LEPTON NUMBER SYMMETRY AT THE ORIGIN OF NEUTRINO MASSES, LEPTOGENESIS AND DARK MATTER?

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CosPA 2017 (December 12th 2017, YITP Kyoto)

Based on work in collaboration with A. Abada, G. Arcadi and V. Domcke:
arXiv:1709.00415, 1507.06215, 1406.6556, 1401.1507

Observational problems of the SM

At least 3 observations cannot be accounted for in the SM

Neutrinos are massive and mix

$$|U| = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, arXiv:1409.5439 [hep-ph]

The Universe has a dark matter component

$$\begin{aligned} \Omega_m h^2 &= 0.1426 \pm 0.0020 \\ \Omega_b h^2 &= 0.02226 \pm 0.00023 \\ \Omega_c h^2 &= 0.1186 \pm 0.0020 \end{aligned}$$

P.A.R. Ade *et al.* [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO]

The Universe has a negligible amount of antimatter

$$\eta_{\Delta B} = (6.10 \pm 0.04) \times 10^{-10}$$

Neutrino masses within the SM

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 $\Rightarrow$ $\cancel{M \overline{\nu^c_L} \nu_L}$ No Majorana mass term
- Renormalizability $\Rightarrow$ $\cancel{\left(\overline{l^c_L} \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger l_L\right)}$ No dim > 4 operators

$m_\nu \neq 0$ requires physics BSM

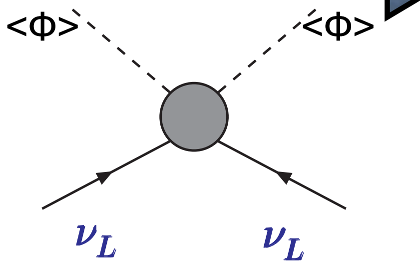
B - L conservation: accidental SM symmetry

SM as an effective theory

Relaxing the renormalizability condition there is only one dim=5 gauge invariant operator (Weinberg operator) S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566

ΔL = 2

$$\frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{l^c_{L\alpha}}\,\widetilde{\Phi}^*\right)\left(\widetilde{\Phi}^\dagger l^\beta_L\right)+h.c. \xrightarrow{\text{EWSB}} \frac{v^2}{2}\frac{c_{\alpha\beta}}{\Lambda}\overline{\nu^c_{L\alpha}}\,\nu_{L\beta}+h.c.$$



New physics scale

$$c_{\alpha\beta}\,\frac{v}{\Lambda}\,v \lesssim \text{eV} \ll v$$

Why are neutrinos so light?

Suppression mechanisms

$$\left\{\begin{array}{ll} \dfrac{v}{\Lambda} \ll 1 & \text{High NP scale} \\[2ex] c_{\alpha\beta} \ll 1 & \text{Symmetry (Lepton number)} \end{array}\right.$$

Unveiling neutrino mass generation mechanism

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \boxed{\frac{c_5}{\Lambda}\mathcal{O}^{d=5}} + \boxed{\frac{c_6^i}{\Lambda^2}\mathcal{O}_i^{d=6} + \ldots}$$

ν masses and mixing
common to all SM extensions
with Majorana ν

New physics effects

If only Λ at work $\frac{c_6^i}{\Lambda^2} \approx \left(\frac{c_5}{\Lambda}\right)^2 \simeq \left(\frac{m_\nu}{v^2}\right)^2$

New physics effects
strongly suppressed
by the ν mass scale

If symmetry at work $c_5 \ll 1$ and $c_6^i \approx \mathcal{O}(1)$ possible for some i

Hypothesis

Lepton number as an approximate symmetry

No violation of L observed so far

$$\Delta L\left(\mathcal{O}^{d=5}\right) = 2$$

Example: 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, ν_R
- fermionic sterile singlets, s

In the basis $n_L \equiv (\nu_L, \nu_R^C, s)^T$ the ISS neutrino mass terms read:

+1 -1 +1

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

t'Hooft naturalness criterium: terms violating L are "small", i.e.
$|\mu| << |n|, |d|$

Neutrino masses in the limit $|\mu| << |d| << |n|$:

$$m_\nu \simeq d \left(n^{-1}\right)^{\mathrm{T}} \mu \left(n^{-1}\right) d^{\mathrm{T}}$$

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 (ν anomalies or DM candidates)

ISS mass scales

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

E.g.

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

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

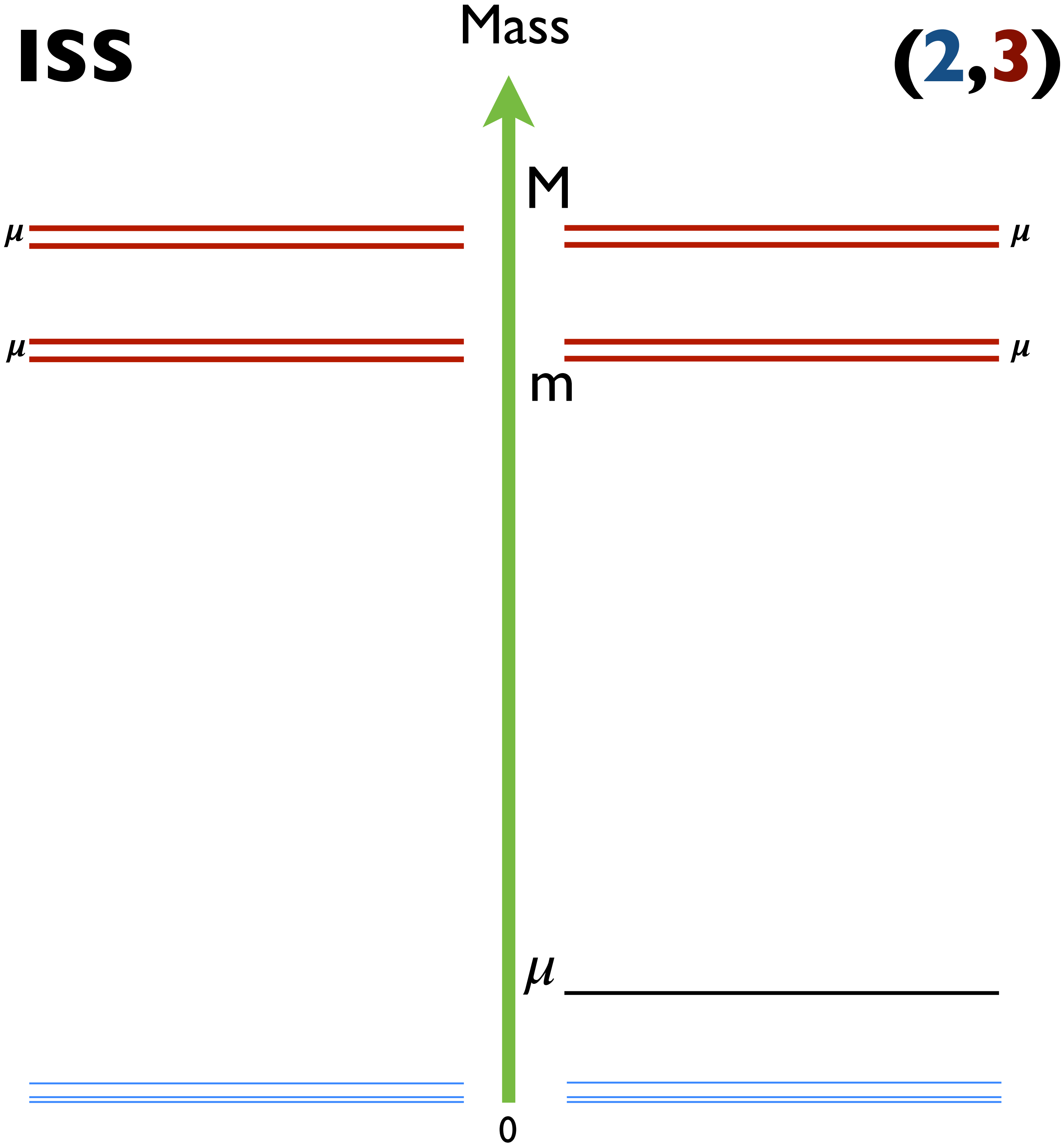
$\#\nu_L$ active neutrinos $\sim \mathcal{O}(\mu)\mathcal{O}(k)$ meV

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

Minimal ISS spectra

(2,2) ISS

(2,3) ISS



4 heavy states
(pseudo-Dirac pairs)

3 active neutrinos

4 heavy states
(pseudo-Dirac pairs)

1 light sterile state

3 active neutrinos

L-symmetry and SM observational problems

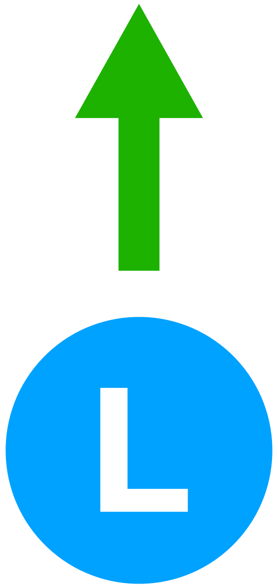
$m_\nu \ll$ EW scale with sizeable couplings and low NP scale

