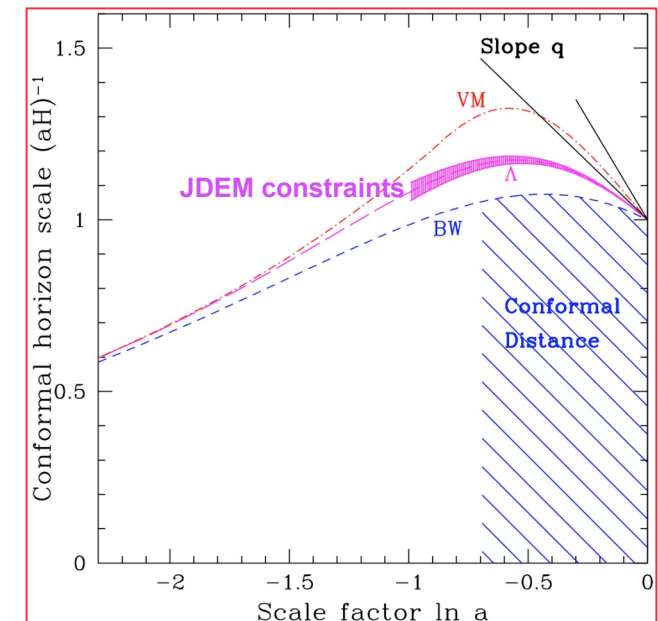
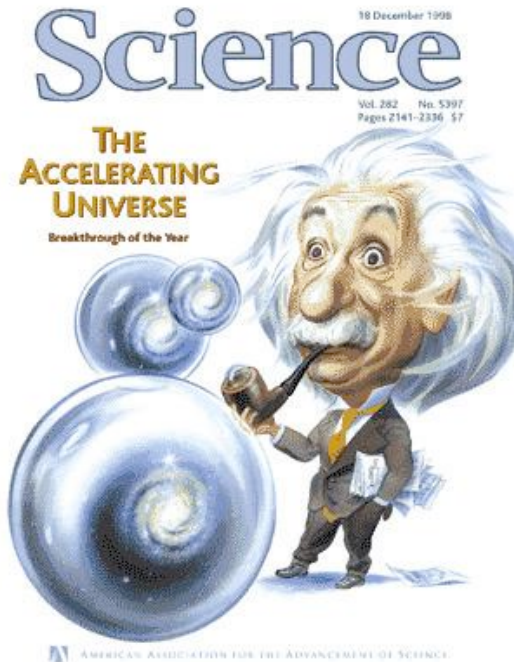


# Whither Beyond Einstein?

## or The 5 Stages of Dark Energy

**Eric Linder**

University of California, Berkeley  
Lawrence Berkeley National Lab



# The 5 Stages of Dark Energy

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**When confronted with the diagnosis of an accelerating universe, one may experience:**

- **Denial**
- **Anger**
- **Bargaining**
- **Depression**
- **Acceptance**

# The 5 Stages of Dark Energy

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When confronted with the diagnosis of an accelerating universe, one may experience:

- **Denial** —————→ There is no acceleration (blame grey dust,  $H_0$ , backreaction, etc.). But this fades before SN+CMB+BAO+age+LSS+ISW...
- **Anger**
- **Bargaining**
- **Depression**
- **Acceptance**

# The 5 Stages of Dark Energy

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When confronted with the diagnosis of an accelerating universe, one may experience:

- Denial

- **Anger**



**Fine tuning / Coincidence causing anger and anthropic arguments**

- Bargaining

- Depression

- Acceptance

# The 5 Stages of Dark Energy

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When confronted with the diagnosis of an accelerating universe, one may experience:

- Denial

- Anger

- Bargaining

→ Dynamical DE,  
Modified gravity

- Depression

- Acceptance

# The 5 Stages of Dark Energy

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When confronted with the diagnosis of an accelerating universe, one may experience:

- Denial
- Anger
- Bargaining
- **Depression**
- Acceptance

Too many models, degeneracies, string theory, back to  $\Lambda$ ?

# The 5 Stages of Dark Energy

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When confronted with the diagnosis of an accelerating universe, one may experience:

- Denial
- Anger
- Bargaining
- Depression
- **Acceptance** —————→ **Let's do the experiments!**

# Dynamics of Quintessence



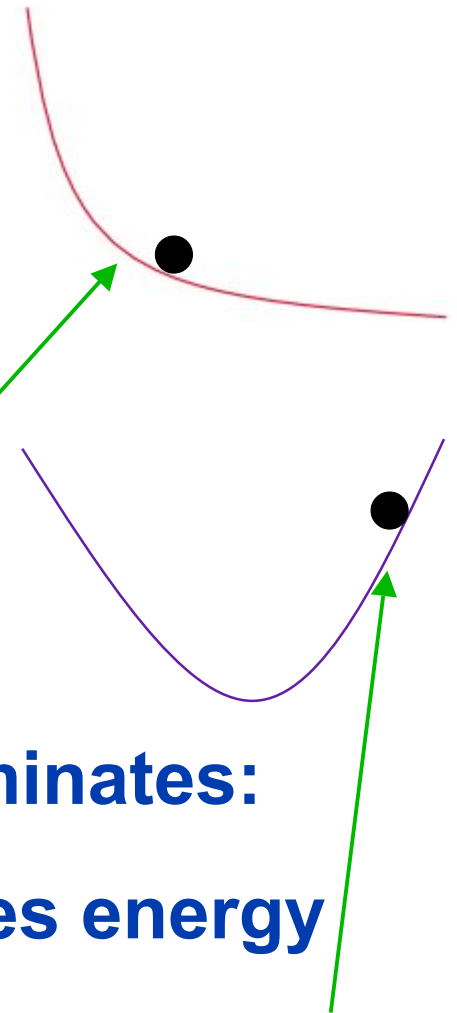
Equation of motion of scalar field

$$\ddot{\phi} + 3H\dot{\phi} = -dV(\phi)/d\phi$$

- driven by steepness of potential
- slowed by Hubble friction

Broad categorization -- which term dominates:

