

Title: Dynamics of Dark Energy

Date: Oct 25, 2005 05:00 PM

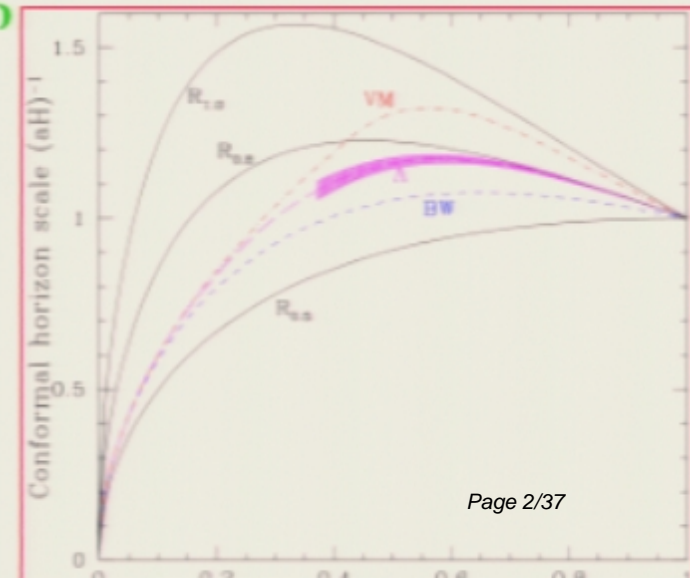
URL: <http://www.pirsa.org/05100048>

Abstract:

Dynamics of Dark Energy

Eric Linder

University of California, Berkeley
Lawrence Berkeley National Lab



Slide 66: What to expect from on-going efforts?

Slide 67: "Combo" MC data-set: w/o systematics

Slide 68: Abstract pattern with black, green, and yellow pixels.

Slide 69: Abstract pattern with black and green pixels.

Slide 70: Abstract pattern with blue and green pixels.

Slide 71: Abstract pattern with blue and black pixels.

Slide 72: Abstract pattern with blue, black, and brown pixels.

Slide 73: Abstract pattern with black and grey pixels.

Slide 74: Abstract pattern with black and green pixels.

Slide 75: Abstract pattern with red, black, and green pixels.

Slide 76: Abstract pattern with blue and black pixels.

Slide 77: Abstract pattern with blue, black, and red pixels.

Slide 78: Abstract pattern with black and grey pixels.

Slide 79: Abstract pattern with black and green pixels.

Slide 80: Abstract pattern with red, black, and green pixels.

Slide 81: Abstract pattern with black and pink pixels.

Slide 82: Abstract pattern with black, red, and green pixels.

Slide 83: Abstract pattern with blue, black, and green pixels. (Highlighted)

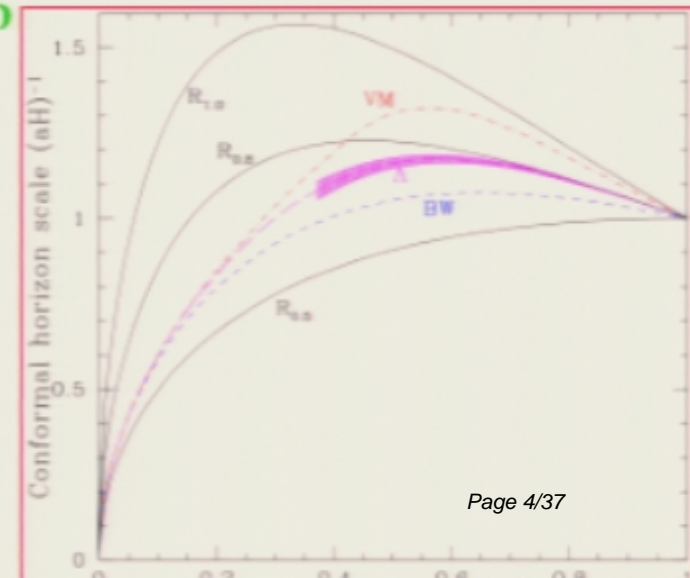
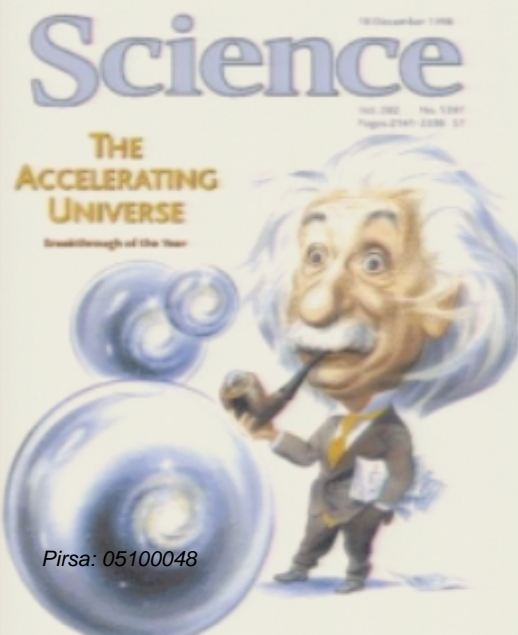
Slide 84: Abstract pattern with black and blue pixels.

Slide 85: Abstract pattern with black and green pixels.

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Acceleration \neq Acceleration



Dark energy and Inflation are very different.

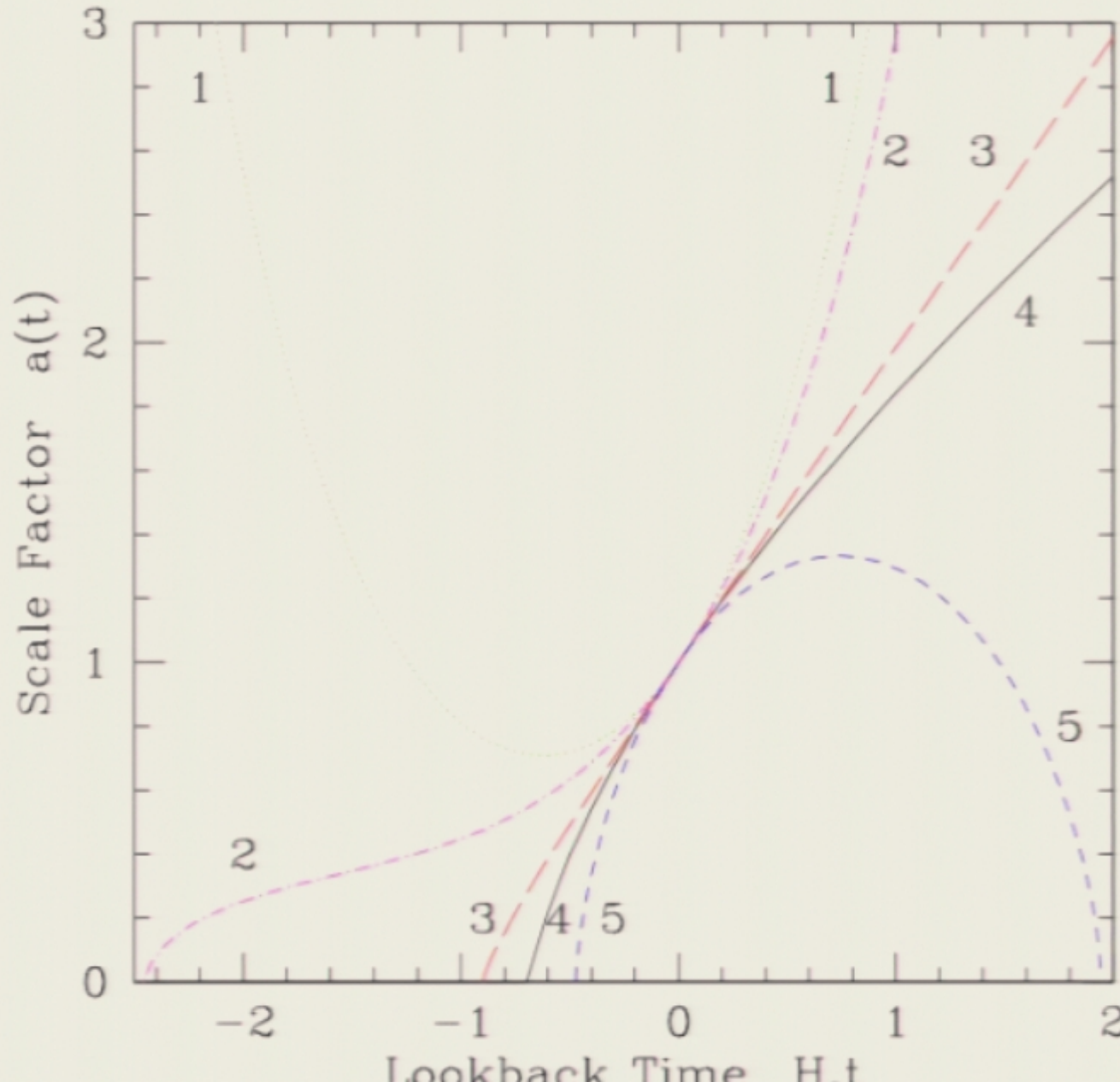
Dark energy is:

- Not slow roll
- Not completely dominant

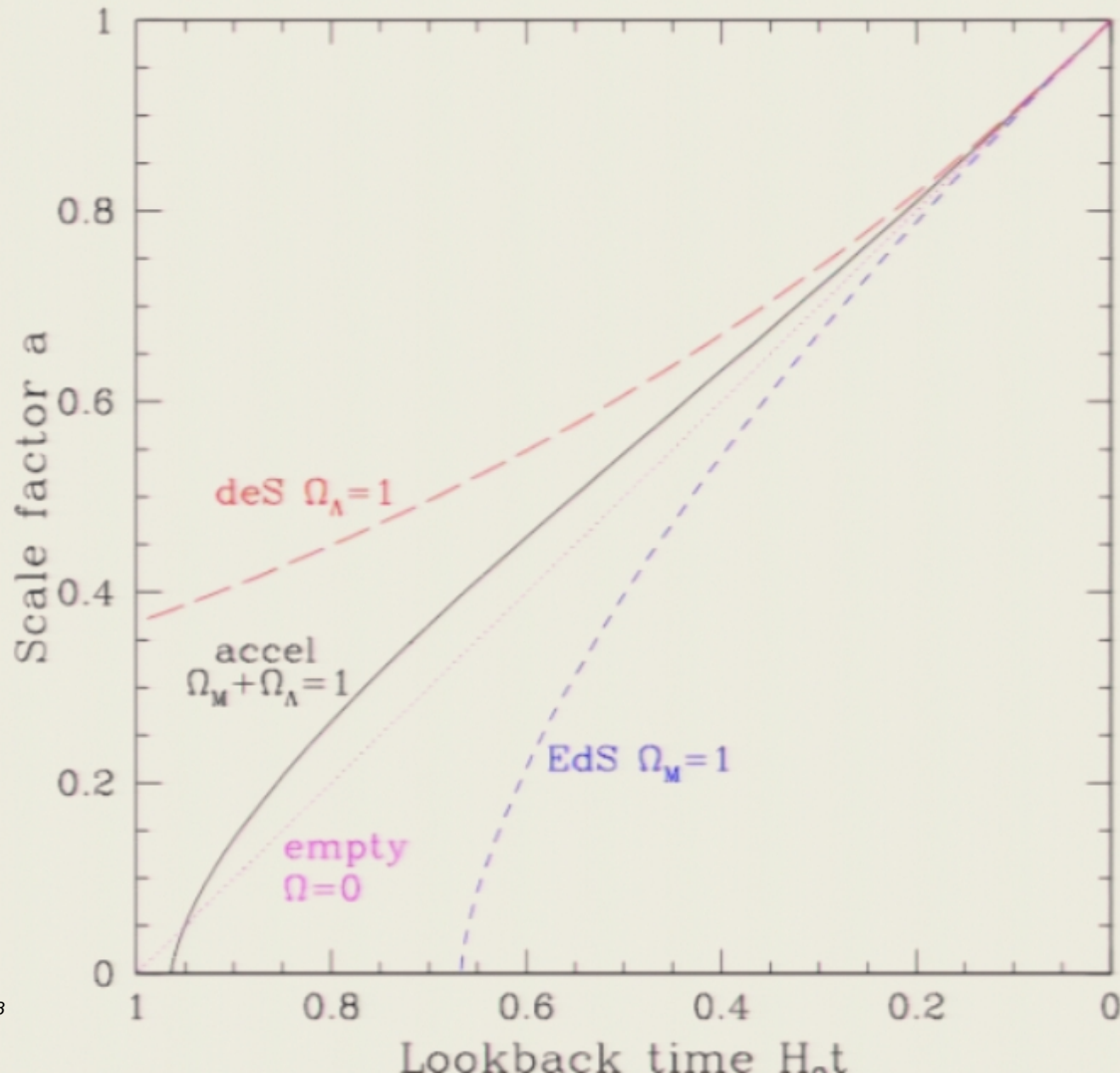
Goldilocks problem:

- Dynamically important, but not fully dominant
 $\Omega_{DE} \sim 0.7$
- Accelerating, $w < -0.8$, but need fast-slow roll else fine tune
- Λ or Not Λ ?

