MODIFIED GRAVITY & FRIENDS:

MASSIVE NEUTRINOS AND Ω_K

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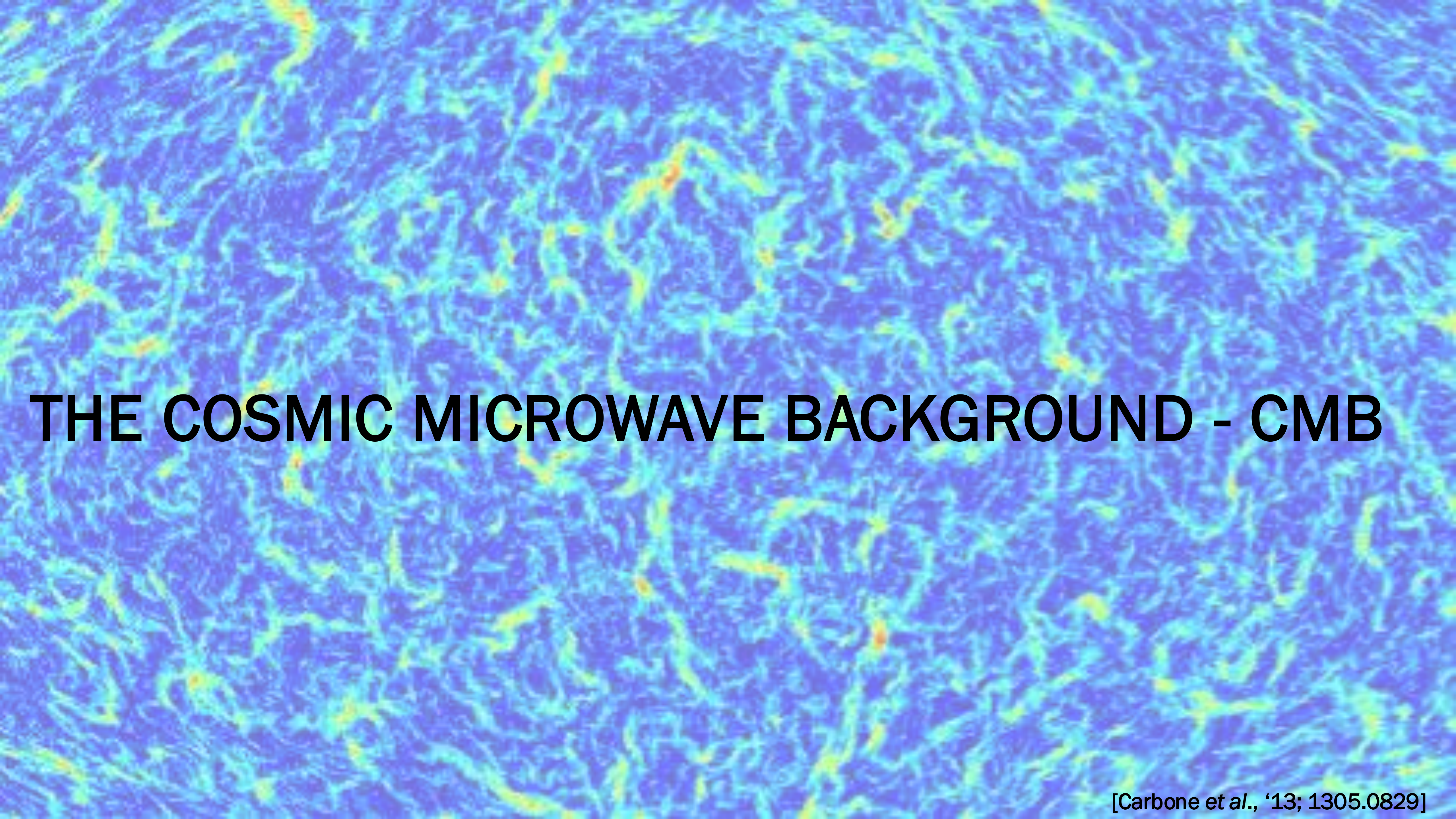
What is this talk about?

- The *lensing anomaly*: a problem between ΛCDM and the bending of primordial light.

- We re-interpret it by:

  1. Modifying the standard growth of structures.
  2. Letting the total neutrino mass free to roam.
  3. Allowing the universe to ‘curve’ freely.

