Cosmological constraints on the Sessaw Scale

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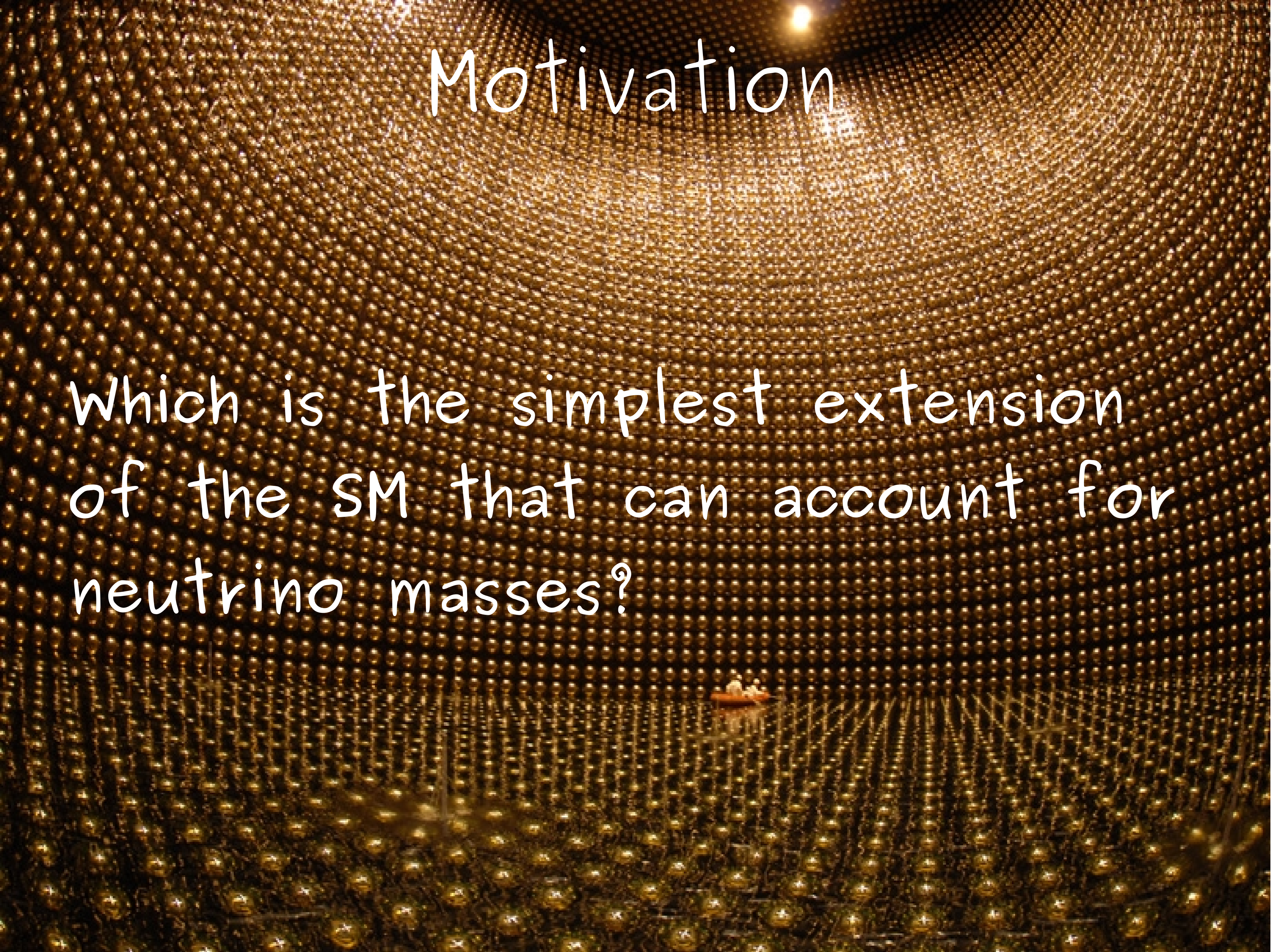

Motivation

Which is the simplest extension of the SM that can account for neutrino masses?

Seesaw Model

- As simple as just adding singlet fermions (sterile neutrinos) to the SM field content.

- If lepton number conservation is not imposed, the *most general Lagrangian* is given by

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} - \frac{1}{2}\overline{\nu_{si}} M_{ij} \nu^c_{sj} - (Y)_{i\alpha}\overline{\nu_{si}}\widetilde{\phi}^\dagger L_\alpha + {\rm h.c.}$$

Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

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New Physics Scale ($m_\nu \sim Y^2 v^2 / M$)

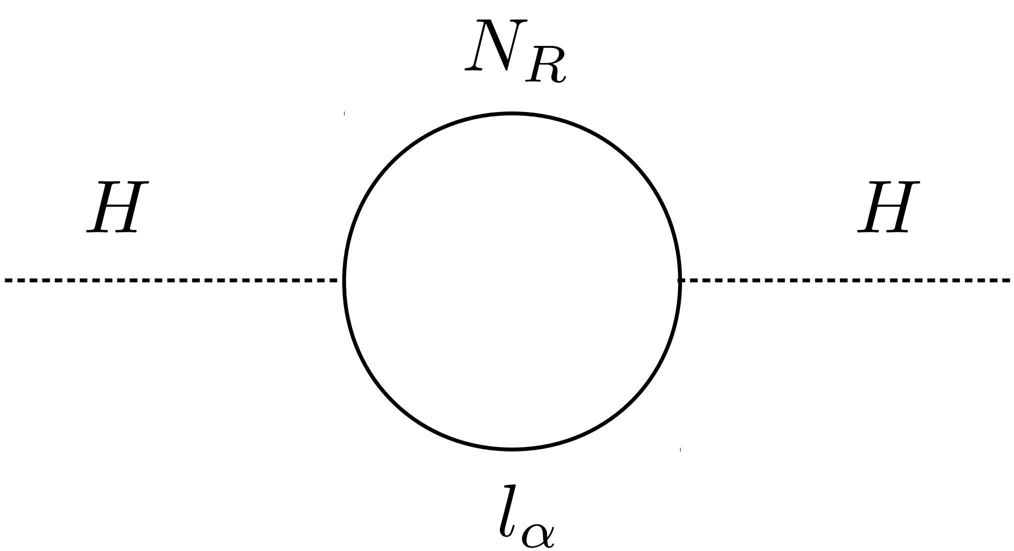
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

A New Physics scale

- Low scale models require small Yukawa couplings. With the exception of TeV scale models as the inverse seesaw.

  Mohapatra, Valle 1986

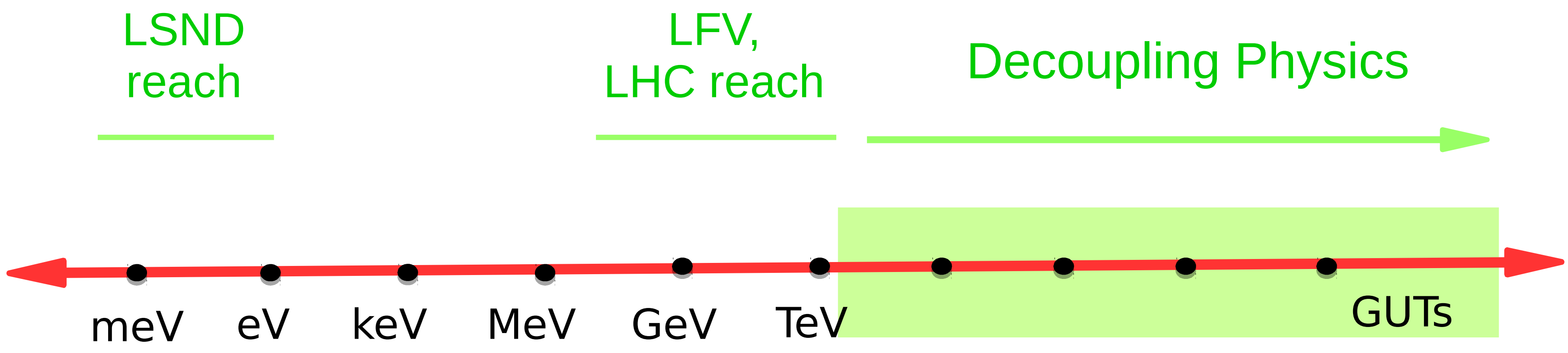
- Contrary to the high scale models, a low Majorana scale does not worsen the Higgs mass hierarchy problem.



$$[\delta M_H^2]_{N_R} \propto M^2$$

Vissani 1998

The New Physics Scale is Unbounded



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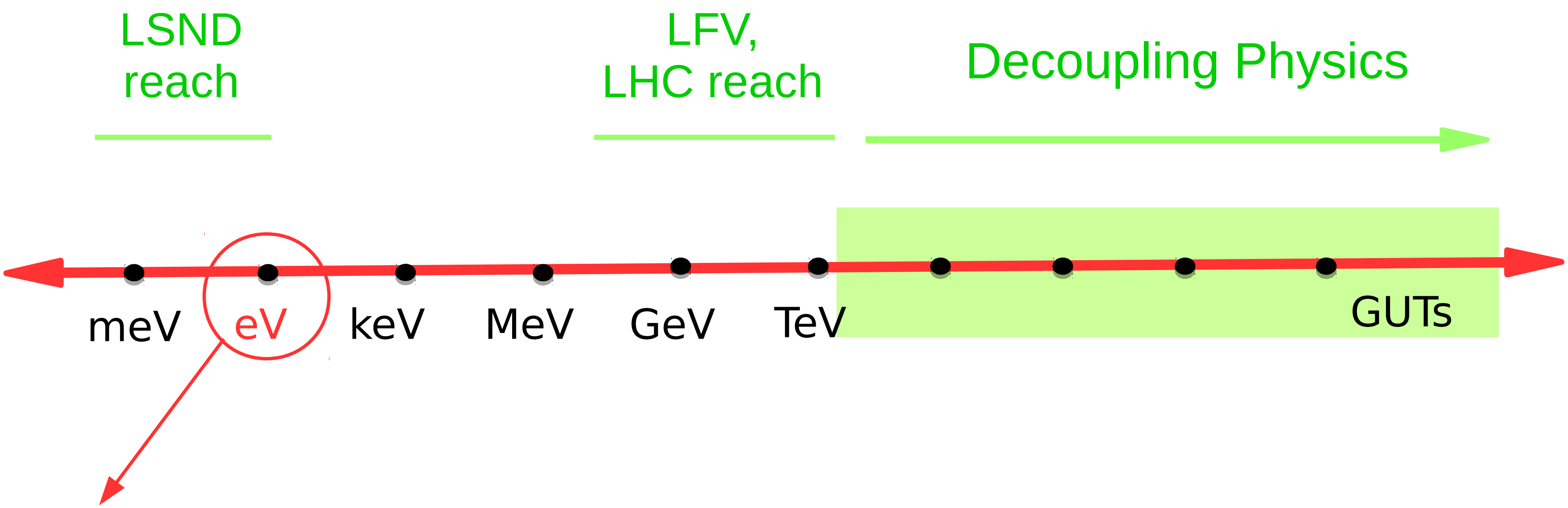

Explanation to neutrino anomalies pointed out mainly by LSND and reactor experiments.

