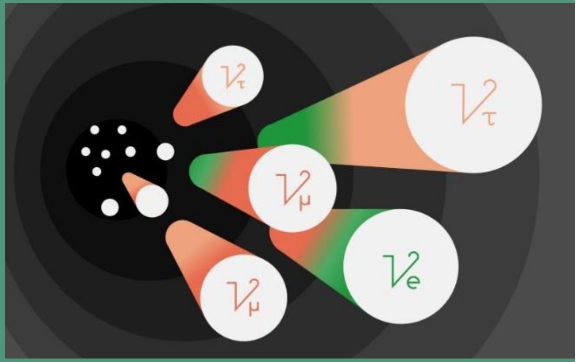
Cosmological limits to Non-Standard Interactions of the neutrino



Abdel Pérez-Lorenzana
Cinvestav-IPN

ICN, JANUARY 2023

In coll. with J.A. Venzor, J. De Santiago and G. Garcia-Arroyo.

Overview

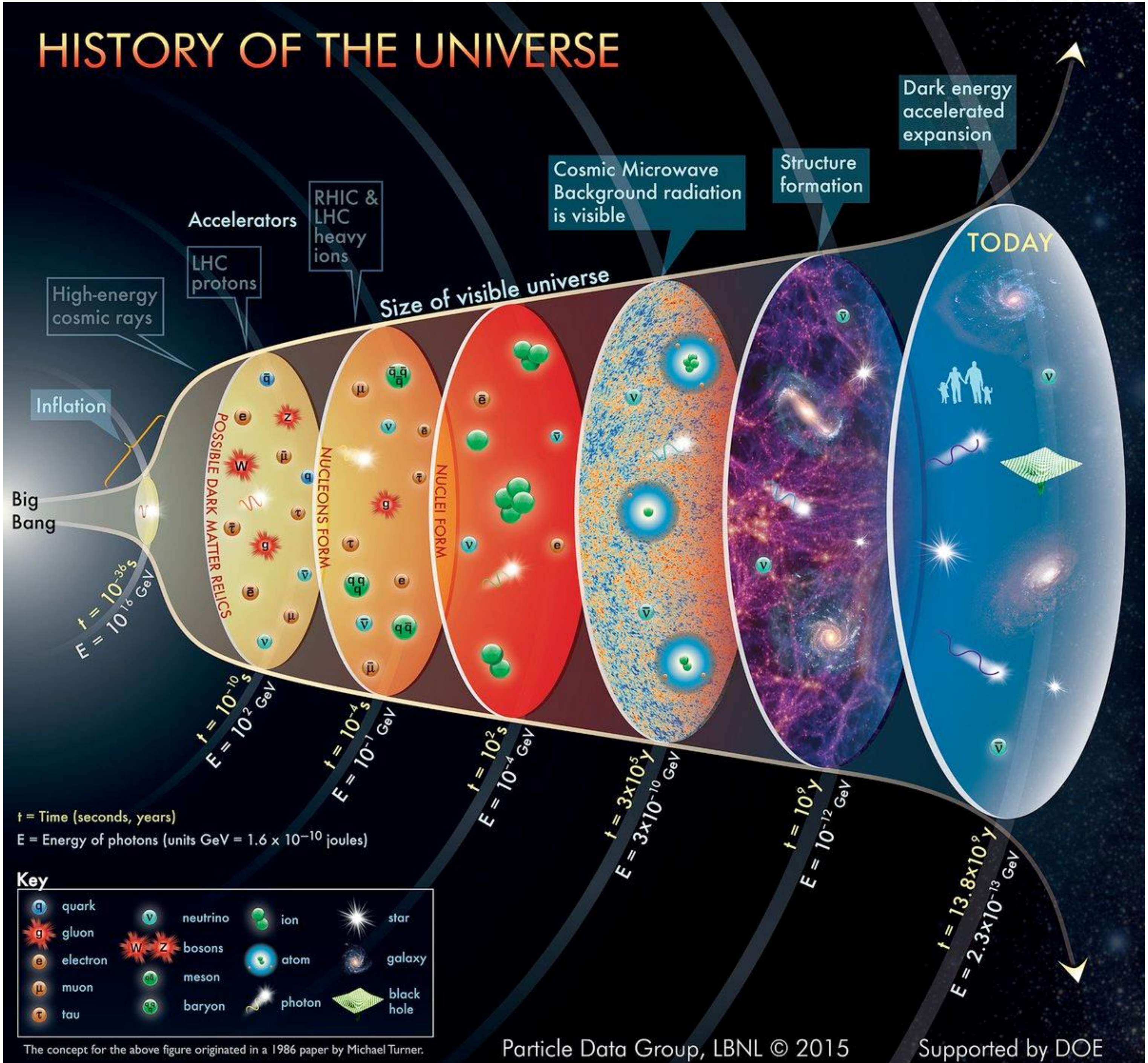
Neutrinos have mass and mix

BSM

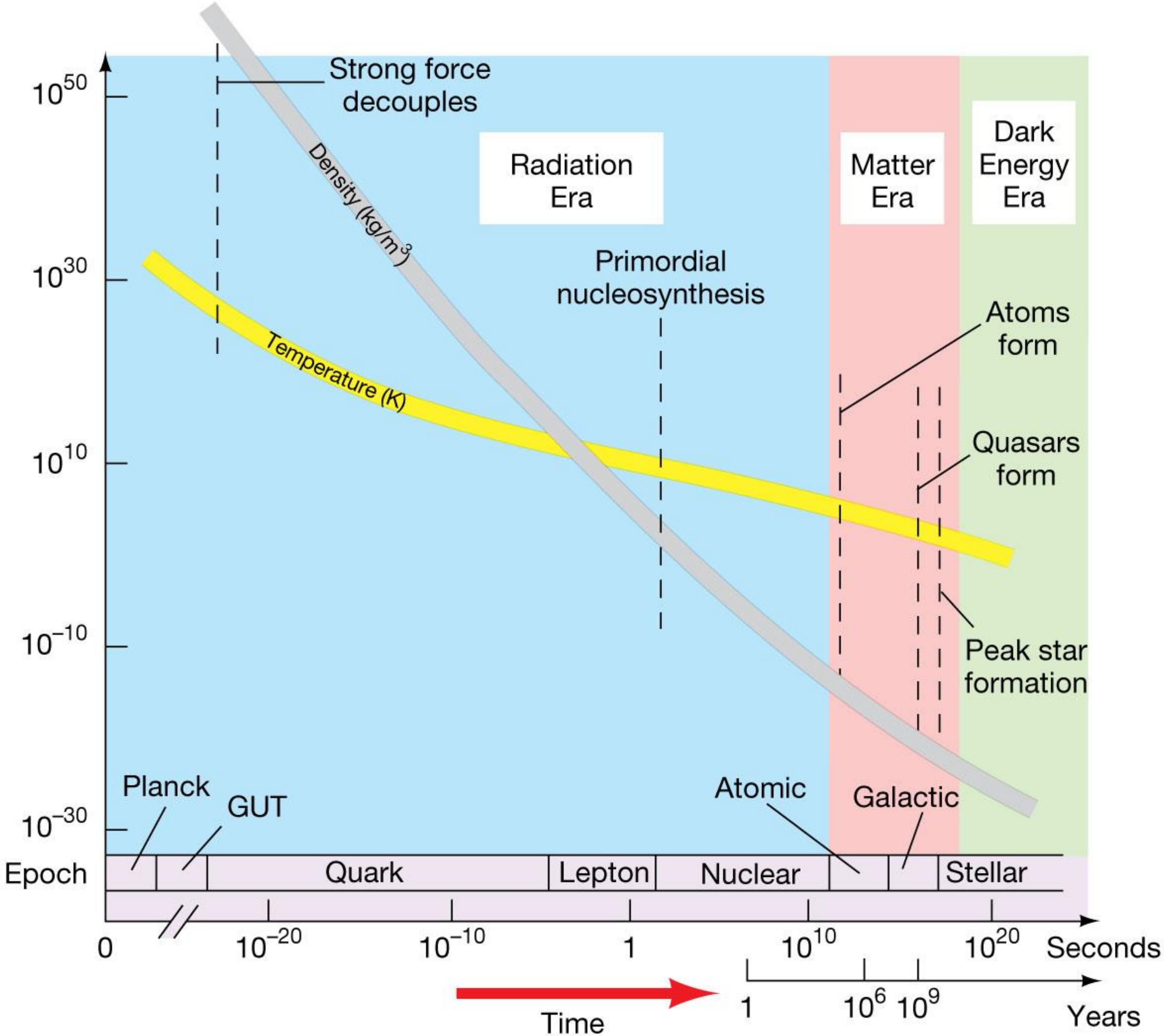
New Fermions (N)
or
New Scalars (flavor symmetries)

New particles come with new phenomenology

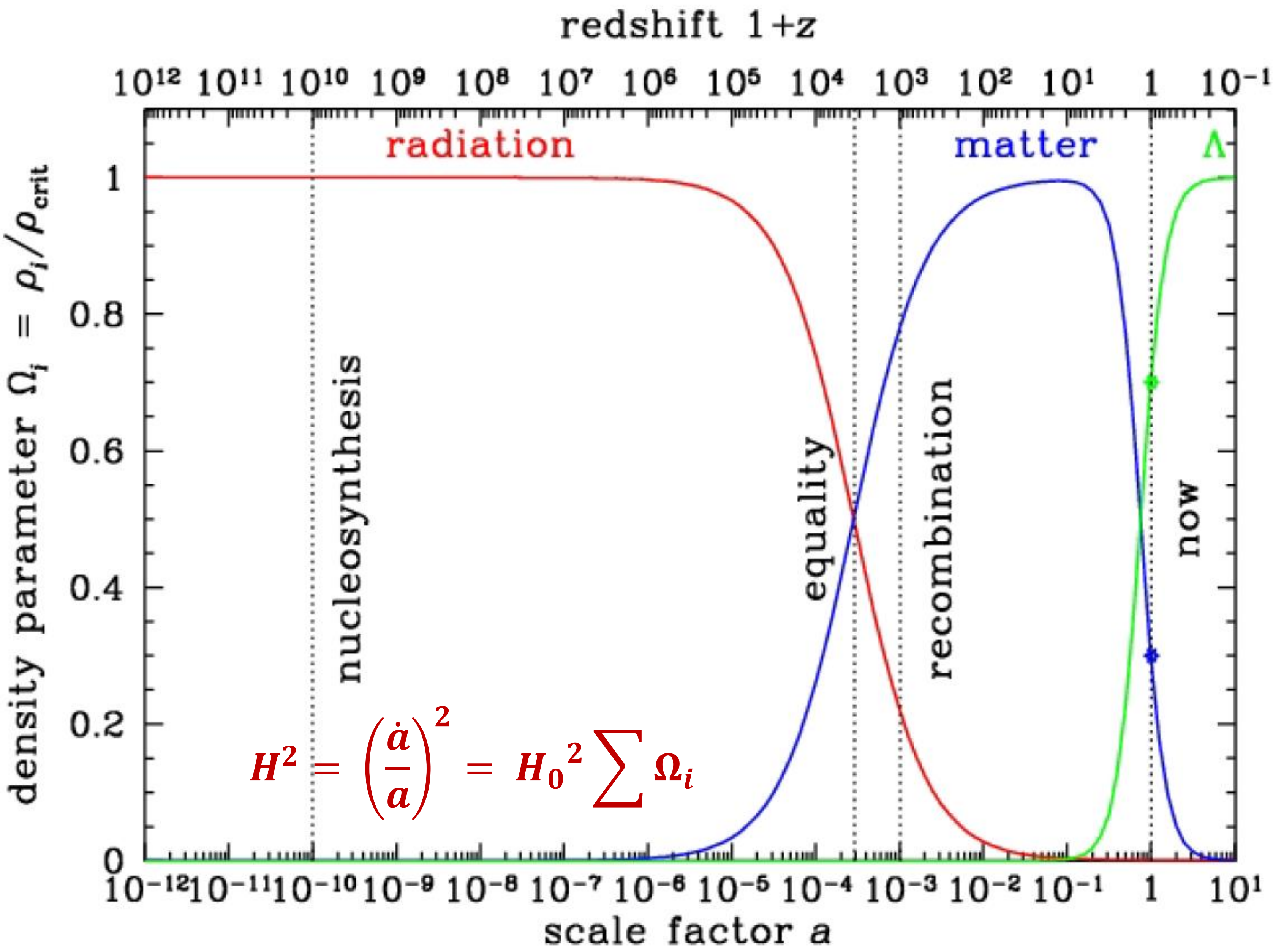
Early Universe is a good playground to look for it



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



Strong force decouples
Density (kg/m^3)
Radiation Era
Matter Era
Dark Energy Era
Primordial nucleosynthesis
Atoms form
Temperature (K)
Quasars form
Peak star formation
10^{50}
10^{30}
10^{10}
10^{-10}
10^{-30}
Planck
GUT
Atomic
Galactic
Epoch
Quark
Lepton
Nuclear
Stellar
0
10^{-20}
10^{-10}
1
10^{10}
10^{20}
Seconds
Time
1
10^6
10^9
Years



$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = {H_0}^2 \sum \Omega_i$$

Relic Neutrino Background

At decoupling $e^+e^- \nleftrightarrow \nu\bar{\nu}$ **and** $e\nu \nleftrightarrow e\nu$ **:** $T_\nu = T_\gamma$

Decoupling occurs when: $H \approx \Gamma = \langle \sigma v \rangle\, \eta$

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$$T \approx \mathcal{O}(1) \left(\frac{M_W}{M_P} \right)^{1/3} \frac{M_W}{\alpha_w^{2/3}} \approx 1.5 \; MeV$$

A neutrino background

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Entropy balance: $S_{e^\pm} + S_\gamma$ and S_ν are diluted at the same rate

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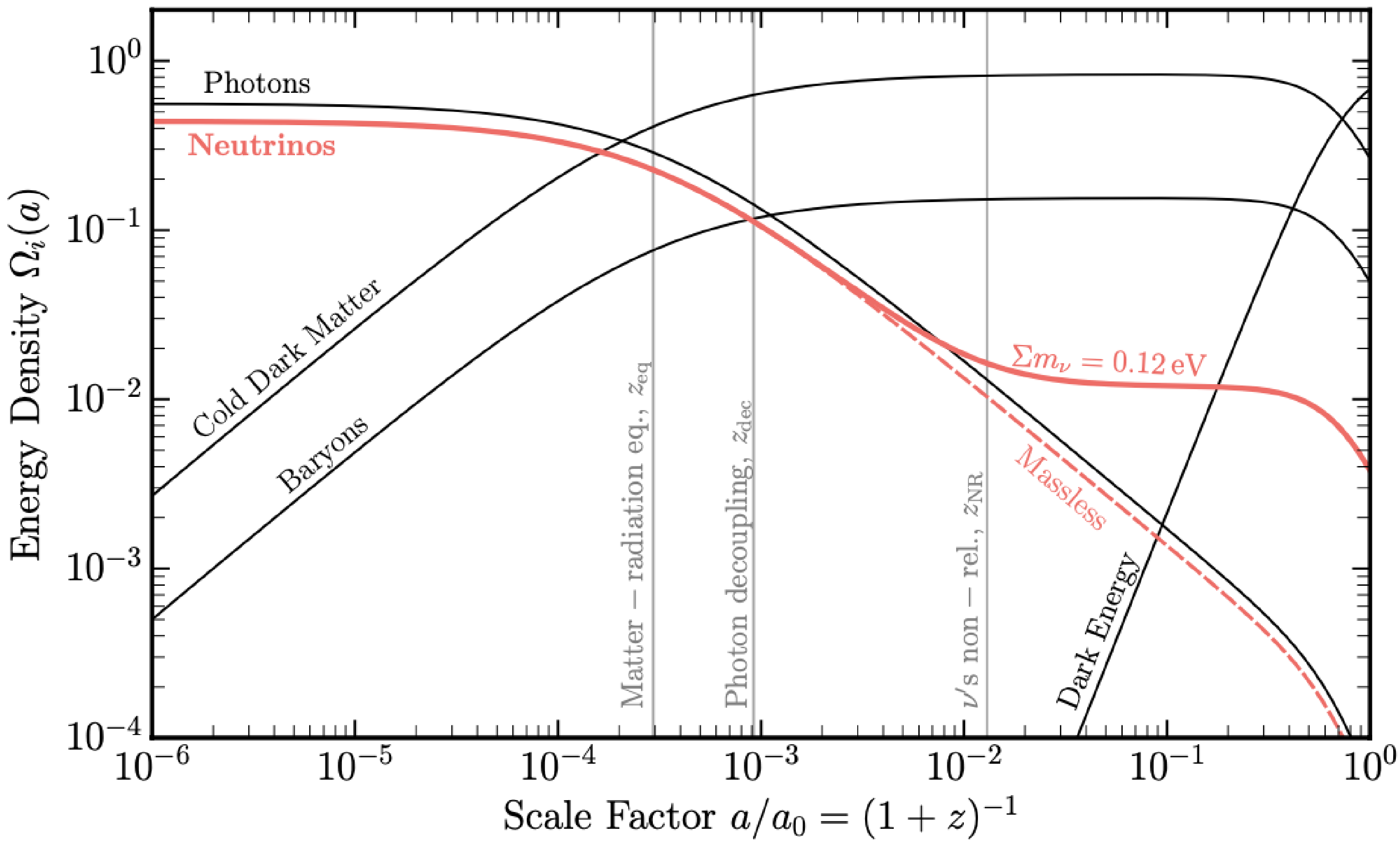
Thus, after pair annihilation: $\left(\frac{T_\gamma}{T_\nu}\right) = \left(\frac{11}{4}\right)^{1/3}$ $\therefore\ T_\nu = 1.95\ K$

