The Hubble Tension:
A Particle Physics Perspective

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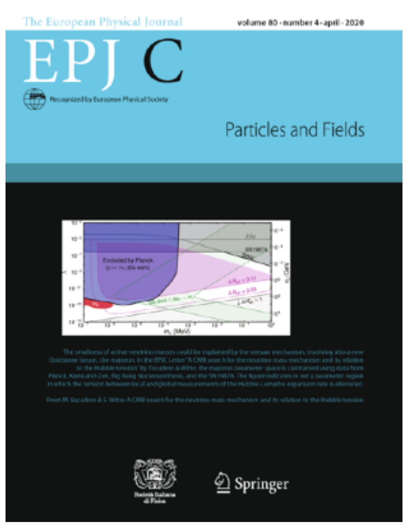
short review + original work based on:



ArXiv:1909.04044, EPJC 80 (2020) 4, 294
ArXiv:2004.01470, NuPhys19 Proceedings
ArXiv:2103.03249, EPJC 81 (2021) 6, 515

with Sam Witte

Indian Institute of Technology Mumbai
10-06-2022

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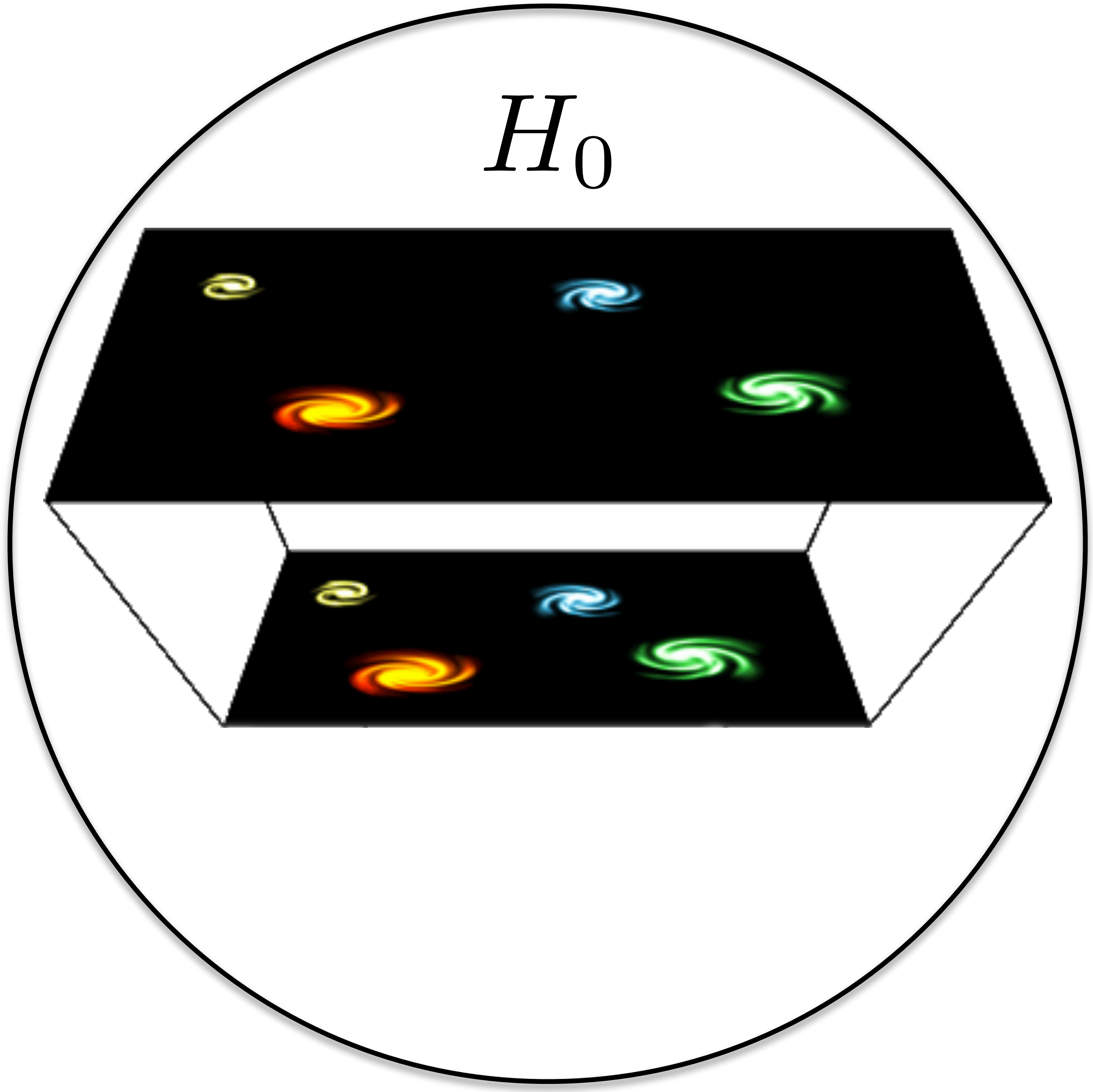


Riess *et al.* 2112.04510

Local Measurements

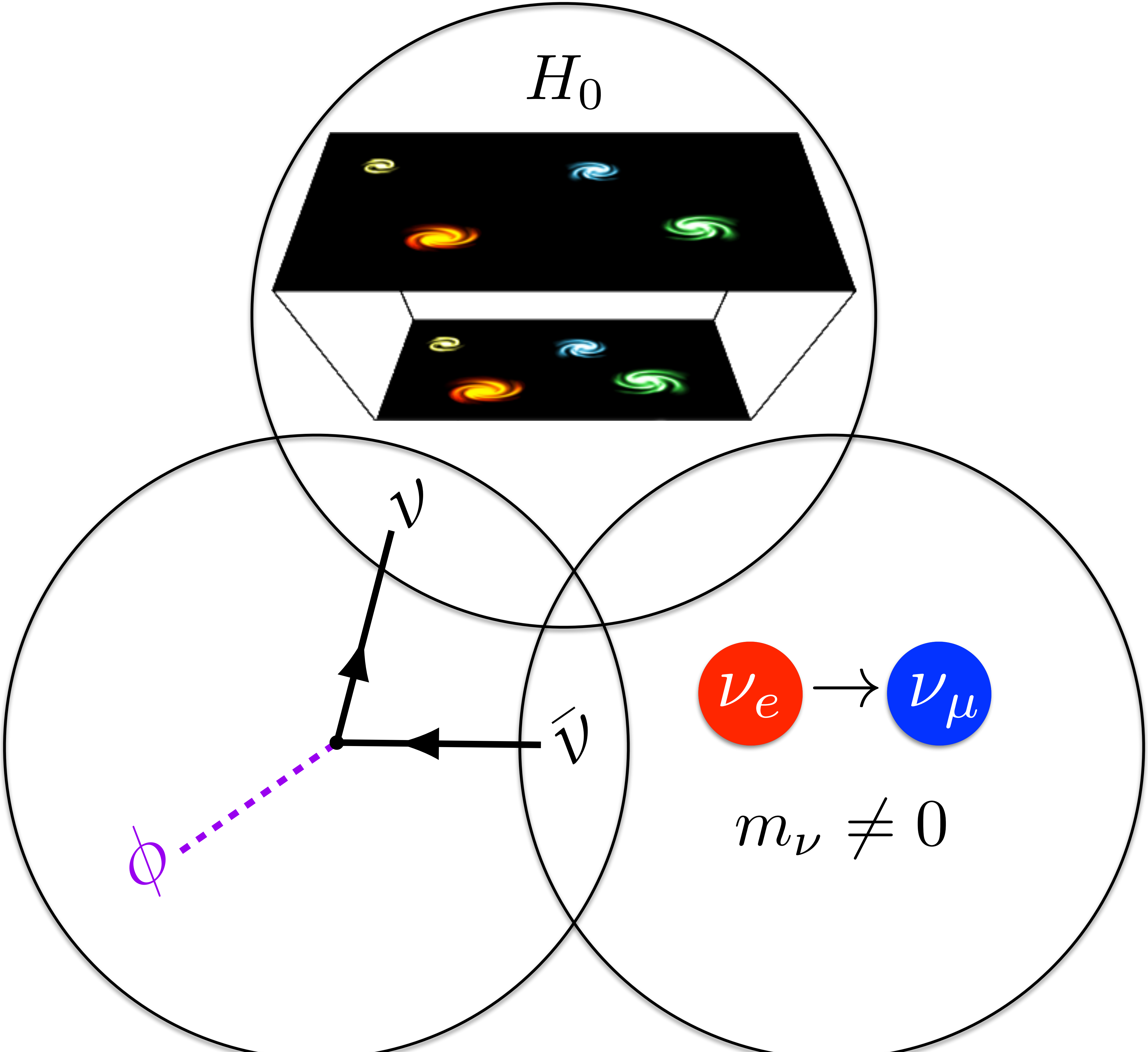
$$H_0 = 73.04 \pm 1.04\,\mathrm{km/s/Mpc}$$

5σ tension within ΛCDM!

Planck 2018 1807.06209

ΛCDM Prediction

$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$



H_0
ν
$\bar{\nu}$
ϕ
$\nu_e \rightarrow \nu_\mu$
$m_\nu \neq 0$

Outline

1) The Hubble Tension

- Observational Evidence
- Brief review of Models

2) The Majoron as a solution to the H_0 tension

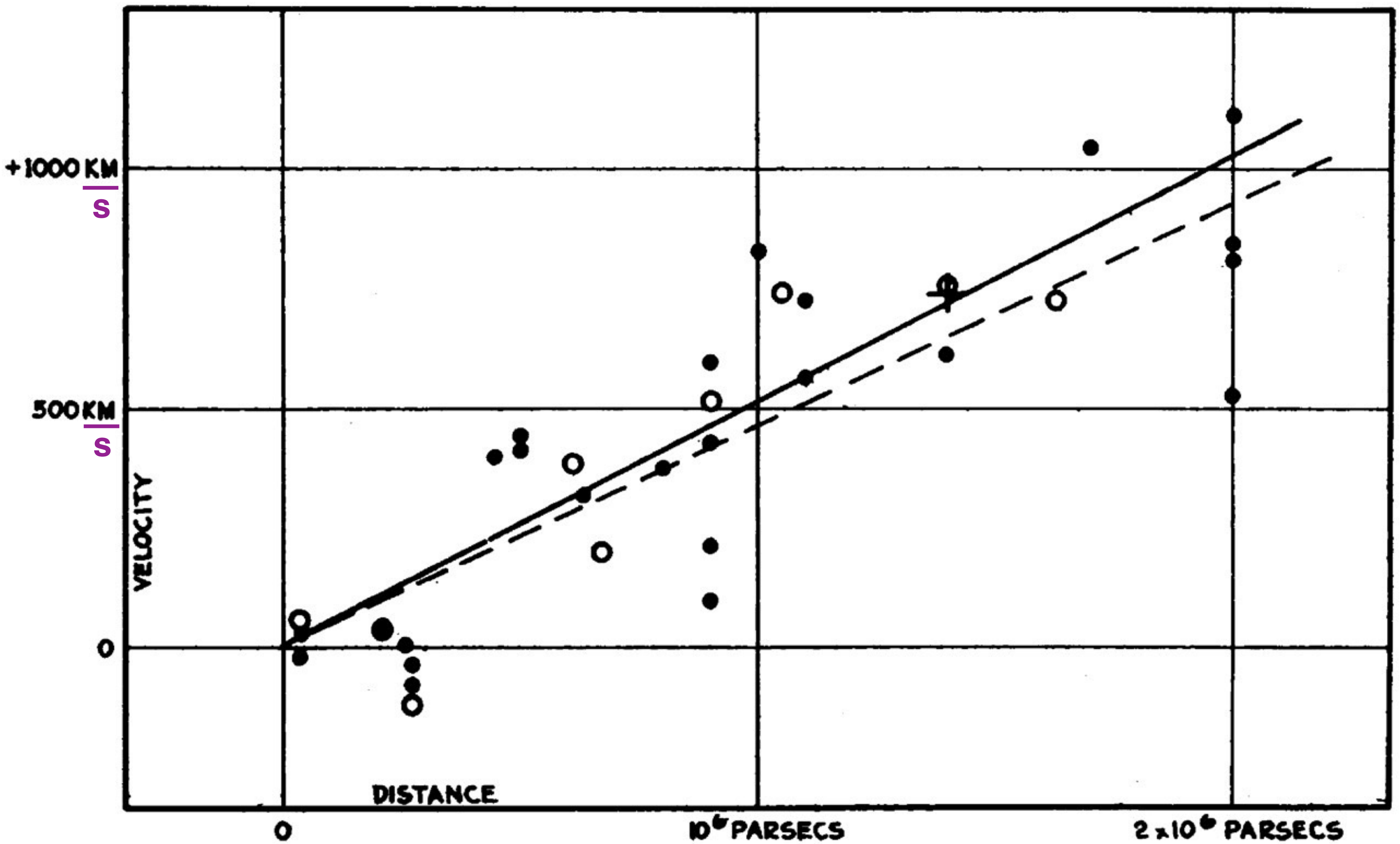
- The singlet Majoron model
- Majoron Cosmology

3) Conclusions and Outlook

The Hubble Law

The Universe is expanding!

