Low Scale Minimal Seesaw Models

Jacobo López-Pavón

News in Neutrino Physics
NORDITA, Stockholm, 17 April, 2014

Outline

- Motivations

- Minimal seesaw models vs N_{eff}

  - General Bounds on 3+2 models
  - General Bounds on 3+3 models (work in progress)

  P. Hernandez, M. Kekic, JLP
  arXiv:11311.2614 (PRD ... (2014)) + **Work in progress**

- Minimal seesaw models vs oscillation anomalies

A. Donini, P. Hernandez, JLP, M. Maltoni, T. Schwetz
arXiv:1205.5230 (JHEP **1207** (2012) 161)

- Conclusions

Motivation

- The recent LHC results seem to indicate that the Higgs mechanism, with $m_H \sim 125$ GeV, is the responsible of the mass generation of the SM particles.
  ATLAS, CMS 2012

- However, the origin of light neutrino masses, which existence is supported by neutrino oscillation experiments, still remains unknown.

- Although the light neutrino masses could also be generated through the Higgs mechanism, their smallness in comparison with the SM particles might be calling for a different explanation

A different point of view...

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

A different point of view...

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

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

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

A New Physics scale

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• The Majorana mass scale constitutes a New Physics scale introduced to account for the light neutrino masses.

• Since the light neutrino masses are a combination of Yukawa couplings, Majorana scale and electroweak scale. The Majorana mass scale can in principle be anywhere between 0 and $\mathcal{O}\left(10^{15}\right) GeV$

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Dirac neutrino limit

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Dirac neutrino limit

Standard Type-I sesaw limit

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

A New Physics scale

- It is often assumed that the scale M is much higher than the electroweak scale. But it is also worth to explore other possibilities:

$M \sim eV$ Could provide an explanation to neutrino anomalies pointed out mainly by LSND and reactor experiments.

$M \sim KeV$ Could still be a valid candidate for warm DM. Moreover, after the recent X-ray signal/hint. Bulbul et al (arXiv:1402.2301)

Dodelson and Widrow 1994
Shi and Fuller 1999

$M \sim GeV$ Could account for baryon asymmetry in the Universe.

Akhmedov, Rubakov, Smirnov 1998
Asaka, Blanchet, Shaposhnikov 2005

A New Physics scale

• Small M technically natural since in the limit $M \to 0$ a global lepton number symmetry is recovered.

• A low Majorana scale does not worsen the Higgs mass hierarchy problem.

$$[\delta m_H^2]_{\nu_R} \propto M^2$$

Vissani 1998
hep-ph/9709409

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.

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

What is the New Physics scale?

- 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
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Seesaw limit

Donini, Hernandez, JLP, Maltoni 2011

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3+2 Minimal Seesaw Model

vs

Cosmology

P. Hernandez, M. Kekic, JLP 2013
ArXiv:1311.2614

Extending Casas-Ibarra parameterization

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

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

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active mixing

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

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$$R = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}$$

Casas-Ibarra complex orthogonal matrix

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

Gives deviations from 3x3 unitarity

Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3, M_1, M_2, \delta, \alpha, \theta_{45}, \gamma_{45}$

Advantages of our parameterization

- EXACT. No expansion made.

- It does not explode for large values of the imaginary part of the complex angle. No necessary to introduce any extra theoretical constraint.

- Transparent. Easy to recover the Casas-Ibarra parameterization (at leading order in the seesaw expansion, $\mathcal{O}\left(m/M\right), H = \overline{H} = 1$)

- Corrections are important for very low Majorana mass scales, $\mathcal{O}\left(eV\right)$

- An alternative general parameterization was found by Blennow and Fernández-Martínez.

Blennow, Fernández-Martínez 2011
arXiv:1107.3992

Extra radiation, N_{eff}

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

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

$$N^{BBN}_{eff} = 3.68(3.80)^{+0.80}_{-0.70}\,(2\sigma)$$

Izotov, Thuan 2010 (arXiv:1303.076)

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

Cooke et al; arXiv:1308.3240

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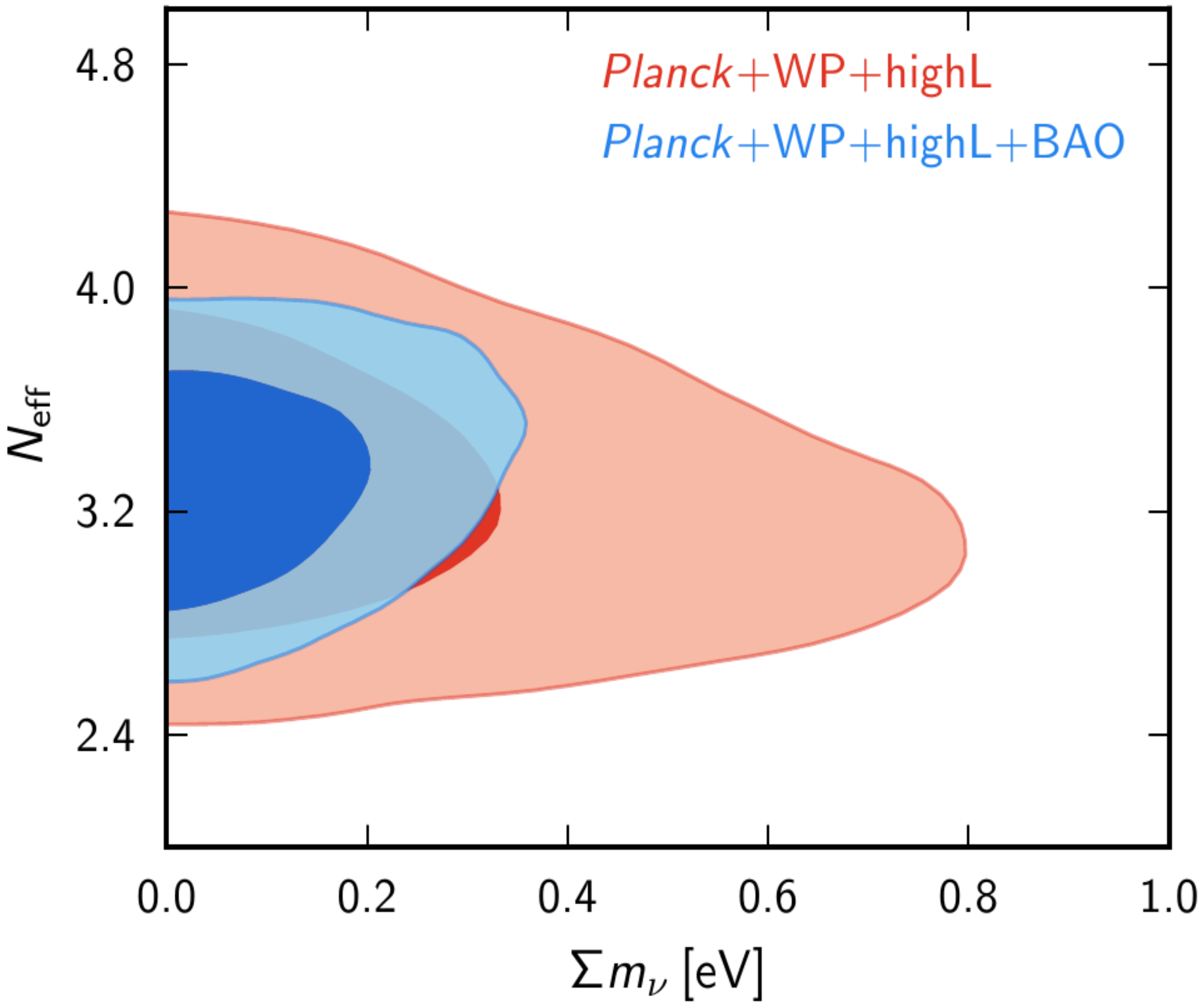
Extra radiation, N_{eff}

CMB



Planck Collboration 2013 (arXiv:1303.076)

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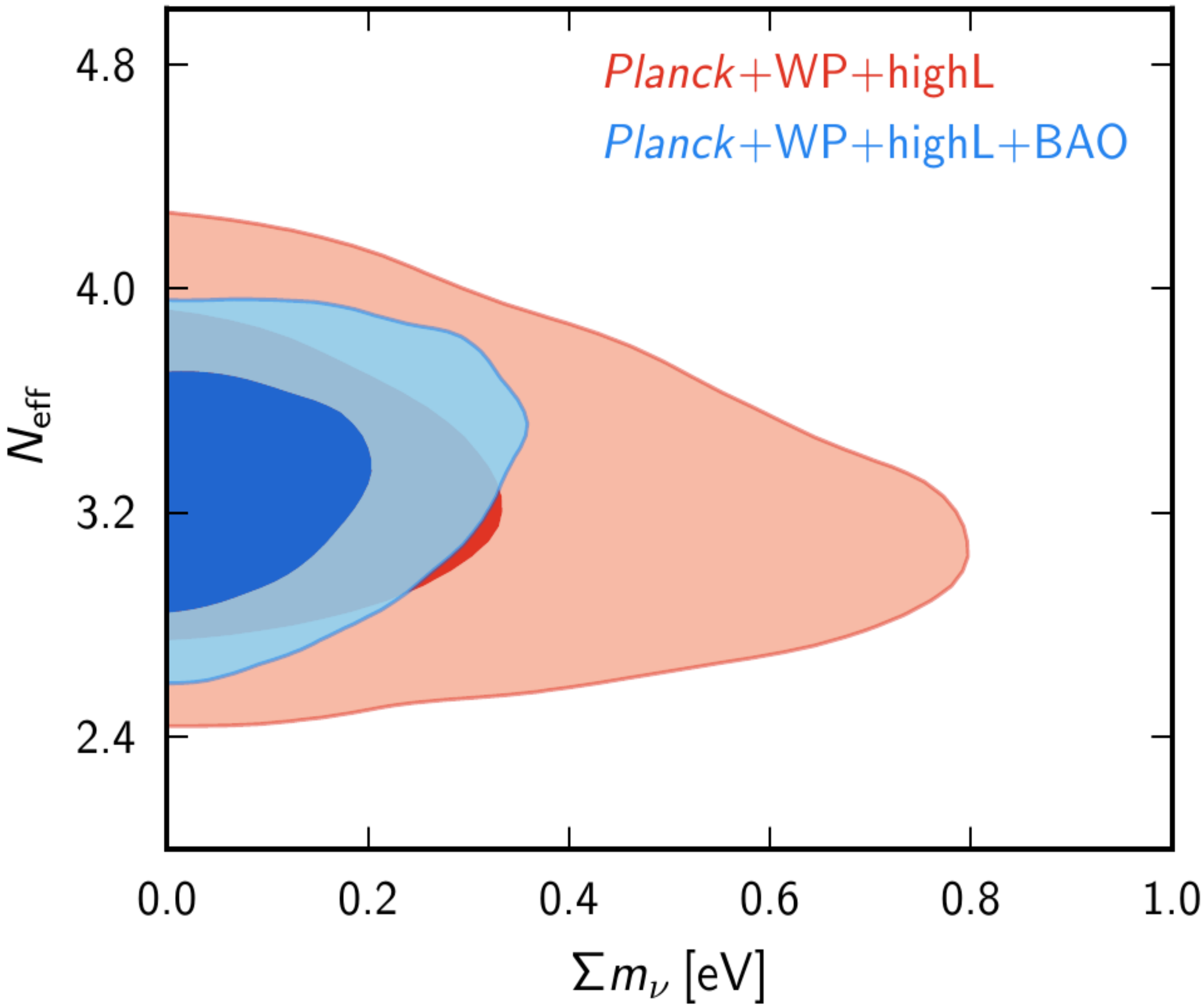

Including BICEP2 can relax the CMB bound. Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena 2014; arXiv:1403.4852

See also:
Archidiacono,Fornengo, Gariazzo, Giunti, Hannestad, Laveder. ArXiv:1404.17942.