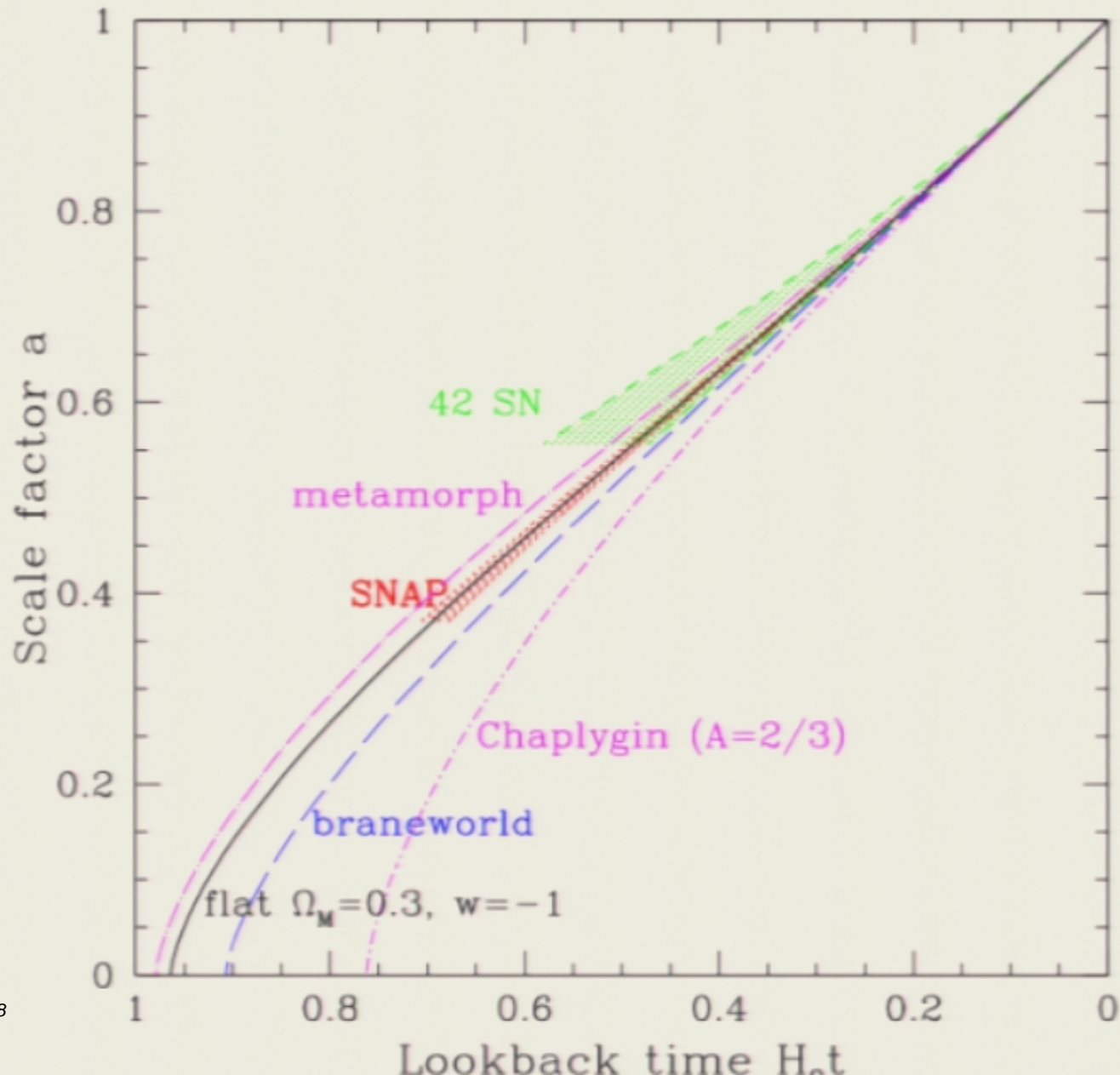
Exploring Dark Energy



Exploring Dark Energy



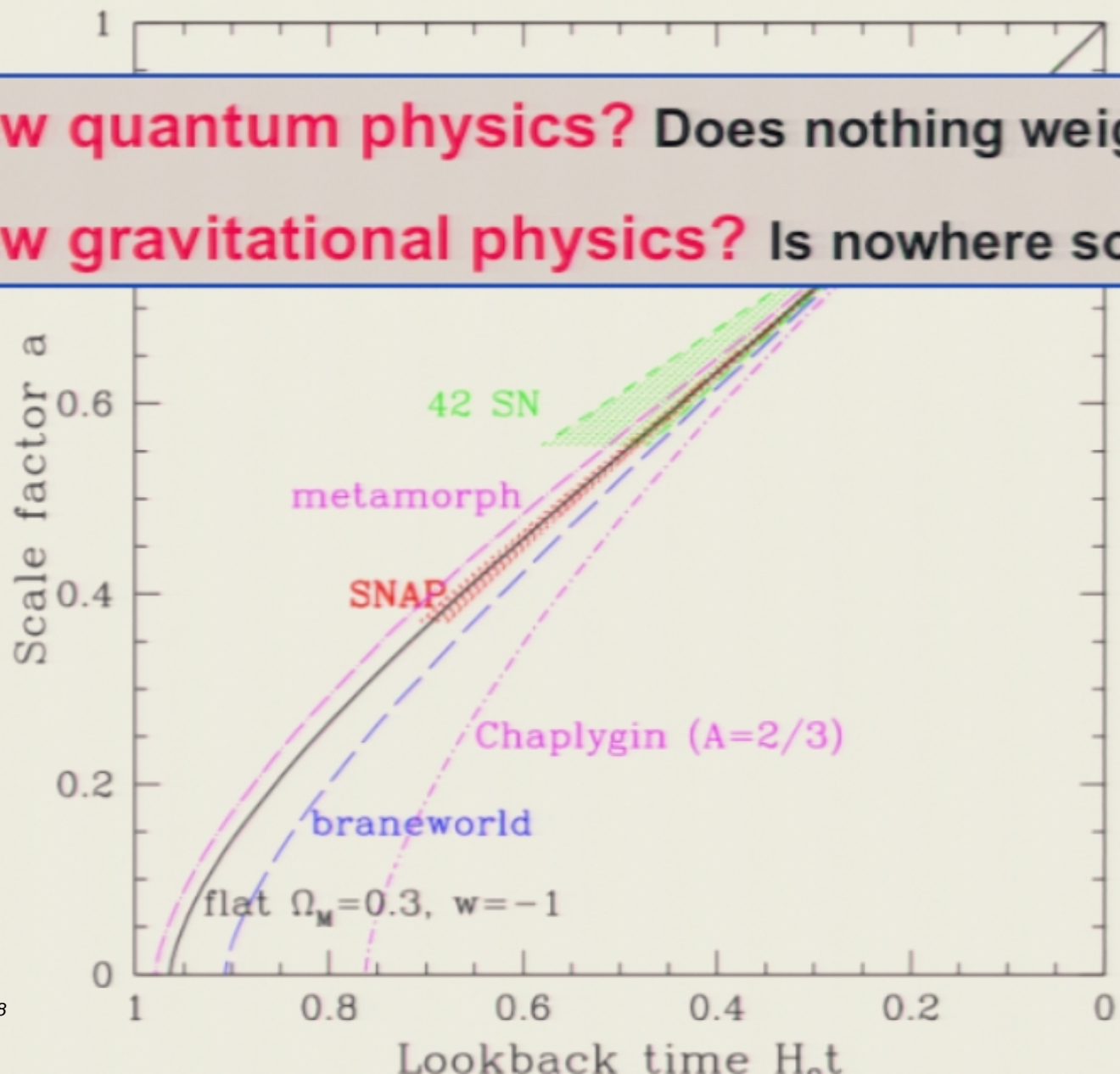
Exploring Dark Energy



Exploring Dark Energy



New quantum physics? Does nothing weigh something?
New gravitational physics? Is nowhere somewhere?



Equation of State



Reconstruction from EOS:

$$\rho(a) = \Omega_{\phi} \rho_c \exp\{ 3 \int d \ln a [1+w(z)] \}$$

$$\phi(a) = \int d \ln a H^{-1} \sqrt{\rho(a) [1+w(z)]}$$

$$V(a) = (1/2) \rho(a) [1-w(z)]$$

$$K(a) = (1/2) \dot{\phi}^2 = (1/2) \rho(a) [1+w(z)]$$

But, $\dot{\phi} \sim \sqrt{[(1+w)\rho]} \sim \sqrt{(1+w)} H M_p$

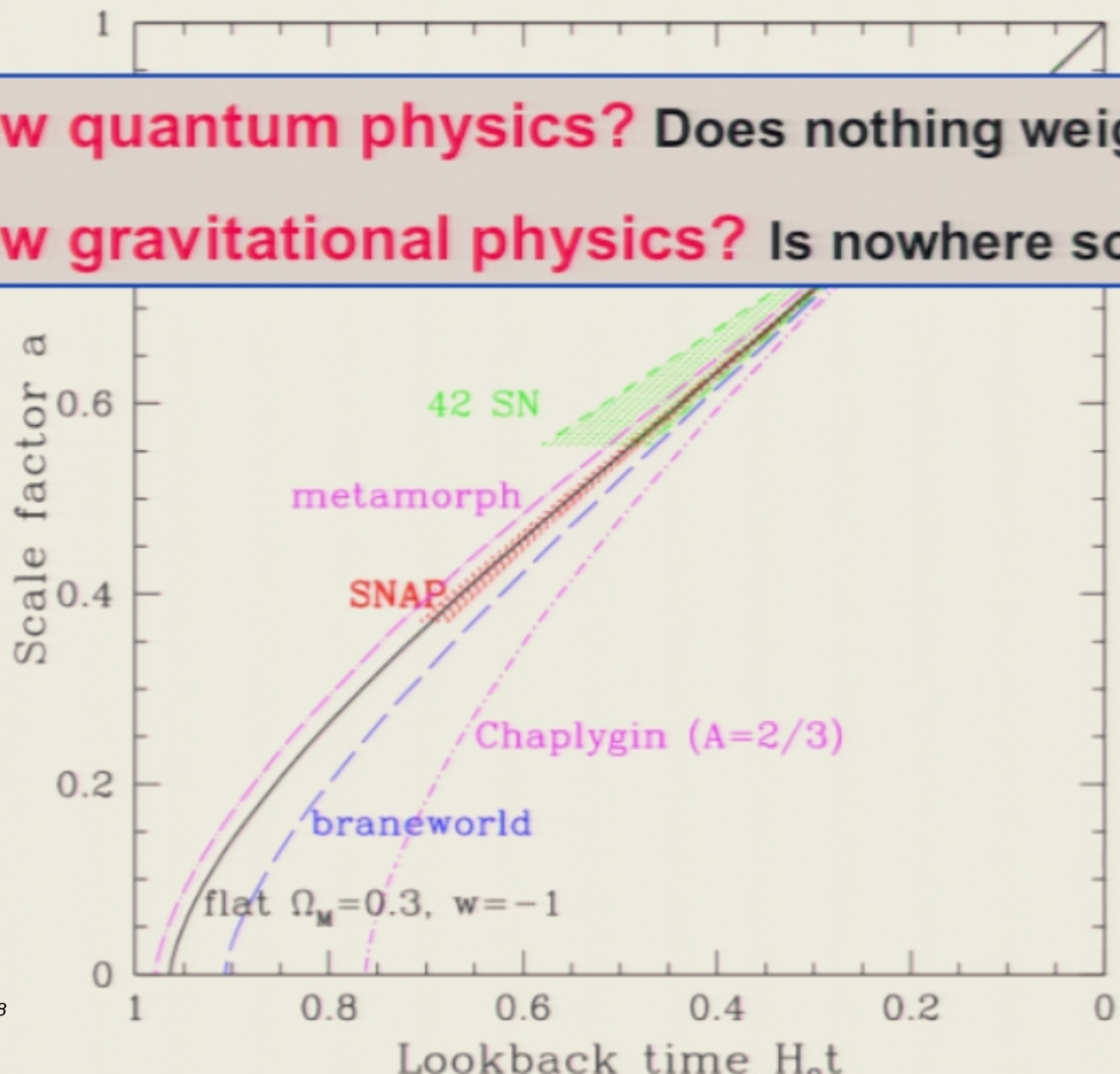
So if $1+w \ll 1$, **then** $\Delta\phi \sim \dot{\phi}/H \ll M_p$.

It is very hard to directly reconstruct the potential.

Exploring Dark Energy



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How Many EOS Parameters?



Dark energy equation of state is an effective quantity describing dynamics.

Minimal useful characterization is value and variation, or tilt $1+w$ and running w' .

Can we do more? Do we need more?

