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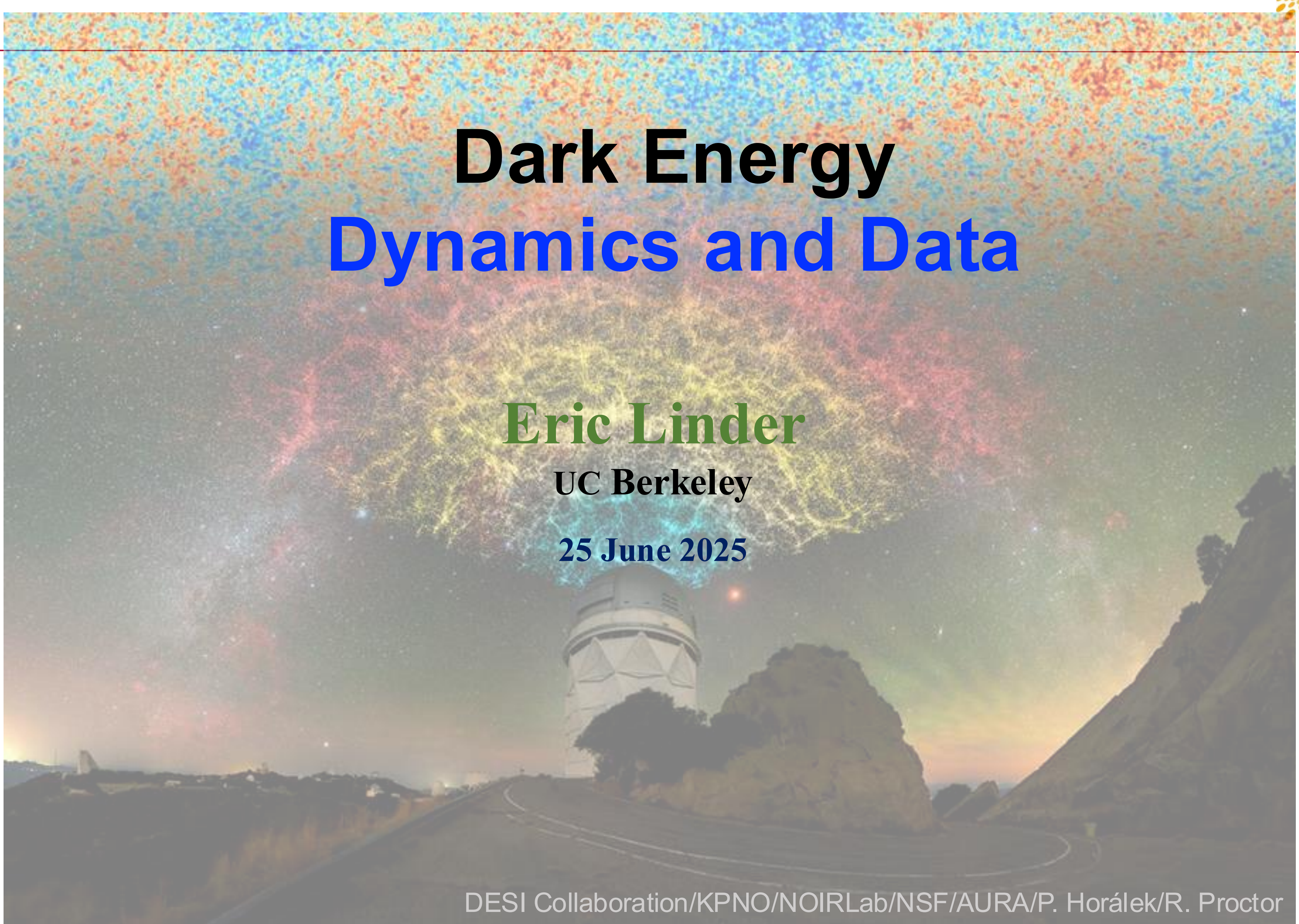


Dark Energy
Dynamics and Data

Eric Linder

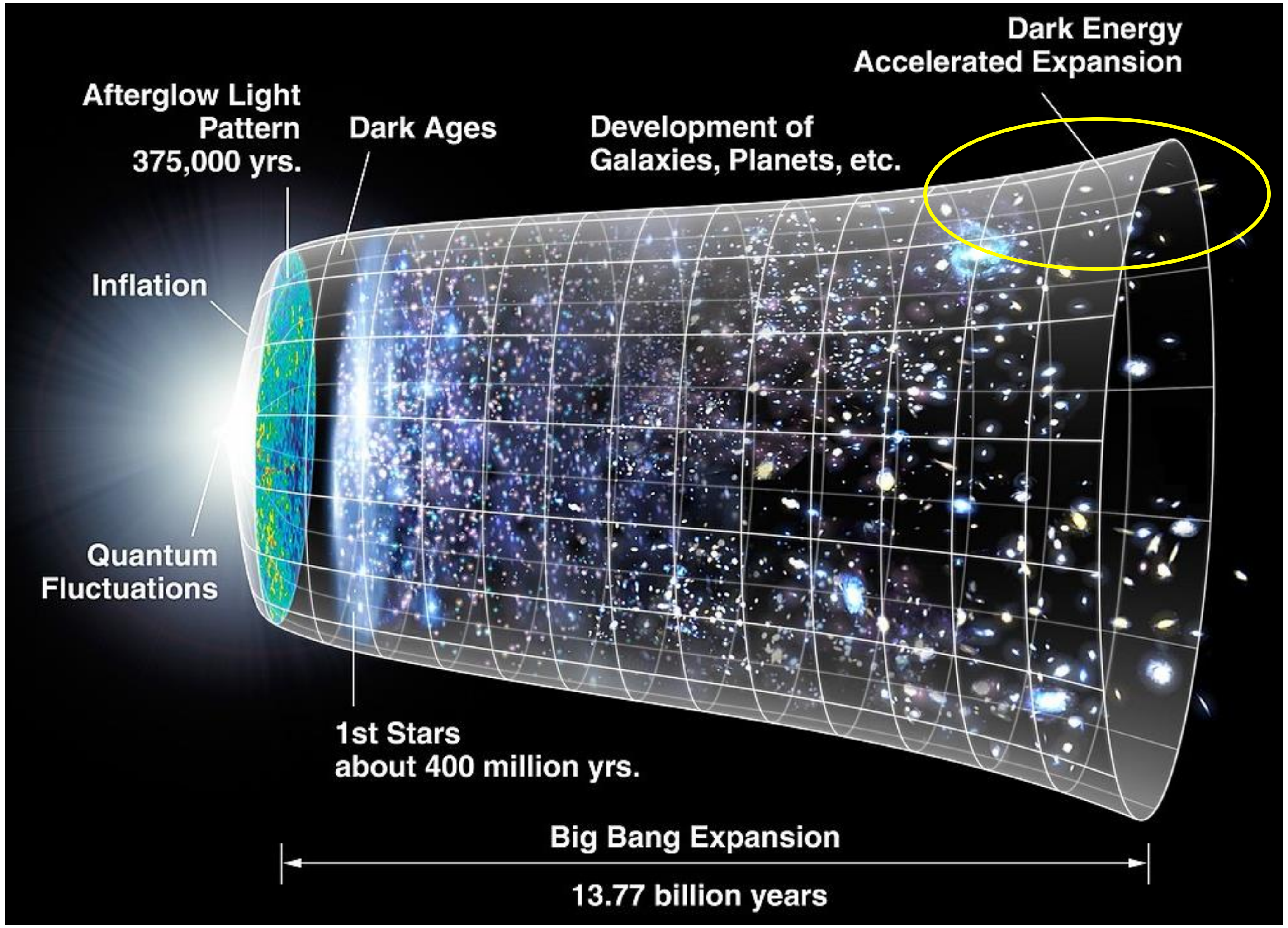
UC Berkeley

25 June 2025

DESI Collaboration/KPNO/NOIRLab/NSF/AURA/P. Horálek/R. Proctor

Accelerating Universe – a Surprise

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



We did not expect this turnaround.

