Origin of cosmological neutrino mass bounds:

background *versus* perturbations

Toni Bertólez-Martínez,
University of Wisconsin-Madison

CETUP* Workshop 2026

Based on work with R. Hajjar, I. Esteban, J. Salvadó, O. Mena

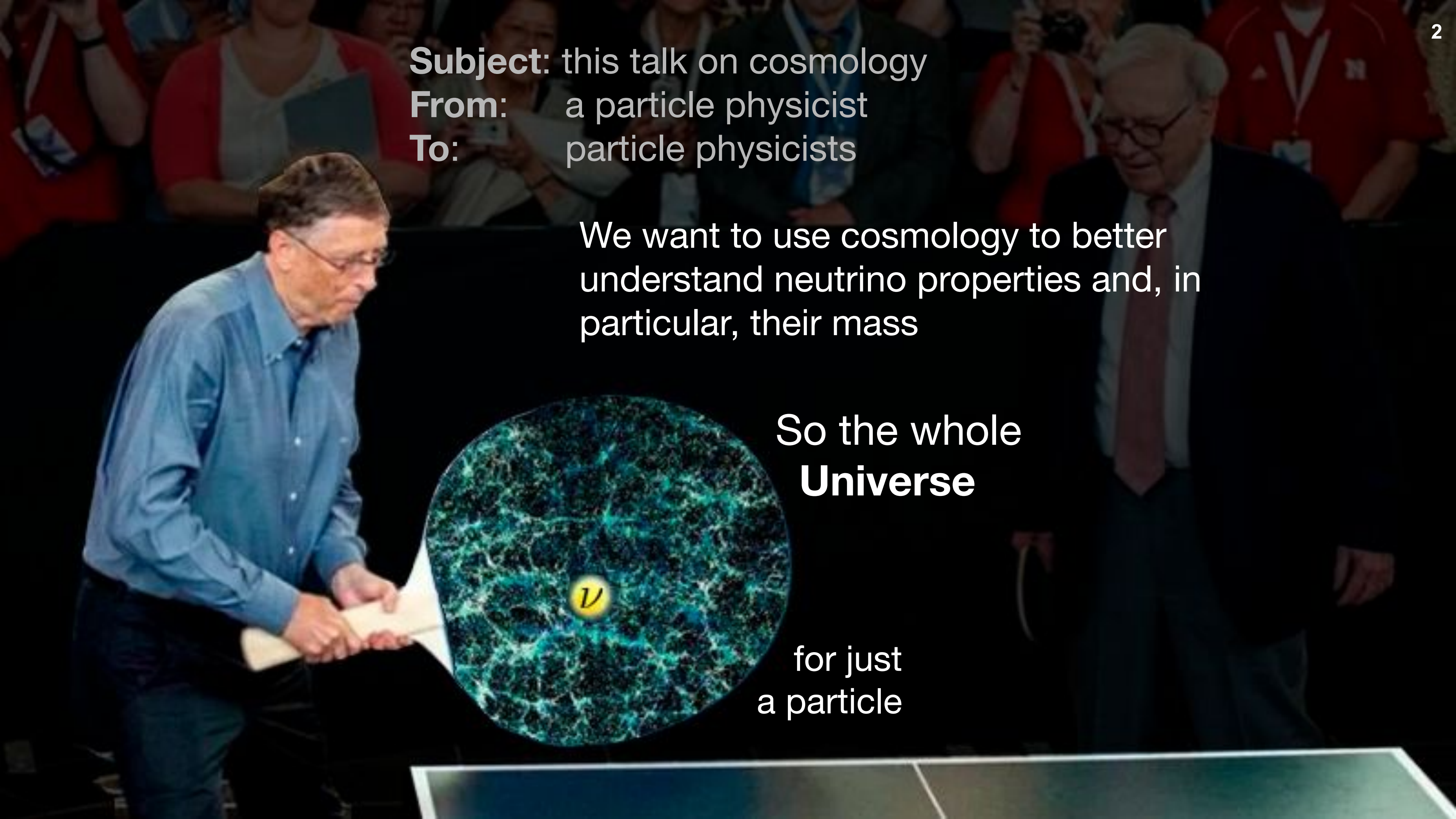
arXiV: 2411.14524, 2609.XXXX

Department of Physics
UNIVERSITY OF WISCONSIN–MADISON

WIPAC
WISCONSIN ICECUBE
PARTICLE ASTROPHYSICS CENTER

Subject: this talk on cosmology
From: a particle physicist
To: particle physicists

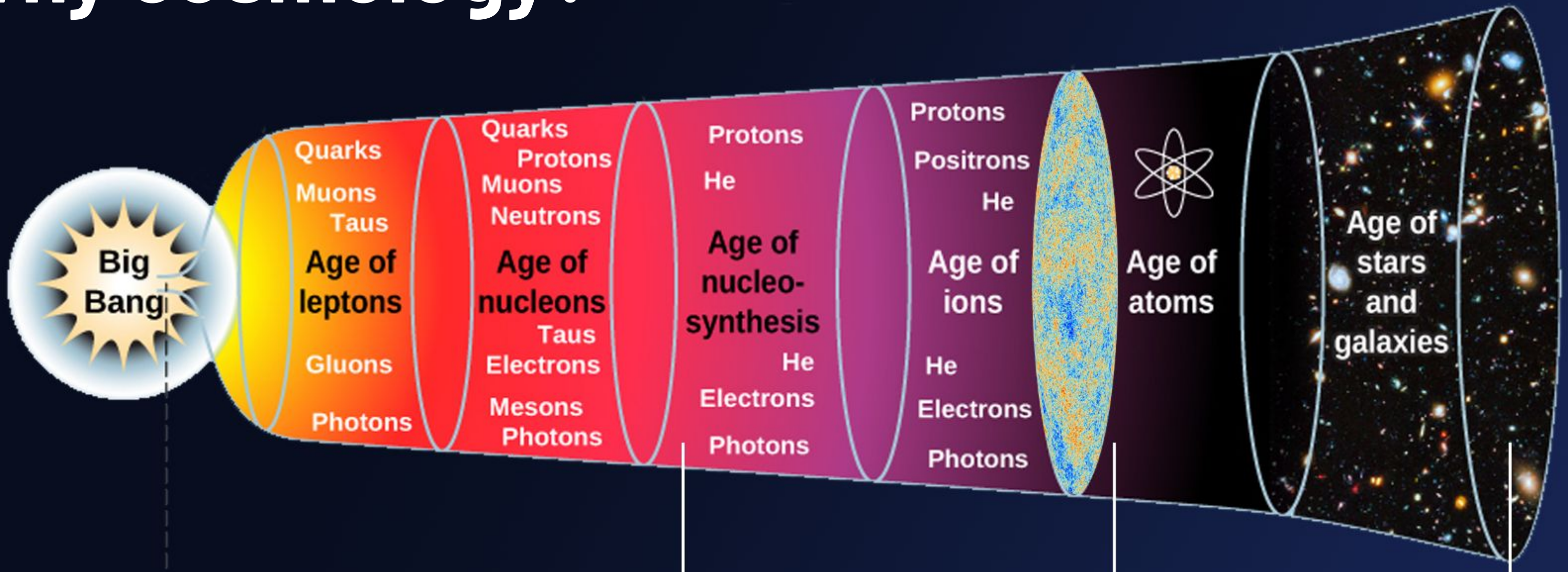
We want to use cosmology to better understand neutrino properties and, in particular, their mass



So the whole
Universe

for just
a particle

Why cosmology?



At 5 minutes
T ~ 1000000 eV
40% of the Universe

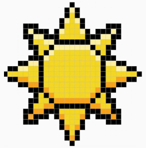
At 500.000 years
T ~ 1 eV
10% of the Universe

Today
T ~ 0.0001 eV
0.3% of the Universe

Neutrinos have decoupled

They can only affect gravitationally

What we know from the lab

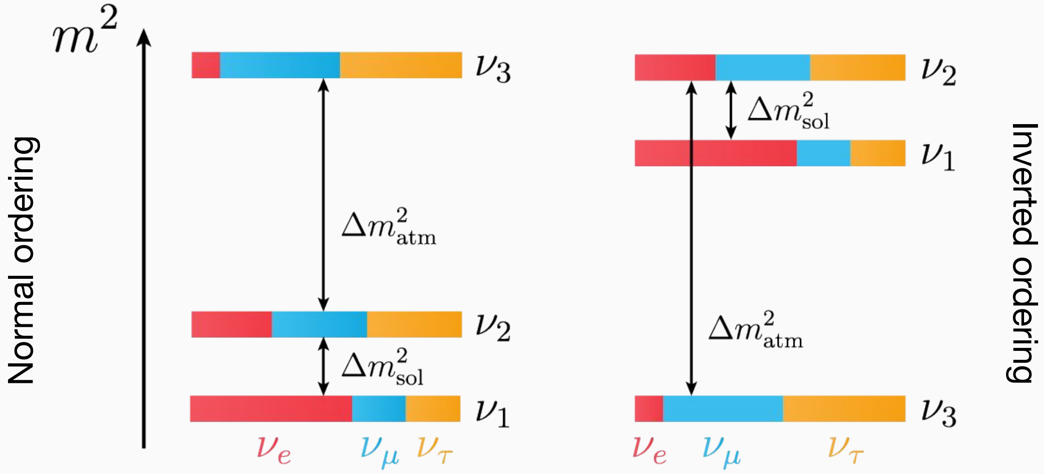


Historically from solar oscillations, we know:

$$\Delta m^2_{\rm sol} \equiv m_2^2 - m_1^2 = (7.42 \pm 0.21) \times 10^{-5}\,{\rm eV}^2$$

From atmospheric oscillations, we know:

$$\Delta m^2_{\rm atm} \equiv |m_3^2 - m_1^2| \approx (2.50 \pm 0.03) \times 10^{-3}\,{\rm eV}^2$$



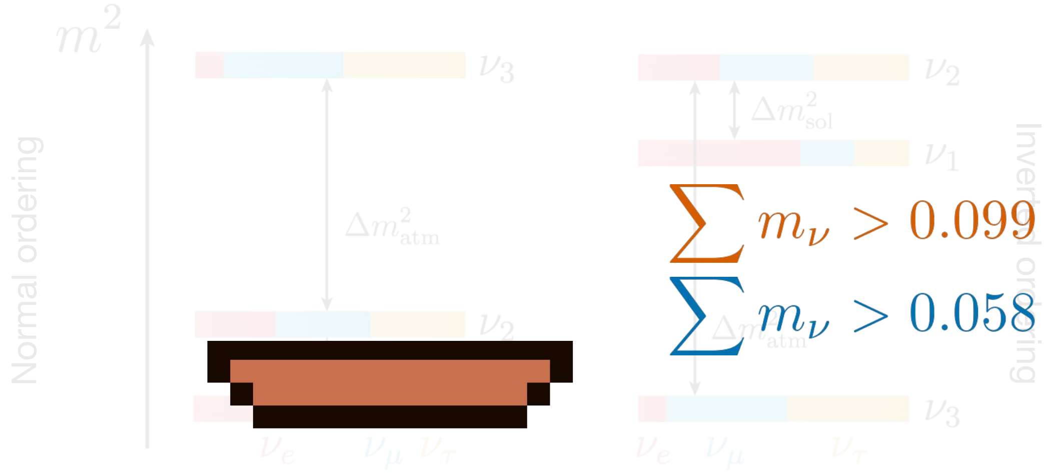
$$\sum m_\nu > 0.058\,{\rm eV} \qquad \sum m_\nu > 0.099\,{\rm eV}$$

Historically from solar oscillations, we know:

$$\Delta m^2_{\text{sol}} \equiv m_2^2 - m_1^2 = (7.42 \pm 0.21) \times 10^{-5}\,\text{eV}^2$$

From atmospheric oscillations, we know:

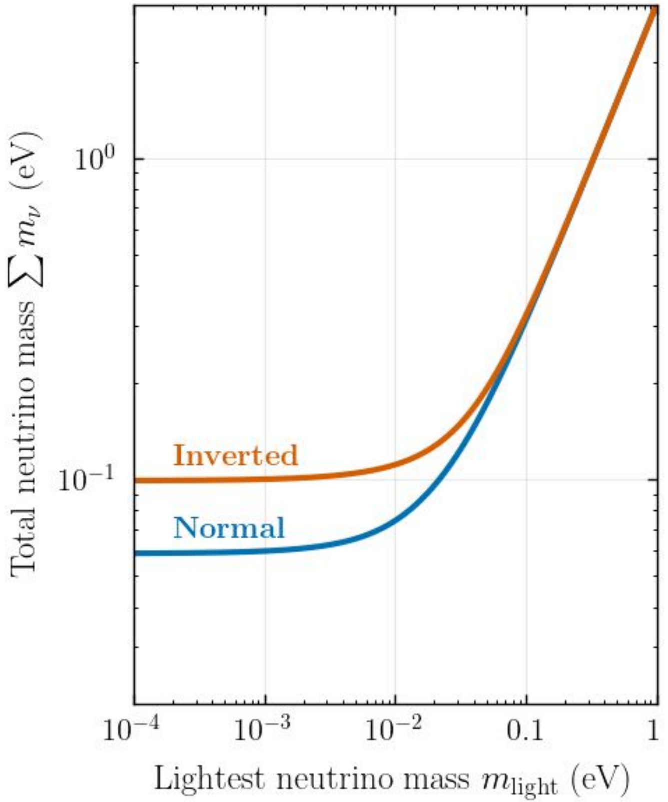
$$\Delta m^2_{\text{atm}} \equiv |m_3^2 - m_1^2| \approx (2.50 \pm 0.03) \times 10^{-3}\,\text{eV}^2$$



$$\sum m_\nu > 0.099\,\text{eV}$$

$$\sum m_\nu > 0.058\,\text{eV}$$

$$\sum m_\nu > 0.058\,\text{eV} \qquad \sum m_\nu > 0.099\,\text{eV}$$

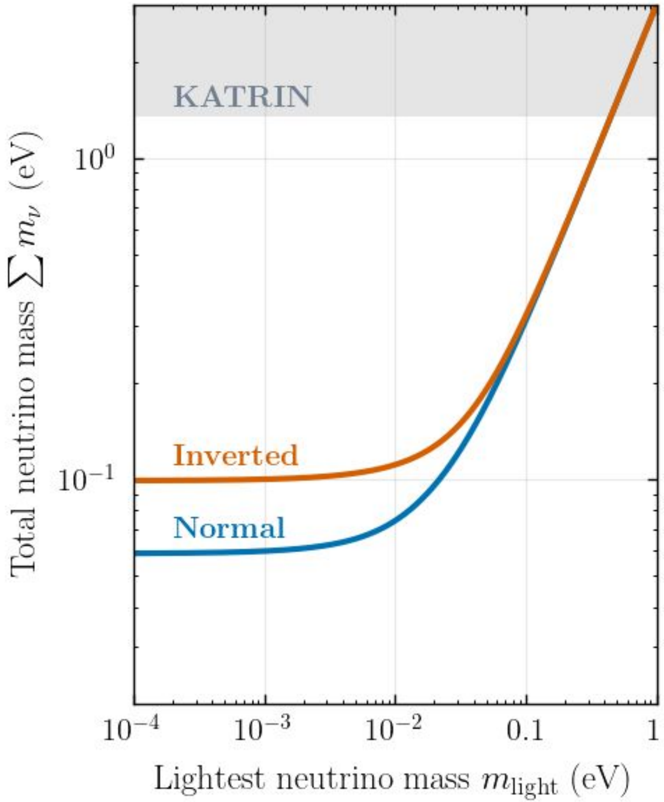


KATRIN kinematic bounds

$$\sum m_\nu < 1.35\,\text{eV}$$

$$\sum m_\nu > 0.099\,\text{eV}$$

$$\sum m_\nu > 0.058\,\text{eV}$$



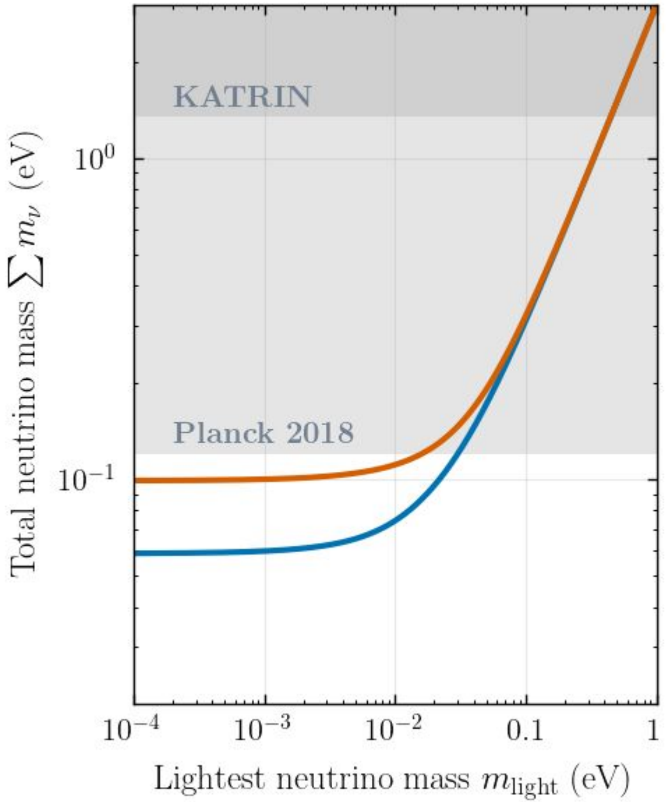
(all bounds reported in this talk are at the 95% C.L.)

