

Cosmological constraints on the Sessaw Scale

Jacobo López-Pavón



Invisibles15

IFT UAM/CSIC, Madrid (Spain)
22-26 June, 2015

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

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

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

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

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

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

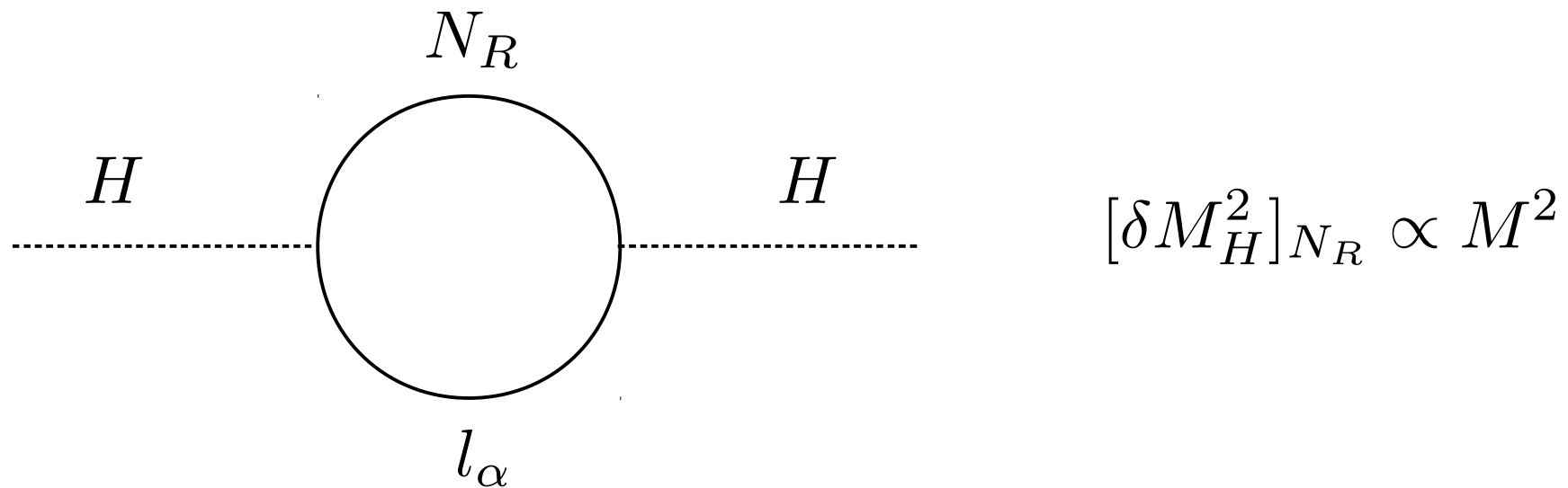
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

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

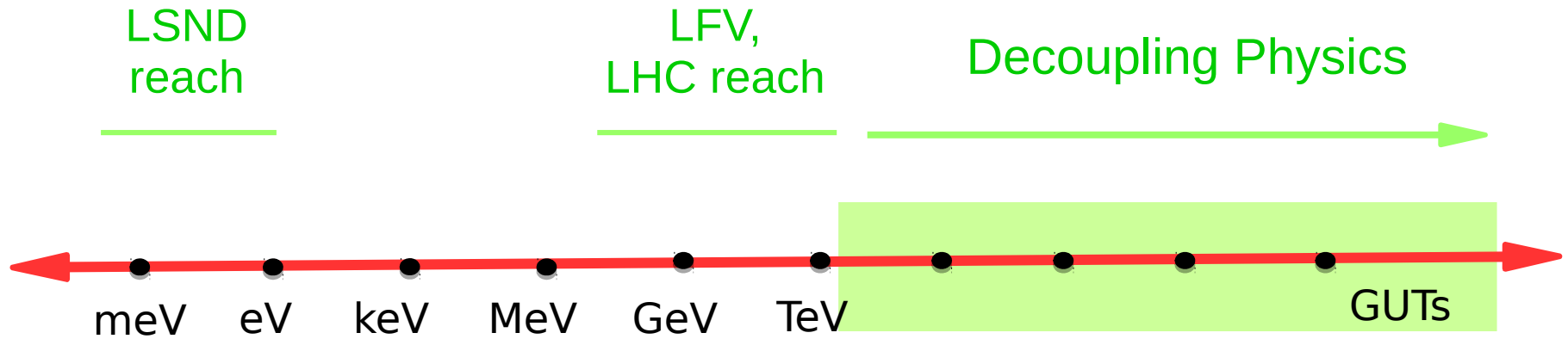
- Contrary to the high scale models, a low Majorana scale does not worsen the Higgs mass hierarchy problem.



