

Neutrinos in Cosmology

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Motivation

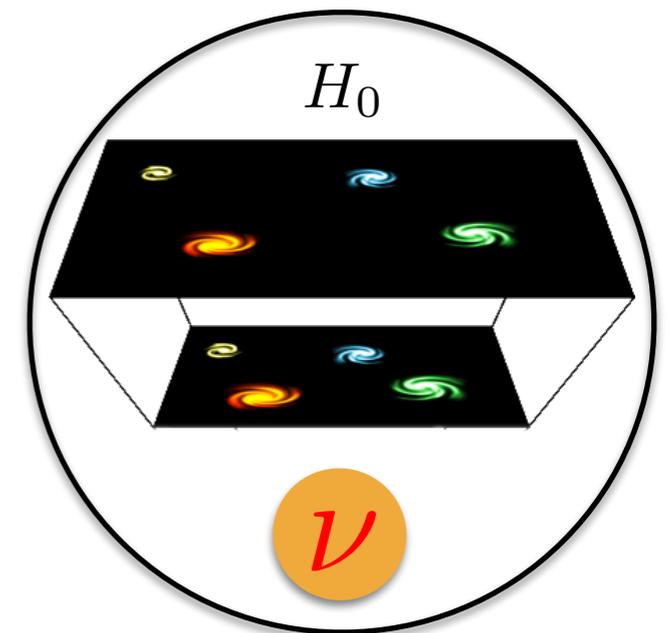
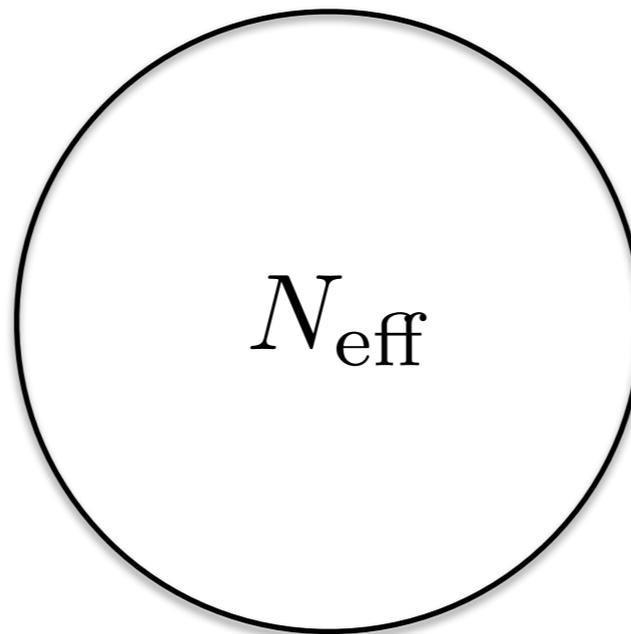
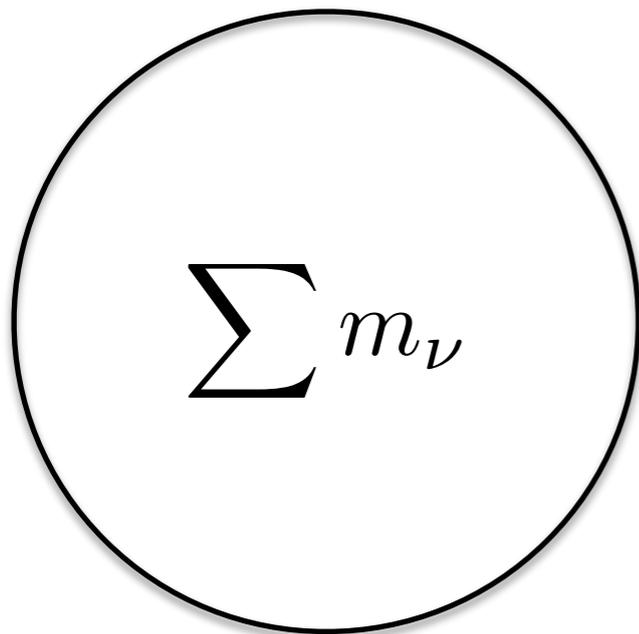
- Neutrinos are ubiquitous in Cosmology

Use cosmological data to understand their properties

- Neutrino masses are the only laboratory evidence of physics beyond the Standard Model

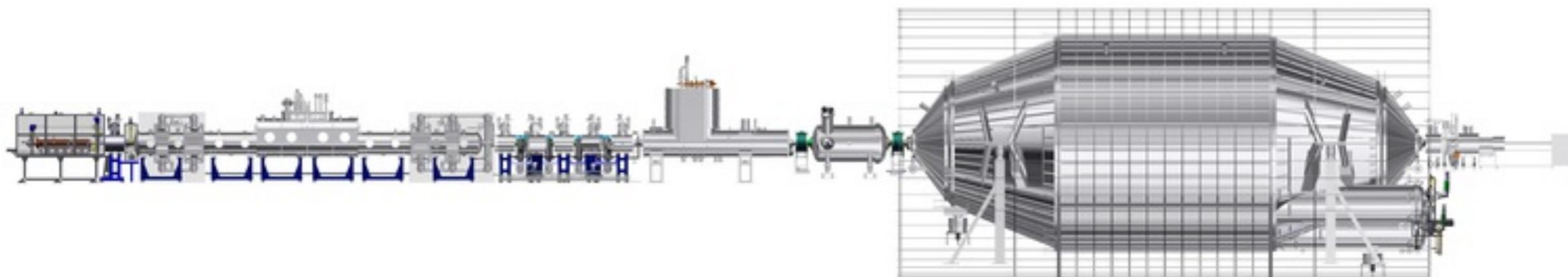
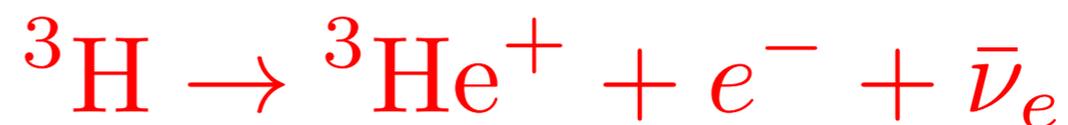
Use them as a link to BSM physics

Topics Covered (from a Particle Physics perspective):



New Laboratory Neutrino Mass Bound

KATRIN experiment



Mainz and Troitsk (2004):

$$m_{\nu_e} < 2.2 \text{ eV} \quad (95 \% \text{ CL})$$

Current laboratory bound:
2105.08533+1909.06048 (PRL)

$$m_{\nu_e} < 0.8 \text{ eV} \quad (90 \% \text{ CL, FC})$$

$$\sum m_\nu < 2.4 \text{ eV} \quad (90 \% \text{ CL, FC})$$

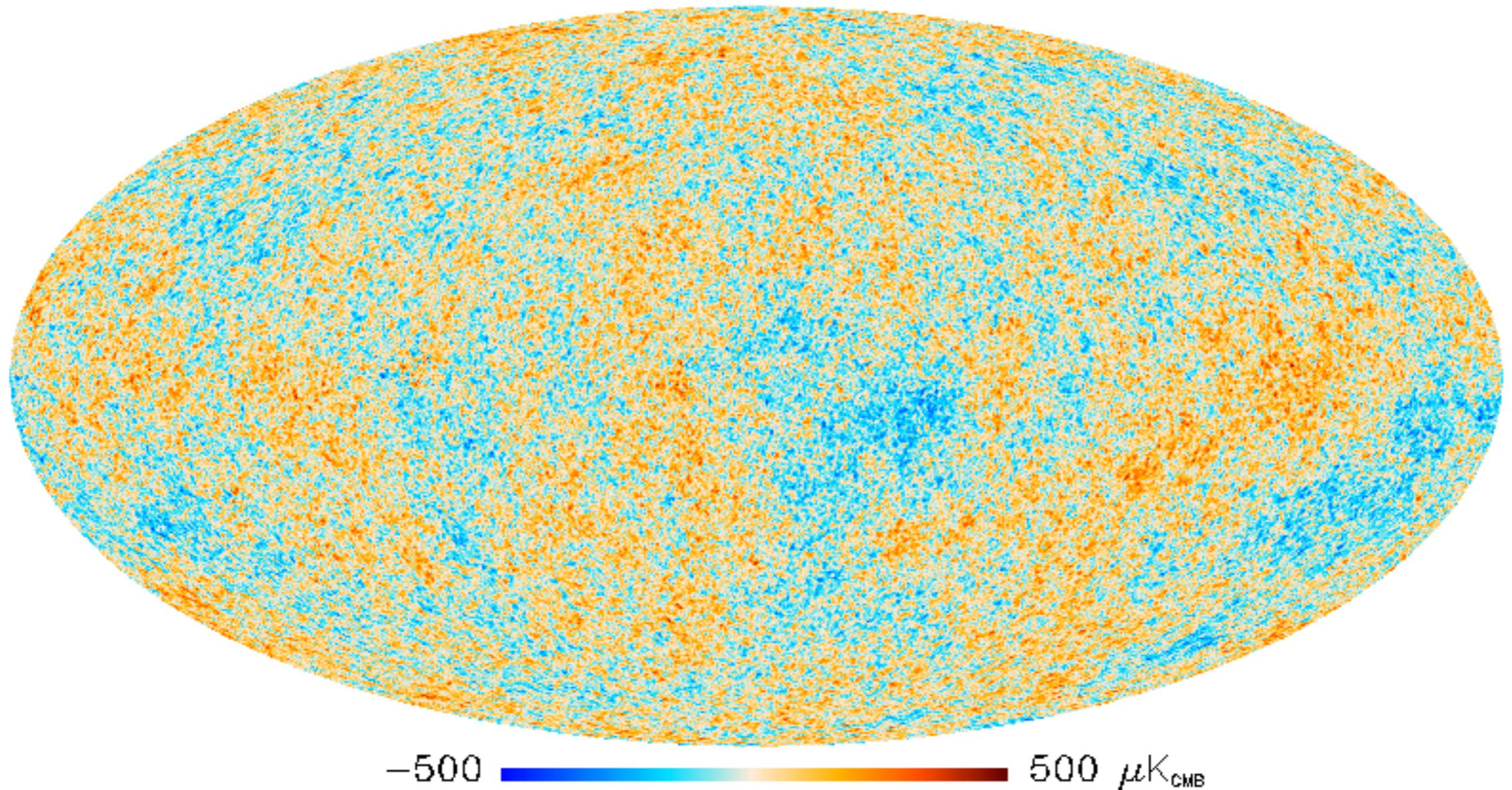
KATRIN expected reach
(in ~3 years)

