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CCAPP THE OHIO STATE UNIVERSITY

Origin of cosmological neutrino mass bounds: `Background vs Perturbations`

Rasmi E. Hajjar Muñoz

based on *JCAP* 06 (2025) 058, in collaboration with

T. Bertólez-Martínez

I. Esteban

O. Mena

J. Salvado

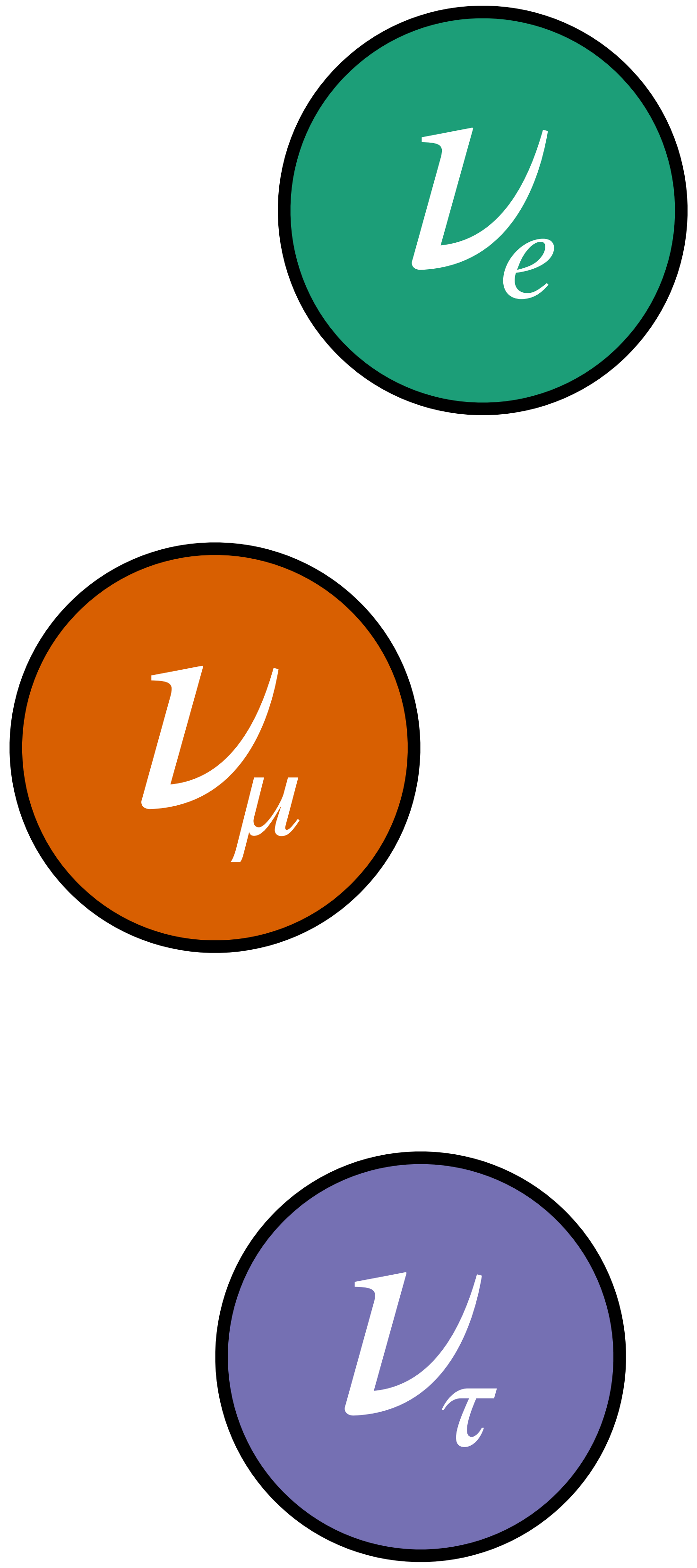
Sum of neutrino masses: oscillations

Detection/
production

Vacuum
transport

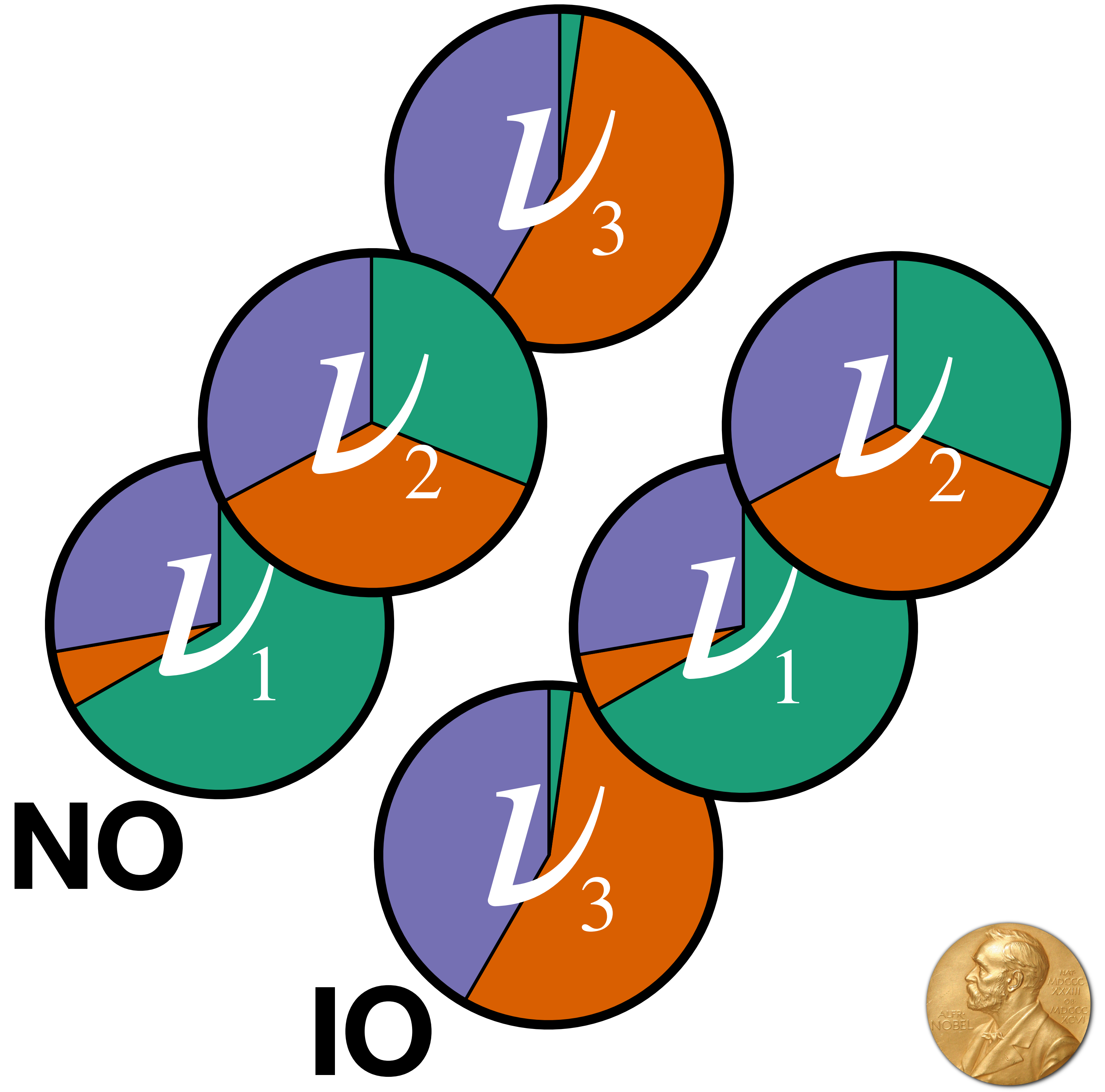
Sum of neutrino masses: oscillations

Detection/
production

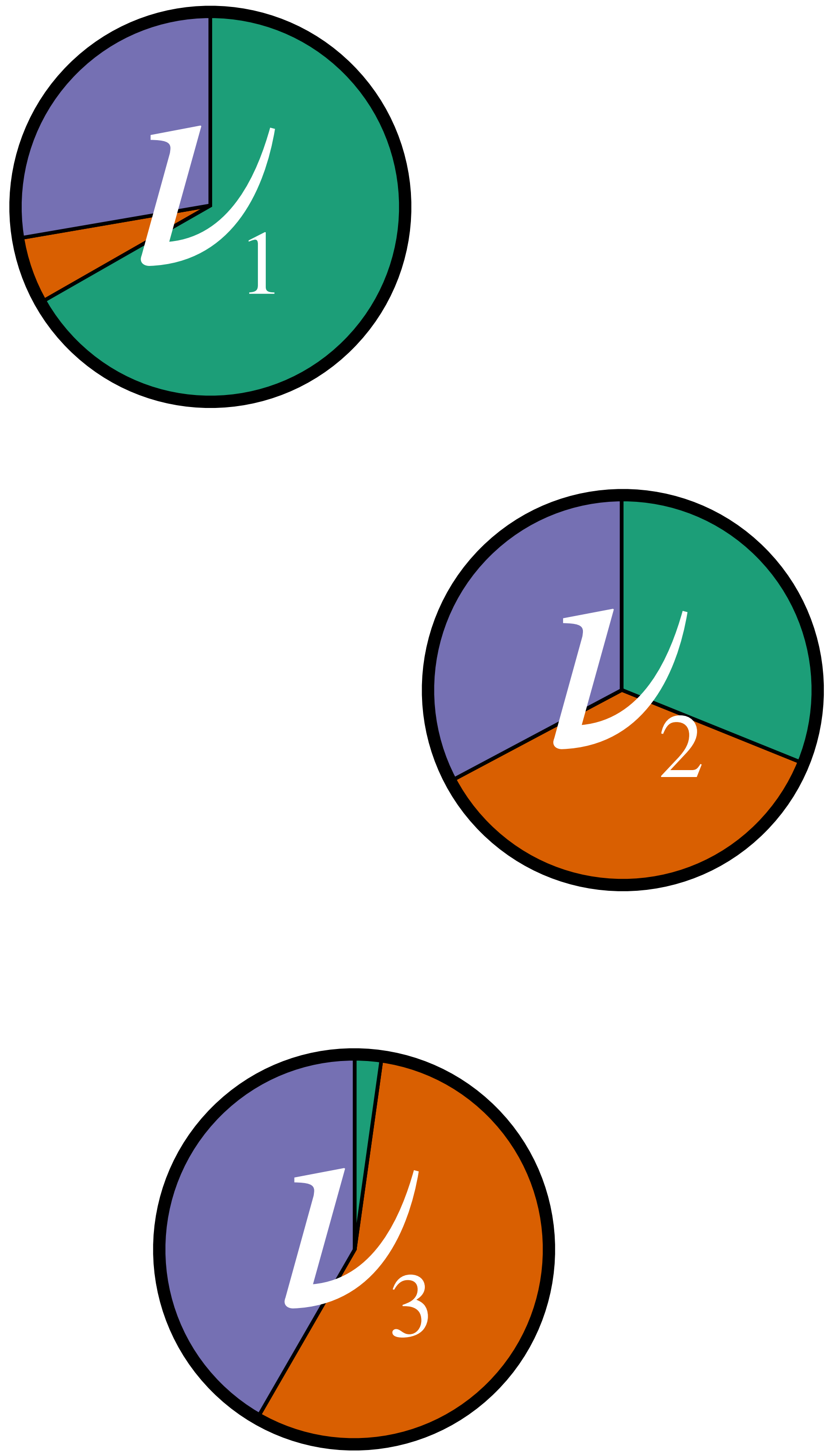


$$\Delta m^2_{21} \simeq 7.5 \cdot 10^{-5}\ \mathrm{eV}^2$$

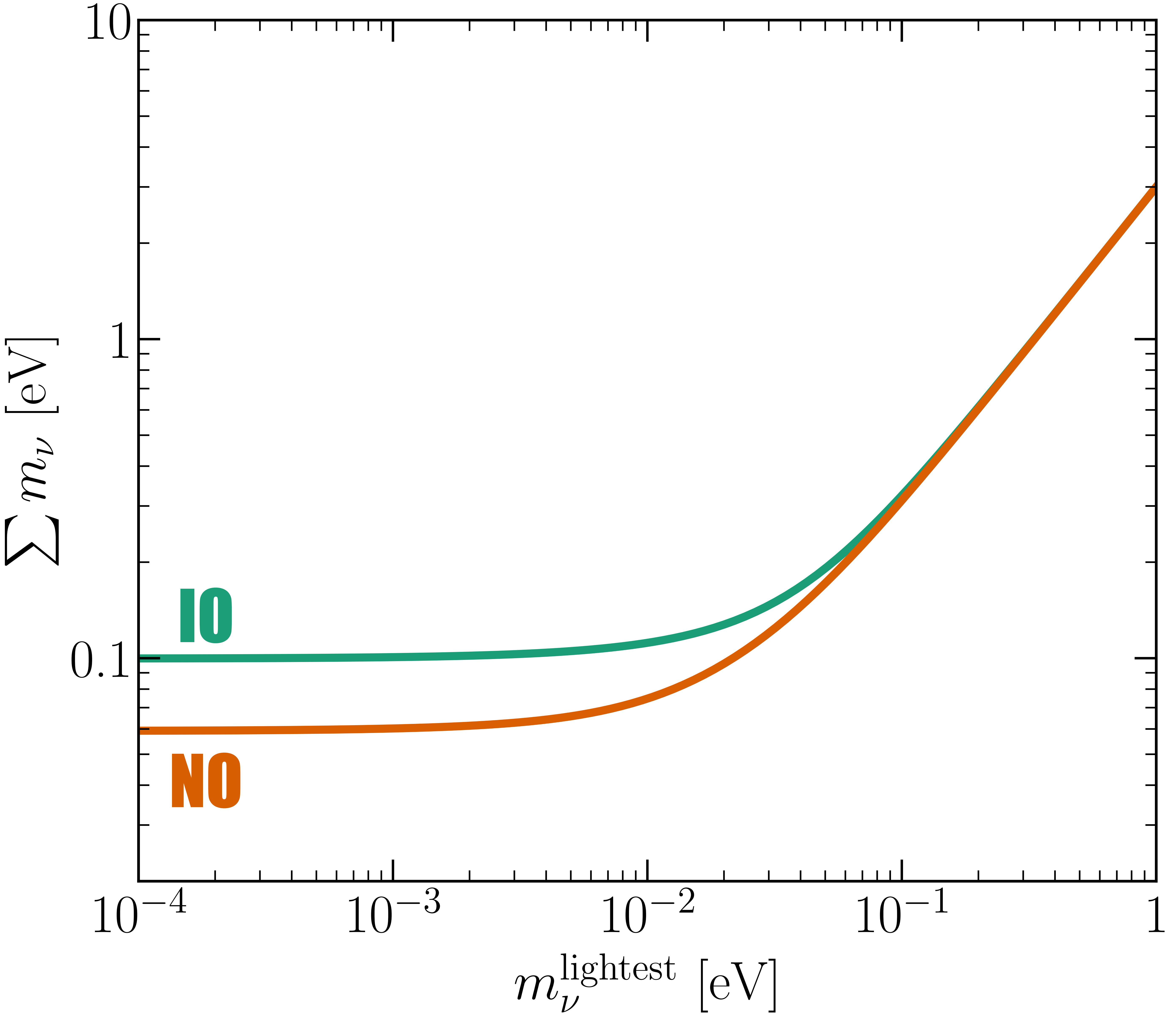
$$|\Delta m^2_{31}| \simeq 2.5 \cdot 10^{-3}\ \mathrm{eV}^2$$



Vacuum
transport

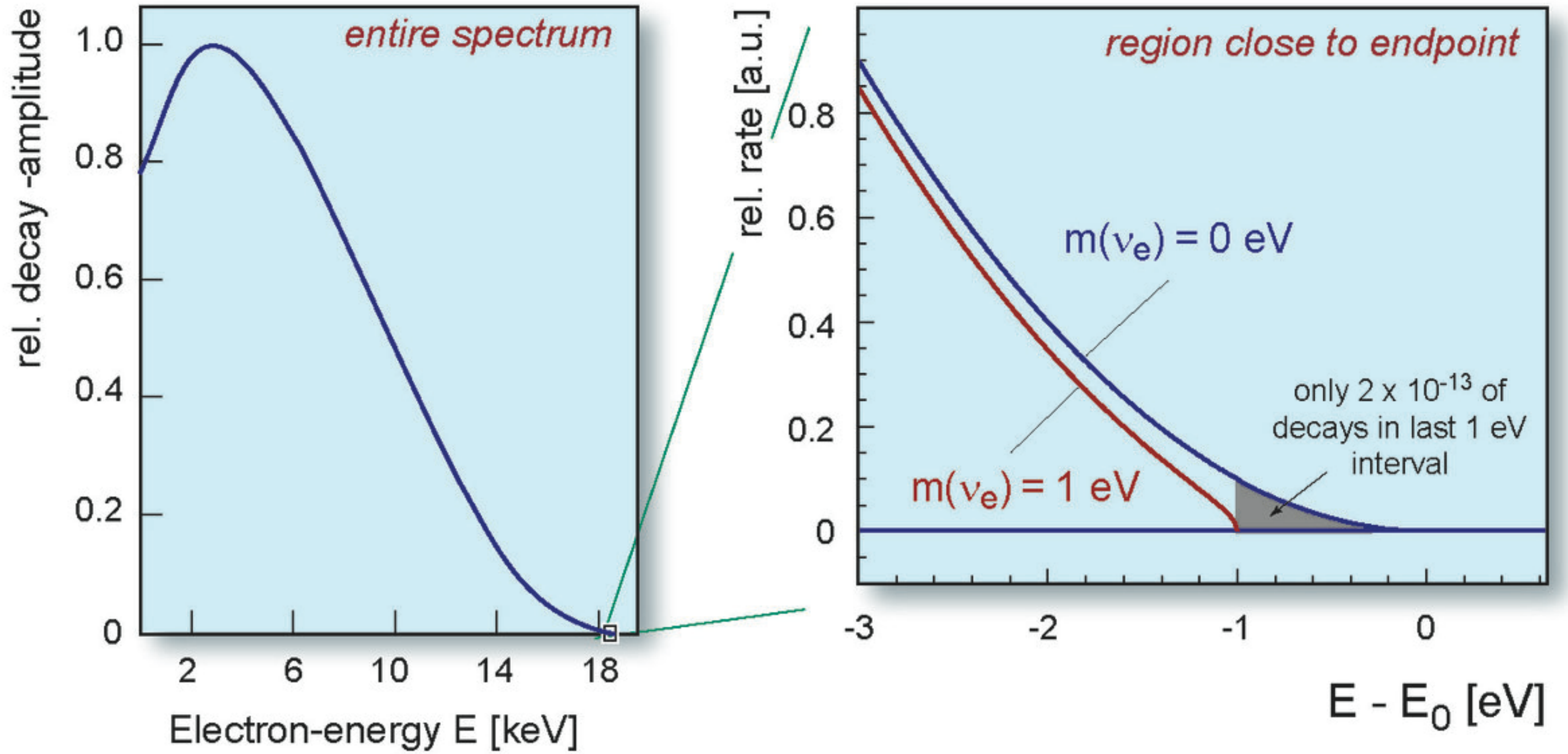


Sum of neutrino masses: oscillations



$\sum m_\nu^{\rm NO} \geq 0.06\,{\rm eV}$ $\sum m_\nu^{\rm IO} \geq 0.1\,{\rm eV}$

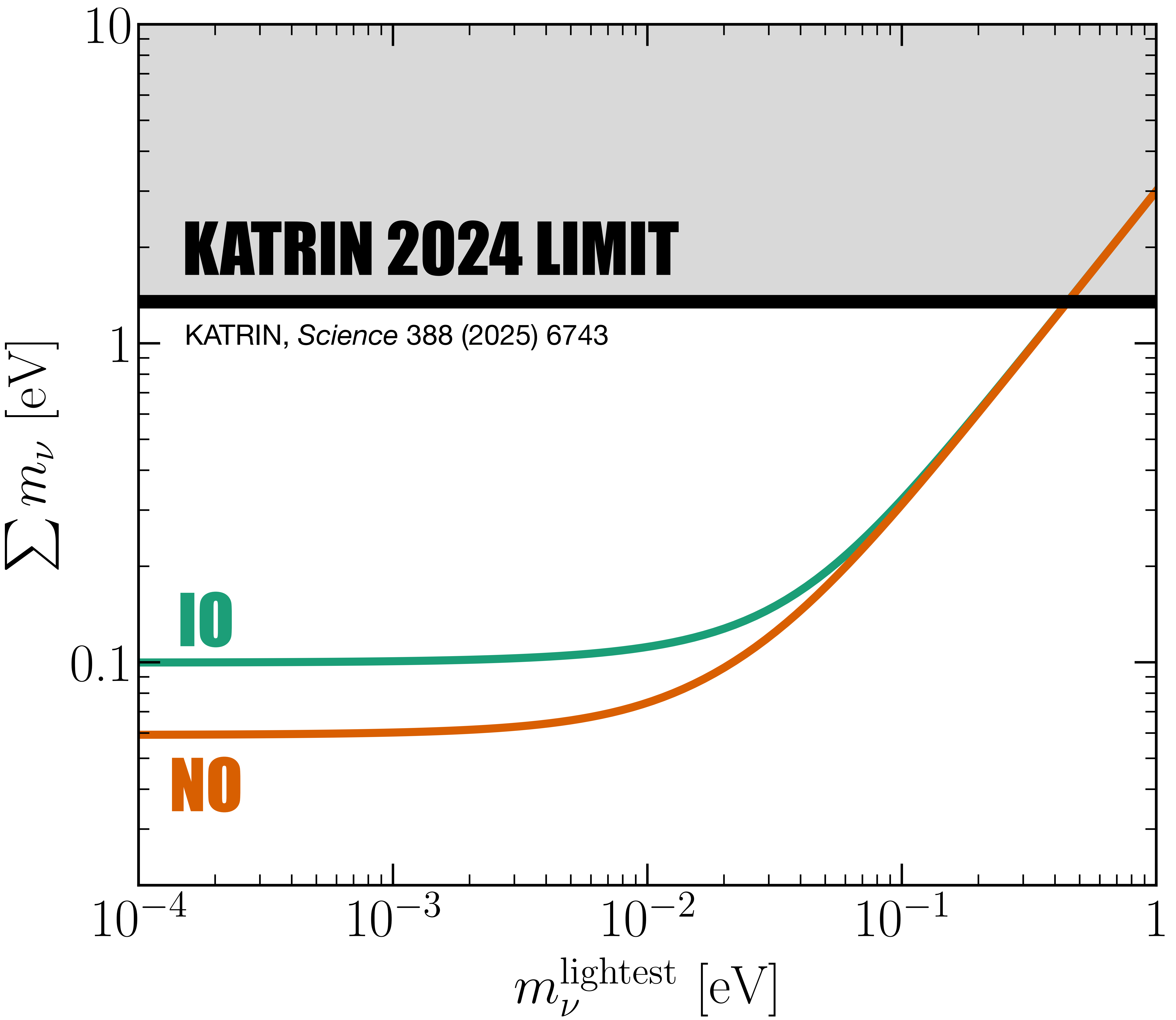
Sum of neutrino masses: KATRIN



$$\sum m_\nu^{\mathrm{KATRIN}} < 1.35\,\mathrm{eV} \qquad \text{(90\% CL)}$$

KATRIN Collaboration, *Science* 388 (2025) 6743, adq9592

Sum of neutrino masses: KATRIN



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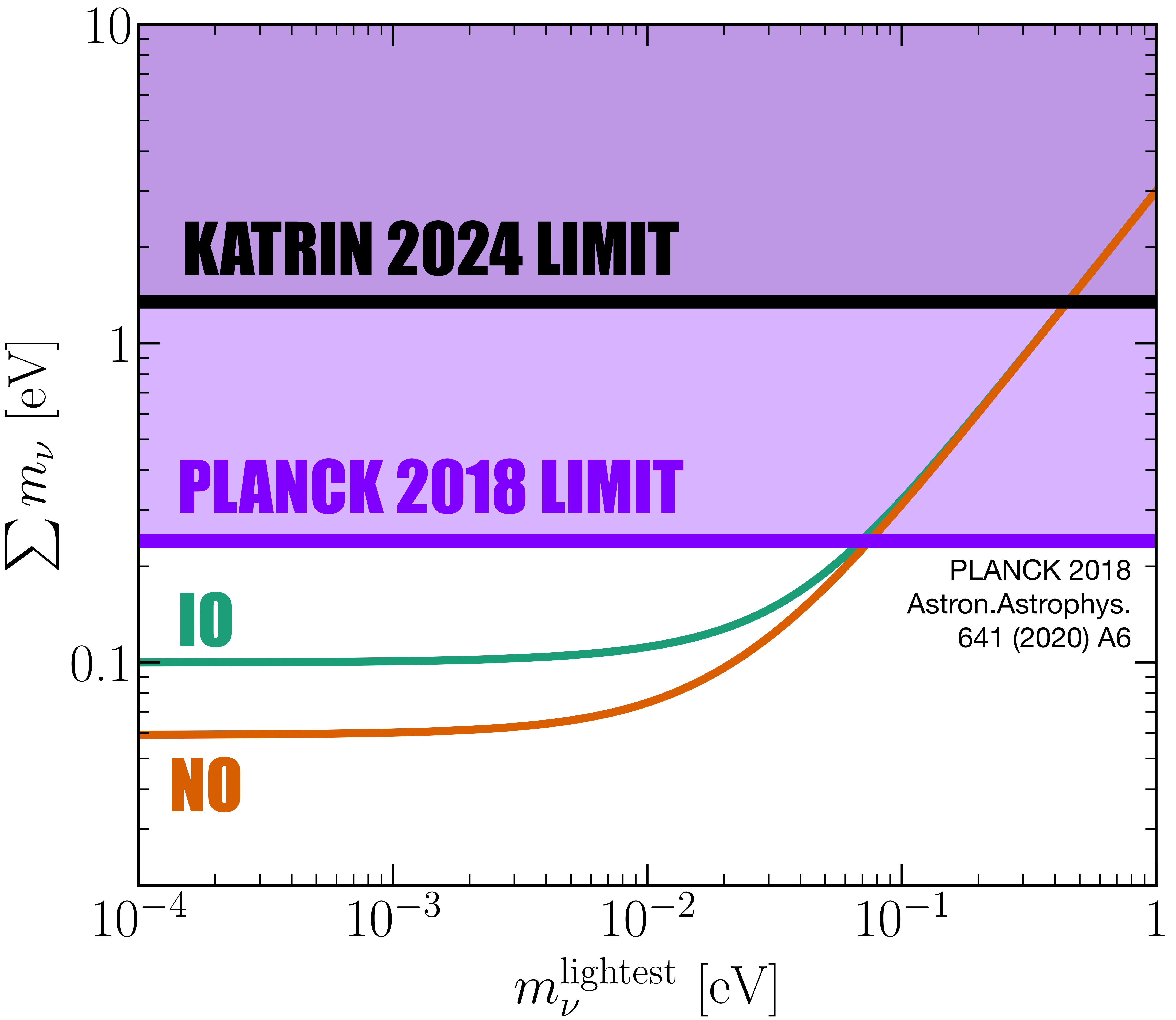
Sum of neutrino masses: cosmology