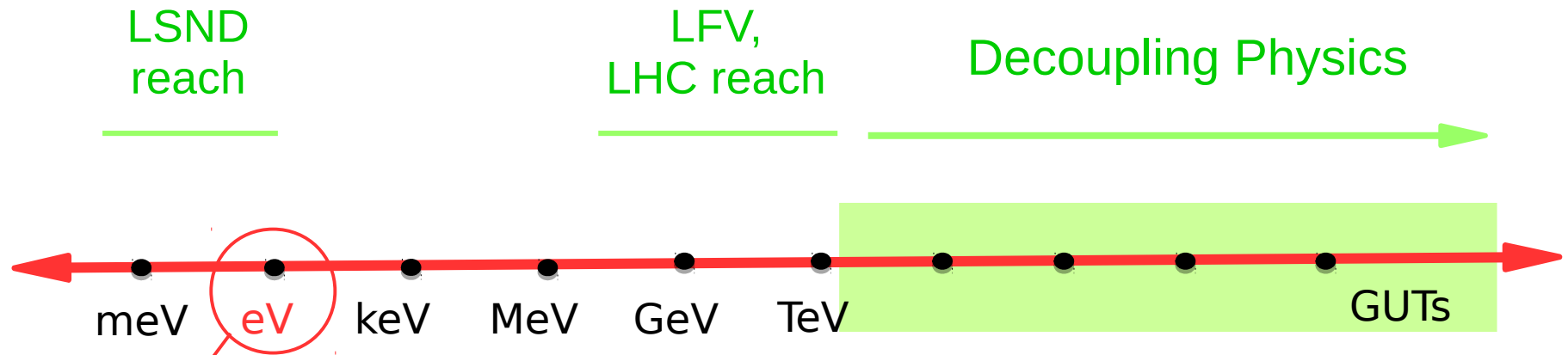
Vissani 1998

Casas, Espinosa, Hidalgo 2004

The New Physics Scale is Unbounded



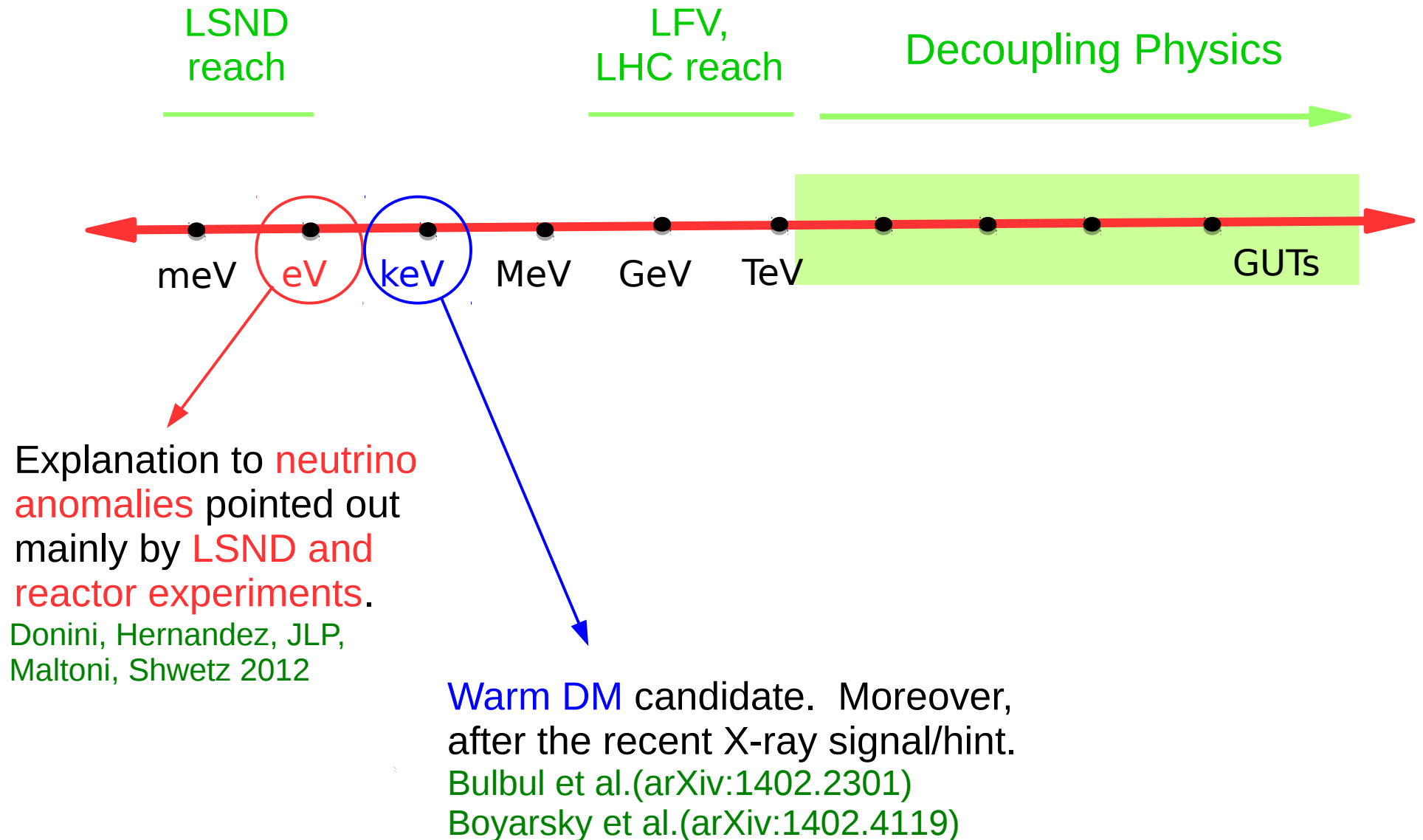
The New Physics Scale is Unbounded



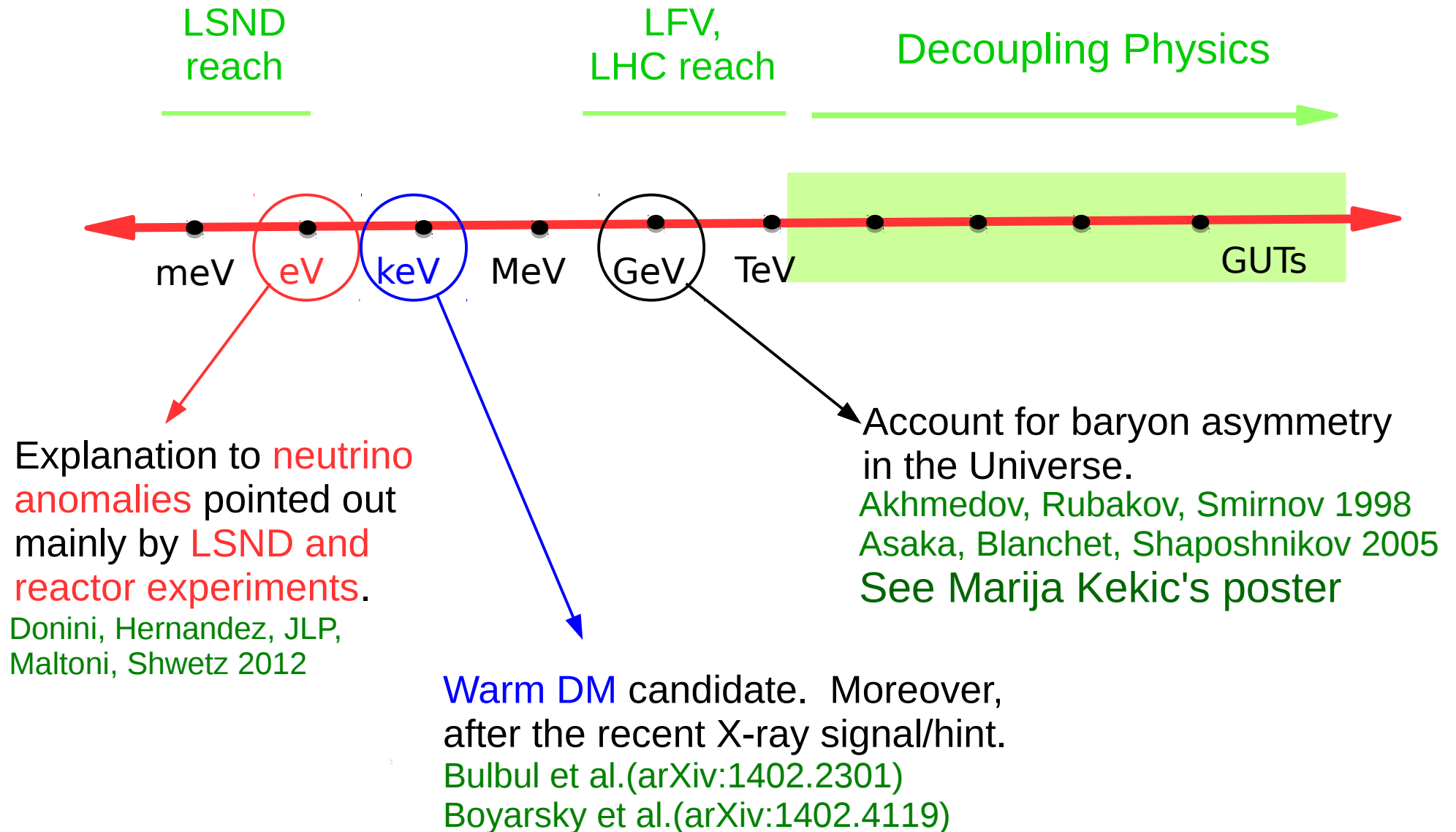
Explanation to **neutrino anomalies** pointed out mainly by **LSND and reactor experiments**.

Donini, Hernandez, JLP, Maltoni, Shwetz 2012

The New Physics Scale is Unbounded



The New Physics Scale is Unbounded



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.

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

$$\cancel{n_R = 1}$$

Excluded by neutrino oscillation data.

Donini, Hernandez, JLP, Maltoni 2011

$$n_R = 2$$

In agreement with neutrino oscillation data.

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

$$\cancel{n_R = 1}$$

Excluded by neutrino oscillation data.

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

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

$$N_{eff}^{BBN} = 3.5 \pm 0.2 [1\sigma] \quad (N_{eff}^{BBN} < 4 [2.2\sigma])$$

Cooke et al; arXiv:1308.3240

Extra radiation, N_{eff}

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

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

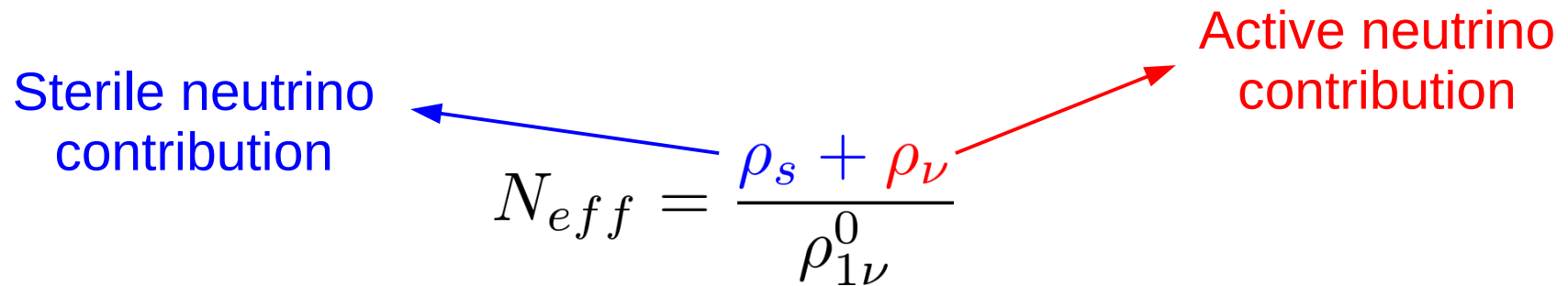
Active neutrino contribution

$$N_{eff}^{BBN} = 3.5 \pm 0.2 [1\sigma] \quad (N_{eff}^{BBN} < 4 [2.2\sigma])$$

Cooke et al; arXiv:1308.3240

Extra radiation, N_{eff}

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



The diagram shows the equation $N_{eff} = \frac{\rho_s + \rho_\nu}{\rho_{1\nu}^0}$ with a blue arrow pointing from the numerator to the text "Sterile neutrino contribution" and a red arrow pointing from the numerator to the text "Active neutrino contribution".