$(1.68 \times 10^{-4} eV)$

Neutrino cosmology parameters



$$H^2(a) = H_0^2 \frac{\rho(a)}{\rho_{crit}} \qquad \rho_{crit} \equiv \frac{3H_0^2}{8\pi G} \qquad \Omega_r h^2 = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\Omega_\gamma h^2$$

Free streaming and structure formation

Over dense regions collapse

while

neutrinos fly away

Collapse time scale:

$$\Delta t_{\text{collapse}} \equiv (4\pi G \rho a)^{-1/2}$$

Escape time scale:

$$\Delta t_{\text{escape}} \equiv \frac{\lambda}{v_{\text{thermal}}}$$

Evolution of primordial (matter) perturbations:

$$\ddot{\boldsymbol{\delta}} + (\boldsymbol{Pressure} - \boldsymbol{gravity})\boldsymbol{\delta} = \mathbf{0}$$

Neutrino free streaming scale:

$$\lambda_{\text{FS}} \equiv \sqrt{\frac{8\pi^2 c_\nu^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\text{eV}}{m_\nu}\right) \quad h^{-1}\ \text{Mpc}$$

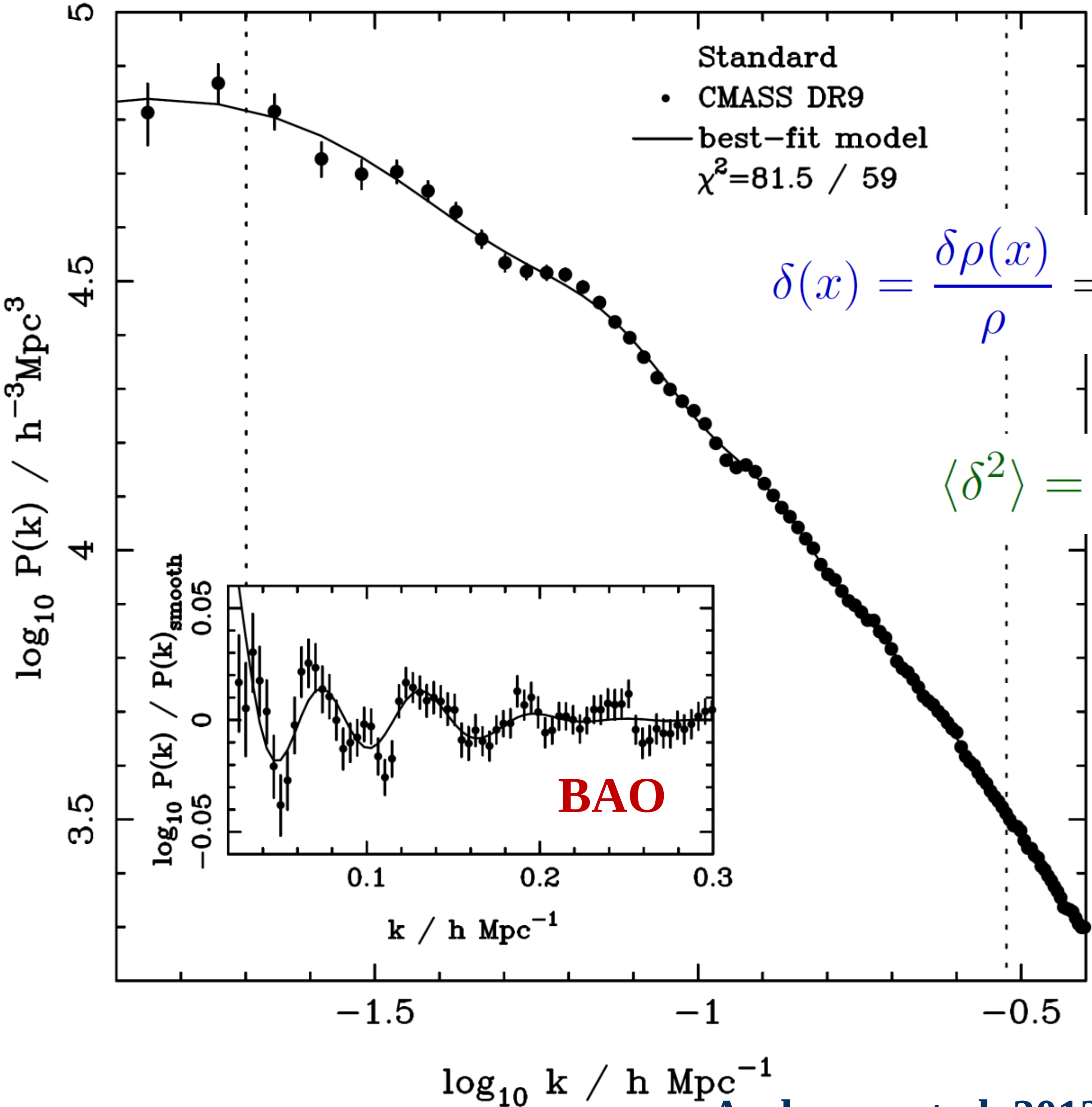
$$k_{\text{FS}} \equiv \frac{2\pi}{\lambda_{\text{FS}}}$$

$\boldsymbol{k \gg k_{FS}}$: $\boldsymbol{\delta_\nu}$ **vanishes**

metric pert. are reduced

- **Shifts CMB power spectra & damps its amplitude**
- **Structures don’t form**

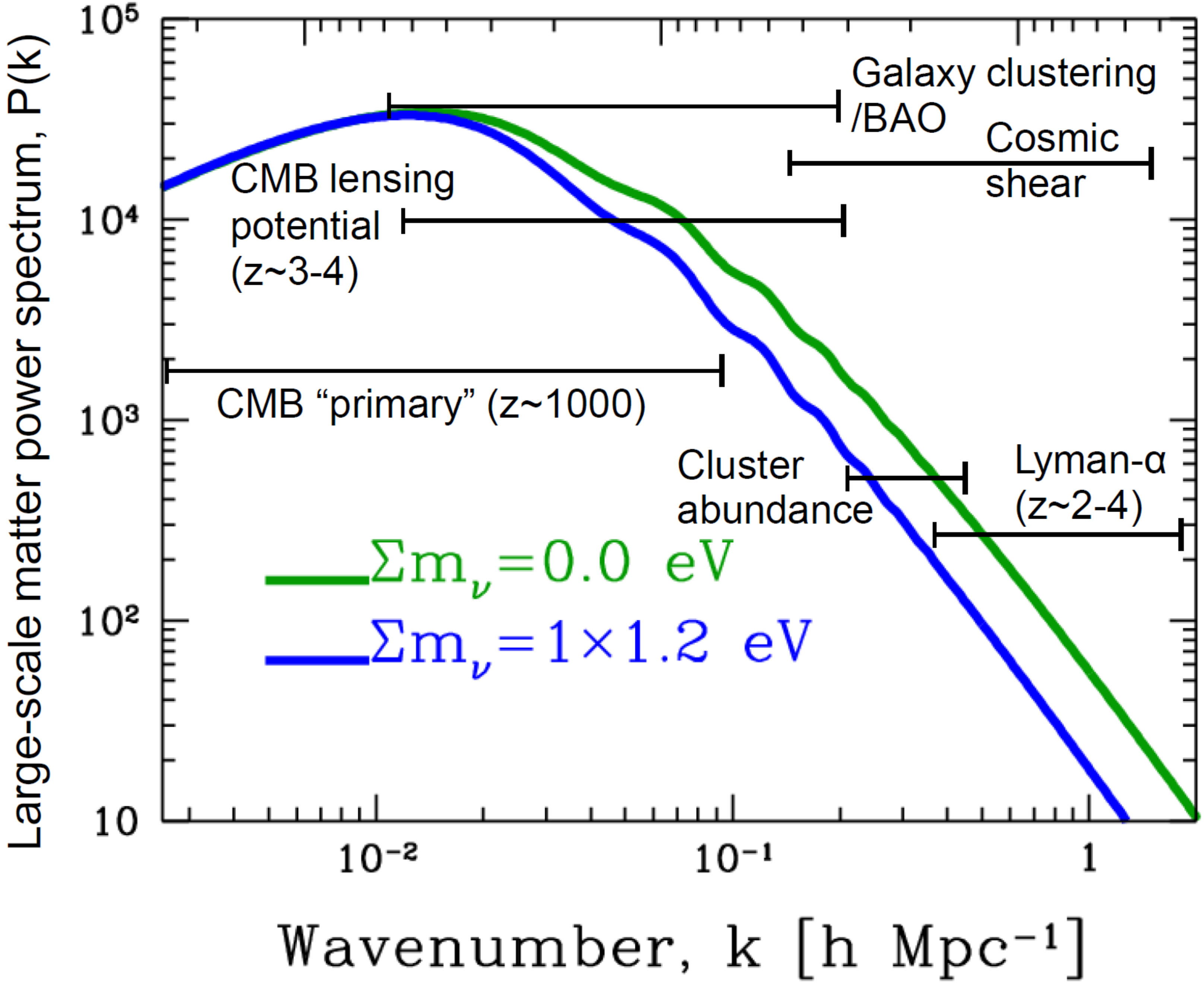
Matter power spectrum



$$\delta(x) = \frac{\delta\rho(x)}{\rho} = \sum \delta_k e^{-i\vec{k}\cdot\vec{x}}$$

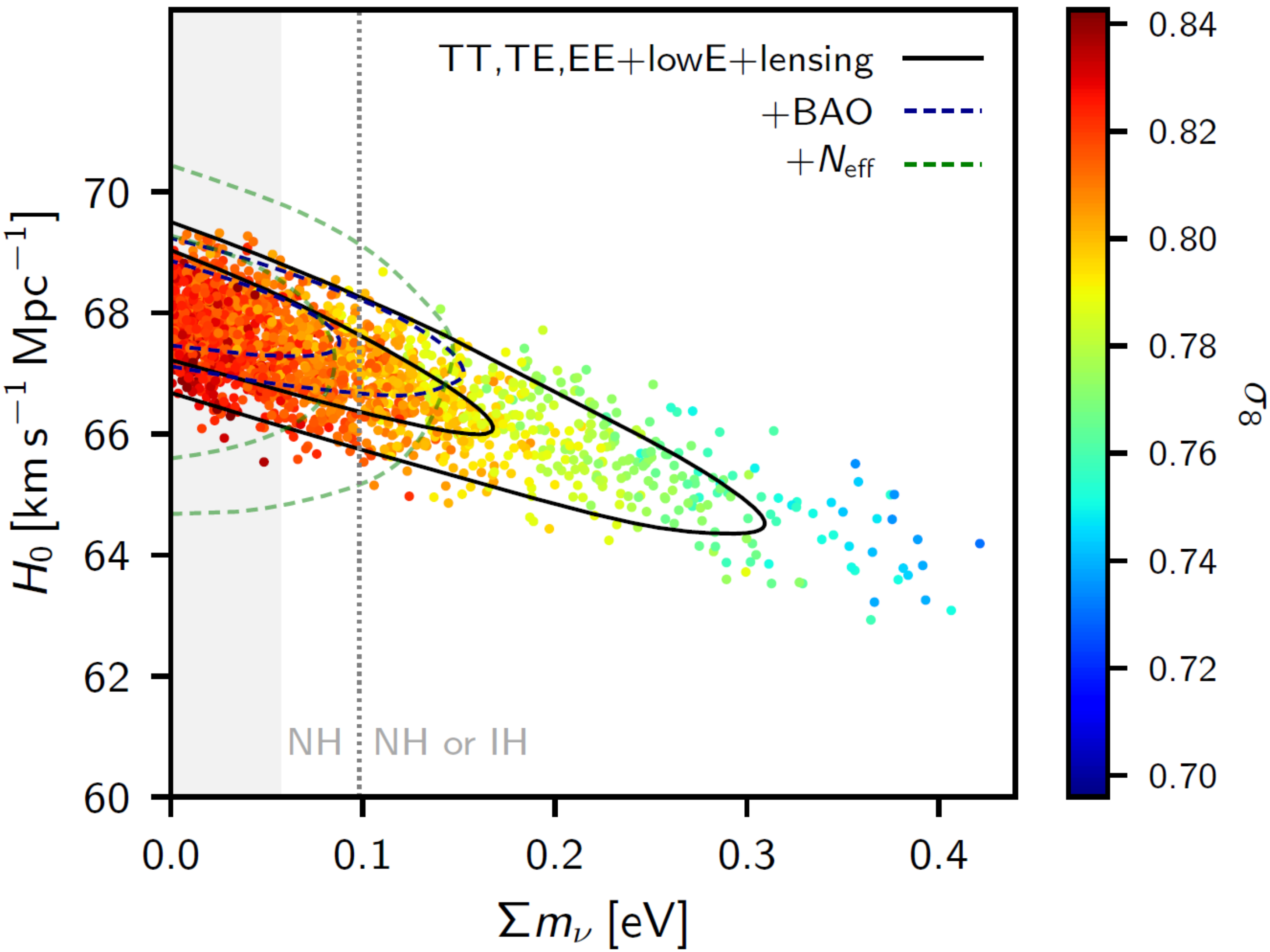
$$\langle\delta^2\rangle = \sum P(k)$$

Anderson et al. 2013 [SDSS BOSS]



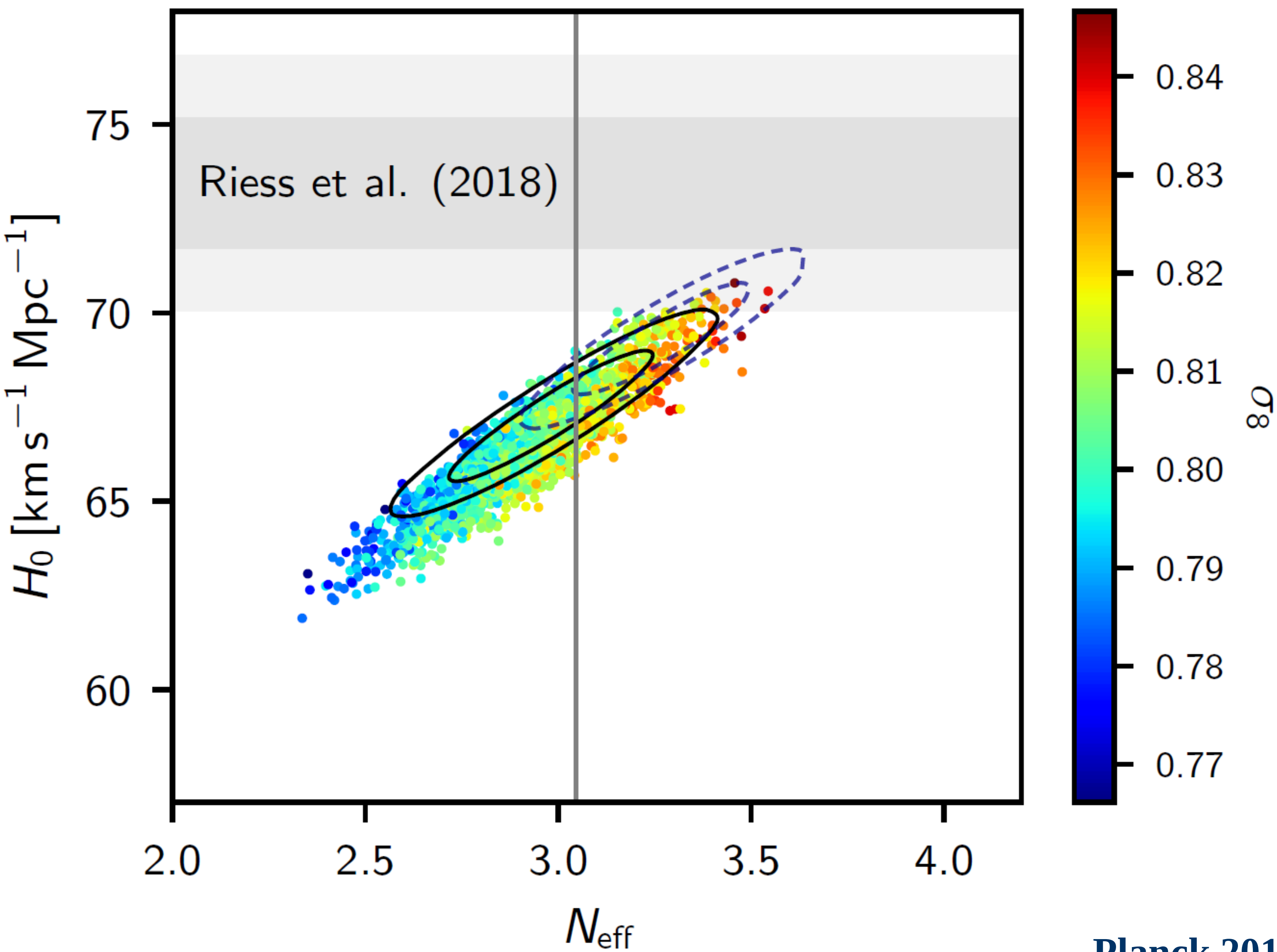
Large-scale matter power spectrum, P(k)
Wavenumber, k [h Mpc⁻¹]
10⁵
10⁴
10³
10²
10
10⁻²
10⁻¹
1
Galaxy clustering
/BAO
Cosmic
shear
CMB lensing
potential
(z~3-4)
CMB "primary" (z~1000)
Cluster
abundance
Lyman-α
(z~2-4)
Σmν=0.0 eV
Σmν=1×1.2 eV

