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|---|---|---|
| ANR | Programme Chaires d'excellence<br>« Senior Longue Durée » | Réservé à l'organisme gestionnaire du programme<br>N° de dossier : ANR-08-XXXX-00<br>Date de révision : |
| | Document de soumission **B** | **Edition 2008** |

# AIDE A L'ACCUEIL DE CHERCHEURS ET D'ENSEIGNANTS-CHERCHEURS DE HAUT NIVEAU VENANT DE L'ETRANGER

**Les documents de soumission doivent impérativement être envoyés :**

1) **Documents A et B** : par courrier électronique* avant le **vendredi 28 mars 2008 à 12h00** ***(la date d'envoi du courriel faisant foi).***

2) **Document A** : par courrier postal (1 exemplaire original et 2 copies), revêtu des signatures et cachets originaux **pour le mercredi 9 avril 2008 au plus tard** *(cachet de la poste faisant foi)* à l'adresse ci-dessous :

Université de Versailles Saint-Quentin-en-Yvelines
SDRV - Programme Chaires d'Excellence 2008
55, avenue de Paris
78035 VERSAILLES Cedex

*** Procédure pour la soumission électronique**

- envoyer un courriel à **: Exc2008.admin@admin.uvsq.fr**
- le **sujet du mail doit** s'intituler : **Exc2008_SLD_NOMcandidat**
- **le document B doit** être constitué d'un **fichier unique**, joint en **fichier attaché** et **nommé** : **Exc2008_SLD_NOMcandidat** (formats acceptés : .doc, .pdf),
- seuls les dossiers de taille inférieure à 1Mo seront acceptés (de façon à pouvoir être transmis aux experts par voie électronique),
- **joindre également** en fichier attaché le document A de soumission **Exc2008_SLD_NOMcandidat.xls**
- les documents envoyés sous forme électronique n'ont besoin ni de lettre d'accompagnement, ni des visas ou signatures originales mais doivent être identiques dans leur contenu aux documents envoyés par courrier postal.

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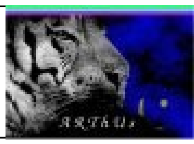
| **Acronyme/*Acronym*** | **a r t h U s**  |
| **Titre du projet/*Proposal title***<br>*(en francais/ in French)* | avances dans la recherche théorique de l'Univers sombre |
| **Titre du projet/*Proposal title***<br>*(en anglais/ in English)* | advances in the research on theories of the dark Universe |

# Sommaire (Contents)

*Les pages seront numérotées et l'acronyme du projet devra figurer sur toutes les pages du document en pied de page.*
*Un sommaire du document est bienvenu*

# 1. Programme scientifique et technique/Description du projet. *Technical and scientific description of the activities.*

*La majeure partie de cette section 1 sera rédigée de préférence en anglais (sauf si l'usage du français s'impose pour le sujet proposé), à l'exception du § 1.1.1.*

## 1.1.Présentation du candidat. *Applicant's presentation (8 pages maximum).*

### 1.1.1.Biographie résumée. *Summed up biography (10 lignes maximum).*

*Fournir une brève notice biographique en français ainsi que sa traduction en anglais.*

Thomas Buchert a travaillé comme chercheur associé au M.P.A. (Max–Planck–Institut Astrophysik), Garching, Allemagne, pendant la période 1984–1995 où il a obtenu son Diplôme de Physique (1984) et son Doctorat de Physique Théorique à l'Université de Munich (L.M.U.) (1988). Pendant la période 1988–1994 il a été postdoc au M.P.A. et a été invité pour des visites à court terme en Europe, par exemple Nordita (Copenhague), à l'Observatoire de Paris (France), et à l'Université de Valence (Espagne), Étant membre (et coord. pour Allemagne) d'un Réseau Européen de Cosmologie (E.C.N.). Sa recherche a été concentrée sur des théories cosmologiques de formation de structure, où le coeur de ce travail a été défini dans un projet de cinq ans du `Schwerpunkt Kosmische Plasmen' de la D.F.G. (Fondation de Recherche Allemande) menant à son degré d'Habilitation (H.D.R.) dans l'Astronomie à L.M.U. (1994). Il a organisé des projets d'échange avec la France et l'Espagne et a été actif dans l'échange entre le M.P.A. et l'Académie Chinoise des Sciences. En 1995 il a obtenu le degré `Privatdozent' (Professeur Libre) à L.M.U. Depuis lors, jusqu'en 2006, il a travaillé comme chercheur associé à L.M.U. et à T.U.M. (Université Technique de Munich), et en tant qu'enseignant (Professeur libre) à L.M.U. Pendant ce temps il a conduit un groupe de recherche à L.M.U. comme représentant de projet du S.F.B.375 (D.F.G.) sur des statistiques morphologiques de structure cosmique. De 1998 jusqu'à présent il a pris plusieurs positions comme professeur visitant à long terme en tant que `Membre Associé du Personnel' au C.E.R.N., Genève, comme `Professeur Visitant de Tomalla' à l'Université de Genève, comme `Professeur C.O.E.' ('Center of Excellence') à l'Observatoire Astronomique National de Tokio (N.A.O.), et en tant que `Professeur Monkasho' à l'Université de Tokio (au Centre de Recherches pour l'Univers Primordial, R.E.S.C.U.E.), à l'Université de Tohoku à Sendai, et à l'Institut de de la Technologie de Tokio (T.I.T.E.C.H.). Pendant 2006 il a pris une Chaire de Physique Théorique à l'Université de Bielefeld, Allemagne, et il a travaillé régulièrement à l'Observatoire de Paris (L.U.T.H.) en tant que Professeur Invité. À partir de septembre 2007 il est membre permanent à l'Observatoire de Lyon, et Professeur à l'Université Claude Bernard Lyon 1. Il est aussi membre du S.D.S.S. (Sloan Digital Sky Survey Groupe).

Thomas Buchert worked as Research Associate at MPA (Max-Planck-Institut Astrophysik), Garching, Germany, in the period 1984-1995 during which he obtained his Master degree and his Ph.D. in Theoretical Physics at Munich University (LMU) (1988). During the period 1988-1994 he took several short-term visiting positions in Europe, e.g. at Nordita, Copenhagen, the Observatory of Paris, and the University of Valencia, being member (and coordinator for Germany) of a European Cosmology Network (E.C.N.). His research was focussed on cosmological structure formation theories, where the heart of this work was defined within a five years project of the DFG (German Science Foundation) `Schwerpunkt Kosmische Plasmen' leading to his Habilitation degree in Astronomy at the LMU (1994). He organized exchange projects with France and Spain and was active in the MPA exchange with the Chinese Academy of Sciences. In 1995 he obtained the degree Privatdozent at LMU. Since then until 2006 he worked as Research Associate at LMU and TUM (Technical University Munich), and as a Lecturer at LMU. During that time he conducted a research group at the LMU as Project Representative of the SFB 375 on morphological statistics of cosmic structure. From 1998 until now he took several long-term visiting positions as `Associated Member of Personnel' at CERN, Geneva, as `Tomalla Visiting Professor' at the University of Geneva, as `COE Researcher' at the National Astronomical Observatory in Tokyo, and as `Monkasho Invited Professor' at the University of Tokyo (R.E.S.C.U.E.: Research Center for the Early Universe), during which he also worked as Visiting Professor at Tohoku University in Sendai, and the Tokyo Institute of Technology (T.I.T.E.C.H.). During the summer term 2006 he took a Chair position in Theoretical Physics at the University of Bielefeld, and he worked regularly at the Observatory of Paris as Invited Professor. From September 2007 he is Staff Member at the Observatory of Lyon, and Professor at the University Claude Bernard Lyon 1. He is also member of the S.D.S.S. (Sloan Digital Sky Survey Group).

### 1.1.2. Présentation détaillée. *Detailed presentation.*

*Fournir un CV et une notice de titres et travaux synthétique.* ***1: CURRICULUM VITAE SUCCINT (EN FRANCAIS)***
***2: CURRICULUM VITAE LONG (EN ANGLAIS)***

# *Curriculum Vitae Succinct*

## *— Thomas Buchert*

## Information personnelle

*Date/Lieu de Naissance :* 18.08.1959, VS–Schwenningen, Allemagne
*Web / Email :* www.cosmunix.de / buchert@obs.univ-lyon1.fr

## Education

*1966–1978 :* Ecole primaire et lycée : Villingen–Schwenningen, Allemagne
*1978–1984 :* Etudes de Physique Théorique : Ludwig–Maximilians–Universität (L.M.U.), Munich, Allemagne
*1983–1984 :* Thèse ('Diplôme allemand') : Max–Planck–Institut f. Astrophysik (M.P.A.), Garching, Allemagne
*Octobre 26., 1984 :* Diplôme allemand : Physique Théorique (Dipl.–Phys.) : L.M.U., Munich, Allemagne
*1984–1988 :* Thèse de Doktorat : M.P.A., Garching, Allemagne
*Juillet 14., 1988 :* Doktorat : Physique Théorique (Dr.rer.nat.) : L.M.U., Munich, Allemagne
*1989–1993 :* Thèse de Doktorat pour l'Habilitation : M.P.A., Garching, Allemagne
*Juillet 13., 1994 :* Doktorat (Habilitation) : Astronomie (Dr.rer.nat.habil.) (H.D.R.) : L.M.U., Munich, Allemagne
*Juillet 18., 1995 :* Professeur libre (PRU libre) (Priv.–Doz.) : L.M.U., Munich, Allemagne

## Positions

*1984–1995 :* Chercheur Associé: M.P.A., Garching, Alllemagne
*1995–1997 :* Chercheur Associé et PRU libre : L.M.U., Allemagne
*1997–1998 :* Chercheur Associé: Technische Universität München (T.U.M.) et PRU libre (L.M.U.), Allemagne
*1998–1999 :* Membre Associé: C.E.R.N., Genève, Suisse
*1999–2000 :* C.O.E. ('Center of Excellence') Professeur Visitant, National Astron. Observatory, Tokio, Japon
*2001–2006* : Chercheur Associé: T.U.M. et PRU libre (L.M.U.), Allemagne
*2006* : Chaire de Physique Théorique (PRU), Université de Bielefeld, Allemagne
*2007* : Professeur de l'Université Lyon 1 Claude Bernard, Lyon

## Positions Visitantes

*1988 :* Chercheur Visitant : N.O.R.D.I.T.A., Copenhague, Danemark
*1989–1994 :* Chercheur Visitant : Observatoire de Paris, D.A.E.C., et I.A.P., Paris, France
*1994 :* Chercheur Visitant : Aspen Center for Physics, Etats-Unis
*1997 :* Professeur Visitant : Université de Osaka, et Tohoku Université de Sendai, Japon
*1997 :* Professeur Visitant : Université de Kansas, Lawrence, Etats-Unis
*1999 /2000 :* Tomalla Professeur : Université de Genève, Suisse
*1999–2000 :* Professeur Visitant *:* Tohoku Université de Sendai, Japon
*2000 :* Professeur Visitant : Tokyo Institute of Technology, Japon
*2000–2007 :* Professeur Visitant : Université de Pavia, Italie

*2001 :* J.S.P.S. Invited Fellow : Tokyo Institute of Technology, Japon
*2002–2003 :* Monkasho Invited Professor : The University of Tokyo, R.E.S.C.E.U., Tokio, Japon
*2003 :* Professeur Visitant : Observatoire de Nice, France
*2004 :* Professeur Visitant : Tohoku Université de Sendai, Japon
*2004/2005 :* Professeur Visitant : C.P.T., Marseille, France
*2005 :* Professeur Visitant : Observatoire de Paris, L.U.T.H., France
*2006 :* Professeur Visitant : Dept. of Math. and Appl. Math., Cape Town, Afrique du Sud
*2007 :* Professeur Visitant : Observatoire de Paris, L.U.T.H., France
*2007 :* Professeur Visitant : Université Paris 7, France

## Enseignement

*1990 :* Séminaire (Structures aux Grandes Echelles et Formation de Galaxie), L.M.U., Allemagne
*1993 :* Cours expérimental de Physique, L.M.U., Allemagne
*1993 :* Ecole de Physique (Evolution des Galaxies), Bad Honnef, Allemagne
*1994 :* Séminaire (Cosmologie Newtonienne et Statistiques), L.M.U., Allemagne
*1995 :* Ecole pour les professeurs de l'école (Cosmologie), Bad Honnef, Allemagne
*1995 :* Ecole Enrico Fermi (Matière Sombre), Varenna, Italie
*1996–1997 :* Cours (Cosmologie I et II), L.M.U., Allemagne
*1997–1998 :* Cours (Théorie Cinétique), L.M.U., Allemagne
*1998 :* Cours (Mécanique Théorique TLI), L.M.U., Allemagne
*2001–2002 :* Cours (Théorie Cinétique), L.M.U., Allemagne
*2003 :* Cours (Gravitation Newtonienne), L.M.U., Allemagne
*2003–2004 :* Cours (Formation des Structures), L.M.U., Allemagne
*2004 :* VII. Ecole de Cosmologie, Marseille, France
*2004–2005 :* Cours (Cosmologie Newtonienne et Relativiste), L.M.U., Allemagne
*2005–2006 :* Cours (Cosmologie et Relativité Générale), L.M.U., Allemagne
*2006 :* Cours, International Graduate School (Théories de la Gravitation de Newton & Einstein), Université de Bielefeld, Allemagne
en association avec Univ. de Paris 6, Paris 7, Paris–Sud 11, Saclay, France
*2006 :* XIIth. Brazilian School of Cosmology & Gravitation, Rio de Janeiro, Brésil
*2006 :* Cours (Le Sujet de 'Backreaction' en Cosmologie Relativiste), Université de Cape Town, Afrique du Sud
*2007–2008 :* Cours Master 1 (Introduction aux Théories de la Gravitation), Ecole Normale Supérieure de Lyon, France
*2008 :* Cours Doctoral (Moyenne spatiale des équations d'Einstein et le problème de l'énergie noire en cosmologie), Ecole Normale Supérieure de Lyon, France
*2008 :* Travaux Dirigés, Agrégation Physique, Ecole Normale Supérieure de Lyon, France
*2008 :* Travaux Pratiques, Thermodynamique L1, Université Lyon 1, France

## Direction de Thèse

Dirigé et Co–dirigé :
11 Etudiants en thèse : Diplôme allemand, 1 an ;
1 Etudiante en thèse : Prof. de l'école, 1 an ;
10 Etudiants en thèse de doktorat, 3 ans, (un en cours).

*Récemment: 2 stagiaires de Master 2, et 1stagiaire de Master 1.*

## Accomplissements de recherches

Thomas Buchert est connu par la plupart des chercheurs en cosmologie principalement pour trois travaux originaux que sont :

1. la théorie Lagrangienne de formation des structures,
2. l'introduction des Fonctionnelles de Minkowski pour la morphométrie des structures cosmiques, et
3. Les modèles cosmologiques et le problème de lissage des distributions non–homogènes en relation avec le problème de l'Energie Noire.

Il a donné plus de 70 séminaires invités en Allemagne, en Autriche, en Suisse, en France, en Espagne, en Italie, au Danmark, en Angleterre, aux Pays Bas, aux Etats Unis, en Chine, au Japon, au Brésil et en Afrique du Sud.
Il a organisé des conférences et des ateliers internationaux.
Il est régulièrement lecteur (referee) pour un grand nombre de journaux, des fondations de recherche et de rédacteurs internationaux de livre.

