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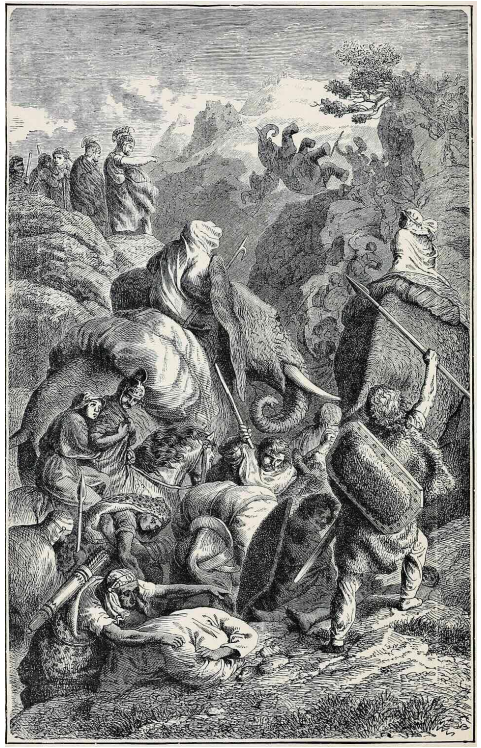
Invading Florence with Elephants Across the Phantom Divide

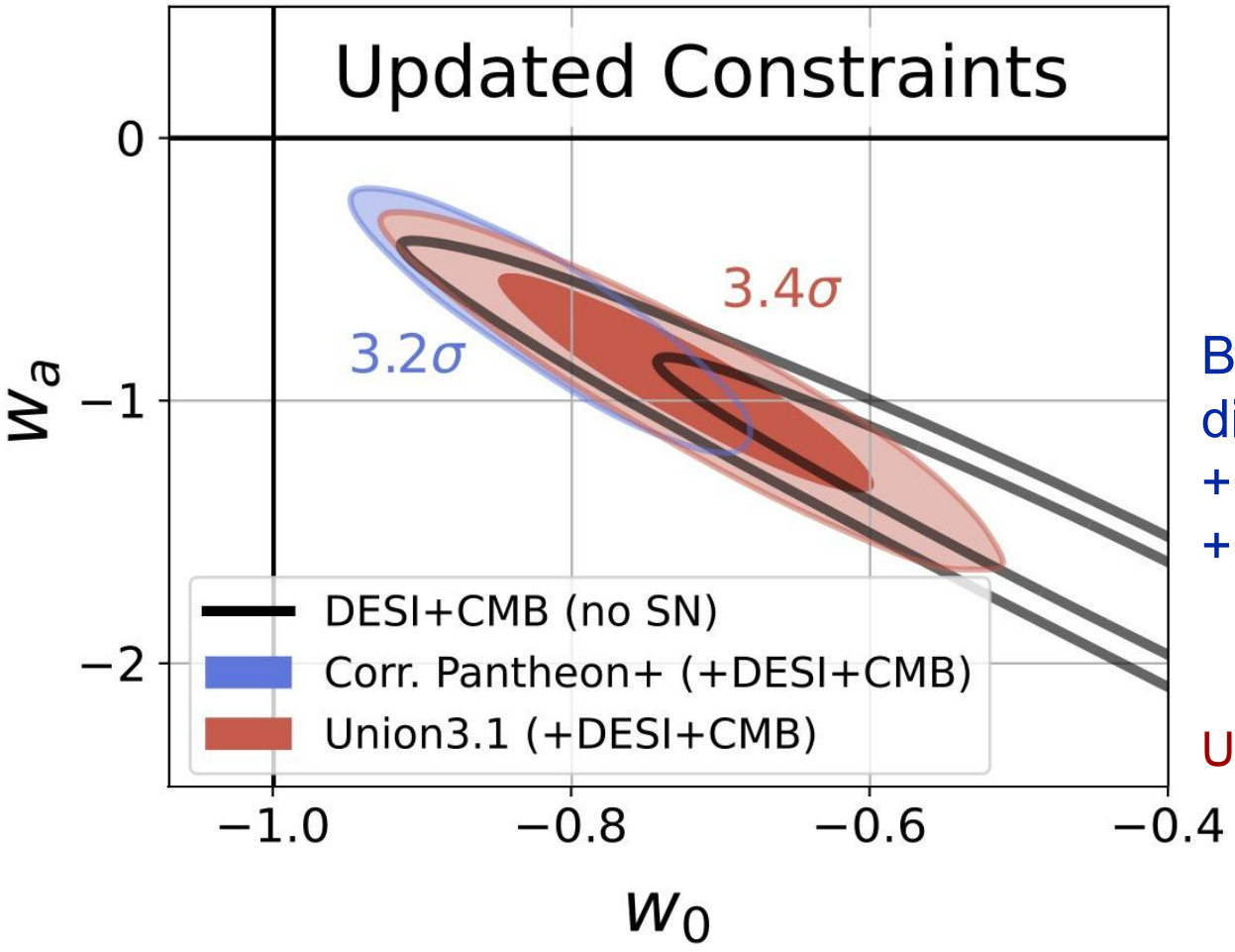
Eric Linder

UC Berkeley

GGI Exploring New Frontiers in Cosmology
20 July 2026



Dark Energy in 2026



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

Union3.1 Hoyt+ 2601.19424

Λ? Thawing? In an impossible place?

Battle Royal: Phenomenology → Theory

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George Biddell Airy
Astronomer Royal of England

I should not have believed it had I not seen it with my eyes.

William Rowan Hamilton*
Astronomer Royal of Ireland

How different we are! I should not have believed it had I not proved it.

* Hilarious Hamilton parody from acapellascience
www.youtube.com/watch?v=SZXHoWwBcDc

The Standard Lore of Dark Energy

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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.

Dark energy will either be frozen initially and then thaw – move away from Λ, or roll initially and then freeze – move toward Λ.