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 $\Delta N_{eff} \approx 1$ when decouples.

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

Hubble expansion rate

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Hubble expansion rate

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

Sterile Neutrino Thermalization

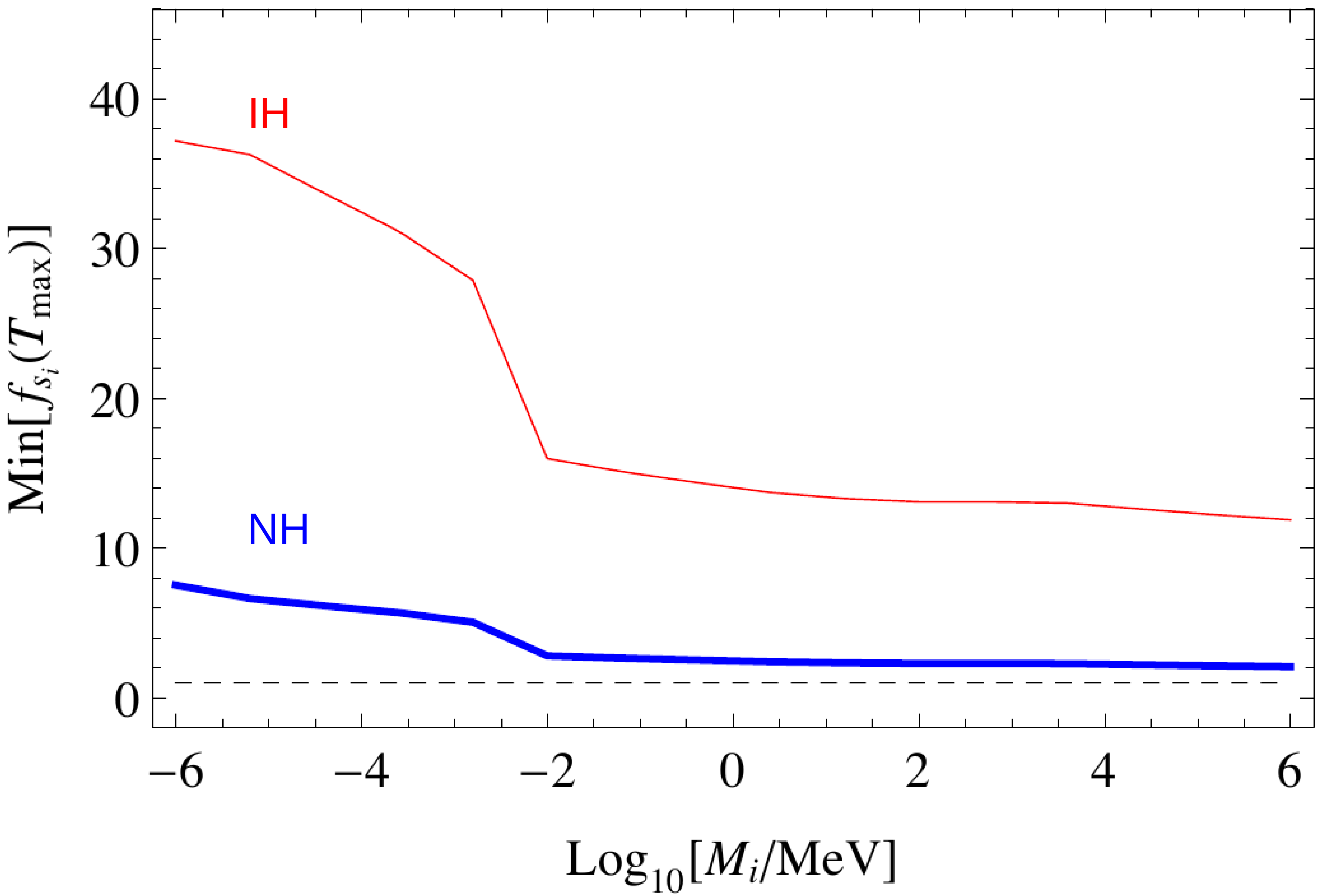
- $f_s(T)$ reaches a maximum at some temperature T_{max} and if the maximum is larger than one, thermalization will be achieved. At decoupling we can estimate:

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

$$\Downarrow$$

$$\Delta N_{eff}$$

Sterile Neutrino Thermalization



Sterile Neutrino Thermalization

- Same result for both sterile neutrinos, N_1 and N_2

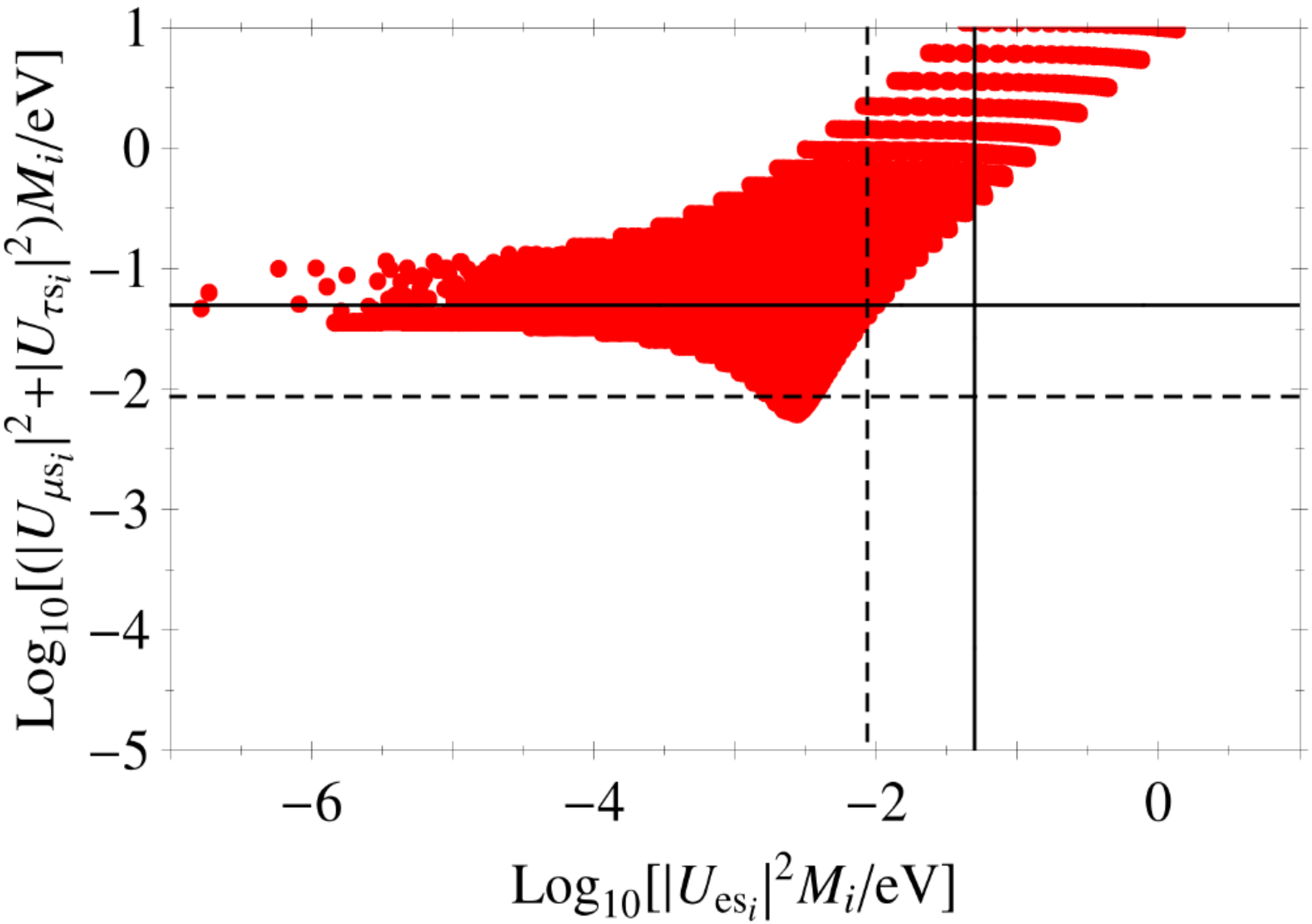
- Thermalization rate basically indepent of the seesaw scale. The small dependece is modulated by $g_*(M)$

$$f_{s_j}(T_{max}) \sim \frac{\sum_\alpha |U_{\alpha s_j}|^2 M_j}{\sqrt{g_*(T_{max})}} \qquad |U_{\alpha s_j}|^2 \sim m/M_j$$

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

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.



Sterile Neutrino Thermalization

- In the 3+2 Minimal Seesaw Model sterile neutrinos always thermalize.

- Each sterile neutrino contributes with $\Delta N_{eff} \approx 1$ when they decouple from the thermal bath. Therefore,

$\Delta N_{eff} \approx 2$ @ decopling (sterile neutrino freeze out)

Can we thus rule out
the 3+2 minimal seesaw model?

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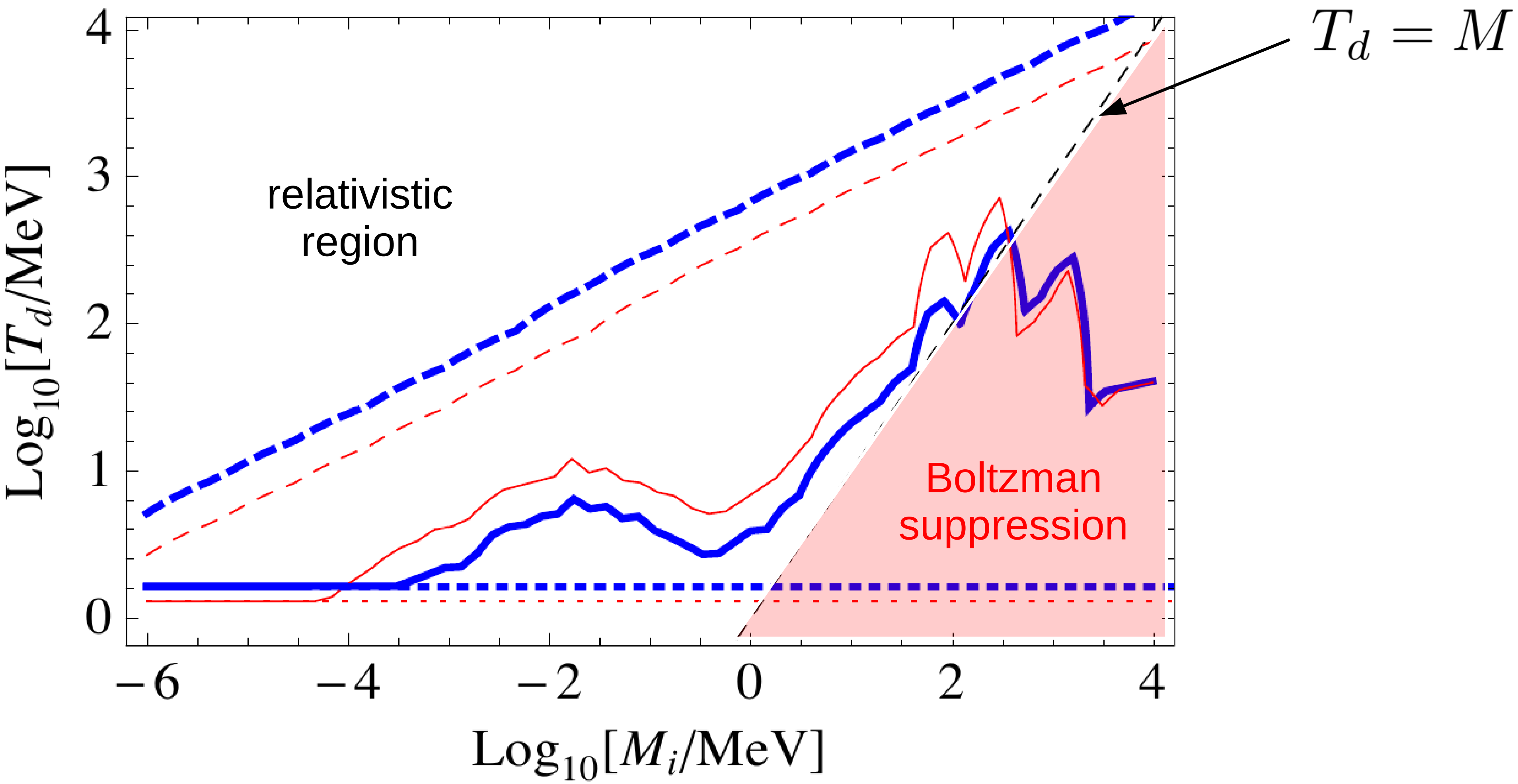
the 3+2 minimal seesaw model?

