UNDERSTANDING BETTER THE COSMOLOGICAL BOUNDS ON NEUTRINO MASSES

Toni Bertólez-Martínez, R. Hajjar, I. Esteban, O. Mena, J. Salvadó

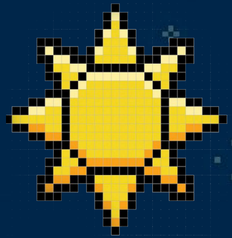
arXiV 2410.XXXXX (very soon!)

ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
EXCELENCIA MARÍA DE MAEZTU 2020-2024

INTRO, PART 1.

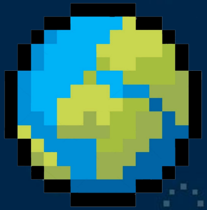
WHAT PARTICLE PHYSICS KNOWS

NEUTRINO OSCILLATIONS



From solar oscillations, we know:

$$\Delta m^2_{21} \equiv \Delta m^2_{\text{sol}} = 7.41 \times 10^{-5}\,\text{eV}^2$$

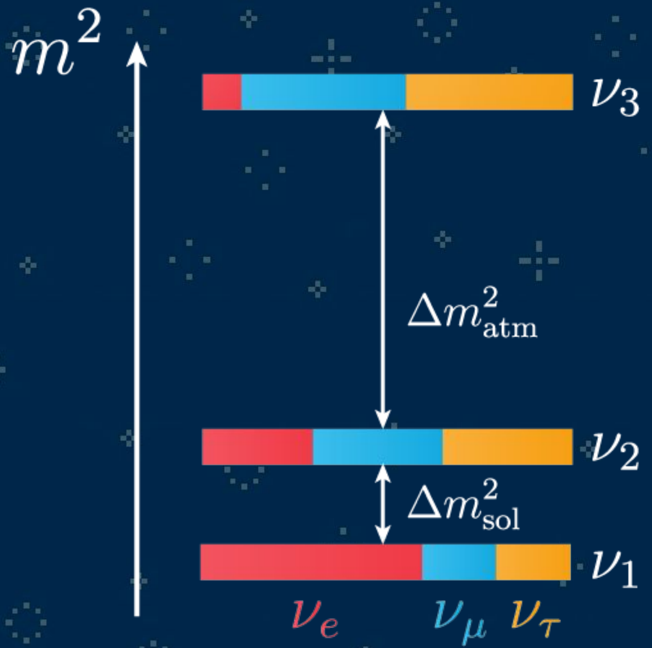


From atmospheric oscillations, we know:

$$|\Delta m^2_{3\ell}| \equiv \Delta m^2_{\text{atm}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2$$

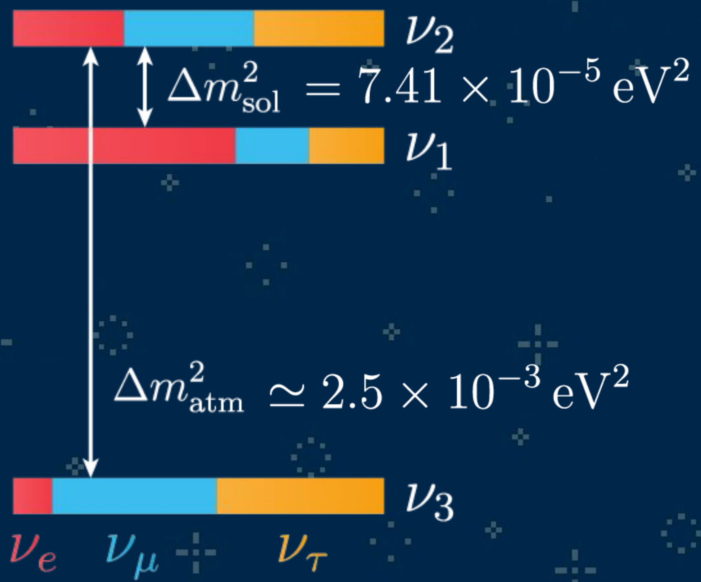
Esteban et al (NuFit), 2007.14792

Normal hierarchy



$$\sum m_\nu > 0.06\,\mathrm{eV}$$

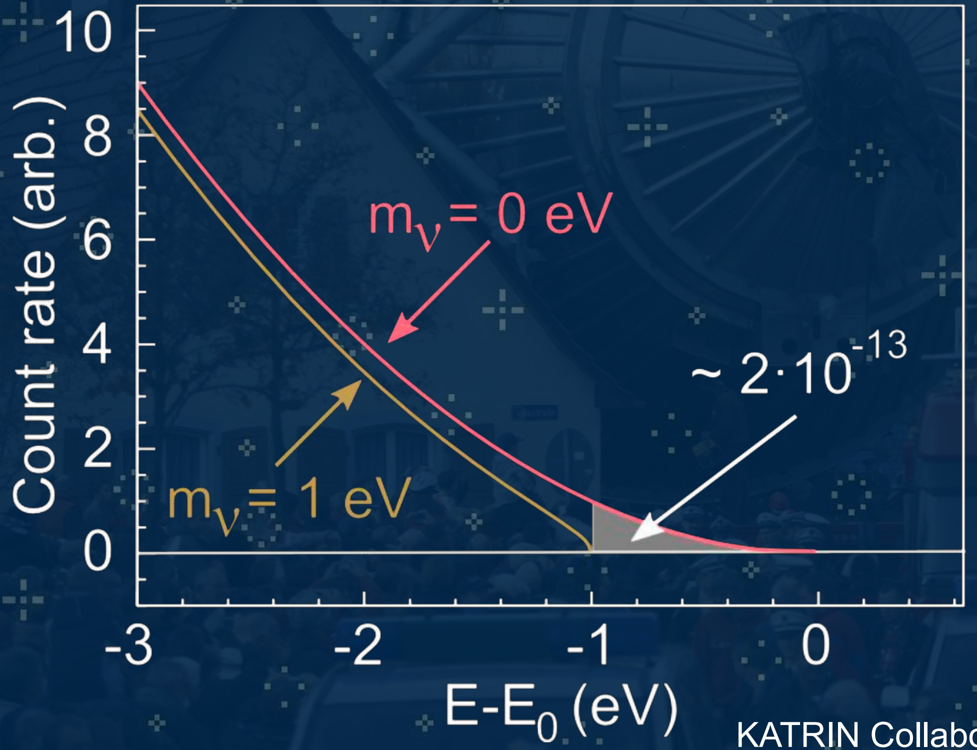
Inverted hierarchy



$$\sum m_\nu \gtrsim 0.1\,\mathrm{eV}$$

KATRIN BOUNDS

From the beta decay spectrum of tritium:



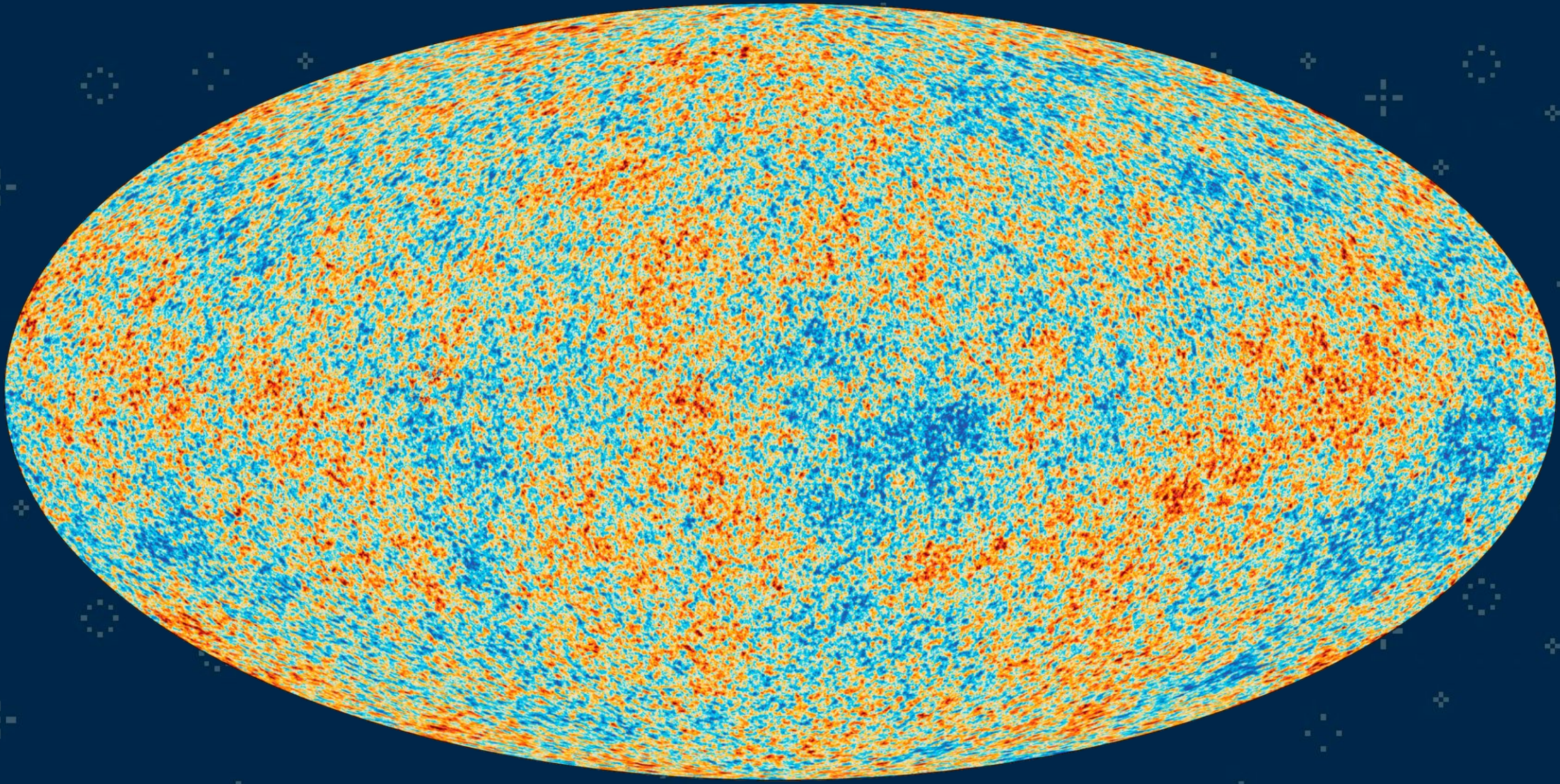
$$\sum m_\nu < 1.35\,\mathrm{eV}$$
$$(90\%\ \mathrm{C.L.})$$

This is a *kinematic* measurement: we understand it and trust it.

