Title: Neutrinos in Cosmology after Planck: What are their masses, properties, and relationship with the Hubble tension?

Speakers: Miguel Escudero

Series: Particle Physics

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Abstract: Neutrinos are a key (although implicit) ingredient of the standard cosmological model, LambdaCDM. Firstly, neutrinos directly participate in neutron freeze out during BBN, and secondly, they represent 40% of the energy density of the Universe after electron positron annihilation up to almost matter radiation equality. The latter fact makes neutrinos a necessary element to understand CMB observations.

In this talk, I will review the cosmological implications of neutrinos. I will explain how current cosmological observations can be used to constrain their masses, their abundances, and their properties -- such as their interaction rate with other species. In particular, I will highlight that the typically very stringent constraint on their masses can be substantially relaxed if neutrinos decay on cosmological timescales. I will illustrate the implications of neutrino decays in cosmology with a few well-motivated neutrino mass models in which neutrinos can decay. I will then show that Planck CMB observations are a powerful tool to constraint neutrino interactions with neutrinophilic bosons. In particular, I will demonstrate that Planck legacy constraints neutrinophilic bosons with couplings as small as 10^{-13} with neutrinos for boson masses in the 0.1 eV < m < 300 eV range. I will finish by reviewing the role neutrinos can play with regards to the outstanding Hubble tension. I will show that pseudogoldstone bosons (majorons) interacting with neutrinos right before recombination represent a well motivated possibility to ameliorate (and potentially solve) the Hubble tension.

Neutrino Cosmology after Planck

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European Research Council
Established by the European Commission

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**

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- **Neutrinos are ubiquitous in Cosmology**

  Use Cosmological data to understand their properties

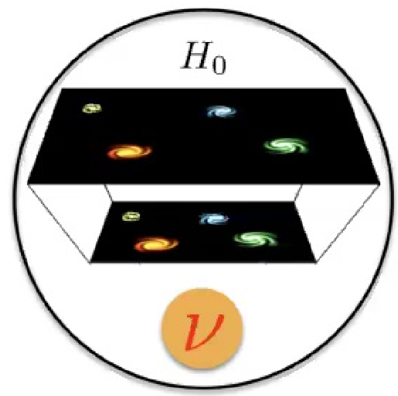
- **Neutrino masses are the only laboratory evidence of physics beyond the Standard Model**

  Use them as a link to BSM physics

Topics Covered:

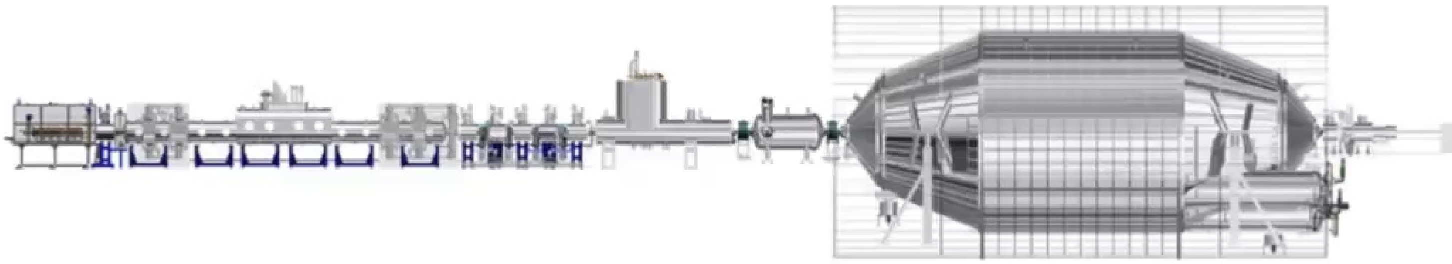
$\sum m_\nu$

N_{eff}



New Laboratory Neutrino Mass Bound

KATRIN experiment $^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$



Mainz and Troitsk (2004): $m_{\nu_e} < 2.2\,\mathrm{eV}$ **(95 % CL)**

Current laboratory bound: $m_{\nu_e} < 0.9\,\mathrm{eV}$ **(90 % CL, FC)**
(PRL 2019, 1909.06048)

$\sum m_\nu < 2.7\,\mathrm{eV}$ **(95 % CL, FC)**

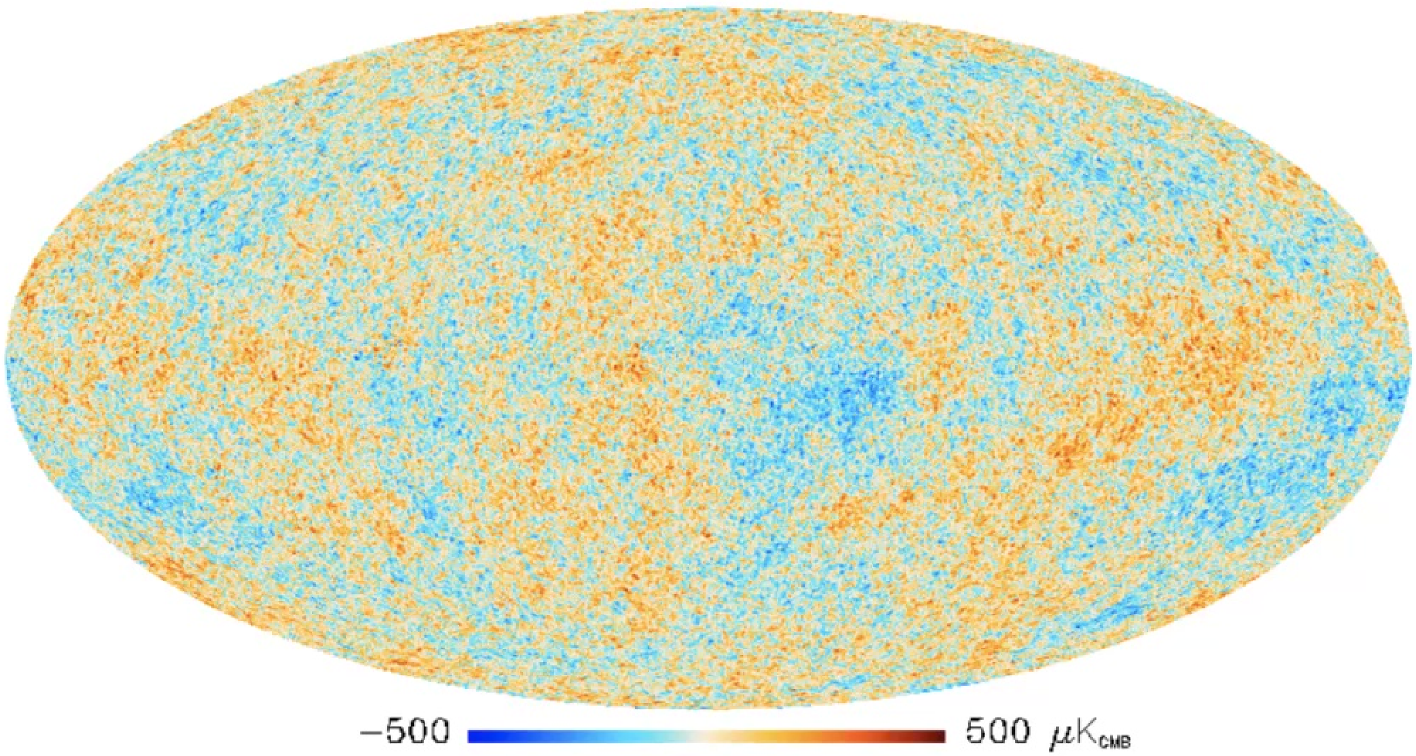
KATRIN expected reach
(in ~4-years)
Neutrino2020

$m_{\nu_e} < 0.2\,\mathrm{eV}$ **(90 % CL)**

$\sum m_\nu < 0.6\,\mathrm{eV}$

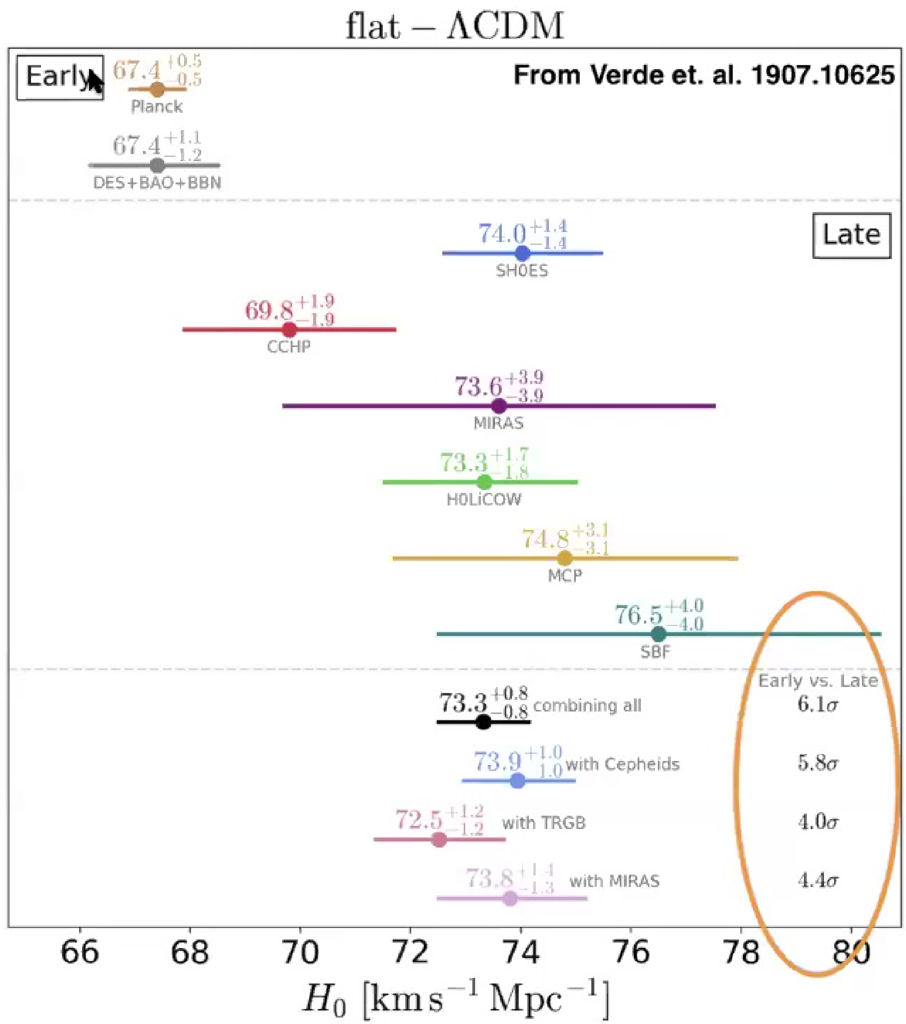
Planck Legacy Data is now Public

Planck Likelihoods 1907.12875



CLASS/CAMB MontePython/CosmoMC

The Hubble Tension Increases



Outline

1) Neutrinos and ΛCDM

2) Neutrino Masses
   Cosmological Constraints
   Neutrino Decays to relax Σm_ν bounds

3) Neff
   BBN and the CMB
   Constraints on BSM Physics

Outline

1) **Neutrinos and ΛCDM**

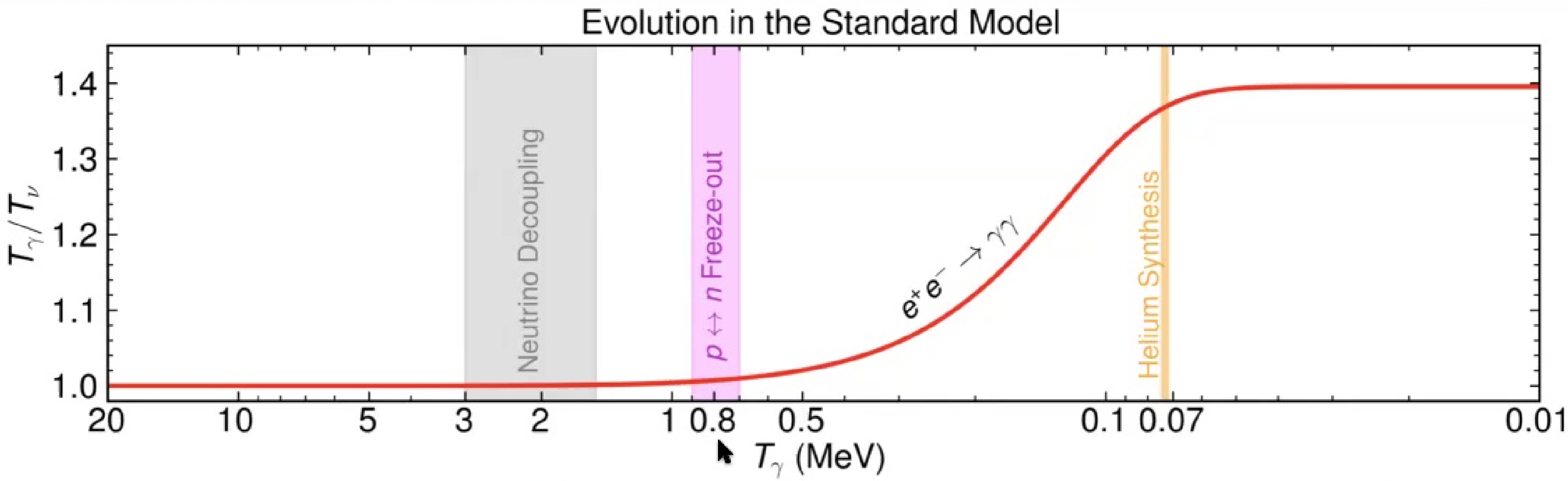
2) **Neutrino Masses**
   - Cosmological Constraints
   - Neutrino Decays to relax Σm_ν bounds

