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

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based on ArXiv:1907.XXXXX with Sam Witte

Beyond 2019
Warsaw

KING'S College LONDON

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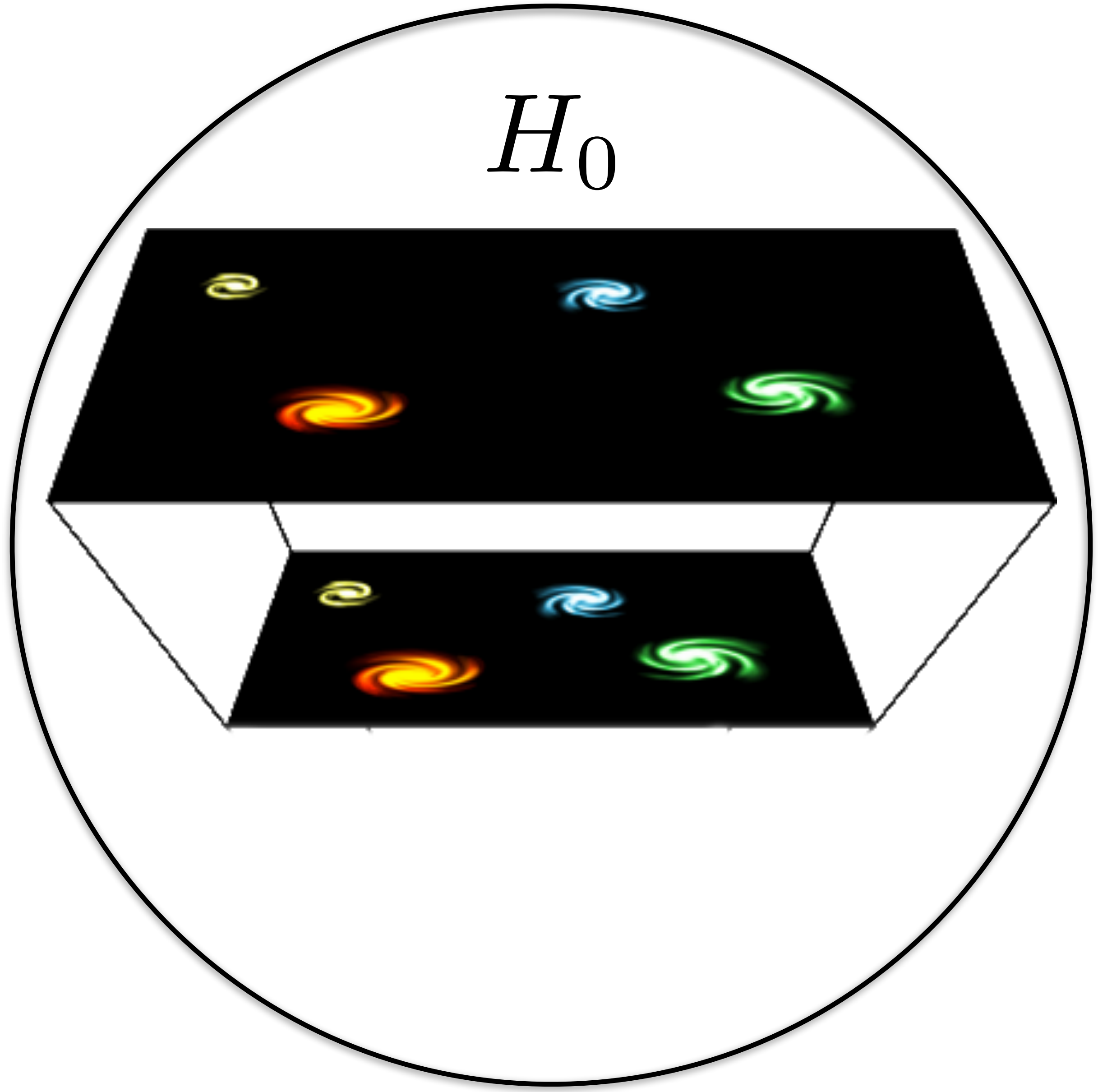
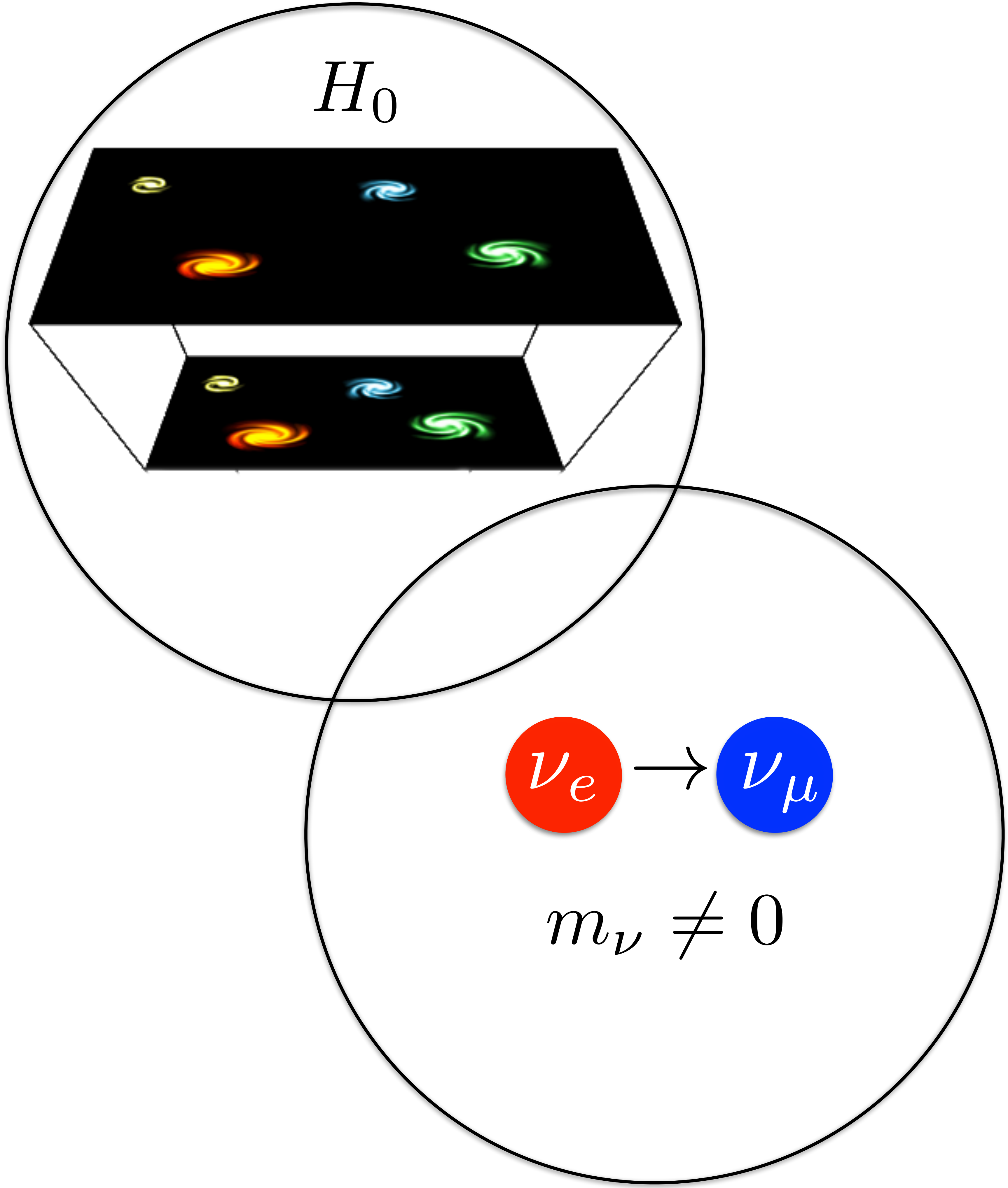
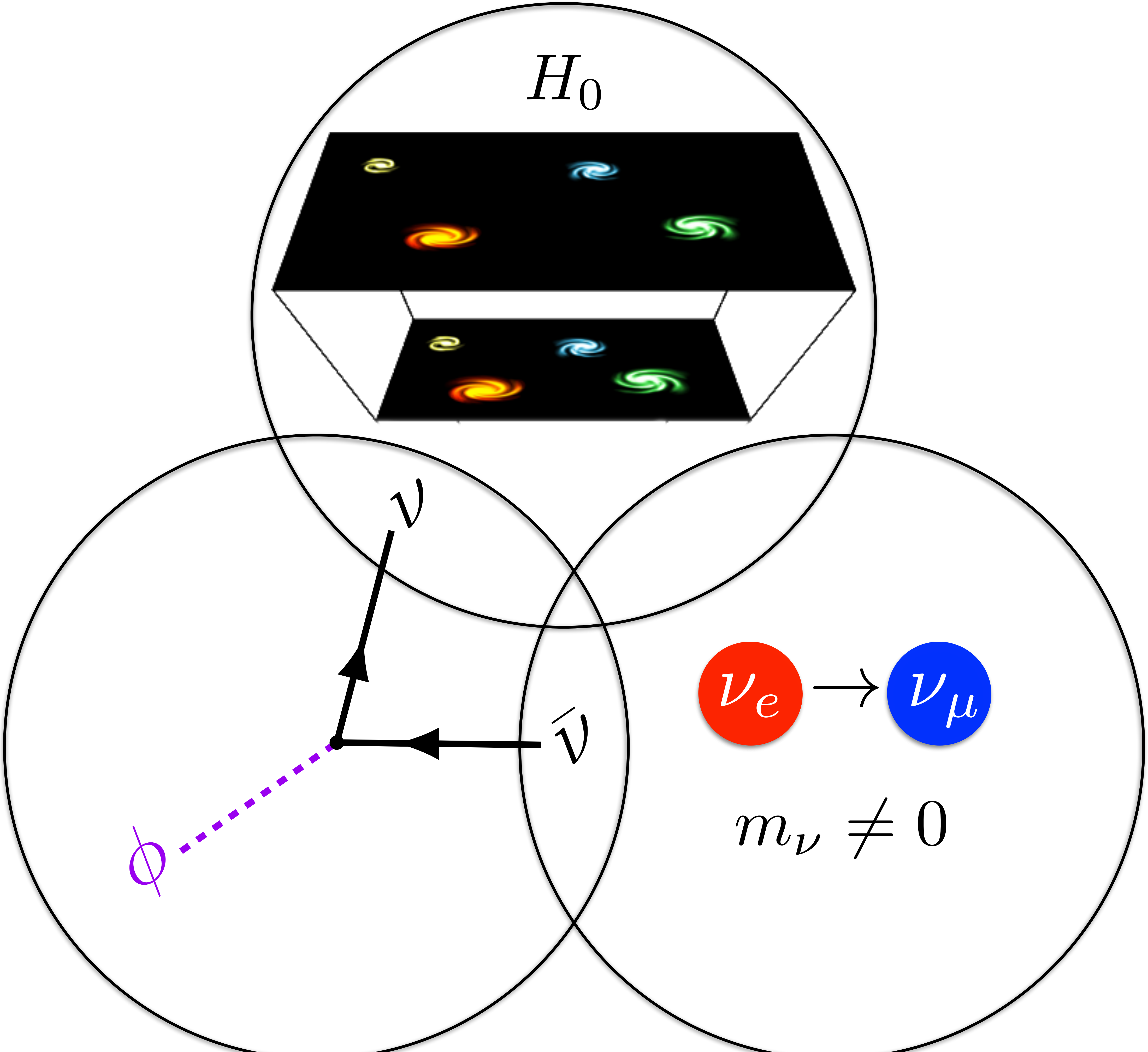

