An Overview of Dark Energy

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The key dark energy questions

- What is the underlying nature of dark energy?
- How can we reconstruct dark energy?
- What dark energy properties can we measure observationally?

The key dark energy questions

- What is the underlying nature of dark energy?

$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

Adjustment to the FRW cosmology?

–Non-minimal couplings to gravity?

–Higher dimensional gravity?

Adjustment to matter components?

– Vacuum energy, Λ?

– An ‘exotic’, dynamical matter component?

– ‘Unified Dark Matter’?

– Matter on a brane?

Is the explanation anthropic?

The key dark energy questions

- How can we reconstruct dark energy?

  – expansion properties today

  –temporal evolution?

  – dark energy clustering?

  – coupling to gravity or other matter?

The key dark energy questions

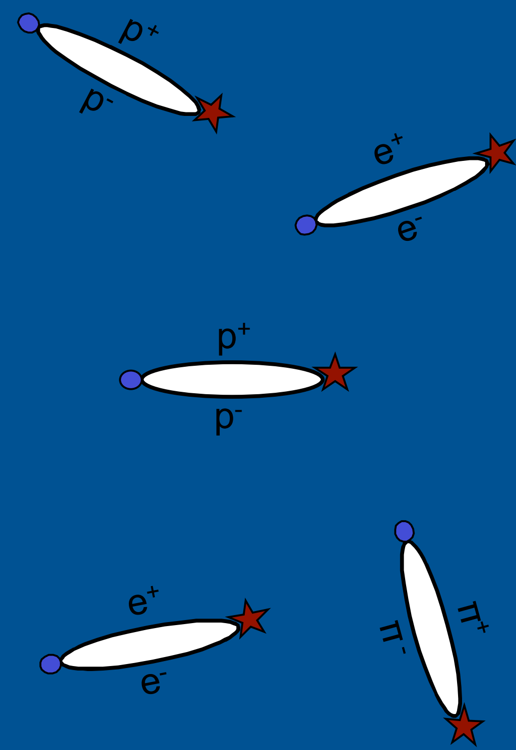
- What can we measure observationally?
  - Time evolution of H(z)
  - Temporal evolution and spatial distribution of structure
  - Local tests of general relativity and the equivalence principle

The key dark energy questions

- What is the underlying nature of dark energy?
- How can we reconstruct dark energy?
- What dark energy properties can we measure observationally?

The problem with Λ as dark energy : Why so small?

- Lamb shift and Casimir effect proved that vacuum fluctuations exist
- UV divergences are the source of the problem



$$\Lambda = 8\pi G\langle T_{00}\rangle_{vac} \propto \int_0^\infty \sqrt{k^2+m^2}\,k^2 dk = ?$$

a) ∞?
b) regularized at the Planck scale = 10^{76} GeV^4?
c) regularized at the QCD scale = 10^{-3} GeV^4?
d) 0 until SUSY breaking then = 1 GeV^4?
e) all of the above = 10^{-47} GeV^4?
f) none of the above = 10^{-47} GeV^4?
g) none of the above = 0 ?

The problem with Λ as dark energy: why now?

- Coincidence problem

  – Any earlier → chronically affects structure formation; we wouldn't be here

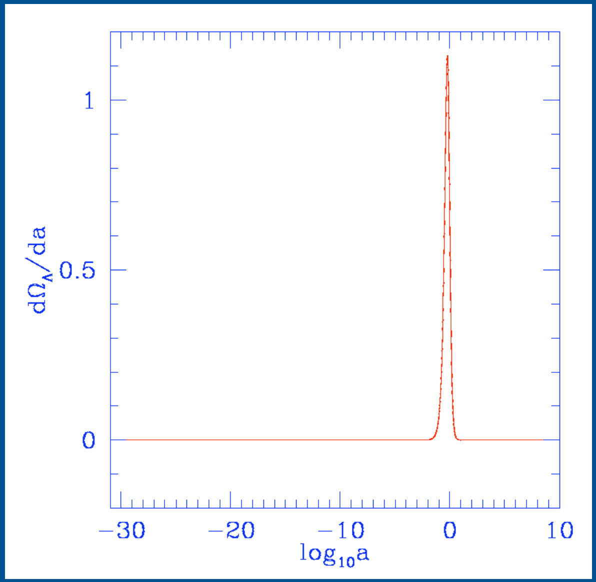
  –Any later → Ω_Λ still negligible, we would infer a pure matter universe

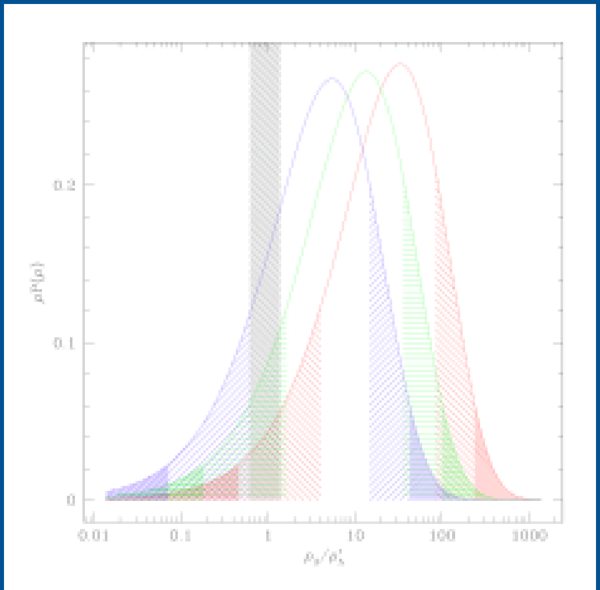
- Led to anthropic arguments

  – Key factors are:
  - dark energy density at epoch of galaxy ρ_G
  - assume an unpeaked prior in $P(\rho_\Lambda)$

  - If $\rho_\Lambda < \rho_G$ less galaxies to observe from
  - If $\rho_\Lambda < \rho_G$ less universes predicted
  - Observation implies $\rho_\Lambda \sim \rho_G$

  –But all hinges on prior assumption
  - But the Λ question is fundamentally about understanding this prior

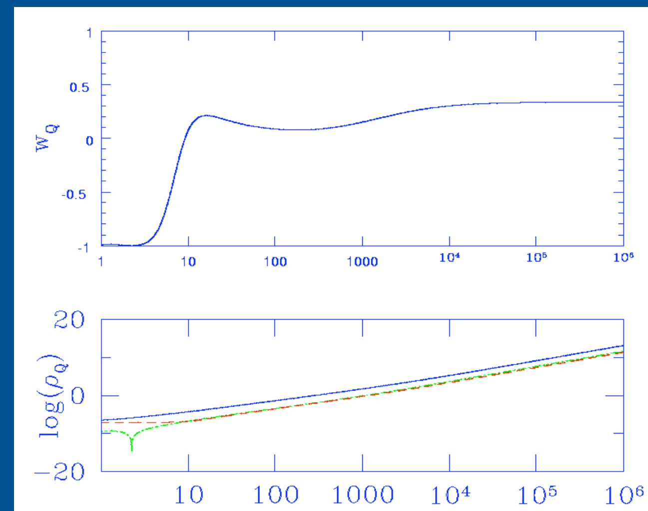




Pogosian, Vilenkin,Tegmark 2004

Tackling the fine-tuning problem

- Dynamical scalar field "quintessence" models
  - –Explaining $\Omega_Q \sim \Omega_m$ whilst allowing freedom in initial conditions.



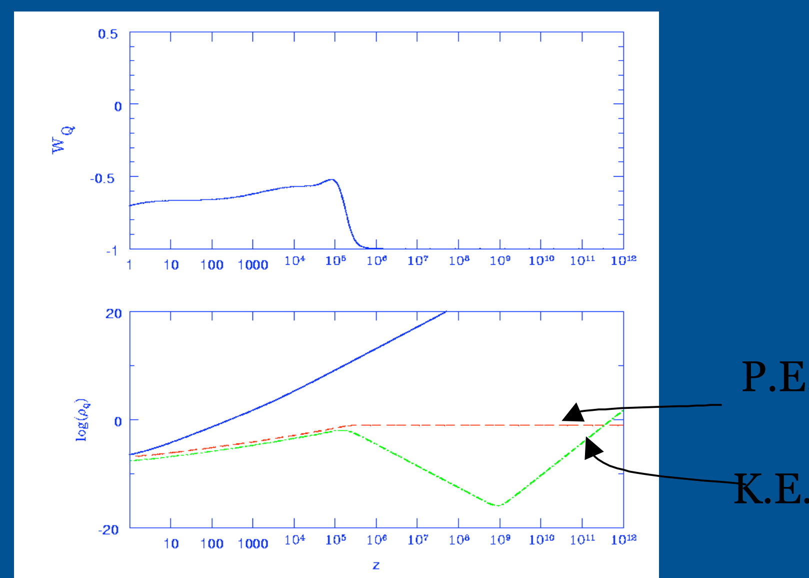
- E.g. Scaling potentials

$V \sim e^{-\lambda Q}$ — Wetterich 1988, Ferreira & Joyce 1998

– Need feature to create acceleration

$V \sim ((Q-a)^b+c)\, e^{-\lambda Q}$ — Albrecht & Skordis 2000

- E.g. Tracker potentials



$V \sim Q^{-\alpha}$ — Ratra & Peebles 1988

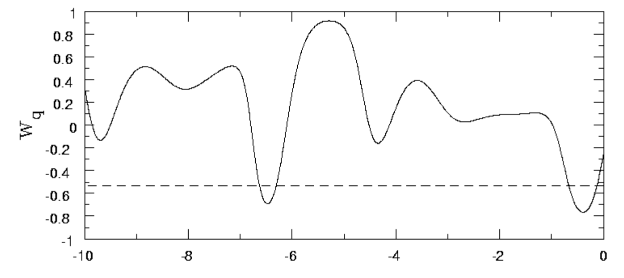
$V \sim \exp(M/Q-1)$ — Wang, Steinhardt, Zlatev 1999