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

Sterile neutrino contribution

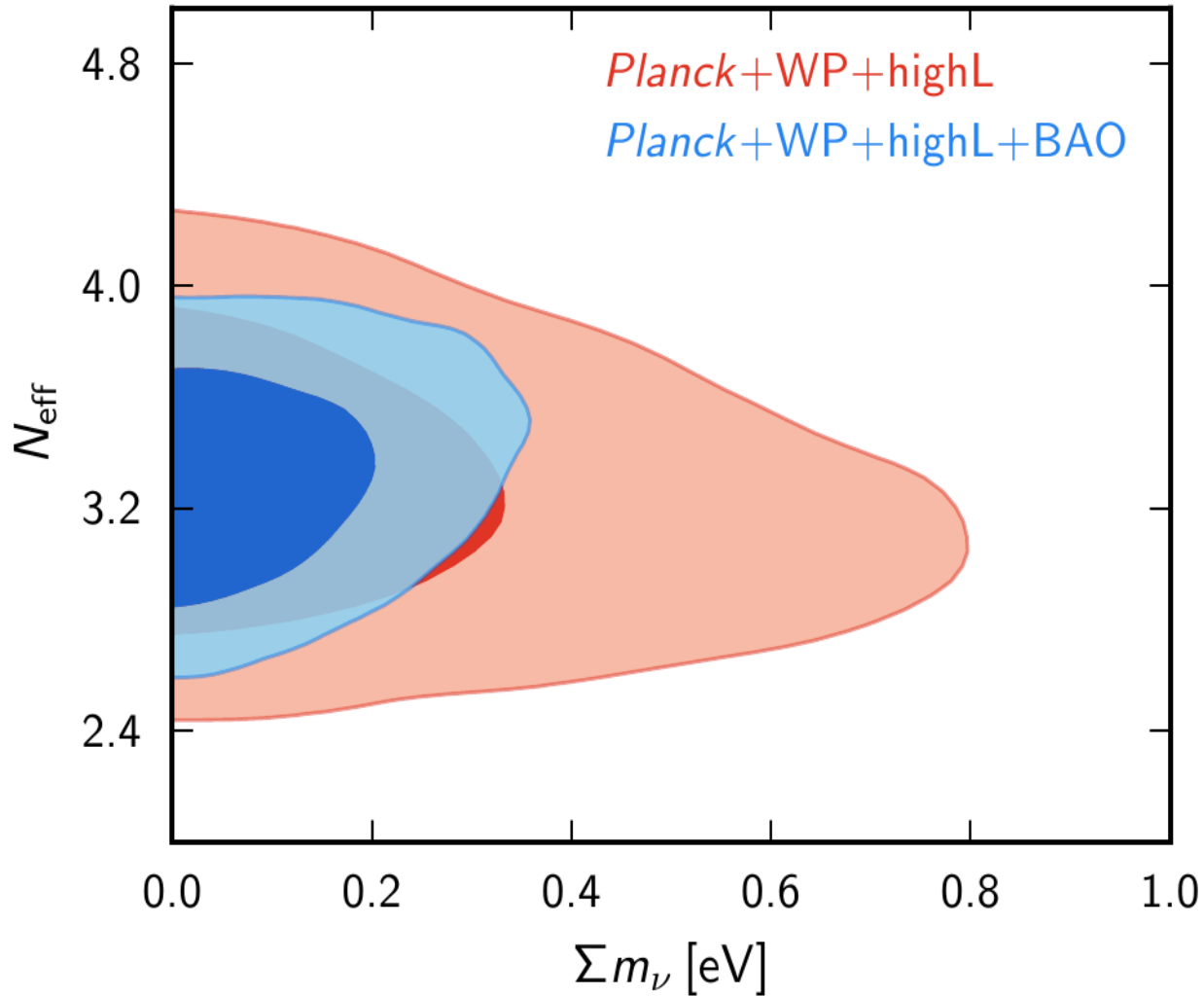
Active neutrino contribution

$$N_{eff}^{BBN} = 3.5 \pm 0.2 [1\sigma] \quad (N_{eff}^{BBN} < 4 [2.2\sigma])$$

Cooke et al; arXiv:1308.3240

Extra radiation, N_{eff}

CMB



Planck Collaboration 2013 (arXiv:1303.076)
See talk by Silvia Galli

Extra radiation, N_{eff}

- The 3 active neutrinos contribute with $N_{\text{eff}}^{\text{SM}} \approx 3$
- One fully thermal extra sterile state that decouples being relativistic contributes with $\Delta N_{\text{eff}} \approx 1$ 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:

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

Sterile Neutrino Thermalization

- Sterile neutrino thermalization is controlled by:

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

Barbieri, Dolgov 1990; Kainulainen 1990;

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

Sterile neutrino collision
rate

Sterile Neutrino Thermalization

- Sterile neutrino thermalization is controlled by:

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

Barbieri, Dolgov 1990; Kainulainen 1990;

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

Sterile neutrino collision rate

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

Hubble expansion rate

Sterile Neutrino Thermalization

- Sterile neutrino thermalization is controlled by:

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

Barbieri, Dolgov 1990; Kainulainen 1990;

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

Sterile neutrino collision rate

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

Hubble expansion rate

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

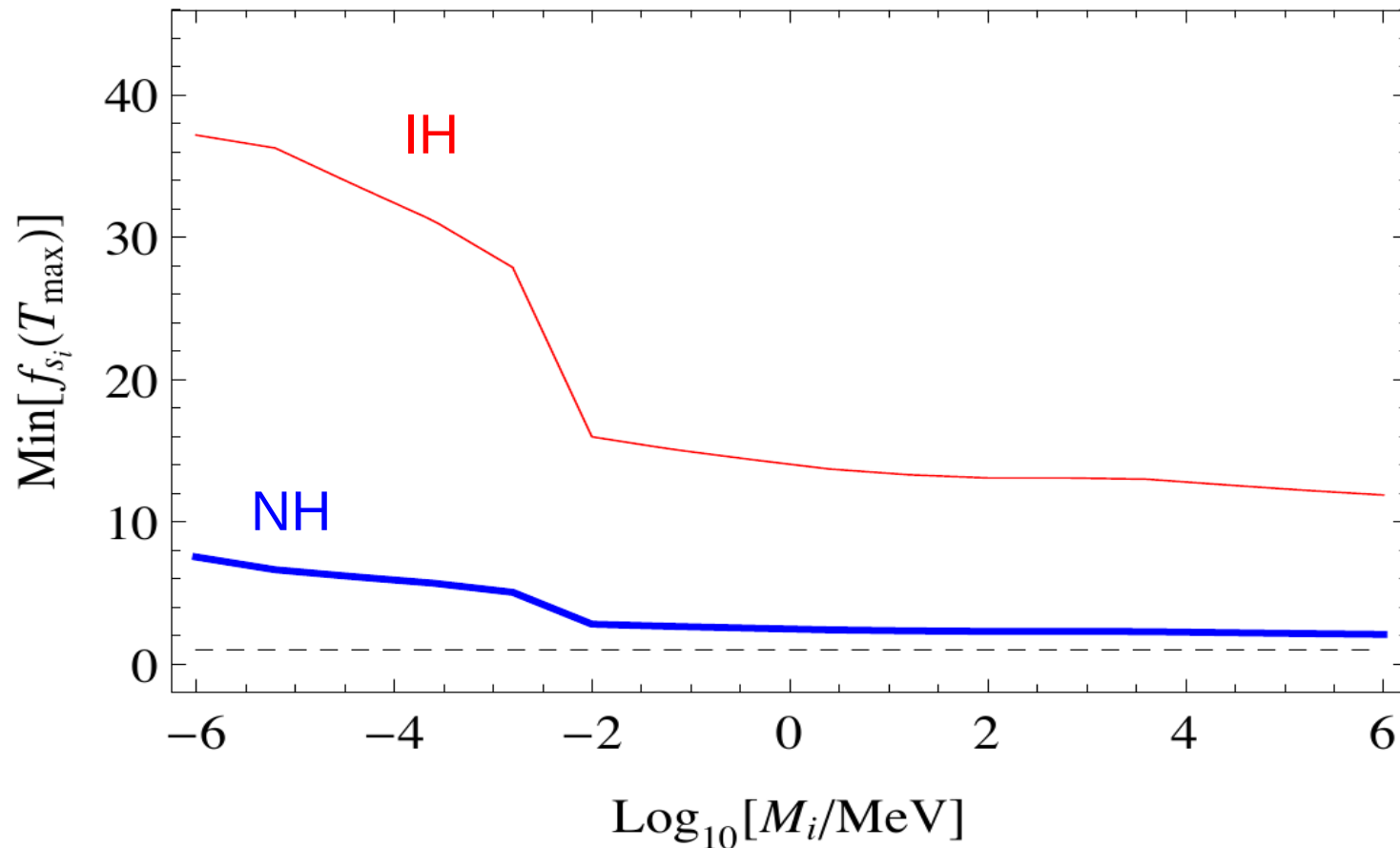
Sterile Neutrino Thermalization

- $f_s(T)$ 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:

$$N_{eff} \approx N_{eff}^{SM} + \sum_j (1 - \exp(-\alpha f_{s_j}(T_{max})))$$


$$\Delta N_{eff}$$

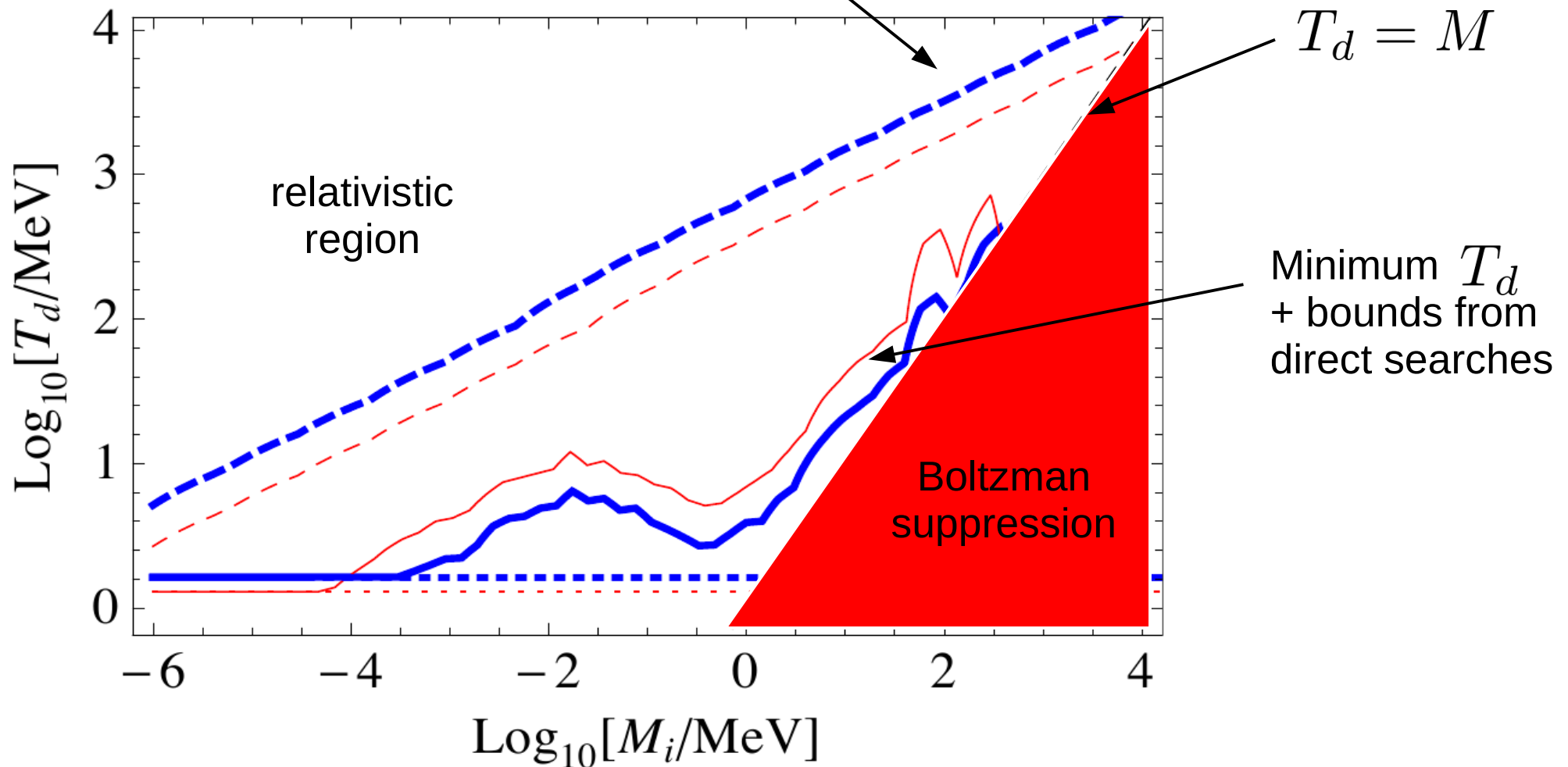
Sterile Neutrino Thermalization



- Thermalization rate basically independent of the seesaw scale.
- In the 3+2 type-I seesaw model, for the whole parameter space, the sterile neutrinos always thermalize at some point of the thermal history.

