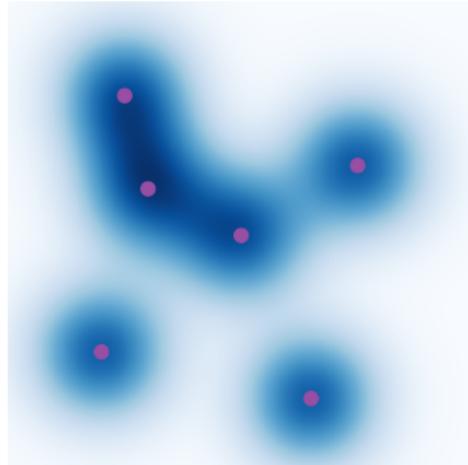


# Neutrino mass from cosmology: the impact of long-ranged interactions

SUSY 2023



Ivan Esteban

17<sup>th</sup> July 2023



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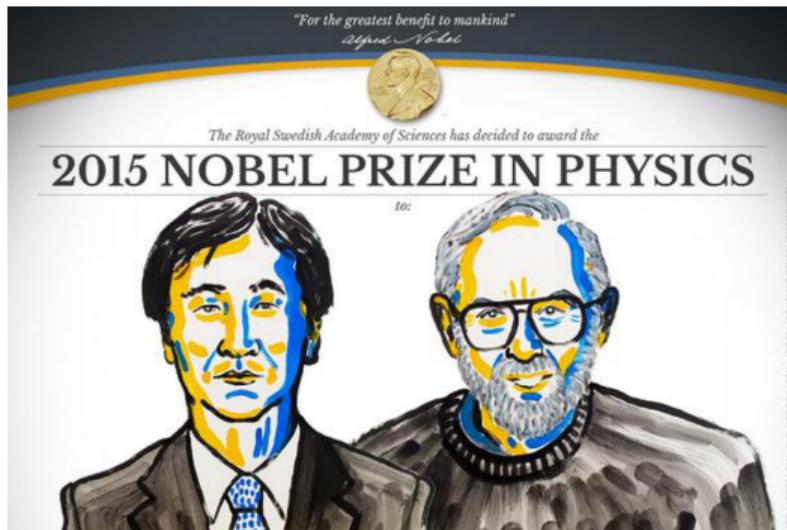


THE OHIO STATE UNIVERSITY  
CENTER FOR COSMOLOGY AND  
ASTROPARTICLE PHYSICS

# Introduction

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Precision cosmology means precision neutrinos



Non-zero neutrino masses mean **New Physics**. But, what is the scale?

# Introduction

[hep-ph] 14 Mar 2022

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Submitted to the Proceedings of the US Community Study  
on the Future of Particle Physics (Snowmass 2021)

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## Synergy between cosmological and laboratory searches in neutrino physics: a white paper

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We conclude this section with prospects from upcoming and next-generation surveys. Simons Observatory (data taking to start in 2023) will be able to measure the sum of neutrino masses at the  $1\sigma$  sensitivity level or more (depending on the true value of  $\Sigma m_\nu$ ) with three different combinations of probes (i.e., CMB lensing reconstruction, thermal SZ power spectrum, and SZ cluster count, combined with either BAO data or weak lensing measurements) [94], therefore providing a robust handle of this important parameter. These figures will be improved once cosmic-variance-limited measurements of CMB large-scale polarization will be available with e.g., the next CMB space mission LiteBIRD (expected launch in 2029) [160]. In any case, different combinations of next-generation surveys, both CMB-oriented and LSS-oriented, will push the sensitivity of cosmological probes down to  $\sim 4 - 5\sigma$  even in the case of  $\Sigma m_\nu = 0.06$  eV (minimal mass expected in normal ordering) [95, 129].

# Open questions

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- How robust will the mass measurement be?
- What other physics can disguise it?  
Can we probe it elsewhere?
- Are we ready for surprises?

Cosmology will probably **lead** and **shape** the field in the near future.

We have to be ready!

# Introduction

How is (post-BBN) cosmology sensitive to neutrinos?

