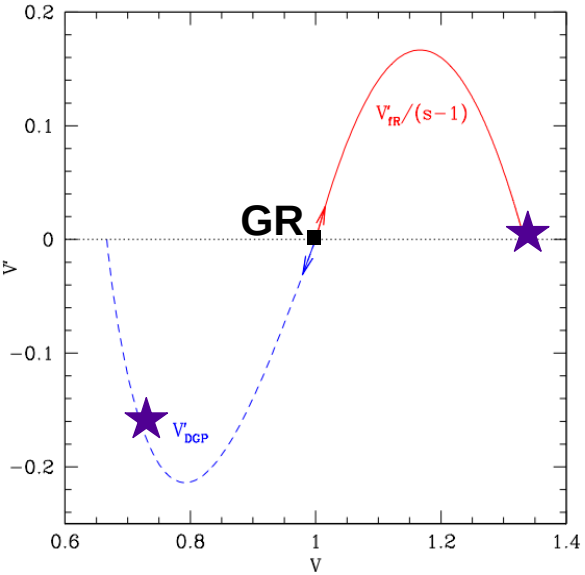
Chasing Down
Cosmic Acceleration



Eric Linder

October 2011

UC Berkeley & Berkeley Lab

Institute for the Early Universe
Ewha University, Korea

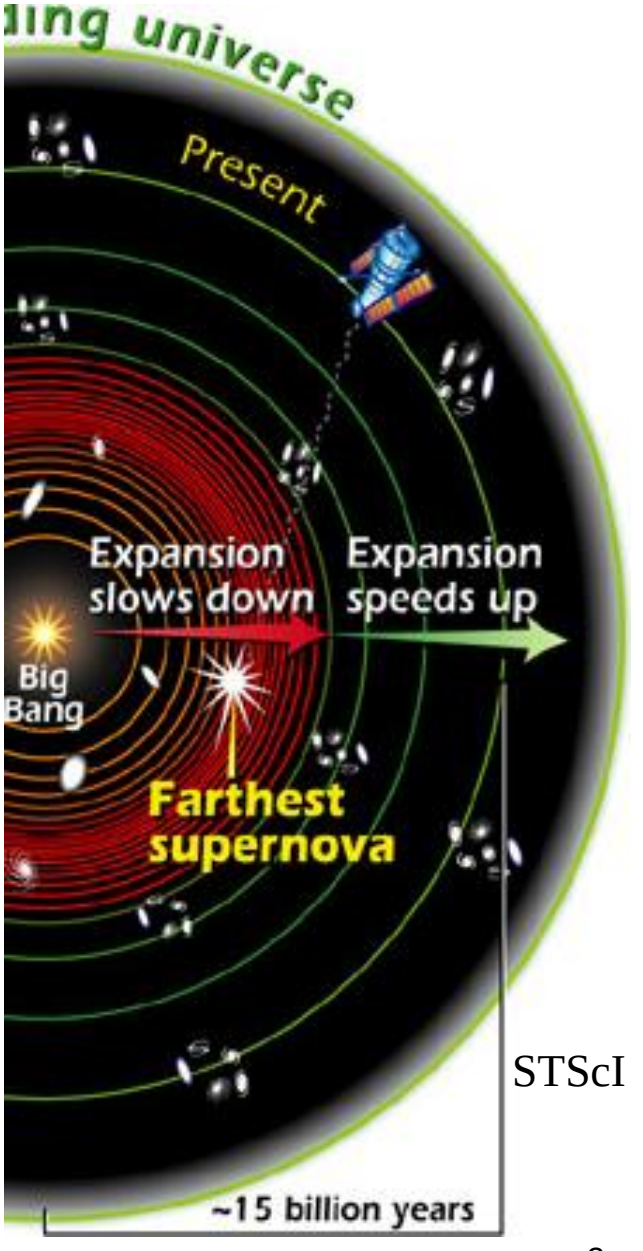
Describing Our Universe

STScI

95% of the universe is unknown!

Mapping Our History

The subtle slowing down and speeding up of the expansion, of distances with time: a(t), maps out cosmic history like tree rings map out the Earth's climate history.



STScI

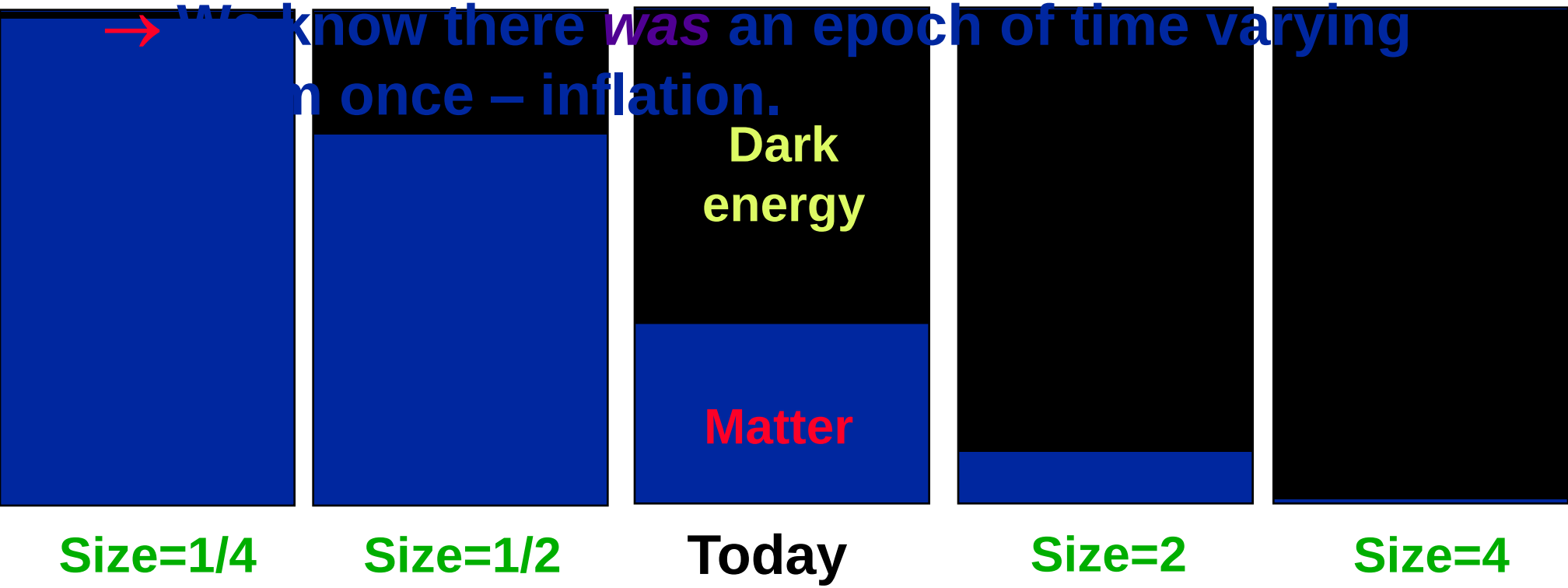
Cosmic Coincidence

Why not just settle for a cosmological constant Λ?

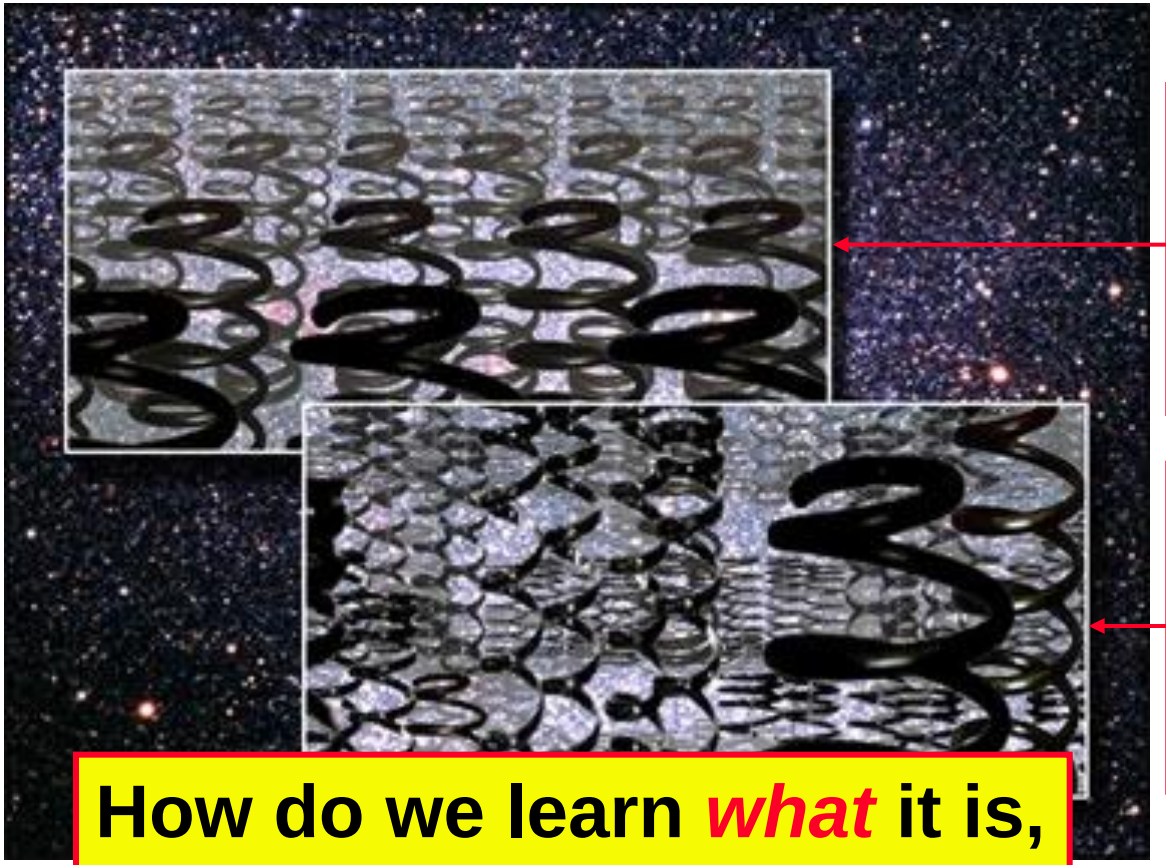
We cannot calculate the vacuum energy to within 10^{120}. For 90 years we have tried to understand why Λ is at least 10^{120} times smaller than we would expect – *and failed*.

→ 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 in once – inflation.



Nature of Acceleration



Is dark energy static? Einstein's cosmological constant Λ.

Is dark energy dynamic? A new, time- and space-varying field.

How do we learn *what* it is, not just *that* it is?

How much dark energy is there? Ω_{DE}

How springy/stretchy is it? $w=P/\rho$

On Beyond Λ!

"You'll be sort of surprised what there is to be found
Once you go beyond Λ and start poking around."
– Dr. Seuss, à la "On Beyond Zebra"

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?

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

Dark Energy as a Teenager

14 years after discovery of the acceleration of the universe, where are we?

From 60 Supernovae Ia at cosmic distances, we now have ~600 published distances, with better precision, better accuracy, out to z=1.75.

CMB plus external data (H_0) points to acceleration. (Didn't even have acoustic peak in 1998.)

BAO detected. Concordant with acceleration.