It is not part of the Standard Model of particle physics.

Accelerating Universe – a Gap in Physics

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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 (ed. E. Linder):

- 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

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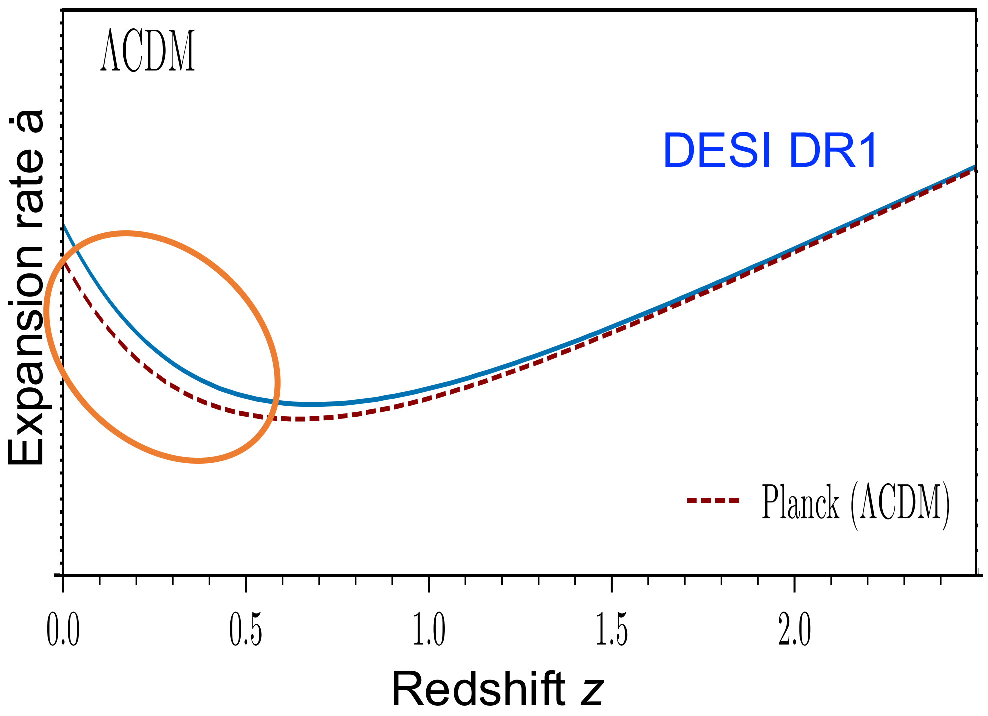
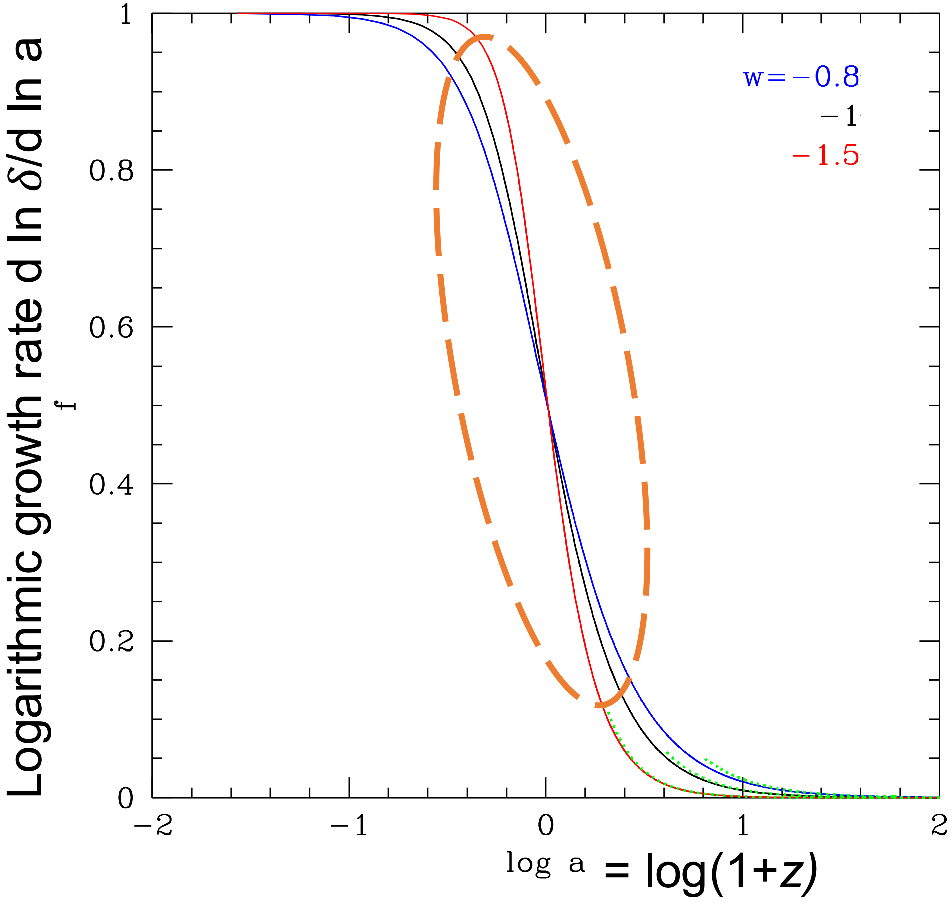
A cosmological constant Λ, as simple as you can get, still has profound effects on cosmic expansion (distances) and cosmic growth (large scale structure).





The Clarity of Dark Energy

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

Dark energy does not exist in a vacuum. ☺

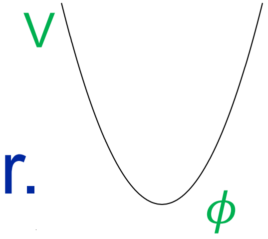
Dark energy evolved over many e-folds in an expanding universe dominated by radiation and matter.

Just 2 forces: the Hubble friction from expansion and the driving term – steepness of the (effective) potential – govern dark energy evolution.

Thawing and Freezing

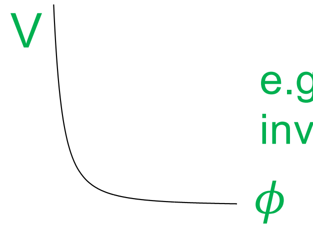
If the Hubble friction dominates, the (effective) field is frozen in place.

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 toward cosmological constant behavior.

