The Cosmological Model: an overview and an outlook

Alan Heavens
University of Edinburgh

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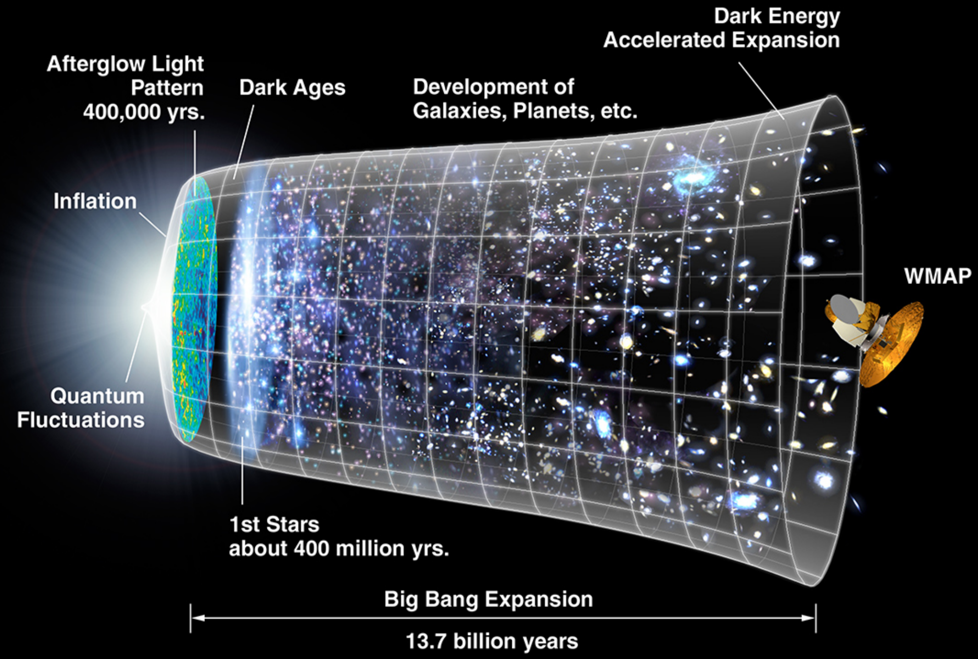
The Standard Cosmological Model

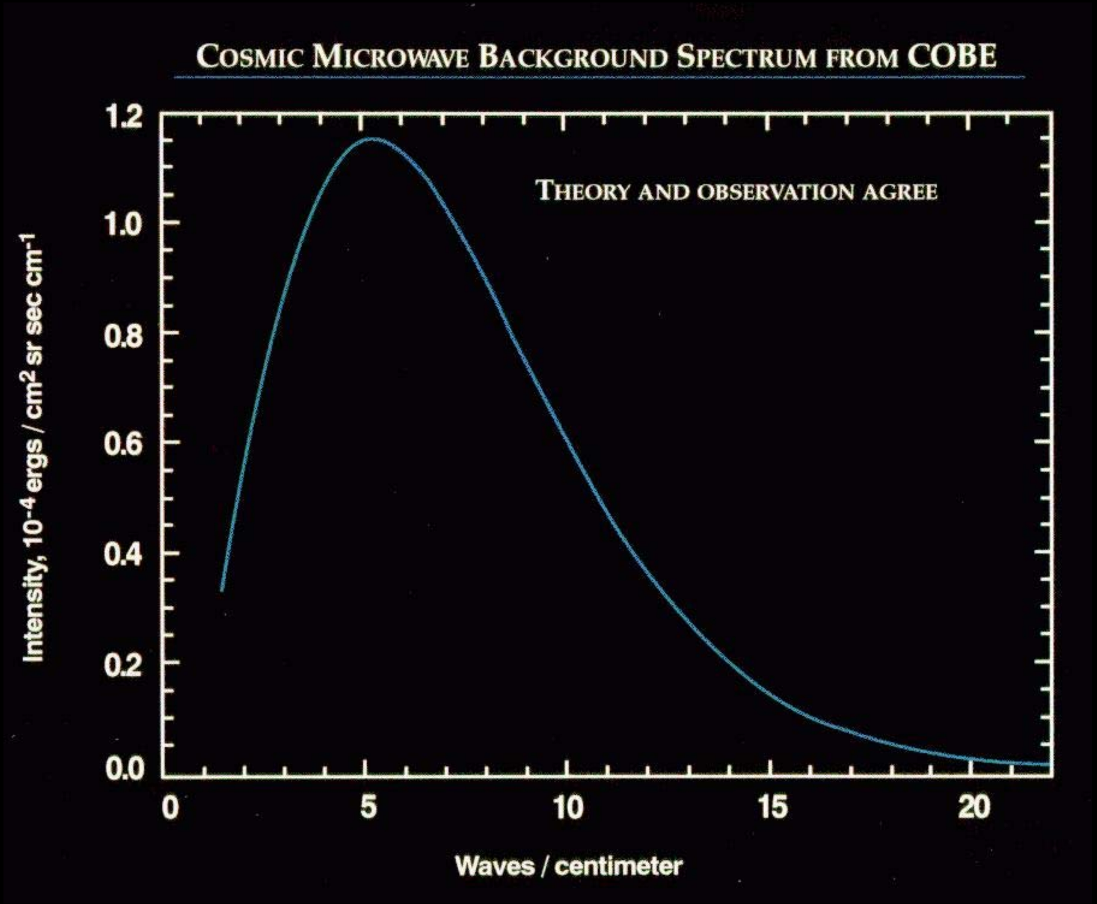


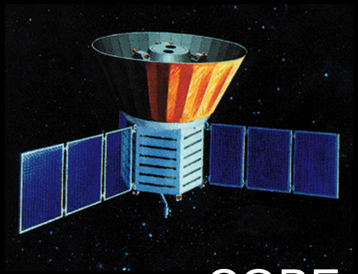
- Universe started with Big Bang
- Einstein gravity
- CDM, baryons, photons (++)
- Cosmological Constant
- Inflation
- adiabatic, near-gaussian fluctuations

NASA/WMAP Science Team

Evidence

- Universe thermalised at microwave frequencies





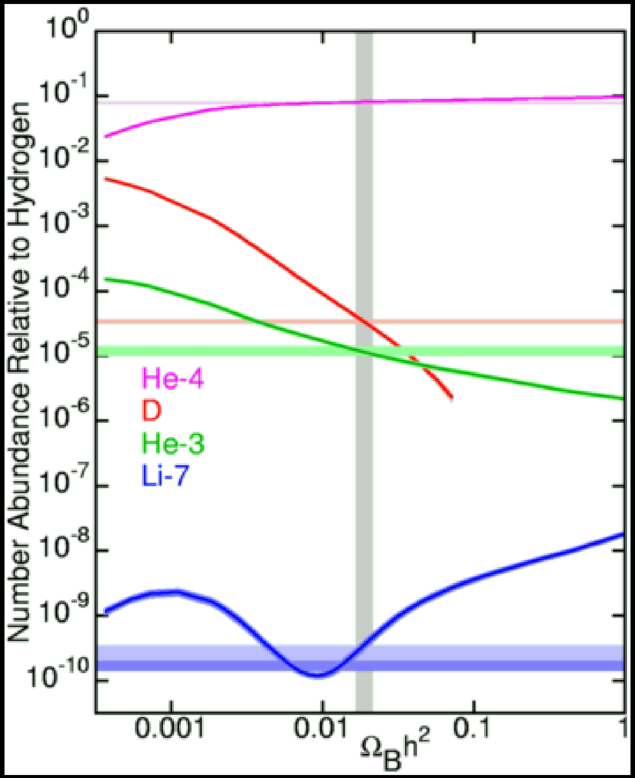
COBE

Cosmological Parameters and Effects

- Cosmological Parameters:
  - Matter density Ω_m
  - Baryon density Ω_b
  - Hubble parameter h (= H_0/100 km s^{-1} Mpc^{-1}) H=d(lna)/dt
  - Cosmological constant Λ
  - Initial amplitude σ_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 ~ 1 MeV
- t ~ 3 minutes

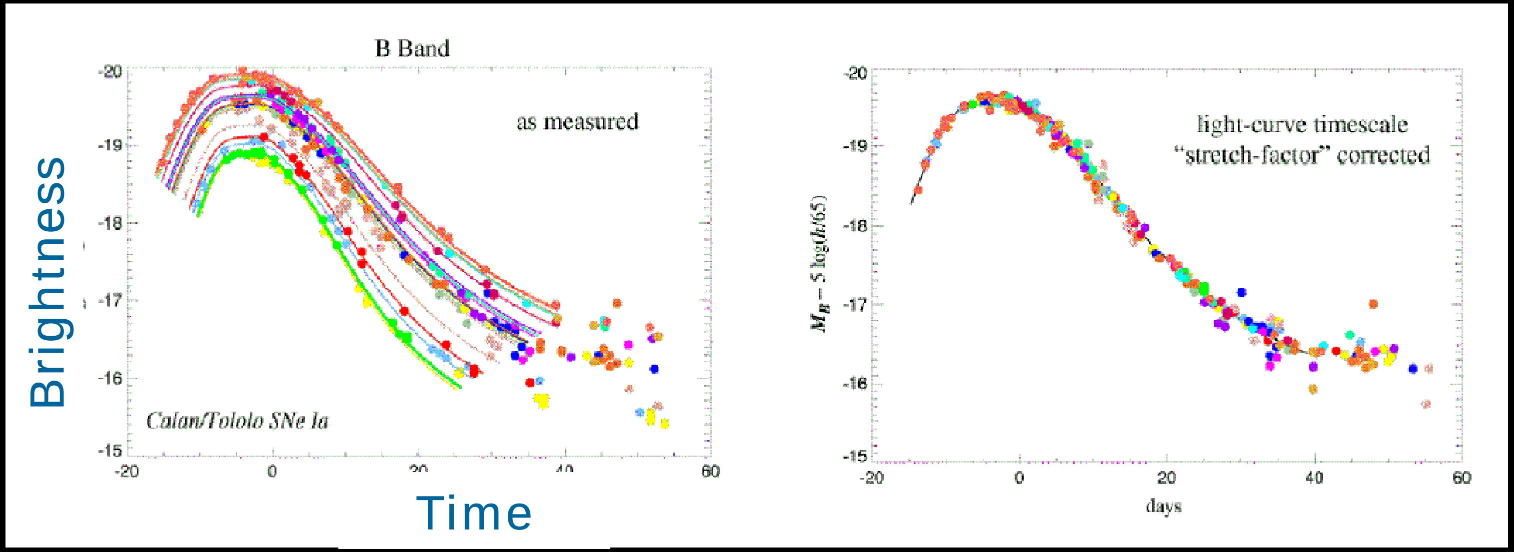


$\Omega_b h^2 = 0.020 \pm 0.002$

(e.g. Fields and Sarkar 2006)

