Sterile neutrino dark matter in Inverse Seesaw realisations

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Planck 2014, May 29th 2014

Based on:

A. Abada and M.L., *arXiv:1401.1507 [hep-ph]*
A. Abada, G. Arcadi and M.L., *in preparation*

Neutrino masses within the SM

Matter of fact:
neutrinos are massive

Standard Model: $\left\{ \begin{array}{c} \text{Field content} \\ \text{Gauge symmetries} \\ \text{Renormalizability} \end{array} \right\} \Rightarrow m_\nu = 0$

- ν_L but not ν_R $\Rightarrow$ $\cancel{m_D \overline{\nu}_L \nu_R}$ No Dirac mass term
- No Higgs triplet $\Rightarrow$ $\cancel{M \overline{\nu_L^c} \nu_L}$ No Majorana mass term
- Renormalizability $\Rightarrow$ $\cancel{\left(\overline{l_L^c} \widetilde{\phi}^*\right)\left(\widetilde{\phi}^\dagger l_L\right)}$ No dim > 4 operators

$m_\nu \neq 0$ requires physics BSM

B - L conservation: accidental SM symmetry

The Inverse Seesaw (ISS) idea

R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D 34 (1986) 1642

M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. B 216 (1989) 360

F. Deppisch and J. W. F. Valle, hep-ph/0406040

Enlarge the SM field content with:
- right handed neutrino fields, $\boldsymbol{\nu}_R$;
- fermionic sterile singlets, s.

In the basis $n_L \equiv (\boldsymbol{\nu}_L, \boldsymbol{\nu}_R{}^C, s)^T$ the ISS neutrino mass terms read:

$$-\mathcal{L}_{m_\nu} = \frac{1}{2} n_L^T \, C \, \mathcal{M} \, n_L + h.c., \qquad \mathcal{M} = \begin{pmatrix} 0 & d & 0 \\ d & m & n \\ 0 & n & \mu \end{pmatrix}$$

t'Hooft naturalness criterium: terms violating L are "small", i.e.

$|m|,|\boldsymbol{\mu}| << |n|,|d|$

G. 't Hooft, NATO Adv. Study Inst. Ser. B Phys. 59 (1980) 135

Lightest mass eigenvalue in the limit $|\boldsymbol{\mu}| << |d| << |n|$: $\quad m_\nu \approx \mu \left(\frac{d}{n}\right)^2$

One could link the smallness of μ with the one of m_ν (mechanism viable with large Yukawas), thus interesting phenomenology

Presence of sterile states ($\boldsymbol{\nu}$ anomalies or DM candidates)

Methodology

ν_R and s, are gauge singlets → No interactions with gauge bosons
No contribution to anomalies

What is the minimal number of ν_R and **s** in order to accommodate neutrino data while complying with all experimental requirements?

Define:

- $\#\nu_R \equiv$ number of ν_R fields ($\neq 0$);
- $\#s \equiv$ number of s fields ($\neq 0$);

Let us call each model realisation ($\#\nu_R$,$\#s$) ISS

We studied realisations obtained with $\#\nu_R$, $\#s$ = 1,2,3

($\#\nu_R$ and #s not necessarily equal)

Perturbative approach

$$M = \underbrace{\begin{pmatrix} 0 & d & 0 \\ d & 0 & n \\ 0 & n & 0 \end{pmatrix}}_{M_0} + \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & \mu \end{pmatrix}}_{\Delta M},$$

or

$$M^\dagger M = \underbrace{M_0^\dagger M_0}_{M_0^2} + \underbrace{\Delta M^\dagger M_0 + M_0^\dagger \Delta M}_{M_I^2} + \underbrace{\Delta M^\dagger \Delta M}_{M_{II}^2}$$

Light states: $\lim_{\Delta m \to 0} m_i \; = \; 0, \; \Rightarrow m_i \propto \mu, m$

Heavy states: $\lim_{\Delta m \to 0} m_i \; \neq \; 0, \; \Rightarrow m_i \propto n, d$

Mass spectra and mixing

			Analytical diagonalization			Numerical diagonalization	
# new fields	$\#\nu_R$	# s	$\#m_i^2=0$ when $\Delta M=0$	$\#\begin{pmatrix} m_i^2=0 \\ \downarrow {\scriptstyle \Delta M \neq 0} \\ m_i^2 \neq 0 \end{pmatrix}$	# of different light m_i	ν's mass spectrum	PMNS matrix
2	1	1	3	1	2	✗	✗
3	1	2	4	2	3	✓(s)	✗
3	2	1	2	1	2	✗	✗
4	1	3	5	3	4	✓(a)	✗
4	2	2	3	2	3	✓(s)	✓
4	3	1	1	1	1	✗	✗
5	2	3	4	3	4	✓(a)	✓
5	3	2	2	2	2	✗	✗
6	3	3	3	3	3	✓(s)	✓

ISS viable only if $\#s \geq \#\nu_R$

(2,2) ISS: minimal realisation to account for the 3 flavour mixing

M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez, arXiv:0906.1461 [hep-ph]

(2,3) ISS: minimal realisation to account for the (3+1) mixing

ISS mass scales

For each ISS realisation:
- $\#\nu_L + (\#s - \#\nu_R)$ light states;
- $2\ \#\nu_R$ heavy states ($\#\nu_R$ pseudo-Dirac couples);

Mass

E.g.

$2\ \#\nu_R$ heavy states $\approx \mathcal{O}(n)$ TeV (testable)

