Next Steps for Dark Energy

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GGI Exploring New Frontiers in Cosmology
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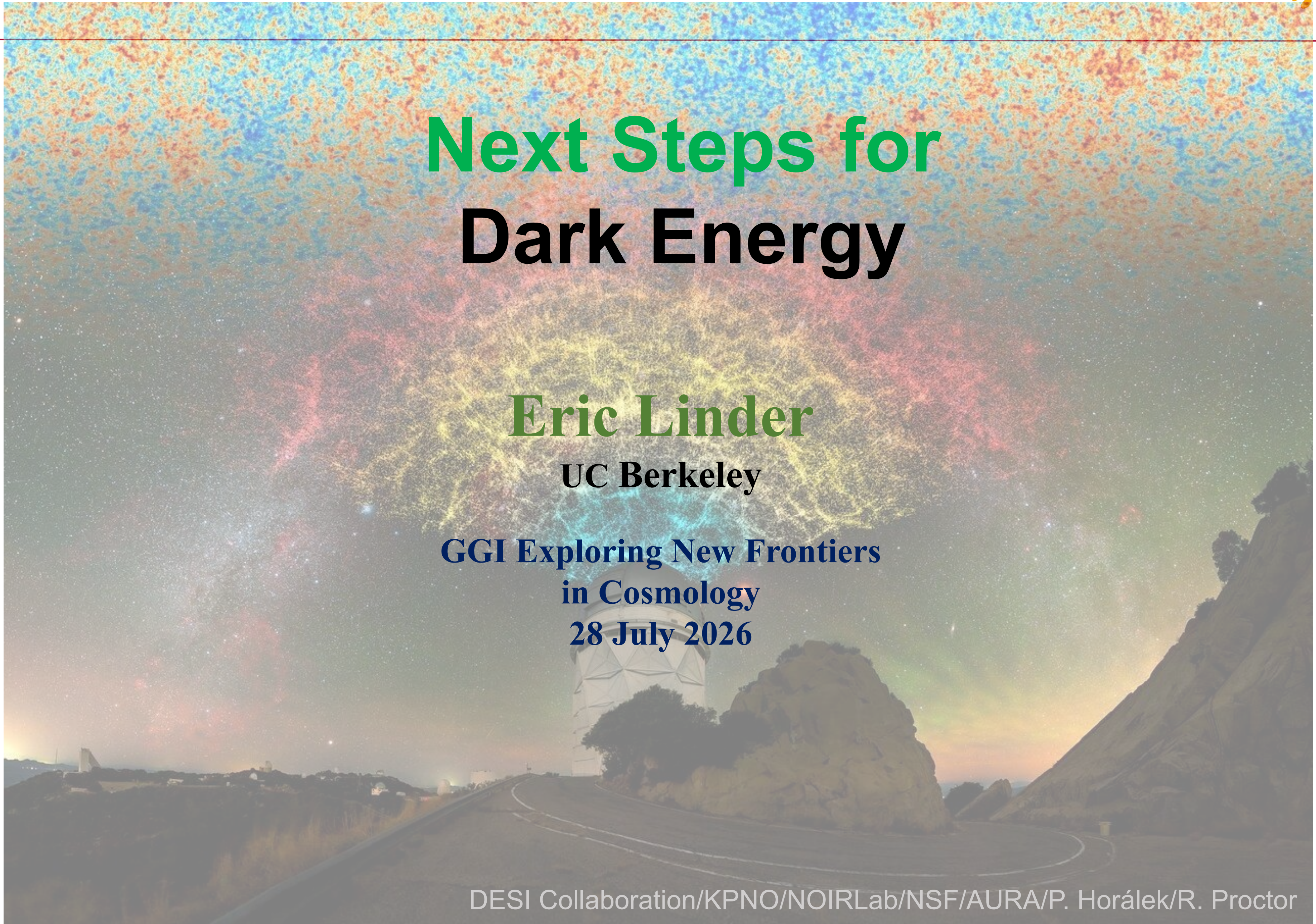

DESI Collaboration/KPNO/NOIRLab/NSF/AURA/P. Horálek/R. Proctor

What is Dark Energy Doing?