Testable models

Neutrino masses and mixing

pseudo-Dirac neutrino pairs $\Delta M \ll M$

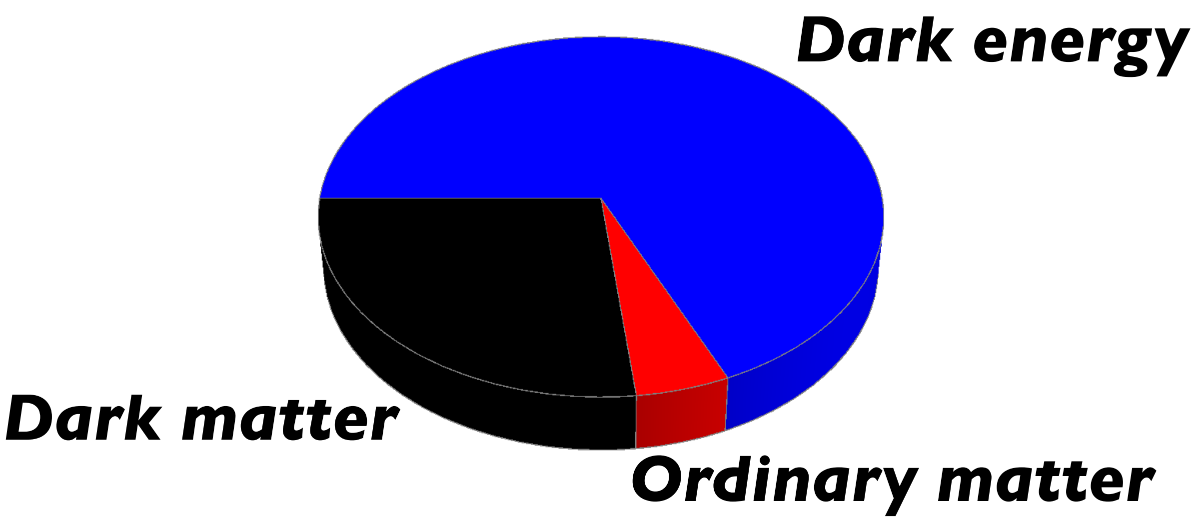
Connection with BAU



Dark matter

Baryon asymmetry of the Universe

Sterile ν as Dark Matter



$$\Omega_B h^2 = 0.02205 \pm 0.00028$$

$$\Omega_{DM} h^2 = 0.1199 \pm 0.0027 \qquad h = 0.673 \pm 0.012$$

$$\Omega_\Lambda = 0.685^{+0.018}_{-0.016}$$

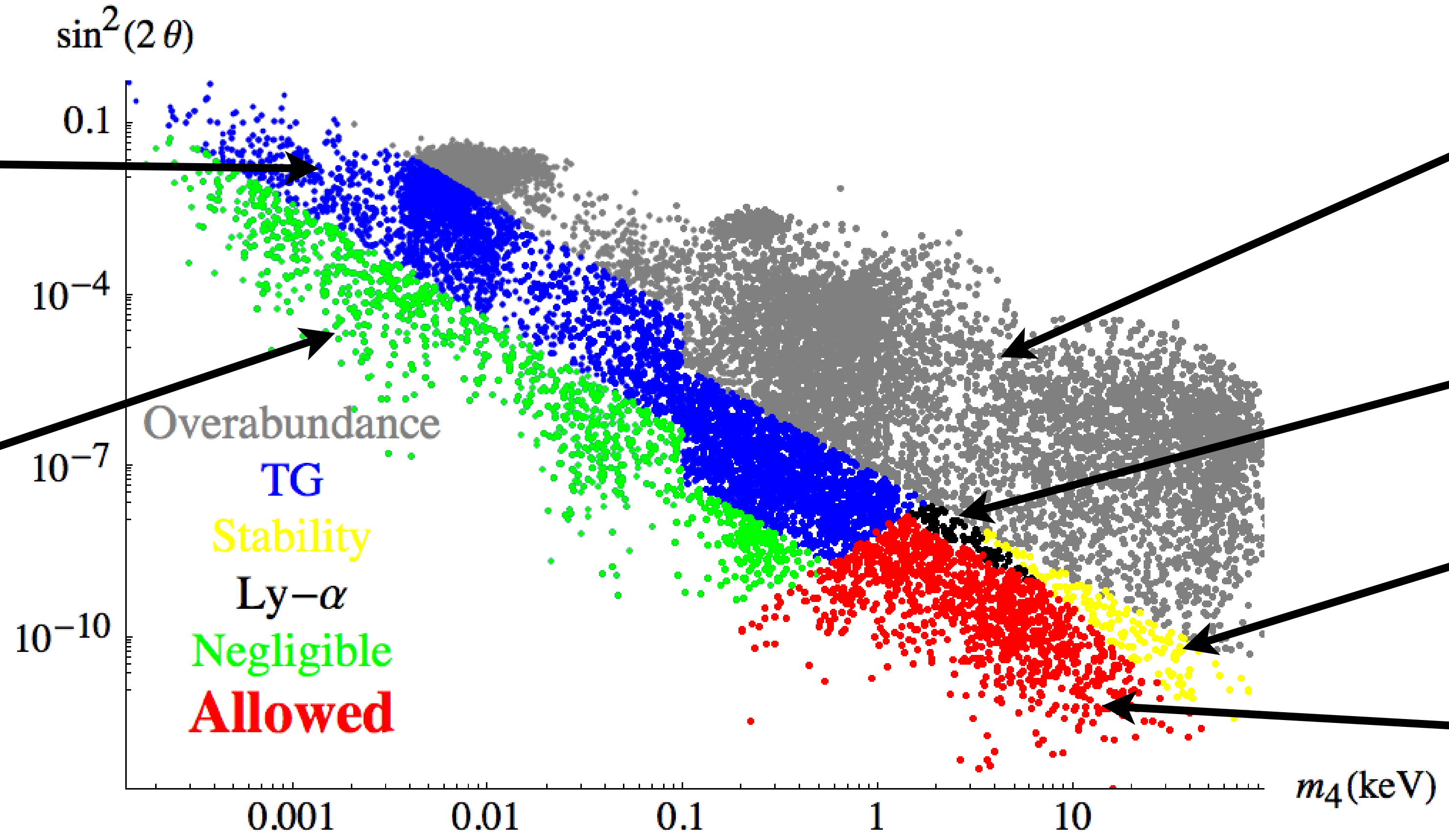
P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO]

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

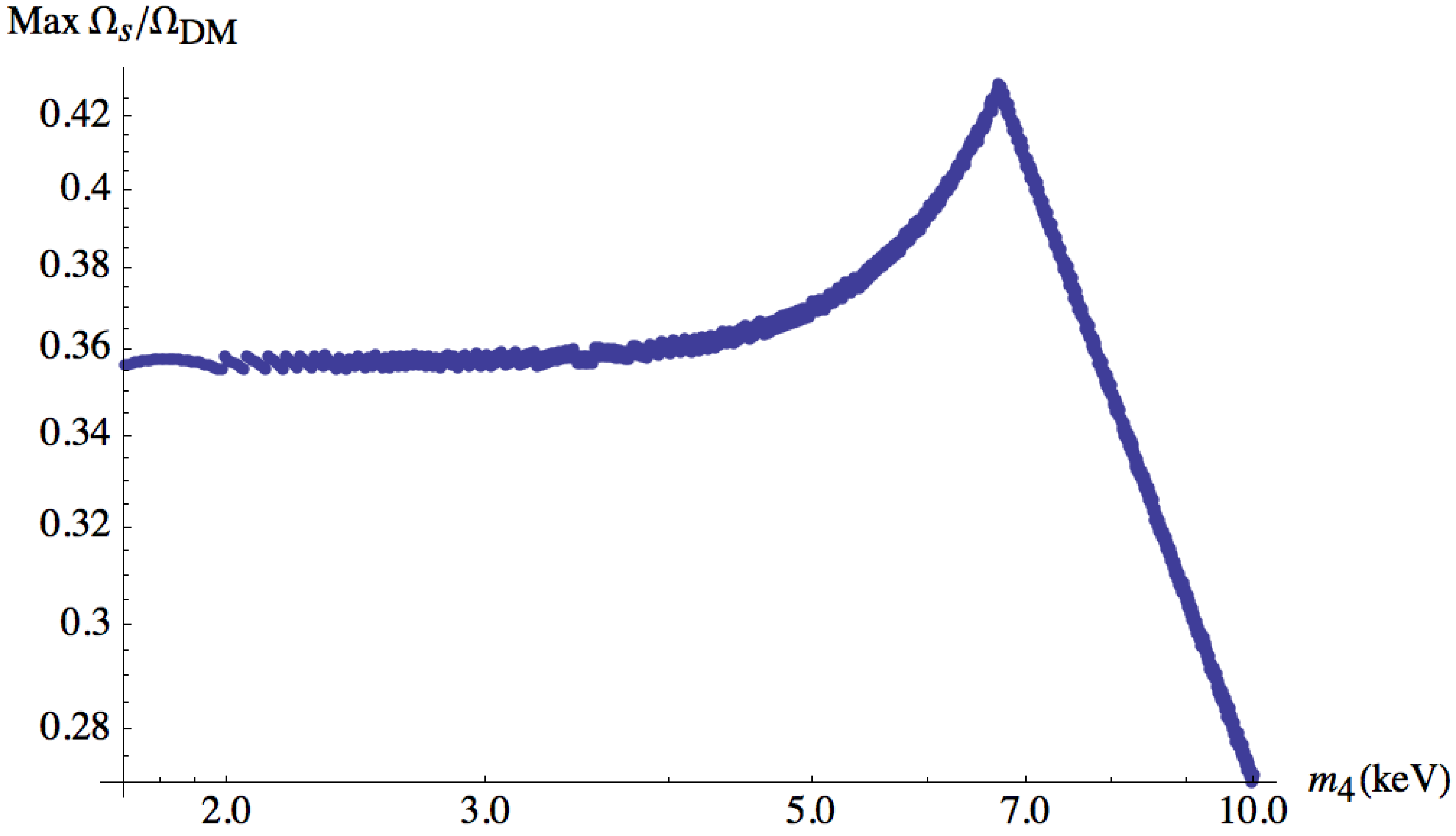
Negligible abundance (< 1%)

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

Ly-α exluded

ID excluded

Allowed region

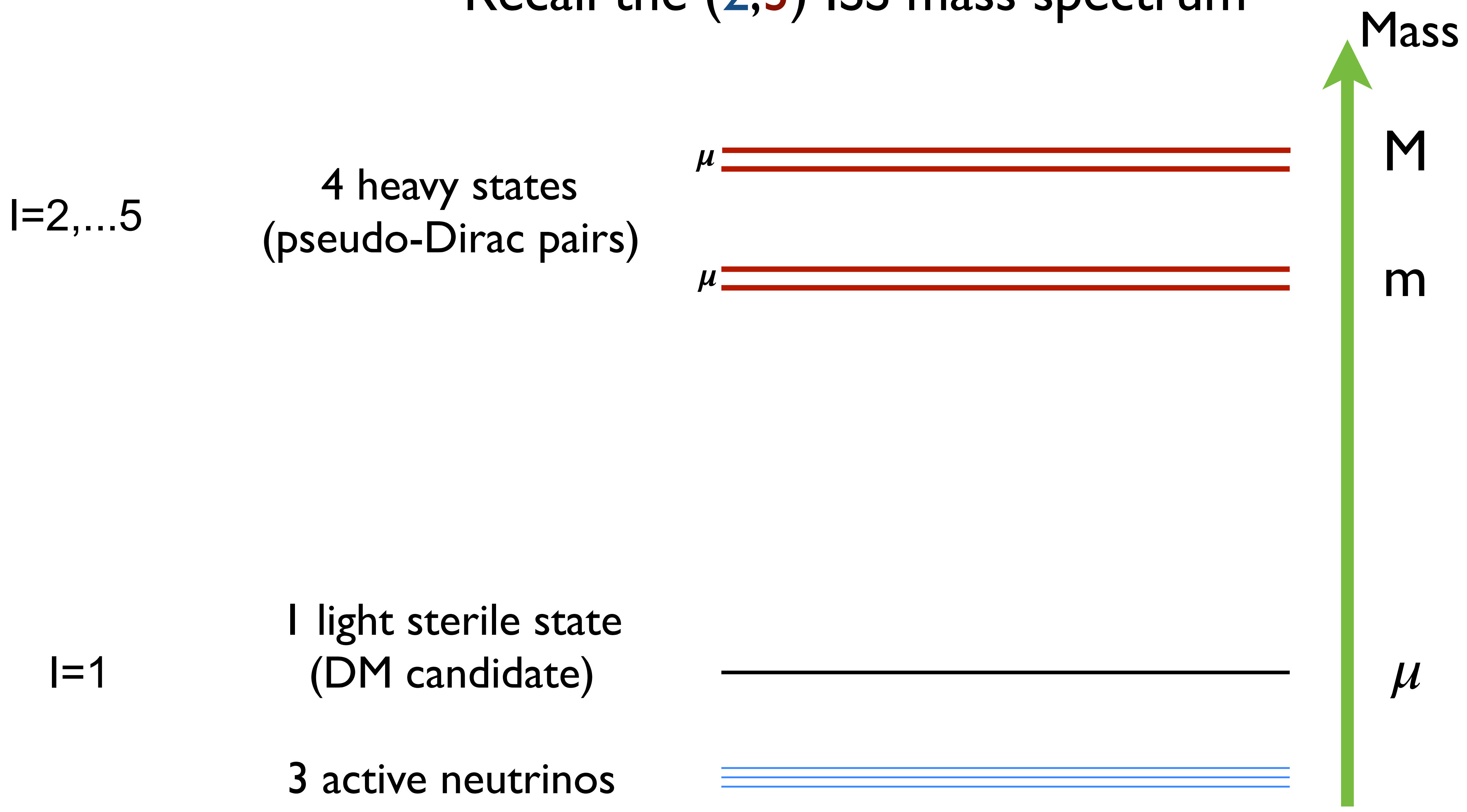


Ly-α
and
x-ray
constraints

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

Effects of heavy sterile states

Recall the (2,3) ISS mass spectrum



Mass

M

m

μ

I=2,...5

4 heavy states
(pseudo-Dirac pairs)

μ

μ

I=1

1 light sterile state
(DM candidate)

3 active neutrinos

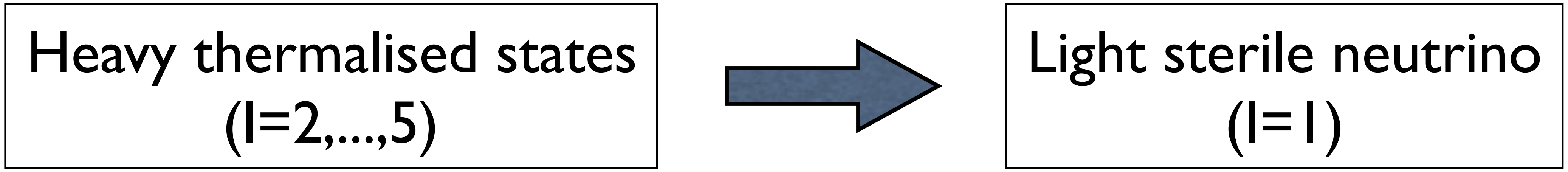
ISS can accommodate tiny ν masses with large O(1) Yukawas