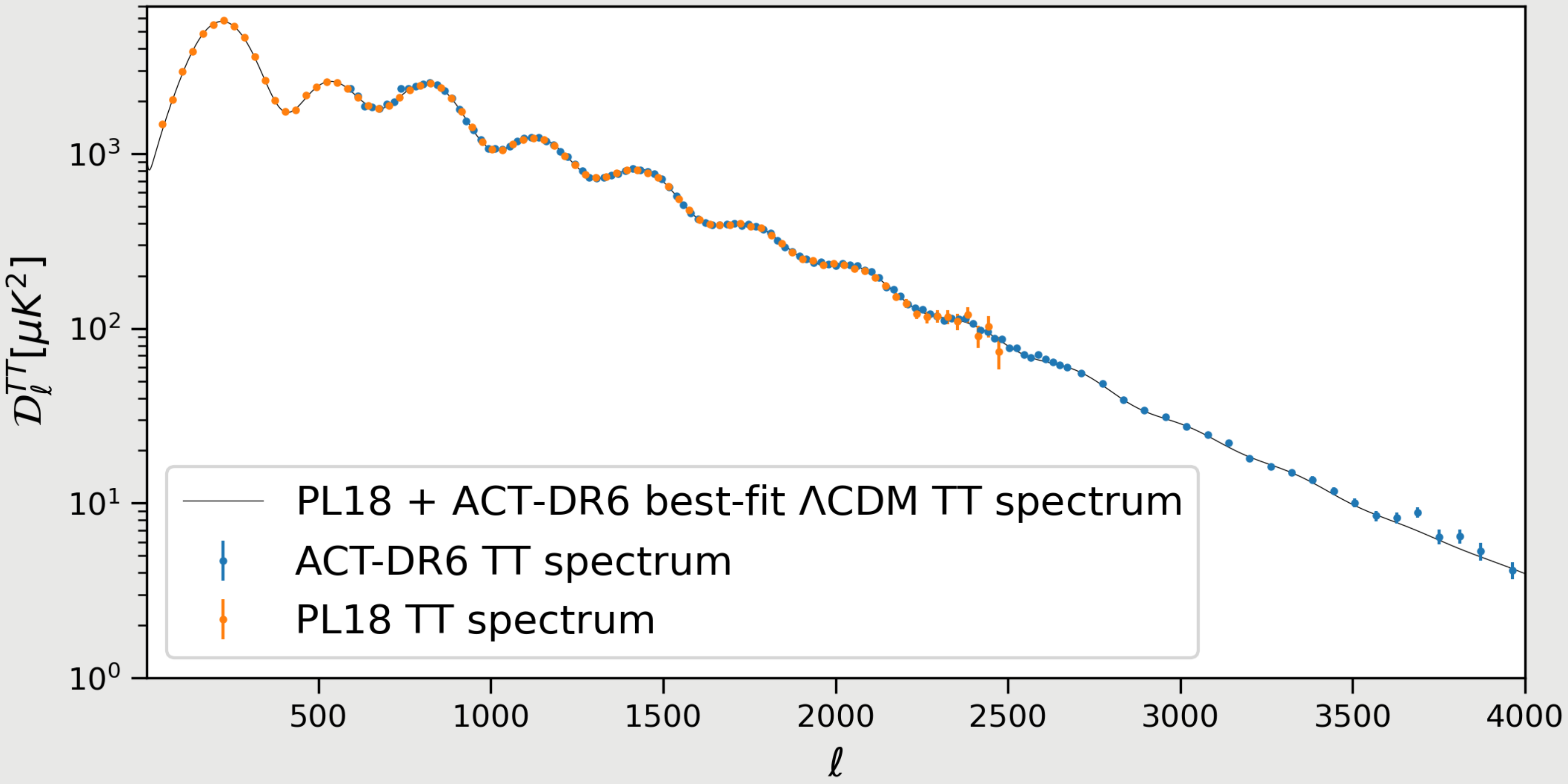
THE COSMIC MICROWAVE BACKGROUND - CMB



[Carbone *et al.*, ‘13; 1305.0829]

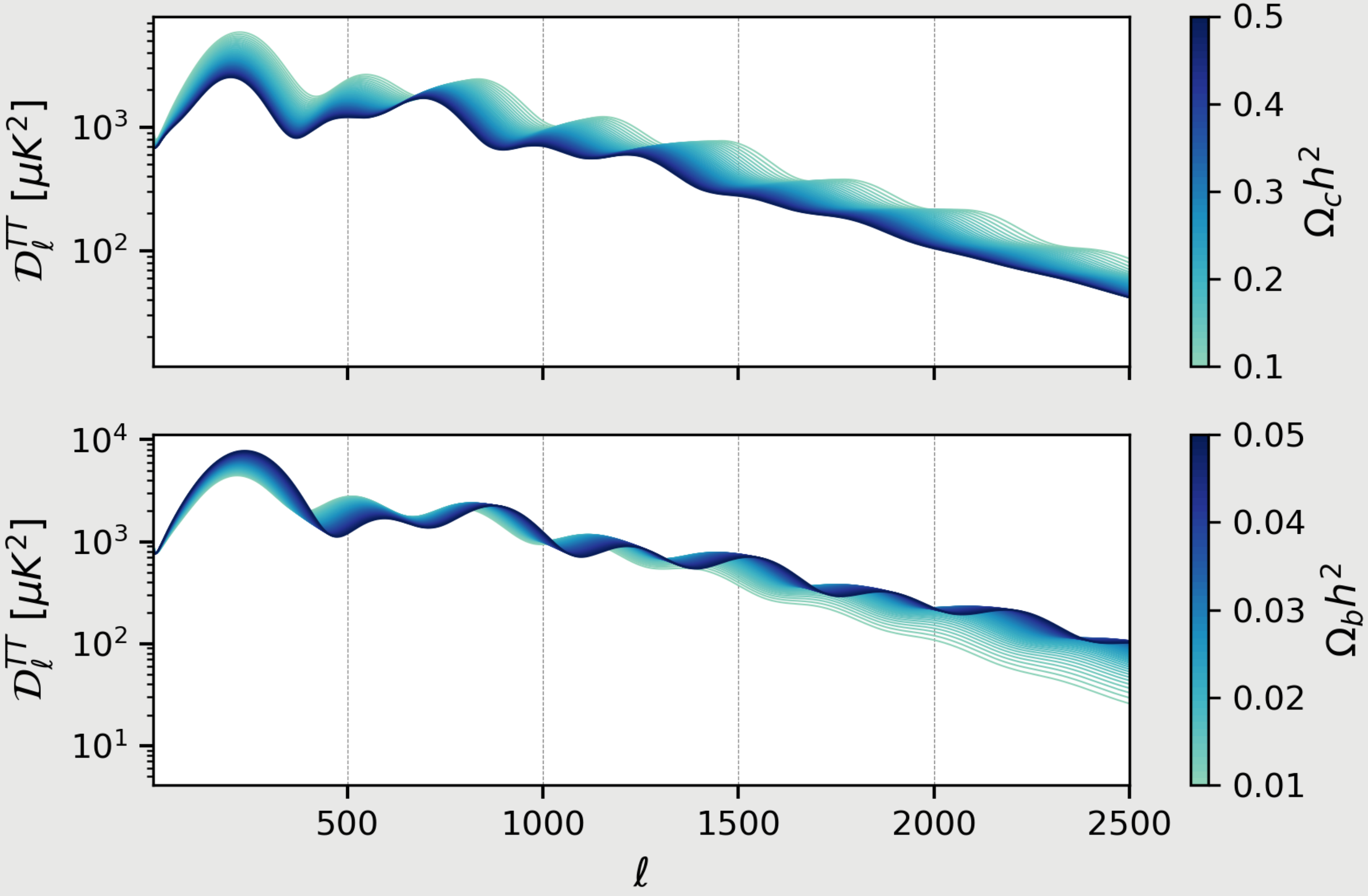
The CMB in ΛCDM

- $\mathcal{D}_\ell^{TT} = \ell(\ell+1)\mathcal{C}_\ell^{TT}/(2\pi)$, where $\mathcal{C}_\ell^{TT}$ is the temperature spectrum of the CMB.
- The close match between theory and data exemplifies the success of ΛCDM.
- We can use these measurements to do cosmology: change ΛCDM and see!



[Thibaut *et al.*, '25; 2503.14452]

