INTRODUCTION TO DARK ENERGY AND DARK MATTER

PAUL H. FRAMPTON
Department of Physics and Astronomy, University of North Carolina,
Chapel Hill, NC 27599-3255

In an introductory manner, the nature of dark energy is addressed, how it is observed and what further tests are needed to reconstruct its properties. Several theoretical approaches to dark energy will be discussed. Finally, the dark matter especially WIMPs is introduced.

1 Plan of Introduction to Dark Energy

- What observations and theoretical assumptions underly dark energy (DE)?

- If general relativity (GR) holds at all length scales, the most conservative assumption, then DE follows from the supernovae Type 1A (SNe1A) or, independently, from the Cosmic Microwave Background (CMB) combined with Large Scale Structure (LSS).

- Should we seriously query GR at large distance scales?

2 Einstein-Friedmann Equation

The Einstein equations relate geometry on the Left-Hand-Side (LHS) to the distribution of mass-energy on the Right-Hand-Side (RHS)

\[ G_{\mu\nu} = -8\pi G T_{\mu\nu} \]  

We hesitate to change the LHS but it is really checked with precision only at Solar System (SS) scales. At cosmological length scales, we may consider using a modification such as higher-dimensional gravity.

On the RHS, if we include only luminous and dark matter it is insufficient (keeping the LHS intact) and there is needed a further term which could be a cosmological constant or, more generally, dark energy.
3 Observational Issues

How can we constrain DE?

- Measurement of the expansion history $H(t)$
- The time-dependence of the equation of state $w(t)$
- Looking for any clustering property of DE. No evidence for this presently.
- How does DE couple to Dark Matter (DM)? This is related to the question of clustering.
- Local tests of GR and the equivalence principle, though the extrapolation from the SS to the Universe is some 13-15 orders of magnitude comparable to the extrapolation from the weak scale to the GUT scale in particle phenomenology. The usual prior is a desert hypothesis.

4 $\Lambda$ as DE: Why $10^{-122}$ (Planck Mass)$^4$?

We know from the Lamb Shift and Casimir Effect in quantum electrodynamics that vacuum fluctuations are real effects.

If we calculate the value of $\Lambda$, it will naively be ultra-violet (UV) quartically divergent. The most natural UV cut-off in GR is the Planck mass $\sim 10^{19} GeV$ whereupon

$$\Lambda \sim (10^{19} GeV)^4 = (10^{28} eV)^4 = 10^{112}(eV)^4$$

If we use, instead, the weak scale $\sim 100 GeV$ as our UV cut-off, we arrive at

$$\Lambda \sim (100 GeV)^4 = (10^{11} eV)^4 = 10^{44}(eV)^4$$

The observed value for $\Lambda$, by contrast, is approximately

$$\Lambda \sim (3 \times 10^{-3} eV)^4 \sim 10^{-10}(eV)^4$$

5 Coincidence Problem

As if the fine-tuning problem for $\Lambda$ were not enough, there is a second problem with $\Lambda$, the coincidence problem. Let us define $\Omega_\Lambda = \rho_\Lambda / \rho_C$ as the fraction of the critical density $\rho_C$.

The present value is $\Omega_\Lambda \sim 0.7$ but it scales, since $\rho_\Lambda$ is constant and assuming $\Omega_{TOT} = 1$, like $\rho_C^{-1} \sim (1 + Z)^{-3}$ so at a redshift $Z > 10$ it was $\Omega_\Lambda < 0.001$ while for a future redshift $Z < -0.9$ one has $\Omega_\Lambda > 0.999$.

If we plot $\Omega_\Lambda$ versus log $R$ over cosmic history from $-60 < \log_{10} R < +60$, it appears like a step function changing from zero to one abruptly around the present era. Even more dramatic is a plot of $d\Omega_\Lambda / dR$ which approximates a Dirac delta function and the coincidence problem is then why we live right in the middle of the spike of the delta function.

If the dark energy had appeared earlier it would have interfered with structure formation: if later, we would still be unaware of it.

