Probing neutrino nonstandard interactions with cosmological data

Jorge Venzor -XV Edición del Simposio Latinoamericano de Física de Altas Energías (SILAFAE).

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Outline

- State-of-the-art of standard neutrinos.

- Neutrino NSI in cosmology

- Neutrino self-interactions with light and not so light mediators

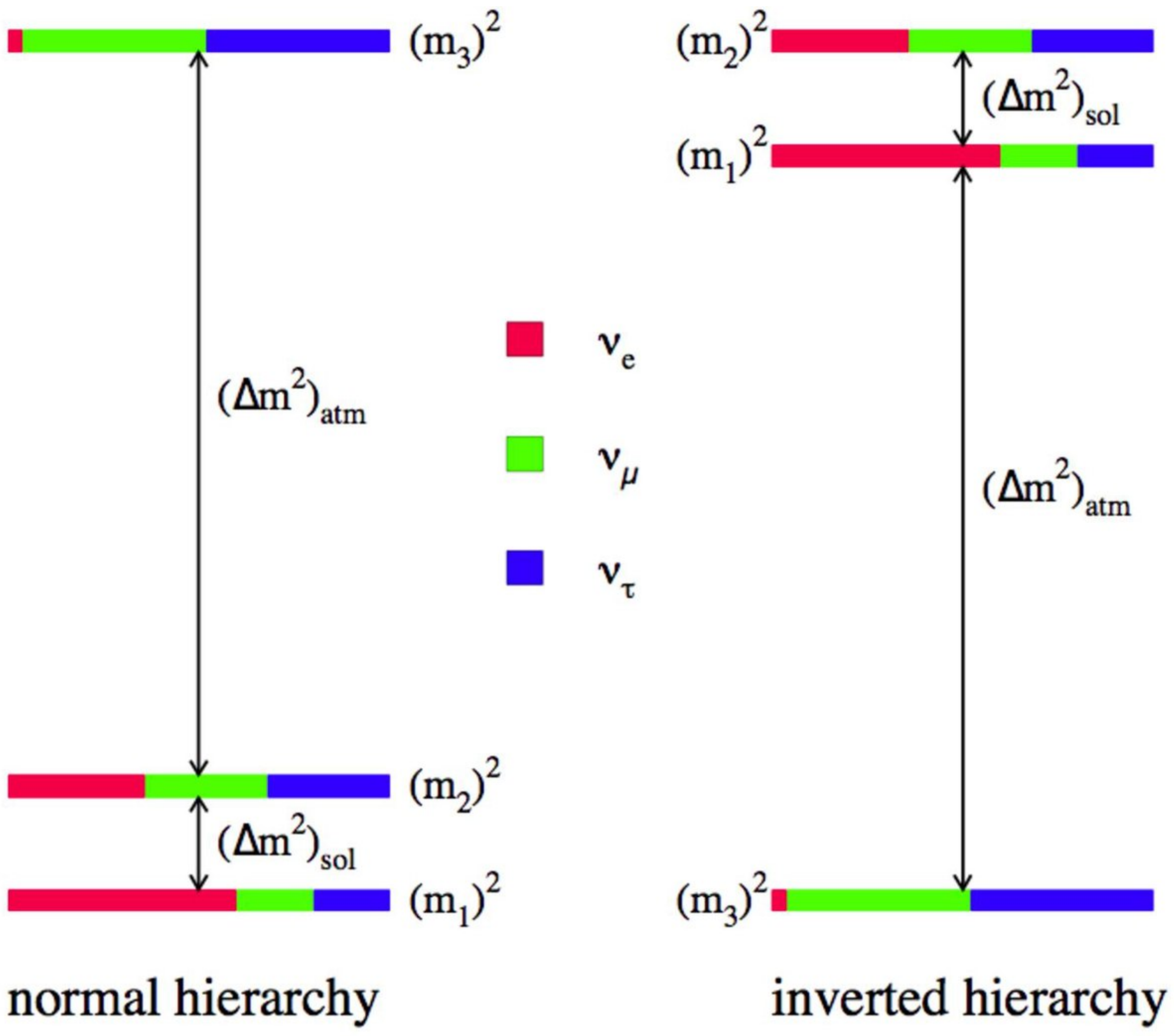
Neutrinos

$$\Delta m^2_{\rm sol} = \Delta m^2_{21} = m^2_2 - m^2_1 = 7.42^{+0.21}_{-0.20} \times 10^{-5}\ {\rm eV}^2$$

$$\text{NH} \longrightarrow \Delta m^2_{\rm ATM} = \Delta m^2_{31} = m^2_3 - m^2_1 = 2.517^{+0.026}_{-0.028} \times 10^{-3}\ {\rm eV}^2$$

$$\text{IH} \longrightarrow \Delta m^2_{\rm ATM} = \Delta m^2_{23} = m^2_2 - m^2_3 = 2.498^{+0.028}_{-0.028} \times 10^{-3}\ {\rm eV}^2$$

2020 Esteban+ JHEP



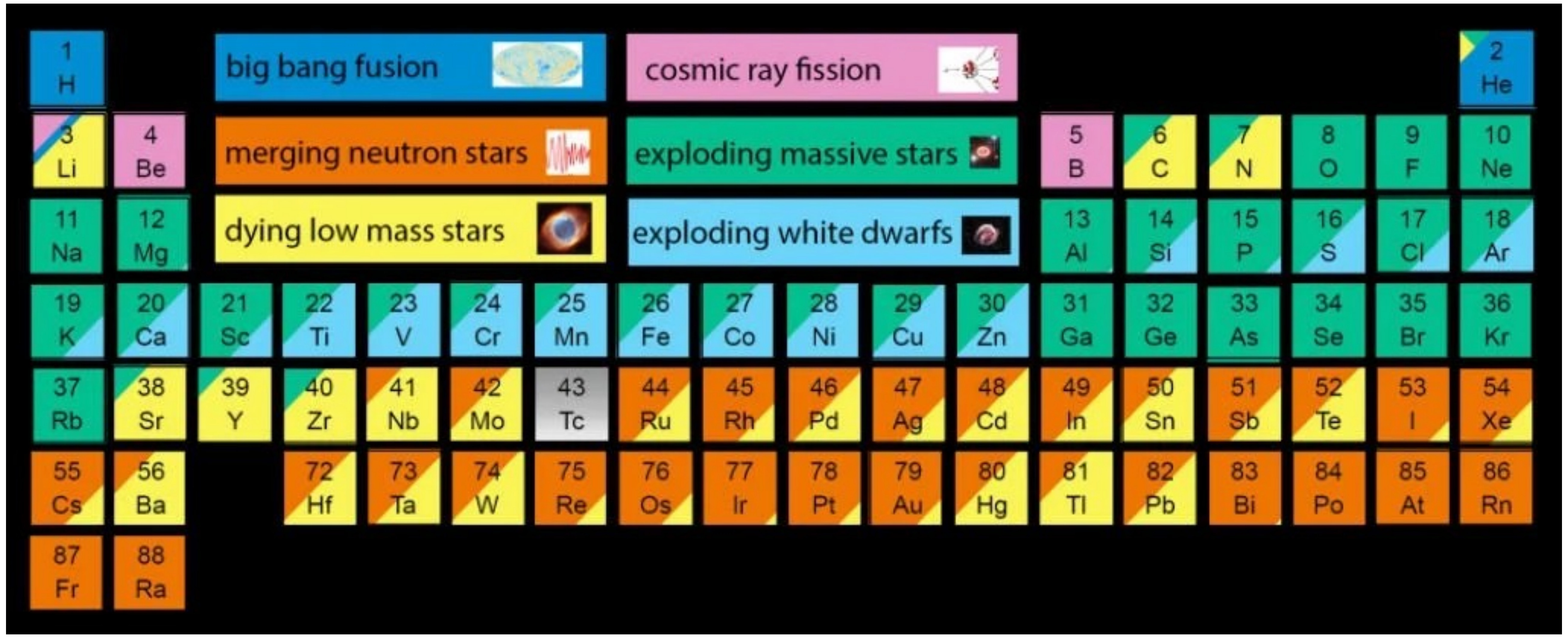
We know that neutrinos have mass. We don't have a direct measurement of them

