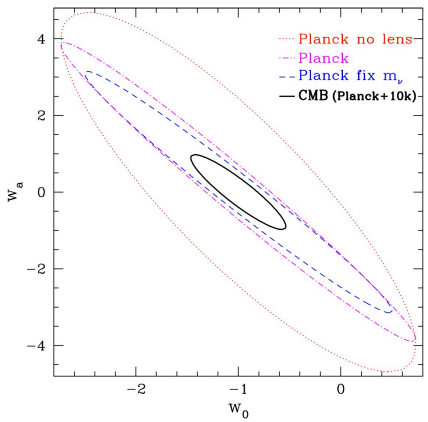
Chasing Down
Cosmic Acceleration

Eric Linder

24 July 2013



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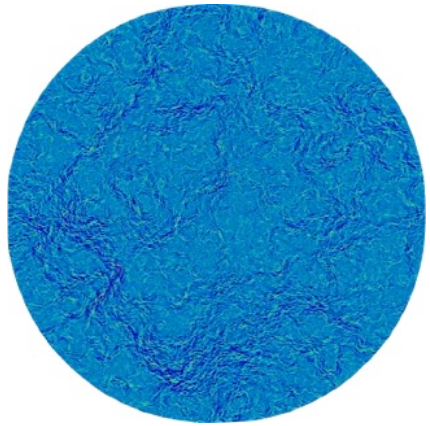


Role of Observations

But Λ, what big teeth you have!

Before we jump into bed with Λ, we should be sure it is not something more beastly.

Role of Theory

"He is a barbarian, and thinks that the customs of his tribe and island are the laws of nature."

– George Bernard Shaw, *Caesar and Cleopatra*

Copernican Principle / Cosmic Modesty:

- **Our galaxy is not the center of the universe.**
- **Our particles are not the matter/energy of the universe.**
- **Is our vacuum the vacuum of the universe?**
- **Is our gravity the gravity of the universe?**

Dark Energy as a Teenager

15 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=1.7.

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.

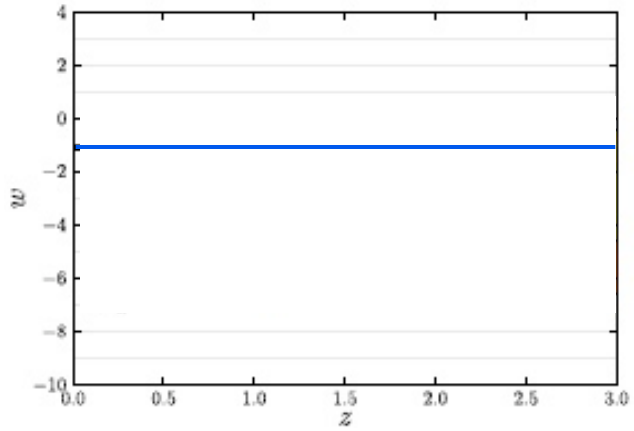
Weak lensing detected. Concordant with acceleration.

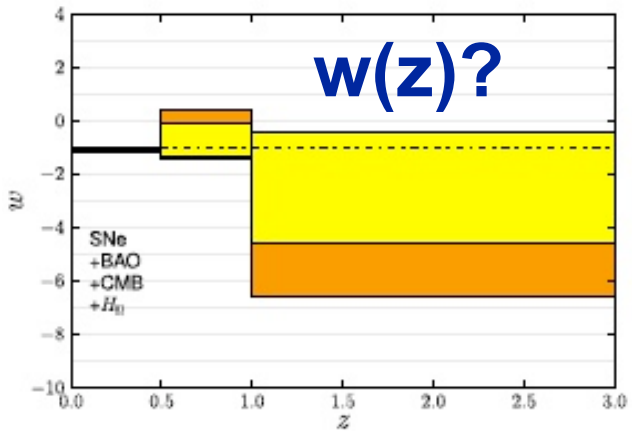
Cluster masses calibrated. Concordant with acceleration.

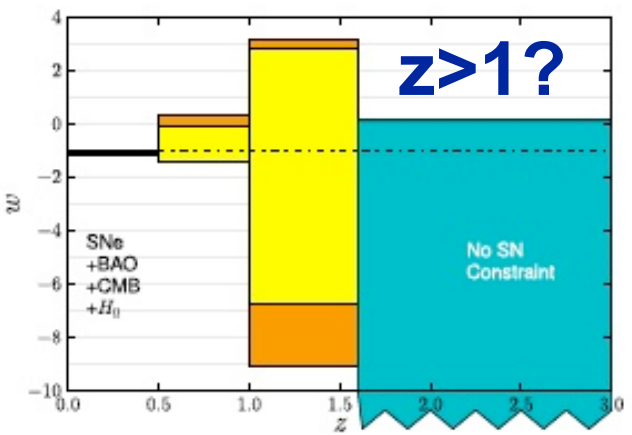
Strong concordance among data: Ω_{DE}~0.73, w~-1.

