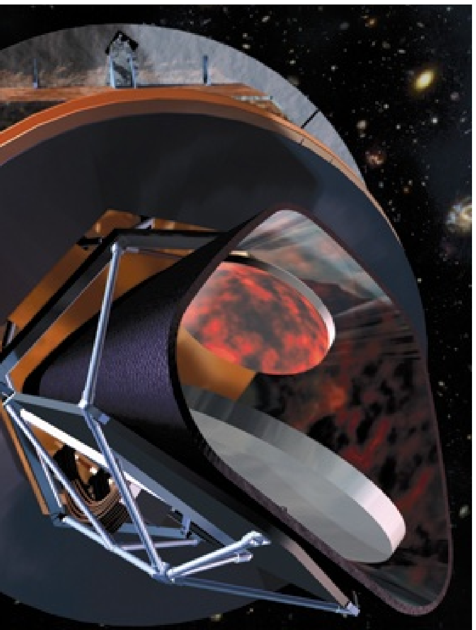
Dark Energy
in Dark Antarctica

Eric Linder

21 July 2009



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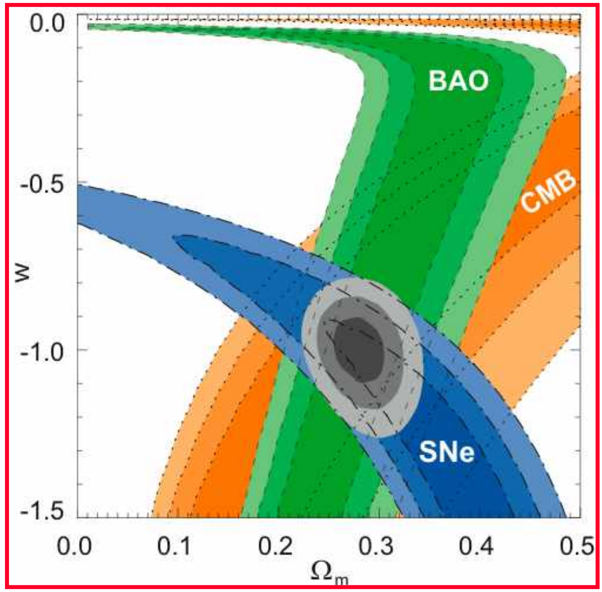
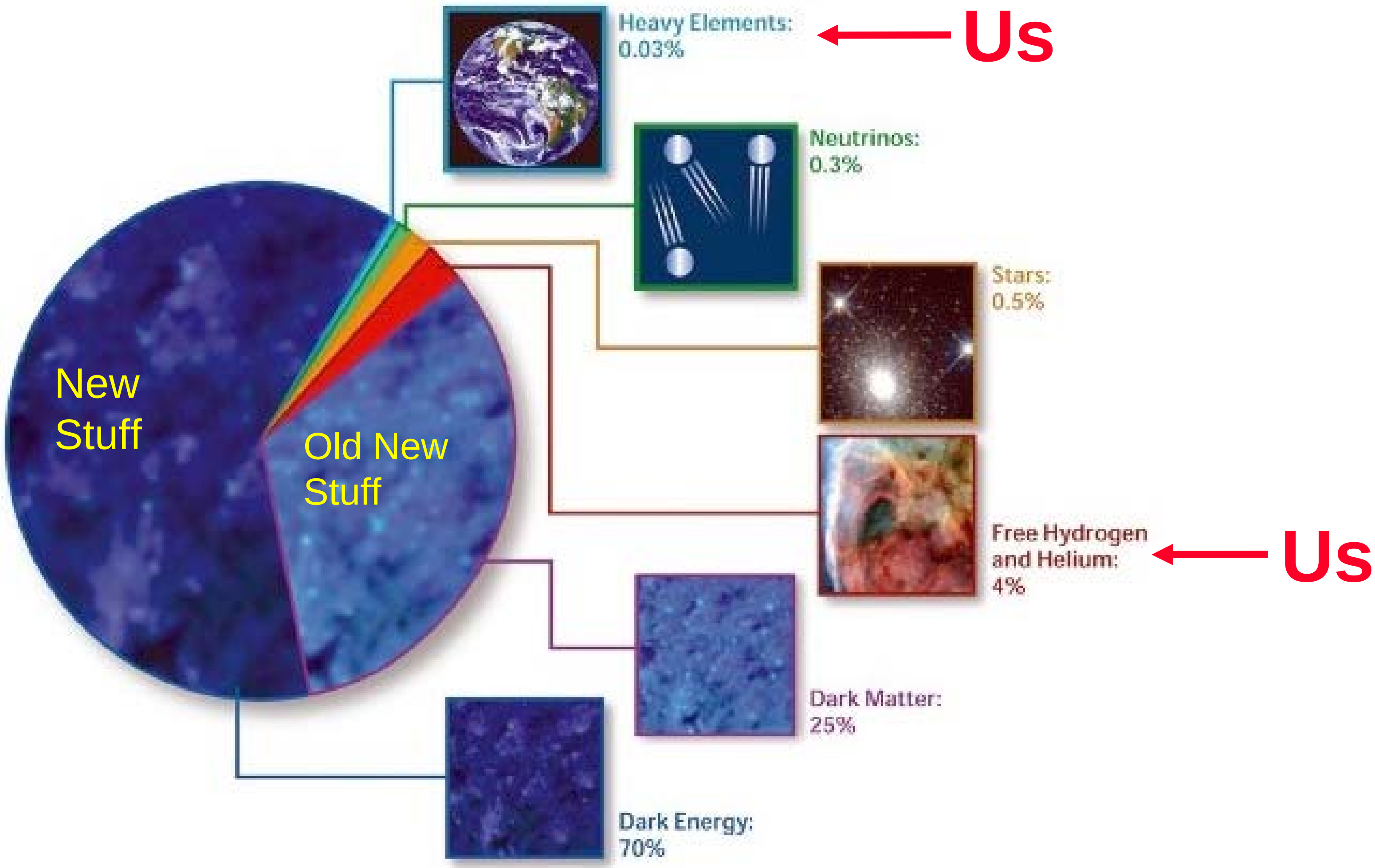


Describing Our Universe



STScI

95% of the universe is unknown!

