The Hubble Tension as a Signal of low-scale Leptogenesis and Neutrino Mass Generation

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ArXiv:2004.01470, NuPhys19 Proceedings
ArXiv:2102.XXXX, to appear soon

with **Sam Witte**

IPPP, Durham University

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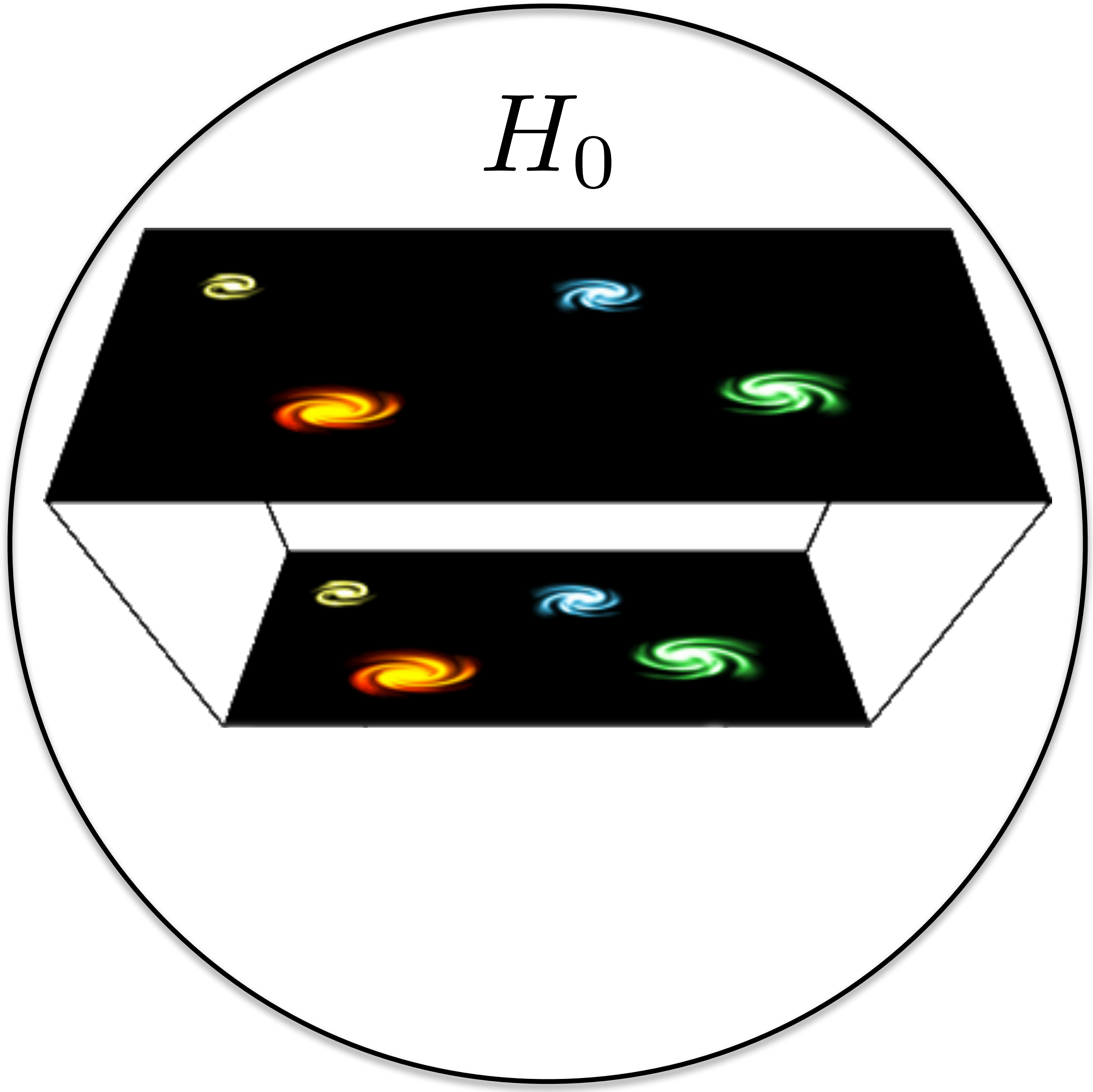


Riess *et al.* 1903.07603

Local Measurements

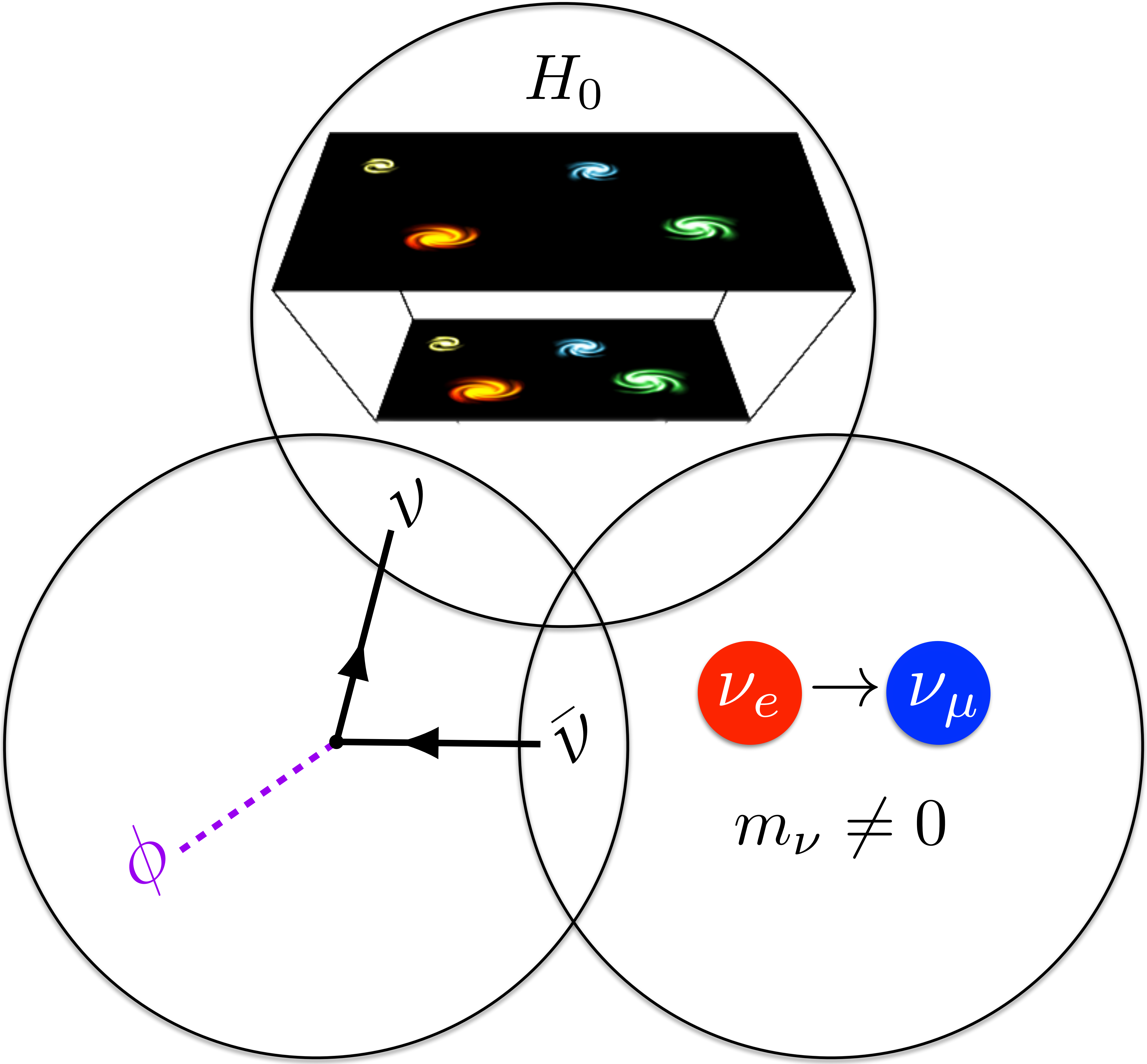
$$H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

4.4 σ tension within ΛCDM!

Planck 2018 1807.06209

CMB Measurements

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



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

The Hubble tension and the Majoron

Escudero & Witte 19'

- **Can substantially ameliorate the tension for:**

$$m_\phi \sim (0.1 - 1)\,\mathrm{eV}$$
$$\lambda \simeq 10^{-13} - 10^{-12}$$
$$\Delta N_{\rm eff} \sim 0.5$$

- **Couplings from seesaw**

$$\lambda \simeq 10^{-13}\frac{m_\nu}{0.05\,\mathrm{eV}}\frac{\mathrm{TeV}}{v_L}$$
$$v_L \sim (0.1 - 1)\,\mathrm{TeV}$$

- **Mass from Planck-scale physics**

$$m_\phi \sim (0.1 - 1)\,\mathrm{eV}$$

- $\Delta N_{\rm eff} \sim 0.5$**?**

Escudero & Witte 21'

- $\Delta N_{\rm eff} \sim 0.5$ **as a product of low-scale Baryogenesis**
- H_0 **tension as a signal of** $m_\nu \neq 0$ **and Leptogenesis**

Outline

1) Neutrinos in ΛCDM

Neff

2) The Hubble Tension

Neutrinophilic approaches

3) The Majoron

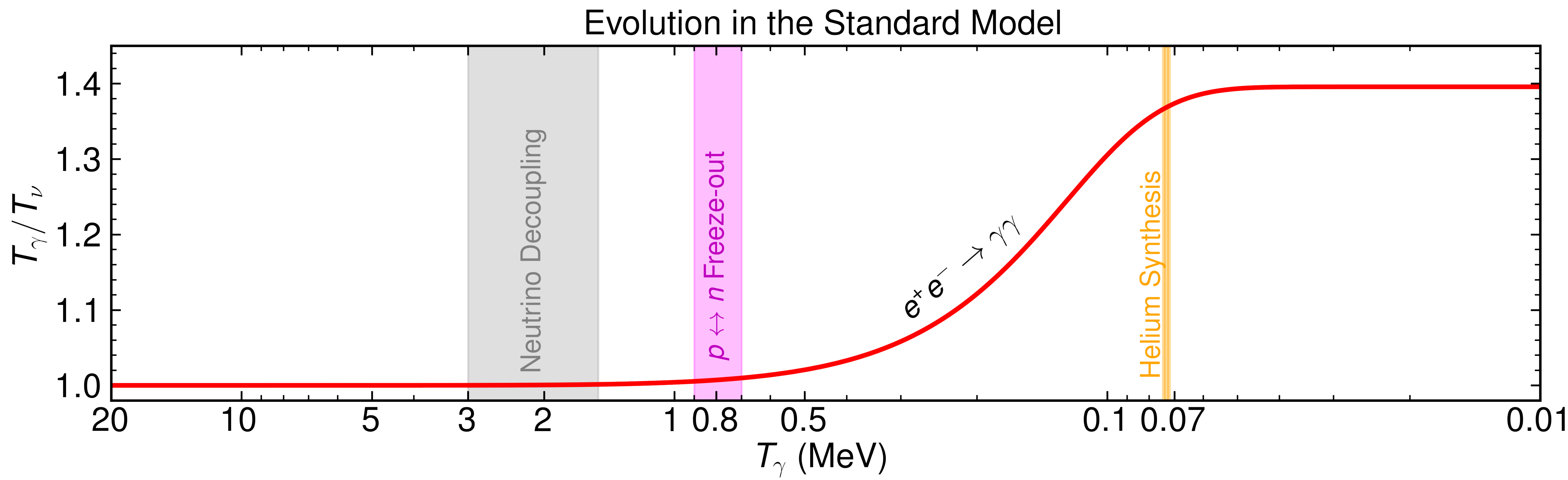
The singlet Majoron model

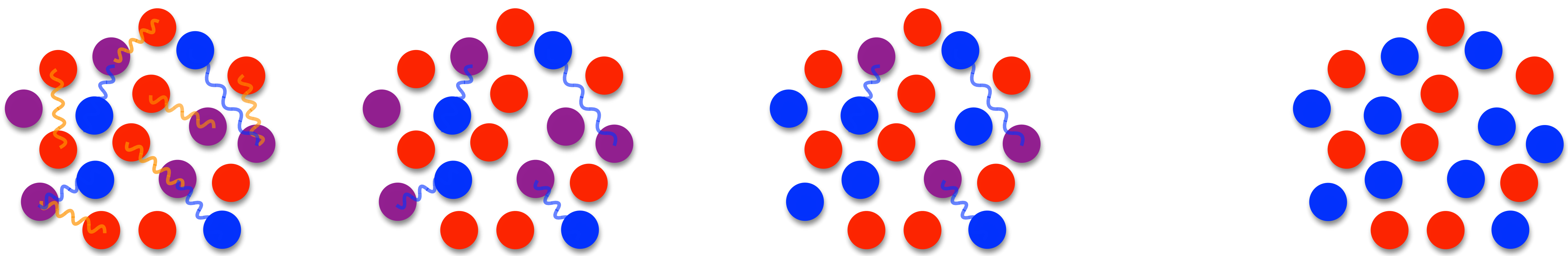
The Majoron as a potential solution to the H0 tension