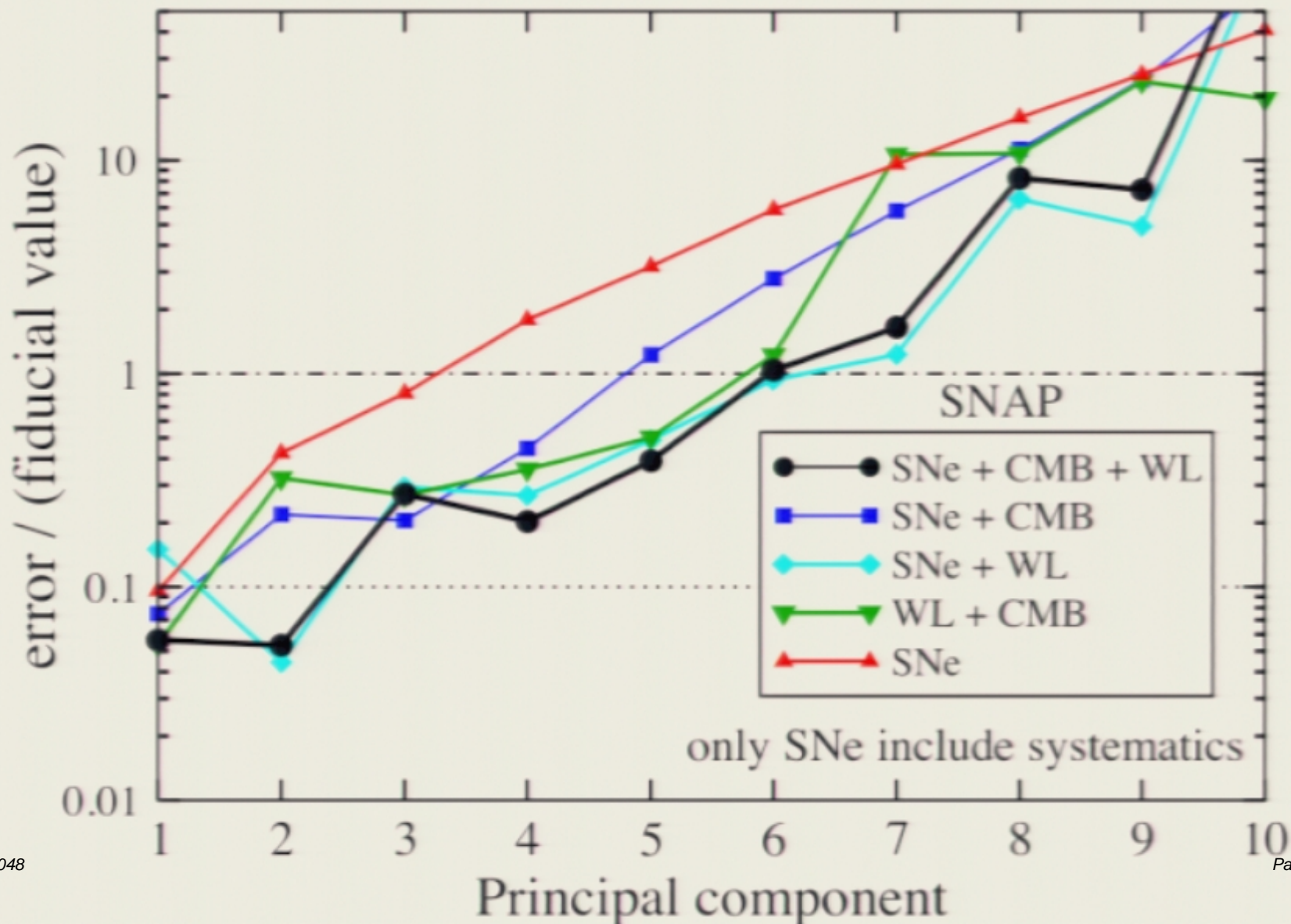
Success criterion of 10% in value, 0.2H in variation:

Next generation SN+CMB+WL fit only 2 parameters.

Principal Component Analysis



Linder & Huterer 2005: PRD 72, 043509 [astro-ph/0505330]



Dynamics of Quintessence



Equation of motion of scalar field

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

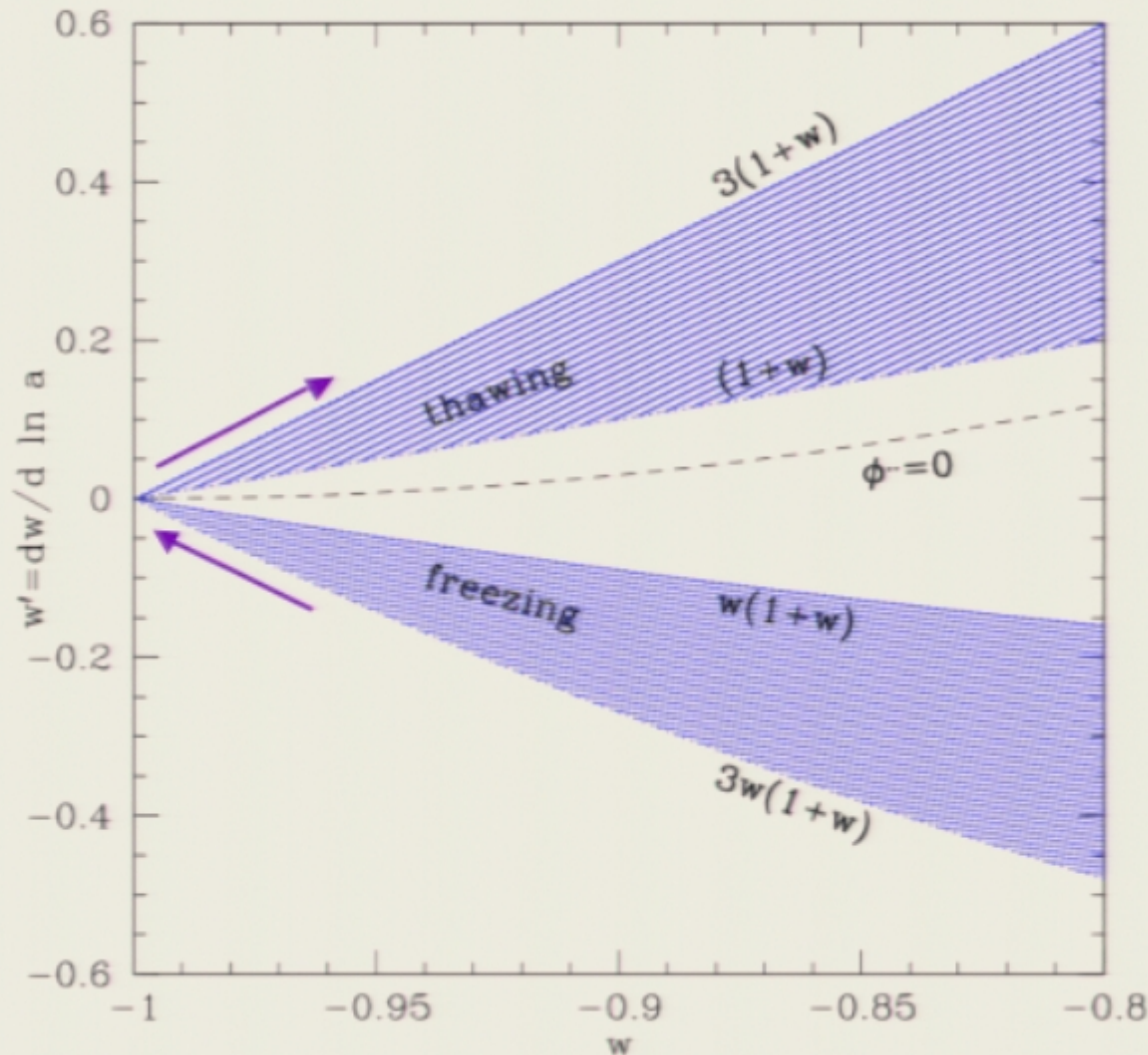
- driven by steepness of potential
- slowed by Hubble friction

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



Distinct, narrow regions of $w-w'$

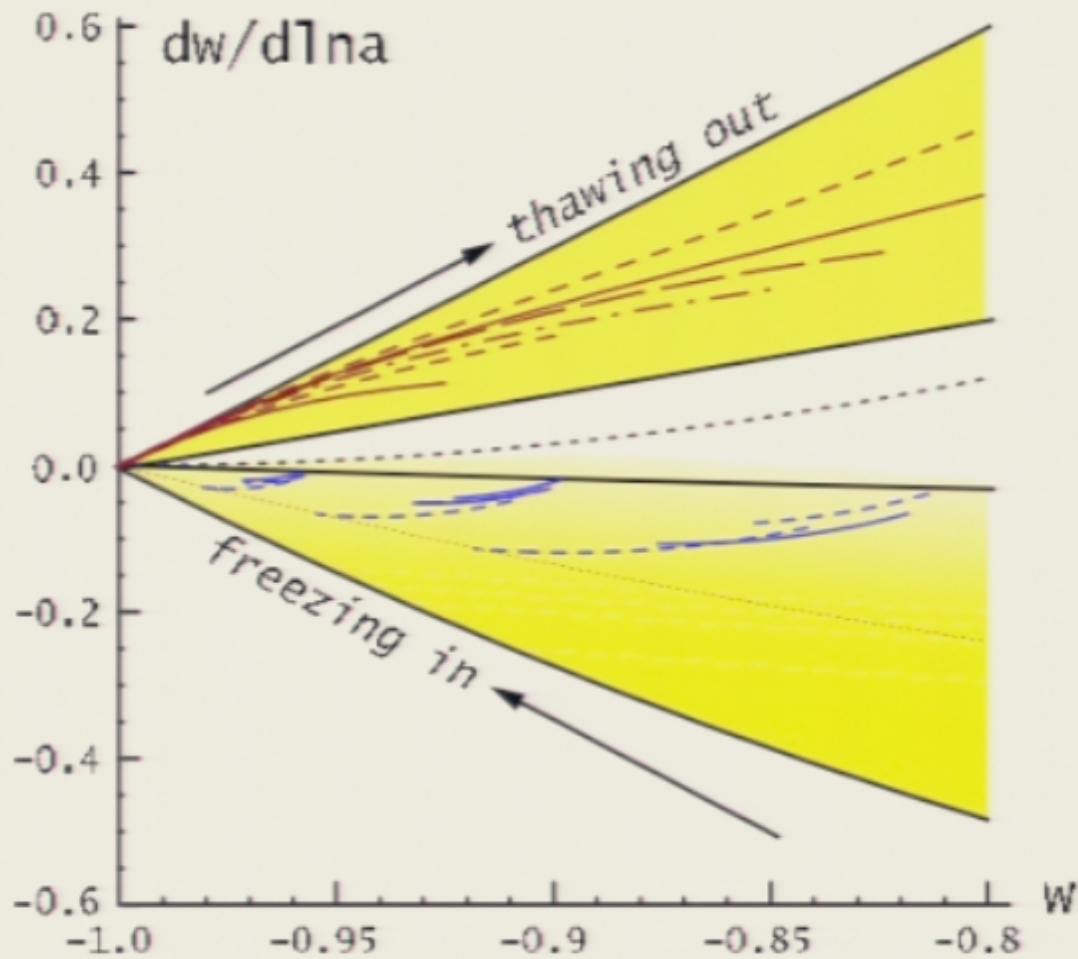
Works for:
linear, quadratic,
quartic, PNGB,
 ϕ^{-n} , SUGRA,
exponential

Caldwell & Linder 2005
PRL 95, 141301;
astro-ph/0505494

Entire “thawing” region looks like $w_{\text{constant}} = -1 \pm 0.05$.