Equation of State

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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 $H=\dot{a}/a$

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

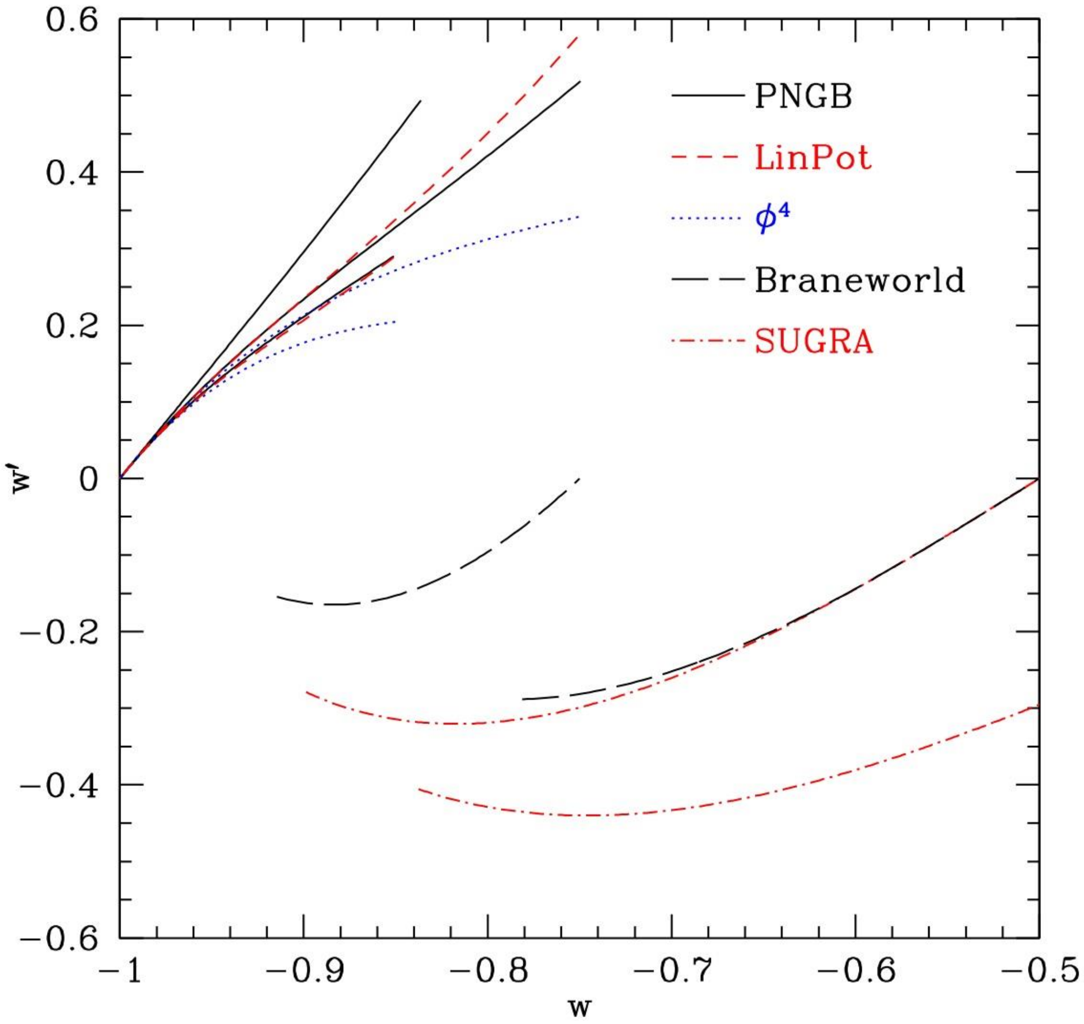
and cleaner if the dark energy isn't really a scalar field.

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



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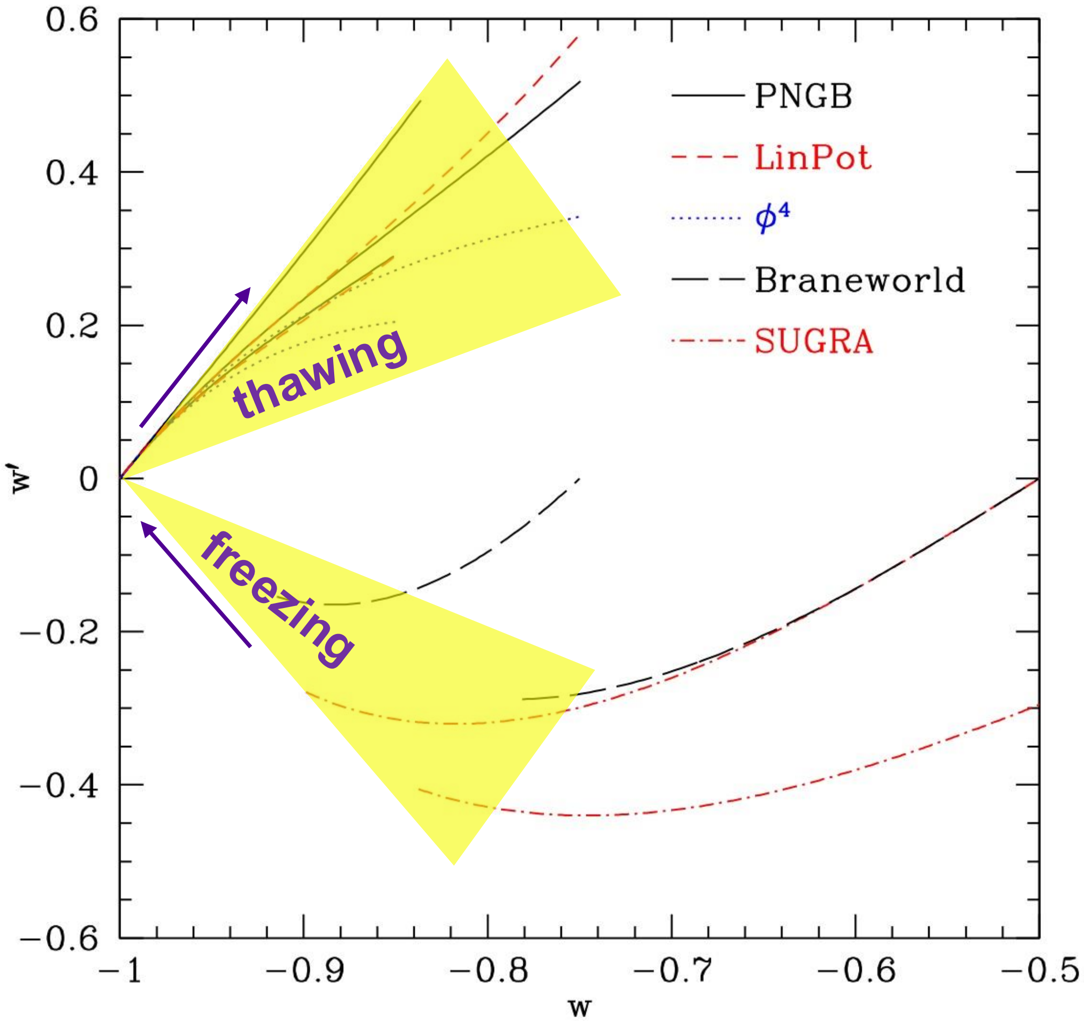
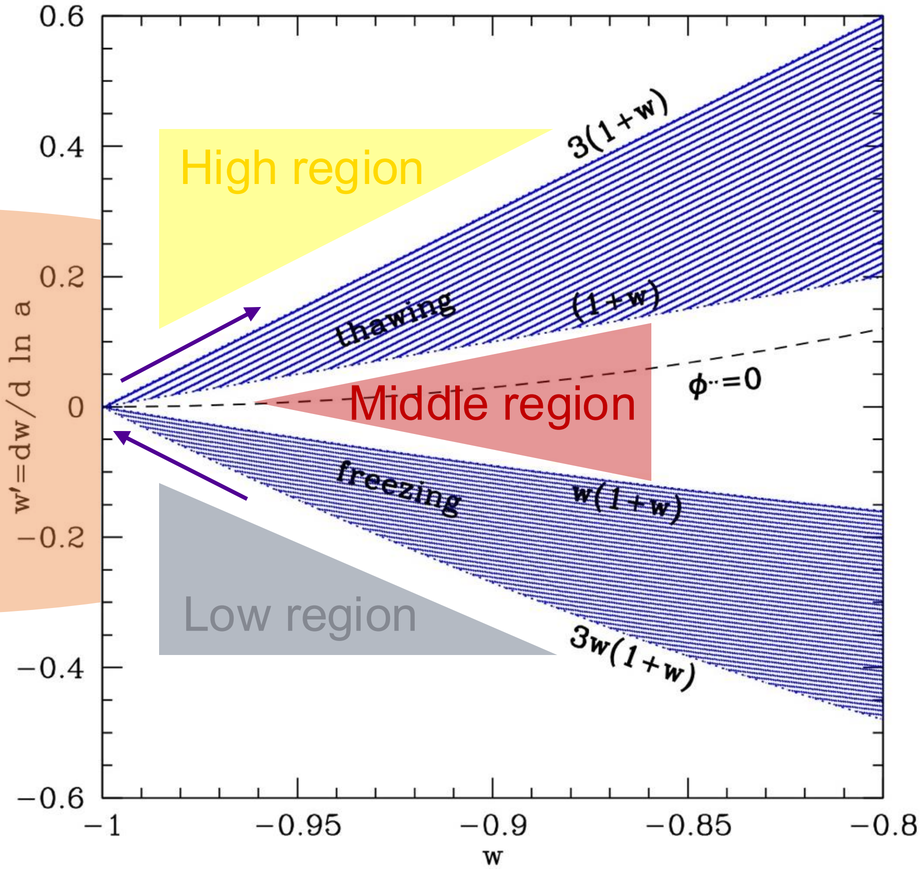