Donini, Hernandez, JLP, Maltoni, Shwetz 2012

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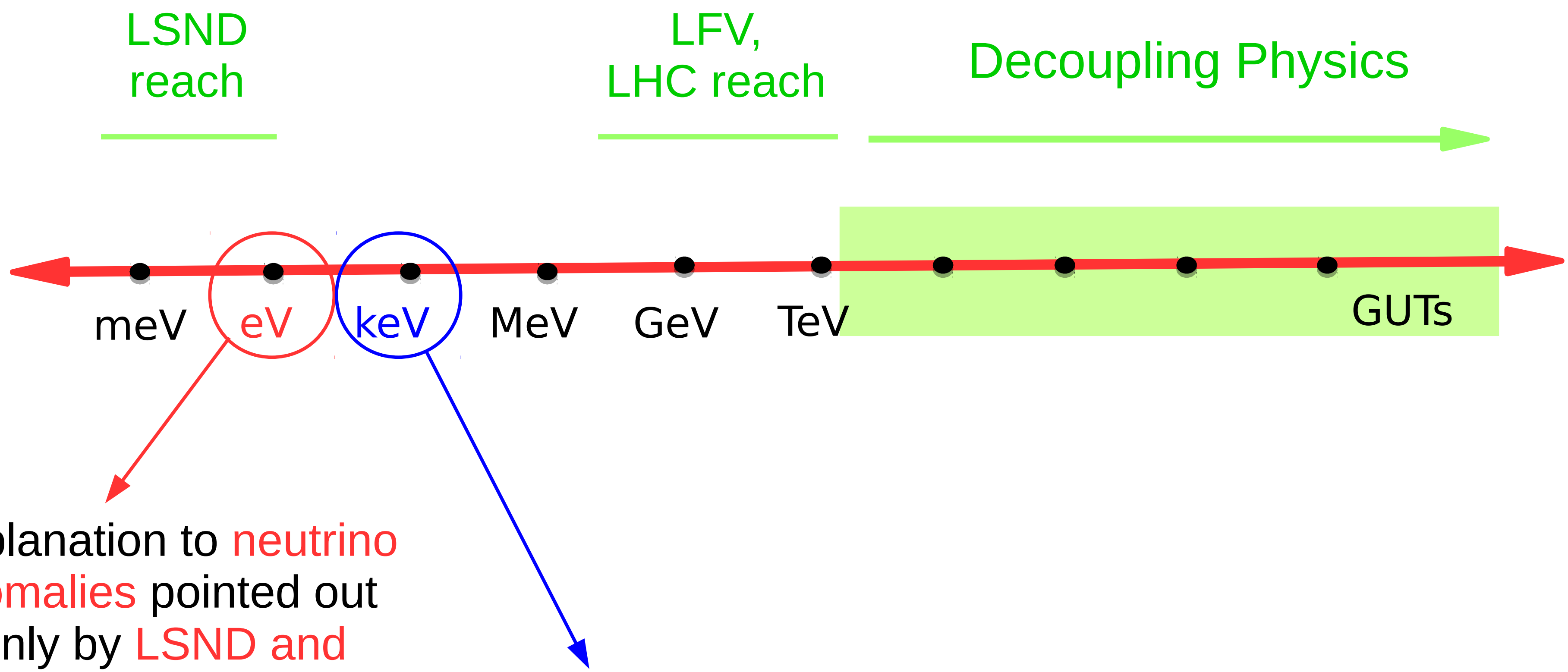

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Warm DM candidate. Moreover, after the recent X-ray signal/hint.

Bulbul et al.(arXiv:1402.2301)

Boyarsky et al.(arXiv:1402.4119)

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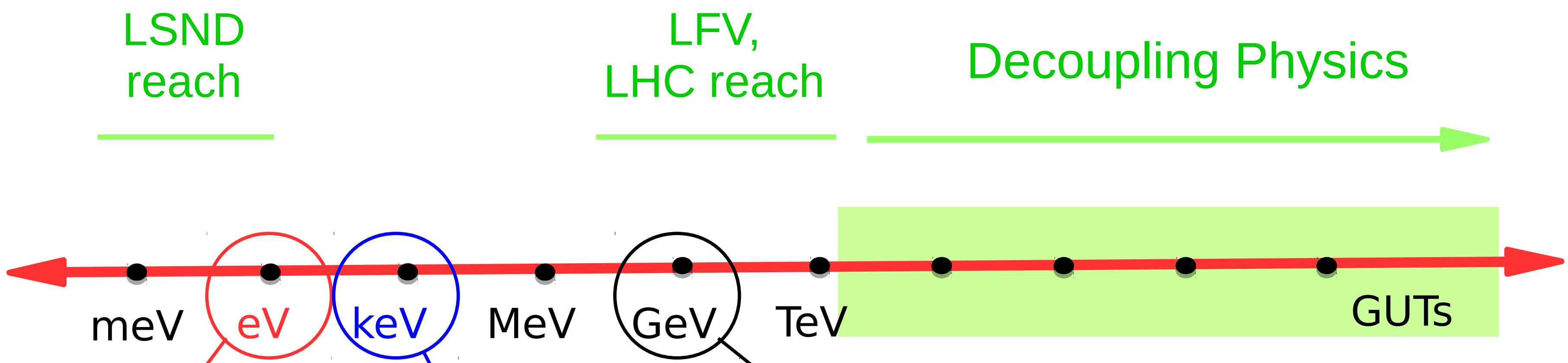

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Account for baryon asymmetry in the Universe.
Akhmedov, Rubakov, Smirnov 1998
Asaka, Blanchet, Shaposhnikov 2005

A different point of view...

- We start from the lowest level of complexity. Minimum number of extra fermionic degrees of freedom (fermion singlets) n_R

$n_R = 1$ Excluded by neutrino oscillation data.

Donini, Hernandez, JLP, Maltoni 2011

$n_R = 2$ In agreement with neutrino oscillation data.

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Donini, Hernandez, JLP, Maltoni 2011

$n_R = 2$ In agreement with neutrino oscillation data. **Minimal Model**

We do not assume any hierarchy for the new parameters of the model.

Can we obtain general bounds on the Majorana scale without assuming a priori anything about the parameters of the model?

3+2 Minimal Seesaw Model

vs

Cosmology

P. Hernandez, M. Kekic, JLP 2013
ArXiv:1311.2614
(PRD89 (2014) 073009)

Extra radiation, N_{eff}

The energy density of the extra sterile neutrino species is usually quantified in terms of

$$N_{eff} = \frac{\rho_s + \rho_\nu}{\rho^0_{1\nu}}$$

$$N^{BBN}_{eff} = 3.5 \pm 0.2[1\sigma] \quad \left(N^{BBN}_{eff} < 4\,[2.2\sigma]\right)$$

Cooke et al; arXiv:1308.3240

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Sterile neutrino contribution

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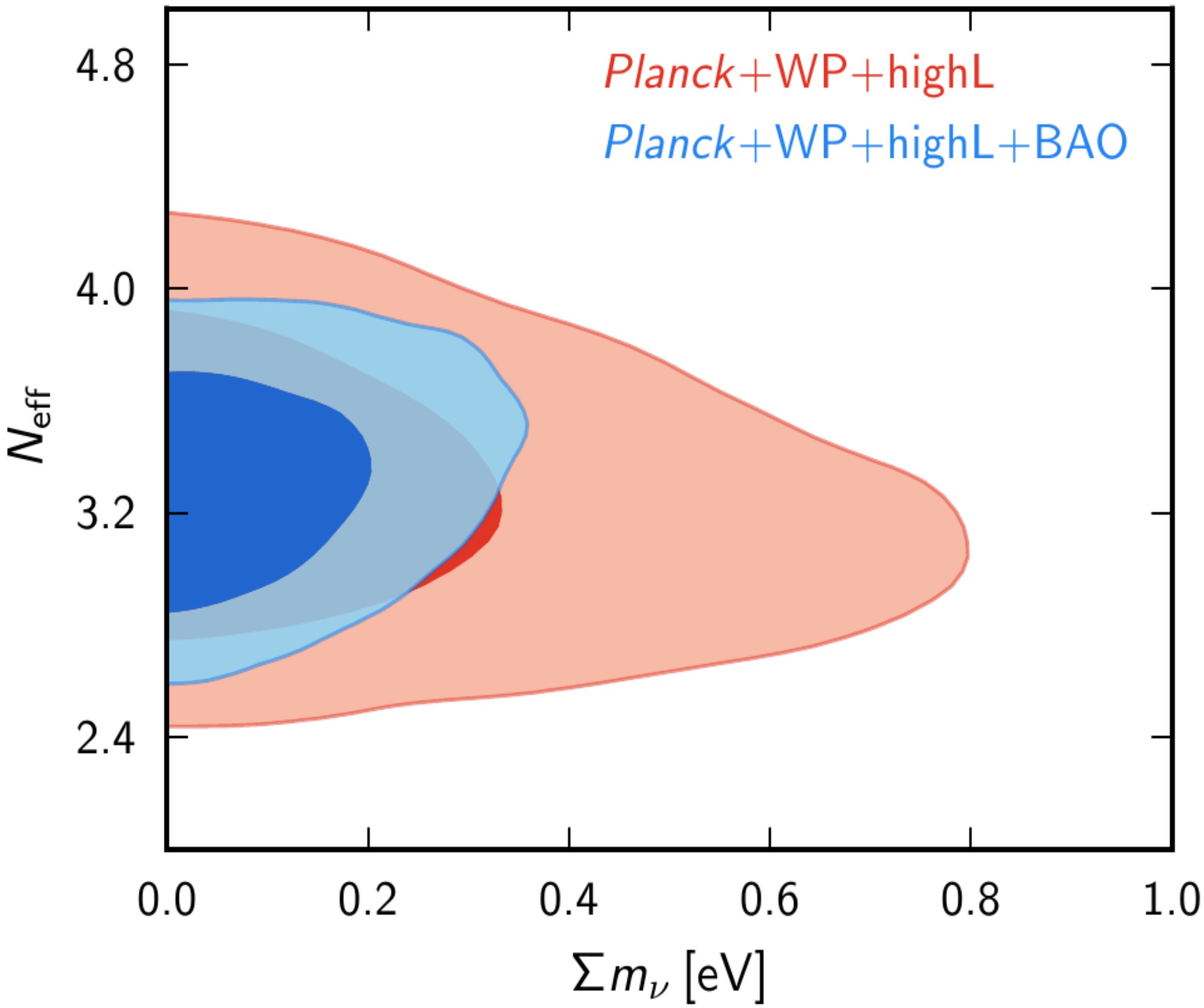
Extra radiation, N_{eff}

CMB



Planck Collboration 2013 (arXiv:1303.076)

Extra radiation, N_{eff}

- The 3 active neutrinos contribute with $N_{eff}^{SM} \approx 3$

- One **fully thermal** extra sterile state that decouples being relativistic contributes with $\Delta N_{eff} \approx 1$ when freezes out.