Zones of Avoidance

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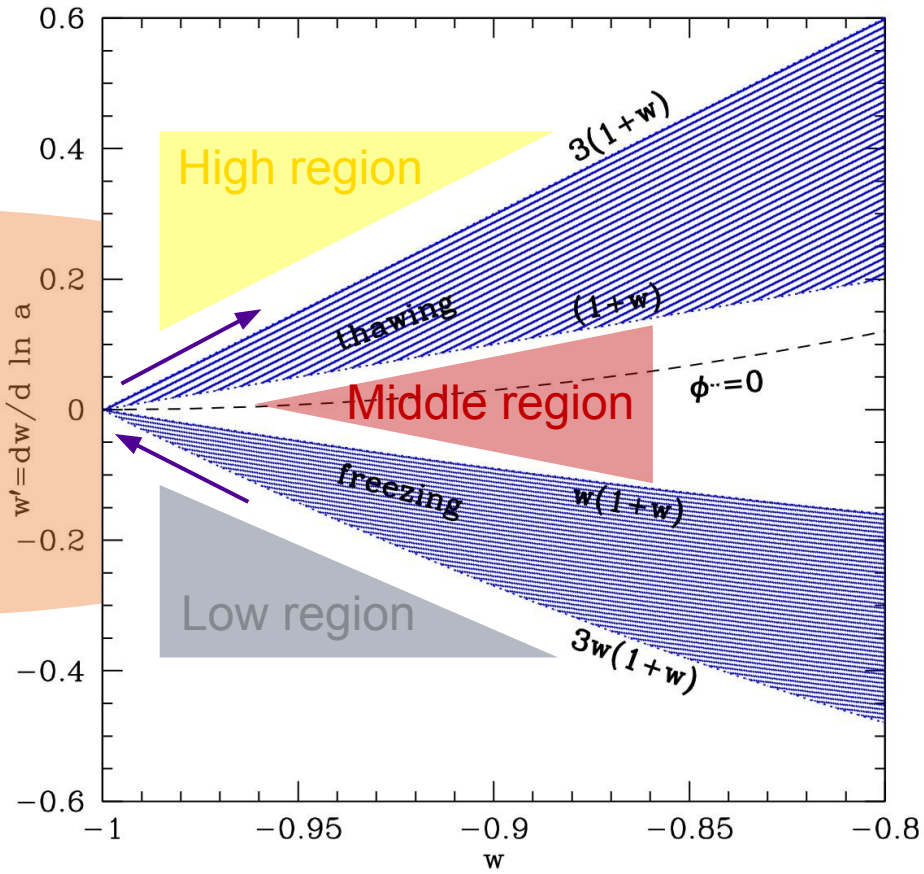
Thaw / freeze define narrow regions in phase space. What about the rest of the phase space?

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)

Calibrating Dark Energy

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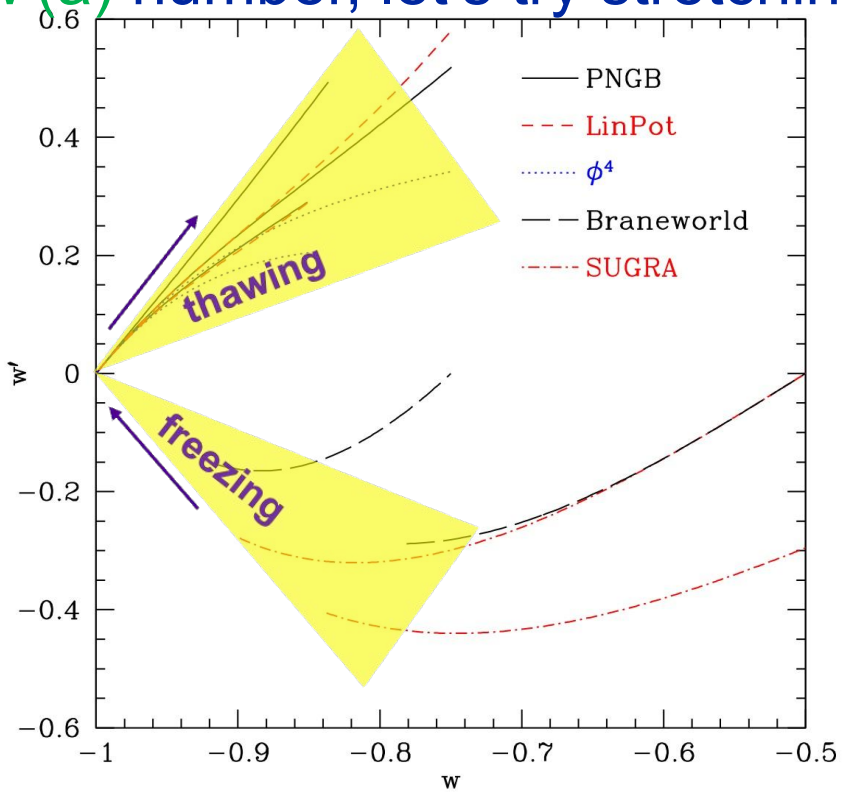
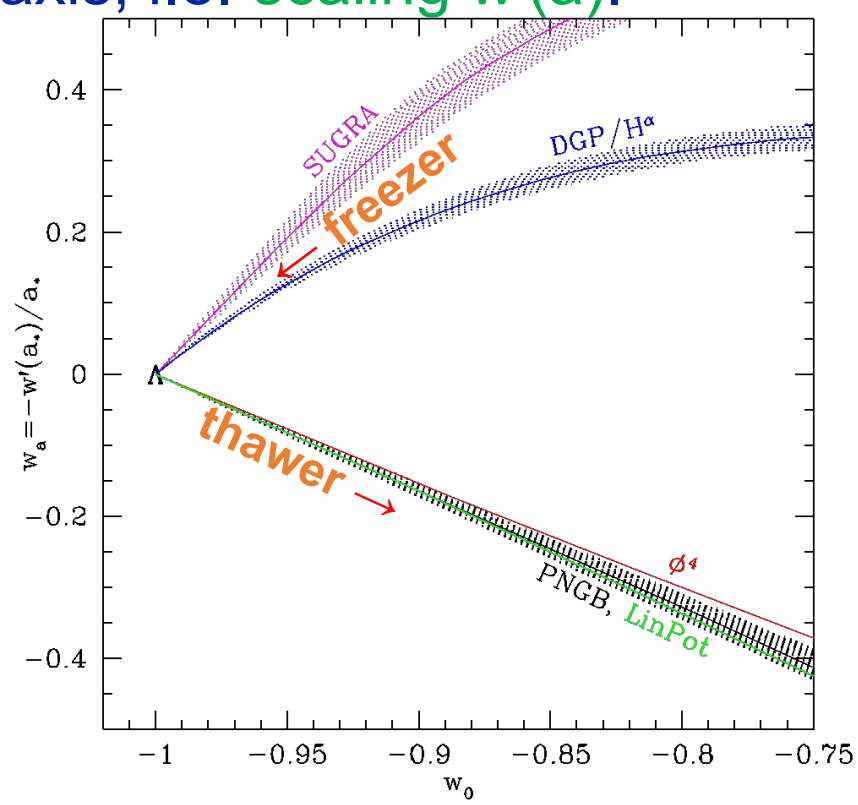
Current data can only fit 2 DE EOS parameters. Linder & Huterer 2005