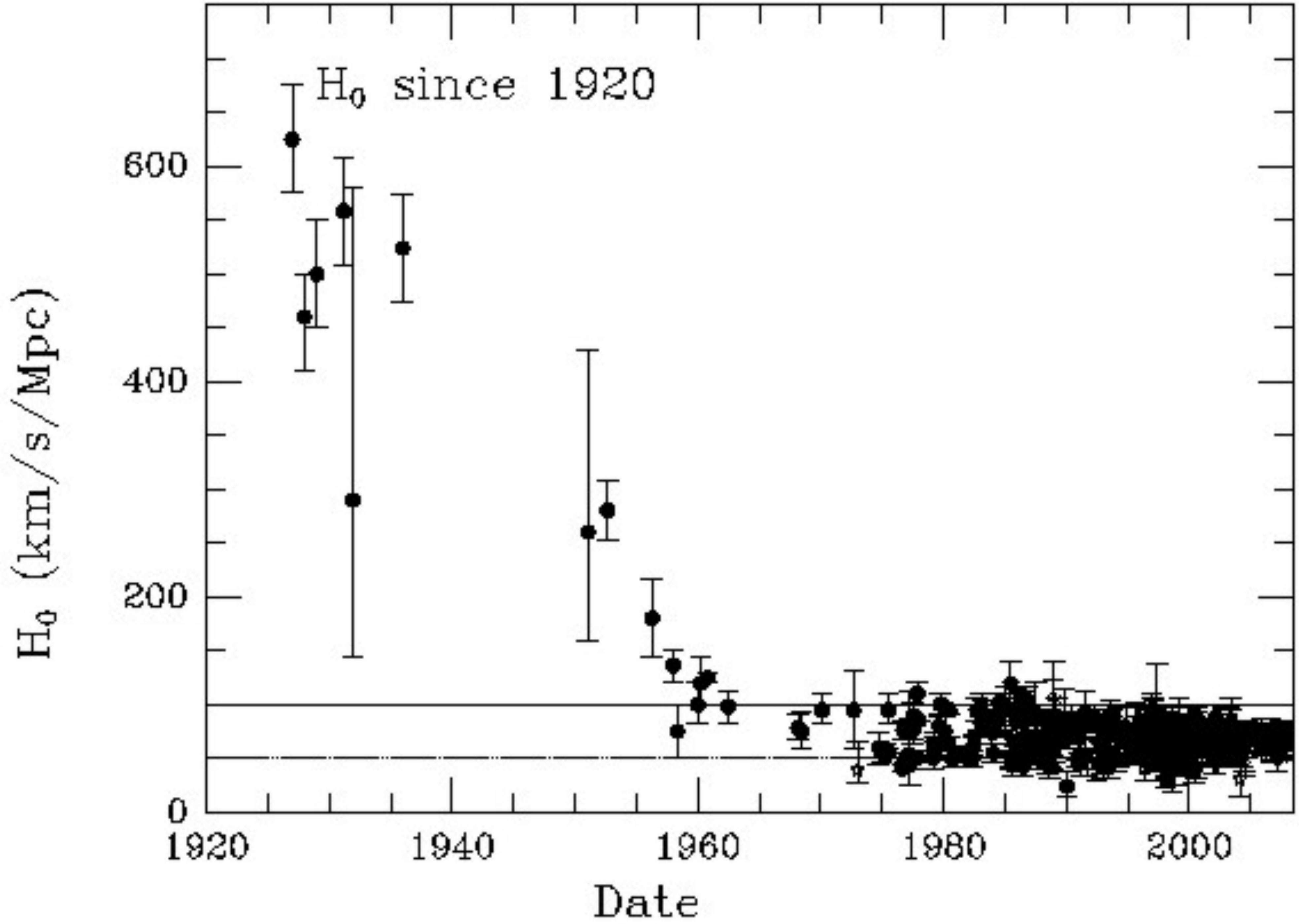
Hubble (1929): $v = H_0\, d$



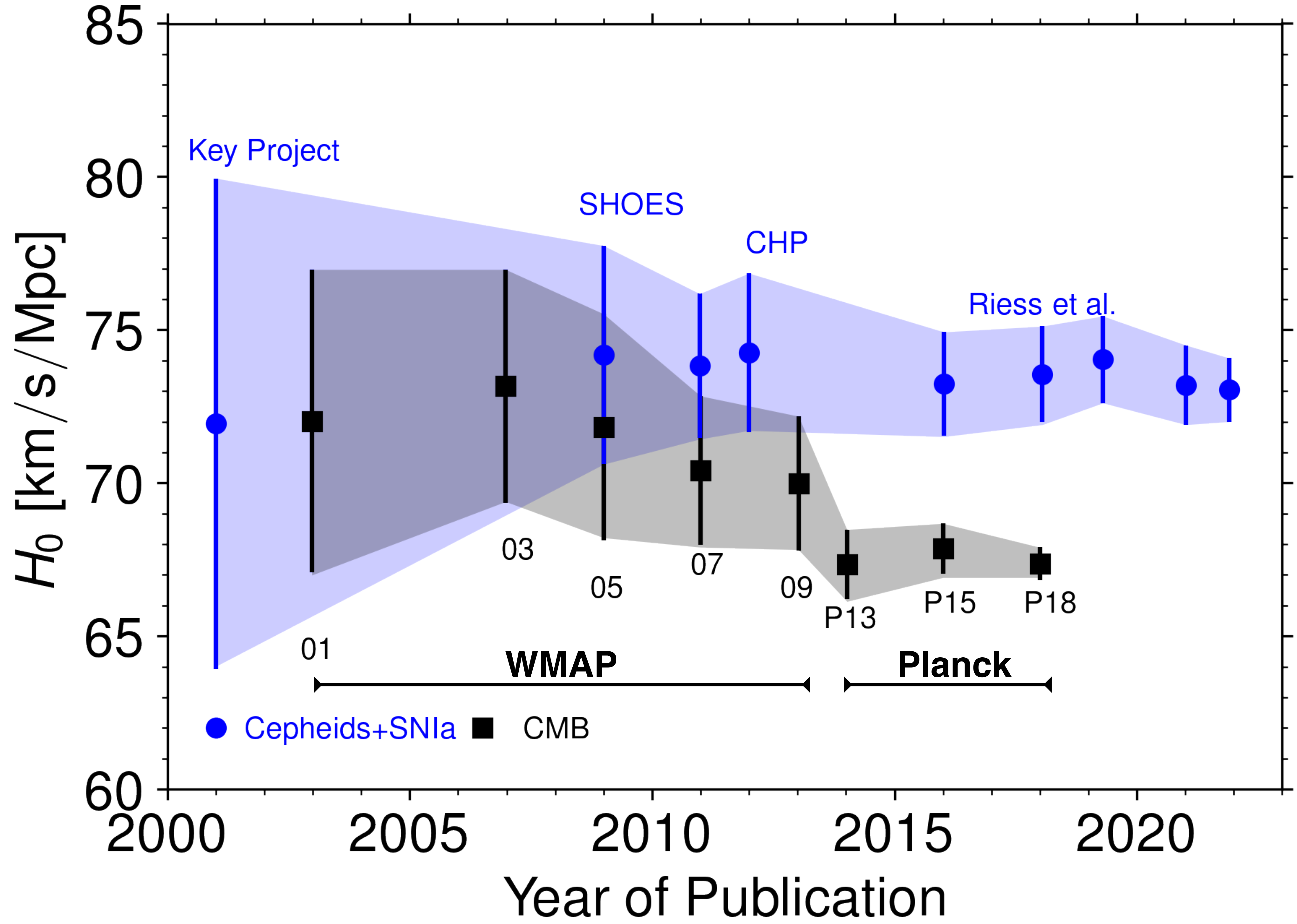
The Hubble Tension in Perspective

Hubble law (1929): $v = H_0 \, d$

https://lweb.cfa.harvard.edu/~dfabricant/huchra/hubble/



The Hubble Tension in Perspective



The Hubble Tension

- **The Hubble Tension:**

$$H_0 = 73.04 \pm 1.04\,\mathrm{km/s/Mpc}$$ **Riess *et al.* 2112.04510**

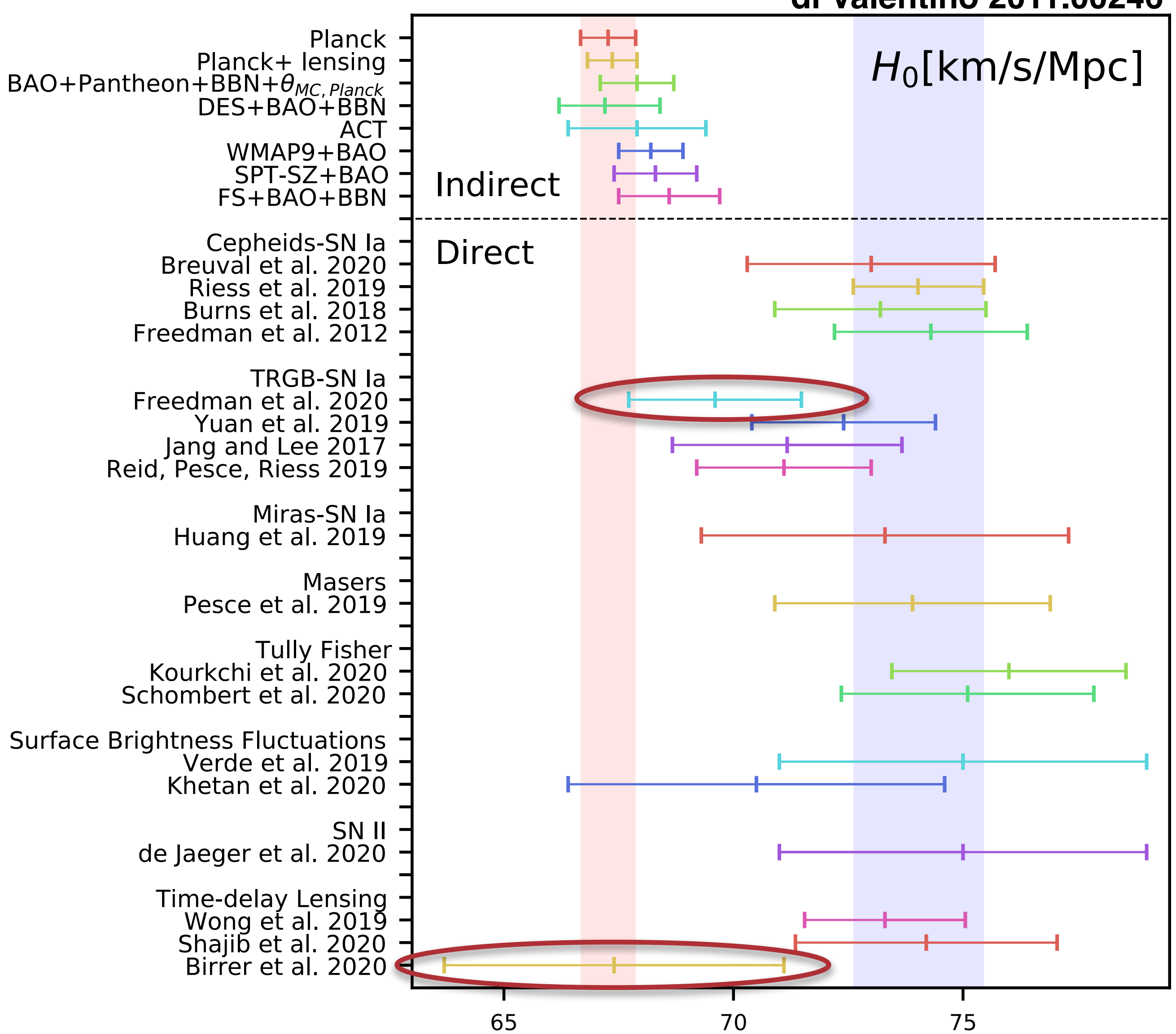
$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$ **Planck 2018 1807.06209**

5σ 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 are among the most precise and they point to $H_0 \sim (73 \pm 1)\,\mathrm{km/s/Mpc}$**
  - **Some direct measurements do point to smaller values, Freedman et al. 20' and Birrer et al. 20'**

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:** **See 2103.01183 by di Valentino et al. for a review (over 1000 references …)**

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

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

The Hubble Tension: Theory

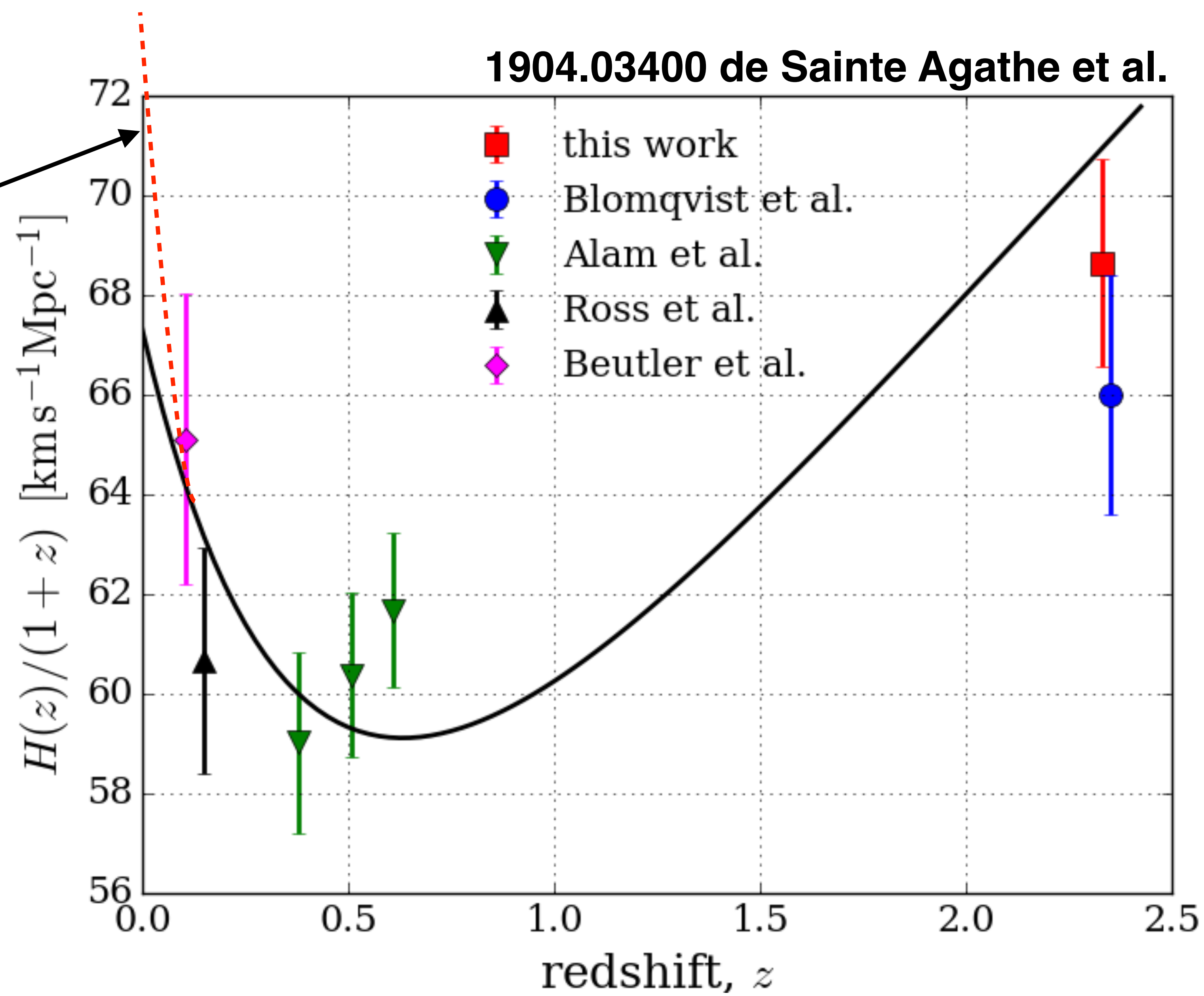
Why late Universe modifications do not work?

see e.g. 2103.08723 by Efstathiou

Because type Ia SN and Baryon Acoustic Oscillations constrain the expansion history of the Universe at $z < 2.5$ and they agree with the predictions of ΛCDM

This would not work!

1904.03400 de Sainte Agathe et al.



(H_0 is measured locally, at $z < 0.15$)

The Hubble Tension: Theory

- **Why Early Universe modifications could work?**

Because the CMB does not measure H_0 directly!

Planck measures the positions of the peaks: $\theta_s \equiv r_s / D_M(z_\star)$

(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

Model Building task: **The game is to make r_s smaller by ~8% so that H_0 can be the one reported by Riess. But, not spoiling the fit to ultra precise CMB data from Planck!**

simplest:

Knox and Millea 1908.03663

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

Dark Radiation as a solution?