Planck 2018 + BAOs + lensing

$$\sum m_\nu < 0.12\,\mathrm{eV}$$

$$\sum m_\nu > 0.099\,\mathrm{eV}$$

$$\sum m_\nu > 0.058\,\mathrm{eV}$$



(all bounds reported in this talk are at the 95% C.L.)

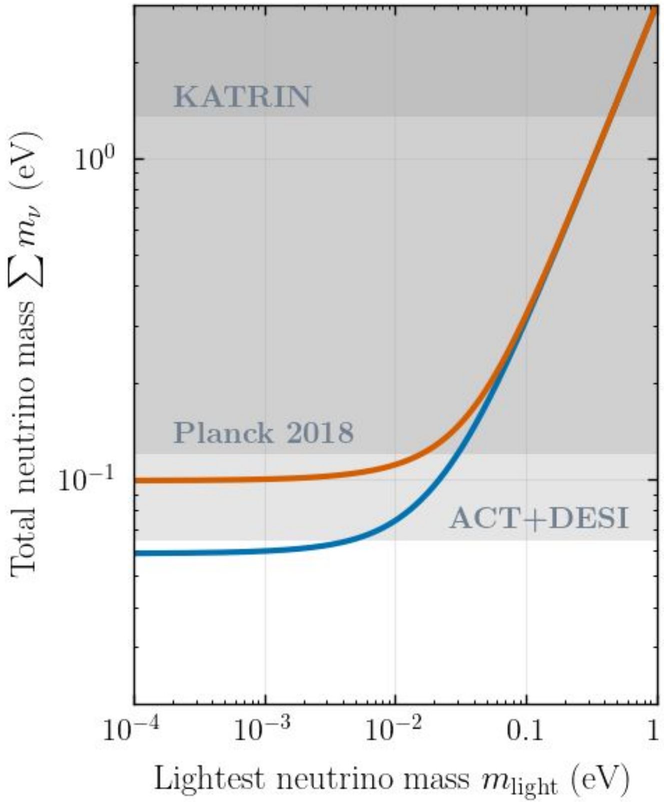
ACT + Planck 2018 + DESI + lensing

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

$$\cancel{\sum m_\nu > 0.099\,\mathrm{eV}}$$

$$\sum m_\nu < 0.064\,\mathrm{eV}$$

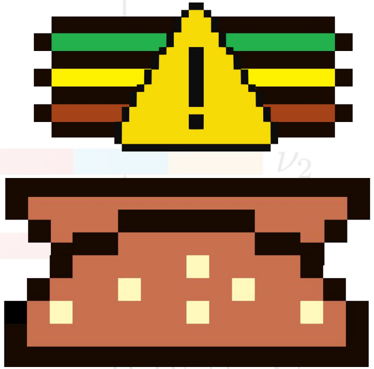
$$\sum m_\nu > 0.058\,\mathrm{eV}$$



(all bounds reported in this talk are at the 95% C.L.)

SPT + ACT + Planck 2018 + DESI + lensing

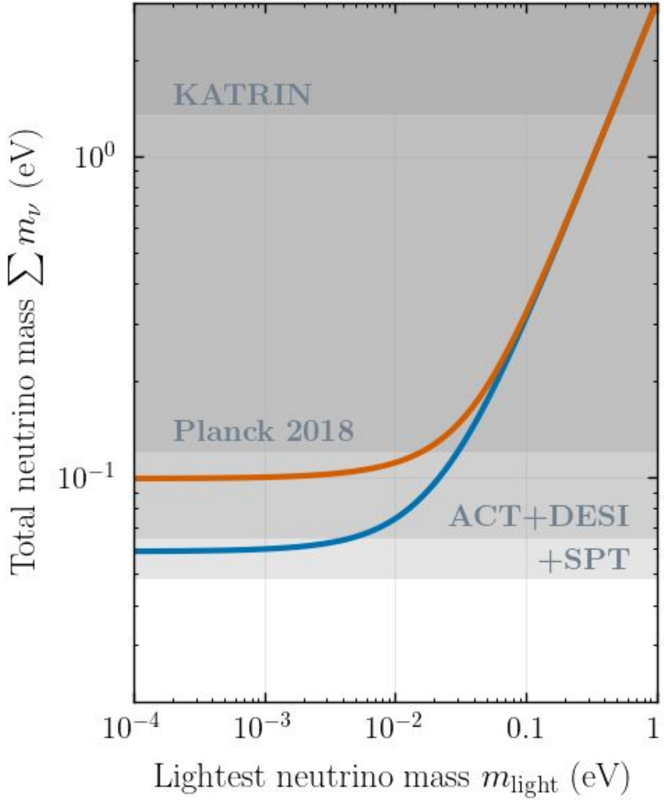
$$\sum m_\nu < 1.35\,\mathrm{eV}$$



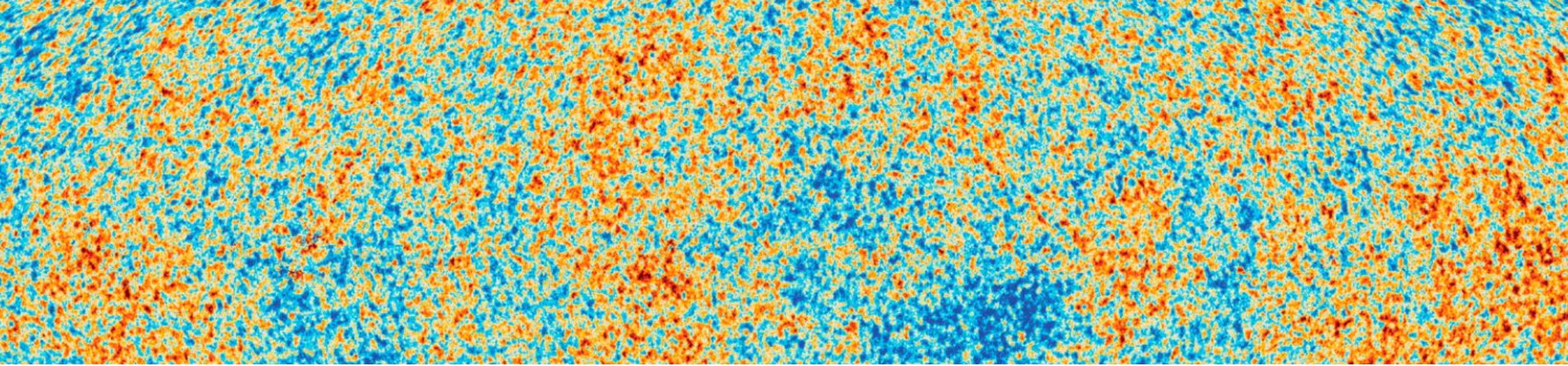
$$\cancel{\sum m_\nu > 0.099\,\mathrm{eV}}$$

$$\cancel{\sum m_\nu > 0.058\,\mathrm{eV}}$$

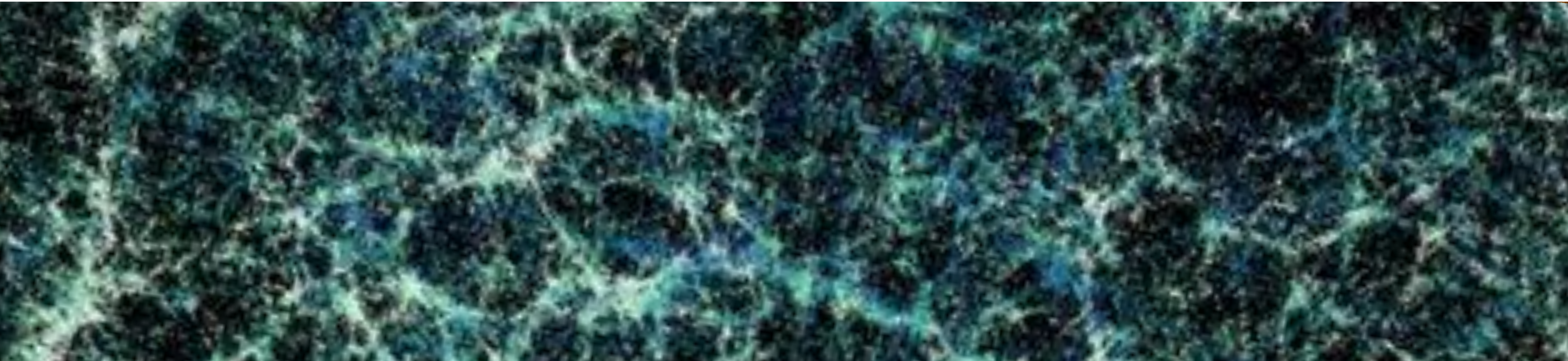
$$\sum m_\nu < 0.048\,\mathrm{eV}$$



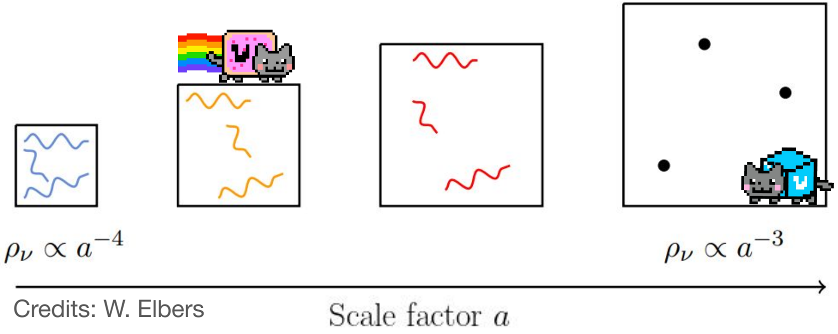
(all bounds reported in this talk are at the 95% C.L.)



Neutrino masses in cosmology



Neutrino masses **on the background**



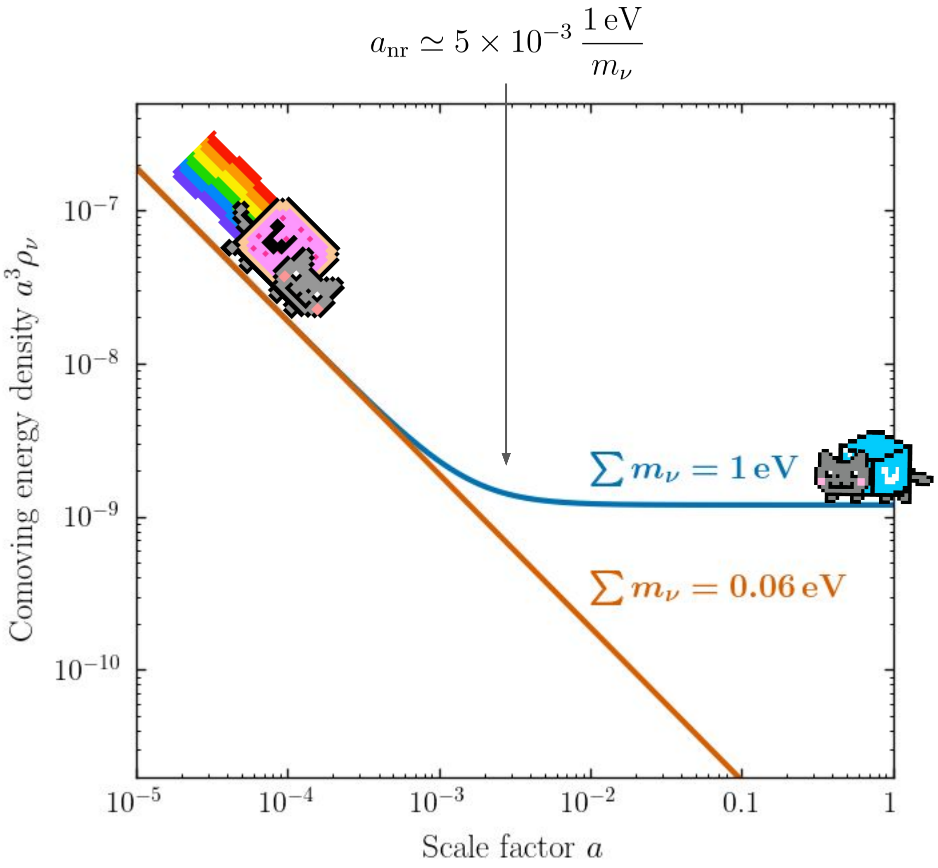
Increases matter energy budget

Increases the expansion rate

$$\Omega_\nu h^2 \simeq \frac{\sum m_{\nu,i}}{94.1\,\mathrm{eV}}$$

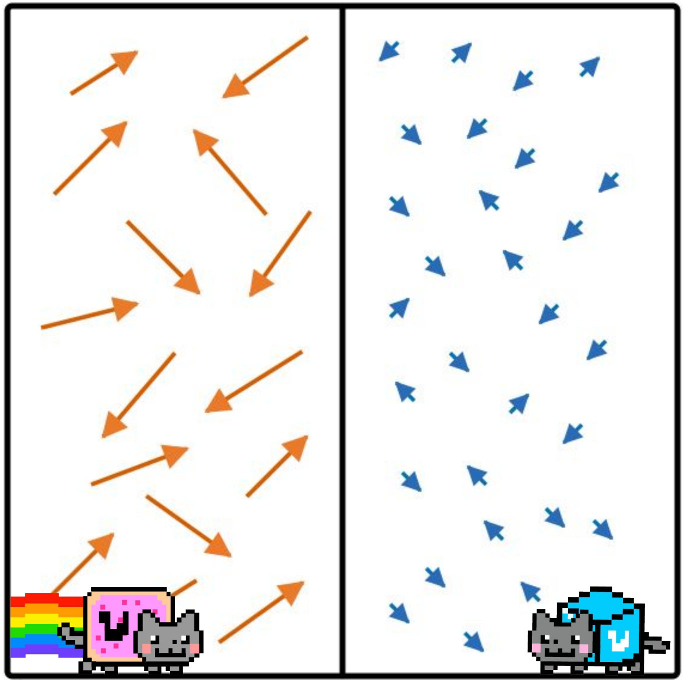
$$H^2 \supset H_0^2 \Omega_m$$

This is a thermodynamic property!

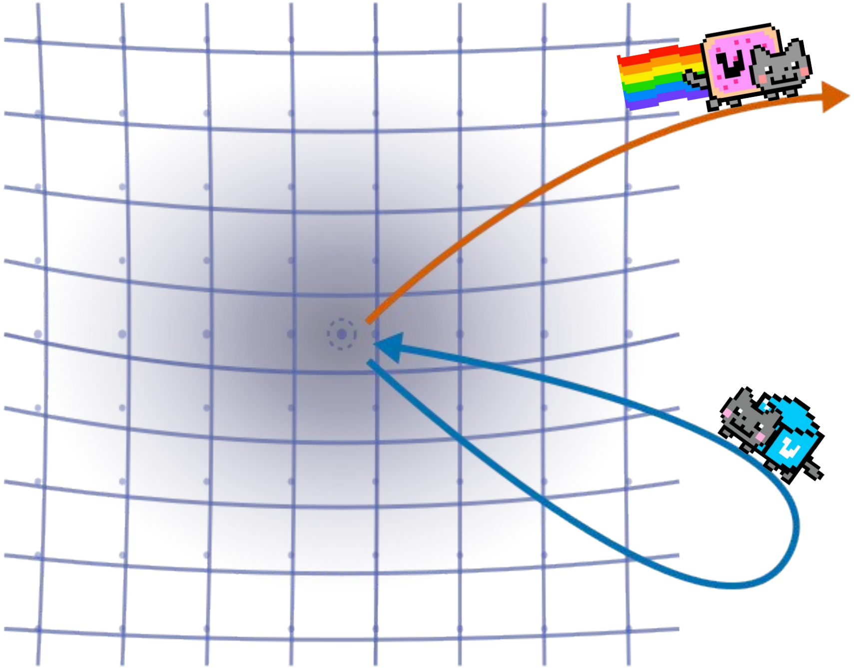


Neutrino masses **on perturbations**

Neutrino masses reduces their velocity dispersion when they go non-relativistic.