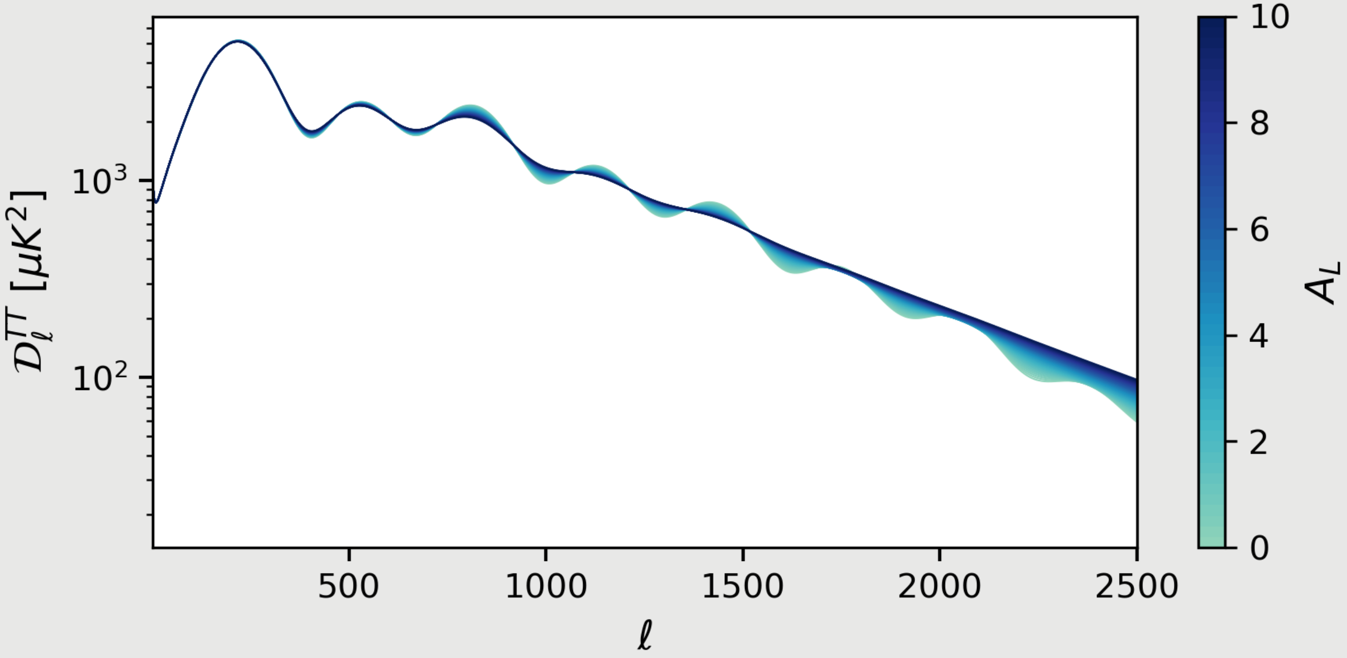
The CMB in ΛCDM

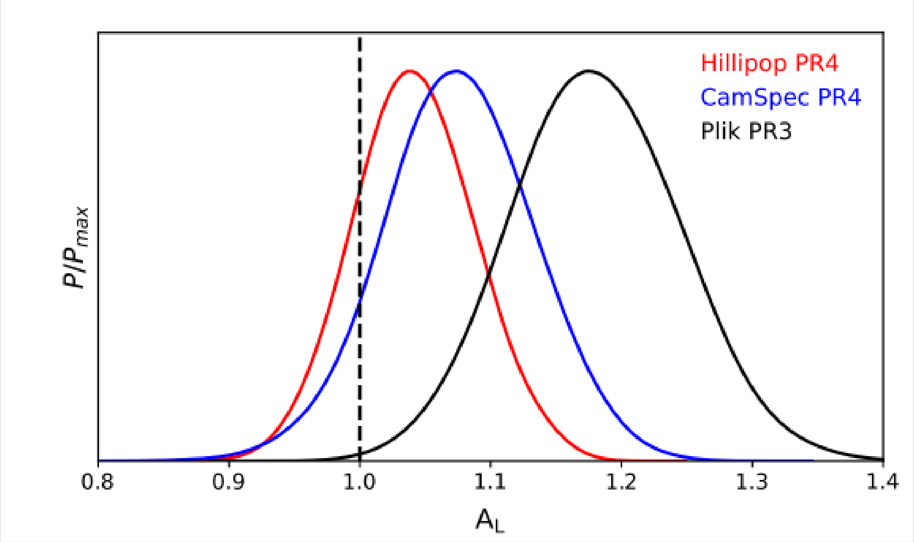


- The CMB is sensitive to the ΛCDM parameters like the baryon ($\Omega_b h^2$) or the CDM ($\Omega_c h^2$) densities.
- The variations shown here are much larger than what the PL18+ACT DR6 error bars allow.
- This explains the sub-percent precision of the CMB constraints.

A CMB problem: the lensing anomaly

- Lensing consistency check: introduce the lensing parameter A_L as $\mathcal{D}_\ell^{\phi\phi} \equiv A_L \mathcal{D}_\ell^{\phi\phi}$.
- Is $A_L = 1$, as expected within ΛCDM? Not according to Planck [Aghanim *et al.*, 2018; 1807.06209].





[M. Tristram *et al.*, '23; 2309.10034]

- Another possible resolution: consider a beyond-ΛCDM scenario.

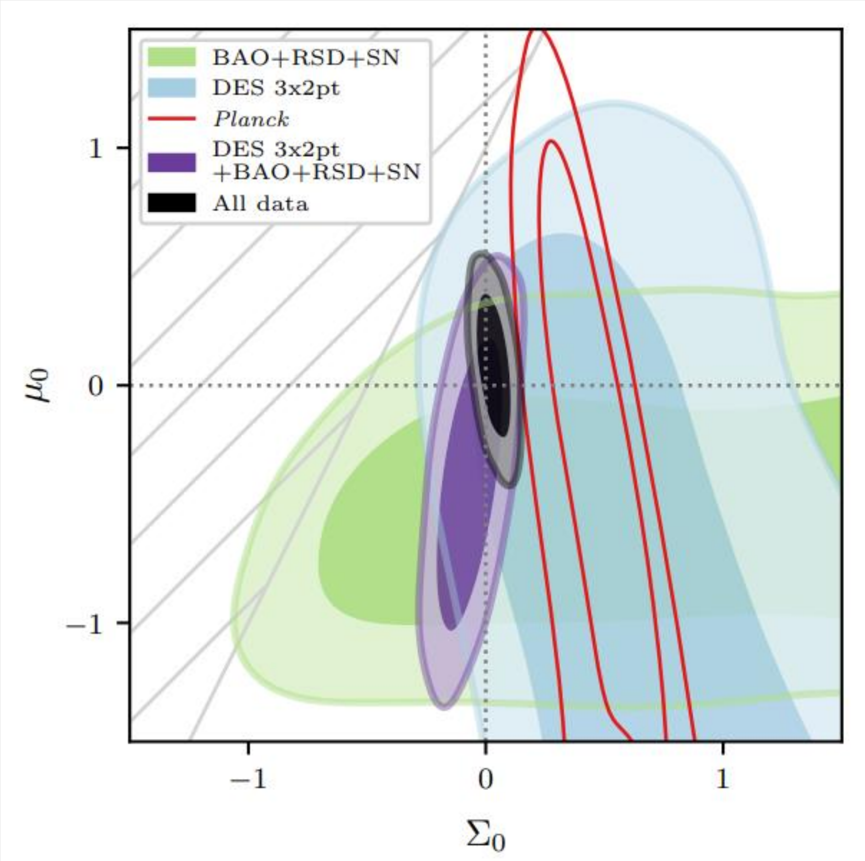
MODIFIED GRAVITY

[E. Schaan and S. Ferraro/Berkeley Lab]