😃 **By far the simplest possibility, we have $\mathcal{O}(10^3)$ models that can do it:**

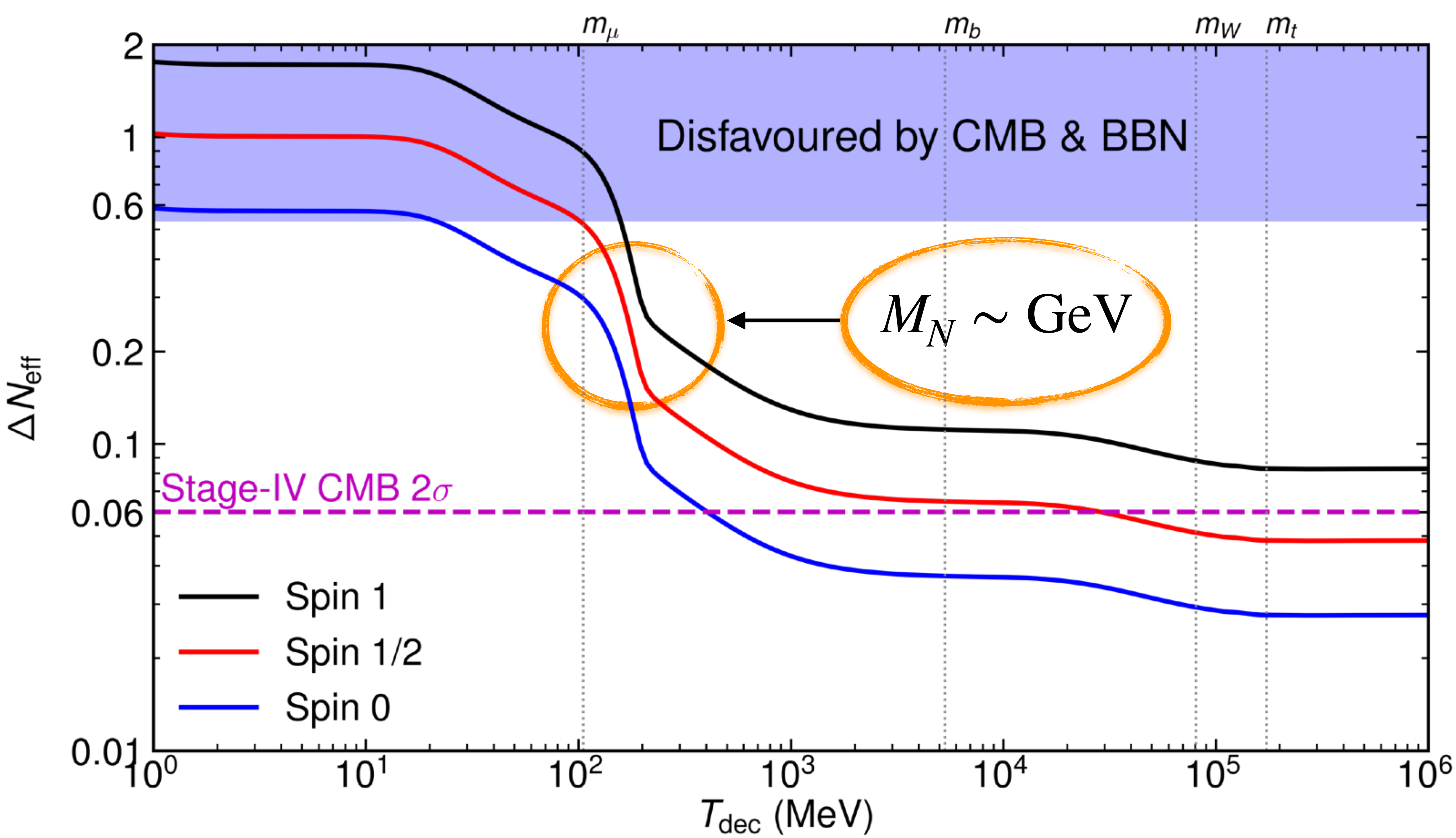
$$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM} > 0 \qquad N_{\rm eff}^{\rm SM} \simeq 3.04$$

Editors' Suggestion

Goldstone Bosons as Fractional Cosmic Neutrinos

Steven Weinberg
Phys. Rev. Lett. **110**, 241301 – Published 10 June 2013

Typically interpreted as additional massless dark radiation as a relic from the Big Bang



Neff as a solution to the H_0 Tension?

- How large would $\Delta N_{\rm eff}$ need to be to solve the tension?

$$\boxed{H_0 \simeq \left[67.4 + 6.2\,\Delta N_{\rm eff}\right]\ \mathrm{km/s/Mpc}}$$

Vagnozzi 1907.07569

😃 $\Delta N_{\rm eff} \simeq 1$ would yield the value of H_0 reported by Riess

😐 Problem 1) BBN constraints indicate that: $\Delta N_{\rm eff}^{\rm BBN} < 0.5$ **Pisanti et al. 2011.11537**

- Constraints are dominated by Helium measurements (that could suffer from systematics)
- In many models $\Delta N_{\rm eff}^{\rm CMB} \neq \Delta N_{\rm eff}^{\rm BBN}$

☹️ Problem 2) Within the framework of ΛCDM Planck is compatible with $N_{\rm eff} \simeq 3$

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

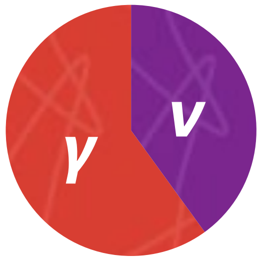
Planck 2018

Maybe there is an effect that can compensate a large Neff at the level of the CMB fit?

😃 Neutrinos interactions can lead to a relevant impact on the CMB spectra

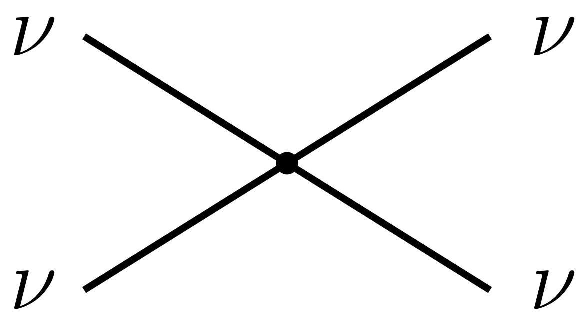
Bashinsky and Seljak astro-ph/0310198

$$\delta G_{\mu\nu} = 8\pi G\,\delta T_{\mu\nu}$$



Neutrinos and the Hubble Tension

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

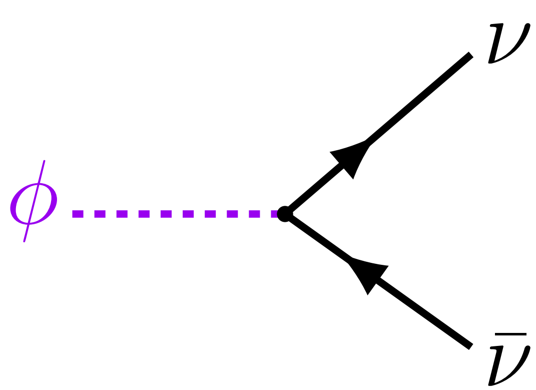


H_0 tension solved if TEEE data is ignored

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



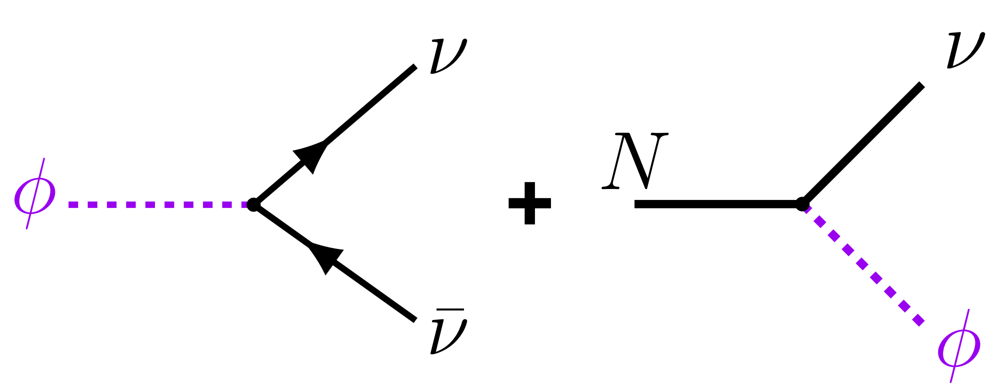
H_0 tension from 4.4σ to 2.5σ

CMB fit is not degraded

Direct connection with Seesaw

Ad hoc $\Delta N_{\rm eff} \sim 0.5$

- **Primordial population of light scalars** Escudero & Witte 2103.03249



Sterile neutrinos can source $\Delta N_{\rm eff} \sim 0.4$

Sterile neutrinos can lead to Leptogenesis

H_0 tension from 5σ to 2.5σ

The Hubble Tension: Theory

- **Hundreds of Models in the market** **See 2103.01183 by di Valentino et al.**

Most of them do not work well. They either lead to a bad CMB fit or do not shift H_0 enough

Schöneberg et al. 2107.10291: *The H_0 Olympics: A fair ranking of proposed models*

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X

How large is the Hubble tension?
small values here are better!

How good is the CMB fit?
negative values are good here!

The Hubble Tension: Theory

- **Hundreds of Models in the market** **See 2103.01183 by di Valentino et al.**

Most of them do not work well. They either lead to a bad CMB fit or do not shift H_0 enough

Schöneberg et al. 2107.10291: *The H_0 Olympics: A fair ranking of proposed models*

best performance:

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.9σ	✗	-4.60	-2.60	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.6σ	✗	-3.77	-1.77	✗	✗
DR-DM	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-7.82	-3.82	✗	✗
mixed DR	2	-19.388 ± 0.026	3.2σ	3.7σ	✗	-6.40	-2.40	✗	✗
SIν+DR	3	-19.440 ± 0.038	3.7σ	3.9σ	✗	-3.56	2.44	✗	✗
Majoron	3	-19.380 ± 0.027	3.0σ	2.9σ	✓	-13.74	-7.74	✓	✓ ②
primordial B	1	-19.390 ± 0.018	3.5σ	3.5σ	✗	-10.83	-8.83	✓	✓ ③
varying m_e	1	-19.391 ± 0.034	2.9σ	3.2σ	✗	-9.87	-7.87	✓	✓ ③
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.7σ	✓	-16.11	-12.11	✓	✓ ①
EDE	3	-19.390 ± 0.016	3.6σ	1.6σ	✓	-20.80	-14.80	✓	✓ ②
NEDE	3	-19.380 ± 0.021	3.2σ	2.0σ	✓	-17.70	-11.70	✓	✓ ②
CPL	2	-19.400 ± 0.016	3.9σ	4.1σ	✗	-4.23	-0.23	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.0σ	✓	4.76	4.76	✗	✗
MPEDE	1	-19.400 ± 0.022	3.6σ	4.0σ	✗	-2.21	-0.21	✗	✗
DM $\to$ DR+WDM	2	-19.410 ± 0.013	4.2σ	4.4σ	✗	-4.18	-0.18	✗	✗
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.2σ	✗	0.11	4.11	✗	✗

- **None of them fully solves the Hubble tension!**
- **Most of those that can ameliorate the tension are not theoretically well motivated**

The Hubble Tension: Theory

A critical review of the best performing models

Schöneberg et al. 2107.10291: *The H_0 Olympics: A fair ranking of proposed models*

Model	$\Delta N_{\mathrm{param}}$	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist
Majoron	3	-19.380 ± 0.027	3.0σ	2.9σ	✓	-13.74	-7.74	✓	✓ 2
primordial B	1	-19.390 ± 0.018	3.5σ	3.5σ	X	-10.83	-8.83	✓	✓ 3
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NEDE	3	-19.380 ± 0.021	3.2σ	2.0σ	✓	-17.70	-11.70	✓	✓ 2

- **Primordial magnetic fields & $m_e(t) + \Omega_k$**

  The idea here is that recombination happens earlier than in ΛCDM by either

  a) **using primordial magnetic fields of ~ 1 nGauss on kpc scales** [Jedamzik & Pogosian 2004.09487]

  b) **enhancing $m_e(t)$ at recombination by ~ 2%** [Hart & Chluba 1912.03986]

  😐 **Good exercises, not much theoretical motivation for $m_e(t)$ but maybe yes for B fields.**

- **Early Dark Energy** Poulin, Smith, Karwal, Kamionkowski 1811.04083 Agrawal, Cyr-Racine, Pinner, Randall 1904.01016

  The idea is that there is an early dark energy component just acting right before recombination

  This can be done with a very light scalar field with $m_\phi \sim 10^{-27}\,\mathrm{eV}$ that yields $f_{\mathrm{EDE}} \sim 10\,\%$ but with a very particular potential:

  $$V_\phi \sim m^2 f^2 \left[1 - \cos\phi/f\right]^3 \sim m^2\phi^6/f^4$$

  😐 **Highly unclear where such potential could come from and there is a coincidence problem …**

- **New Early Dark Energy**

  Another possibility is to trigger a 1st order phase transition at $T \sim \mathrm{eV}$ [Niedermann & Sloth 1910.10739]

  😐 **It appears rather involved … Dark gauge sector, DM, neutrinos, inverse seesaw…** see [Niedermann & Sloth 2112.00759, 2112.00770]

The Hubble Tension

1) Observational evidence

There is strong observational evidence from Cepheids+SNIa

However, it is still just a tension. It needs to be confirmed by other methods

We expect significant improvements in ~3-4 years, particularly with upcoming data from Gaia & the James Webb telescope

2) Theoretical modeling

Despite the strong efforts, we have no perfect model so far

Most of the models lack theoretical motivation

My personal view as a particle physicist:

Exciting opportunity to try to learn about fundamental physics

Mid Seminar Pause =)