Tackling the coincidence problem

- We're not special: universe sees periodic epochs of acceleration

$V \sim M^4 e^{-\lambda Q}(1+A\sin \nu Q)$

Dodelson , Kaplinghat, Stewart 2000



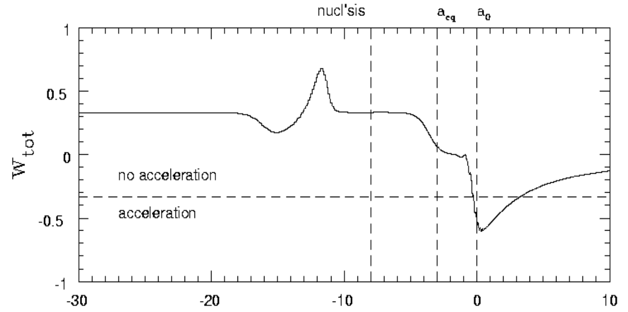
Oscillatory potential

- We're special: the key is our proximity to the matter/ radiation equality

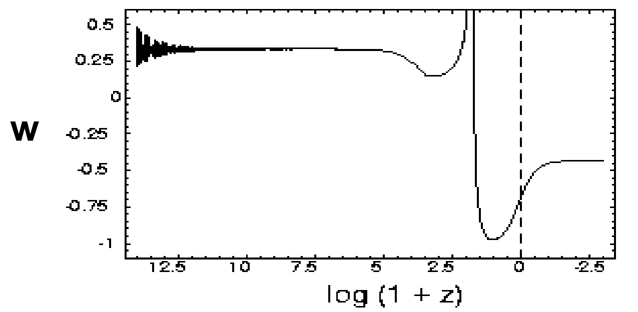
  – Non-minimal coupling to matter
  e.g. Bean & Magueijo 2001

  – Non-minimal coupling to gravity
  e.g. Perrotta & Bacciagalupi 2002

  – k-essence : A dynamical push after z_{eq} with non-trivial kinetic Lagrangian term
  Armendariz-Picon, et al 2000



Non-minimal coupling to matter



k-essence

- But still too much freedom in parameter choices

Modifications to gravity: dark energy in braneworlds

- Quintessential inflation (e.g. Copeland et al 2000)

  – Randall Sundrum scenario

  $$H^2 = \frac{8\pi G_4}{3}\left(\rho + \frac{\rho^2}{2\sigma}\right) + \frac{\Lambda_4}{3} + \frac{\mathcal{E}}{a^4}$$

  – ρ^2 term increases the damping of ϕ as rolls down potential at early (inflationary) times

  –inflation possible with V (ϕ) usually too steep to produce slow-roll

  $$\epsilon \approx 4\epsilon_{FRW}\left(\frac{V}{\sigma}\right)^{-1} \quad \eta \approx 2\eta_{FRW}\left(\frac{V}{\sigma}\right)^{-1}$$

- Unrelated phenomenological approach is the Cardassian expansion (e.g. Frith 2003)

  –Adjustment to FRW, n<0, affects late time evolution

  $$H^2 = A\rho + B\rho^n$$

- Curvature on the brane (Dvali ,Gabadadze Porrati 2001)

  –Gravity 5-D on large scales $l>l_c$ i.e. modified at late times

  $$H = \sqrt{\frac{8\pi G}{3}\rho + \frac{1}{l_c^2}} + \frac{1}{l_c}$$

Tackling the dark matter and dark energy problems

- 'Unified' dark matter/ dark energy
  - –at early times like CDM $w\sim0$, $c_s^2\sim0$
  - –at late times like Λ $w<0$
- E.g. Chaplygin gases
  - –an adiabatic fluid, parameters w_0, α

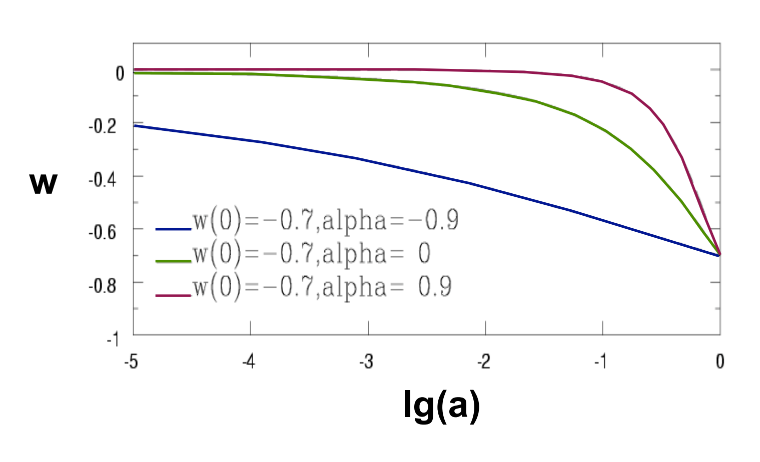
$$p = -\frac{|w_0|}{\rho^\alpha}$$

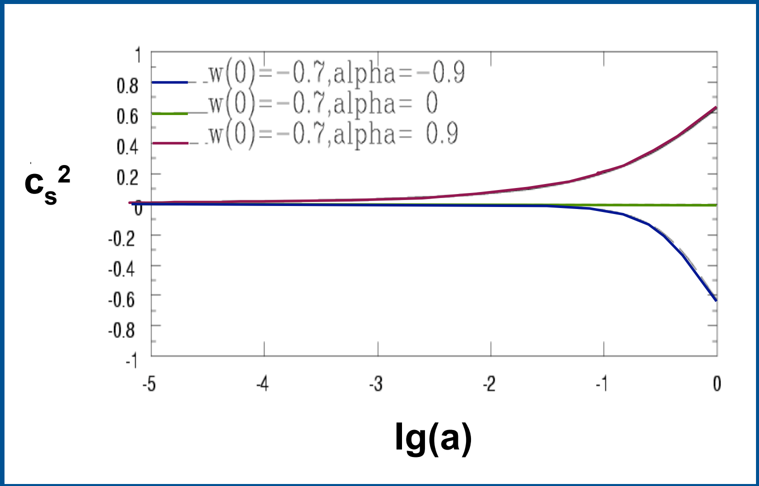
$$c_s^2 = \alpha\, |w|$$

–An example is an effective tachyonic action (Gibbons astro-ph/0204008)

$$\mathcal{L}(\phi, X) = \sqrt{-g}V(\phi)\,(1+X)^{\frac{1}{2}}$$

$$V(\phi) = \frac{\lambda}{cosh(\phi/\phi_0)}$$





Bean and Dore 2003

Phantom dark energy : w<-1

- Breaking both the strong and dominant energy conditions
  - "matter produced from nothing"

- e.g. Scalar field lagrangian with the 'wrong' sign in the kinetic term (Carroll, Hoffman, Trodden 2003)

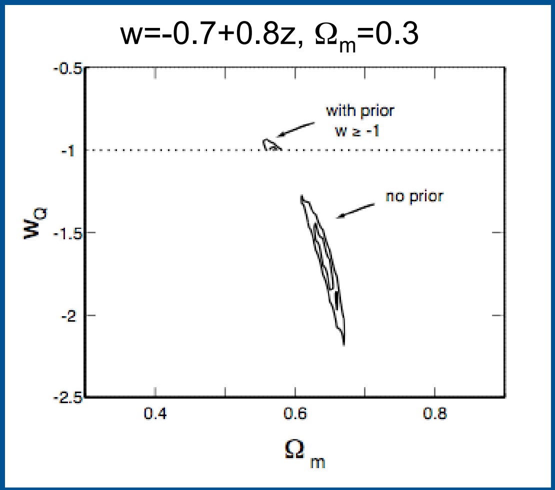
$$\rho_\phi = -\frac{1}{2}\dot{\phi}^2 + V(\phi)\,,$$
$$p_\phi = -\frac{1}{2}\dot{\phi}^2 - V(\phi)\,,$$
$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 + V(\phi)}{\frac{1}{2}\dot{\phi}^2 - V(\phi)}$$

–But quantum instabilities require cut off scale ~3MeV (Cline, Jeon & Moore 2003)

- Brane world models can predict temporary w<-1 (Alam & Sanhi 2002)

$$H^2 + \frac{\kappa}{a^2} = \frac{\rho+\sigma}{3m^2} + \frac{2}{l^2}\left[1 \pm \sqrt{1 + l^2\left(\frac{\rho+\sigma}{3m^2} - \frac{\Lambda_b}{6} - \frac{C}{a^4}\right)}\right].$$

- Can result from misinterpretation of the data
  - –assuming w constant when strongly varying (Maor et al. 2002)



The key dark energy questions

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- How can we reconstruct dark energy?
- What dark energy properties can we measure observationally?