Heavy states can thermalise in the early Universe

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

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

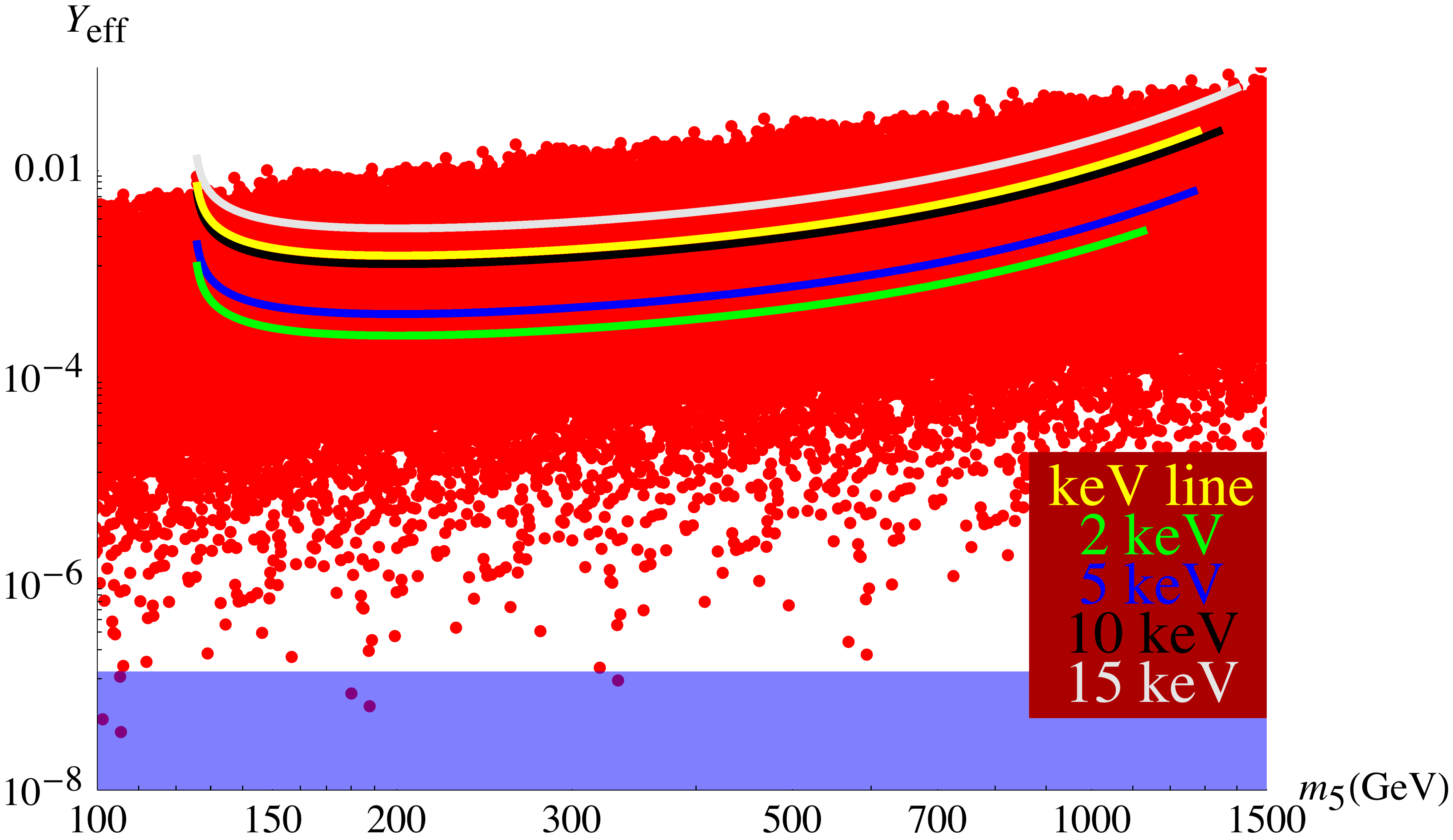
$$\Gamma\left(N_I \to h \ + \ {\rm DM}\right) = \frac{m_I}{16\pi} Y_{\rm eff,I}^2 \sin^2\theta \left(1 - \frac{m_h^2}{m_I^2}\right)$$

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

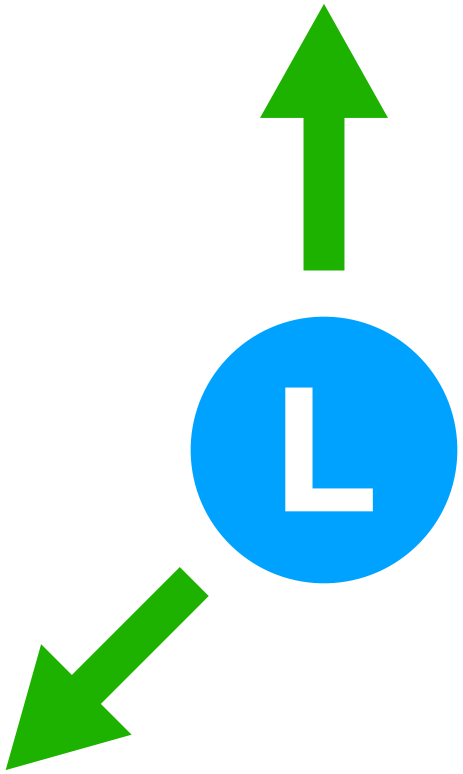
$\Omega h^2 \simeq 0.12$ compatible with ID bounds

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

Dark Matter Production in the (2,3) ISS



L-symmetry and SM observational problems



$m_\nu \ll$ EW scale with sizeable couplings and low NP scale

Testable models

Neutrino masses and mixing

pseudo-Dirac neutrino pairs
$\Delta M \ll M$

Connection with BAU

Dark matter

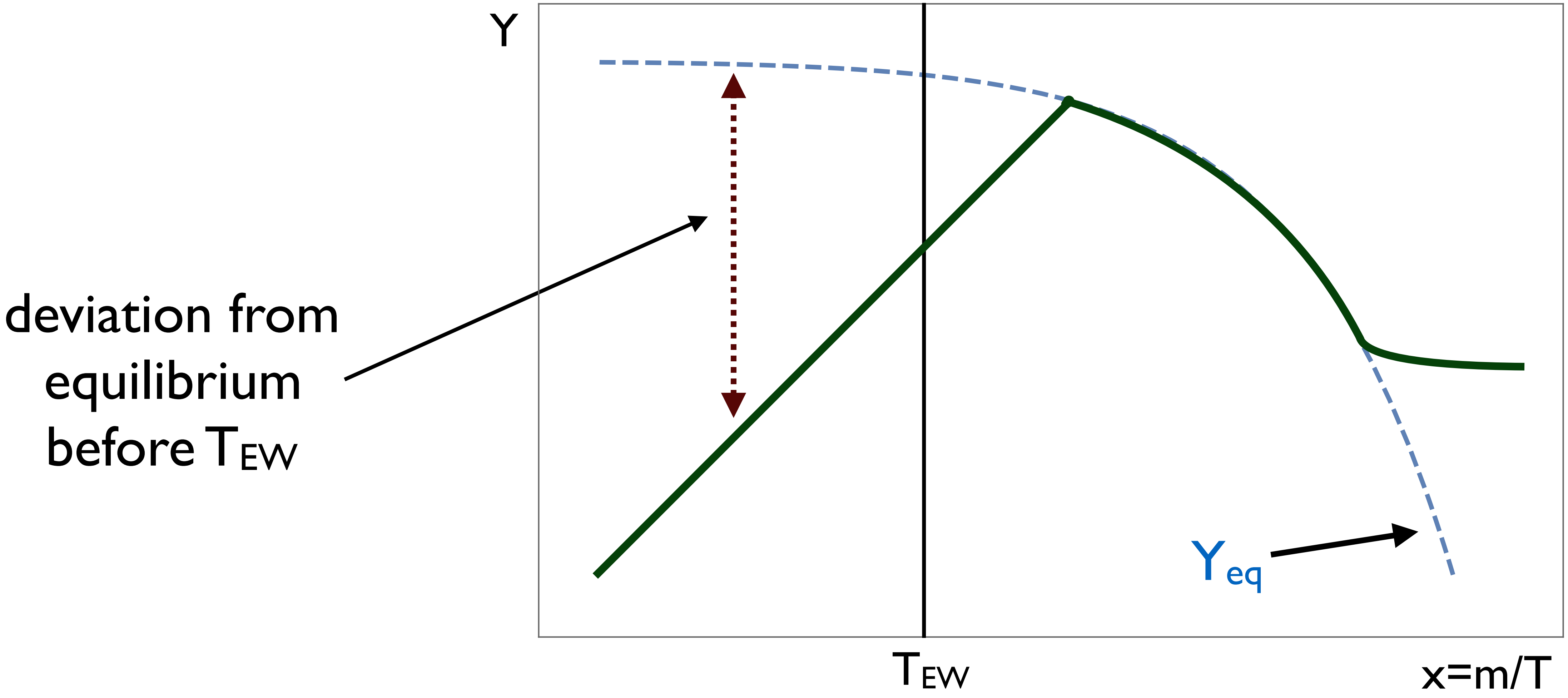
Sizeable Yukawa couplings allow viable DM production

Baryon asymmetry of the Universe

ARS mechanism

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

Sterile neutrinos out of equilibrium at large temperatures



deviation from equilibrium before T_{EW}

From the seesaw relation

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger \simeq 0.3 \left(\frac{\mathrm{GeV}}{M}\right) \left(\frac{Y^2}{10^{-14}}\right) \ \mathrm{eV}$$

M ~ GeV to reproduce ν masses → **Testable**

Naturalness argument

Need a pair of **degenerate neutrinos** or **hierarchical yukawas**:
fine-tuning or **symmetry**

Approximate lepton number at the origin of mass degeneracy

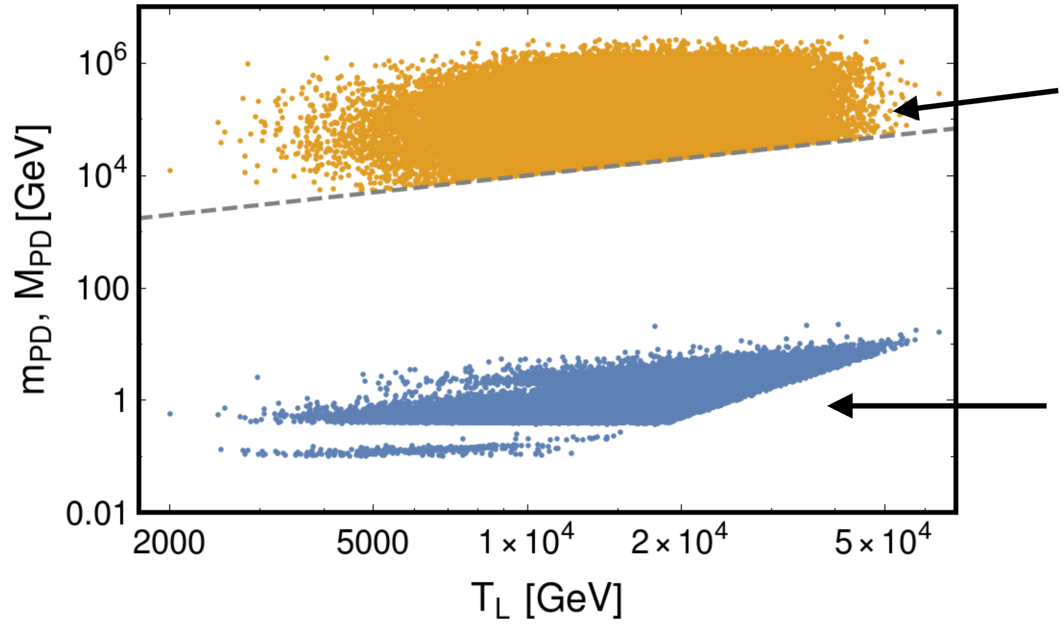
$$M = \underbrace{M_0}_{\Delta L=0} + \underbrace{\Delta M}_{\Delta L\neq 0}$$

$||\Delta M|| \ll ||M_0||$ → **degenerate pseudo-Dirac pairs of sterile neutrinos**

In the Inverse Seesaw

$m_{DM} \sim \mu \sim \Delta M$

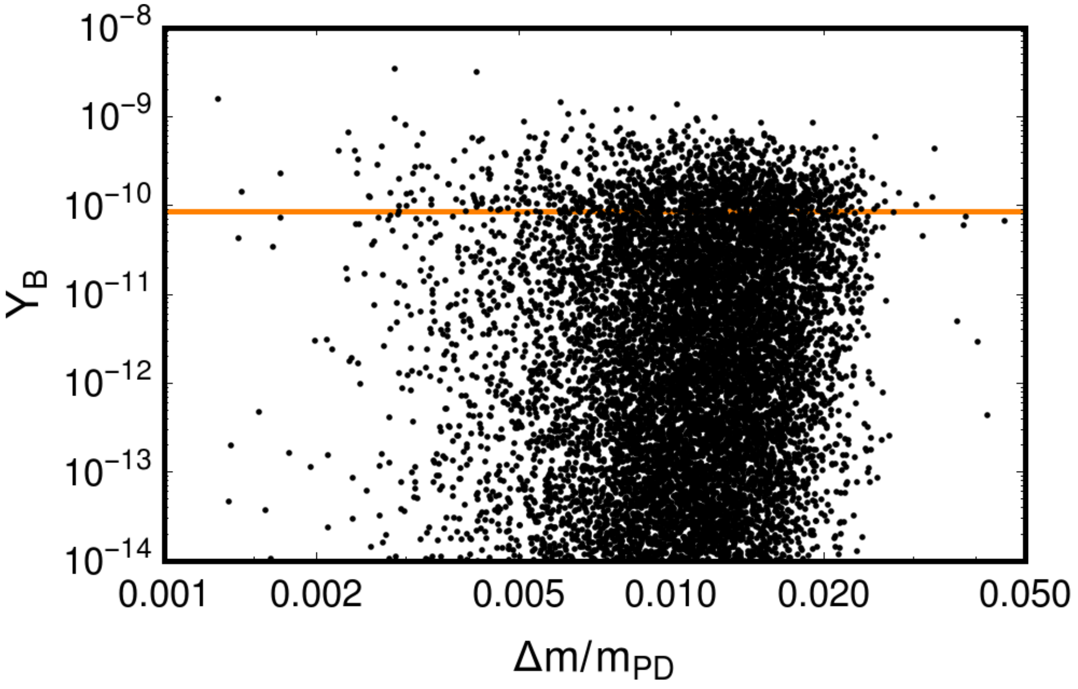
We want to consider the DM possibility as well