4) ARS Leptogenesis within the Majoron model

5) Conclusions and Outlook

Neutrino Decoupling



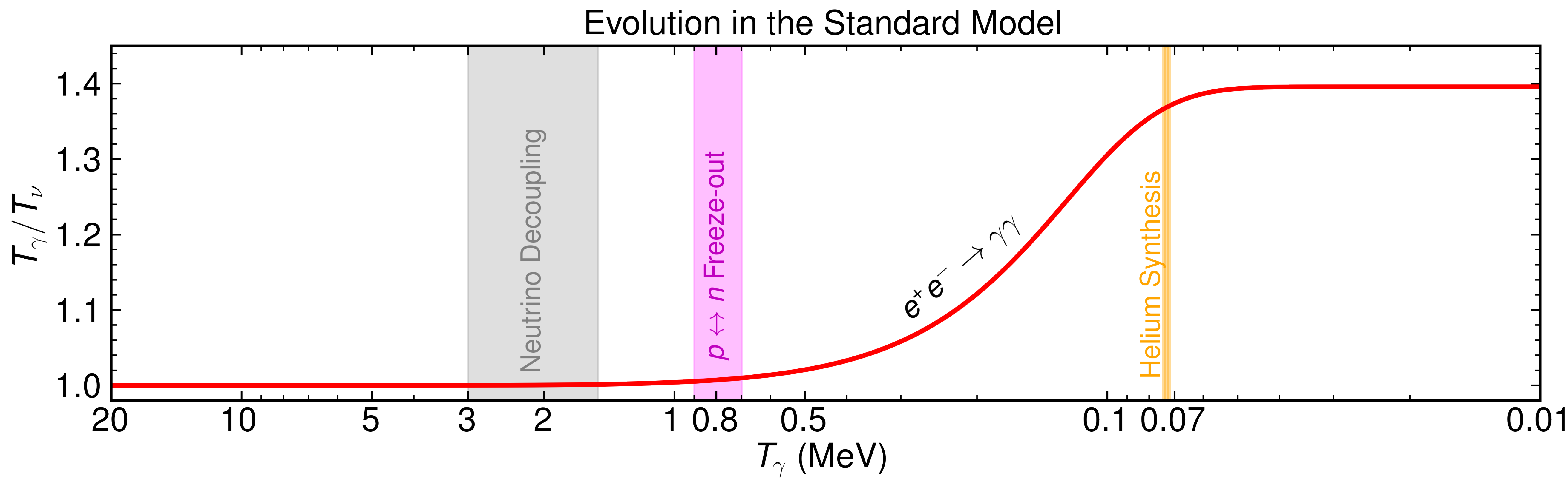


$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$

$$e^\pm\nu_i \leftrightarrow e^\pm\nu_i$$

Neutrinos **Electrons** **Photons** **Z-W (off-shell)**

Neutrino Decoupling



- $$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right) \qquad N_{\rm eff} = 3\left(\frac{1.4 T_\nu}{T_\gamma}\right)^4$$

- $$N_{\rm eff}^{\rm SM} = 3.044(1)$$

de Salas & Pastor 1606.06986
Bennett, Buldgen, Drewes, Wong 1911.04504
Escudero 2001.04466

Akita & Yamaguchi 2005.07047
Froustey, Pitrou & Volpe 2008.01074
Gariazzo, de Salas, Pastor et al. 2012.02726
Hansen, Shalgar, Tamborra 2012.03948

Relic Neutrino Decoupling

$$t \sim 0.1\,{\rm s}$$
$$T_\nu \sim 2\,{\rm MeV}$$

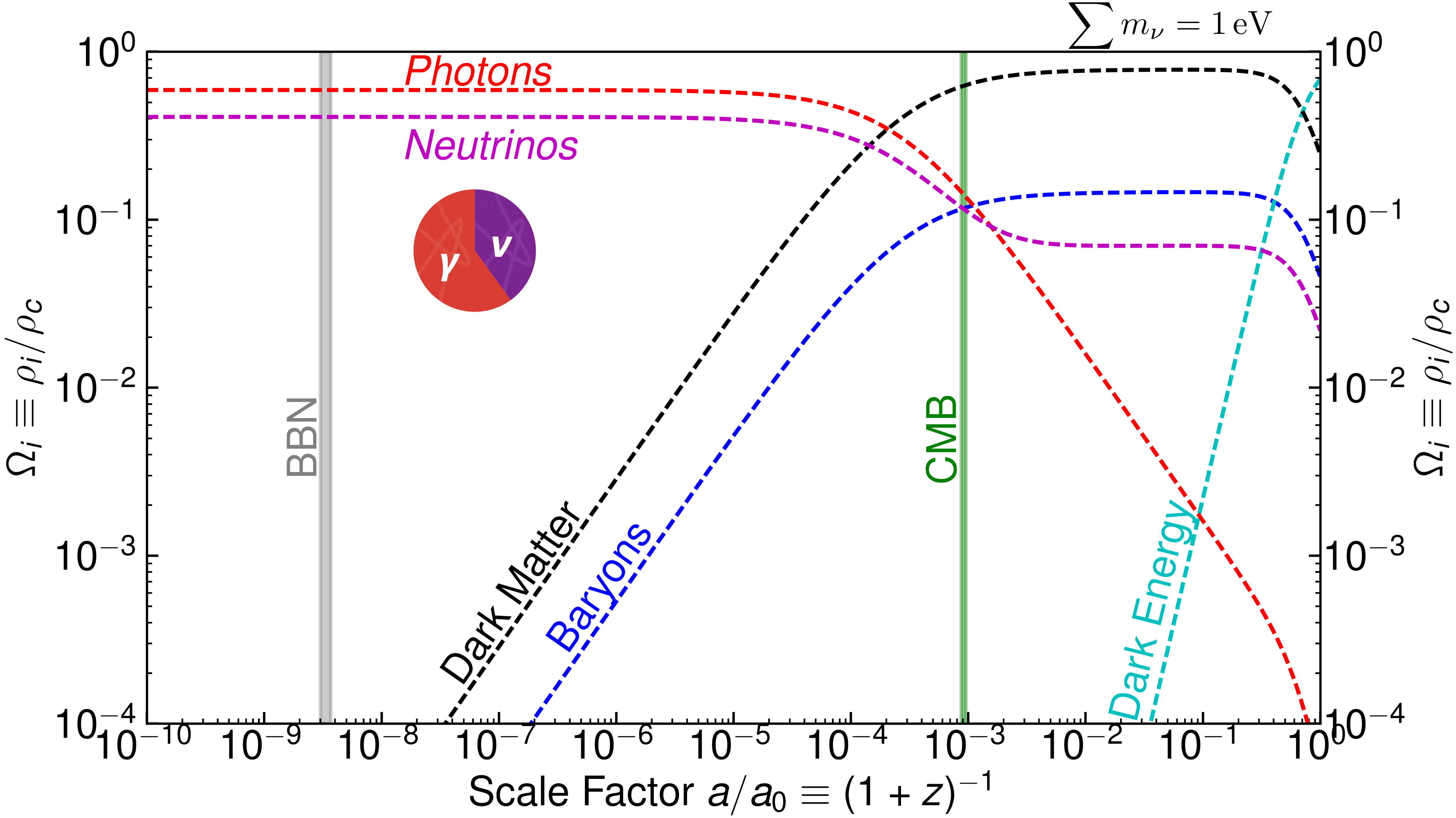
Why is it not 3?

Some e^+e^- heating
Non-instantaneous decoupling
QED thermal corrections
Neutrino Oscillations

Excellent review by Dolgov hep-ph/0202122

Neutrino Evolution

Neutrinos are always a relevant species in the Universe's evolution



Non-Rel: $z_\nu^{\mathrm{non-rel}} \simeq 600\,\dfrac{m_\nu}{0.3\,\mathrm{eV}}$ **DM:** $\Omega_\nu h^2 = \sum m_\nu/(93.14\,\mathrm{eV})$

Current Constraints on Neff

Big Bang Nucleosynthesis

$N_{\rm eff}$ **is, at the moment, constrained by** Y_p **as a result of change in the time to temperature relationship**

There are various Y_p **measurements (see Pisanti et al. 2011.11537):**

$$Y_P = 0.2446 \pm 0.0029 \quad \rightarrow \quad N_{\rm eff} = 2.84 \pm 0.20$$

$$Y_P = 0.2449 \pm 0.0040 \quad \rightarrow \quad N_{\rm eff} = 2.86 \pm 0.28$$

(most used, PDG but with warning)

$$Y_P = 0.2551 \pm 0.0022 \quad \rightarrow \quad N_{\rm eff} = 3.60 \pm 0.17$$

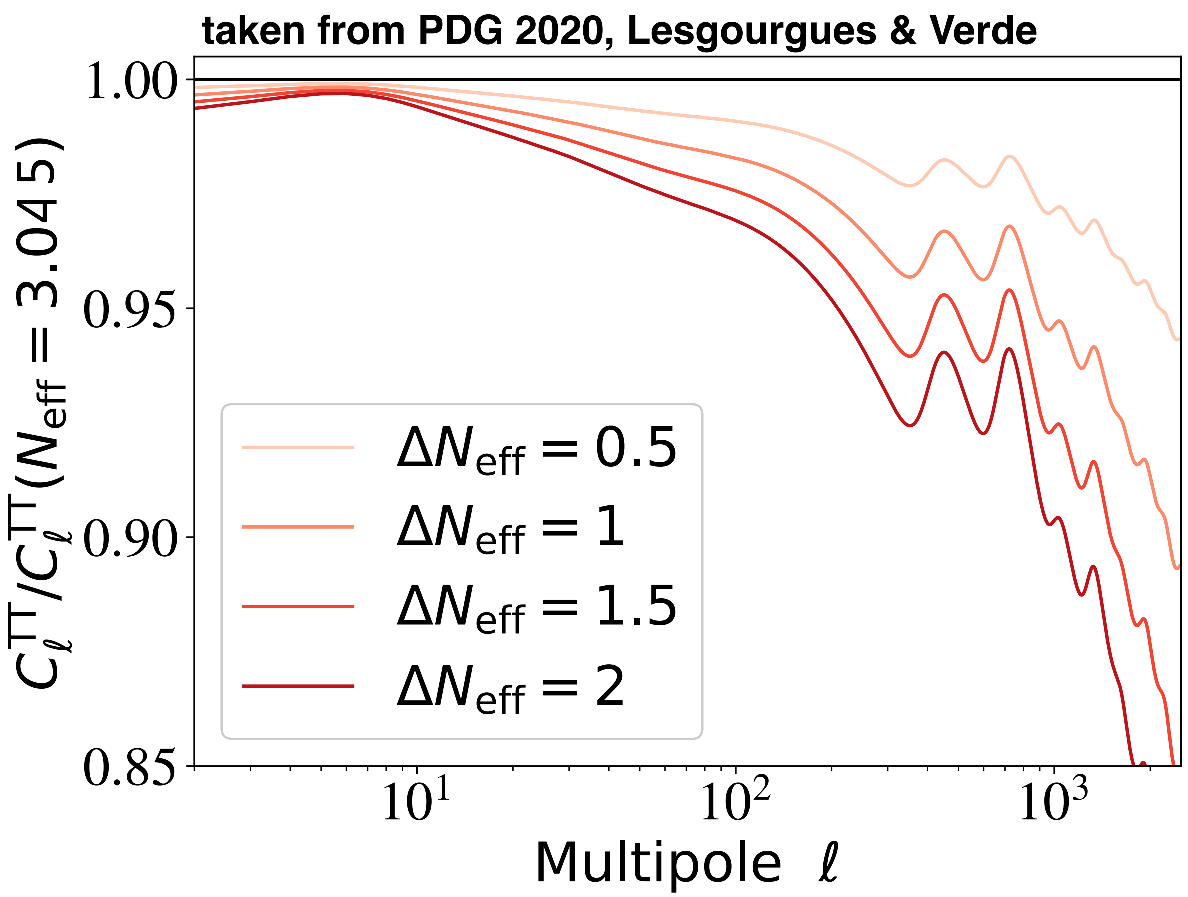
$$Y_P = 0.2436 \pm 0.0040 \quad \rightarrow \quad N_{\rm eff} = 2.78 \pm 0.28$$

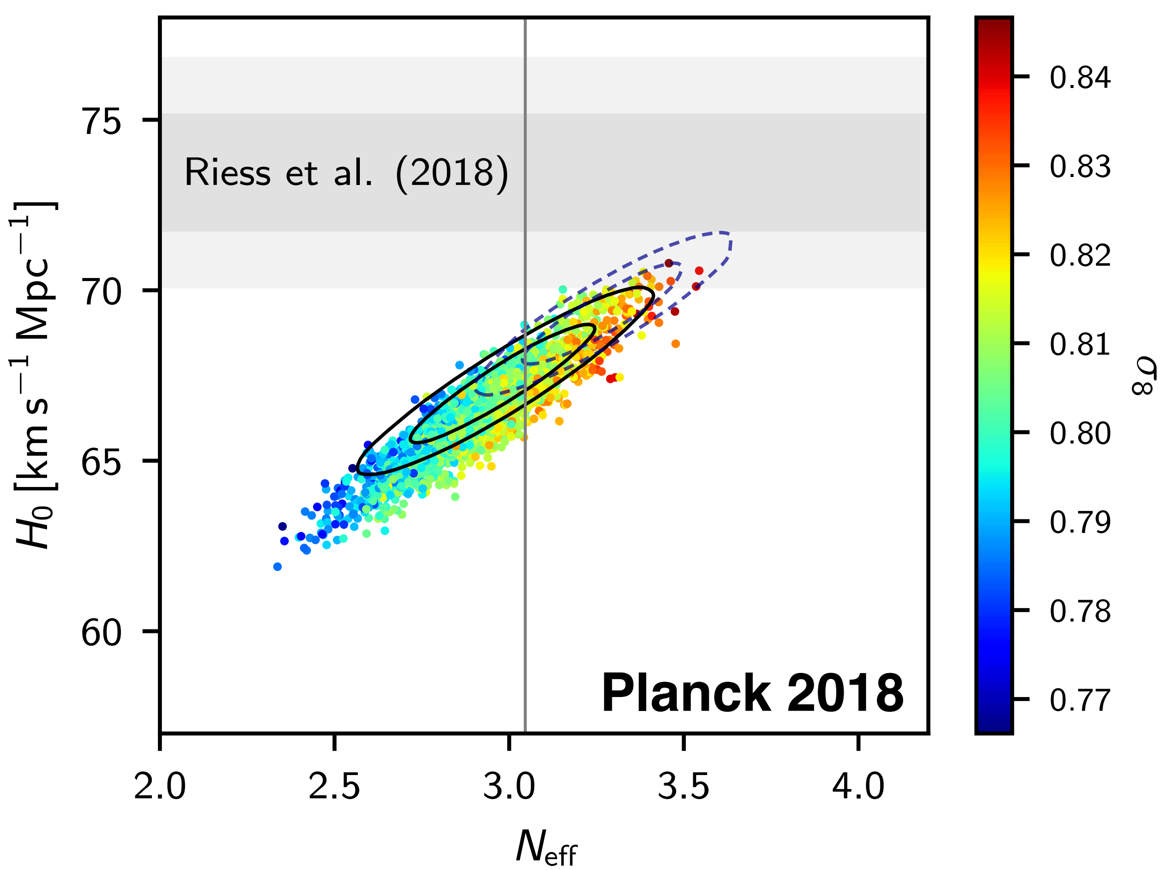
Take away: **likely** $\Delta N_{\rm eff}^{\rm BBN} < 0.4$ **but it could be that** $\Delta N_{\rm eff}^{\rm BBN} = 0.55$