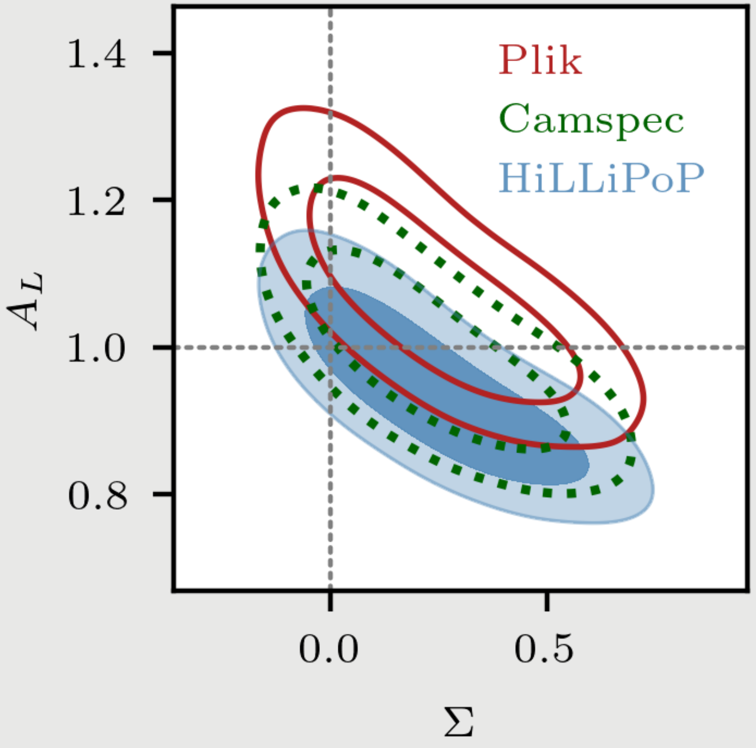
Recasting A_L into Σ

- Take the following modification to the lensing equation: $k^2(\Psi + \Phi) = -8\pi G a^2(\mathbf{\Sigma} + \mathbf{1})\rho_m \delta_m$.

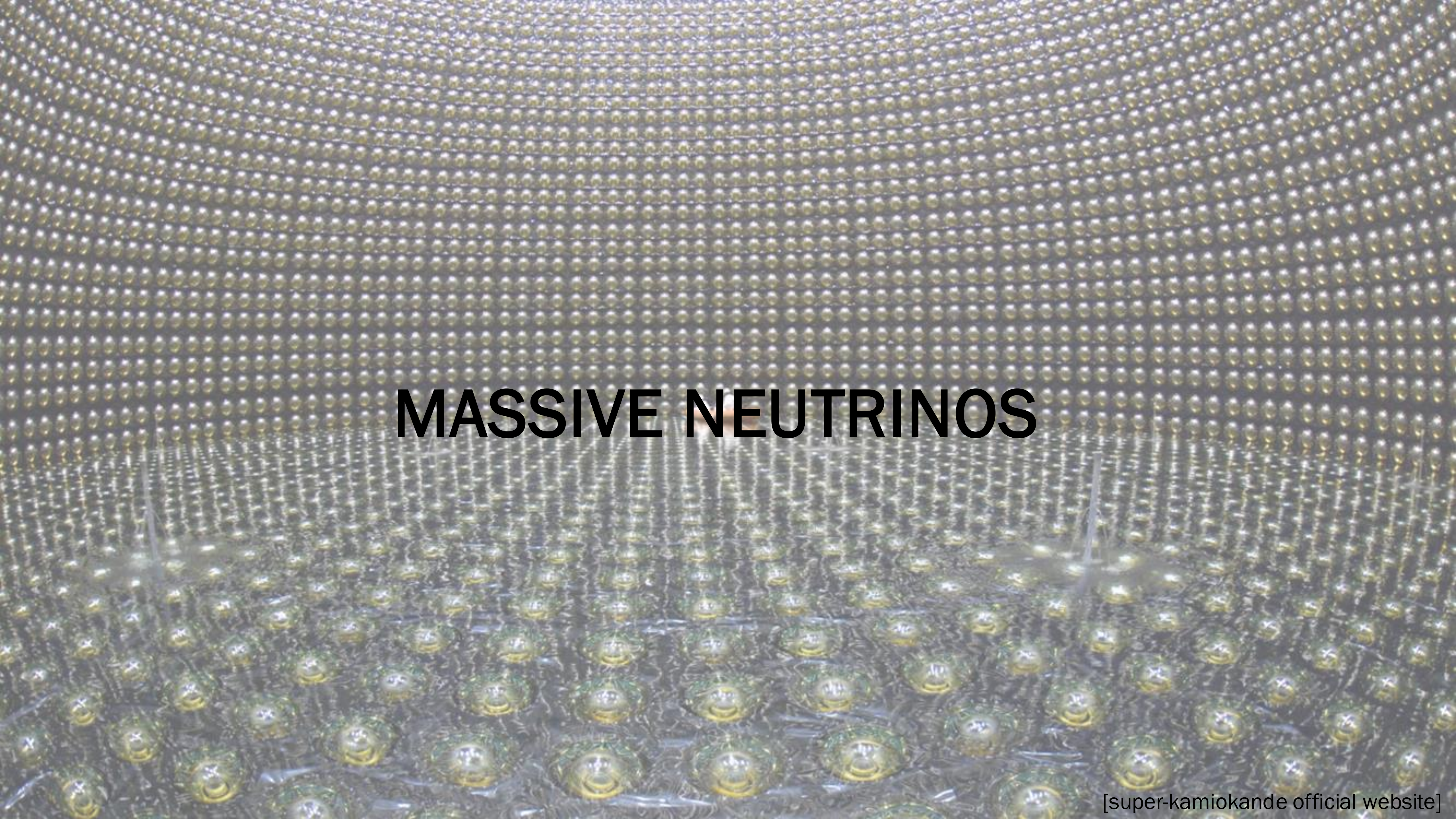
[Abbott *et al*., '22; 2207.05766]



[ES, Giarè, Di Valentino, '24; 2411.03896]