No! But a huge portion of the seesaw scale
(**8 orders of magnitude**) is **excluded!!!**

Sterile Neutrino Decoupling



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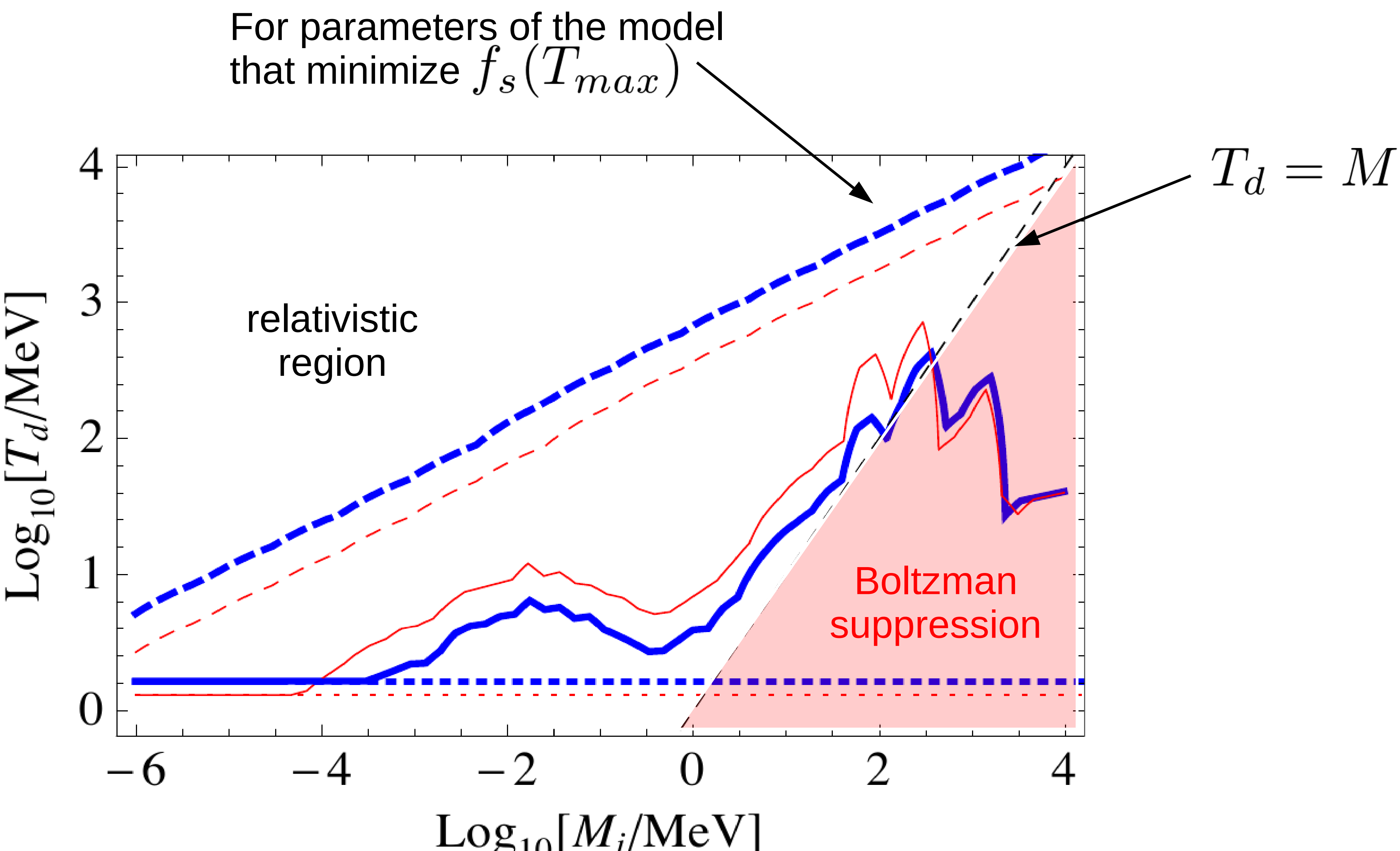

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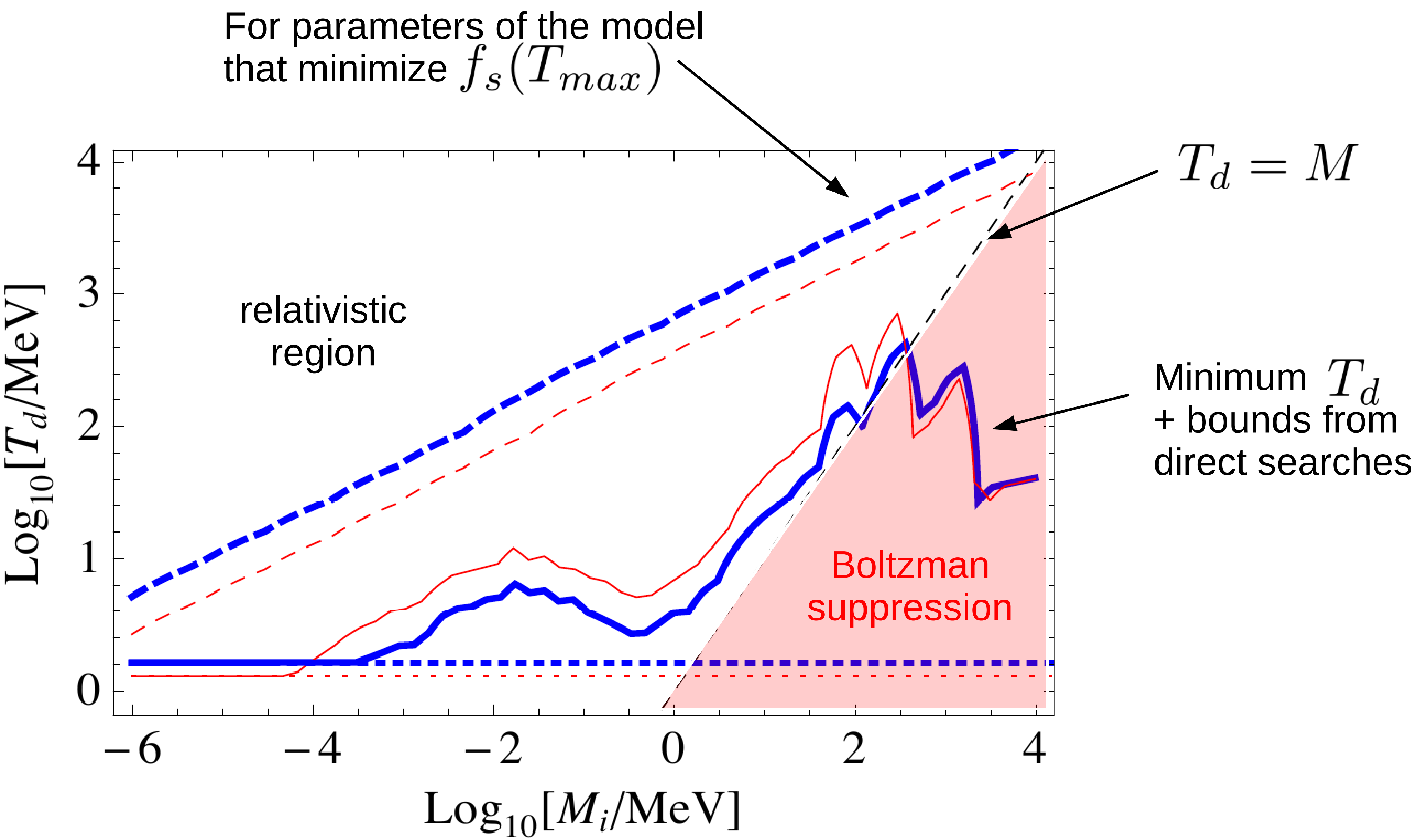


Sterile Neutrino Decoupling

- Above $\sim 1GeV$, there is Boltzman suppression. The bounds do not apply for

$$M \gtrsim 1GeV$$

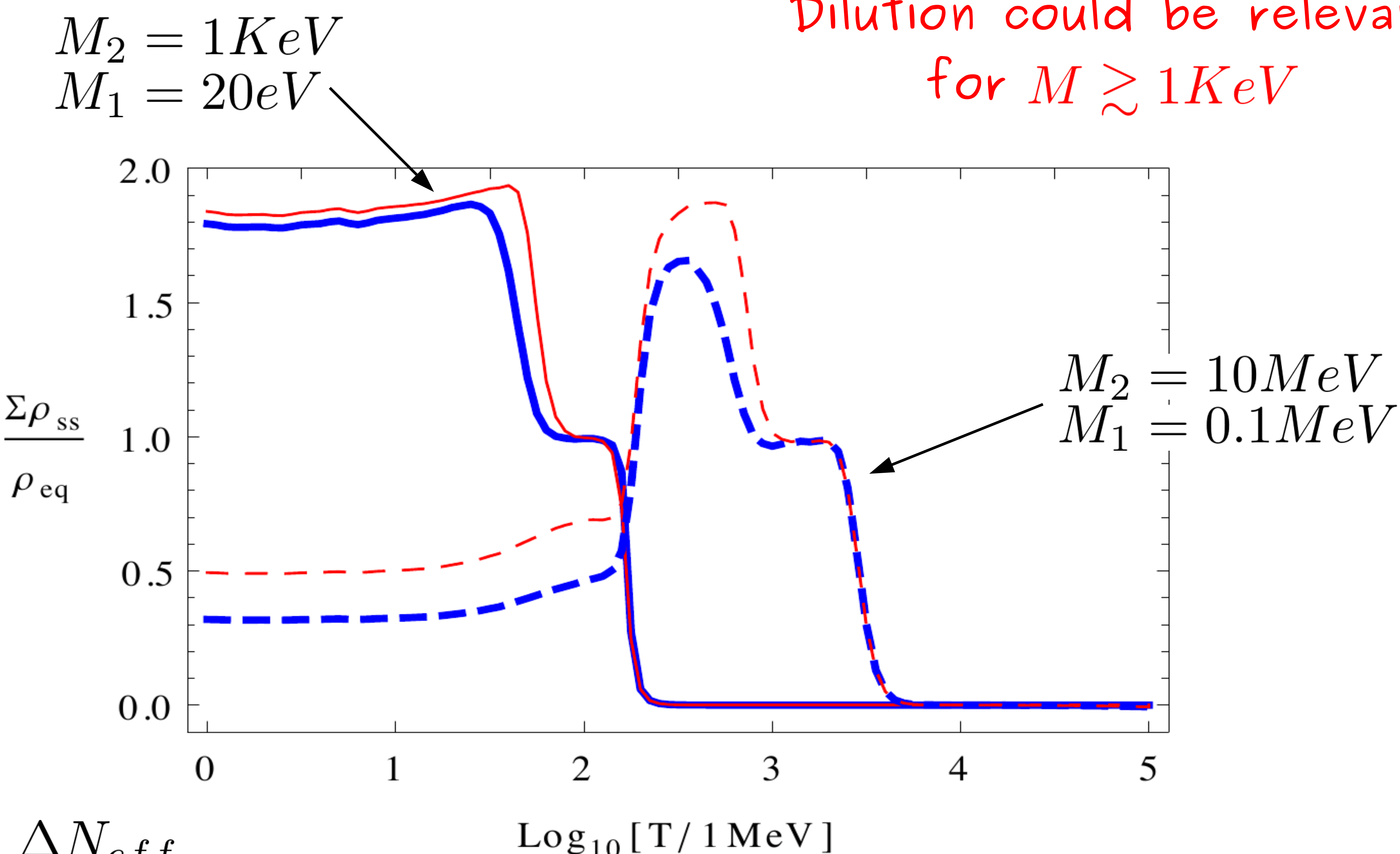
- Moreover, after sterile neutrino decoupling two effects could modify ΔN_{eff}, before BBN:

(i) Dilution

(ii) Decay

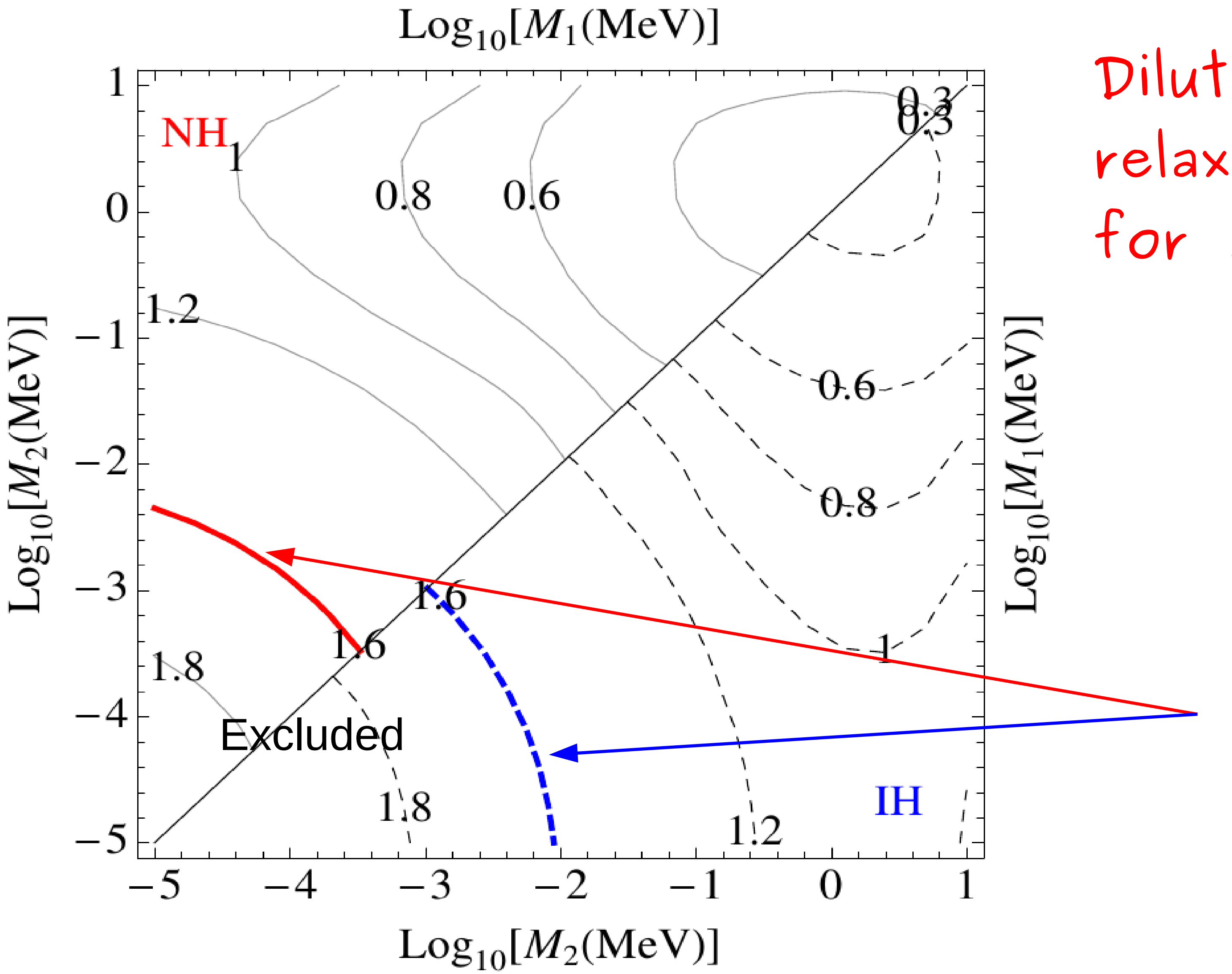
Entropy dilution

Dilution could be relevant for $M \gtrsim 1KeV$



ΔN_{eff}

Entropy dilution



$\Delta N_{eff}(T_{BBN})$

Dilution allows to relax BBN bound for $M \gtrsim 10KeV$

Izotov, Thuan 2010
arXiv:1303.076

Entropy dilution

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

$$10KeV \lesssim M \lesssim 1GeV$$

- 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

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

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

- 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.

sterile neutrino decay

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

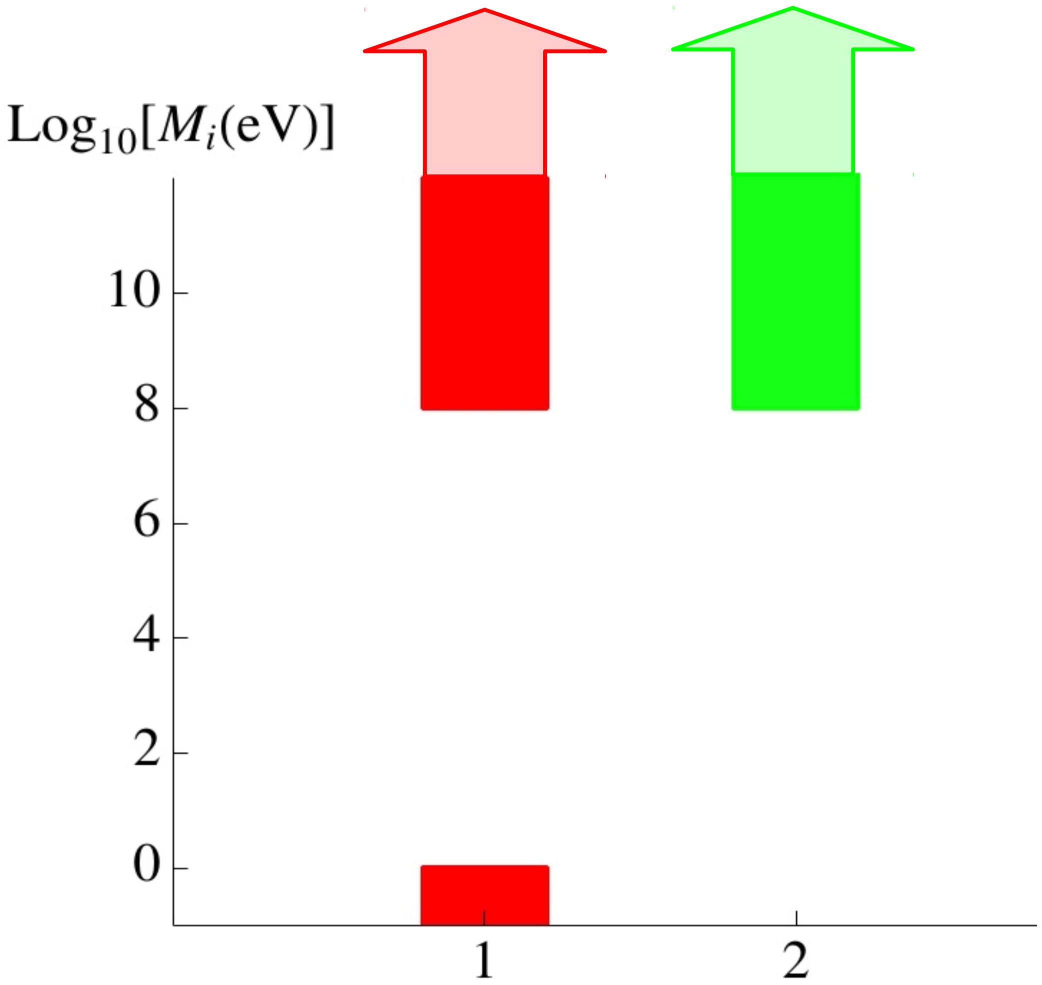
Dolgov, Hansen, Raffelt, Semikoz 2000
Fuller, Kishimoto, Kusenko, 2011
Ruchayskiy, Ivashko, 2012

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

Ruchayskiy, Ivashko, 2012

Summary 3+2 vs cosmology

- In summary, cosmology allow us to exlude 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

(work in progress)

In collaboration with P. Hernandez and M. Kekic

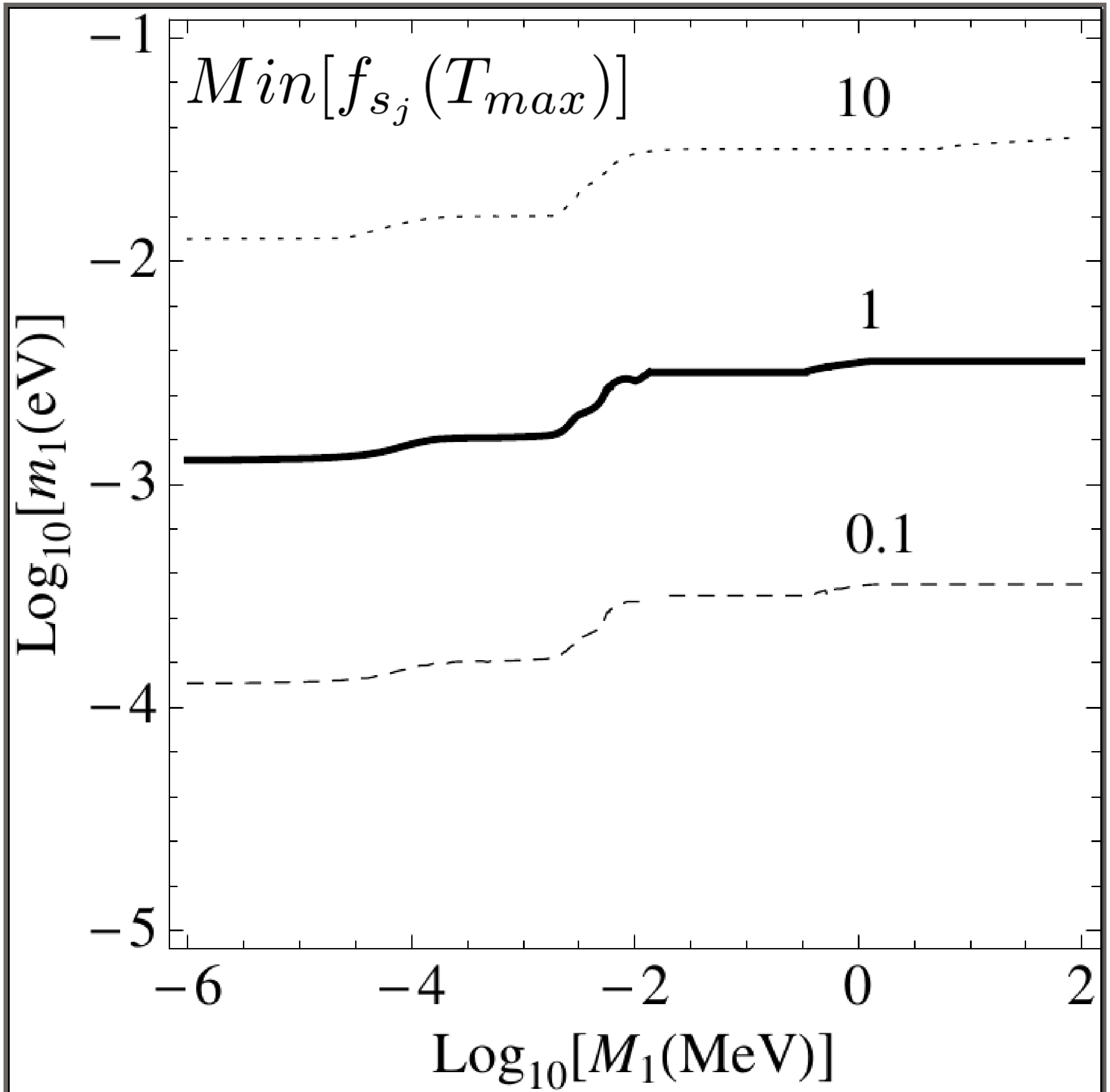
3+3 Minimal Seesaw Model

- 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



Analytical lower bound

- Analytical lower bound on thermalization rate

$$f_{s_j}(T_{max}) \geq g(M_j)h_j \geq g\,(M_j)m_1$$

$$h_j \equiv \sum_\alpha |U_{\alpha s_j}|^2 M_j = \sum_i |R_{ij}|^2 m_i \geq m_1$$