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!]

Hannibal (Lecter) in Florence

"A census taker once tried to say w0-wa was a Taylor expansion.
I explained the error on a walk by the Ponte Vecchio…"

From Parameters to Properties – Gaussian Process

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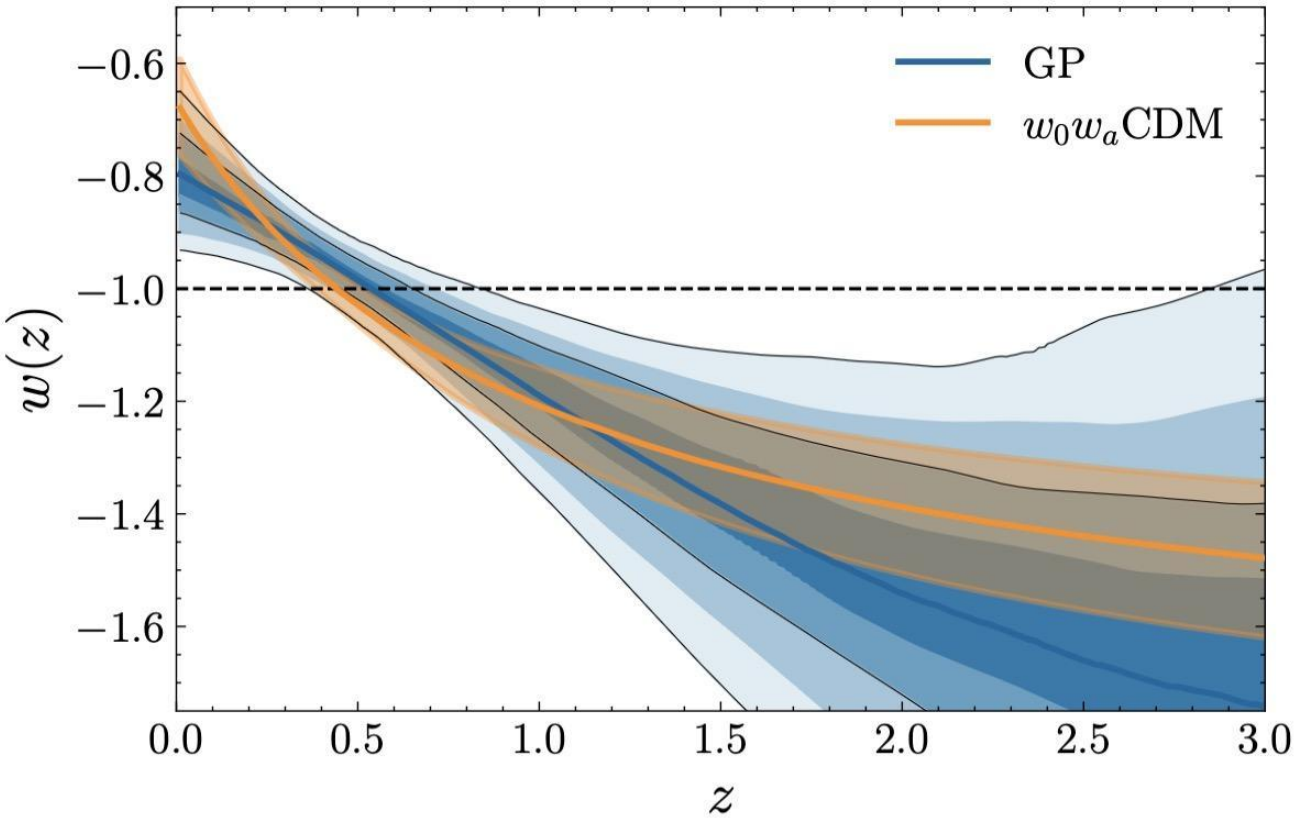

