Dark Energy and Modified Gravity in the DESI Era

breaking degeneracies with multi-probe strategies

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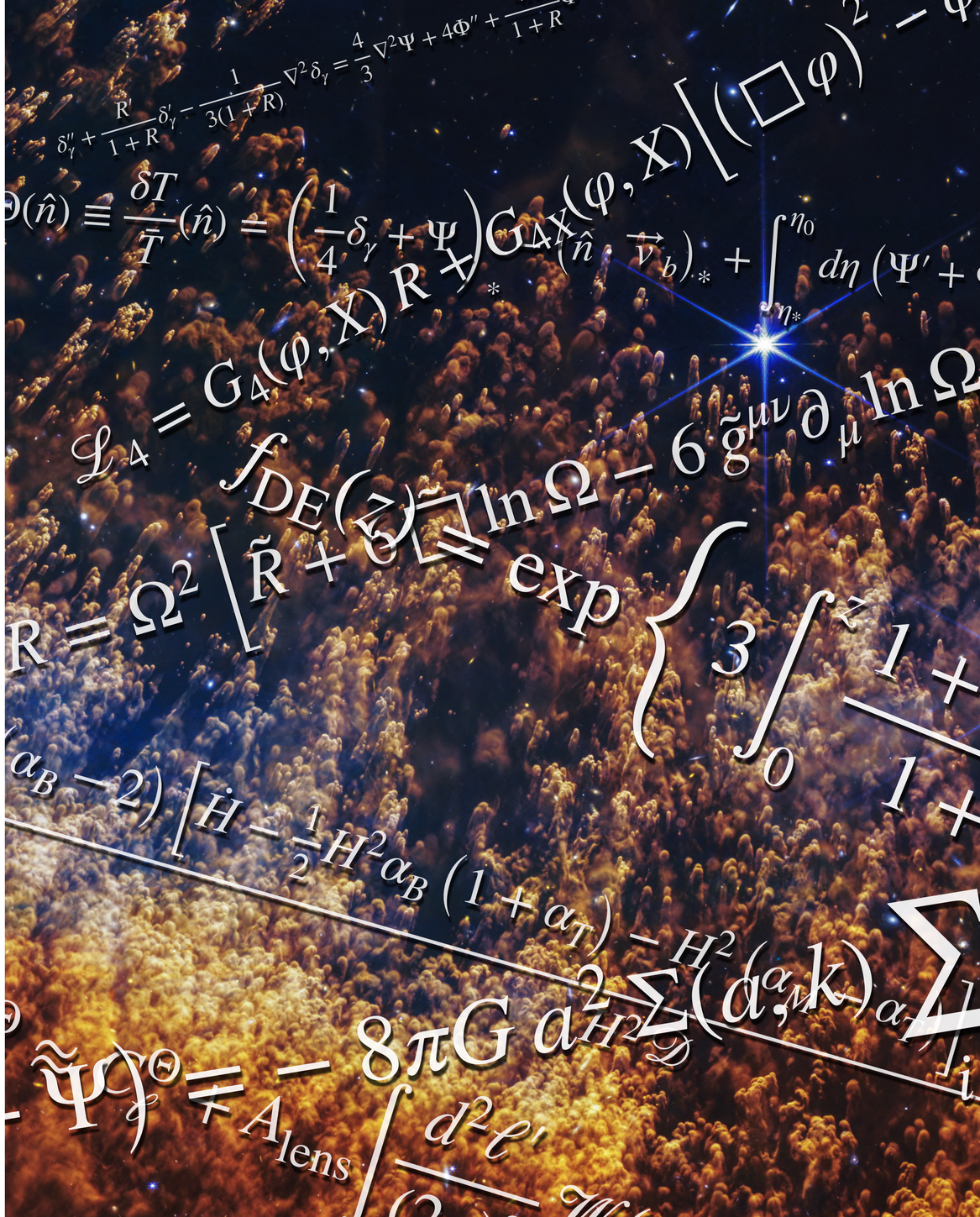
Exploring New Frontiers in Cosmology
July 20th 2026 - Firenze



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Dark Energy and Modified Gravity in the DESI Era

Model-independent cosmology with joint observations of gravitational waves and γ-ray bursts

A short blanket for cosmology: the CMB lensing anomaly behind the preference for a negative neutrino mass



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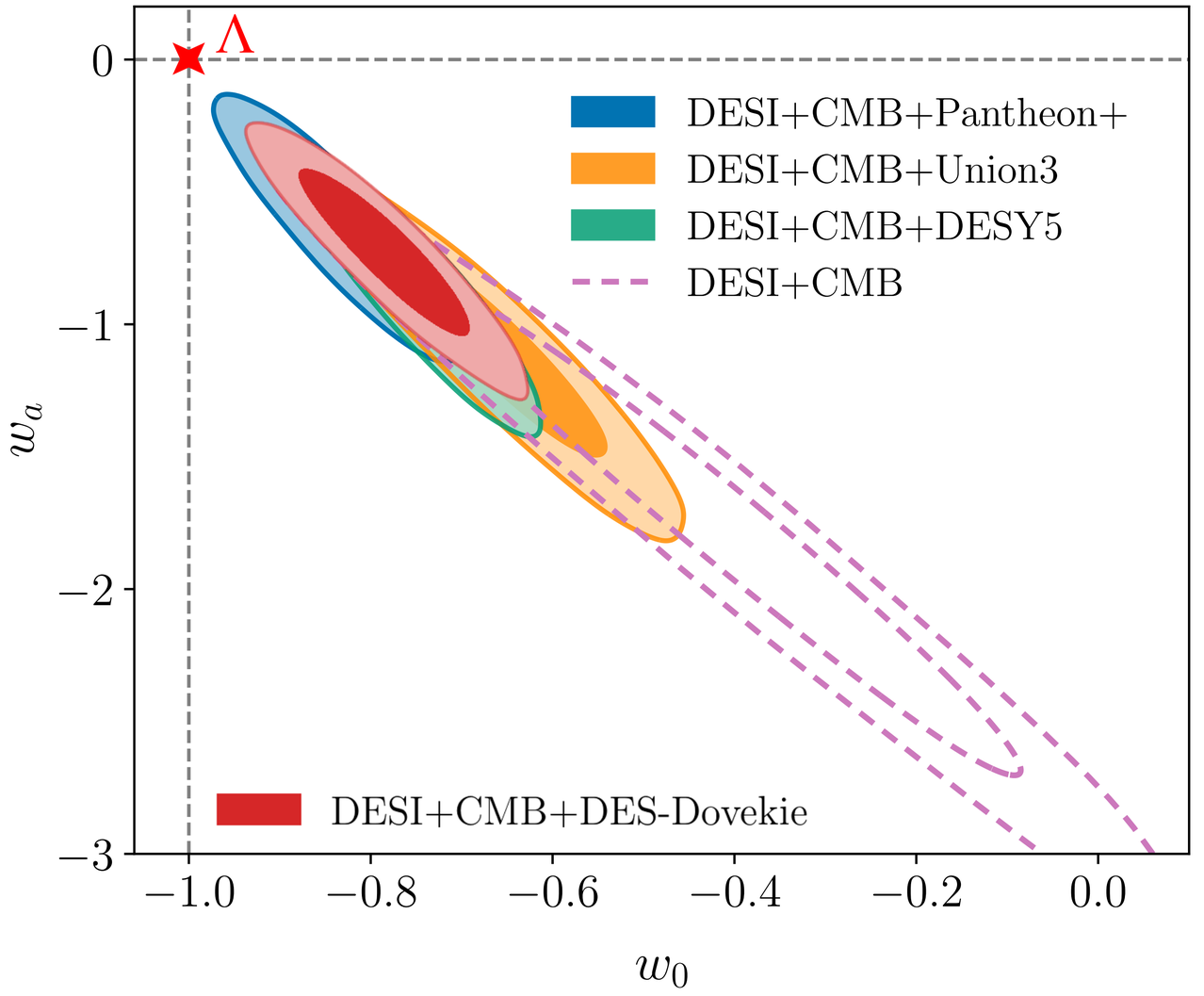
DESI RESULTS

A $3-4\sigma$ preference for dynamical dark energy

$$H(z) = H_0\sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{\mathrm{DE},0}\exp\left[3\int_0^z \frac{1+w_{\mathrm{DE}}(z')}{1+z'}dz'\right]}$$

$$w_{\mathrm{DE}}(z) = w_0 + w_a\frac{z}{1+z}$$

DESI collaboration, Karim+, 2025



THE NEUTRINO MASS ANOMALY

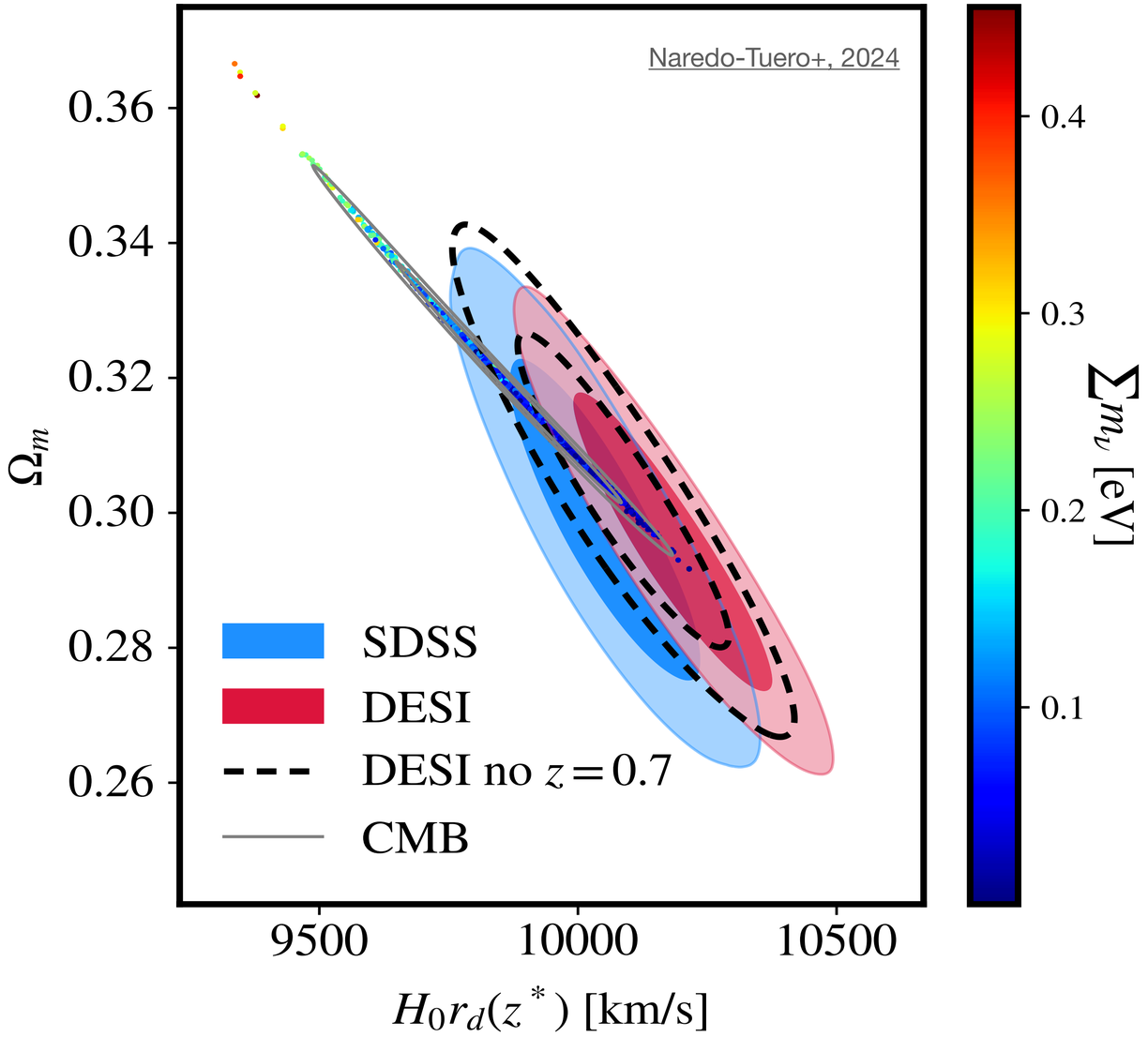
This is actually phrased in terms of discrepancy among θ_s and $\theta_{\rm BAO}$