Direct probes of geometry: Supernovae

- Standard(isable) candles



From Garcia-Bellido 2004

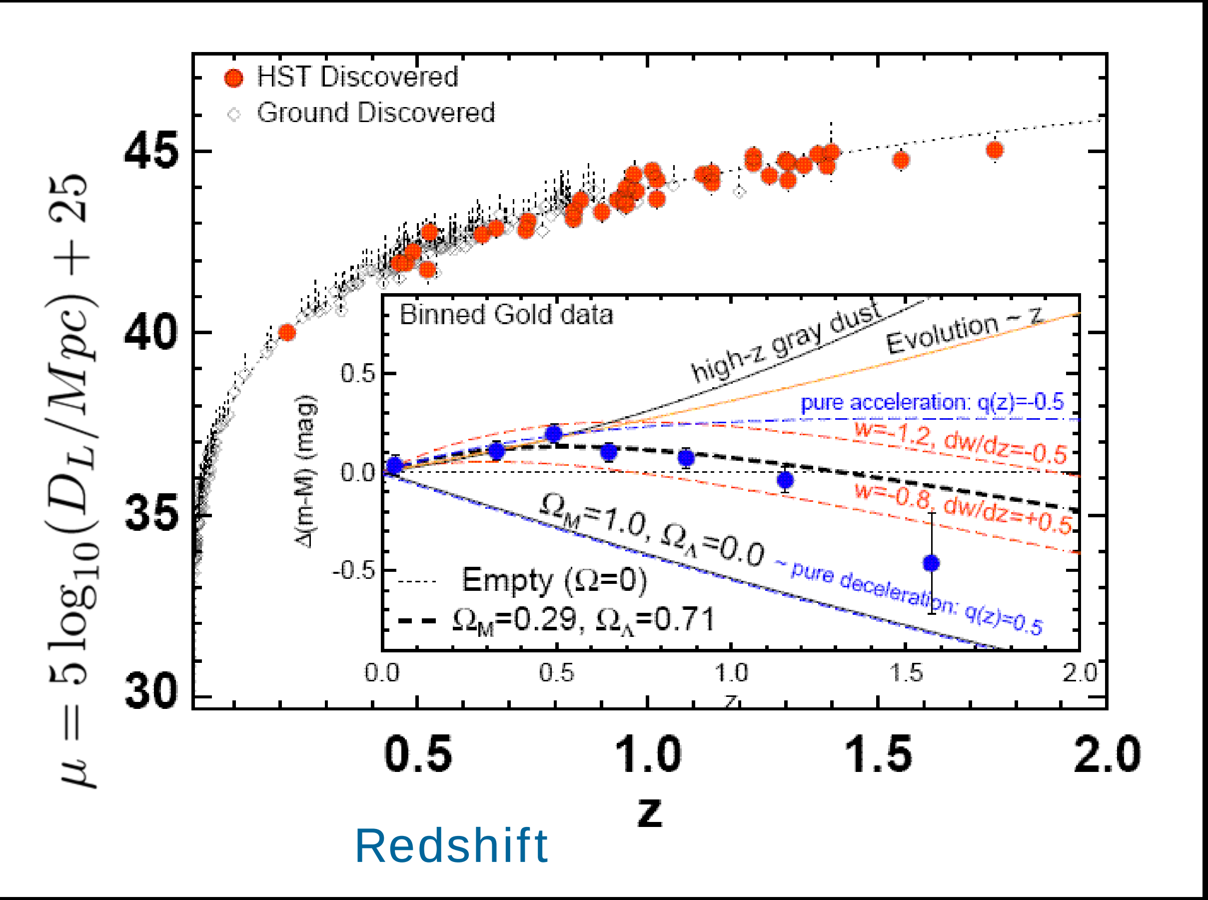
Apparent brightness → luminosity distance

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

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

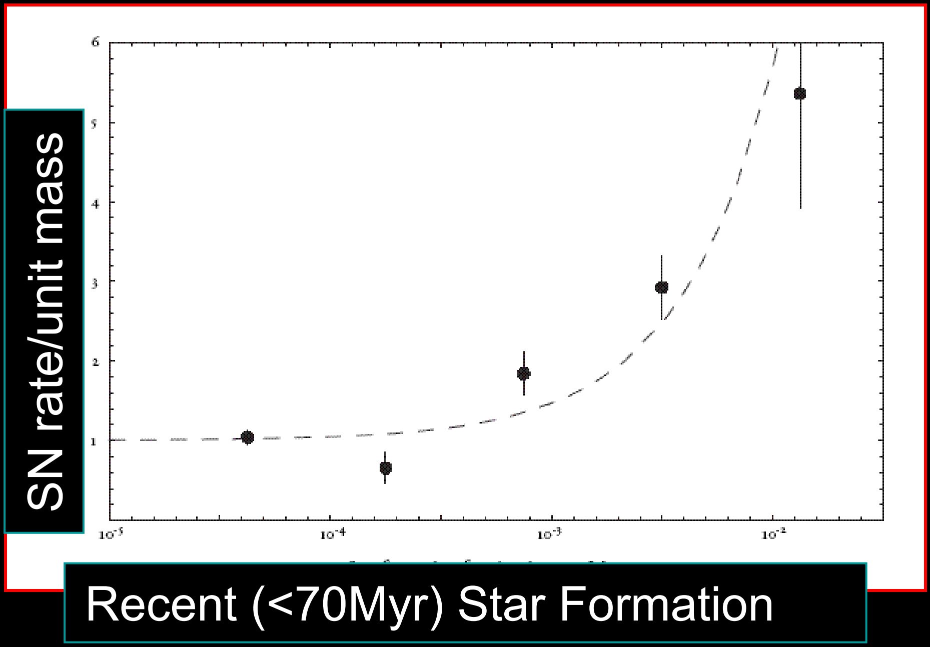
Supernova Hubble diagram

- Evidence for acceleration/cosmological constant



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

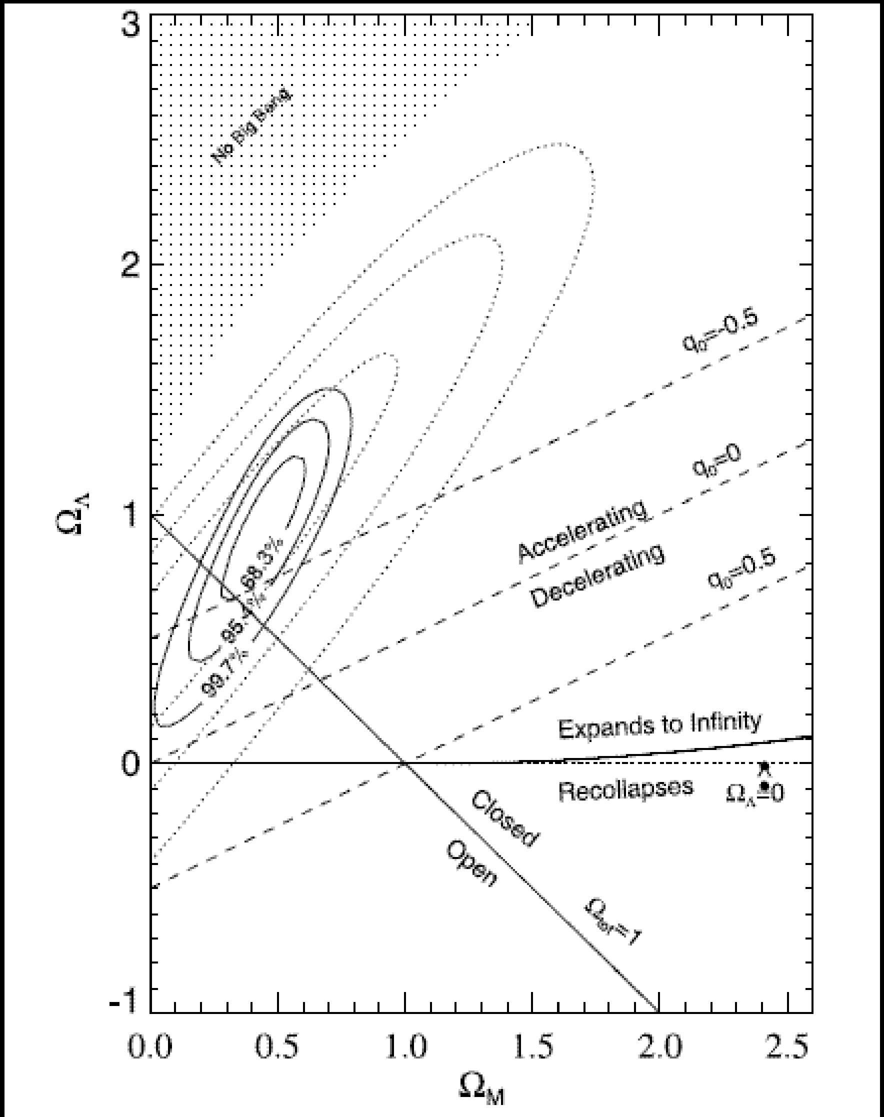
Do both types obey the same stretch-luminosity relation? Unknown