- Can the sterile neutrinos escape from thermalization in the 3+2 Minimal Seesaw Models?

Sterile Neutrino Thermalization

- Sterile neutrino thermalization is controlled by:

$$f_{s_j}(T) \equiv \frac{\Gamma_{s_j}(T)}{H(T)}$$

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Barbieri, Dolgov 1990; Kainulainen 1990;

$$\Gamma_{s_j}(T) \approx \frac{1}{2}\sum_{\alpha}\langle P\left(\nu_\alpha \to \nu_{s_j}\right)\rangle \times \Gamma_{\nu_\alpha}$$

Sterile neutrino collision rate

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Sterile neutrino collision rate

$$H\left(T\right) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_{Planck}}$$

Hubble expansion rate

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$$H\left(T\right) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_{Planck}}$$

Hubble expansion rate

- The sterile neutrinos thermalize if $f_s(T) \geq 1$

Sterile Neutrino Thermalization

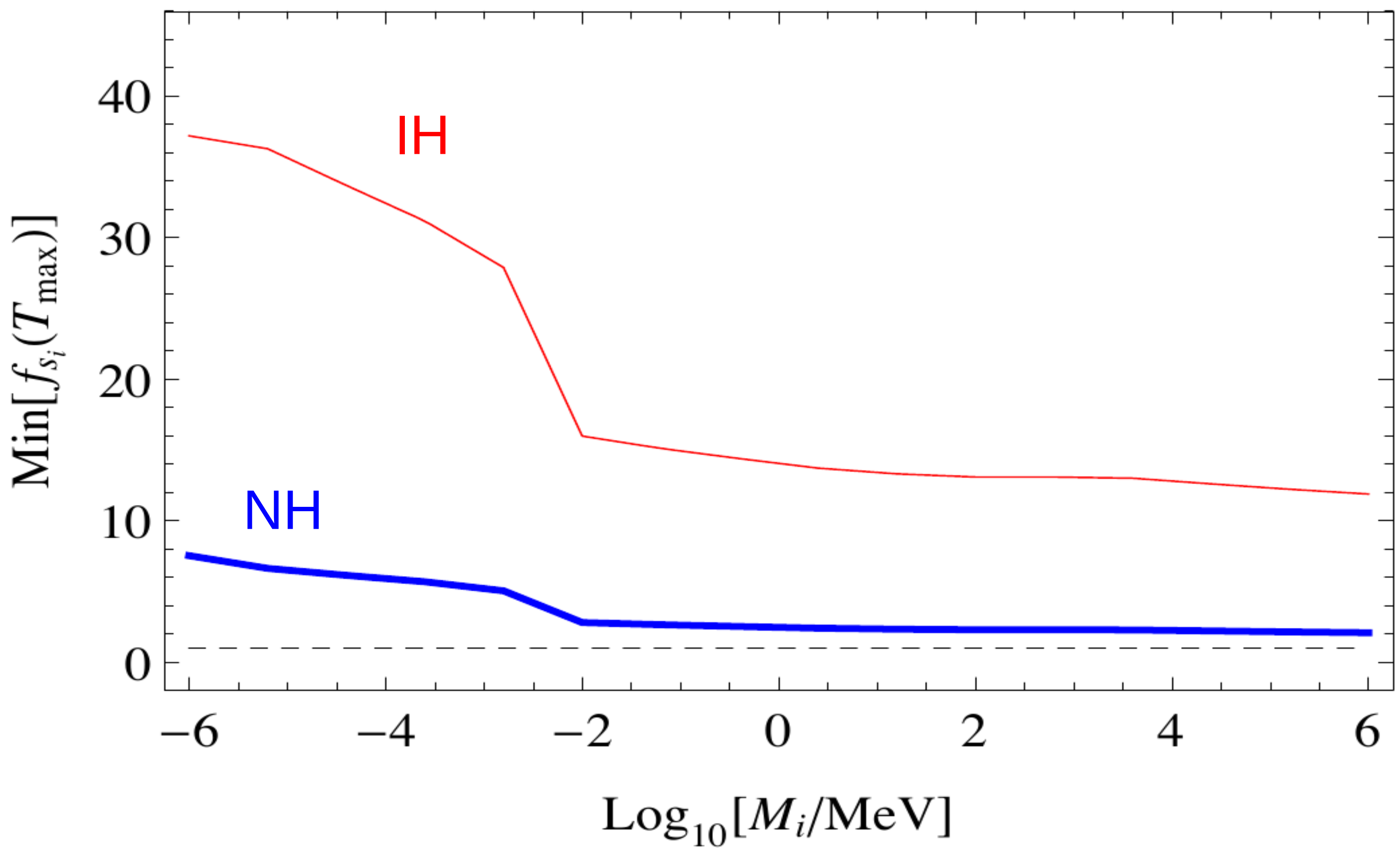
- $f_s(T)$ reaches a maximum at some temperature T_{max} and if the maximum is larger than one, thermalization will be achieved. At decoupling we can estimate:

$$N_{eff} \approx N_{eff}^{SM} + \boxed{\sum_j \left(1 - exp\left(-\alpha f_{s_j}(Tmax)\right)\right)}$$

$$\Downarrow$$

$$\Delta N_{eff}$$

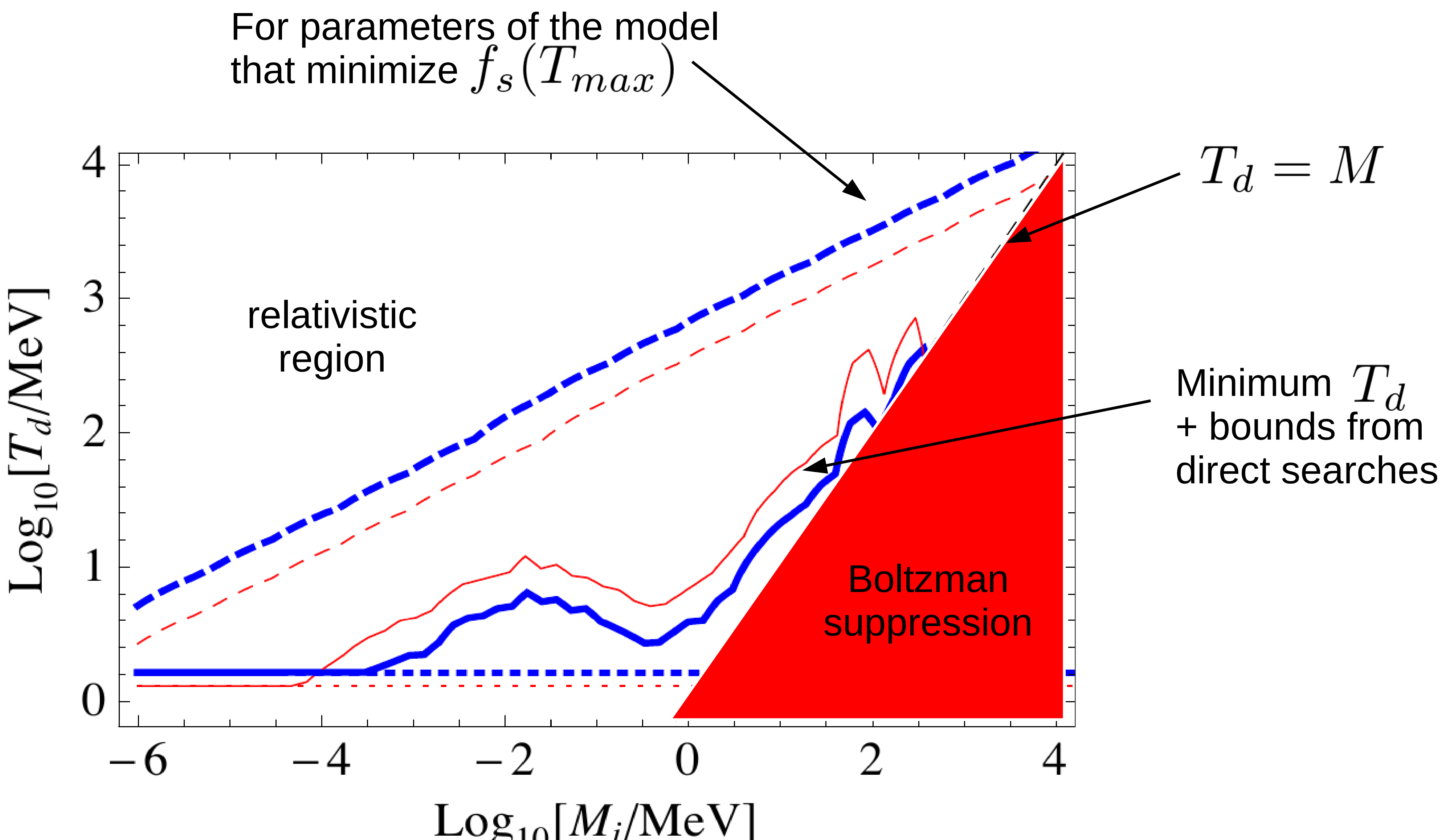
Sterile Neutrino Thermalization



- Thermalization rate basically indepent of the seesaw scale.

- In the 3+2 type-I seesaw model, for the whole parmeter space, the sterile neutrinos always thermalize at some point of the thermal history.