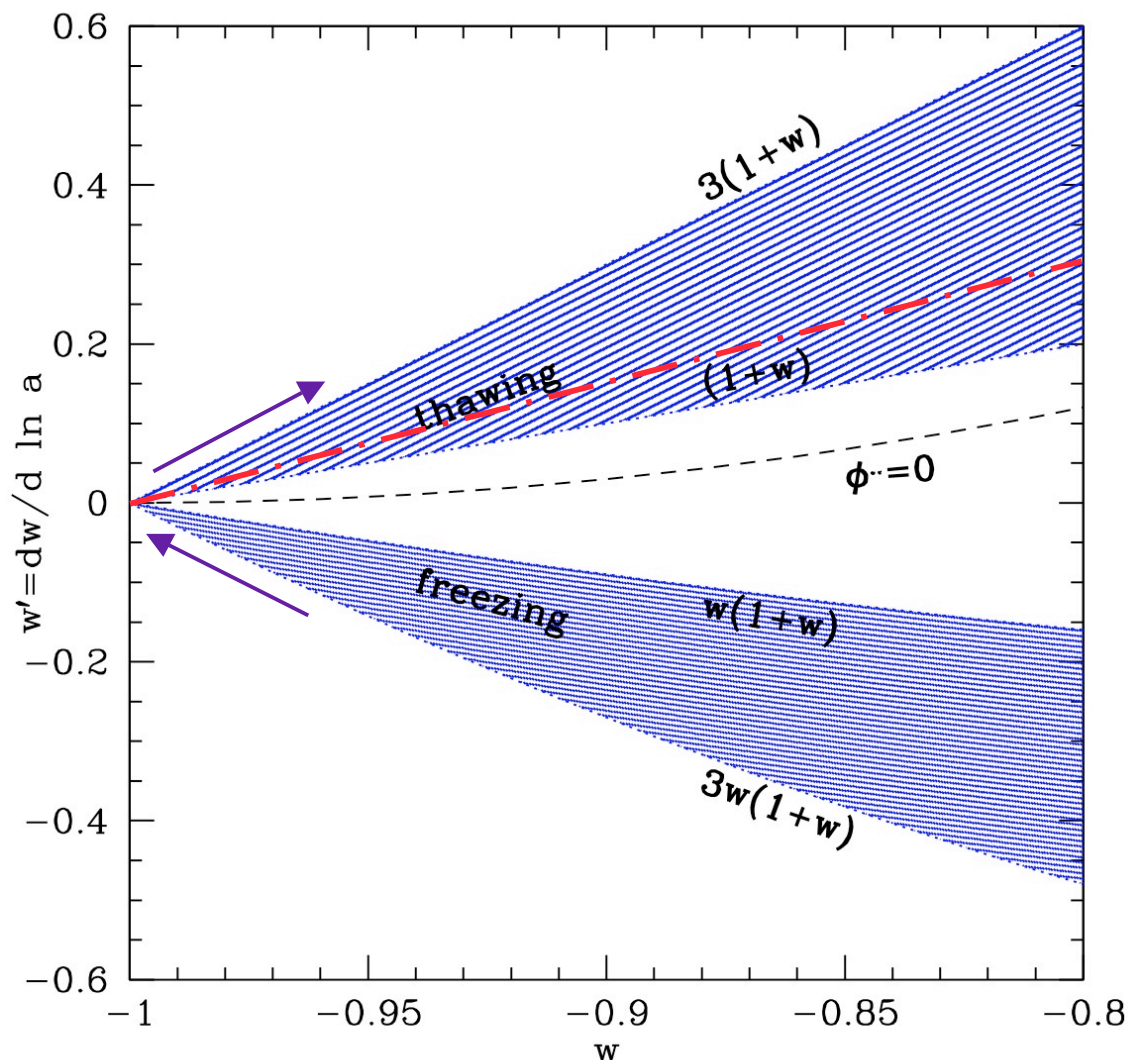
- field rolls but decelerates as dominates energy
- field starts frozen by Hubble drag and then rolls