Neutrino mass limits



Planck 2018: $\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

Neff



Planck 2018

Big Bang Nucleosynthesis

Nucleosynthesis era:

$100\ \mathrm{Me}V \gtrsim T \gtrsim 0.05\ MeV$

$t \sim 3-5\ min$

$10^{8} < z < 10^{12}$

But at $T \sim 1-2\ MeV$

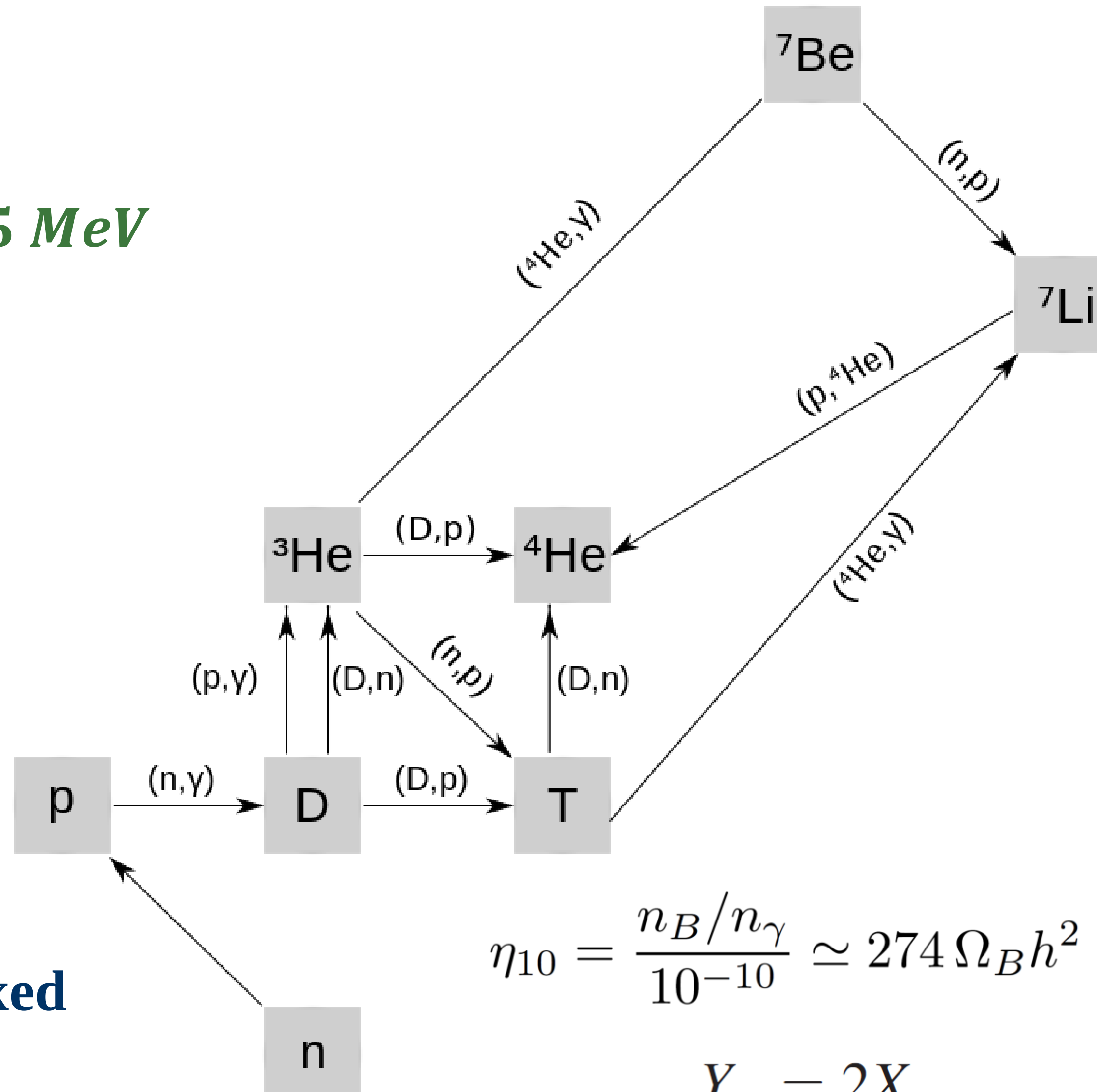
$(t \sim 0.2\ sec)$

neutrinos decouple

$$e + p \nleftrightarrow \nu + n$$

$$e + n \nleftrightarrow \bar{\nu} + p$$

$$Y_p \approx \frac{2(n/p)}{1+(n/p)}$$ **gets fixed**



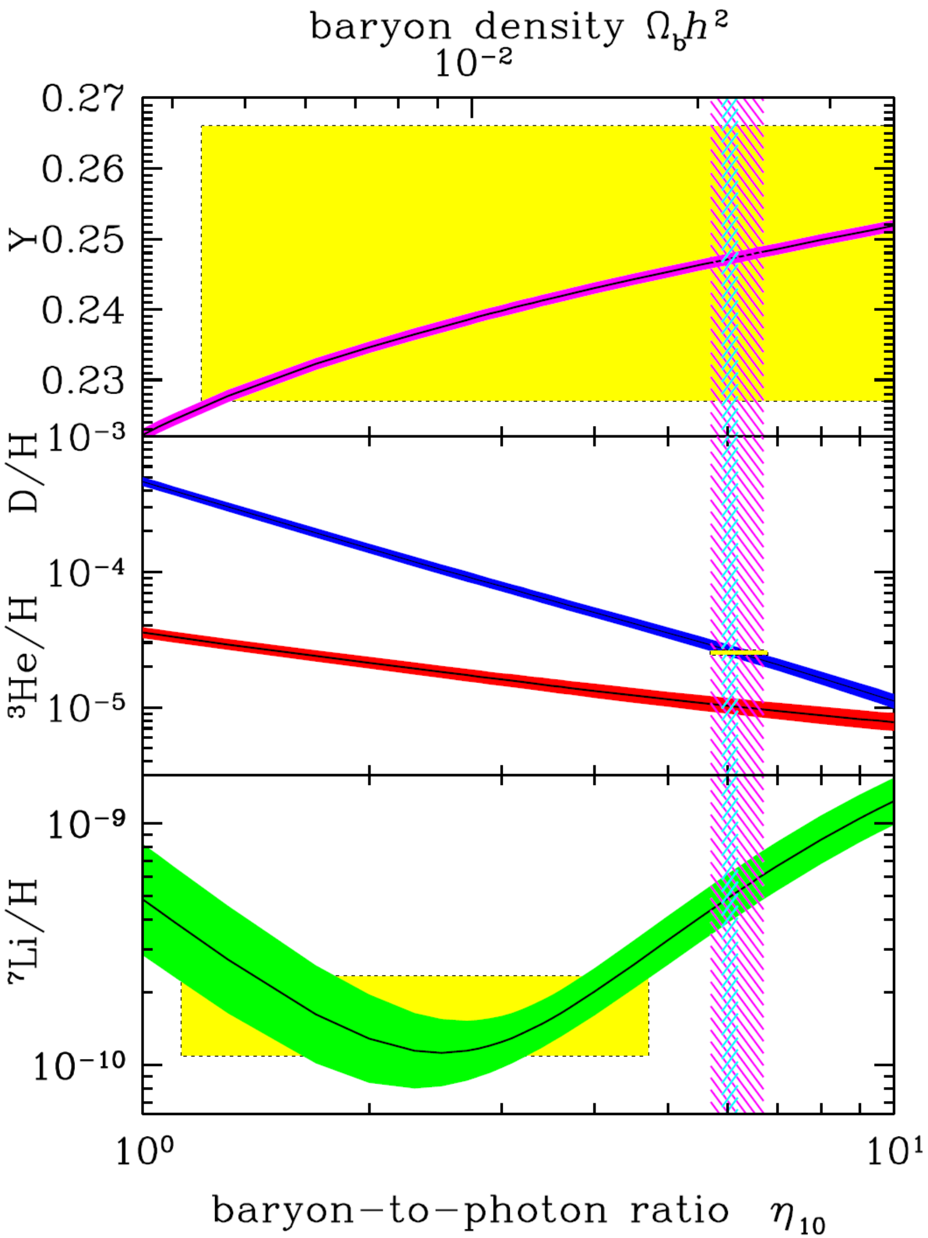
$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

$$Y_p = 2X_n$$

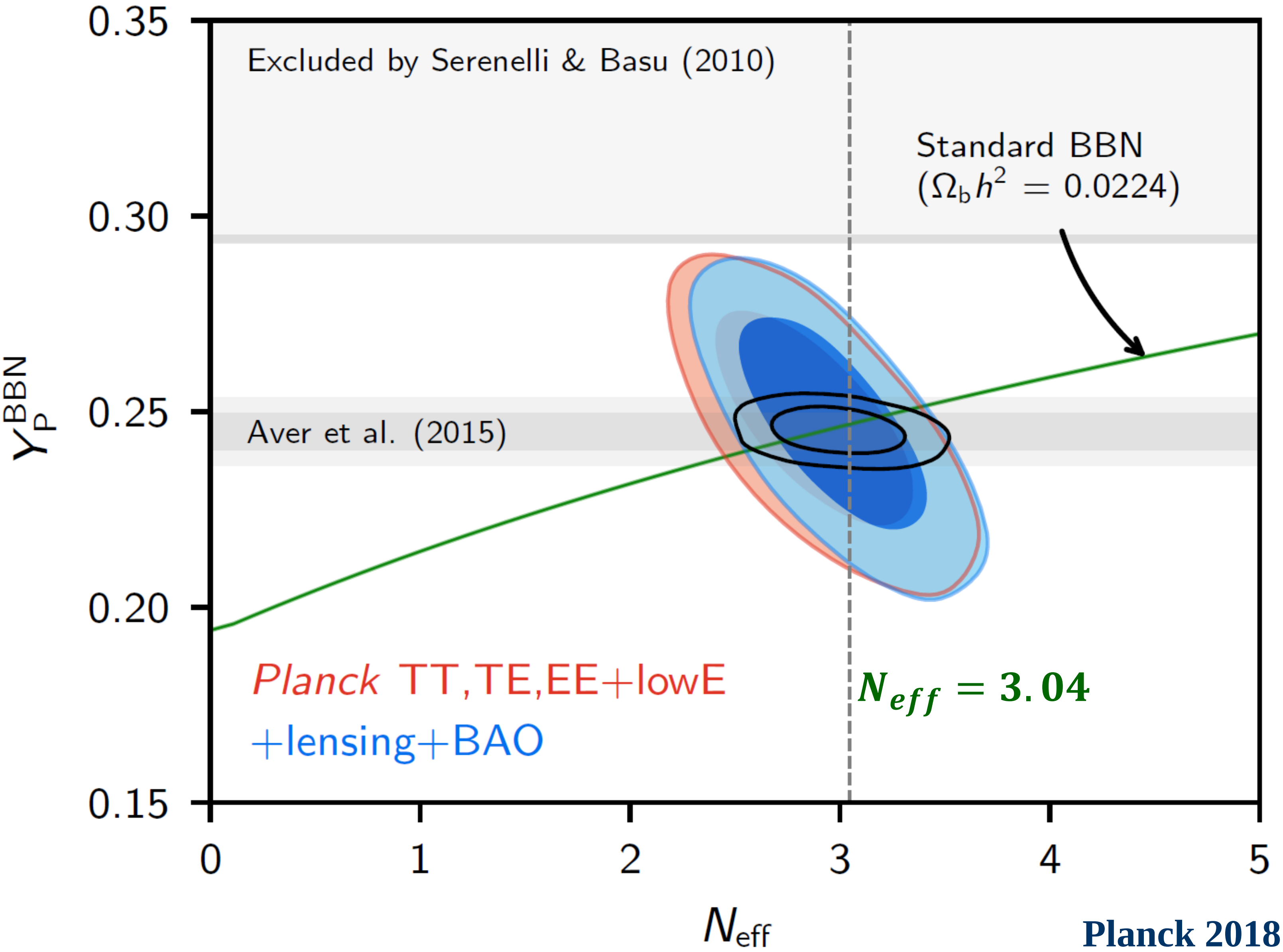
$$\frac{dX_n}{dt} = \lambda_{np}[(1-X_n)e^{-\Delta m/T} - X_n]$$

$$\lambda_{np} = n_\nu^{(0)}\langle \sigma v \rangle$$

Nucleosynthesis outputs



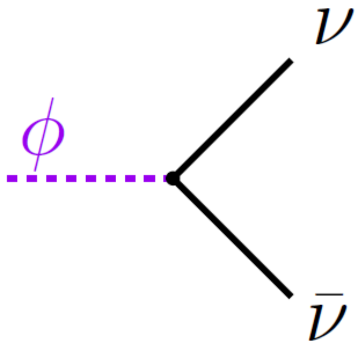
Neff



Planck 2018

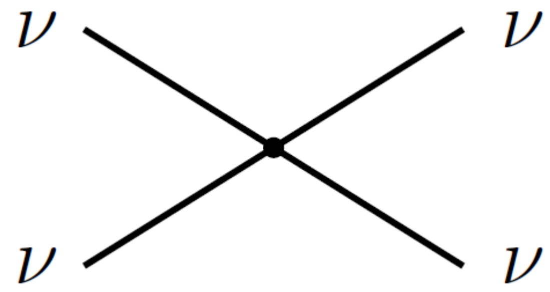
Neutrino - scalar NSI

Neutrinophilic bosons

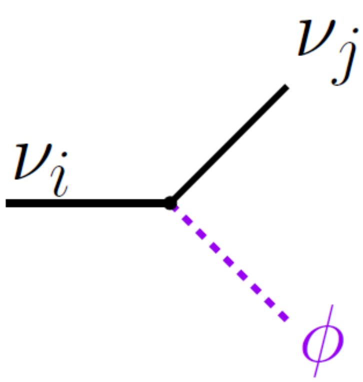


$$g_{ij}\bar{\nu}_i\nu_j\varphi$$

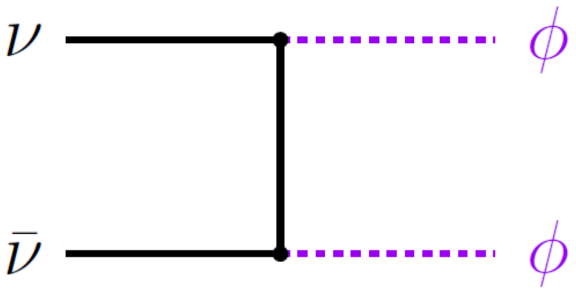
Neutrino scatterings



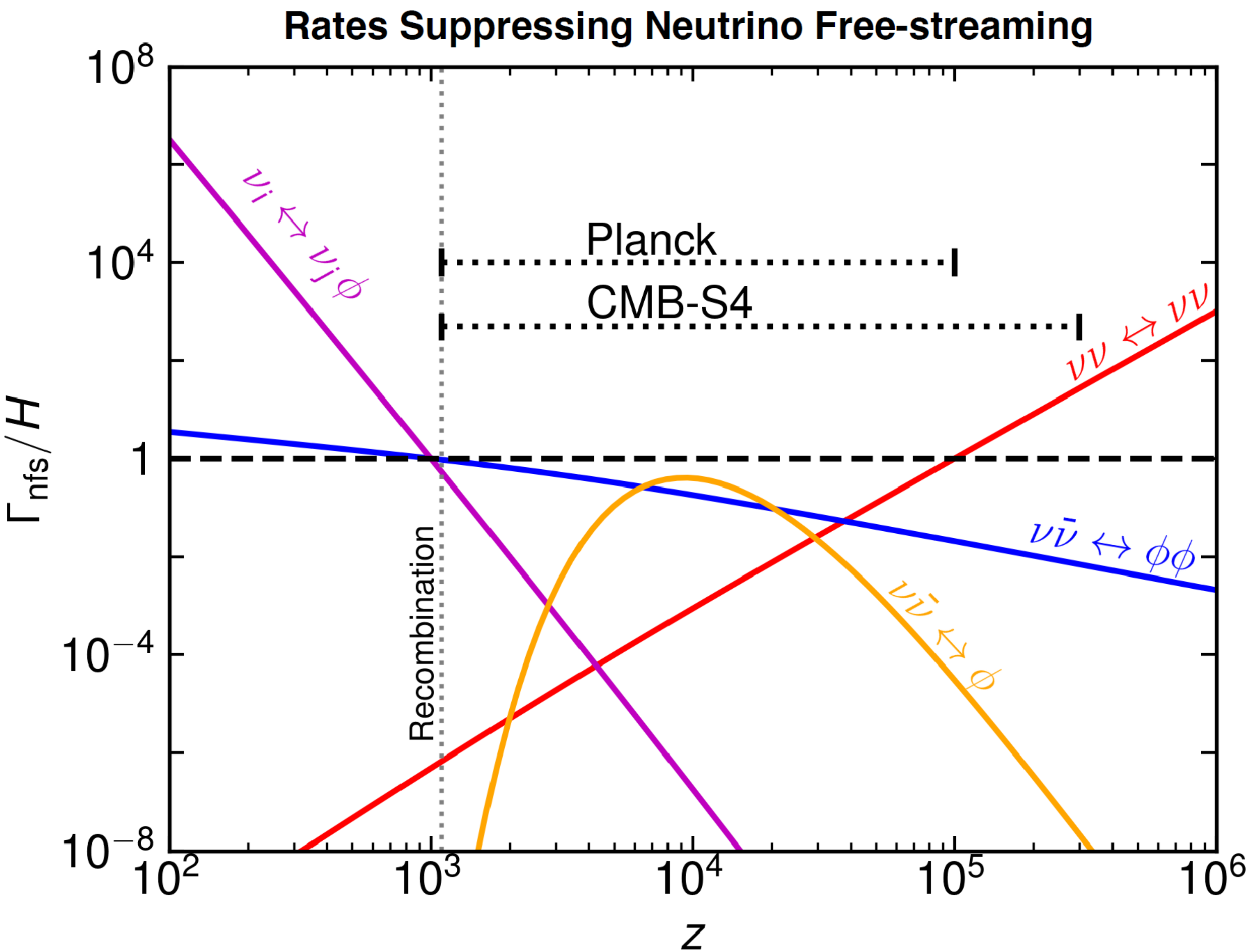
Neutrino decays



Neutrino annihilations



Neutrino - scalar NSI



Taule et al, 2022

Neutrino NSI

$$\sigma_\nu \to \delta G_{\mu\nu} \to \delta T_{\mu\nu}|_\gamma \to \delta T_\gamma$$