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe. **- Shakespeare, *Henry***

Cosmic Coincidence

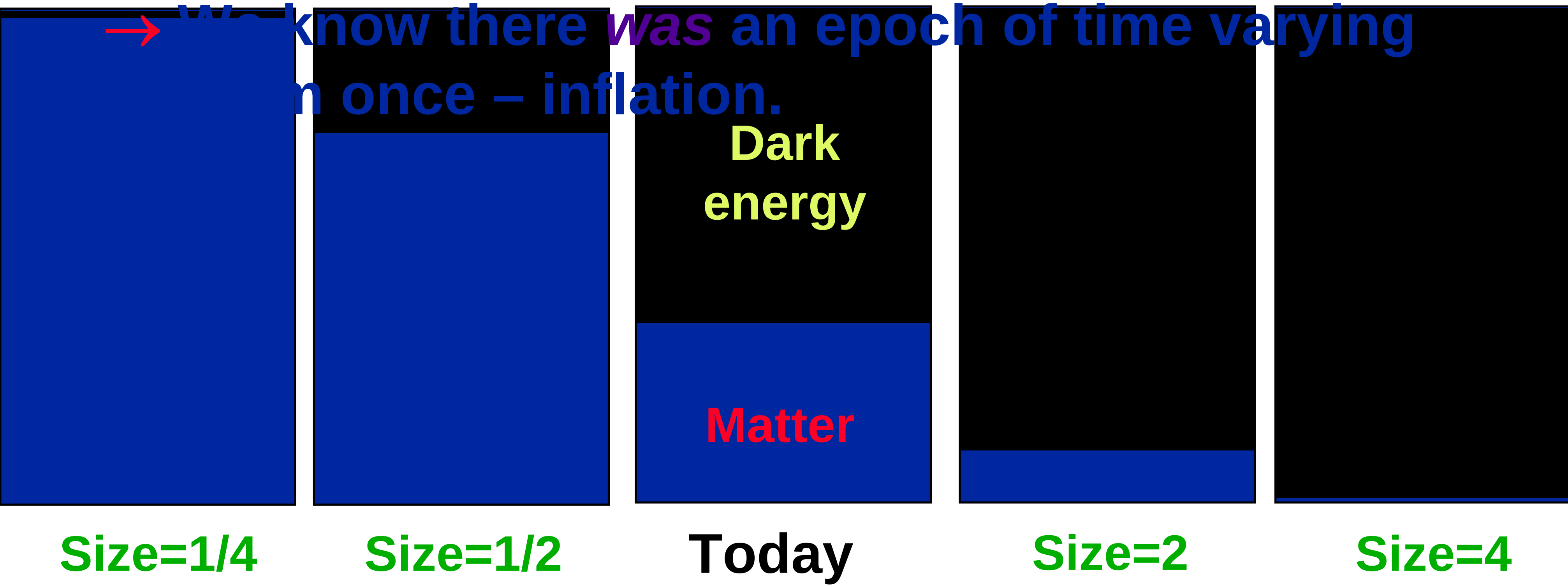
Why not just settle for a cosmological constant Λ?

→ For 90 years we have tried to understand why Λ is at least 10^{120} times smaller than we would expect – *and failed*.

We cannot calculate the vacuum energy to within 10^{120}.

But it gets worse: Think of the energy in Λ as the level of the quantum "sea". At most times in history, matter is either drowned or dry.

→ We know there was an epoch of time varying … n once – inflation.



On Beyond Λ!

We need to explore further frontiers **in high energy physics, gravitation, and cosmology.**

New quantum physics? **Does nothing weigh something?**

Einstein's cosmological constant, Quintessence, String theory

New gravitational physics? **Is nowhere somewhere?**

Quantum gravity, extended gravity, extra dimensions?

Beyond the Standard Model

Consider ΛCDM as Standard Model of Cosmology.

Describe expansion history through model independent w_0, w_a : *accurate to 10^{-3} level.*

Describe growth history *distinct* from expansion history effects through model independent growth index γ to test gravity: *accurate to 10^{-3} level.*

Describe early growth through calibration g_* to test matter domination : *accurate to 10^{-3} level.*

This is the theory framework -- we will need clever new observations to match.

Physics of Growth

Growth $g(a)=(\delta\rho/\rho)/a$ depends on the expansion history $H(z)$ -- *and* gravity theory.

$$g'' + \left[5 + \frac{1}{2}\frac{d\ln H^2}{d\ln a}\right] g' a^{-1} + \left[3 + \frac{1}{2}\frac{d\ln H^2}{d\ln a} - \frac{3}{2} G\,\Omega_m(a)\right] g a^{-2} = 0$$

Expansion effects via $H(a)$ or $w(z)$, but *separate* effects of gravity on growth.