**Freezers vs. Thawers**



# Limits of Quintessence



$$w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

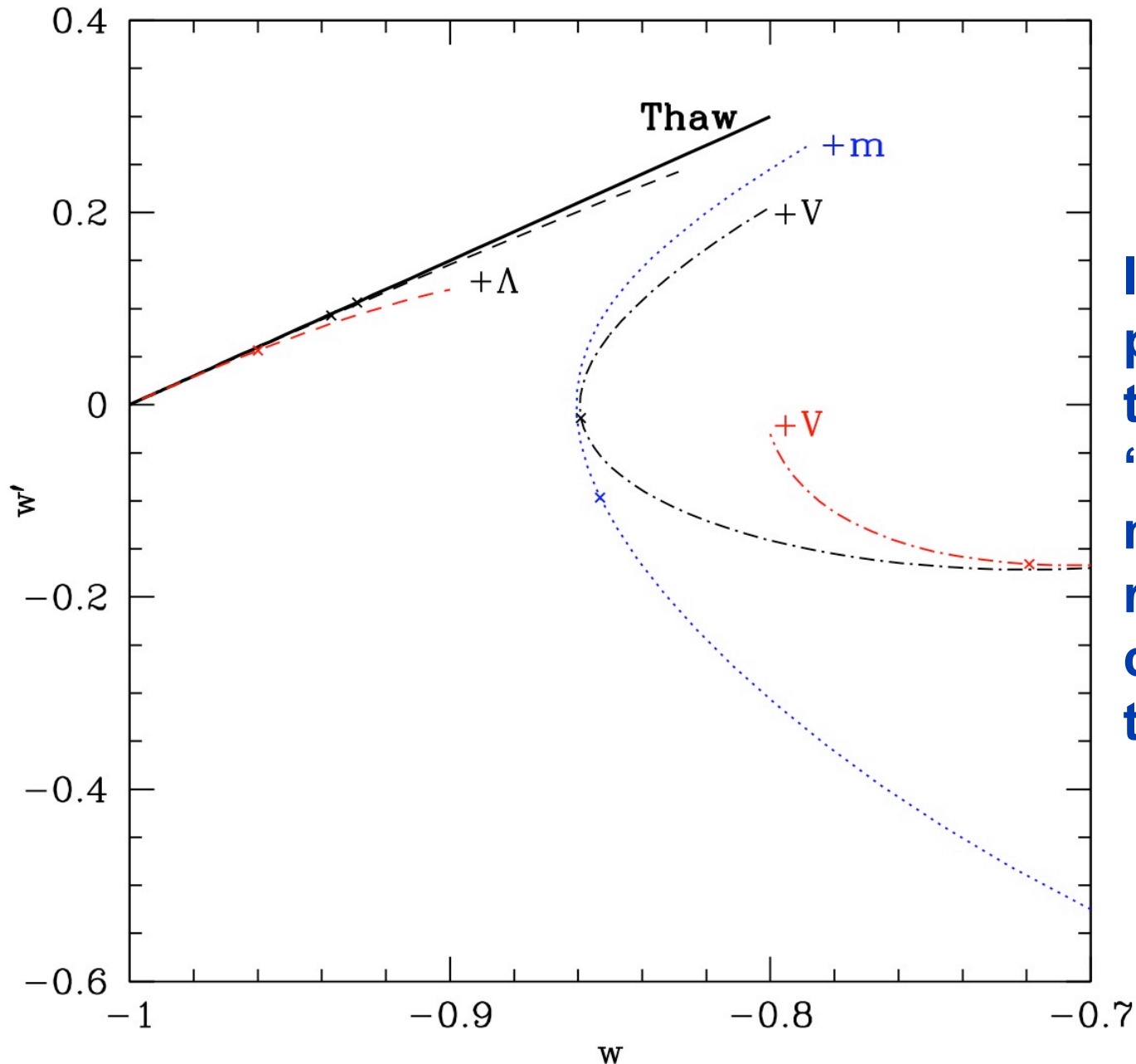
Distinct, narrow regions of  $w-w'$

Caldwell & Linder 2005  
PRL 95, 141301

Entire “thawing” region looks like  $\langle w \rangle = -1 \pm 0.05$ .

Need  $w'$  experiments with  $\sigma(w') \approx 2(1+w)$ .

# The Quintessence of Dynamics

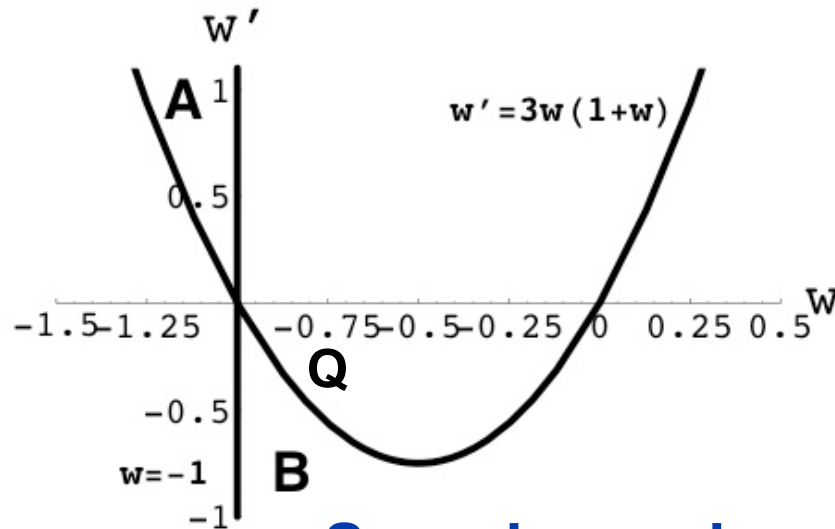


**If one conflates physics, rather than taking “fundamental modes”, or one randomizes initial conditions, any track is possible.**

# A Purely Kinetic World



**Kinetic k-essence: no potential to fine tune, non-canonical kinetic term  $L=F(X)$**

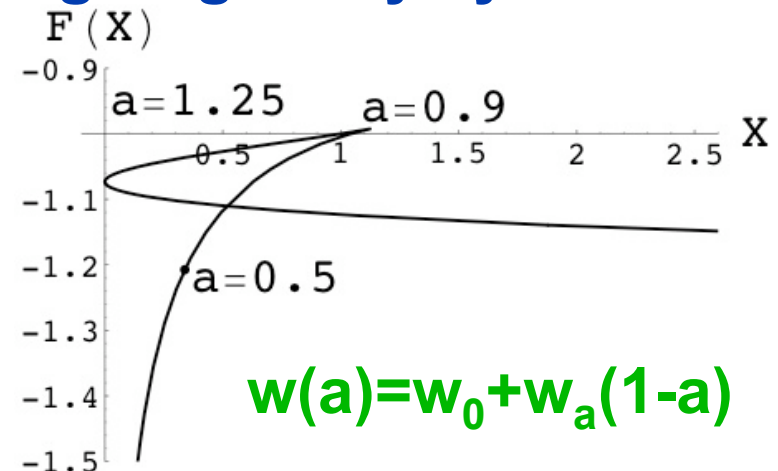
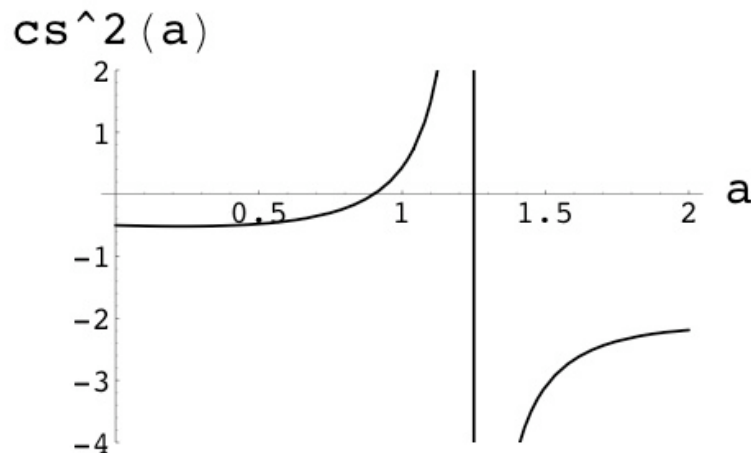


**K-essence separated from quintessence**

Scherrer 2006, de Putter & Linder 2007

Sen 2006, de Putter & Linder 2007

**Sound speed  $c_s \neq 1$ , distinct from quintessence. Can read off valid Lagrangian by eye.**



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

# Beyond Scalar Fields



Observations that map out expansion history  $a(t)$ , or  $w(a)$ , tell us about the fundamental physics of dark energy.