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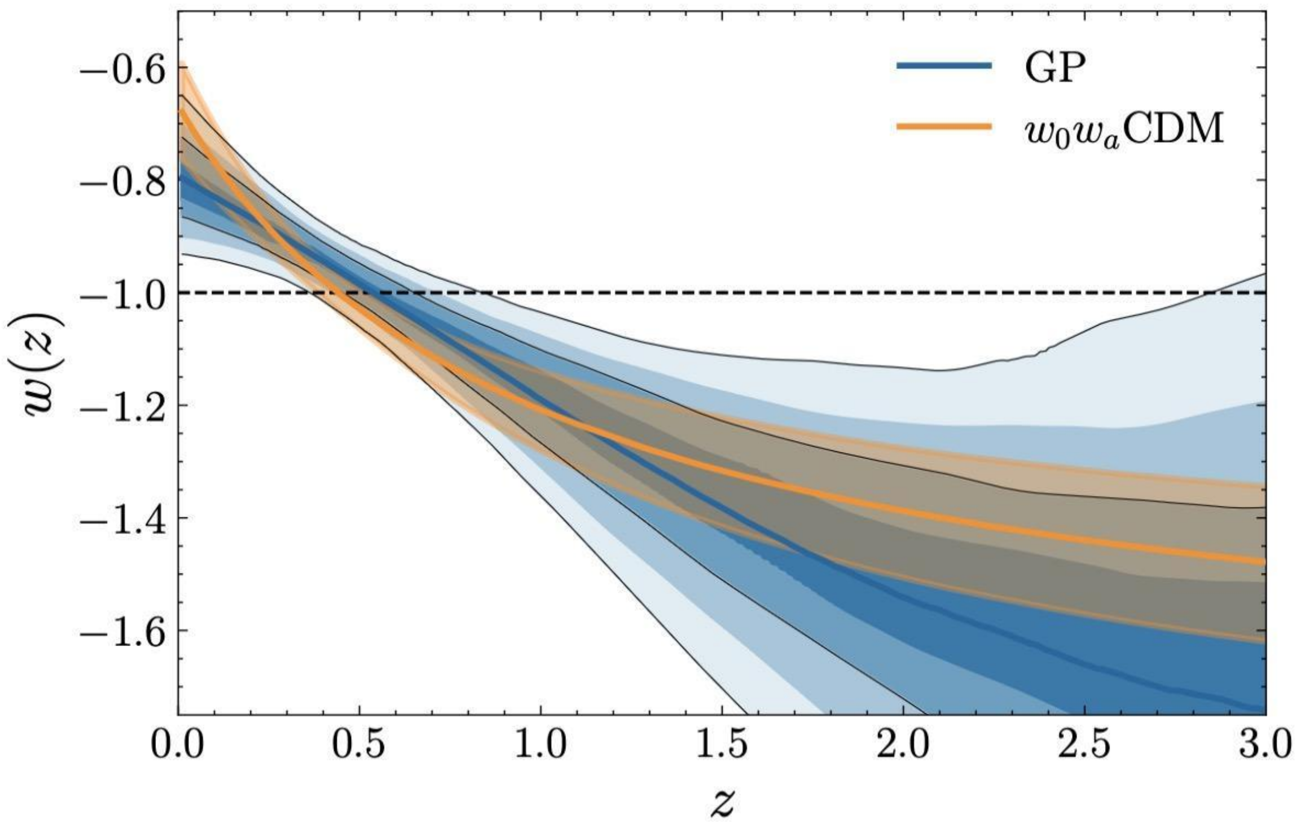

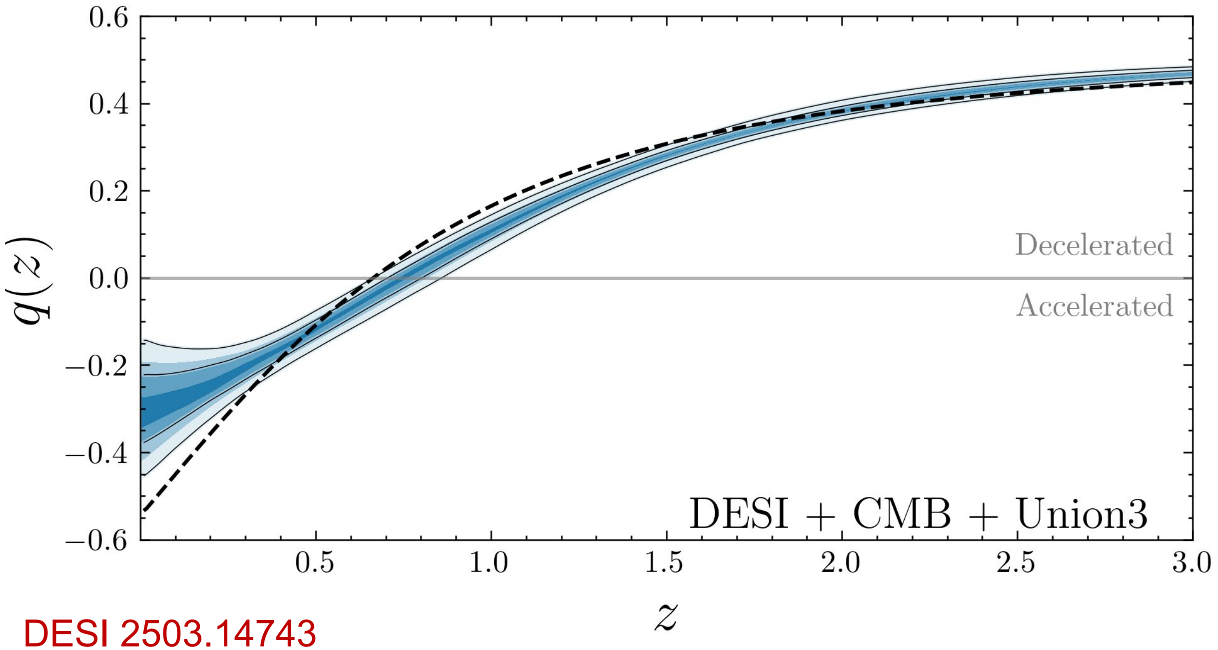

DESI 2503.14743

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

Effing the Ineffable

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Dark energy is a persistent puzzle.
(We haven't even known what to do with Λ for over 100 years!)

