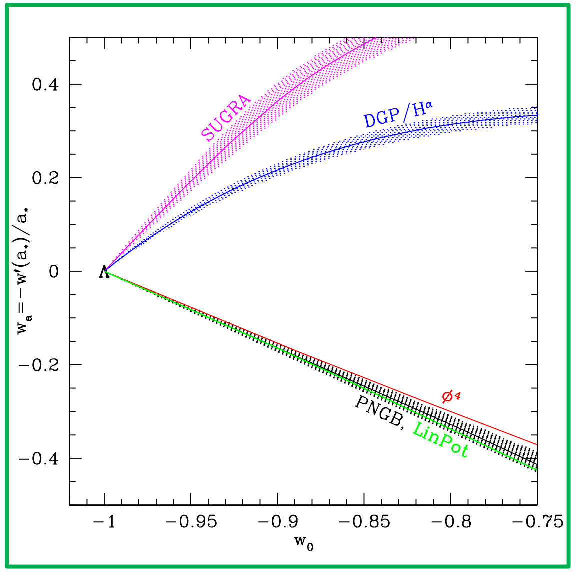
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

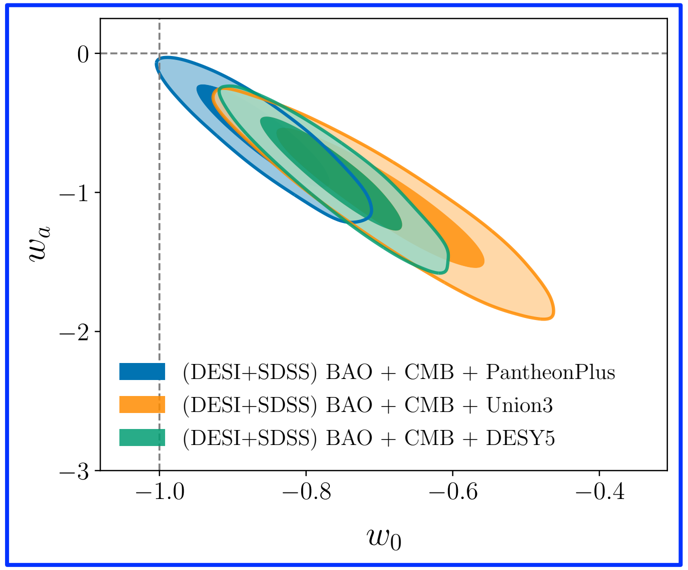
Status of Dark Energy

Eric Linder

UC Berkeley

IFPU 13 May 2024





Accelerating Universe

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Let's not lose sight of how amazing cosmic acceleration is!

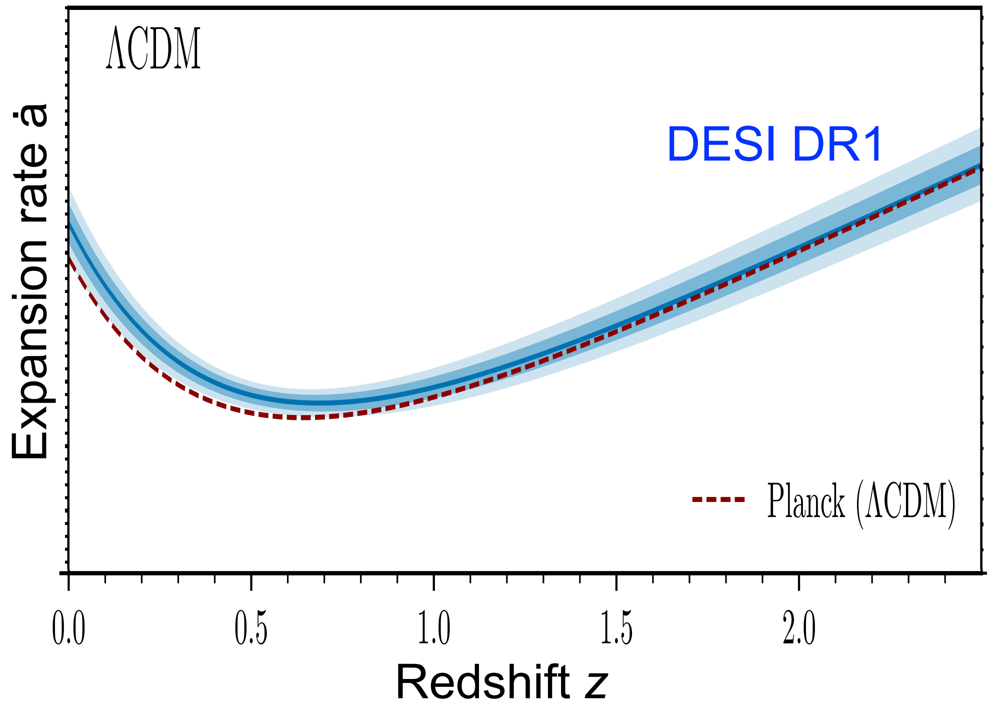
We've been taught since we were infants that gravity is attractive. An (effective) energy density that speeds up the cosmic expansion, pulling things apart rather than together, is extraordinary!