Neutrino NSI

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Phase space distribution function

$$f(\mathbf{x}, \mathbf{q}, \tau) = f^0(q)\left[1 + \Theta(\mathbf{x}, q, \mathbf{n}, \tau)\right]$$

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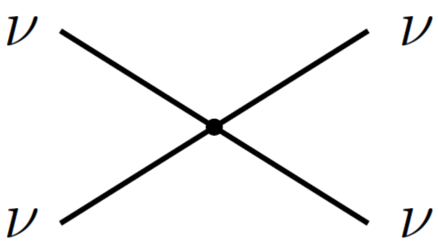
In synchronous gauge:

Boltzmann Eq. **(in Fourier space)** $\mu = \hat{k} \cdot \hat{n}$

$$f^0\left[\frac{\partial\Theta}{\partial\tau} + ik\frac{q}{\epsilon}\mu\Theta + \frac{d\ln f^0_\alpha}{d\ln q}\left[\dot{\eta} - \frac{\dot{h}+6\dot{\eta}}{2}\mu^2\right]\right] = a\tilde{C}^{(1)}[f]$$

Neutrino NSI

$$\nu_i(\mathbf{p}_1)+\nu_j(\mathbf{p}_2)\leftrightarrow\nu_k(\mathbf{p}_3)+\nu_l(\mathbf{p}_4).$$



$$\tilde{C}=\frac{1}{2E}\int d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4\delta^4(P+P_2-P_3-P_4)\mathcal{M}^2 F(\mathbf{k},\mathbf{p},\mathbf{p_2},\mathbf{p_3},\mathbf{p_4},\tau)$$

$$d\Pi=\frac{g_* d^3p}{2E(2\pi)^3}$$

$$\begin{aligned}F(\mathbf{x},\mathbf{p_1},\mathbf{p_2},\mathbf{p_3},\mathbf{p_4},\tau) = {} & f(\mathbf{x},\mathbf{p_3},\tau)f(\mathbf{x},\mathbf{p_4},\tau)[1-f(\mathbf{x},\mathbf{p_1},\tau)][1-f(\mathbf{x},\mathbf{p_2},\tau)] \\ & -f(\mathbf{x},\mathbf{p_1},\tau)f(\mathbf{x},\mathbf{p_2},\tau)[1-f(\mathbf{x},\mathbf{p_3},\tau)][1-f(\mathbf{x},\mathbf{p_4},\tau)]\end{aligned}$$

Neutrino NSI

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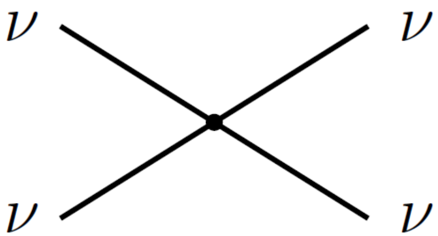

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Legendre mode decomposition:

$$\Theta(\mathbf{k},q,\mathbf{n},\tau) = \sum_{\ell=0}^{\infty}(-i)^{\ell}(2\ell+1)\theta_\ell(k,q,\tau)P_\ell(\mu)$$

Boltzmann neutrino hierarchy

$$\frac{\partial\theta_\ell}{\partial\tau} - \frac{kq}{(2\ell+1)\epsilon}\left[\ell\,\theta_{\ell-1} - (\ell+1)\theta_{\ell+1}\right] + \frac{d\ln f^0}{d\ln q}\left[\frac{\dot h + 6\dot\eta}{15}\delta_{\ell 2} - \frac{\dot h}{6}\delta_{\ell 0}\right] = \frac{a}{f^0}\tilde{C}_\ell$$

$$\tilde{C}^{(1)} = \frac{\mathrm{g}_*^3 T}{128\pi^3 z}\frac{d\ln f^{(0)}(z)}{d\ln p}\sum_{\ell=0}^{\infty}(-i)^\ell(2\ell+1)\vartheta_\ell P_\ell(\mu)\left[\mathcal{A}(z) + \mathcal{B}_\ell(z) - 2\mathcal{D}_\ell(z)\right]$$

$$z = \epsilon/T_0$$

Boltzmann neutrino hierarchy (RTA)

$$f(x^i, q_j, \tau) = f_0(q)\left[1 + \Psi(x^i, q, \hat{n}_j, \tau)\right]$$

Relaxation time approximation $C/_{f_0} \approx a\,\Gamma\,\Psi$

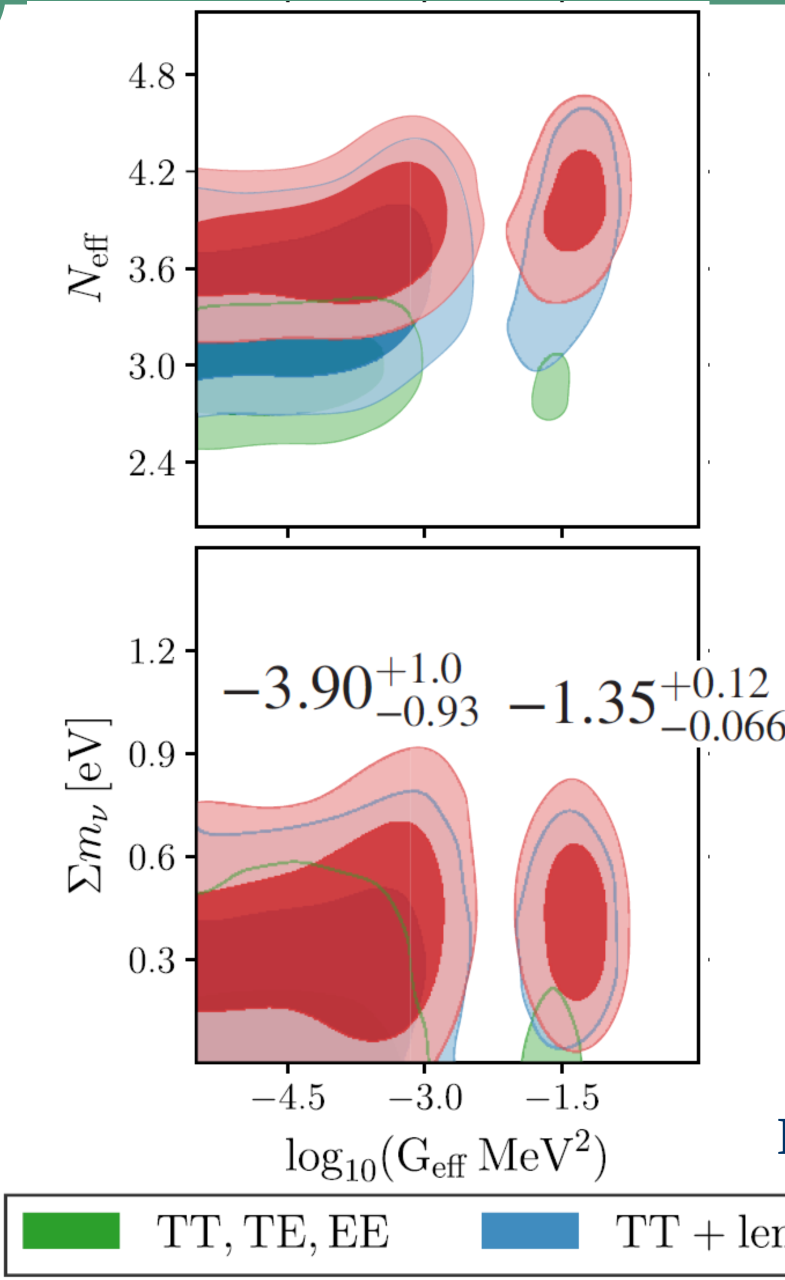
$$\dot{\Psi}_0 = -\frac{qk}{\epsilon}\Psi_1 + \frac{\dot{h}}{6}\frac{d\ \ln\ f_0}{d\ \ln\ q},$$

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

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

$$\dot{\Psi}_{l\geq 3} = \frac{qk}{(2l+1)\epsilon}(l\Psi_{l-1} - (l+1)\Psi_{l+1}) - a\Gamma\Psi_l.$$

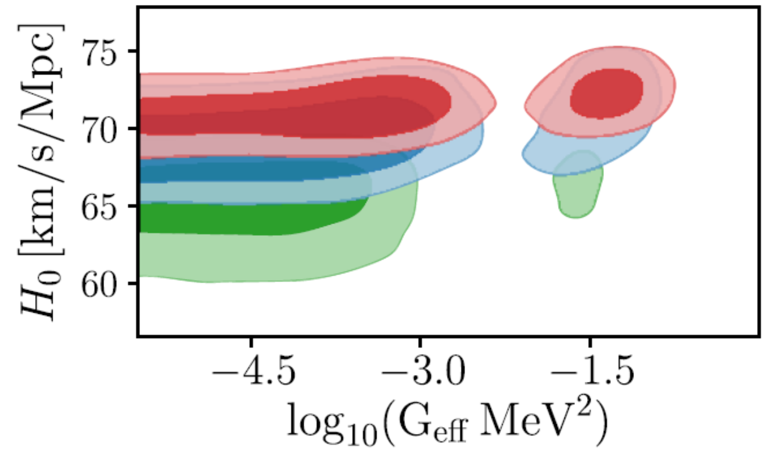
NSI bounds for heavy scalar mediator



Heavy scalar mediator:

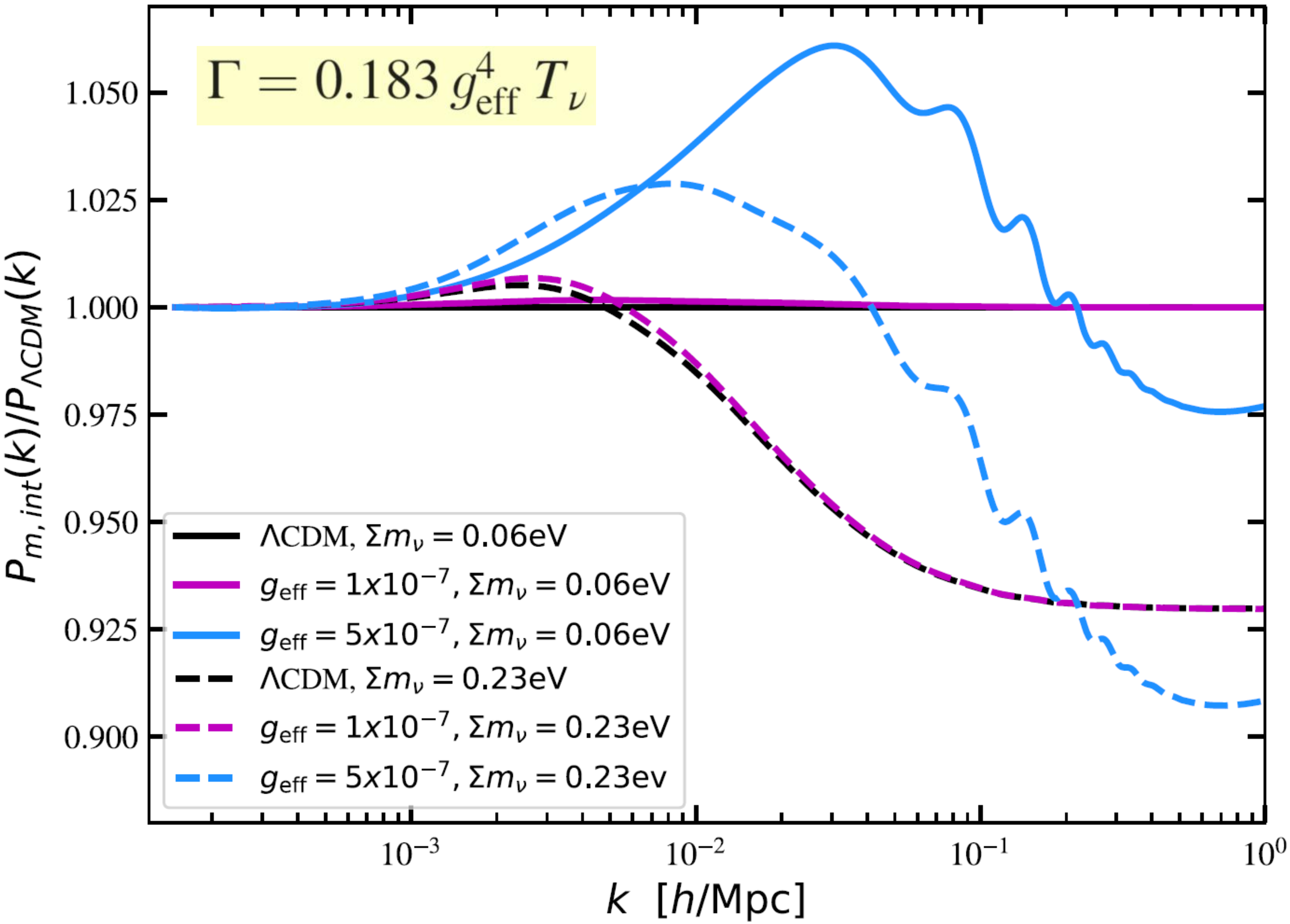
$$|\mathcal{M}|^2 = 2G_{eff}^2(s^2 + t^2 + u^2)$$