Alterations to Friedmann framework  $\rightarrow w(a)$

Suppose we admit our ignorance:

$$H^2 = (8\pi/3) \rho_m + \delta H^2(a)$$

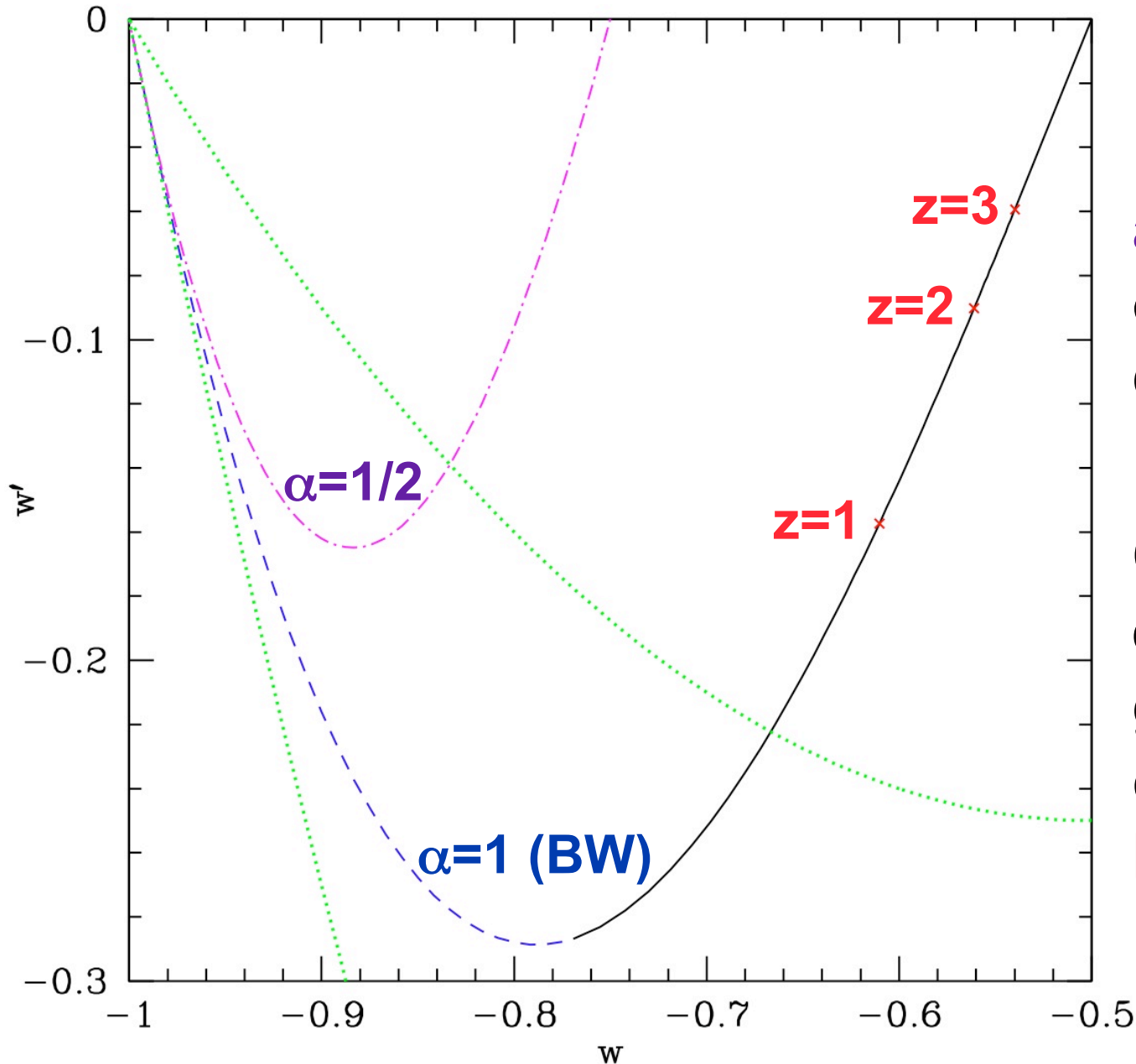
gravitational extensions  
or high energy physics

Effective equation of state:

$$w(a) = -1 - (1/3) d \ln (\delta H^2) / d \ln a$$

Modifications of the expansion history are equivalent to time variation  $w(a)$ . Period.

# Gravity Beyond 4D



**DGP Braneworld,  
and  $H^\alpha$  mods,  
obey freezer  
dynamics in  $w-w'$**

**Can reproduce  
expansion *or*  
growth with  
quintessence,  
*but not both.***

**Growth  $g(a)=(\delta\rho/\rho)/a$  depends purely 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  $w(z)$ , but *separate* effects of gravity on growth.**

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

Linder 2005

**Growth index  $\gamma = 0.55 + 0.05[1 + w(z=1)]$**

**Works to 0.05 – 0.2%!**

# Revealing the Nature of the Physics



To test Einstein gravity, we need growth and expansion measures, e.g. Supernovae and Weak Lensing.

Keep expansion history as  $w(z)$ , growth *deviation* from expansion by  $\gamma$ .