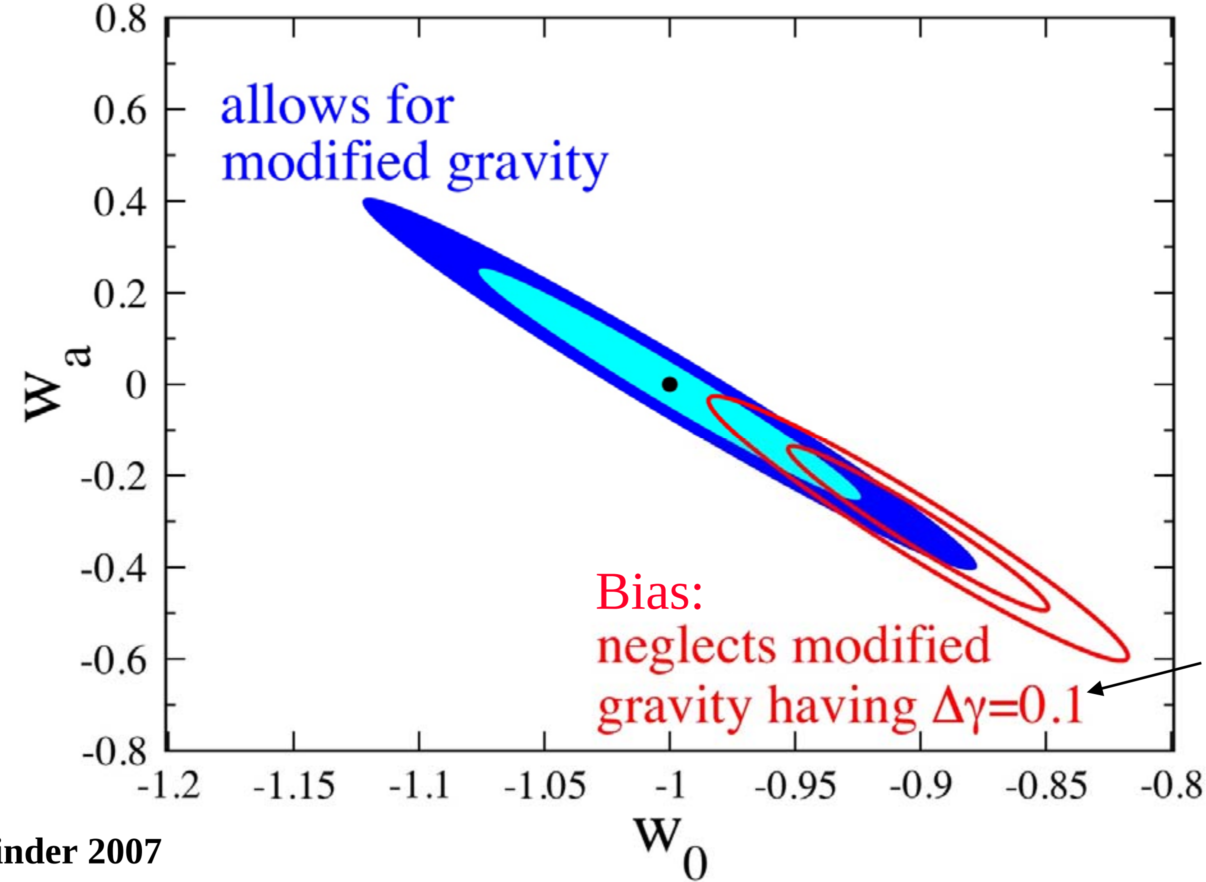
$$g(a) \approx \exp\left\{ \int_0^a d\ln a\, [\Omega_m(a)^\gamma - 1] \right\}$$

Growth index γ can describe extensions to general relativity (modified gravity).

The Nature of Gravity

To test Einstein gravity, we need growth and expansion.
Tension between distance and LSS mass growth reveals deviations from GR.

Keep expansion history as w(a), growth *deviation* from expansion (modGR) by γ. Fit both simultaneously.



Δγ gives deviations in growth from GR

Huterer & Linder 2007

Extending the Growth Framework

Consider $$g(a) = g_\star e^{\int_0^a (da'/a')\,[\Omega_m(a')^\gamma - 1]}$$

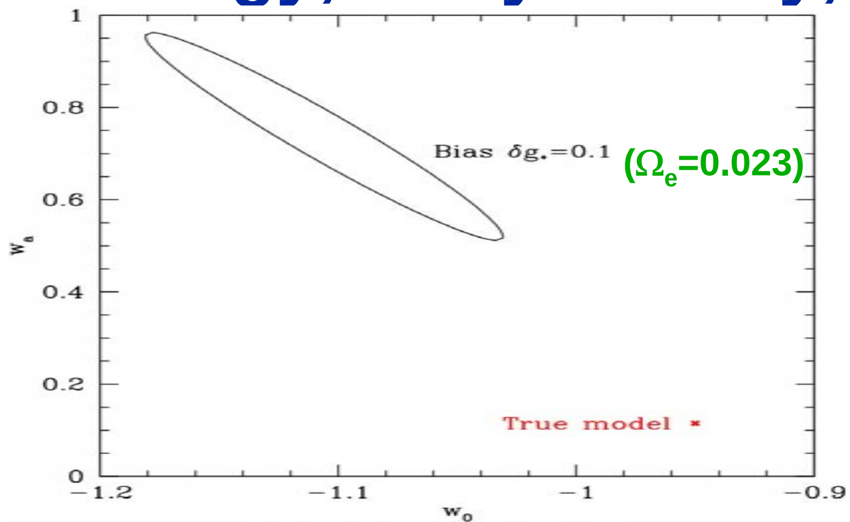
In standard high-z matter dominated cases, $g_* = 1$.

$g_* > 1$ allows enhanced growth.
$g_* < 1$ allows suppression distinct from expansion and late time gravity effects.

g_* is window on Early Dark Energy, Early Gravity, Early Acceleration.

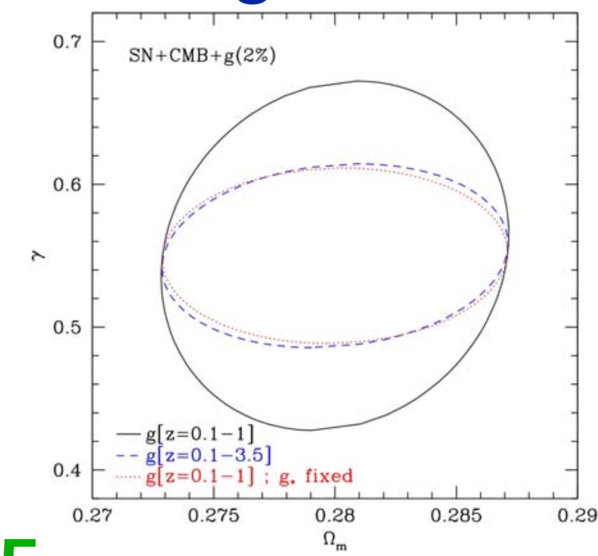
Example: $g_* = 1 - 4.4\,\Omega_e$

Don't ignore g_*!