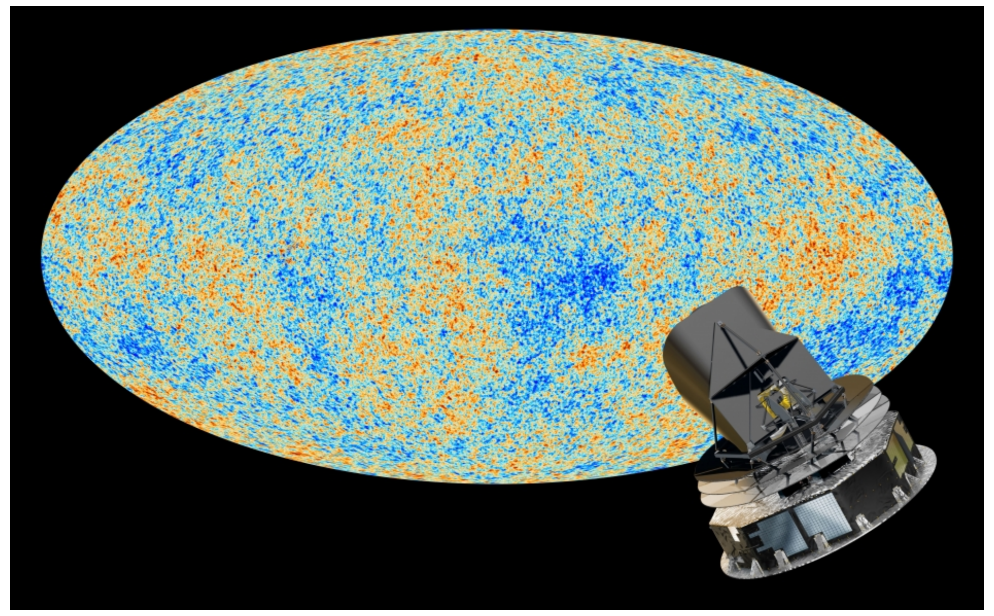
★ The standard model does not explain neutrino mass

★ The most popular neutrino mass models require a neutrino NSI

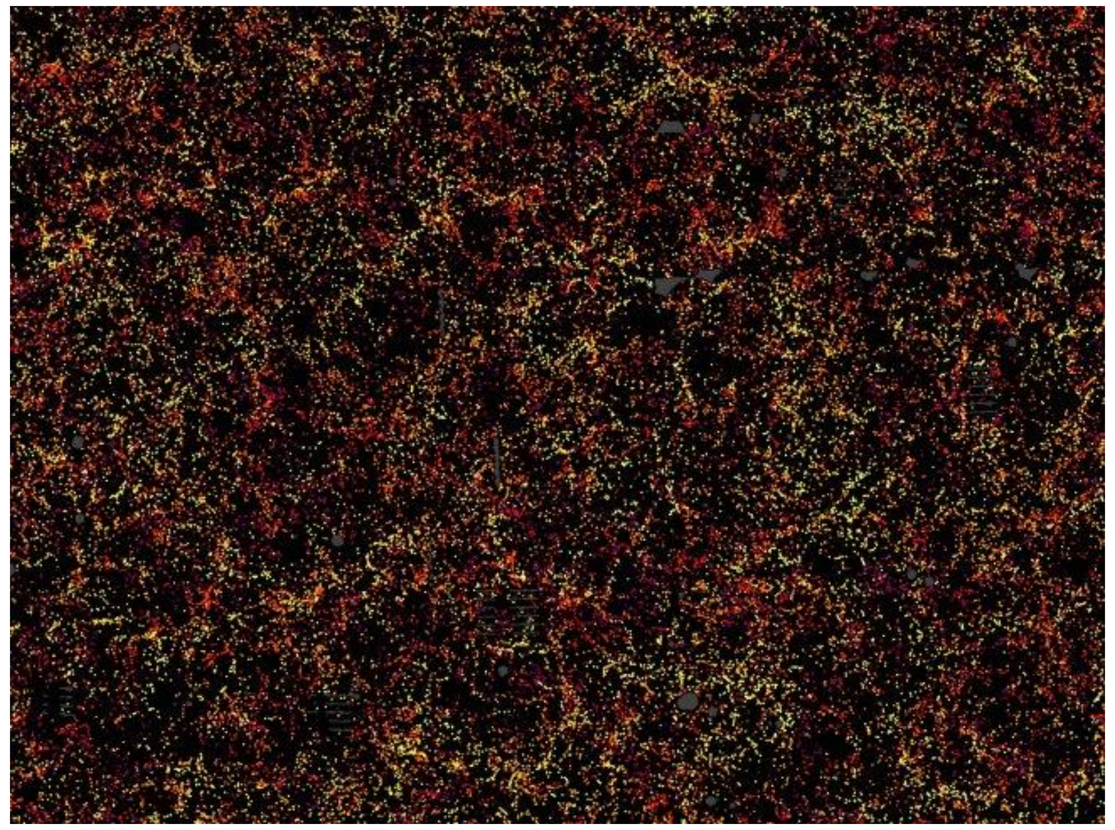
Neutrinos are a main character in cosmology

BBN, supernovas





Planck/ESA



Basically, they destroy structure

SDSS

Theoretical computation

$$N_{\text{eff}} = 3.044$$

$$N_{\text{eff}} = 2.99 \pm 0.17 \ (68\,\% \quad \text{C.L.})$$

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

2021 Planck collab. A&A

$$N_{\text{eff}}$$

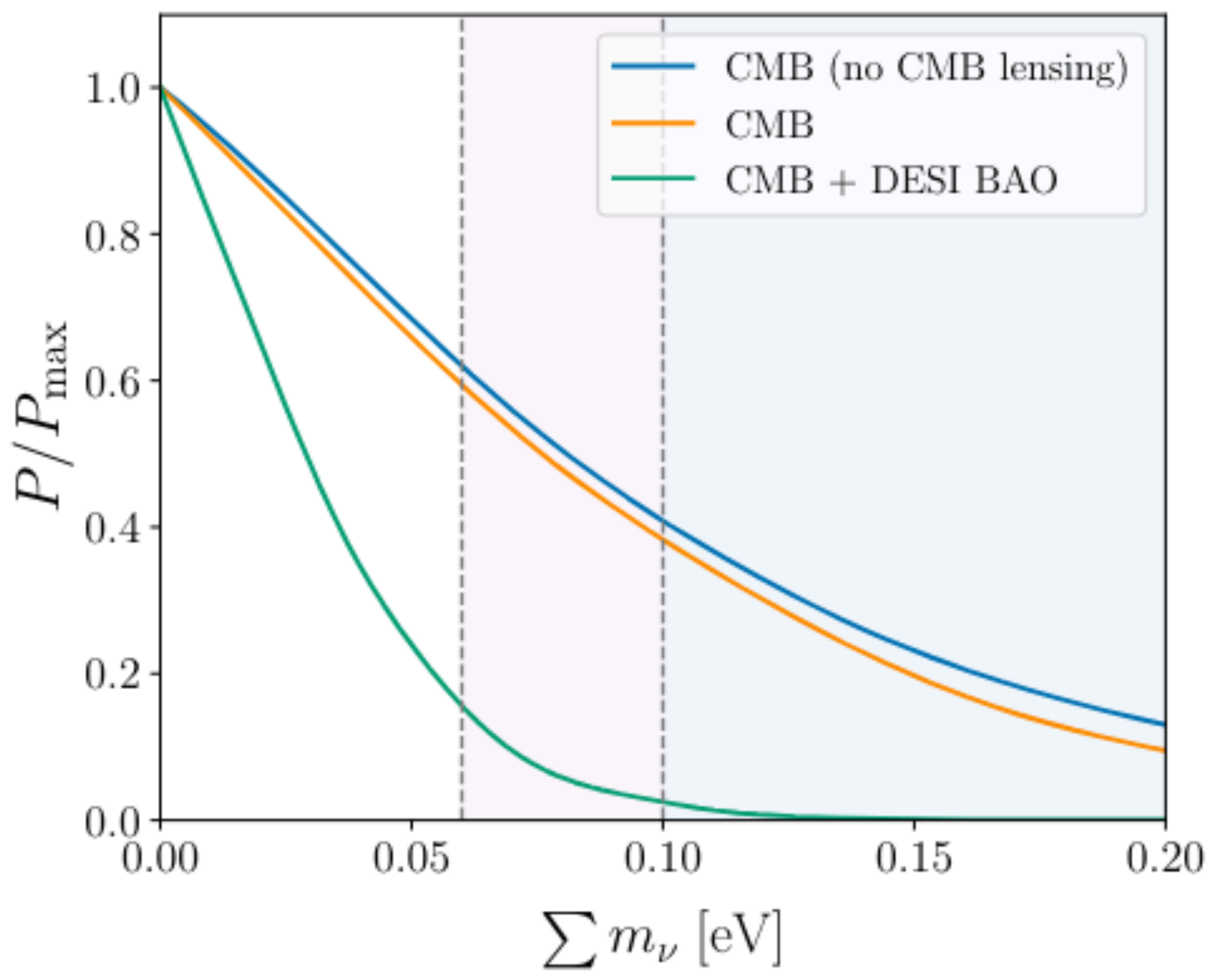
They behave as radiation in the early Universe