How should we speak about the unspeakable?
(Ineffable: literally "what cannot be spoken of" – too overwhelming or sacred for words.)

The root word is the Latin "fari" (like parlare/parler/parlar). See

- infant - one unable to speak
- fable - spoken story
- fate - that spoken by the gods
- preface - that spoken beforehand

Effing the Ineffable

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So, our study of dark energy is in its infancy…

Where we tell stories about the fate of the universe…

And this talk is just a preface to the questions we will discuss in this workshop.

Interpreting The Data

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Is the interpretation of the data robust?

The data has been analyzed many many different ways, from sturdy parametrization ($w_0 w_a$) to form-independent methods (redshift bins of w, of ϱ_{de}, splines, weights, PCA, basis functions, Gaussian process).

Phantom appears real.

[plus see slide 10]

The Data Itself

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The blade itself
Incites to violence

– Homer, The Odyssey

Should we trust the data, or is there some (artificial) property of it pushing to phantom behavior?

Statistical fluctuations can certainly exist, and ~3σ isn't unheard of.

However, BAO, CMB, SN are pulling in the same direction (especially in pairwise combinations), and have different systematics. Clustering data (growth, 3x2 point) are not yet as incisive but seem consistent.

The Data Itself

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Moreover, each probe is rather consistent among datasets, e.g.

- BAO – DESI BGS / LRG / ELG / QSO / LyA; vs SDSS; vs DES photo
- CMB – Planck (PR3 vs PR4); vs SPT; vs ACT
- SN – DES-Dovekie vs Union3.1

And all probes will be delivering new data, often with much better statistics and precision.

DESI will have >2x times BAO this year (and operates thru 2028).
Simons Observatory will have independent CMB.
Rubin will have clustering data (and 1 year Rubin+DESI SN can give 5σ).

Truong+ 2604.18859

The Data Itself

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Are there any odd properties of the data to worry about now?

There is some divergence in the values of Ω_m that each probe prefers.
What happens if you fix Ω_m=0.31, say, and then fit – does w0-wa shift?

And what about the low / negative sum of neutrino masses?
This is actually a feature, not a bug!

Making Neutrino Mass Positive

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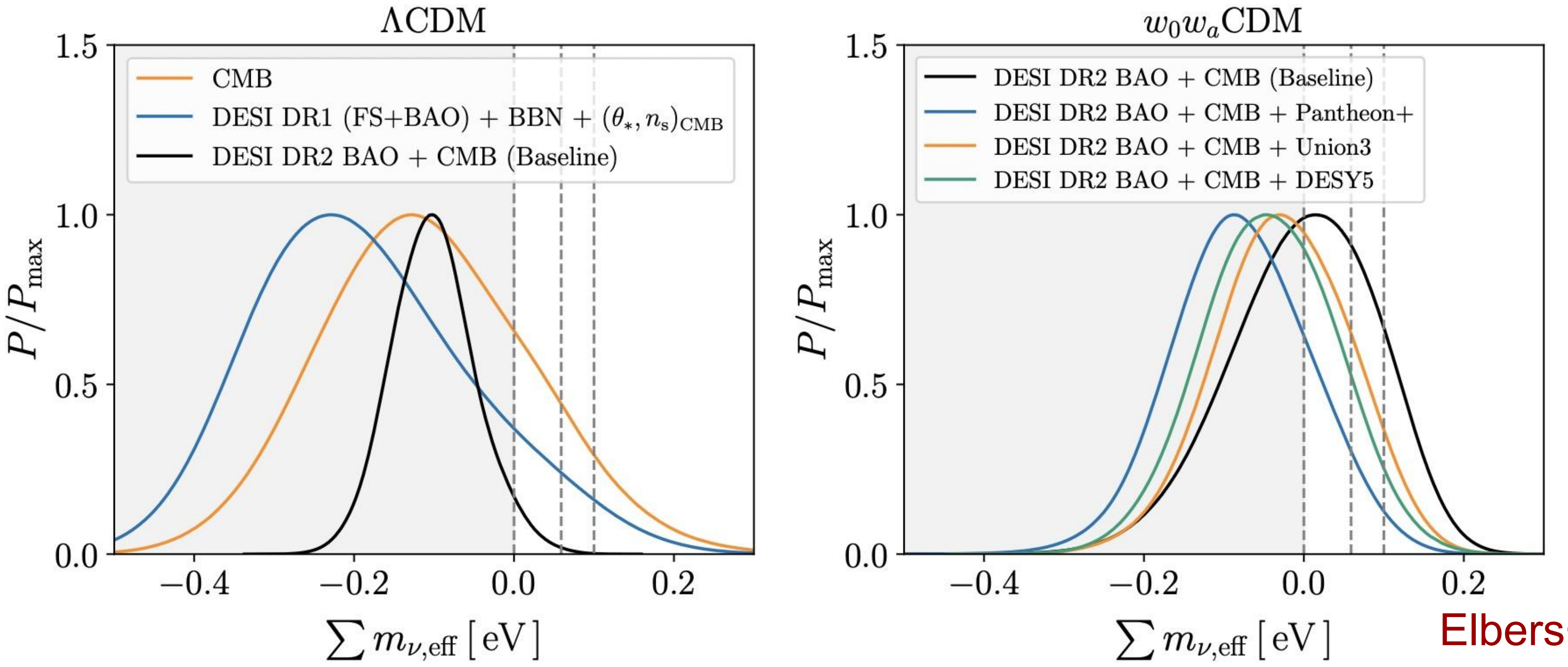
In ΛCDM current data gives $m_\nu < 0$ at ~95% CL. But w_0w_aCDM brings much of the posterior to (physical) $m_\nu > 0$.