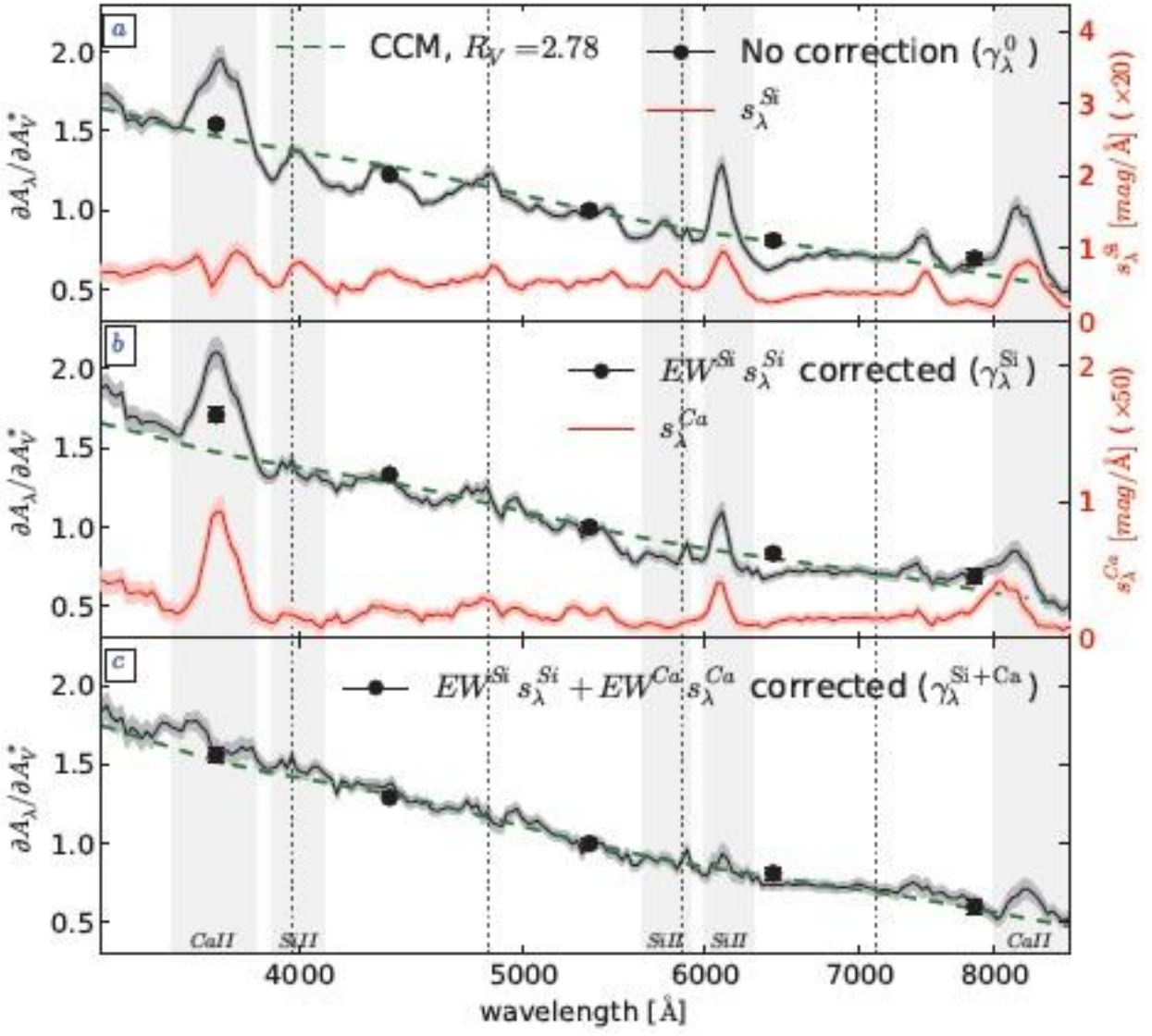
Weak lensing detected. Concordant with acceleration.

Cluster masses point to acceleration.

Strong concordance among data: Ω_{DE}~0.73, w~-1.

Improving Supernovae

EW of supernova spectral features can separate color variation and dust extinction.



Nearby Supernova Factory

400 SN Ia *with spectra*, z=0.03-0.08

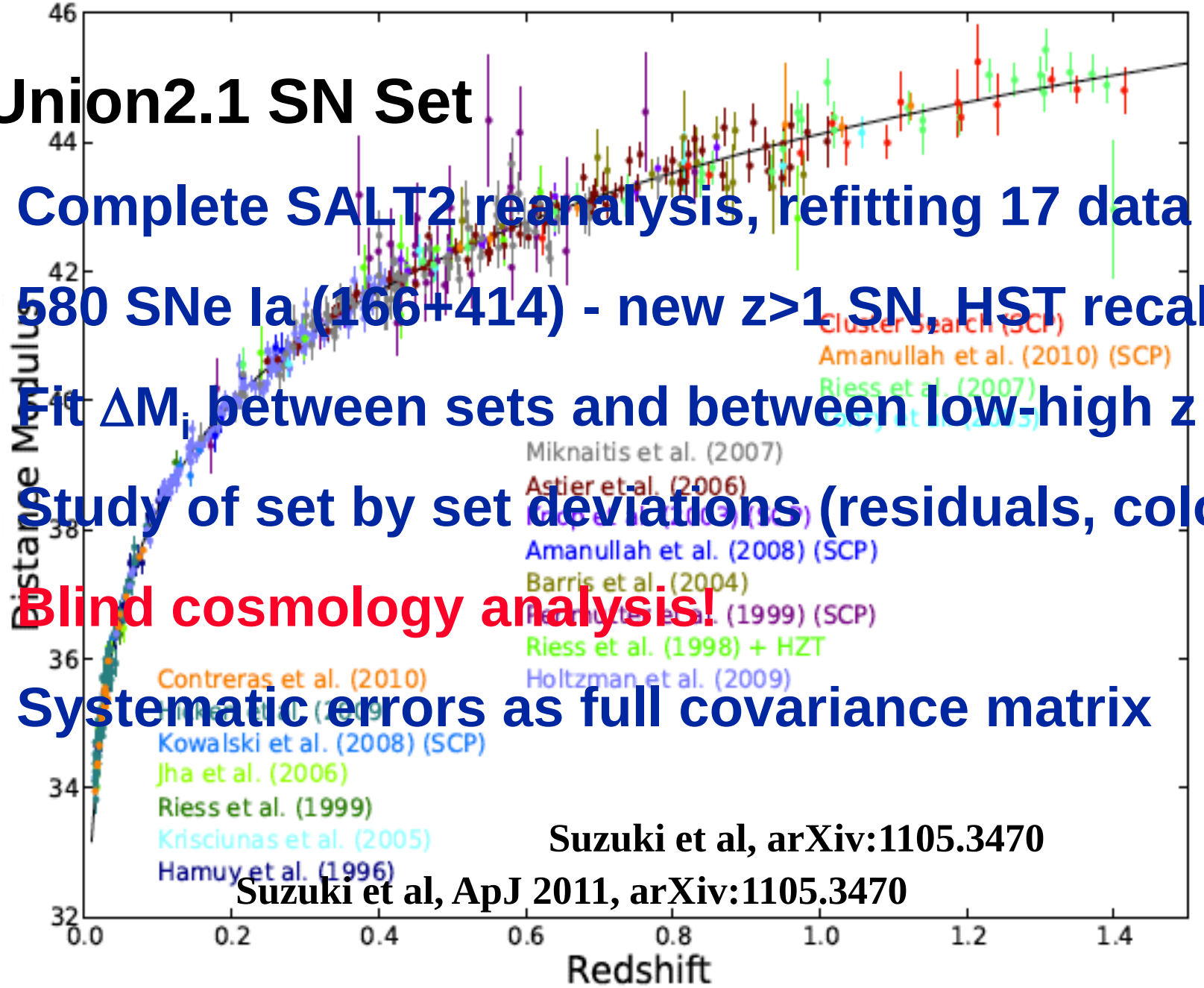
>3000 Ia spectra

Chotard+ 1103.5300

Latest Data

Union2.1 SN Set

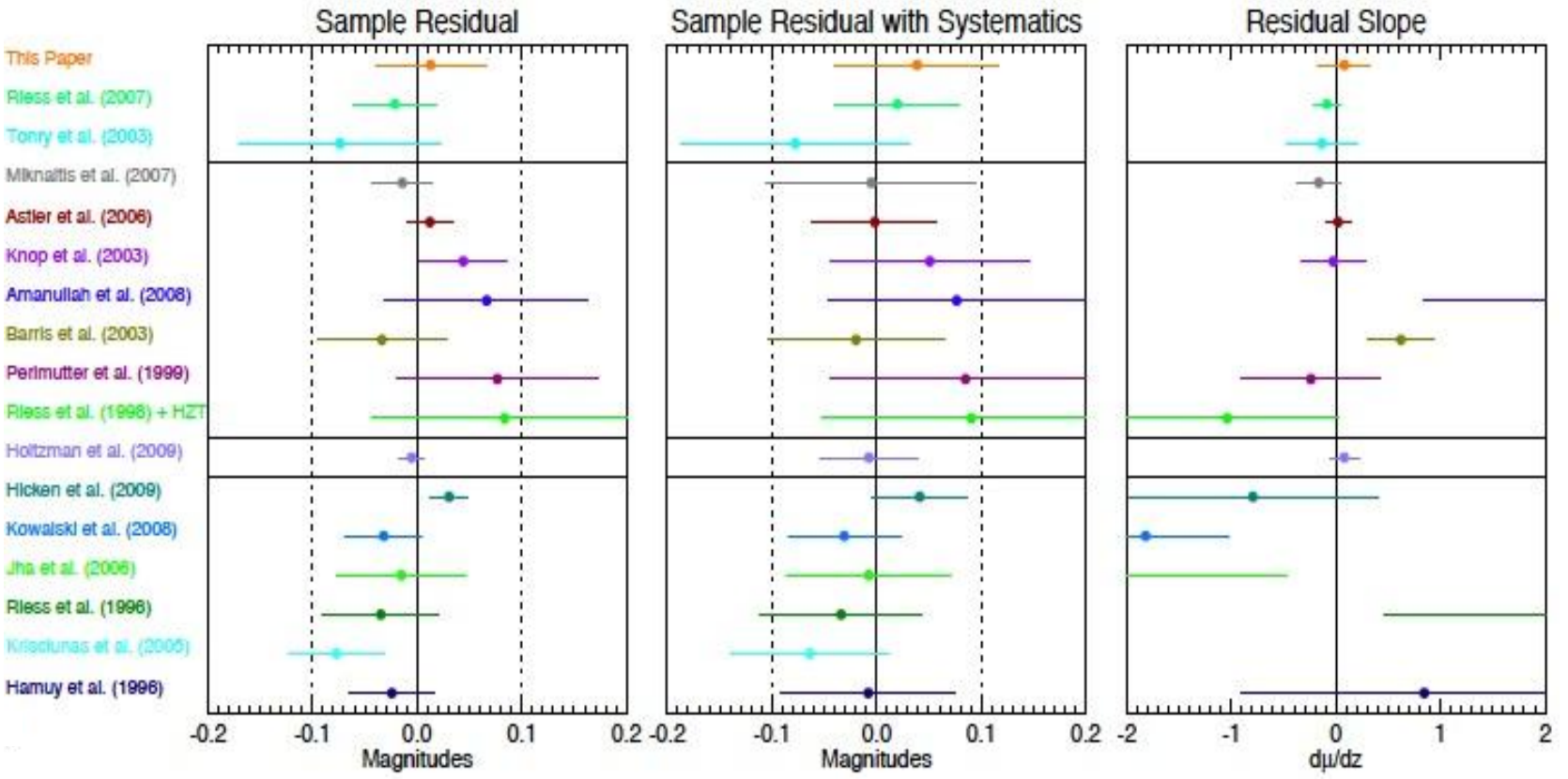
- Complete SALT2 reanalysis, refitting 17 data sets
- 580 SNe Ia (166+414) - new z>1 SN, HST recalib
- Fit ΔM_i between sets and between low-high z
- Study of set by set deviations (residuals, color)
- Blind cosmology analysis!
- Systematic errors as full covariance matrix



