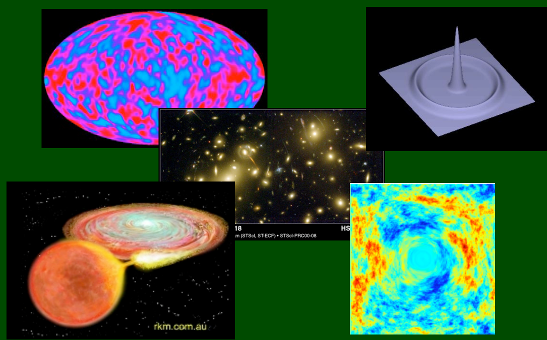
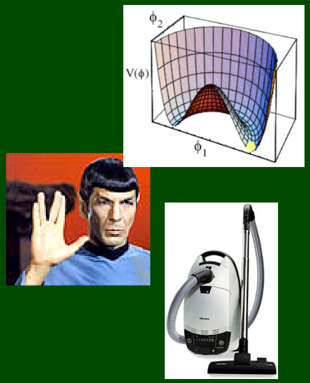


Linking Dark Energy Observations and Theory



Aspen Winter Conference

Particle Physics at the Verge of Discovery

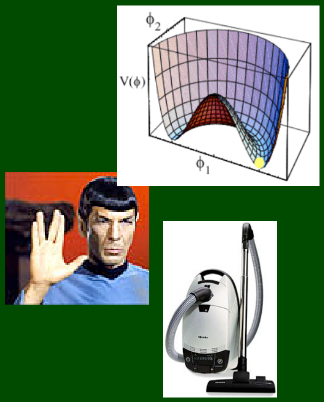
February 17th 2006

Rachel Bean

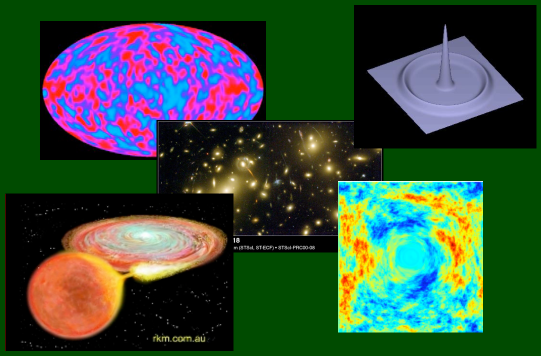
Cornell University

Overview

- Brief overview of theoretical approaches to dark energy



- Links to observational tests for dark energy



The key dark energy questions

- How do we modify Einstein's Field Equations?

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

Adjustment to gravity?

- Non-minimal couplings to gravity?

–Higher dimensional gravity?

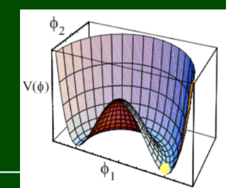
–Effects of anisotropy and inhomogeneity

Cosmological constant "Λ"?

-"Vacuum energy" left over from early phase transitions?

-Holographic?

-Anthropic?



Adjustment to matter?

-An 'exotic', dynamical matter component "Quintessence"?

– 'Unified Dark Matter'?

Distinctions between dark energy alternatives

Cosmological constant "Λ"?

- Purely affects background expansion
- No fluctuations in energy density

- Equation of state $w=p/\rho$, $w= -1$ for all time

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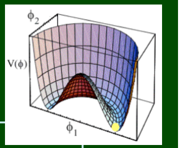


Adjustment to matter?

- Dynamical component from $V(\phi)$, mainly affecting background expansion
- Fluctuations modify behavior on large scales

- Equation of state $w=p/\rho$
- $w\neq-1$, $w(z)$
- 'speed of sound' $c_s^2=\delta p/\delta\rho$

Distinctions between dark energy alternatives

Adjustment to gravity?

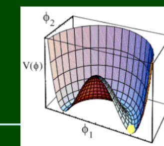
- Modification of Einstein's equations beyond 4D FLRW
- Affects background and fluctuation growth

- $w(z)$, effective measure from background evolution
- Distinct $w(z)$ from structure growth
- Other evidence from GR tests (solar system, equivalence principle)?

Cosmological constant "Λ"?

- Purely affects background expansion
- No fluctuations in energy density

- Equation of state $w=p/\rho$, $w= -1$ for all time



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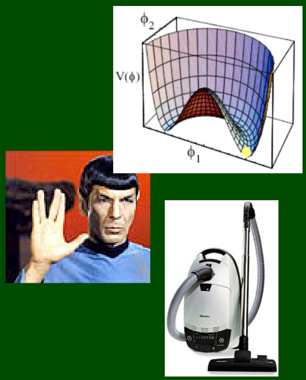
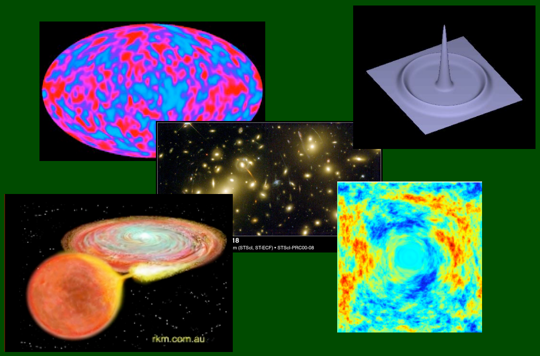
Overview

- Brief overview of theoretical approaches to dark energy



➡ Links to observational tests for dark energy



Linking theory and observations

- 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

SN 1a HST Legacy, Essence, DES, SNAP

Baryon Oscillations SDSS
Alcock-Paczynski test

CMB WMAP

CMB/ Globular cluster

Tests probing background evolution only

Linking theory and observations

- 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, SZ and X-rays from ICM
SDSS, ACT, APEX, DES, SPT

Weak lensing CFHTLS, SNAP, DES, LSST

CMB and cross correlation
WMAP, PLANCK, with SNAP, LSST, SDSS

Linking theory and observations

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

- Early time probes of $\Omega_Q(z)$
  - Early expansion history sensitivity to relativistic species

BBN/ CMB WMAP

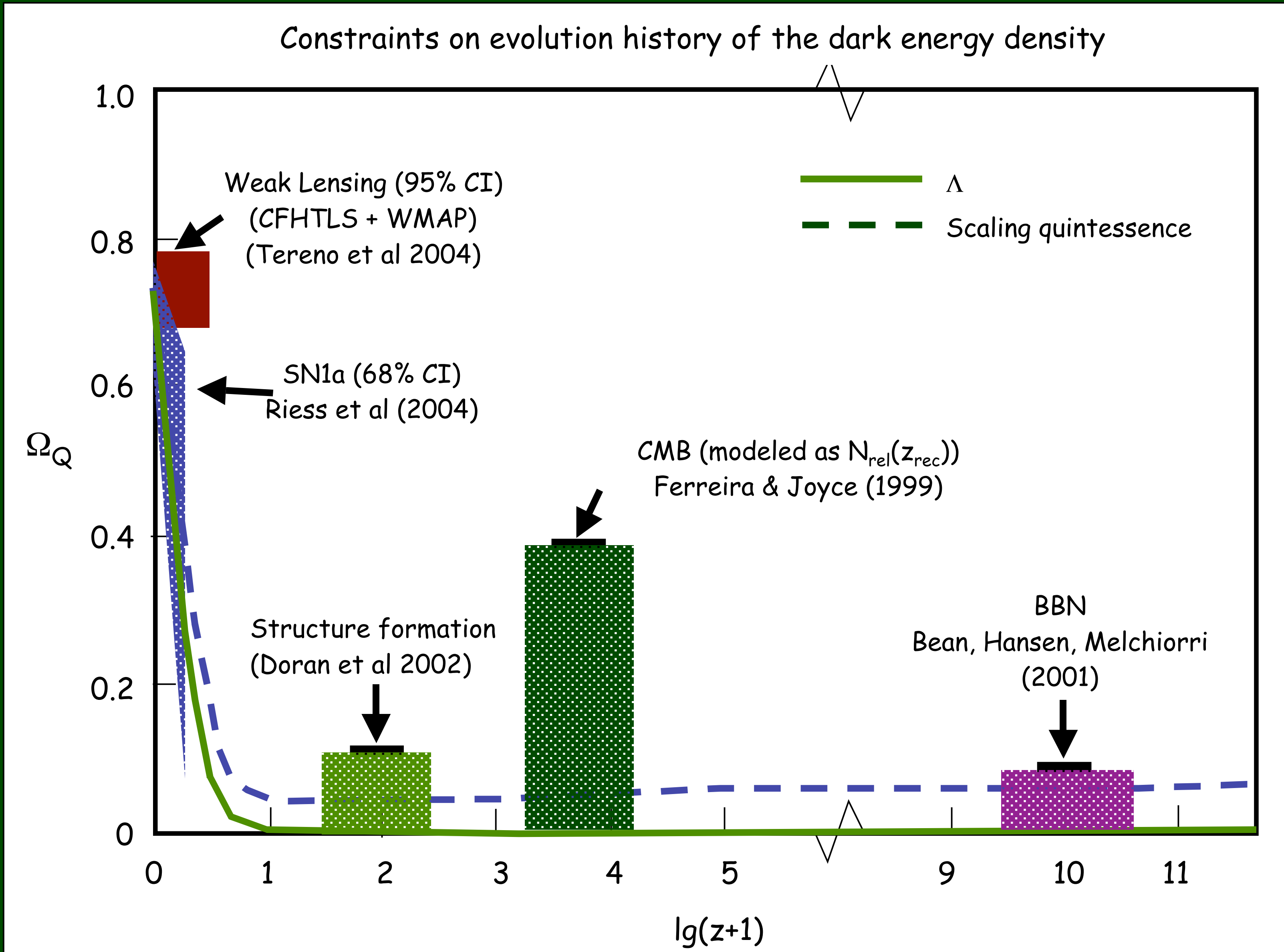
Tests probing early behavior of dark energy