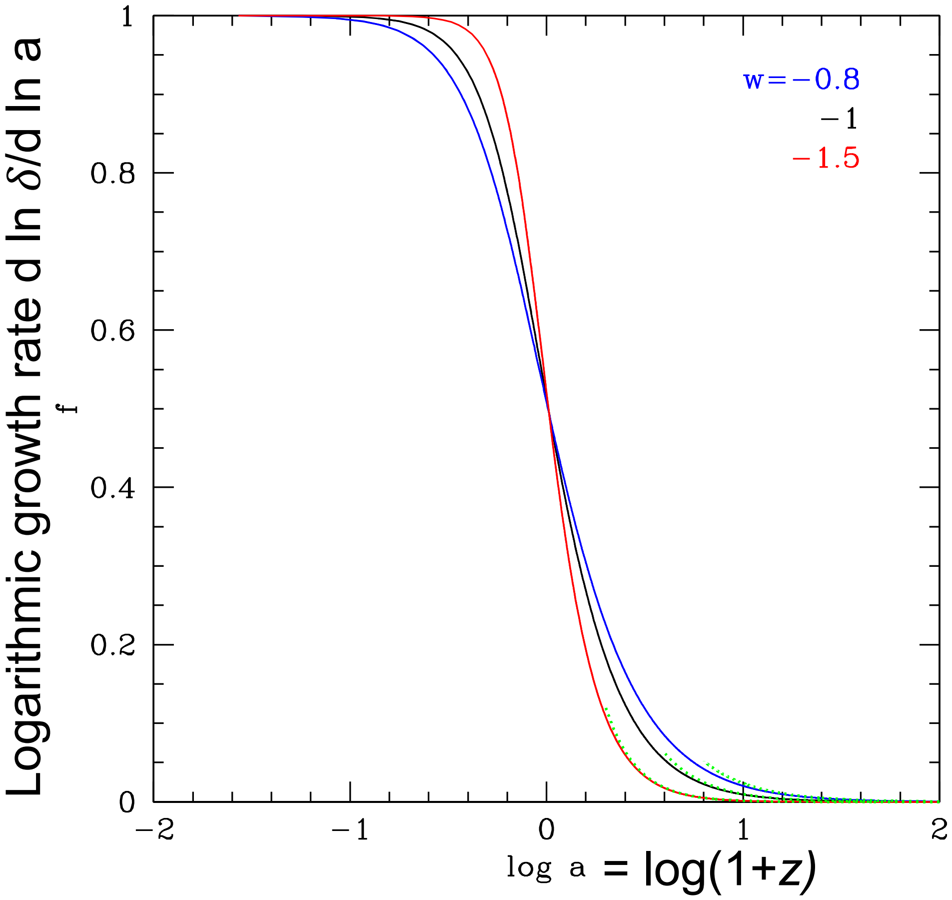
2001 Resource Book on Dark Energy:

- Weinberg: "Until it is solved, the problem of the dark energy will be a roadblock on our path to a comprehensive fundamental physical theory."
- Wilczek: "This disparity [cosmological constant value] is the biggest and most profound gap in our current understanding of the physical world."
- Witten: "For the future development of fundamental physics, it is vitally important to know if the cosmological 'constant', as inferred from these observations, is truly constant."