H_0



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



H_0
ν
$\bar{\nu}$
ϕ
ν_e
ν_μ
$m_\nu \neq 0$

Outline

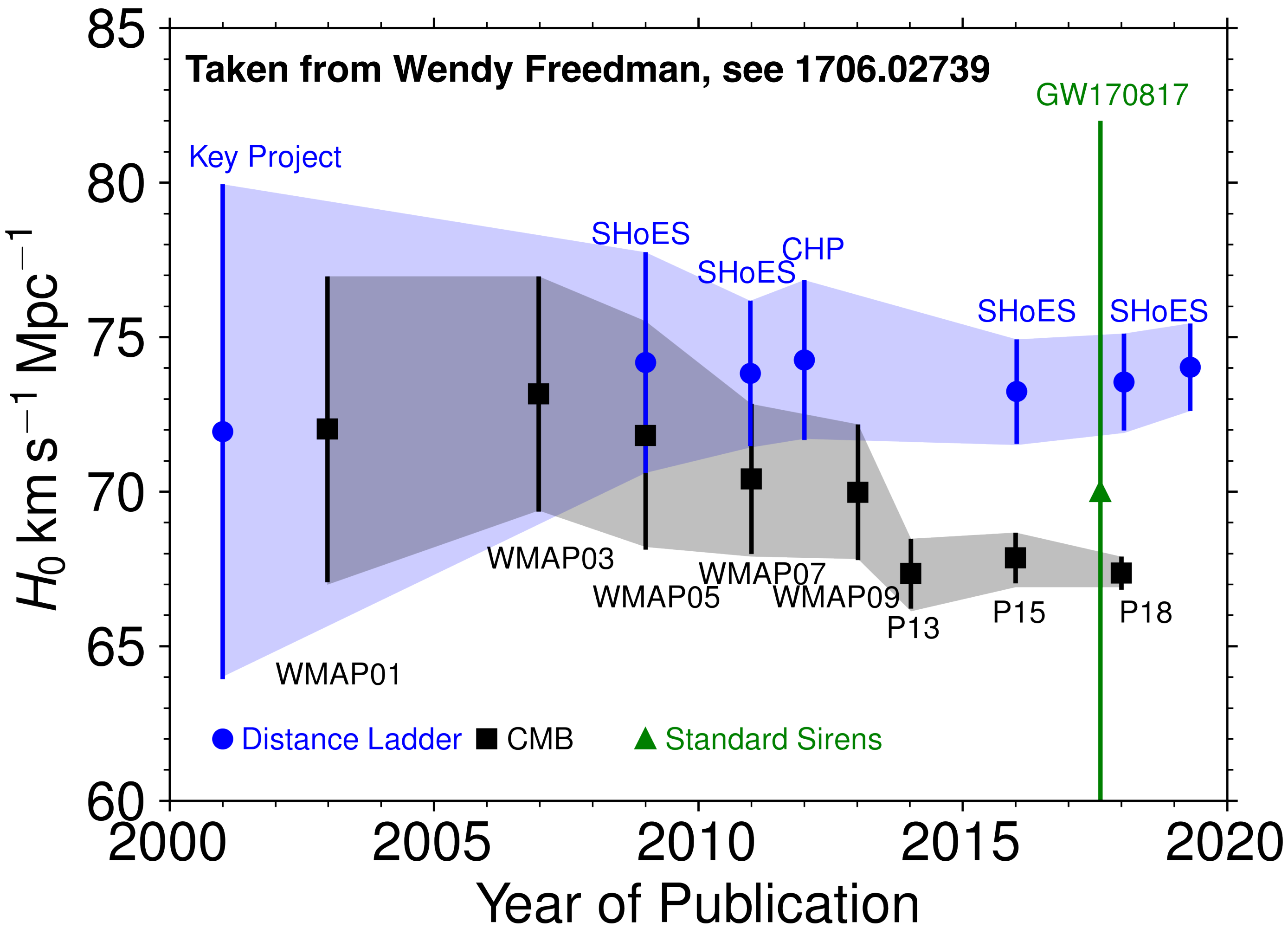
1) The Hubble Tension

2) The Scenario

3) Cosmology with a light Majoron

4) Conclusions

The Hubble Tension



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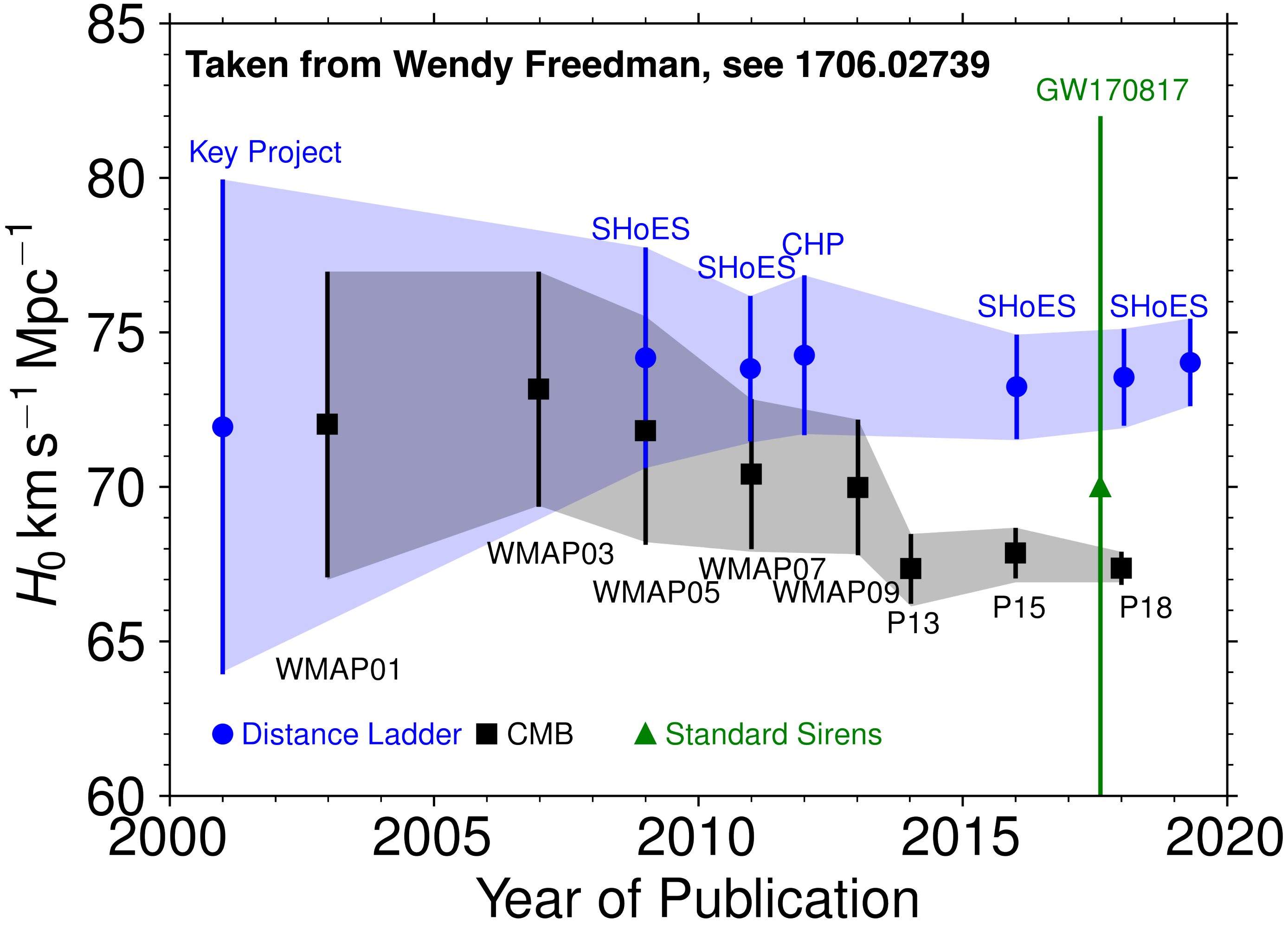

Riess *et al* 1903.07603

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

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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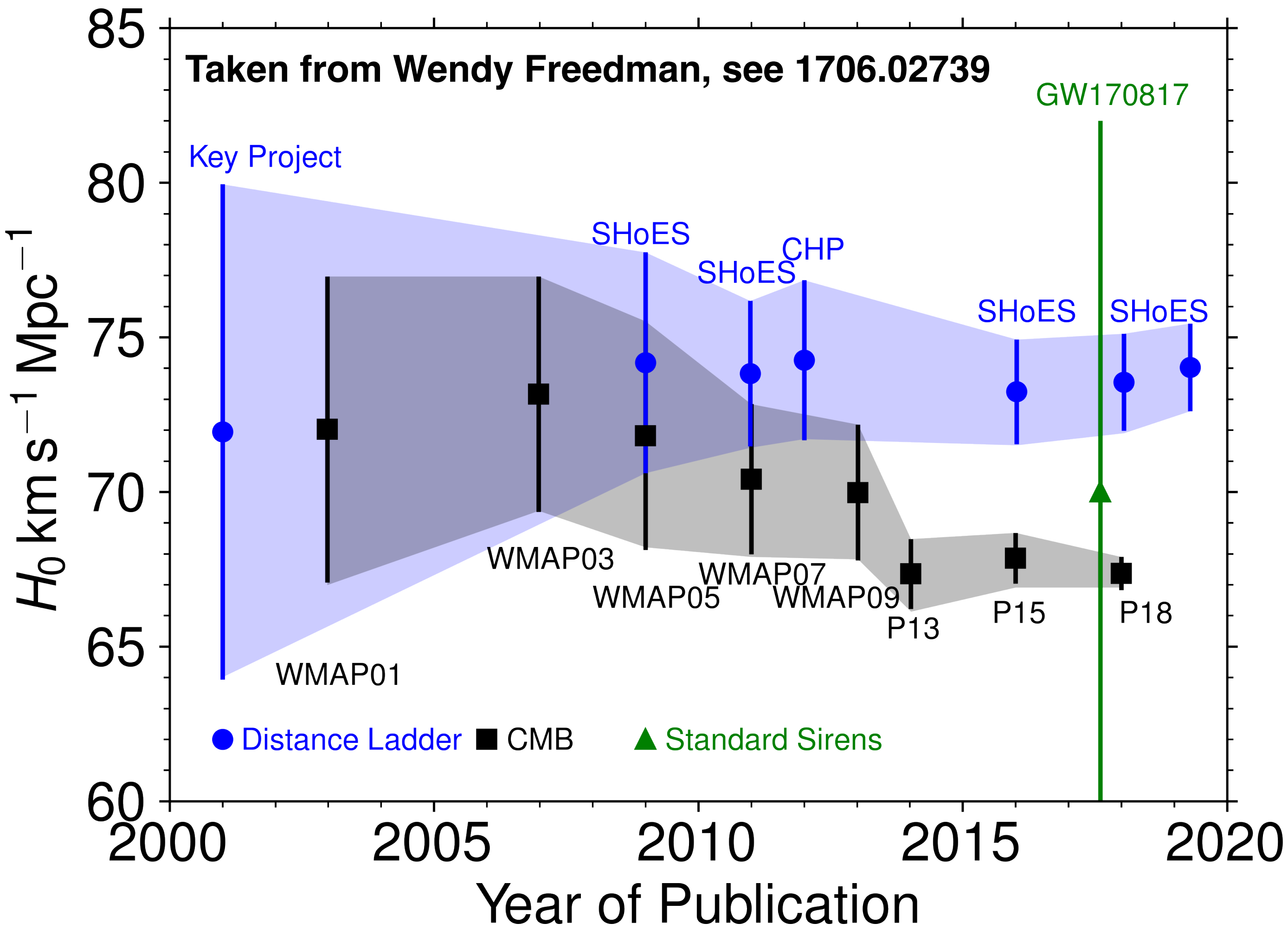

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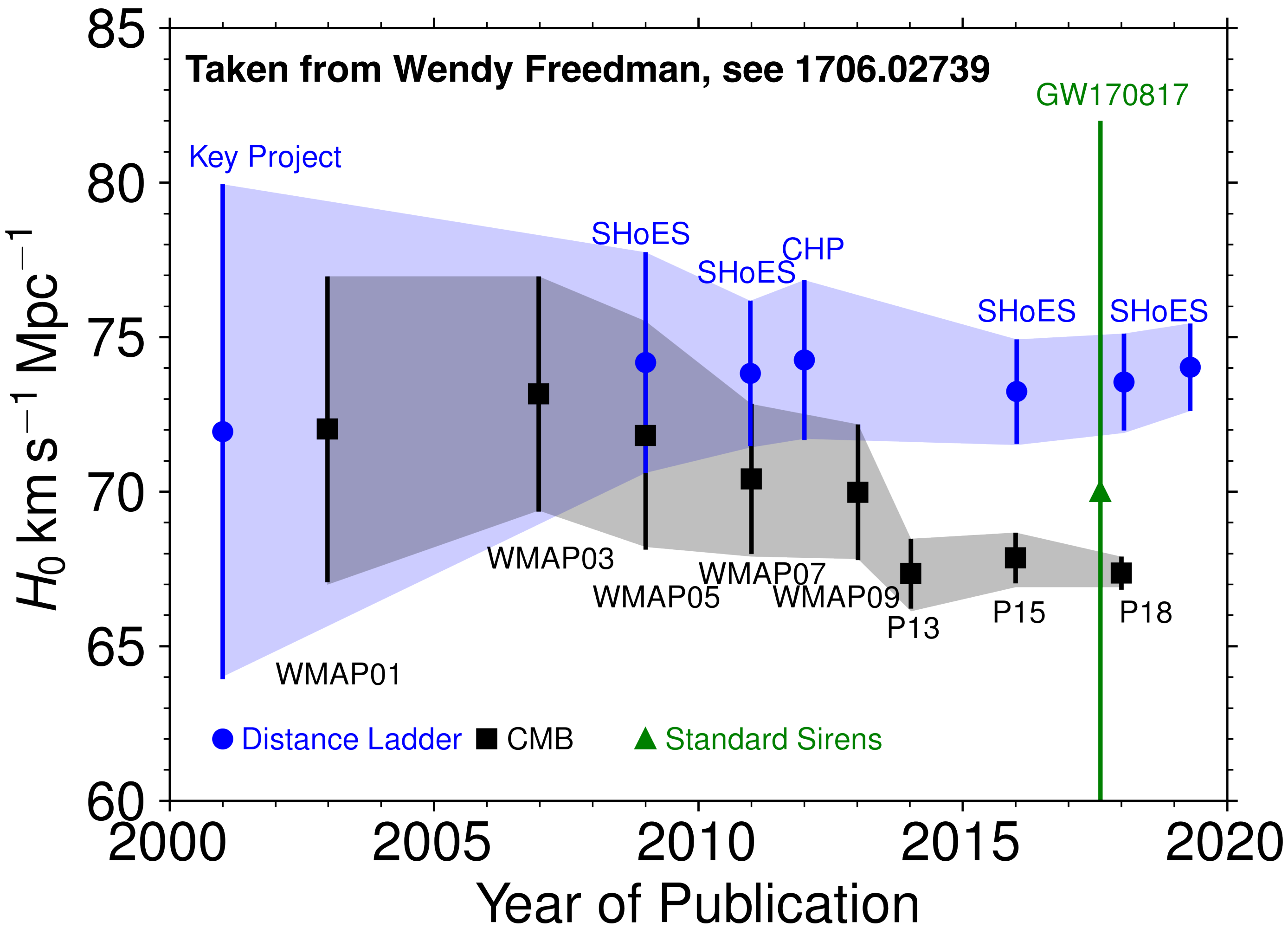

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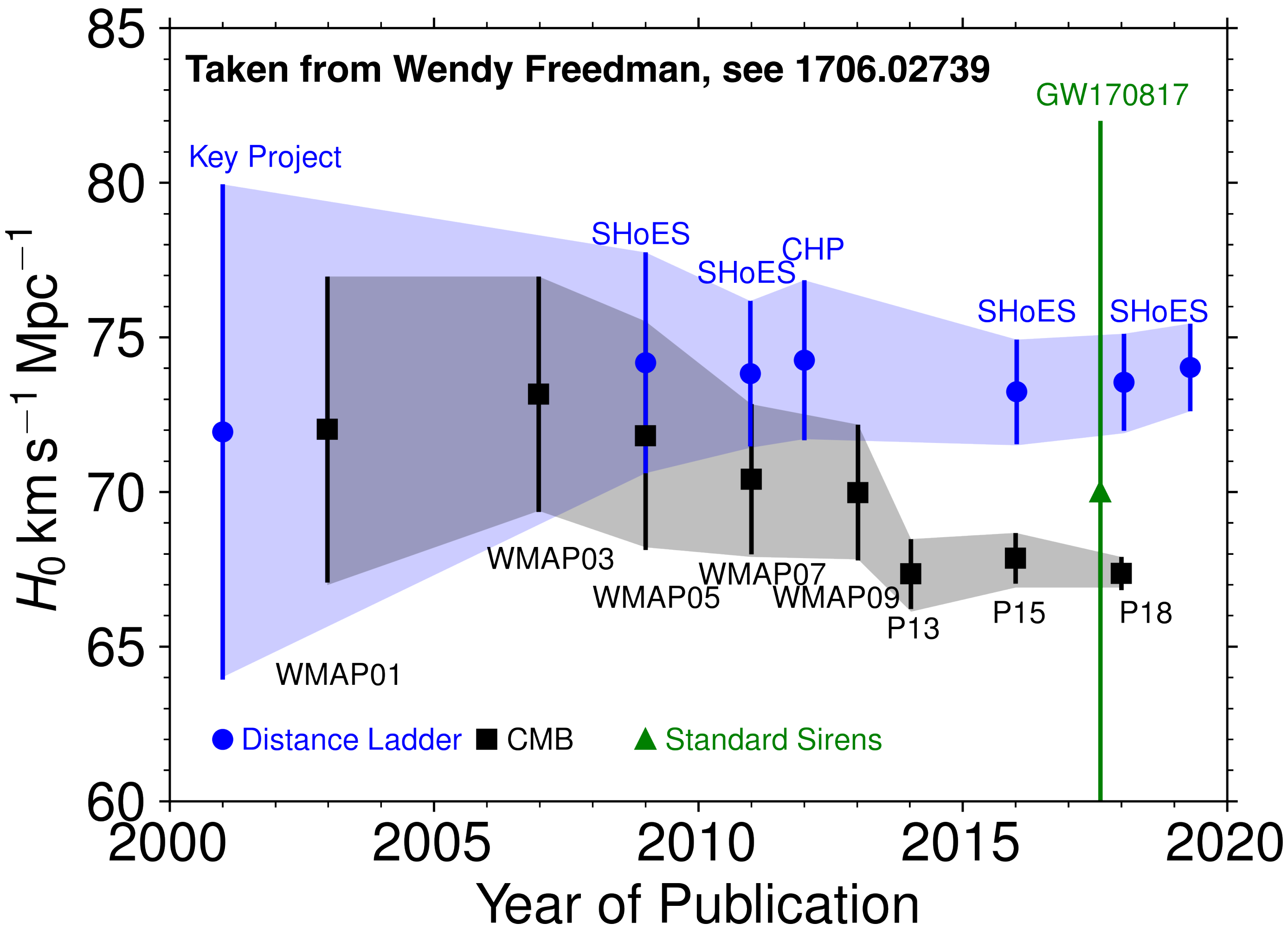