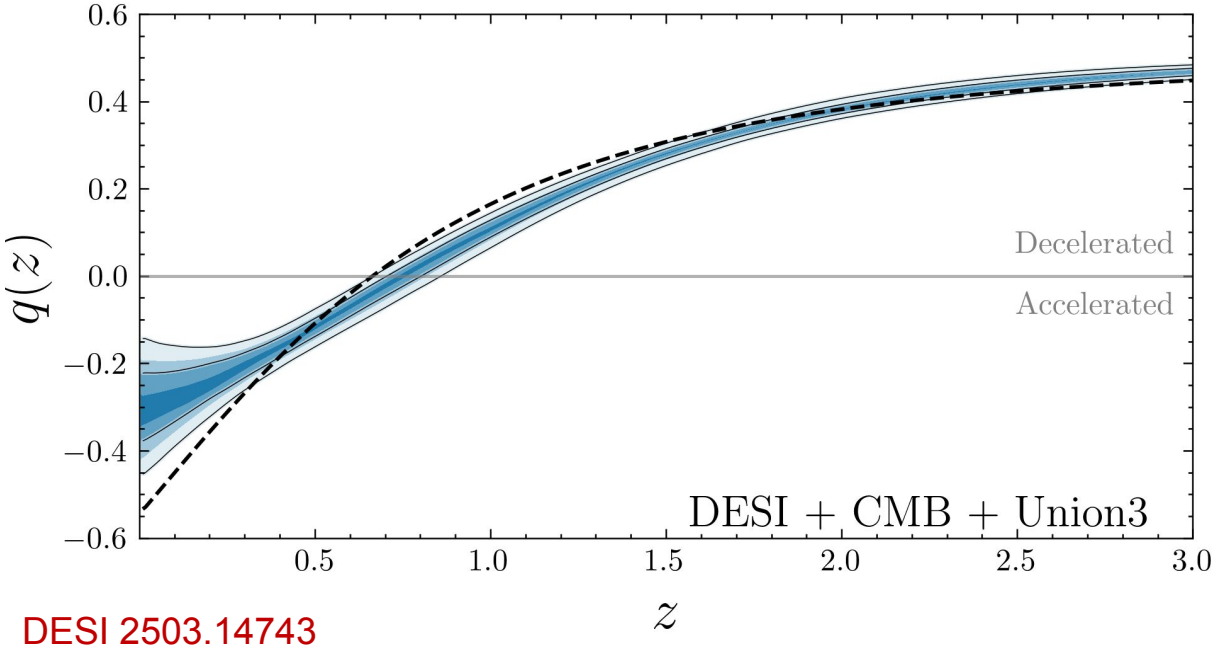

DESI 2503.14743

DESI also tested results through form-independent redshift bins in both w(z) and $\varrho_{de}(z)$, orthogonal polynomial expansion.

Interpretation?

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Beautifully bizarre!

Dark energy appears [phenomenology] to

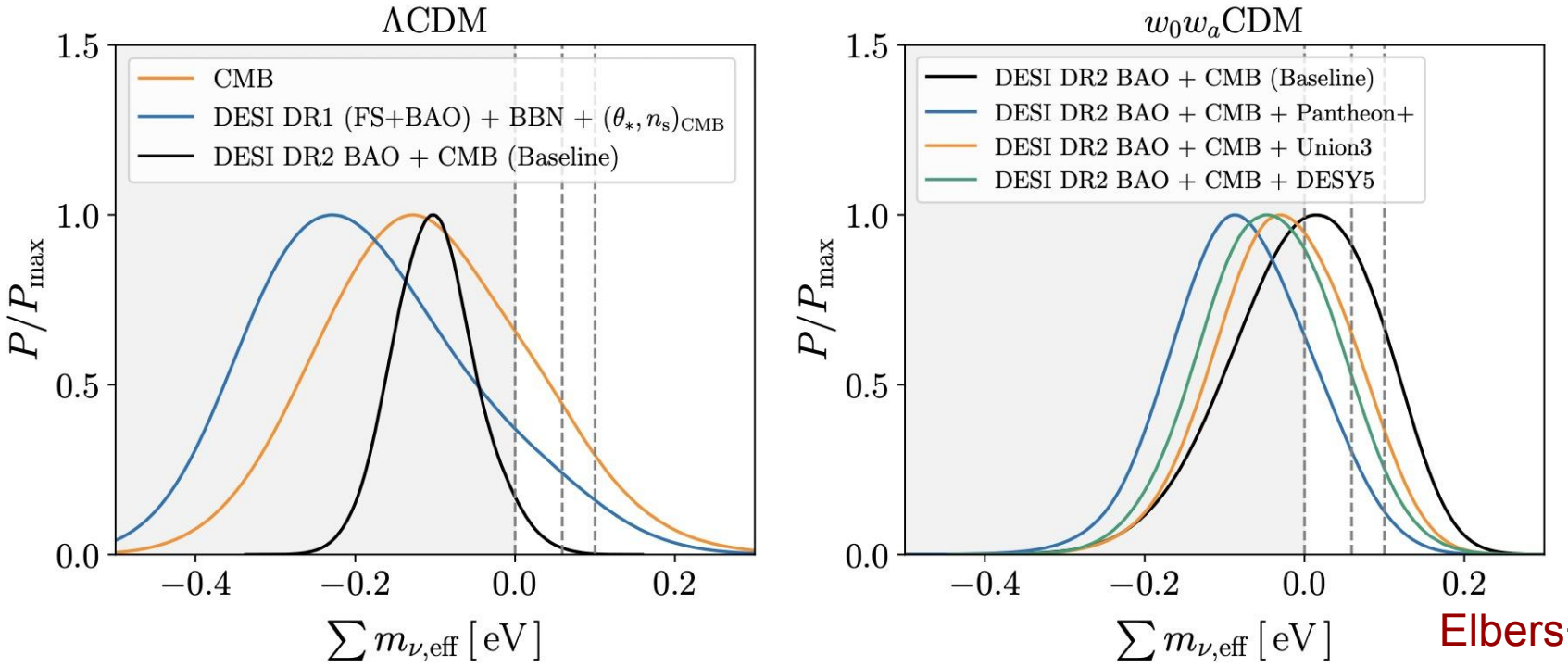
1) be phantom at z>1, then
2) "superevolve" faster than Hubble friction seemingly allows, then
3) cross w = -1 ("the phantom divide")*, and
4) evolve away from Λ to less negative w_0.

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

* This is not NEC violation! Caldwell & Linder 2026

Making Neutrino Mass Positive

In ΛCDM current data gives $m_\nu < 0$ at ~95% CL. But w_0w_aCDM brings much of the posterior to (physical) $m_\nu > 0$.



Elbers+ (DESI) 2503.14744

What property of dynamic DE enables positive neutrino mass?