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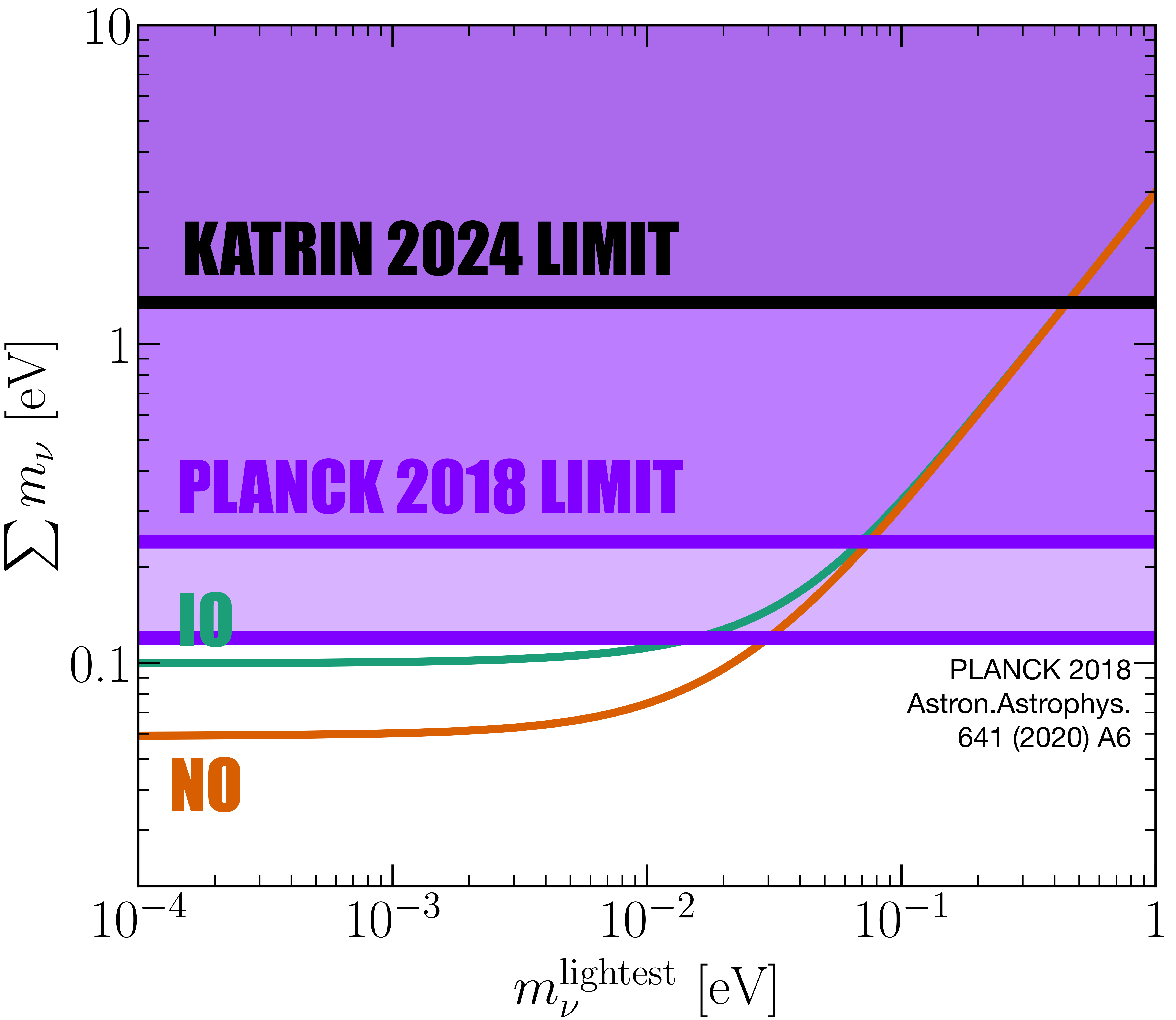

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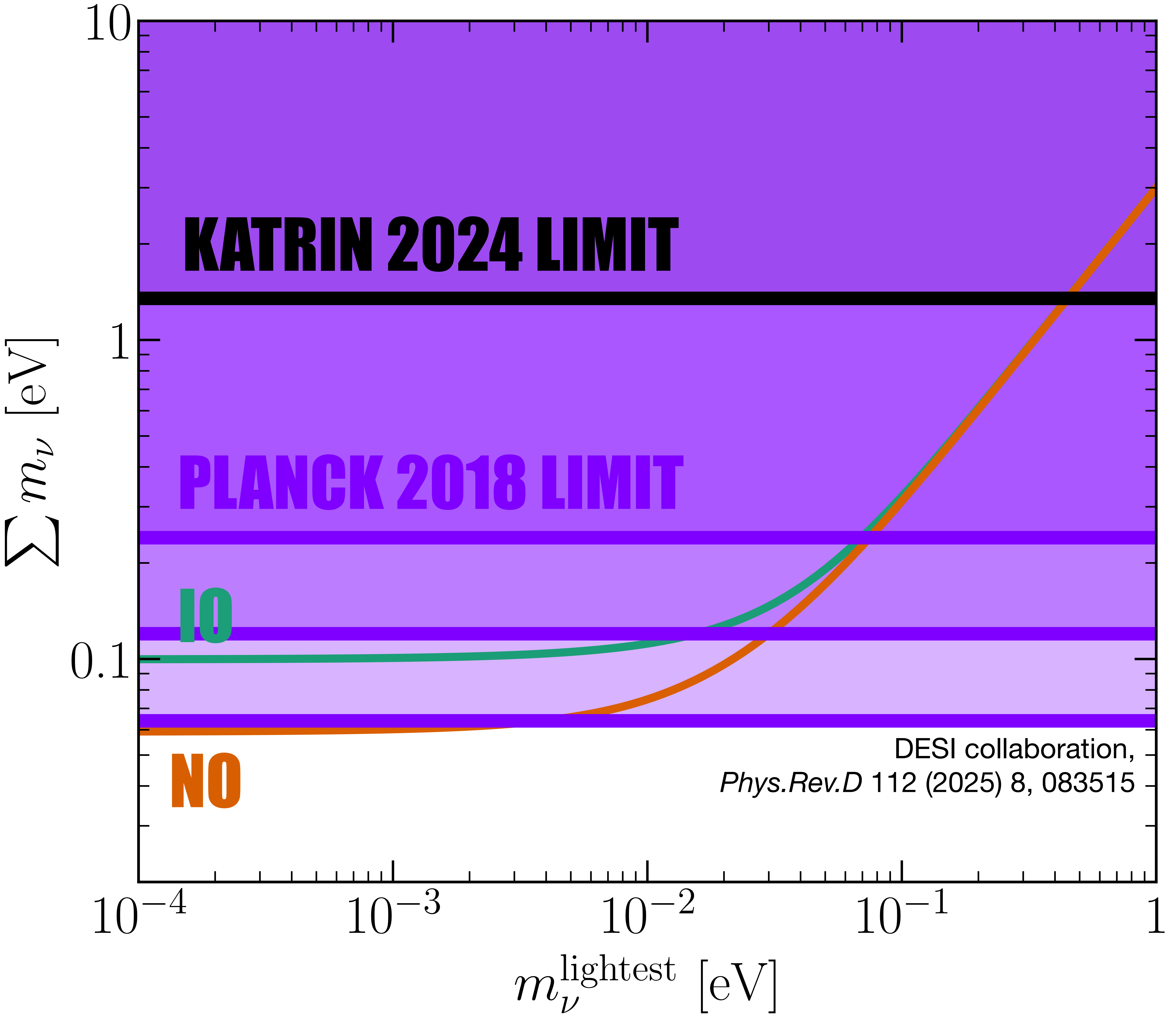

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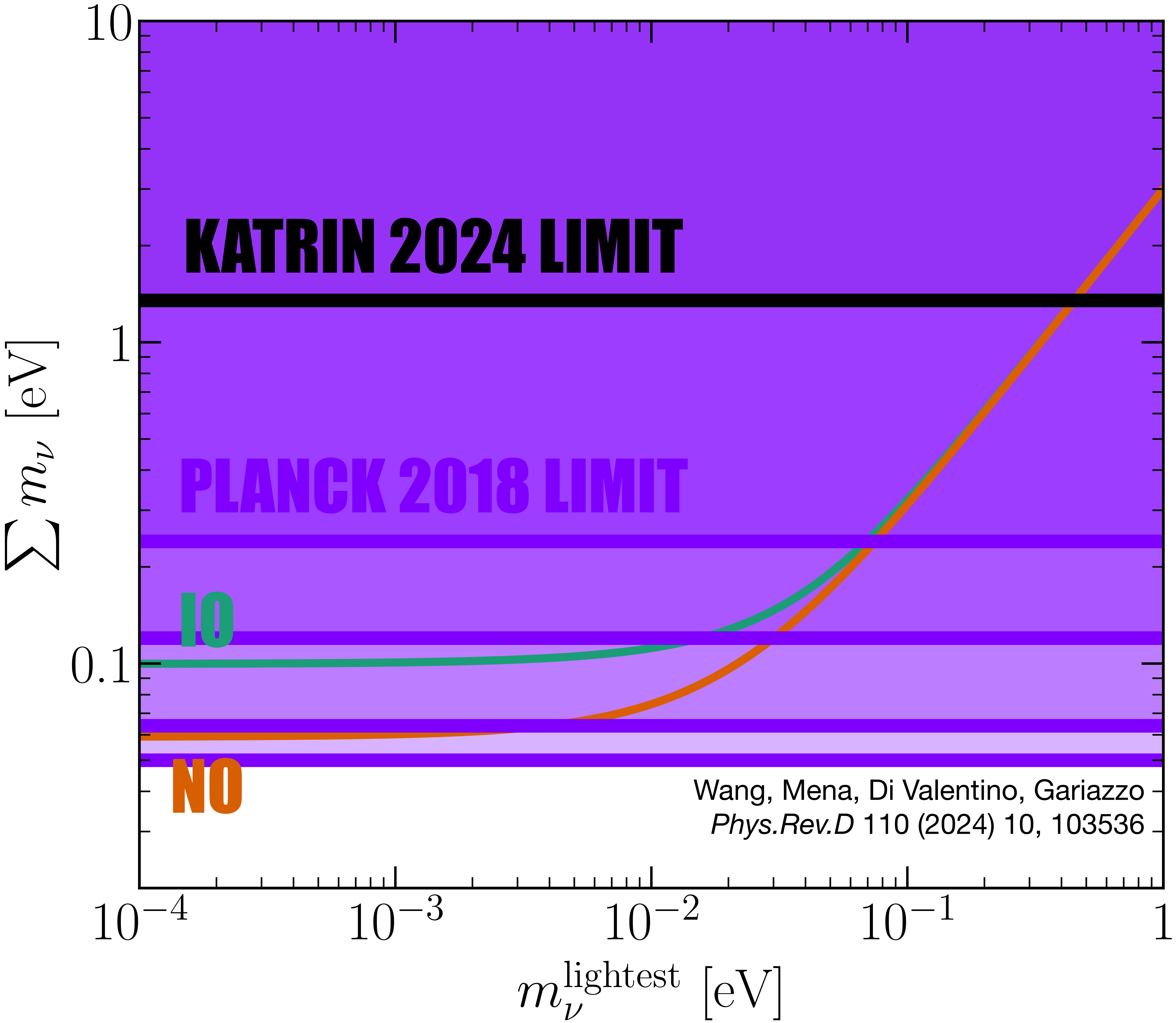
Sum of neutrino masses: cosmology



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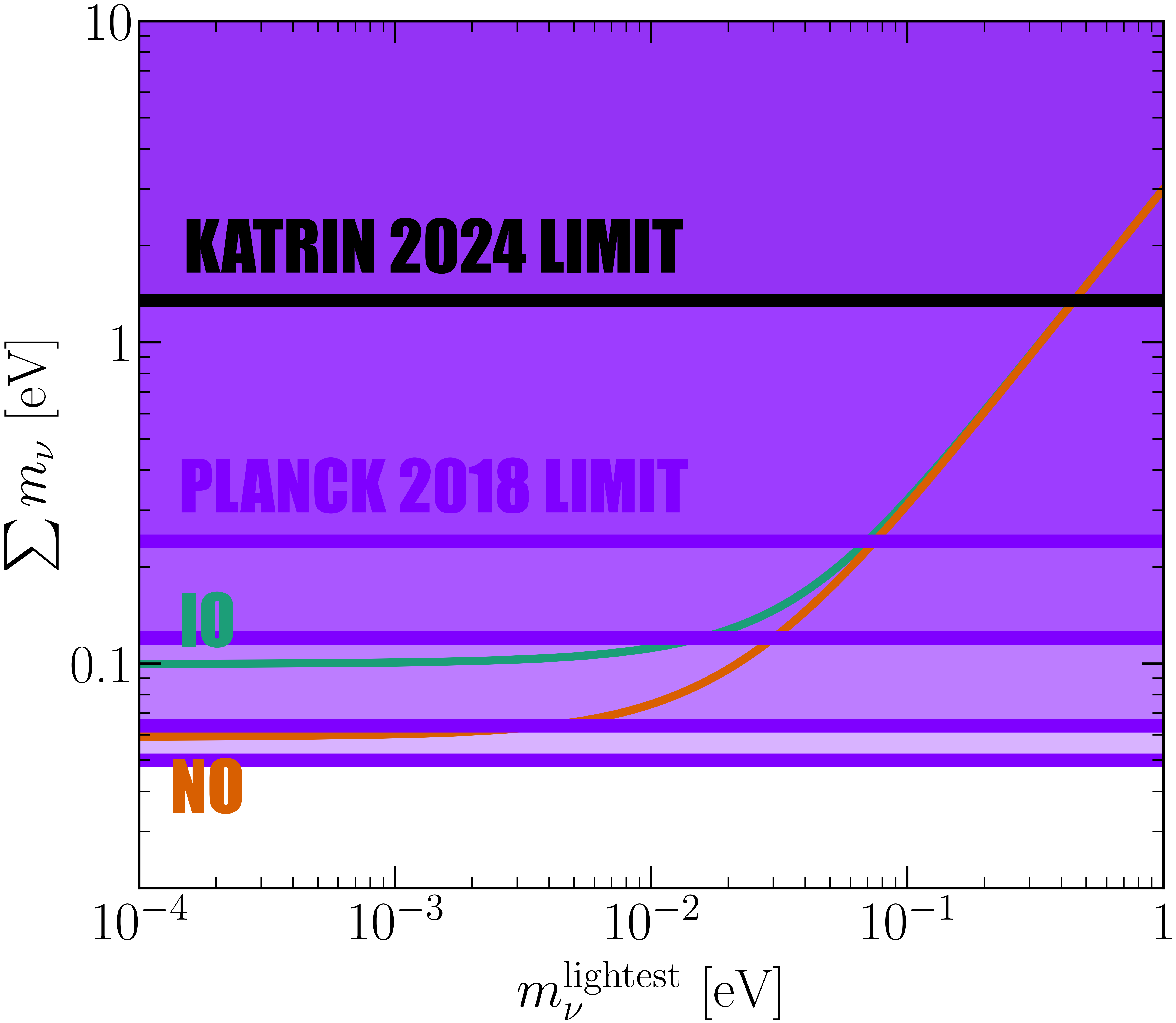
$\sum m_\nu^{\text{CMB+DESI+SN+GRB}} < 0.049\,\text{eV}$

Sum of neutrino masses: Tension!



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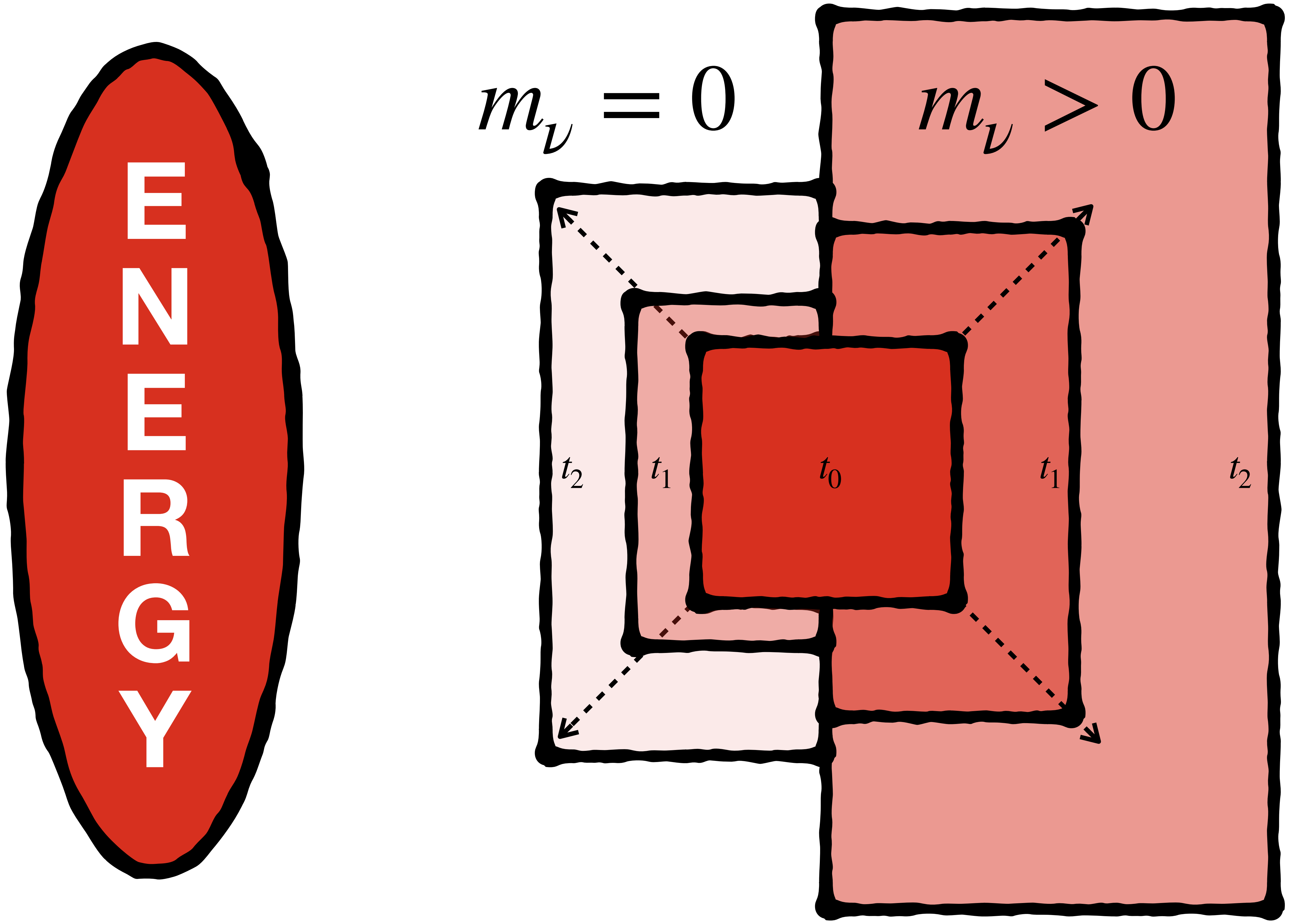
Cosmo bounds: where do they come from?

The cosmological bound on neutrino masses is an indirect measurement.

Cosmo bounds: where do they come from?

Cosmological observables are predictions of:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

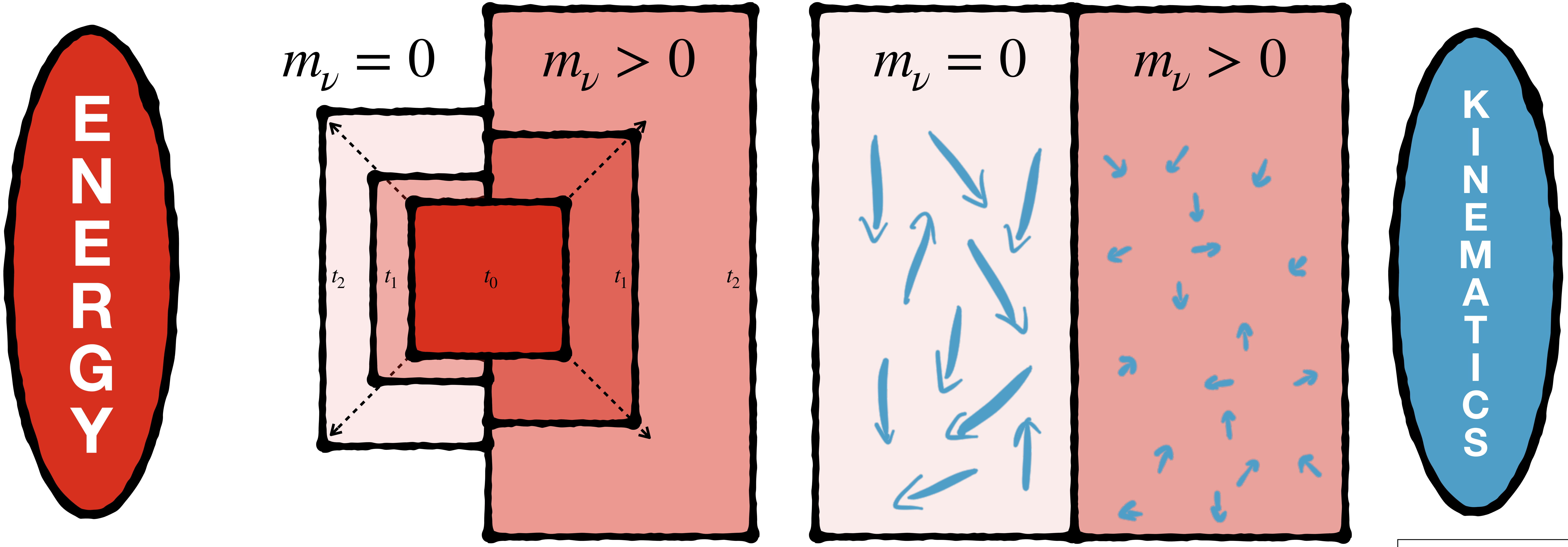


Cosmo bounds: where do they come from?

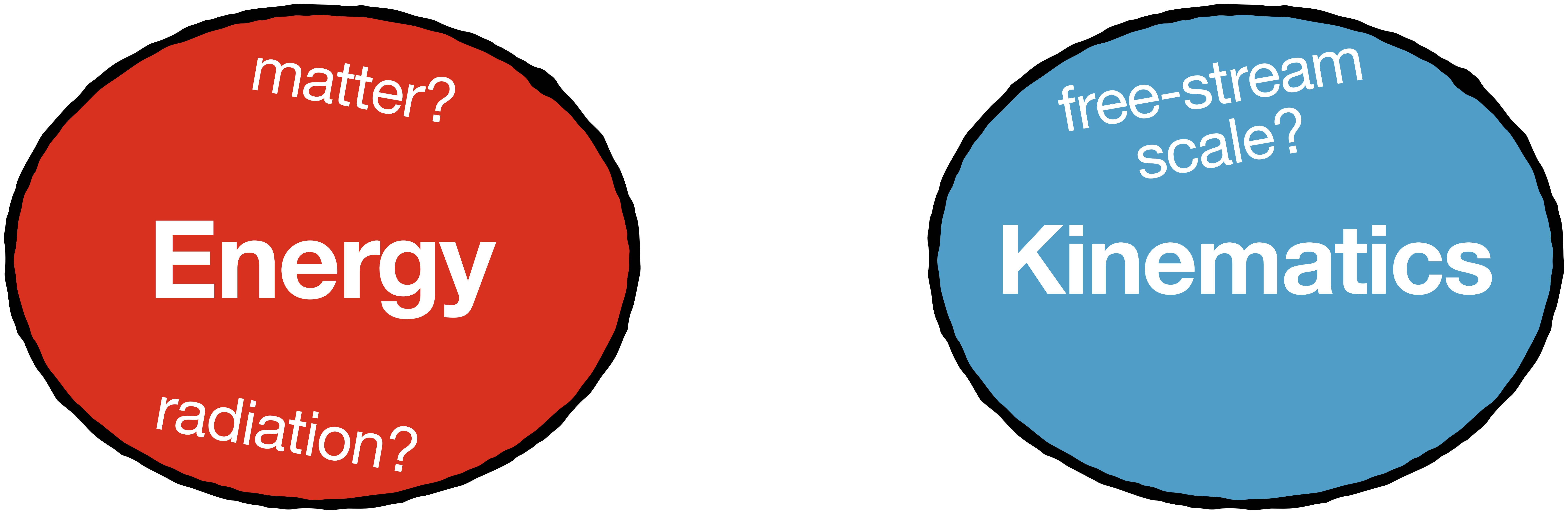
Cosmological observables are predictions of:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\delta G_{\mu\nu} = 8\pi G\, \delta T_{\mu\nu}$$

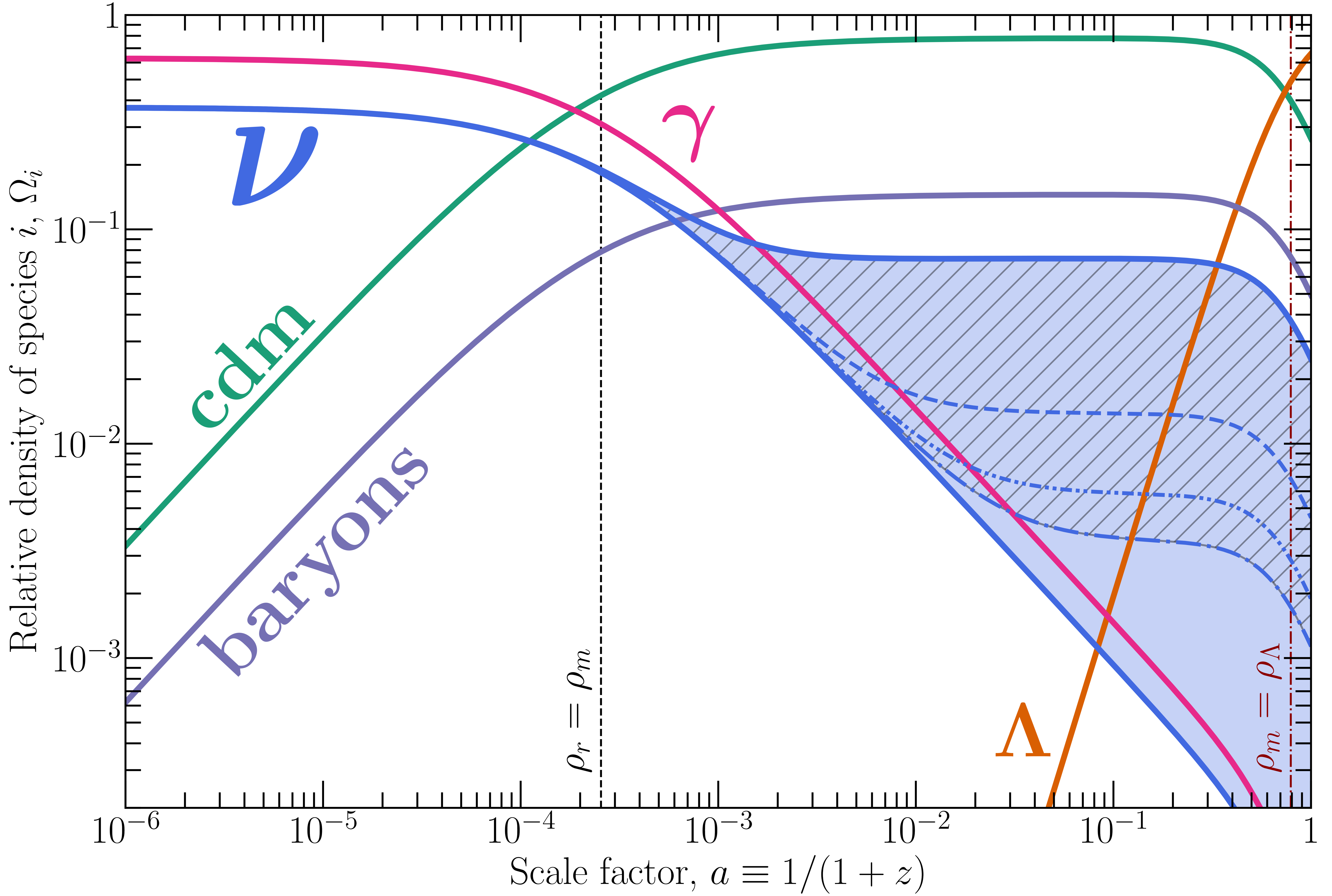


Breaking down the cosmological bound

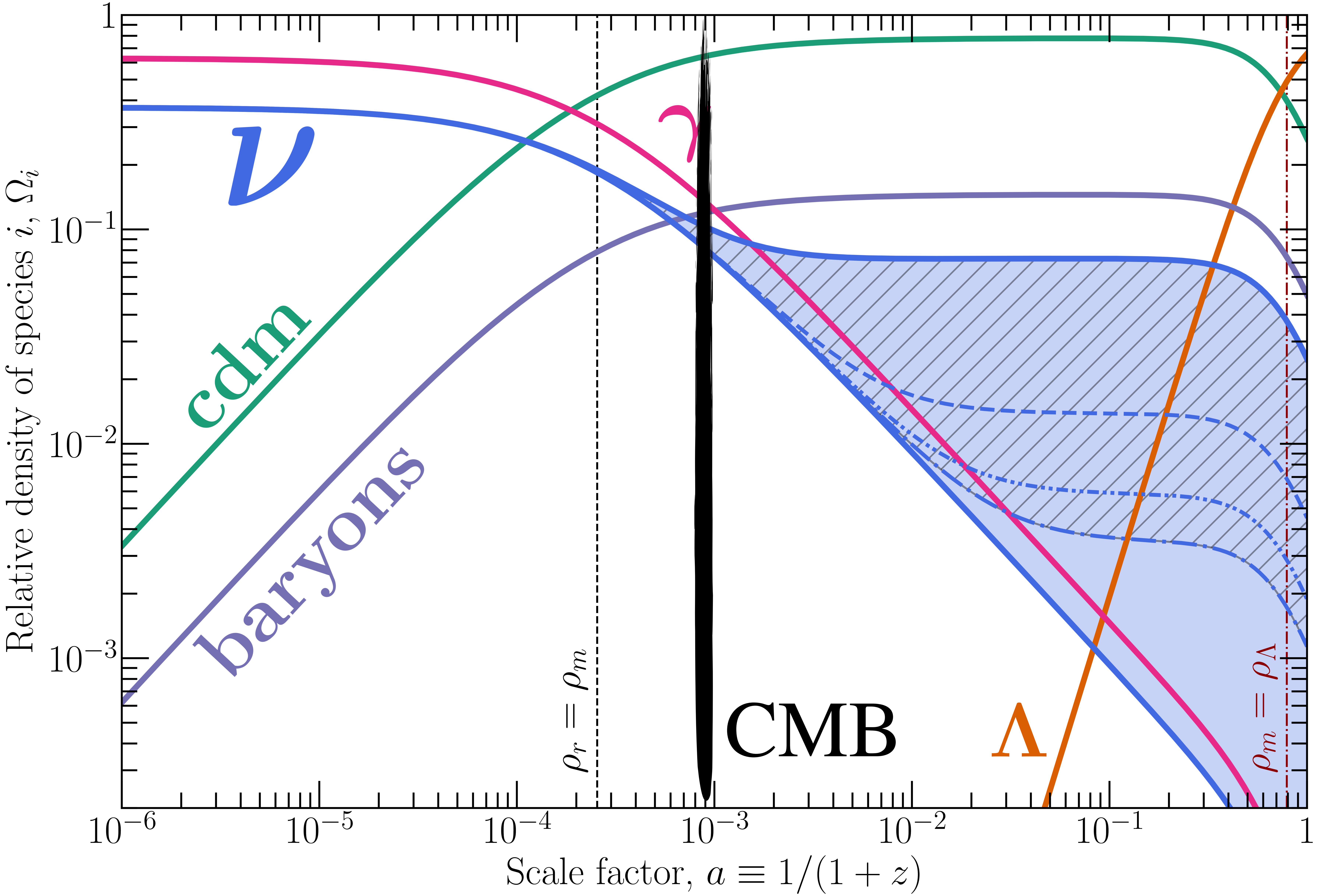


In the neutrino case:
what is cosmology measuring?