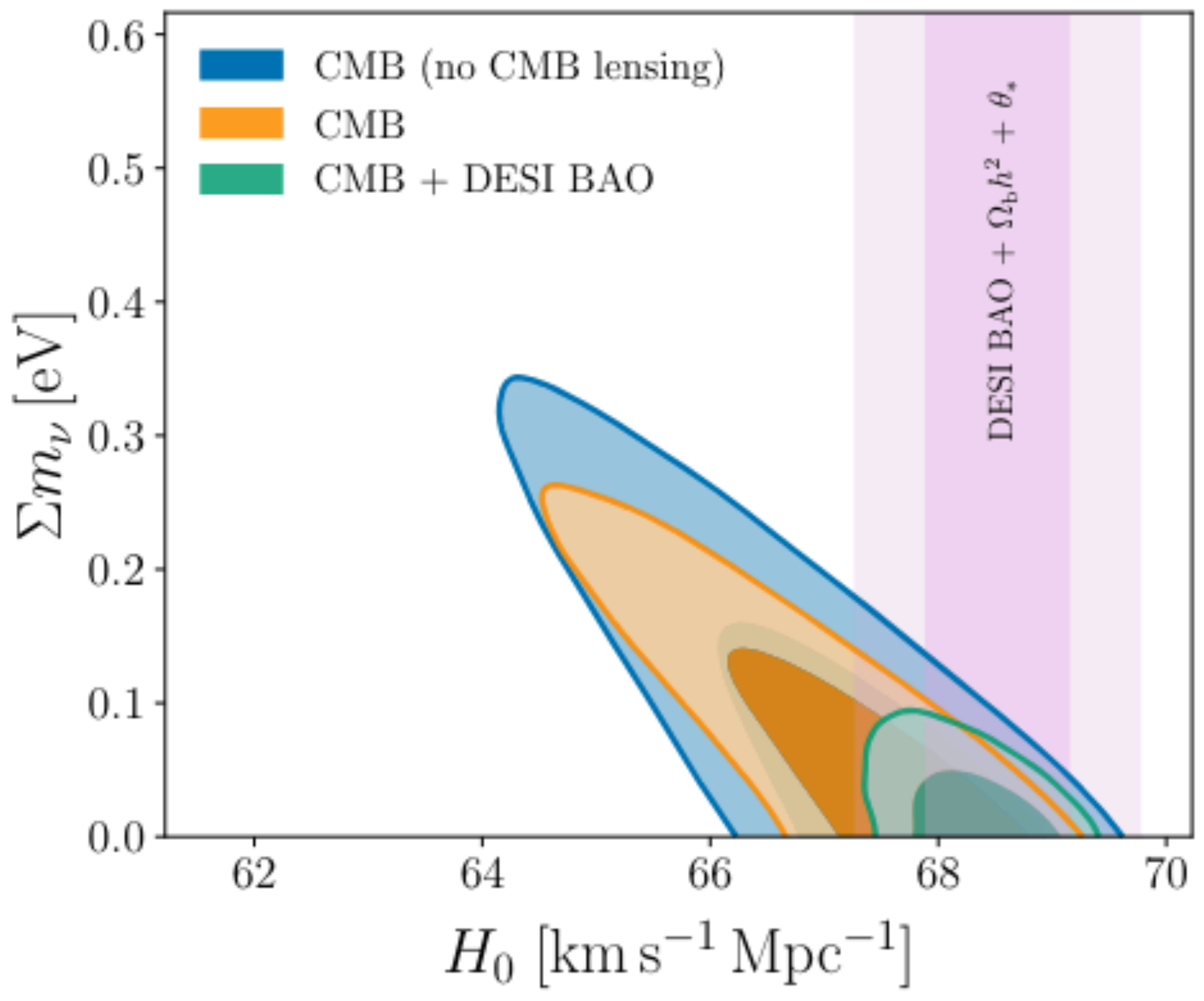
(Around 40% of the totalrad)

$$\sum m_\nu = m_1 + m_2 + m_3$$

Lately, they behave as matter

Neutrino cosmology - a new tension





$$\sum m_\nu < 0.072 \ (95\,\% \quad \mathrm{C.L.})$$

Fixed Neff, LCDM

2024 DESI collab. 2404.03002

$$m_\beta < 0.45\mathrm{eV} \qquad m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

(90% C.L.) KATRIN 2024

Direct measurement

From neutrino oscillations

$$\sum m_{\nu\mathrm{NH}} \gtrsim 0.06\mathrm{eV} \qquad \sum m_{\nu\mathrm{IH}} \gtrsim 0.1\mathrm{eV}$$