6 The Quintessence Possibility

One parametrization of the dark energy can be made using a dynamical scalar field, now generically called quintessence.
6.1 Scaling potentials
Examples are:

\[ V \sim e^{-\lambda \Phi} \]  

as in 12.

\[ V \sim ((\Phi - A)^2 + C)e^{-\lambda \Phi} \]  

as in 3.

6.2 Tracker Potentials
Examples are

\[ V \sim \Phi^{-\alpha} \]  

as in 4.

\[ V \sim \exp\left(\frac{M}{Q} - 1\right) \]  

as in 5.

6.3 Approaches to the Coincidence Problem
We may assume that our universe sees periodic epochs of acceleration6 with potential

\[ V \sim M^4 e^{-\lambda \Phi}(1 + A \sin a \Phi) \]  

Another possibility is that it is important that our epoch is close to the matter/radiation equality time. This may be incorporated by having a non-minimal coupling to matter7, to gravity8 or in a k-essence theory with a non-trivial kinetic term in the lagrangian9.

7 Dark Energy with Equation of State \( w = p/\rho < -1 \)
Present data on SNe1A, CMB and LSS are consistent with \( w = -1 \) as for a cosmological constant.
Since the possibility that \( w < -1 \) is still allowed10, I shall spend a disproportionate amount of time on it because, if it persisted, it could well signal new physics.
One interpretation of dark energy comes from string theory, closed strings on a toroidal cosmology11. This leads generically to \( w < -1 \).
In general, without dark energy (as in most cosmology texts pre-1998), the destiny of the Universe was tied to geometry in a simple manner: the Universe will expand forever if it is open or flat; it will stop expanding and contract to a Big Crunch if it is closed.
With Dark Energy, this connection between geometry and destiny is lost and the future fate depends entirely on how the presently-dominant dark energy will evolve.
This question is studied in 13,14,15. If \( w < -1 \) and is time-independent, the scale factor diverges at a finite future time - the Big Rip. Generally, this will be at least as far in the future as the Big Bang was in the past.
Such a cosmology may have philosophical appeal? There is more symmetry between past and future.
If one allows a time-dependent \( w(t) \), there are two other possible fates:
(i) An infinite-lifetime universe where dark energy dominates at all future times.
(ii) A disappearing dark energy where the Universe becomes (again) matter dominated. The case $w < -1$ gives rise to some exceptionally interesting puzzles for theoretical physics.

There is the question of violation of the weak energy condition universally assumed in general relativity. This means there are inertial frames where the energy density is negative signaling vacuum instability. Let us make three assumptions, any or all of which may be incorrect, just so that we may say something more: that (i) There is a stable vacuum with $\Lambda = 0$; (ii) The dark energy decays to it by a 1st-order phase transition; (iii) There is some, albeit feeble, interaction between dark energy and the electromagnetic field.

Then one can use old arguments to investigate nucleation. The result is that even with the tiniest coupling of dark energy to the electromagnetic field the dark energy would have spontaneously decayed long ago unless the appropriate bubble radius is at least galactic in size.

In this model, because the energy density of the DE is so small compared to $e.g.$ the energy density in a common macroscopic magnetic field of, say, 10T the 1st order phase transition can be adequately suppressed only by decoupling the DE completely from all but gravitational forces or by arguing that a collision would need to be between galaxies or larger objects to be effected. Certainly, no terrestrial experiment can be influenced: for one contrary suggestion of a Josephson junction experiment which might well be justified for other reasons, see $e.g.$

Of course, this is only a toy model but the general conclusion is probably correct - that there can be no microscopic effect of the dark energy.

This makes the DE very difficult or impossible to investigate except through astronomical observations.

8 Dark Energy and Neutrinos

It has been pointed out by many theorists that the density of the dark energy $\sim (10^{-3} eV)^4$ is suggestive of the neutrino mass.

Very interesting attempts to strengthen such a connection have been made. Such mass-varying neutrino models seek to make a direct identification of the DE density with neutrino mass itself.

9 Precision Experiment

We know well of the precision experiments to test Newton’s Law of Gravity down to a distance of 100 microns and below.