## Direction de Projets et Service Professionnel

Investigateur principal : S.F.B. 375 (Recherche de Physique d'Astroparticule)
Collaborateur externe : SDSS (Sloan Digital Sky Survey)
Organisateur : Conférences, Ecoles
Evaluations régulières : journaux, livres, organismes scientifiques

## Financements :

Thomas Buchert a formé et financé un groupe sur la morphologie statistique à partir d'avril 1995 jusq'à 2006, qui comprenait typiquement, en permanence, 1-2 postdocs et 1 étudiant en thèse. Il a participé activement aux demandes de financement pour des étudiants et des postdocs pendant les 18 dernières années. Cela a commencé par des projets d'échanges avec la France et l'Espagne, et a continué avec le « Sonderforschungsbereich 375 » (un projet de longue durée entre plusieurs instituts et universités) pour la Physique des Astroparticules, qu'il a aidé à constituer et a reçu des financements pour des postdocs et des étudiants en thèse depuis 1995. Il a également reçu d'autres financements de la D.F.G. (Fondation de Recherche Allemande), et il a organisé un certain nombre de positions de postdoc à l'étranger pour ses étudiants.

## Bourses et Projets d'Echange pour les Etudiants

*1991–1993 :* Programme d'Echange : Max–Planck–Society et Chinese Academy of Sciences, M.P.G.–C.A.S.
*1995–1997 :* Bourse d'échange pour les étudiants : La France (D.A.A.D.)
*1996 :* Bourse d'échange pour les étudiants : l'Espagne (Acciones Integradas)
*1995–1998 :* Coordonnateur pour Munich : E.C.N. (European Cosmology Network)
*1995–1997 :* S.F.B. 375 : Bourses pour 1 Etudiant en thèse de doctorat et 1 Postdoctorant
*1998–2000 :* S.F.B. 375 : Bourses pour 1 Etudiant en thèse de doctorat et 2 Postdoctorants
*1999–2002 :* D.F.G. : Bourse pour 1 Etudiant en thèse de doctorat
*2001–2003 :* S.F.B. 375 : Bourses pour 2 Postdoctorants
*2004–2006 :* S.F.B. 375 : Bourses pour 1 Etudiant en thèse de doctorat et 1 Postdoctorant

*Veuillez, s.v.p., consulter le CV long pour plus de détails*

# Curriculum Vitae

## — Thomas Buchert

### Personal Information

| | |
|---|---|
| *Birth :* | August 18th, 1959, in Germany |
| *Other Languages :* | Fluent in English and French (spoken and written) |
| *Profession :* | Professor at Université Claude Bernard, Lyon, France |
| *Memberships :* | Staff member at the Observatory of Lyon, C.R.A.L., Lyon, France |
| | S.D.S.S. Collaboration |
| *Coordinates :* | www.cosmunix.de |
| *Email :* | buchert@obs.univ-lyon1.fr |

### Education/Career

| | |
|---|---|
| *1966–1978 :* | Primary and High–School in Villingen–Schwenningen |
| *1978–1984 :* | Studies of Theoretical Physics at Ludwig–Maximilians–Universität (L.M.U.), Munich |
| *1983–1984 :* | Diploma thesis at Max–Planck–Institut f. Astrophysik (M.P.A.) in Garching |
| *Oct. 26th, 1984 :* | Diploma in Theoretical Physics (Dipl.–Phys.) |
| *1984–1988 :* | Ph.D. thesis at M.P.A. in Garching |
| *July 14th, 1988 :* | Ph.D. in Theoretical Physics (Dr.rer.nat.) |
| | Thesis topic : *'The Pancake Theory of Formation of Supergalactic Structures – Analytical Foundations'* ; Thesis advisors : Prof. G. Börner and Prof. J. Ehlers |
| *1989–1993 :* | Habilitation thesis at M.P.A. in Garching |
| *July 13th, 1994 :* | Ph.D. in Astronomy – Habilitation – (Dr.rer.nat.habil.) |
| *July 18th, 1995 :* | Lecturer Degree (Priv.–Doz.) at L.M.U. in Munich |
| | Thesis topic : *'Inhomogeneous Newtonian Cosmogony'* |
| *2005 :* | Qualification as University–Professor in France |
| *Sept. 1st, 2007 :* | Titularisation as University–Professor in France |

### Positions

| | |
|---|---|
| *1984–1995 :* | Research Associate at M.P.A. Garching, Germany |
| *1995–1997 :* | Research Associate at L.M.U. Munich,Germany |
| *1997–1998 :* | Research Associate at T.U.M. Garching, Germany |
| *1998–1999 :* | Assoc. Member of Personnel at C.E.R.N. Geneva, Switzerland |
| *1999–2000 :* | C.O.E. Researcher at National Astronomical Observatory, Tokyo, Japan |
| *2001–2006 :* | Research Associate at T.U.M. Garching, Germany |
| *SSem 2006 :* | Chair of Theoretical Physics, University of Bielefeld, Germany |
| *Since 1995 :* | Privat–Dozent at L.M.U. Munich, Germany |
| *Since 2007 :* | Professor at Université Lyon 1 'Claude Bernard', Lyon, France |

### Visiting Positions

| | |
|---|---|
| *1988 :* | Visiting Researcher at N.O.R.D.I.T.A., Copenhagen, Denmark |
| *1989–1994 :* | Visiting Researcher at Observatory of Paris, D.A.E.C., and I.A.P., Paris, France |
| *1994 :* | Guest Scientist at the Aspen Center for Physics, U.S.A. |
| *1997 :* | Visiting Professor at University of Osaka, and Tohoku University Sendai, Japan |
| *1997 :* | Visiting Professor at Kansas University, Lawrence, U.S.A. |
| *1999/2000 :* | Tomalla Visiting Professor at University of Geneva, Switzerland |

*1999–2000 :* Visiting Professor at Tohoku University Sendai, Japan
*2000 :* Visiting Professor at Tokyo Institute of Technology, Japan
*2000–2007 :* Visiting Professor at University of Pavia, Italy
*2001 :* J.S.P.S. Invited Fellow at Tokyo Institute of Technology, Japan
*2002–2003 :* Monkasho Invited Professor at The University of Tokyo, R.E.S.C.E.U., Tokyo, Japan
*2003 :* Visiting Professor at Observatory of Nice, France
*2004 :* Visiting Professor at Tohoku University Sendai, Japan
*2004/2005 :* Visiting Professor at C.P.T. Marseille, France
*2005 :* Visiting Professor at Observatory of Paris, L.U.T.H., France
*2006 :* Visiting Professor at Dept. of Appl. Math., Cape Town, South Africa
*2007 :* Visiting Professor at Observatory of Paris, L.U.T.H., France
*2007 :* Visiting Professor at Paris University 7, France

### Shortlisted/Interview for the following Positions :

*1995 :* Associate Professor at L.M.U. Munich, Germany
*1995 :* Permanent Research Position at M.P.A. Garching, Germany
*2000 :* Associate Professor at L.M.U. Munich, Germany
*2001 :* Associate Professor at Würzburg University, Germany
*2002 :* Reader at Portsmouth University, U.K.
*2003 :* Full Professor at Lancaster University, U.K.
*2005 :* Associate Professor at T.U.M. Garching, Germany
*2006 :* Scientific Coordinator, I.M.P.R.S. School, Max–Planck–Institut f. Physik, Germany
*2007 :* Full Professor at Université Claude Bernard, Lyon, France**
*2007 :* Full Professor at Ecole Normale Supérieure, Lyon, France
* offered ** offered and accepted

## Awards and Grants

*1978 :* Scheffel Award by German Literature Society
*1988–1994 :* 'Schwerpunkt'–Grant by Deutsche Forschungsgemeinschaft (D.F.G.)
*1995–2006 :* Project Representative 'Sonderforschungsbereich S.F.B. 375' :
(Research grants in Astro–Particle physics)
*1998 :* Associate Membership at C.E.R.N. Geneva, Switzerland
*1999 :* Tomalla Foundation, Switzerland
*1999–2000 :* Center of Excellence Grant, National Astronomical Observatory Tokyo, Japan
*2000 :* Tomalla Foundation, Switzerland
*2001 :* J.S.P.S. Invitation Fellowship, Japan
*2002–2003 :* Monkasho Award, The University of Tokyo, Japan

## Teaching

*1990 :* Seminar (Large–scale Structure and Galaxy Formation), L.M.U. (in German)
*1993 :* Experimental Physics Tutorial (Advanced Lab. Course), L.M.U. (in German)
*1993 :* Lector : Physics School (The Evolution of Galaxies), Bad Honnef (in English)
*1994 :* Seminar (Newtonian Cosmology and Statistics), L.M.U. (in German)
*1995 :* Lector : School for Teachers (Cosmology), Bad Honnef (in English)
*1995 :* Lector : Enrico Fermi School (Dark Matter), Varenna, Italy (in English)
*1996–1997 :* Lecture Courses (Cosmology I and II), L.M.U. (in German)
*1997–1998 :* Lecture Course (Kinetic Theory), L.M.U. (in German)
*1998:* Lecture Course (Theoretical Mechanics TLI), L.M.U. (in German)
*2001–2002 :* Lecture Course (Kinetic Theory), L.M.U. (in German)
*2003 :* Lecture Course (Newtonian Gravity), L.M.U. (in German)
*2003–2004 :* Lecture Course (Structure Formation), L.M.U. (in German)
*2004 :* Lector : VII. Ecole de Cosmologie, Marseille, France (in French)

*2004–2005 :* Lecture Course (Newtonian & Relativistic Cosmology), L.M.U. (in German)
*2005–2006 :* Lecture Course (General–relativistic Cosmology), L.M.U. (in German)
*2006 :* Lecture Course, International Graduate School (Newton's & Einstein's gravitation theories of continuous media), University of Bielefeld , Germany (in German) in association with Univ. of Paris 6, Paris 7, Paris–Sud 11, Saclay, France
*2006 :* Lector : XIIth. Brazilian School of Cosmology & Gravitation, Rio de Janeiro, Brazil (in English)
*2006 :* Lecture Series (Backreaction Issues in Relativistic Cosmology), University of Cape Town, South Africa (in English)
*2007–2008 :* Lecture Course (Introduction to Theories of Gravitation), Master 1, Ecole Normale Supérieure de Lyon, France (in French)
*2008 :* Doctoral Course (The Averaging Problem in General Relativity and Dark Energy), Ecole Normale Supérieure de Lyon, France (in French)
*2008 :* \`Agrégation Physique', Ecole Normale Supérieure de Lyon, France (in French)
*2008 :* Laboratory Course (Thermodynamics), University Lyon 1, France (in French)

## Supervising

Supervised and Co–supervised :
11 Diploma students (1 year),
1 Teacher Exam student (1 year),
10 Ph.D. Students (3 years) (one ongoing).

## Fund Raising and Exchange Programs

*1991–1993 :* Exchange Program of Max–Planck–Society and Chinese Academy of Sciences, M.P.G.–C.A.S.
*1995–1997 :* Student exchange grants for France (D.A.A.D.)
*1996 :* Student exchange grant for Spain (Acciones Integradas)
*1995–1998 :* Coordinator for Munich : E.C.N. Cosmology (planning phase)
*1995–1997 :* S.F.B. 375 (Research in Astro–Particle physics) : Grants for 1 Ph.D. student and 1 postdoc
*1998–2000 :* S.F.B. 375 (Research in Astro–Particle physics) : Grants for 1 Ph.D. student and 2 postdocs
*1999–2002 :* D.F.G. grant for Ph.D. student
*2001–2003 :* S.F.B. 375 (Research in Astro–Particle physics) : Grants for 2 postdocs
*2004–2006 :* S.F.B. 375 (Research in Astro–Particle physics) : Grants for 1 Ph.D. student and 1 postdoc

## Workshop Organization

*1989 :* M.P.A. Progress Report on *Cosmology and Gravitational Lensing*
*1993 :* 4th M.P.G.–C.A.S. Workshop on *High–energy Astrophysics*
*1996 :* 2nd S.F.B. Workshop on *Astro–particle Physics*
*2005 :* Spacetime in Action : *One hundred years of Relativity*, University of Pavia, Italy
*2007 :* Cosmology School and Workshop, Cargèse, France
*2008 :* 2nd C.R.A.L./I.P.N.L. Conference on *Dark Energy and Dark Matter*, Lyon, France
*2009 :* U.N.E.S.C.O. Conference on *The Invisible Universe*, Paris, France

## Refereeing

Regular scientific refereeing for International Journals, e.g. *Astron. & Astrophys.*, *New Astronomy*, *Mon. Not. Roy. Astr. Soc.*, *The Astrophys. J.*, *Phys. Rev. D*, *Phys. Lett. A, B*, *Gen. Rel. Grav.*, *Class. Quant. Grav.*, *Annalen der Physik*, *Physica Scripta A*, as well as for Student Fund Organizations (e.g. *DFG* ; *Studienstiftung*) and for Books, e.g. *Cambridge Univ. Press*.

## Selected Invited Talks and Colloquia

*Not included in this list : Talks at 'local' institutes (Max–Planck–Institut f. Astrophysik, Max–Planck–Institute f. Extraterrestrische Physik, Max–Planck–Institut f. Physik, European Southern Observatory, Ringberg Castle and Bad Honnef) and local universities (Ludwig–Maximilians–U., Technical U. and Astronomical Institute) in Munich/Garching.*

*1984 :* Z.I.F., Bielefeld, Germany
*1988 :* N.O.R.D.I.T.A., Copenhagen, Denmark
*1989 :* Perugia, Italy
*1989 :* Amsterdam and Leiden, The Netherlands
*1989 :* Highlight–Lecture of the Astronomical Society, Graz, Austria
*1990 :* Max–Planck–Institute for Astronomy, Heidelberg, Germany
*1990 :* Huangshan, PR China
*1990 :* University of Valencia, Spain
*1990 :* Observatoire de Paris, D.A.E.C., France
*1991 :* University of Valencia, Spain
*1991 :* Observatoire de Meudon, D.A.E.C., France
*1993 :* Niels–Bohr–Institute, Copenhagen, Denmark
*1994 :* Aspen, Colorado, U.S.A.
*1994 :* Observatoire de Paris, D.A.E.C., France
*1994 :* Nandaihe, PR China
*1994 :* Geltow, Potsdam, Germany
*1995 :* Int. School Enrico Fermi, Varenna, Italy
*1995 :* Observatoire de Paris, D.A.E.C., France
*1995 :* University of Valencia, Spain
*1995 :* Berlin Dahlem, Germany
*1996 :* E.T.H., Zurich, Switzerland
*1996 :* L.A.E.F.F., Madrid, Spain
*1997 :* Lawrence, Kansas, U.S.A.
*1997 :* Osaka University, Japan
*1997 :* Tohoku University Sendai, Japan
*1998 :* University of Essen, Germany
*1998 :* Shanghai Observatory, PR China
*1999 :* C.E.R.N., Geneva, Switzerland
*1999 :* University of Geneva, Switzerland
*1999 :* National Astronomical Observatory, Tokyo, Japan
*1999 :* Tohoku University Sendai, Japan
*1999 :* Hiroshima, Japan
*2000 :* University of Geneva, Switzerland
*2000 :* Tohoku University Sendai, Japan
*2000 :* Tokyo Institute of Technology, Japan
*2000 :* R.E.S.C.E.U., The University of Tokyo, Japan
*2001 :* University of Pavia, Italy
*2001 :* C.N.R.S., Institut Henri Poincaré, Paris, France
*2001 :* University of Würzburg, Germany
*2001 :* Tokyo Institute of Technology, Japan
*2001 :* R.E.S.C.E.U., The University of Tokyo, Japan
*2002 :* Waseda University, Tokyo, Japan
*2002 :* University of Portsmouth, U.K.
*2002 :* Tokyo Institute of Technology, Japan
*2002 :* R.E.S.C.E.U., The University of Tokyo, Japan
*2002 :* University of Pavia, Italy
*2003 :* Observatoire de la Côte d'Azur, Nice, France
*2003 :* University of Lancaster, U.K.
*2003 :* Tokyo Institute of Technology, Japan
*2004 :* 21st C.O.E. Symposium, Tohoku University Sendai, Japan
*2004 :* Tohoku University Sendai, Japan
*2004 :* C.I.R.M. and C.P.T., Marseille, France
*2004 :* University of Pavia, Italy
*2005 :* C.N.R.S., Observatoire de Paris, France
*2005 :* Observatoire de Paris, L.U.T.H., France
*2005 :* C.I.R.M., Marseille, France
*2005 :* University of Geneva, Switzerland
*2005 :* Observatoire de Paris, L.U.T.H., France
*2006 :* R.W.T.H., University of Aachen, Germany
*2006 :* C.N.R.S., I.A.P. Paris, France
*2006 :* University of Bielefeld, Germany
*2006 :* XII. B.S.C.G., Rio de Janeiro, Brazil
*2006 :* Dept. of Appl. Math., Cape Town, South Africa
*2007 :* Spinoza Institute, University of Utrecht, The Netherlands
*2007 :* Observatoire de Paris, L.U.T.H., France
*2007 :* Observatoire de Lyon, C.R.A.L., France
*2007 :* C.N.R.S., Observatoire de Paris, France
*2007 :* Université Claude Bernard, Lyon, France
*2007 :* Albert Einstein Institute, Golm, Germany
*2007 :* University of Pavia, Italy
*2007 :* Dark Energy Workshop, Montpellier, France
2007: University of Ulm, Germany