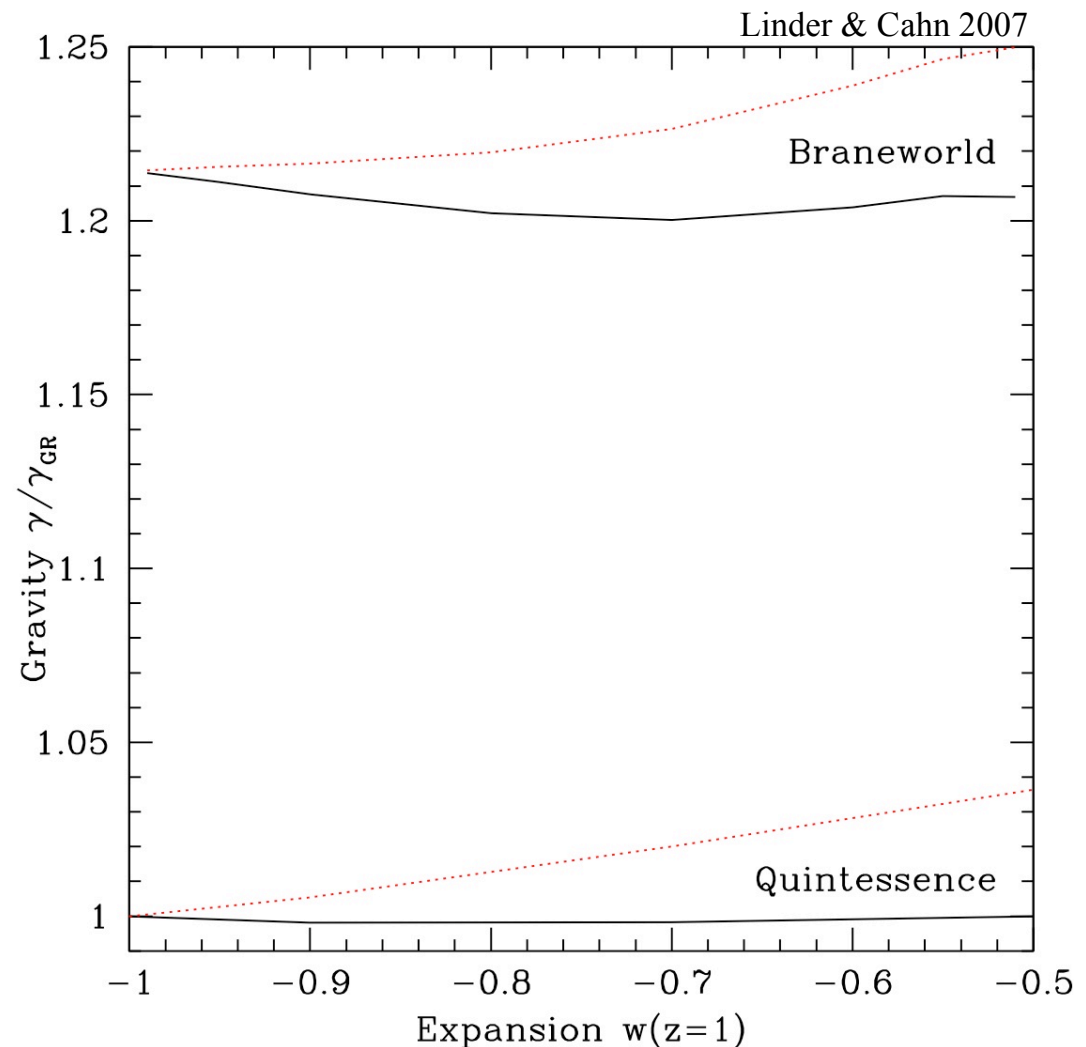
Clear signal: 20% vs. 0.2%

**Paradigm:**

To reveal the origin of dark energy, measure  $w$ ,  $w'$ , and  $\gamma$ .

$w$ ,  $w'$ , and  $\gamma$ . Minimal Modified Gravity (MMG)

e.g. use SN+WL.

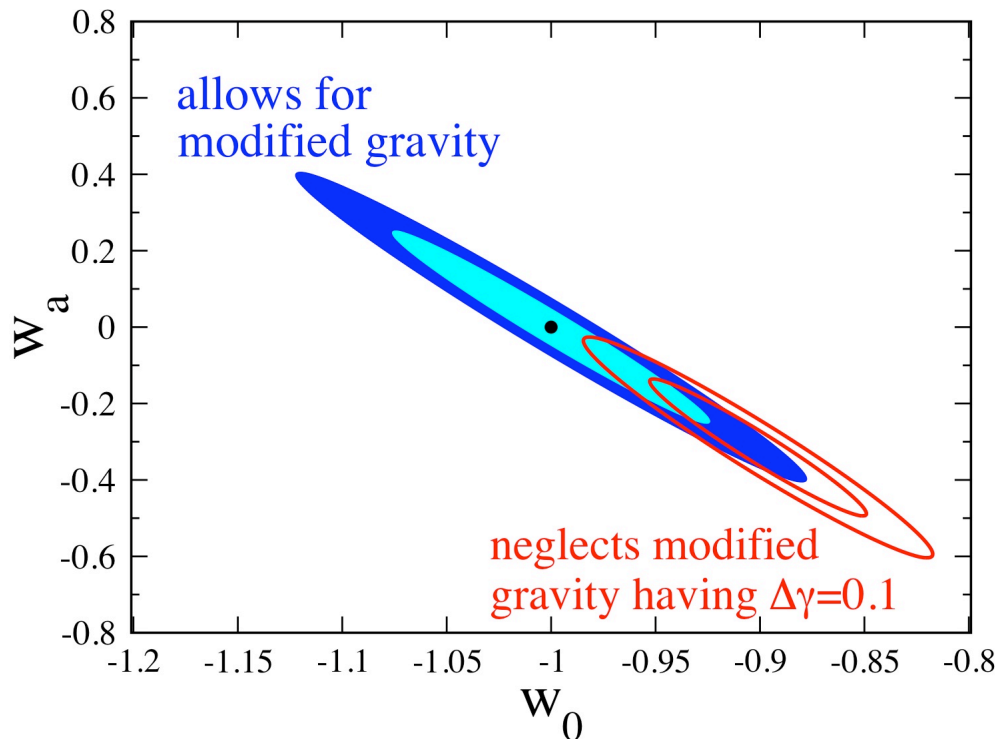




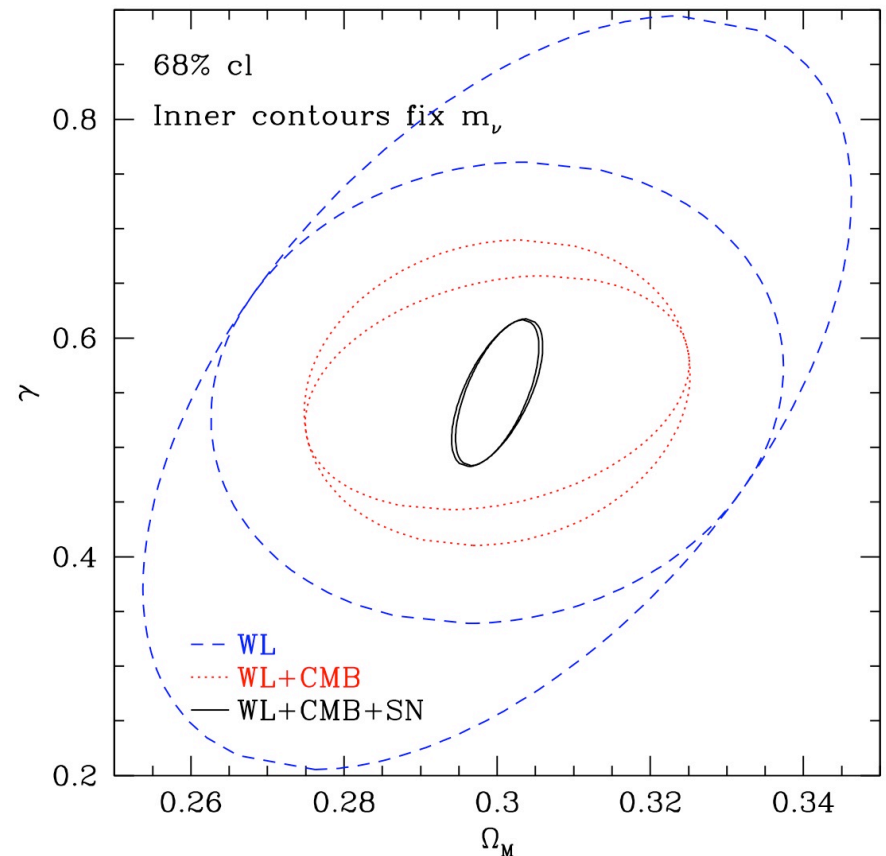
# Gravity's Bias



Neglecting modified gravity will **bias** the cosmology unless gravity is properly accounted for (e.g.  $\gamma$ ).