Cosmological Constant

A cosmological constant Λ, as simple as you can get, still has profound effects on cosmic expansion (distances) and cosmic growth (large scale structure).





Dynamical Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Unfortunately there is no good* theory for Λ.

Once you go beyond Λ, dark energy is dynamical. Both its pressure and energy density (and their ratio, the equation of state w(a)) are time dependent.

Dark energy may be a scalar field rolling in its potential**, or it may be a modification of general relativity – which we can treat as an effective field (though more complicated).

* "good" means someone other than the author and friends believes it.
** But you would still need to explain what happened to Λ, i.e. quantum vacuum.

Is Dark Energy a Horror?

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Recently, dark energy (other than Λ) was described as coming from a confuse-aton.

The Clarity of Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Actually, we understand the basics of dark energy very well.

Dark energy does not exist in a vacuum.

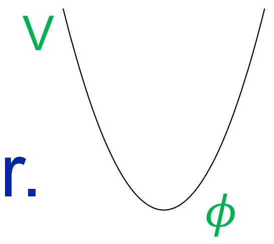
Dark energy evolved over many e-folds in an expanding universe dominated by radiation and matter.

The Hubble friction from expansion and the driving term – steepness of the (effective) potential – govern dark energy evolution.

Thawing and Freezing

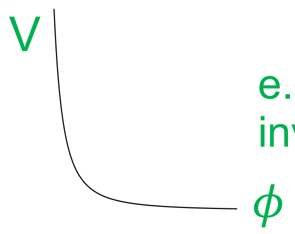
If the Hubble friction dominates, the (effective) field is frozen in place.

Only at late times does radiation/matter dilute sufficiently that the expansion weakens and the field is released – “thaws”.



e.g. $V \sim \phi^2$ or ϕ^4

That is, it moves away from cosmological constant behavior.



e.g. exponential or inverse power law

If the potential slope dominates, the field rolls.

But it eventually approaches the potential minimum where the slope weakens and the field slows – “freezes”.

That is, it moves away from cosmological constant behavior.

Equation of State

Rather than a field phase space, ϕ-$\dot{\phi}$, it is convenient to work in an equation of state $w=P/\rho$ phase space, w-w′.

This is closer to the cosmic expansion history $H=\dot{a}/a$

$$(\ln H^2)' \equiv \frac{d\ln H^2}{d\ln a} = -3\left[1+\sum w_i(a)\Omega_i(a)\right]$$