Researchers eventually questioned the standard assumptions about ***neutrino mass***…

… going as far as to consider **UNPHYSICAL** values

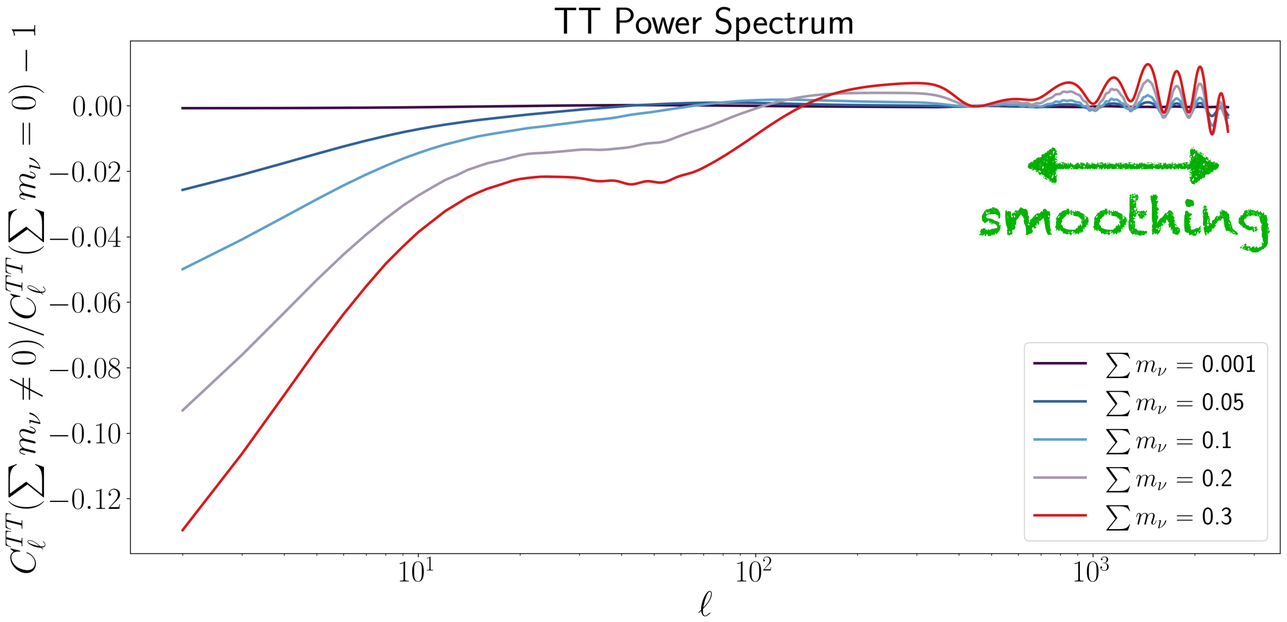
The matter deficit problem (What's the matter with **Σmν**?)

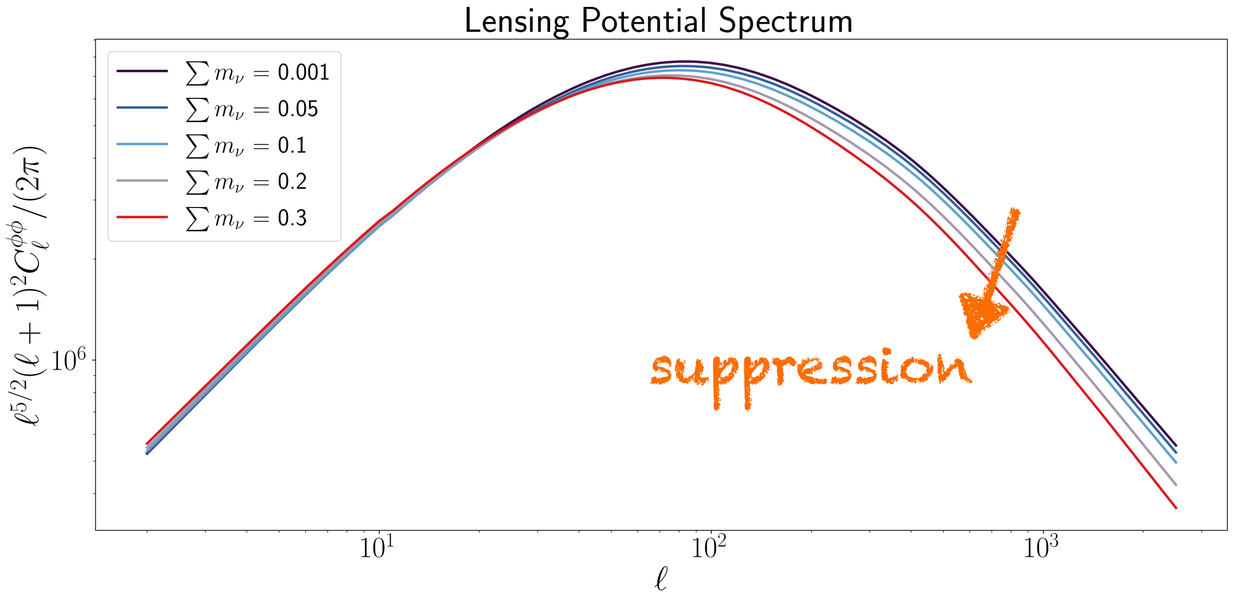
(see also Elbers+, 2024 Graig+, 2024 Green+, 2024 Allali+, 2024 ….)



