Cosmology as a neutrino lab

Jorge Venzor (CINVESTAV)

6 de junio 2024 RADPyC

Outline

- State-of-the-art of standard neutrinos.
- Neutrino NSI in cosmology
- Neutrino self-interactions with light and not so light mediators

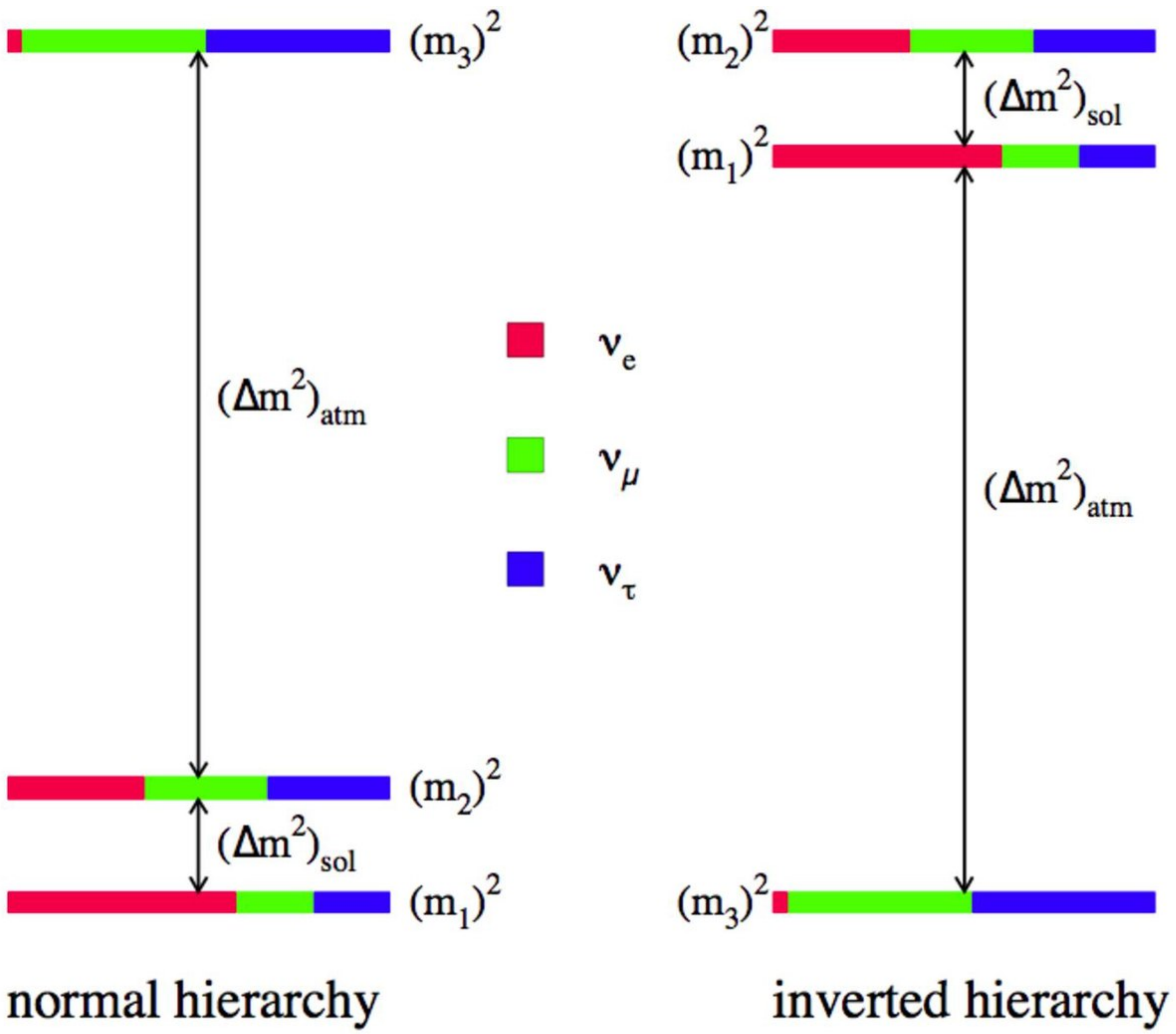
Neutrinos

$$\Delta m^2_{\rm sol} = \Delta m^2_{21} = m_2^2 - m_1^2 = 7.42^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

$$\mathrm{NH} \longrightarrow \Delta m^2_{\rm ATM} = \Delta m^2_{31} = m_3^2 - m_1^2 = 2.517^{+0.026}_{-0.028} \times 10^{-3}\ \mathrm{eV}^2$$

$$\mathrm{IH} \longrightarrow \Delta m^2_{\rm ATM} = \Delta m^2_{23} = m_2^2 - m_3^2 = 2.498^{+0.028}_{-0.028} \times 10^{-3}\ \mathrm{eV}^2$$

2020 Esteban+ JHEP



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

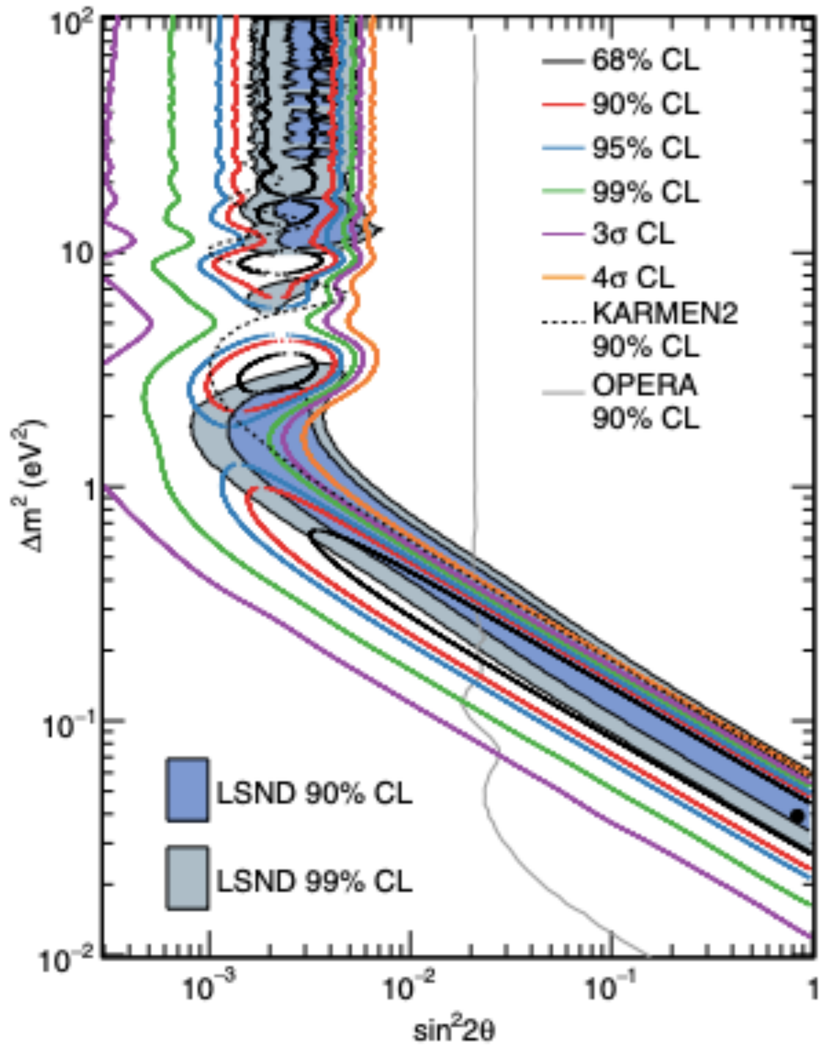
★ The standard model does not explain neutrino mass

★ The most popular neutrino mass models require a neutrino NSI

Anomalies

LSND -> MiniBoone $\nu_\mu \to \nu_e$

Two decade anomaly with a S/N of 6 sigmas:



Excess of nu_e

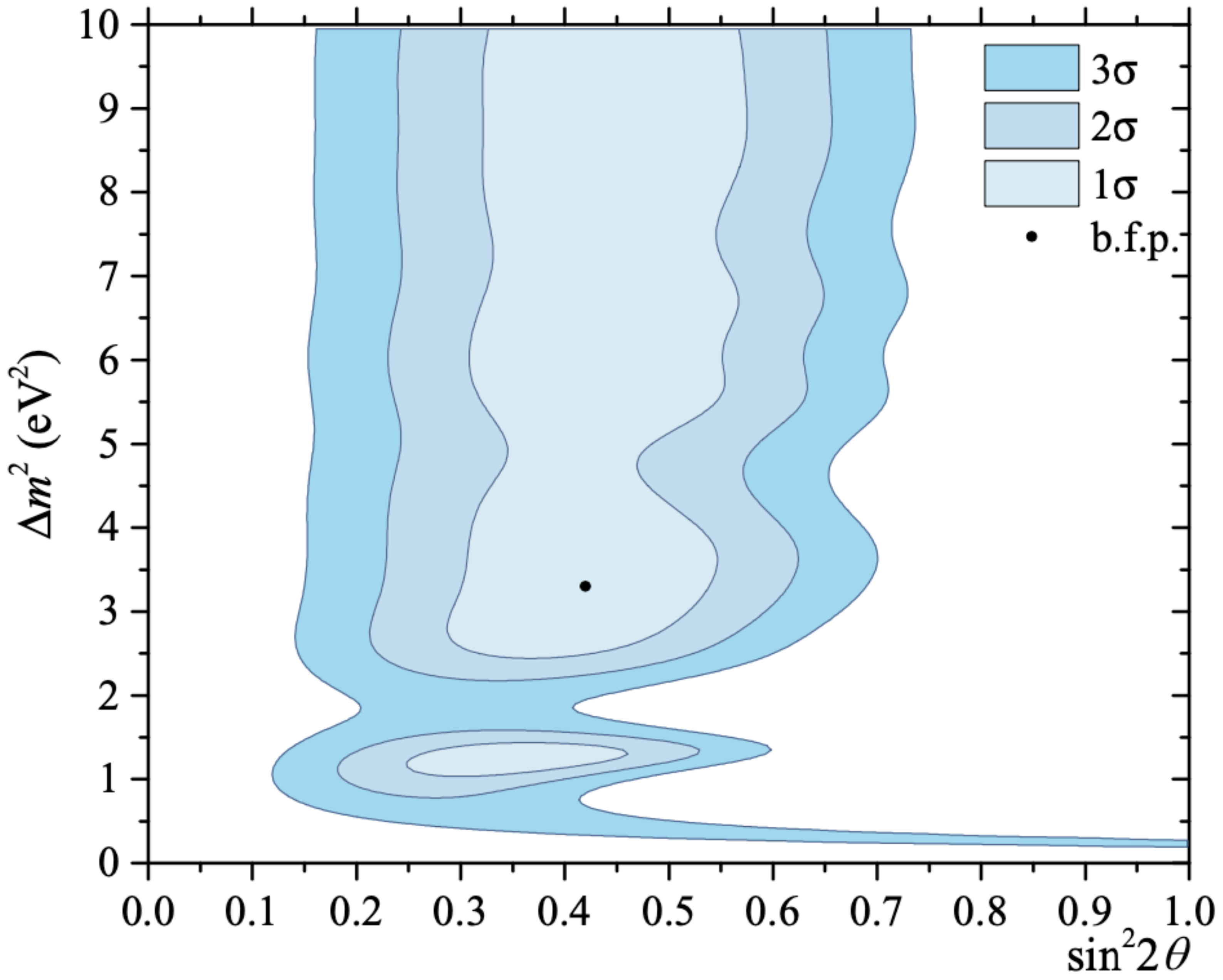
2018 MiniBooNE PRL

Wasn't confirmed by MicroBoone

2022 MicroBooNE PRL

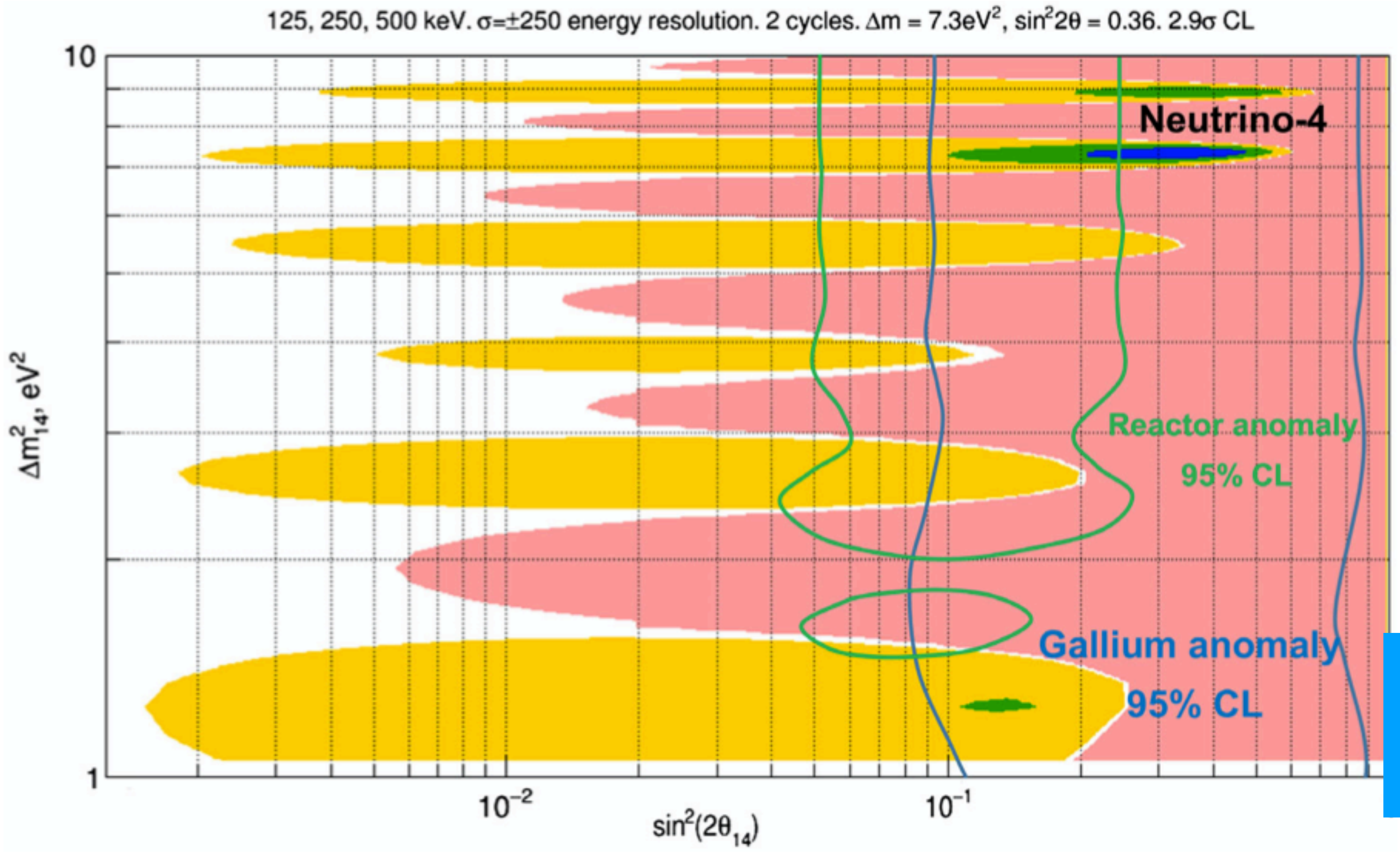
Galium:

SAGA/Gallex



They observe less events than expected in Ga-71 detectors

2022 BEST PRC

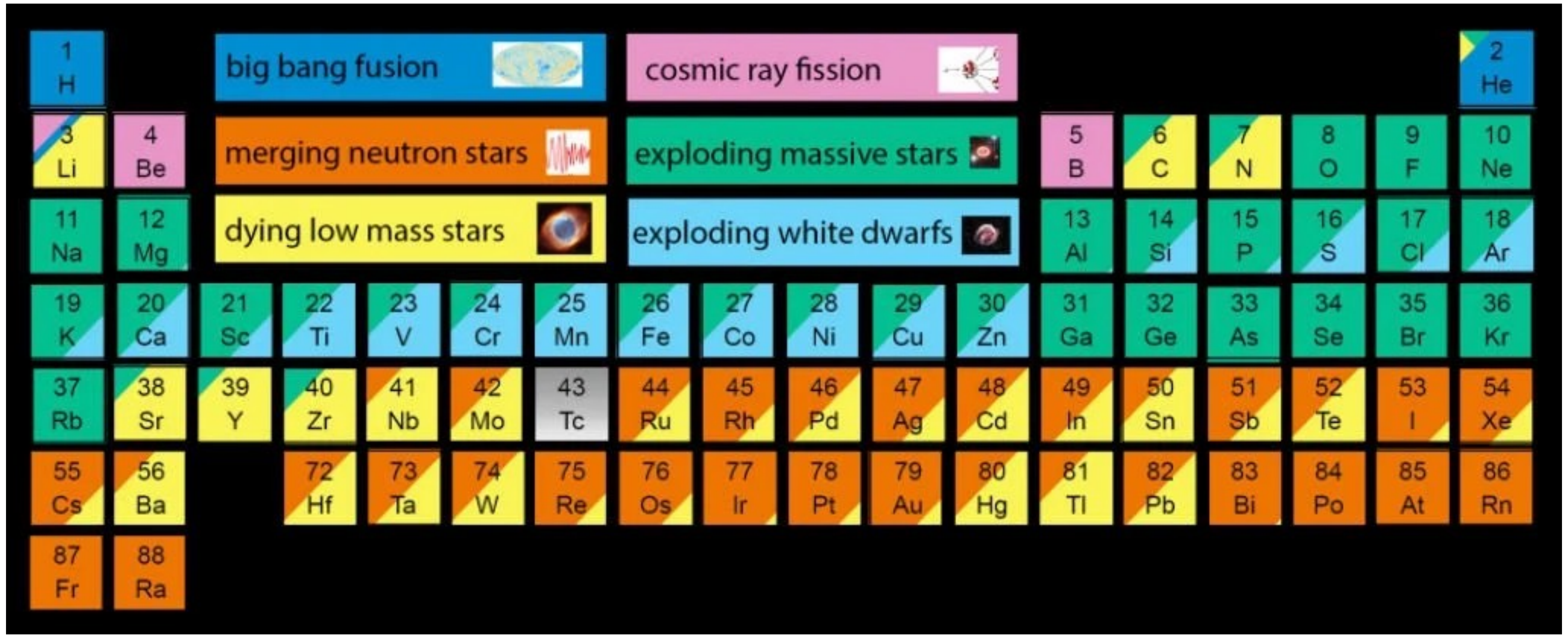


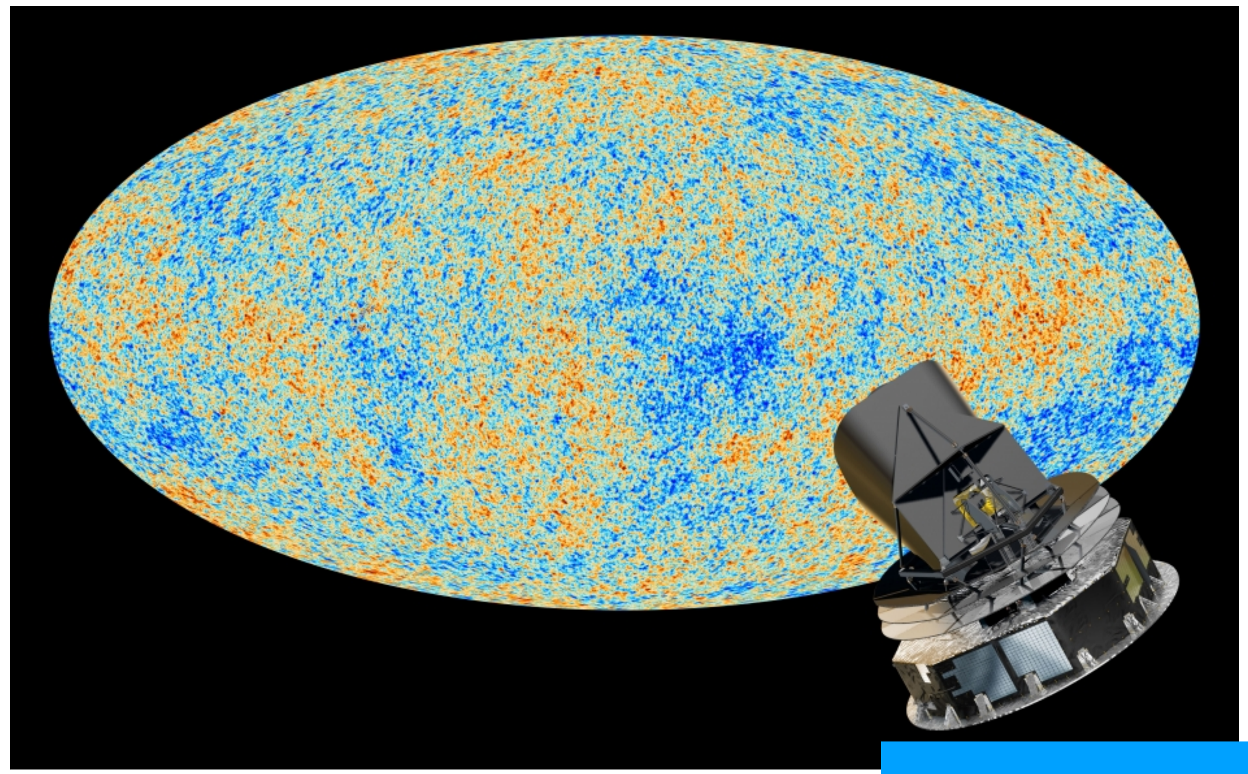
Deficit of anti(nu_e)

2021 Neutrino-4 PRD

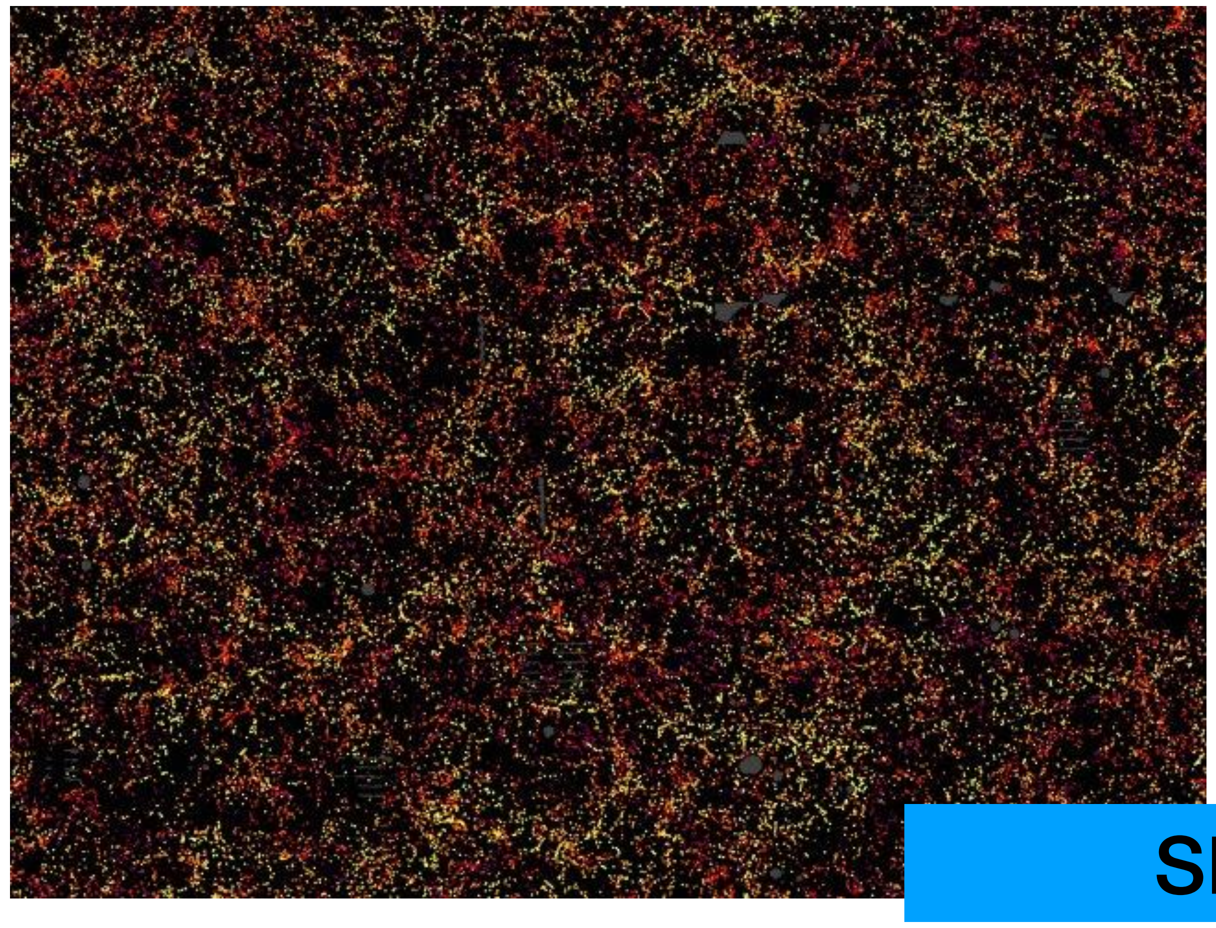
Neutrinos are a main character in cosmology

BBN, supernovas





Planck/ESA



SDSS

Basically, they destroy structure

Neutrino cosmology

Theoretical computation

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

We need two params

N_{eff} They behave as radiation in the early Universe (Around 40% of the totalrad)

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

$\sum m_\nu = m_1 + m_2 + m_3$ Lately, they behave as matter

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

2021 Planck collab. A&A

When the rad/matter transition occurs?

It depends on the neutrino mass

Neutrino cosmology

$$N_{\text{eff}} = 2.99 \pm 0.17 \; (68\,\% \quad \text{C.L.})$$
$$\sum m_\nu < 0.12 \; (95\,\% \quad \text{C.L.})$$

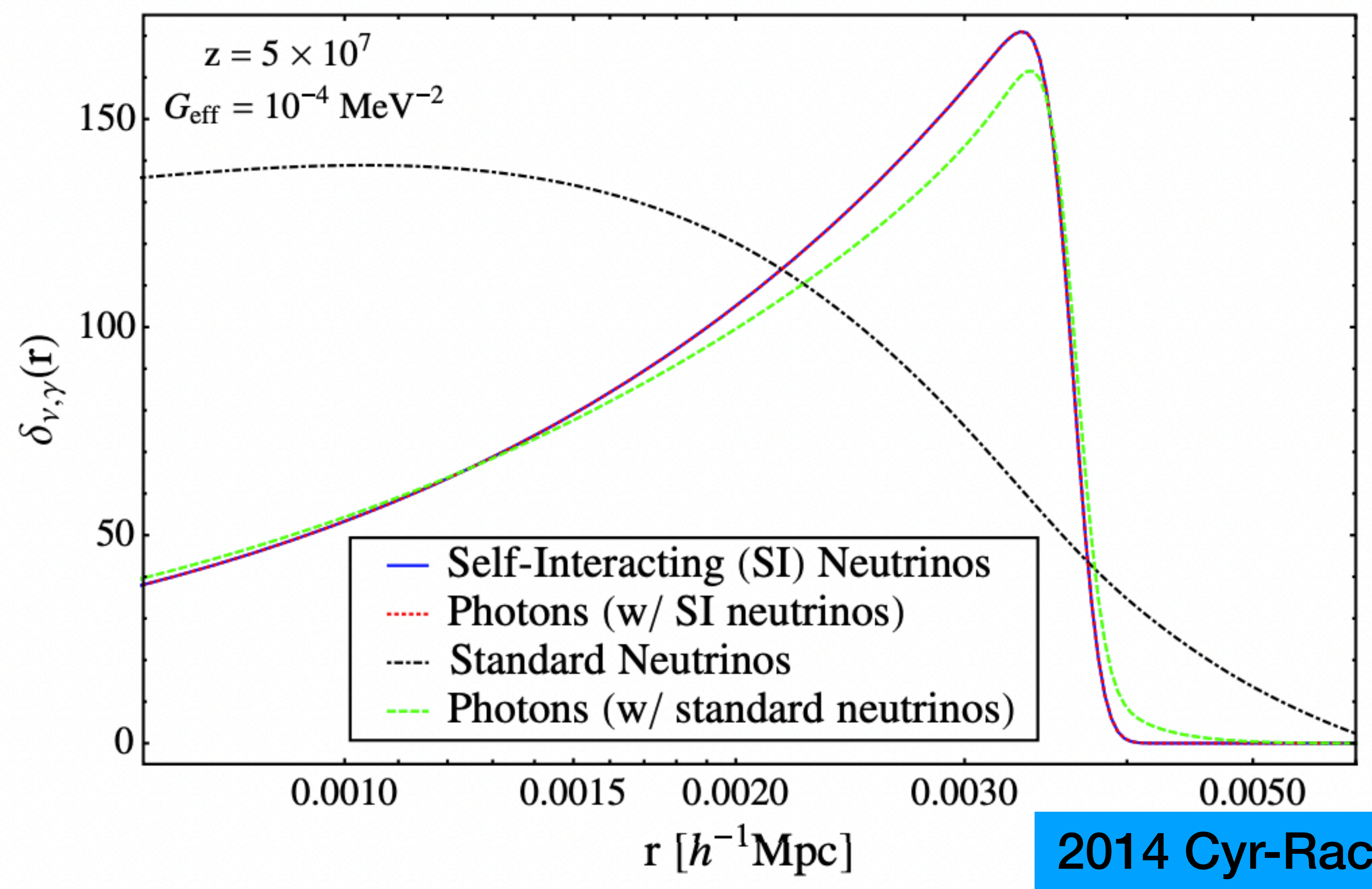
2021 Planck collab. A&A

★ In general, they suppress the matter and temperature spectra

★ They also induce a phase in the acoustic peaks that cannot be mimicked by other cosmo params

↓

This is due to the fact that they propagate faster than sound speed on the plasma