Elbers+ (DESI) 2503.14744

What property of dynamic DE enables positive neutrino mass?

Making Neutrino Mass Positive

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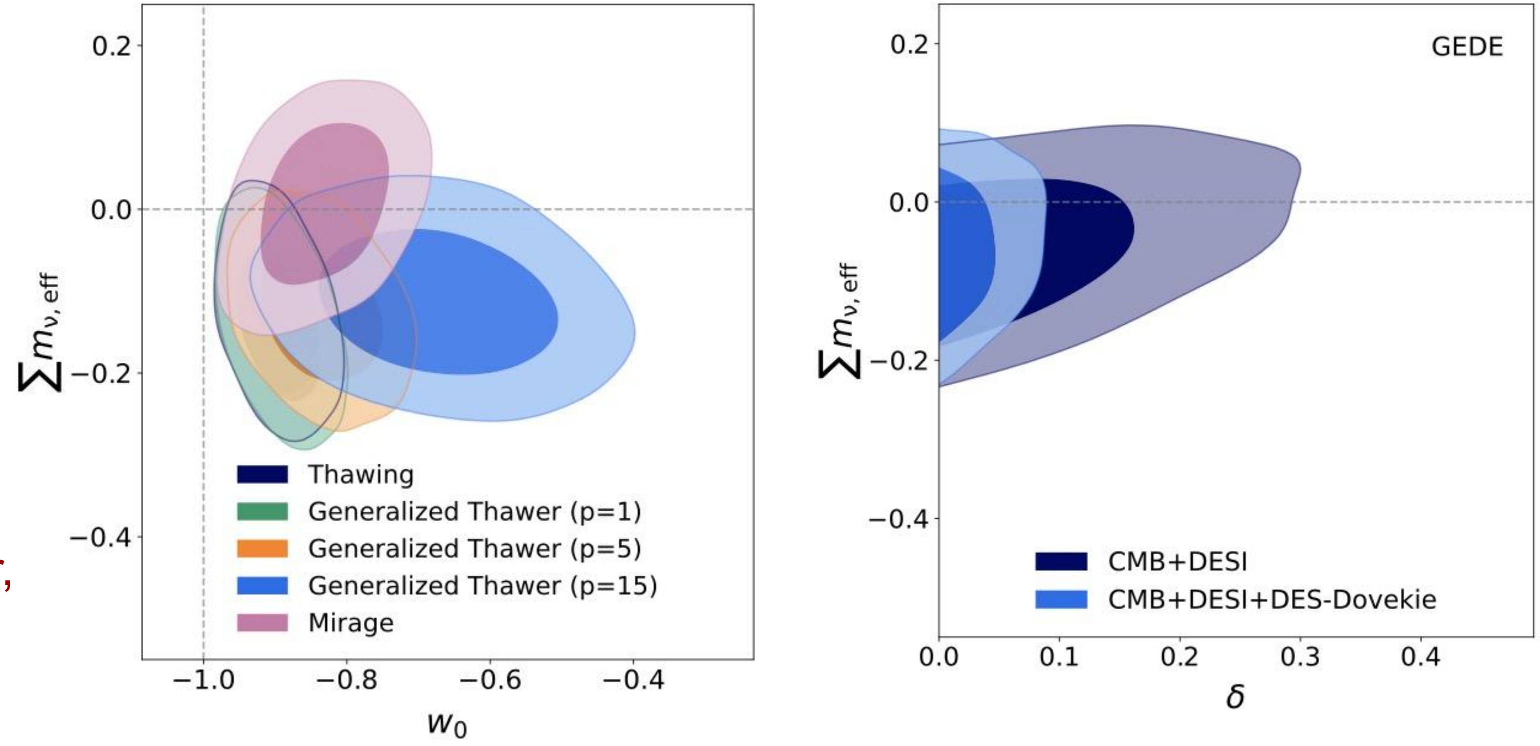
Using 6 1-parameter DE models we checked: 1) Is it parameter space volume (degeneracy)?, 2) Rapid DE evolution?, 3) Phantom crossing?, 4) Phantom at high z?