NEUTRINOS AT COSMOLOGICAL SCALES

How neutrinos act on cosmological scales





$$A_{\rm lens}^{\rm TTTEEE}$$

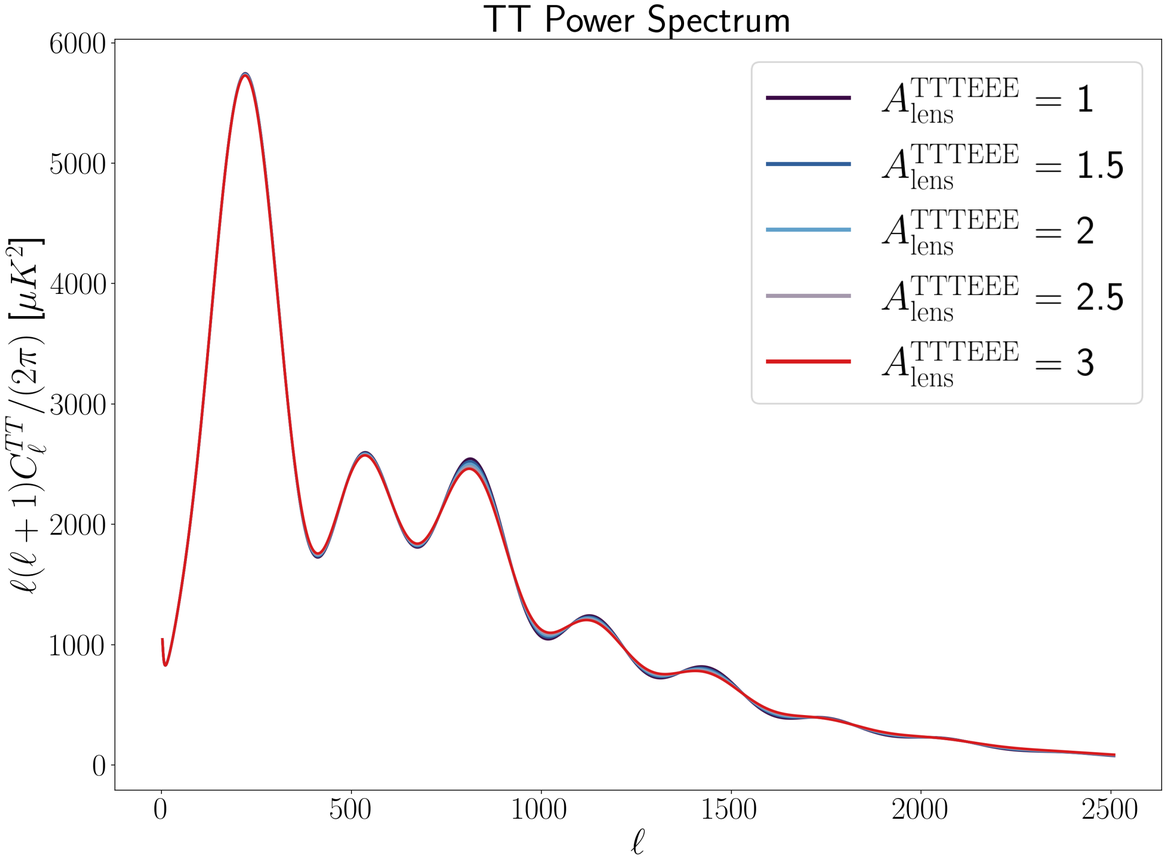
$$A_{\rm lens}^{\phi\phi}$$

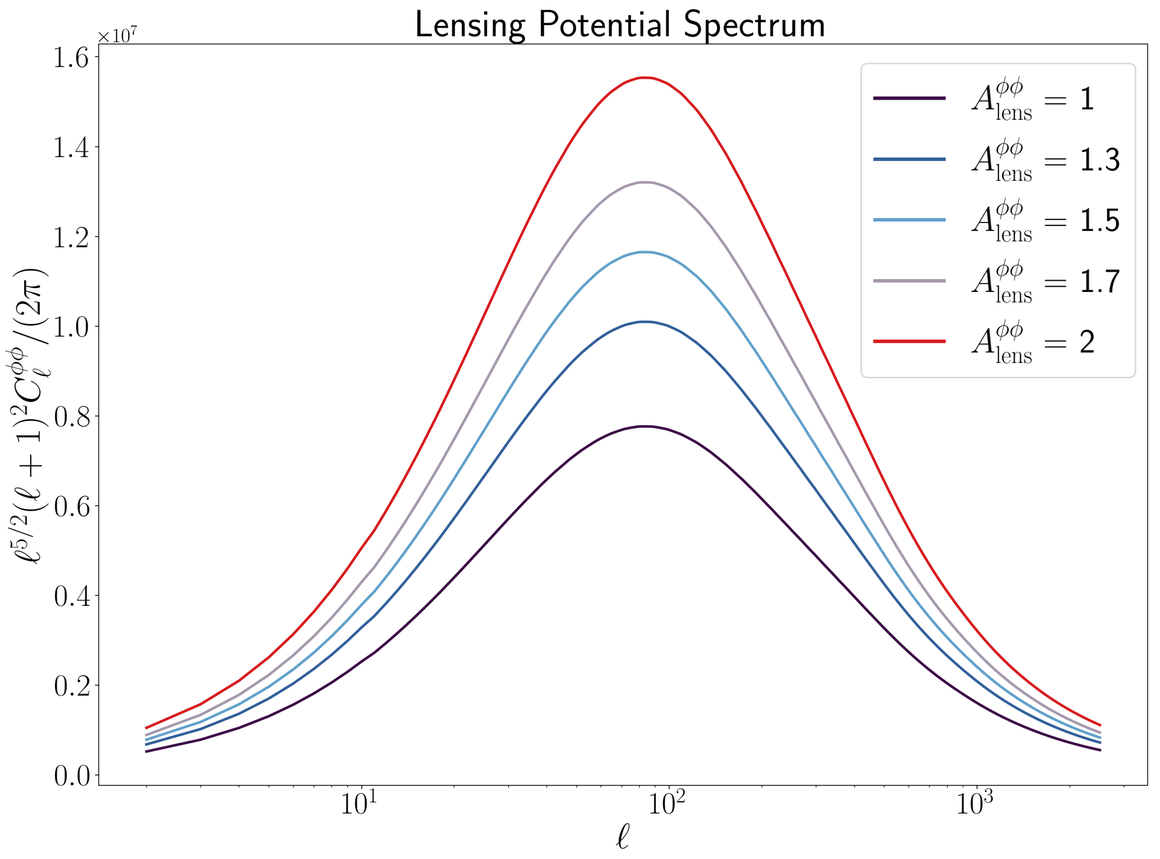
THE LENSING ANOMALY EFFECT

How lensing amplitude parameters act on cosmological scales

Simard+, 2018

Murgia+, 2020



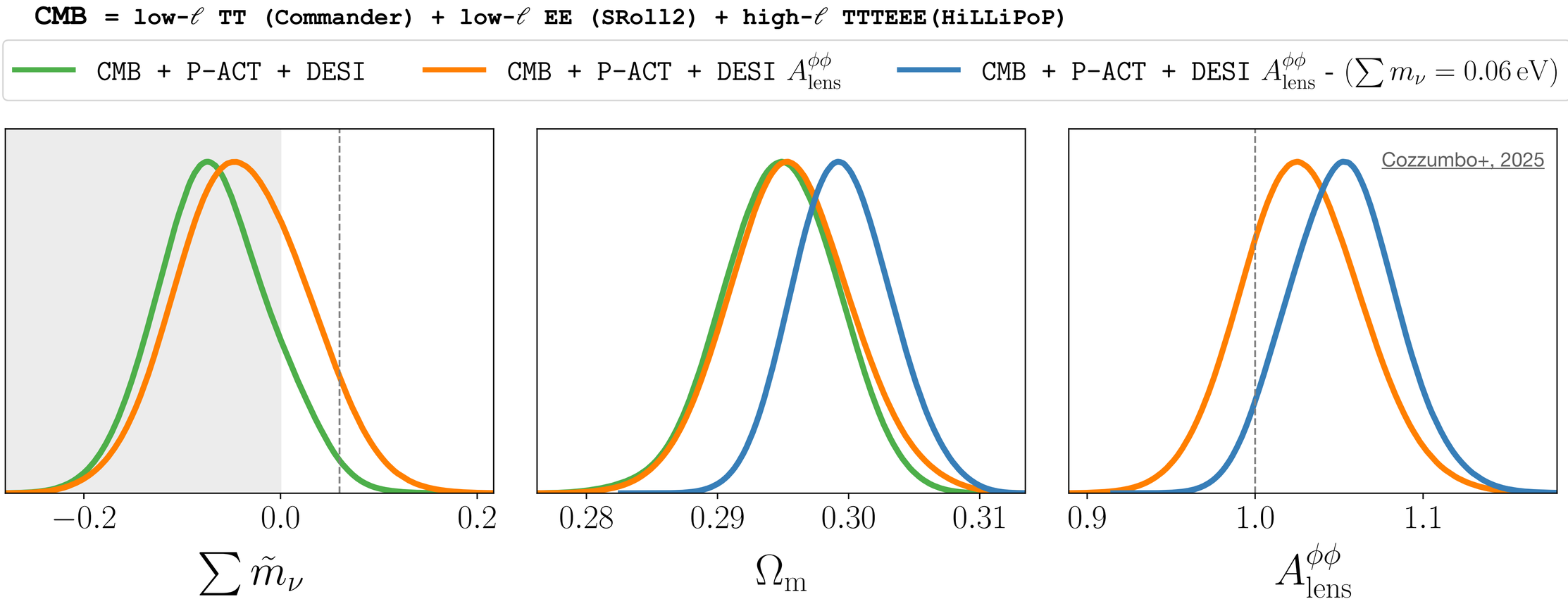


Extra smoothing at high ℓ

Scaling of $C_\ell^{\phi\phi}$

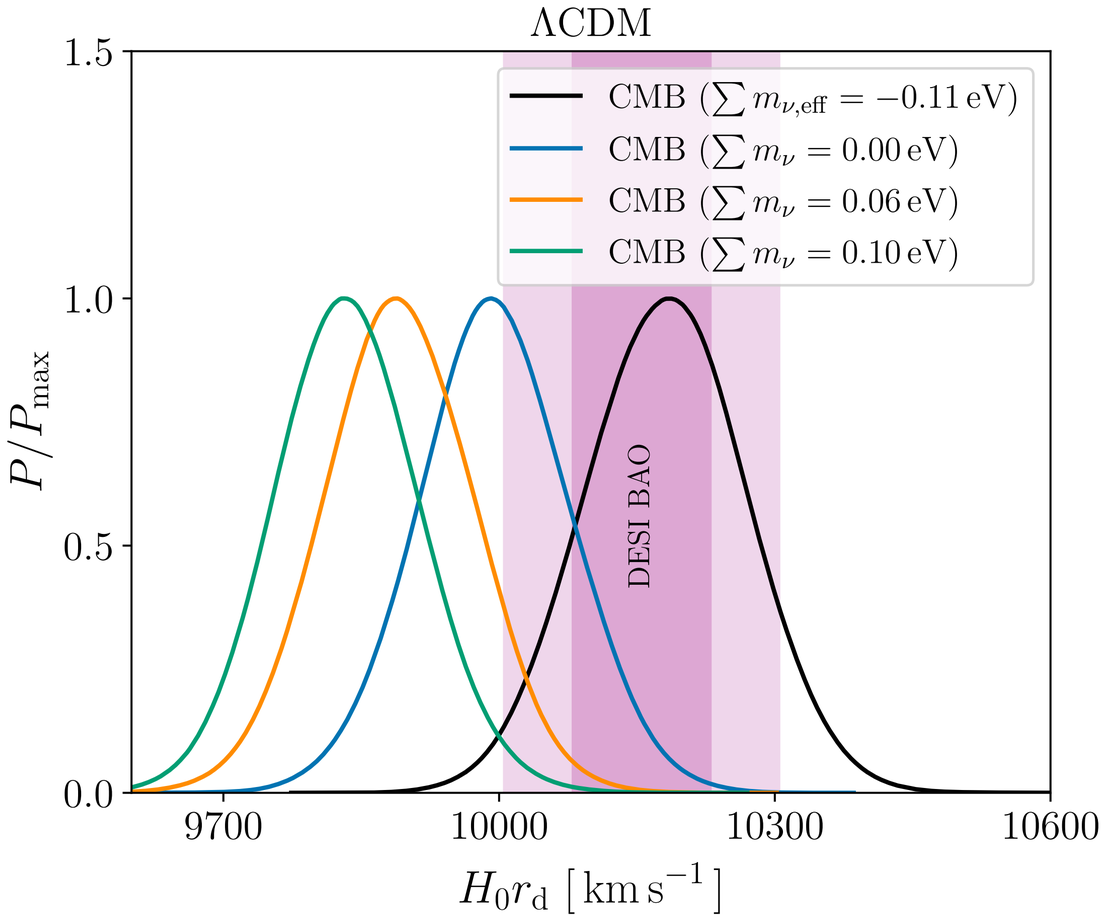
MASS OR LENSING PROBLEM ?

Swap one anomaly for the other

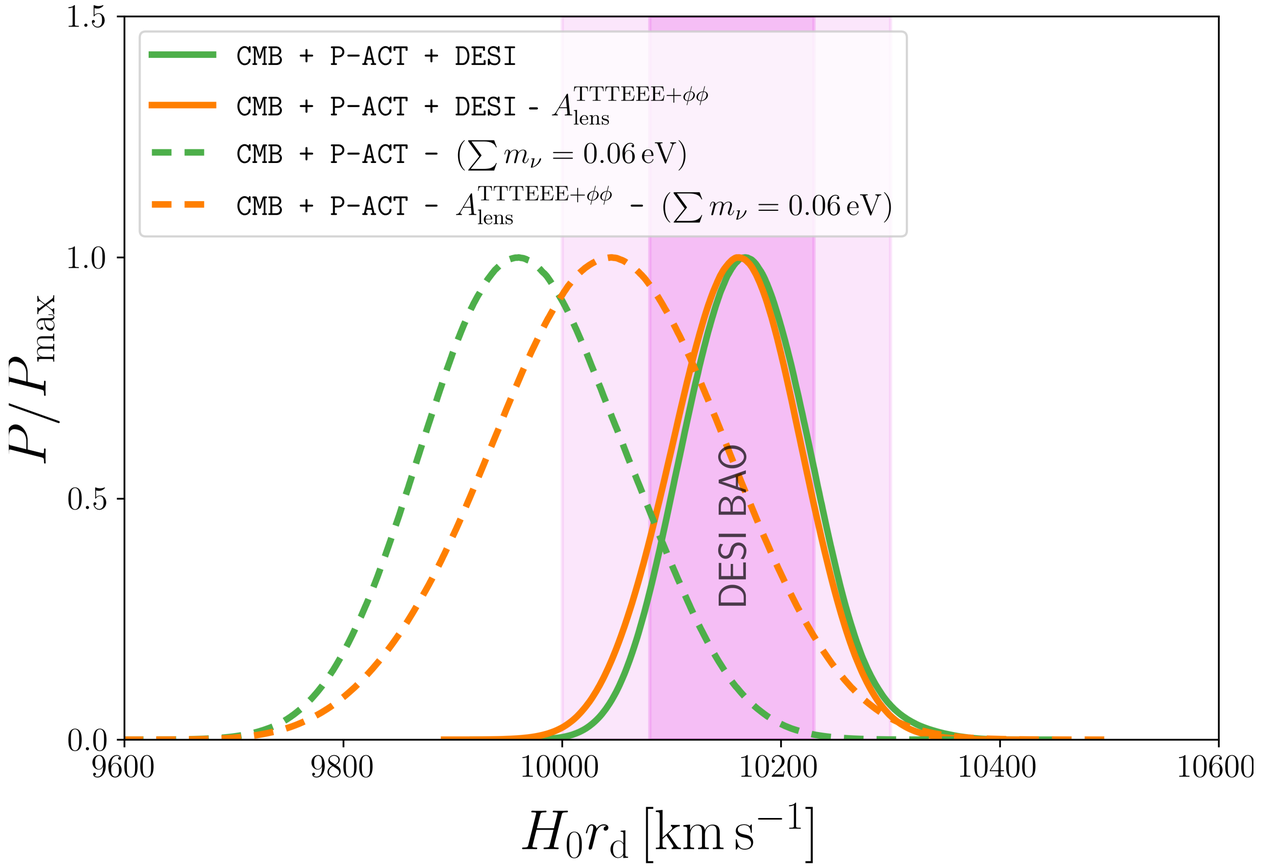


MASS OR LENSING PROBLEM ?