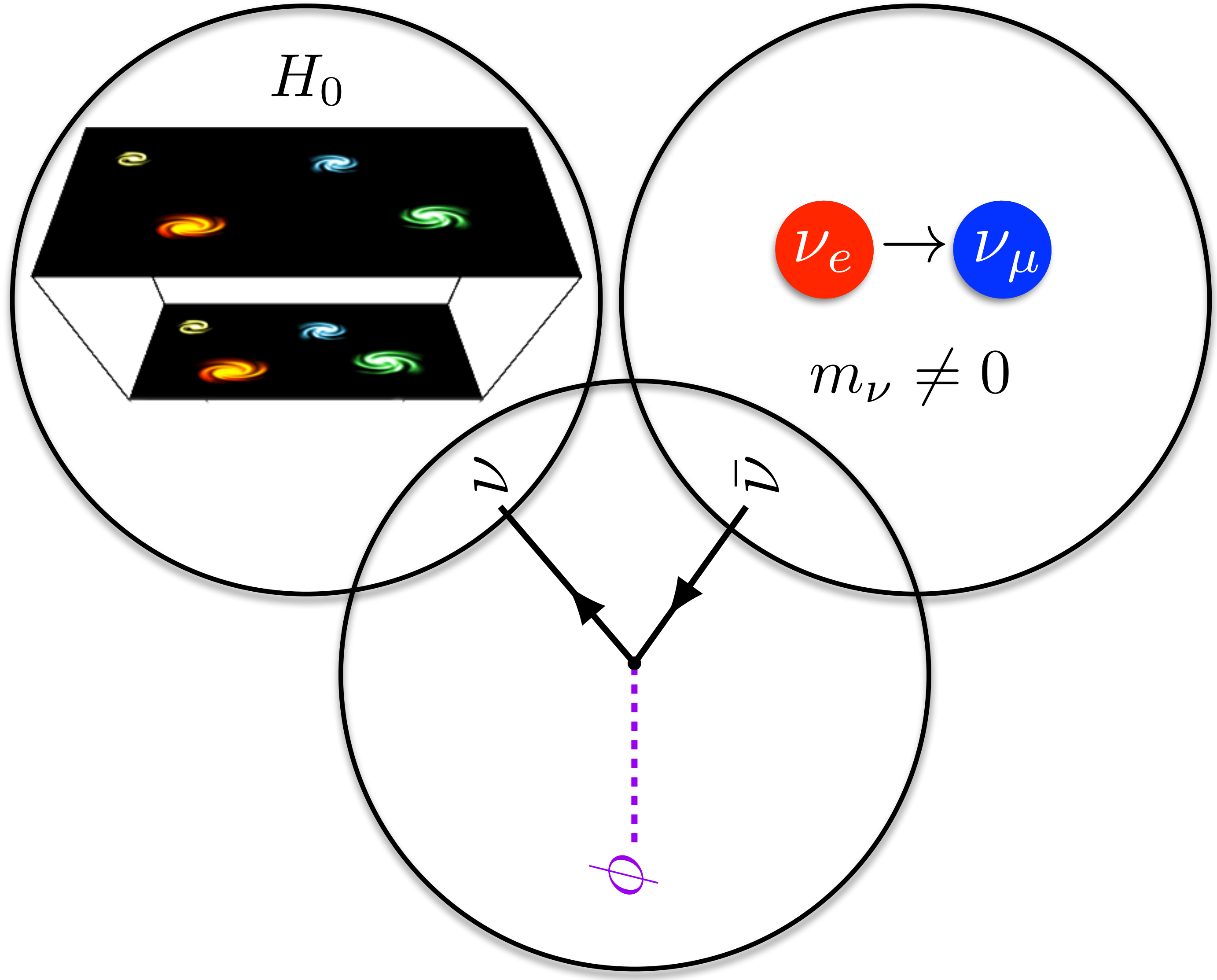
Questions?

Comments?

Criticism?

All are most welcome!

The Idea



What is the Majoron?

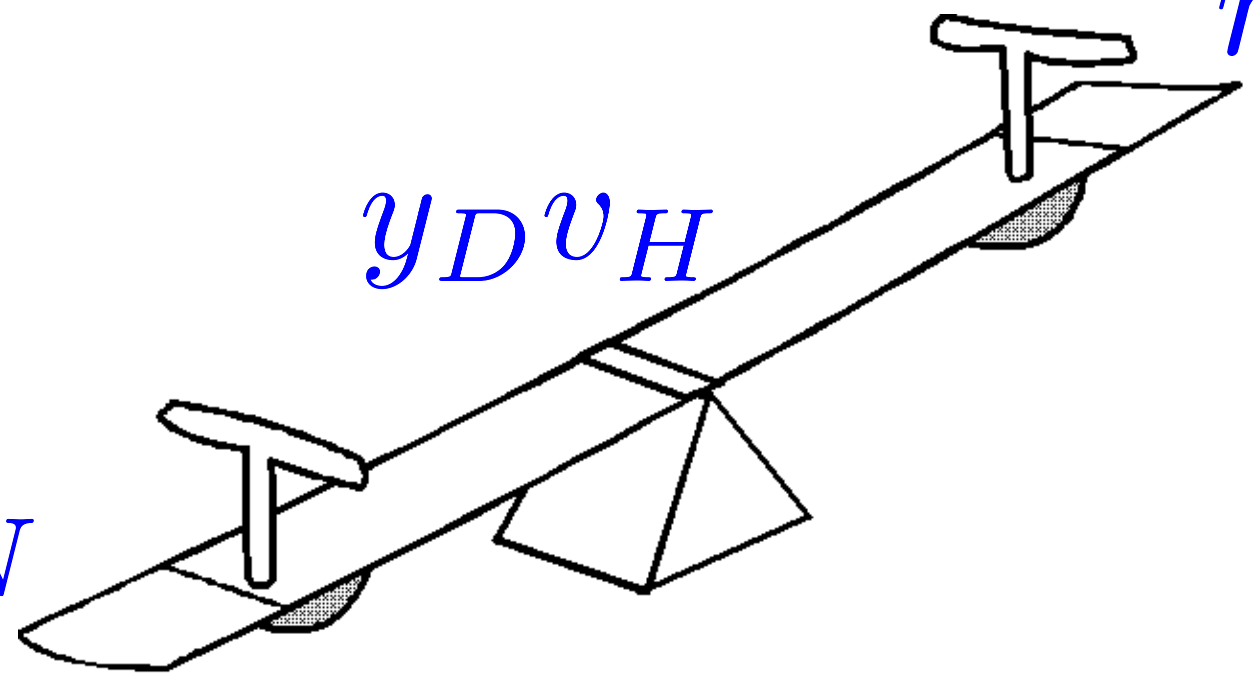
What are its properties and its cosmology?

Why can it address the Hubble tension?

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

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

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

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

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

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

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

Interactions

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

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

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

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

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

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

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

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

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

Relevant parameter space

Parameter Space

$10^{-15} \lesssim \lambda < 10^{-3}$

$0.1\,\mathrm{eV} < m_\phi < \mathrm{MeV}$

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

Key coincidence!!

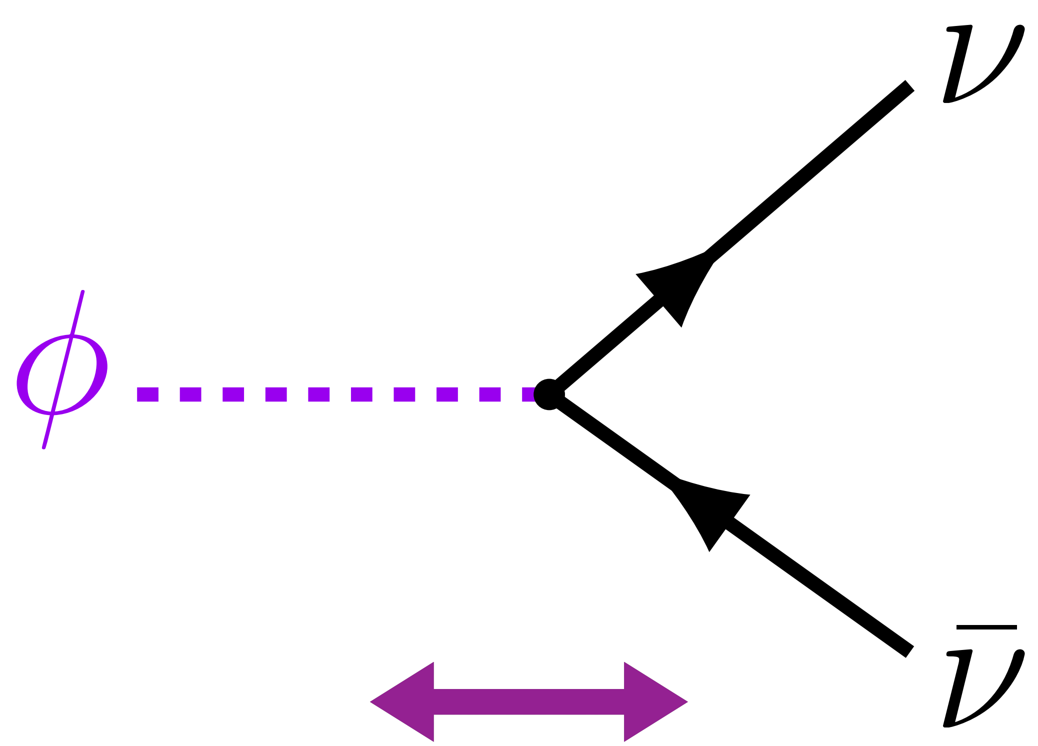
$\tau_\phi \sim t_{\rm rec}/10$

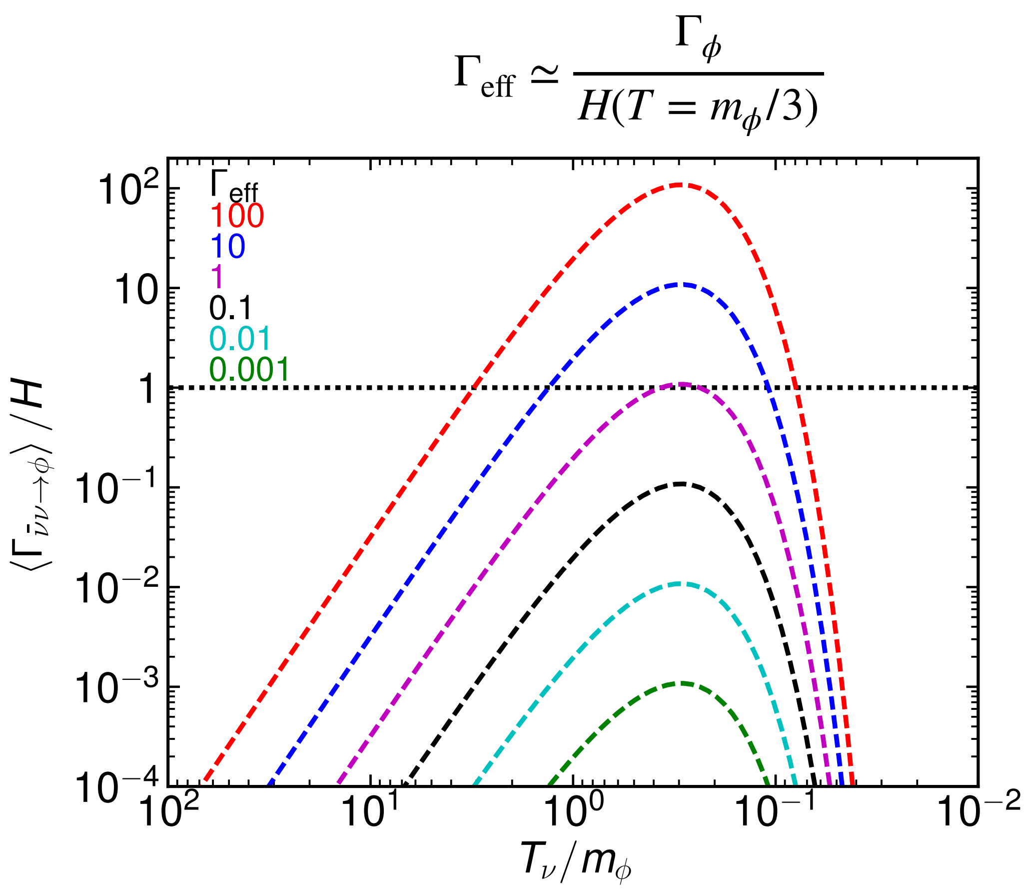
for $m_\phi \sim \mathrm{eV},\, v_L \sim 1\,\mathrm{TeV}$

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

Cosmological Implications

Only Relevant Process: provided $\Gamma_\phi \geq H(T_\nu = m_\phi/3)$



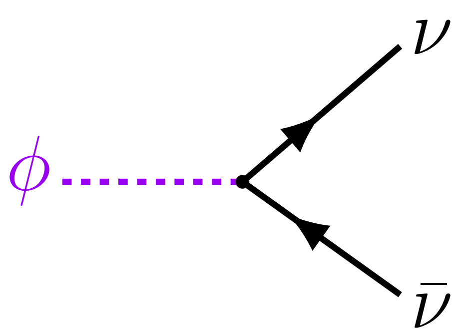


Two main effects:

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

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

Cosmological Analysis



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

Background

We solve the Boltzmann equation of the neutrino-majoron system

Escudero 1812.05605 & 2001.04466

$$
\begin{aligned}
\frac{dT_\phi}{dt} &= \frac{1}{\frac{\partial n_\phi}{\partial \mu_\phi}\frac{\partial \rho_\phi}{\partial T_\phi} - \frac{\partial n_\phi}{\partial T_\phi}\frac{\partial \rho_\phi}{\partial \mu_\phi}} \left[-3H\left((p_\phi+\rho_\phi)\frac{\partial n_\phi}{\partial \mu_\phi} - n_\phi \frac{\partial \rho_\phi}{\partial \mu_\phi}\right) + \frac{\partial n_\phi}{\partial \mu_\phi}\frac{\delta \rho_\phi}{\delta t} - \frac{\partial \rho_\phi}{\partial \mu_\phi}\frac{\delta n_\phi}{\delta t}\right] \\
\frac{d\mu_\phi}{dt} &= \frac{-1}{\frac{\partial n_\phi}{\partial \mu_\phi}\frac{\partial \rho_\phi}{\partial T_\phi} - \frac{\partial n_\phi}{\partial T_\phi}\frac{\partial \rho_\phi}{\partial \mu_\phi}} \left[-3H\left((p_\phi+\rho_\phi)\frac{\partial n_\phi}{\partial T_\phi} - n_\phi \frac{\partial \rho_\phi}{\partial T_\phi}\right) + \frac{\partial n_\phi}{\partial T_\phi}\frac{\delta \rho_\phi}{\delta t} - \frac{\partial \rho_\phi}{\partial T_\phi}\frac{\delta n_\phi}{\delta t}\right] \\
\frac{dT_\nu}{dt} &= \frac{1}{\frac{\partial n_\nu}{\partial \mu_\nu}\frac{\partial \rho_\nu}{\partial T_\nu} - \frac{\partial n_\nu}{\partial T_\nu}\frac{\partial \rho_\nu}{\partial \mu_\nu}} \left[-3H\left((p_\nu+\rho_\nu)\frac{\partial n_\nu}{\partial \mu_\nu} - n_\nu \frac{\partial \rho_\nu}{\partial \mu_\nu}\right) - \frac{\partial n_\nu}{\partial \mu_\nu}\frac{\delta \rho_\phi}{\delta t} + 2\frac{\partial \rho_\nu}{\partial \mu_\nu}\frac{\delta n_\phi}{\delta t}\right] \\
\frac{d\mu_\nu}{dt} &= \frac{-1}{\frac{\partial n_\nu}{\partial \mu_\nu}\frac{\partial \rho_\nu}{\partial T_\nu} - \frac{\partial n_\nu}{\partial T_\nu}\frac{\partial \rho_\nu}{\partial \mu_\nu}} \left[-3H\left((p_\nu+\rho_\nu)\frac{\partial n_\nu}{\partial T_\nu} - n_\nu \frac{\partial \rho_\nu}{\partial T_\nu}\right) - \frac{\partial n_\nu}{\partial T_\nu}\frac{\delta \rho_\phi}{\delta t} + 2\frac{\partial \rho_\nu}{\partial T_\nu}\frac{\delta n_\phi}{\delta t}\right] \\
\frac{dT_\gamma}{dt} &= -H\, T_\gamma\,,
\end{aligned}
$$

