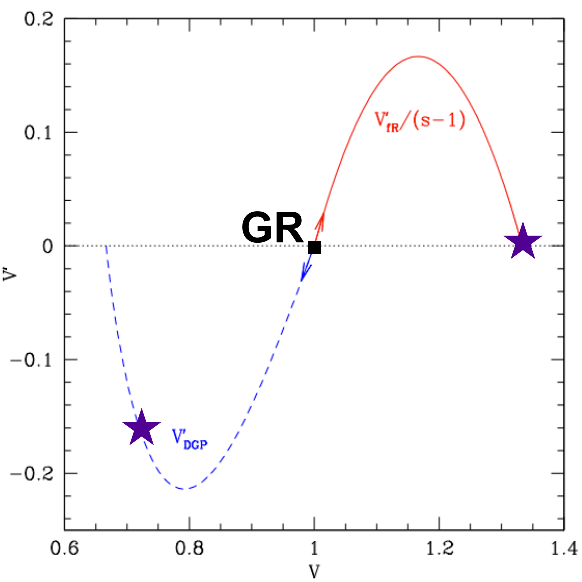
# Chasing Down Cosmic Acceleration

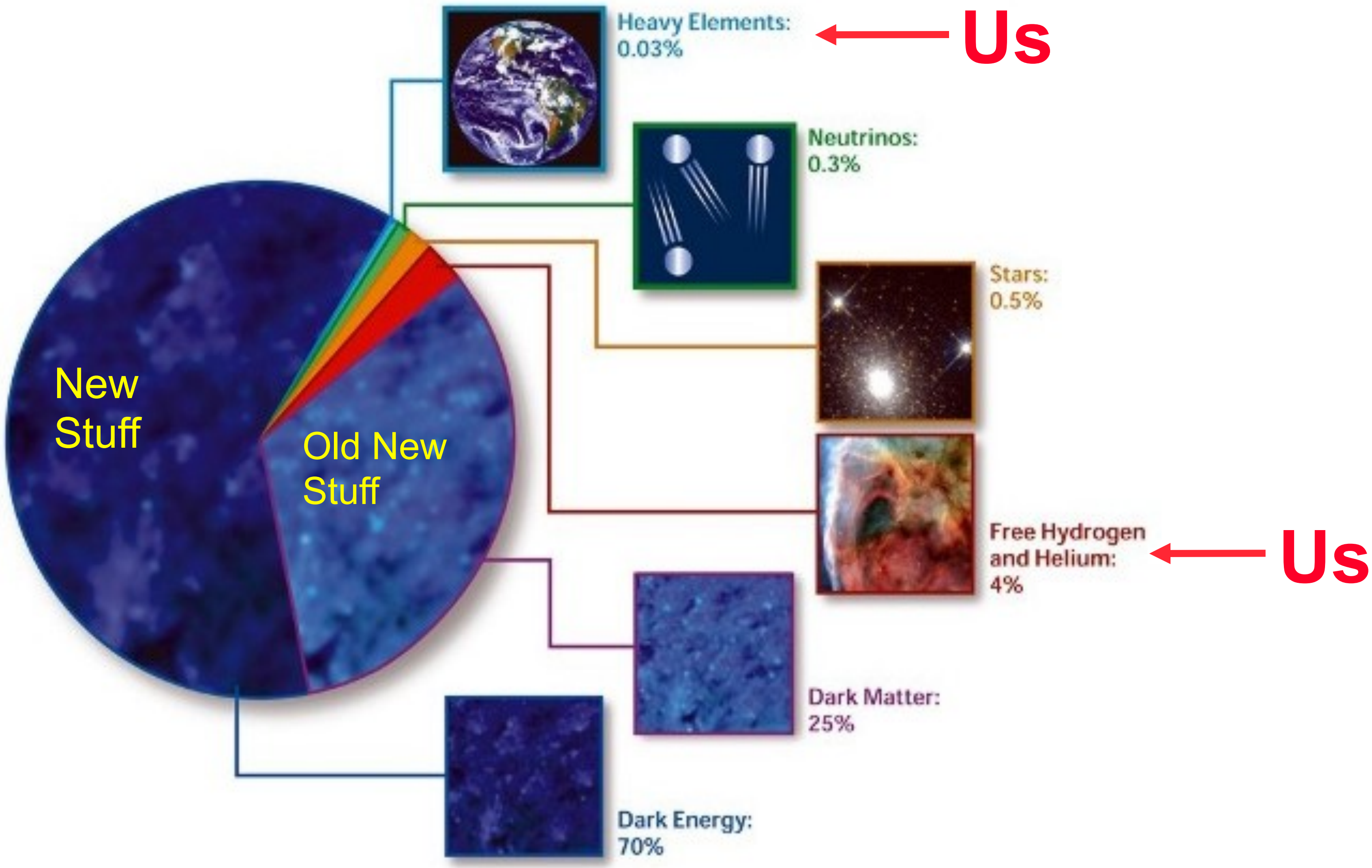

Eric Linder


7 June 2012


UC Berkeley & Berkeley Lab


# Describing Our Universe

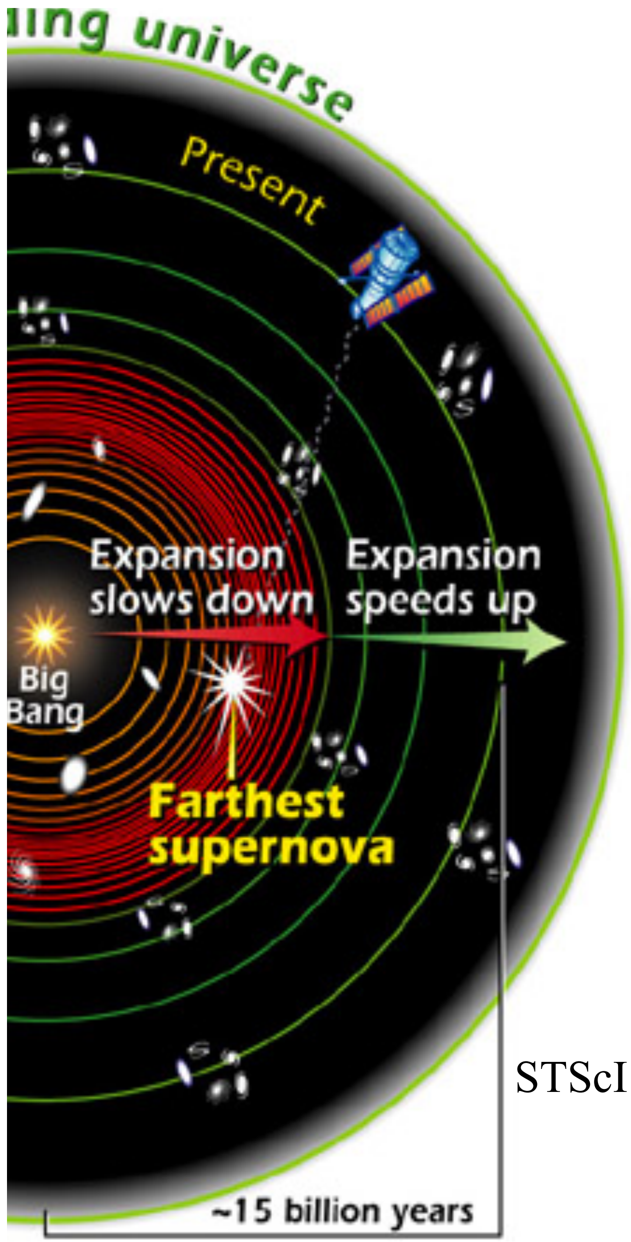



STScI

**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?

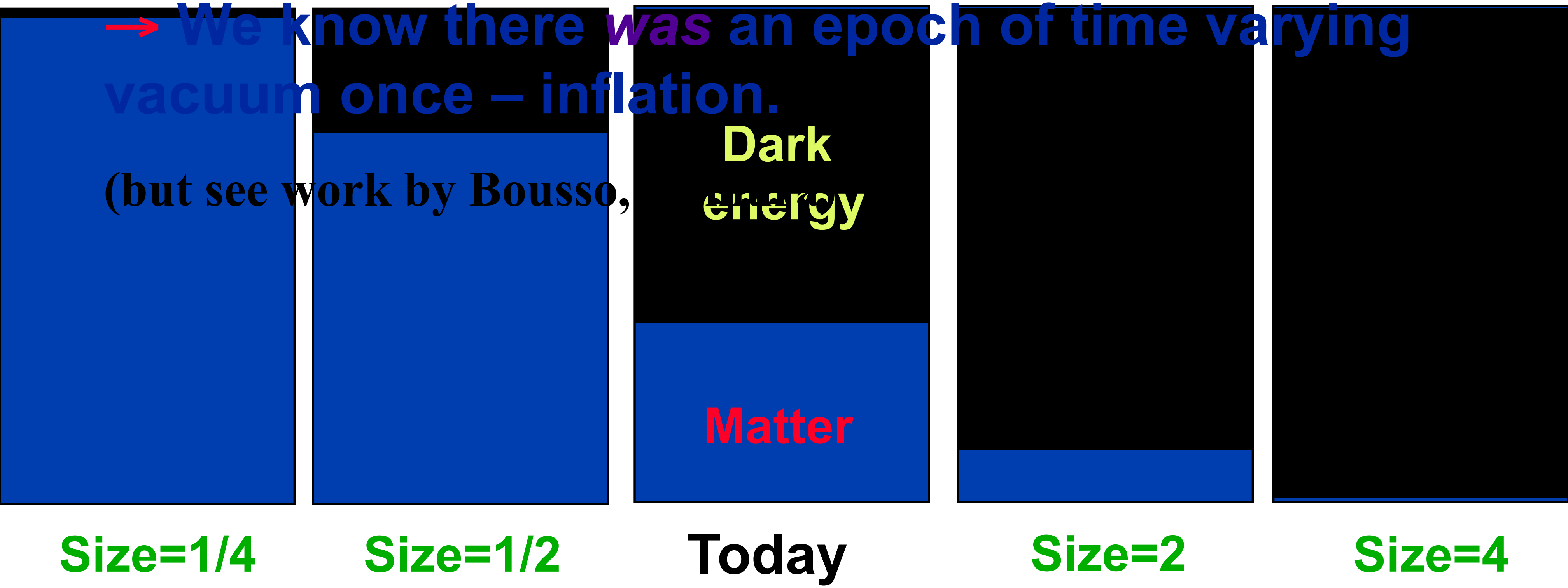
→ For 90 years we have tried to understand why Λ is at least $10^{120}$ times smaller than we would expect – and failed.

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

(but see work by Bousso, ...)

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.



# On Beyond $\Lambda$!

*"You'll be sort of surprised what there is to be found*
*Once you go beyond $\Lambda$ 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 ~800 published distances, with better precision, better accuracy, out to z=1.75.

CMB *and its lensing* points to acceleration. (Didn't even have acoustic peak in 1998.) Das+ 2011, Sherwin+ 2011, Keisler+ 2011, van Engelen+ 2012

BAO detected. Concordant with acceleration.

