Testing Dark Energy and Gravity

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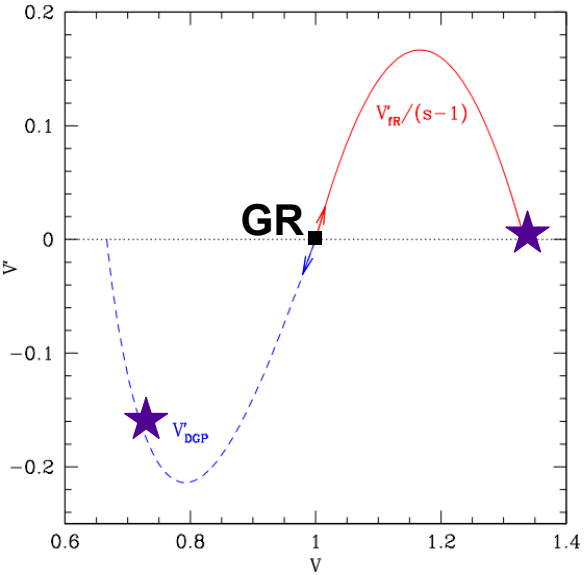
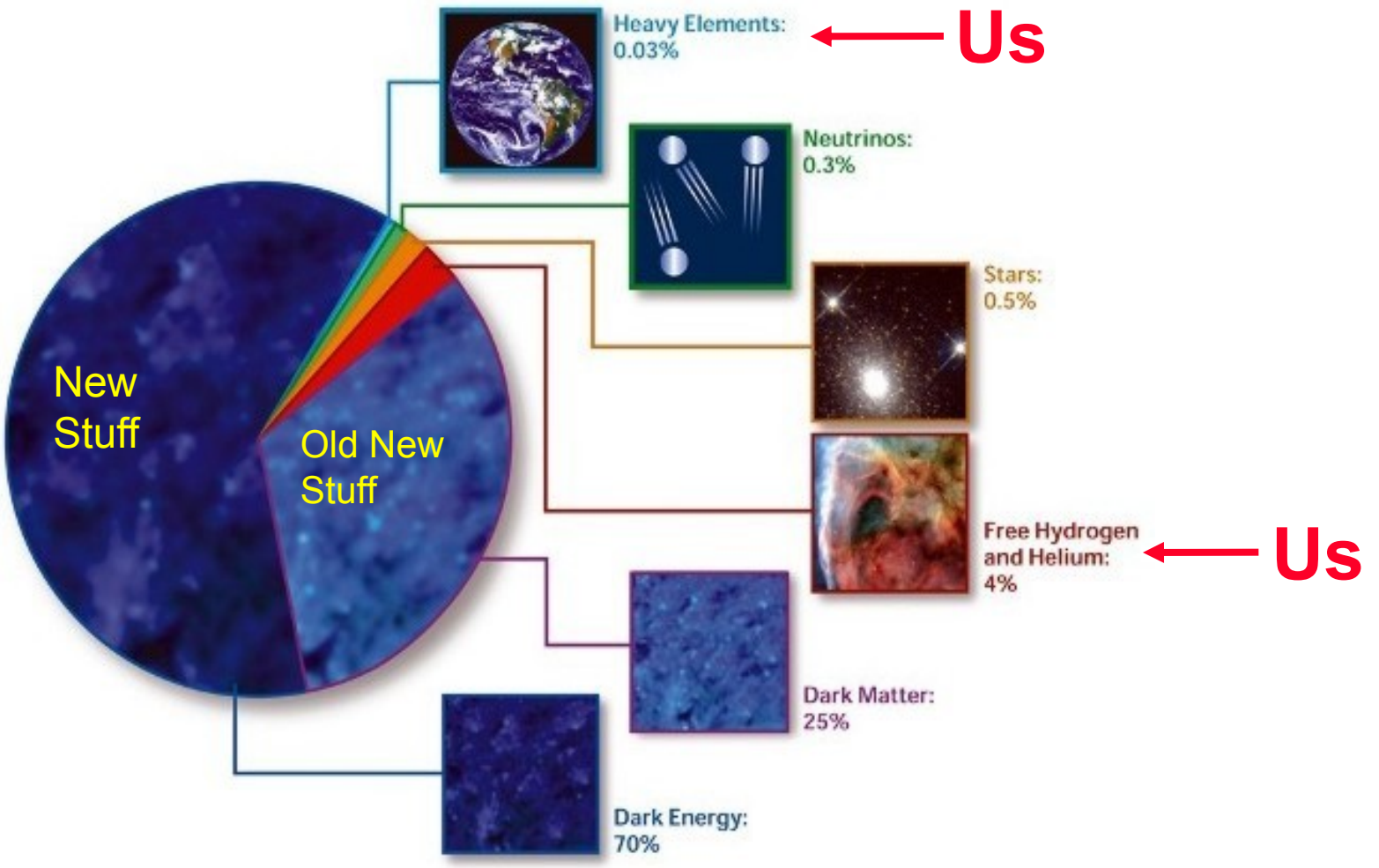


Describing Our Universe



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 V*, act IV**

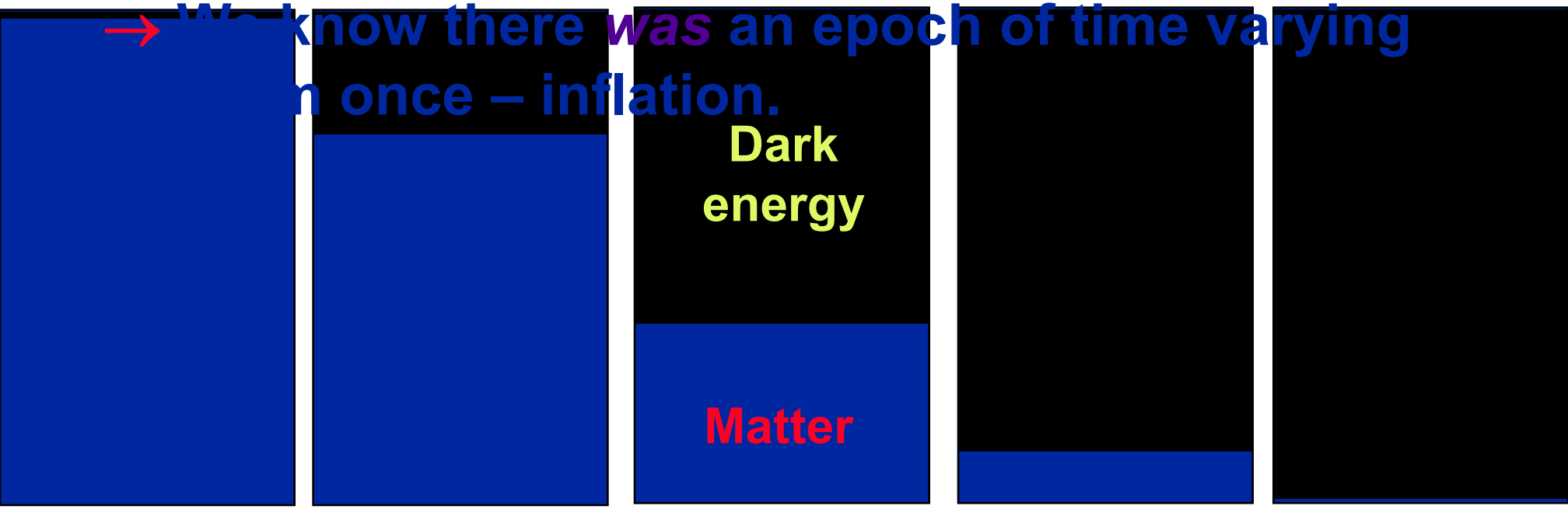
Cosmic Coincidence

Why not just settle for a cosmological constant Λ?