Evolution of H(z) is a key quantity

- In a flat universe, many measures based on the comoving distance

$$r(z) = \int_0^z dz' / H(z')$$

- Luminosity distance

$$d_L(z) = r(z)\,(1+z)$$

- Angular diameter distance

$$d_A(z) = r(z) / (1+z)$$

- Comoving volume element

$$dV/dzd\Omega(z) = r^2(z) / H(z)$$

- Age of universe

$$t(z) = \int_z^{\infty} dz/[(1+z)H(z)]$$

Reconstructing dark energy : first steps

- Ansatz for H(z), $d_l(z)$ or w(z)

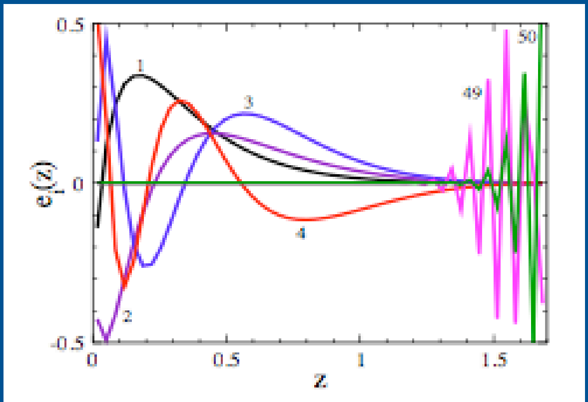
- w(z) applies well to ϕ as well as many extensions to gravity Linder 2003

$$\Delta = H^2 - \frac{8\pi G}{3}\rho_m$$
$$w(z) = -1 + \frac{1}{3}\frac{d\ln(\Delta/H_0^2)}{d\ln(1+z)}$$

  – Taylor expansions robust for low-z

$$w(z) = w_0 + w_a(1-a)$$

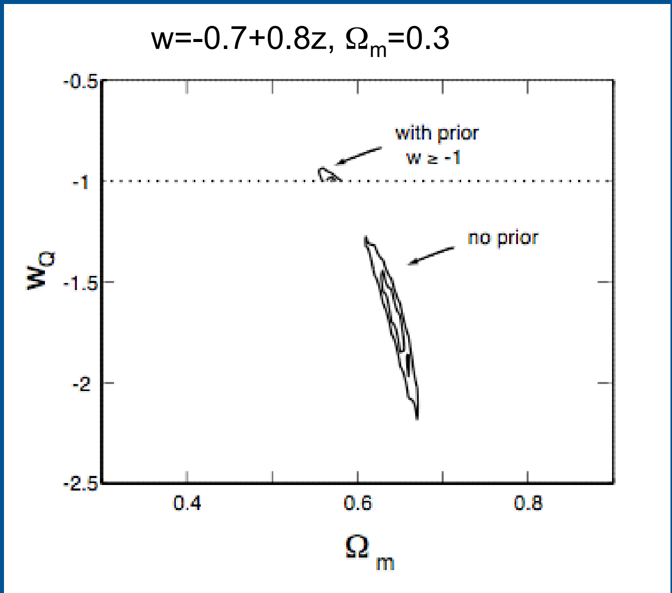
  – In longer term use PCA of the observables



Huterer & Starkman 2003

- But remember we are just parameterizing our ignorance, any number of options
  – Statefinder parameters
  – expansions in H^n
  – orbit precession estimates

- And parameterizations can mislead



Maor et al 2002

Reconstructing dark energy: Complicating the issue

- Dark energy couplings and smoothness may not be so simple
  - – dark energy clustering (including c_s^2 as a parameter)?
  - – effects on equivalence and fifth force experiments?
- Realistically : Add in a nuisance parameter
- For the optimistic future : Actually search for these properties?
  - – Natural extension to looking for $w \neq -1$,$dw/dz \neq 0$
  - – To distinguish between theories …
    - deviations in the background (braneworld scenarios)
    - contributions to structure formation (e.g.coupled quintessence)
    - dark matter and dark energy being intertwined (e.g. Chaplygin gas)?

The key dark energy questions

- What is the underlying nature of dark energy?
- What dark energy properties can we measure observationally?
- How can we reconstruct dark energy?

What are the different constraints?

- Late time probes of w(z)
  - – Luminosity distance vs. z ← SN 1a
  - – Angular diameter distance vs. z ← Alcock-Paczynski test, Baryon Oscillations
- Probes of w_{eff}
  - – Angular diameter distance to last scattering ← CMB
  - – Age of the universe ← CMB/ Globular cluster

Tests probing background evolution only

What are the different constraints?

- Late time probes of w(z)
  - – Luminosity distance vs. z
  - – Angular diameter distance vs. z
- Probes of w_{eff}
  - – Angular diameter distance to last scattering
  - – Age of the universe
- Late time probes of w(z) and $c_s^2(z)$
  - –Comoving volume * no. density vs. z
  - –Shear convergence
  - –Late time ISW

Tests probing perturbations and background

Galaxy /cluster surveys, X-rays from ICM, SZ

Weak lensing

CMB and cross correlation

What are the different constraints?

- Late time probes of w(z)
  - – Luminosity distance vs. z
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- Late time probes of w(z) and $c_s^2(z)$
  - –Comoving volume * no. density vs. z
  - –Shear convergence
  - –Late time ISW

- Early time probes of $\Omega_Q(z)$
  - –N_{eff} ← BBN/ CMB

Tests probing early behavior of dark energy

What are the different constraints?

- Late time probes of w(z)
  - – Luminosity distance vs. z
  - – Angular diameter distance vs. z

- Probes of w_{eff}
  - – Angular diameter distance to last scattering
  - – Age of the universe

- Late time probes of w(z) and $c_s^2(z)$
  - –Comoving volume * no. density vs. z
  - –Shear convergence
  - –Late time ISW

- Early time probes of $\Omega_Q(z)$
  - –N_{eff}

- Probes of non-minimal couplings between dark energy and R/ matter
  - – Varying alpha tests
  - – Equivalence principle tests
  - – Rotation of polarization from distant radio sources.
  - – Deviation of solar system orbits

Tests probing wacky nature of dark energy

Tests probing background evolution

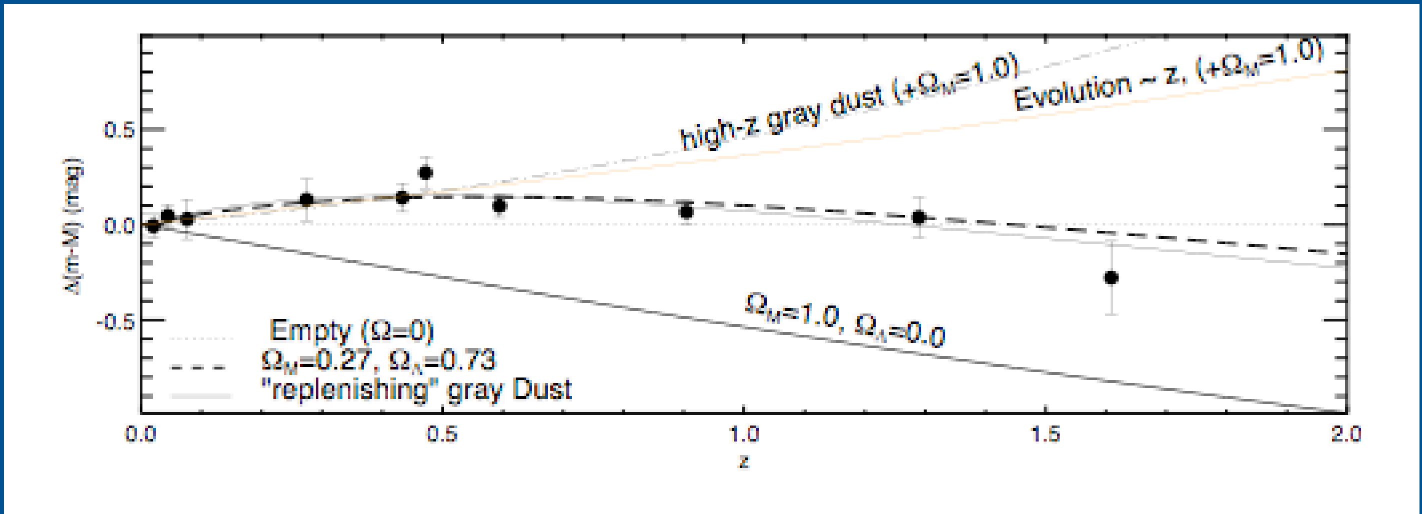
- SN1a
- Angular diameter distance to last scattering
- Age of universe
- Alcock Paczynski

SN1a: first evidence for dark energy

- Saul's talk
- Luminosity distance observed by using a normalized peak magnitude/z-relation

$$m_B (z)=5 \lg d_L(z) +25$$

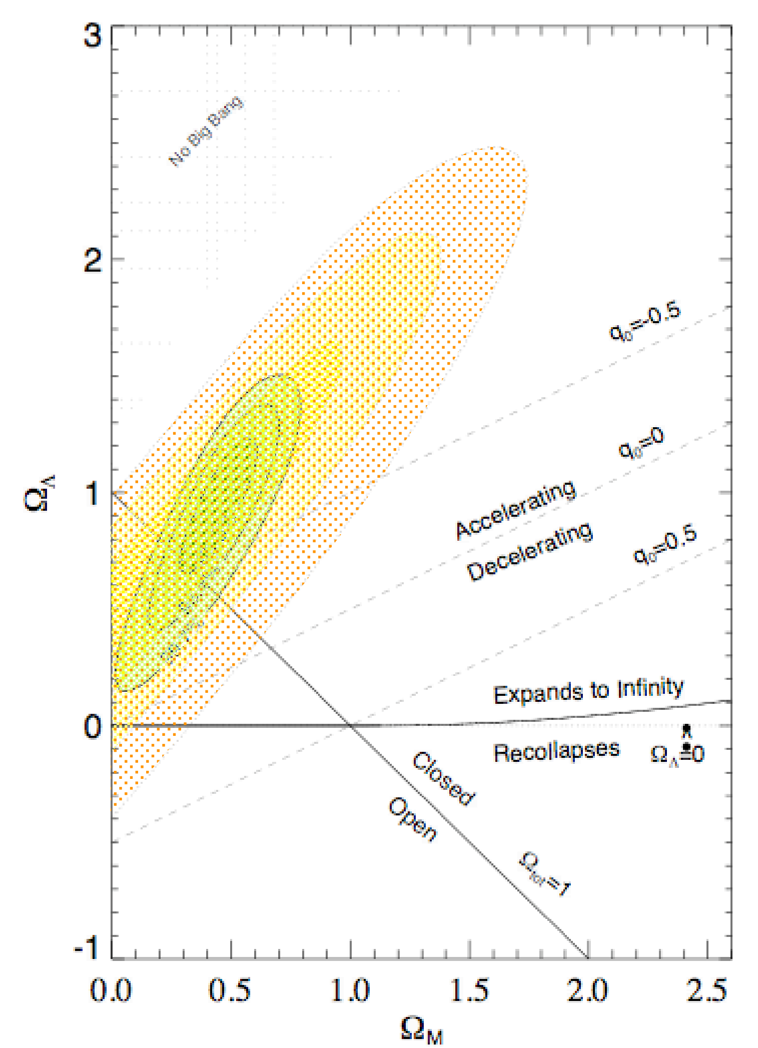
- Advantages:
  - –single objects (simpler than galaxies)
  - –observable over wide z range
  - –Independent of structure of growth
- Challenges
  - –Extinction from dust
  - – chemical composition/ evolution
  - – understanding mechanism behind stretch