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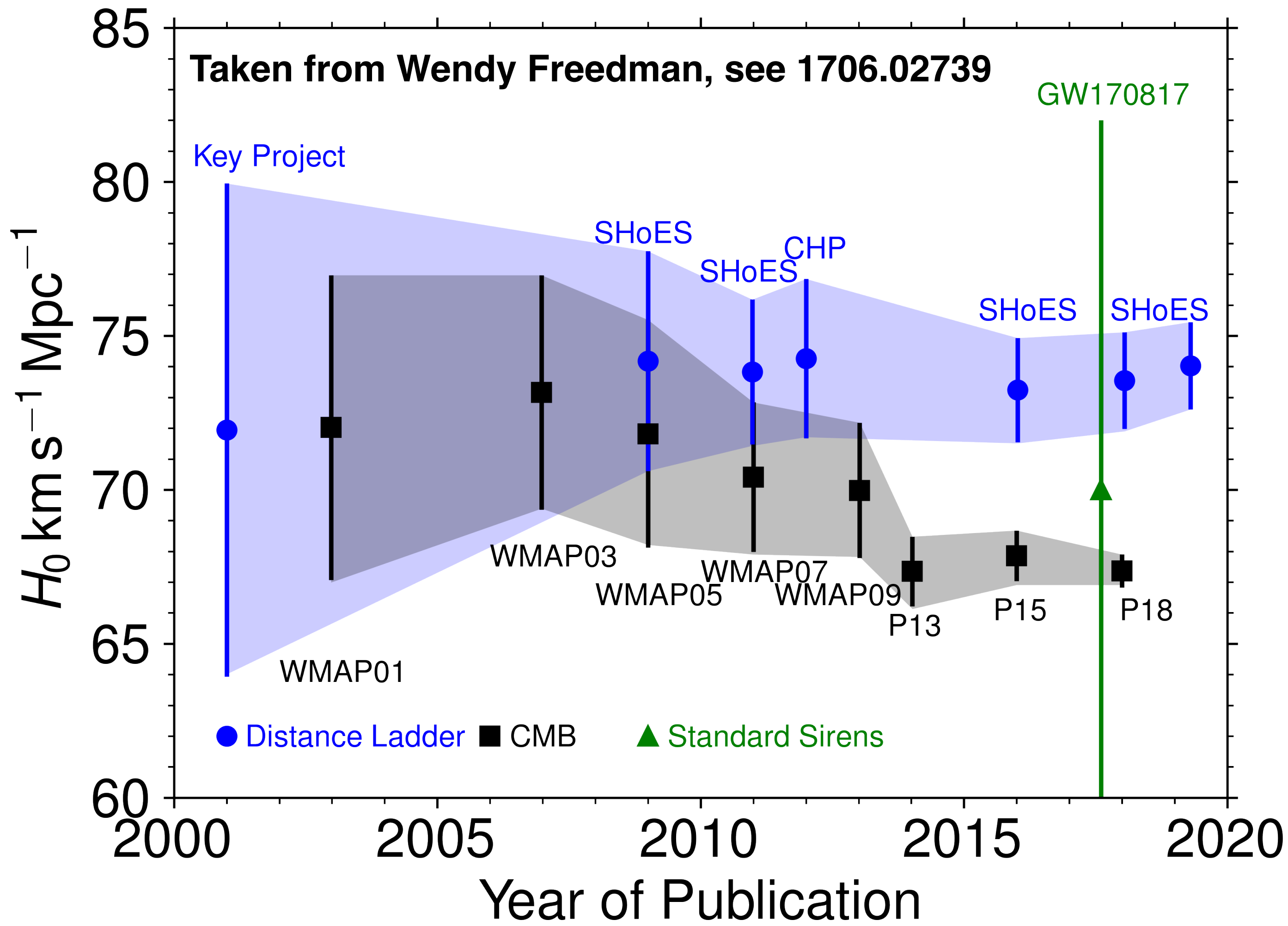

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- **Future measurements from BAO, local, lensing, GW ...**

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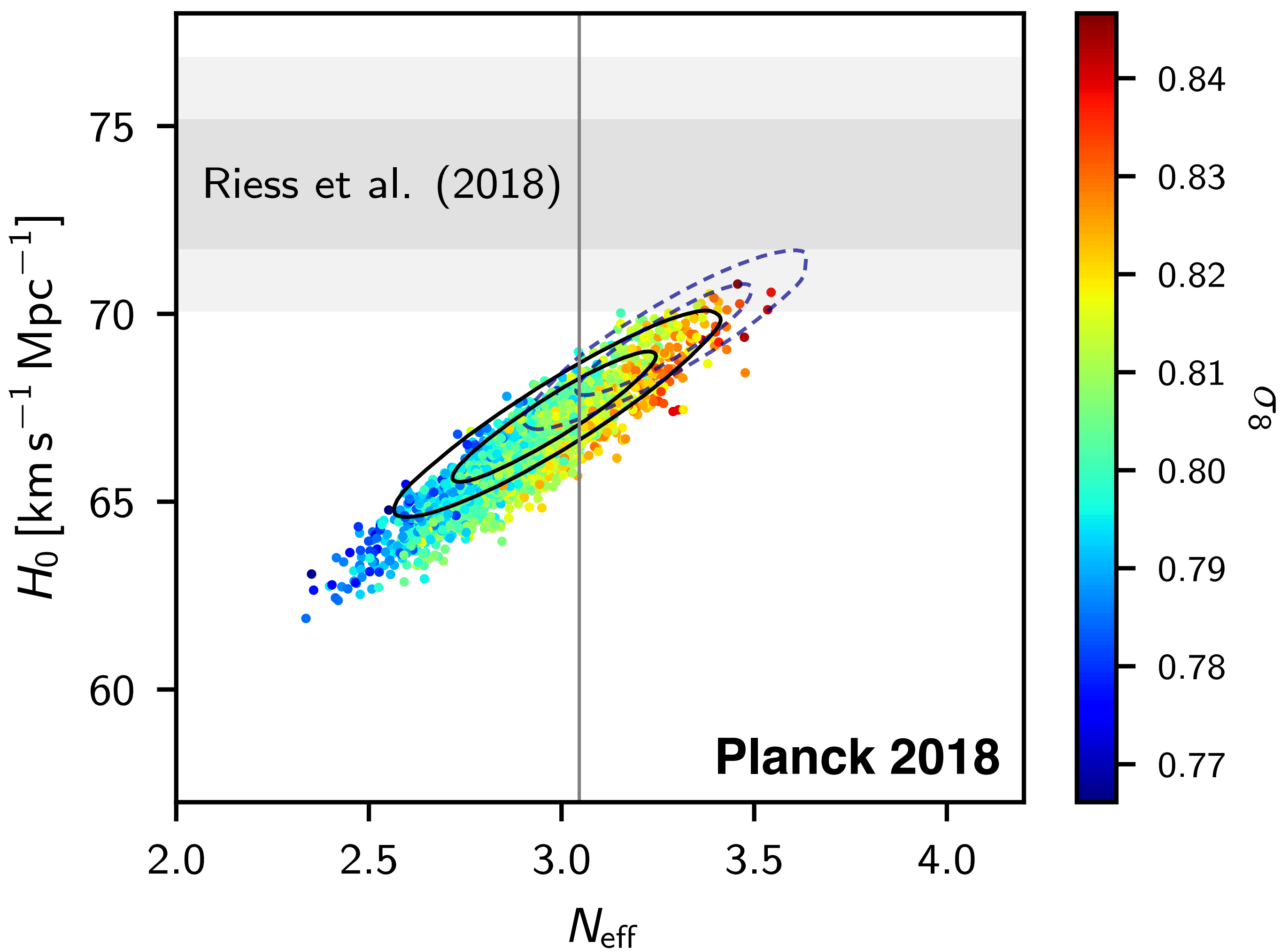
Perhaps the simplest one is to increase N_{eff}:



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

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

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

The Scenario

Global $U(1)_L$ Spontaneously Broken Symmetry

Chikashige, Mohapatra, Peccei (1981)

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

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

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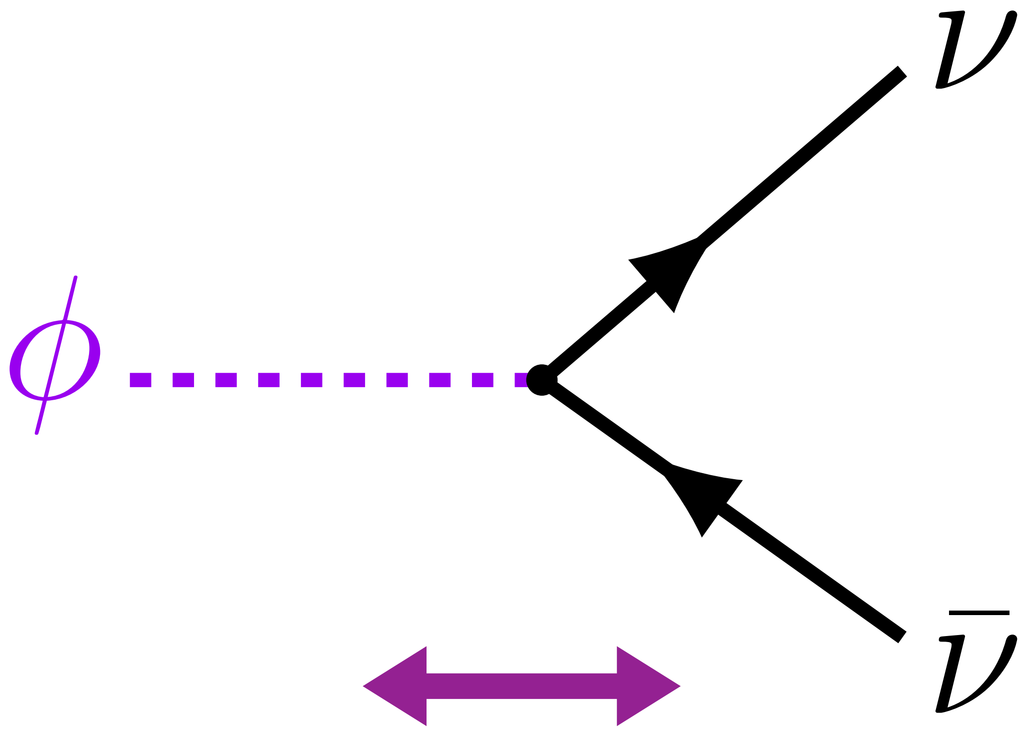
Parameter Space:
$$10^{-15} < \lambda < 10^{-3}$$
$$0.1\,{\rm eV} < m_\phi < {\rm MeV}$$

Cosmological Implications

Only Relevant Process:



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

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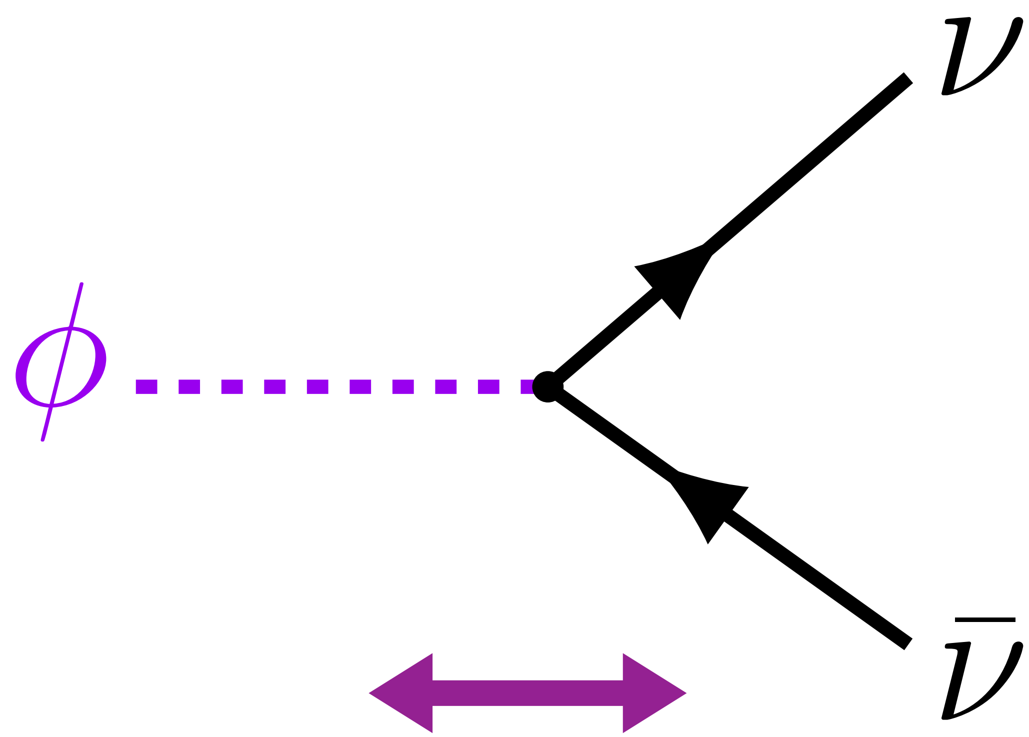

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Two main effects:

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

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

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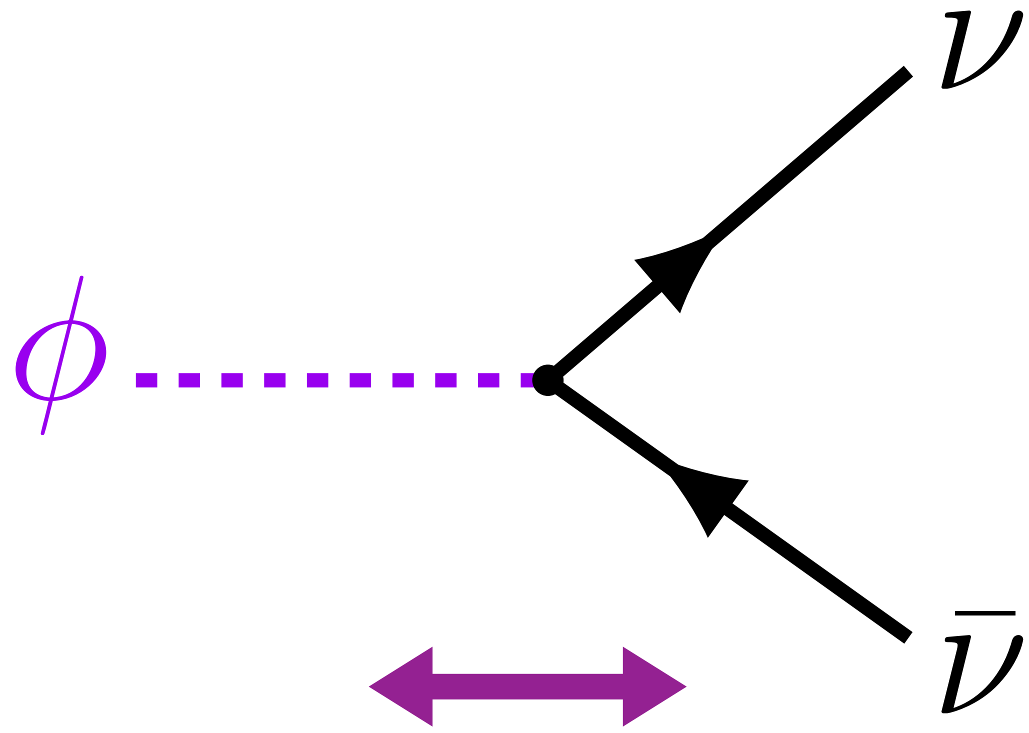

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Two main effects:

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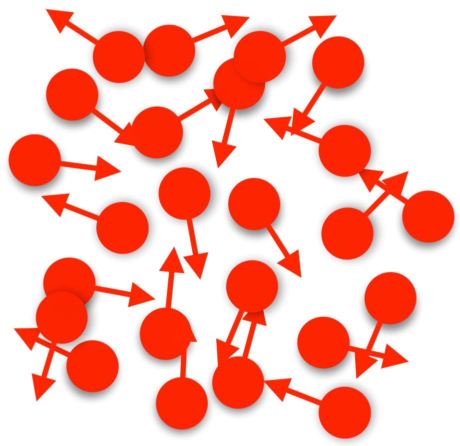
- **Non-standard expansion history**
- **Erase the neutrino anisotropic stress**

- **We solve the full Boltzmann/Liouville equation for the background**
- **We include the full neutrino-majoron Boltzmann hierarchy in CLASS**

Cosmological Implications

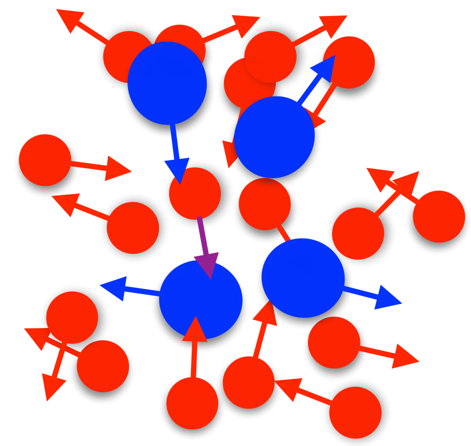
$T \gg m_\phi$



Production

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

Equilibrium

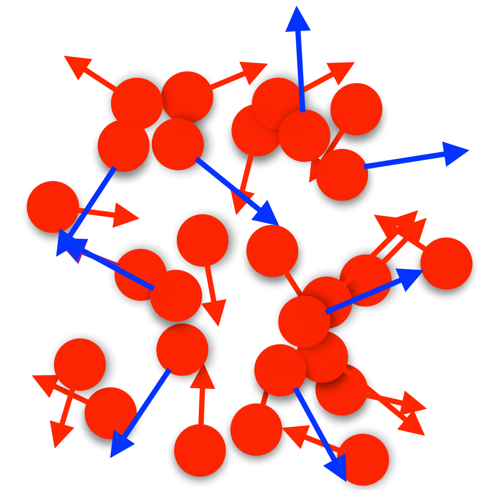


Decay

$T \sim m_\phi/3$

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

Final State



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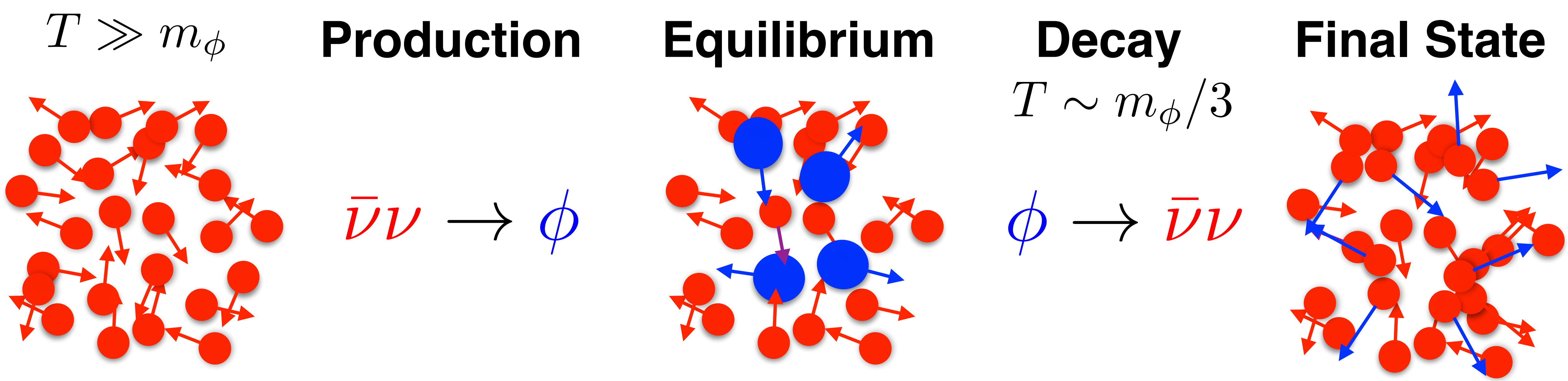
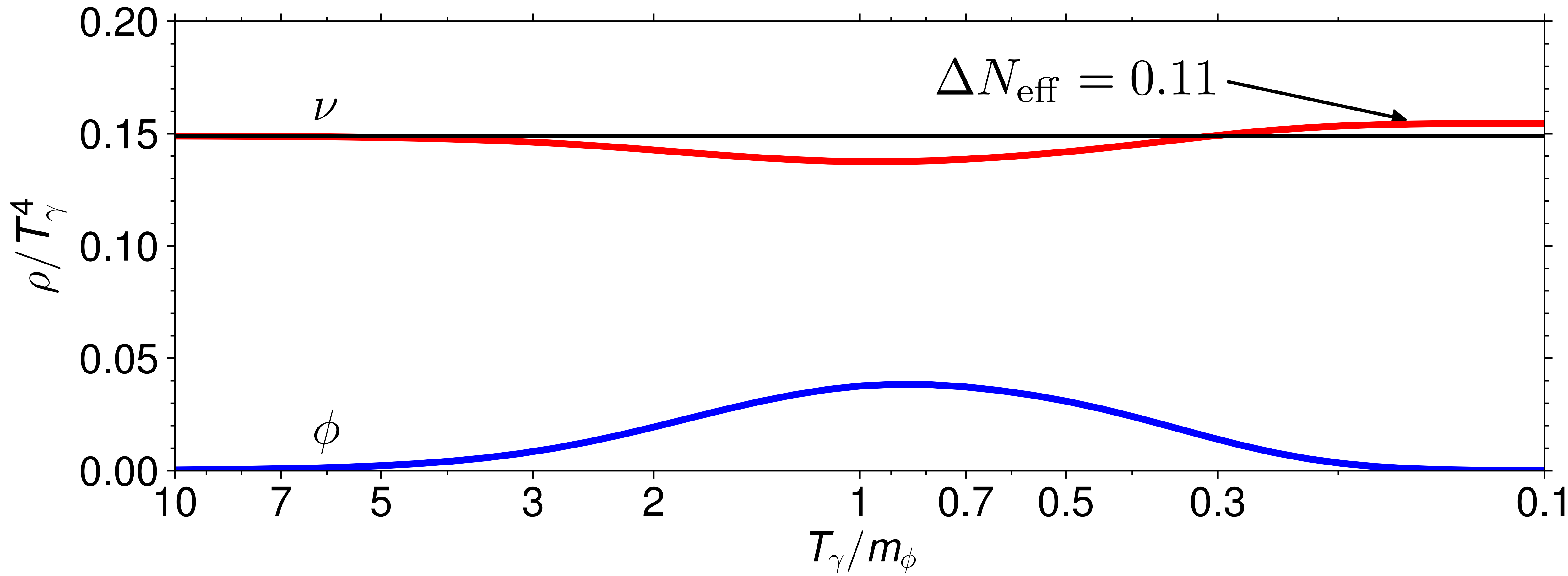
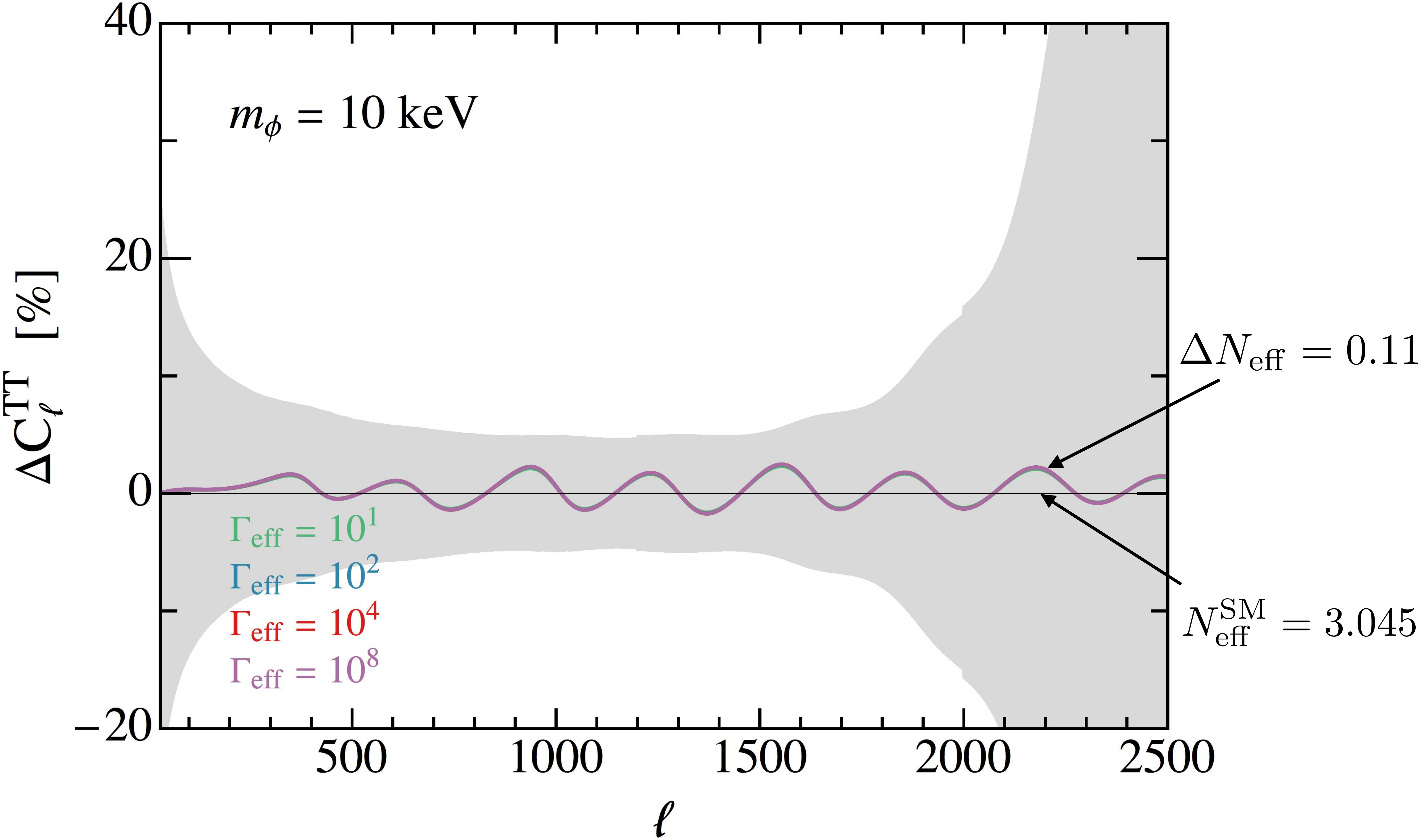


$$\Gamma_\phi \simeq H(T_\nu = m_\phi/3)$$



Effects on the CMB

$$\Gamma_{\rm eff} = \left(\frac{\lambda}{4\times10^{-12}}\right)^2 \left(\frac{1\,{\rm keV}}{m_\phi}\right)$$