Yang, Di Valentino, Linder, Zhang, Pan 2603.15422

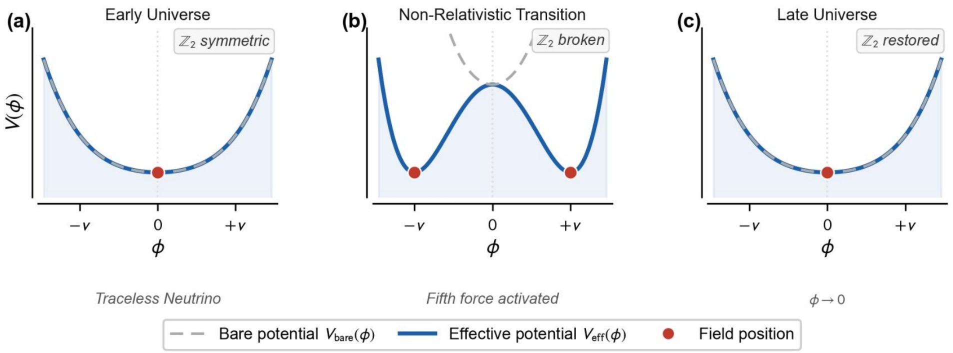
Answer: the required property is phantom DE at z>1 for $m_\nu > 0$, and phantom crossing at z<1 for good fit to data. Supports phantom is real.

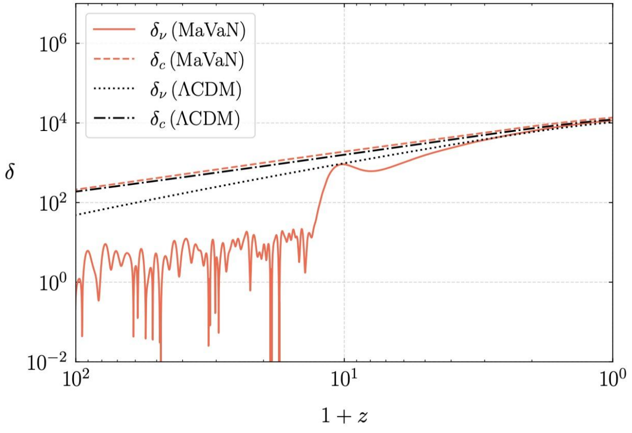
Neutrinos

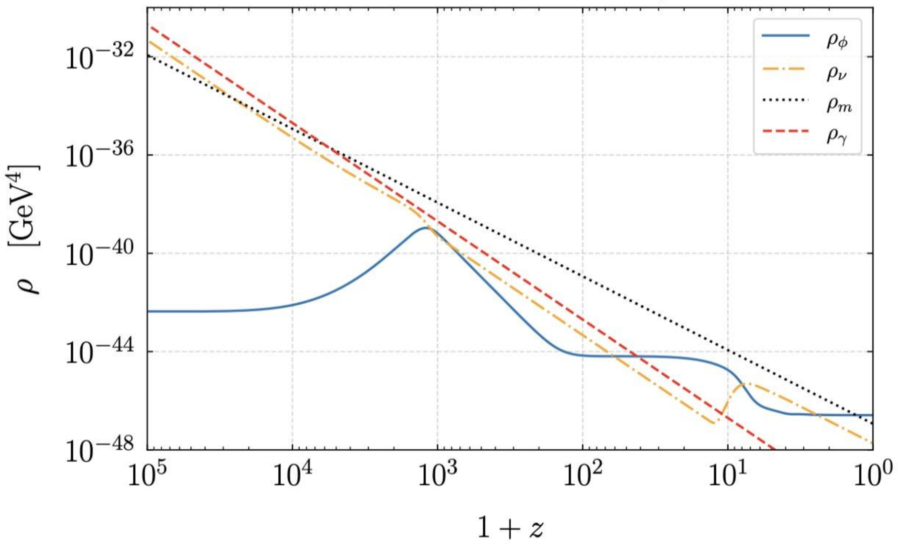
Neutrinos are also a safer species to couple to DE.
Long standing "Mass Varying Neutrino" (MaVaN) scenario.

$$m_\nu(\phi) = \hat{m}_\nu\, A(\phi)$$

An issue is growth instability on large scales.
Solved by "inverse symmetron" mechanism.
And this can give early DE for H_0 issue. Not late time phantom though?







Baidya, Christensen, da Fonseca, Linder, Mota 2606.07391

Dark Energy Interpretation?

Beautifully bizarre!

