MODIFIED GRAVITY & FRIENDS:

MASSIVE NEUTRINOS AND Ω_K

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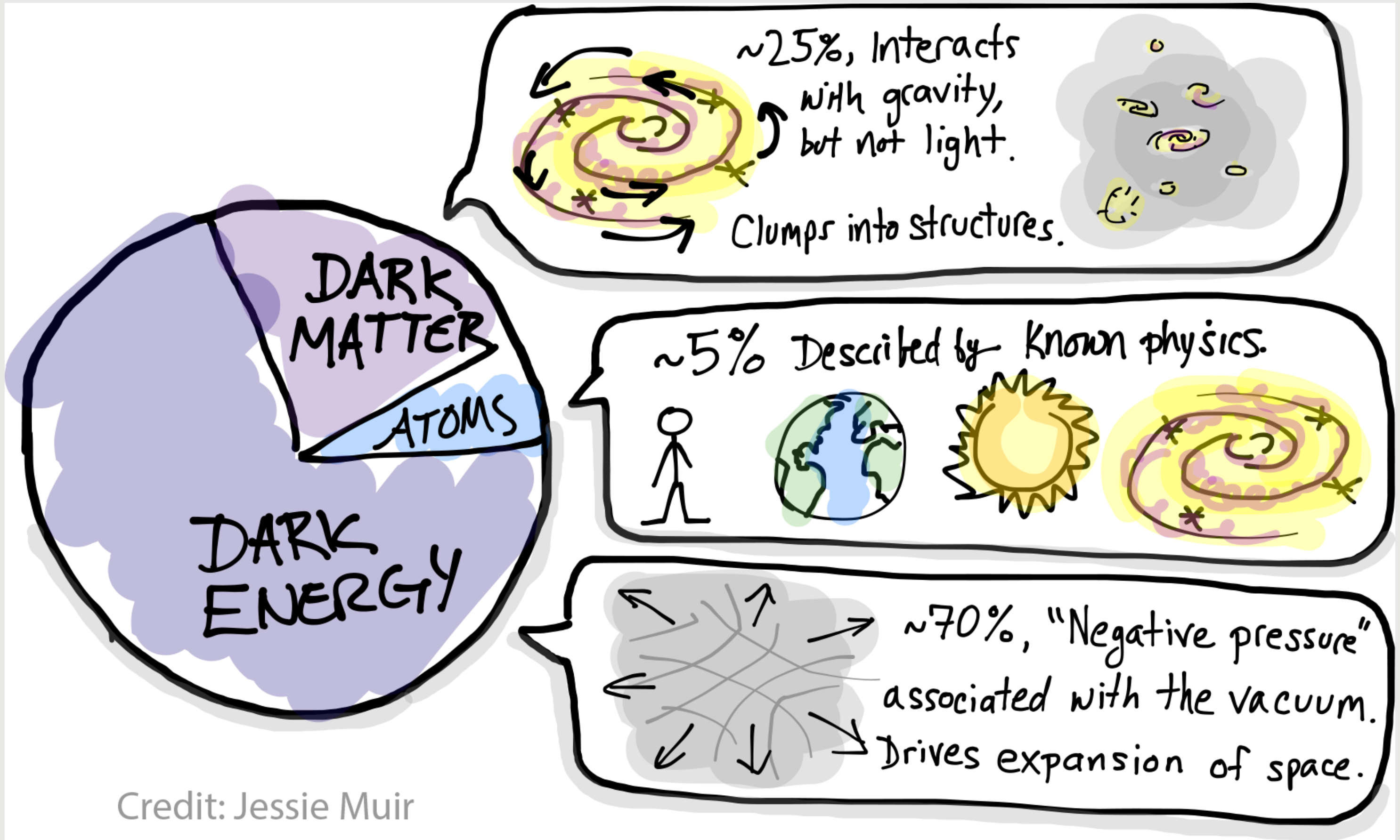
What is this talk about?

- A quick overview of the standard theory: the ΛCDM model.
- 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.

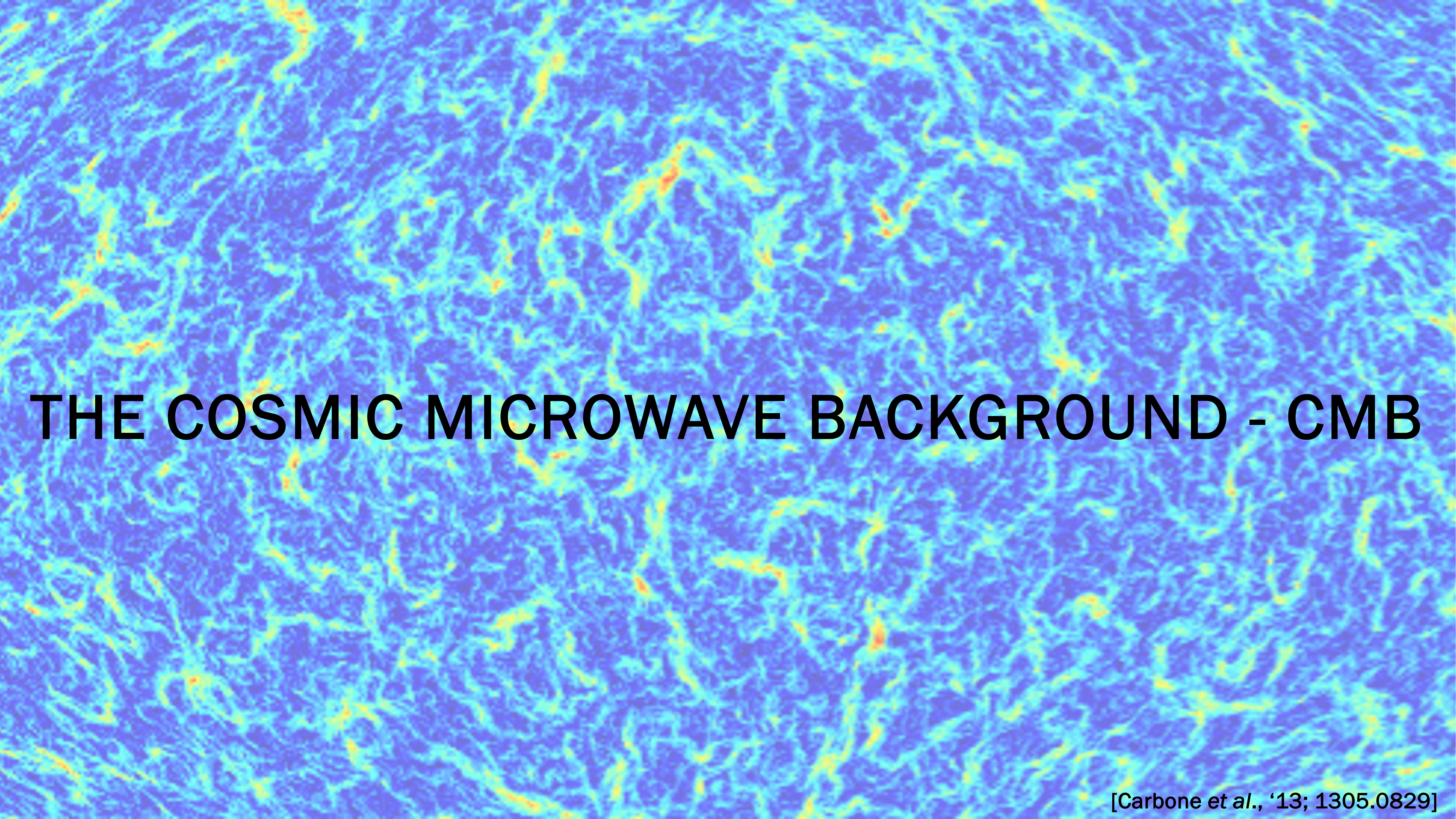
ΛCDM, the standard model



A few honourable mentions

- **Inflation:** the original seeds of these 'structures'.
- **Radiation:** negligible to the overall dynamics of the current universe, but so useful to test ΛCDM!