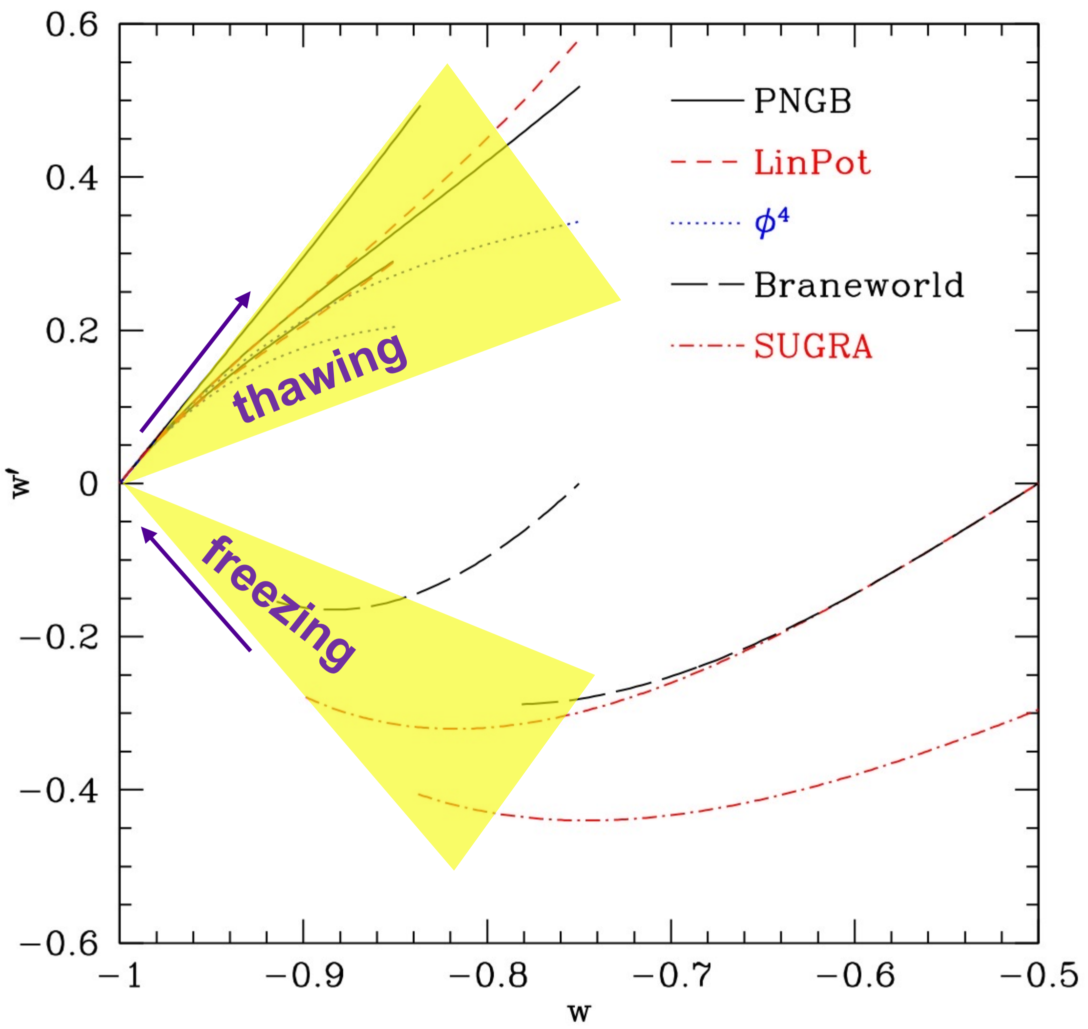
and cleaner when dark energy isn't really a scalar field.

Dark Energy in Phase Space

Illustrating a variety of exact solutions (Klein-Gordon equation) for various potentials and initial conditions.

Due to "*dark energy does not exist in a vacuum*", i.e. Hubble friction, the many diverse evolutionary tracks lie in two narrow regions:

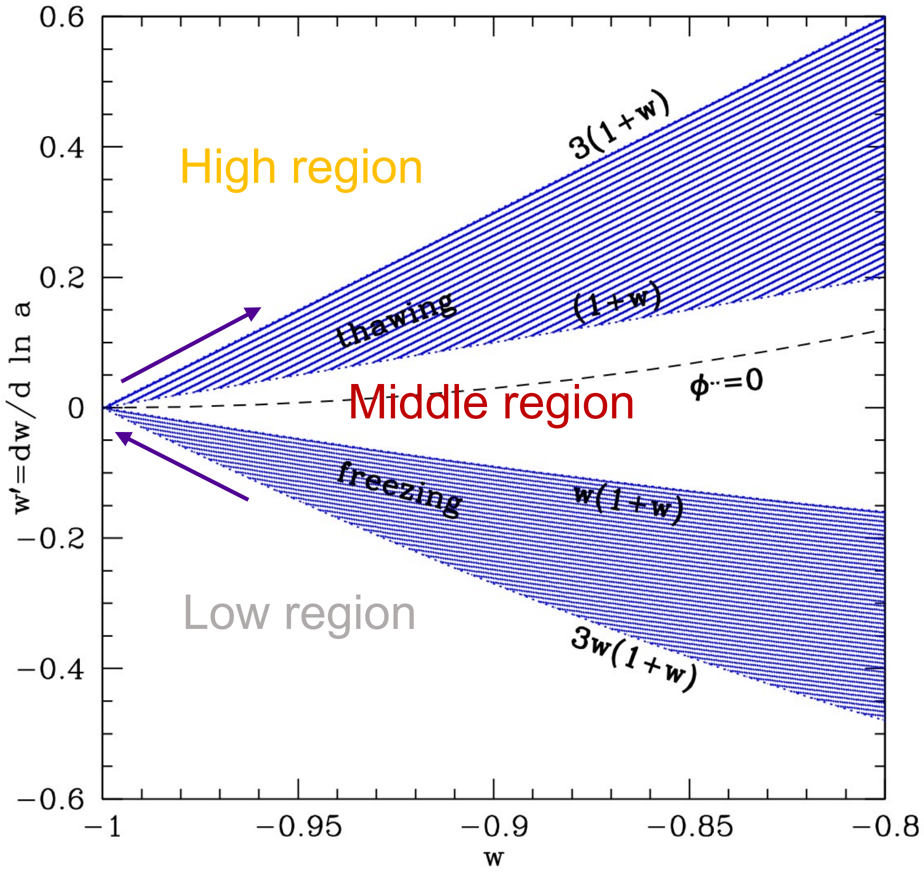
Thawing and Freezing classes



Zones of Avoidance

What about the rest of the phase space?
Physically disfavored.

Phantom region [w<-1]:
e.g. negative kinetic term



High region [w′>3(1+w)]: violate early radiation/matter domination
Middle region [(1+w)<w′<w(1+w)]: fine tuning so coast, $\ddot{\phi} = 0$
Low region [w′<3w(1+w)]: field rolls upslope (e.g. k-essence)

Describing Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

While w-w' is great, with lots of physics, it's a bit much to fit 2 free functions w(a), w′(a) to observations.

Recall that observations depend on (multiple) integrals over w(a) so they don't see the details of the functions.

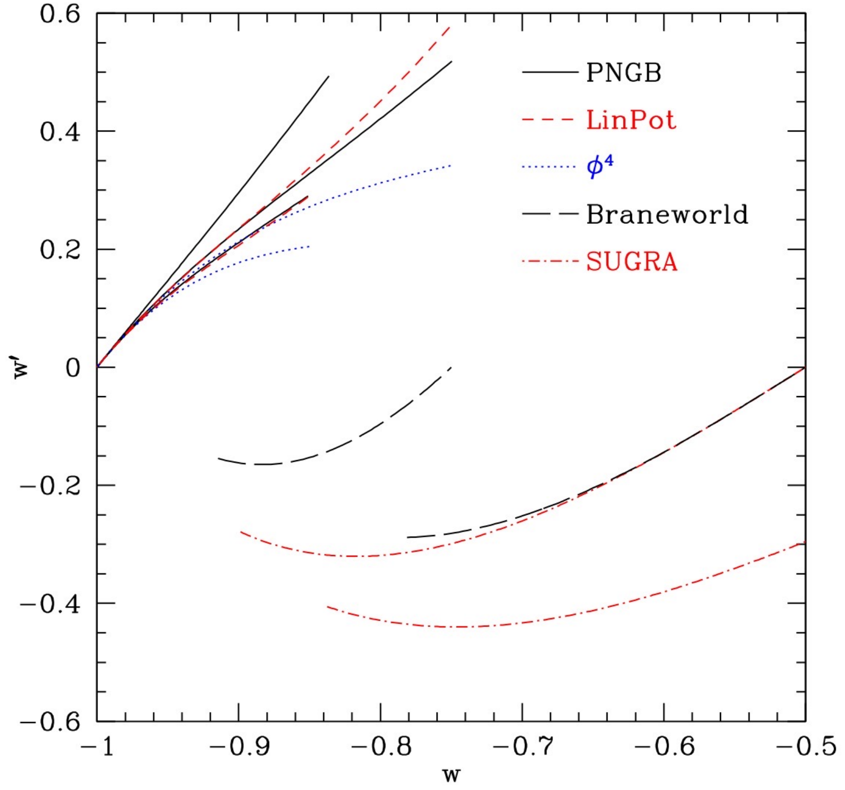
In fact PCA or equivalent methods show that observations are sensitive to just 2 "modes" built from w(a), w′(a), i.e. just two numbers rather than functions. [At least until observations possess better than 0.1% precision.]

The art is choosing the right two quantities to preserve the physics.