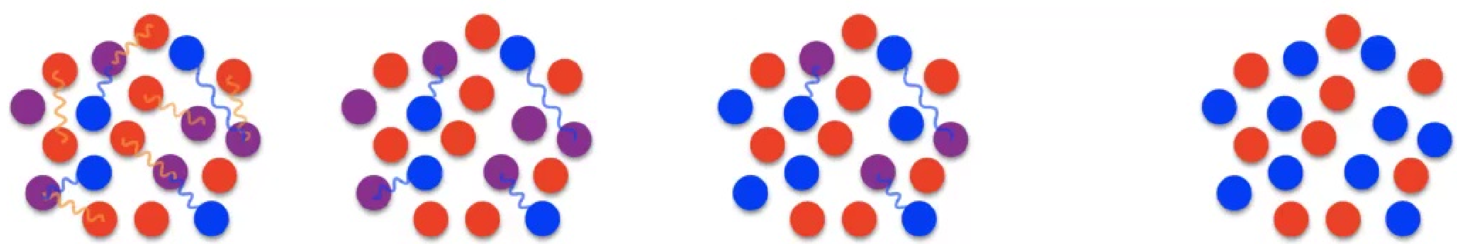
3) **Neff**
   - BBN and the CMB
   - Constraints on BSM Physics

4) **Neutrinos and the Hubble Tension**
   - The Majoron: Ameliorating the tension within the seesaw

5) **Conclusions and Outlook**

Neutrino Decoupling

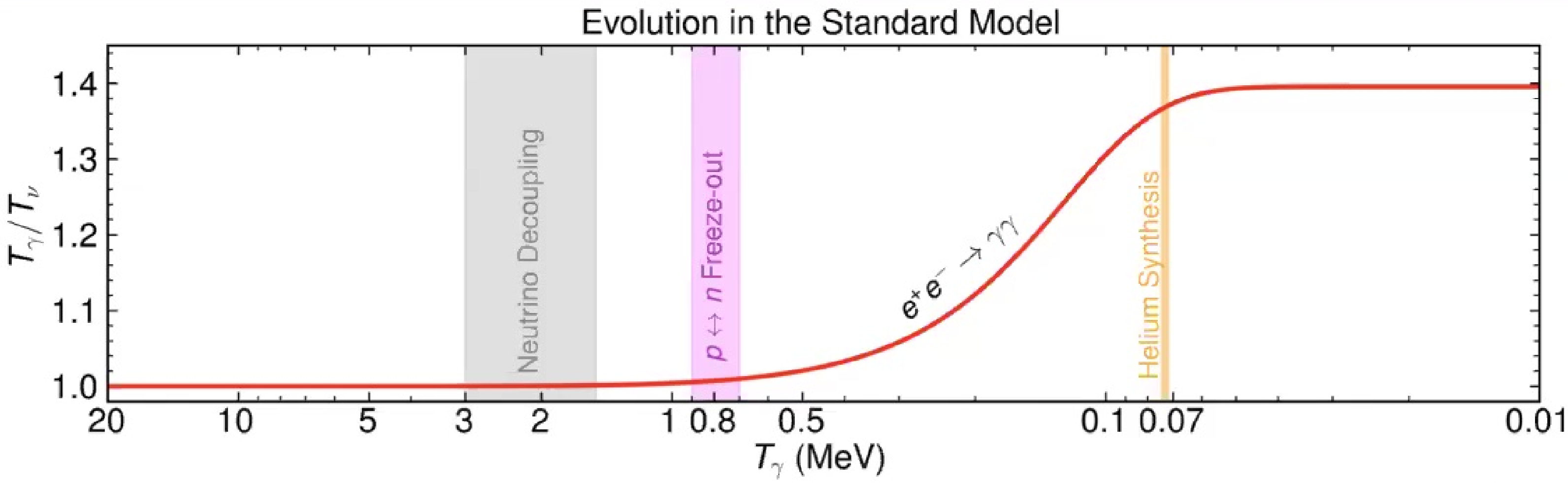




$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$
$$e^\pm\nu_i \leftrightarrow e^\pm\nu_i$$

Neutrinos Electrons Photons Z-W (off-shell)

Neutrino Decoupling



- $N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right)$ $\qquad N_{\rm eff} = 3\left(\frac{1.4T_\nu}{T_\gamma}\right)^4$
- $N_{\rm eff}^{\rm SM} = 3.045$ **de Salas & Pastor 1606.06986** **Escudero 2001.04466**

Relic Neutrino Decoupling

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

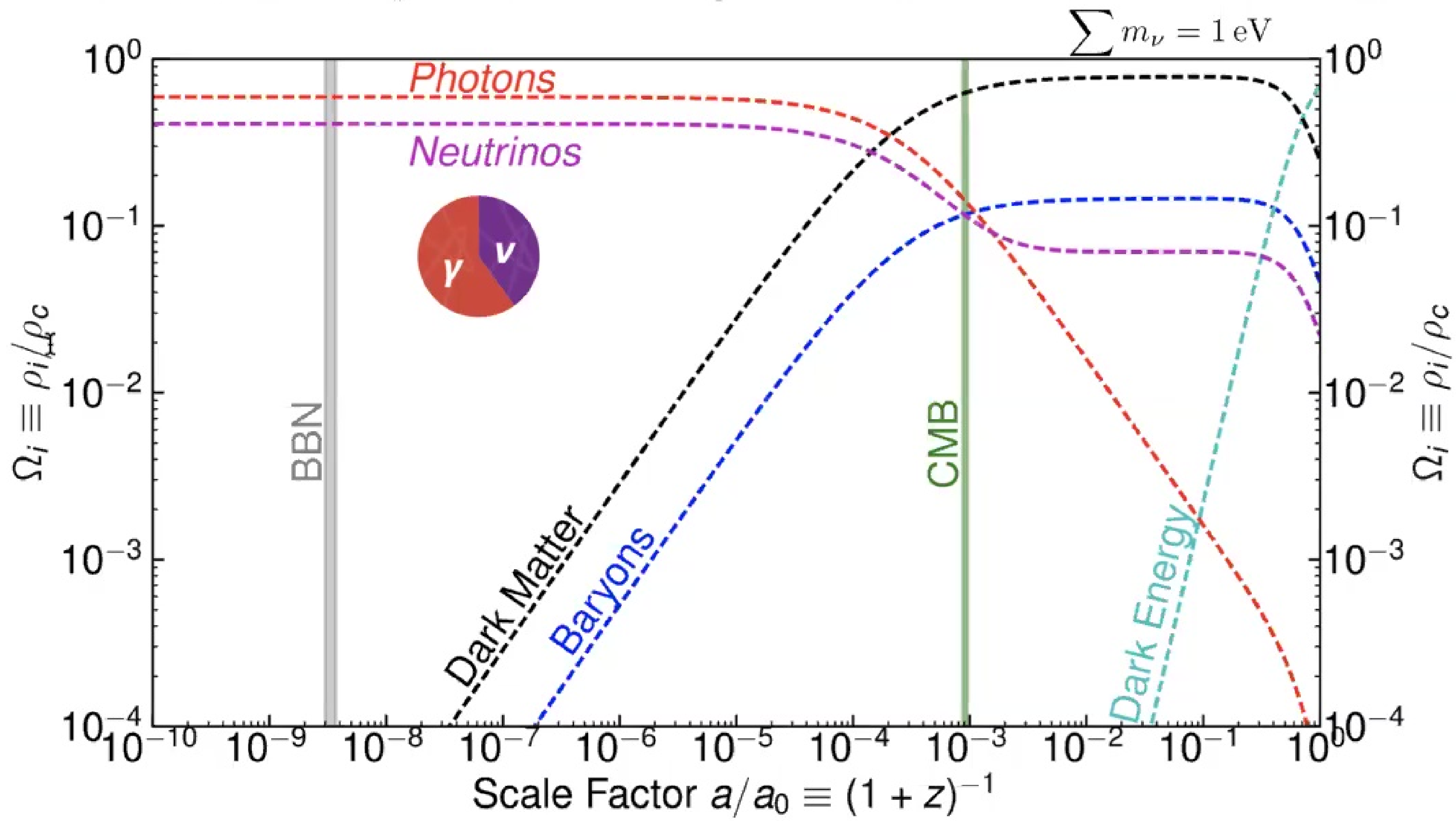
Why is it not 3?

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

Excellent review by Dolgov hep-ph/0202122

Neutrino Evolution

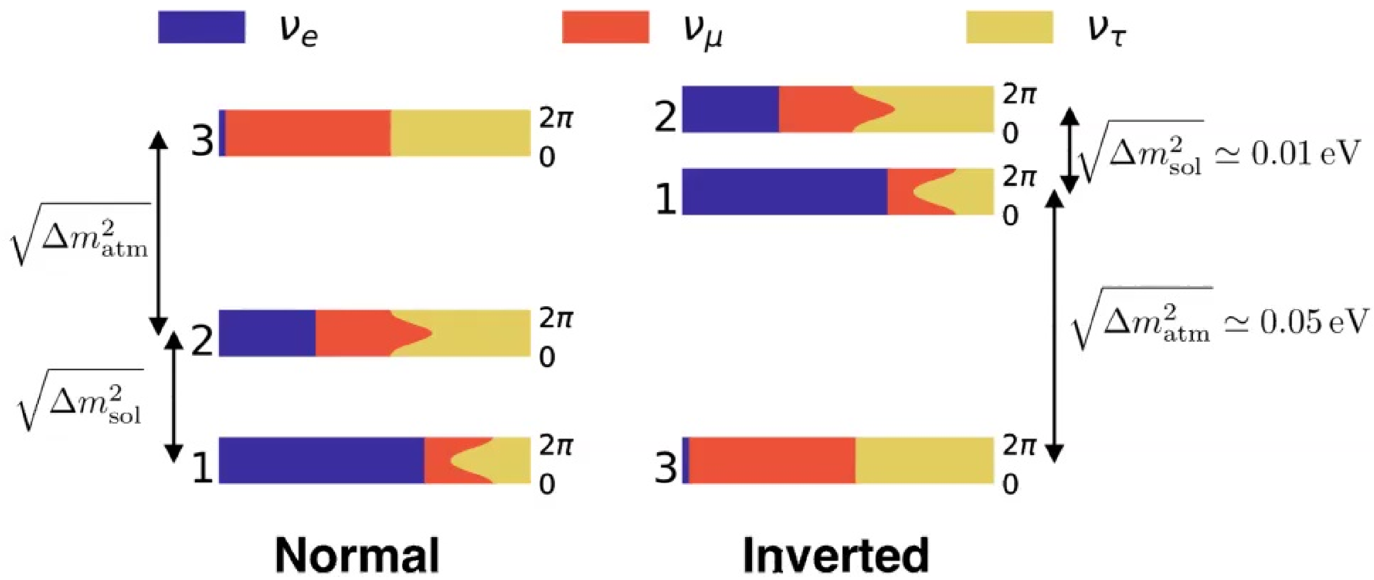
Neutrinos are always a relevant species in the Universe's evolution



