Could the H_0 Tension be Pointing Toward the Neutrino Mass Mechanism?

Miguel Escudero Abenza
miguel.escudero@kcl.ac.uk

based on ArXiv:1909.04044 with Sam Witte

PALS
Paris 27/09/19

KING'S College LONDON

European Research Council
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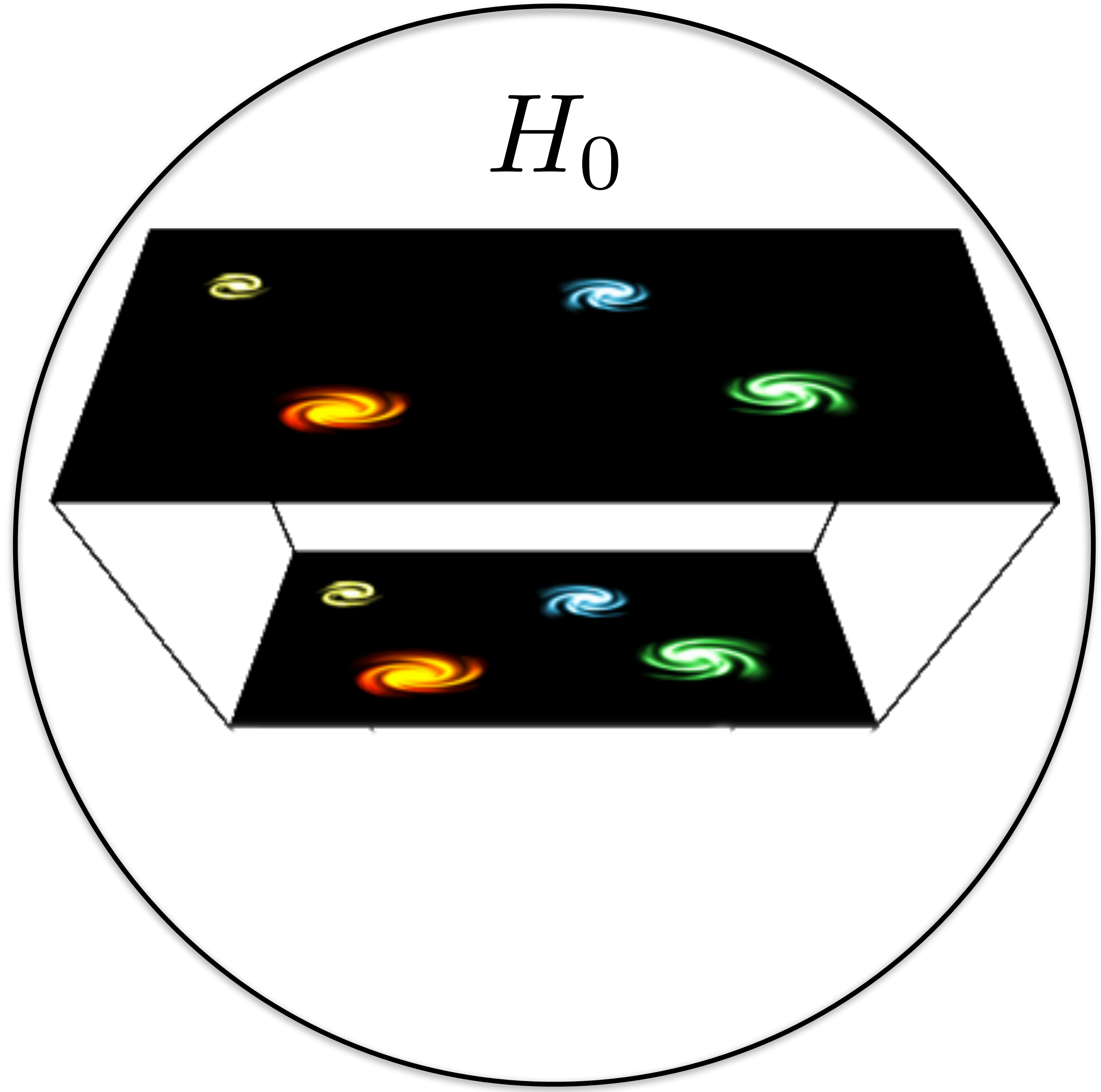
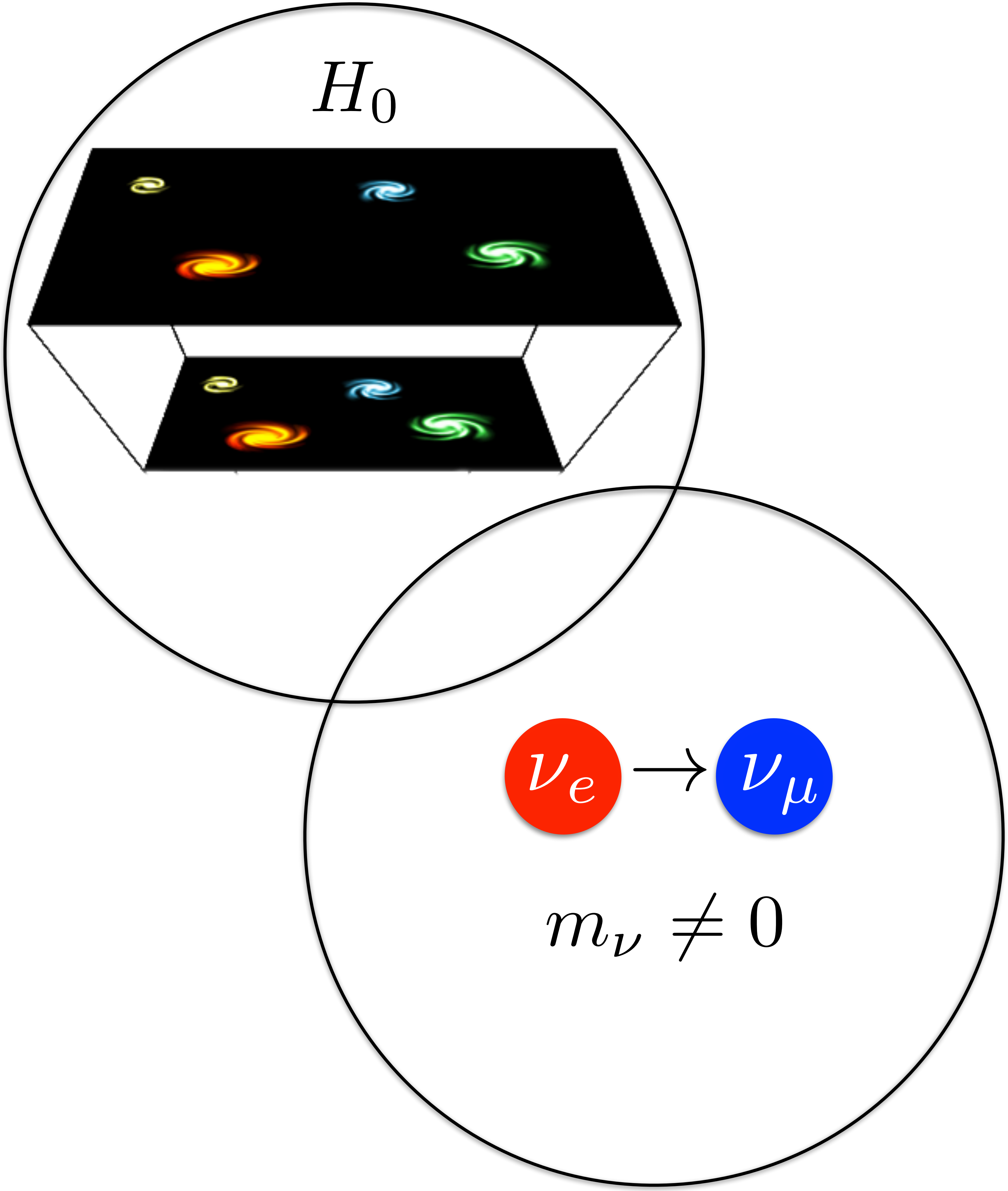
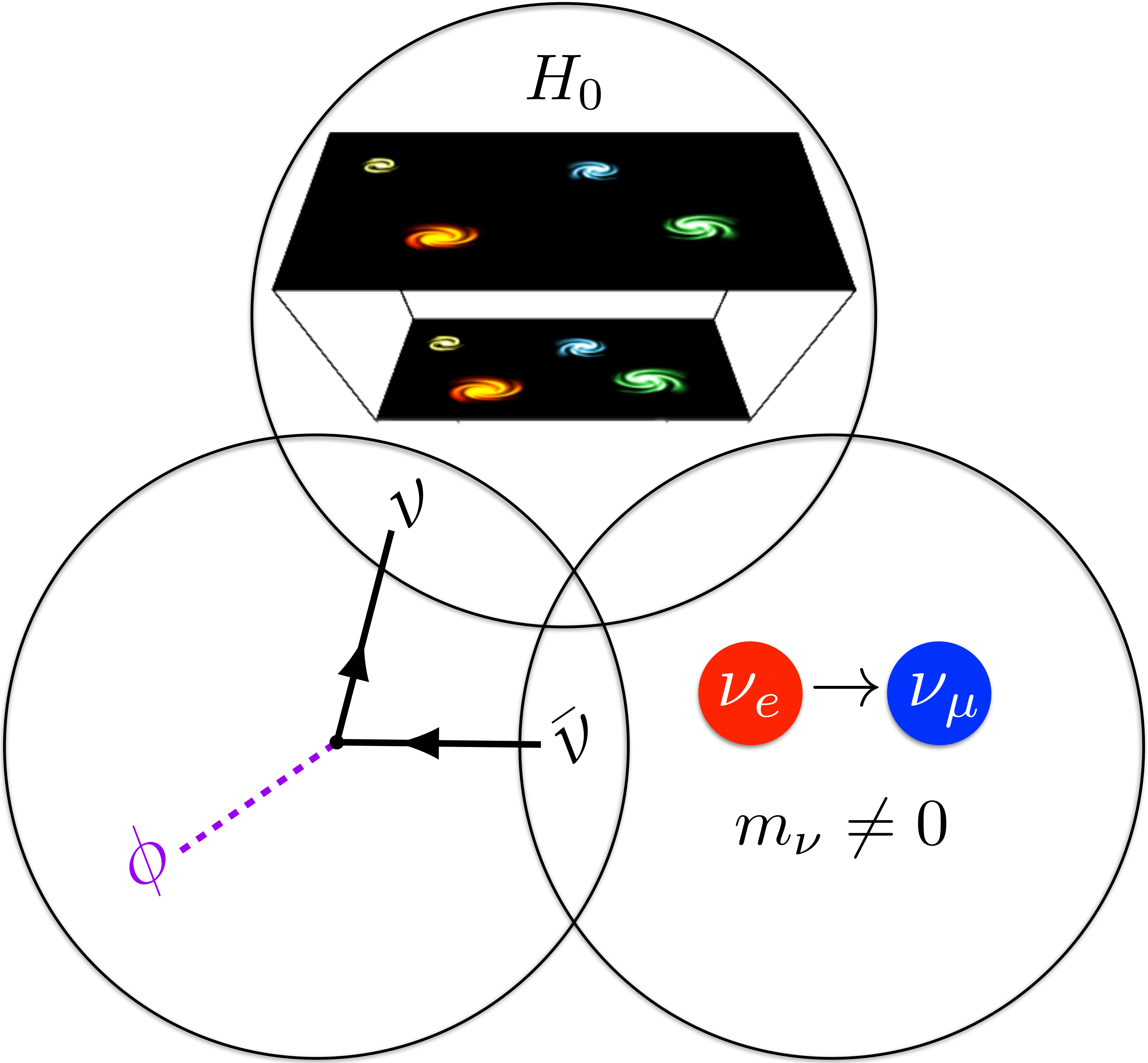

H_0


H_0
$\nu_e \rightarrow \nu_\mu$
$m_\nu \neq 0$


H_0
ν
$\bar{\nu}$
ϕ
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Outline

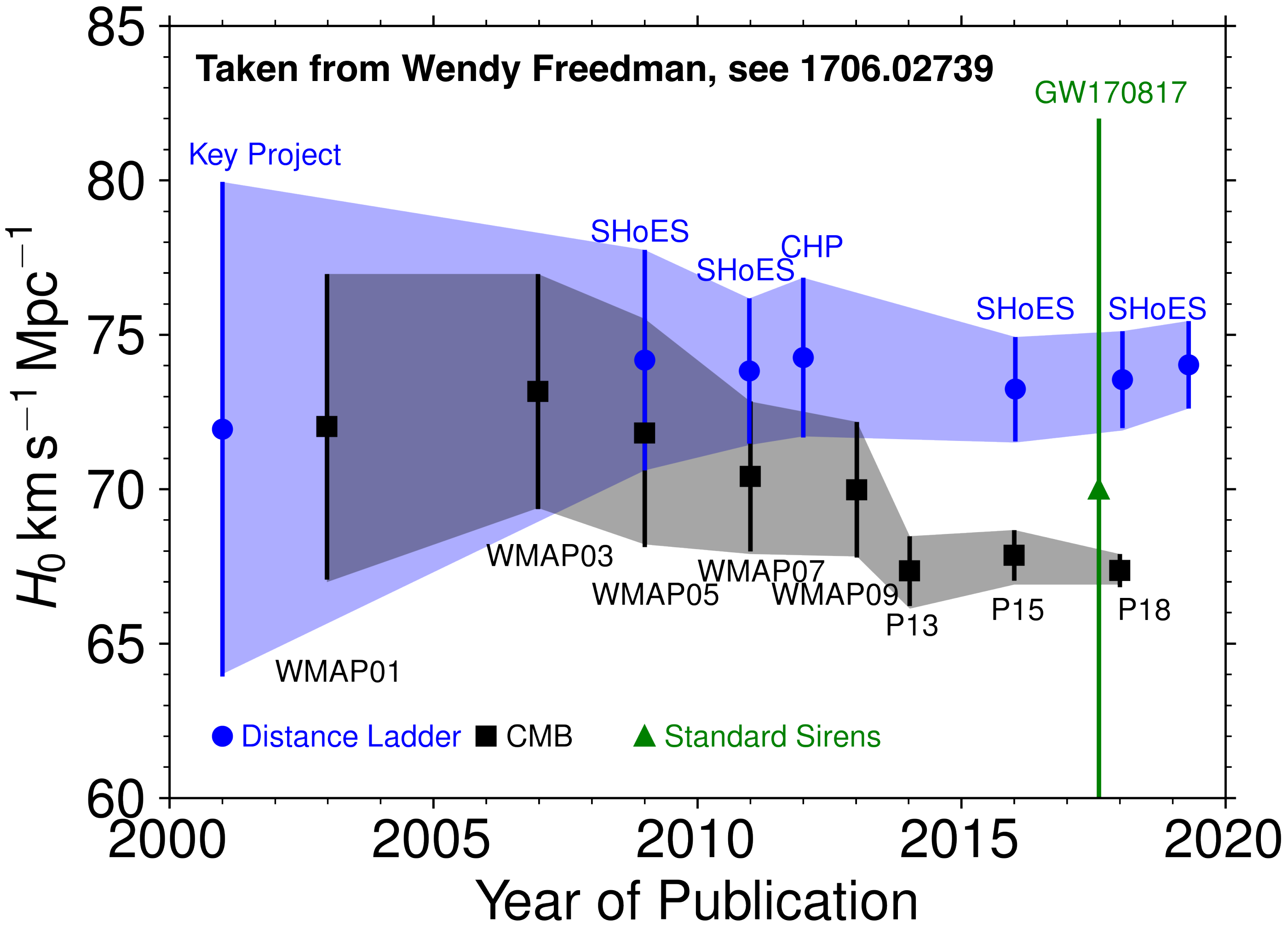
1) The Hubble Tension

2) The Scenario

3) Cosmology with a light Majoron

4) Conclusions

The Hubble Tension



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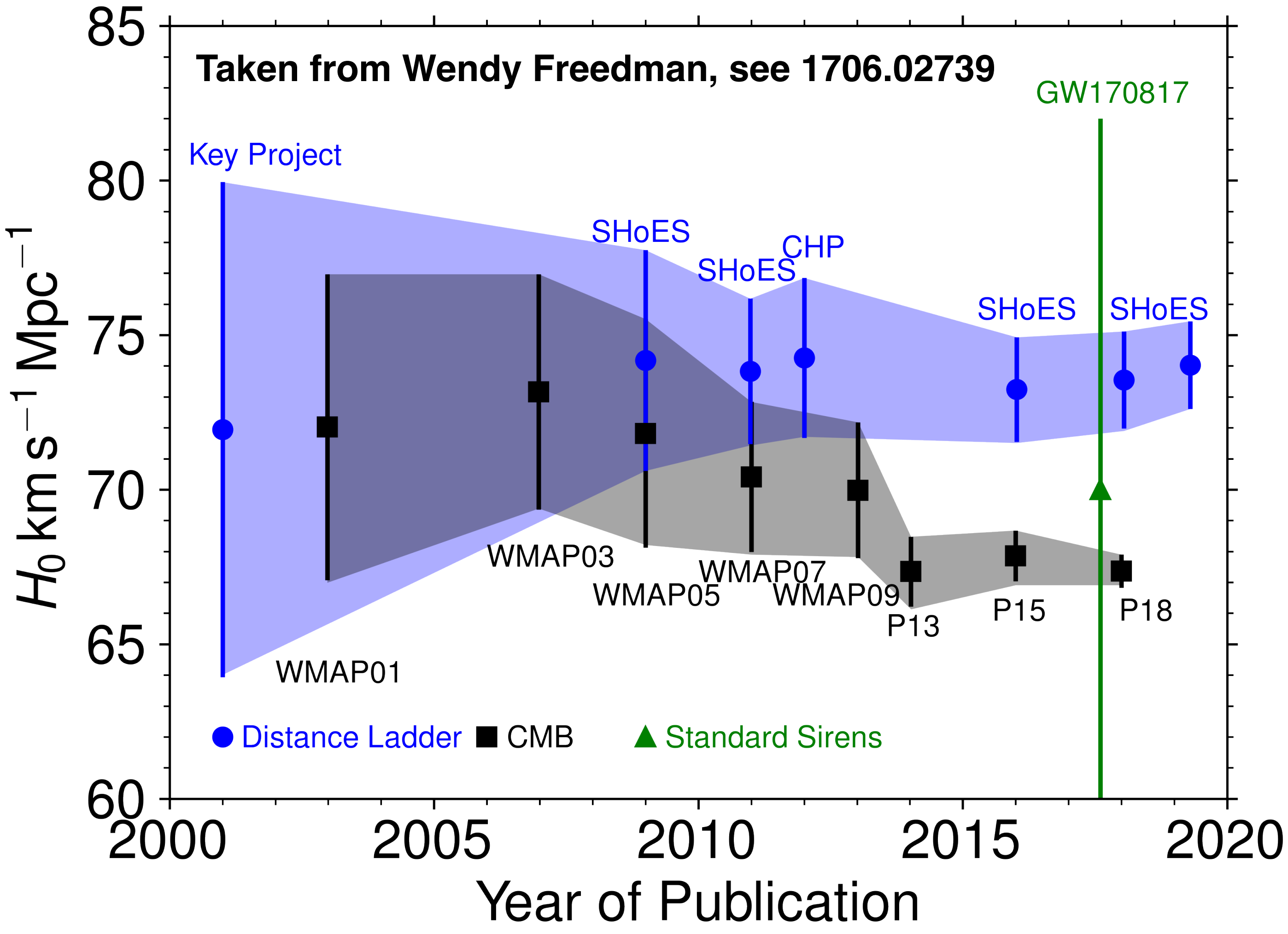

Riess *et al* 1903.07603

$$H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

4.4 σ tension within ΛCDM!

$$H_0 = 67.36 \pm 0.54\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Planck 2018 1807.06209