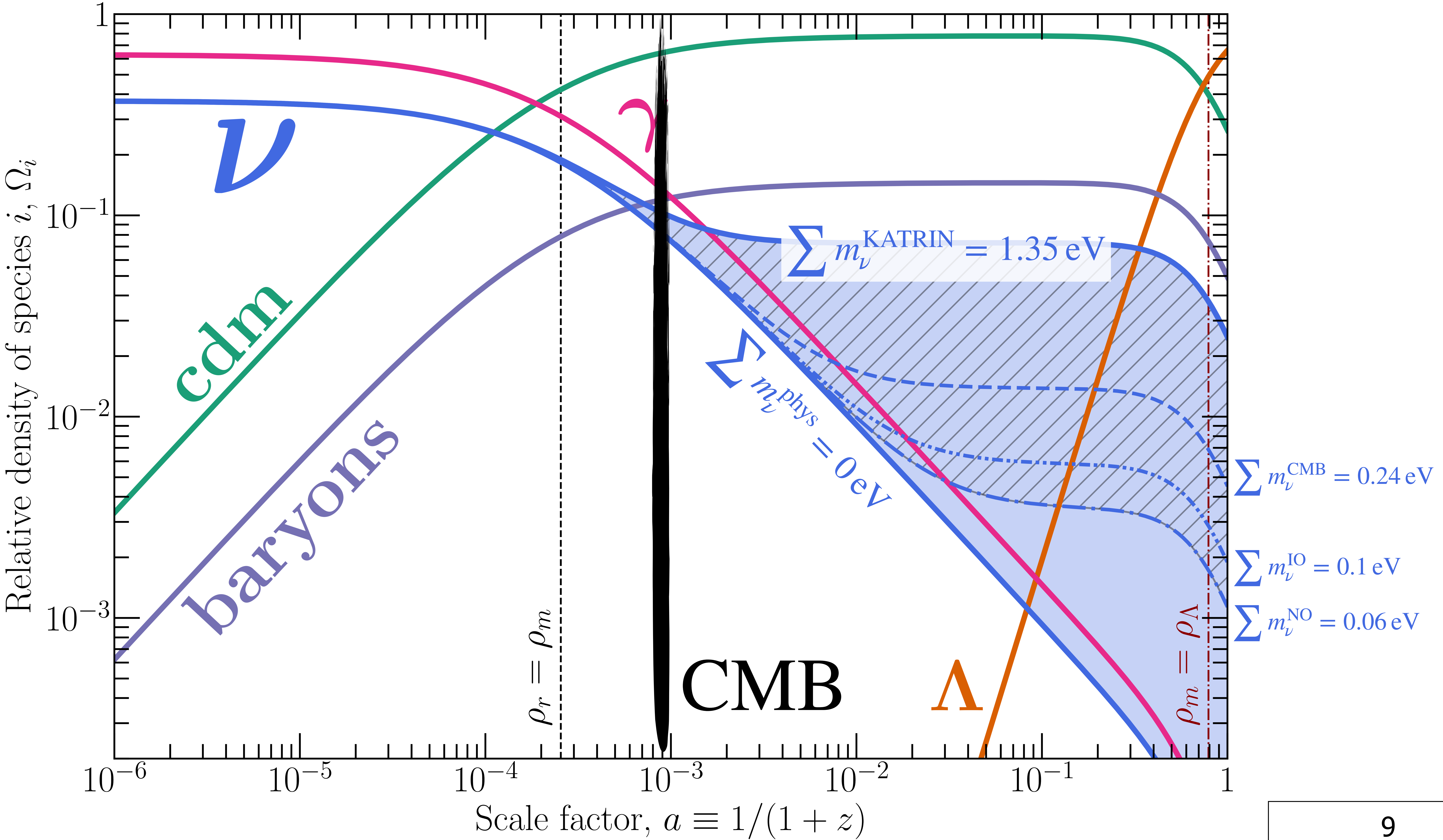
Background evolution (energy)



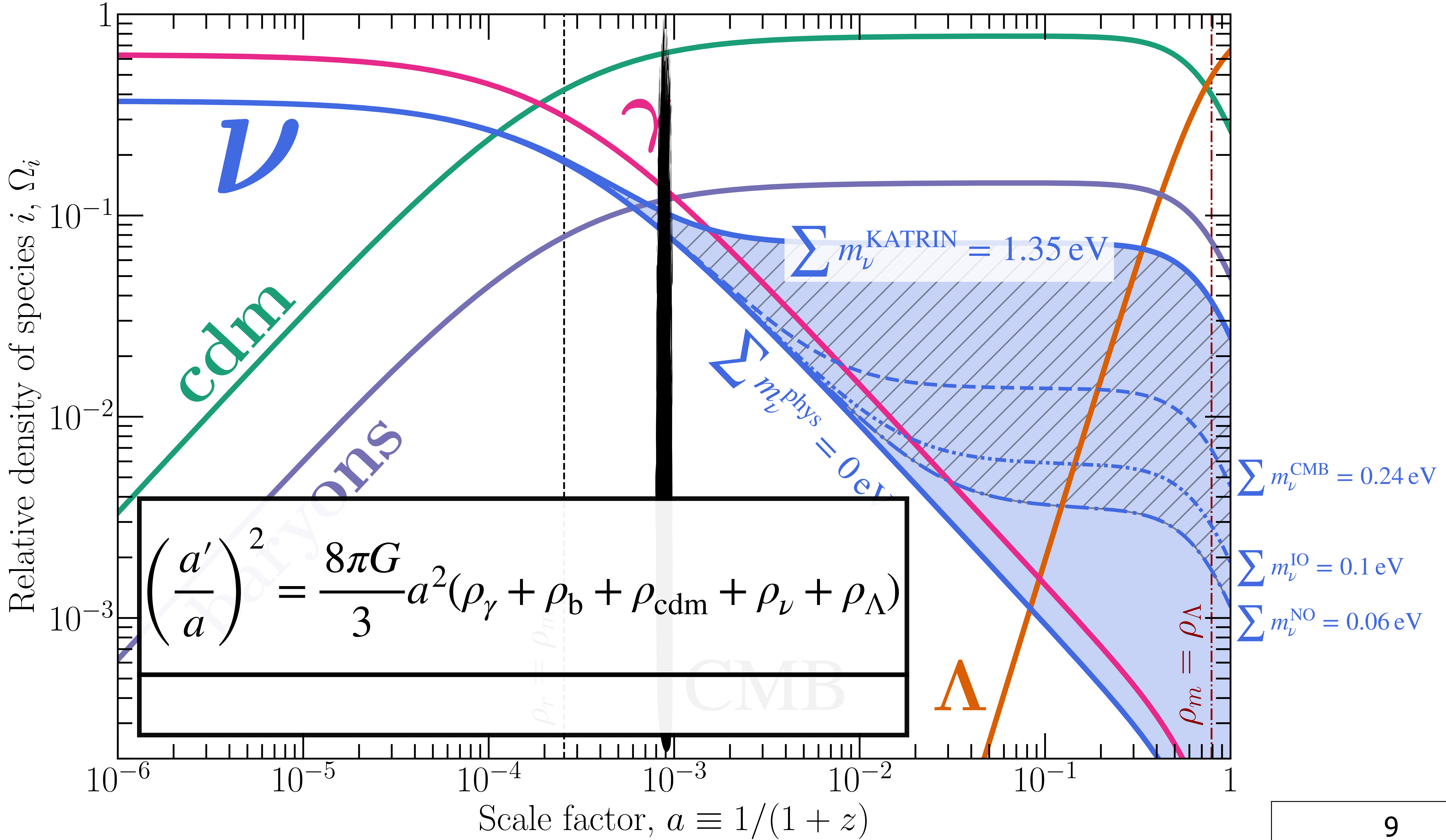
Background evolution



Background evolution



Background evolution



$$\left(\frac{a'}{a}\right)^2 = \frac{8\pi G}{3} a^2 (\rho_\gamma + \rho_{\rm b} + \rho_{\rm cdm} + \rho_\nu + \rho_\Lambda)$$

Background evolution

Friedmann equation:

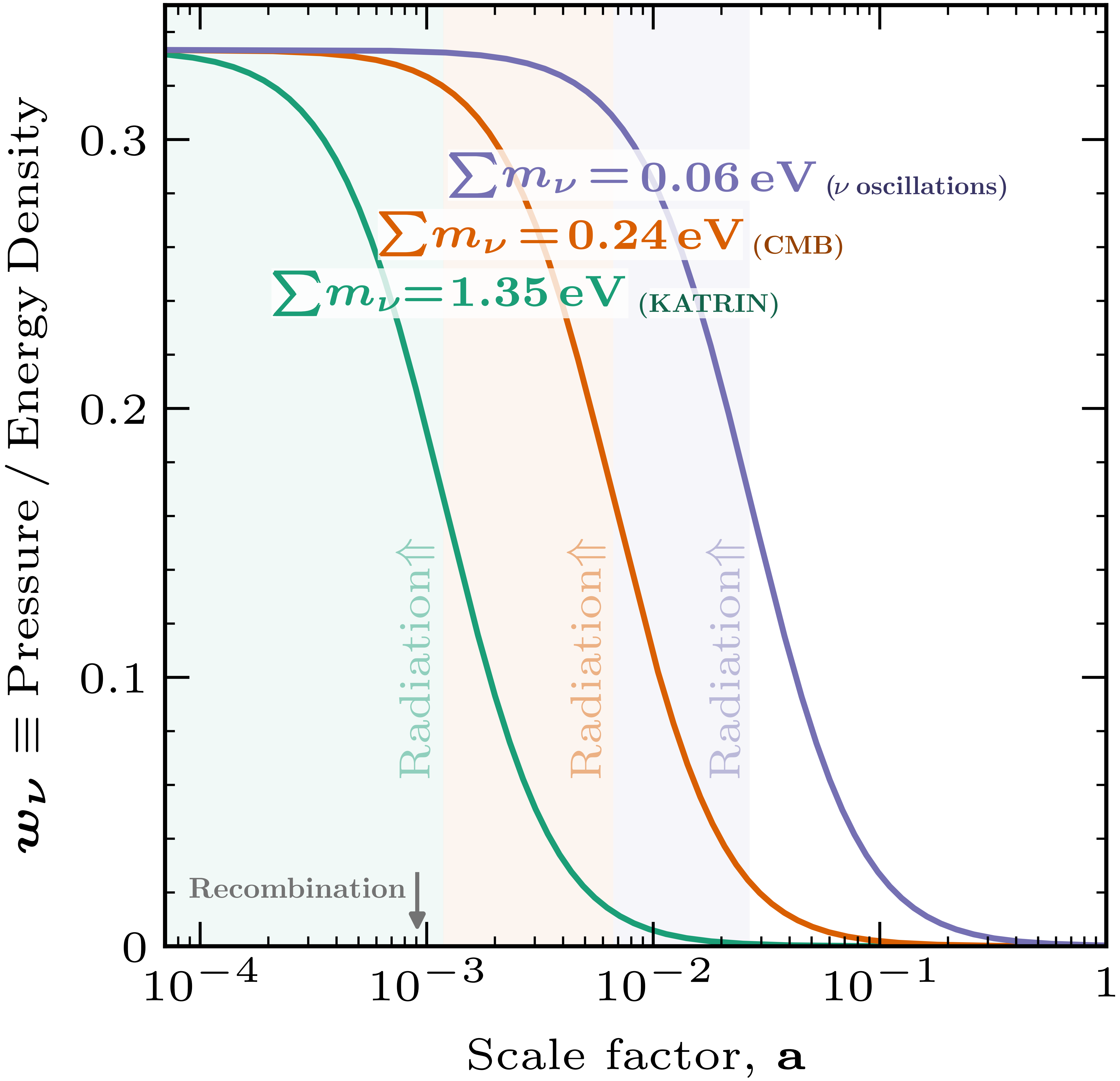
$$\left(\frac{a'}{a}\right)^2 = \frac{8\pi G}{3}a^2(\rho_\gamma + \rho_\mathrm{b} + \rho_\mathrm{cdm} + \rho_\nu + \rho_\Lambda)$$

Neutrino energy density evolution:

$$\frac{1}{\rho_\nu}\frac{\mathrm{d}\rho_\nu}{\mathrm{d}\ln a} = -3[1 + w_\nu(a)]$$

Equation of state controls energy dilution:

$$w_\nu(a, m_\nu) = \frac{P_\nu}{\rho_\nu}$$



Perturbations evolution (kinematics)

Neutrino sources

$\delta \equiv \frac{\delta\rho}{\rho}$ *density contrast*

$\theta \sim \vec{\nabla} \cdot \vec{v}$ *velocity divergence*

$c^2_{\rm eff} \equiv \frac{\delta P}{\delta \rho}$ *isotropic momentum flux*

σ *neutrino momentum anisotropy*

Neutrino model

Perturbed Einstein equations

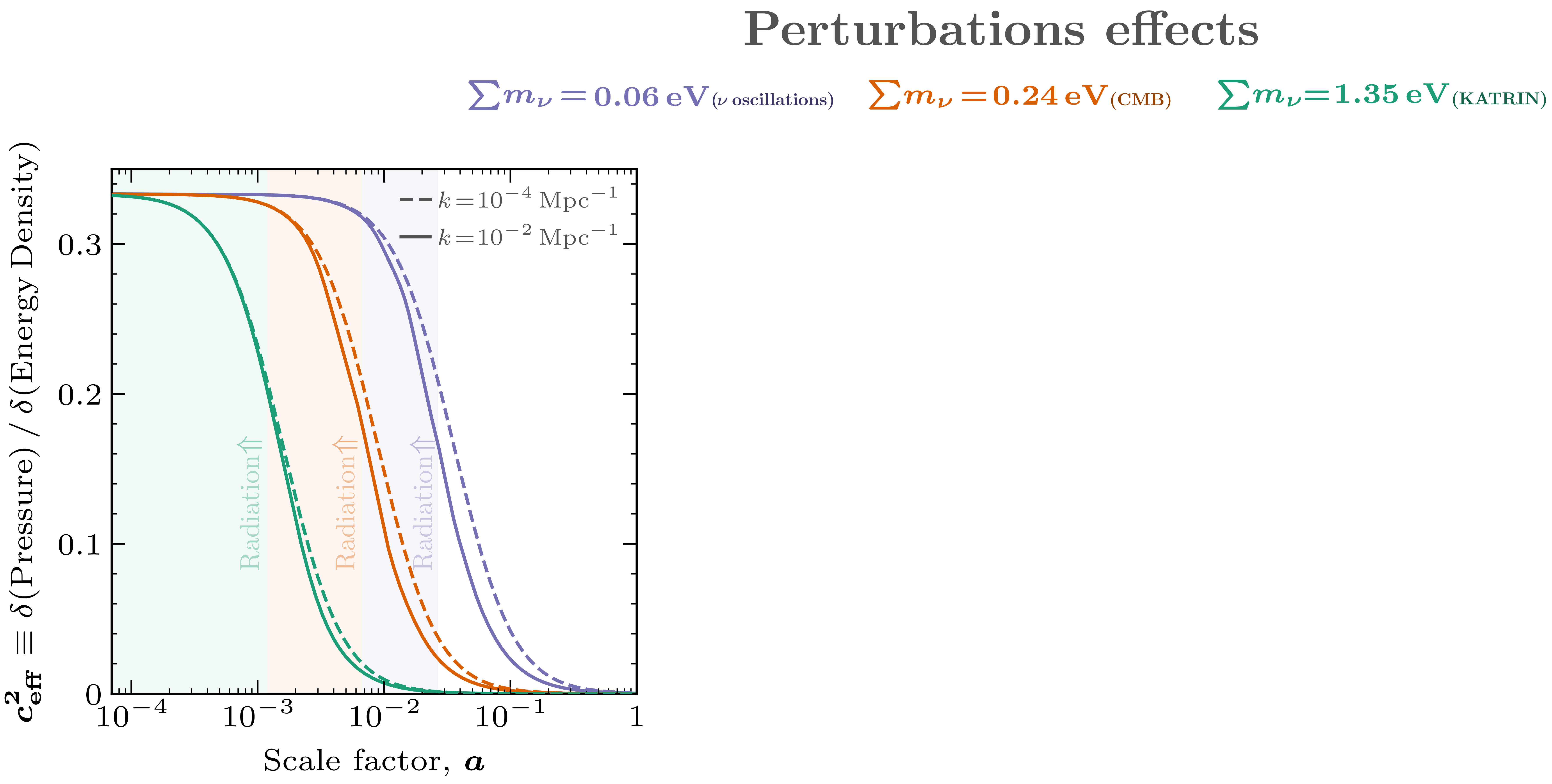
$$\delta G_{\mu\nu} = 8\pi G\, \delta T_{\mu\nu}$$

Sources evolution

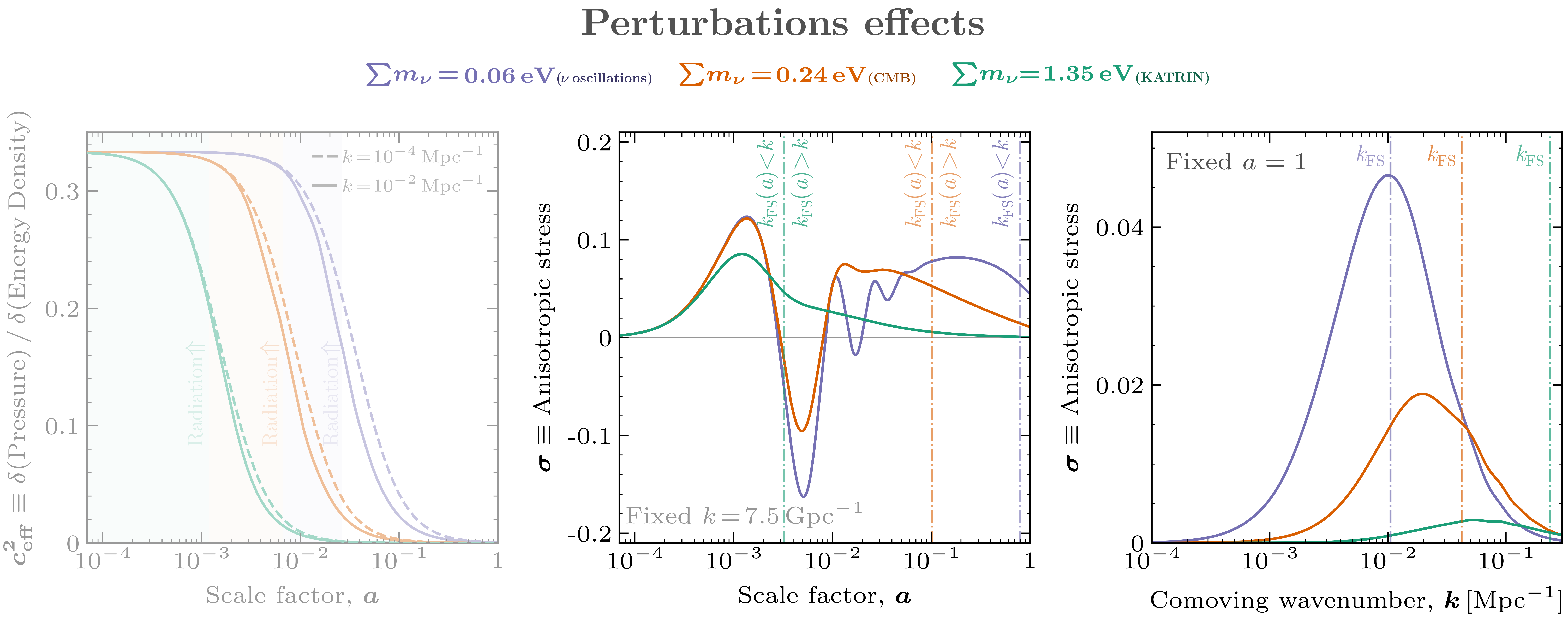
$$\delta' = -(1+w_\nu)\theta + 3(1+w_\nu)\phi' - 3\frac{a'}{a}\left(c_s^2 - w_\nu\right)\delta$$

$$\theta' = -\frac{a'}{a}(1-3c_{\rm ad}^2)\theta + \frac{c_s^2}{1+w_\nu}k^2\delta - k^2\sigma + k^2\psi$$

Perturbations evolution

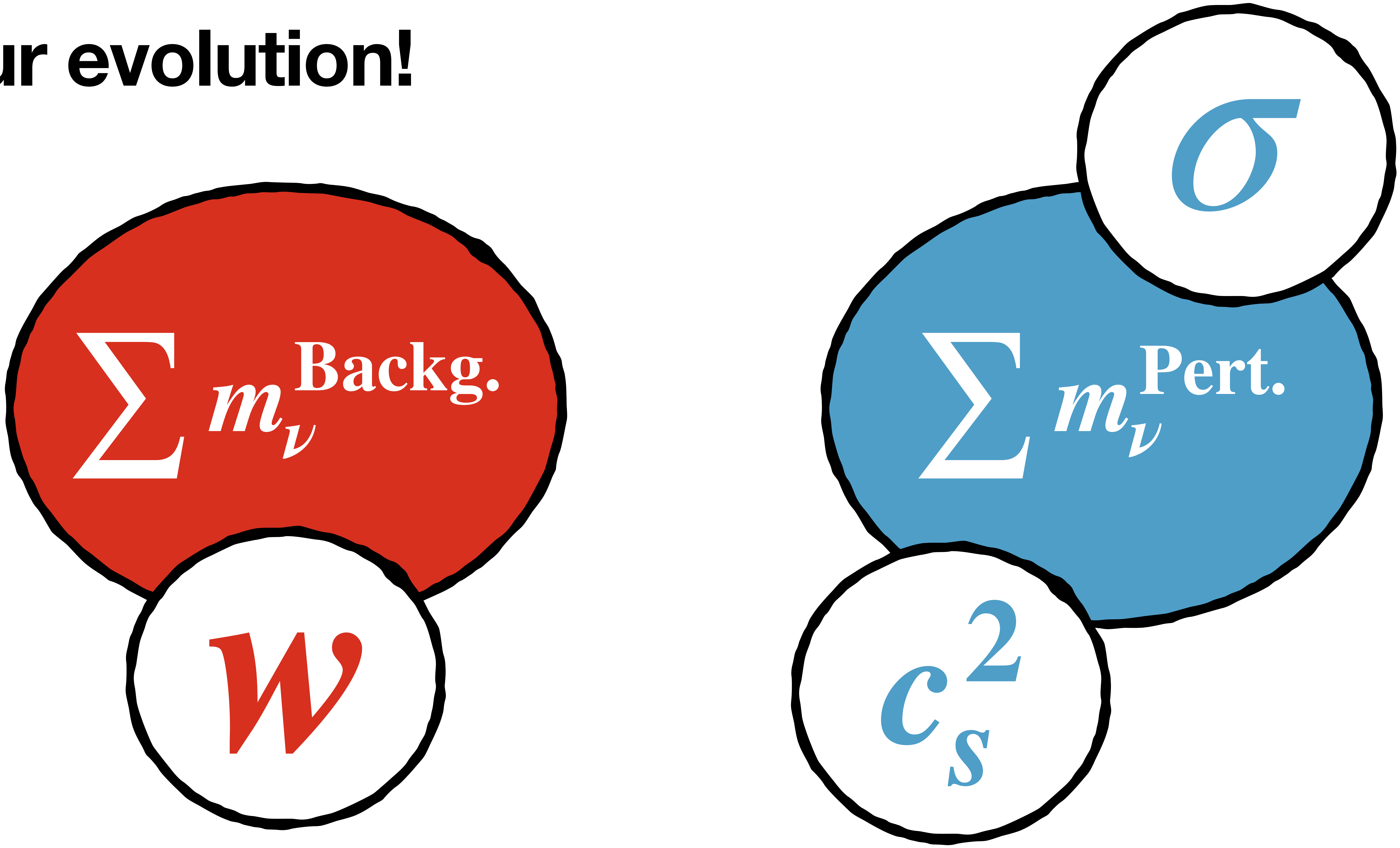


Perturbations evolution

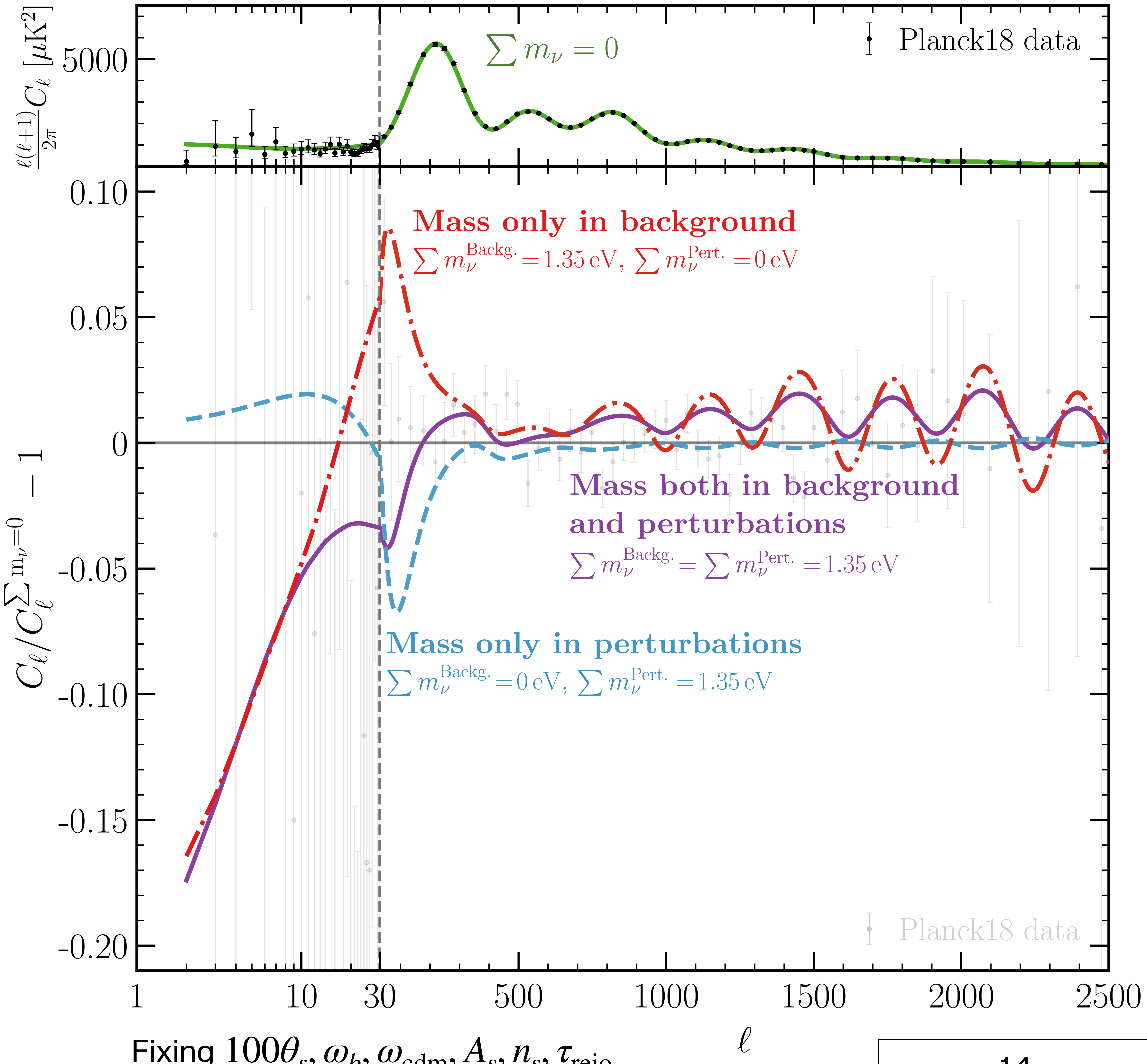


$$k_{\rm FS}(a) \simeq 0.776 \frac{a^2 H(a)}{H_0} \left(\frac{m_\nu}{1\,\text{eV}} \right) h \text{ Mpc}^{-1}$$

Our evolution!