$$G_{eff} = |g_\nu|^2/m_\varphi^2$$

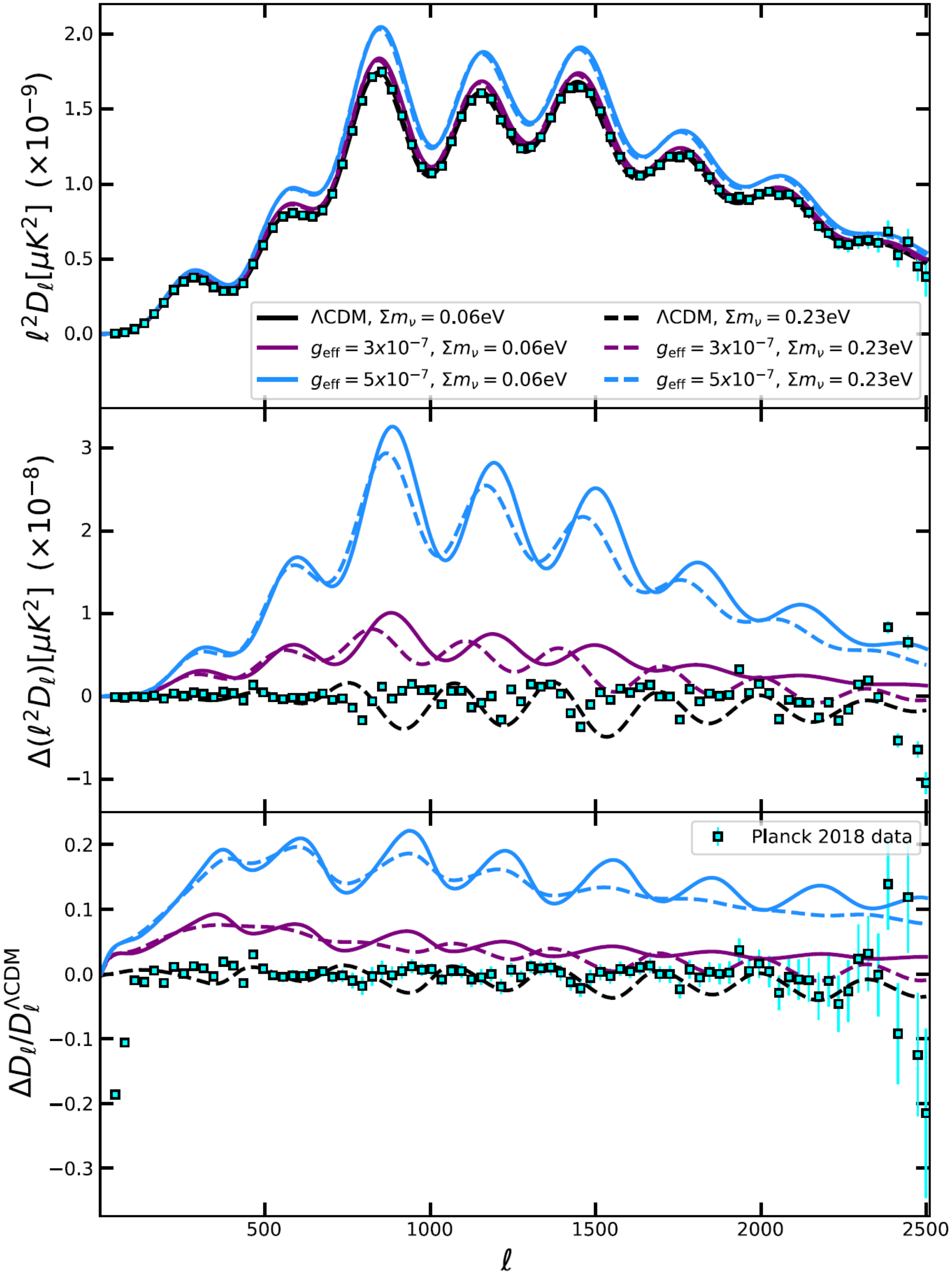


Kreisch, Cyr-Racine, Dore, PRD 2020

NSI bounds for light scalar mediator



J. Venzor,G. García-Arrollo, APL, J. de Santiago, PRD 105, 123539 (2022)



$\ell^2 D_\ell [\mu K^2]$ $(\times 10^{-9})$
ΛCDM, $\Sigma m_\nu = 0.06$eV
ΛCDM, $\Sigma m_\nu = 0.23$eV
$g_{\rm eff} = 3\text{x}10^{-7}$, $\Sigma m_\nu = 0.06$eV
$g_{\rm eff} = 3\text{x}10^{-7}$, $\Sigma m_\nu = 0.23$eV
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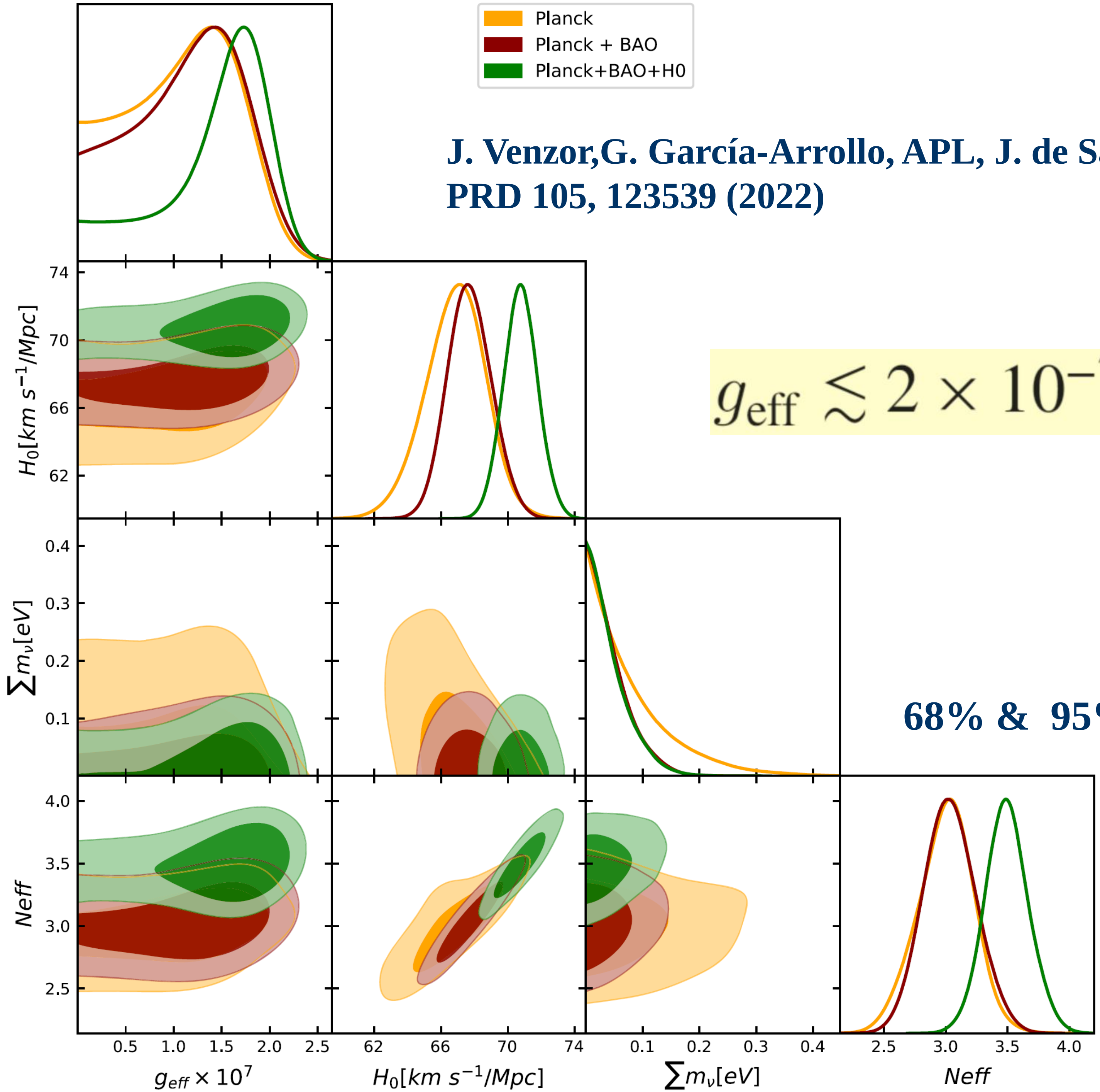
$g_{\rm eff} = 5\text{x}10^{-7}$, $\Sigma m_\nu = 0.23$eV
$\Delta(\ell^2 D_\ell)[\mu K^2]$ $(\times 10^{-8})$
Planck 2018 data
$\Delta D_\ell / D_\ell^{\Lambda\rm CDM}$
ℓ



J. Venzor,G. García-Arrollo, APL, J. de Santiago, PRD 105, 123539 (2022)

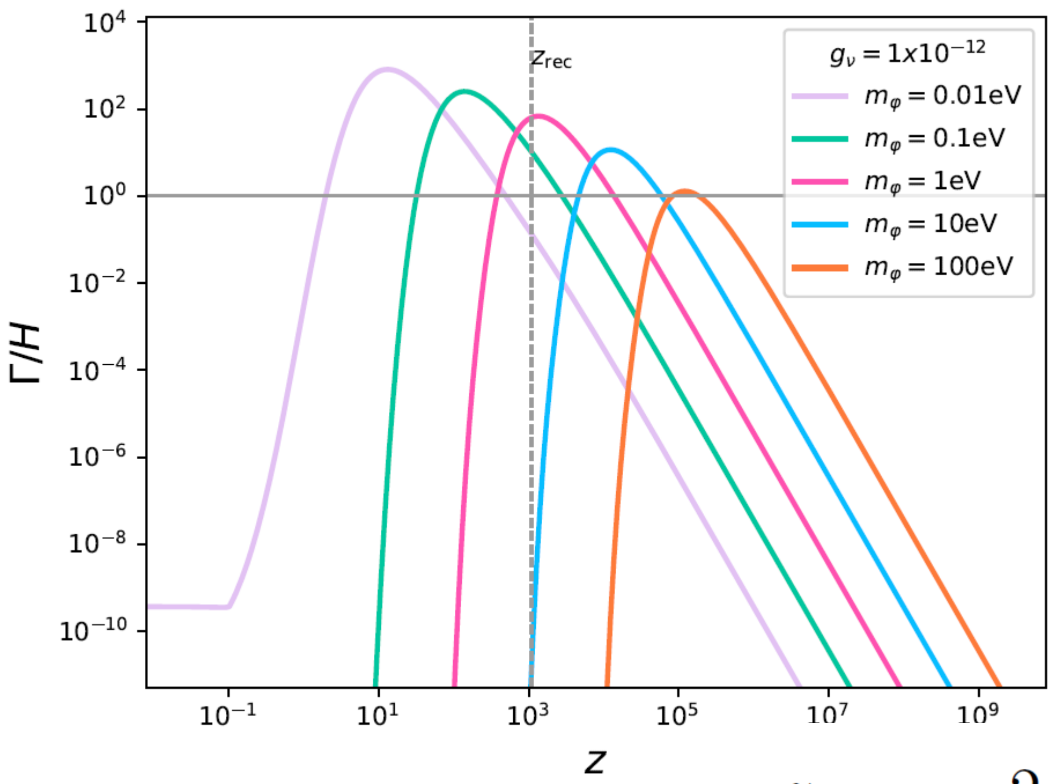
$$g_{\rm eff} \lesssim 2 \times 10^{-7}$$

68% & 95% C.L

Resonant NSI effects

$$10^{-3}eV \ll m_\varphi \ll 10^{3}eV$$

$$\sigma(s) = \frac{g_\upsilon{}^4}{4\pi}\frac{s}{\left(s-m_\varphi^2\right)^2+\Gamma_\varphi^2 m_\varphi^2} \xrightarrow[\Gamma_\varphi\to 0]{} \frac{g_\upsilon^2}{m_\varphi^2}s\delta(s-m_\varphi^2)$$

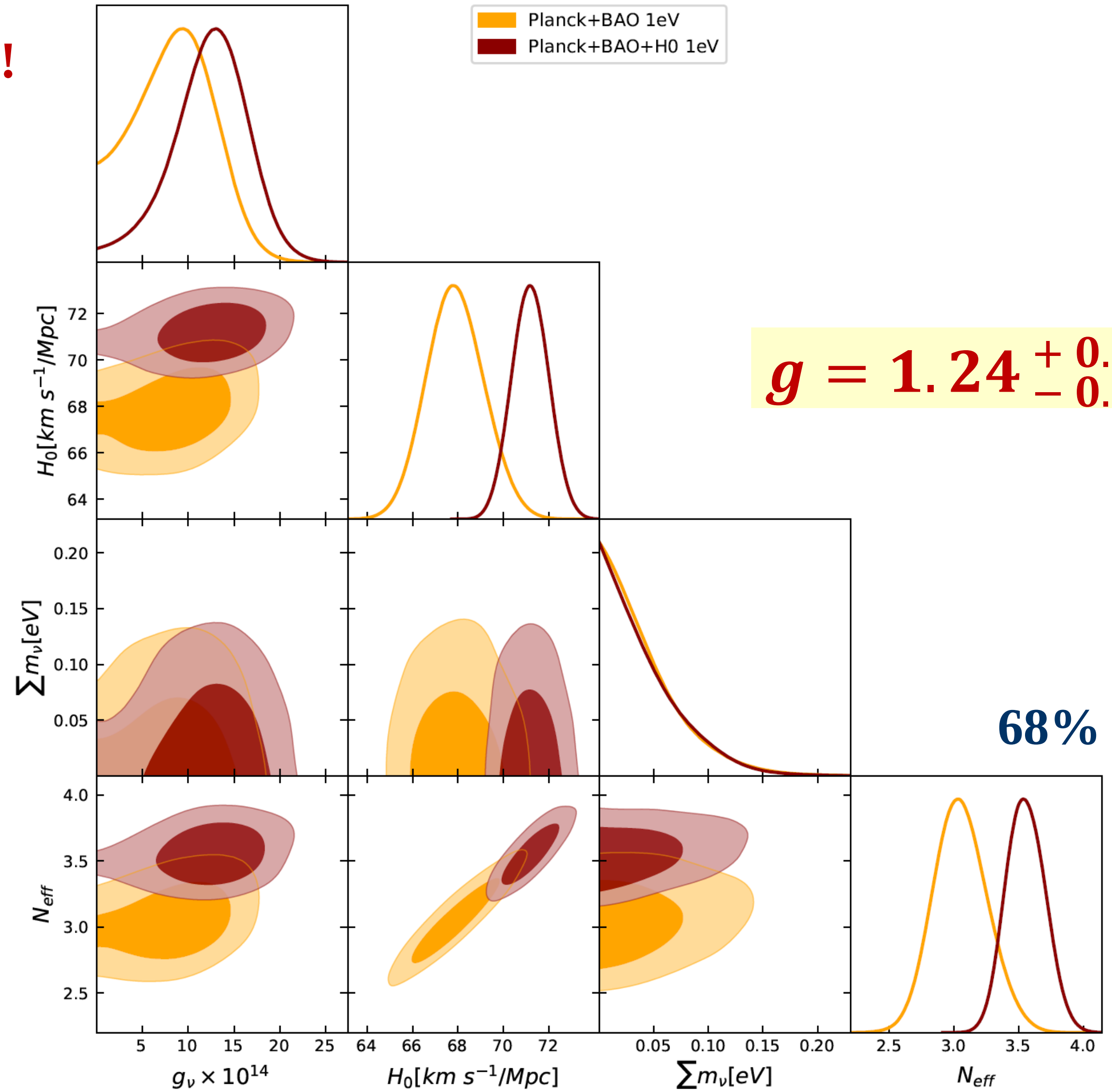


$$\Gamma_{\rm scatt} = \langle \sigma v_{\rm MOL}\rangle\, n_\nu,$$

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

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

Preliminary!



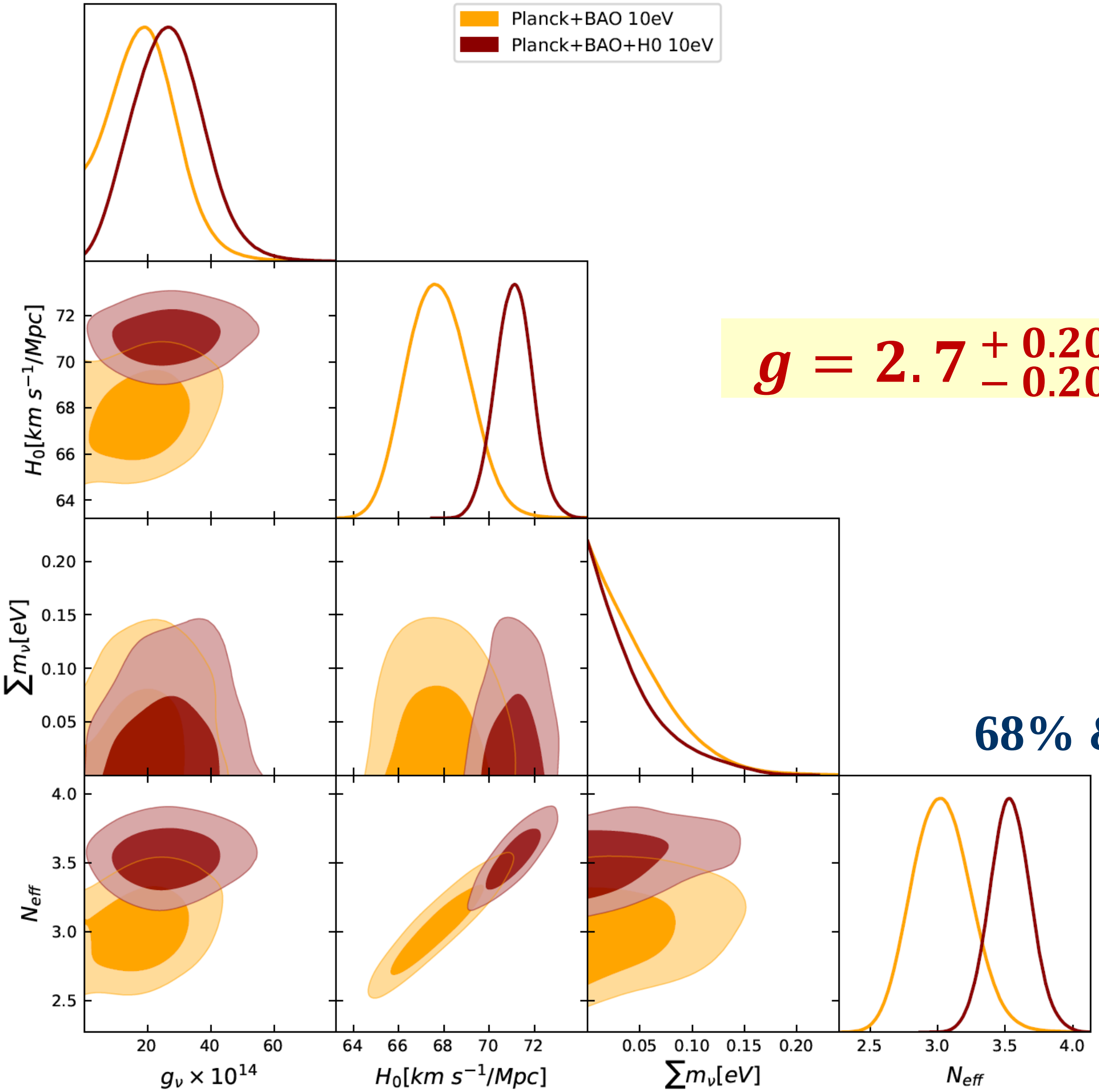
$$g = 1.24^{+0.78}_{-0.89} \times 10^{-13}$$

95% C.L.

68% & 95% C.L

FIG. 11. Posterior probability for different sets of data and for $M_\phi = 1\text{eV}$

Preliminary!