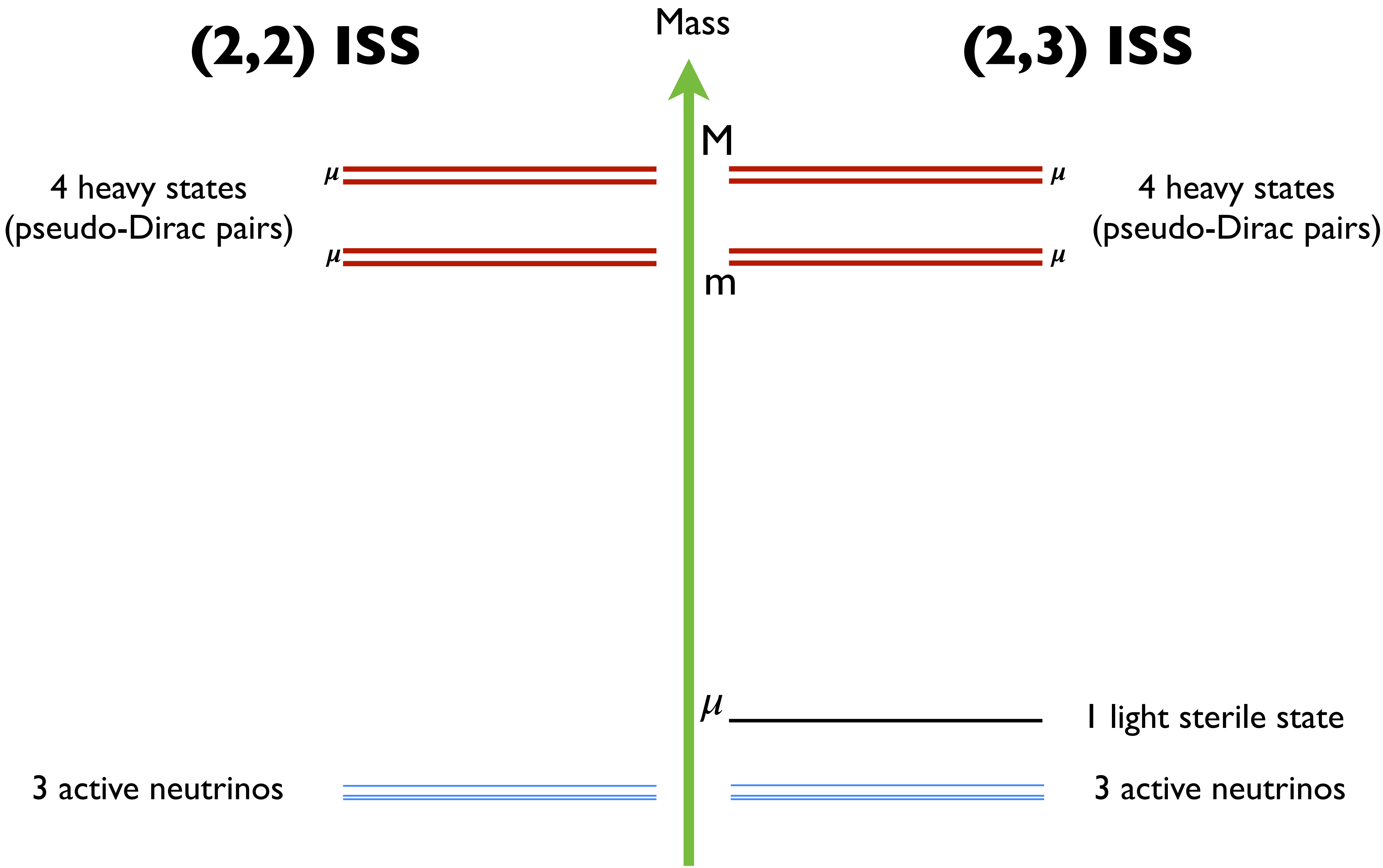
only if $\#s > \#\nu_R$

$(\#s - \#\nu_R)$ light sterile states $\sim \mathcal{O}(\mu)$ eV

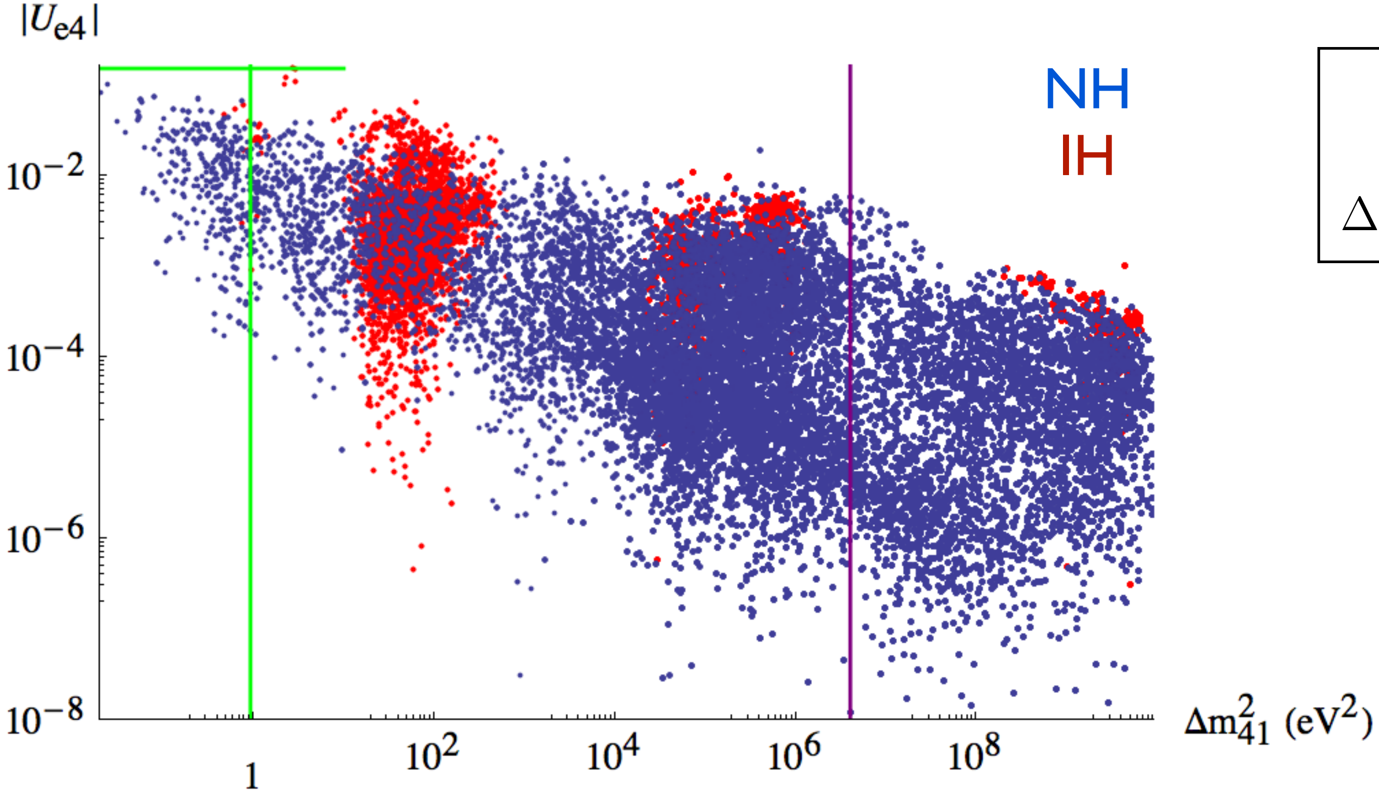
$\#\nu_L$ active neutrinos $\sim \mathcal{O}(\mu)\mathcal{O}(k)$ meV

$$k = \frac{|d|}{|n|}$$

Minimal ISS spectra



(2,3) ISS: light sterile state



(3+1) best-fit points

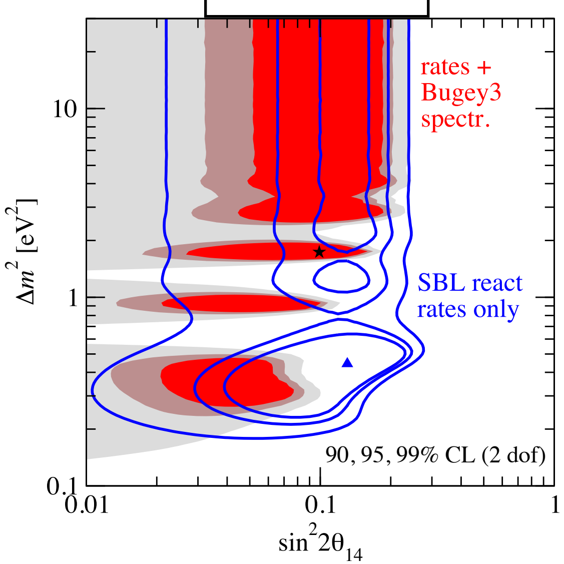
hep-ph:1303.3011

$$\Delta m^2_{41} = 0.93\ \mathrm{eV}^2, |U_{e4}| = 0.15$$

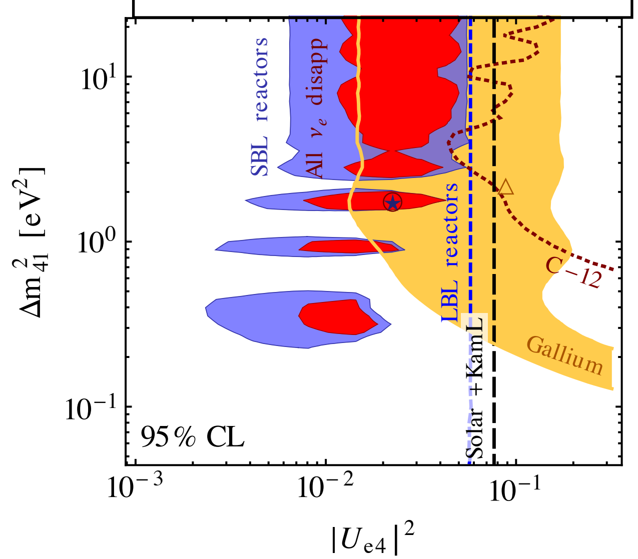
de Vega, Sanchez: astro-ph.CO:1304.0759

$m_{DM} \approx 2$ KeV

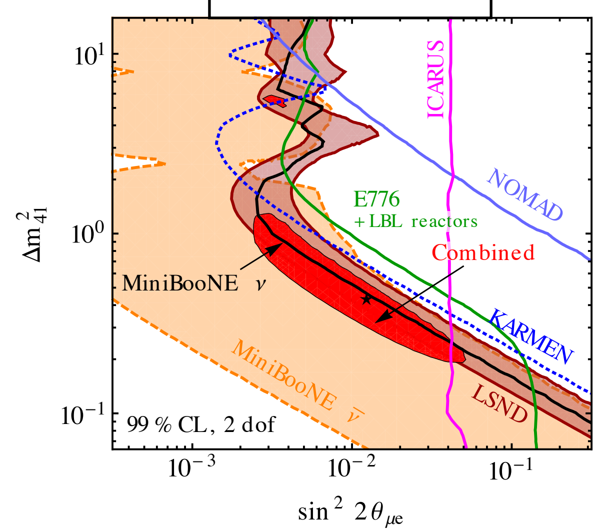
SBL reactors



Global ν_e and $\overline{\nu}_e$ disappearance



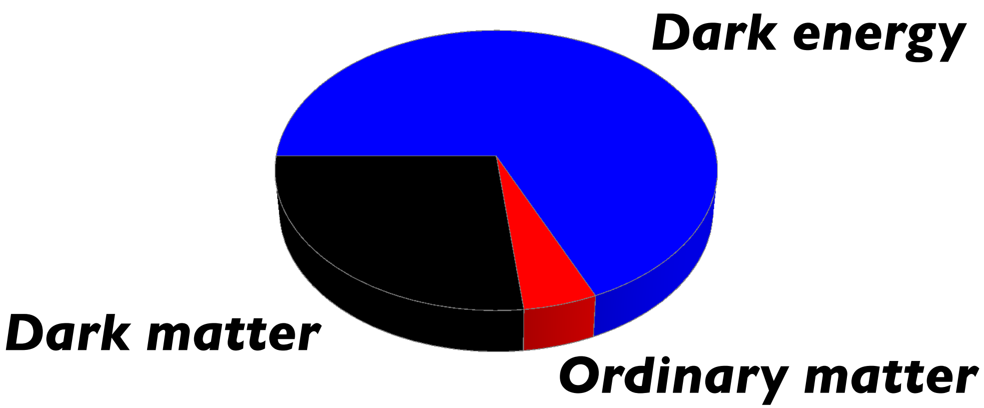
SBL accelerators



J. Kopp, P. A. N. Machado, M. Maltoni and T. Schwetz, 1303.3011 [hep-ph]

Sterile ν as Dark Matter

The Cosmic Pie:



$$\begin{aligned} \Omega_B h^2 &= 0.02205 \pm 0.00028 \\ \Omega_{DM} h^2 &= 0.1199 \pm 0.0027 \\ \Omega_\Lambda &= 0.685^{+0.018}_{-0.016} \end{aligned}$$

$$h = 0.673 \pm 0.012$$

P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO]

Sterile neutrinos could be viable DM candidates: they are produced by oscillations of active ones as long as an active-sterile mixing is present

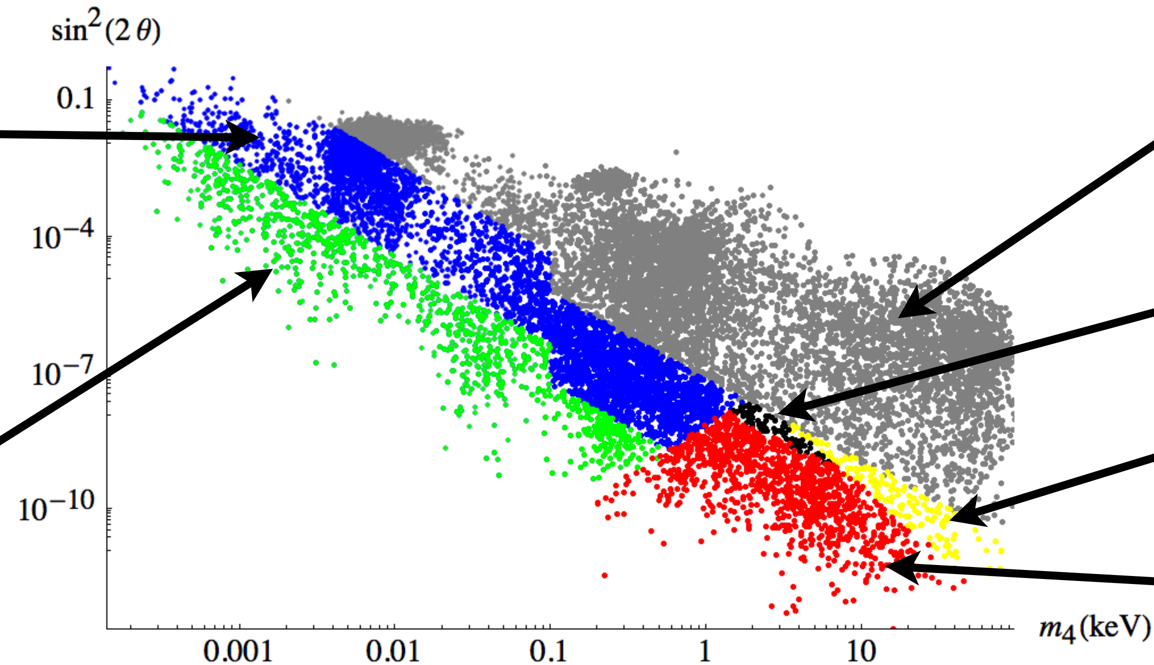
S. Dodelson and L. M. Widrow, hep-ph/9303287

WDM constraints

DW produced sterile ν are warm dark matter

Too dense phase-space

Negligible abundance (< 1%)