Making Neutrino Mass Positive

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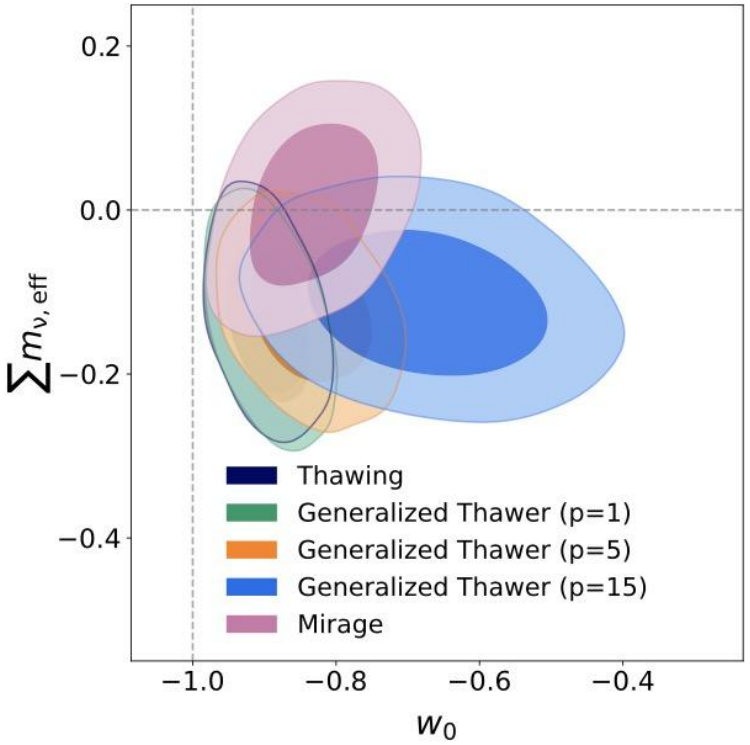
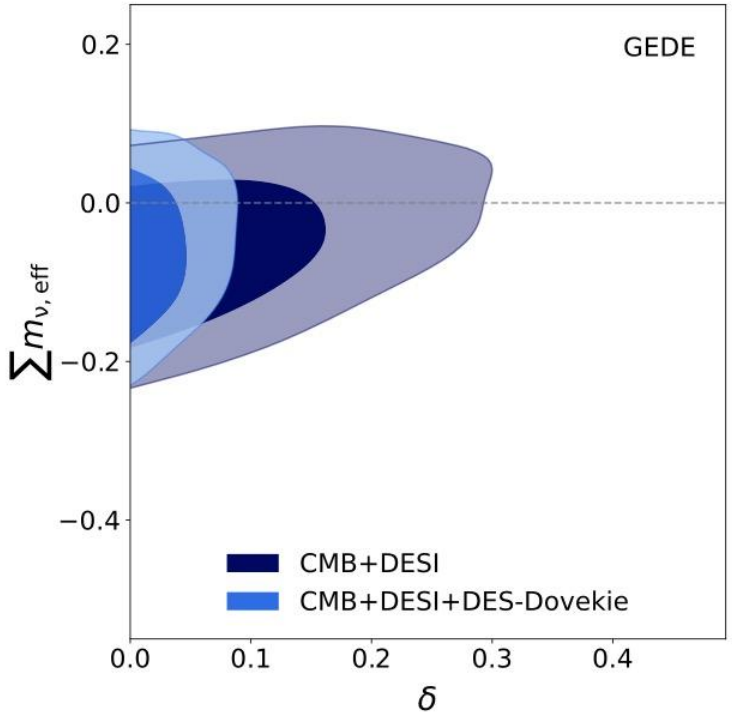
Using 6 1-parameter DE models we checked: 1) Is it parameter space volume (degeneracy)?, 2) Rapid DE evolution?, 3) Phantom crossing?, 4) Phantom at high z?

Yang, Di Valentino, Linder, Zhang, Pan 2603.15422





The answer: the required property is phantom DE at z>1 for $m_\nu > 0$, and phantom crossing at z<1 for a good fit to data.

Interpretation?

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Testing the Framework

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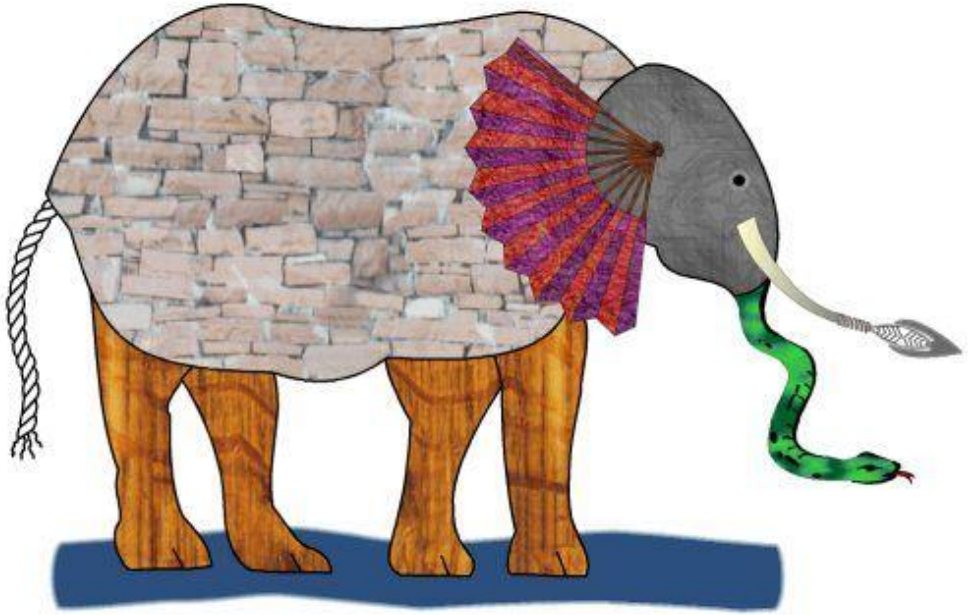
Is dark energy an elephant or a chimera?