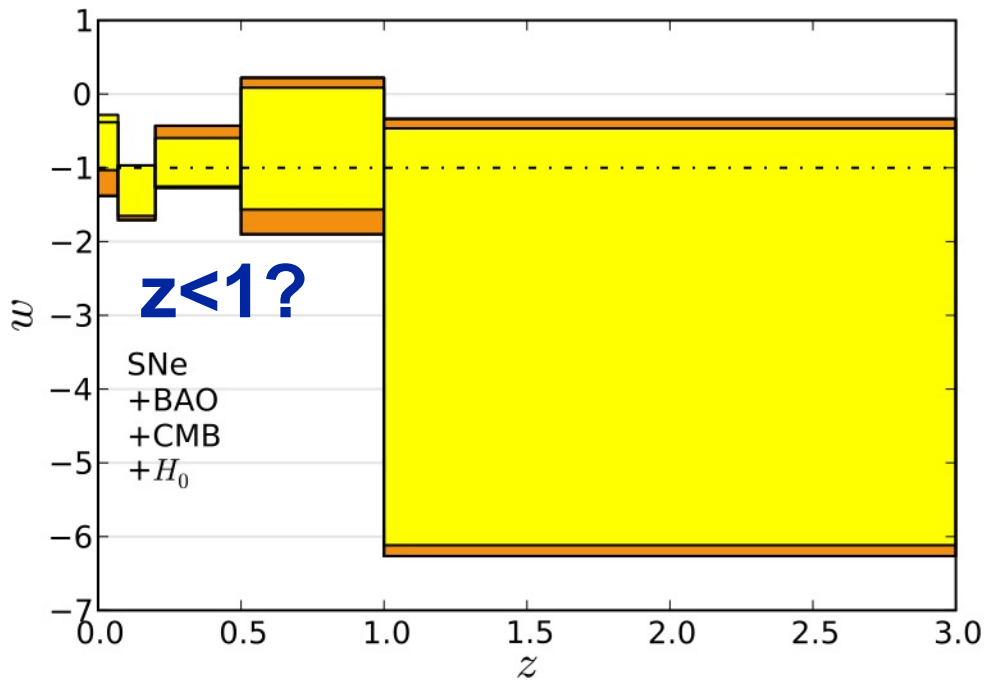
Are We Done?