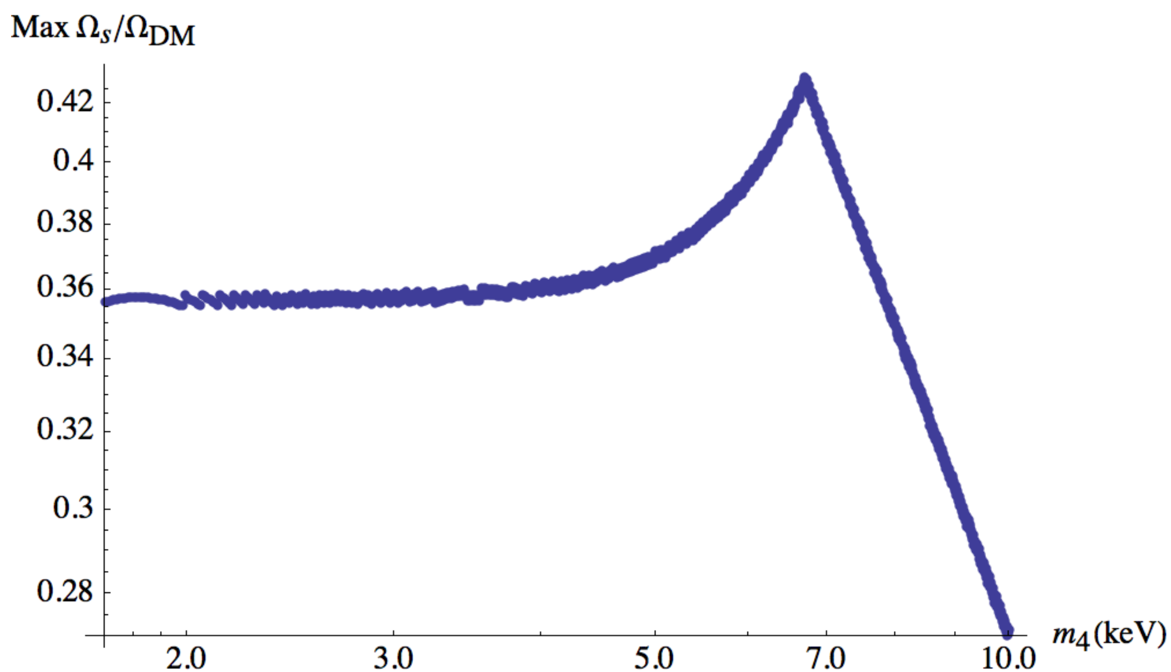


$$f_{\mathrm{WDM}} \equiv \frac{\Omega_s}{\Omega_{DM}} > 1$$

Ly-α exluded

ID excluded

Allowed region



Ly-α

and

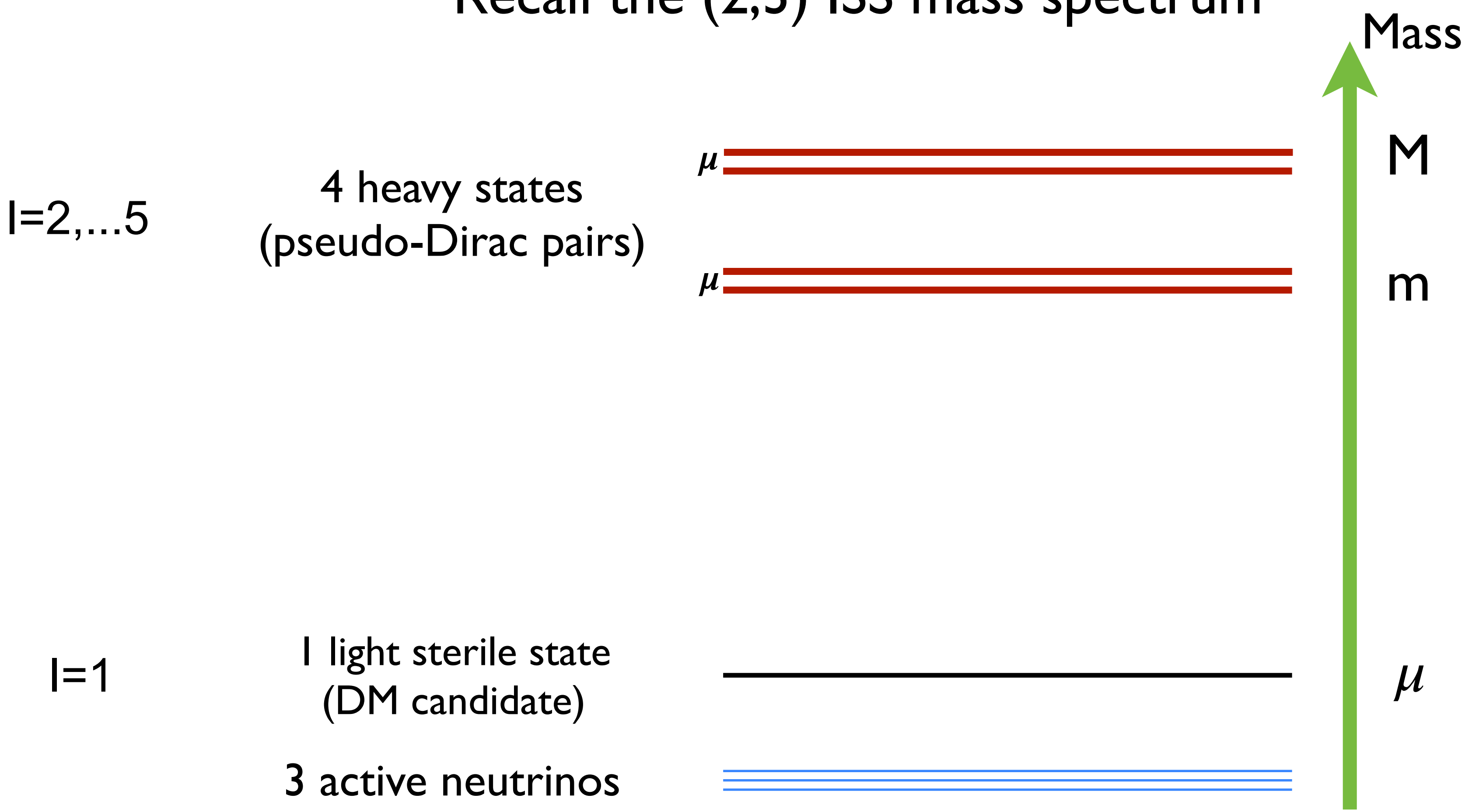
x-ray

constraints

$$\sin^2 2\theta \equiv 4 \sum_\alpha |U_{\alpha s}|^2$$

Effects of heavy sterile states

Recall the (2,3) ISS mass spectrum

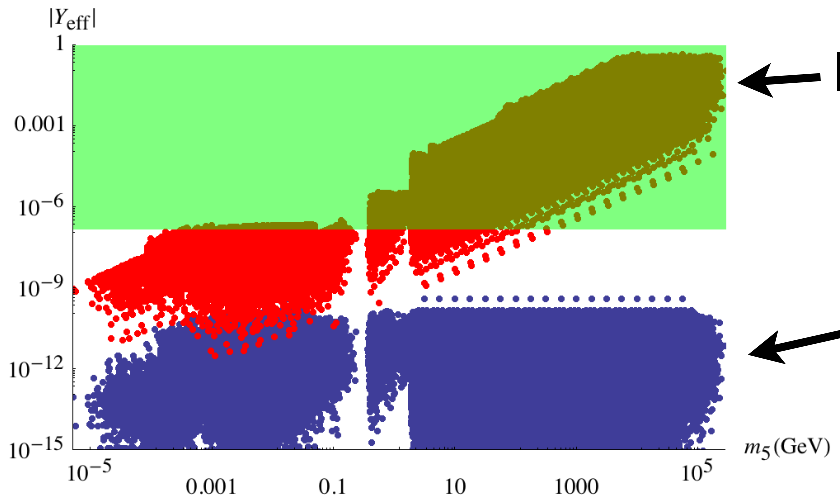


ISS can accommodate tiny ν masses with large O(1) Yukawas

Heavy states can thermalise in the early Universe

Thermalization of the heavy sterile states

- Unbroken EW phase: efficient interactions via Higgs scattering



$$Y_{\alpha\beta}\,\overline{l_L}^{\alpha}\,\widetilde{\Phi}\,\nu_R^{\beta} = Y_{\alpha\beta}\,\overline{l_L}^{\alpha}\,\widetilde{\Phi}\,U_{\beta i}\nu_i$$