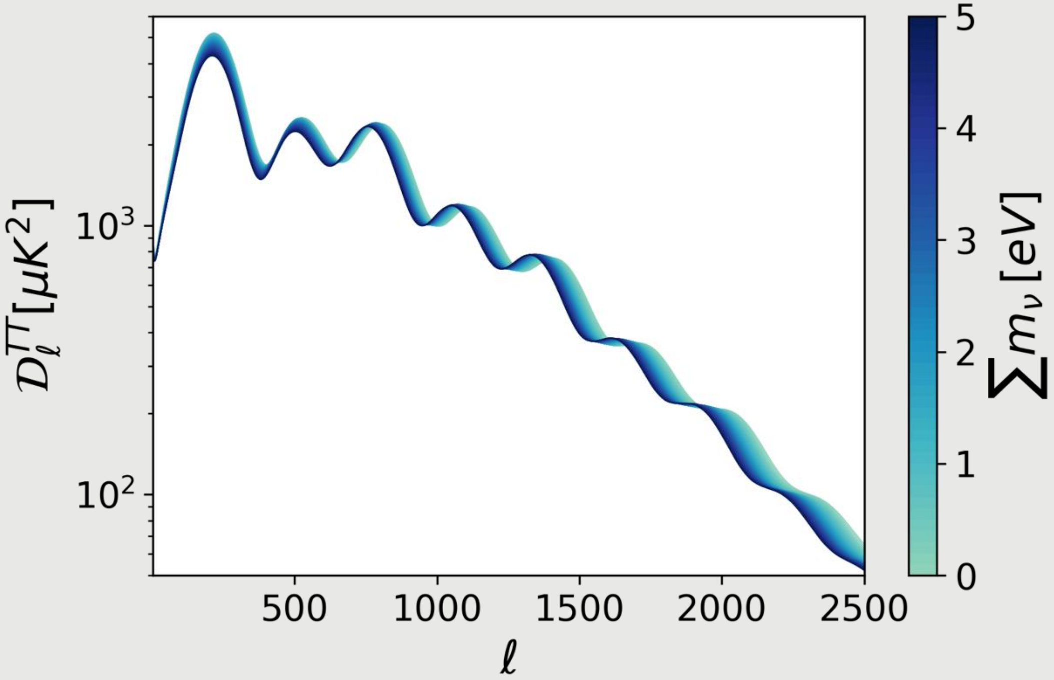
MASSIVE NEUTRINOS

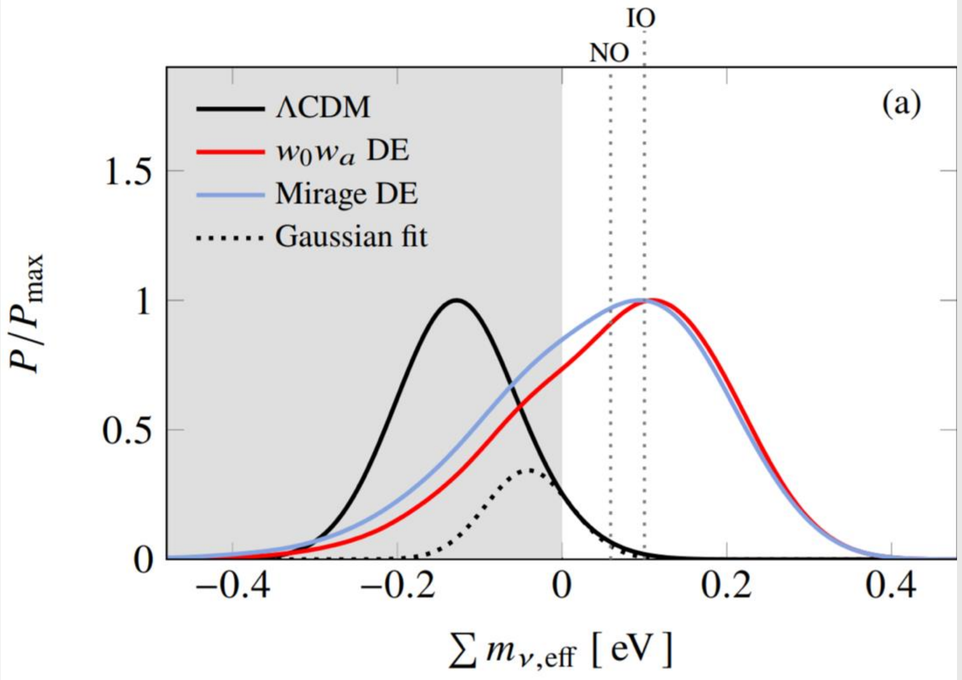


[super-kamiokande official website]

Growth suppression induced by $\Sigma m_\nu > 0$ eV

- We now compare the growth suppression induced by $\Sigma m_\nu \neq 0$ eV against modified gravity described by γ.
- Can a modification by γ relax DESI's constraint on Σm_ν?





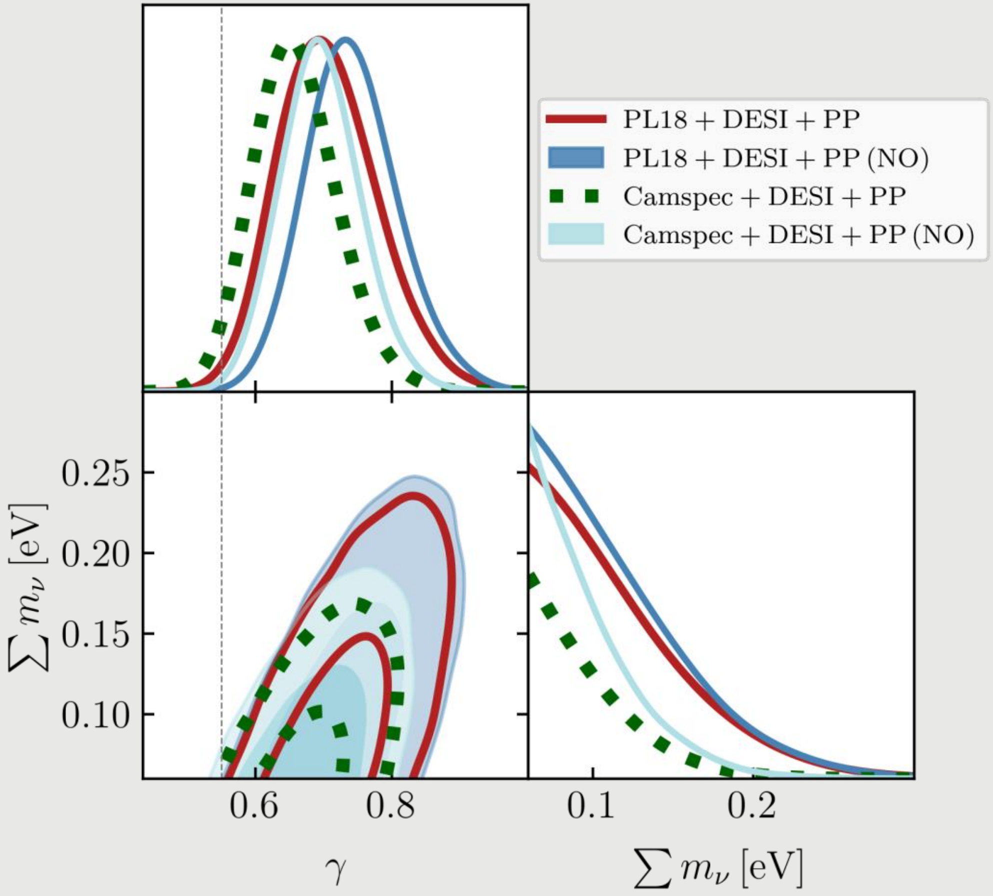
[2407.10965]

DESI DR2 + PR4 (Camspec) + PR4 lensing + Pantheon+	$\boldsymbol{\Sigma m_\nu < 0.0295}$ **eV** [Giarè, Mena, **ES**, Di Valentino, '25; 2507.01848]

Relaxing DESI's Σm_ν constraints (kind of)