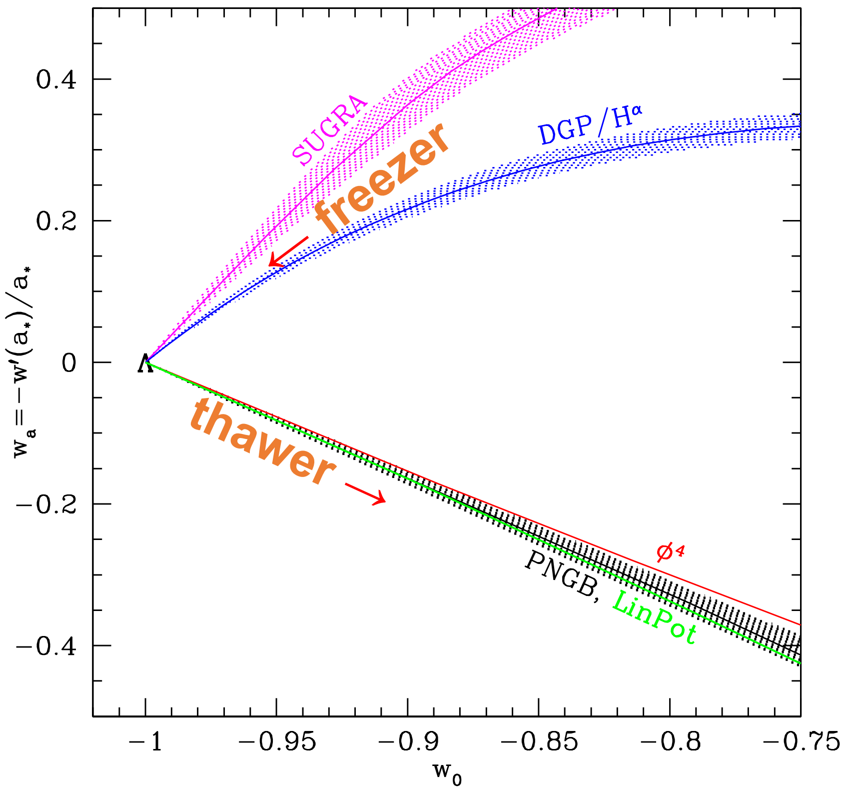
Calibrating Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

For our w(a) number, let's try the value today, w(z=0).
For our w′(a) number, let's try stretching the time axis, i.e. scaling w′(a).



w_0-w_a
"calibration"



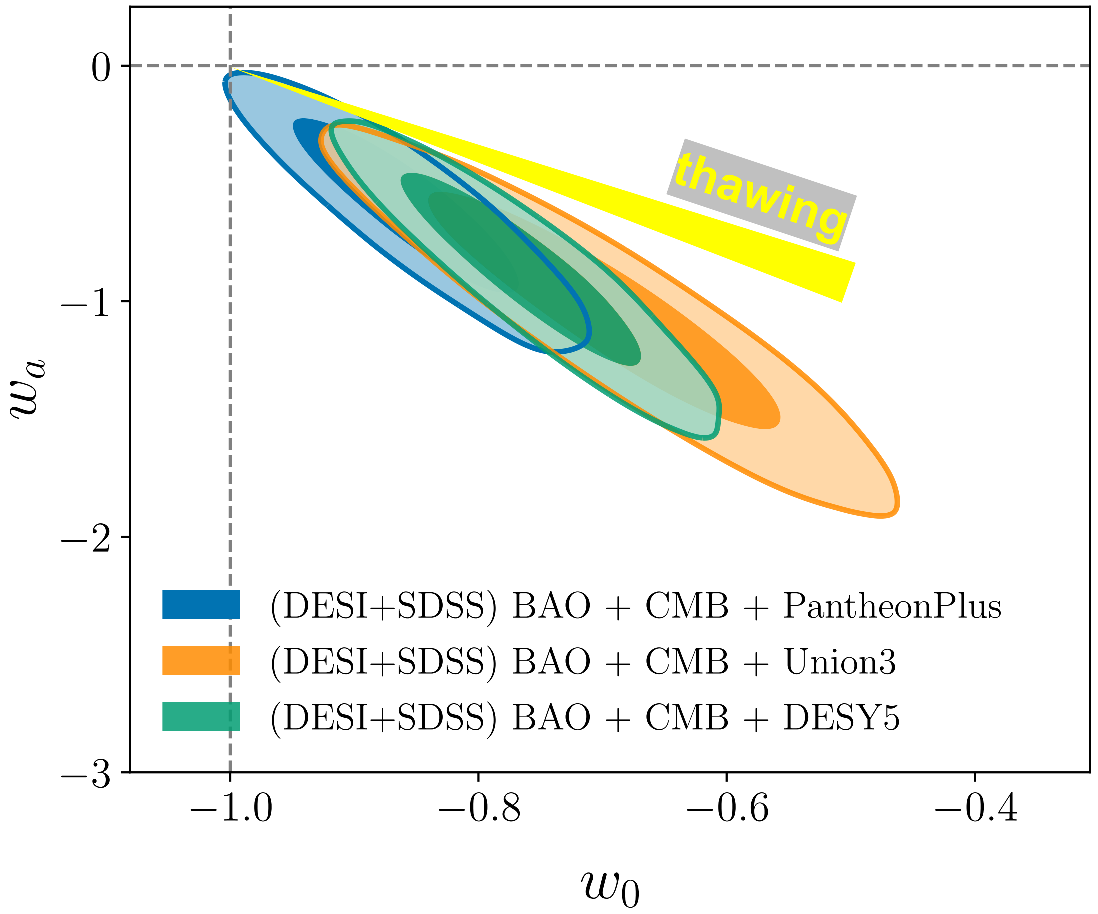
That is the meaning of w_0-w_a , where $w(a)=w_0+w_a(1-a)$.
It is a physics-based encapsulation of 2 full functions.