sterile Neutrino Decoupling

For parameters of the model
that minimize $f_s(T_{max})$



sterile Neutrino Decoupling

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

$$M \gtrsim 100MeV$$

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

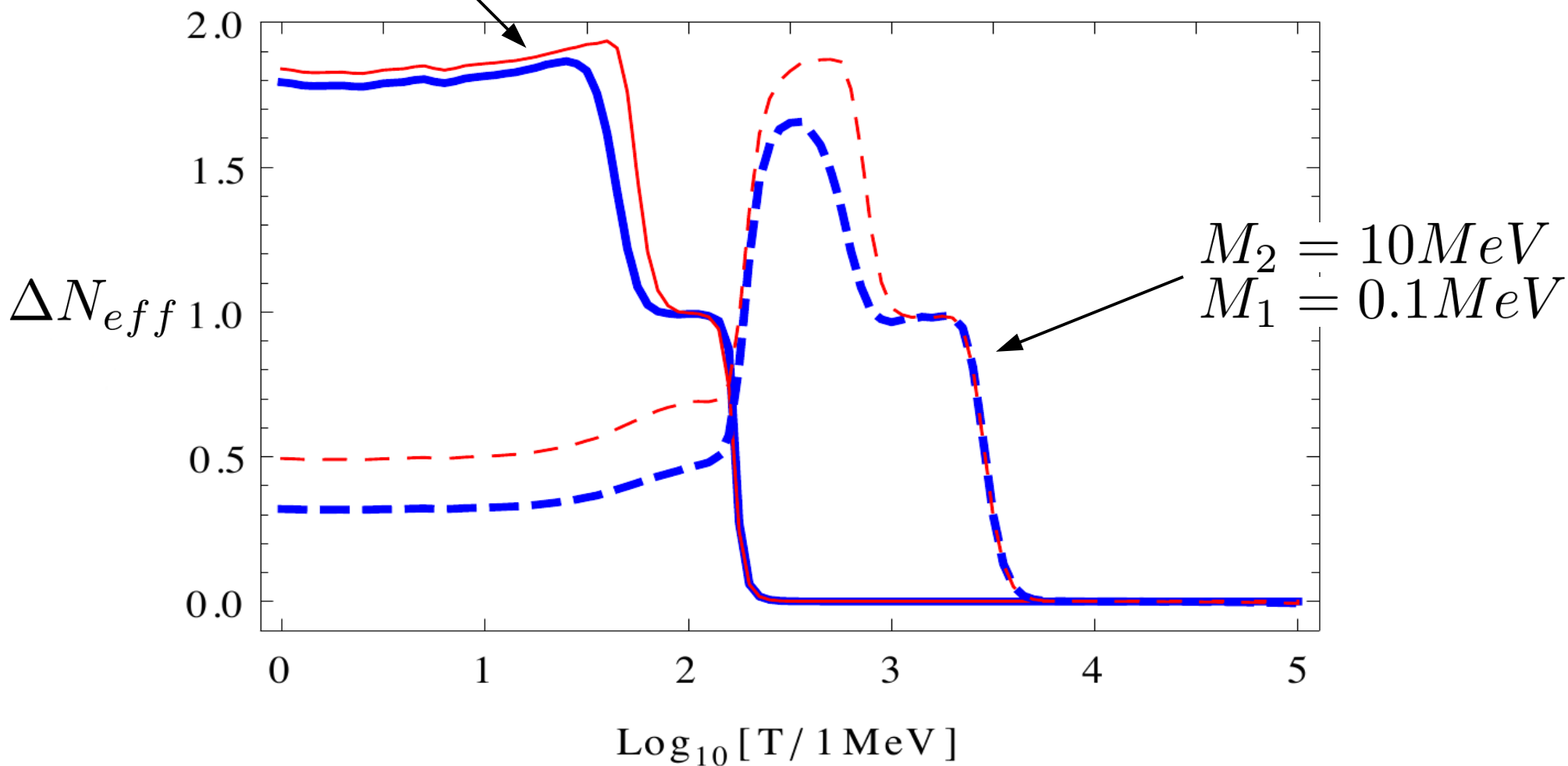
(i) Dilution

(ii) Decay

Entropy dilution

$$M_2 = 1\text{KeV}$$
$$M_1 = 20\text{eV}$$

Dilution could be relevant
for $M \gtrsim 10\text{KeV}$



Entropy dilution

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

$$10\text{KeV} \lesssim M \lesssim 100\text{MeV}$$

- However, those sterile neutrinos would give a huge contribution to the energy density when they become non-relativistic later, modifying 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 neutrinos 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

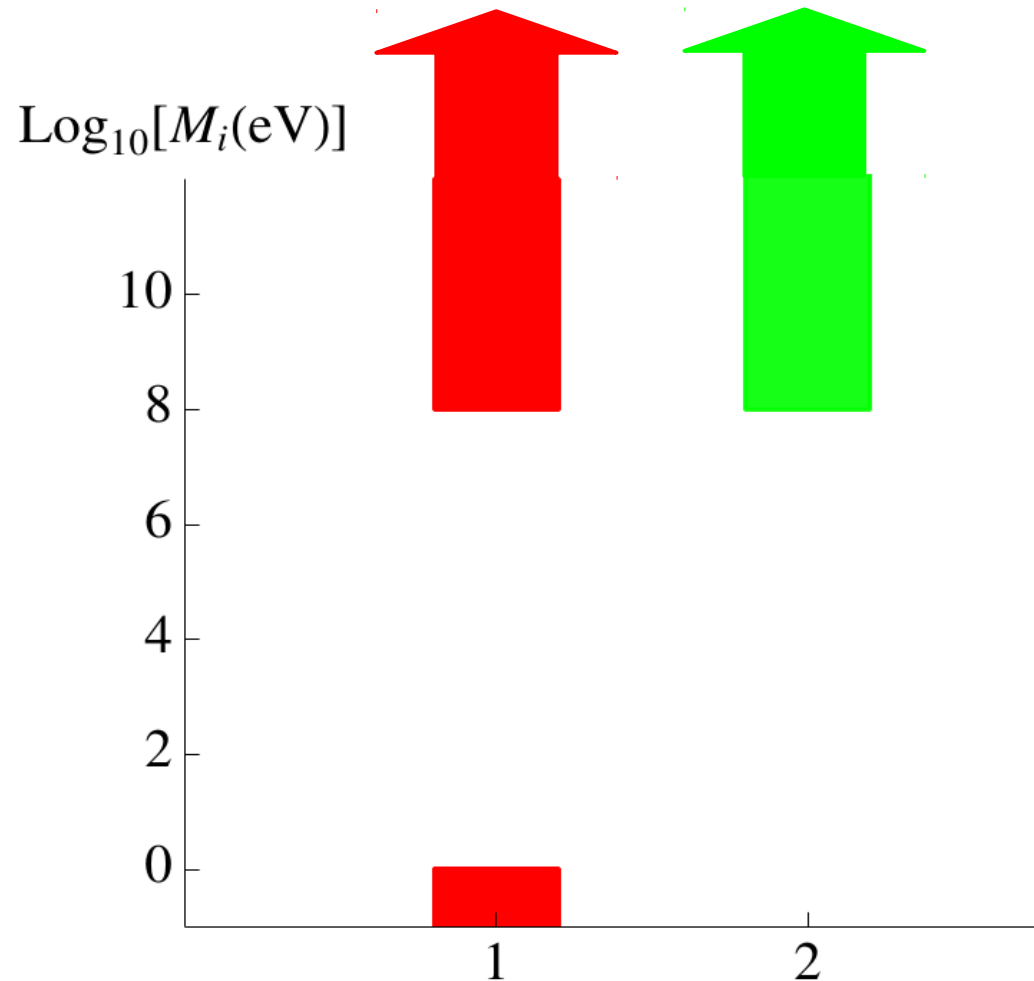
- Very **strong bounds** found combining BBN and direct accelerator searches, **excluding the sterile neutrino decay before BBN in the minimal model for $M \lesssim \mathcal{O}(100MeV)$**