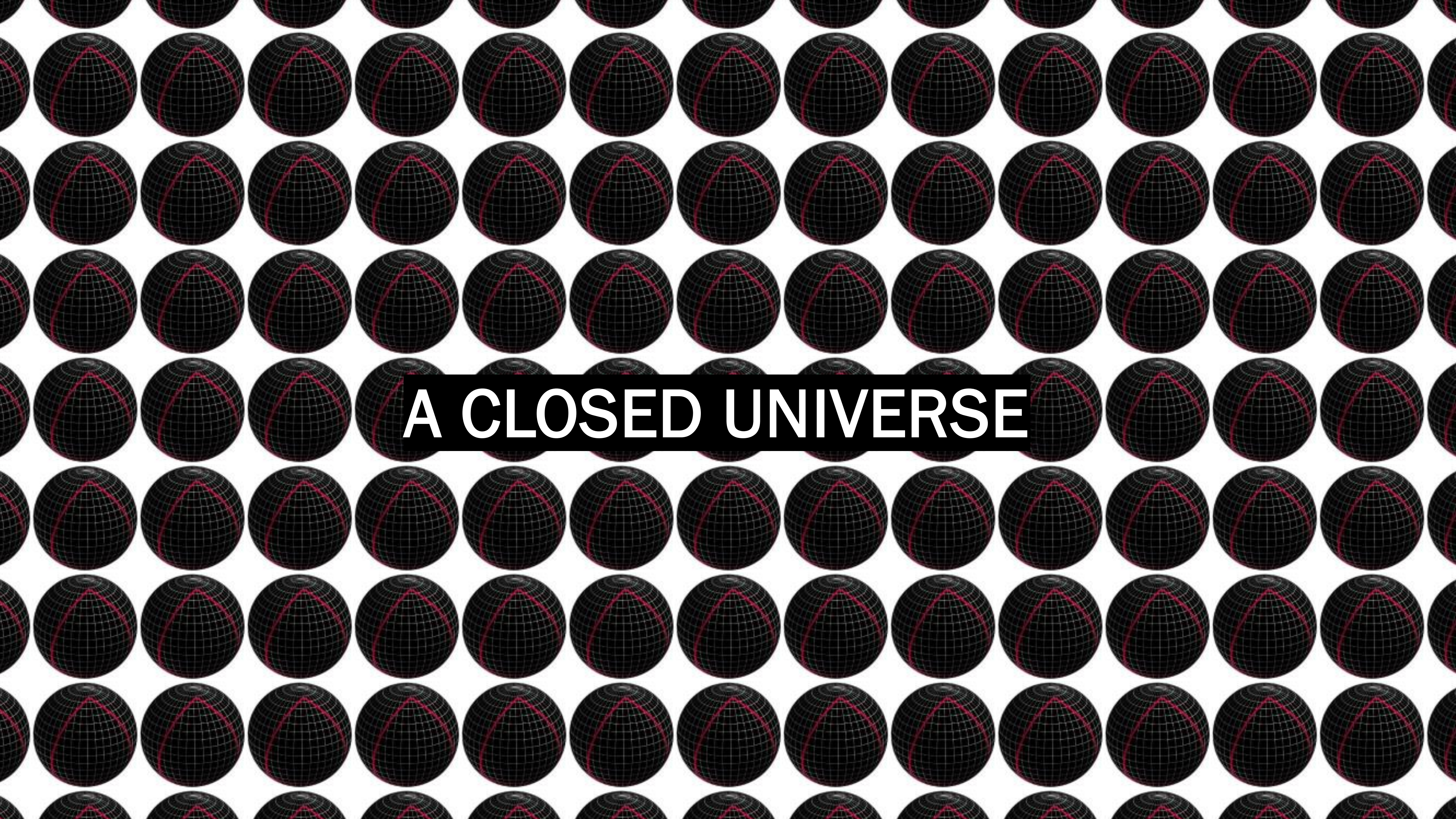
- 'NO' is the case enforcing $\Sigma m_\nu > 0.06$ eV.

[Giarè, Mena, **ES**, Di Valentino, '25; 2507.01848]



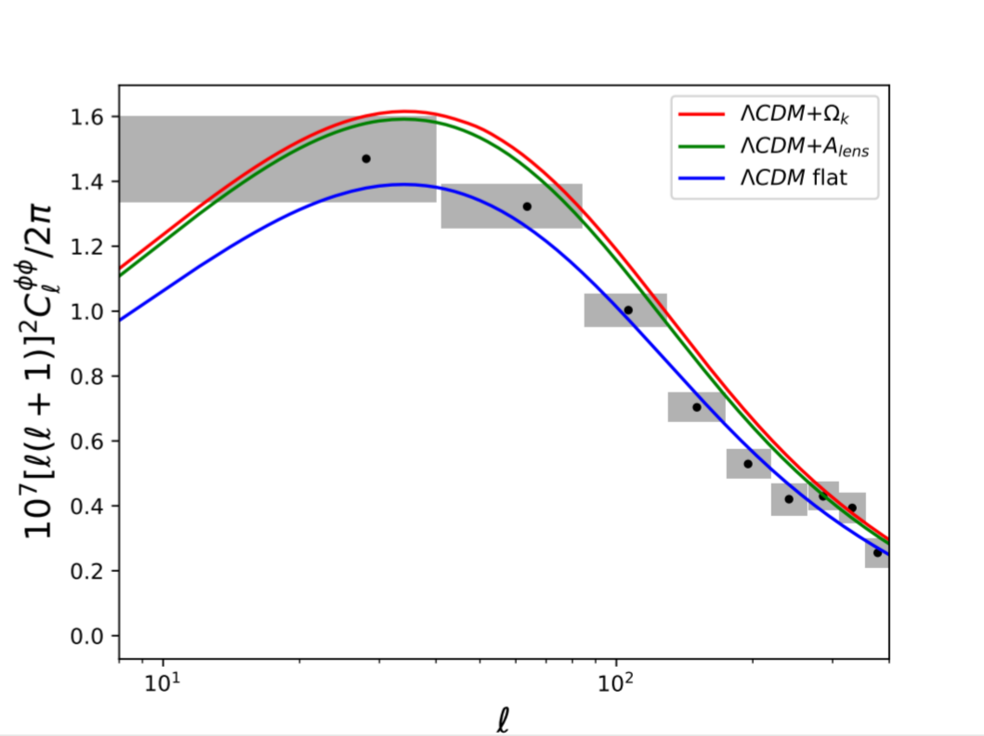
	PL18+ lensing+ DESI+ PP	Camspec+ lensing+ DESI+ PP
$\boldsymbol{\Sigma m_\nu}$ **[eV]**	< 0.0985	< 0.0666
$\boldsymbol{\gamma}$	$0.707^{+0.064}_{-0.083}$	$0.660^{+0.055}_{-0.068}$

[Giarè, Mena, **ES**, Di Valentino, '25; 2507.01848]

