The Cosmological Model: an overview and an outlook

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The Standard Cosmological Model

- Universe started with Big Bang
- Einstein gravity
- CDM, baryons, photons (++)
- Cosmological Constant
- Inflation
- adiabatic, near-gaussian fluctuations
Evidence

- Universe thermalised at microwave frequencies

[COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE]

Theory and observation agree

[Graph showing the cosmic microwave background spectrum from COBE]
Cosmological Parameters and Effects

- Cosmological Parameters:
  - Matter density $\Omega_m$
  - Baryon density $\Omega_b$
  - Hubble parameter $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$
    \[ H = \frac{\text{d}(\ln a)}{\text{d}t} \]
  - Cosmological constant $\Lambda$
  - Initial amplitude $\sigma_8$ and slope $n$ of power spectrum of fluctuations
  - $+$ but 6 parameter model is a reasonably good fit

- Affect many observables, through
  - Geometry of Universe
  - Power spectrum of fluctuations
  - Light element abundances
Big Bang Nucleosynthesis

- $T \sim 1$ MeV
- $t \sim 3$ minutes

$\Omega_b h^2 = 0.020 \pm 0.002$

(e.g. Fields and Sarkar 2006)
Direct probes of geometry: Supernovae

- Standard(isable) candles

$D_L = (1 + z)c \int_0^z \frac{dz'}{H(z')}$

$H^2(z) = H_0^2 \left[ \Omega_m (1 + z)^3 + (1 - \Omega)(1 + z)^2 + \Omega_\Lambda \right]$
Supernova Hubble diagram

- Evidence for acceleration/cosmological constant

\[ \mu = 5 \log_{10}(D_L/Mpc) + 25 \]

\[ z \]

\[ \Omega_M = 0.29, \quad \Omega_\Lambda = 0.71 \]
Two types of Supernova 1a?

- 257 SNe, with Star Formation Rates and $M_*$ from SDSS/VESPA (Aubourg et al 2007, astroph)

Convincing evidence for two populations of SNe
Prompt component will be dominant at high z
Do both types obey the same stretch-luminosity relation? Unknown
Bronder et al (2007) suggest high- and low-z SNe same

Recent (<70Myr) Star Formation

Also good news – see SNe to higher redshift
Conclusions from Supernovae

- $\Lambda$ is non-zero

Riess et al 2004
Cosmic Microwave Background

- CMB with WMAP satellite
CMB fluctuation spectrum

- Theoretical expectation (relatively straightforward):

\[ \Delta T (\mu K) \]

\( l \)

Initial Conditions

Sound Waves

Baryon Loading

Radiation Driving

Dissipation

W. Hu
First peak tests geometry of Universe

GEOMETRY OF THE UNIVERSE

OPEN  FLAT  CLOSED
WMAP power spectrum

Polarisation? See Sugiyama’s talk
Large-scale structure

- Anglo-Australian Telescope 2dF galaxy redshift survey, and SDSS

In linear perturbation theory, \( \delta = \rho / \langle \rho \rangle - 1 \) grows:

\[
\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_m \delta = 0
\]

- probes \( H(z) \) as well
Galaxy power spectrum

- From 2dF Galaxy Redshift Survey

Bias?

- Galaxies are not necessarily where the mass is.

On large scales, detailed statistical analysis shows galaxies and mass do follow the same distribution (Verde et al 2002; Seljak et al 2005).
Baryon Acoustic Oscillations

- Remnants of acoustic fluctuations

Physical scales depend on $\Omega_m h^2$ and $\Omega_b h^2$

Angular scale depends on $D_A(z)$ – angular diameter distance

Radial dependence depends on $dr = c \frac{dz}{H(z)}$

Powerful geometric test: $H(z)$ and $D_A(z)$
Baryon Acoustic Oscillations in SDSS and 2dF

- Both show evidence of ‘wiggles’
Constraints on $\Omega_m$ and $\Omega_b$

- From 2dF

Non-baryonic Dark Matter dominates
Weak lensing

- ...probes matter distribution directly
- Distorts images of distant sources by \(~1\%\)
- Simple physics
Recent weak lensing results

- Lower amplitude agrees better with WMAP (better knowledge of how far away the sources are)

Benjamin et al 2007
Lyman alpha forest clustering

- Small scale clustering information, at early times (z=2-4)
Matter power spectrum

- From CMB, LSS, Ly$\alpha$, cluster abundances and weak lensing

Effect of non-zero neutrino masses

Courtesy Tegmark
Cosmological Parameters

- Universe close to flat
- $\Omega_\Lambda \sim 0.74$
- $\Omega_m \sim 0.26$
- ...of which $\Omega_b \sim 0.04$
- $\Sigma m_\nu < 0.17\text{eV}$
Beginning to probe inflation

- Constraining inflationary potentials

Scalar spectral index $P(k) \propto k^n$
Cosmological Constant?