"We have to remember that what we observe is not nature in itself, but nature exposed to our method of questioning." – Werner Heisenberg 1958

Testing the Framework

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Unified origin (elephant), e.g.

- Interacting sectors
- Modified gravity
- Nonstandard vacuum, e.g. negative potential, Phase transition

Disparate origin (chimera), e.g.

- Multiple fields (cf. hybrid inflation)
- Phake phantoms^{TM} (misassignment of other component to DE)

And use more observations: distance crosschecks and

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

Elephants Across the Phantom Divide

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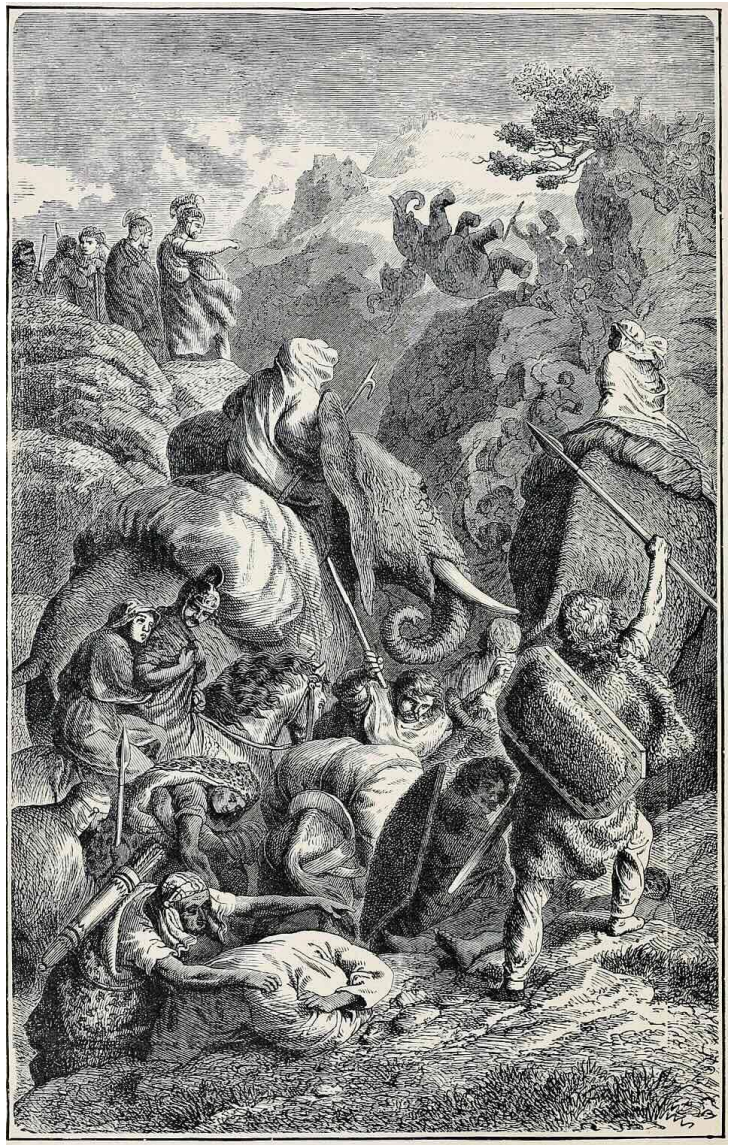
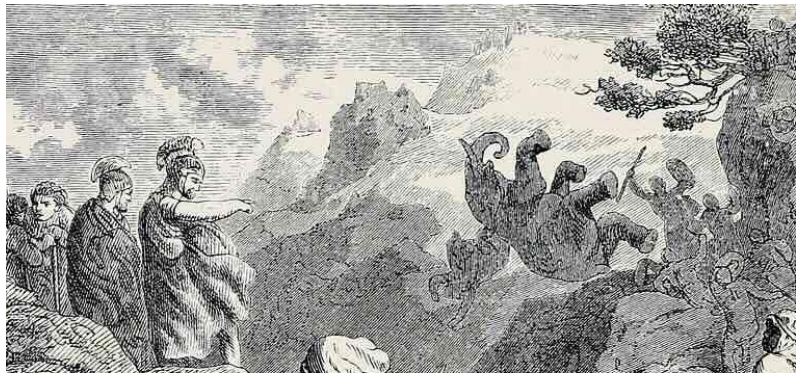


What unified physics (elephants) can cross the phantom divide (w = -1)?

- Interactions
- Modified gravity
- Phase Transition



Not all of these will survive the crossing!

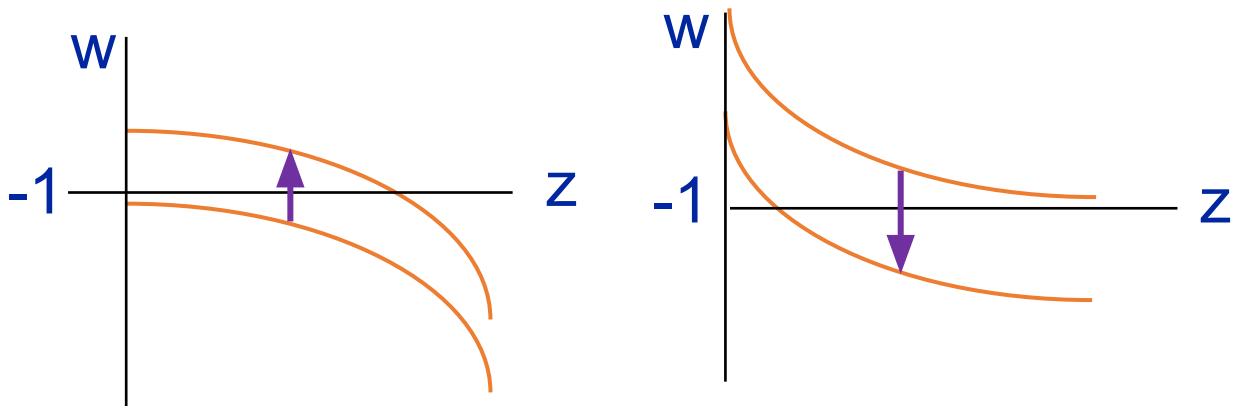
Interactions

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

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

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

Issues for LSS growth and CMB.