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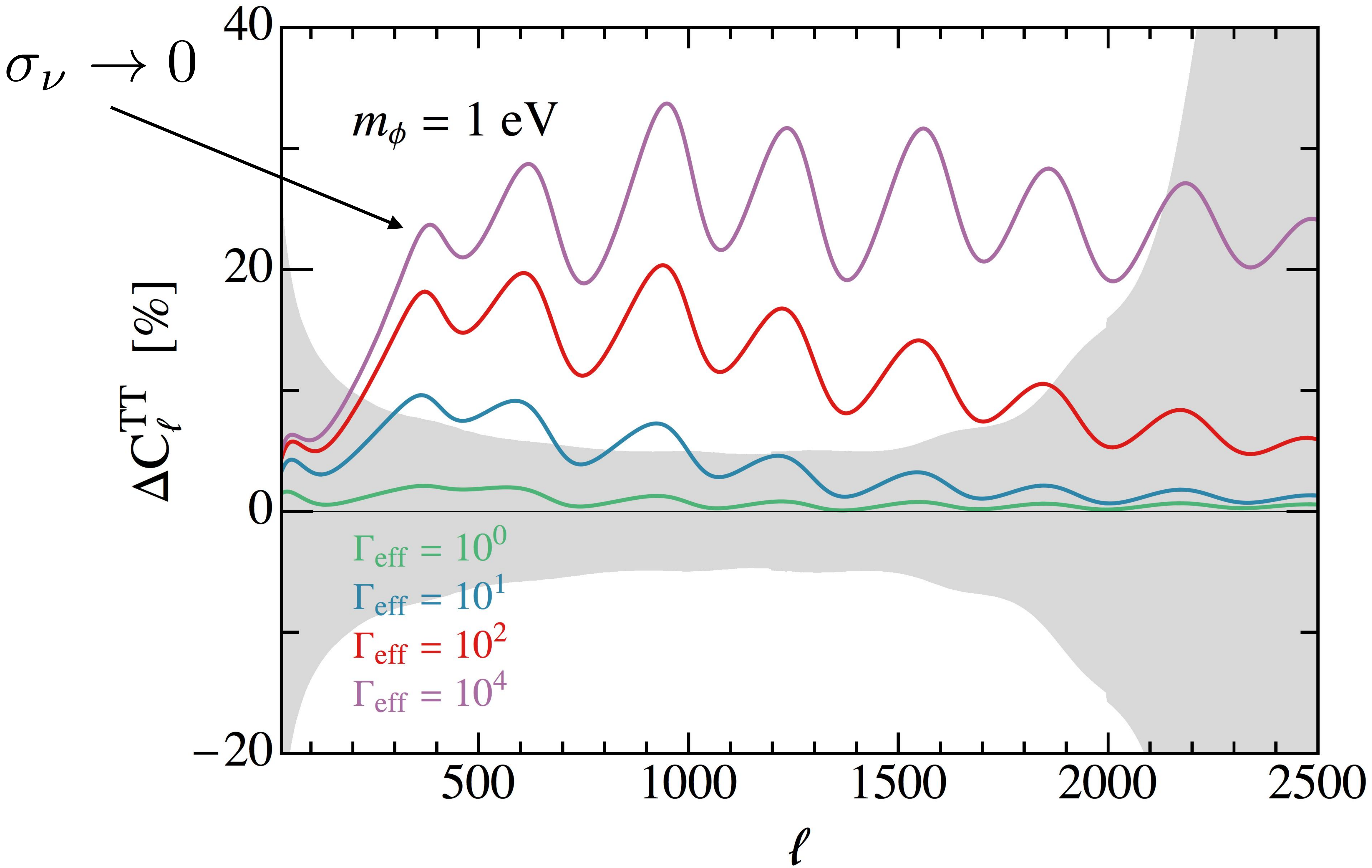
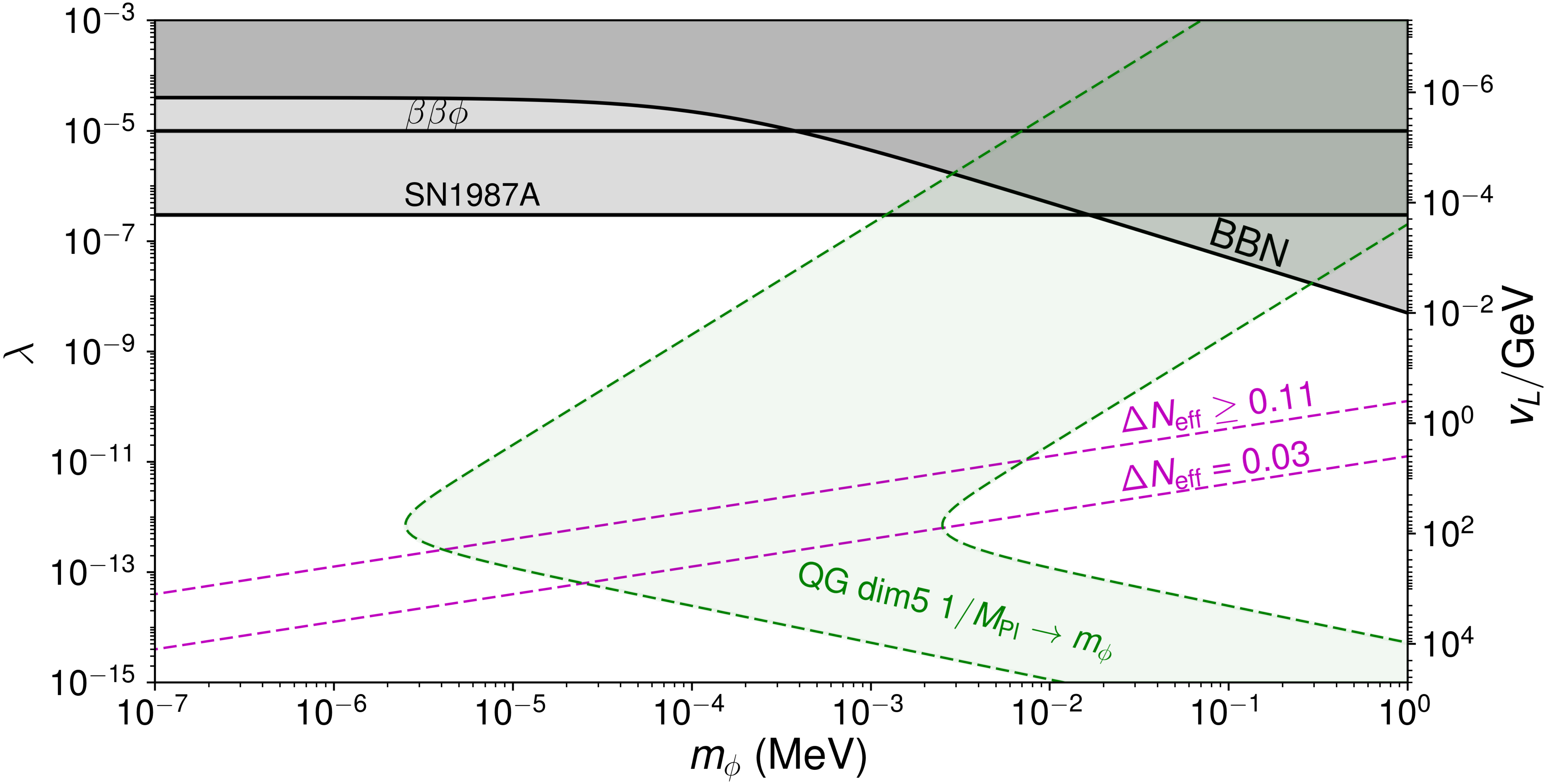


Parameter Space



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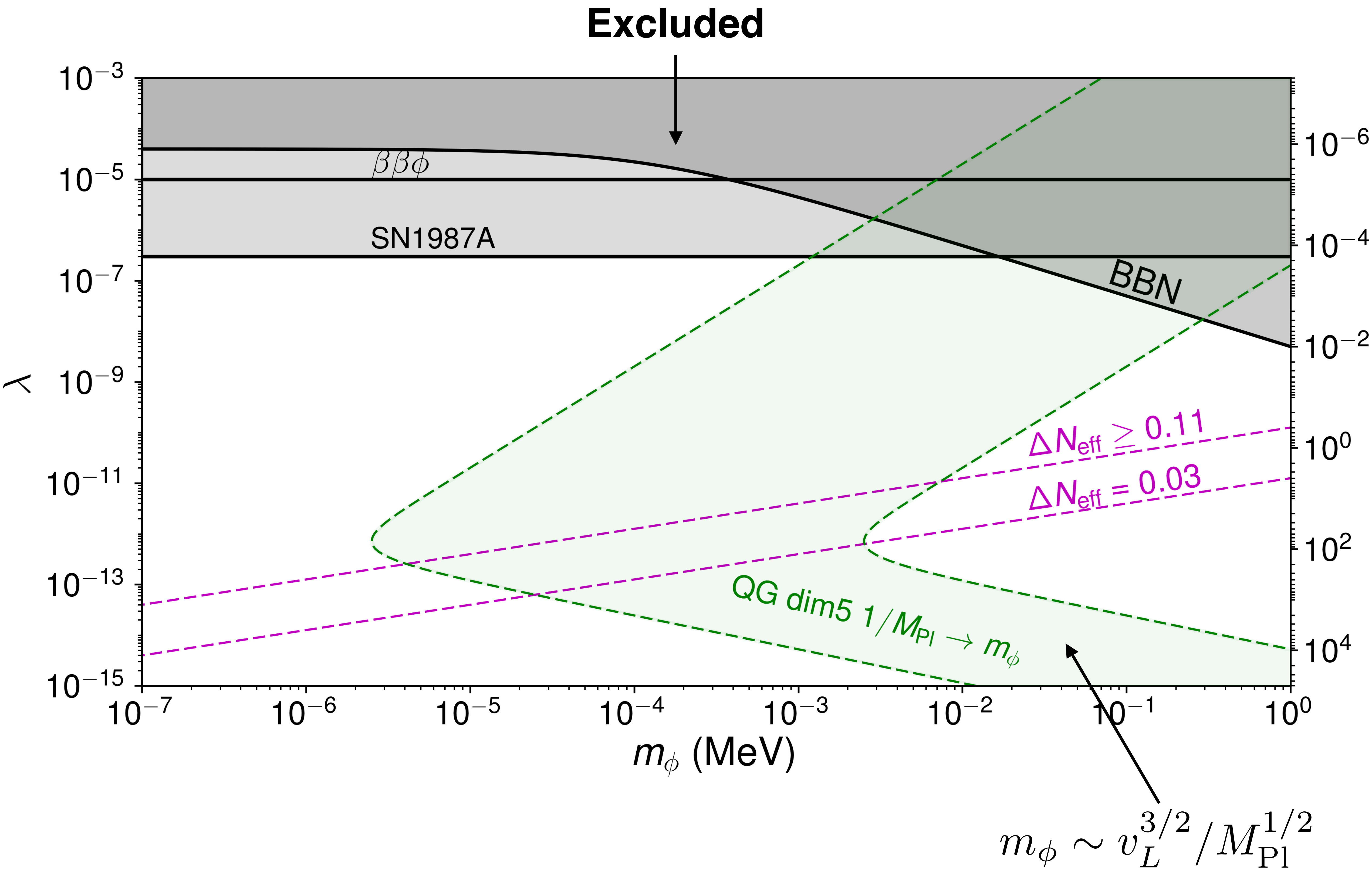

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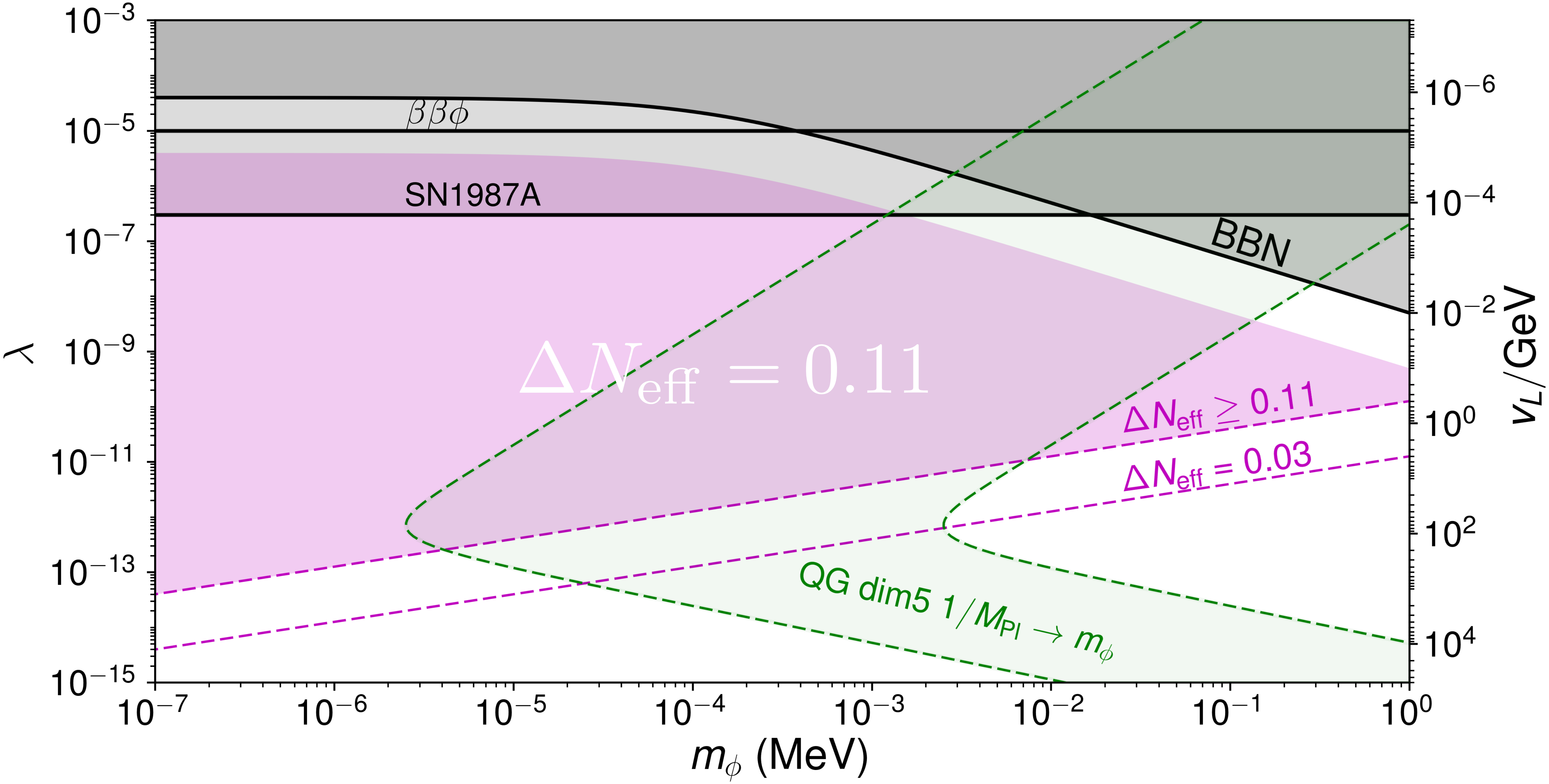