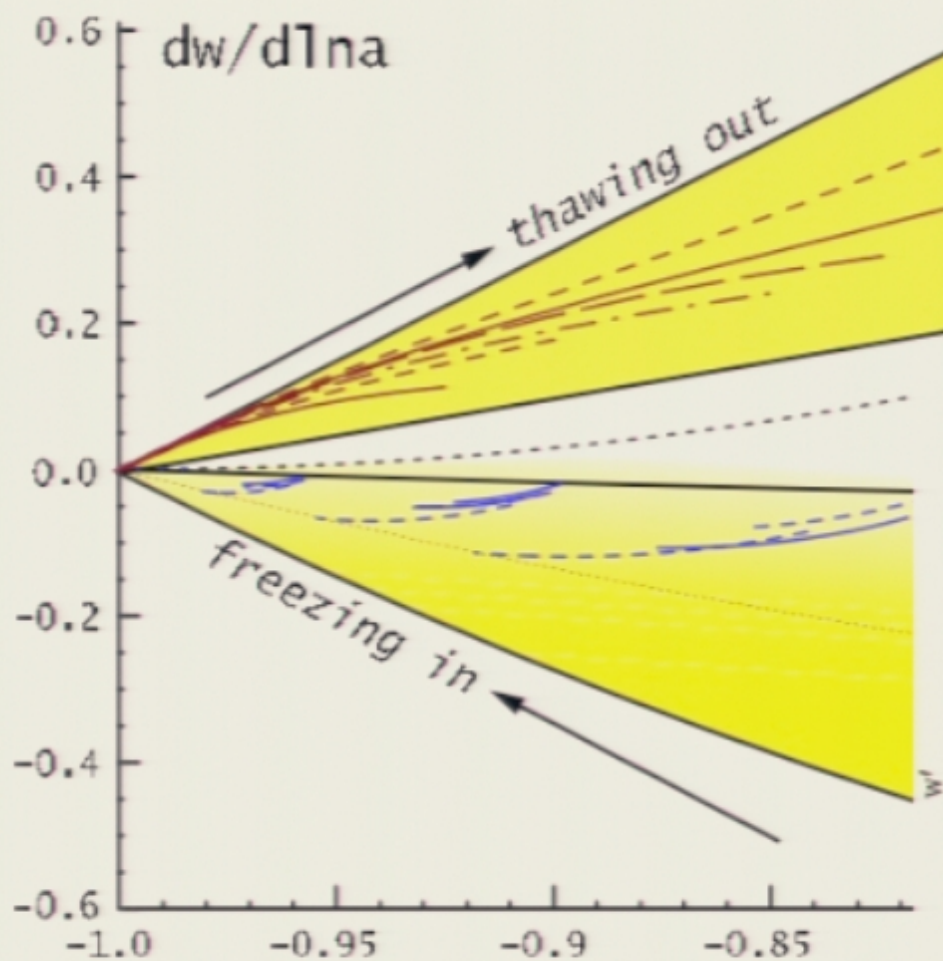
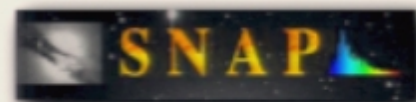
Need w' experiments with $\sigma(w') \approx 2(1+w)$.

Dynamics and Physics

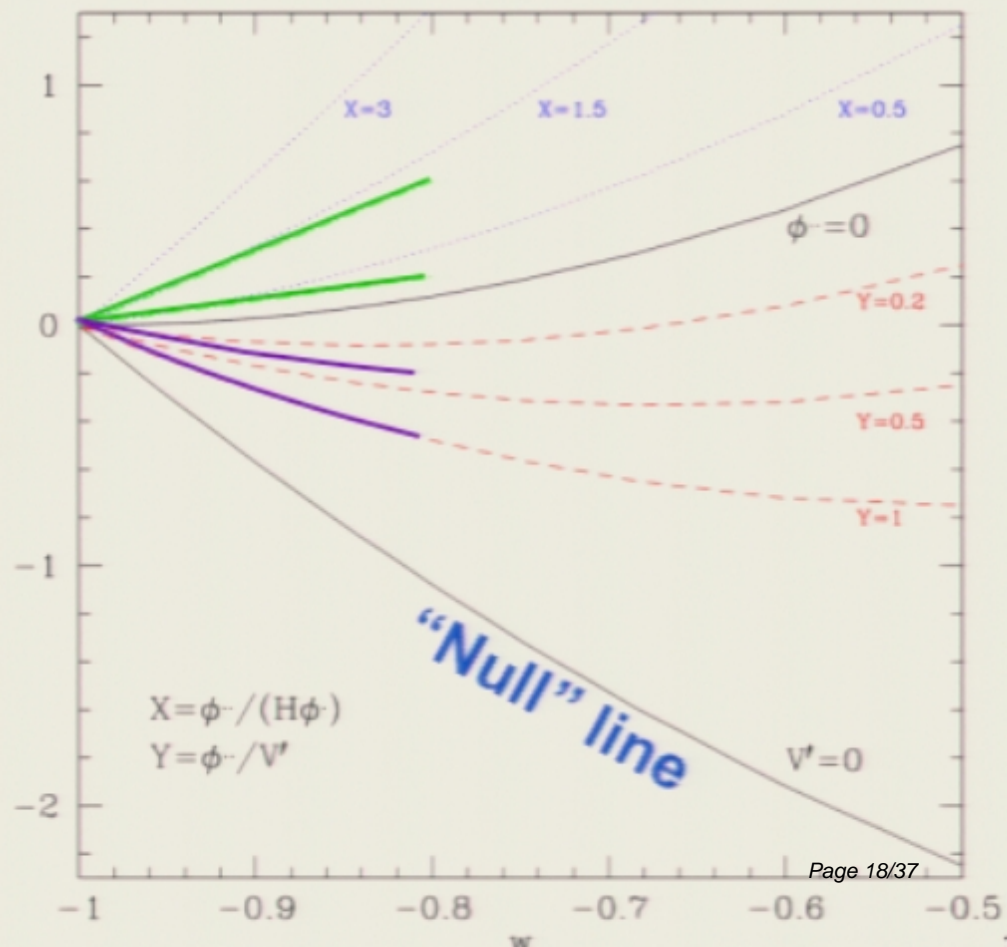


Phase plane $w-w'$

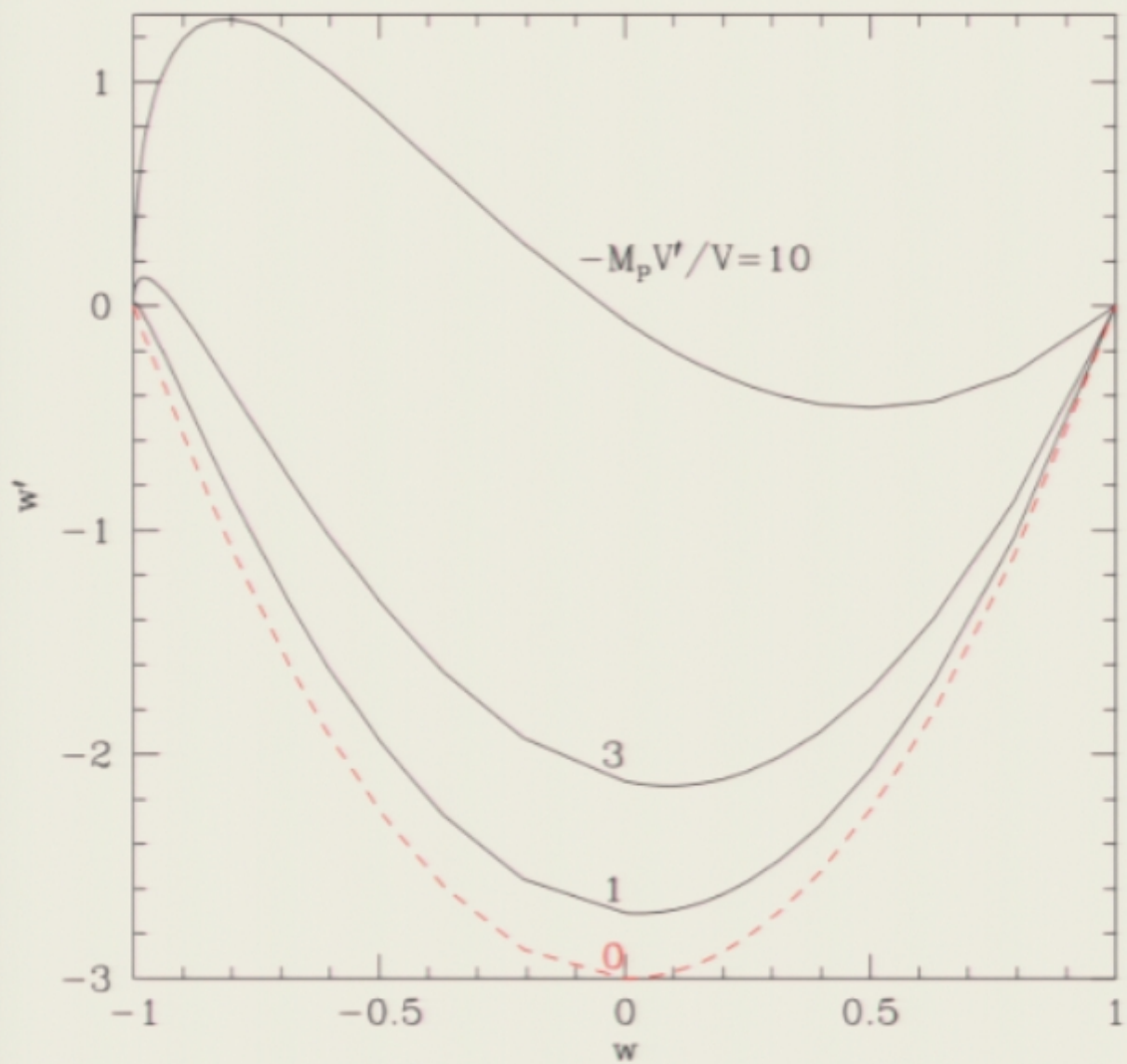
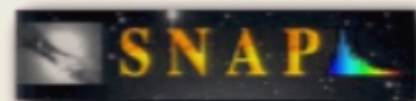
Dynamics and Physics



Phase plane $w-w'$

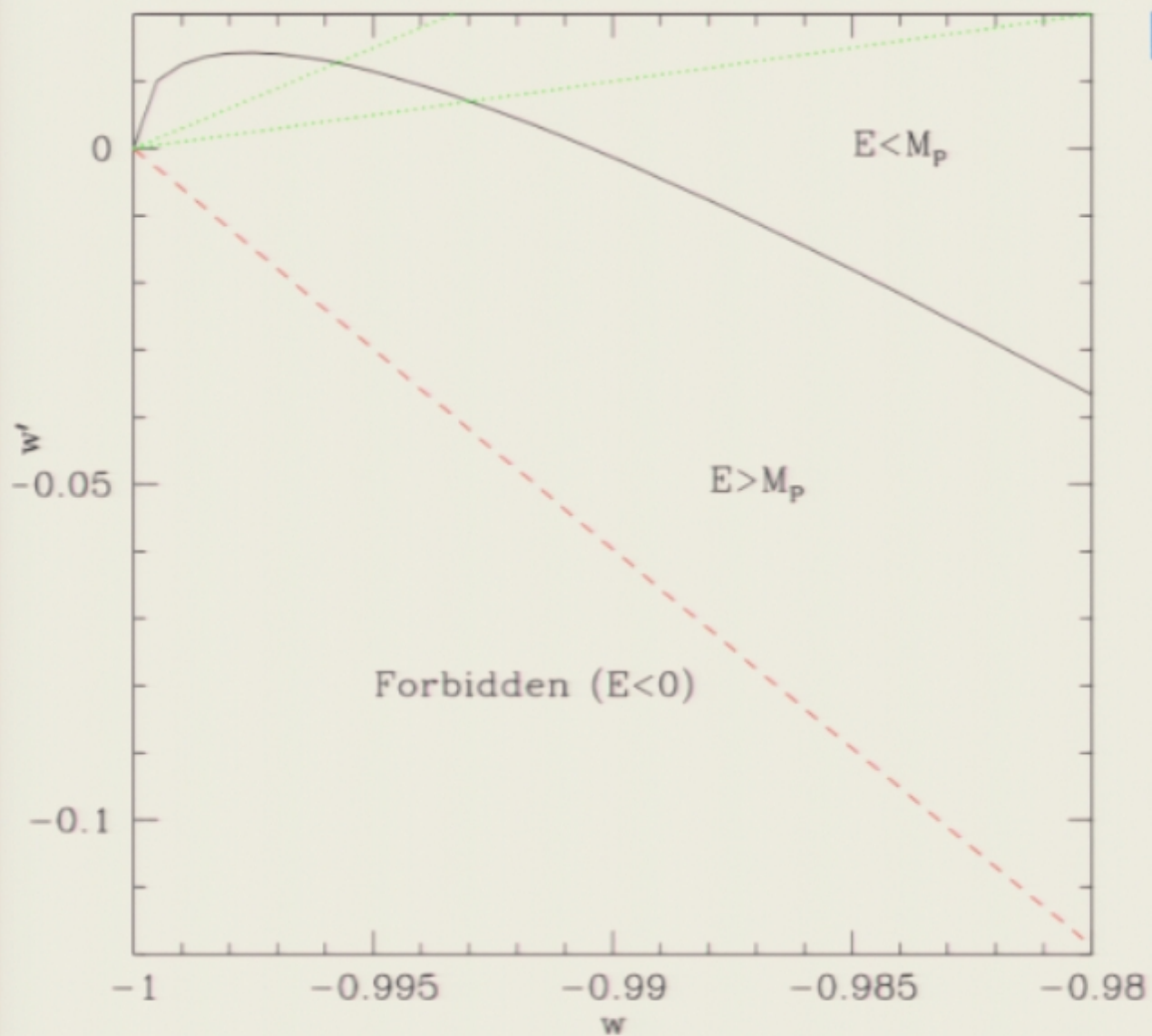
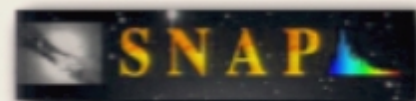