Observations Required

To measure $\{w_0, w_a, \gamma, g_*\}$ one needs expansion (distance) probes, e.g. Supernovae, CMB, and growth probes, e.g. Weak Lensing (CMB), Ly α.



$\sigma(\gamma)$=0.081, $\sigma(g_*)$=0.018 (+Lyα 0.042, 0.006)

Measurements of g_* to 2% reveal:

Early dark energy to $\sigma(\Omega_e)$=0.005.

Early gravity to $\delta G/G$=1.4%.

Early acceleration to 1.7% of a Hubble time.

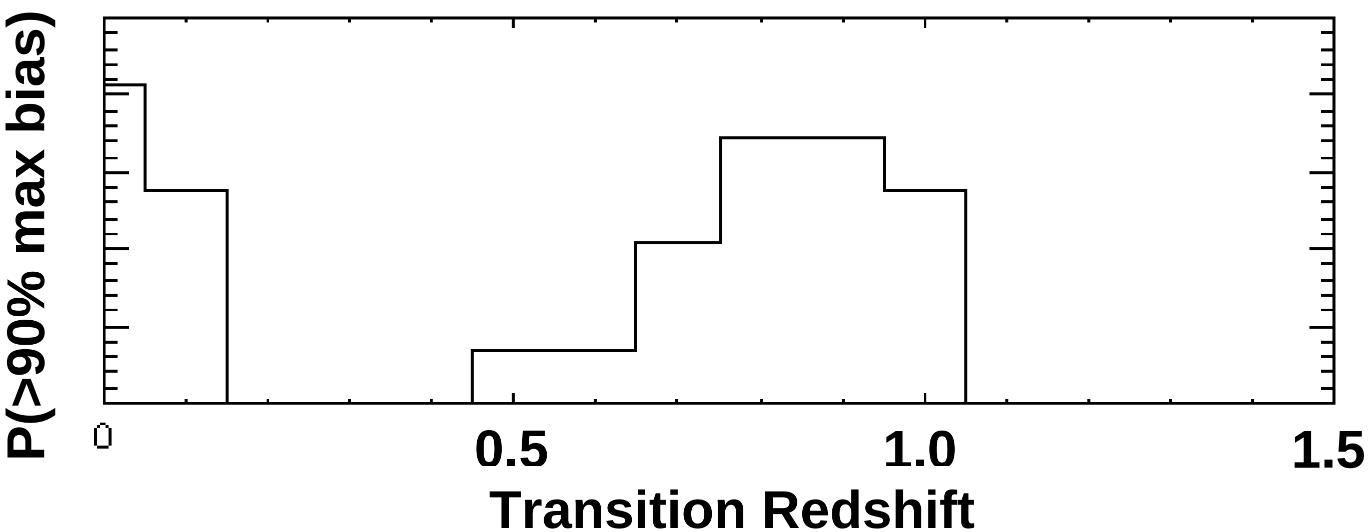
Next generation Dark Energy Missions can truly test the expansion/gravity/early time framework of cosmological physics!

Supernovae Surveys

The cleanest method for measuring dark energy effects on expansion is Type Ia Supernovae.

Next generation measurements must concentrate on systematics.

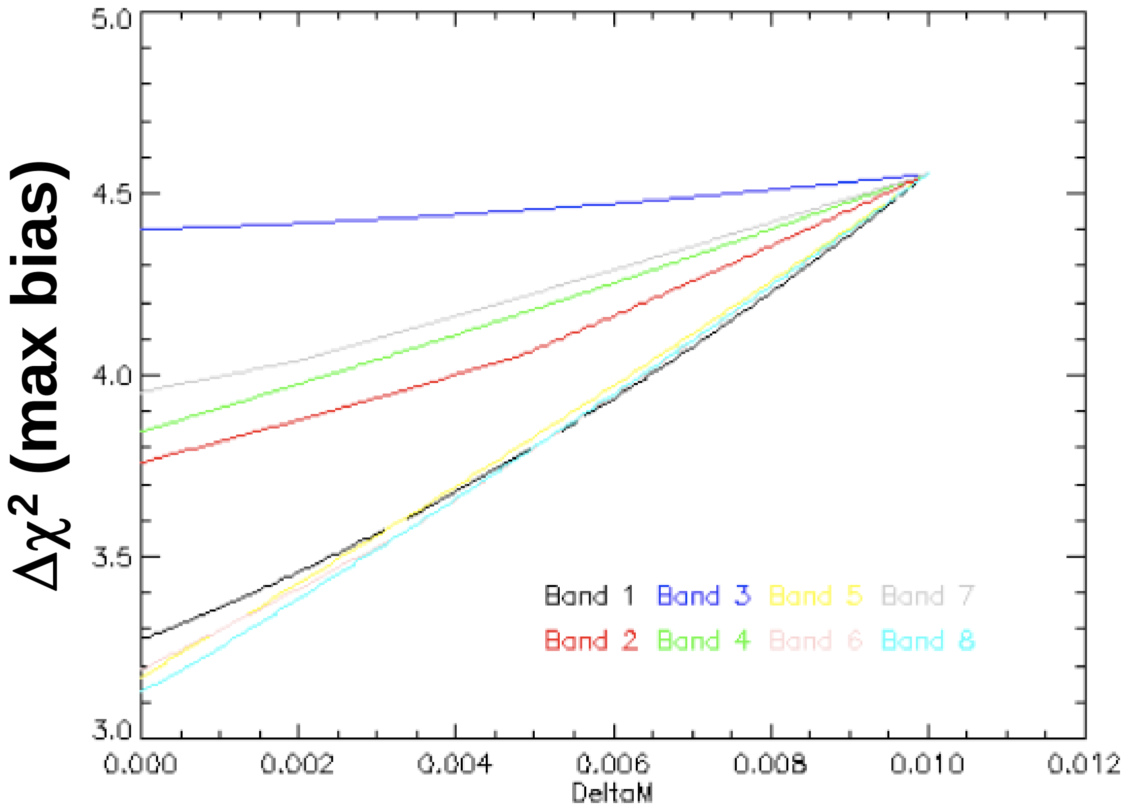
If there is unrecognized population drift, this biases cosmology. Where is it worst?