Modified Gravity Phenomenology

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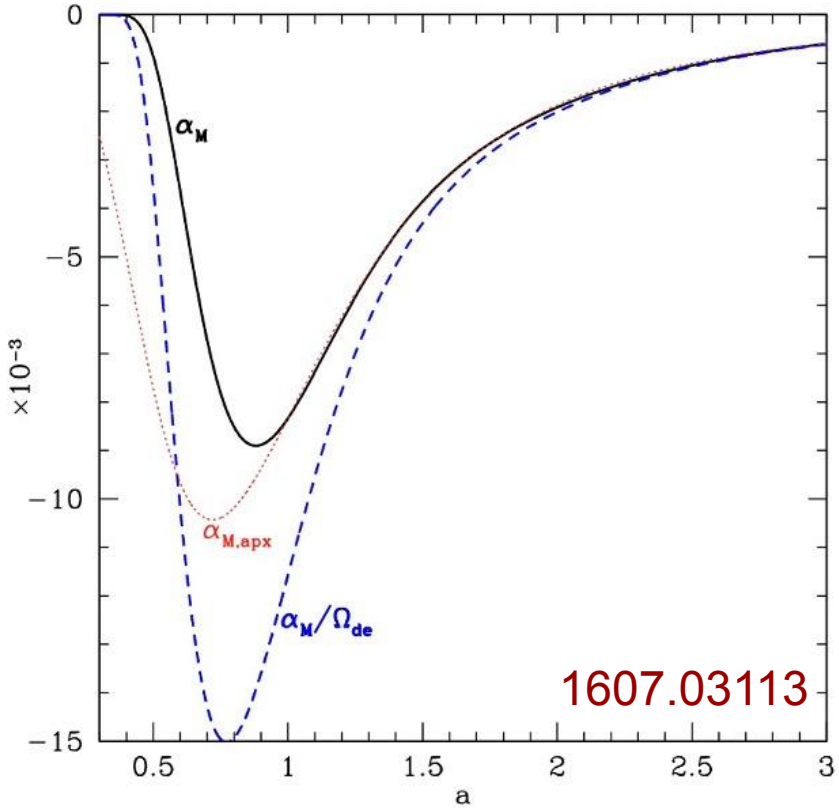
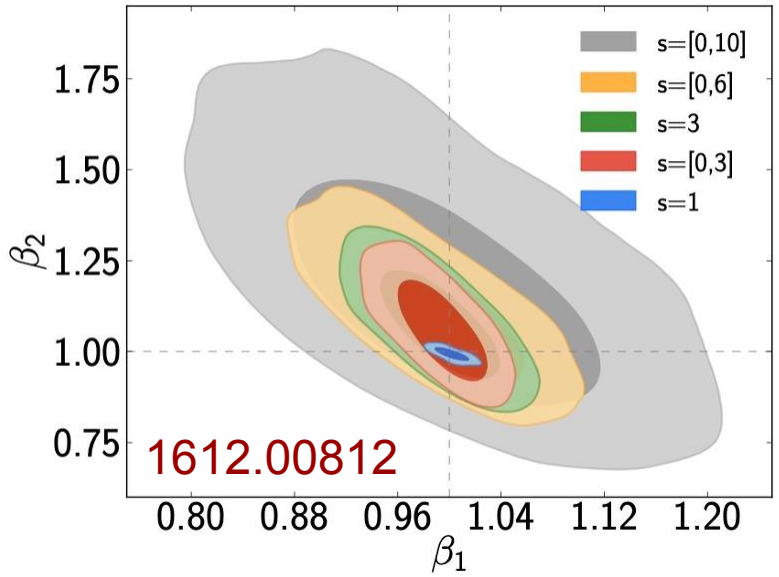
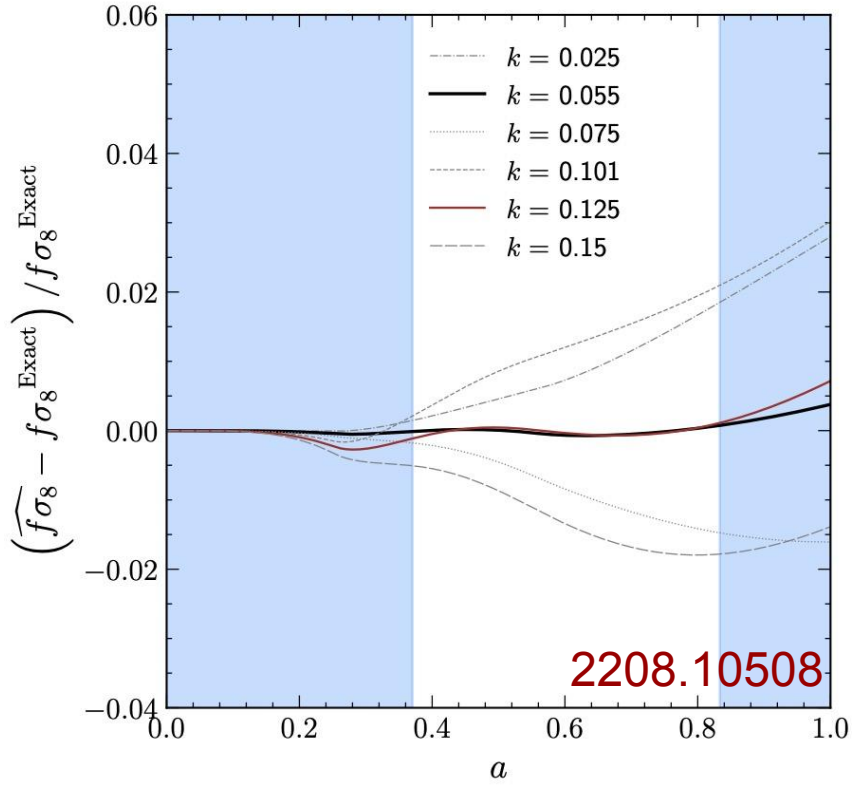
Nothing in modified gravity is proportional to $\Omega_{de}(a)$ or a^s. Never use them.