- ★ **Better be careful with data analysis and tensions among different data**

2024 Naredo-Tuero

2024 Craig No vs is Good News

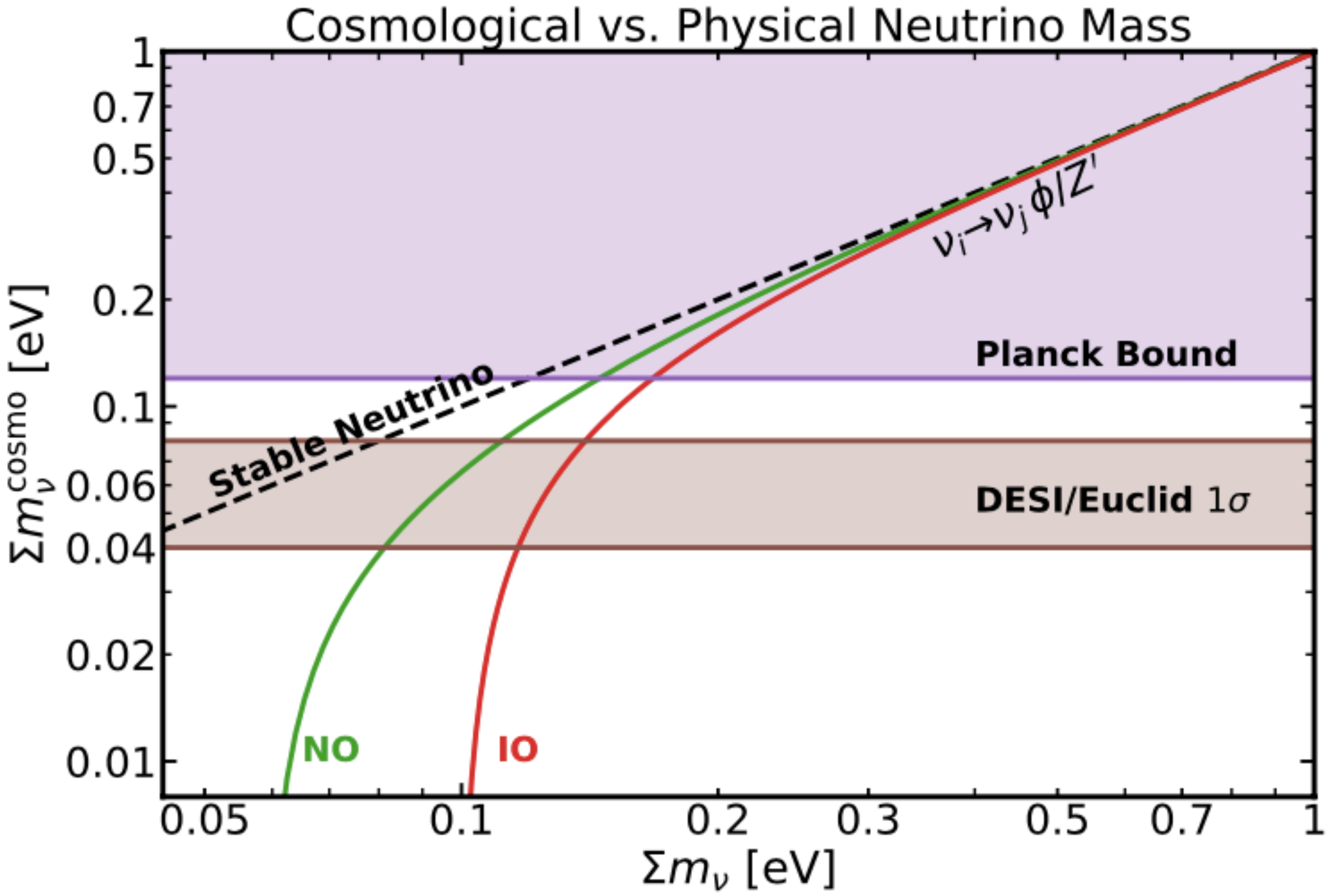
- ★ **What if the tension leads to new physics?**

Neutrino NSI- A window for new physics

NSI could explain why cosmology can have strong mass bounds

$$\nu + \nu \rightarrow \phi + \phi$$

$$\nu_i \rightarrow \nu_j + \phi$$



2020 Escudero+ JHEP
2004 Beacom+ PRL

★ We can test if nonstandard particle physics is enough to solve the neutrino tension

2021 Barenboim+ JCAP
2022 Chen+ EPJC 2021 Chacko+
2022 Abellan+ JHEP

★ At worst case, cosmology would require some fundamental changes

And that is pretty exciting too!

Perturbations (cosmological)

$\nu\nu \to \nu\nu$

Relaxation Time Approximation (RTA)

$$\frac{1}{f_0} C(f) = -a\Gamma_{\text{scatt}} \Psi$$

$$\Gamma_{\text{scatt}} = \langle \sigma_0 v \rangle n_\nu$$

Density fluctuation →

$$\dot{\Psi}_0 = -\frac{q}{\epsilon} k \Psi_1 + \frac{1}{6} \dot{h} \frac{d \ln f_0}{d \ln q}$$

For l=0 y l=1 null change mean
Neutrino number and momenta is conserved

Peculiar velocity →

$$\dot{\Psi}_1 = \frac{qk}{3\epsilon} (\Psi_0 - 2\Psi_2)$$

Anisotropic streets →

$$\dot{\Psi}_2 = \frac{qk}{5\epsilon} (2\Psi_1 - 3\Psi_3) - \left(\frac{1}{15} \dot{h} + \frac{2}{5} \dot{\eta} \right) \frac{d \ln f_0}{d \ln q} - a\Gamma_{\text{scatt}} \Psi_2$$

Self-interactions suppress shear y and higher multipoles

$$\dot{\Psi}_l = \frac{qk}{(2l+1)\epsilon} [l\Psi_{l-1} - (l+1)\Psi_{l+1}] - a\Gamma_{\text{scatt}} \Psi_l \qquad l \geq 3$$

Neutrino self-interactions

.... The mediator mass dictates the dynamics

$$\Gamma_{\text{scatt}} = \Rightarrow$$

$0.183 g_{\text{eff}}^4 T_\nu$	For	$m_\varphi < 10^{-3}$ eV	Light mediators
$\Gamma_{\text{res}}(g_\nu^2, m_\varphi; T_\nu)$	For	10^{-3} eV $< m_\varphi < 10^3$ eV	Resonances
$\alpha_l G_H^2 T_\nu^5$	For	$m_\varphi > 10^3$ eV	Heavy mediator

$$G_H = \frac{|g_\nu|^2}{m_\varphi^2}$$

G_H can be up to 9 order of magnitude larger than G_F

$$g_{\text{eff}} = \xi^{1/4} g_\nu$$

★ **... It all depends on WHEN**

Heavy mediator affect the early Universe, while the light mediator is important lately

Self-interactions

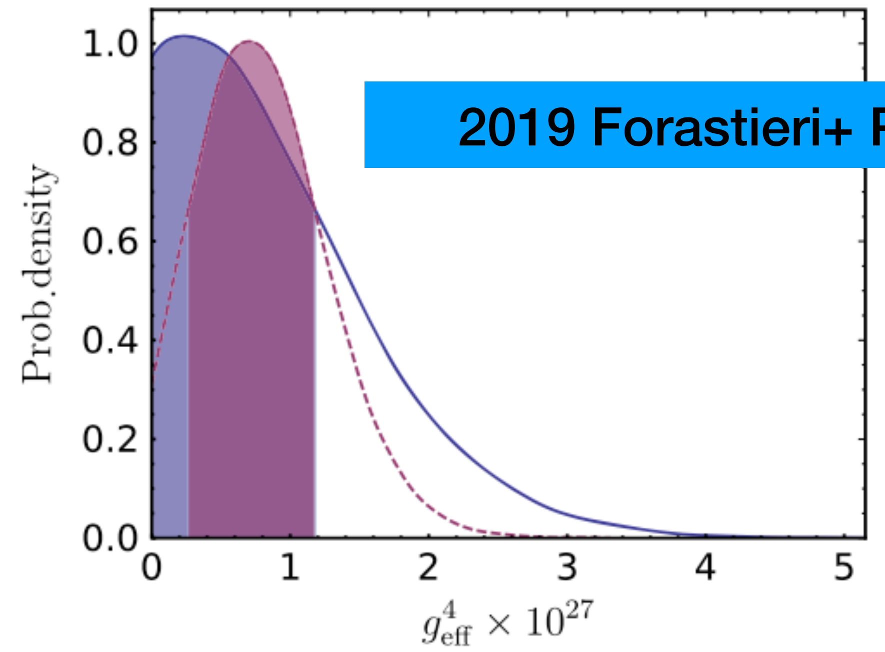
Heavy mediator

- A bimodal posterior is observed with CMB temperature a BOSS-Full shape data
- The effective coupling values are large, testable by experiments
- The non null coupling is disfavored by CMB polarization

2020 Kreisch+ PRD
2019 Blinov+ PRL
He+ PRD (2024) 2309.03956
Kreisch+ PRD (2024)2207.03164
Camarena+ PRD (2023) 2309.03941
2021 Choudhury+ JCAP
2021 Esteban+ PRD
Das&Ghosh JCAP 2303.08843