Supernovae Surveys

For z~1.0 systematics, want NIR. Improvement in bias is linear in ΔM down to 0.01mag.

Where in wavelength is greatest improvement for dust correction systematic?



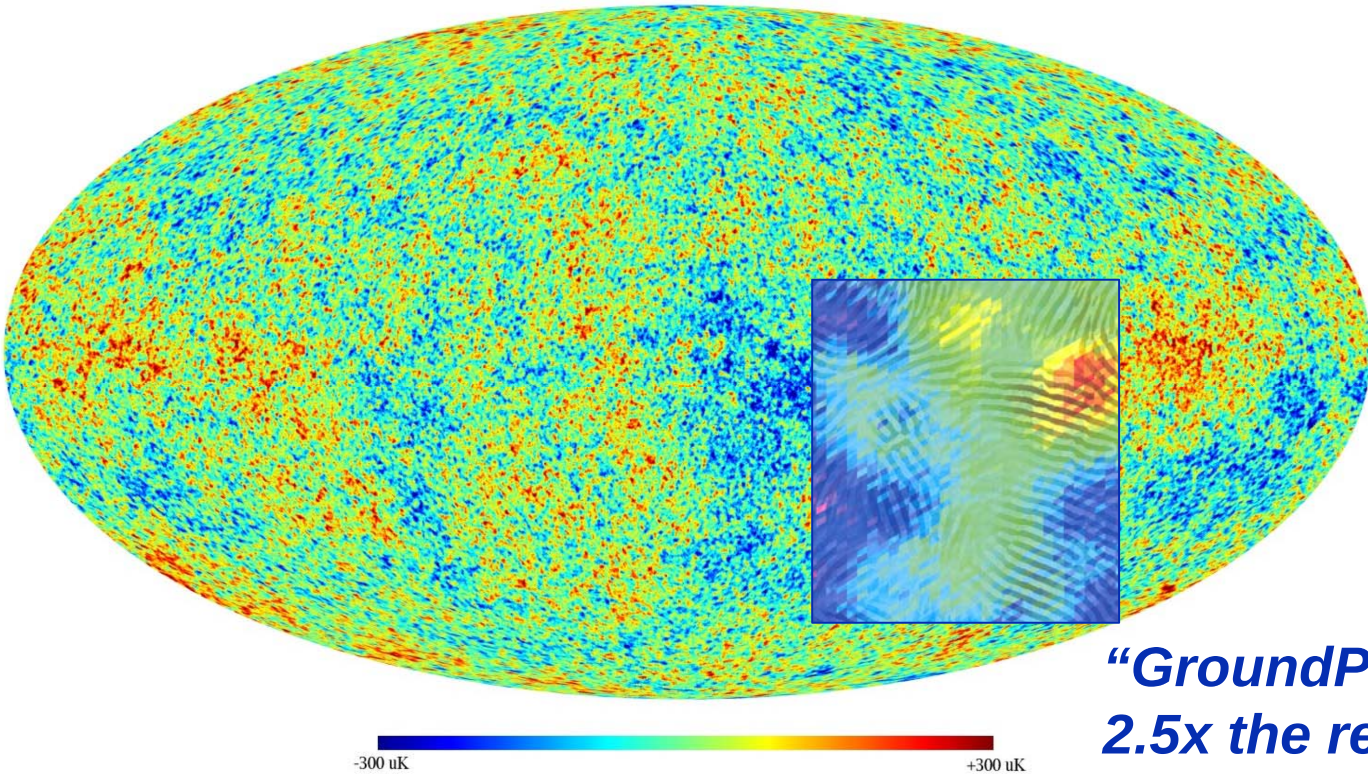
Observer B, I, H bands (1,5,8).

de Putter, Linder, Samsing 2009

What do we see in the CMB?

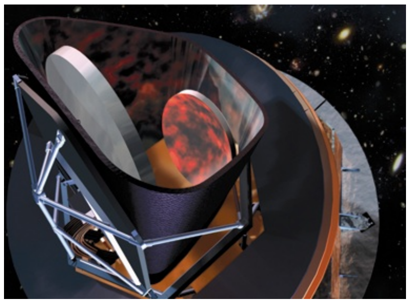
COBE

WMAP



"GroundPol" has 2.5x the resolution and 1/5x the noise

Planck



A view of the universe 99.997% of the way back toward the Big Bang - and much more.