CMB effects

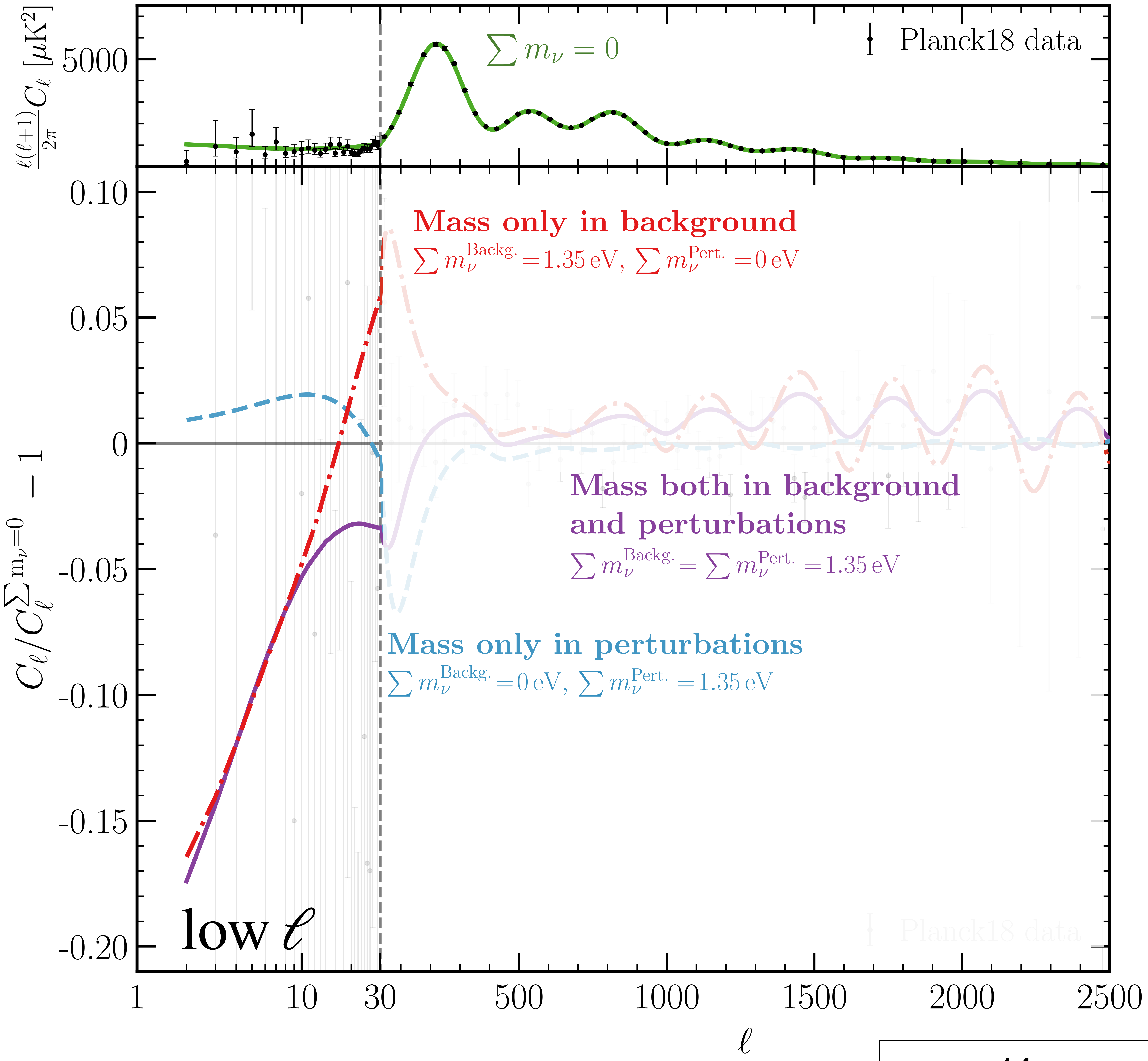


Fixing $100\theta_s, \omega_b, \omega_{\rm cdm}, A_s, n_s, \tau_{\rm reio}$

CMB effects

low ℓ

Tiny constraining power, mostly background



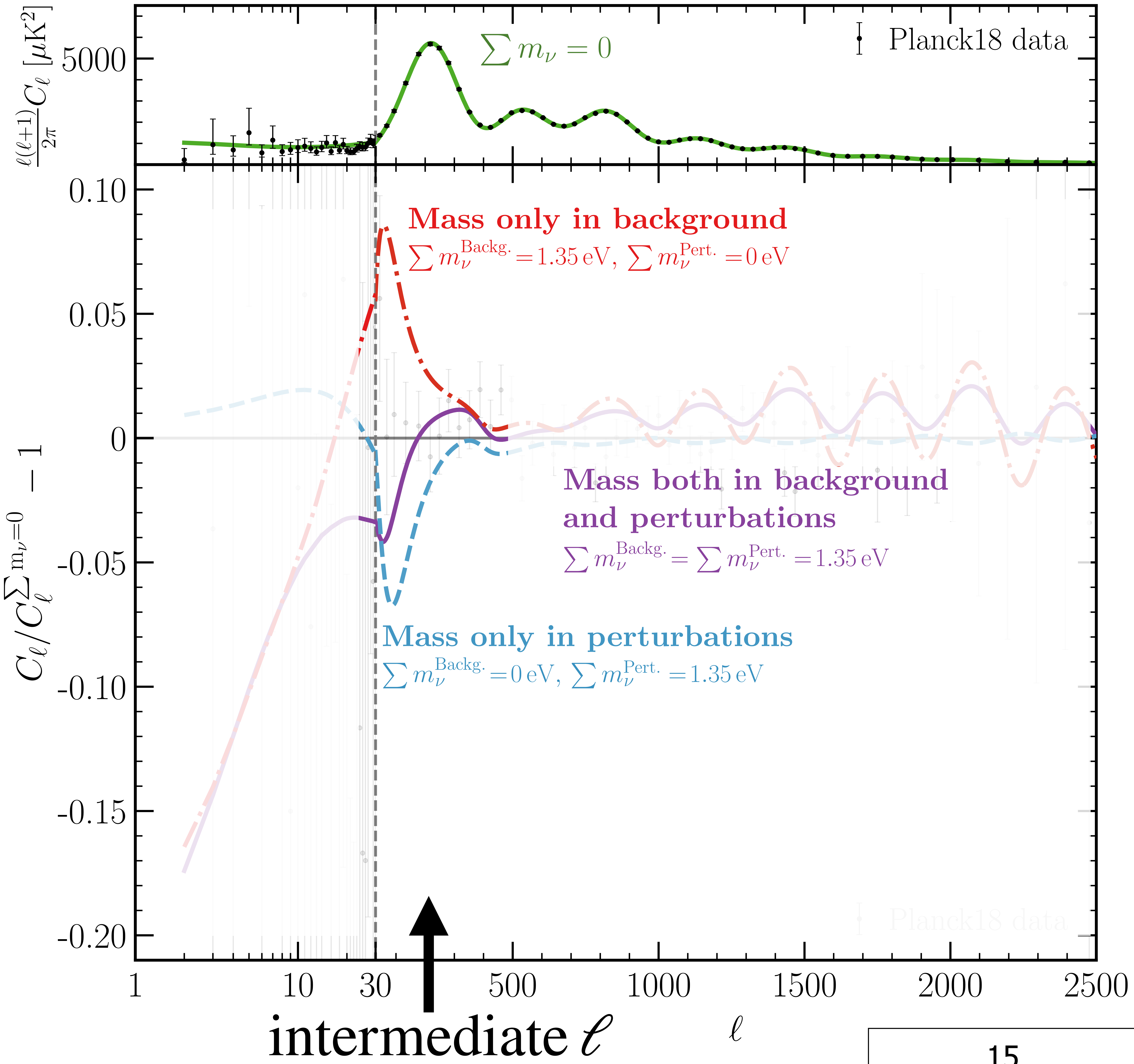
CMB effects

low ℓ — Tiny constraining power, mostly background

intermediate ℓ

$\uparrow \sum m_\nu^{\text{Backg.}} \rightarrow$ Higher expansion rate, more decay of grav. pot.

$\uparrow \sum m_\nu^{\text{Pert.}} \rightarrow$ Higher clustering, less decay of grav. pot.



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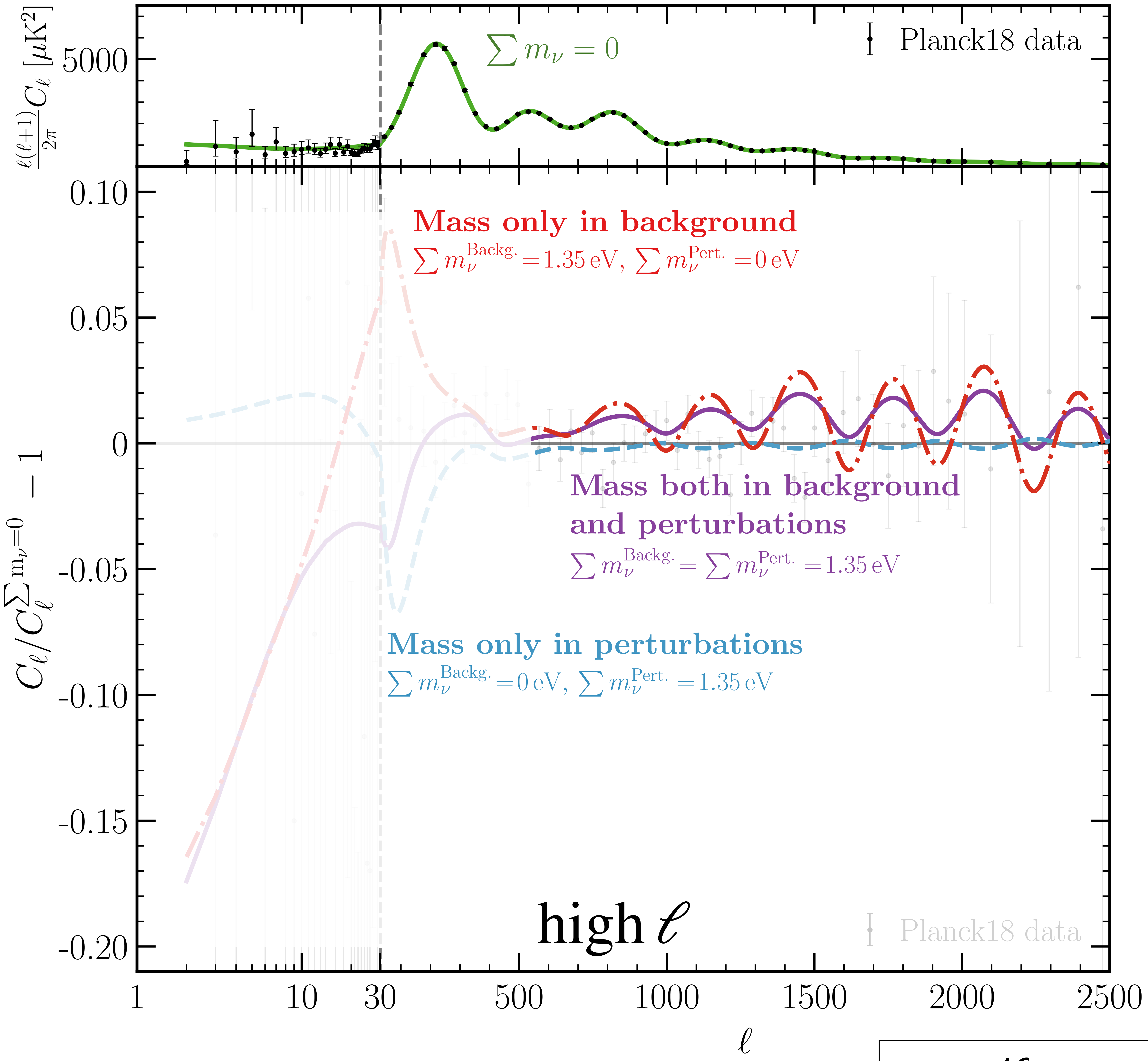
high ℓ

$\uparrow \sum m_\nu^{\text{Backg.}} \rightarrow$ Higher expansion rate, lower diffusion damping



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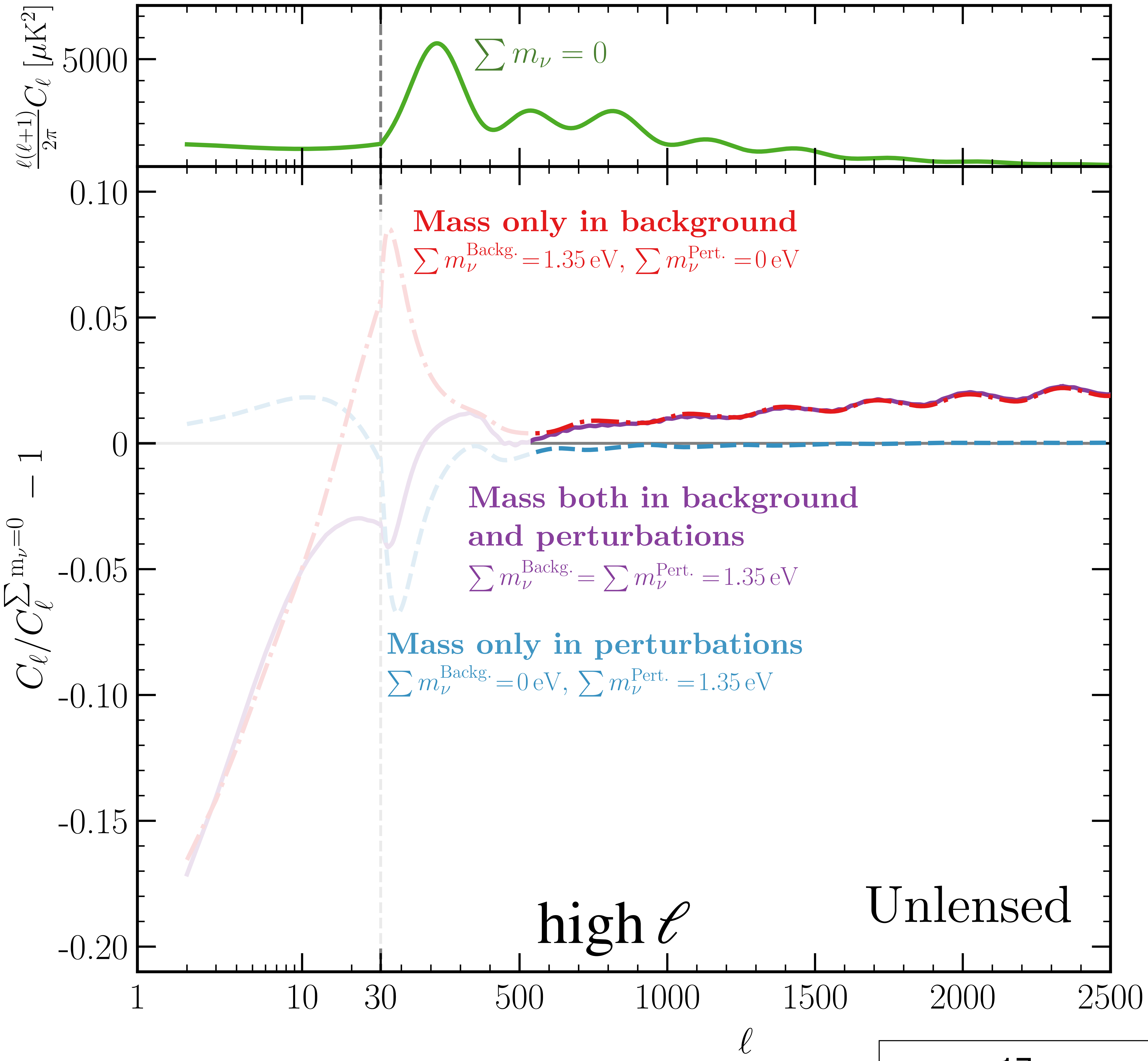

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high ℓ

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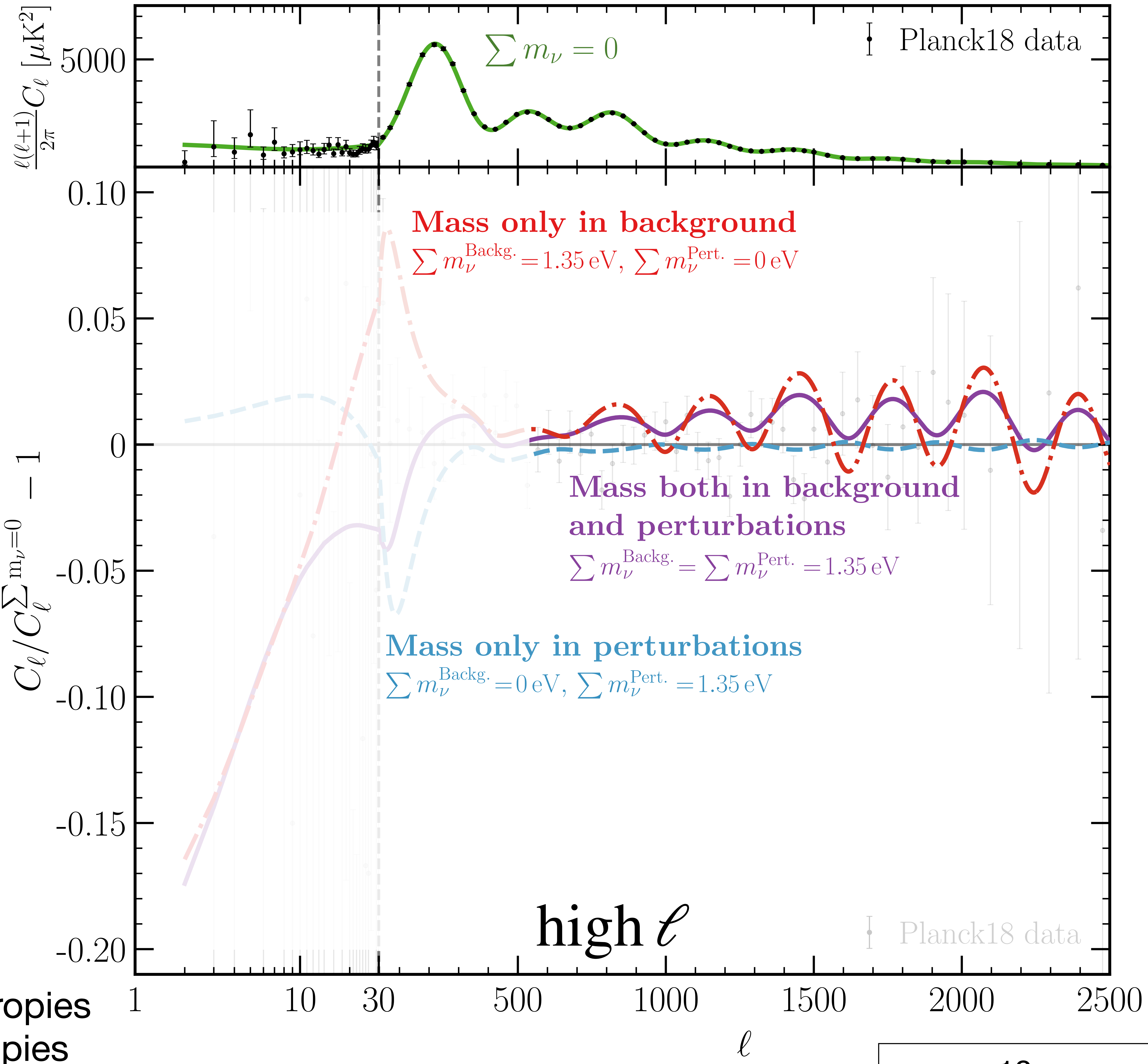
+ same effects than intermediate ℓ affecting lensing: Backg: less lensing, boost anisotropies
Pert: more lensing, erase anisotropies



CMB effects

low ℓ — Tiny constraining power, mostly background

intermediate ℓ

$\uparrow \sum m_\nu^{\text{Backg.}}$ … e, … grav. pot.

Intermediate ℓ measure Pert.

… Higher clustering, less decay of grav. pot.

high ℓ

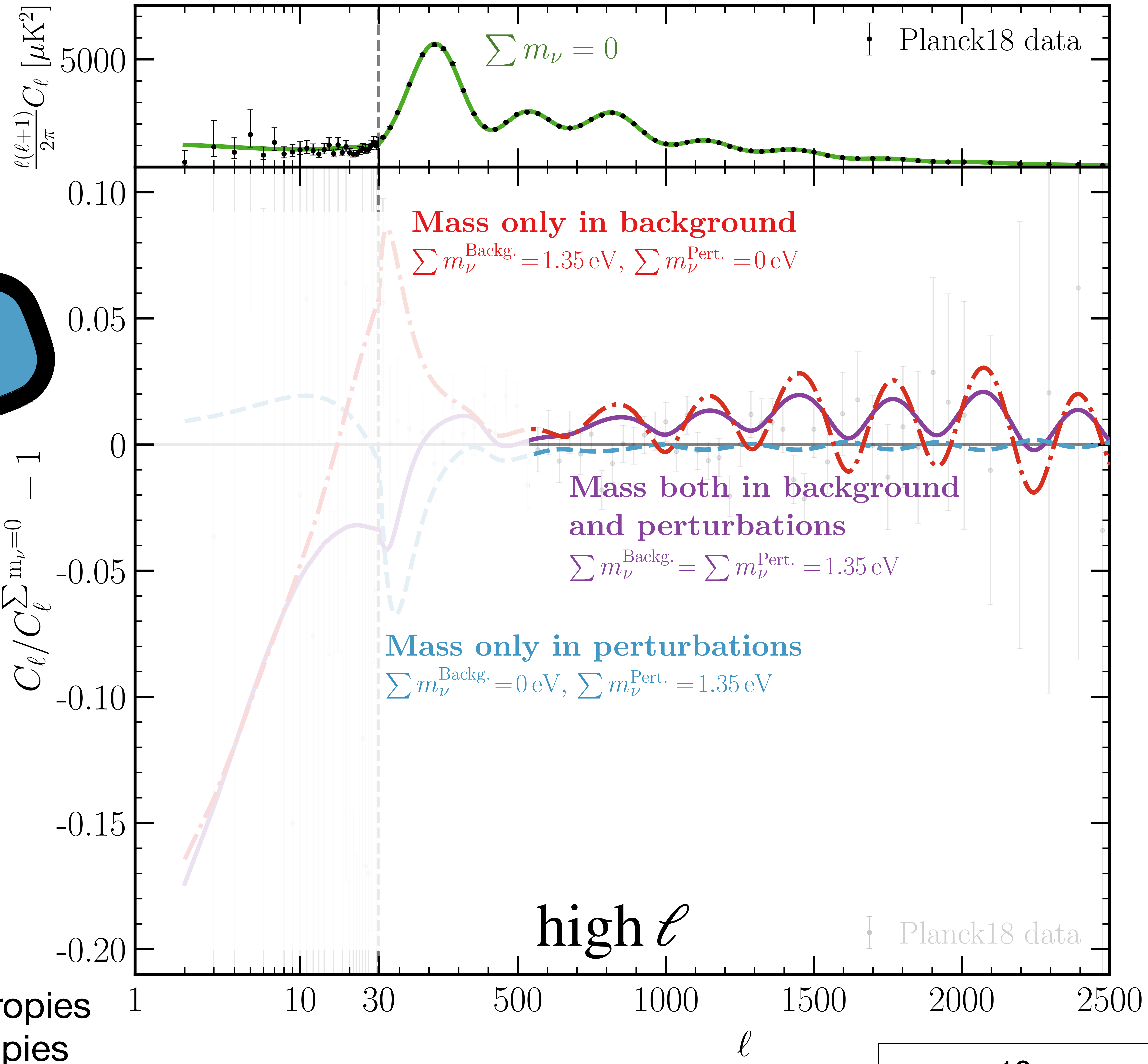
$\uparrow \sum m_\nu^{\text{Backg.}} \rightarrow$ High … ping

High ℓ measure Backg.