Zones of Avoidance

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

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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.

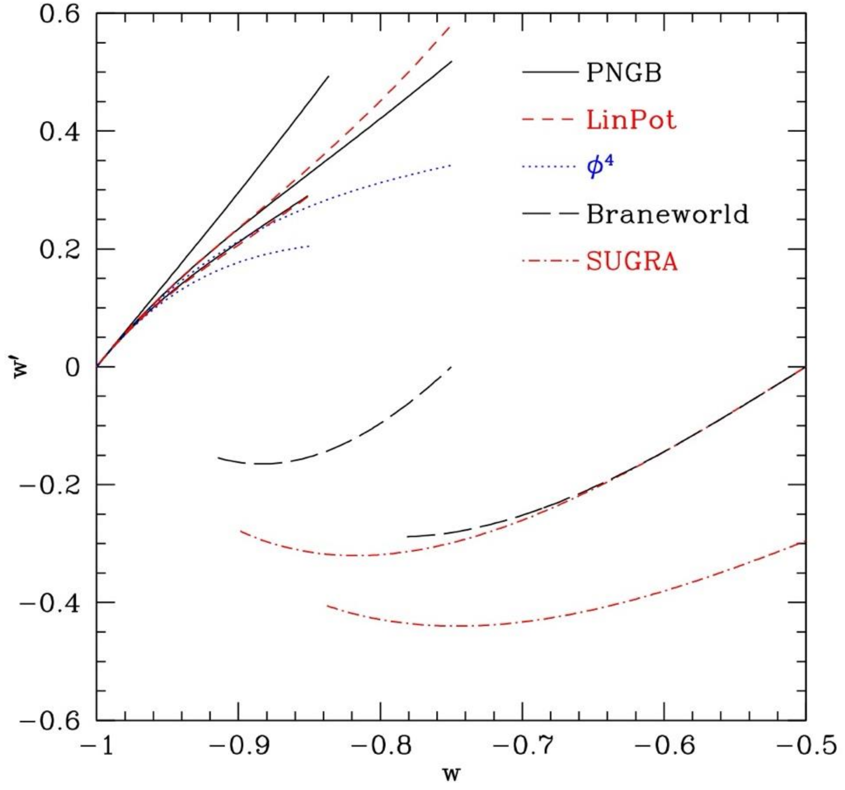
Recall that observations depend on (multiple) integrals over $w(a)$ so they don't see the details of the functions.

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.]

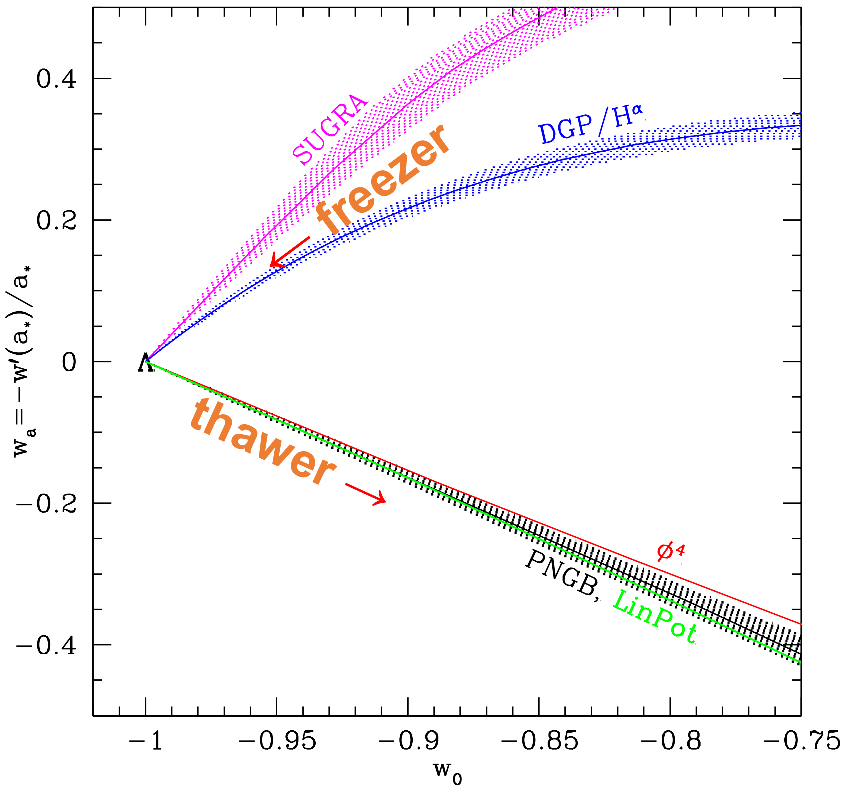
The art is choosing the right two quantities to preserve the physics.

Calibrating Dark Energy

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.