CMB and Dark Energy

CMB provides a lever to break degeneracies

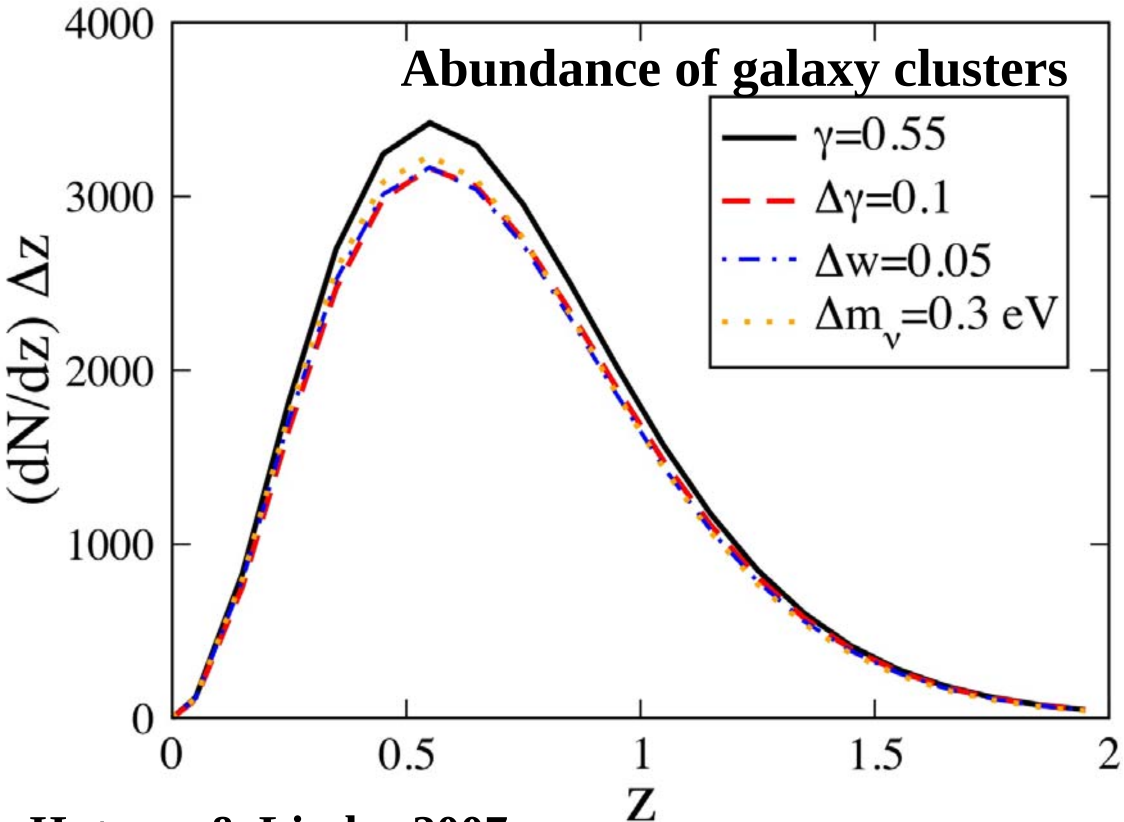
CMB provides a key window on microphysics of dark energy - spatial fluctuations $\delta\phi$ and sound speed c_s^2

CMB Polarization (B-mode) is dominated at small angles by high redshift lensing by gravitational potentials of structure - hence high z structure formation.

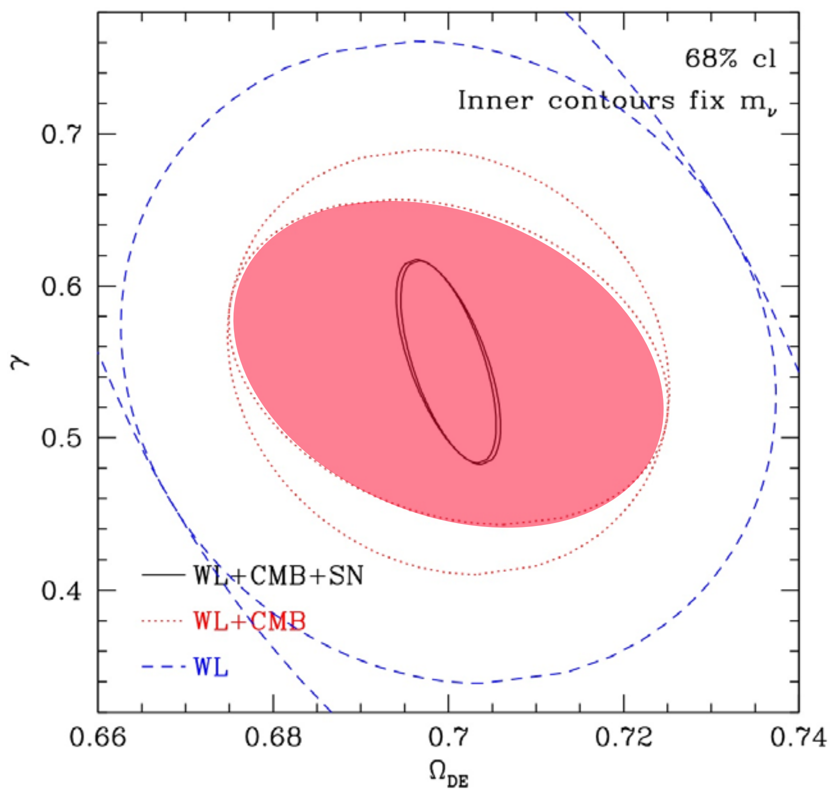
Polarization lensing "focuses" on the universe at z=1-4, giving a window on early dark energy, and neutrinos.

Neutrinos and Dark Energy

Neutrino masses, dark energy equation of state, and gravity all can suppress growth. Must fit all simultaneously to avoid bias.