Linking theory and observations

- 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 $\Omega_Q(z)$
  - Early expansion history sensitivity to relativistic species
- Alternate probes of non-minimal couplings between dark energy and R/ matter or deviations from Einstein gravity
  - Equivalence principle tests
  - Deviation of solar system orbits
  - Varying alpha tests

Tests probing general deviations in GR or 4D existence

Sensitive to different epochs of evolution history



Evolution of H(z) is the primary observable

- 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

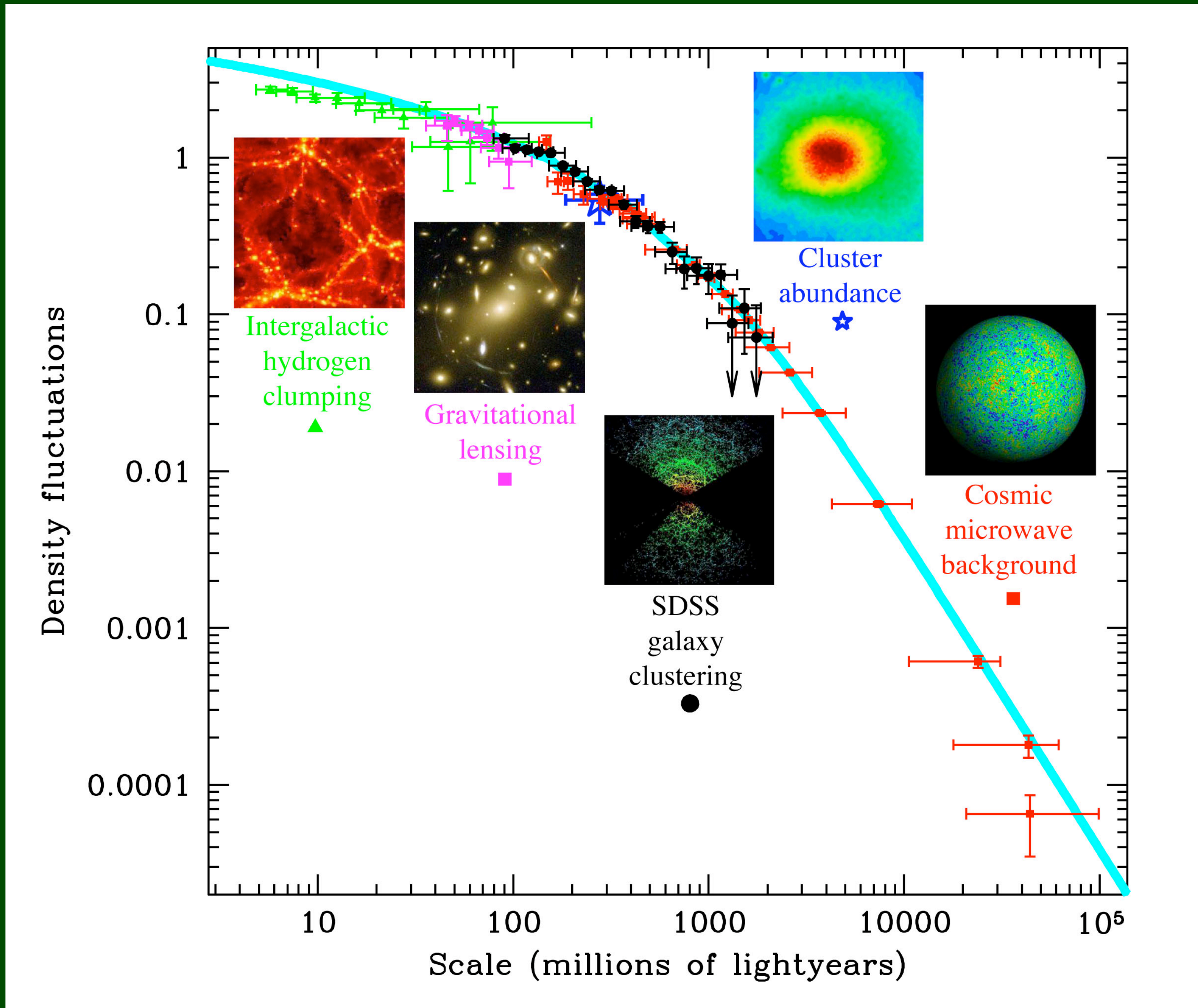
$$dV/dzd\Omega(z) = r^2(z) / H(z)$$

- Age of universe

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

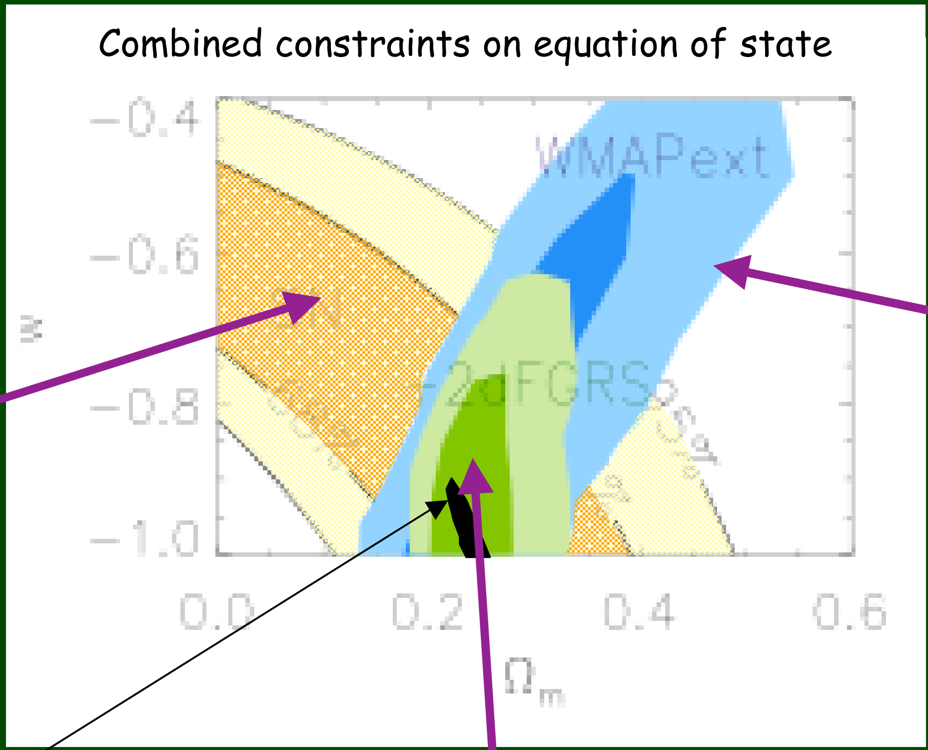
But fluctuations promise to be significant ….