Suzuki et al, arXiv:1105.3470

Suzuki et al, ApJ 2011, arXiv:1105.3470

Tests for Systematics and Evolution

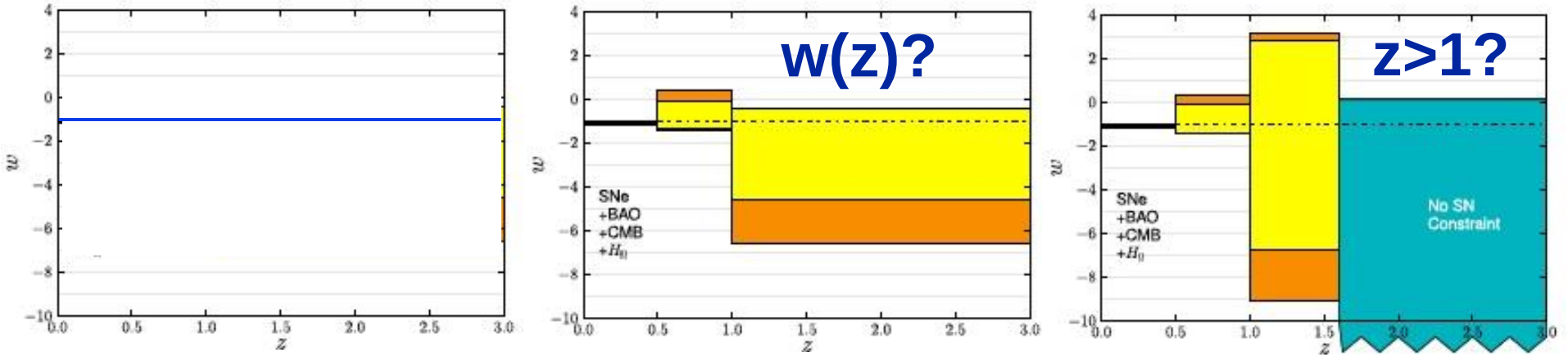


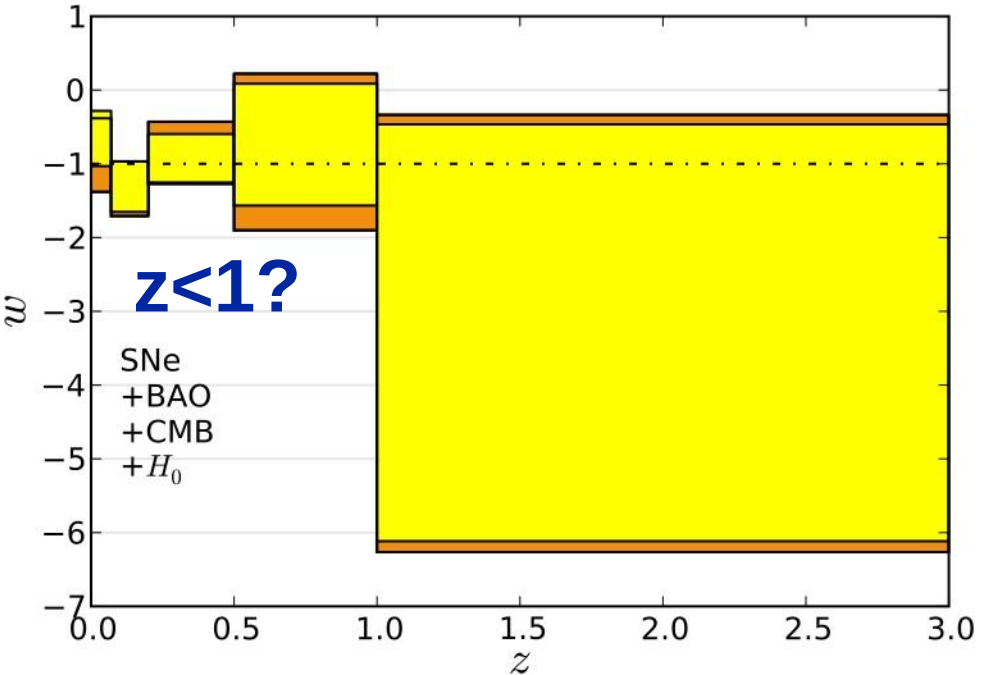
No significant deviations from mean of Hubble diagram, or (mostly) in residual slope.

No evolution seen in redshift or population tests.

Are We Done?

$$w = -1.013^{+0.068}_{-0.073}$$ **(stat+sys)**





There is a long way to go still to say we have measured dark energy!

Chasing Down Cosmic Acceleration

How can we measure dark energy in detail?

A partial, personal view of promising advances:

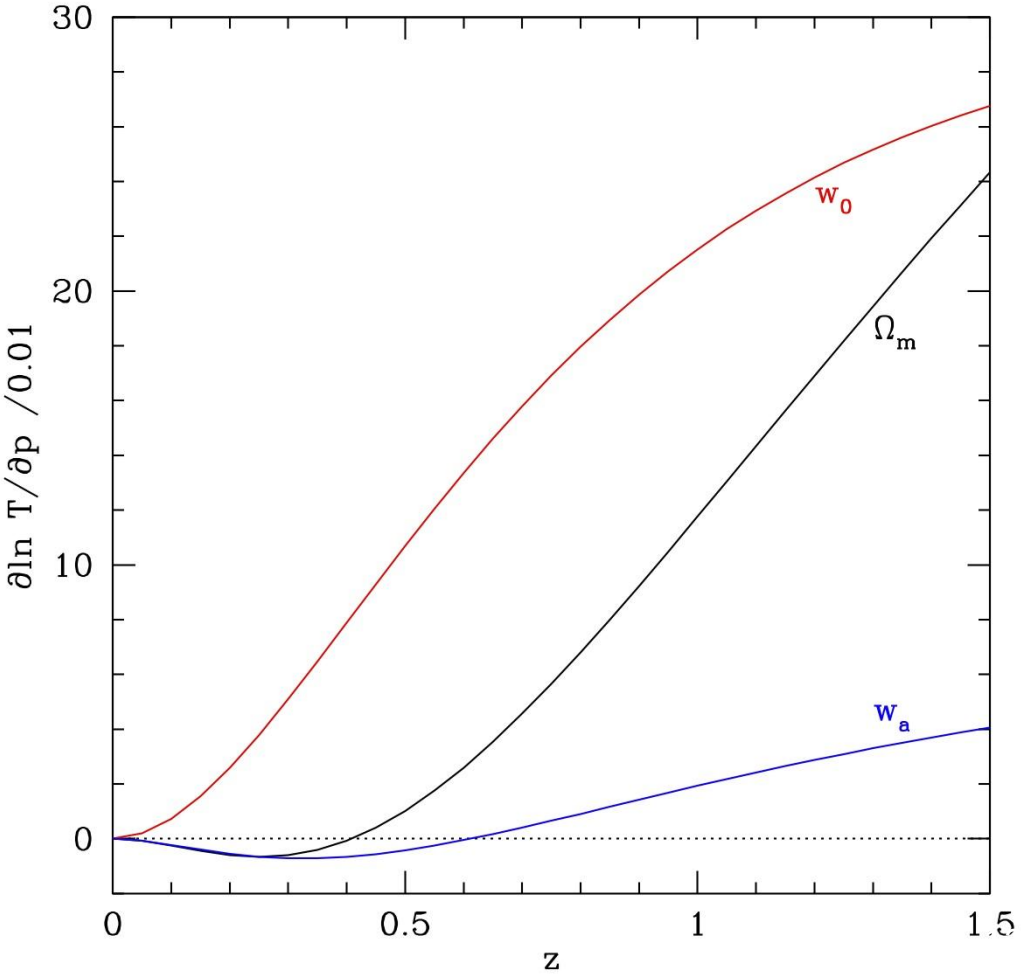
- **Strong lensing time delays**
- **Galaxy surveys**
- **Redshift space distortions**
- **Weak lensing**
- **CMB lensing**
- **Testing gravity**
- **Testing gravity and expansion simultaneously**

Lensing Time Delays

Strong lensing time delays involve distance *ratios*, which have different parameter dependences than solo distances.

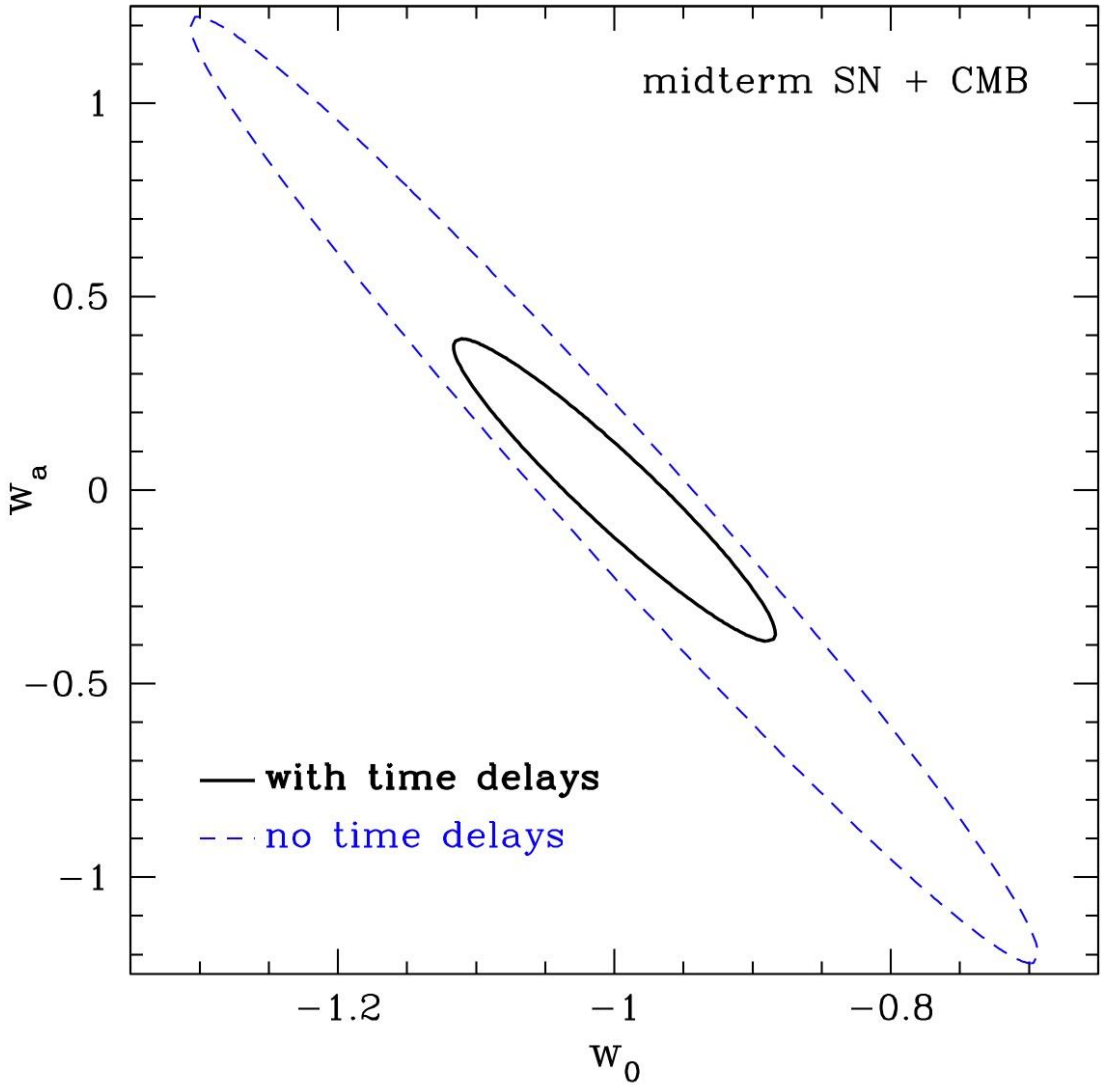
$$T \equiv \frac{r_l r_s}{r_{ls}}$$

Unusually sensitive to w_0, insensitive to Ω_m, and positively correlated w_0-w_a for z=0.1-0.6.