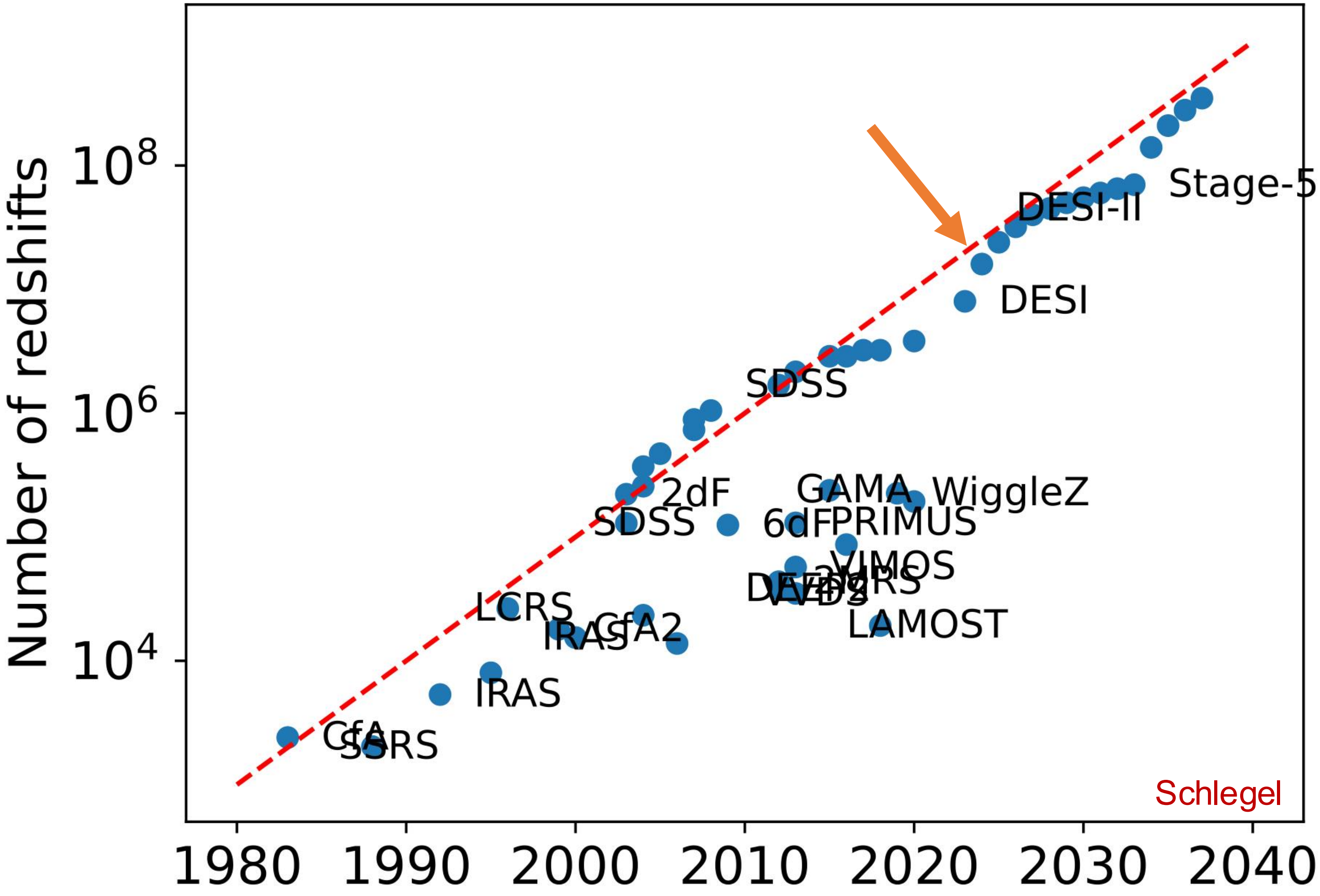
[Never say it is a Taylor expansion!]

Mapping the Universe in 3D

DESI Collaboration/KPNO/NOIRLab/NSF/AURA/P. Horálek/R. Proctor

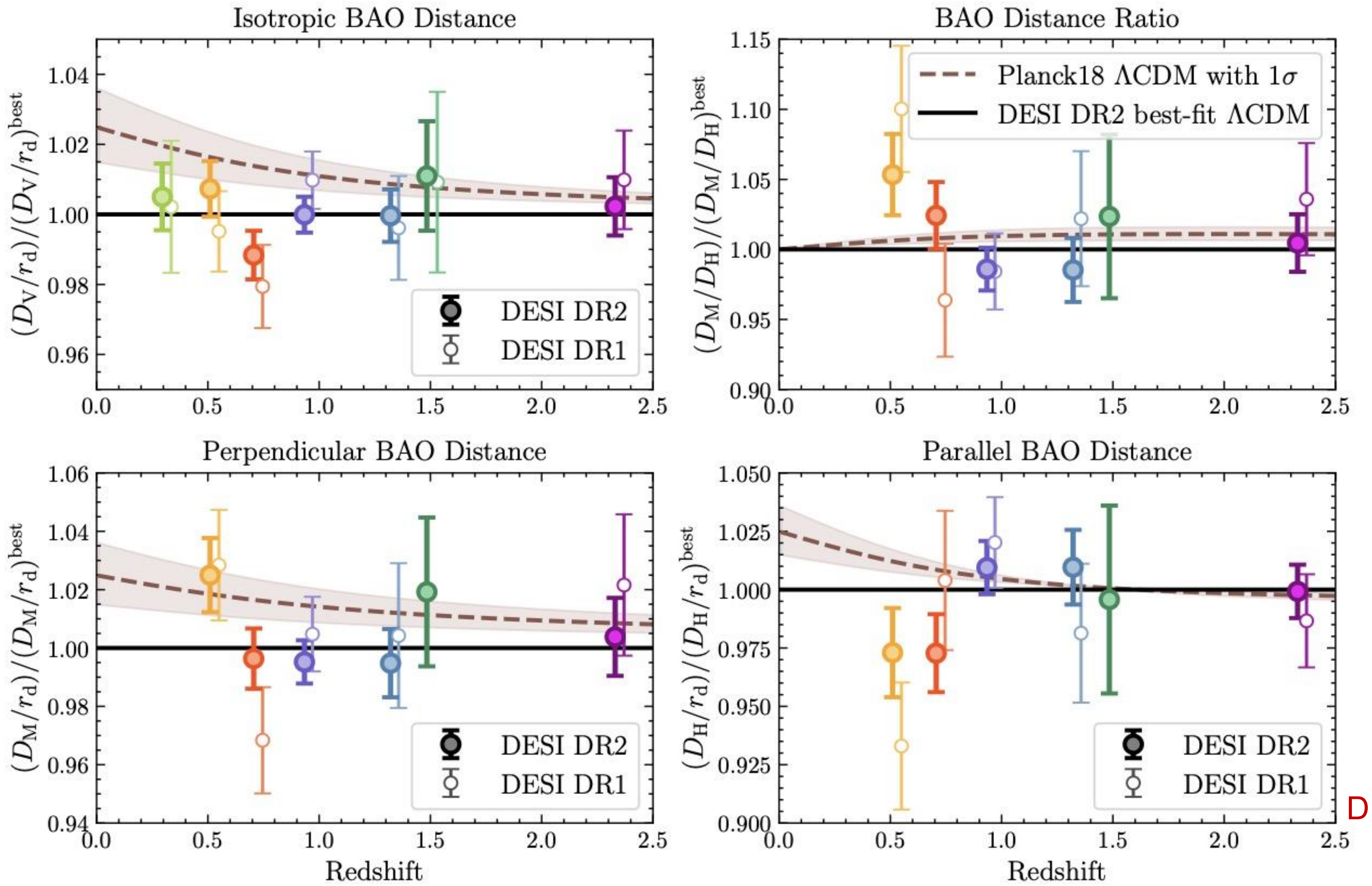
A New Map

Dark Energy Spectroscopic Instrument (DESI) has mapped ~10x more galaxies than all previous surveys.



Results!

So, what does data in 2025 say dark energy is?



DESI 2503.14738

Results!