$$Y^{eff}_{\alpha i} \equiv Y_{\alpha\beta}U_{\beta i}$$

Thermalization if $Y^{eff} > 10^{-7}$

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov hep-ph/9803255

- Broken EW phase: DW production

T. Asaka, M. Shaposhnikov and A. Kusenko, hep-ph/0602150

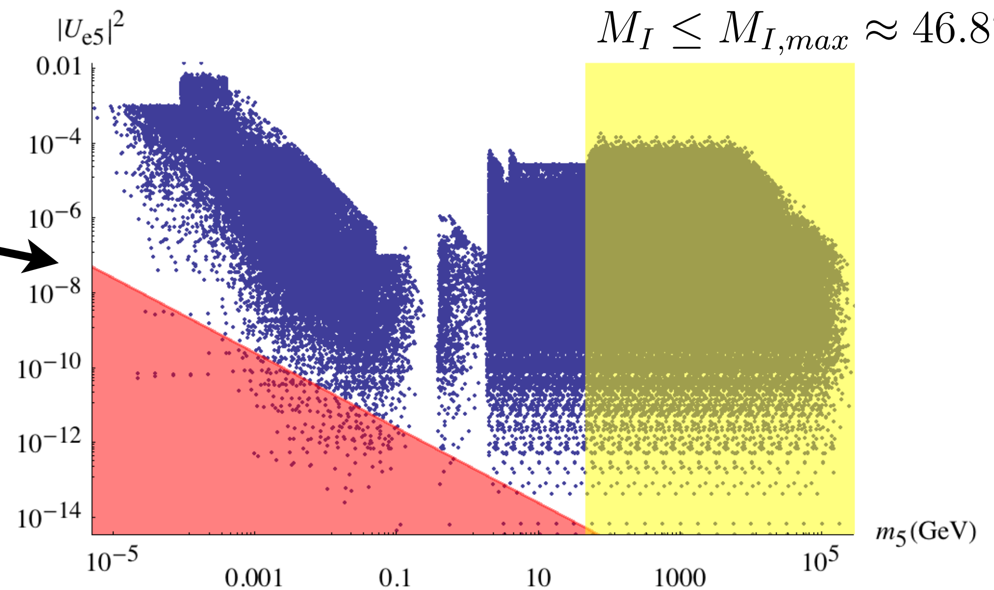
Thermalization if

$$\theta > 5\cdot 10^{-4}\left(\frac{1\ \mathrm{keV}}{M_s}\right)^{1/2}$$

Peak production at

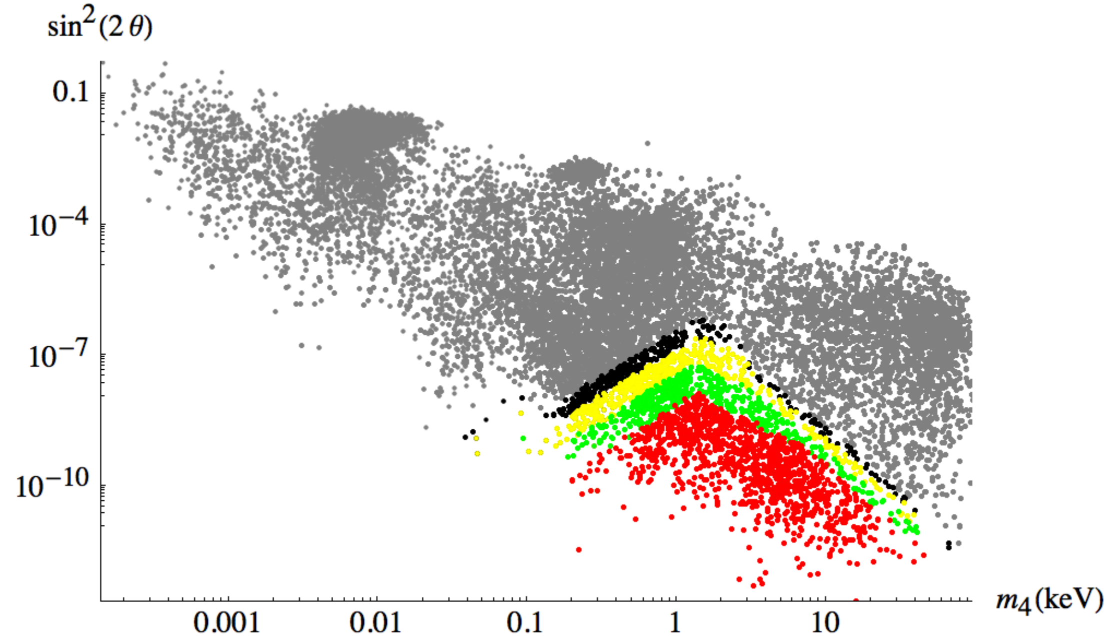
$$T_{\max} \simeq 130\left(\frac{M_I}{1\mathrm{keV}}\right)^{\frac{1}{3}}\mathrm{MeV} \geq M_I$$

$$M_I \leq M_{I,max} \approx 46.87\ \mathrm{GeV}$$

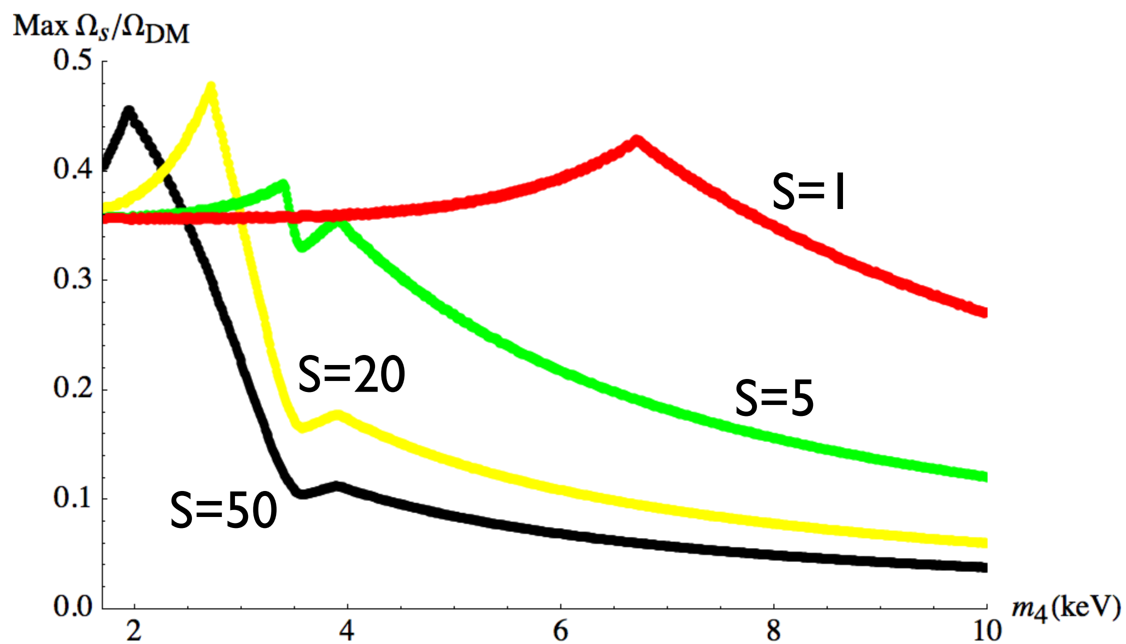


WDM summary with entropy injection

Thermalised heavy states eventually decay producing an entropy injection



The entropy injection enlarges the allowed parameter space but it is not effective to make $\Omega_s = \Omega_{DM}$ viable



Is $\Omega_s = \Omega_{DM}$ still viable?

Cosmological constraints, although relaxed by entropy injection, make impossible to produce the whole DM abundance via DW mechanism

$$\max f_{WDM} \approx 0.5$$

Are there other production mechanisms that can account for the missing DM abundance?

Dark Matter Production from heavy neutrino decays

Freeze-in: decay of a thermalised species into one which is out of equilibrium

L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, arXiv:0911.1120 [hep-ph]

Heavy thermalised states (I=2,...,5)	→	Light sterile neutrino (I=1)

Effective if $Y_{eff} > 10^{-7}$ and $Y_{eff}\, \sin\theta < 10^{-7}$ and $m_h < M_I < 1$ TeV

$$\Omega_{\rm DM} h^2 \simeq \frac{1.07\times 10^{27}}{g_*^{3/2}} \sum_I g_I \frac{m_{\rm DM}\Gamma\left(N_I \to {\rm DM} + {\rm anything}\right)}{m_I^2}$$

$$\Gamma\left(N_I \to h + DM\right) = \frac{m_I}{16\pi} Y_{\rm eff,I}^2 \sin^2\theta \left(1 - \frac{m_h^2}{m_I^2}\right)$$

$$\boxed{\Omega h^2 \approx 2.16\times 10^{-1} \left(\frac{\sin\theta}{10^{-6}}\right)^2 \left(\frac{m_{\rm DM}}{1~{\rm keV}}\right) \sum_I g_I \left(\frac{Y_{\rm eff,I}}{0.1}\right)^2 \left(\frac{m_I}{1{\rm TeV}}\right)^{-1} \left(1 - \frac{m_h^2}{m_I^2}\right) \chi\left(m_I\right)}$$

$\Omega h^2 \simeq 0.12$ compatible with ID bounds

The spectrum of the produced DM is "colder" than the DW one, evading the Ly-α bounds

Example: explaining the XMM 3.56 keV line

E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S. W. Randall, arXiv:1402.2301 [astro-ph.CO]

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, arXiv:1402.4119 [astro-ph.CO]

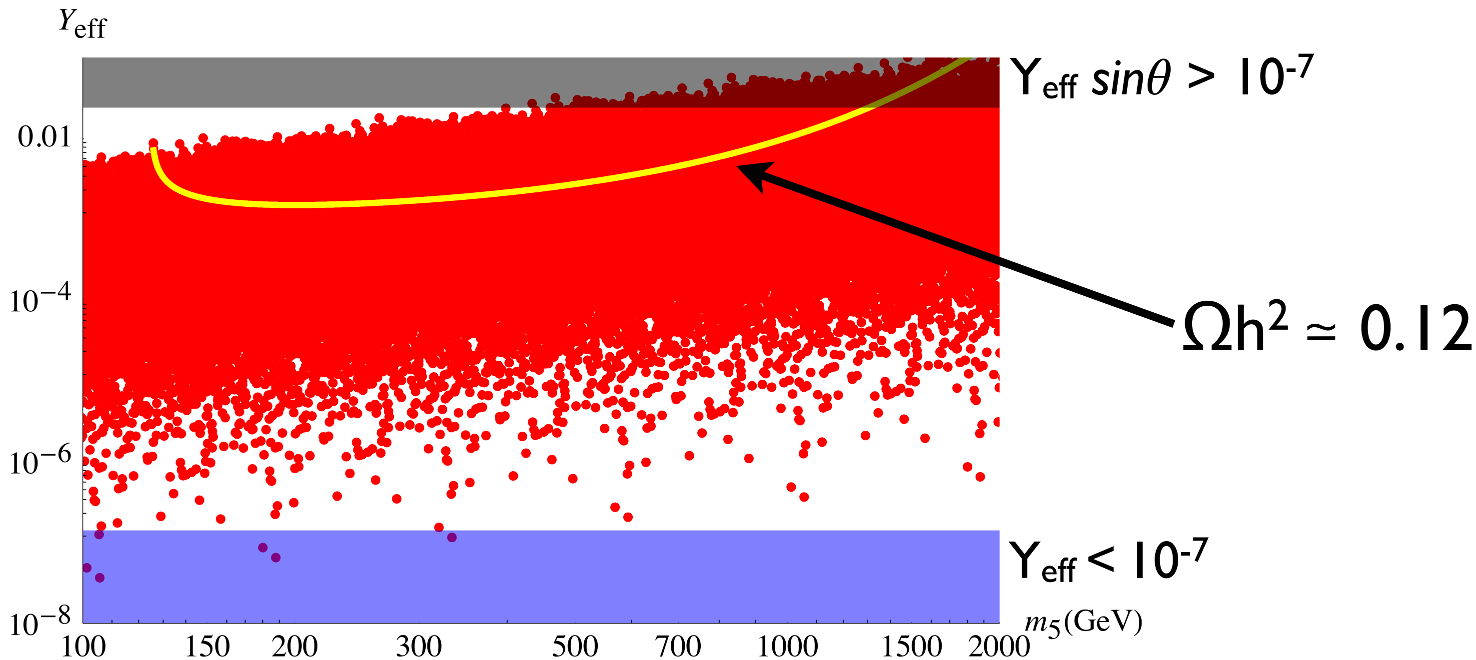
Interpreting the recently discovered unidentified line in x-ray spectra of galaxy clusters as a sterile ν decay would require

$$m_s \simeq 7.1\ \mathrm{keV} \qquad \sin^2 2\theta \approx 7\cdot 10^{-11}$$

giving f_{WDM} from DW ≃ 0.037 and an abundance from decay

$$\Omega h^2 \approx 2.68\times 10^{-1}\sum_I g_I\left(\frac{Y_{\mathrm{eff,I}}}{0.01}\right)^2\left(\frac{m_I}{1\mathrm{TeV}}\right)^{-1}\left(1-\frac{m_h^2}{m_I^2}\right)\chi\left(m_I\right)$$