… leveraging evolution on different spatial scales



From Max Tegmark for SDSS

Current observations provide consistent constraints



Luminosity distance to SN1a

Angular diameter distance to last scattering

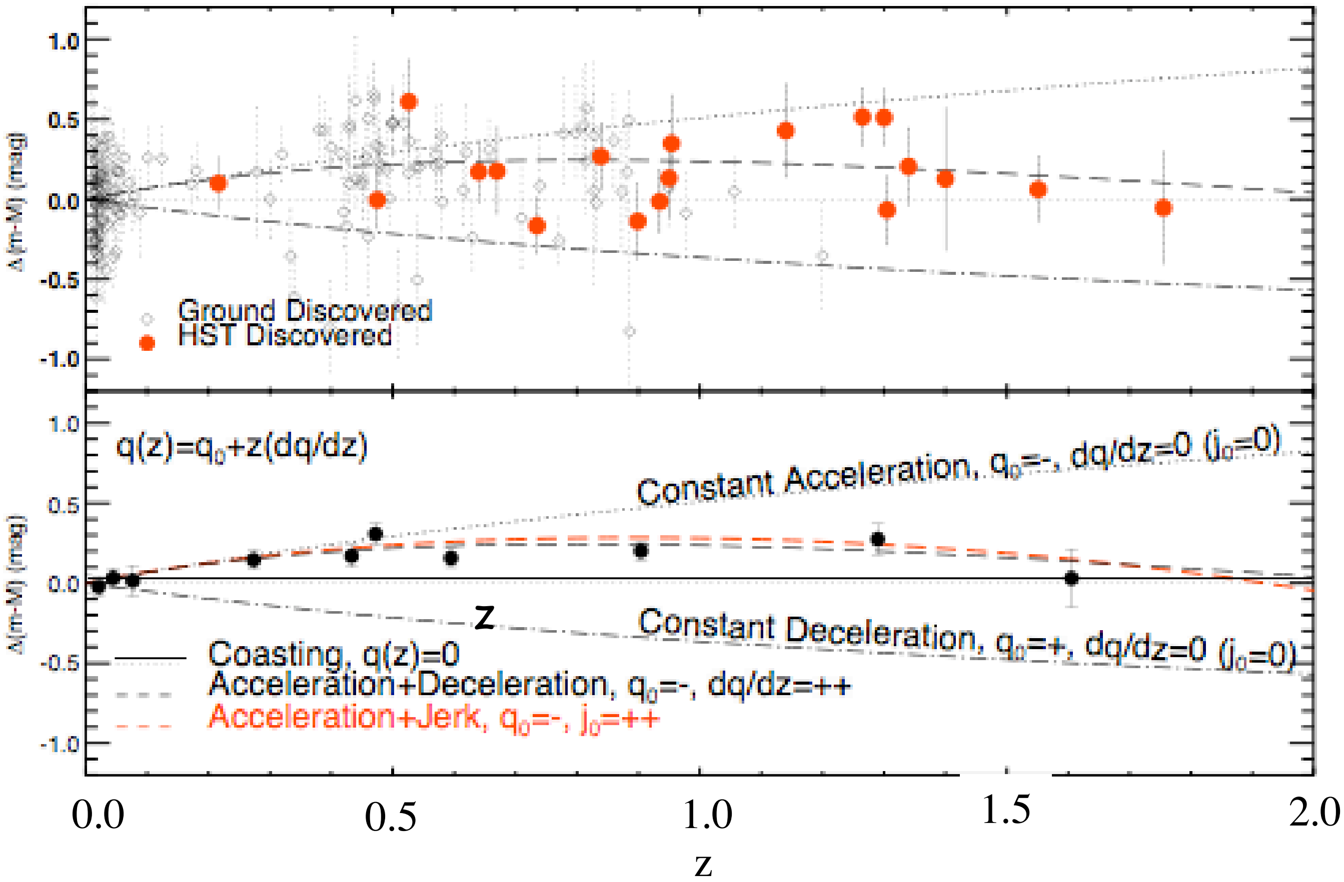
SNAP prospective
Huterer & Turner 2001

Linear growth factor to galaxy

Spergel et al. 2003

& first evidence of earlier period of deceleration

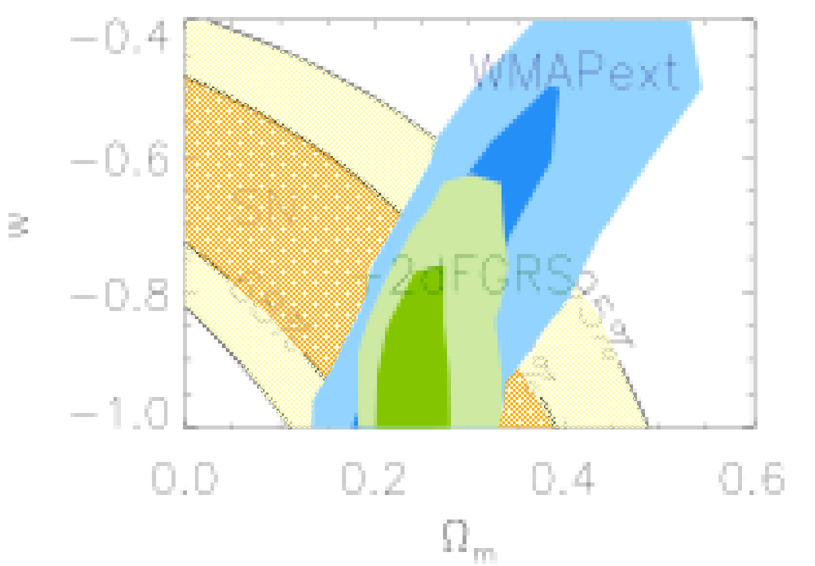
z evolution of luminosity distance of Supernovae in HST/Goods survey



Riess et al 2004

Inference based purely on background evolution

Combined constraints on equation of state



Spergel et al. 2003

- Implicit priors in this ‘consistent’ picture:
  - a constant w in a FLRW metric
  - no dark energy clustering
  - Einstein gravity

- Do these implicit assumptions bias our interpretation?
- Can we test for different properties of dark energy rather than making implicit assumptions about them?

Reconstructing dark energy : a cautionary note

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

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

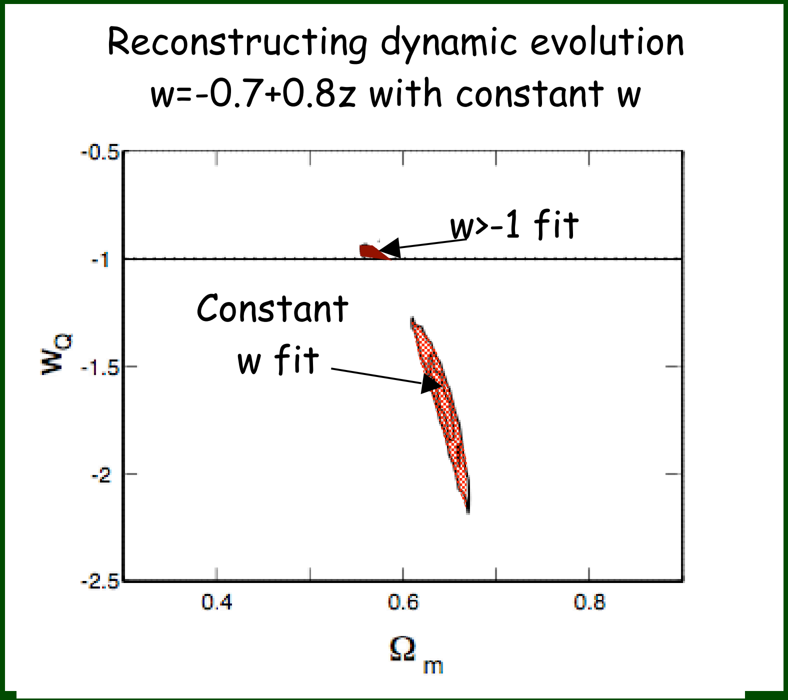
$$\Delta = H^2 - \frac{8\pi G}{3}\rho_m$$
$$w(z) = -1 + \frac{1}{3}\frac{d\ln(\Delta/H_0^2)}{d\ln(1+z)}$$

–Taylor expansions robust for low-z

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

- Do parameterizations relate to microphysical properties (w=p/ρ, and $c_s^2 = \delta p/\delta\rho$) or just an effective description?
  - –Need to have multi pronged observational approach