Current Constraints on Neff

Planck

$N_{\rm eff}$ **is constrained by the high-ℓ multipoles, i.e. Silk Damping**





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

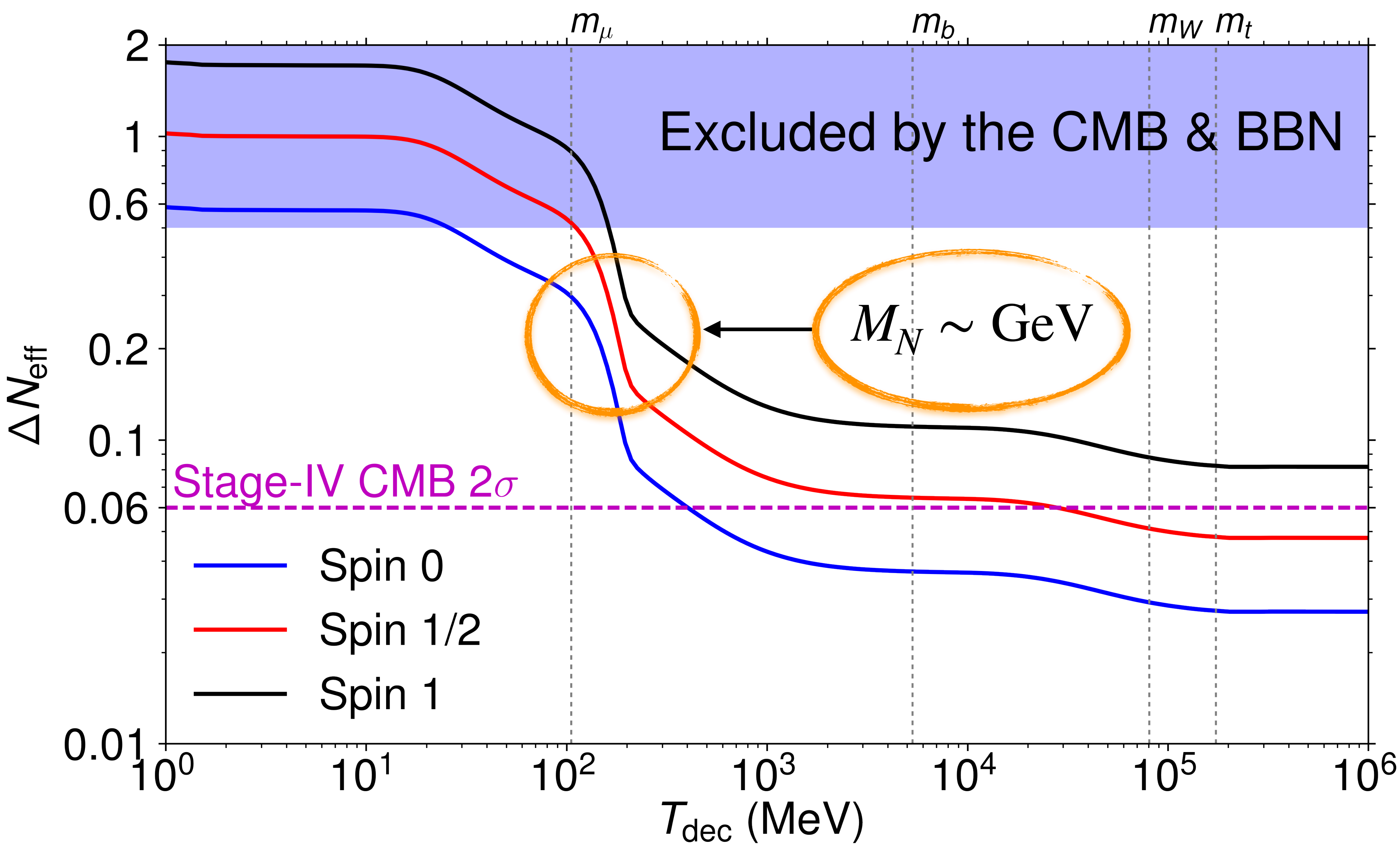
When taking the Reiss value as a prior, then the value of Neff is

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

ΔN_{eff} ~ 0.2-0.5 ameliorates the tension but is not favoured by Planck data!

Neff Scenarios

- **Sterile Neutrino** $m_N \sim \mathrm{eV}$ $\Delta N_{\rm eff} = 1$ **(e.g. Gariazzo, de Salas & Pastor 1905.11290)**
- **Goldstone Bosons** **Weinberg 1305.1971**
- **Other sterile long-lived particles** **Gravitino, axino, hidden sector particles ...**



The Hubble Tension

- **The Hubble Tension:**

$$H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$ **Riess *et al.* 1903.07603**

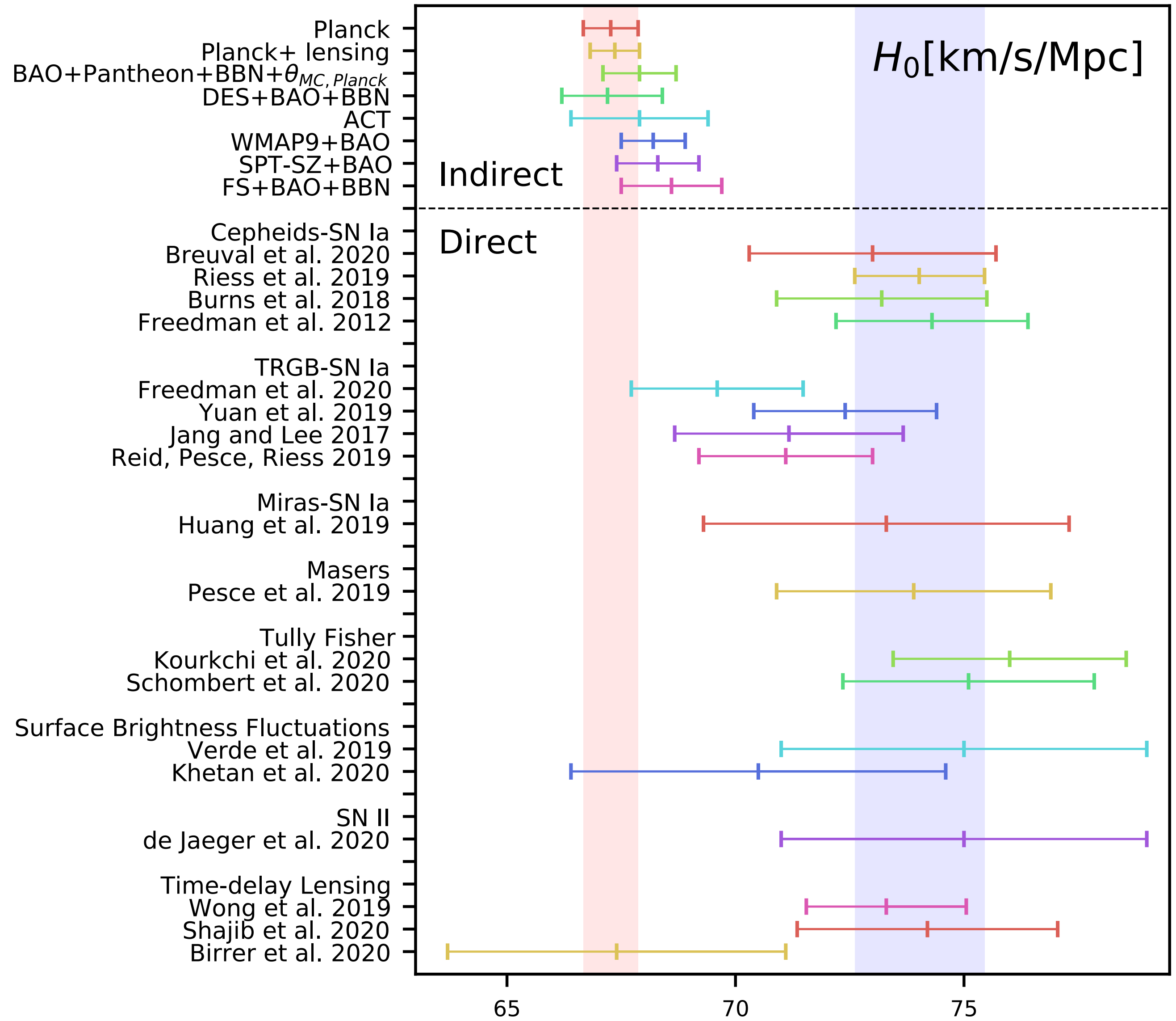
$$H_0 = 67.36 \pm 0.54\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$ **Planck 2018 1807.06209**

4.4 σ tension within ΛCDM!

- **A pattern has clearly emerged:**
  - **4-6 σ tension depending upon the datasets included**

    see Verde, Treu, Riess 1907.10625 for a review
  - **Baryon Acoustic Oscillations point to small H_0**
  - **Cepheids+Type-Ia SN and Strong lensing are among the most precise and they point to** $H_0 \sim (74 \pm 2)\,\mathrm{km/s/Mpc}$

di Valentino 2011.00246



The Hubble Tension

- **Possible resolutions:**

  1) Systematics in the CMB data — **very unlikely**

  2) Systematics in local measurements — **none so far**

  3) New feature of ΛCDM

- **Possibilities Beyond ΛCDM (Knox and Millea 1908.03663):**

  1) Late Universe Modifications — **very unlikely**

  2) Early Universe Modifications — **hard but doable**

The Hubble Tension: Theory

- **Way to Resolve the Hubble Tension** (Knox and Millea 1908.03663):

Enhance the expansion history of the Universe prior and close to recombination!

CMB fixes: $\theta_s \equiv r_s / D_M(z_\star)$ **(0.03% precision)**

$$r_s = \int_{z_\star}^{\infty} \frac{c_s}{H(z')} dz'$$

Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

H_0

By how much? $H_0 \simeq \left[73.6 + 6.2(\Delta N_{\rm eff} - 1)\right]$ km/s/Mpc see Vagnozzi 1907.07569

Neutrinos and the Hubble Tension

Why Neutrinos?

1) Neutrinos are always a relevant species in the evolution of the Universe

2) Neutrino masses are the only Laboratory evidence of Physics Beyond the Standard Model

Neutrinos and the Hubble Tension

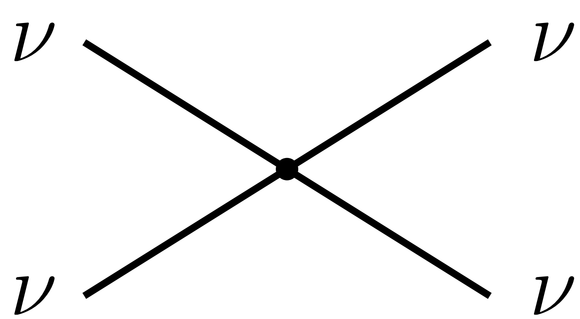
Dark Radiation

$$\Delta N_{\rm eff} = 0.23 \pm 0.15$$

(68 % CL, Planck+BAO+H0)

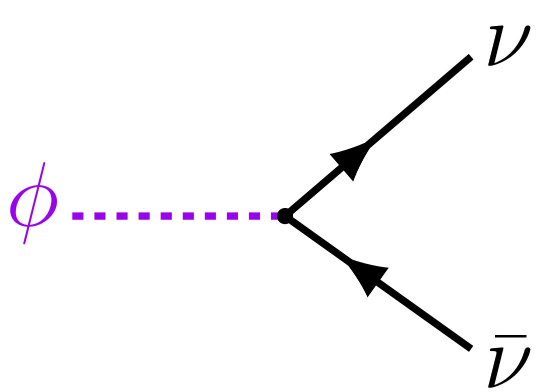
- Clear Interpretation 😃
- H_0 tension from 4.4σ to 3σ 😐
- CMB fit is degraded ☹️

Strong Neutrino Scattering + Dark Radiation
Kreisch, Cyr-Racine, Doré 1902.00543



- H_0 tension solved if TEEE data is ignored 😃
- If pol data is included no solution for H_0 😐
- Almost excluded by Lab data (Blinov++1905.02727) ☹️

Light Neutrinophilic Scalar + Dark Radiation
Escudero & Witte 1909.04044



- H_0 tension from 4.4σ to 2.5σ 😐
- CMB fit is not degraded 😃
- Direct connection with Seesaw 😃
- Ad hoc $\Delta N_{\rm eff} \sim 0.5$ 😐

Neutrinos and the Hubble Tension

- **Early Dark Energy sourced by neutrinos** — Sakstein & Trodden 1911.11760

  Nice way to solve the coincidence problem 😃

  Use $\sum m_\nu = 1.5\,\mathrm{eV}$ (10% of DM) which can be dangerous 😐

  But the Cl's have not been calculated yet … 😐

  Some progress has been made — Carrillo González et al. 2011.09895 😃

- **An eV-scale Sterile Neutrino interacting with a pseudoscalar**

  Archidiacono, Hannestad, Hansen & Tram 1404.5915, 1508.02504
  Archidiacono, Gariazzo, Giunti, Hannestad, Hansen, Laveder, Tram 1606.07673
  Archidiacono, Gariazzo, Giunti, Hannestad, Tram 2006.12885