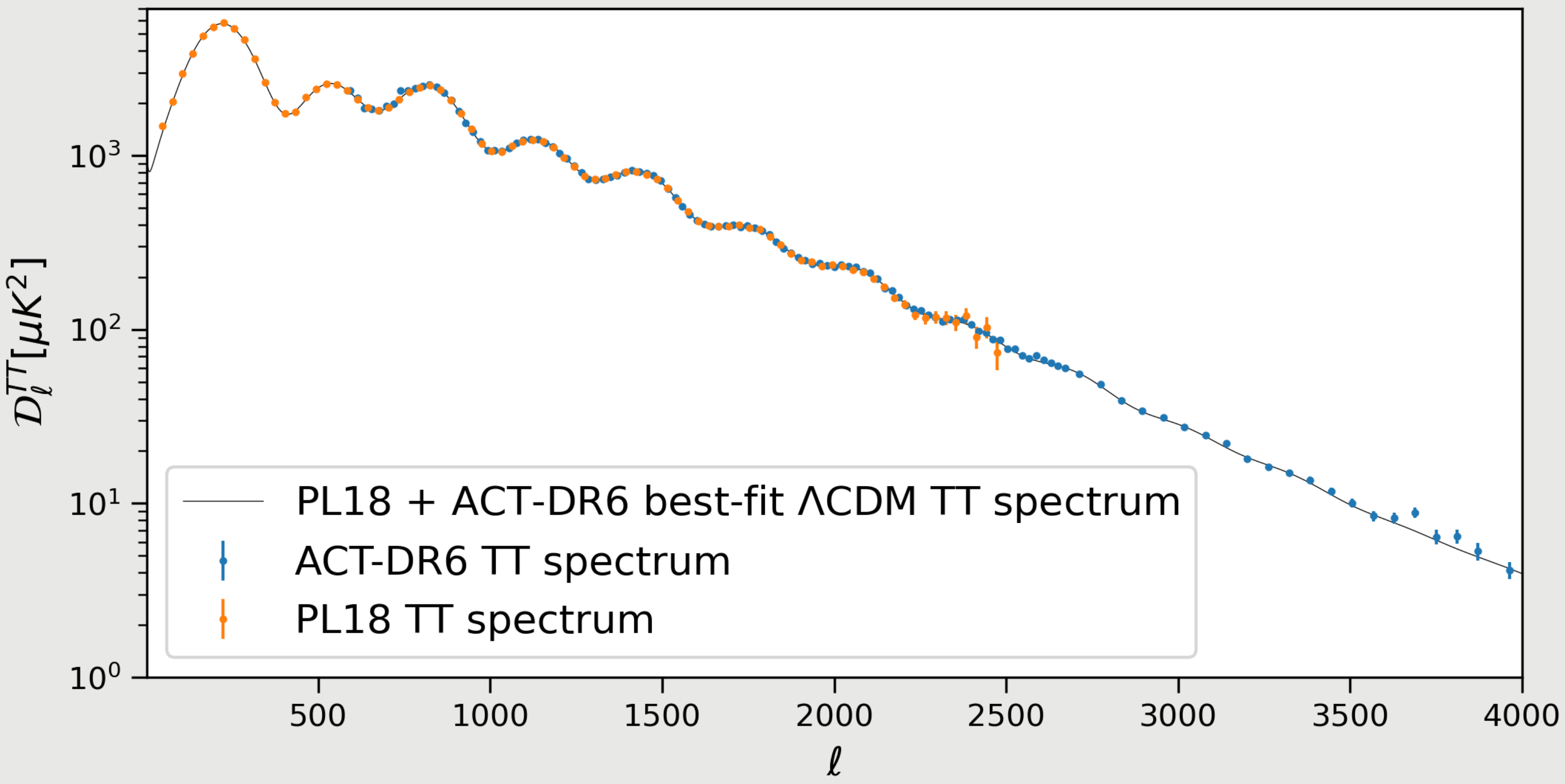
THE COSMIC MICROWAVE BACKGROUND - CMB



[Carbone *et al.*, ‘13; 1305.0829]