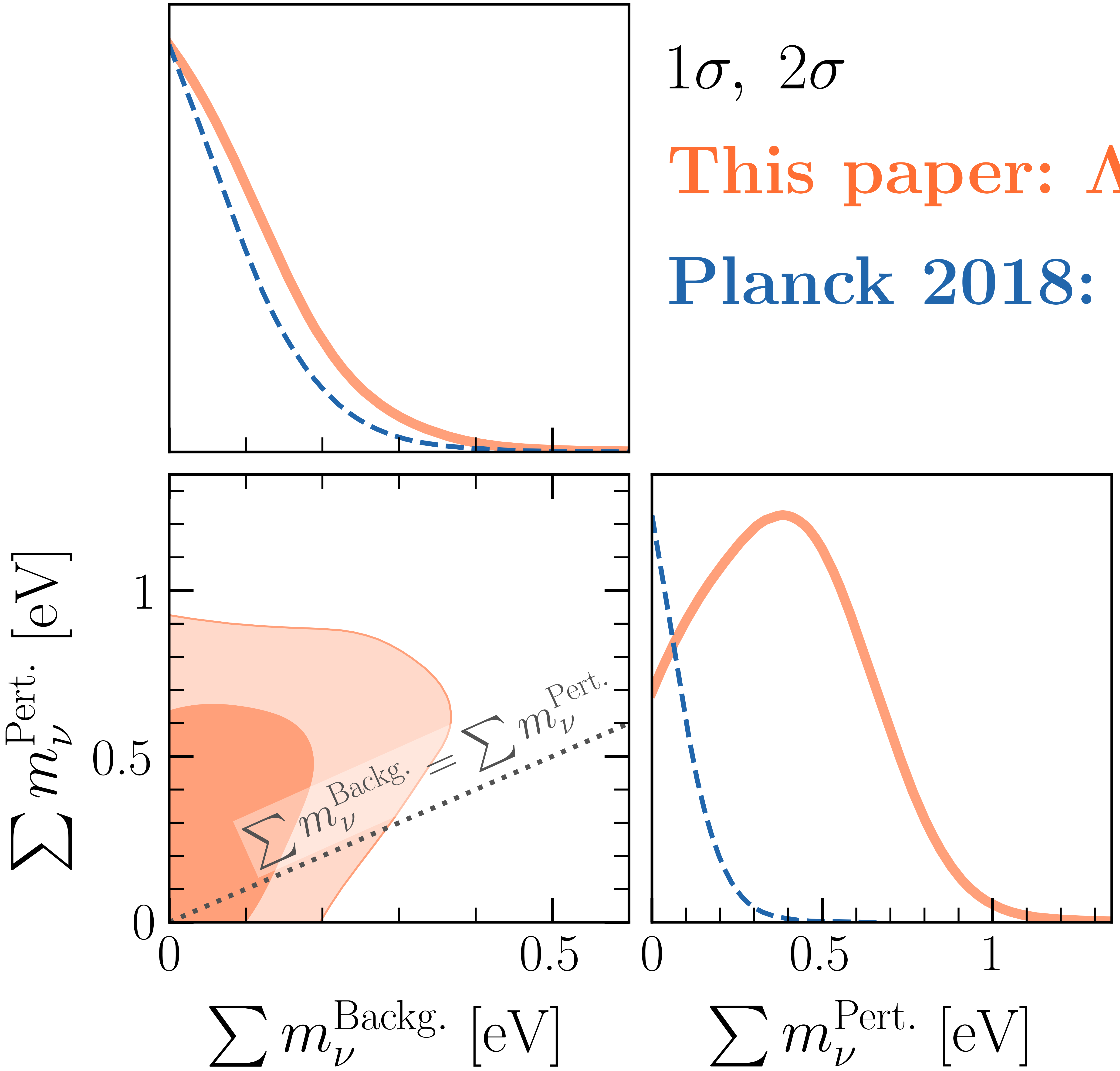
+ sa… ediate ℓ affecting

l… g: less lensing, boost anisotropies

Pert: more lensing, erase anisotropies



Results

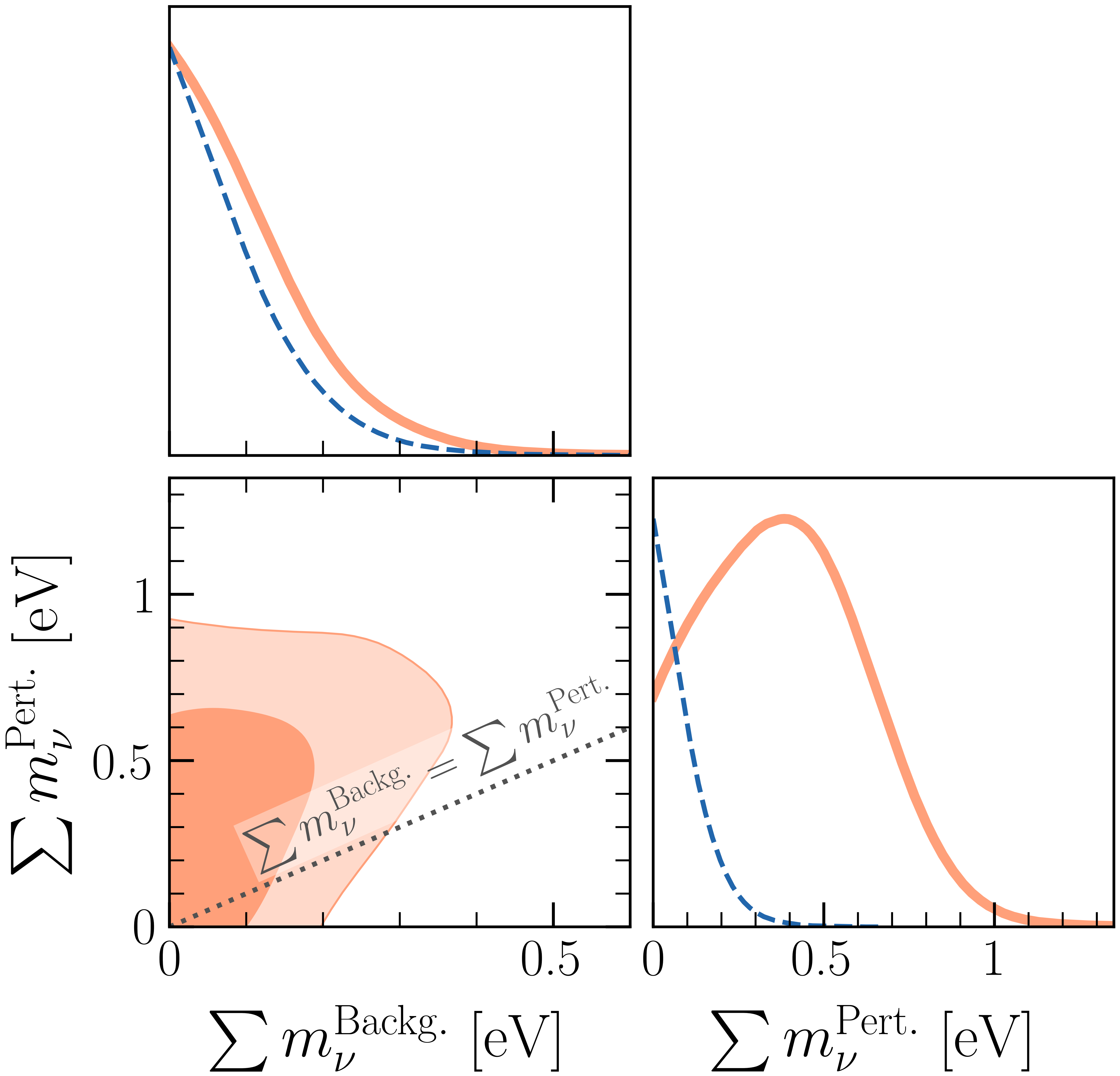


$1\sigma,\ 2\sigma$

This paper: ΛCDM $+ \sum m_\nu^{\text{Backg.}} + \sum m_\nu^{\text{Pert.}}$

Planck 2018: ΛCDM $+ \sum m_\nu$

Results



$\sum m_\nu < 0.24\,\mathrm{eV}$ (PLANCK 2018)

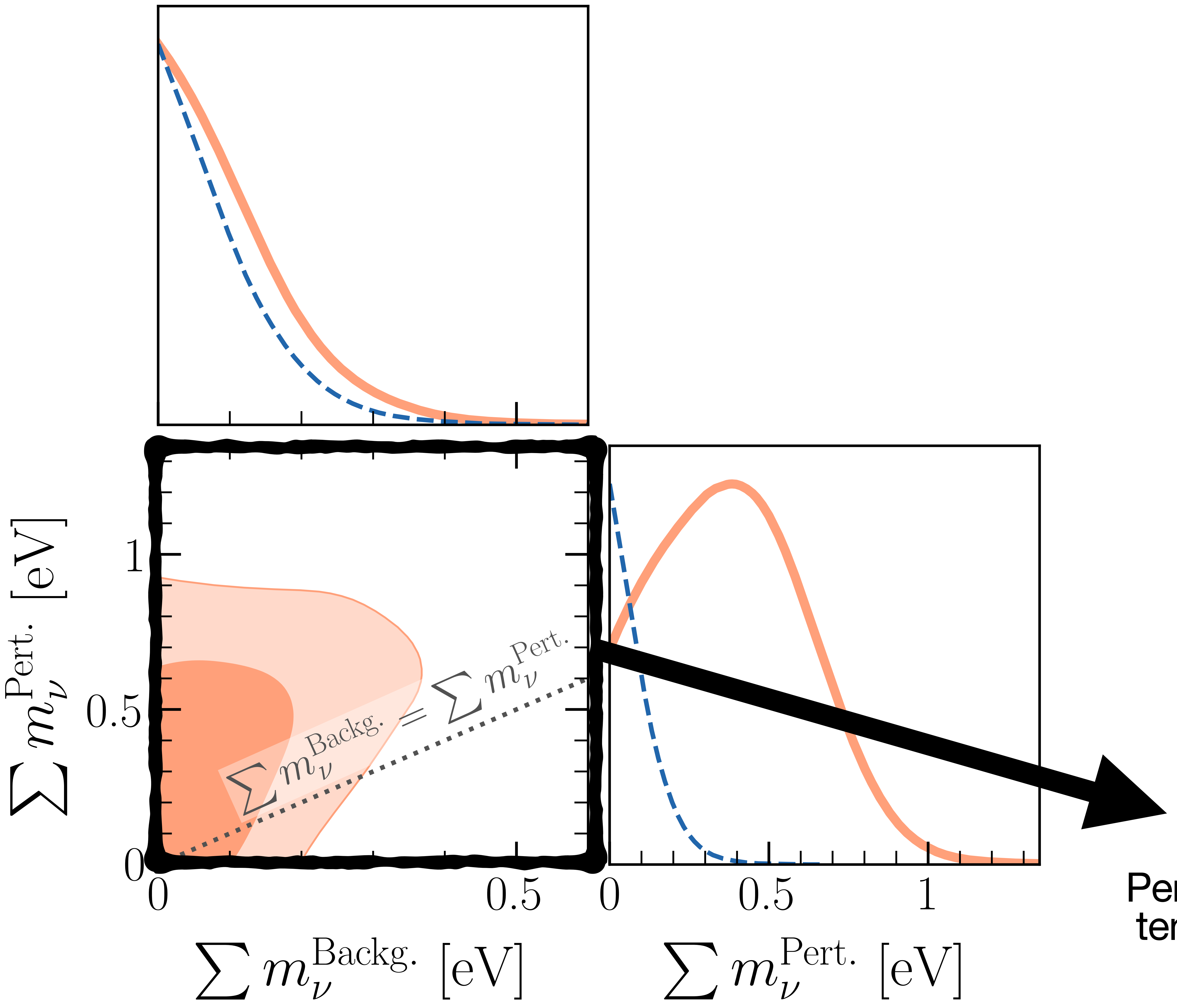
$\sum m_\nu^{\mathrm{Backg.}} < 0.29\,\mathrm{eV}$

(This work)

$\sum m_\nu^{\mathrm{Pert.}} < 0.79\,\mathrm{eV}$

95% CL

Results



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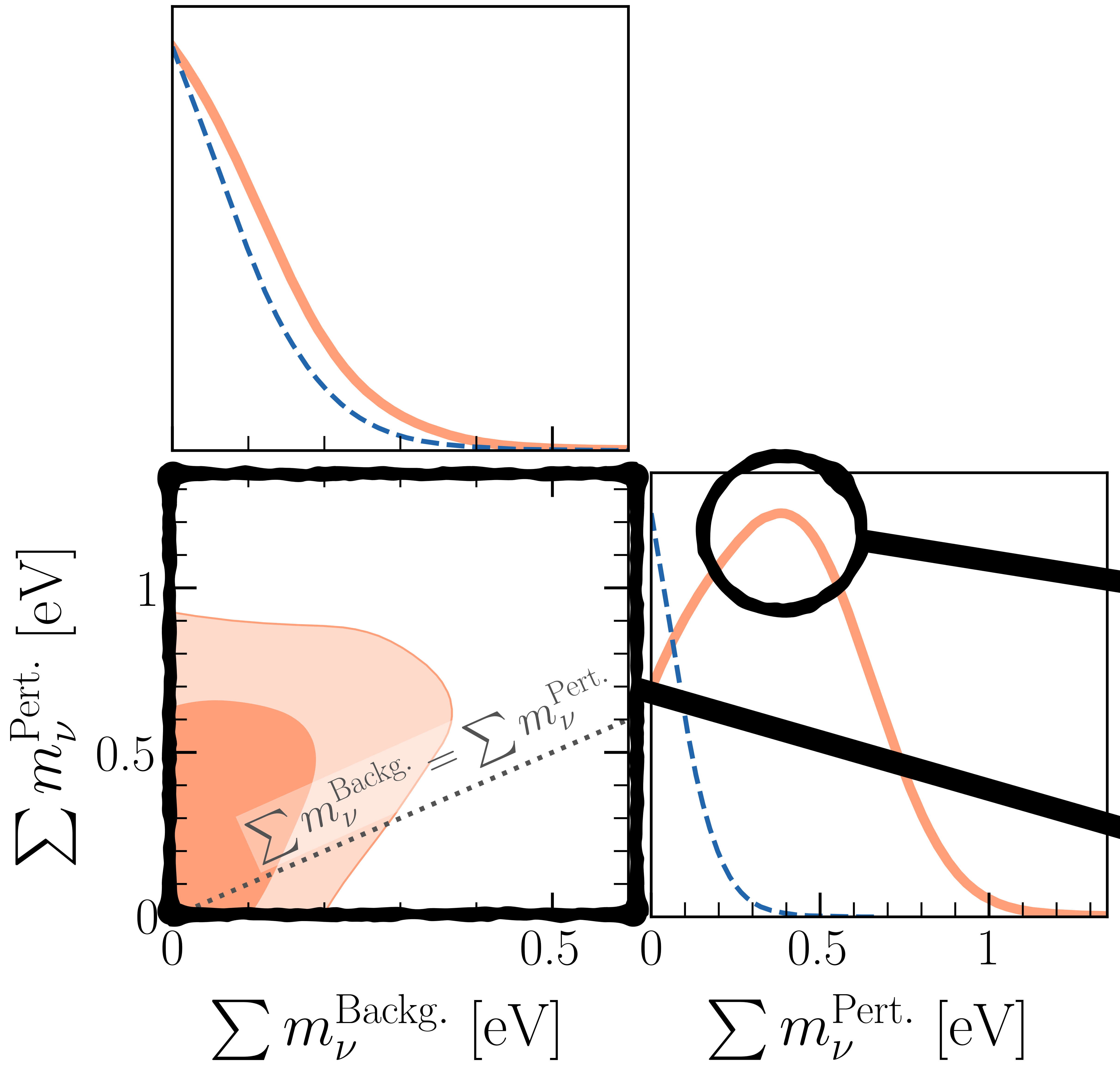
95% CL

Degeneracy!

Perturbations mass helps in accommodating the tension at high multipoles of background mass.

Results



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(This work)

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95% CL

Mass? Probably lensing anomaly feature

(Planck 2018 wants more lensing)

Degeneracy!

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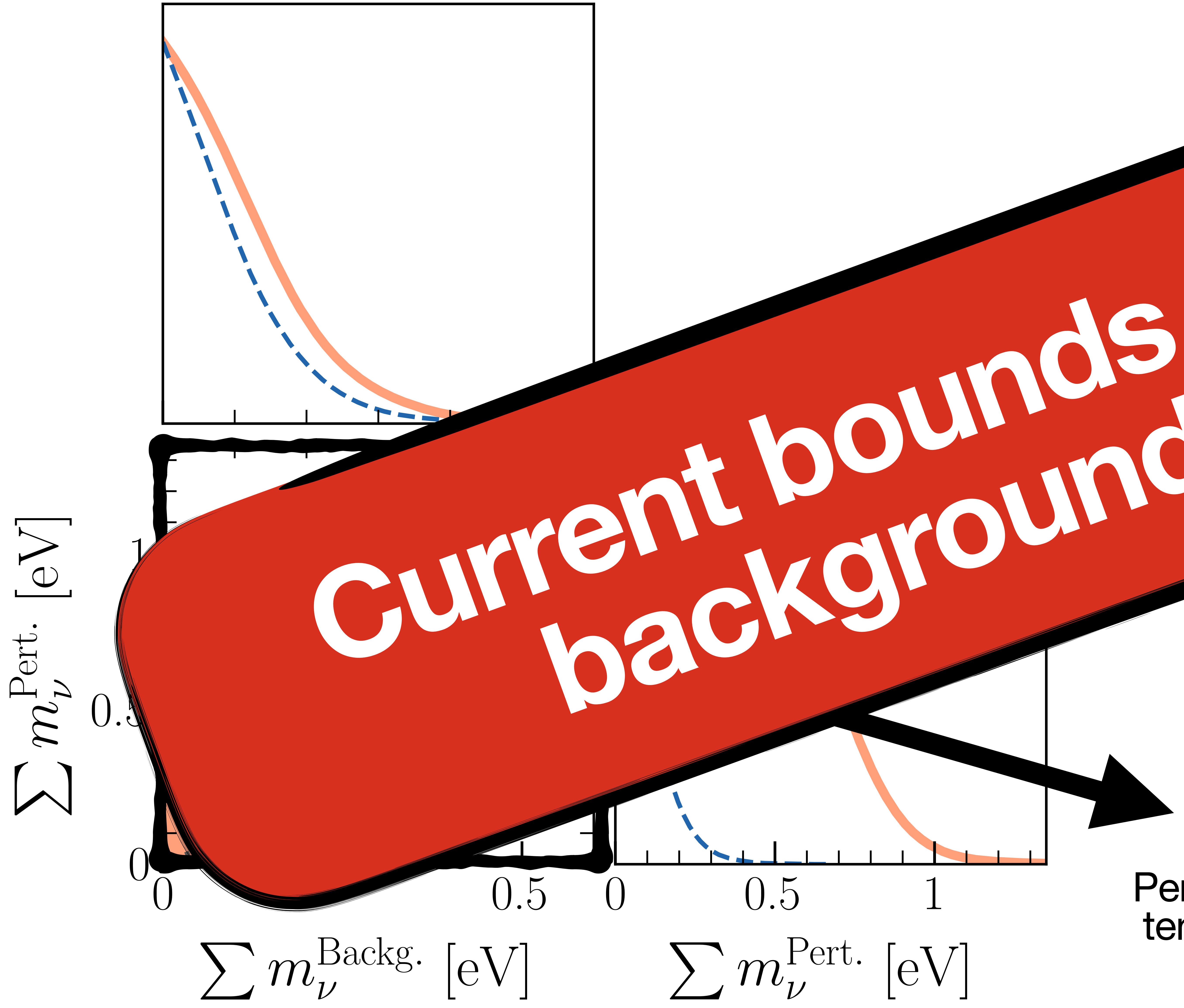
Results

$\sum m_\nu < 0.24\,\mathrm{eV}$ (PLANCK 2018)

work)

95% CL

Current bounds come from background effects!



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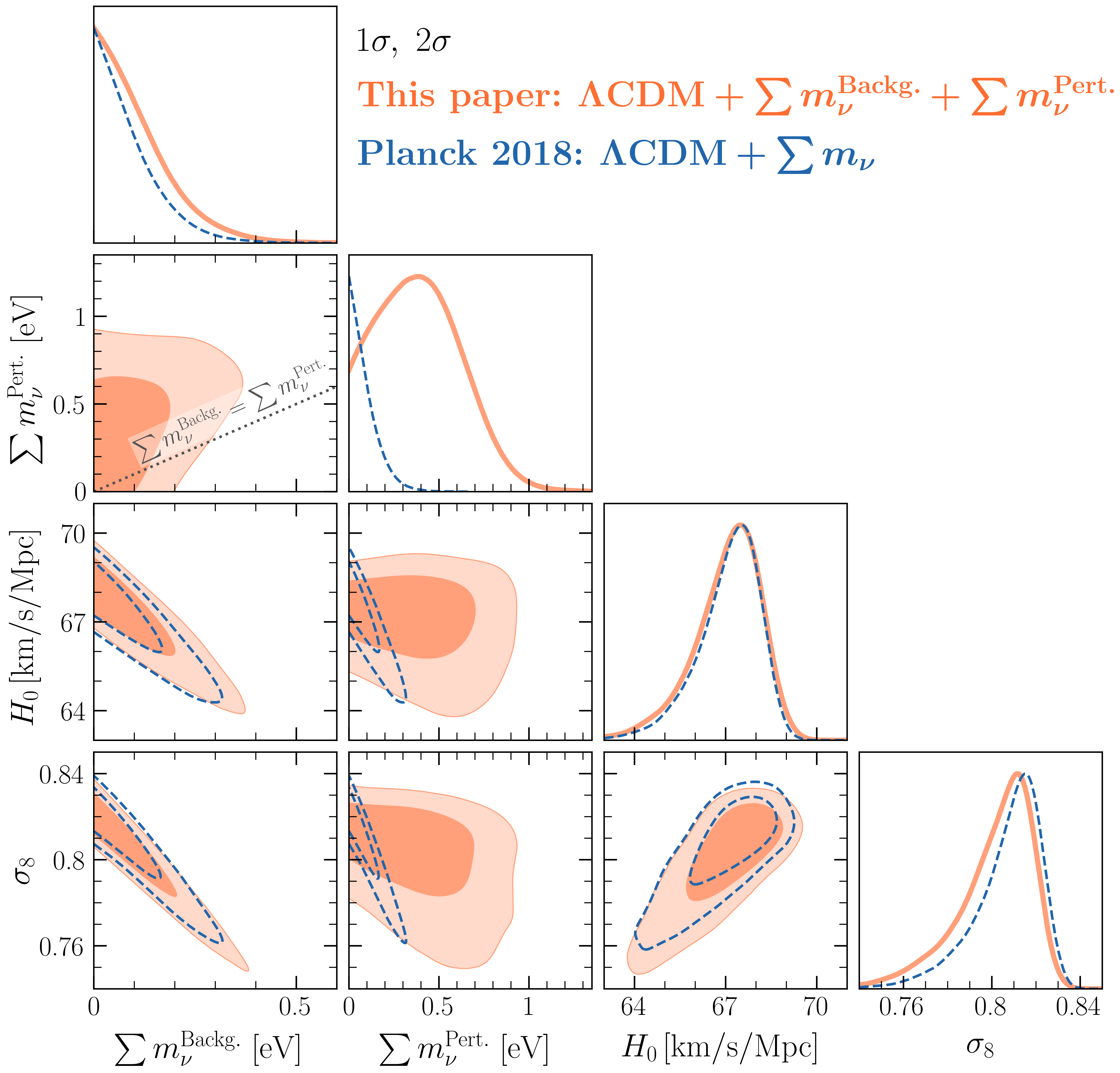
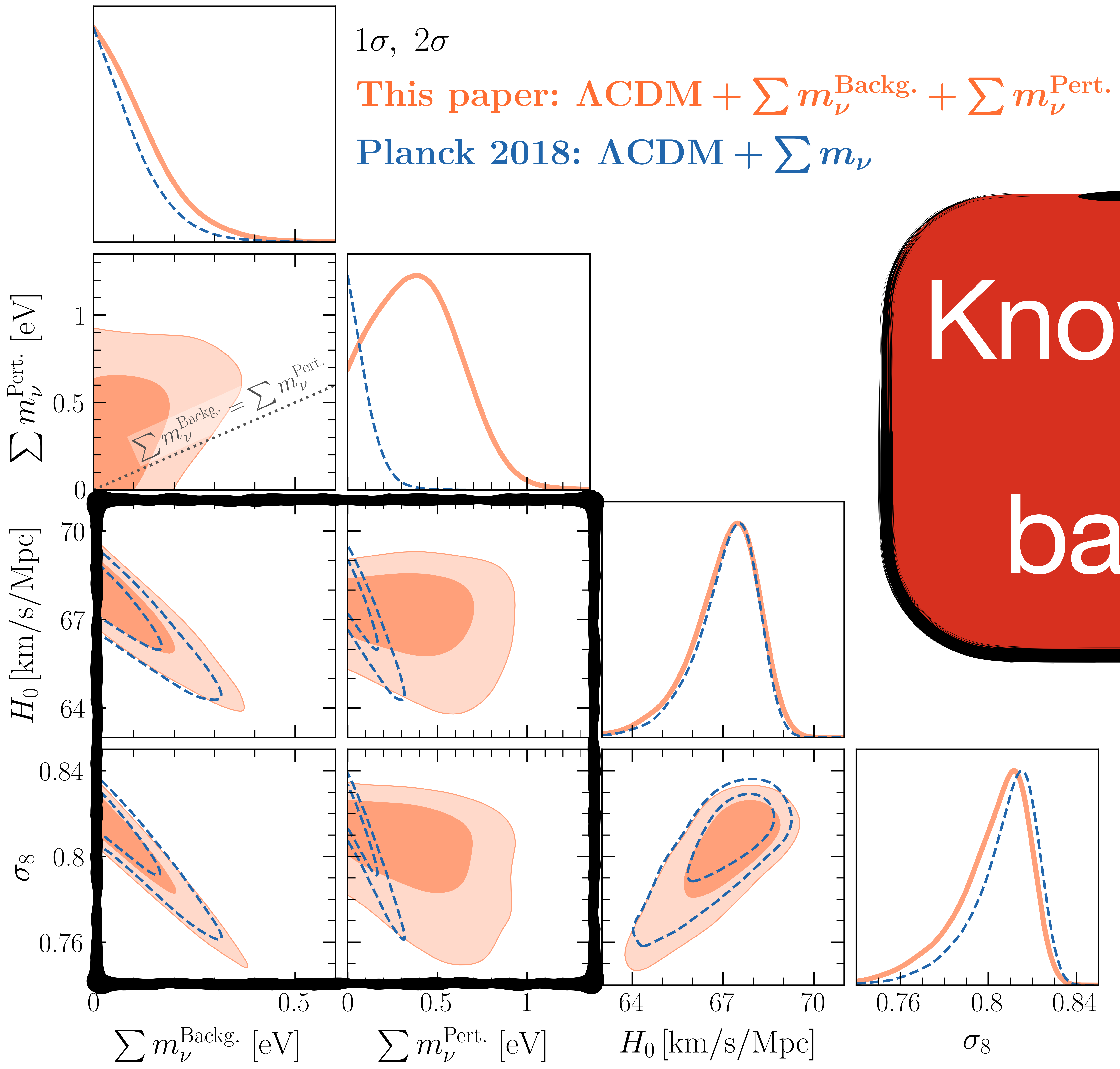


$1\sigma,\ 2\sigma$
This paper: ΛCDM $+ \sum m_\nu^{\rm Backg.} + \sum m_\nu^{\rm Pert.}$
Planck 2018: ΛCDM $+ \sum m_\nu$
$\sum m_\nu^{\rm Backg.} = \sum m_\nu^{\rm Pert.}$
$\sum m_\nu^{\rm Pert.}$ [eV]
H_0 [km/s/Mpc]
σ_8
$\sum m_\nu^{\rm Backg.}$ [eV]
0
0.5
1
64
67
70
0.76
0.8
0.84

Results



Known degeneracies are at the background level!

Degeneracies due to the total energy density contribution of neutrinos.

Take home message:

- Cosmological bounds on neutrino masses come from the **background** evolution.