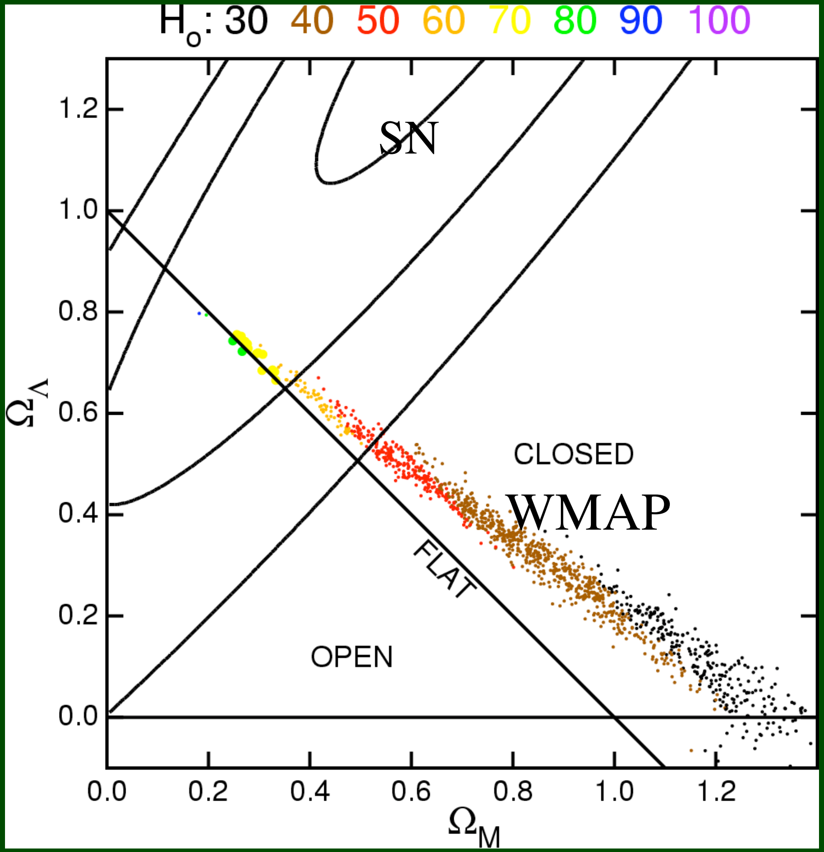
- But, parameterizations can mislead



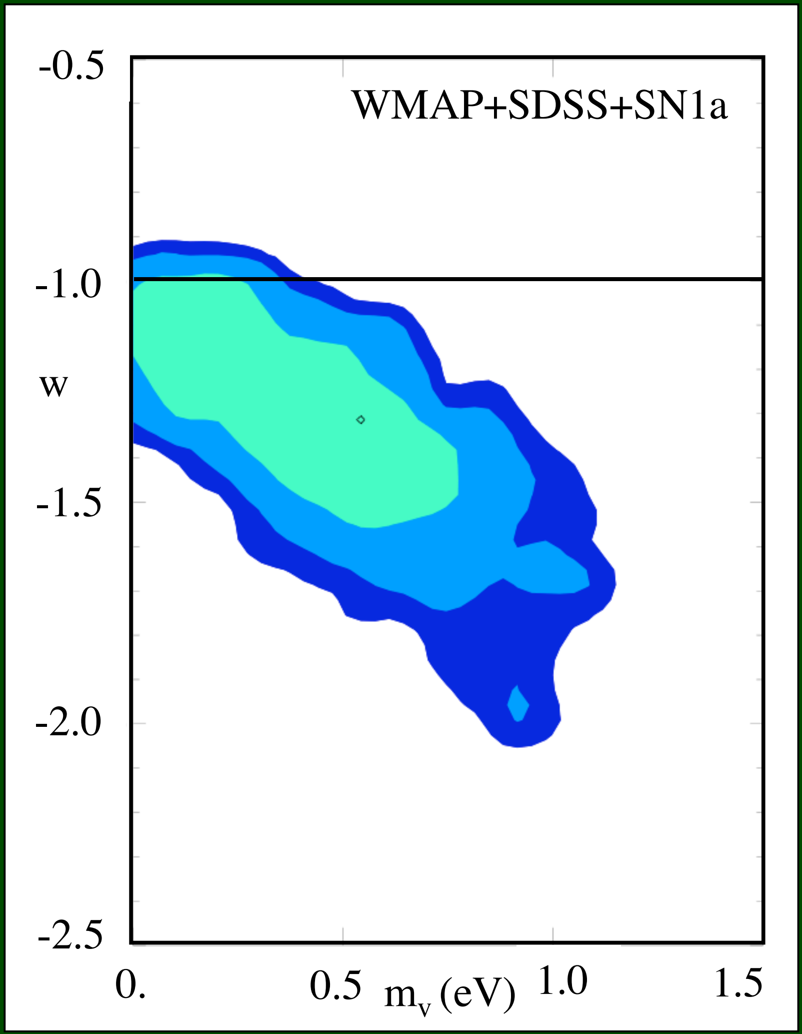
Maor et al 2002

Uncertainties in other cosmological parameters

- H0 probably not going to be measured to better than 1% accuracy
- Intrinsic curvature/ DE degeneracy



- Neutrino mass uncertainties expand w constraints



ISW: Dark energy signature in CMB photons

- Dark energy domination suppresses growth in gravitational potential wells , Ψ

$$\nabla^2 \Phi = 4\pi G a^2 \rho\delta$$

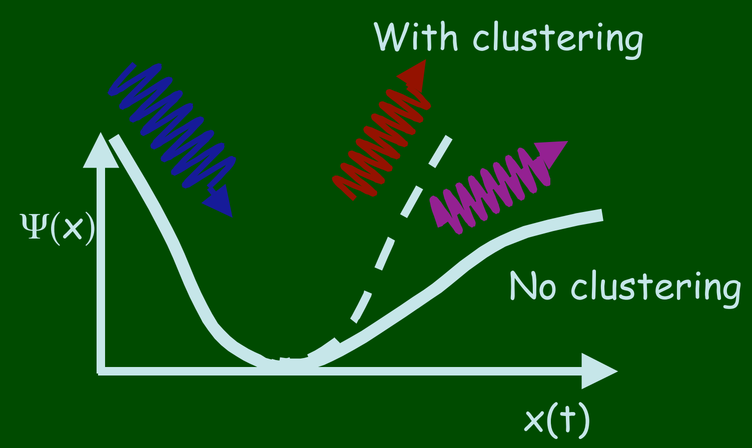
- Late time Integrated Sach's Wolfe effect (ISW) in CMB photons results

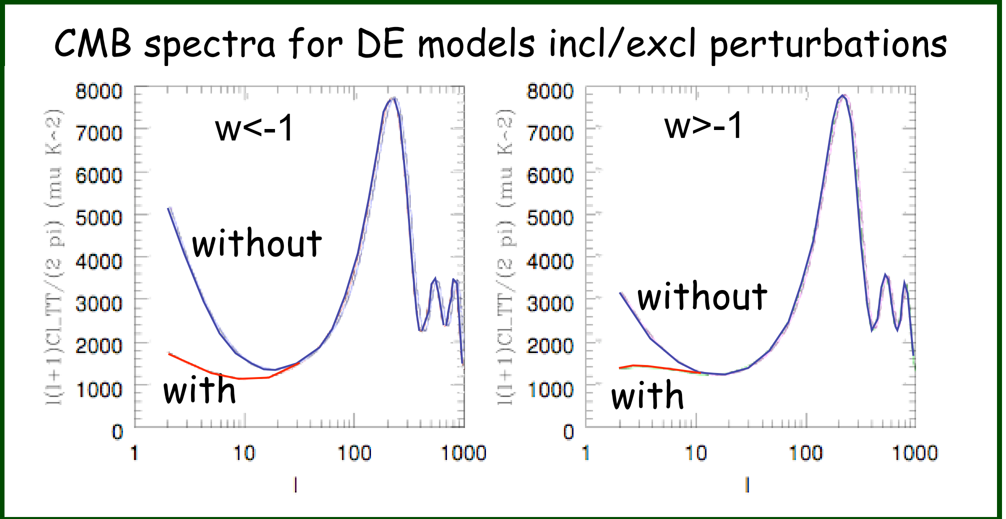
  - Net blue shifting of photons as they traverse gravitational potential well of baryonic and dark matter on way.

