Nature of Dark Energy

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Overview

- The LCDM model
- Observations and what they tell us
- The assumptions behind the model
- ...and questioning those assumptions
- Theorists' playground: alternatives to the cosmological constant
What is Dark Energy?

Whatever makes the Universe accelerate!
Is it accelerating?

SN Ia

CMB

LS S

IS W

What is causing it?
Cosmic Pancake (≠pie)

- Cosmological concordance model
- $\Lambda$CDM-model
- universe is flat
- cold dark matter
- a dominant dark energy component exists
- 13.7 billion years old
Basic equations

I: Geometry (FLRW metric)

- *isotropic* and *homogeneous*
- (maximally symmetric subspace)

\[
ds^2 = g_{\mu\nu}dx^\mu dx^\nu
\]
\[
= dt^2 - a(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2(\theta)d\varphi^2) \right)
\]

*comoving coordinates*
Basic equations

II: Matter

- perfect isotropic fluid

\[ \dot{\rho} + 3 \frac{\dot{a}}{a} (\rho + p) = 0 \]

\[ p_r = \frac{1}{3} \rho_r \rightarrow \rho_r \sim a^{-4} \]

\[ p_m = 0 \rightarrow \rho_m \sim a^{-3} \]

\[ p = \omega \rho \rightarrow \rho_m \sim a^{-3(1+\omega)} \]

Relavistic matter

\[ E = \hbar / \lambda \]
Principle of Equivalence (A. Einstein 1907): We shall therefore assume the complete physical equivalence of a gravitational field and the corresponding acceleration of the reference frame. This assumption extends the principle of relativity to the case of uniformly accelerated motion of the reference frame.

Einstein's equations

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu} \]
Basic equations

FLRW metric + isotropic fluid

(only two non-trivial independent equations)

Friedmann equation

\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho + \frac{1}{3} \Lambda - \frac{k}{a^2}
\]

Hubble parameter

\[
H(t) \equiv \frac{\dot{a}}{a}
\]

acceleration:

\[
\ddot{a} = -\frac{4\pi G}{3} (\rho + 3p) + \frac{\Lambda}{3}
\]

\[
p = \omega \rho
\]

\[
\omega < -\frac{1}{3}
\]

contents:

- matter
- radiation
- curvature \( \Lambda \)
Basic equations

\[ H^2 = H_0^2 \left( \Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda \right) \]

- Four cosmological parameters
  - (only three independent) \( \Omega_r + \Omega_m + \Omega_k + \Omega_\Lambda = 1 \)
- Radiation density is well known by the CMB observations
  \[ \Omega_r \sim \frac{G}{H_0^2} T_{CMB}^4 \approx 10^{-5} \]
- Baryon density can be inferred from BBN and from direct observations
  \[ \Omega_b \sim 10^{-2} \]
- What about the rest?  

\[ \Omega_m = 1 \]
What's the pancake recipe?

The three major observational tools:
- Supernova type IA observations (S NIA)
- Cosmic Microwave Background (CMB) experiments
- Large Scale Structure observations (LSS)
Supernova type Ia are believed to be (sort of) standard candles, releasing $10^{51}$ ergs ($10^{44}$ J) of energy in a thermonuclear explosion. The redshift and the apparent luminosity of the SN is measured. Absolute luminosity known => probe of cosmological expansion.
Distant supernovae are fainter than expected! 

\[ m = M + 5 \log \left( H_0 (1 + z) \int_0^z \frac{ds}{H(s)} \right) \]
Supernova data prefers a universe with a large $\Omega_m$ and a closed universe but is consistent with a flat universe. It is not consistent with a matter only universe (and in particular not with a flat matter only universe).
Observational tools: CMB

Recombination at $z \approx 1100$ produces the microwave background radiation.
CMB observations have become a precision tool for cosmology.

- COBE, Boomerang, CBI, WMAP, PLANCK

Observation of the CMB blackbody spectrum:
- Hot Big Bang
The WMAP experiment

The Wilkinson Microwave Anisotropy Probe (WMAP) has measured the Cosmic Microwave Background to a good accuracy making the CMB a real precision tool for cosmology.
What’s that wiggly curve?