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

Neutrino Properties

Figure from de Salas et. al. 1806.11051



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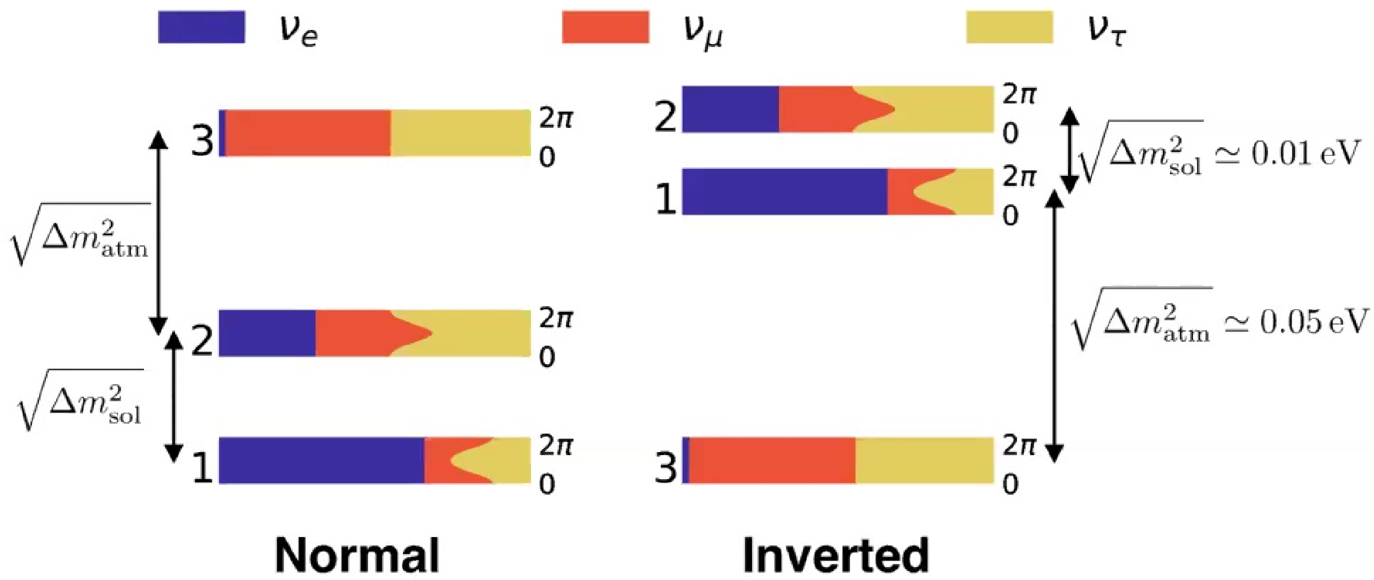

$$\sum m_\nu \gtrsim 0.06\,{\rm eV} \qquad \sum m_\nu \gtrsim 0.10\,{\rm eV}$$

- **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. Σm_ν? i.e. m_{min}?**

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Neutrino Masses from Cosmology

Planck 2018 (1807.06209)

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

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

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

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

Very robust bounds from linear Cosmology

1) Other not that linear data sets?

2) Dependence upon the Cosmological Model

Neutrino Masses from Cosmology

Data beyond Planck and BAO within ΛCDM

$\sum m_\nu < 0.26\,\mathrm{eV}$	**Planck**	**Planck 1807.06209**
$\sum m_\nu < 0.12\,\mathrm{eV}$	**Planck+BAO**	**Planck 1807.06209**
$\sum m_\nu < 0.86\,\mathrm{eV}$	**BOSS P(k)**	**Ivanov et. al. 1909.05277**
$\sum m_\nu < 0.16\,\mathrm{eV}$	**Planck+BOSS P(k)**	**Ivanov et. al. 1912.08208**
$\sum m_\nu < 0.58\,\mathrm{eV}$	**Lyman-α+H_0prior**	**Palanque-Delabrouille et. al. 1911.09073**
$\sum m_\nu < 0.10\,\mathrm{eV}$	**Planck+Lyman-α**	
$\sum m_\nu < 0.08\,\mathrm{eV}$	**Planck+BAO+H_0**	**Choudhury & Hannestad 1907.12598.**

- **Planck is driving current cosmological constraints**
- **Non-linear or mildly non-linear data sets break degeneracies in the fit**
- **The larger H_0 is, the stronger the constraint on $\sum m_\nu$ is**

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+BAO and 3 degenerate neutrinos

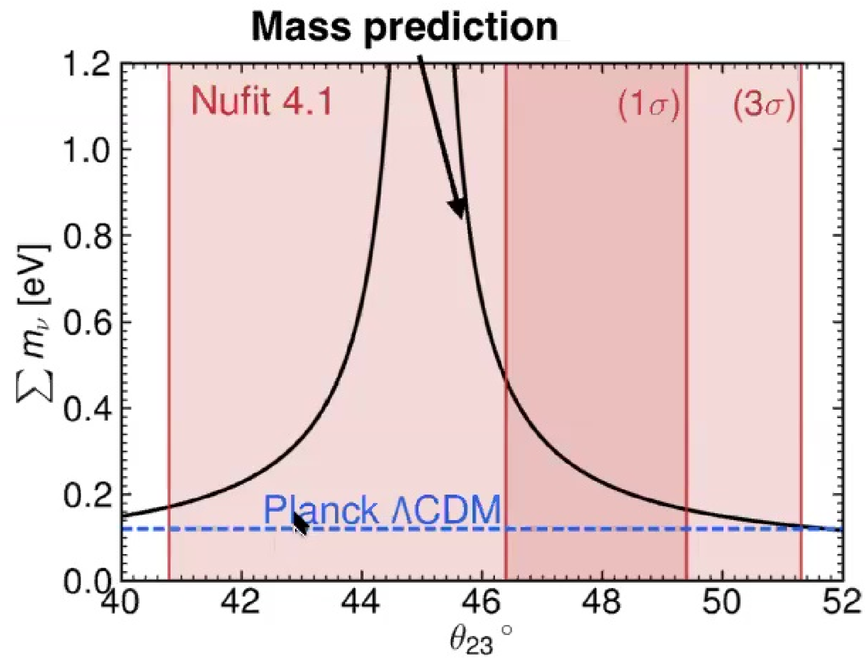
$\sum m_\nu < 0.12\,\mathrm{eV}$	**Standard Case** Planck 1807.06209	ΛCDM+m_ν
$\sum m_\nu < 0.25\,\mathrm{eV}$	**Dark Energy dynamics** Choudhury & Hannestad 19'	CDM+m_ν+ω_a+ω
$\sum m_\nu < 0.15\,\mathrm{eV}$	**Varying Curvature** Choudhury & Hannestad 19'	ΛCDM+m_ν+Ω_k
$\sum m_\nu < 0.23\,\mathrm{eV}$	**Varying N_{eff}** Planck 1807.06209	ΛCDM+m_ν+N_{eff}
$\sum m_\nu < 0.17\,\mathrm{eV}$	**Varying N_{eff}+ω+α_s+m_ν** di Valentino et al. 1908.01391	CDM+m_ν+N_{eff}+ω+α_s+m_ν

- **Constraints are robust upon standard modifications of ΛCDM**

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:

$$0.17\,\mathrm{eV} < \sum m_\nu < 0.47\,\mathrm{eV}$$

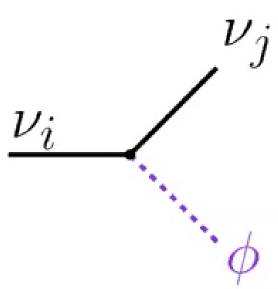


Neutrino Masses from Cosmology

Cosmological Model Dependence

More exotic scenarios:

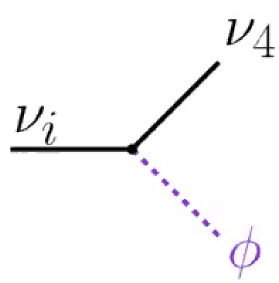
Invisible Neutrino Decay



$\sum m_\nu$ **relaxed up to 0.1 eV**

Escudero & Fairbairn 1907.05425

Invisible Neutrino Decay



$\sum m_\nu \lesssim 1\,\mathrm{eV}$

Chacko et. al. 1909.05275

Time dependent Neutrino Masses

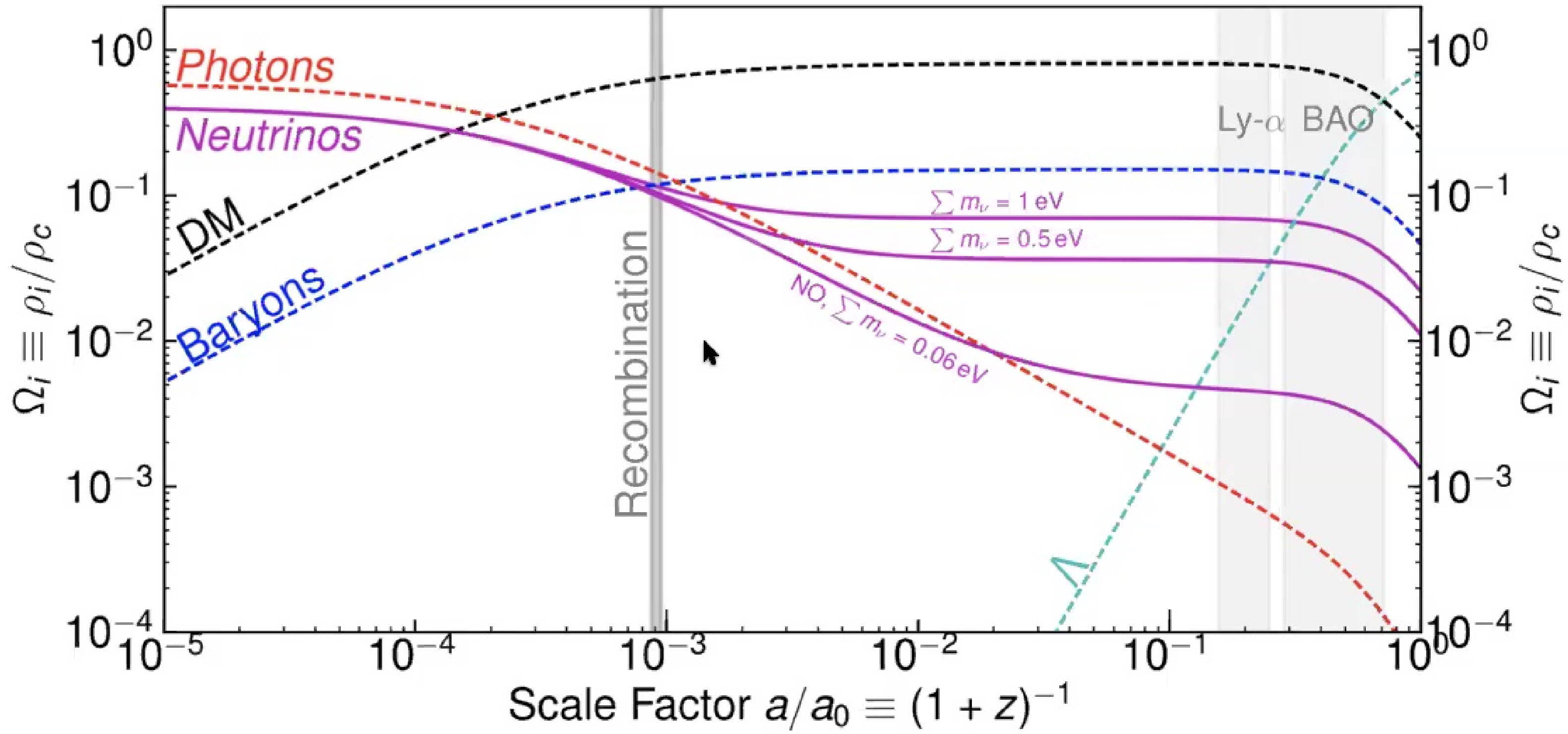
$$m_\nu(t)$$

$\sum m_\nu < 4.8\,\mathrm{eV}$

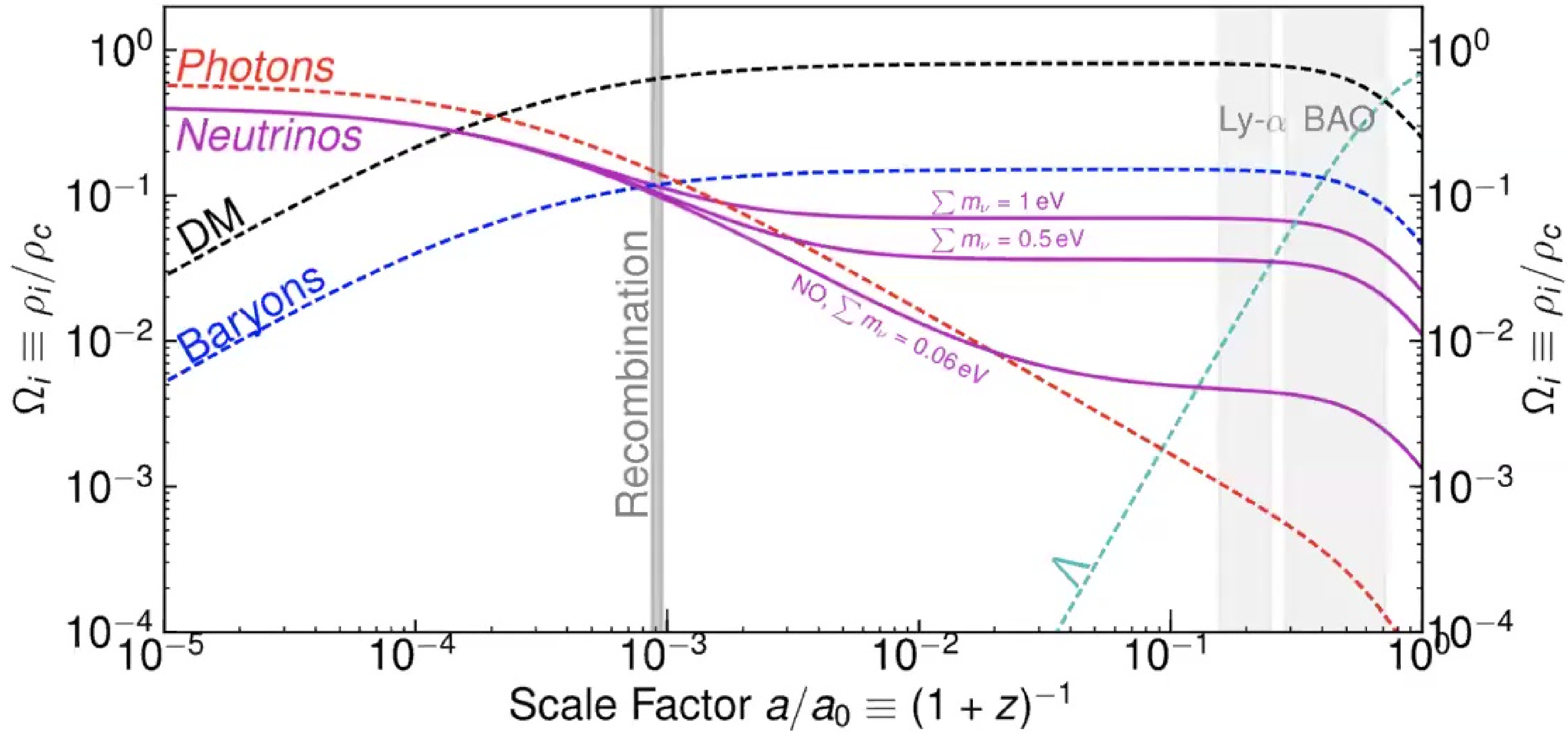
Lorenz et. al. 1811.01991

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

Neutrino Masses from Cosmology



Neutrino Masses from Cosmology



CMB peaks fix:

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

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

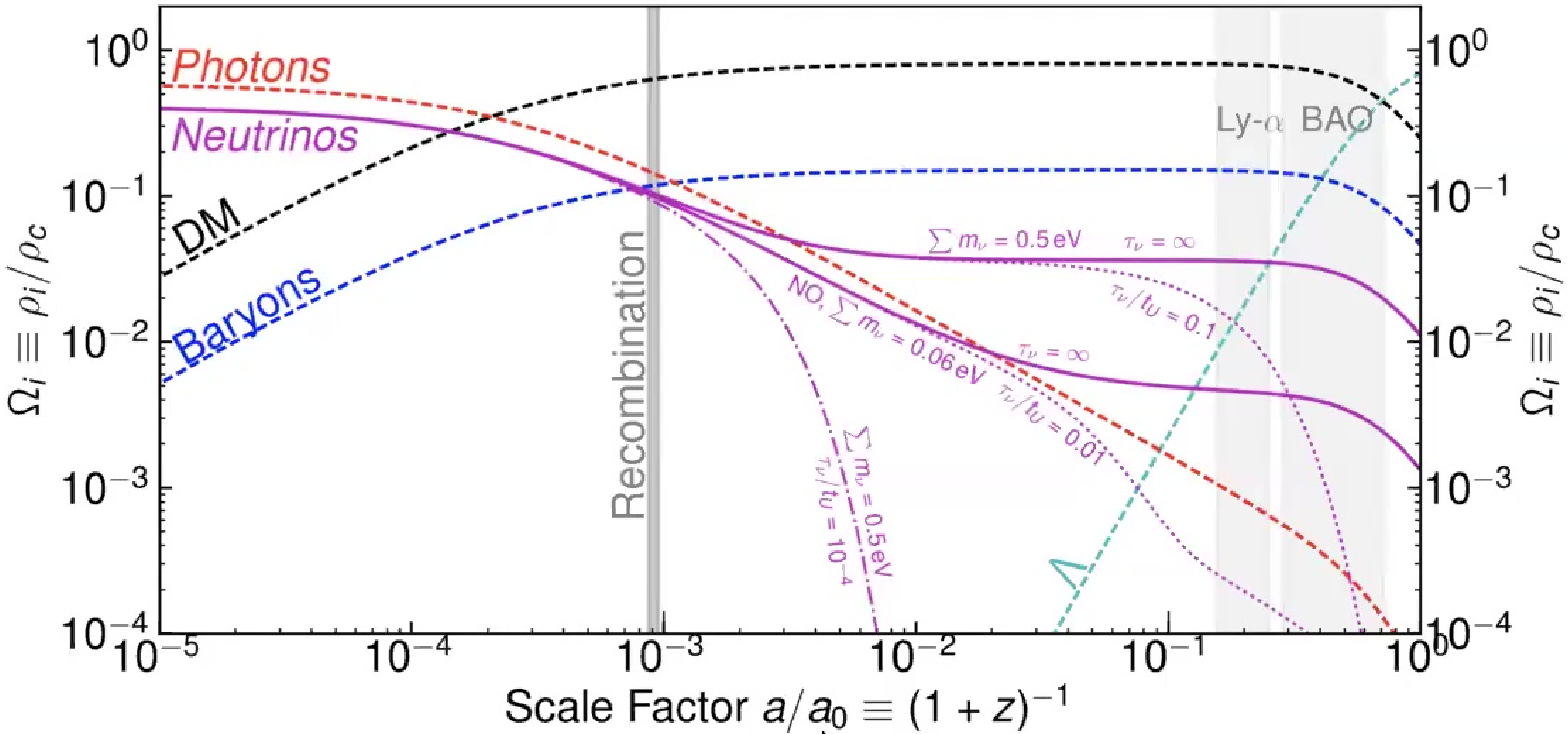
Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

Massive neutrinos

Neutrino Decays



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

Unstable Neutrinos can ameliorate the bounds on Σm_ν!

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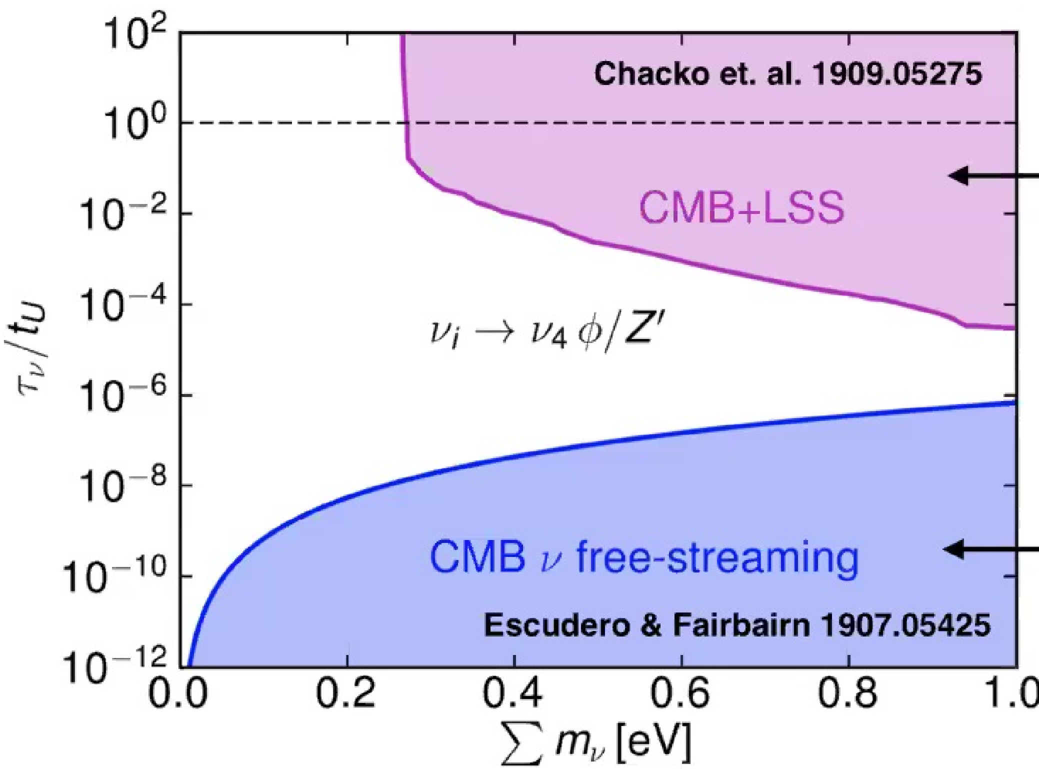
Neutrino Decay Landscape

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



Matter Power Spectrum

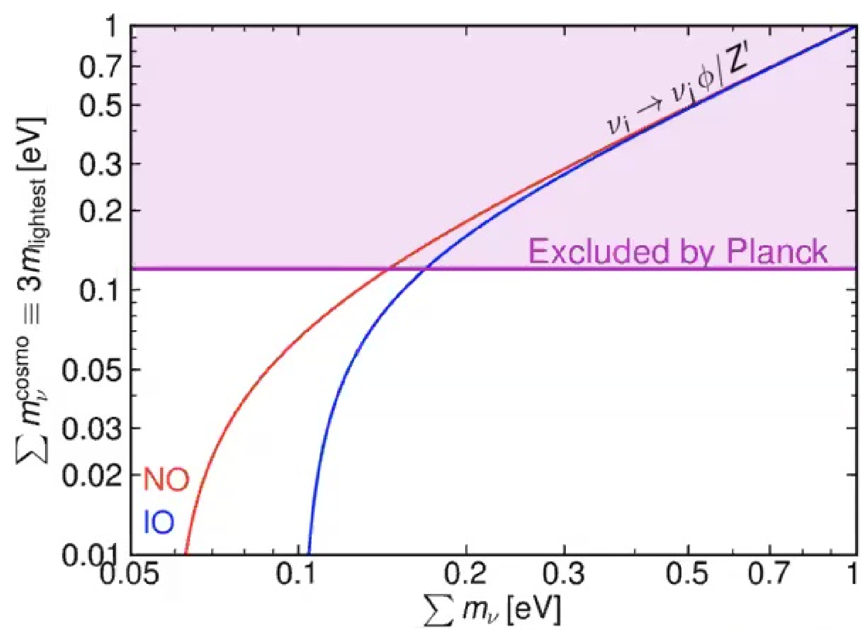
Dodelson et. al. astro-ph/9806116
Hannestad astro-ph/9804075

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

Bashinsky & Seljak astro-ph/0310198
Hannestad & Raffelt hep-ph/0509278

Implications for Mass Models

- **Take the previous neutrino mass model based on** $U(1)_{\mu-\tau}$
- **Neutrinos decay on cosmological timescales in weakly coupled realizations:**
  - **Gauge:** $\nu_i \to \nu_j Z'$ $\quad m_{Z'} \ll m_{\nu_i}$ $\quad m_{Z'}/g_{\mu-\tau} < 30\,\mathrm{TeV}$
  - **Global:** $\nu_i \to \nu_j \phi$ $\quad m_\phi \ll m_\nu$ $\quad v_{\mu-\tau} < 30\,\mathrm{TeV}$
- **Unfortunately, these decay modes cannot relax the neutrino mass bound more than 0.06 eV for NO and 0.1 eV for IO**



Neutrino Mass and Decay Models

- $\nu_i \to \nu_4\,\phi$ **Can relax the bounds significantly**
- **Have an almost massless sterile state but that:**
  1) Does not to 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, 2006.XXXXX
  Add global $U(1)_X$ symmetry with a scalar field and a singlet left-handed state S_L