$$m_{\nu_e} < 0.2 \text{ eV} \quad (90 \% \text{ CL})$$

$$\sum m_\nu < 0.6 \text{ eV}$$

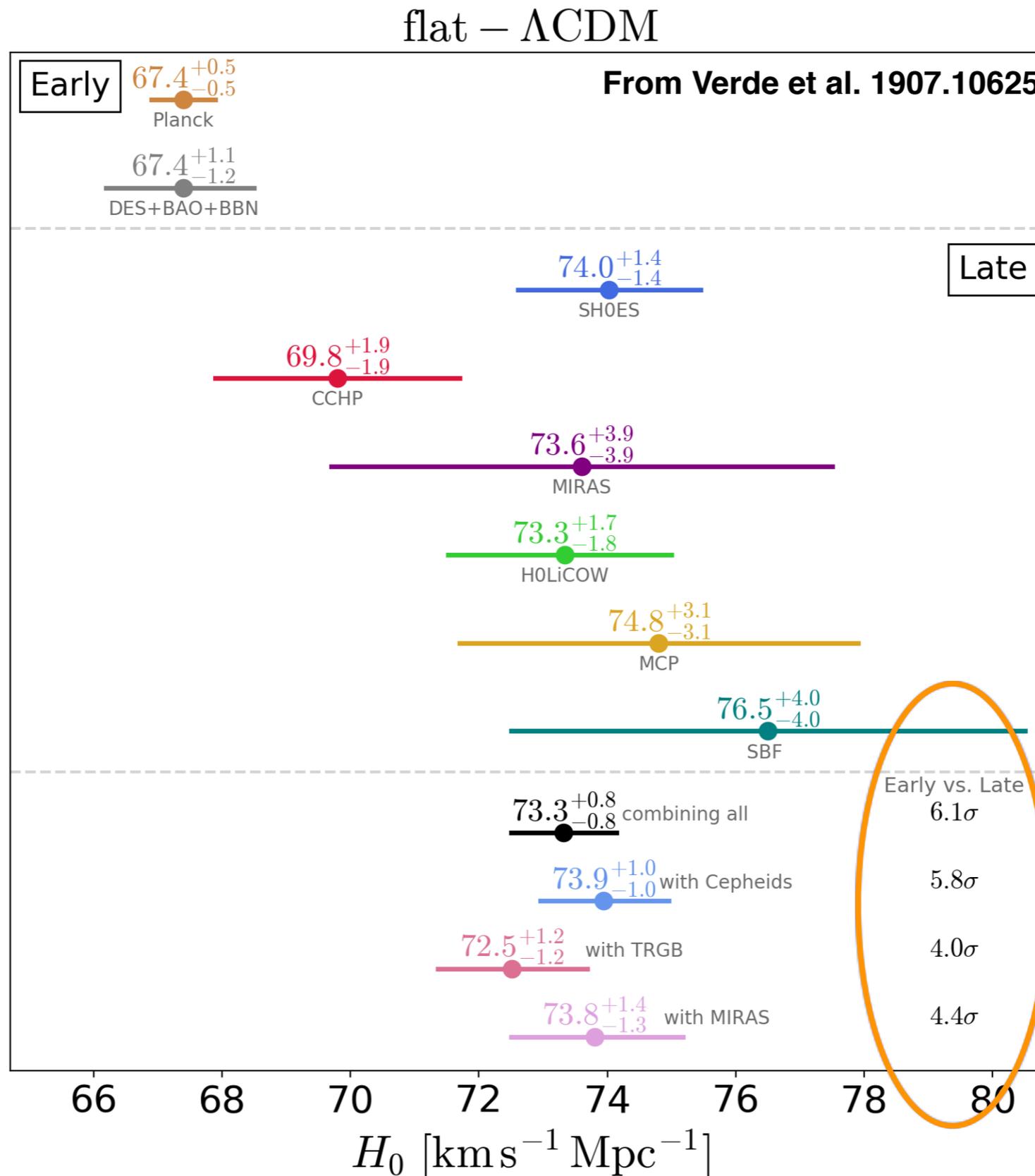
Planck Legacy Data is Public

Planck Likelihoods 1907.12875



CLASS/CAMB MontePython/CosmoMC

The Hubble Tension Increases



Outline

1) Neutrinos and Λ CDM

2) Neutrino Masses

Cosmological Constraints

Neutrino Decays to relax Σm_ν bounds

3) N_{eff}

BBN and the CMB

Constraints on BSM Physics

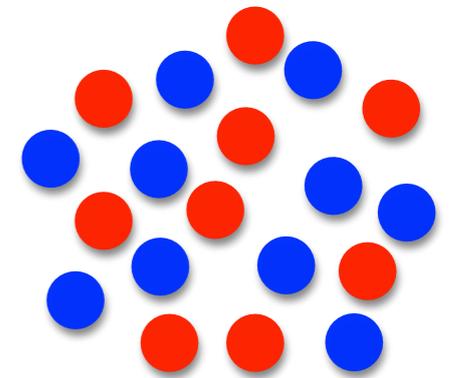
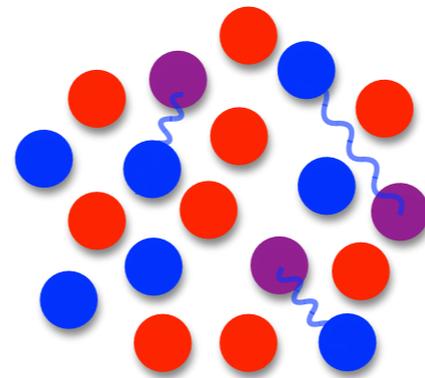
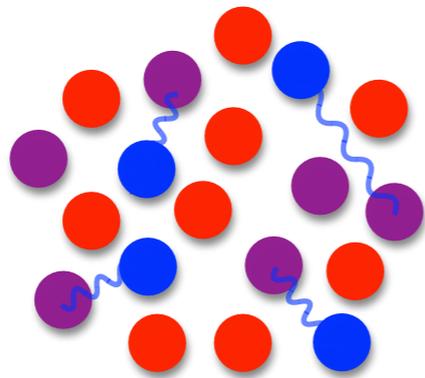
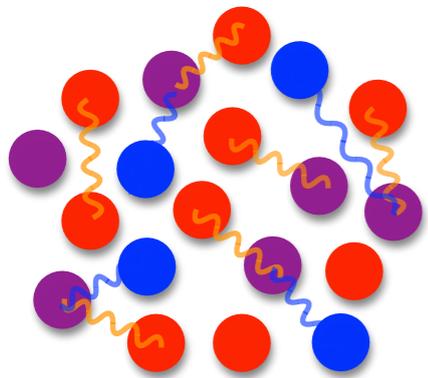
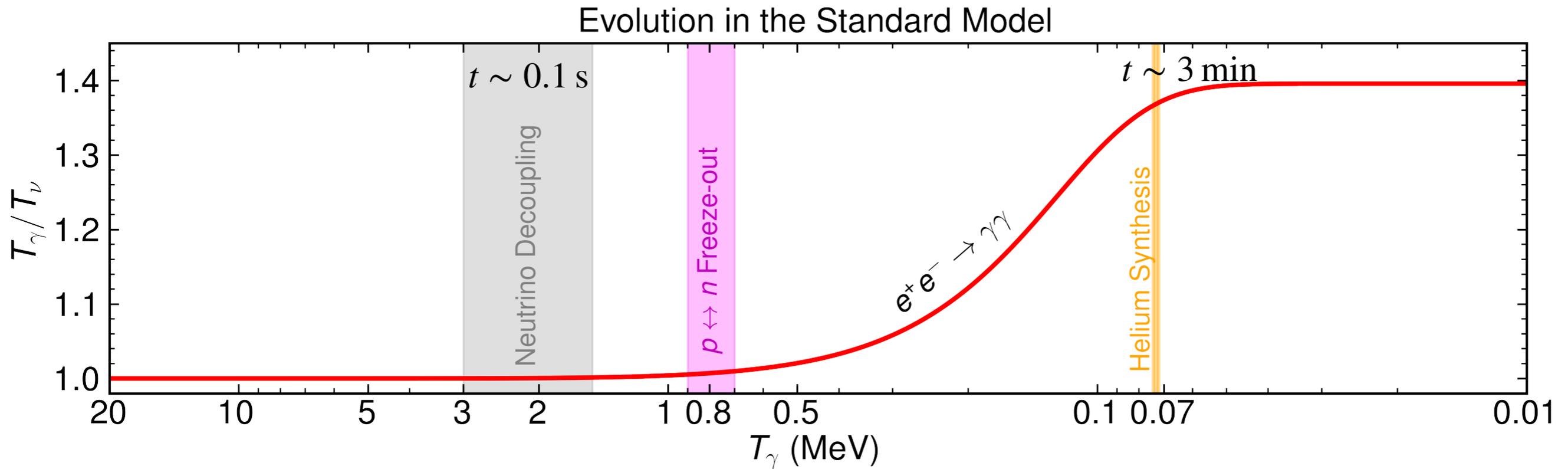
4) Neutrinos and the Hubble Tension

Could the Hubble tension be pointing to the neutrino mass mechanism?

5) Conclusions and Outlook

-1) Cosmic Neutrino Background at PTOLEMY

Neutrino Decoupling

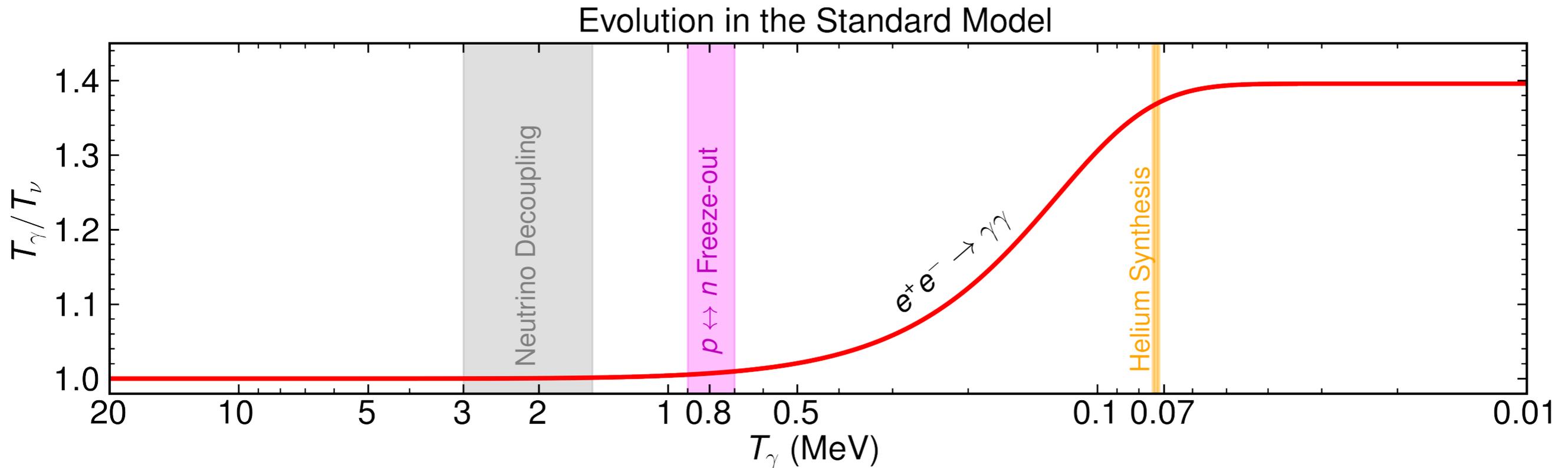


$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$

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



Neutrino Decoupling



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

$$N_{\text{eff}} = 3 \left(\frac{1.4 T_{\nu}}{T_{\gamma}} \right)^4$$

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

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

$$t \sim 0.1 \text{ s}$$

$$T_{\nu} \sim 2 \text{ MeV}$$

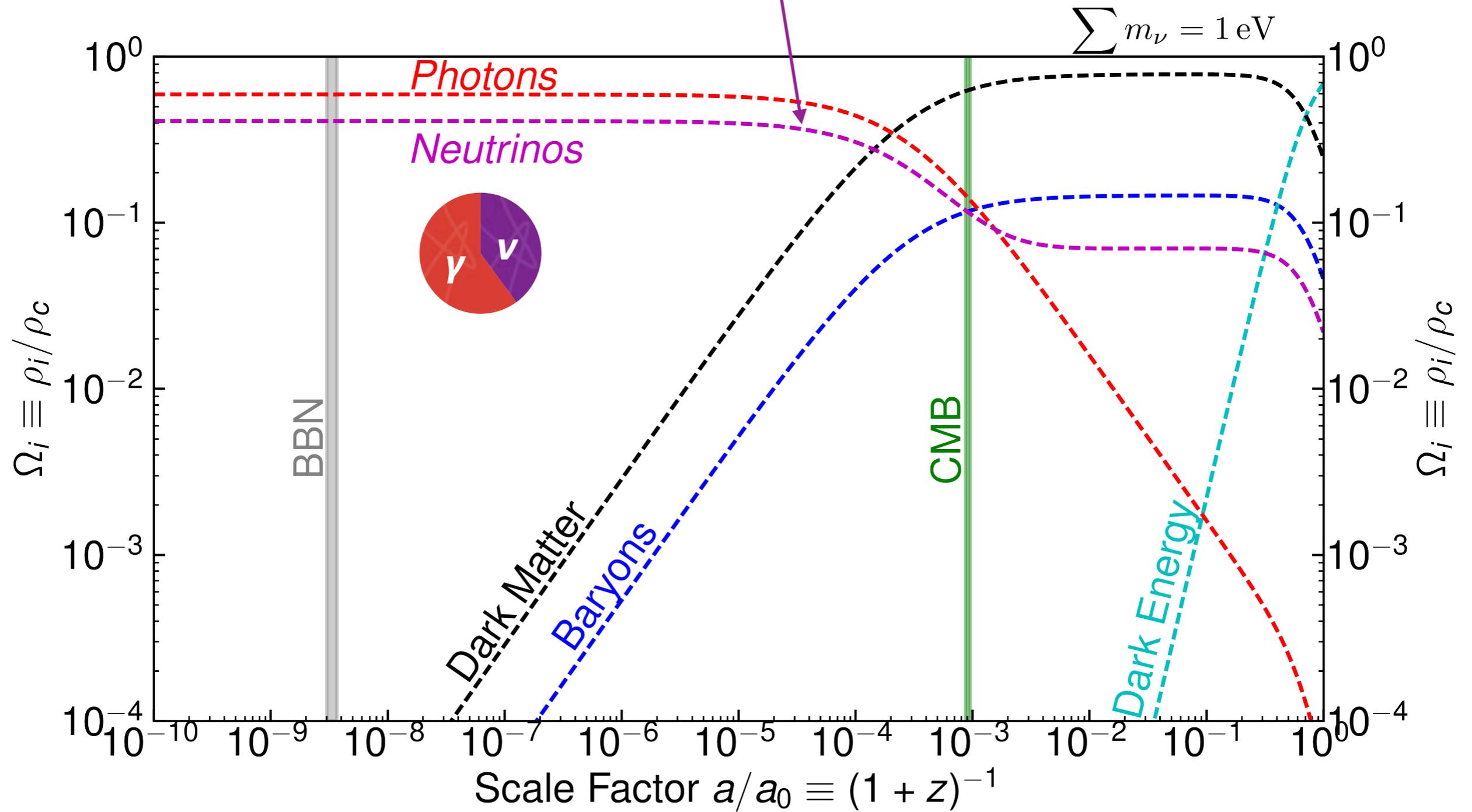
Why is it not 3?

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

Excellent review
 by Dolgov hep-ph/0202122

Neutrino Evolution

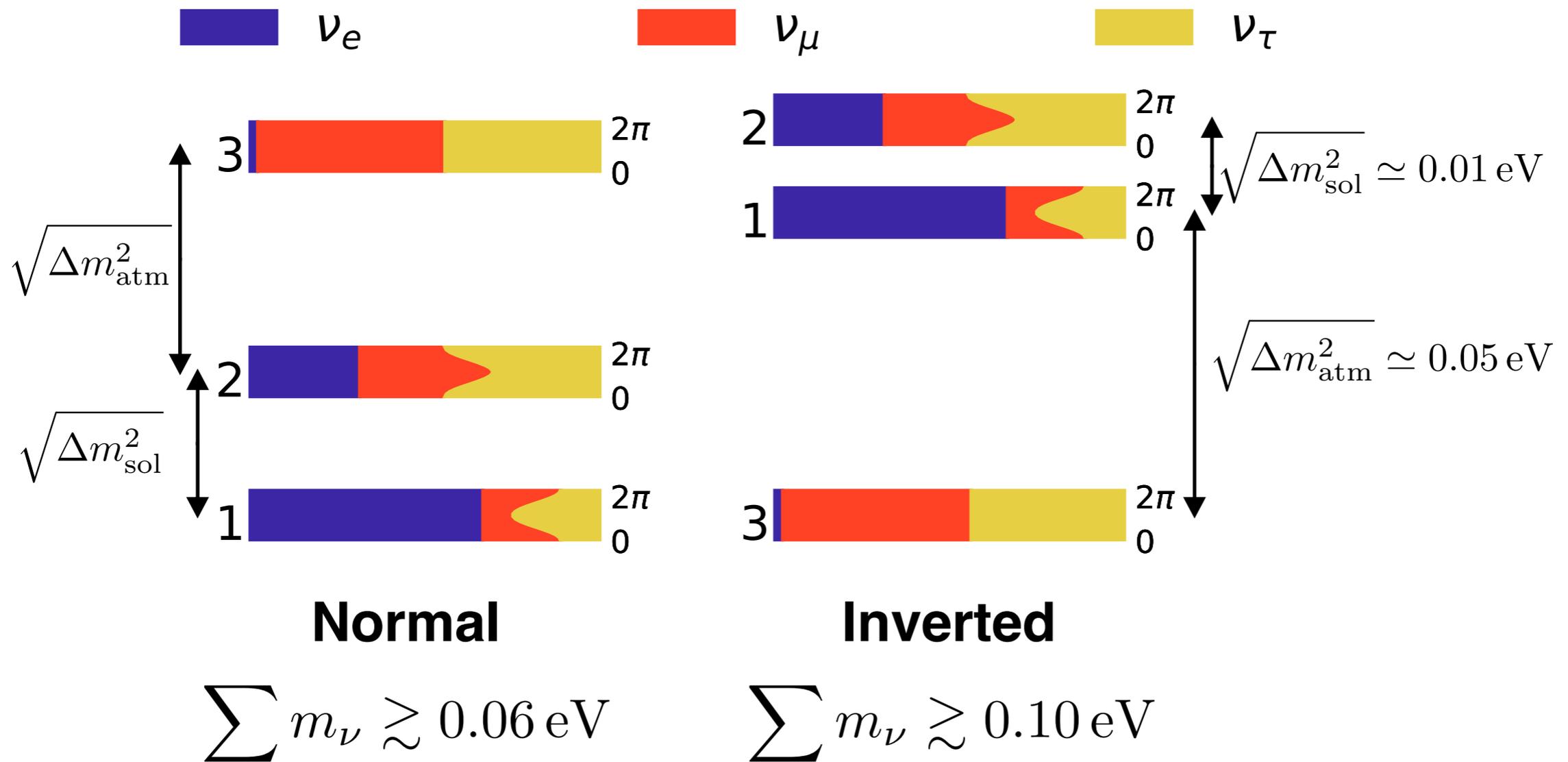
Neutrinos are always a relevant species in the Universe's evolution



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

Neutrino Properties

Figure taken from de Salas et al. 1806.11051



- Mass differences and mixings measured with high precision
- What is Delta CP and what is the mass ordering? [Neutrino Oscillations](#)
- What is the neutrino mass scale? i.e. $\sum m_\nu$? i.e. m_{lightest} ?