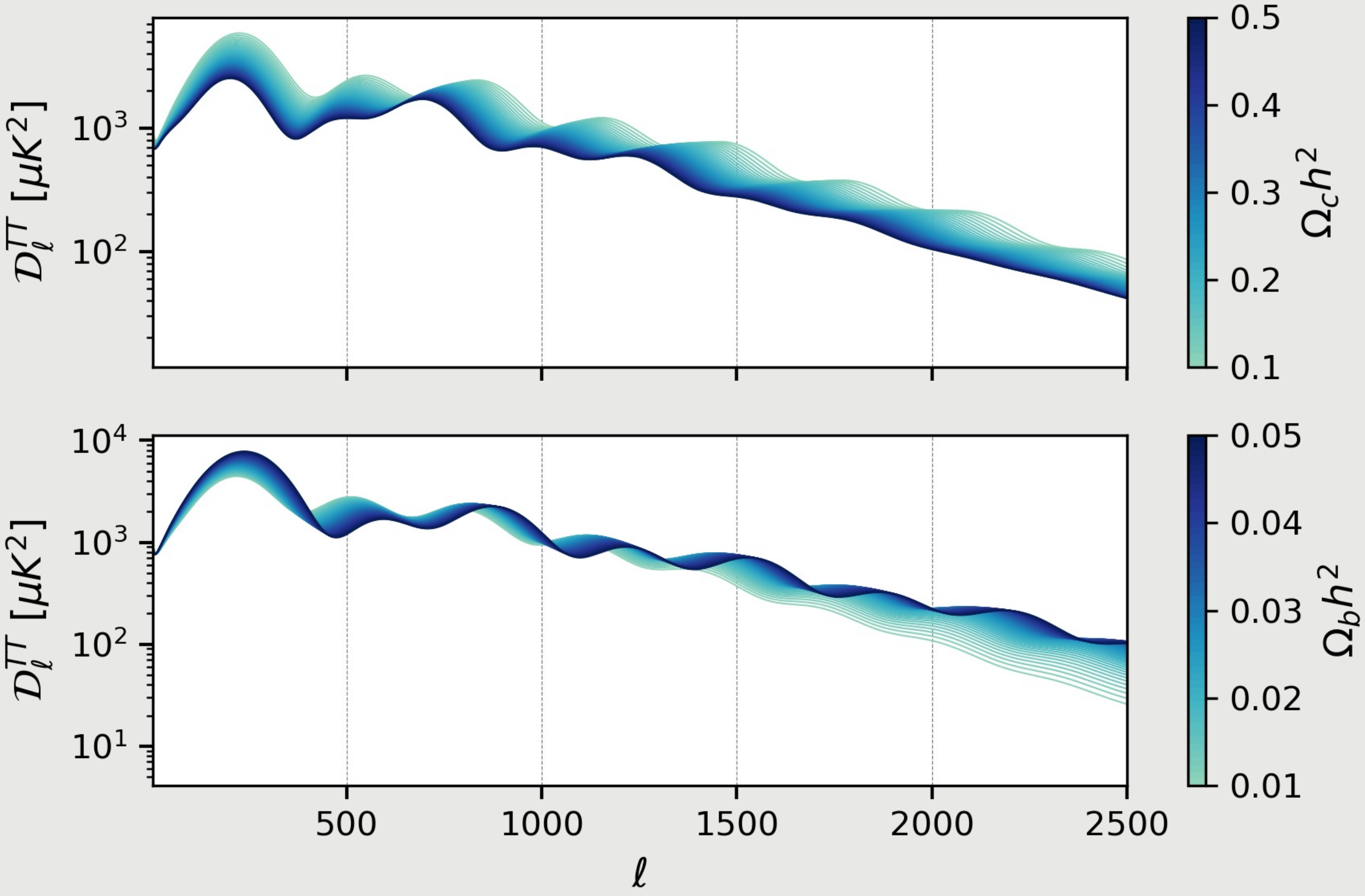
The CMB in ΛCDM

- $\mathcal{D}_\ell^{TT} = \ell(\ell+1)\mathcal{C}_\ell^{TT}/(2\pi)$, 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]

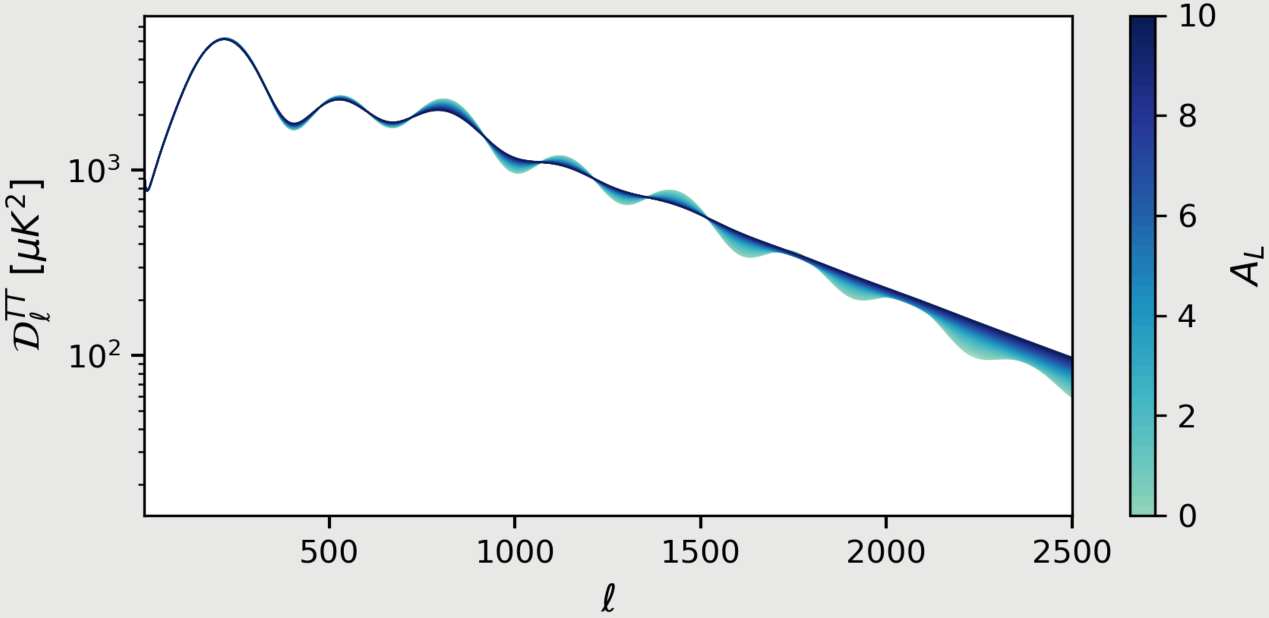
The CMB in ΛCDM

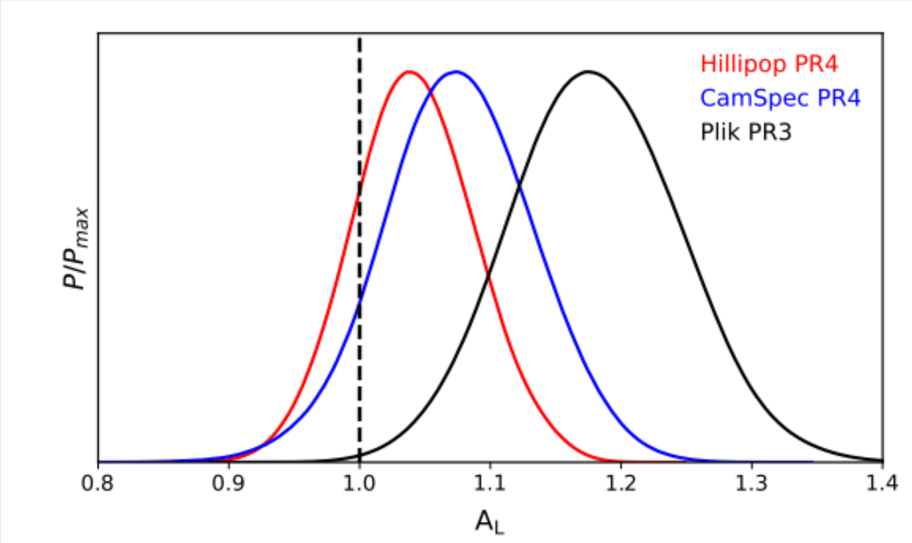


- The CMB is sensitive to the ΛCDM parameters like the baryon ($\Omega_b h^2$) or the CDM ($\Omega_c h^2$) densities.
- The variations shown here are much larger than what the PL18+ACT DR6 error bars allow.
- This explains the sub-percent precision of the CMB constraints.

A CMB problem: the lensing anomaly

- Lensing consistency check: introduce the lensing parameter A_L as $\mathcal{D}_\ell^{TT} \equiv A_L \mathcal{D}_\ell^{TT}$.
- 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]

- Possible resolution: substitute the high-ℓ likelihood **`plik`** with either **`Camspec`** or **`HiLLiPoP`**, the anomaly gradually disappears.
- Another possible resolution: consider a beyond-ΛCDM scenario.