Note: ensemble averages ≠ averages over sky (cosmic variance)
WMAP Data: Implications for inflation

- power at large scales ($l < 70$) $\Rightarrow$ superhorizon fluctuations (Sachs-Wolfe effect)

\[ C_l = 4\pi \int T_{\Theta}^2(k, l) P_R(k) \frac{dk}{k} \]

- CMB Transfer function (depends on cosmology)
- Initial spectrum $P_R \sim k^{n-1}$

fit the parameters of your favorite model...
WMAP Data + powerlaw initial spectrum

\[ C_l = 4\pi \int T_\Theta^2(k, l) P_R(k) \frac{dk}{k} \]

\[ P_R \sim k^{n-1} \]

Assuming

- adiabatic fluctuations
- LCDM model (flat)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Omega_b h^2 )</td>
<td>0.022( \pm )0.001</td>
</tr>
<tr>
<td>( \Omega_m h^2 )</td>
<td>0.13( \pm )0.02</td>
</tr>
<tr>
<td>( h )</td>
<td>0.73( \pm )0.04</td>
</tr>
<tr>
<td>( n )</td>
<td>0.95( \pm )0.02</td>
</tr>
</tbody>
</table>

\[ \chi^2 = 1.041 \]

(982 DOF)
WMAP Data

- allowing non-flatness, degeneracy along $\Omega_\Lambda - \Omega_m$
- eg. $\Omega_\Lambda = 0$, $h = 0.30$, $\Omega_{tot} = 1.3$, consistent with data
- EdS is not consistent
- Adding dark energy with a constant equation of state gives a further degeneracy

Further information is needed to break degeneracies
Observational tools: Large Scale Structure

The primordial fluctuations and the evolution of the universe is also probed by the distribution of matter in the universe. Studying the distribution of galaxies gives us information on the cosmological parameters, particularly on the matter content. Galaxy surveys: 2DFGRS, SDSS. Question of bias: how well do galaxies trace the dark matter?
Observational tools: LS S
Matter power is most sensitive to the contents of the universe.

- the shape constrains well $\Omega_m h^2$
- no significant hot dark mater component
- not very sensitive to the background expansion (c.c. does not fluctuate), expect for the overall normalization.

Image: M. Tegmark
Bottom line:

- the LCDM model with a minimal inflationary scenario is consistent with all observational data
- not a perfect fit
- relaxing assumptions on the primordial spectrum and Hubble parameter can still accommodate an EdS model
- supports inflation
- the simplest model includes dark energy and dark matter
Case for Inflation

- Inflation predicts:
  - flat universe
  - homogeneous universe
  - power on very large scales
  - nearly scale invariant primordial spectrum

Solves problems and is well supported by observations
So is Dark Energy really there?

i.e. does the Universe really accelerate?

Direct evidence:
- S N Ia prefer an accelerating universe
- the Integrated Sachs Wolfe Effect

Indirect evidence: CMB + LSS
The ISW-effect

- The ISW effect probes the whole expansion history from the last scattering surface until present.
- Evolving gravitational potentials have an effect on the CMB photons.
- Hence, the ISW effect is also a probe of the evolution of dark matter.
- And therefore a probe of dark energy.
- In a matter-only universe there is no ISW effect.
- Matter-CMB cross-correlation signals.
ISW Effect consistent with LCDM
Dark Energy: What is it?

**Candidate #1**: Cosmological constant, $w=-1$

- Existence is well motivated by QFT
- But suffers from extreme fine-tuning

$$\rho^\text{obs}_\Lambda \sim 10^{-47} \text{ GeV}^4$$

$$\rho_{\text{vac}} \sim m_{\text{Pl}}^4 \sim 10^{76} \text{ GeV}^4 \quad \text{(at least at Planck time)}$$

- SUSY helps but does not remove the problem
- Also changes in vacuum energy during phase transitions are hard to add up

- Does not fluctuate (no clumping of c.c.)
- Appears naturally in Einstein’s equations
Cosmology beyond the $\Lambda$CDM-model?

- Why consider alternatives to the concordance model?
  - low quadrupole
  - theoretical problems with $\Lambda$
  - moduli fields
  - extra dimensions
  - modified gravity
  - ...