Neutrino Masses from Cosmology

Planck 2018 (1807.06209)

$$\sum m_\nu < 0.54 \text{ eV} \quad (95 \% \text{ CL, TT+lowE})$$

$$\sum m_\nu < 0.26 \text{ eV} \quad (95 \% \text{ CL, TTTEEE+lowE})$$

$$\sum m_\nu < 0.24 \text{ eV} \quad (95 \% \text{ CL, TTTEEE+lowE+lensing})$$

$$\sum m_\nu < 0.12 \text{ eV} \quad (95 \% \text{ CL, TTTEEE+lowE+lensing+BAO})$$

Very robust bounds from linear Cosmology

But, all cosmological bounds are cosmological model dependent.

What is the dependence upon the assumed Cosmological Model?

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+BAO and 3 degenerate neutrinos

$$\sum m_\nu < 0.12 \text{ eV}$$

Standard Case

Planck 1807.06209

Λ CDM+m_ν

$$\sum m_\nu < 0.25 \text{ eV}$$

Dark Energy dynamics

Choudhury & Hannestad 19'

CDM+m_ν+ω_a+ω

$$\sum m_\nu < 0.15 \text{ eV}$$

Varying Curvature

Choudhury & Hannestad 19'

Λ CDM+m_ν+Ω_k

$$\sum m_\nu < 0.23 \text{ eV}$$

Varying N_{eff}

Planck 1807.06209

Λ CDM+m_ν+N_{eff}

$$\sum m_\nu < 0.17 \text{ eV}$$

Varying N_{eff}+ω+a_s+m_ν

di Valentino et al. 1908.01391

CDM+m_ν+N_{eff}+ω+a_s+m_ν

- Constraints are robust upon standard modifications of Λ CDM

Neutrino Mass Models

- Many neutrino mass models have large regions of parameter space with $\Sigma m_\nu > 0.12$ eV.
- Most of the 2-zero neutrino mass textures predict $\Sigma m_\nu > 0.12$ eV.
See e.g. Alcaide, Santamaría & Salvadó, 1806.06785.
- Well motivated example: Neutrino models based on $U(1)_{\mu-\tau}$
 - $U(1)_{\mu-\tau}$ anomaly free
 - Very minimal:
 - 3 Sterile Neutrinos, N
 - 1 Charged scalar field, Δ
 - + Z' if $U(1)$ is gauge
 - Studied extensively:
 - Choubey & Rodejohann, hep-ph/0411190
 - Araki, Heeck & Kubo, 1203.4951
 - Asai et al.: 1705.00419, 1811.07571, 1907.04042, 1909.08827

- Only one problem:

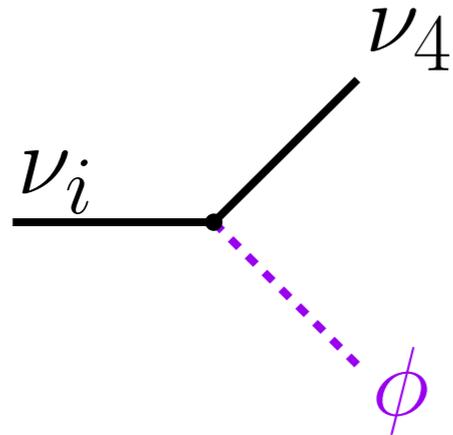
$$0.17 \text{ eV} < \sum m_\nu < 0.47 \text{ eV}$$

Neutrino Masses from Cosmology

Cosmological Model Dependence

More exotic scenarios:

Invisible Neutrino Decay



$$\sum m_\nu \lesssim 1 \text{ eV}$$

Chacko et al. 1909.05275

Time Dependent Neutrino Masses

Late phase transition

$$\sum m_\nu < 1.4 \text{ eV}$$

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

$$\sum m_\nu < 3 \text{ eV}$$

Esteban & Salvadó 2101.05804
Wetterich et al. 1009.2461 & 1407.8414

Non-standard Neutrino Populations

$$T_\nu < T_\nu^{\text{SM}}$$

$$\sum m_\nu < 3 \text{ eV}$$

Farzan & Hannestad 1510.02201
Renk et al. 2009.03286

$$f_\nu \neq f_\nu^{\text{SM}}$$

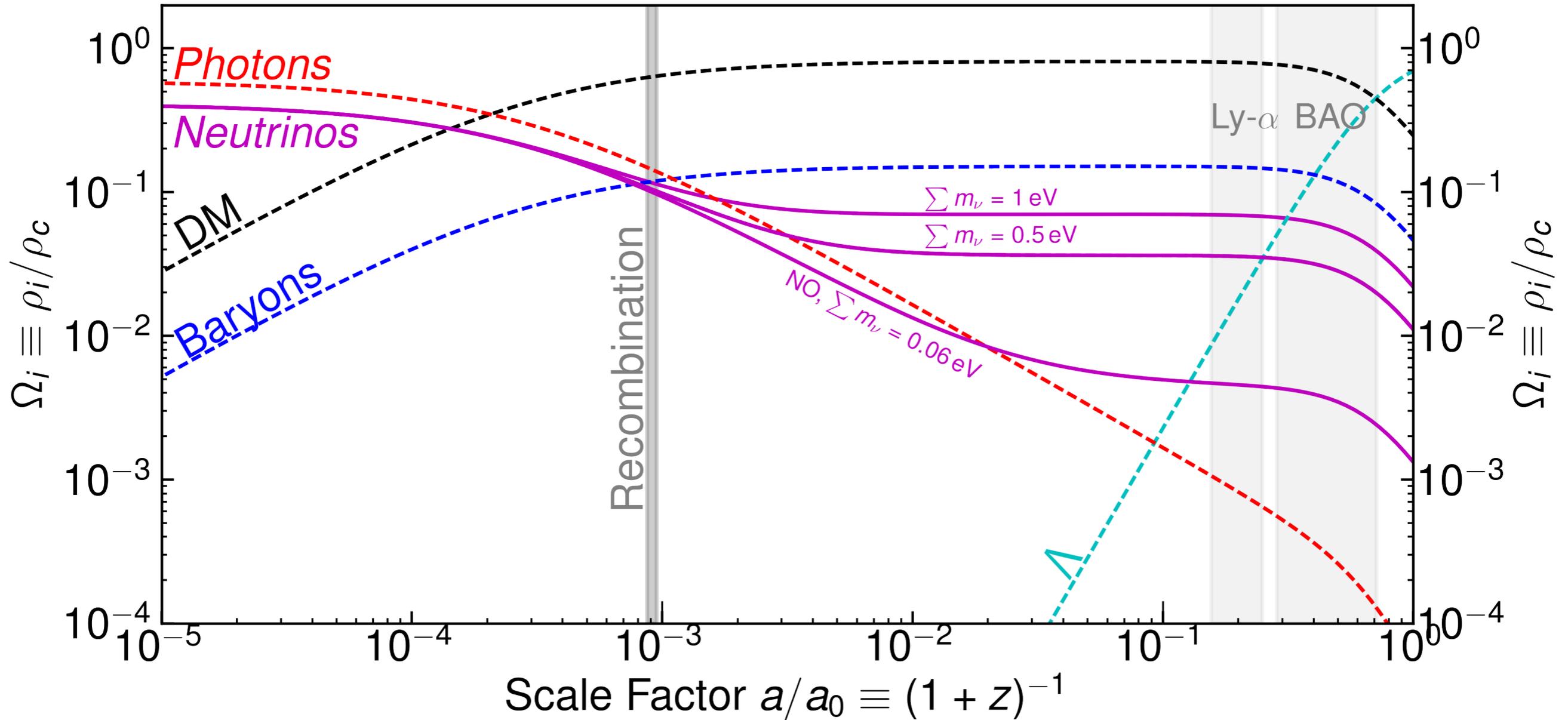
$$\sum m_\nu < 3 \text{ eV}$$

Oldengott et al. 1901.04352
Sabti, Alvey & Escudero 2110.XXXXX

- **Bounds can significantly loosen in some extensions of Λ CDM. They typically require modifications to the neutrino sector.**

But Why? and How?

Neutrino Masses from Cosmology



CMB peaks fix:

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

Comoving sound horizon (Early Universe)

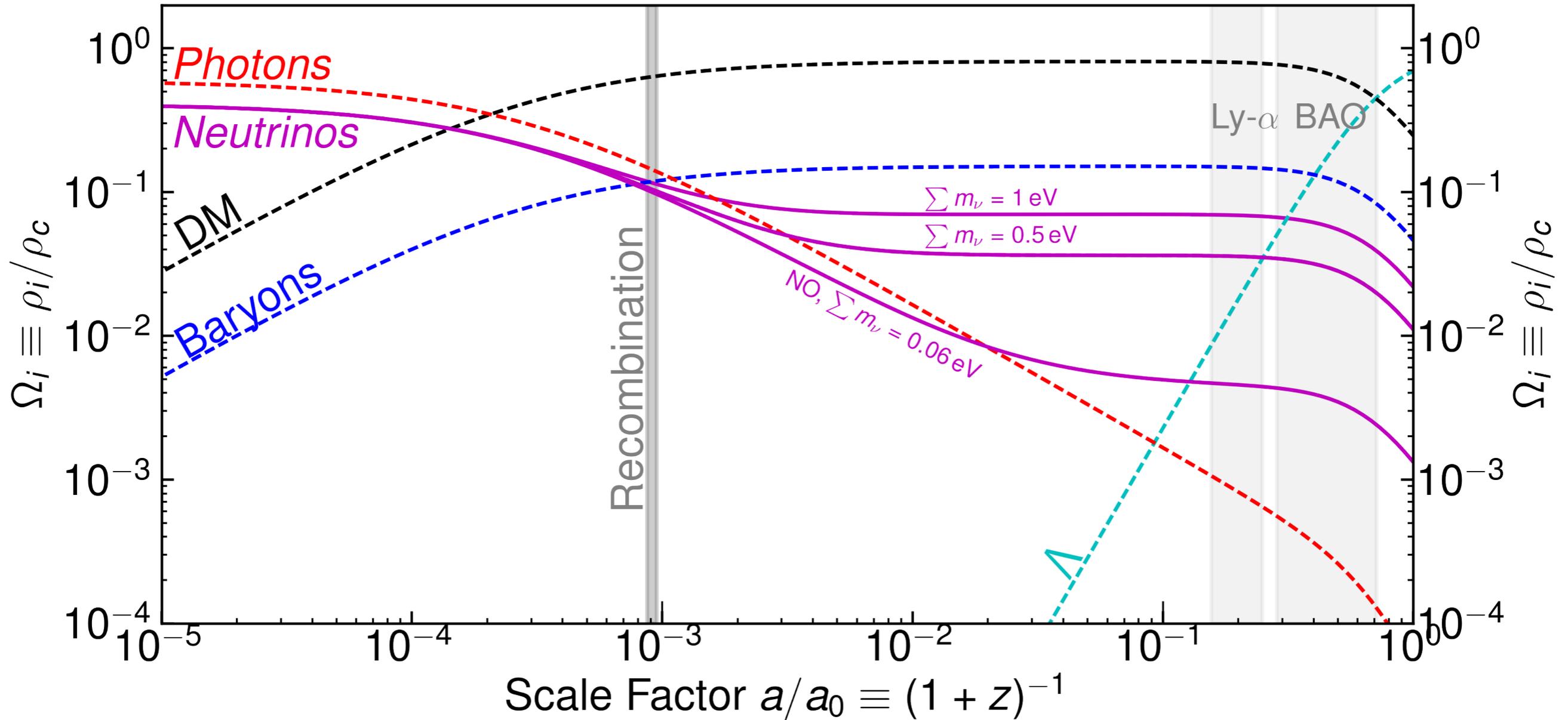
$$r_s = \int_{z_*}^{\infty} \frac{c_s}{H(z')} dz'$$

Comoving angular diameter distance (Late Universe)

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

Massive neutrinos →

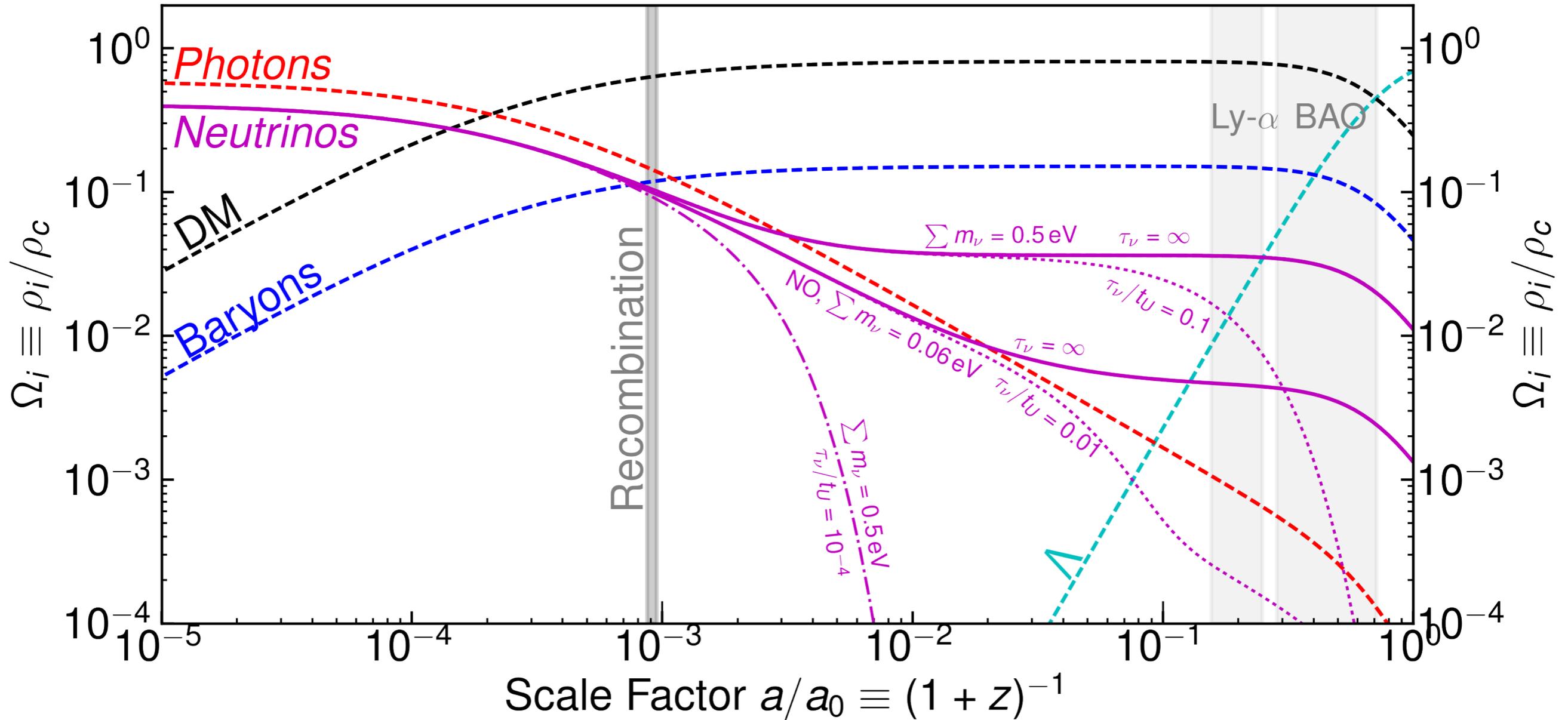
Neutrino Masses from Cosmology



Not only a background effect:

Massive neutrinos also affect CMB lensing $\propto \Omega_\nu$

Neutrino Decays



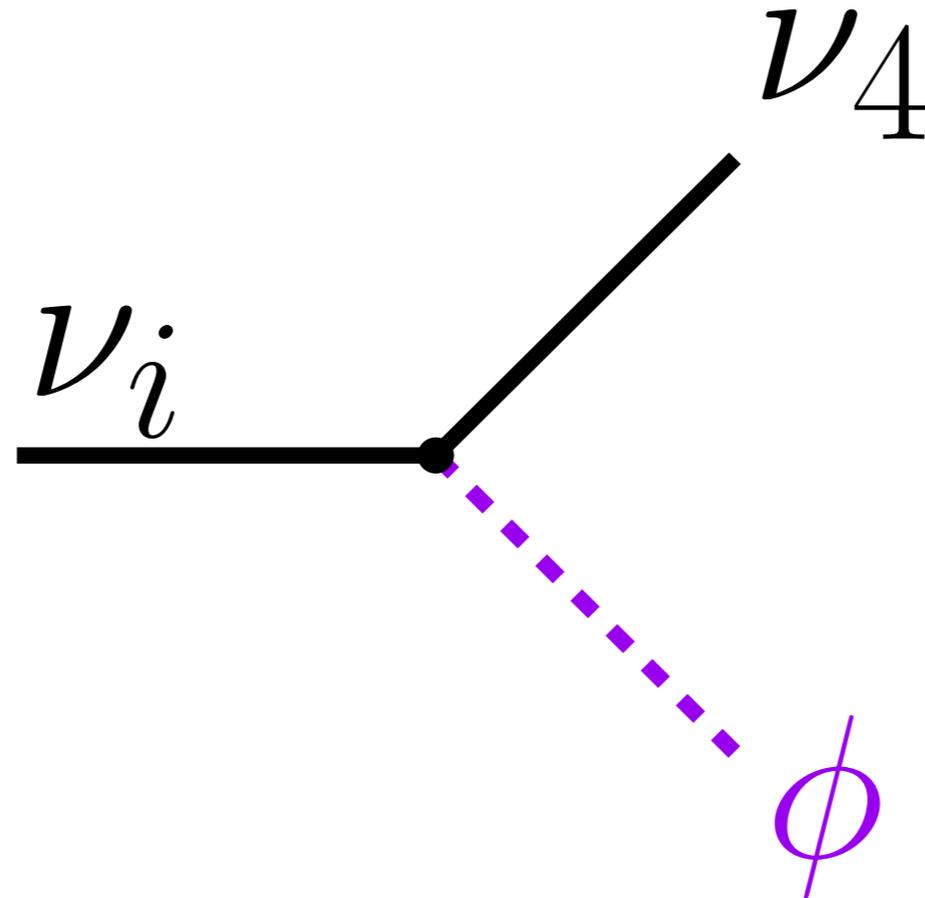
Neutrinos decaying with $\tau_\nu \lesssim t_U/10$ do not impact $D_M(z_{\text{CMB}})$

Effect of induced neutrino Lensing is substantially reduced

Unstable Neutrinos can ameliorate the bounds on Σm_ν !

Neutrino Decay Landscape

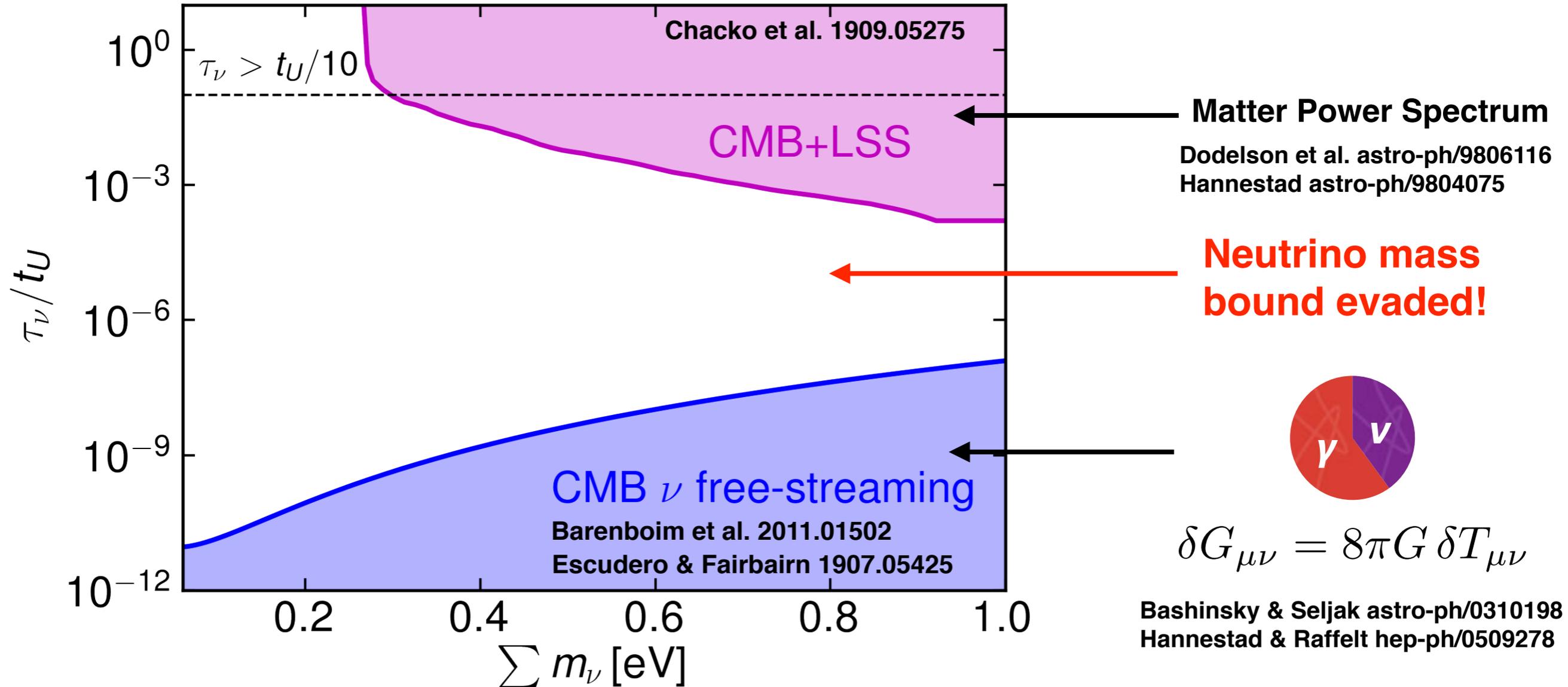
- **2 Neutrinos decay in the SM but with** $\tau_\nu \sim (G_F^2 m_\nu^5)^{-1} > 10^{33} \text{ yr} \gg t_U$
- **Radiative decays are strongly constrained:** $\tau_\nu > 10^2 - 10^{10} t_U$
- **Invisible neutrino decays are substantially less constrained:**



Neutrino Decay Landscape

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- **Radiative decays are strongly constrained:** $\tau_\nu > 10^2 - 10^{10} t_U$
- **Invisible neutrino decays are substantially less constrained:**

$$\nu_i \rightarrow \nu_4 \phi / Z'$$



Neutrino Mass and Decay Models

- $\nu_i \rightarrow \nu_4 \phi$ Can relax the bounds significantly
- Have an almost massless sterile state but that:
 - 1) Does not spoil the neutrino mass mechanism
 - 2) Is weakly coupled so that evades constraints on $U_{\alpha 4}$
 - 3) But not so weakly coupled so that $\tau_\nu < 0.1 t_U$
- **Simple solution:** Escudero, López-Pavón, Rius & Sandner, [2007.04994](#)

Add global $U(1)_X$ symmetry with a scalar field and a singlet left-handed state S_L

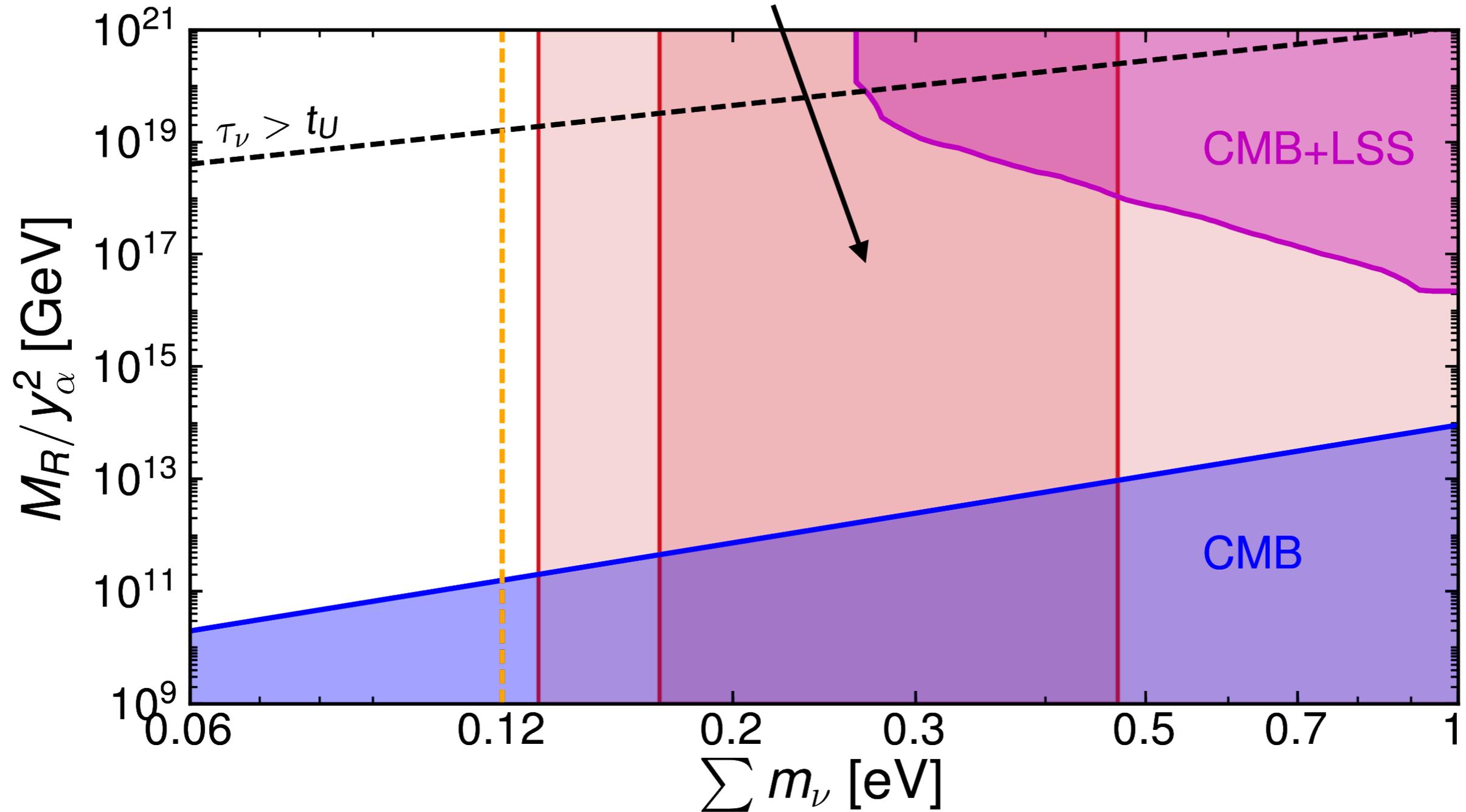
$$\mathcal{L} = y\Phi\bar{N}_R S_L \quad M_\nu|^{7\times 7} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^t & M_R & y_\alpha v_\Phi \\ 0 & (y_\alpha v_\Phi)^t & 0 \end{pmatrix}$$

- Provided $y_\alpha v_\Phi \ll m_D$
- Seesaw mechanism at play $m_\nu \simeq m_D^2/M_R$
 - Right ν_4 properties: $m_{\nu_4} \simeq 0 \quad U_{\alpha 4} \sim \frac{y_\alpha v_\Phi}{m_D} \ll 1$

Cosmological decays: $\Gamma(\nu_i \rightarrow \nu_4 \phi) \sim 10^6 t_U^{-1} y_\alpha^2 \left(\frac{m_\nu}{0.3\text{eV}}\right)^2 \left(\frac{10^{14}\text{ GeV}}{M_R}\right)$

Neutrino Mass and Decay Models

Mass predictions for $U(1)_{\mu-\tau}$



Cosmological Neutrino mass bounds are indeed relaxed!

Check out: 2007.04994 with López-Pavón, Rius & Sandner

Mid Seminar Pause =)

Questions?

Comments?

Criticism?

All are most welcome!

Current Constraints on N_{eff}

- **Current Constraints**

BBN

$$N_{\text{eff}} = 2.92 \pm 0.28$$

Fields et al. 1912.01132

Planck+BAO

$$N_{\text{eff}} = 2.99 \pm 0.17$$

Planck 2018, 1807.06209

Planck+BAO+H0

$$N_{\text{eff}} = 3.27 \pm 0.15$$

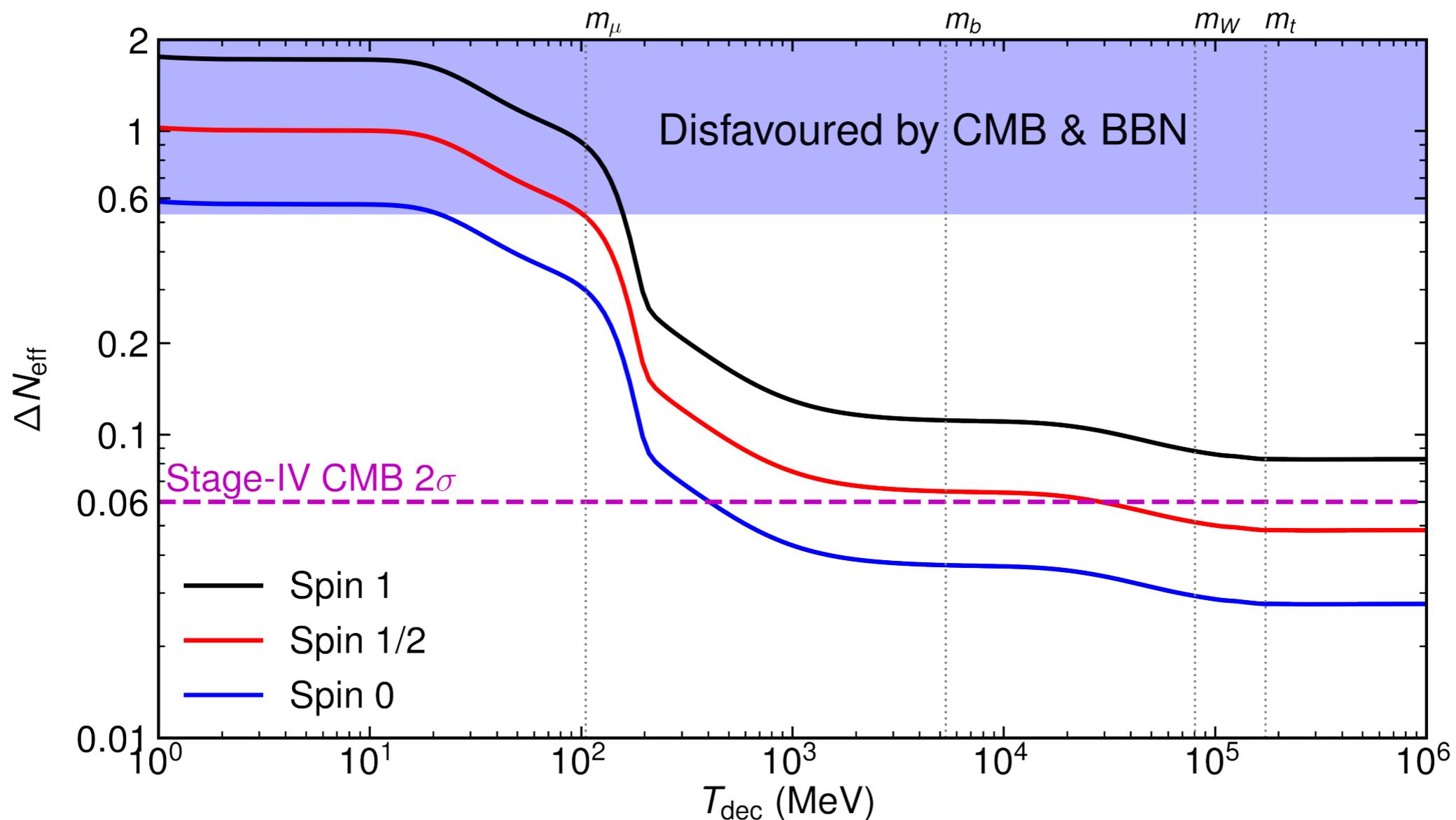
Planck 2018, 1807.06209

- **Standard Model Prediction:** $N_{\text{eff}}^{\text{SM}} = 3.044$

- **Data is in excellent agreement with the Standard Model prediction**

Constraints from N_{eff}

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



Constraints from Neff

Constraints are relevant in many other BSM settings:

- **WIMPs**

$$m_{\text{WIMP}} > (4 - 10) \text{ MeV}$$

Sabti et al. 1910.01649
Boehm et al. 1303.6270

- **GeV-Sterile Neutrinos**

$$\tau_N \lesssim 0.05 \text{ s}$$

Sabti et al. 2006.07387
Dolgov et al. hep-ph/0008138

- **Vector Bosons**

$$g \lesssim 10^{-10} \quad m \lesssim 10 \text{ MeV}$$

Escudero et al. 1901.02010
Kamada & Yu 1504.00711

- **Axions**

Raffelt et al. 1011.3694
Blum et al. 1401.6460

- **Low Reheating**

$$T_{\text{RH}} > (2 - 5) \text{ MeV}$$

de Salas et al. 1511.00672
Hasegawa et al. 1908.10189

- **Variations of G_N**

$$G_{\text{BBN}}/G_0 = 0.98 \pm 0.03$$

Alvey et al. 1910.10730
Copi et al. astro-ph/0311334

- **PBHs**

$$6 \times 10^8 \text{ g} < M_{\text{PBH}} < 2 \times 10^{13} \text{ g}$$

Carr et al. 0912.5297
Keith et al. 2006.03608

Check out a recent review on non-standard expansion histories:

[2006.16182](#) Vaskonen & Tenkanen et al. (Escudero & Poulin)

The Hubble Tension

- **The Hubble Tension:**

$$H_0 = 73.2 \pm 1.3 \text{ km/s/Mpc}$$

Riess et al. 2012.08534

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

Planck 2018 1807.06209

4.2 σ tension within Λ CDM!

- **A pattern has clearly emerged:**

- **4-6 σ tension depending upon the datasets included**

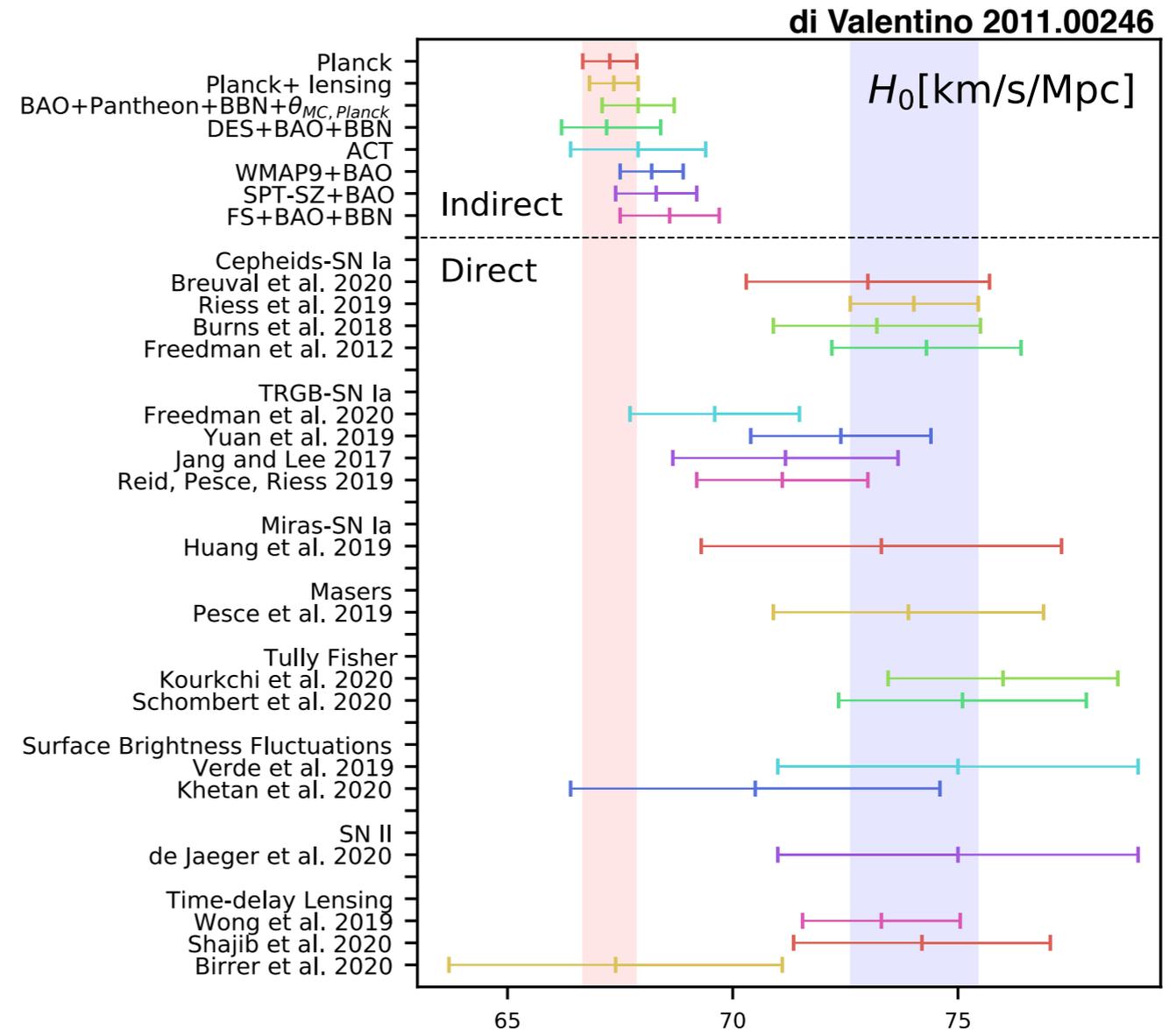
see Verde, Treu, Riess 1907.10625 for a review

- **Baryon Acoustic Oscillations point to small H_0**

- **Cepheids+Type-Ia SN are among the most precise and they point to**

$$H_0 \sim (74 \pm 2) \text{ km/s/Mpc}$$

- **Some analyses do point to smaller values: Freedman et al. 20' and Birrer et al. 20'**



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 Λ CDM**

- **Possibilities beyond Λ CDM:** See 2103.01183 by di Valentino et al. for a review

- 1) **Late Universe Modifications** **very unlikely**
- 2) **Early Universe Modifications** **hard but doable**

*After 7 years of intense scrutiny, it has been pointed out recently that perhaps dust could play a relevant role Mortsell et al. 2105.11461

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: $\theta_s \equiv r_s / D_M(z_*)$ (controls the positions of the peaks)

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

**Comoving sound horizon
(Early Universe)**

$$D_M(z) = \int_0^z \frac{1}{H(z')} dz' \longleftarrow H_0$$

**Comoving angular diameter distance
(Late Universe)**

$$H_0 \simeq [67.5 + 6.2 \Delta N_{\text{eff}}] \text{ km/s/Mpc} \quad \text{Vagnozzi 1907.07569}$$

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

Neutrinos and the Hubble Tension

Why Neutrinos?

- 1) Neutrinos are always a relevant species in the Universe evolution**
- 2) Neutrino masses are the only Laboratory evidence of Physics Beyond the Standard Model**

Neutrinos and the Hubble Tension

● Dark Radiation

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

(68 % CL, Planck+BAO+H0)

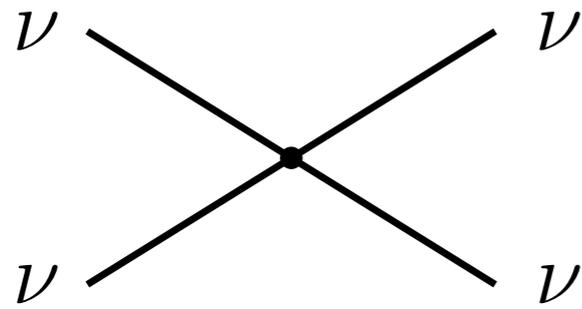
Clear Interpretation

H₀ tension from 4.4σ to 3σ

CMB fit is degraded



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



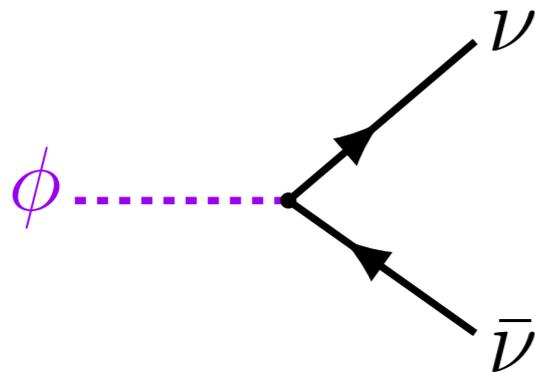
H₀ tension solved if TEEE data is ignored

If pol data is included no solution for H₀

Almost excluded by Lab data (Blinov++1905.02727)



● Light Neutrinophilic Scalar + Dark Radiation Escudero & Witte 1909.04044



H₀ tension from 4.4σ to 2.5σ

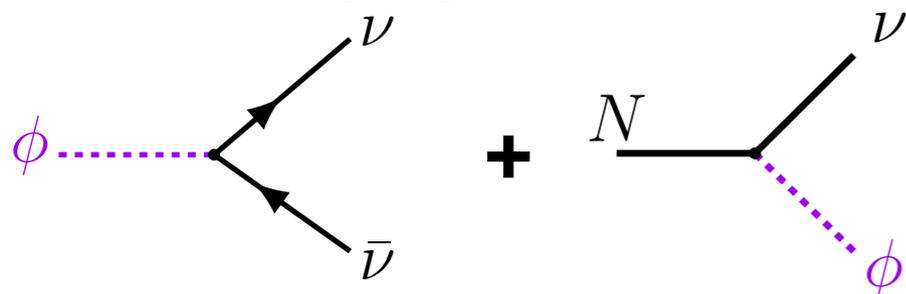
CMB fit is not degraded

Direct connection with Seesaw

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



● Primordial population of light scalars Escudero & Witte 2103.03249



Sterile neutrinos can source $\Delta N_{\text{eff}} \sim 0.5$

Sterile neutrinos can lead to Leptogenesis

H₀ tension from 4.2σ to 2σ

Neutrinos and the Hubble Tension

● Early Dark Energy sourced by neutrinos

Sakstein & Trodden 1911.11760

Nice way to solve the coincidence problem 

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

But the CI'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 

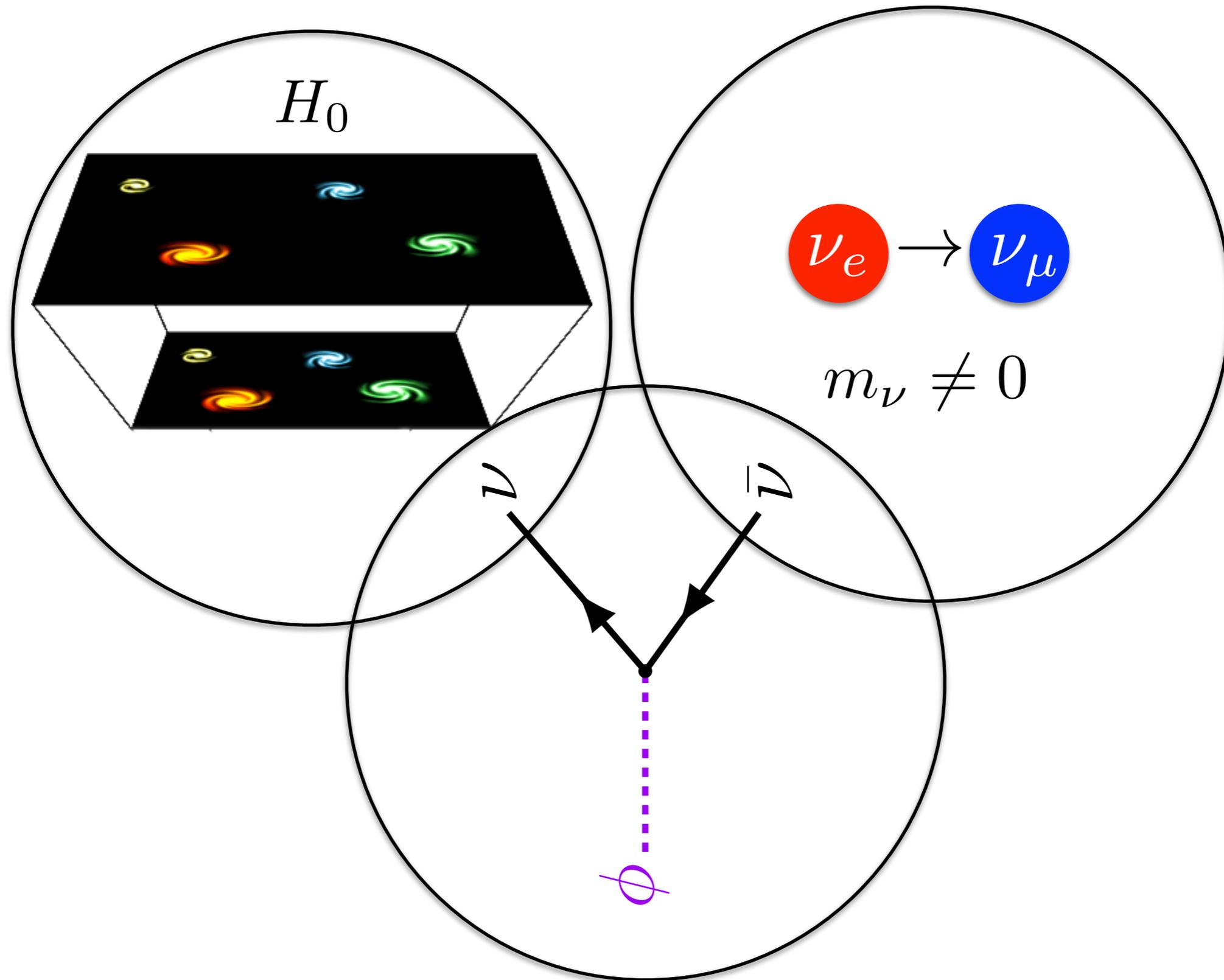
Nice idea to try to avoid the cosmo problems with $m_s \sim \text{eV}$ 