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

Provided $y_\alpha v_\Phi \ll m_D$

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

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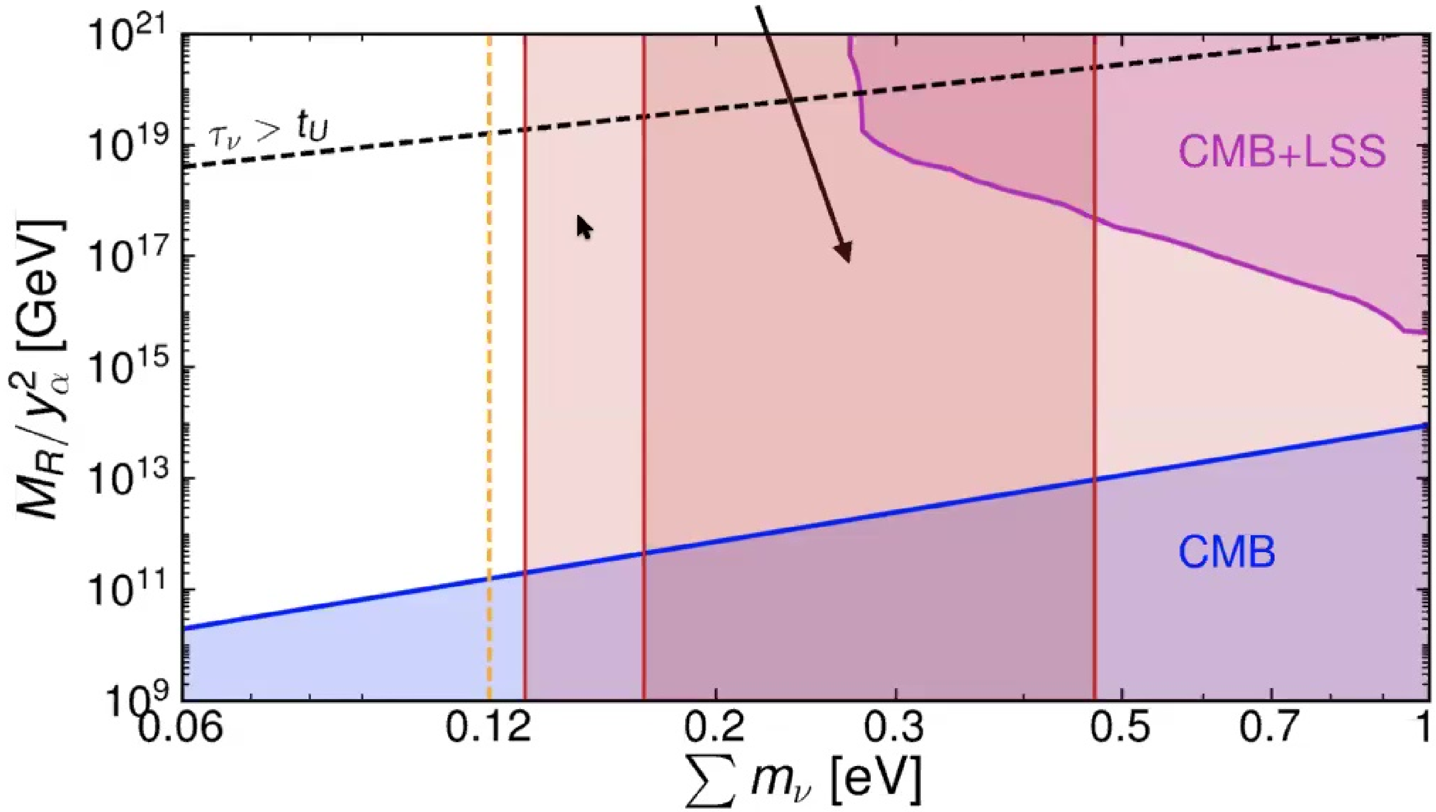
Cosmological decays: $\Gamma(\nu_i \to \nu_4\phi) \sim 10^6 t_U^{-1}\, y_\alpha^2 \left(\frac{m_\nu}{0.3\text{eV}}\right)^2 \left(\frac{10^{14}\,\text{GeV}}{M_R}\right)$

Neutrino Mass and Decay Models

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



Cosmological Neutrino mass bounds are indeed relaxed!

Check out: 2006.XXXXX with López-Pavón, Rius & Sandner

Current Constraints on Neff

- **Current Constraints**

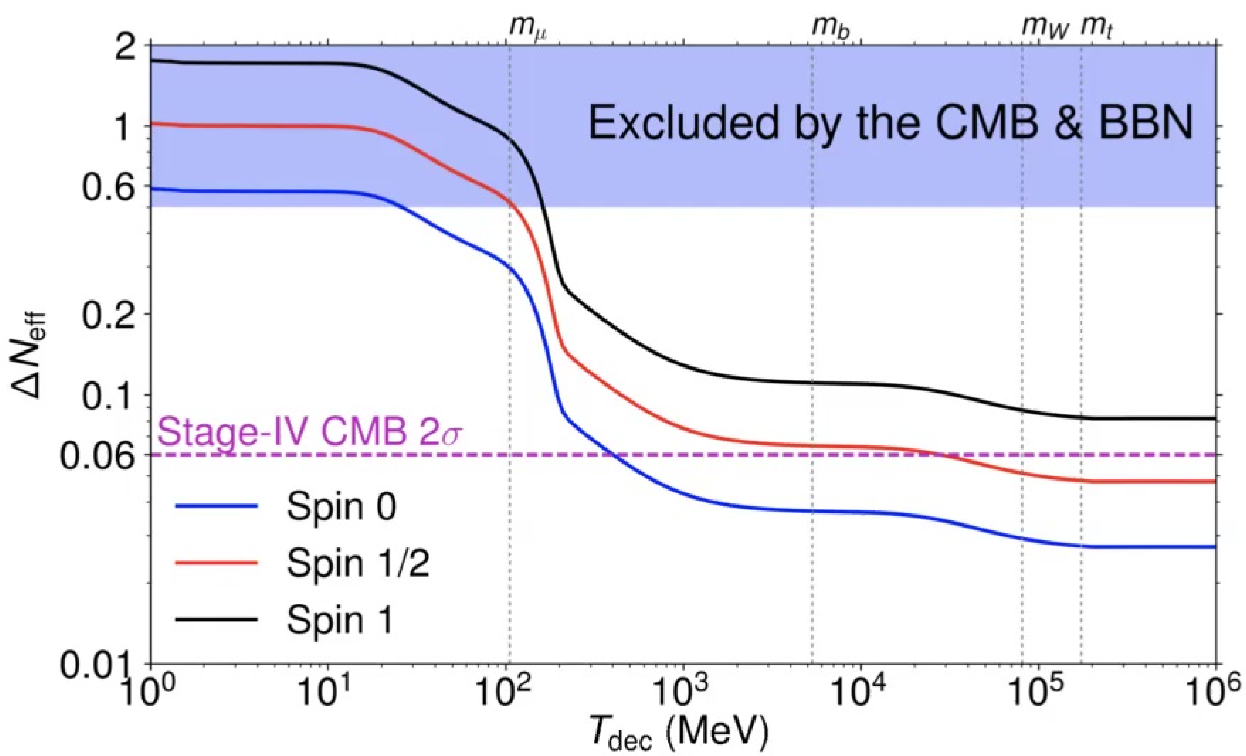
BBN	$N_{\rm eff} = 2.92 \pm 0.28$	Fields et. al. 1912.01132
Planck+BAO	$N_{\rm eff} = 2.99 \pm 0.17$	Planck 2018, 1807.06209
Planck+BAO+H0	$N_{\rm eff} = 3.27 \pm 0.15$	Planck 2018, 1807.06209

- **Standard Model Prediction:** $N_{\rm eff}^{\rm SM} = 3.045$

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

Constraints from Neff

- **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	$m_{\rm WIMP} > (4-10)\,{\rm MeV}$	Sabti et. al. 1910.01649 Boehm et. al. 1303.6270
GeV-Sterile Neutrinos	$\tau_N \lesssim 0.05\,{\rm s}$	Sabti et. al. 2006.07387 Dolgov et. al. hep-ph/0008138
Vector Bosons	$g \lesssim 10^{-10} \quad m \lesssim 10\,{\rm MeV}$	Escudero et. al. 1901.02010 Kamada & Yu 1504.00711
Axions		Raffelt et. al. 1011.3694 Blum et.al. 1401.6460
Low Reheating	$T_{\rm RH} > (2-5)\,{\rm MeV}$	de Salas et. al. 1511.00672 Hasegawa et. al. 1908.10189
Variations of GN	$G_{\rm BBN}/G_0 = 0.98 \pm 0.03$	Alvey et. al. 1910.10730 Copi et.al. astro-ph/0311334
PBHs	$6\times 10^8\,{\rm g} < M_{\rm PBH} < 2\times 10^{13}\,{\rm g}$	Carr et. al. 0912.5297 Keith et.al. 2006.03608

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!

- **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: $$\theta_s \equiv r_s / D_M(z_\star)$$

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

Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

H0

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

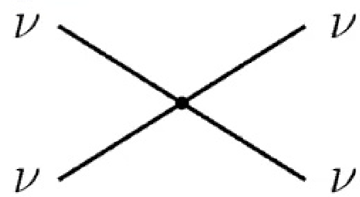
- **Dark Radiation**

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

(68 % CL, Planck+BAO+H0)

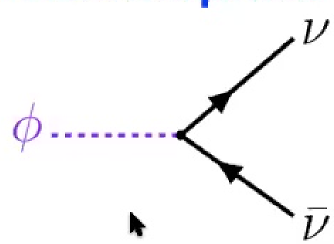
Clear Interpretation
H_0 tension from 4.4σ to 3σ
CMB fit is degraded

- **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

Neutrinos and the Hubble Tension

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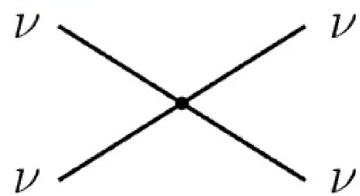

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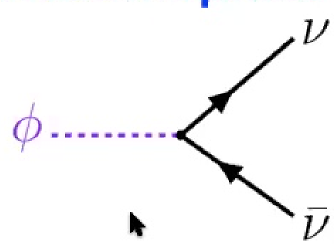

H_0 tension from 4.4σ to 2.5σ
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Direct connection with Seesaw

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

Neutrinos and the Hubble Tension

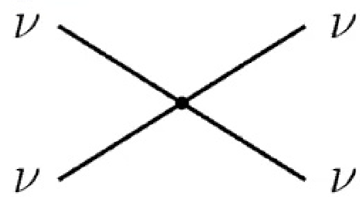
- **Dark Radiation**

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

(68 % CL, Planck+BAO+H0)

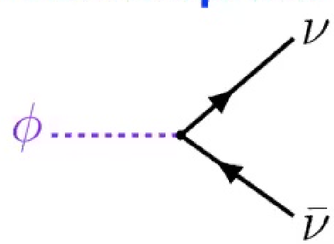
Clear Interpretation 😃
H_0 tension from 4.4σ to 3σ 😐
CMB fit is degraded ☹️