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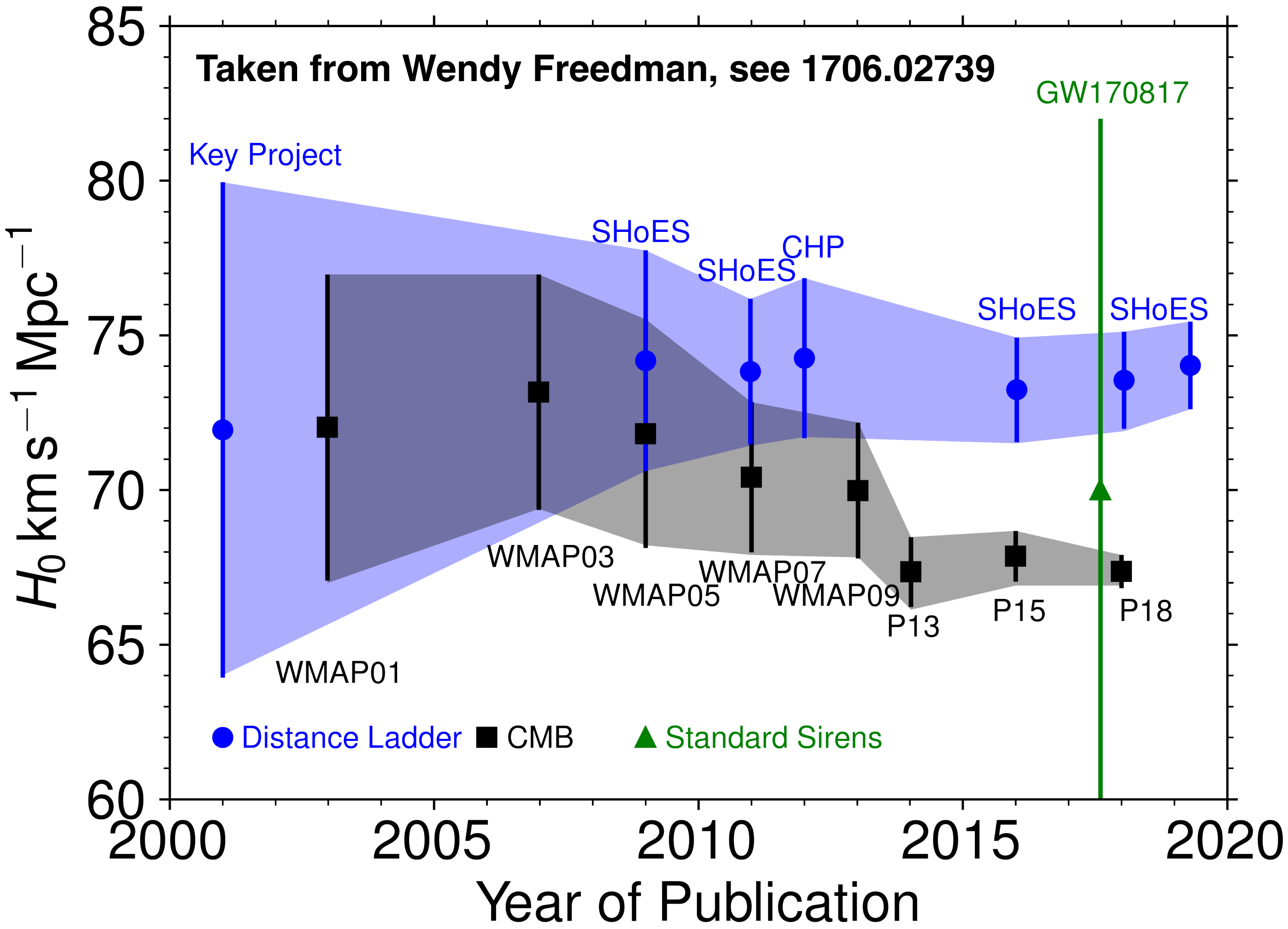

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- **Tension very unlikely generated by CMB systematics**

  see e.g. Spergel *et al* 1312.3313, Addison *et al* 1511.00055, Verde et al 1601.01701, Planck 1608.02487

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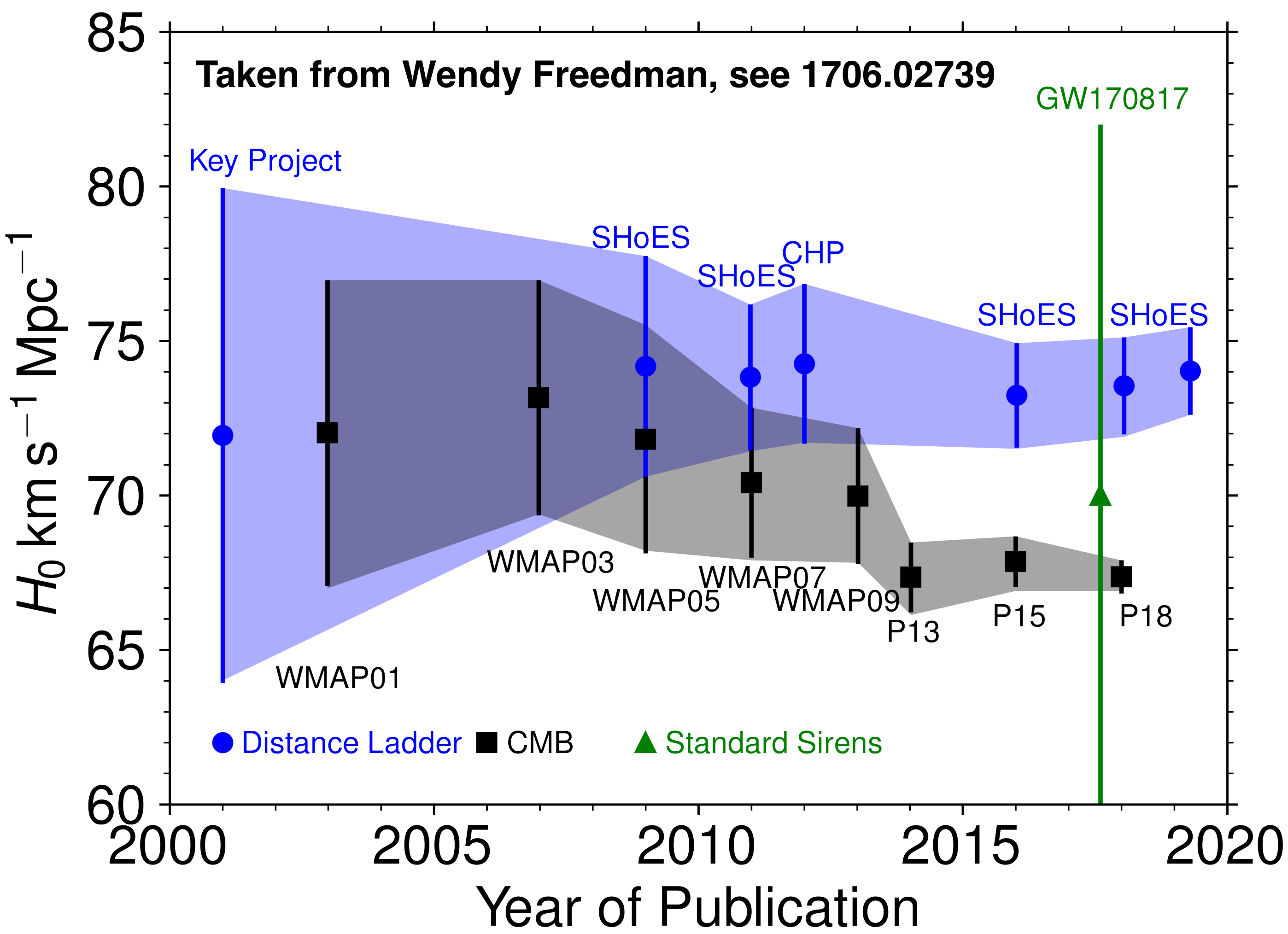

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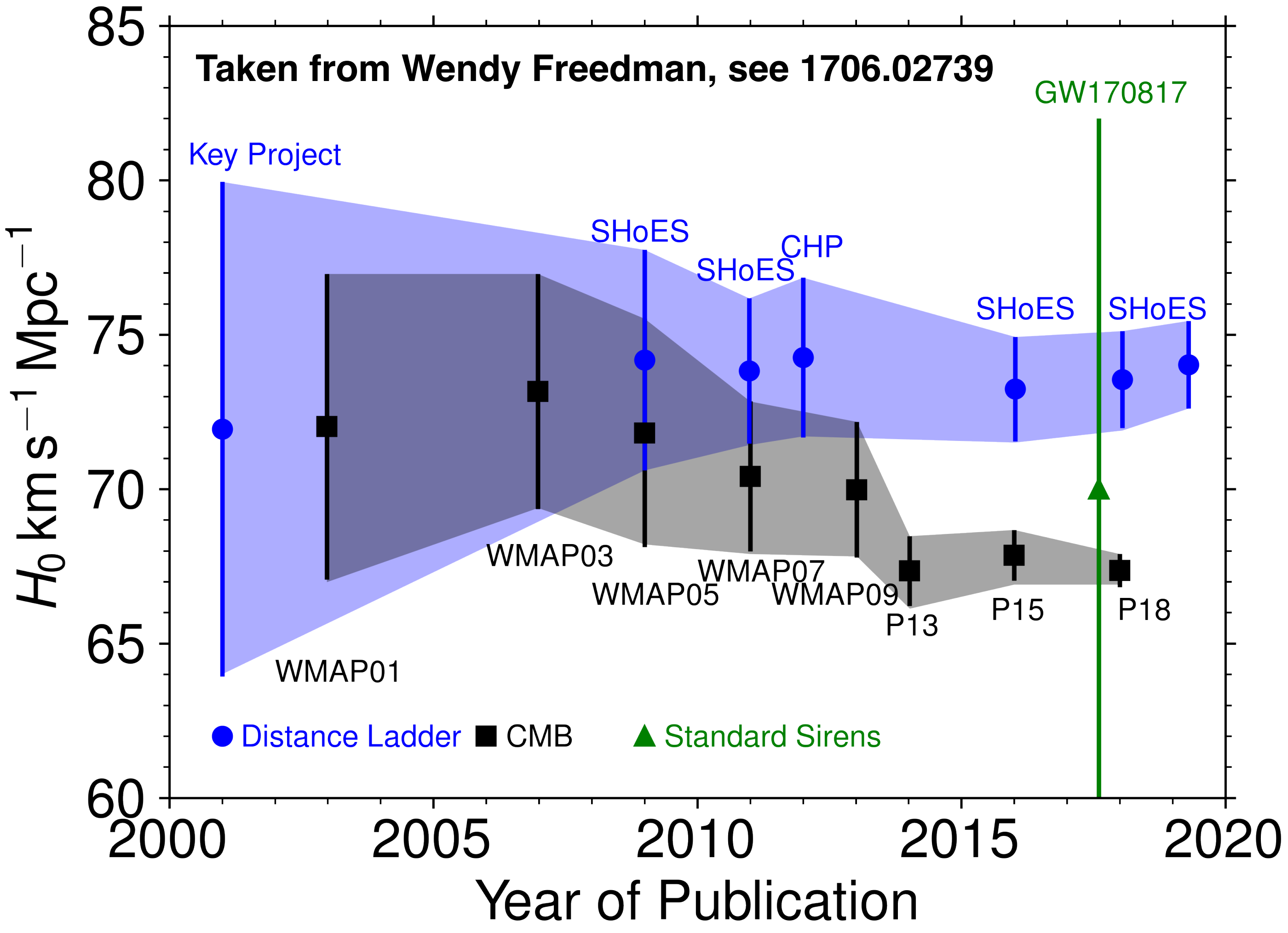

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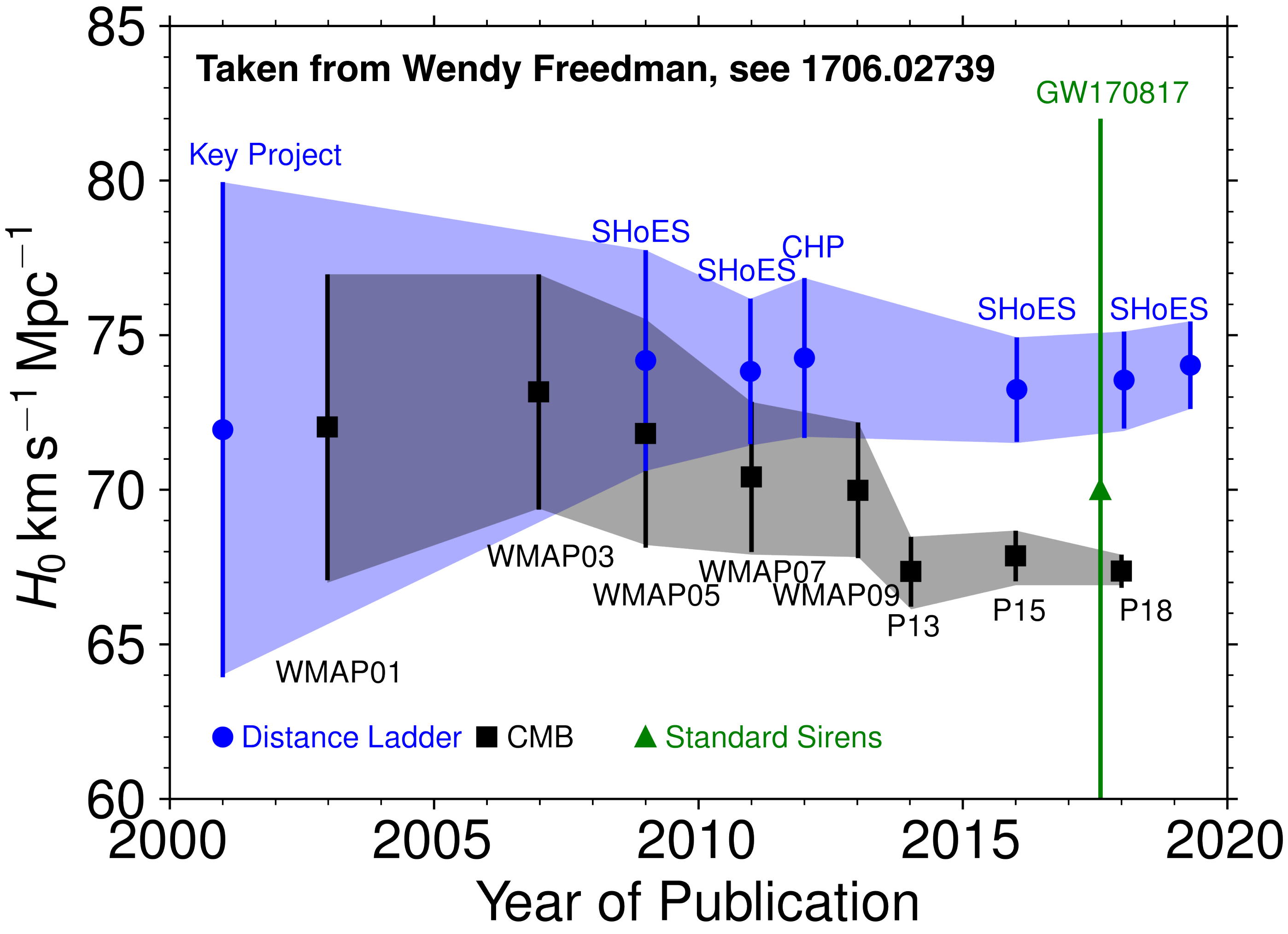
The Hubble Tension



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- **Although other calibrations lead to different results**

  see Freedman et. al. 1907.05922 but also see Riess *et. al.* 1908.00993

- **Tension between H_0 local and BAO is also present**

  see Addison *et al* 1707.06547, Font-Ribera *et al* 1906.11628, Schöneberg et al 1907.11594

The Hubble Tension

Beyond ΛCDM possibilities:

- **Early Dark Energy** — Poulin, Smith, Karwal, Kamionkowski 1811.04083; Agrawal, Cyr-Racine, Pinner, Randall 1904.01016
- **Decaying Dark Matter** — Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia 1803.03644
- **Increasing N_{eff}** — *e.g.* Weinberg 1305.1971

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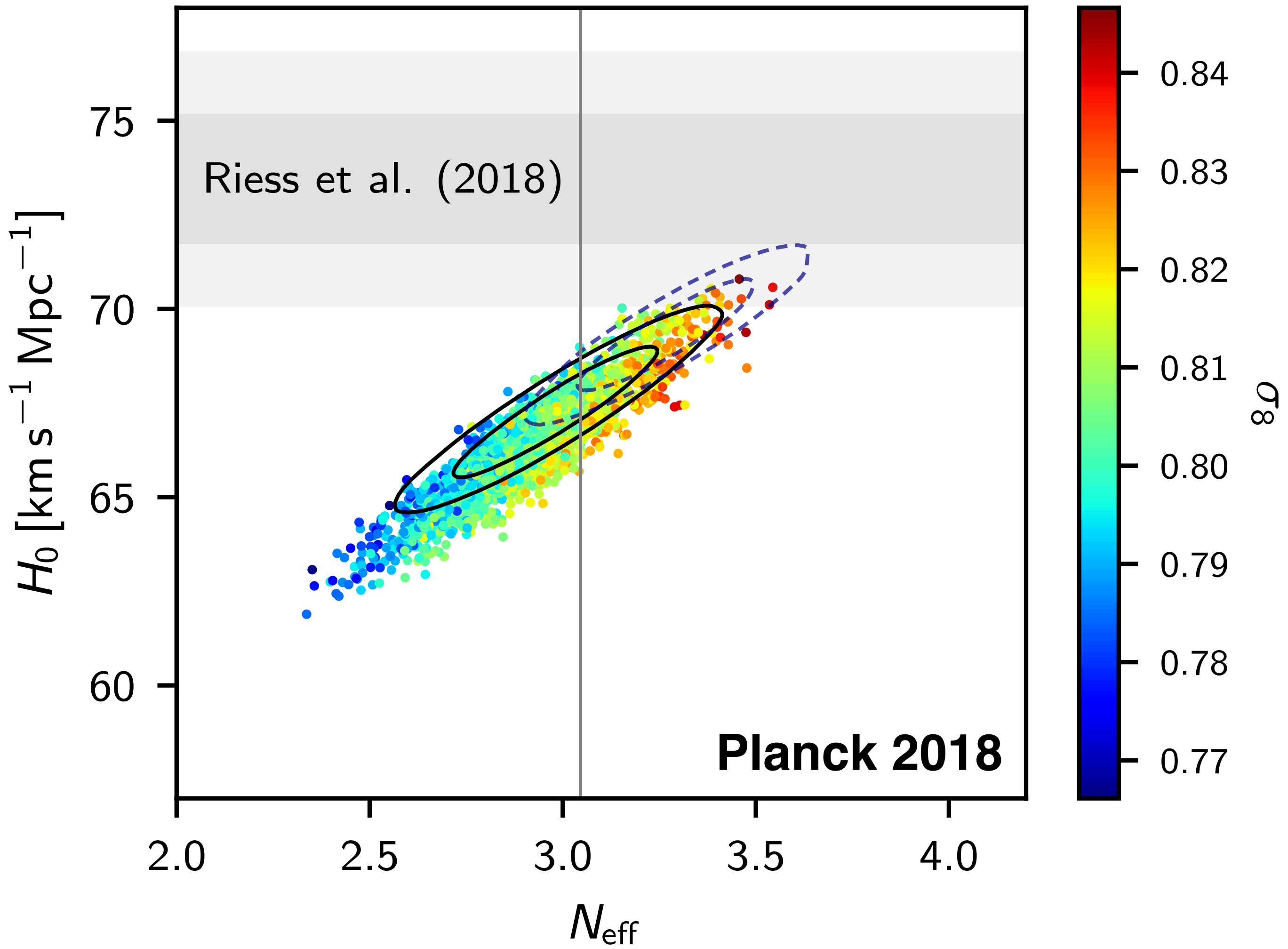
Perhaps the simplest one is to increase N_{eff}:



$$N_{\rm eff}^{\rm CMB+BAO} = 2.99 \pm 0.17$$

$$N_{\rm eff}^{{\rm CMB+BAO+}H_0} = 3.27 \pm 0.15$$

$$N_{\rm eff}^{\rm BBN} < 3.4$$ **Pitrou et al 1801.08023**

The Physics

1)

CMB — **380.000 yr** — $T_\gamma = 0.26\,\mathrm{eV}$

BBN — **3 min** — $T_\gamma = 0.07\,\mathrm{MeV}$

The Universe has expanded by a factor of 10^5!