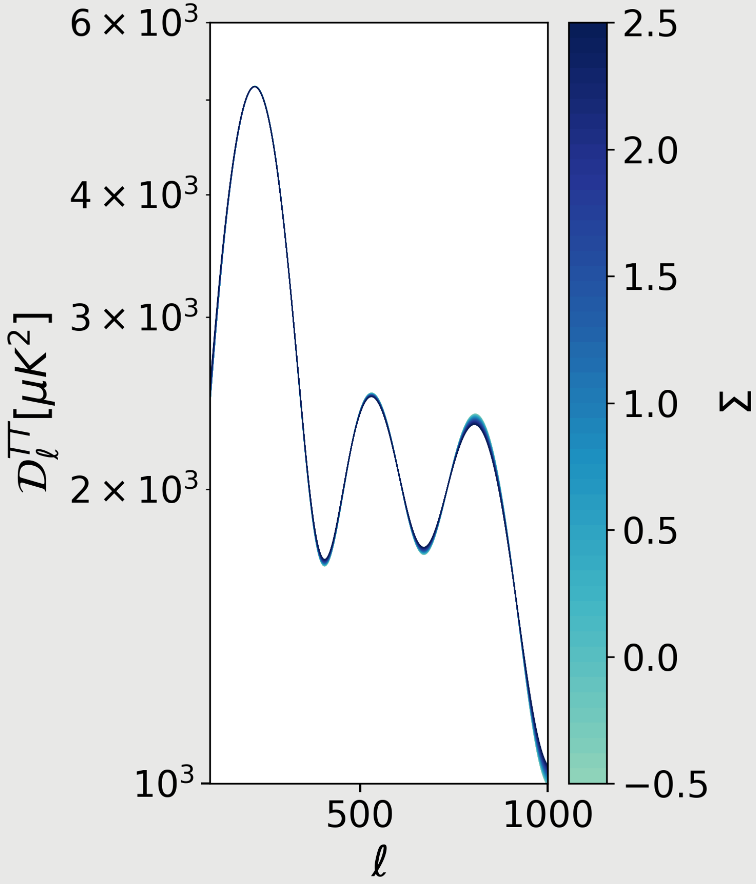
MODIFIED GRAVITY

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

A modification of the linear matter perturbations

- We consider two model-agnostic ‘deviations’ from ΛCDM at the level of the linear matter perturbations δ_m.
- Ψ and Φ are the scalar potentials perturbing the FLRW metric.
- These deviations are encoded by: $\boldsymbol{\mu}, \boldsymbol{\Sigma}$ (CASE 1) and $\boldsymbol{\gamma}$ (CASE 2).
- ΛCDM is recovered when: $\boldsymbol{\mu} = \mathbf{0}, \boldsymbol{\Sigma} = \mathbf{0}$ (CASE 1) and $\boldsymbol{\gamma} \approx \mathbf{0.55}$ (CASE 2).

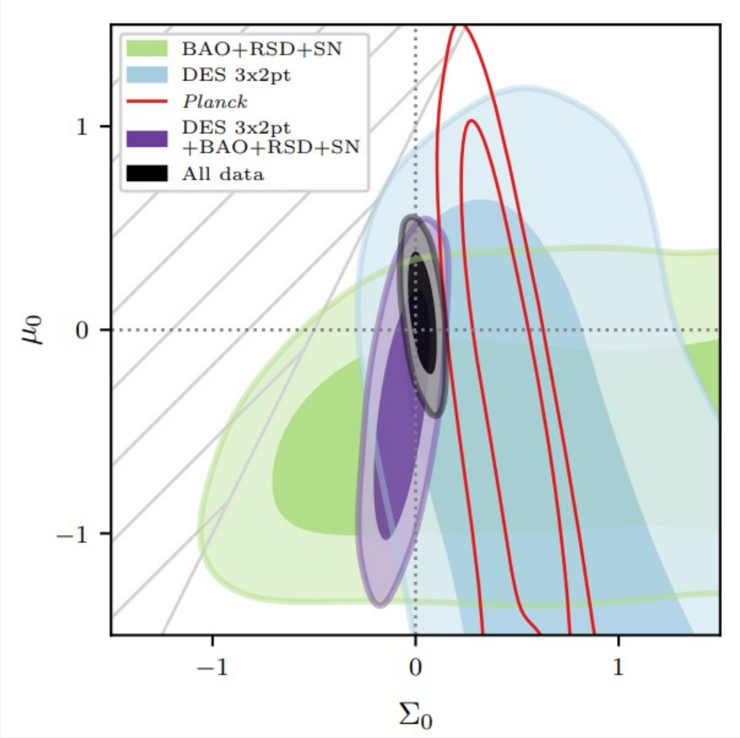
CASE 1 [Amendola, Kunz & Sapone, ‘07; 0704.2421]	**CASE 2** [Linder, ‘02; astro-ph/0208512]
Change the Poisson equation: $k^2\Psi = -4\pi G a^2(\boldsymbol{\mu} + \mathbf{1})\rho_m\delta_m$ Change the lensing equation: $k^2(\Psi + \Phi) = -8\pi G a^2(\boldsymbol{\Sigma} + \mathbf{1})\rho_m\delta_m$	Change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



