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Review and Status of Dark Energy

PPC 2015

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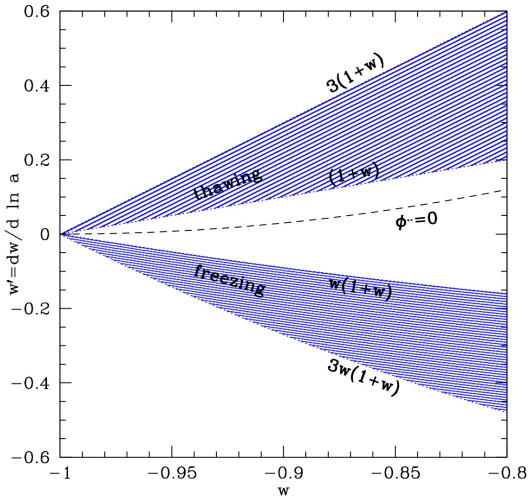

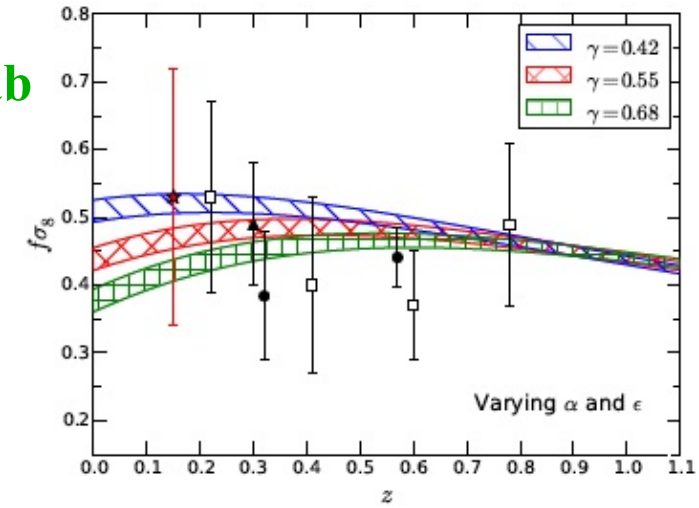

What is Dark Energy?

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Rene Magritte
The Treachery of Images

"This is not dark energy."

What is Dark Energy?

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How many dark rectangles do you see?

Physics of Dark Energy

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There is no equivalent of the Standard Model of particle physics to guide us for dark energy.

But if there was, should we expect it to be less complicated, i.e. just a single, canonical, minimally coupled scalar field?

Early approach – choose a model

Standard approach – phenomenological

New approach – Effective Field Theory

Gubitosi, Piazza, Vernizzi 1210.0201
Bloomfield, Flanagan, Park, Watson 1211.7054
Gleyzes, Langlois, Piazza, Vernizzi 1304.4840
Bellini & Sawicki 1404.3713

Model Approach

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Very little motivation. Highly arbitrary. Lots of fine tuning, subject to quantum corrections.

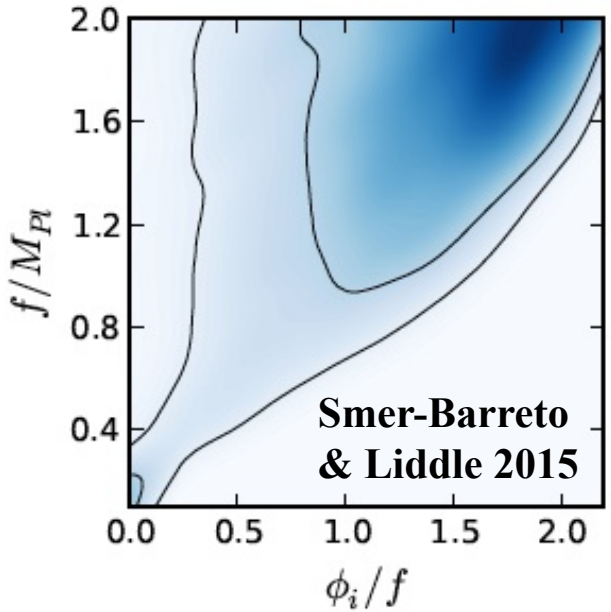
Observations rule out (push to Λ) tracker models that relieve initial fine tuning.

One model I still have some fondness for:

PNGB (pseudo-Nambu Goldstone boson)

$$V(\phi) = M^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

Frieman, Hill, Stebbins, Waga 1995



Has a shift symmetry giving technical naturalness. Connections with axion physics. In excellent agreement with observations.