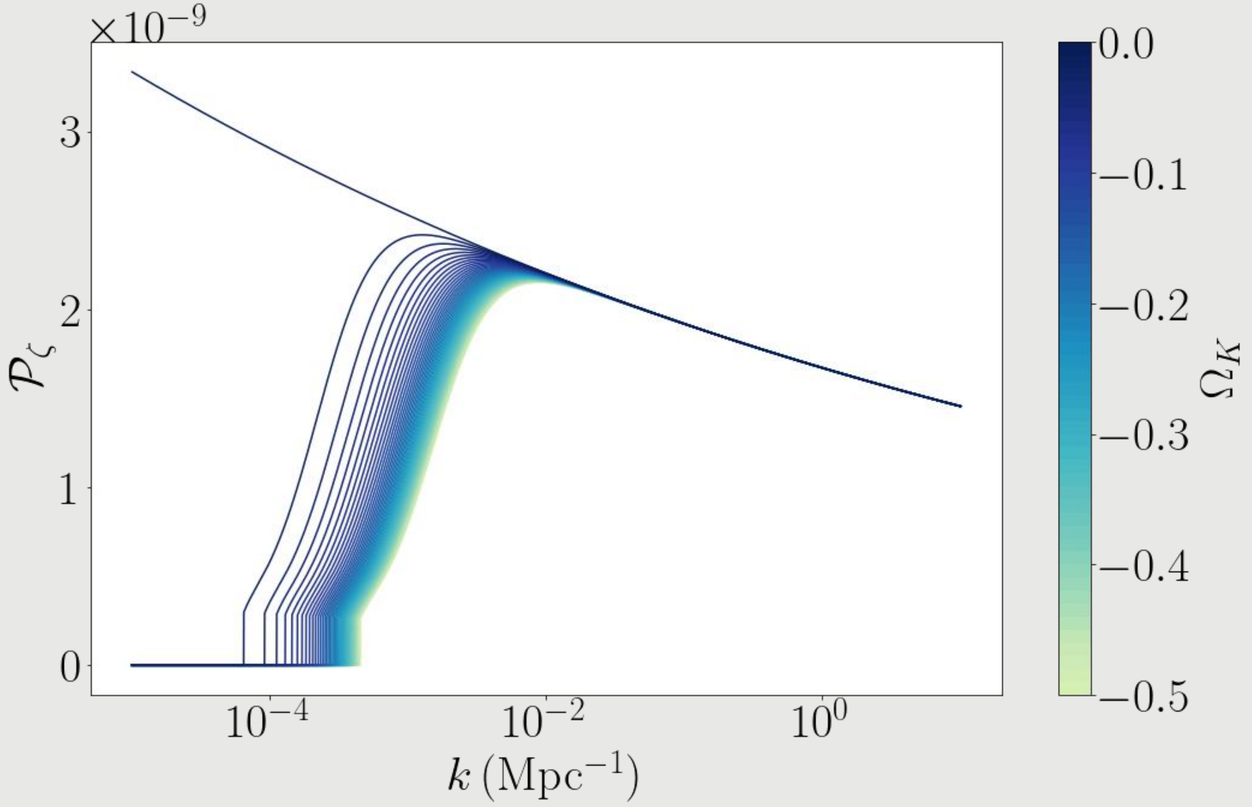

A CLOSED UNIVERSE

Primordial perturbations suppression by $\Omega_{\mathrm{K}} < 0$

- By assuming $P_\zeta \propto \frac{(k^2-4\mathrm{K})}{k(k^2-\mathrm{K})} k^{n_s-1}$, Planck's 2018 data show mild evidence for $\Omega_{\mathrm{K}} < 0$.
- Does this still hold if P_ζ is calculated for $\mathrm{K} = 1$ explicitely [Vardanyan & Kiefer, '23; 2302.07001]?



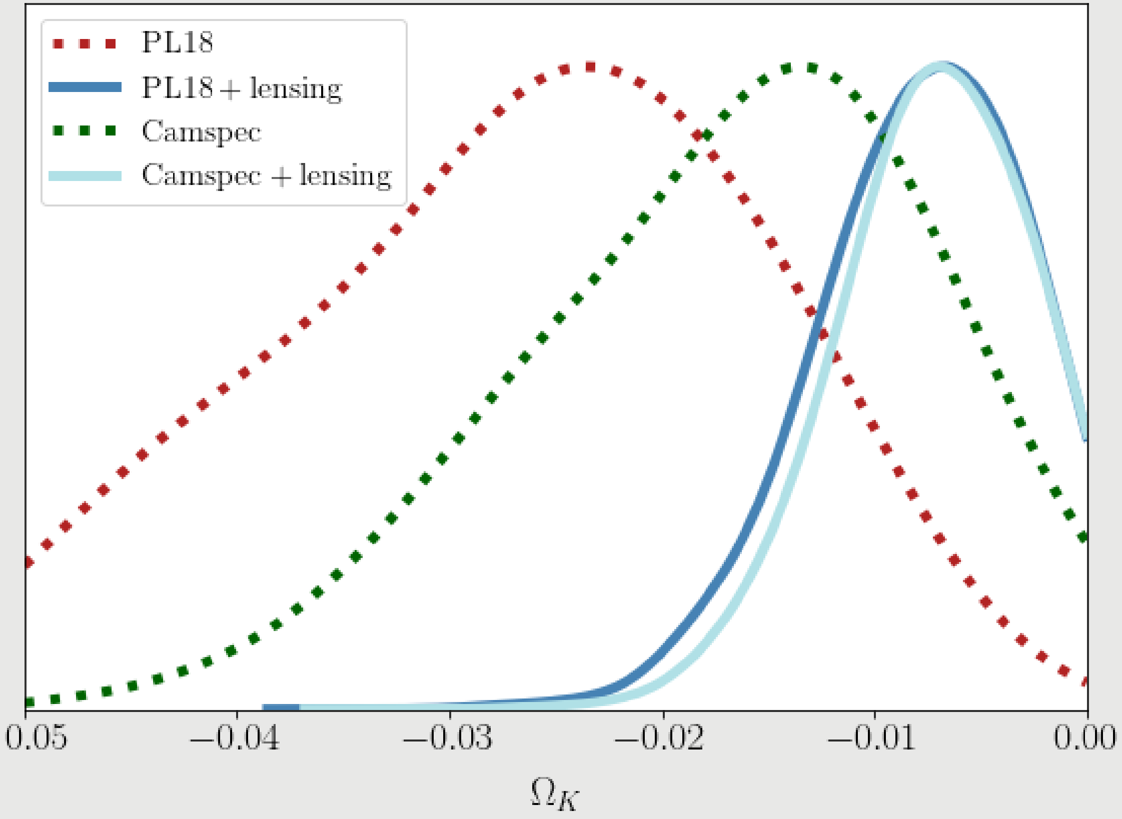
[Di Valentino, Melchiorri & Silk, '19; 1911.02087]



Consistency with $\Omega_K = 0$

- We looked for evidence of P_ζ suppression in the data.

	PL18	PL18+lensing
$\mathbf{\Omega_K}$ (our model)	$-0.026^{+0.013}_{-0.010}$	$-0.0083^{+0.0062}_{-0.0035}$
$\mathbf{\Omega_K}$ (Planck)	< -0.0304	$-0.0107^{+0.0070}_{-0.0047}$



[Giarè, **ES**, Vardanyan & Di Valentino, '25; 2509.26263]

Conclusions

- We considered a series of extensions of the ΛCDM model, connected through their impact on the CMB power spectrum and the growth of large-scale structure.
- While solving the A_L anomaly, Planck's PR4 data also show consistency with general relativity.
- The Σm_ν constraint by DESI can be slightly relaxed by introducing the growth index γ in the evolution of δ_m.
- Even when the inflationary spectrum changes w.r.t. ΛCDM, we find consistency with $\Omega_\mathrm{K} = 0$.