One originator of such ideas suggests a different precision test, of the Earth-Moon distance, to a similar accuracy of 100 microns, presumably the distance between the centers of mass. A particular modification of gravity might have a tiny effect on our lunar system. Clearly if this experiment can be achieved, the present accuracy being at the level of centimeters, it would be an impressive achievement.

10 Conclusions on Dark Energy

- The theoretical community has yet to come up with a definitive proposal to explain the dark energy.
- The nature of the dark energy is so profound for cosmology and particle physics that we desperately need more SNe1A observations from important proposed experiments $e.g.$ SNAP (for which NASA funding has sadly been suspended for 5 years as a result of prioritizing sending humans to Mars!), as well as complementary observational constraints on the CMB from $e.g.$ the Planck mission.
• The equation of state will be decisive. If \( w = -1 \), it’s a cosmological constant with its fine-tuning and coincidence problems. If \( w > -1 \) quintessence will receive a shot in the arm.

• If the data would settle down to a value \( w < -1 \) we could be at the dawn of a revolution in theory with general relativity at the largest distance scales called into question.

11 Introduction to Dark Matter

Existence of dark matter is supported by disparate cosmological measurements.

Values of energy and matter densities at the present time, determined by: the temperature fluctuations in the CMB data; distance-luminosity for supernovae type 1A; distribution of galaxies on large scales (LSS); abundance of light elements (BBN).

In terms of the critical density \( \Omega \) for the various components is found to be as follows (taking \( h^2 = 0.5, h = 0.707 \)).

- Relativistic particles, radiation e.g. the CMB photons. Only \( \Omega_\gamma = 5.934 \pm 0.008 \times 10^{-5} \).

- \( \Omega_\Lambda = 0.72 \pm 0.08 \) in a smoothly distributed dark energy.

- \( \Omega_M = 0.27 \pm 0.016 \) in non-relativistic particles (Matter) of which
  - \( \Omega_b = 0.0448 \pm 0.0018 \) in baryons (protons and neutrons)
  - \( \Omega_{HDM} < 0.0152(95\% CL) \) in non-baryonic hot dark matter.
  - \( \Omega_{CDM} = 0.223 \pm 0.016 \) in non-baryonic cold dark matter.

The excess of total matter density (0.27) over baryonic mass density (0.0224) constitutes the evidence for non-baryonic dark matter. **No known elementary particle can account for the non-baryonic dark matter.**

One obvious candidate, the neutrinos, are so light they constitute hot dark matter and contribute to the \( \Omega_{HDM} < 0.0152 \).

Many hypothetical particles have been proposed for the CDM. Some come from extensions of the standard model, most notably the axion and the lightest supersymmetric particle.

Other possibilities include Wimpzillas, solitons, self-interacting dark matter, Kaluza-Klein dark matter, etc.

The class of non-baryonic dark matter candidate of greatest interest are the Weakly Interacting Massive Particles (WIMPs). Therefore I shall focus on their detection and the claims to have discovered them.
12 WIMPs and their detection

WIMPs are appealing because of the simple mechanism by which they can achieve the appropriate present cosmic density. In the early universe they were in thermal and chemical equilibrium with the rest of matter and radiation. With the expansion of the Universe, their reactions (including annihilation) slowed down and decoupled from the rest of the world leaving a constant number of WIMPs expanding with the Universe.

The correct present density is obtained for WIMPs with couplings of order the weak interactions and masses in the 1 GeV - 1 TeV range. The neutralino is the most popular example although in any extension of the standard model one typical seeks a WIMP candidate, e.g. the nark is a WIMP candidate in the sark model. Detection can be direct or indirect.

Direct signals are from collisions with nuclei in a detector. A very sensitive low-background detector (bolometer) records the amount of energy deposited by WIMPs and (in the future) the direction of motion of the struck nucleus.

Indirect signals come from WIMP reactions in planets, stars or galaxies. The most common reaction is WIMP annihilation with anti-WIMP. Out of this annihilation come $\nu$, $e^+$, $\bar{p}$ and high-energy $\gamma$. Such annihilations occur at a detectable rate where the anti-WIMPs are concentrated e.g. in the center of the Sun, the center of the Earth and in galactic centers including the Milky Way. Neutrino telescopes, gamma-ray telescopes and cosmic-ray detectors can be used in these indirect searches.