- **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**

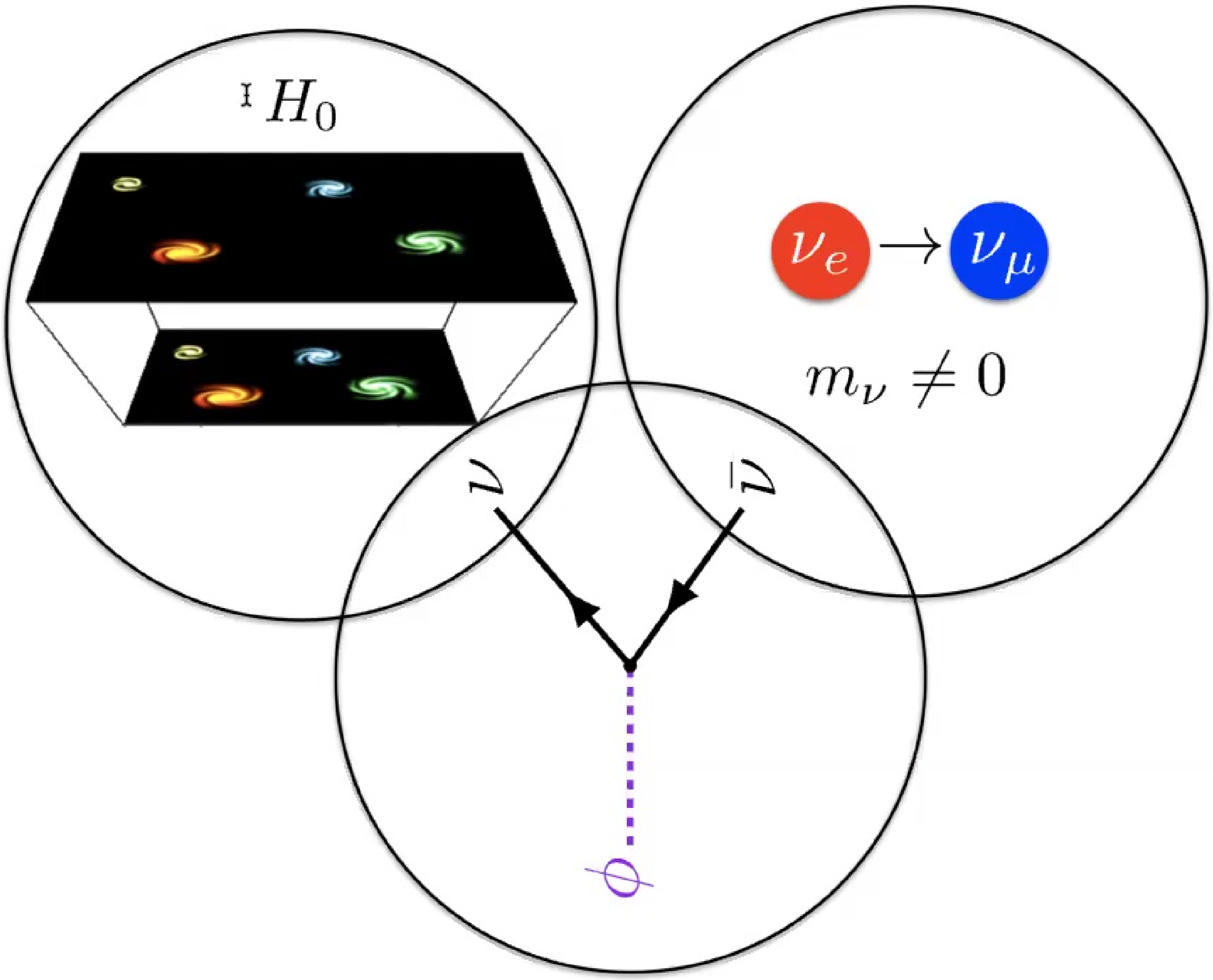


H_0 tension from 4.4σ to 2.5σ 😐
CMB fit is not degraded 😃
Direct connection with Seesaw 😃

- **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 😐

Escudero & Witte 19'



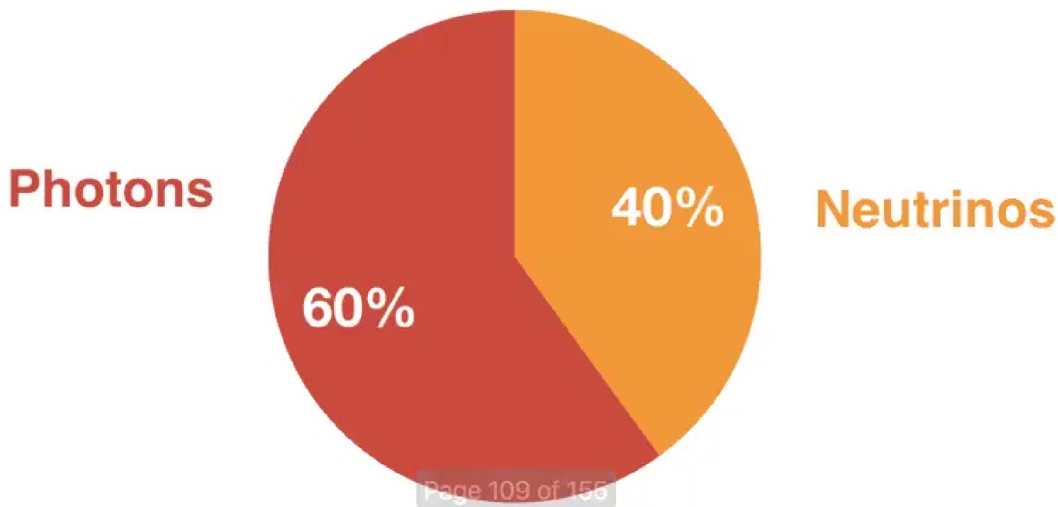
The Physics

1) **CMB** 380.000 yr — **BBN** 3 min

$T_\gamma = 0.26\,\mathrm{eV}$ $\qquad$ $T_\gamma = 0.07\,\mathrm{MeV}$

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

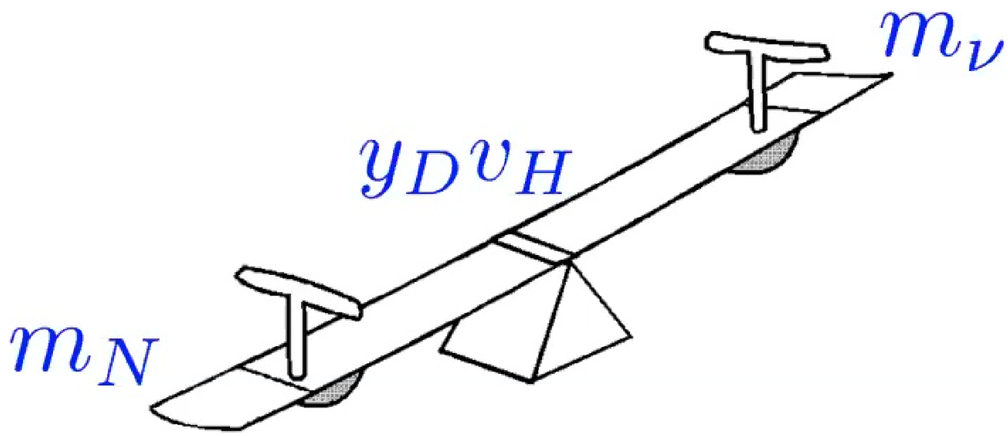
2)



The Seesaw Mechanism

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

Type-I seesaw



Neutrinos are very light Majorana particles:

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

The Scenario

Global U(1)$_L$ Spontaneously Broken Symmetry

Chikashige, Mohapatra, Peccei (1981)

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

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

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

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

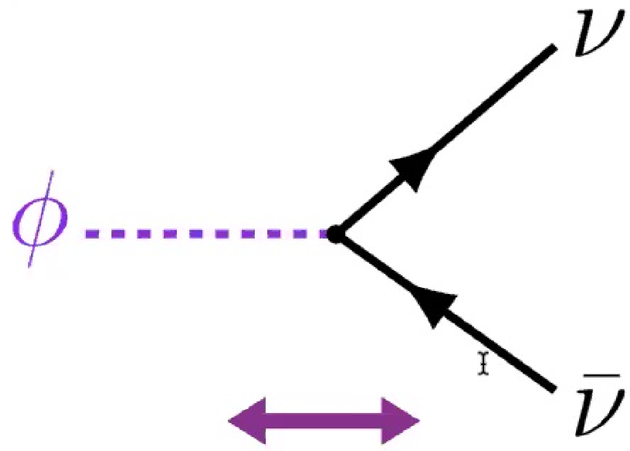
Rothstein, Babu, Seckel hep-ph/9301213
Akhmedov, Berezhiani, Mohapatra, Senjanovic hep-ph/9209285

Parameter Space:

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

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**

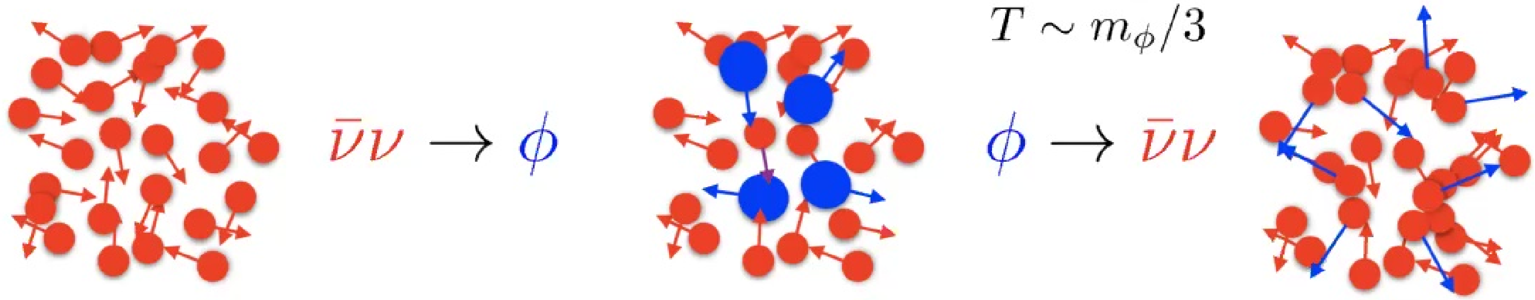
- **We solve the Boltzmann equation for the background**
  Escudero 1812.05605, 2001.04466
- **We include the full neutrino-majoron Boltzmann hierarchy in CLASS**

Cosmological Implications

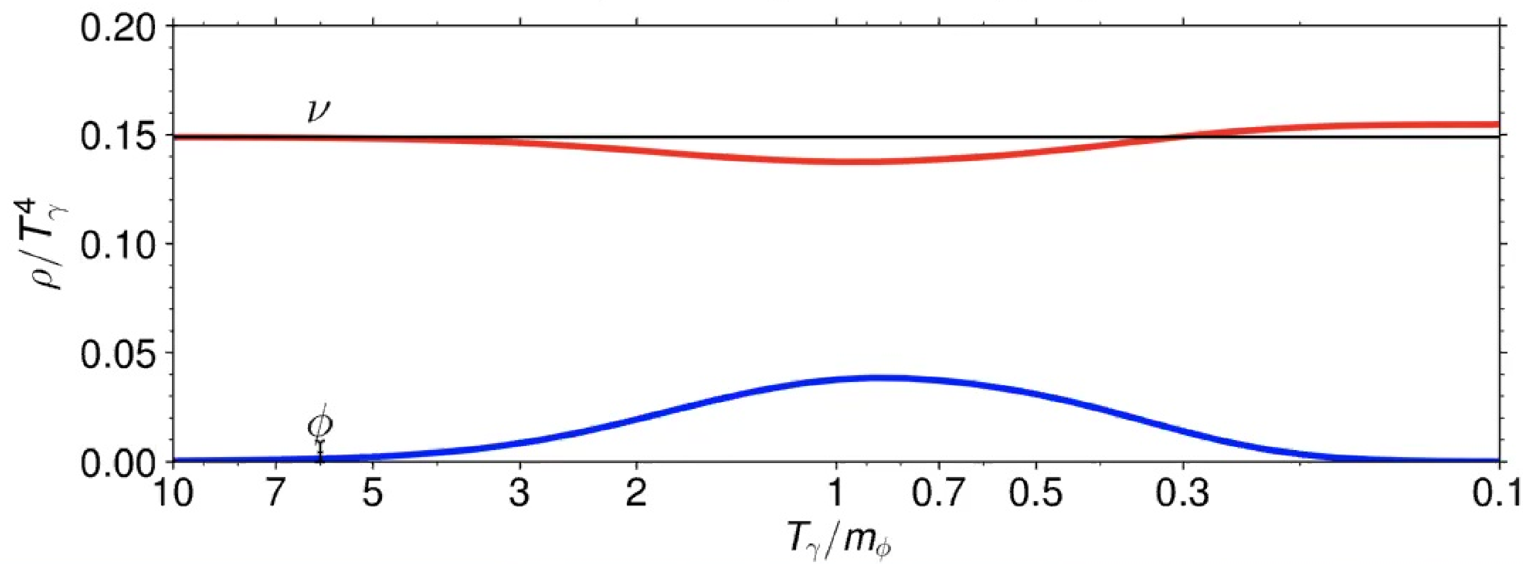
$T \gg m_\phi$ **Production** **Equilibrium** **Decay** **Final State**