This shows a potential inconsistency between early and late Universe observations, rather than a negative $\sum m_\nu$



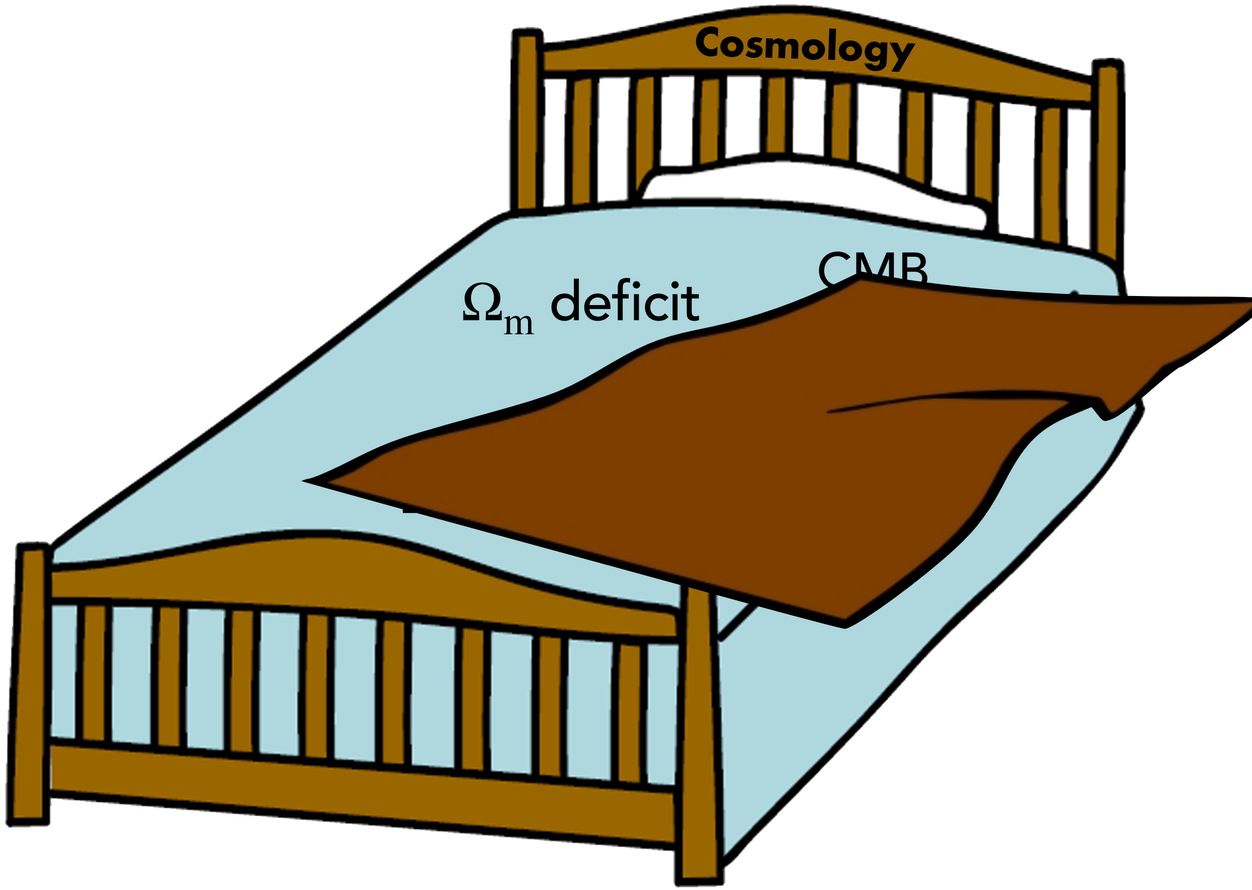
DESI collaboration, Elbers+, 2025



Cozzumbo+, 2025

A SHORT COSMOLOGICAL BLANKET





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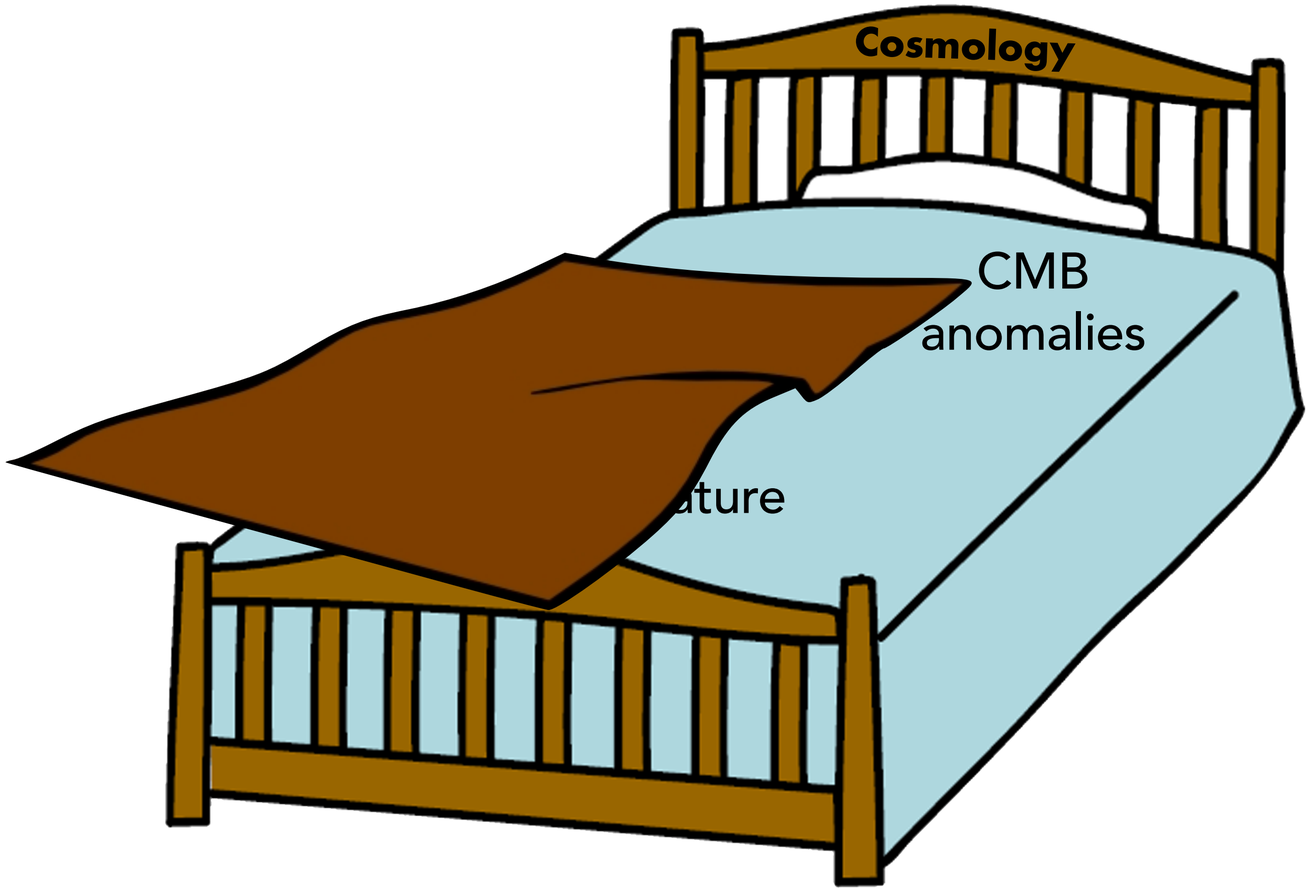

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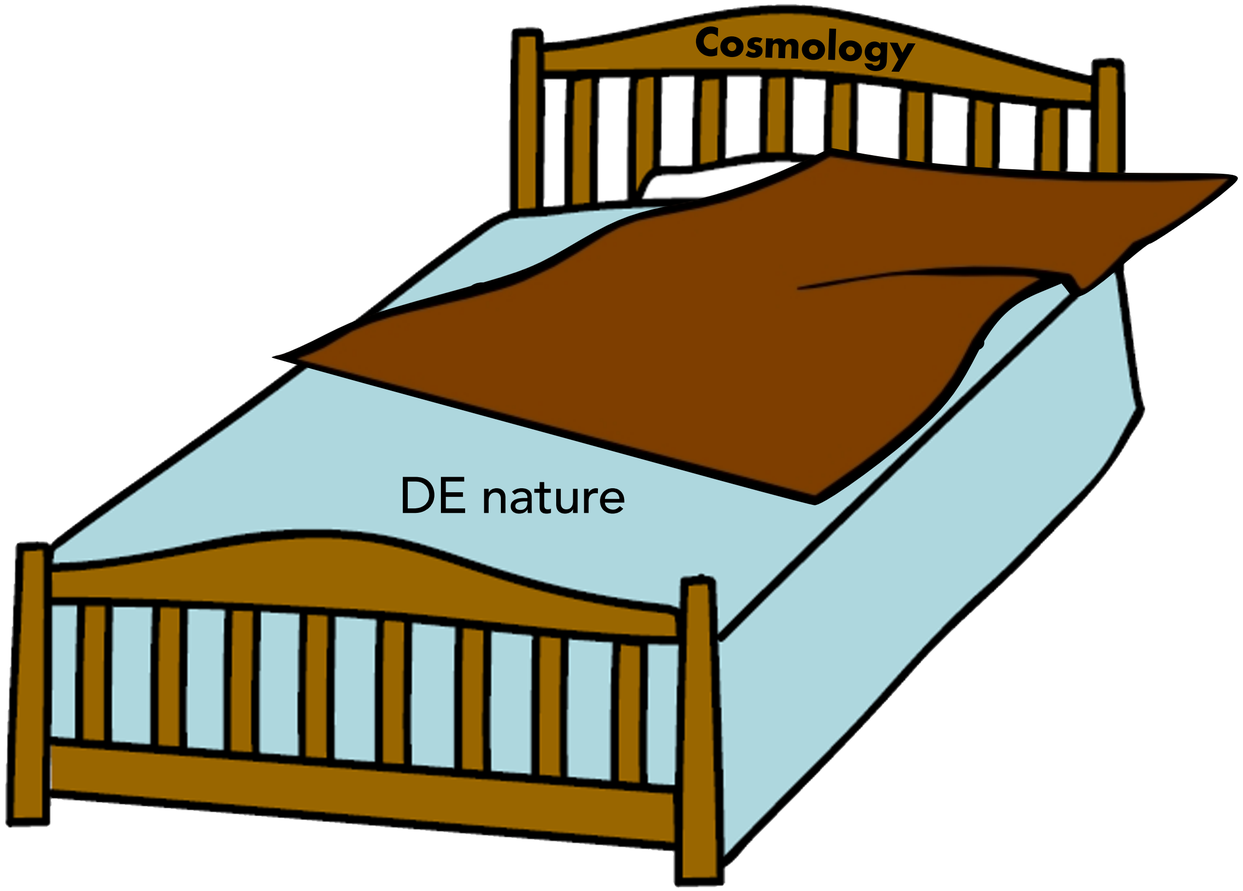

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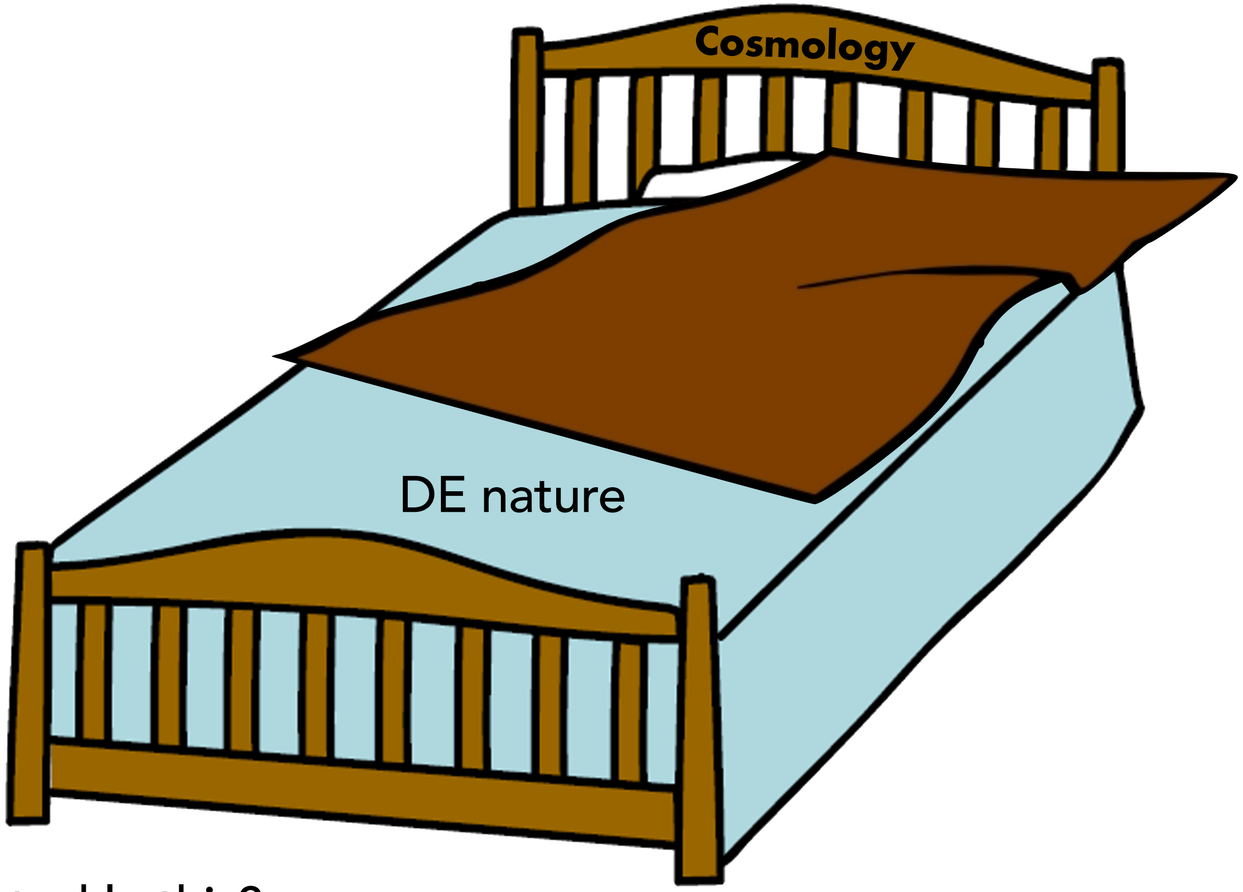


How do we tackle this?