(assuming for simplicity same masses and Y_{eff} for the 4 heavy states)



Conclusions

The Inverse Seesaw is a viable mechanism to generate tiny ν masses with sizable Yukawas and low seesaw scale

In a generic realisation (#s - #ν_R) light sterile states are present

The (2,3) ISS can provide an explanation for ν anomalies or a viable DM candidate

Due to the large Yukawas heavy states can thermalise in the early Universe, relaxing cosmological bounds or producing the correct DM abundance

The model can generate pure CDM as well as C+WDM (max $f_{WDM} \approx 0.4$)

Backup

Constraints: abundance

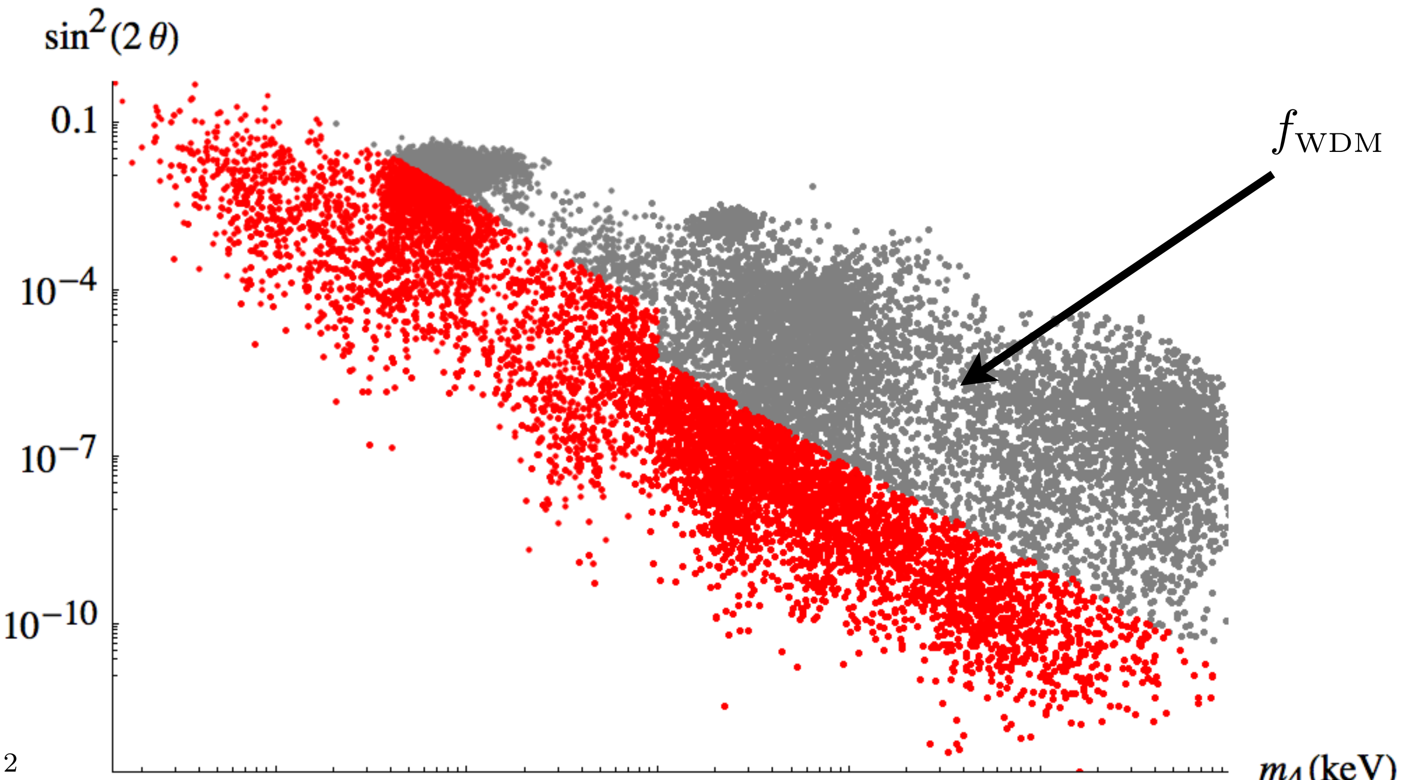
DW: as long as an active-sterile mixing is present, a population of sterile ν is produced by oscillations in the primordial plasma

S. Dodelson and L. M. Widrow, hep-ph/9303287

Recent evaluation gives

$$\Omega_s h^2 = 1.1 \cdot 10^7 \sum_\alpha C_\alpha(m_s)\,|U_{\alpha s}|^2 \left(\frac{m_s}{\mathrm{keV}}\right)^2, \quad \alpha = e, \mu, \tau$$

T. Asaka, M. Laine and M. Shaposhnikov, hep-ph/0612182



$\sin^2 2\theta \equiv 4 \sum_\alpha |U_{\alpha s}|^2$

(K. Abazajian, G. M. Fuller and M. Patel, 023501 [astro- ph/0101524] for m < 0.1 keV)

Constraints: phase-space density

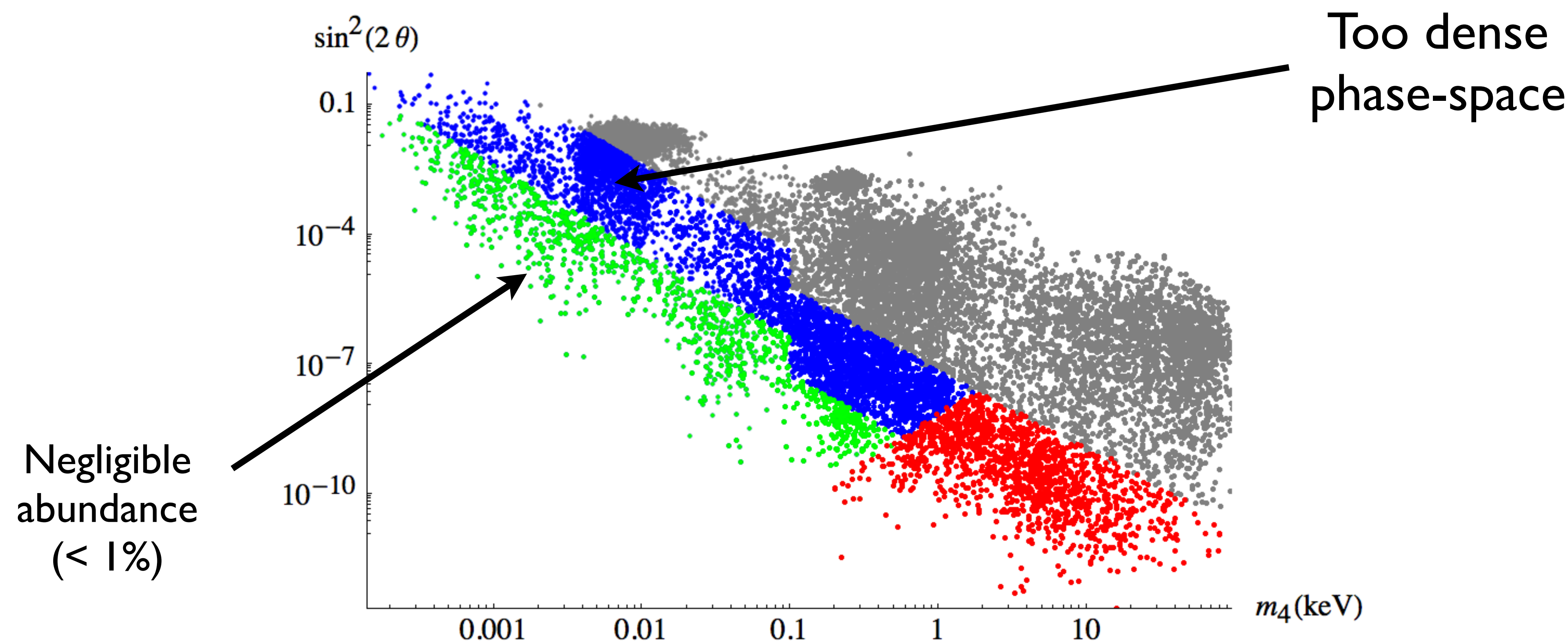
For fermionic DM, Pauli exclusion principle impose a maximum on its distribution function (degenerate Fermi gas). Imposing that inferred phase-space density does not excess this bound, it is possible to extract a lower bound on the DM mass

S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42 (1979) 407

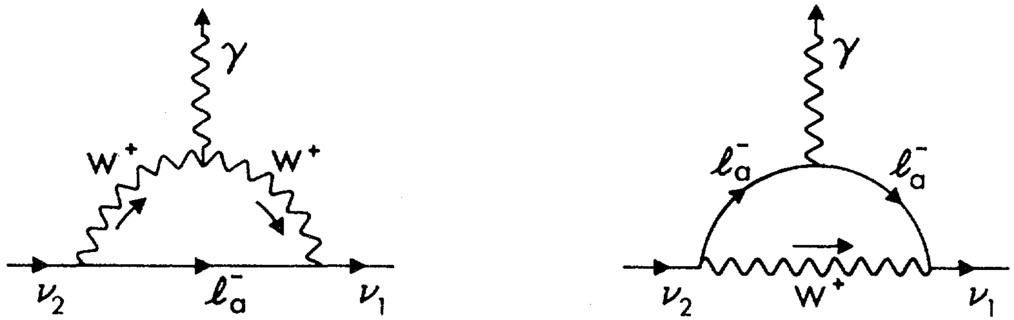
$$f_{max,\mathrm{NRP}} = \frac{94\ \omega_{\mathrm{DM}}}{2\,(2\pi\hbar)^3}\frac{m^3_{\mathrm{NRP}}}{\mathrm{eV}^3} \Rightarrow m_{\mathrm{NRP}} > 1.77\ \mathrm{keV}$$

from dSphs observations

A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, 0808.3902 [hep-ph]



Constraints: stability and indirect detection (ID)