Huterer & Linder 2007

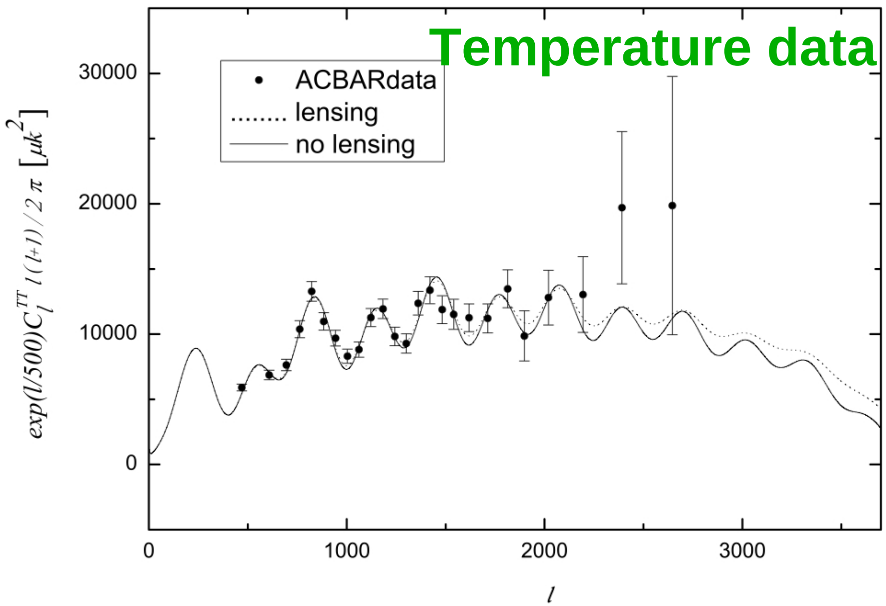


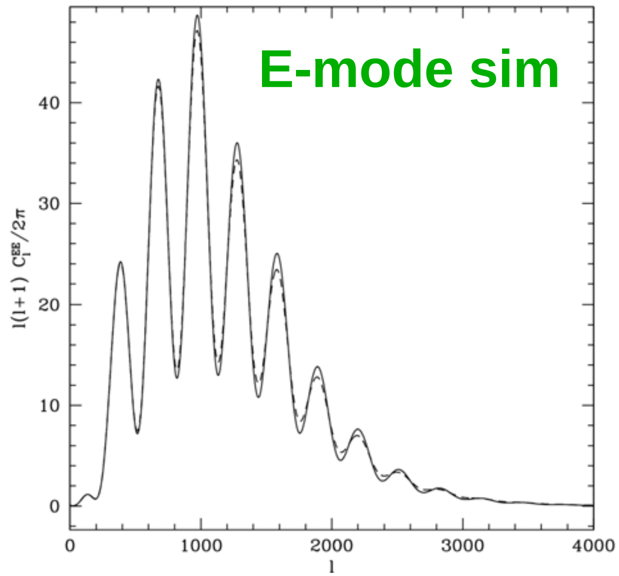
CMB Lensing and Growth

Cosmic microwave background is sensitive to structure (so neutrinos, DE) through gravitational lensing of the CMB. Review: Lewis & Challinor 2006

Shuffling of photons smears the acoustic peaks and also induces power in the CMB polarization spectra.

Detection of CMB lensing claimed by Smith et al. 2007, Hirata et al. 2008, Calabrese et al. 2008, Reichardt et al. 2009

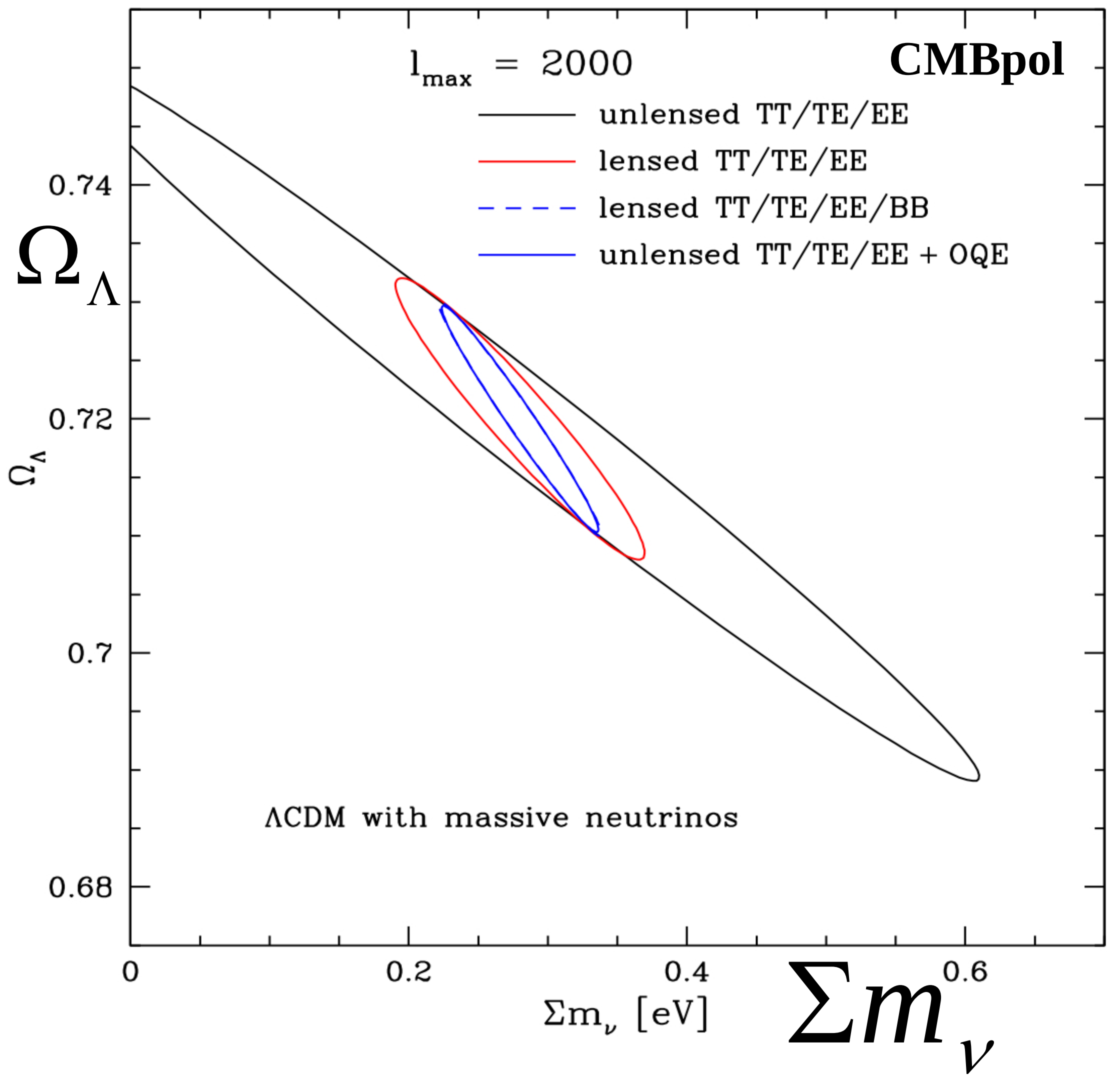




Neutrinos and Dark Energy

Must account for neutrino/dark energy degeneracy.