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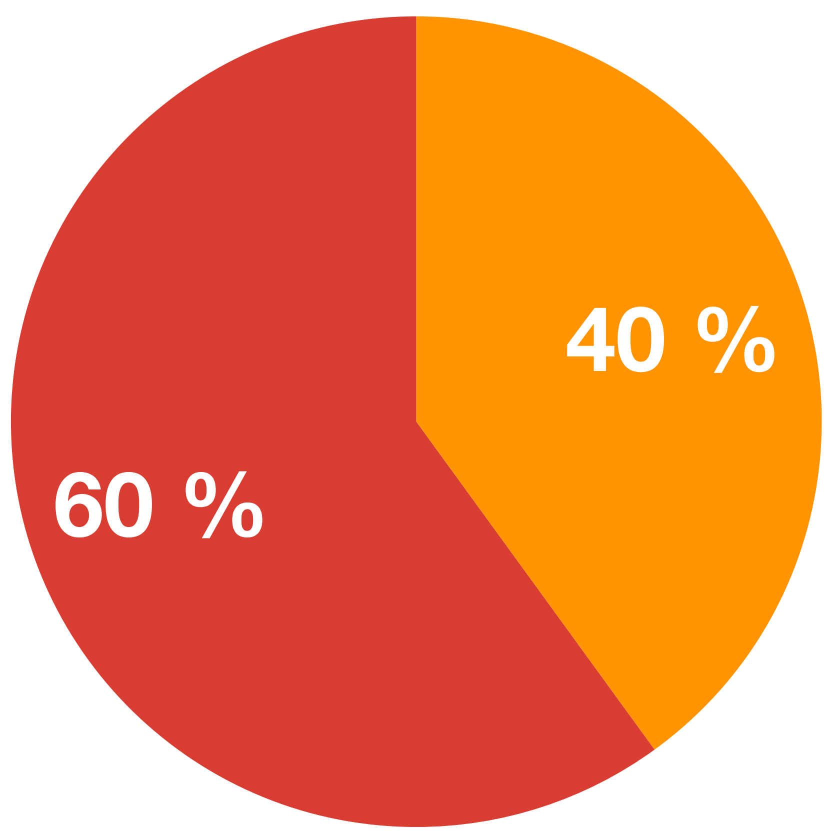
2)

Photons

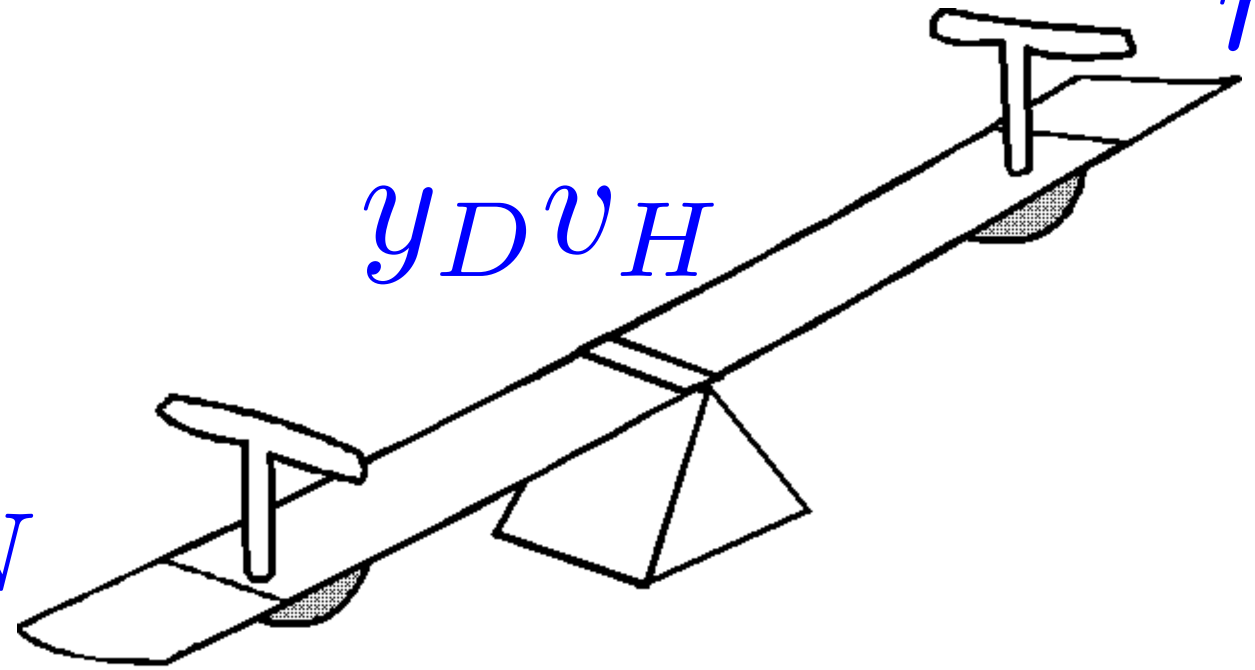


Neutrinos

The Seesaw Mechanism

Minkowski, Yanagida, Gell-Mann, Ramond, Slansky, Glashow, Mohapatra, Senjanovic, Schechter, Valle

Type-I seesaw



Neutrinos are very light Majorana particles:

$$m_\nu \simeq 0.03\,\mathrm{eV} \left(\frac{y_D}{10^{-6}}\right)^2 \frac{\mathrm{TeV}}{M_N}$$

The Scenario

Global $U(1)_L$ Spontaneously Broken Symmetry

Chikashige, Mohapatra, Peccei (1981)

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Dimension-5 Planck suppressed operators: $$m_\phi \simeq v_L \sqrt{\frac{v_L}{M_{\rm Pl}}} \lesssim \mathrm{keV}$$

Rothstein, Babu, Seckel hep-ph/9301213
Akhmedov, Berezhiani, Mohapatra, Senjanovic hep-ph/9209285

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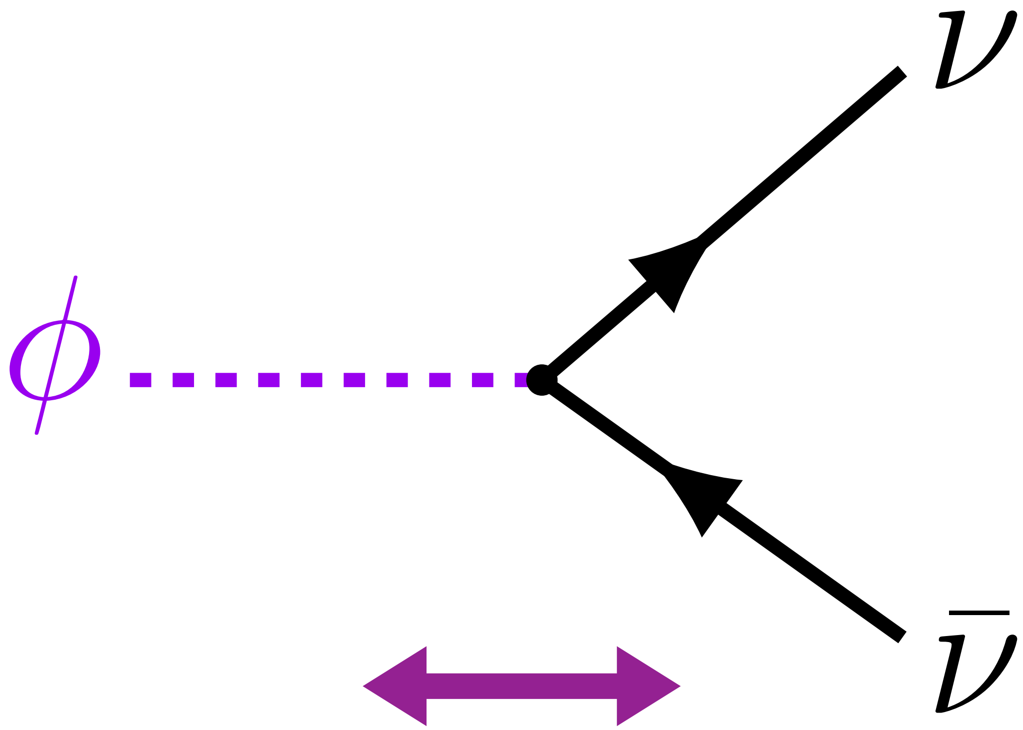
Parameter Space:

$$10^{-15} < \lambda < 10^{-3}$$
$$0.1\,\text{eV} < m_\phi < \text{MeV}$$

Cosmological Implications

Only Relevant Process:



provided $\Gamma_\phi \geq H(T_\nu = m_\phi/3)$

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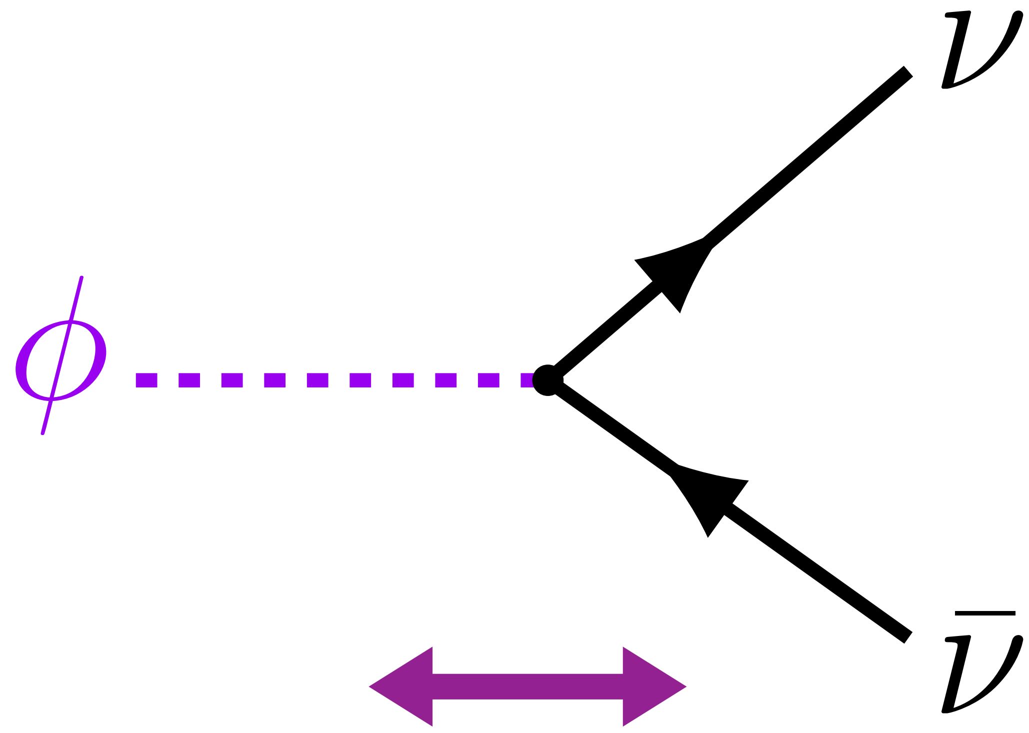

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Two main effects:

Chacko, Hall, Okui, Oliver hep-ph/0312267

- **Non-standard expansion history**
- **Erase the neutrino anisotropic stress**

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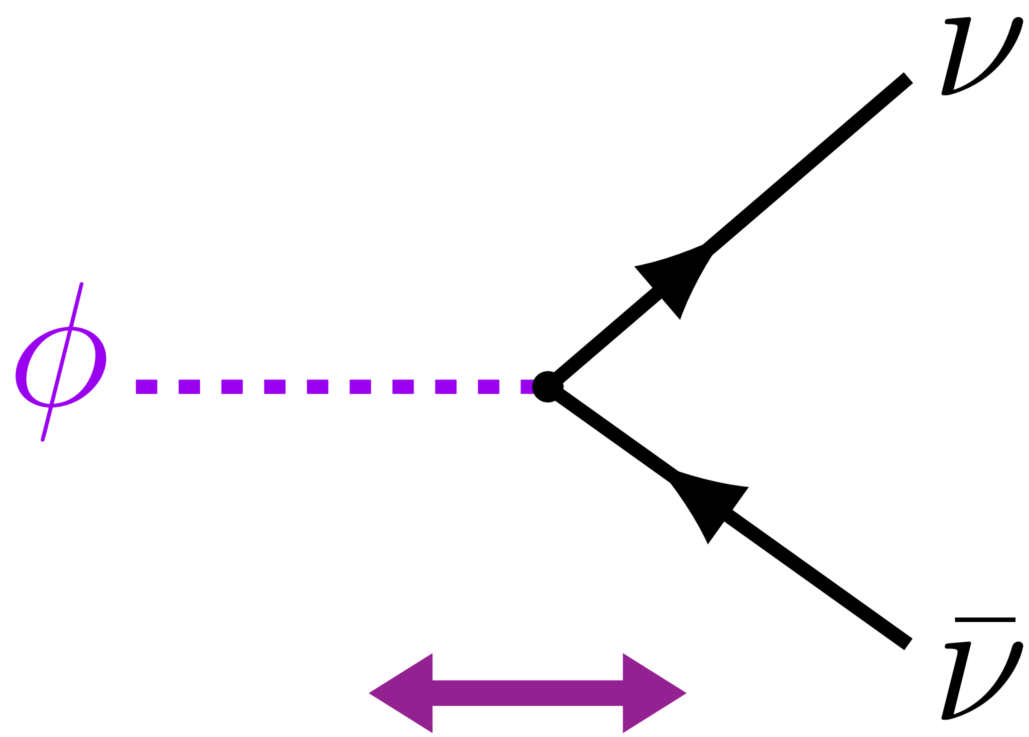

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Two main effects:

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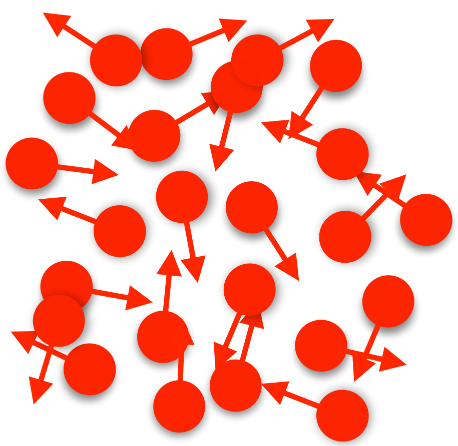
- **Non-standard expansion history**
- **Erase the neutrino anisotropic stress**

- **We solve the Boltzmann equation for the background**
  Escudero 1812.05605, 1910.XXXXX
- **We include the full neutrino-majoron Boltzmann hierarchy in CLASS**

Cosmological Implications

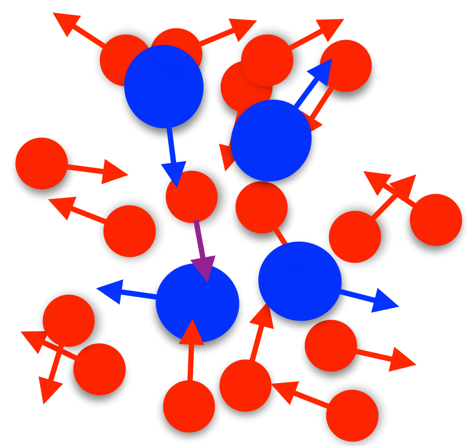
$T \gg m_\phi$



Production

$\bar{\nu}\nu \to \phi$

Equilibrium

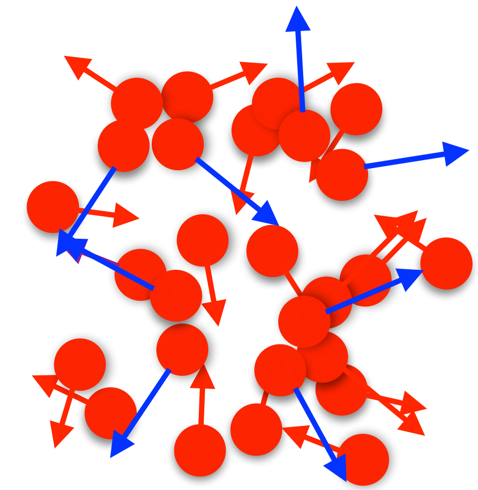


Decay

$T \sim m_\phi/3$

$\phi \to \bar{\nu}\nu$

Final State



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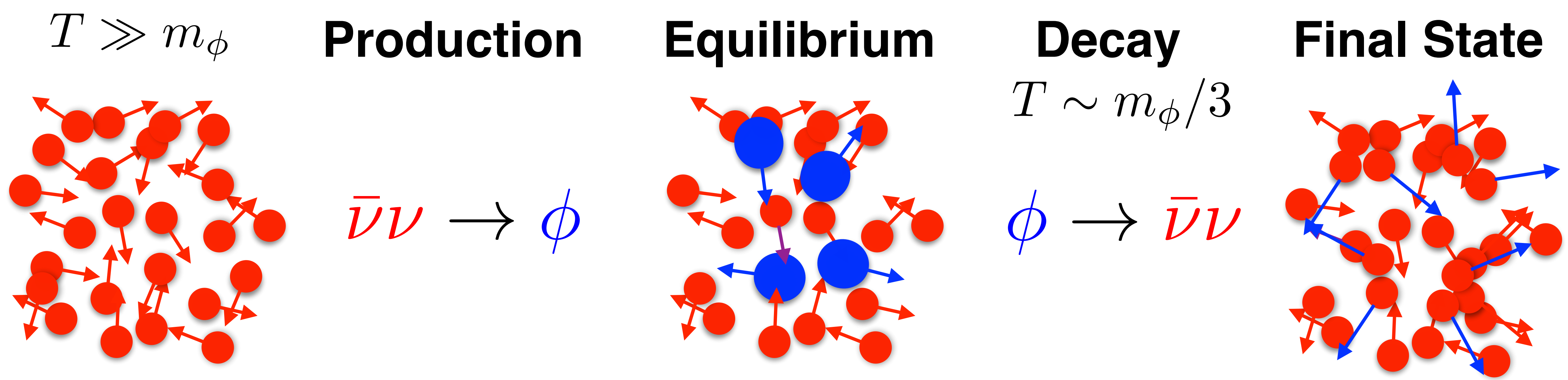
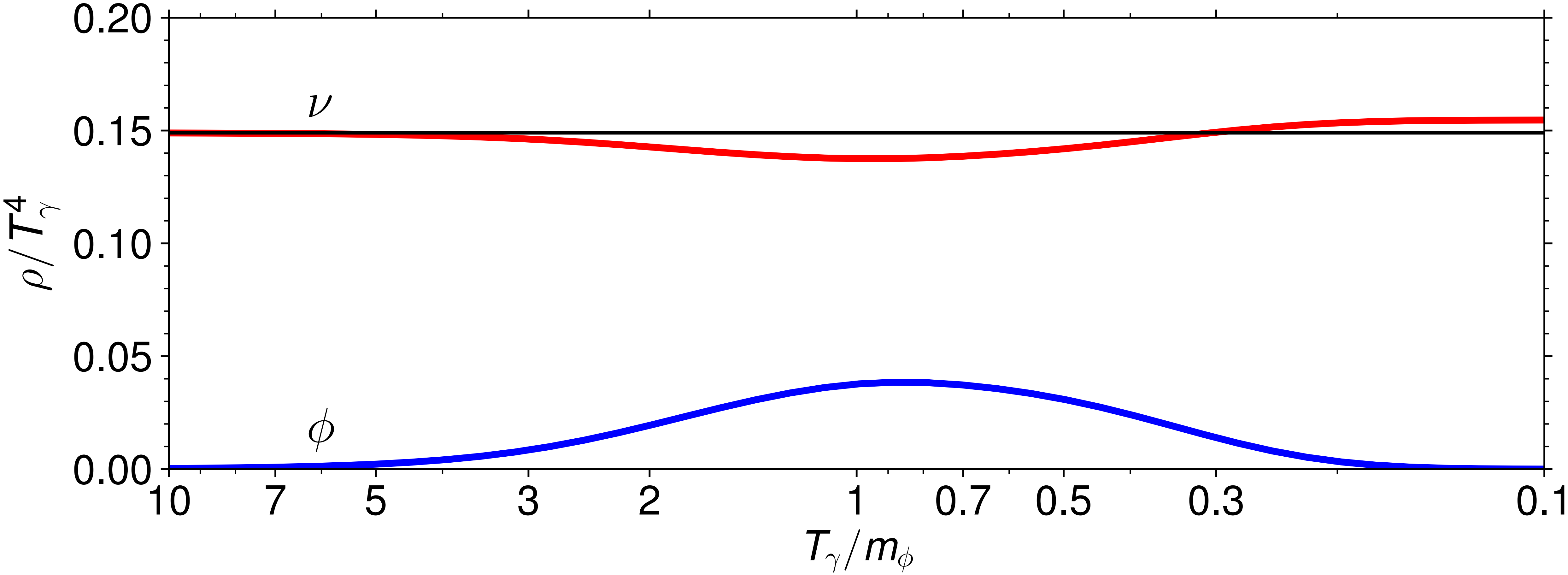


$$\Gamma_\phi \simeq H(T_\nu = m_\phi/3)$$



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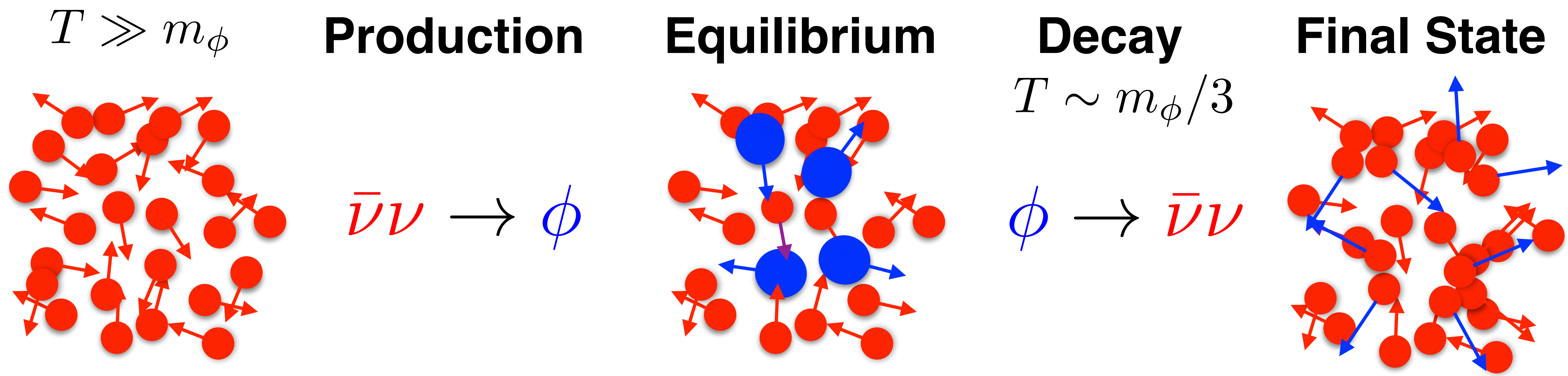