Huterer & Linder 2007



But next generation SN+WL+CMB have the power to test Einstein framework and **fit** for gravity.

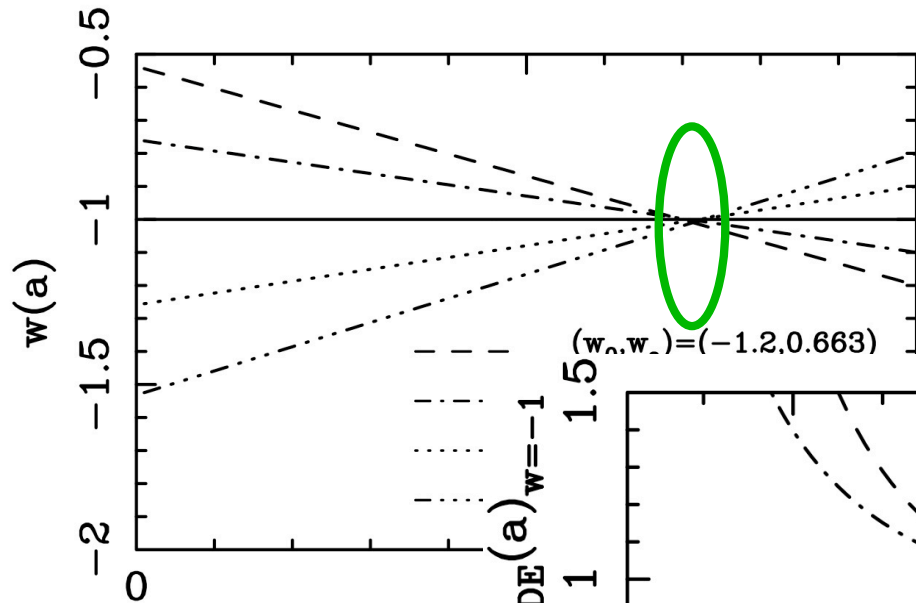


# Going Nonlinear

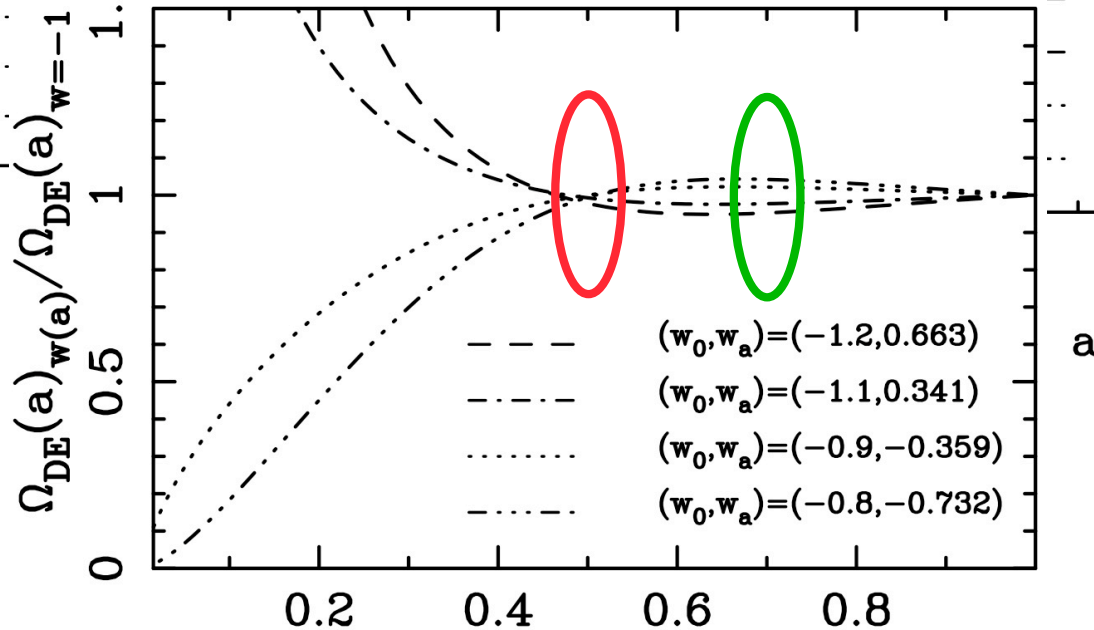
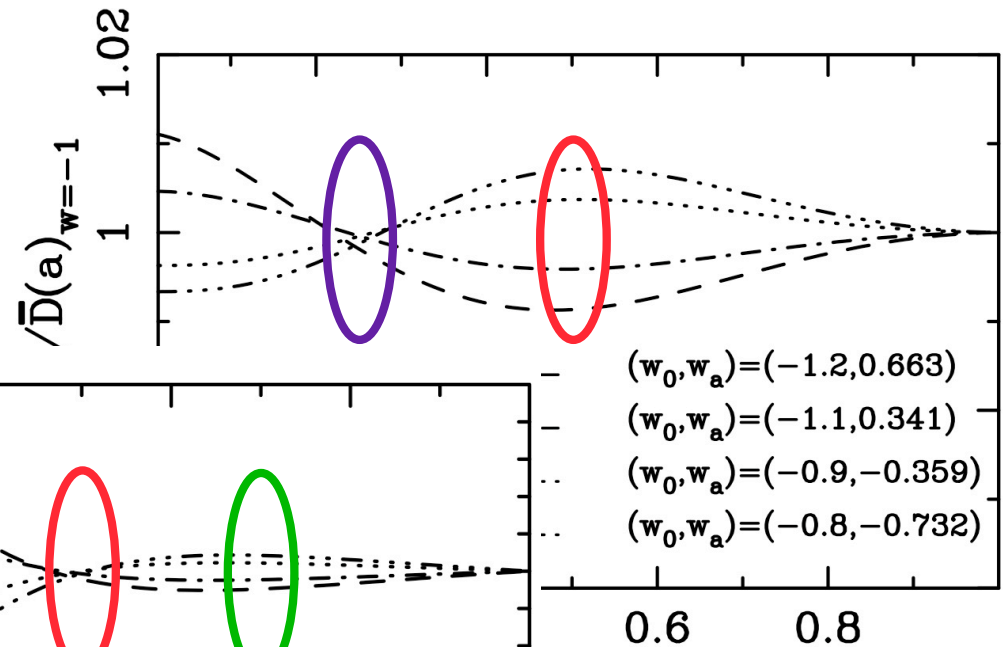


Start with CMB foundation in high redshift universe.