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

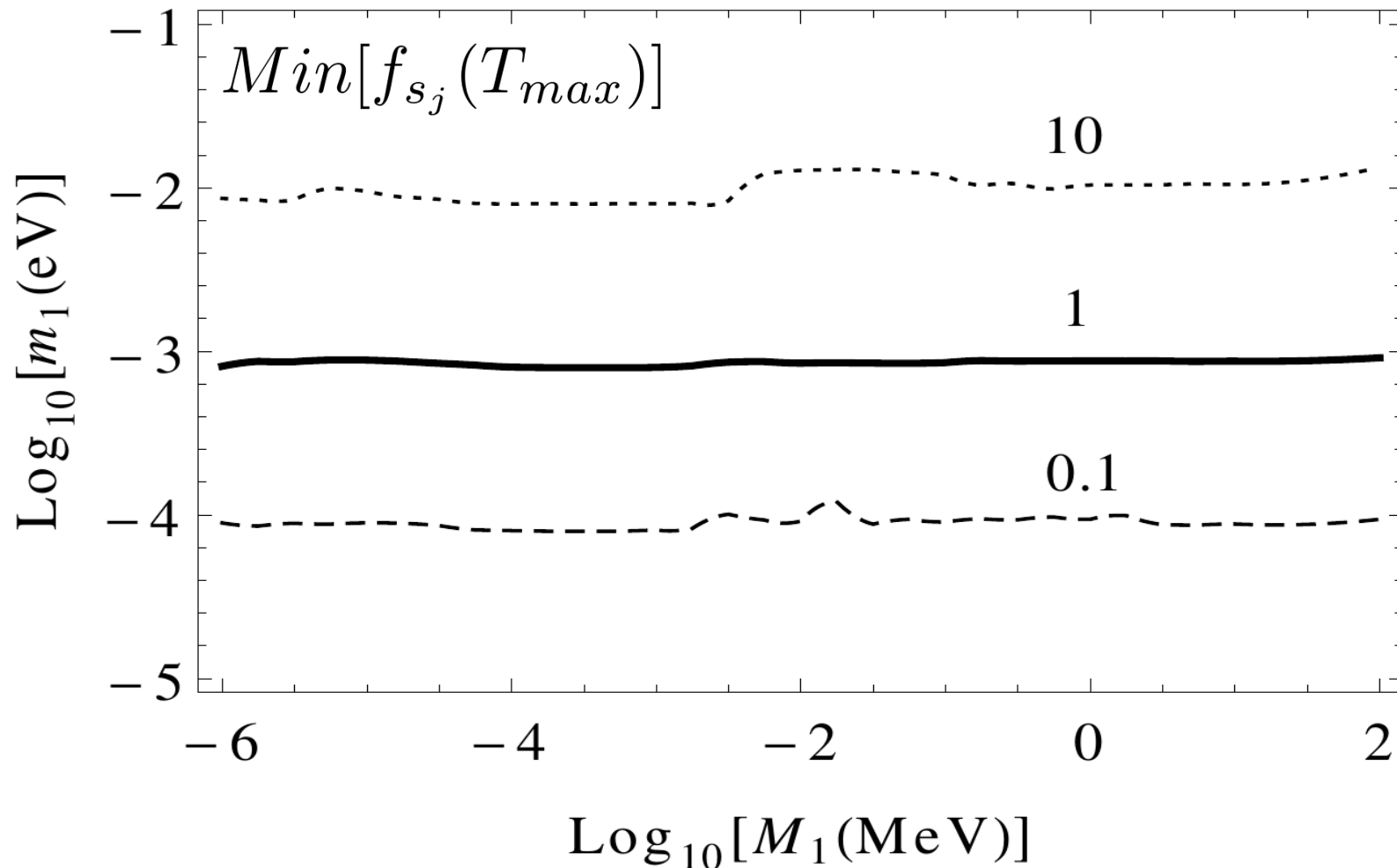
ArXiv:1406.2961

(PRD 90 (2014) 065033)

3+3 Minimal Seesaw Model

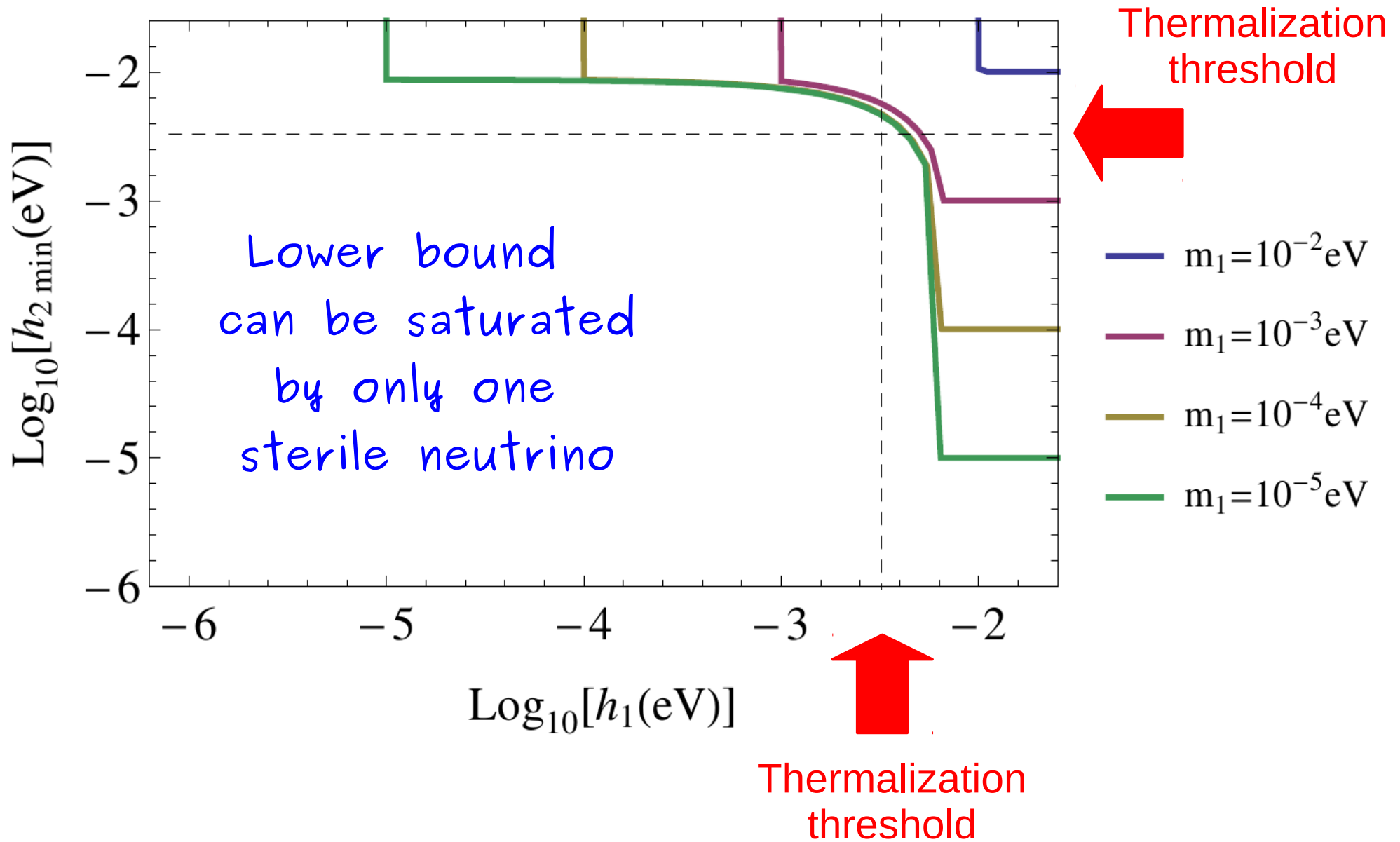
- Larger parameter space: 3 light masses + 3 heavy masses +6 angles + 6 CP-phases.
- We have explored the whole parameter space allowed by neutrino oscillation data.
- In spite of the larger parameter space, **only one sterile neutrino can escape from thermalization. The thermalization being basically controlled by the lightest neutrino mass.**

3+3 Minimal Seesaw Model



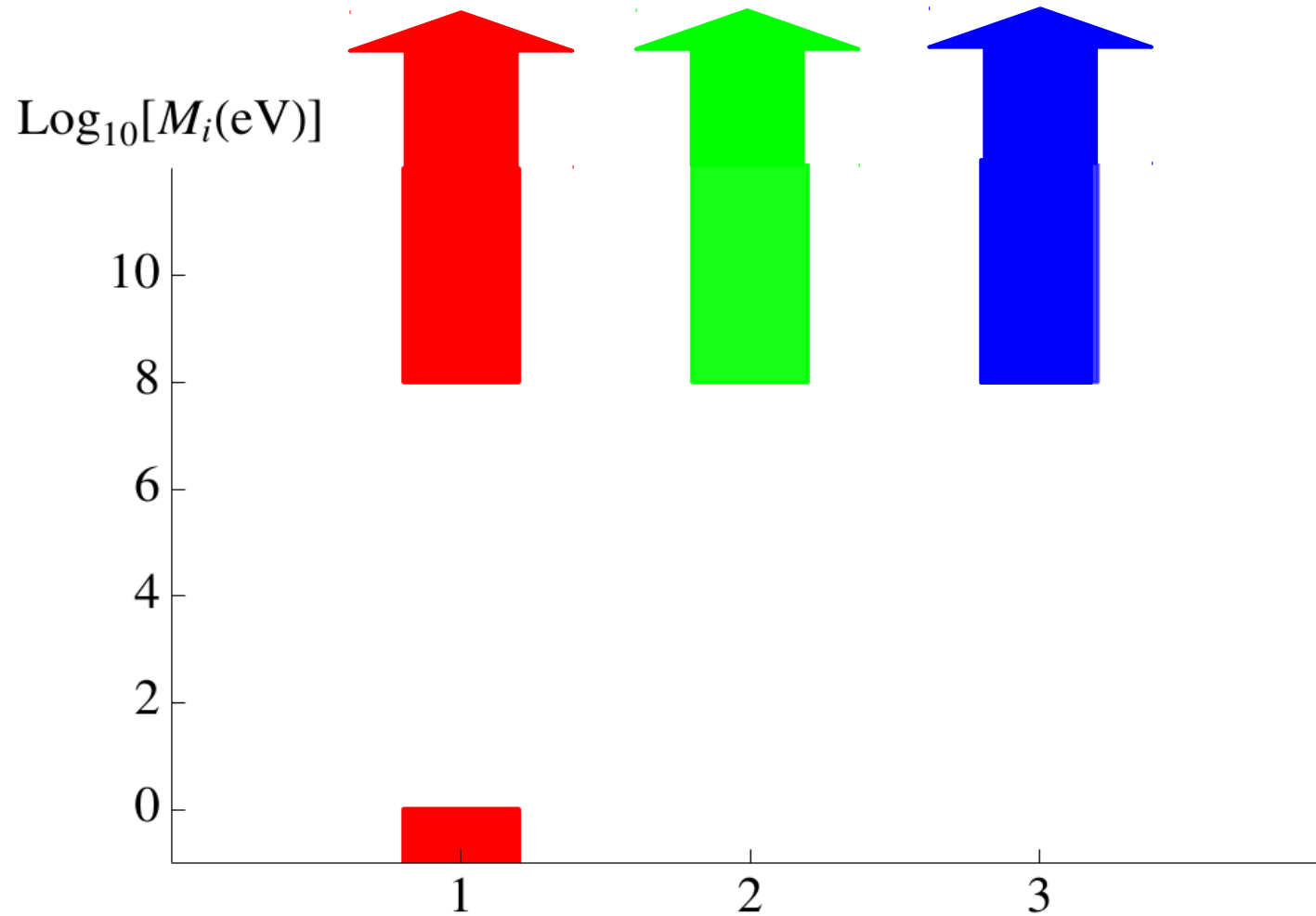
If $m_1 \geq \mathcal{O}(10^{-3} \text{ eV})$ the 3 sterile neutrinos thermalize