2014 Cyr-Racine+ PRD

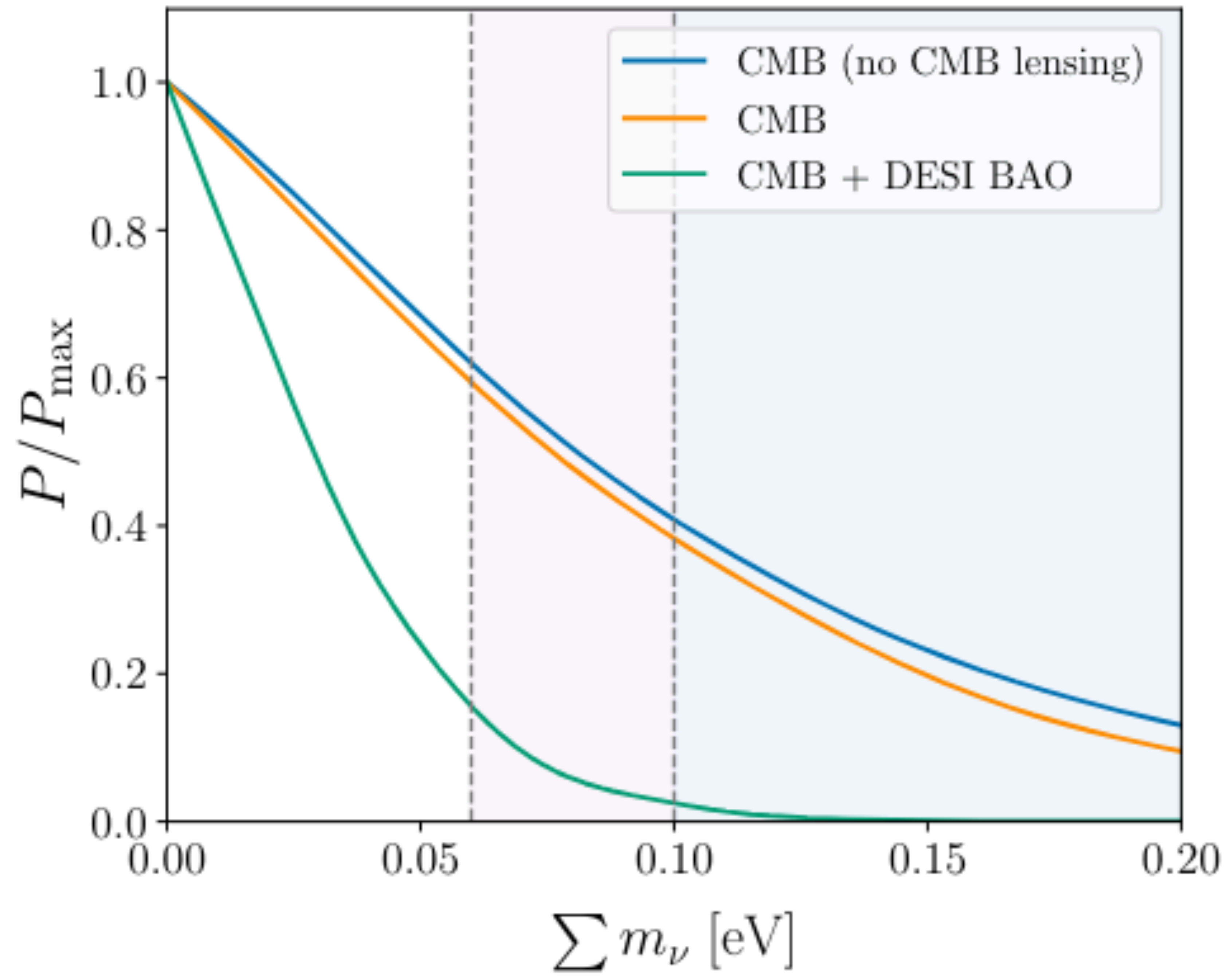
2004 Bashinsky & Seljak PRD

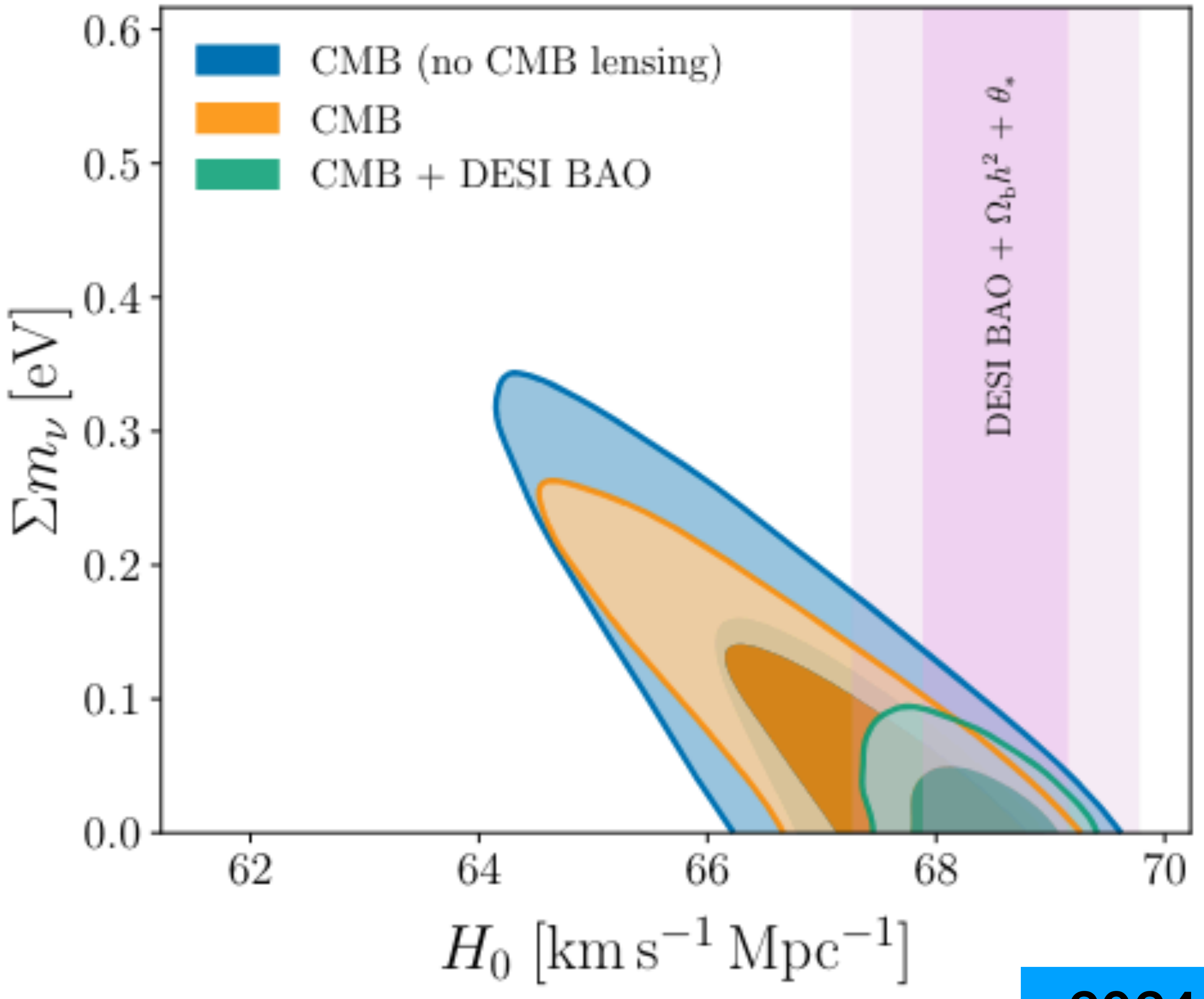
2015 Follin+ PRL

2019 Baumann+ Nat. Astrom.

→ Neutrino free-streaming

Neutrino cosmology - 2024





2024 DESI collab. 2404.03002

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

Fixed Neff, LCDM

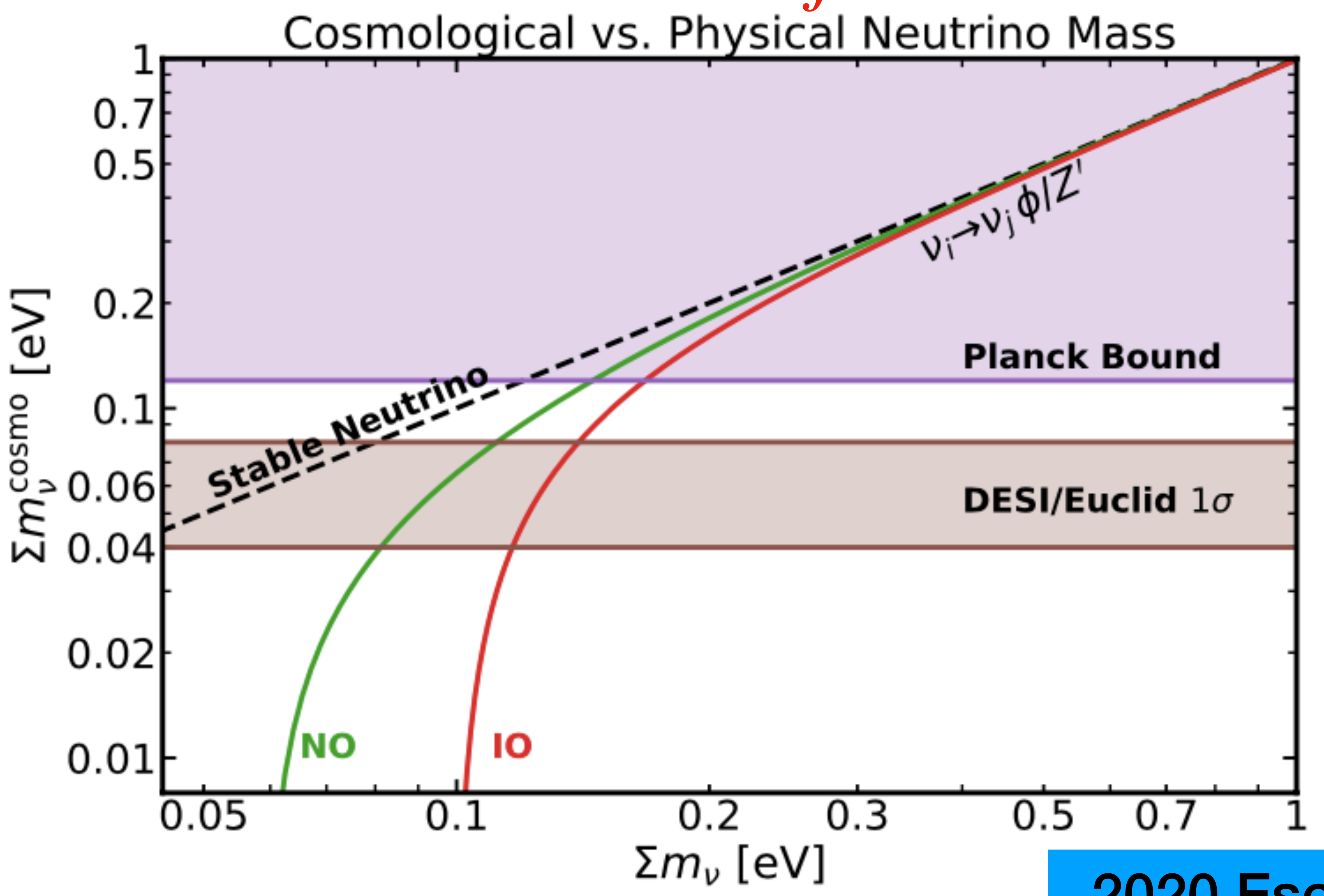
Neutrinos NSI (order zero effects)

….. a very incomplete list

NSI can explain why cosmology can have strong mass bounds

$$\nu + \nu \to \phi + \phi$$

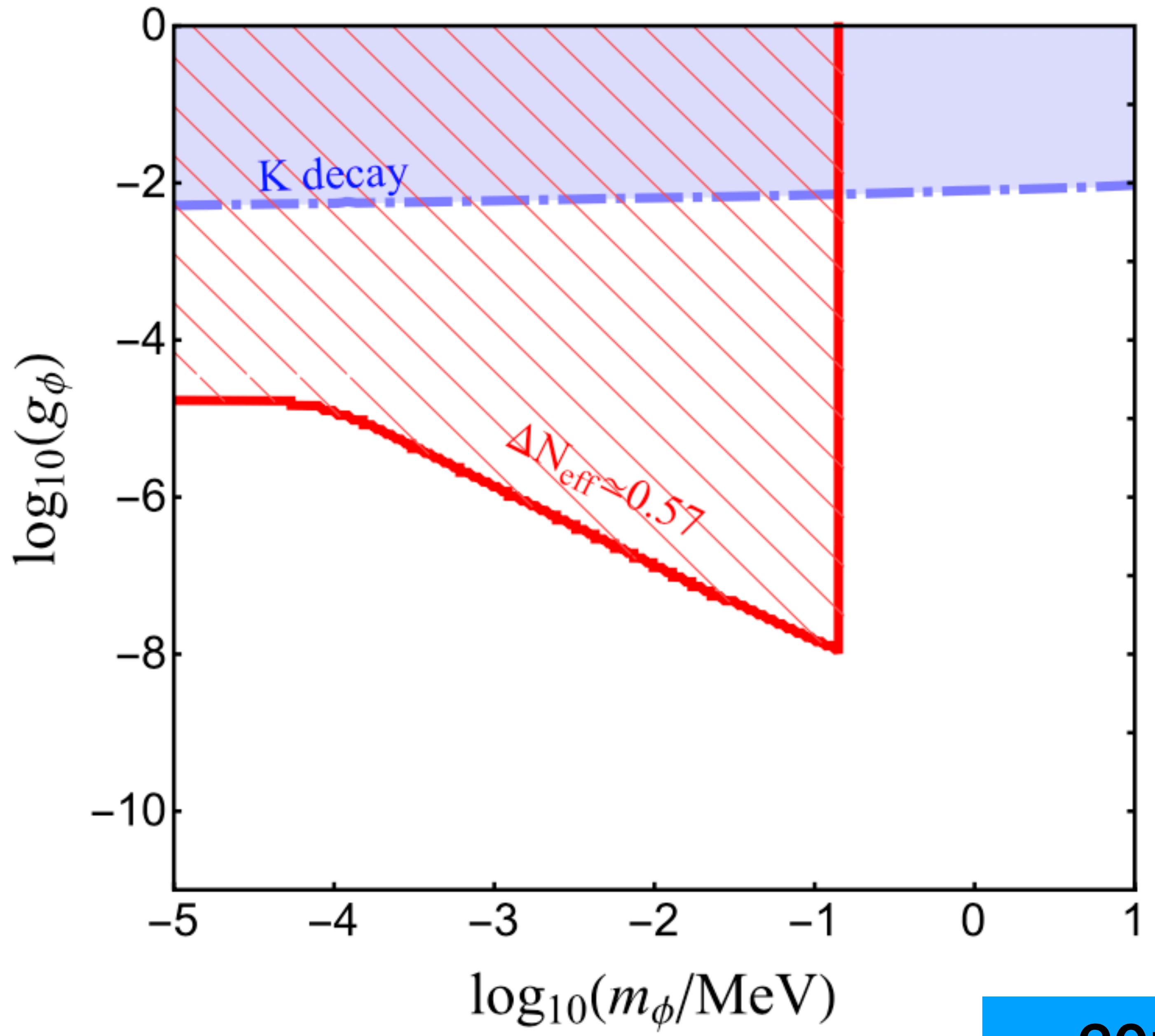
$$\nu_i \to \nu_j + \phi$$



2020 Escudero+ JHEP

2004 Beacom+ PRL

The mediator can contribute to Neff



$$\nu + \nu \leftrightarrow \phi + \phi$$

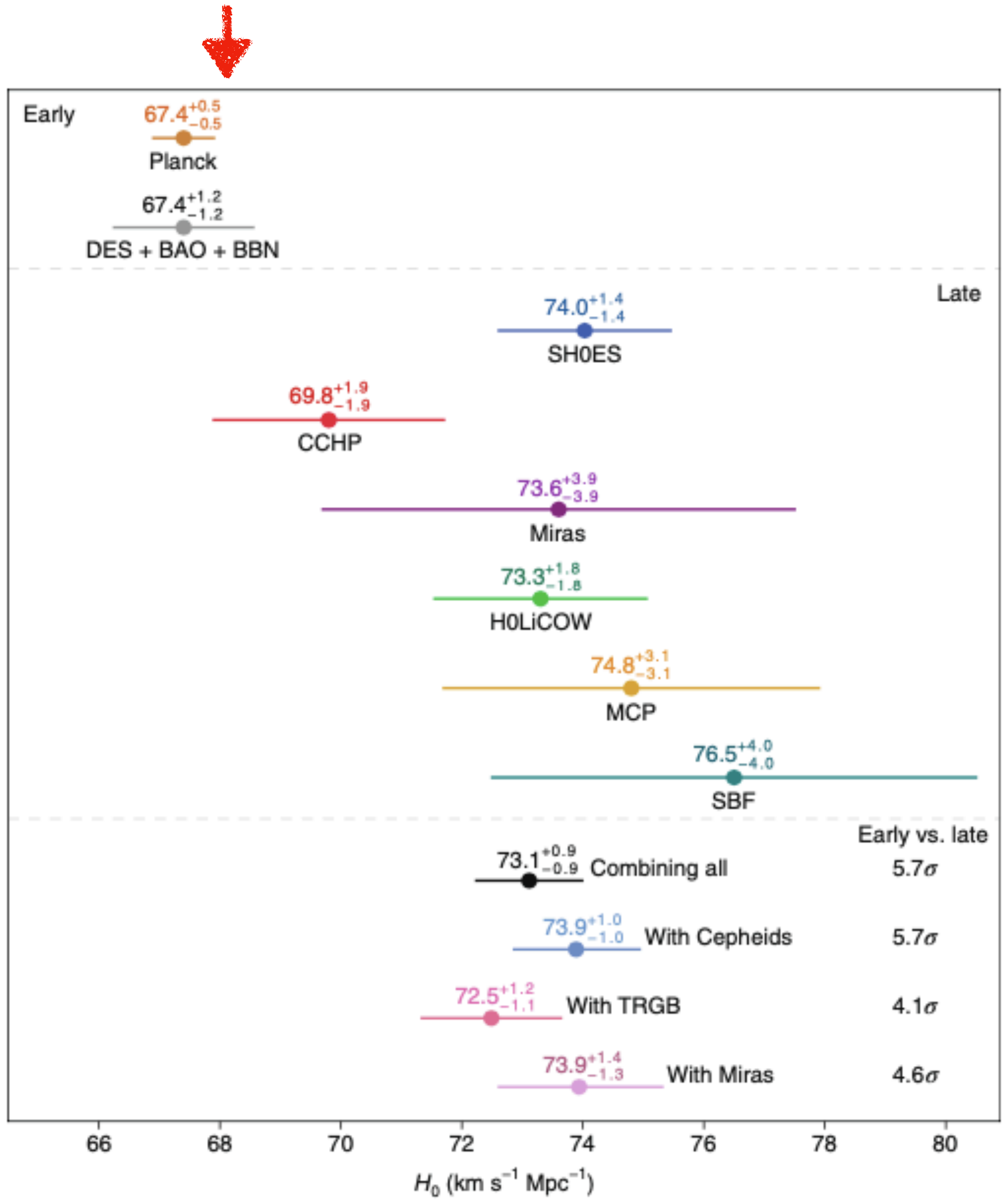
$$\nu + \phi \to \nu + \phi$$

Even if there is not thermal equilibrium

2018 Huang+ PRD

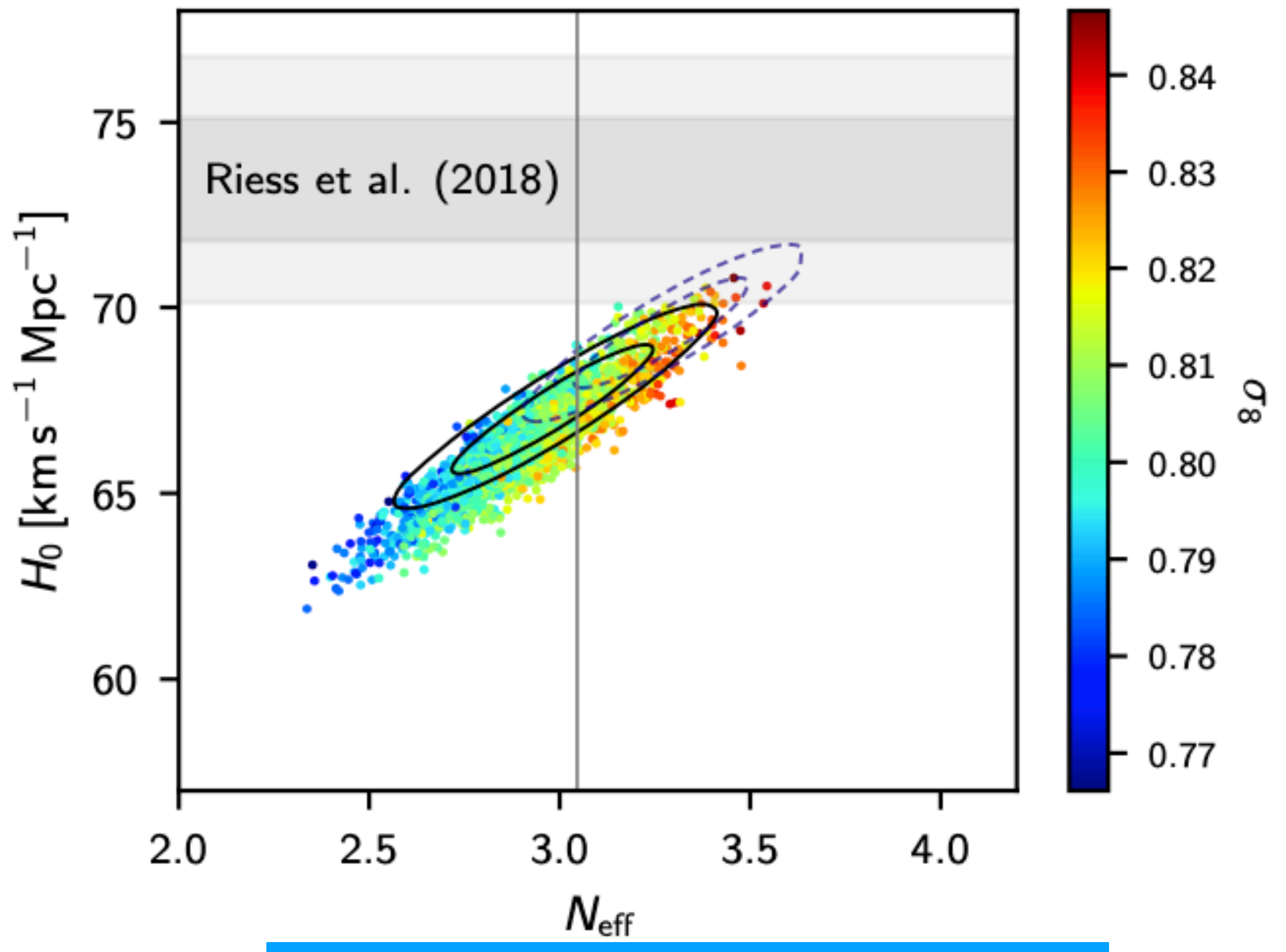
Neutrino self-interactions… and the H0 tension