Phenomenological Approach

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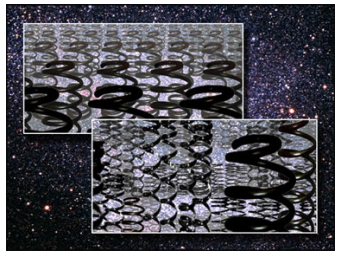
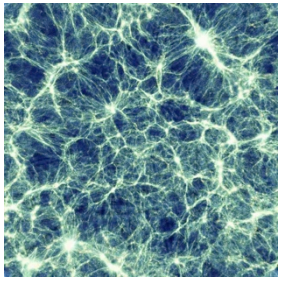
Handles on dark energy:

Expansion history → eq of state w(z)



Clustering → sound speed $c_s(z)$



Growth vs expansion → modified gravity, DE clustering, DE coupling, neutrinos

These help determine whether dark energy is a physical (scalar) field, or a modification of gravity.

Cosmic Expansion History

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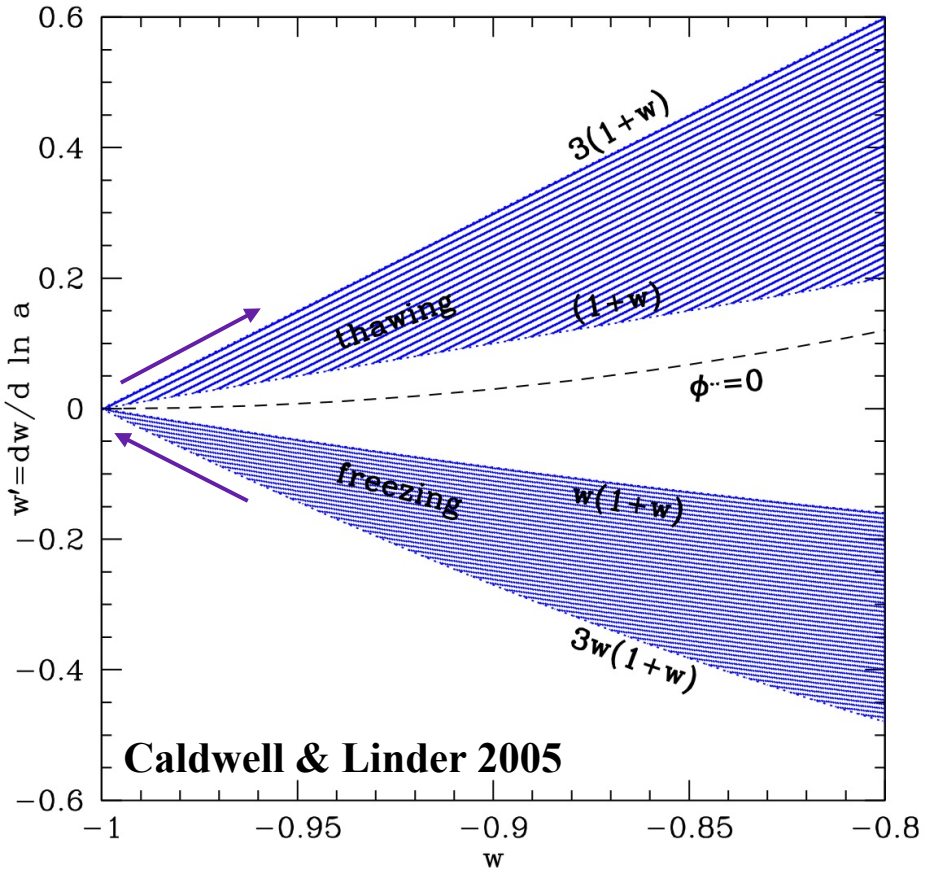
Expansion history a(t) is completely equivalent to an (effective) dark energy equation of state w(z).

The phase space w-w′ has distinct regions corresponding to different physics.



Entire "thawing" region looks like <w> ~ -1 ± 0.05.

Need experiments sensitive to σ(w′)≈2(1+w).