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G \mathbf{T}_{\mu\nu}$$

$$\delta G_{\mu\nu} = 8\pi G \delta \mathbf{T}_{\mu\nu}$$

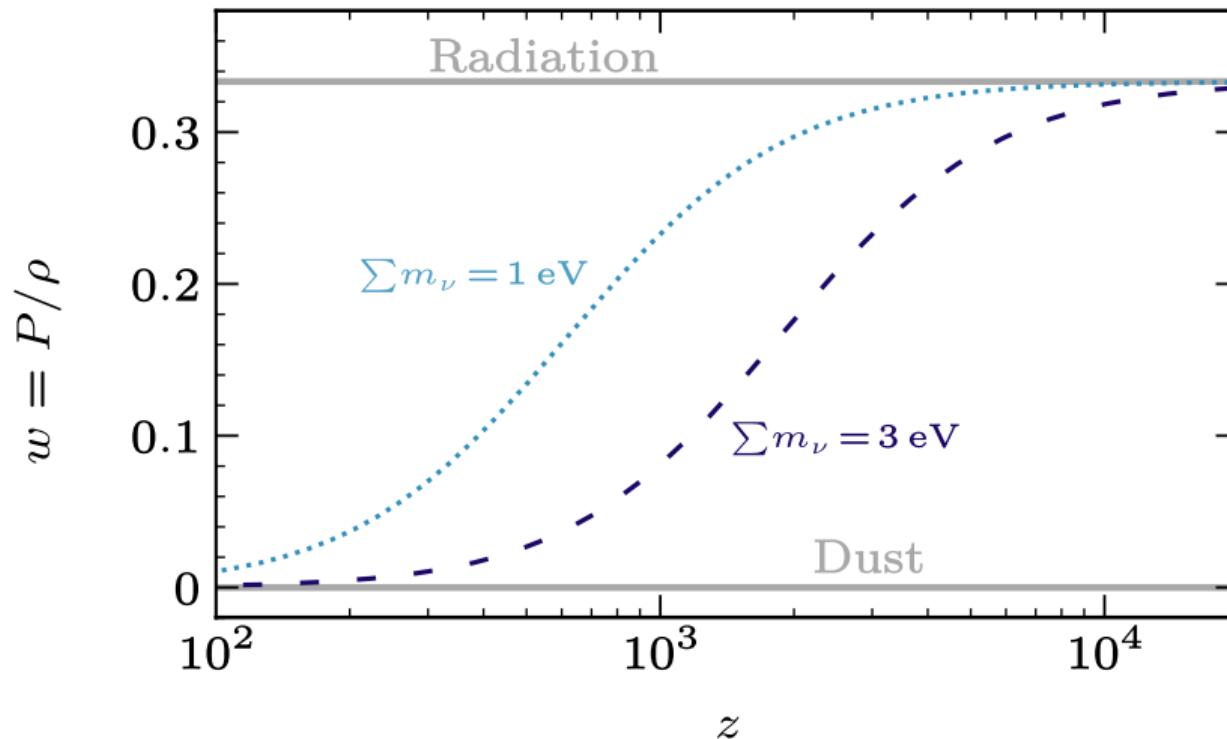
$\mathbf{T}_{\mu\nu} \sim \{\text{energy density, pressure}\} \sim \{\text{energy density, equation of state } w = p/\rho\}$

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

# Introduction

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The neutrino mass shapes the neutrino equation of state



# Long-range interactions

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Esteban and Salvado; 2101.05804 (JCAP)

We know that the equation of state is sensitive to long-range forces

Let's take a simple example!

$$\mathcal{L} = -\textcolor{brown}{m}_\nu \bar{\nu} \nu - \textcolor{brown}{g} \bar{\nu} \nu \phi - \frac{1}{2} \textcolor{brown}{M}_\phi^2 \phi^2$$

Relevant if

- Neutrino separation  $\lesssim M_\phi^{-1}$
- Neutrinos are not extremely relativistic

# Long-range interactions

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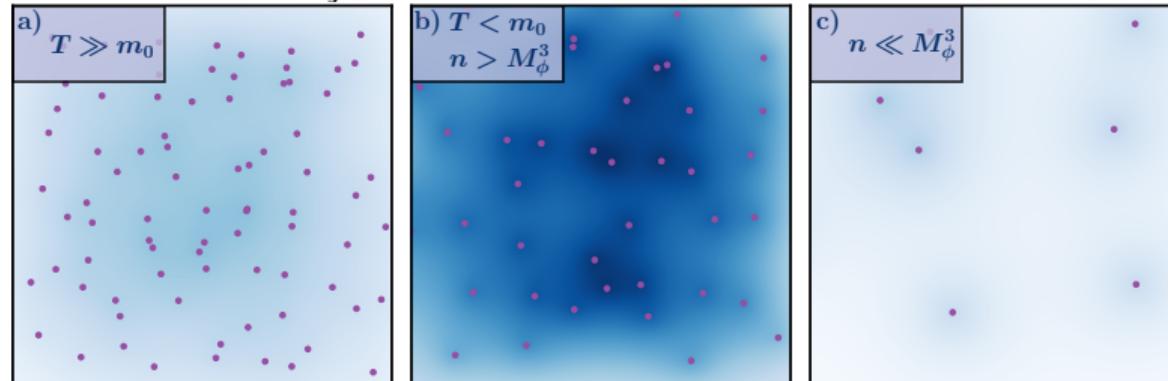
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# The technical slide

$$\mathcal{L} = -m_\nu \bar{\nu}\nu - g \bar{\nu}\nu\phi - \frac{1}{2} M_\phi^2 \phi^2$$

- 1 We solve the classical equations of motion. For homogeneous + isotropic,

$$\tilde{m}(\phi) = m_\nu + g\phi$$

$$M_\phi^2 \phi = -g \langle \bar{\nu}\nu \rangle = -g \int d^3p \frac{\tilde{m}(\phi)}{\sqrt{p^2 + \tilde{m}(\phi)^2}} f(p)$$

- 2 Once we self-consistently obtain  $\phi$  and  $\tilde{m}$ , we can compute

$$\rho = M_\phi^2 \phi^2 + \int d^3p \sqrt{p^2 + \tilde{m}^2} f(p); \quad P = -M_\phi^2 \phi^2 + \int d^3p \frac{p^2}{3\sqrt{p^2 + \tilde{m}^2}} f(p); \quad w = P/\rho$$

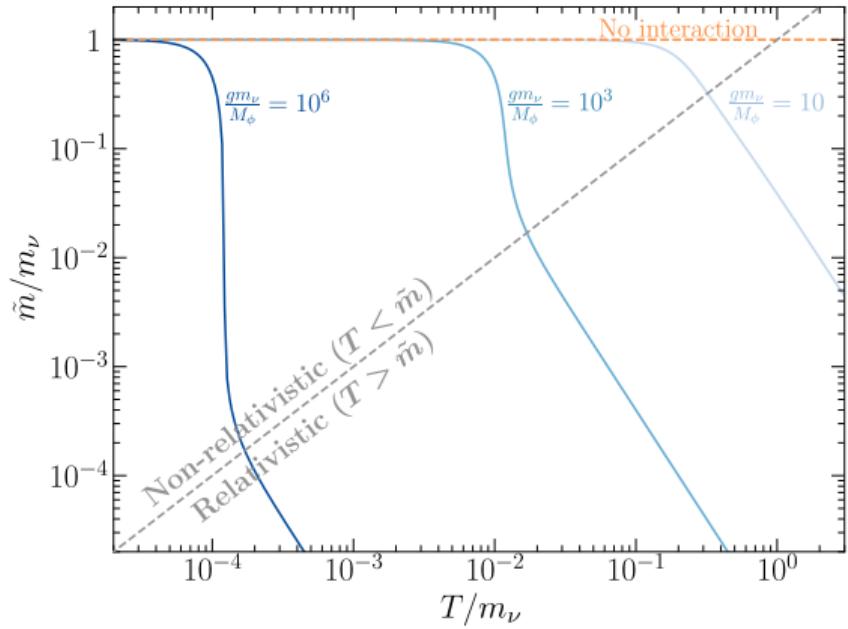
$\phi$  must *not* be Hubble-frozen:  $M_\phi \gtrsim 10^{-25}$  eV