Similar results with ACT, SPT, BICEP



2019 Verde+ Nature

Positive correlation between N_{eff} H_0



2021 Planck collab. A&A

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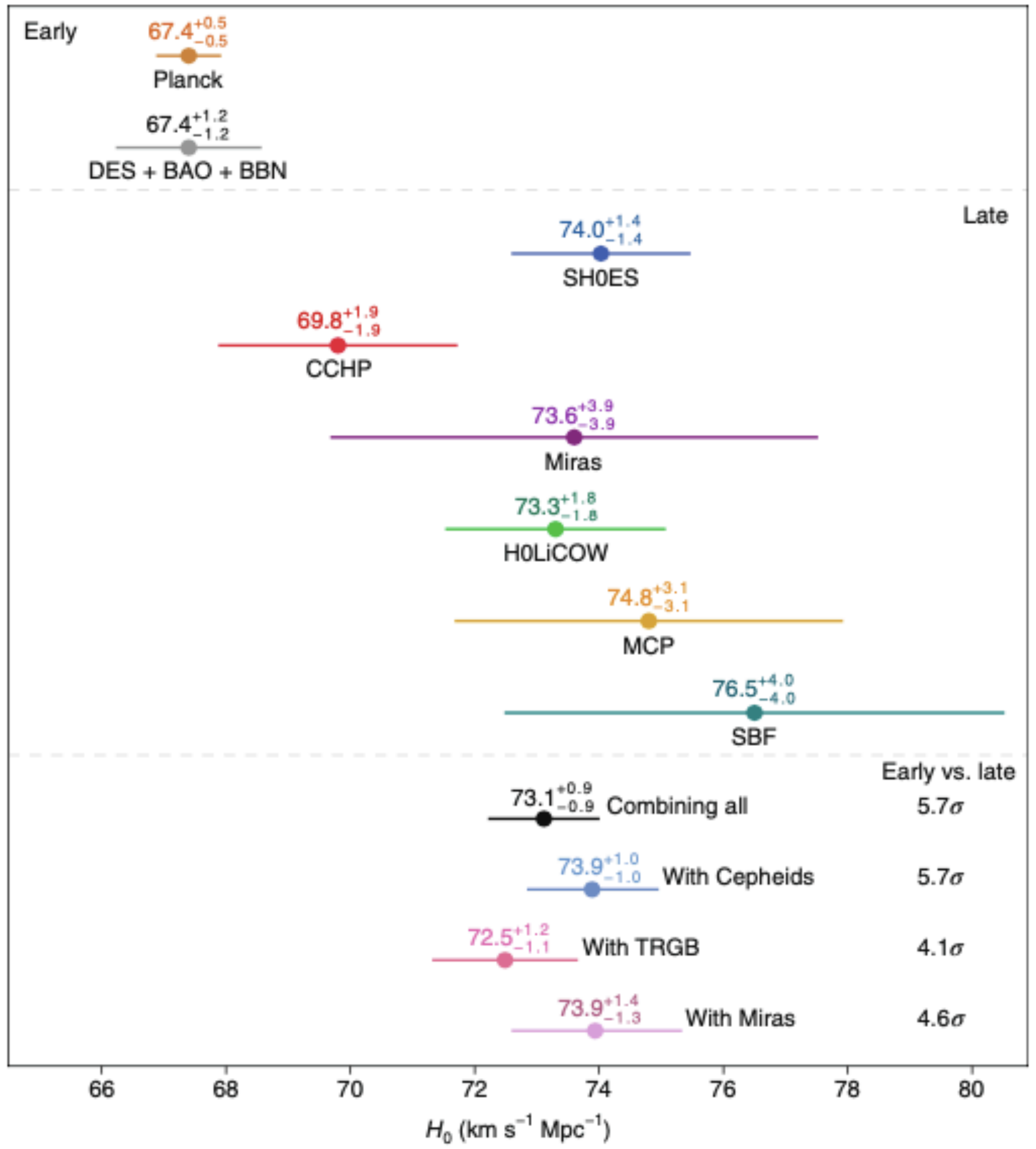

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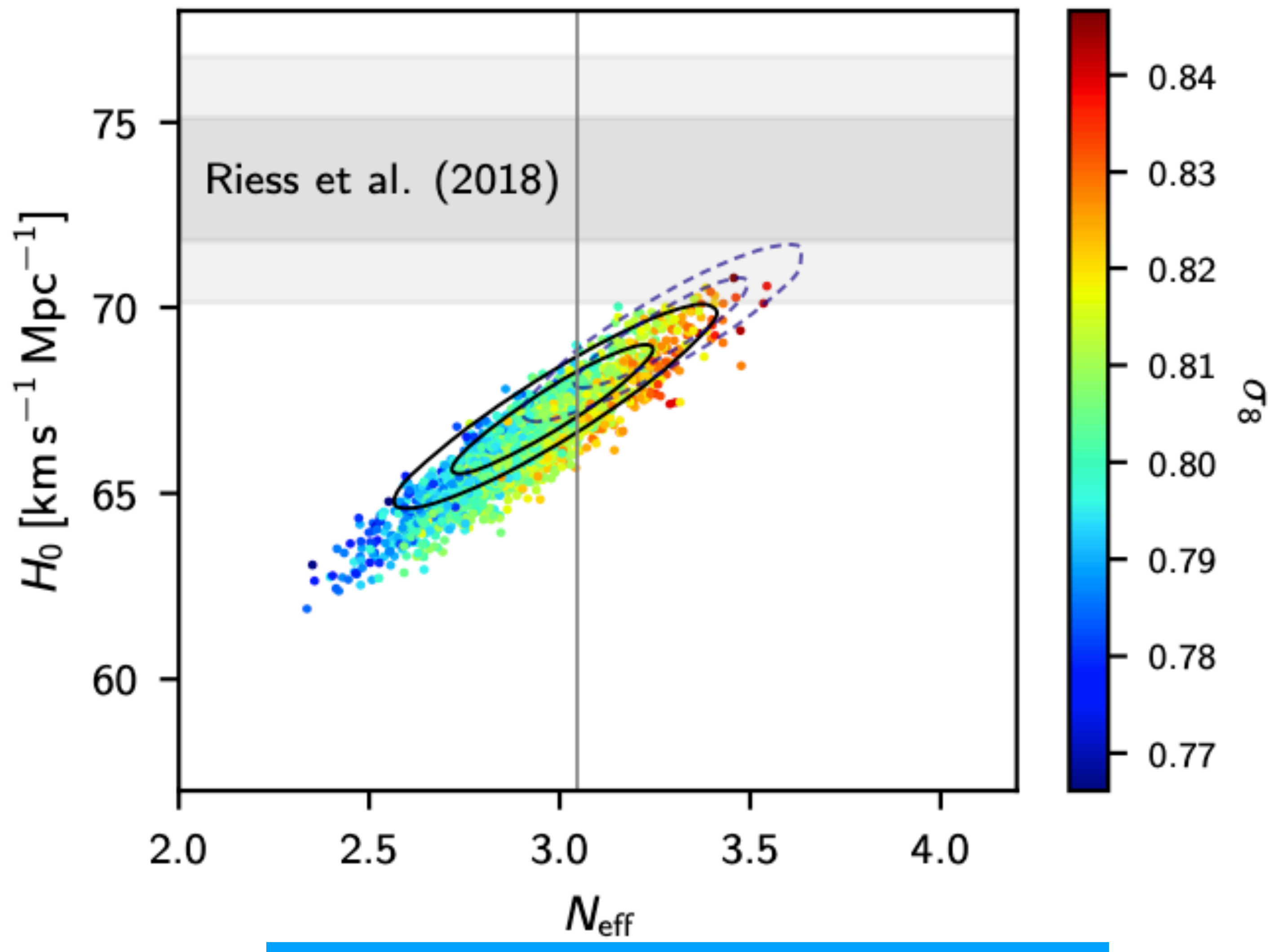


2021 Planck collab. A&A

$$H_0 = 73.04 \pm 1.04\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

2112.04510

Self-interacting neutrinos lose their free-streaming

↓

Params adjust to have N_{eff} bigger than 3.04

↓

Neutrino NSI imply a larger H_0

Perturbations (cosmological)

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

Relaxation Time Approximation (RTA)

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

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

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

Self-interactions suppress shear y and higher multipoles

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

Neutrino self-interactions

.... The mediator mass dictates the dynamics

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

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

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

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

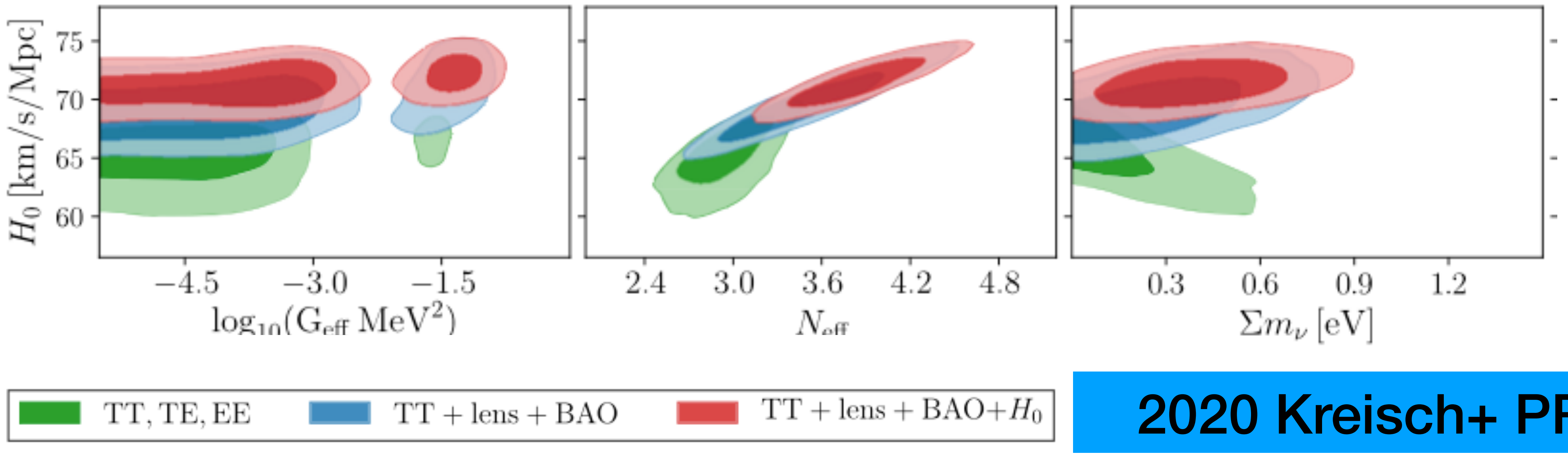
★ .. It all depends on WHEN

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

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

Self-interactions… up to 2022

Heavy mediator

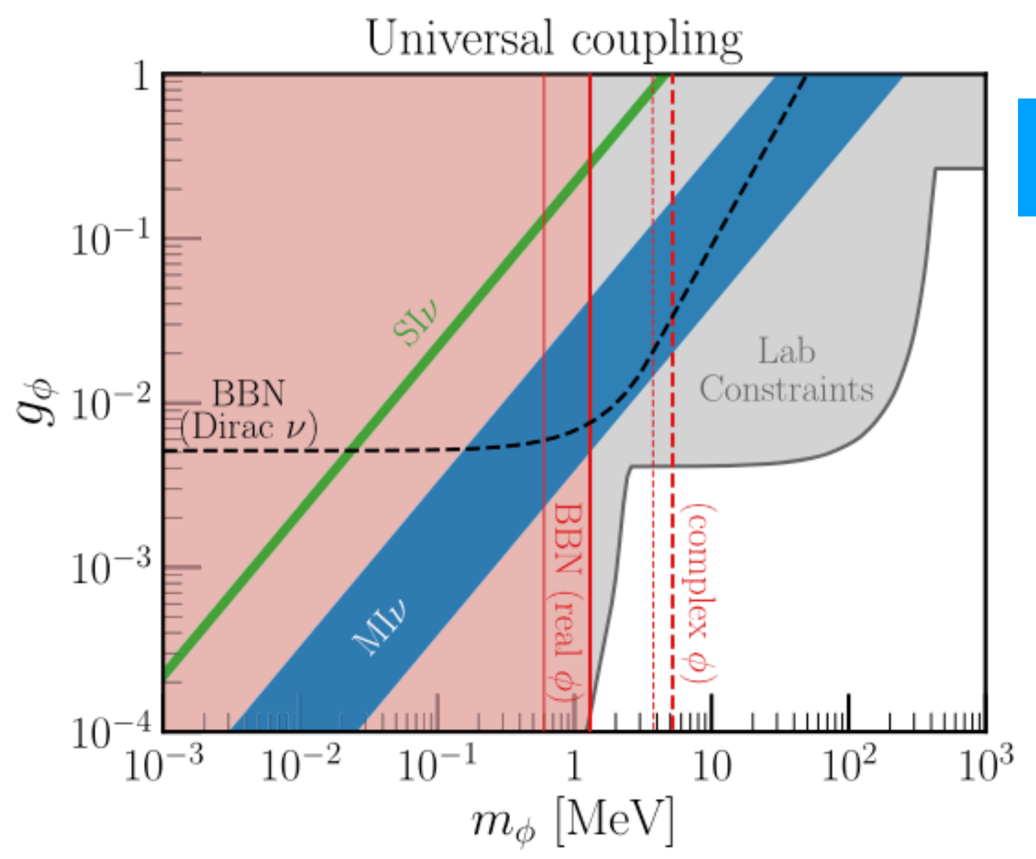


2020 Kreisch+ PRD

The tension can be solved (partially)

2021 Choudhury+ JCAP

The GH values are so large to not to be seen on experiments, astrophysics and BBN