Perturbations

We use the relaxation time approximation to model the effects of interactions in the perturbations:

$$
\begin{aligned}
\dot{\delta}_{\nu\phi} &= -\frac{4}{3}\theta_{\nu\phi} - \frac{2}{3}\dot{h}\,, \\
\dot{\theta}_{\nu\phi} &= k^2\left(\frac{1}{4}\delta_{\nu\phi} - \sigma_{\nu\phi}\right)\,, \\
\dot{F}_{\nu\phi 2} &= 2\dot{\sigma}_{\nu\phi} = \frac{8}{15}\theta_{\nu\phi} - \frac{3}{5}kF_{\nu\phi\,3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} - 2a\Gamma\sigma_{\nu\phi}\,, \\
\dot{F}_{\nu\phi\,\ell} &= \frac{k}{2\ell+1}\left[\ell\, F_{\nu\phi\,(\ell-1)} - (\ell+1)F_{\nu\phi\,(\ell+1)}\right] - a\Gamma F_{\nu\phi\,\ell}\,,\ \ \ell \geq 3\,.
\end{aligned}
$$

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

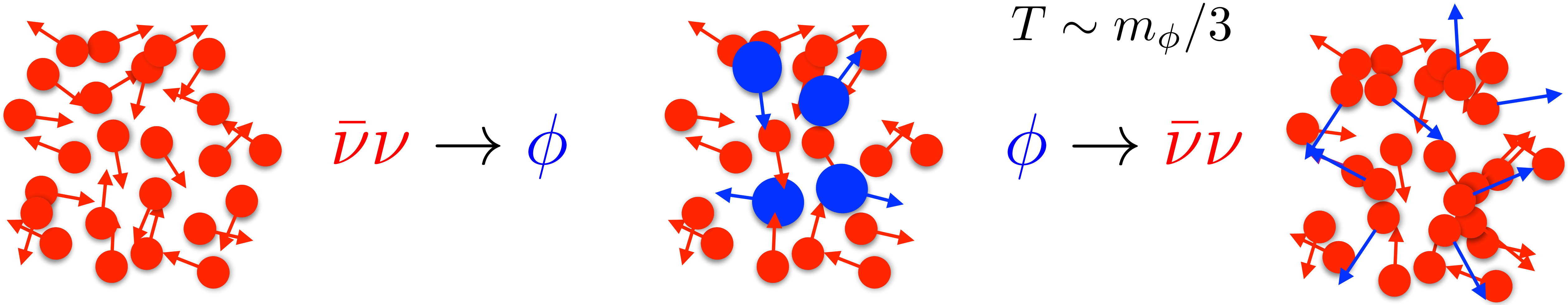
- **We include in CLASS all of these effects**

Cosmological Implications

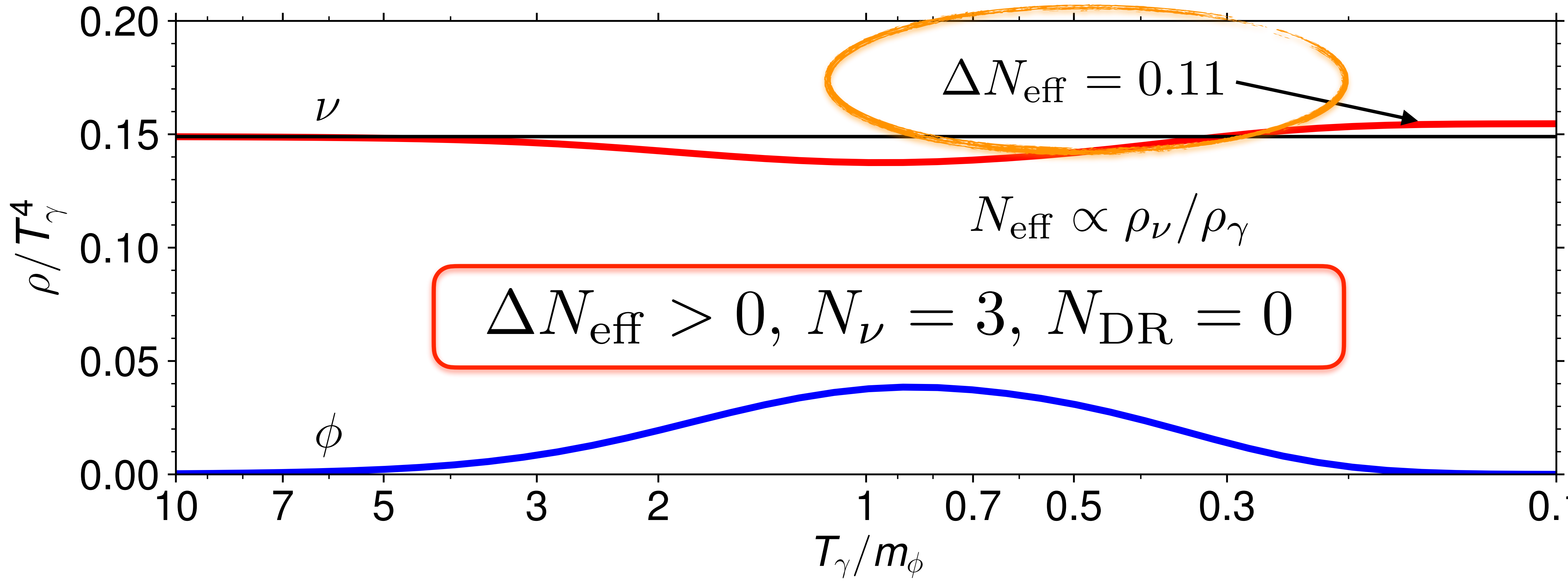
$T \gg m_\phi$ **Production** **Equilibrium** **Decay** **Final State**

$T \sim m_\phi/3$

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



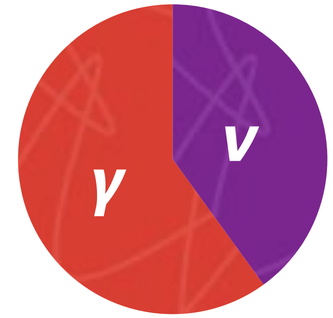
$$\Gamma_\phi \simeq H(T_\nu = m_\phi/3)$$



$$\boxed{\Delta N_{\rm eff} > 0,\ N_\nu = 3,\ N_{\rm DR} = 0}$$

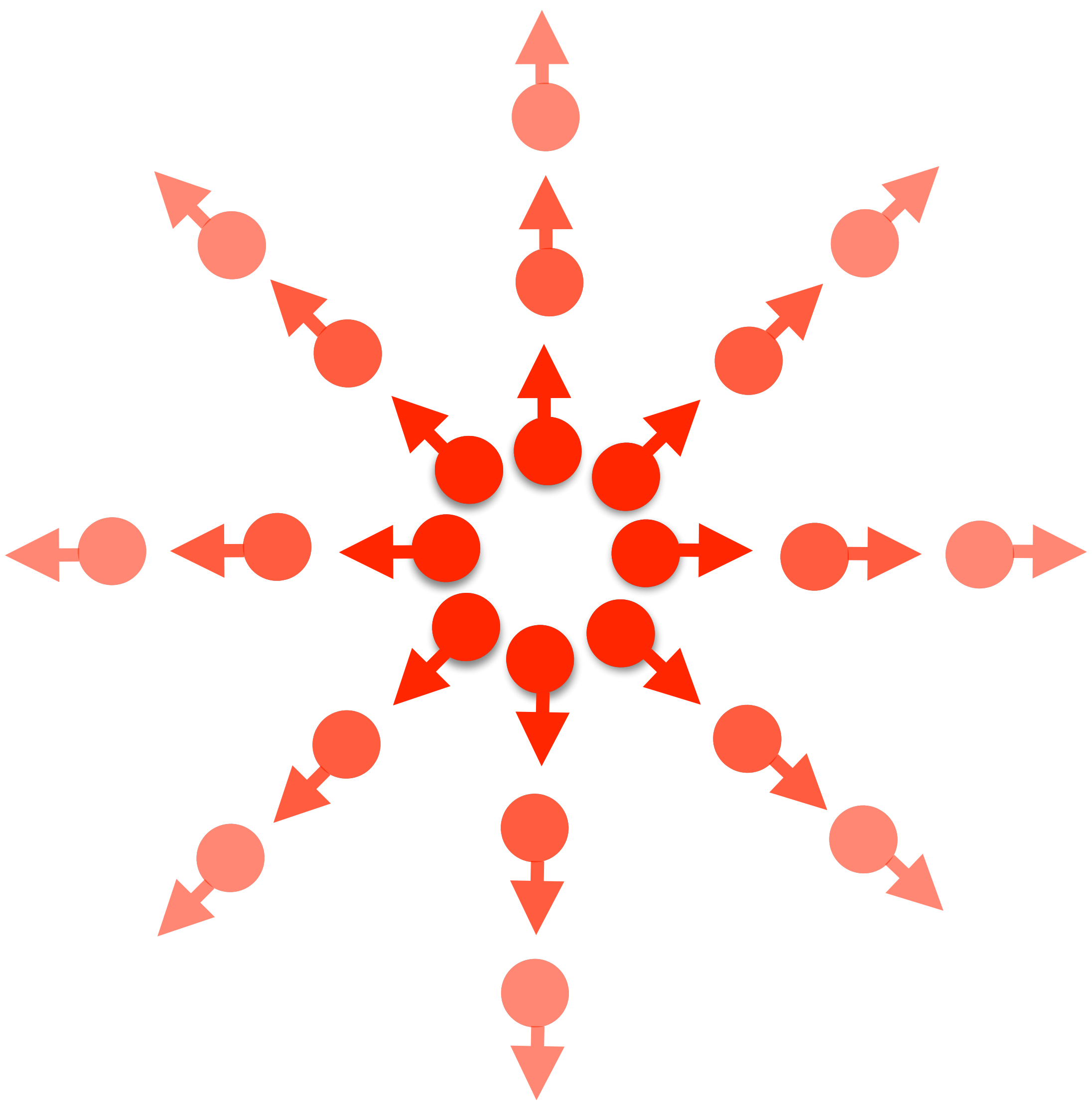
Neutrino Perturbations

Neutrino perturbations are key:

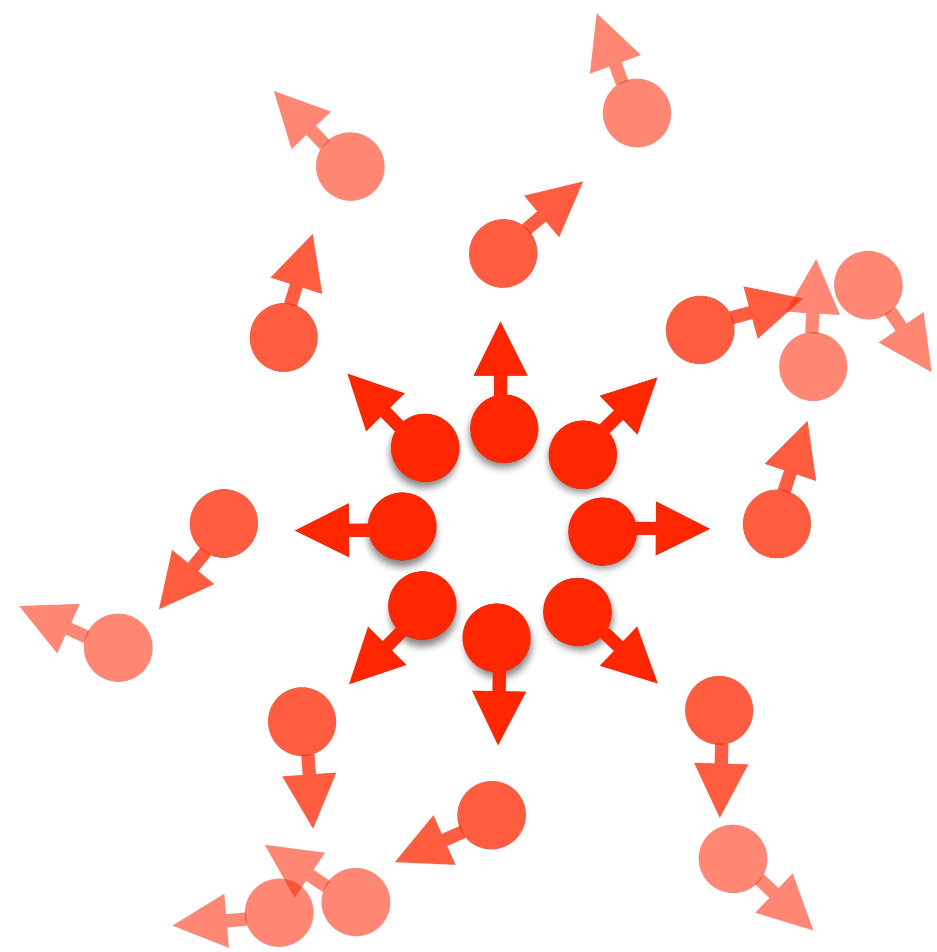


$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

Free Streaming Neutrinos $\sigma_\nu \neq 0$



Interacting Neutrinos $\sigma_\nu \to 0$

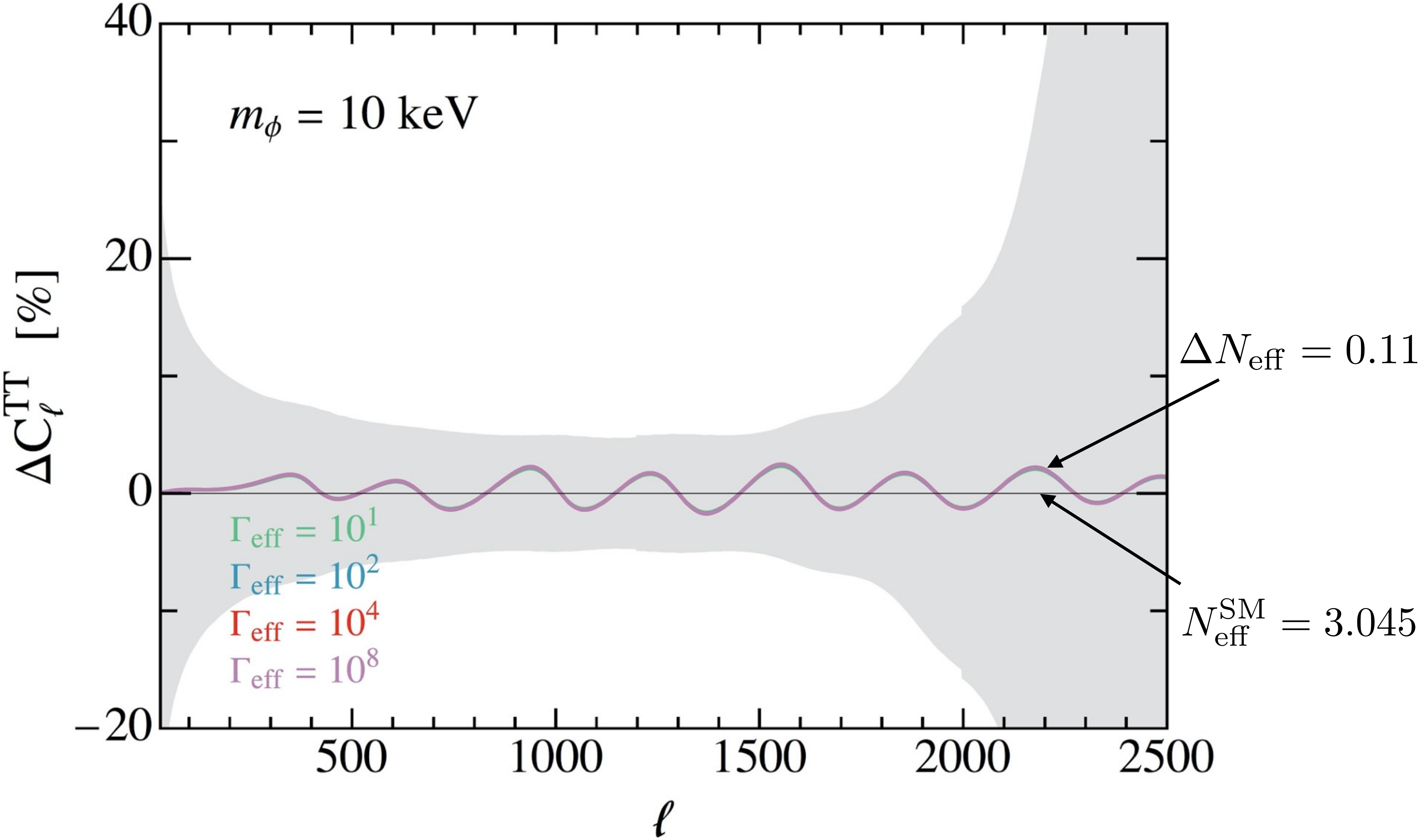


Effect on the CMB is to shift the positions of the peaks!