Background cosmology

Multi-Messenger Cosmology

Perturbation cosmology

Testing Modified Gravity theories

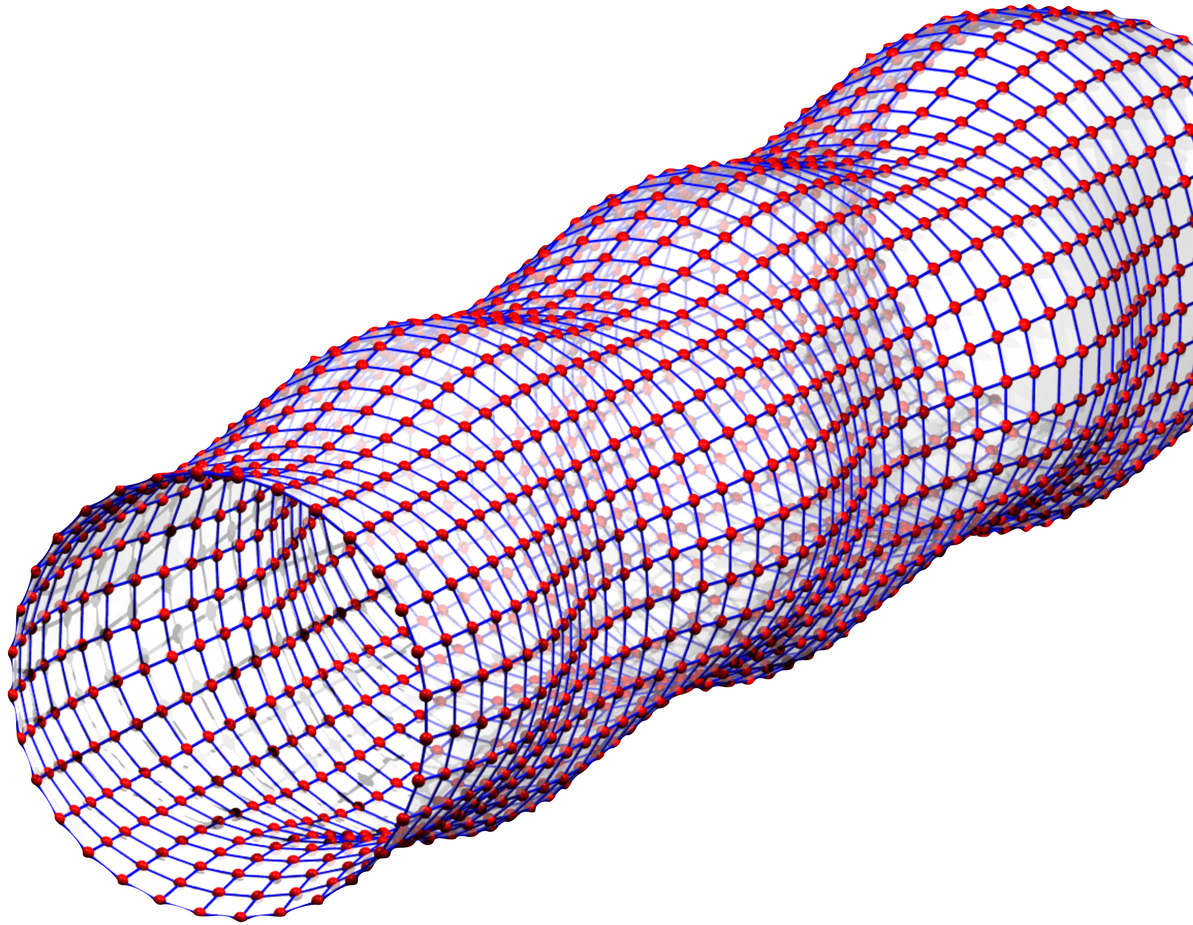
MULTI-MESSENGER COSMOLOGY

Gravitational waves as a new cosmological tracer

$$d_L(z) = c\,(1 + \overset{?}{z}) \int_0^z \frac{dz'}{H(z')}$$

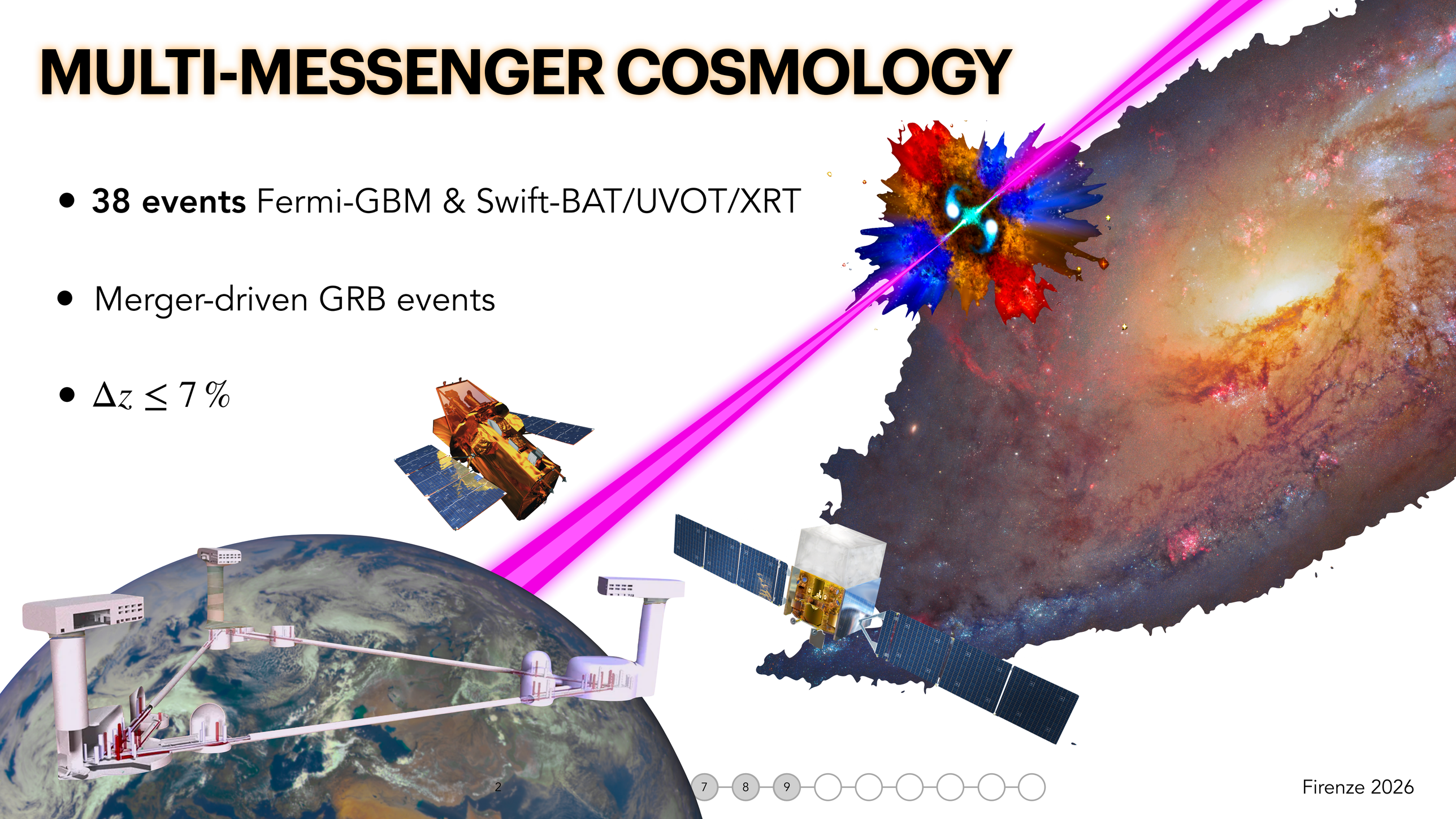
$$\tilde{h}_+(f) \propto \frac{\mathscr{M}^{5/6}}{2\,d_L} f^{-7/6}\, e^{i\phi(\mathscr{M},f)} \left(1 + \cos^2(\iota)\right)$$

$$\tilde{h}_\times(f) \propto \frac{\mathscr{M}^{5/6}}{d_L} f^{-7/6}\, e^{i\phi(\mathscr{M},f)+i\,\pi/2} \cos(\iota)$$