### 1.1.3. Liste des publications. *List of publications.*

*Fournir une liste de « publications choisies » du candidat destinée à éclairer le comité d'évaluation ; préciser le mode de sélection retenu pour établir cette liste ; les publications les plus significatives feront l'objet d'une référence complète avec le titre de l'article, son nombre de pages et éventuellement son facteur d'impact ; indiquer également le nombre total de publications dans les revues avec comité de lecture.*

***Nombre Total de publications dans les revues avec comité de lecture: 52***

***Autres publicatons: 47 (invited papers) / 13 (editorial work)***

### Les « publications choisies »:

(Criteria are explained at the beginning of each paragraph, i.e. their relevance to the project listed below is emphasized.)

**: ADS cites > 100 / *: ADS cites > 50. Total ADS cites: 1700 Total ADS cites/author: 1000

**Publications that concern the construction of Lagrangian models for inhomogeneities in the Newtonian context, providing the relevant basis for ARTHUS, Research Line I:**

A class of solutions in Newtonian cosmology and the pancake theory, **
T. Buchert, *Astron. Astrophys*. **223**, 9-24 **(1989)**

Lagrangian theory of gravitational instability of Friedmann-Lemaître cosmologies and the `Zel'dovich approximation,**
T. Buchert, *M.N.R.A.S.* **254**, 729-737 **(1992)**

Lagrangian theory of gravitational instability of Friedmann-Lemaître cosmologies - second-order approach: an improved model for nonlinear clustering,*
T. Buchert and J. Ehlers, *M.N.R.A.S.* ***264***, 375-387 **(1993)**

Lagrangian theory of gravitational instability of Friedmann-Lemaître cosmologies - a generic third-order model for nonlinear clustering,*
T. Buchert, *M.N.R.A.S.* ***267***, 811-820 **(1994)**

*Newtonian cosmology in Lagrangian formulation: foundations and perturbation theory,*
J. Ehlers and T. Buchert, *G.R.G*. **29,** 733-764 **(1997)**

*Modeling multi-stream flow in collisionless matter: approximations for large-scale structure beyond shell-crossing,*
T. Buchert and A. Dominguez, *Astron. Astrophys.* **335**, 395-402 **(1998)**

*Adhesive gravitational clustering,*
T. Buchert and A. Dominguez, *Astron. Astrophys.* **438**, 443-460 **(2005)**

**Publications that concern the statistical and morphological analysis of inhomogeneities, providing the relevant basis for ARTHUS, Research Line II:**

Robust morphological measures for large-scale structure in the Universe,**
K.R. Mecke, T. Buchert and H. Wagner, *Astron. Astrophys*. **288**, 697-704 **(1994)**

*Beyond genus statistics: a unifying approach to the morphology of cosmic structure*,*
J. Schmalzing and T. Buchert, *The Astrophysical Journal* **482**, L1-L4 **(1997)**

*Morphometry of spatial patterns,*
C. Beisbart, T. Buchert and H. Wagner, *Physica A* **293**, 592-604 **(2001)**

*Minkowski Functionals of SDSS galaxies I: Analysis of Excursion Sets,*
Hikage, J. Schmalzing, T. Buchert, Y. Suto, I. Kayo, A. Taruya, M.S. Vogeley, F. Hoyle, J.R. Gott III and J. Brinkmann, *PASJ* **55,** 911-931 **(2003)**

**Publications that concern the basic averaging equations that are employed in the whole project:**

Averaging inhomogeneous Newtonian cosmologies,*
T. Buchert and J. Ehlers, *Astron. Astrophys*. **320**, 1-7 **(1997)**

*On average properties of inhomogeneous fluids in general relativity: dust cosmologies,**
T. Buchert, *G.R.G.* **32**, 105-125 **(2000)**

*Backreaction of inhomogeneities on the expansion: the evolution of cosmological parameters,*
T. Buchert, M. Kerscher and C. Sicka, *Phys. Rev. D* **62,** 043525-1-21 **(2000)**

*On average properties of inhomogeneous fluids in general relativity: perfect fluid cosmologies,**
T. Buchert, *G.R.G.* **33,** 1381-1405 **(2001)**

**Publications that concern extensions of the averaging framework related to exact solutions of the averaging equations, and the geometrical analysis of spatial sections of the Universe, relevant for ARTHUS, Sub-Lines i and ii:**

*Regional averaging and scaling in relativistic cosmology,*
T. Buchert and M. Carfora, *Class. Quant. Grav.* **19**, 6109-6145 **(2002)**

*Cosmological parameters are dressed,*
T. Buchert and M. Carfora, *Phys. Rev. Lett.* **90**, 031101-1-4 **(2003)**

*Information entropy in cosmology,*
A. Hosoya, T. Buchert and M. Morita, *Phys. Rev. Lett.* **92**, 141302-1-4 **(2004)**

*On globally static and stationary cosmologies with or without a cosmological constant and the Dark Energy problem,*
T. Buchert, *Class. Quant. Grav.* **23**, 817-844 **(2006)**

*Correspondence between kinematical backreaction and scalar field cosmologies – the `morphon field',*
T. Buchert, J. Larena and J.-M. Alimi, *Class. Quant. Grav.* **23**, 6379-6408 **(2006)**

Dark Energy from structure - a status report,
T. Buchert, (Invited Review for special issue on Dark Energy), *G.R.G.* **40**, 467-527 **(2008)**

## 1.2. Problème posé. *Rationale (1/2 page maximum).*

*Présentation générale du problème qu'il est proposé de traiter dans le projet et du cadre de travail.*

### The Dark Energy problem and a new strategy to resolve it

In the standard model of cosmology one has to conjecture the existence of two constituents, if observational constraints are met, that both have yet unknown origin :
first, a dominant repulsive component is thought to exist that can be modeled either by a positive cosmological constant or a scalar field, e.g. a so–called *quintessence field*. The physical nature of this component, dubbed *Dark Energy*, is yet unkown.
There is, secondly, a non–baryonic component that should considerably exceed the contribution by luminous and dark baryons and massive neutrinos. This component, dubbed *Dark Matter,* is thought to be provided by exotic forms of matter, not yet detected in (non–gravitational) experiments.
According to the *concordance model* of standard cosmology [75], [5, 115], the contribution of the former converges to about 3/4 and that for the latter to about 1/4 of the total source of the standard cosmological equations (*Friedmann's equations*), up to a few percent that have to be attributed to baryonic matter, radiation and neutrinos. Given the framework of the standard model, most of the researchers support the parameter values of this concordance cosmology. There are, however, other voices [14, 13].

In the present project we shall investigate whether the *effect of inhomogeneities in the Universe* could explain the missing dark components in the standard model. We shall focus on the *Dark Energy* problem, but there are also relations to the *Dark Matter* problem, since both may be (partially or fully) understood on the grounds of the same effect that we are going to study in this project.
Effective terms, in addition to the standard sources of Friedmann's equations, arise through *spatial averaging* of inhomogeneous cosmological models. It has been demonstrated that these additional terms can play the role of *Dark Energy* on large scales, but they can also mimic a kinematical *Dark Matter* on intermediate scales (scales of current galaxy surveys) and smaller scales. The effect leading to this behavior will be described in detail below. Its underlying rationale is that kinematical fluctuations in the Universe *generically couple* to spatially averaged intrinsic properties of space, such as its averaged scalar curvature, thus changing the *global evolution history* of the effective (spatially averaged) cosmological model. At present, we understand this effect *qualitatively*, and this project is directed towards a *quantitative* evaluation of the effect.

## 1.3. Contexte et enjeux du projet. *Background, state of the art, issues and hypothesis (1 à 5 pages maximum).*

*Décrire* ***le contexte et les enjeux scientifiques*** *dans lequel se situe le projet en présentant un* ***état de l'art national et international*** *en incluant les références nécessaires.*

### The averaging problem in relativistic cosmology and the proposed solution

The standard model of cosmology does not, like the standard model of particle physics, enjoy appreciable generality ; it is based on the simplest conceivable class of (homogeneous–isotropic) solutions of Einstein's laws of gravitation. It is clear that the inhomogeneous properties of the Universe cannot be described by such a strong *idealization*. The key–issue is whether they can

be described so *on average*, and this is the subject of considerable debate and controversy, especially in the recent literature, and it will be in the focus of the present project.
Thus, the *key–question* is : does an inhomogeneous model of the Universe evolve on average like a homogeneous solution of Einstein's or Newton's laws of gravitation ? This question is not new to researchers in general relativity, who think that the answer is certainly, in general, *no*, not only in view of the nonlinearity of the theories mentioned [50], [52]. The problem was and still is the notion of averaging whose specification and unambiguous definition turned out to be an endeavor of high magnitude, mainly because it is not straightforward to give a unique meaning to the averaging of tensors, e.g., a given metric of spacetime. It was George Ellis [50], who first brought the subject into the fore, and there have been a number of efforts since then, directed to resolve the averaging problem (references may be found in [52]). It was only recently that a larger community recognized the averaging problem as being crucial for a realistic description of the Universe, thanks to the *Dark Energy* debate.

The reason why many researchers realized the potential solution to explain *Dark Energy* (and eventually also *Dark Matter*) as being *partially or fully* an effect of structure formation in the Universe was a transparent framework of averaged cosmological equations that has been provided by the P.I. of this project in 2000 and 2001 [23, 25]. This new framework gives a partial but exact solution of the averaging problem by restricting attention to scalar quantities (such as the cosmological parameters). Since 2005, a strongly growing number of international research groups employs this framework (references will be given below) that allows to access the average properties of the Universe without entering the full geometrical averaging problem, (for a recent review, see [29]). Besides this framework, the P.I. of this project also works on the full geometrical problem, and, based on these more general insights, we shall in this project also aim at constructing generalizations of this commonly employed framework. However, the main research lines described below will focus on applications of the existing framework.

As indicated above, *earlier work* on the averaging problem was pursued by general relativity groups, here mainly in the Department of Applied Mathematics in Cape Town University, South Africa (around George Ellis). Reseachers in Japan (Futamase), Russia (Zalaletdinov), and Poland (Krasínski) were among the first to join discussions of this problem and do some detailed calculations, also highlighting that the problem is essential for cosmology.
The *revival* of this question, around 2005, mainly advocated by Edward Kolb, Sabino Matarrese and Toni Riotto, took the focus on the *Dark Energy* problem. They have combined a perturbation analysis of inhomogeneities with the general averaging framework proposed in 2000 and 2001 [23, 25].
Thereafter, the point of view that *Dark Energy* may emerge from inhomogeneities became popular in the international community, as will described more in detail below.

## The state-of-the-art

Contemporary research to uncover the enigmas *Dark Energy* and *Dark Matter* of the standard model pursues essentially two directions : one focusses on generalizations of the geometry of spacetime mostly restricting attention to modifications of the underlying theory of gravitation, the other invokes new sources in the energy momentum tensor and so implies a challenge for particle physics. As for the former, a *Dark Energy* component may possibly derive either from higher–order Ricci curvature Lagrangians [39], [48], or string–motivated low–energy effective actions [15]. As for the latter, a *fundamental scalar field* describing an exotic fluid is thought to exist, and studied on a phenomenological basis (see, e.g. the reviews [111], [102], [119], [47], [109]).

The word 'exotic' refers to the fact that such a fluid has to violate standard properties of a fluid (energy conditions), if observational data are met. It should be emphasized that these two research directions are pursued by a large number and the majority of researchers in the international community.

The present project is based on a third new research direction that aims at understanding and resolving the *Dark Energy* problem on the basis of a *more realistic description* of the Universe, i.e. it remains within general relativity, and it does not assume new sources in the energy–momentum tensor. It simply questions the priors of the standard model, namely the conjecture that the average properties of the Universe can be described by a homogeneous solution of Einstein's laws of gravitation.

We shall also address the first of the above–mentioned research directions with the aim of understanding the differences between terms that arise from a more general theory of gravitation with those that may simply result from the effect of inhomogenetities in classical general relativity.

This new research subject is involved : while the first research direction mentioned above extracts cosmological information by also employing strong symmetry assumptions within a more general theory of gravitation, yielding generalized cosmological equations with additional homogeneous sources, and while the second works entirely within homogeneous cosmology, research that takes into account inhomogeneities has to deal with the full generality of Einstein's equations. While *Dark Energy* is modeled by a fundamental homogeneous scalar field or by effective homogeneous terms, either stemming from higher–order gravity terms, or effective terms as remnants from higher dimensions that are compactified or even non–compactified as in « braneworld cosmologies » [83], here potentially *Dark Energy* emerges from inhomogeneities and, as has recently been shown within the collaboration CRAL/LUTH, can be also modeled by an *effective scalar field* – the *morphon* [36]. This field is not phenomenological, but its parameters are fully determined by initial data for the inhomogeneities in Einstein's theory. This allows attributing *Dark Energy* to the classical vacuum in the form of an exchange of energies : averaged intrinsic scalar curvature appears as potential energy, and averaged extrinsic curvature invariants (kinematical fluctuations) as kinetic energy of an effective scalar field. As we understand now, the principle difference between a standard quintessence field, describing fluctuations on the background of the standard model, and a « morphon quintessence » is provided by the fact that the Klein–Gordon dynamics of the scalar field couples fluctuations to the geometry of the effective model in the latter case, while this coupling is absent in the former. The coupling of fluctuations to average properties of the Universe is the new effect under study in the project ARTHUS.