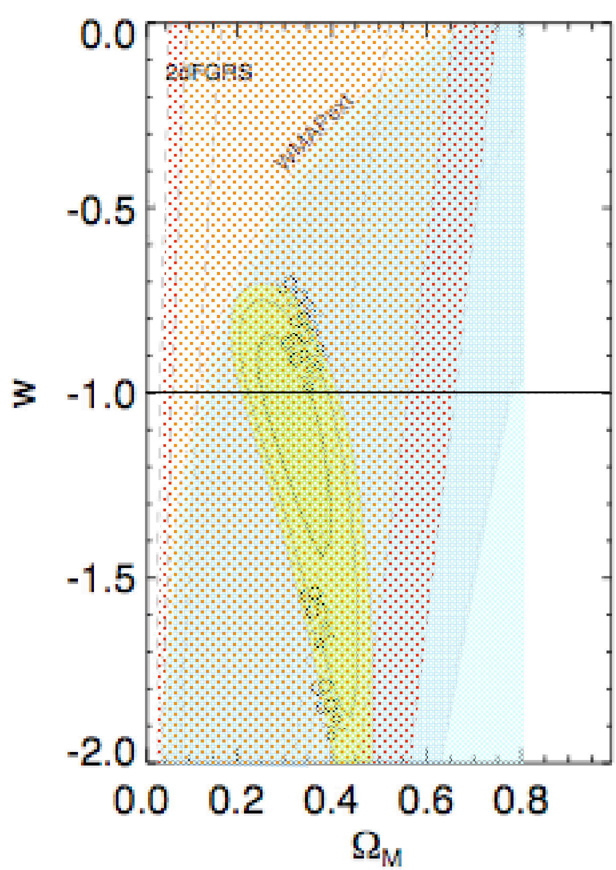


Riess et al 2004

157 SN1a out to z=1.775

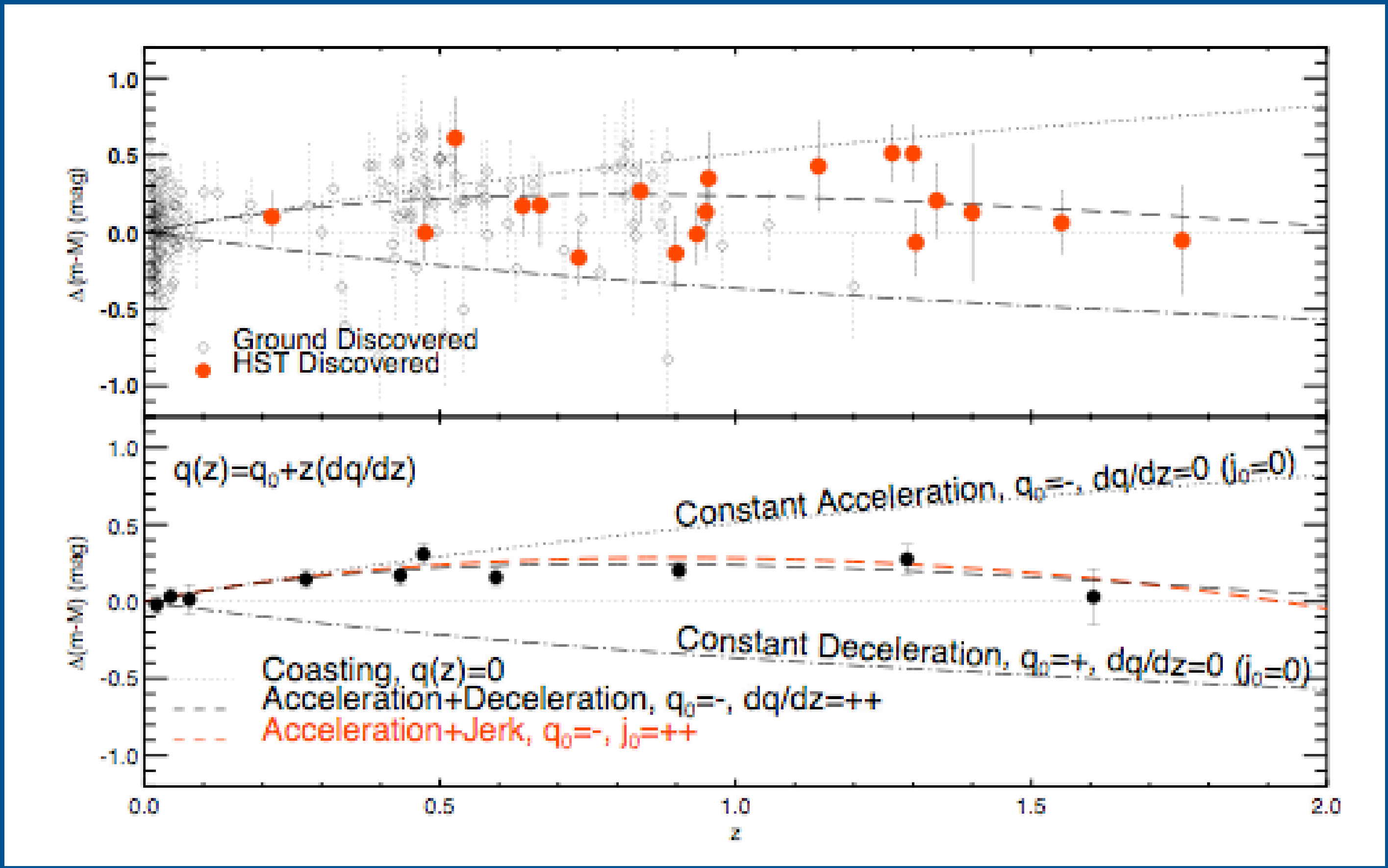
SN1a: current evidence entirely consistent with Λ





Riess et al 2004

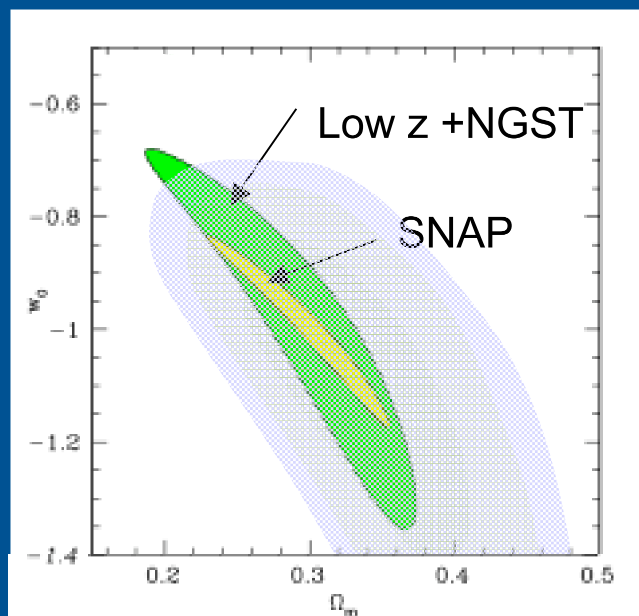
SN: first real evidence of earlier deceleration

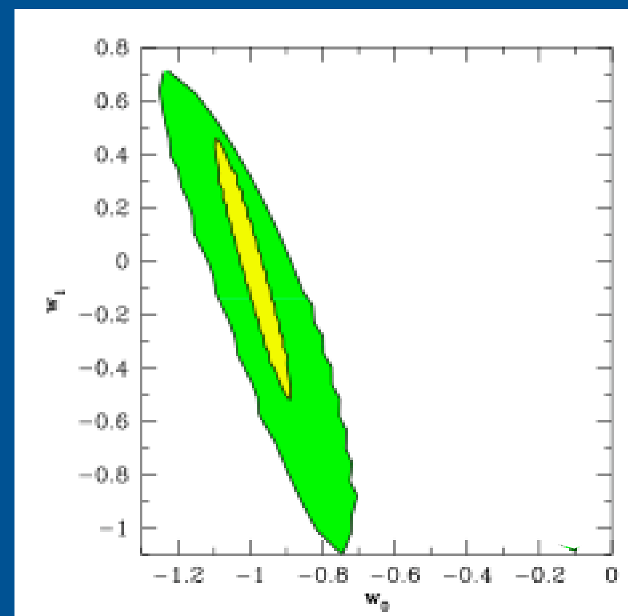


Riess et al 2004

SN1a: prospective constraints

- SNAP
  - assuming 2000 SN1a out to z=1.7 in first 2 years of survey, σ(z)~0
- NGST
  - assuming 100 SN1a at z=2-2.5 with 160 low z, z=0.1- 0.55