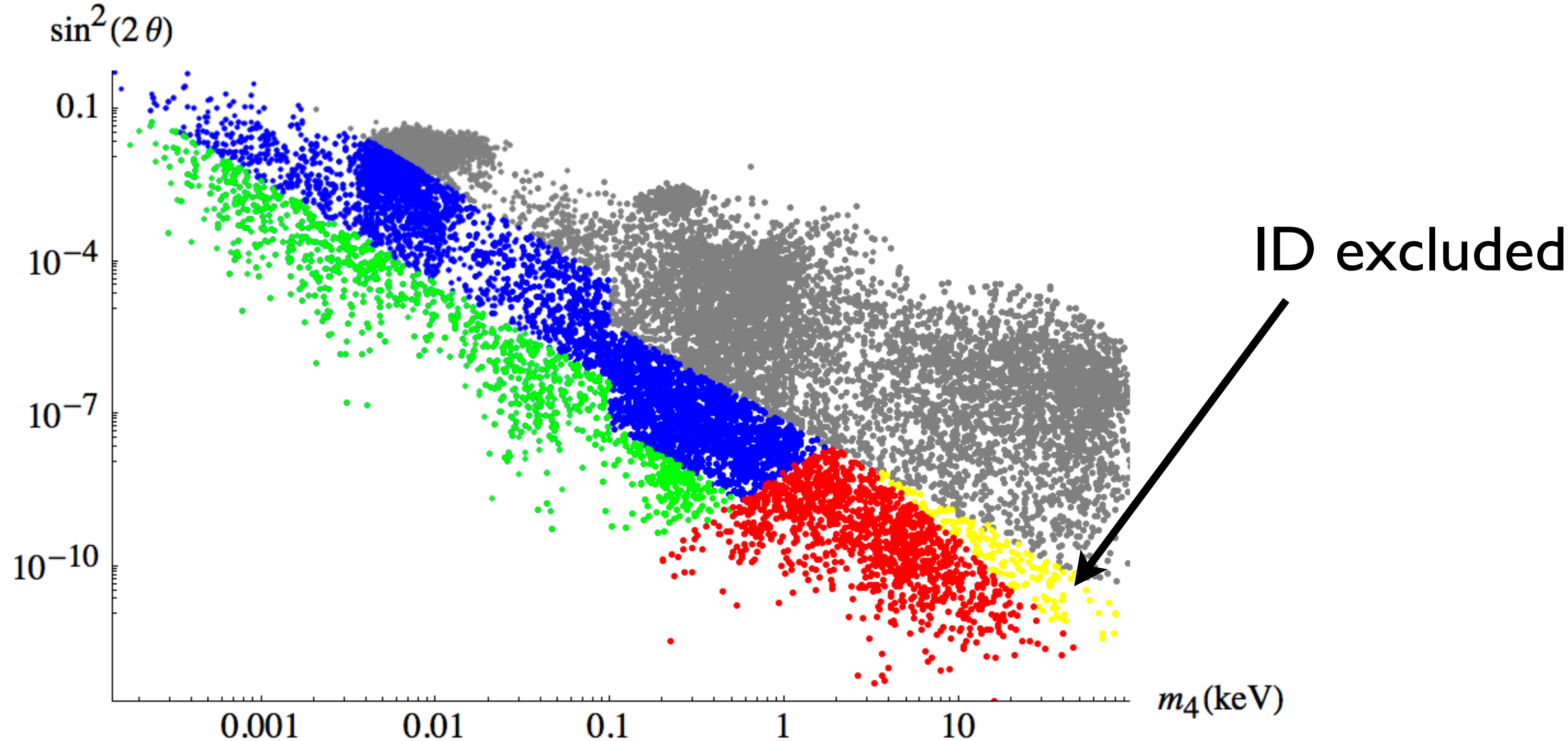


P. B. Pal and L. Wolfenstein, Phys. Rev. D 25 (1982) 766

Massive ν can decay radiatively producing monochromatic γ

Due to the lack of signature (e.g. CHANDRA, XMN)

$$f_{\rm WDM} \sin^2 2\theta \lesssim 1.5 \times 10^{-4} \left(\frac{m_s}{1\text{keV}}\right)^{-5}$$



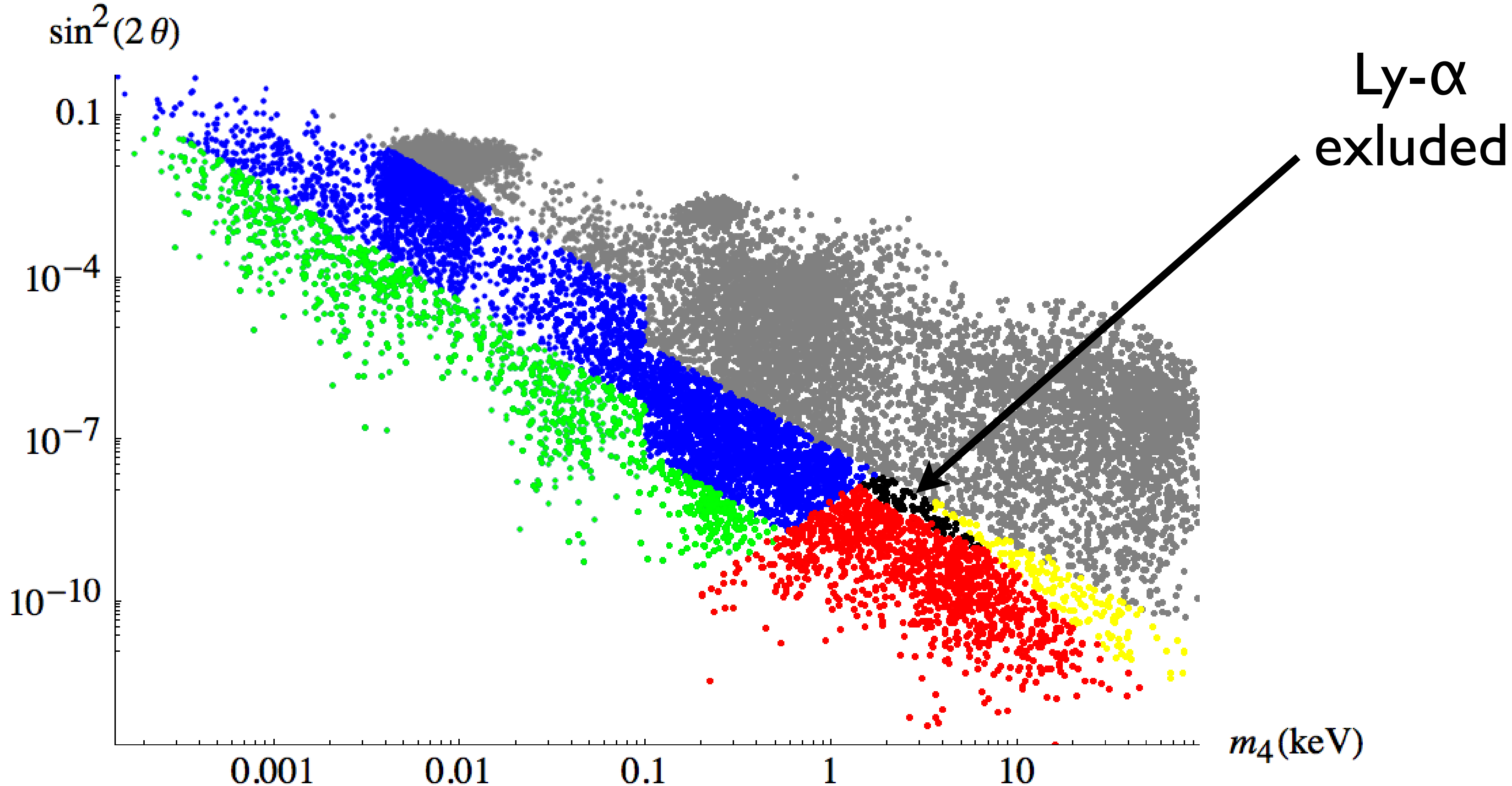
Constraints: Lyman-α

The absorption in the spectra of QSOs by the H (Ly-α: 1s → 2p) in IGM can trace matter distribution at scales: 1-80 h^{-1} Mpc

Narayanan, Vijay K.; Spergel, David N.; Davé, Romeel; Ma, Chung-Pei, Astrophys. J. 543, 103 (2000)

Ly-α constraints highly model dependent → limits for DW produced sterile ***ν***

A. Boyarsky, J. Lesgourgues, O. Ruchayskiy and M. Viel, 0812.0010 [astro-ph]



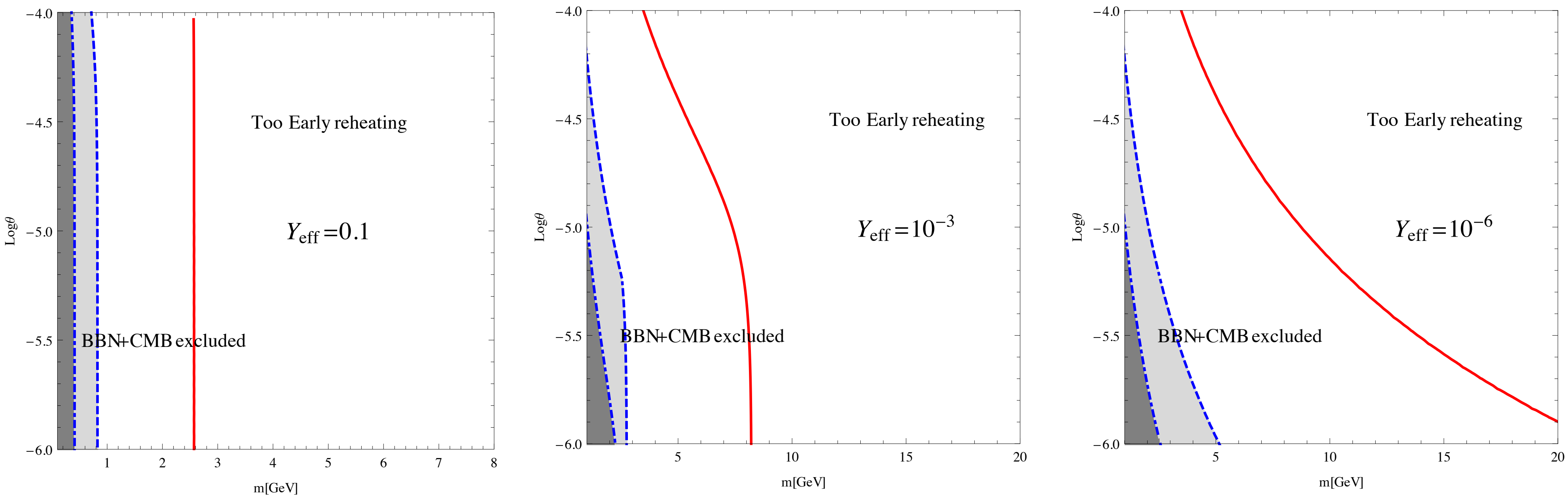
Entropy injection

If the heavy states thermalise they dominate the energy density of the Universe from $\overline{T}$ until their decay at $(T_{r,M}, T_{r,m})$

$$\overline{T} \approx 6.4\,\mathrm{MeV}\left(\frac{m_2}{1\mathrm{GeV}}\right)\left(\frac{\sum_I m_I Y_I}{m_2 Y_2}\right)$$

If they decay *after* the WDM production (≈150 MeV) its abundance is reduced and its momentum distribution is redshifted

$$\Gamma_Z = \frac{G_F^2 m_I^5 \theta_I^2}{192\pi^3} \qquad \Gamma_h = \frac{Y_{\rm eff}^2 m_I^5}{128(2\pi)^3 m_h^4}\sum_f y_f^2\left(1-\frac{4m_f^2}{m_I}\right)$$