Dynamics and Physics



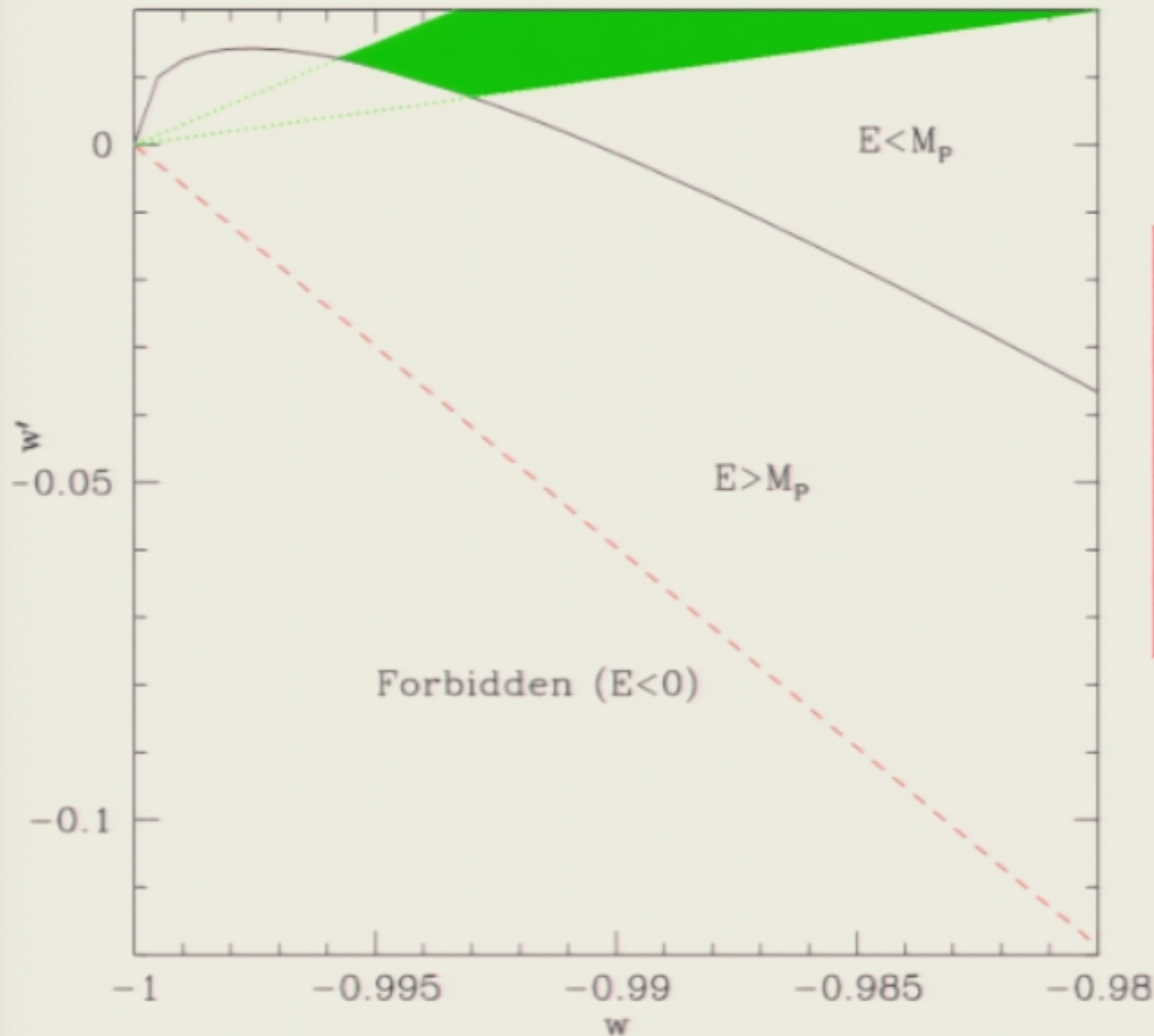
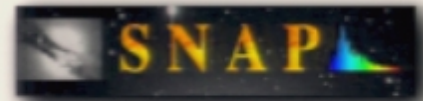
$$E = -V/V'$$

Dynamics and Physics



$$E = -V/V'$$

Dynamics and Physics



$$E = -V/V'$$

For the first time, we have a “barrier” around Λ , defining a distance, or precision $\sigma(w)$.

Phantoms without Ghosts



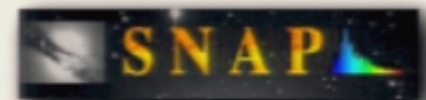
5 Ways to have $w < -1$ without “bad” physics:

What do you mean bad?

Imagine all life as you know it stopping instantaneously and every molecule in your body exploding at the speed of light. – Ghostbusters

- **Vacuum metamorphosis** Parker & Raval 1999: PRD 60, 063512
- **Coupling: $w_{\text{eff}} = w - \Gamma/(3H)$** Turner 1985, Linder 1988, Linder 0507263
- **Curvature: $\Omega_{\text{total}} > 1$ ($k > 0$) + $\Lambda \rightarrow w_{\text{eff}} < -1$** Linder 0508333
- **Climbing field** Csaki, Kaloper, Terning 0507148
- **Two components, e.g. brane+ Λ** Lue & Starkman 2004, CKT 2005

Expansion History



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.

Expansion History



For modifications δH^2 , define an effective scalar field with

$$V = (3M_p^2/8\pi) \delta H^2 + (M_p^2 H_0^2/16\pi) [d \delta H^2/d \ln a]$$

$$K = - (M_p^2 H_0^2/16\pi) [d \delta H^2/d \ln a]$$

Example: $\delta H^2 = A(\rho_m)^n$

Freese & Lewis

$$w = -1+n$$

Example: $\delta H^2 = (8\pi/3) f(\rho_m)$

cf. Scherrer astro-ph/0509890

$$w = -1 + d \ln f / d \ln \rho_m$$

Violates Caldwell-Linder freezing bound *if* phantom

$$w' = 3w(1+w) - 3(\rho_m^{-2}/f) d^2 f/d^2 \ln \rho_m$$

Scalar-Tensor Gravity



$R/(8\pi G) \rightarrow F(\phi)$ R : possesses “R-boost” attractor

Matarrese, Baccigalupi, & Perrotta
PRD 70, 061301 (2004)

$$(3/8\pi G) \delta H^2 = V + (1/2)F_{\phi}^2(q-1)(q+5) + 3H^2 [F - 1/(8\pi G)]$$

Effective equation of state

$$1+w \sim 1/\omega_{\text{JBD}}$$

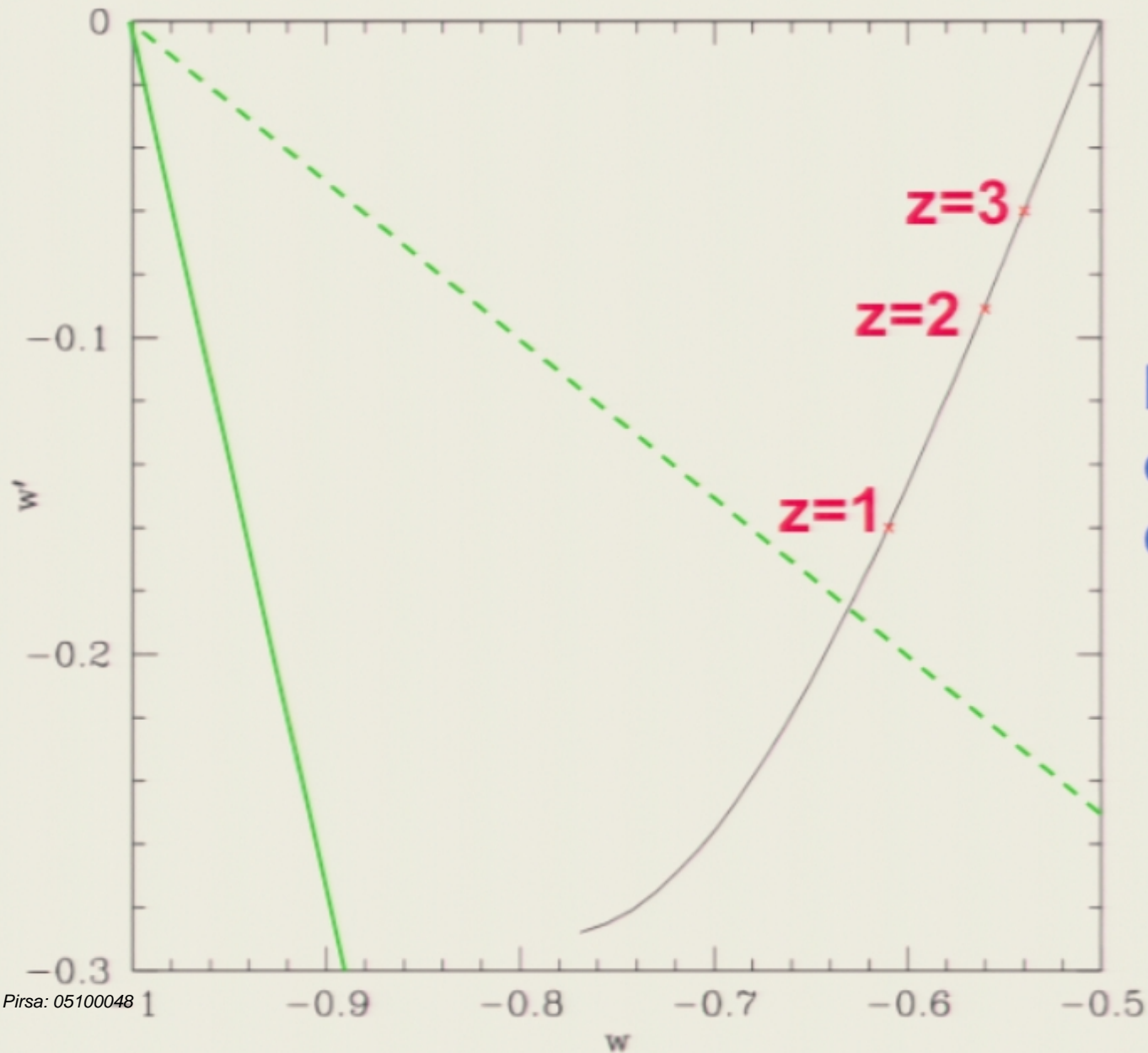
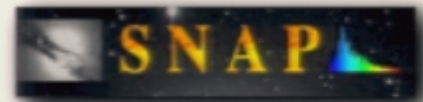
$$w' = dw/d \ln a \sim 1/\omega_{\text{JBD}}$$

BMP
Linder

Note $\omega_{\text{JBD}} > 40000$ (or is it?) so “extended quintessence” has attractor solution to GR, and acts like cosmological constant. [Freezer]

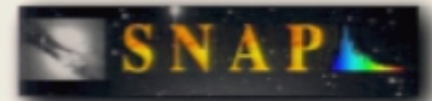
However, has non-vanishing anisotropic stress, so may affect structure growth.

DGP Braneworld Dynamics



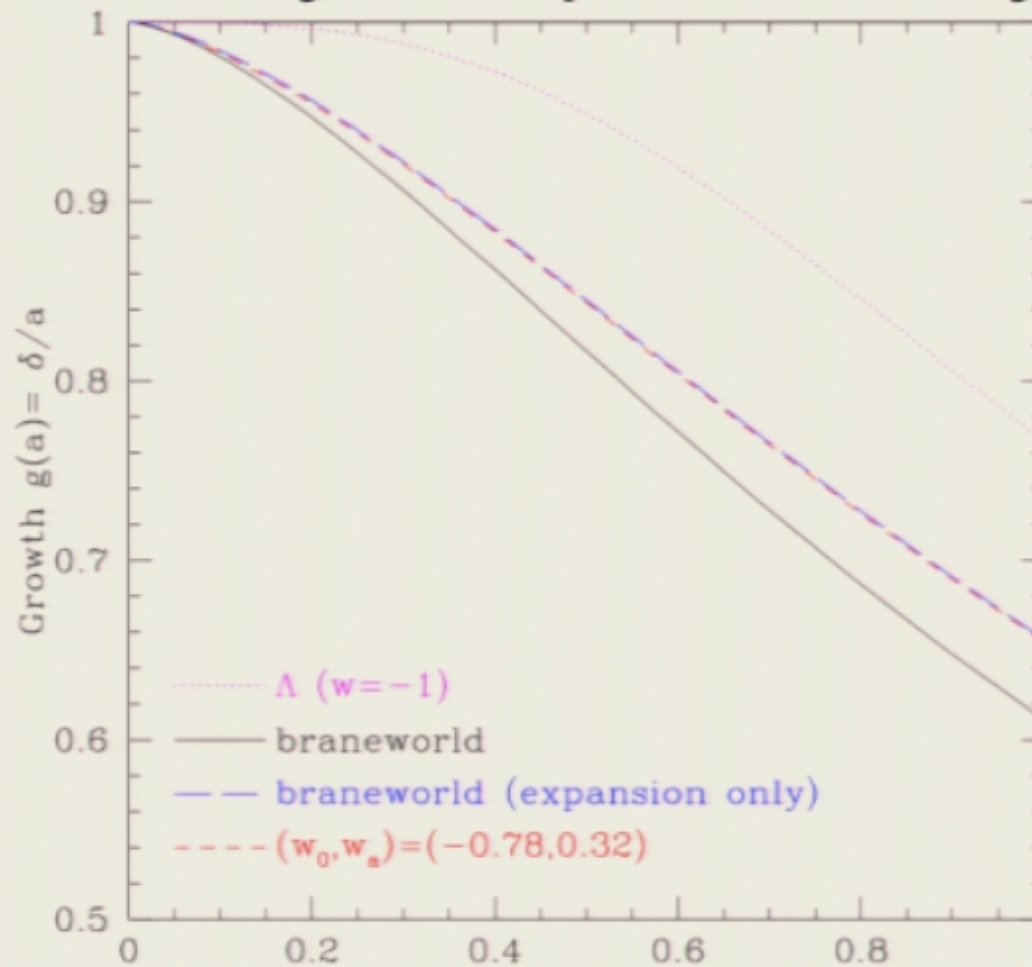
DGP Braneworld
obeys freezer
dynamics in $w-w'$

Revealing Physics



- Time variation $w(z)$ is a critical clue to fundamental physics.
- Modifications of the expansion history = $w(z)$.
- But need an underlying theory - $\delta\phi$? beyond Einstein gravity?