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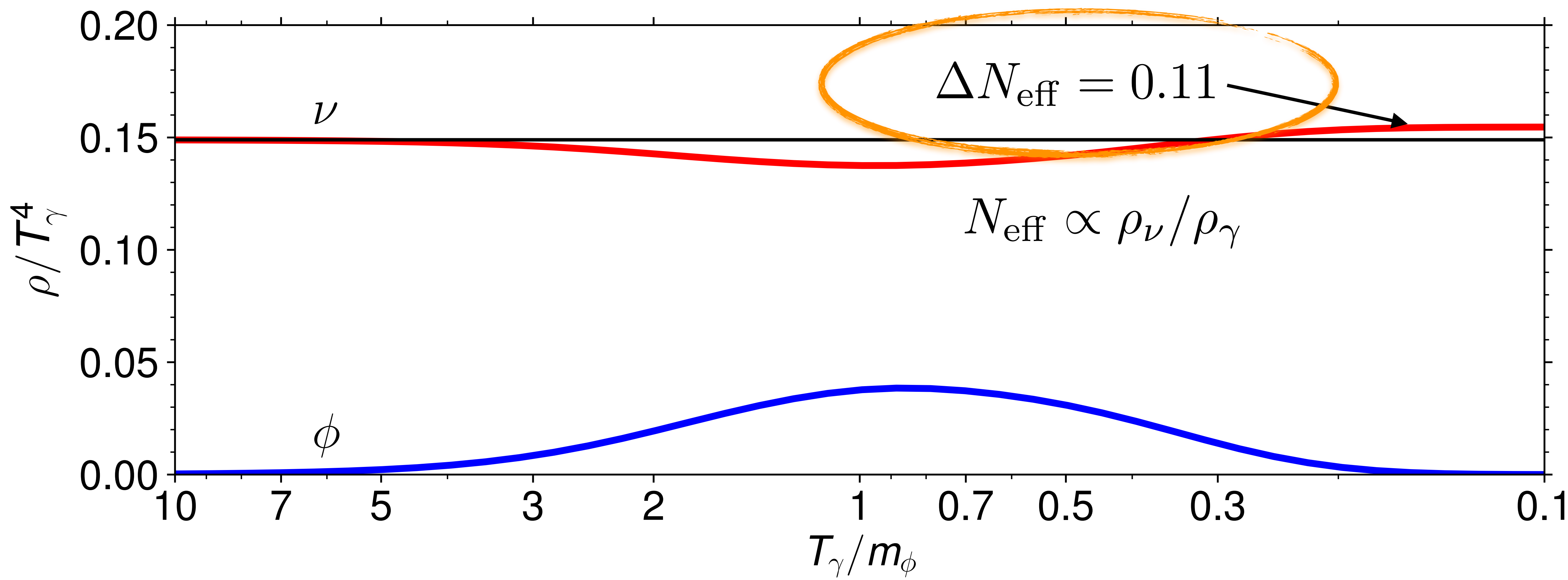
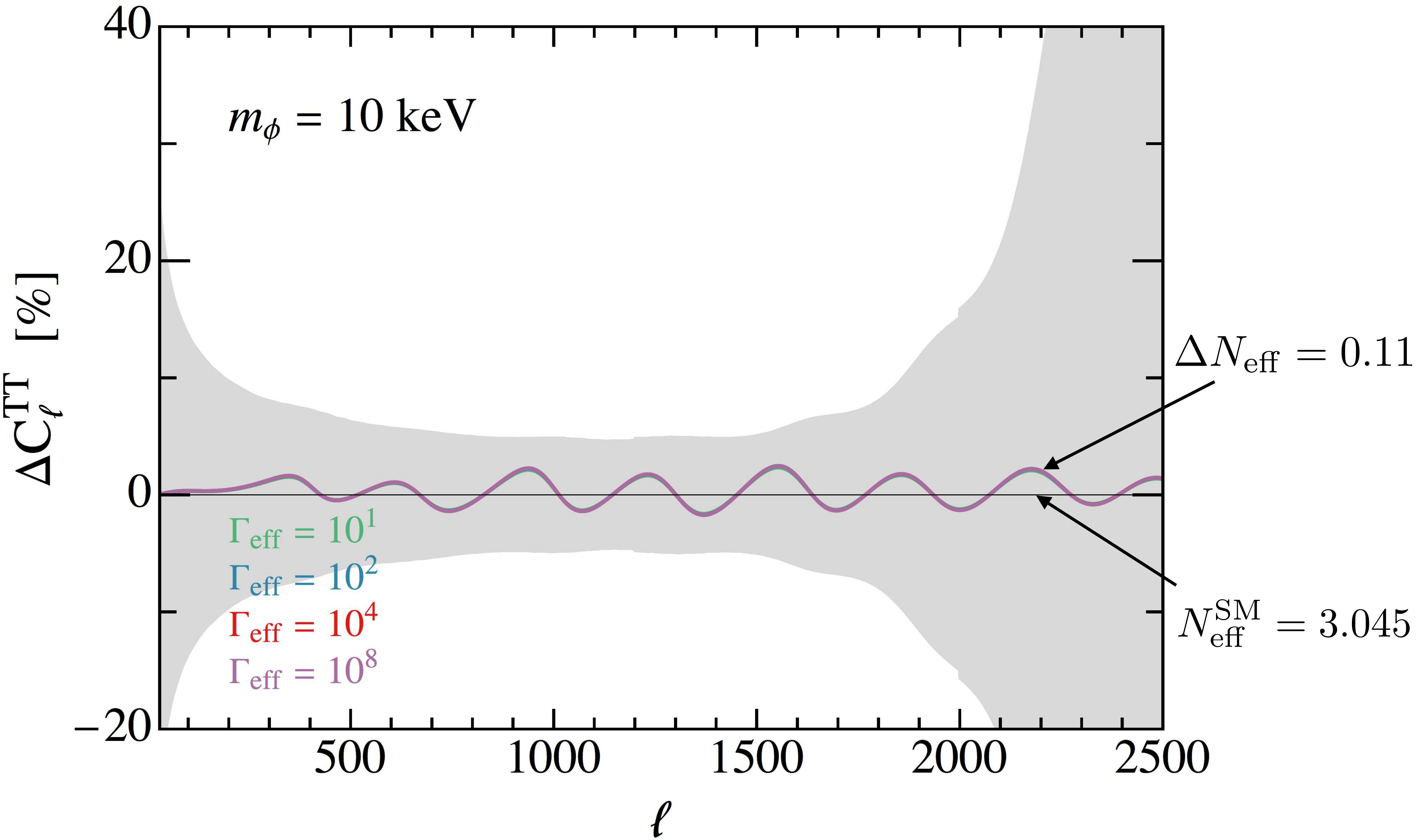


Effects on the CMB

$$\Gamma_{\rm eff} = \left(\frac{\lambda}{4\times 10^{-12}}\right)^2 \left(\frac{1\,{\rm keV}}{m_\phi}\right)$$

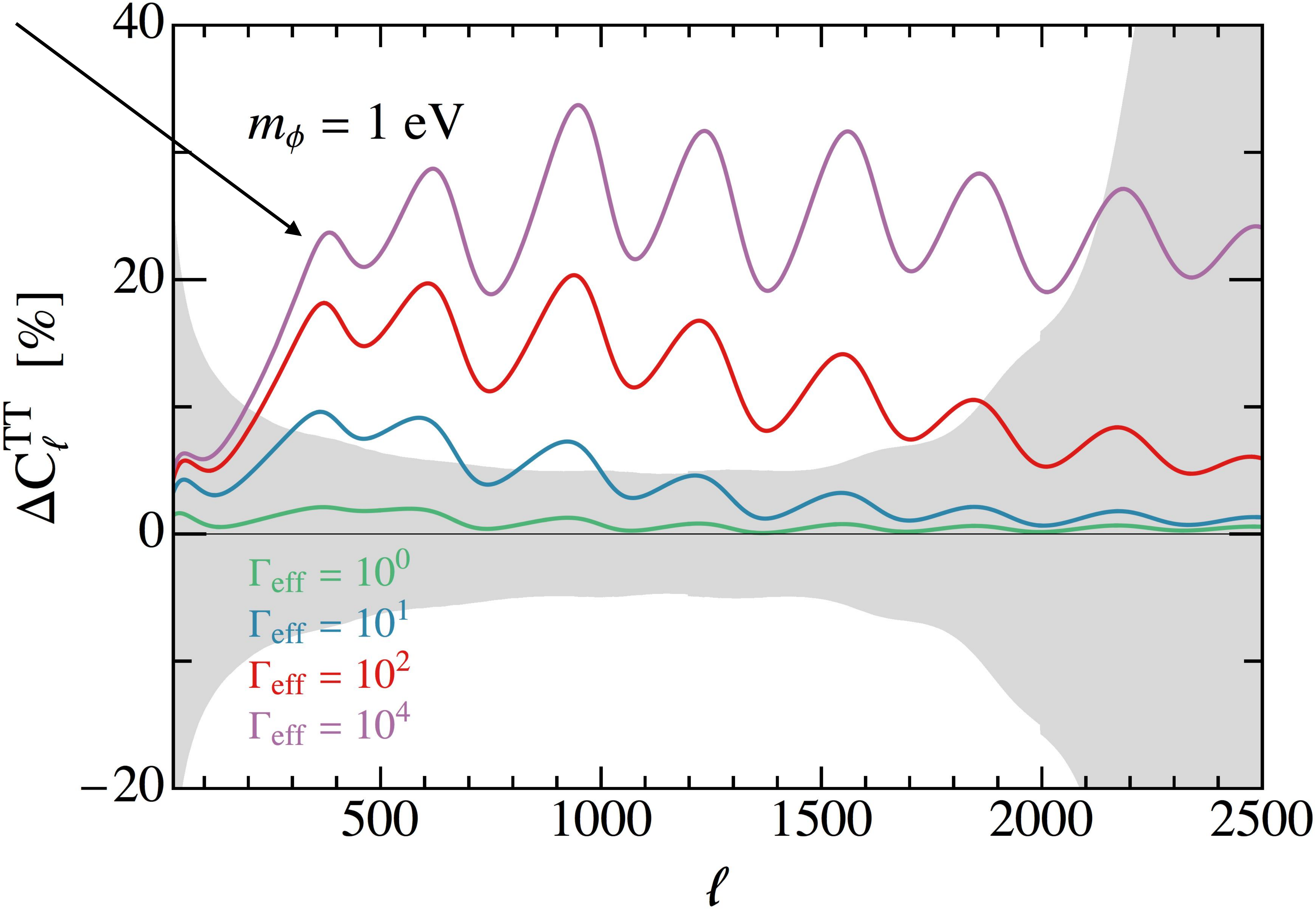


Effects on the CMB

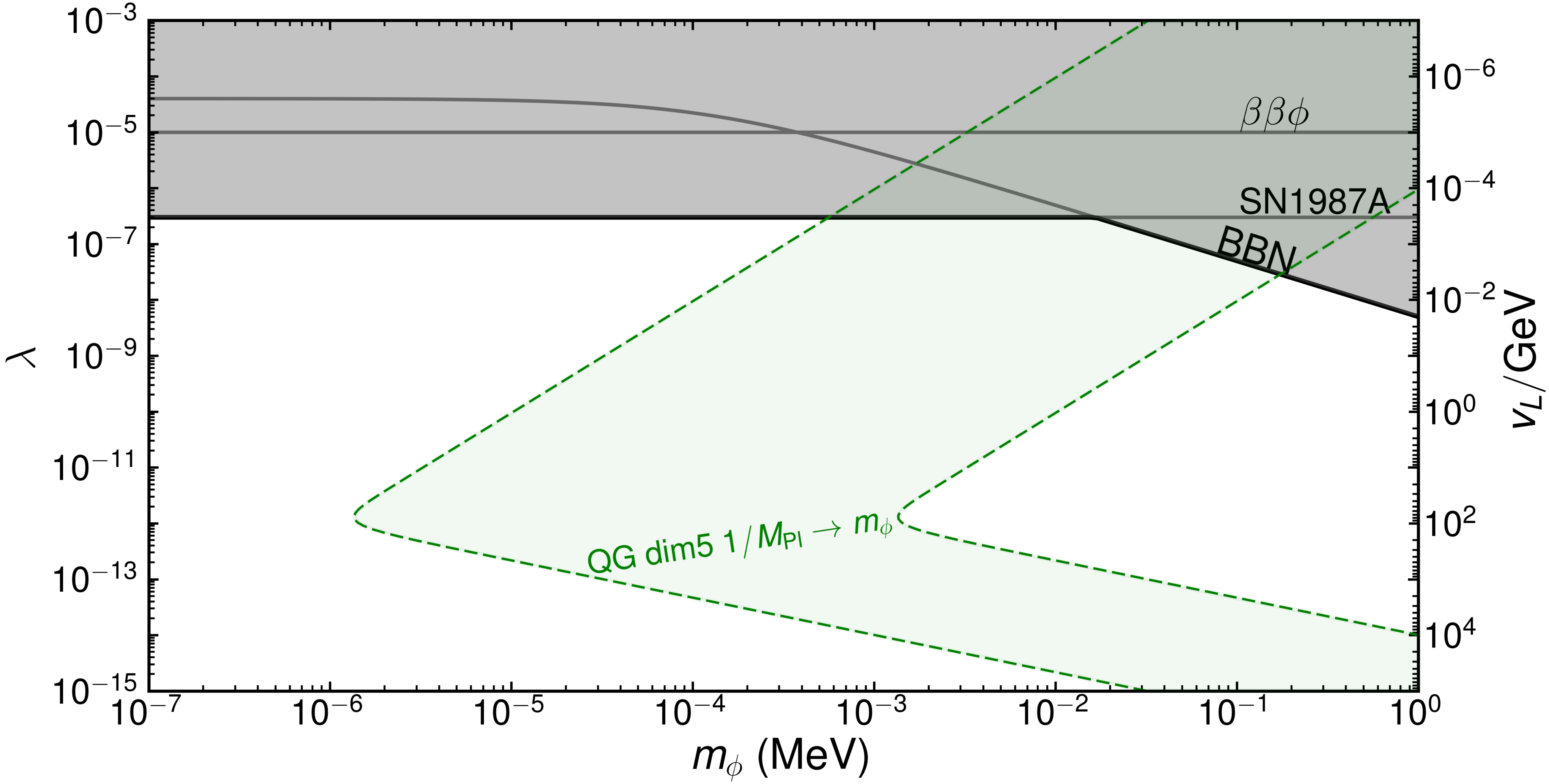
see Bashinsky and Seljak astro-ph/0310198

$$\Gamma_{\rm eff} = \left(\frac{\lambda}{4\times 10^{-12}}\right)^2 \left(\frac{1\,{\rm keV}}{m_\phi}\right)$$

$\sigma_\nu \to 0$



Parameter Space



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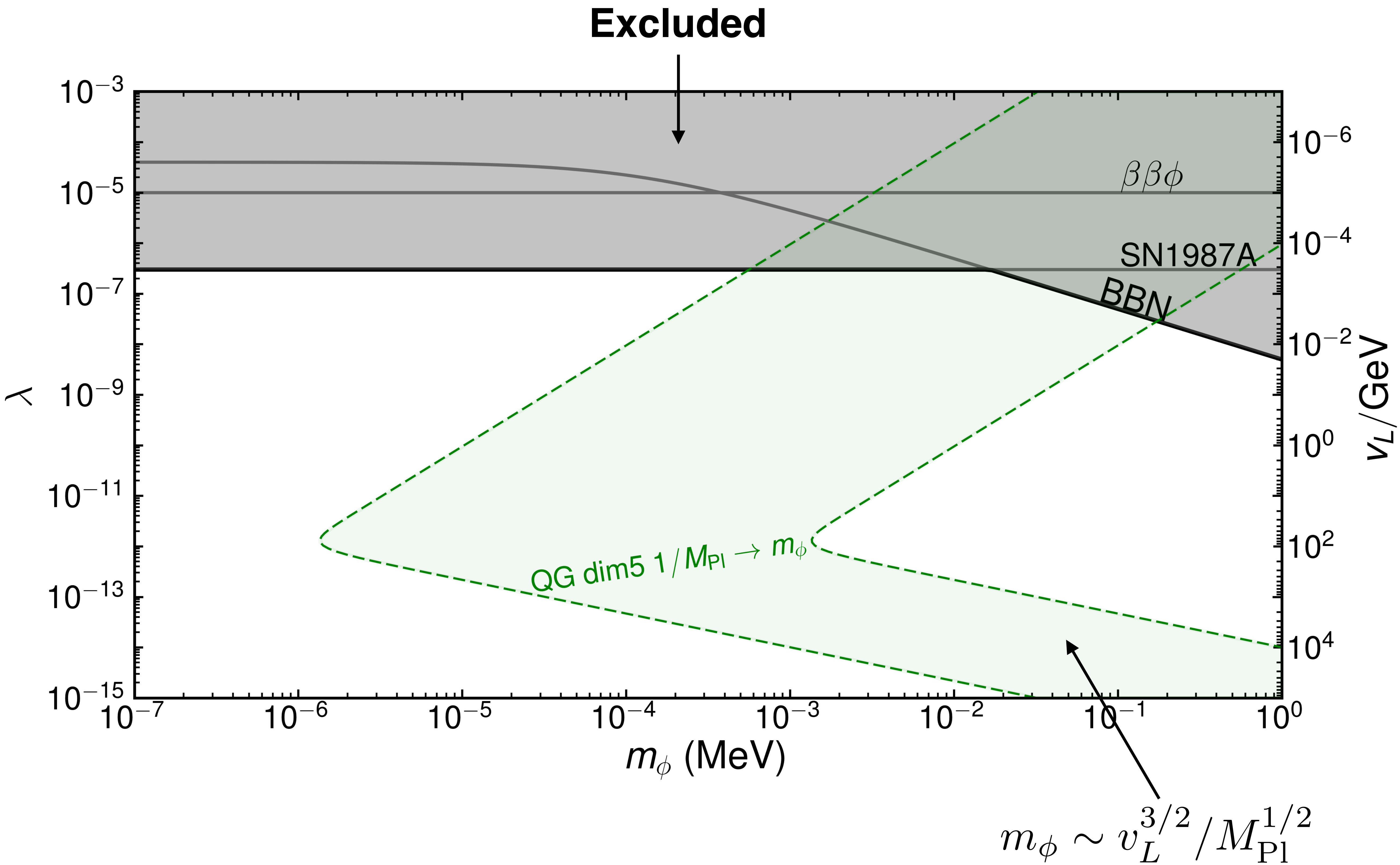