KATRIN Collaboration, 2406.13516

INTRO, PART 2.

WHAT COSMOLOGY KNOWS



PLANCK BOUNDS

Assuming LCDM, with
Planck+lensing+BAOs:

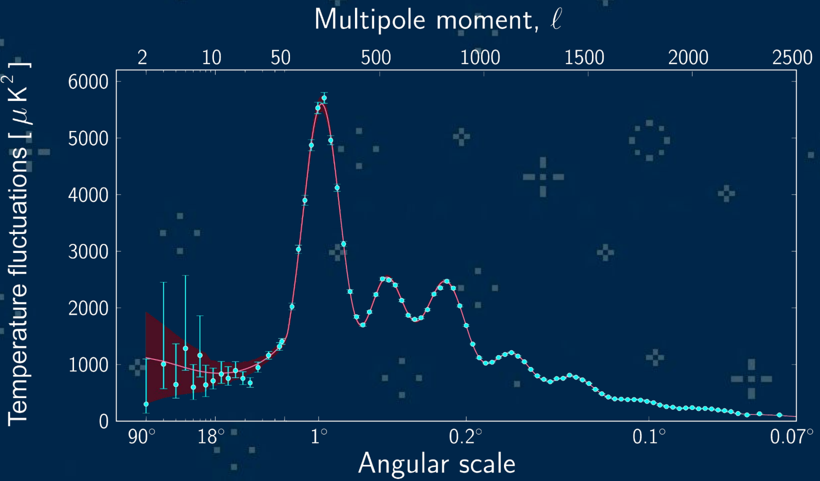
$$\sum m_\nu < 0.12\,\mathrm{eV}\ \ (95\%\ \mathrm{C.L.})$$

Planck Collaboration, 1807.06209

Only with Planck+lensing:

$$\sum m_\nu < 0.27\,\mathrm{eV}\ \ (95\%\ \mathrm{C.L.})$$

What does this measurement actually *mean*? Like, physically.



For brevity, today I only consider CMB constraints.

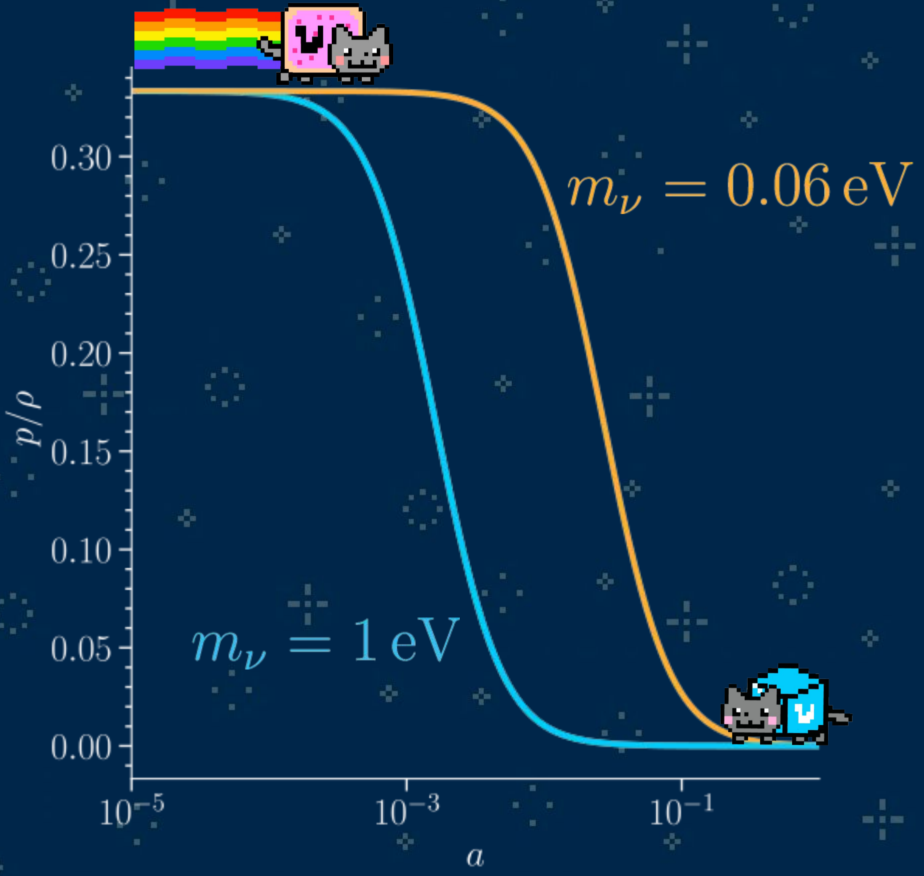
(w/DESI, BAO/LSS measurements are a whole thing on their own, e.g., negative neutrino masses, running cosmological constant…)

MASS EFFECT @BACKGROUND

The neutrino mass modifies when do neutrinos transition from behaving like UR radiation to behaving like NR matter.

This modifies the pressure of the neutrino fluid, described by the **equation of state**.

$$w = \frac{p}{\rho}$$

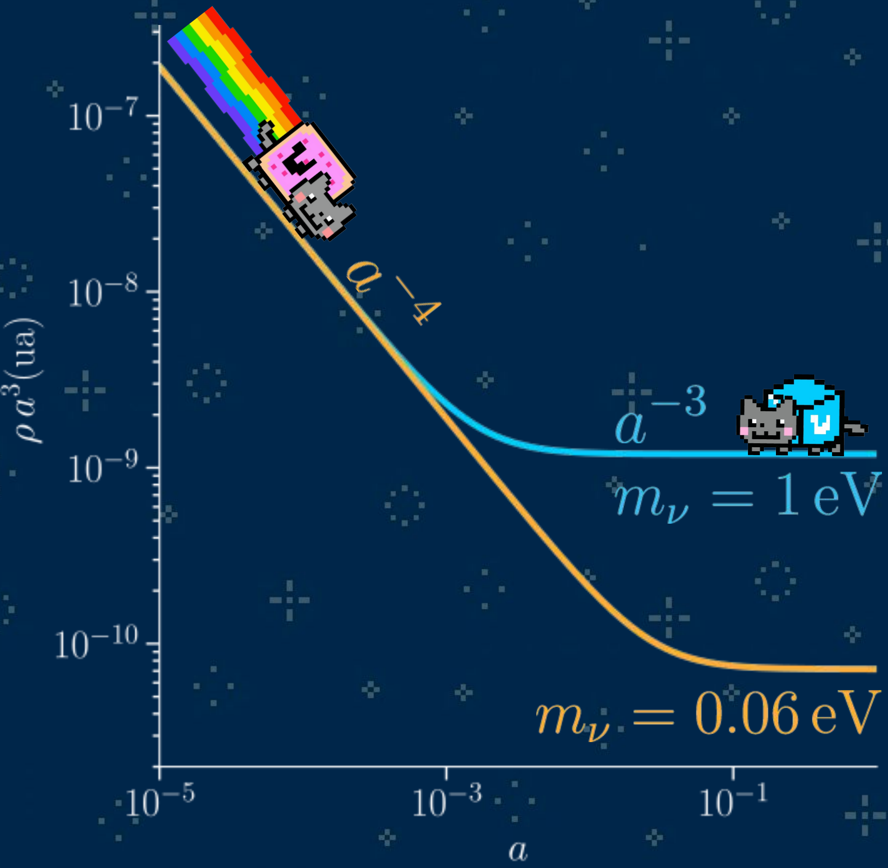


MASS EFFECT @BACKGROUND

Modifying the equation of state modifies how does the neutrino energy density scale with the expansion of the Universe. This also affects how fast the Universe expands: more mass, larger H, faster expansion.

$$\dot{\rho} = -3H(1+w)\rho$$

This is a *thermodynamical* (and scale-independent) effect.

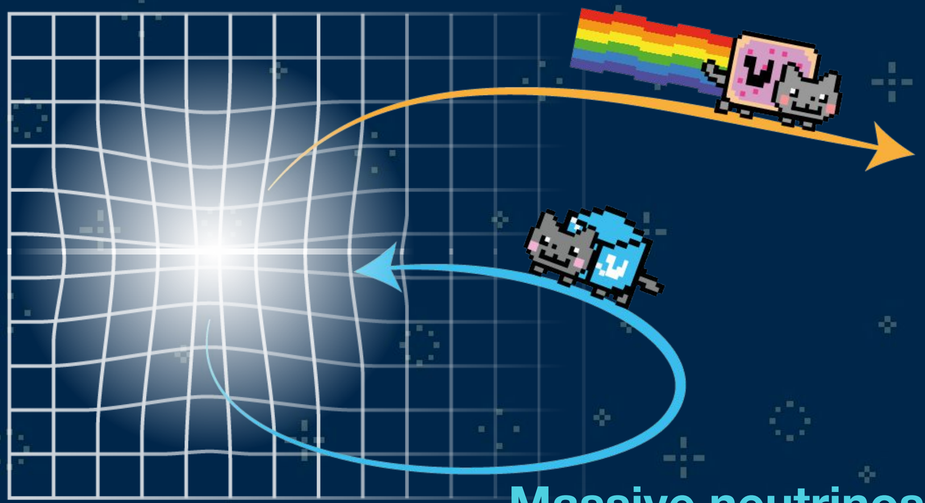


MASS EFFECT @PERTURBATIONS

Massive neutrinos are pulled more by gravity. This is described by the **free-streaming scale**:

$$\lambda_{\mathrm{fs}}(a) \equiv 2\pi \sqrt{\frac{2}{3}\frac{c_\nu(a)}{H(a)}}$$

For perturbation scales smaller than this scale, neutrinos free-stream and help erase inhomogeneities. For larger scales, neutrinos cluster and help increase inhomogeneities.