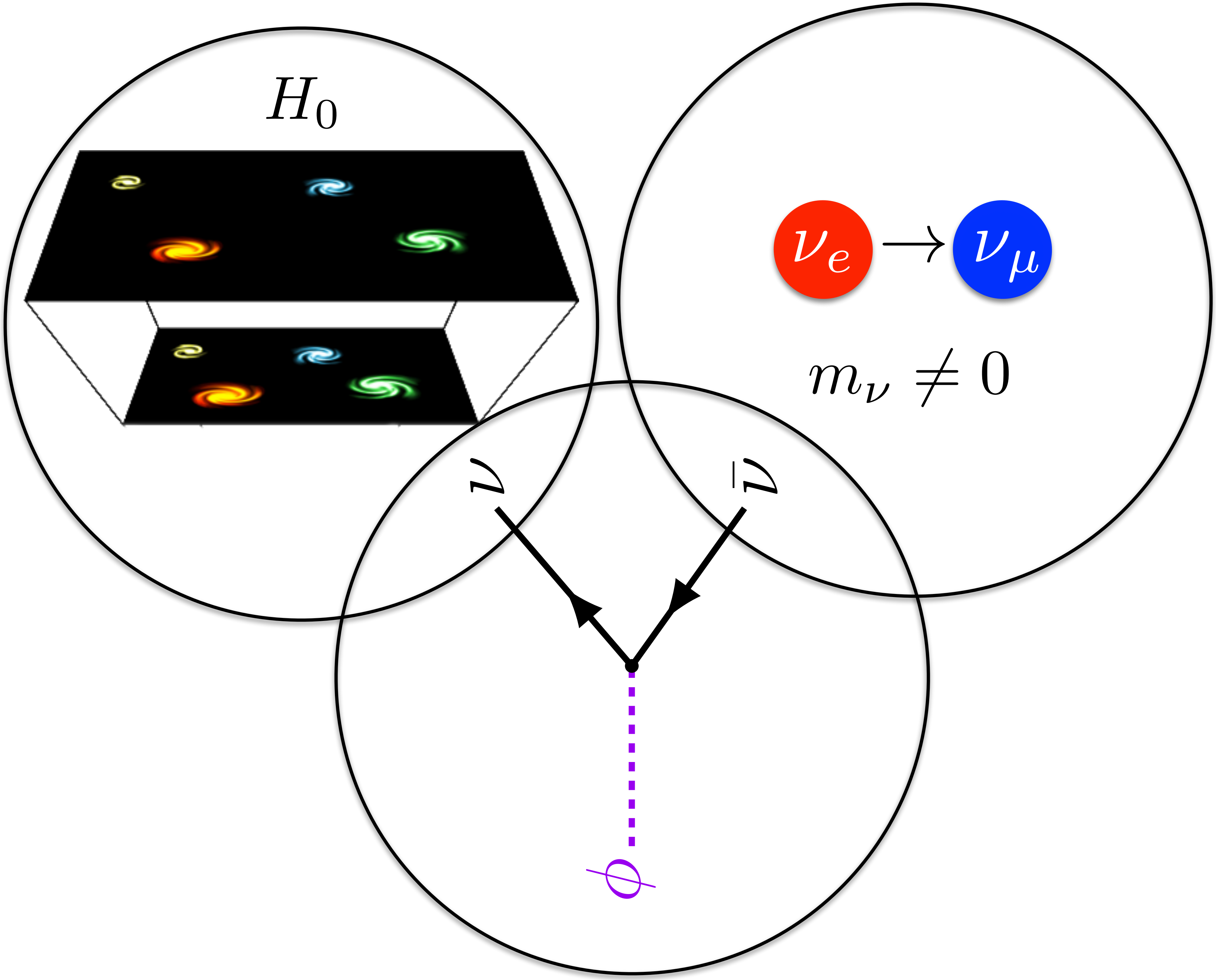
  Clearly motivated by short-baseline neutrino experiments 😃

  Nice idea to try to avoid the cosmo problems with $m_s \sim \mathrm{eV}$ 😃

  The Hubble Tension could be solved if $\Delta N_{\rm eff} = 1$ 😃

  But that leads to a bad CMB fit $\Delta\chi^2 = 13 - 32$ 😐

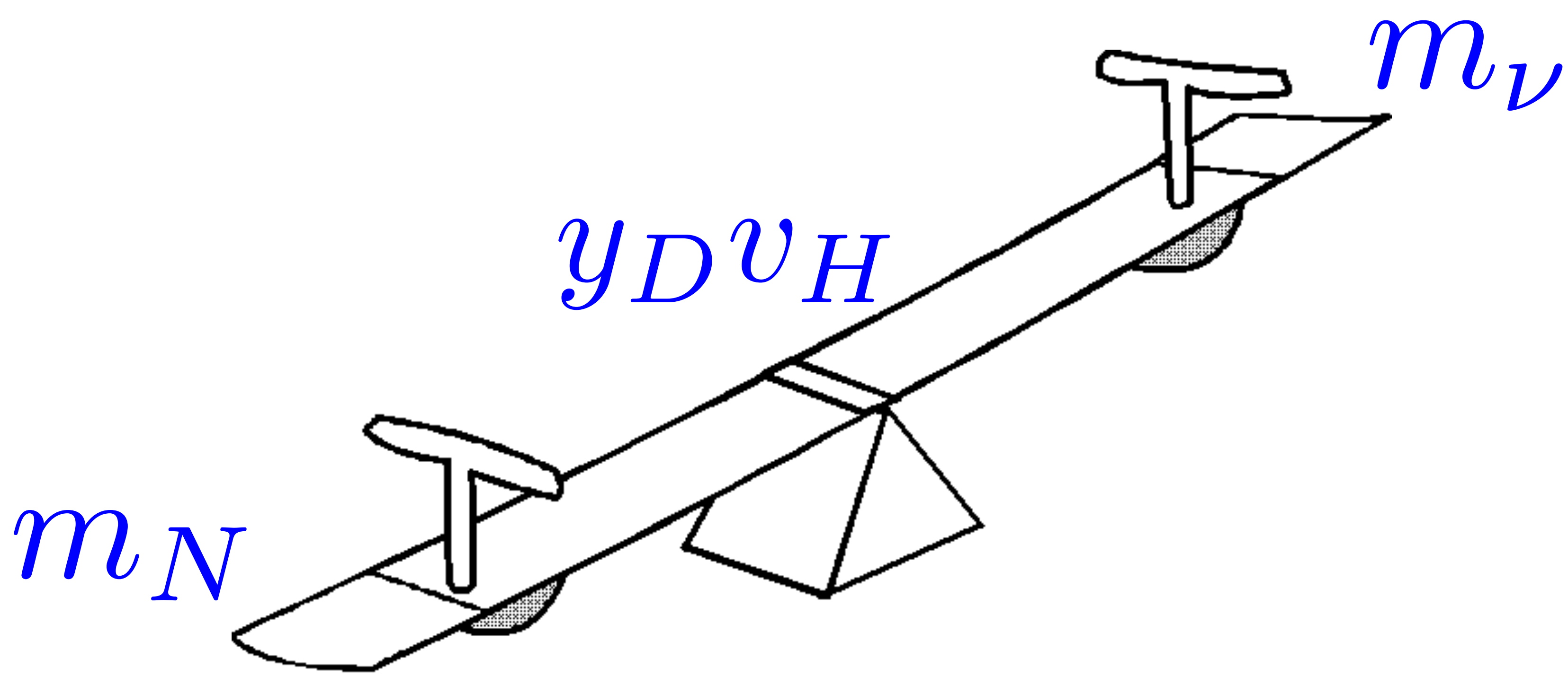
The Idea:



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

Spontaneously Broken Symmetry Global U(1)$_L$

Chikashige, Mohapatra, Peccei (1981)

Sterile Neutrinos

$$\mathcal{L} = -\frac{\lambda_{N_{ij}}}{\sqrt{2}}\Phi\,\overline{N}_{R,\,i}N^c_{R,\,j} - h_{\alpha i}\overline{L}^{\alpha}_L H N_{Ri} + \text{h.c.}\,,\qquad L[\Phi]=2 \quad L[N]=1$$

SSB: $\Phi \to v_L/\sqrt{2} \longrightarrow M_N = \lambda_N v_L \xrightarrow{\text{seesaw}} m_\nu \simeq h^2 v_H^2/(2M_N)$

Scalar Sector

$$V_\Phi = -\mu_\Phi^2 \Phi^\dagger\Phi + \lambda_\Phi(\Phi^\dagger\Phi)^2 - \lambda_{\Phi H}(H^\dagger H)(\Phi^\dagger\Phi)$$

$$\Phi = \frac{v_L+\rho}{\sqrt{2}}e^{i\phi/v_L}$$

$\rho \equiv \text{CP}-\text{even scalar}$ $\qquad m_\rho^2 = 2\lambda_\Phi v_L^2$

$\phi \equiv \text{Majoron}$ $\qquad$ **pseudo-Goldstone:** $m_\phi \simeq 0$

Interactions

$$\mathcal{L}_{\text{eff}} = -\frac{\lambda_N}{2}\left[\rho\bar{N}N - i\phi\bar{N}\gamma_5 N\right] - \frac{\lambda_{N\nu}}{2}\left[\rho\bar{N}\nu - i\phi\bar{N}\gamma_5\nu\right] + \text{h.c.} - \frac{\lambda_\nu}{2}\left[\rho\bar{\nu}\nu - i\phi\bar{\nu}\gamma_5\nu\right]$$

$$\lambda_\nu \ll \lambda_{N\nu} \ll \lambda_N$$

$$\lambda_\nu \simeq |\theta|\lambda_{N\nu} \simeq |\theta|^2\lambda_N$$

$$|\theta|^2 \simeq 5\times 10^{-11}\frac{m_\nu}{0.05\,\text{eV}}\frac{1\,\text{GeV}}{M_N}$$

The Scenario

Spontaneously Broken Symmetry Global $U(1)_L$

Chikashige, Mohapatra, Peccei (1981)

The Majoron: ϕ $\qquad \mathcal{L}_{\rm int} = i\lambda\,\phi\,\bar{\nu}\,\gamma_5\,\nu$

Very weakly interacting: $\lambda \simeq 10^{-13}\,\frac{m_\nu}{0.05\,\rm eV}\,\frac{\rm TeV}{v_L}$ **(seesaw)**

Extremely feebly interacting with matter: $\lambda_{\phi ee} \sim 10^{-20}$

Dimension-5 Planck suppressed operators: $m_\phi \sim v_L \sqrt{\frac{v_L}{M_{\rm Pl}}} \lesssim 0.1\,\rm keV$

$$\Delta V = \beta\left(\Phi^\star\Phi\right)^2 \frac{\Phi^\star + \Phi}{M_{\rm Pl}}$$

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

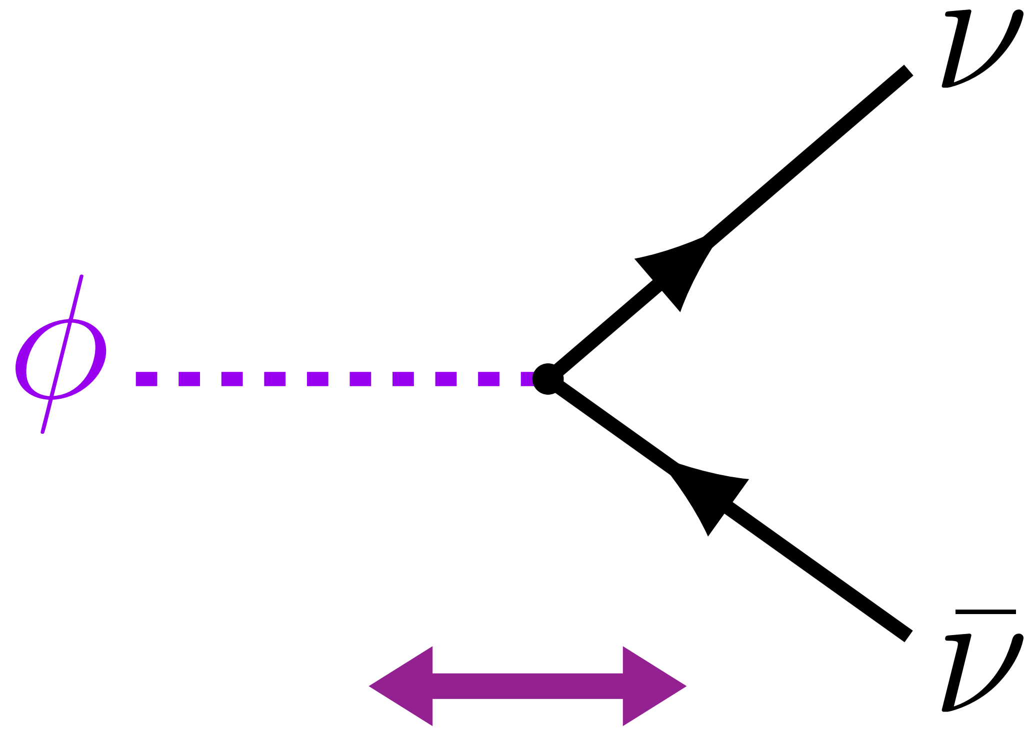
Parameter Space:

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

And assume that $n_\phi = 0$ at BBN

Cosmological Implications

Only Relevant Process:



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

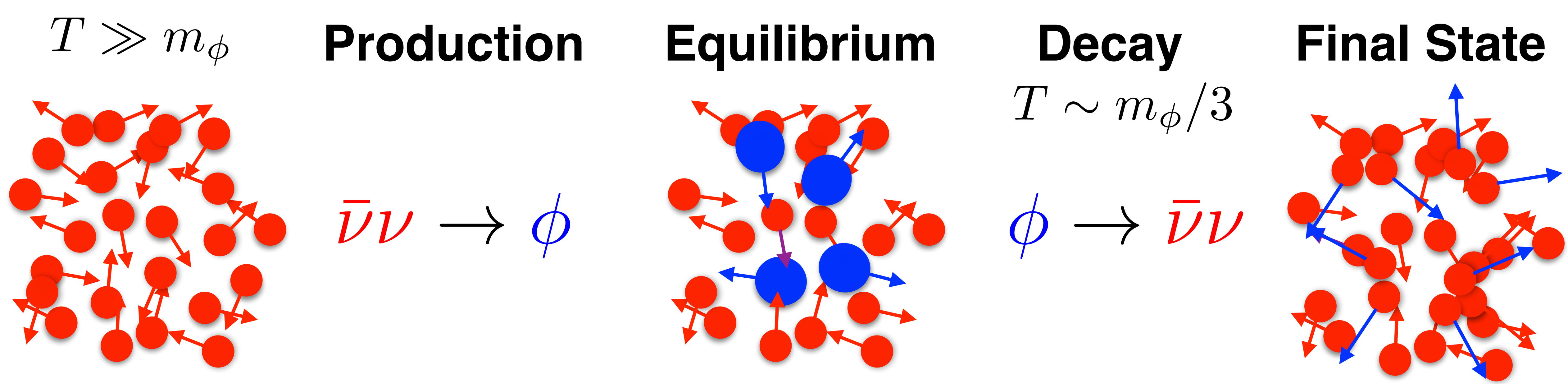
Two main effects:

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

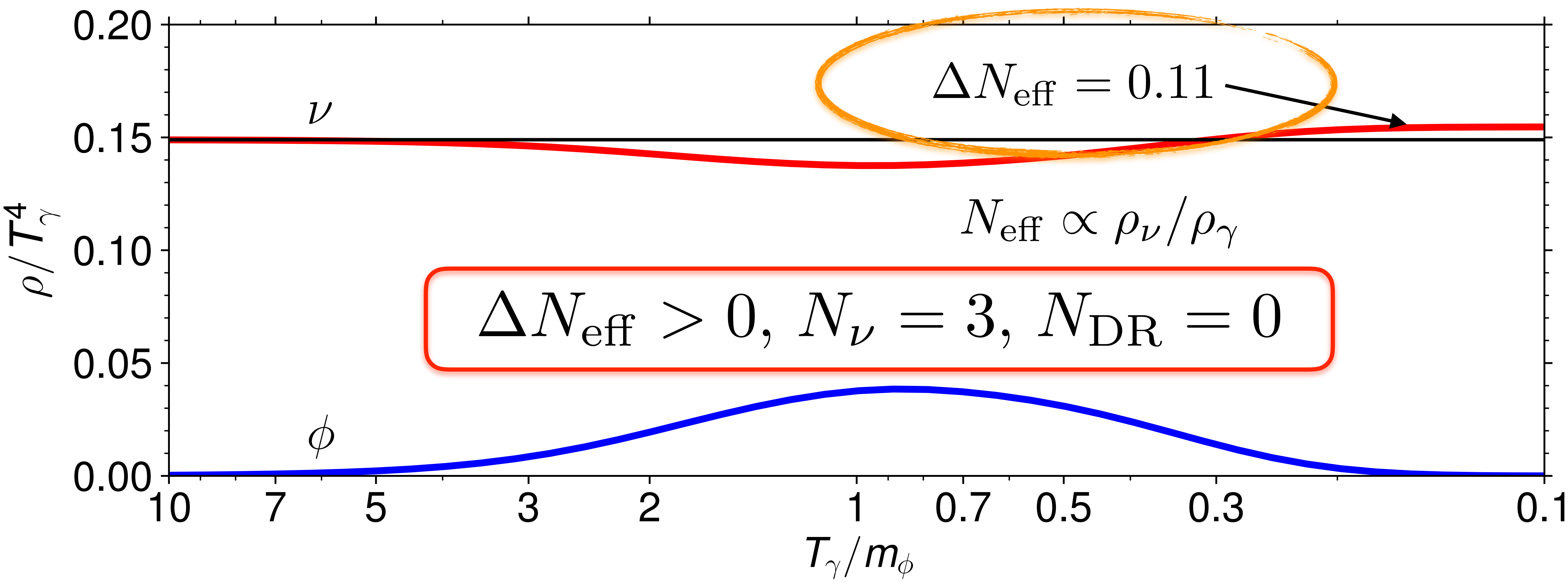
- **Non-standard expansion history**
- **Erase the neutrino anisotropic stress**

- **We solve the Boltzmann equation for the background**
  Escudero 1812.05605, 2001.04466
- **We include the neutrino-majoron Boltzmann hierarchy in CLASS**

Cosmological Implications

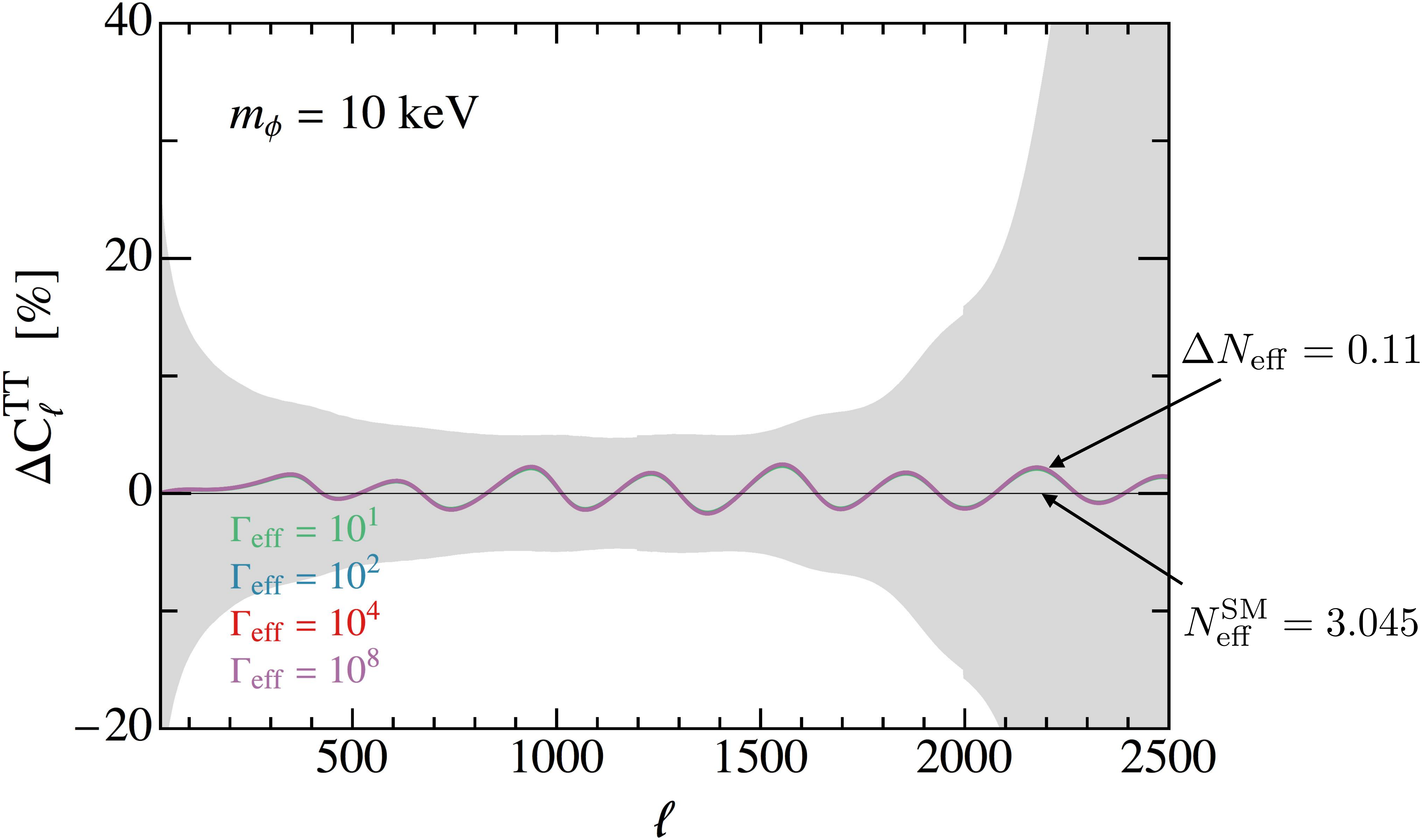


$$\Gamma_\phi \simeq H(T_\nu = m_\phi/3)$$



Effects on the CMB

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

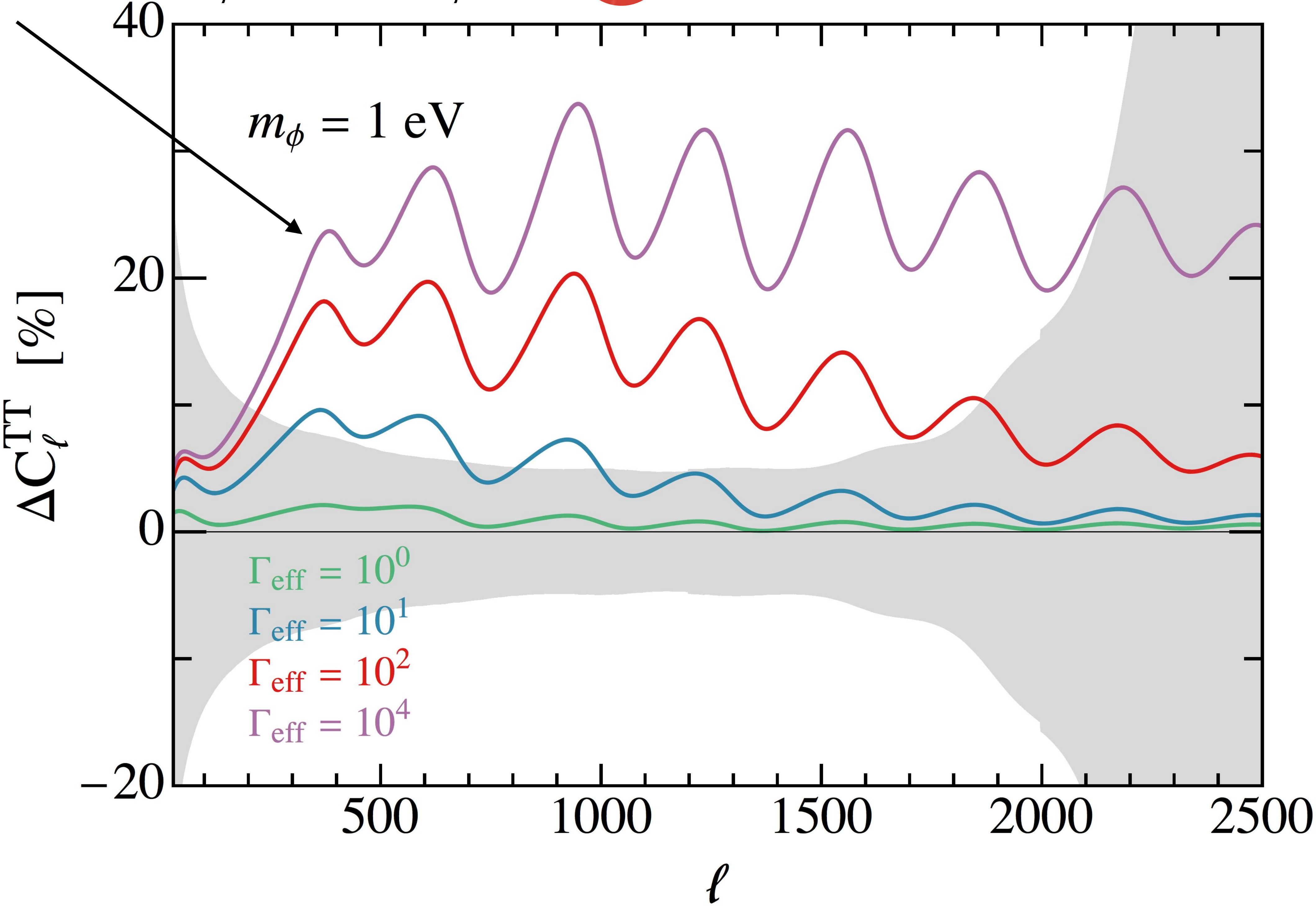


Effects on the CMB

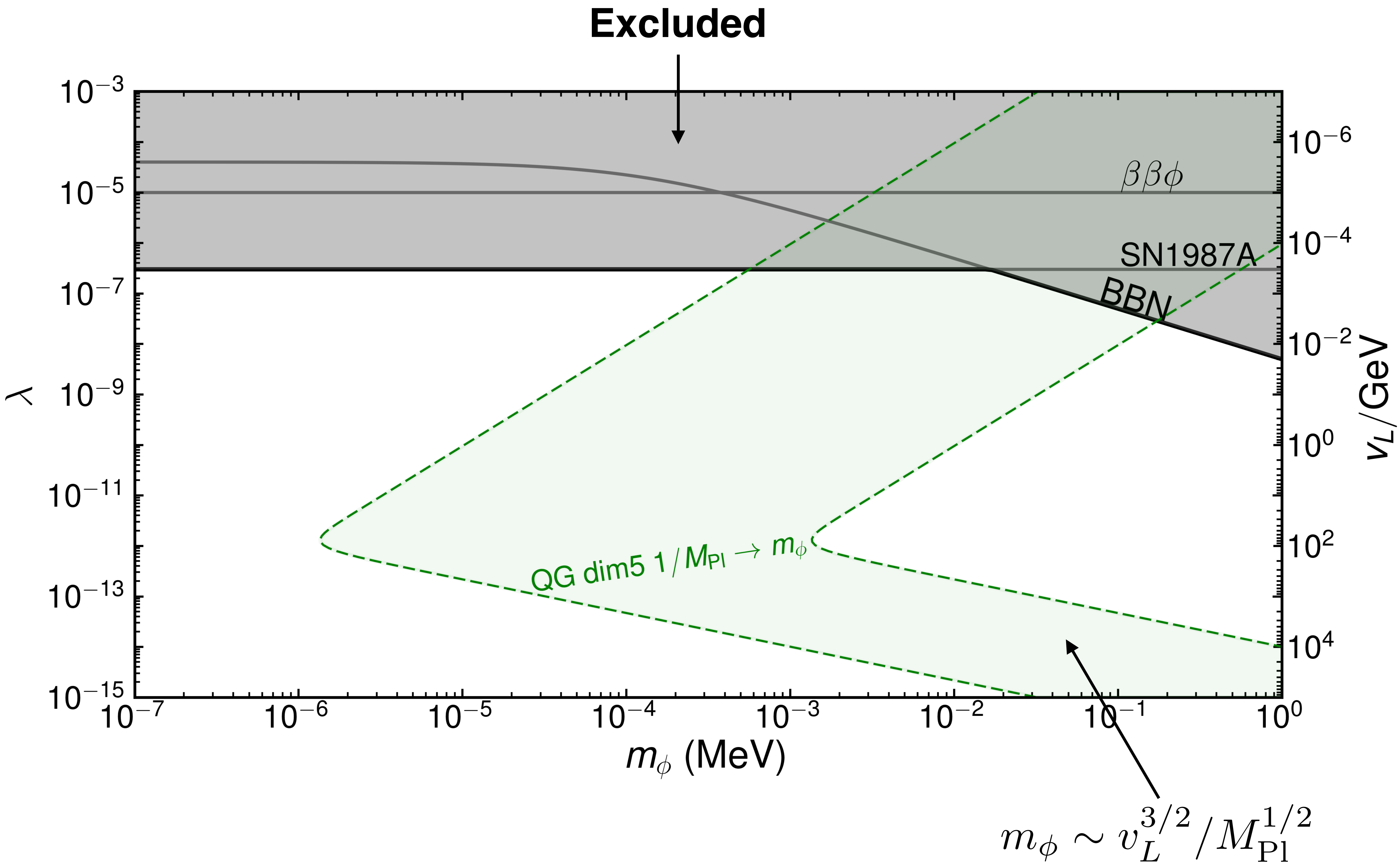
see Bashinsky and Seljak astro-ph/0310198