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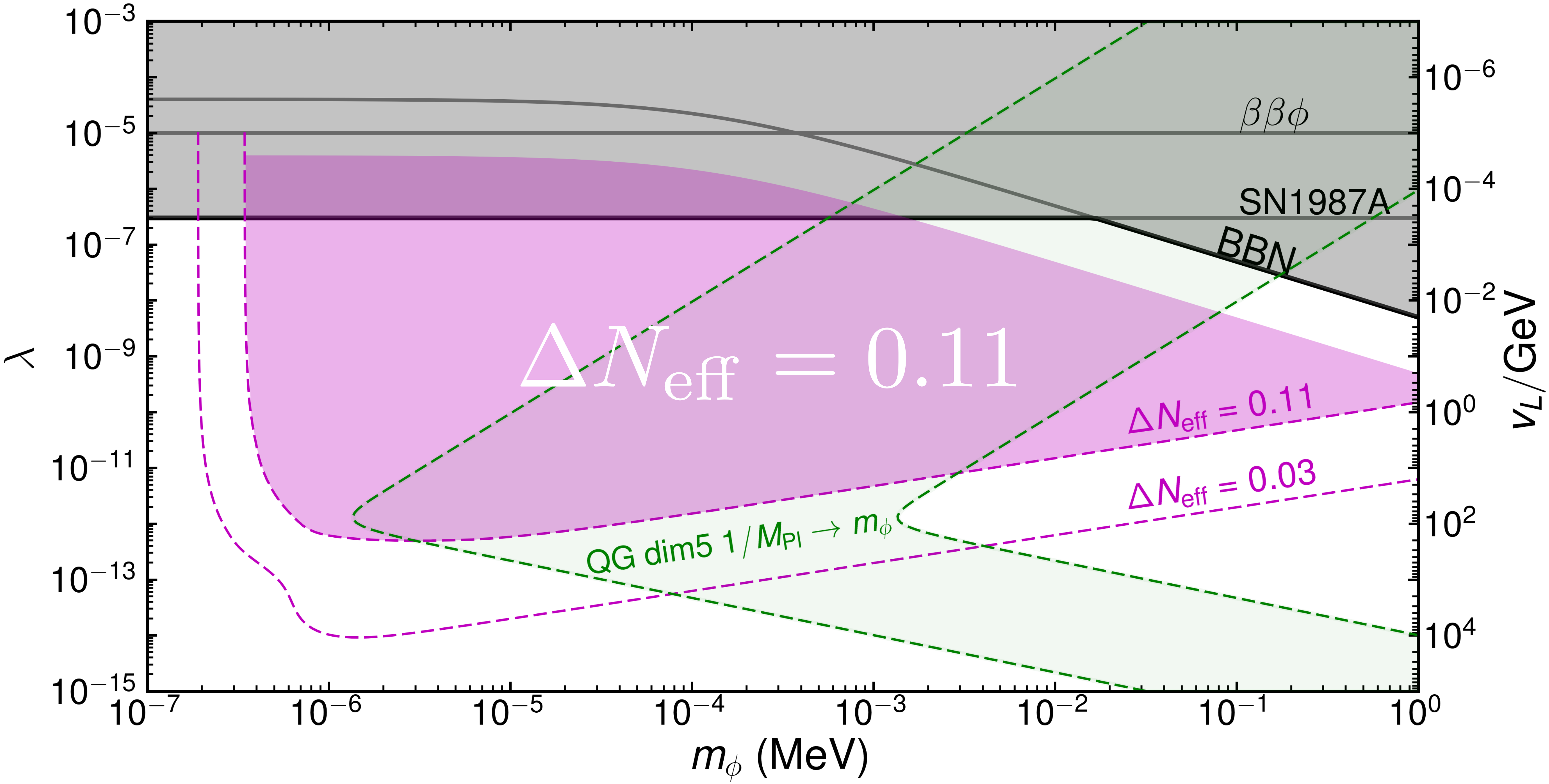
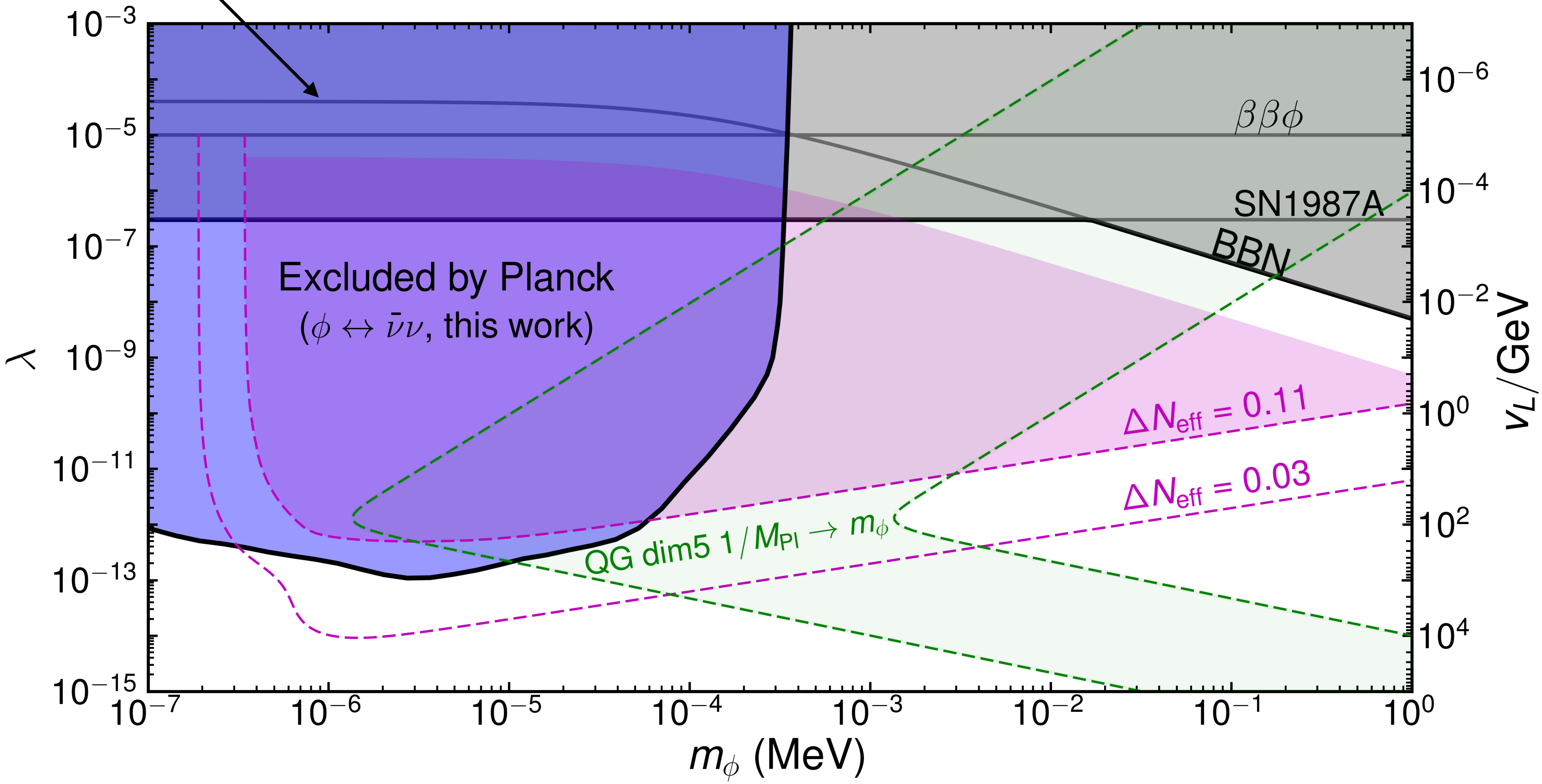


Parameter Space

Full MCMC to Planck 2018 data



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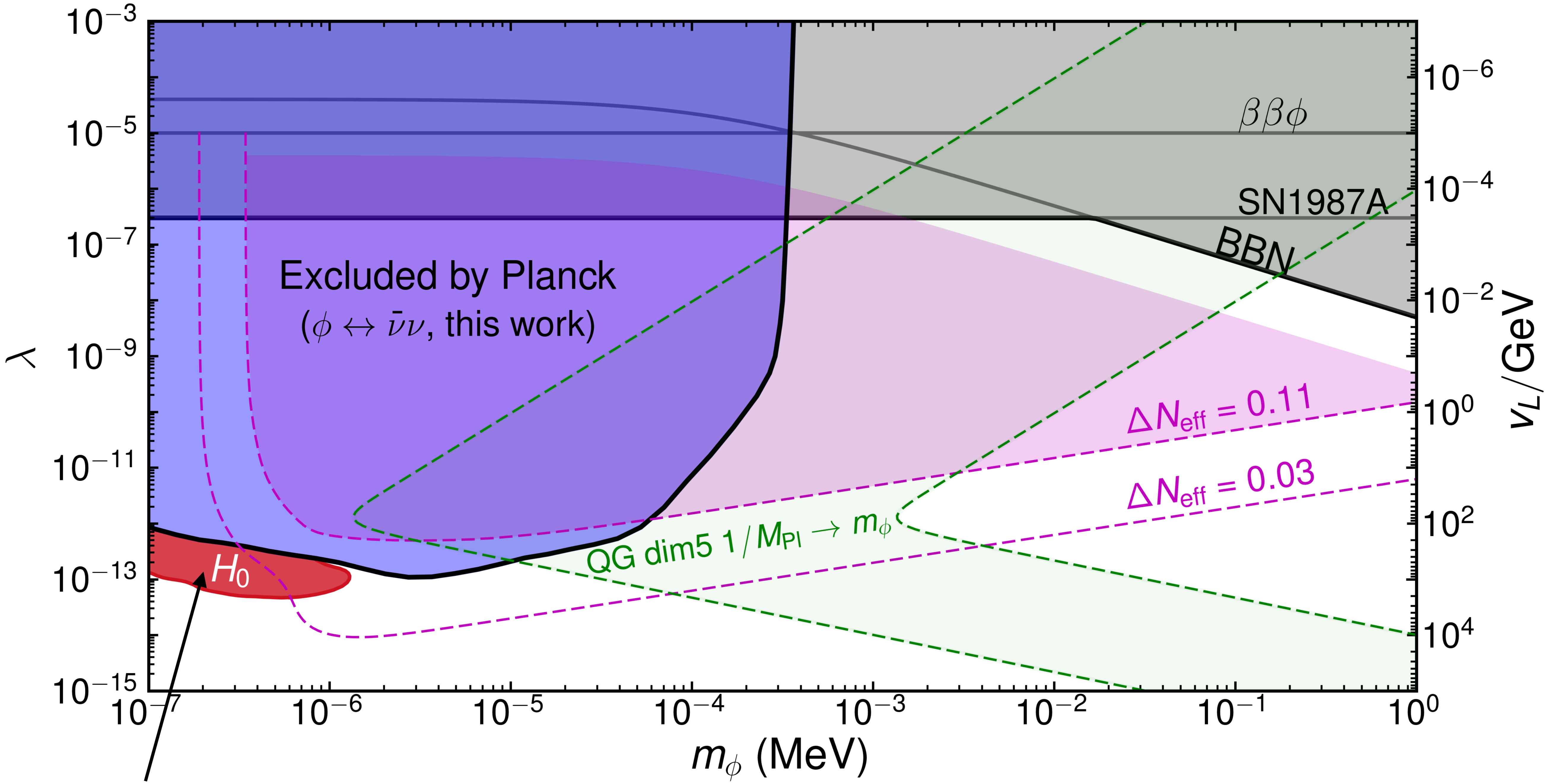
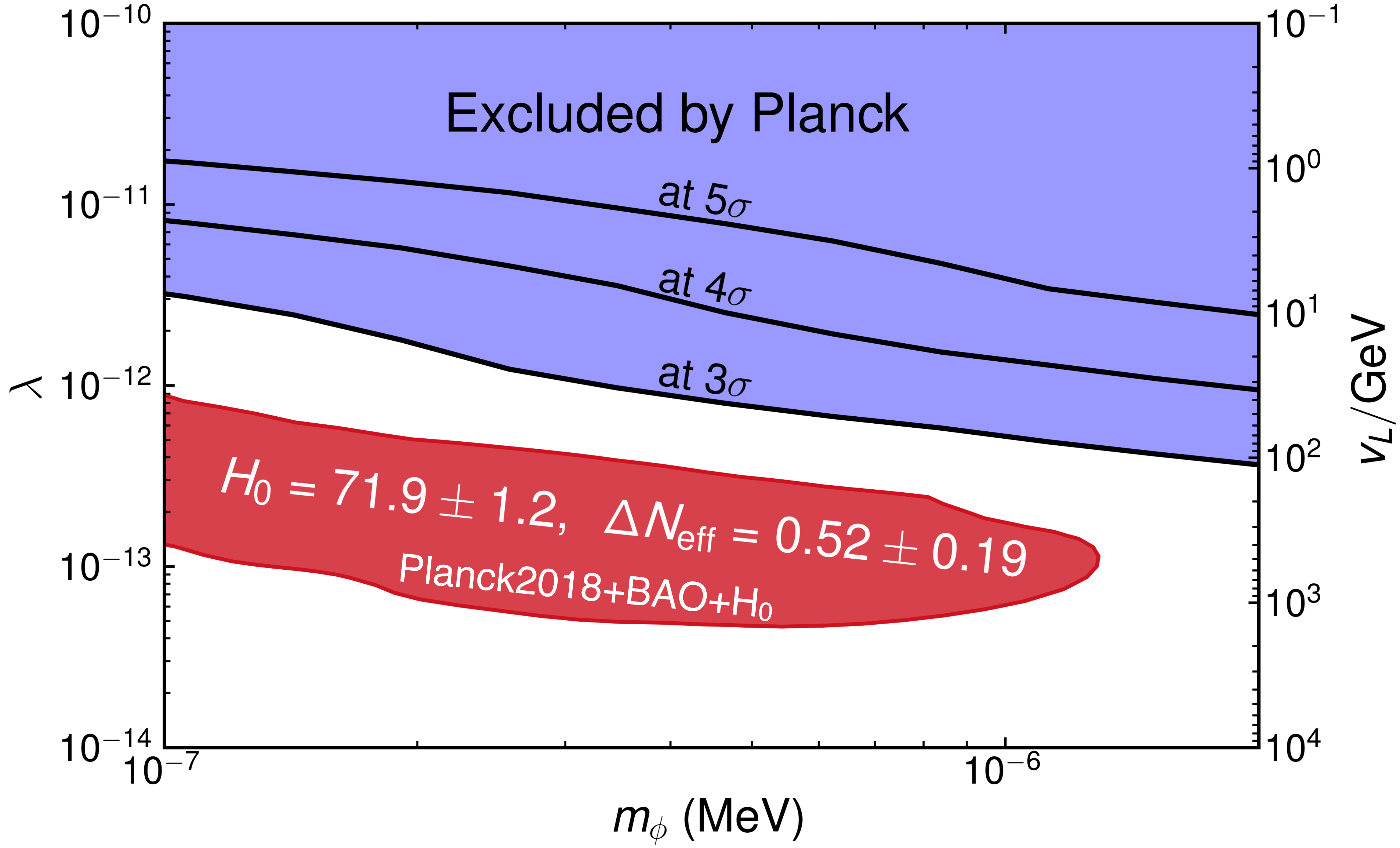


1σ preference when including H_0 in the fit and an additional $\Delta N_{\rm eff}$

Parameter Space for H_0



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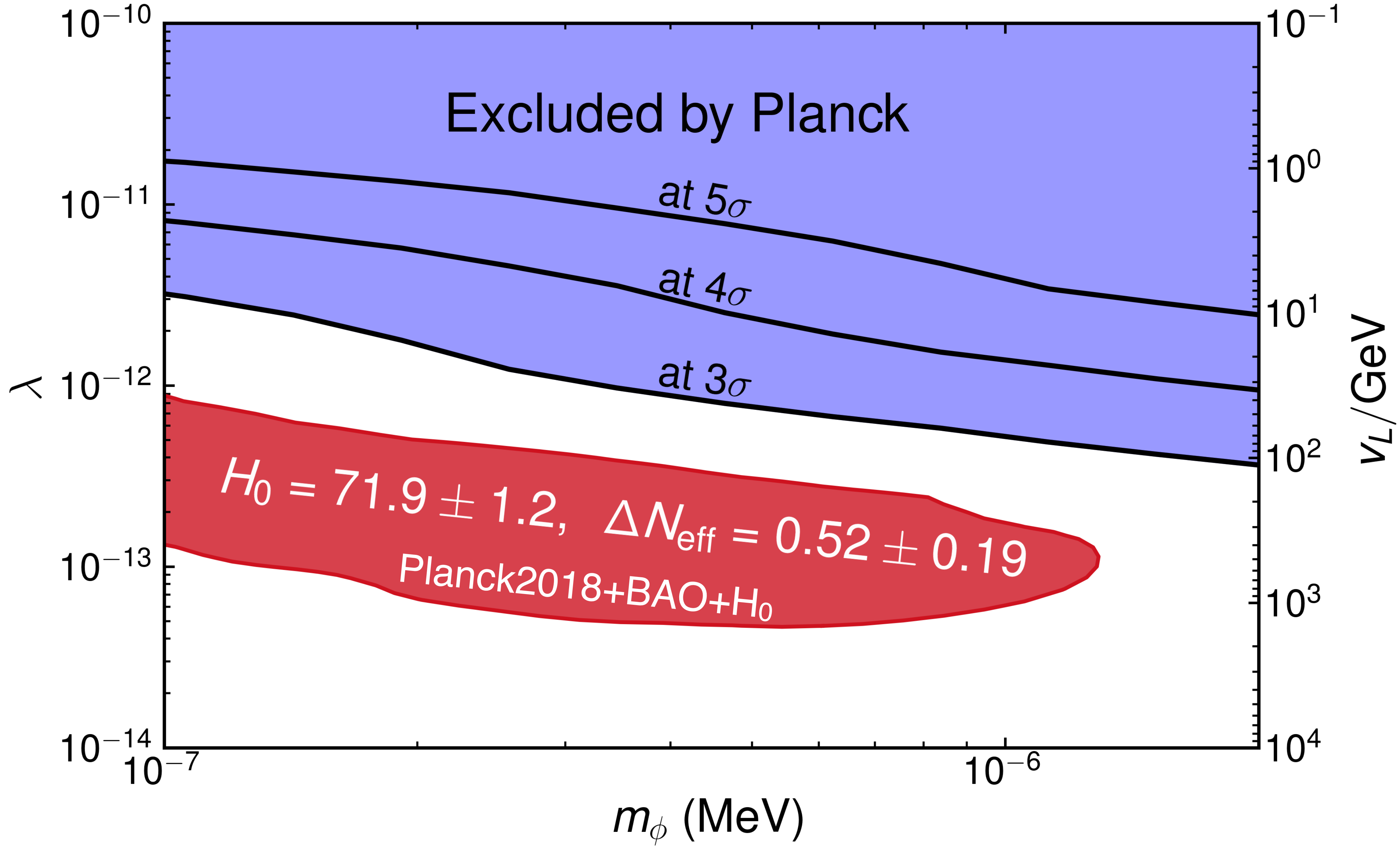


H_0

- **Requires a positive $\Delta N_{eff} \sim 0.5$**
- **Planck 2018 fit is not degraded wrt ΛCDM**
- **Very close to the electroweak scale** $v_L \sim (0.1 - 1)\,\mathrm{TeV}$

Conclusions

- **The H_0 tension: Beyond ΛCDM?**

Conclusions

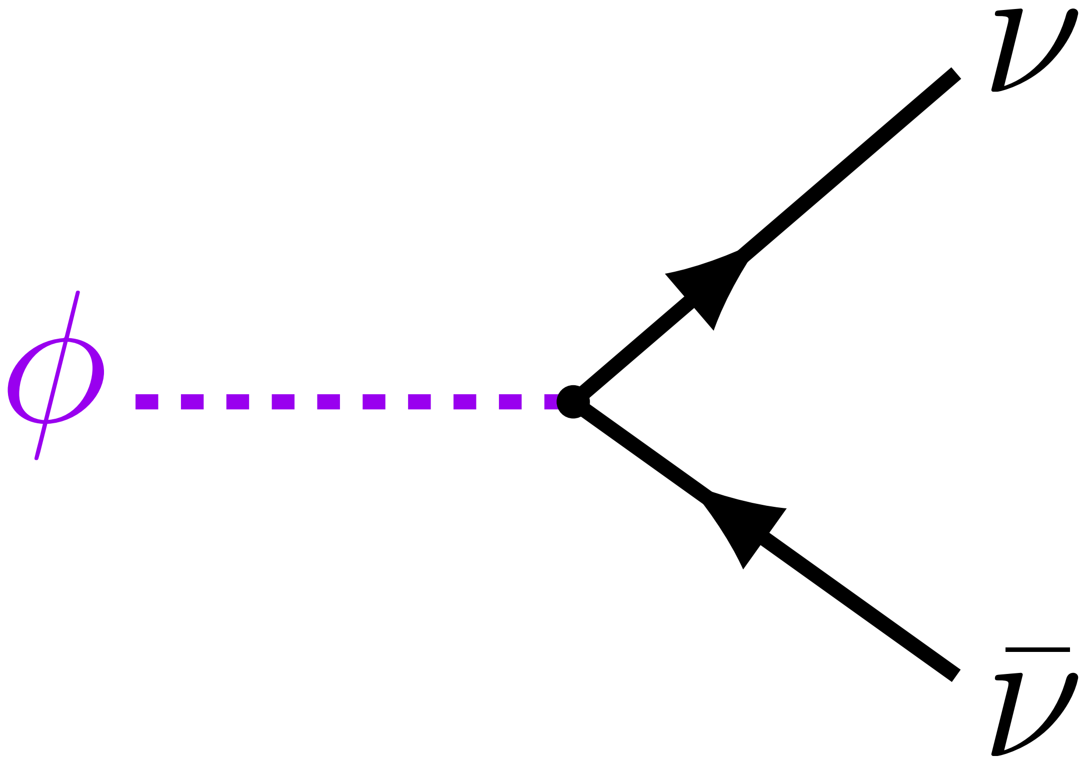
- The H_0 tension: Beyond ΛCDM?