Massless neutrinos free-stream

Massive neutrinos can cluster

See *Neutrino Cosmology* - Lesgourgues et al., for more

MASS EFFECT @PERTURBATIONS

The inhomogeneous effect of neutrino masses is described by four variables:

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

Density contrast

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

Velocity divergence

$$c_s^2 = \frac{\delta P}{\delta\rho}$$

Sound speed

$$\sigma$$

$$\sigma \sim -(\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij})({T^i}_j - {\delta^i}_j {T^k}_k/3)$$

Anisotropic stress (shear)

Conservation laws fix two of them. The sound speed and the shear remain free and are fixed by a model (e.g. standard neutrinos).

$$\dot{\delta} = -(1+w)(\theta - 3\dot{\phi}) - 3H\left(c_s^2 - w\right)\delta$$

$$\dot{\theta} = -H(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma + k^2\psi$$

BACKGROUND: SCALE-INDEP

$$w$$

PERTURBATIONS: SCALE-DEPENDENT

$$c_s^2, \sigma$$

KEY POINT

These are not *direct kinematic* effects, but collective properties. Many BSM extensions can modify these properties without changing the individual kinematic mass.

Neutrino long-range interactions

Esteban, Salvadó [2101.05804]
Smirnov, Xu [2201.00939]

Neutrino decay

Escudero, Schwetz, Terol-Calvo [2211.01729]
Archidiacono, Hannestad [1311.3873]
Oldengott, Wong et al. [2203.09075]

Non-standard neutrino populations

Farzan & Hannestad [1510.02201]
Alvey, Escudero & Sabti [2111.14870]...

BACKGROUND: SCALE-INDEP

$$w$$

KEY POINT

These are not *direct kinematic* effects, but collective properties. Many BSM extensions can modify these properties without changing the individual kinematic mass.

PERTURBATIONS: SCALE-DEPENDENT

$$c_s^2,\ \sigma$$

THEN...

Can we build a measurement more robust against BSM?

How can particle physicists understand (and trust) better the measurement from cosmology?

OUR WORK

DISENTANGLING THE EFFECT OF NU MASSES

(as a learning tool and as a consistency check)

DISENTANGLING THE EFFECT OF NEUTRINO MASSES ON THE CMB

Since mass is not directly observable, we have the freedom to define two parameters which disentangle observable quantities:

$$m_{\mathrm{bkg}} \xrightarrow{\text{describes}} w \qquad\qquad m_{\mathrm{pert}} \xrightarrow{\text{describes}} c_s^2\,,\ \sigma$$

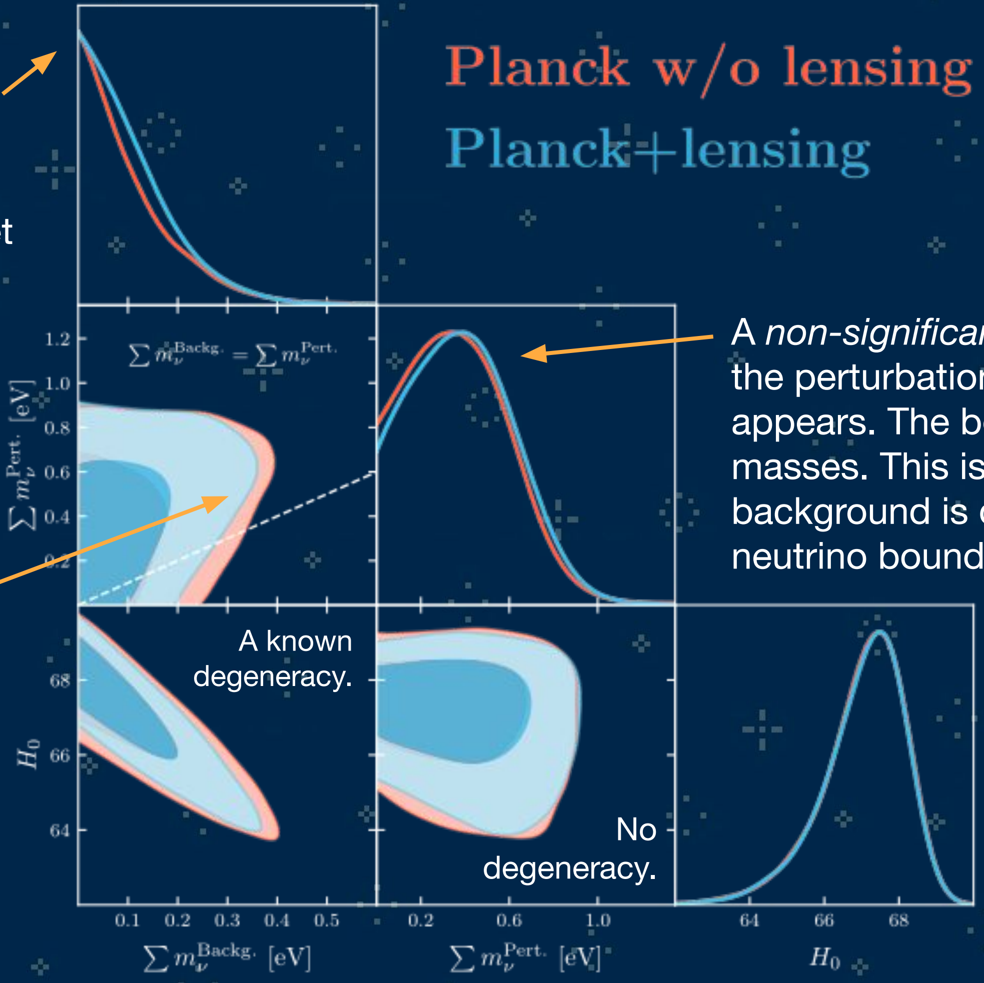
This parameterization allows to answer (at least) two questions:

1. **What is cosmology exactly measuring?** Background or perturbations?
2. **How robust is the measurement?** Both masses should point in the same direction. *If they didn't, this could be a hint of BSM Physics.*

A LOT OF TECHNICAL STUFF

The background parameter is consistent with standard results: no measurement of neutrino masses has happened yet and a similar bound is obtained.

Due to a compensation of effects, a higher background mass allows a higher perturbations mass.



A known degeneracy.

No degeneracy.

A *non-significant* measurement of the perturbation parameter appears. The best fit is at positive masses. This is a hint that the background is driving the current neutrino bound.

NEXT STEPS!

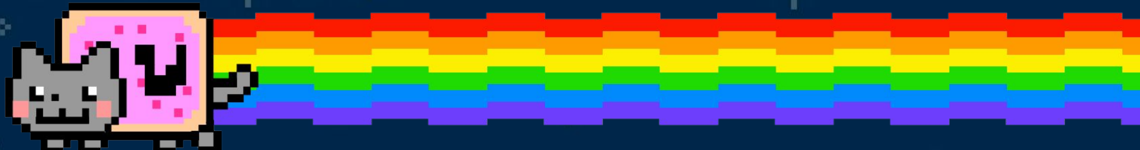
Explain CMB lensing in this context.

Make the code public to the community.

Understand the measurement of neutrino masses in BAO/LSS surveys in this context.

Generalize this formalism to constrain BSM.

Thanks for your attention,
and many thanks
to the whole team!