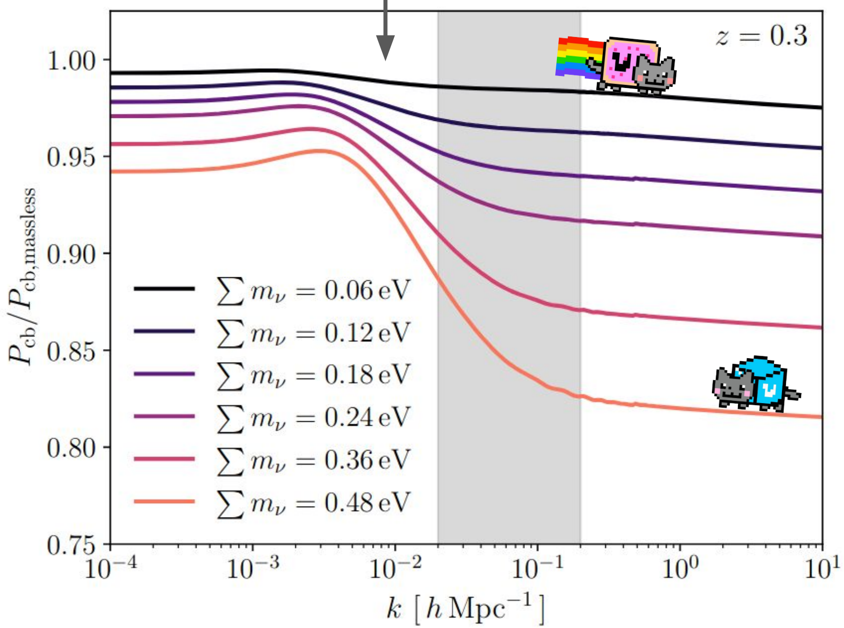
Massive neutrinos fall into large-scale potential wells, while massless wouldn't.



Neutrino masses **on perturbations**

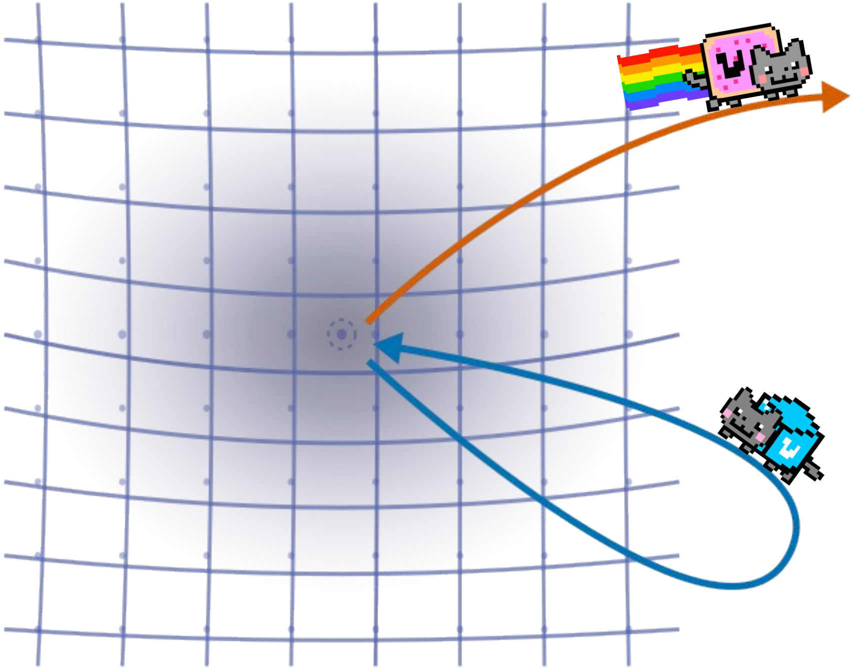
Neutrino mass suppress the power spectrum above the **free-streaming scale**.

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



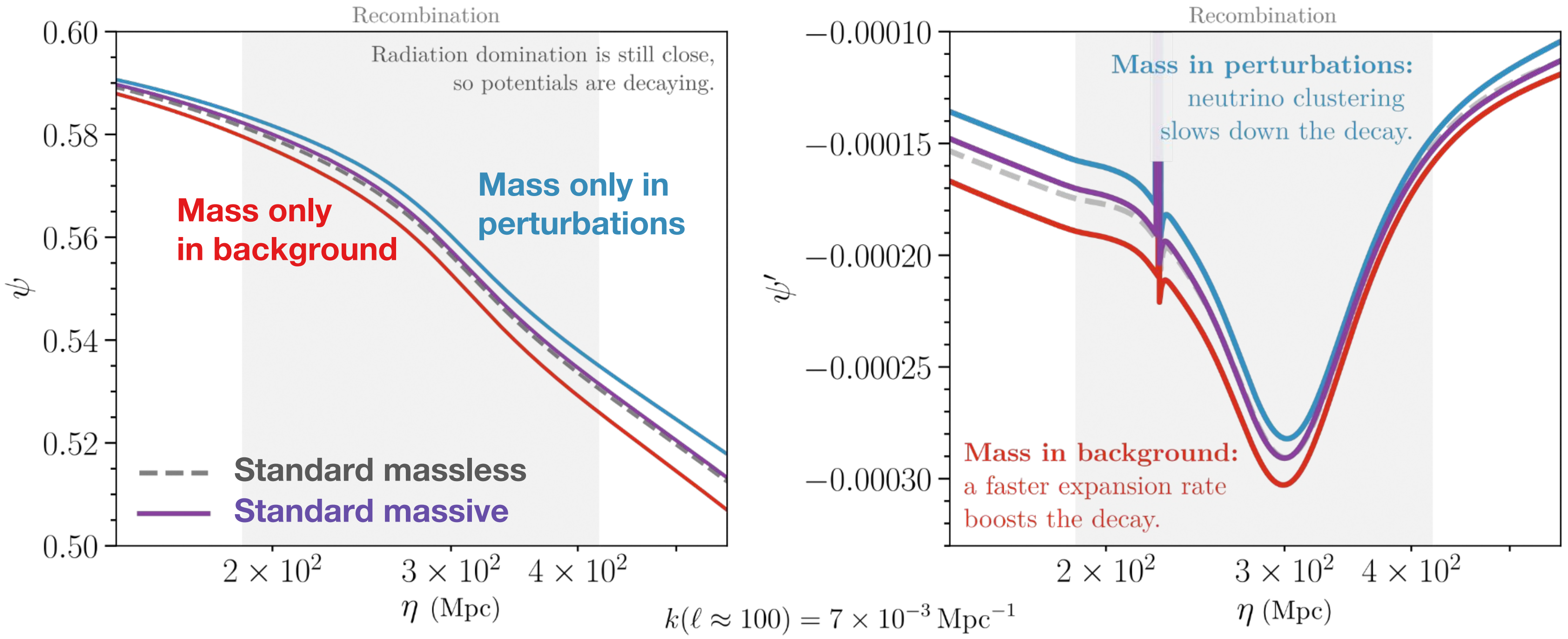
Elbers et al., 2503.14744

Massive neutrinos fall into large-scale potential wells, while massless wouldn't.



Note 1:

Expansion rate and clustering may be **competing effects**



Compare purple with gray. Both standard massless and massive neutrinos have the same effect on the gravitational potential, due to these two effects cancelling each other.

Note 2:

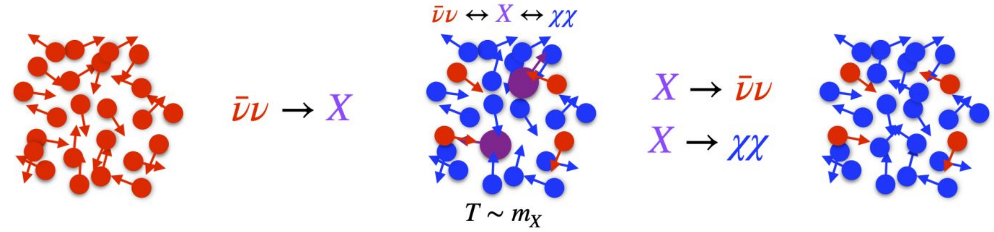
These are **collective effects sensitive to BSM**

Since cosmology mostly measures the energy density of neutrinos, BSM can modify the collective neutrino fluid **without changing the individual neutrino mass**.

Neutrino annihilation or decay

$$\sum m_\nu < 0.12\,\mathrm{eV}\,(1 + g_\chi N_\chi/6)$$

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

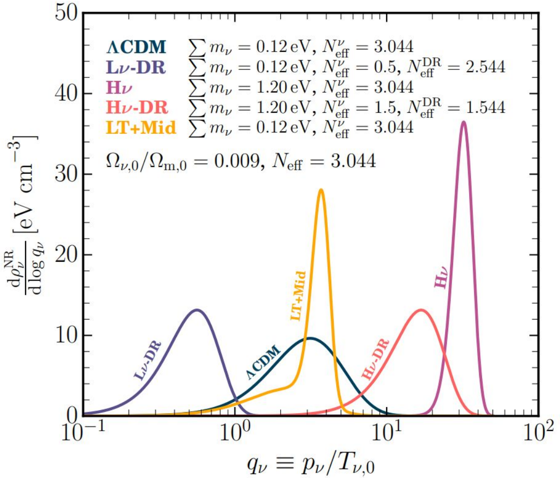


Non-standard neutrino populations

$$\sum m_\nu < 0.37\,\mathrm{eV}$$

(or even further)

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

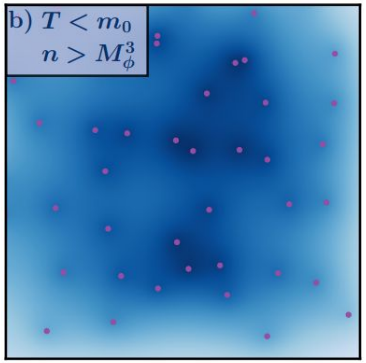


Long-range interactions mediated by an ultralight scalar

$$\sum m_\nu < 3\,\mathrm{eV}$$

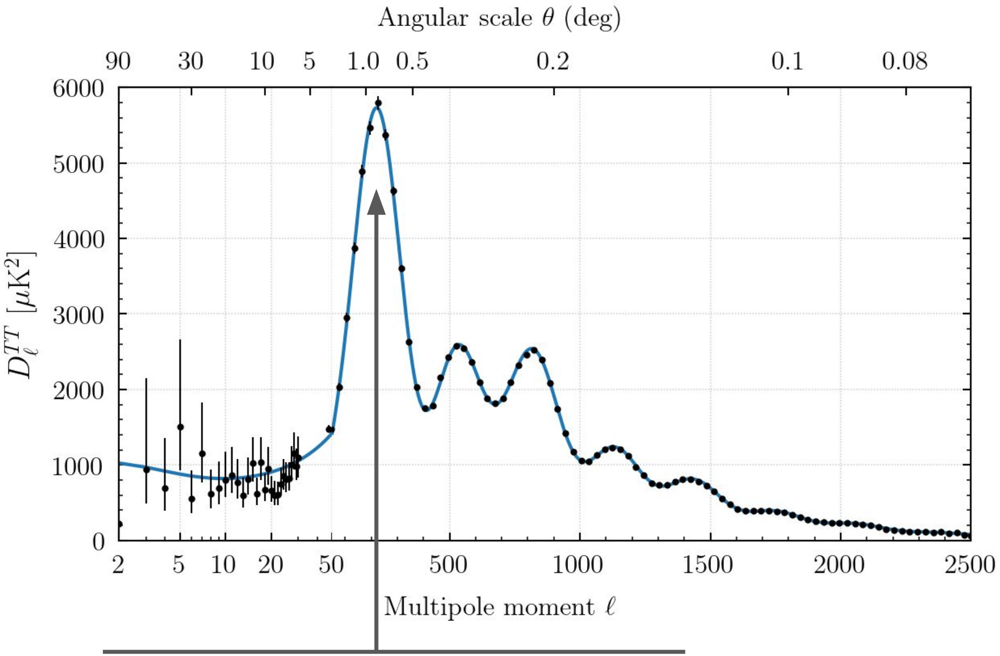
$$\text{for } g/M_\phi \sim 10^5\,\mathrm{eV}^{-1}$$

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



Observing neutrino masses

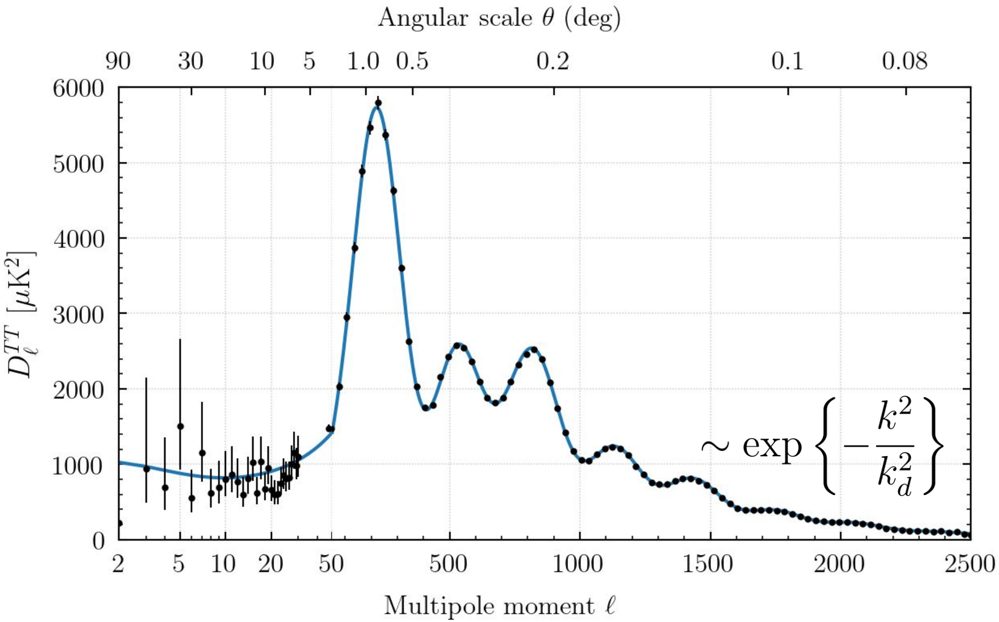
CMB spectra: sound horizon and damping scale



$$\theta_s = \int_{z_{\rm rec}}^{\infty} \frac{c_{s,\gamma}(z)\,\mathrm{d}z}{H(z)} \Big/ \int_0^{z_{\rm rec}} \frac{\mathrm{d}z}{H(z)}$$

is precisely measured,
strongly constraining massive neutrinos.

CMB spectra: sound horizon and damping scale



$$\theta_s = \int_{z_{\rm rec}}^{\infty} \frac{c_{s,\gamma}(z)\,\mathrm{d}z}{H(z)} \Big/ \int_0^{z_{\rm rec}} \frac{\mathrm{d}z}{H(z)}$$

is precisely measured,
strongly constraining massive neutrinos.

With θ_s fixed, constraining power comes from diffusion damping at high multipoles, with scale

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

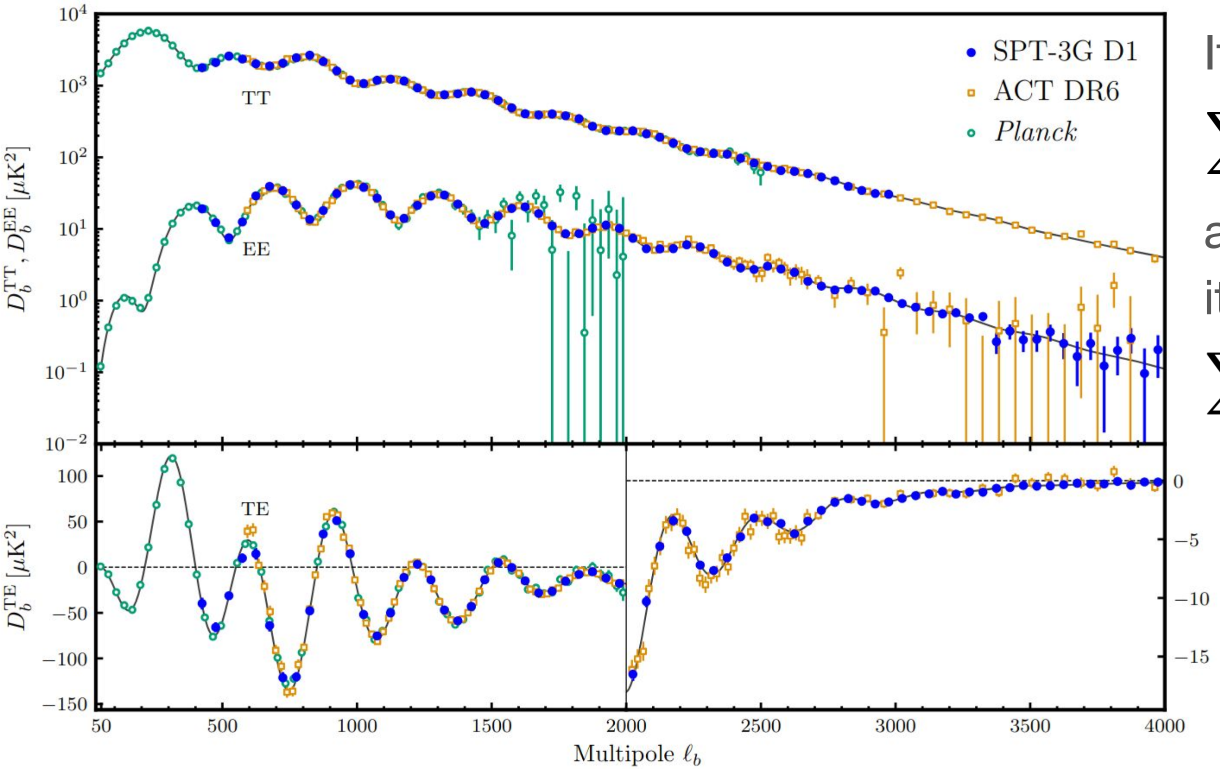
Only from CMB power spectrum and lensing, Planck 2018 gives a first bound:

$$\sum m_\nu < 0.24\,\mathrm{eV}$$

ACT & SPT: precision on the damping tail

SPT Collaboration, 2506.20707

ACT and SPT have reported a greatly improved measurement of small-scale anisotropies!