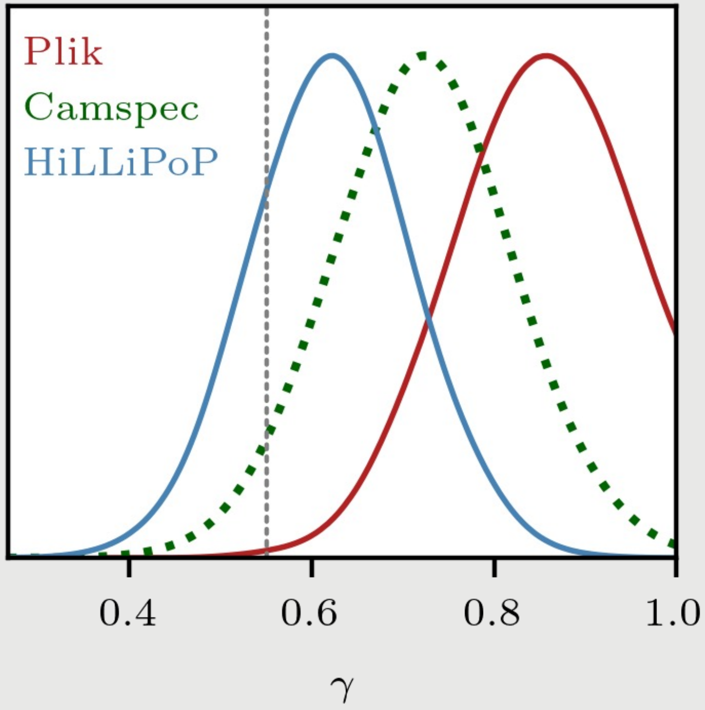
Recasting A_L into Σ and γ

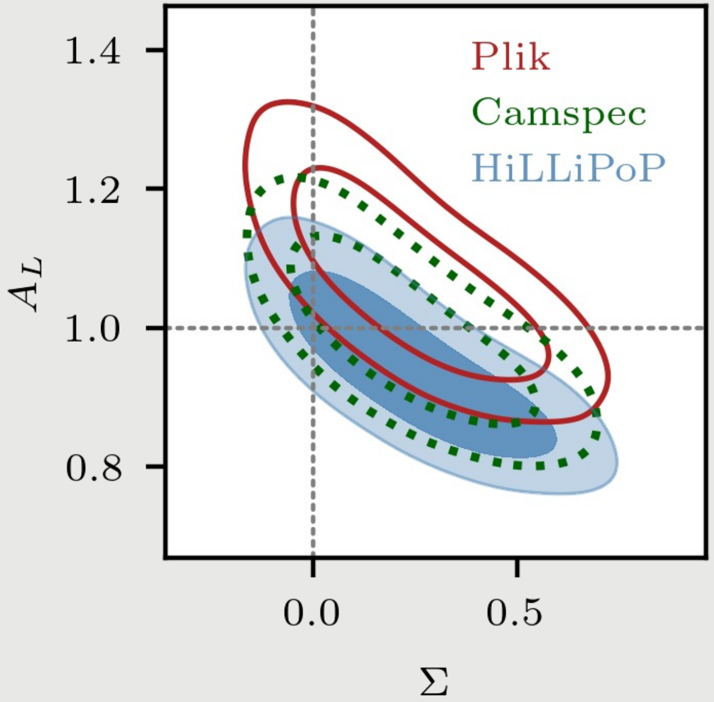
- Planck 2018 data, 3 different high-ℓ likelihoods, 2 CAMB patches [Nguyen, Huterer & Wen, '23; 2302.01331][Wang *et al.*, '23; 2305.05667].
- Like in the A_L case, we found both Σ and γ to be consistent with ΛCDM.

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



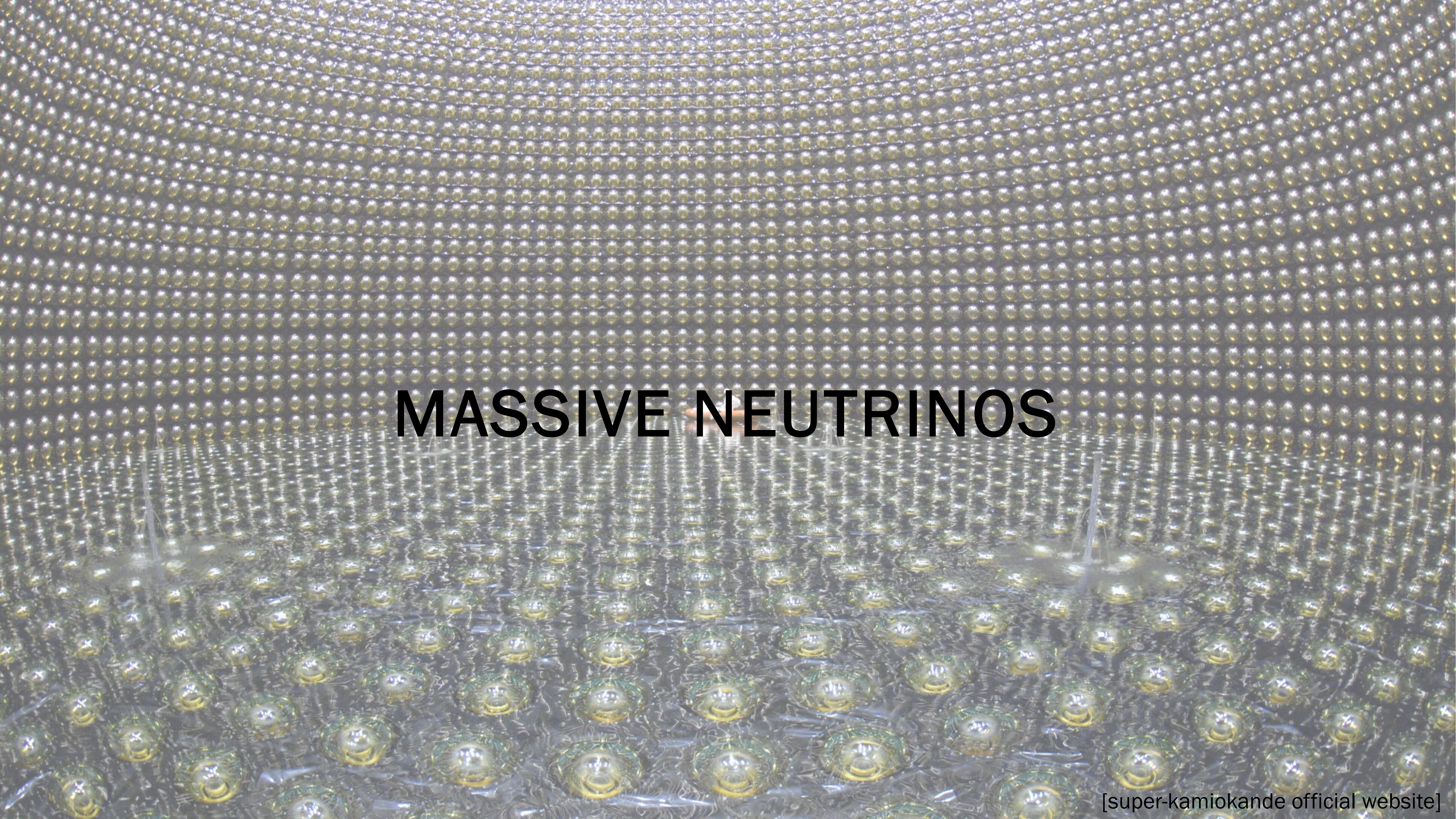
[ES, Giare, Di Valentino, '24; 2411.03896]