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

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

**Common features of all approaches:
New interactions and an enhanced expansion history**

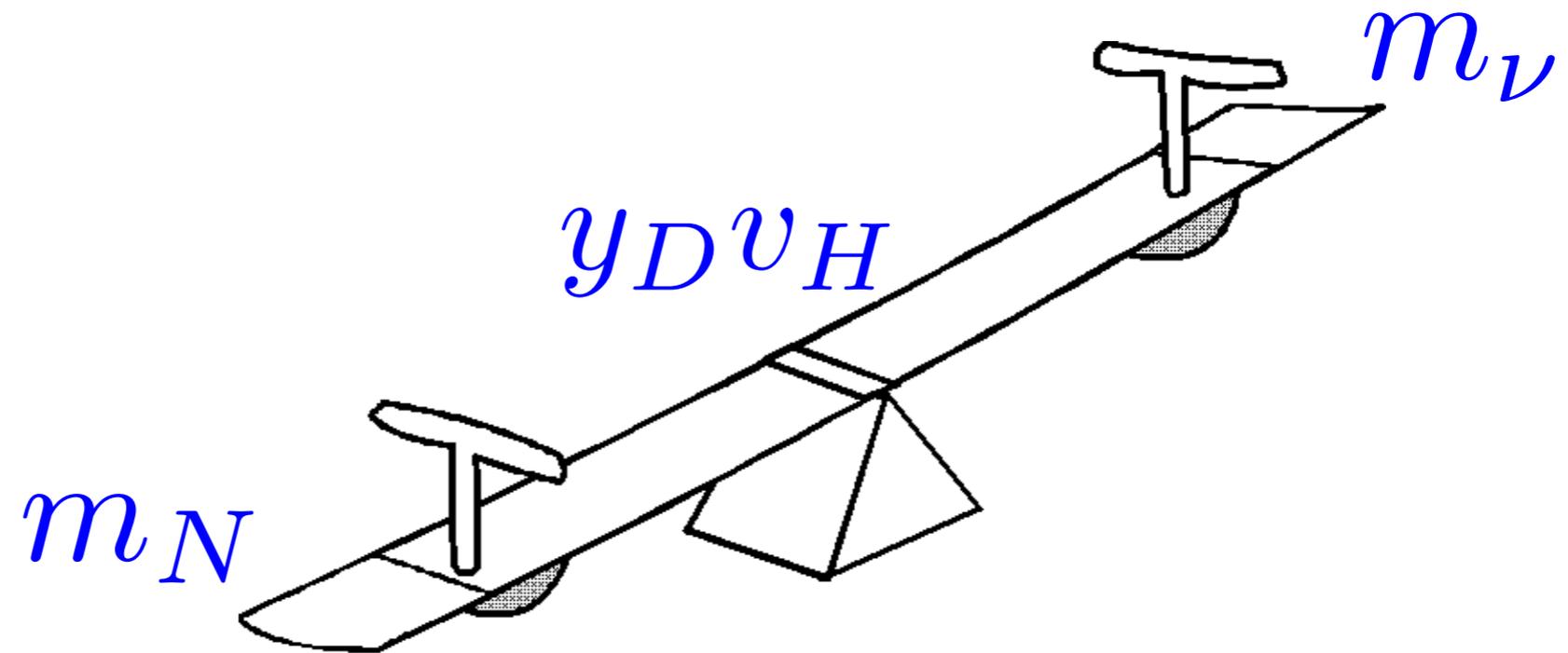
Escudero & Witte 19'-21'



The Seesaw Mechanism

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

Type-I seesaw



Neutrinos are very light Majorana particles:

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

The Scenario

Global $U(1)_L$ Spontaneously Broken Symmetry

Chikashige, Mohapatra & Peccei (1981)

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

Very weakly interacting: $\lambda \simeq 10^{-13} \frac{m_\nu}{0.05 \text{ eV}} \frac{246 \text{ GeV}}{v_L}$ (type-I seesaw)

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

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

Rothstein, Babu, Seckel hep-ph/9301213

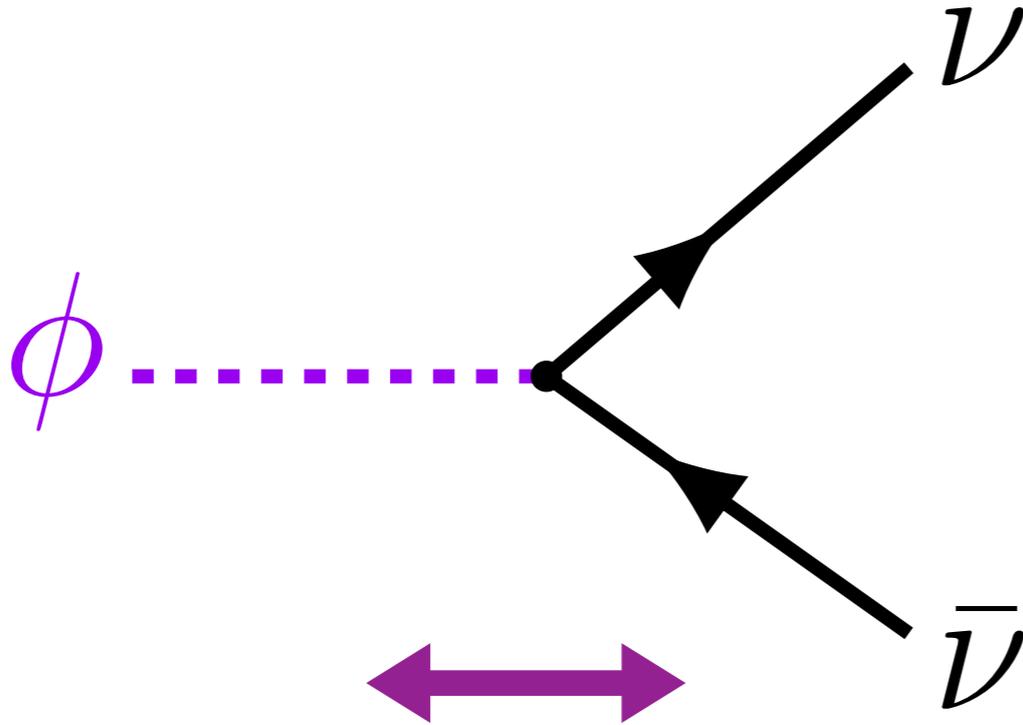
Akhmedov, Berezhiani, Mohapatra, Senjanovic hep-ph/9209285

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

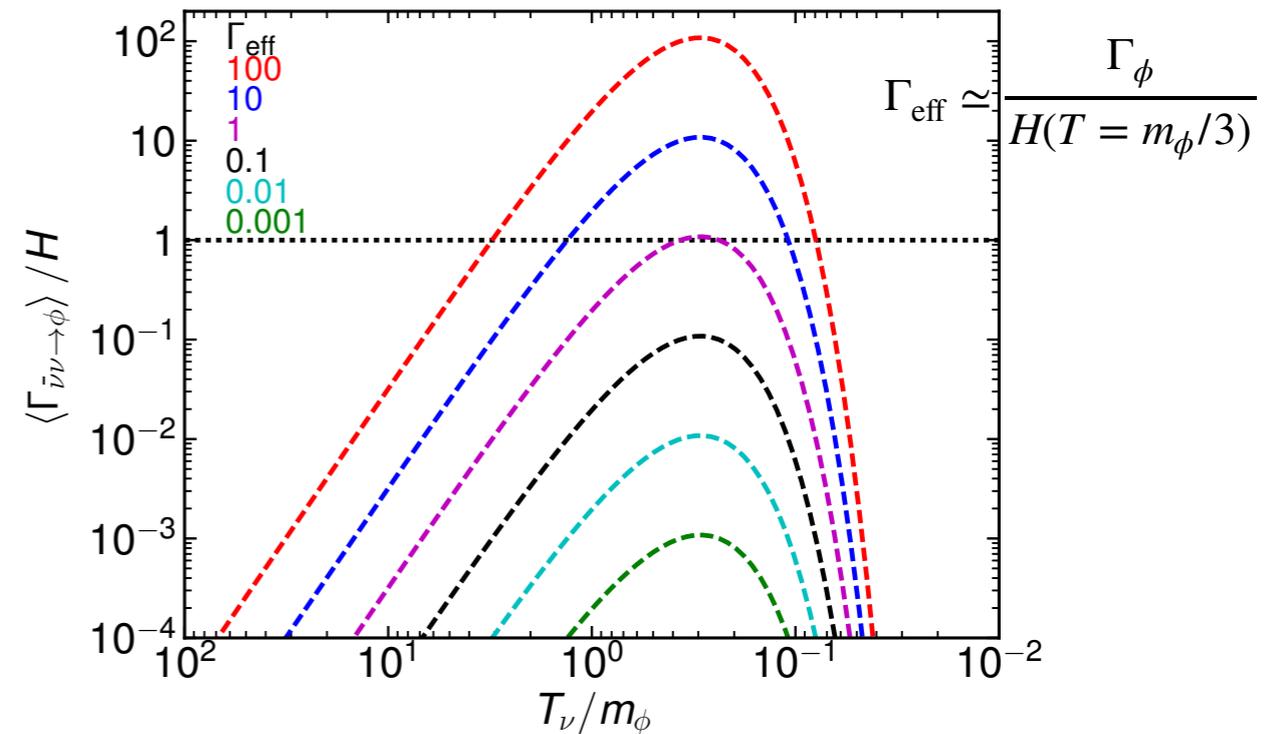
$\phi \rightarrow \bar{\nu}\nu$ $\tau_\phi \sim t_{\text{rec}}/10$
for $m_\phi \sim \text{eV}, v_L \sim 1 \text{ TeV}$

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

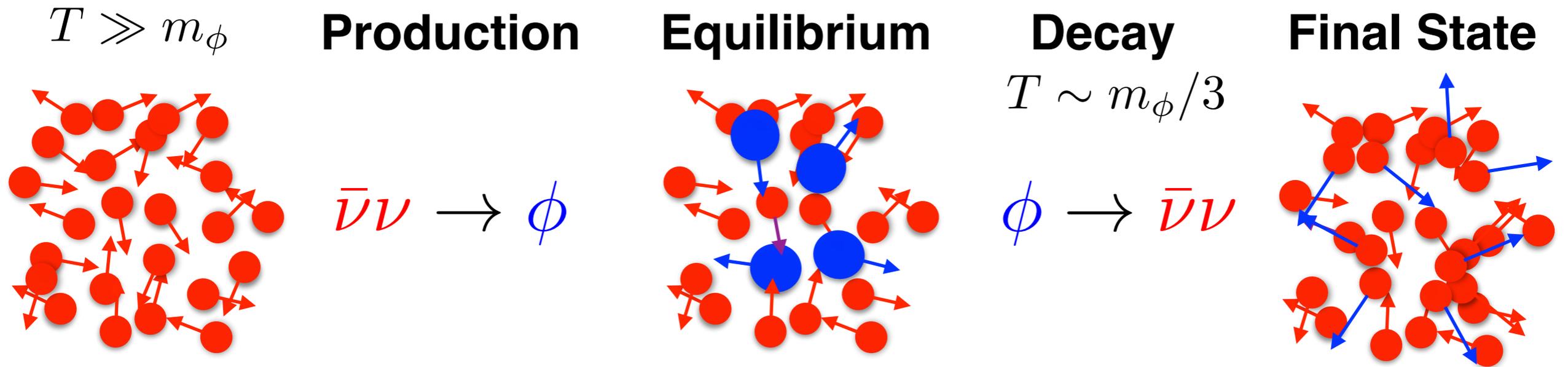
- **Non-standard expansion history**
- **Erase the neutrino anisotropic stress**