Bashinsky and Seljak astro-ph/0310198

Effects on the CMB

$$\Gamma_{\rm eff} = \left(\frac{\lambda}{4\times 10^{-14}}\right)^2 \left(\frac{0.1\,{\rm eV}}{m_\phi}\right)$$

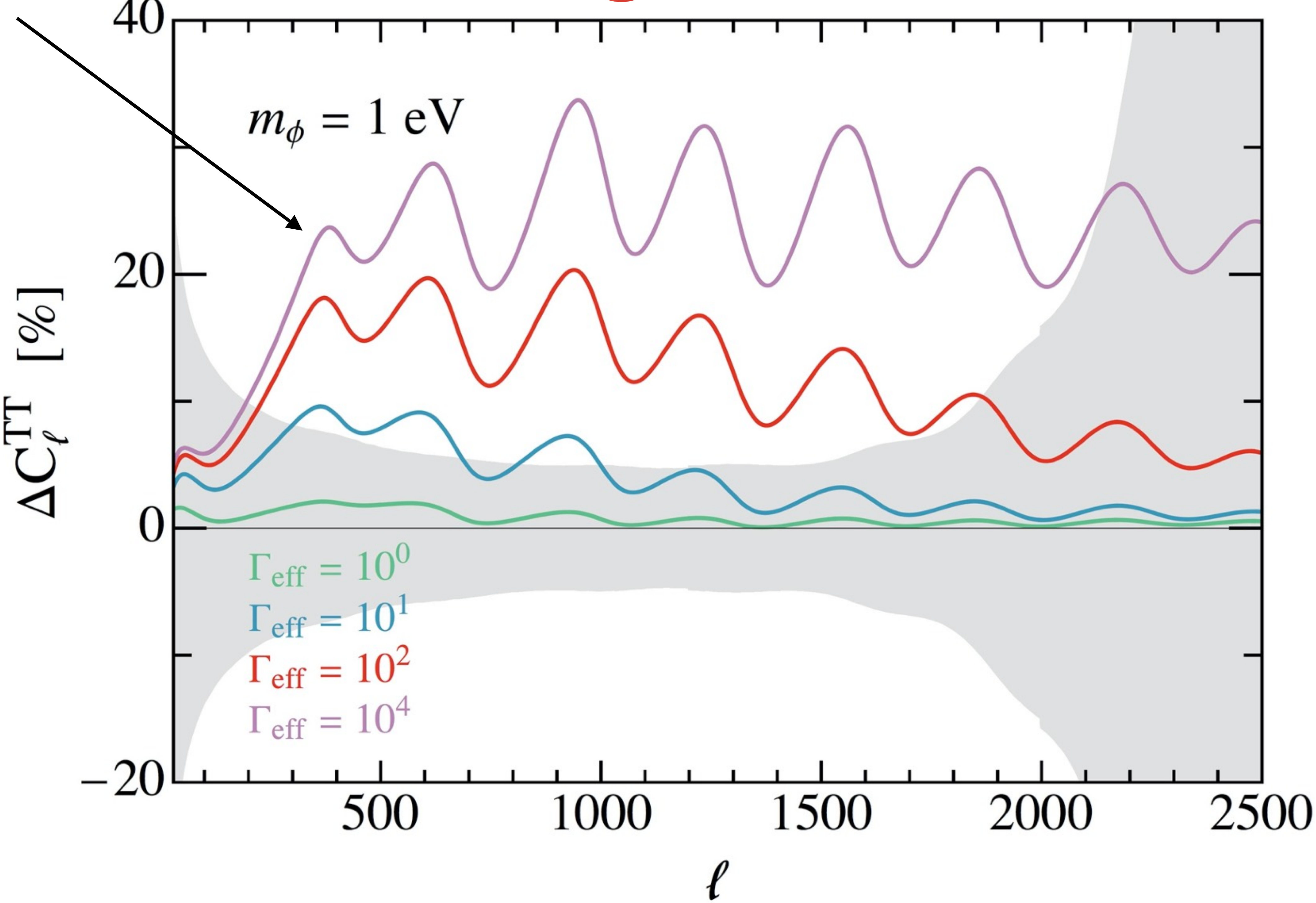


Effects on the CMB

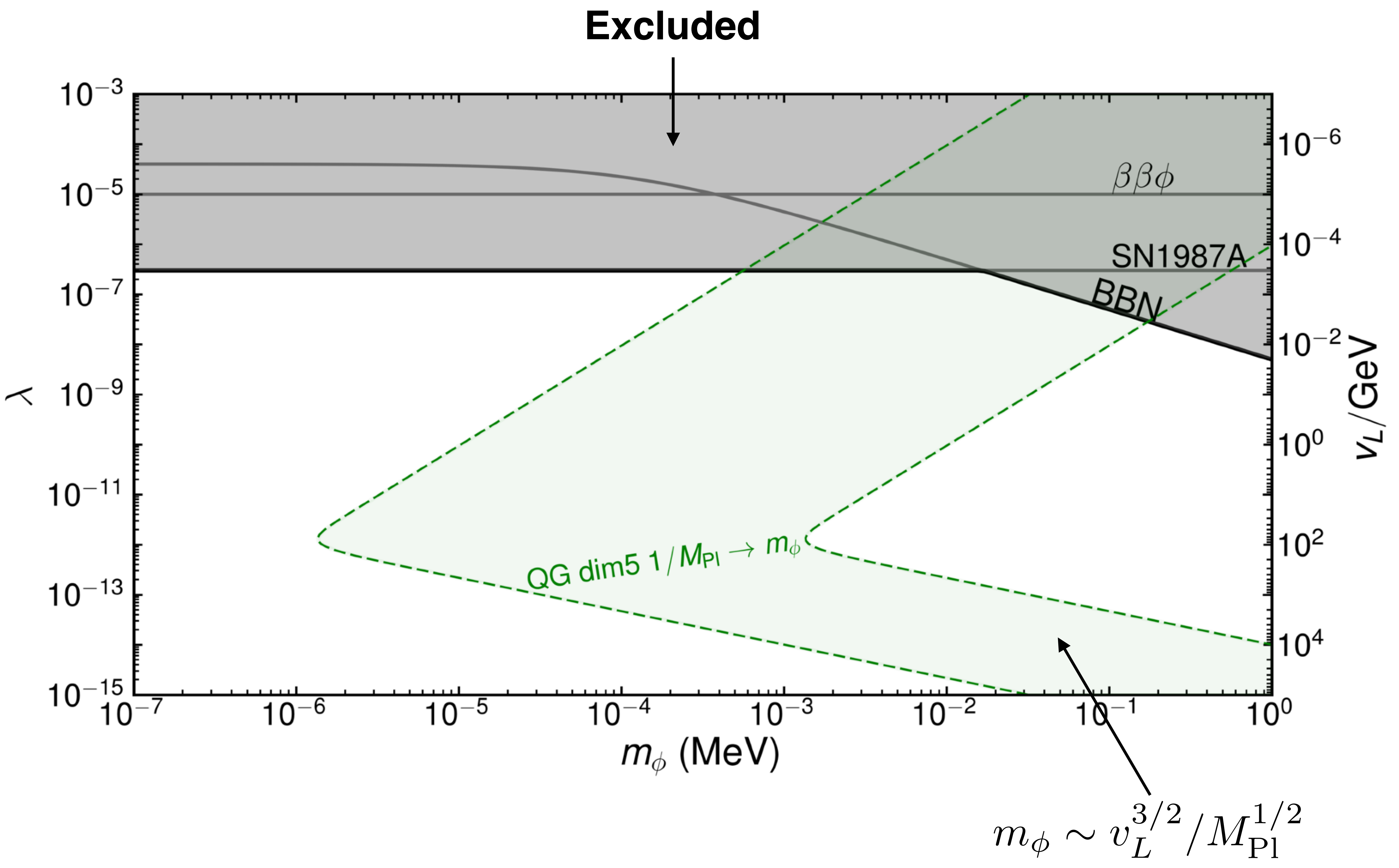
see Bashinsky and Seljak astro-ph/0310198

$$\Gamma_{\rm eff} = \left(\frac{\lambda}{4\times 10^{-14}}\right)^2 \left(\frac{0.1\,\mathrm{eV}}{m_\phi}\right)$$

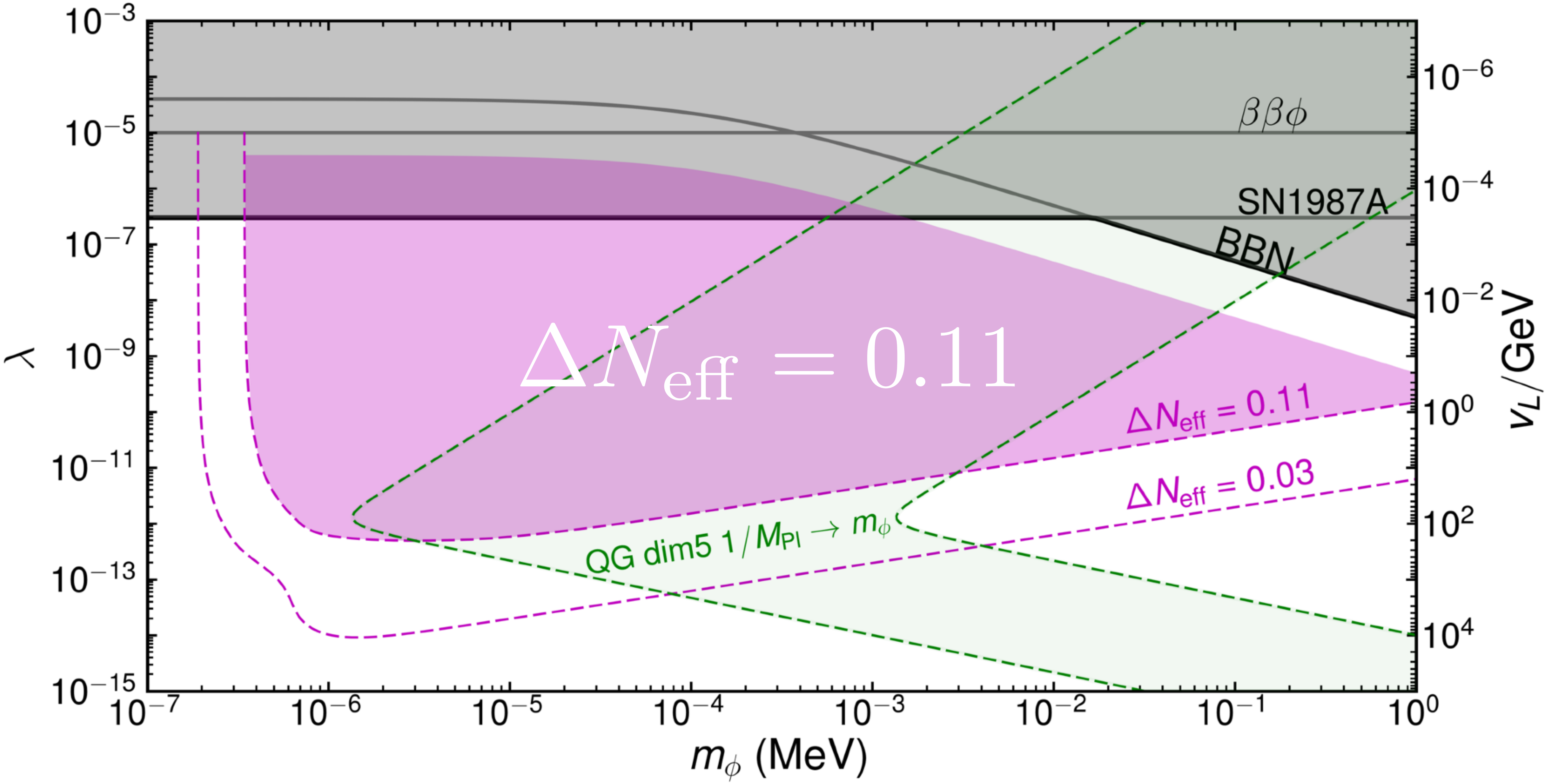
$\sigma_\nu \to 0$ $\quad \delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$