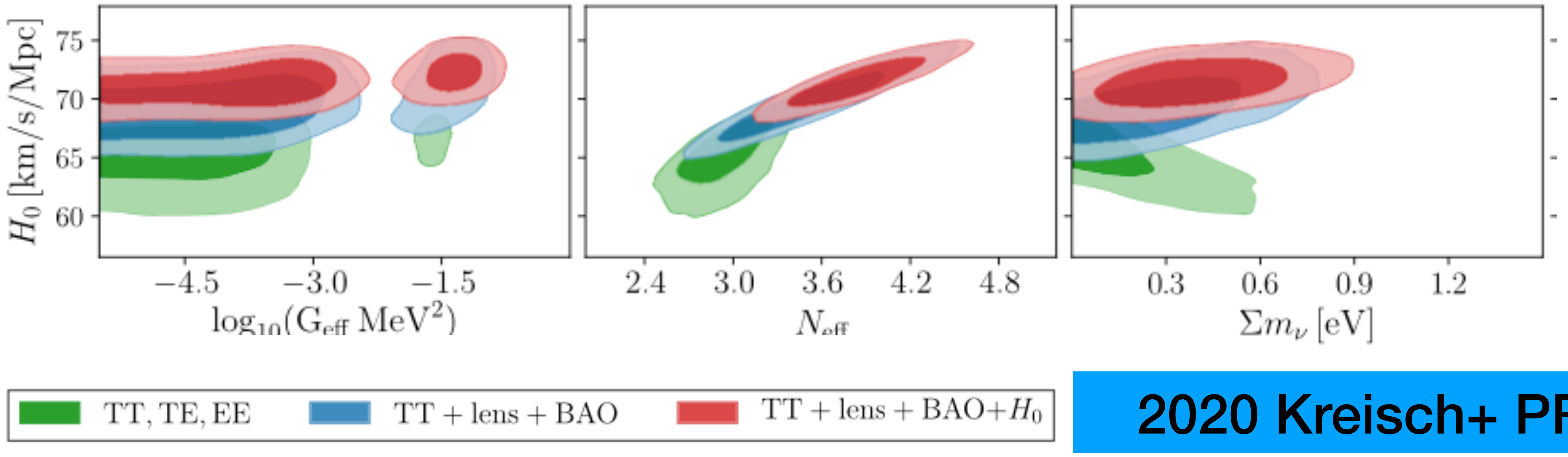


2019 Blinov+ PRL

Hot Topic

Self-interactions… up to 2022

Heavy mediator



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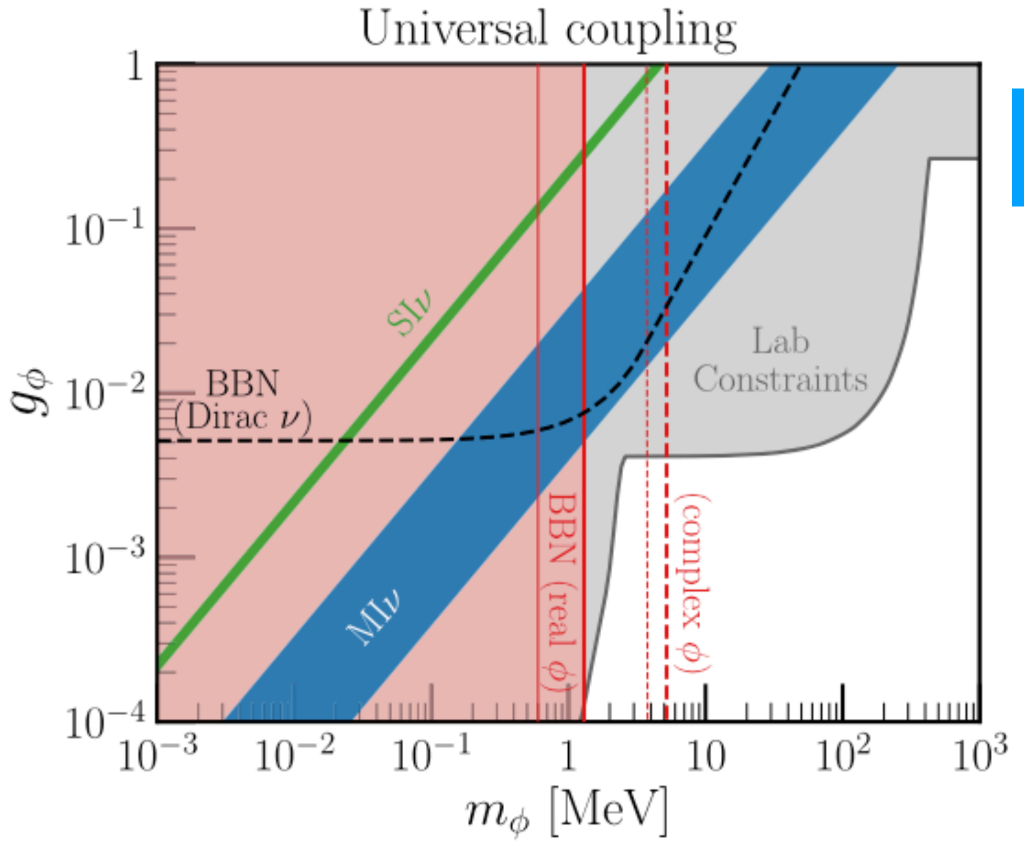
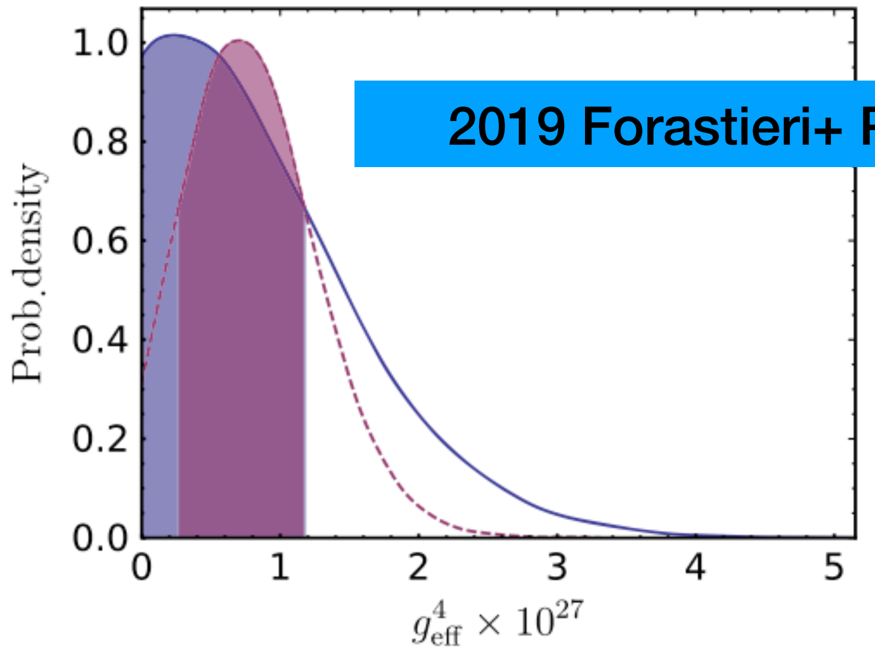


2019 Blinov+ PRL

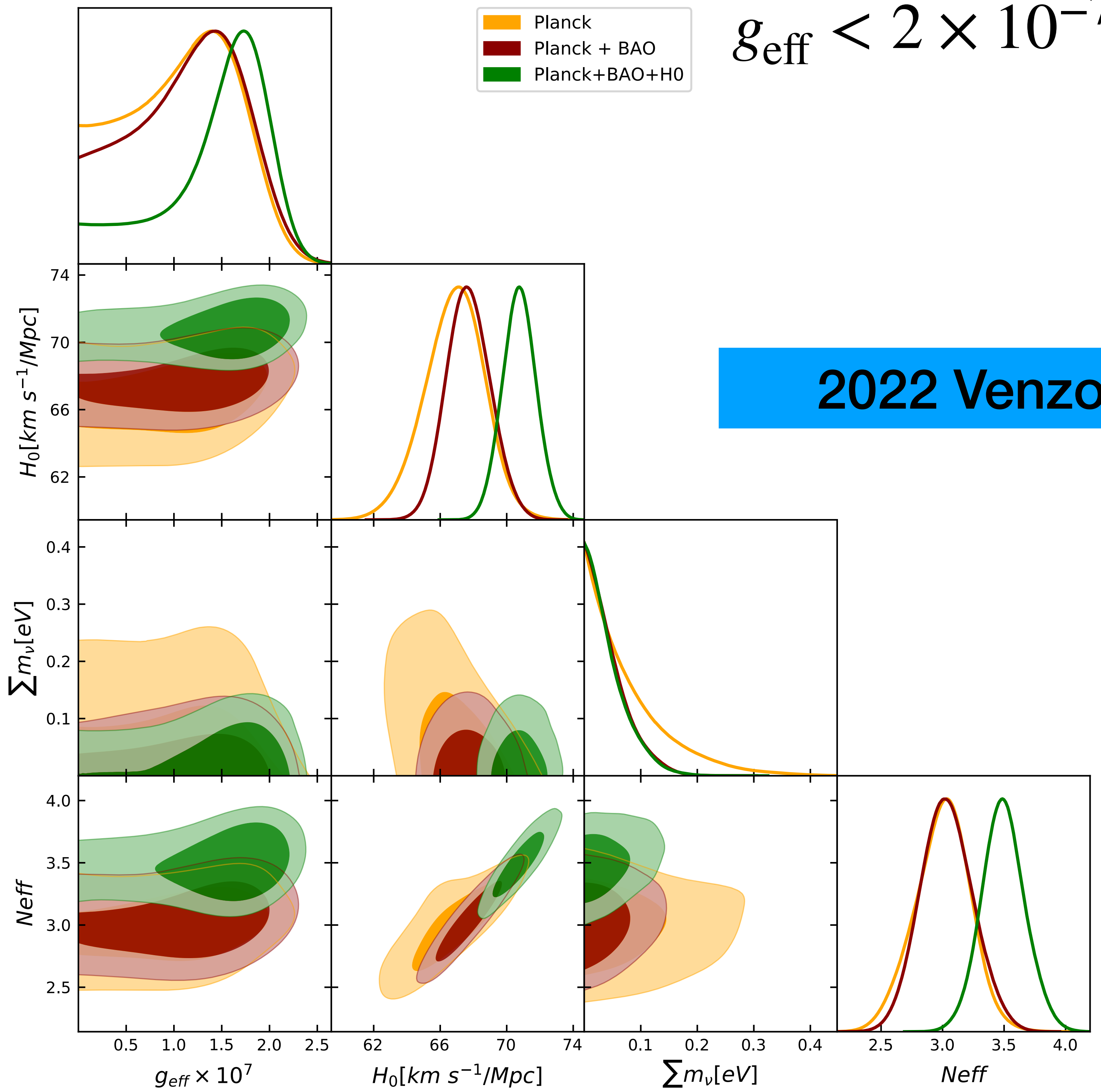
Hot Topic

Light mediator



2019 Forastieri+ PRD

Not that exotic results

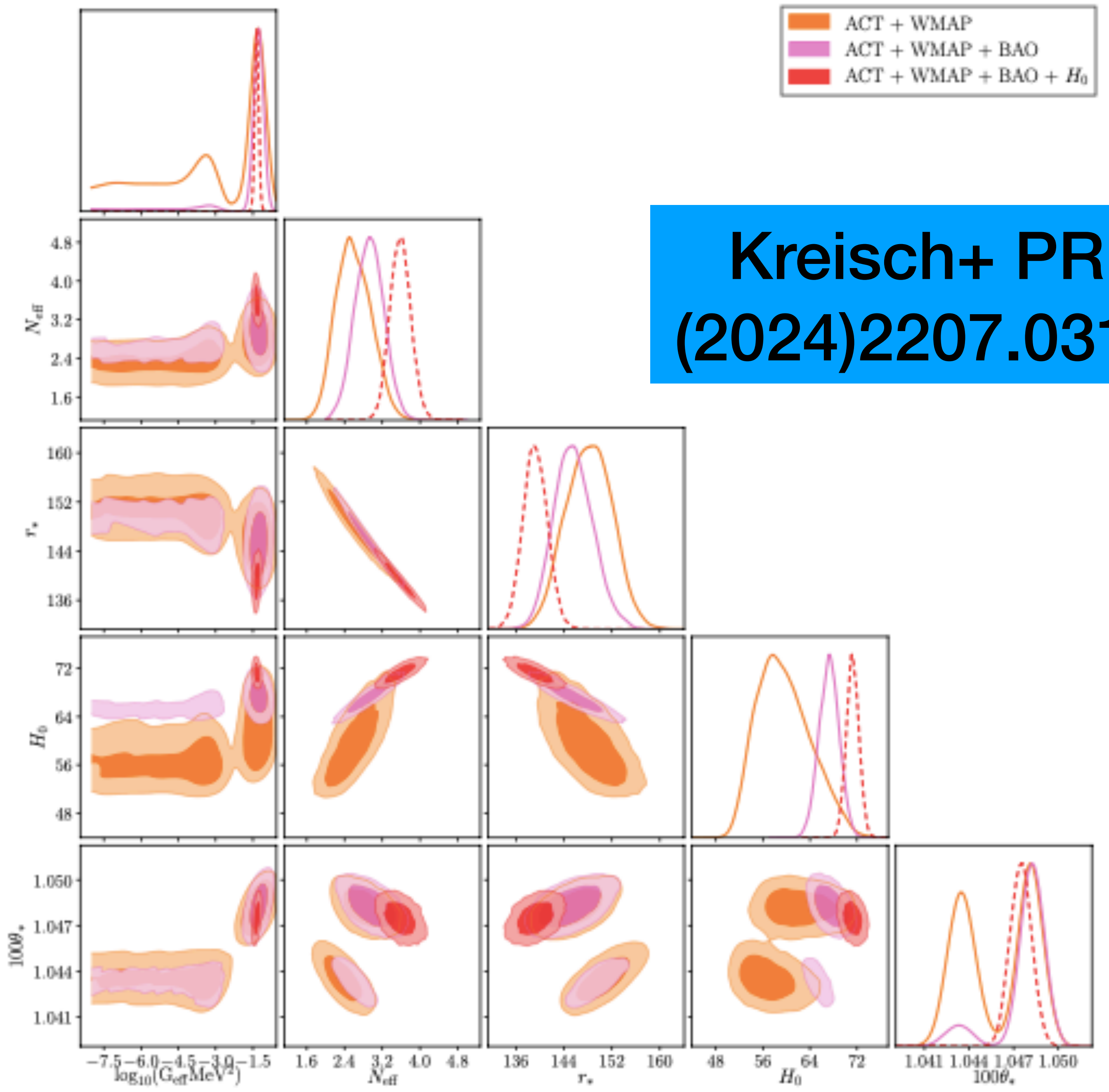


$$g_{\rm eff} < 2 \times 10^{-7} \quad (95\,\% \quad {\rm CL})$$

2022 Venzor+ PRD

Update..