If we want to ignore scattering,  $g \lesssim 10^{-7}$

# First results

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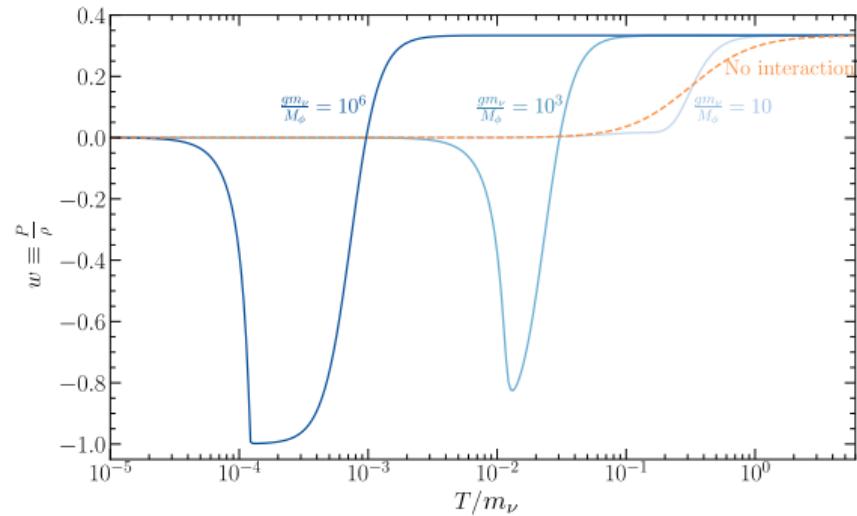
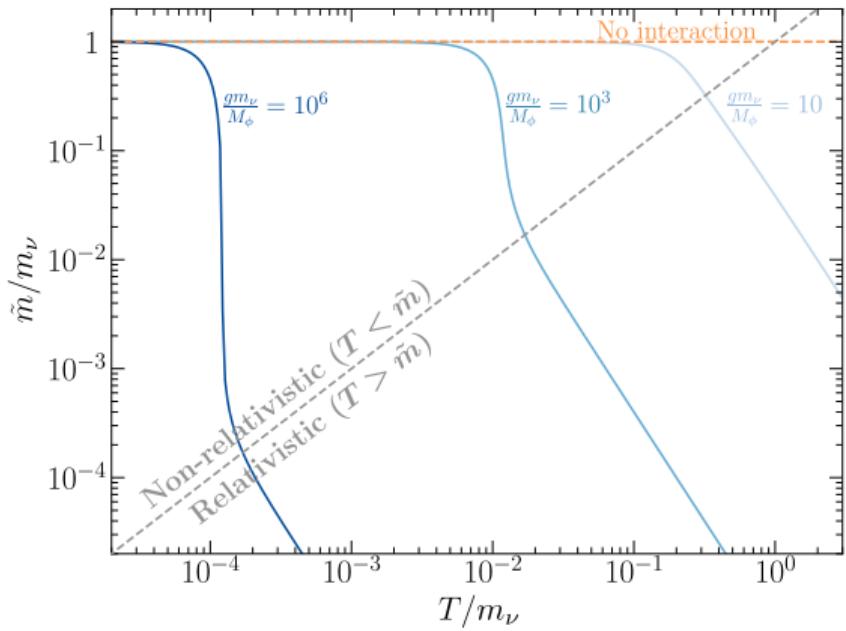
Esteban and Salvado; 2101.05804 (JCAP)



# First results

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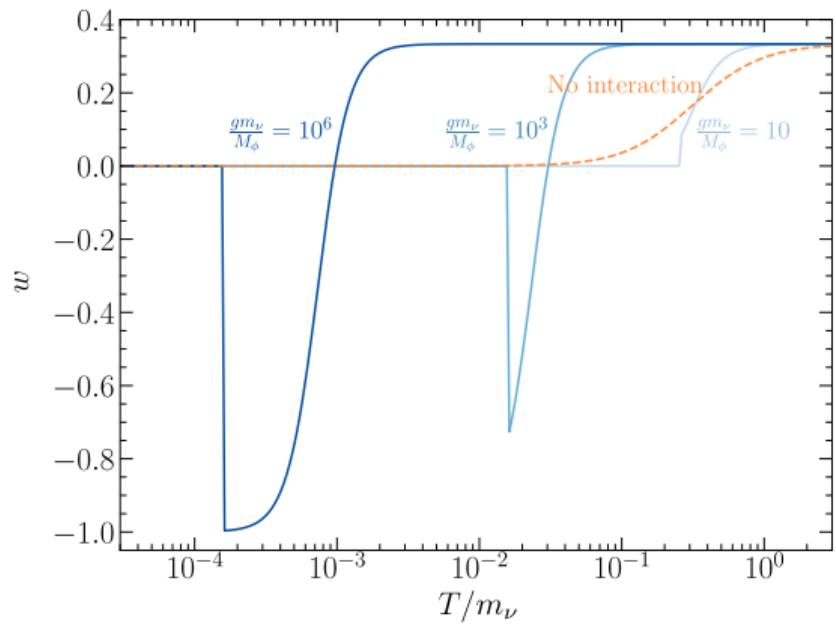
# Neutrino clumps