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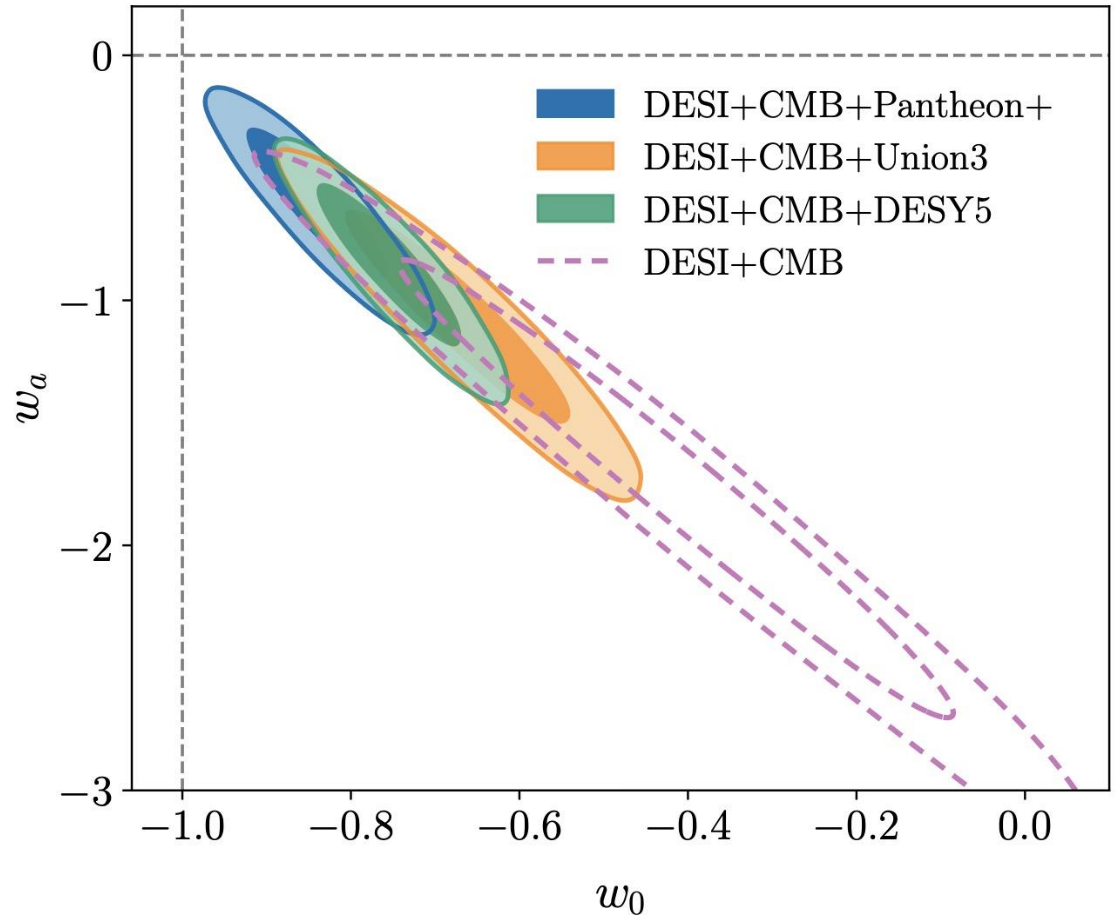

Baryon acoustic oscillation (standard ruler) distances
+ supernova (standard candle) distances
+ cosmic microwave background fluctuations

DESI 2503.14738

Λ? Thawing? In an impossible place?

Results!

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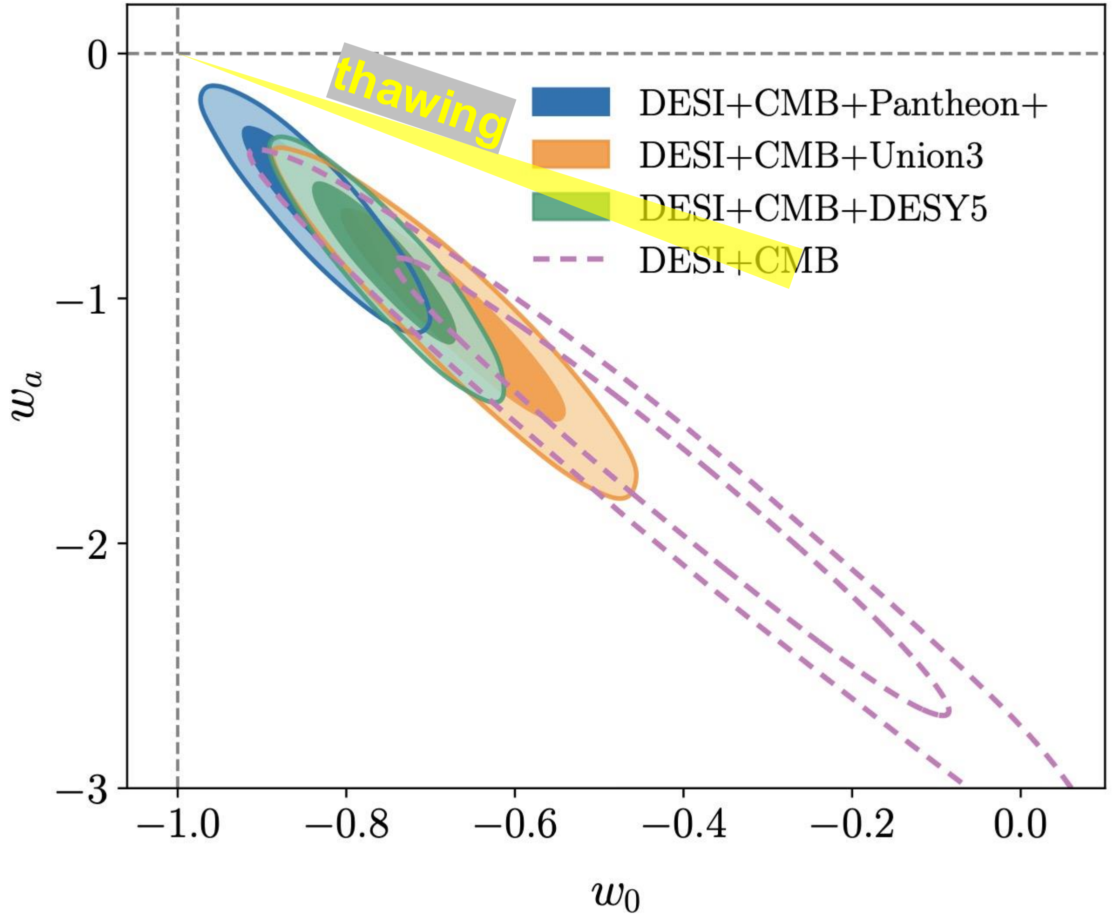