Bronder et al (2007) suggest high- and low-z SNe same

Also good news – see SNe to higher redshift

Conclusions from Supernovae

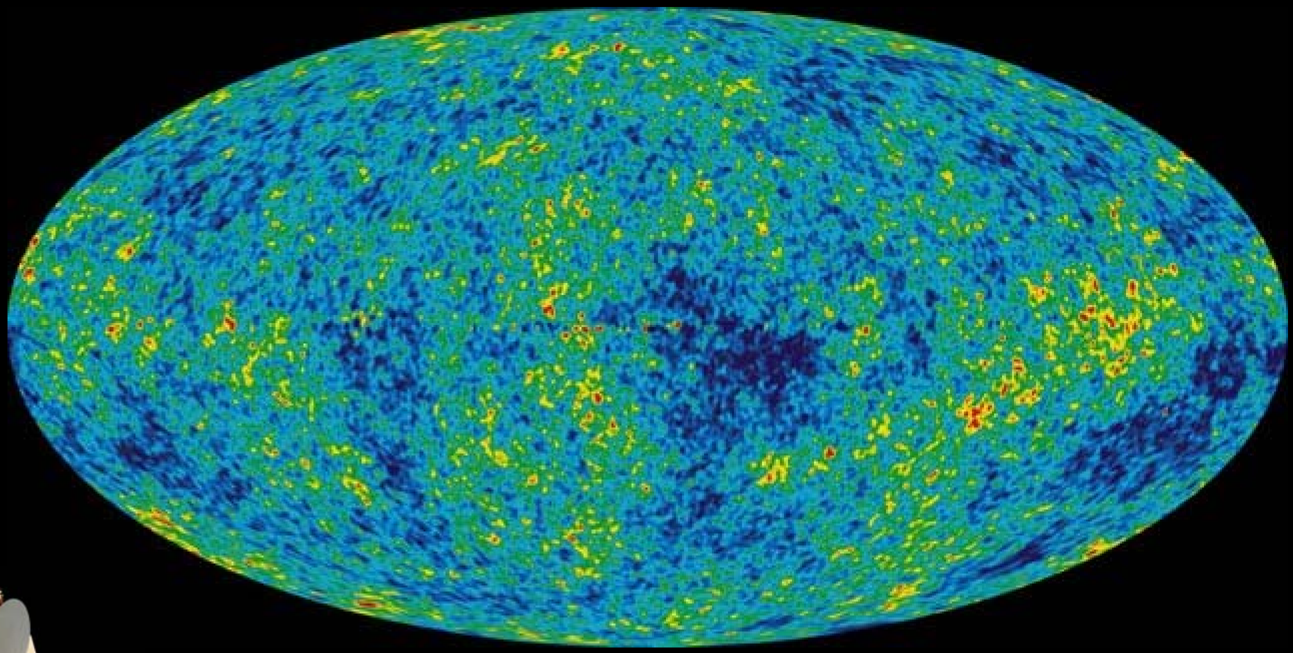
- Λ is non-zero

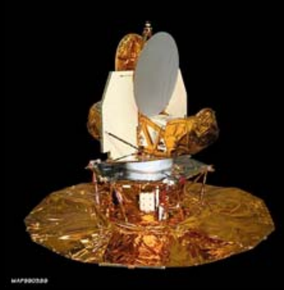


Riess et al 2004

Cosmic Microwave Background

- CMB with WMAP satellite

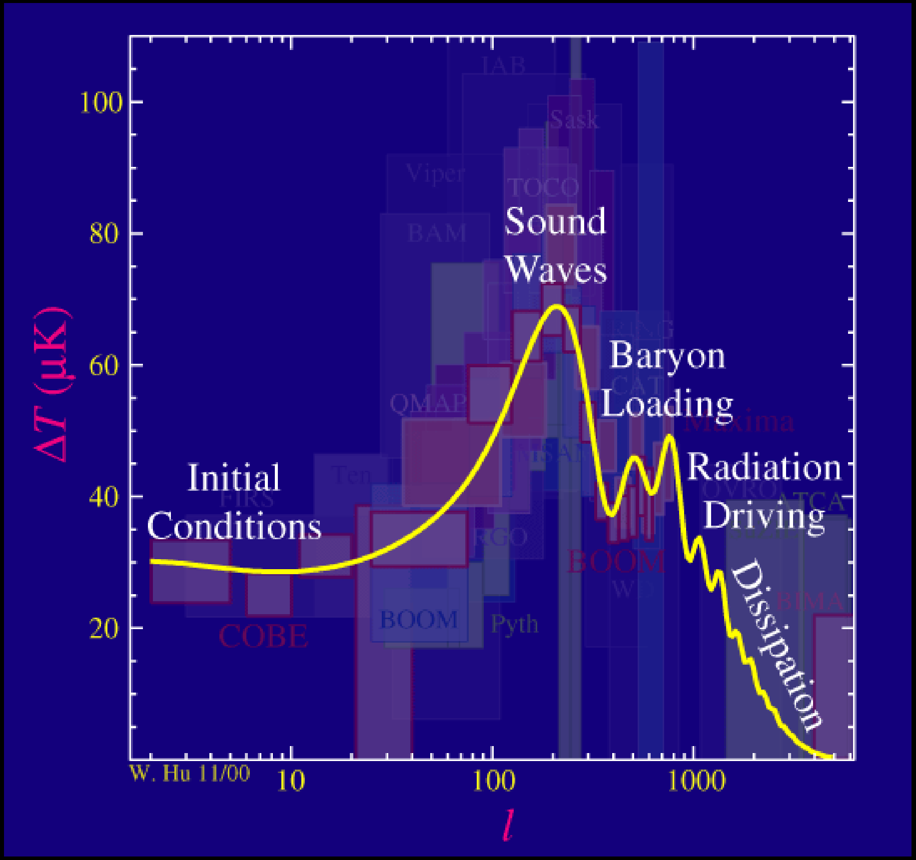




WMAP

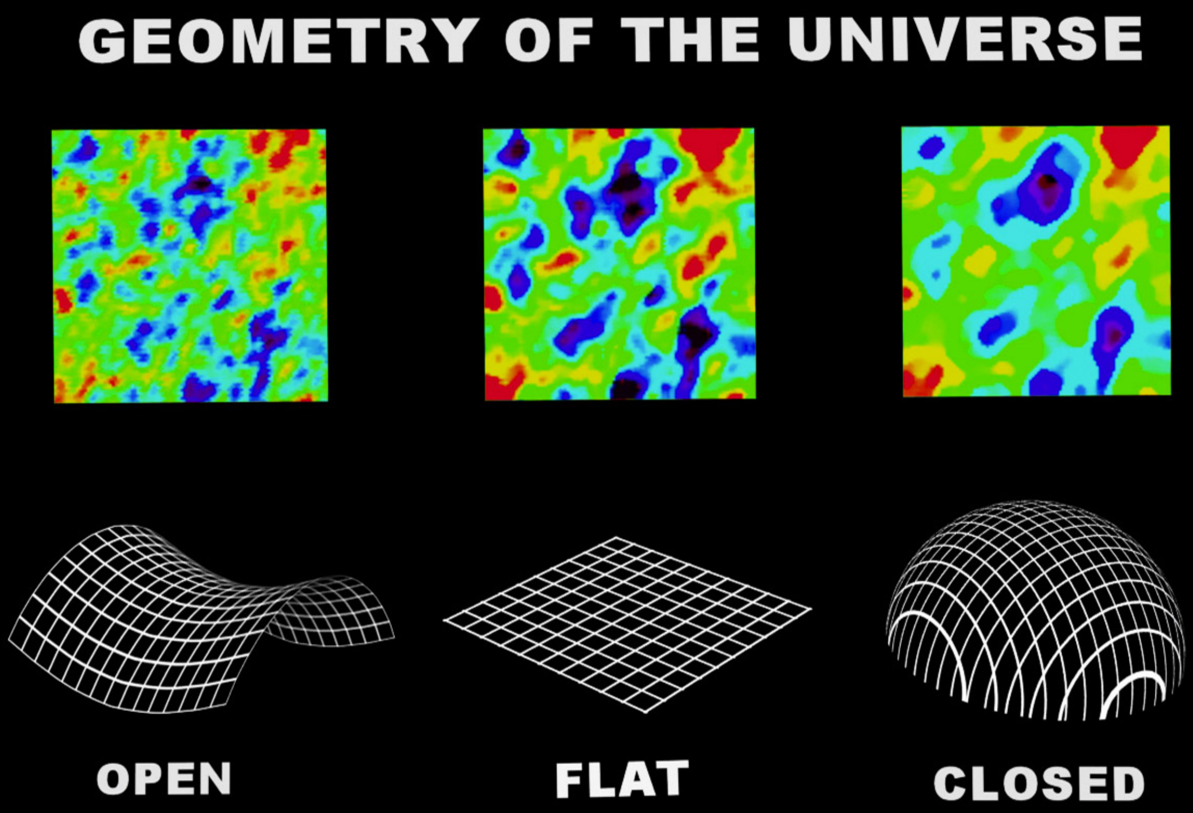
CMB fluctuation spectrum

- Theoretical expectation (relatively straightforward):

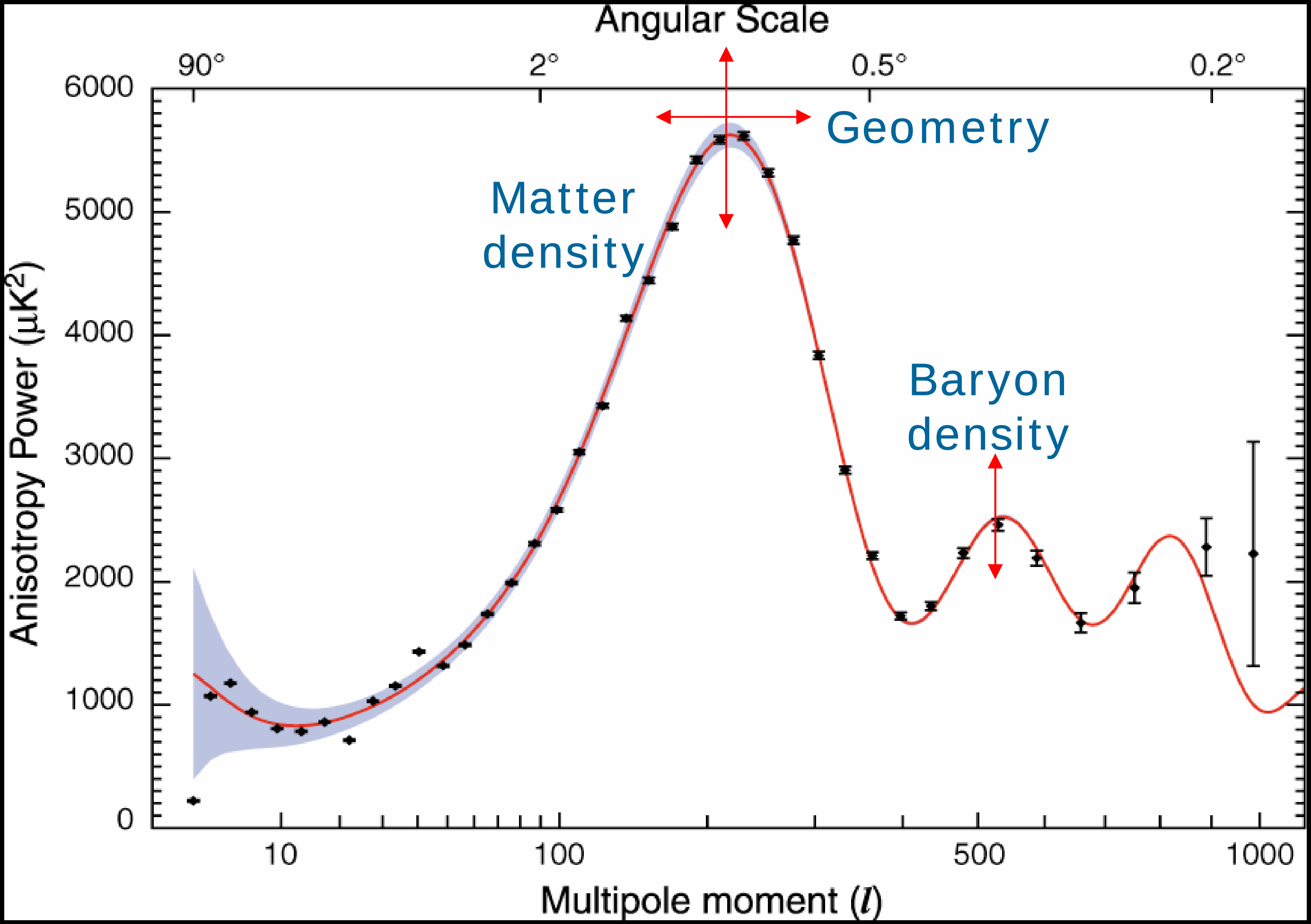


W. Hu

First peak tests geometry of Universe



WMAP power spectrum

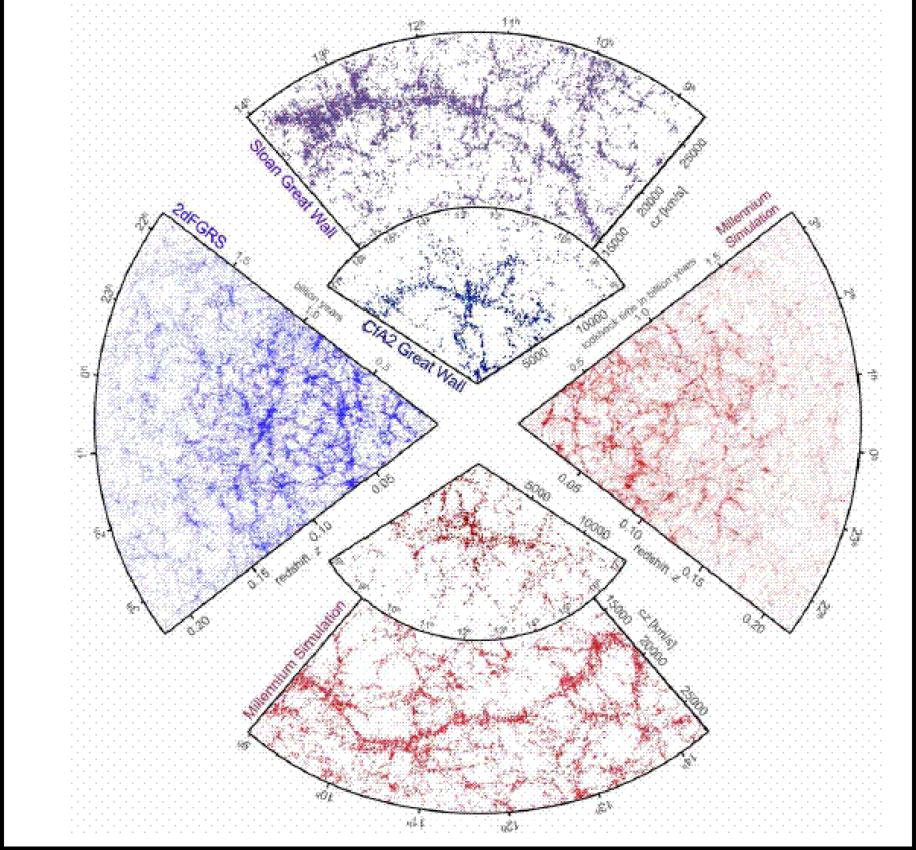


Polarisation?