Parameter Space

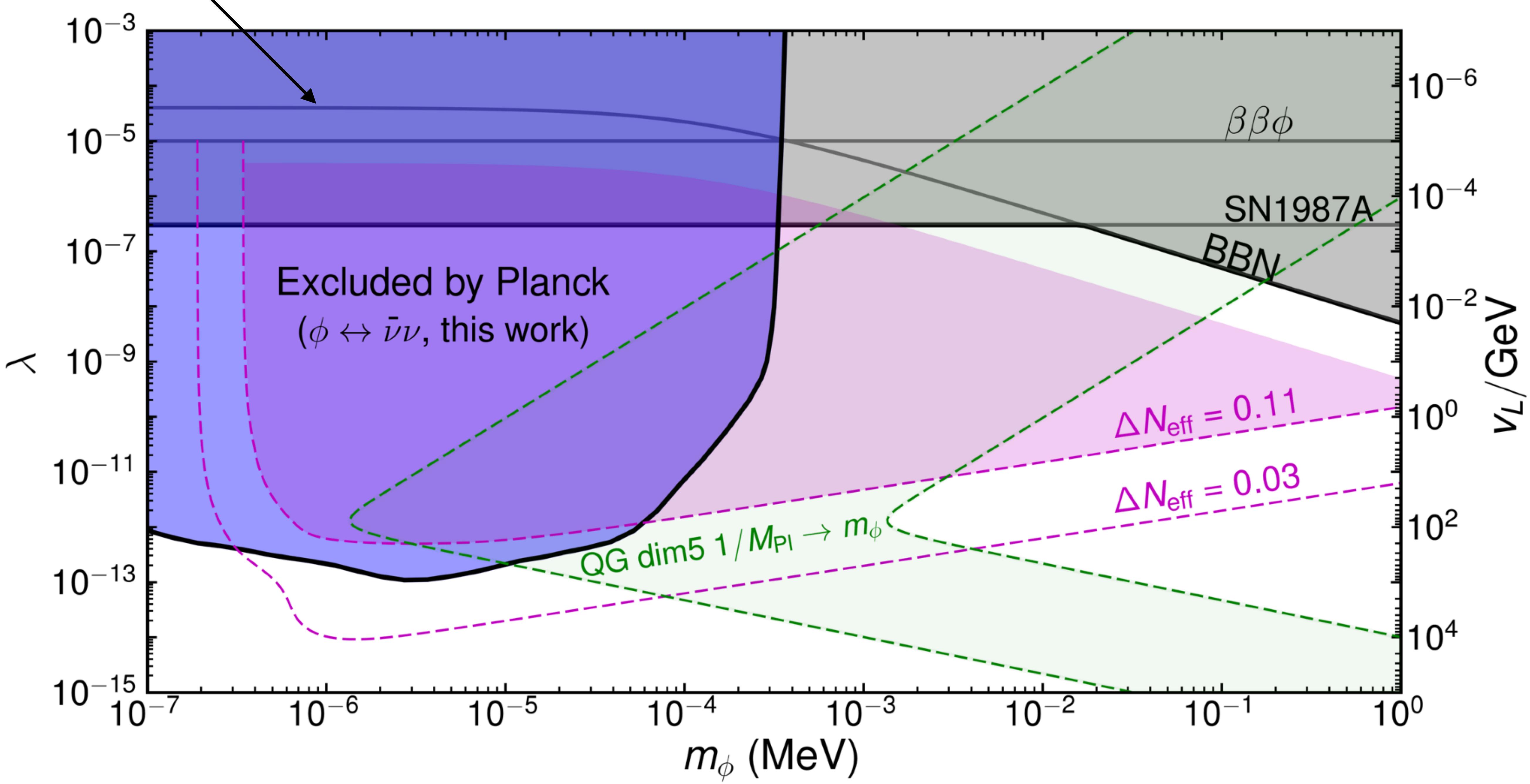


Parameter Space

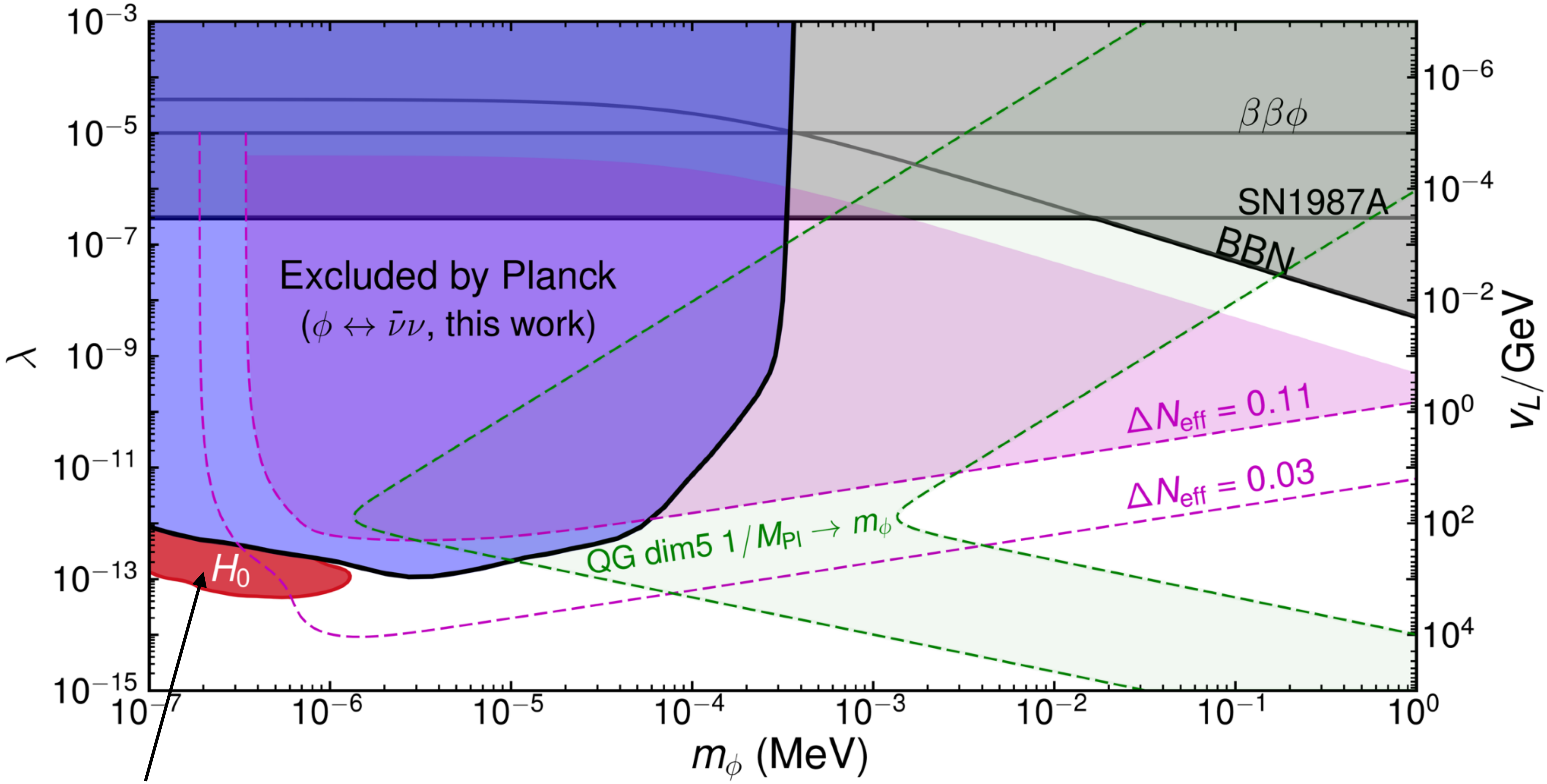


Parameter Space

Full MCMC to Planck 2018 data

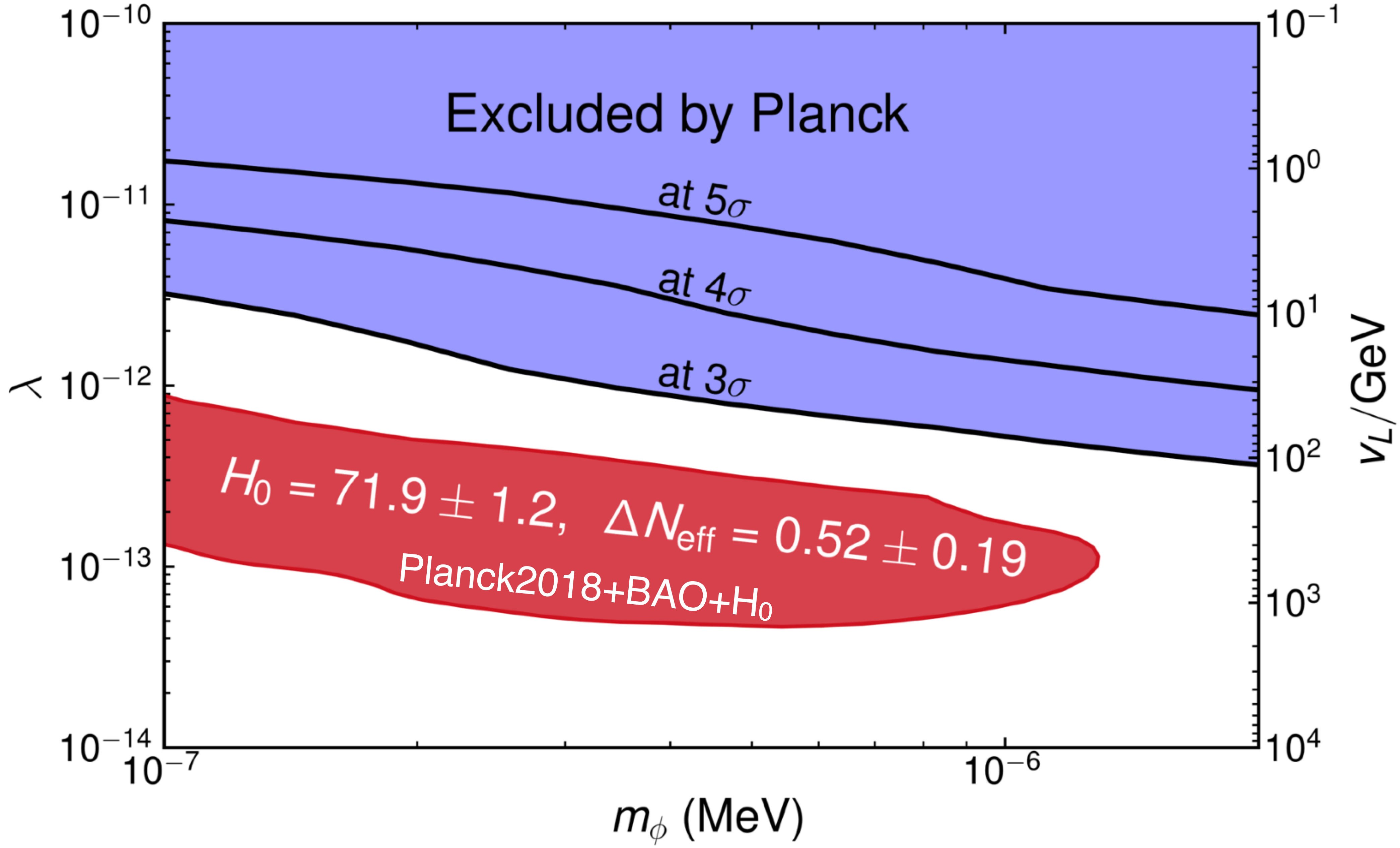


Parameter Space



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 Escudero & Witte 19'

- **The Majoron and the Hubble tension**

  - **Planck sets very stringent constraints**

  - **The CMB-S4 experiment can test large regions of parameter space since** $\sigma(N_{\rm eff}) \simeq 0.03$

  - **Can reduce the tension if:** $m_\phi \sim (0.1-1)\,\mathrm{eV}$, $v_L \sim (0.1-1)\,\mathrm{TeV}$, $\Delta N_{\rm eff} \sim 0.5$

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

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

Primordial Majorons

- **There are sterile neutrinos in the model**

  since $v_L \lesssim 1\,\mathrm{TeV}$ **then we can expect** $M_N \sim 1\,\mathrm{GeV}$

- **The decays of GeV-scale sterile neutrinos in the early Universe can lead to** $\Delta N_{\rm eff}^{\rm BBN} \sim 0.3$ **since** $T_d \sim M_N/10$

- **Neutrino-Majoron interactions can rise it to** $\Delta N_{\rm eff}^{\rm CMB} \sim 0.6$

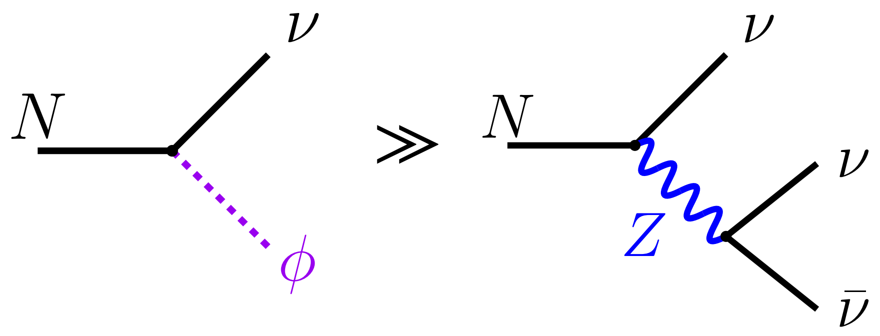
- **These sterile neutrinos can do ARS Leptogenesis!**

Production of Majoron population

- **Sterile neutrinos have masses ~ GeV and interact with the majoron**

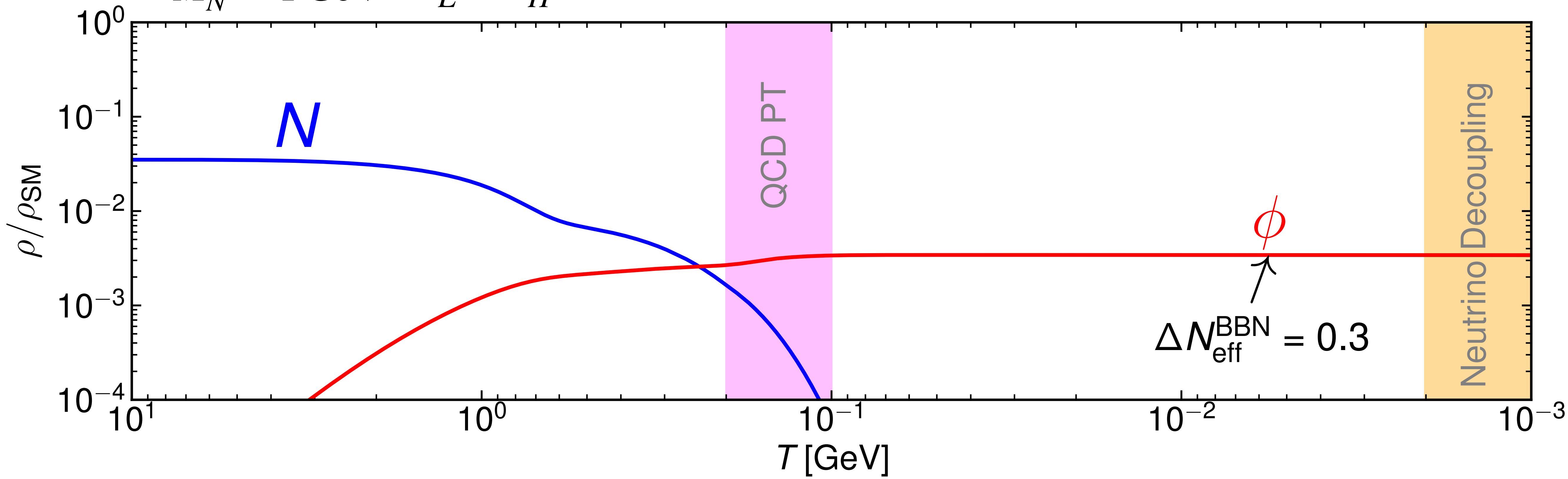
Sterile neutrinos that give mass to the active ones thermalize **(Ghiglieri & Laine 1605.07720)**