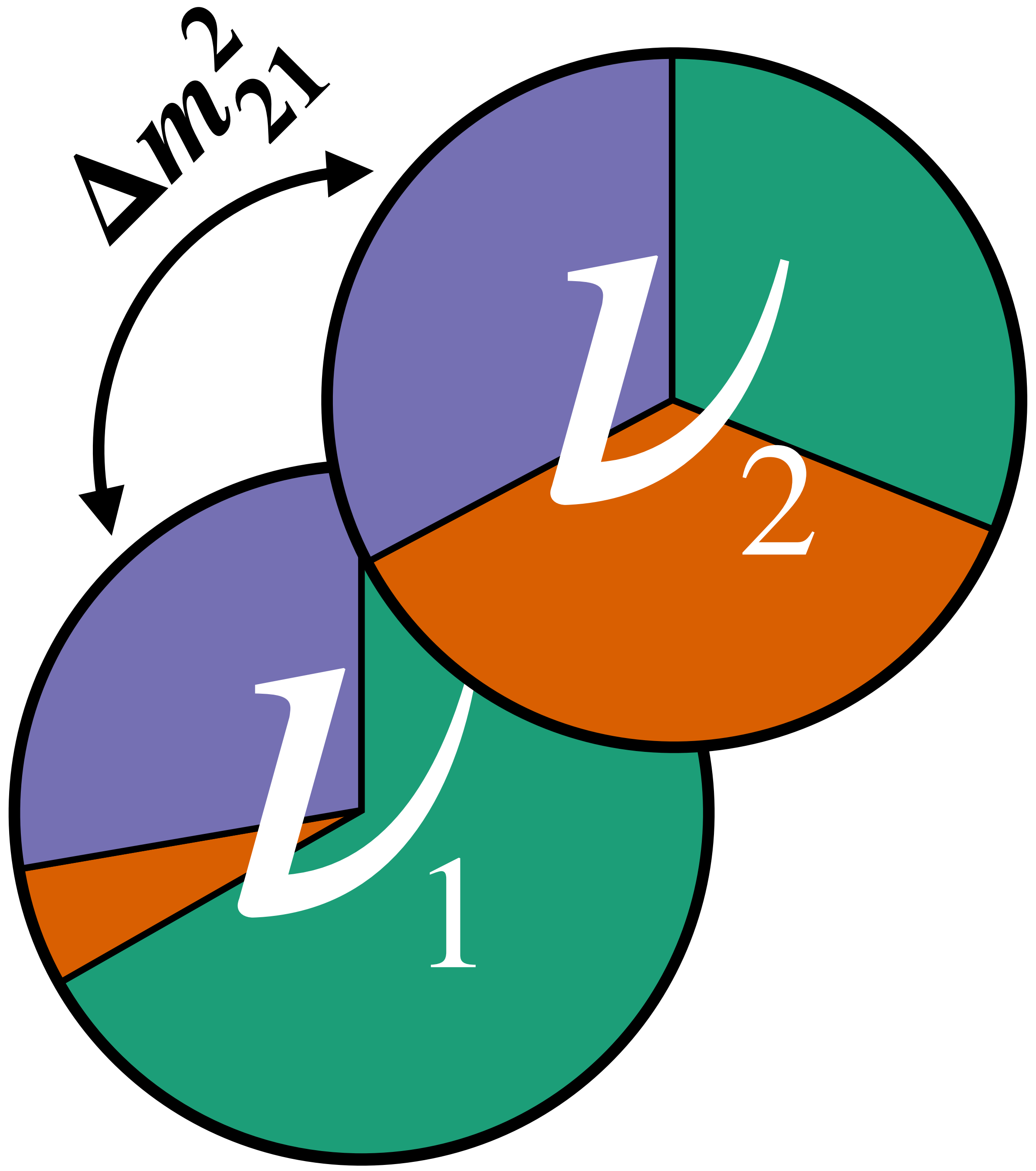
- Standard constraints apply to Background mass while Perturbations mass gets relaxed to $\sum m_\nu^{\text{Pert.}} < 0.8\,\text{eV}$.

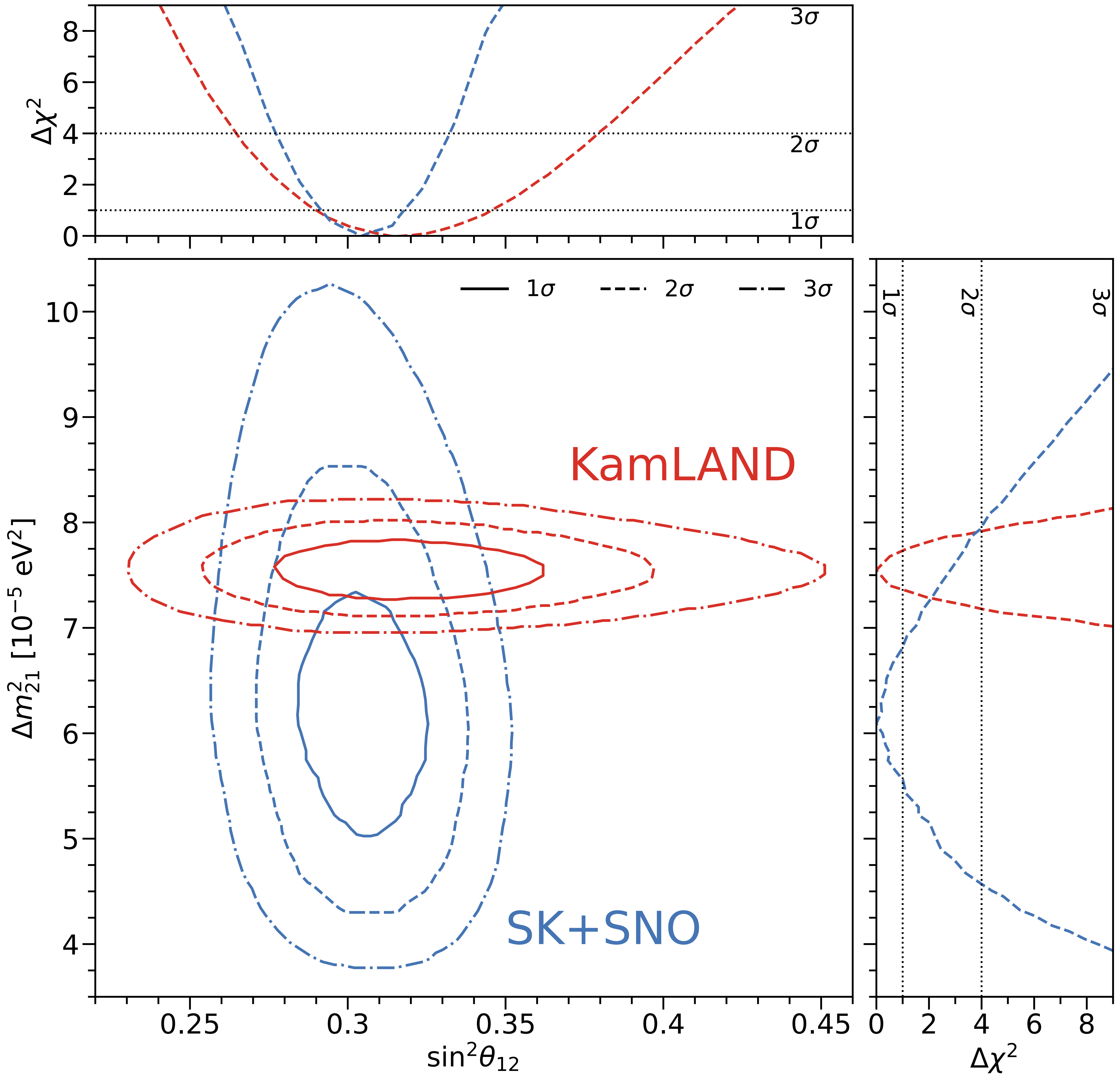
➡ If a model modifies the expansion history alone one could evade the stringent constraints on neutrino masses.

Origin of cosmological neutrino mass bounds:
background vs perturbations

BACKUP

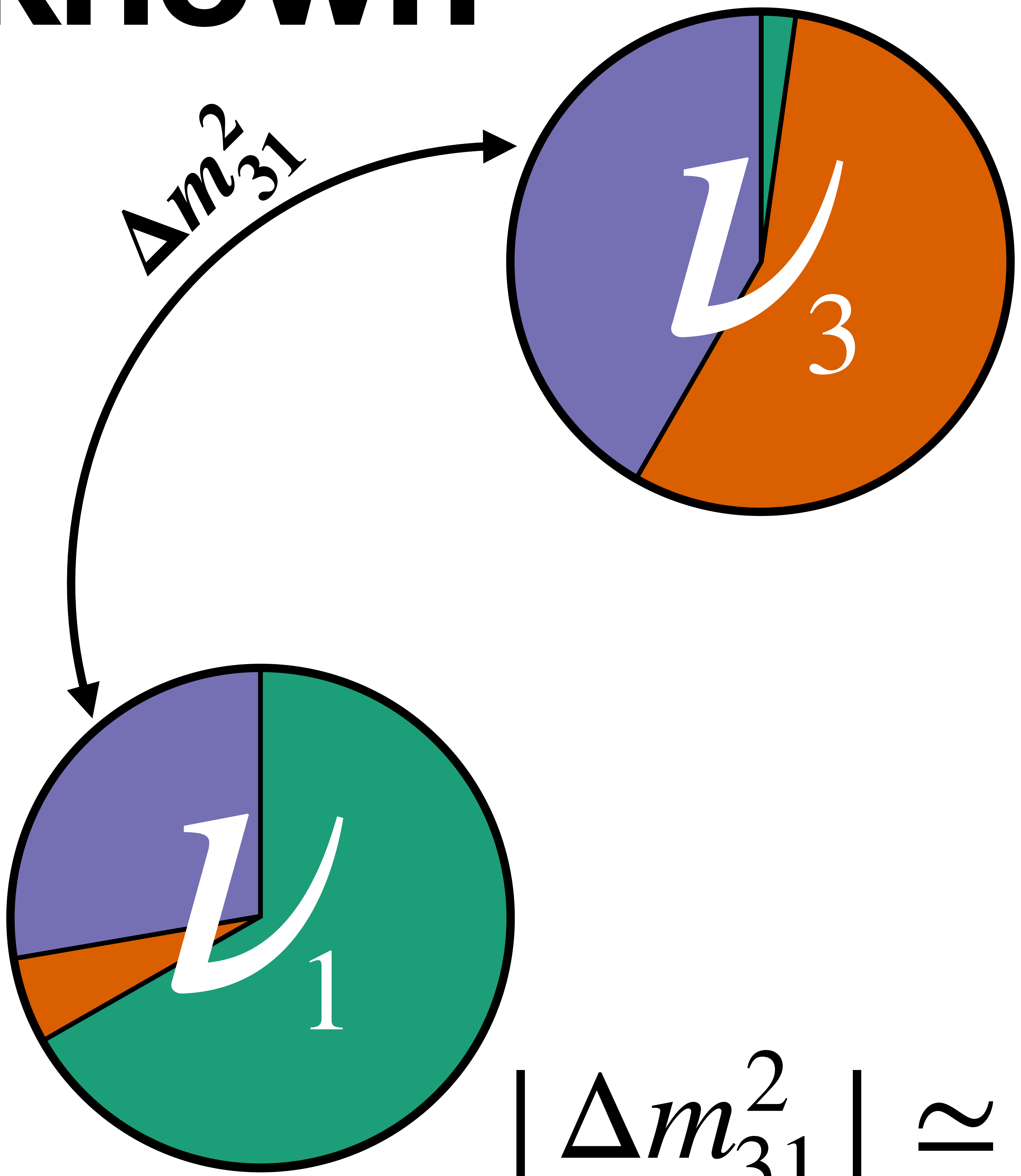
Solar mass splitting known

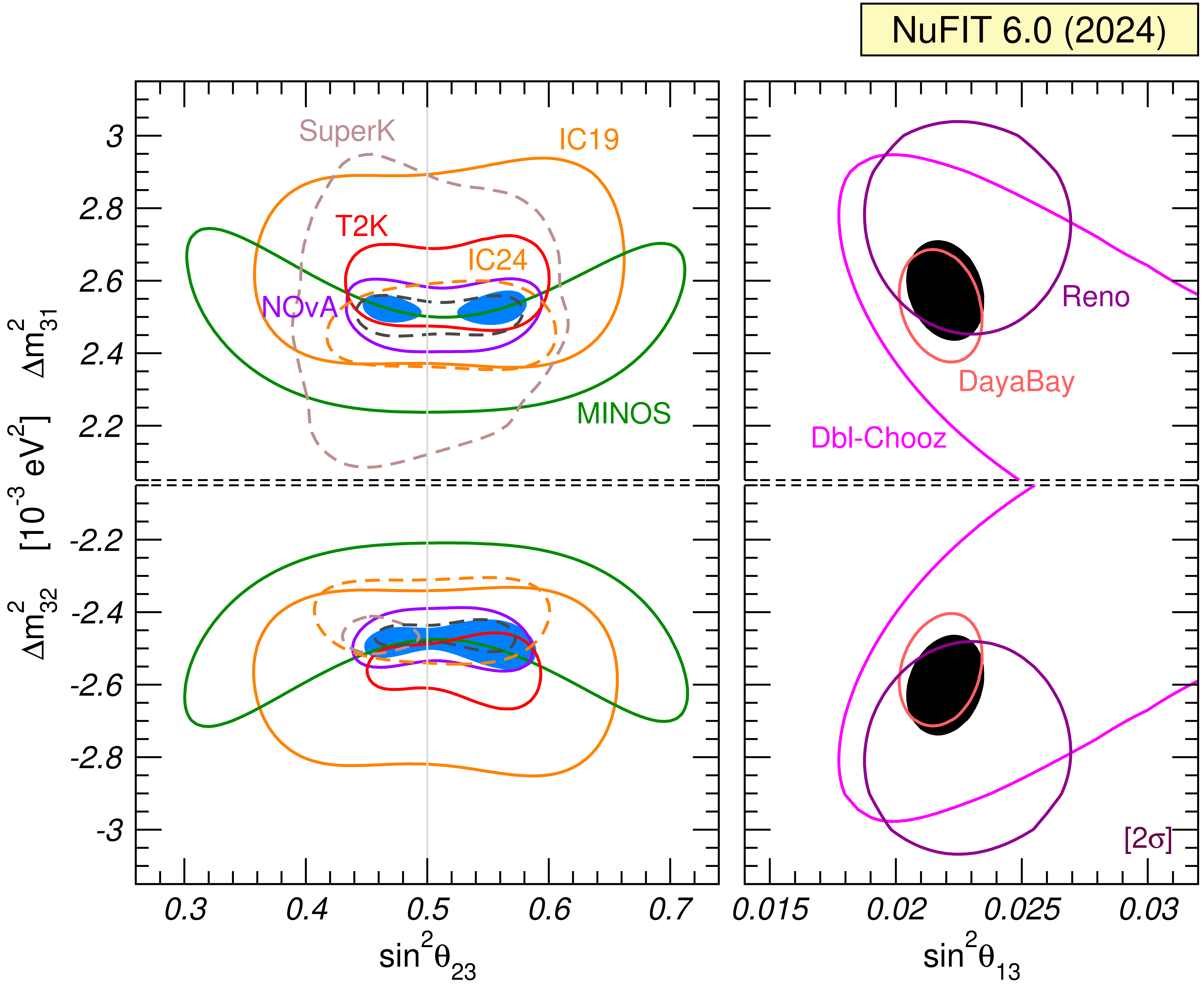




$$\Delta m^2_{21} \simeq 7.5 \cdot 10^{-5}\ \mathrm{eV}^2$$

Atmospheric mass splitting known



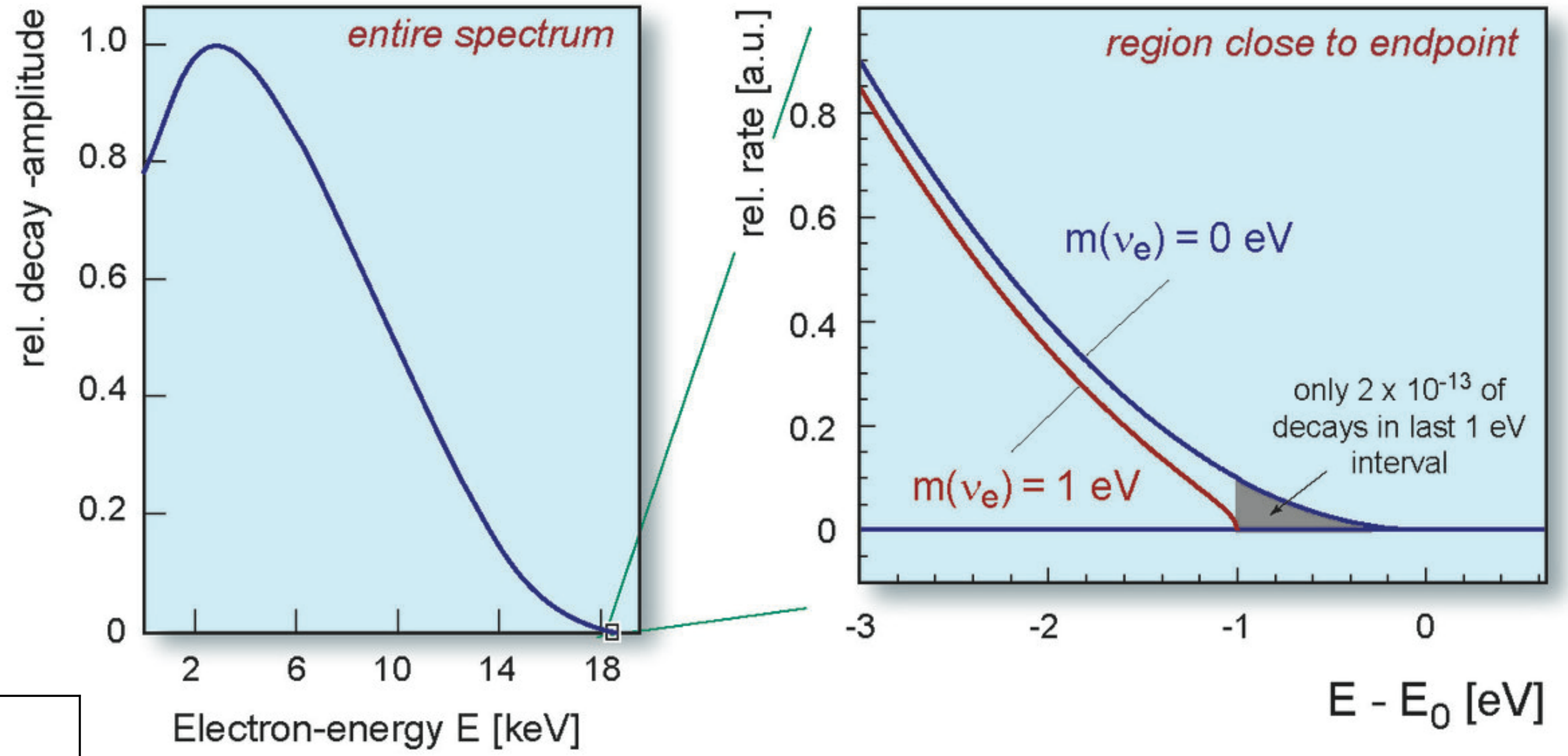


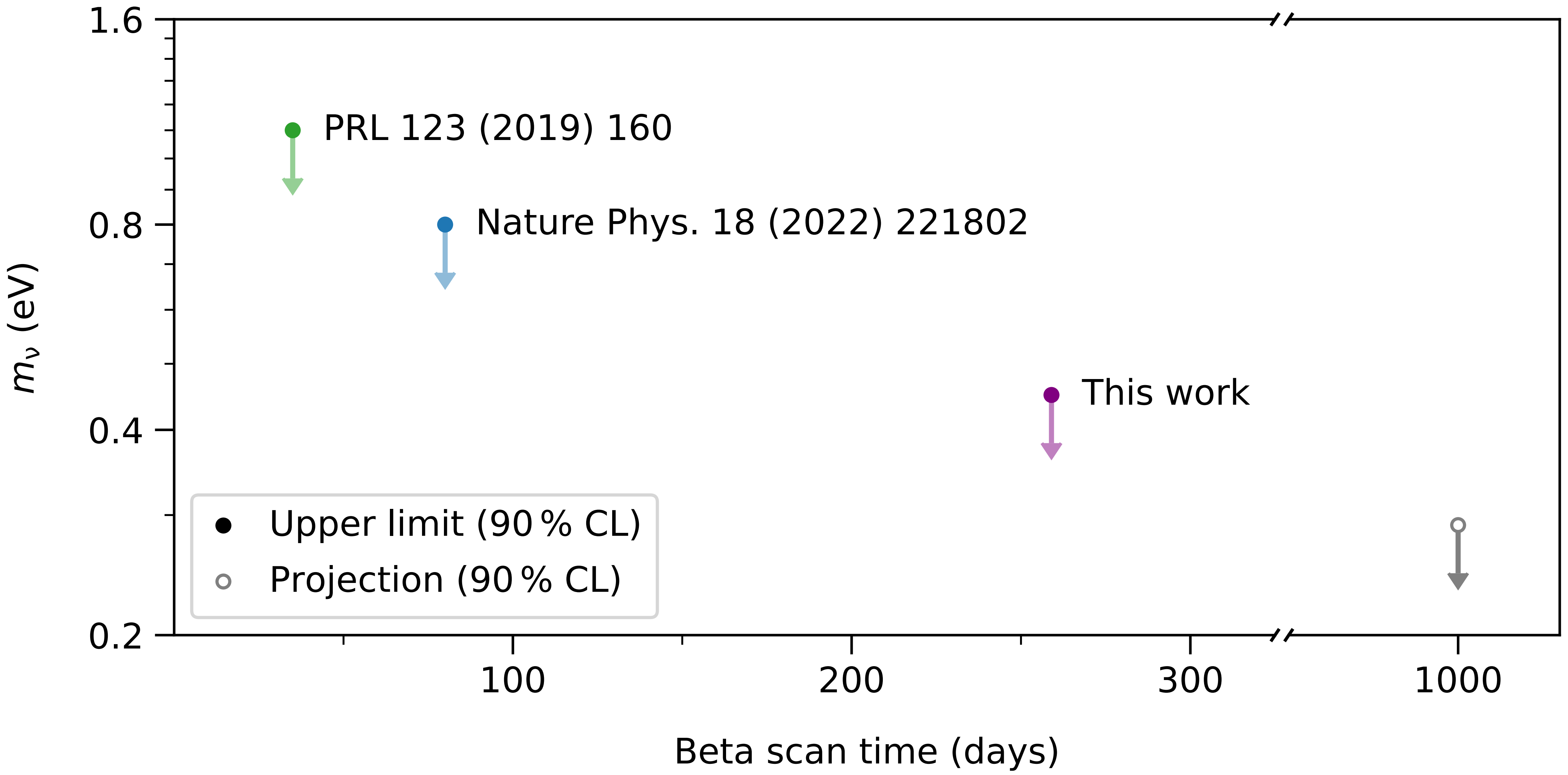
$$|\Delta m^2_{31}| \simeq 2.5 \cdot 10^{-3}\ \mathrm{eV}^2$$

Sum of neutrino masses: KATRIN

$$K^2 = (Q-T)\sqrt{(Q-T)^2 - m_\beta^2}$$

$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

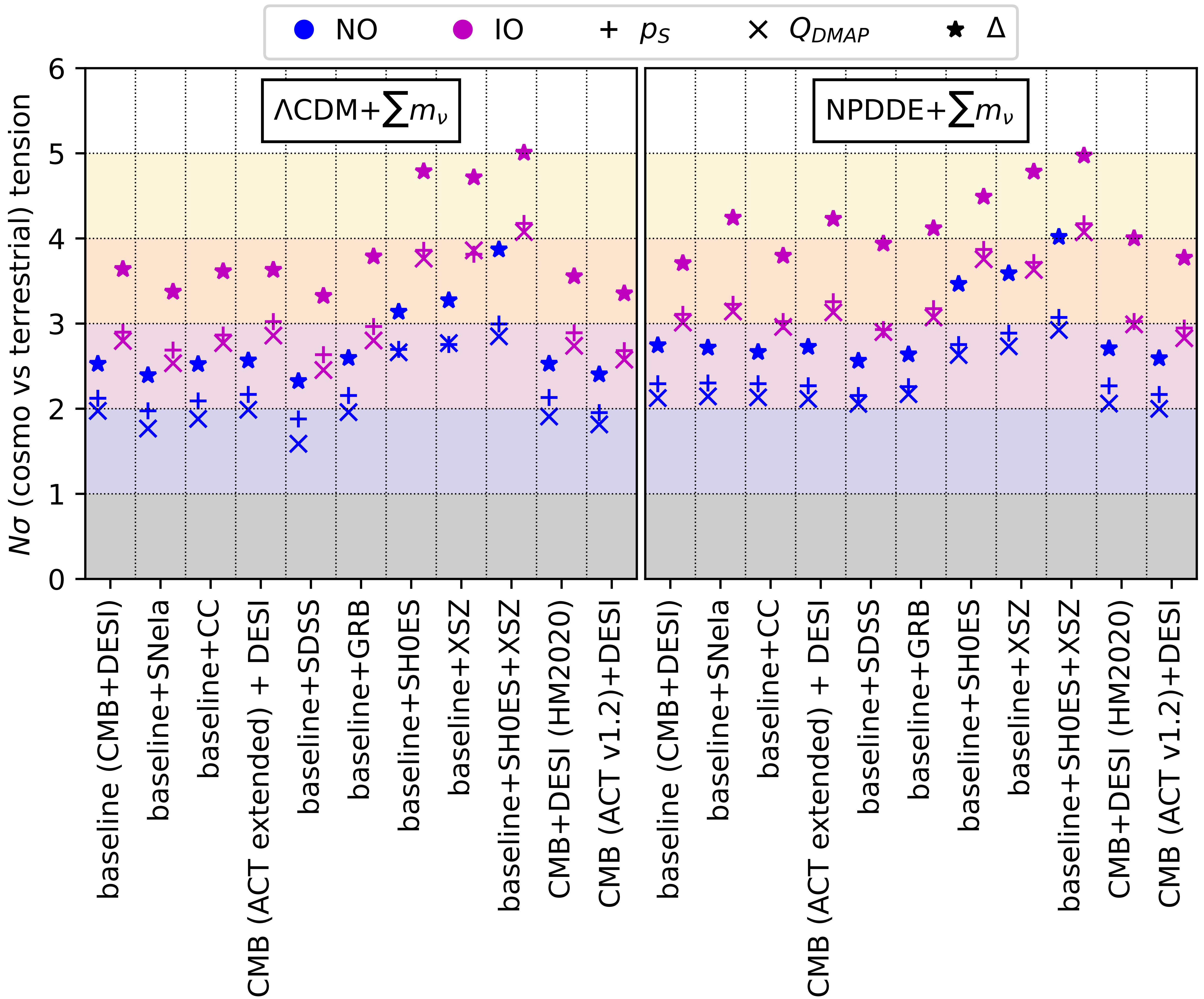




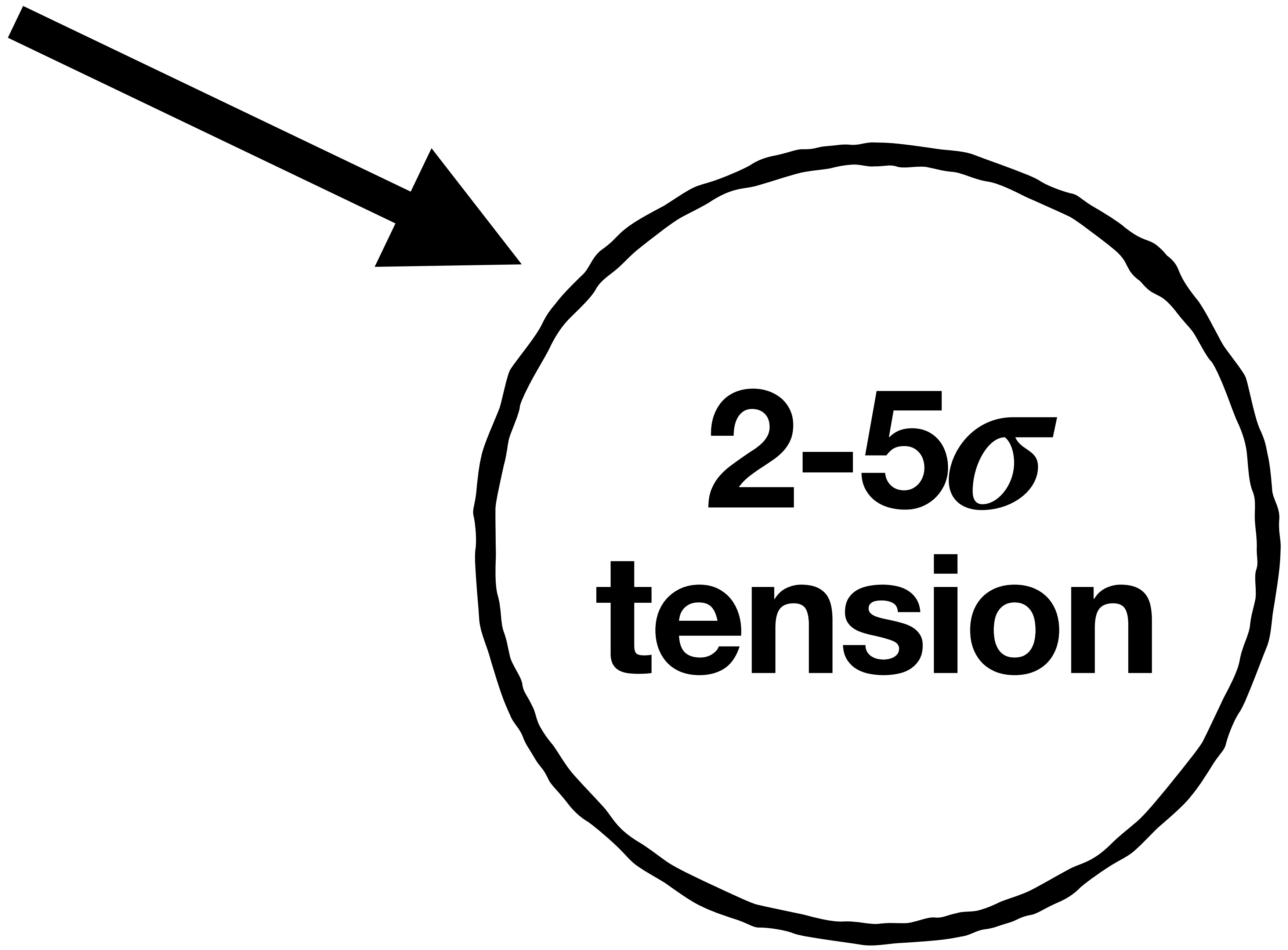
$$\sum m_\nu^{\mathrm{KATRIN}} < 1.35\,\mathrm{eV}$$

KATRIN Collaboration, *Science* 388 (2025) 6743, adq9592

Sum of neutrino masses: Tension!