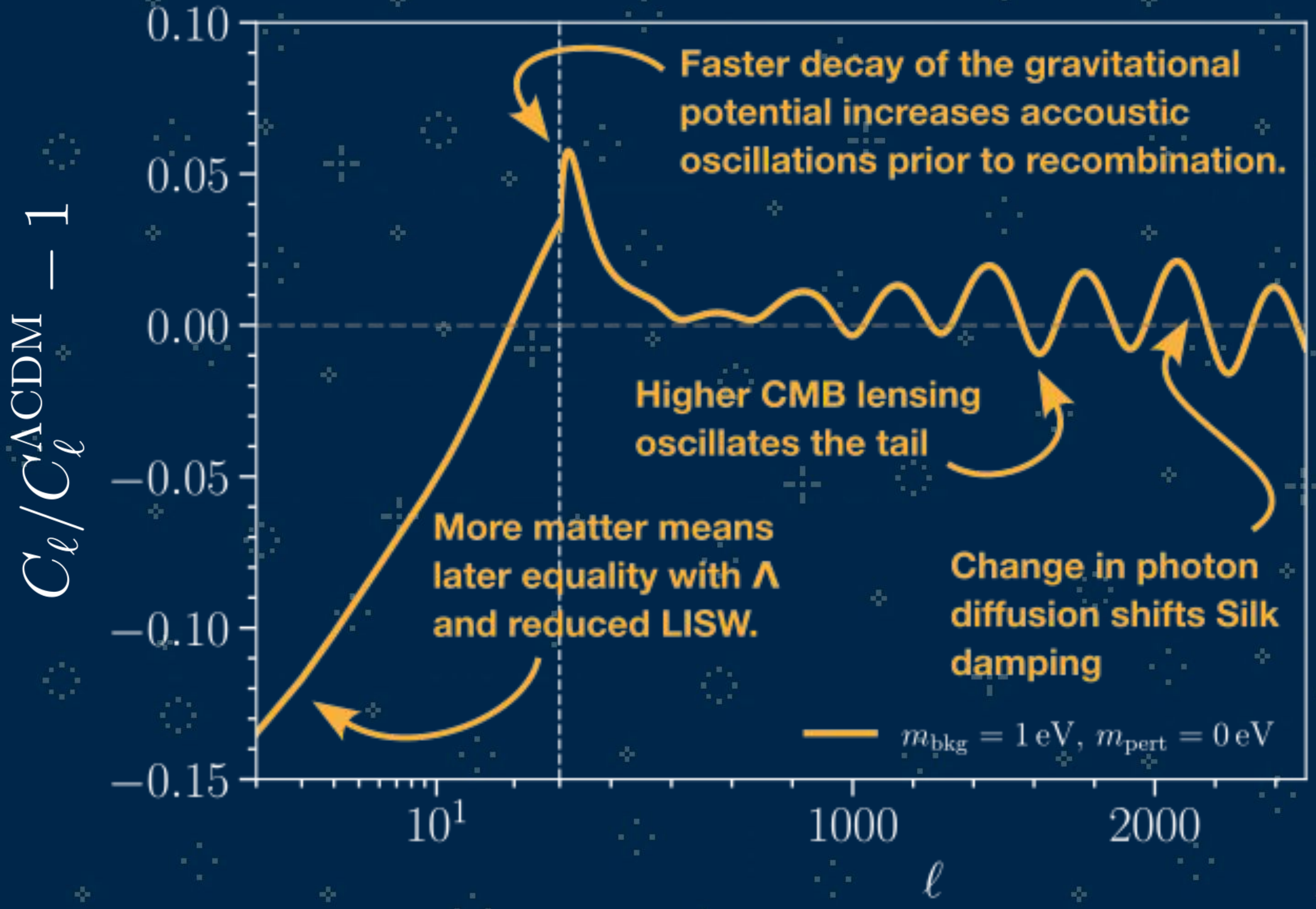


🌐 tbertolez.github.io

✉ antoni.bertolez@fqa.ub.edu

BACKUP:

MORE THINGS I WOULD LOVE TO TELL YOU

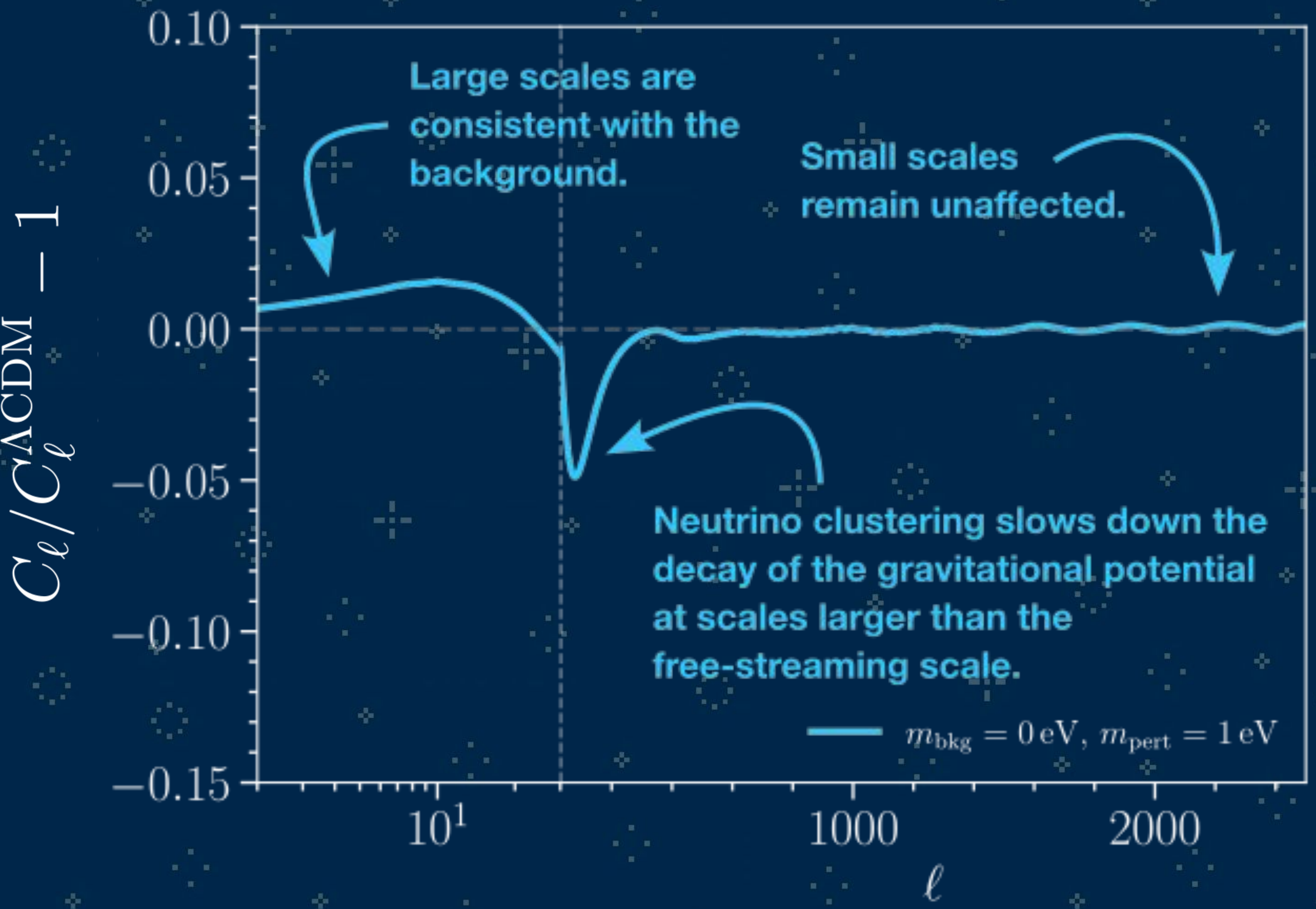


Faster decay of the gravitational potential increases accoustic oscillations prior to recombination.

Higher CMB lensing oscillates the tail

More matter means later equality with Λ and reduced LISW.

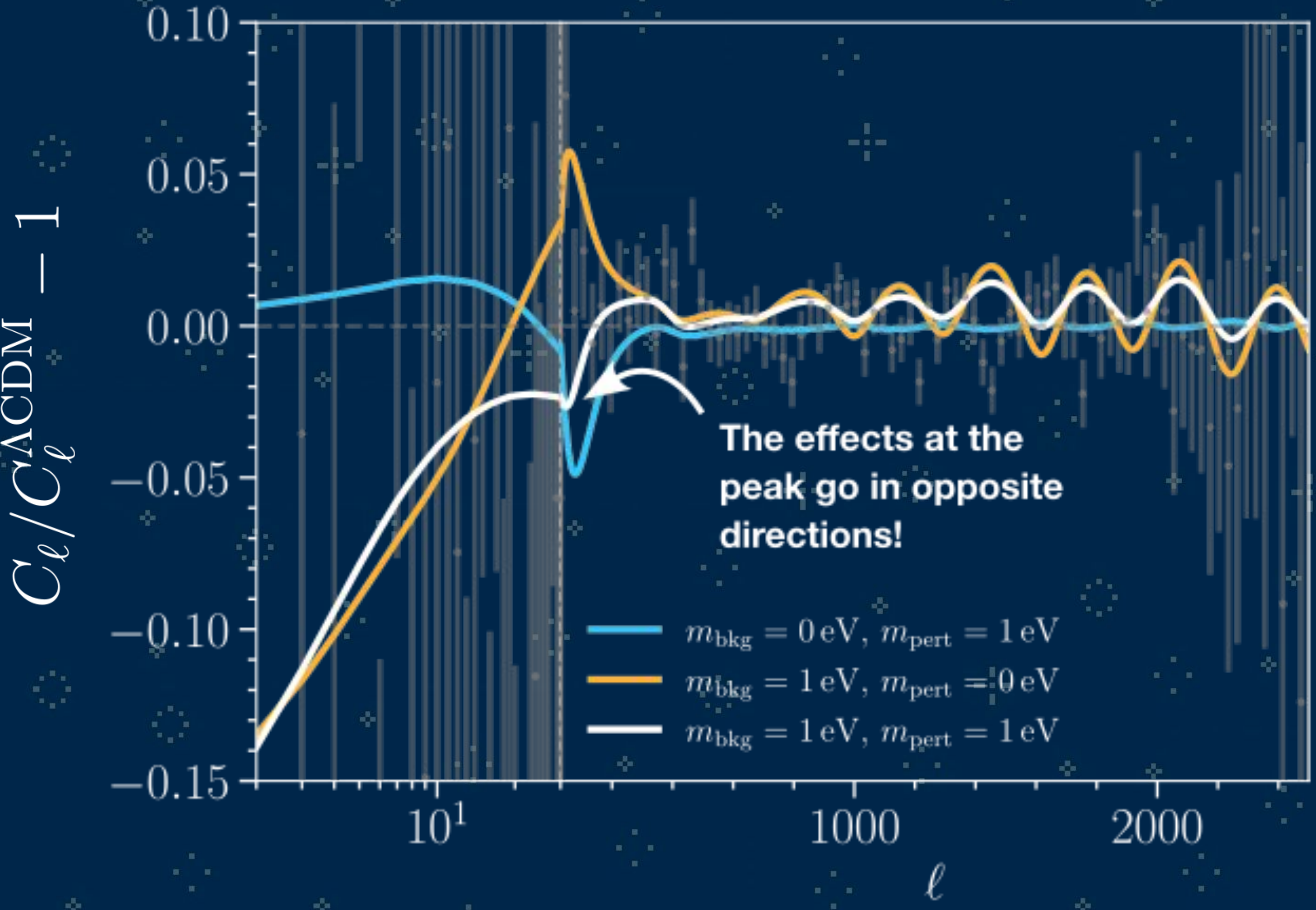
Change in photon diffusion shifts Silk damping