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At  $T < \tilde{m}$ , if  $gm_\nu/M_\phi \gtrsim 10$   
(i.e., if there are long-range effects),  
the interaction is much stronger than gravity  
 $\Rightarrow$  neutrinos form **clumps** that redshift as dust

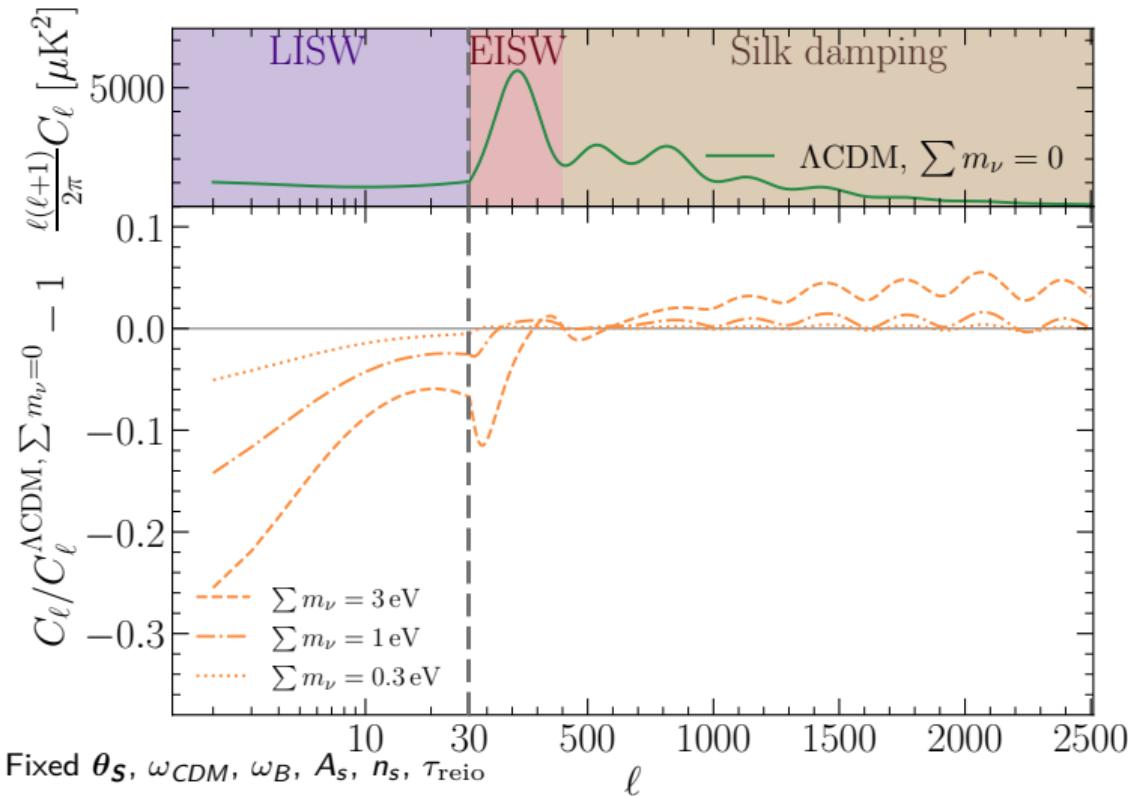
See Afshordi, Zaldarriaga and Kohri; astro-ph/0506663



# Impact on CMB: Neutrino masses

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J. Lesgourgues, G. Mangano, G. Miele,  
S. Pastor, Neutrino Cosmology (2013)

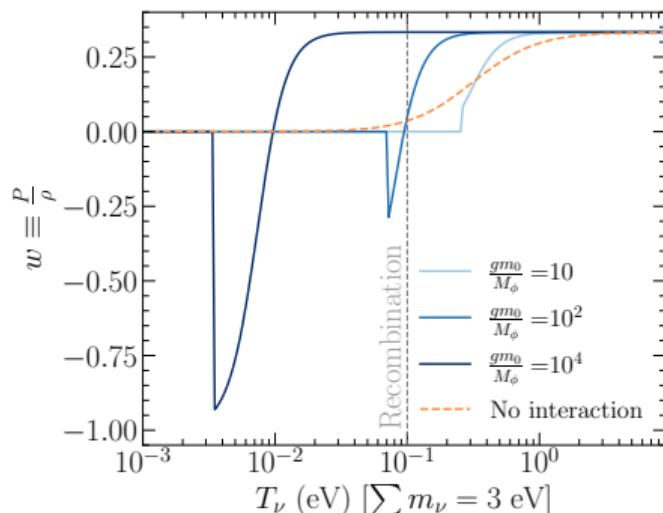
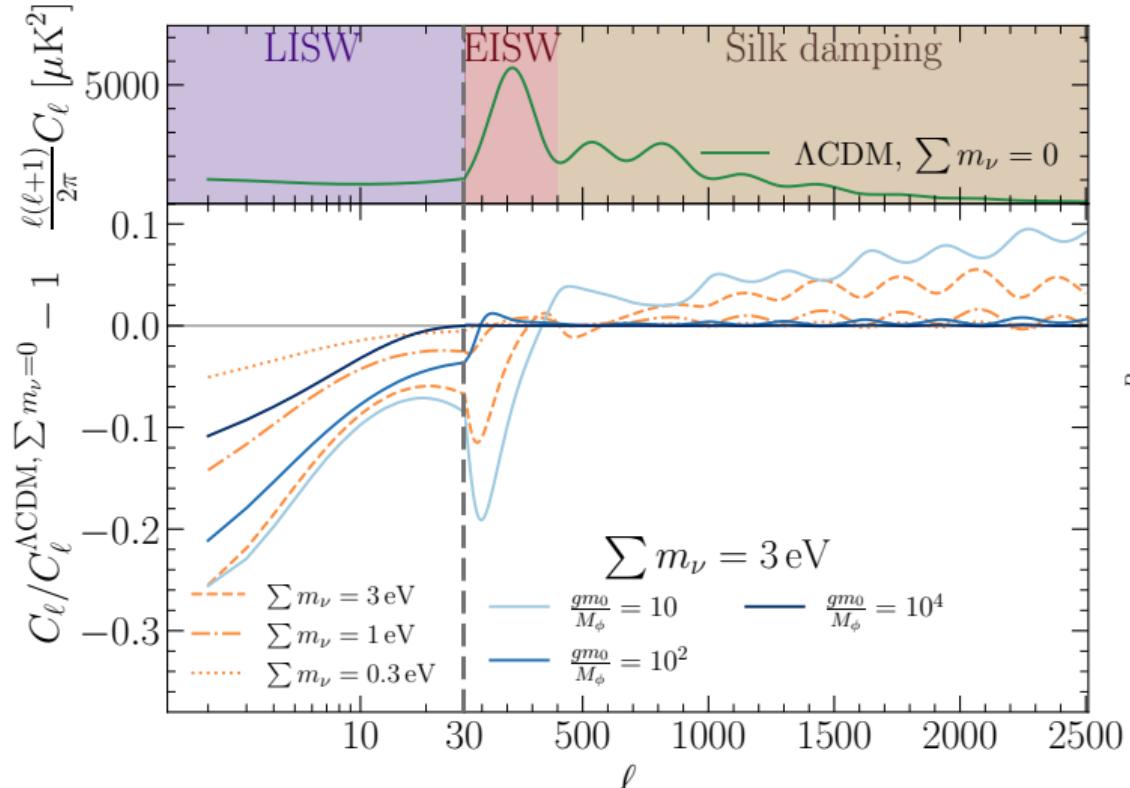
For fixed  $\theta_S = \frac{\int_{z_{\text{rec}}}^{\infty} c_s \frac{dz'}{H(z')}}{\int_0^{z_{\text{rec}}} \frac{dz'}{H(z')}}$ ,  
 $\sum m_\nu \neq 0$  has 3 main effects:

- 1 EISW, which directly tests the *equation of state*.
- 2 To keep  $\theta_S$  fixed,  $H_0$  decreases  
 $\Rightarrow \Omega_\Lambda$  decreases  $\Rightarrow$  less LISW.
- 3  $\theta_D \sim \frac{\sqrt{\int_{z_{\text{rec}}}^{\infty} \frac{1}{a n_e \sigma_T} \frac{dz'}{H(z')}}}{\int_0^{z_{\text{rec}}} \frac{dz'}{H(z')}}$

# Impact on CMB: Adding the interaction

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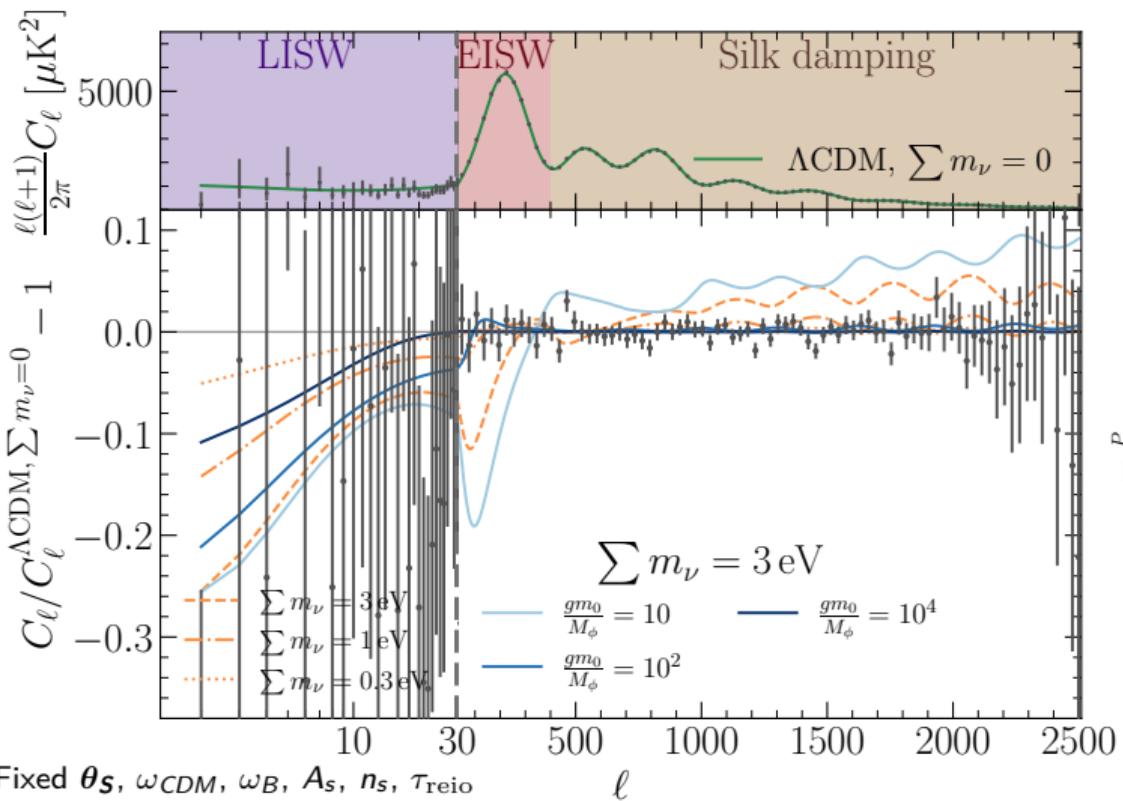
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Fixed  $\theta_S, \omega_{CDM}, \omega_B, A_s, n_s, \tau_{reio}$

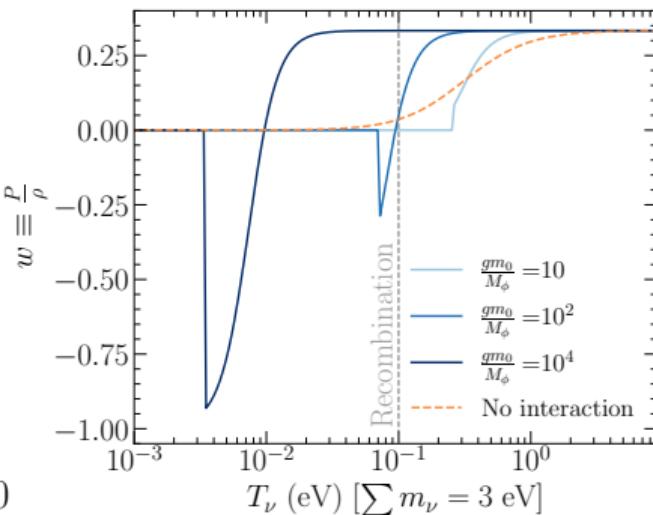
# Impact on CMB: Data

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The Planck constraint will be essentially *behave like radiation* for  $T > T_{\text{rec}}$ .

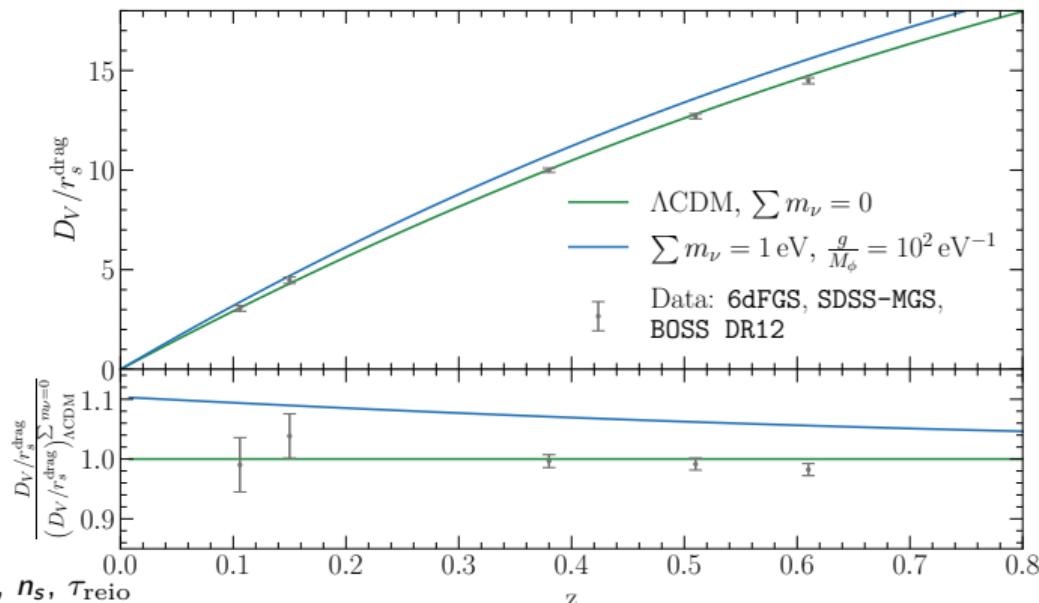


# Impact on BAO

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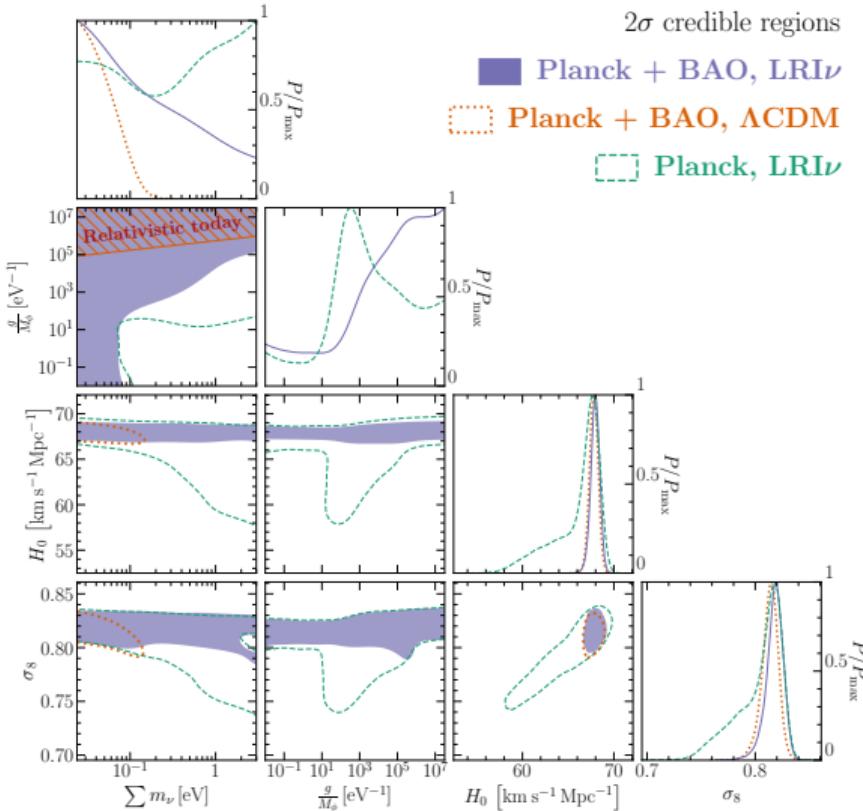
BAO approximately measure  $\frac{\int_{z_{\text{drag}}}^{\infty} c_s \frac{dz'}{H(z')}}{\left[ \frac{z}{H(z)} \left( \int_0^z \frac{dz'}{H(z')} \right)^2 \right]^{1/3}}$ , sensitive to late-time evolution of  $H$ , i.e., to  $\rho$ .

Fixed  $\theta_S, \omega_{CDM}, \omega_B, A_s, n_s, \tau_{\text{reio}}$

# Constraints

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- BAO more sensitive: this is late-time physics.
- Neutrino mass bound *fully avoided*.  
**KATRIN could see something!**
- Take-home message: cosmology is a unique laboratory, but beware of indirect measurements!

# Conclusions and future directions

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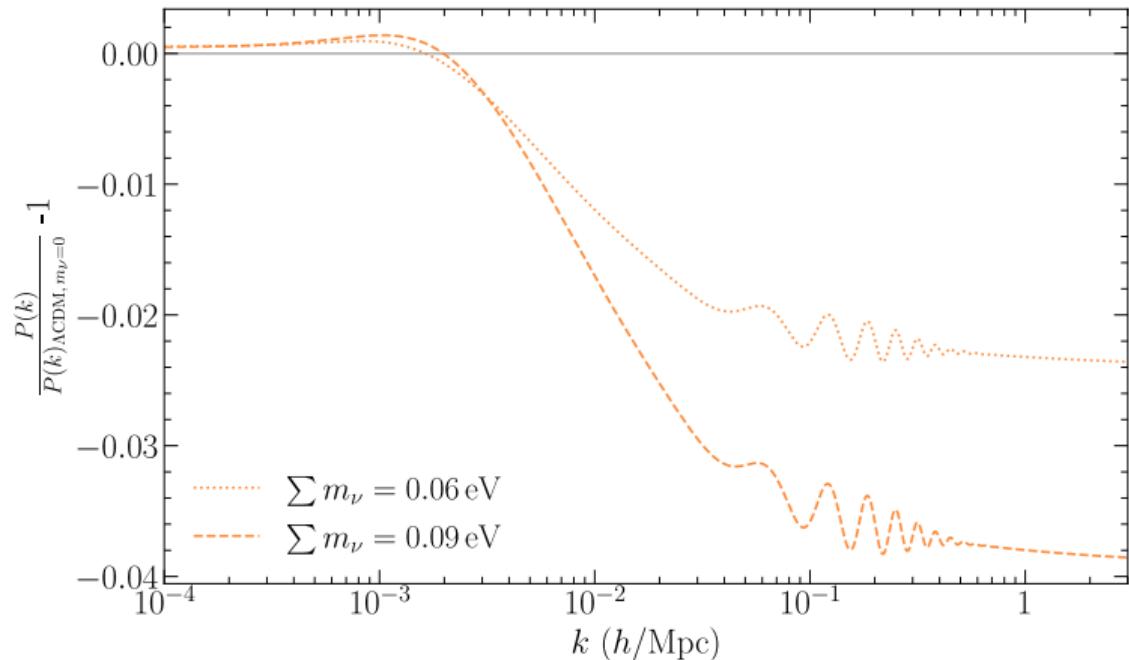
- Cosmology is a **unique** environment to probe New Physics.  
It is a blessing but also a curse, because of model dependence.  
We need **many cosmology observables** to convince the broad community!
- Cosmology will **lead** the neutrino mass sensitivity.
- But the measurement is **indirect**, through gravitational effects.  
This is sensitive to the **equation of state**.
- Even the simplest model has a very interesting phenomenology,
  - Non-trivial impact on many observables
  - $\sum m_\nu$  bound can be completely avoided. I didn't show it, but future cosmology may not measure neutrino masses!
  - Interesting lensing signal! Check arXiv:2202.04656

What about potentials for  $\phi$ ? Or pseudoscalars? Or vectors? Or other fermions?
- We have to take the most out of **complementarity**,
  - KATRIN?
  - Are there consequences of these scenarios in laboratory/astrophysics? Sun? Supernovae?
  - Are clumps detectable?

# Moving forward: impact on LSS

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Fixed  $\Omega_M$ ,  $\omega_{CDM}$ ,  $\omega_B$ ,  $A_s$ ,  $n_s$ ,  $\tau_{\text{reio.}}$ ,  $z = 0$ .