We cannot calculate the vacuum energy to within 10^{120} or 90 orders of magnitude. Think of the energy in Λ as the level of the sea. At most times in history, land is either drowned or dry.

→ But it gets worse: The kind of dark energy we see is at least 10^{120} times smaller than we would expect – *and fine-tuned*.

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



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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

13 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 (*if* asystematic) ~1.5σ for acceleration.

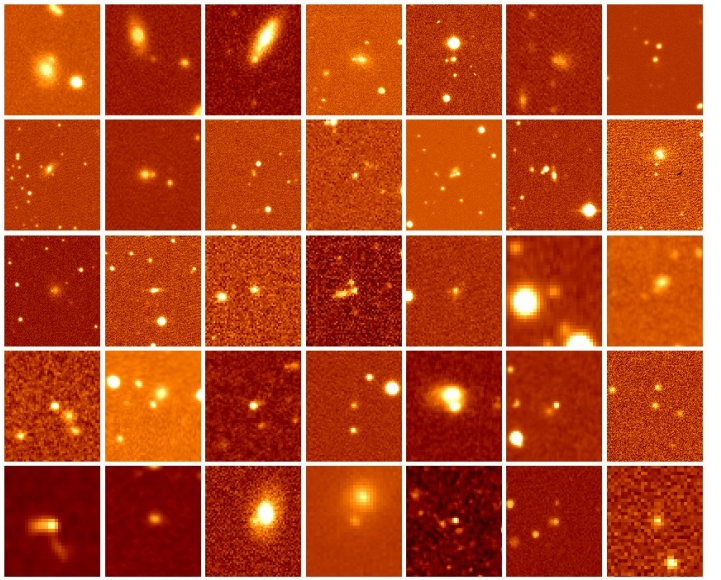
Strong concordance among data: Ω_{DE}~0.73, w~-1.

Understanding Supernovae

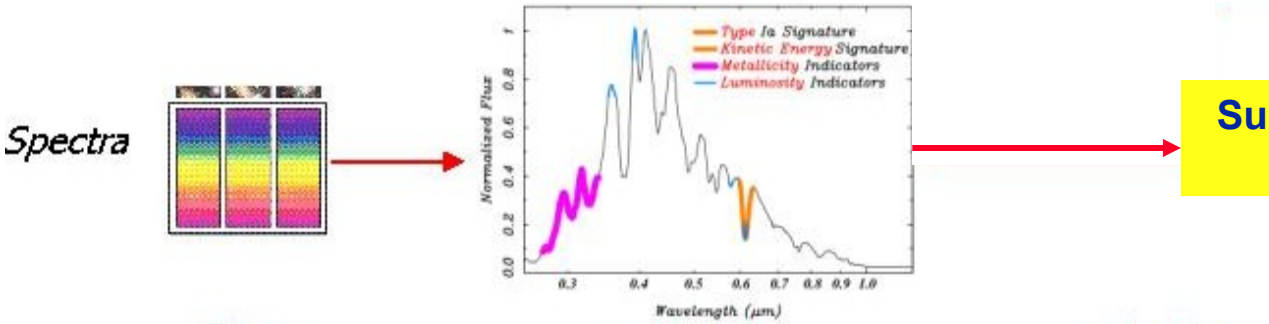
Nearby Supernova Factory

400 SN Ia *with spectra*, z=0.03-0.08
>3000 spectra of SN Ia

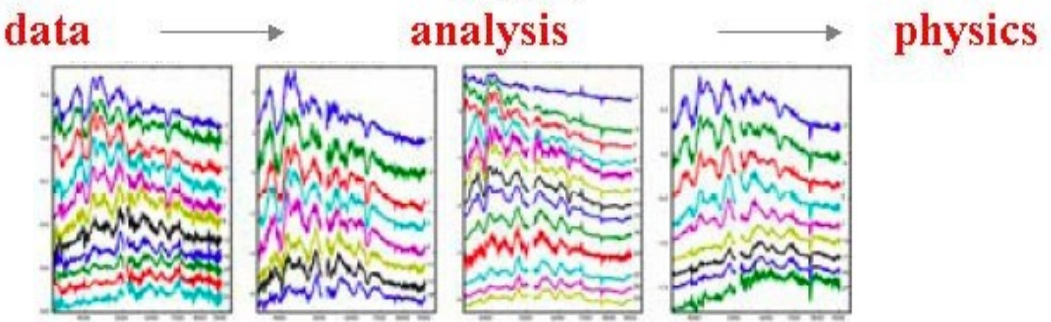
Cleanly understood astrophysics leads to cosmology (and astrophysics!)