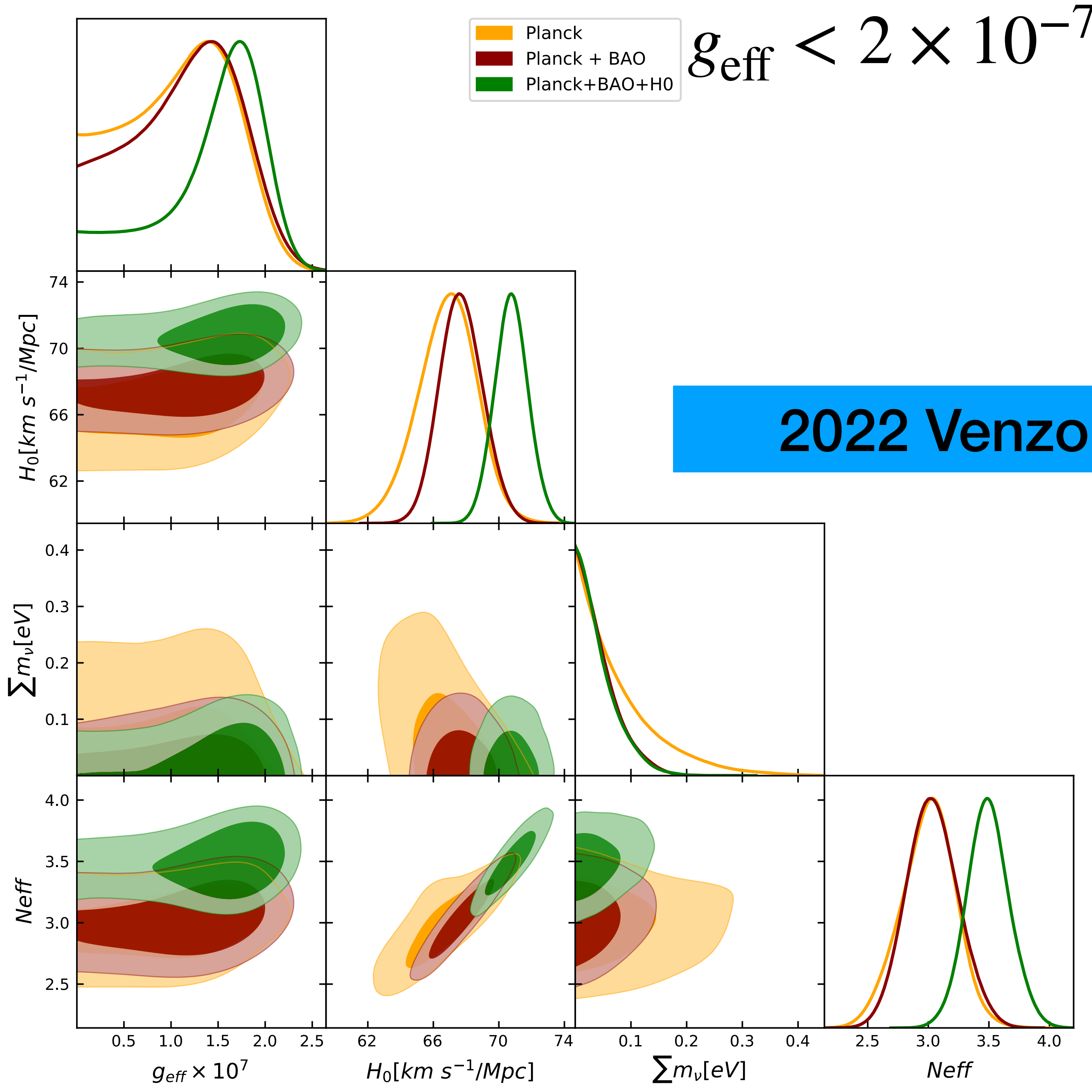
Hot Topic

Light mediator



2019 Forastieri+ PRD

Not that exotic results, but a fairly strong bound



$$g_{\rm eff} < 2 \times 10^{-7} \quad (95\,\% \quad {\rm CL})$$

2022 Venzor+ PRD

Neutrino self-interactions

.... The mediator mass dictates the dynamics

$$\Gamma_{\rm scatt} = \Rightarrow$$

$0.183 g_{\rm eff}^4 T_\nu$	Para	$m_\varphi < 10^{-3}$ eV
$\Gamma_{\rm res}(g_\nu^2, m_\varphi; T_\nu)$	Para	10^{-3} eV $< m_\varphi < 10^3$ eV ← **Resonances**
$\alpha_l G_H^2 T_\nu^5$	Para	$m_\varphi > 10^3$ eV

Resonant region

$10^{-3}\ \mathrm{eV} < m_\varphi < 10^{3}\ \mathrm{eV}$

$$\Gamma_{\mathrm{scatt}} = \langle \sigma_0 v \rangle\, n_\nu$$

We use a Breit-Wigner cross-section

$$\sigma_0(s) = \frac{g_\nu^4}{4\pi} \frac{s}{[s - m_\phi^2]^2 + \Gamma_\phi^2 m_\phi^2}$$

$$\Gamma_\phi = \frac{g_\nu^2 m_\phi}{4\pi} \qquad s = E_{\mathrm{CM}}^2$$

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When the width is pretty small

$$\lim_{\Gamma_\phi \to 0} \sigma_0(s) = \frac{4\pi^2 \Gamma_\phi s}{m_\phi^3} \lim_{\Gamma_\phi \to 0} \frac{\Gamma_\phi m_\phi}{[s - m_\phi^2]^2 + \Gamma_\phi^2 m_\phi^2} = \frac{\pi g_\nu^2}{m_\phi^2} s \; \delta(s - m_\phi^2)$$

The cross-section is a Dirac delta

Resonant region

$10^{-3}\ \mathrm{eV} < m_\varphi < 10^{3}\ \mathrm{eV}$

$$\Gamma_{\mathrm{scatt}} = \langle \sigma_0 v \rangle n_\nu$$

$$\langle \sigma_0 v \rangle = \frac{1}{n_\nu^2} \int \frac{d^3 p_1}{(2\pi)^3} \int \frac{d^3 p_2}{(2\pi)^3} f_{FD}(p_1) f_{FD}(p_2) \sigma_0(s) v$$

We have to take into account all the available energies

1991 Gondolo & Gelmini Nucl. Phys. B

2015 Vassh+ PRD

Resonant region

$10^{-3}\ \text{eV} < m_\varphi < 10^{3}\ \text{eV}$

$$\Gamma_{\text{scatt}} = \langle \sigma_0 v \rangle n_\nu$$

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We have to take into account all the available energies