Analytical lower bound



Possible scenarios

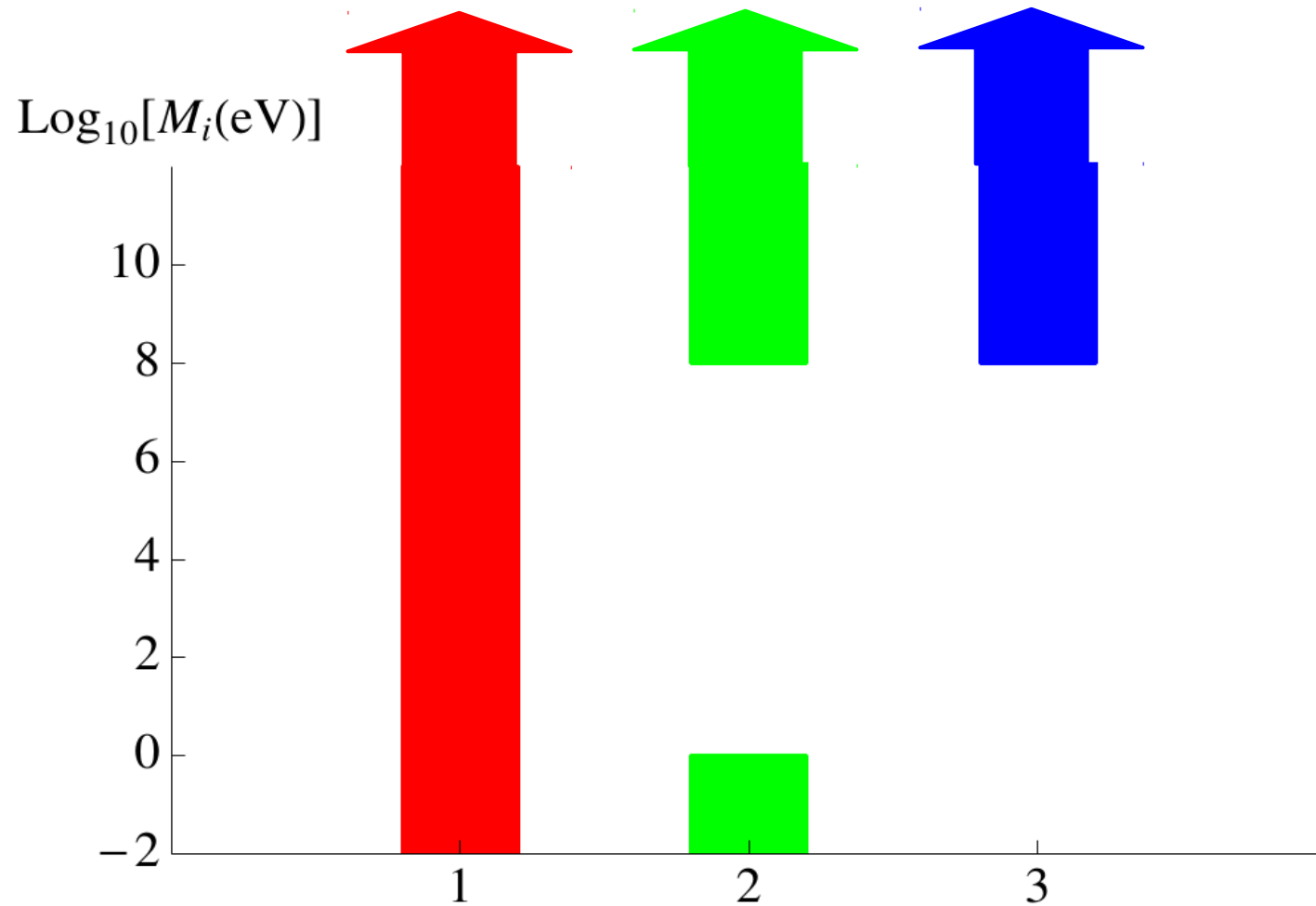
- $m_1 \geq \mathcal{O}(10^{-3} eV)$: the three sterile neutrinos thermalize.



Allowed sterile neutrino spectra

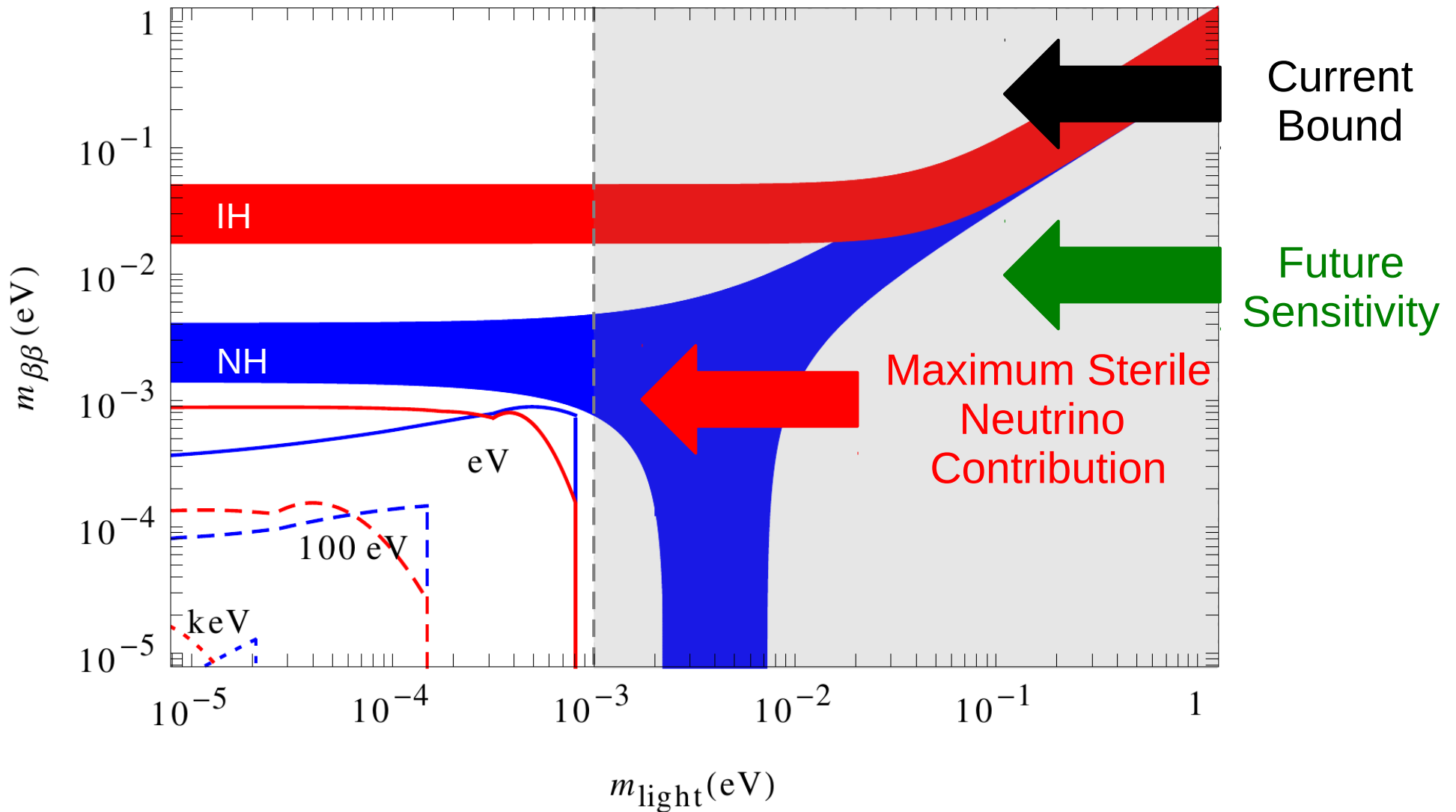
Possible scenarios

- $m_1 \leq \mathcal{O}(10^{-3} eV)$: 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 Neutrinoless Double Beta Decay experiments: [Laura BAUDIS](#)

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 seesaw scale are excluded**, since the sterile neutrinos can not escape 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:**

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

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



Gracias!