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$m_1 \geq g(M_j)^{-1} \approx 1(4) \times 10^{-3} eV$ for $M_1 = eV(1GeV)$

⇩

$$f_{s_j}(T_{max}) \geq 1$$

Lower bound almost independent of M

Mainly controled by lightest neutrino mass

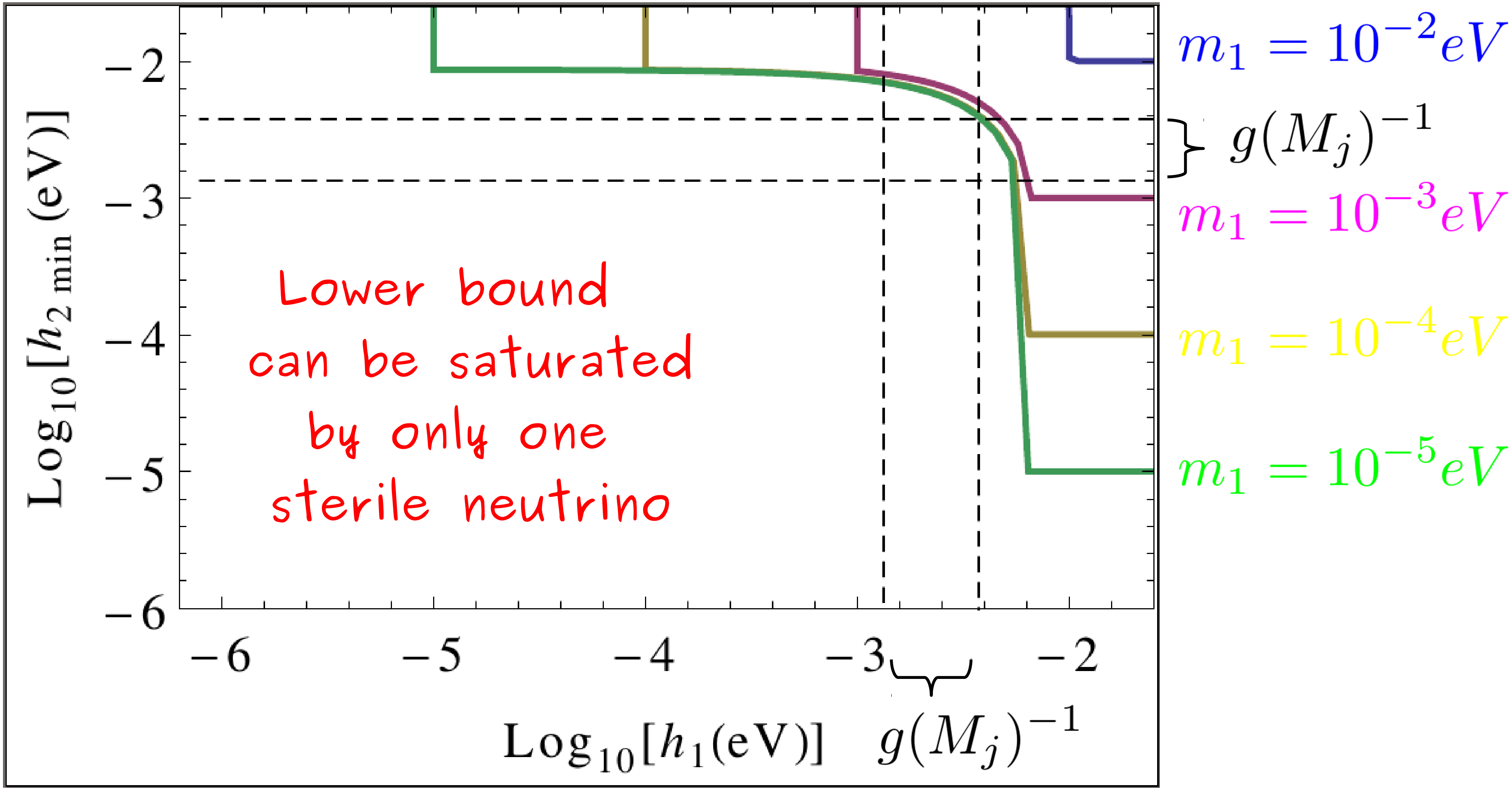
Analytical lower bound

$$h_j \leq g\,(M_j)^{-1} \approx \mathcal{O}\left(10^{-3} eV\right) \quad \Longrightarrow \quad f_{s_j}(T_{max}) \leq 1$$

N_j does NOT thermalizes

How many sterile neutrinos can simultaneusly satisfy this thermalization bound?

Analytical lower bound

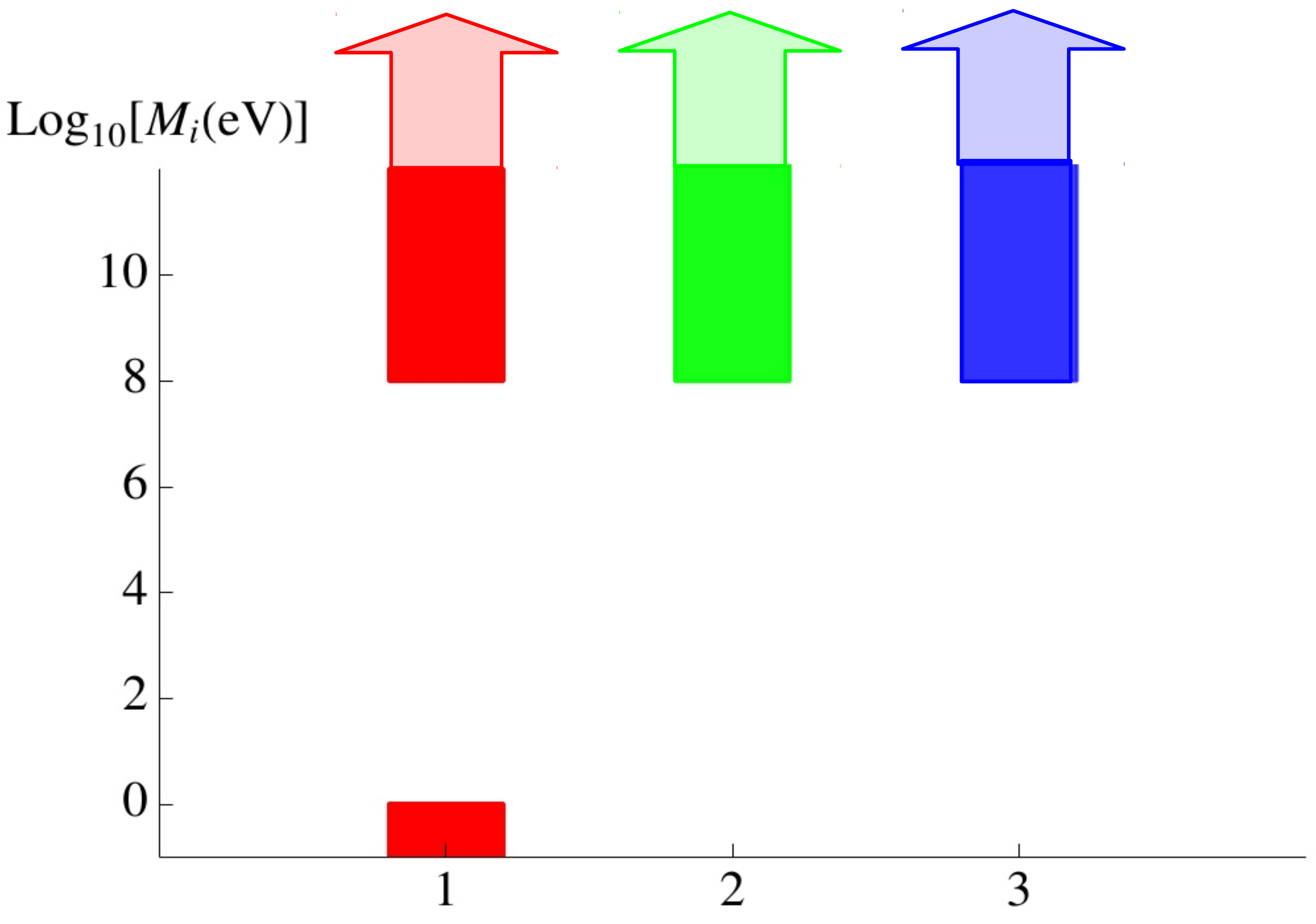


Analytical lower bound

- *Only one sterile neutrino can escape from thermalization.*
- The thermalization is controlled by the lightest neutrino mass.
- **If** $m_1 \geq \mathcal{O}\left(10^{-3} eV\right)$ **the three sterile neutrinos thermalize!**

Possible scenarios

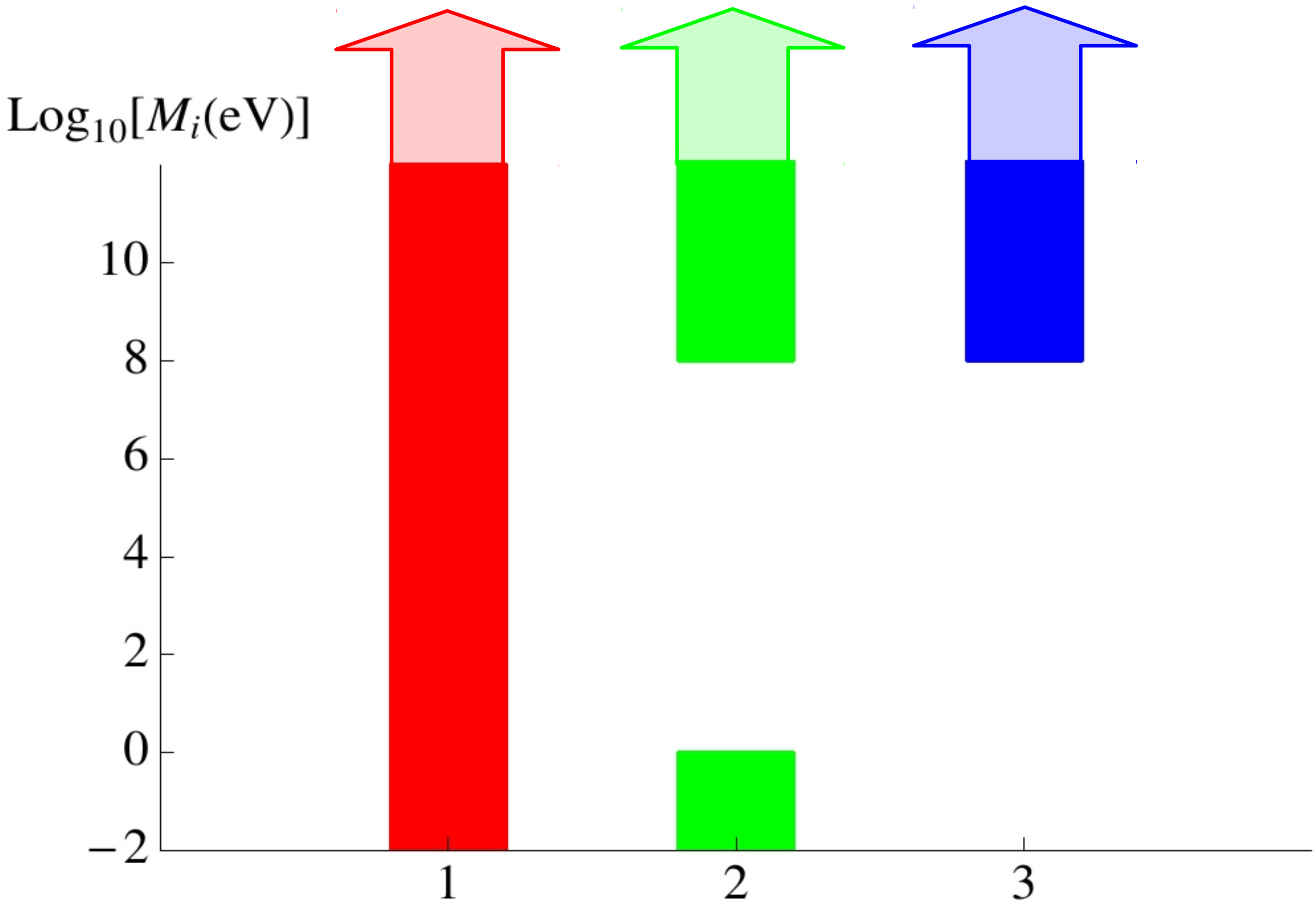
- $m_1 \geq \mathcal{O}\left(10^{-3}eV\right)$: the three sterile neutrinos thermalize.