The *state–of–the–art* of this research has been recently given in a status report [29] within a special *General Relativity and Gravitation* issue on *Dark Energy*. We summarize it here by emphasizing three points : (i) The averaging problem, lying at the basis of models for the inhomogeneous Universe, can be solved for scalar cosmological variables with the help of a framework of averaged cosmological equations given in [23, 25]. This problem has been touched upon in earlier work (e.g. [114, 74, 60, 56, 57, 9, 11, 66, 16, 123, 110, 117]). However, these investigations turned out to be either too restrictive to account for the new effect under study, or they remained qualitative, or they are too complicated to be of any practical use to cosmological research and the interpretation of observations, although many qualitative issues have been pointed out in these papers, and there have been recent efforts to derive the framework given in [23] from one of those approaches [45, 46, 100]. (ii) Since 2005, the framework [23] became popular (for earlier discussions and overviews see [22, 24, 51], and for a recent overview [43]), mainly in view of its comparative simplicity, in relation to cosmological questions. Work that explicitly employs this framework has strongly increased since then (examples are the papers [96, 103, 73, 72, 63, 105, 6, 98, 99, 100, 97, 8, 106, 107, 45, 79, 80, 81, 120, 121, 78, 7, 122, 90, 101, 108]), as well as contributions by the P.I. of this project and his collaborators [34, 35, 69, 30, 31, 32, 62, 26, 27, 28, 36, 76, 77, 40, 33]. In addition, work that deals with explicit solutions of Einstein's equations, in particular the spherically–symmetric Lemaître–Tolman–Bondi (LTB) solution, that has already been suggested earlier in the context of the *Dark Energy problem* [42], is now also compared with the new averaging framework [104, 94, 44, 58, 12, 91, 2, 3, 1, 19, 54, 43, 46]. It is also extended to studies of light propagation through swiss cheese type models, see [116, 118] and the recent papers [86, 87].

The major problem of all these recent studies is their restricted applicability, either by imposing strong symmetry assumptions, or by remaining in the weakly perturbed Friedmannian or quasi-Newtonian regimes of structure formation. This situation calls for a systematic investigation of *non-perturbative models* that are general enough to describe the relevant relativistic effects from inhomogeneities on average properties of the Universe. These are the quests that are faced by ARTHUS.

## 1.4. Objectifs et caractère ambitieux/novateur du projet. *Specific aims of the proposal, highlighting the originality and the novelty (1 à 2 pages maximum).*

*Décrire les **objectifs scientifiques/techniques** du projet.*
*Présenter l'**avancée scientifique** attendue. Préciser l'originalité et le caractère ambitieux du projet.*

*Détailler les **verrous scientifiques et techniques** à lever pour la réalisation du projet.*
*Décrire éventuellement **le ou les produits finaux développés** à l'issue du projet montrant le **caractère innovant** du projet.*

### The project ARTHUS – aims and general strategy

Based on the framework of averaged cosmological equations [23, 25] , the project ARTHUS aims at a *quantitative* evaluation of the effect of inhomogeneities with the ambition to *partially or fully* replace the need for *Dark Energy*. Even if the ambituous goal of a full explanation may not be achieved, any study of the effect of inhomogeneities is highly relevant for the interpretation of observational data, especially since many researchers in cosmology state that we have entered an era of high–precision cosmology, where the cosmological parameters of the standard model are determined with a precision of the order of a percent.

The project therefore deals with *three principal aspects* : (1) the investigation of *explicit models* for structure formation in relativistic cosmology, (2) the *interpretation of observational data* within the new framework of averaged inhomogeneous cosmologies, and (3) aspects of *averaging strategies* that are not addressed by the existing framework for scalar characteristics, but that bear relevance for a comprehensive treatment of inhomogeneous relativistic cosmologies. With (3) we shall also touch on the problem whether solutions of the *Dark Energy* and *Dark Matter* problems, proposed by more general theories of gravitation, could also be understood on the grounds of classical general relativity by including the effect due to inhomogeneities. Also, we shall address the question whether these two problems are related and could have the same physical origin. We shall also spend a considerable effort on the generalization of the averaging scheme itself.
As a consequence the project will be structured into *two main research lines* corresponding to (1) and (2). Point (3) will be subdivided into *two research sub–lines* (see below).

### The project ARTHUS – advances

Despite the recent large efforts in the community, directed towards answering the basic question of whether the effect is sufficient to explain a *Dark Energy* componenent, no definite answer has been found thus far. One group of researchers has advanced the *qualitiative* understanding of the relevant new effect, i.e. the *mechanism* how inhomogeneities can play the role of *Dark Energy,* another group has investigated *toy models* to *quantify* the effect, employing them to compare with observational data, yet another group has combined *standard perturbative analyses* with the general averaged equations, including *quantitative estimates* on the magnitude of the effect in the perturbative framework. None of these approaches seems sufficient.
In this situation, a more involved effort is needed. Clearly, pursuing more general paths of research, i.e. without resorting to standard perturbation analysis or known highly symmetric models, requires to work with more involved analytical strategies. ARTHUS proposes such strategies to bring this research field into a new phase.

As can be seen in the detailed description of the project below, we can indeed *open new ways of research* by (1) developing relativistic models for the generic evolution of inhomogeneities that to date do not exist at this level of generality, (2) by comparing these new models and concepts (i.e. in combination with the averaging framework) with observational data, we enter a *new phase in observational cosmology* since, thus far, observational data have been interpreted with the only prior of the standard model; hence, not only the cosmological model is generalized but also *observational strategies* will be improved, based on research results provided by ARTHUS.
Finally, (3) such new concepts are based on a comparatively simple solution of the – more involved – averaging problem. The research field is new, but it already calls for generalizations of the averaging framework, accounting for an improved understanding of the importance of general relativity to concrete problems in observational cosmology. To develop tools and concepts that realize these more general aspects already prepares future developments in this research field. The project ARTHUS is an initiative at the right time of an eventual paradigm change that might happen to cosmology in the near future. .

## 1.5. Positionnement du projet. *Progress beyond the state of the art and relevance to the call for proposals (1 page maximum).*

*Préciser le* ***positionnement du projet par rapport au contexte*** *développé précédemment : vis-à-vis des projets concurrents, de l'état de l'art national et international, des brevets et standards….*

### The postion of ARTHUS within international projects

There are large projects created that deal with the *Dark Energy problem*, but so far these projects mostly address a *generalization of the laws of gravitation*, or they study phenomenlogical models for postulated fundamental new fields.
For example, in Germany a large interregional project was recently created that, however, excluded so far the new question whether the problem could eventually be resolved by the effect of inhomogeneities (SFB TRR 33: *The Dark Universe*).

Other large experiments are conducted world wide to search for *Dark Matter.* This, but also the idea that *Dark Energy* is due to a *fundamental scalar field*, associated to the non-classical vacuum, challenge current theories of particle physics.

Both these broad lines of research activities, influencing on the one hand theoretical research inluding string theory and other candidates of a quantum theory of gravitation, and driving on the other hand

huge-scale experimental projects, demonstrates the exceptional relevance of a third research direction that *has the potential to alter these activities essentially*.
ARTHUS proposes to invest a considerable effort in order to reach a conclusive level of rigour, and to give an answer to the question whether the potential explanation can indeed be realized.

In France, the cosmology group LUTH at the Observatory of Paris in Meudon, is among the first that invests efforts in this new research direction. A collaboration with the P.I. of this project has been set out and first results have been published. Due to the fact that the P.I. of this project was offered a professor position in Lyon, the conditions to unify forces within France directed to these research efforts have considerably improved. There are a number of other researchers in France who are directly interested to understand the implications of inhomogeneities for their research fields. For example M. Joyce at IAP (related to the analysis of supernovae), and a number of other people at IAP, D. Polarski in Montpellier, A. Blanchard in Toulouse, R. Triay at CPT in Marseille.
With the project ARTHUS we aim at strengthening this situation, giving the new research direction a *center* at CRAL with high international visibility, and in the course of the project we aim at solidifying existing links within France in addition to the axis LUTH/CRAL.

It is fair to say that, until present, the international community is divided into those that advance arguments to support that the effect may be quantitatively insignificant (or better insufficient, since the significance of the effect cannot be denied given the results of the recent literature), and those that entered a detailed investigation of the new effect in order to reach quantitative conclusions. The subject has been taken up by a number of well–known relativists and cosmologists, among them John Barrow, Robert Brandenberger, Jürgen Ehlers, George Ellis, Kari Enqvist, Edward Kolb, Roy Maartens, Sabino Matarrese, Robert Wald, their students and postdocs, and many others.
Besides those, researchers who are known to have substantially contributed to develop the consequences of the new averaging framework are Syksy Räsänen, Aseem Paranjape, Tejinder Singh, Teppo Mattson, David Wiltshire, Dominik Schwarz and his students.

## The project ARTHUS – public outreach

The new research direction has now attracted public interest, which is demonstrated by a number of commentaries that have been quite recently published or are just now prepared by ***Nature***, ***Physics Today***, ***New Scientist***, ***Scientific American, Spektrum der Wissenschaft*** (*Scientific American* German issue*),* and other journals for a broader audience including newspapers (e.g. Zurich journal).
Recently, the French journal ***CIEL & espace*** has also commented twice on this research field, and I was invited to write an article for ***Pour La Science*** (*Scientific American French issue*).
ARTHUS aims at strongly supporting public outreach of research results.

***See especially:*** ***the comment by George Ellis in Nature*** : **13th March issue, Vol 452, p.158**
***the cover story in New Scientist*** : **8th March issue, Vol 2646**
***the cover story in CIEL & espace*** : **March 08 454, p.38 (see also: Mai 07 444, p.26)**

## Scheduled Conferences related to the research subject of ARTHUS

On the occasion of the second ***CRAL/IPNL conference on Dark Energy and Dark Matter*** in July 2008, the P.I. of this project also emphasizes this research direction by inviting a number of people that were mentioned above.
On the occasion of a larger ***UNESCO conference on The Invisible Universe*** in July 2009, organized by LUTH, the P.I. of this project acts as coorganizer and scientific advisor for a parallel session that will bring together most of the researchers who study the relation between inhomogeneities and *Dark Energy*.

## 1.6 Description des travaux : programme scientifique et technique. *Detailed description of the work (10 pages maximum).*

*Décrire le programme de travail en cohérence avec les objectifs poursuivis.*

The project ARTHUS is based on *two main research lines* and *two parallel sublines*.
They incorporate a defined schedule of subsequent research steps that will be described below.

(I) Explicit construction of inhomogeneous relativistic models
– investigation of their average properties
(II) Comparison with observations
– numerical realization and statistical analysis
(i) Generalizations of the averaging framework
– extensions of their rangeof applicability
(ii) Advances on the averaging problem
– geometrical analysis, effective description of generalized gravitation theories

Specifically, we now list the lined–up projects together with the defined collaborations.

One major axis of the collaborations within France is sustained with the laboratory LUTH at the Observatory of Paris, Meudon. Other national collaborations will built up during the project, in particular with CPT Marseille, the University of Toulouse, GRAAL Montpellier, and IAP Paris.

International collaborations in Europe are defined with researchers in Switzerland (University of Geneva), Italy (University of Pavia), Germany (Universities of Bielefeld, Ulm, Würzburg and Munich, as well as the Albert–Einstein–Institute in Golm), and the U.K. (Universities of Portsmouth, Brighton and Nottingham).

International collaborations overseas involve Japan (The Universities of Tokyo and Okinawa, the Tokyo Institute of Technology), South Africa (The University of Cape Town), and some researchers in the U.S.

### Main Research Line (I)

The status of importance of the effect of inhomogeneities on averaged properties of the Universe and their potential to explain the *Dark Energy problem* mainly depends on a sufficiently general *quantitative* evaluation of the effect. Previous studies (within a standard perturbation approach) indicate that this is a major problem, since it essentially requires the construction of *non–perturbative models* for accessing the nonlinear regime of structure formation. Furthermore, technical restrictions of a standard perturbation analysis provide obstacles to estimate the relevant relativistic effect. For example, the additional backreaction term is restricted to be a full divergence on some large scale (e.g. [79]), a property that is shared with Newtonian models [34], and implies a technical suppression of the effect under study.
In Research Line (I), but also in most of the other subprojects, we shall maintain many substantial cornerstones of the standard model of cosmology. In particular, we assume that the *early stages of cosmic evolution* are well-described by the standard model until the epoch of the CMB, and that there exists a *scale of homogeneity.* This helps to focus on the study of the main effect without loosing essential current-day observational constraints (CMB, BAO, etc.).

With this project we define a line of research with the aim of installing *explicit inhomogeneous models* in the framework of general relativity that allow us to go *beyond the perturbative regime* of structure formation, and that do not suffer from those technical restrictions.

As for the concrete project, we essentially "bet on one horse" in this research line, an approximation scheme that has been very successful in the context of Newtonian cosmology and that allows to construct explicit non–perturbative models analytically. We shall work out a generalization of this scheme in the framework of general relativity, which in turn allows to combine this analytical model with the framework of the exact averaged Einstein equations.We have several reasons to do so :
a) current numerical simulations rest on the Newtonian framework and can therefore not be employed to study a genuinly relativistic effect ; b) the approximation scheme envisaged has proved to be very powerful in comparison with numerical simulations in the Newtonian context and much of the existing Newtonian tools can be generalized in a straightforward way ; c) standard relativistic perturbation theory describes fluctuations on a fixed background solution, while the model envisaged takes the coupling of fluctuations to the geometrical properties of the "background" into account. It therfore allows to describe the non–perturbative regime of structure formation, and finally d) the P.I. of this project was ealier one of the main developer of the Newtonian framework (he introduced the Lagrangian formulation of the Newtonian equations) and so provides the analytical, numerical and statistical expertise needed to successfully conduct this project.

### I.1 On relativistic generalizations of Zel'dovich's approximation :

### Lagrangian framework and definition of the approximation .

T. Buchert (CRAL), 1st ANR postdoc and Ph.D. students at CRAL, M. Ostermann (Munich, Germany).

In this first work we generalize a successful model of Newtonian cosmology known as the Zel'dovich approximation [124, 125]. This approximation can be systematically derived from a Lagrangian perturbation approach [20, 21, 10], see the review [49], and allows to analytically describe the nonlinear distribution of matter and matches, on a sufficiently large smoothing scale of the order of about 10 Mpc, the results from N-body simulations [93], [18]. It so allows to considerably go beyond the predictive power of a standard Eulerian perturbation approach.

Although there have been suggestions in the literature to formulate a corresponding approximation within general relativity [67] and follow–up work (interesting related work has been done also in [88]), these suggestions do not furnish a consequent generalization, e.g. they lead to essentially perturbative metrical properties. (This would be fine for the metric itself, since metric perturbations are indeed small, but not for the curvature, since derivatives of the metric can be large, an this fact leads us beyond standard perturbation theory.) Based on a fully Lagrangian description of Newtonian cosmology and their (Lagrangian) perturbative solutions, we can systematically construct corresponding models in general relativity by formulating Einstein's equations in terms of a single dynamical variable only (the Cartan co–frames) and employing Lagrangian perturbation techniques to define the relativistic analog of the successful Newtonian model.

This work requires the following steps : a) Formulation of evolution and constraint equations of Einstein's theory with the matter model "dust" *exclusively* in terms of Cartan co–frame fields ; b) applying Lagrangian perturbation techniques to the resulting system of equations ; c) representing all relevant relativistic variables as (non–perturbative) functionals of the first–order (Lagrangian) solution.

This yields non–perturbative expressions for metrical properties and their derived quantities, in particular the Ricci curvature of the space sections.