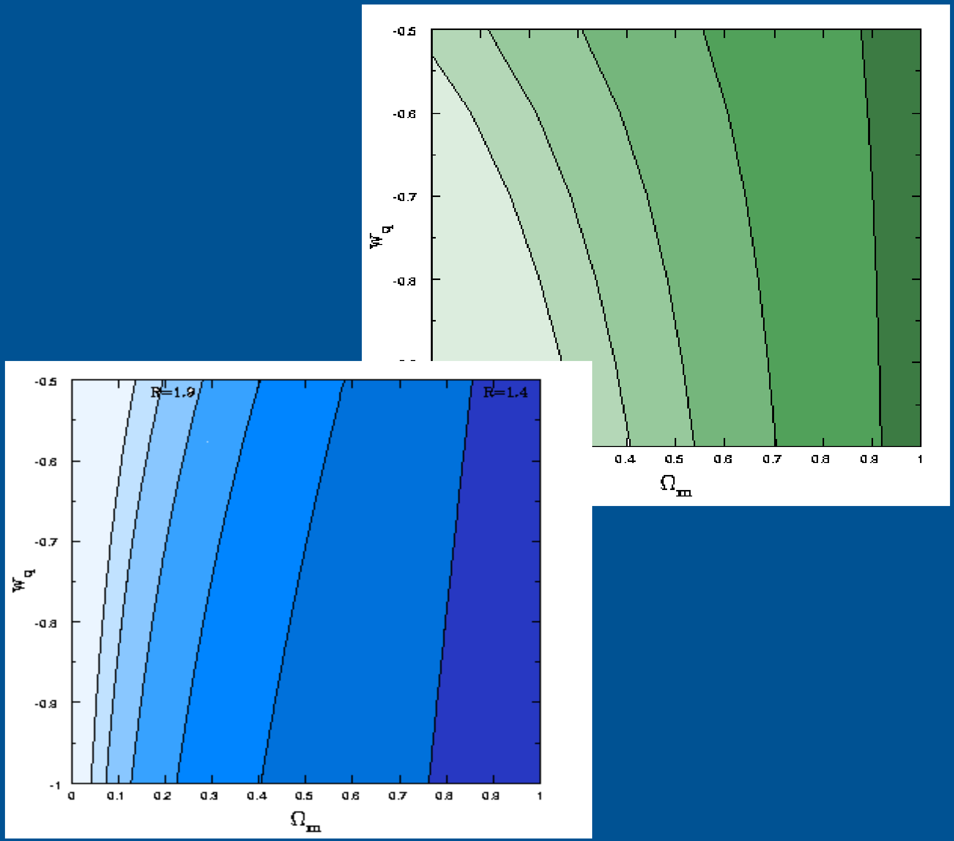


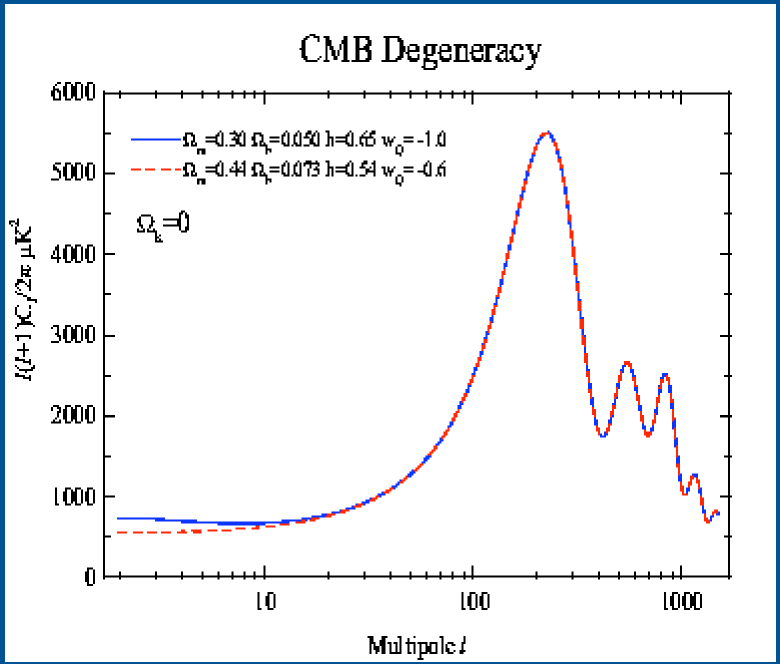


Projected 99% confidence contours
Weller and Albrecht 2001

CMB: angular diameter distance

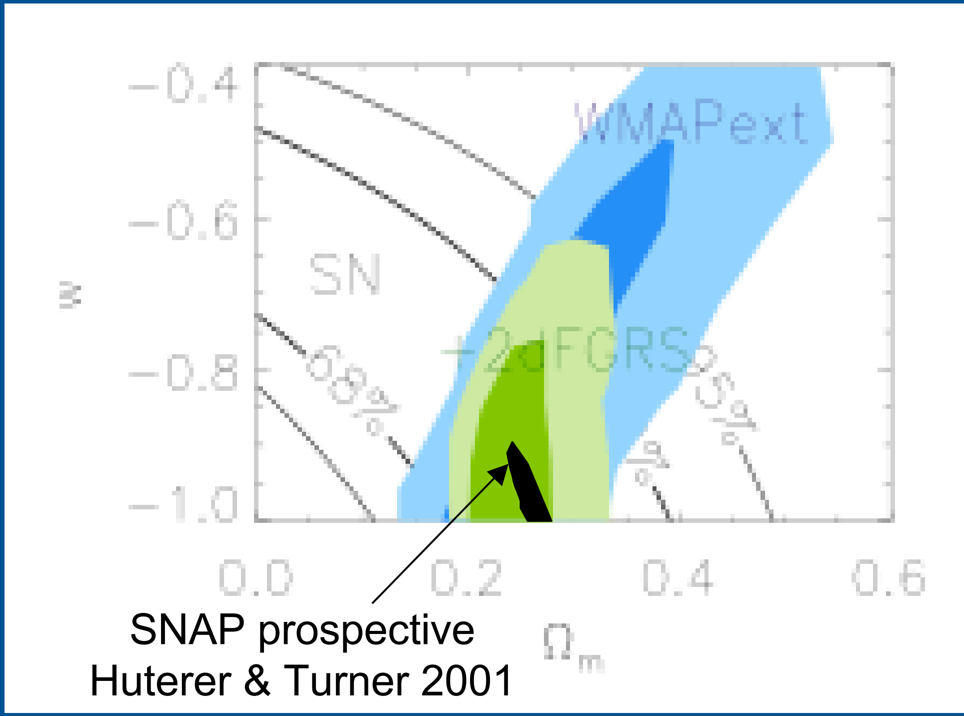
- Degeneracy in angular diameter distance between w and Ω_M but complementary to that in supernovae
- Gives measure of averaged, effective equation of state
- Most importantly ties down key cosmological parameters





Bean and Melchiorri 2001

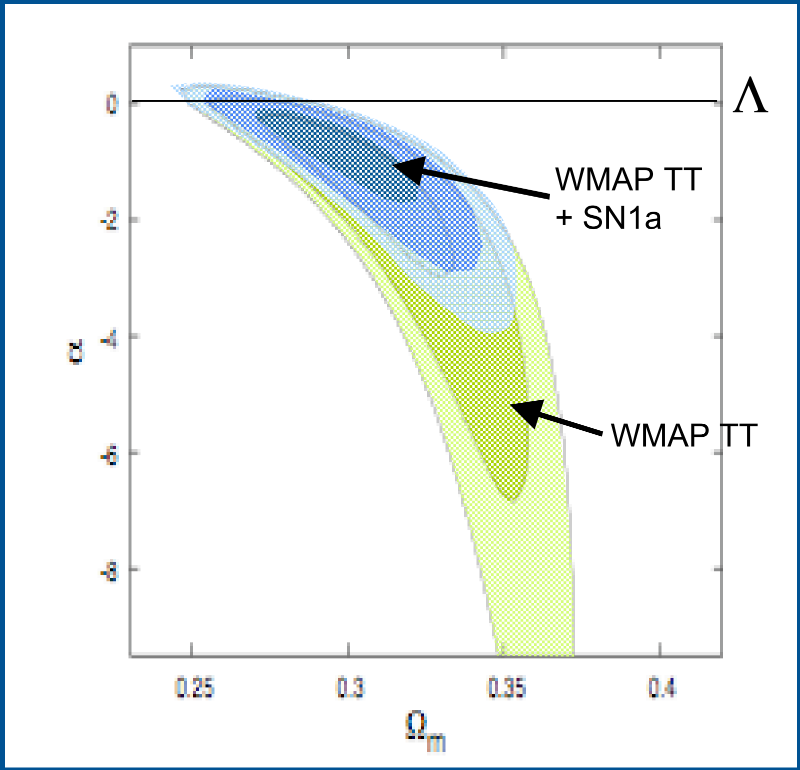
Combined constraints provide consistent evidence of dark energy



Spergel et al. 2003

But could equally signal deviations from FRW

$$\left(\frac{H}{H_0}\right)^2 = \Omega_m(1+z)^3 + (1-\Omega_m)\left(\frac{H}{H_0}\right)^\alpha$$

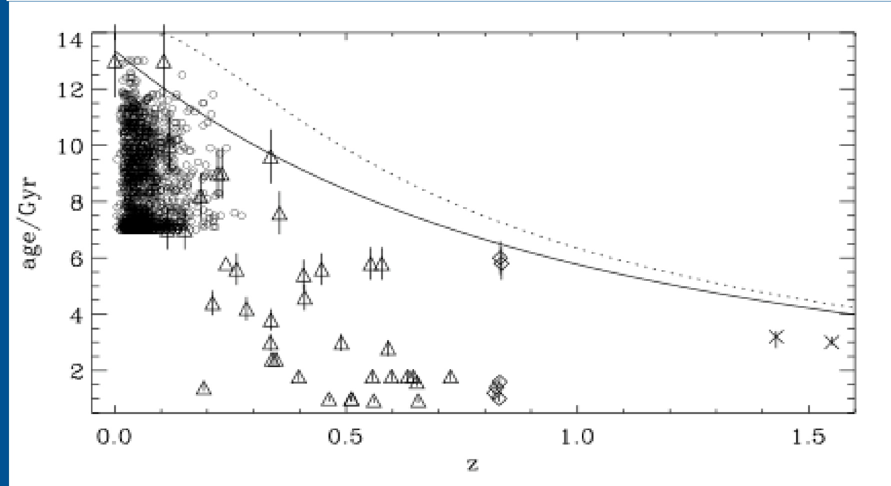


ElgarØy and Multimäki 2004

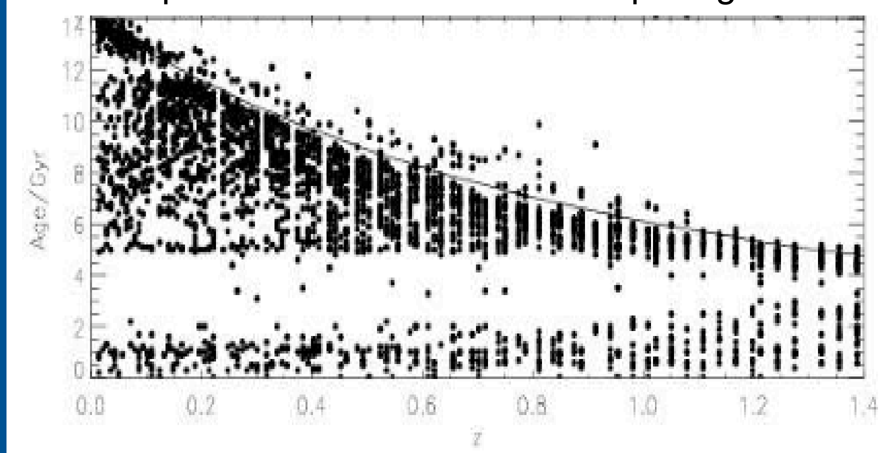
Age of universe: independent probe of w

- Constrain w_0 independent of other cosmological parameters
  - –using age of stars in globular clusters, and
  - –Position of first peak from WMAP,
- Fit stellar populations
  - –using 2 parameter model with age and metallicity and
  - –marginalize over metallicity
- Uncertainties in stellar modelling but nice complementary check