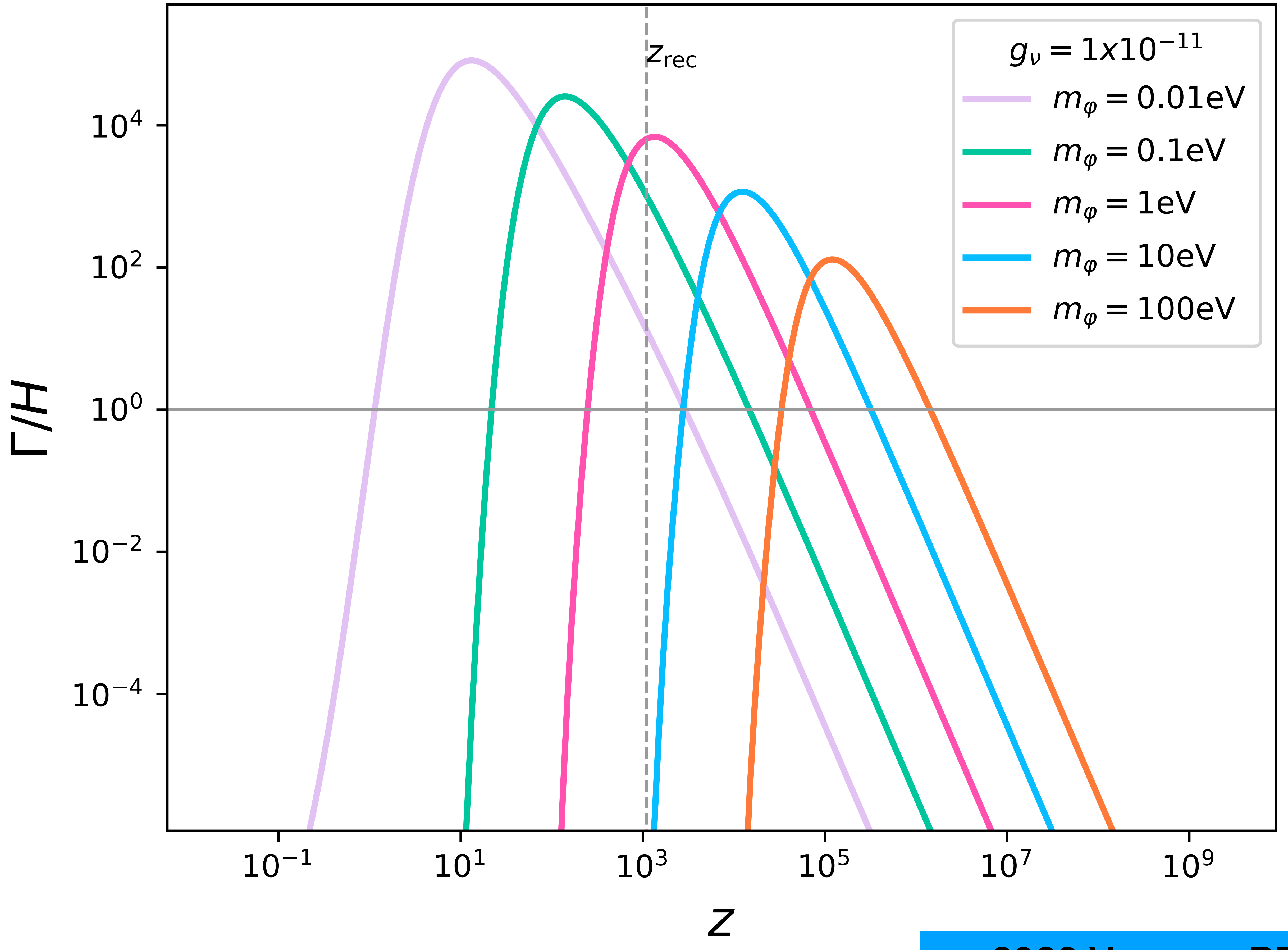
$$\langle \sigma_0 v \rangle \to \langle \sigma_0 v_{\text{MOL}} \rangle = \frac{4\pi^2 T^2}{(2\pi)^6 n_\nu^2} \int_0^\infty \sigma_0(s) s F(s;T) ds$$

$$F(s;T) = \int_{\sqrt{s}/T}^{\infty} dx \frac{e^{-x}}{1-e^{-x}} \left[\frac{\sqrt{x^2 - s/T^2}}{2} + \ln(G(x;s,T)) \right]$$

$$G(x;s,T) = \frac{1 + e^{-1/2[x + \sqrt{x^2 - s/T^2}]}}{1 + e^{-1/2[x - \sqrt{x^2 - s/T^2}]}}$$

1991 Gondolo & Gelmini Nucl. Phys. B

2015 Vassh+ PRD

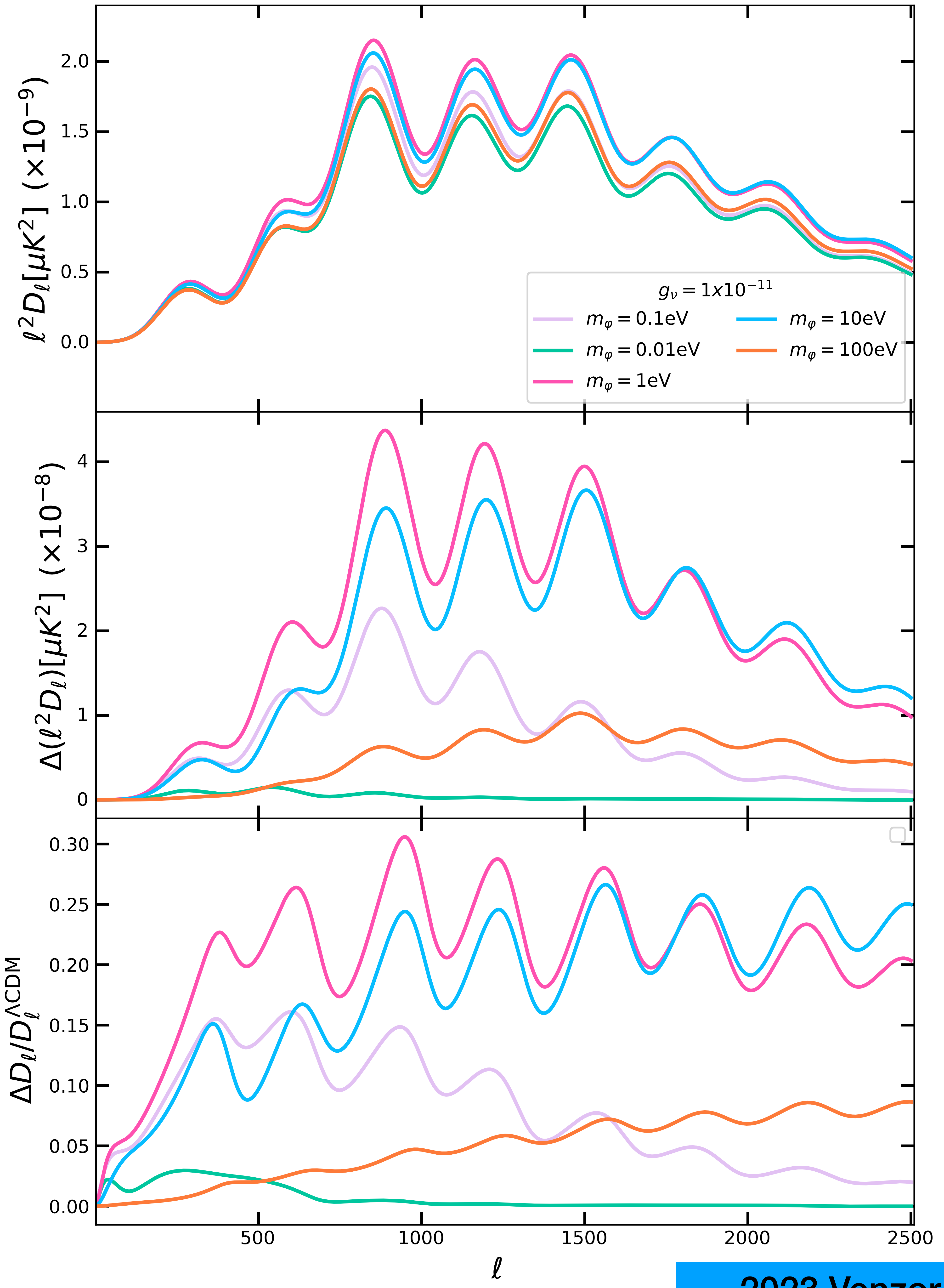


2023 Venzor+ PRD

$$\Gamma_{\rm res} = \frac{g_\nu^2 \pi^5 m_\varphi^2}{24\zeta(3) T_\nu} F(m_\varphi^2; T_\nu)$$