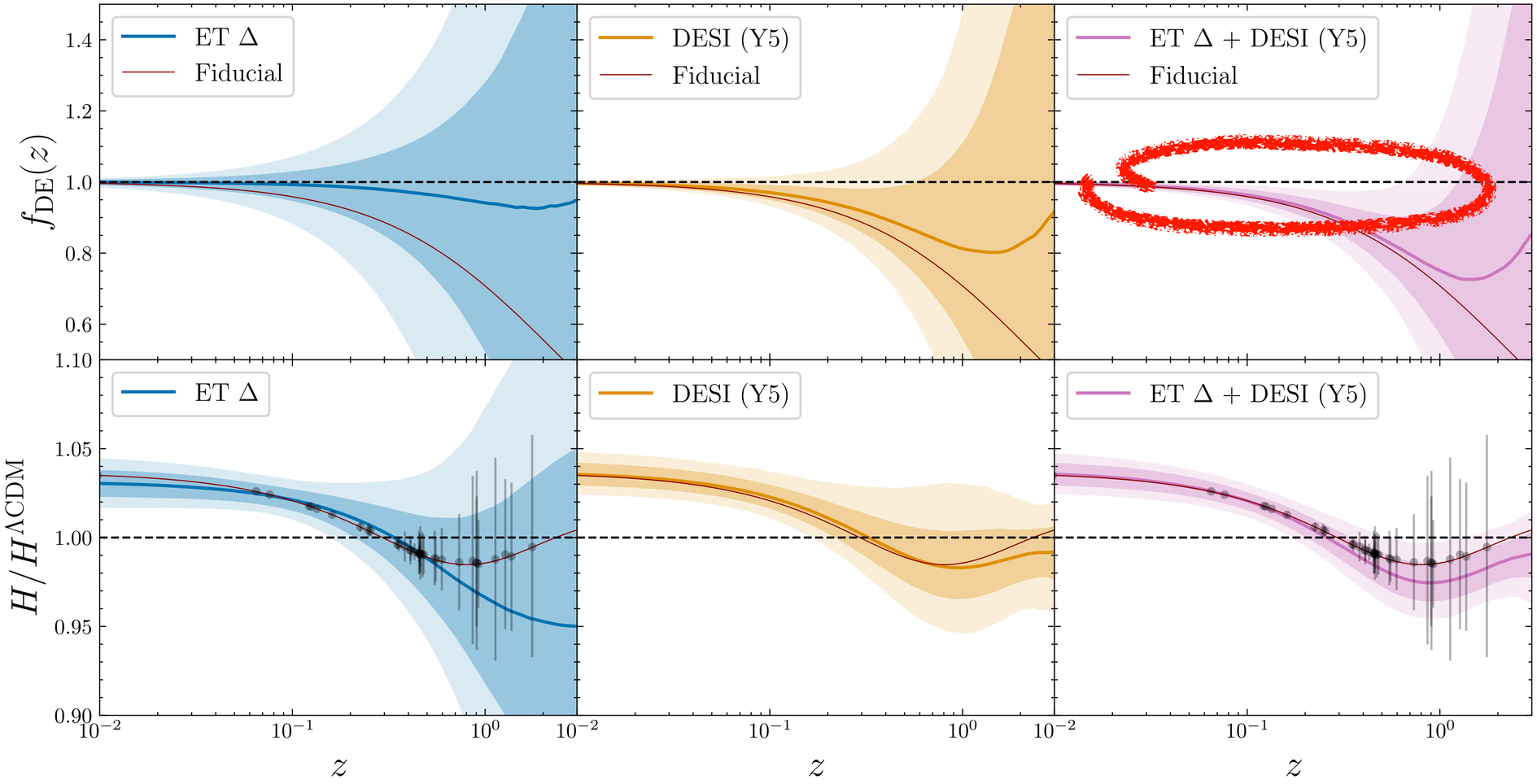
MULTI-MESSENGER COSMOLOGY

- **38 events** Fermi-GBM & Swift-BAT/UVOT/XRT
- Merger-driven GRB events
- $\Delta z \leq 7\,\%$



DYNAMICAL DARK ENERGY

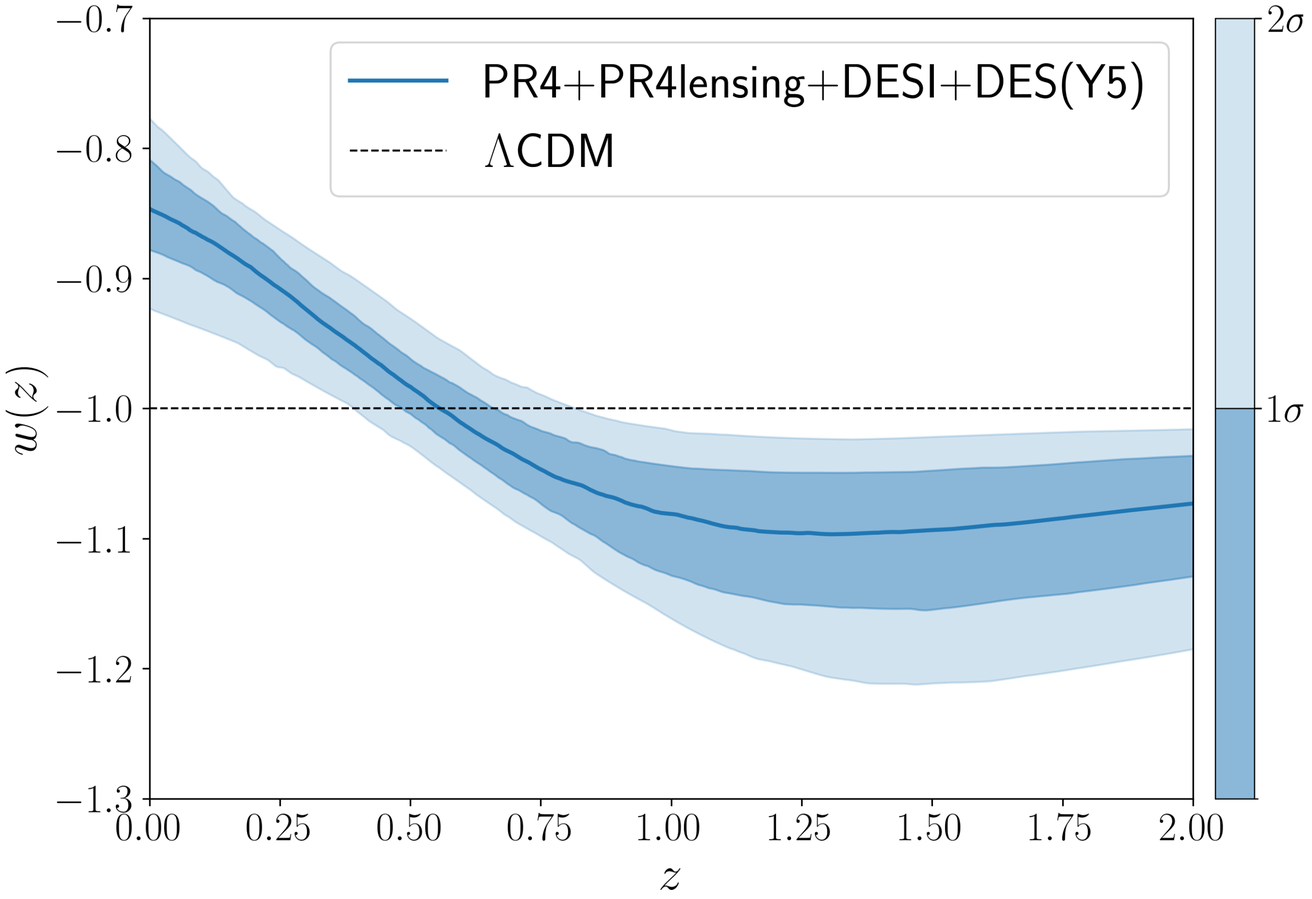
Using model-independent approaches to infer the signature of a dynamical dark energy



Cozzumbo+, 2024

NON-MINIMAL COUPLING TO GRAVITY

Crossing $w = -1$ without ghosts: the case for a non-minimal coupling



$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}F(\varphi)R + \frac{1}{2}K(\varphi)X - V(\varphi)\right]$$

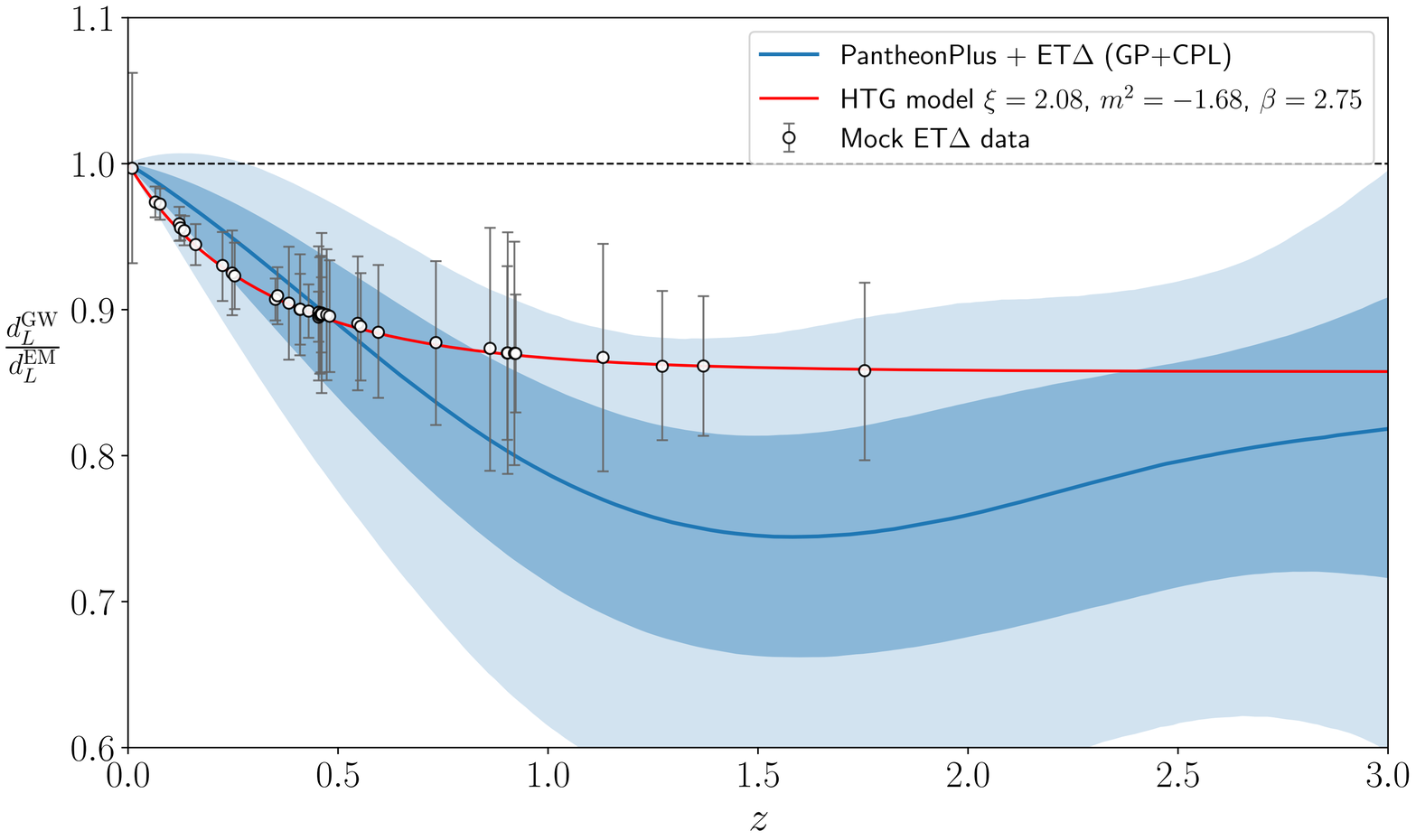
$$X = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi \qquad K(\varphi) = 1$$

$$F(\varphi) = 1 - \xi\varphi^2 \qquad V(\varphi) = V_0 + \beta\varphi + \frac{1}{2}m^2\varphi^2$$