Extending Casas-Ibarra parameterization

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

$$U = \begin{pmatrix} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{pmatrix} \longrightarrow \text{active-sterile mixing}$$

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

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

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

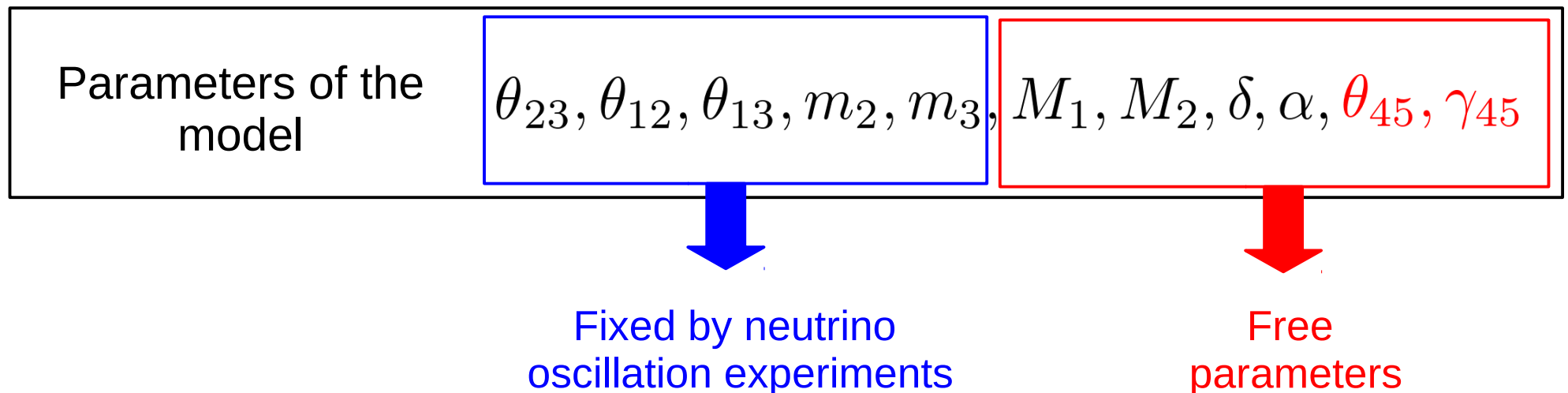
Keep in mind!
“Sterile neutrinos”
interact with particles
in thermal bath **via**
this mixing.

Extending Casas-Ibarra parameterization

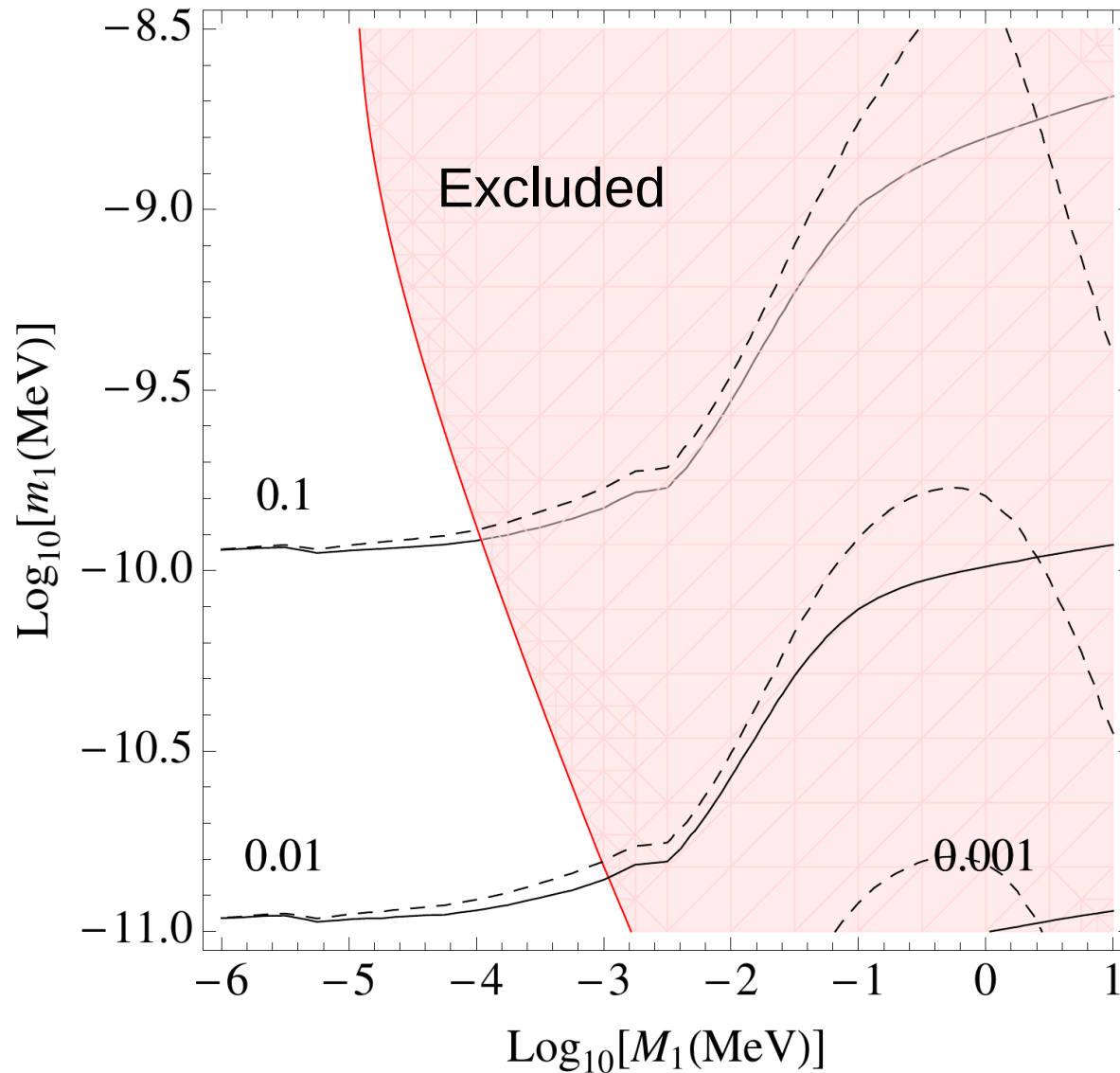
Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

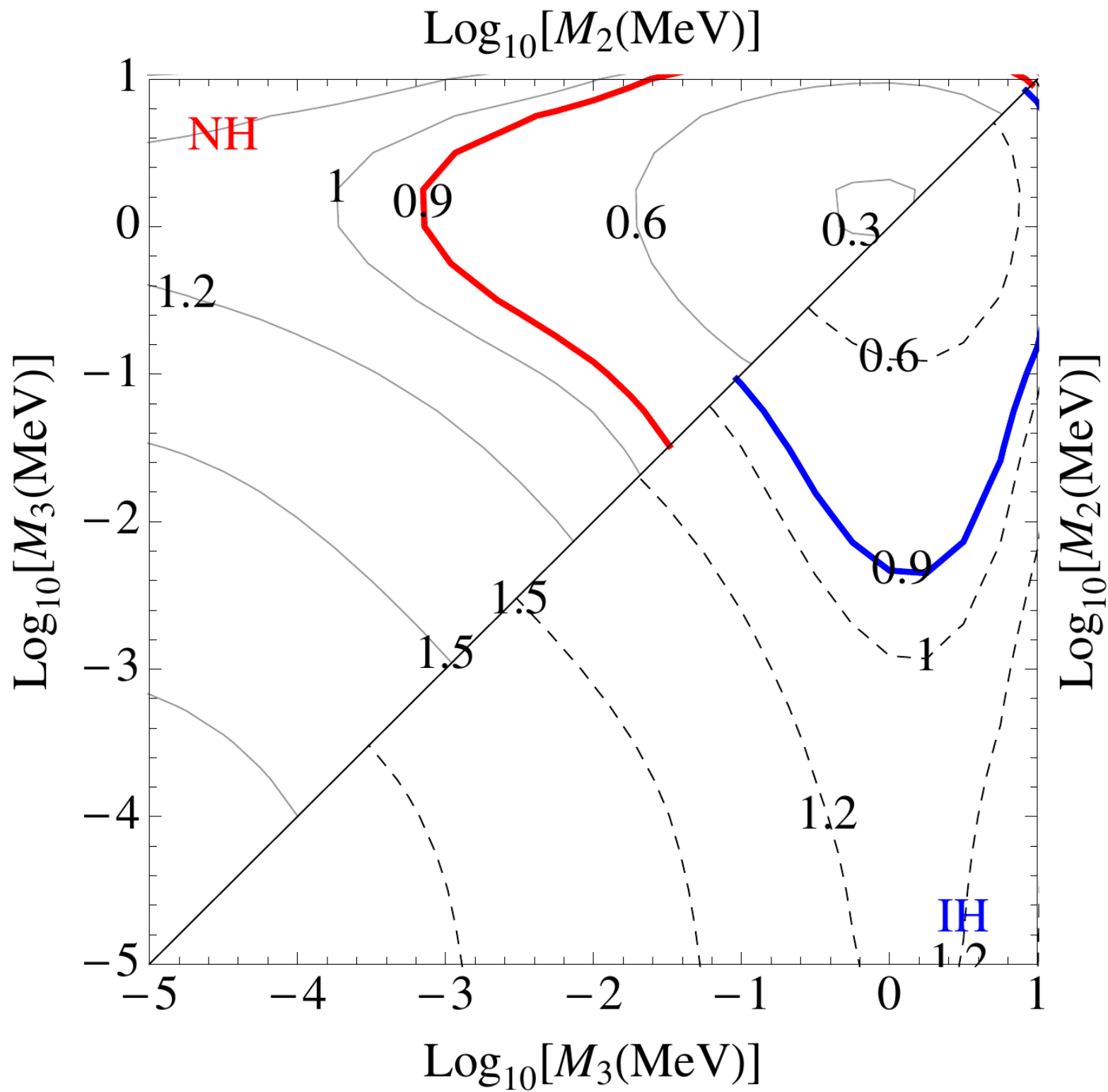
$$U = \begin{pmatrix} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{pmatrix} \longrightarrow \text{active-sterile mixing}$$