Growth history and expansion history work together.



Linder 2004, Phys. Rev. D 70, 023511
cf. Lue, Scoccimarro, Starkman
Phys. Rev. D 69 (2004) 124015
for braneworld perturbations

Physics of Growth



Growth $g(a)=(\delta\rho/\rho)/a$ depends purely on the expansion history $H(z)$ -- *and gravity theory.*

$$g'' + \left[5 + \frac{1}{2} \frac{d \ln H^2}{d \ln a}\right] g' a^{-1} + \left[3 + \frac{1}{2} \frac{d \ln H^2}{d \ln a} - \frac{3}{2} G \Omega_m(a)\right] g a^{-2} = S(a)$$

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
PRD 72, 043529;
astro-ph/0507263

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

Works to 0.05 – 0.2%!

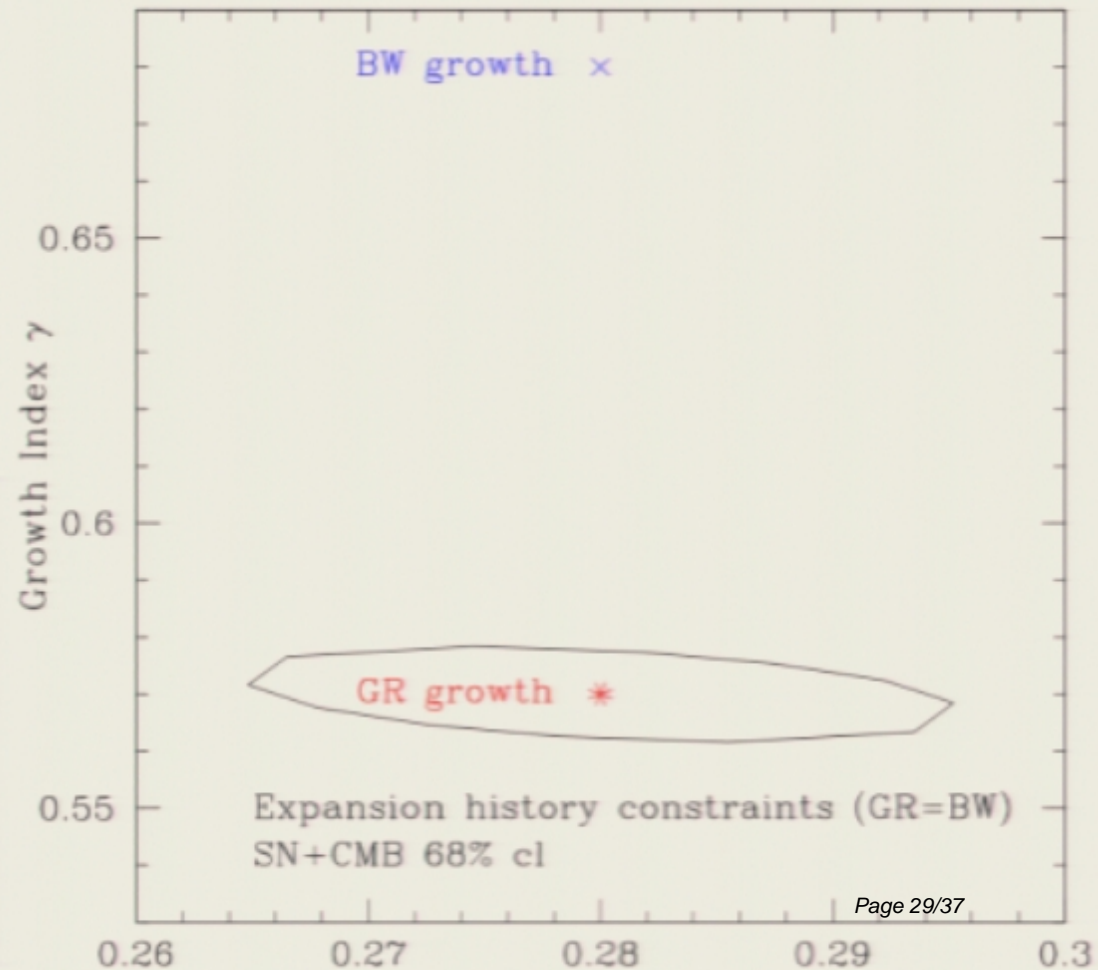
Growth and Expansion



With γ as free fit parameter, we can test framework, and the origin of dark energy.

Keep expansion history as $w(z)$, growth deviation from expansion by γ .

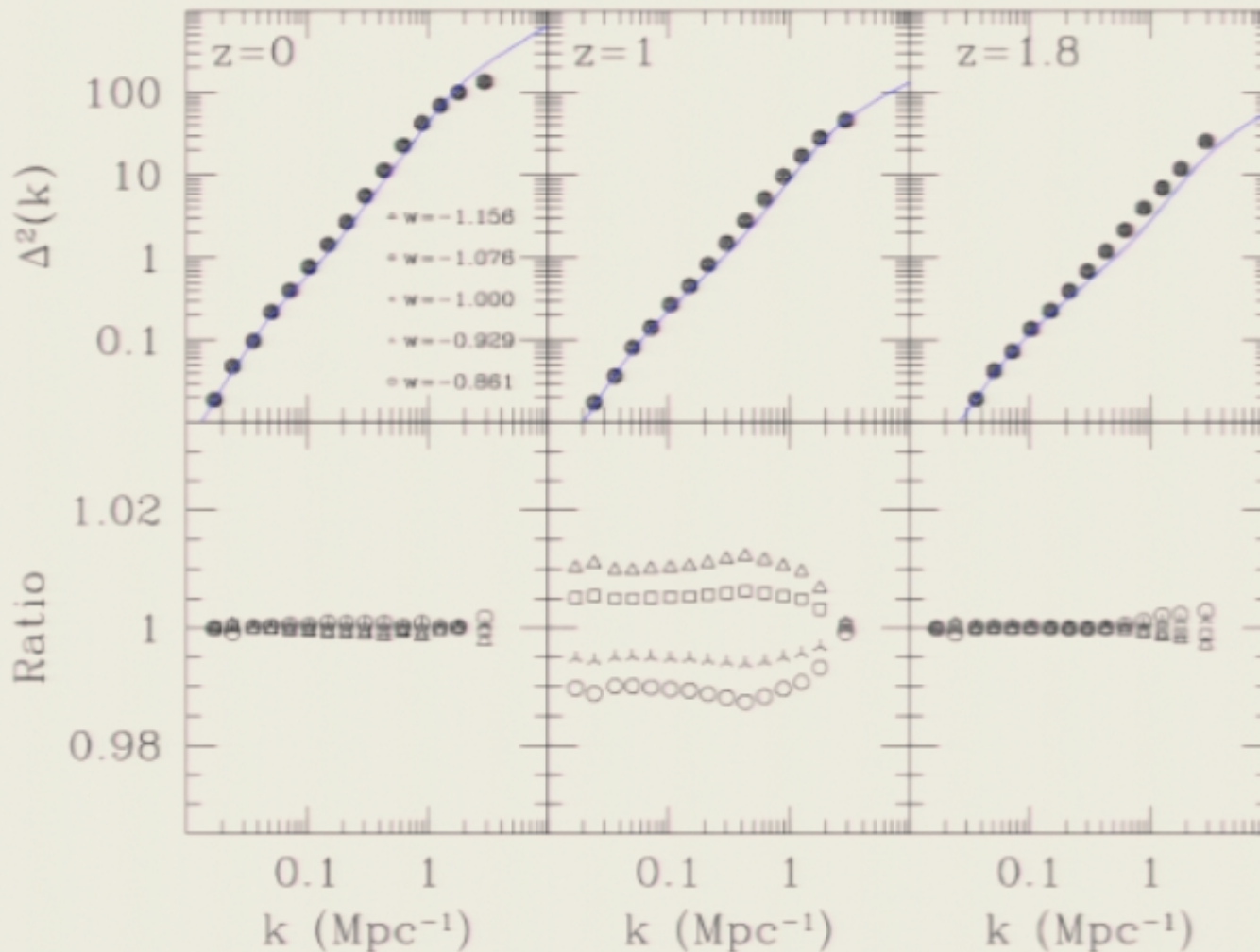
New paradigm:
To reveal the origin of dark energy, measure w , w' , and γ .
e.g. use SN+WL.



Going Nonlinear



Previous fit functions were only good to ~10% -- for Λ .



Linder & White 2005
PRD 72, 061304(R)
astro-ph/0508401

New discovery: **growth** $\rightarrow d_{\text{ISS}}$

So our prescription automatically "includes" CMB priors!

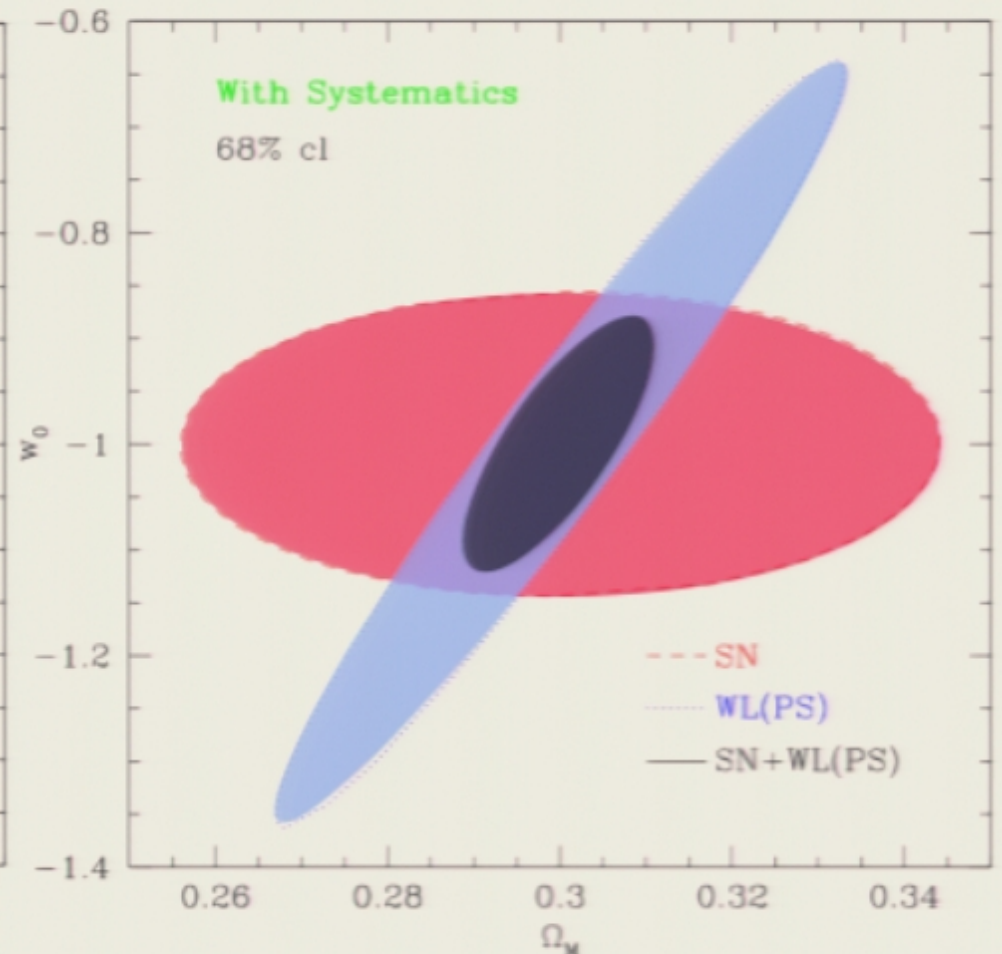
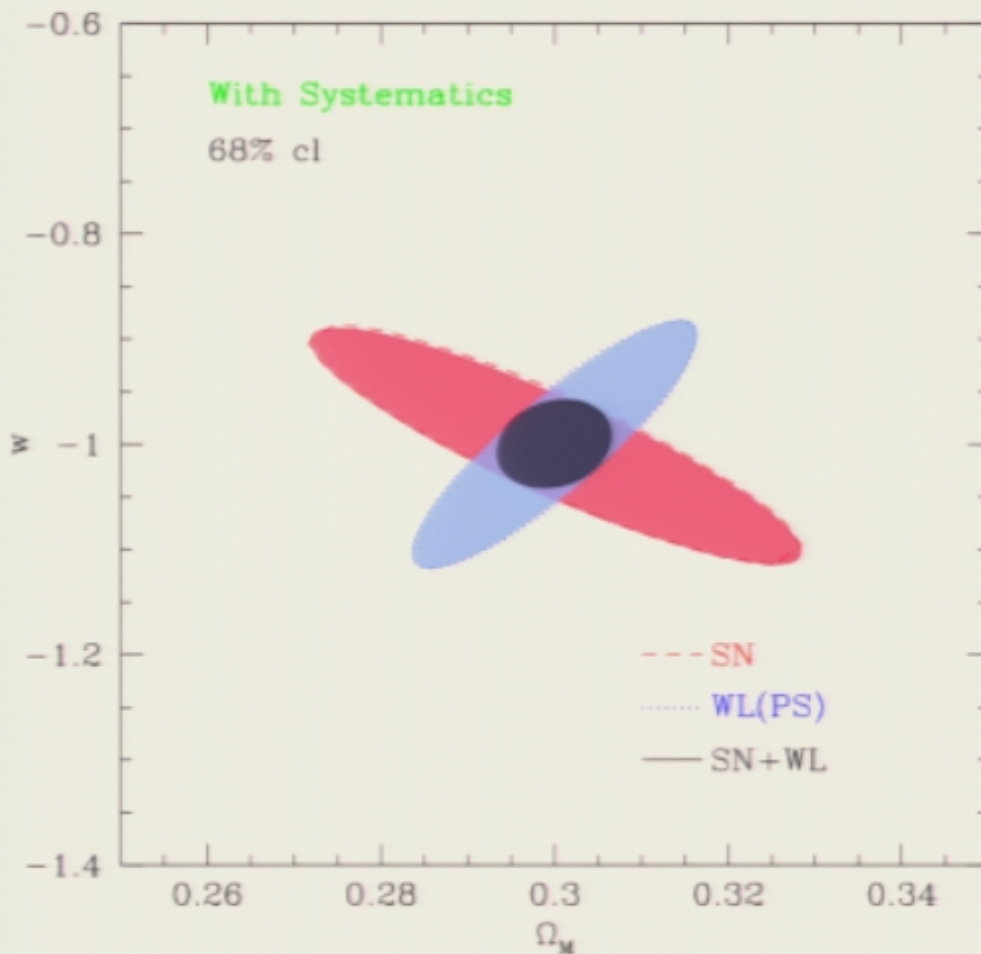