- The specific case of the Majoron:
  - Compelling extension of the SM
  - Couplings from seesaw and mass from gravity
  - Planck sets very stringent constraints
  - Ameliorates H_0 tension via $\Delta N_{\rm eff} = 0.11$
  - May solve the tension for:

$$m_\phi \sim (0.1 - 1)\,\mathrm{eV}$$
$$v_L \sim (0.1 - 1)\,\mathrm{TeV}$$
$$\Delta N_{\rm eff} \sim 0.5$$

Questions and Comments?

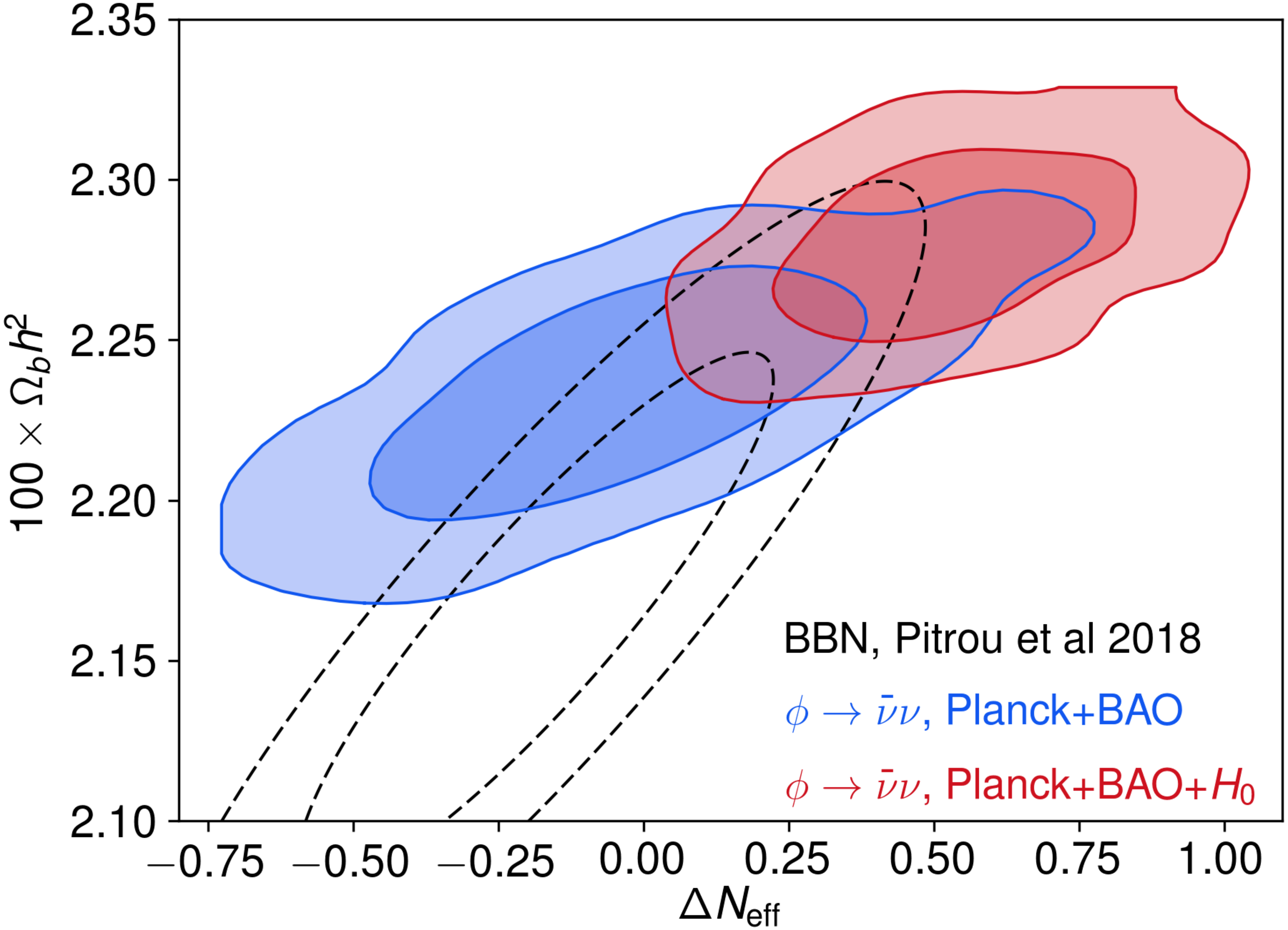
Thank you for your attention!



Check ArXiv:1909.04044 with Sam Witte!

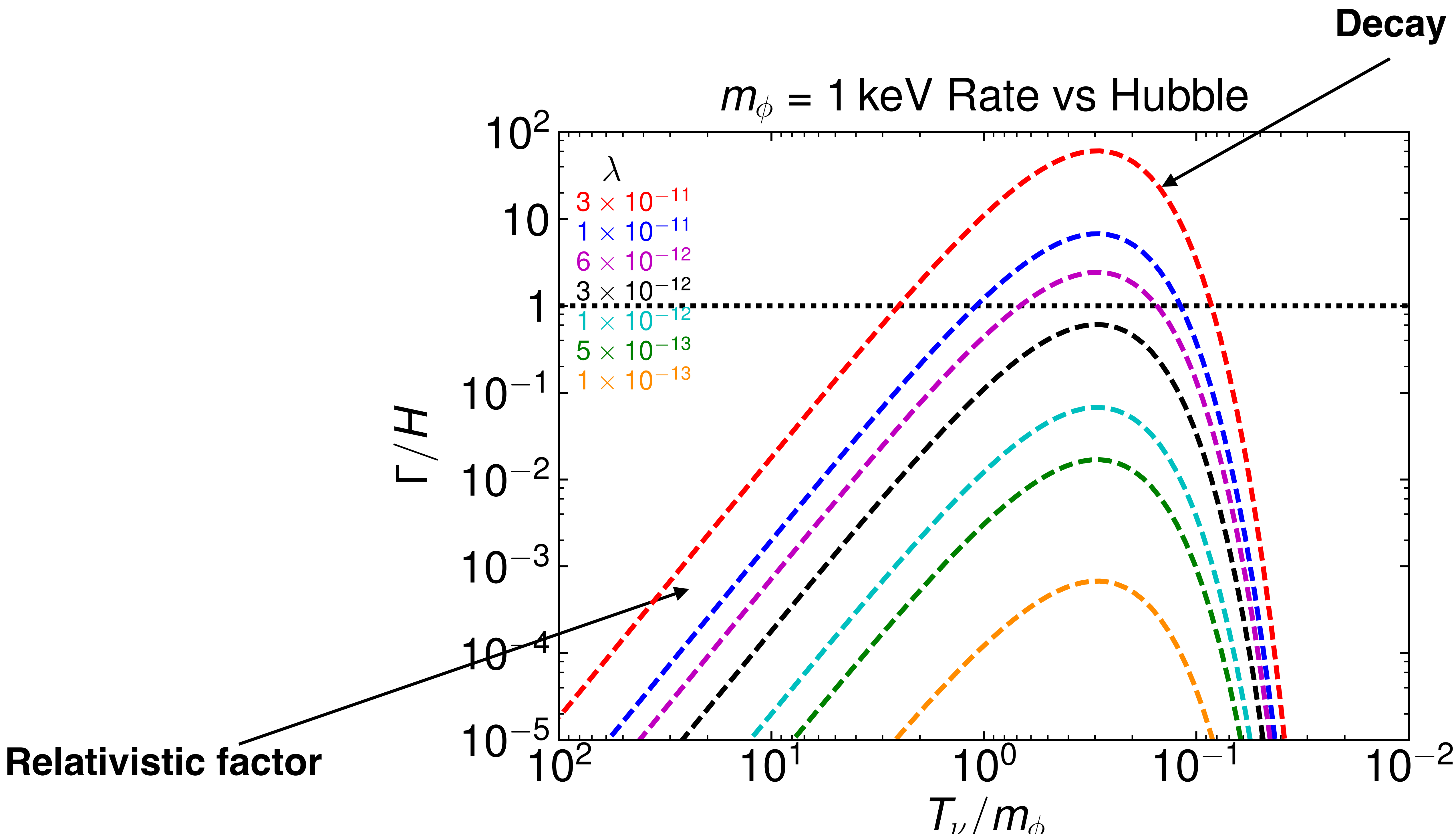
Back Up

Neff and BBN

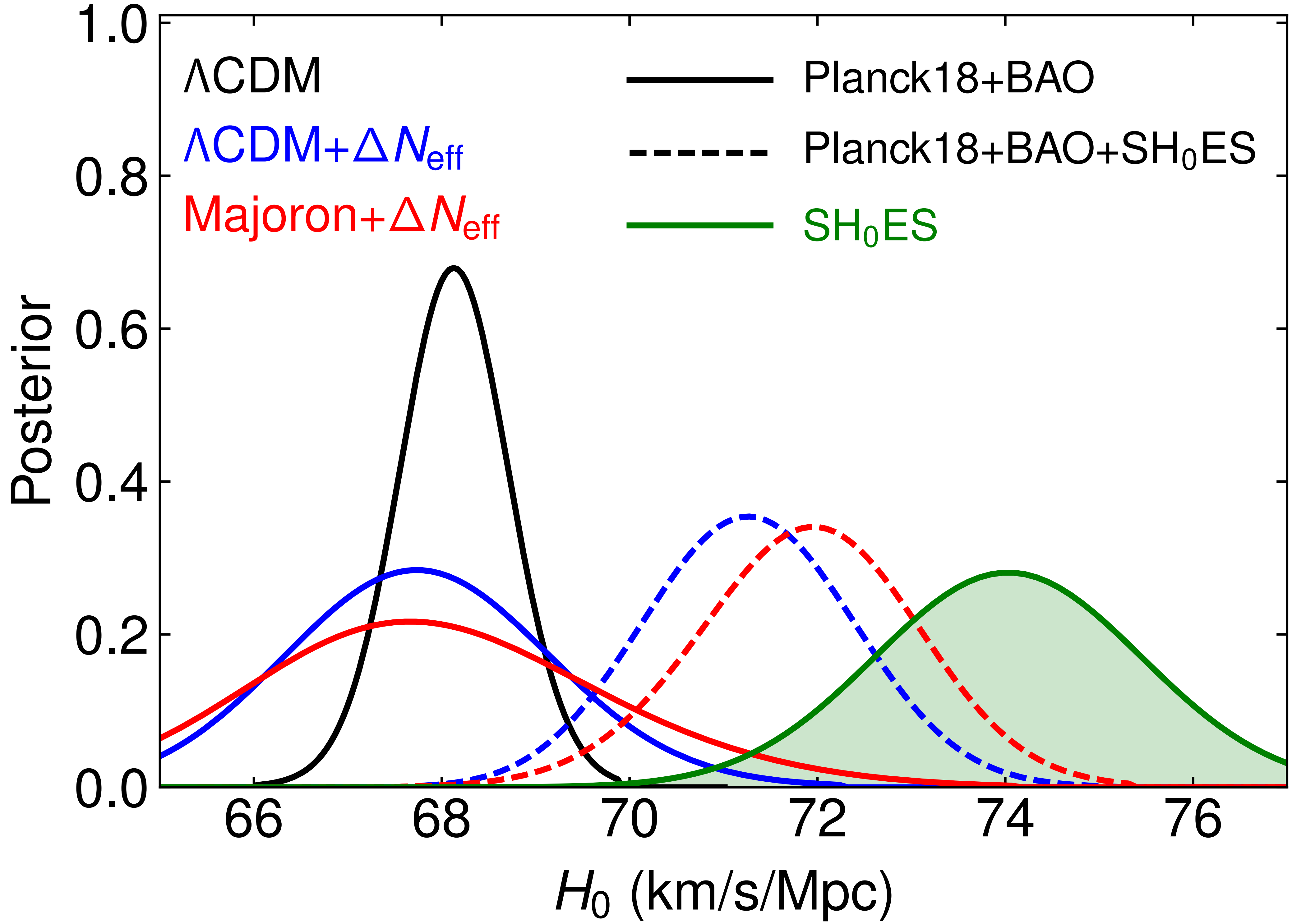


2.35
2.30
2.25
2.20
2.15
2.10
$100 \times \Omega_b h^2$
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
$\Delta N_{\rm eff}$
BBN, Pitrou et al 2018
$\phi \to \bar{\nu}\nu$, Planck+BAO
$\phi \to \bar{\nu}\nu$, Planck+BAO+H_0

The Physics: Interaction Strength

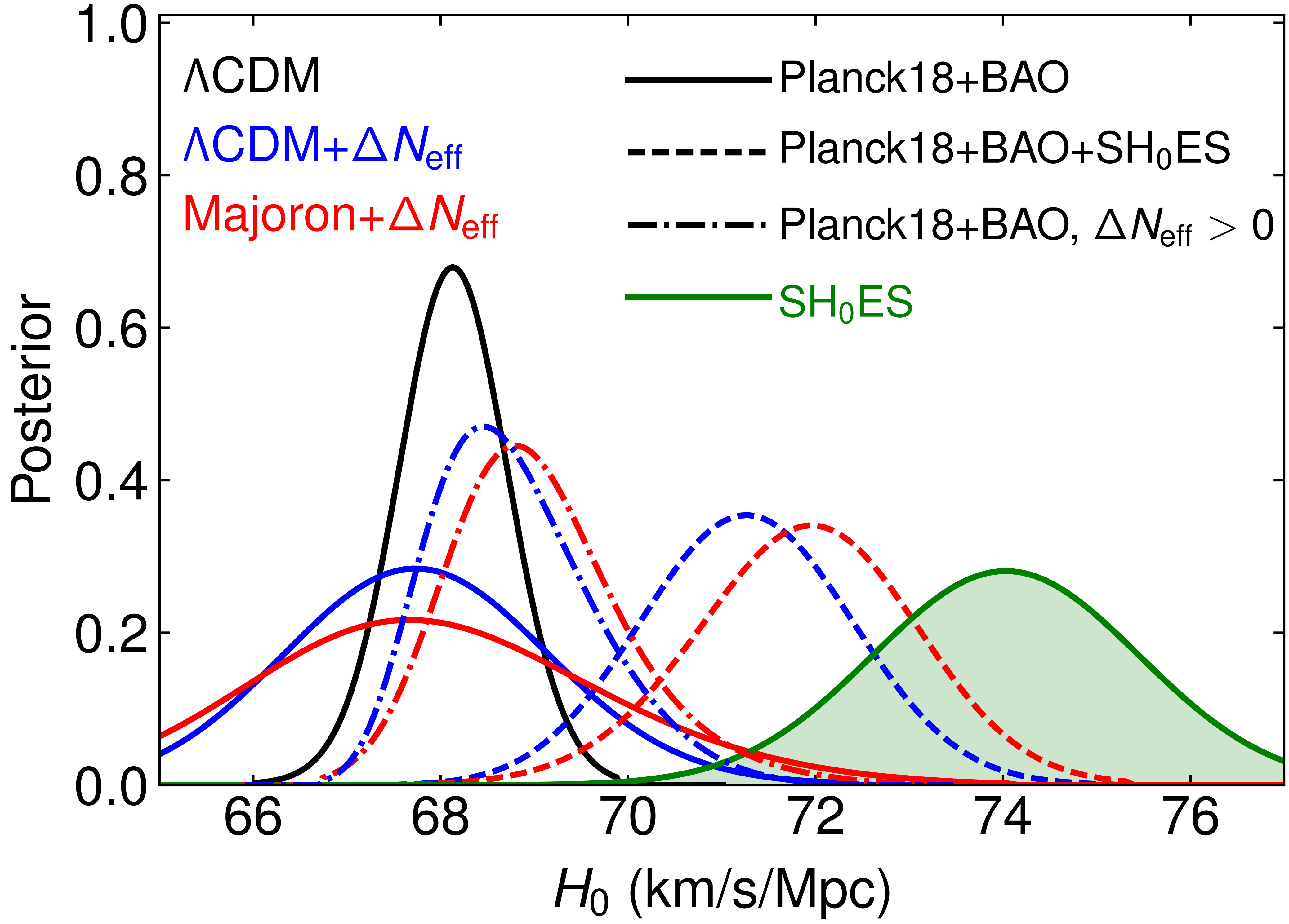


H0 Plots



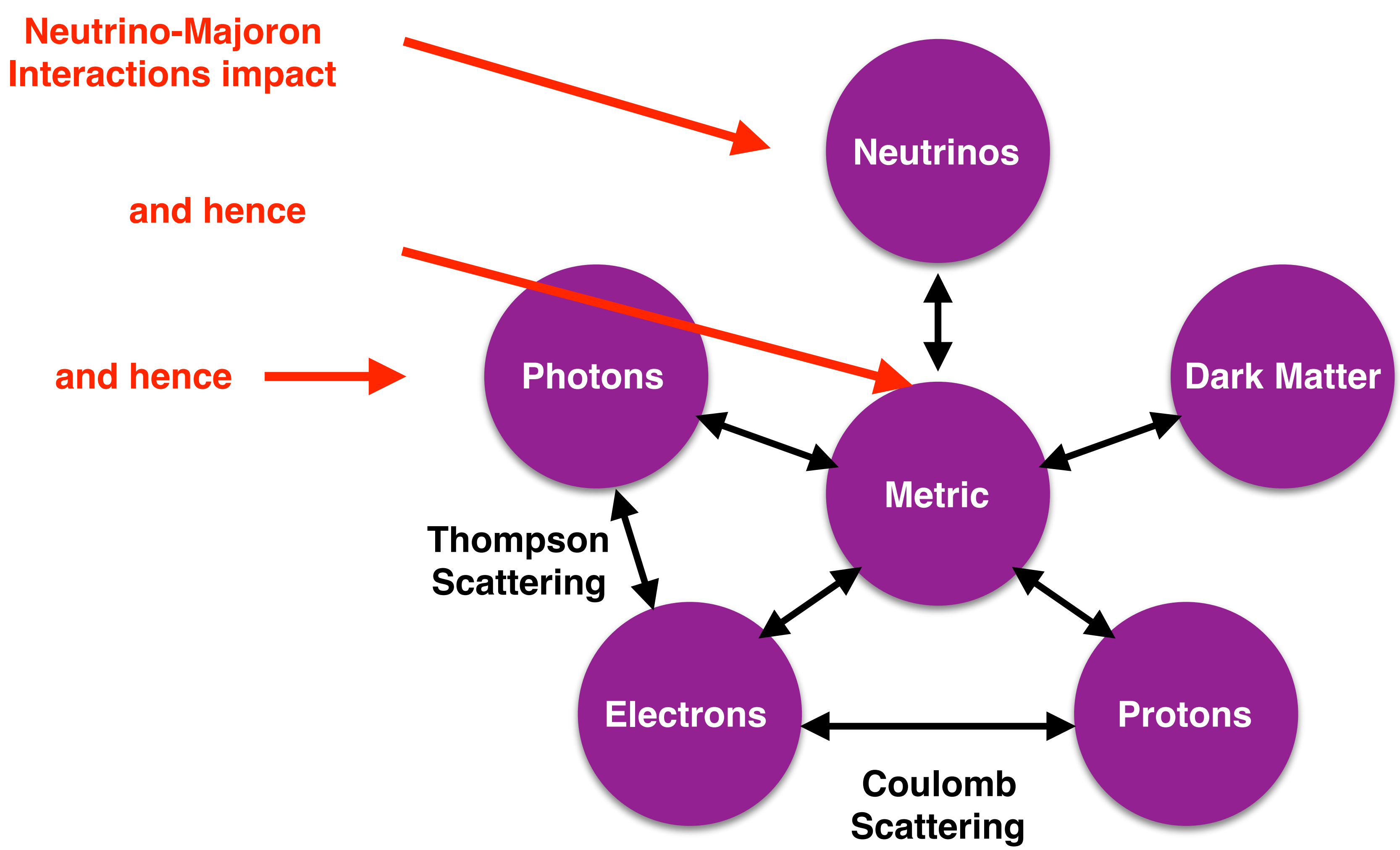
1.0
0.8
0.6
0.4
0.2
0.0
Posterior
ΛCDM
ΛCDM+ΔNeff
Majoron+ΔNeff
Planck18+BAO
Planck18+BAO+SH0ES
SH0ES
66
68
70
72
74
76
H0 (km/s/Mpc)

H0 Plots


1.0
0.8
0.6
0.4
0.2
0.0
Posterior
ΛCDM
ΛCDM+Δ$N_{\rm eff}$
Majoron+Δ$N_{\rm eff}$
Planck18+BAO
Planck18+BAO+SH$_0$ES
Planck18+BAO, Δ$N_{\rm eff} > 0$
SH$_0$ES
66
68
70
72
74
76
H_0 (km/s/Mpc)

The Physics: Neutrino Perturbations

see Bashinsky and Seljak astro-ph/0310198



The Physics: Neutrino Perturbations

$$f(x^i, p^i, t) = f_0(p)\left[1 + \Psi(x^i, p^i, t)\right]$$

$$\Psi = \textstyle\sum_0^\infty (-i)^\ell \,(2\ell+1)\, \Psi_\ell \, P_\ell(\mu)$$

$$\dot{\delta}_{\nu\phi} = -\frac{4}{3}\theta_{\nu\phi} - \frac{2}{3}\dot{h}\,,$$