Time Delays + Supernovae

Lensing time delays give superb complementarity with SN distances plus CMB.



T to 1% for z=0.1, 0.2,… 0.6

SN to 0.02(1+z)mag for z=0.05, 0.15... 0.95

Factor 4.8 in area

Ω_m to 0.0044

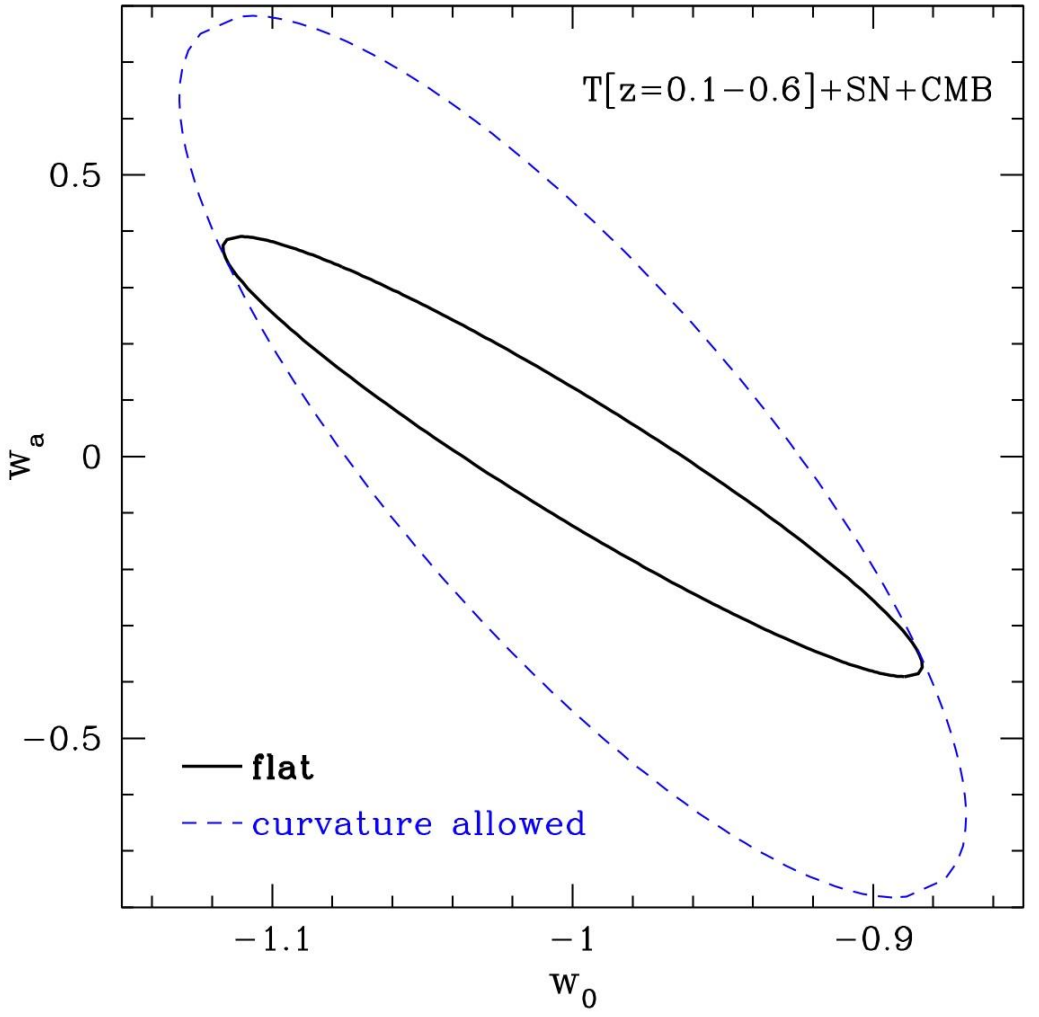
h to 0.7%

w_0 to 0.077

w_a to 0.26

Time Delays and Curvature

If fit for curvature, time delays reduce degeneracy by factor 5. Except for w_a, estimates degrade by <30%, and find Ω_k to 0.0063.



Time Delay Surveys

Best current time delays at 5% accuracy, 16 systems. To get to 1%, either improve systematics, increase sample by 1 OOM, or both.

Need 1) high resolution imaging for lens mapping and modeling, 2) high cadence imaging, 3) spectroscopy for redshift, lens velocity dispersion, 4) wide field of view for survey.

Synergy: KDUST (2.5m Antarctica) + DES. Overlapping southern fields. NIR/visible partnering. SN survey included. Only low redshift z<0.6 needed for lenses.

(Alternate approach through high statistics stacking rather than detailed modeling, e.g. Oguri & Marshall 2010, Coe & Moustakas 2009)

Higher Dimensional Data

Cosmological Revolution:

From 2D to 3D – CMB anisotropies to tomographic surveys of density/velocity field.

Data, Data, Data

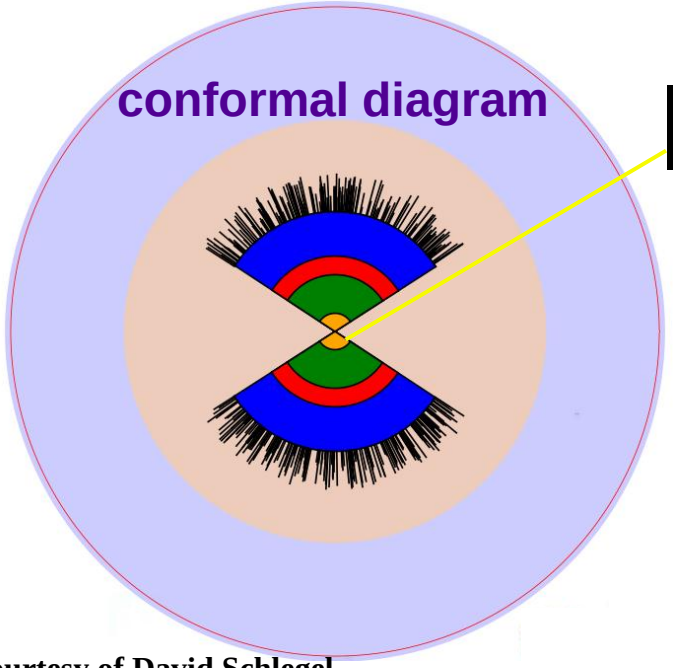
As wonderful as the CMB is, it is 2-dimensional.

The number of modes giving information is *l(l+1)* or ~10 million.

BOSS (SDSS III) will map 400,000 linear modes.

BigBOSS will map 15 million linear modes.

N. Padmanabhan



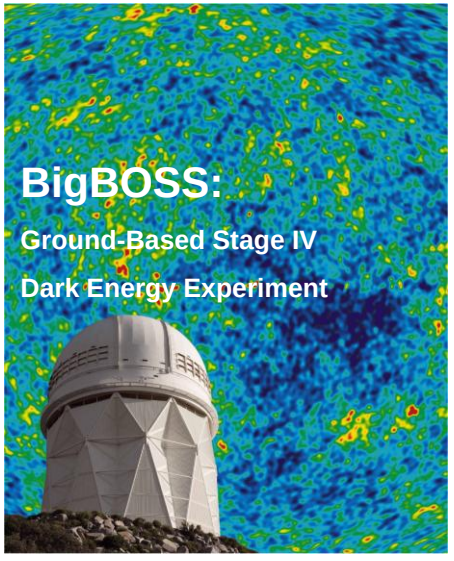
courtesy of David Schlegel

SDSS I, II, 2dF

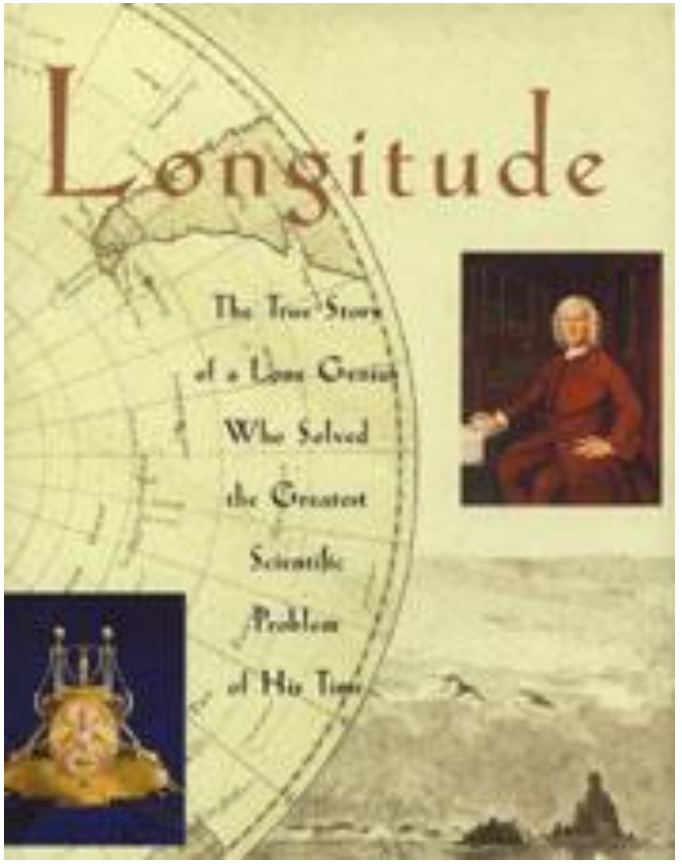
BOSS (SDSS III)

BigBOSS
18 million galaxies
z=0.2-1.5

600,000 QSOs
z=1.8-3



"Greatest Scientific Problem"

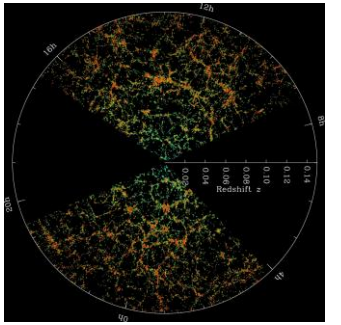


"When I'm playful I use the meridians of longitude and parallels of latitude for a seine, drag the Atlantic Ocean for whales."