Allowed sterile neutrino spectra

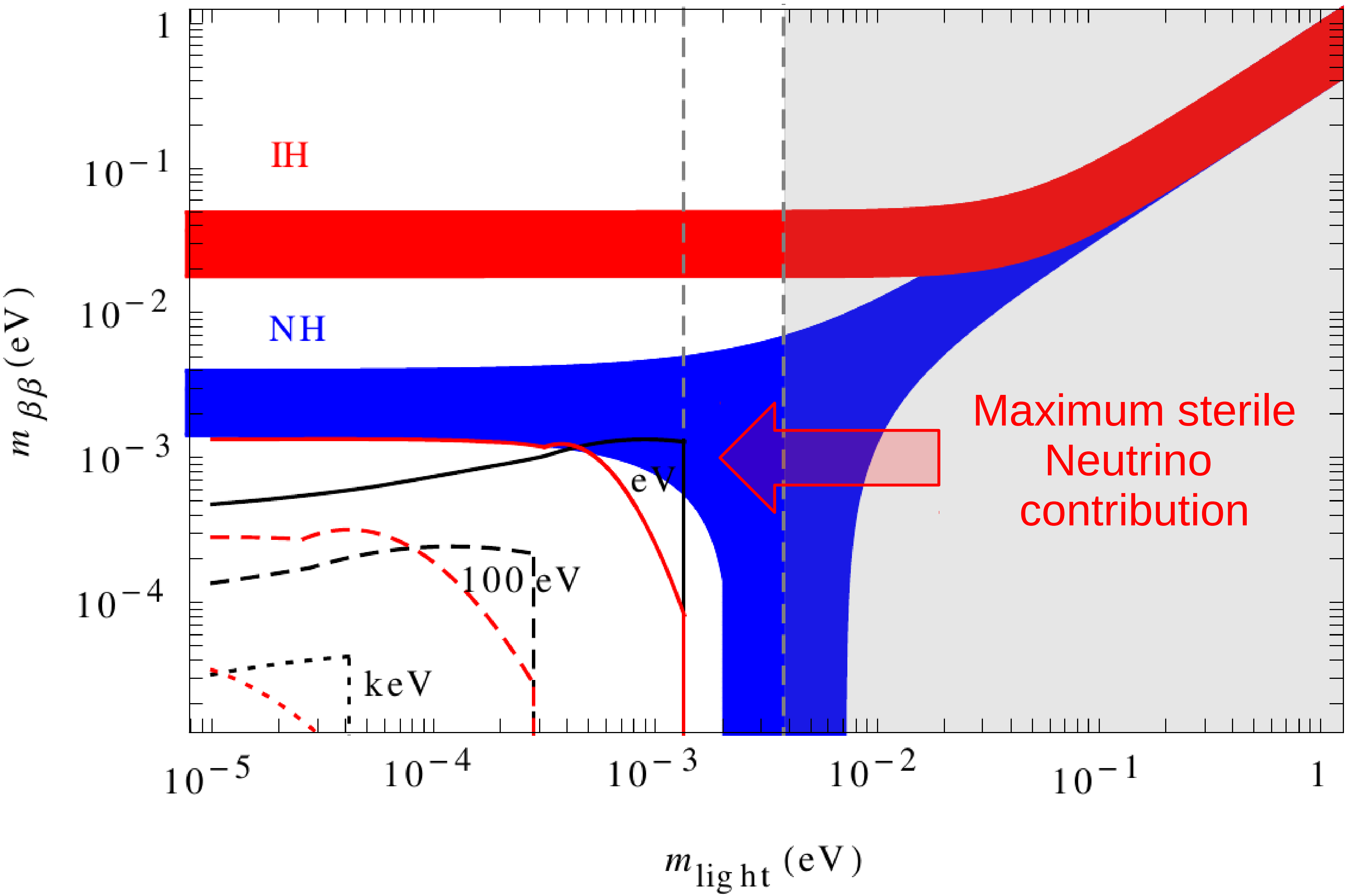
Possible scenarios

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



Only a sub-eV sterile neutrino can give a significant contribution!

3+2 Minimal Seesaw Model

vs

Neutrino Anomaly

A. Donini, P. Hernandez, JLP, M. Maltoni, T. Schwetz 2012
arXiv:1205.5230

Neutrino anomaly & Sterile neutrinos

- LSND/reactors anomaly requires at least an extra $\Delta m^2_{LSND} \sim 1eV^2$

- Tension between appearance and disappearance experiments. Difficult to accommodate all data.

  See for instance: Kopp, Machado, Maltoni and Schwetz 2013, arXiv:1303.3011

See light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

Neutrino anomaly & sterile neutrinos

- Tension between appearance and disappearance experiments

$$P_{\mu e} \sim |U_{se}|^2 |U_{s\mu}|^2$$ ☺ LSND/MB signal

$$P_{ee} \sim |U_{se}|^2$$ ☺ reactor anomaly

$$P_{\mu\mu} \sim |U_{s\mu}|^2$$ ✗ no signal...

- Difficult to accommodate all data. Convincing signal should appear in all these channels.

3+2 Phenomenological Models (PM)

- Best fits in the 3+2 phenomenological model (PM). Number of free parameters: 9 angles + 5 phases + 4 neutrino mass differences.

$3+2$ PM	$\lvert\Delta m^2_{41}\rvert(\mathrm{eV}^2)$	$\lvert\Delta m^2_{51}\rvert(\mathrm{eV}^2)$	$\lvert U_{e4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{45}
KMS[13]	0.47	0.87	0.128	0.138	0.165	0.148	$1.64\ \pi$
GL[14]	0.9	1.61	0.13	0.13	0.14	0.078	$1.51\ \pi$

Kopp, Maltoni, Schwetz (KMS) arXiv:1103.4570
Giunti, Laveder, (GL) arXiv:1107.1452

See also more recent analysis by Kopp, Machado, Maltoni and Schwetz 2013, arXiv:1303.3011

- Phenomenological models are model independent. Realistic models are much more constrained.

3+2 Mini Seesaw Model

- Mini-seesaw model (MM). Minimal model accounting for neutrino masses.

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

- More predictive than the phenomenological models (PM).

Mini-Seesaw have 7 parameters less than the PM !

Model	# Δm^2	# Angles	# Phases	Total
3 ν	2	3	1	6
3+2 MM	4	4	3	11
3+2 PM	4	9	5	18

...and, in the Mini-Seesaw, active-sterile mixing and mass parameters are strongly correlated!!

3+2 Mini Seesaw Model

- We performed a global fit in the context of the 3+2 mini-seesaw model.

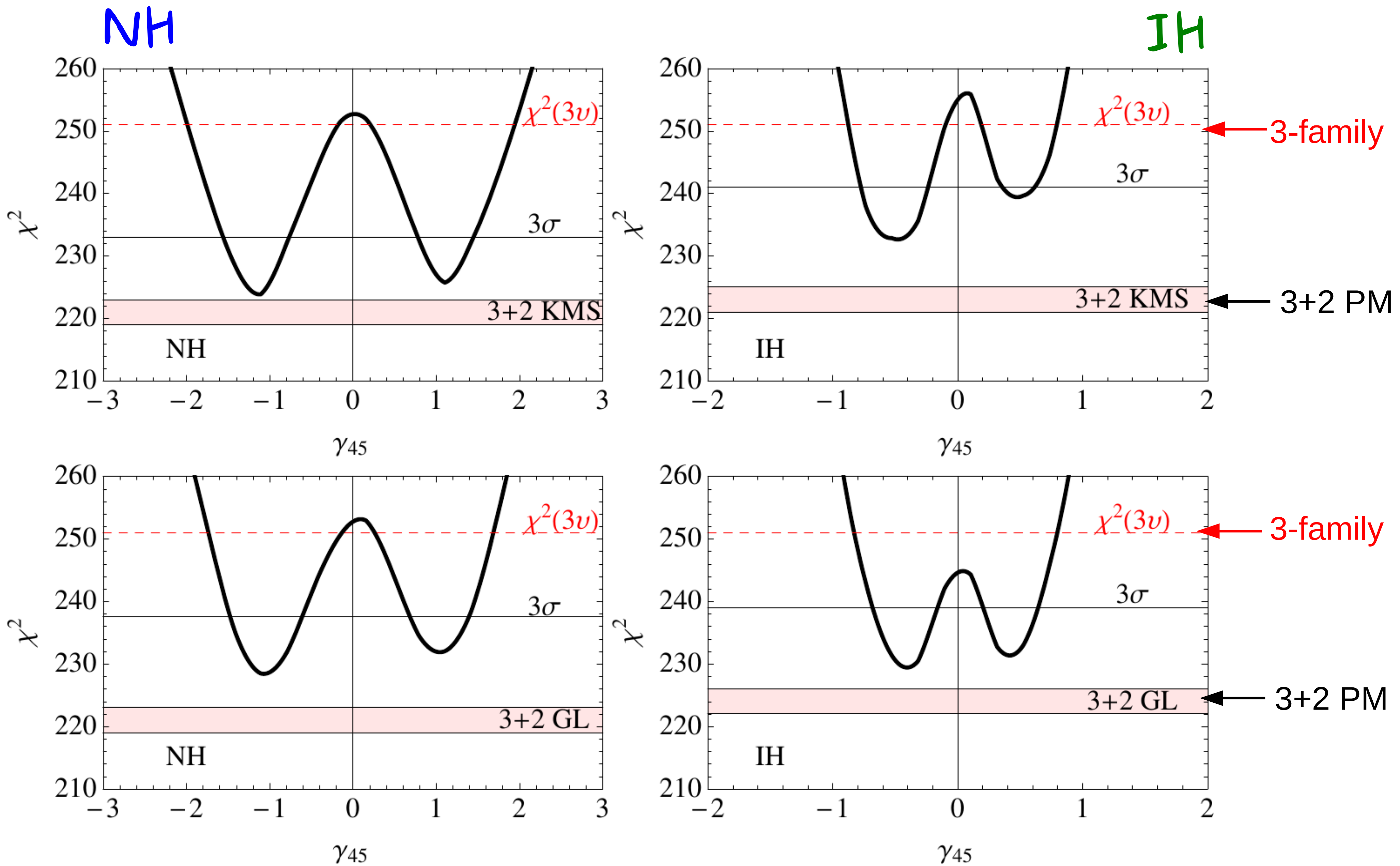
- LBL and SBL can not be decoupled. Correlation between active and sterile mixing is not negligible. Active-sterile mixing and heavy squared mass diferences strongly correlated.