- ISW important at large scales

- Dark energy clustering counters suppression due to accelerative expansion

  –Decreases ISW signature



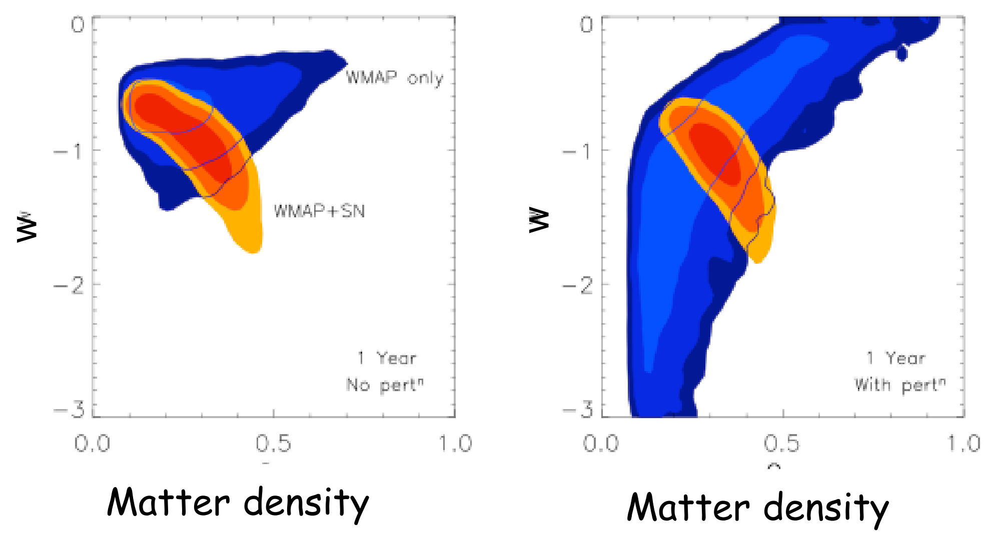


Hu 1998, Bean & Dore PRD 69 2003

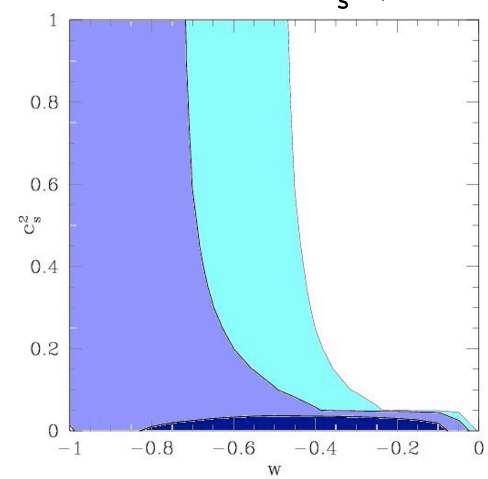
ISW: Perturbations and CMB & LSS inferences

- Degeneracies & cosmic variance prevent constraints on clustering itself
  - –Large scale anisotropies also altered by spectral tilt, running in the tilt and tensor modes
- Dark energy clustering <u>will</u> be factor in combining future high precision CMB with supernova data.
- Avoid degeneracies by cross correlating ISW with other observables
  - – galaxy number counts
  - – Radio source counts
  - – Weak lensing of galaxies or CMB

Constraints on w from CMB+ SN1a incl/excl perturbations

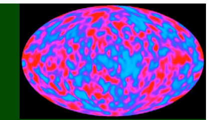


'Constraints' on w and c_s^2 from WMAP

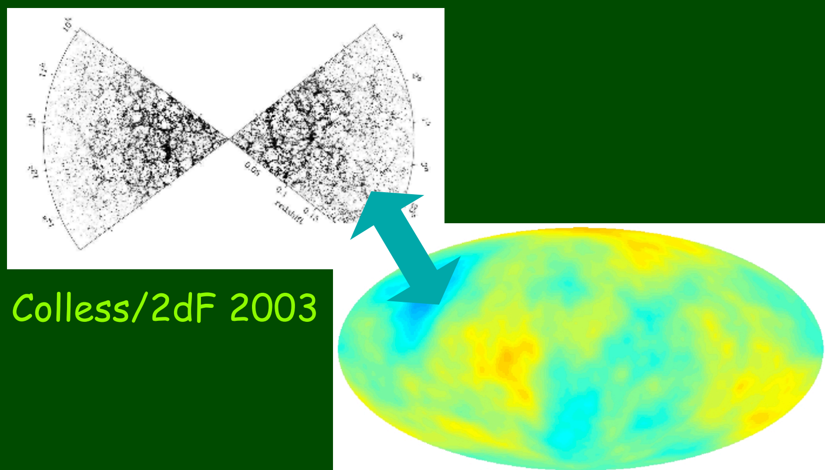


Bean & Dore 2003

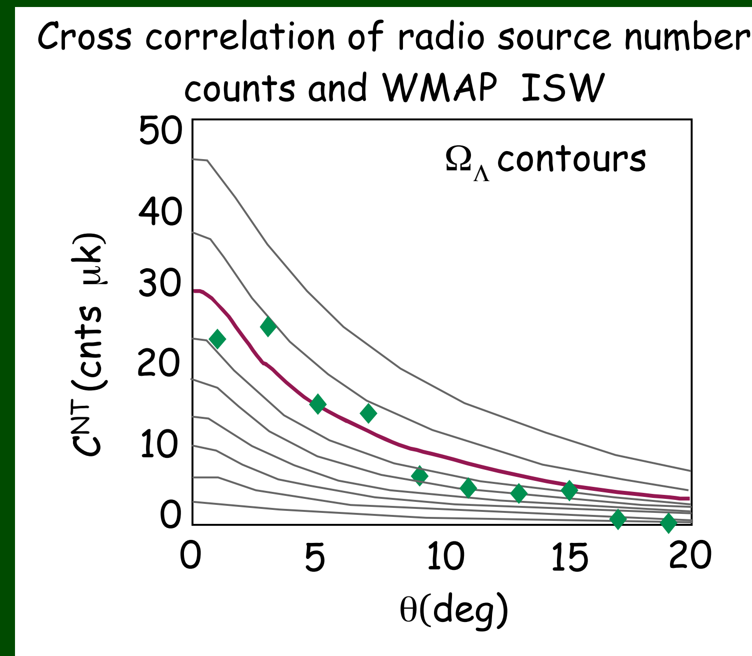
ISW: CMB cross correlation with LSS



- ISW intimately related to matter distribution



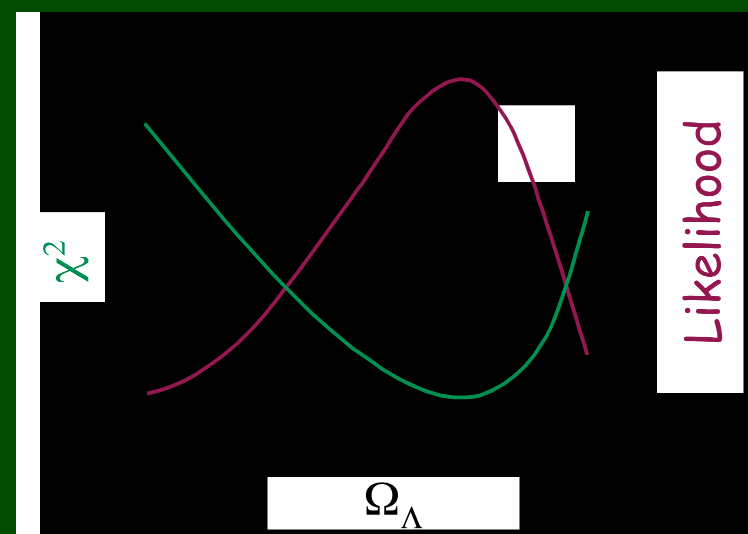
Colless/2dF 2003



- Observed cross-correlation of CMB ISW with LSS. e.g. NVSS radio source survey (Boughn & Crittenden 2003 Nolta et al 2003, Scranton et al 2003)

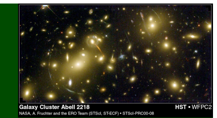
- Current observations cannot distinguish dark energy features (Bean and Dore PRD 69 2003) ,

- But Future large scale surveys which are deep, ~z=2, such as LSST might well be able to (if w≠ -1) (Hu and Scranton 2004)