THANK YOU ☺

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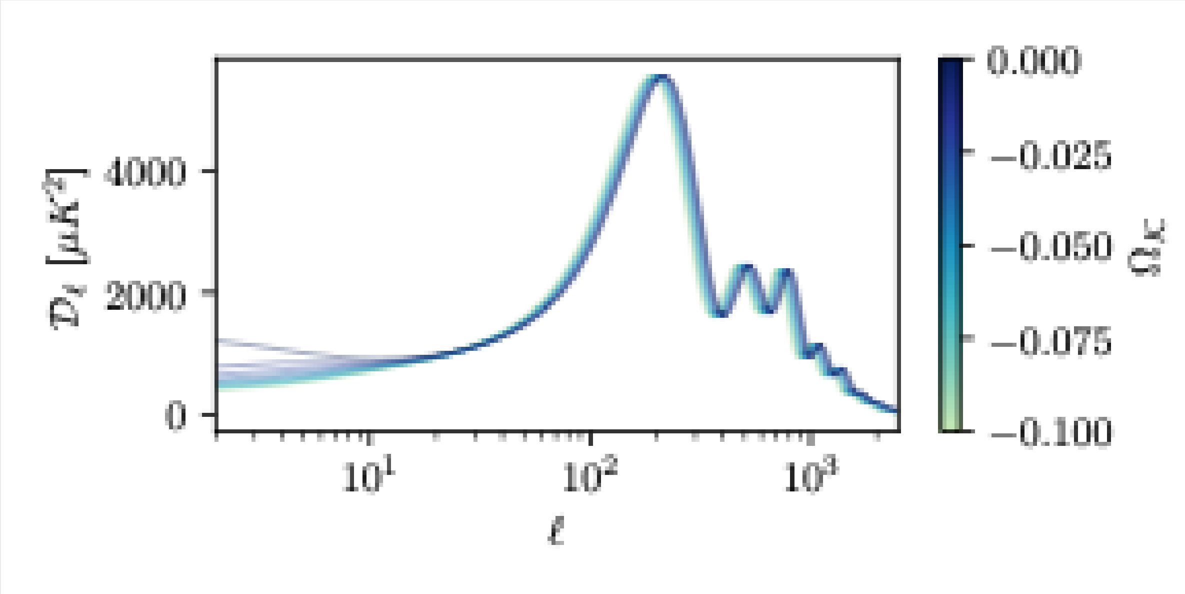
CASE 1 [Amendola, Kunz & Sapone, ‘07; 0704.2421]	CASE 2 [Linder, ‘02; astro-ph/0208512]
Change the Poisson equation: $k^2\Psi = -4\pi G a^2(\boldsymbol{\mu}+\mathbf{1})\rho_m\delta_m$ Change the lensing equation: $k^2(\Psi + \Phi) = -8\pi G a^2(\boldsymbol{\Sigma}+\mathbf{1})\rho_m\delta_m$	Change δ_m itself: $\delta_m \sim \exp\left(-\int_a^1 da' \frac{\Omega_m^{\gamma}}{a'}\right)$

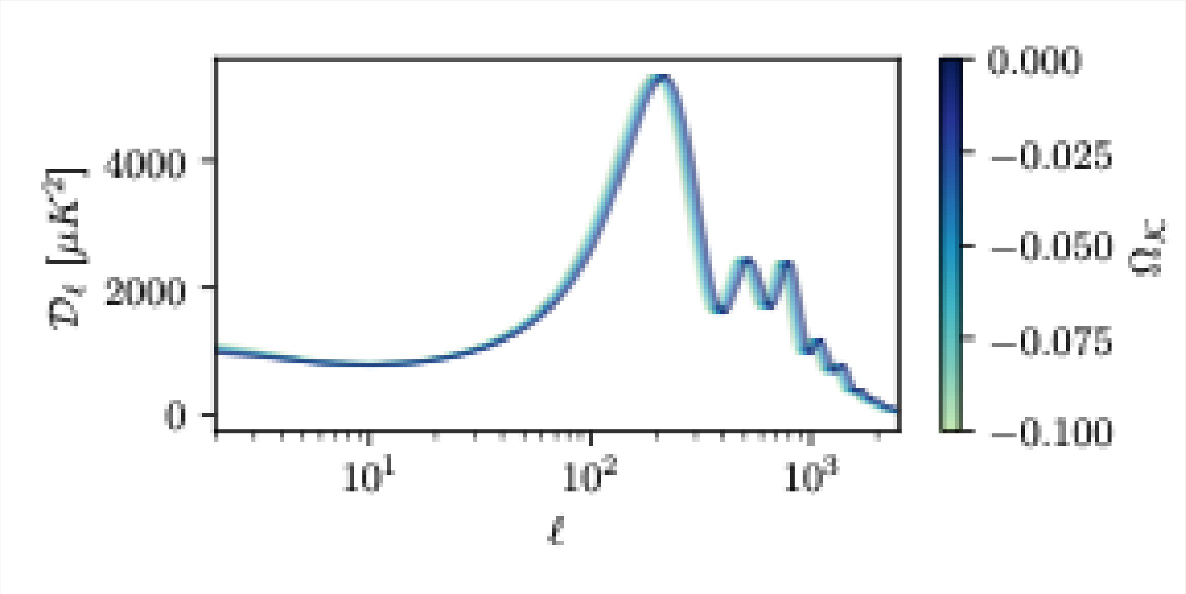
- Primordial spectrum of [Vardanyan & Kiefer, '23; 2302.07001].
- δ, ϵ are the slow roll parameters.
- $n^2 = \mathrm{k}^2 + \mathrm{K}$.

$$\Phi(n,\epsilon,\delta)\big|_{n=aH} = \frac{\varepsilon}{\left(\varepsilon + \frac{\mathcal{K}}{n^2}\right)} \left(1 - \frac{\mathcal{K}}{n^2}\right) \left[1 + \frac{\mathcal{K}}{n^2 - 4\mathcal{K}} \left(\varepsilon + \frac{\mathcal{K}}{n^2}\right)\right] (f(n))^{-2\gamma-3} \Bigg|_{n=aH} \qquad (4.7)$$

$$f(n) := \lim_{\varepsilon \to 0} f_\varepsilon(n) = \sqrt{1 - \frac{\mathcal{K}}{n^2} - \frac{\mathcal{K}}{n^2 - 4\mathcal{K}} \left(2 - \frac{\mathcal{K}}{n^2} - \frac{9\mathcal{K}}{n^2 - 4\mathcal{K}} \left(1 - \frac{\mathcal{K}}{n^2}\right)\right)}, \qquad (2.1)$$



Modified Ω_K model



ΛCDM+Ω_K