G. Aldering (LBL)

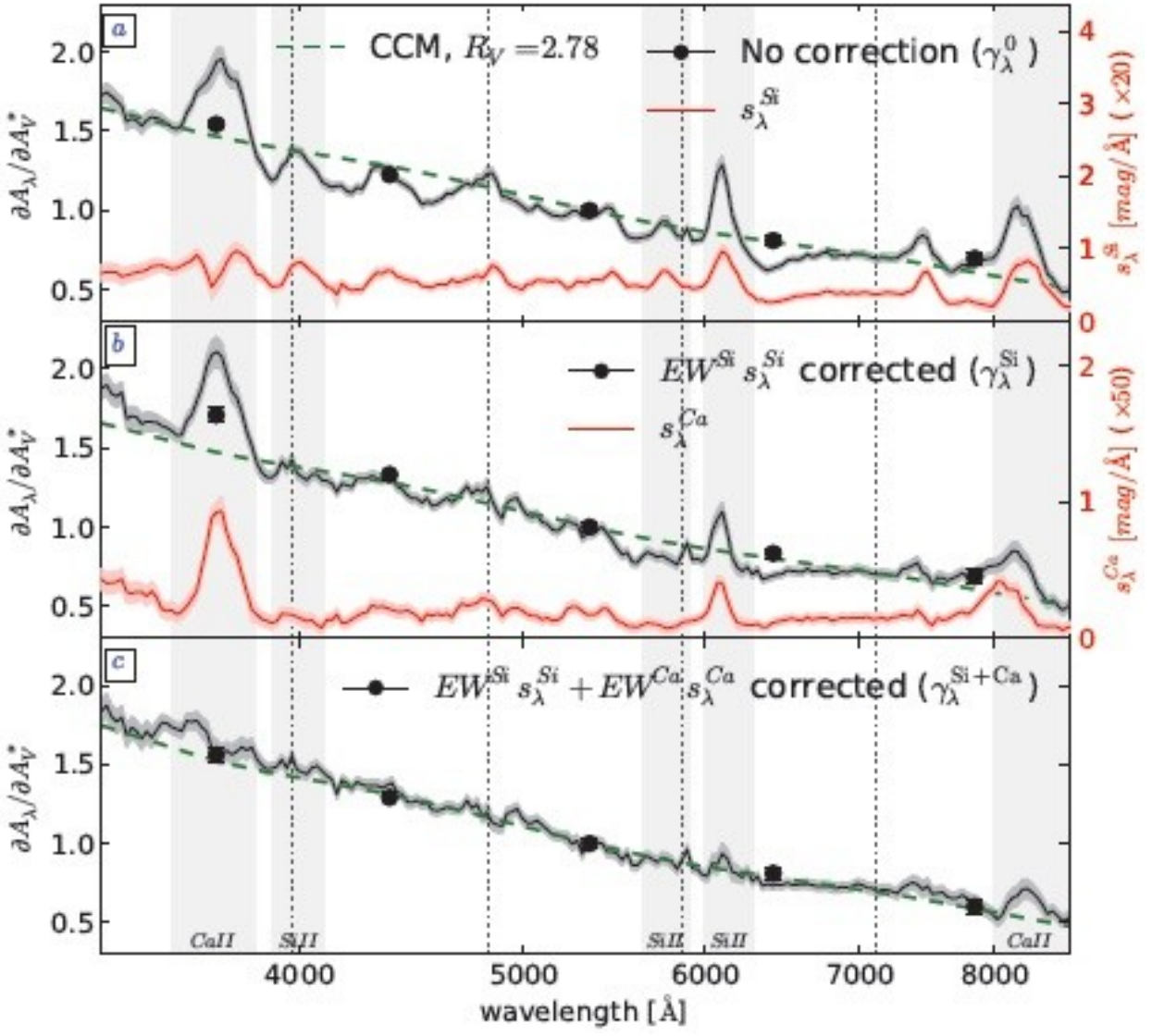


Supernova Properties
Astrophysics



Improving Supernovae

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

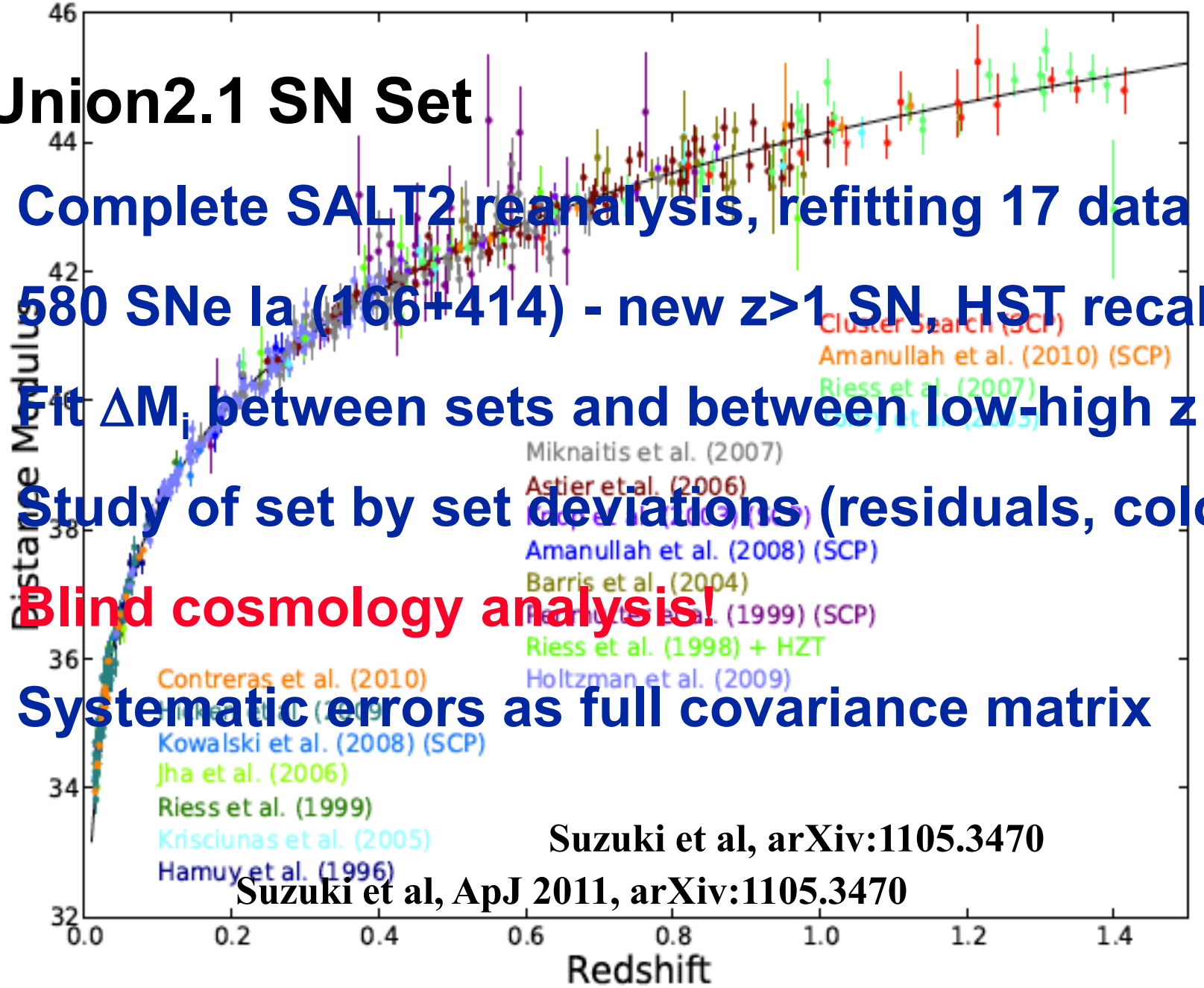


Chotard++ 1103.5300
A&A Letters 2011

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

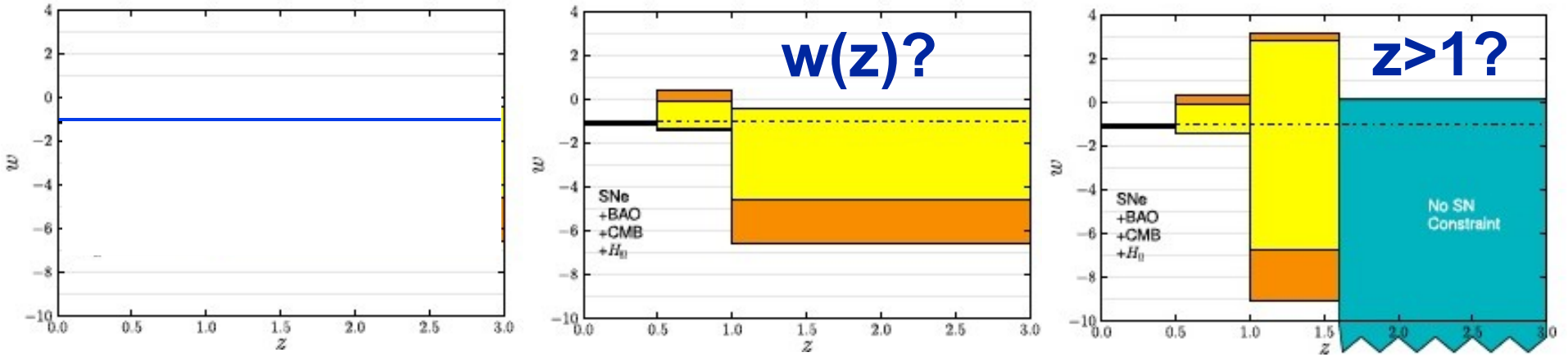


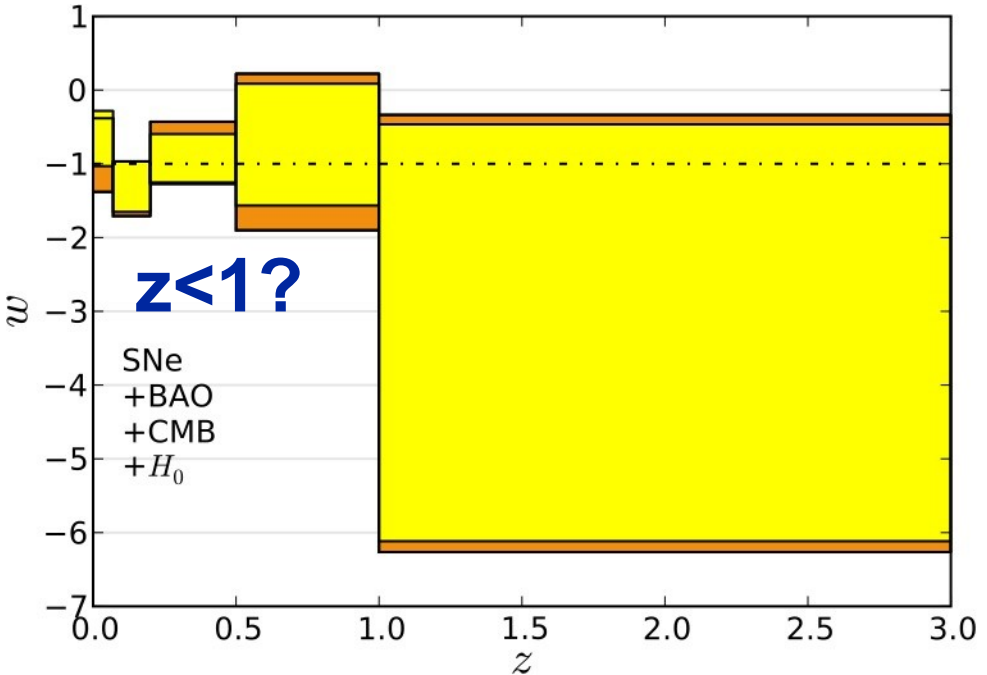
Suzuki et al, arXiv:1105.3470

Suzuki et al, ApJ 2011, arXiv:1105.3470

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!

Dark Energy + 13

13 years after today, where will we be?

CMB: Planck data, ground based polarization and CMB lensing