cf. Lesgourgues et al. 2006, Smith, Hu, Kaplinghat 2006, Smith et al. 2008



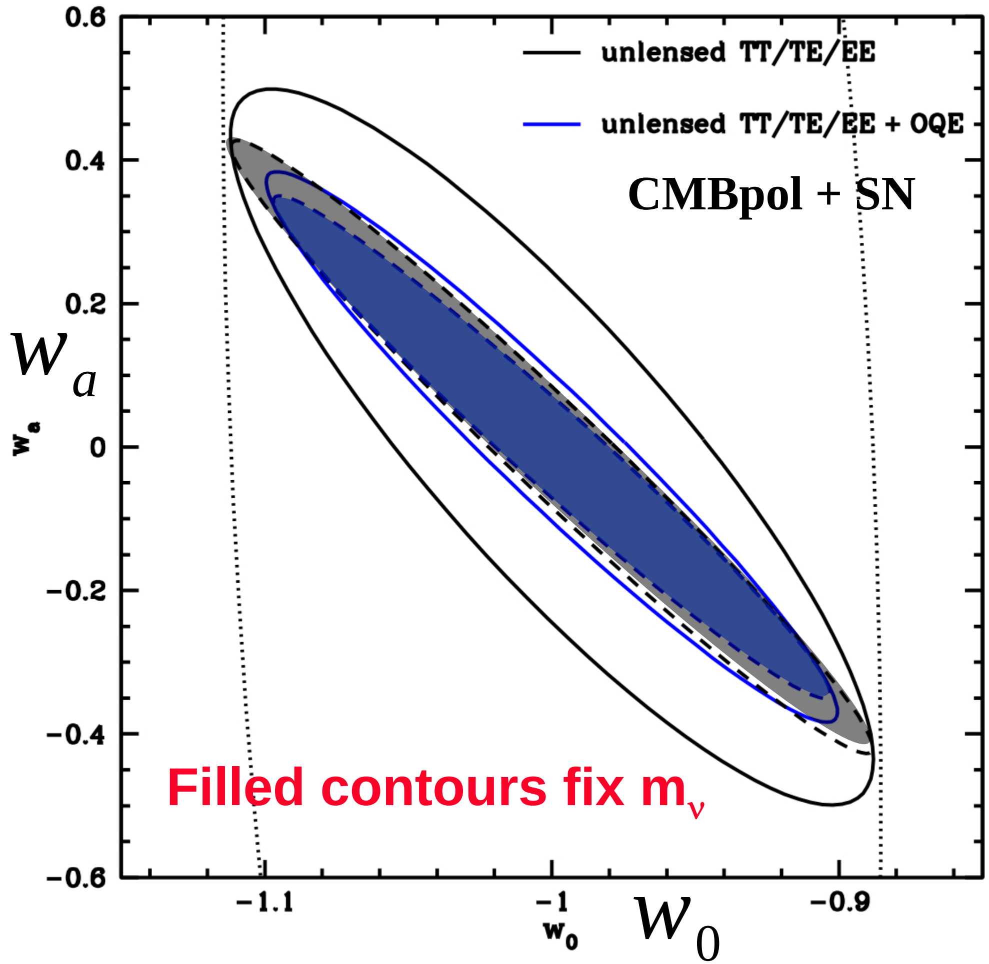
CMB lensing is a powerful tool for neutrino bounds.

de Putter, Zahn, Linder 2009

Dark Energy and CMB

Dangerous to fix neutrino mass (dashed) rather than marginalizing (solid). Overtight DE constraints.

DE equation of state $w(a) = w_0 + w_a(1\text{-}a)$



CMB, Dark Energy, Neutrinos

CMB Lensing will tightly constrain fundamental physics such as neutrino mass.

With Supernovae, it can reveal dark energy properties.

Model	Experiment	$\sigma(w_0)$	$\sigma(w_a)$	$\sigma(\Omega_e)$	$\sigma(\Sigma m_\nu)$ [eV]
ΛCDM	Planck	–	–	–	0.11
ΛCDM	CMBpol	–	–	–	0.037
w_0-w_a	Planck+SN	0.074	0.32	–	0.13
w_0-w_a	CMBpol+SN	0.068	0.27	–	0.044
w_0-Ω_e	Planck+SN	0.032	–	0.0042	0.15
w_0-Ω_e	CMBpol+SN	0.018	–	0.0020	0.050

Institute for the Early Universe

Institute for the Early Universe

Korea set up a "World Class University" program to advance international research collaboration.

3 Berkeleyites (Linder, Seljak, Smoot).
4 faculty at Ewha Womans University, Seoul.

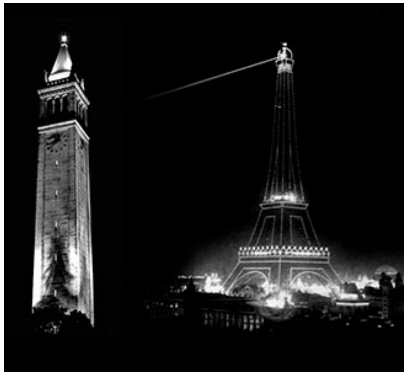
6 postdocs hired, 4 more open, 3 new faculty open.

Visit IEU at Ewha!

Paris-Berkeley Dark Energy Cosmology workshop:

**systematics control,
observations needed,
ground+space**

**14-18 Sep 2009
Paris, France**
darkenergy09.in2p3.fr



Antarctic Advantage

Antarctic Surveys can make significant contributions in advancing Supernova Cosmology, with an emphasis on systematics control.
NIR Observing ; Detailed Lightcurves.
See talks by Helou, Huang, Kim, Nugent, Zheng

Antarctic Surveys can make significant contributions in advancing CMB Lensing, with emphasis on low noise, high resolution, wide area.
Dry, stable atmosphere ; Long observing runs.
See talks by Smoot, Zhang.

Plus structure survey for DE: see talks by Rhodes, Saunders, Schlegel, Zhan.