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





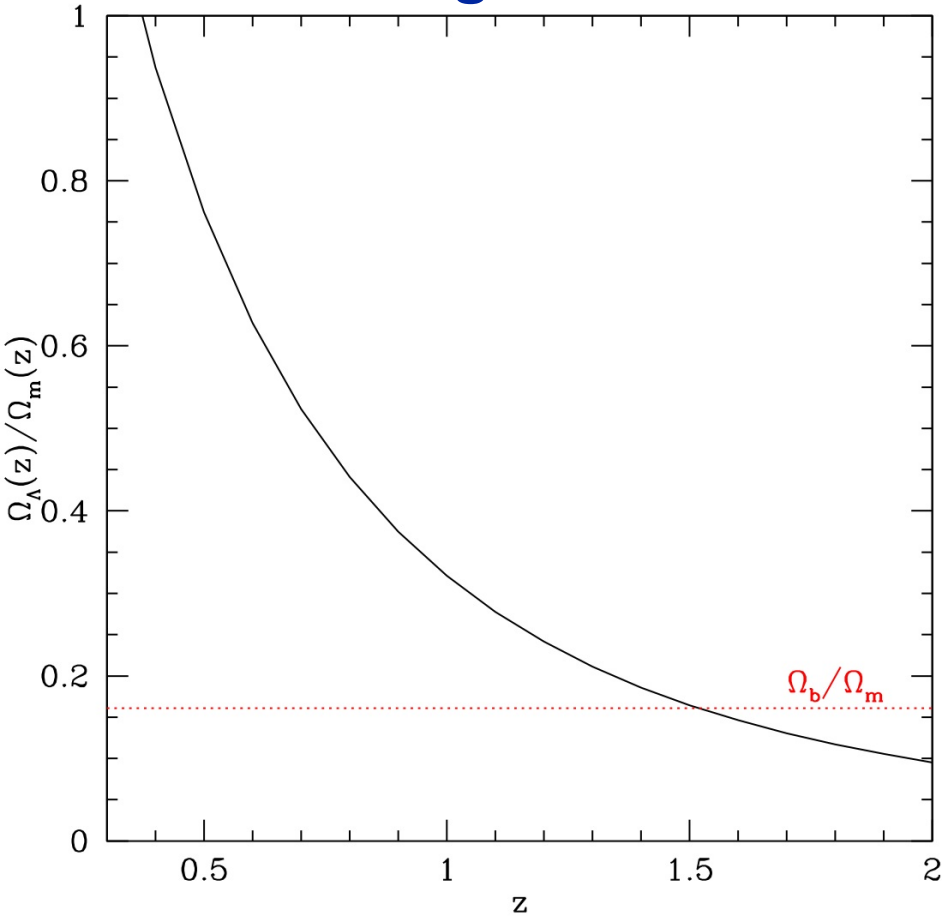


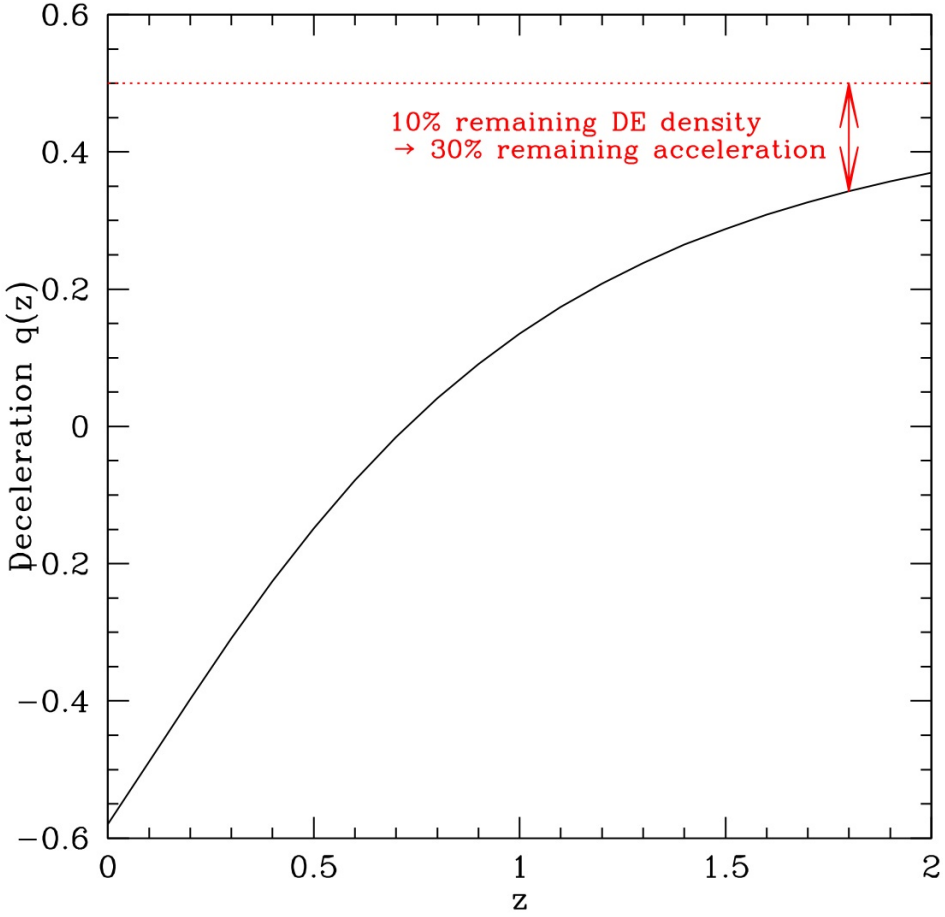


There is a long way to go still to say we have measured dark energy!

Redshift Range for Acceleration

Acceleration is not just "recent universe", z<<1. Over what redshift range should we measure it?





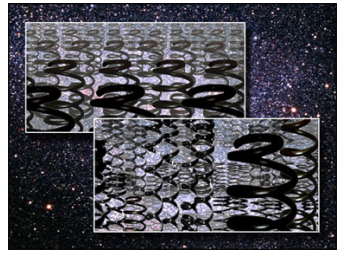
Deep enough that is less than 10% energy density? Not next-to-dominant?

Deep enough that have accounted for >2/3 of the acceleration?

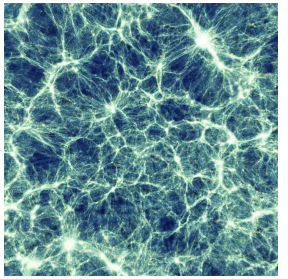
Nature of Dark Energy

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

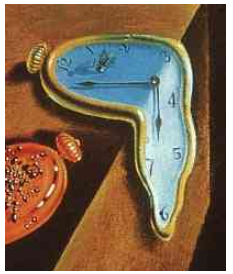
Dynamics: Theories other than Λ give time variation w(z). [SN+CMB/BAO]



Degrees of freedom: Quintessence has sound speed $c_s^2=1$. But generally w(z), $c_s^2(z)$. Is DE cold ($c_s^2<<1$), enhance perturbations?
[CMB lensing, WL]



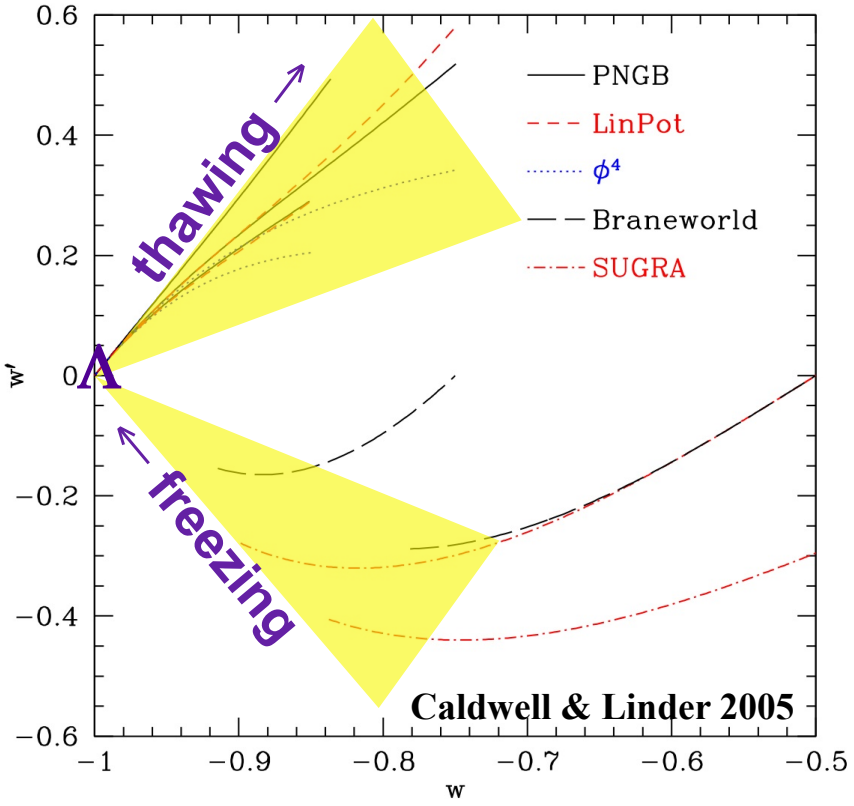
Persistence: Is there early DE (at z>>1)?
$\Omega_\Lambda(z_{CMB})\sim10^{-9}$ but observations allow 10^{-2}.
[CMB lensing, CMB x Galaxies]