Dark energy appears 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 2511.07526

Testing the Framework

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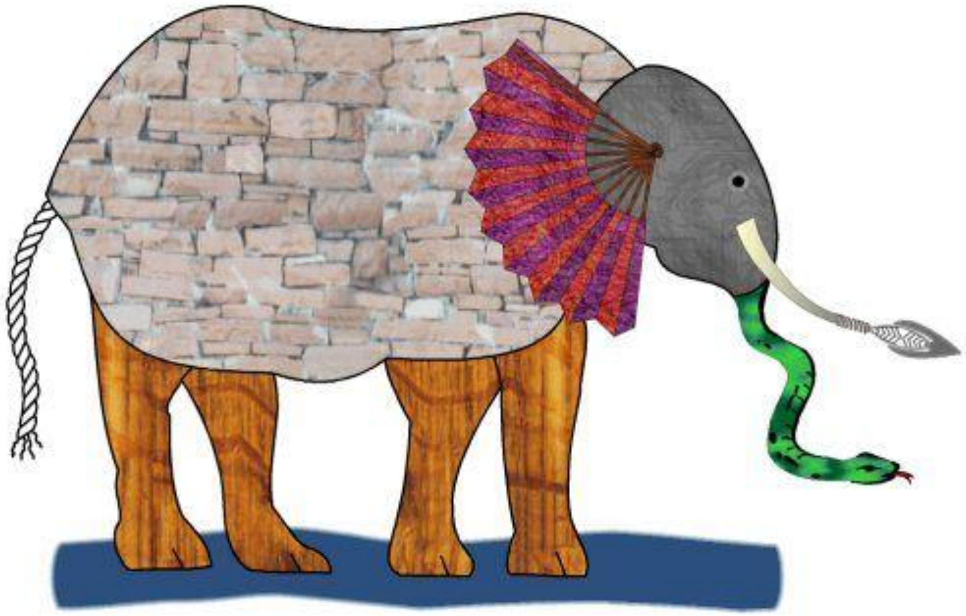
Is dark energy an elephant or a chimera?



"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

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™ (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)

Interactions

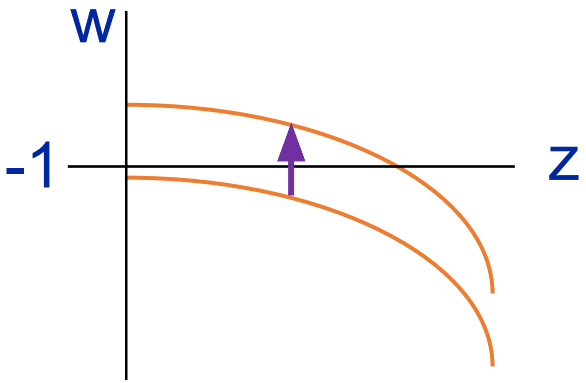
Could crossing w=-1 be due to dark sector interactions?

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

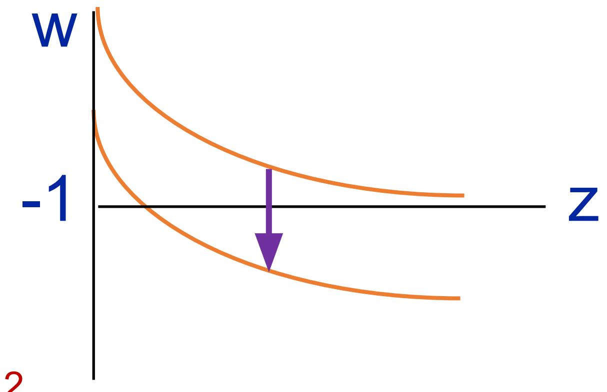
$$\Rightarrow$$

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

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



Linder 2506.02112



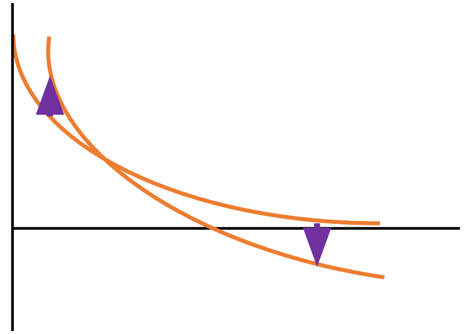
The problem is this shifts the coupled, e.g. dark matter, density too.

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

Issues for LSS growth and CMB/ISW.

Interactions

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.

Decay (e.g. DE → DM or DM → DE) causes same issue.