See Sugiyama's talk

Large-scale structure

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



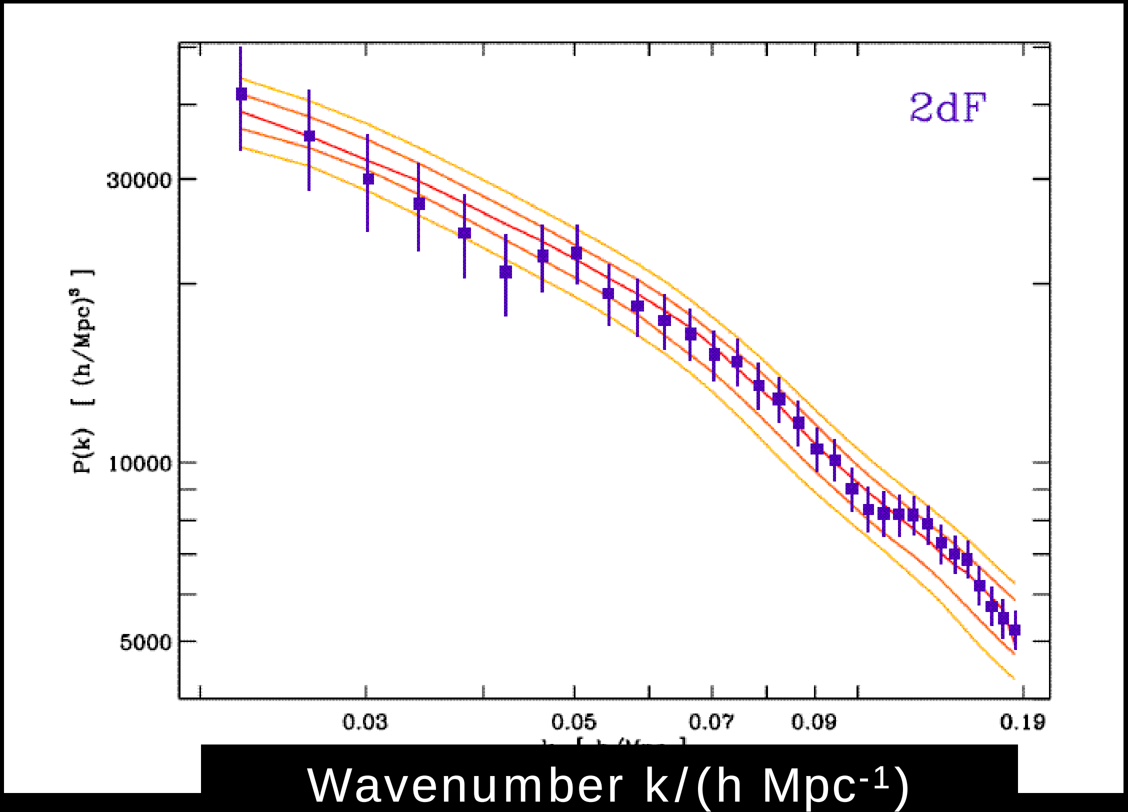
In linear perturbation theory, $\delta=\rho/\langle\rho\rangle-1$ grows:

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

- probes H(z) as well

Galaxy power spectrum

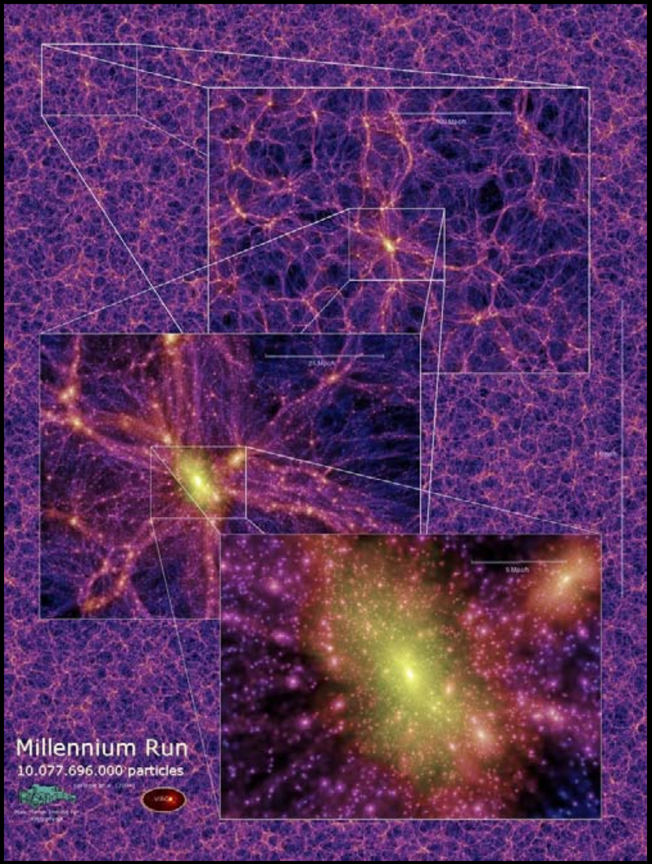
- From 2dF Galaxy Redshift Survey

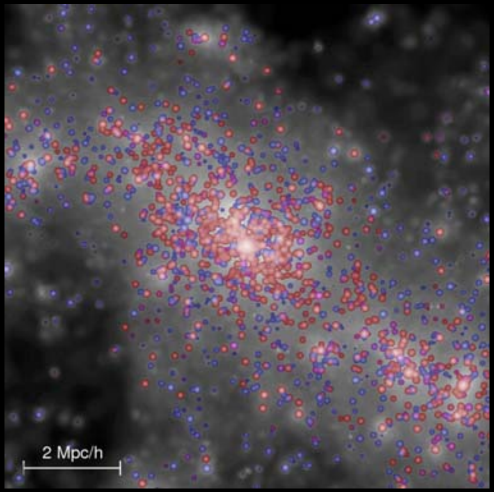


Spergel et al 2007. 2dF: Percival et al 2006

Bias?

- Galaxies are not necessarily where the mass is

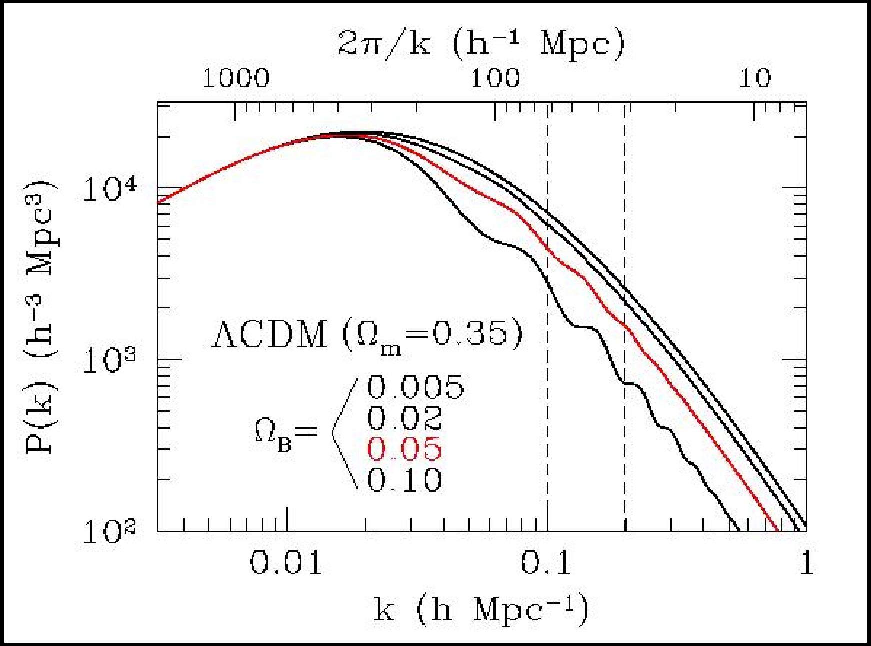




On large scales, detailed statistical analysis shows galaxies and mass DO follow the same distribution (Verde et al 2002; Seljak et al 2005)

Baryon Acoustic Oscillations

- Remnants of acoustic fluctuations



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

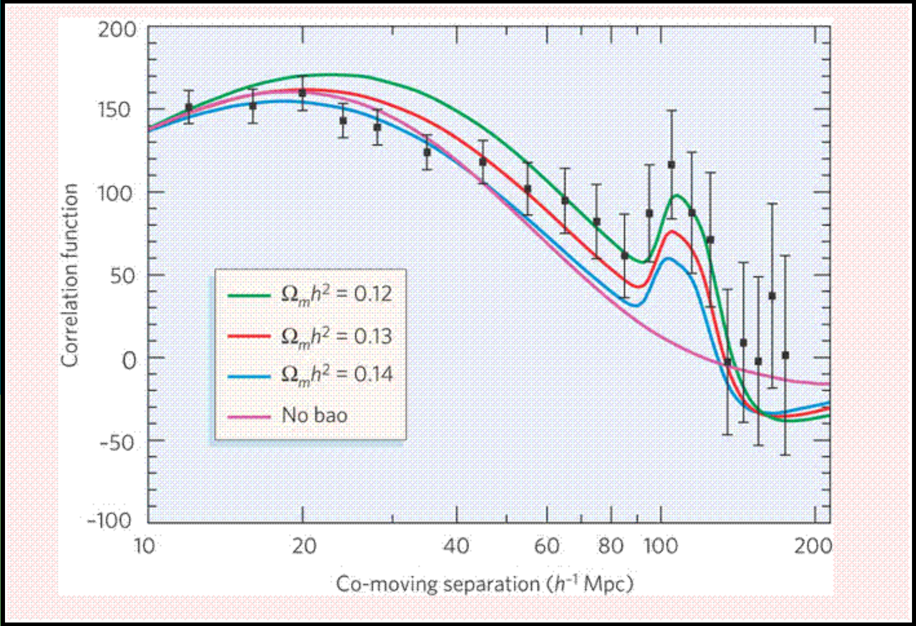
Angular scale depends on $D_A(z)$ – angular diameter distance