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

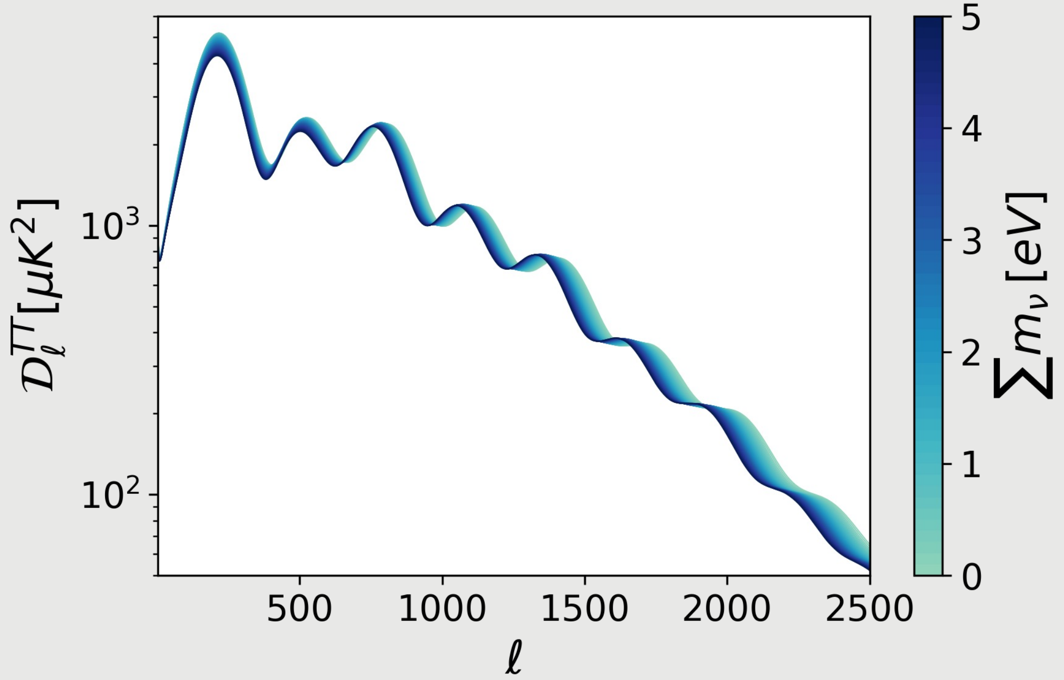
MASSIVE NEUTRINOS

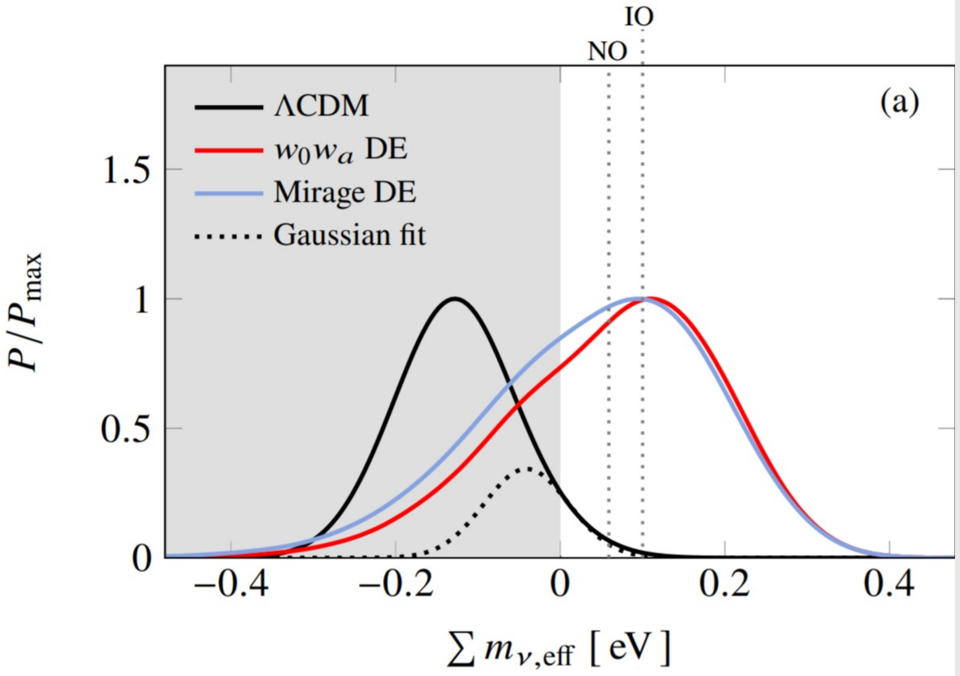


[super-kamiokande official website]

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.
- Expectation/hope: can a modification by γ relax DESI's constraint on Σm_ν?





[2407.10965]

ν oscillation experiments [Capozzi *et al.*, '25; 2503.07752]	$\Sigma m_\nu > 0.1$ eV (*Inverted Ordering*) $\Sigma m_\nu > 0.06$ eV (*Normal Ordering*)
DESI DR2 + PR4 (Camspec) + PR4 lensing + Pantheon+ [Giare, Mena, ES, Di Valentino, '25; *in prep.*]	$\Sigma m_\nu < 0.0295$ eV

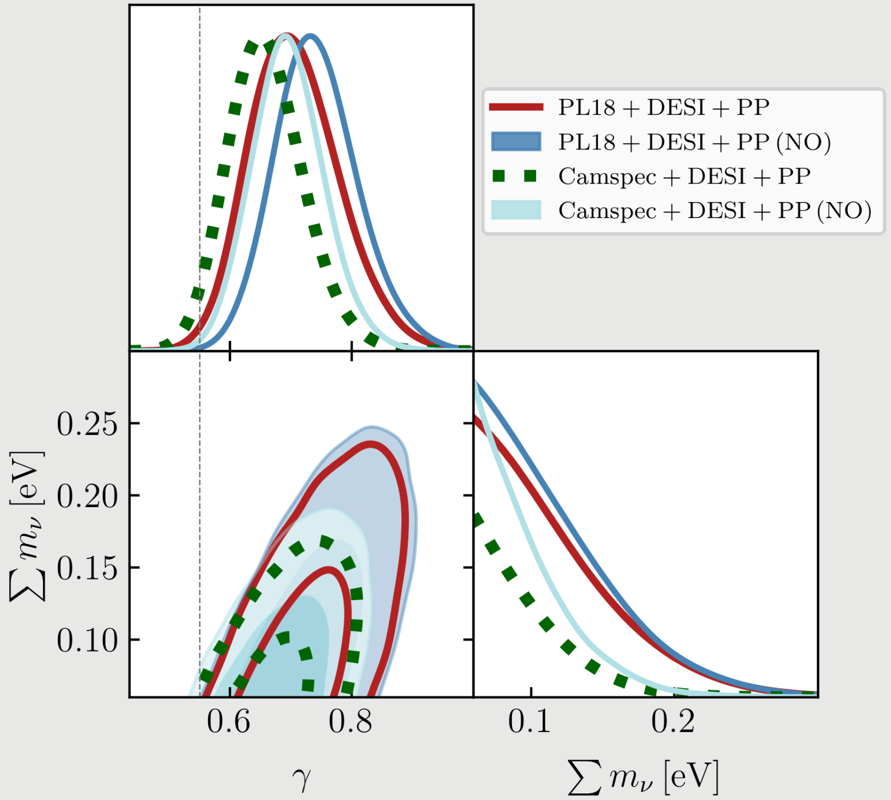
Relaxing DESI's Σm_ν constraints (kind of)