Now we look at three claims for seeing WIMPs.

13 HEAT positron detection

Two separate balloon flights with different detectors have seen more cosmic ray positrons above $\sim 7$ GeV than predicted in models for cosmic ray propagation in the galaxy. Wimp annihilation can be invoked to explain this excess.

The extra positrons can be fitted by a assuming neutralino annihilation. The best fit requires WIMP mass of 238 GeV.

The positron spectrum lacks any discriminating feature which clearly singles out WIMP annihilation.

14 $\gamma$-Rays from Galactic Bulge

Gamma rays from WIMP annihilation offer a characteristic signature in the spectrum: a gamma-ray line. Each photon will carry an energy equal to the WIMP mass, 10GeV to 100 TeV. No competing process is know that could produce such a line.
No line has been detected yet. The estimates for GLAST (launch scheduled 2006) are encouraging.

Another suggestion\(^\text{30}\) has been that the 511 keV gamma excess from the galactic bulge arises from positrons associated with unexpectedly light WIMP annihilation. The necessary WIMP mass is in the region between 1 MeV and 100 MeV. There are other explanations for the 511 keV line including primordial black holes as dark matter\(^\text{31}\).

15 DAMA Annular Modulation

Because the Earth’s motion changes the relative speed of the Earth and WIMPs the WIMP detection rate varies\(^\text{32}\) and repeats itself every year. The maximum occurs in June for the canonical halo model with Maxwellian velocity distribution.

The DAMA group has claimed\(^\text{33}\) to have detected such annual modulation in their NaI data. No alternative explanation of the DAMA data has been forthcoming.

No other direct detection of such a WIMP signal has been made by any other group but there are differences between the targets used as well as the nuclear spin thereof. So comparison between experiments requires some theoretical assumptions.

Nevertheless, it does appear that CDMS data\(^\text{34}\) completely or almost (?) excludes the DAMA claim.

Future detectors will measure the direction of motion of the recoil nucleus and enable a more clearcut WIMP signature.

16 Conclusions on DARK MATTER

How to be Sure of WIMP Detection?

We require features that can be due to WIMPs and nothing else.

- (i) Gamma-ray annihilation from WIMP annihilation should show a gamma-line in correspondence with the WIMP mass.

- (ii) Annual modulation should show the correct periodicity both in rate and, in future, directional dependence.

Compatible indirect (i) and direct (ii) detection could provide compelling evidence for WIMPs. Better would be production in a collider consistent with cosmological detection!

Acknowledgments

We thank Tran Thanh Van for the invitation to La Thuile. This work was supported in part by the US Department of Energy under Grant No. DE-FG02-97ER-41036.
References