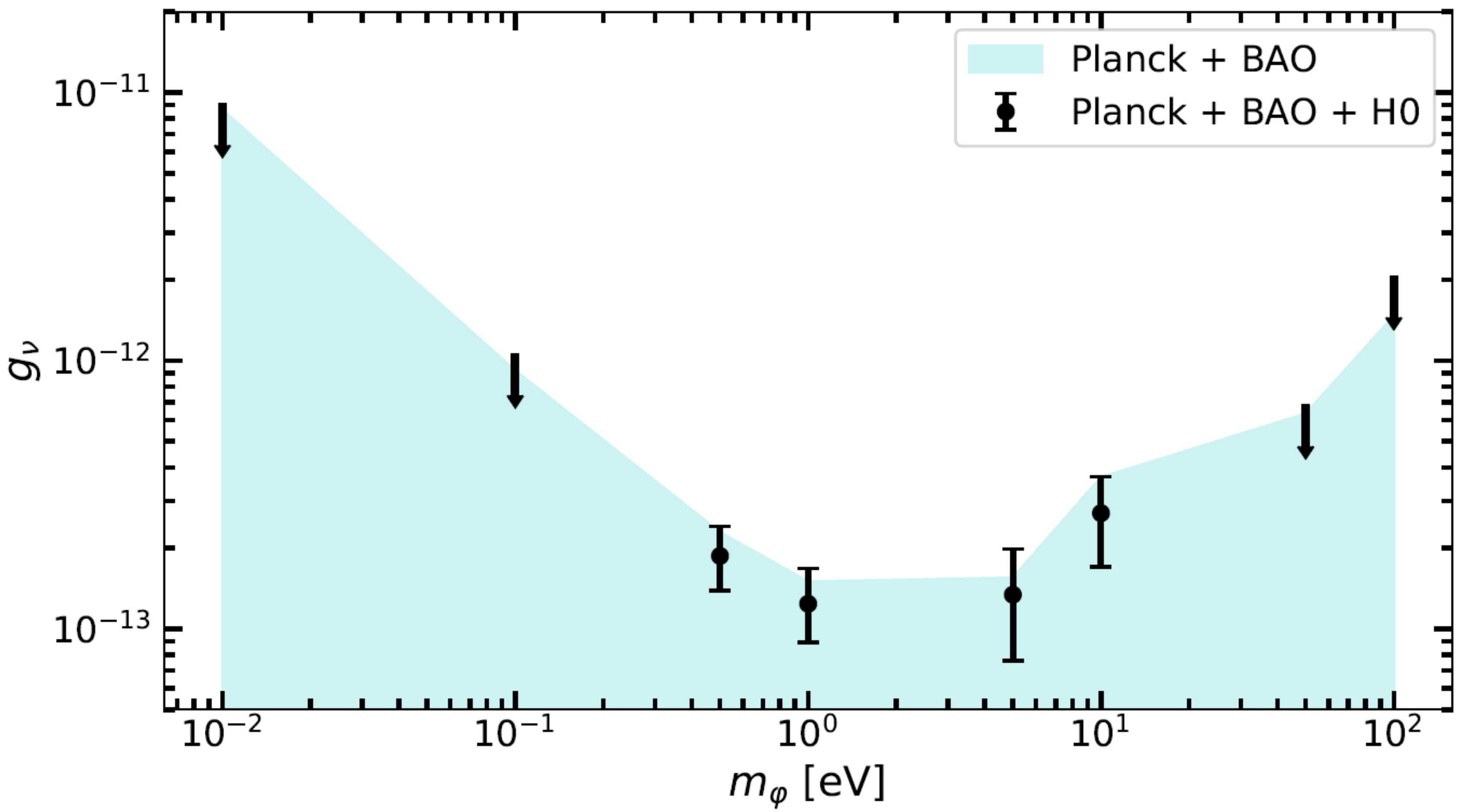
$$g = 2.7^{+0.20}_{-0.20} \times 10^{-13}$$

95% C.L.

68% & 95% C.L

FIG. 12. Posterior probability for different sets of data and for $M_\phi = 10\text{eV}$

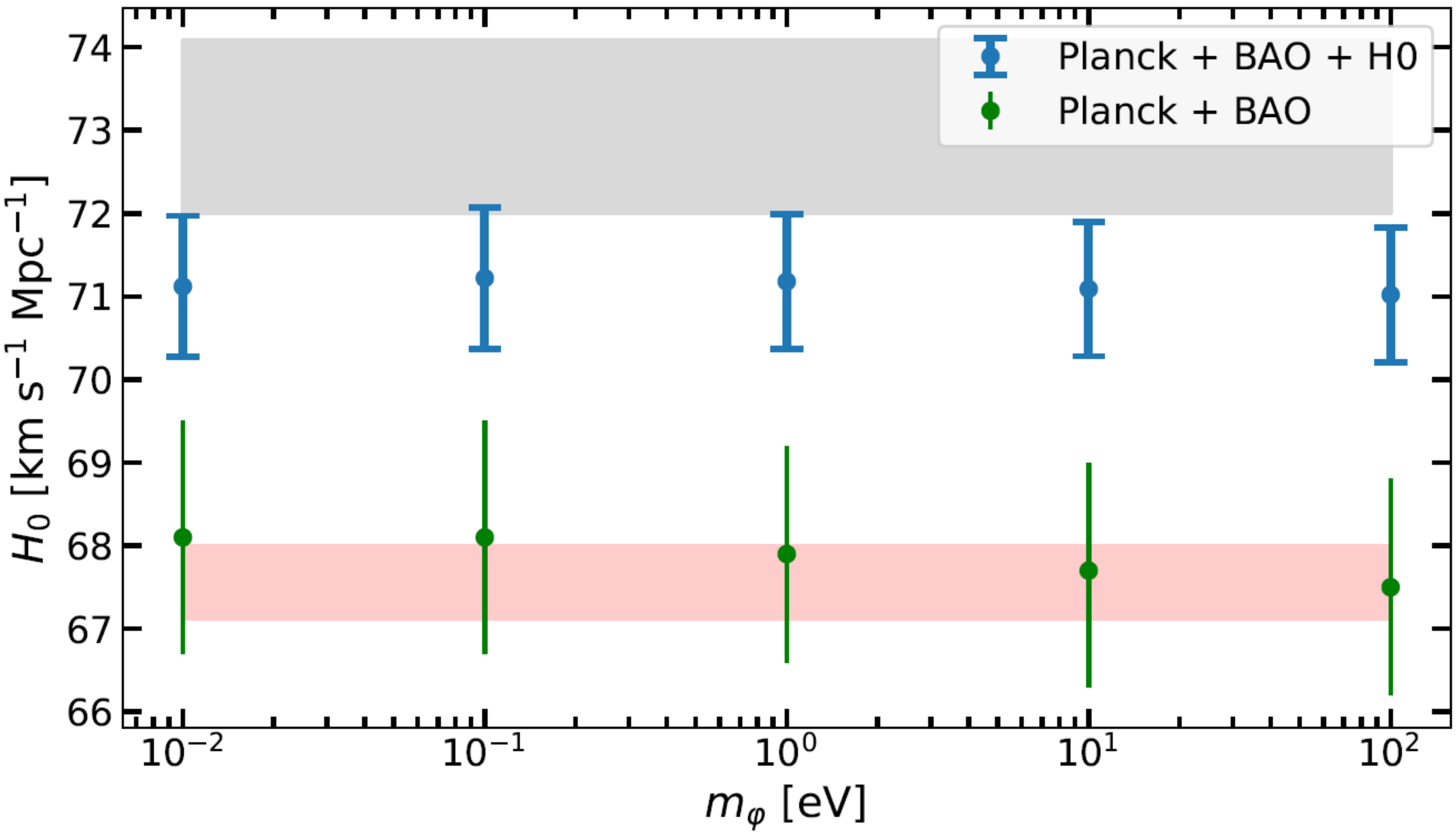
Resonant NSI bounds



Preliminary!

Resonant NSI effect on H_0

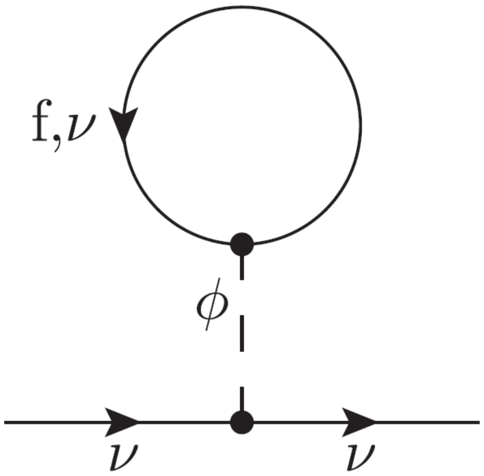
Preliminary!



Tension decreased down to about 2.8σ – 3.3 σ

Effective thermal mass from scalar NSI

$$\Delta m(m_f;T) = \frac{m_f}{\pi^2}\int_{m_f}^{\infty} dk\sqrt{k^2 - m_f^2}f(k)$$

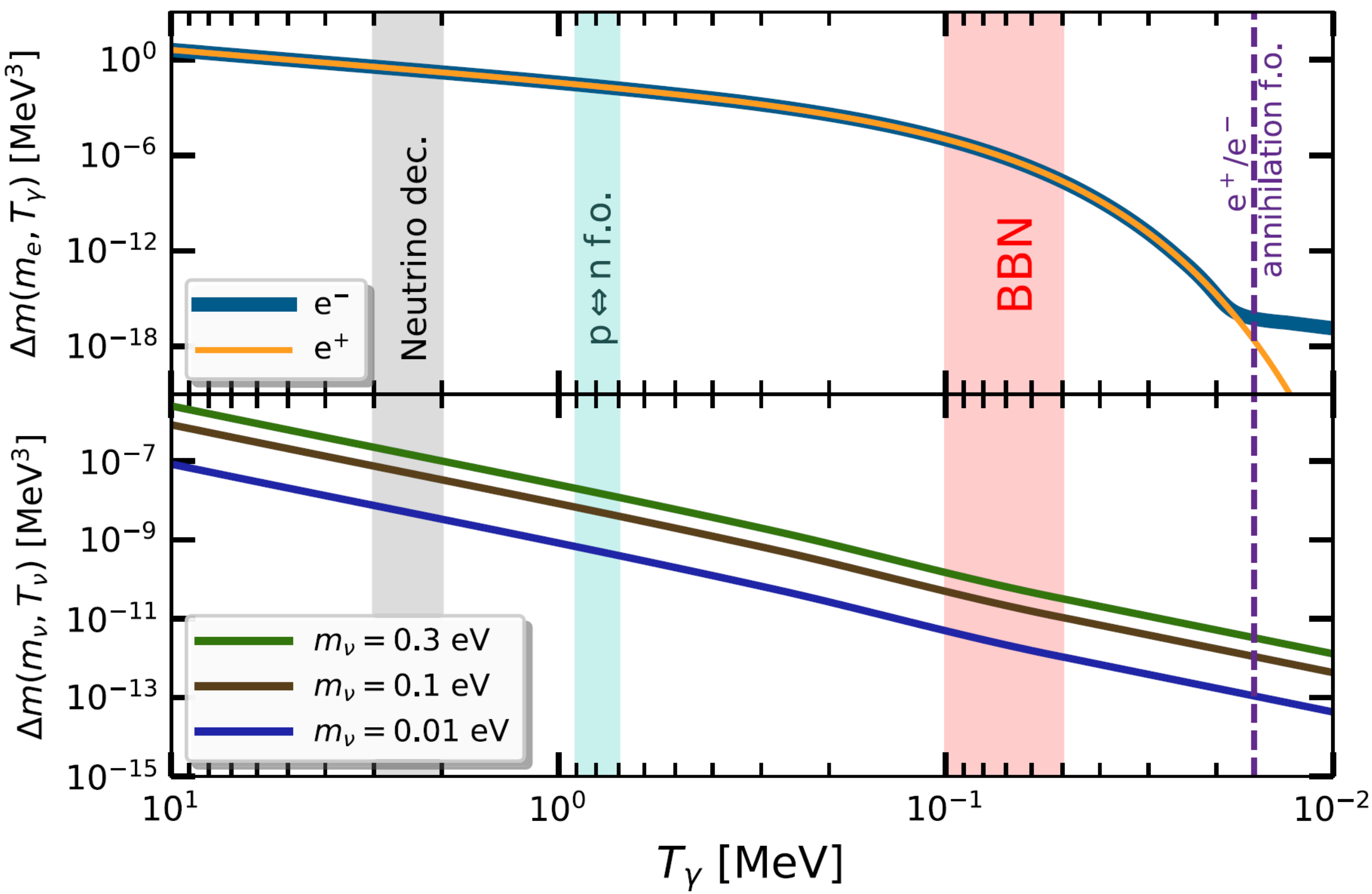


$$m_{\text{eff}} = m_\nu + 2G_{\text{eff}}\Delta m(m_e;T_\gamma) + 3G_{\text{S}}\Delta m(m_\nu;T_\nu)$$

$$\boxed{G_{\text{eff}} = \frac{g_f g_\nu}{m_\phi^2}} \qquad \boxed{G_{\text{S}} = \frac{g_\nu^2}{m_\phi^2}}$$

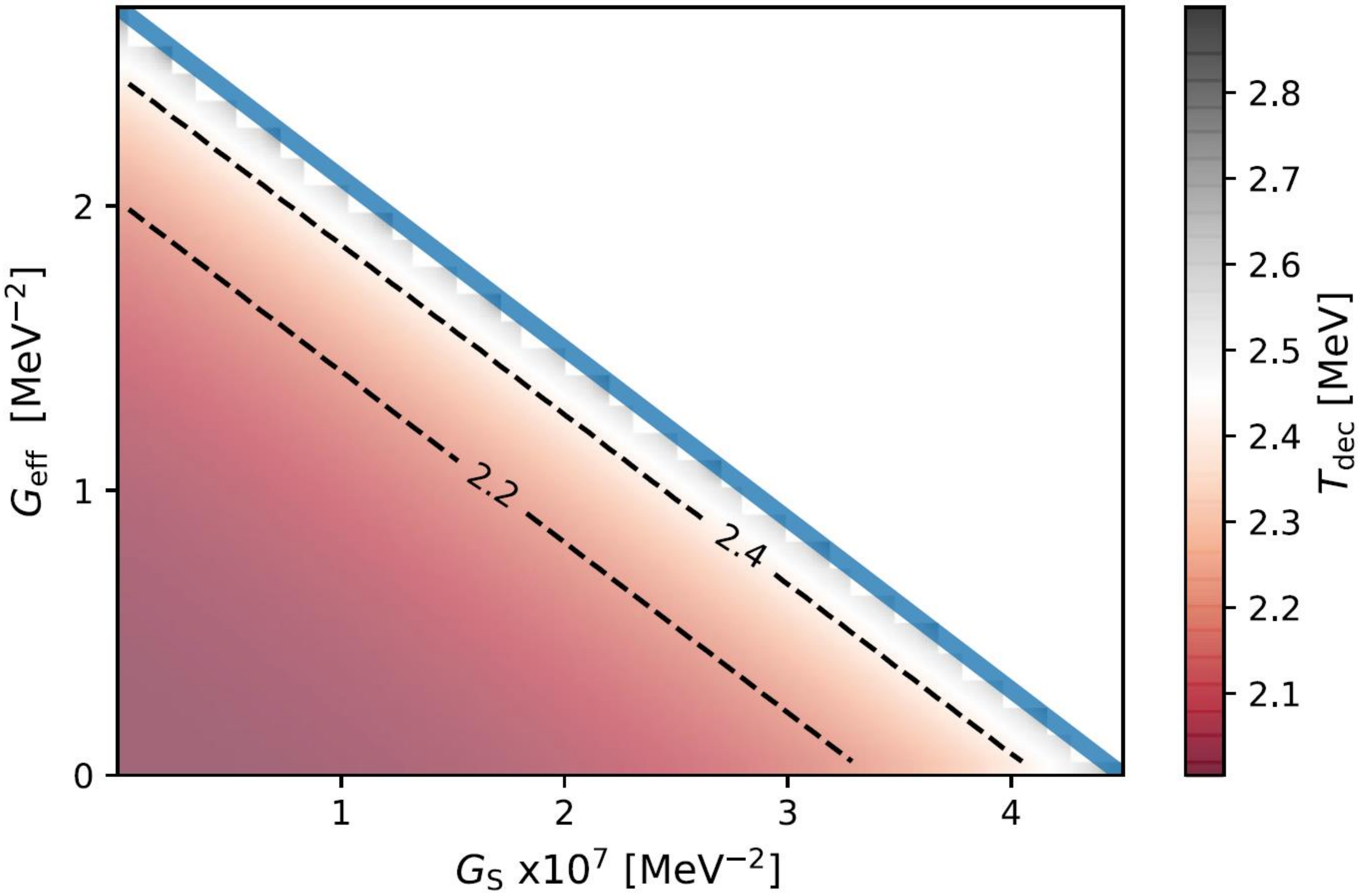
K. S. Babu, G. Chauhan, and P. S. B. Dev, PRD 101 (2020)