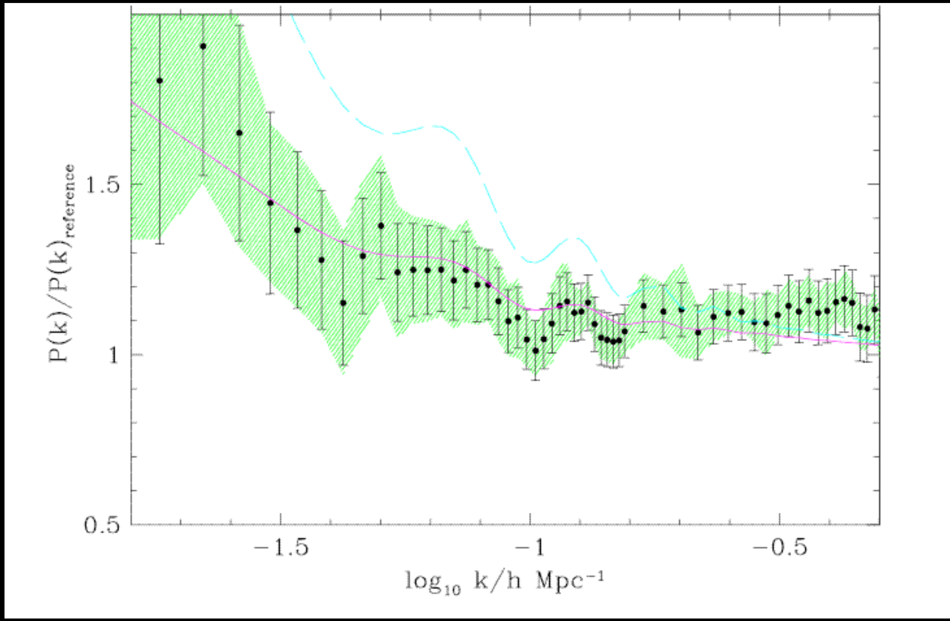
Radial dependence depends on $dr = c\, dz/H(z)$

Powerful geometric test: $H(z)$ and $D_A(z)$

Baryon Acoustic Oscillations in SDSS and 2dF

- Both show evidence of 'wiggles'



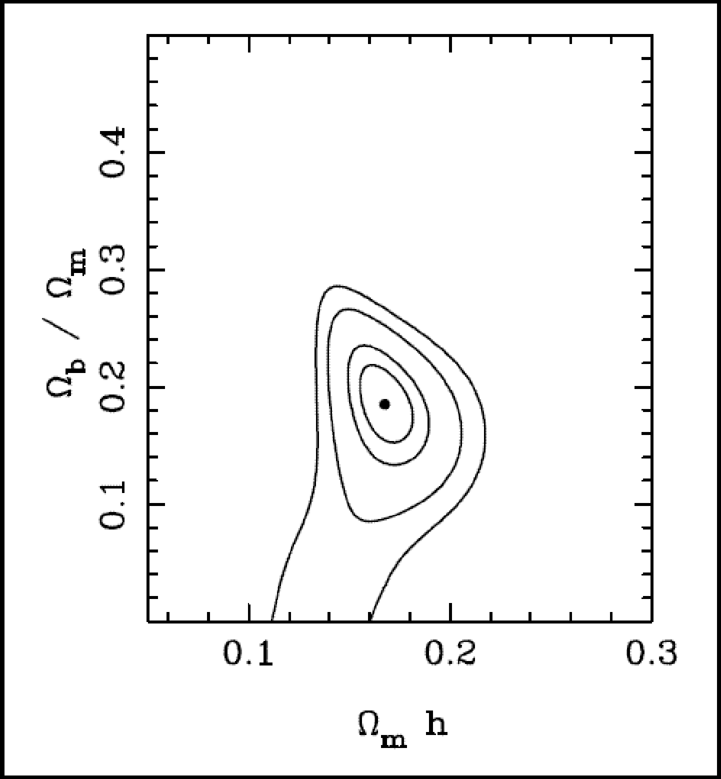


SDSS

2dF

Constraints on Ω_m and Ω_b

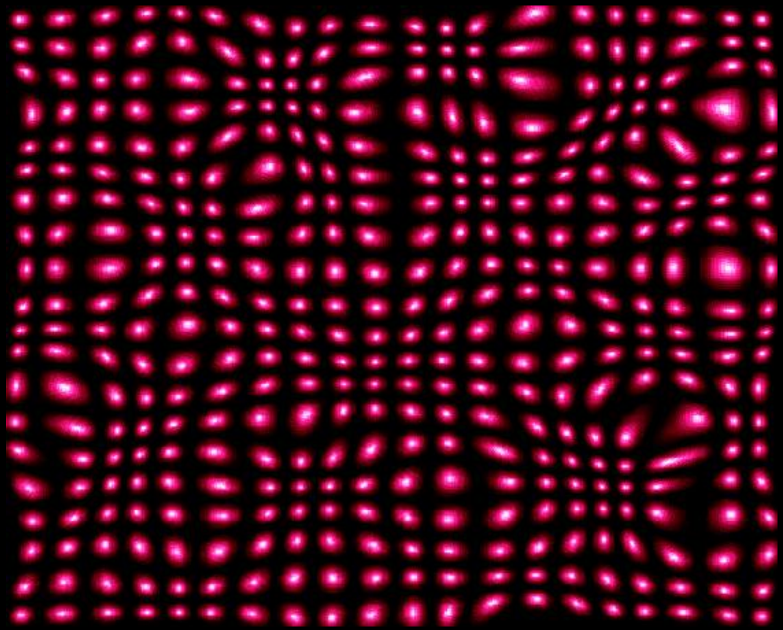
- From 2dF



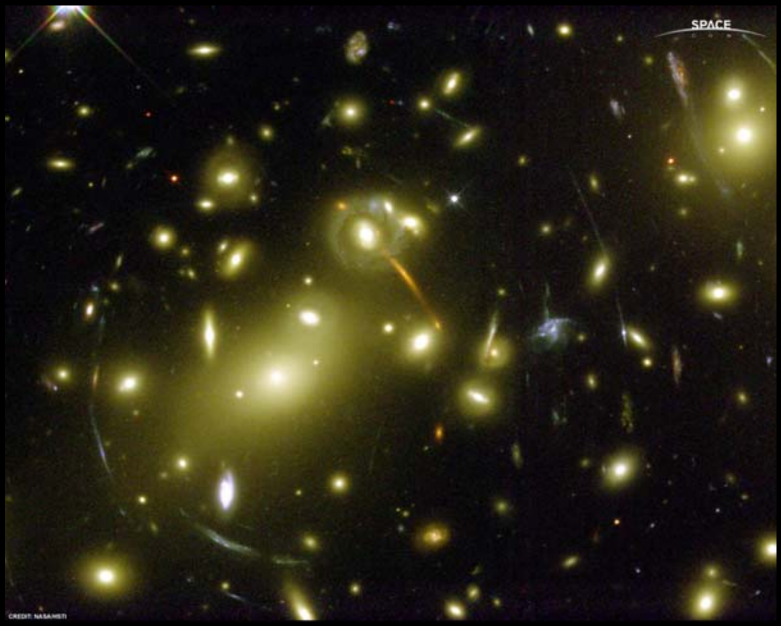
Non-baryonic Dark Matter dominates

Weak lensing

- ...probes matter distribution directly
- Distorts images of distant sources by ~1%
- Simple physics