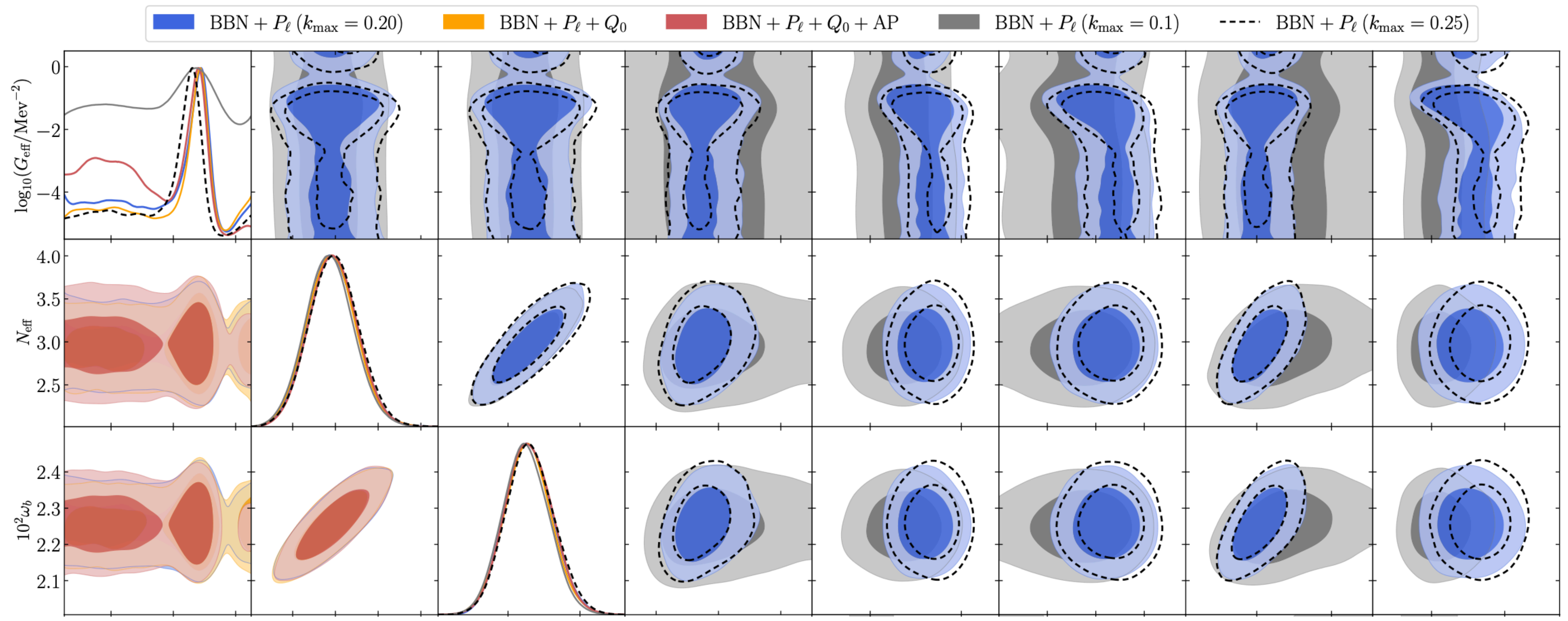
Heavy mediator



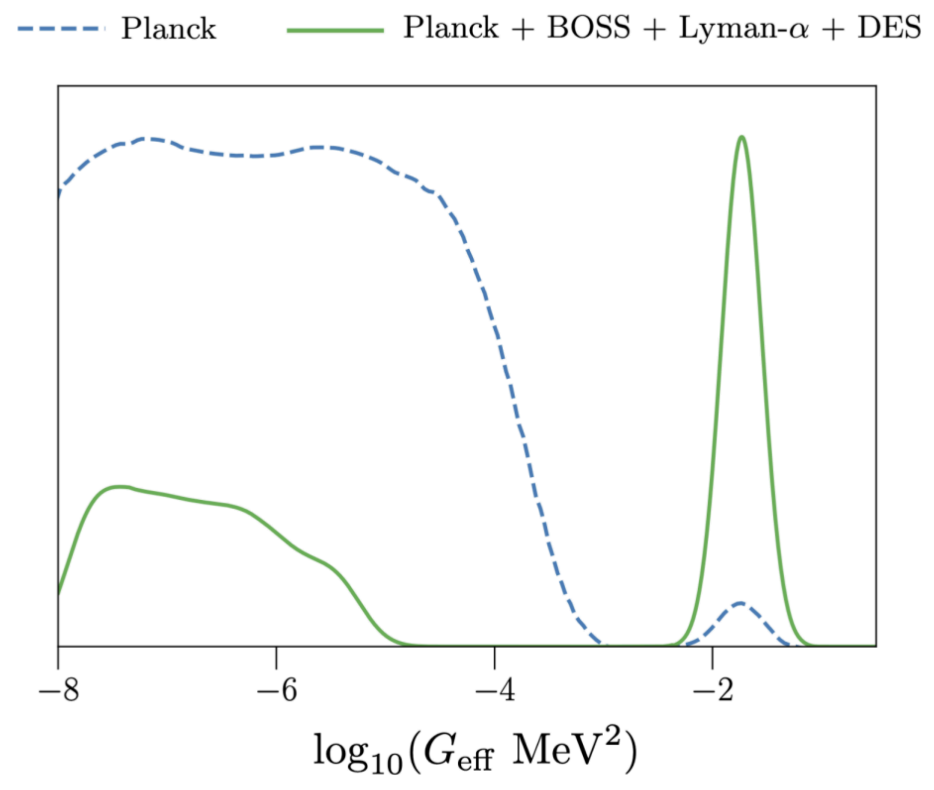
Kreisch+ PRD (2024)2207.03164

CMB sin Planck

Large Scale Structure Galaxy FS PS



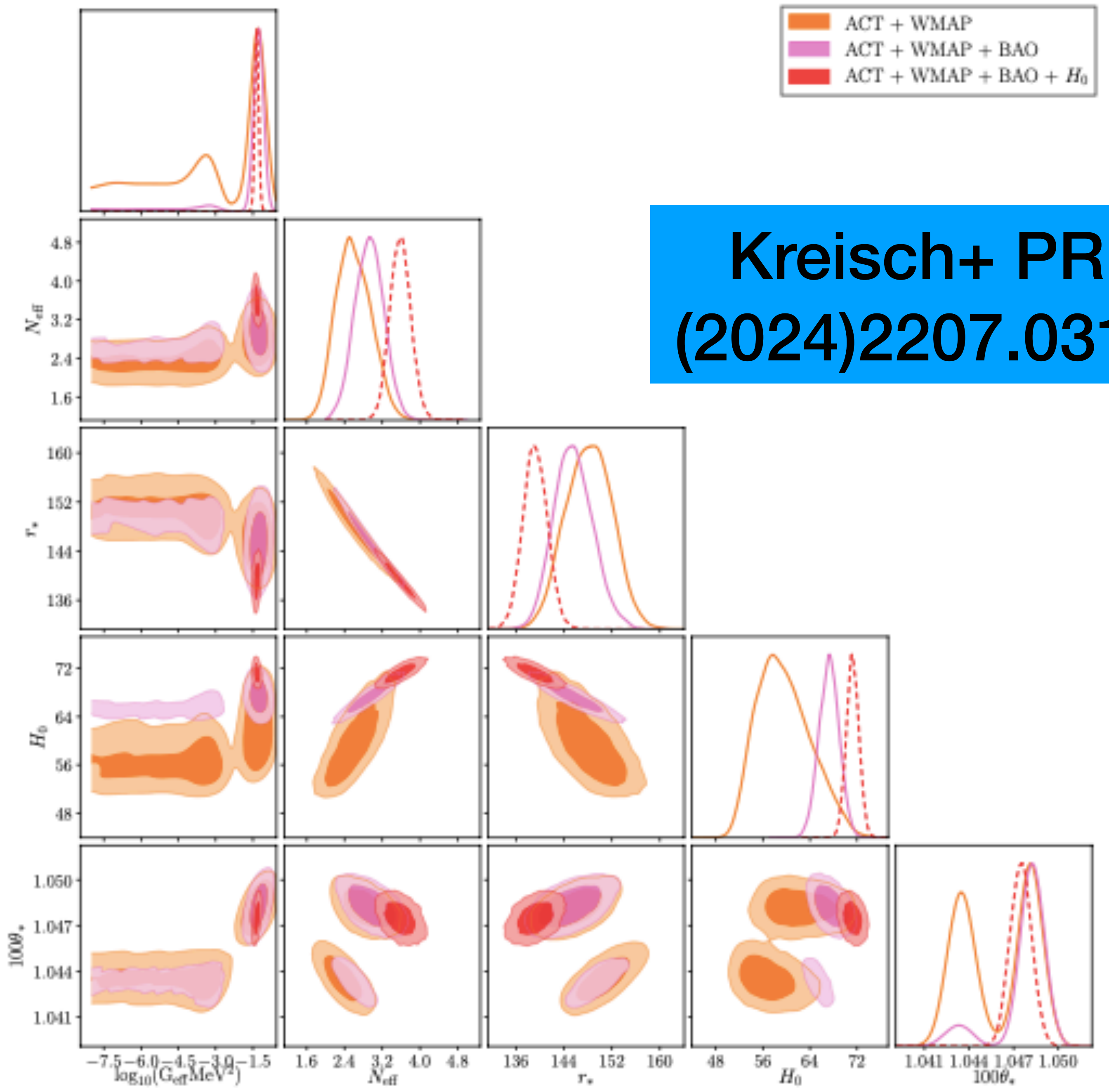
Camarena+ PRD (2023) 2309.03941



He+ PRD (2024) 2309.03956

Update..

Heavy mediator



Kreisch+ PRD (2024)2207.03164

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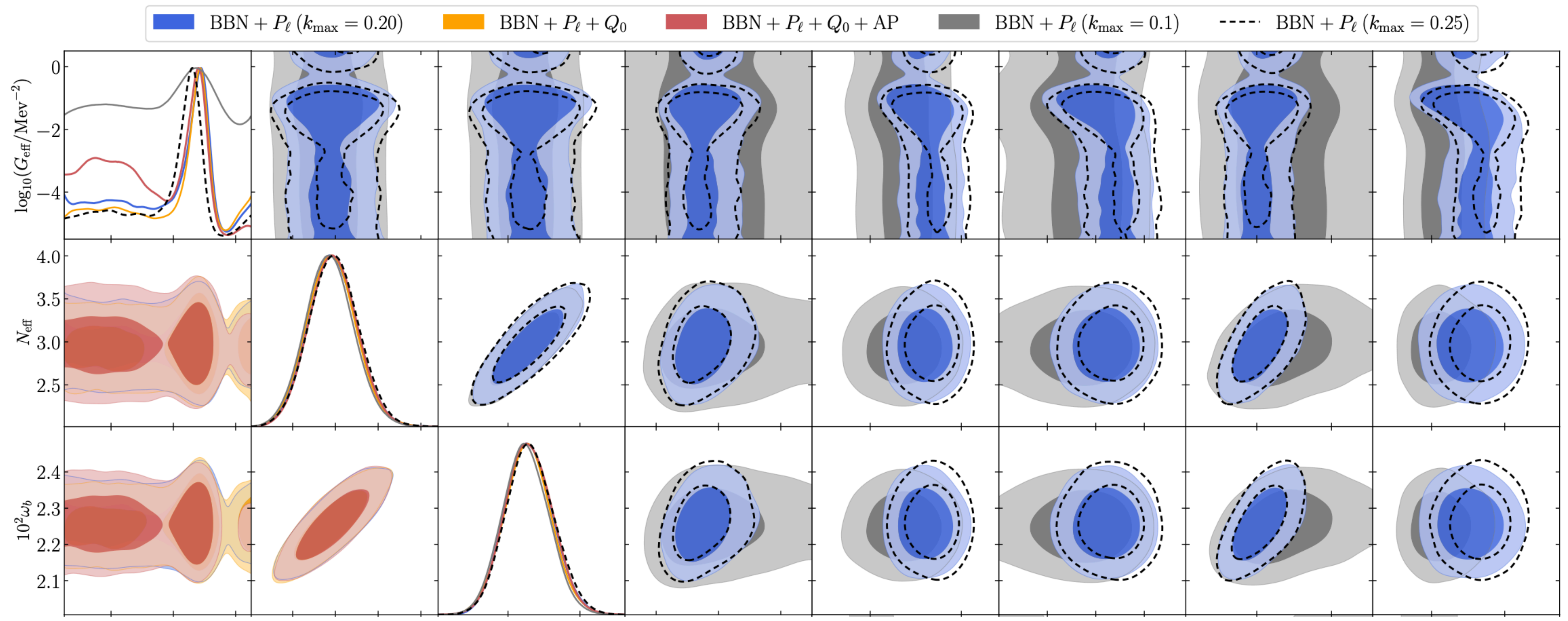
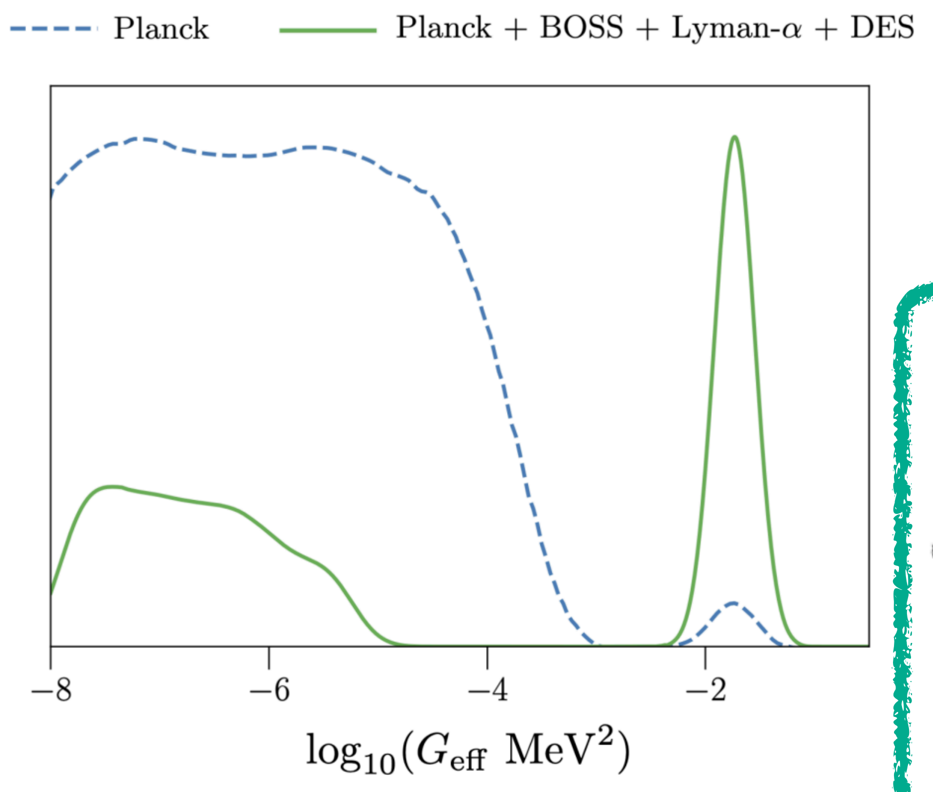
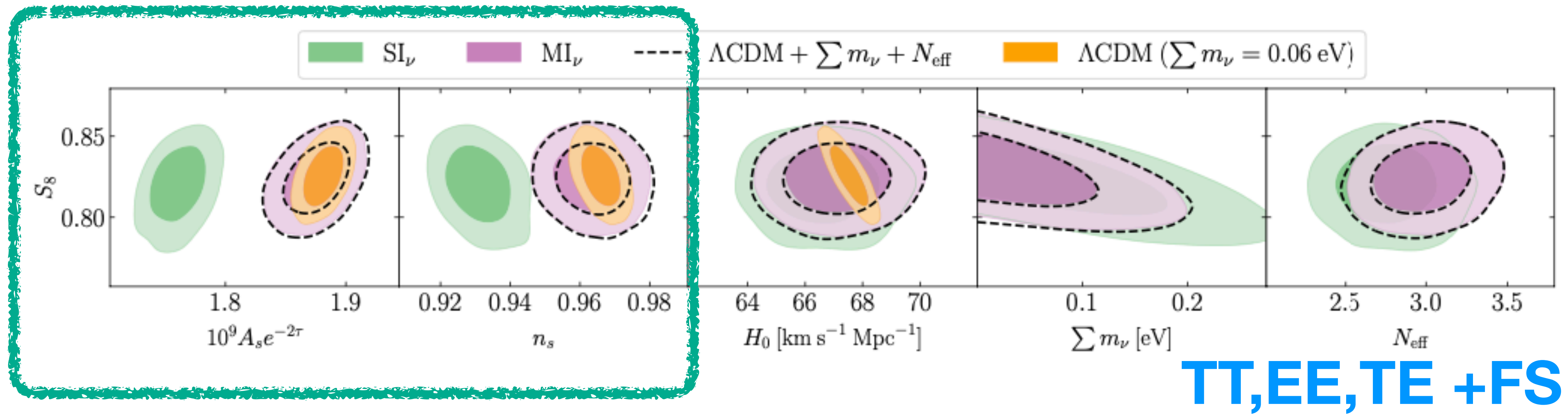


Camarena+ PRD (2023) 2309.03941



He+ PRD (2024) 2309.03956

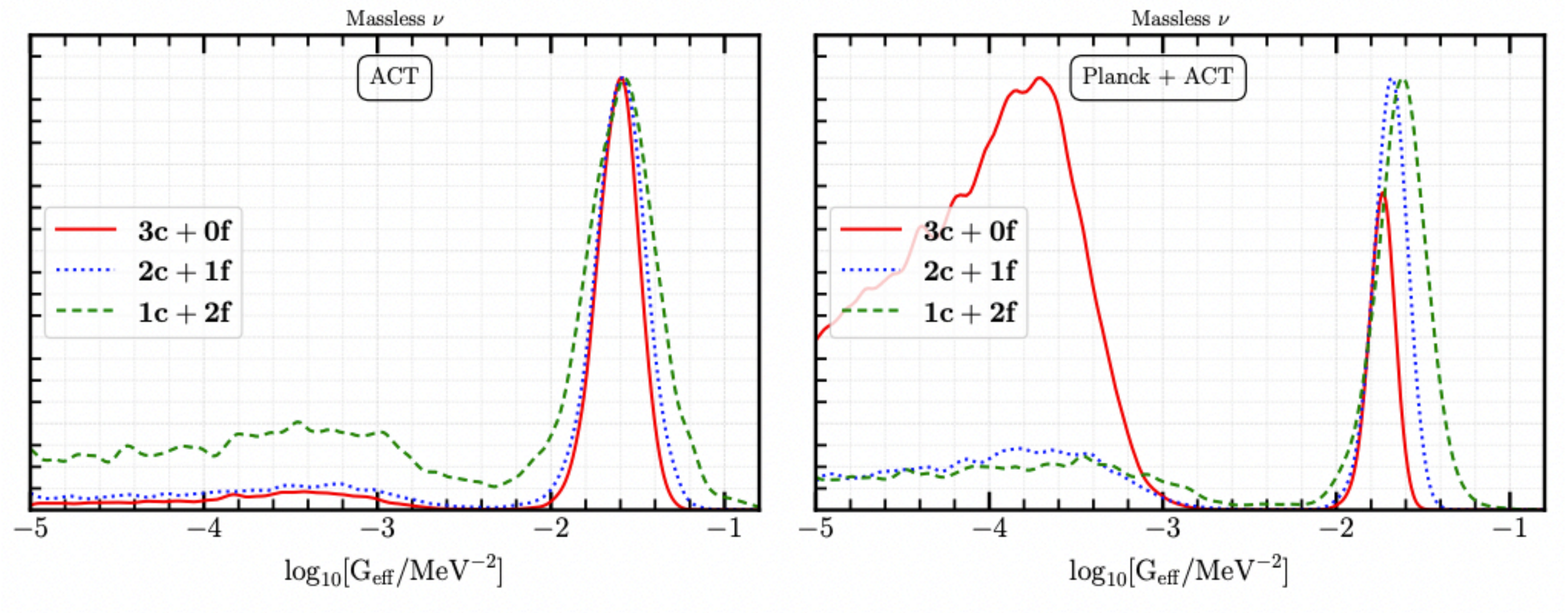


TT,EE,TE +FS

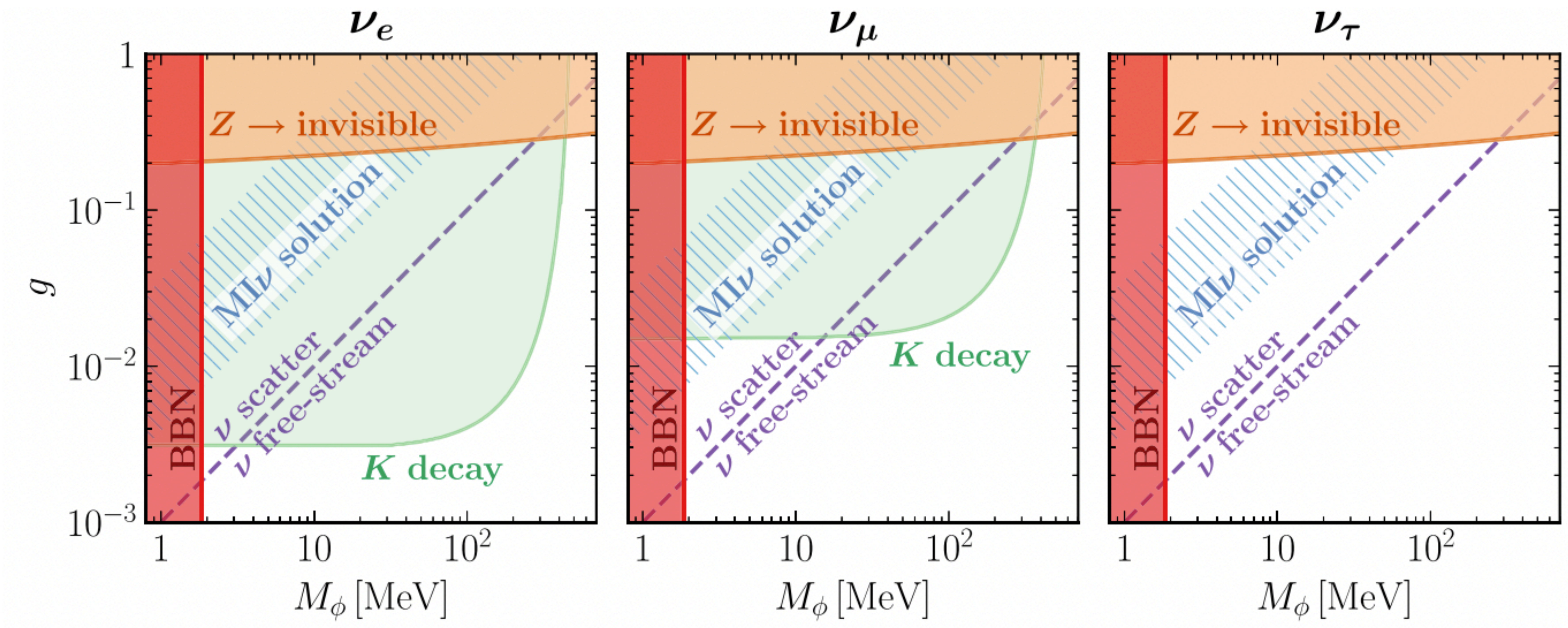
Camarena+ 2403.05496

Update…

Including flavor physics



Das&Ghosh JCAP
2303.08843



2021 Esteban+
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

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

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

We use a Breit-Wigner cross-section

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

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

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

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} eV $< m_\varphi <$ 10^3 eV