Wolf+, 2025

NON-MINIMAL COUPLING TO GRAVITY

A distinct signature on GW propagation



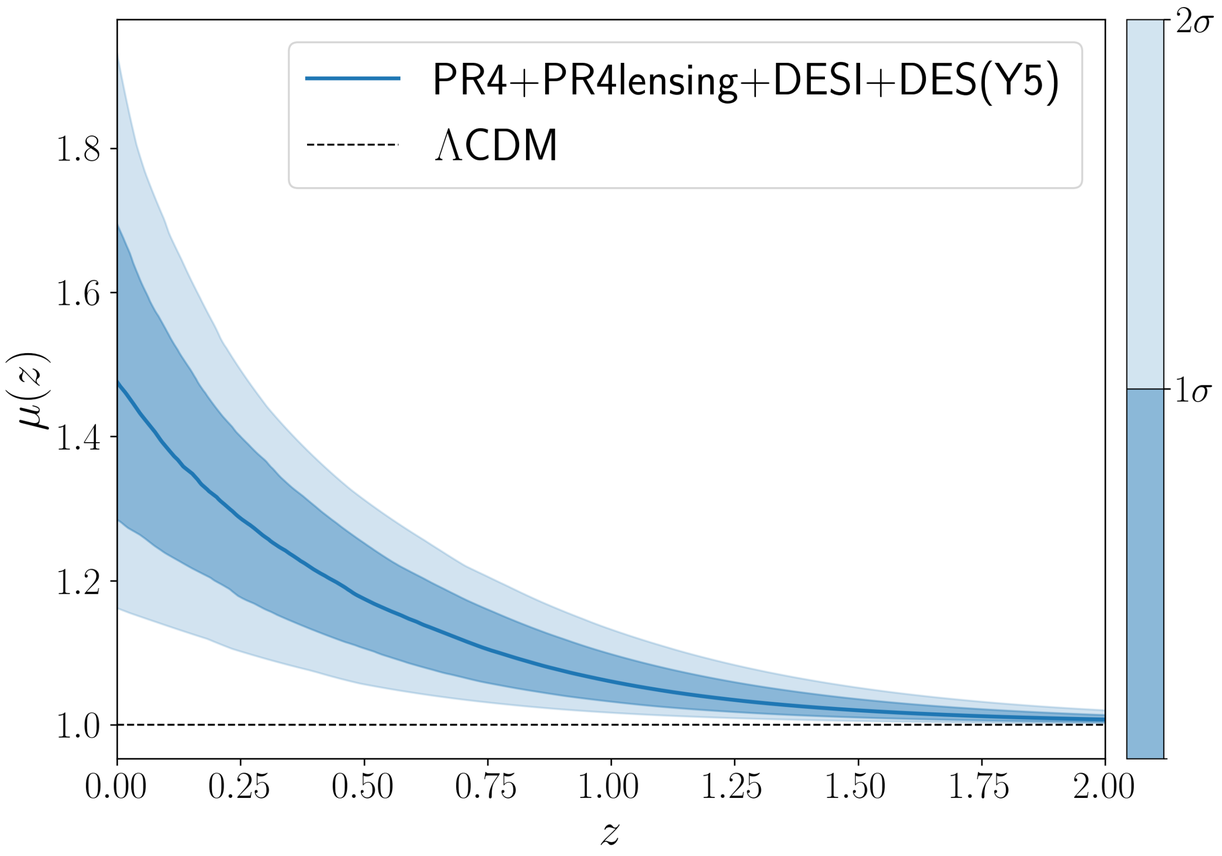
$$h_{ij}'' + 2\mathscr{H}\left[1+\alpha_M\right]h_{ij}' + k^2 h_{ij} = 0$$

$$\alpha_M = -\frac{d\ln M_*}{d\ln a} \qquad d_L^{\rm GW} = d_L^{\rm EM}\int_0^z \frac{\alpha_M(z')}{1+z'}dz'$$

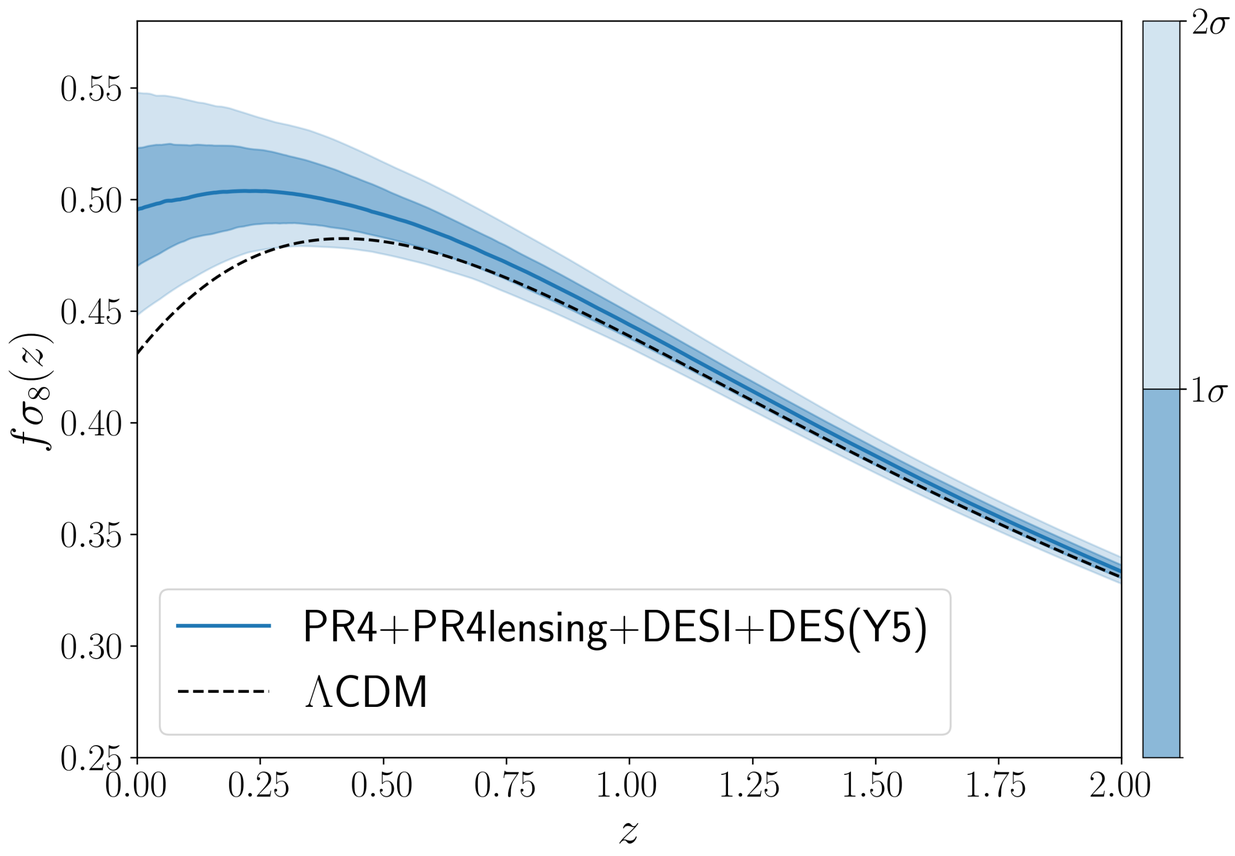
$$\frac{d_L^{\rm GW}(z)}{d_L^{\rm EM}(z)} = \frac{M_*(0)}{M_*(z)}$$

NON-MINIMAL COUPLING AND PERTURBATIONS

Late-time enhancement of the effective gravitational coupling - $\mu(z=0) = G_{\rm eff}/G \approx 1.5$

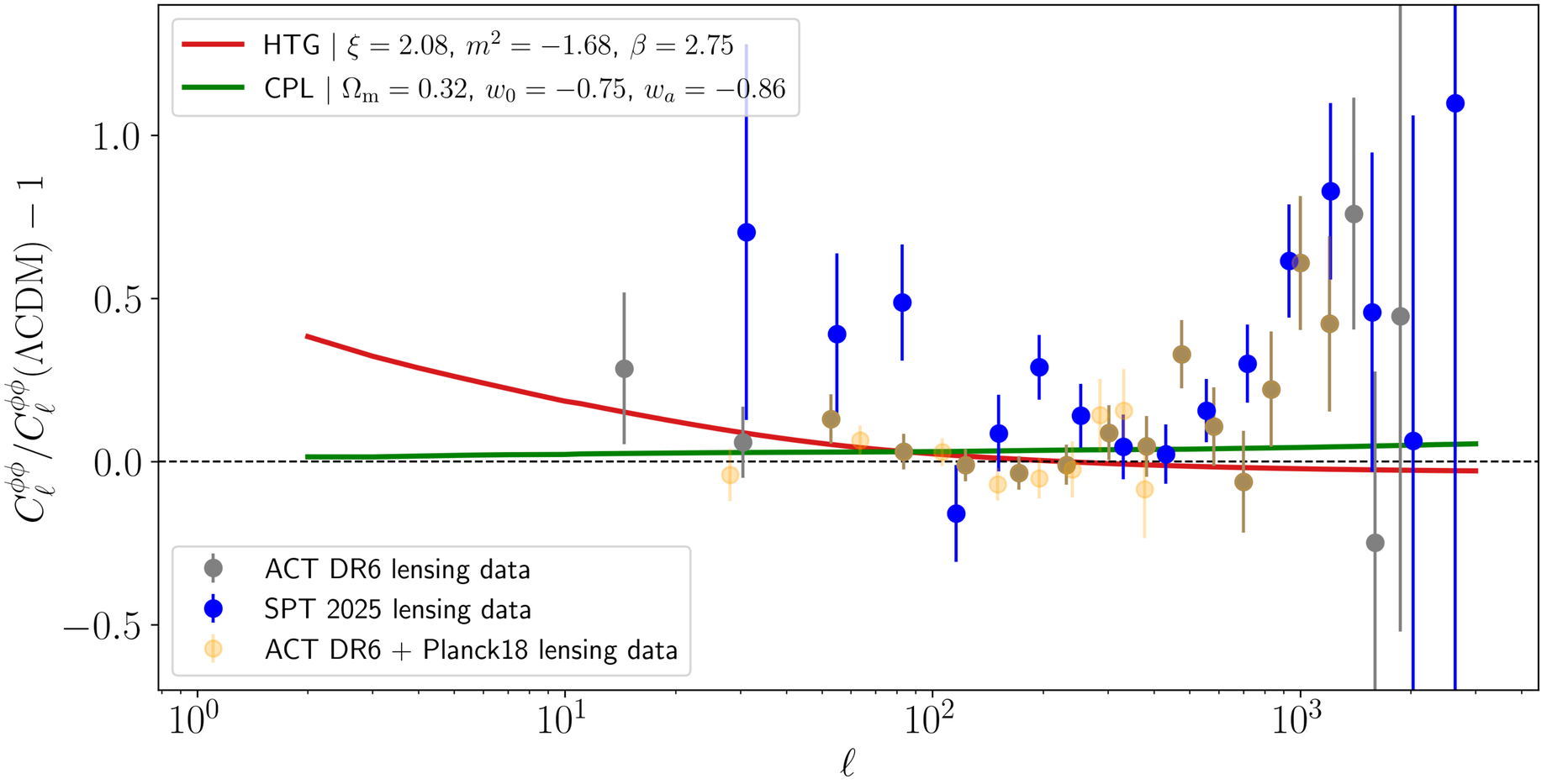


Boosted structure growth $f\sigma_8$ at $z \lesssim 0.5$



NON-MINIMAL COUPLING AND PERTURBATIONS

the $\xi\varphi^2$ coupling sources a genuine modification of lensing ($\Sigma \neq 1$), producing a low-ℓ enhancement inaccessible to background-only modifications.



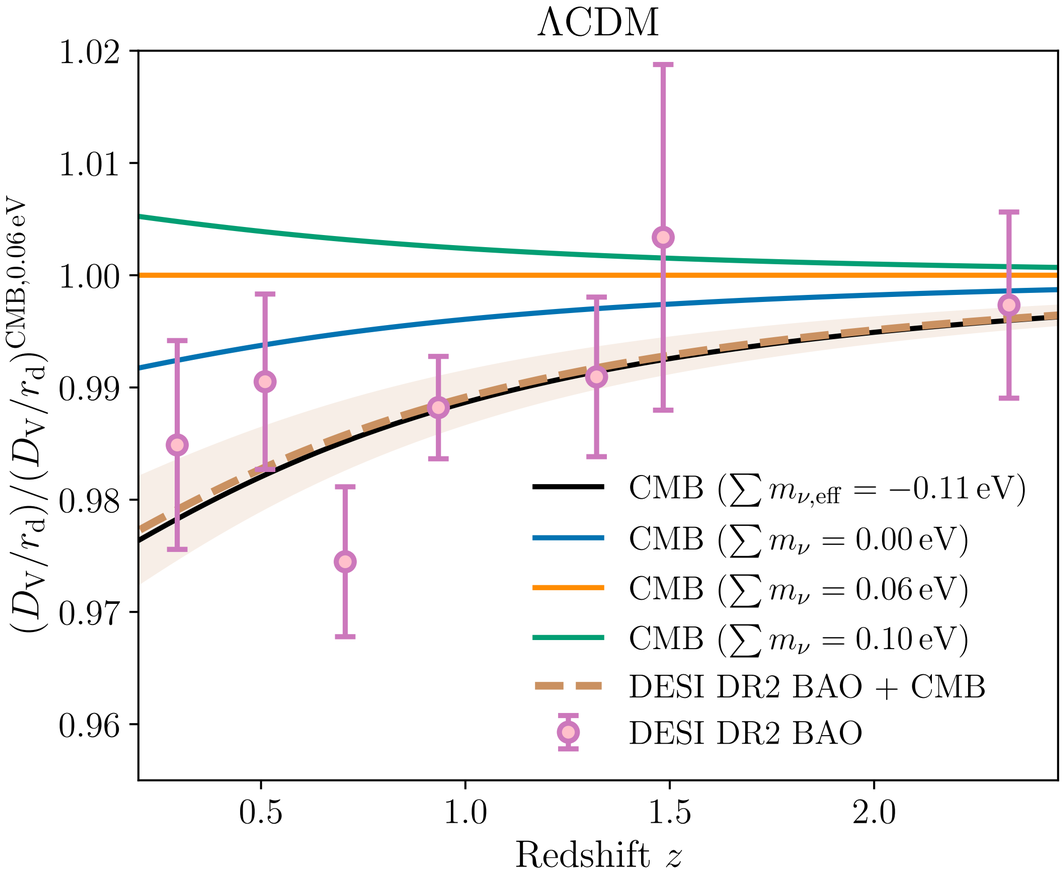
CONCLUSIONS

- The apparent negative neutrino mass can be interpreted as an anomaly in the lensing amplitudes ($A_{\rm lens}^{\rm TTTEEE}$, $A_{\rm lens}^{\phi\phi}$) reflecting a mismatch between early- (Planck TTTEEE) and late-time (ACT lensing, DESI BAO) data.