Calibrating Dark Energy

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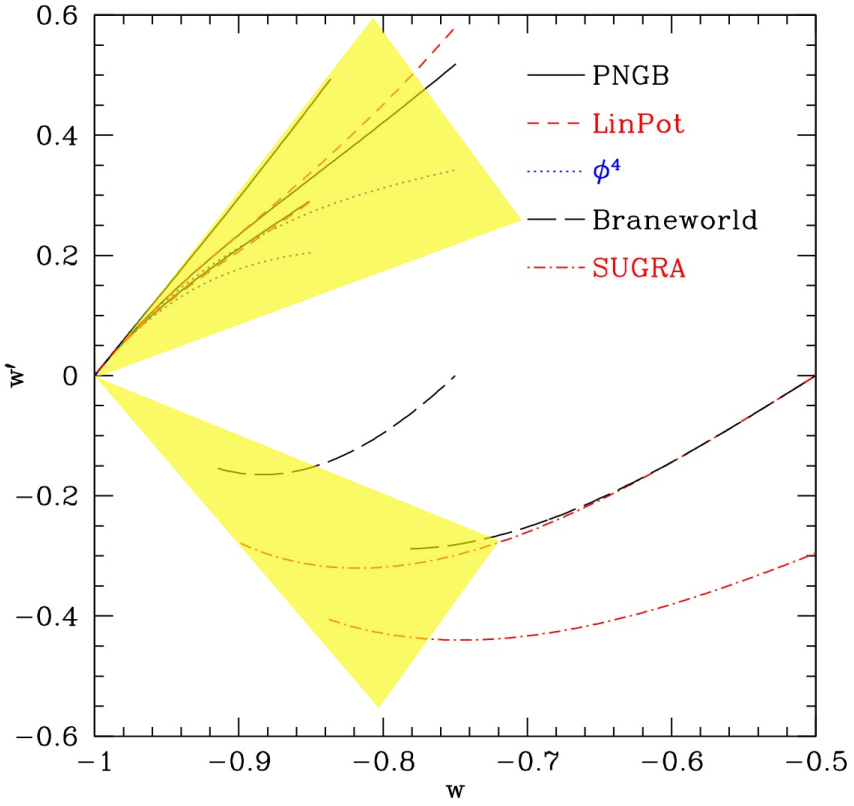
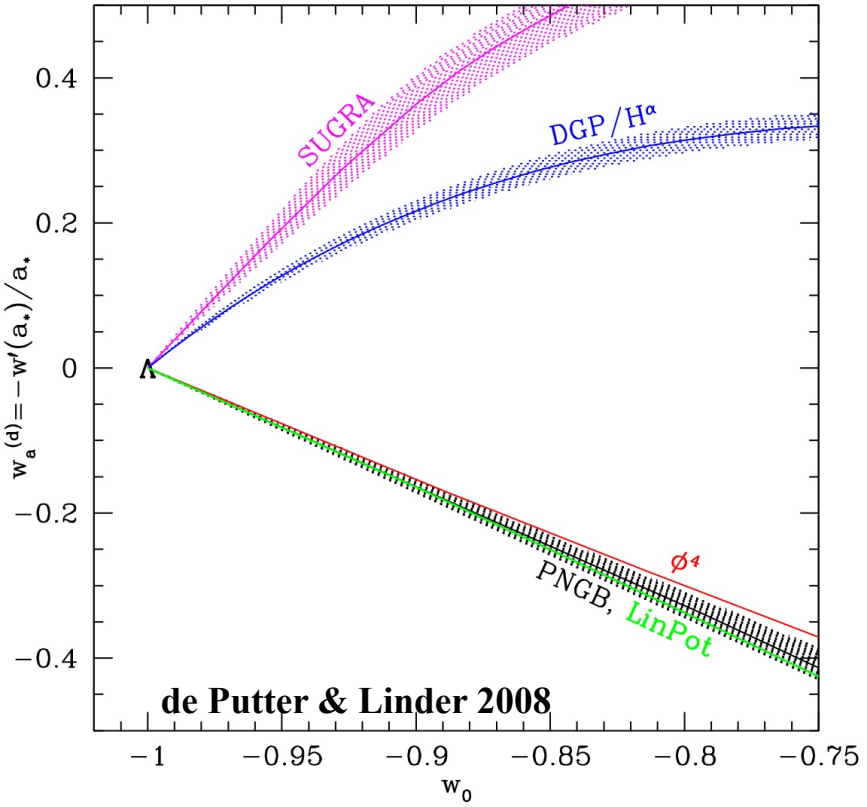
Models have a diversity of behavior, within thawing and freezing.



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

Calibrated parameters w_0, w_a.