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We have to take into account all the available energies

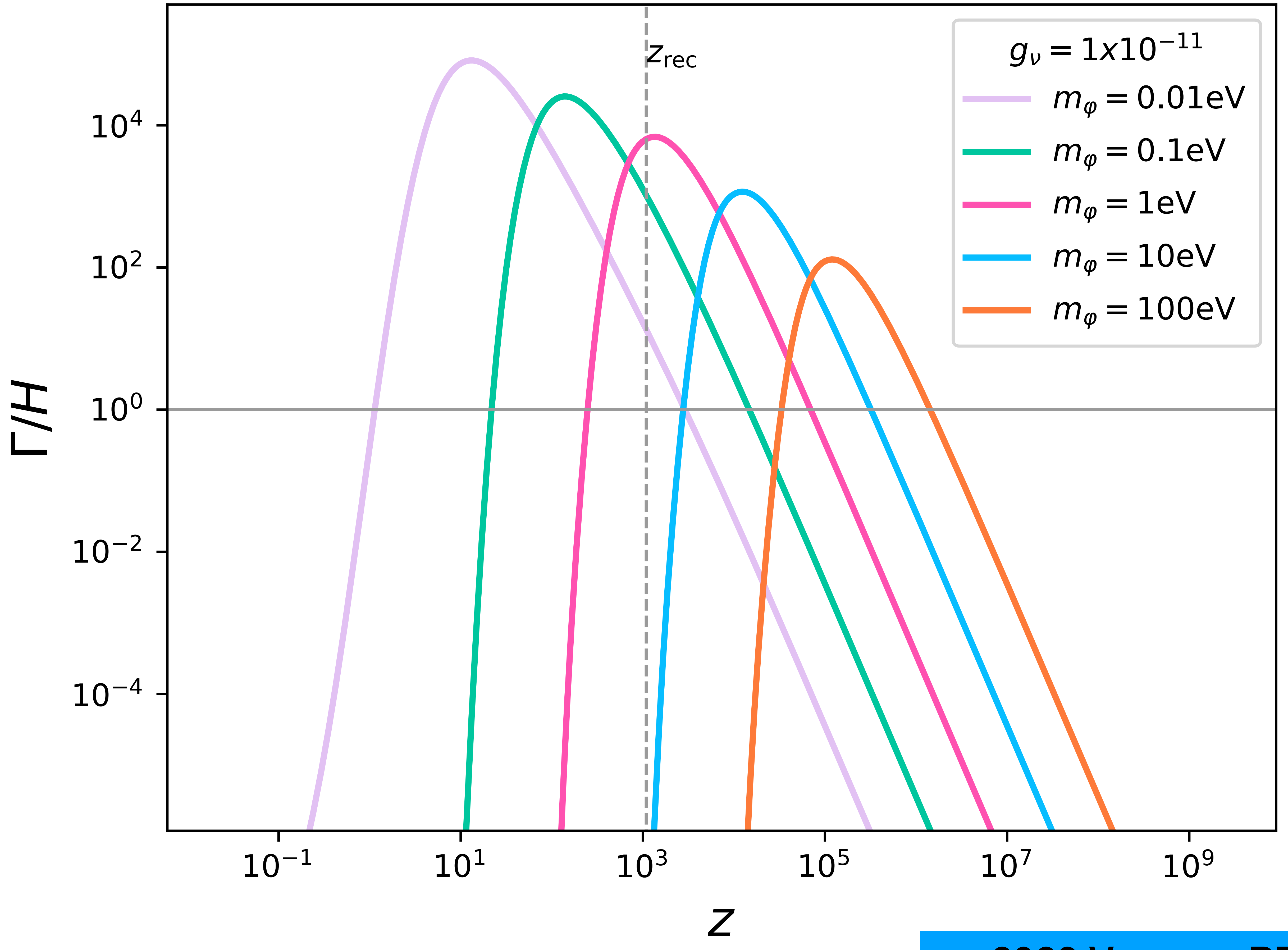
$$\langle \sigma_0 v \rangle \rightarrow \langle \sigma_0 v_{\text{MOL}} \rangle = \frac{4\pi^2 T^2}{(2\pi)^6 n_\nu^2} \int_0^\infty \sigma_0(s) s F(s; T) ds$$

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

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

1991 Gondolo & Gelmini Nucl. Phys. B

2015 Vassh+ PRD

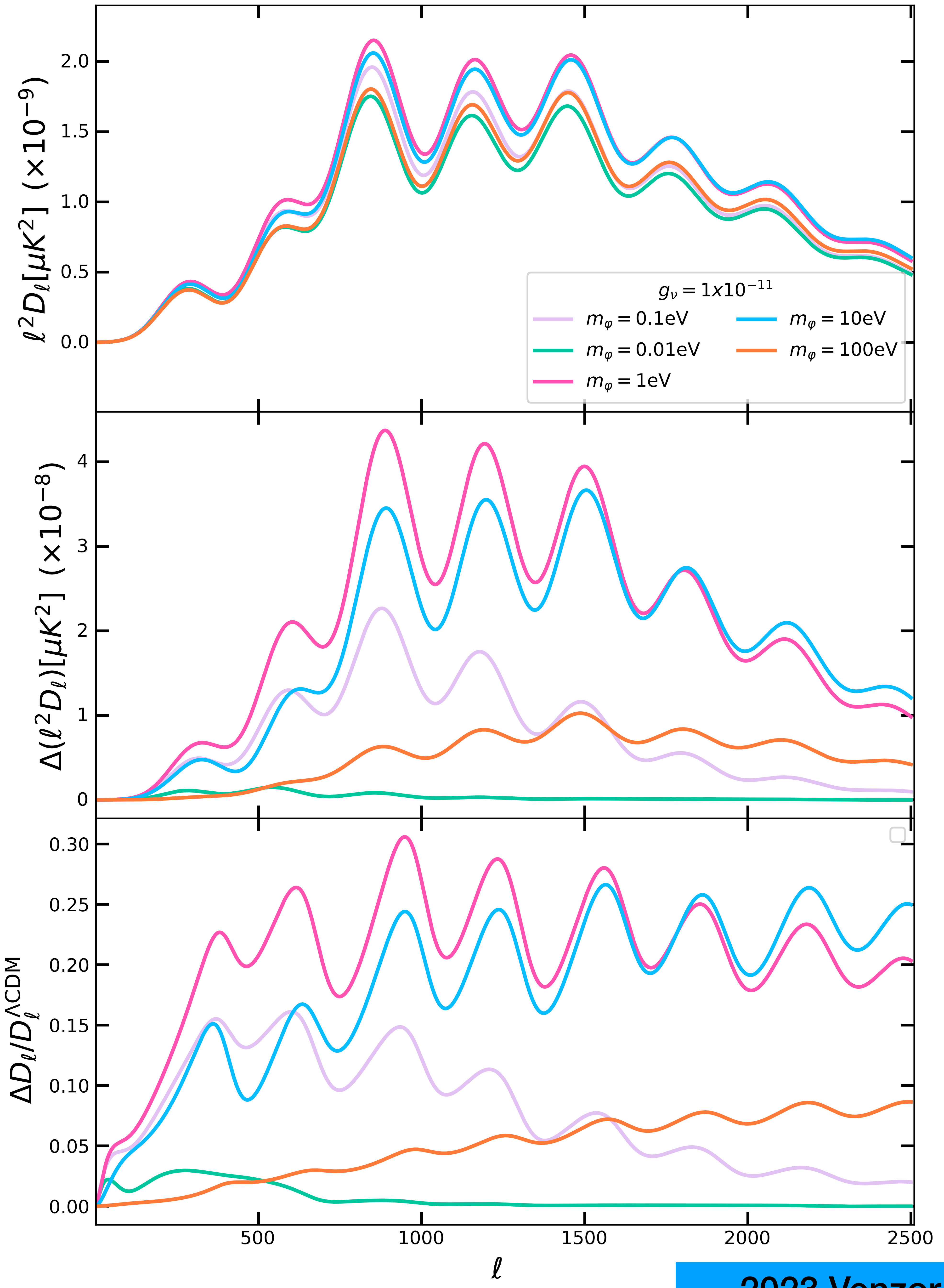


2023 Venzor+ PRD

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

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

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



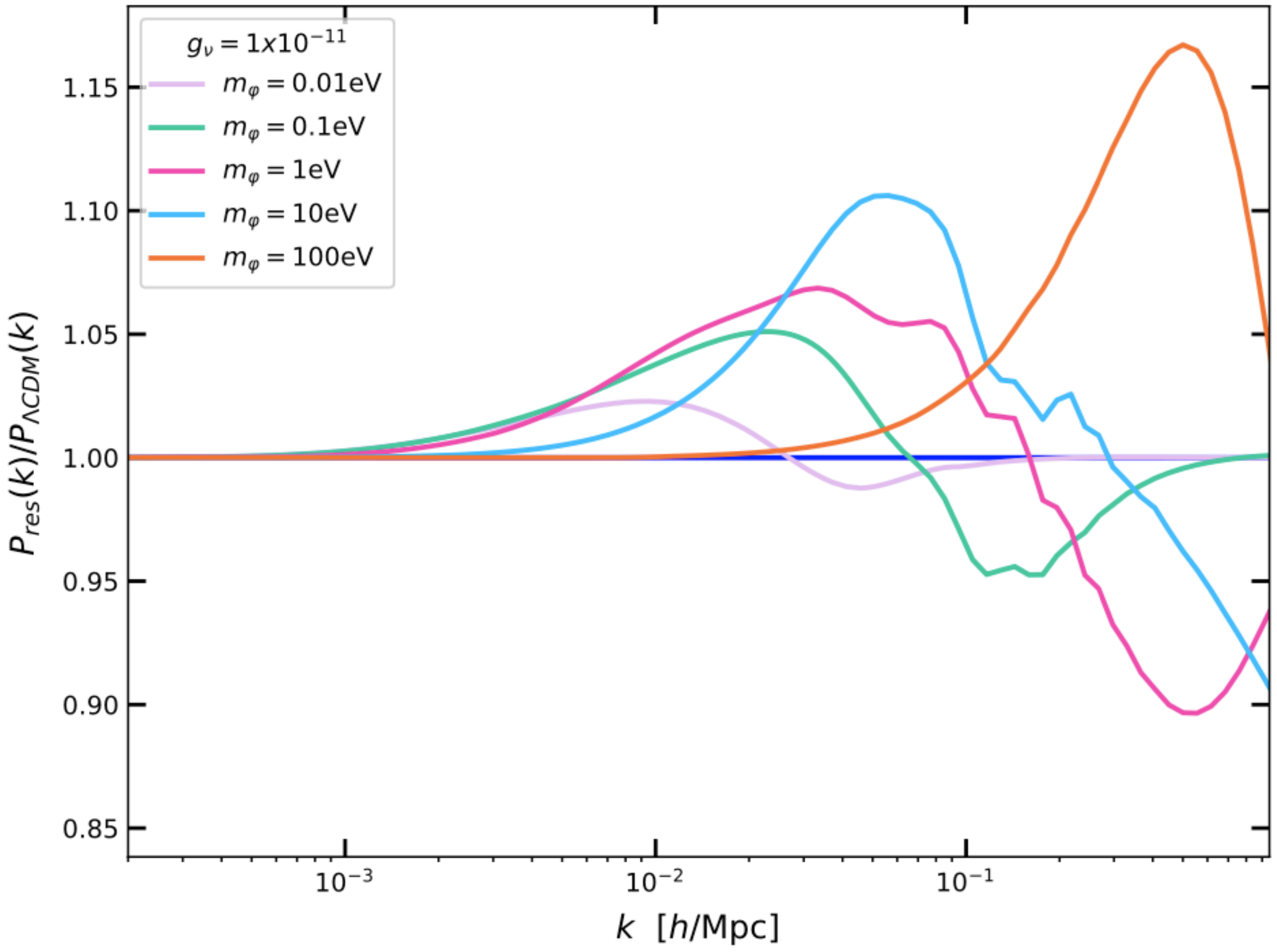
2023 Venzor+ PRD

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

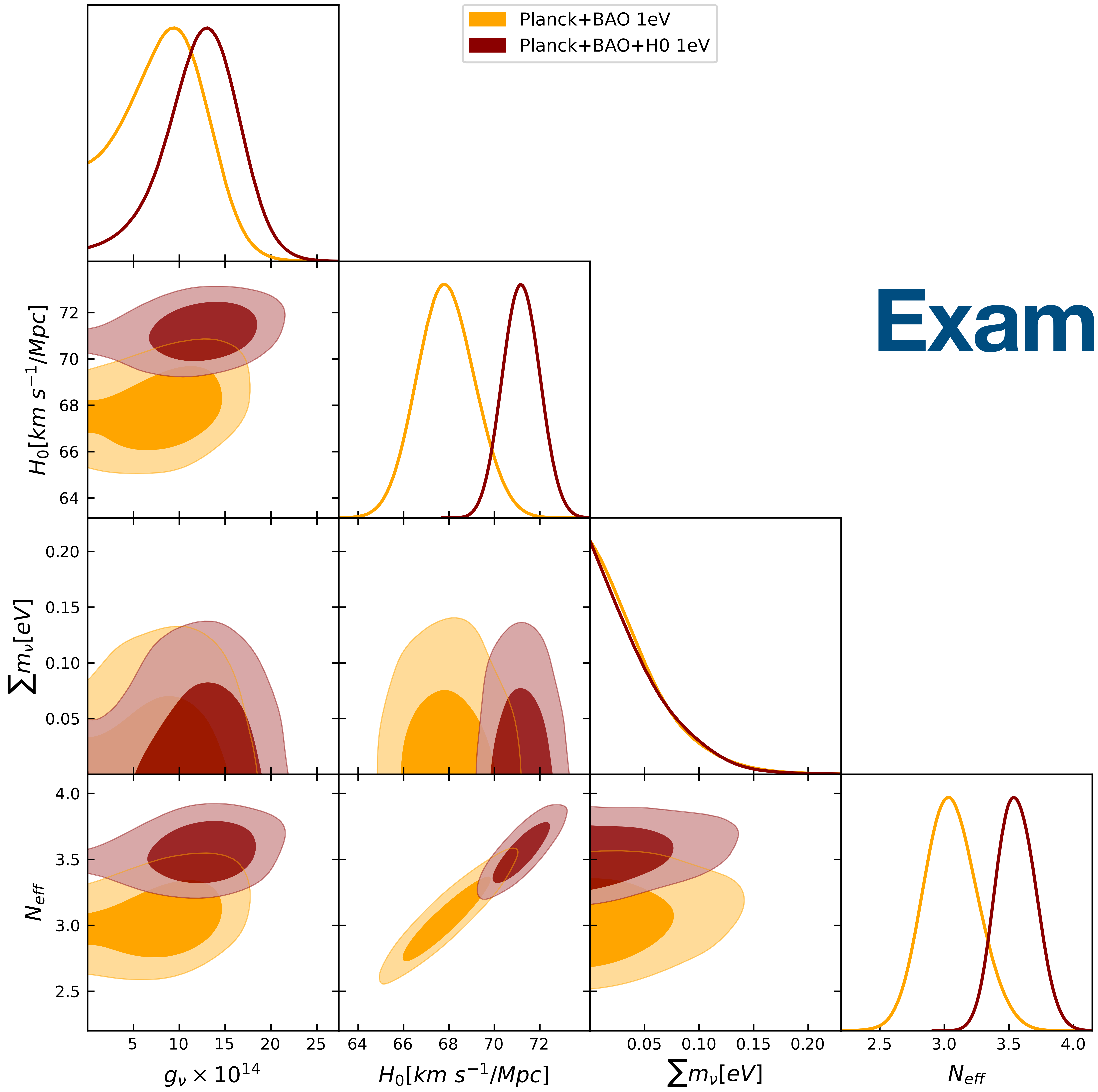
Small mass → Large scales



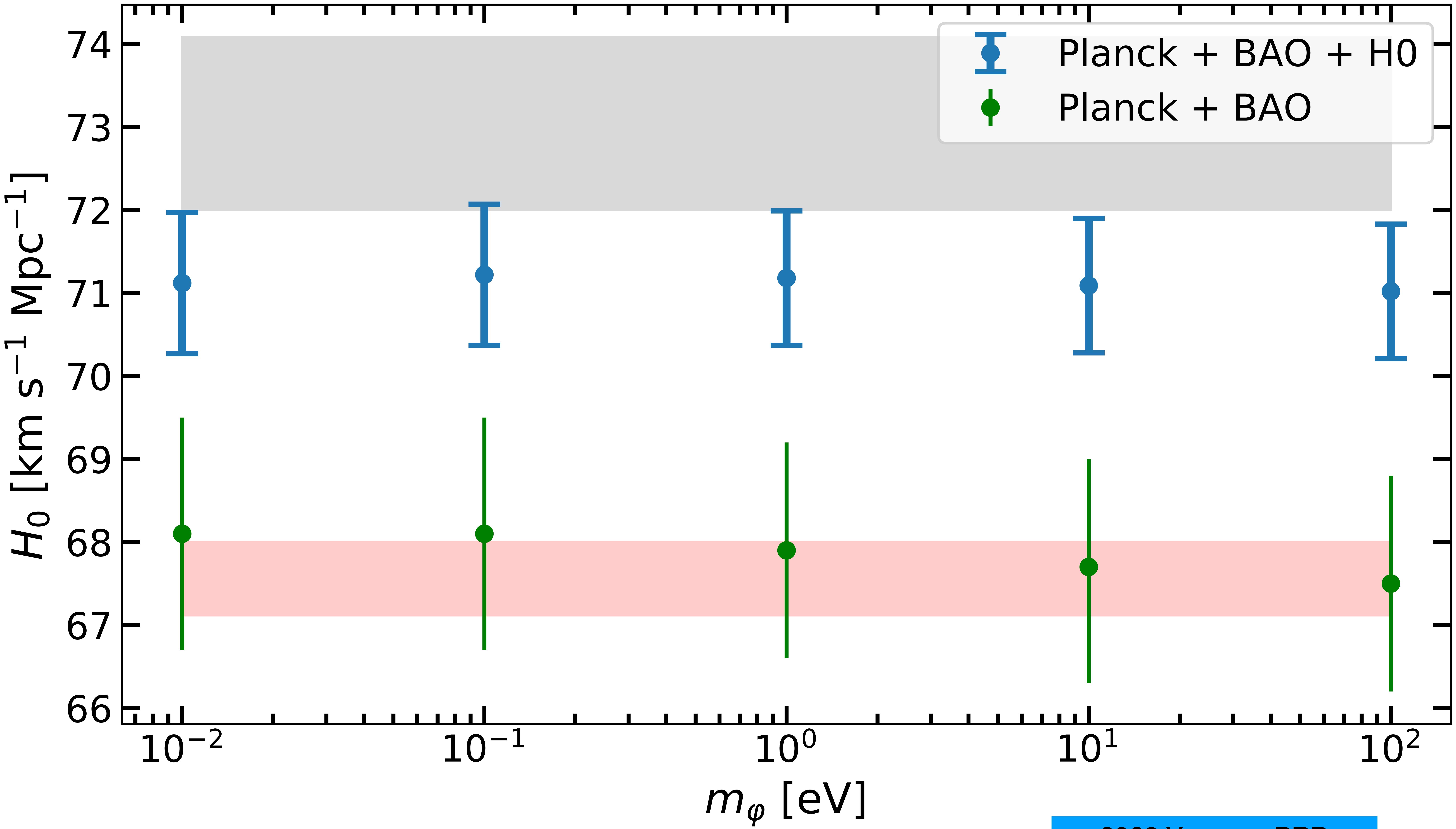
Larger masses enter to the horizon first