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Baryon acoustic oscillation (standard ruler) distances
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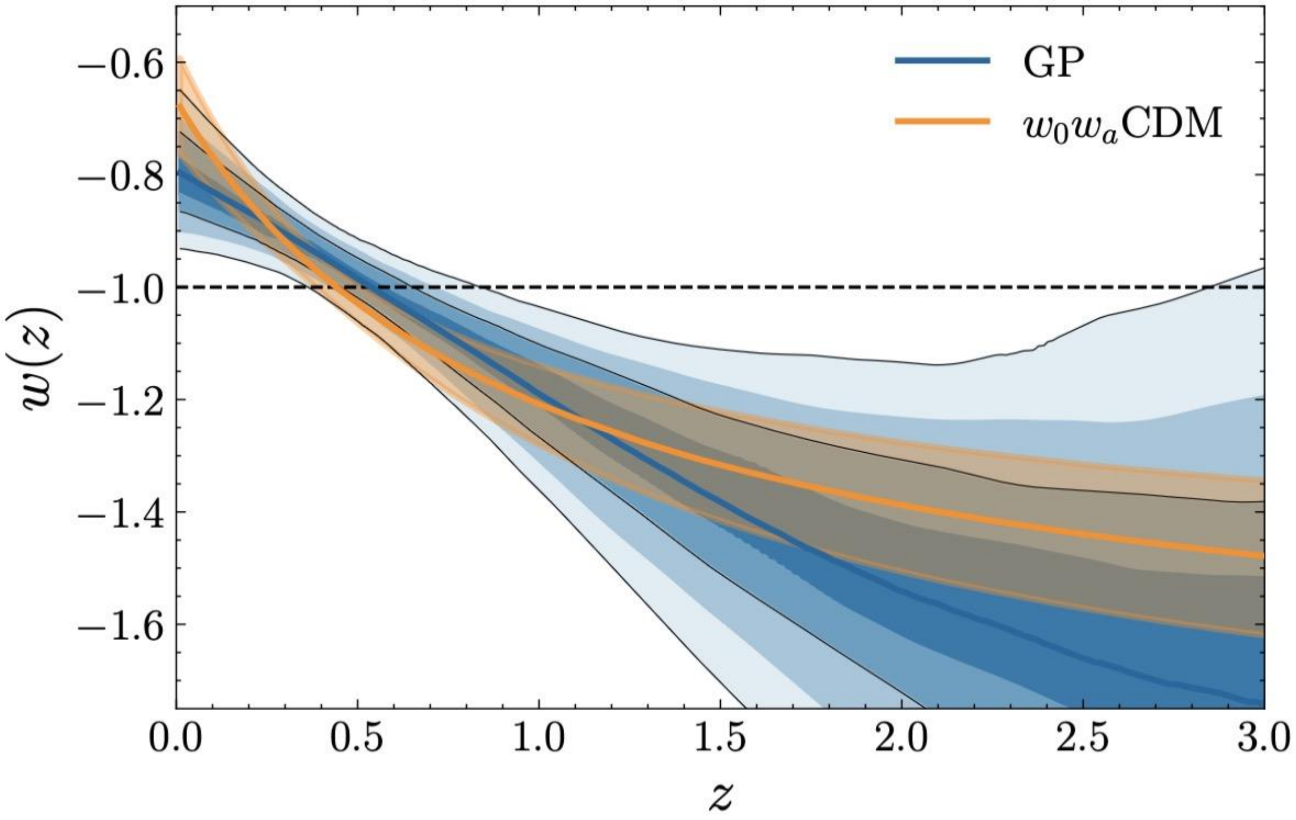
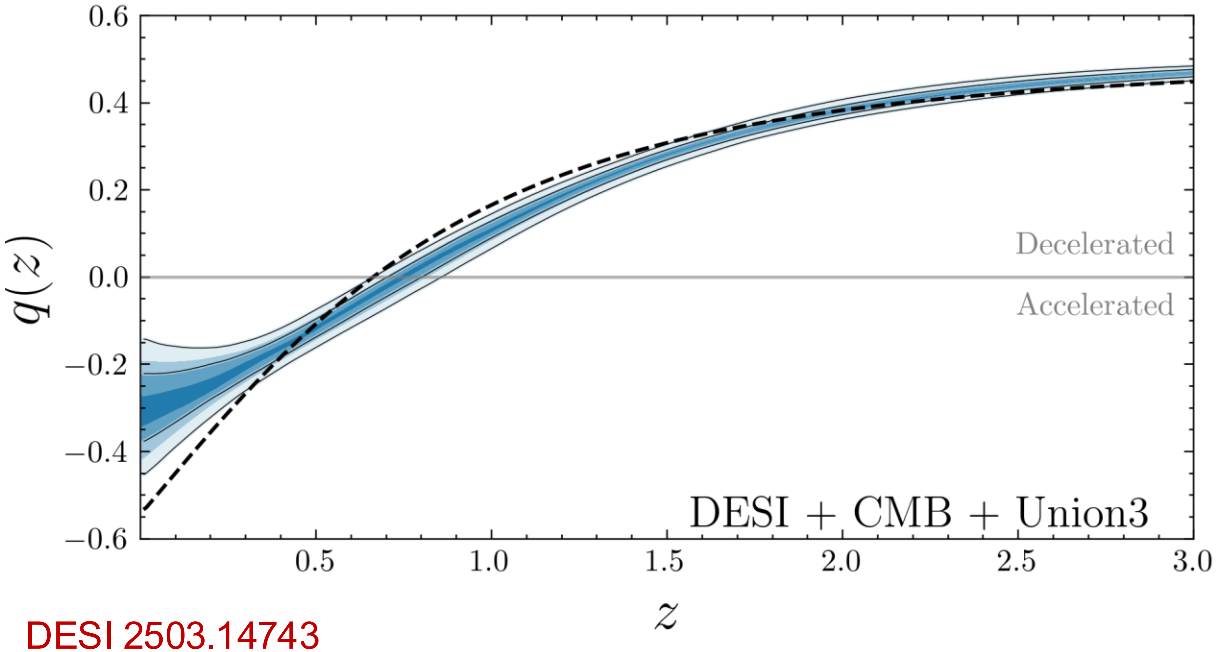
Λ? Thawing? In an impossible place?

Results! – Gaussian Process (form independent)





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So, what does data in 2025 say dark energy is?

Beautifully bizarre!

Interpretation?

The statistical significance is 2.8-4.2σ away from Λ.
DESI says "ΛCDM is being challenged".

What if we take the best fit at face value? (agrees with mirage dark energy (2007))

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 Λ to less negative w_0.

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

Testing the Framework

What we are really doing is testing the framework, not fitting parameters or models.

Any cosmic expansion history can be treated as an effective scalar field, i.e. w-w′.

So an answer in a Zone of Avoidance is testing the framework of the physics of the scalar field, not one particular model. We are checking the dynamical equation (Klein-Gordon) itself.

We do the same thing with inflation: beyond dynamics (n_s) we look at non-Gaussianity (f_{NL}) and primordial gravitational waves (r).

New Windows on Dark Energy Physics

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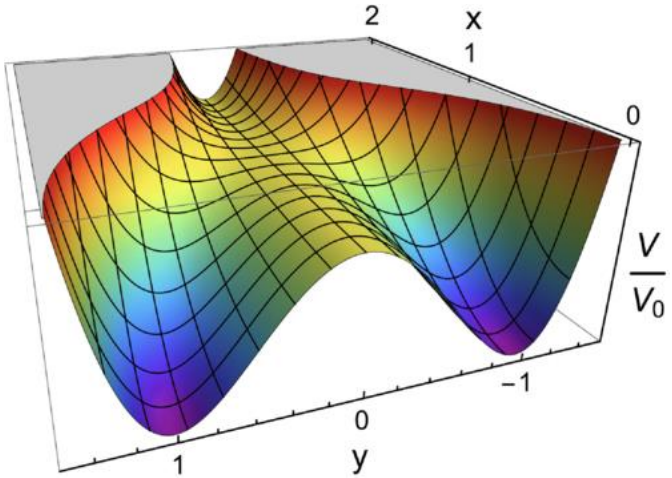
Very exciting!
Thus we can now look for, not non-Gaussianity, but non-Klein-Gordon-ness. Like inflation:



- Noncanonical kinetic term
- Multiple fields
- Nonstandard vacuum, e.g. negative potential, Phase transition

And we can look for, not primordial GW, but gravity beyond GR.