– Mark Twain, *Life on the Mississippi*

Cosmic Structure

Galaxy 3D distribution or power spectrum contains information on:



- **Growth - evolving amplitude**
- **Matter/radiation density, H - peak turnover**
- **Distances - baryon acoustic oscillations**
- **Growth rate - redshift space distortions**
- **Neutrino mass, non-Gaussianity, gravity, etc.**

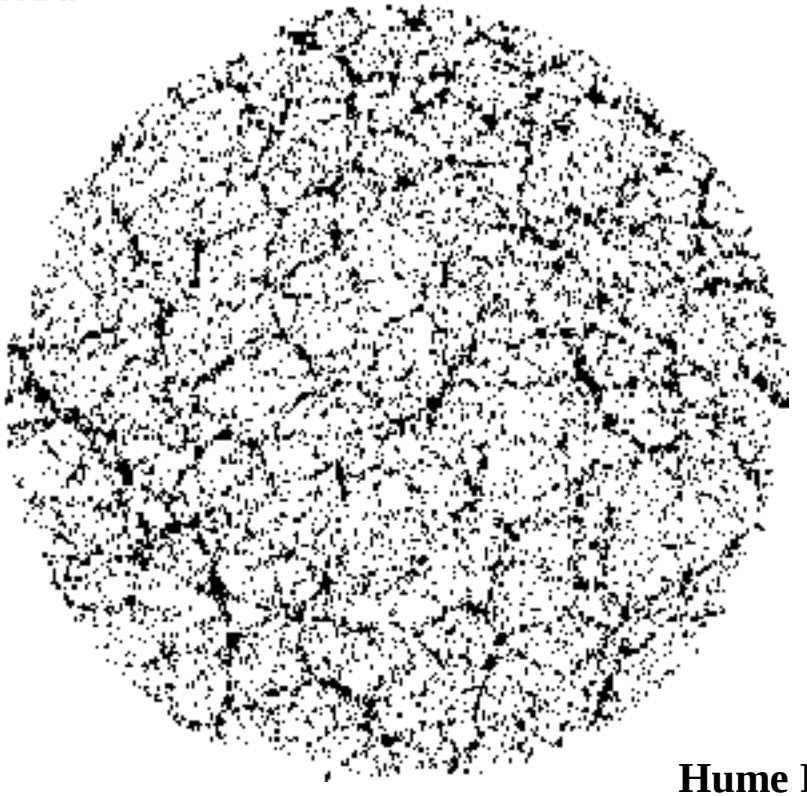
BigBOSS: initial approval for Kitt Peak/NOAO 4m.

arXiv:1106.1706 ; http://bigboss.lbl.gov

Redshift Space Distortions

Redshift space distortions (RSD) map velocity field along line of sight. Gets at growth rate f, one less integral than growth factor (like H vs d).

$\Omega_m = 0.00$



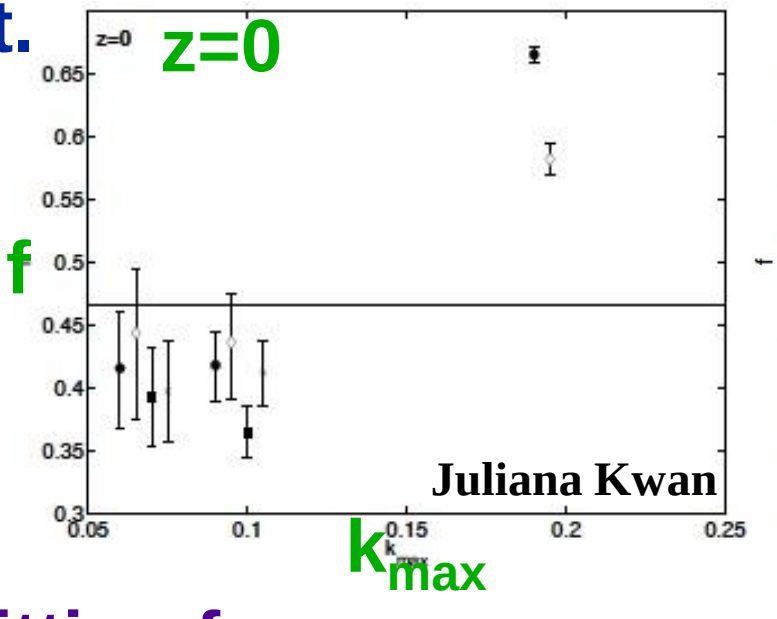
$$f = \frac{d \ln D}{d \ln a} \sim \Omega_m(a)^\gamma$$

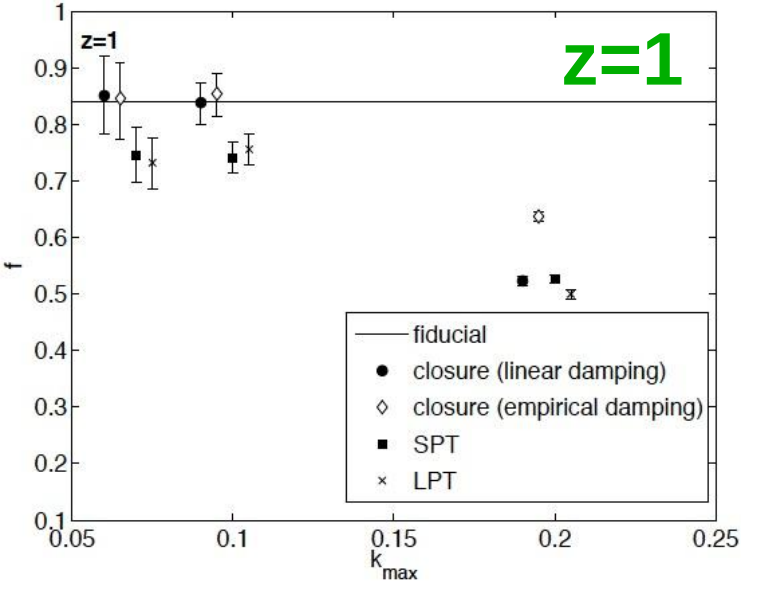
gravitational growth index γ

Hume Feldman

Redshift Space Distortions

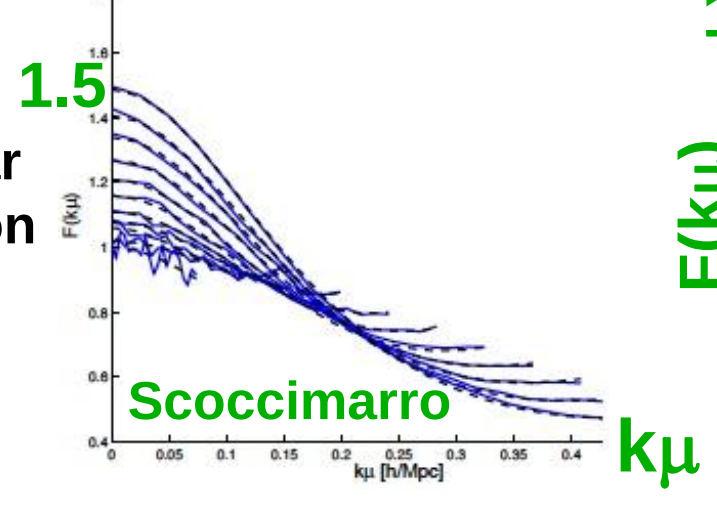
Powerful probe, even of gravity, but linear theory insufficient.