- ‘Equation of state’ of Dark Energy \( w = p/\rho \)
- \( \Lambda \) has \( w = -1 \)
- Affects geometry, and growth rate

Seljak et al. 2006 \( w = -1.04 \pm 0.06 \)
Coupled neutrinos

- Self-gravity alters growth of perturbations

Number of free-streaming neutrinos
Number of self-coupled neutrinos

Friedland et al 2006
Problems with $\Lambda$CDM

- “There are only two problems with $\Lambda$CDM, $\Lambda$, and CDM” - Tom Shanks
Not enough small galaxies

- Simulations show many small halos

- SDSS has found some very low-mass galaxies, but not enough

- Baryon physics – e.g. feedback from star formation, can blow out gas and make small halos dim
Dwarf galaxies have very few baryons

- Dwarf spheroidals are heavily dark-matter dominated: only 1-10% of mass in baryons

- Resolution of missing satellites is probably in heating/feedback effects
Mass loss from low-mass galaxies

- SFR + Kennicutt law $\rightarrow$ Gas Mass
- More gas has been lost from low-mass galaxies:

![Graph showing the fraction of gas lost vs. lookback time and log(MGM/M$_{\odot}$).](image)

Calura et al 2007
Dwarf galaxy profiles

- Dark Matter dominated → good test of models
- CDM predicts steeper inner profiles

- Warm Dark Matter? No (Ly α)
- Self-interacting Dark Matter?
- Resolution may be in bars, or triaxial halos
- Dark Matter in Milky Way is almost certainly not astrophysical objects (microlensing)
‘Bullet cluster’

- Challenges MOND, TeVeS

- Hot Gas (X-ray)
- Galaxies
- Dark Matter (Lensing)

Markevitch et al 2002
Clowe et al 2004
Self-interacting Dark Matter?

- Spergel and Steinhardt (2000): Self-interacting Dark Matter could remove cusps if $\sigma/m \sim 0.05-0.5 \text{ m}^2/\text{kg}$

- Bullet cluster $\rightarrow \sigma/m < 0.12 \text{ m}^2/\text{kg}$ (Randall et al 2007)
Prospects: Weak Lensing and BAOs

- Weak Lensing: Pan-STARRS
  
  Will map 75% of the sky with weak lensing accuracy (current largest is 0.2%)

- BAOs: Many in progress or planned. Wiggle-z, PAU, FastSound etc
Joint Dark Energy Mission

- Recommended by NSF to be next NASA Beyond Einstein mission
- ADEPT, DESTINY, SNAP

- (≥ 2 of) Supernovae, BAO, Weak Lensing
Capability of next generation surveys

- Weak lensing, BAO, Supernova and CMB experiments should establish Dark Energy equation of state accurately:

\[ w(a) = w_0 + w_a (1-a) \]

- \( a = \) scale factor

- \( w(z) \) at \( z \sim 0.4 \) may be known very accurately:
  
  Error <1%

Courtesy: Tom Kitching
Testing inflation

- Inflation predicts B-modes in CMB polarisation on large scales, from gravity waves
Beyond Einstein Gravity?

- Next generation experiments can also address qualitatively different questions:
  - Is there evidence for gravity beyond Einstein’s General Relativity (e.g. Braneworld Gravity)?
  - Growth rate of perturbations is altered
  - Weak Lensing probes this
Prospects for testing gravity

- DUNE could detect evidence for Braneworld gravity

\[ \ln(\text{Probability of favouring Beyond Einstein gravity over GR}) \approx 12\sigma \text{ detection possible} \]
Neutrinos

- Should be strongly constrained by Planck
- With Ly $\alpha$, $\sigma[\Sigma m_\nu] < 0.06\text{eV}$ (Gratton et al 2007) or $0.05\text{eV}$ with weak lensing (Hannestad et al 2006) or $0.025\text{eV}$ with high-z clustering (Takada et al 2007)
- Strong constraints on self-coupled $\nu$

Number of free-streaming neutrinos
Number of self-coupled neutrinos

Friedland et al 2006

0.2
Conclusions

- Standard Cosmological Model is in Good Health
- Astrophysics may deal with remaining issues
- Neutrino mass not yet cosmologically detected
- Dark Energy seems very similar to $\Lambda$
- Excellent prospects for future measurements of Dark Energy, neutrinos, and even evidence for Braneworlds and inflation