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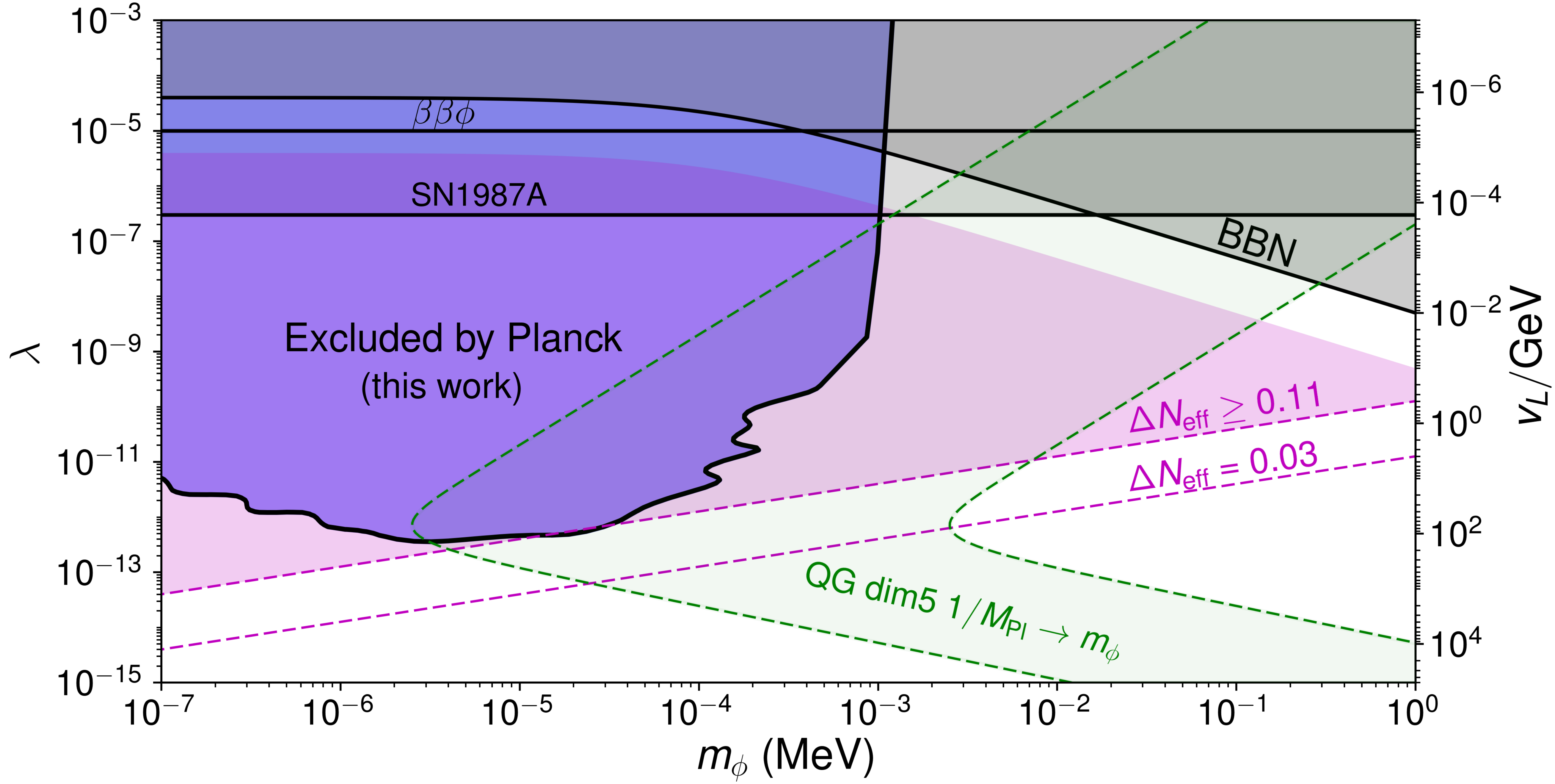

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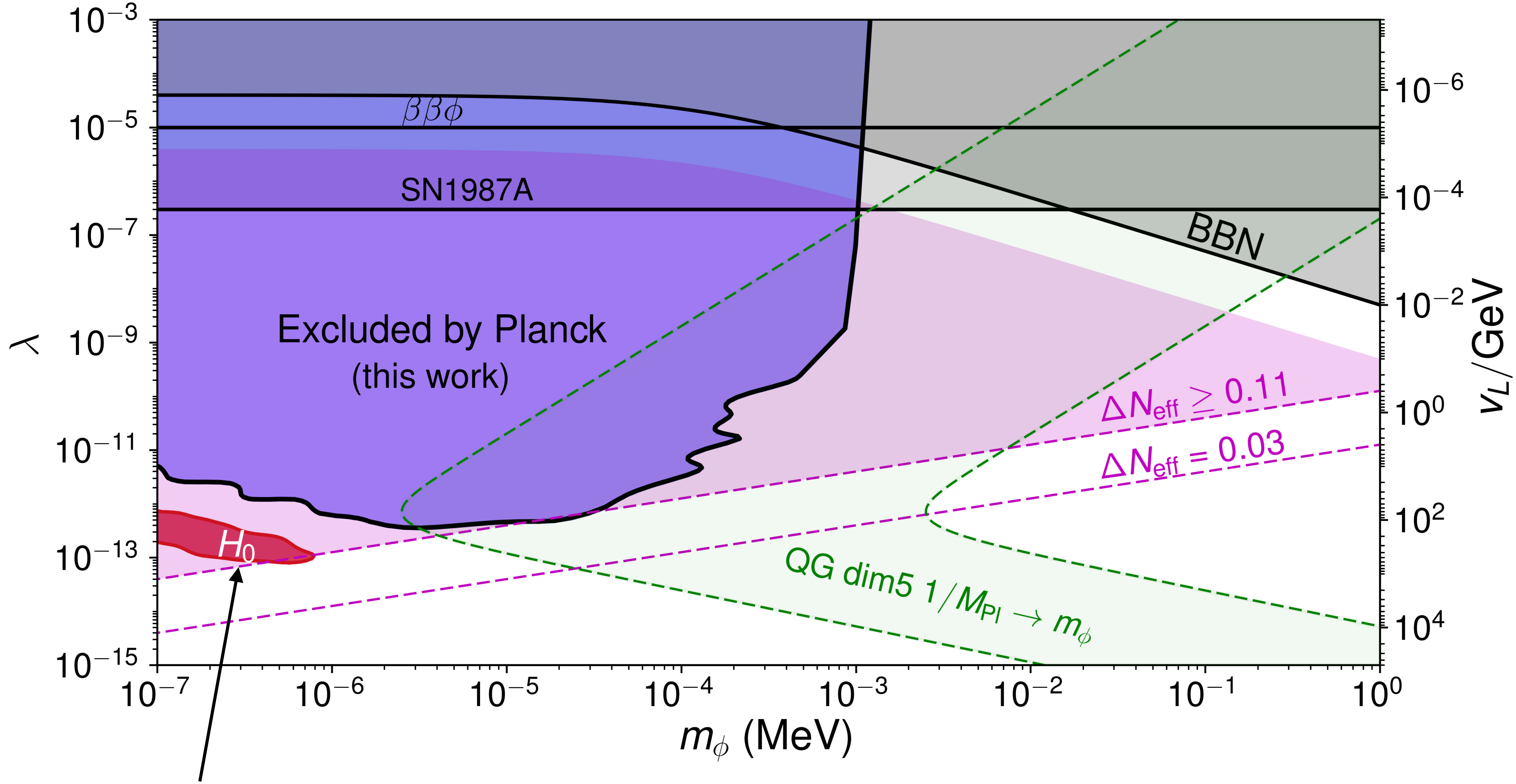


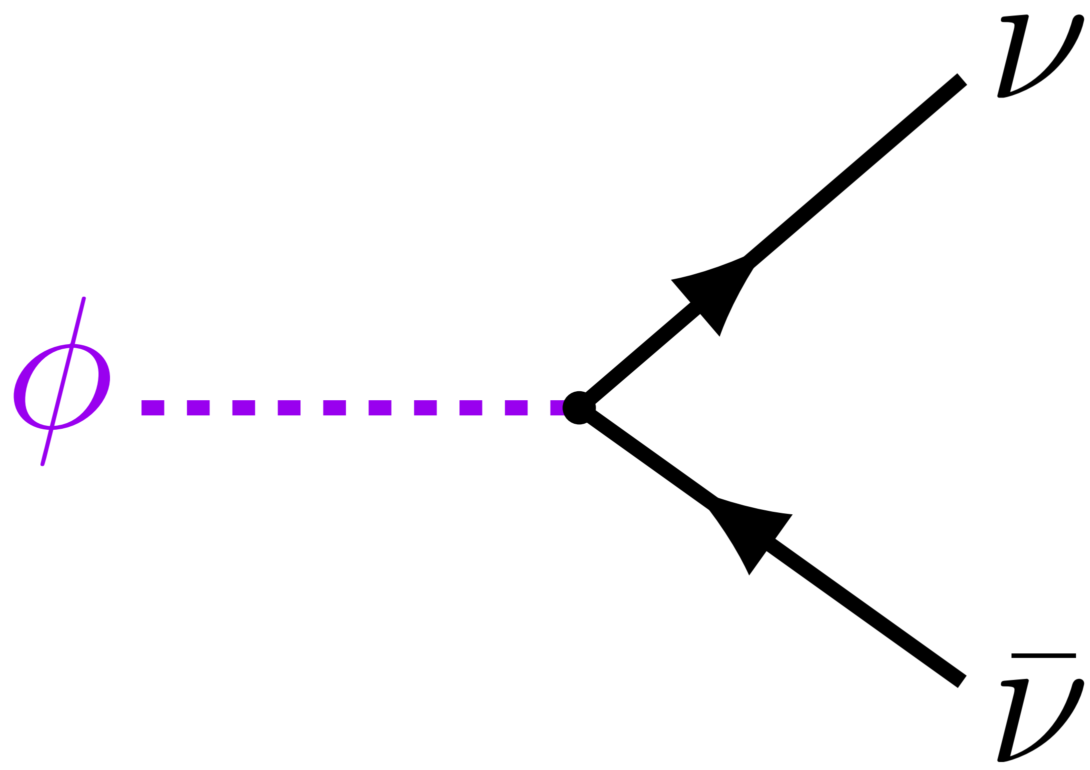
PRELIMINARY

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 stringent constraints**
  - **Ameliorates H_0 tension via** $\Delta N_{\rm eff} = 0.11$
  - **May solve the tension for:** $m_\phi \sim 0.1 - 1\,\mathrm{eV}$, $v_L \sim 0.1 - 1\,\mathrm{TeV}$

Questions and Comments?

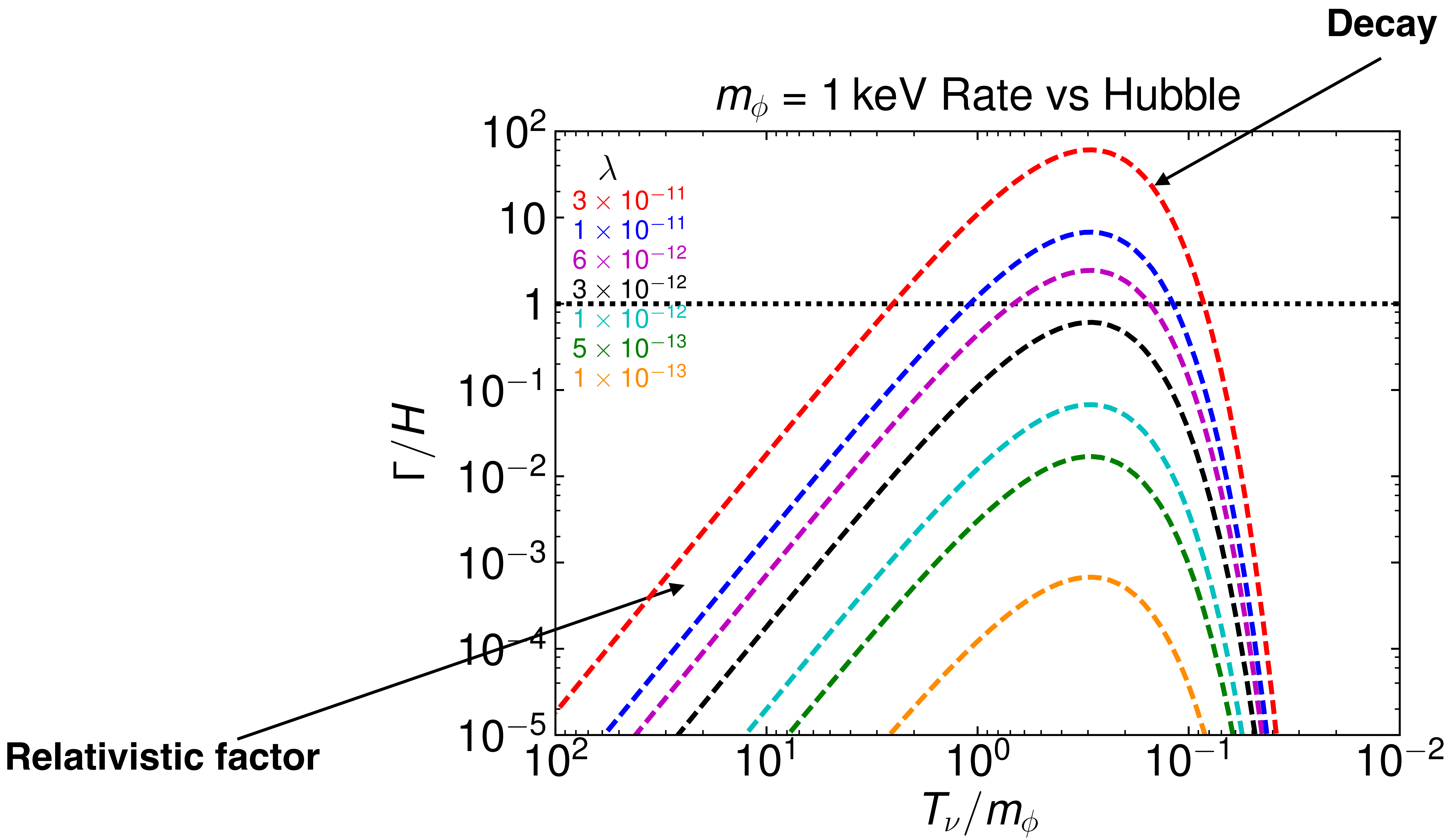
Thank you for your attention!