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



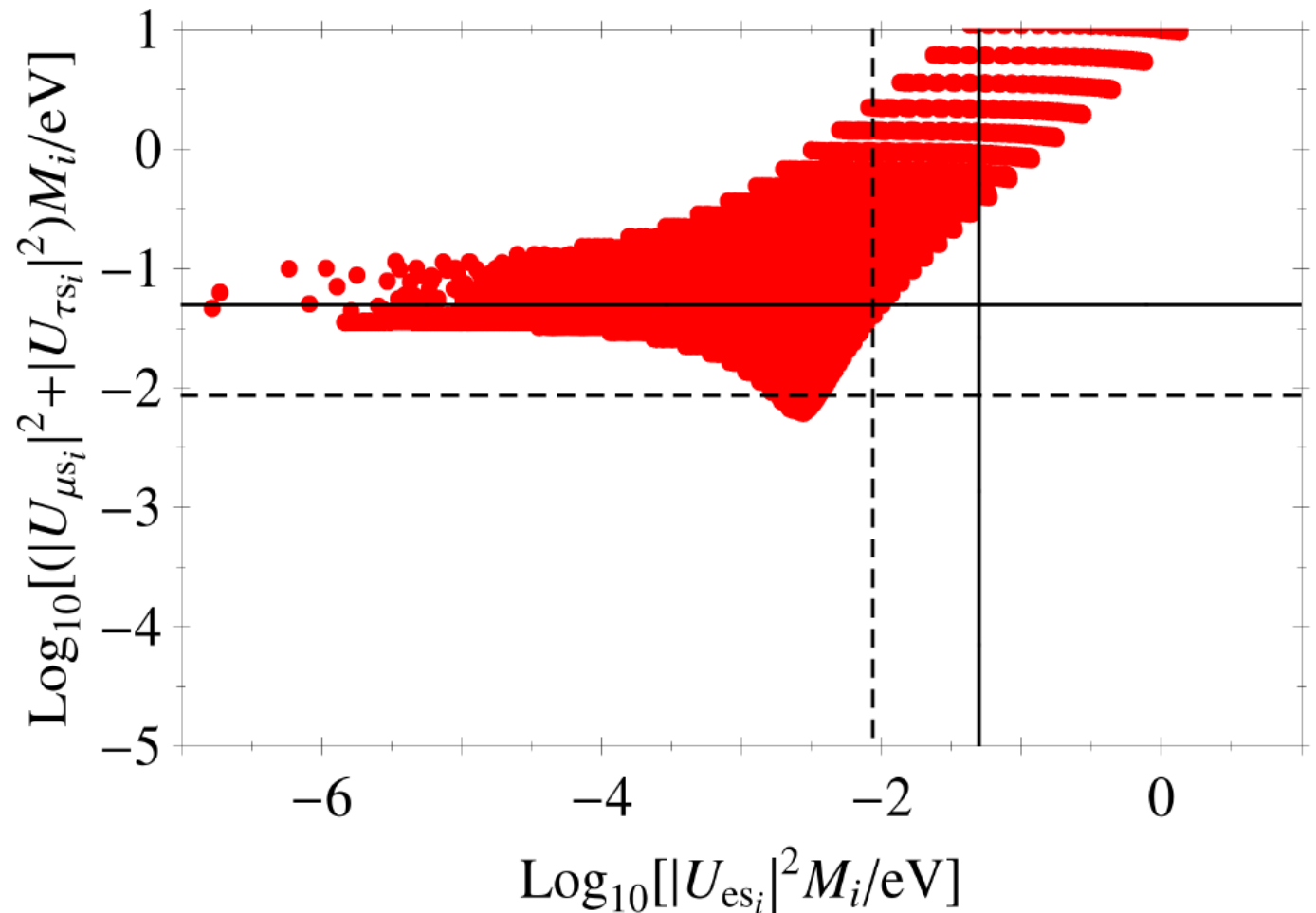
- $m_1 \leq \mathcal{O}(10^{-3} eV)$: one sterile neutrino does not thermalize. The other two contribute as in the 3+2 model.





Sterile Neutrino Thermalization

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



Analytical lower bound

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

$$f_B(T_{max}^\tau) \leq f_{s_j}(T_{max}^\tau) \leq f_{s_j}(T_{max}).$$

$$f_{s_j}(T_{max}) \geq f_B(T_{max}^\tau) = \frac{\sum_{\alpha} |(U_{as})_{\alpha j}|^2 M_j}{3.25 \cdot 10^{-3} \text{eV}}.$$

$$h_j \equiv \sum_{\alpha} |U_{\alpha s_j}|^2 M_j = \underbrace{\sum_i |R_{ij}|^2 m_i}_{\text{Independent of PMNS parameters}} \geq m_1$$

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.

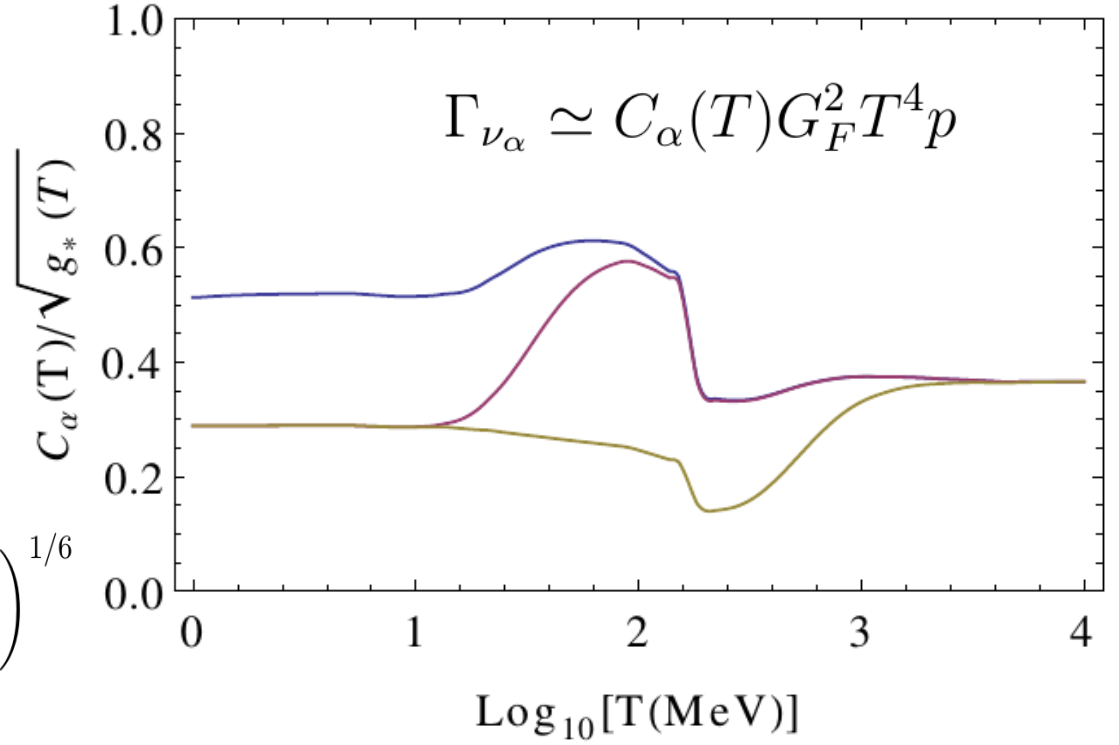
$$\tau \sim 6 \times 10^{11} s \left(\frac{MeV}{M} \right)^4 \frac{0.05eV}{|U_{\alpha s}|^2 M}$$

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

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

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

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



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

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

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

with

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

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

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

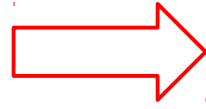
$$\dot{\rho}_{AS} = -i(H_A\rho_{AS} + H_{AS}\rho_S - \rho_{AS}H_S) - \frac{1}{2}\Gamma_A\rho_{AS},$$

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

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

$$\begin{aligned} \dot{\rho}_{ss} &= - \left(H_{AS}^\dagger \left\{ \frac{\Gamma_{AA}}{(H_{AA} - H_{ss})^2 + \Gamma_{AA}^2/4} \right\} H_{AS} \right)_{ss} \tilde{\rho}_{ss} \\ &\simeq -\frac{1}{2} \sum_a \langle P(\nu_s \rightarrow \nu_a) \rangle \Gamma_a \tilde{\rho}_{ss}, \end{aligned} \quad \tilde{\rho}_S \equiv \rho_S - \rho_{eq}I_S$$

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



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

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

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

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

$$x_f = 1 \quad Hx \frac{\partial}{\partial x} \rho_{ss}(x, y) \Big|_y = - \left(H_{AS}^\dagger \left\{ \frac{\Gamma_A}{(H_A - \tilde{H}_s)^2 + \Gamma_A^2/4} \right\} H_{AS} \right)_{ss} \tilde{\rho}_{ss}(x, y),$$

$$x_i \rightarrow 0, \quad \rho_{ss} = 0,$$

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

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

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

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

N_j does NOT thermalizes

How many sterile neutrinos can simultaneously satisfy this thermalization bound?