- Bright-siren measurements from next-generation GW observatories will directly probe the non-minimal coupling of a scalar degree of freedom.

- A multi-probe approach is the natural way forward: growth constrains μ, lensing constrains Σ, and standard sirens constrain $\alpha_{\rm M}$, three independent observational tests of a single underlying coupling

BACKUP



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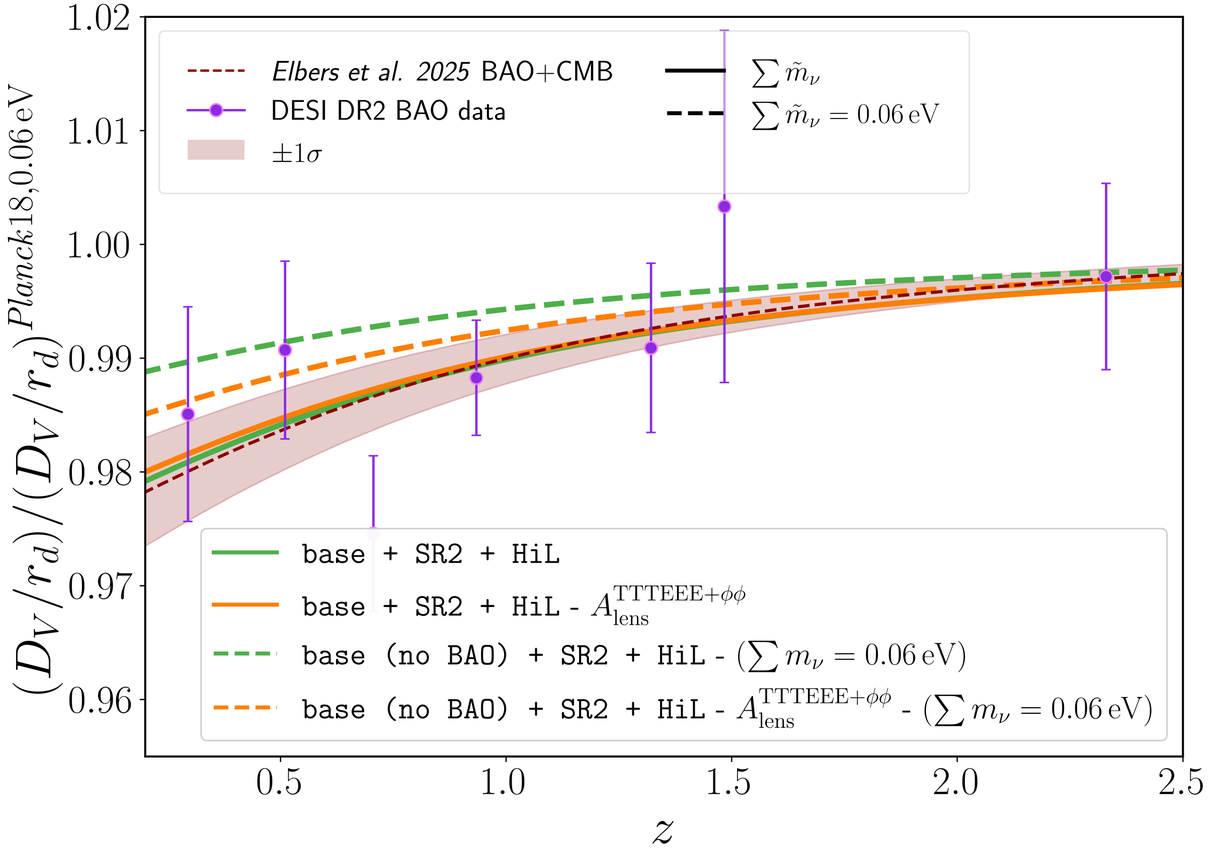
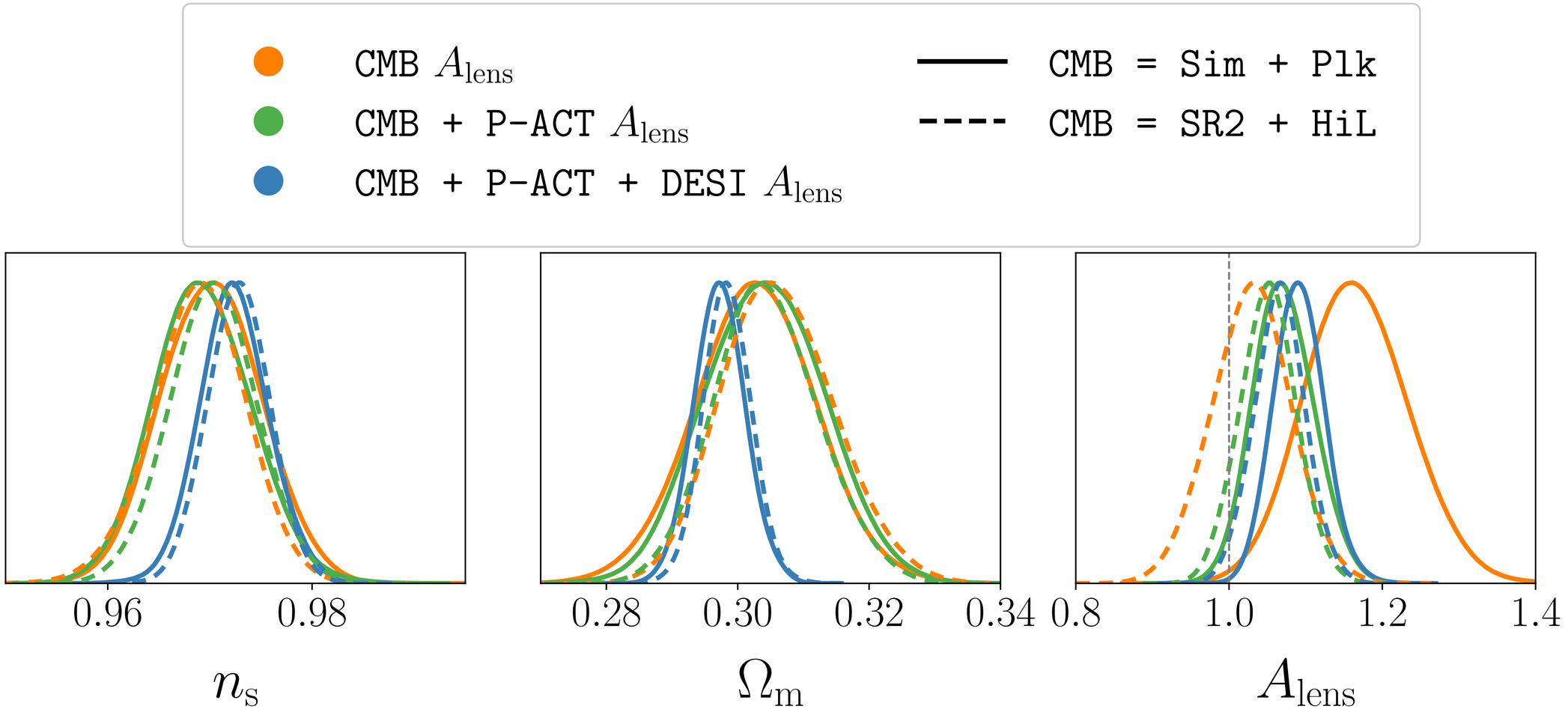
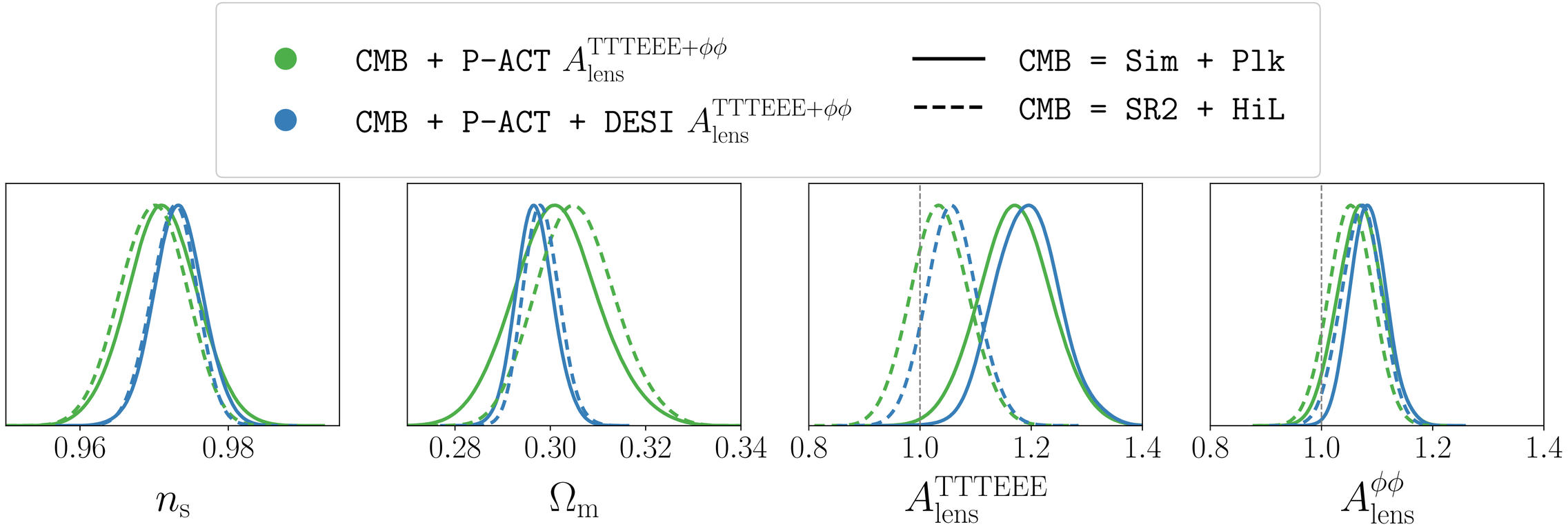


Cozzumbo+, 2025


CMB $A_{\rm lens}$
CMB + P-ACT $A_{\rm lens}$
CMB + P-ACT + DESI $A_{\rm lens}$
CMB = Sim + Plk
CMB = SR2 + HiL
0.96
0.98
$n_{\rm s}$
0.28
0.30
0.32
0.34
$\Omega_{\rm m}$
0.8
1.0
1.2
1.4
$A_{\rm lens}$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