2023 Venzor+ PRD

Example: mass=1eV



2023 Venzor+ PRD



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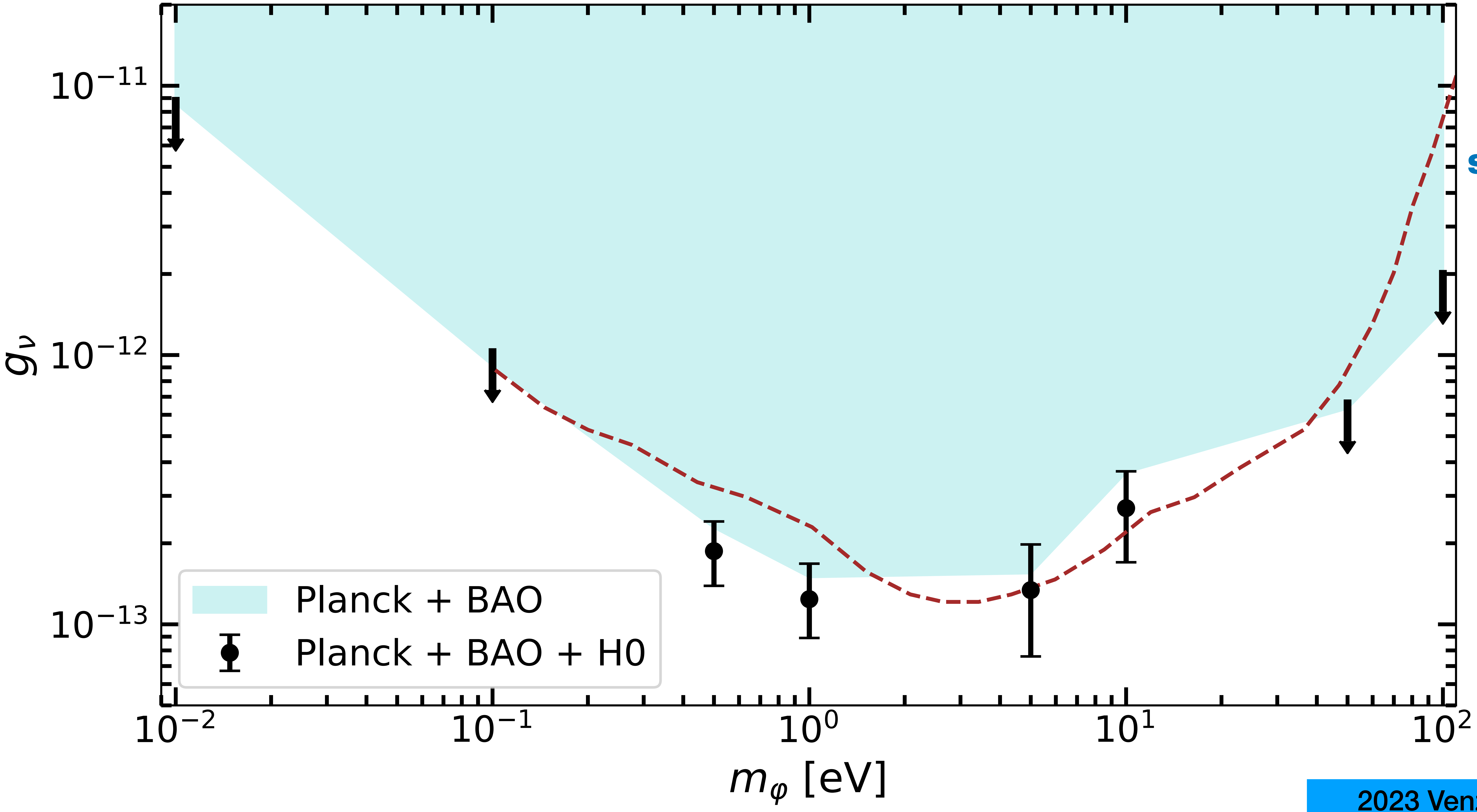
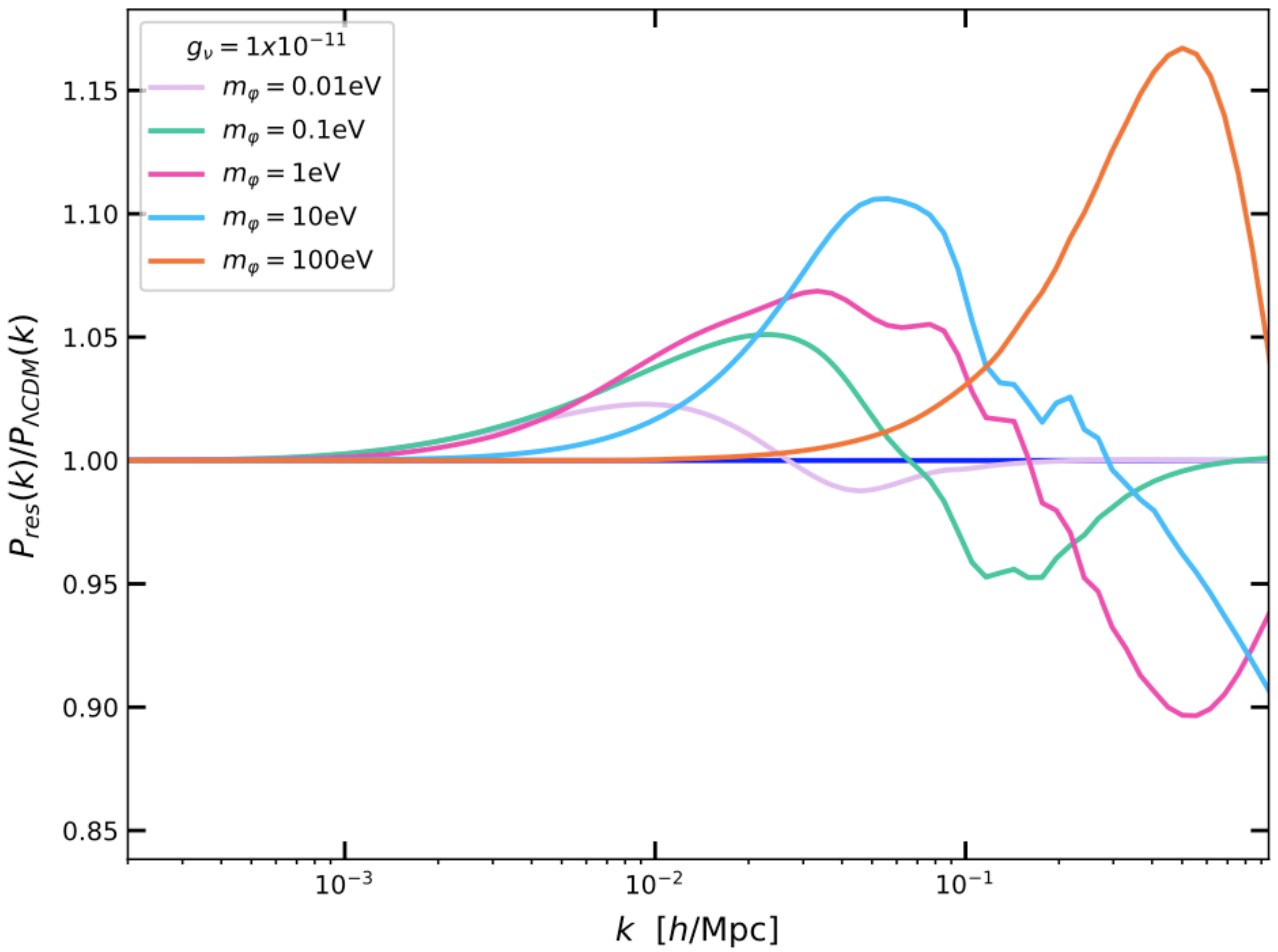


Dashed line is the singlet majaron model

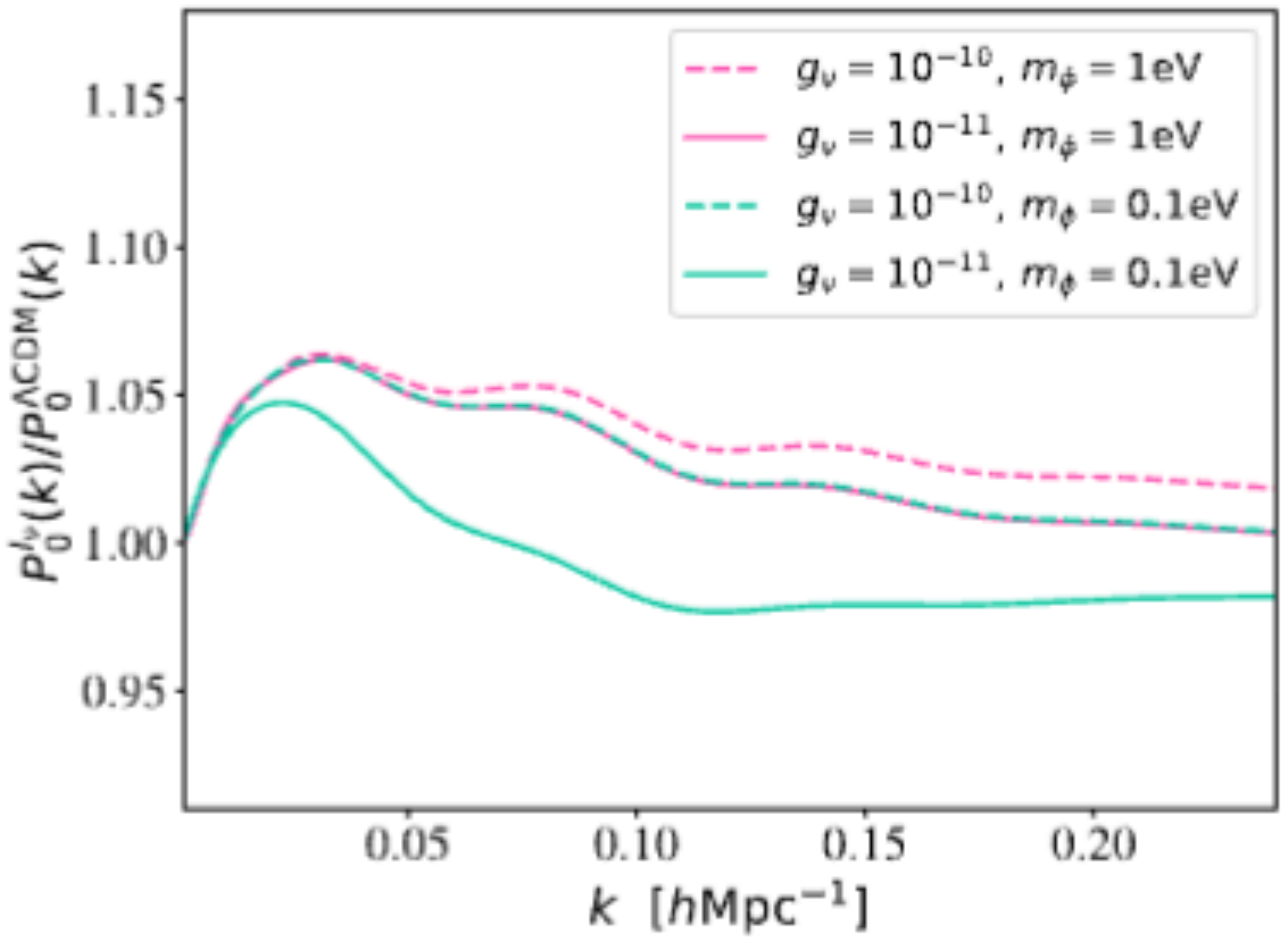
2020 Escudero&Witte EPJC

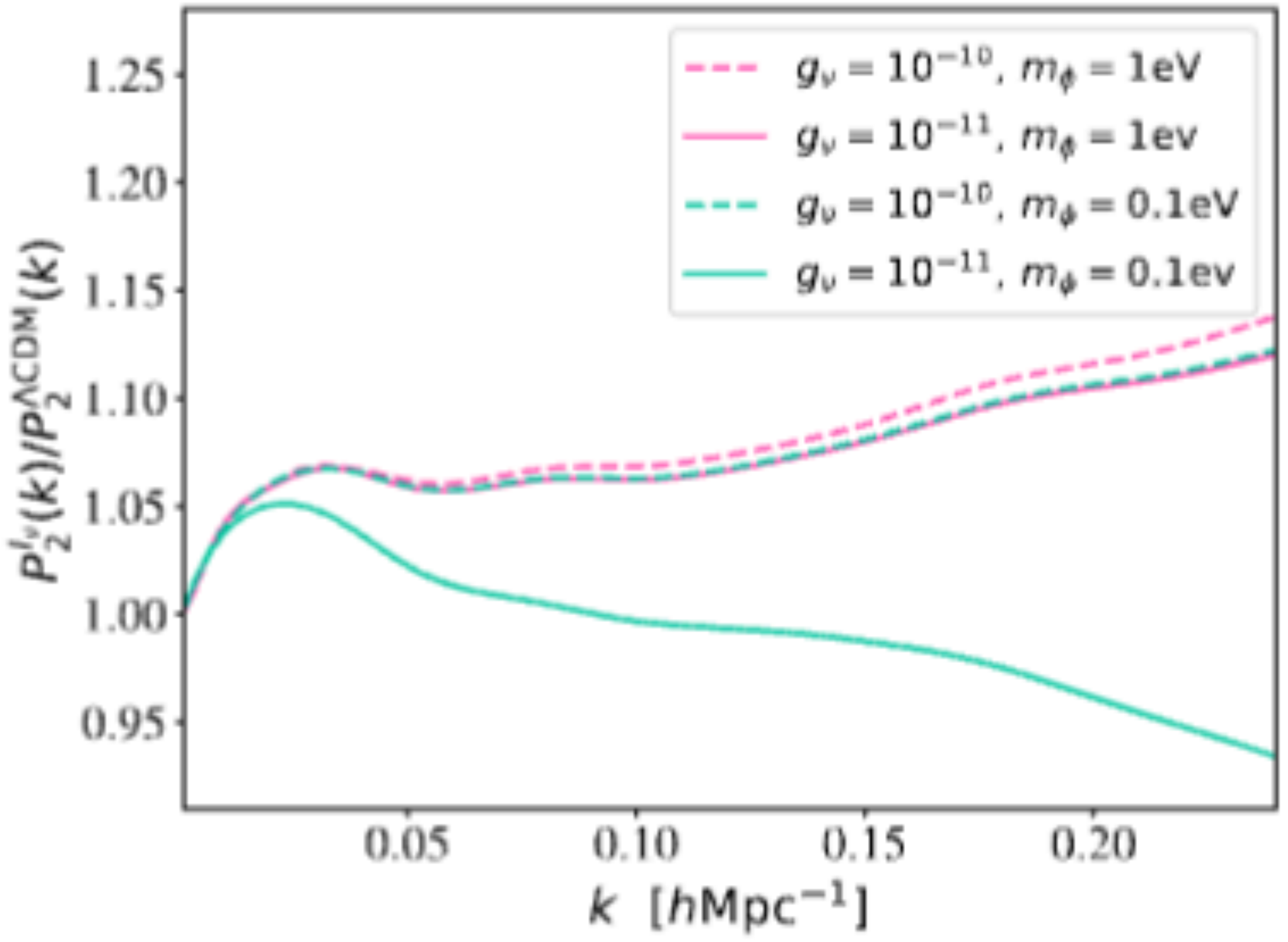
2023 Venzor+ PRD

Full Shape Galaxy spectrum



2023 Venzor+ PRD





Non linear effects on the Matter Power Spectrum

Recently developed Zaldarriaga, Simonovic, Ivanov, Cox, Scoccimarro ....

Larger masses enter to the horizon first

Preliminary

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 need to include non-elastic processes into the analysis.

¡Thanks!