Weak lensing detected. Concordant with acceleration.

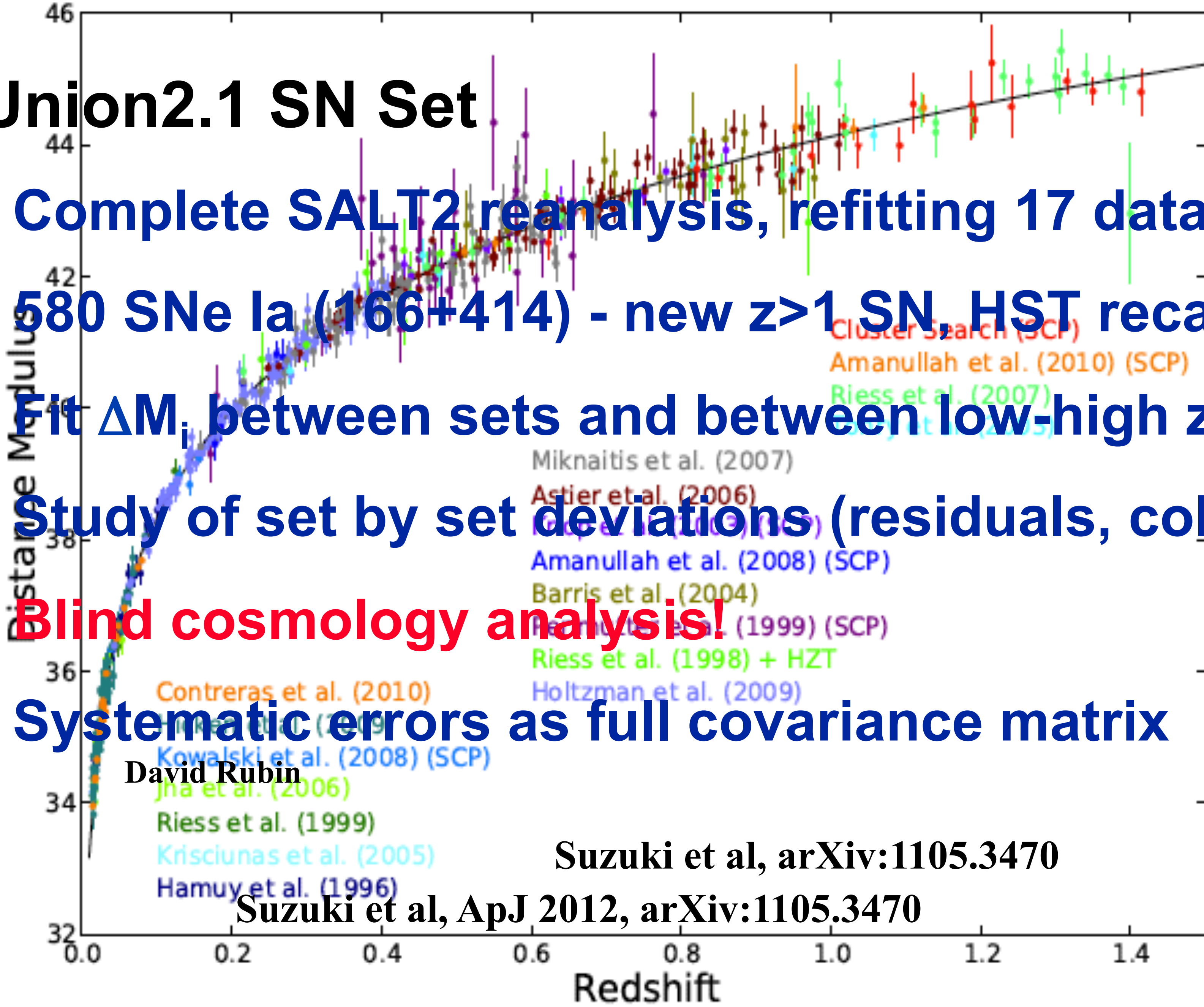
Cluster masses (*if* asystematic) ~1.5$\sigma$ for acceleration.

Strong concordance among data: $\Omega_{DE}$~0.73, w~-1.

# 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 $\Delta M_i$ between sets and between low-high z
- Study of set by set deviations (residuals, color)
- Blind cosmology analysis!
- Systematic errors as full covariance matrix



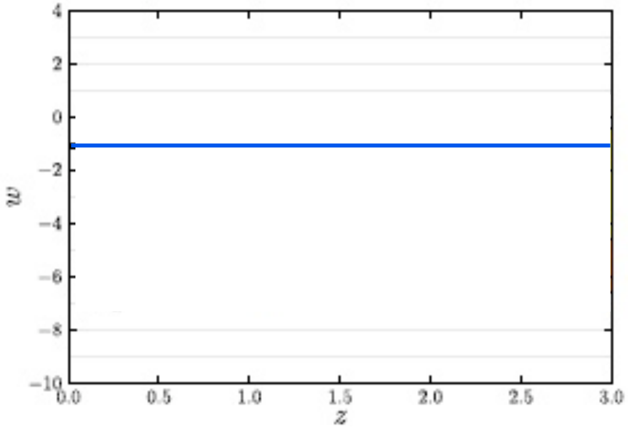

David Rubin

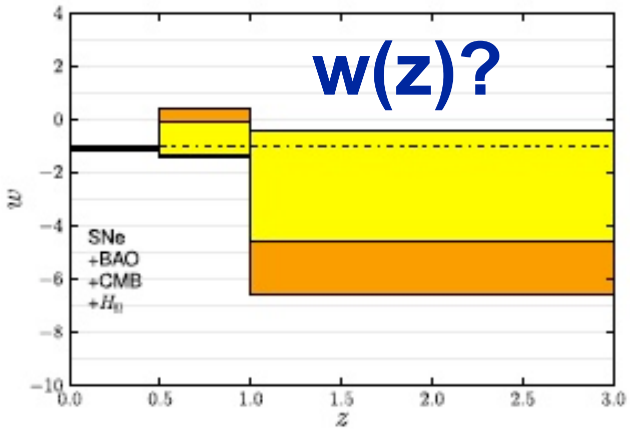
Suzuki et al, arXiv:1105.3470

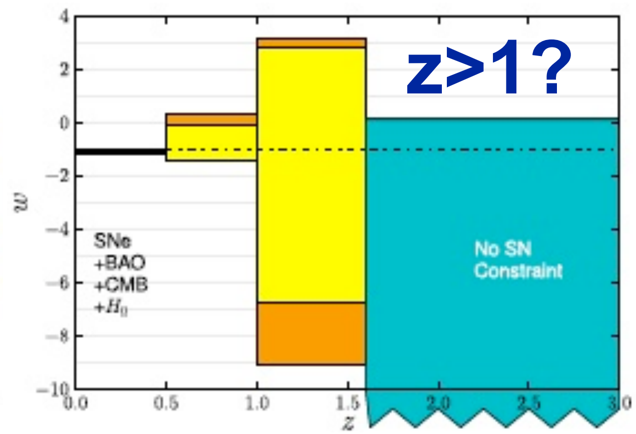
Suzuki et al, ApJ 2012, arXiv:1105.3470

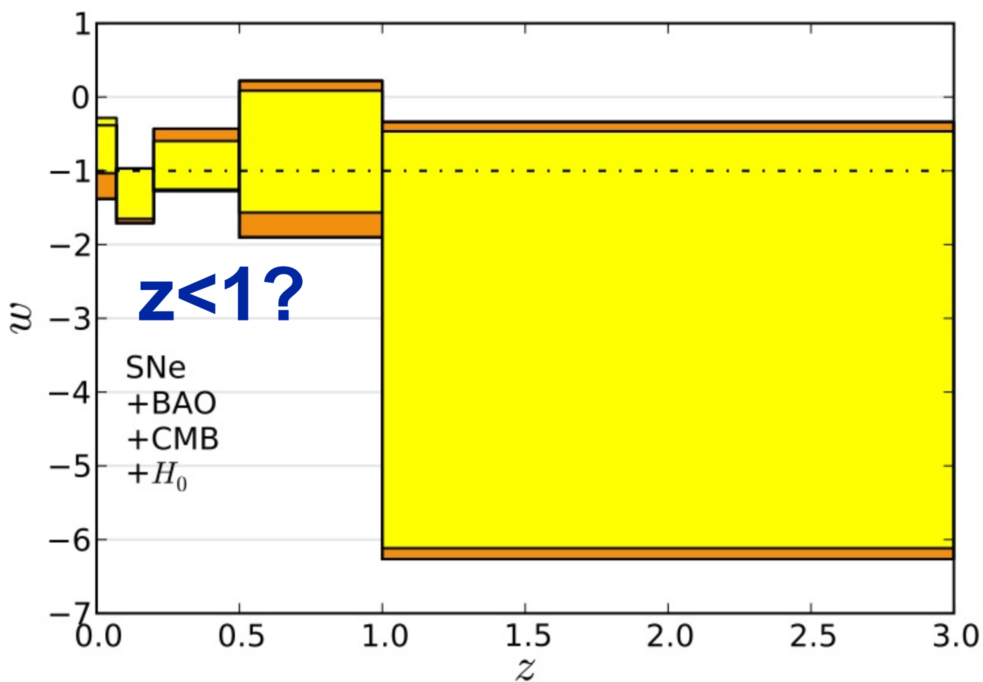
# Are We Done?