BAO: BOSS (on sky), WiggleZ, SuMIRe, HETDEX… Full power spectrum (redshift space distortions)

Clusters: SZ Effects - ACT, SPT

Supernovae: *smarter*, not just more

Multiprobe: DES, KDUST? (Dome A), GSMT?

Euclid? LSST? WFIRST? (EuFIRST, USlater?) Stage IV from the ground – BigBOSS?

Higher Dimensional Data

Cosmological Revolution:

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

Data, Data, Data

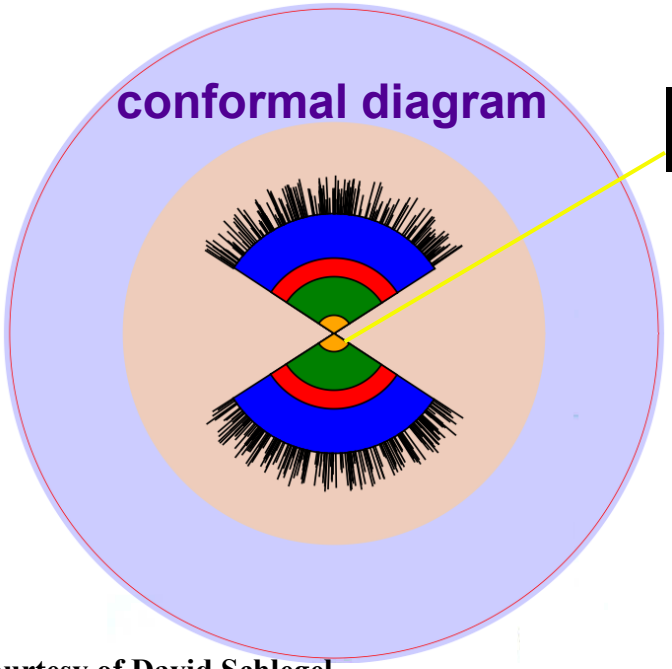
As wonderful as the CMB is, it is 2-dimensional.

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



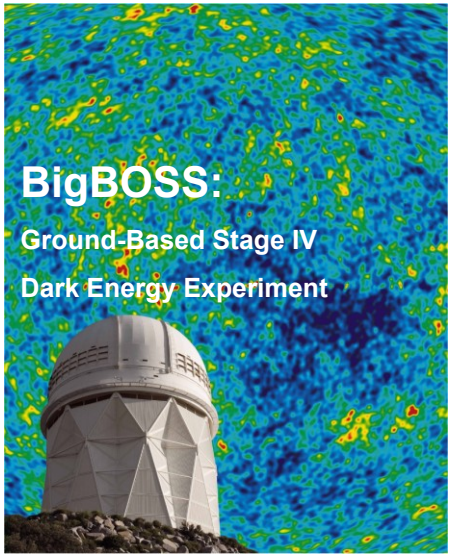
courtesy of David Schlegel

SDSS I, II, 2dF

BOSS (SDSS III)