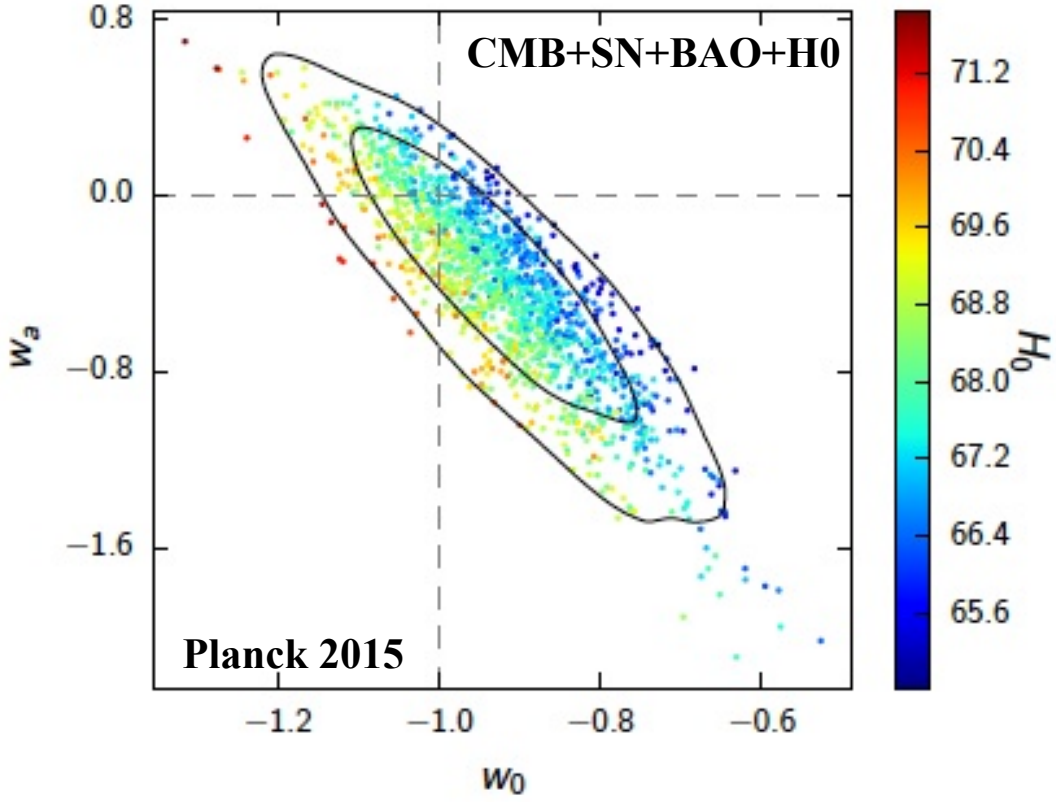


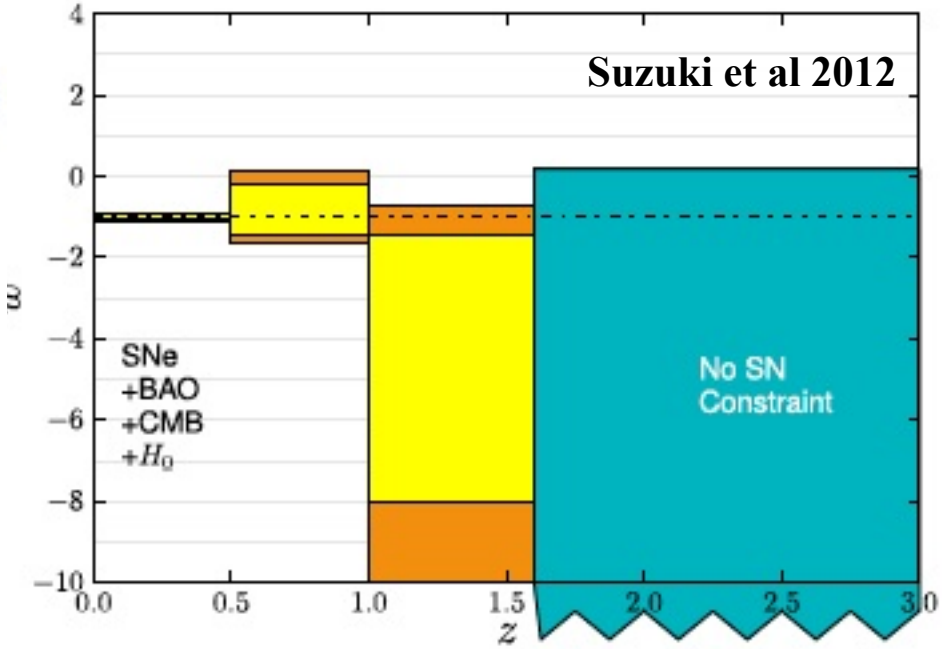
The two parameters w_0, w_a achieve 10^{-3} level accuracy on observables d(z), H(z).

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

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

Current Constraints





Current data consistent with Λ, but also wide range of w_0, w_a.

Model independent constraints are good at z<0.5, fading at z=0.5-1, and ~nil at z>1.