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



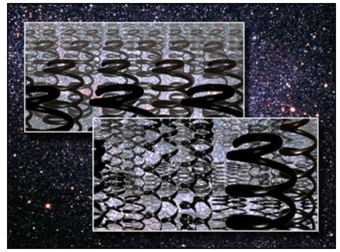




**There is a long way to go still to say we have measured dark energy!**

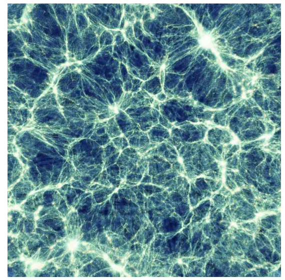
# Dark Energy Properties

**Dark energy is very much *not* the search for one number, "w".**

**Dynamics: Theories other than $\Lambda$ give time variation $w(z)$. Form $w(z)=w_0+w_a z/(1+z)$ accurate to 0.1% in observable.**



**Degrees of freedom: Quintessence determines sound speed $c_s^2=1$. Barotropic DE has $c_s^2(w)$. But generally have $w(z)$, $c_s^2(z)$. Is DE cold ($c_s^2<<1$)? Cold DE enhances perturbations.**



**Persistence: Is there early DE (at $z>>1$)? $\Omega_\Lambda(z_{CMB})\sim10^{-9}$ but observations allow $10^{-2}$.**

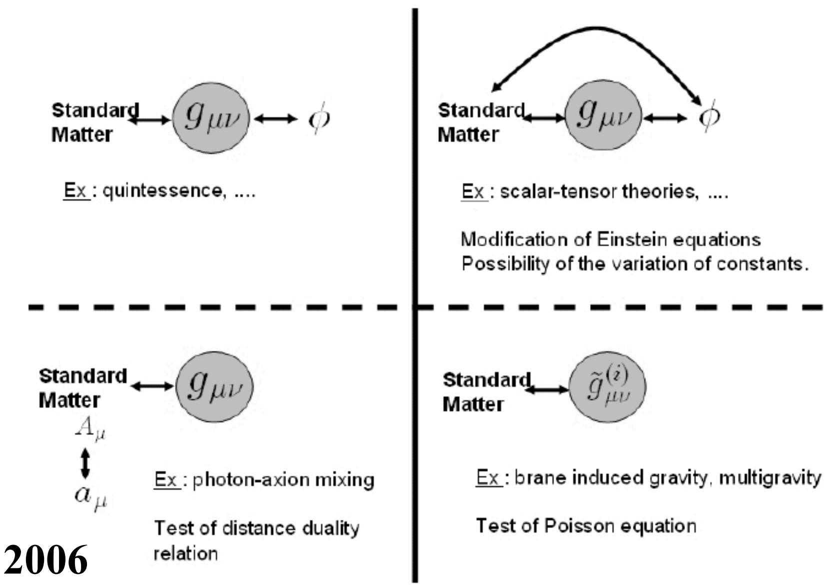
# Beyond Einstein Gravity

## Expansion is not the only determiner of growth of massive structure. "The Direction of Gravity"

**Metric fluctuations:** $\phi$, $\psi$

**Energy-momentum:** $\delta$, $v$

$$\begin{tikzcd}
\phi \arrow[r, "\text{Anisotropic Stress/Gravitational Slip}"] \arrow[d, "\text{Poisson equations}"'] & \psi \arrow[d, "\text{Euler equation}"] \\
\delta \arrow[r, "\text{Continuity equation}"'] & v
\end{tikzcd}$$




Uzan 2006

**Need to know:**

**Expansion**
**DE perturbations**
**Couplings**
**Gravity**

# Observational Leverage

**Dynamics:** High+low redshift, complementarity (e.g. SN+SL, SN+CMB/BAO)

**Degrees of freedom:** Sensitivity to perturbations (CMB lensing, Galaxy clustering)

**Persistence:** High z probes (CMB lensing, Crosscorrelate CMB x Galaxies)

**Test Gravity:** Expansion vs growth (SN/BAO + CMBlens/Gal/WL)

**Very much a *program*:**
Multiple, complementary, diverse observations.
Equal weighting of Theory/Simulation/Observation essential.

# The Direction of Gravity

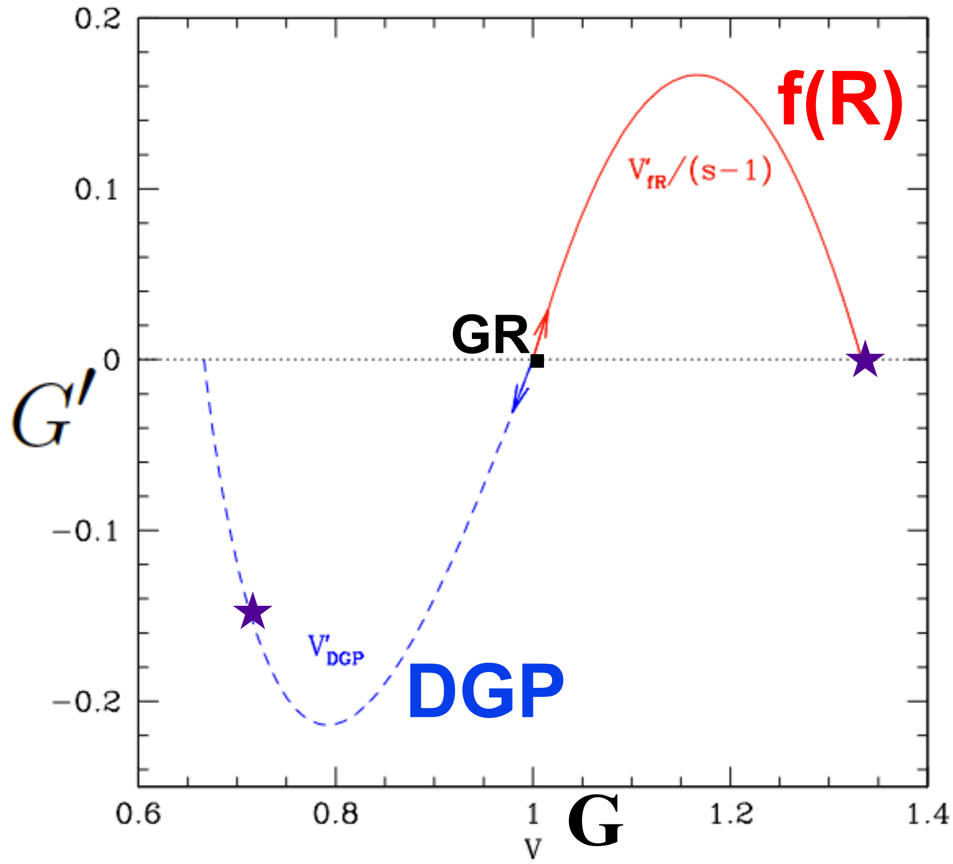
Scalar field dark energy (and $\Lambda$) have problems with **naturalness** of potential and high energy corrections.

Can avoid *both* problems by having a purely **geometric** object with no potential.

**Galileon fields** arise as geometric objects from higher dimensions and have shift symmetry protection (like DGP).

They also have **screening** (Vainshtein), satisfying GR on small scales.

Nicolis+ 2009, Deffayet+ 2009



# Galileon Gravity

**Scalar field $\pi$ with shift symmetry $\pi \rightarrow \pi + c$, derivative self coupling, guaranteeing 2nd order field equations.**

$$S = \int d^4x \sqrt{-g} \left[ \left(1 + 2c_0 \frac{\pi}{M_{\rm pl}}\right) \frac{M_{\rm pl}^2 R}{2} - \frac{c_2}{2}(\partial\pi)^2 - \frac{c_3}{M^3}(\partial\pi)^2 \Box\pi \right.$$
$$\left. - \frac{c_4 \mathcal{L}_4}{2} - \frac{c_5 \mathcal{L}_5}{2} - \frac{M_{\rm pl}}{M^3} c_G G^{\mu\nu} \partial_\mu\pi \partial_\nu\pi - \mathcal{L}_{\rm m} \right]$$

**GR**

**Linear coupling**

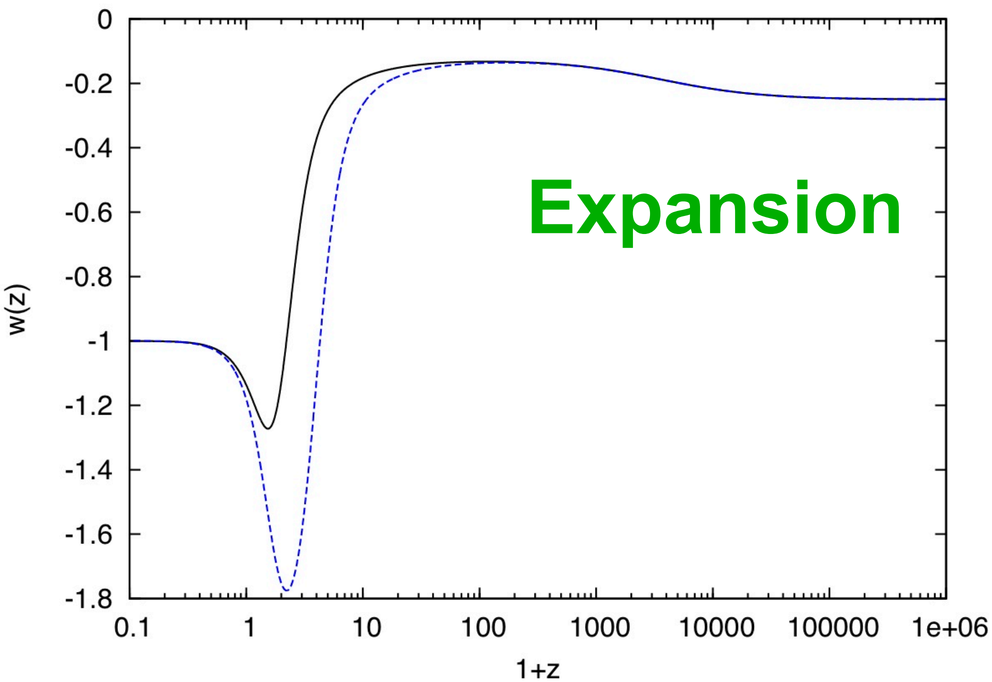
**Derivative coupling**

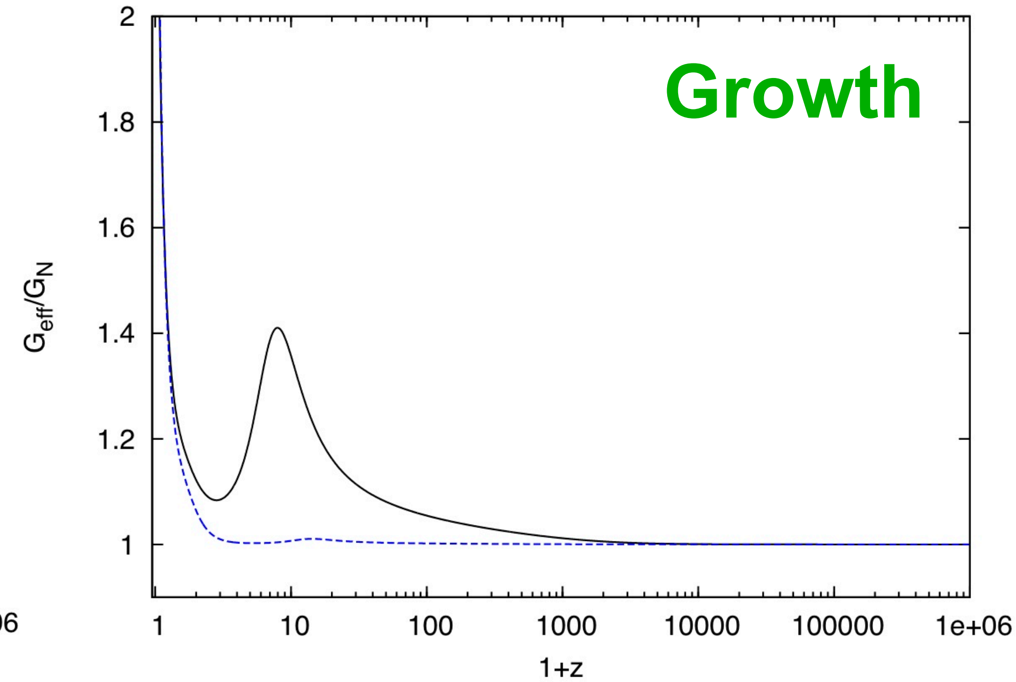
**Standard Galileon**

**Coupled Galileons ruled out by** Appleby & Linder 2012a **due to instabilities.**

# Data vs Gravity

**Galileon cosmology has early time tracker solutions (no fine tuning) and late time de Sitter attractor. Beautiful class of theories!**