Effective mass from νNSI



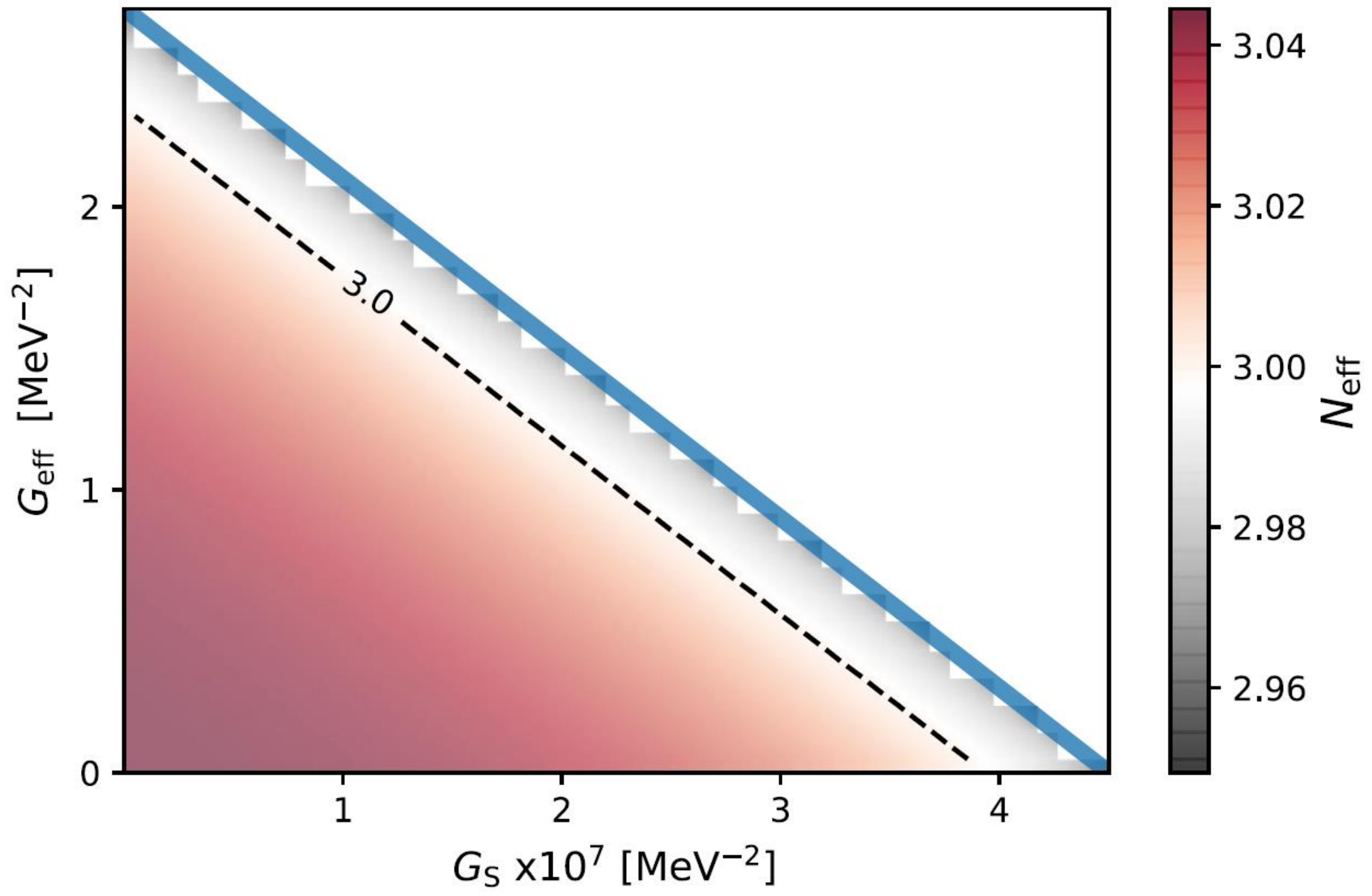
J. Venzor, APL, J. de Santiago, PRD 103 (2020)

NSI effective mass effects on Tdec



J. Venzor, APL, J. de Santiago, PRD 103 (2020)

Light scalar NSI effects on Neff



J. Venzor, APL, J. de Santiago, PRD 103 (2020)

BBN bounds on light scalar NSI

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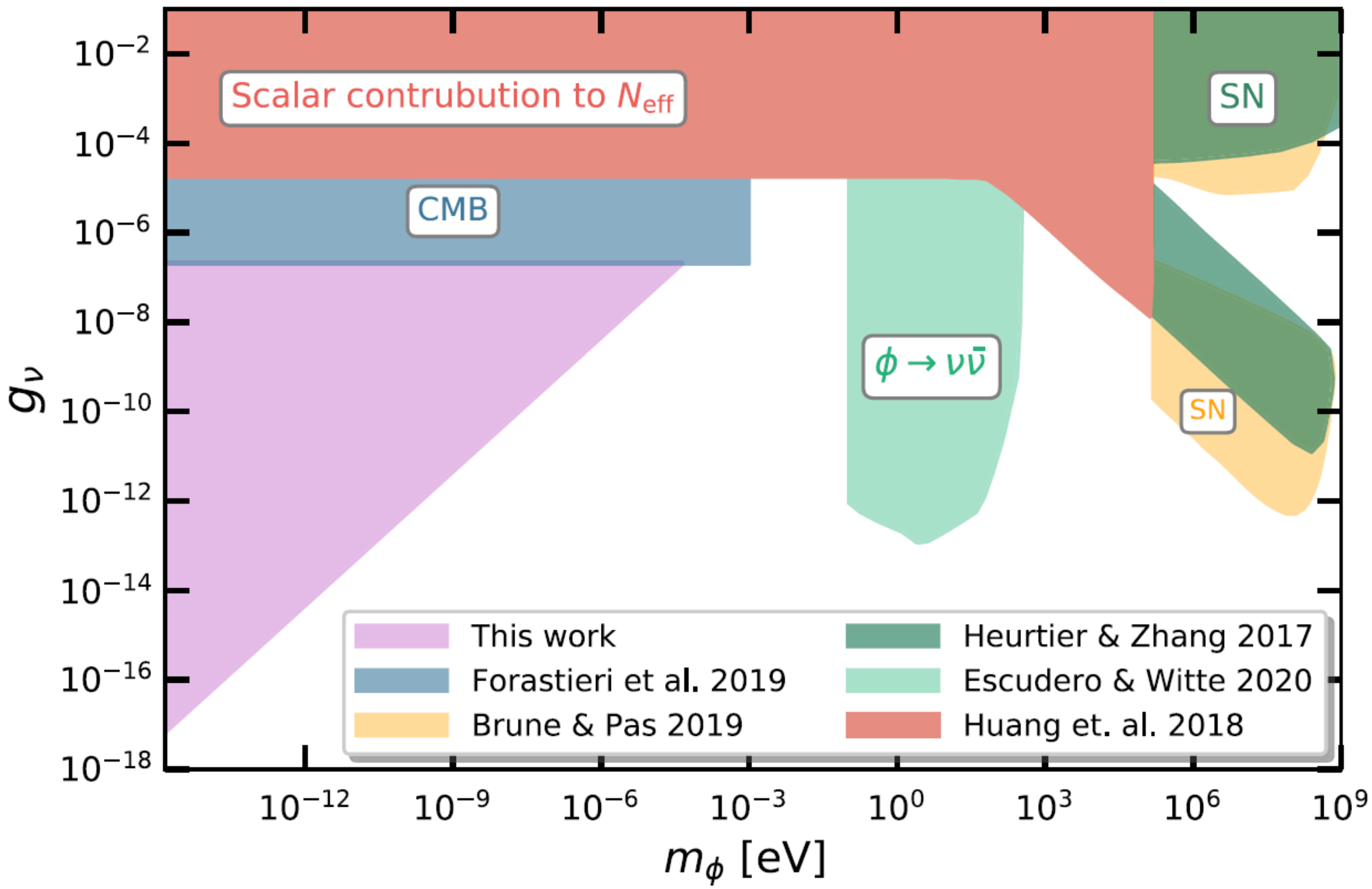
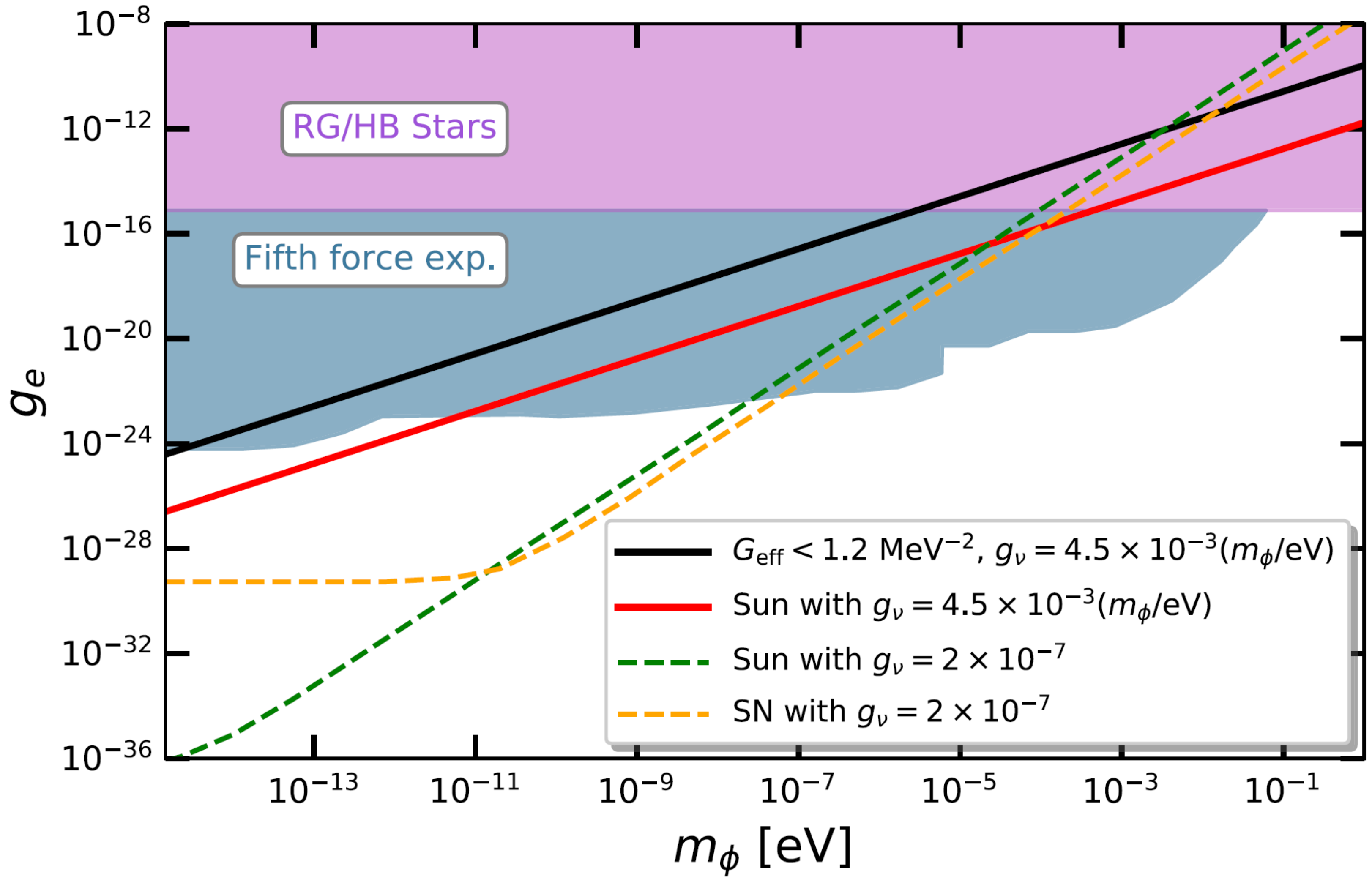


$$G_{\rm eff} < 1.2\ {\rm MeV}^{-2} \quad (68\%\ {\rm C.L.})$$

$$g_\nu < 4.5 \times 10^{-3} \left(\frac{m_\phi}{\rm eV}\right) \quad (68\%\ {\rm C.L.}).$$

BBN bounds on light scalar NSI



$$G_S < 2.0 \times 10^7 \ \mathrm{MeV}^{-2} \quad (68\% \ \mathrm{C.L.})$$

$$g_e < 2.7 \times 10^{-10} \left(\frac{m_\phi}{\mathrm{eV}} \right)$$

Concluding remarks

- Neutrinos play an important role along termal history of the Universe.

- Cosmological data (CMB, Matter spectrum, BBN) are sensible to neutrino physics through

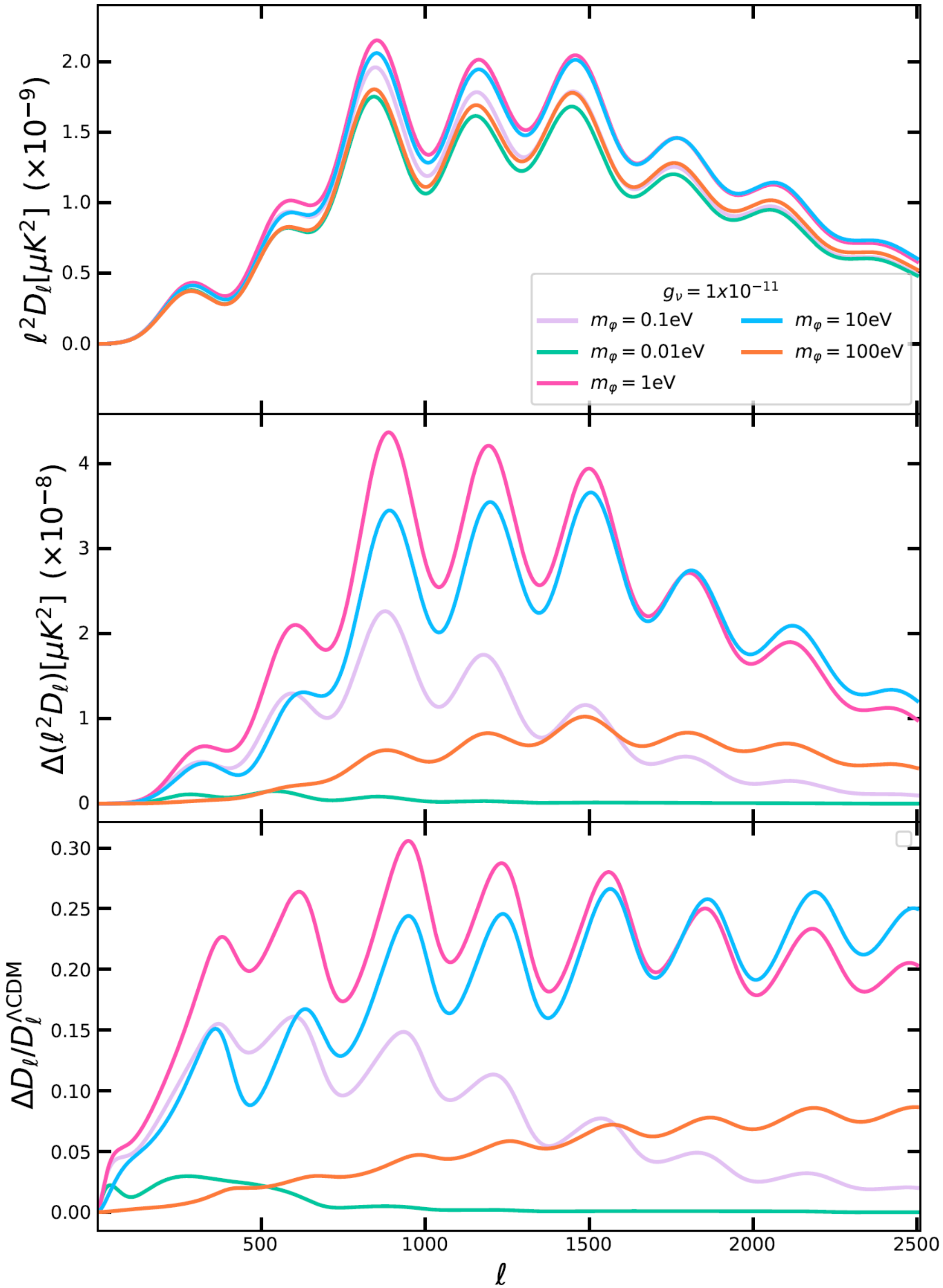
$$T_{dec}, \qquad \sum m_\nu , \qquad N_{eff}, \qquad (k_{FS})$$

- NSI may alter such parameters, providing a way to explore for observational bounds to the new couplings