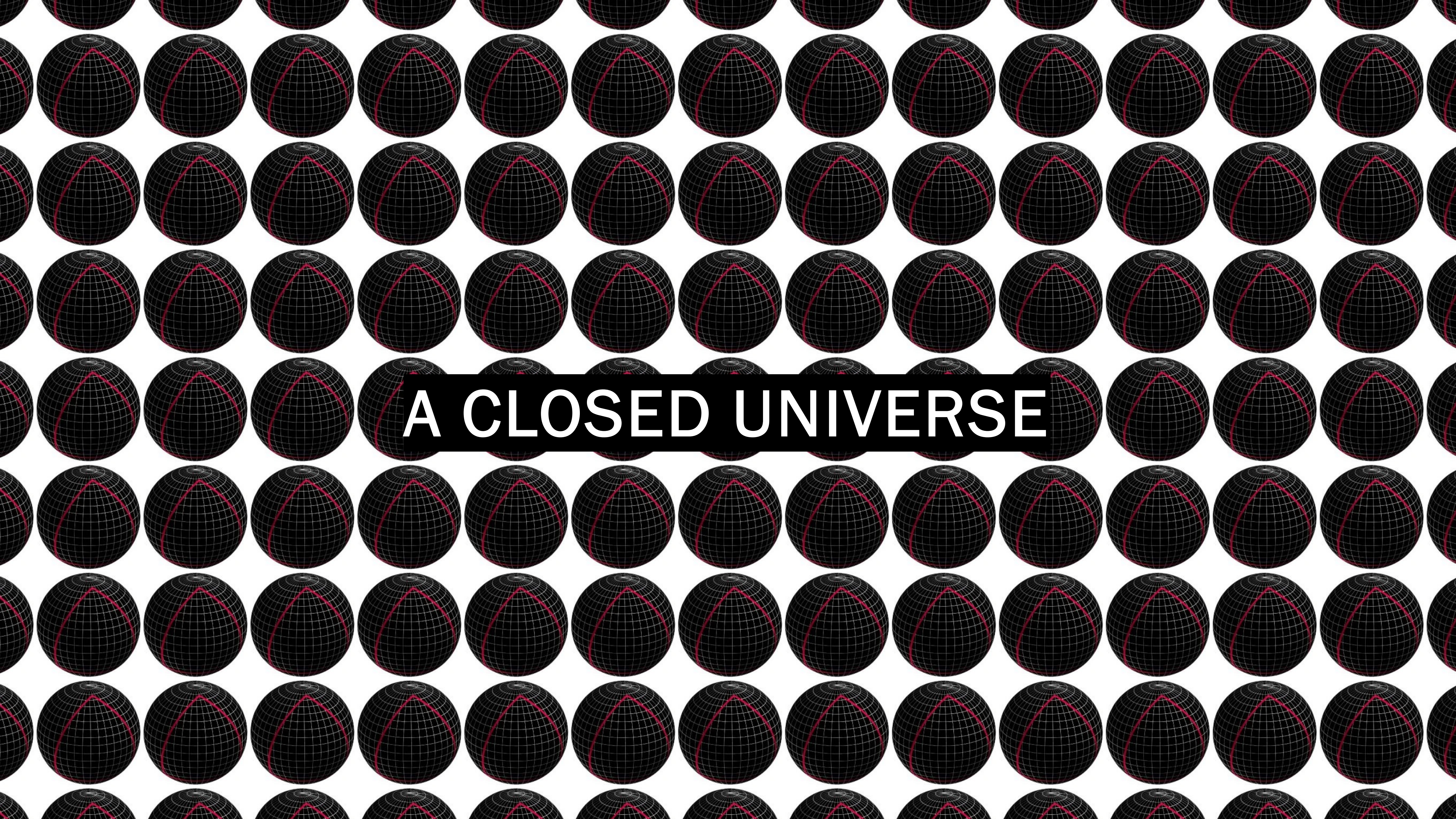
- We tested the ΛCDM extension containing both γ and Σm_ν.
- CMB TTTEEE (Planck, high-ℓ with **plik** and **Camspec**) + CMB lensing (PR4) + BAO (DESI DR2) + supernovae (Pantheon+).
- 'NO' is the case enforcing $\Sigma m_\nu > 0.06$ eV.

	PL18+ lensing+ DESI+ PP	PL18+ lensing+ DESI+ PP (NO)	Camspec+ lensing+ DESI+ PP	Camspec+ lensing+ DESI+ PP (NO)
$\boldsymbol{\Sigma m_\nu}$ **[eV]**	< 0.0985	< 0.132	< 0.0666	< 0.106
$\boldsymbol{\gamma}$	$0.707^{+0.064}_{-0.083}$	$0.742^{+0.061}_{-0.074}$	$0.660^{+0.055}_{-0.068}$	$0.696^{+0.055}_{-0.062}$

[Giare, Mena, ES, Di Valentino, '25; *in prep.*]

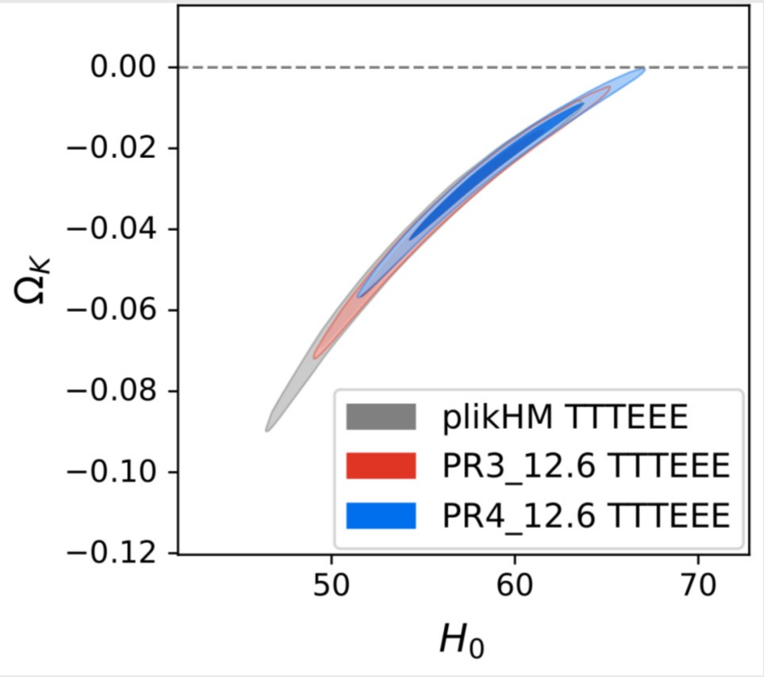
[Giare, Mena, ES, Di Valentino, '25; *in prep.*]