**But** Appleby & Linder 2012b **rule out Standard Galileon with $\Delta\chi^2_{LCDM}$>30 from current data. Data kill entire class of gravity!**

# Weirder Gravity (and $\Lambda$)

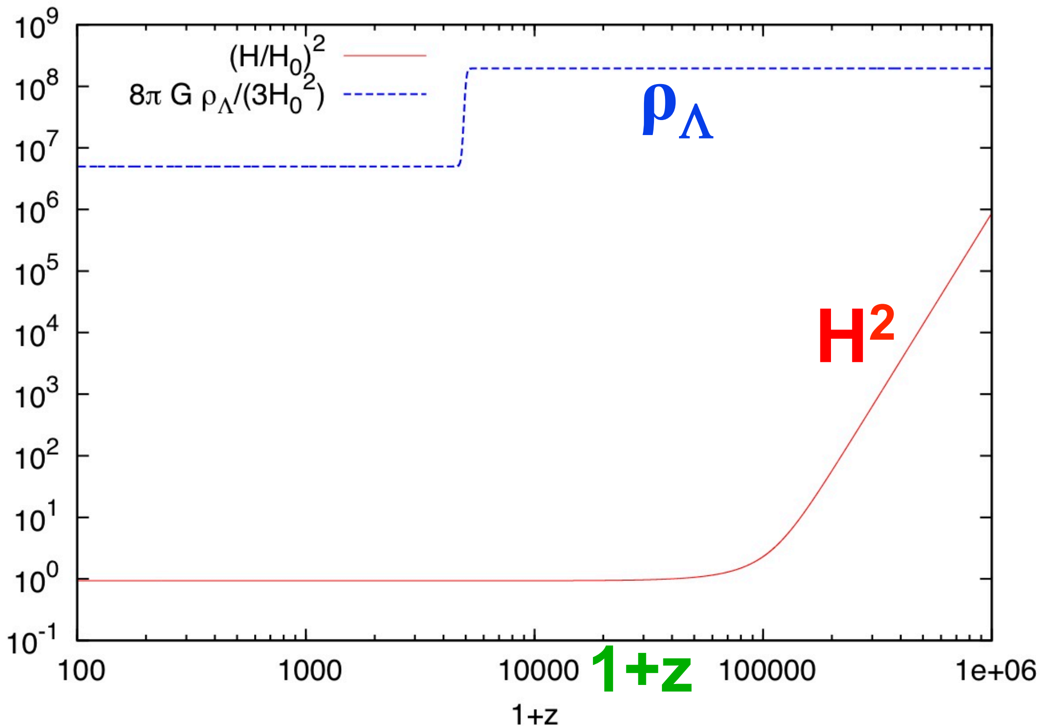
**Symmetries determine gravity action, e.g. Horndeski most general scalar-tensor theory with 2nd order EOM.**

Charmousis+ 2011 **found "Fab 4" unique self tuning terms.**

Appleby, De Felice, Linder 2012 **promote to nonlinear, mixed function.**

$$f\left(c_2 g^{\mu\nu}\phi_\mu\phi_\nu + c_G G^{\mu\nu}\phi_\mu\phi_\nu\right)$$

**"Fab 5 Freddy"**


**Has tracker, dS attractor, GW, no extra dof!, self tuning.**

**$\phi$ dynamically adjusts to cancel $\Lambda$, even thru phase transition.**

**$\Lambda$ is invisible!**

# Chasing Down Cosmic Acceleration

How can we measure dark energy in detail – *in the next 5 years*?

New prospects in data (a partial, personal view):

- Strong lensing time delays
- Redshift space distortions
- CMB polarization lensing

New prospects in theory (a partial, personal view):

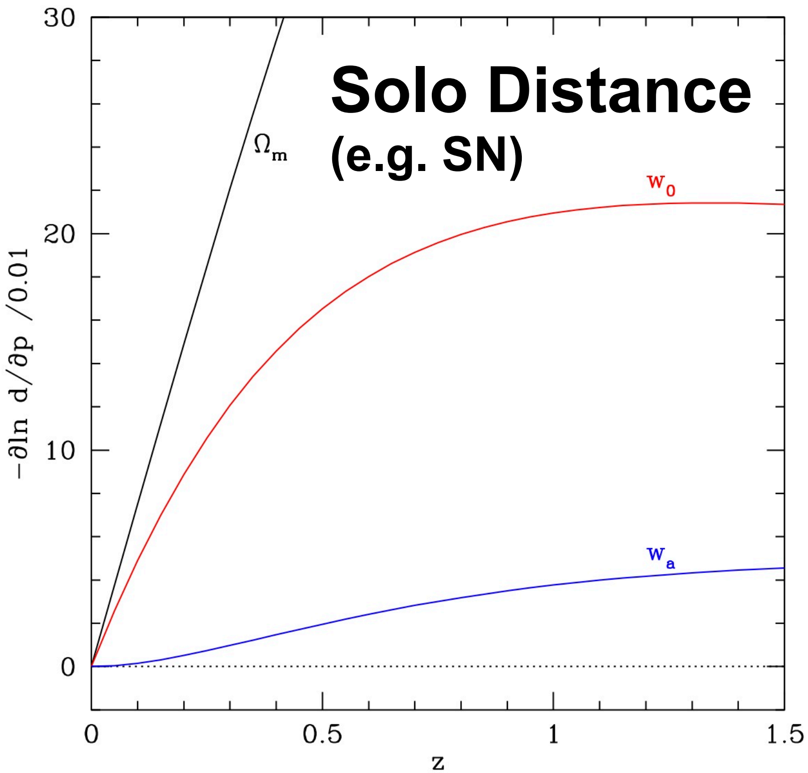
- Higher dimensional gravity/field theory/symmetry

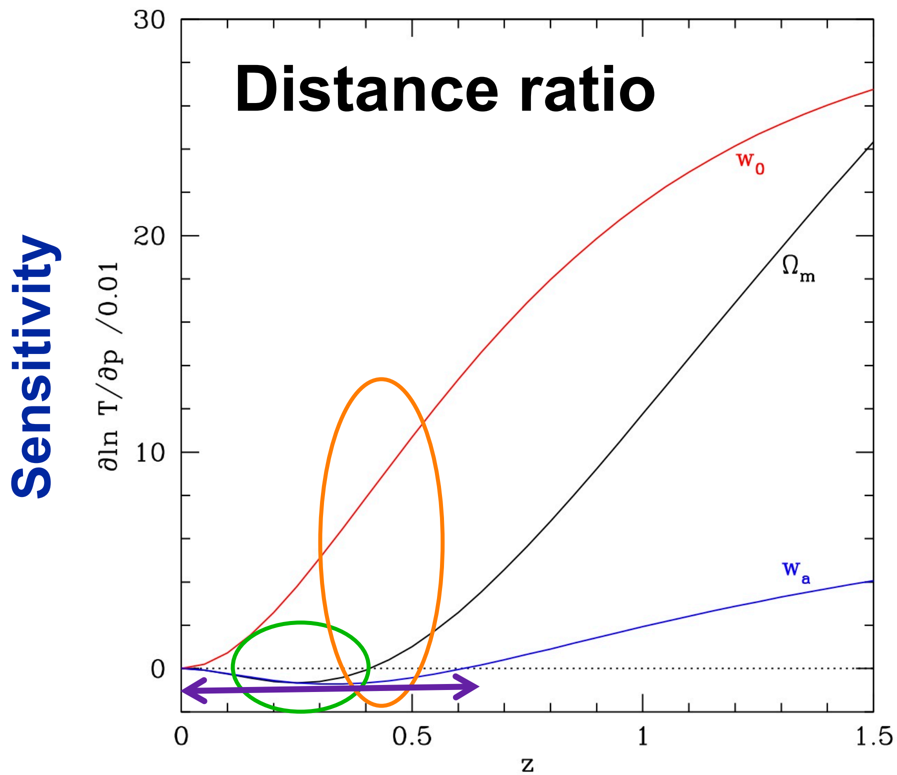
Old school leverage (a partial, personal view):

- Enhanced low z supernova data

# Strong Lensing Time Delays

Strong gravitational lensing creates multiple images (light paths) of a source. Time delays between paths probe **geometric path difference** and lensing potential. Key parameter is distance ratio $T \equiv \frac{r_l r_s}{r_{ls}}$

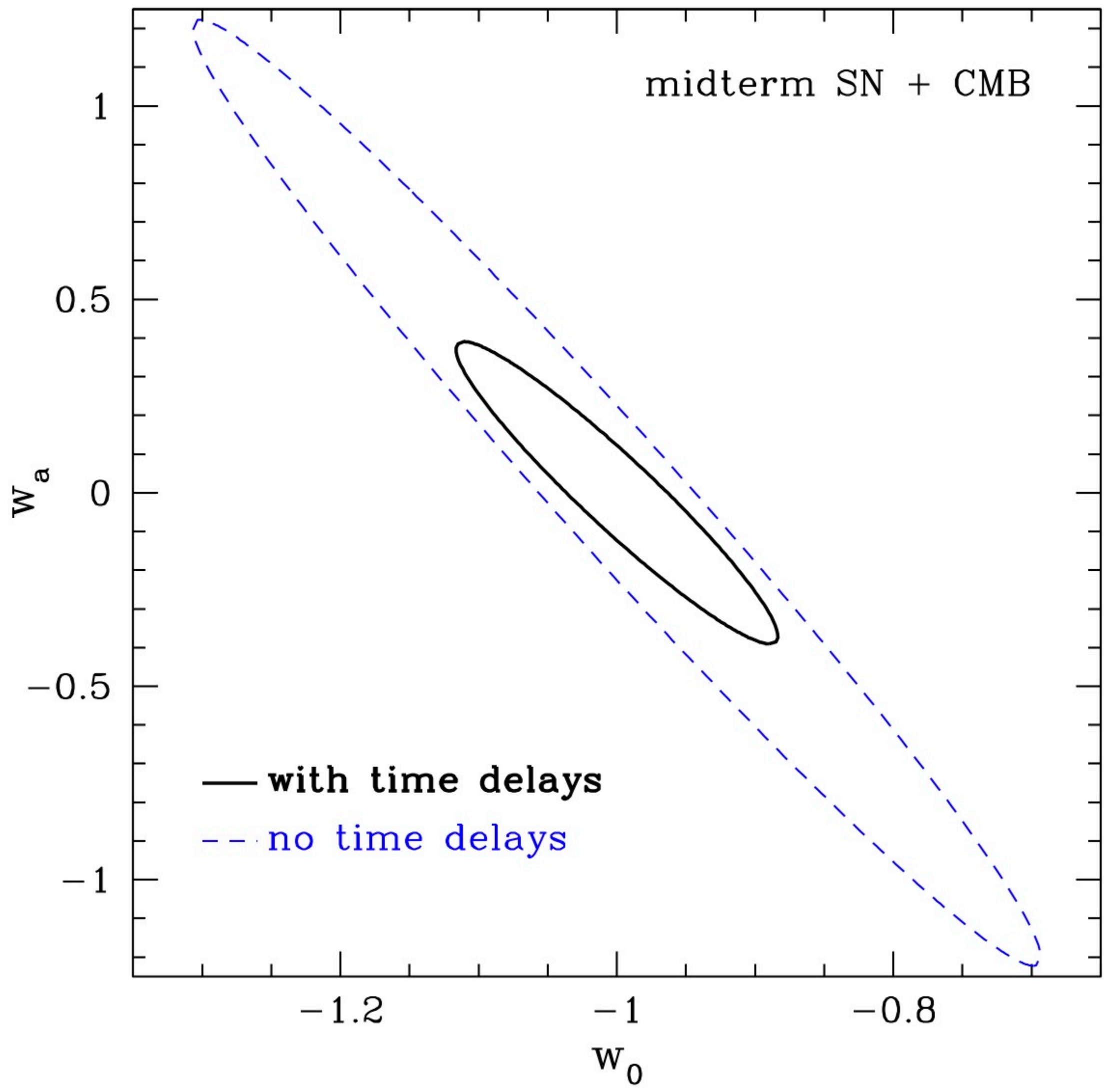



Strong complementarity first id'd by Linder 2004, first used by WMAP7 (Komatsu+ 2011), modeling advances now make it practical.

# 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
$\Omega_m$ to 0.0044
h to 0.7%
$w_0$ to 0.077
$w_a$ to 0.26

# Time Delay Surveys

Best current time delays at 5% accuracy, 16 systems. 5 year aim: 38 systems, 5% accuracy = 230 orbits HST.

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: HST/Keck/VLT+ DES/BOSS. SN survey included. Only low redshift $z<0.6$ needed for lenses.

Systematics control via image separations, anomalous flux ratios (probe DM substructure!). Need good mass modeling, computationally intensive.

# Higher Dimensional Data

## Cosmological Revolution:


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

# Data, Data, Data

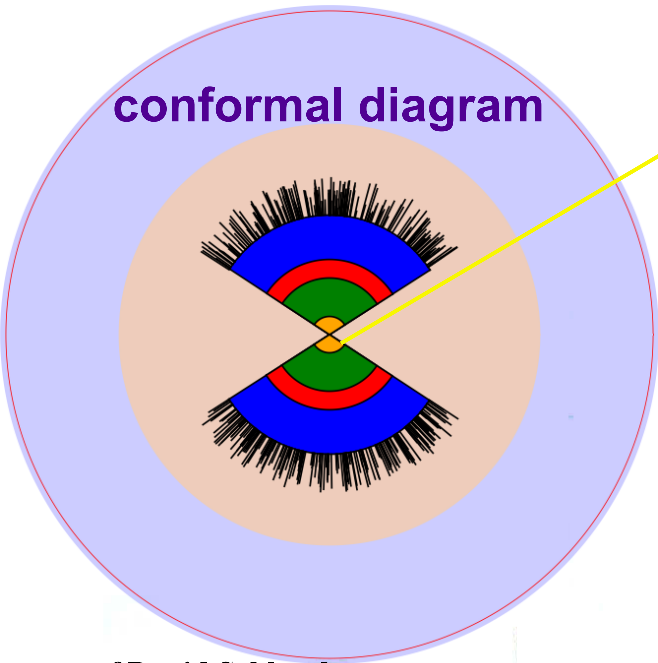
As wonderful as the CMB is, it is 2-dimensional.

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

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

N. Padmanabhan

BigBOSS will map 15 million linear modes.




SDSS I, II, 2dF

BOSS (SDSS III)

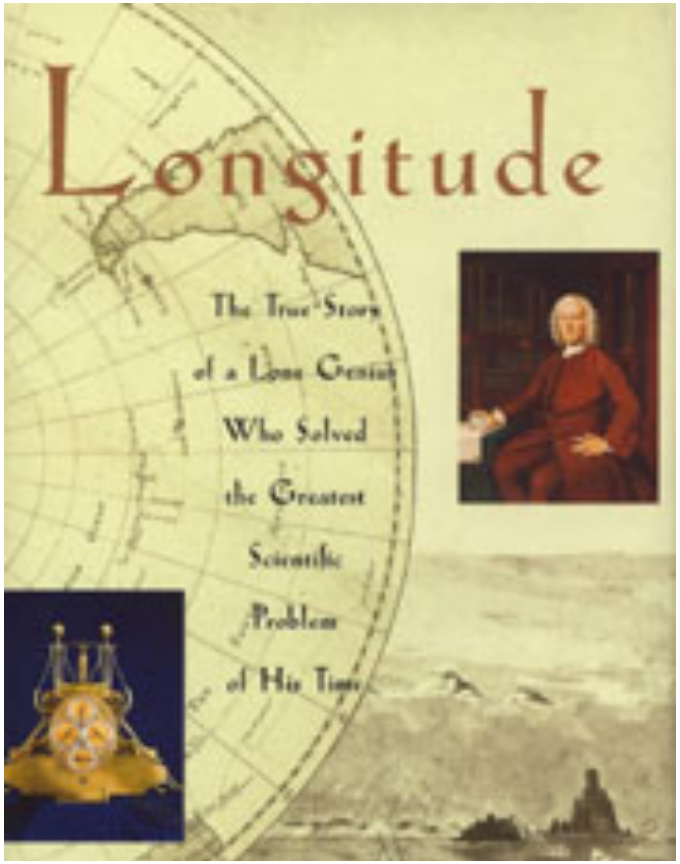
BigBOSS
18 million galaxies
z=0.2-1.5

600,000 QSOs
z=1.8-3

Maps of
*density*
*velocity*
*gravity*

courtesy of David Schlegel

# "Greatest Scientific Problem"





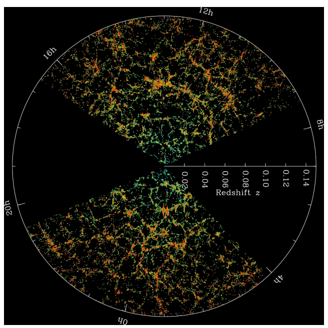
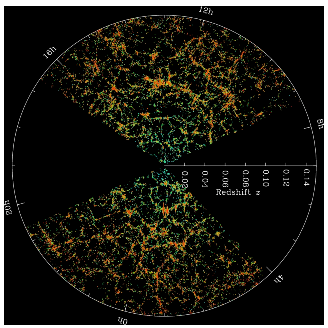
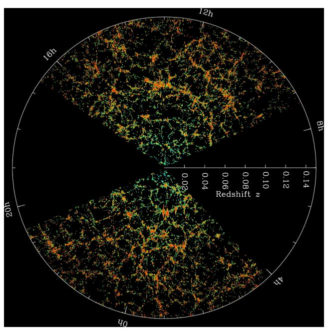
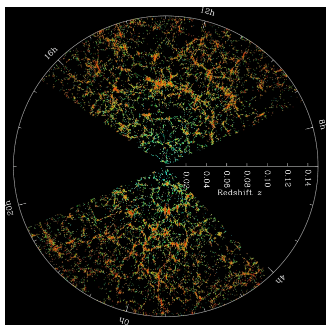
**"When I'm playful I use the meridians of longitude and parallels of latitude for a seine, drag the Atlantic Ocean for whales."**

**– Mark Twain,** ***Life on the Mississippi***

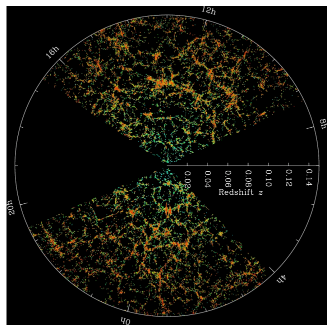
# Cosmic Structure

**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.**

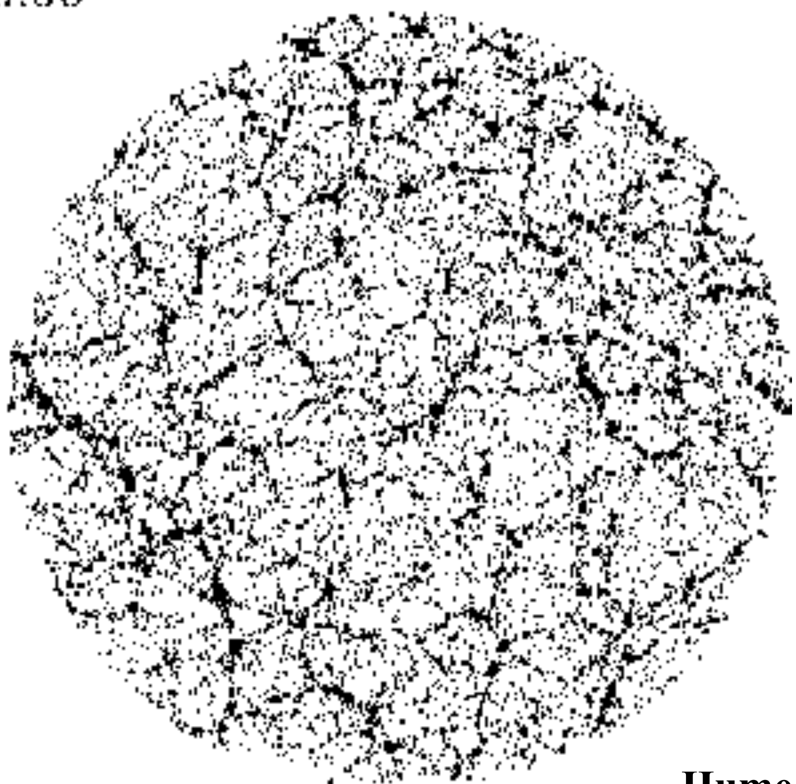
**x25**
**(x7 LRG)**
**…**



# 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



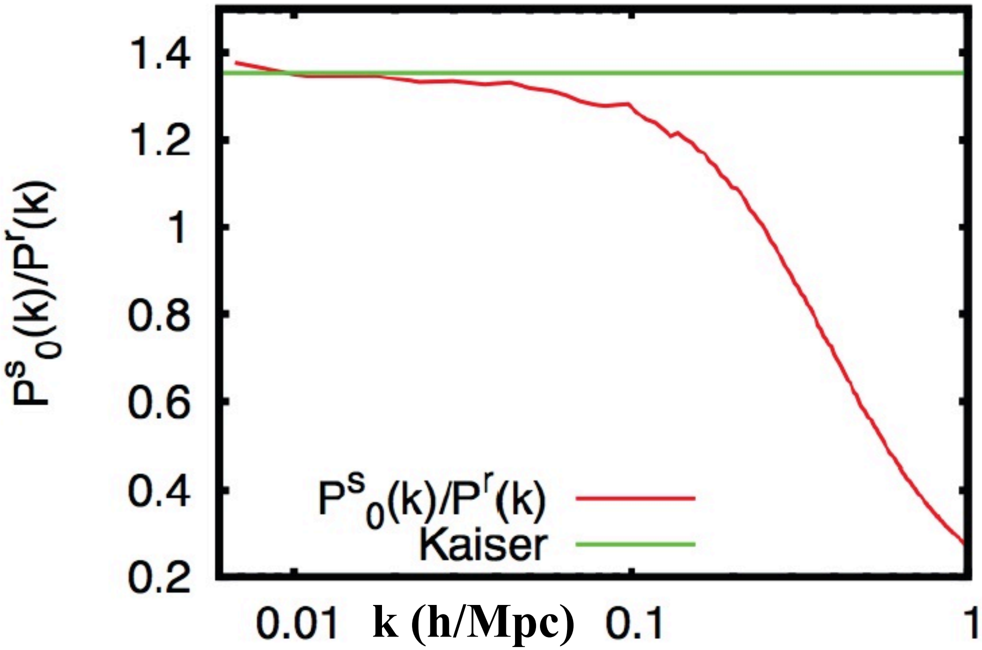
Hume Feldman

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

**gravitational growth index $\gamma$**

# Redshift Space Distortions

$$P_{gg}(k,z) = (b + f\mu^2)^2\, P_{\delta\delta}(k,z)$$ **Kaiser formula inaccurate**



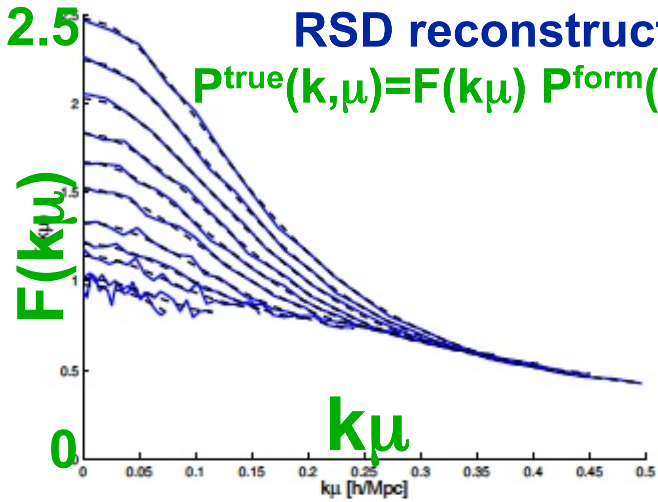

**Even monopole (averaged over RSD) is poor.**

**Anisotropic redshift distortion hopeless – *without better theory*.**

**Simulation fitting function**

Kwan, Lewis Linder 2011

**highly accurate to higher kμ.**




also see Okumura, Seljak, McDonald, Desjacques 2011; Reid & White 2011

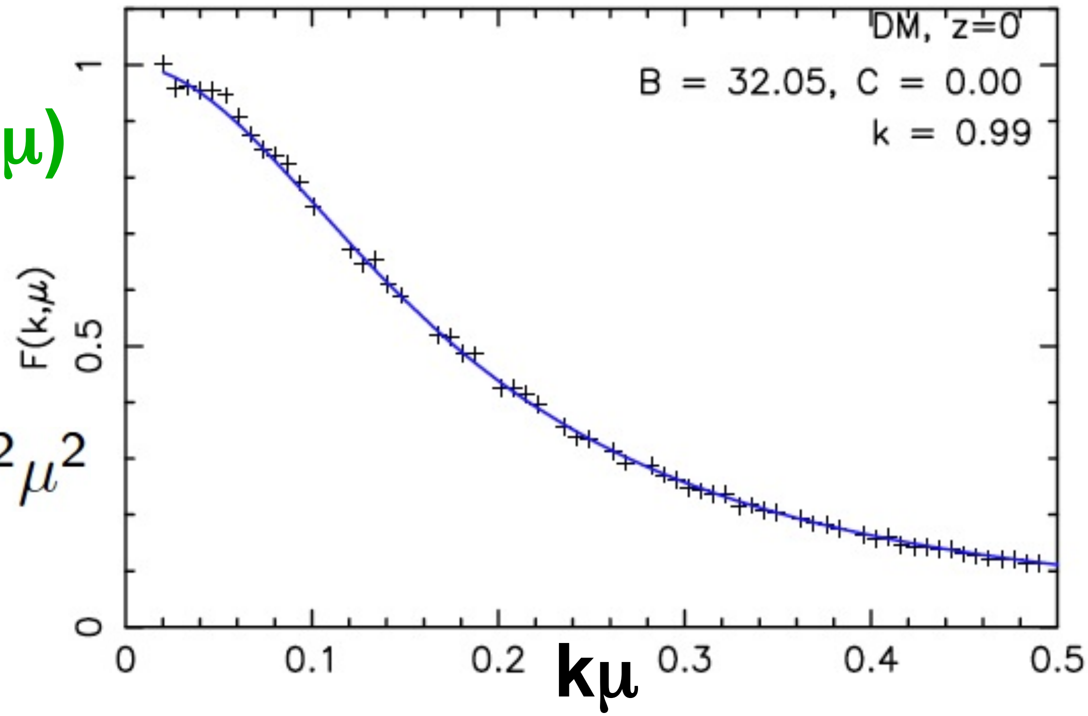
# Redshift Space Distortions

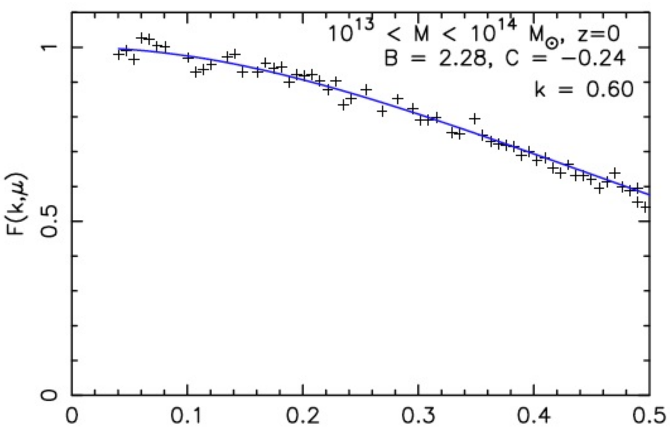
## Reconstruction function works great!

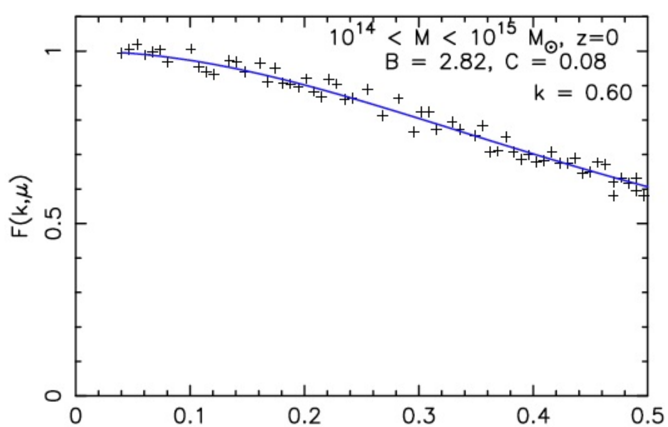
**$P^{true}(k,\mu)=F(k\mu)\ P^{form}(k,\mu)$**

