Neutrino Masses and Hubble Tension via a Majoron in MFV

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Based on: 2009.01848, FAA, E. Fernández-Martínez, M. González-López, L. Merlo.

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Outline

- Introduction
- The Majoron Mechanism
- The Majoron and Axion from a MFV Setup
- Phenomenological Signatures
- Conclusions

Introduction

- The Hubble Tension:
  - Early Universe vs local measurements of H_0 differ up to $4-6\,\sigma$ L. Verde, T. Treu, and A. Riess, 1907.10625 K. C. Wong et. al., H0LiCOW XIII, 1907.04869
- This may be solved by:
  - Systematics
  - New cosmological model
  - **Particle physics. E.g.: a Majoron** M. Escudero and S. J. Witte, 1909.04044
- Study its compatibility with solutions to other SM problems
  - Light neutrino masses $\rightarrow$ Type-I Seesaw
  - Flavour puzzle $\rightarrow$ flavour continuous global symmetries
  - Strong CP Problem $\rightarrow$ Axion

Introduction

- The Majoron, ω, is the NGB associated to the breaking of LN
- For it to alleviate the H_0 tension it needs:
  - A mass in the range of

$$m_\omega \in [0.1, 1] \text{ eV}$$

  - Coupling to neutrinos of order

$$\lambda_{\omega\nu\nu} \in [5 \times 10^{-14}, 10^{-12}]$$

- Phenomenology of this Majoron in a Type-I Seesaw
  - **Collider signatures**: N_R, Higgs invisible decay, new scalar
  - Astrophysical effects: CAST and Red Giant observations
  - Majoron emission in $0\nu\beta\beta$ decays

The Majoron Mechanism

- SM extended with 3 RH neutrinos and a singlet scalar χ, with LN $-\boldsymbol{L_N}$ and $\boldsymbol{L_\chi}$ respectively

$$-\mathcal{L}_\nu = \left(\frac{\chi}{\Lambda_\chi}\right)^{\frac{1+L_N}{L_\chi}} \bar{l}_L \widetilde{H} \mathcal{Y}_\nu N_R + \frac{1}{2}\left(\frac{\chi}{\Lambda_\chi}\right)^{\frac{2L_N - L_\chi}{L_\chi}} \chi \bar{N}_R^c \mathcal{Y}_N N_R + \mathrm{h.c.}, \qquad \chi = \frac{\sigma + v_\chi}{\sqrt{2}} e^{i\frac{\omega}{v_\chi}}, \qquad \varepsilon_\chi = \frac{v_\chi}{\sqrt{2}\Lambda_\chi}$$

- Heavy and light neutrino masses generated after LN SSB

$$m_\nu = \frac{\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} v^2}{\sqrt{2} v_\chi} \mathcal{Y}_\nu \mathcal{Y}_N^{-1} \mathcal{Y}_\nu^T, \qquad m_N = \varepsilon_\chi^{\frac{2L_N - L_\chi}{L_\chi}} \frac{v_\chi}{\sqrt{2}} \mathcal{Y}_N$$

- Axion coupling to light neutrinos:

$$\mathcal{L}_\omega^{low-energy} \supset i \frac{\lambda_{\omega\nu\nu}}{2} \omega \bar{\nu}_L \nu_L^c, \qquad \lambda_{\omega\nu\nu} = 2\frac{m_\nu}{L_\chi v_\chi}$$

The Majoron Mechanism

- Combining those expressions with the bound on $\lambda_{\omega\nu\nu}$

$$|L_\chi|\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}}\mathcal{Y}_\nu\mathcal{Y}_N^{-1}\mathcal{Y}_\nu^T \in [1.2\times10^{-13}, 2.4\times10^{-12}]$$

$$\frac{\varepsilon_\chi^{\frac{2L_N-L_\chi}{L_\chi}}}{|L_\chi|}\mathcal{Y}_N \gg 3.5\times10^{-14}$$

- A renormalizable scenario is possible, but it is very fine-tuned

$$L_N = -1, L_\chi = -2$$

$$\mathcal{Y}_\nu\mathcal{Y}_N^{-1}\mathcal{Y}_\nu^T \in [1.2\times10^{-13}, 2.4\times10^{-12}]$$

- Can fine-tuning be avoided exploiting ε_χ?