Cosmic Growth History

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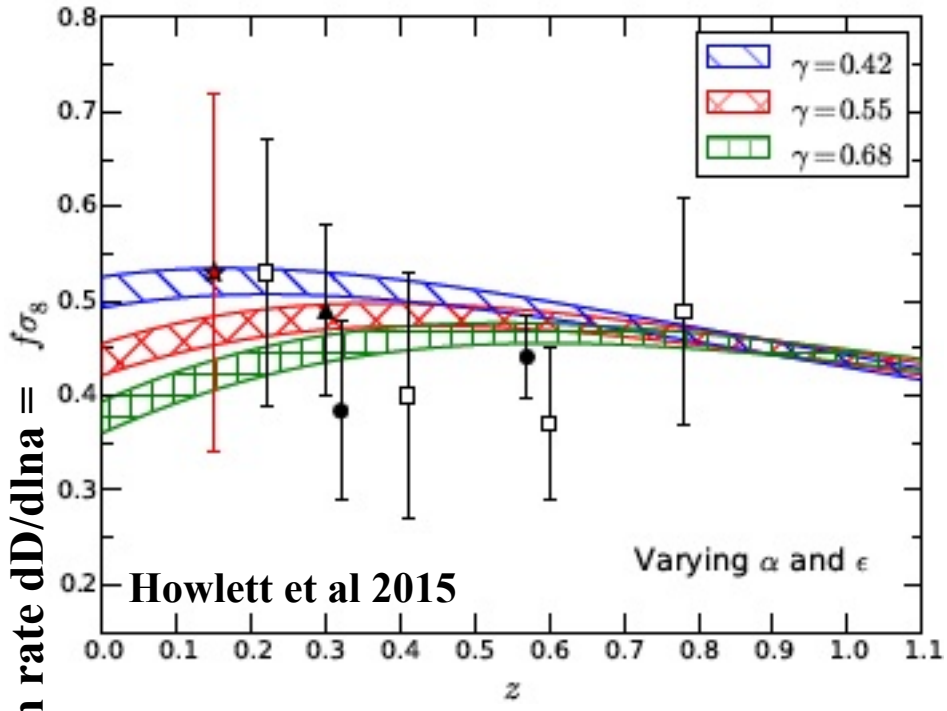
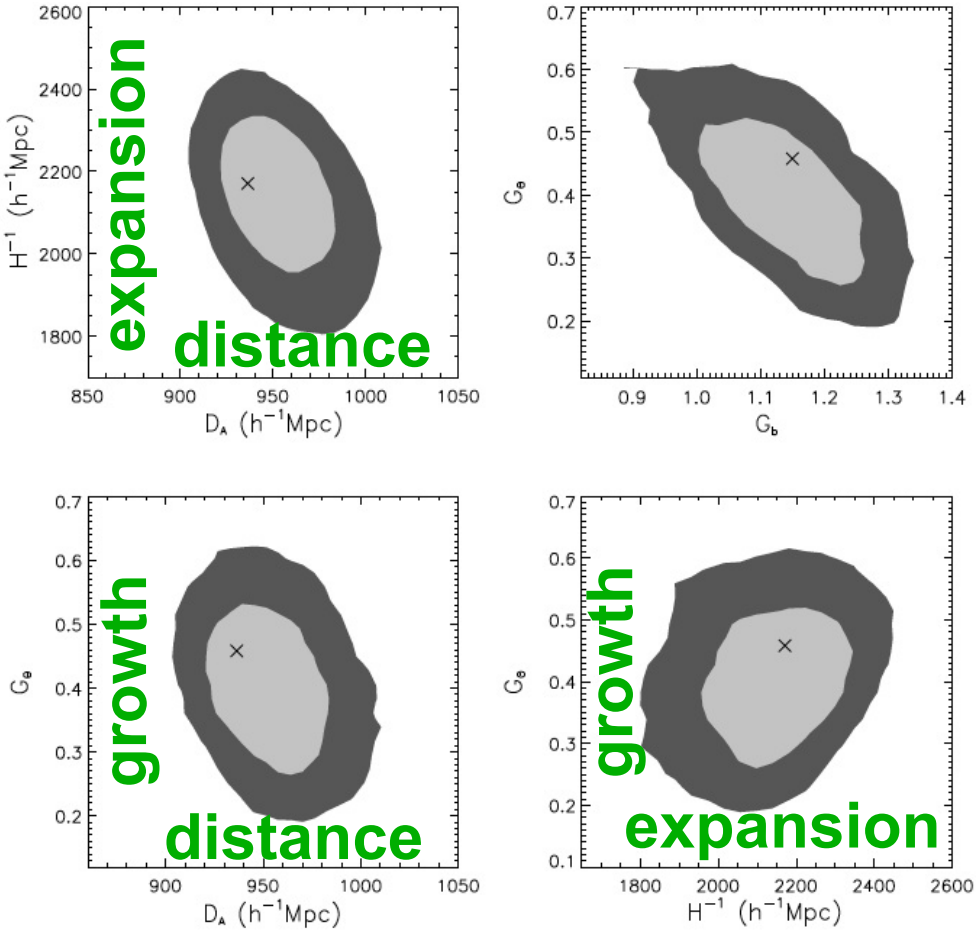
In general relativity, (linear) growth of structure and expansion are tied together – one predicts the other. Cosmic growth tests GR.

