CAPUT DARK ENERGY TOPICS, 2013

1. The Cosmological Constant

- The acceleration of the Universe may be ascribed to the cosmological constant. That is, just that, the cosmological constant as curvature term in the Einstein field equation and not a form of dark energy. Provide a critical discussion of this point of view, both including arguments pro and con.
- *Literature suggestions:*
  - Kolb R., Bianchi E., Rovelli C., 2010
    Is dark energy really a mystery ?
    Nature, 466, 321 (July 2010)
  - Padmanabhan T., 2003
    Cosmological Constant - Weight of the Vacuum
    arXiv:hep-th/0212290
  - Peebles P.J.E., Ratra B., 2003
    The cosmological constant and dark energy
    Rev. Mod. Phys., 75, 559
  - Triay R., 2010
    Dark energy: fiction or reality ?
    arXiv: 1004.0091

2. Supernovae, Dark Energy and the Accelerating Universe

- With the realization that Supernovae Ia can be used as standard candles, in 1998 supernovae surveys came to the startling conclusion that our Universe is accelerating. This is commonly seen as the strongest support for the existence of dark energy. Provide a review of supernova cosmology and the prospects for using future supernova surveys for measuring the equation of state, its possible evolution, and determining the nature of dark energy.
- *Literature suggestions:*
  - Leibundgut B., 2001
    Cosmological Implications from Observations of Type Ia Supernovae
    Annual Review Astronomy Astrophysics, 39, 67-98
  - Frieman J.A., Turner M.S., Huterer D., 2008
    Dark Energy and the Accelerating Universe
    Annual Review Astron. Astrophys., 46, 385
  - Astier P., 2012
    The expansion of the universe observed with supernovae
    Physics Reports
  - Perlmutter S., Schmidt B., Riess A., 2012,
    Nobel Lectures
    Reviews of Modern Physics, Vol. 84 (July-Sept. 2012)

3. Baryonic Acoustic Oscillations

- Baryonic oscillations in the power spectrum of galaxy clustering have recently been detected from the 2dFGRS and SDSS galaxy redshift survey. At the moment various deep redshift surveys are being designed to measure the baryonic oscillations and get a precise measurement of the equation of state of dark energy from this purely geometric and robust method. Give a discussion of the fundamental physics behind the oscillations, on the detection and measurement of the oscillations and on the prospects to study dark energy.

- *Literature suggestions:*
  - Eisenstein D.J. and C.L. Bennett
    Cosmic sound waves rule
    Physics Today, april 2008, 44
  - Colless M.
    The WiggleZ Dark Energy Survey
    KIAS workshop 2008, ppt (on request from RvdW).
  - Eisenstein D.J., Hu W., 1997
    Baryonic Features in the Matter Transfer Function
    ApJ 496, 605
  - Seo H-J, Eisenstein D.J., 2005
    Baryon Acoustic Oscillations in Simulated Galaxy Redshift Surveys
    ApJ 633, 575
  - Seo H-J, Eisenstein D.J., 2005
    Probing Dark Energy with Baryonic Acoustic Oscillations
    ASP, Vol. 399
  - White M., 2005
    Baryon Oscillations
    Astroparticle Physics 24, 334
  - Bassett B.A., Hlozek R., 2009
    Baryon Acoustic Oscillations
    arXiv:0910.5224

4. Gravitational Lensing and Dark Energy Measurement

- One of the main probes for the accurate measurement of dark energy parameters is gravitational weak lensing. Provide a thorough discussion of the theoretical basis of this, as well as the observational and practical challenges involved and the prospects in the light of upcoming surveys suchs as KIDS, DES, Euclid and LSST.

- *Literature Suggestions*
  - ESA
    Euclid, Mapping the geometry of the dark Universe
    ESA/SRE(2011)12, July 2011
  - Heavens A., 2011
    Cosmology with gravitational lensing
    arXiv:1109.1121
  - Hoekstra H., Jain B., 2008
    Weak Gravitational Lensing and Its Cosmological Applications
    Ann. Rev. Nucl. Part. Physics, 58, 99
  - Huterer D., 2010
    Weak lensing, dark matter and dark energy
    arXiv:1001.1758
  - Laszlo I., Bean R., Kirk D., Bridle S.
    Disentangling dark energy and cosmic tests of gravity from weak lensing systematics
  - Mellier Y., 1999
    Probing the Universe with Weak Lensing
    Ann. Rev. Astron. Astrophys. 37, 127-189
  - van Waerbeke L., Mellier Y., 2003
    Gravitational Lensing by Large Scale Structures: A Review
    arXiv:astro-ph/0305089