● **We solve the Boltzmann equation for the background**

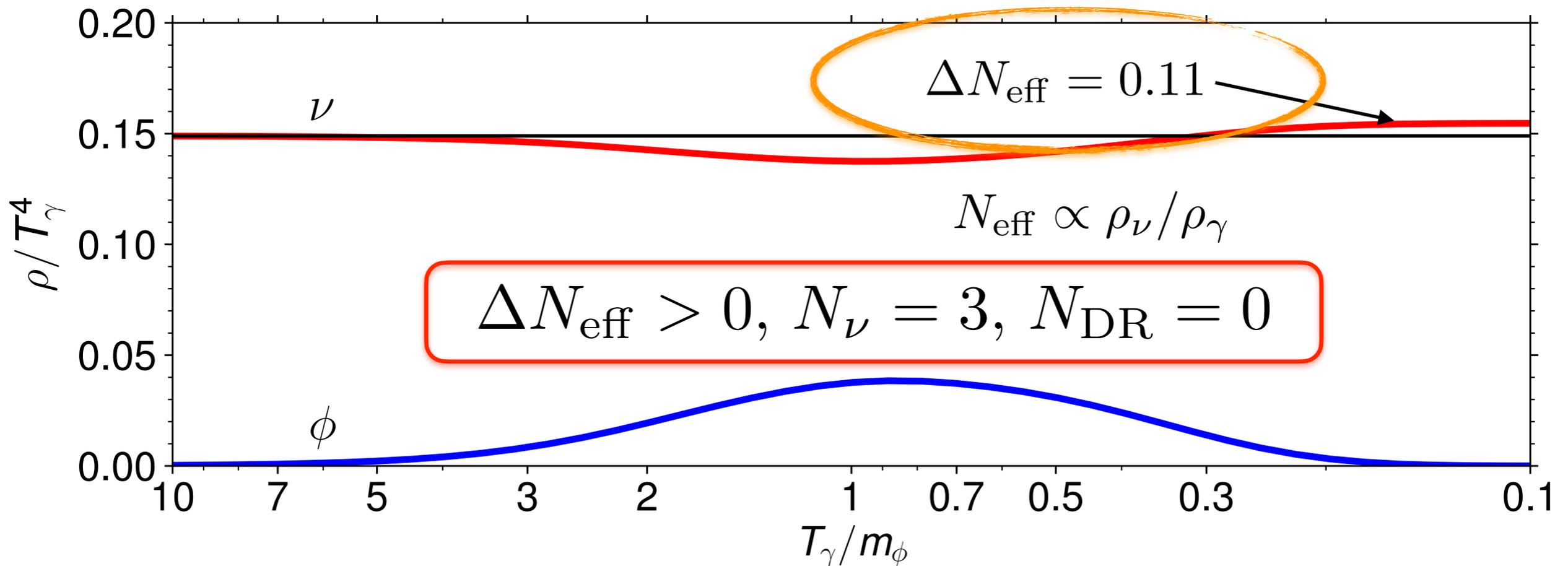
Escudero 1812.05605, 2001.04466

● **We include the neutrino-majoron Boltzmann hierarchy in CLASS**

Cosmological Implications

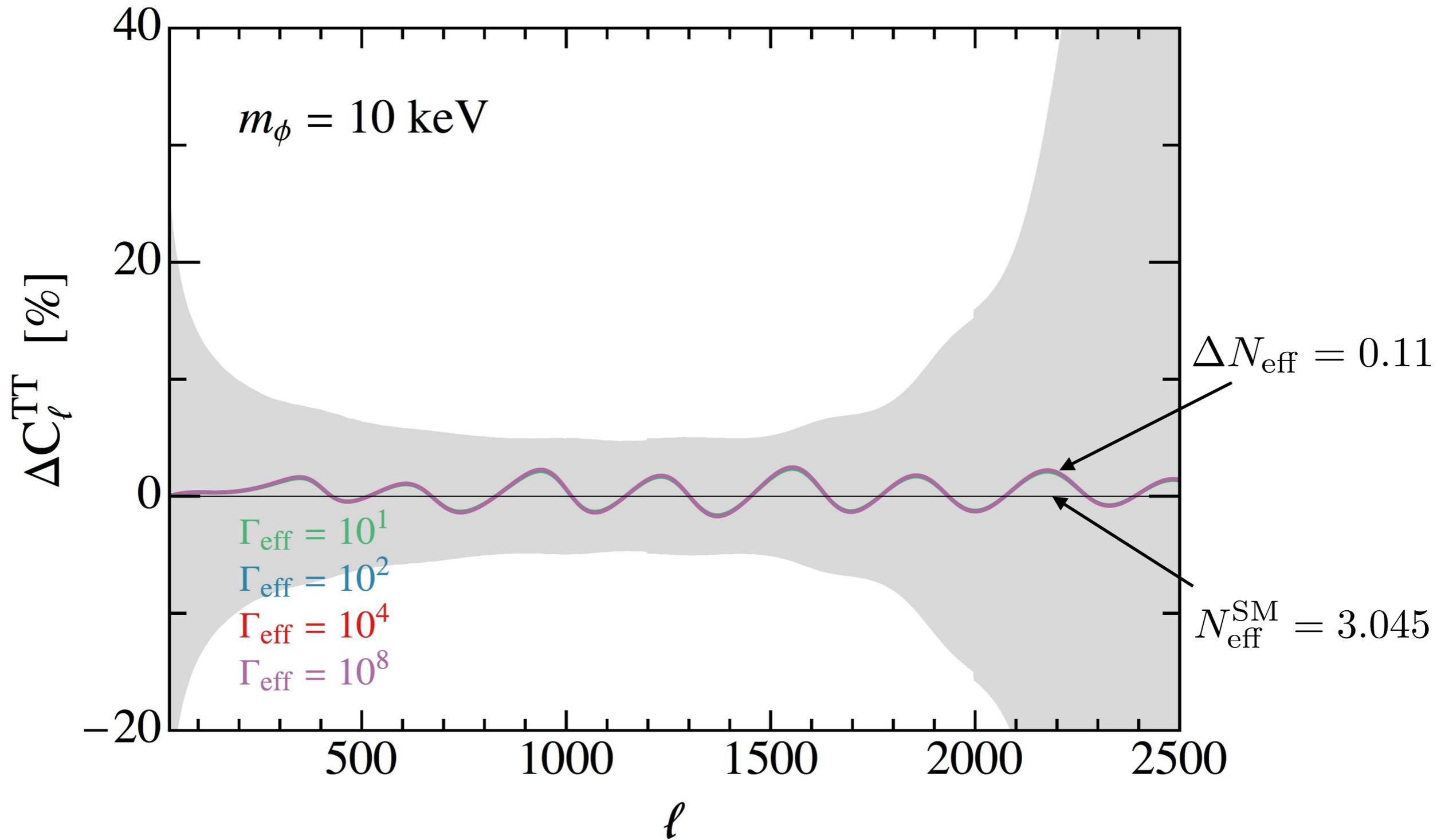


$$\Gamma_\phi \simeq H(T_\nu = m_\phi/3)$$



Effects on the CMB

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



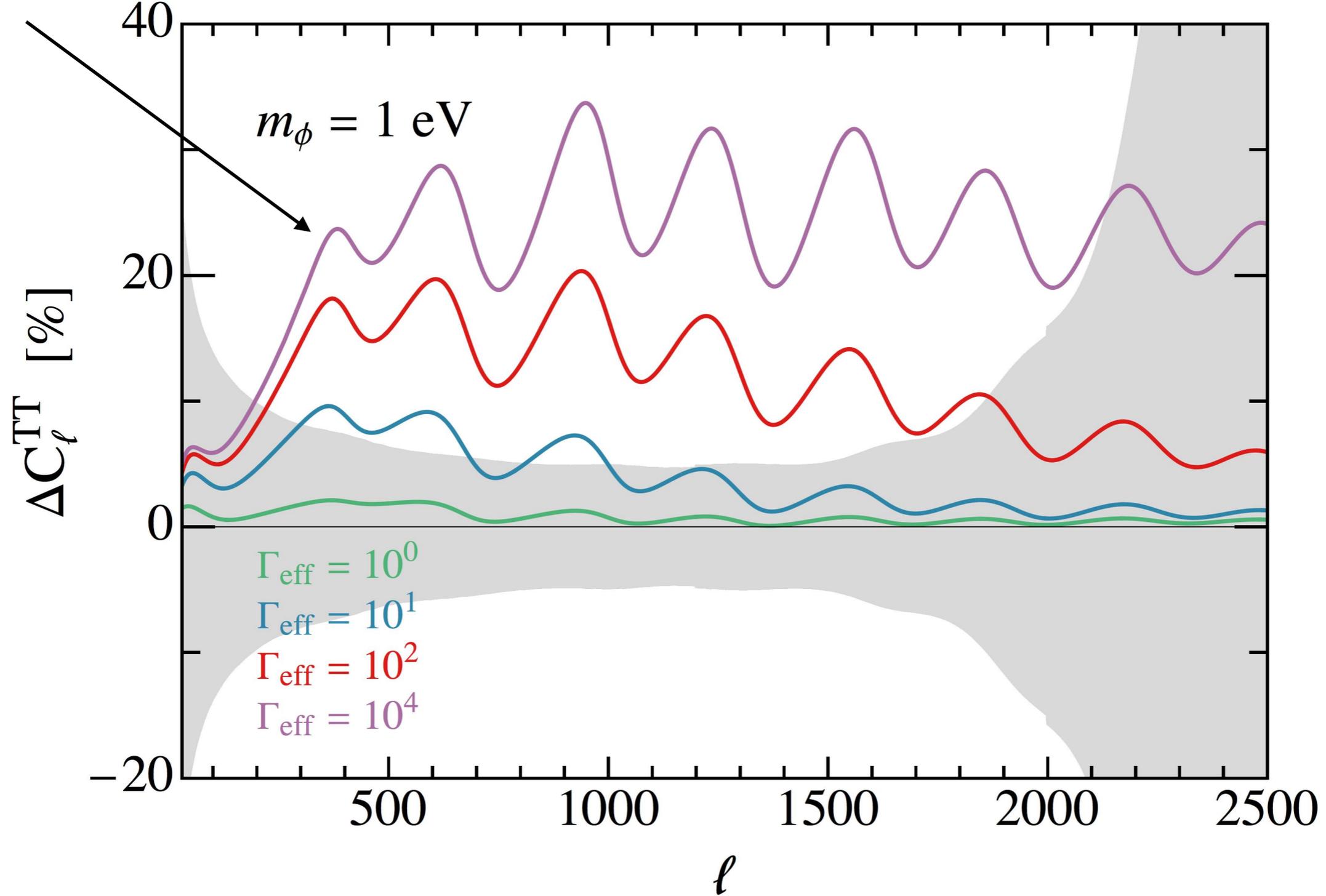
Effects on the CMB

see Bashinsky and Seljak astro-ph/0310198

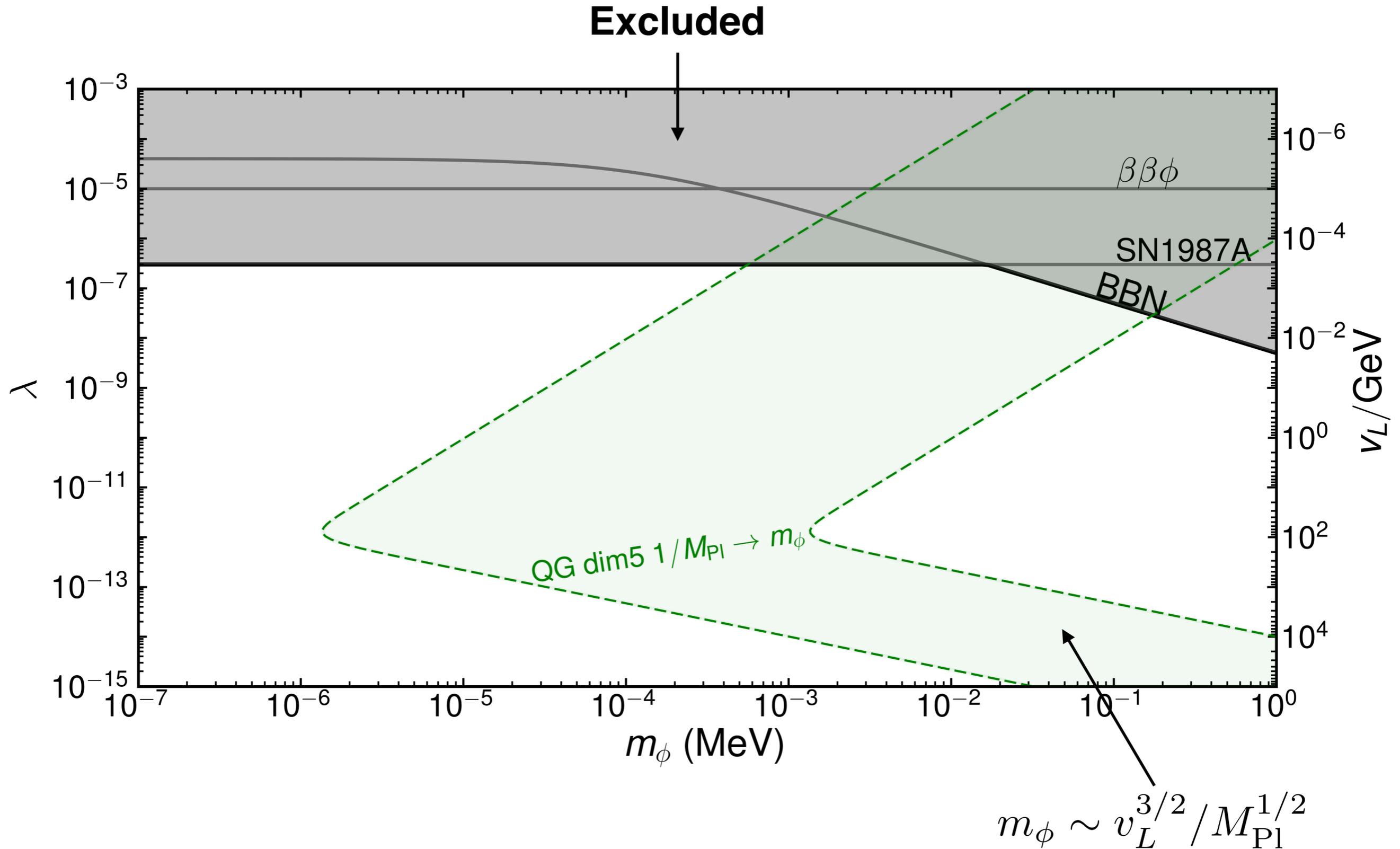
$$\Gamma_{\text{eff}} = \left(\frac{\lambda}{4 \times 10^{-12}} \right)^2 \left(\frac{1 \text{ keV}}{m_\phi} \right)$$