- In the analysis we fix the values of M_1 and M_2 to the results of the above PM best fits.

- We use a general parameterization which generalizes Casas-Ibarra to the case in which corrections are important (as in this case)

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

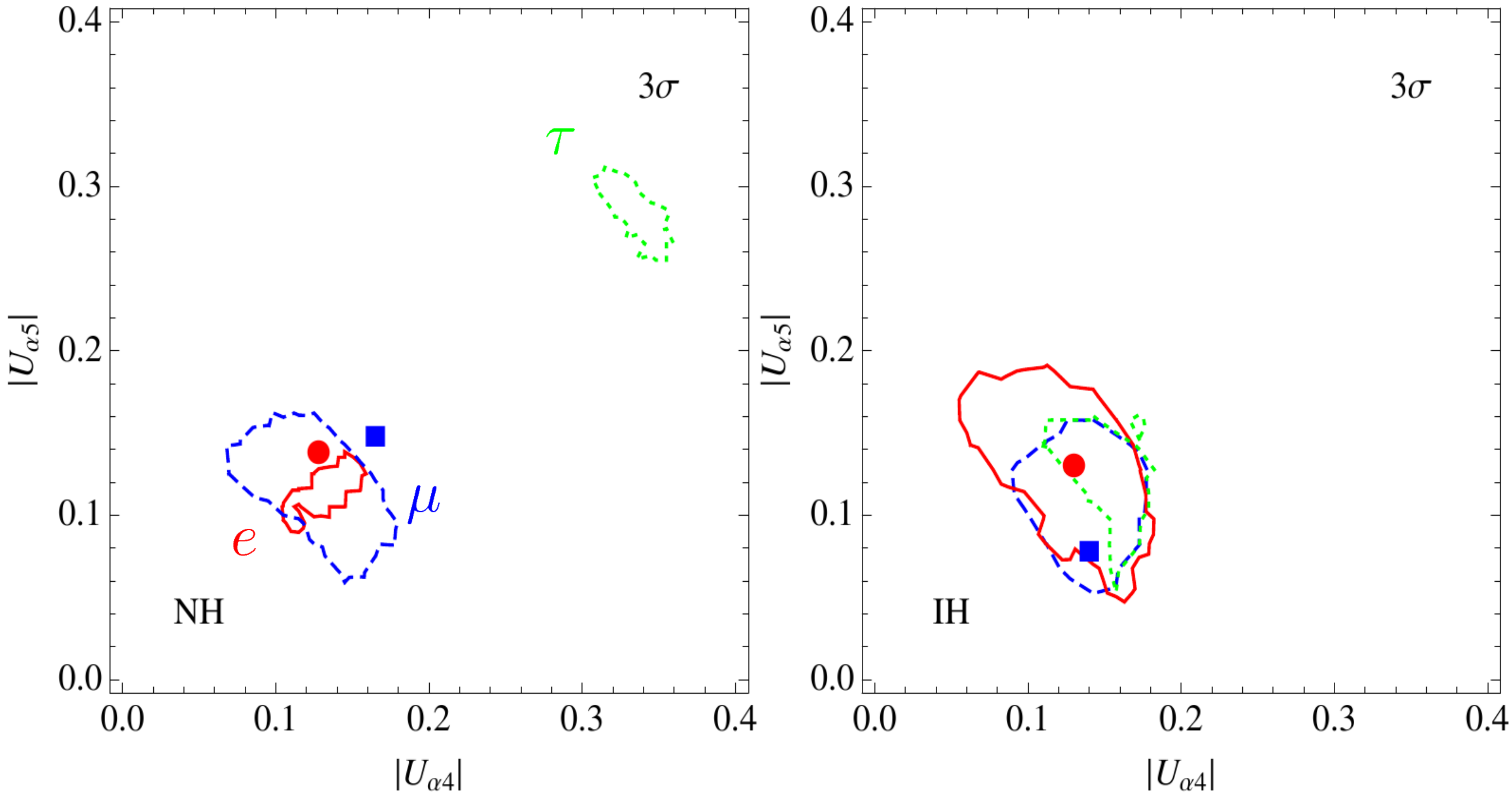
Global fit



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

Best fit: active-sterile mixing

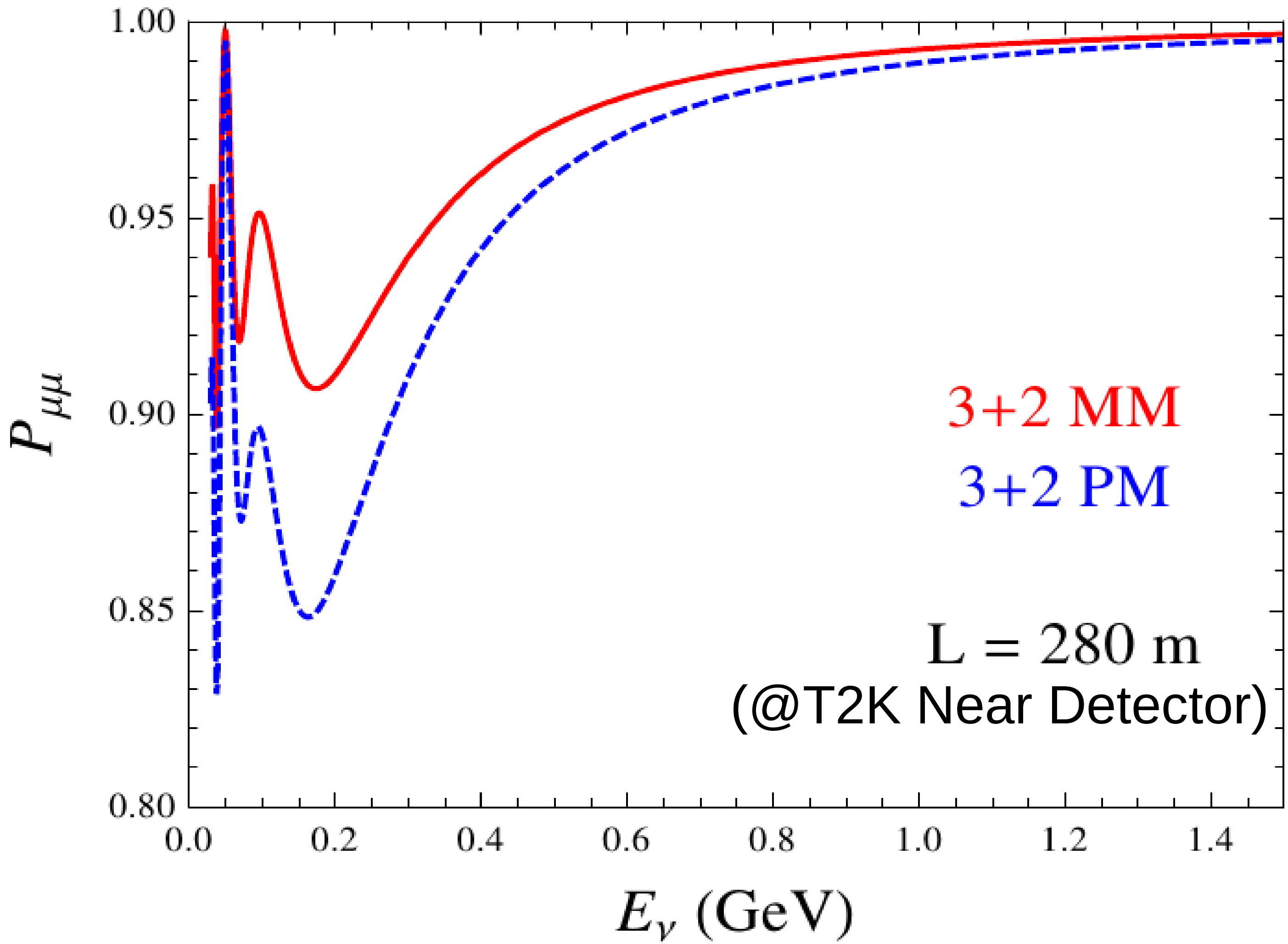
Prediction: large tau-mixing with extra states for NH!



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

Minimal Sterile Neutrino Model

- But large tension appearance/disappearance in μ sector remains.



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

Conclusions

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

- The minimal model requires two sterile neutrinos and is able to explain the neutrino anomaly at the same level as the phenomenological models.

- However, low scale 3+2 minimal seesaw models are strongly constrained by cosmology since the sterile neutrinos can not scape from thermalization.

- A huge part of the parameter space and the seesaw scale **(8 orders of magnitude)** of the 3+2 MM can be exluded thanks to cosmology.

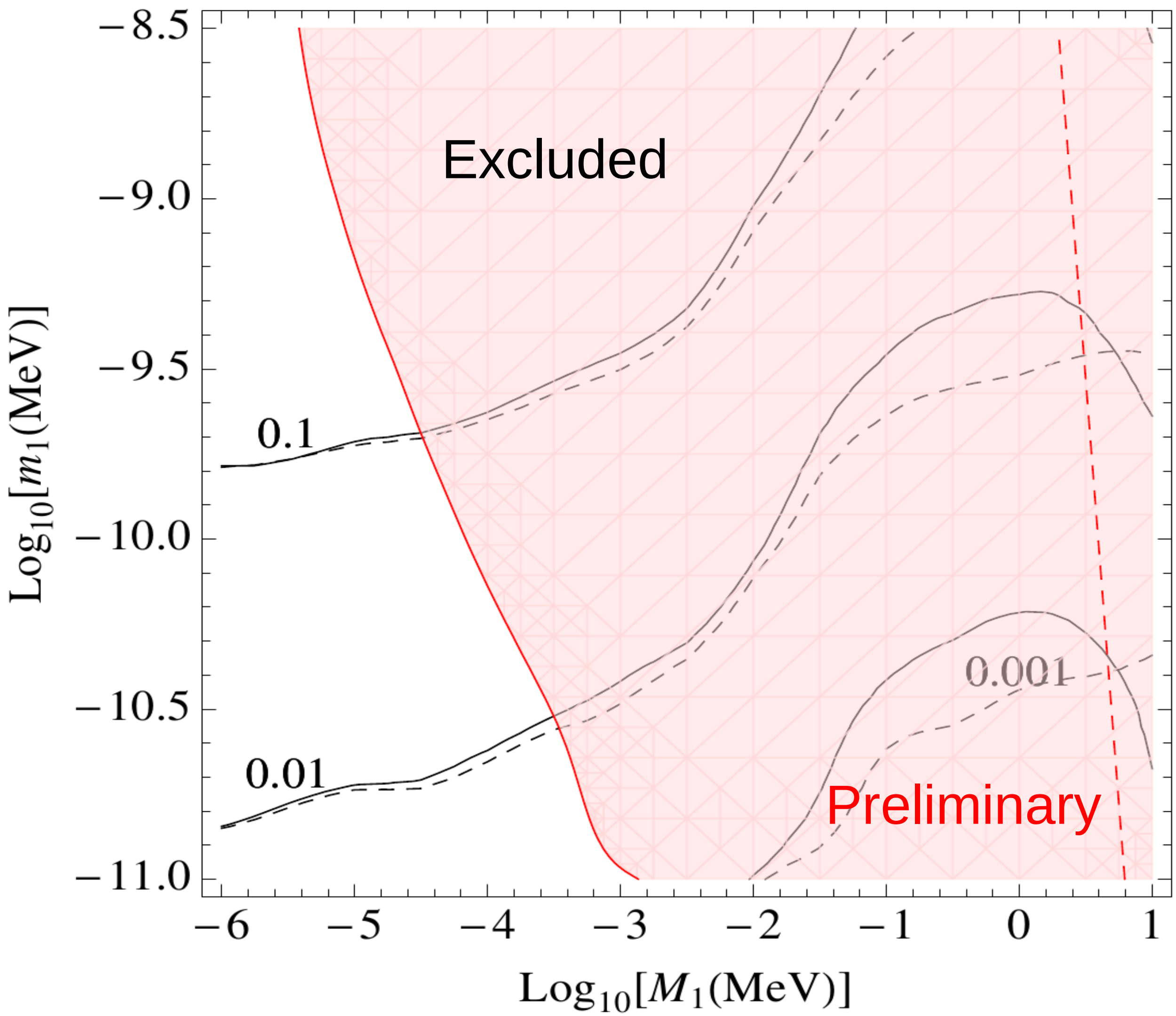
- Low scale 3+3 minimal seesaw models are also very constrained by cosmology. ***Only one sterile neutrino might escape from thermalization.*** Thermalization is controlled by the lightest neutrino mass, being the threshold: $m_1 = \mathcal{O}\left(10^{-3} eV\right)$

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

Tack!