In the majoron model sterile neutrinos have a new decay mode

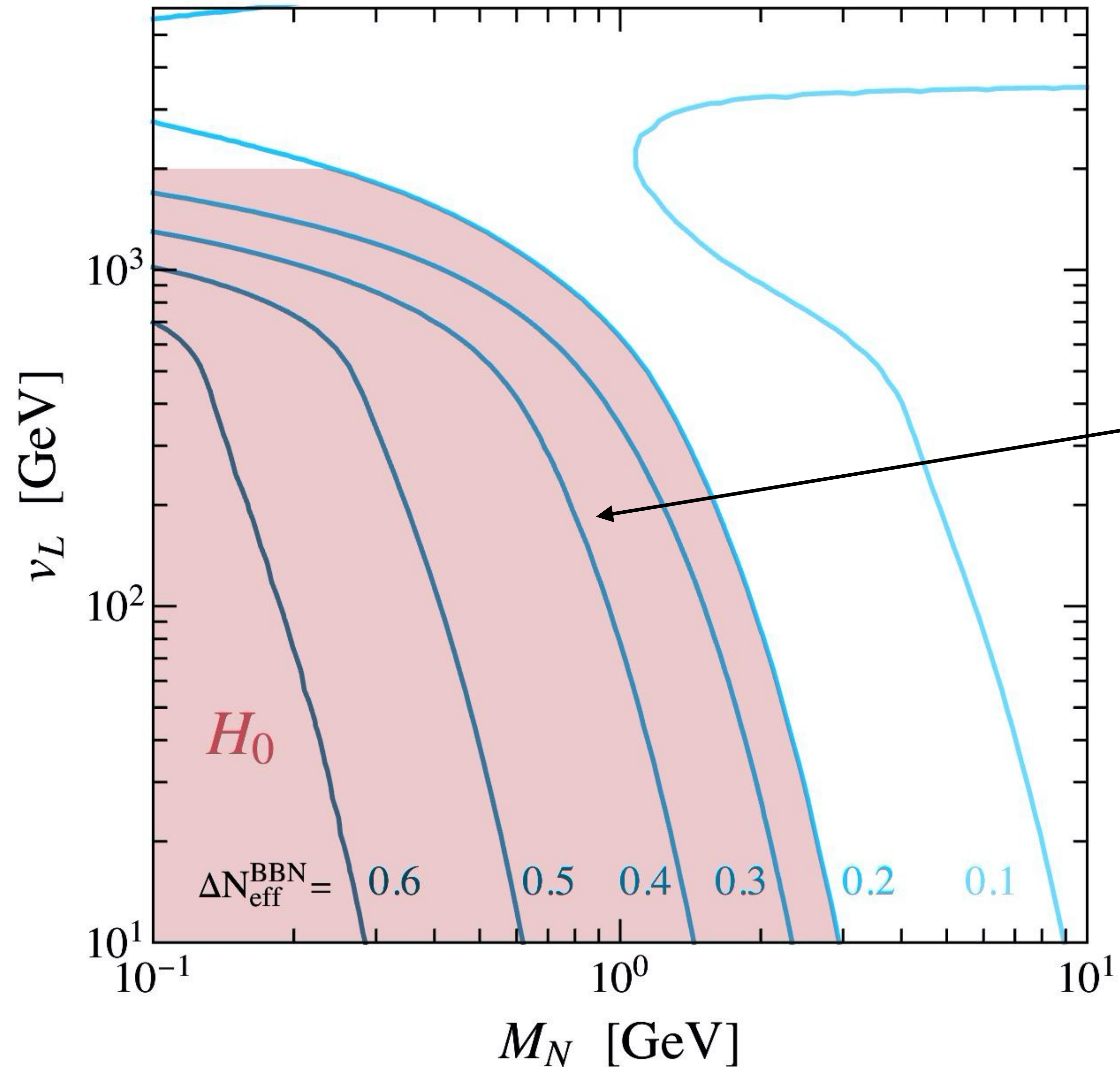


$$\boxed{\frac{\Gamma(N\to\nu\phi)}{\Gamma(N\to \mathrm{SM})}\simeq 4\times 10^3\left(\frac{1\,\mathrm{GeV}}{M_N}\right)^2\left(\frac{1\,\mathrm{TeV}}{v_L}\right)^2}$$

$M_N = 1\,\mathrm{GeV} \quad v_L = v_H$



Parameter Space

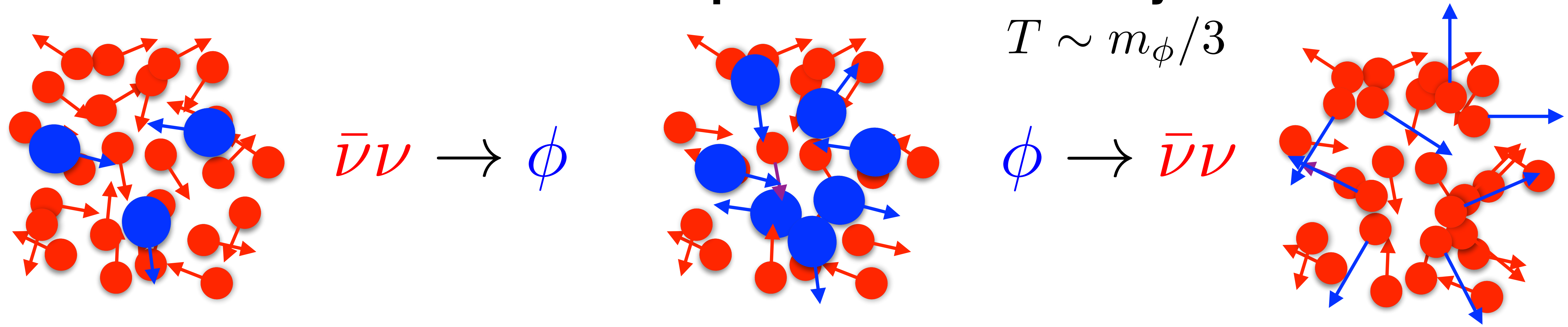


Naturally leading to:

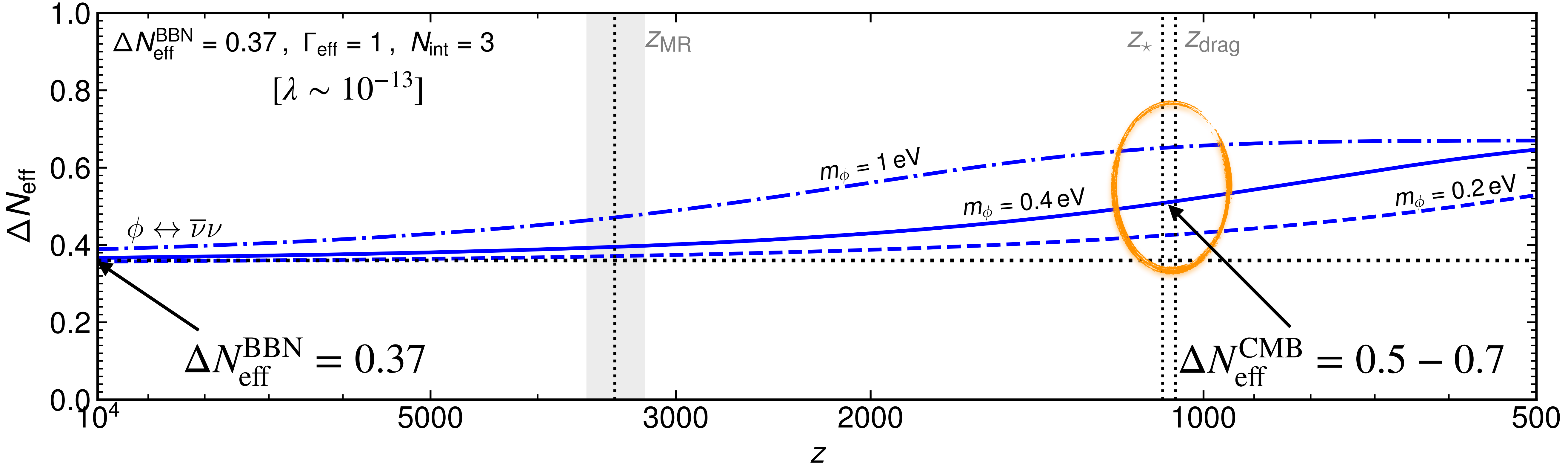
$\Delta N_{\rm eff}^{\rm BBN} \sim 0.4$

Cosmological Implications

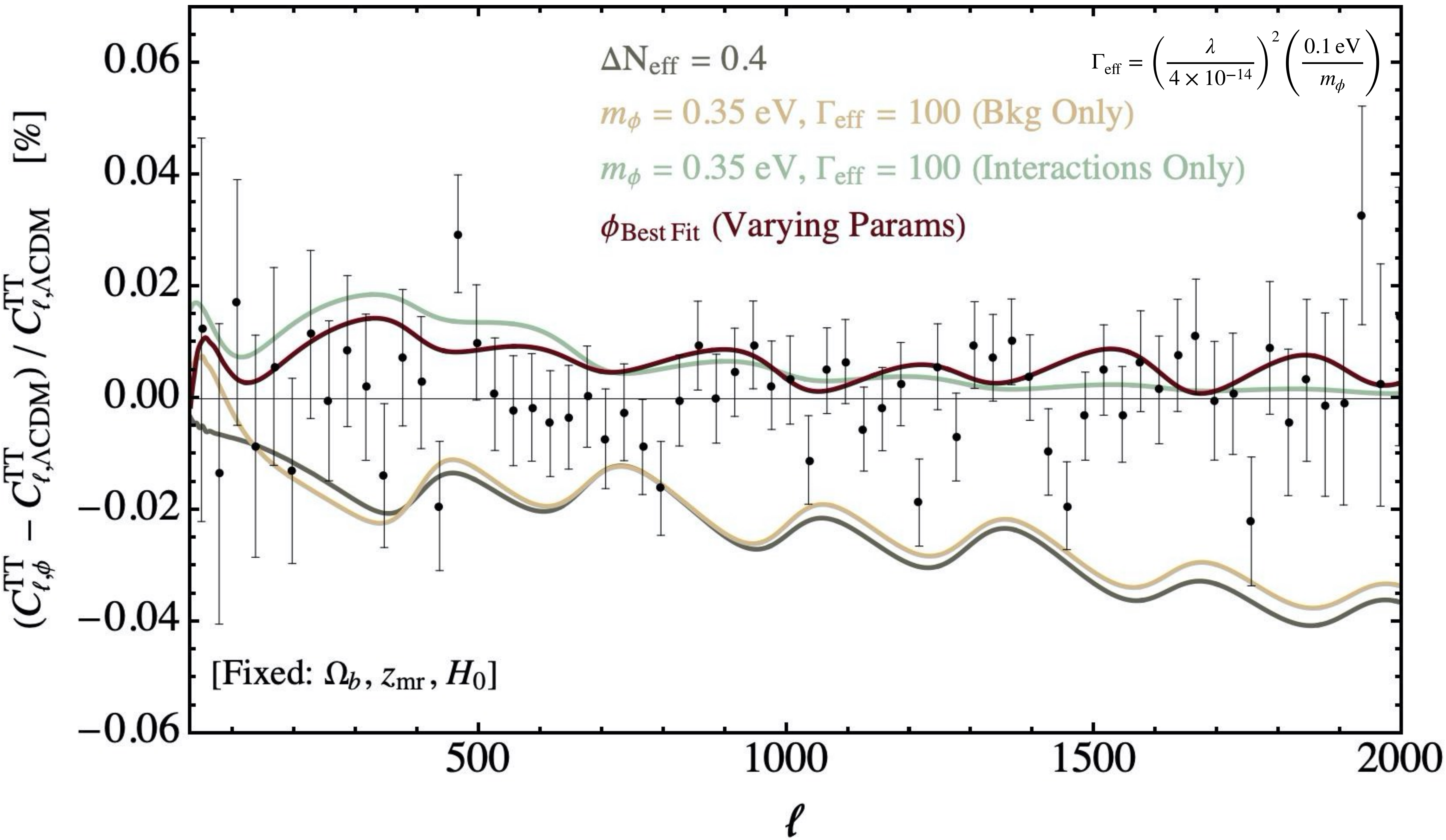
$T \gg m_\phi$	Production	Equilibrium	Decay $T \sim m_\phi/3$	Final State



The effect is enhanced if there is a primordial population:



Effect on the CMB



Neutrino-Majoron interactions can compensate the enhanced expansion history!

Summary of Escudero & Witte 21'

- **Sterile Neutrinos can provide just the right primordial majoron population**
- **A full Planck Legacy data analysis shows that:**

for $\Delta N_{\rm eff}^{\rm BBN} = 0.37$

$$m_\phi = (0.1 - 0.8)\ \text{eV}$$
$$v_L = (0.05 - 2)\ \text{TeV}$$
$$M_N \sim \text{GeV}$$

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

This makes the tension $5\sigma \to 2.5\sigma$ but with a better CMB fit than ΛCDM!

- **We argue that in the parameter space of interest these sterile neutrinos can lead to the baryon asymmetry of the Universe via their CP violating oscillations. ARS-Leptogenesis**

Akhmedov, Rubakov & Smirnov, hep-ph/9803255
See also Asaka & Shaposhnikov, hep-ph/0505013

provided $|\lambda_{\phi H}| < 10^{-7} \dfrac{v_L}{1\,\text{TeV}} \sqrt{\dfrac{10^5\,\text{GeV}}{T_c}}$

which requires some fine tuning but at least is protected under RGE flow

Our expectations have been confirmed by:

2109.10908 Flood, Porto, Schlesinger, Shuve & Thum
2110.14499 Fischer, Lindner & van der Woude

Final Summary

The Majoron as a solution to the Hubble tension

- **The Majoron can substantially relax the tension and can accommodate $H_0 \simeq 70\,\mathrm{km/s/Mpc}$ while providing a good CMB fit.**

- **The Majoron is a well motivated particle:**
  - **It is predicted within the type-I seesaw with a global Lepton number symmetry**
  - **Its interaction rate with neutrinos is naturally very feebly**
  - **The Majoron mass could be understood from Planck-scale physics and points to $m_\phi \sim \mathrm{eV}$**

- **Parameter space to ameliorate the Hubble tension is well motivated: $v_L \sim v_H$**

- **The sterile neutrinos in the model play a crucial role:**

  By providing by their decays $\Delta N_{\mathrm{eff}}^{\mathrm{BBN}} \sim 0.3$

  In addition, they could be responsible for low-scale Leptogenesis

Outlook

- **Collider tests** $K \to \mu N$ **(NA62)**

  $\pi \to e N$ **(PIENU)**

- **Refined cosmological analysis**

  We are doing a careful cosmological analysis
  Improved collision term: <u>Stefan Sandner</u>, Escudero & Witte 2208.XXXXX

- **Cosmological tests**

  There are signals for ongoing/upcoming CMB experiments:

  ACT, SPT, Simons Observatory and CMB-S4

- **My main conclusion:**

  Regardless of what happens with the Hubble tension, we will learn about fundamental physics! Probing a well motivated neutrino mass model with $\Lambda \sim 1\,\mathrm{TeV}$!

Acknowledgements

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Alexander von Humboldt Foundation

Sam Witte!

Time for Questions and Comments

Thank you a lot for the invitation and for your attention!