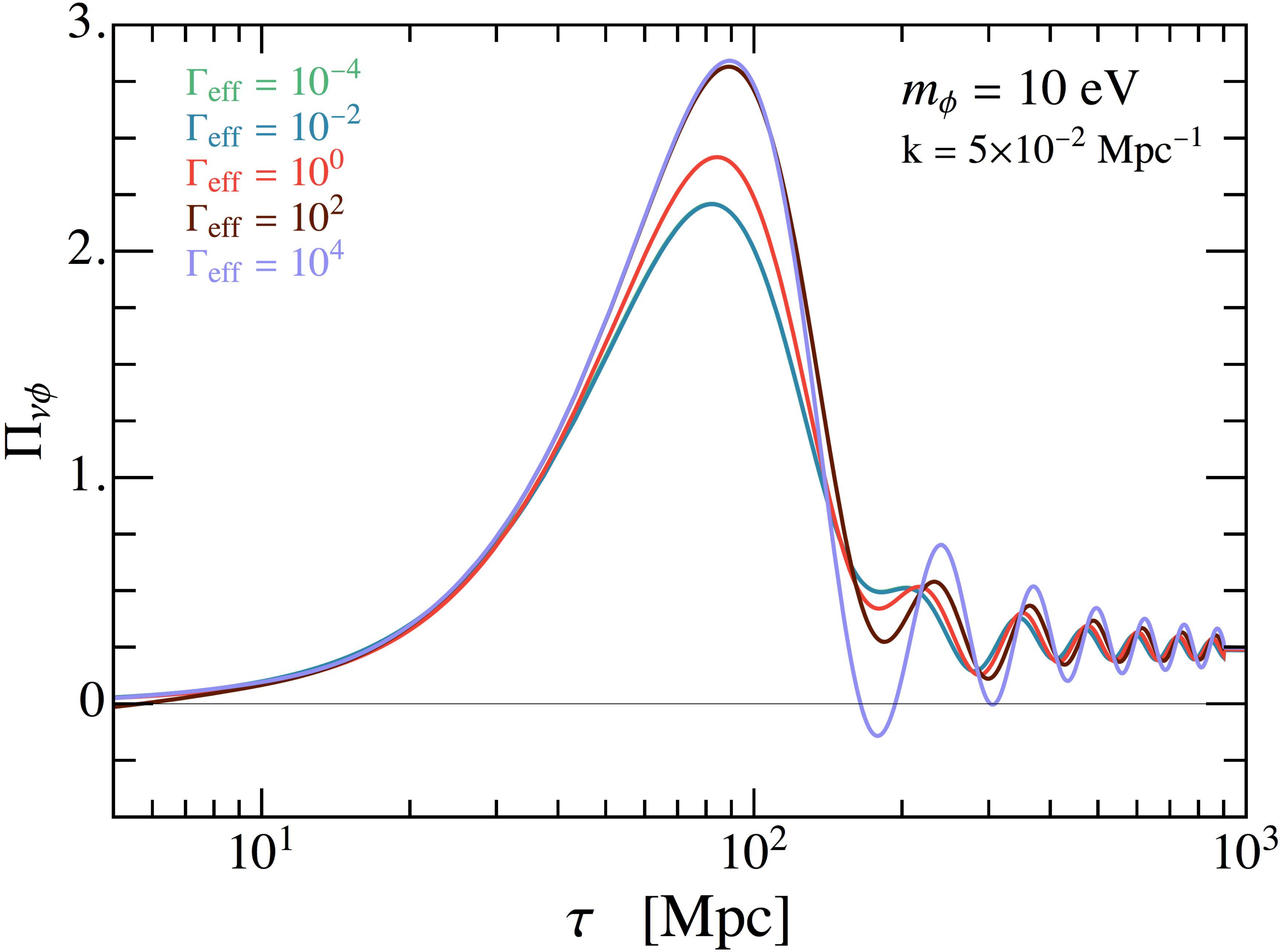
Stay tuned for: 1907.XXXXX with Sam Witte!

Back Up

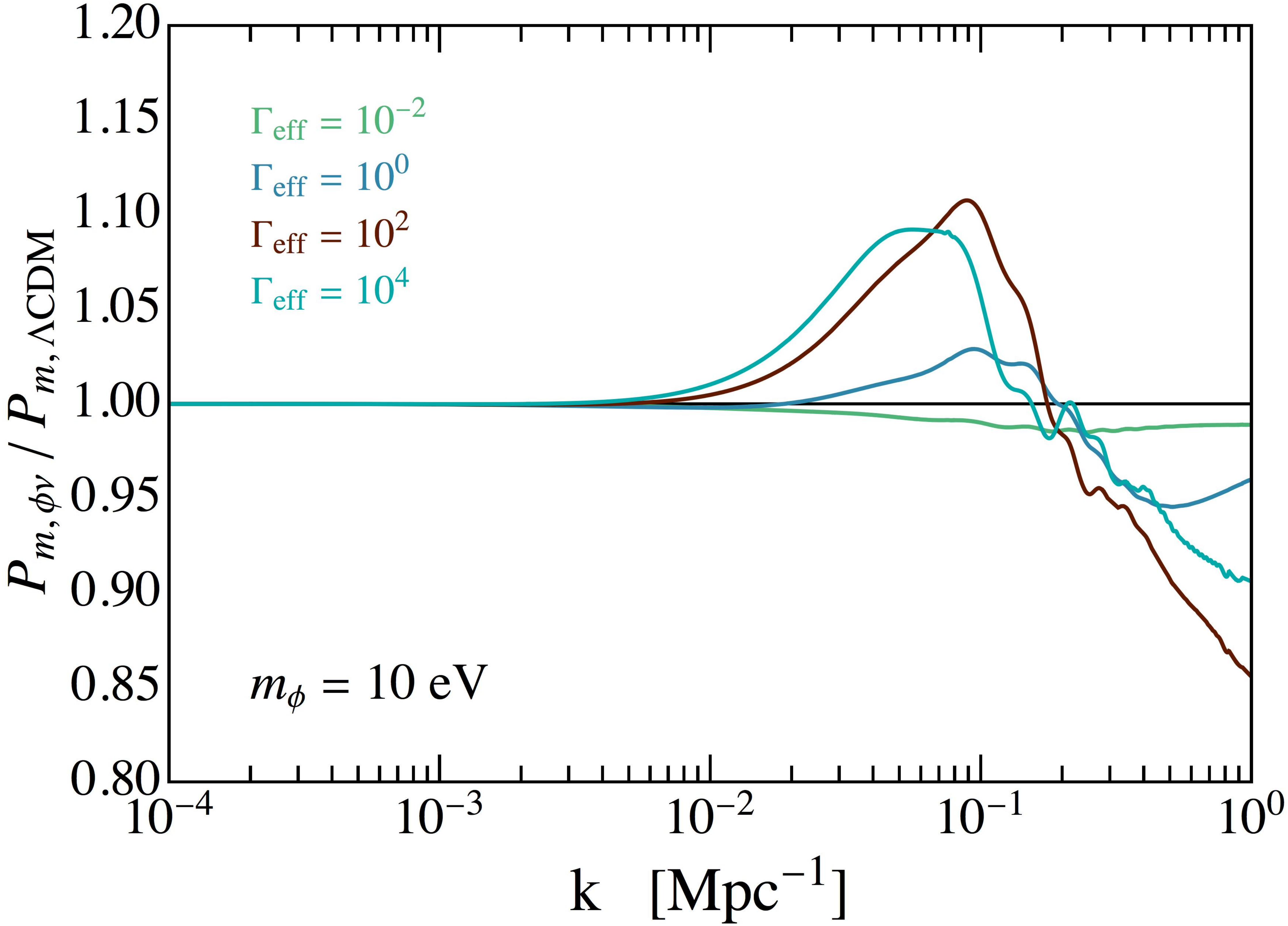
The Physics: Interaction Strength



The Physics: Neutrino Perturbations



The Physics: Power Spectrum



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

$$D_M(z) = \int_0^z \frac{1}{H(z')}\, dz'$$

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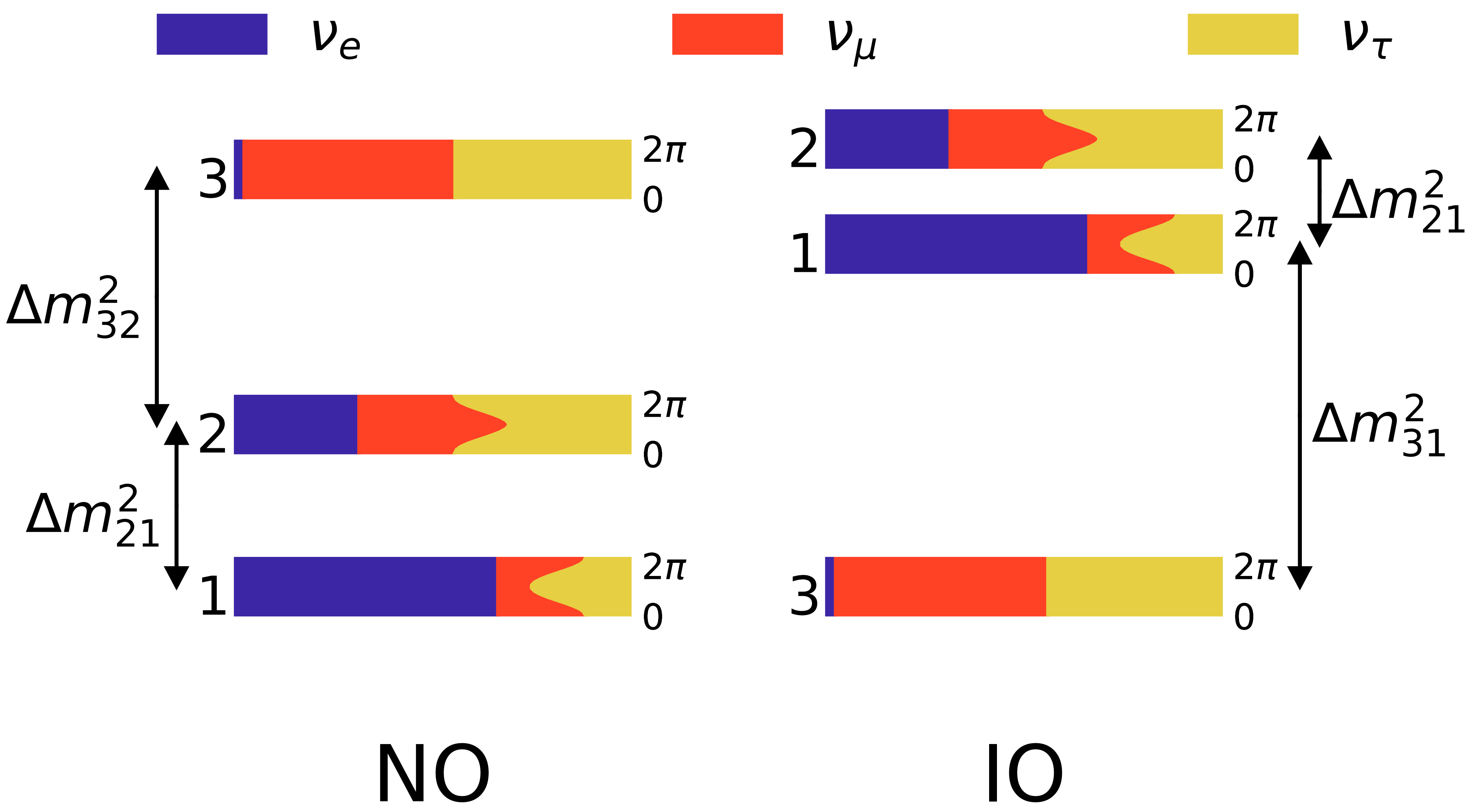
$$D_M(z) = \int_0^z \frac{1}{H(z')}\, dz'$$ **Comoving angular diameter distance**

Comoving sound horizon is the easiest thing to modify

Enhance the expansion prior to recombination

Neutrino Masses

At least two neutrinos are massive

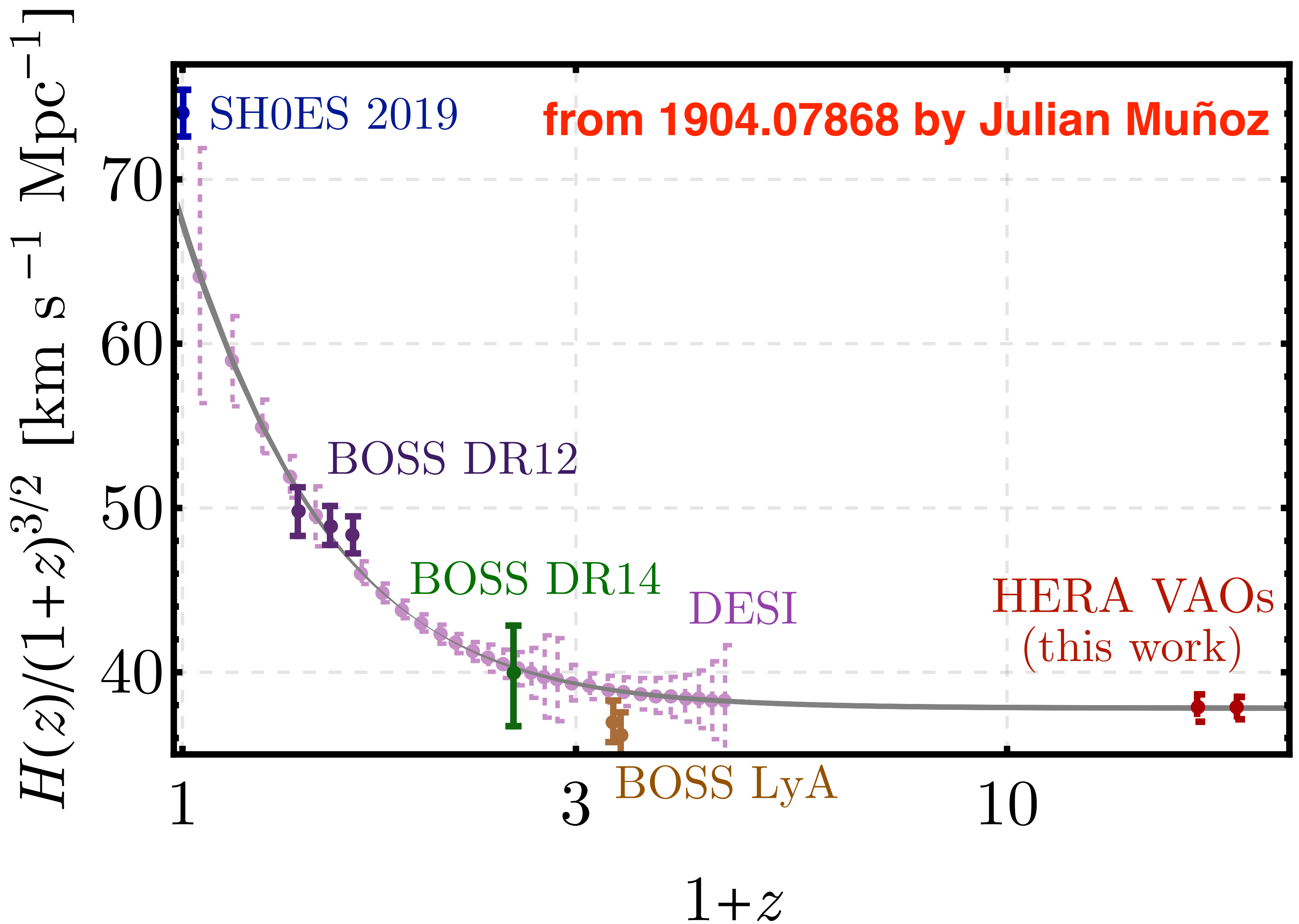


1806.11051, de Salas et. al.