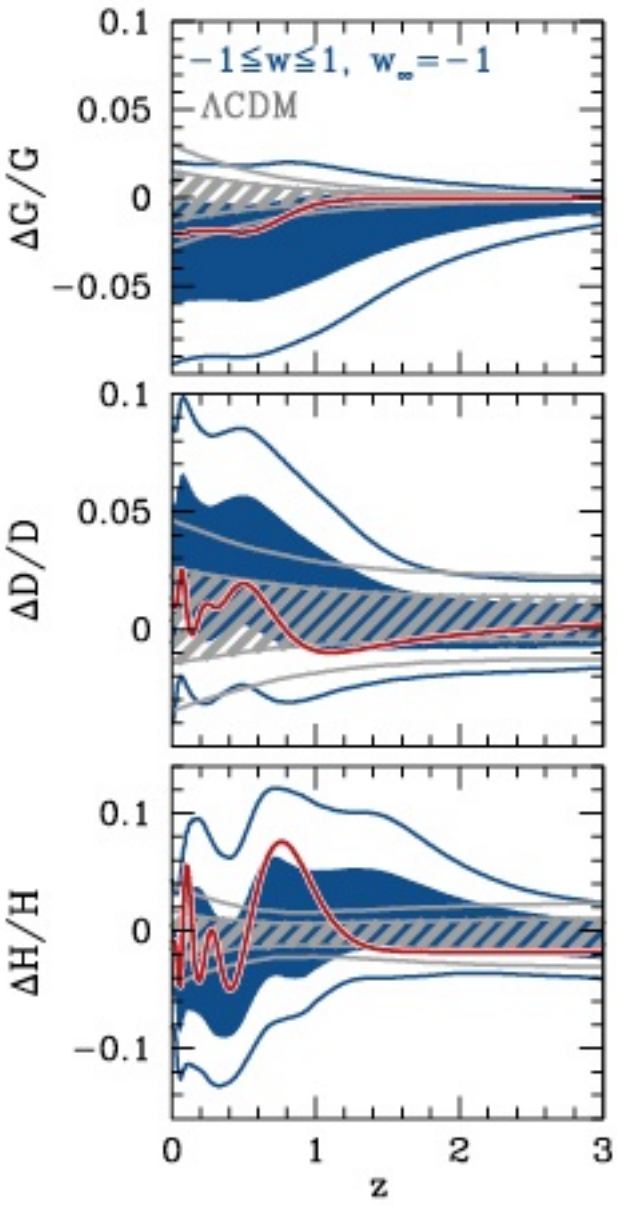


SDSS-3 BOSS galaxy redshift survey



Song et al 2014

Falsifying Paradigms



Mortonson, Hu, Huterer 2010

Testing frameworks:

Grey shows the suite of all ΛCDM models.

Blue shows all quintessence.

Almost impossible to enhance growth. Possible signature of scalar-tensor gravity.

CMB is a superb probe of early dark energy (Ω_{EDE}<0.4%), and early growth. CMB lensing will be an important dark energy probe.

Neutrino Hierarchy

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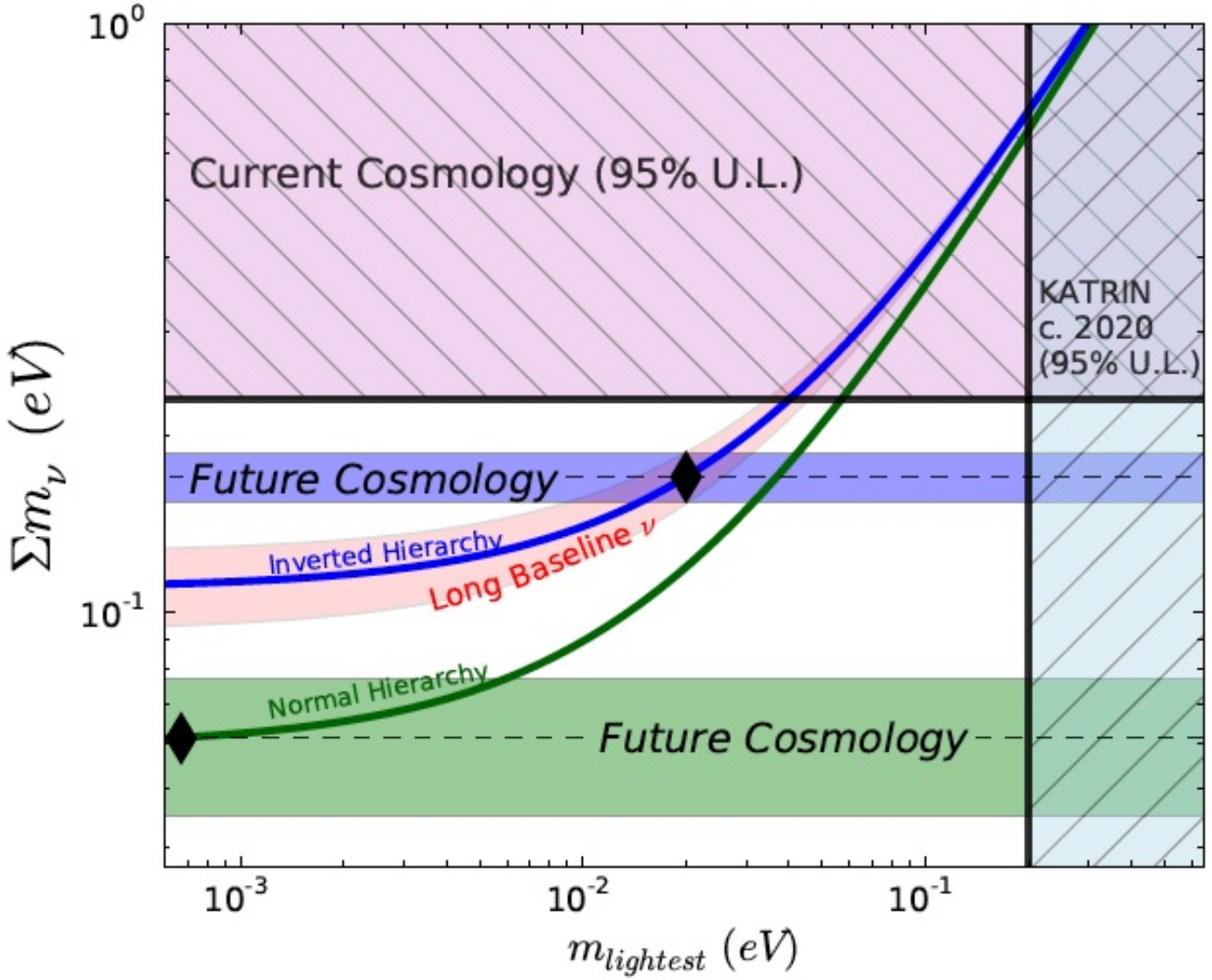
Complementarity between cosmic and lab experiments. Can distinguish mass hierarchy.