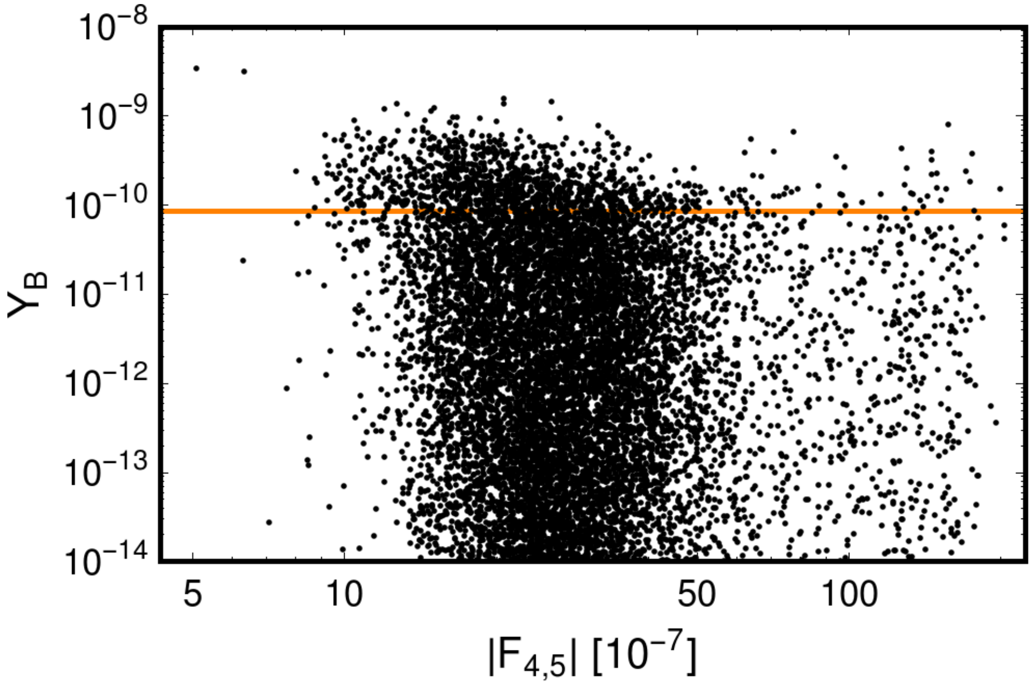


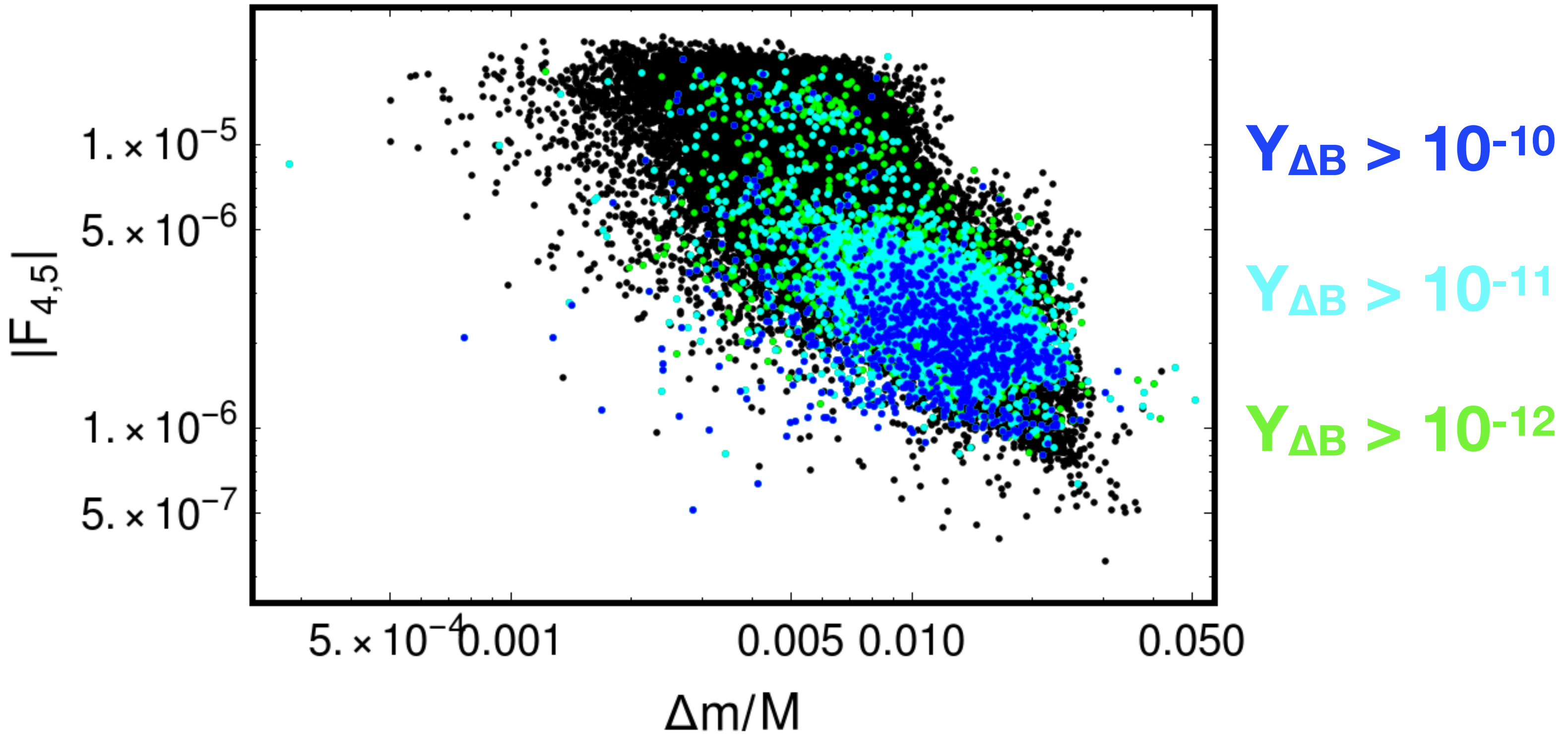
Freeze-in DM?

Leptogenesis

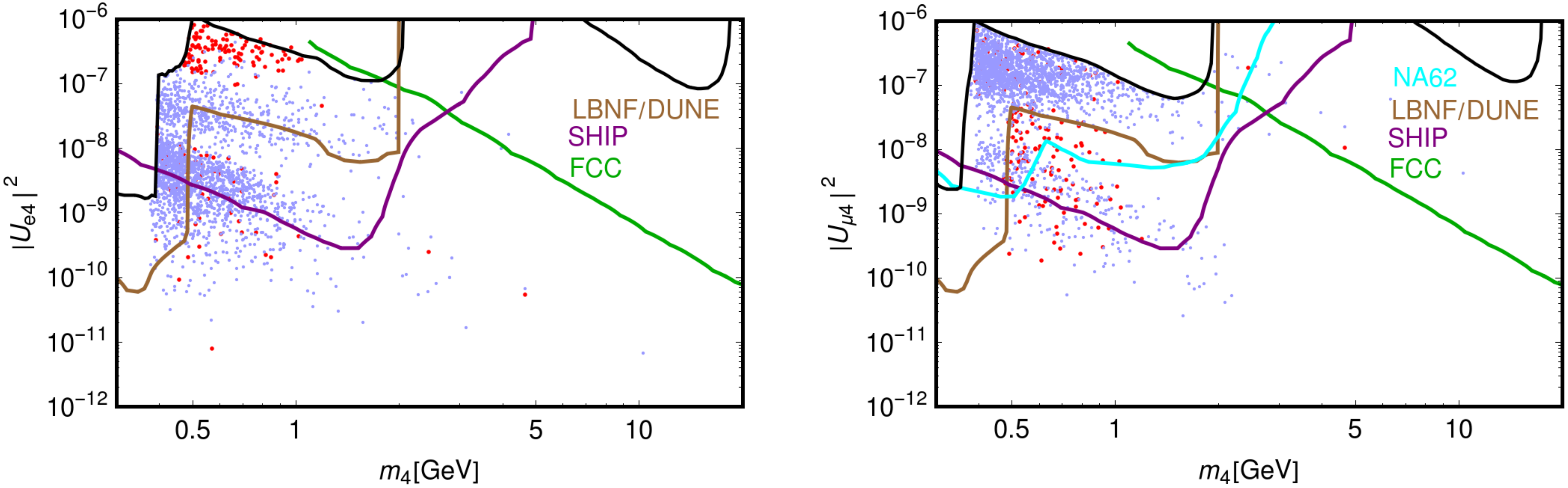
Low-scale leptogenesis in the (2,2) ISS


Mass splitting


Yukawas

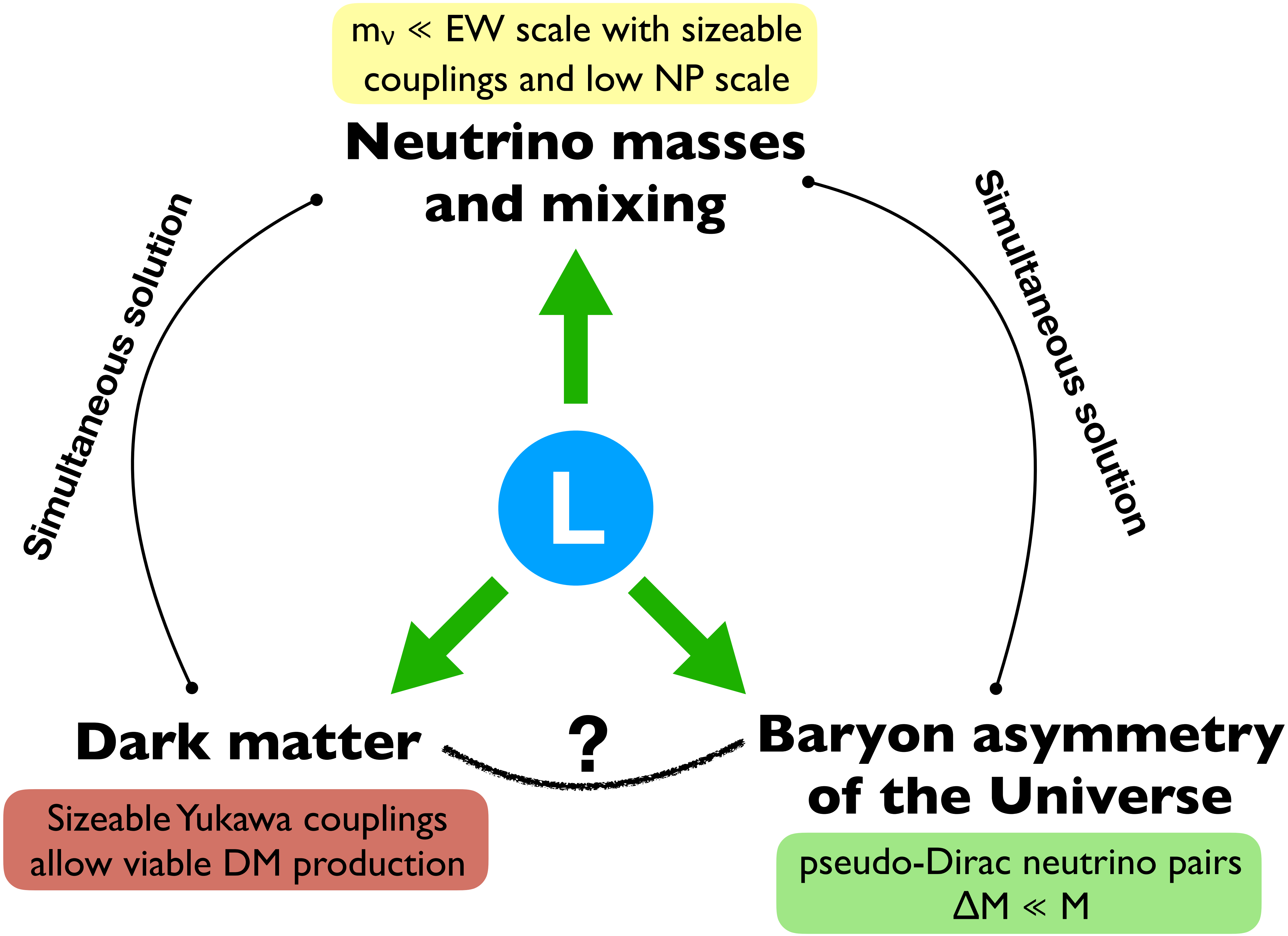


Testability



A large fraction of solutions is testable in future experiments

L-symmetry and SM observational problems



$m_\nu \ll$ EW scale with sizeable couplings and low NP scale

Neutrino masses and mixing

Simultaneous solution

L

Simultaneous solution

Dark matter

?