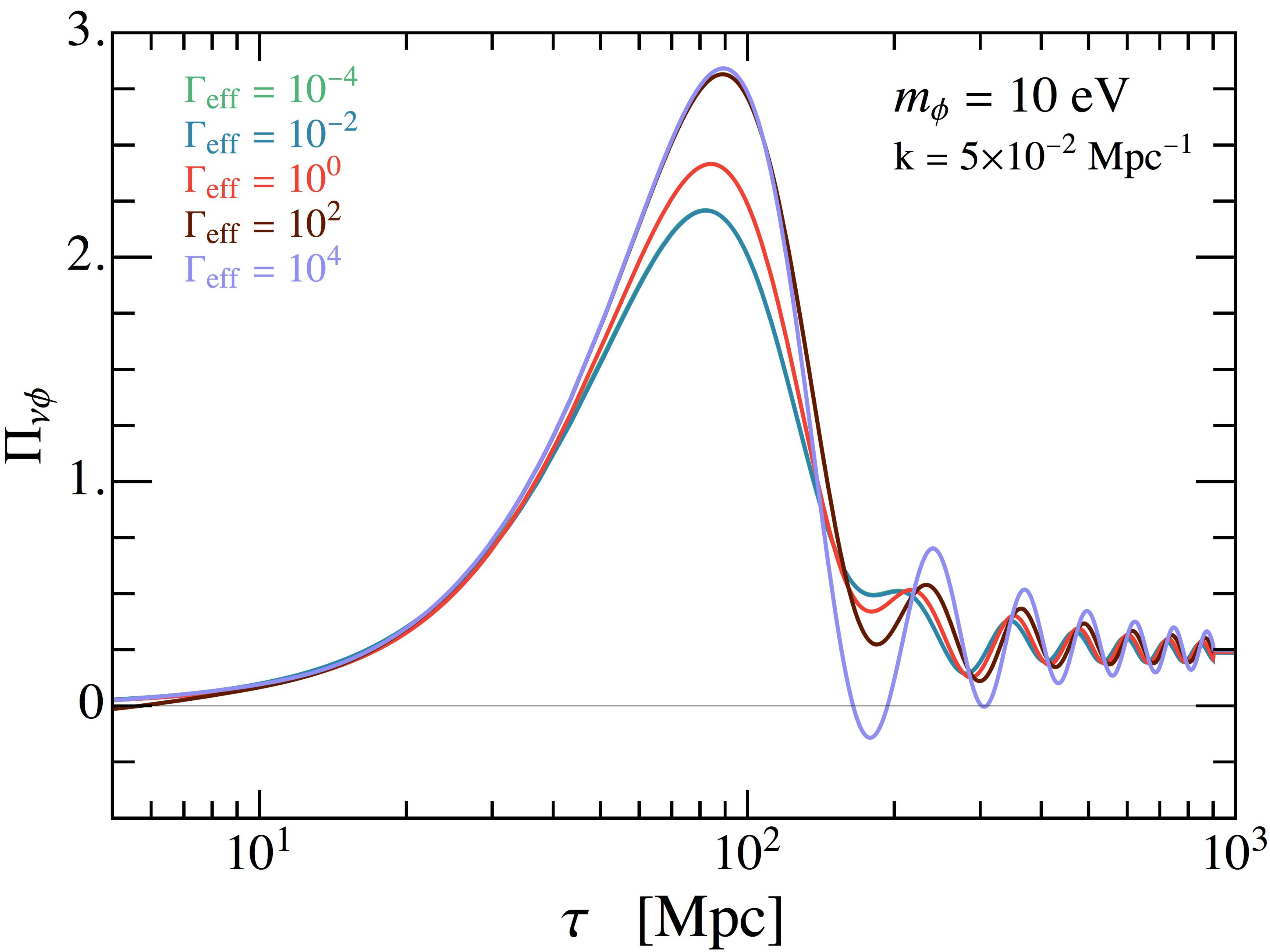
$$\dot{\theta}_{\nu\phi} = k^2\left(\frac{1}{4}\delta_{\nu\phi} - \sigma_{\nu\phi}\right)\,,$$

$$\dot{F}_{\nu\phi 2} = 2\dot{\sigma}_{\nu\phi} = \frac{8}{15}\theta_{\nu\phi} - \frac{3}{5}kF_{\nu\phi\,3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} - 2a\Gamma\sigma_{\nu\phi}\,,$$

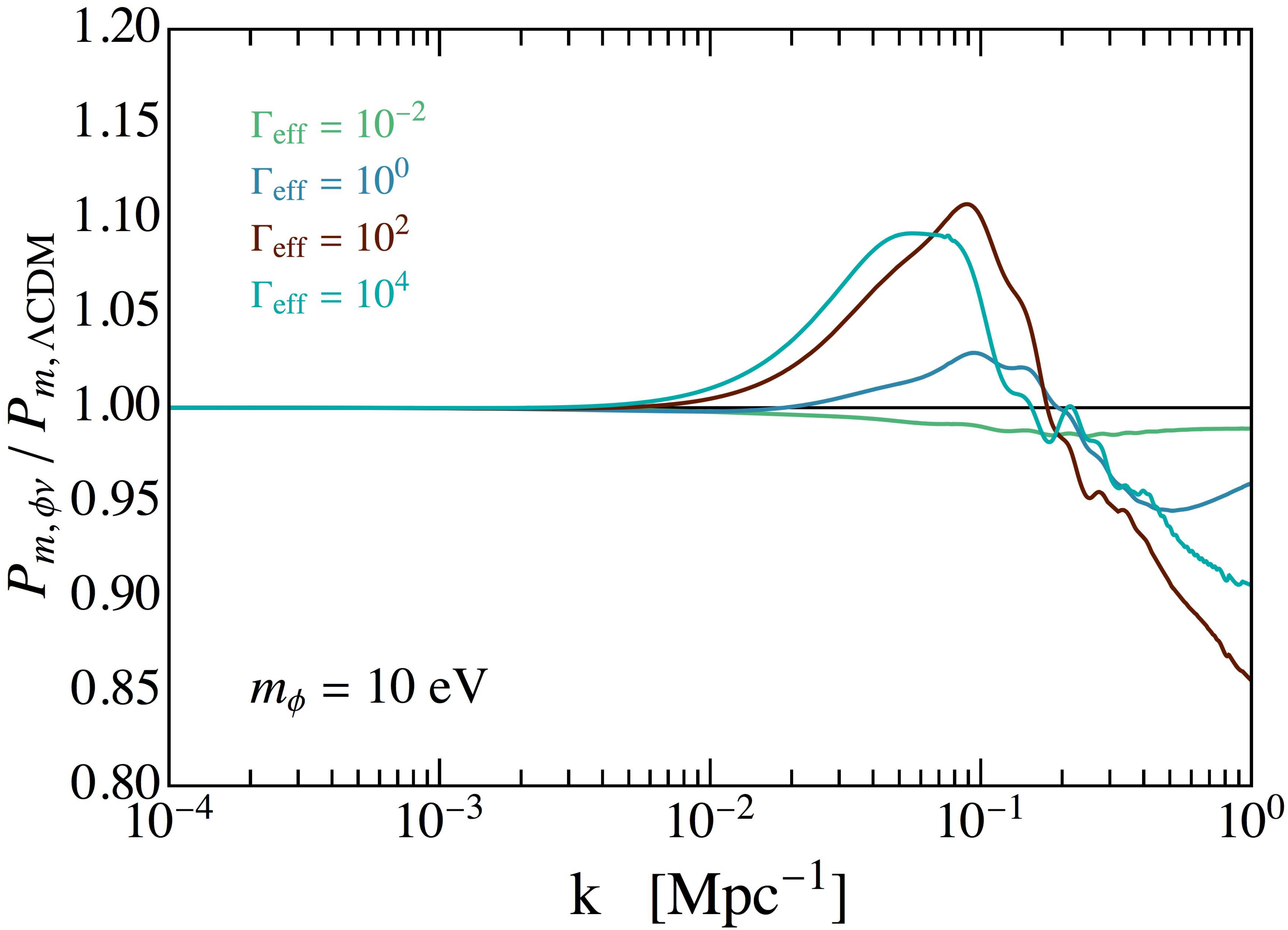
$$\dot{F}_{\nu\phi\,\ell} = \frac{k}{2\ell+1}\left[\ell\, F_{\nu\phi\,(\ell-1)} - (\ell+1)F_{\nu\phi\,(\ell+1)}\right] - a\Gamma F_{\nu\phi\,\ell}\,,\;\; \ell \geq 3\,.$$

$$\Gamma \equiv \frac{1}{n_\nu}\,\frac{\delta n_\nu}{\delta t}\bigg|_{\text{forward}} = \frac{\Gamma_\phi}{2}\,\frac{m_\phi^2}{T_\nu^2}\,e^{\frac{\mu_\nu}{T_\nu}}\,K_1\left(\frac{m_\phi}{T_\nu}\right)$$

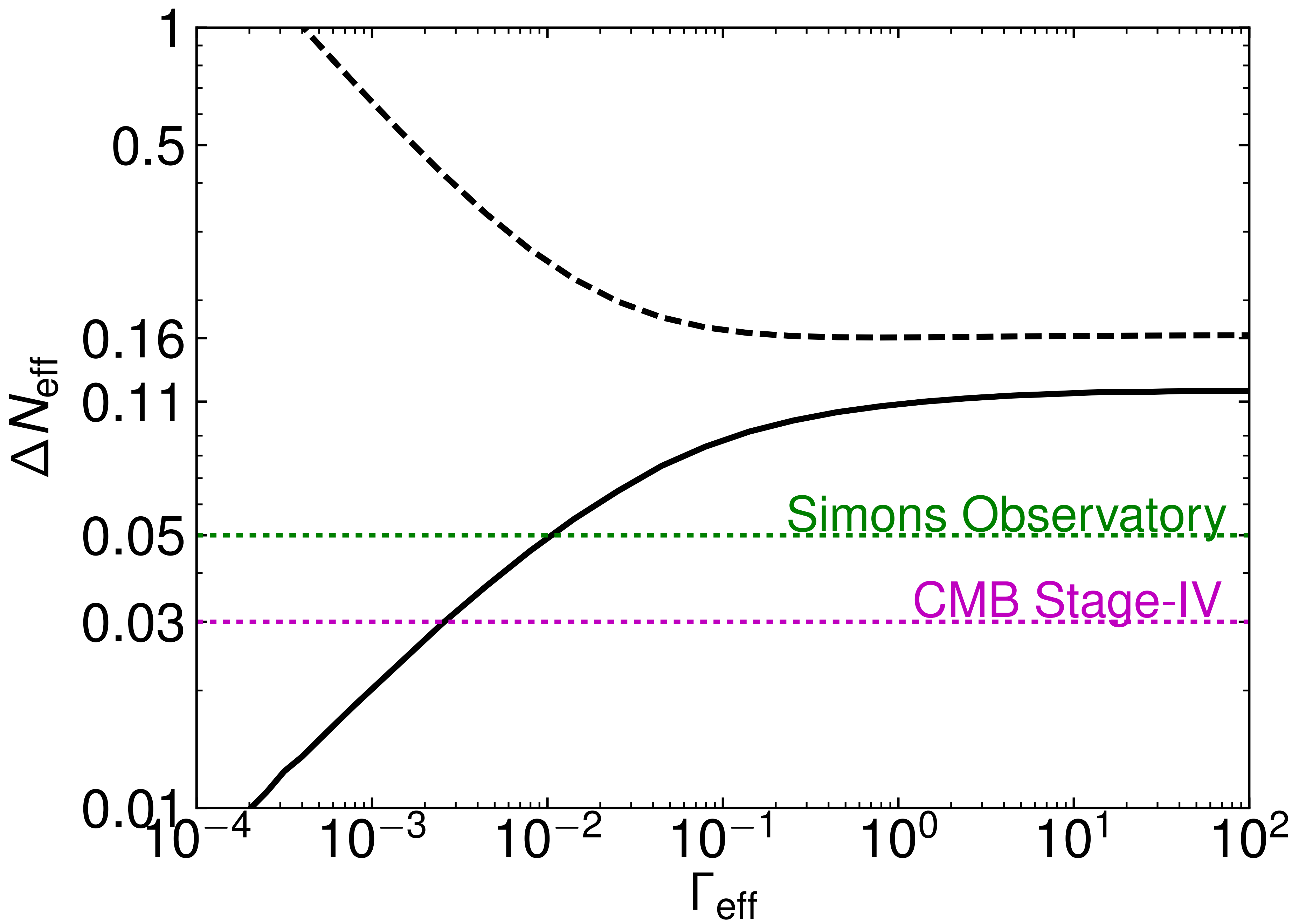
The Physics: Neutrino Perturbations



The Physics: Power Spectrum



Primordial Abundance Neff



Hubble Constant from the CMB

CMB measurements provide a H_0 prediction from:

$$\theta_s \equiv r_s / D_M(z_\star)$$

$$r_s = \int_{z_\star}^{\infty} \frac{c_s}{H(z')}\, dz'$$ **Comoving sound horizon**

$$D_M(z) = \int_0^{z} \frac{1}{H(z')}\, dz'$$ **Comoving angular diameter distance**

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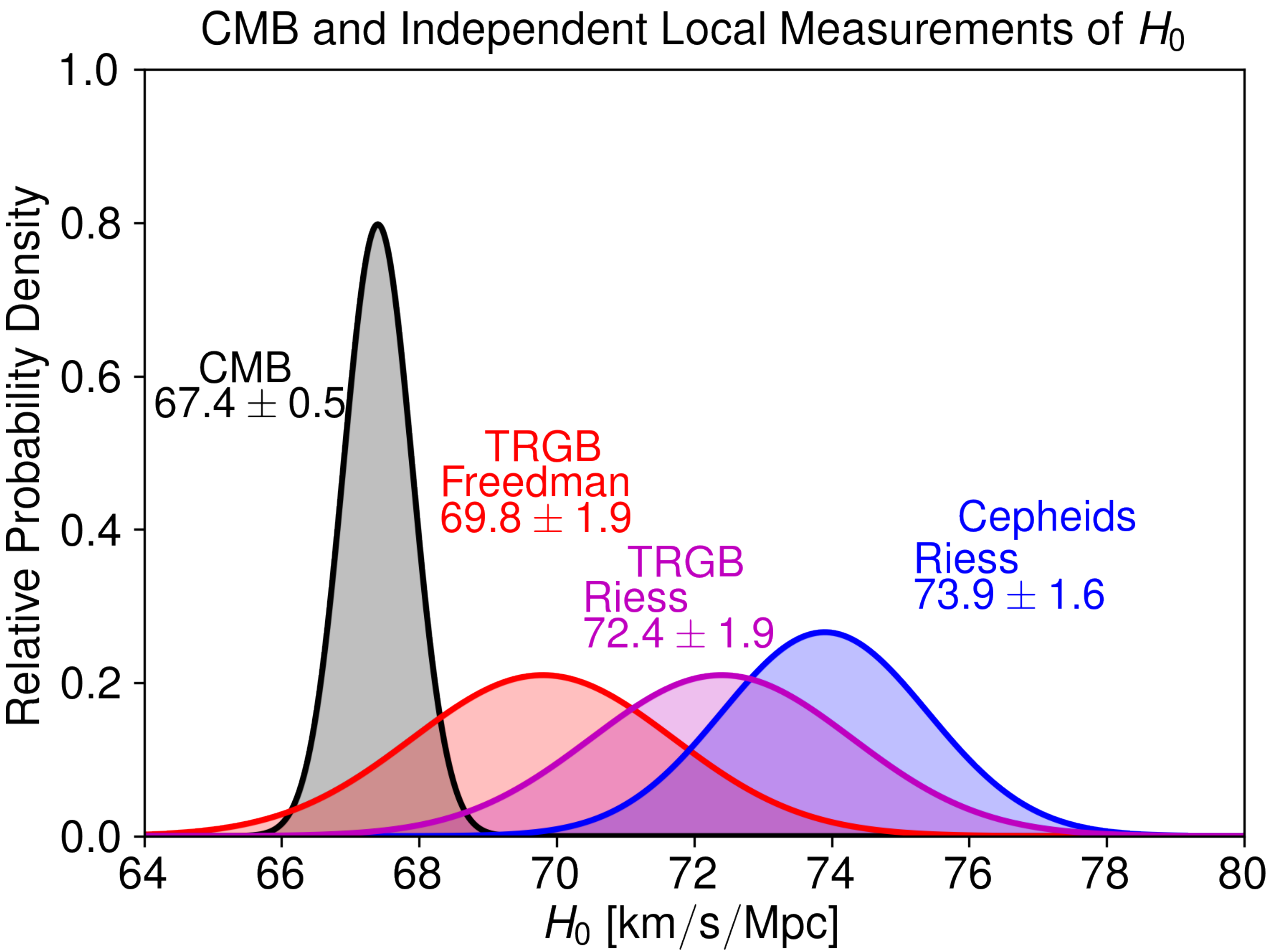
Comoving sound horizon is the easiest thing to modify