Snowmass 1308.5383

Progress in Distances

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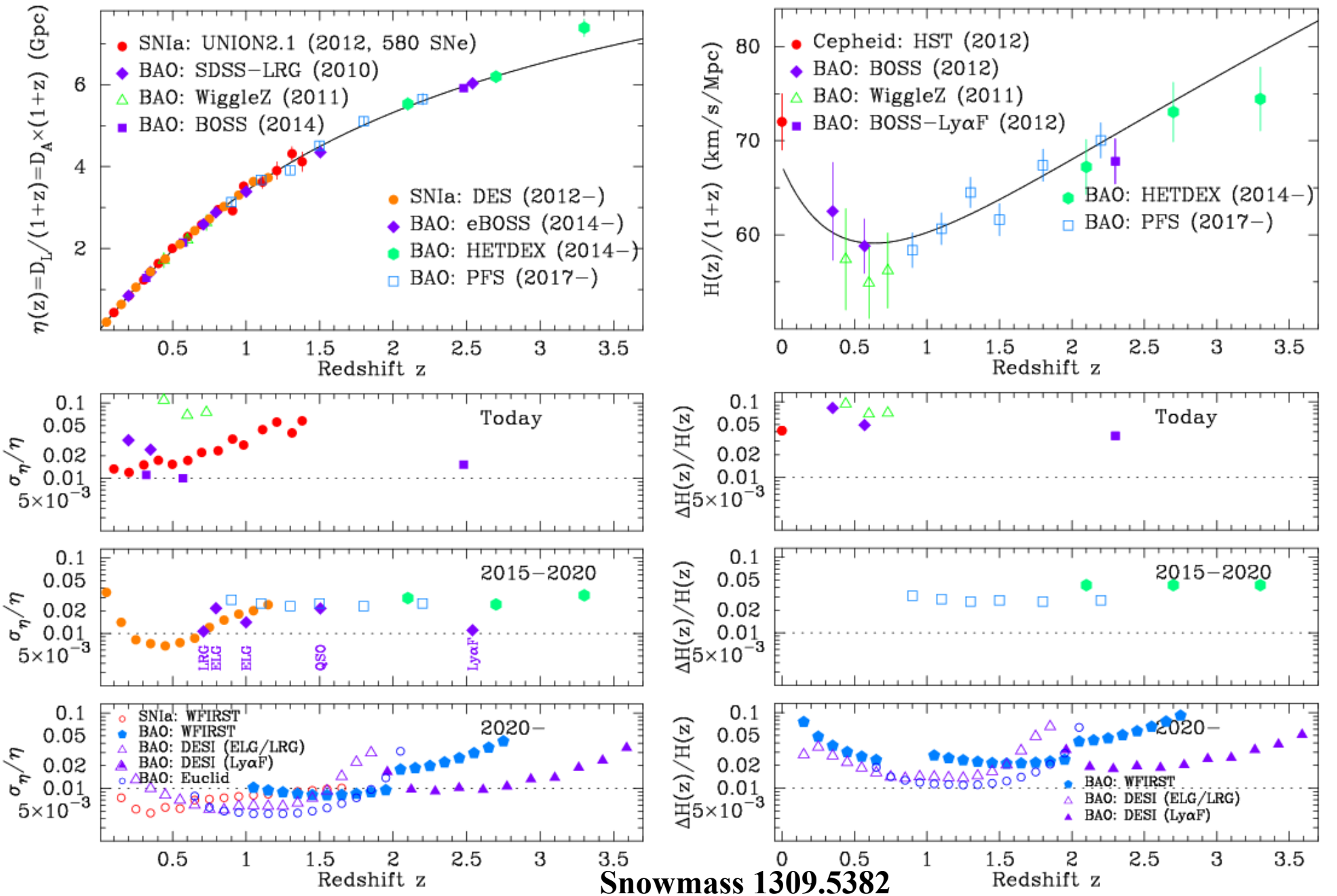