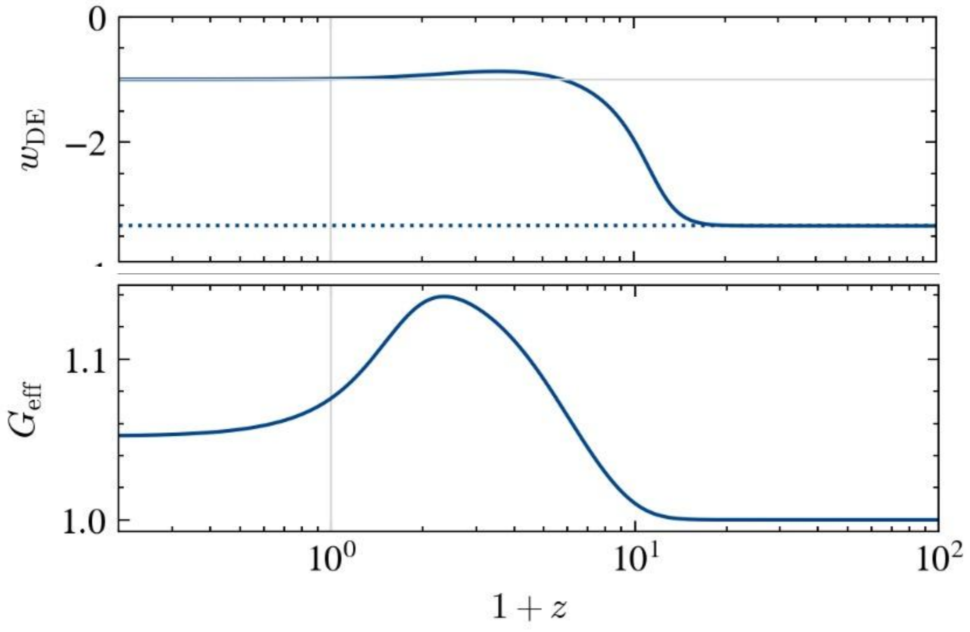
Any interaction with matter is problematic for LSS, CMB?

Modified Gravity

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.

Most quantum protected potential is V = $\lambda\phi$. This can cross w = -1 but does not look like the data.



Calderón & Linder
2605.26259

See interactive app at
https://rcalderonb6.github.io/phantom-X/

Modified Gravity

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Why I'm in an "off" phase on modified gravity:

- We've had to give up disformal gravity ("adding" to the metric).
- We've had to give up shift symmetry.
- We have to become potential dominated, where MG is secondary.

Time to retry disformal MG, i.e. $c_{GW} \neq 1$?

GW170817 limit near strong coupling scale, and at $z \approx 0$.

de Rham & Melville 1806.09417

We would really like to know c_{GW} away from ~100 Hz (LISA, PTA).