Examples with different $Y_{\rm eff}$ values $\qquad Y_{\alpha i}^{eff} \equiv Y_{\alpha\beta}U_{\beta i}$

Entropy dilution

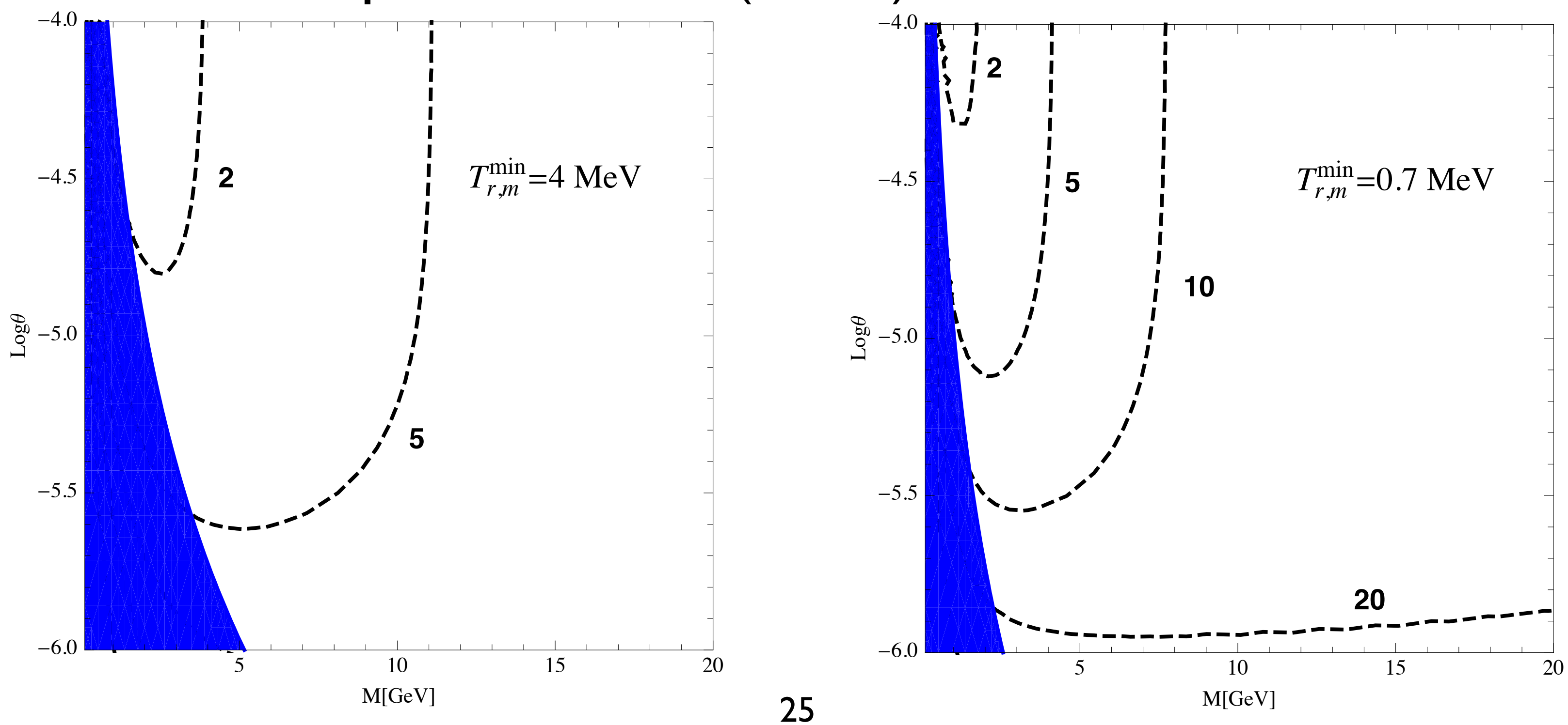
Consider the two pseudo-Dirac pairs with masses M > m ($\mu \simeq 0$)

$$S_M = \left[1 + 2.95\left(\frac{2\pi^2}{45} g_*(T_{r,M})\right)^{1/3} \left(\frac{\sum_\alpha m_\alpha Y_\alpha}{M\ Y_M}\right)^{1/3} \frac{(M\ Y_M)^{4/3}}{(\Gamma M_{\rm PL})^{2/3}}\right]^{3/4}$$

$$S_{\rm m} = \left[1 + 2.95\left(\frac{2\pi^2}{45} g_*(T_{r,m})\right)^{1/3} 2^{1/3} \frac{\left(\frac{m\ Y}{S_{\rm M}}\right)^{4/3}}{(\Gamma M_{\rm PL})^{2/3}}\right]^{3/4}$$

$$S = S_m \times S_M$$

Examples of S with (m, θ_m) chosen to fix $T_{r,m}$

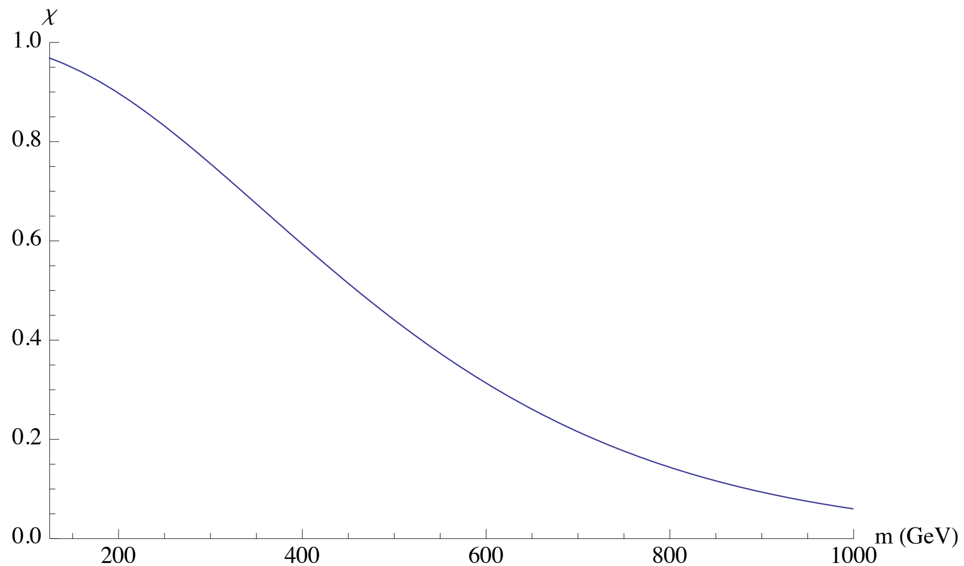


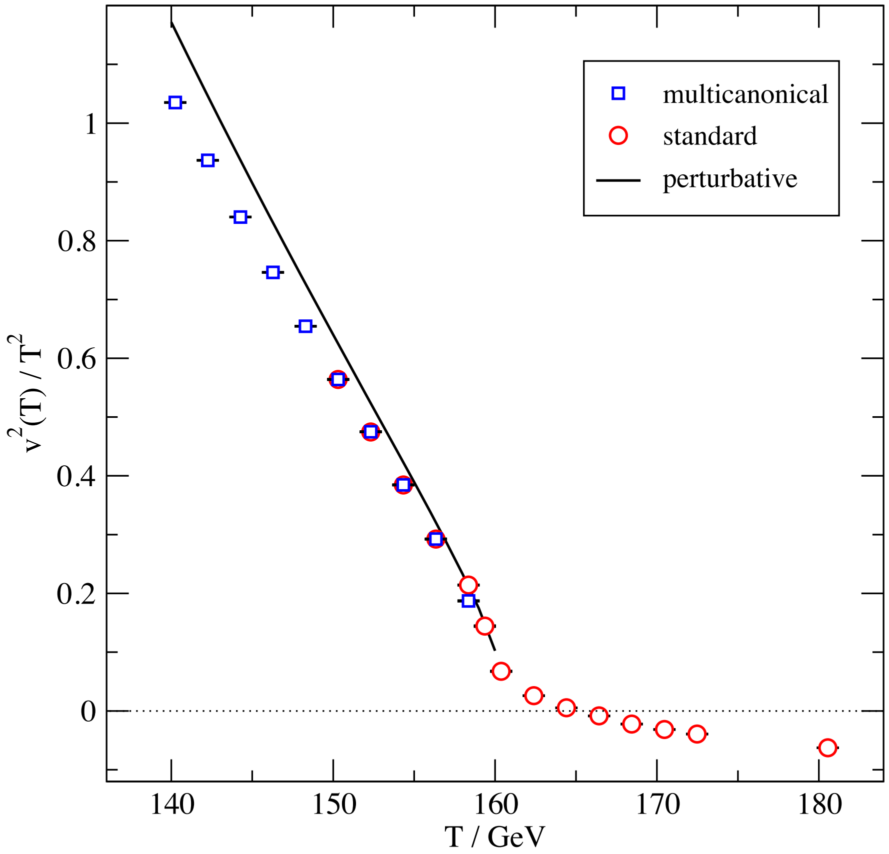
Mixing temperature dependance

The leptonic mixing matrix is temperature-dependent

$$\mathcal{M} = \begin{pmatrix} 0 & d & 0 \\ d & m & n \\ 0 & n & \mu \end{pmatrix} \qquad d_{\alpha\beta} = \frac{v(T)}{\sqrt{2}} Y^*_{\alpha\beta}$$

In the limit v = 0 neutrinos are massless and do not mix





M. D'Onofrio, K. Rummukainen and A. Tranberg
arXiv:1404.3565 [hep-ph]

Toy model

One generation for each kind of field

0th order

$$m_0^{2\,(0)} = 0, \qquad m_{1,2}^{2\,(0)} = |d|^2 + |n|^2,$$

$$\mathbf{x}_0^{(0)} = \begin{pmatrix} -\frac{nd^*}{|d|\sqrt{|d|^2+|n|^2}} \\ 0 \\ \frac{|d|}{\sqrt{|d|^2+|n|^2}} \end{pmatrix}, \quad \mathbf{x}_1^{(0)} = \begin{pmatrix} -\frac{d^*\left(m|d|^2+m|n|^2+n^2\mu^*\right)}{\sqrt{2}\sqrt{|d|^2+|n|^2}\left|n^{*2}\mu+m|d|^2+m|n|^2\right|} \\ \frac{1}{\sqrt{2}} \\ -\frac{n^*\left(m|d|^2+m|n|^2+n^2\mu^*\right)}{\sqrt{2}\sqrt{|d|^2+|n|^2}\left|n^{*2}\mu+m|d|^2+m|n|^2\right|} \end{pmatrix}, \quad \mathbf{x}_2^{(0)} = \begin{pmatrix} \frac{d^*\left(m|d|^2+m|n|^2+n^2\mu^*\right)}{\sqrt{2}\sqrt{|d|^2+|n|^2}\left|n^{*2}\mu+m|d|^2+m|n|^2\right|} \\ \frac{1}{\sqrt{2}} \\ \frac{n^*\left(m|d|^2+m|n|^2+n^2\mu^*\right)}{\sqrt{2}\sqrt{|d|^2+|n|^2}\left|n^{*2}\mu+m|d|^2+m|n|^2\right|} \end{pmatrix}.$$