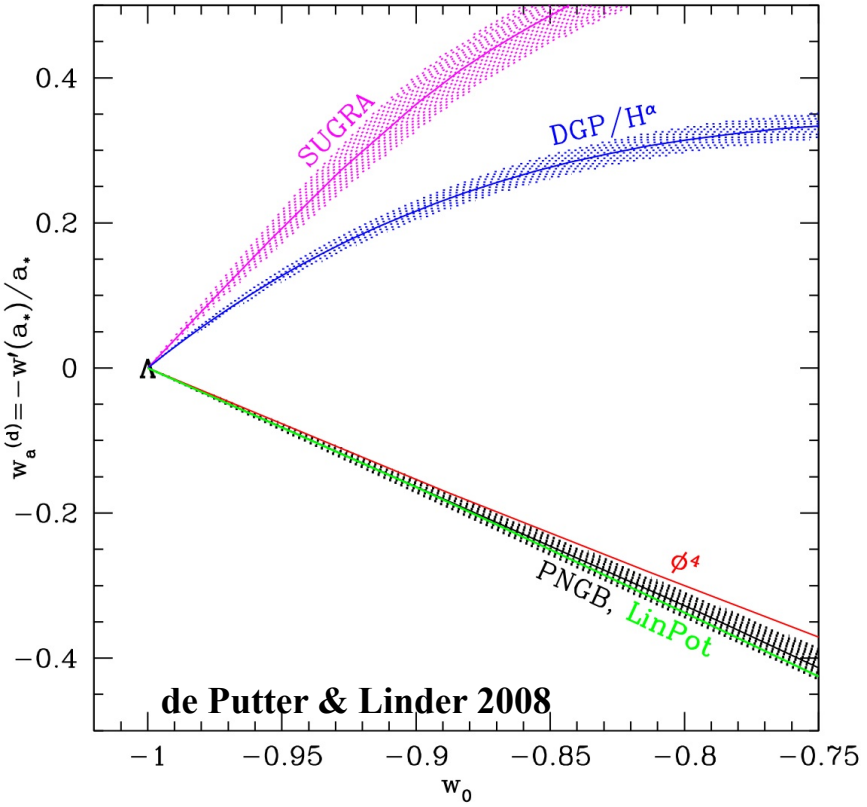
Test Gravity: Expansion vs growth
[SN/BAO + CMBlens/WL/Gal]

1. Dynamics

Models have a diversity of behavior, within thawing and freezing.



But we can calibrate w' by "stretching" it: $w' \rightarrow w'(a_*)/a_*$.
Calibrated parameters w_0, w_a.



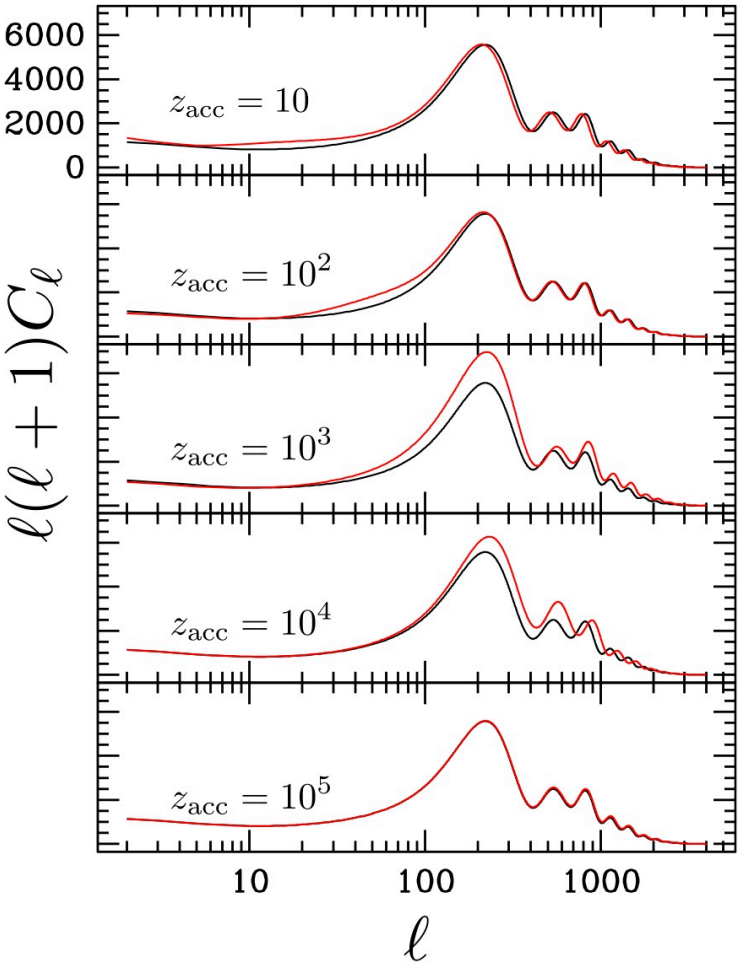
The two parameters w_0, w_a achieve 10^{-3} level accuracy on observables d(z), H(z).

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

This is from physics (Linder 2003). It has *nothing* to do with a Taylor expansion.

2. Persistence

We have 7 orders of magnitude of unexplored $\Omega_{DE}(z_{rec})=10^{-[2-9]}$
Was there early acceleration (solve coincidence)?
Was there early dark energy?



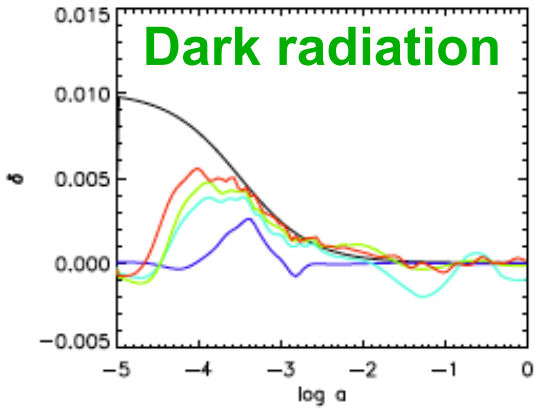
Linder & Smith 2010

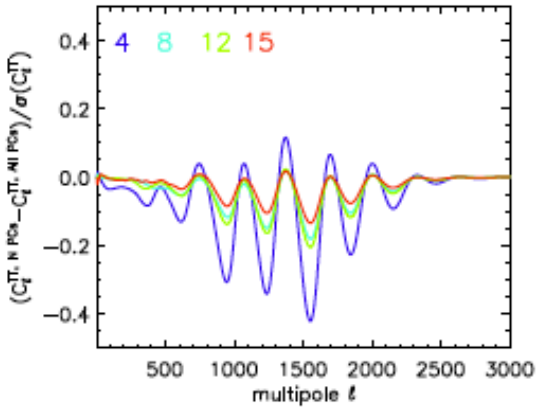
Effect of 0.1 e-fold of acceleration

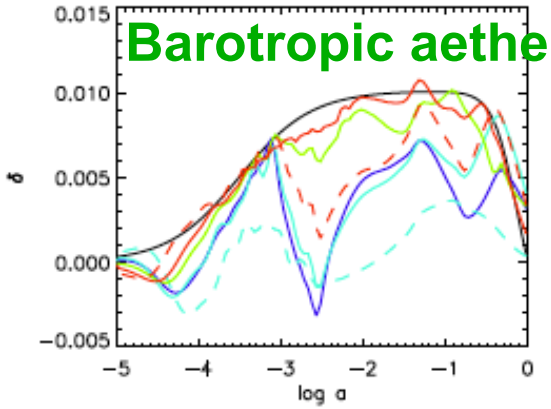
Post-recombination,
peaks → left and adds ISW.
Pre-recombination,
peaks → right and adds SW.

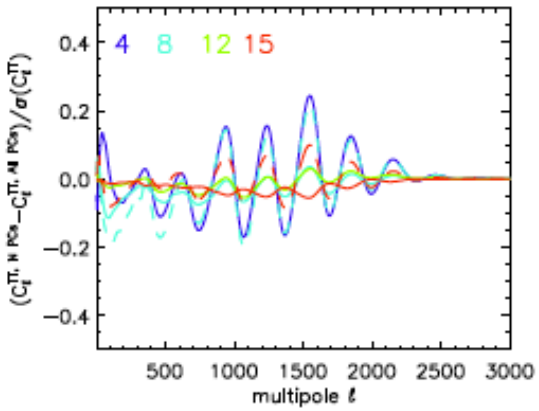
Current acceleration unique within last factor 100,000 of cosmic expansion!

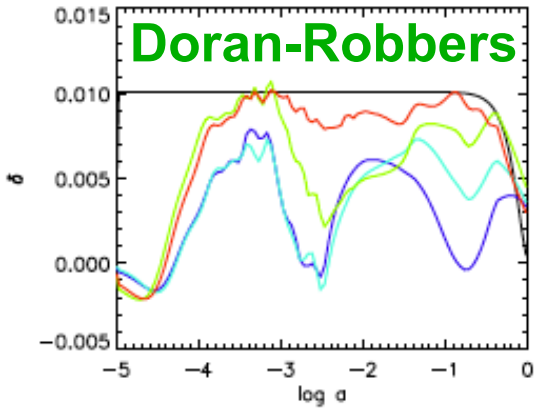
Early Dark Energy

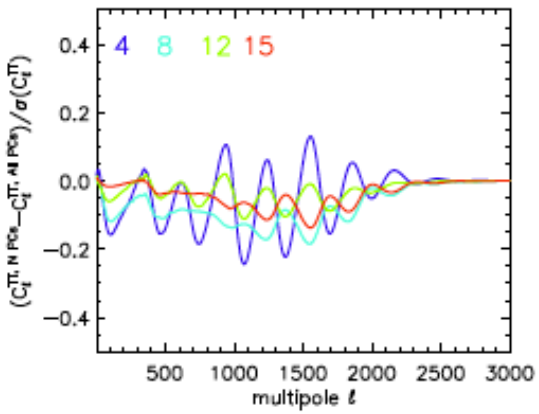












Predicted by many high energy theories.

3 classes of models rising/falling/constant energy density during recombination.

Identify through PCA (principal component analysis).

Samsing, Linder, Smith 2012

Early Dark Energy

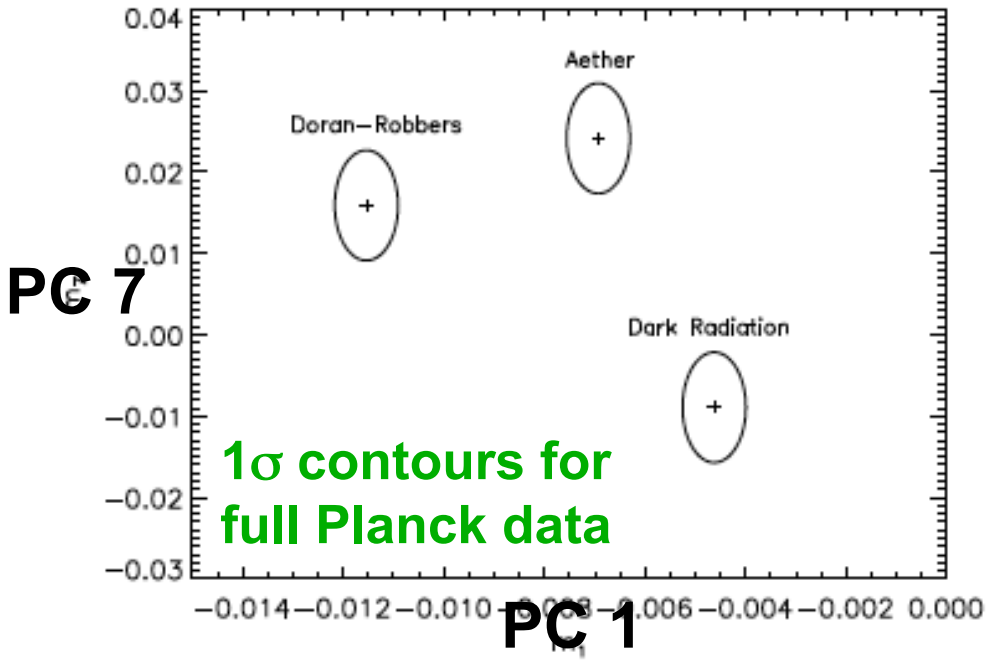
Planck+ constraint of 0.9% EDE only applies to easiest case.

	Aether	Dark Radiation	Doran-Robbers
Ω_e	0.019	0.033	0.012

gives $N_{eff}>3$

Hojjati, Linder, Samsing 2013

Planck data will easily separate the 3 classes into distinct regions of eigenspace.



3. Perturbations / Microphysics

DE internal degrees of freedom can give rise to DE perturbations (inhomogeneity).

Only significant when 1+w is not small. Since <w(z<1)> ~ -1, this implies need early dark energy.

Perturbations only grow outside the sound horizon ~ c_s/H so we need the sound speed $c_s<<1$.

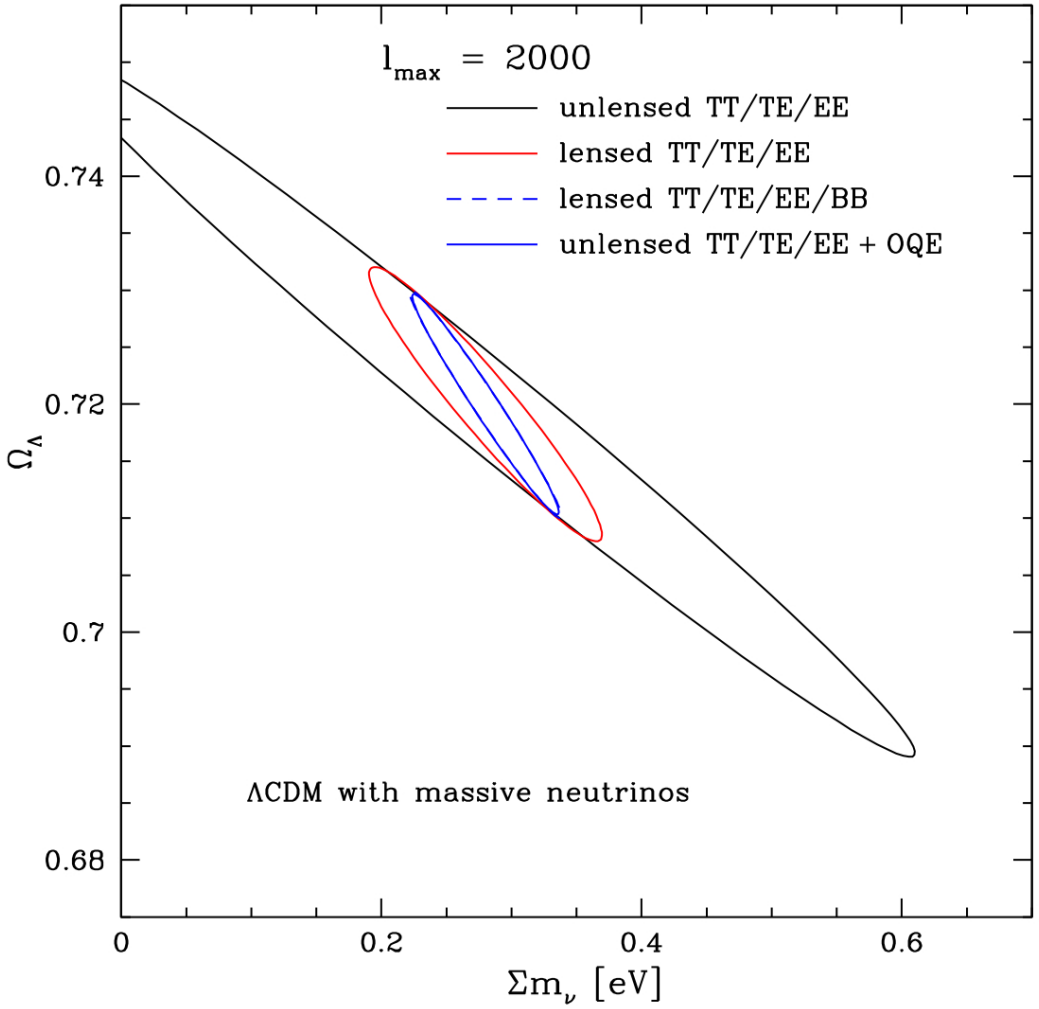
Thus persistence → early dark energy.

Degrees of freedom → cold early dark energy.

(These go together in many classes of DE theories, e.g. Dirac-Born-Infeld or string dilaton)