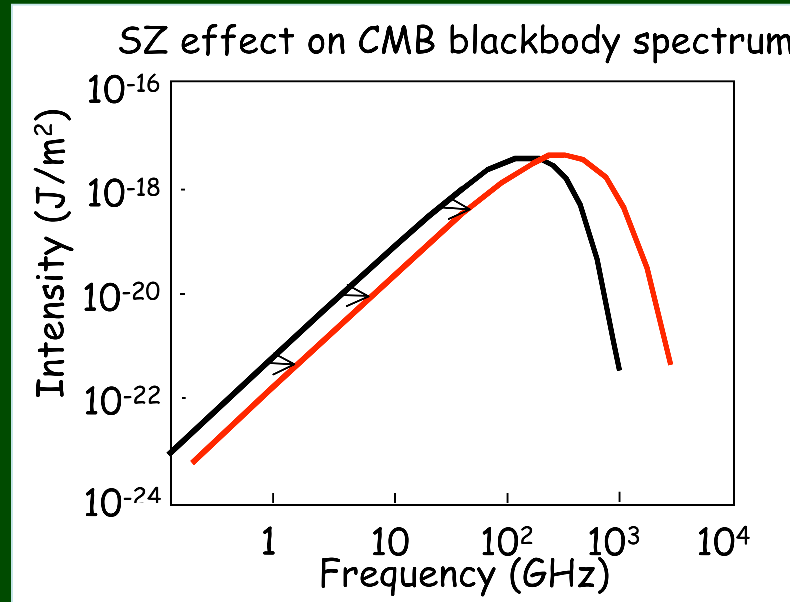


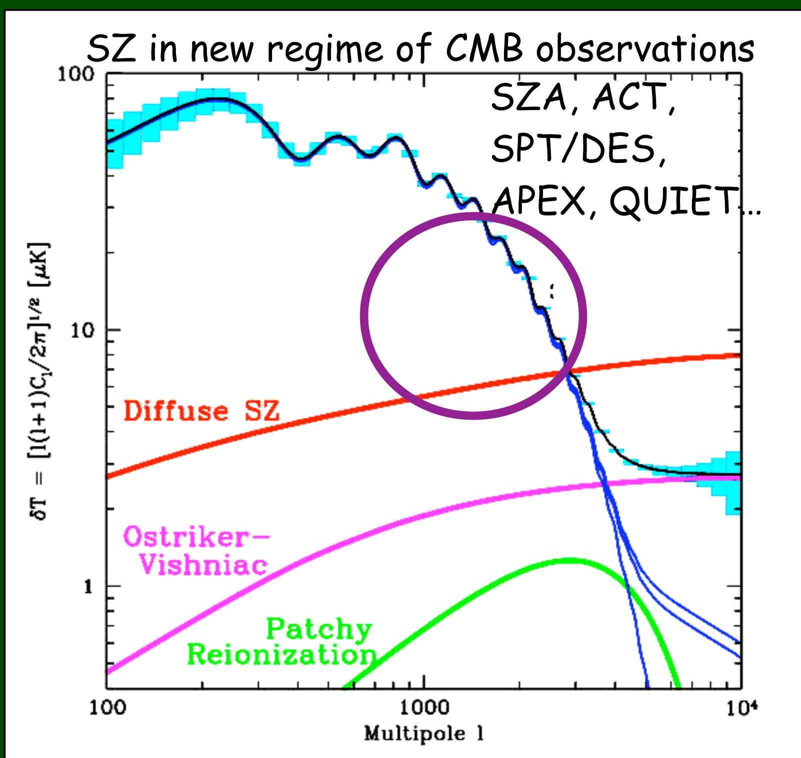
Nolta et al 2003

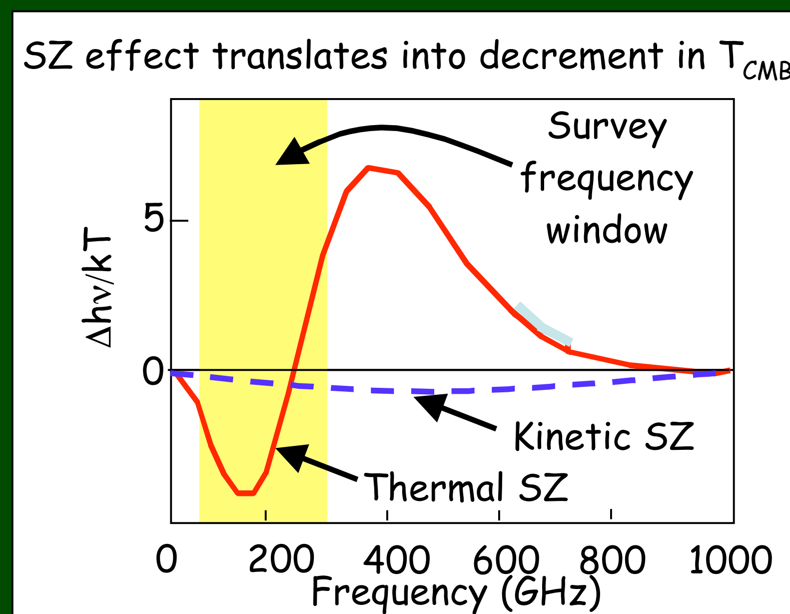
Dark energy prospects : cluster counts from SZ



- The passage of the CMB through a hot e^- cloud distorts the spectrum of the γ_{CMB} due to Compton interactions
- Due to the high energy of the e^-'s, and the homogeneity and isotropy of the CMB, the γ gain energy.
- SZ signal not attenuated with z

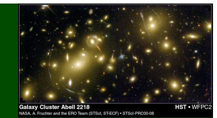






de Oliveira-Costa

Dark energy prospects : cluster counts from SZ



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

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

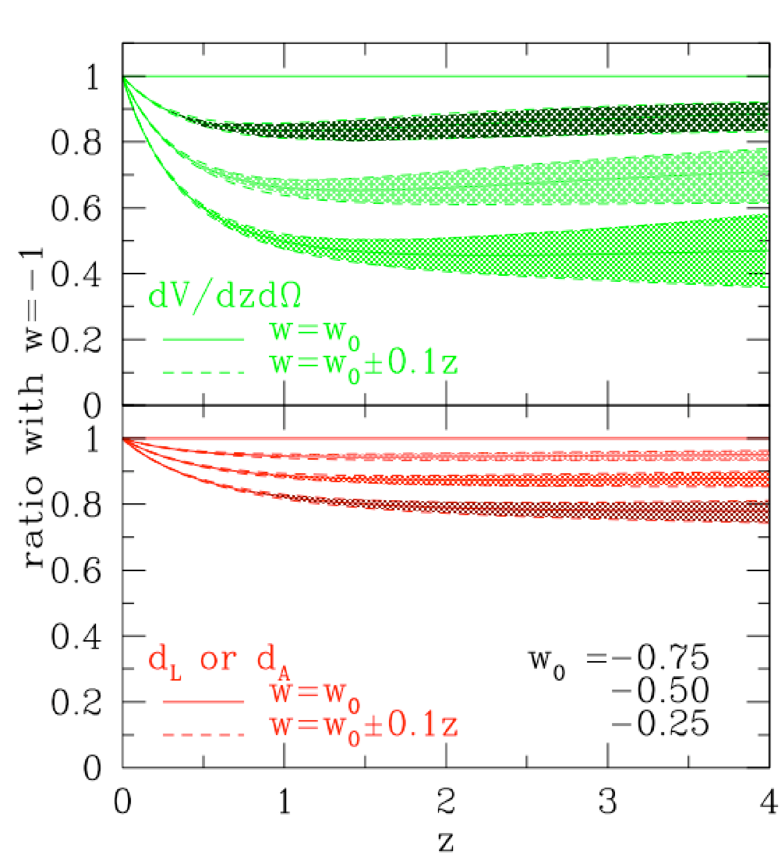
- Number counts related to underlying matter distribution and $\delta_c(z)$ add complications
  - inherent modeling sensitivity

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

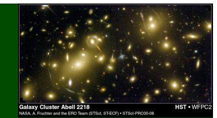
e.g. cluster mass function Jenkins et. al 2000