1. C. Wetterich, Nucl. Phys. B302, 668 (1988).
2. P.G. Ferreira and M. Joyce, Phys. Rev. D58, 023503 (1998).
3. A. Albrecht and S. Skodis, Phys. Rev. Lett. 84, 2076 (2000); Phys. Rev. D66, 043523 (2002).
4. B. Ratra and P.J. E. Peebles, Phys. Rev. D37, 3406 (1988).
   P.J. E. Peebles and B. Ratra, Ap. J. 325, 217 (1988).
5. P.J. Steinhardt, L.-M. Wang and I. Zlatev, Phys. Rev. D59, 123504 (1999).
6. S. Dodelson, M. Kaplinghat and E. Stewart, Phys. Rev. Lett. 84, 2076 (2000).
7. R. Bean and J. Magueijo, Phys. Rev. D66, 063505 (2002).
8. F. Perrotta and C. Baccigalupi, Phys. Rev. D65, 23505 (2002).
9. C. Armendariz-Picon, V. Mukhanov and P.J. Steinhardt, Phys. Rev. Lett. 85, 4438 (2000).
10. A. Melchiorri, L. Mersini, C.J. Odman and M. Trodden, Phys. Rev. D68, 043509 (2003).
    astro-ph/0211522
11. M. Bastero-Gil, P.H. Frampton and L. Mersini, Phys. Rev. D65, 106002 (2002).
    P.H. Frampton, Dark Energy from Strings. In Coral Gables Conference 2001 on Cosmology and Elementary Particle Physics.
    Editors: B. Kursunoglu, S.L. Mintz and A. Perlmutter.
    AIP Conference Proceedings Volume 624 (2002). Pages 59-68.
    hep-th/0202063
12. P.H. Frampton, Phys. Lett. B555, 139 (2003) astro-ph/0209037
13. R. Kallosh and A. Linde, JCAP 0302: 002 (2003).
14. P.H. Frampton and T. Takahashi, Phys. Lett. B557, 135 (2003). astro-ph/0211544
   P.H. Frampton and T. Takahashi, Astropart. Phys. 22, 307 (2004). astro-ph/0405333
   J.L. Crooks, J.O. Dunn, P.H. Frampton, H.R. Norton and T. Takahashi, Astropart. Phys. 20, 361 (2003).
   P.H. Frampton. astro-ph/0305495
15. R.R. Caldwell, Phys. Lett. B545, 23 (2002).
16. P.H. Frampton, Mod. Phys. Lett. A19, 801 (2004). hep-th/0302007
17. S.M. Carroll, M. Hoffman and M. Trodden, Phys. Rev. D68, 023509 (2003).
    astro-ph/0311273
18. P.H. Frampton, Phys. Rev. Lett. 37, 1378 (1976); Phys. Rev. D15, 2922 (1977).
19. C. Beck and M.C. Mackey. astro-ph/0406504
20. P.Q. Hung. hep-ph/0010126 P.Q. Hung and H. Paes. astro-ph/0311131
21. R. Fardon, A.E. Nelson and N. Weiner. astro-ph/0309800
   D.B. Kaplan, A.E. Nelson and N. Weiner. hep-ph/0401099
22. P.H. Frampton and P. Vogel, Physics Reports 82, 339 (1982).
23. P.H. Frampton. hep-ph/0403164 hep-ph/0310217 P.H. Frampton, S.T. Petcov and
   W. Rodejohann, Nucl. Phys. B687, 31 (2004). hep-ph/0401206 P.H. Frampton, S.L.
   Glashow and T. Yanagida, Phys. Lett. B548, 119 (2002). hep-ph/0208157 P.H. Frampton,
   M.C. Oh and T. Yoshikawa, Phys. Rev. D66, 033007 (2002). hep-ph/0204273.
   Phys. Rev. D65, 073014 (2002). hep-ph/0110300 P.H. Frampton, S.L. Glashow and
   D. Marfatia, Phys. Lett. B536, 79 (2002). hep-ph/0201008 P.H. Frampton and S.L.
   Glashow, Phys. Lett. B461, 85 (1999). hep-ph/9906375.
24. G. Dvali, A. Gruzinov and M. Zaldarriaga, Phys. Rev. D68, 024012 (2003).
25. G.R. Dvali, G. Gabadadze and M. Porrati, Phys. Lett. B485, 208 (2000).
26. H. Goldberg, Phys. Rev. Lett. 50, 1419 (1983).
27. J. Agrawal, P.H. Frampton, Y.J. Ng, H. Nishino and O. Yasuda, Nucl. Phys. B351, 161 (1991).
28. P.H. Frampton and Y.J. Ng, Phys. Rev. D42, 3242 (1990).
29. M.A. DuVernois, et al., Astrophys. J. 559, 296 (2001).
30. C. Boehm, et al., Phys. Rev. Lett. 92, 101301 (2004).
31. P.H. Frampton and T.W. Kephart. Mod. Phys. Lett. A (in press). hep-ph/0503267
32. A.K. Drukier, K. Freese and D. Spergel, Phys. Rev. D33, 3495 (1986);
K. Freese, J.A. Frieman and A. Gould, Phys. Rev. D37, 3388 (1988).
33. R. Bernabei, et al., Nucl. Phys.(Suppl.) B70, 79 (1999);
R. Bernabei, et al., Phys. Lett. B480, 23 (2000).
34. D.S. Akerib, et al., Phys. Rev. Lett. 93, 211301 (2004).