Enhance the expansion prior to recombination

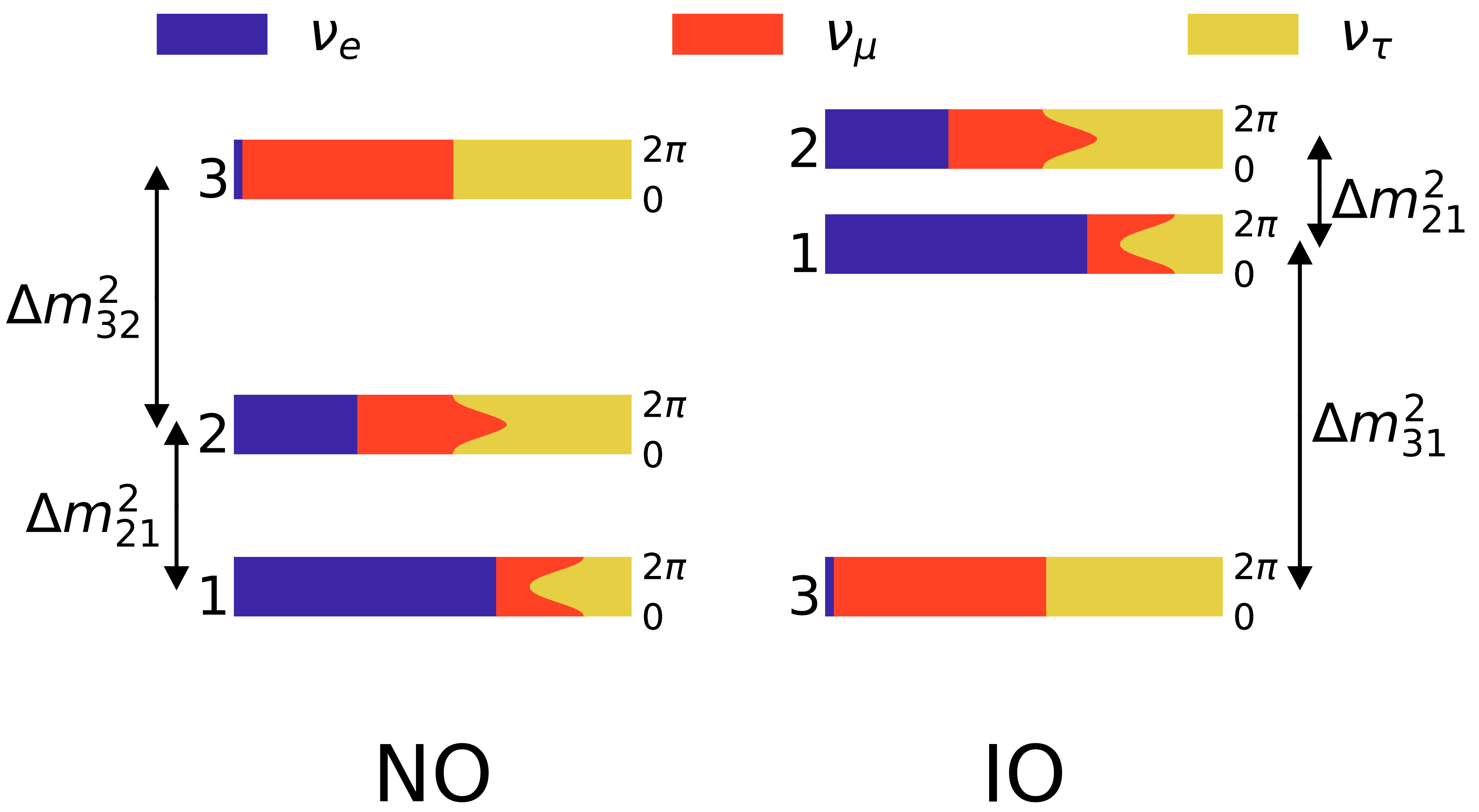
The Hubble Tension as of today

1908.00993 Riess et. al.



Neutrino Masses

At least two neutrinos are massive

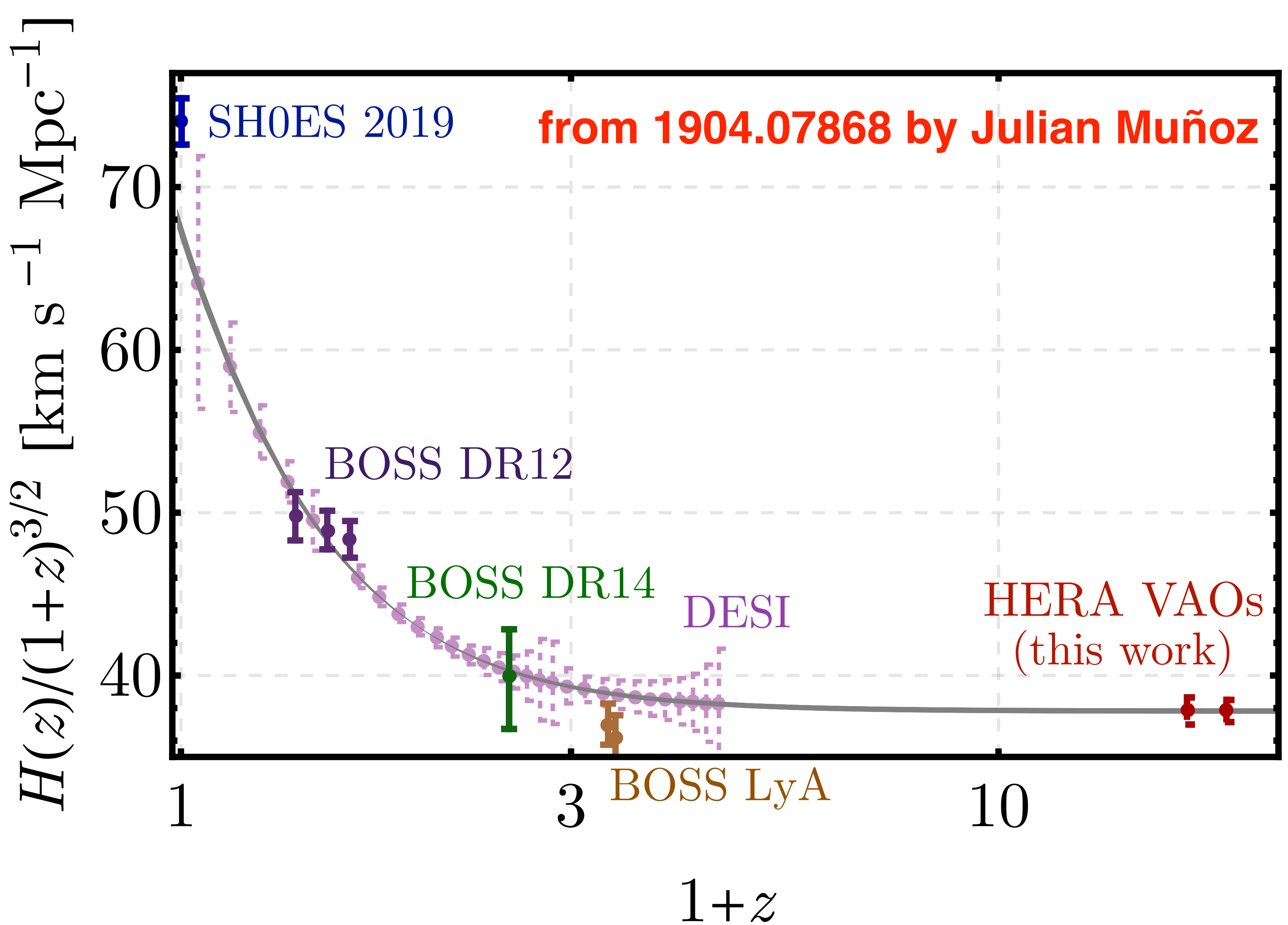


1806.11051, de Salas et. al.

$$\sqrt{|\Delta m^2_{31}|} \simeq 0.05\,\mathrm{eV} \qquad \sqrt{\Delta m^2_{21}} \simeq 0.01\,\mathrm{eV}$$

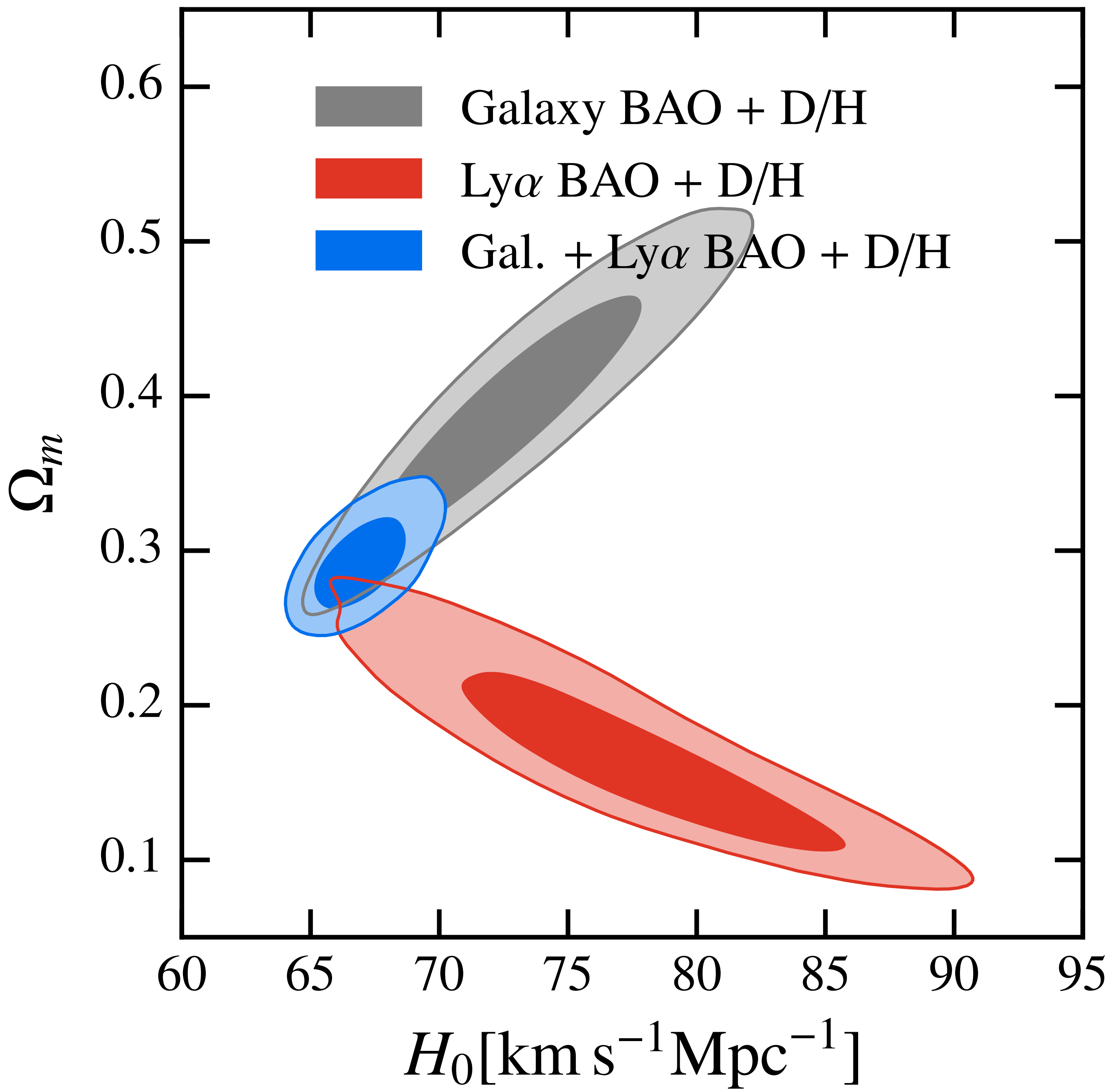
Future Measurements

- **1% local determination of H_0 in the next decade**
- **Future CMB missions, Simons, Stage-IV experiments**
- **Expansion History in the next decade:**



The Hubble Tension

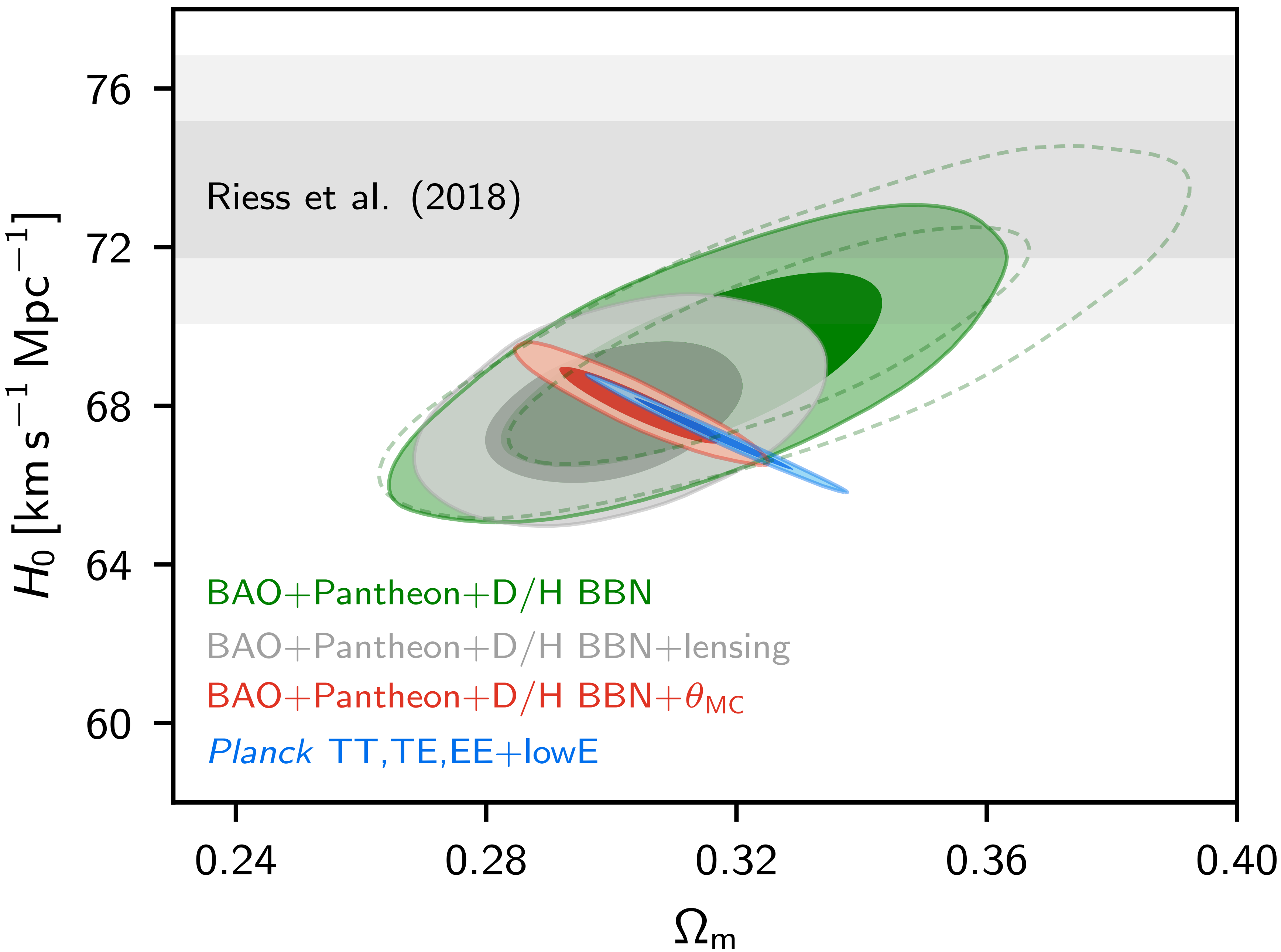
- **Tension is also present in BAO**

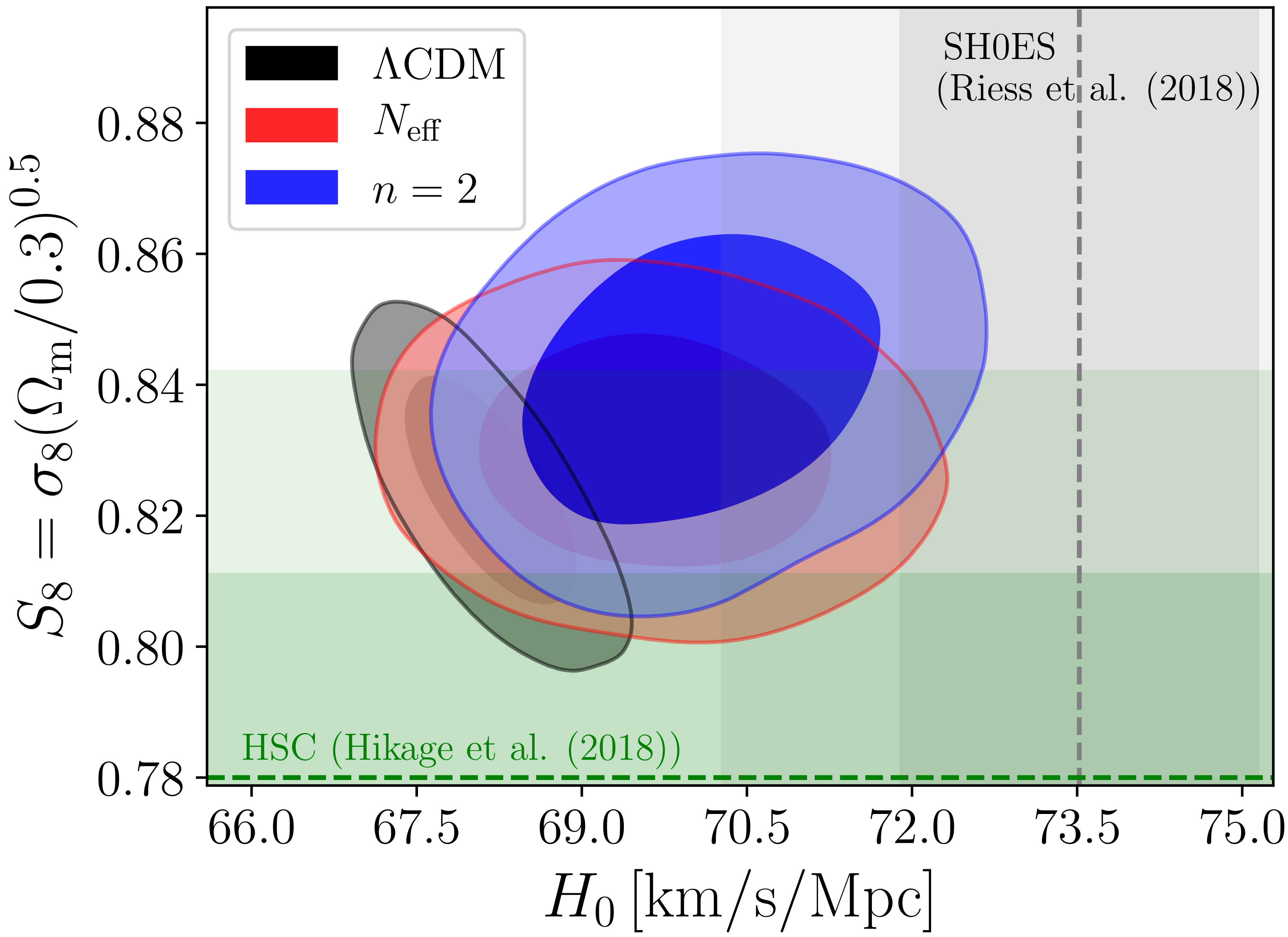


Addison *et al* 1707.06547

The Hubble Tension

- **Tension is also present when compared with BAO and SNIa (Parthenon) using $\Omega_b h^2$ from BBN**





from 1904.01016 Agrawal, Cyr-Racine, Pinner, Randall

Neutrino Decoupling

Definition:

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right)$$

SM prediction: $N_{\rm eff}^{\rm SM} = 3.045$

1606.06986 de Salas & Pastor
hep-ph/0506164 Mangano *et. al.*

Why is it not 3? **for an excellent review see hep-ph/0202122 by Dolgov**

1) Neutrino Decoupling not instantaneous $\sigma \sim G_F^2 E_\nu^2$

2) Weak Interactions freeze out at T = 2-3 MeV
hence, some heating from e^+e^- annihilation $n\,\langle \sigma v\rangle \simeq G_F^2 T^5 \simeq H$

3) Finite Temperature QED corrections $\delta m_e^2(T),\, \delta m_\gamma^2(T)$

4) Neutrino oscillations are active at T < 3 MeV

Simplified approach: **Escudero arXiv:1812.05605, JCAP 1902 (2019) 007**

Beyond ΛCDM

Early Universe or late Universe modifications?

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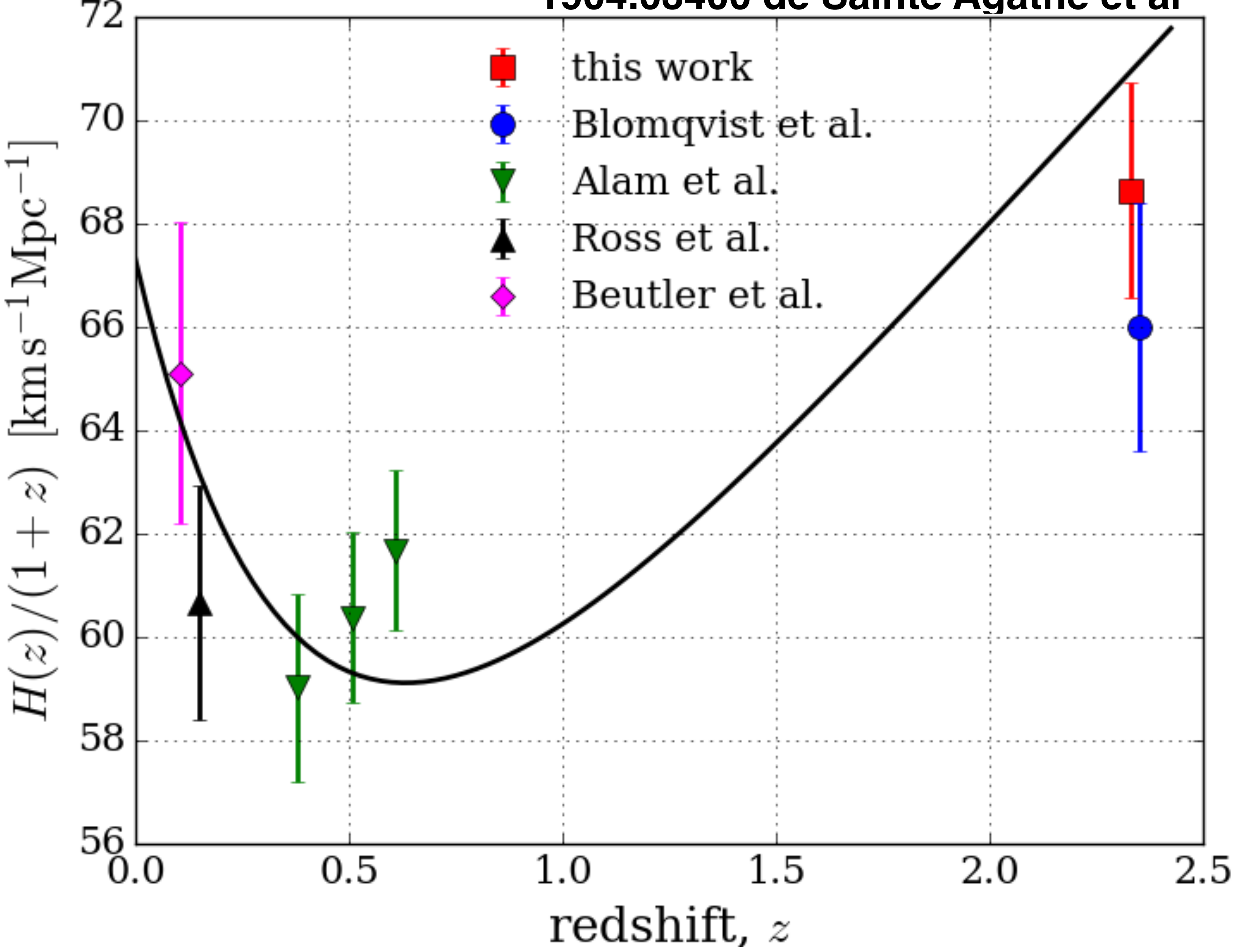
Early Universe or late Universe modifications?

1904.03400 de Sainte Agathe et al



BAO measurements point toward an early Universe effect