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

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

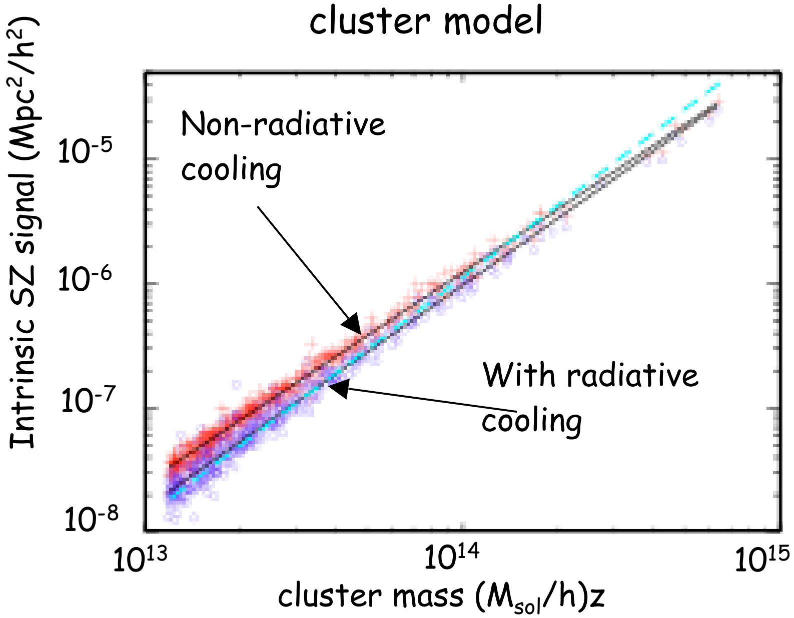


Cluster masses from SZ : systematic concerns



- Uncertainty in of mass-scaling relations from theoretical cluster physics modeling
- Effects of radiative cooling and pre-heating on mass - SZ/ Xray luminosities scaling relations

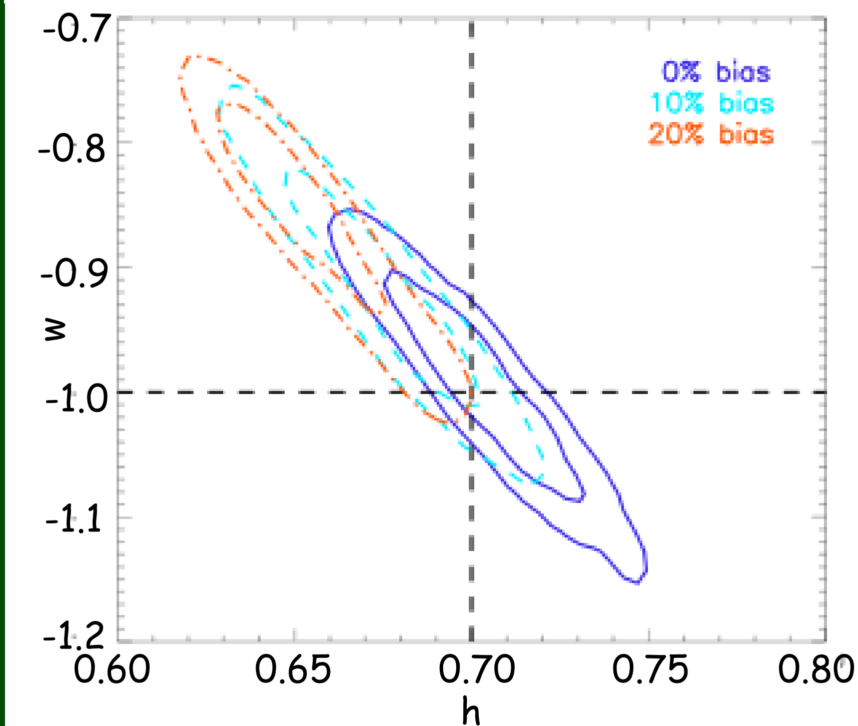
Cluster mass- SZ scaling relation dependency on cluster model



daSilva et al 2003

- Equates to a systematic error in cluster mass estimate, to which matter content and DE parameters are exponentially sensitive

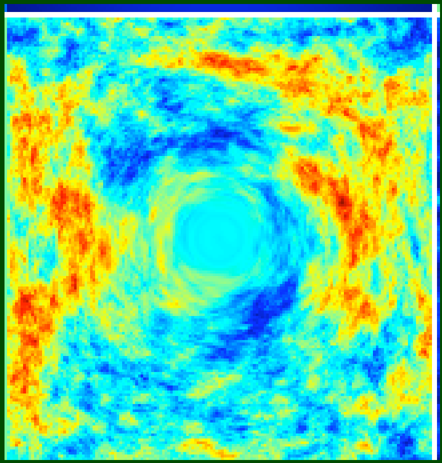
Effect of mass bias on cosmological parameter estimation from Planck-like +ACT-like surveys



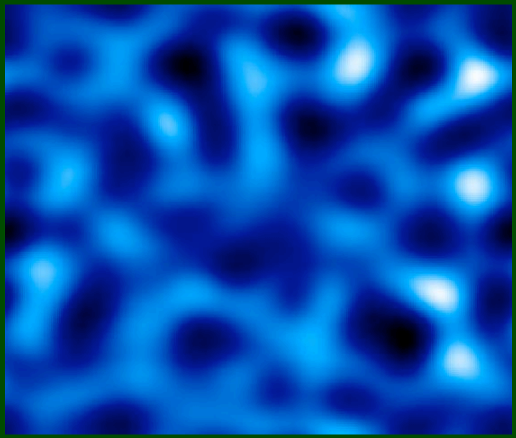
Francis, Bean, Kosowsky 2005

Weak lensing: avoids baryon physics biases

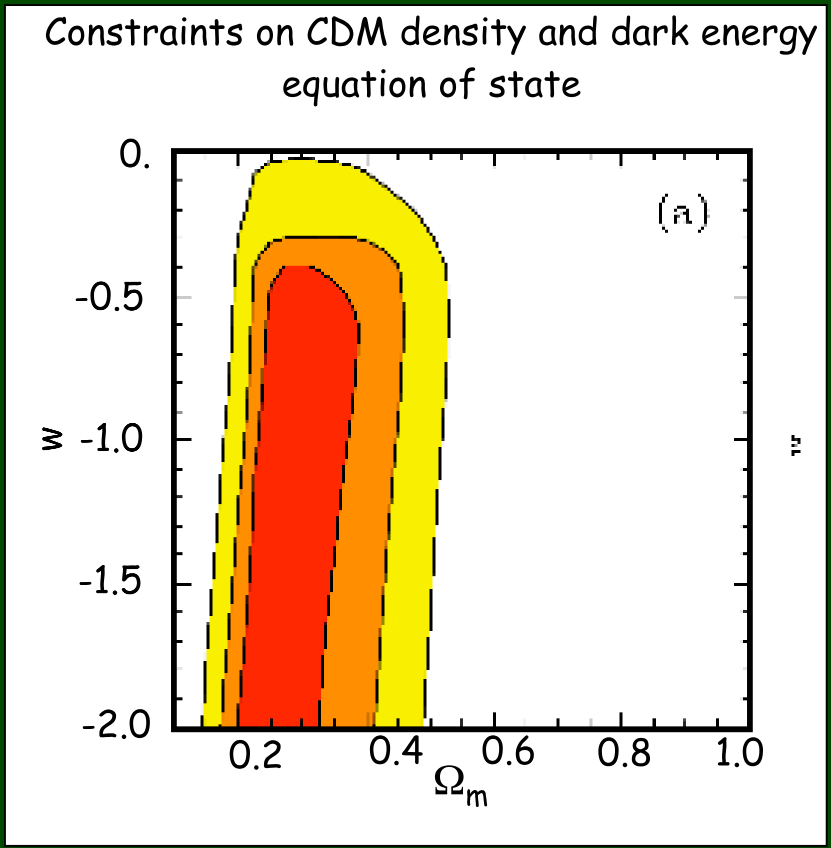
- Weak lensing uses all the mass information not just luminous matter (baryons)
- Lensing of the images of galaxies and quasars and of the Cosmic Microwave Background more distant than the lensing halo