Baryon asymmetry of the Universe

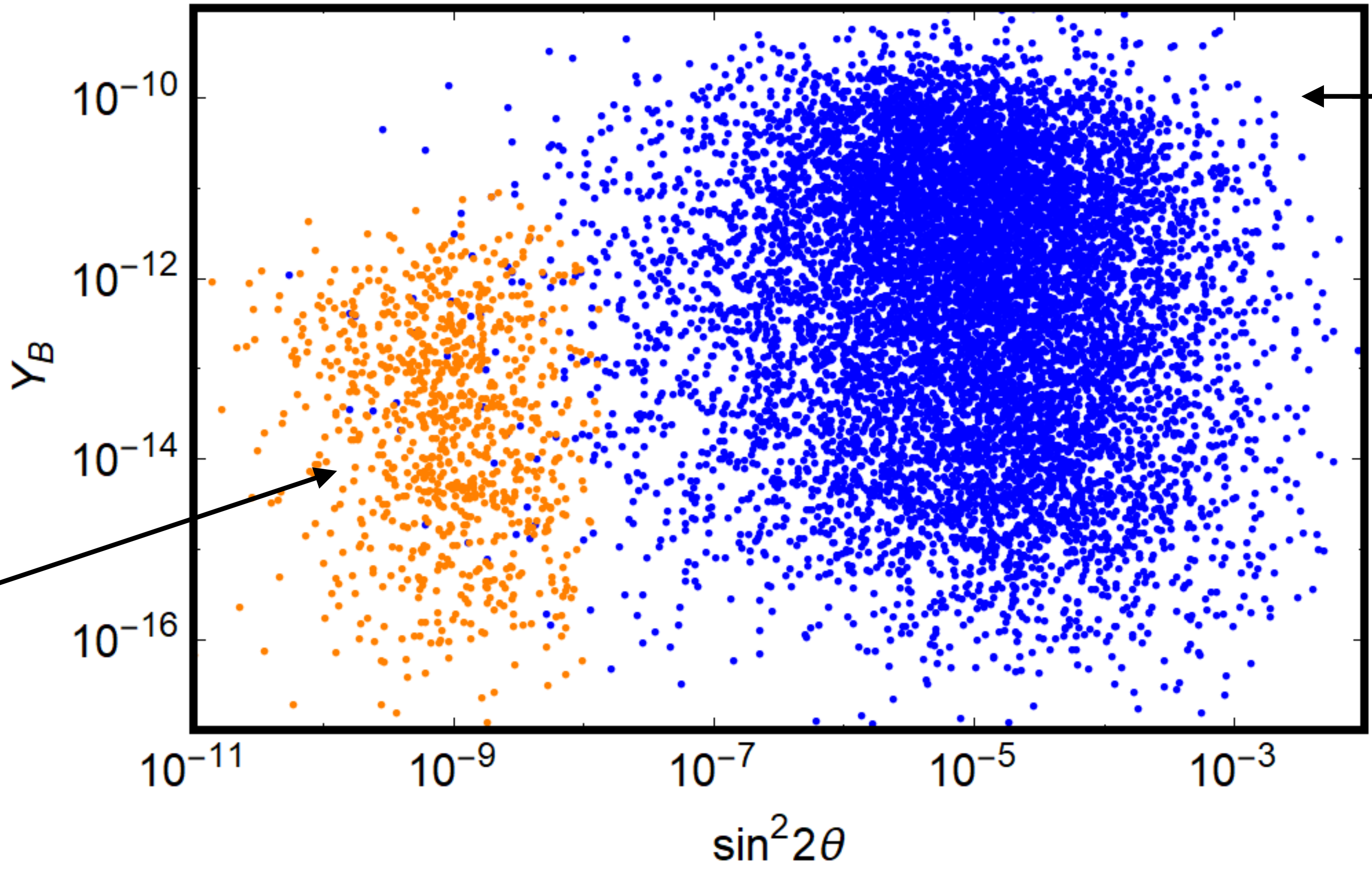
Sizeable Yukawa couplings allow viable DM production

pseudo-Dirac neutrino pairs $\Delta M \ll M$

Putting all together?

The ISS can provide a common framework to account for neutrino masses and dark matter, or for neutrino masses and BAU.

Common solution for the three problems?



Viable BAU points overproduce DM

Viable DM points provide too small BAU

Conclusion

Approximate Lepton number is an interesting symmetry

Neutrino mass generation with sizeable Yukawas and low new-physics scale

In turn sizeable Yukawas and TeV scale sterile neutrinos allow viable DM production

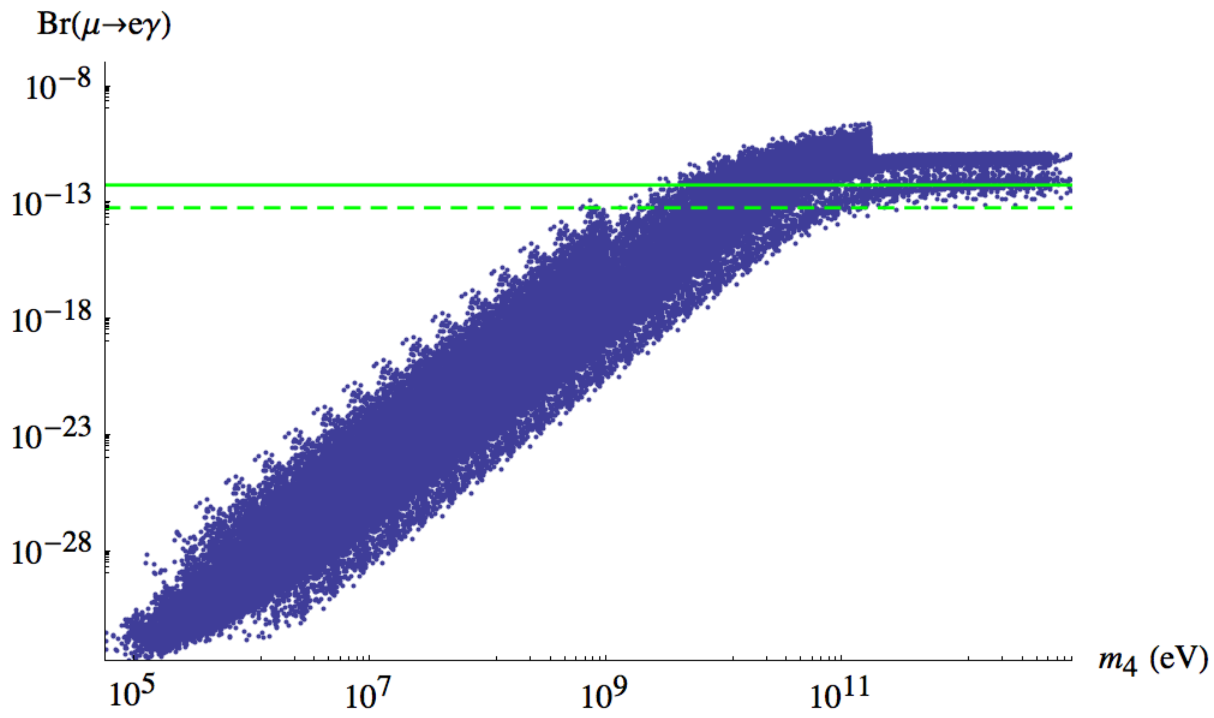
Approximate L-symmetry implies the existence of mass-degenerate pseudo-Dirac neutrinos: successful BAU

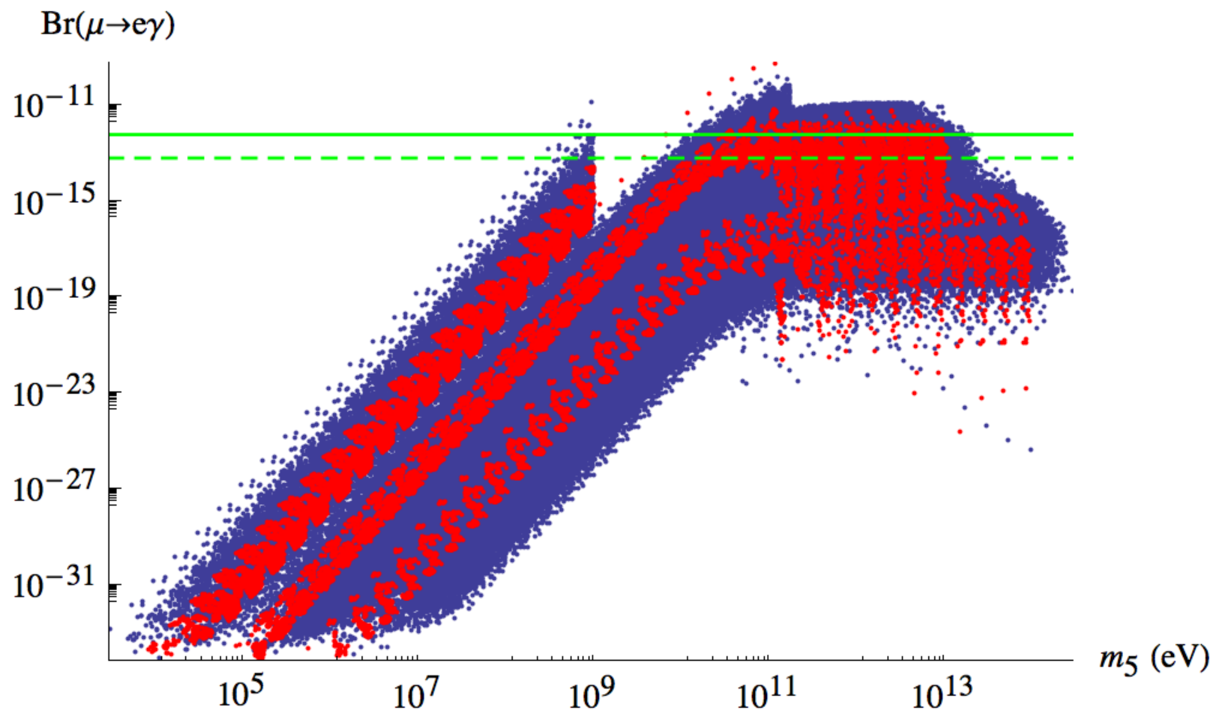
We used the Inverse Seesaw as a working framework to implement the idea:
simultaneous neutrino and DM or neutrino and BAU solutions

<u>but DM and BAU solutions appear to mutually exclude themselves</u>

Backup

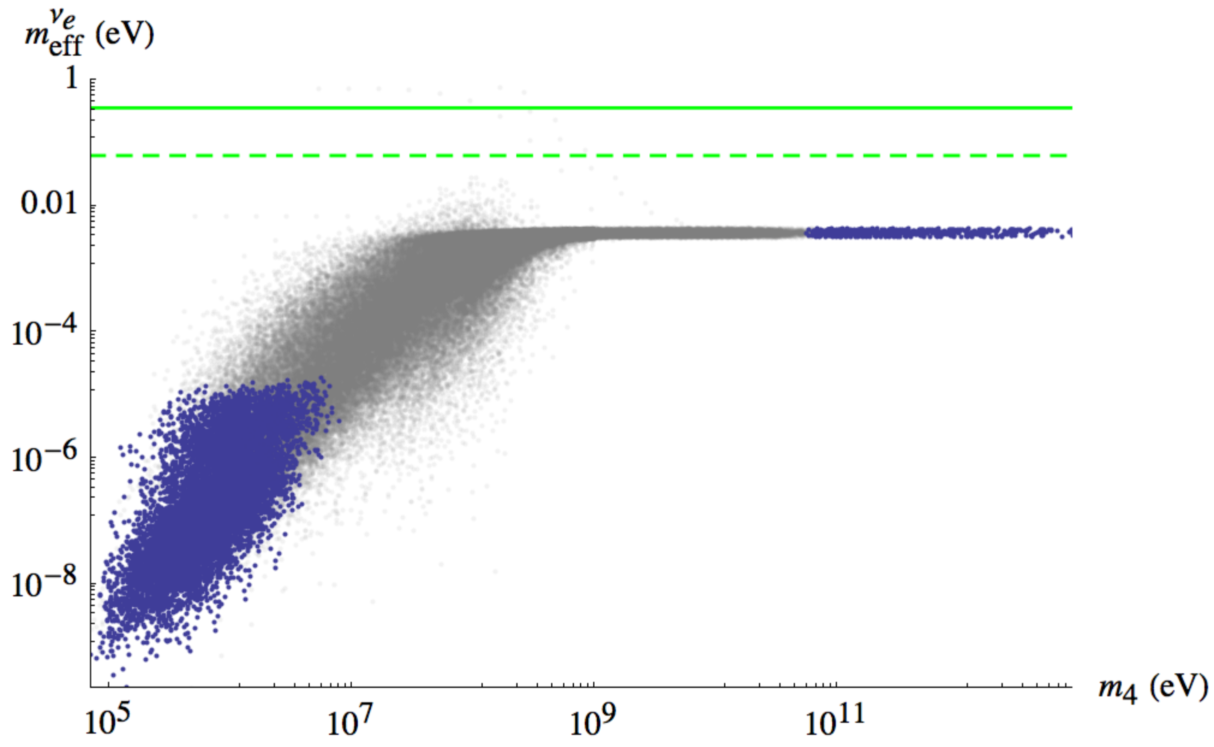
Lepton and flavour number violation in the ISS