Refregier

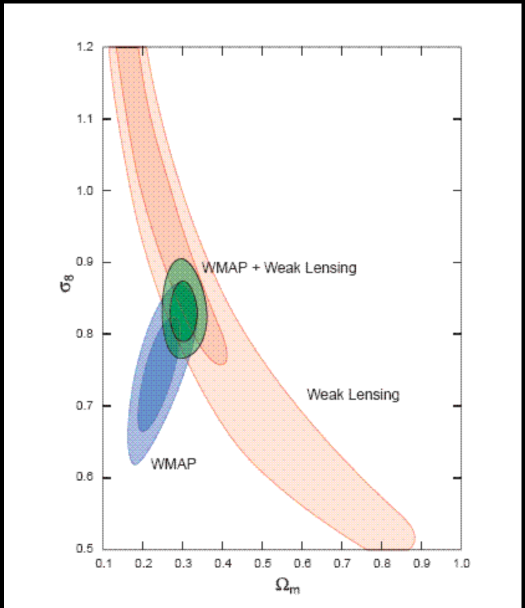


A2218 HST

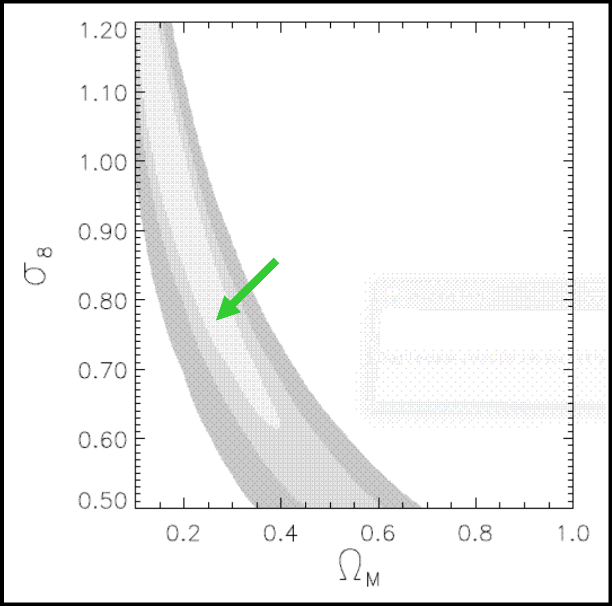
Recent weak lensing results

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

Amplitude of fluctuations



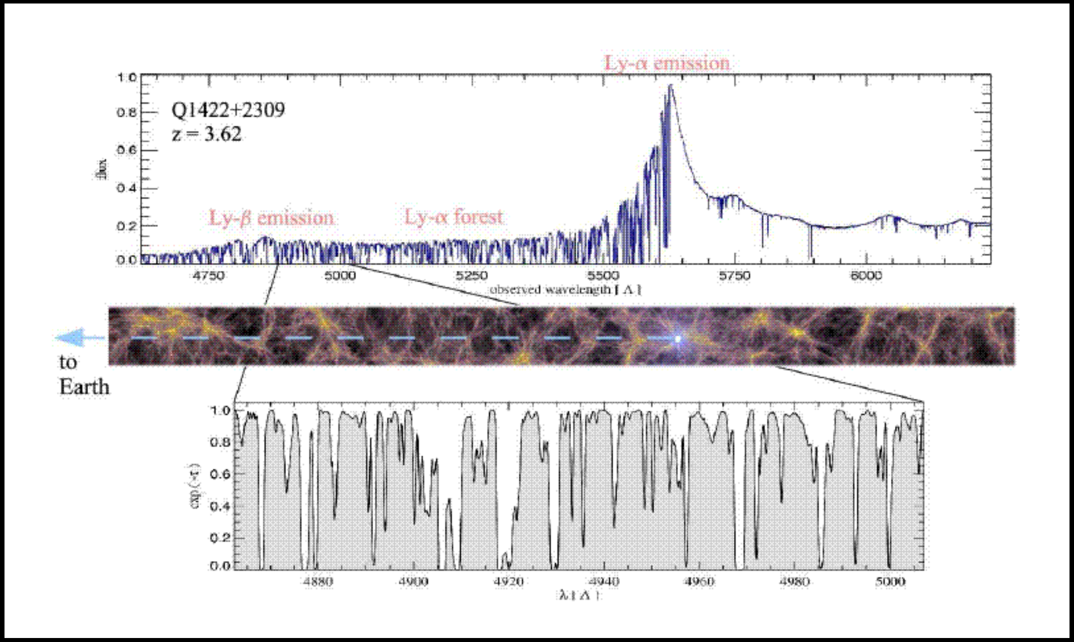
Ω_m



Benjamin et al 2007

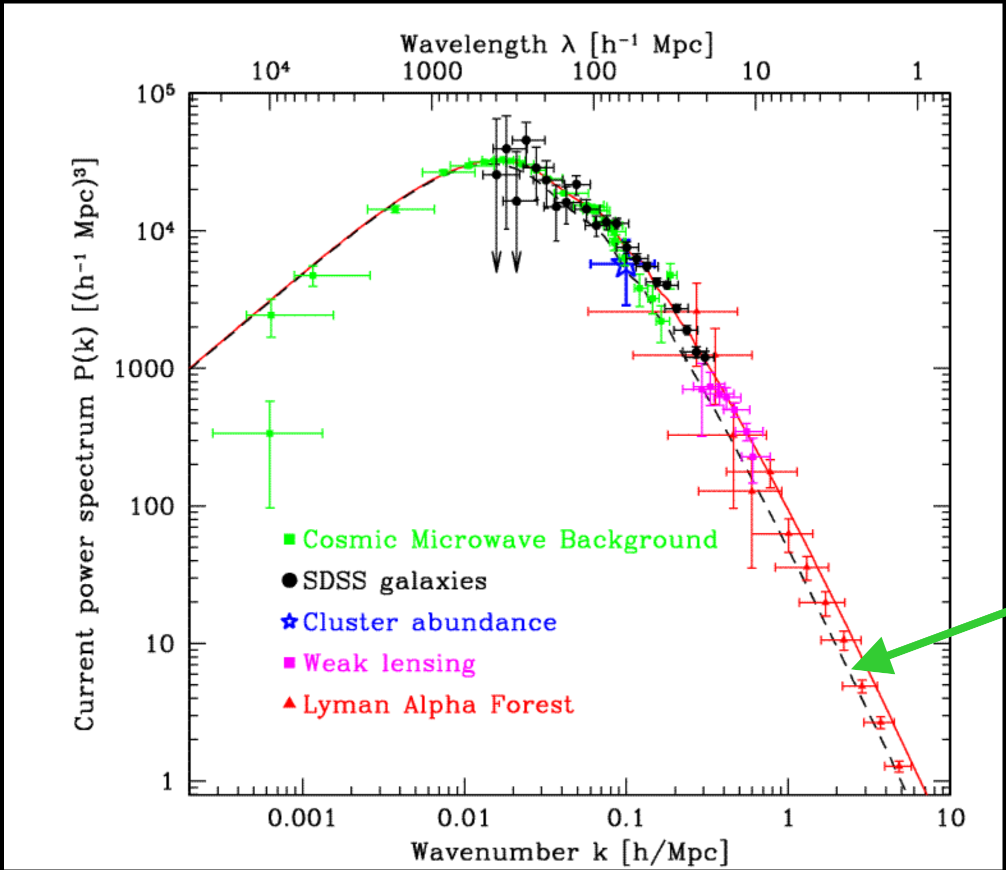
Lyman alpha forest clustering

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



Matter power spectrum

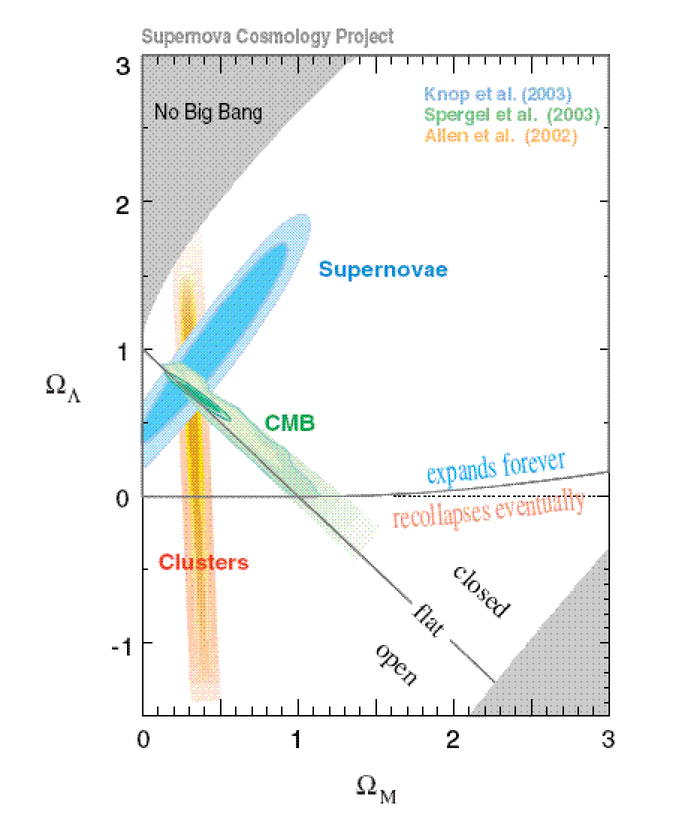
- From CMB, LSS, Lyα, cluster abundances and weak lensing

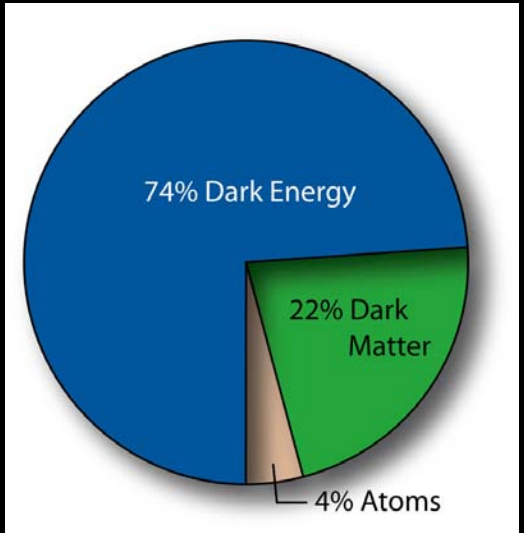


Courtesy Tegmark

Cosmological Parameters

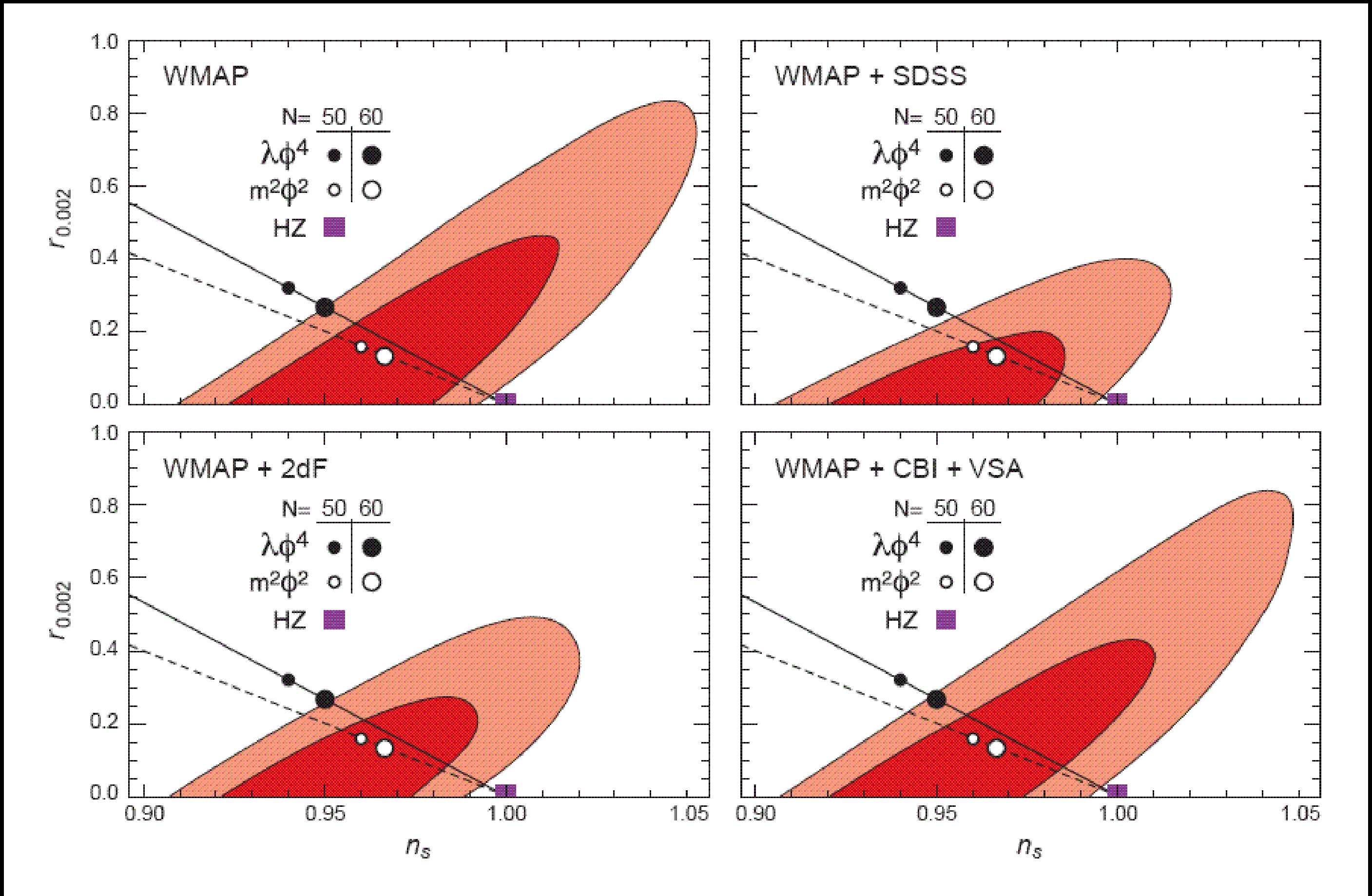
- Universe close to flat
- $\Omega_\Lambda \sim 0.74$
- $\Omega_m \sim 0.26$
- ...of which $\Omega_b \sim 0.04$
- $\Sigma m_\nu < 0.17 eV$





Beginning to probe inflation

- Constraining inflationary potentials

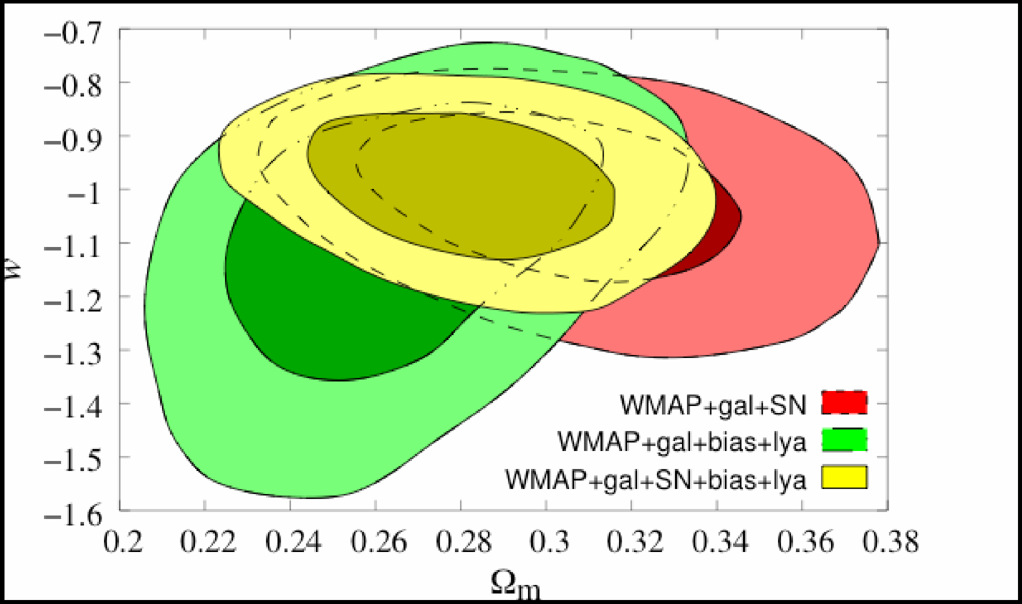


Tensor to scalar ratio

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

Cosmological Constant?

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



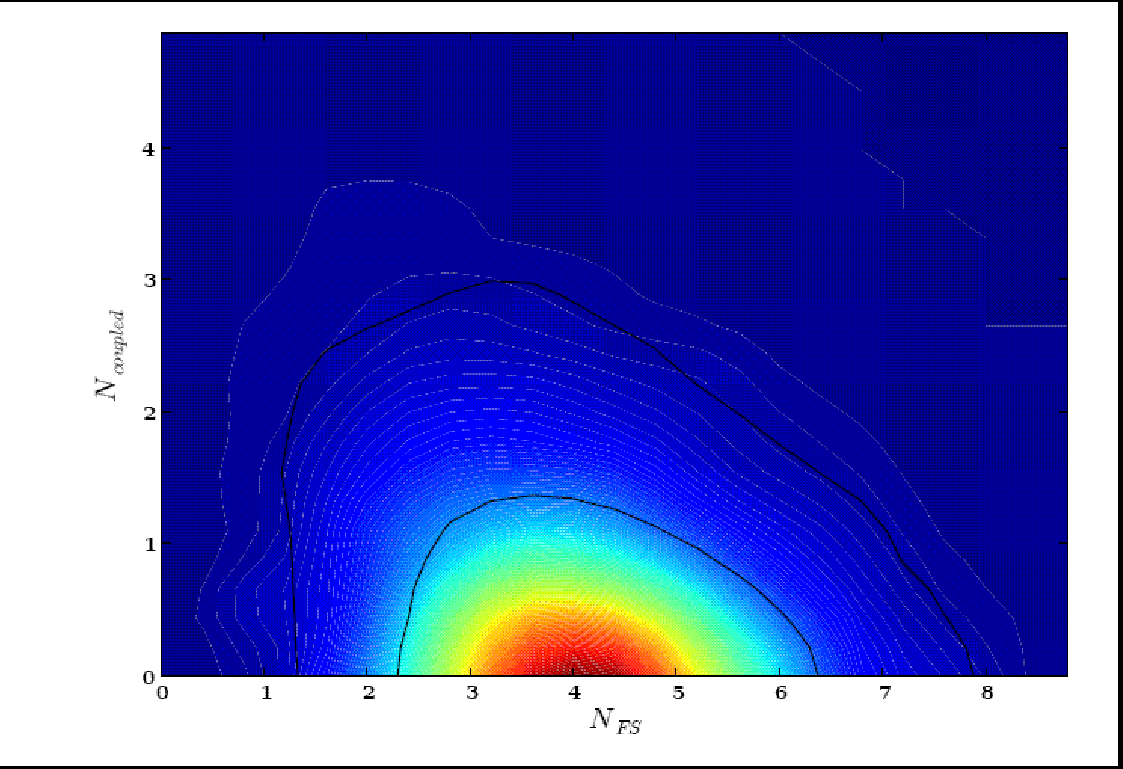
Seljak et al 2006

$w = -1.04 \pm 0.06$

Coupled neutrinos

- Self-gravity alters growth of perturbations

Number of self-coupled neutrinos



Number of free-streaming neutrinos

Friedland et al 2006

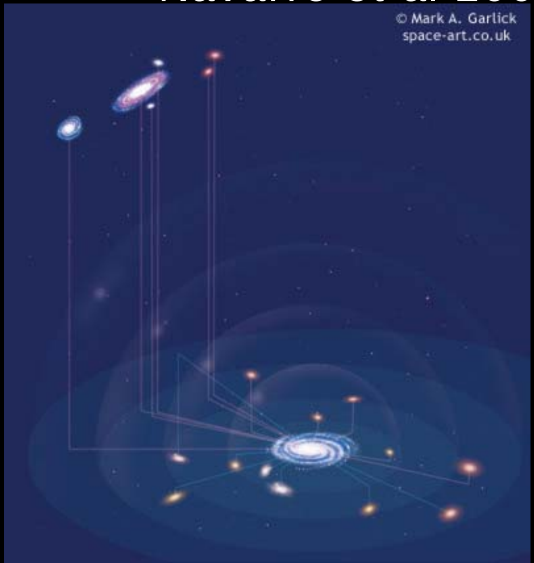
Problems with ΛCDM

- "There are only two problems with ΛCDM, Λ, 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

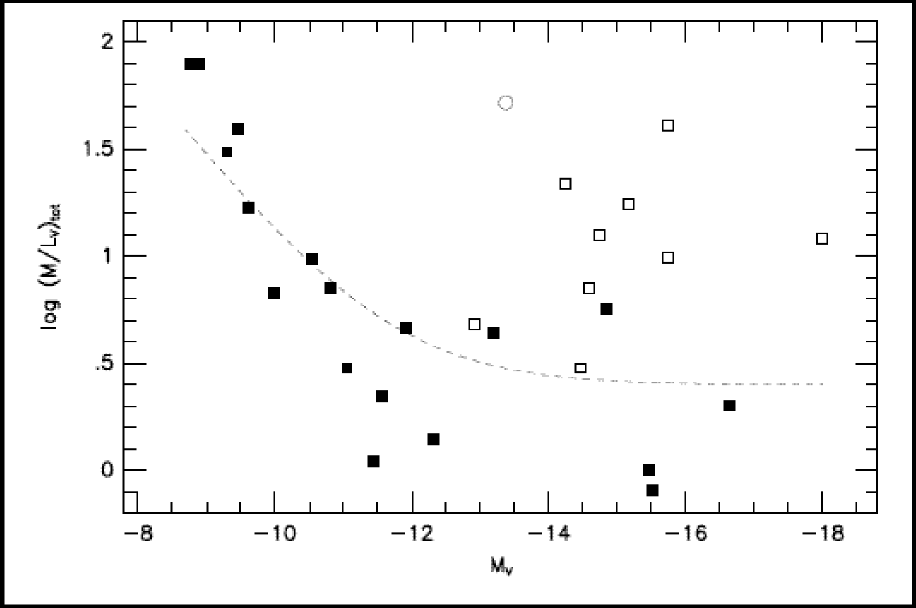
Navarro et al 2006



Dwarf galaxies have very few baryons

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

Mass-to-light ratio

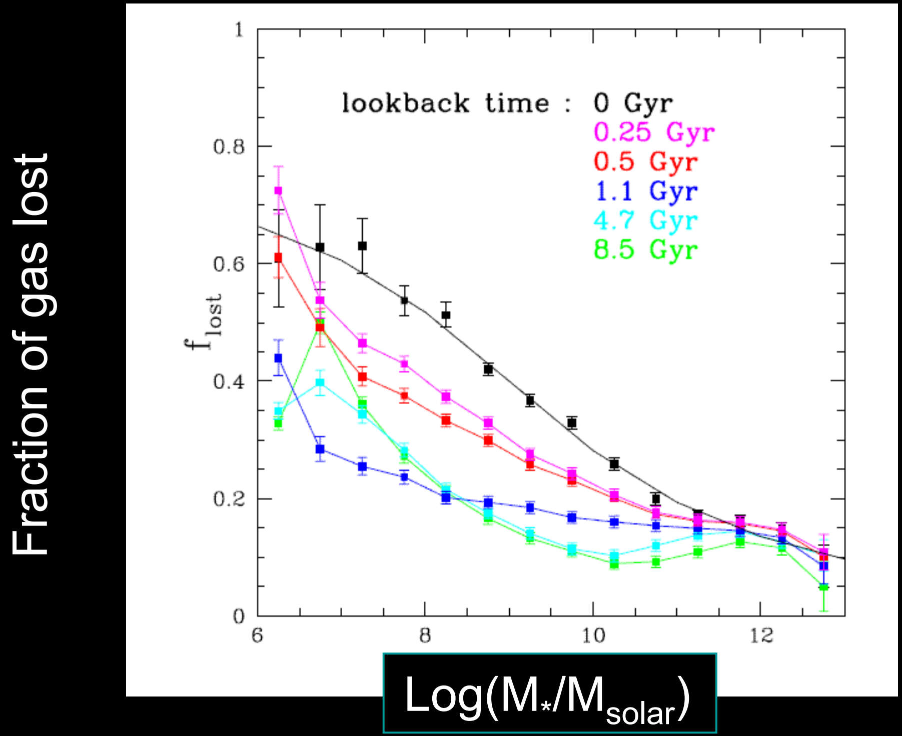


Mass

- Resolution of missing satellites is probably in heating/feedback effects

Mass loss from low-mass galaxies

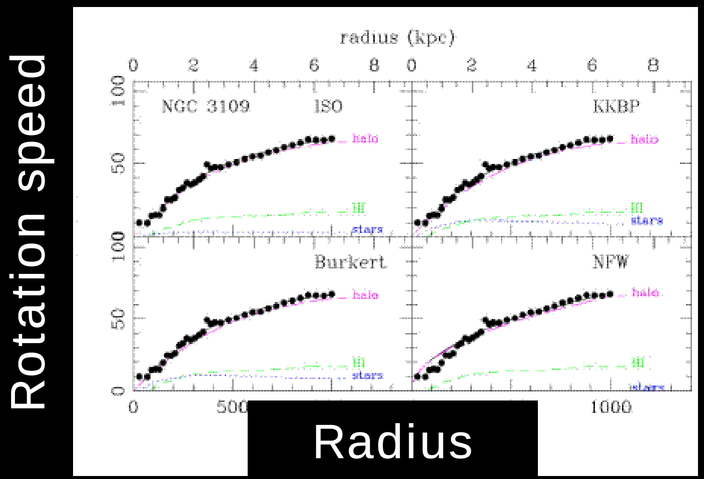
- SFR + Kennicutt law → Gas Mass
- More gas has been lost from low-mass galaxies:



Calura et al 2007

Dwarf galaxy profiles

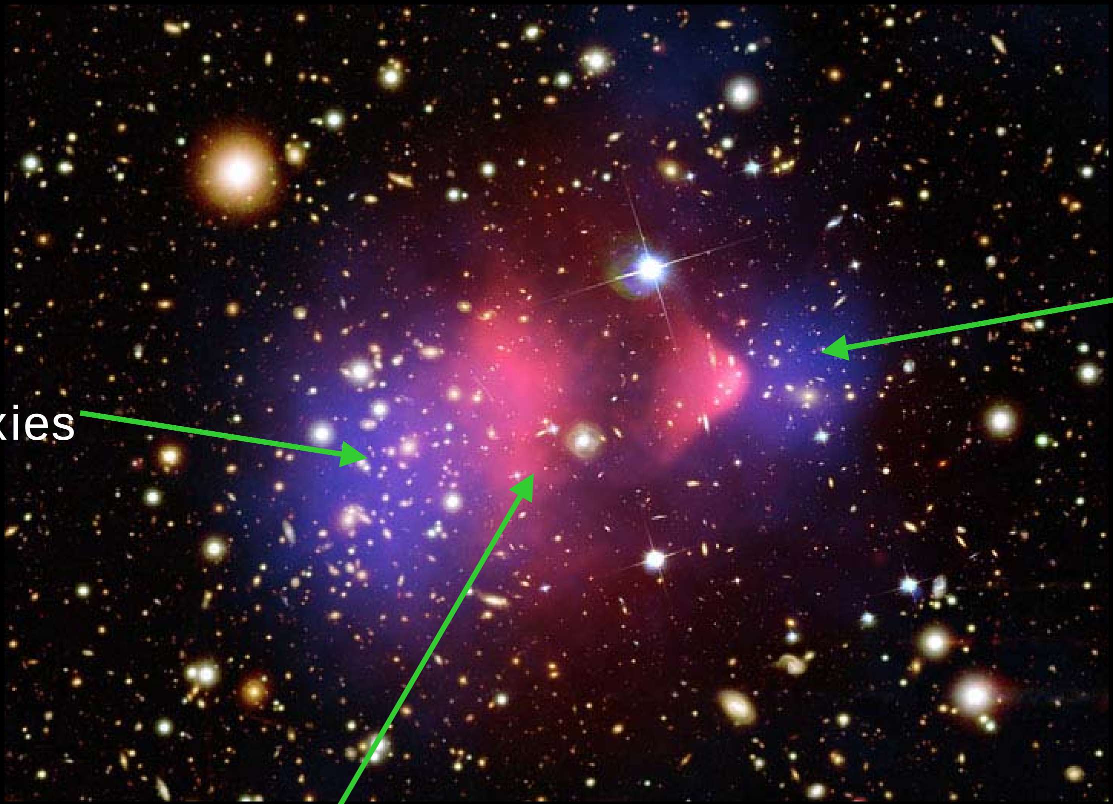
- Dark Matter dominated → good test of models
- CDM predicts steeper inner profiles



- 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



Markevitch et al 2002

Clowe et al 2004

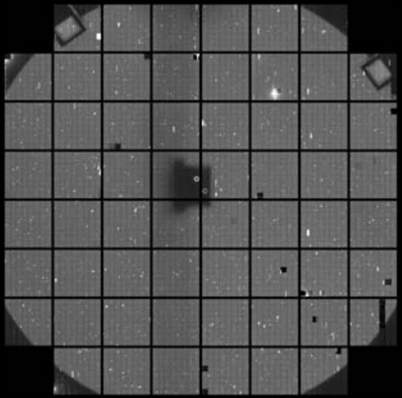
Self-interacting Dark Matter?

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

- Bullet cluster → $\sigma/m < 0.12\ m^2/kg$ (Randall et al 2007)

Prospects: Weak Lensing and BAOs

- Weak Lensing: Pan-STARRS

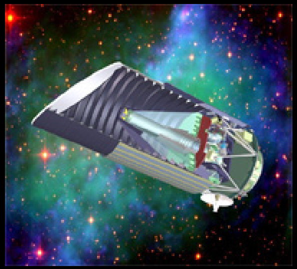


Will map 75% of the sky with weak lensing accuracy (current largest is 0.2%)

- BAOs: Many in progress or planned. Wiggle-z, PAU, FastSound etc

Joint Dark Energy Mission

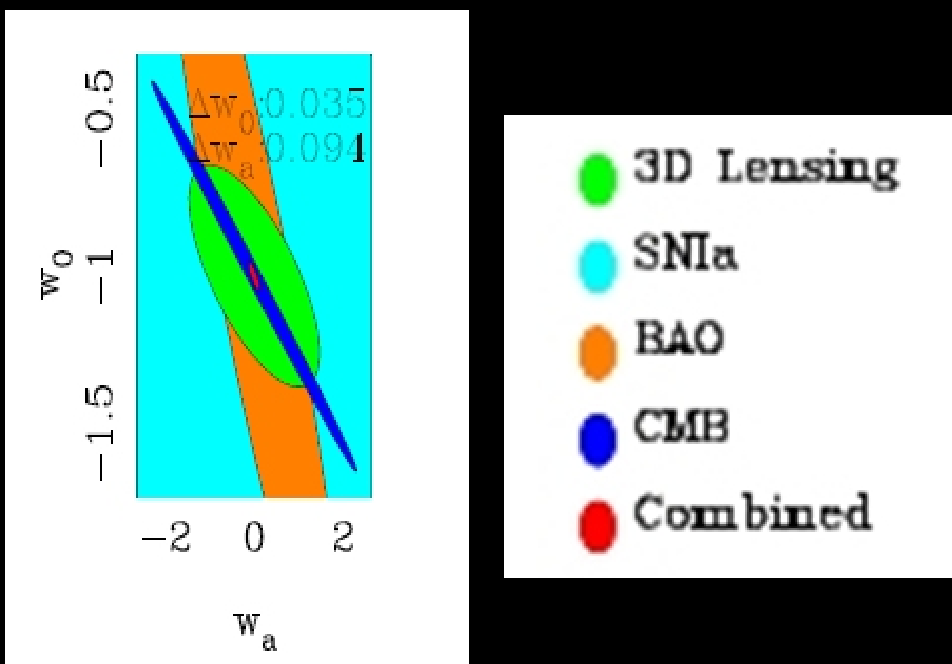
- Recommended by NSF to be next NASA Beyond Einstein mission
- ADEPT, DESTINY, SNAP



- ($\geq$ 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

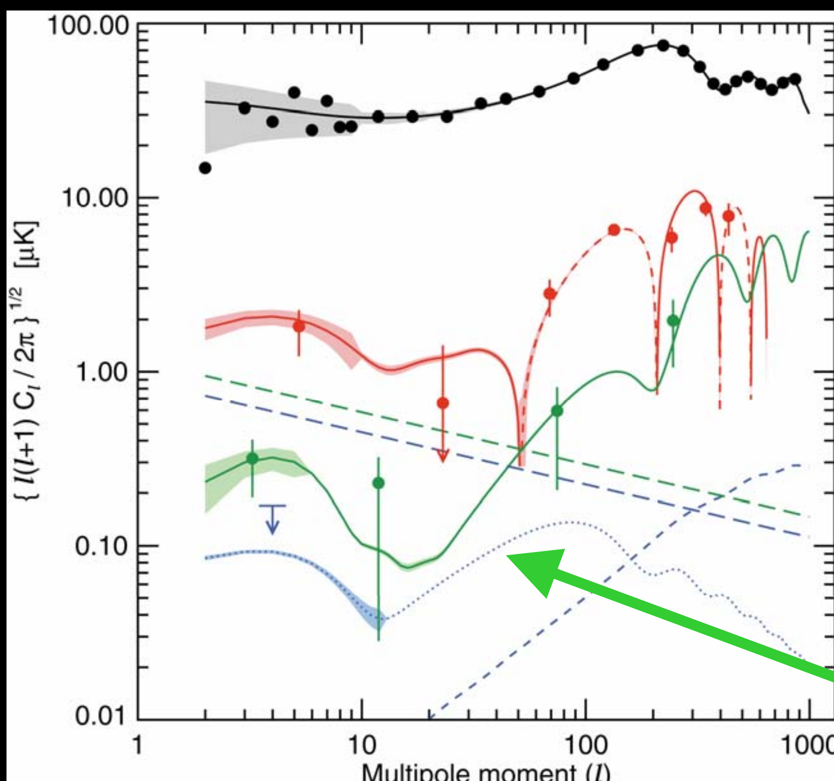
w(z) at z~0.4 may be known very accurately:

Error <1%

Courtesy: Tom Kitching

Testing inflation

- Inflation predicts B-modes in CMB polarisation on large scales, from gravity waves



B-modes from gravity waves

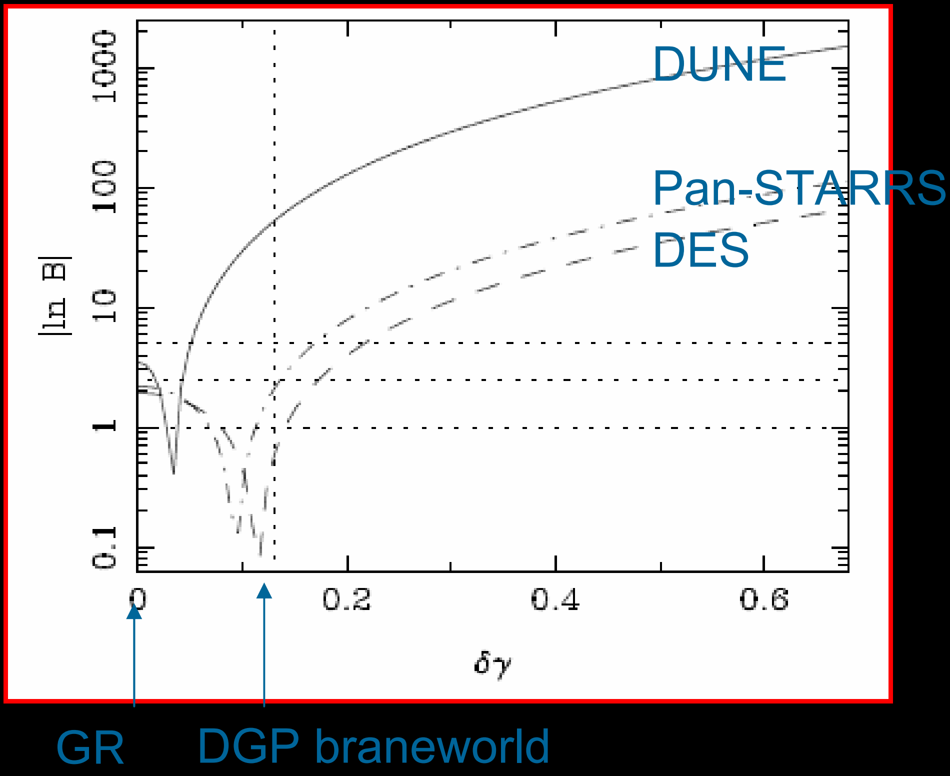
Beyond Einstein Gravity?

- 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(Probability of favouring Beyond Einstein gravity over GR)

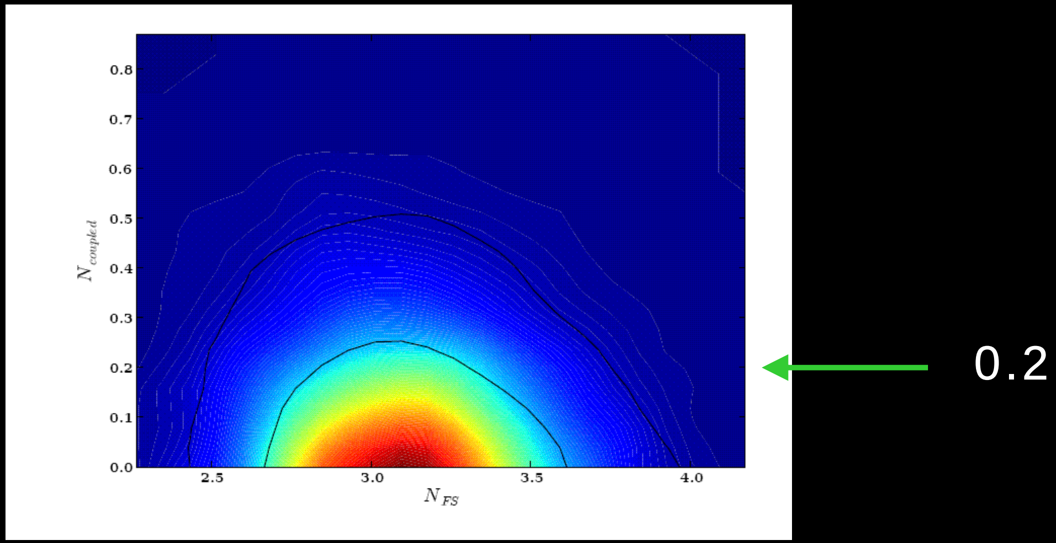


~12 σ detection possible

Neutrinos

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

Number of self-coupled neutrinos



Number of free-streaming neutrinos

Friedland et al 2006

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 Λ
- Excellent prospects for future measurements of Dark Energy, neutrinos, and even evidence for Braneworlds and inflation