[Never say it is a Taylor expansion!]

Results!

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

So, what does data in 2024 say dark energy is?



Λ? Thawing? In an impossible place?

Interpretation?

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

The statistical significance is not very significant, ~2-3σ. DESI calls it a "tantalizing suggestion of deviations".

What if we take the best fit at face value? Can we eff the ineffable?

It would require dark energy to

1) be phantom at z>1, then
2) "superevolve" faster than Hubble friction seemingly allows, then
3) cross w=-1 ("the phantom divide"), and
4) evolve away from L to less negative w0.

We know the physics to do each piece, but they generally don't all go together!

Moving Forward Model Independently

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Results should be checked on both the data side and analysis side.

DESI looked at data cuts and did blind analysis – excellent start!

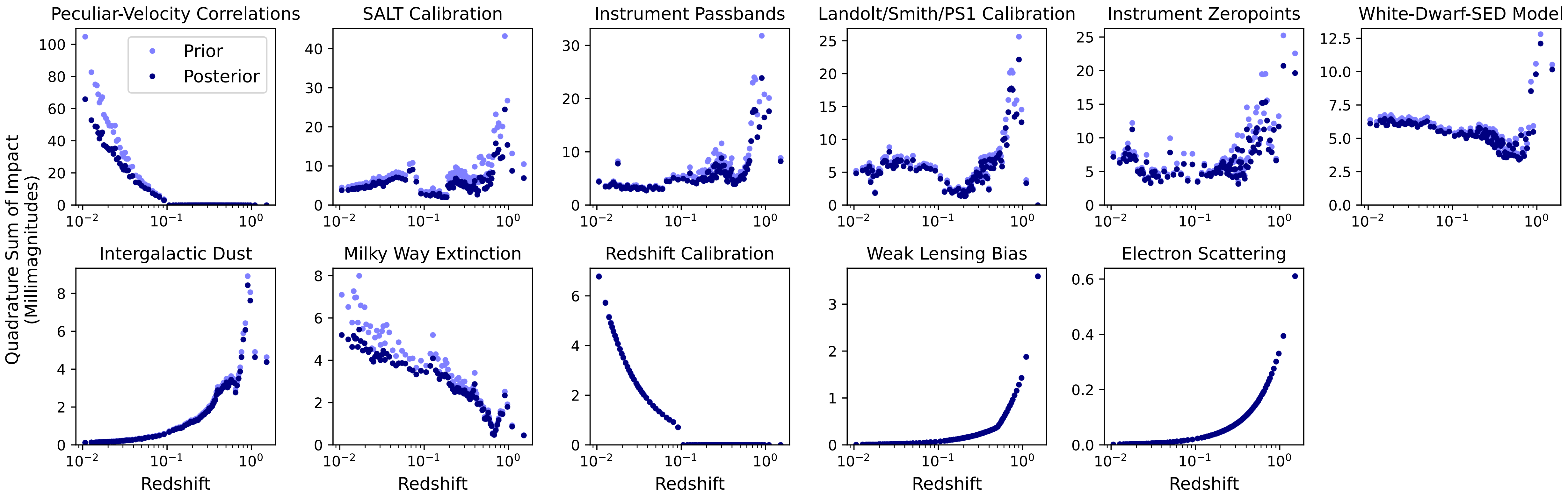
Null tests are very common in CMB analysis: testing instruments (different sensors), survey (scan properties), sky (sun/moon).