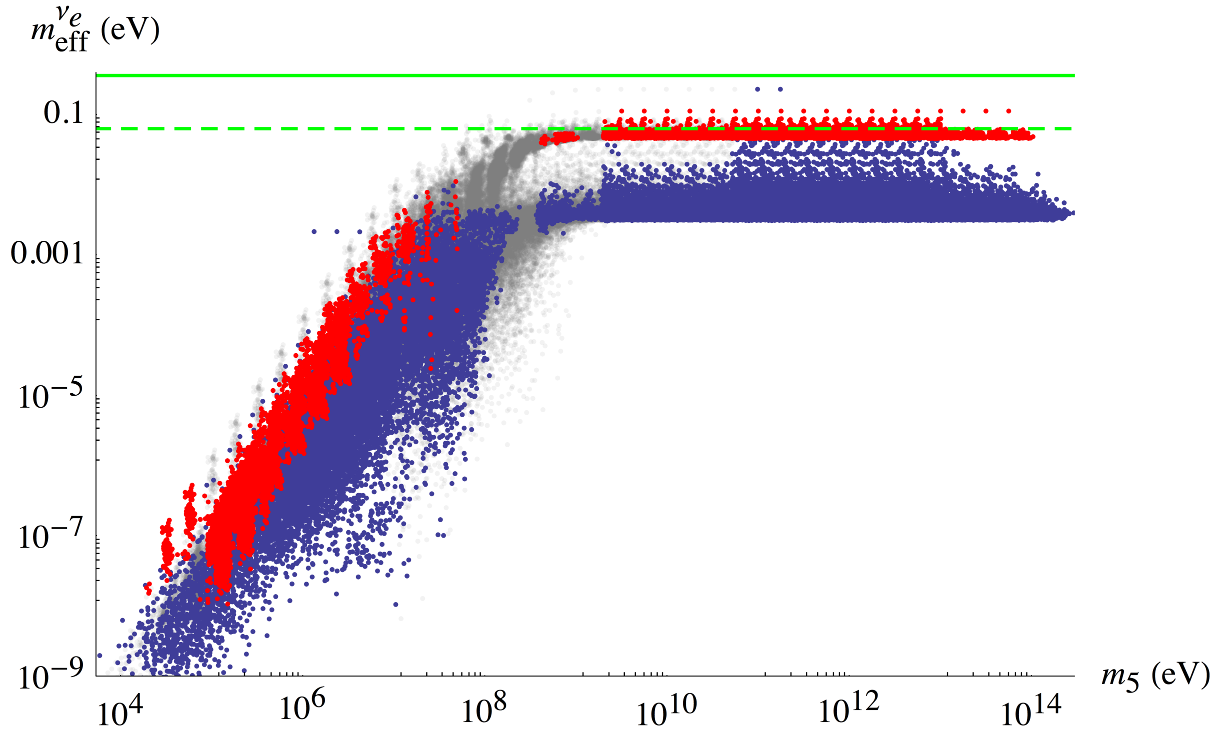




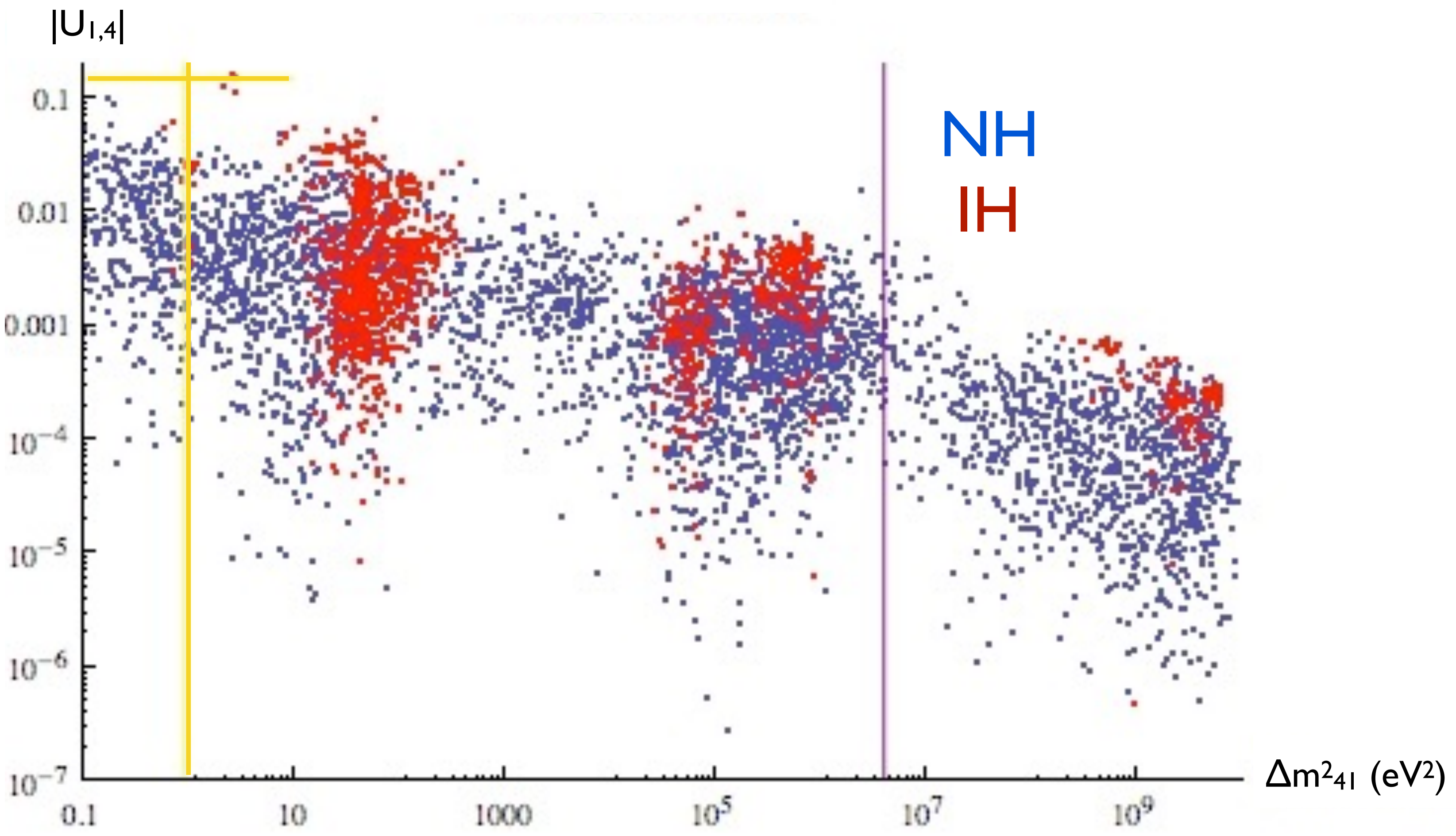
(2,2) ISS

(2,3) ISS





(2,3) ISS: light sterile state



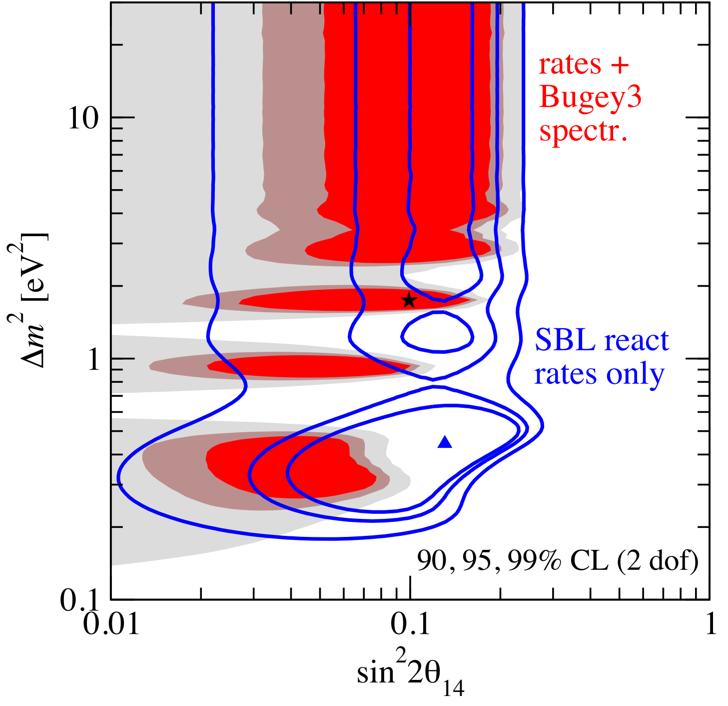
(3+1) best-fit points

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

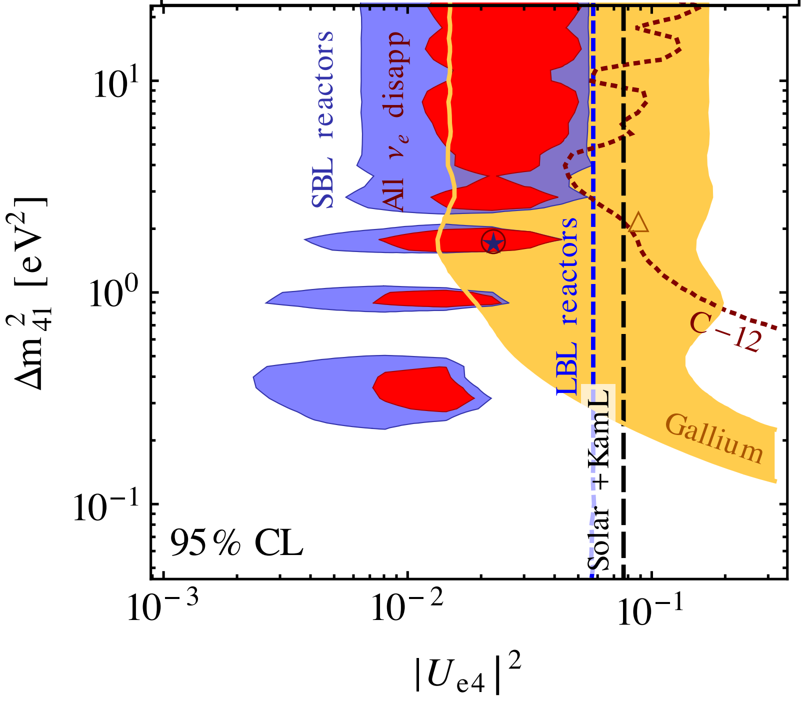
sterile ν as DM

$m_{DM} \approx$ keV

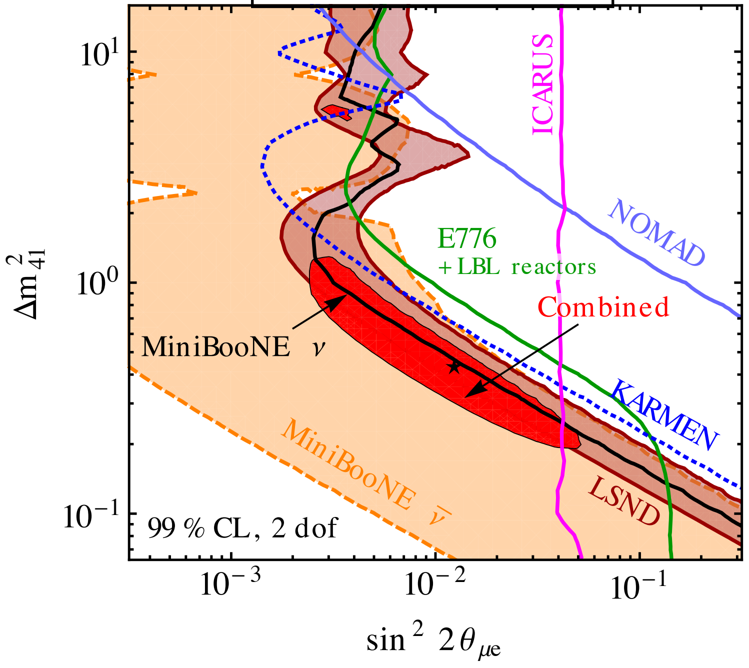
SBL reactors



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]