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.



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

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

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

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

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

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

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

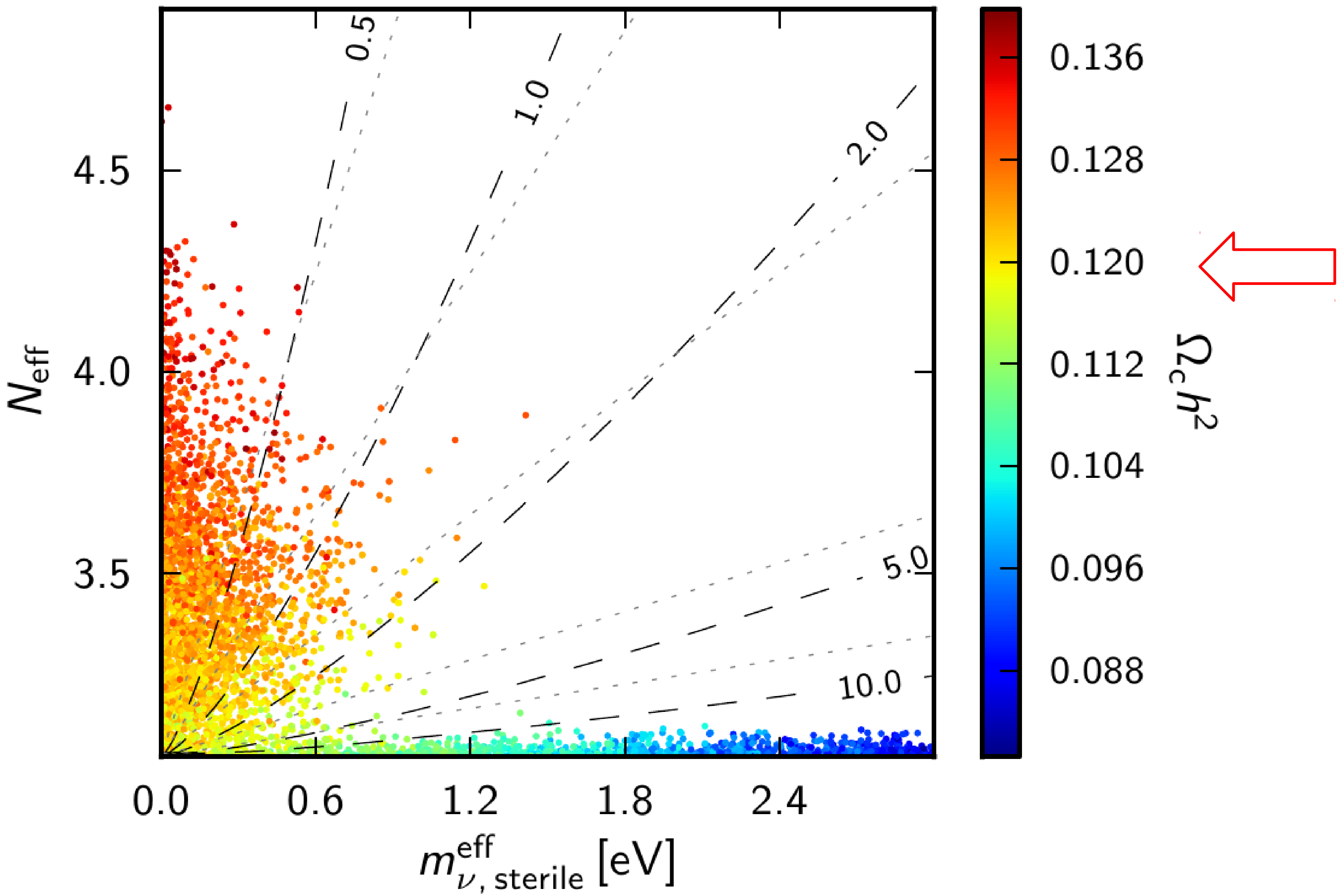
$$\tilde{\rho}_S \equiv \rho_S - \rho_{eq} I_S$$

Sterile Neutrino Thermalization

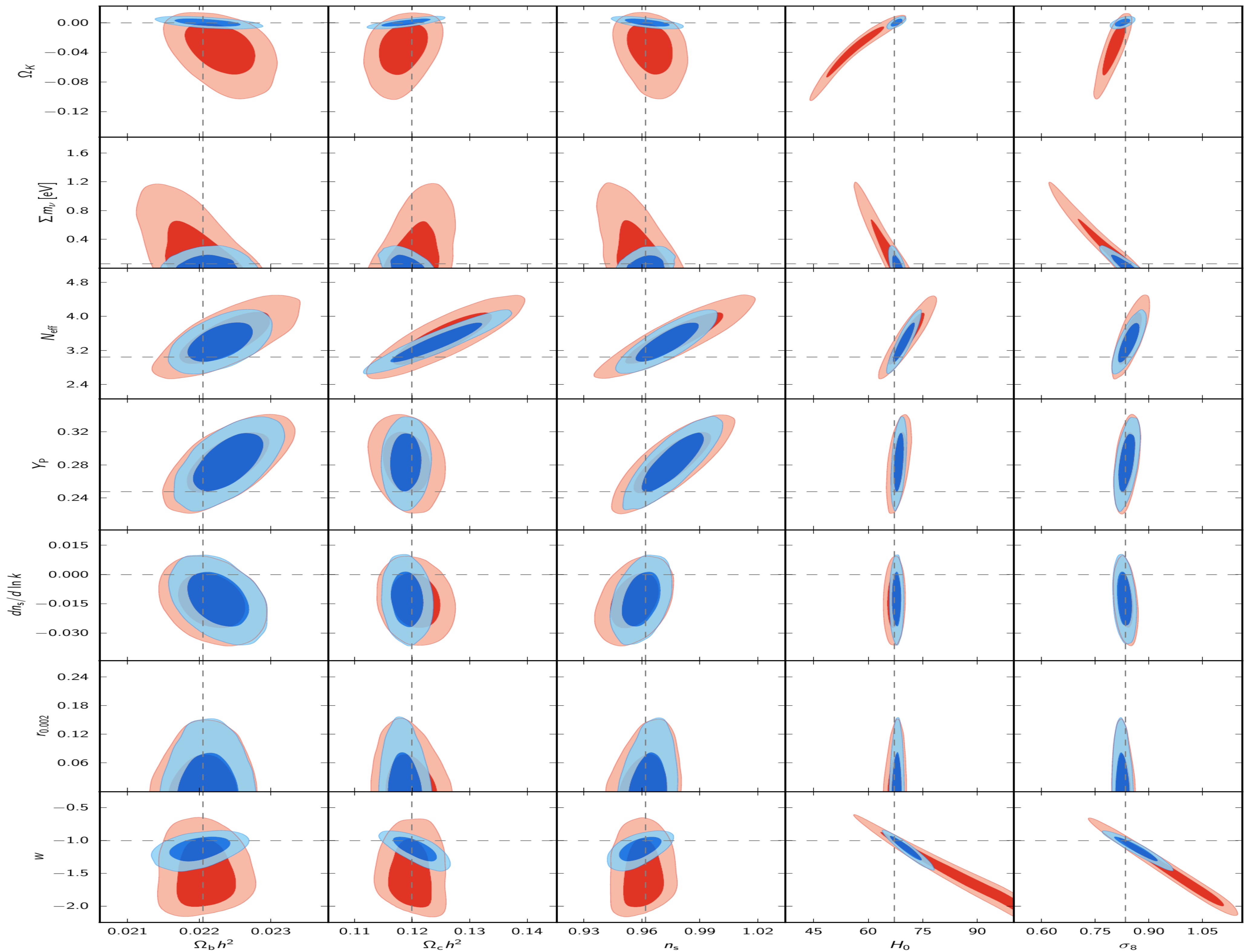
- Necesary to go beyond the two family approximation. Expanding over m/M we have computed the time-averaged probability:

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

$$\begin{cases} (\tau)\ \ T \gtrsim 180 \text{ MeV: } n_\alpha = 1 \text{ and } V_\alpha = A\,T^4 p, \\ \\ (\mu)\ \ 20 \text{ MeV} \lesssim T \lesssim 180 \text{ MeV: } n_e = n_\mu = 1,\ n_\tau = 9/13,\ V_e = V_\mu = A\,T^4 p \text{ and } \\ \qquad V_\tau = B\,T^4 p, \\ \\ (e)\ \ T \lesssim 20 \text{ MeV: } n_e = 1,\ n_\mu = n_\tau = 9/13,\ V_e = A\,T^4 p \text{ and } V_\mu = V_\tau = B\,T^4 p. \end{cases}$$



0.5
1.0
2.0
5.0
10.0
4.5
4.0
3.5
$N_{\rm eff}$
0.0
0.6
1.2
1.8
2.4
$m_{\nu,\,\rm sterile}^{\rm eff}$ [eV]
0.136
0.128
0.120
0.112
0.104
0.096
0.088
$\Omega_c h^2$



Ω_K
Σm_ν [eV]
$N_{\rm eff}$
$Y_{\rm P}$
$dn_s/d\ln k$
$r_{0.002}$
w
$\Omega_b h^2$
$\Omega_c h^2$
n_s
H_0
σ_8
0.00 −0.04 −0.08 −0.12
1.6 1.2 0.8 0.4
4.8 4.0 3.2 2.4
0.32 0.28 0.24
0.015 0.000 −0.015 −0.030
0.24 0.18 0.12 0.06
−0.5 −1.0 −1.5 −2.0
0.021 0.022 0.023
0.11 0.12 0.13 0.14
0.93 0.96 0.99 1.02
45 60 75 90
0.60 0.75 0.90 1.05

Global fit

- DATA

  LBL: KamLAND, MINOS, T2K

  SBL: LSND, MiniBooNE, KARMEN, NOMAD, CDHS, Bugey, ROVNO, Krasnoyarsk, Gösgen, CHOOZ, Palo Verde, Double CHOOZ, Daya Bay, RENO.

$$\chi^2 = \chi^2_{LBL} + \chi^2_{SBL}$$

$$\theta_{23}, \theta_{12}, m_2, m_3$$

$$M_1, M_2$$

$$\theta_{13}, \theta_{45}, \gamma_{45}, \delta, \alpha$$

Analytical lower bound

- Analytical lower bound on thermalization rate!

$$f_{s_j}(T) \geq \frac{9}{16}\frac{\Gamma_{\nu_e}(T^{\tau}_{max})}{H(T^{\tau}_{max})}\sum_i |U_{\alpha s_j}|^2 \propto \frac{\sum_\alpha |U_{\alpha s_j}|^2 M_j}{\sqrt{g_*\left(T^{\tau}_{max}\right)}}$$

$$h_j \equiv \sum_\alpha |U_{\alpha s_j}|^2 M_j = \underbrace{\sum_i |R_{ij}|^2 m_i \geq m_1}$$

Independent of PMNS parameters

Extending Casas-Ibarra parameterization

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

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

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