Selection effects are systematics. How detailed is the modeling and does the residual effect give unbiased results? e.g.

- magnitude limit
- bright star avoidance
- fiber collisions

Example: Supernova Survey Analysis (Union3)

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS



Note: 22 mmag = 1% distance uncertainty

Consistency between Data Sets

DESI compared dark energy contours of DESI vs DESI+SDSS. The shift is $\lesssim 0.5\sigma$.

Supernova data sets (Pantheon+, Union3, DES-SN5yr) give consistent dark energy contours, especially in combination with BAO or CMB. The shift is $\lesssim 0.5\sigma$.

BAO distances and SN distances appear fairly consistent with each other, but this can be tested more thoroughly. (see Keeley+ 2010.03234, Liao+ 2002.10605, L'Huillier+ 1812.03623, Shafieloo+ 1804.04320, L'Huillier & Shafieloo 1606.06832 and many more)

And test vs strong lensing distances ($D_{\Delta t}$, D_A) and gravitational wave distances D_L^{GW}.

What Drives the Extreme Values?

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

It is useful to understand what cosmology (other parameters) the edges of the contours correspond to, especially from individual probes.

Is the posterior being pulled by extreme values, e.g. very high or low Ω_m?

They may also correspond to “insensitivity” regions, e.g. if very little dark energy density $\rho_{DE}(z)$ then the DE equation of state is mostly moot.

Can be useful to color code a plot of chain samples by a third parameter, e.g. Ω_m or H_0.

Model Independent(-ish) Statistics

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Lots of good literature on model independent statistics.

Bins in redshift – easy physical interpretation, localized, uncorrelated at the theory level. (I prefer not to spline as that induces correlations.)

Gaussian processes – good quantification of deviations, handles heterogeneous data, handles derivatives well. Caution: don't use a black box! (see e.g. Hwang+ 2206.15081)

Basis functions/Expansions – main issue is truncation: finite number of terms **is** adopting a cosmology. Too many terms can give wiggles.

PCA – nonlocal and hard to interpret. Caution: use S/N not just $\sigma(\alpha_i)$!

What is the Impact of Priors?

BERKELEY CENTER for COSMOLOGICAL PHYSICS

We all know that priors matter. Even nuisance parameter priors can distort results.

Don't adopt arbitrary functional forms (e.g. $\delta X \sim \Omega_{DE}(a)$). This artificially weights the data and biases results. (See Mueller+ 1612.00812 for excellent illustration.)

Be very wary of priors where effects vanish, e.g. low ρ_{DE}, low $|f_{R0}|$.

Even physical priors can be tricky. Should the prior on sum of neutrino masses be >0? >0.058 eV? uniform PMNS prior (Long+ 1711.08434)? or, say, [-0.5,+0.5] eV (cf. Craig+ 2405.00836)?

Let's do the calculation this week!

Summary

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

We understand a lot (model ~independently) about how dark energy *should* behave… and about what it means if it doesn't.

Λ? Thawing? In an impossible place? is still to be determined.

Model independent approach will be key – from data cuts to null tests to blind analysis to interpretation.

Test consistency between data sets, between probes (understand extrema and priors), and use robust statistical techniques.

We know how to do all this, and this workshop is a great start!