Theory and Data



Springiness of Space *allowing other than Λ*

Stretching the Spring *allowing w to vary*



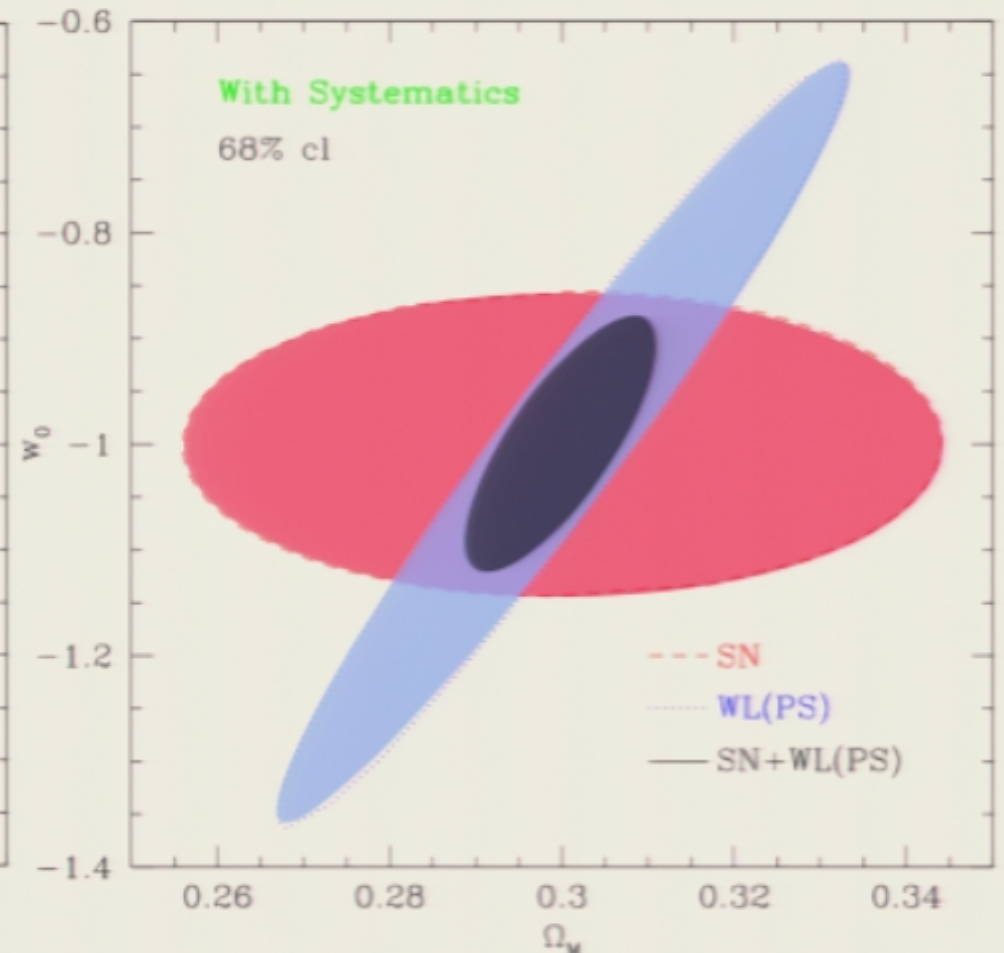
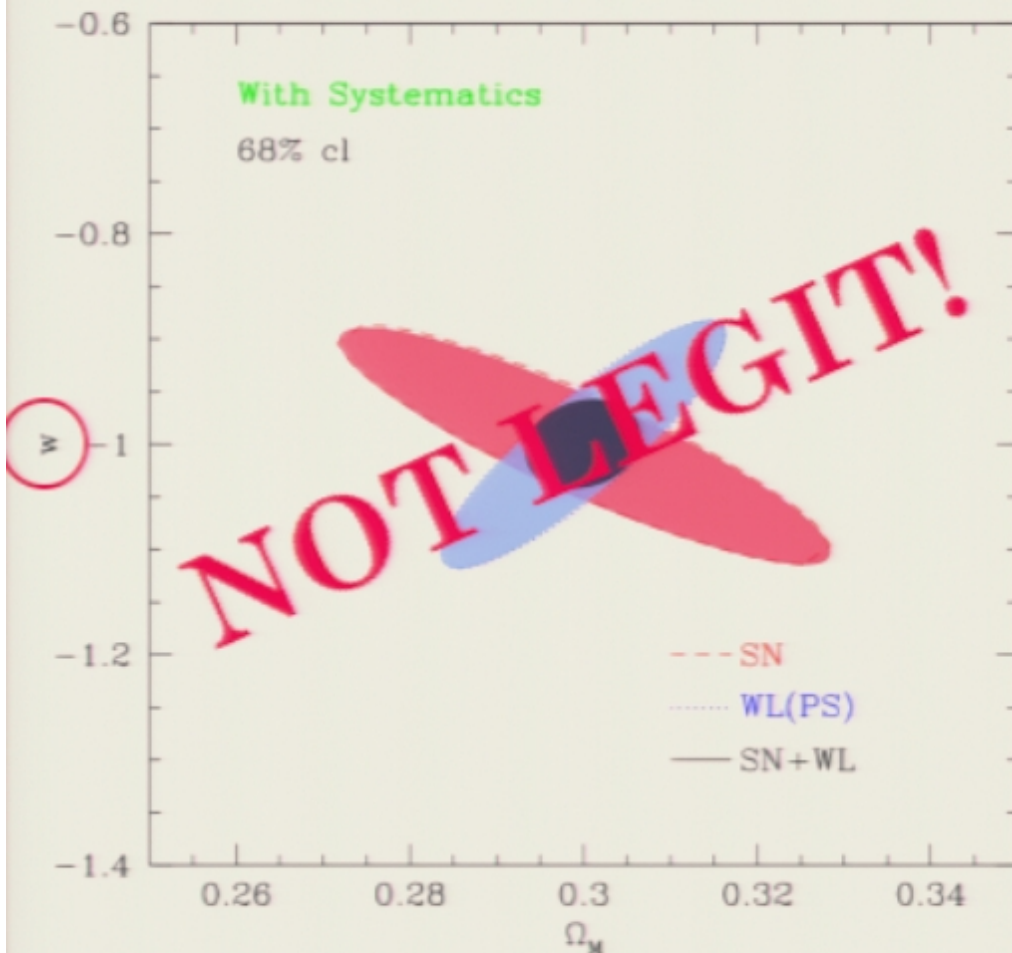