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

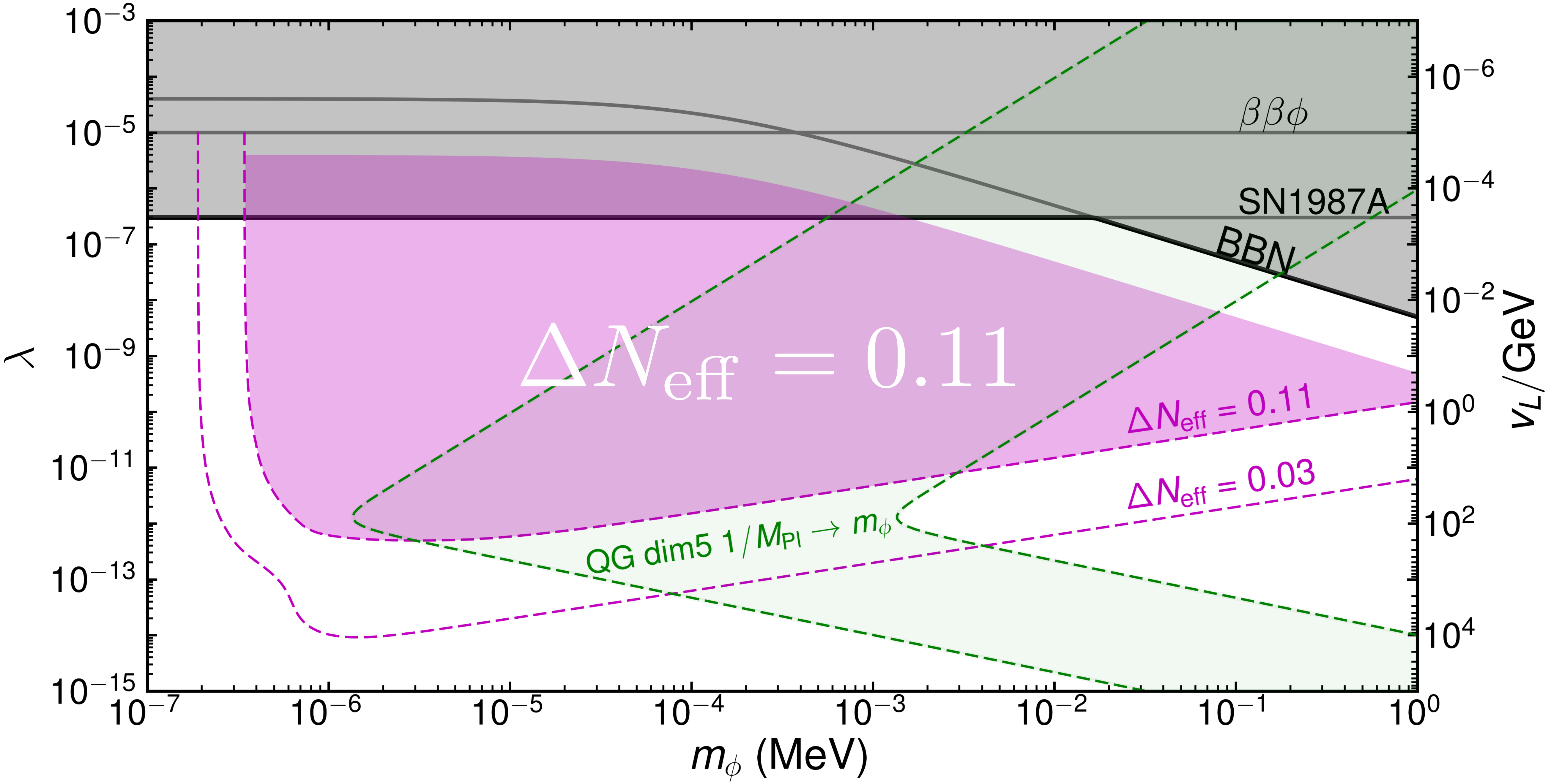
$\sigma_\nu \to 0$ $\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$



Parameter Space

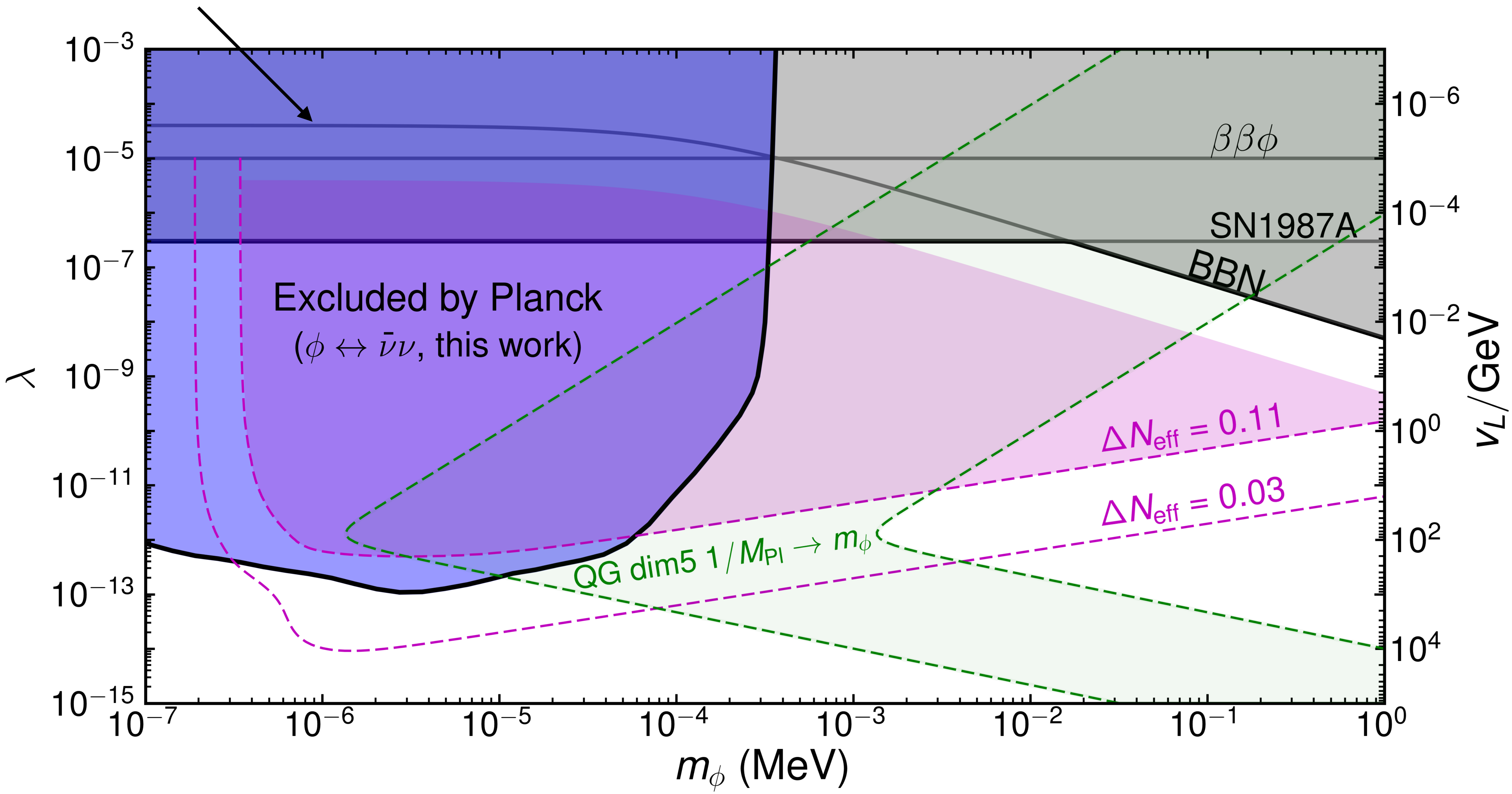


Parameter Space

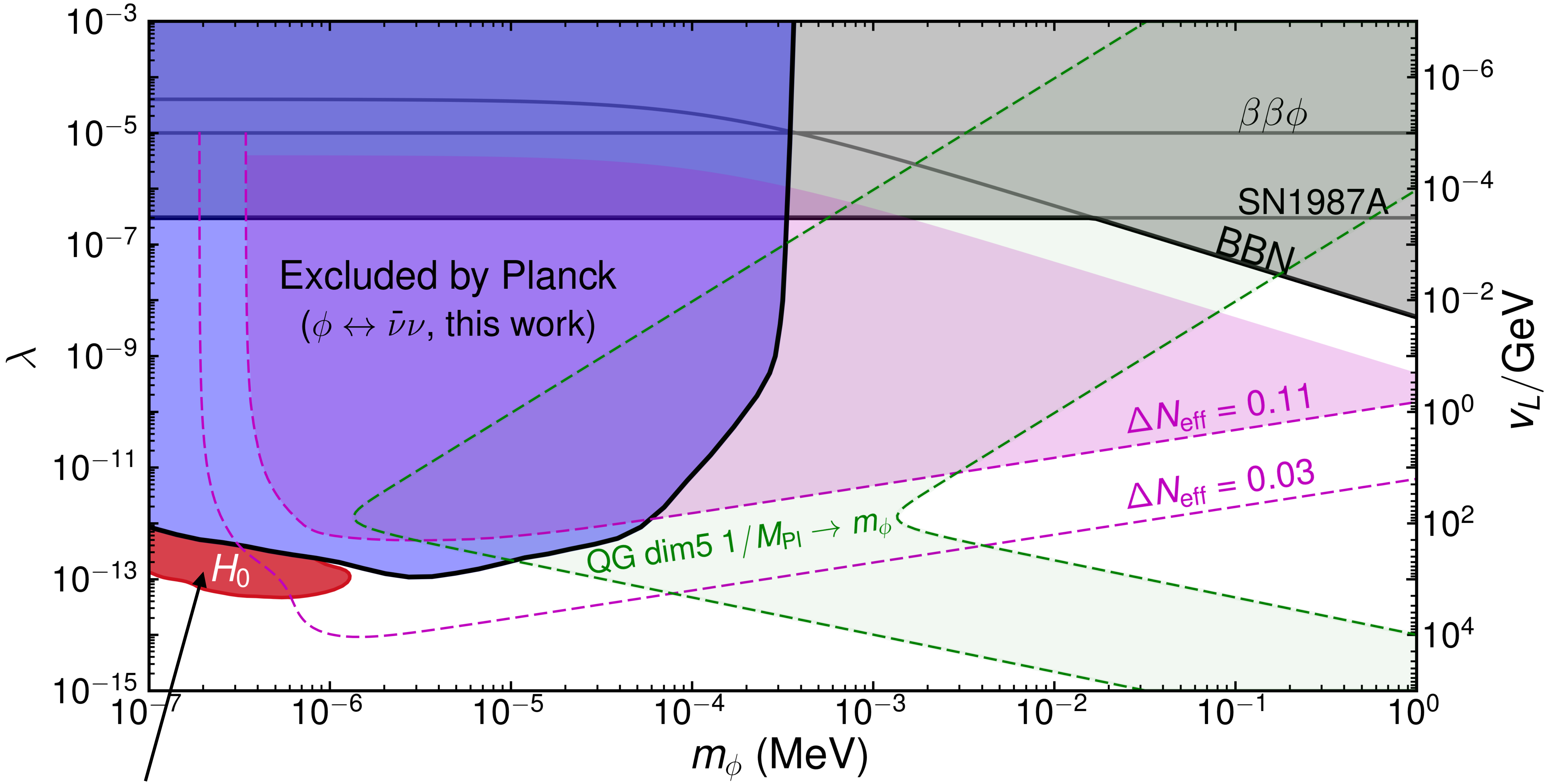


Parameter Space

Full MCMC to Planck 2018 data

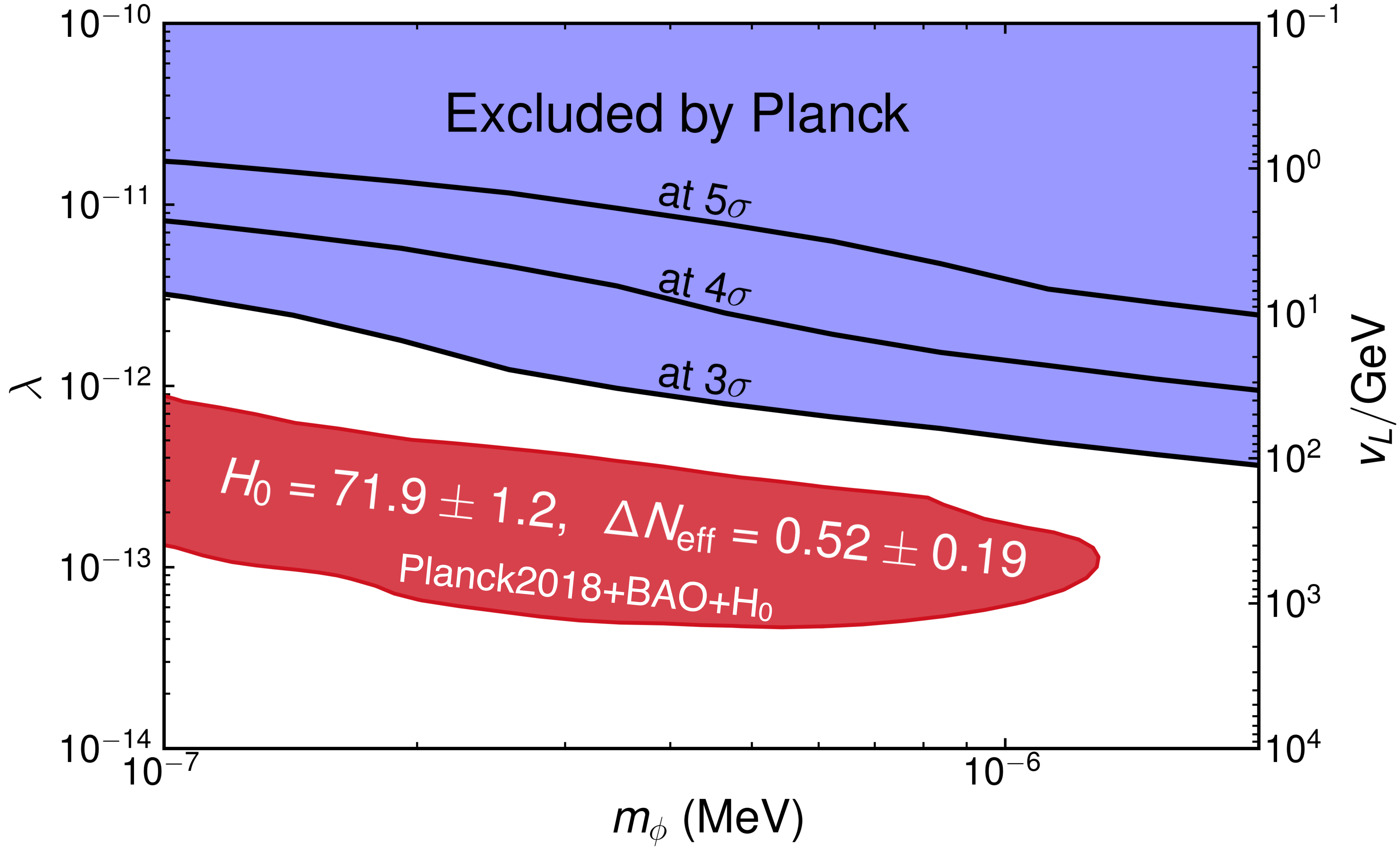


Parameter Space



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

Parameter Space for H_0



H_0

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

Summary of 2019

- **The Majoron and the Hubble tension**
  - **Couplings from seesaw and mass from gravity**
  - **Planck sets very stringent constraints**
  - **Ameliorates H_0 tension via** $\Delta N_{\rm eff} = 0.11$
  - **CMB S4 experiments will test this region** $\sigma(N_{\rm eff}^{\rm CMB}) \sim 0.03$
  - **May significantly reduce the tension if:** $m_\phi \sim (0.1-1)\,{\rm eV}$, $v_L \sim (0.1-1)\,{\rm TeV}$, $\Delta N_{\rm eff} \sim 0.5$

😐 $\Delta N_{\rm eff} \sim 0.5$ **is somewhat ad hoc**

😃 **Now we have a very good reason for it!**

Leptogenesis with the Majoron

- **The Majoron and Baryogenesis**
  - **Electroweak Baryogenesis:** Cohen, Kaplan, Nelson 90'-91'
  - **Thermal Leptogenesis:** Aristizabal-Sierra, Tortola, Valle, Vicente 1405.4706
  - **Resonant Leptogenesis:** Pilaftsis 0805.1677
  - **ARS Leptogenesis:** Caputo, Hernández & Rius 1807.03309

Let's stick with ARS because since $v_L \sim v_H$ we can easily get $M_N \sim \mathrm{GeV}$

Conclusion from 1807.03309 is that: $v_L > 10^5\,\mathrm{GeV}$ **for successful ARS Leptogenesis**

I will argue that that is not necessarily true!