Jiang et. al.
arXiv:2407.18047



Perturbations evolution

Perturbation sources:

δ

Density contrast

$$\delta \equiv \frac{\delta\rho}{\rho}$$

θ

Velocity divergence

$$\theta \sim \vec{\nabla} \cdot \vec{v}$$

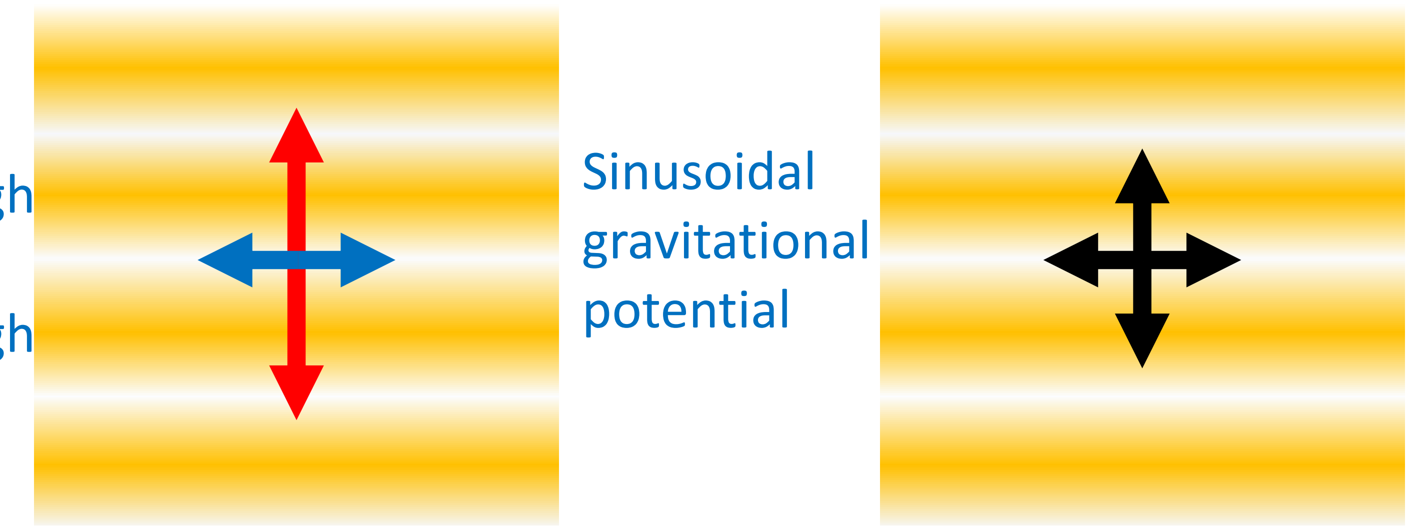
$c^2_{\rm eff}$

sound speed
(Isotropic momentum flux)

$$c^2_{\rm eff} \equiv \frac{\delta P}{\delta\rho}$$

σ

neutrino momentum anisotropy



Plot extracted from Yvonne Y. Y. Wong talk @ GGI Neutrino Frontiers 2024 https://www.ggi.infn.it/talkfiles/slides/slides7150.pdf

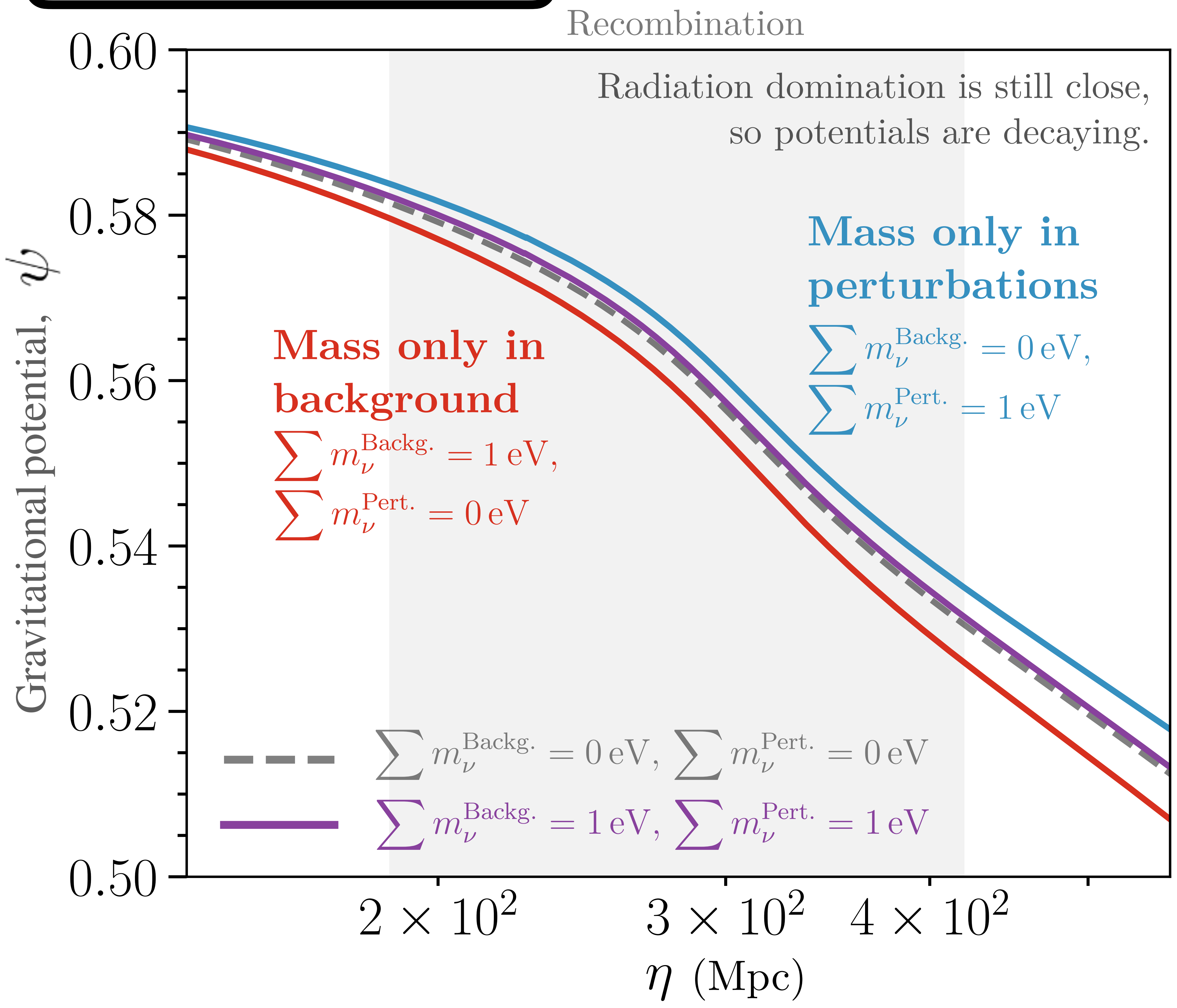
General evolution equations:

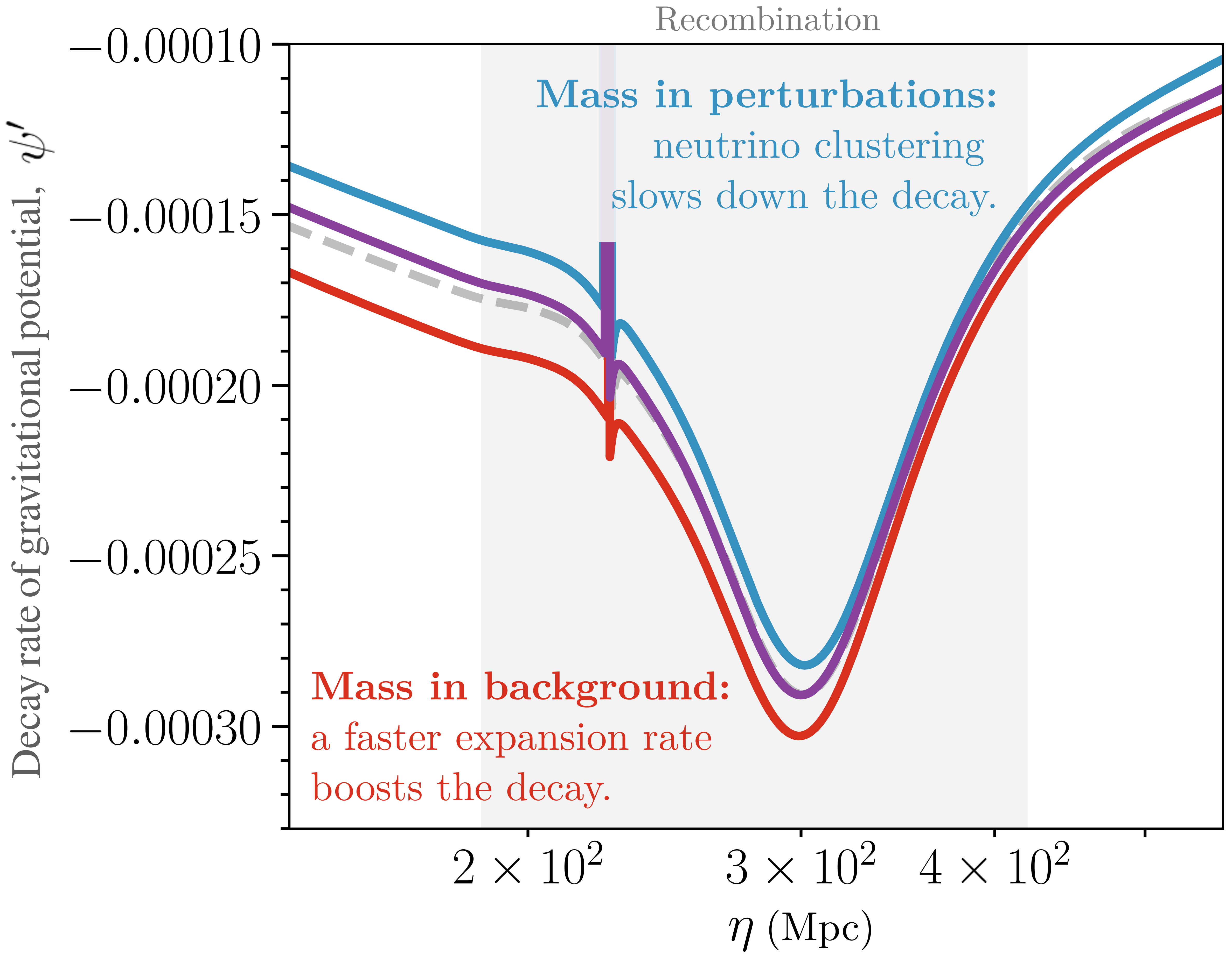
$$\delta' = -(1+w_\nu)\theta + 3(1+w_\nu)\phi' - 3\frac{a'}{a}\left(c_s^2 - w_\nu\right)\delta$$

$$\theta' = -\frac{a'}{a}(1-3c_{\rm ad}^2)\theta + \frac{c_s^2}{1+w_\nu}k^2\delta - k^2\sigma + k^2\psi$$

intermediate ℓ

$k(\ell \sim 100) \sim 7 \cdot 10^{-3}\,\mathrm{Mpc}^{-1}$

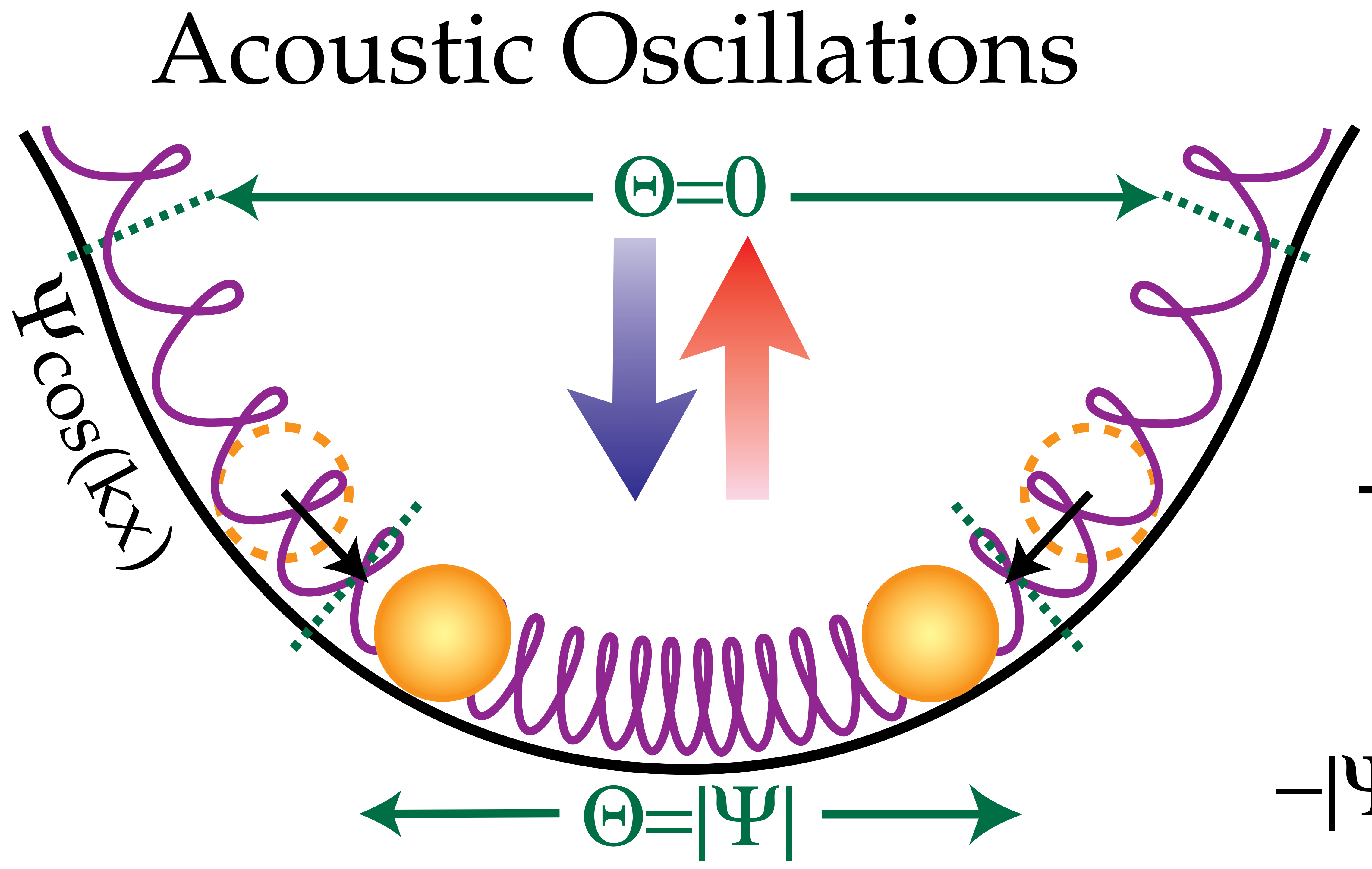


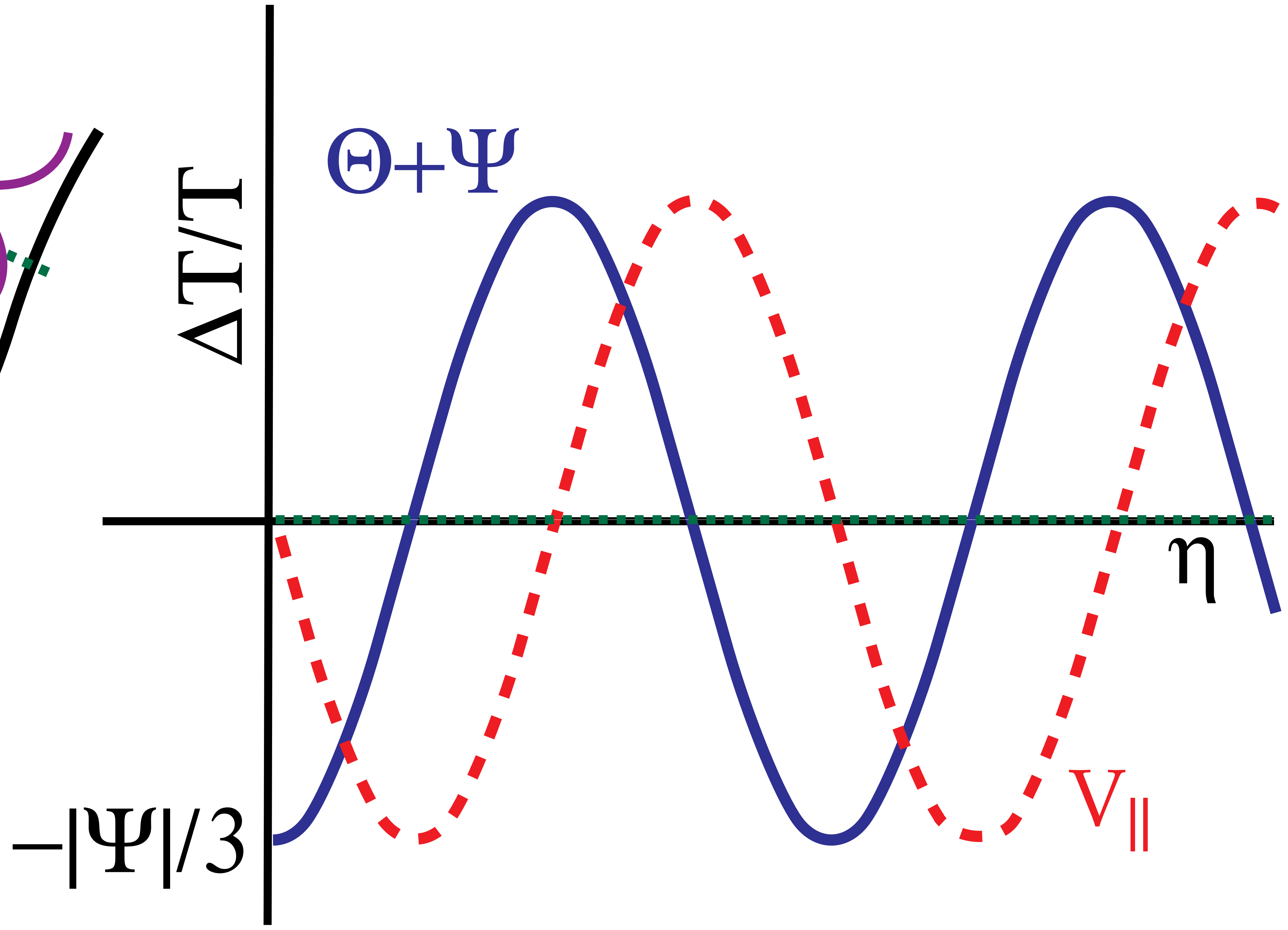


Gravitational potentials are decaying. Neutrino effects at background and perturbations level have “opposite” behavior.

intermediate ℓ constant potentials

Hu, Sugiyama, Silk, astro-ph/9604166

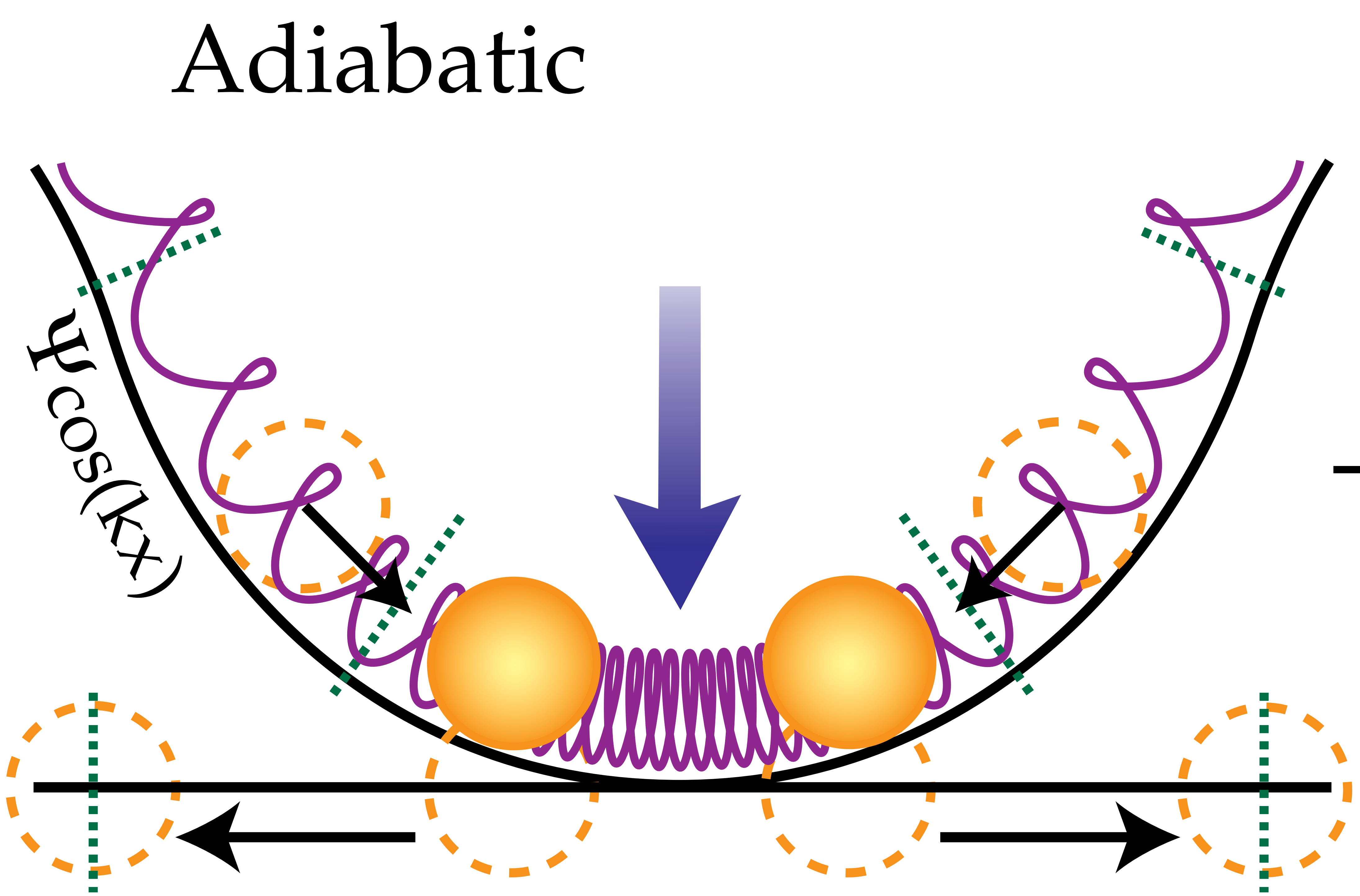


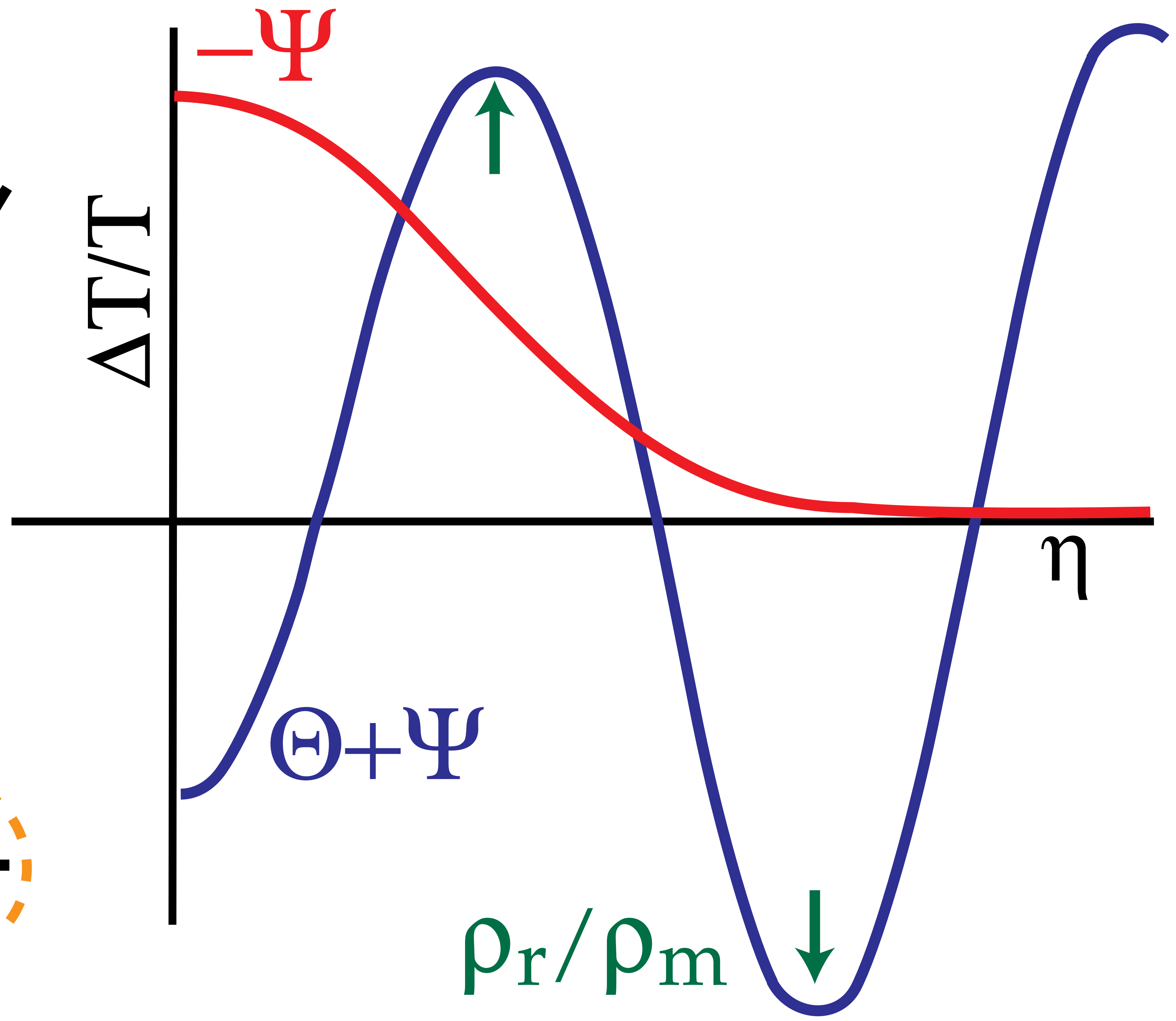


Gravity displaces the zero point, effective temperature: $\Theta + \Psi$

Size of constant potentials does not modify amplitude of oscillations intermediate ℓ decaying potentials