- Growth vs expansion
- Gravity effects on matter and light
- Gravity friction on gravitational waves (BH, NS)

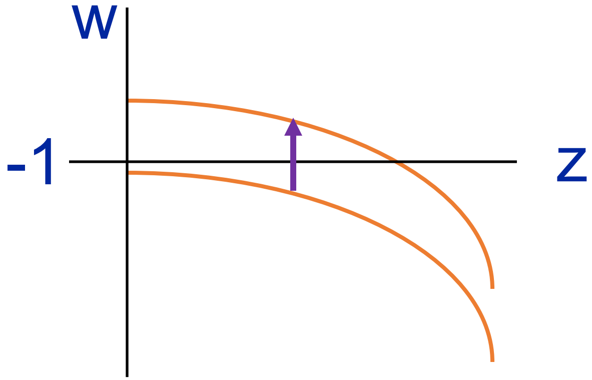
Interactions

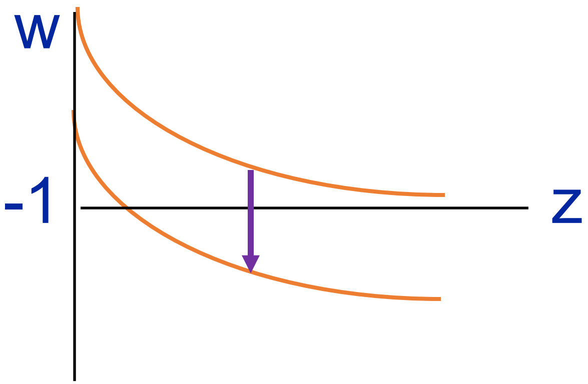
Crossing w=-1 isn't an illusion (favored by >3σ) but could it be due to dark sector interactions?

$$\dot{\rho_{\rm de}} + 3H(1+w_{\rm de})\rho_{\rm de} = -Q$$
$$\dot{\rho}_m + 3H\rho_m = Q\ .$$

$$w_{\rm de}^{\rm eff} = w_{\rm de} + \frac{Q}{3H\rho_{\rm de}}$$
$$w_m^{\rm eff} = \frac{-Q}{3H\rho_m}\ .$$

We can uplift from phantom or depress quintessence to cross w=-1.





Linder 2506.02112

Interactions

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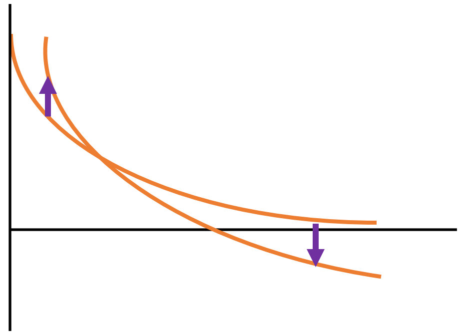
The problem is this shifts the coupled, e.g. dark matter, density too.

$$w_m^{\rm eff} \approx w_{\rm de} - w_{\rm de}^{\rm eff}$$

This will tend to cause problems for LSS growth and CMB/ISW.

What about tilting DE, by evolving Q across 0?



Tilting is difficult in particle physics but easy in modified gravity, e.g. conformal Horndeski $G_4(\phi)R$.

$$Q = -\alpha_M H \rho_m^{\rm eff}$$

$$\alpha_M \equiv \frac{d\ln G_4}{d\ln a}$$

Still shifts w_m, maybe less severe. Needs further investigation.

Moving Forward Model Independently

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)

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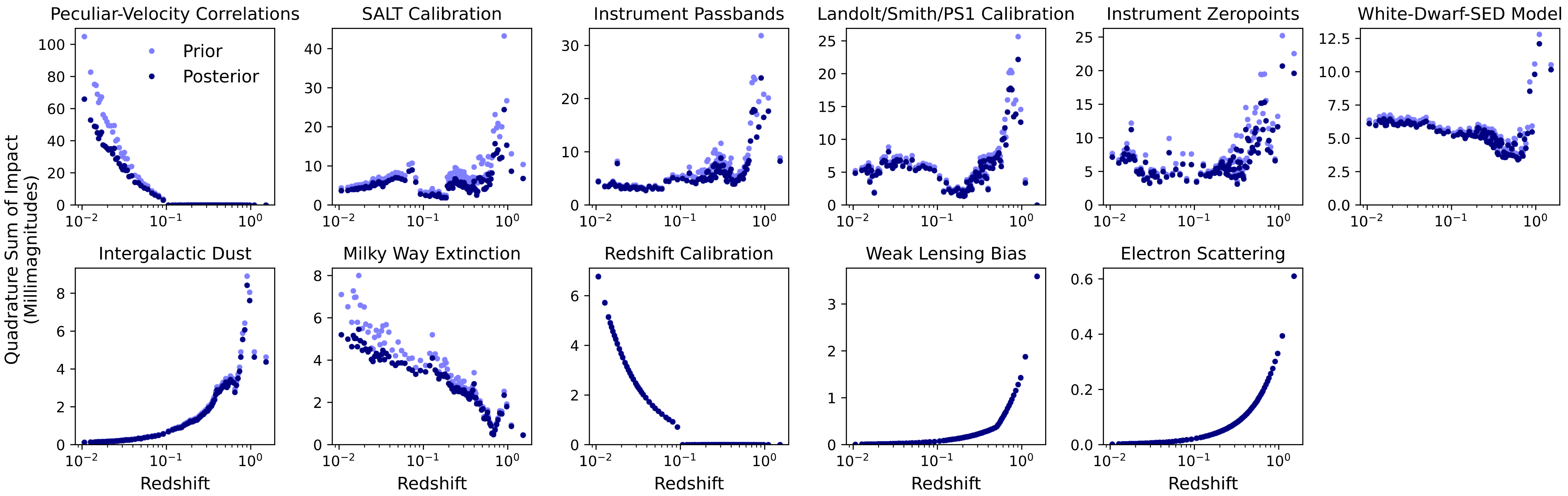

Note: 22 mmag = 1% distance uncertainty

Supernova distances in the next year

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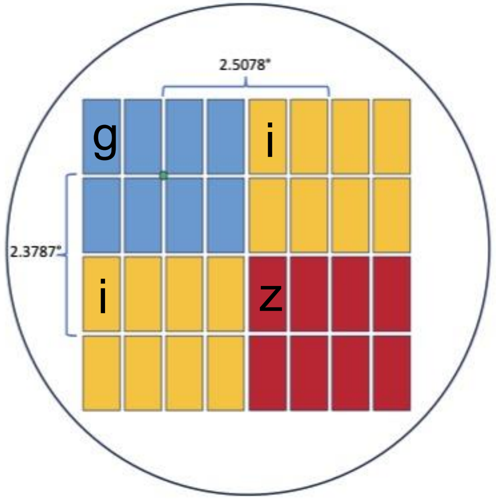
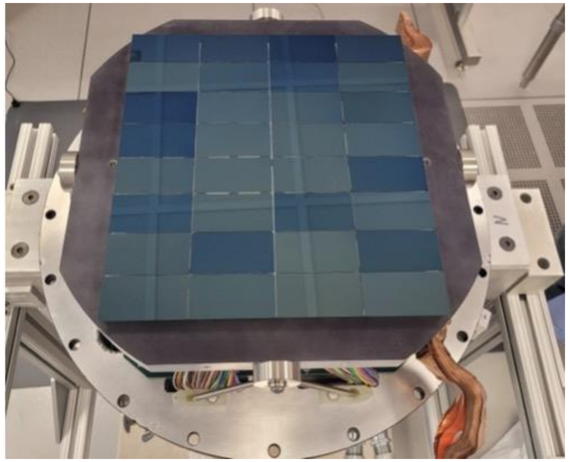
Zwicky Transient Facility (ZTF) – 2500+ SN Ia at z<0.2

La Silla Schmidt Southern Survey (LS4) is now on sky!

- High cadence
- ~3000 deg^2/night
- AB ~21 mag
- Lensed supernovae
- Peculiar velocities (growth)





Possibly new SN results from Subaru HSC, Hubble (HST), JWST

Summary

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Cosmic acceleration is fascinating physics, whatever it is.

We understand a good part of the basics of dark energy.

But the universe can throw us surprises! What will the answer end up being? – test the framework of physics.

We can ask the same questions we do for inflation: non-KG and GW.

Not long to wait! Even the next year will bring important new large scale structure, CMB, and supernova data.