Snowmass 1309.5382

An Active Future

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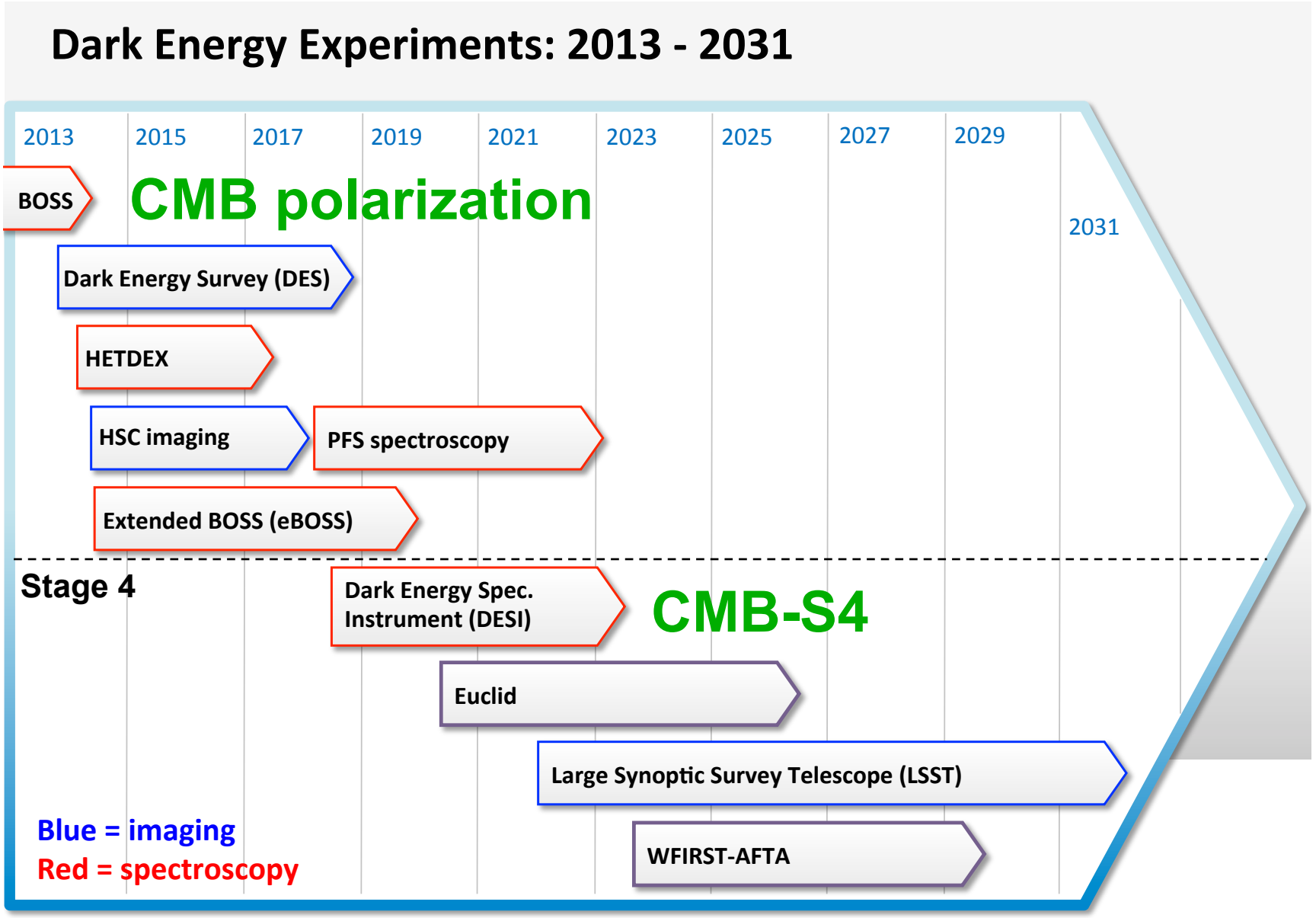

see Snowmass 1309.5380 for details

Role of Observations

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But Λ, what big teeth you have!

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

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Rene Magritte
The Treachery of Images

"This is not dark energy."

But we're going to find out what is dark energy.