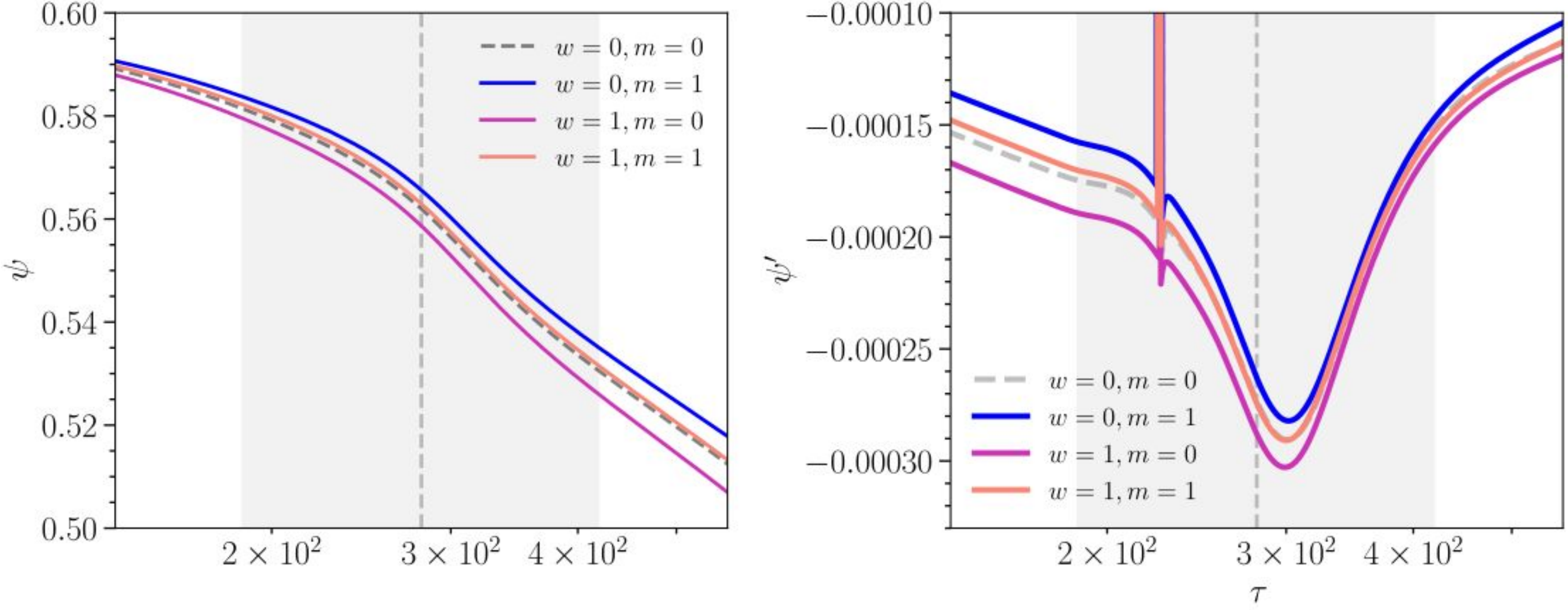
Large scales are consistent with the background.

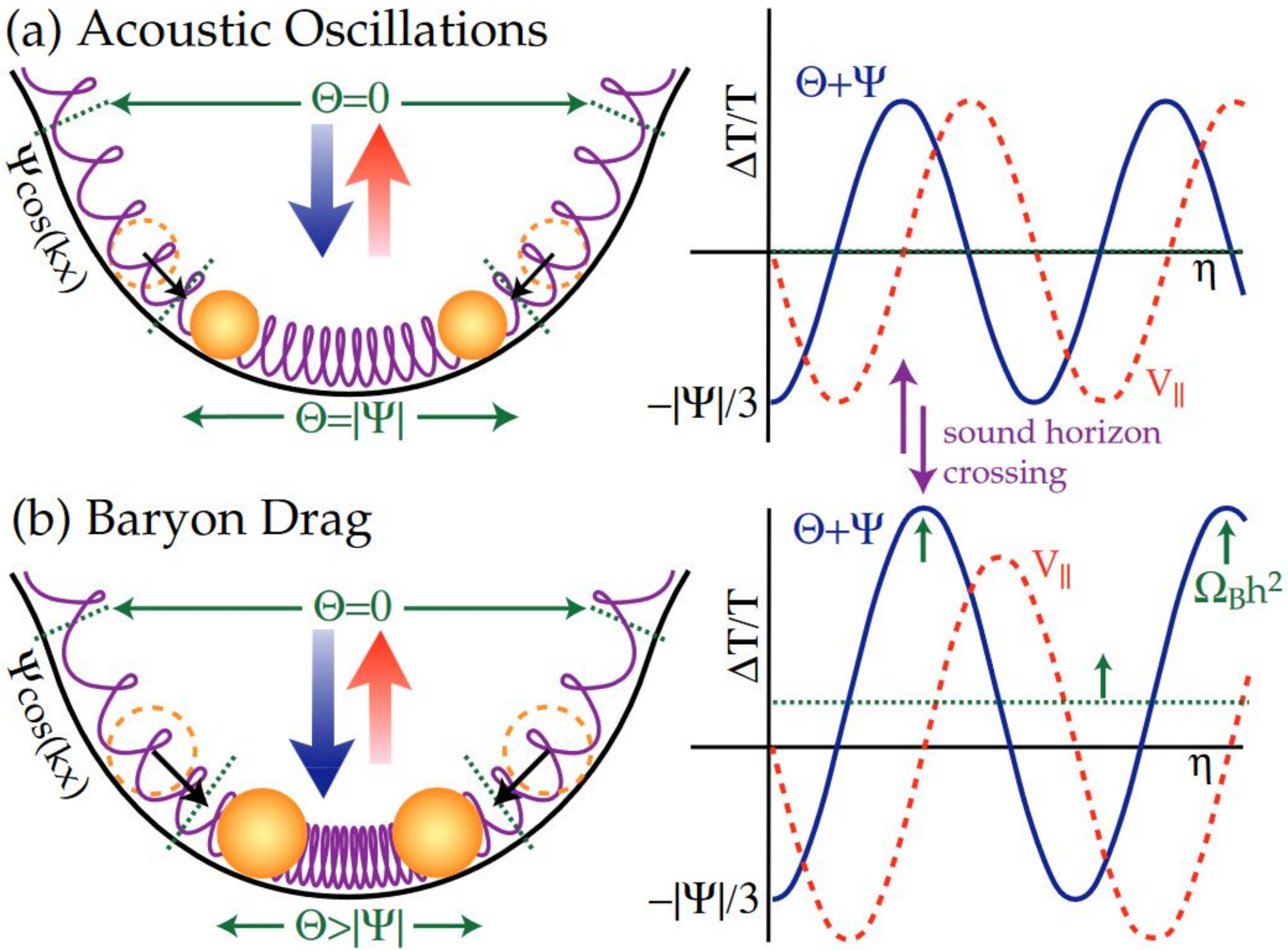
Small scales remain unaffected.

Neutrino clustering slows down the decay of the gravitational potential at scales larger than the free-streaming scale.



The effects at the peak go in opposite directions!

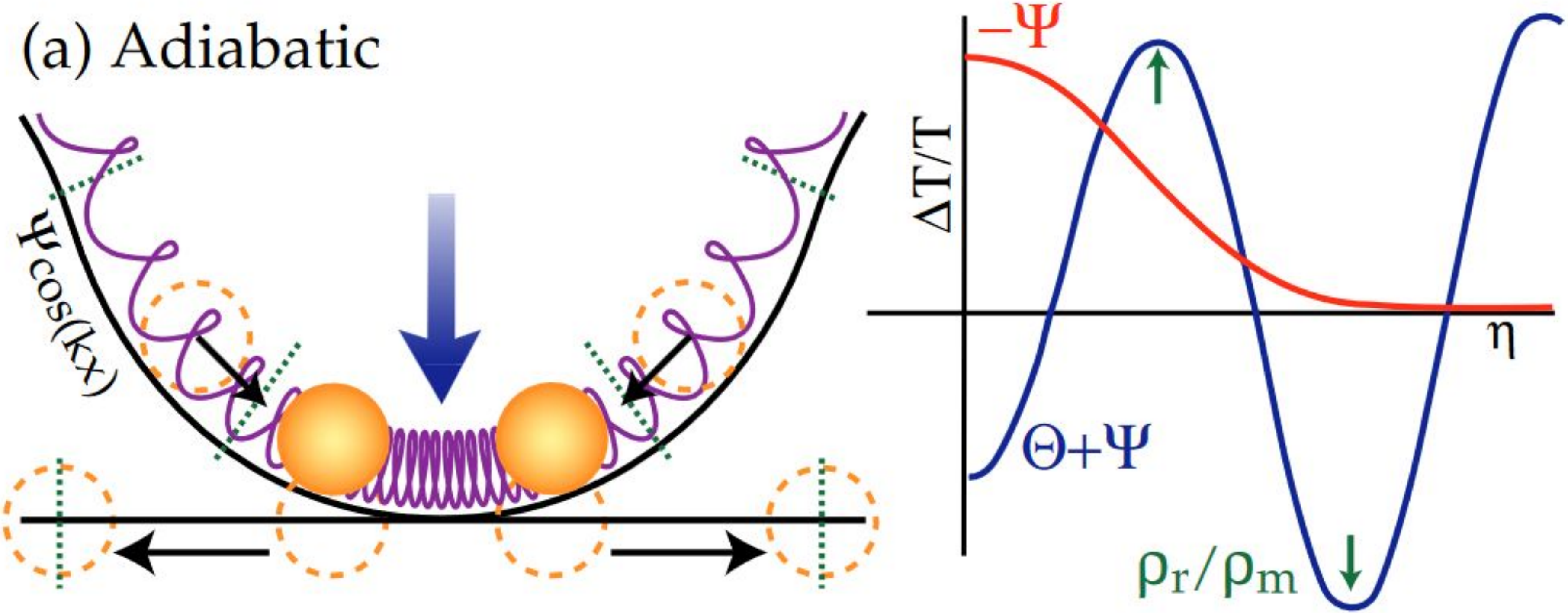

0.60
0.58
0.56
0.54
0.52
0.50
ψ
2×10^2
3×10^2
4×10^2
$w = 0, m = 0$
$w = 0, m = 1$
$w = 1, m = 0$
$w = 1, m = 1$
−0.00010
−0.00015
−0.00020
−0.00025
−0.00030
ψ'
2×10^2
3×10^2
4×10^2
τ
$w = 0, m = 0$
$w = 0, m = 1$
$w = 1, m = 0$
$w = 1, m = 1$