5. Redshift Space Distortions, Growth Rate and Dark Energy

- E. Linder pointed out that it should be possible to determine the cosmic structure growth rate history by looking at the redshift space distortion in the clustering of galaxies. Deep galaxy redshift surveys may thus provide strong constraints on the nature of dark energy. Provide a discussion of the fundamentals of the method, and subsequently provide a critical assessement of the observational projects that have been carried out and will be carried out along these lines.
- *Literature suggestions:*
  - Guzzo L., et al., 2008
    A test of the nature of cosmic acceleration using galaxy redshift distortions
    Nature, 451, Jan. 2008
  - Huterer D., Kirkby D., 2013
    Growth of Cosmic Structure: Probing Dark Energy Beyond Expansion
    arXiv:1309.5385
  - Linder E.V., 2005
    Cosmic growth history and expansion history
    Phys. Rev. D., 72, 043529
  - Linder E., 2007
    Redshift Distortions as a Probe of Gravity
    arXiv:0709.1113
  - Majerotto E., Guzzo L., et al., 2012
    Probing deviations from General Relativity with the Euclid spectroscopic survey
    MNRAS, 2012, arXiv:1205.6215

6. Integrated Sachs-Wolfe effect and Dark Energy

- The effect of dark energy on the evolution of gravitational potential perturbations is probed by the integrated Sachs-Wolfe effect. To this end, one needs to combine the large scale cosmic microwave background perturbations with the measured mass perturbations along the line of sight. Describe the theoretical context of the ISW, and discuss the complications and results of attempts towards measuring the ISW.
- *Literature suggestions:*
    - Crittenden R., Turok N., 1996,
      Looking for a Cosmological Constant with the Rees-Sciama Effect
      Phys. Rev. Lett., 76, 575
    - Giannantonio T., et al., 2008,
      Combined analysis of the integrated Sachs-Wolfe effect and cosmological implications
      Phys. Rev. D., 77, 123520
    - Giannantonio T., Crittenden R., Nichol R., Ross A.J., 2012,
      The significance of the integrated Sachs-Wolfe effect revisited
      MNRAS, 2012, arXiv:1209.2125
    - Hu W., Dodelson S., 2002
      Cosmic Microwave Background Anisotropies
      ARAA, 40, 171-216
    - Hu W., Sugiyama N., Silk J., 1997,
      The Physics of the Microwave Background Anisotropies
      Nature, Vol. 386, p. 37-43
    - Planck, 2013,
      Planck 2013 Results XIX. The Integrated Sachs-Wolfe effect.
      Astron. Astrophys., arXiv:1303.5079
    - Samtleben D., Staggs S., Winstein B., 2007,
      The Cosmic Microwave Background for Pedestrians: A Review for Particle and Nuclear Physicists
      Ann. Rev. Nucl. Part. Sci., 57, 245-283
    - Granett B.R., Neyrinck M.C., Szapudi I., 2008
      An imprint of superstructures of the microwave background due to the ntegrated Sachs-Wolfe effect
      Astrophys. J., 683, L99-L102

7. Dark Energy and Voids

- A recent very interesting observation is that voids in the mass distribution are highly sensitive probes of dark energy. Investigate the dynamical origin of this sensitivity, review recent studies on this, and discuss the prospects of using this sensitivity for probing dark energy in upcoming large surveys.
- *Literature suggestions:*
  - Bos E.G.P., van de Weygaert R., Dolag K., Pettorino V., 2012
    The darkness that shaped the void: dark energy and cosmic voids
    MNRAS, 426, 440
  - Lavaux G., Wandelt B.D., 2010 2
    Precision cosmology with voids: definition, methods, dynamics
    MNRAS, 403, 1392
  - Lavaux G., Wandelt B.D., 2012
    Precision Cosmography with Stacked Voids
    Astrophys.J., 754, 109
  - Lee J., Park D., 2009
    Constraining the Dark Energy Equation of State with Cosmic Voids
    Astrophys. J., 696, 10
  - van de Weygaert R., Platen E., 2011
    Cosmic Voids: Structure, Dynamics and Galaxies
    IJMPS, 1, 41, arXiv:0912.2997

8. Cosmic Backreaction

- According to some cosmologists, the observed acceleration of the Universe is the result of an artefact, resulting from the fact that in a general relativistic description inhomogeneities in the mass distribution cause complex non-linear couplings between the curvature perturbations that will reveal themselves as an artificial acceleration term when assuming a uniform (FRW) background. There has been ample discussion on whether the amplitude of this effect is noticeable or not. Provide a discussion on the theoretical underpinning of this argument, and subsequently a balanced discussion between the different arguments pro and con this explanation.