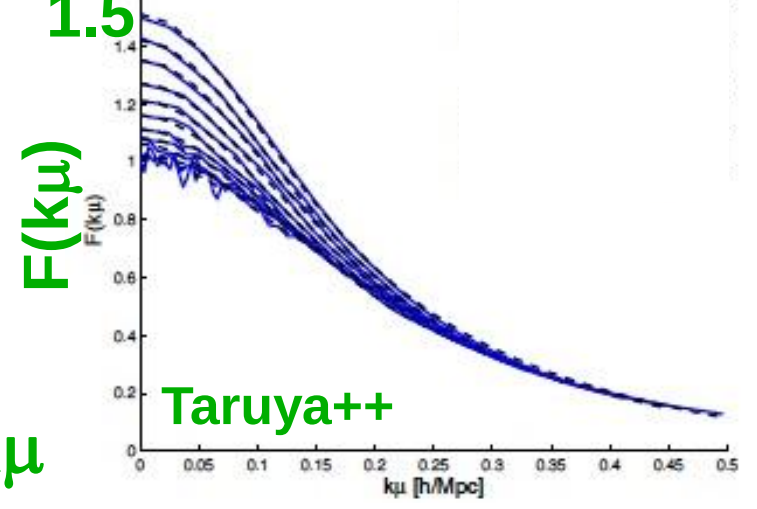




Empirical fitting form Kwan, Lewis Linder 2011 **highly accurate to higher kμ.**

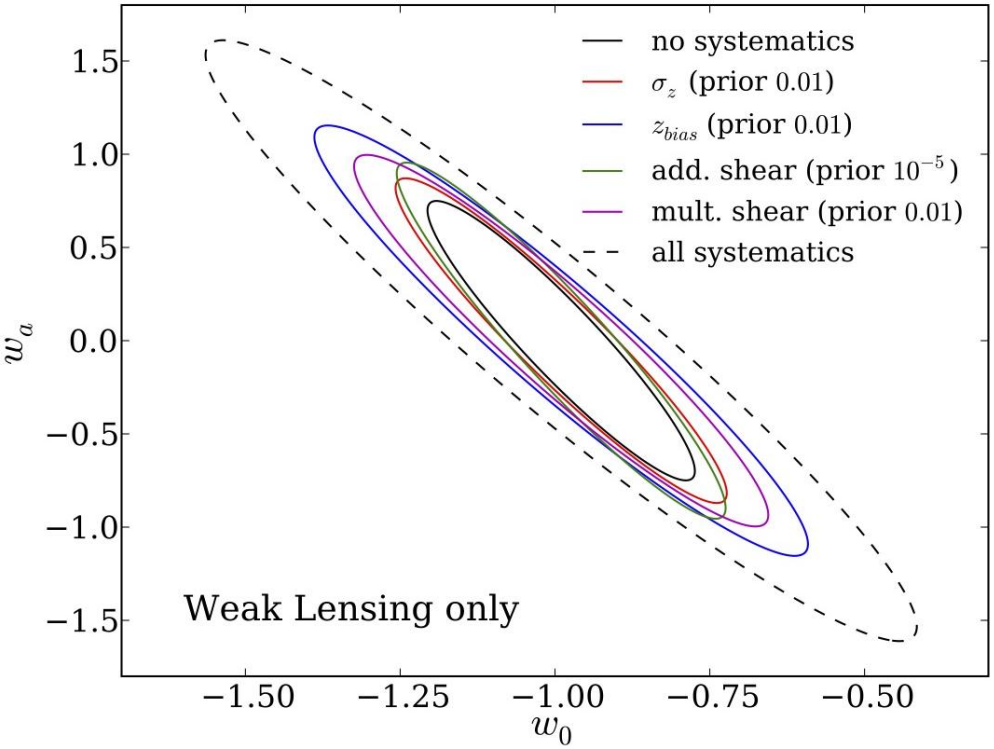
Nonlinear correction factor





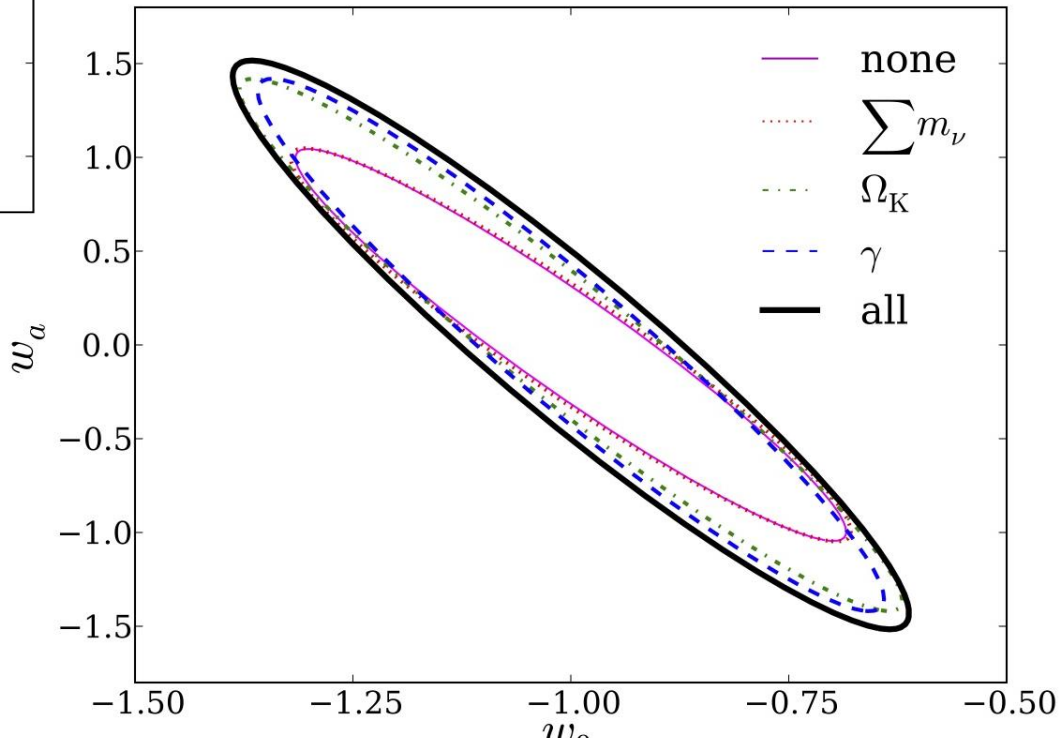
also see Okumura, Seljak, McDonald, Desjacques 2011

Weak Lensing



Data systematics

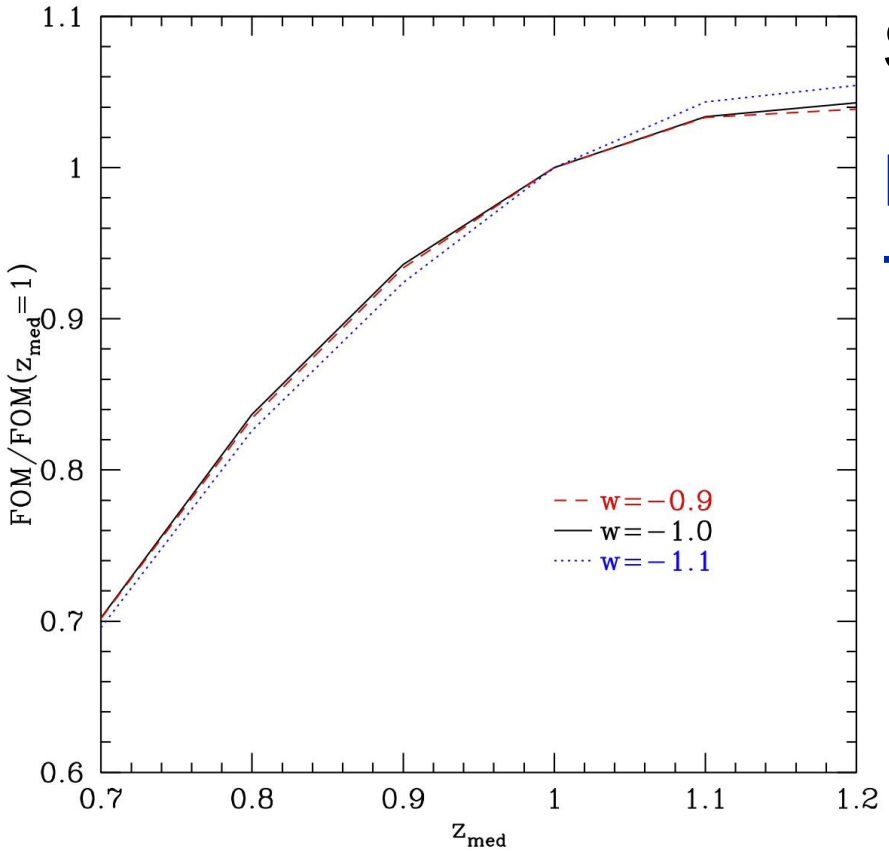
Theory systematics



Berkeley Weak Lensing code (soon public)

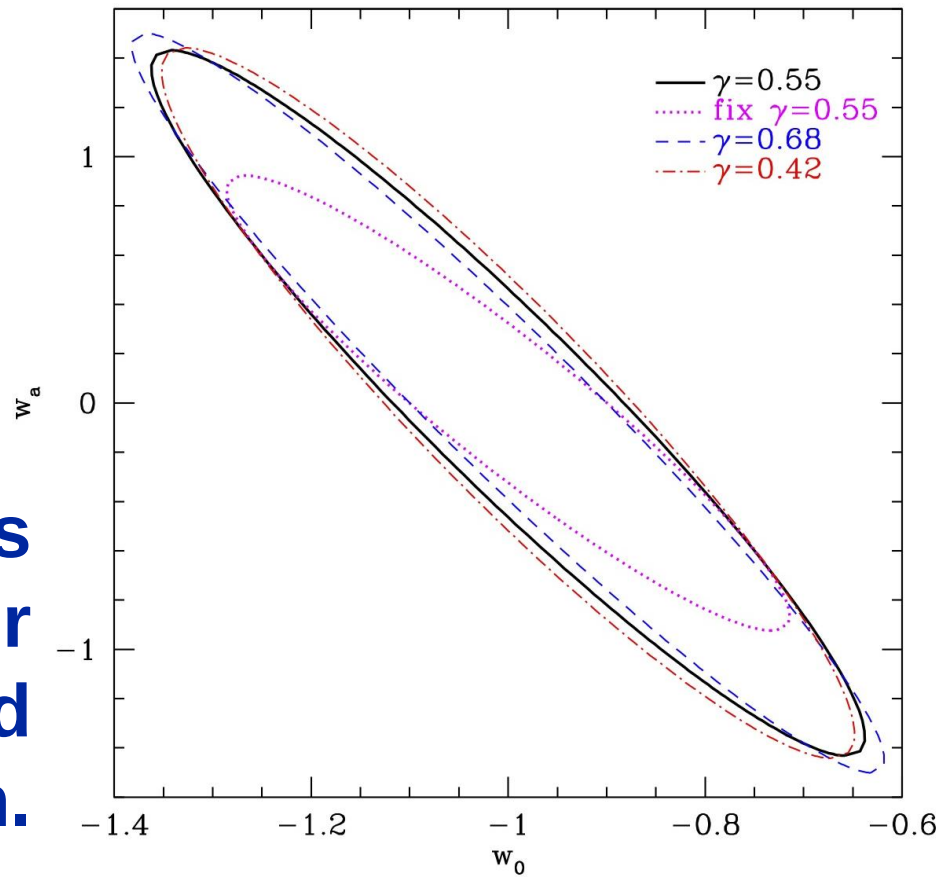
Das, de Putter, Linder, Nakajima 1102.5090

Weak Lensing



Survey science study:

Deep surveys z_{med}~1 are good for any fiducial cosmology

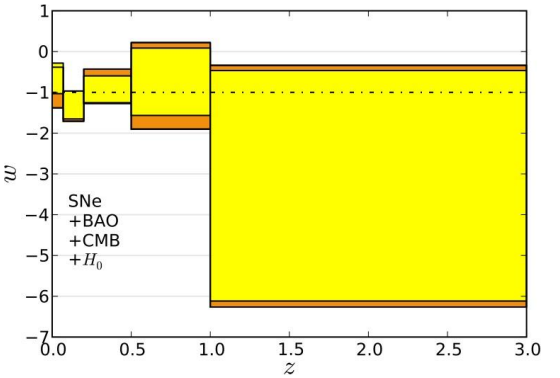


Non-GR growth index γ gives bias Δw_a~8Δγ but can fit for expansion with good distinction from growth.

Future of Dark Energy

Today we know the dark energy equation of state, *constant* w to ~10%.

Future experiments look bright for dark physics. We must test for varying w (no real theory predicts constant w).



If w(a) ~ -1, is Λ the conclusion?

No! Many, diverse physics theories give w(a)~-1.

Approaching Λ: Microphysics, High Energy Physics, Gravity.

Λ from Microphysics

Barotropic fluids are defined through an explicit equation of state $P=p(\rho)$.

The dynamics is related to microphysics

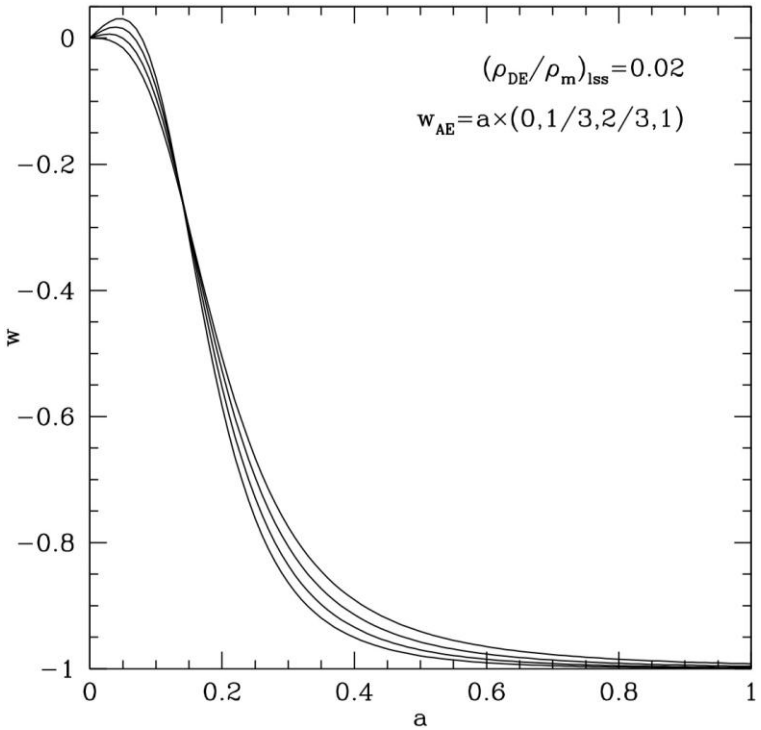
$$w' = -3(1+w)(c_s^2-w)$$

Since this has an attractor solution at w=-1, it motivates w~-1 today.

Rapid evolution (w decreases from -0.1 to -0.9 in a factor <4 of expansion) - no coincidence problem!