$\sigma_\nu \rightarrow 0$

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

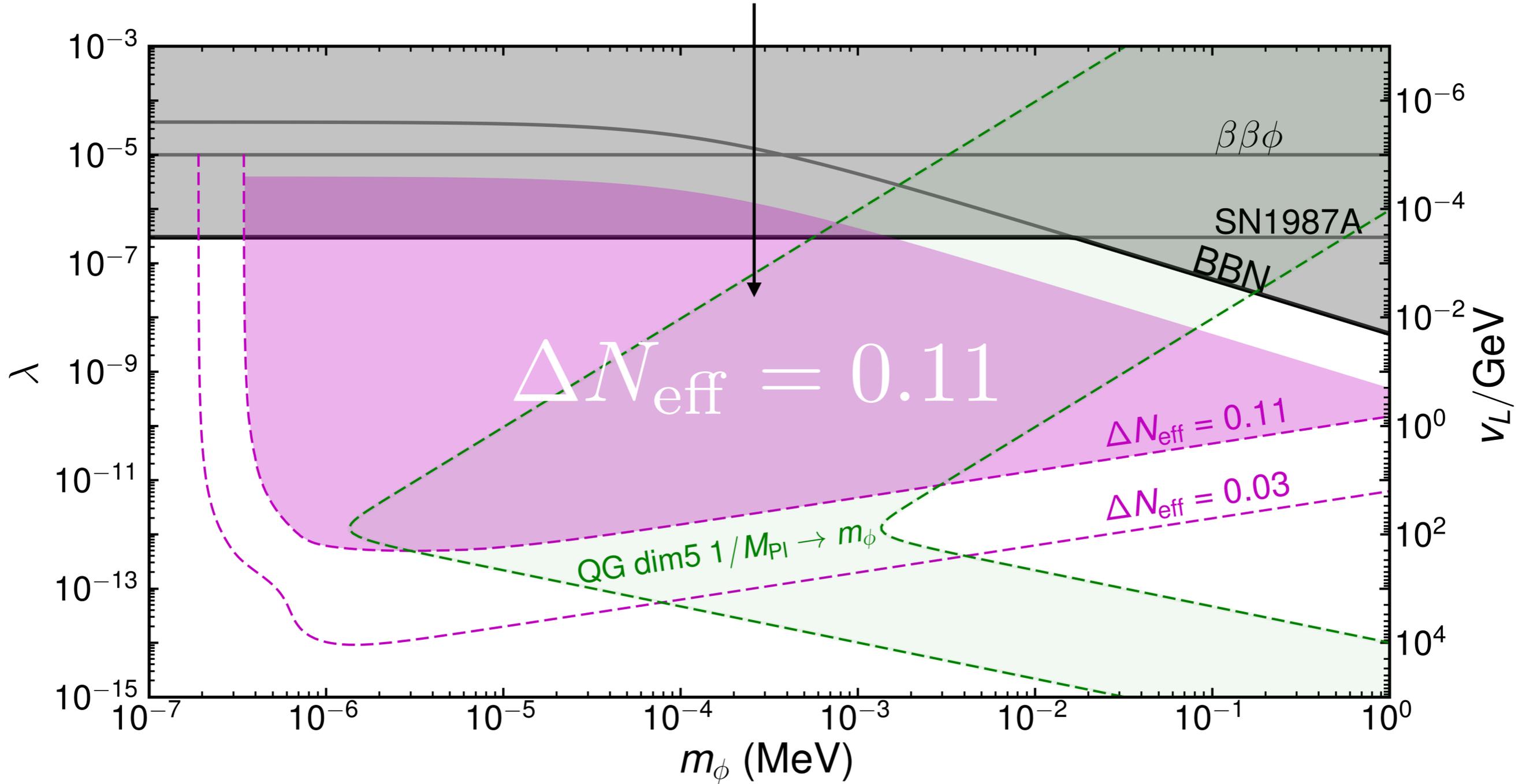


Parameter Space



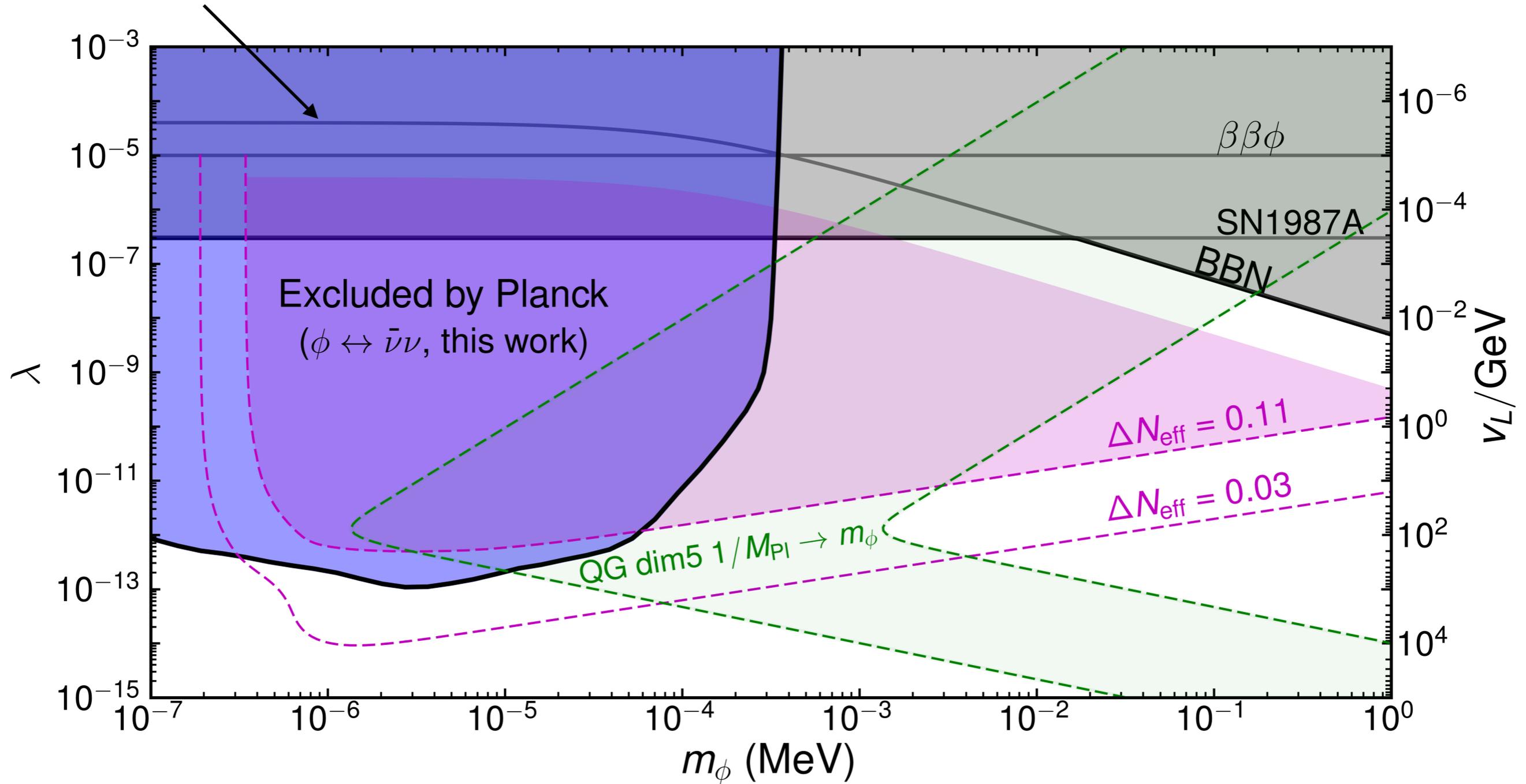
Parameter Space

Enhanced expansion history

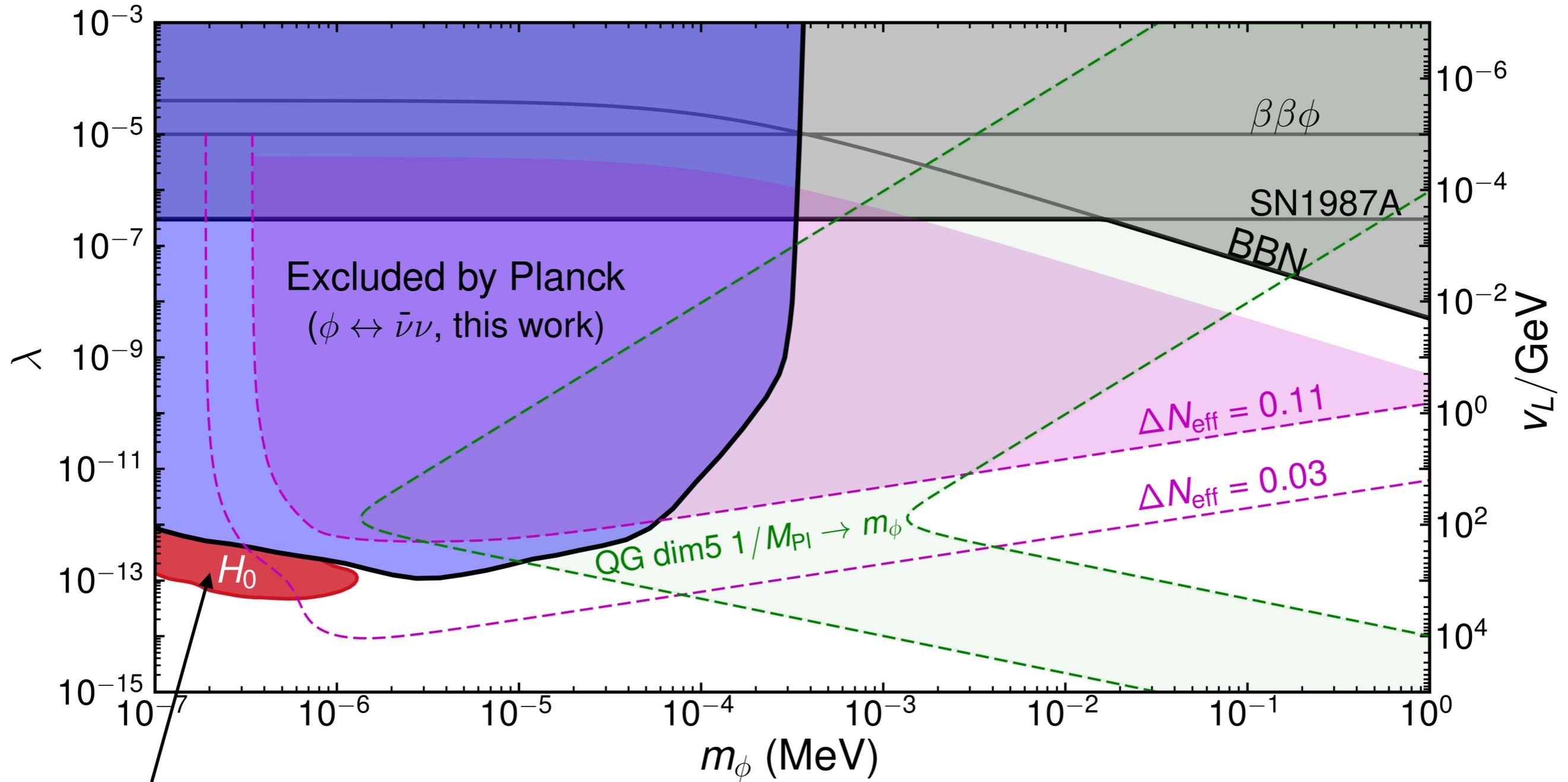


Parameter Space

Full MCMC to Planck 2018 data

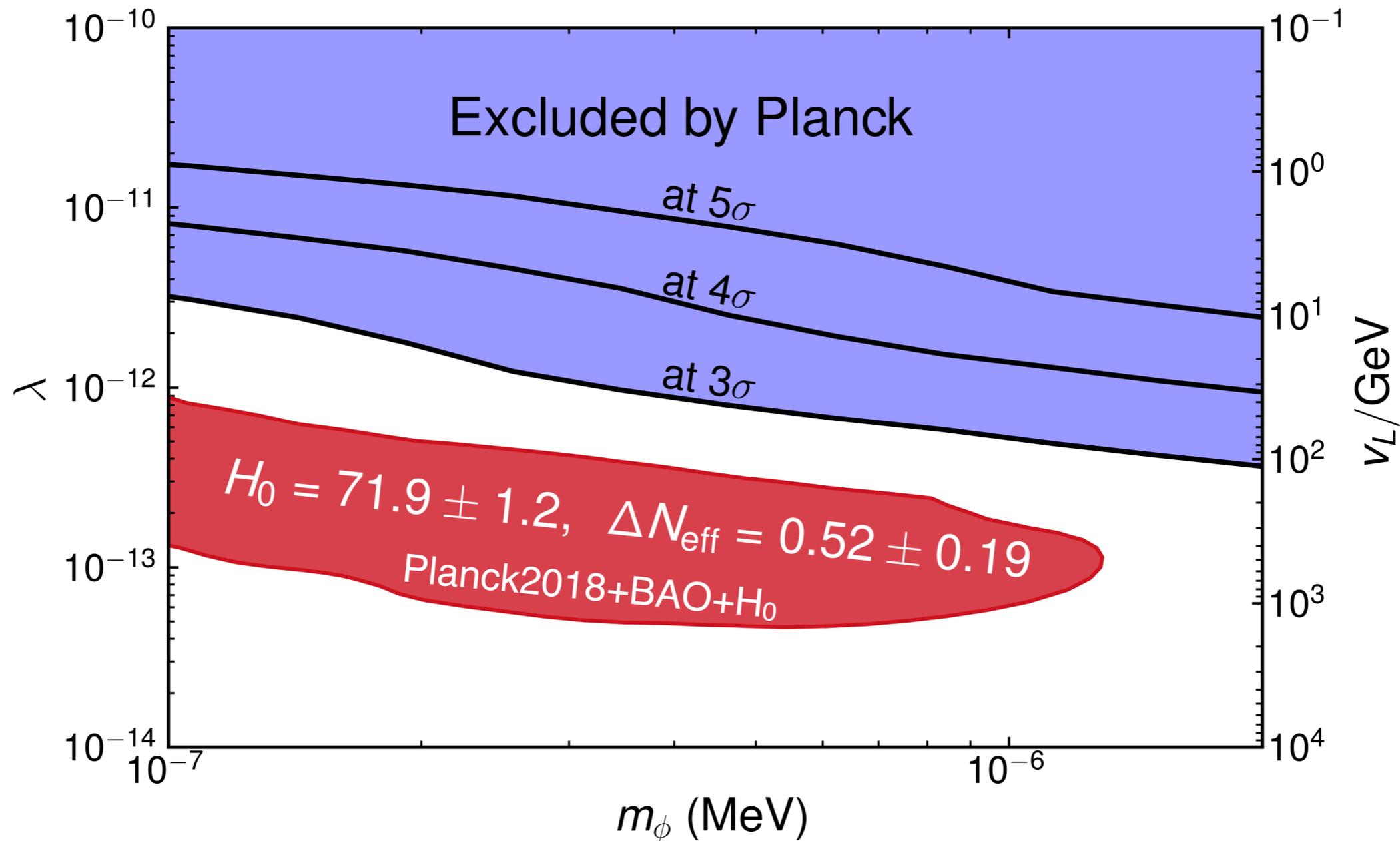


Parameter Space



1 σ preference when including H_0 in the fit and an additional ΔN_{eff}

Parameter Space for H_0



- Requires a positive $\Delta N_{\text{eff}} \sim 0.5$
- H_0 Planck 2018 fit is not degraded wrt ΛCDM
- Very close to the electroweak scale $v_L \sim (0.1 - 1) \text{ TeV}$

The Majoron behind the H_0 tension?

- **The H_0 tension: Beyond Λ CDM?**
- **The specific case of the Majoron:**
 - **Compelling extension of the SM**
 - **Couplings from seesaw and mass from gravity**
 - **Planck sets very stringent constraints**
 - **Could substantially ameliorate the tension for:**
 - $m_\phi \sim (0.1 - 1) \text{ eV}$
 - $v_L \sim (0.1 - 1) \text{ TeV}$
 - $\Delta N_{\text{eff}} \sim 0.5$
 - 😐 $\Delta N_{\text{eff}} \sim 0.5$ is somewhat ad hoc
 - 😊 Now we have a very good reason for it!

Escudero & Witte 21':
2103.03249 (EPJC)

- a) $\Delta N_{\text{eff}} \sim 0.3$ can arise from the decays of sterile neutrinos in the early Universe
- b) These sterile neutrinos can be responsible for Leptogenesis!
- c) H_0 tension from 4.2σ to 2σ

Conclusions

Neutrino Masses:

Cosmological Bounds are very stringent $\sum m_\nu < 0.12 \text{ eV}$ (95 % CL)

Invisible Neutrino decays are a particle physics avenue to relax the bounds

N_{eff}:

Planck: $N_{\text{eff}} = 2.99 \pm 0.17$

BBN: $N_{\text{eff}} = 2.92 \pm 0.28$

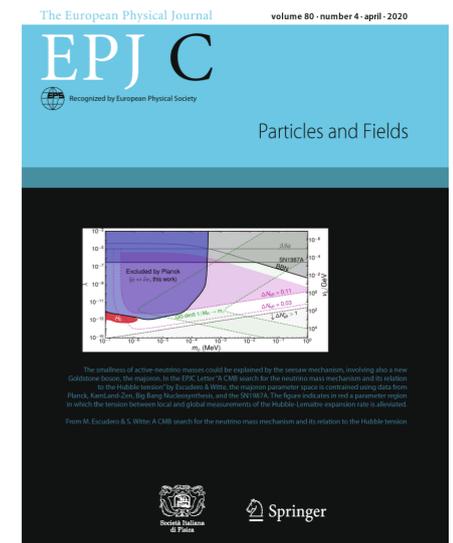
Excellent agreement with SM prediction

Strong constraint BSM, e.g. $m_{\text{WIMP}} > 4 \text{ MeV}$

The Hubble Tension:

Many neutrino related approaches

The Majoron represents a well-motivated possibility



Outlook

Neutrino Masses:

KATRIN reach:

$$\sum m_\nu < 0.6 \text{ eV} \quad (90\% \text{ CL})$$

Next Galaxy Surveys+CMB should detect neutrino masses

e.g.: 1308.4164 Font-Ribera et al., 1408.7052 Kitching et al.

DESI/EUCLID+Planck: $\sigma \left(\sum m_\nu \right) \simeq 0.02 \text{ eV} \quad (1 \sigma)$

Neff:

Stage-IV experiments will reach 1% precision, e.g. CMB-S4
Strong constraints on new physics

The Hubble Tension:

Further data on the way: Gaia, Strong Lensing, GW, DESI ...
More models will appear and neutrinos will play a leading role

Time for Questions and Comments

Upcoming years are going to be exciting!



Thank you for your attention!