- *Literature suggestions:*
  - Buchert T., 2007
    Dark Energy from Structure - A Status Report
    Gen. Rel. Grav., arXiv:0707.2153
  - Célérier M-N., 2012
    Effects of inhomogeneities on the expansion of the Universe: a challenge to dark energy
    arXiv:1203.2814
  - Clarkson C., Ellis G., Larena J., Umeh O., 2011
    Does the growth of structure affect our dynamical models of the universe
    arXiv:1109.2314
  - Collins H., 2010,
    The influence of inhomogeneities on the large-scale expansion of the universe
    arXiv:1011,2946
  - Kolb E.W., Marra V., Matarrese S., 2009
    Cosmological background solutions and cosmological backreactions
    Gen. Rel. Grav., arXiv: 0901.4566
  - Schwarz D.J., 2010
    Cosmological Backreaction
    arXiv:1003.3026
  - Singh T.P., 2011
    The Effect of Cosmic Inhomogeneities On The Average Cosmological Dynamics
    arXiv:1105.3450
  - Wiltshire D.L., 2013
    Cosmic structure, averaging and dark energy
    arXiv:1311.3787

9. Modified Gravity and Dark Energy

- As a fundamental alternative to dark energy, one can ask whether the acceleration of the Universe is caused by a modification of gravity on large scales, i.e. departure from General Relativity, rather than an exotic form of energy. This possibility has generated a significant amount of theoretical work over the past decade; it furthermore provides strong motivation to search for and constrain modifications to GR using cosmological observations. There have been a range of suggested options for modified gravity models, amongst which f(R) gravity is amongst the best studied. f(R) gravity is a type of modified gravity theory which generalizes Einstein's General Relativity. f(R) gravity is actually a family of theories, each one defined by a different function of the Ricci scalar. Provide a review of possible options for modified gravity, and relate this to the observational evidence for dark energy. Amongst all options, you may want to concentrate on f(R) gravity models.
- *Literature suggestions:*
  - Carroll S.M., Duvvuri V., Trodden M., Turner M., 2004
    Is cosmic speed-up due to new gravitational physics ?
    Phys. Rev. D. 70, 043528
  - Faraoni V., 2008
    f(R) gravity: successes and challenges
    arXiv:0810.2602
  - Huterer D., Kirkby D., 2013
    Growth of Cosmic Structure: Probing Dark Energy Beyond Expansion
    arXiv:1309.5385
  - Laszlo I., Bean R., Kirk D., Bridle S.
    Disentangling dark energy and cosmic tests of gravity from weak lensing systematics
  - Sotiriou T.P., Fararoni V., 2010
    f(R) theories of gravity
    Rev. Mod. Physics, 82, 451, Jan-March 2010
  - Tsujikawa S., 2011
    Modified gravity models of dark energy
    arXiv:1101.0191

10. Dark Energy and the Vacuum

- One of the most immediate suggestions for the nature of dark energy concerns vacuum energy. However, it involves a major problem. Estimates of vacuum energy are a bit off, by 120 orders of magnitude. Discuss this —it Cosmological Constant Problem, the various proposals and options for vacuum energy, and possible solutions to the problem
- *Literature suggestions:*
  - Weinberg S., 1989
    The Cosmological Constant Problem
    Rev. Mod. Phys., 61, 1-23
  - Maggiore M., 2010
    Zero-point quantum fluctuations and the cosmological expansion
    arXiv:1004.1782
  - Zeldovich Y., 1967
    Cosmological Constant and Elementary Particles
    ZhETF Pis ma Redaktsiiu, Vol. 6, p.883
  - Ziaeepour H., 2012
    Issues about vacuum energy as the origin of dark energy
    arXiv:1205.3304