$\sum m_\nu \neq 0$  has two main effects:

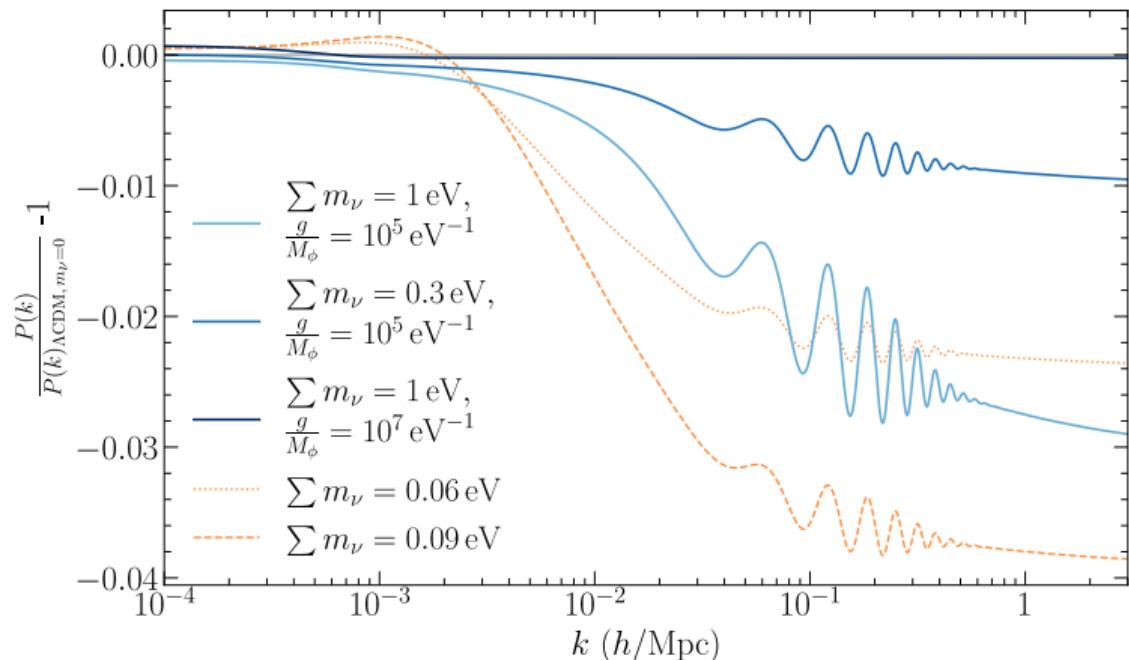
- 1 Small enhancement at  $k \sim 10^{-3} h/\text{Mpc}$ , due to clustering.
- 2 Suppression at large  $k$ , as for  $w < 1/3$  neutrinos redshift slower and contribute more to Hubble friction.

Sensitive to energy density in neutrinos and **equation of state!**

# Moving forward: impact on LSS

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# Future sensitivity

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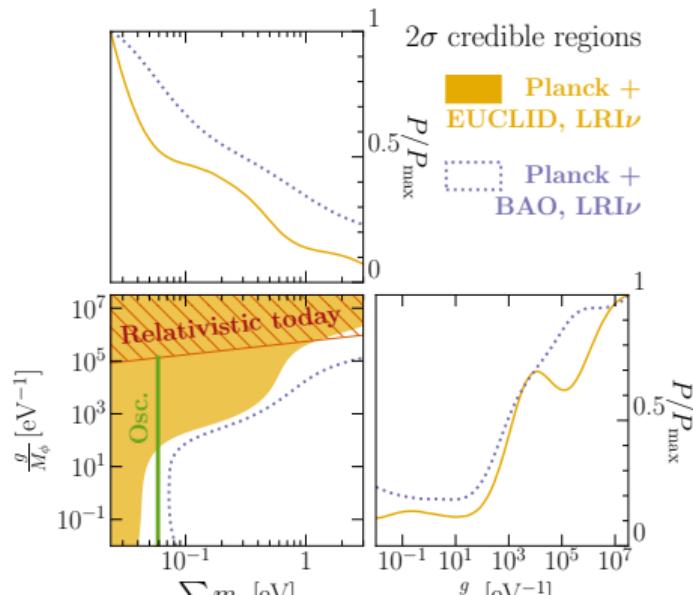
Esteban and Salvado; 2101.05804 (JCAP)

■ T. Sprenger *et al.*, "Cosmology in the era of Euclid and the Square Kilometre Array," arXiv:1801.08331.

Late-time probes can efficiently explore neutrino long-range interactions.

This decade, we expect precise probes of late-time structure formation!

**Scenario 1: Euclid compatible with  $\sum m_\nu = 0$**



Euclid should have  $\sim 2\text{--}3\sigma$  sensitivity to  $\sum m_\nu = 0.06$  eV, the smallest value allowed by oscillations.

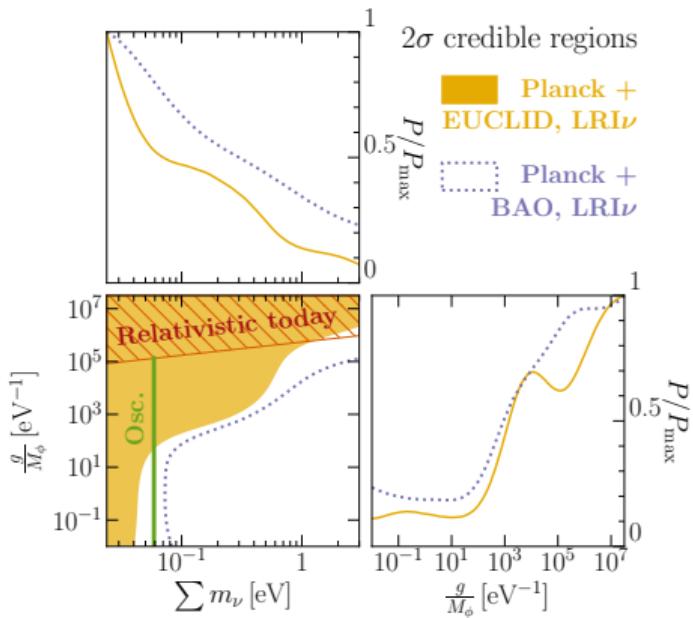
# Future sensitivity

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Interesting complementarity with KATRIN!

**Scenario 1: Euclid compatible with  $\sum m_\nu = 0$**



**Scenario 2: Euclid measures  $\sum m_\nu = 0.08$  eV**