In the LCDM model, we are making a number of assumptions:

- Homogeneous isotropic metric
- Inflationary spectrum
- Matter content
- Form of dark energy (i.e. cosmological constant)

- General Relativity
Dark Energy: What is it?

FLRW metric + isotropic fluid + GR

Friedmann equation

\[ \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho + \frac{1}{3} \Lambda - \frac{k}{a^2} \]
Homogeneous metric?

- Relaxing the assumption of homogeneity one can explain acceleration without dark energy

- Bondi-Lemaître-Tolman - models
- problems with CMB
- very specific observers
Inflationary spectrum

- More complicated initial spectra can fit a pure matter model
- Breaks in the primordial spectra
- Phase transitions etc.

- Complicated particle physics at high energies
Dark Energy properties

- models different from c.c. with exotic matter predict an evolving $w$
- S N data does seem to prefer an evolving $w$
- but current data is not good enough to really distinguish between models
- c.c. can mimic a changing $w$ due to insufficient data

- the cosmological constant is still the safest bet
Dark Energy: What is it?

**Candidate #2: Quintessence**

- scalar field in an expanding background

\[
\rho_\phi = \frac{1}{2} \dot{\phi}^2 - V(\phi)
\]

\[
p_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi)
\]

\[
\ddot{\phi} + 3 \frac{\dot{a}}{a} \dot{\phi} + V'(\phi) = 0
\]

- evolving $w$

---

Main Entry: quin-tes-sence
Pronunciation: kwin-'te-s&n(t)s
Function: noun
Etymology: Middle English, from Middle French quinte essence, from Medieval Latin quinta essentia, literally, fifth essence
1: the fifth and highest element in ancient and medieval philosophy that permeates all nature and is the substance composing the celestial bodies
2: the essence of a thing in its purest and most concentrated form
3: the most typical example or representative
- quin-tes-sen-tial /"kwin-t&-'sen(t)-sh&l/ adjective
- quin-tes-sen-tial-ly adverb
Dark Energy: What is it?

 Candidate #N: Chaplygin gas
- motivated by a rolling tachyon
  \[ p = -\frac{A}{\rho^\alpha} \]
- behaves like dust at early times but has negative pressure at late times; Unified dark Matter model
- can be fitted to S N Ia observations
- fluctuation spectrum (LSS observations) constrains the model severely
Cardassian Models: an example

- MPC model (Freese, Gondolo & Wang, 2003)
- $q > 0$, $n < 2/3$
- no dark energy, only CDM

- at early times, CDM like behaviour, at late times cosmological constant type behaviour
- linear perturbation growth can be radically different
- "Star Trek inspired"

\[
H^2 = \frac{8\pi G}{3} \rho_M \left( 1 + \left( \frac{\rho_M}{\rho_c} \right)^{q(n-1)} \right)^{1/q}
\]
General Relativity?

- Modifying gravity offers an interesting alternative to the cosmological constant
- Brane-worlds
- Choosing the gravitational action
- High-energy corrections / quantum gravity
DGP-model

(Dvali, Gabadadze, Porrati 2000)

$$S = \frac{M_{Pl}^2}{r_c} \int d^4x \, dy \sqrt{g^{(5)}} \mathcal{R} + \int d^4x \sqrt{g}(M_{Pl}^2 R + \mathcal{L}_{SM})$$

- 5-dimensional universe (gravity)
- flat extra dimension
- SM lives on the brane
DGP-model cntd.

add a cosmological metric:

\[ ds_5^2 = g^{\text{FRW}} ds_4^2 - dy^2 \]

Friedmann equation on the brane:

\[ H^2 \pm \frac{H}{r_c} = \frac{8\pi G}{3} \rho_m \]

induced metric on the brane:

\[ g_{\mu\nu}(x) = g_{\mu\nu}^{(5)}(x, y = 0) \]
Conclusions

- current data is *consistent* with the concordance LCDM model within GR with a significant dark energy component and a simple inflationary scenario
- Supernovae and ISW effect give independent evidence for acceleration
- data is not good enough to discriminate between dark energy models
- there is no outstanding good, and correct, dark energy candidate from theory
  - anthropic arguments, the string landscape, ...
- future will tell us more: PLANCK, SNAP/JDEM, LHC, LISA, ...

*It S tinx But It Rocks!*