$T \sim m_\phi/3$

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

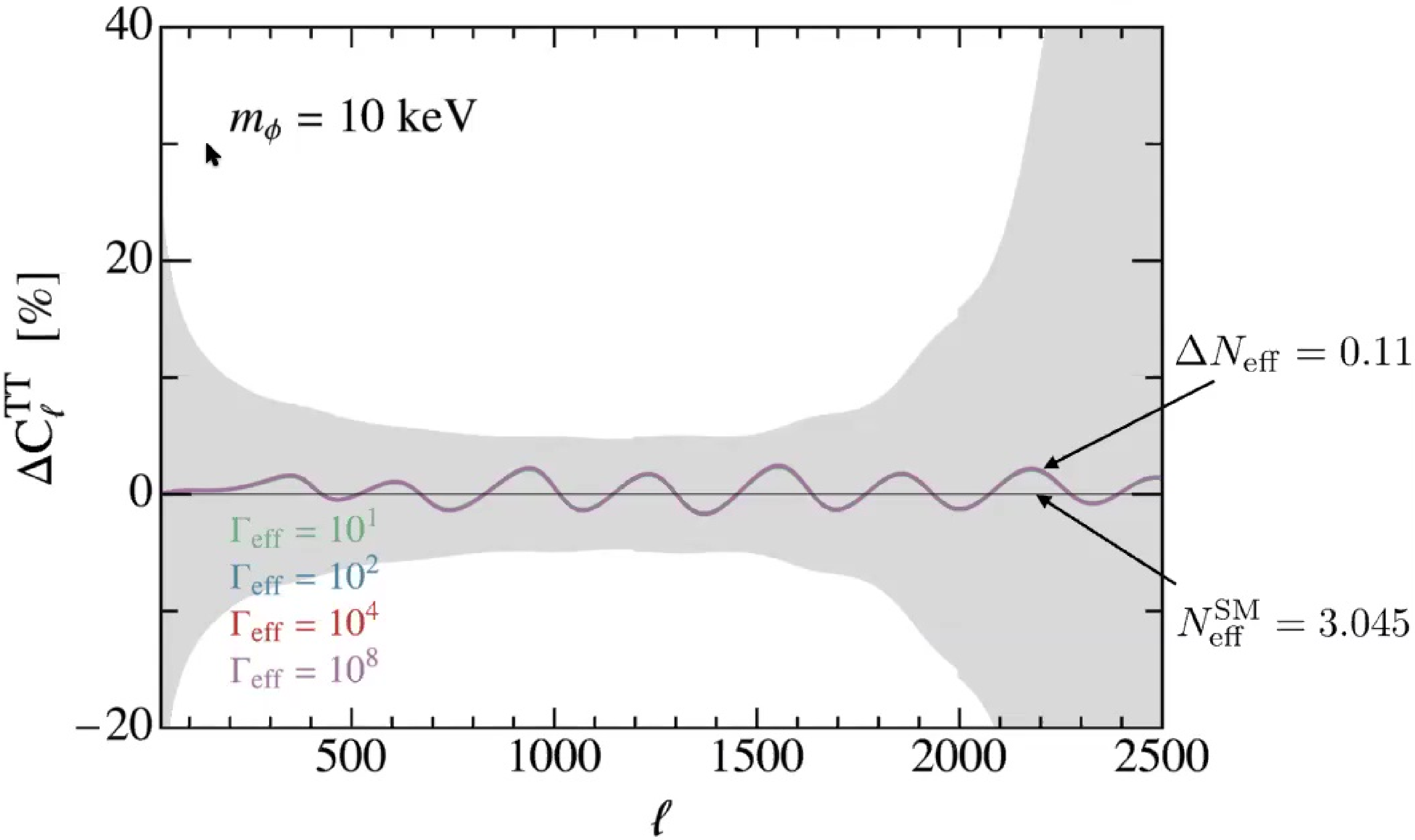


$$\Gamma_\phi \simeq H(T_\nu = m_\phi/3)$$

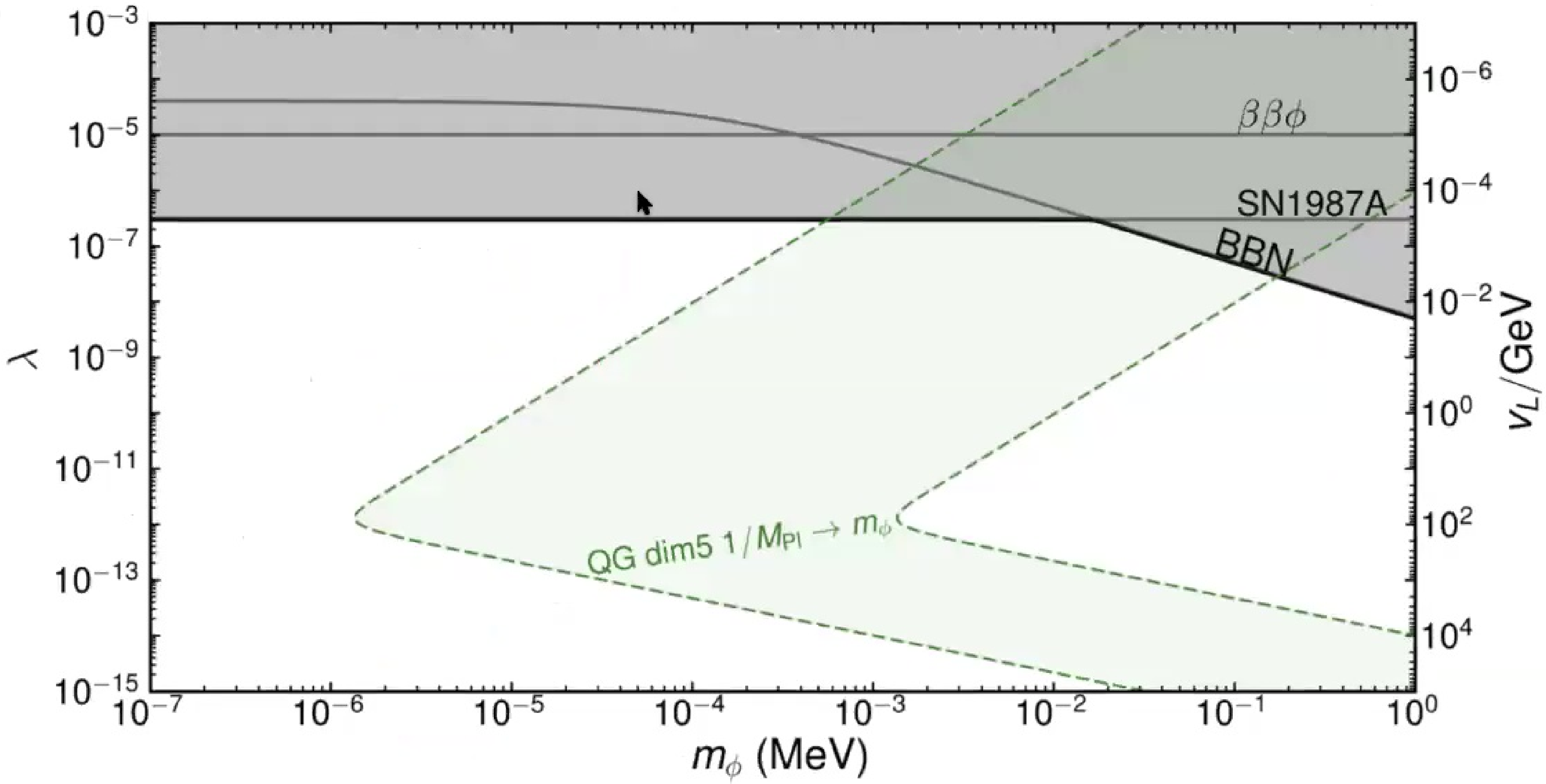


Effects on the CMB

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



Parameter Space



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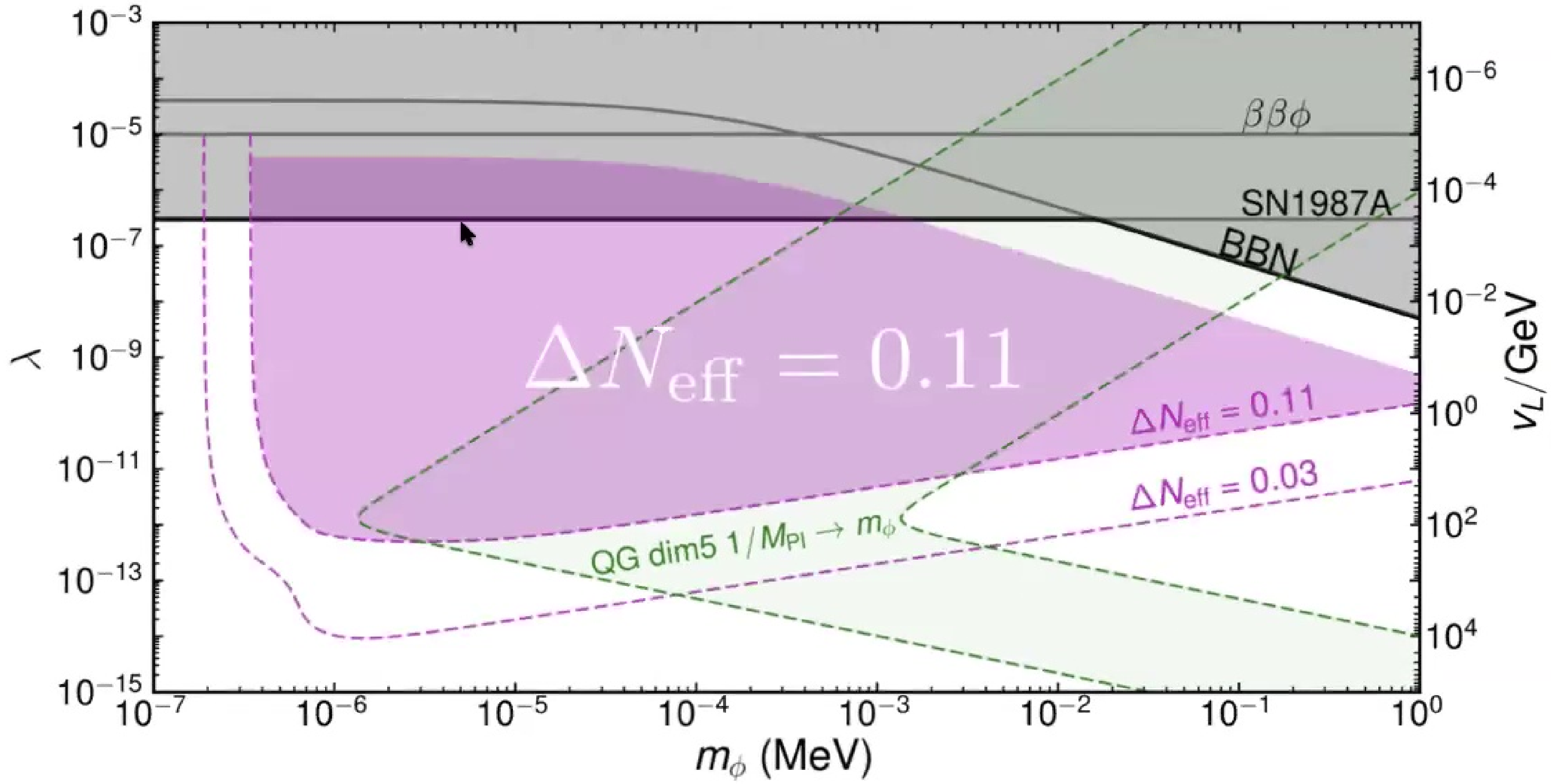
Parameter Space