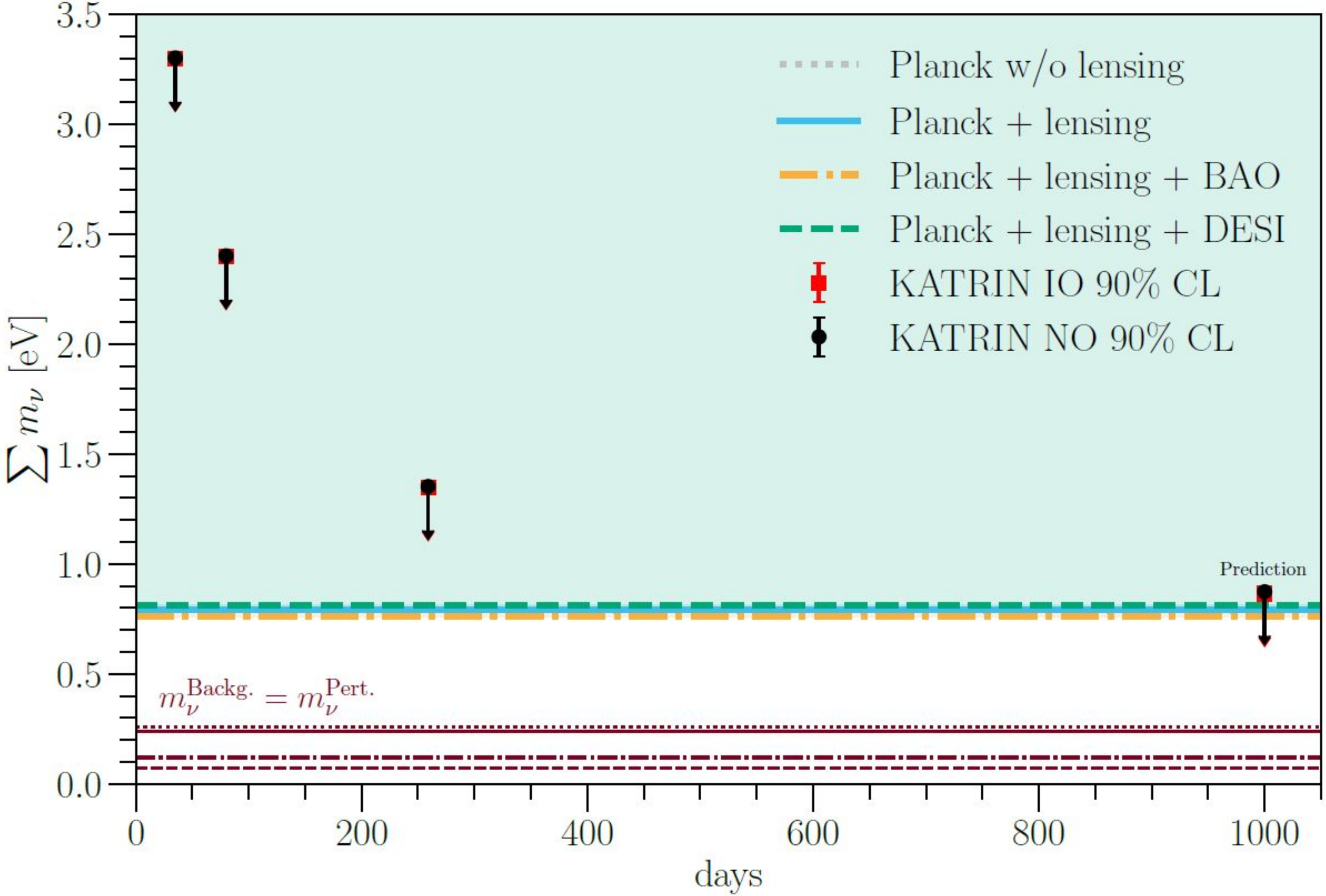


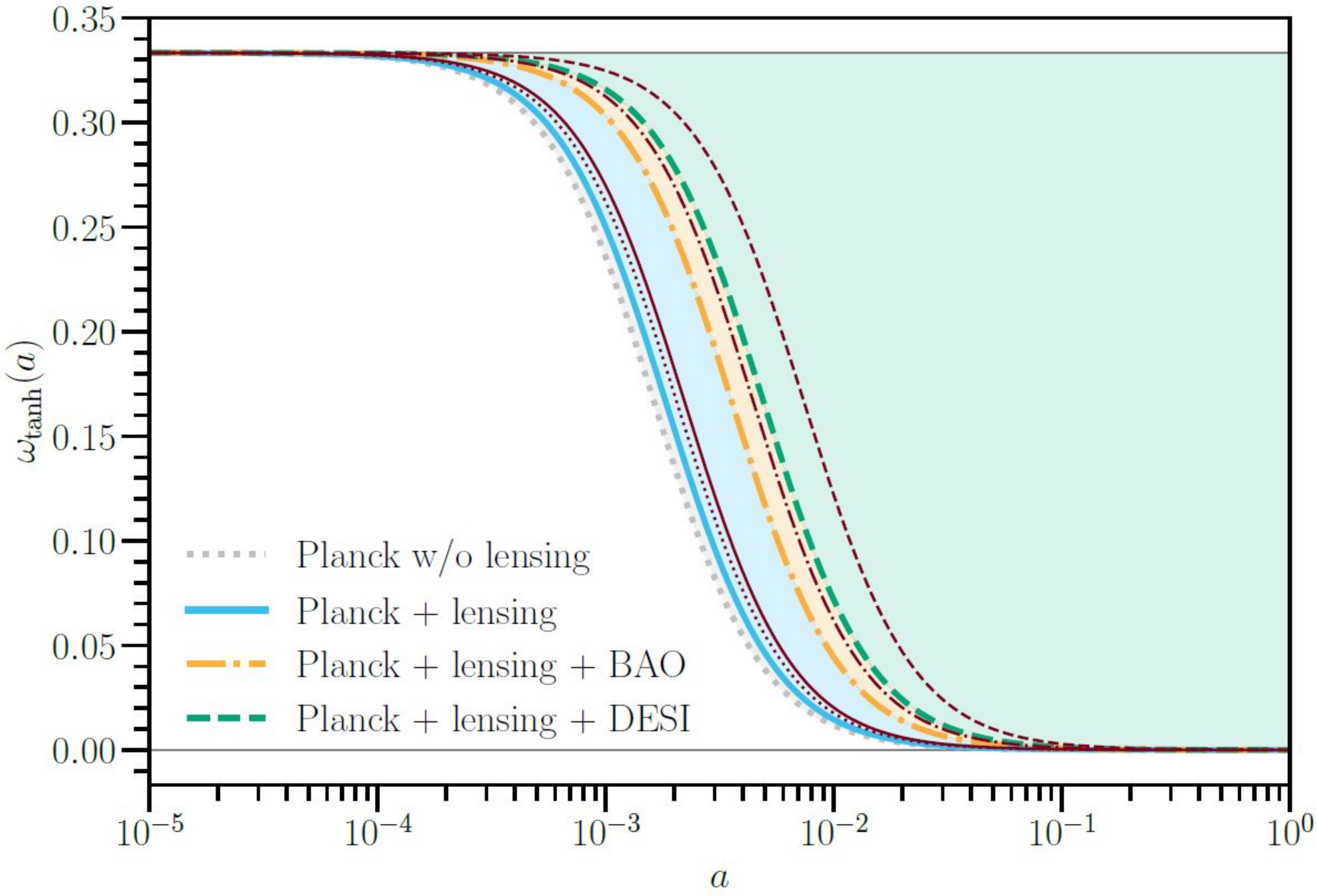
(a) Acoustic Oscillations

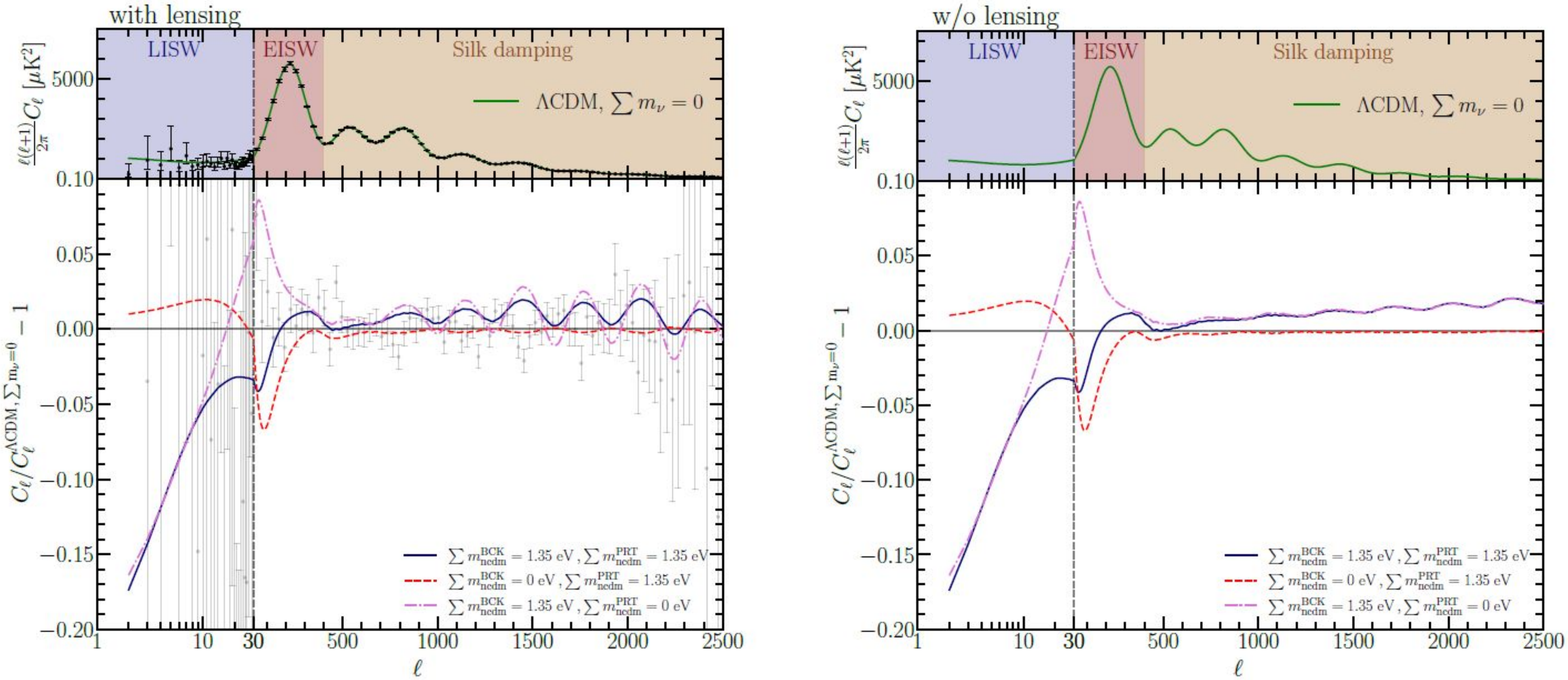
(b) Baryon Drag

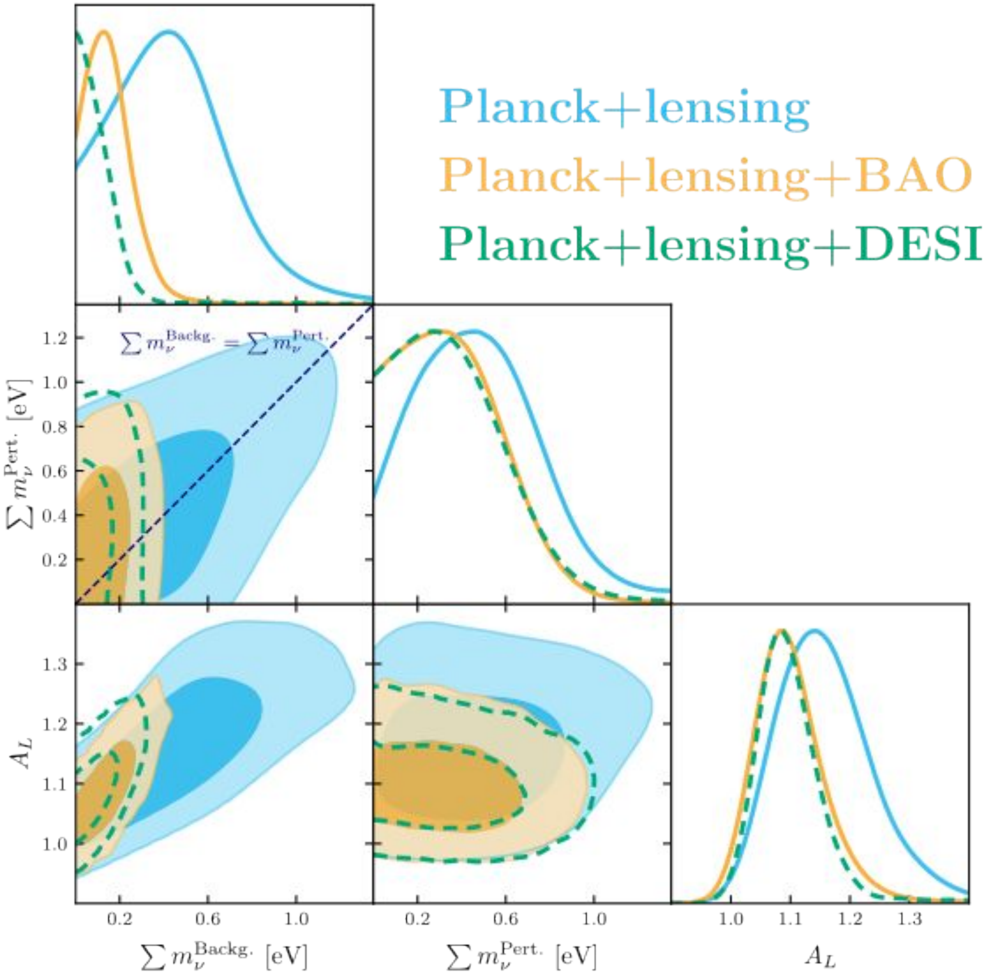
THE PHYSICS OF MICROWAVE BACKGROUND ANISOTROPIES - Hu, Sugiyama, Silk, astro-ph/9604166

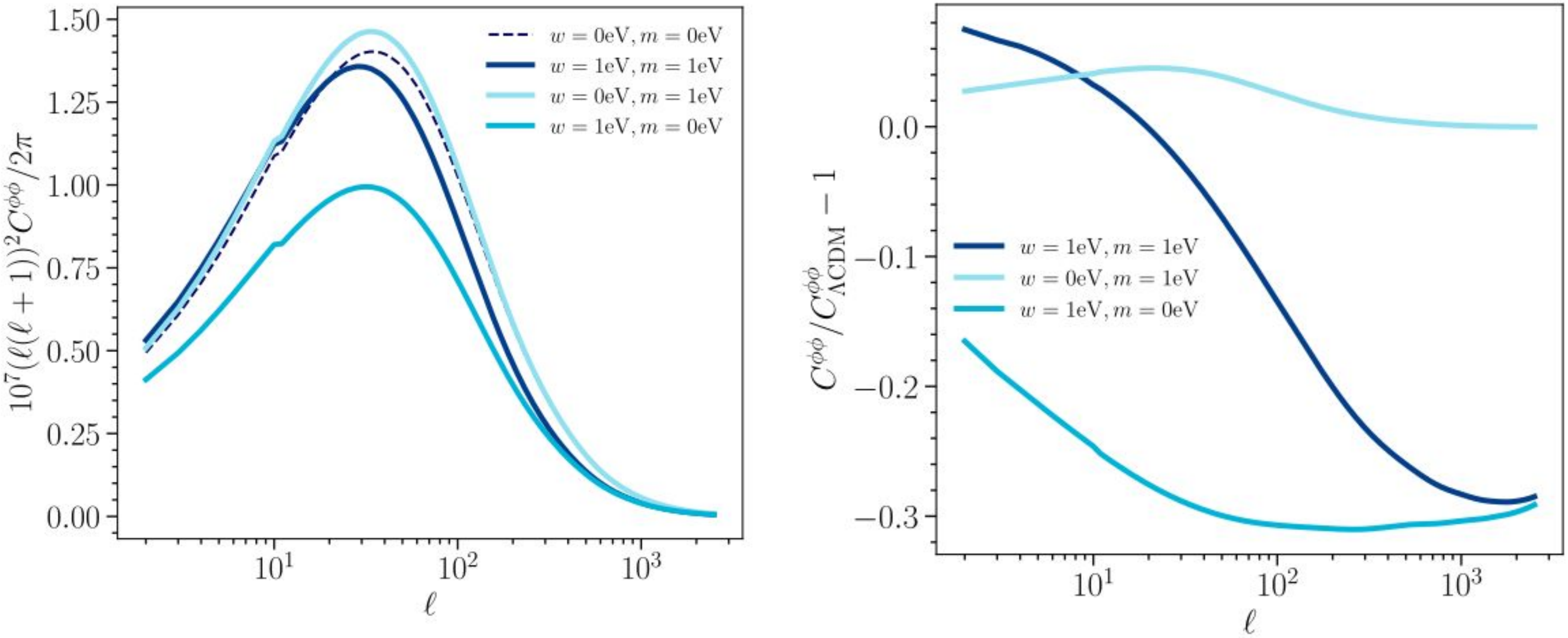


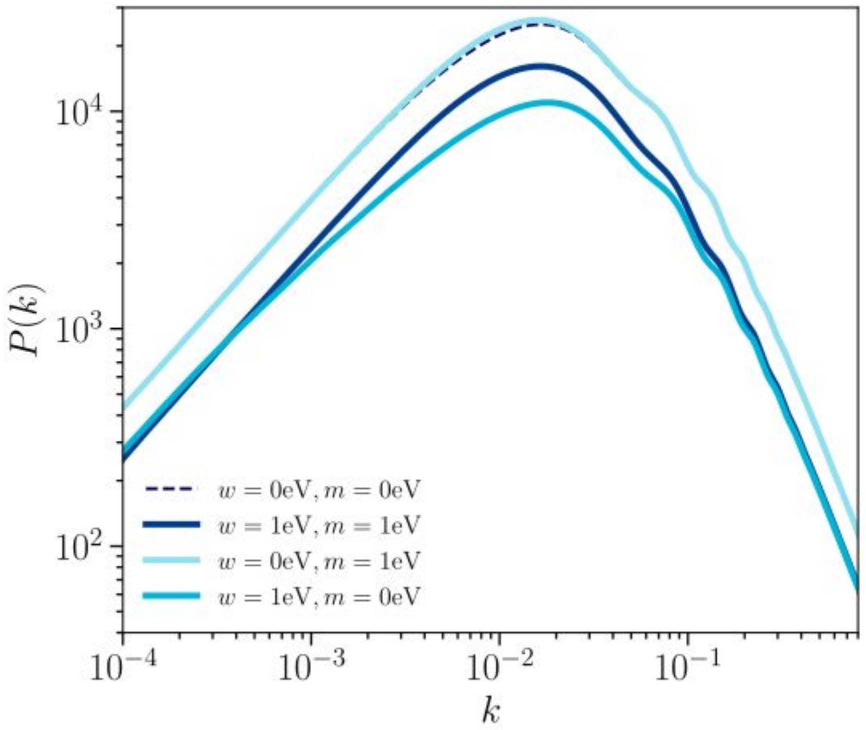

$\sum m_\nu$ [eV]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
days
Planck w/o lensing
Planck + lensing
Planck + lensing + BAO
Planck + lensing + DESI
KATRIN IO 90% CL
KATRIN NO 90% CL
Prediction
$m_\nu^{\text{Backg.}} = m_\nu^{\text{Pert.}}$