If Planck measured

$$\sum m_\nu < 0.24\,\mathrm{eV}$$

adding SPT and ACT, it improves to

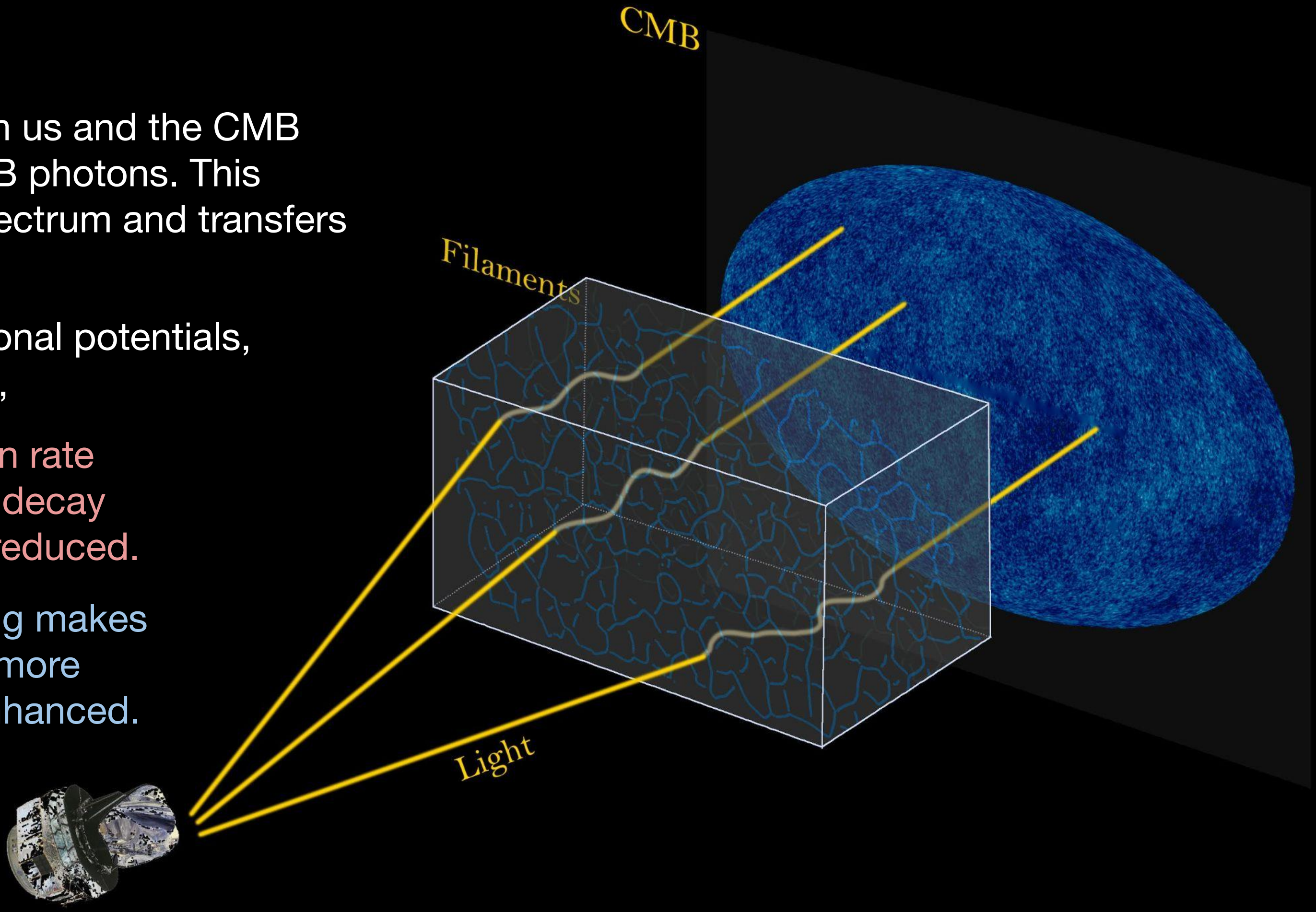
$$\sum m_\nu < 0.17\,\mathrm{eV}$$

CMB lensing

Potential wells between us and the CMB slightly deflect the CMB photons. This smooths the power spectrum and transfers power to small scales.

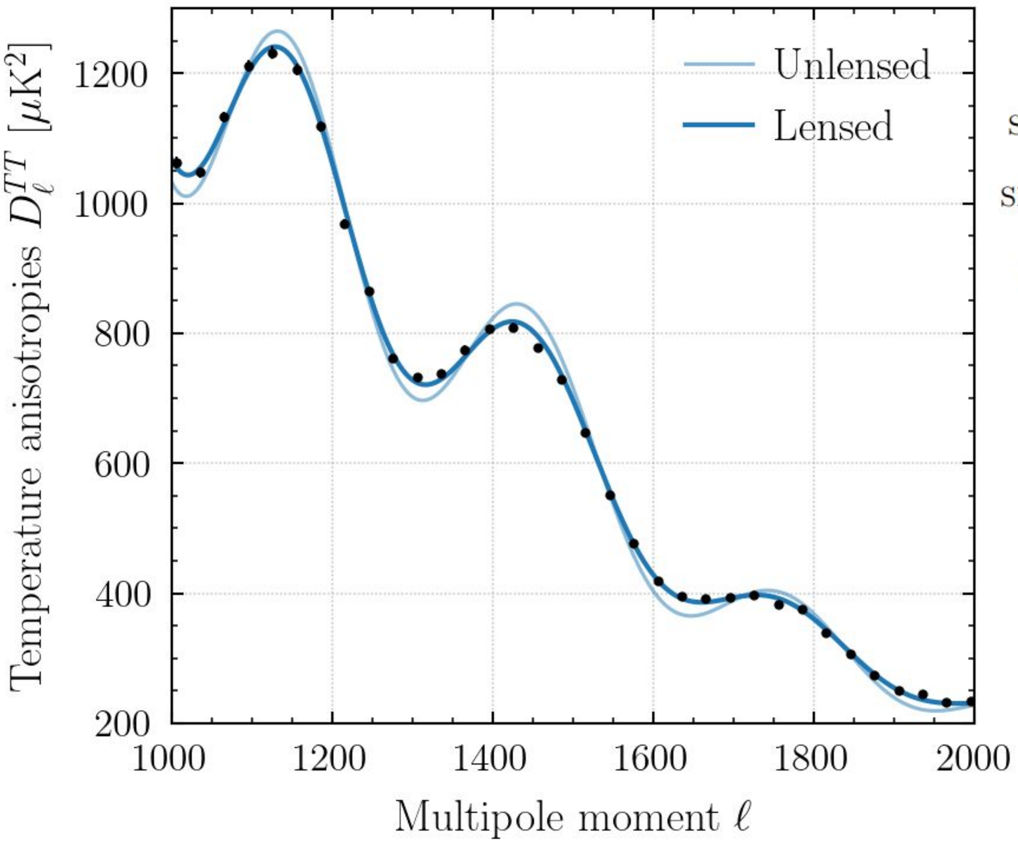
The larger the gravitational potentials, the more lensing. Thus,

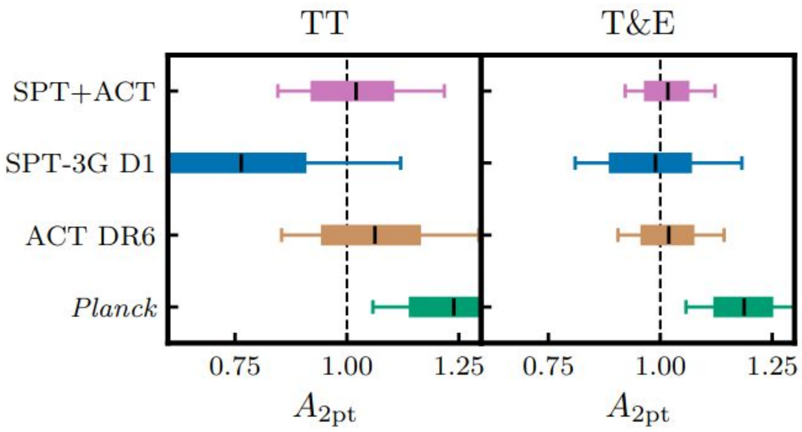
- ➢ A larger expansion rate makes potentials decay faster: lensing is reduced.
- ➢ Neutrino clustering makes potentials decay more slowly: lensing enhanced.



Negative neutrino masses I: **lensing anomaly in Planck**

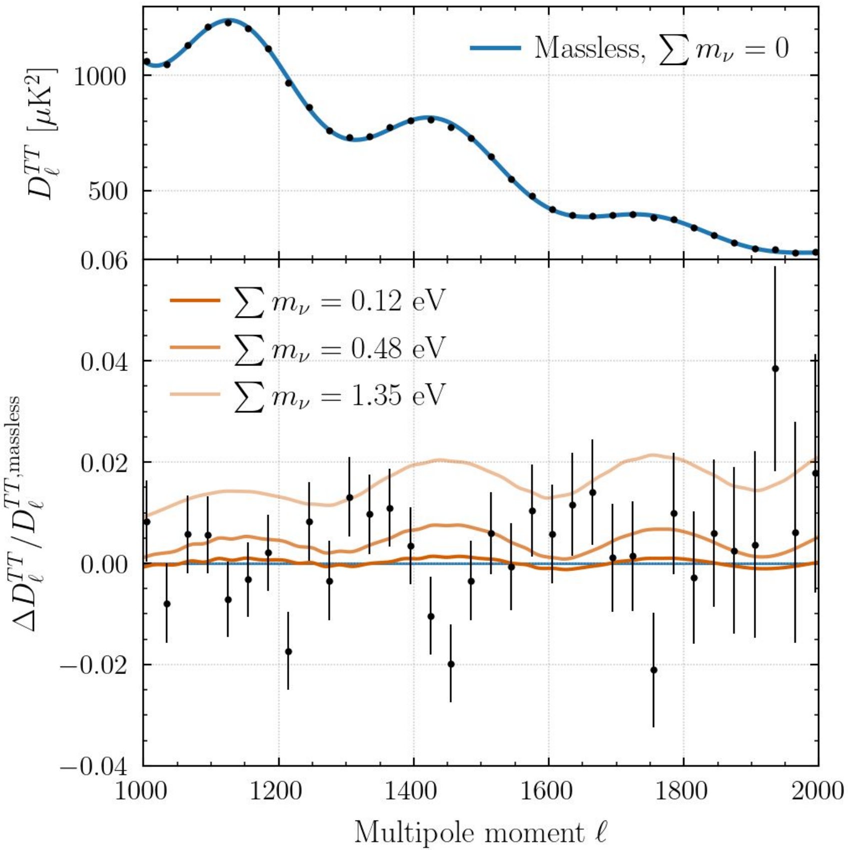
SPT Collaboration, 2506.20707





The Planck CMB features a **lensing anomaly**:
the TT spectrum requires more lensing ($A_{2\mathrm{pt}}$) than the ΛCDM best fit provides.

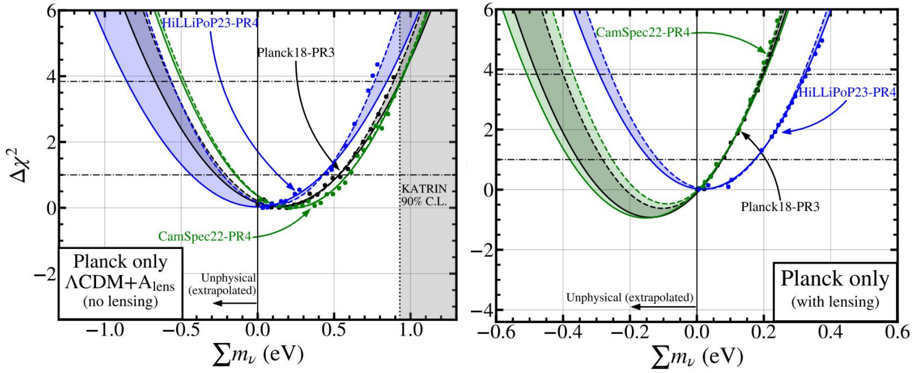
Negative neutrino masses I: **lensing anomaly in Planck**



However, **massive neutrinos reduce the lensing of the CMB** (by increasing the expansion rate).

If neutrinos have negative energy, they increase lensing and provide a better fit.

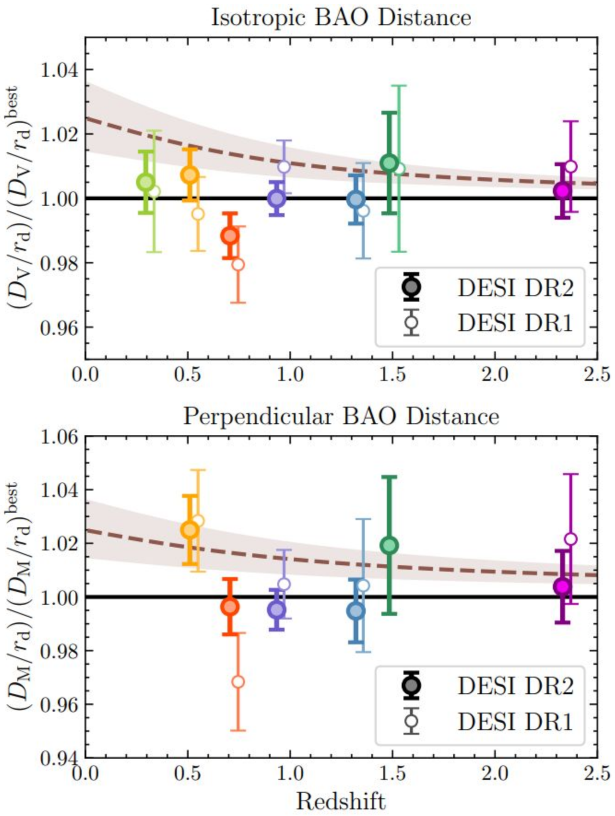
$$\epsilon_{\rm eff} = {\rm sgn}(m_{\nu,\rm eff})\sqrt{p^2 + a^2 m_{\nu,\rm eff}^2},$$



Naredo-Tuero et al., 2407.13831

Negative neutrino masses II: **DESI BAOs**

DESI Collaboration, 2503.14738



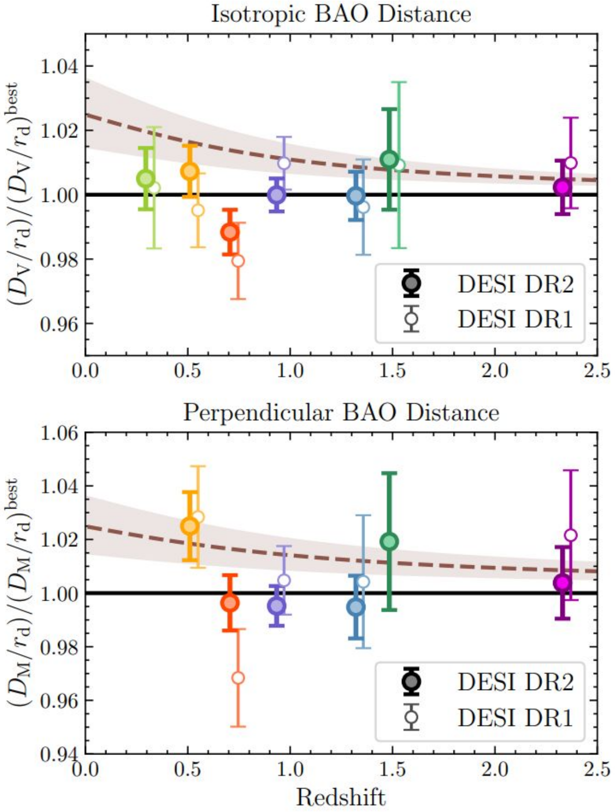
BAOs uniquely measure the expansion rate via

$$D_M(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{H(z')/H_0} \qquad D_H(z) = \frac{c}{H(z)}$$

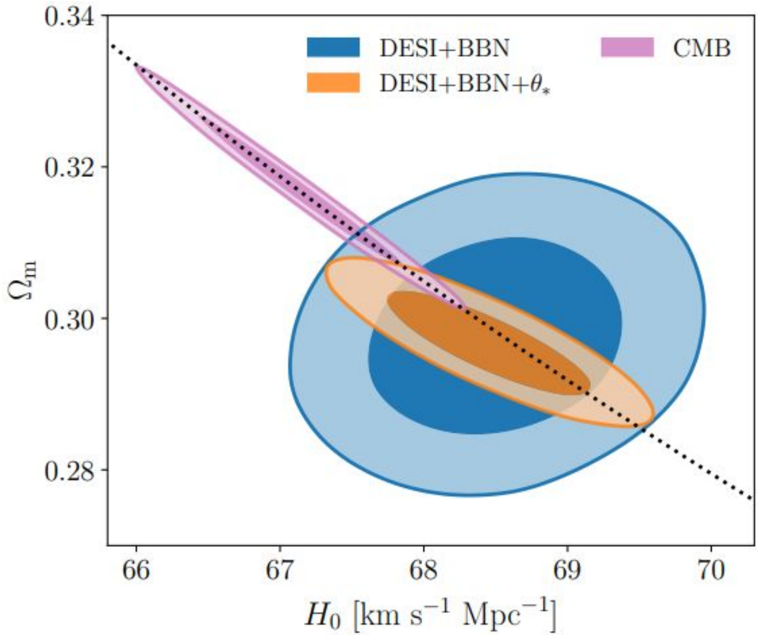
They are *insensitive* to neutrino free-streaming.