Constraints: abundance

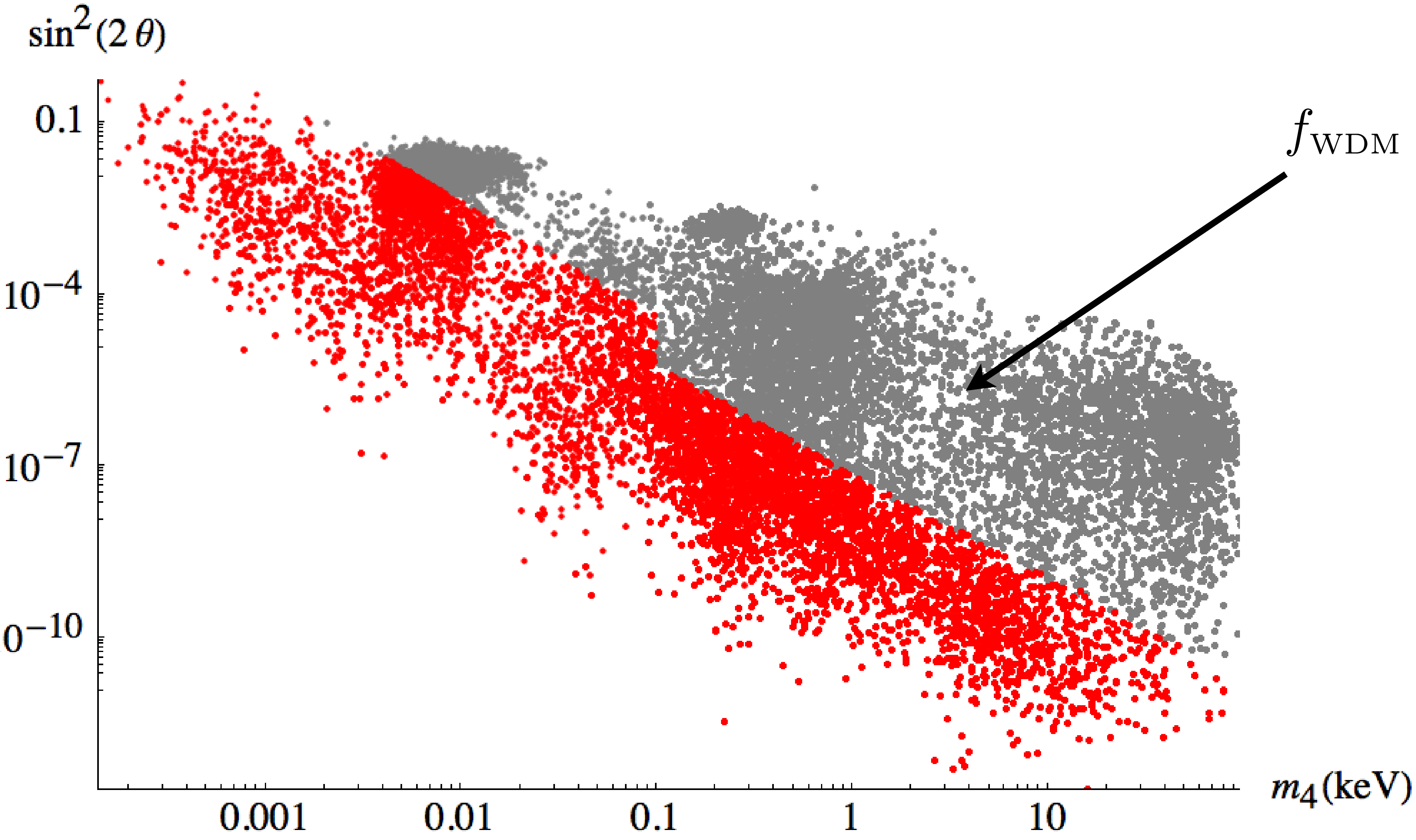
DW: as long as an active-sterile mixing is present, a population of sterile ν is produced by oscillations in the primordial plasma

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



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

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

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

Constraints: phase-space density

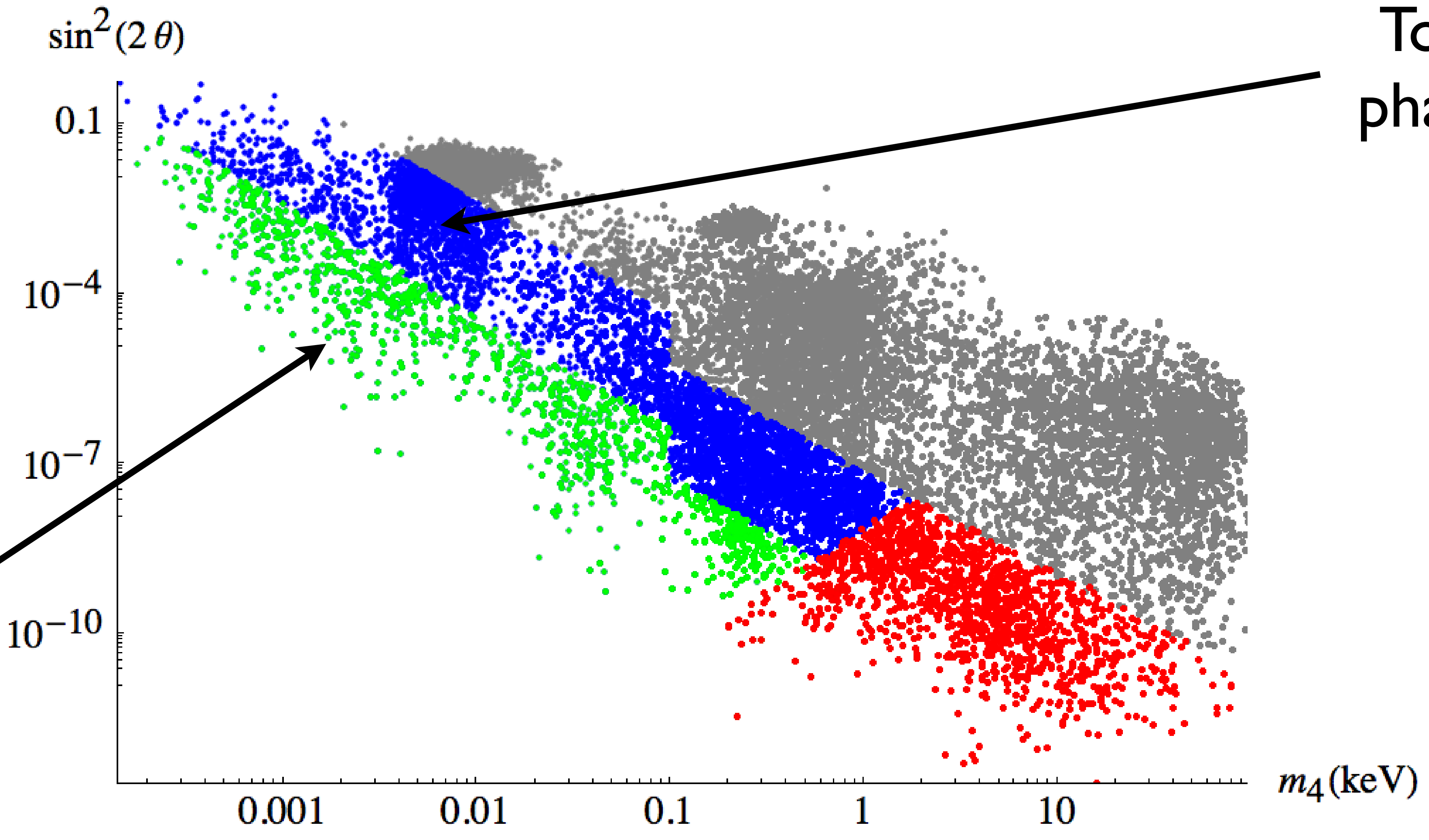
For fermionic DM, Pauli exclusion principle impose a maximum on its distribution function (degenerate Fermi gas). Imposing that inferred phase-space density does not excess this bound, it is possible to extract a lower bound on the DM mass

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

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

from dSphs observations

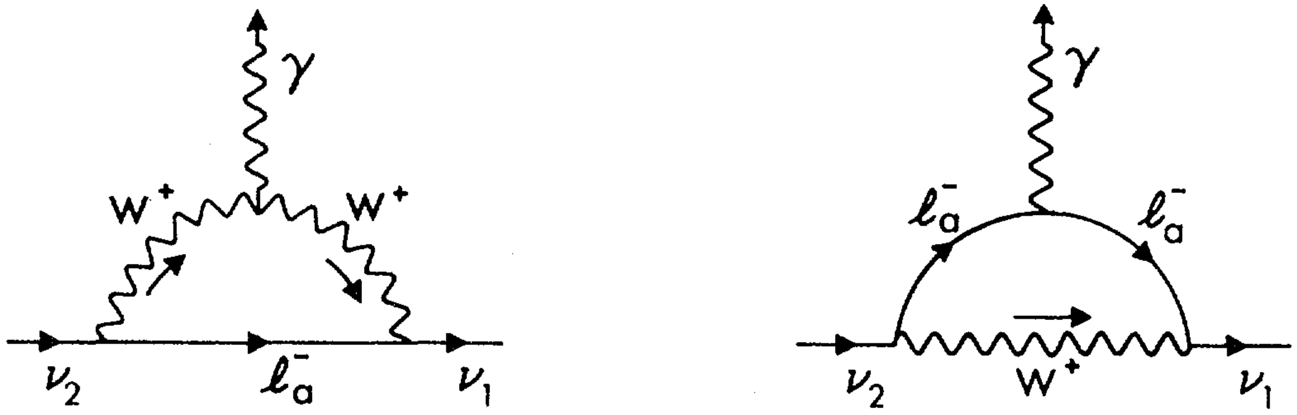
A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, 0808.3902 [hep-ph]



Too dense phase-space

Negligible abundance (< 1%)

Constraints: stability and indirect detection (ID)