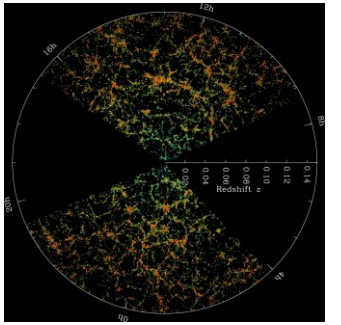
BigBOSS
18 million galaxies
z=0.2-1.5

600,000 QSOs
z=1.8-3



Cosmic Structure

Galaxy 3D distribution or power spectrum contains information on:

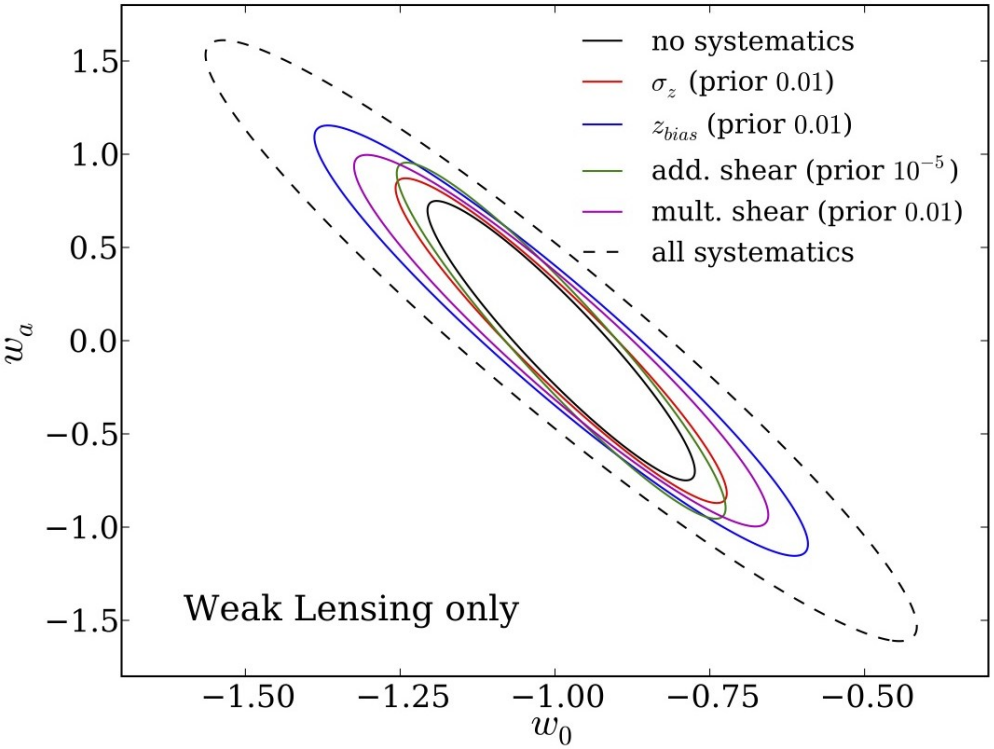


- Growth - evolving amplitude
- Matter/radiation density, H - peak turnover
- Distances - baryon acoustic oscillations
- Growth rate - redshift space distortions
- Neutrino mass, non-Gaussianity, gravity, etc.

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

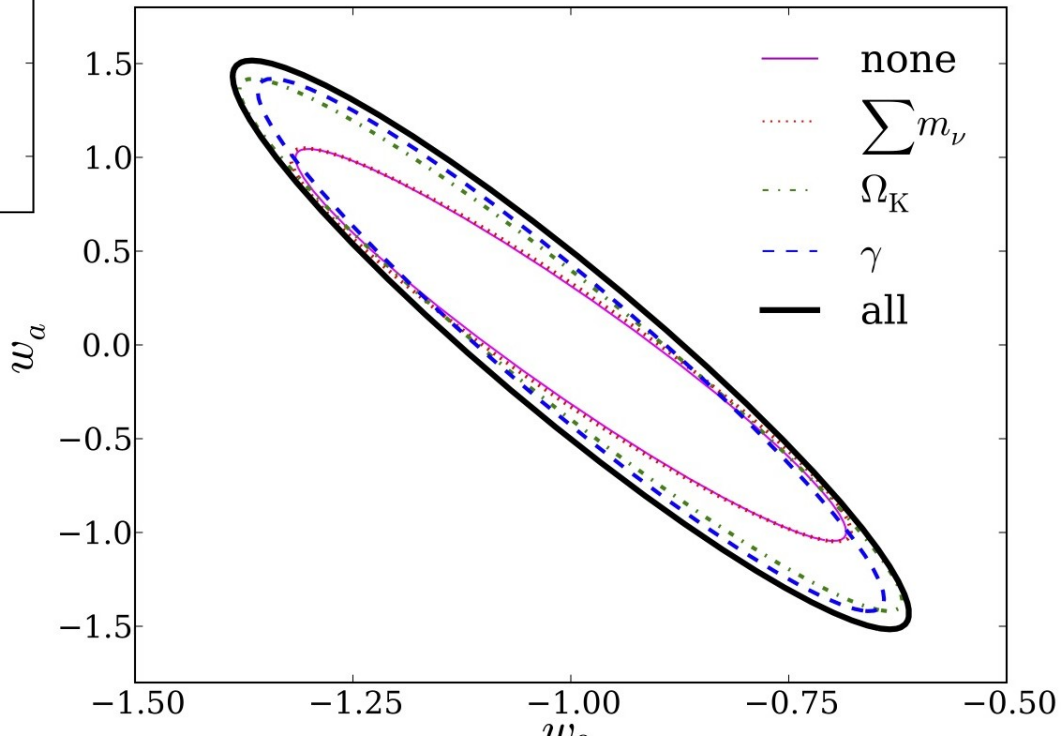
arXiv:1106.1706 ; http://bigboss.lbl.gov

Weak Lensing



Data systematics

Theory systematics



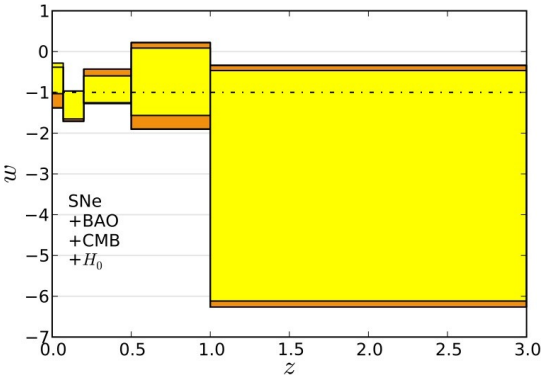
Berkeley Weak Lensing code (soon public)

Das, de Putter, Linder, Nakajima 1102.5090

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.