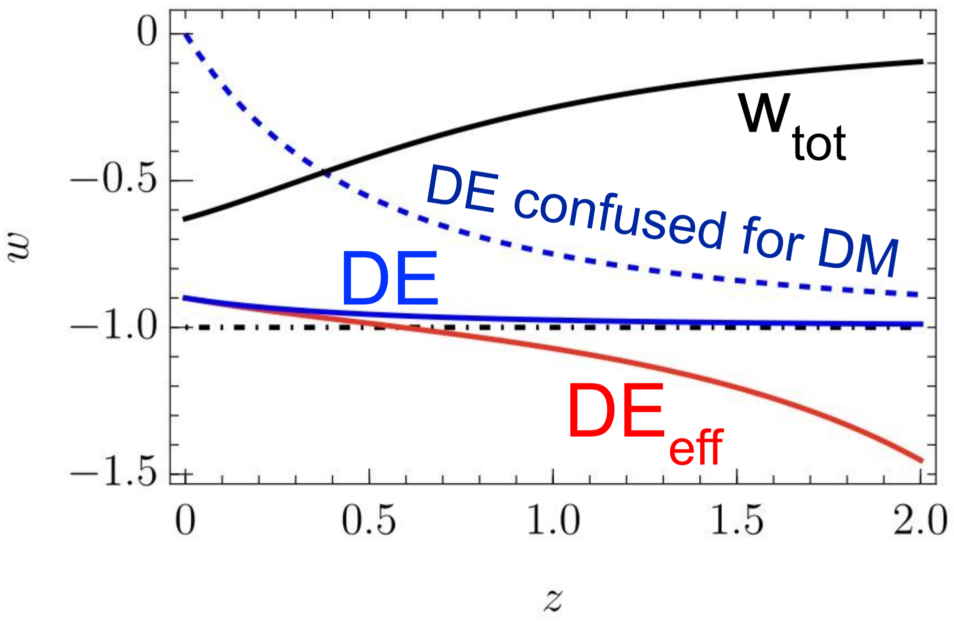
Misunderstanding Matter

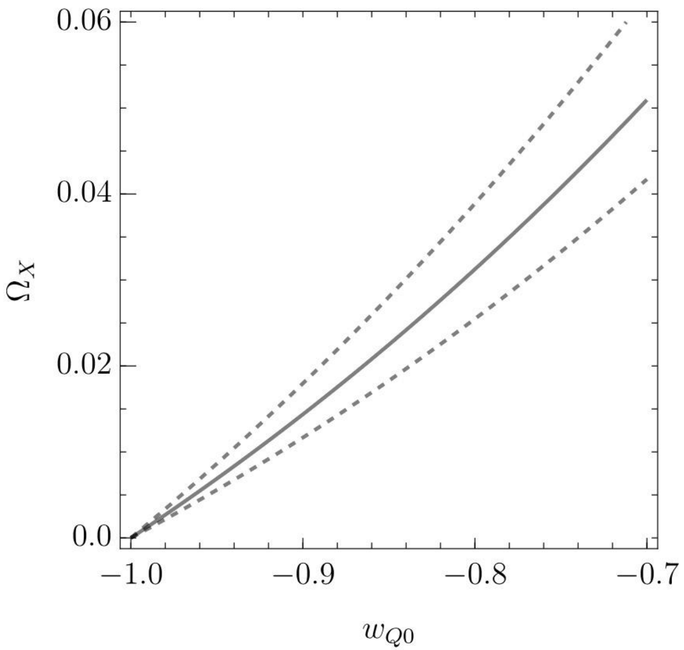
DE can be effectively phantom if we subtract the wrong matter contribution from the Hubble expansion. [No interactions!]

This can be from changing matter properties (e.g. DM EOS) – which runs into many LSS/growth problems – or a component that sometimes acts like matter (w=0) and sometimes not (Bob Scherrer called this phake phantom)

Caldwell & Linder 2511.07526

Also see Khoury, Lin, Trodden 2503.16415; Liu, Zhu, Hu, Miranda 2510.14957 for axion-type models





Phake Phantoms

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We might not want multiple DE fields for phake phantom (chimera), but is this worse than the physics needed for a real phantom?
Or can we turn the chimera into an elephant?

One could try an analysis for $\Omega_m+\delta\Omega_m(z)$, e.g. in z bins, or fit for $\delta\Omega_m^{thaw}$.
The latter case could have just 1 extra parameter, so it would be interesting to see the χ^2.

Phase Transition (Vacuum Metamorphosis)

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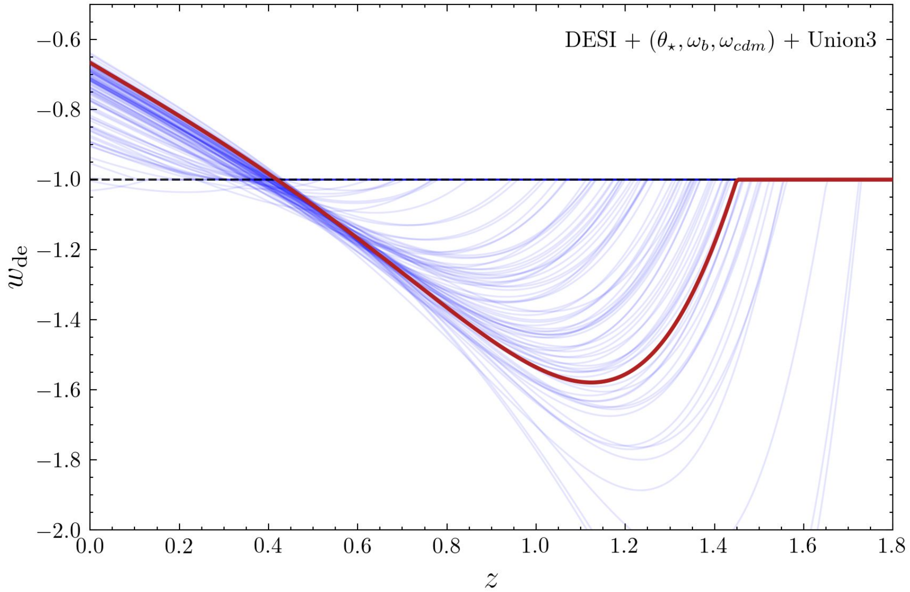
A vacuum phase transition can give phantom DE. Parker+ 1999+ did a nonperturbative summation of QFT effects on action, with Ricci scalar R acting as an order parameter. When R = m^2 (scalaron mass) then Lenz' law freezes R constant (giving cosmic acceleration, phantom DE).

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 Γ~H_t!

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

Compendium of Questions for Discussion

- Is the interpretation of the data robust?
- Should we trust the data, or is there some (artificial) property of it pushing to phantom behavior?
- Are there any odd properties of the data to worry about now? What happens if you fix Ω_m=0.31, say, and then fit - does w0-wa shift?
- MaVaN can give early DE for H_0 issue; late time phantom possible?
- Time to retry disformal MG, i.e. $c_{GW} \neq 1$?
- Is a phake phantom worse than physics needed for a real phantom?
- Analysis for $\Omega_m+\delta\Omega_m(z)$, e.g. in z bins, or fit for $\delta\Omega_m^{\rm thaw}$ (1 par)?
- Further signatures of phase transition?

Summary

Phantom divide crossing of dark energy appears robust.
(also see m_ν argument)

Data has been extensively crosschecked, but more is coming, and we can continue new directions of analysis (growth vs expansion, Ω_m).

Modified gravity, nonminimal coupling, interactions all have issues.
Neutrinos are interesting from a number of angles.
Phake phantoms may be worth looking at more (chimera vs elephant).
Phase transition from QFT-GR impressive on expansion history.

This is a great week to eff the ineffable!