I will further argue that N decays can lead to a primordial ΔN_{eff}

ARS Leptogenesis

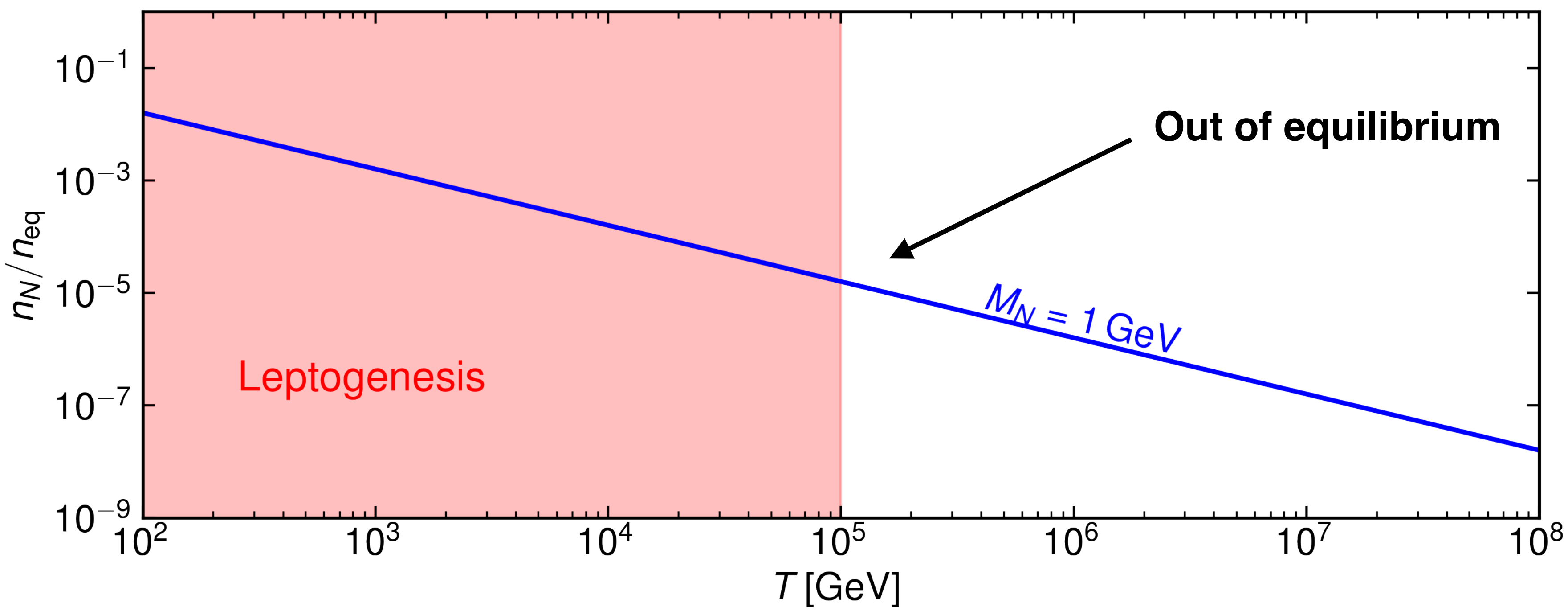
- **Baryogenesis via Sterile Neutrino Oscillations**

Akhmedov, Rubakov & Smirnov, hep-ph/9803255.
See also Asaka & Shaposhnikov, hep-ph/0505013, Shaposhnikov 0804.4542
Nice review by Hernández et al. 1711.02862

- **The Idea & key Ingredients:**

1) Reheating leads to only SM particles, i.e. $n_N(T = \infty) = 0$

2) Sterile Neutrinos are slowly produced via their Yukawas, e.g. $Q_3\,\bar{t} \to \ell\, N$



ARS Leptogenesis

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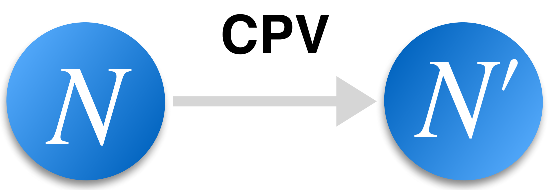
- **The Idea & key Ingredients:**

  1) Reheating leads to only SM particles, i.e. $n_N(T=\infty)=0$

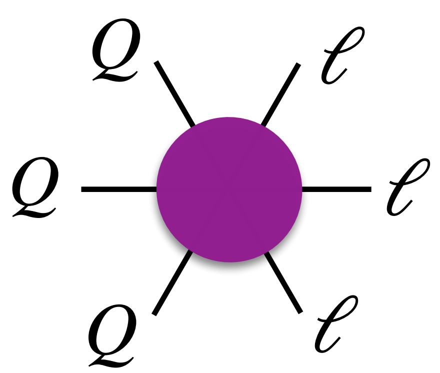
  2) Sterile Neutrinos are slowly produced via their Yukawas, e.g. $Q_3\,\bar{t} \to \ell\, N$

  3) These sterile neutrinos undergo CP violating oscillations



  Majorana masses are small and lepton number is conserved

  However, via the interactions with leptons an effective asymmetry is produced in the standard model because $L = L_e + L_\mu + L_\tau + L_{N_1} + L_{N_2} = 0$



  4) Baryogenesis occurs due to sphaleron freeze-out at $T_{\rm SPH} \sim 130\,{\rm GeV}$

- **Parameter Space n = 2:**

  see e.g. Eijima, Shaposhnikov & Timiryasov, 1808.10833

$$0.1\,{\rm GeV} \lesssim M_N \lesssim 10\,{\rm GeV}$$

$$\Delta M/M_N \sim 10^{-7} - 10^{-5}$$

ARS Leptogenesis + Majoron

Necessary requirements:

1) Sterile Neutrinos cannot be in thermal equilibrium prior to $T_{\rm SPH} \sim 130\,{\rm GeV}$

2) Sterile Neutrinos need to oscillate

$$T_{\rm Lepto} \sim 0.17\,(M_N \Delta M M_{\rm Pl})^{1/3} \sim 2\times 10^4\,{\rm GeV}\left(\frac{M_N}{10\,{\rm GeV}}\right)^{2/3}\left(\frac{\Delta M}{10^{-6}\,M_N}\right)^{1/3}$$

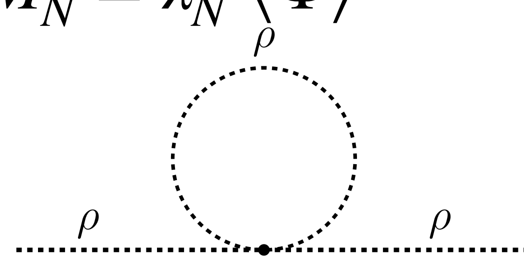
Threats in the Majoron model:

Threat to 1) $\phi\phi \leftrightarrow N\bar{N}$ $\rho\rho \leftrightarrow N\bar{N}$ $\rho \leftrightarrow \bar{N}N$

- If $\rho's$ are present after reheating, then: $v_L > 10^5\,{\rm GeV}$ Caputo, Hernández & Rius 1807.03309
- Not a problem provided if $\rho's$ and $\phi's$ are not populated during reheating
- There are no $\rho's$ if $\lambda_{\Phi H} < 10^{-7}$ $(\rho\rho \leftrightarrow HH)$
- The smallness is respected by quantum corrections $\beta(\lambda_{\Phi H})^{(1)} \propto \lambda_{\Phi H}$ $\beta(\lambda_{\Phi H})^{(2)} \propto h_N^2 \lambda_N^2$

Threat to 2) Symmetry could be unbroken! $M_N = \lambda_N \langle \Phi \rangle$

- It is fine provided: $|\lambda_{\Phi H}| < 10^{-7}\frac{v_L}{1\,{\rm TeV}}\sqrt{\frac{10^5\,{\rm GeV}}{T_c}}$



$$m_\rho^2(T) \sim \frac{n_\rho}{n_\rho^{\rm eq}}\lambda_\Phi\,\Phi^2$$

ARS Leptogenesis + Majoron

- **Necessary requirements:**

  1) **Sterile Neutrinos cannot be in thermal equilibrium prior to** $T_{\rm SPH} \sim 130\,{\rm GeV}$

  2) **Sterile Neutrinos need to oscillate**

$$T_{\rm Lepto} \sim 0.17\,(M_N \Delta M M_{\rm Pl})^{1/3} \sim 2\times 10^4\,{\rm GeV}\left(\frac{M_N}{10\,{\rm GeV}}\right)^{2/3}\left(\frac{\Delta M}{10^{-6}\,M_N}\right)^{1/3}$$

- **Conclusion**

  ARS Leptogenesis is compatible with the singlet Majoron model!

  This works for low v_L provided:

  No $\rho's$ and $\phi's$ are produced during reheating

$$|\lambda_{\Phi H}| < 10^{-7}\frac{v_L}{1\,{\rm TeV}}\sqrt{\frac{10^5\,{\rm GeV}}{T_c}}$$

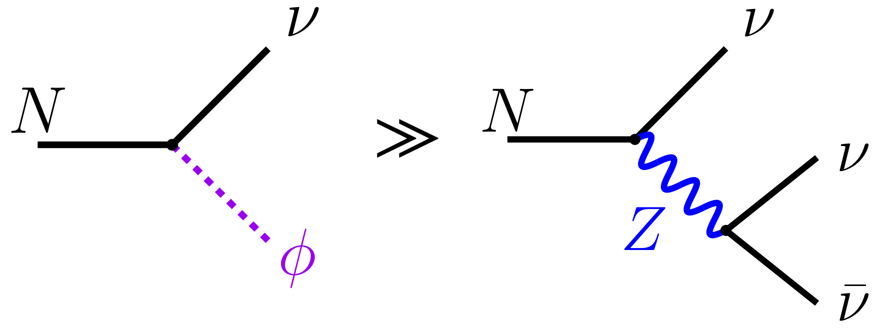
(which is stable under RGE flow)

Production of Majoron population

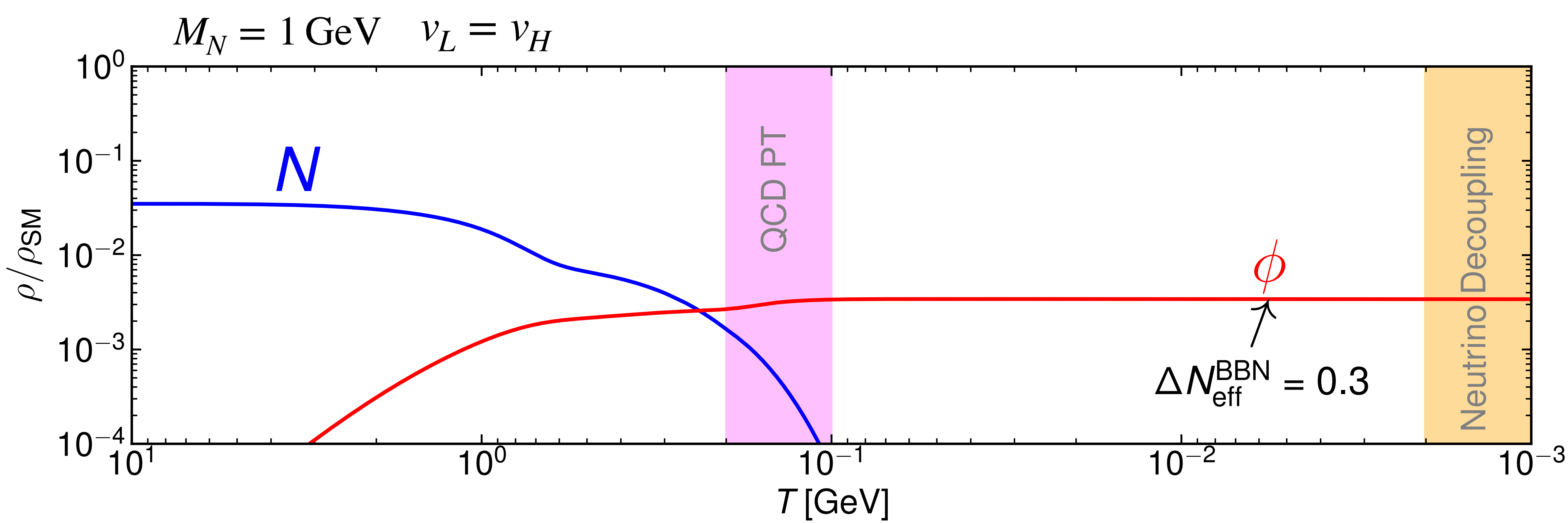
- **Evolution after Baryogenesis**

Sterile Neutrinos that give mass to the active neutrinos thermalize Ghiglieri & Laine, 1605.07720