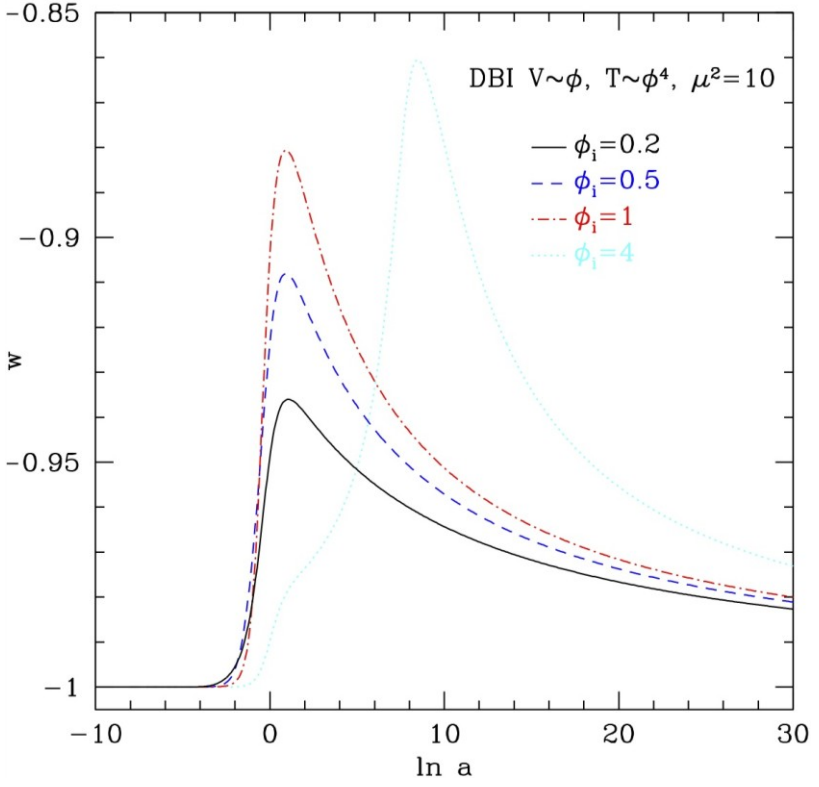
Approaching Λ: Microphysics, High Energy Physics, Gravity.

Λ Attractor from High Energy Physics

Quintessence suffers from HEP corrections and fine tuning.

DBI action is relativistic generalization solving both.

$$\mathcal{L} = -T\sqrt{1-\dot{\phi}^2/T} + T - V \qquad \gamma = (1-\dot{\phi}^2/T)^{-1/2}$$



w=-1 in past, and attracted toward w~-1 in future. So today, not so far from w=-1.

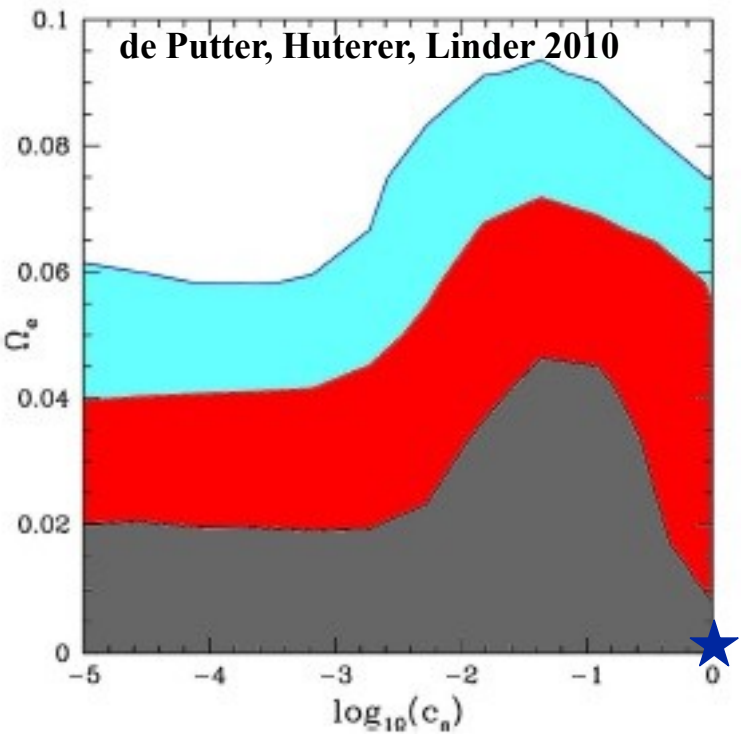
V, T are brane properties. Deviation from w=-1 related to "mass" $\mu^2=(V/T)_{Pl}$.

Ahn, Kim, & Linder 2009a,b

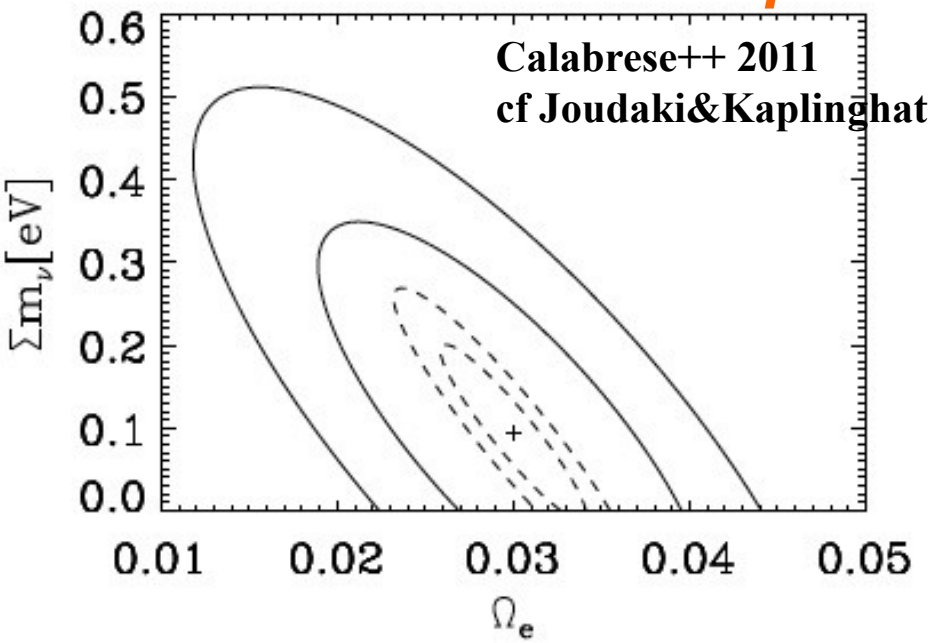
Two interesting signatures: sound speed $c_s \neq 1$ and early dark energy (dilaton, scaling) $\Omega_{DE}(z=10^3) >> \Omega_\Lambda(z=10^3)=10^{-9}$.