$w(a)$  for the  $w=-1$  Central Models



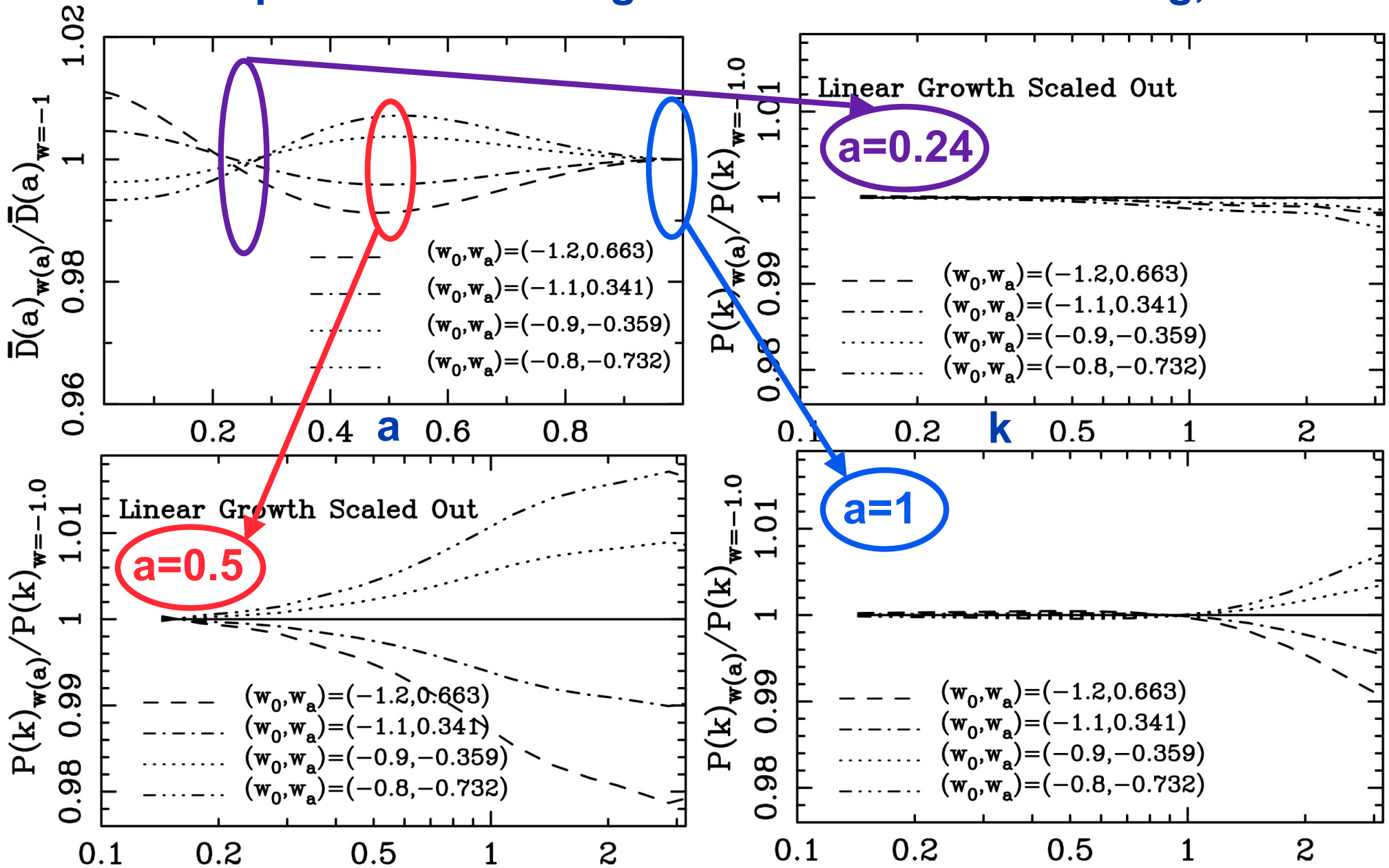
Linear Growth, Central Model  $w=-1$



# Power Spectrum Evolution



Power spectrum matching accurate to <1% matching,  $z=0-3$



# Finding Our Way in the Dark

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**Dark energy is a completely unknown animal.**

**Not completely dark?** [coupling to (dark) matter, to itself]

**Not energy?** [modified gravity -- physics, not physical]

**Track record:**

**Inner solar system motions → General Relativity**

**Outer solar system motions → Neptune**

**Galaxy rotation curves → Dark Matter**

**Moral: Given the vast uncertainties, go for the most unambiguous insight.**

**What could go wrong?**

**SN distances come from the FRW metric. Period.**

**Lensing distances depend on deflection law (gravity) even if separate mass (gravity) --  $(\Phi-\Psi), c_s, \pi_s, G(k,t)$**

**BAO depends on *standard* CDM (matter perturbations being blind to DE). --  $(\Phi+\Psi), c_s, \Gamma, \pi_s, G(k,t)$**

**What could go right? Ditto.**

“Yesterday’s sensation is Today’s calibration and  
Tomorrow’s background.”  
--Feynman