*The first step has been worked out within an ongoing Ph.D. work of M. Ostermann (Univ. of Munich, Germany), so that the outcome of step a) is known to be successful and allows the evaluation of the following next research steps. Finalized article expected : mid of 2009.*

### I.2 On relativistic generalizations of Zel'dovich's approximation :

**Non-perturbative approach to backreaction**

T. Buchert (CRAL), ANR postdocs and Ph.D. students at CRAL,
M. Kerscher (Univ. of Munich, Mathematics Department, Germany)

In a second research step we realize the spatial averages of the above model and its key–variables. Paraphrasing again a previous Newtonian investigation [35], we can use tools that have been applied to the corresponding Newtonian approximation – in particular a numerical code that has been developed by M. Kerscher to integrate the averaged cosmological equations.

This work requires the following steps : a) calculation of the average properties of the relativistic approximation developed above ; b) study of generic initial conditions, in particular working out the differences to the degrees of freedom in the initial data of the corresponding Newtonian model ;
c) adapting the numerical code to integrate the averaged cosmological equations in the relativistic setting; d) analyzing the statistical properties of the so–obtained effect as a function of spatial scale ;
e) comparison with results from a standard (Eulerian) perturbation analysis that were obtained recently in the literature; f) scale–dependent estimate of the strength of the backreaction effect and estimate on bounds of the averaged scalar curvature at the present epoch ; g) statement of the relative strengths predicted by this model with the needed amount of Dark Energy in its dependence on initial conditions.

*Publishing of the first results is expected already towards the end of 2009 ; finalized mid 2010.*

### I.3 On relativistic generalizations of Zel'dovich's approximation :

**Light–propagation in generic models .**

T. Buchert (CRAL), ANR postdocs and Ph.D. students at CRAL, eventually including :
R. Durrer (Univ. of Genève, Switzerland), E. Kolb (Univ. of Chicago, U.S.), S. Matarrese (Univ. of Padova, Italy), and their students/ postdocs.

In a third research step we exploit the fact that we cannot only estimate averaged kinematical properties of the spacetime modelled by this relativistic approximation, but we can explicitly use the spacetime metric to study light–propagation in this model. Previous investigations employed the hypothesis that fluctuations are described by small deviations from the standard homogeneous–isotropic model of cosmology. Here, we can study the effect from nonlinear structures allowing us to investigate light–propagation within a realistic inhomogeneous distribution of matter and curvature.
This opens the doors to many problems in observational cosmology (like e.g. gravitational lensing).

However, in this work, we shall first focus on formally understanding the direct influence of inhomogeneities on light–propagation to prepare a modeling strategy that can be best employed for the interpretation of observational data.

This work requires the following steps : a) analytical set–up of the light–cone in the relativistic approximation ; b) numerical implementation of the light–cone using the numerical code developed above ; c) implementation of additional observables such as the luminosity distance ; d) set–up of a modeling strategy for observables.

*Finalized article expected : end of 2010.*

The main research line I will be finalized – within the project – after the second year. It provides the basis for a continuation of the main research line II. However, the model we shall construct here bears potential for further applications, and we shall judge those in view of the concrete developments of the research field by then.

## Main Research Line (II)

This research line applies the model investigated above, but also models that are constructed on the basis of the Research Sub-lines (see below) to observational data. We shall confront our models with (1) data from supernovae observations, (2) constraints from the Cosmic Microwave Background, (3) galaxy survey data (e.g. SDSS), and others.

### II.1 Confronting averaged cosmologies with SN1a and CMB observations I .

J. Larena (LUTH & Univ. of Cape Town, South Africa), J.–M. Alimi (LUTH),
T. Buchert (CRAL), Ph.D. students and ANR postdocs at CRAL,
P.–S. Corasaniti (LUTH), M. Kunz (Univ. of Sussex, Brighton, U.K.).

This work is the next research step in a continuous collaboration between the laboratories LUTH and CRAL. We evaluate our hypothesis of a cosmological model with "backreaction", employing an effective metric that is parametrized by the exact average properties of an inhomogeneous cosmological model. The evaluation is executed with supernova SN Ia data and constraint by CMB (Cosmic Microwave Background) observations. The goal is to explain these data without introducing a cosmological constant or an external field of quintessence.

This work requires the following steps : a) parametrization of a constant–curvature template metric using the exact kinematical properties of an inhomogeneous model using the averaging framework discussed above ; b) evaluation of the luminosity distance in the template metric ; c) likelihood analysis of the model using SN 1a and CMB/BAO data ; d) evaluation of the best–fit scaling solution [36], see Figs.1,2, in comparison with a corresponding standard quintessence model [82] ; e) illustration of the best–fit model in terms of the evolution of the cosmological parameters ; f) designing an observational test to discriminate a backreaction–driven model from standard quintessence scenarii.

*First results will be published already in 2008. A more detailed analysis follows in 2009, which is supposed to be finalized already mid of 2009.*

### II.2 Minkowski Functionals of SDSS galaxies : analysis of Boolean grain models .

**The SDSS collaboration :**

T. Buchert (CRAL), J. Blaizot (CRAL), C. Rimes (CRAL),
Y. Suto (Univ. of Tokyo, Japan), H. Wagner (Univ. of Munich, Germany),
Ph.D. students and ANR postdocs at CRAL and the University of Tokyo,
C. Hikage (Univ. of Nottingham, U.K.) , M. Kerscher (Univ. of Munich, Germany),
and collaborators of the SDSS collaboration.

The SDSS data are now complete enough to realistically study large-scale fluctuation properties of the catalogue. We shall target at the Data Release 6.
To determine the magnitude and the significance of those fluctuations on large scales (100 – 200 Mpc) allows us to constrain the magnitude of "backreaction terms" in the averaged cosmologies.
A new numerical code for the morphological analysis of a large number of galaxies has been developed over the last three years by the cosmology group in Munich. J. Blaizot (a new permanent member at CRAL and expert in the construction of artificial catalogues of SDSS), and C. Rimes (postdoctoral researcher at CRAL), are currently testing this new code on simulated "mock"–catalogues of the SDSS survey. In continuous collaboration with researchers at the University of Tokyo, in the United States and the U.K., we so prepare the morphological analysis of fluctuations using Minkowski Functionals, an integral–geometric tool that has been introduced into cosmology by the P.I. of this project [92, 112]. In an earlier paper we have employed the excursion set approach [61] that smoothes the data, which was appropriate for the given completeness of the catalogue at that time. Now, we can directly analyze the data without smoothing by using a Boolean grain method. Further expertise in looking at fluctuation properties of catalogues has been developed in earlier work [70, 71].

This work requires the following steps : a) the construction of volume–limited large–scale samples of the catalogue (including technical work on the data masks, the nearest–neighbour lists and systematic magnitude selection) ; b) the construction of corresponding "mock–"samples in the simulated catalogues ; c) conducting the morphological analysis for the four Minkowski Functionals, depicted as a function of scale (including the error analysis) ; d) estimate of the « backreaction term » an determination of the statistical significance of given fluctuation amplitudes as a function of spatial scale.

*Finalized article expected : mid of 2010.*

### II.3 Confronting averaged cosmologies with SN1a and CMB observations II .

T. Buchert (CRAL), Ph.D. students and ANR postdocs at CRAL,
J. Larena (LUTH & Univ. of Cape Town, South Africa), J.–M. Alimi (LUTH),
P.–S. Corasaniti (LUTH), M. Kunz (Univ. of Sussex, Brighton, U.K.).

Interaction with the Project Sub–line (i) (described below) will deliver more general models as those used in the above first project. The above–employed scaling assumption provides a simple closure condition of the averaged cosmological equations, having as a free–parameter the scaling index (see Figs. 1,2). In the above work it is included as a further parameter, marginalized over all the other parameters of the problem. In this work we employ the results on closure assumptions of Project i.3 in order to construct more general models. We shall repeat and refine the above analysis involving essentially the same steps as those described above.

Results on a scale–dependent description obtained in (i.1.) will be employed to eventually include further observational data (like the SDSS survey) on regional scales.
This will, however, rely in particular on the numerical implementation envisaged in (i.1.).

*This work will be finalized not before the end of 2010, depending on the progress of Projects i.1. and i.3. As for the latter, we want to use the most general closure assumptions that will be obtained in this subproject.*

## Research Sub–Line (i)

This Sub–line supports work on generalizations of the existing averaging formalism employed in Research Line (I). At the same time it is structured in such a way that it provides necessary insight and tools needed in Research Line (II) on schedule.

### i.1 Scale–dependent partitioning of spatial sections:

**estimates of backreaction and curvature of the present–day Universe .**

T. Buchert (CRAL), ANR postdocs and Ph.D. students at CRAL,
M. Carfora (Univ. of Pavia, Italy) ; eventually including :
S. Colombi (IAP, Paris) and his students..

This work provides a scale–dependent evaluation of the effect of inhomogeneities on the global averaged properties of the present–day Universe. It will make the averaged variables accessible to a scale–dependent interpretation of observables. In a first step we formulate a partitioning of spatial sections into void–dominated and matter–dominated typical regions, and we shall concentrate first on global estimates on backreaction and averaged scalar curvature as functions of parameters of the partitioning. Such a formalism is also necessary to provide a link between an estimate of the effect on regional scales (such es the expansion fluctuation in voids and matter–dominated regions) and global bounds on average properties. In turn this provides the link to regional estimates drawn from standard numerical simulations and from their comparison with catalogues (such as the SDSS survey).

This work requires the following steps : a) formulation of the partioning of space in a generic spatial section (using the general ADM formalism of general relativity) ; b) evaluation of backreaction and averaged curvature in terms of the parametrization of the partitioning ; c) estimate of a priori not directly observable quantities (such as geometrical properties) from directly accessible ones (such as the expansion fluctuations on regional scales) ; d) a detailed discussion of parameter choices drawn from different cosmological model assumptions ; e) set–up of a controlled N–body simulation that parametrizes the analytical estimates within a consistent set of assumptions ; f) quantitative results drawn from standard Cold–Dark–Matter initial conditions on the values of the regional parameters and the consequences for global bounds on backreaction and averaged scalar curvature.

*First results have been made available to the community addressing the points a) –c) [33]. Analysis of the following points will start in 2009, where point d) will be finalized early in 2009, the points e) and f) may need considerable time and results are not expected before the end of 2010.*

**i.2 On the averaging problem in geometric optics and its cosmological consequences .**

T. Buchert (CRAL), ANR postdocs at CRAL,
J. Larena (LUTH & Univ. of Cape Town, South Africa), A. Rakić (Univ. of Würzburg, Germany),
D.J. Schwarz (Univ. of Bielefeld, Germany), eventually including :
M. Carfora (Univ. of Pavia, Italy), S. Räsänen (Univ. of Geneva, Switzerland),
F. Steiner (Univ. of Ulm, Germany) and his students and postdocs.

The goal of this project is to formulate effective laws of light propagation along our inhomogeneous past light cone. We expect a great advantage of considering "light cone averages" instead of spatial averages, since the resultant framework helps to establish direct relations with observational data at all times of the cosmic history. Characteristics of the Cosmic Microwave Background enter directly into the initial data of the averaged propagation laws, and integrated, secondary effects are directly incorporated by integrating the averages on the light fronts over their propagation history, linking the initial data with observables at the present epoch. In Research Line (I) we develop in parallel an explicit inhomogeneous metric to study how light propagation is affected by the presence of local inhomogeneities. Here, an averaging formalism incorporates these effects on average and does not rely on approximate assumptions on the metrical properties of spacetime. However, the expected averaged equations will not form a closed system of equations, but they allow to implement closure assumptions (Subproject i.3) and, thus, it provides complementary information to the results obtained by an approximation of the type developed in Research Line (I).

This work requires the following steps : a) Double projection of Einstein's equations on two–dimensional light fronts ; b) averaging the resulting equations over the light fronts ; c) set–up of propagation equations for the averaged variables and their integration for specific closure assumptions (e.g. scaling laws for the relevant observables as a first step) ; d) detailed comparison with the results that are obtained for homogeneous and weakly perturbed light cones [64, 65, 17, 68] ; e) interpretation of the differences in terms of sufficiency to explain the Dark Energy problem ; finally, an interesting point that could be analyzed here with the developed methods : f) calculating global integral properties (i.e. averaged over the whole light front propagating to us) and linking these to global integral–geometric descriptors such as the Minkowski Functionals, allowing to set up a link to a commonly used statistics in CMB analyses [113] and perturbation theory [89].

*In this project already the first two steps are quite involved and we hope to finalize these basic issues towards mid of 2009 ; the point c) bears relations to project (i.3) (described below) and the closure assumptions we are going to use might become more general than the assumption of scaling laws (which help to explore the solution space, but have to admit a free parameter) ; including the analysis of the following points will bring us into 2011. It is difficult to estimate when this work will be finalized, especially since we expect this project to bear a number of interesting consequences, in general, for the interpretation of observations. These consequences will probably bring us into the future of ARTHUS.*

**i.3 Closure assumptions imposed on averaged cosmological equations .**

T. Buchert (CRAL), J. Larena (LUTH & Univ. of Cape Town, South Africa),
P. Dunsby (Univ. of Cape Town, South Africa), his students,
ANR postdocs and Ph.D. students at CRAL., eventually including:
D. Wiltshire (Univ. of Canterbury, New Zealand)

The averaged cosmological equations used in Research Lines (I) and (II), but also the averaging framework obtained in Project (i.2), are general in the sense that they do not impose any symmetry or approximative assumptions on the Einstein equations. However, such equations need a closure assumption. This can be either in the form of giving an explicit model for the inhomogeneities (like in Research Line I), or in the form of effective dynamical equations of state that, e.g., link the backreaction to the averaged scalar curvature. One such example is provided by assuming scaling laws, so that there is a scaling index as a free parameter that can be adjusted as to match observational data [36] and Figs. 1,2. Other, relatively simple, examples are currently studied by two M2 students at CRAL. One of them studies the Chaplygin equation of state [59] that has become very popular in parametrizations of Dark Energy, the other studies the spherically symmetric LTB (Lemaître–Tolman–Bondi) solution and its effective equation of state. The new input in these two studies is to use the equations of state to close the general averaged equations and to study the physical properties implied by these imposed relations.
In this project, we are going to analyze, in the same spirit, other closure assumptions. However, we pursue a more involved strategy by going back to the Einstein equations and first derive general evolution equations for the backreaction variables. Then, on a deeper level of the hierarchy of equations, we consider dynamical closure assumptions. This strategy leads to the possibility of imposing dynamically justified relations between the backreaction variables.

This work requires the following steps : a) continuation of the M2 projects (by Ph.D. students) leading to a comprehensive understanding of various dynamical equations of state and their mutual relations for the purpose of closure ; b) deriving (second–order) evolution equations for backreaction variables ; c) studying the weak–backreaction limit in order to recover known results from perturbation theory ; d) imposing closure assumptions on the deeper level of the hierarchy of equations (involving intrinsic geometrical fields instead of extrinsic ones as in the previously studied closure assumptions) ; e) while the above points are meant for the existing (spatial) averaging scheme, we can implement, along these lines, closure assumptions on the light cone averages developed in Project i.2.

*We expect to subsequently publish the results ; for a) finalized towards mid of 2009, for b) and c) towards end of 2009, for d) towards mid of 2010, and for e), depending on the development of the Project (i.2), later.*

## Research Sub–Line (ii)

This research sub–line contains selected projects the results of which are not directly needed in the superordered projects, but shed light on the various aspects touched upon in the other projects. They are selected on the criterion of importance, as it is suggested by ongoing work in the international community. The headline of every project listed below is to provide a relation to the effect of inhomogeneities in classical general relativity. In particular, there is a large international community that believes that the *Dark Energy* problem points to the need of generalizing the laws of gravitation. They do not assume that *Dark Energy* could be explained by sources, e.g. a fundamental quintessence field, they rather construct effective fields emerging from terms that have their origin in a more general theory of gravitation. Given this situation, we shall also consider such theories and their consequences for the modeling of *Dark Energy*, however, focussing on the possibility that the extra terms, postulated to originate from generalizations of the laws of gravitation, could also be modelled within classical general relativity, i.e. we are going to compare them with the effective geometrical backreaction terms emerging in the classical theory by the averaging of inhomogeneities, and exploit the established relations to observations.