Negative neutrino masses II: **DESI BAOs**

DESI Collaboration, 2503.14738



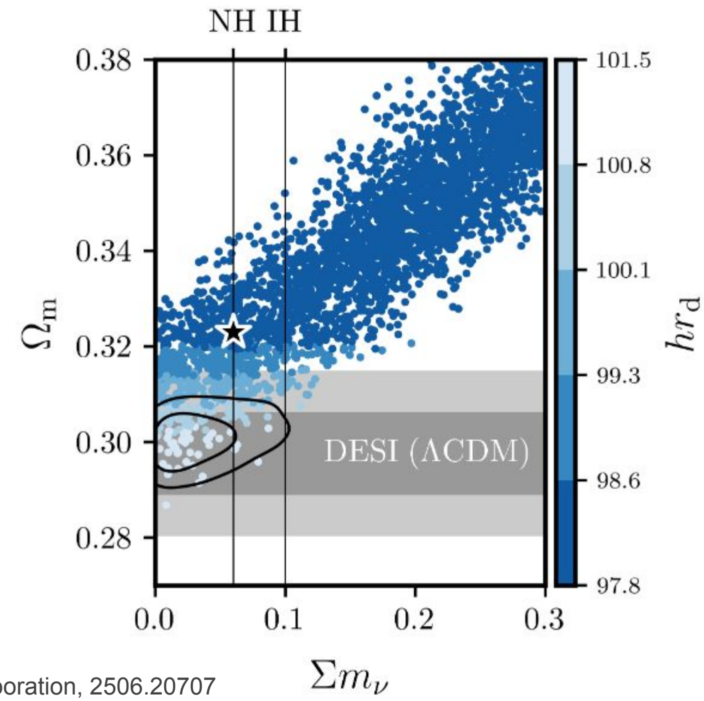
DESI finds smaller Ω_m than CMB, with a tension of about 2.3σ.



This smaller Ω_m pushes the CMB towards having **less lensing**!

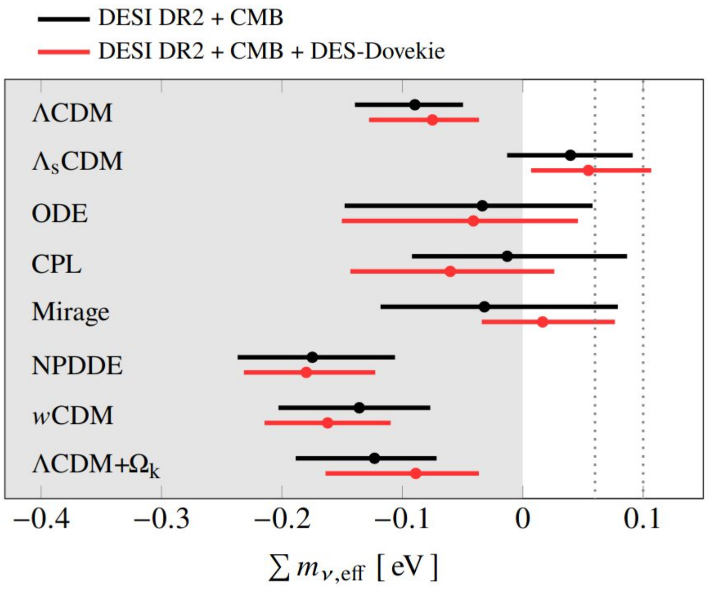
The preference towards **negative neutrino masses**

As of today, it is due to a ~2σ tension between DESI and CMB, added to CMB lensing preferring more late-time structure.



SPT Collaboration, 2506.20707

It can be alleviated by assuming dynamical dark energy, but these are not necessarily correlated.



$$\epsilon_{\mathrm{eff}} = \mathrm{sgn}(m_{\nu,\mathrm{eff}})\sqrt{p^2 + a^2 m_{\nu,\mathrm{eff}}^2}$$

Elbers et al., 2605.21456

An independent measurement: **power spectrum shape**

The shape of the power spectrum measures neutrino masses beyond their effect on the expansion rate. Can we make a **kinematic** measurement of m_ν?

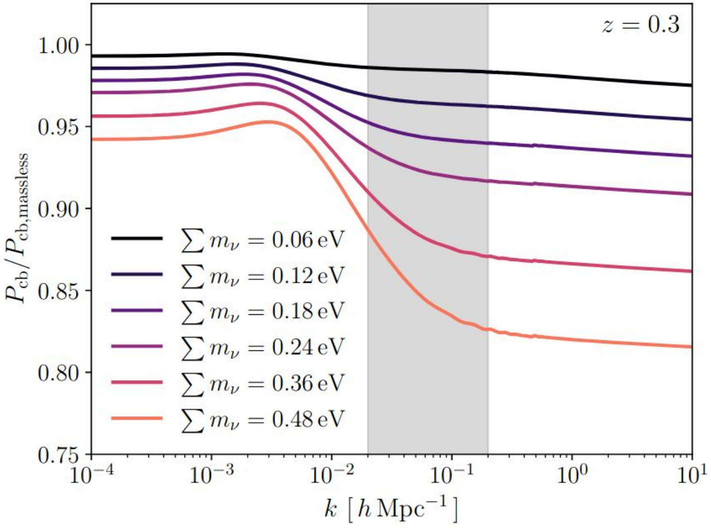
Using the power spectrum and the bispectrum we do not find negative neutrino masses!
There is some hope :)

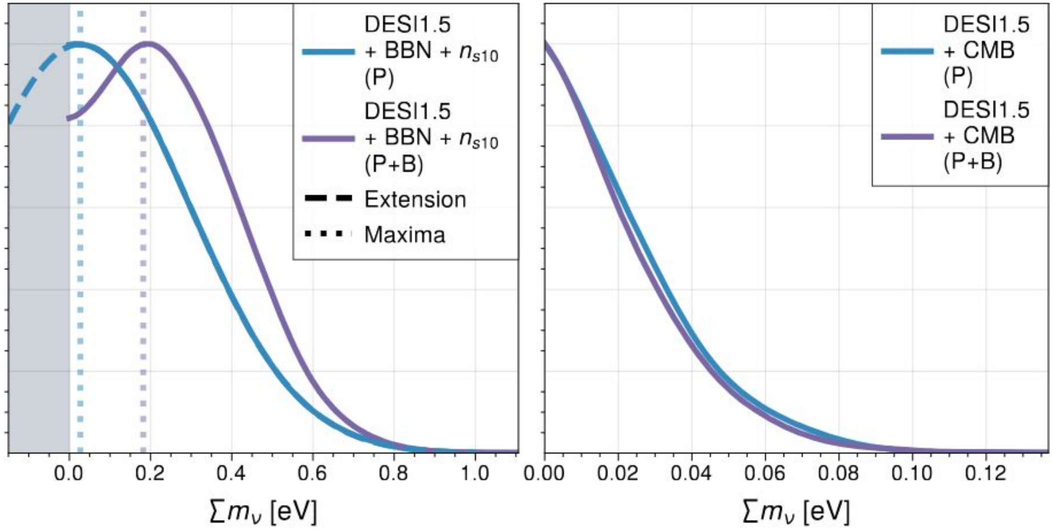
Power spectrum (P):

$$\sum m_\nu < 0.5419\,\mathrm{eV}$$

+ Bispectrum (P+B):

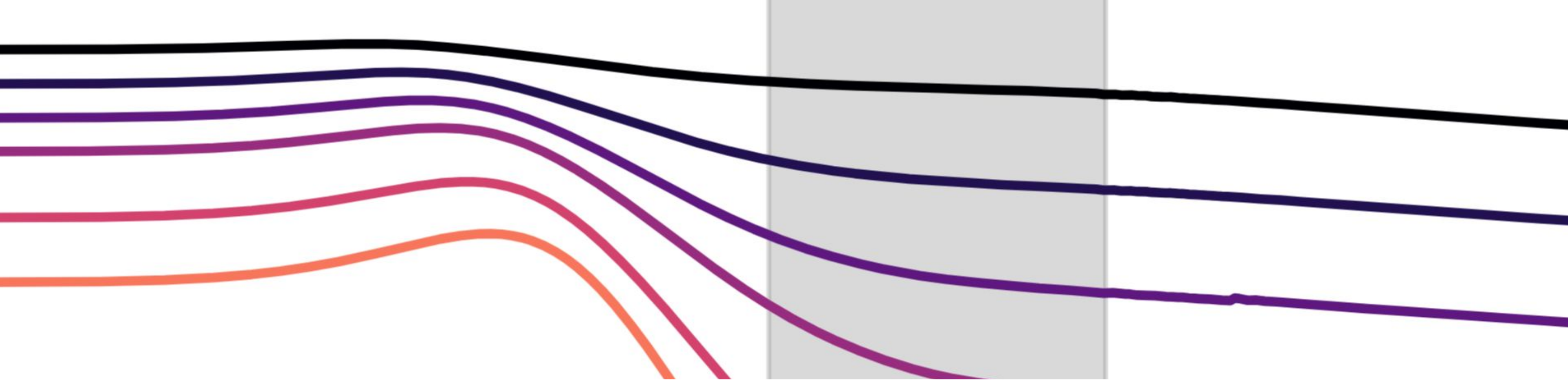
$$\sum m_\nu < 0.5698\,\mathrm{eV}$$



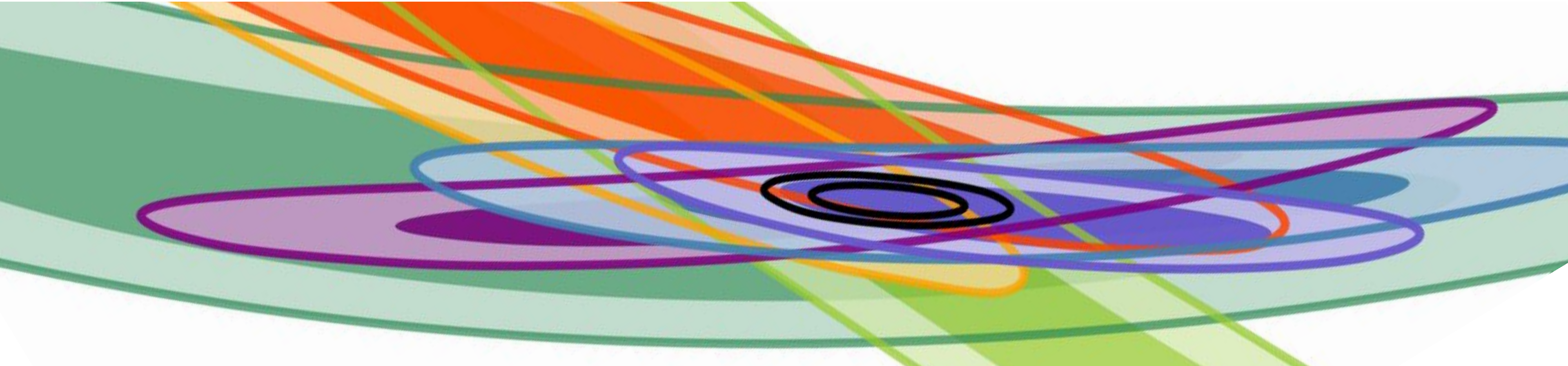


Elbers et al., 2503.14744

Forero-Sánchez et al., 2606.23936



The origin of cosmological mass bounds



Two (six) questions from particle physics to cosmologists

What are our bounds physically measuring?

Or: which physical effect is the culprit behind these anomalous *negative* neutrino masses?

Or: if we need BSM to solve neutrino masses in cosmology, which generic properties does it need to have?

Can we make a *kinematic* measurement of the mass?

Or: if we can't trust the measurement of neutrino masses because it is anomalous, can we surpass it?

Or: if we were to have a consistent measurement, could we add a further degree of robustness to it?

These need **quantitative** answers.

A parameterization to answer them

TBM, Esteban, Hajjar, Mena, Salvadó; 2411.14524

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

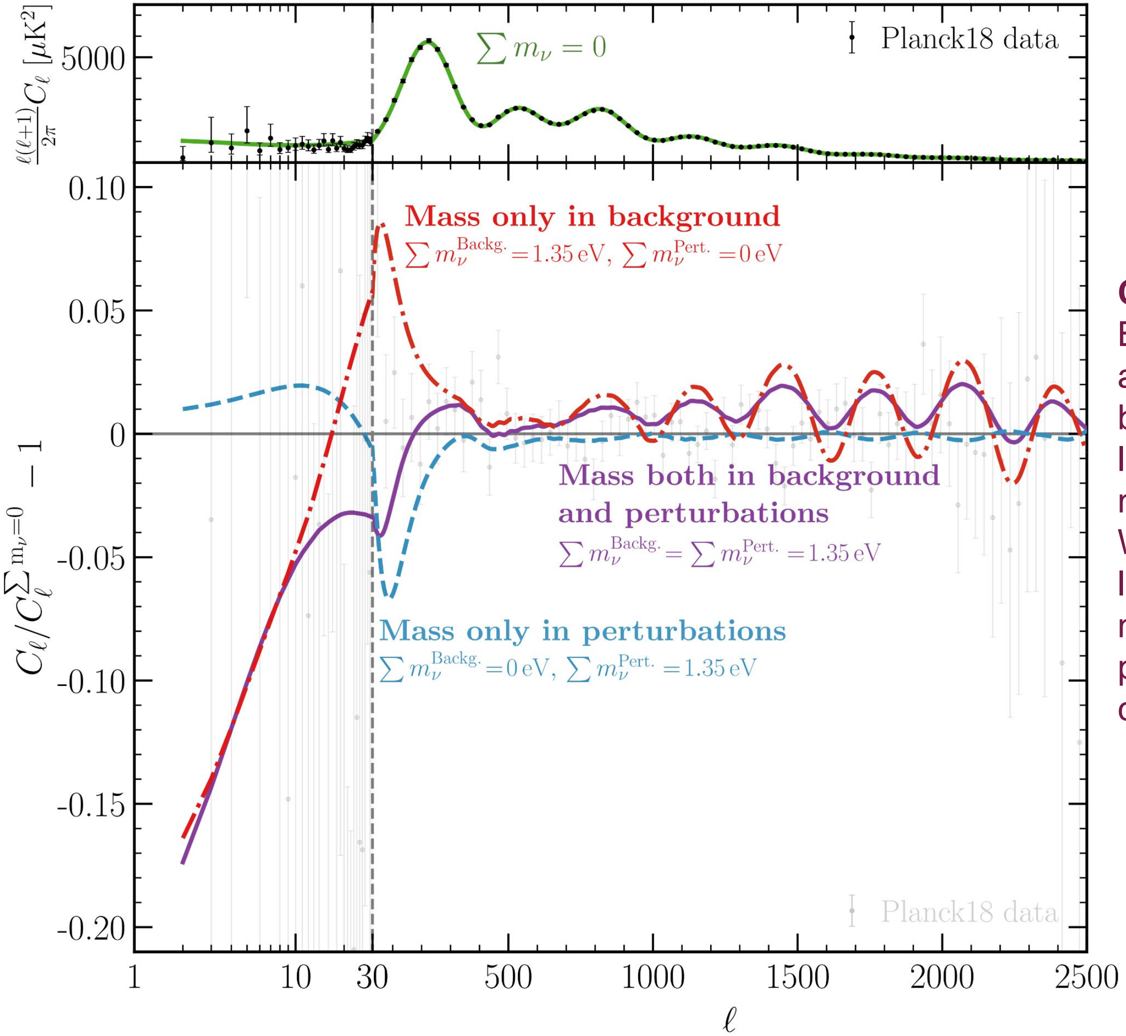
$m_{\rm bkg}$ $\rho_\nu(a)$ describes energy density and expansion rate.

$m_{\rm pert}$ $c_\nu(a)$ describes free-streaming scale (clustering).