1st order

$$m_0^{2\,(1)} = 0, \qquad m_1^{2\,(1)} = -\frac{\left|\mu^* n^2+m|d|^2+m|n|^2\right|}{\sqrt{|d|^2+|n|^2}}, \qquad m_2^{2\,(1)} = \frac{\left|\mu^* n^2+m|d|^2+m|n|^2\right|}{\sqrt{|d|^2+|n|^2}},$$

2nd order

$$m_0^{2\,(2)} = \frac{|d|^4|\mu|^2}{\left(|d|^2+|n|^2\right)^2} = \frac{k^4|\mu|^2}{\left(1+k^2\right)^2} \qquad k = \frac{|d|}{|n|}$$

$m_\nu = f(\mu, k)$

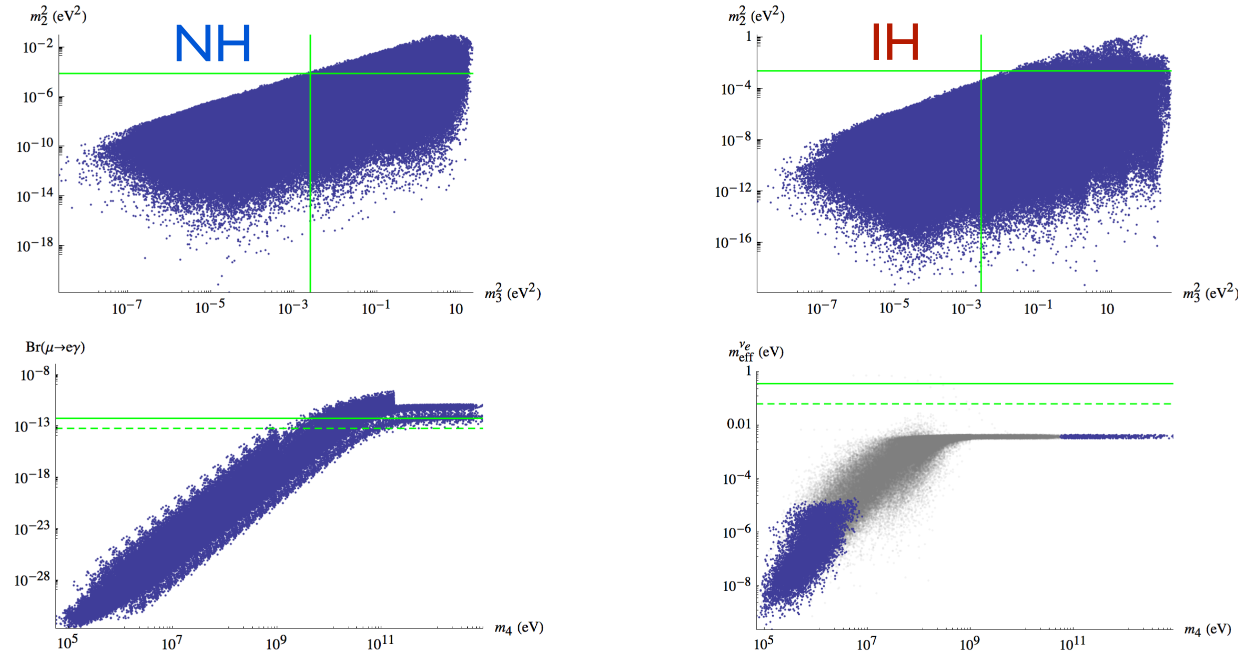
PMNS non-unitarity $\propto k$

Low-energy neutrino parameters only function of μ and k

Minimal ISS realisations

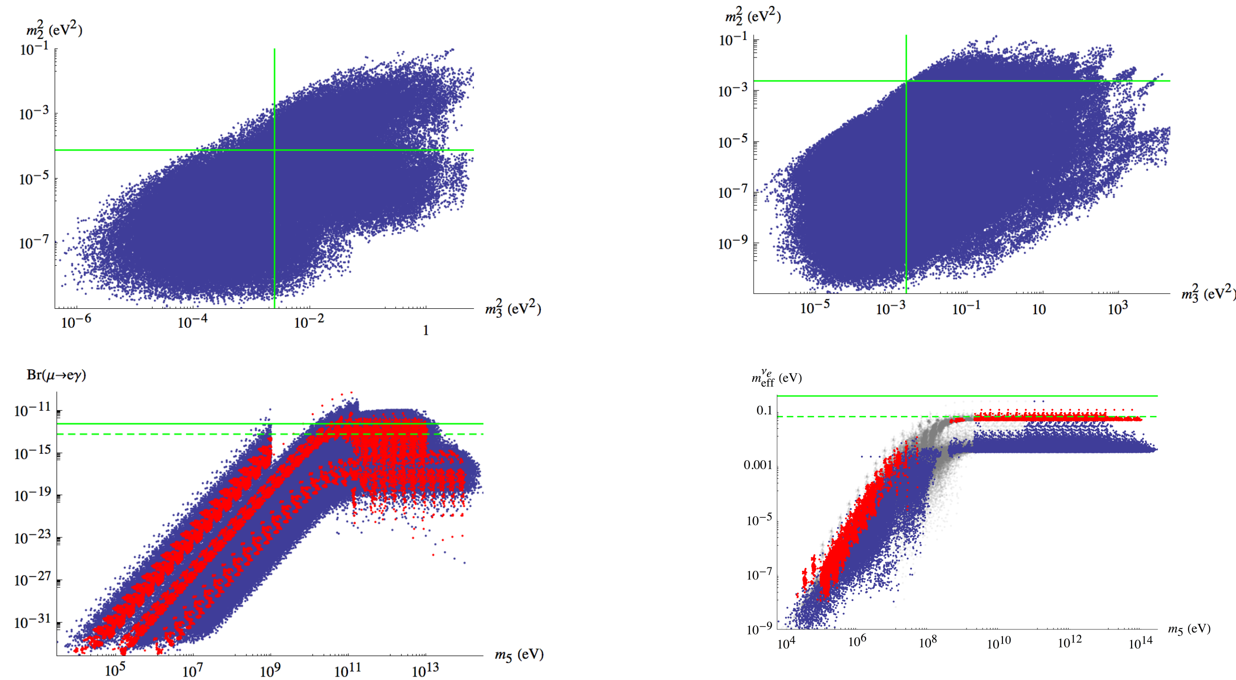
(2,2) ISS

- fine tuned;
- only Normal Hierarchy;
- 3 flavour mixing;

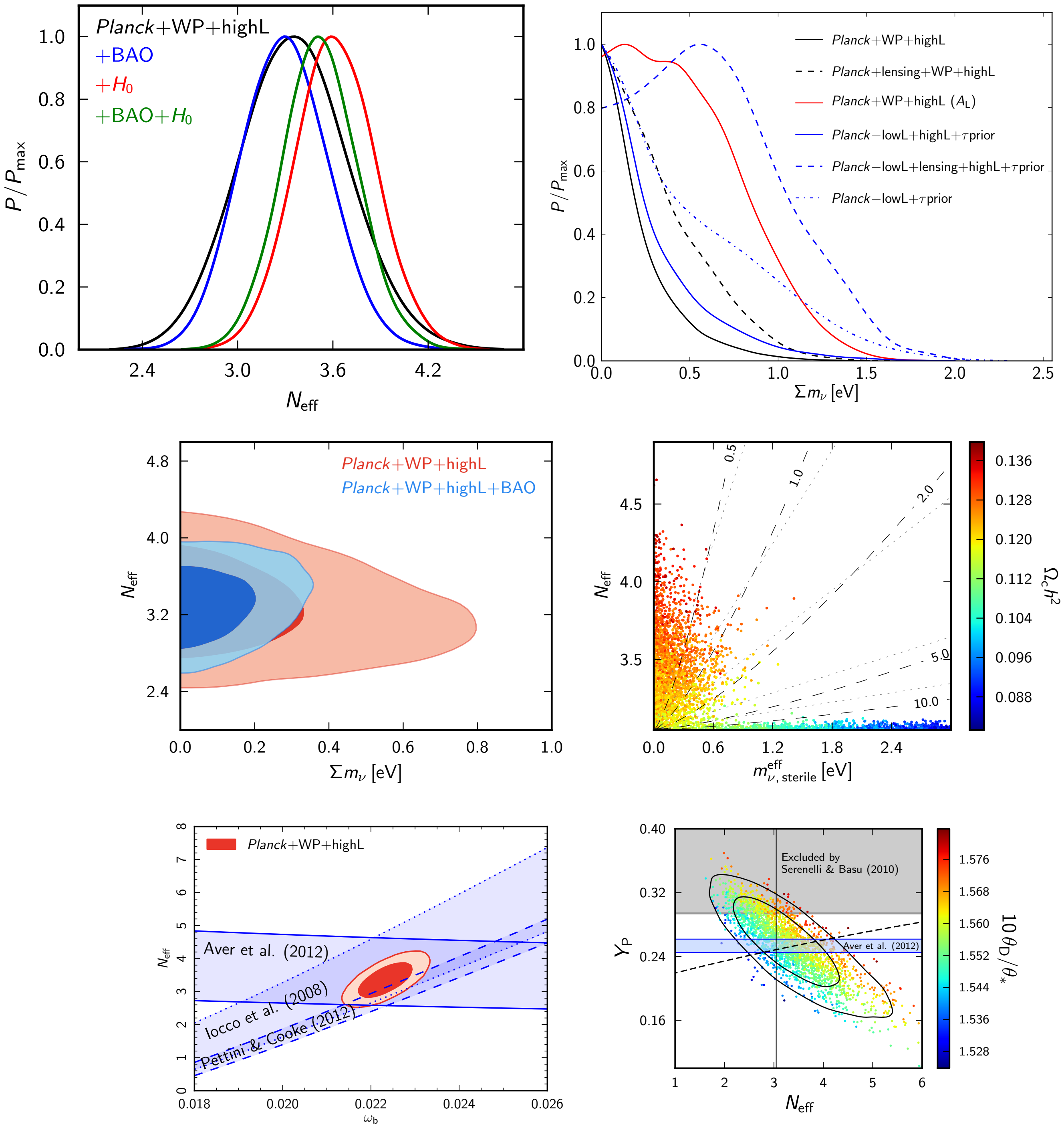


(2,3) ISS

- both Normal and Inverted Hierarchies;
- light sterile state (neutrino anomalies or WDM);
- $0\nu\beta\beta$ previsions in the sensibility of ongoing experiments;



Sterile ν in CMB



P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO]