

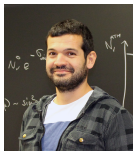
Exploring neutrino long-range interactions in the cosmos

EPS-HEP 2021

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Based on [arXiv:2101.05804](#), *JCAP* 05 (2021) 036



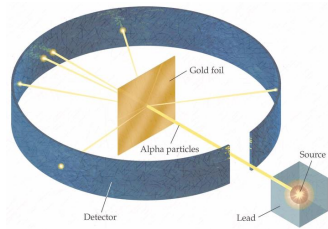
In collaboration with J. Salvado (ICCUB)

29th July 2021

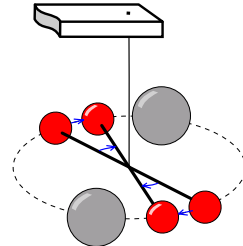


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ASTROPARTICLE PHYSICS

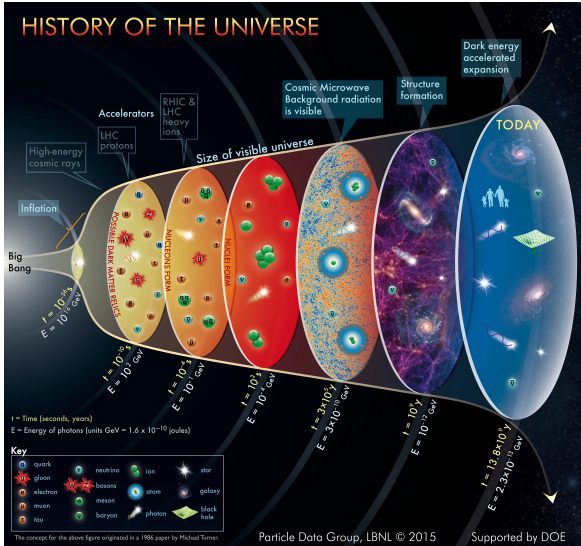
Short distances (heavy mediators)



Long distances (light mediators, small couplings)



Looking for new interactions: cosmology



In the past, densities were *high*:

- Big Bang Nucleosynthesis: $\sim 10^{29} \text{ cm}^{-3}$
- Cosmic Microwave Background: $\sim 10^{14} \text{ cm}^{-3}$

New long-range interactions could have *observational* consequences.

Looking for new interactions: cosmology

- What are the cosmological consequences of light mediators \iff long-range interactions?
How does a long-range interaction affect ρ , p , $w \dots$, commonly assumed to follow an ideal gas?
E.g., Van der Waals gas.
- What are the observational consequences and possible bounds?
 - Cosmic Microwave Background anisotropies
 - Large Scale Structure observations (Baryon Acoustic Oscillations)

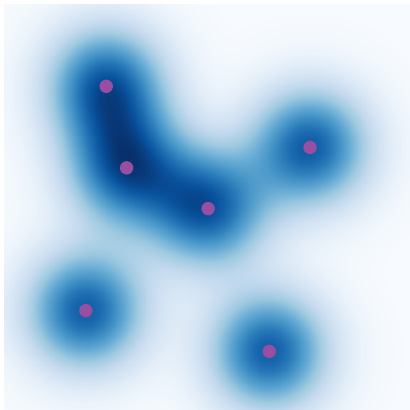
There are many recent works on cosmological consequences of neutrino self-interactions (neutrino mass models, H_0 tension, short baseline anomalies. . .) (Archidiacono et. al. (2013-2016); Hannestad et. al. (2013); Dasgupta et. al.

(2013); Forastieri et. al. (2019); Kreisch et. al. (2019); Escudero et. al. (2019); Park et. al. (2019); Blinov et. al. (2019); Beacom et. al. (2004).

But these have *heavy* mediators (they just induce ν - ν scattering), and we are interested in *long-range* effects.

Yukawa interaction

$$\mathcal{S} = \int \sqrt{-g} d^4x \left(-\frac{1}{2} D_\mu \phi D^\mu \phi - \frac{1}{2} M_\phi^2 \phi^2 + i \bar{\nu} \not{D} \nu - m_0 \bar{\nu} \nu - g \phi \bar{\nu} \nu \right)$$



- Being a scalar interaction,
 - both neutrinos and antineutrinos equally contribute,
 - both spins equally contribute,
 - is suppressed for relativistic neutrinos ($\bar{\nu}\nu = \bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L$).
- Neutrinos will source scalar field ϕ , with
 - strength $\sim g$,
 - range $\sim 1/M_\phi$.
- The field will *backreact on the neutrinos*.
- This will be important for **neutrino energies** $\lesssim m_0$ and **number densities** $\gtrsim M_\phi^3$.

N.B.: we will ignore scatterings, a good approximation for $g \lesssim 10^{-7}$.

Equations of motion

$$i\not{D}\nu - (m_0 + g\phi)\nu = 0 \quad \Longrightarrow \quad \text{Effective neutrino mass } \tilde{m}(\phi) \equiv m_0 + g\phi.$$

Time-dependent as ϕ evolves.

$$\underbrace{-D_\mu D^\mu \phi + M_\phi^2 \phi}_{\supset 3H\dot{\phi}} = -g\bar{\nu}\nu$$

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For $M_\phi \gg H$ and average rhs over neutrino (+antineutrino) distribution $f(p)$,

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

N.B.: $M_\phi \gg H$ means $M_\phi \gtrsim 10^{-25}$ eV. I.e., we are exploring interaction ranges \ll Mpc. Otherwise, we recover quintessence.

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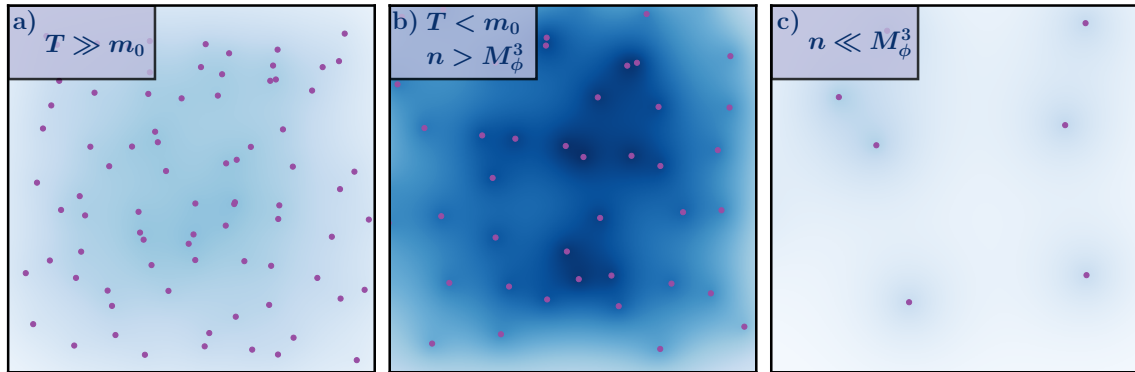
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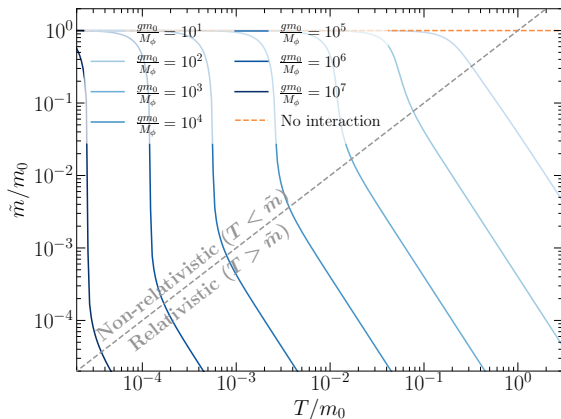
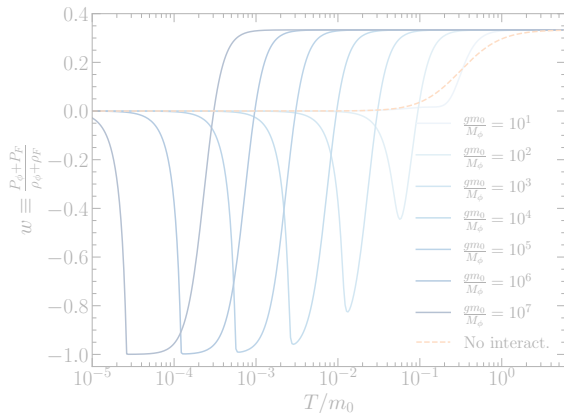
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Pictorial overview

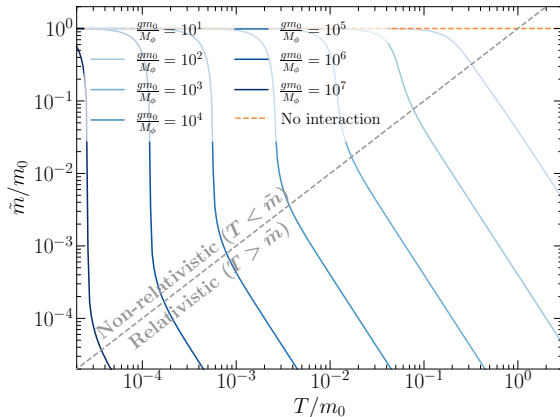
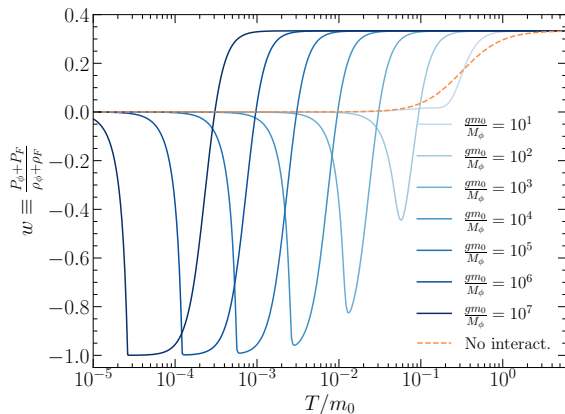


Numerical results



Neutrinos will stay *relativistic* as long as there are many neutrinos within the interaction range.

Numerical results



The equation of state $w \equiv \frac{P}{\rho}$ is relevant as $\frac{1}{\rho} \frac{d\rho}{dt} = -3H(1 + w)$ (i.e., how fastly ρ changes)


Let's look for this!

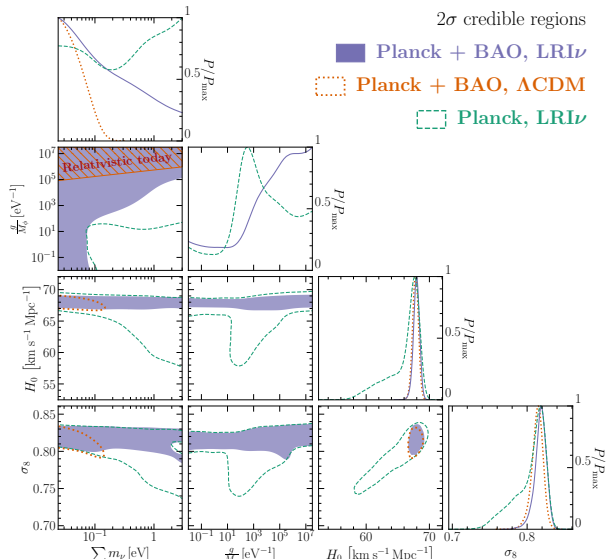
- Neutrinos abundantly exist.
- Self-interactions are poorly constrained.
- They become non-relativistic relatively late.
- Cosmology can provide a measurement of neutrino mass, **the energy scale of our first laboratory evidence of BSM physics**. Current bounds well beyond KATRIN laboratory sensitivity.

We will assume three degenerate neutrinos of vacuum mass m_ν , with a scalar universally coupling to all mass eigenstates.

We will study consequences in

- CMB anisotropies (Planck).
- Large Scale Structure (BAOs + Euclid).

CLASS + MontePython:  github.com/jsalvado/class_public_lrs



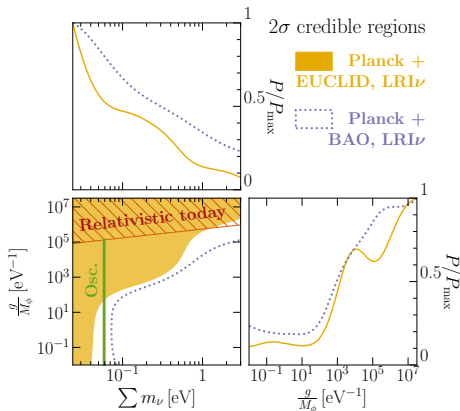
- Both BAO and Planck data are quite sensitive to the neutrino equation of state.
- Neutrino mass bound *fully avoided*.
KATRIN could see something!



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

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

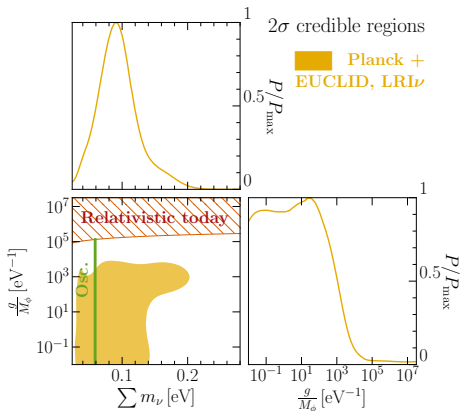
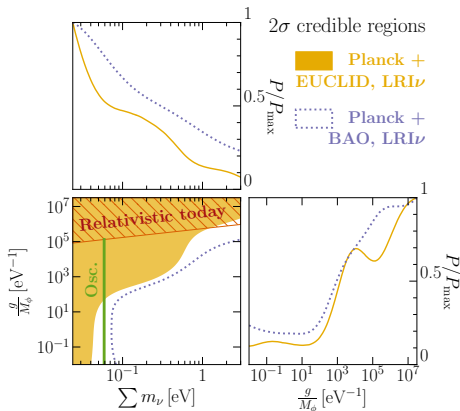
Scenario 1: Euclid compatible with $\sum m_\nu = 0$



Interesting complementarity with KATRIN!

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

Scenario 2: Euclid measures $\sum m_\nu = 0.08 \text{ eV}$




- We have consistently addressed the cosmological effects of a scalar long range interaction among neutrinos.
- Up to now, studies mostly focused on either
 - Interactions with cosmological ranges: *modified gravity*.
 - Scattering effects (*heavy mediators*).

in between, there are ~ 15 orders of magnitude with a very rich phenomenology!

- The effects turn on at $T \sim m_0$, and can be summarized as

Radiation (even for $T \ll m_0$) \implies Dark energy \implies Dust

relevant for $\frac{gm_0}{M_\phi} > 1$.

- When analyzing the data:
 - Neutrino mass bound is **completely avoided**. KATRIN could see something!
 - Planck + BAO constraint $\frac{gm_\nu}{M_\phi} \gtrsim 10^2(10^4)$ for $\sum m_\nu = 0.1(1)$ eV.
- LSS could be very powerful, and has an interesting complementarity with Katrin & oscillations.
- The formalism could also be applied to other fermions.  github.com/jsalvado/class_public_lrs

Thanks!

Homogeneous background: approximate solutions

We will assume a fermion thermal *relic*

$$f(p) = \frac{g}{(2\pi)^3} \frac{1}{e^{p/T} + 1},$$

for which the scalar field equation can be approximately solved in 2 limits

$$T \gg \tilde{m}$$

$$T \ll \tilde{m}$$

$$\phi = -\frac{\frac{g}{24} g T^3 \frac{m_0}{T}}{M_\phi^2 + \frac{g}{24} g^2 T^2}$$

$$\text{coupling} \times \text{fermion number density} \times \frac{m_0}{T}$$

\div effective scalar mass

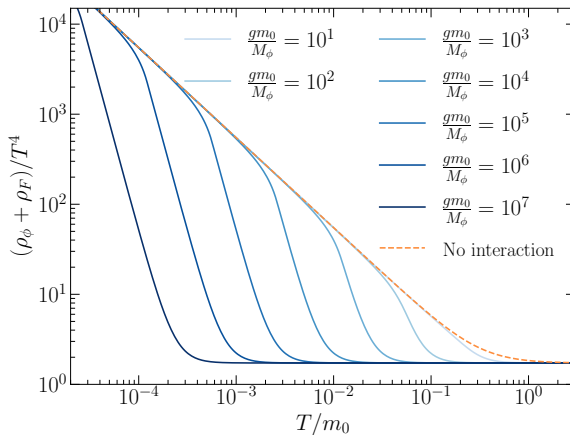
$$\tilde{m} = m_0 \frac{1}{1 + \frac{g}{24} \frac{g^2 T^2}{M_\phi^2}}$$

$$\text{relativistic as long as } T \gg \frac{M_\phi}{g} \sqrt{\frac{m_0}{T}}$$

$$\phi = -\frac{3\zeta(3)g}{4\pi^2} g \frac{T^3}{M_\phi^2}$$

$$\tilde{m} = m_0 \left(1 - \frac{3\zeta(3)g}{4\pi^2} \frac{g^2 T^2}{M_\phi^2} \frac{T}{m_0} \right)$$

Energy density



$$\rho_\phi = \frac{1}{2} M_\phi^2 \phi^2 ; \quad \rho_F = \int d^3 p \sqrt{p^2 + \tilde{m}^2} f(p).$$

Notice that $\rho \leq \rho_{\text{No interaction}}$: Yukawas are *attractive*.

Perturbation equations & instability

In the Newtonian gauge,

$$f = f_0(q)[1 + \Psi(\vec{q}, \tau, \vec{x})]$$

$$\psi'_0 = -\frac{qk}{\varepsilon}\psi_1 - \phi' \frac{d \log f_0}{d \log q},$$

$$\psi'_1 = \frac{qk}{3\varepsilon}(\psi_0 - 2\psi_2) - \left[\varepsilon\psi + g\delta\phi \frac{\tilde{m}}{\varepsilon} a^2 \right] \frac{k}{3q} \frac{d \log f_0}{d \log q},$$

$$\psi'_\ell = \frac{qk}{(2\ell+1)\varepsilon} [\ell\psi_{\ell-1} - (\ell+1)\psi_{\ell+1}] \quad \forall \ell \geq 2.$$

$$\phi = \phi_0(\tau) + \delta\phi(\vec{x}, \tau)$$

For $M_\phi \gg H$,

$$\delta\phi \simeq \frac{-g \frac{4\pi}{a^2} \int dq q^2 \frac{\tilde{m}}{\varepsilon} f_0(q) \Psi_0(\vec{q}, \tau, \vec{k})}{(k/a)^2 + M_\phi^2 + M_T^2}$$

$$M_T^2 \equiv g^2 \int d^3p \frac{p^2}{[p^2 + \tilde{m}^2]^{3/2}} f_0(p).$$

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N. Afshordi, M. Zaldarriaga and K. Kohri, "On the stability of dark energy with mass-varying neutrinos," Phys. Rev. D **72**, 065024 (2005) arXiv:astro-ph/0506663.

See also Bjælde et al, arXiv:0705.2018; Bean et al, arXiv:0709.1124; Beca and Avelino, arXiv:astro-ph/0507075; Kaplinghat and Rajaraman, arXiv:astro-ph/0601517 ...

There is a new attractive force, stronger than gravity: perturbations at scales $a/k \gtrsim 1/M$ are **unstable**.

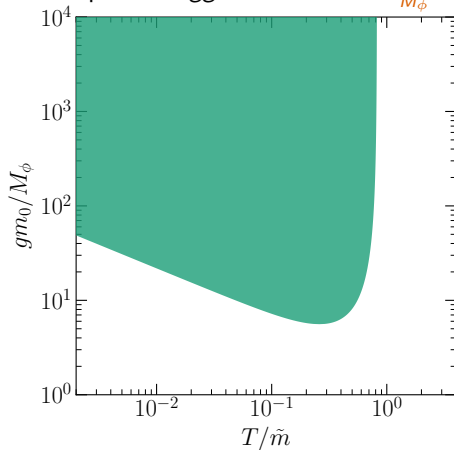
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When they become non-relativistic, in a time $\ll \frac{1}{M_\phi}$, fermions will collapse in *nuggets* with size $\ll \frac{1}{M_\phi}$. These will behave as dust, as no scalar field is left out.

- We have numerically verified this for a large fraction of parameter space (shaded).



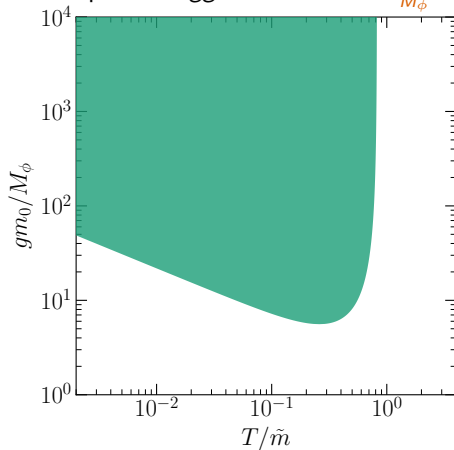
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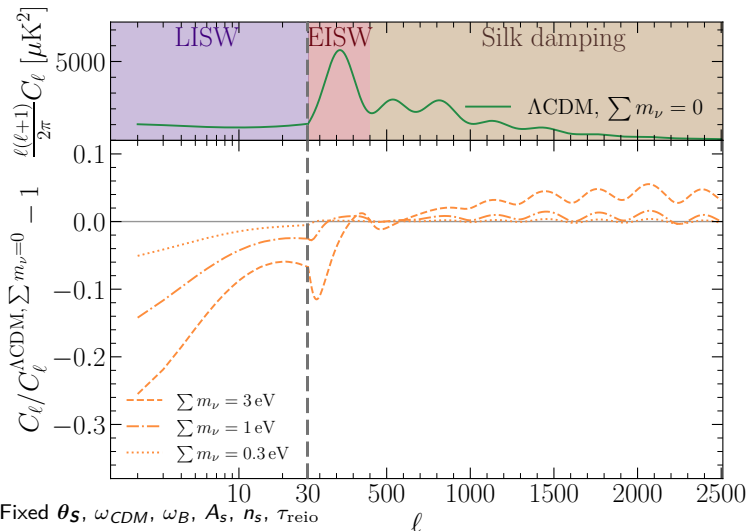
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- We have numerically verified this for a large fraction of parameter space (shaded).
- Nevertheless, as $M_\phi \gg H$, the involved scales are much smaller than cosmological scales!
As $M_\phi \lesssim H$, we recover modified gravity
For $m_0 \sim \text{eV}$, $1/M_\phi \sim \text{km} - \text{pc} \sim 10^{-6} \text{ s} - \text{year}$
- For the purpose of cosmological observables, we can assume an *instantaneous* transition to dust-like behaviour.



Neutrino masses



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

$$\text{For fixed } \theta_S = \frac{\int_{z_{\text{rec}}}^{\infty} c_s \frac{dz'}{H(z')}}{\int_0^{z_{\text{rec}}} \frac{dz'}{H(z')}} ,$$

$\sum m_\nu \neq 0$ has 3 main effects:

- 1 EISW, which directly tests the *equation of state*.
- 2 To keep θ_S fixed, H_0 decreases $\Rightarrow \Omega_\Lambda$ decreases \Rightarrow less LISW.

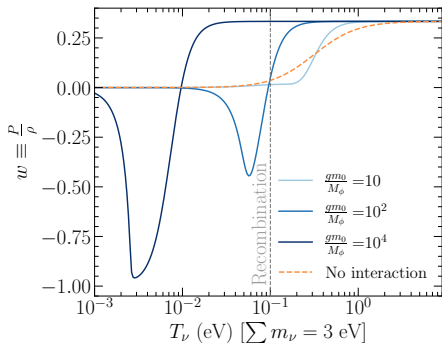
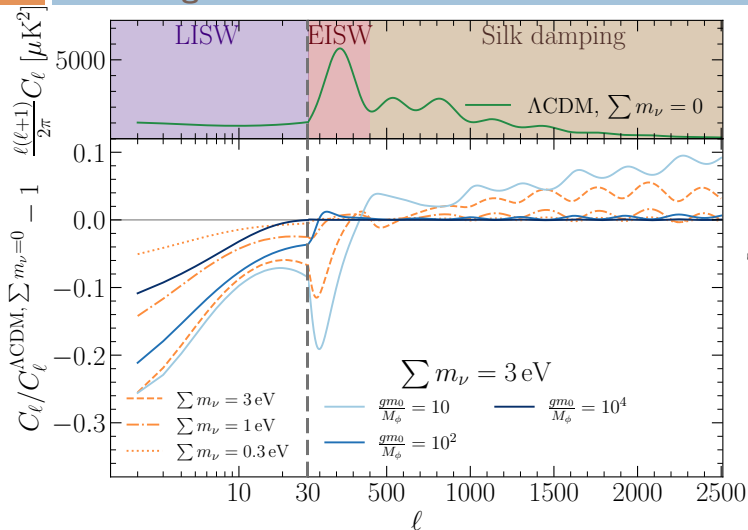
$$3 \quad \theta_D \sim \sqrt{\frac{\int_{z_{\text{rec}}}^{\infty} \frac{1}{a n_e \sigma_T} \frac{dz'}{H(z')}}{\int_0^{z_{\text{rec}}} \frac{dz'}{H(z')}}}$$

Backup: effects on CMB

Ivan Esteban, Ohio State University
arXiv:2101.05804

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Adding the interaction



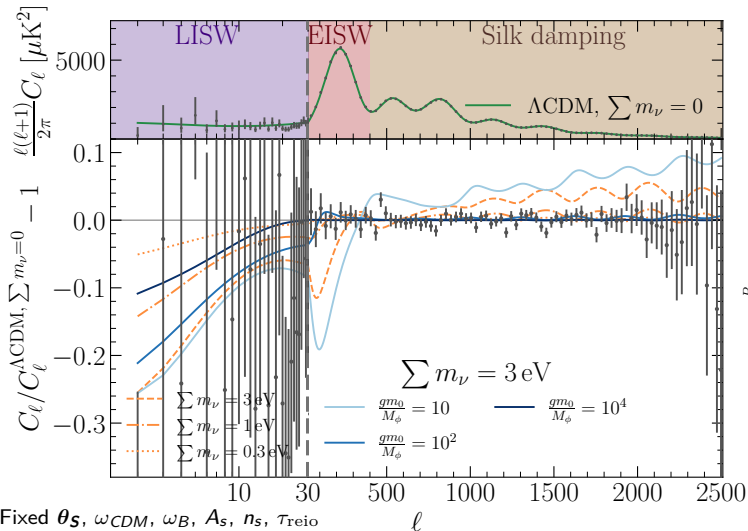
Fixed $\theta_S, \omega_{\text{CDM}}, \omega_B, A_s, n_s, \tau_{\text{reio}}$

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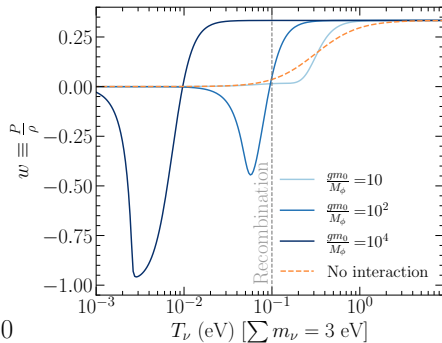
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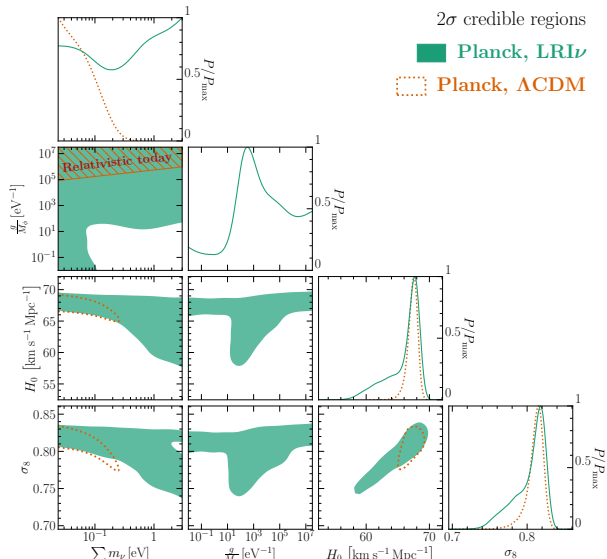
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Data