11. Quintessence

- One of the first candidates for a dynamically evolving form of dark energy is quintessence. Quintessence differs from the cosmological constant explanation of dark energy in that it is dynamic, changing over time, unlike the cosmological constant which always stays constant. The name comes from the classical elements in ancient Greece. The aether, a pure "fifth element", was thought to fill the Universe beyond Earth. Similarly, modern quintessence would be the fifth known contribution to the overall mass-energy content of the Universe.It is suggested that quintessence can be either attractive or repulsive depending on the ratio of its kinetic and potential energy. Prepare a review on the physics of quintessence, and its dynamical evolution.
- *Literature suggestions:*
  - Amendola L., 2000
    Coupled quintessence
    Phys. Rev. D., 62, 043511
  - Ostriker JP, Steinhardt P
    The Quintessential Universe
    Scientific American, 284, 46, (Jan. 2001)
  - Peebles P.J.E., Ratra B., 1988
    Cosmology with a time-variable cosmological 'constant'
    Astrophys. J. Lett., 325, 17
  - Peebles P.J.E., Ratra B., 2003
    The cosmological constant and dark energy
    Rev. Mod. Phys., 75, 559
  - Pettorino V., Baccigalupi C., 2008
    Coupled and extended quintessence: Theoretical differences and structure formation
    Phys. Rev. D., 77, 103003
  - Steinhardt P.J., Wang L., Zlatev I., 1999
    Cosmological tracking solutions
    Phys. Rev. D., 59, 123504

12. Phantom Dark Energy

- Phantom dark energy is a hypothetical form of dark energy with an equation of state parameter $w < -1$, ie. it is even stronger than the cosmological constant at increasing the expansion of the universe. If it exists, it could cause the expansion of the universe to accelerate so quickly that a scenario known as the Big Rip would occur. As a result of its growing energy density and repulsive nature, it would bring about the gravitational unbinding of structures, starting with the largest superclusters and hypothetically down to microscopic scales of planets, rocks, etc. Discuss whether this is a physically viable scenario, or whether there are causality problems with such a scenario. In addition, discuss observational probes that seem as yet to allow the possibility for such a form of dark energy.
- *Literature suggestions:*
  - Cadlwell R.R., 2002
    A phantom menace: cosmological consequences of a dark energy component with super-negative equation of state
    Phys. Lett. B., 545, 23, arXiv:astro-ph/9908168
  - Caldwell R.R., Kamionkowski M., Weinberg N.N., 2003
    Phantom Energy: Dark Energy with w¡-1 Causes a Cosmic Doomsday
    Phys Rev Lett., 91, 071301-1, arXiv:astro-ph/0302506
  - Hu W., 2005
    Crossing the phantom divide: Dark energy internal degrees of freedom
    Phys. Rev. D., 71, 047301, arXiv:astro-ph/0410680
  - Novosyadlyj, Sergijenko O., Durrer R., Pelykh V., 2012
    Do the cosmological observational data prefer phantom dark energy ?
    arXiv:1206.5194

13. Holographic Dark Energy

- The holographic principle of quantum gravity theory has been applied to the dark energy problem. So far, three holographic dark energy models have been proposed: the original holographic dark energy model, the agegraphic dark energy model, and the holographic Ricci dark energy model. Give a discussion of these various candidates for dark energy.
- *Literature suggestions:*
  - Gao C., Fengquan W., Xuelei C., Shen Y-G., 2009
    Holographic dark energy model from Ricci scalar curvature
    Phys. Rev. D., 79, 043511
  - Li M., Li X-D., Wang S., Zhang X., 2009
    Holographic dark energy models: A comparison from the latest observational data
    JCAP 06, 036, arXiv:0904.0928
  - Li M., Li X-D., Lin C-S., Wang Y., 2009
    Holographic Gas as Dark Energy
    Comm. Theor. Phys., 51, 181, arXiv:0811.3332

14. Future Dark Energy Surveys: Euclid and LSST

- In the coming decade, two huge systematic survey instruments will be focussed on the determination of the equation of state of dark energy. These are the ESA Euclid mission and the Large Synoptic Telescope. Discuss these instruments, and their promise for the determination of dark energy. This involves a detailed discusssion of the improvement of the determination of dark energy parameters by various dark energy probes, such as gravitational weak lensing, supernova acceleration measurements, baryonic acoustic oscillations, etc.
- *Literature suggestions:*
    - Amendola L., et al., 2012
      Cosmology and fundamental physics with the Euclid satellite
      arXiv:1206.1225
    - ESA
      Euclid, Mapping the geometry of the dark Universe
      ESA/SRE(2011)12, July 2011
    - Abate A., et al., 2012
      Large Synoptic Survey Telescope Dark Energy Science Collaboration
      arXiv:1211.0310