The Majoron Mechanism

- Two phenomenologically interesting non-renormalizable scenarios:

	L_N	L_χ	v_χ	ε_χ	$\langle M_N \rangle$	Λ_χ
CASE NR1	1	1	$[0.1, 2]$ TeV	$[0.49, 1.4] \times 10^{-4}$	$[3.5, 200]$ MeV	$[1.4 - 11] \times 10^3$ TeV
CASE NR2	1	2	$[0.05, 1]$ TeV	$[2.4, 11] \times 10^{-7}$	$[35.4, 707]$ GeV	$[1.4 - 6.5] \times 10^5$ TeV

The Majoron Mechanism

- Apart from a small coupling to neutrinos, the Majoron needs a specific mass
  - Wormhole effects fall short R. Alonso and A. Urbano, 1706.07415
  - Planck-suppressed operators provide a mass too large E. K. Akhmedov et al., hep-ph/9209285
  - Explicit breaking of LN via a Majorana mass term

- Additional scalar d.o.f. to the Majoron: the radial part of χ, σ
- Through the quartic coupling $gH^\dagger H\chi^*\chi$, h and σ mix with an angle ϑ

$$g = \frac{M_\sigma^2 - M_h^2}{2vv_\chi}\sin 2\vartheta$$

$$\sin^2\vartheta \lesssim 0.11$$ ATLAS Collaboration, 1909.02845

The Majoron and Axion from a MFV setup

R. S. Chivukula and H. Georgi, PLB **188**, 99-104 (1987)

- Minimal Flavour Violation assumption: only Yukawas violate flavour symmetry

- Flavour Symmetry Group identified in the limit of vanishing Yukawas

D'Ambrosio et al., 020736
Cirigliano et al., 0507001

$$\mathcal{G}_F = U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{l_L} \times U(3)_{N_R} \times U(3)_{e_R}$$

$$\mathcal{G}_F \supset \mathcal{G}_F^A = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_{e_R} \times U(1)_{N_R}$$

- The PQ charges are chosen to explain m_b/m_t and m_τ/m_t

$$x_{q_L} = x_{l_L} = x_{u_R} = x_{N_R} = 0, x_{d_R} = x_{e_R} = 3$$

FAA & Merlo, 1709.07039

- As with LN, PQ is made an exact symmetry by the addition of a scalar field Φ with $x_\Phi = -1$

$$\Phi = \frac{\rho + v_\Phi}{\sqrt{2}} e^{i\frac{a}{v_\Phi}}$$

The Majoron and Axion from a MFV setup

$$-\mathcal{L}_Y = \bar{q}_L \widetilde{H} \mathcal{Y}_u u_R + \left(\frac{\Phi}{\Lambda_\Phi}\right)^3 \bar{q}_L H \mathcal{Y}_d d_R + \left(\frac{\Phi}{\Lambda_\Phi}\right)^3 \bar{l}_L H \mathcal{Y}_e e_R$$

$$+ \left(\frac{\chi}{\Lambda_\chi}\right)^{\frac{1+L_N}{L_\chi}} \bar{l}_L \widetilde{H} \mathcal{Y}_\nu N_R + \frac{1}{2}\left(\frac{\chi}{\Lambda_\chi}\right)^{\frac{2L_N - L_\chi}{L_\chi}} \chi \bar{N}_R^c \mathcal{Y}_N N_R + \mathrm{h.c.}$$

- The matrices $\mathcal{Y}_{u,d,e,\nu,N}$ must become spurions transforming under the non-Abelian part of $\mathcal{G}_F$

$$\langle \mathcal{Y}_u \rangle = c_t V^\dagger \mathrm{diag}\left(\frac{m_u}{m_t}, \frac{m_c}{m_t}, 1\right), \langle \mathcal{Y}_d \rangle = c_b \mathrm{diag}\left(\frac{m_d}{m_b}, \frac{m_d}{m_b}, 1\right), \langle \mathcal{Y}_e \rangle = c_\tau \mathrm{diag}\left(\frac{m_e}{m_\tau}, \frac{m_e}{m_\tau}, 1\right)$$