CMB Lensing

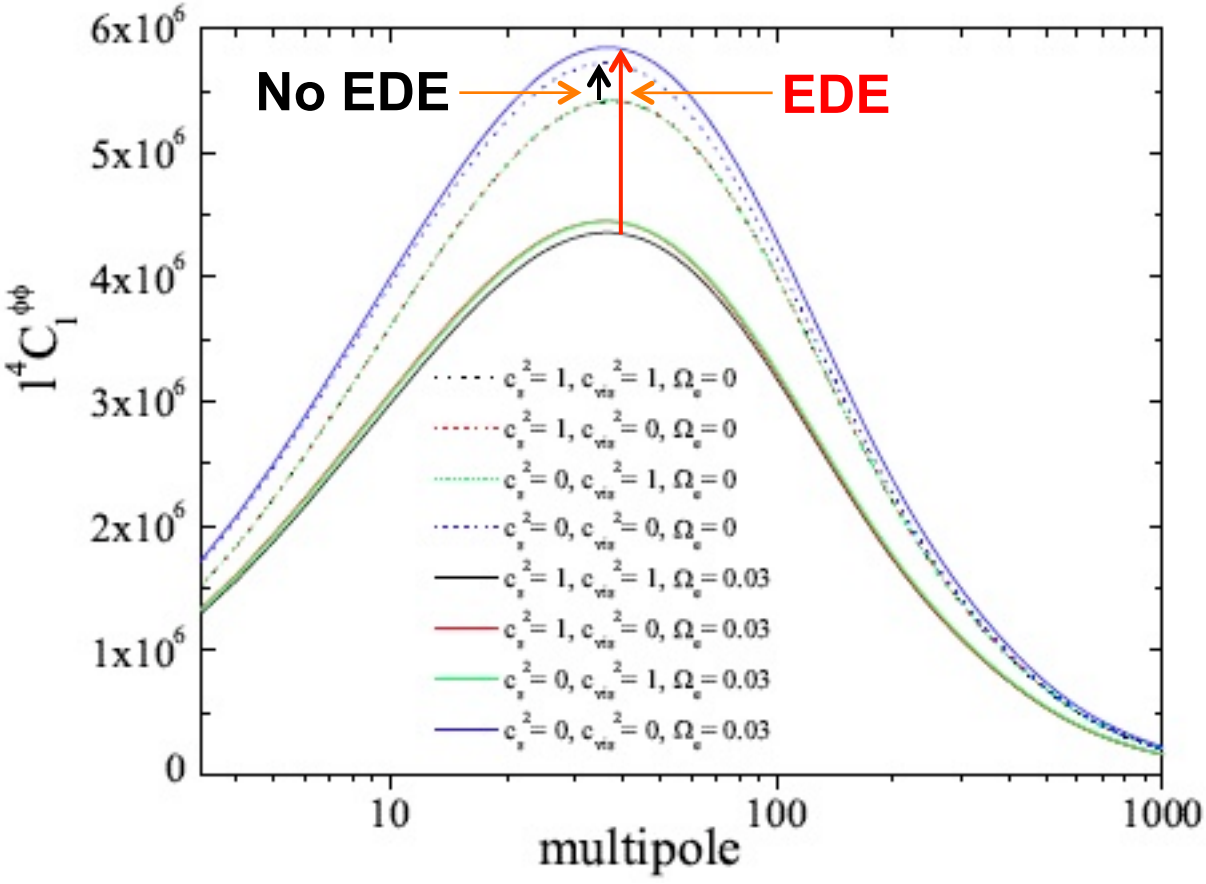
CMB as a source pattern for weak lensing. Probes z~1-5 effects, e.g. neutrino masses and early dark energy.

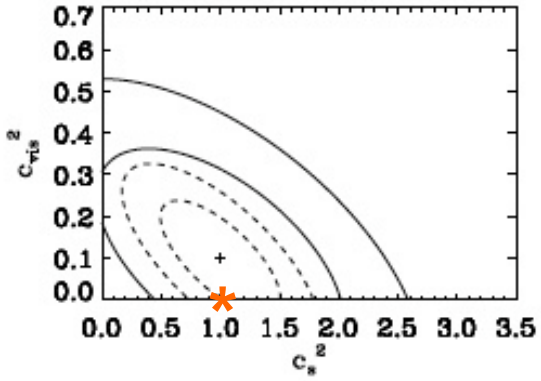


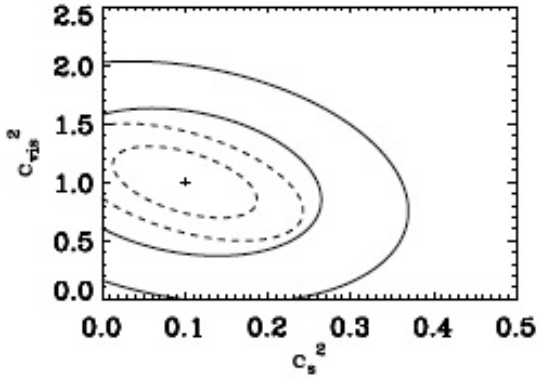
Planck gets ~25σ for Λ from CMB lensing.

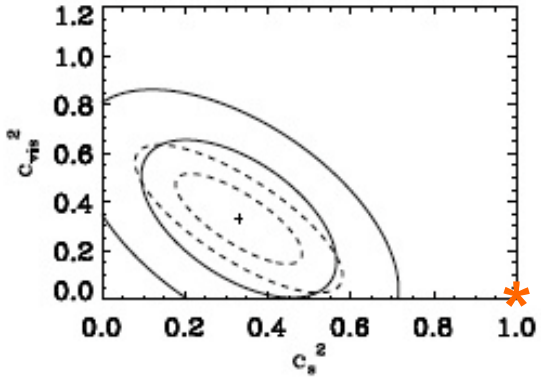
CMB Lensing and Cold EDE

DE perturbations affect matter power spectrum and so CMB lensing. $c_s \neq 1$? $c_{vis} \neq 0$? Hu 1998









4. Test Gravity

Test gravity in model independent way.

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

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

Are ϕ and ψ the same? (yes, in GR)

Tie to observations via modified Poisson equations:

$$\nabla^2(\phi+\psi) = 8\pi G_N\, a^2\, \delta\rho \times G_{\rm light}$$

$$\nabla^2\psi = 4\pi G_N\, a^2\, \delta\rho \times G_{\rm matter}$$

$G_{\rm light}$ tests how light responds to gravity: central to lensing and integrated Sachs-Wolfe.

cf Bertschinger & Zukin 2008

$G_{\rm matter}$ tests how matter responds to gravity: central to growth and velocities (γ is closely related).

Extending Gravity

Interesting recent theories extending gravity for cosmic acceleration often have shift symmetries (depend on ϕ_μ not ϕ) **and higher order kinetic terms** (related to higher dimensions or massive gravity).

From Horndeski general scalar-tensor theory,

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

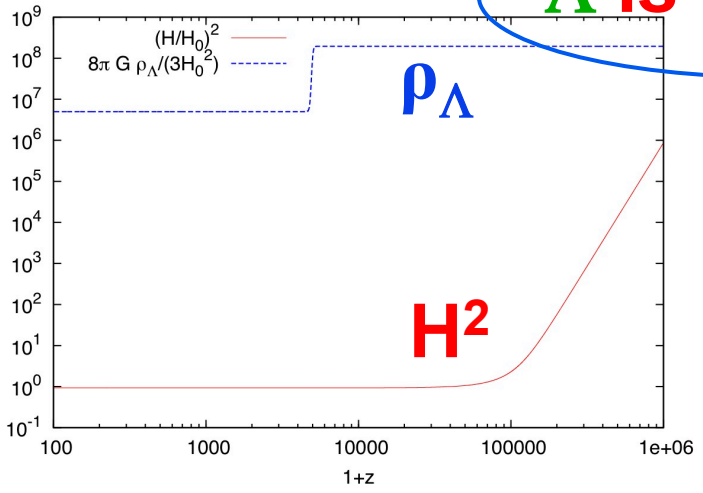
Appleby, De Felice, Linder 2012 promote to nonlinear, mixed function.