We'll set cosmological bounds to know which of the two effects we measure. For the measurement to be robust, both parameters must coincide.

We modify the **CLASS** code to solve the Boltzmann equations for neutrino evolutions in this framework, and compute posteriors with **Cobaya**.

Conclusion 1:
Perturbations masses are constrained by mid-multipoles.
This is the only region where perturbations masses could be measured, but are masked by the effect from the background :(



Conclusion 2:
Background masses are mostly constrained by their effect on lensing at high multipoles.
We can accommodate larger background masses if we have a perturbations mass to compensate for it.

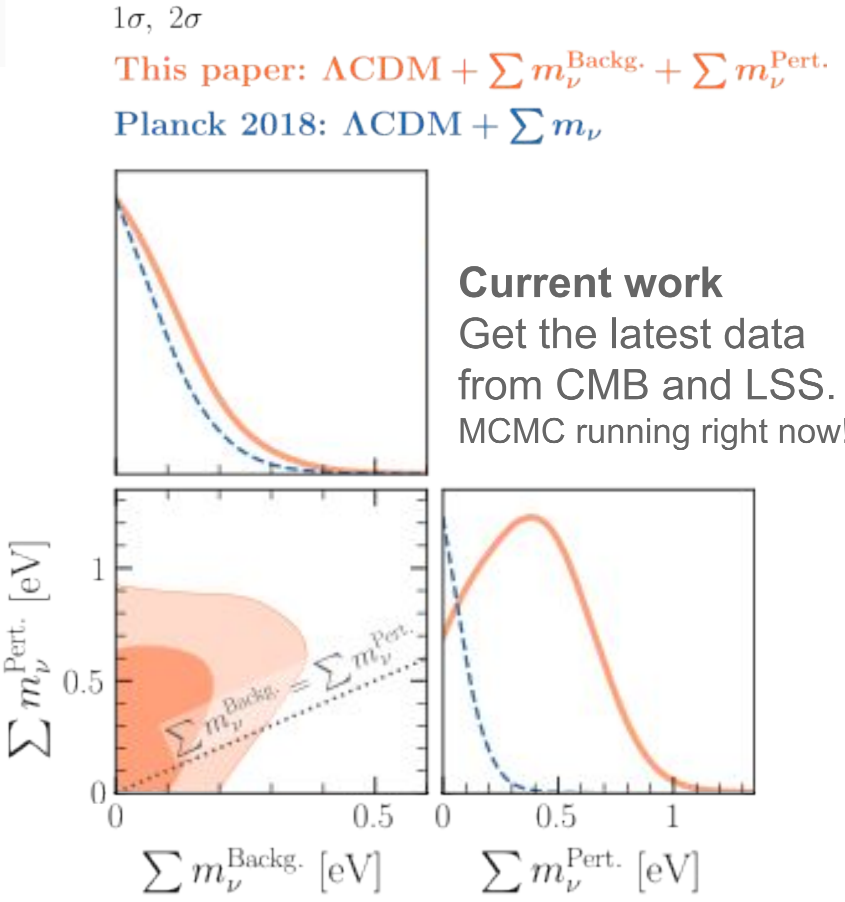
Results from Planck 2018

At the 95% level:

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

$$\sum m_\nu^{\mathrm{Backg.}} < 0.29\ \mathrm{eV}$$
(2411.14524)
$$\sum m_\nu^{\mathrm{Pert.}} < 0.79\ \mathrm{eV}$$

Quantitative conclusion
Current bounds from the CMB are coming from background effects. The free-streaming scale may be having an effect, but it's certainly subleading.



Current work
Get the latest data from CMB and LSS.
MCMC running right now!

CMB + BAOs @2026

Official results for Planck, ACT, SPT and DESI DR2:

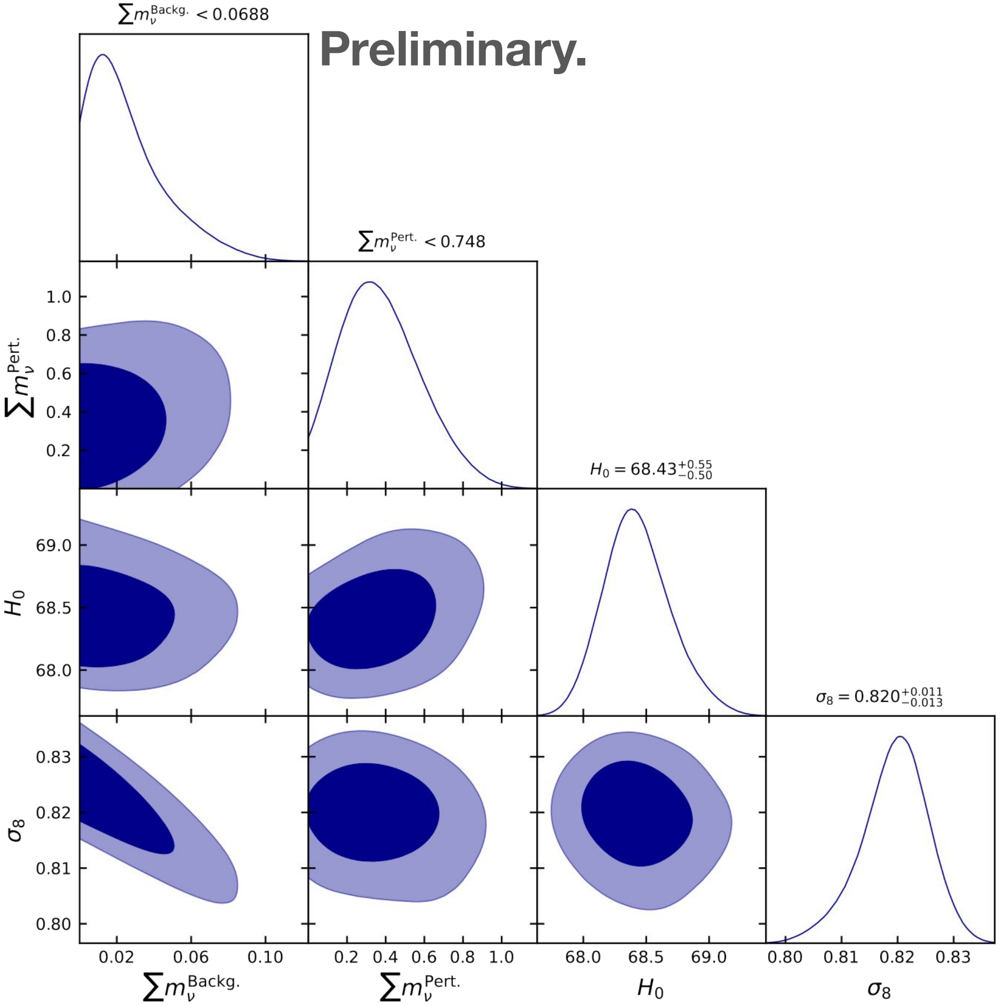
$$\sum m_\nu < 0.048\,\mathrm{eV}$$

Our results (using DESI DR1):

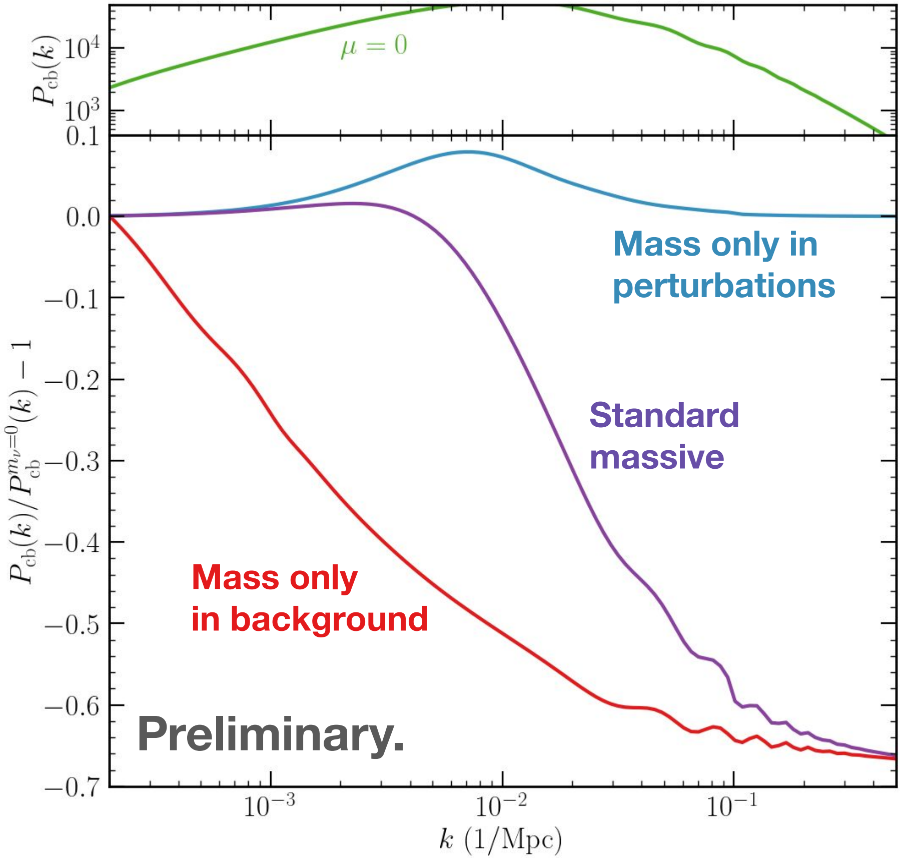
$$\sum m_\nu^{\mathrm{Backg.}} < 0.0688\,\mathrm{eV}$$

$$\sum m_\nu^{\mathrm{Pert.}} < 0.748\,\mathrm{eV}$$

Which gives us similar conclusions. This is expected since BAOs are leading the constraints.



Separating effects in Large Scale Structure



A dip in the power spectrum is present even if cosmology lacks a neutrino free-streaming scale.

A bump in the power spectrum is present even if neutrinos expand as if they were massless.

Current question: **can Euclid measure neutrino free-streaming?** This would help us surpass *negative* neutrino mass anomalies!

Conclusions (for now!)

Current cosmological bounds are not sensitive to standard neutrino free-streaming, and are a measurement of a **modified expansion rate**.

Negative neutrino masses are weird and anomalous, but there might be hope for a **kinematic measurement of neutrino masses.**

Thanks for your attention and for having me here!

bertolezmart@wisc.edu

And many thanks to the whole team!

Backup slides

SCALE-INDEP. MASS EFFECT

The equation of state modifies the scaling of the neutrino energy density.

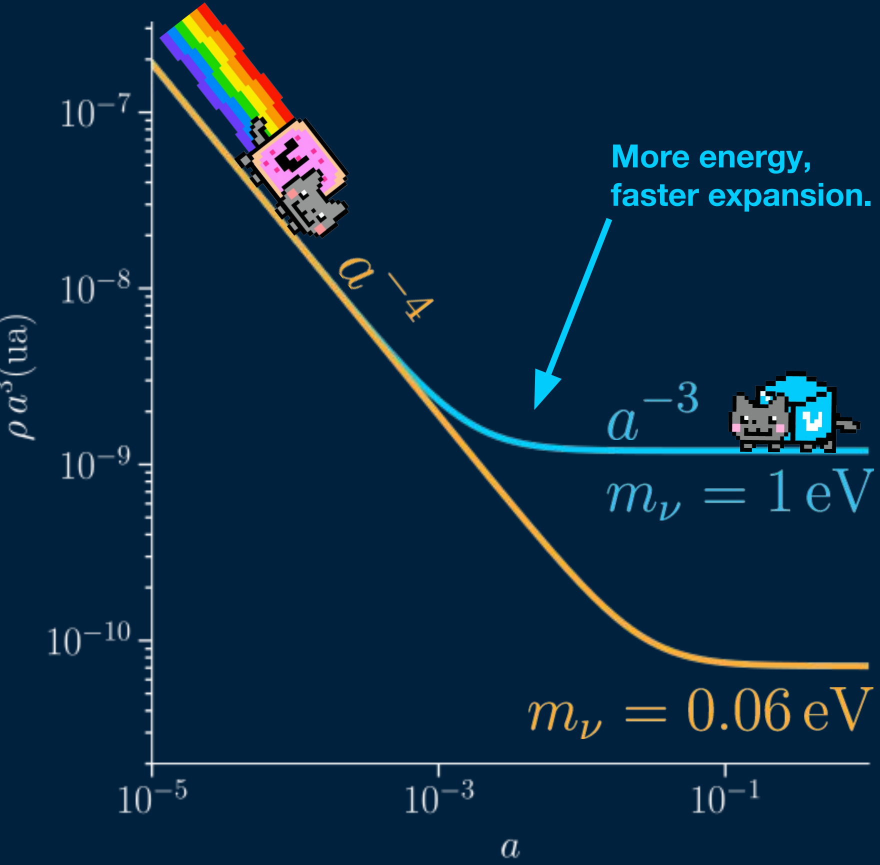
$$\dot{\rho} = -3H(1+w)\rho$$

This affects the expansion rate:

$$H^2 = \frac{8\pi G}{3} a^2 \sum \rho_i$$

More mass, larger H, faster expansion.

⚠ This is a ***thermodynamical*** property.



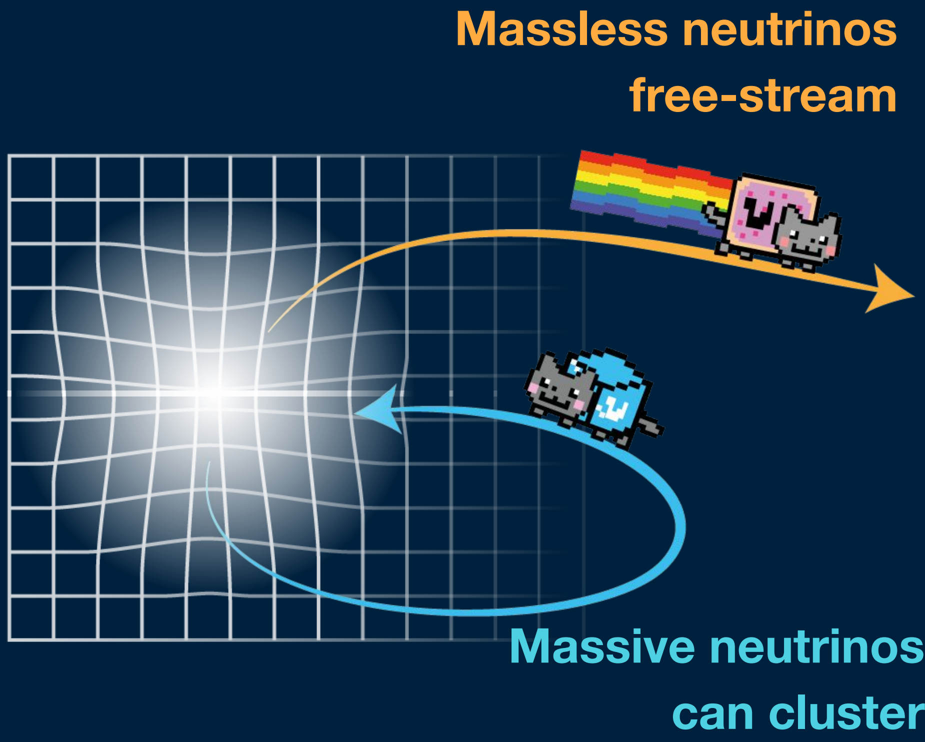
SCALE-DEPENDENT MASS EFFECT

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

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

If $\lambda < \lambda_{\rm fs}$: neutrinos **free stream**, **erase** inhomogeneities.

If $\lambda > \lambda_{\rm fs}$: neutrinos **cluster**, inhomogeneities **grow**.



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

SCALE-DEPENDENT MASS EFFECT

We describe neutrinos as a fluid

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

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

with

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

Sound speed

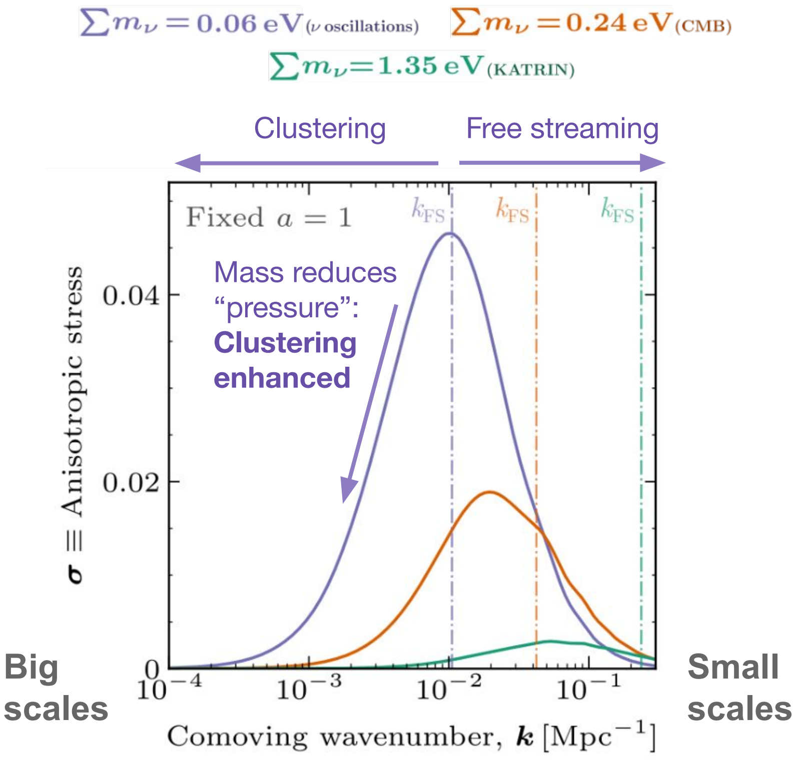
$$\sigma$$

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

Anisotropic stress (shear)

Both these scale-dependent parameters are not fixed by cosmology, but require a microscopic theory (e.g., massive neutrinos).