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

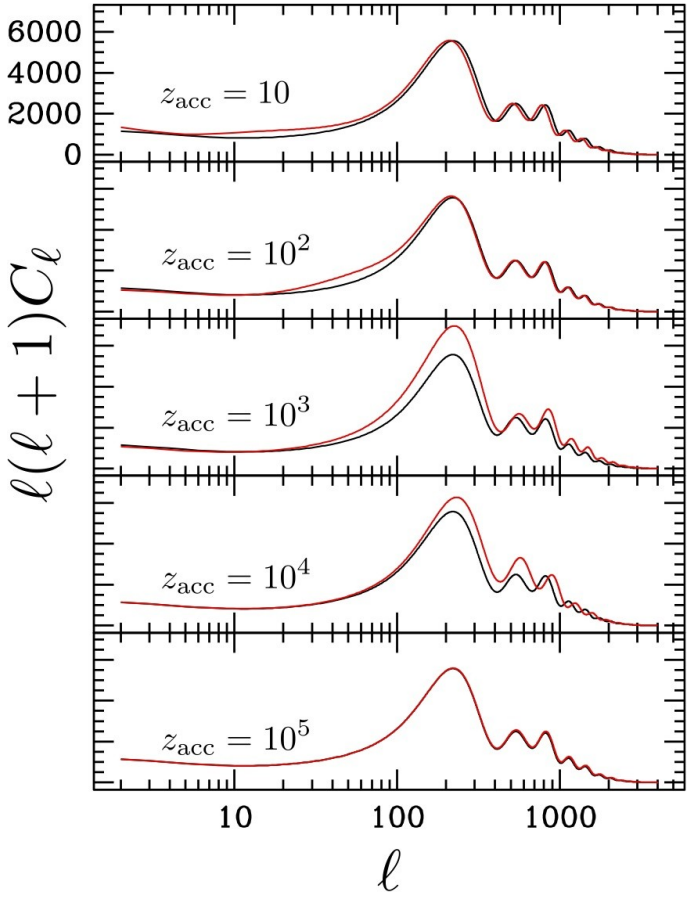


Best fit Ω_e=0.02, c_s=0.04, w_0=-0.95 but consistent with Λ within 68% cl.

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



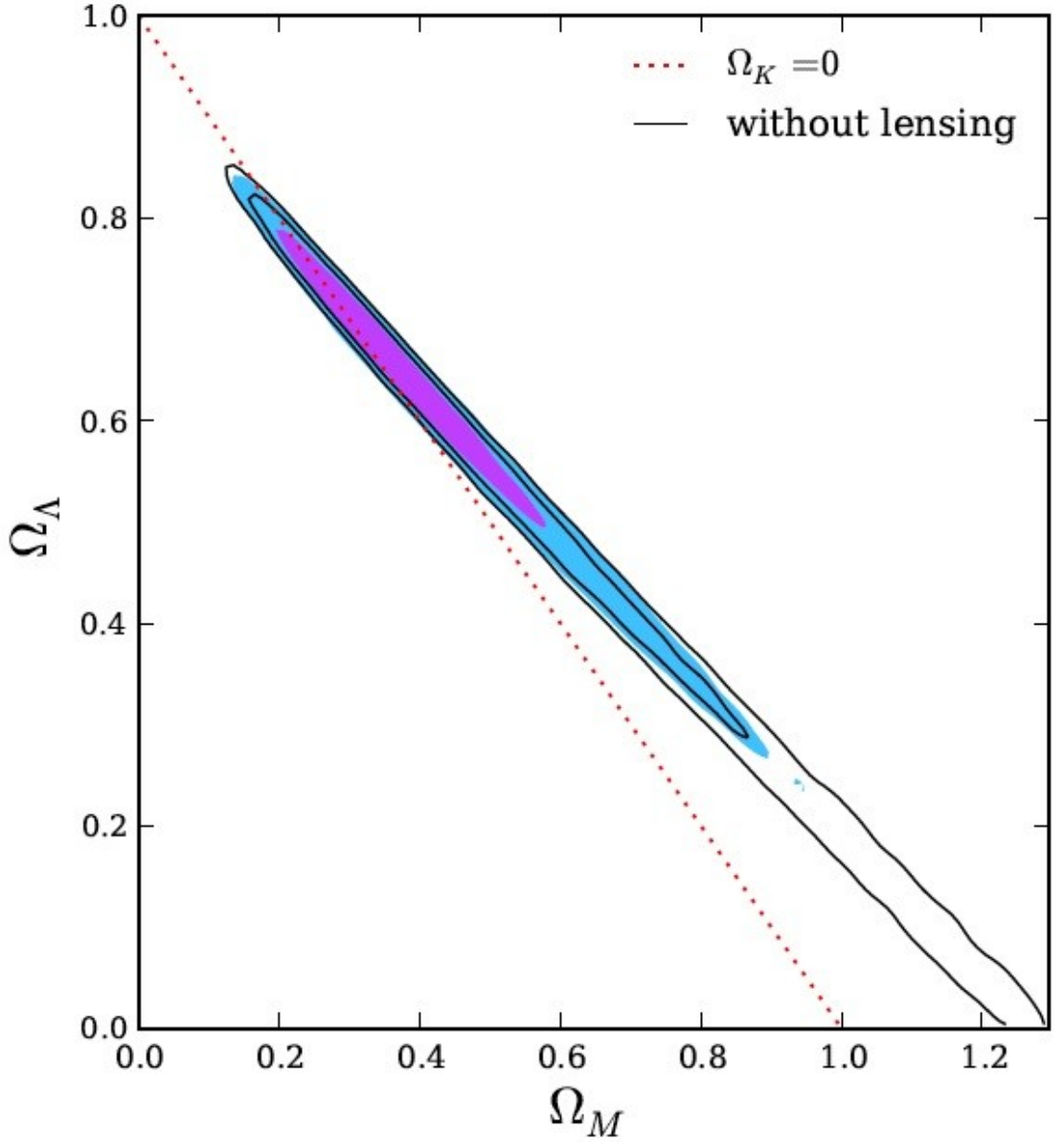
Linder & Smith 2010

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!

CMB Lensing

CMB lensing *alone* now sees 3.2σ evidence for Λ.



Sherwin++ 1105.0419 ACT

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:

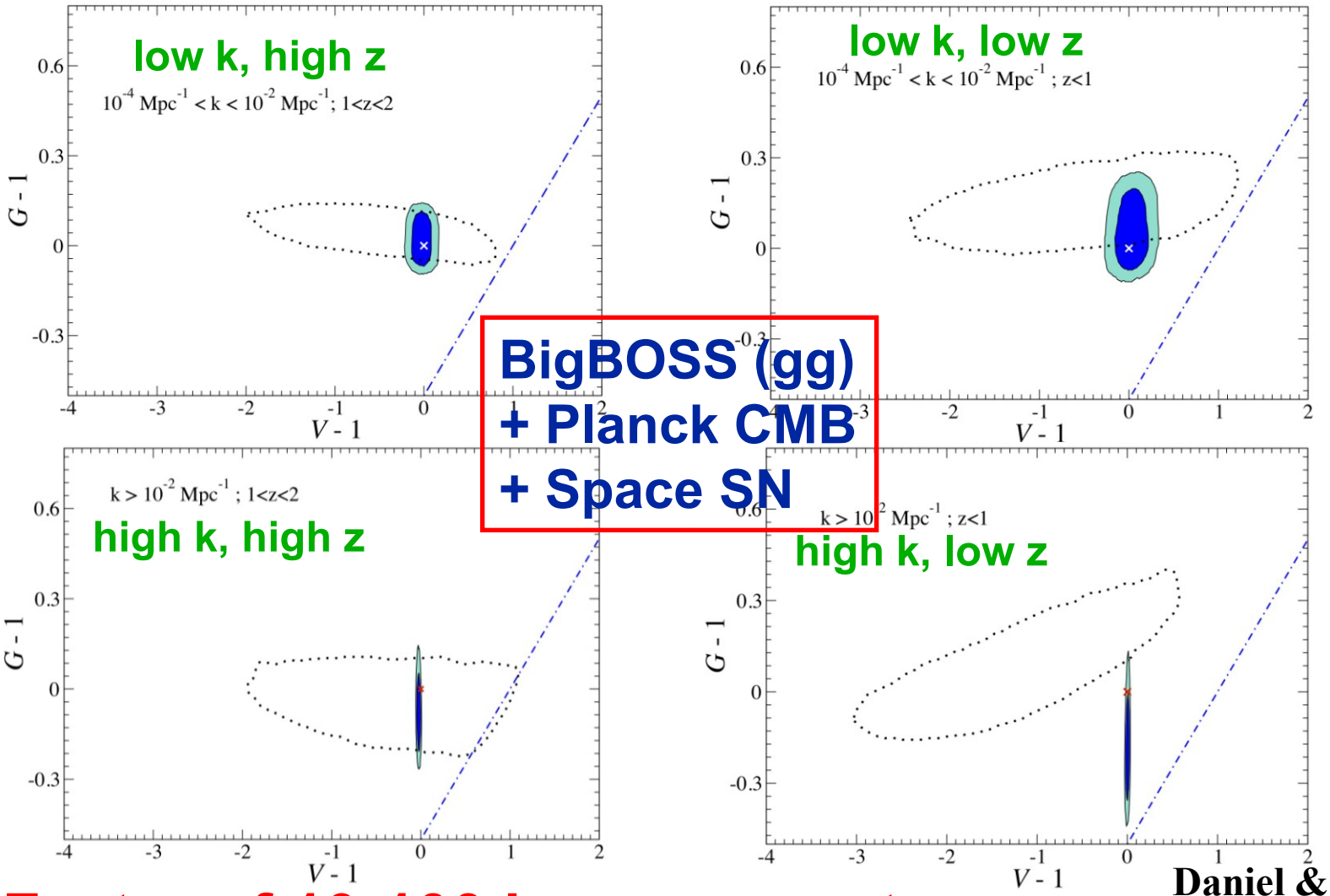
$$\nabla^2(\phi+\psi) = 8\pi G\, a^2\, \delta\rho \times \mathcal{G}$$
$$\nabla^2\psi = 4\pi G\, a^2\, \delta\rho \times \mathcal{V}$$

$\mathcal{G}$ 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"



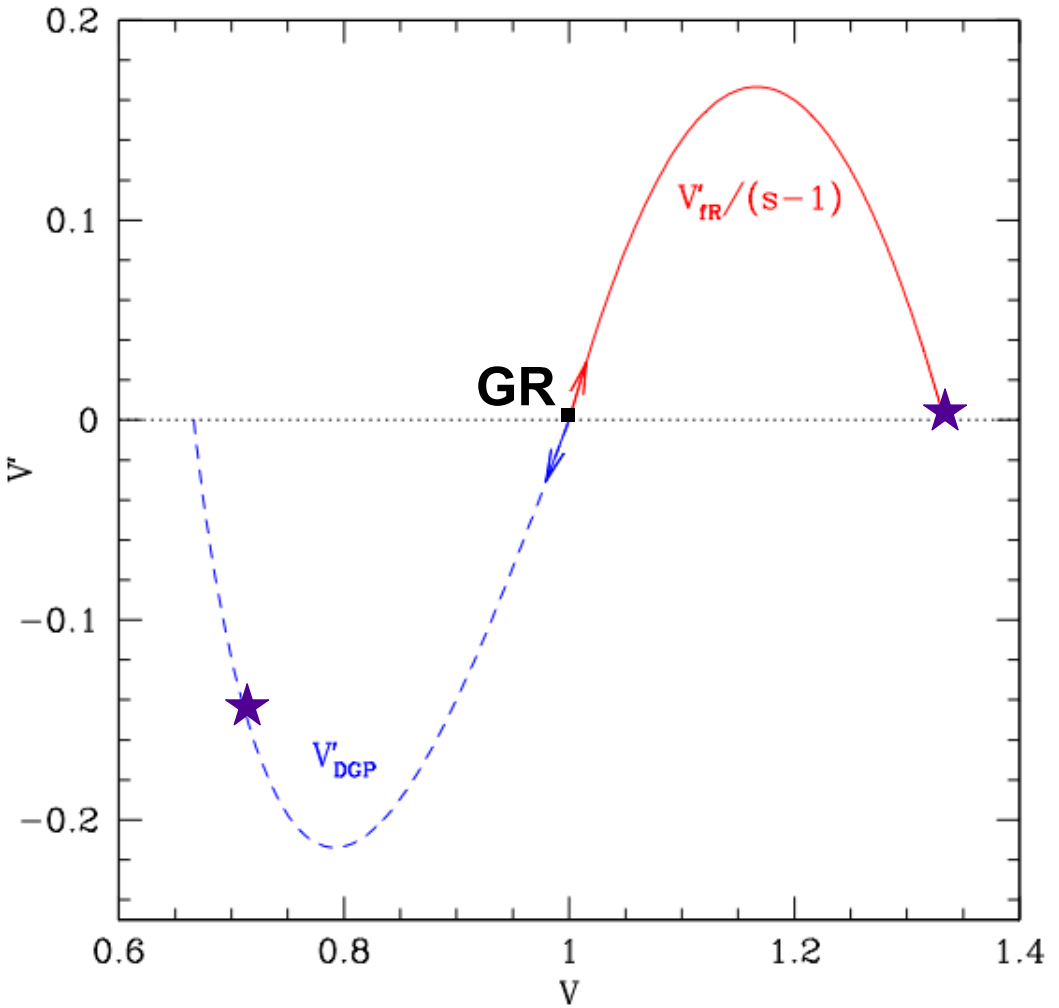
Daniel & Linder 2010
cf Song+, Zhao+

Factor of 10-100 improvement;

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, $\Delta\mathcal{V}\sim\pm0.3$ and have gravity requirement: 3σ measure requires $\sigma(\mathcal{V})\sim0.1$.



Linder 1103.0282

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, including sound speed and early dark energy.

Absolute requirement on testing gravity – 10% on γ.

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