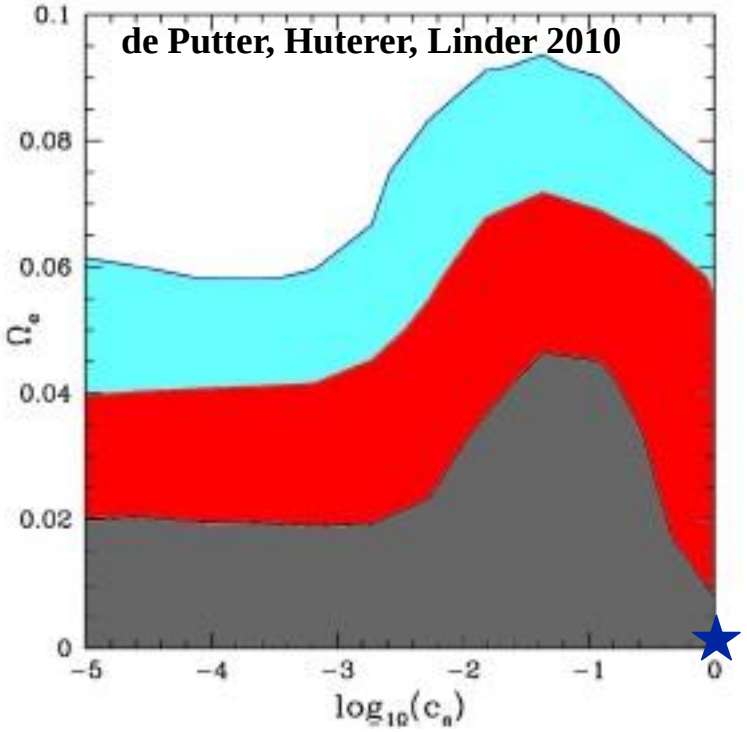
Can also acts as dark radiation and change N_{eff}.

Linder & Scherrer 2009

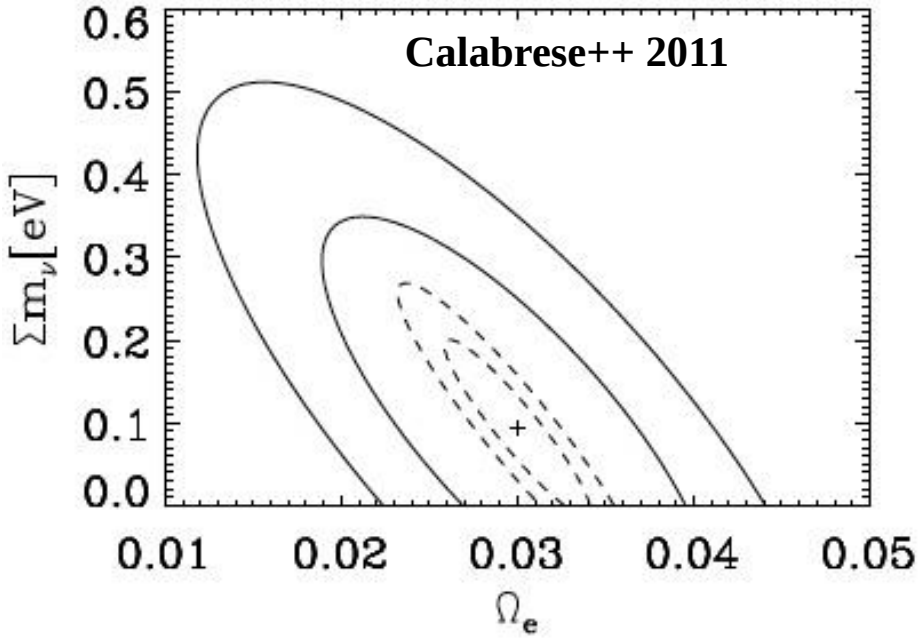


The Speed of Dark

Current constraints on c_s using CMB (WMAP5), CMB × gal (2MASS,SDSS,NVSS), gal (SDSS).



Future constraints from Planck or CMBpol

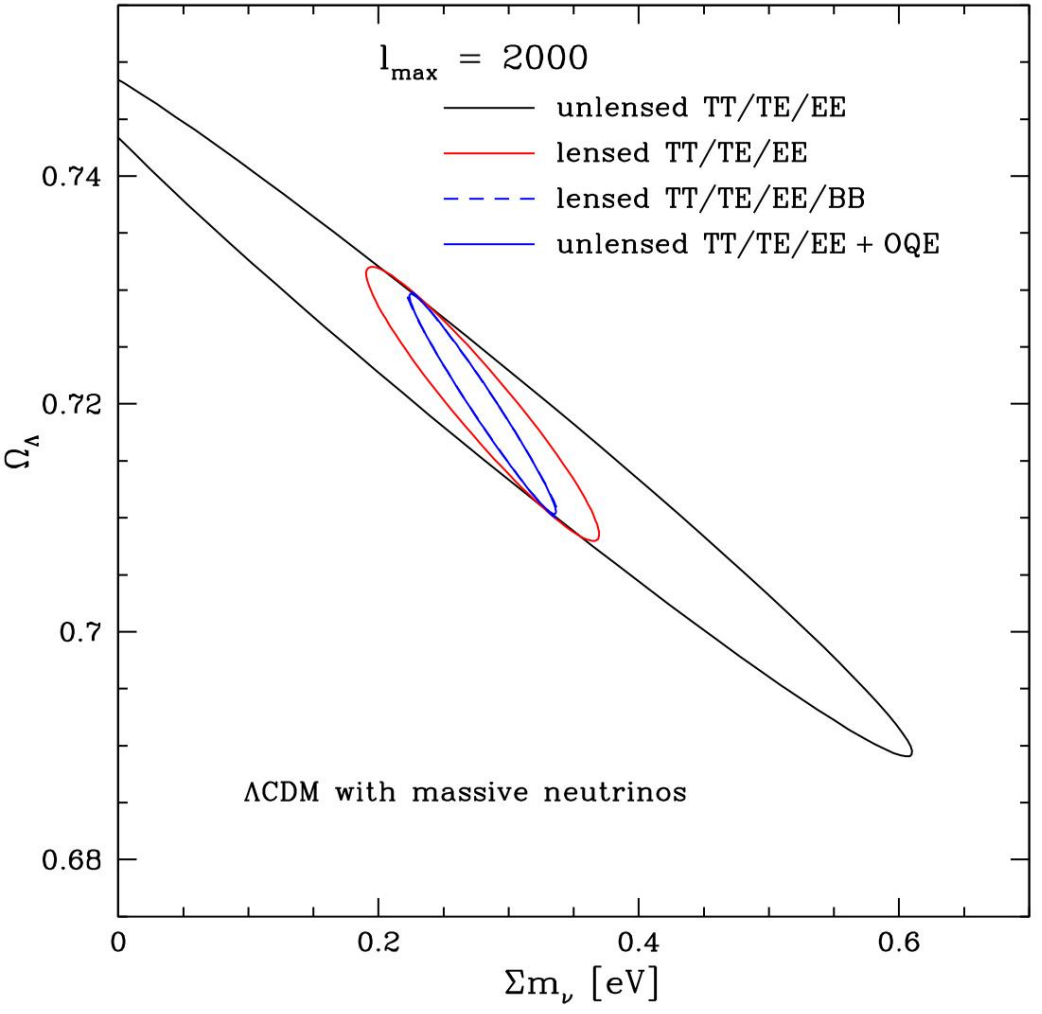


Best fit Ω_e=0.02, c_s=0.04, w_0=-0.95 but consistent with Λ within 68% cl.

"Early, Cold, or Stressed DE"
cf. Generalized DE
Hu 1998

CMB Lensing

CMB as a source pattern for weak lensing. Probes z~1-5 effects, e.g. neutrino masses and early dark energy.



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

de Putter, Zahn, Linder 2009

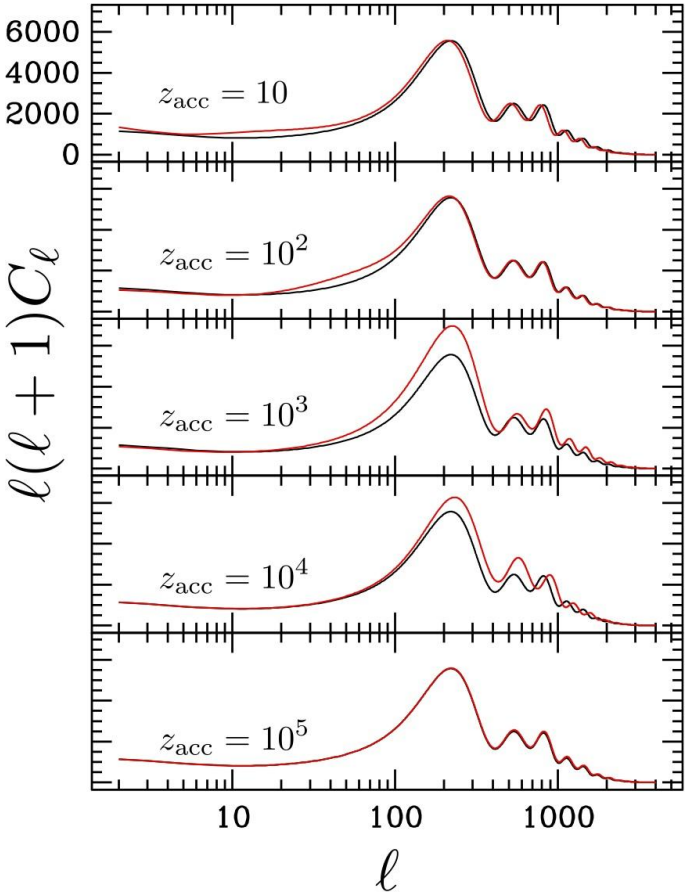
ACT gets 3.2σ for Λ from CMB lensing.

Sherwin+ 1105.0419

CMB Probes of Acceleration

How well do we really know the standard picture of radiation domination → matter domination → dark energy domination?Maybe acceleration is occasional. (Solve coincidence)

Effect of 0.1 e-fold of acceleration



Linder & Smith 2010

Post-recombination, peaks → left and adds ISW.
Pre-recombination, peaks → right and adds SW.

Current acceleration unique within last factor 100,000 of cosmic expansion!

Testing Gravity

Test gravity in model independent way.