Seljak and Zaldarriaga



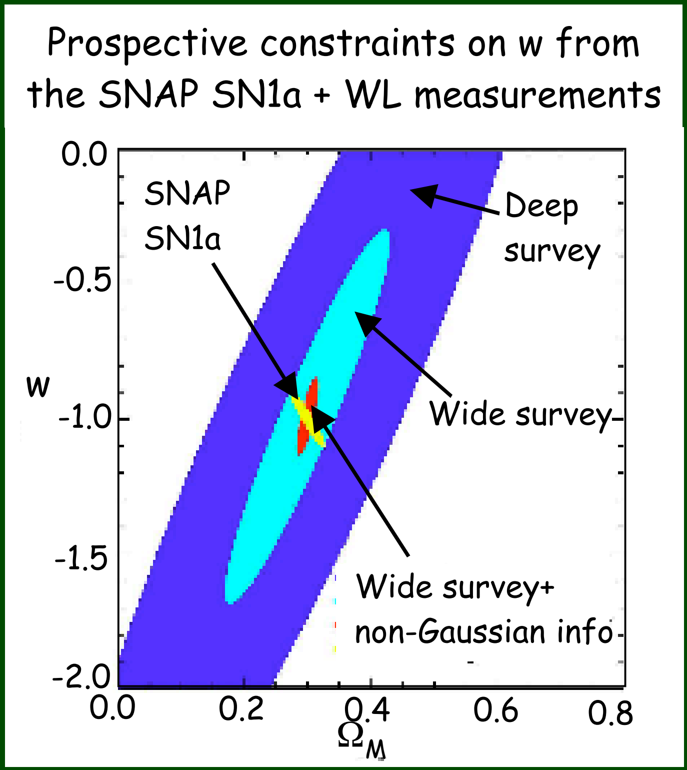
A. Refregier



Constraints from CFHT Legacy Survey Wide Field Survey (22sq deg)
Hoekstra et al 2005, Semboloni et al 2005

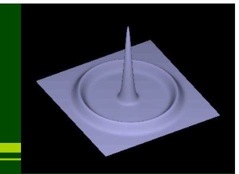
Weak lensing tomography :prospects

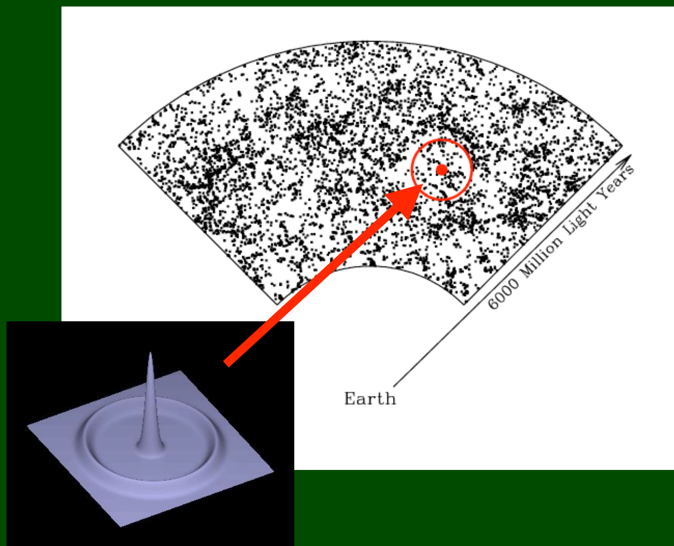
- SNAP and LSST offer amazing prospects for WL
  - SNAP measuring 100 million galaxies over 300 sqdeg
- Spectroscopic followup of galaxy surveys allow redshift slicing (tomography)
- Tomography => bias independent z evolution of DE
- Possibly apply technique to compare dark energy theories ?
- Understanding theoretical and observational systematics key
  - effect of non-linearities in power spectrum
  - Reconstructing anisotropic point spread function
  - z-distribution of background sources and foreground halo
  - inherent ellipticities …

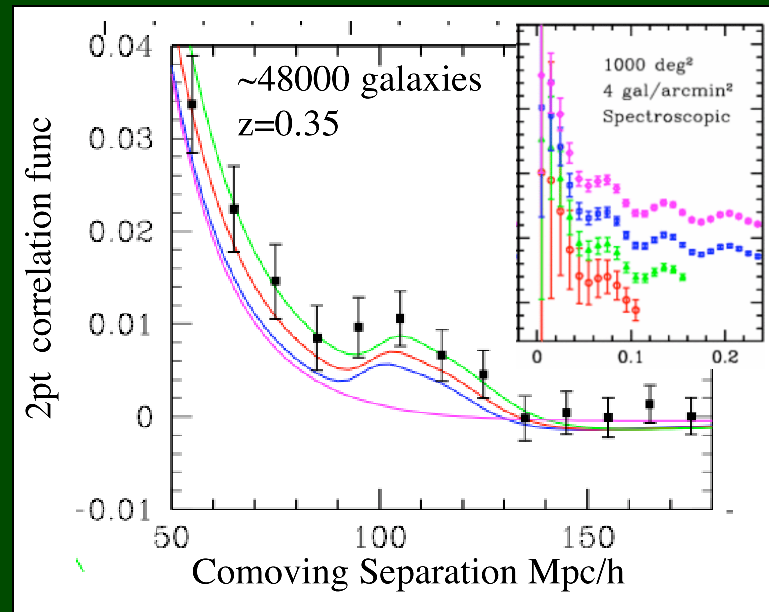


SNAP collaboration
Aldering et al 2004

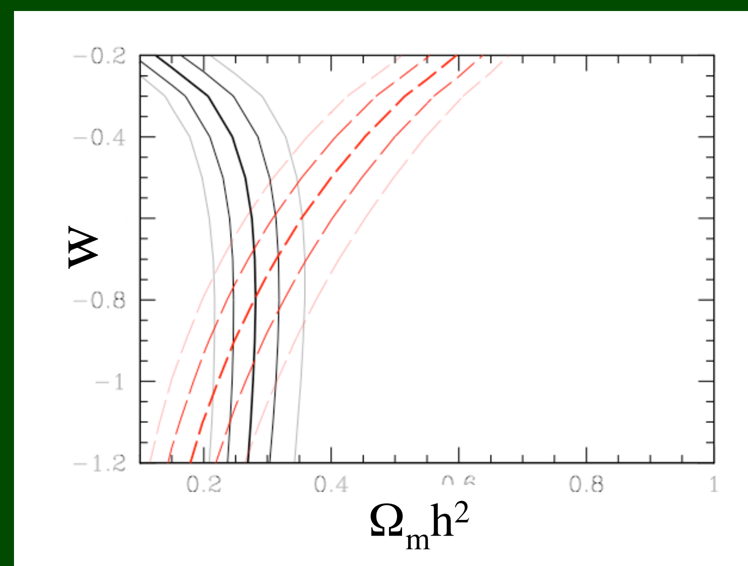
Acoustic baryon oscillations







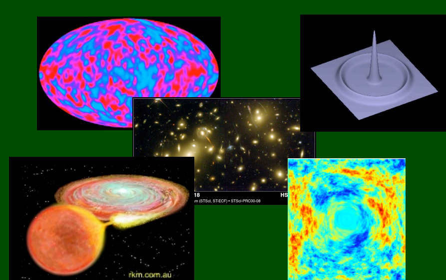
- Systematics do not create oscillatory features in correlation spectrum (Seo and Eisenstein 2003) but still need to be characterised.
  - Dust extinction,
  - galaxy bias,
  - redshift distortion
  - non-linear corrections

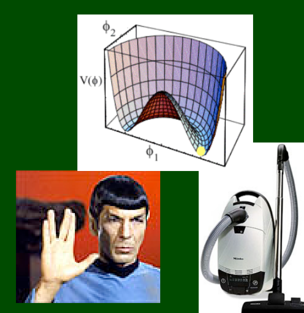


Eisenstein et al 2004

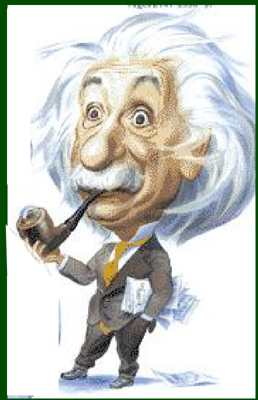
Linking Dark Energy Observations and Theory

- Theories are making testable predictions
  - from horizon scales (dark energy perturbations) down to solar system scales (modified gravity)
- Still outstanding issues about other cosmological parameter uncertainties
  - Hubble's constant, neutrino mass and intrinsic spatial curvature
- Significant broadening of cosmological constraints in the next 5-10 years
  - Order of magnitude increase in number of high z SN1a and galaxies
  - with a lever arm tying down both large (ISW) and small scale (SZ, weak lensing, baryon acoustic oscillations) anisotropies





Linking Dark Energy Observations and Theory



<u>Einstein on Observation:</u>
"Joy in looking and comprehending is nature's most beautiful gift."

<u>Einstein on Theory:</u>
“If an idea does not appear absurd at first then there is no hope for it”