We *do know* how to treat gravity model independently – bins in G_{eff} give <0.3% accuracy. Important to divide k bins at k~0.1 h/Mpc. 1709.08709, 2208.10508

Modified Gravity

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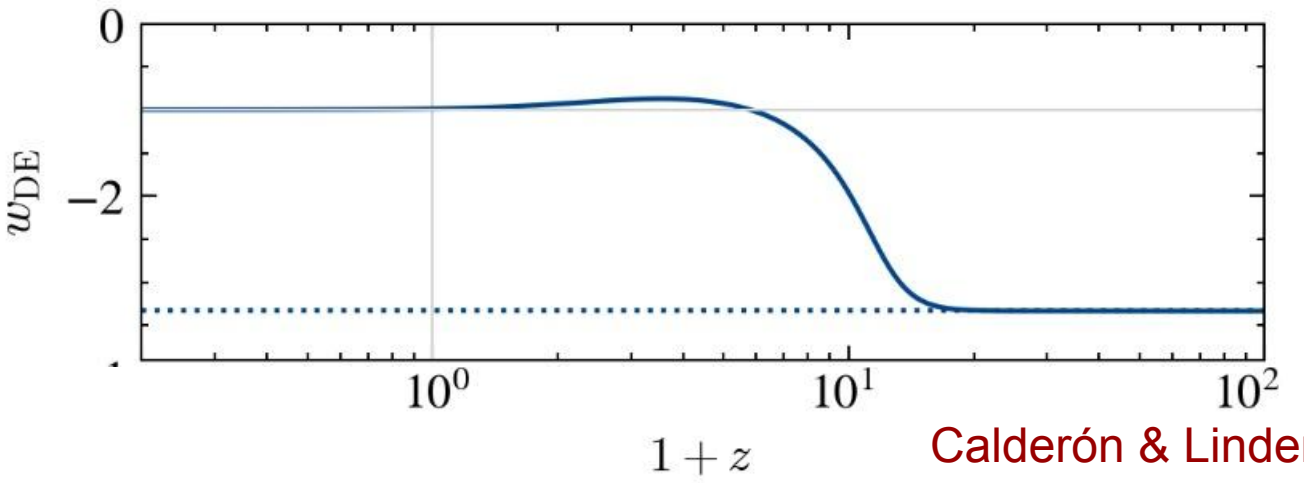
As said, nonminimal coupling of gravity to matter can be problematic.

In Horndeski gravity, this leaves only K and G_3 terms. Can we use a shift symmetric theory (for quantum protection)? Alas, no – this cannot cross w = -1. It needs a "push" from a potential.

Quantum protected V = $\lambda\phi$ can cross w=-1, but poor data fit.



Calderón & Linder 2605.26259

Forced to be large field, potential dominated; MG secondary

Phase Transition (Vacuum Metamorphosis)

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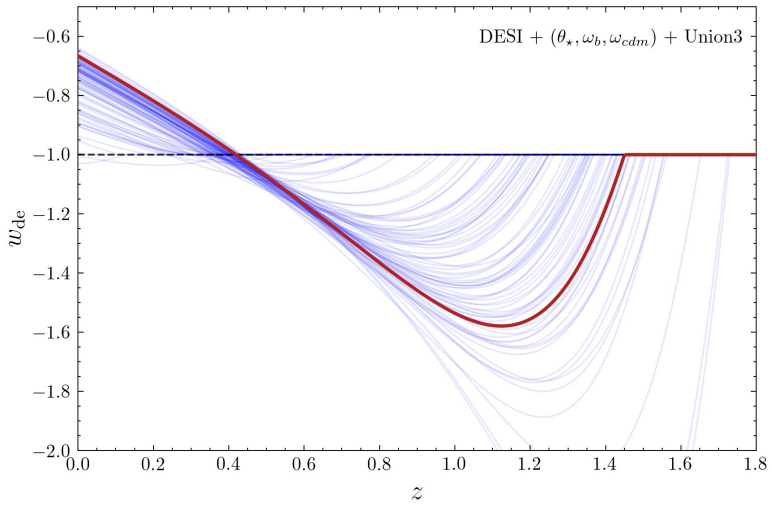
A vacuum phase transition can give phantom DE. Parker+ 1999+ did a nonperturbative summation of quantum effects on action, with Ricci scalar R acting as an order parameter. When $R = m^2$ (scalaron mass) then Lenz' law freezes R constant (giving cosmic acceleration with phantom DE).

Now suppose scalar field decays after the transition, into light scalars, essentially DE → DE. (Doesn't affect matter!)

Fits the data as well as w_0w_aCDM, same N_{par}, with natural decay $\Gamma \sim H_t$!



Lodha, Caldwell, Di Valentino, Linder (in prep)

Elephants in the Room

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It's ok to have elephants in the room! (if alive; chimeras less welcome…)

Phenomenology → theory:

- Positive m_ν from phantom DE – phantom+crossing inferred
- Modified gravity phenomenology – form free, binning works!
- Modified gravity – matter coupling  , shift sym  , small potential 
- Vacuum metamorphosis – phase transition, QFT origin – works!?

Summary

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The data, under many different varieties of analysis, many crosschecks, and many data sets, give the phenomenology of phantom crossing ($w < -1 \rightarrow w > -1$).

Neutrino mass limits give an interesting corroboration of crossing.

Further crosschecks in distance, growth, lensing, new data, GW.

To go from phenomenology to theory, elephant vs chimera.
Not all elephants survive!

Florence has many…

Uffizi Gallery:
Valois tapestry; da Vinci