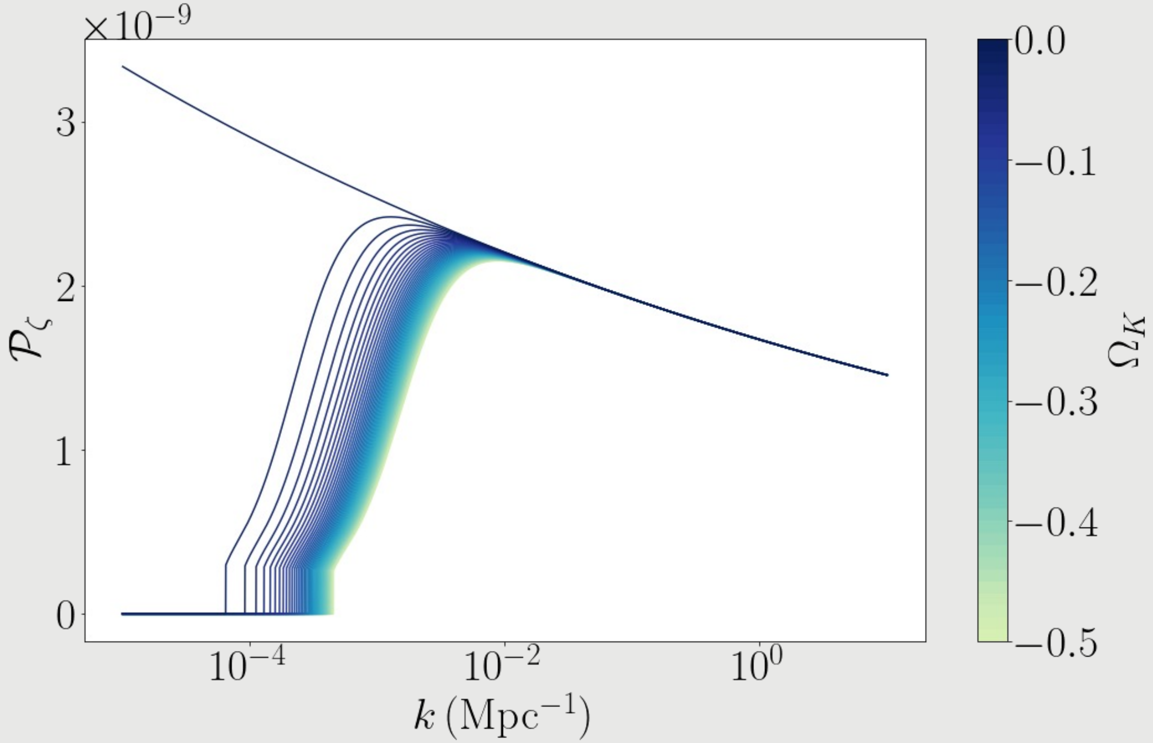

A CLOSED UNIVERSE

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

- We consider a primordial spectrum with a correction that suppresses power at large scales: $P_{\zeta} \propto \phi(k, \mathrm{K})\, k^{n_s - 1}$.
- By assuming $\phi(k,\mathrm{K}) \sim \frac{(k^2-4\mathrm{K})}{k(k^2-\mathrm{K})}$ (not motivated any particular model), Planck's 2018 analysis finds mild evidence for $\Omega_{\mathrm{K}} < 0$: an indirect effect of the lensing anomaly [Di Valentino, Melchiorri & Silk, '19; 1911.02087].
- Does this still hold for a correction factor based on quantum gravity [Vardanyan & Kiefer, '23; 2302.07001]?



[Rosenberg, Gratton & Efstathiou, '22; 2205.10869]

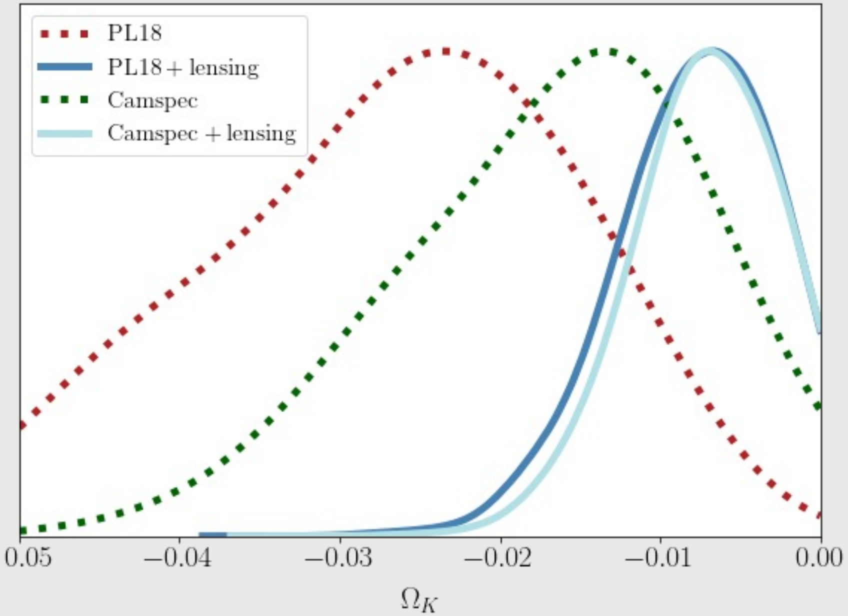


Consistency with $\Omega_K = 0$

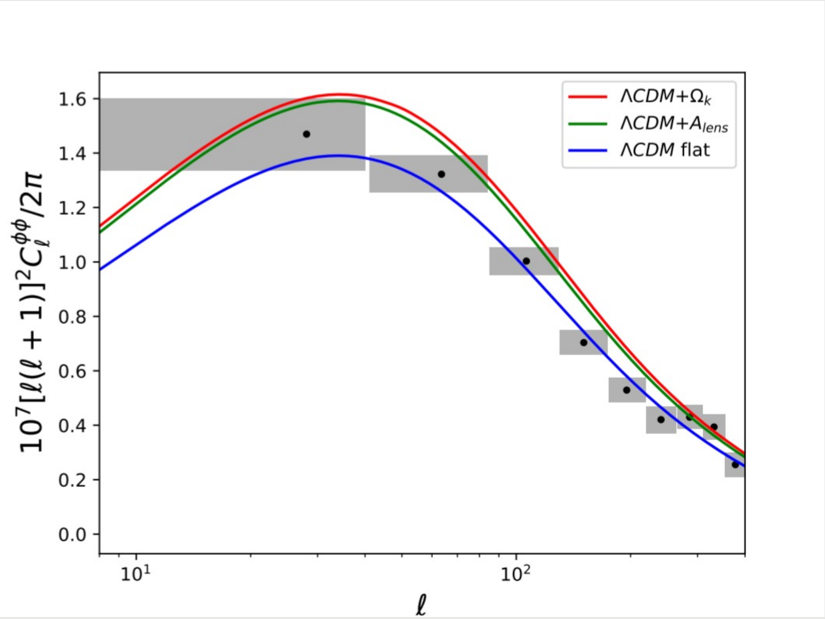
- We looked for evidence of P_ζ suppression in the data.
- CMB TTTEEE (Planck, high-ℓ with **`plik`** and **`Camspec`**) + CMB lensing (PR3).

	PL18	PL18+lensing	Camspec	Camspec+lensing
$\mathbf{\Omega_K}$ (our model)	$-0.026^{+0.013}_{-0.010}$	$-0.0083^{+0.0062}_{-0.0035}$	$-0.0174^{+0.012}_{-0.0073}$	$-0.0077^{+0.0056}_{-0.0033}$
$\mathbf{\Omega_K}$ (Planck)	/	$-0.0107^{+0.0070}_{-0.0047}$	$-0.022^{+0.014}_{-0.010}$	$-0.0114^{+0.0069}_{-0.0052}$

[Giare, ES, Vardanyan & Di Valentino, ‘25; *in prep.*]



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



Conclusions

- We considered a series of extensions of the ΛCDM model, all of which are connected to each other through the comparable impact they have 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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- Primordial spectrum of [Vardanyan & Kiefer, ’23; 2302.07001].
- δ, ϵ are the slow roll parameters.
- $n = \mathrm{k}^2 + \mathrm{K}$.

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

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

ΛCDM problems: the CMB anomalies

Discrepancies between CMB datasets:

- Evidence for non-vanishing spatial curvature $\mathbf{\Omega_k}$ in Planck, but not in ACT.
- Indication for $n_s = 1$ in ACT DR4, but not in Planck (solved in DR6).
- Neither can be explained by ACT's lack of data in the low-ℓ TT, TE and EE spectra.

Discrepancies common to all CMB datasets:

- Lower-than-expected power (or correlation) at large scales.
- Sky direction-dependent ΛCDM constraints.
- The dipole anomaly.