Theory and Data



Springiness of Space
allowing other than Λ

Stretching the Spring
allowing w to vary

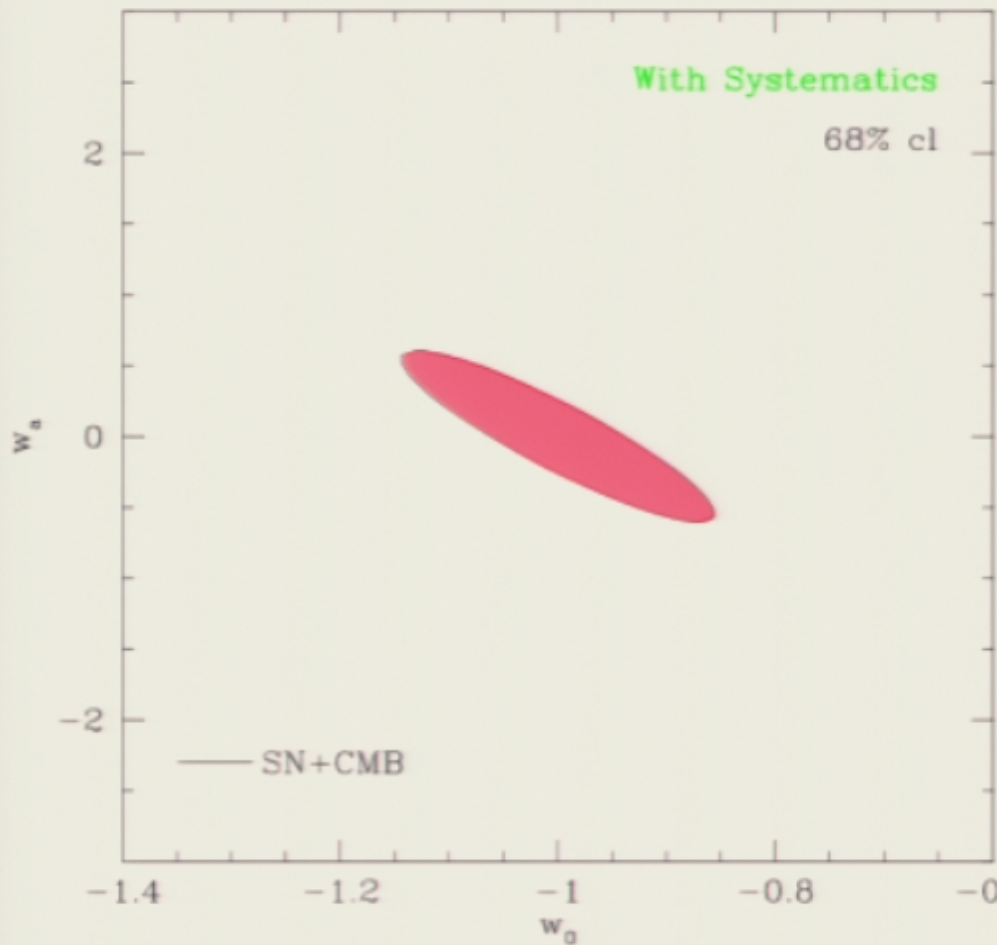




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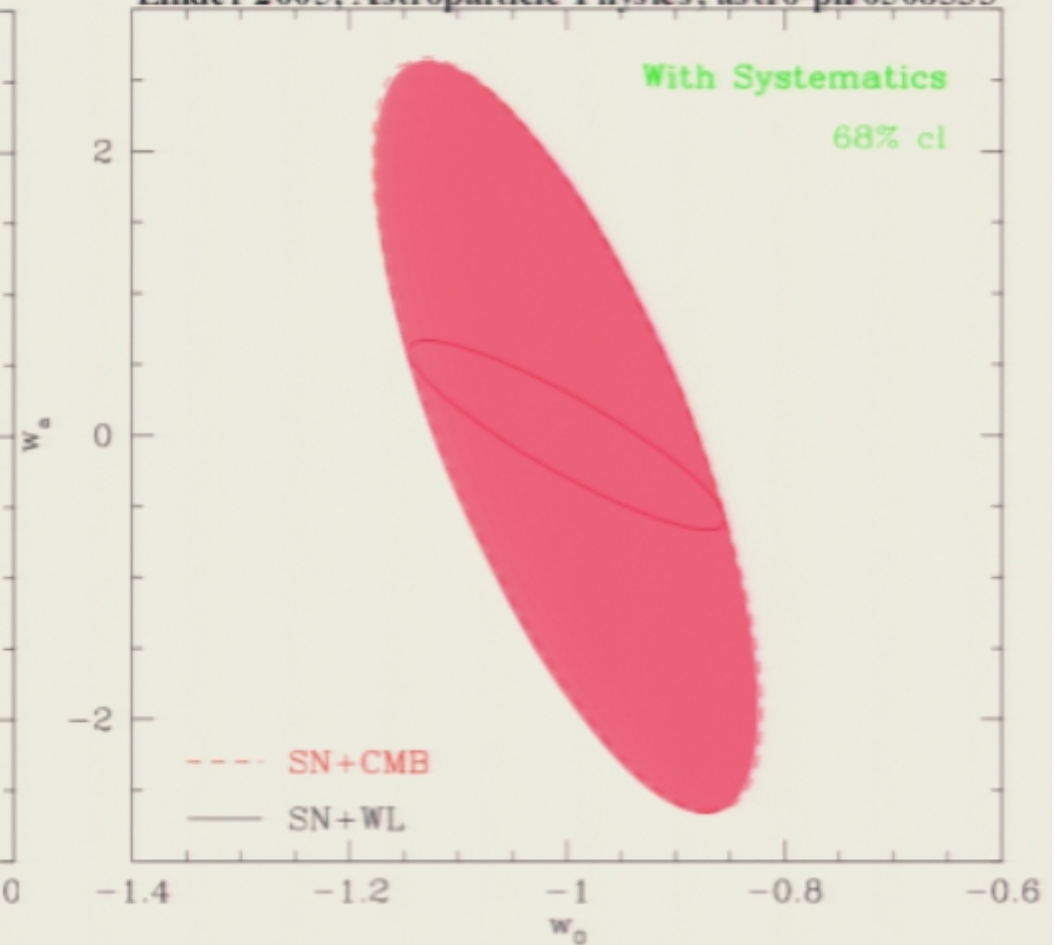


Pinpointing Physics dynamics



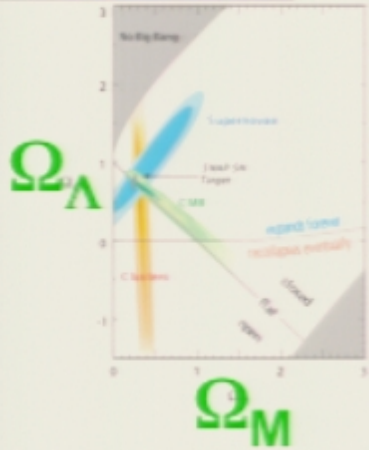
Checking Geometry *allowing curvature*

Linder 2005, Astroparticle Physics; astro-ph/0508333



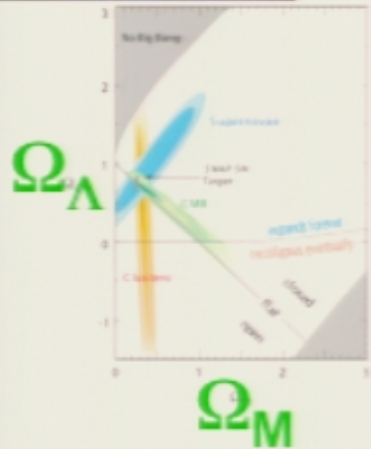


Testing the Framework

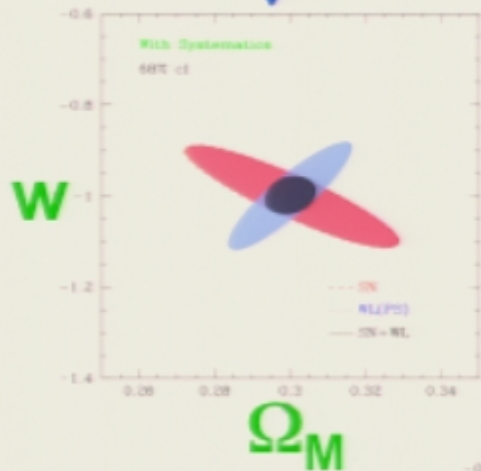




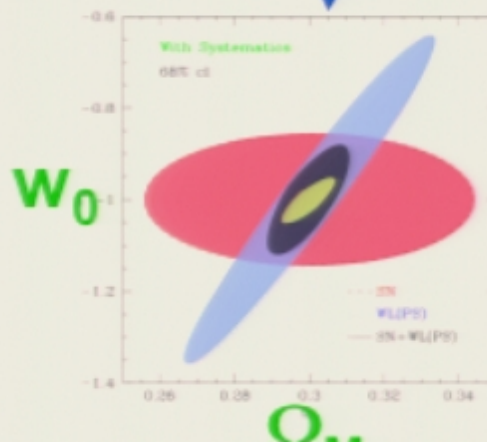
Testing the Framework



Test Λ

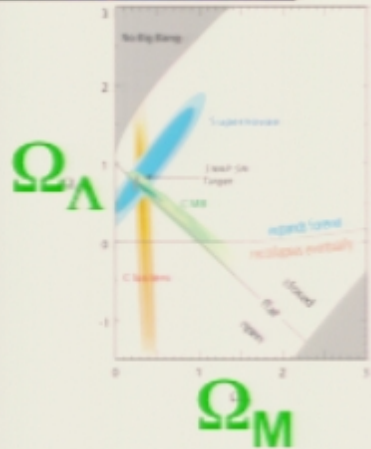


Test dynamics

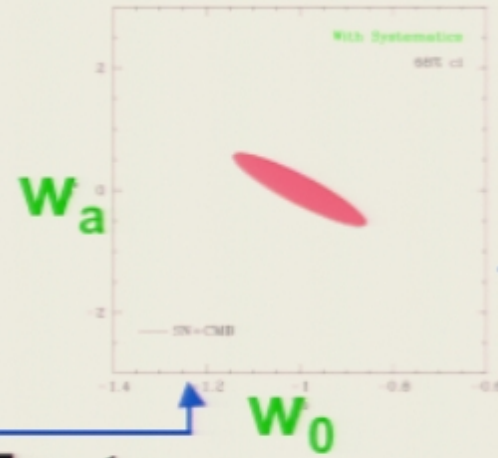




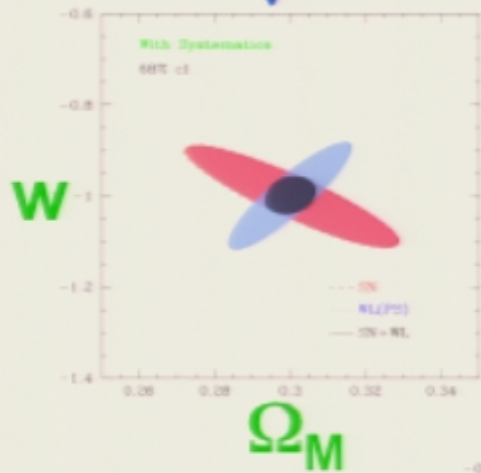
Testing the Framework



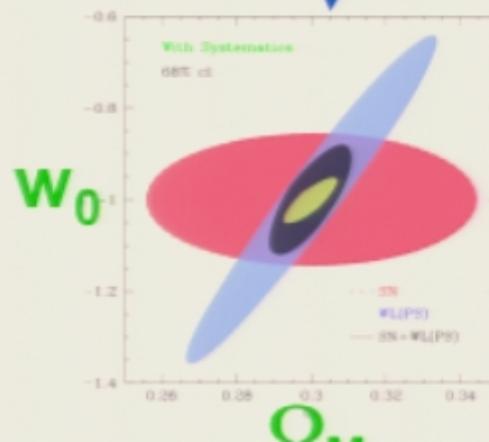
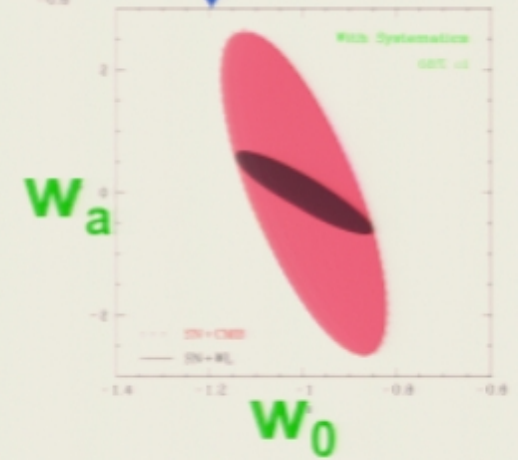
Test Δ



Test geometry

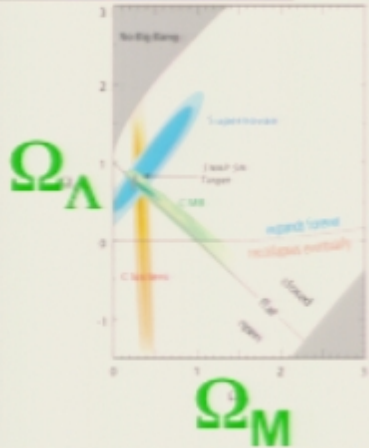


Test dynamics

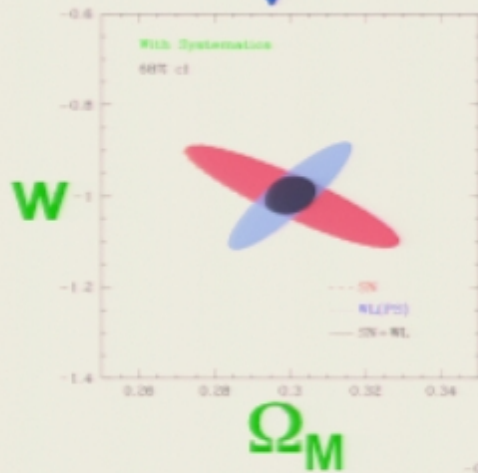




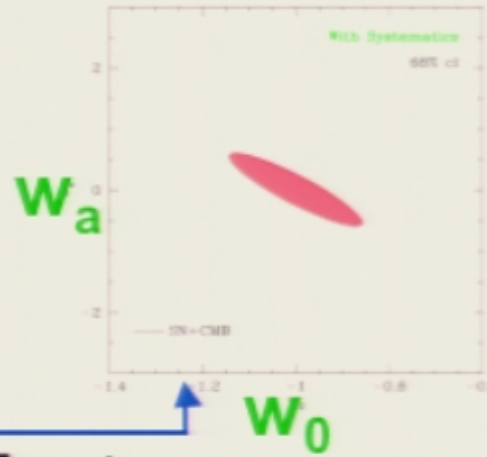
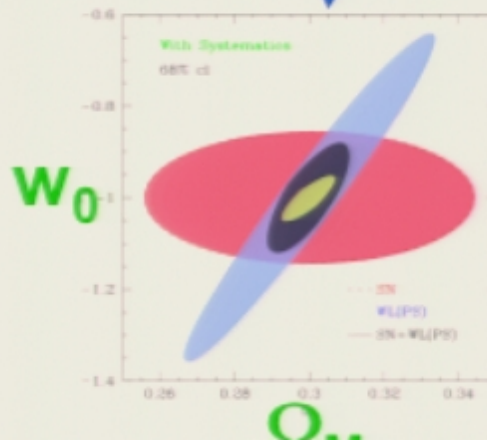
Testing the Framework



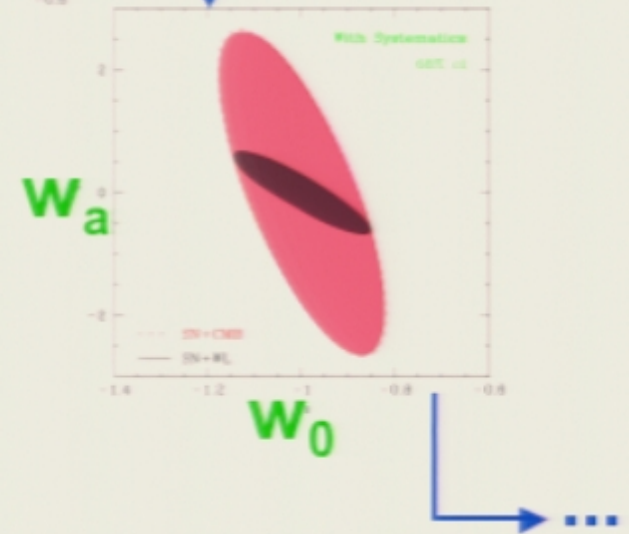
Test Λ



Test dynamics



Test geometry



Test GR