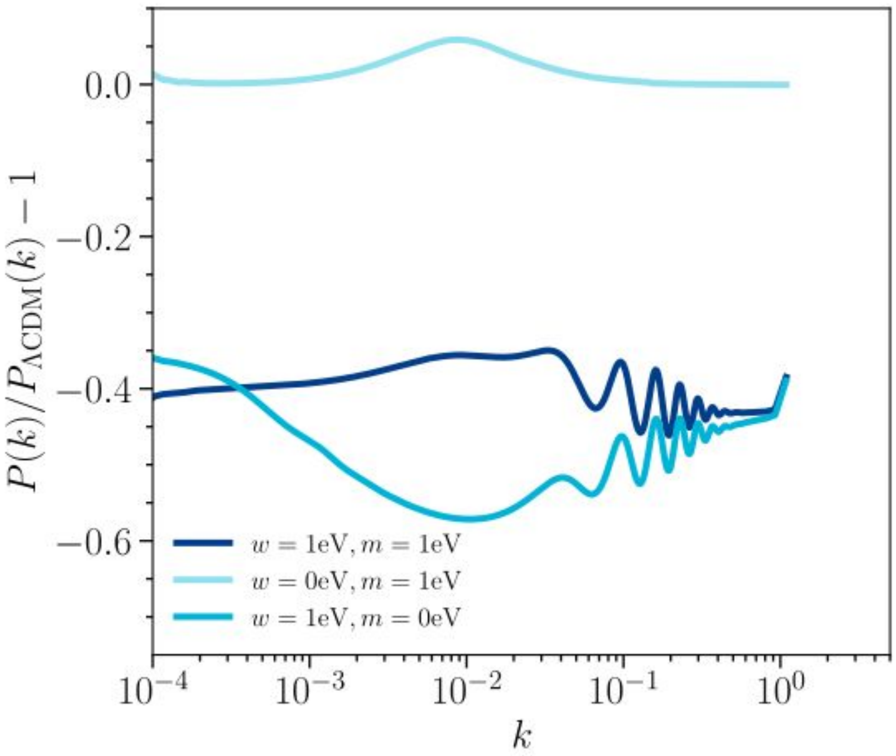

$\omega_{\rm tanh}(a)$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
a
Planck w/o lensing
Planck + lensing
Planck + lensing + BAO
Planck + lensing + DESI

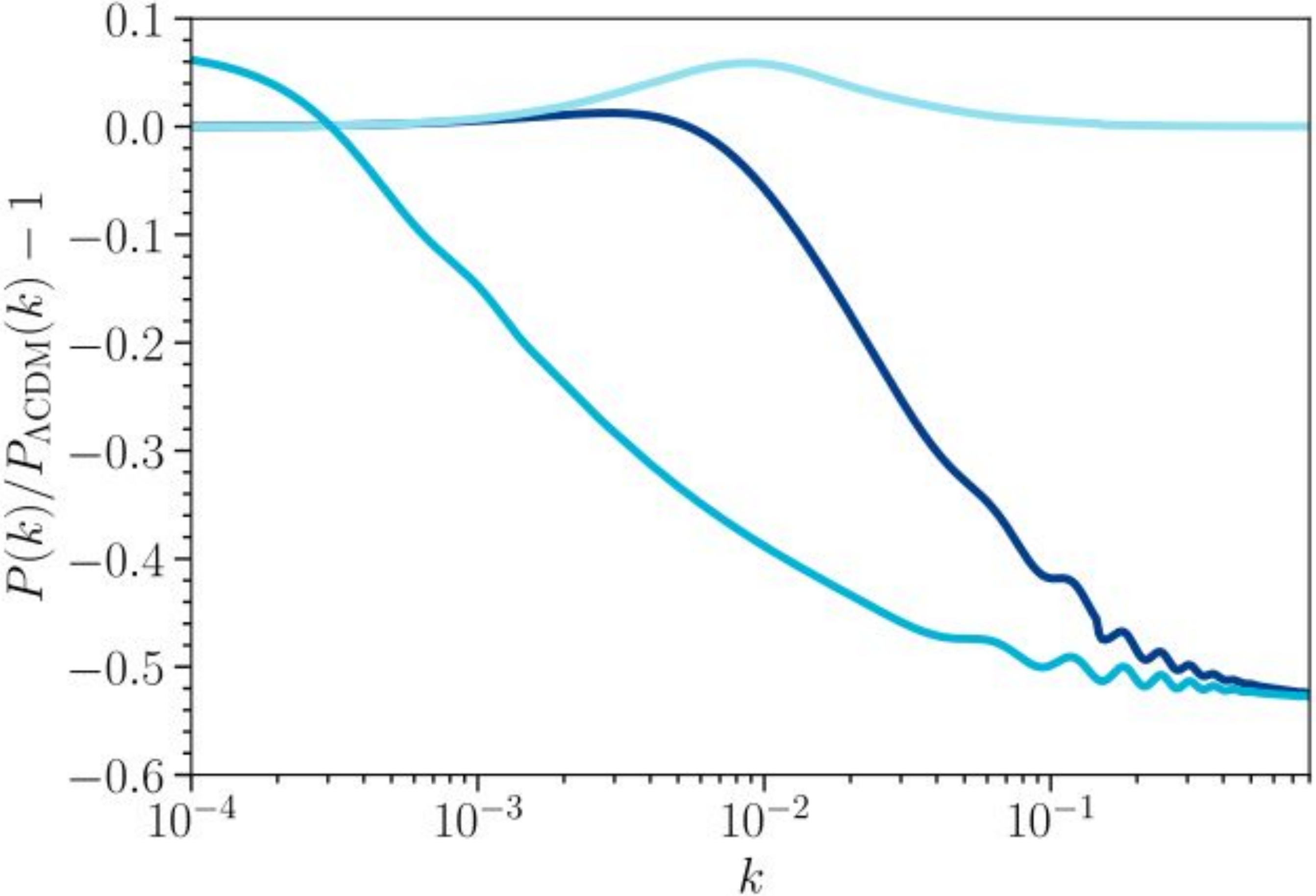

with lensing
w/o lensing
LISW
EISW
Silk damping
$\frac{\ell(\ell+1)}{2\pi}C_\ell\ [\mu\mathrm{K}^2]$
5000
0.10
ΛCDM, $\sum m_\nu = 0$
$C_\ell / C_\ell^{\Lambda\mathrm{CDM},\sum m_\nu=0} - 1$
0.05
0.00
−0.05
−0.10
−0.15
−0.20
1
10
30
500
1000
1500
2000
2500
ℓ
$\sum m_{\mathrm{ncdm}}^{\mathrm{BCK}} = 1.35$ eV , $\sum m_{\mathrm{ncdm}}^{\mathrm{PRT}} = 1.35$ eV
$\sum m_{\mathrm{ncdm}}^{\mathrm{BCK}} = 0$ eV , $\sum m_{\mathrm{ncdm}}^{\mathrm{PRT}} = 1.35$ eV
$\sum m_{\mathrm{ncdm}}^{\mathrm{BCK}} = 1.35$ eV , $\sum m_{\mathrm{ncdm}}^{\mathrm{PRT}} = 0$ 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]
0.2
0.4
0.6
0.8
1.0
1.2
A_L
1.0
1.1
1.2
1.3
0.2
0.6
1.0
$\sum m_\nu^{\rm Backg.}$ [eV]
0.2
0.6
1.0
$\sum m_\nu^{\rm Pert.}$ [eV]
1.0
1.1
1.2
1.3
A_L


$10^7(\ell(\ell+1))^2 C^{\phi\phi}/2\pi$
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^1
10^2
10^3
ℓ
$w = 0\mathrm{eV}, m = 0\mathrm{eV}$
$w = 1\mathrm{eV}, m = 1\mathrm{eV}$
$w = 0\mathrm{eV}, m = 1\mathrm{eV}$
$w = 1\mathrm{eV}, m = 0\mathrm{eV}$
$C^{\phi\phi}/C^{\phi\phi}_{\Lambda\mathrm{CDM}} - 1$
0.0
−0.1
−0.2
−0.3
10^1
10^2
10^3
ℓ
$w = 1\mathrm{eV}, m = 1\mathrm{eV}$
$w = 0\mathrm{eV}, m = 1\mathrm{eV}$
$w = 1\mathrm{eV}, m = 0\mathrm{eV}$


$P(k)$
10^4
10^3
10^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
k
$w = 0\mathrm{eV}, m = 0\mathrm{eV}$
$w = 1\mathrm{eV}, m = 1\mathrm{eV}$
$w = 0\mathrm{eV}, m = 1\mathrm{eV}$
$w = 1\mathrm{eV}, m = 0\mathrm{eV}$


$P(k)/P_{\Lambda\mathrm{CDM}}(k) - 1$
0.0
−0.2
−0.4
−0.6
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
k
$w = 1\mathrm{eV}, m = 1\mathrm{eV}$
$w = 0\mathrm{eV}, m = 1\mathrm{eV}$
$w = 1\mathrm{eV}, m = 0\mathrm{eV}$



0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
$P(k)/P_{\Lambda\mathrm{CDM}}(k) - 1$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
k