- The PQ SSB explains the m_b/m_t and m_τ/m_t ratios assuming

$$\frac{v_\Phi}{\sqrt{2}\Lambda_\Phi} \simeq 0.23$$

- Non-renormalizable flavour violating operators are Yukawa suppressed: $1 - 10$ TeV scale, accessible at colliders

The Majoron and Axion from a MFV setup

- MFV in the lepton sector: $\mathcal{Y}_\nu$ and $\mathcal{Y}_N$ cannot be directly identified in terms of neutrino masses or the PMNS elements.
- Two possible ways out:
  - $\mathcal{G}_L^{NA} = SU(3)_{l_L} \times SU(3)_{e_R} \times SO(3)_{N_R} \times CP \Rightarrow \mathcal{Y}_N \propto \mathbb{1}, \mathcal{Y}_\nu \in \mathbb{R}$

Cirigliano et al., 0507001

S. Davidson and F. Palorini, hep-ph/0607329

$$m_\nu = \frac{\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} v^2}{\sqrt{2} v_\chi} \mathcal{Y}_\nu \mathcal{Y}_\nu^T$$

  - $\mathcal{G}_L^{NA} = SU(3)_{l_L+N_R} \times SU(3)_{e_R} \Rightarrow \mathcal{Y}_\nu \propto \mathbb{1}$ R. Alonso et al., 1103.5461

$$m_\nu = \frac{\varepsilon_\chi^{\frac{2+L_\chi}{L_\chi}} v^2}{\sqrt{2} v_\chi} \mathcal{Y}_N^{-1}$$

- The axion arising from the PQ SSB couples to gluons and behaves as the usual QCD Axion solving the Strong CP Problem

N. Viaux et al., 1311.1669

O. Straniero et al., 1802.10357

S. A. Díaz et al., 1910.10568

$$m_a \sim 6\ \mu\text{eV} \left(\frac{10^{12}\text{GeV}}{f_a} \right), \qquad f_a = \frac{v_\Phi}{9} \gtrsim 8 \times 10^8\ \text{GeV}$$

Phenomenological Signatures

- Coupling to photons

$$\mathcal{L}_{\omega}^{low-energy} \supset \frac{1}{4}\lambda_{\omega\gamma\gamma}\omega F^{\mu\nu}\tilde{F}_{\mu\nu}, \qquad \lambda_{\omega\gamma\gamma} \lesssim 10^{-10}\ \text{GeV}^{-1}$$

CAST Collaboration, 1705.02290

  - Matching the effective coupling with the 2 loop explicit expression yields

C. García-Cely and J. Heeck, 1701.07209

$$\lambda_{\omega\gamma\gamma} = \frac{\alpha m_{\omega}^2}{384\sqrt{2}\pi^3 m_e^2 v_{\chi}} \varepsilon_{\chi}^{\frac{2+2L_N}{L_\chi}} \text{Tr}(\mathcal{Y}_\nu \mathcal{Y}_\nu^\dagger)$$

- Coupling to electrons

$$\mathcal{L}_{\omega}^{low-energy} \supset i\lambda_{\omega ee}\omega\bar{e}e, \qquad \lambda_{\omega ee} \lesssim 4.3 \times 10^{-13}$$