Hu, Sugiyama, Silk, astro-ph/9604166





Highly compressed fluid maintains photon pressure, allowing potential to decay

Less gravity + same pressure enhances amplitude of oscillations

CMB effects

low ℓ

Tiny constraining power, mostly background

intermediate ℓ

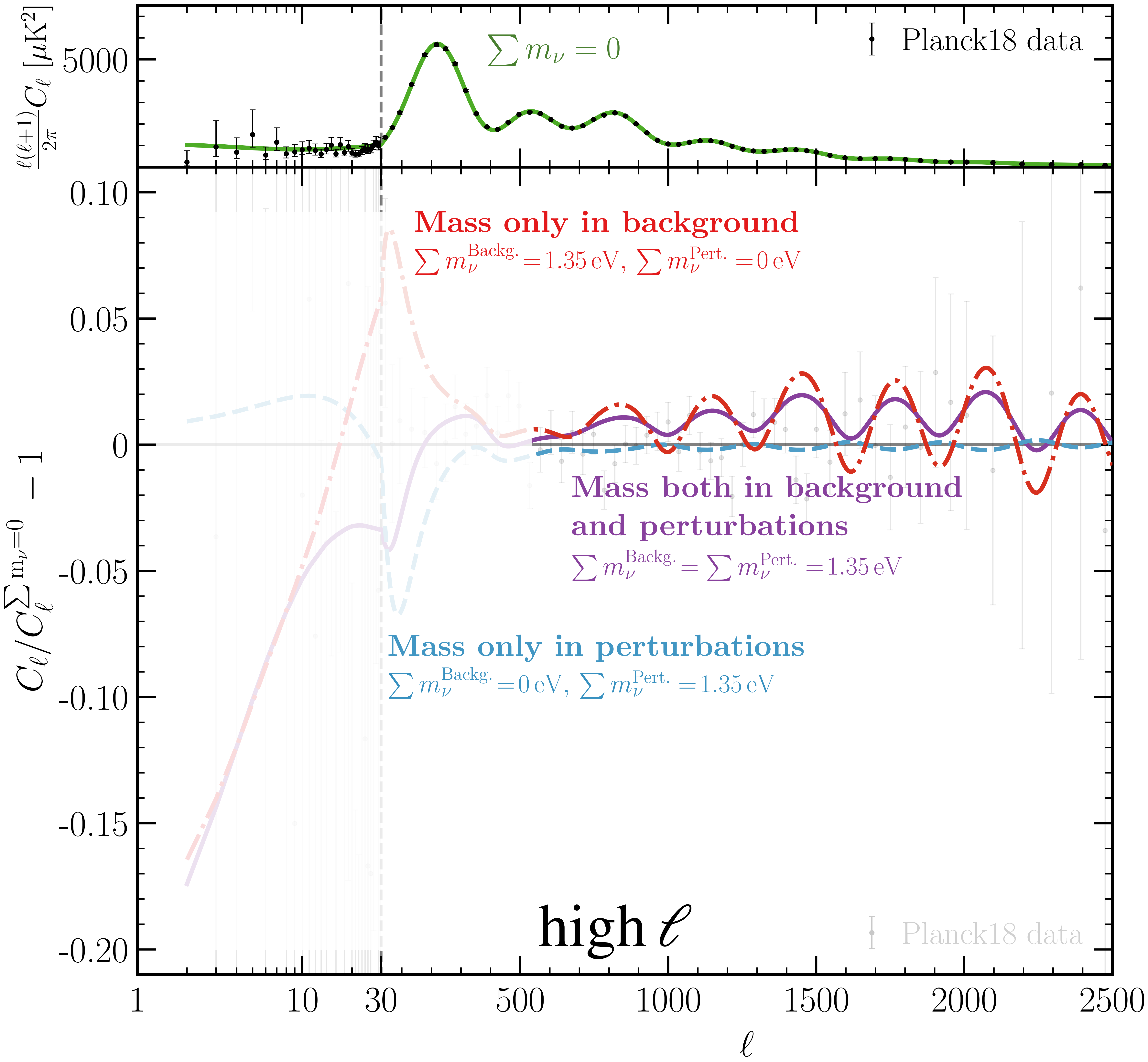
$\uparrow \sum m_\nu^{\text{Backg.}} \rightarrow$ Higher expansion rate, more decay of grav. pot.

$\uparrow \sum m_\nu^{\text{Pert.}} \rightarrow$ Higher clustering, less decay of grav. pot.

high ℓ

$\uparrow \sum m_\nu^{\text{Backg.}} \rightarrow$ Higher expansion rate, lower diffusion damping

$$\theta_D \sim \sqrt{\int_{z_{\text{rec}}}^{\infty} \frac{1+z}{n_e(z)\sigma_T} \frac{dz}{H(z)}} \Bigg/ \int_0^{z_{\text{rec}}} \frac{dz}{H(z)}$$

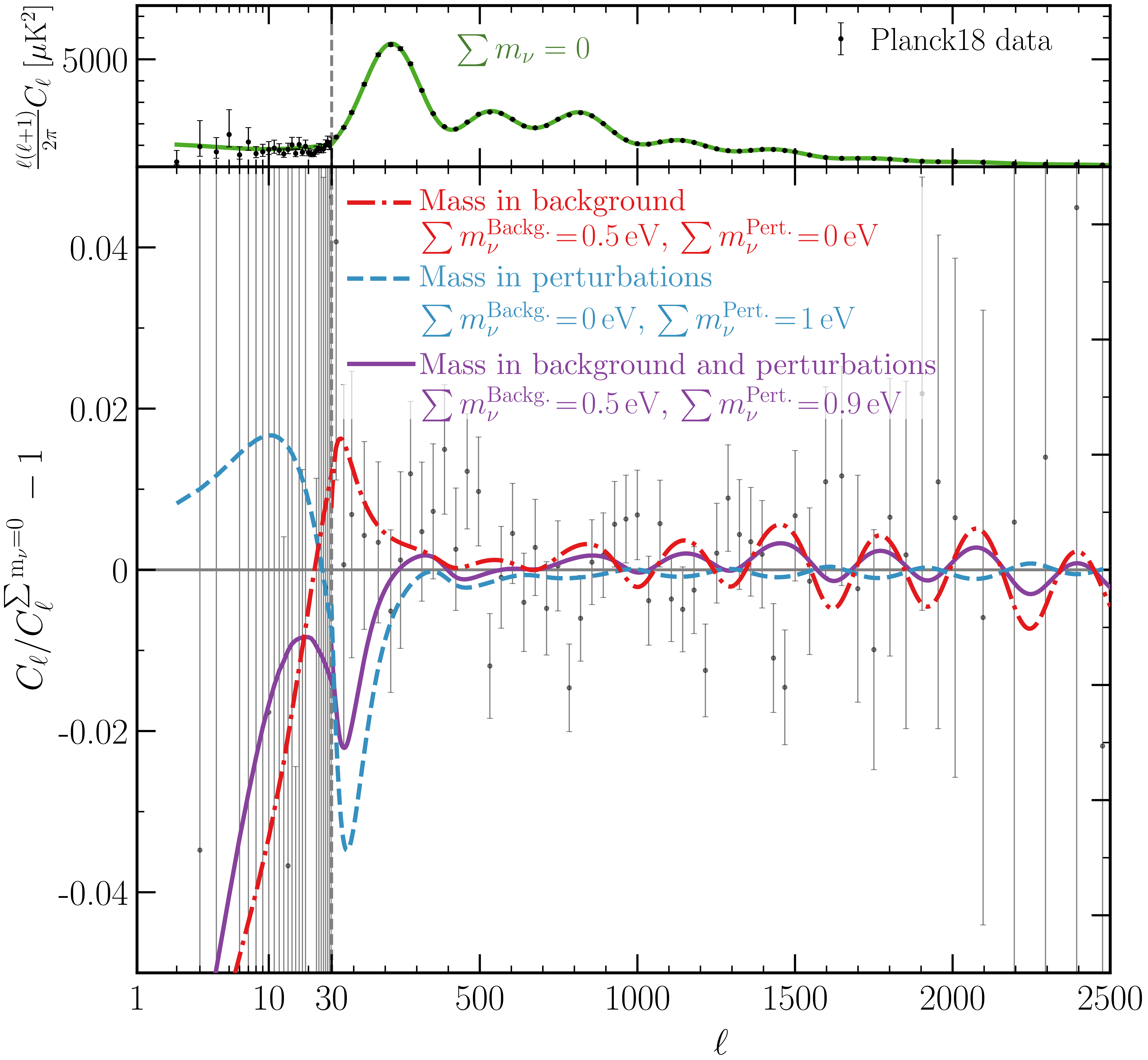


Secondly, high multipoles ($\ell \gtrsim 500$) correspond to modes that enter the horizon much before recombination. There are two main ways in which neutrino masses affect these modes, both of which are mainly sensitive to background effects.

On the one hand, these modes are damped below a characteristic angular scale θ_D due to the finite mean free path of photons, where [83]

$$\theta_D \sim \sqrt{\int_{z_{\rm rec}}^{\infty} \frac{1+z}{n_e(z)\sigma_T} \frac{\mathrm{d}z}{H(z)}} \Big/ \int_0^{z_{\rm rec}} \frac{\mathrm{d}z}{H(z)} \,, \tag{22}$$

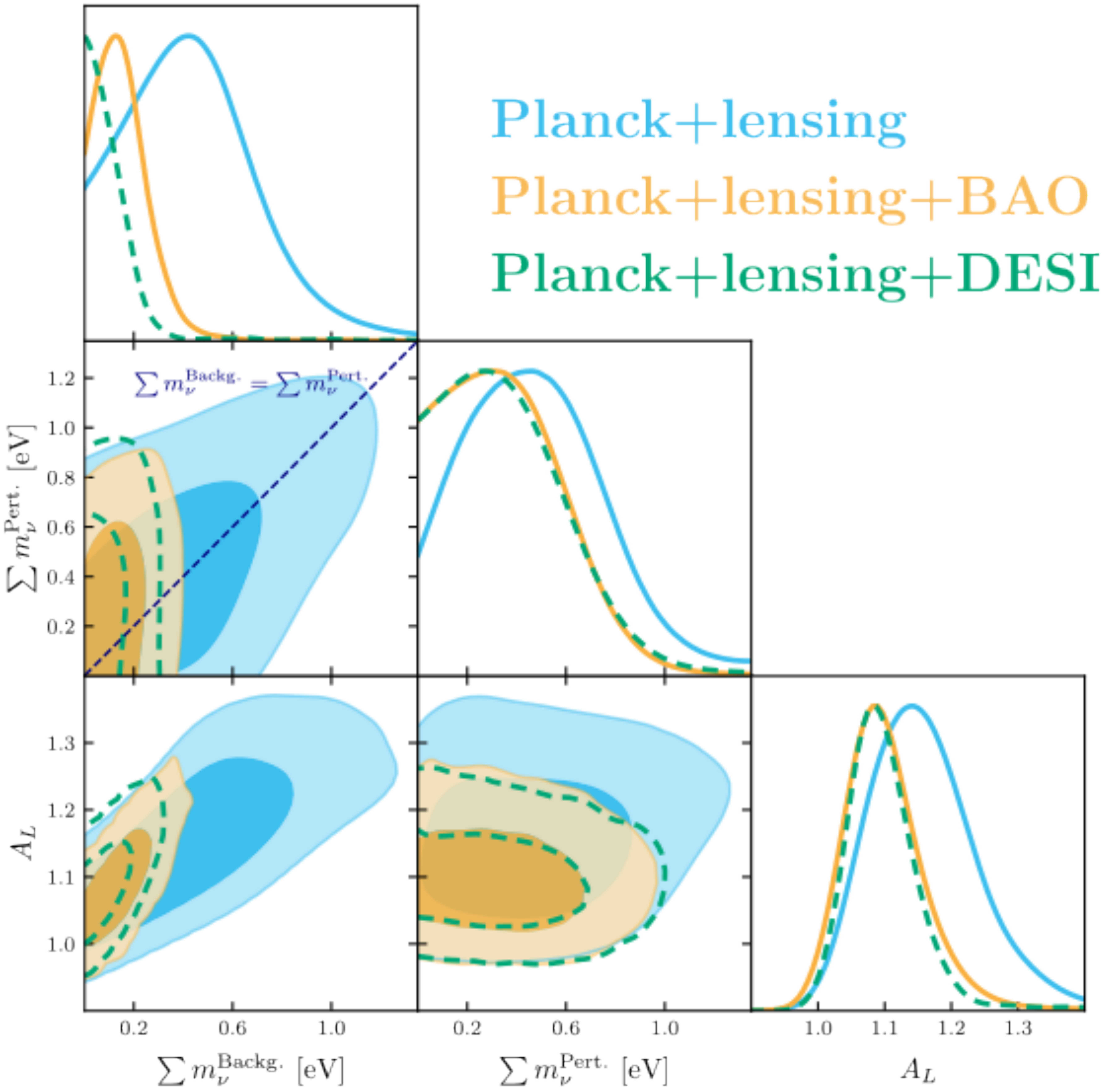
with n_e the electron density and σ_T the Thomson scattering cross section. $\sum m_\nu^{\rm Backg.}$ slows down the dilution of the neutrino energy density, increasing $H(z)$ both in the numerator and denominator. Overall, $\theta_{\rm D}$ gets reduced, which is visible as an excess at high ℓ in Fig. 3. As the



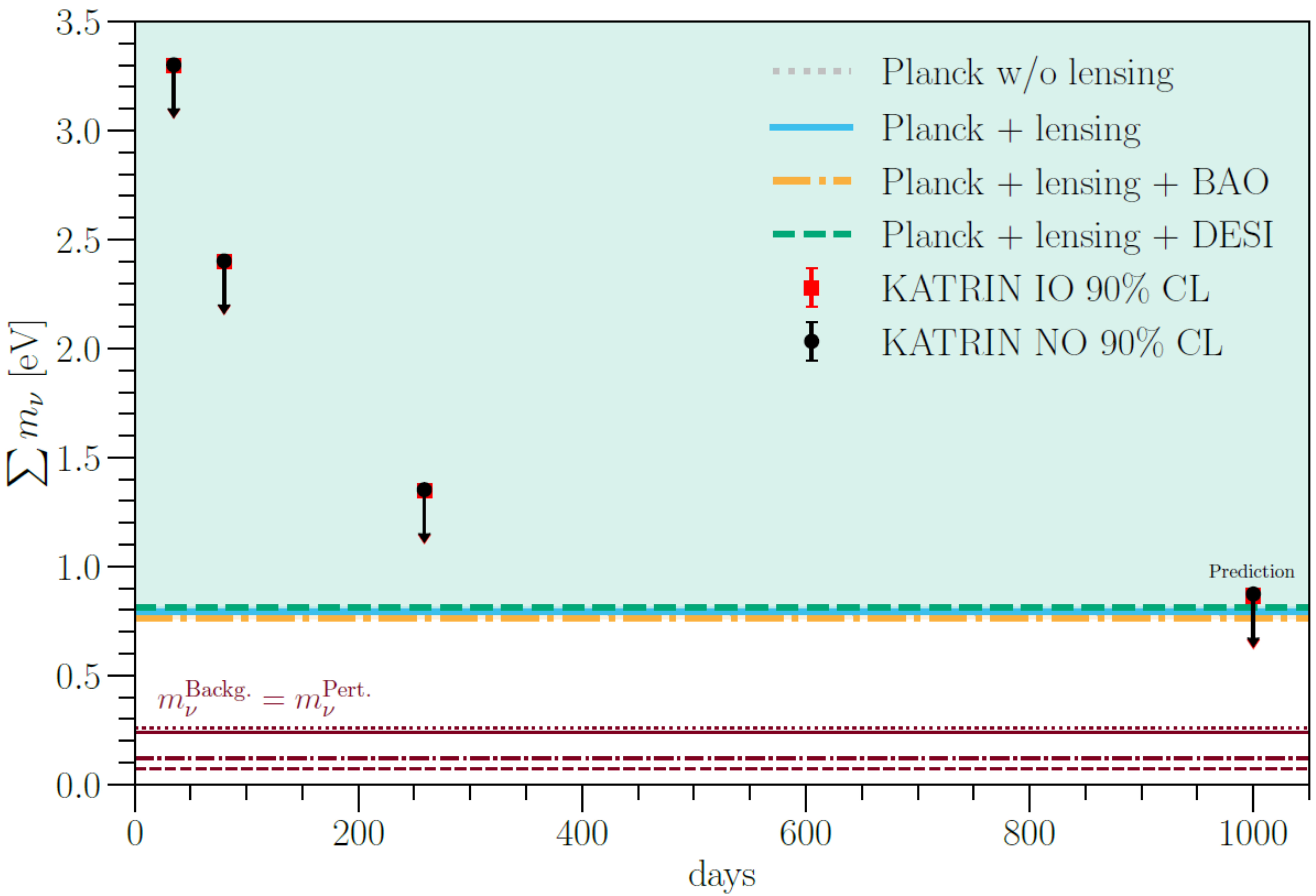
$\frac{\ell(\ell+1)}{2\pi}C_\ell\ [\mu K^2]$
5000
$\sum m_\nu = 0$
Planck18 data
Mass in background
$\sum m_\nu^{\rm Backg.} = 0.5\,{\rm eV},\ \sum m_\nu^{\rm Pert.} = 0\,{\rm eV}$
Mass in perturbations
$\sum m_\nu^{\rm Backg.} = 0\,{\rm eV},\ \sum m_\nu^{\rm Pert.} = 1\,{\rm eV}$
Mass in background and perturbations
$\sum m_\nu^{\rm Backg.} = 0.5\,{\rm eV},\ \sum m_\nu^{\rm Pert.} = 0.9\,{\rm eV}$
$C_\ell / C_\ell^{\sum m_\nu = 0} - 1$
0.04
0.02
0
-0.02
-0.04
1
10
30
500
1000
1500
2000
2500
ℓ

Planck 2018; TT, TE, EE+lowE+lensing

Mass type	68% CL	95% CL	99% CL
$\sum m_\nu$	$< 0.11\,\mathrm{eV}$	$< 0.24\,\mathrm{eV}$	$< 0.35\,\mathrm{eV}$
$\sum m_\nu^{\mathbf{Backg.}}$	$< 0.13\,\mathrm{eV}$	$< 0.29\,\mathrm{eV}$	$< 0.40\,\mathrm{eV}$
$\sum m_\nu^{\mathbf{Pert.}}$	$0.40^{+0.19}_{-0.29}\,\mathrm{eV}$	$< 0.79\,\mathrm{eV}$	$< 0.97\,\mathrm{eV}$



Planck+lensing
Planck+lensing+BAO
Planck+lensing+DESI
$\sum m_\nu^{\rm Backg.} = \sum m_\nu^{\rm Pert.}$
$\sum m_\nu^{\rm Pert.}$ [eV]
A_L
$\sum m_\nu^{\rm Backg.}$ [eV]
$\sum m_\nu^{\rm Pert.}$ [eV]
A_L



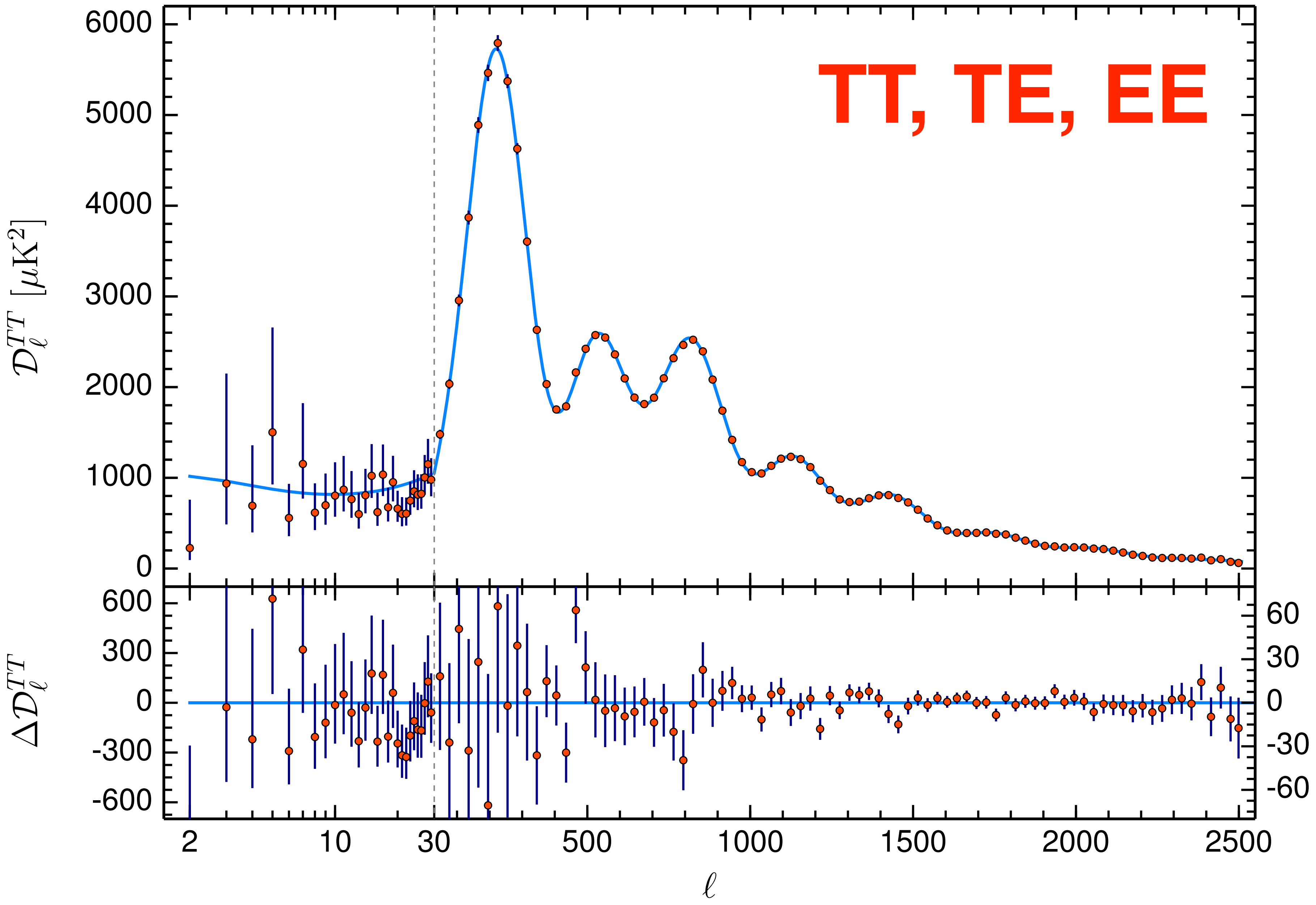
Planck w/o lensing
Planck + lensing
Planck + lensing + BAO
Planck + lensing + DESI
KATRIN IO 90% CL
KATRIN NO 90% CL
Prediction
$m_\nu^{\rm Backg.} = m_\nu^{\rm Pert.}$
$\sum m_\nu$ [eV]
days
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000

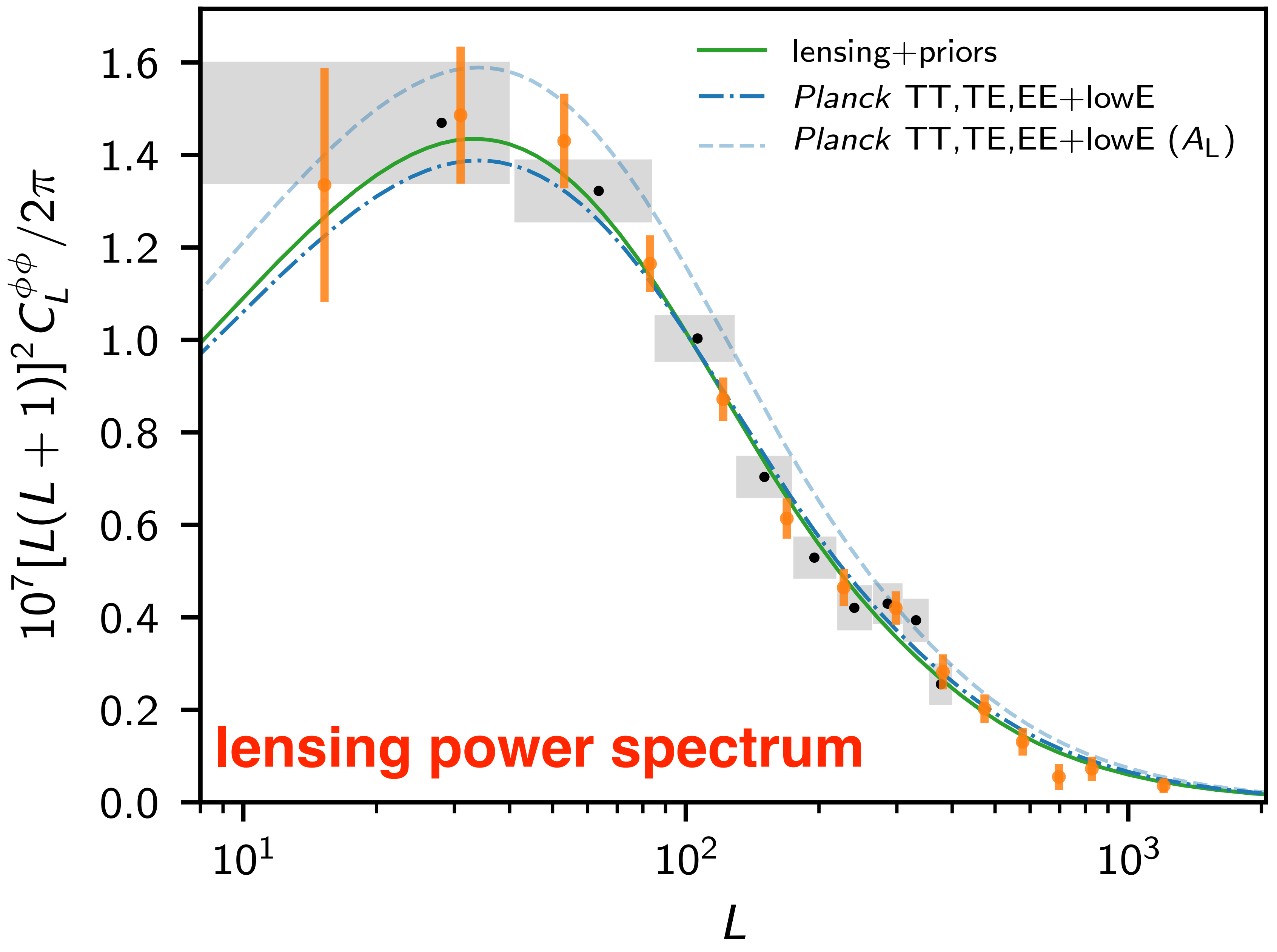
Lensing anomaly @ Planck 2018

The *Planck* data then mainly constrain lower masses via the lensing power spectrum and the impact of lensing on the CMB power spectra. Since the CMB power spectra prefer slightly more lensing than in the base-ΛCDM model, and neutrino mass can only suppress the power, we obtain somewhat stronger constraints than might be expected in typical realizations of a minimal-mass neutrino model.

The Data: CMB anisotropies from Planck

Lensing anomaly @ Planck 2018





Latest cosmological results in 2018 but in 2020 new map reanalyses were provided:

1) **with 8% more data**
2) **with less noise and systematics**

This is critical for neutrino mass inferences because Planck data featured the so called lensing anomaly (~3sigma) in the same parts of the spectrum where the neutrino mass signal appears.

- **Planck 2018:** $\sim 2.8\sigma$ **[1807.06209]**
- **CamSpec:** $\sim 1.7\sigma$ **Rosenberg et al. [2205.10869]**
- **Hillipop:** $\sim 0.75\sigma$ **Tristram et al. [2309.10034]**