Current results



Prospective results with 60 stars per age bin



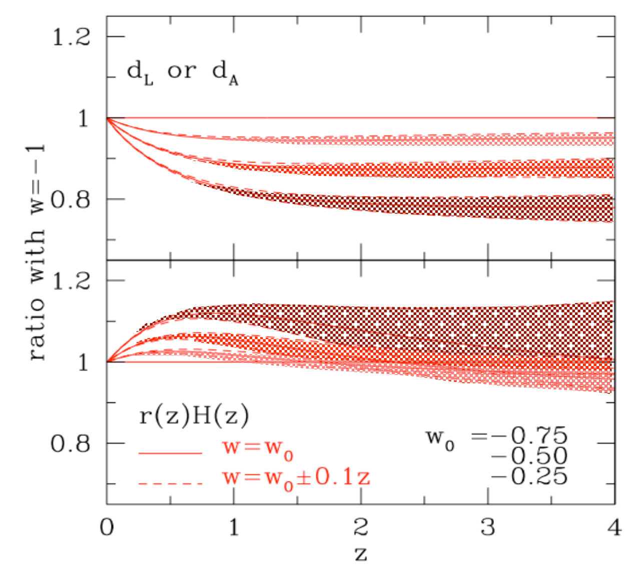
Jimenez et al 2003

Comparing transverse and line of sight scales

- Alcock-Paczynski : From line of sight and transverse extent Δz and $\Delta\theta$ of spherical object you can calculate distortion without knowing true object size

$$r_{||} = \frac{c\Delta z}{H(z)} \quad , \quad r_{\perp} = d_A(z)\Delta\theta$$

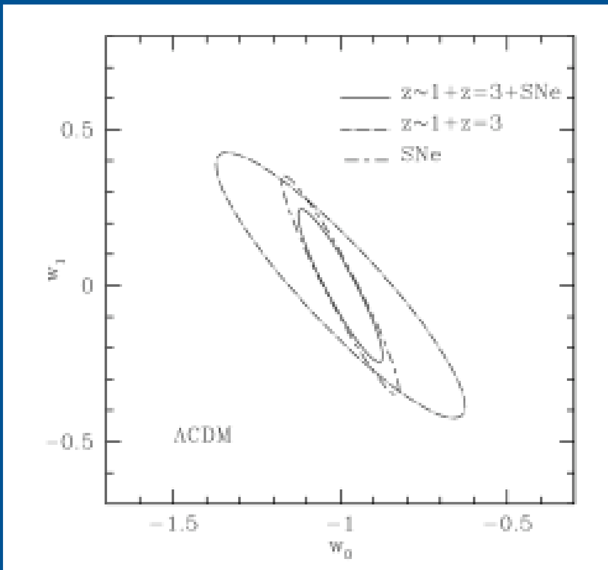
$$\Delta z / \Delta\theta = d_A(z)H(z)$$



Comparison to w=-1 , h, $\Omega_c h^2$ $\Omega_b h^2$ fixed

- Naively less sensitive than d_L .Unfeasible so far with QSO's or Ly-alpha clouds

- Baryon fluctuations seem to be far more promising
  - -sound horizon scale is known
  - -but complications from redshift distortions, non-linear clustering and galaxy biasing
  - (Seo & Eisenstein 2003 and Derek Dolney's poster)



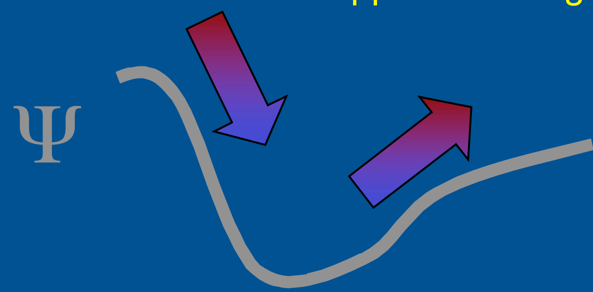
Seo & Eisenstein 2003

Tests probing perturbations and background evolution

- Late time ISW and cross correlation with galaxy distributions
- Galaxy/ cluster number counts
- SZ
- Weak lensing

CMB :late time ISW effect

- ISW arises from late time suppression of growth by Λ

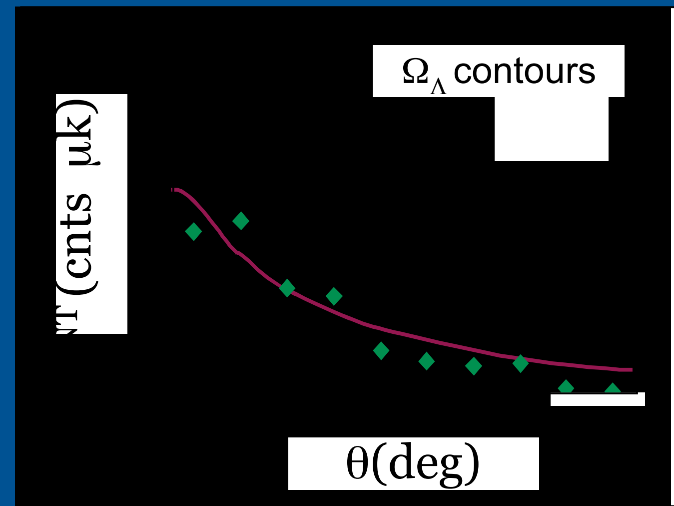


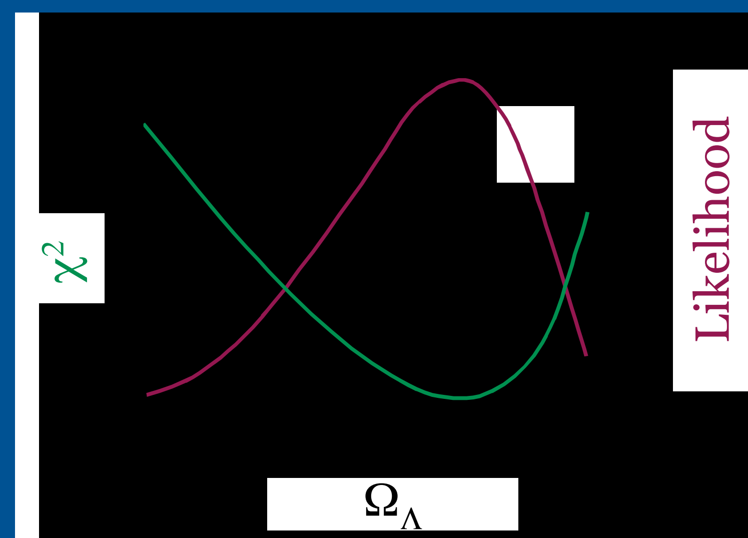
- ISW intimately related to matter distribution that mirrors potential wells
- Should see cross-correlation of CMB ISW with LSS. e.g. NVSS radio source survey