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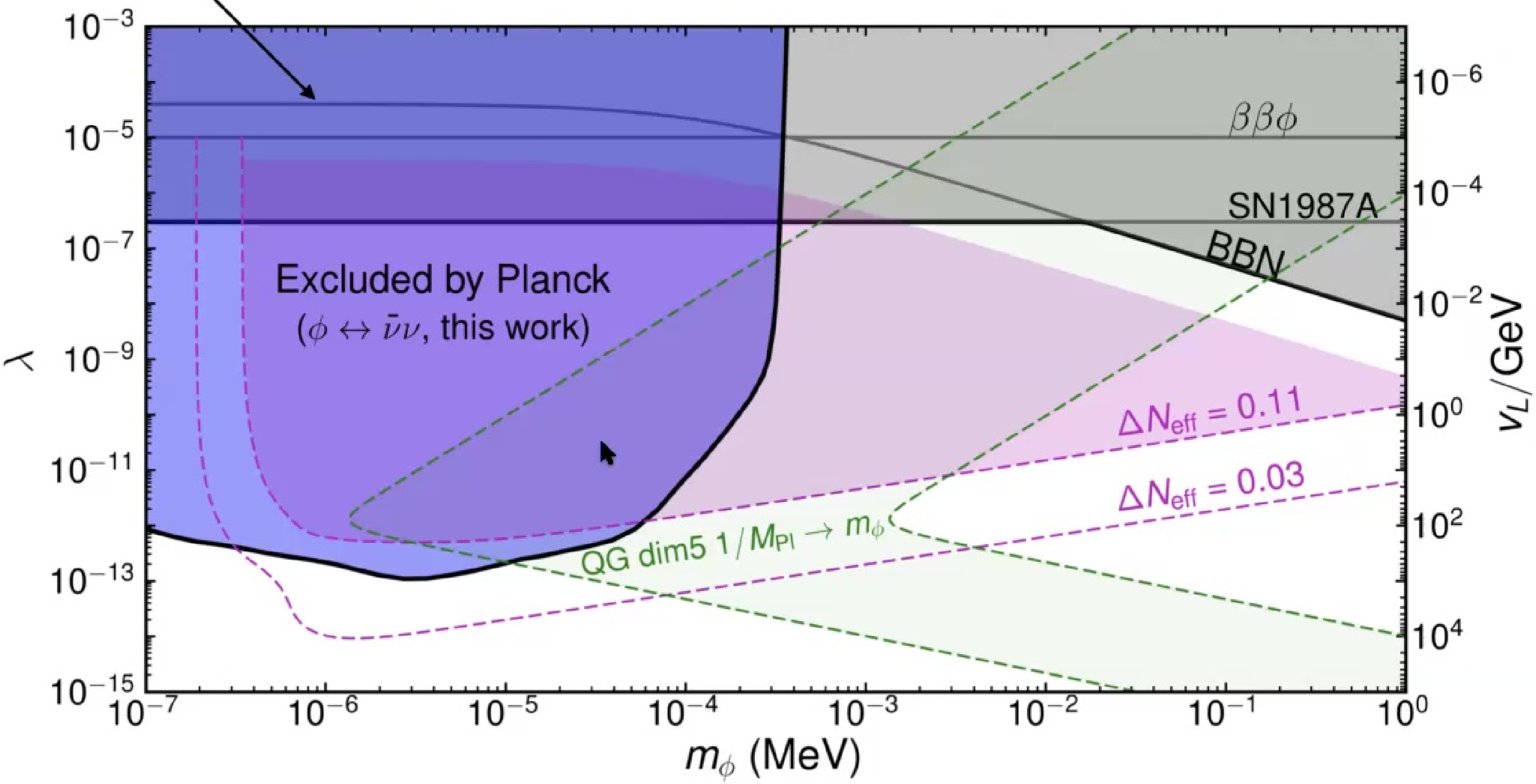
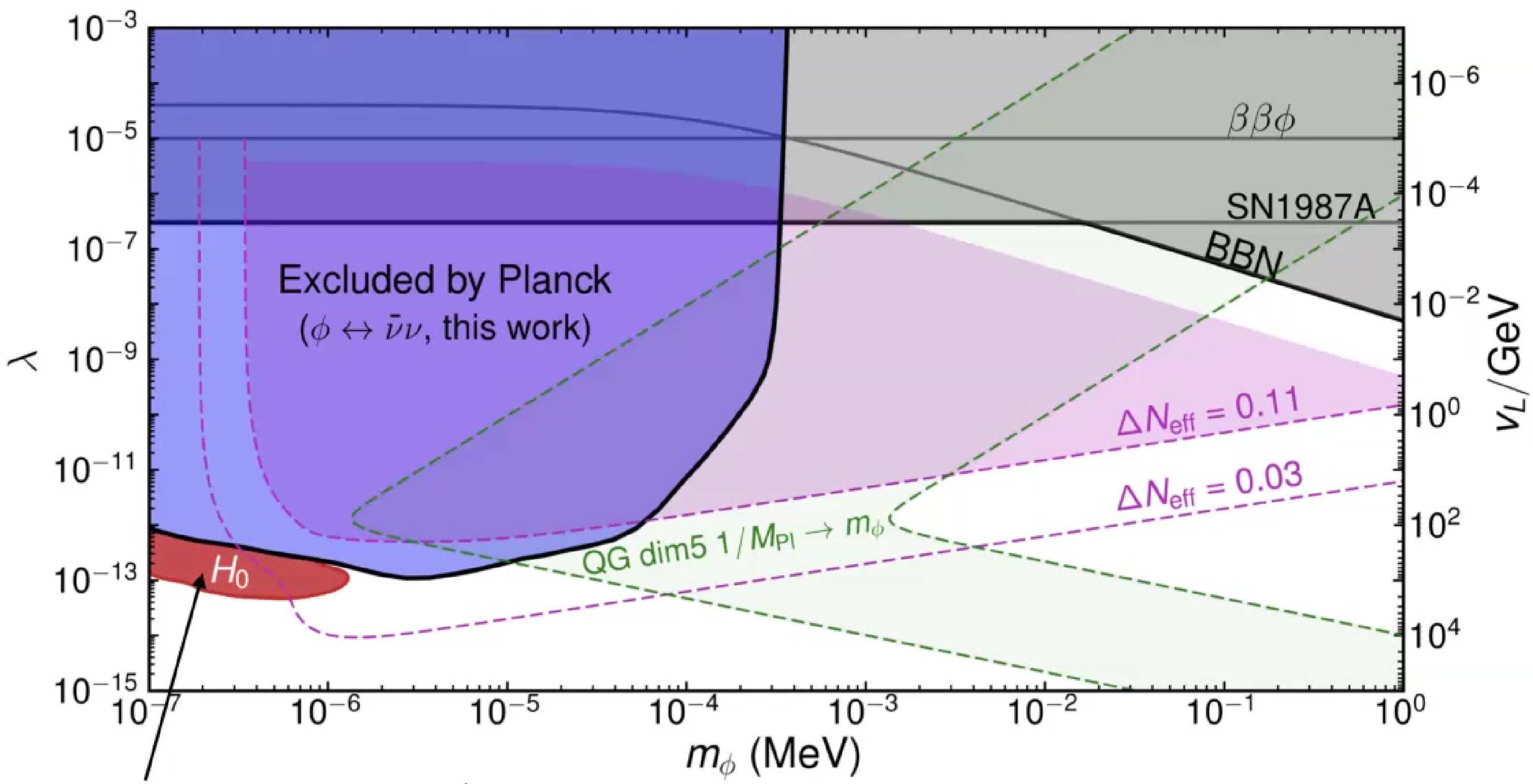
Parameter Space

Full MCMC to Planck 2018 data

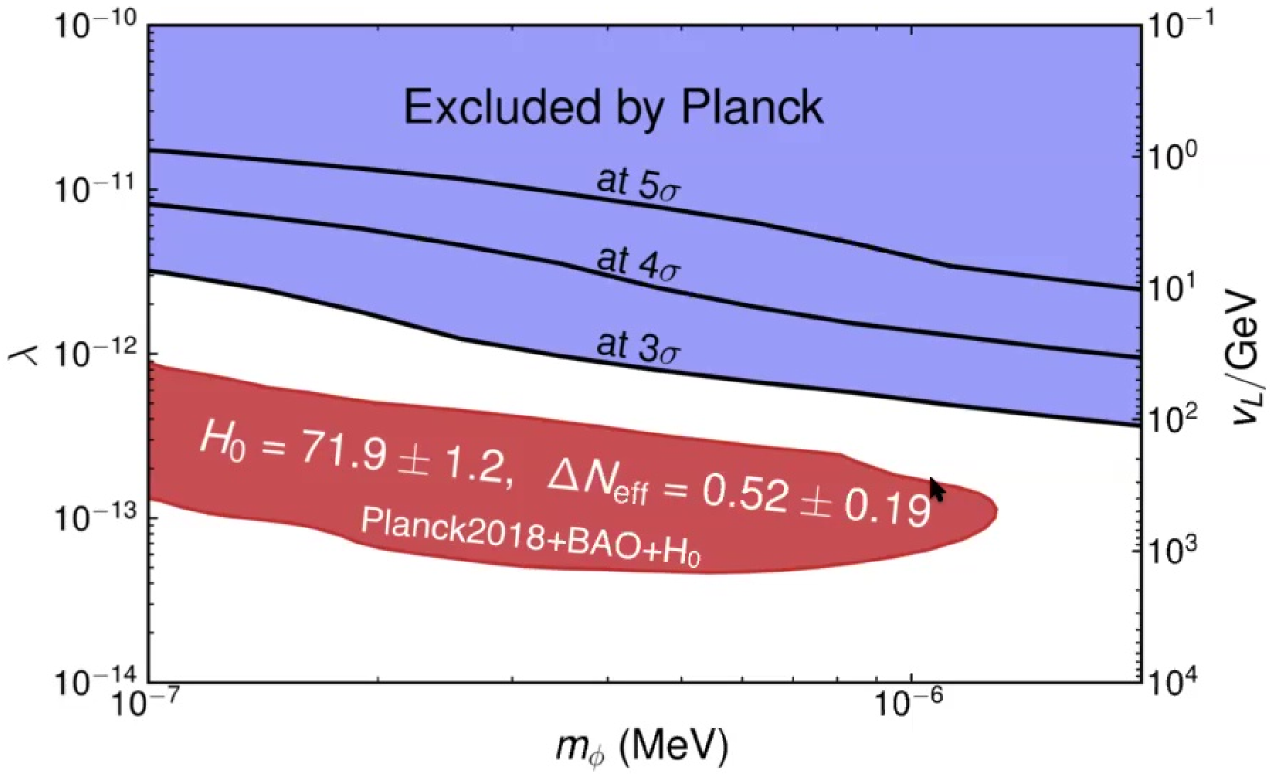


Parameter Space

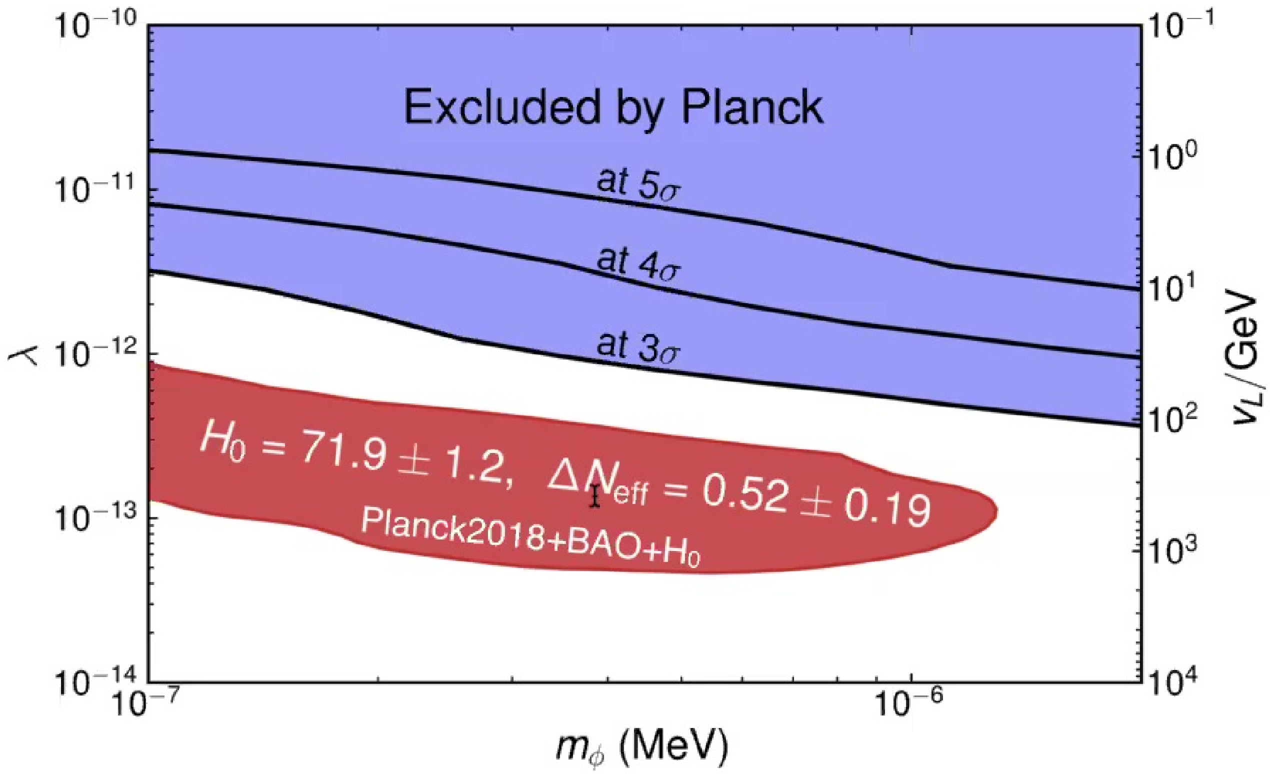


1σ preference when including H_0 in the fit and an additional $\Delta N_{\rm eff}$

Parameter Space for H_0



Parameter Space for H_0



H_0

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

The Majoron behind the H_0 tension?

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

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

Conclusions

Neutrino Masses:

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

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

Neff:

Planck: $N_{\rm eff} = 2.99 \pm 0.17$ **BBN:** $N_{\rm eff} = 2.92 \pm 0.28$

Excellent agreement with SM prediction

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

The Hubble Tension:

Many neutrino related approaches

The Majoron represents a well-motivated possibility

Outlook

Neutrino Masses:

KATRIN reach: $\sum m_\nu < 0.6\,\mathrm{eV}$ **(90% 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: $\sigma\left(\sum m_\nu\right) \simeq 0.02\,\mathrm{eV}\ \ (1\,\sigma)$

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!

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Thank you for your attention!