Gravity and growth: $\nabla^2\phi = 4\pi G\, a^2\, \delta\rho$

Gravity and acceleration: $-\nabla\psi = \ddot{x}$

Are ϕ and ψ the same? (yes, in GR)

Use relativistic / nonrelativistic geodesic parameters:

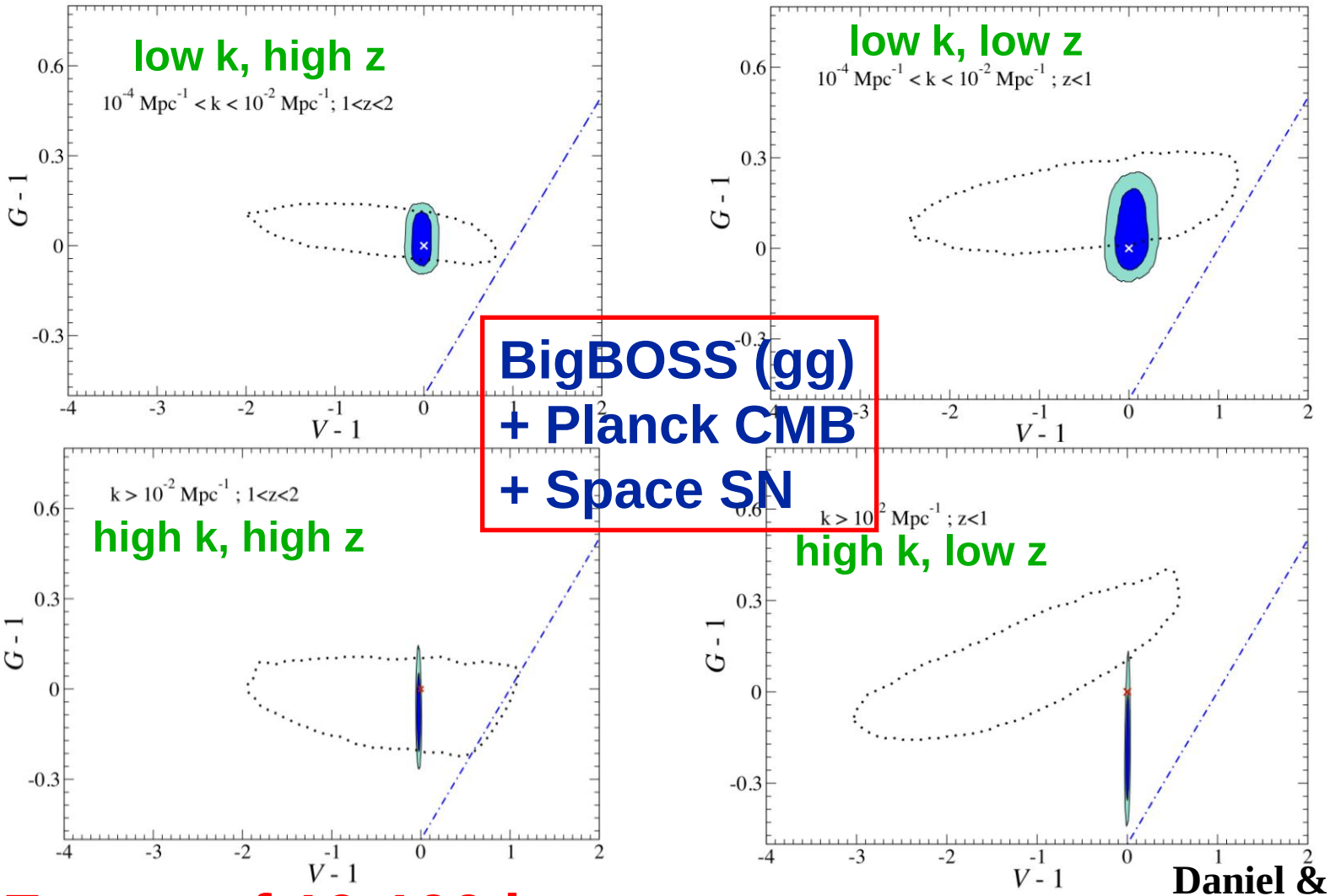
$$\nabla^2(\phi+\psi) = 8\pi G\, a^2\, \delta\rho \times \mathcal{G}$$
$$\nabla^2\psi = 4\pi G\, a^2\, \delta\rho \times \mathcal{V}$$

$\mathcal{G}$ relates the metric to the density (Poisson+ eq); central to ISW and lensing.

$\mathcal{V}$ relates the metric to the motion (velocity/growth eq); central to growth (γ closely related).

Future Data Leverage

Model independent "2 x 2 x 2 gravity"



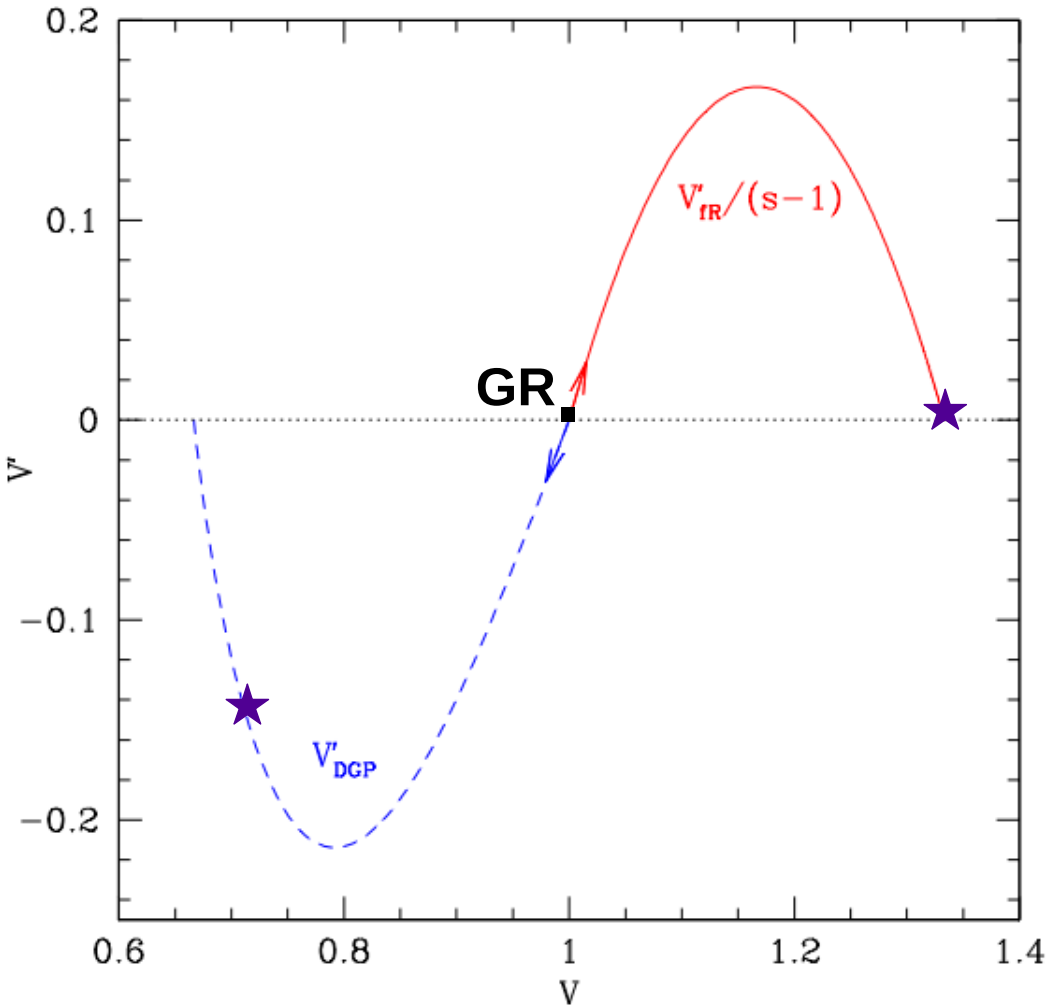
Daniel & Linder 2010

Factor of 10-100 improvement; **5-**

10% test of 8 parameters of model-independent gravity.

Gravity Requirement

Look at $\mathcal{V}$-$\mathcal{V}'$ phase space dynamics, just like for w-w′ of dark energy. Today, $\Delta\mathcal{V}$~±0.3 and have gravity requirement: 3σ measure requires $\sigma(\mathcal{V})$~0.1.

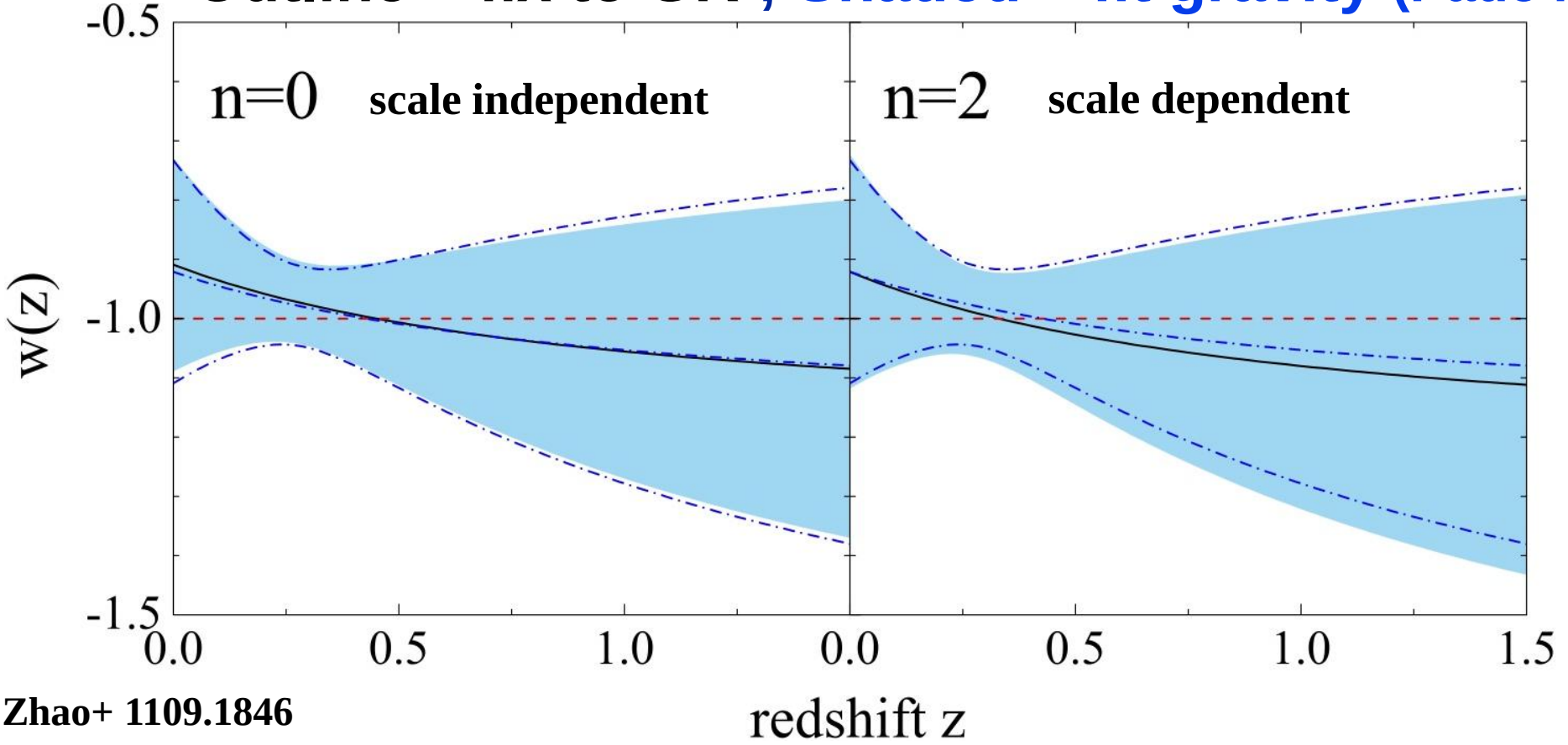


Linder 1103.0282

Expansion and Gravity

Importantly, we can fit gravity and expansion simultaneously. For current data there is little degradation. Expansion fit unaffected by gravity fit.

Outline – fix to GR ; Shaded – fit gravity (Padé k,z)



Zhao+ 1109.1846

Summary

Exciting new data from SN, CMB, LSS.

BigBOSS can give 3D map to z<1.5 from ground.

Approaching Λ is very natural from a wide variety of physics - microphysics (barotropic), high energy physics (DBI string theory), gravity (f(R)) - and does *not* default to Λ.

Deviations from Λ testable with variety of probes.

Absolute requirement on testing gravity – 10% on γ.

Expansion history can be tested to z~10^5. Current acceleration appears unique!

Institute for the Early Universe

"World Class University" program in Seoul, Korea.
Berkeley (Linder, Seljak, Smoot) + Ewha University.