$$z_{\rm peak} \sim 2.13 \times 10^3 \left(\frac{m_\varphi}{\rm eV} \right)$$

We have to fix the mediator mass, the only new free parameter is the coupling



2023 Venzor+ PRD

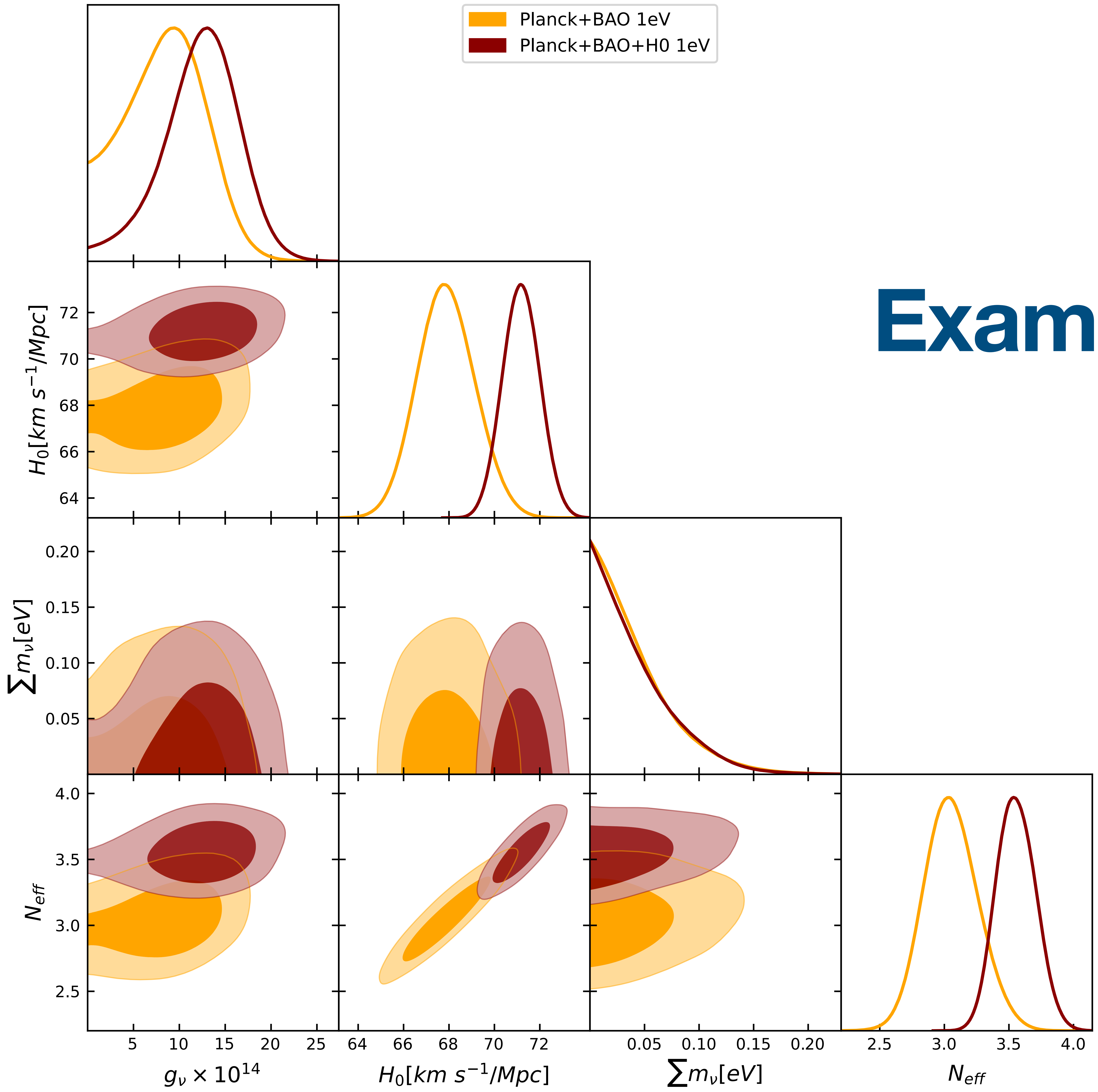
We can see an enhancement on the temperature spectral

1 and 10 eV have a stronger effect (with the same coupling)