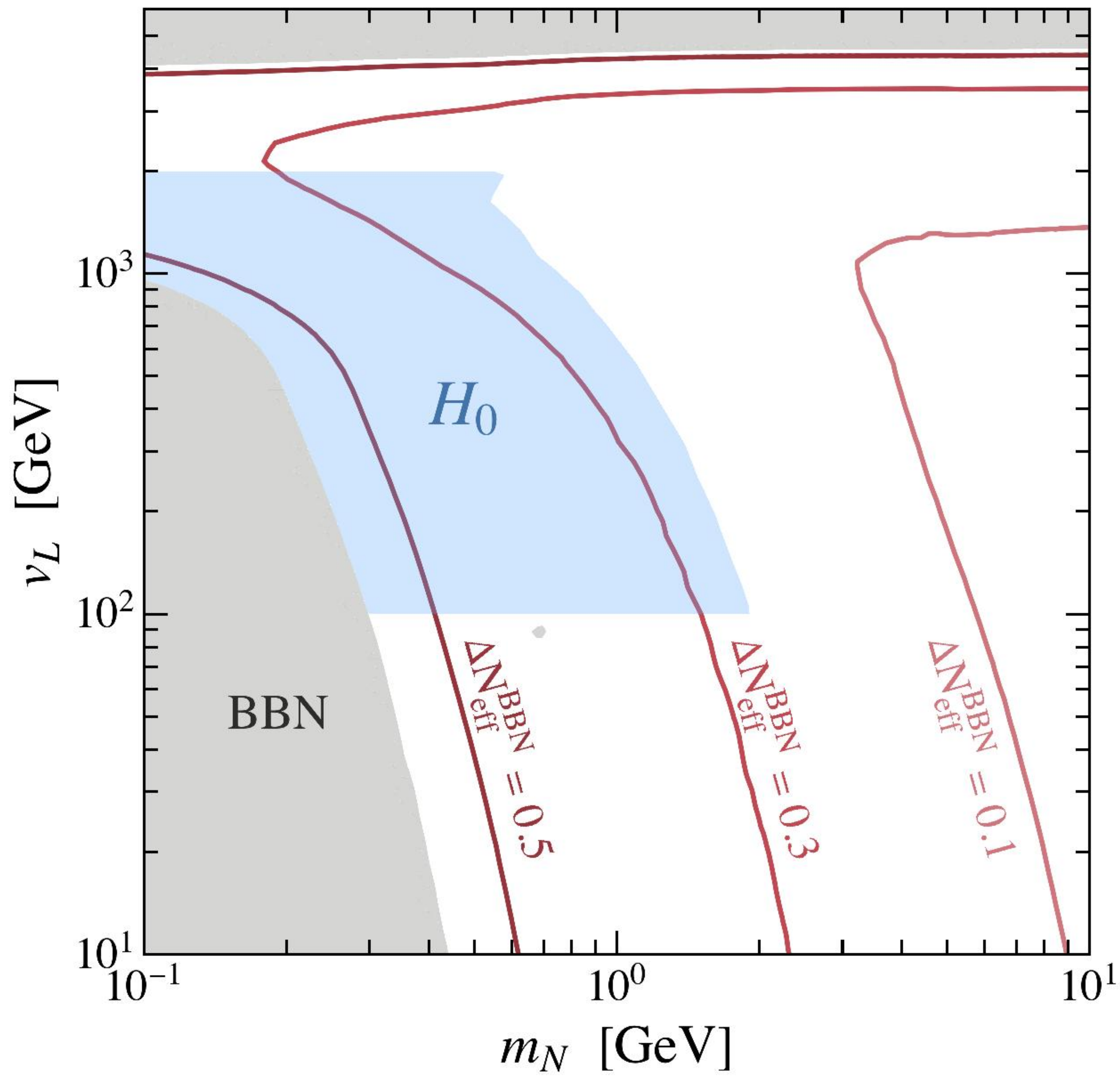
In the majoron model sterile neutrinos have a new decay mode



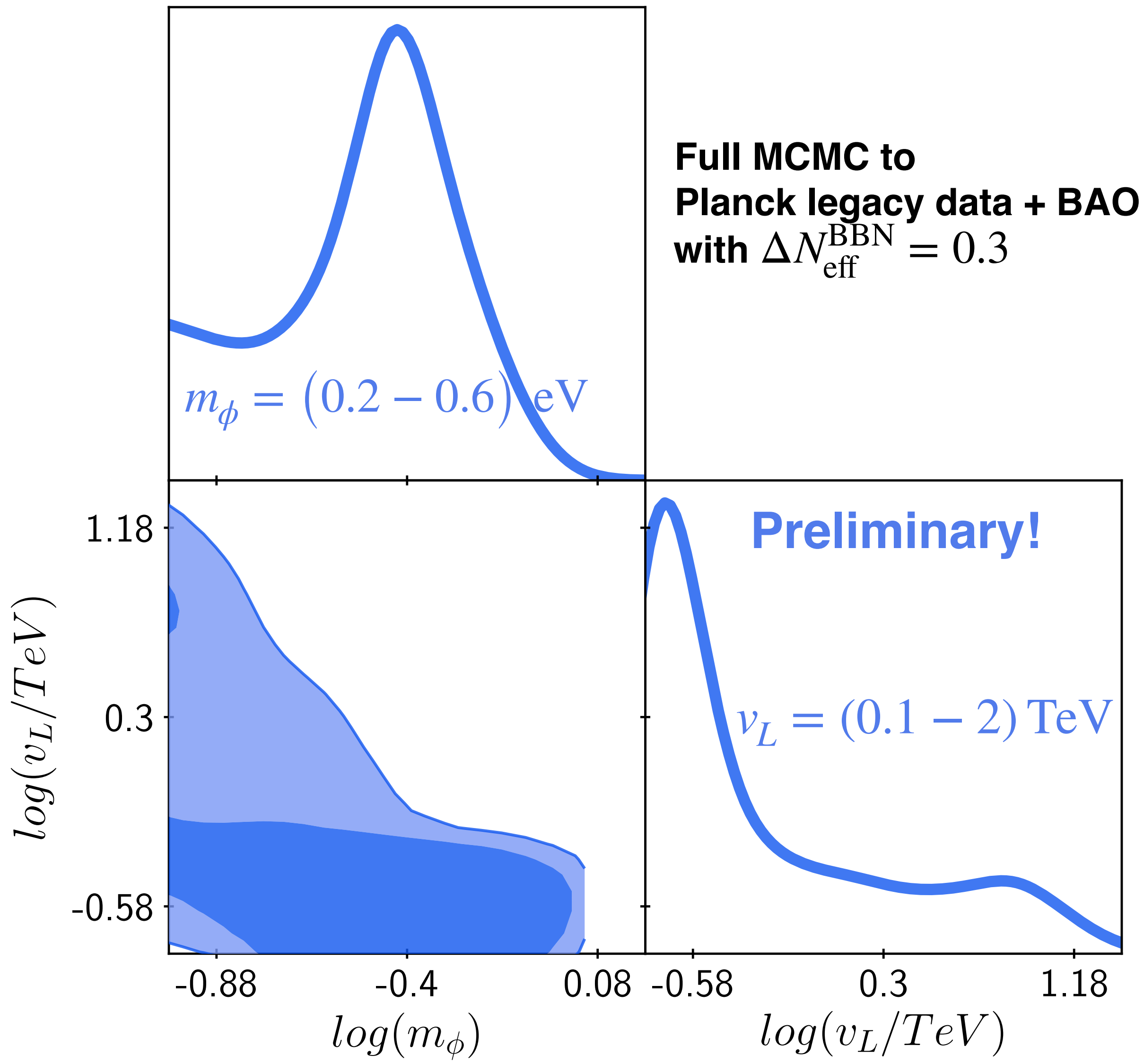
$$\frac{\Gamma(N \to \nu\phi)}{\Gamma(N \to \text{SM})} \simeq 4 \times 10^3 \left(\frac{1\,\text{GeV}}{M_N}\right)^2 \left(\frac{1\,\text{TeV}}{v_L}\right)^2$$

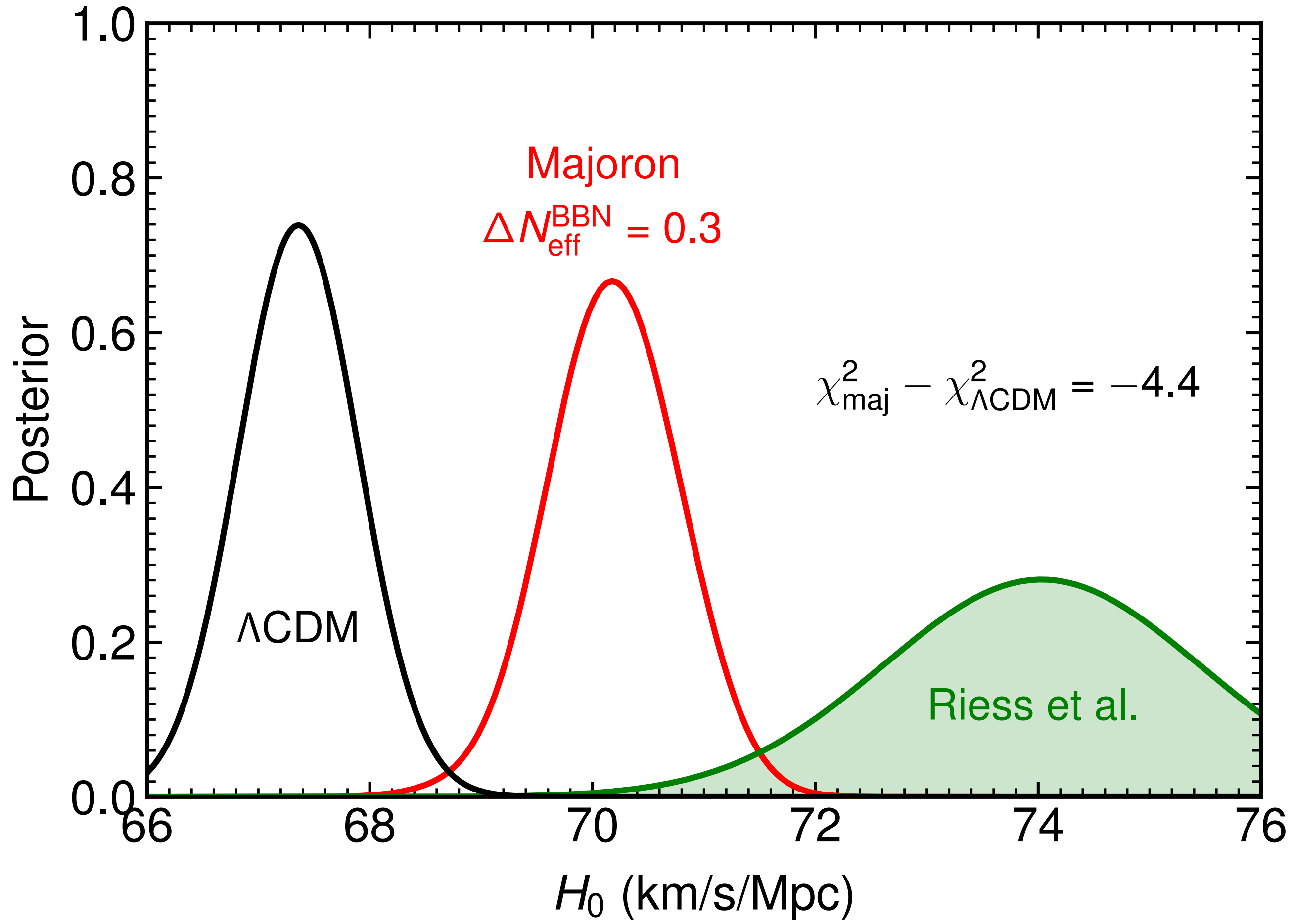


Parameter Space



Key Results





- **H_0 tension down to 2.5σ**

$$m_\phi = (0.2 - 0.6)\ \text{eV}$$
$$v_L = (0.1 - 2)\ \text{TeV}$$

- **Excellent fit to Planck data**

$$\Delta\chi^2 = \chi^2_{\rm maj} - \chi^2_{\Lambda\rm CDM}$$
$$\Delta\chi^2 = -4.4$$

Summary of Escudero & Witte 21'

- **ARS can work in the Majoron model for $v_L > 1\,\mathrm{GeV}$**

provided $|\lambda_{\phi H}| < 10^{-7} \frac{v_L}{1\,\mathrm{TeV}} \sqrt{\frac{10^5\,\mathrm{GeV}}{T_c}}$ **which is protected under RGE flow**

- **Sterile Neutrinos can provide just the right primordial majoron population**

- **A full Planck Legacy data analysis shows that:**

for $\Delta N_{\rm eff}^{\rm BBN} = 0.3$

$$m_\phi = \left(0.2 - 0.6\right)\,\mathrm{eV}$$

$$v_L = (0.1 - 2)\,\mathrm{TeV}$$

$$H_0 = (70.2 \pm 0.6)\,\mathrm{km/s/Mpc}$$

$$M_N = (0.2 - 2)\,\mathrm{GeV}$$

This makes the tension $4.4\sigma \to 2.5\sigma$ but with a better CMB fit than ΛCDM!

Conclusions

- **The Hubble Tension:**

  Could be pointing to physics beyond ΛCDM

  There are several neutrino related approaches

  Further data on the way: Gaia, Strong Lensing, GW, DESI ...

- **The Majoron**

  Can substantially relax the tension down to the level of 2.5σ

  Directly linked to the neutrino mass mechanism

  Mass can be understood from planck-scale effects

  Parameter space to solve the tension very well motivated: $v_L \sim v_H$

  The solution can be sourced by low-scale Leptogenesis!

Outlook

- **Could the $\Delta N_{\rm eff}^{\rm BBN} = 0.5$ case fully solve the tension?**

  We are investigating this at the moment!

- **Including Neutrino masses in the analysis**

  This can be relevant to the S_8 tension

  In preparation, Witte & Poulin

- **Performing an ARS Leptogenesis calculation**

  Never performed in the literature

  Regardless of what happens to H_0,
  $\Delta N_{\rm eff}$ can be a probe of Leptogenesis!

  In preparation, Ciscar, Escudero & Ibarra

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Sam Witte!

Time for Questions and Comments

Thank you for your attention!