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

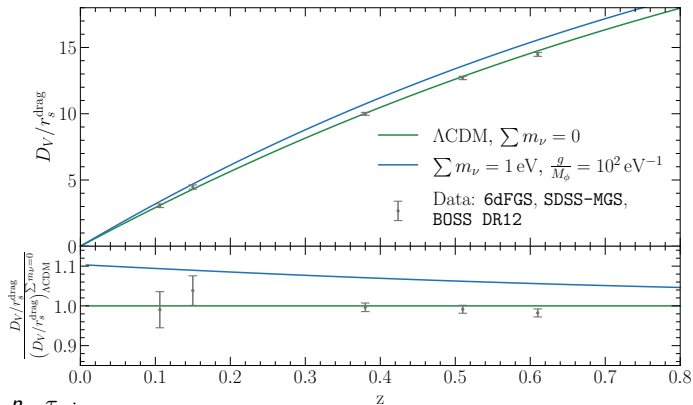




All the allowed region has essentially the same behavior before recombination: neutrinos with $w = 1/3$.

Data

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 ρ .



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

Future: Large Scale Structure

- As we have seen, late-time probes can efficiently explore neutrino long-range interactions.
- This decade, we expect precise LSS probes of the matter power spectrum!



L. Amendola *et al.* [Euclid Theory WG], “Cosmology and fundamental physics with the Euclid satellite,” arXiv:1606.00180.



R. Maartens *et al.* [SKA Cosmology SWG], “Overview of Cosmology with the SKA,” arXiv:1501.04076.



J. Pritchard *et al.* [Cosmology-SWG and EoR/CD-SWG], “Cosmology from EoR/Cosmic Dawn with the SKA,” arXiv:1501.04291.

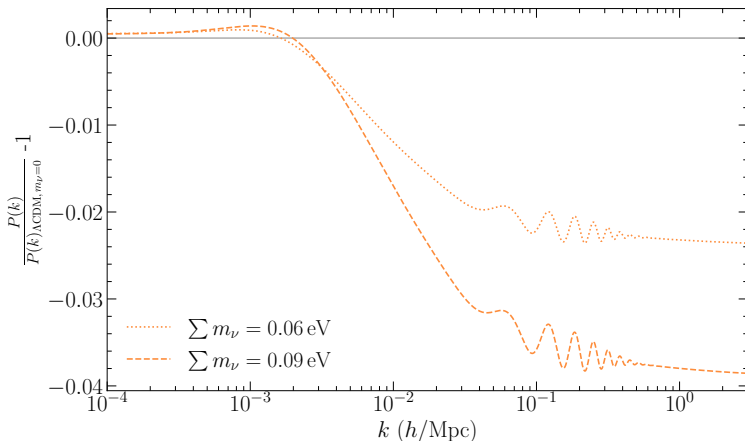


P. A. Abell *et al.* [LSST Science and LSST Project], “LSST Science Book, Version 2.0,” arXiv:0912.0201.



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

Impact on matter power spectrum

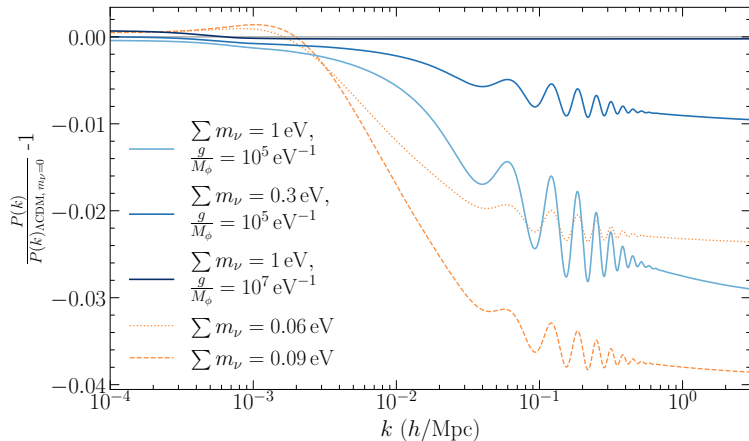


$\sum m_\nu \neq 0$ has two main effects:

- 1 Small enhancement at $k \sim 10^{-3} \text{ h/Mpc}$, 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!**

Impact on matter power spectrum



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

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