$$C_l^{NT} = 4\pi \int_0^\infty \frac{dk}{k} \Delta^2(k) f_l^N(k) f_l^T(k)$$

Transfer function perturbation (w & c_s^2) dependence

Window functions purely background (w) dependent

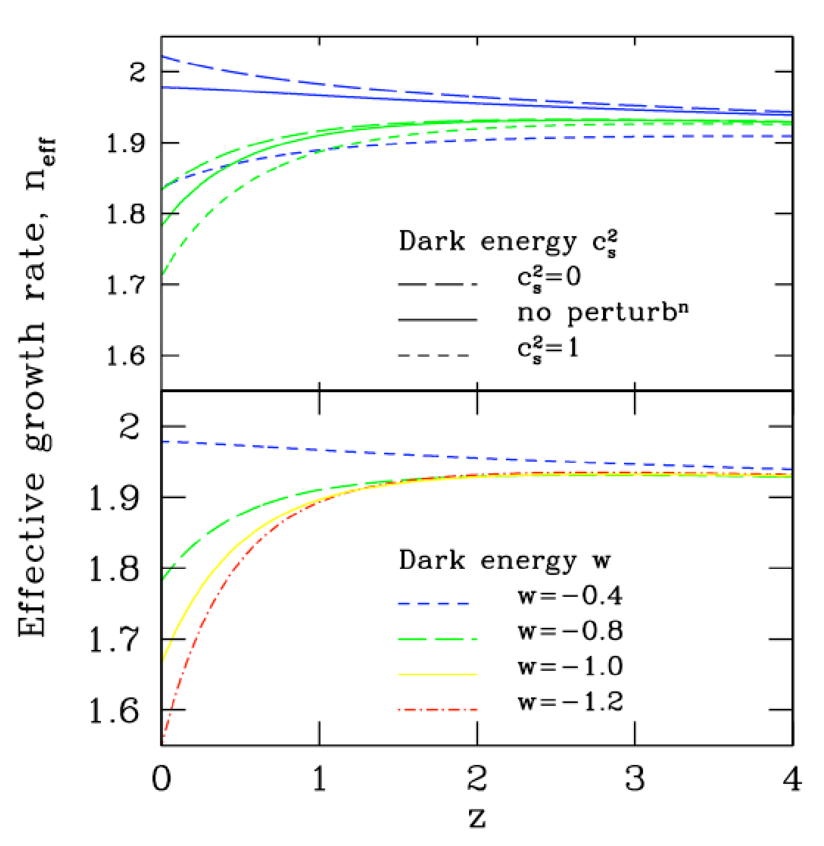


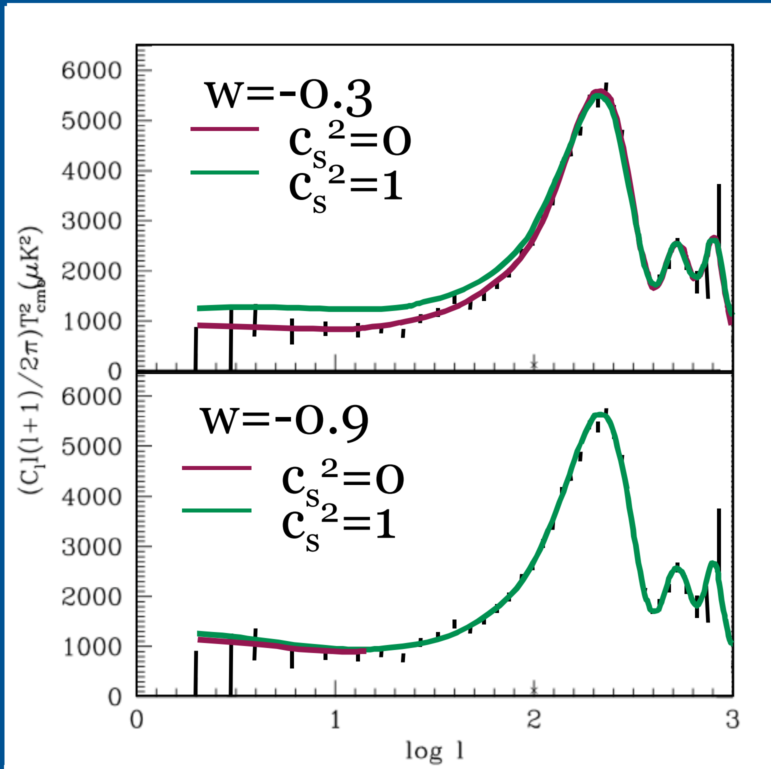


Nolta et al. 2003 (Boughn & Crittenden 2003, Scranton et al 2003)

Dark energy affects late time structure formation

- w and c_s^2 both affect structure formation at late times -> affect ISW
- But caught up in cosmic variance and highly degenerate with other cosmological parameters





CMB spectrum comparisons varying w & c_s^2

Hu1998, Bean & Dore 2003

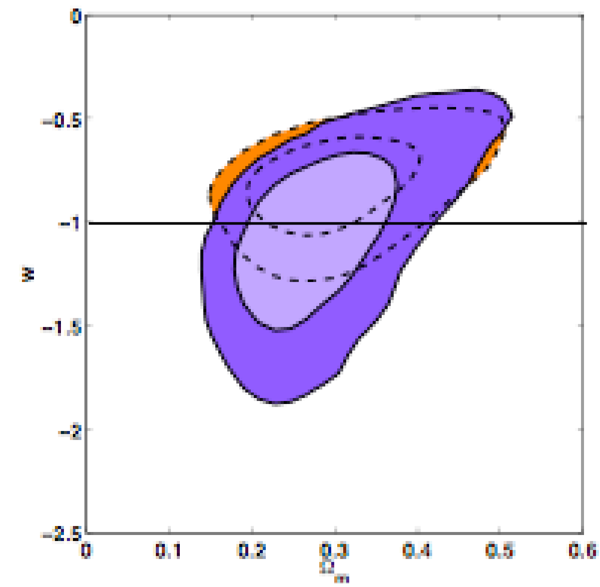
Dark energy clustering as a nuisance parameter

- Dark energy perturbation alter constraints from perturbation sensitive observations e.g. CMB
  (Bean & Dore 2003, Weller & Lewis 2003)

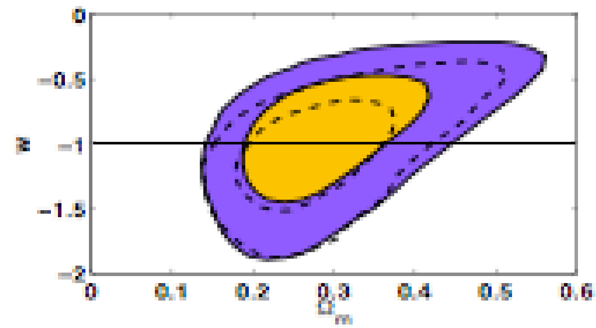
- Phantom models are more sensitive to dark energy clustering.

  –Although treatment of perturbations for w<-1 ultimately model dependent

- Issue for the future - what is a consistent treatment of dark energy evolution with CMB?



CMB Likelihood contours of w including (full) and excluding (dashed) DE perturbations



CMB Likelihood contours of w with c_s^2=1 (full) and varying (dashed)

Weller & Lewis 2003

Galaxy / cluster number counts

- Volume element has better sensitivity to w and w' than luminosity distance

$$dV/dzd\Omega(z) = r^2(z) / H(z)$$

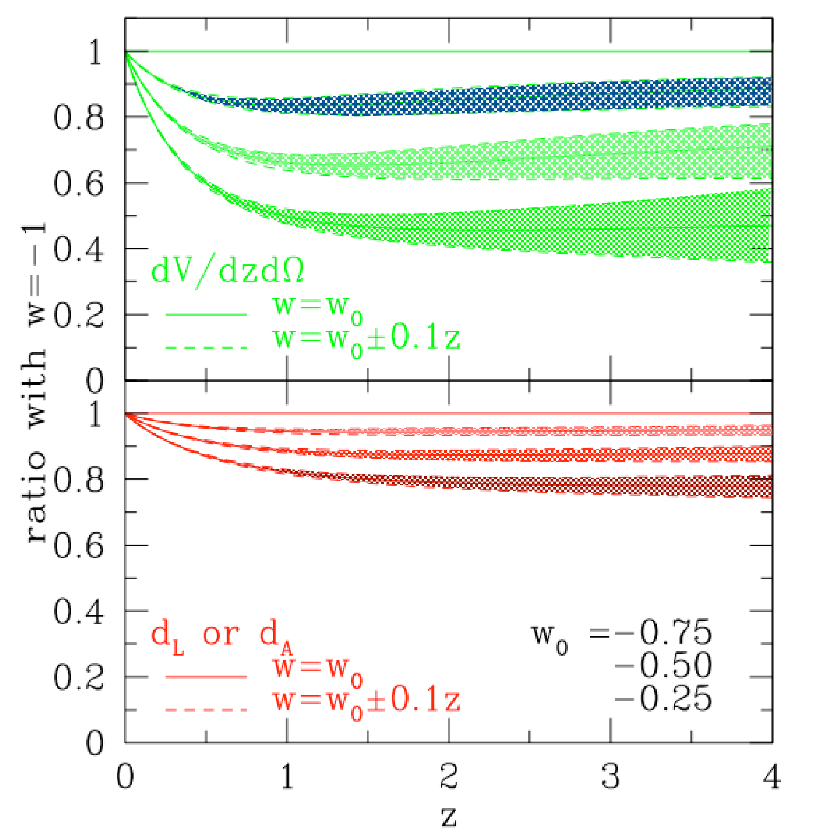
- Number counts related to underlying matter distribution and $\delta_c(z)$

  – inherent modelling sensitivity

$$\frac{dN}{dzd\Omega} = \frac{dV}{dzd\Omega}\int_{m_{lim}(z)}^{\infty} dM \frac{dn(M,z)}{dM}$$

e.g. cluster mass function Jenkins et. al 2000

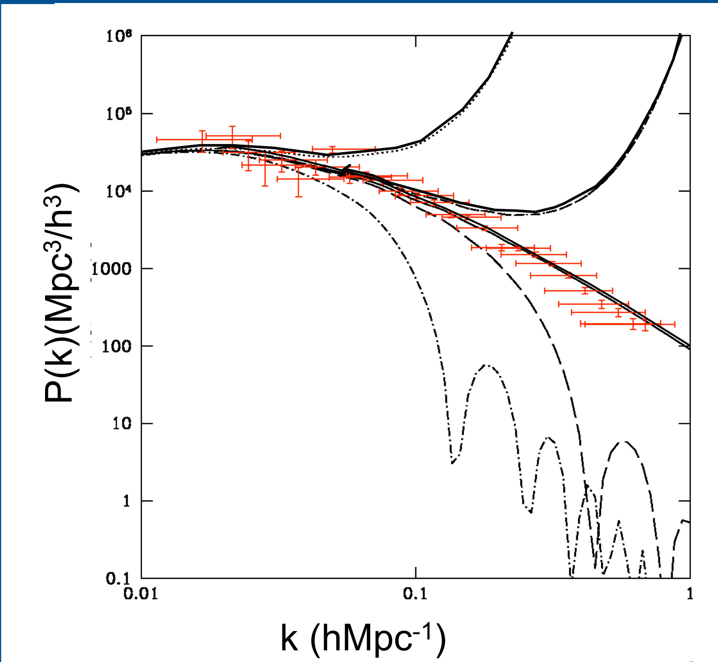
$$\frac{dn(M,z)}{dM} \propto exp\left\{-|0.61 - log\left(\frac{\delta_c(z)\sigma_M}{\delta_c(0)}\right)|^{3.8}\right\}$$