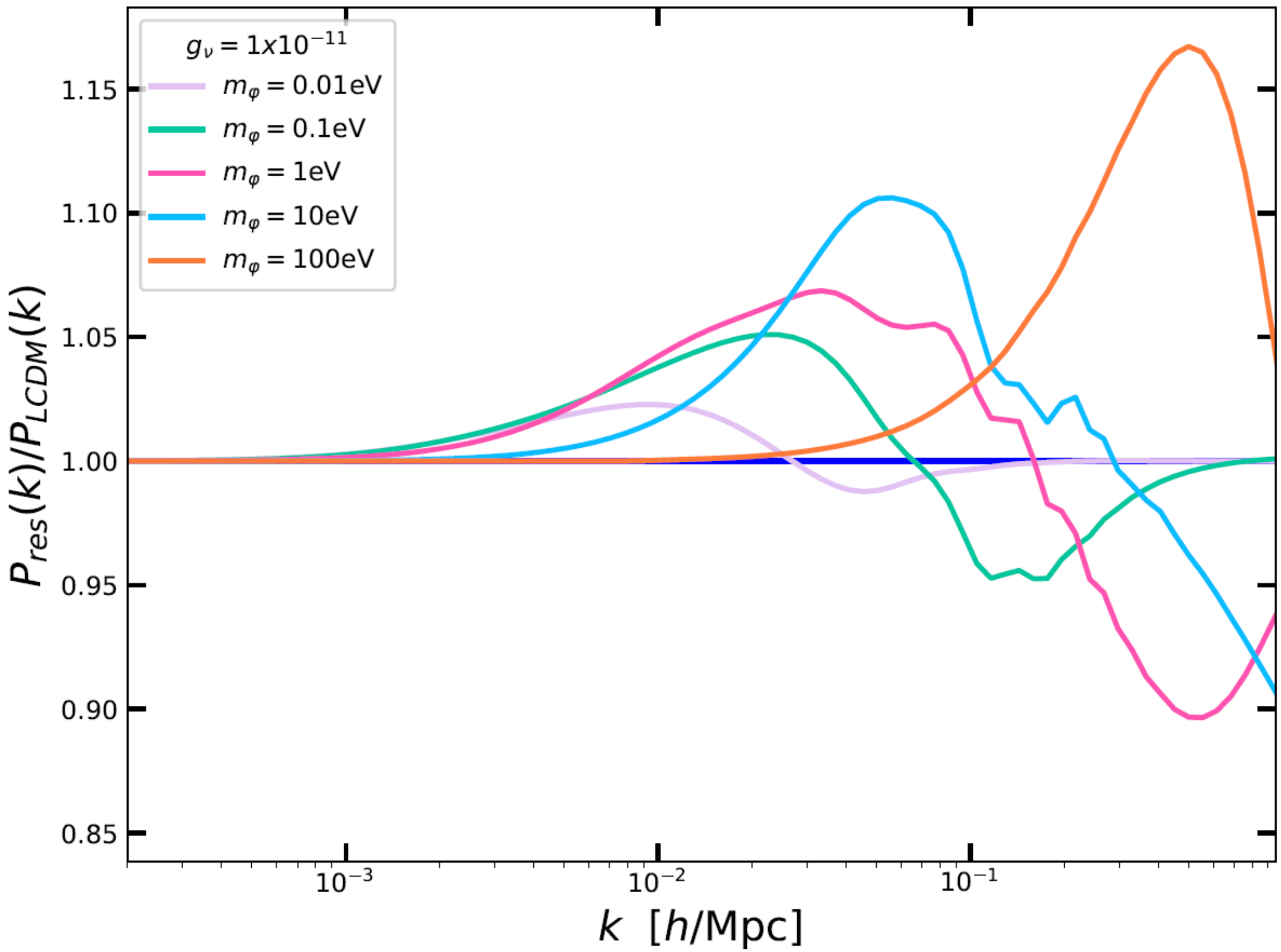
- We have explored NSI effects on CMB-BAO-H0 data and BBN for light scalar mediators, and around resonance

More work underway…

TT-PS

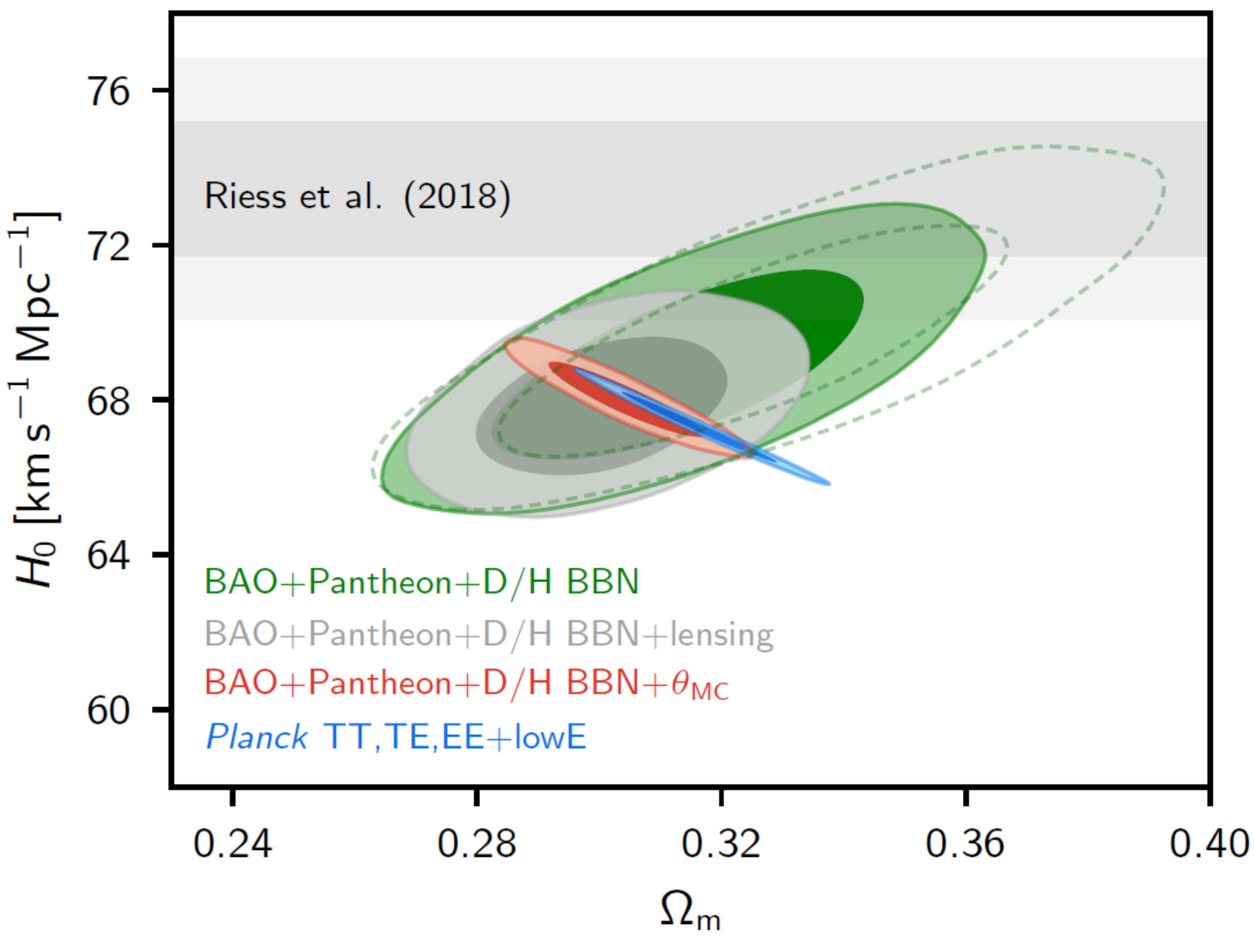


$\ell^2 D_\ell[\mu K^2]$ $(\times 10^{-9})$
$g_\nu = 1x10^{-11}$
$m_\varphi = 0.1$eV
$m_\varphi = 0.01$eV
$m_\varphi = 1$eV
$m_\varphi = 10$eV
$m_\varphi = 100$eV
$\Delta(\ell^2 D_\ell)[\mu K^2]$ $(\times 10^{-8})$
$\Delta D_\ell / D_\ell^{\Lambda\mathrm{CDM}}$
ℓ



$g_\nu = 1x10^{-11}$
$m_\varphi = 0.01$eV
$m_\varphi = 0.1$eV
$m_\varphi = 1$eV
$m_\varphi = 10$eV
$m_\varphi = 100$eV
$P_{res}(k)/P_{LCDM}(k)$
1.15
1.10
1.05
1.00
0.95
0.90
0.85
10^{-3}
10^{-2}
10^{-1}
k [h/Mpc]

H_0 Tension



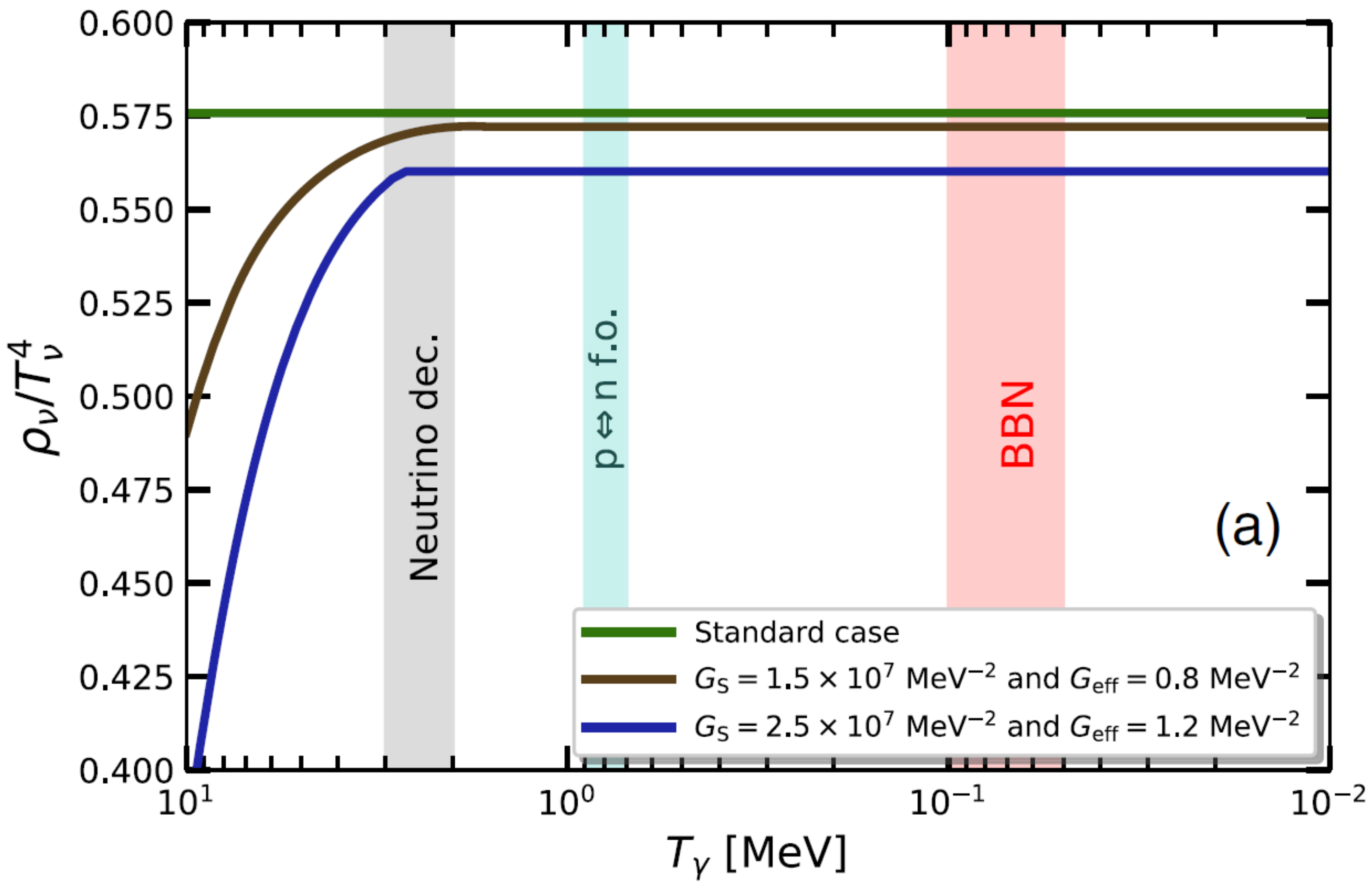
Riess et al. (2018)
76
72
68
64
60
H_0 [km s^{-1} Mpc^{-1}]
BAO+Pantheon+D/H BBN
BAO+Pantheon+D/H BBN+lensing
BAO+Pantheon+D/H BBN+θ_{MC}
Planck TT,TE,EE+lowE
0.24
0.28
0.32
0.36
0.40
Ω_m

Resonant NSI interaction limits

Data: Planck +	BAO	BAO+H0	BAO	BAO+H0	BAO	BAO+H0	BAO	BAO+H0	BAO	BAO+H0
M_ϕ[eV]	10^{-2}		10^{-1}		1		10		100	
H_0[km s^{-1}/Mpc]	$68.1^{+2.8}_{-2.8}$	$71.1^{+1.8}_{-1.8}$	$68.1^{+2.7}_{-2.7}$	$71.2^{+1.6}_{-1.7}$	$67.9^{+2.5}_{-2.3}$	$71.2^{+1.6}_{-1.6}$	$67.7^{+2.6}_{-2.6}$	$71.1^{+1.6}_{-1.6}$	$67.5^{+2.6}_{-2.7}$	$71.0^{+1.7}_{-1.7}$
N_{eff}	$3.12^{+0.47}_{-0.44}$	$3.58^{+0.31}_{-0.29}$	$3.12^{+0.43}_{-0.43}$	$3.59^{+0.31}_{-0.31}$	$3.05^{+0.42}_{-0.39}$	$3.56^{+0.30}_{-0.27}$	$3.03^{+0.43}_{-0.39}$	$3.54^{+0.30}_{-0.30}$	$3.02^{+0.42}_{-0.41}$	$3.54^{+0.29}_{-0.28}$
$\sum m_\nu$[eV]	< 0.110	< 0.119	< 0.114	< 0.123	< 0.112	< 0.110	< 0.120	< 0.117	< 0.110	< 0.0915
$g_\nu \times 10^{14}$	< 861	< 909	< 91.7	< 106	< 15.0	$12.4^{+7.8}_{-8.9}$	< 36.7	27^{+20}_{-20}	< 147	< 207

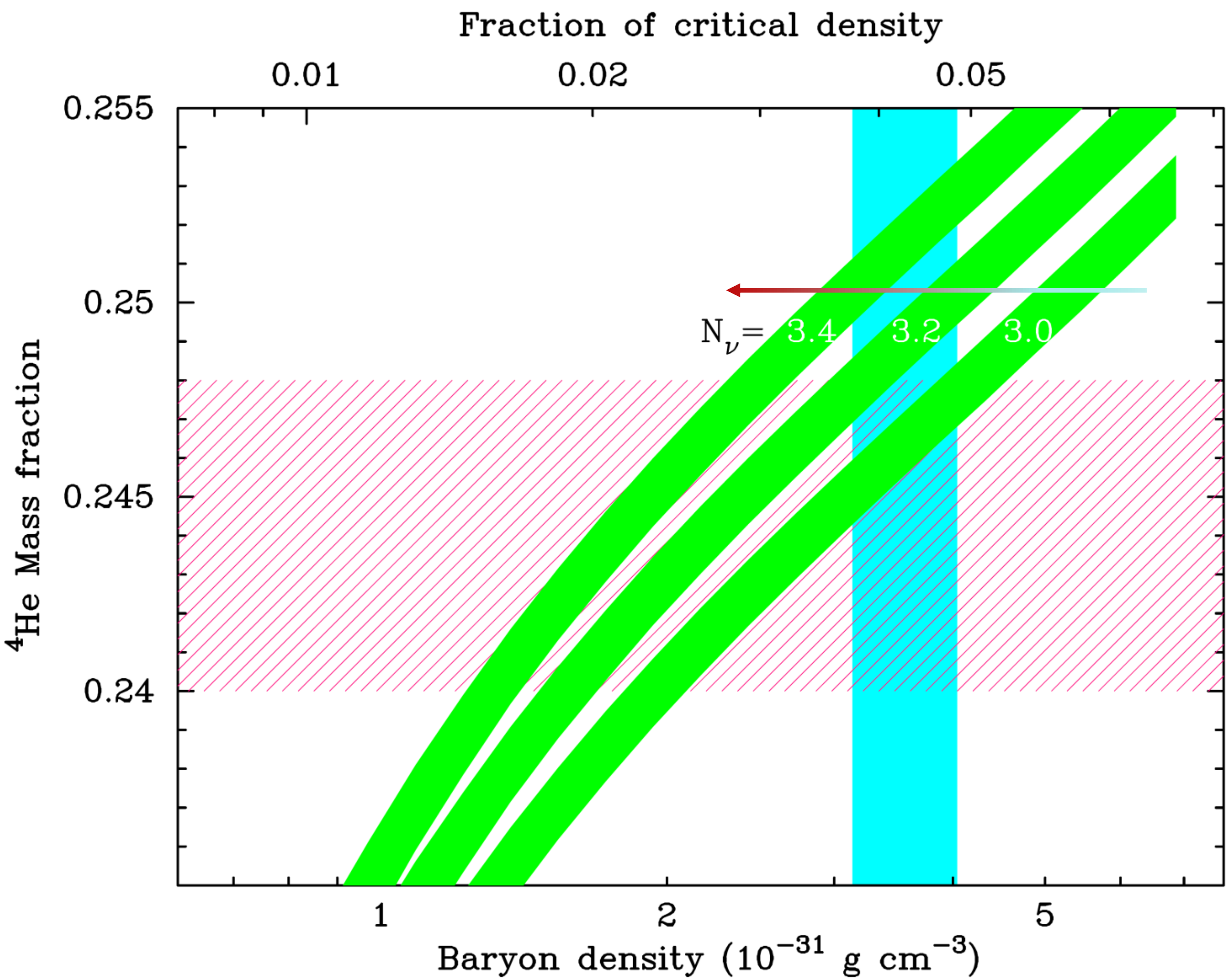
TABLE I. Observational limits at 95% confidence for different models with varying N_{eff} and m_ν. We see that for 1 and 10 M_ϕ the interaction is non zero at more than 2σ.

NSI effective mass effects on neutrino density



J. Venzor, APL, J. de Santiago, PRD 103 (2020)

Neff vs BBN



Burles, Nollett & Turner 1999