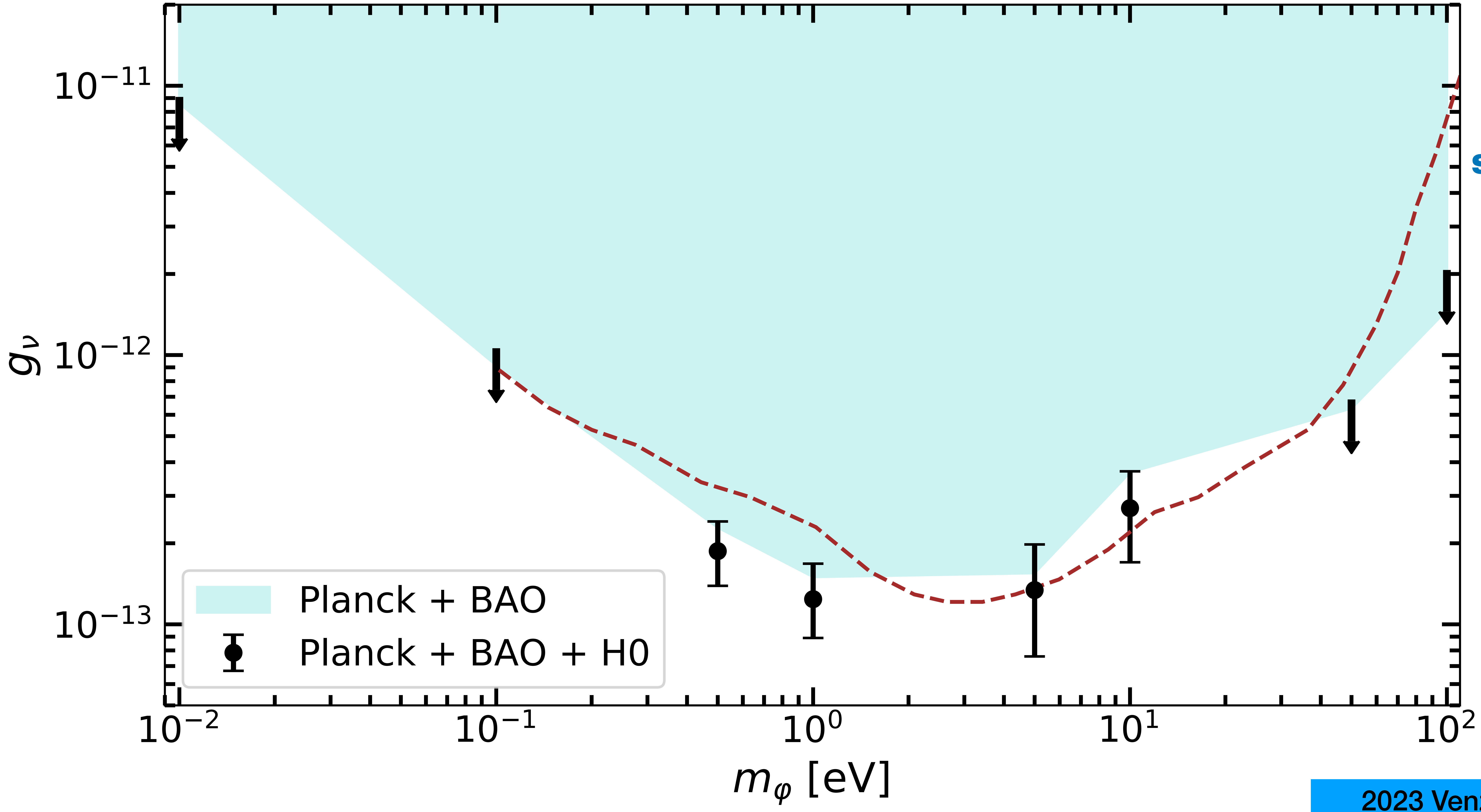
Large mediator mass → Small scales

Small mass → Large scales

Example: mass=1eV



2023 Venzor+ PRD

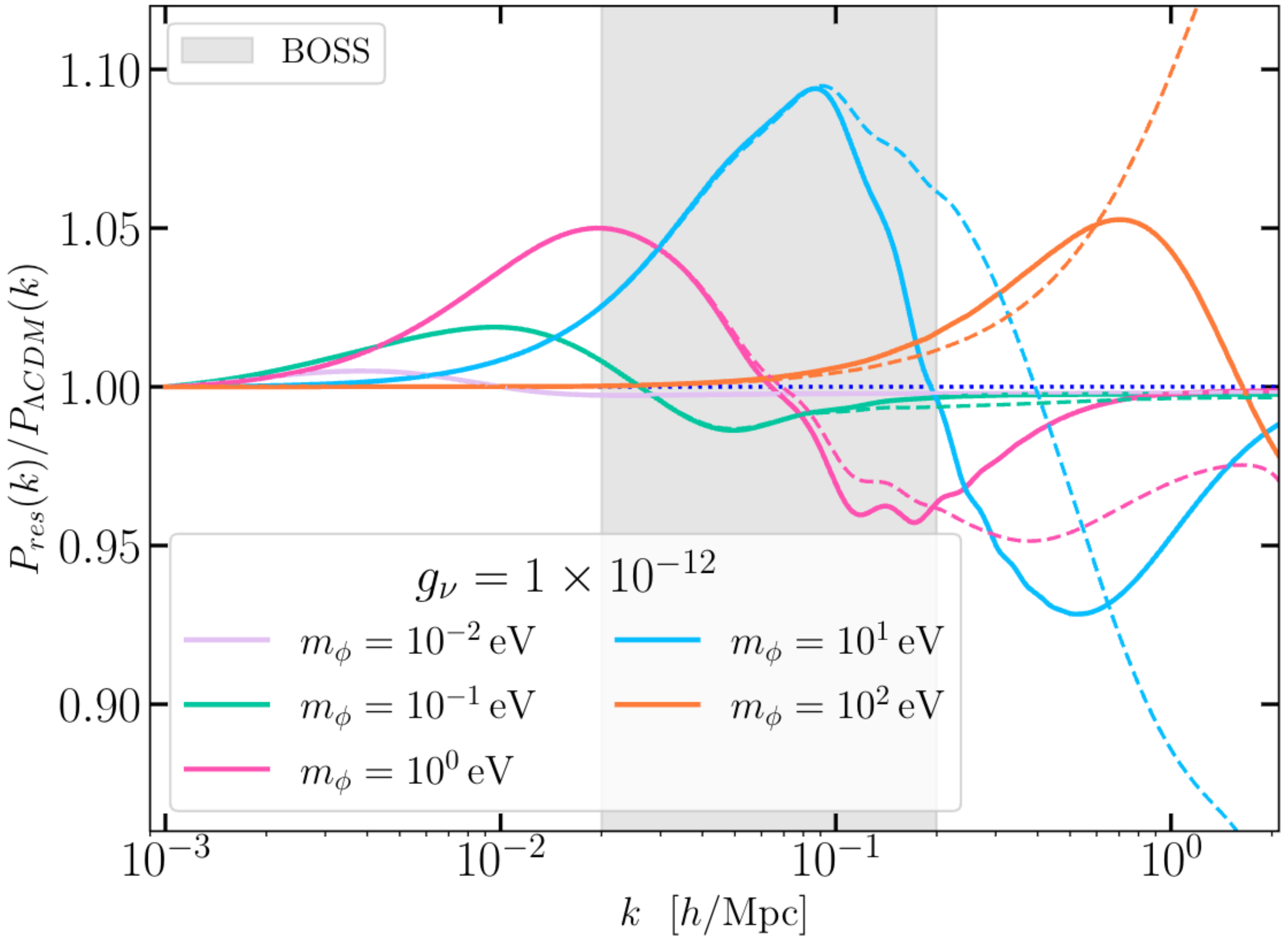


Dashed line is the singlet majaron model

2020 Escudero&Witte EPJC

2023 Venzor+ PRD

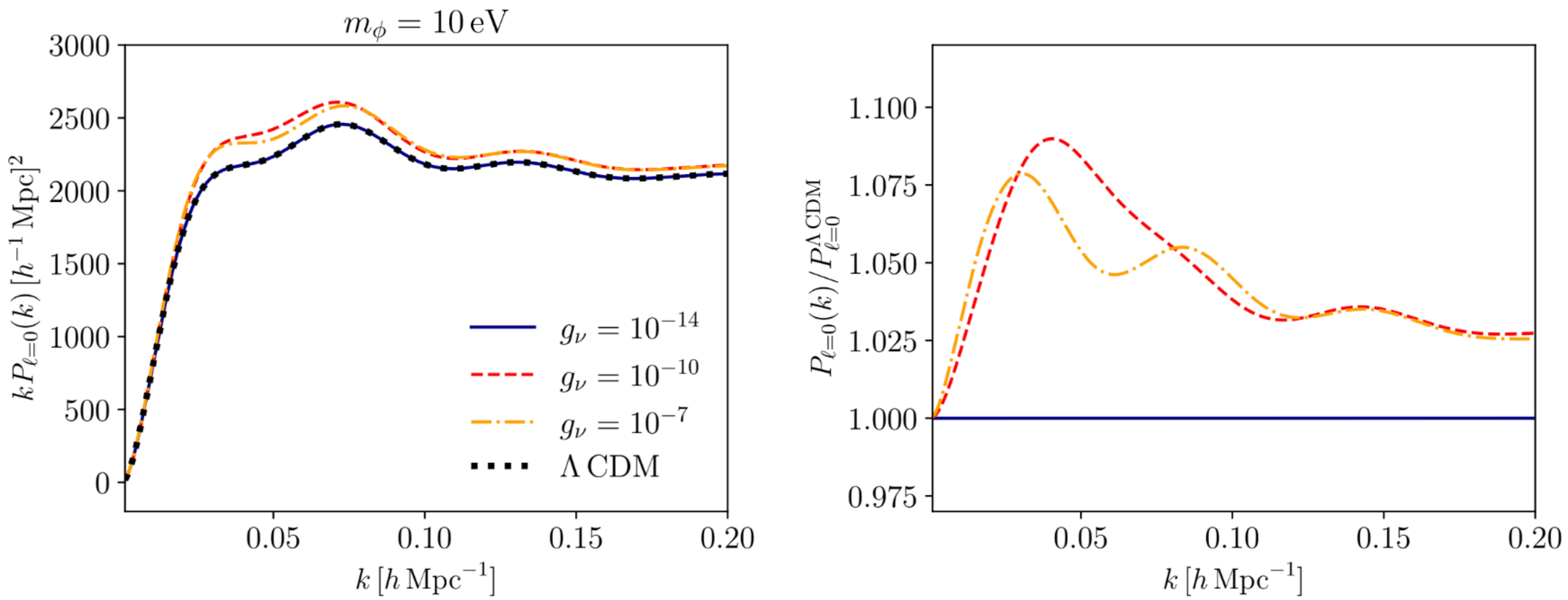
Full Shape Galaxy spectrum



2023 Venzor+ PRD

Larger masses enter to the horizon first

Monopole



Only m=10 eV can be constrained with FS-BOSS+BBN

FS+Planck are very similar results to BAO+Planck

Preliminary- Hernan E. Noriega+ 2024

Perspectives

- All neutrino self-interaction cases require extra radiation
- In the heavy mediator case the bimodality of the coupling posterior has not disappeared.
- For the light and resonant cases we are working on including nonelastic processes into the analysis (annihilations and decays).
- Is there enough room in neutrino NSI to ameliorate the neutrino mass tension?

Thanks!