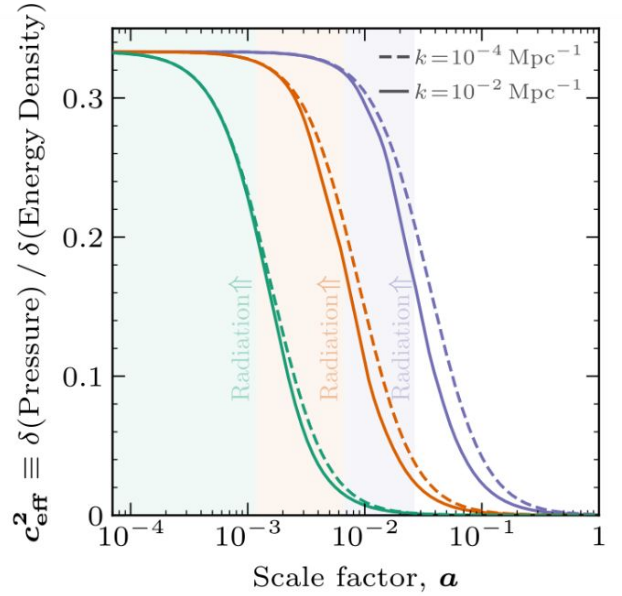
Ma, Bertschinger, astro-ph/9506072



In LCDM, only neutrinos do this,
it's a smoking gun!

MASS EFFECT @PERTURBATIONS

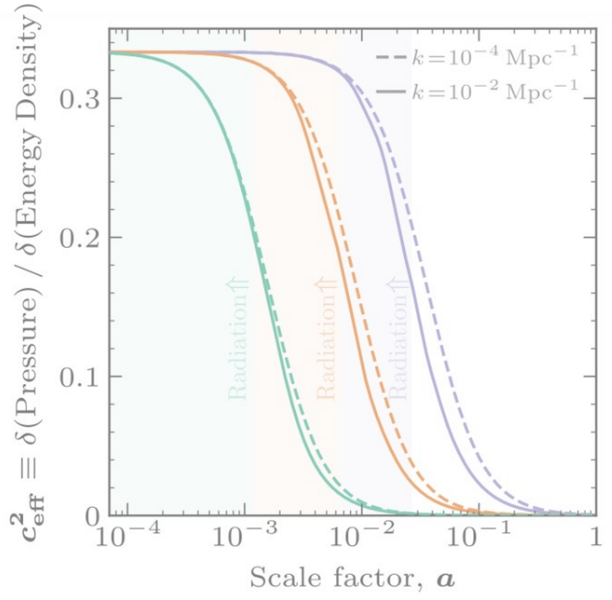
$\sum m_\nu = 0.06\,\mathrm{eV}$ (ν oscillations) $\sum m_\nu = 0.24\,\mathrm{eV}$ (CMB) $\sum m_\nu = 1.35\,\mathrm{eV}$ (KATRIN)



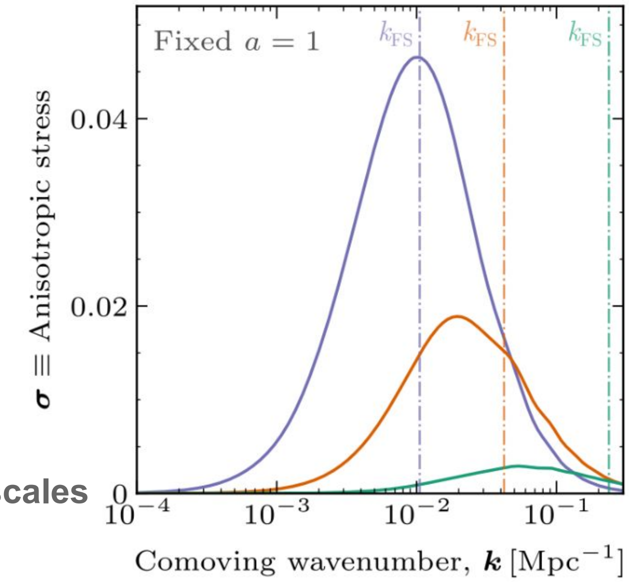
The sound speed only has
a minor scale-dependence.
Of course, the background effect
also enters in perturbations.

MASS EFFECT @PERTURBATIONS

$\sum m_\nu = 0.06\,\mathrm{eV}$ (ν oscillations) $\sum m_\nu = 0.24\,\mathrm{eV}$ (CMB) $\sum m_\nu = 1.35\,\mathrm{eV}$ (KATRIN)



Big scales



Small scales

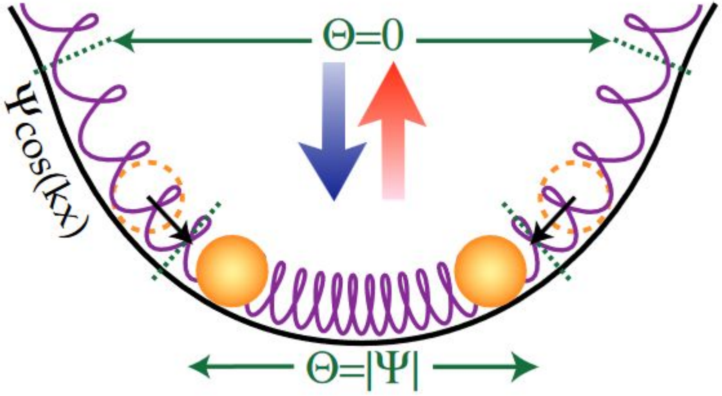
The sound speed only has
a minor scale-dependence.
Of course, the background effect
also enters in perturbations.

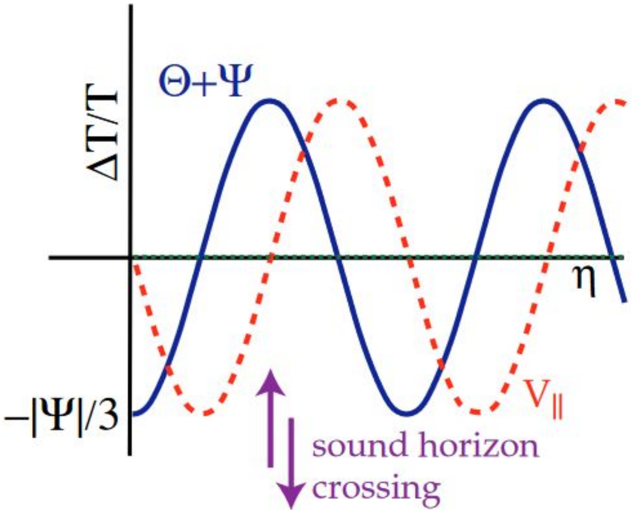
Free-streaming is imprinted
in the anisotropic stress.
Mass reduces “pressure”.

ACOUSTIC OSCILLATIONS

Baryon-photon acoustic oscillations happen in potential wells:

- ➢ Overdensities have a higher temperature Θ.
- ➢ When photons leave the potential well, they are redshifted by the potential ψ.





Therefore, having a larger constant potential does not modify the amplitude of the oscillations of the effective temperature Θ+ψ.

However, *what if the potential decays?*

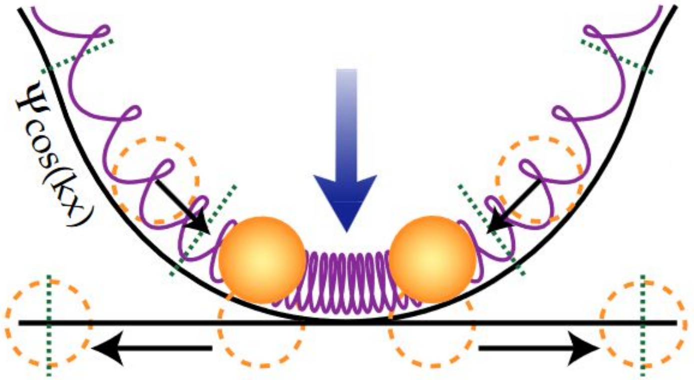
Figures taken from "The Physics of Microwave Background Anisotropies" - Hu, Sugiyama, Silk, astro-ph/9604166.

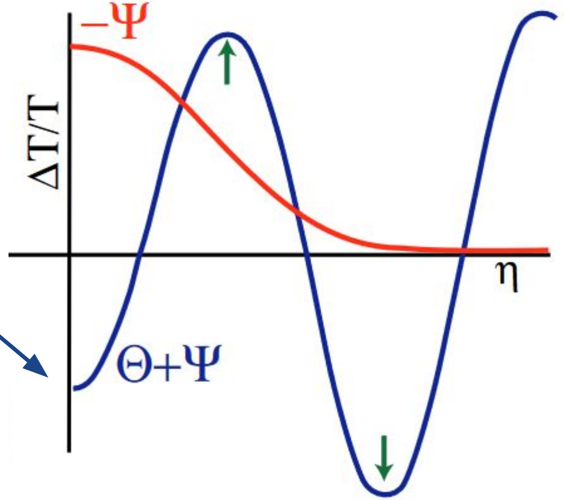
EFFECT IN ACOUSTIC OSCILLATIONS

If the gravitational potential is initially larger, the fluid starts in a highly-compressed state. If the potential decays, there is less gravity and the amplitude of oscillations increases.

- ➢ **More decay, more anisotropies.**

(there is another effect coming from the spatial potential Φ, which also decays and boosts anisotropies)



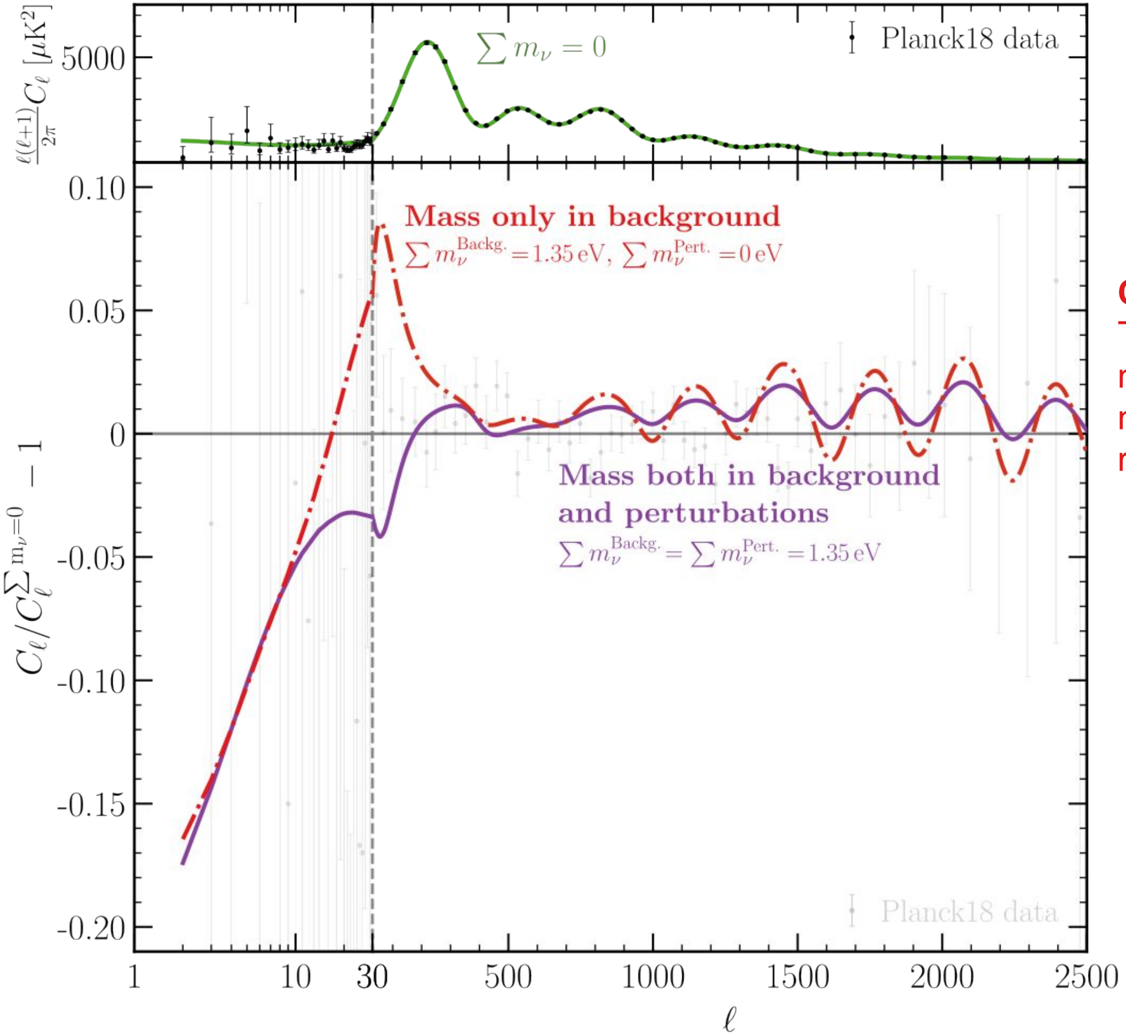


Therefore:

- ➢ A background mass increases CMB anisotropies.
- ➢ A perturbations mass decreases them.

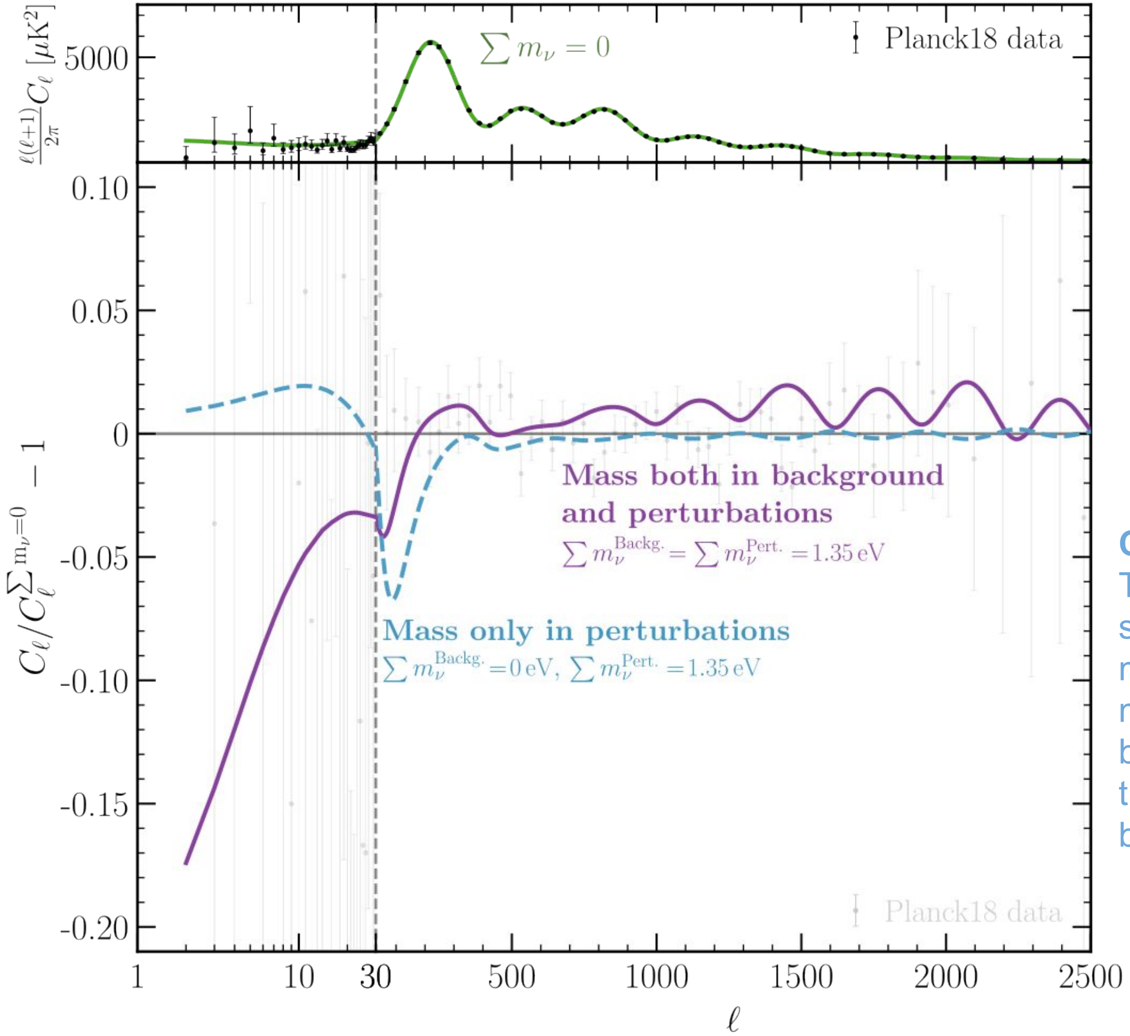
Figures taken from “The Physics of Microwave Background Anisotropies” - Hu, Sugiyama, Silk, astro-ph/9604166.