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

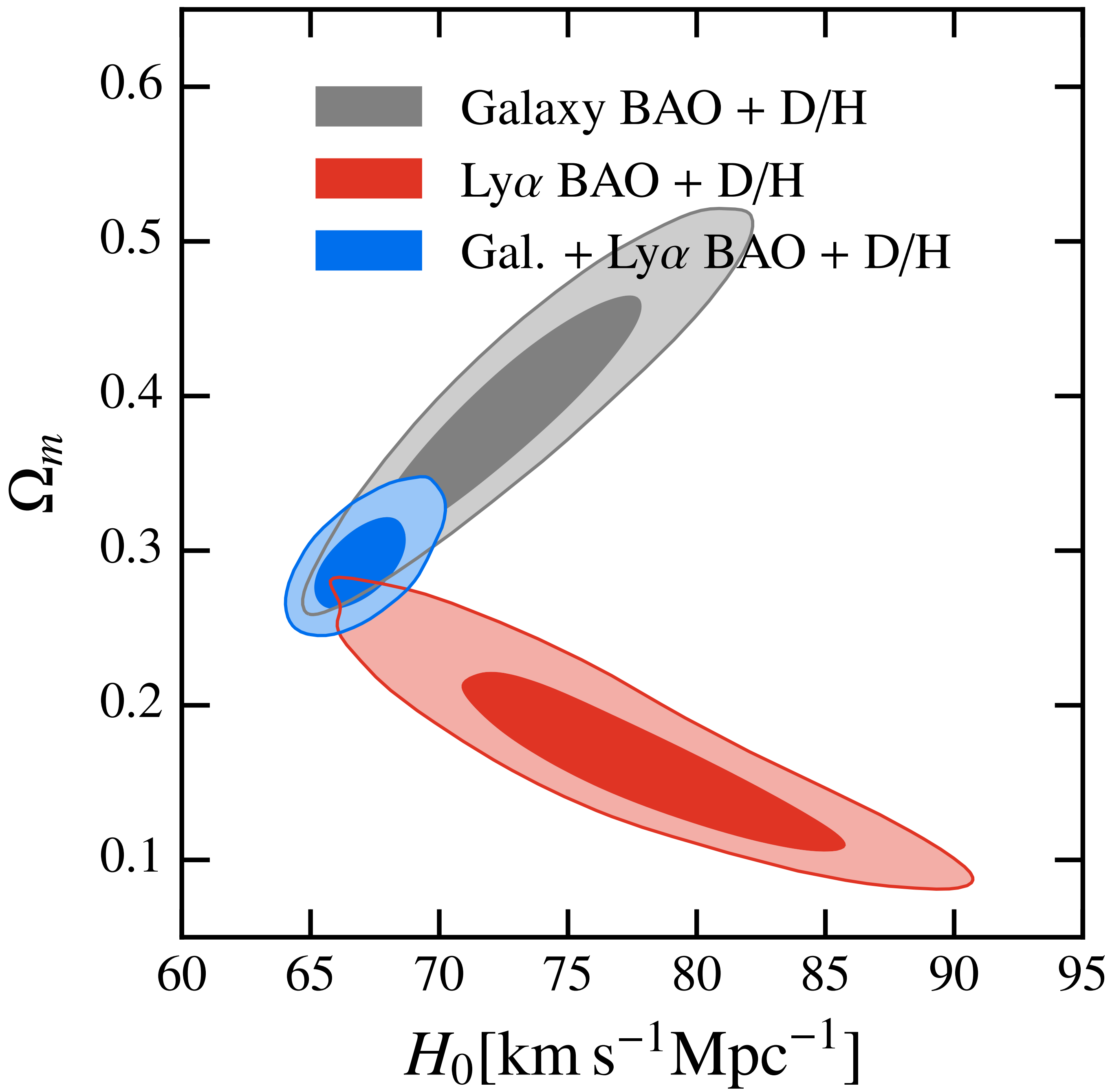
Future Measurements

- **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

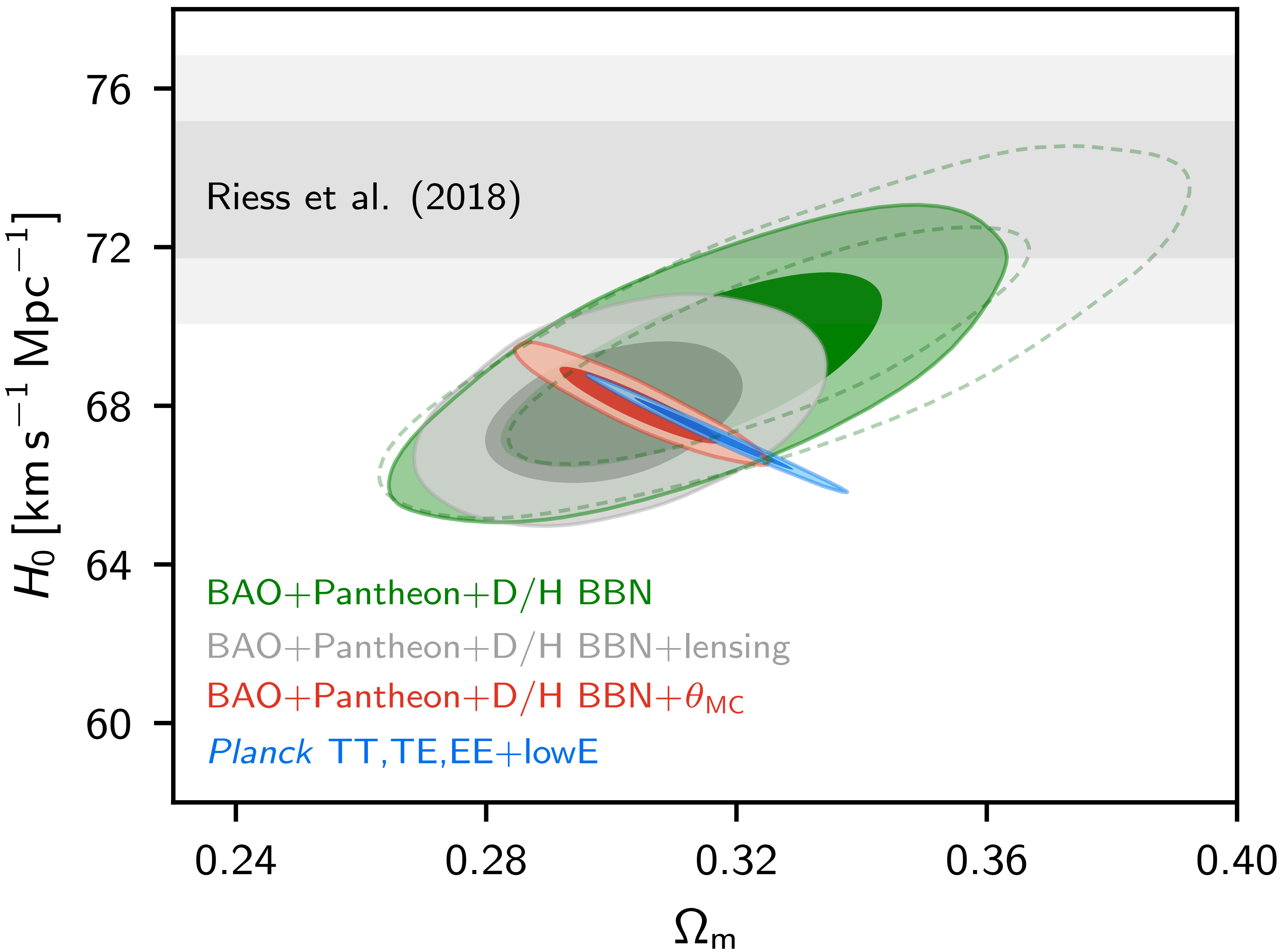
- **Tension is also present in BAO**

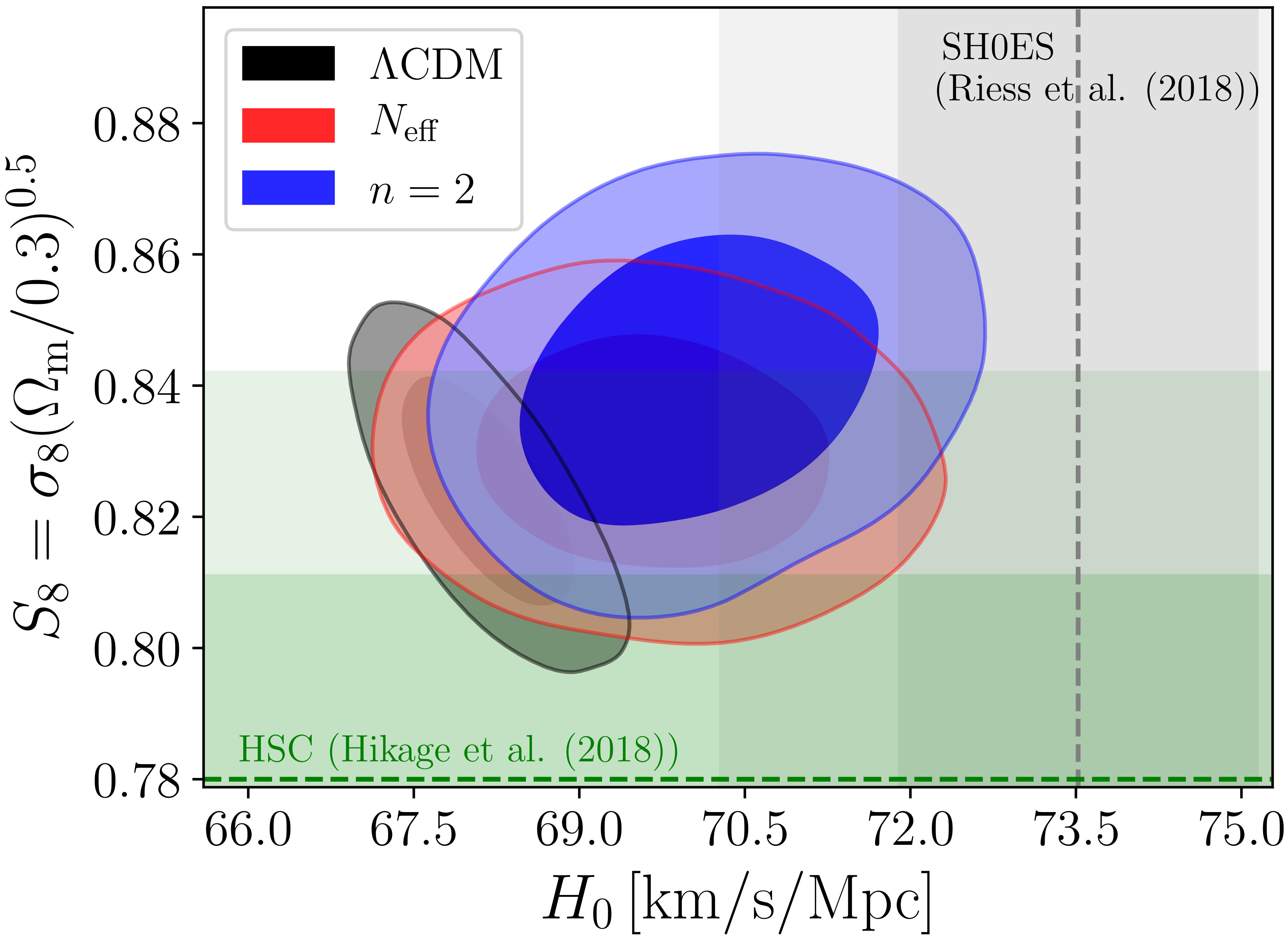


Addison *et al* 1707.06547

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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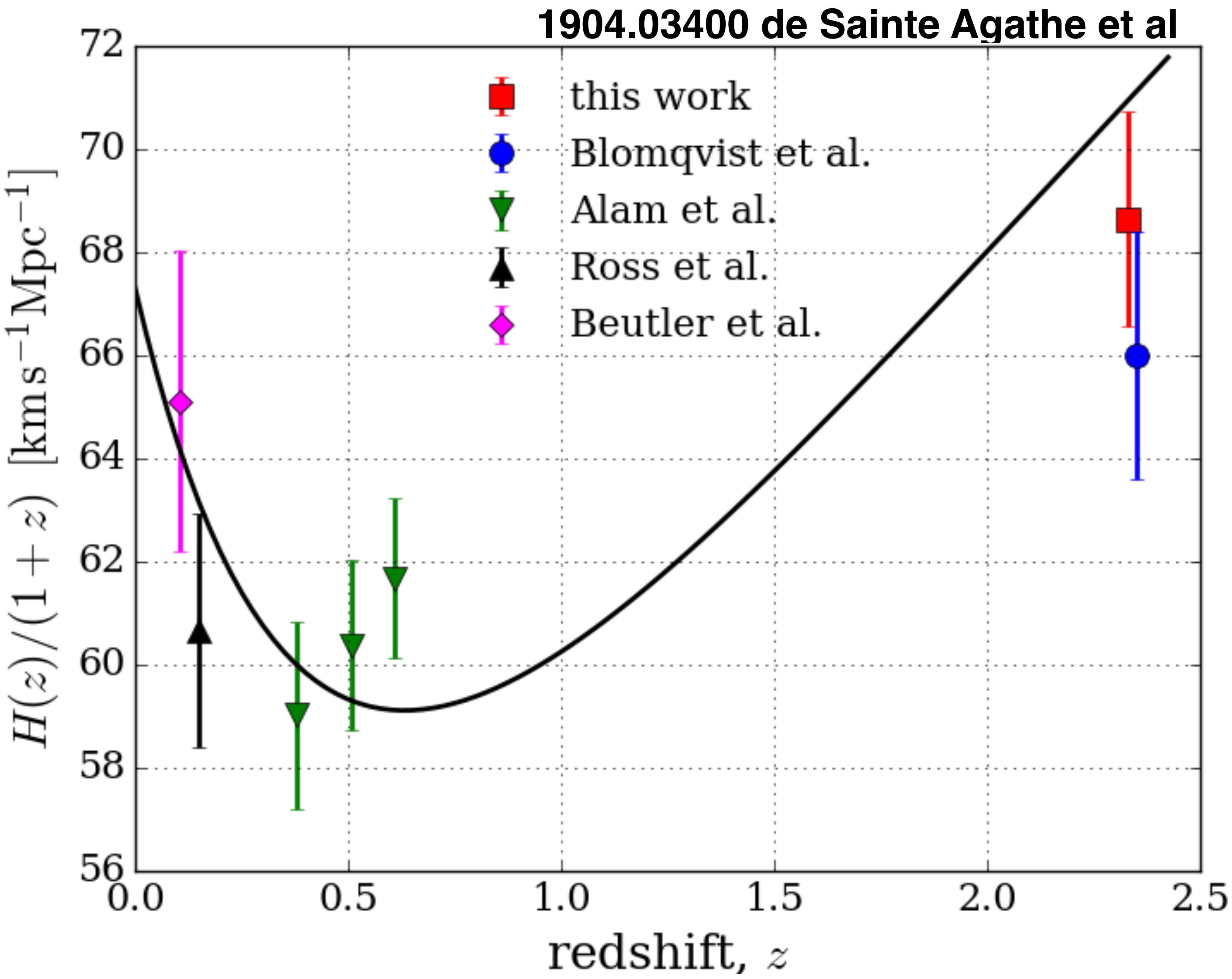

BAO measurements point toward an early Universe effect