N. Viaux et al., 1311.1669

  - The explicit expression can be found at the 1 loop level

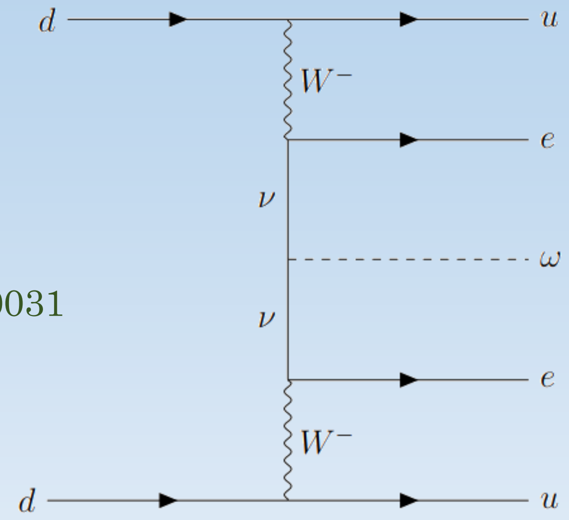
C. García-Cely and J. Heeck, 1701.07209

$$\lambda_{\omega ee} = \frac{1}{16\pi^2}\frac{m_e}{v_\chi} \varepsilon_{\chi}^{\frac{2+2L_N}{L_\chi}} \left((\mathcal{Y}_\nu \mathcal{Y}_\nu^\dagger)_{11} - \text{Tr}(\mathcal{Y}_\nu \mathcal{Y}_\nu^\dagger)\right)$$

Phenomenological Signatures

- Coupling to neutrinos
  - Constrained by Majoron emission in $0\nu\beta\beta$ decays

$$\lambda_{\omega\nu\nu} < 10^{-5}$$ R. Cepedello et al., 1811.00031

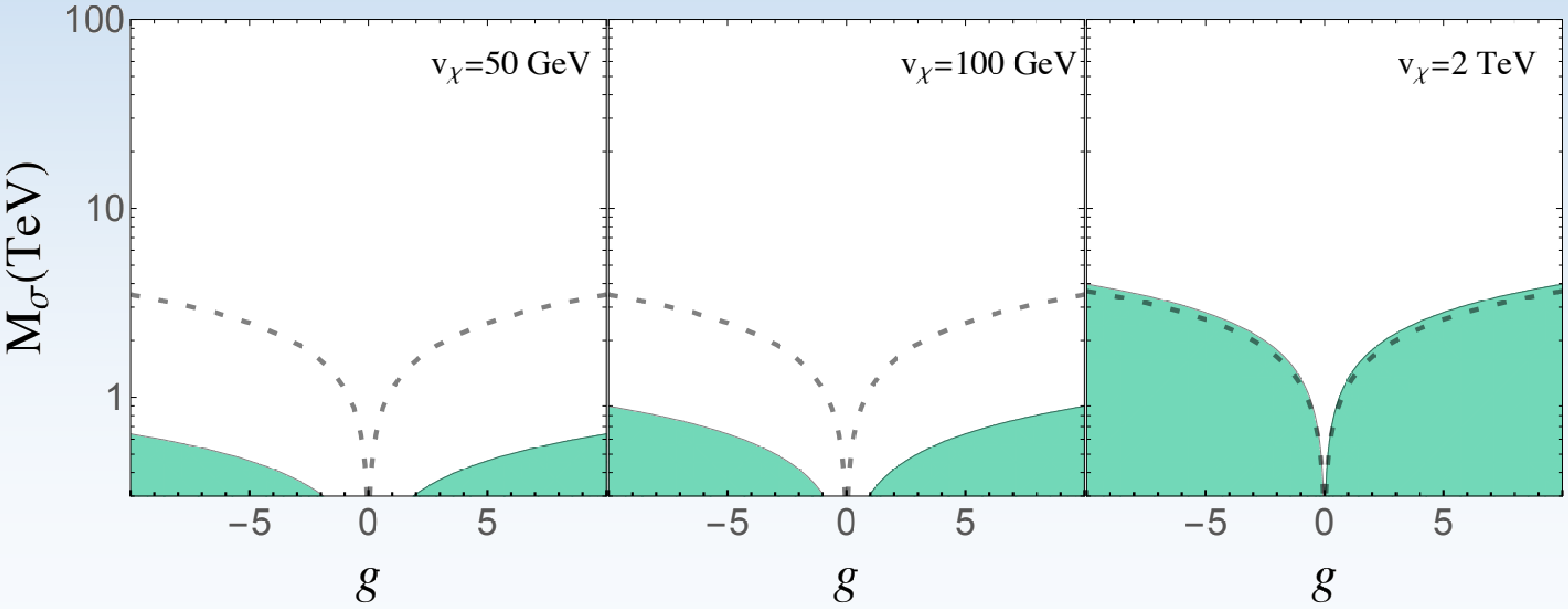


<table>
<tr><th></th><th>$\lambda_{\omega\gamma\gamma}$</th><th>$\lambda_{\omega ee}$</th><th>$\lambda_{\omega\nu\nu}$</th></tr>
<tr><td>CASE NR1</td><td>$[10^{-39}, 10^{-36}]$ GeV^{-1}</td><td>$[10^{-25}, 10^{-24}]$</td><td rowspan="2">$[10^{-14}, 10^{-12}]$</td></tr>
<tr><td>CASE NR2</td><td>$[10^{-34}, 10^{-32}]$ GeV^{-1}</td><td>10^{-20}</td></tr>
<tr><td>Exp. Upper bounds</td><td>10^{-10} GeV^{-1}</td><td>10^{-13}</td><td>10^{-5}</td></tr>
</table>

Phenomenological Signatures

- Coupling with the Higgs
  - Apart from the $h - \sigma$ mixing angle ϑ, the Higgs invisible decay $h \to \omega\omega$ is constrained

CMS collaboration, 1809.05937 $\Gamma_{h\to\omega\omega} = \frac{\sin^2\vartheta\, M_h^3}{32\pi v_\chi^2} \lesssim 0.8\ \text{MeV} \Rightarrow \frac{v_\chi}{|\sin\vartheta|} \gtrsim 5\ \text{TeV}$



Phenomenological Signatures

- Heavy neutrinos
  - Case NR1 testable at beam dump experiments or near detectors at oscillation experiments like DUNE or SHiP
  - Case NR2 interesting for production at LHC or future colliders
- $N \to 3\nu$ in the early universe may disfavour some scenarios
  - If it happens after BBN, as it may happen in Case NR1 with $\langle M_N \rangle \in [3.5, 200]$ MeV, the light-heavy neutrino mixing θ_s is bound by

$$\sin^2\theta_s \equiv \frac{\langle m_\nu \rangle}{\langle M_N \rangle} \lesssim 10^{-15} - 10^{-17}$$

A. C. Vincent et al., 1408.1956

  - The heavier masses in Case NR2 allow for decay before BBN, evading that cosmological bound

	$\langle M_N \rangle$	$\sin^2\theta_s$	$\Gamma^Z_{N\to 3\nu}$	$\Gamma^\omega_{N\to 3\nu}$
CASE NR1	$[3.5, 200]$ MeV	$[2.5\times 10^{-10},\ 1.4\times 10^{-8}]$	$\mathcal{O}(10^{-38})$	$\mathcal{O}(10^{-68})$
CASE NR2	$[35.4, 707]$ GeV	$[7.1\times 10^{-14},\ 1.4\times 10^{-12}]$	$\mathcal{O}(10^{-27})$	$\mathcal{O}(10^{-66})$

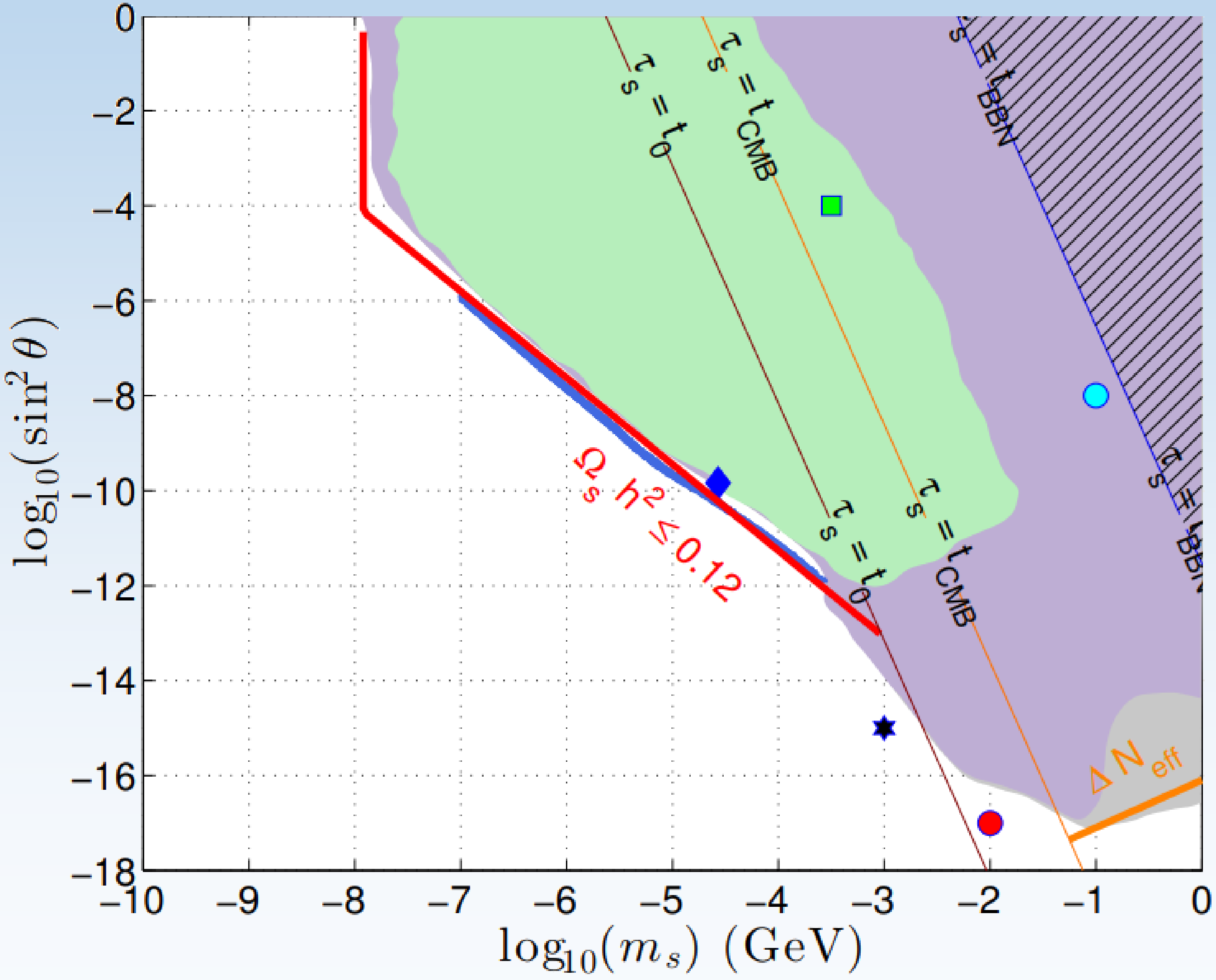
Conclusions

- Majorons can alleviate the Hubble tension
- The smallness of neutrino masses was addressed here with a Majoron
- This Majoron can easily be embedded in MFV, where also a QCD axion can arise
- Cosmology sets strong bounds
- Colliders may see several signals: "Light" Heavy neutrinos, new scalar or Higgs invisible decay

Thank you for your attention

Backup slides

Phenomenological Signatures



Plot from A. C. Vincent, E. F. Martínez, P. Hernández, M. Lattanzi, and O. Mena, 1408.1956

	$\langle M_N \rangle$	$\sin^2\theta_s$
CASE NR1	$[3.5, 200]$ MeV	$[2.5 \times 10^{-10},\ 1.4 \times 10^{-8}]$

The Majoron Mechanism

- Two phenomenologically interesting non-renormalizable scenarios:

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- Other possibilities
  - $L_N > 0, L_\chi < 0 \Rightarrow \chi \leftrightarrow \chi^\dagger$
  - $L_N < 0, L_\chi > 0 \Rightarrow$ non-local
  - $L_N = L_\chi = -1 \Rightarrow m_\nu \propto \varepsilon_\chi^{-1}$, highly fine-tuned