**Kwan, Lewis, Linder 2012**

$$F(k,\mu) = [Bk^2\mu^2+1]^{-1} + Ck^2\mu^2$$



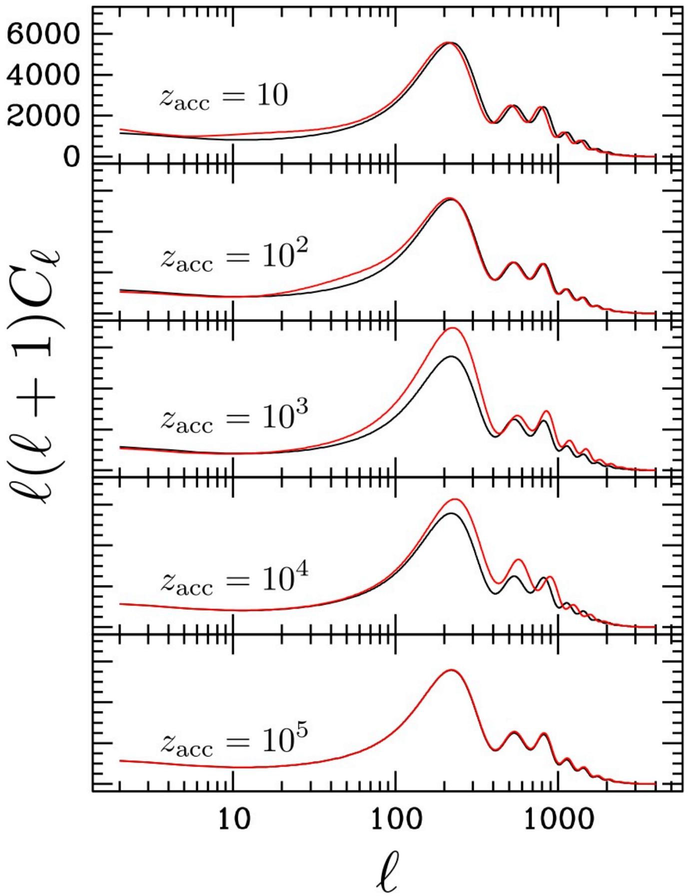

**Also for different z and halos**

# 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**



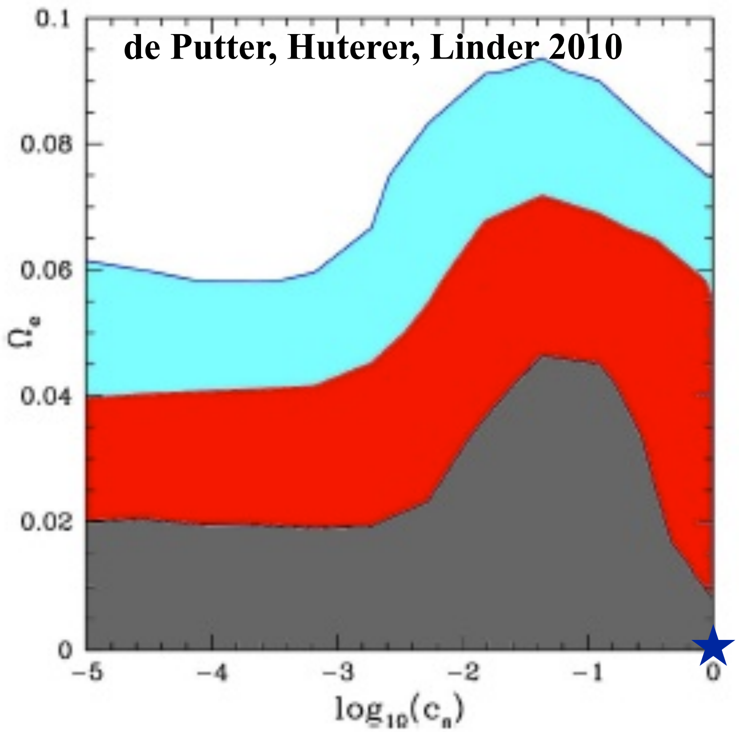

Linder & Smith 2010

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

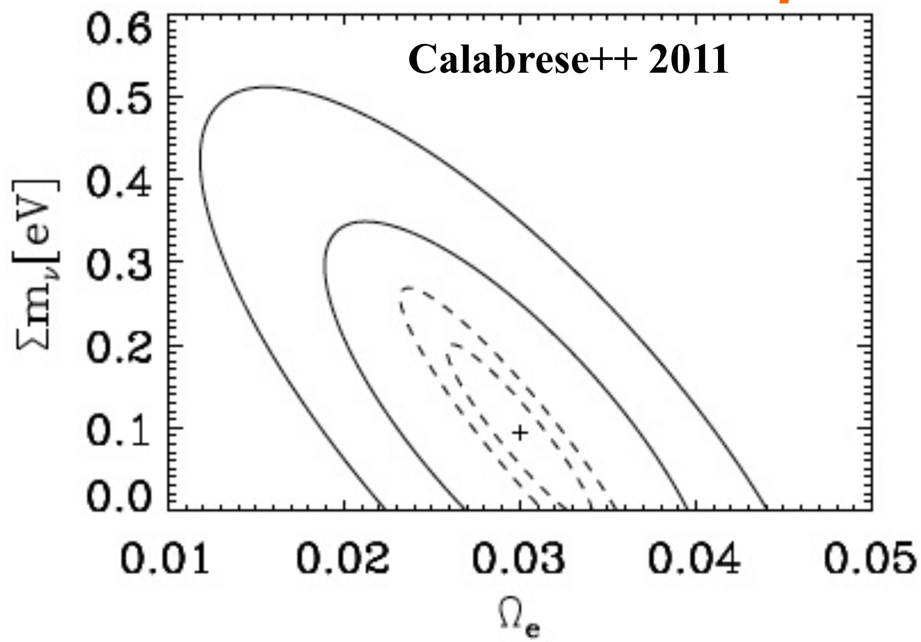
**Current acceleration unique within last factor 100,000 of cosmic expansion!**

# 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*

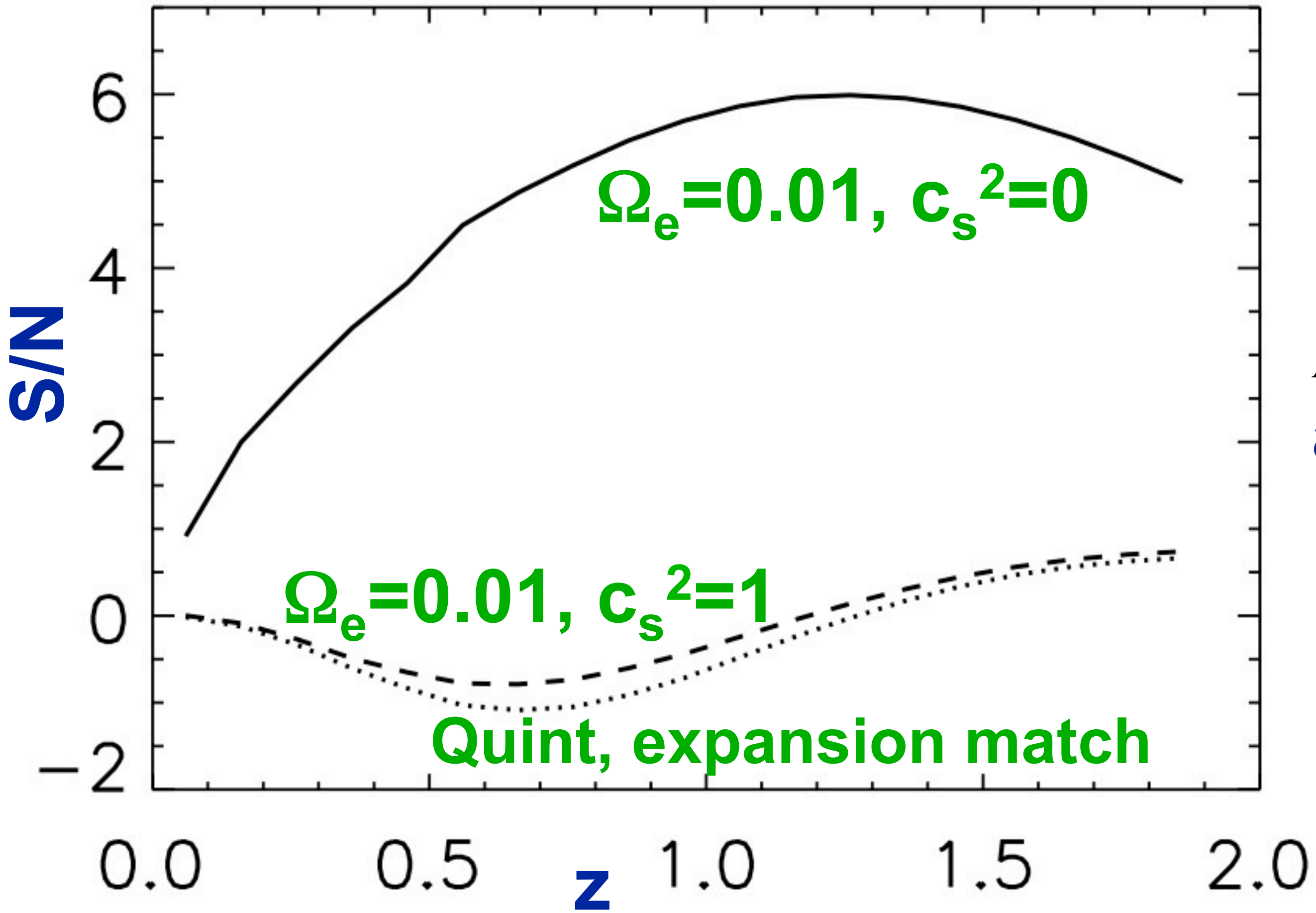



**Best fit $\Omega_e$=0.02, $c_s$=0.04, $w_0$=-0.95 but consistent with $\Lambda$ within 68% cl.**

**"Early, Cold, or Stressed DE"**
**cf. generalized DE Hu 1998**

# Cluster Probes of DE Clustering

**Abundance of galaxy clusters sensitive to DE perturbations (for early DE models).**



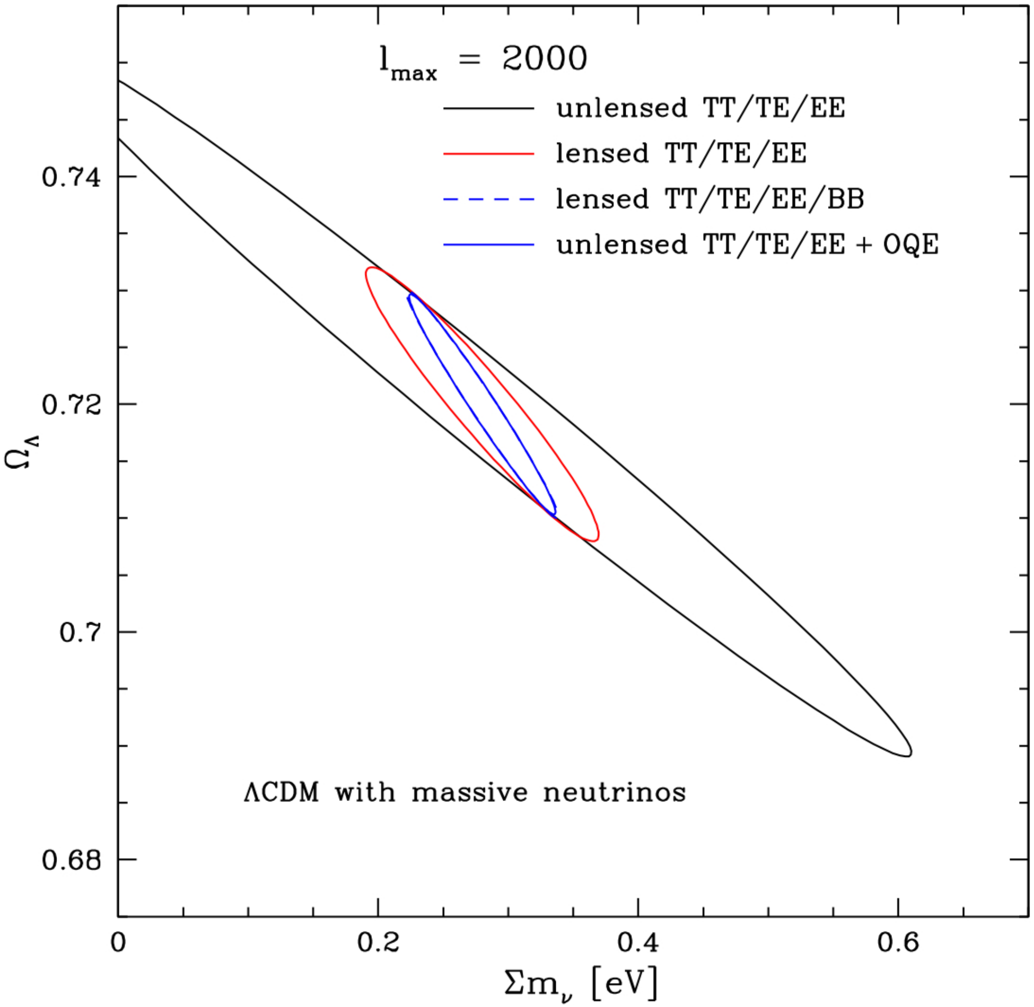

**Euclid study**

Appleby, Linder, Weller 2012

**also for DES**

# 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 |
| $w_0$-$\Omega_e$ | Planck+SN | 0.032 | – | 0.0042 | 0.15 |
| $w_0$-$\Omega_e$ | CMBpol+SN | 0.018 | – | 0.0020 | 0.050 |