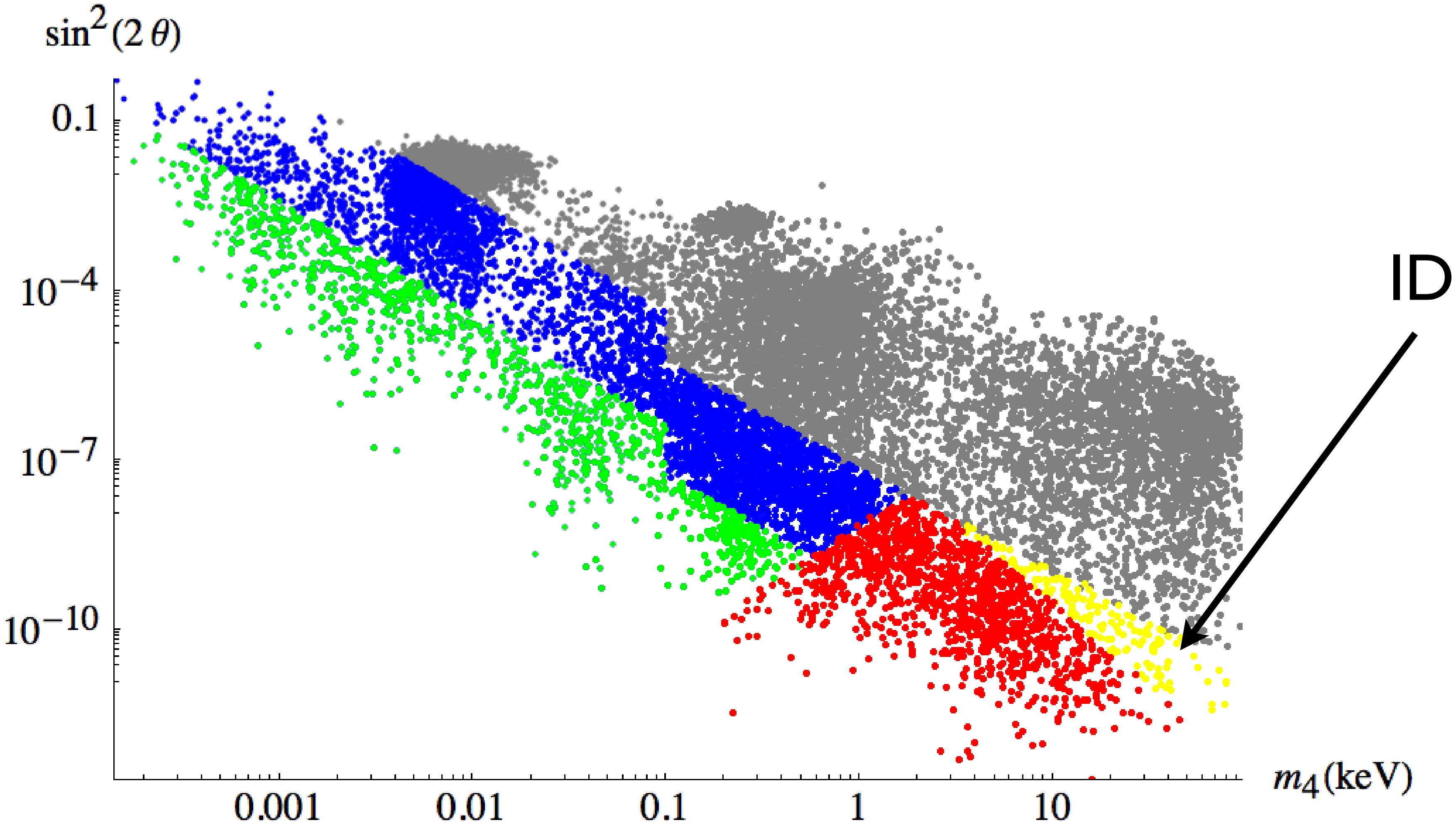


Massive ν can decay radiatively producing monochromatic γ

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

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

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



ID excluded

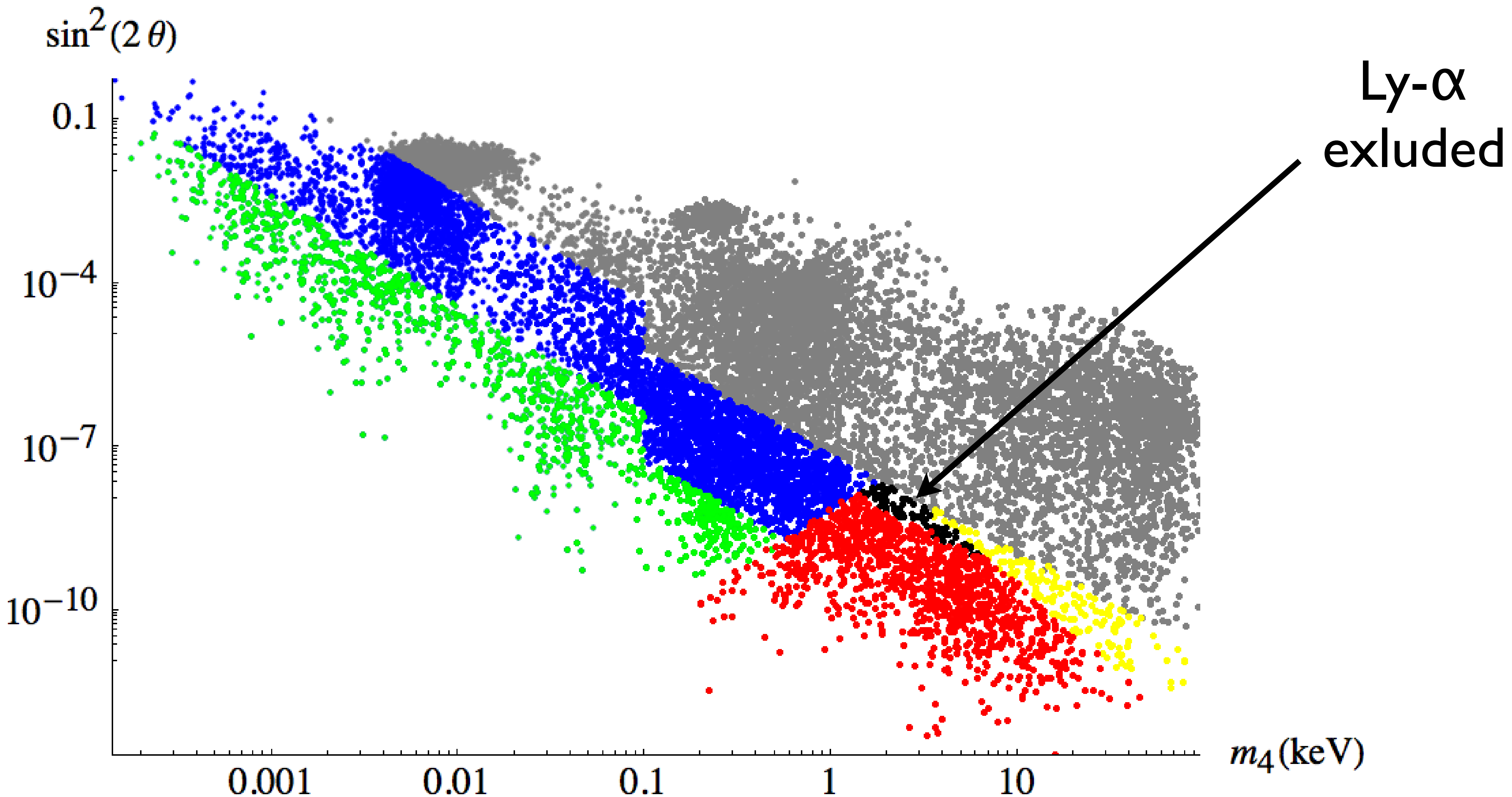
Constraints: Lyman-α

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]

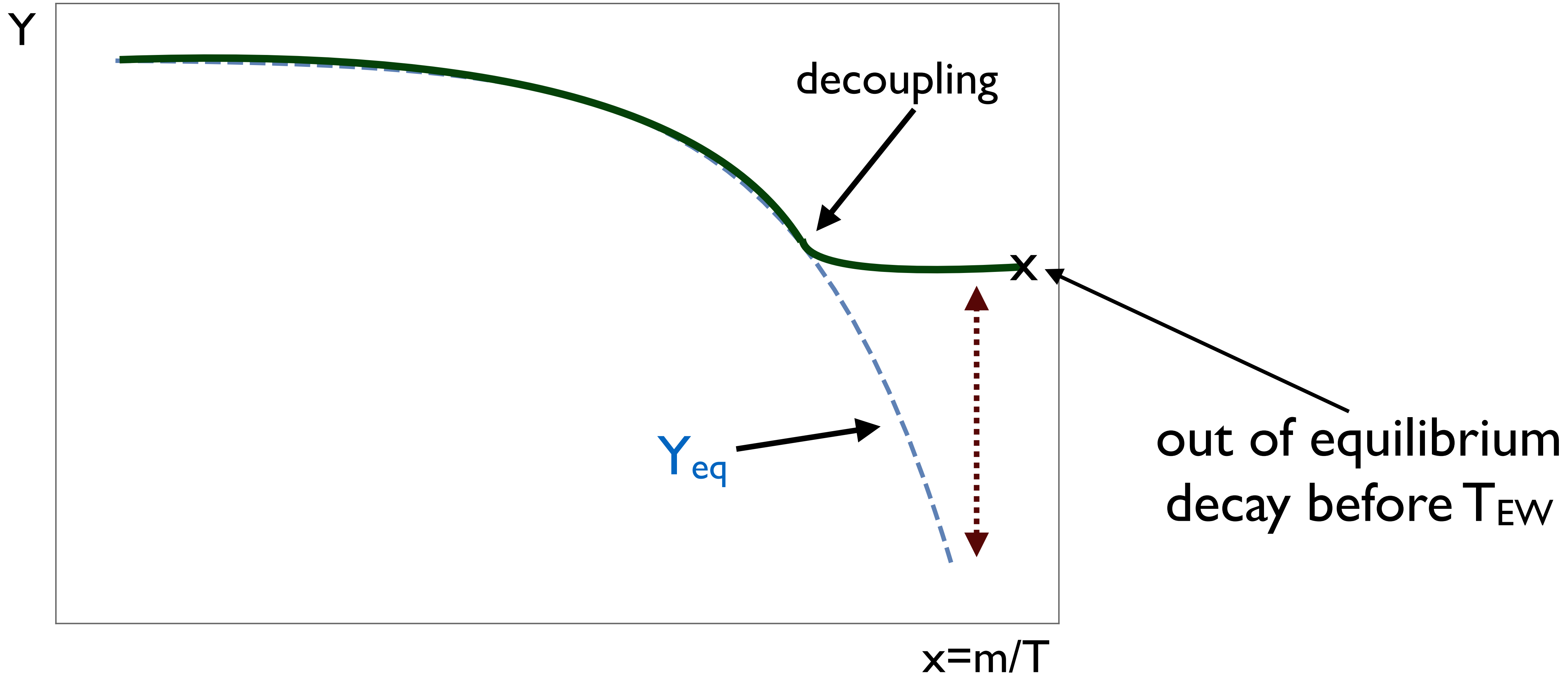


Ly-α exluded

Thermal leptogenesis

Sterile neutrinos in thermal equilibrium if $|Y| \gtrsim 10^{-7}$

Thermal leptogenesis: sterile neutrinos in equilibrium at large temperatures



out of equilibrium decay before T_{EW}

Generation of a lepton asymmetry due to the Majorana character of the particles

M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45

M > 10^8 GeV to reproduce observed BAU (relaxed to M > TeV for degenerate masses)

→

Prohibitive to test in laboratory

S. Davidson, E. Nardi and Y. Nir, arXiv:0802.2962 [hep-ph]
A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0605281
A. Pilaftsis and T. E. J. Underwood, hep-ph/0309342

ARS leptogenesis

$\mathbf{M} \sim \text{GeV} \ll \mathbf{T}$

Negligible Majorana character → total lepton number approximately conserved

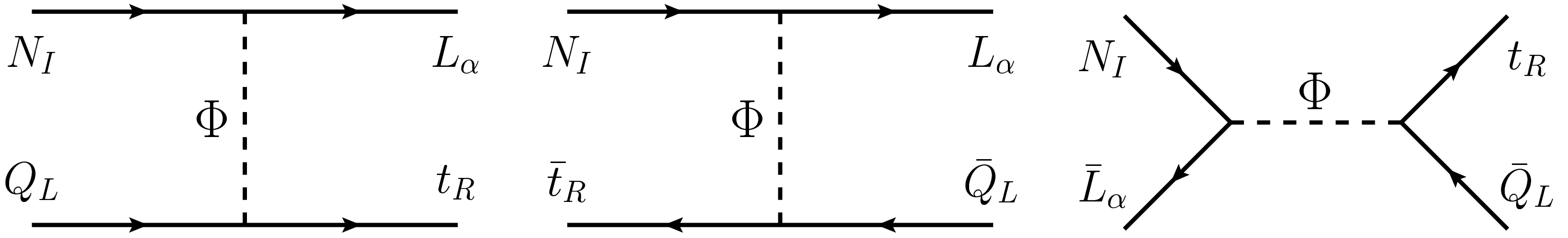
(but not always the case)

T. Hambye and D. Teresi
1606.00017 - 1705.00016 [hep-ph]

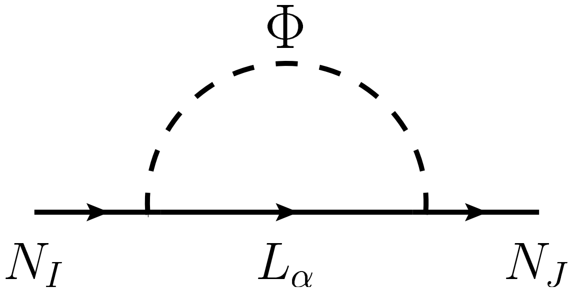
How do the mechanism work?

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255
T. Asaka, S. Blanchet and M. Shaposhnikov, hep-ph/0503065
T. Asaka and M. Shaposhnikov, hep-ph/0505013
M. Shaposhnikov, arXiv:0804.4542 [hep-ph]
T. Asaka, S. Eijima and H. Ishida, arXiv:1112.5565 [hep-ph]
L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]
M. Drewes and B. Garbrecht, arXiv:1206.5537 [hep-ph]
P. Hernández, M. Kekic, J. López-Pavón, J. Racker and N. Rius, arXiv:1508.03676 [hep-ph]
P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, arXiv:1606.06719 [hep-ph]
M. Drewes, B. Garbrecht, D. Gueter and J. Klaric, arXiv:1606.06690 [hep-ph]

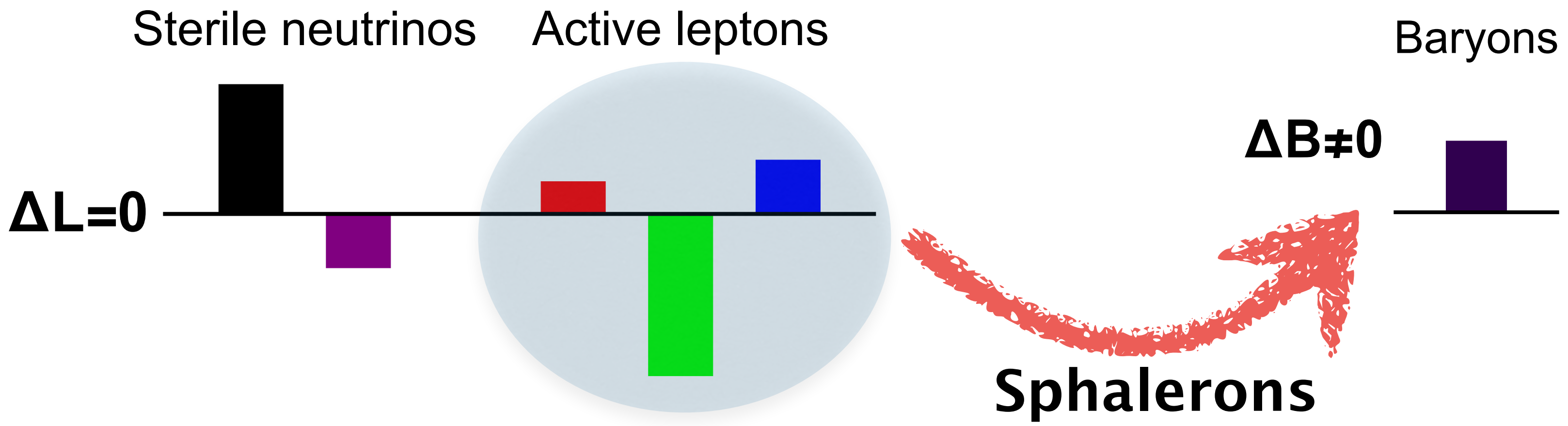
generation of sterile neutrinos



oscillation of sterile neutrinos



asymmetries in **individual** flavours arise



Parameter space for DM in the ISS(2,3)

Consider a toy model with 1 ν_L, 1 ν_R and 2 *s*

$$\mathcal{M} = \begin{pmatrix} 0 & \frac{1}{2}Yv & 0 & 0 \\ \frac{1}{2}Yv & 0 & n_1\Lambda & n_2\Lambda \\ 0 & n_1\Lambda & \xi_1\Lambda & 0 \\ 0 & n_2\Lambda & 0 & \xi_2\Lambda \end{pmatrix}$$

$$\mathcal{U}^T\mathcal{M}\mathcal{U} = \mathrm{diag}(0, m_{\mathrm{DM}}, m_{\mathrm{PD}} - m_{\mathrm{DM}}, m_{\mathrm{PD}} + m_{\mathrm{DM}})$$

$$\sin^2(2\theta_{\mathrm{DM}}) = 4\mathcal{U}_{12}^2 \simeq \frac{2n_1^2 n_2^2(\xi_1 - \xi_2)^2}{(n_1^2 + n_2^2)(n_1^2\xi^2 + n_2^2\xi_1)^2}\,\frac{v^2Y^2}{\Lambda^2}$$

θ_{DM} suppression requires some hierarchy in the entries of the submatrix n