

**Topics for seminars for Models of Dark Energy**  
**Prof. Dr. Luca Amendola, Dr. Valerio Marra**  
**Friday 11:15-12:45**

**1- Growing Neutrino Quintessence**

Neutrino Lump Fluid in Growing Neutrino Quintessence  
Youness Ayaita, Maik Weber, Christof Wetterich  
<http://arxiv.org/abs/arXiv:1211.6589>

Growing neutrino quintessence addresses the "why now" problem of dark energy by assuming that the neutrinos are coupled to the dark energy scalar field. The coupling mediates an attractive force between the neutrinos leading to the formation of large neutrino lumps. This work proposes an effective, simplified description of the subsequent cosmological dynamics. We treat neutrino lumps as effective particles and investigate their properties and mutual interactions. The neutrino lump fluid behaves as cold dark matter coupled to dark energy. The methods developed here may find wider applications for fluids of composite objects.

Structure Formation and Backreaction in Growing Neutrino Quintessence  
Youness Ayaita, Maik Weber, Christof Wetterich  
<http://arxiv.org/abs/arXiv:1112.4762>

A dependence of the neutrino masses on the dark energy scalar field could provide a solution to the why now problem of dark energy. The dynamics of the resulting cosmological model, growing neutrino quintessence, include an attractive force between neutrinos substantially stronger than gravity. We present a comprehensive approach towards an understanding of the full cosmological evolution including the formation of large-scale neutrino structures. Important effects we account for are local variations in the dark energy and the backreaction on the background evolution, as well as relativistic neutrino velocities. For this aim, we develop a relativistic N-body treatment of the neutrinos combined with an explicit computation of the local quintessence field. At its current stage, the simulation method is successful until  $z \sim 1$  and reveals a rich phenomenology. We obtain a detailed picture of the formation of large-scale neutrino structures and their influence on the evolution of matter, dark energy, and the late-time expansion of the universe.

## **2- Variation of fundamental constants, in particular of $\alpha$ from coupling between quintessence and the electromagnetic field**

Varying constants, Gravitation and Cosmology

Jean-Philippe Uzan

<http://arxiv.org/abs/arXiv:1009.5514>

Fundamental constants are a cornerstone of our physical laws. Any constant varying in space and/or time would reflect the existence of an almost massless field that couples to matter. This will induce a violation of the universality of free fall. It is thus of utmost importance for our understanding of gravity and of the domain of validity of general relativity to test for their constancy. We thus detail the relations between the constants, the tests of the local position invariance and of the universality of free fall. We then review the main experimental and observational constraints that have been obtained from atomic clocks, the Oklo phenomenon, Solar system observations, meteorites dating, quasar absorption spectra, stellar physics, pulsar timing, the cosmic microwave background and big bang nucleosynthesis. At each step we describe the basics of each system, its dependence with respect to the constants, the known systematic effects and the most recent constraints that have been obtained. We then describe the main theoretical frameworks in which the low-energy constants may actually be varying and we focus on the unification mechanisms and the relations between the variation of different constants. To finish, we discuss the more speculative possibility of understanding their numerical values and the apparent fine-tuning that they confront us with.

The Wall of Fundamental Constants

Keith A. Olive, Marco Peloso, Jean-Philippe Uzan

<http://arxiv.org/abs/arXiv:1011.1504>

We consider the signatures of a domain wall produced in the spontaneous symmetry breaking involving a dilaton-like scalar field coupled to electromagnetism. Domains on either side of the wall exhibit slight differences in their respective values of the fine-structure constant,  $\alpha$ . If such a wall is present within our Hubble volume, absorption spectra at large redshifts may or may not provide a variation in  $\alpha$  relative to the terrestrial value, depending on our relative position with respect to the wall. This wall could resolve the "contradiction" between claims of a variation of  $\alpha$  based on Keck/Hires data and of the constancy of  $\alpha$  based on VLT data. We derive the properties of the wall and the parameters of the underlying microscopic model required to reproduce the possible spatial variation of  $\alpha$ . We discuss the constraints on the existence of the low-energy domain wall and describe its observational implications concerning the variation of the fundamental constants.

### 3- Void models as alternative to dark energy

Observational constraints on inhomogeneous cosmological models without dark energy

Valerio Marra, Alessio Notari

<http://arxiv.org/abs/1102.1015>

It has been proposed that the observed dark energy can be explained away by the effect of large-scale nonlinear inhomogeneities. In the present paper we discuss how observations constrain cosmological models featuring large voids. We start by considering Copernican models, in which the observer is not occupying a special position and homogeneity is preserved on a very large scale. We show how these models, at least in their current realizations, are constrained to give small, but perhaps not negligible in certain contexts, corrections to the cosmological observables. We then examine non-Copernican models, in which the observer is close to the center of a very large void. These models can give large corrections to the observables which mimic an accelerated FLRW model. We carefully discuss the main observables and tests able to exclude them.

Linear kinetic Sunyaev-Zel'dovich effect and void models for acceleration

James P. Zibin, Adam Moss

<http://arxiv.org/abs/arXiv:1105.0909>

There has been considerable recent interest in cosmological models in which the current apparent acceleration is due to a very large local underdensity, or void, instead of some form of dark energy. Here we examine a new proposal to constrain such models using the linear kinetic Sunyaev-Zel'dovich (kSZ) effect due to structure within the void. The simplified "Hubble bubble" models previously studied appeared to predict far more kSZ power than is actually observed, independently of the details of the initial conditions and evolution of perturbations in such models. We show that the constraining power of the kSZ effect is considerably weakened (though still impressive) under a fully relativistic treatment of the problem, and point out several theoretical ambiguities and observational shortcomings which further qualify the results. Nevertheless, we conclude that a very large class of void models is ruled out by the combination of kSZ and other methods.

Can decaying modes save void models for acceleration?

James P. Zibin

<http://arxiv.org/abs/arXiv:1108.3068>

The unexpected dimness of Type Ia supernovae (SNe), apparently due to accelerated expansion driven by some form of dark energy or modified gravity, has led to attempts to explain the observations using only general relativity with baryonic and cold dark matter, but by dropping the standard assumption of homogeneity on Hubble scales. In particular, the SN data can be explained if we live near the centre of a Hubble-scale void. However, such void models have been shown to be inconsistent with various observations, assuming the void consists of a pure growing mode. Here it is shown that models with significant decaying mode contribution today can be ruled out on the basis of the expected cosmic microwave background spectral distortion. This essentially closes one of the very few remaining loopholes in attempts to rule out void models, and strengthens the evidence for Hubble-scale homogeneity.

## 4- Real time cosmology

Real-time Cosmology

Claudia Quercellini, Luca Amendola, Amedeo Balbi, Paolo Cabella, Miguel Quartin

<http://arxiv.org/abs/arXiv:1011.2646>

In recent years the possibility of measuring the temporal change of radial and transverse position of sources in the sky in real time have become conceivable thanks to the thoroughly improved technique applied to new astrometric and spectroscopic experiments, leading to the research domain we call Real-time cosmology. We review for the first time great part of the work done in this field, analysing both the theoretical framework and some endeavor to foresee the observational strategies and their capability to constrain models. We firstly focus on real time measurements of the overall redshift drift and angular separation shift in distant source, able to trace background cosmic expansion and large scale anisotropy, respectively. We then examine the possibility of employing the same kind of observations to probe peculiar and proper acceleration in clustered systems and therefore the gravitational potential. The last two sections are devoted to the short time future change of the cosmic microwave background, as well as to the temporal shift of the temperature anisotropy power spectrum and maps. We conclude revisiting in this context the effort made to forecast the power of upcoming experiments like CODEX, GAIA and PLANCK in providing these new observational tools.

## 5- Anomalies in the sky

Planck 2013 results. XXIII. Isotropy and Statistics of the CMB

Planck Collaboration

<http://arxiv.org/abs/1303.5083>

The two fundamental assumptions of the standard cosmological model - that the initial fluctuations are statistically isotropic and Gaussian - are rigorously tested using maps of the CMB anisotropy from the \Planck\ satellite. The detailed results are based on studies of four independent estimates of the CMB that are compared to simulations using a fiducial  $\Lambda$ CDM model and incorporating essential aspects of the \Planck\ measurement process. Deviations from isotropy have been found and demonstrated to be robust against component separation algorithm, mask and frequency dependence. Many of these anomalies were previously observed in the \textit{WMAP} data, and are now confirmed at similar levels of significance (around  $3\sigma$ ). However, we find little evidence for non-Gaussianity with the exception of a few statistical signatures that seem to be associated with specific anomalies. In particular, we find that the quadrupole-octopole alignment is also connected to a low observed variance of the CMB signal. The dipolar power asymmetry is now found to persist to much smaller angular scales, and can be described in the low- $\ell$  regime by a phenomenological dipole modulation model. Finally, it is plausible that some of these features may be reflected in the angular power spectrum of the data which shows a deficit of power on the same scales. Indeed, when the power spectra of two hemispheres defined by a preferred direction are considered separately, one shows evidence for a deficit in power, whilst its opposite contains oscillations between odd and even modes that may be related to the parity violation and phase correlations also detected in the data. Whilst these analyses represent a step forward in building an understanding of the anomalies, a satisfactory explanation based on physically motivated models is still lacking.

A measurement of large-scale peculiar velocities of clusters of galaxies: results and cosmological implications

A. Kashlinsky, F. Atrio-Barandela, D. Kocevski, H. Ebeling

<http://arxiv.org/abs/0809.3734>

Peculiar velocities of clusters of galaxies can be measured by studying the fluctuations in the cosmic microwave background (CMB) generated by the scattering of the microwave photons by the hot X-ray emitting gas inside clusters. While for individual clusters such measurements result in large errors, a large statistical sample of clusters allows one to study cumulative quantities dominated by the overall bulk flow of the sample with the statistical errors integrating down. We present results from such a measurement using the largest all-sky X-ray cluster catalog combined to date and the 3-year WMAP CMB data. We find a strong and coherent bulk flow on scales out to at least  $> 300 h^{-1}$  Mpc, the limit of our catalog. This flow is difficult to explain by gravitational evolution within the framework of the concordance  $\Lambda$ CDM model and may be indicative of the tilt exerted across the entire current horizon by far-away pre-inflationary inhomogeneities.

## 6- Bayesian statistical methods

Bayes in the sky: Bayesian inference and model selection in cosmology

Roberto Trotta

<http://arxiv.org/abs/arXiv:0803.4089>

The application of Bayesian methods in cosmology and astrophysics has flourished over the past decade, spurred by data sets of increasing size and complexity. In many respects, Bayesian methods have proven to be vastly superior to more traditional statistical tools, offering the advantage of higher efficiency and of a consistent conceptual basis for dealing with the problem of induction in the presence of uncertainty. This trend is likely to continue in the future, when the way we collect, manipulate and analyse observations and compare them with theoretical models will assume an even more central role in cosmology.

This review is an introduction to Bayesian methods in cosmology and astrophysics and recent results in the field. I first present Bayesian probability theory and its conceptual underpinnings, Bayes' Theorem and the role of priors. I discuss the problem of parameter inference and its general solution, along with numerical techniques such as Monte Carlo Markov Chain methods. I then review the theory and application of Bayesian model comparison, discussing the notions of Bayesian evidence and effective model complexity, and how to compute and interpret those quantities. Recent developments in cosmological parameter extraction and Bayesian cosmological model building are summarized, highlighting the challenges that lie ahead.

Robustness to systematics for future dark energy probes

M. C. March, R. Trotta, L. Amendola, D. Huterer

<http://arxiv.org/abs/arXiv:1101.1521>

We extend the Figure of Merit formalism usually adopted to quantify the statistical performance of future dark energy probes to assess the robustness of a future mission to plausible systematic bias. We introduce a new robustness Figure of Merit which can be computed in the Fisher Matrix formalism given arbitrary systematic biases in the observable quantities. We argue that robustness to systematics is an important new quantity that should be taken into account when optimizing future surveys. We illustrate our formalism with toy examples, and apply it to future type Ia supernova (SNIa) and baryonic acoustic oscillation (BAO) surveys. For the simplified systematic biases that we consider, we find that SNIa are a somewhat more robust probe of dark energy parameters than the BAO. We trace this back to a geometrical alignment of systematic bias direction with statistical degeneracy directions in the dark energy parameter space.

Internal Robustness: systematic search for systematic bias in SN Ia data

Luca Amendola, Valerio Marra, Miguel Quartin

<http://arxiv.org/abs/1209.1897>

A great deal of effort is currently being devoted to understanding, estimating and removing systematic errors in cosmological data. In the particular case of type Ia supernovae, systematics are starting to dominate the error budget. Here we propose a Bayesian tool for carrying out a systematic search for systematic contamination. This serves as an extension to the standard goodness-of-fit tests and allows not only to cross-check raw or processed data for the presence of systematics but also to pin-point the data that are most likely contaminated. We successfully test our tool with mock catalogues and conclude that the Union2.1 data do not possess a significant amount of systematics. Finally, we show that if one includes in Union2.1 the supernovae that originally failed the quality cuts, our tool signals the presence of systematics at over 3.8-sigma confidence level.

others:

- cosmological constant: problems and possible solutions, e.g. anthropic principle + stringscape

Section IV of Dynamics of dark energy

Edmund J. Copeland, M. Sami, Shinji Tsujikawa

<http://arxiv.org/abs/hep-th/0603057>

- Mond theory

- massive gravity