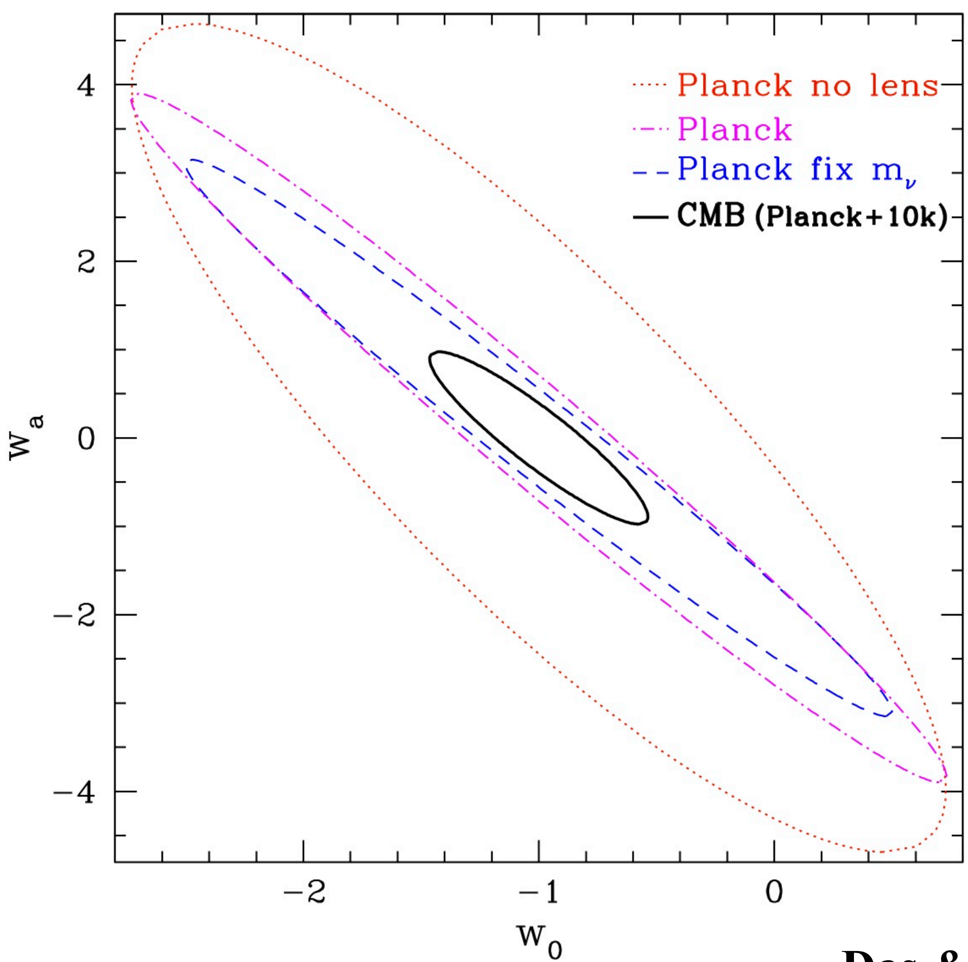
**de Putter, Zahn, Linder 2009**

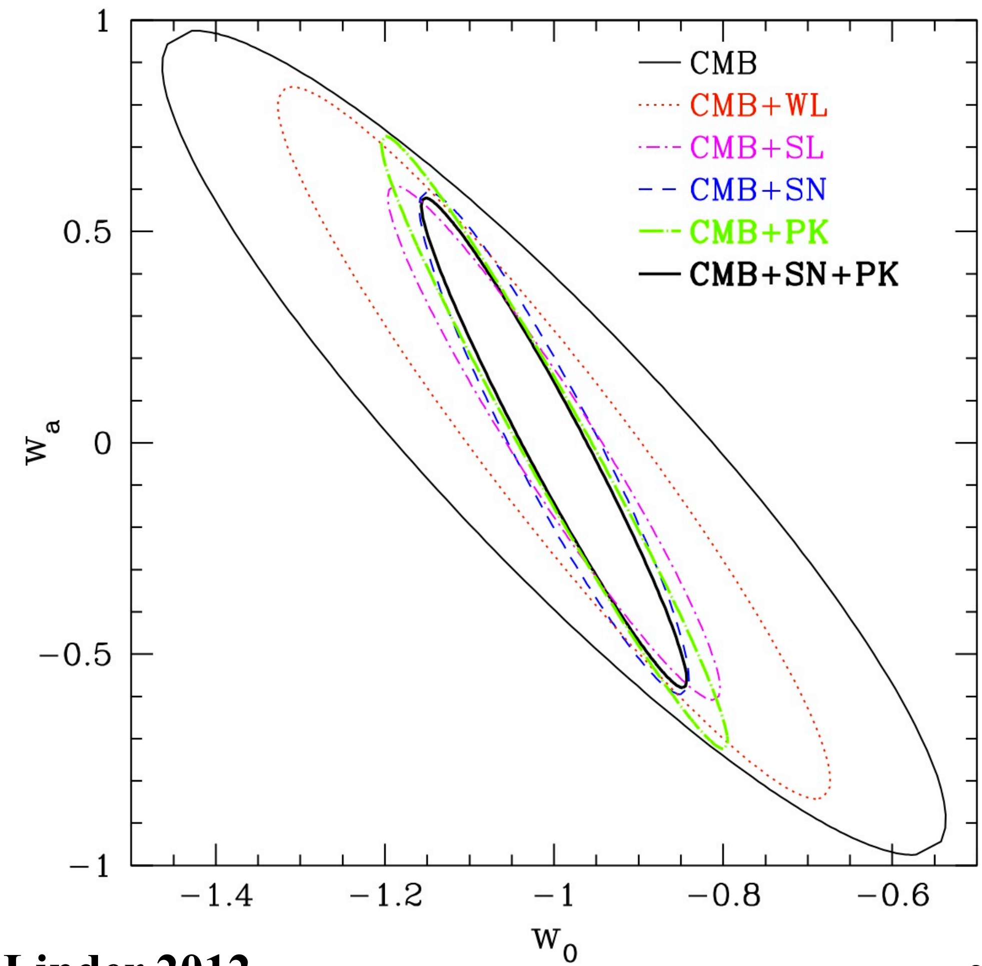
**SPT/ACT gets 8/3.2σ for Λ from CMB lensing.**

**van Engelen+ 2012, Sherwin+ 2011**

# Dawn's Early Light

**Ground based experiments (ACTpol, Polarbear, SPTpol) are doing CMB lensing *now*.  This changes the DE probe landscape.**



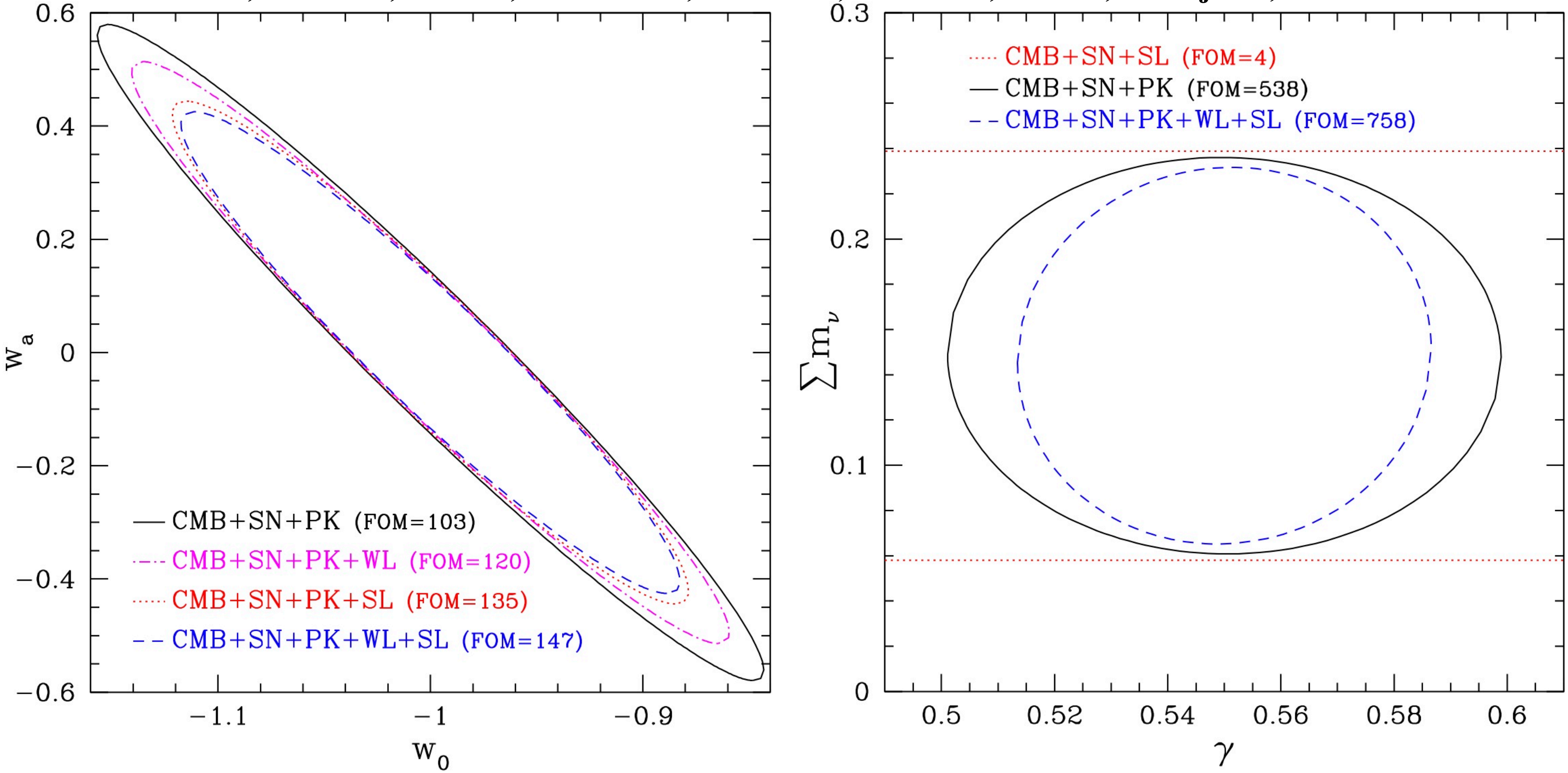




**Das & Linder 2012**

# 5 Year Realization (Cosmology 2017)

**Supernovae (SN) ~ DES ; Galaxy Clustering (PK) ~ BOSS**
**[Weak Lensing (WL) ~ DES ; Strong Lensing (SL) ~ HST?**

**SN: Linder; PK: Das, Linder; CMB: Das; WL: Das, de Putter, Linder, Nakajima; SL: Linder**




**Strong program in place, but also easy to do better!**

# Ideas/Trends/Lessons

Very much a program: multiple, diverse surveys. Ground CMB adds +67% (FOM$w$), +134% (FOM$\nu$).

Strong program in place + easy improvements exist!

Lensing time delays improve FOM by 32%, cost 150-230 HST orbits.

Enhanced low z SN (300 with dm=0.008) improve FOM by 26%.

If weak lensing falters, we can still learn a lot.

Must be realistic: fixing $m_\nu$, $\gamma$ projects FOM x 2.77!

Can learn $\sigma(w_a)=0.25$, $\sigma(m_\nu)=0.055$ eV by 2017.

# Summary

Much progress made: ruling out quintessence trackers, <w>~-1, robust GR tests/extensions.

Dark energy is not the search for one number "w". Explore dynamics, degrees of freedom, persistence.

Gravity and particle physics informing DE models.

CMB polarization, mass power spectrum, (lensing time delays) are important upcoming probes.

Complementary probes: very much a program. Theory/simulate/observe equal weighting essential.

Data in next 5 years has us closing in on our chase of cosmic acceleration.