Results



Conclusion 1:
The expansion rate mostly constrains the neutrino effect on reducing lensing.

Results



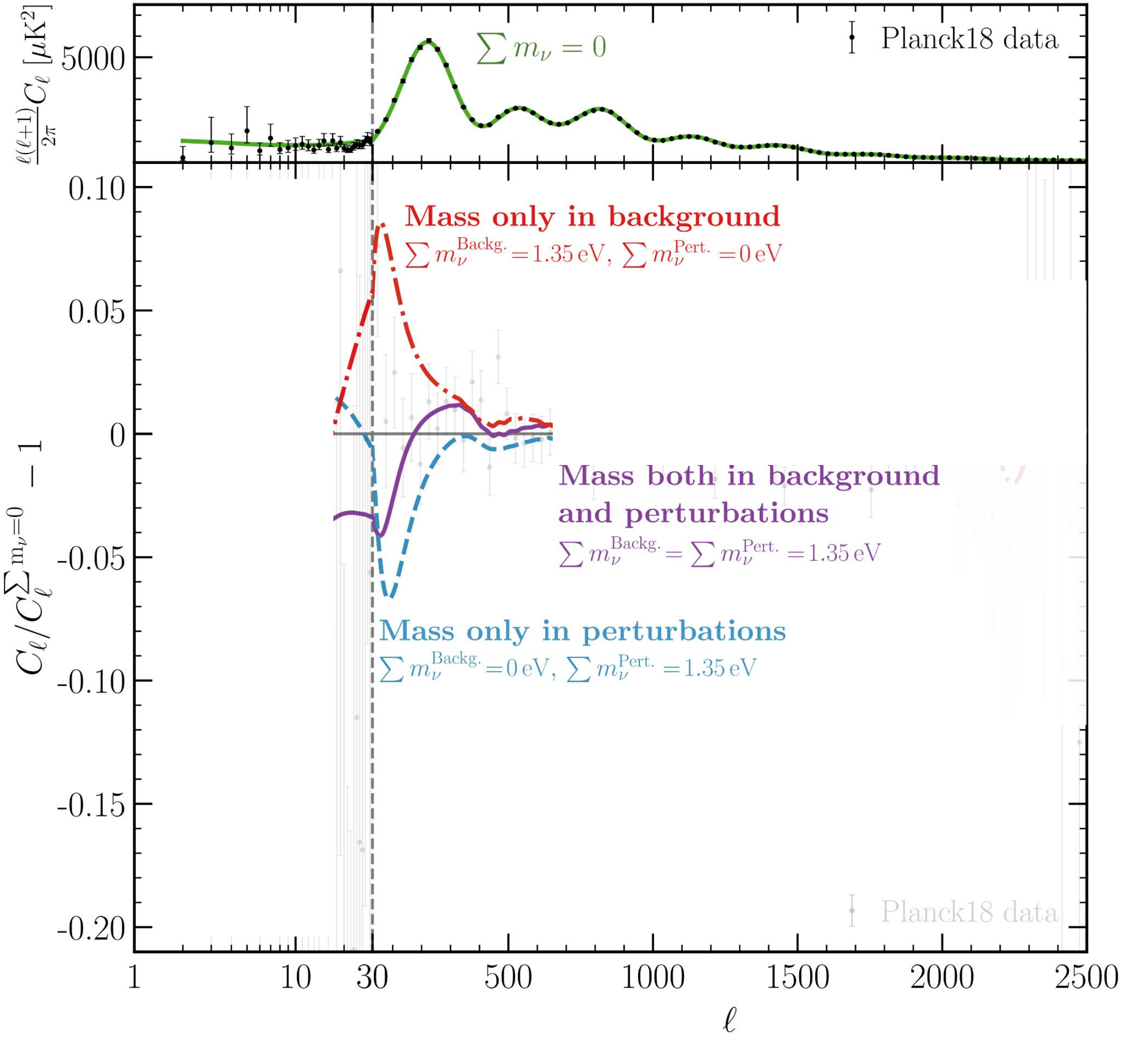
Conclusion 2:
The free-streaming scale can only be measured at mid-multipoles, but is masked by the effect from the background.

INTERMEDIATE MULTIPOLES

$$30 < \ell < 500$$

These are modes which cross the horizon at recombination, shortly before or shortly after.

- ➢ A mass in the background makes potentials decay faster and anisotropies larger.
- ➢ A mass in perturbations makes potentials decay slower and anisotropies smaller.

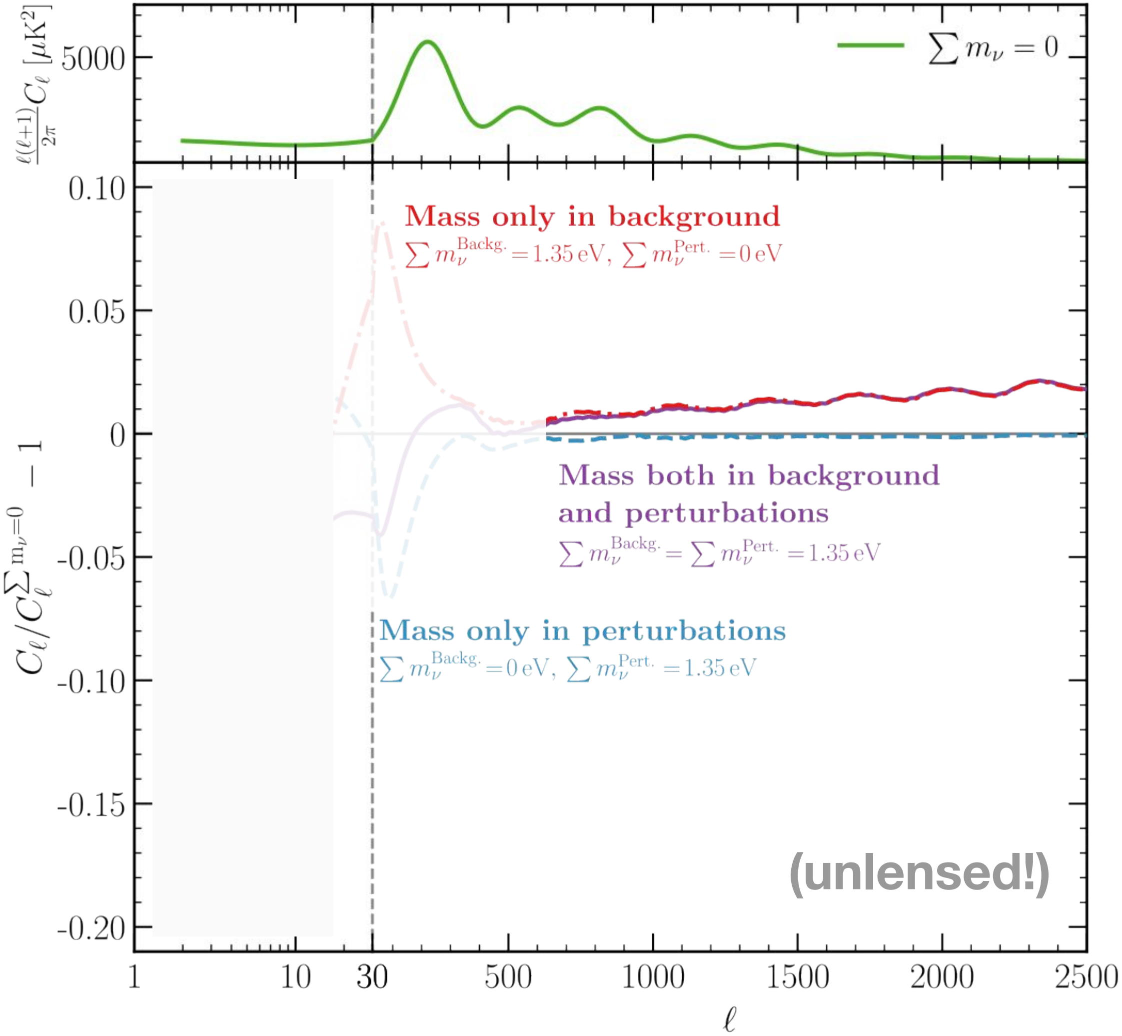


HIGH MULTIPOLES

$\ell > 500$ (unlensed)

These are modes which cross the horizon much before recombination: they have decayed a lot already.

- ➢ Background suffers from diffusion damping: a change in the photon mean free path in the baryon-photon fluid.
- ➢ A mass in perturbations does not modify anything: these scales are much smaller than the free-streaming scale.

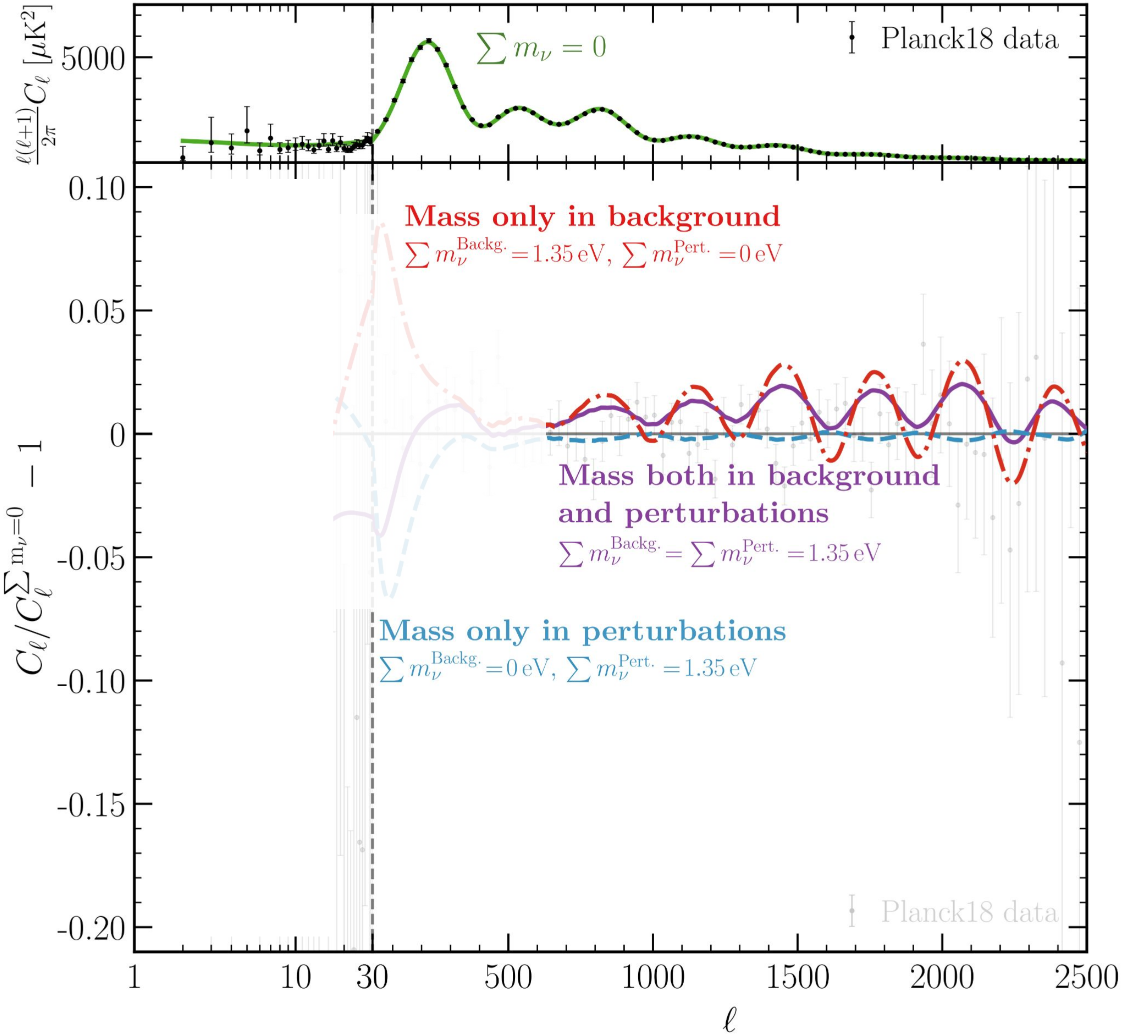


HIGH MULTIPOLES

$\ell > 500$ (w/lensing)

On their way to Earth, CMB photons are deflected by potential wells. Lensing smoothes out the power spectrum and brings power to high multipoles.

- ➢ A mass only in background makes the wiggles larger.
- ➢ Adding a perturbations mass reduces the amount of wiggling.
- ➢ If the background is massless, a perturbations mass does nothing: neutrinos have diluted.



RESULTS

At the 95% level:

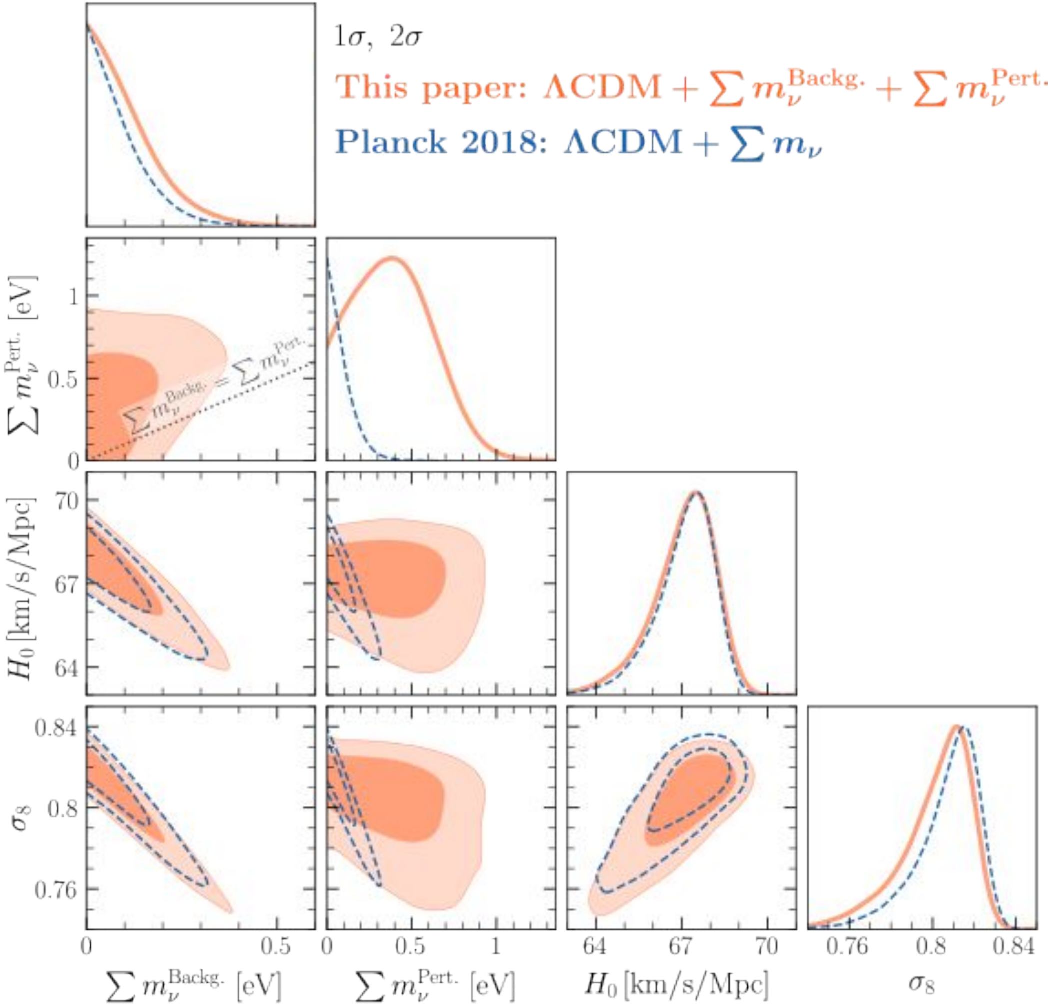
$$\sum m_\nu < 0.24\ \text{eV}$$ (Planck 2018)

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

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

(this work)

Conclusion 4:
Known degeneracies with neutrino masses are at the background level, since they are related to the total energy density of neutrinos. Perturbation masses don't have any degeneracy.



Lensing potential
Effect of the mass
at perturbations