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

"Fab 5 Freddy"

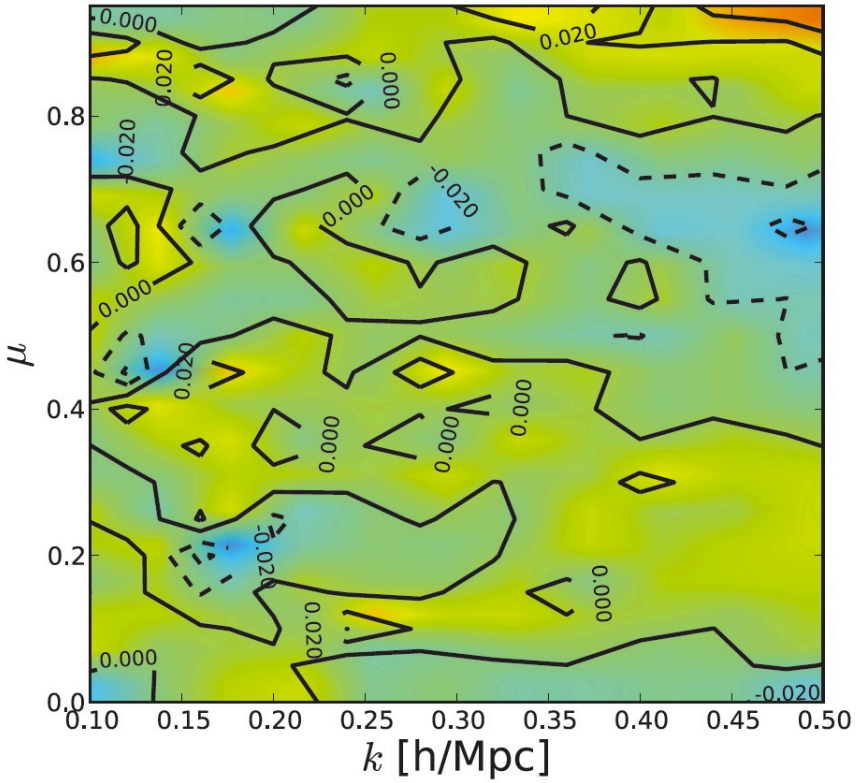
Λ is invisible!

Fab 5 Freddy accelerates, has tracker, dS attractor, no extra dof! – and self tuning.

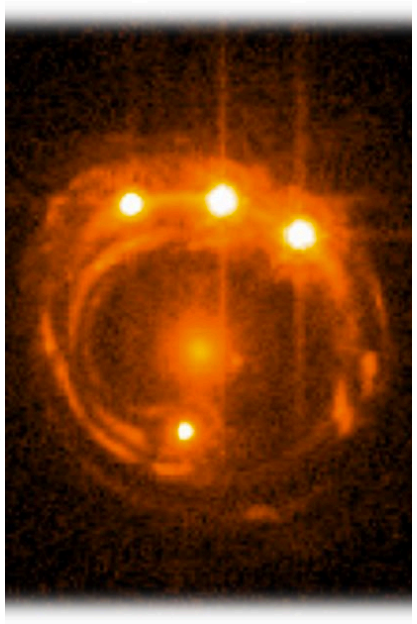


also see Padilla & Sivanesan 2013

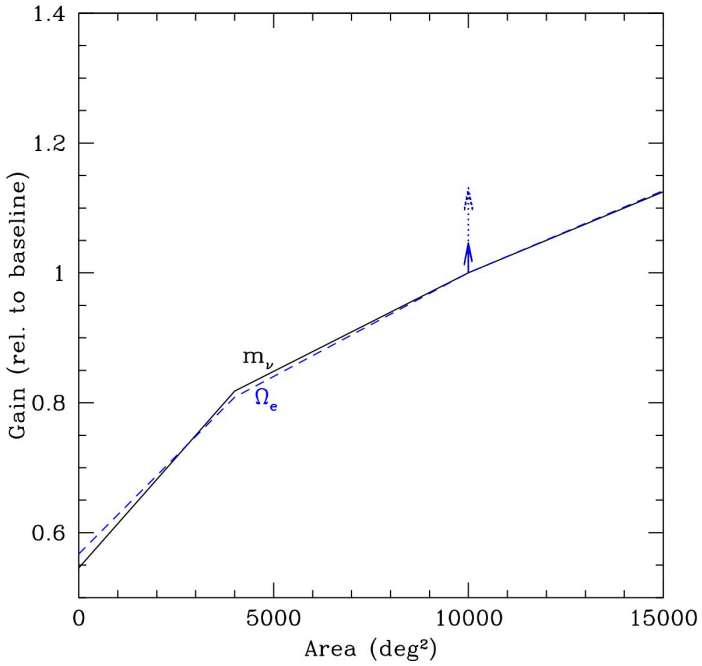
New Probes, New Results



Redshift space distortion modeling to 2%



Strong lensing time delay accuracy to 1%



CMB lensing from ground +50% on dark energy, m_ν

Cosmic Acceleration

Dark energy is not the search for one number "w".
Explore dynamics, degrees of freedom, persistence.
Strong program in place + new probes (CMB,RSD,SL).

Astronomer Royal (Airy):
"I should not have believed it if I had not seen it!"

Astronomer Royal (Hamilton):
"How different we are! My eyes have too often deceived me. I believe it because I have proved it."