Sterile Neutrino Decoupling



Sterile Neutrino Decoupling

- Above $\sim 100 MeV$, there is Boltzman suppression. The bounds do not apply for

$$M \gtrsim 100 MeV$$

- Moreover, after sterile neutrino decoupling two effects could modify ΔN_{eff}, before BBN:

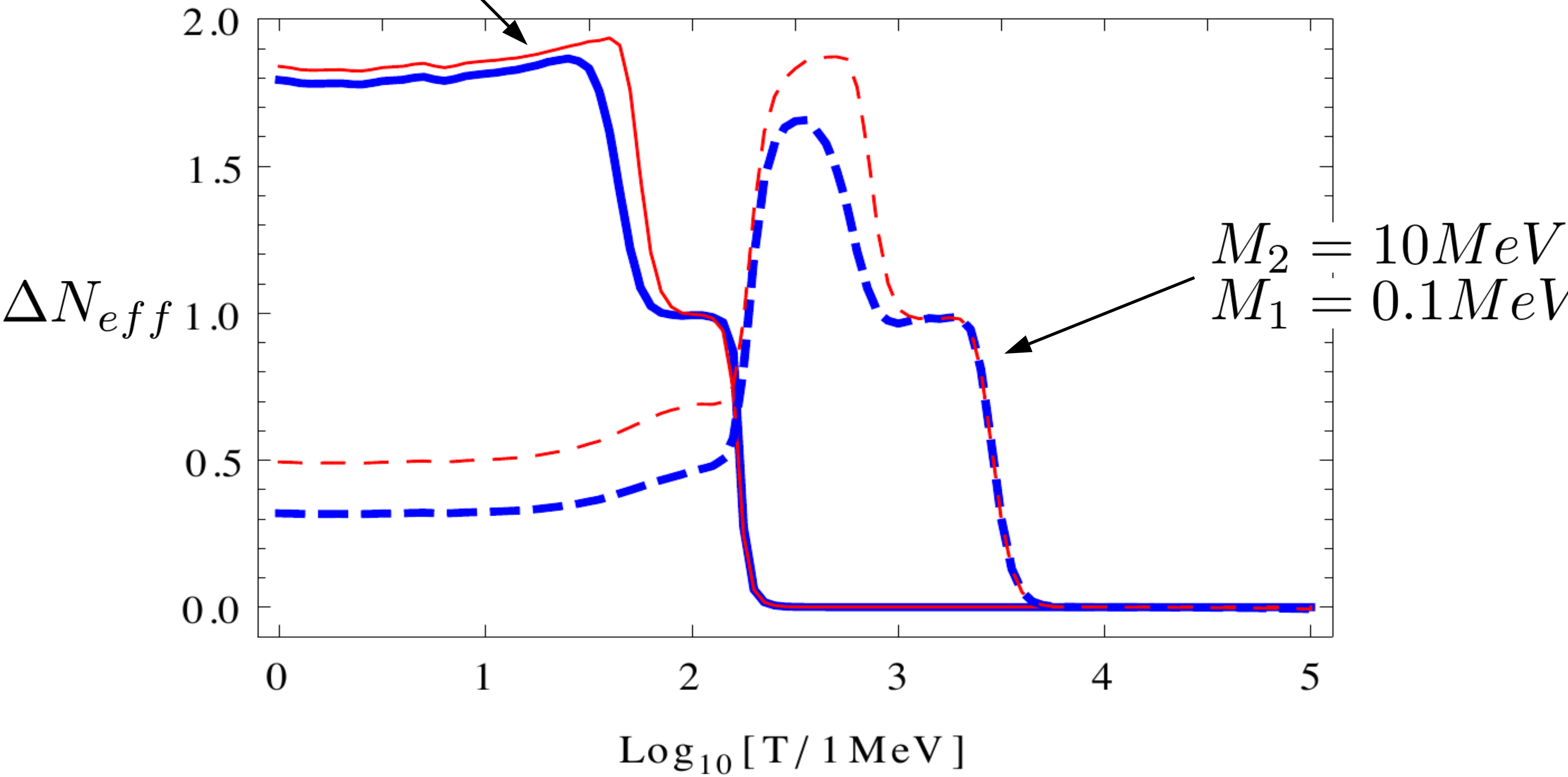
(i) Dilution

(ii) Decay

Entropy dilution

$M_2 = 1KeV$
$M_1 = 20eV$

Dilution could be relevant for $M \gtrsim 10KeV$



Entropy dilution

- Dilution effects allow to relax the bounds for the range of masses

$$10KeV \lesssim M \lesssim 100MeV$$

- However, those sterile neutrinos would give a huge contribution to the energy density when they become non-relativistic later, modyfing in a drastic way CMB and structure formation.

- The only way CMB and BBN bounds can be evaded for this range of masses is if the sterile neutinos decay before BBN.

sterile neutrino decay

- Bounds on short-lived sterile neutrinos with masses on the range $[10MeV, 140MeV]$ have been studied by

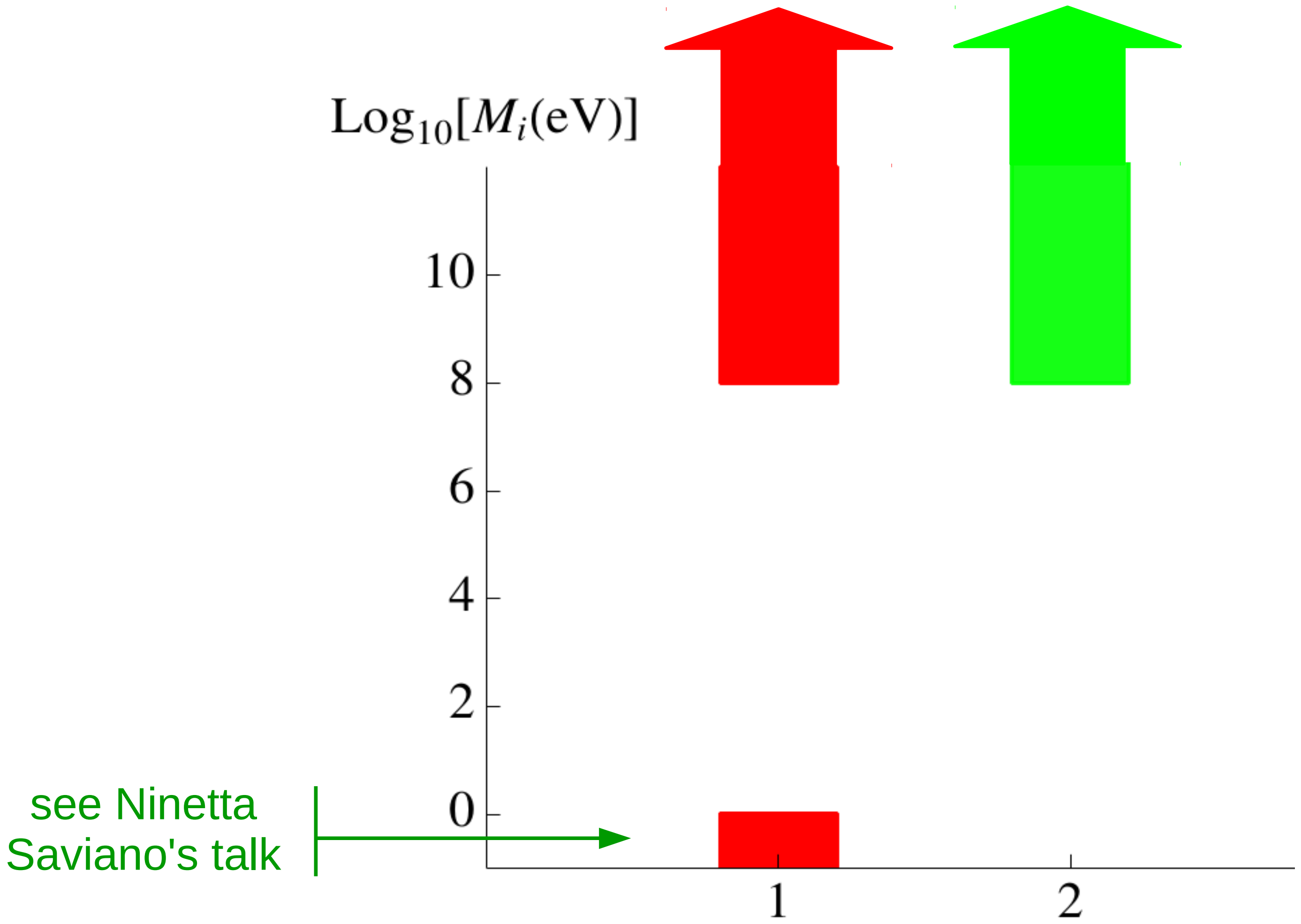
Dolgov, Hansen, Raffelt, Semikoz 2000
Fuller, Kishimoto, Kusenko, 2011
Ruchayskiy, Ivashko, 2012

- Very strong bounds found combining BBN and direct acelerator searches, excluding the sterile neutrino decay before BBN in the minimal model for $M \lesssim \mathcal{O}(100MeV)$

Ruchayskiy, Ivashko, 2012
Vincent , Fernandez-Martinez, Hernandez, Lattanzi, Mena 2014

Summary 3+2 vs cosmology

- In summary, cosmology allow us to exclude a huge part of the parameter space and the seesaw scale (8 orders of magnitude!) of the 3+2 MM.



Allowed sterile neutrino spectra

3+3 Minimal Seesaw Model

vs

Cosmology

P. Hernandez, M. Kekic, JLP 2014
ArXiv:1406.2961
(PRD 90 (2014) 065033)

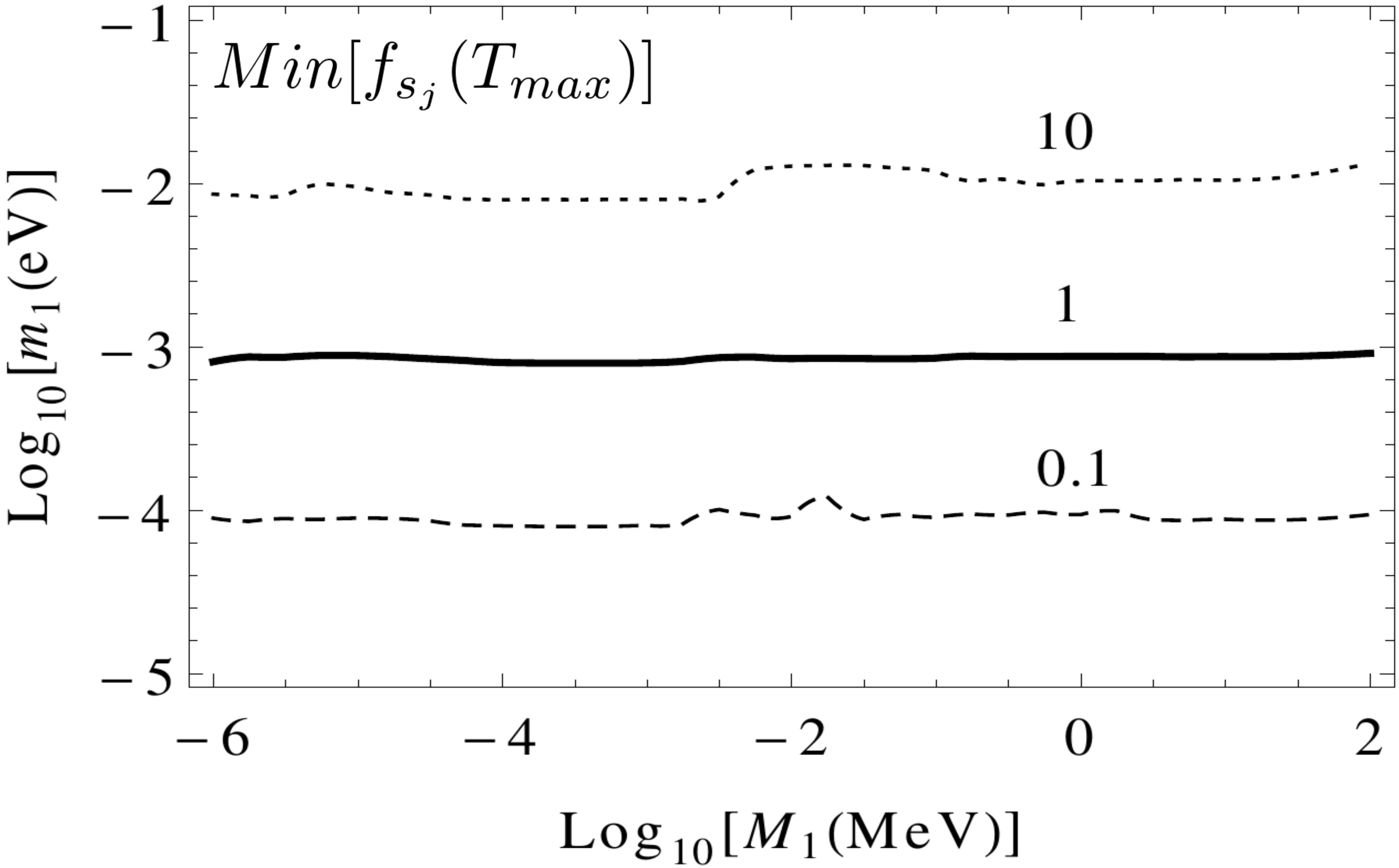
3+3 Minimal Seesaw Model

- Lager parameter space: 3 light masses + 3 heavy masses +6 angles + 6 CP-phases.

- We have explored the whole parameter space allowed by neutrino oscillation data.

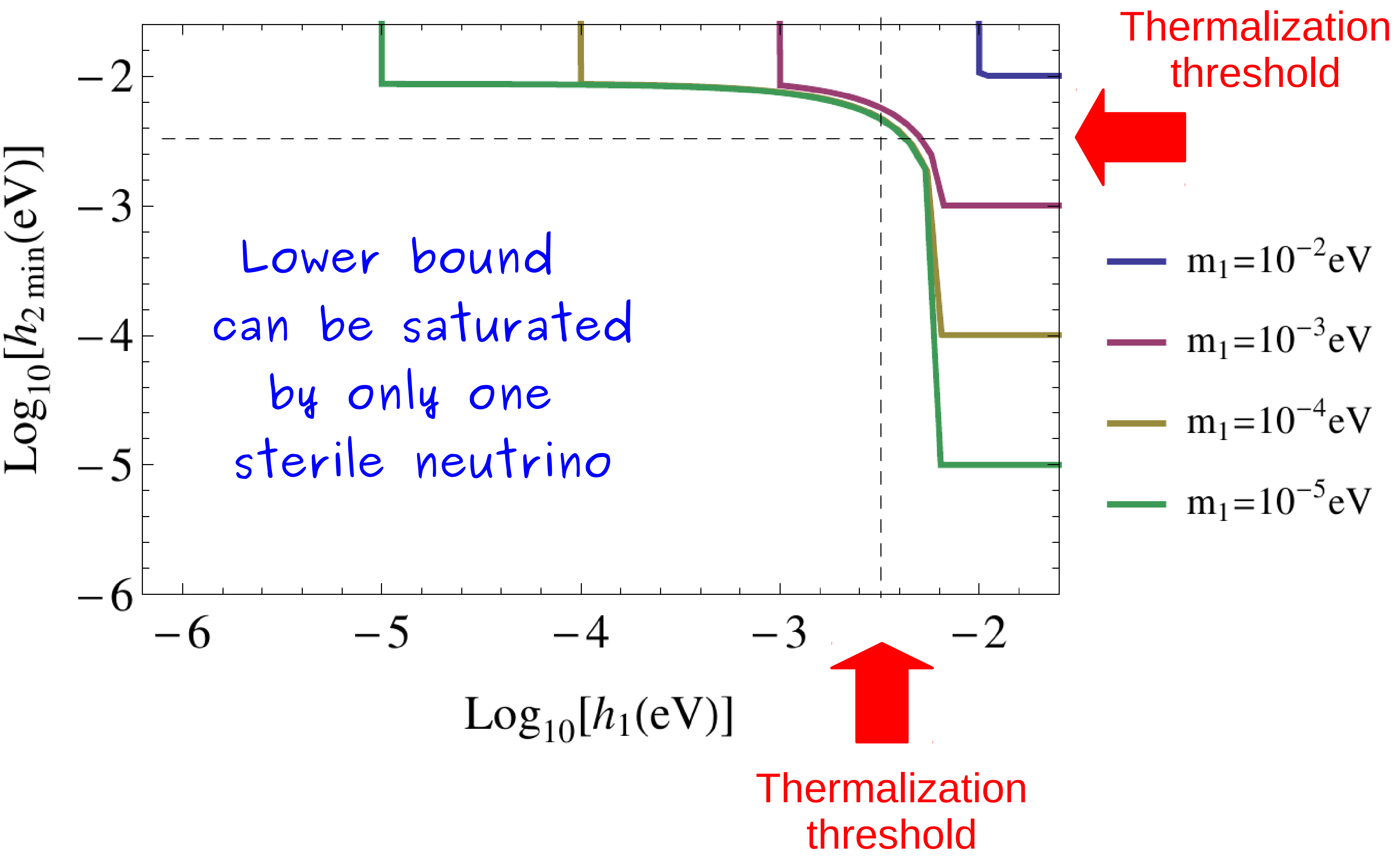
- In spite of the larger parameter space, only one sterile neutrino can escape from thermalization. The thermalization being basically controlled by the lightest neutrino mass.

3+3 Minimal Seesaw Model



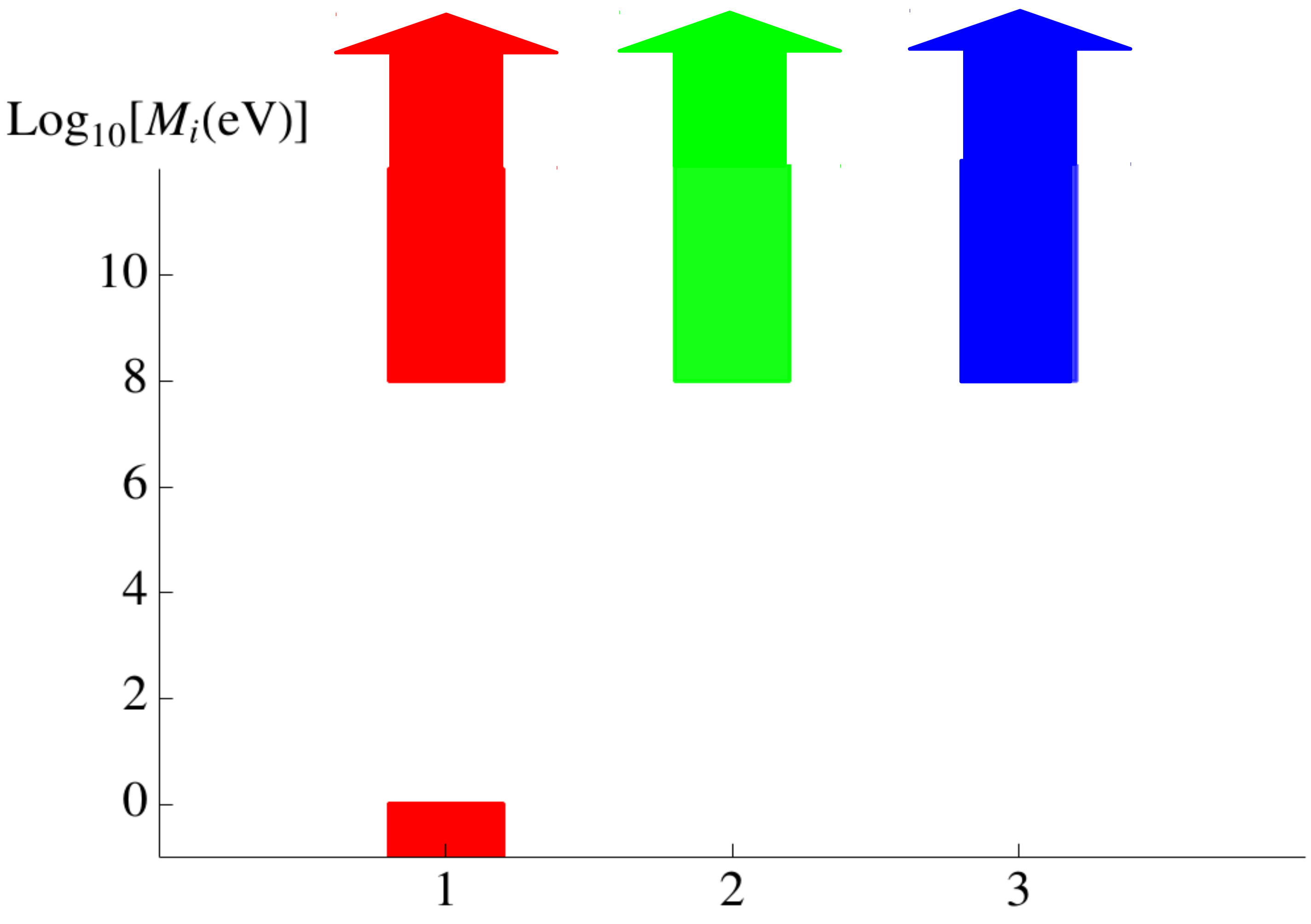
If $m_1 \geq \mathcal{O}\left(10^{-3} eV\right)$ the 3 sterile neutrinos thermalize

Analytical lower bound



Possible scenarios

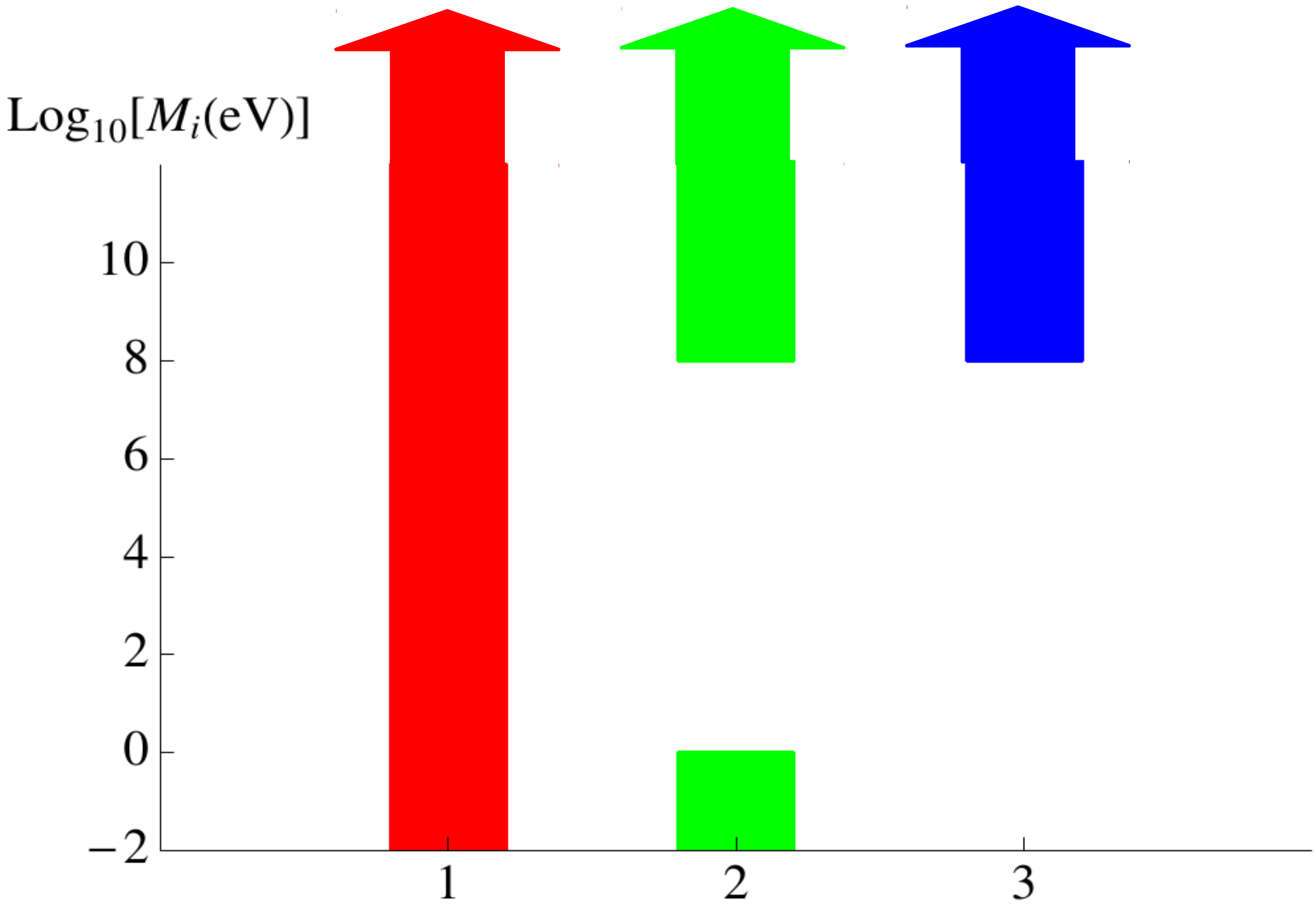
- $m_1 \geq \mathcal{O}\left(10^{-3} eV\right)$: the three sterile neutrinos thermalize.



Allowed sterile neutrino spectra

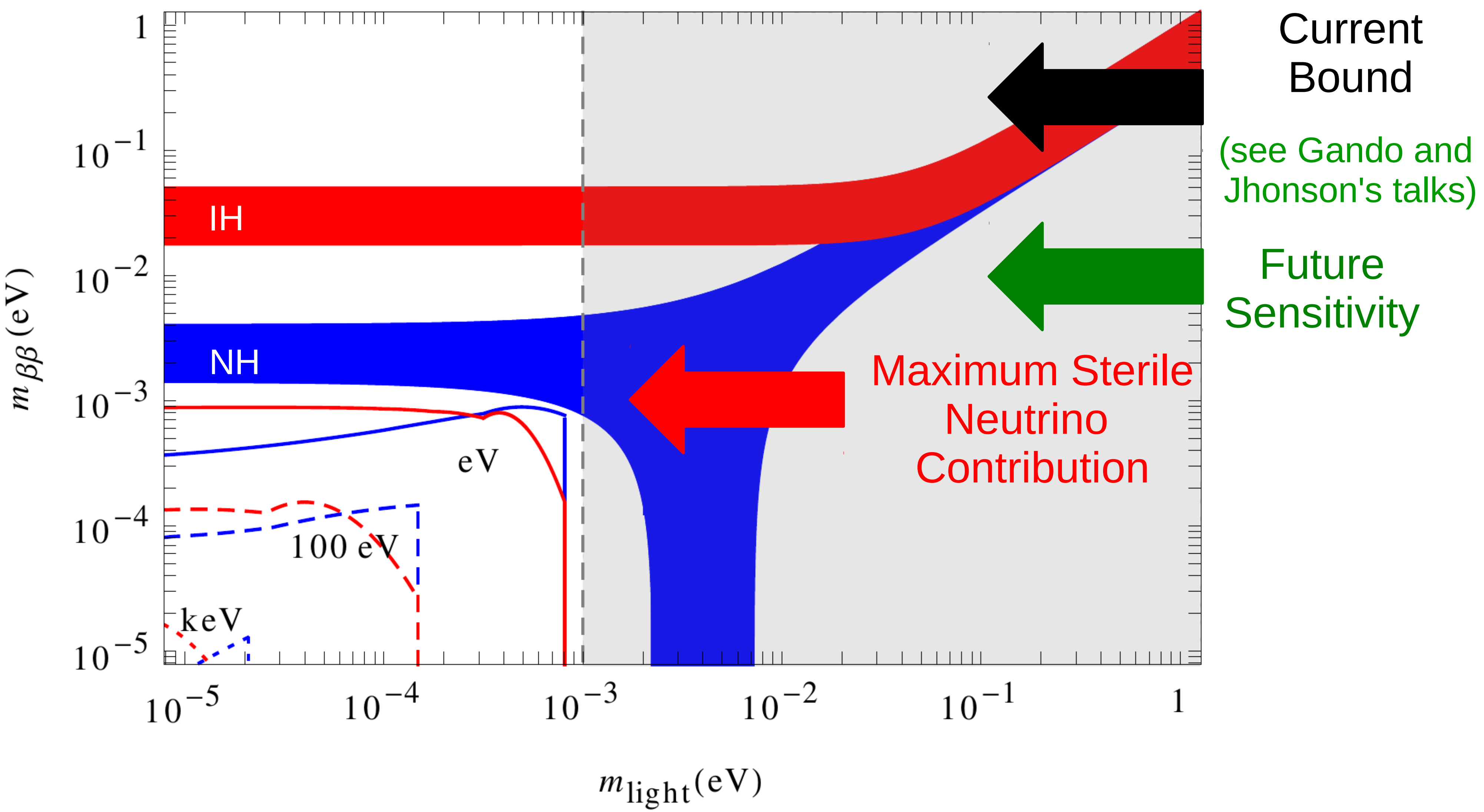
Possible scenarios

- $m_1 \leq \mathcal{O}\left(10^{-3} eV\right)$: one sterile neutrino does not thermalize. The other two contribute as in the 3+2 model.



Allowed sterile neutrino spectra

Impact on neutrinoless double beta decay



More about NMEs and Lepton number violation: Raina Prabhu and Julian Heek

Conclusions

- We have studied in detail the simplest low scale models that can accommodate light neutrino masses: just adding singlet fermions (sterile neutrinos) to the SM.

- In these models the new physics scale introduced to account for neutrino masses is the Majorana mass of the sterile neutrinos. The scale is in general unconstrained.

- The minimal model requires 2 sterile neutrinos and is strongly constrained by cosmology, **8 orders of magnitude of the sessaw scale are excluded,** since the sterile neutrinos can not scape from thermalization.

- Low scale 3+3 minimal seesaw models are also very constrained by cosmology. ***Only one sterile neutrino might escape from thermalization.*** Thermalization is controlled by the lightest neutrino mass, being the threshold:

$$m_1 = \mathcal{O}\left(10^{-3} eV\right)$$

- Strong impact of the cosmological bounds on neutrinoless double beta decay.


Thanks!

Extending Casas-Ibarra parameterization

Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

$$U = \begin{pmatrix} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{pmatrix}$$

→ active-sterile mixing

$$U_{aa} = U_{PMNS} \begin{pmatrix} 1 & 0 \\ 0 & H \end{pmatrix},$$

$$H^{-2} = I + m^{1/2} R^\dagger M^{-1/2} R m^{1/2}$$

$$U_{as} = i U_{PMNS} \begin{pmatrix} 0 \\ H m^{1/2} R^\dagger M^{-1/2} \end{pmatrix},$$

Keep in mind!
"Sterile neutrinos" interact with particles in thermal bath via this mixing.

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U_{as} → active-sterile mixing

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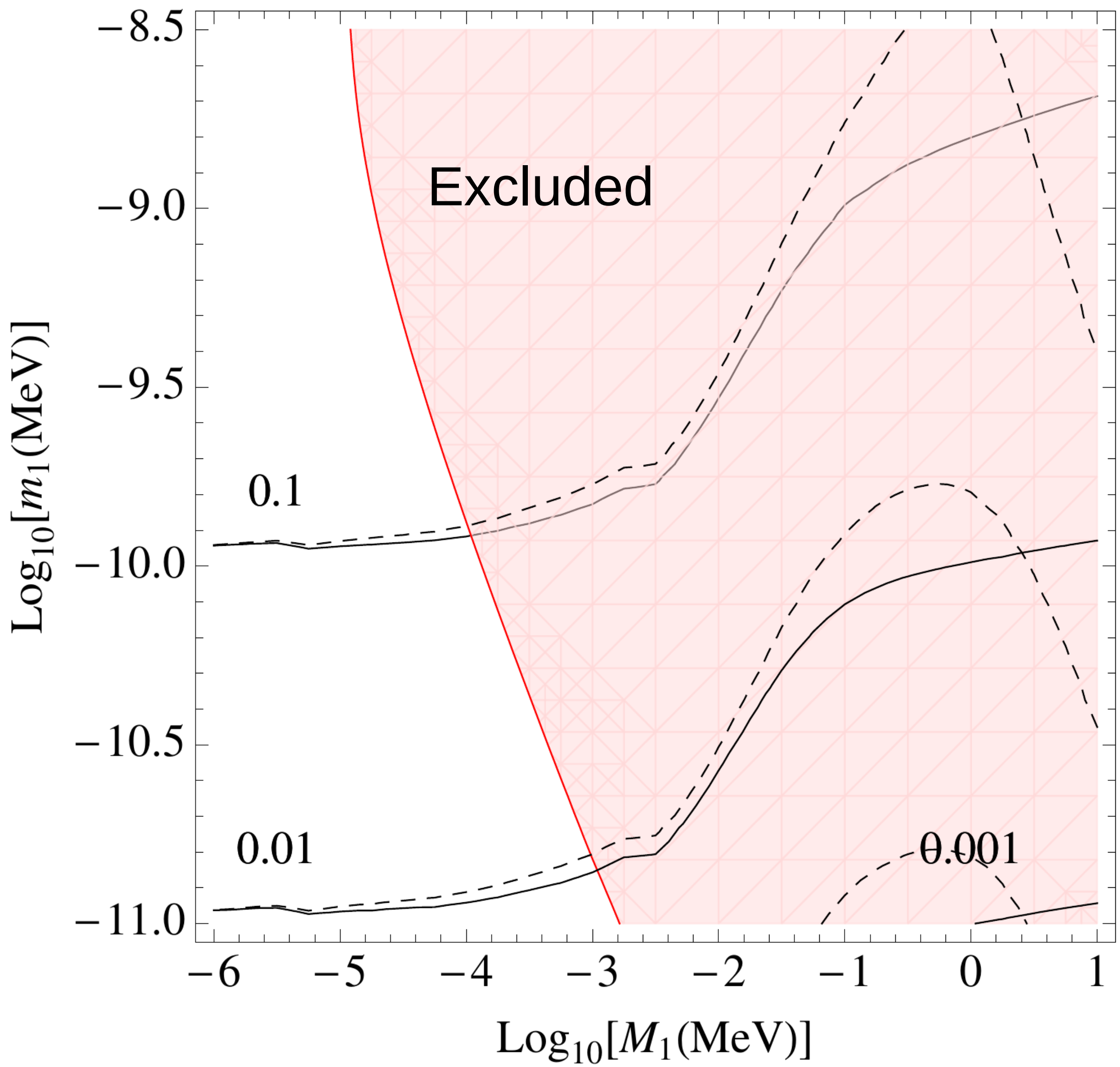
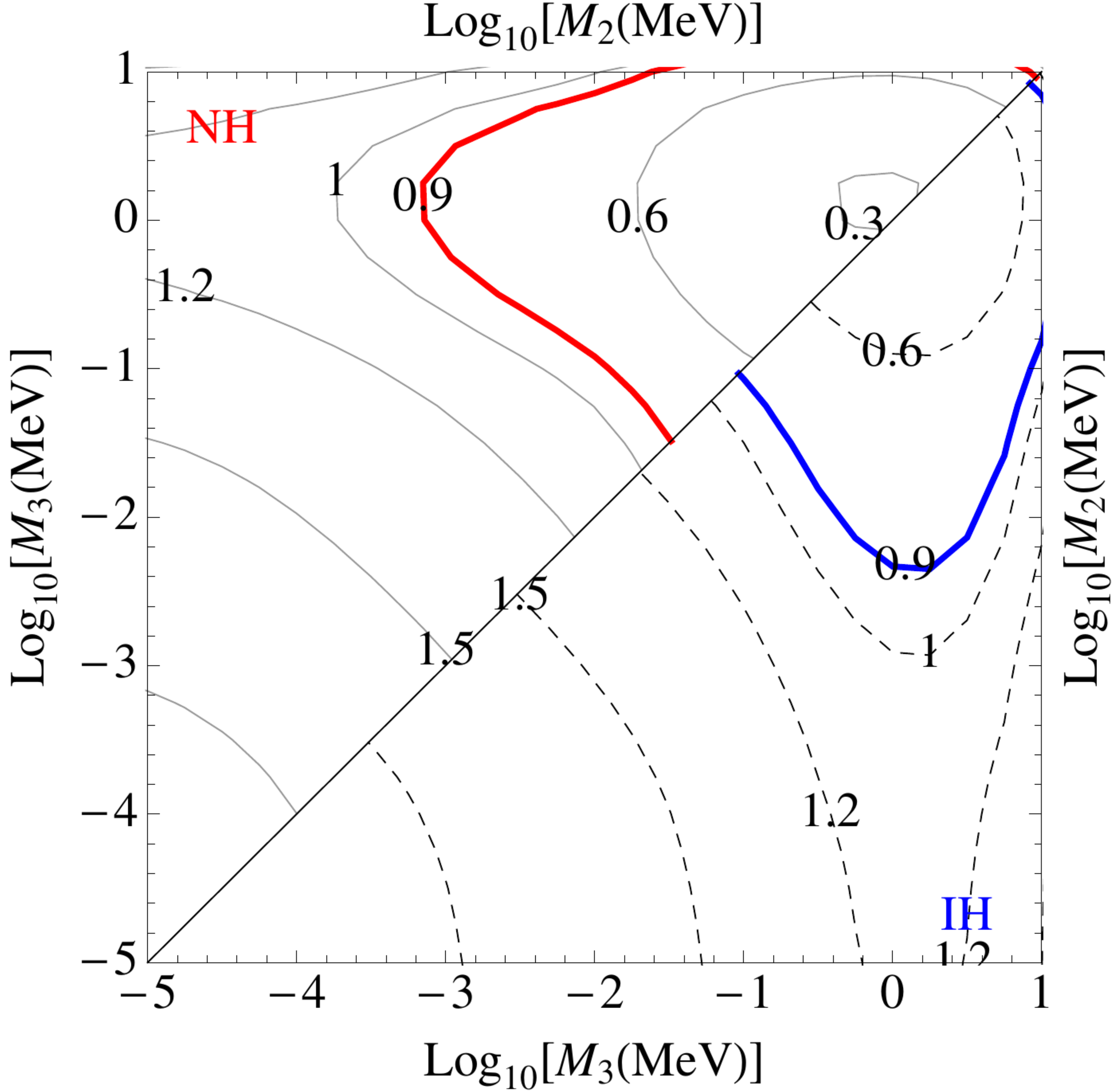
Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3,$	$M_1, M_2, \delta, \alpha, \theta_{45}, \gamma_{45}$
	Fixed by neutrino oscillation experiments	Free parameters

• $m_1 \leq \mathcal{O}\left(10^{-3}eV\right)$: one sterile neutrino does not thermalize. The other two contribute as in the 3+2 model.

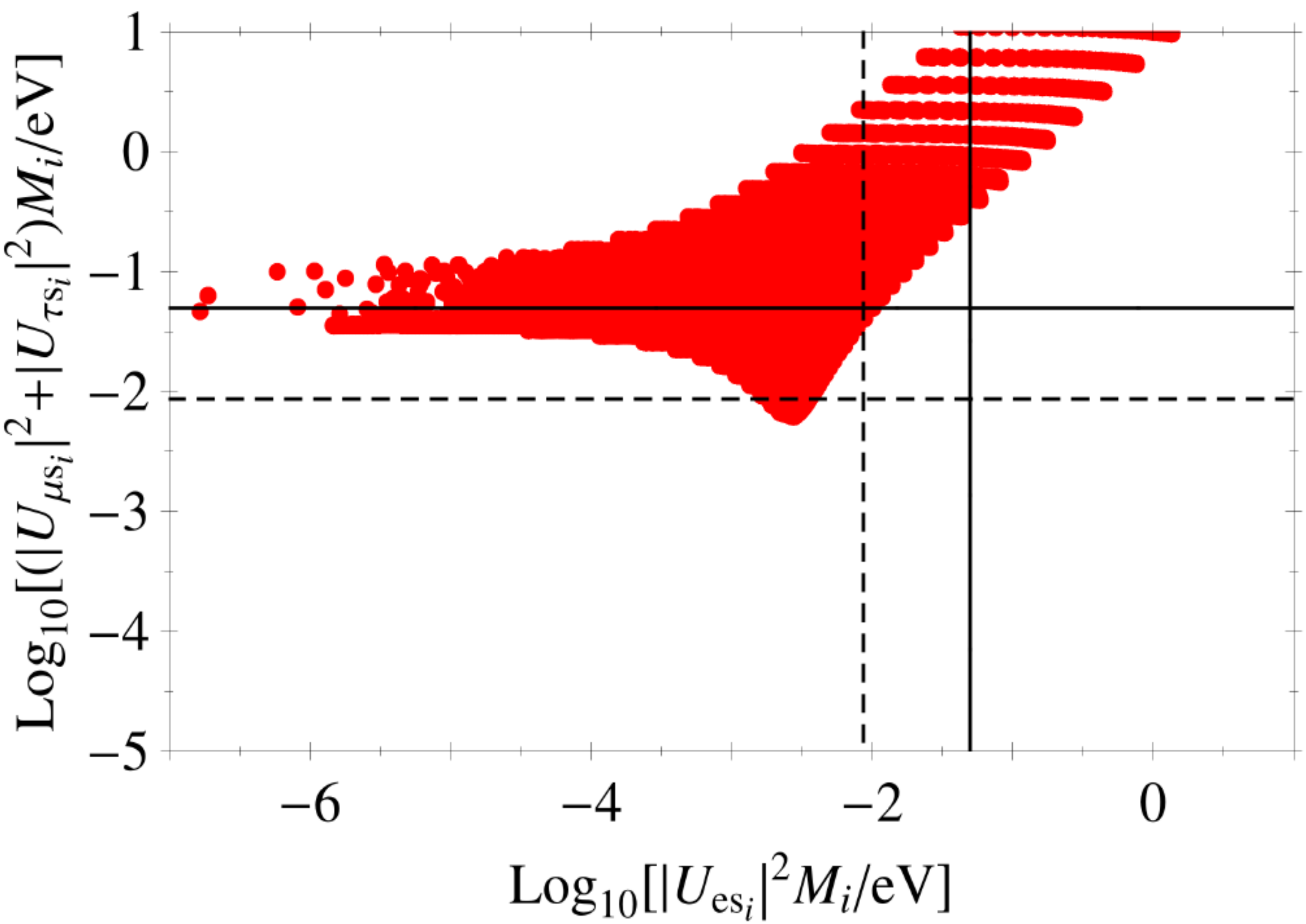




Log10[M2(MeV)]
NH
1
0.9
0.6
0.3
1.2
0.6
0.9
1.5
1.5
1
1.2
IH
1.2
Log10[M3(MeV)]
Log10[M2(MeV)]
Log10[M3(MeV)]
1
0
−1
−2
−3
−4
−5
−5
−4
−3
−2
−1
0
1

Sterile Neutrino Thermalization

- This is because all favours participate in oscillations. The mixing with the three different flavous can not be small enough at the same time due to the correlation.



Analytical lower bound

$$f_{\mathrm{B}}(T) \equiv \mathrm{Min}\left[\frac{C_\tau(T)}{\sqrt{g_*(T)}}\right] \frac{G_F^2 p T^4 \sqrt{g_*(T)}}{H(T)} \left(\frac{M_j^2}{2pV_e - M_j^2}\right)^2 \sum_{\alpha=e,\mu,\tau} |(U_{as})_{\alpha j}|^2 \leq f_{s_j}(T)$$

$$f_{\mathrm{B}}(T^\tau_{max}) \leq f_{s_j}(T^\tau_{max}) \leq f_{s_j}(T_{max}).$$

$$\begin{cases} f_{s_j}(T_{\mathrm{max}}) \geq f_{\mathrm{B}}(T^\tau_{\mathrm{max}}) = \dfrac{\sum_\alpha |(U_{as})_{\alpha j}|^2 M_j}{3.25 \cdot 10^{-3}\mathrm{eV}}. \\ h_j \equiv \sum_\alpha |U_{\alpha s_j}|^2 M_j = \underbrace{\sum_i |R_{ij}|^2 m_i}_{} \geq m_1 \end{cases}$$

Independent of PMNS parameters

sterile neutrino decay

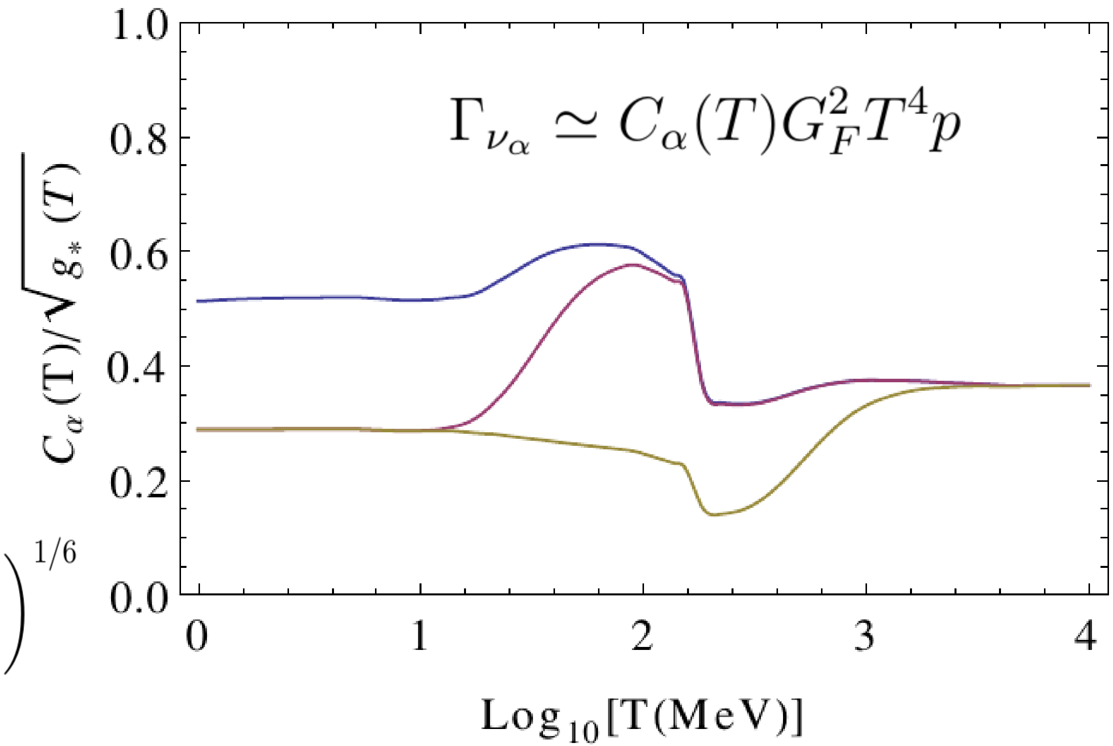
- For sufficiently large M the sterile neutrino could decay before BBN and our analysis does not apply to this case.

$$\tau \sim 6 \times 10^{11} s \left(\frac{MeV}{M} \right)^4 \frac{0.05eV}{|U_{\alpha s}|^2 M}$$

- For natural choices of the mixing decay takes place after BBN. However, for extreme mixings of $\mathcal{O}\left(1\right)$, sterile neutrinos as light as 10 MeV could decay before BBN.

$$f_{s_j}(T) = \sum_{\alpha=e,\mu,\tau} \frac{\Gamma_{\nu_\alpha}(T)}{H(T)} \left(\frac{M_j^2}{2pV_\alpha(T) - M_j^2}\right)^2 |(U_{as})_{\alpha j}|^2$$

$$H(T) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_{\text{Planck}}}$$



$$T_{\max}^\tau \equiv \left(\frac{M_j^2}{59.5\,|A|}\right)^{1/6} \leq T_{\max} \leq \left(\frac{M_j^2}{59.5\,|B|}\right)^{1/6}$$

(τ) $T \gtrsim 180$ MeV: $C_{e,\mu,\tau} \simeq 3.43$ and $V_\alpha = A\,T^4 p$ for $\alpha = e, \mu, \tau$;

(μ) 20 MeV $\lesssim T \lesssim 180$ MeV: $C_{e,\mu} \simeq 2.65$, $C_\tau \simeq 1.26$, $V_e = V_\mu = A\,T^4 p$ and $V_\tau = B\,T^4 p$;

(e) $T \lesssim 20$ MeV: $C_e \simeq 1.72$, $C_{\mu,\tau} \simeq 0.95$, $V_e = A\,T^4 p$ and $V_\mu = V_\tau = B\,T^4 p$.

with

$$B \equiv -2\sqrt{2}\left(\frac{7\zeta(4)}{\pi^2}\right)\frac{G_F}{M_Z^2}, \quad A \equiv B - 4\sqrt{2}\left(\frac{7\zeta(4)}{\pi^2}\right)\frac{G_F}{M_W^2}. \tag{11}$$

$$\dot{\rho} = -i[H,\rho] - \frac{1}{2}\{\Gamma, \rho - \rho_{eq} I_A\};$$

$$\dot{\rho}_A = -i(H_A\rho_A - \rho_A H_A + H_{AS}\rho_{AS}^{\dagger} - \rho_{AS}H_{AS}^{\dagger}) - \frac{1}{2}\{\Gamma_A, \rho_A - \rho_{eq} I_A\}$$

$$\dot{\rho}_{AS} = -i(H_A\rho_{AS} + H_{AS}\rho_S - \rho_{AS}H_S) - \frac{1}{2}\Gamma_A\rho_{AS},$$

$$\dot{\rho}_S = -i(H_{AS}^{\dagger}\rho_{AS} - \rho_{AS}^{\dagger}H_{AS} + H_S\rho_S - \rho_S H_S).$$

$$\Gamma_{\nu_\alpha} \gg H \quad \Longrightarrow \quad \dot{\rho}_A = \dot{\rho}_{AS} = 0$$

$$\dot{\rho}_{ss} = -\left(H_{AS}^{\dagger}\left\{\frac{\Gamma_{AA}}{(H_{AA} - H_{ss})^2 + \Gamma_{AA}^2/4}\right\}H_{AS}\right)_{ss}\tilde{\rho}_{ss}$$

$$\simeq -\frac{1}{2}\sum_a \langle P(\nu_s \to \nu_a)\rangle \Gamma_a \tilde{\rho}_{ss},$$

$$\tilde{\rho}_S \equiv \rho_S - \rho_{eq} I_S$$

$$x = \frac{a(t)}{a_{BBN}}, \quad y = x\frac{p}{T_{BBN}};$$

$$g_{S*}(T)T^3 a(t)^3 = \text{constant}$$

$$\Rightarrow \quad x = \frac{T_{BBN}}{T}\left(\frac{g_{S*}(T_{BBN})}{g_{S*}(T)}\right)^{1/3}$$

$$Hx\frac{\partial}{\partial x}\rho(x,y)\bigg|_y = -i[\hat{H}, \rho(x,y)] - \frac{1}{2}\{\Gamma, \rho(x,y) - \rho_{eq}(x,y)I_A\},$$

$$\rho_{eq}(x,y) = \frac{1}{\exp\left[y(g_{S*}(T(x))/g_{S*}(T_{BBN}))^{1/3}\right] + 1},$$

$$x_f = 1$$

$$x_i \to 0, \; \rho_{ss} = 0,$$

$$Hx\frac{\partial}{\partial x}\rho_{ss}(x,y)\bigg|_y = -\left(H_{AS}^{\dagger}\left\{\frac{\Gamma_A}{(H_A - \tilde{H}_s)^2 + \Gamma_A^2/4}\right\}H_{AS}\right)_{ss}\tilde{\rho}_{ss}(x,y),$$

$$\Delta N_{\text{eff}}^{(j)BBN}|_{energy} = \frac{\int \mathrm{d}y \; y^2 E(y)\rho_{s_j s_j}(x_f, y)}{\int \mathrm{d}y \; y^2 p(y)\rho_{eq}(x_f, y)},$$

$p(y) = \frac{y}{x_f}T_{BBN}$ and $E(y) = \sqrt{p(y)^2 + M_j^2}$.

Bounds from neutrino oscillations

- Can we obtain general bounds on the Majorana scale without assuming a priori anything about the parameters of the model?

- We performed a global analysis of neutrino oscillation experiments, studying the whole parameter space for $n_R = 2$ with degenerate Majorana masses.

$$M \lesssim 10^{-9}(10^{-10})eV$$

bound mainly from solar data

Dirac limit

Gouvea, Huang, Jenkins 2009

Donini, Hernandez, JLP, Maltoni 2011

$$M \gtrsim 0.6(1.6)eV$$

constraint mainly from LBL and reactor data

Seesaw limit

Donini, Hernandez, JLP, Maltoni 2011

Analytical lower bound

- Thermalization threshold

$$h_j = \sum_i |R_{ij}|^2 m_i \leq 3.2 \cdot 10^{-3}\, eV \quad \Rightarrow \quad f_{s_j}(T_{max}) \leq 1$$

N_j does NOT thermalizes

How many sterile neutrinos can simultaneously satisfy this thermalization bound?