Comparison against w=-1 for same h, $\Omega_c h^2$ $\Omega_b h^2$

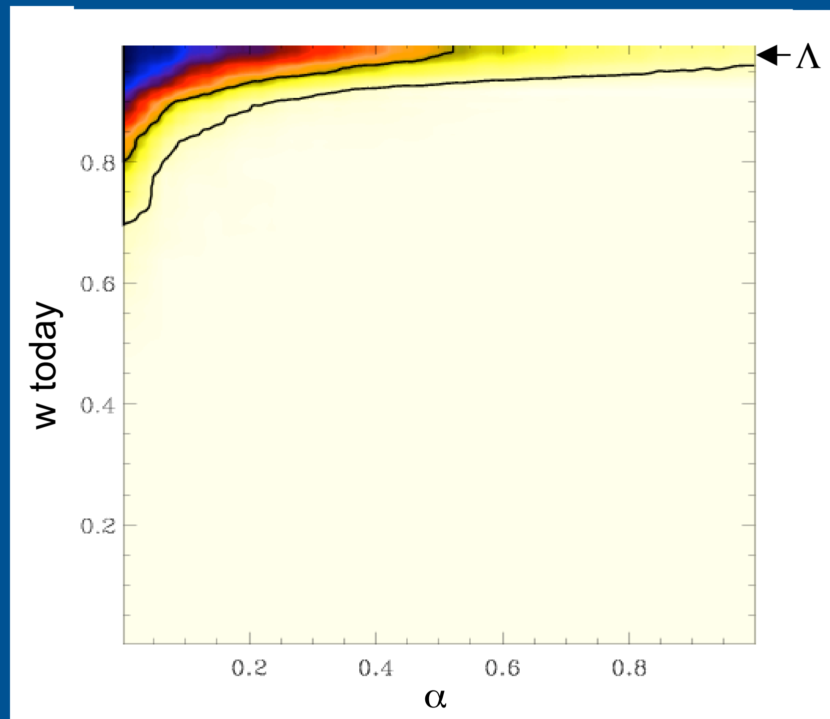
LSS+CMB tightly constrain unified dark matter

- Example : Chaplygin gas $p \propto 1/\rho^{\alpha}$
- Adiabatic so no stabilisation by additional entropy perturbations
  - –rapid growth for $c_s^2<0$
  - –rapid suppression for $c_s^2>0$
- Tight constraints implying preference for ΛCDM
- Baryon fluctuations can go some way to stabilize the dark energy perturbations but model is still highly constrained Beca et al 2003



Matter power spectrum in absence of CDM α varies between -10^{-4} to 10^{-4}

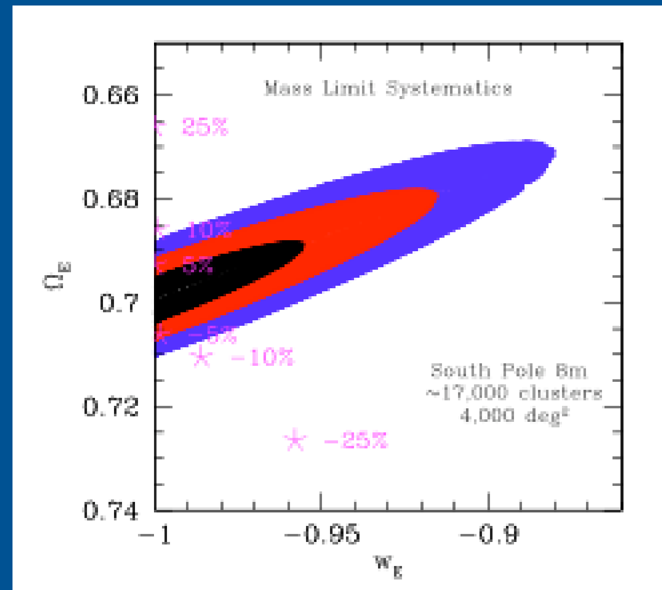
Sandvik et al 2002



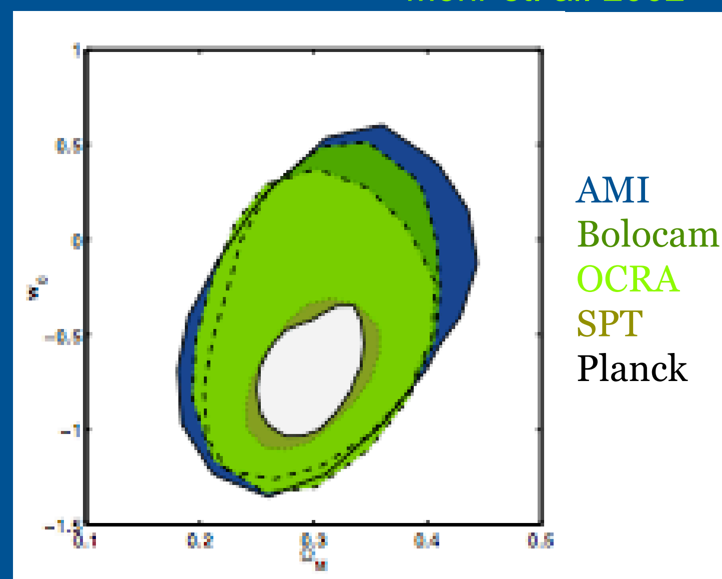
Bean & Dore 2003

Prospective constraints from cluster number counts

- Amber Miller's talk
- Clusters found by
  - –Light emitted by galaxies within them
  - –Gravitational lensing of background galaxies
  - –X rays emitted by intracluster medium
  - –SZ distortions in CMB…..
- Number of future SZ experiments funded e.g
  - –Ground based: ACT , SPT
  - –Satellite: Planck
- Advantages:
  - –Clusters exponentially sensitive to growth factor
  - –SZ signal not attenuated with z
- Challenge: clusters are far from being standard candles
  - –Thermal and enrichment history effect on mass-scaling relation for X ray and SZE, and galaxy luminosity
  - –Projection biasing weak lensing mass estimates
  - –Weak lensing clouding SZ signal



Mohr et. al. 2002



Battye & Weller '03

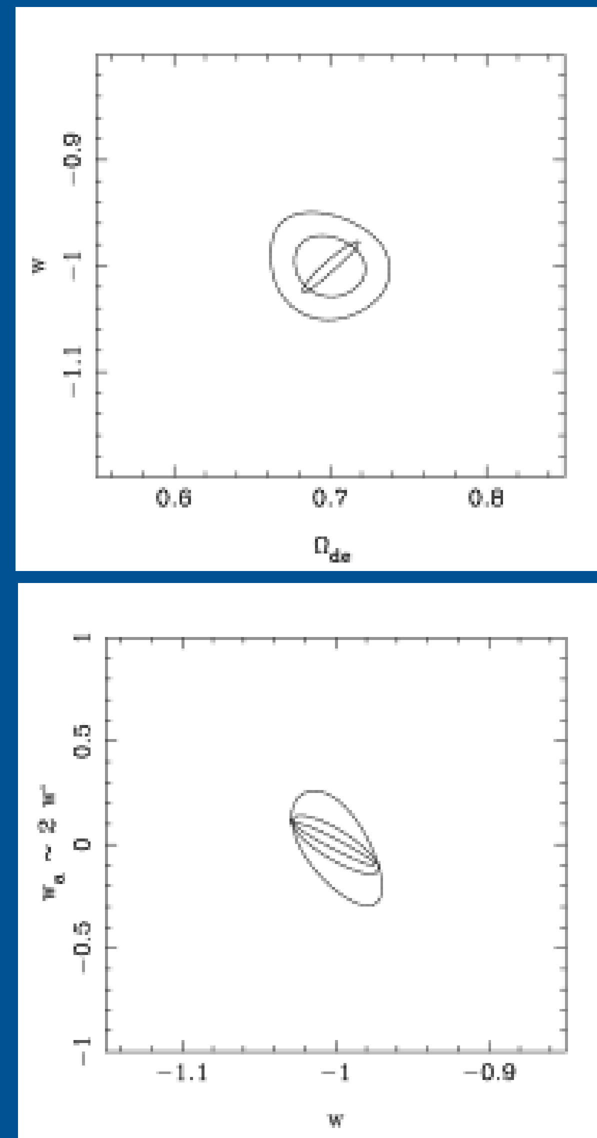
Constraints on w from weak lensing

- Tomography => bias independent z evolution of DE
- Ratios of observables at different z give growth factor independent measurement of w, w'

  - e.g. tangential shear - galaxy cross correlation

$$\frac{w_{x,1}(\theta)}{w_{x,2}(\theta)} = \frac{g_1(r_f)}{g_2(r_f)}$$

- Could probe dark energy clustering as well as background?
- Uncertainties going to be a serious hindrance since effect is so small
  - – z-distribution of background sources and foreground halo,
  - – inherent ellipticities
  - – halo mass estimates
  - – z dependent biases



Jain and Taylor 03

Solar system tests

- Anomalous perihelion precession in modified gravity theories (Dvali et al 2002)

$$\epsilon = \frac{\delta\Psi}{\Psi}, \qquad \Psi = -\frac{GM}{r}$$

$$\epsilon = -\sqrt{\frac{r^3}{GM}}\left(\frac{1}{l_c}\right)$$

$$\delta\phi = \frac{3\pi}{4}\epsilon$$

- Expect correction to precession ~5 μas / year
  - Lunar laser ranging (current) 70 μas / year
  - APOLLO lunar ranging (future) <7 μas / year
  - Pathfinder Mars ranging data 10 μas / year
  - Mercury 430 μas / year
  - Binary Pulsar PS1913+16 Periastron 40000 μas / year

  (Nordtvedt PRD 2000)

- Solar system tests seem best bet for probing deviations from Einstein Gravity

Conclusion: We need wide ranging dark energy probes!

- The theoretical community is yet to come up with a definitive proposal to explain the observations.
  - – Need a mix of strait jackets and food for thought from observations!

- The nature of dark energy is so profound for cosmology and particle physics we need the SN1a results improved on as well as complemented by a range of observational constraints:
  - –with different systematics
  - –with different cosmological parameter degeneracies
  - –with different redshift sensitivities
  - –probing solar system and cosmological scales

There are exciting times ahead !!!