**ii.1 Effective braneworld cosmologies and averaging scales .**

T. Buchert (CRAL), G.F.R. Ellis (Univ. of Cape Town, South Africa),
R. Maartens (Univ. of Portsmouth, U.K.),
involving in the last step an ANR postdoc at CRAL.

Here, we analyze the average properties of a spacetime which does not solve the classical theory of Einstein gravitation, but which includes a higher number of spatial dimensions. Since we do not consider compactified extra dimensions like in string theory, the result will be be an effective "braneworld cosmology", which combines backreaction terms with a modification of the laws of gravitation. We shall ask the question, whether the supplementary terms, coming from higher space–dimensions, have a generically different character than those of the standard fluctuations in matter and geometry of the classical theory, or whether they appear on equal footing with the classical backreaction terms. A further interest in this study is, whether higher–dimensional theories of this type eventually violate classical observational results.

This work involves the following steps : a) averaging the projected five–dimensional Einstein equations within spatial sections according to the standard methods developed [83] (we first consider one extra spatial dimension) ; b) discussion of the symmetry assumptions that have to be invoked ; c) derivation of generalized Friedmann equations that feature extra terms stemming from the higher–dimensional setting plus terms stemming from classical backreaction terms ; d) comparison and quantitative estimates of the relative importance of all the backreaction terms, and discussion of their role for an explanation of Dark Energy.

*First aspects of this work have already been discussed. It will be continued early within the project ARTHUS, but we shall put emphasis on the other projects first, so that we expect to finalize a first article not before the end of 2009. While points a) – c) will probably match this schedule, point d) will be attempted with the help of a postdoctoral researcher at CRAL at the moment of best interaction with other numerical estimates pursued in the other projects.*

**ii.2 "Morphed" inflationary models .**

T. Buchert (CRAL), ANR postdocs and students at CRAL,
J. Larena (LUTH & Univ. of Cape Town, South Africa), J.–M. Alimi (LUTH),
D. Mota (CRAL), A. Arbey (CRAL)

This project has been set out within the collaboration CRAL/LUTH. The basic idea is an inversion of the correspondence between a scalar field cosmology and the backreaction problem, investigated in [36]. Instead of interpreting inhomogeneities through an effective scalar field, we can turn this correspondence around and start with a known scalar field theory, assuming that it is an effective theory modeling inhomogeneities, and then study physical properties of a classical spacetime.
As a highly interesting project here we consider to implement this inversion process for a typical inflationary cosmology. This allows us to study the primordial Universe, however, not restricted to homogeneous distributions of matter and geometry as in the standard implementation of the inflationary paradigm, but in the context of "inhomogeneous inflation". This latter has been considered in the literature several times (e.g.[55]), however, without reaching definite conclusions due to the complications involved by treating inhomogeneities in such a violent expansion phase. Our project assumes that a given inflationary model is an effective one and then reconstructs the average

properties of the resulting spacetime. A first short analysis shows that a generic model will start out with a strongly positive averaged curvature that, during inflation, will converge to an, on average, almost flat Universe. Our further interest is to understand the final conditions at the exit epoch of inflation, which in turn provide the initial data for the structure formation process. This latter point bears relations to Research Line I, related to the possible choices of initial data. In the main research line we assume standard Cold–Dark–Matter initial data, but with the outcome of this project we are able to also analyze the possibilities of non–standard initial data and their compatibility with observational constraints at the CMB epoch [37, 38], [84, 85].

This work involves the following steps : a) selection of "typical" inflationary models that are discussed in the literature to be successful ; b) reconstructing the backreaction variables using the scalar field correspondence developed previously ; c) discussing in detail the physical properties of the resulting spacetime, initial conditions and especially final conditions at the exit epoch ; d) estimating the strength of kinematical backreaction in comparison with the averaged density at the exit epoch;
e) classifying these non–standard final data, which are initial data at the CMB epoch, in comparison with standard Cold–Dark–Matter initial conditions and with observational constraints.

We have just given the reasoning for an inflationary scalar field model ; other scalar field models are of interest as well in this context: the relation to the *Dark Matter problem* has been explored in terms of a scalar field [95], [4], and this is an important question that we pose in parallel to questions related to the *Dark Energy problem*. It is here where we can make this link. Furthermore, it should also be emphasized that the above implementation could be refined by adding radiation to the model. This needs a more refined averaging scheme [25], for which the scalar field correspondence has not been developed, but its development could be envisaged here.

*Although the strategy outlined above is straightforward, especially for points a) –c), the following points can be more involved, especially if we want to test non–standard initial data with the model developed in Research Line I ; another important aspect is that we expect to understand the link to the Dark Matter problem in the context of scalar fields, and the relation of the effect of inhomogeneities to this problem may also get more attention in the international community in the course of time, so that it may become important and interesting to conretize these relations.*
*We therefore give this project room until the end of 2011.*

### ii.3 Averaging geometrical variables, intrinsic backreaction, and fundamental problems .

T. Buchert (CRAL), ANR postdocs and Ph.D. students at CRAL,
G.F.R. Ellis (University of Cape Town, South Africa),
J. Ehlers, L. Andersson (Albert–Einstein–Institute, Golm), H.v. Elst (Merkur Univ. Karlsruhe, Germany);
M. Carfora (University of Pavia, Italy) and his mathematical collaborators,
A. Hosoya (Tokyo Institute of Technology) and his students,
eventually including C. Rovelli (CPT Marseille, France).

We have pointed out in the introductory sections to this project that the main applications of ARTHUS will be based on the averaged cosmological equations for scalar characteristics, that is employed in most of the recent work. However, the root of the averaging problem is a geometrical problem, i.e. the averaging of tensorial variables. The P.I. of this project also contributes experience in this field and many of the previously described projects touch upon these geometrical problems.

Especially the study of closure assumptions in Subproject (i.3) bears direct relations to geometrical averaging. This experience has been developed in the context of the Ricci Hamilton flow that is employed to smooth the spatial Riemannian metric into a constant–curvature space. This flow has attracted much attention in the recent mathematical literature, mainly because Perelman provided the final steps to realize Thurston's geometrization programme to cut a Riemannian manifold into "nice" pieces, among them the three elementary geometries of the standard model of cosmology.

In particular, work with M. Carfora from the University of Pavia has investigated the link of this mathematical programme and its strong results to the cosmological averaging problem (e.g. [30, 31, 40]).We have shown that so–called "intrinsic backreaction terms" arise in addition to the kinematical backreaction terms that are the subject of most of the above projects.
In this subproject we shall take up, e.g. in the context of Subproject (i.3), these geometrical results.

There are other fundamental questions, e.g. the relation of information theoretical measures that allow to globally understand the effect of backreaction. Here, work pursued with A. Hosoya from the *Tokyo Institute of Technology* [62] has not yet been exploited in relation to the above–defined projects. But, also here, these insights will add not only a deeper understanding, but will have practical consequences, in particular, in relation to evolution equations for the backreaction variables.

A number of further aspects (like quantitative estimates on the averaged scalar curvature from first principles) are discussed with J. Ehlers from the *Albert–Einstein–Institute* in Golm, Germany. Quite recently, other researchers at this institute joined into our discussion (e.g. V. Moncrief, L. Andersson and others), and we think that there will be powerful interactions in the future in relation to the ARTHUS project.

*This research project does not schedule publications, but there may well be interesting ones coming out of these discussions, and we shall link ARTHUS to these more fundamental questions.*

## Figures to Chapter 1

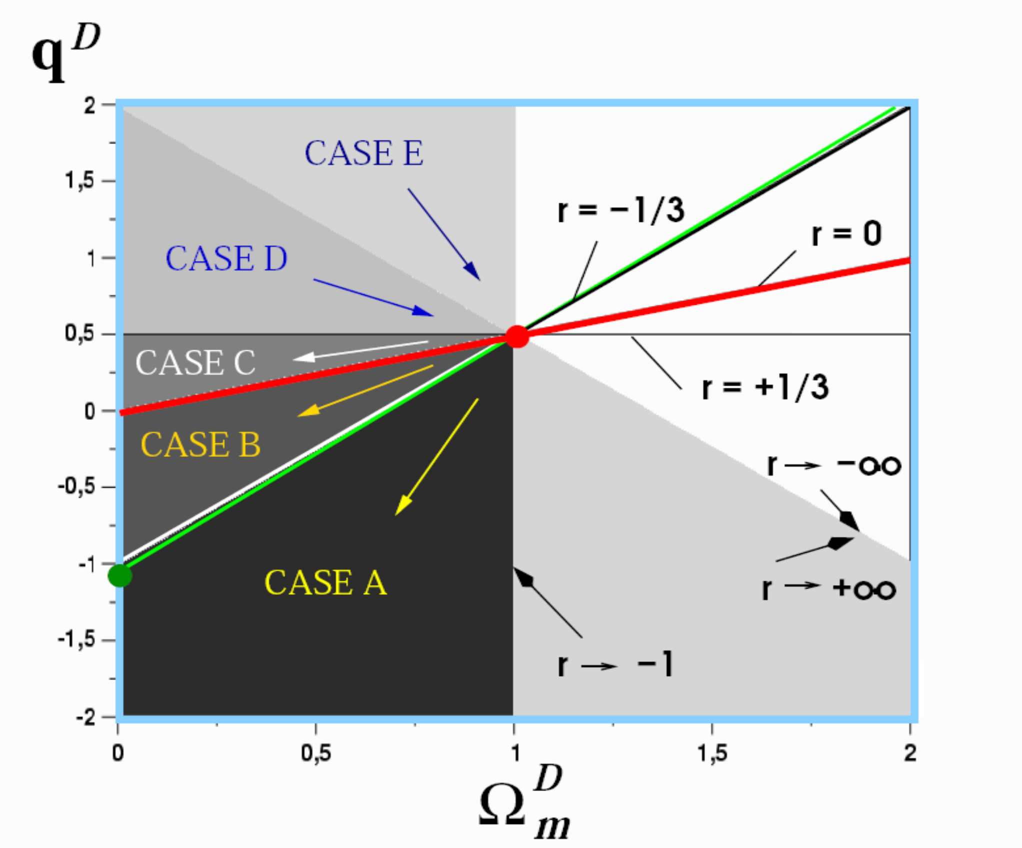



**Figure 1:**

This figure illustrates the solution space of averaged inhomogeneous cosmologies, restricted to a vanishing cosmological constant. The plane is defined by the volume decceleration parameter, that distinguishes non-accelerating universe models (**q** above 0) and accelerating ones (**q** below 0), and the volume density parameter for the total matter content. (Both are indexed with D, since these parameters are scale-dependent spatial averages on a domain D.)
The central point represents a Friedmannian model of standard cosmology without spatial curvature, and the line ermerging from it describes all Friedmannian solutions with a homogeneous (constant) intrinsic curvature.
All lines in this diagram represent *scaling solutions*, employed as a simple closure assumption on the averaged equations, but useful to explore this solution space.
A stability analysis of these scaling solutions helps to classify different sectors, shown above as different cases in the plane of solutions. Cases D and E, corrsponding to decclerating unverse models, are solutions that are attracted by the Friedmannian class of models, i.e. the standard model is stable and describes well the average dynamics. Cases C, B and A show unstable sectors: for these solutions the standard model acts as a repellor and the average dynamics of the universe model deviates from the standard model. This global instability thus happens for the right sectors to explain *Dark Energy*. It is the result of the coupling of fluctuations to the average dynamics, being the effect studied in ARTHUS.
In the correspondence with an effective scalar field [36], Case B corresponds to a standard quintessence model of *Dark Energy*, while Case A corresponds to a phantom quintessence model, having formally negative kinetic energy of the scalar field. We recall that this effective scalar field does not violate energy conditions as in the assumption of an external scalar field source. (The green line corresponds to the scaling solution that fits observational data from supernovae observations.)

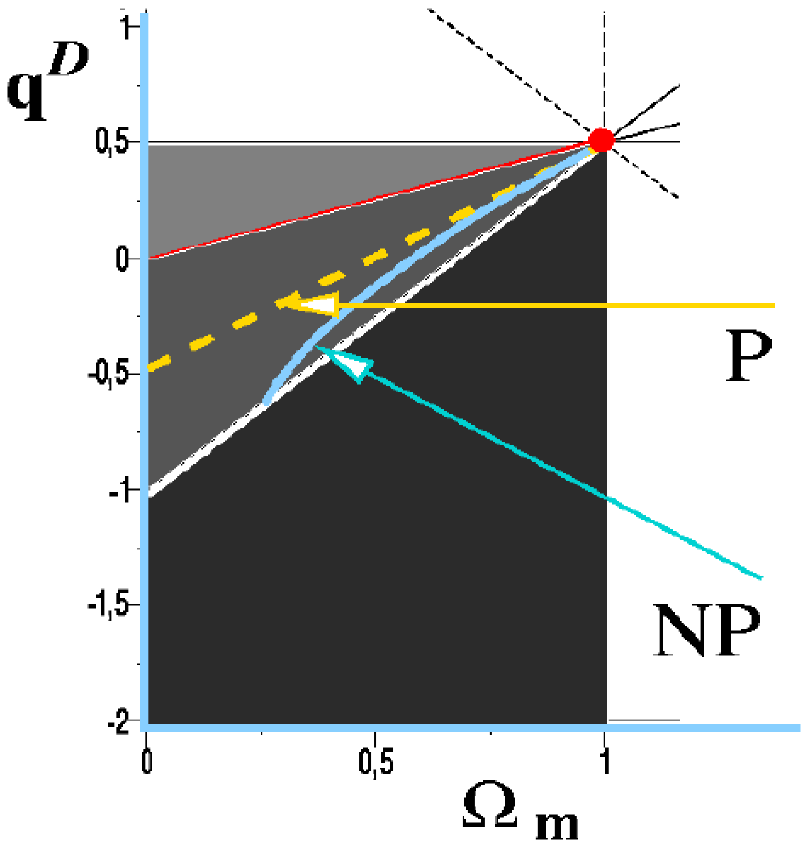



**Figure 2:**

The ***unstable sector*** of Figure 1 is shown again. The dashed yellow line **P** corresponds to a scaling solution that agrees, for small perturbations on a Friedmannian background (i.e. in the vicinity of the central point), with the results from a standard second-order perturbation analysis, see e.g. [79] for a recent analysis. Thus, a perturbation analysis already shows that the leading-order solution falls on a scaling solution in the *quintessence regime*. Extrapolation of this scaling solution into the nonlinear regime of structure formation would not have sufficient impact to fully explain a *Dark Energy* component. Magnitude estimates of the effect at the present time using this scaling behavior [29] are in agreement with (conservative) estimates on scales of about 100 Mpc of a non-perturbative Newtonian model. This latter agrees, in the limit of small perturbations, with results from a perturbation solution in the second-order regime [35], but is restricted by the boundary condition of zero backreaction on larger scales.

The (blue) line emerging from this scaling solution **NP** illustrates the operational regime of ARTHUS. It nails down the expectations we have on the results. (This line ends at the point predicted by observations.)
Research Line I of ARTHUS investigates the approximation [35] in relativistic cosmology, hence including the main effect under study, which is absent in the Newtonian and quasi-Newtonian models due to their limited architectures.

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## 1.7 Présentation du laboratoire d'accueil – Description of the french laboratory *(1/2 page maximum).*

*Présenter les **axes et activités de recherche du** laboratoire d'accueil et les moyens qu'il met à disposition du candidat.*

The CRAL (Centre for Astronomical Research of Lyon) is a Joined Research Unit (UMR 5574) of the *University of Lyon 1* (UCBL), the *École Normale Supérieure de Lyon* (ENS-L), and the *Centre National de la Recherche Scientifique* (CNRS).

The CRAL is hosted by the Observatory of Lyon, a Department of UCBL (OSU, Observatoire des Sciences de l'Univers, article 33), and by the ENS-L, because the team working of the site of ENS-L is associated to the OSU. The activities of the CRAL are carried out on two sites: the Observatory located at Saint-Genis Laval, and the ENS-L in Lyon, in the Gerland district.

The CRAL was funded in 1995 by the merging of three entities:
- the old Observatory of Lyon, whose activites were mainly oriented towards spectroscopic instrumentation and astronomical databases,
- a young team of theoretical astrophysics created at ENS-L in 1992, specialized in physics applied to the structure of compact objects,
- and a team coming from Paris, working in R&D for angular high resolution problems.

During the previous four-years contracts (1995-1998, 1999-2002, 2003-2006), these three entities have been strenghtened by the recruitment of young researchers. In parallel, major instrumental projects emerged. In 2002, it was necessary to create a new team in the field of cosmology to sustain the instrumental project aiming to observe the Universe at higher redshits.

The recruitment of Thomas Buchert as Professor at UCBL builds the basis of a considerable strengthening of cosmological research. We are currently in the process of restructuring the groups and coordinating links between extragalactic aspects of ongoing projects with the newly established theoretical cosmology team.
The institute is prepared to receive a large number of new group members and provides offices and equipments. Thus far, computer facilities and office equipment have been bought for the newly arrived permanent staff members (Blaizot and Buchert).

## 1.8 Résultats escomptés et retombées attendues. *Expected results and potential impact (1/2 page maximum).*

*Présenter les **résultats escomptés** en proposant si possible des critères de réussite et d'évaluation adaptés au type de projet, permettant d'évaluer les résultats en fin de projet**. Préciser comment le projet s'intègre et contribue à la mise en œuvre de la politique scientifique de l'établissement d'accueil et, le cas échéant, des établissements ou laboratoires associés au projet.** Préciser comment le projet peut favoriser l'émergence de synergies nouvelles, susciter des collaborations multi- ou trans-disciplinaires, renforcer l'attractivité de l'établissement d'accueil à l'échelle régionale, nationale ou internationale….*

### *Criteria for the success of the project aims*

A simple, global, criterion to judge the success of ARTHUS would arise in the case where the quantitative outcome of our analyses would identify, unambigously, inhomogeneities as source of *Dark Energy* with a sufficient magnitude.

This would have, of course, a tremendous impact on a large spectrum of international research activities directed towards resolving the *Dark Energy* problem.

However, we are not in the position to forsee such an accomplishment; we think that the systematic development of our understanding of the effect of inhomogeneities on effective properties of the evolution of our Univers is certainly important, and the success of the project may be judged on the grounds of the following outcomes:

(1) successful construction of non-perturbative models including quantification of the effect under study as a function of spatial scale in these models (Research Line I)
(2) successful comparison of the so-constructed models with observational data, i.e. can the averaged inhomogeneous models compete with the standard model in fitting observational data, and – if they do or not - can we understand why or why not (Research Line II)
(3) successful investigation of important generalizations of the averaging framework such as a) the mastering of the effective evolution of inhomogeneous light fronts, b) an improved closure condition that allows to employ physically justified models, in contrast to phenomenlogical ones for the comparison with observational data, c) a successful proposal for an effective implementation of the inflationary paradigm in the framework of inhomogeneous cosmologies (Research Sub-Lines i and ii)
(4) have we convinced the international community of the importance of improving on the standard model of cosmology, through the above results and through fundamental arguments ? In other words: did we constructively contribute to establishing the new research field employing averaged inhomogeneous cosmologies in place of the standard homogeneous cosmologies ?

Although ARTHUS relies on two main research lines that are both doable on schedule, the outcome of the two research sublines determines, *how far* we can go in achieving our ambituous goal to explain *Dark Energy*. As this part of ARTHUS is very involved and requires solution of a number of difficult theoretical questions, we also implement the following *hierarchical structure of priorities*:

(1) *First priority* will be given to results concerning a) the construction of light front averages, since this can be achieved in view of the theoretical expertise of people working in and collaborating with ARTHUS. Here, we open a large door to the interpretation of observational data, and we can consider ARTHUS as being successful, if we have investigated such a fundamental framework that enables to address all relevant questions in observational cosmology. This includes secondary effects of the CMB, propagation of typical scales of baryonic acoustic oscillations (BAO), effective treatment of gravitational lensing, large-scale fluctuation properties of galaxy catalogues, and supernovae observations (among, others).

(2) *Second priority* will be given to those aspects of b) new closure assumptions of the averaging equations that allow to implement strategies of discrimination between averaged cosmologies and the standard model. Here we think that a cornerstone of our success could be found in an unambigous feature that is unique to the averaged models, e.g. a signature in the temporal evolution of key-variables that furnish the proposal of i) an *observational strategy* that can be realized with current observational instruments, and ii) an observational *prediction* of the theoretically identified features. This priority implies that we are not satisfied with a mere consistency between the new models and a variety of observations, but that we wish to unambigously say that we are capable on the grounds of observations to decide, whether the standard model would fail in explaining certain features of the new models.

### *Future prospects of results of ARTHUS*

Given the large planning activity of new survey projects world wide, such as the survey projects *KIDS, PanSTARRS, eROSITA, HETDEX, etc.*, only to mention some, the need for enlarging the interpretational framework is demanding. For example, the acceleration of the Universe, attempted to be more directly accessed by a VLT project, is a model-dependent concept, and if the standard idealized model is the only reference body to which these observations can be compared, then we face the unbalanced situation that on the modeling side there has not been any substantial development (in fact the standard model is known since almost a century), while the standard of observations has tremdendously improved.
This latter asks for the application of the same high standards to modeling techniques. Since these standards are available on the theoretical side, ARTHUS fulfils the longstanding need *to incorporate inhomogeneities in any comparison of model and observations*.
This is not an academic adventure, but inhomogeneities exist and are quantified by all these mentioned observational projects.
Numerical simulations that are nowadays employed to describe inhomogeneites have a Newtonian architecture, and are therefore unable to address the effect we are studying in ARTHUS. Having emphasized this, we are also convinced that future *numerical simulations will have to be generalized*, and again it is ARTHUS that will open the doors to this future activity. We hope that we shall, already during the realization of the projects, provide key-elements for such a generalization of standard modeling techniques.

### *Integration of the project into the policy of CRAL*

CRAL's policy is to establish cosmological research in relation to extragalactic observations. With this project we integrate these needs by focussing on the highly important question of understanding the dark constituents of the Universe. This provides the basis of a) establishing a strong group as a center of this research field in Lyon, in France and world wide; b) implementation of tools and methods at the heart of the larger group at CRAL; c) providing synergies for advanced research topics that naturally define follow-up projects, relevant to an improved interpretation of observational data, as well as a large potential to improve methods and techniques, relevant to other group activities. As for the latter, we provide more details in the following paragraph.

### *Spin–offs from ARTHUS that define future projects in the larger group at CRAL*

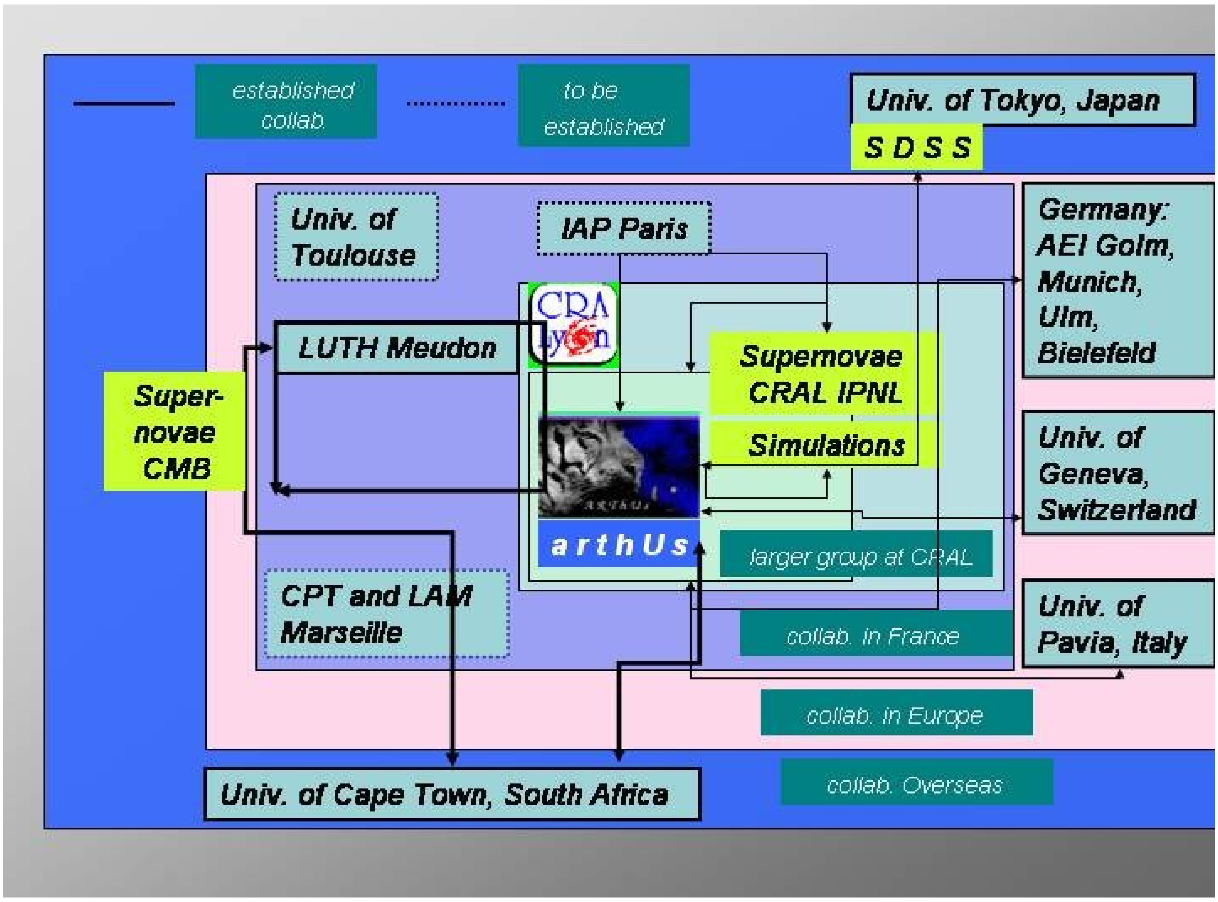
There are a number of other potential projects, not yet precised, that will be relevant for the embedding of the project activities of ARTHUS to the activities in the larger group at CRAL. This latter consists of galaxy physics research, instrumentation issues and numerical simulation efforts.

The expected spin-offs will be the result of a parallel effort to transfer knowledge to the larger group, in particular of innovative statistical measures, that the P.I. of this project has developed during the last 12 years at Munich University. Here, a morphological analysis - employing for example vectorial and tensorial Minkowski valuations - is in the center of these thoughts (for example applied to the morphological classification of galaxies, ATLAS 3D) and the application to substructure detection in the chemodynamic simulations pursued in the large group. Numerical codes that will be implemented at CRAL for the ARTHUS project will be equally useful for other research subjects pursued in the larger group.

Existing bonds to the ANR HORIZON project will be watched, in correspondence with the group members and, in particular, in communication with researchers at IAP, Paris.
Note here that contemporary numerical simulations are built on a Newtonian architecture and are, by construction, not able to simulate the effect studied in the project ARTHUS, since this effect is genuinly relativistic. Relativistic numerical simulations in cosmology are practically non-existing until today. The project ARTHUS, with the analytical results of Research line I, is able to provide key-elements for a future construction of such relativistic simulations. (Note that most of the current Newtonian simulations are initialized with the Zel'dovich approximation, and it is this approximation that will be generalized.) The project ARTHUS will also provide other key-elements to systematically build such simulations, that would be the first world-wide.

A direct link to the supernovae groups at CRAL and IPNL, centered on E. Pécontal and G. Smadja, will already take effect after we have successfully implemented the comparison with supernova data in the averaged models. We then have a tool to compare the interpretation of the data between the standard modeling and the models of ARTHUS. It will give us the opportunity to rediscuss a number of aspects of the conventional strategies followed so far, and we expect an innovative push towards the emphasis of model-prior independent aspects of the database. As mentioned above, we also have the opportunity to design strategies of observations that would discriminate between the different modeling priors.

### *ARTHUS – organigramme of collaborations*



# 2. Justification scientifique des moyens demandés. *Requested budget : detailed financial plan.*

*Présenter ici* ***la justification scientifique et technique*** *des moyens demandés dans le document de soumission*

## 2.1. Equipement. *Large equipment*

*Préciser la nature des équipements et justifier le choix des équipements. Si nécessaire, préciser la part de financement demandé sur le projet et si les achats envisagés doivent être complétés par d'autres sources de financement. Si tel est le cas, indiquer le montant et l'origine de ces financements complémentaires.*

*There are no expenses related to large equipments.*

## 2.2. Personnel. *Personnel.*

*Justifier le personnel non permanent (thèses, post-doctorants,CDD..) financé sur le projet.*
*Fournir les profils des postes à pourvoir pour les personnes à recruter (1/2 page maximum par type de poste).*
*Pour les thèses, préciser si des demandes de bourse de thèse sont prévues ou en cours, en préciser la nature et la part de financement imputable au projet.*

*The successful realization of ARTHUS requires financial support for two postdoctoral research positions lasting for three years each.*

*Profiles of the positions:*

*First postdoctoral position.*

This position is taken by a researcher with a strong background in general relativity, and, generally, with analytical skills to tackle the problems related to the two main Research Lines, as well as Research Sub-Line i, and later contributing to Research Sub-Line ii.
He is the person who is closely associated with the general project plan, its schedule, as well as the coordination between the subprojects. He is supposed to take leadership, in direct correspondence with the P.I,. in the realization of all the projects, he is engaged in the P.I.'s supervision of up to three Ph.D. students working on the project, and he coordinates research visits and envisaged informal and working meetings (round tables) with our national and international collaborators that will be held in Lyon. He also partakes in activities of public outreach.

*Second postdoctoral position.*

This position is taken by a researcher with strong numerical skills. He will focus on the numerical implementation of the models constructed in Research Line I, and interacts with all the other projects as for the setup of numerical strategies to realize the models, analysis techniques, and the presentation of the results. As for the latter, coordinating public outreach of results of ARTHUS is in the focus too. He interacts with other members of CRAL to realize a broader numerical expertise in the group.

He is engaged in the supervision of one Ph.D. student, who will be associated directly with numerical aspects of the projects. The emphasis here will be on aspects of morphological analyses of simulation data and galaxy catalogues and, generally, on novel statistical tools including morphological image analysis. The idea is also to channel information and know-how, via J. Blaizot, to other researchers in the laboratory.
This postdoc so also personalizes the link of the project activity to activities of the larger group, takes track of common strategies and methods, and he is responsable, in correspondence with J. Blaizot and the P.I. of the project, for a successful initialization of spin-offs from the project ARTHUS, that have been described above. Links to the HORIZON project, to the simulation aspects of MUSE, to the analysis of chemodynamical simulations, and to image analysis techniques (ATLAS 3D) lie at the interface of activities pursued in ARTHUS.

Since it may be difficult to find a numerical expert who can be productive in all these issues *immediately*, we already have a candidate in mind (for the first year of this position): Christopher Rimes is currently doing test runs of the Minkowski statistical analysis codes, and his expertise is well-embedded into the current group activities at CRAL.

## *Envisaged Ph.D. Students working in ARTHUS:*

We plan to have two Ph.D. students in the theoretical cosmology group, who start their work directly within the ARTHUS project. We believe that financing these two students can be achieved by other sources. In the case ARTHUS starts, the presence of postdoctorands suggests and allows to gather more students. We would like to attract a third Ph.D. student, starting later in 2009
While the first two will be associated with the main Research Lines I and II, this third student would work on numerical aspects in direct correspondence with the second postdoctorand.

The lively interest of students to work on these questions is documented by a long list of requests for doing stages (Master 1 and Master 2 students) in the newly established group. Three very motivated students started their stages now. There are already applications for the two Ph.D. thesis topics, which have been announced, also from other students within France.

## 2.3. Prestation de service externe. *Services, outward facilities.*

*Préciser :*

*la nature des prestations, le type de prestataire, le coût.*

*There are no costs associated, since the project is essentially based on human resources.*

## 2.4. Missions. *Travels.*

*Préciser :*

- *les missions liées aux travaux d'acquisition sur le terrain (campagnes de mesures…), les missions relevant de colloques, congrès…,le coût estimé*

*.*

***ARTHUS – people***

*The number of researchers who are directly involved in ARTHUS would amount to about 10:*

*(The order of appearence agrees with the table in Part A)*

| | | | |
|---|---|---|---|
| ***T0*** | ***Thomas Buchert*** | ***PRU (CRAL)*** | ***50 %*** |
| ***T1*** | ***N.N.*** | ***1st Postdoctorand (ANR)*** | ***100 %*** |
| ***T2*** | ***N.N.*** | ***2nd Postdoctorand (ANR)*** | ***100 %*** |
| ***T3*** | ***Alexandre Arbey*** | ***MCF (CRAL)*** | ***50 %*** |
| ***T4*** | ***Jérémy Blaizot*** | ***Astronome Adjoint (CRAL)*** | ***20 %*** |
| ***T5*** | ***Emmanuel Pécontal*** | ***Astronome Adjoint (CRAL)*** | ***10 %*** |
| ***T6*** | ***Gérard Smadja*** | ***PRU (IPNL)*** | ***10 %*** |
| ***T7*** | ***David Mota*** | ***Associated*** | ***30 %*** |
| ***T8*** | ***N.N.*** | ***Doctorand (CRAL)*** | ***100 %*** |
| ***T9*** | ***N.N.*** | ***Doctorand (CRAL)*** | ***100 %*** |

*Note: one or two external collaborators coming to CRAL on exchange grants or ATER positions will join the project. Here, David Mota expressed his intention to work in close contact to the project.*

*As a consequence we envisage the following strategy plan for Travels:*

***National Travels:*** *6 per year, each 1 week, to LUTH, but also to other groups within France (Montpellier, Marseille, Toulouse): Estimated: 6000 Euro per year.*

***total estimated: 18000 Euro***

***International Travels:*** *a substantial part of international travels will be covered through financing of the inviting institution (e.g. to Tokyo, Cape Town). However, to support these travels – with a specific short-term task - it is important that one of the group members may join. This implies that we envisage up to 2 travels per year to Tokyo or Cape Town over all group members.*

*Other sites like Pavia, Genève, Munich (and others in Europe) are also targets, and here we envisage in total 4 travels per year. Estimated: 6000 Euro per year.*

***total estimated: 18000 Euro***

*Furthermore, to keep a high standard of communication with our national and international collaborators, we envisage to invite guest researchers, for typically one or two weeks, as follows:*

***National Invitations:*** *6 per year, 1 week each, from LUTH, but also from other groups within France (Marseille, Toulouse, Montpellier). Estimated 6000 Euro per year.*

***total estimated: 18000 Euro***

***International Invitations:*** *8 per year from Tokyo, Cape Town, U.S.A., Pavia, Genève, Munich (and others). As for invitations from overseas, we shall try to keep travel money at a minimum by choosing invitation dates at times where the respective researchers are working in Europe.*

***Combined with: ARTHUS – round tables (see below)***

*These latter invitations are also coordinated with informal working meetings that we wish to organize one time a year (the round tables of ARTHUS). The estimated 8 invitations roughly defines twice the upper limit of invitated international researchers to one of those meetings per year. Altogether estimated: 8000 Euro per year.*

***total estimated: 24000 Euro***

***Note: In the table of Part A, all invitations are taken on the P.I.***

## ARTHUS – people of the *round tables*

***(listed are international guests of ongoing or near-future collaborations only)***

professors — perm. researchers and postdocs

| | | | | | |
|---|---|---|---|---|---|
| ***L. Andersson*** | ***Golm*** | ***Gen. Relativity fund aspects*** | ***J. Behrend*** | ***Ulm*** | ***Averaging Perturbations*** |
| ***M. Carfora*** | ***Pavia*** | ***averaging geometry*** | ***C. Beisbart*** | ***Dortmund*** | ***Morphology Programming*** |
| ***R. Durrer*** | ***Geneva*** | ***Grav. Theories Early universe*** | ***H.v. Elst*** | ***Karlsruhe*** | ***Gen. Relativity Exact Solut.*** |
| ***J. Ehlers*** | ***Golm*** | ***Gen. Relativity Fund. aspects*** | ***C. Hikage*** | ***Nottingham*** | ***SDSS Data Analysis*** |
| ***G.F.R. Ellis*** | ***Cape Town*** | ***Averaging Fund. Aspects*** | ***M. Kerscher*** | ***Munich*** | ***Averaging Programming*** |
| ***D. J. Schwarz*** | ***Bielefeld*** | ***Lightcone CMB Perturbations*** | ***M. Kunz*** | ***Brighton*** | ***Supernovae CMB*** |
| ***F. Steiner*** | ***Ulm*** | ***CMB: Simulations*** | ***J. Larena*** | ***Cape Town*** | ***Averaging Scalar Fields*** |
| ***Y. Suto*** | ***Tokyo*** | ***SDSS Morphology*** | ***A. Rakic*** | ***Würzburg*** | ***Lightcone CMB*** |
| ***H. Wagner*** | ***Munich*** | ***Statistics Fund. Aspects*** | ***S. Räsänen*** | ***Geneva*** | ***Averaging Observations*** |

The *round tables,* that will be held once each year at CRAL, will gather about 4 people from this list. In addition, some researchers from France will be invited (including ***J.M. Alimi*** (Meudon), ***A. Blanchard*** (Toulouse), ***S. Colombi*** (Paris), ***M. Joyce*** (Paris), ***D. Polarski*** (Montpellier), ***C. Rovelli*** (Marseille), ***R. Triay*** (Marseille), and others).They would join together with the local people, so that one table would consist of about 12 people.
These *round tables* will specifically discuss strategies relevant to the development of ARTHUS.

## 2.5. Autres dépenses de fonctionnement. *Other expenses.*

*Justifier toute dépense significative relevant de ce poste.*

*Since the group essentially starts without equipment, except that of the permanent members, it is necessary to buy computer facilities as follows:*

***1)*** *Four Desktop Computers :*

*one out of these four will be bought with an upgrade for the purpose of the numerical aspects of the project. They will be used by two ANR postdocs and two Ph.D. students.*

***total estimated: 9000 Euro***

***2)*** *Four Notebook Computers :*

*one notebook is planned to be a commun one to be used by guest researchers. The other three are distributed among the members of the group.*

***total estimated: 9000 Euro***

*The observatory will provide office equipments for all members of the group. In the course.of restructuring of the groups in the observatory, offices are currently being renovated and their equipment renewed.*

# *A P P E N D I X*

## Statements by International Researchers in support of the project

1. by ***George F.R. Ellis***
   Professor at the University of Cape Town, South Africa

2. by ***Edward W. Kolb***
   Professor at the University of Chicago, U.S.A.

3. by ***Carlo Rovelli***
   Professor at the University of Marseille, France

4. note by ***Jürgen Ehlers***
   Director emeritus and founder of the Albert-Einstein-Institut, Golm, Germany

*University of Cape Town*

Professor George Ellis
*Department of Mathematics and Applied Mathematics*

The issue of averaging in general relativity theory, and hence determining the effective large scale dynamical and observational equations in cosmology, is an important one conceptually. It has recently gained practicle importance through the realisation that, because the recent universe is void dominated, the observations indicating a cosmic acceleration may be at least partly a reflection of this averaging. A research project to investigate this alternative to the main stream view on dark energy is important because the issue of the nature of dark energy is one of the main preoccupations of present day cosmology.

Prof. Buchert is eminently qualified to lead such a project, as he has investigated it in depth and the equations he set up are now widely recognised as crucial to understanding averaging.

Buchert is a very accomplished research worker in the application of General Relativity theory to issues of interest in cosmology and astrophysics, specially relating to the complex issue of structure formation. Here his work on Lagrangian formulations has been strongly influential and is widely quoted. He has many good international collaborations and is widely respected.

The projects listed will indeed be productive and important. There is recently much increased activity in the research fields of the "averaging problem" and its relation to "dark energy"., and Prof. Buchert plays a prominent role here. Now is the tie to undertake this work, when the study of dark energy is a major theme in cosmology. I am pleased that some of this work will be done in collaboration with the Cape Town group, indeed we have hired a postdoc - Julien Larena from the Observatory of Paris - to intensify the French - South African collaboration on these issues.

I strongly support the setting up of such a project under the guidance of Prof. Buchert.

For more details of the issues at stake, please see my News and Views article in
***Nature*** : **13th March issue, Vol 452, p.158***

George Ellis
Cape Town

** for another popular overview see for example:*
***the cover stories in New Scientist, 8th March 08 issue, Vol 2646***
***and in CIEL & espace March 08 issue*** *[ footnote added ]*

THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS
5640 SOUTH ELLIS AVENUE
CHICAGO, ILLINOIS 60637

EDWARD W. KOLB, *Professor and Chair*

March 24, 2008

Prof. Thomas Buchert
Université Lyon 1
Centre de Recherche Astrophysique de Lyon
9 avenue Charles André
F-69230 Saint-Genis-Laval
FRANCE

Dear Thomas,

I would like to express my strong support on behalf of the "Advances in the Research on Theories of the Dark Universe" proposal. In particular, I feel that the approach to dark energy you outline in the proposal is an extremely important attempt to reconcile cosmological observations without the necessity of an ad hoc cosmological constant.

Understanding the phenomenon of dark energy is at the forefront of cosmological research in the US and throughout the world. In the US it is ranked as the top question in cosmology / astrophysics / astronomy. It also ranks very high in the list of important issues of particle physicists.

You have chosen to explore the effect of cosmological inhomogeneities on the averaging problem in relativistic cosmology. As you know, our collaboration is pursuing similar methods. This problem is big enough that it will require a world-wide collaboration and commitment of many people to explore. You have played an enormous role in the subject, and your leadership is crucial for future progress. I hope your proposal is funded, and I look forward collaborating with the new group.

Sincerely,

Edward Kolb

Edward W. Kolb
Arthur Holly Compton Distinguished Service Professor

TELEPHONE: (773) 834-0287 · FAX: (773) 834-0744 · E-MAIL: Rocky.Kolb@uchicago.edu

LUMINY SCIENCES
UNIVERSITÉ DE LA MÉDITERRANÉE
AIX-MARSEILLE II

Université de la Méditerranée
Centre de Physique Théorique
Institut Universitaire de France
*Prof. Carlo Rovelli*

*Marseille, March 15th, 2008*

This is a letter in support of the application by Thomas Buchert to the ANR Chaire d'Excellence initiative ARTHUS.

I have known Thomas Buchert for longtime and have always strongly appreciated his scientific value. He is able to start from mathematical concepts and rapidly understand and derive their physical implications. He is a theoretician with a deep appreciation of relativistic physics, but also capable of understanding and communicating with observations.

The project that Buchert presents is centered on a new strategy to resolve the dark energy problem. This is a major problem in cosmology, which has strong relevance also for theoretical relativity, and particle physics: the issues it raises involve the possibility of modifying general relativity, the possible existence of a fundamental scalar field, and the relation between the cosmological constant that appears in Einstein's equation and the properties of the vacuum of quantum field theory. Major theoretical and observational efforts are currently being directed to address this major conundrum in our understanding of the universe.

In this complex situation, Buchert's ideas offer a refreshing and intriguing alternative: interpretation of the "missing fields" may be the simply the result of the oversimplification of the cosmological model itself. The standard cosmological model is of course simplistic, since it neglects inhomogeneities, and a generalization from the modeling point of view may be due. Buchert has suggested a generalization of the cosmological equations that includes the effect of inhomogeneities, and where the dark energy problem may be take a completely different aspect. I have been very impressed by these ideas on smoothing. I will not be surprised if these ideas will play an increasing role in the near future.

Buchert's proposal is today known and discussed by a large community of researchers in cosmology, but also researchers on gravitational theories in general and of theoretical particle physics. Buchert is the world expert in these projects, and the Chaire d'Excellence is therefore a good opportunity to reinforce the dark energy search, as well as relativistic cosmology in France. These major research directions are perhaps not sufficiently represented in France on the theoretical side. Buchert's project may also help to centralize efforts within France.

As far as the practical implementation of the ambitious goals of the project are concerned, I have no doubt that Buchert provides the substance and the expertise. He has developed a transparent framework of the general problem of dealing with in-homogeneous cosmological models, and he contributed to the deep understanding of the averaging problem in general relativity. The "Buchert equations" on which the framework is based provide a basic tool for addressing all the general questions.

Buchert has a large number of international relations; his collaborators include experts on mathematical physics problems in Riemannian geometry (Mauro Carfora), world experts on general relativity (Jürgen Ehlers), most of the researchers who either contributed in the recent years to investigate the effect predicted by Buchert's equations, and the originators of the averaging problem itself (George Ellis). The link to observational tests is well-formulated. Moreover, the techniques for generalizing structure formation models represent another area of expertise of Buchert, who has earlier pioneered the Lagrangian perturbation approach that furnishes one of the basic ingredients of the project. Finally, Buchert has high pedagogical skills that guarantee successful leadership of the group activities.

The ANR project proposed by Thomas Buchert has the potential for resolving a major problem of wide interest. Even if the final answer to the dark energy problem will not be found, the project can substantially contribute to the development of cosmological model building and the physical interpretation of astronomical data. In any case, the project can contribute substantially to French high-level research and the international visibility of French science.

Carlo Rovelli

Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

*Prof. Jürgen Ehlers*
*Director emeritus*

*Golm, March 17, 2008*

*Dear Thomas,*

*I have read your research proposal ARTHUS with great interest. It seems to me long overdue to investigate carefully and without prejudice, which influence the inhomogeneities have on the overall evolution of the universe. In view of the complex, hierarchical meta distribution with density contrasts on all scales below a few hundred Mpc, and the nonlinearity of the gravitational and hydrodynamic equations such an influence must exist. The question is of which kind and strength it is.*

*I hope your proposal will be accepted and the work will lead to a solid conclusion. In any case, please inform me on the further development.*

*With best regards,*

*Jürgen*