**Moral: Given the vast uncertainties, go for the most unambiguous insight.**

# Dark Energy – The Next Generation



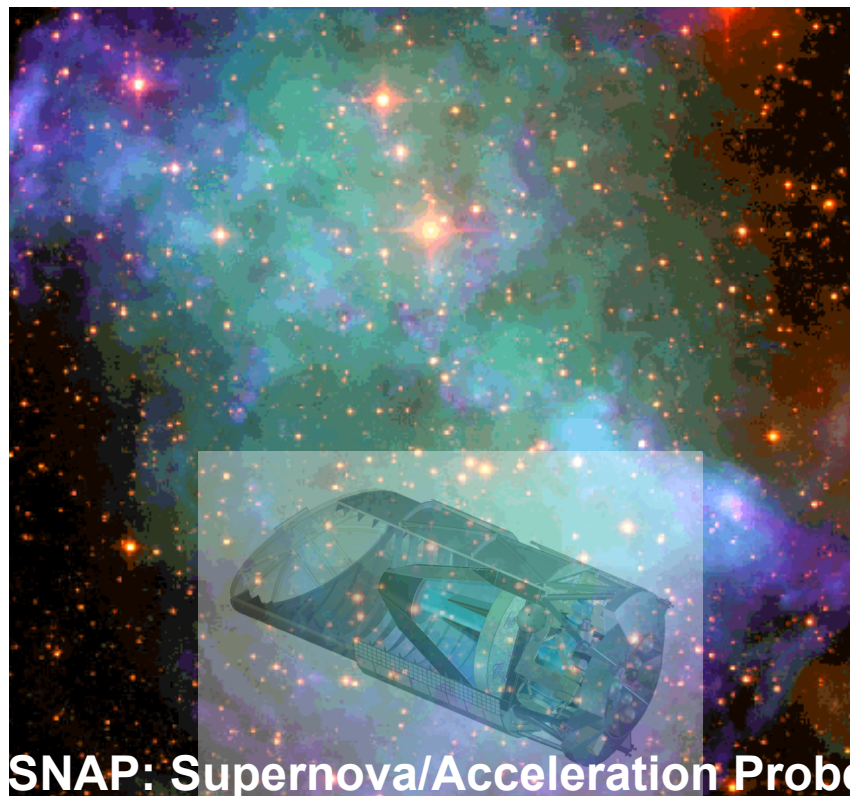
**w i d e**  $10^4 \times$  the Hubble Deep Field [SN]  
*plus*  $10^6 \times$  HDF [WL]

**deep** Redshifts  $z=0-1.7$   
(10 billion years / 70% age of the universe)

**colorful** Optical + IR to see thru dust, to high redshift.

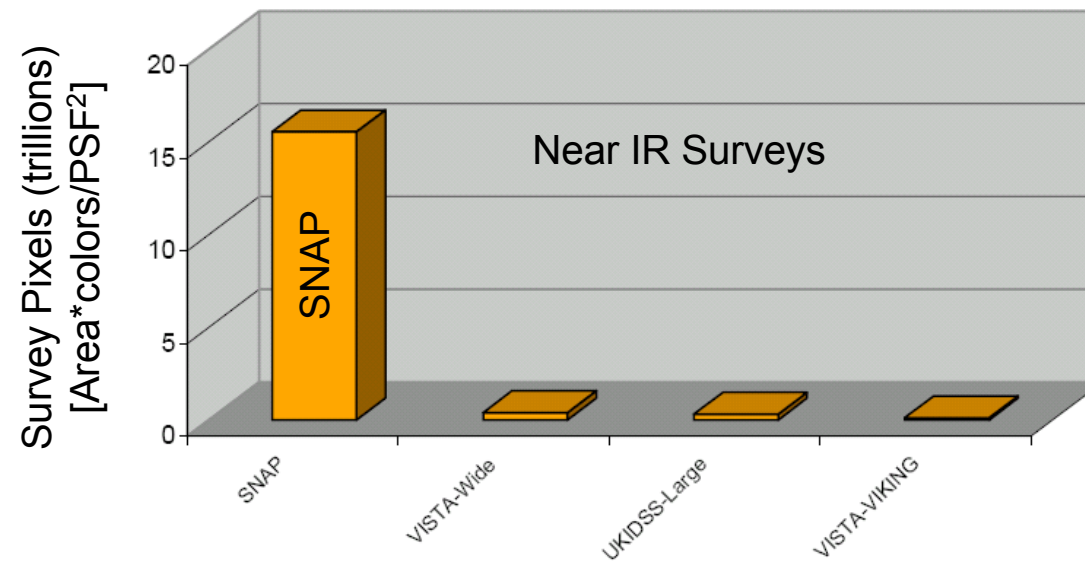
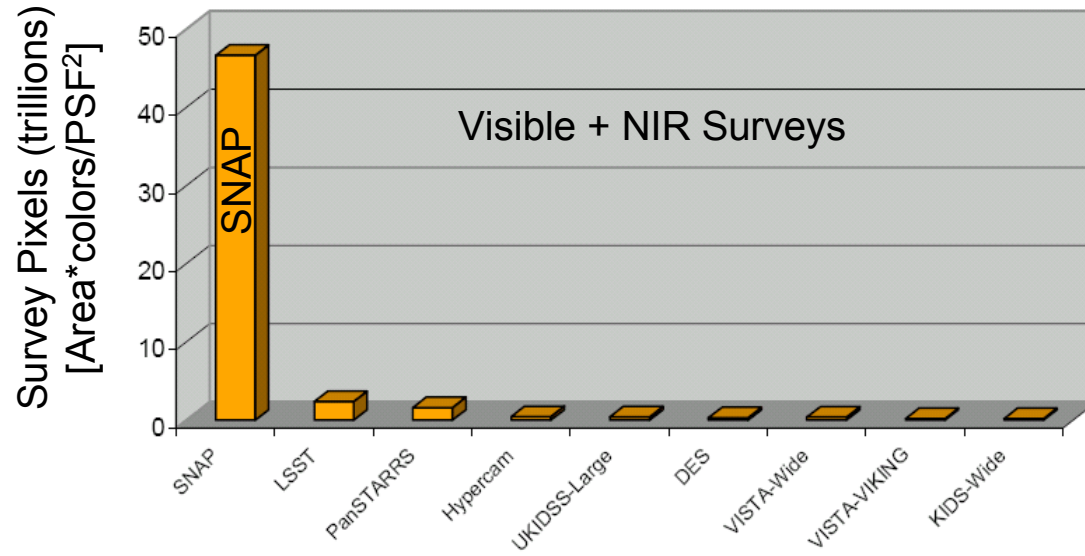
1% distance  
measurements  
over last e-fold  
of expansion  
(Supernovae)

2% growth  
measurements  
over last e-fold  
of expansion  
(Weak Lensing)



SNAP: Supernova/Acceleration Probe

# Trillions of Data





# Whither Beyond Einstein?



**New component or new law?**

Expansion plus growth (e.g. SN+WL) is critical combination.  
We can test *which* new physics.

Dynamics ( $w-w'$ ) can reveal general physics characteristics (even if not quintessence).

Modifying gravity is hard - and many possible effects entwined.

**The 5th Stage - Acceptance - is achievable with next generation experiments giving answers clean in both theory and astrophysical systematics.**

You'll be sort of surprised what there is to be found  
Once you go beyond Einstein and start poking around.  
On beyond Einstein! It's high time you were shown  
That you really don't know all there is to be known.  
-- à la Dr. Seuss, *On Beyond Zebra*