LEPTOGENESIS, DARK MATTER AND NEUTRINO MASSES

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Based on work in collaboration with A. Abada, G. Arcadi, V. Domcke, M. Drewes and J. Klaric

arXiv:1806.xxxx, 1709.00415, 1507.06215, 1406.6556, 1401.1507

UCL
Université
catholique
de Louvain

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

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

The natural (simple) way

Complete the SM field pattern with **right-handed neutrinos**

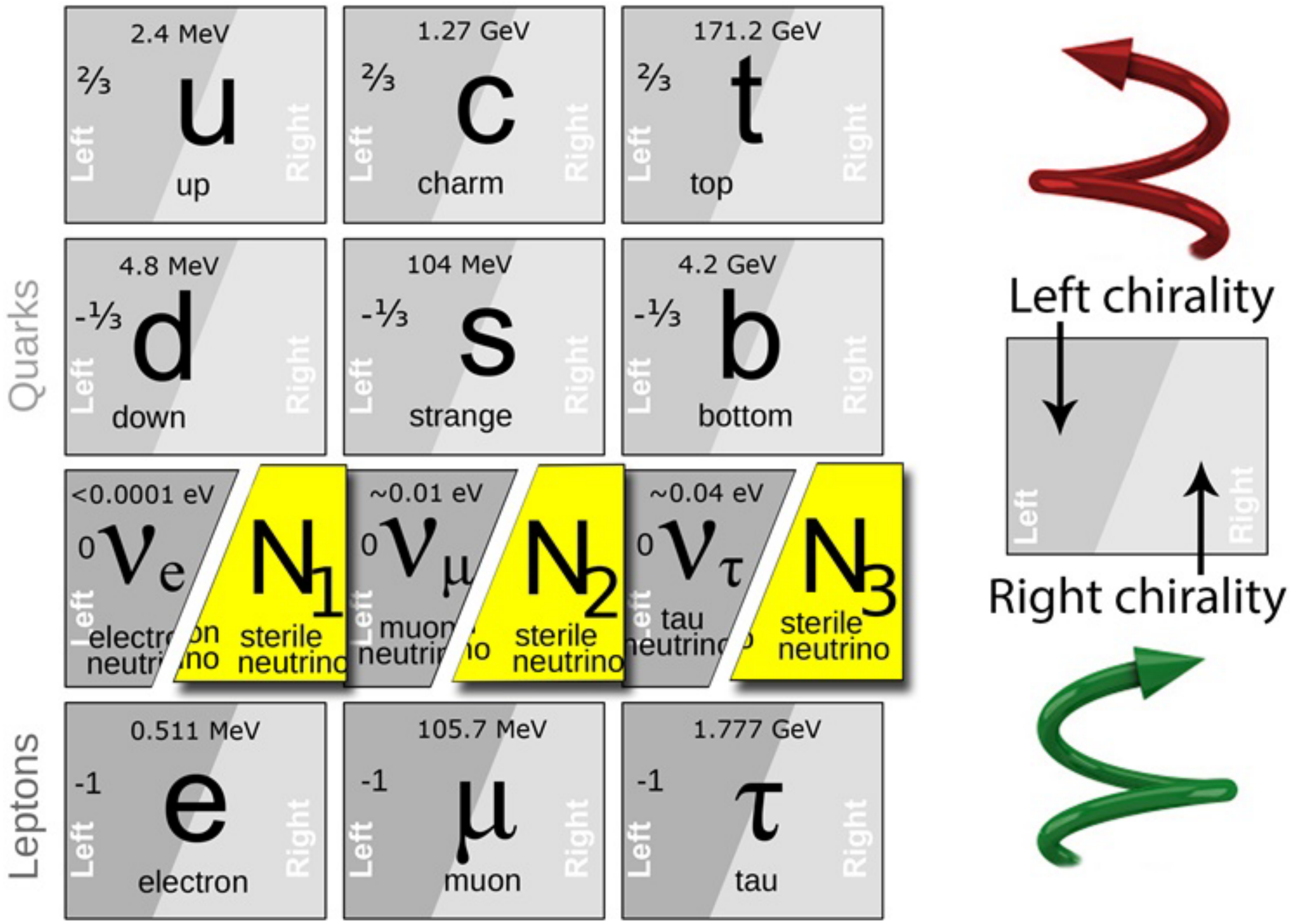

Figure from S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions N_I

$$\mathcal{L} \;=\; \mathcal{L}_{\mathrm{SM}} + i\overline{N_I}\partial\!\!\!/ N_I - \left(Y_{\alpha I}\overline{\ell_\alpha}\widetilde{\phi} N_I + \frac{M_{IJ}}{2}\overline{N_I^c}N_J + h.c.\right)$$

After electroweak phase transition < Φ > = v ≃ 174 GeV

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger$$

The Lagrangian provides the ingredients for leptogenesis too

Sakharov conditions

- Complex Yukawa couplings *Y* as a source of $\cancel{CP}$ ✓
- $\cancel{B}$ from sphaleron transitions until $T_{EW} \simeq 140$ GeV ✓
- sterile neutrinos deviations from thermal equilibrium ✓

Neutrino masses and leptogenesis

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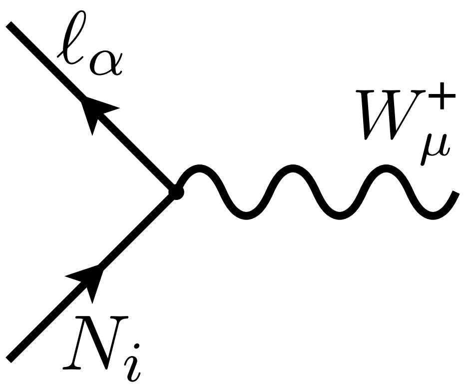
- sterile neutrinos deviations from thermal equilibrium ✓

…and dark matter?

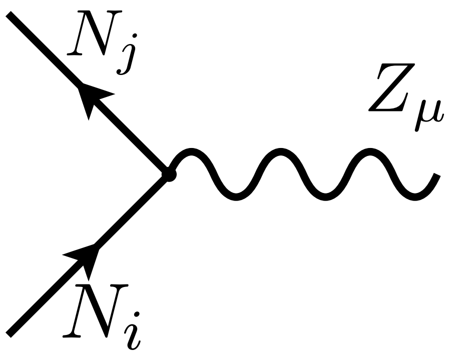
(Sterile) neutrinos are natural DM candidates too

- Massive

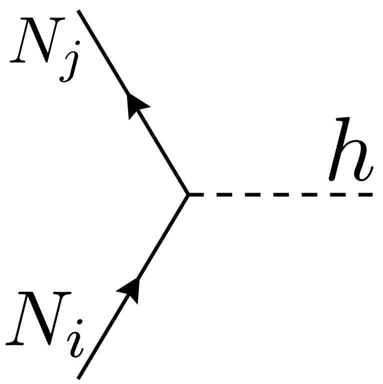
- Weakly interacting



$\propto i \, \frac{g}{\sqrt{2}} \mathcal{U}_{\alpha i}$



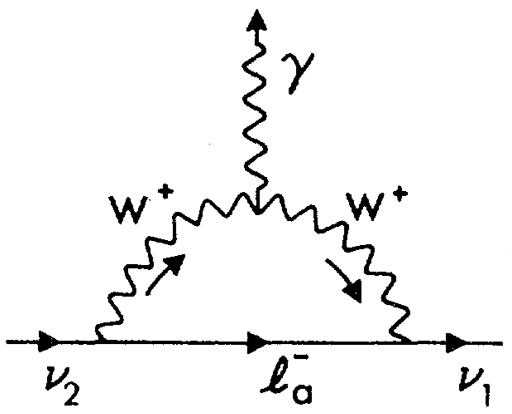
$\propto i \, \frac{g}{4 c_w} C_{ji}$

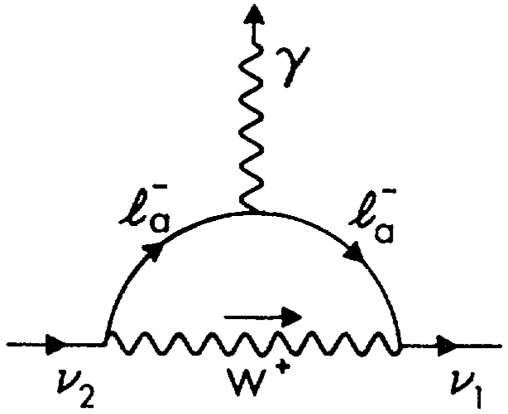


$\propto i \, \frac{g}{4} \frac{m_j}{M_W} C_{ji}$

$$C_{ij} \equiv \sum_{\alpha=e,\mu,\tau} \mathcal{U}^*_{\alpha i} \, \mathcal{U}_{\alpha j}$$

- Possibly metastable on cosmological scales





Leptogenesis realisations

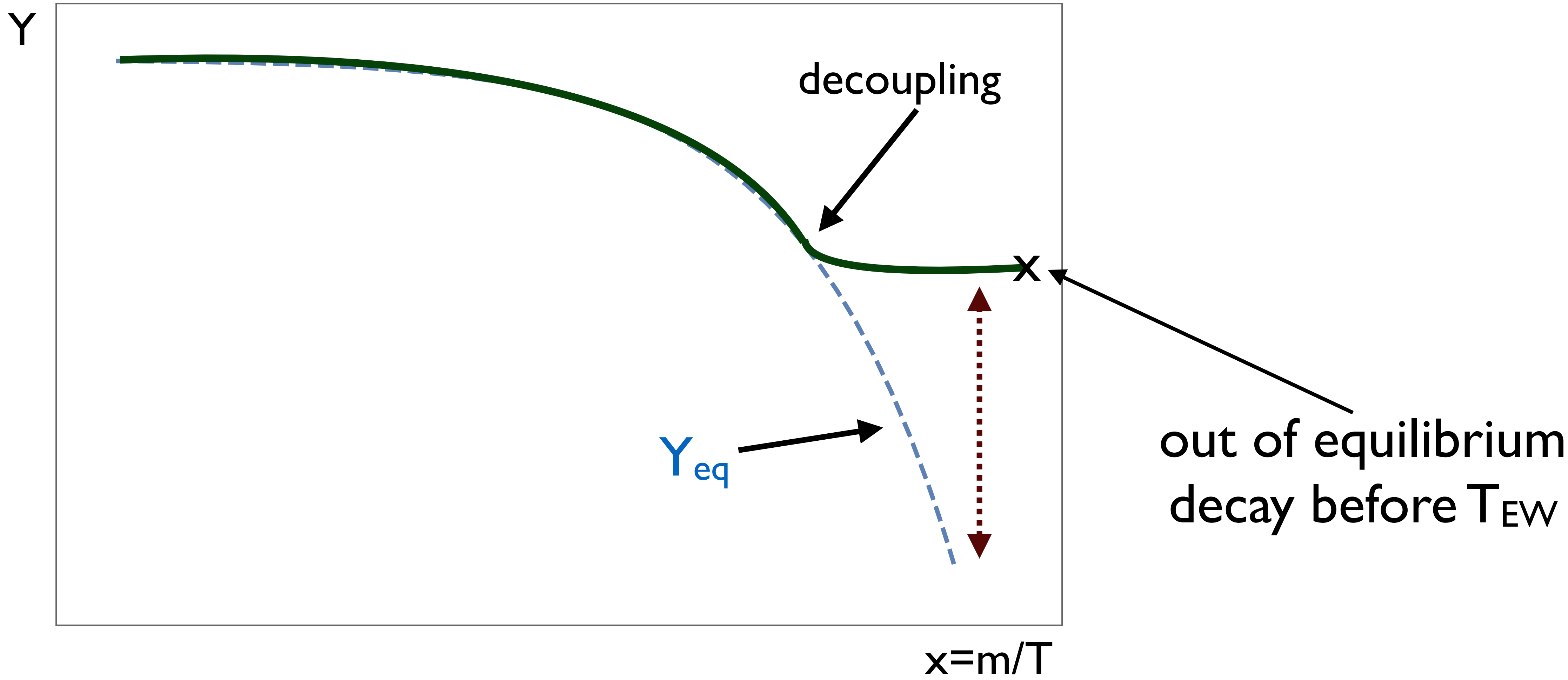
3rd Sakharov condition:
deviation from thermal equilibrium

At which temperature(s) do sterile neutrinos enter/deviate from thermal equilibrium?

BAU I: 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

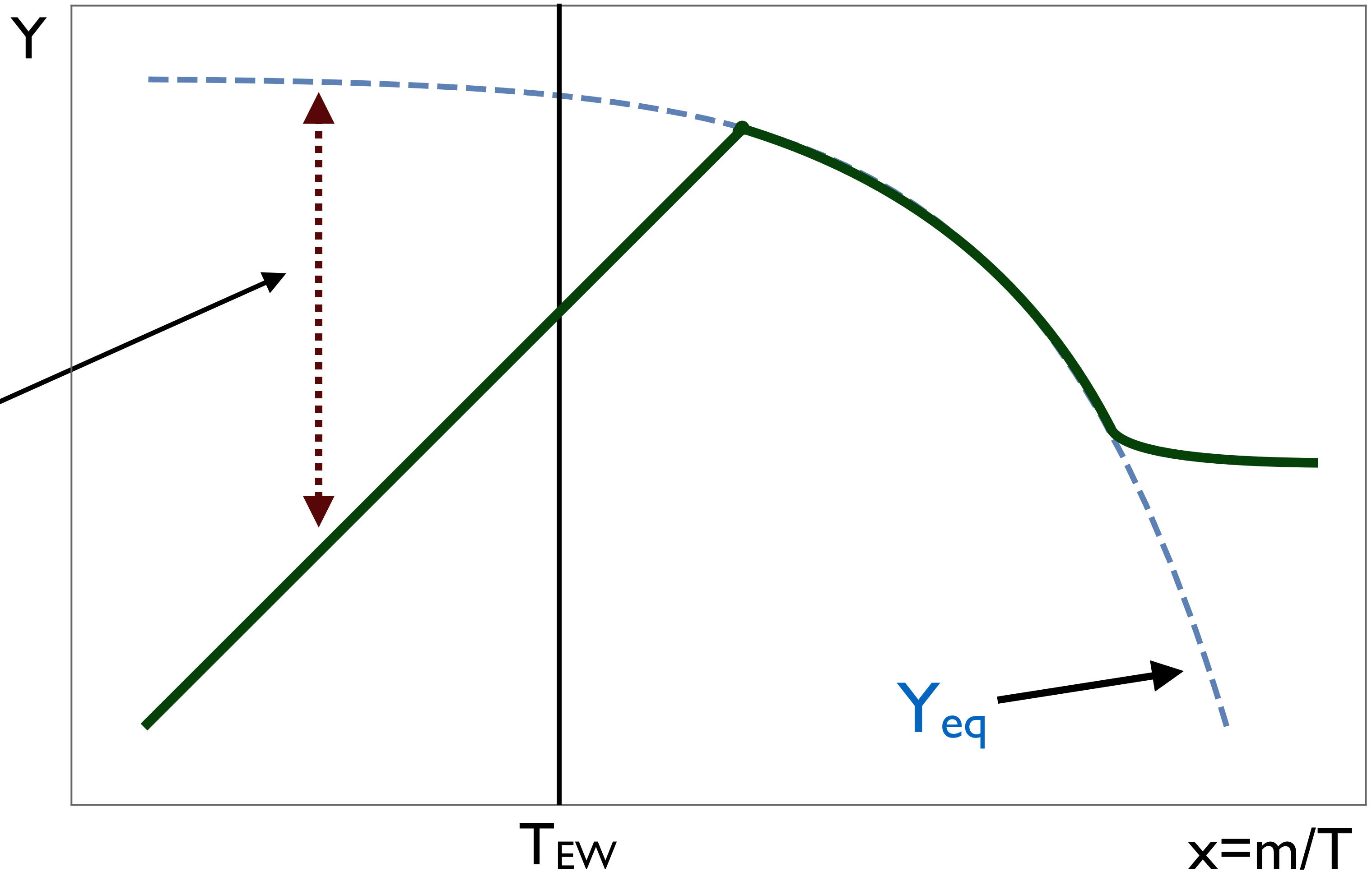
$M > 10^8$ GeV to reproduce observed BAU (relaxed to M > TeV for degenerate masses) → Difficult to test in laboratory

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

BAU II: 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**

ARS leptogenesis

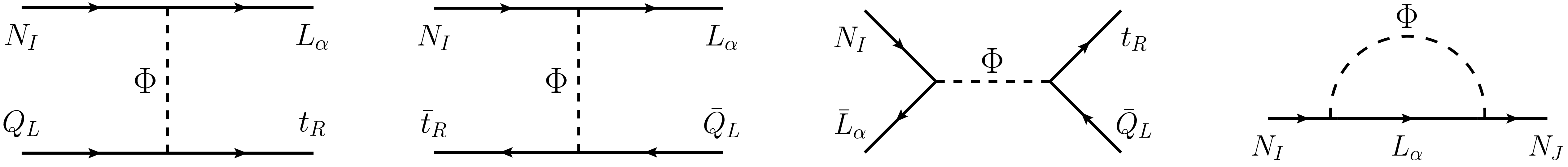
How does the mechanism work?

A. Abada, S. Antusch, E. K. Akhmedov, G. Arcadi, T. Asaka, S. Blanchet, L. Canetti, E. Cazzato, V. Domcke, M. Drewes, S. Eijima, O. Fischer, T. Frossard, B. Garbrecht, D. Gueter, T. Hambye, P. Hernández, H. Ishida, M. Kekic, J. Klaric, J. López-Pavón, M.L., J. Racker, N. Rius, V. A. Rubakov, J. Salvado, M. Shaposhnikov, A. Y. Smirnov, D. Teresi…

Two kinds of $\not{C}\not{P}$ processes

Lepton number conserving

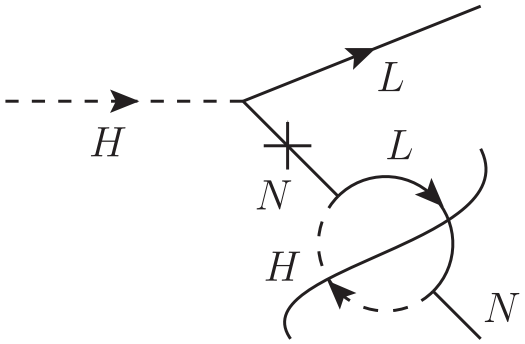
(neutrino generation and oscillations)



Lepton number violating

(thermal Higgs decay)

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



$$\propto \frac{M^2}{T^2}$$

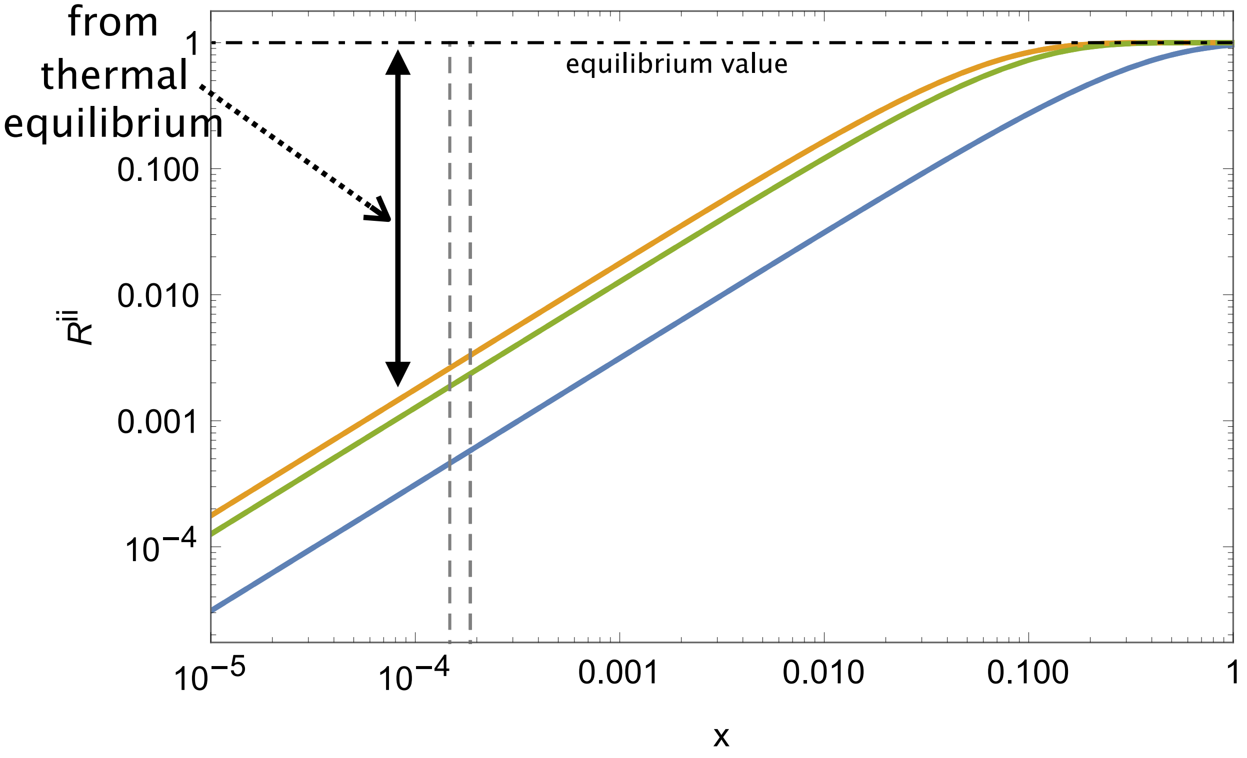
relevant at late times

Asymmetry generation example

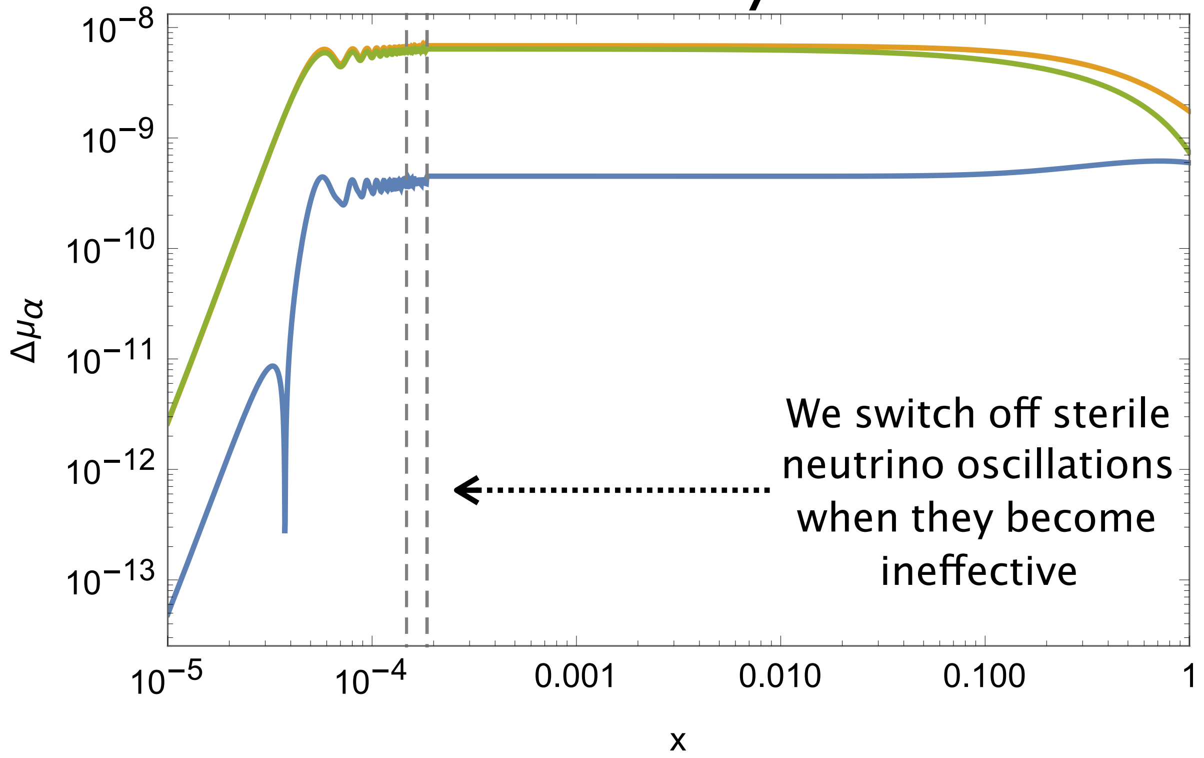
$x = \frac{T}{T_{\mathrm{EW}}}$ T_{EW} = 140 GeV R : sterile neutrinos density matrix μ_α : active flavours chemical potentials

Sterile neutrinos abundances

Deviation from thermal equilibrium

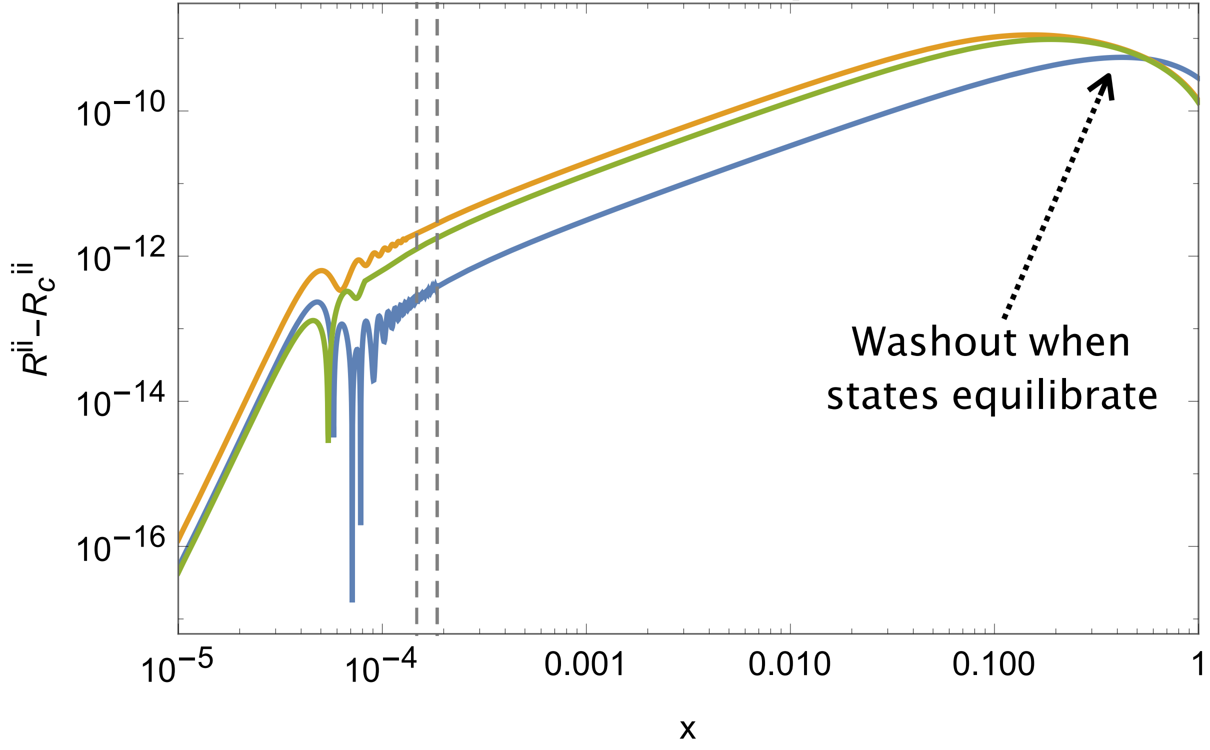


Active flavours asymmetries



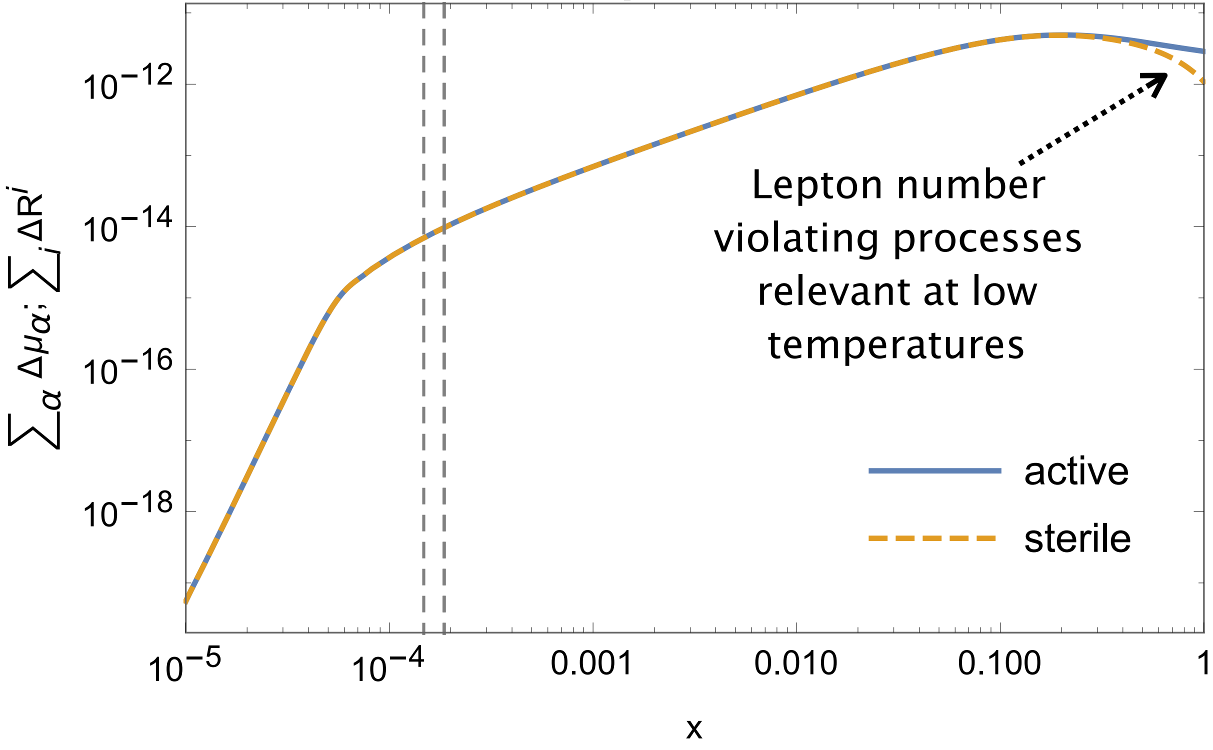
We switch off sterile neutrino oscillations when they become ineffective

Sterile flavours asymmetries



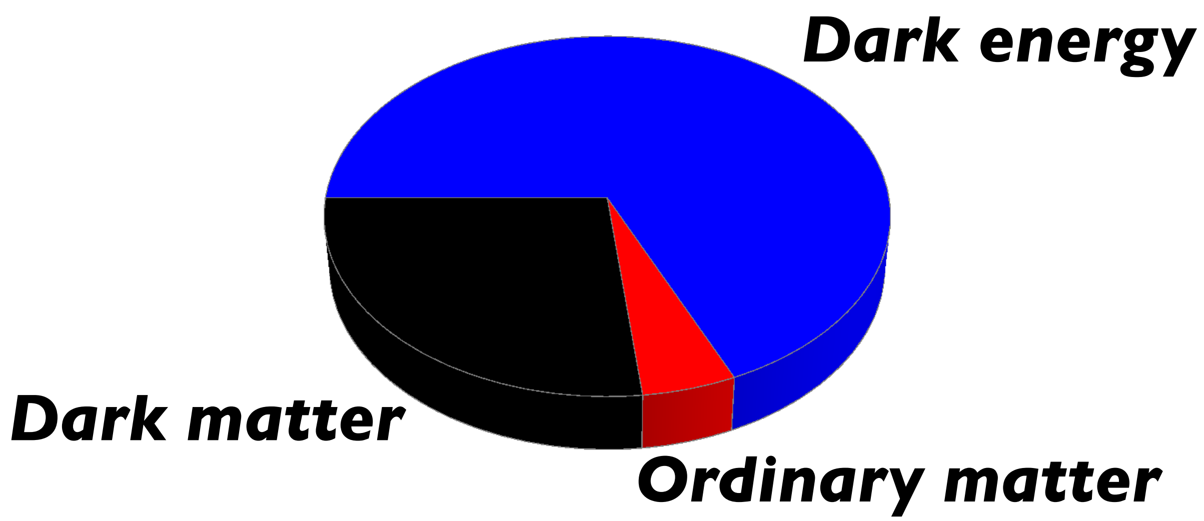
Washout when states equilibrate

Total asymmetries



Lepton number violating processes relevant at low temperatures

Neutrinos as Dark Matter?



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

$$h = 0.673 \pm 0.012$$

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

Constraints: abundance

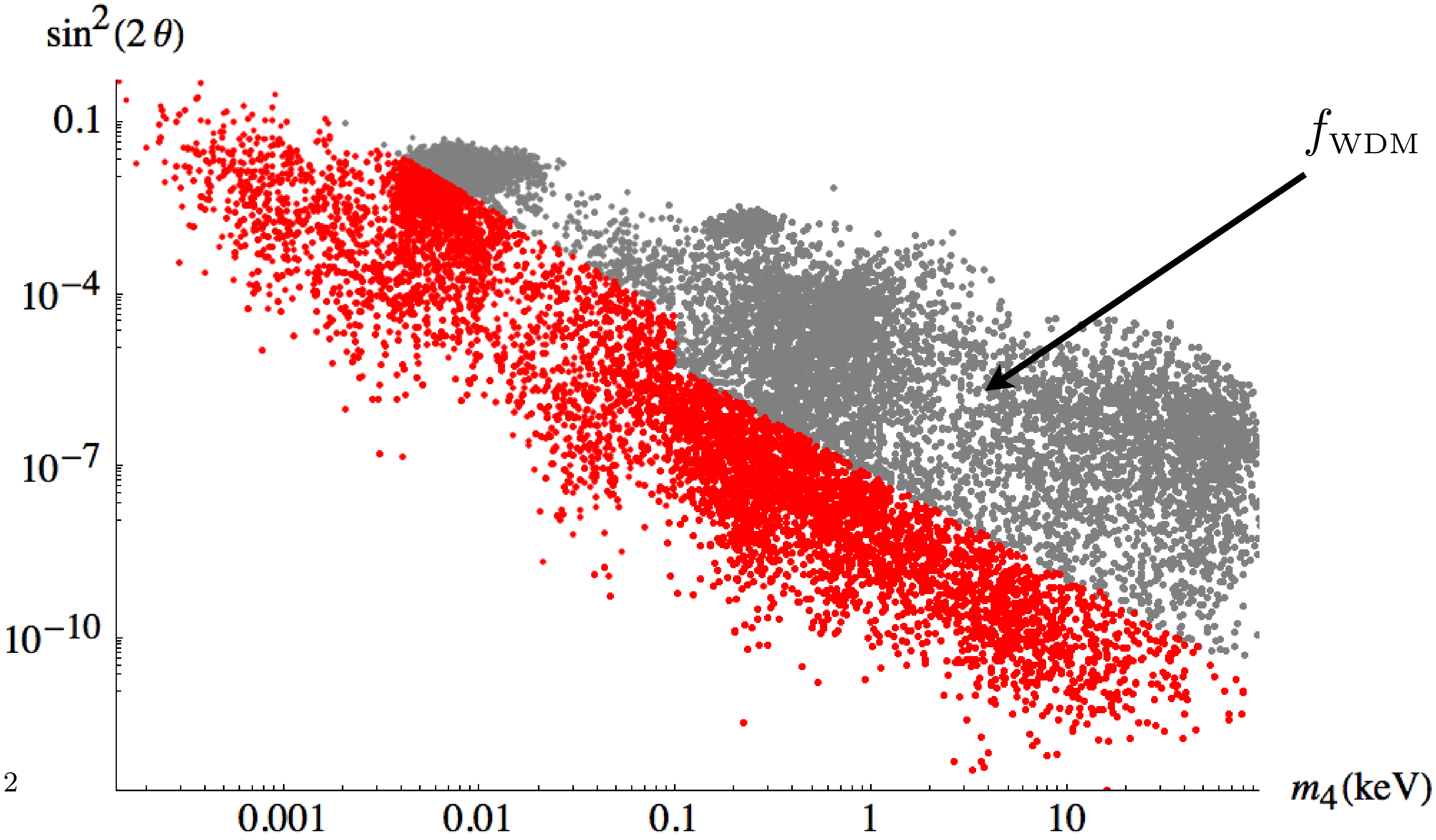
DW: as long as an active-sterile mixing is present, a population of sterile ν is produced by oscillations in the primordial plasma

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

Recent evaluation gives

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

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



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

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

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

Constraints: phase-space density

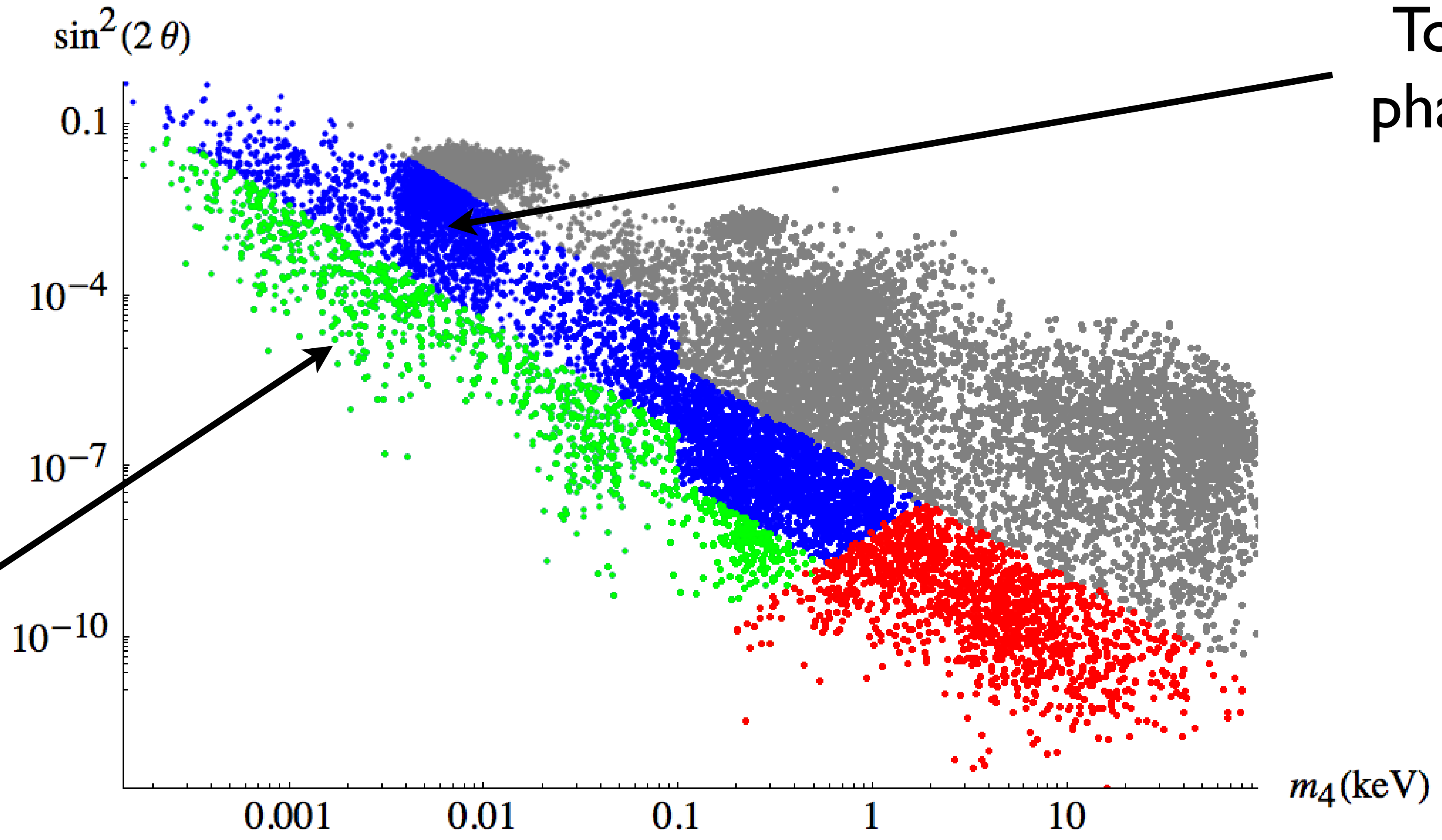
For fermionic DM, Pauli exclusion principle impose a maximum on its distribution function (degenerate Fermi gas). Imposing that inferred phase-space density does not excess this bound, it is possible to extract a lower bound on the DM mass

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

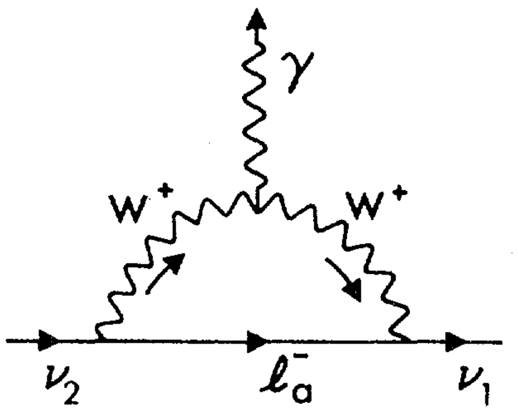
A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, 0808.3902 [hep-ph]

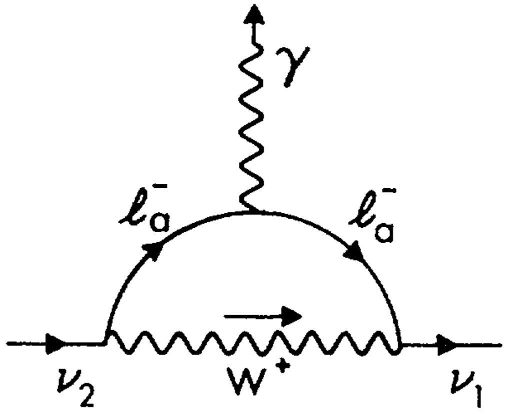


Too dense phase-space

Negligible abundance (< 1%)

Constraints: stability and indirect detection (ID)



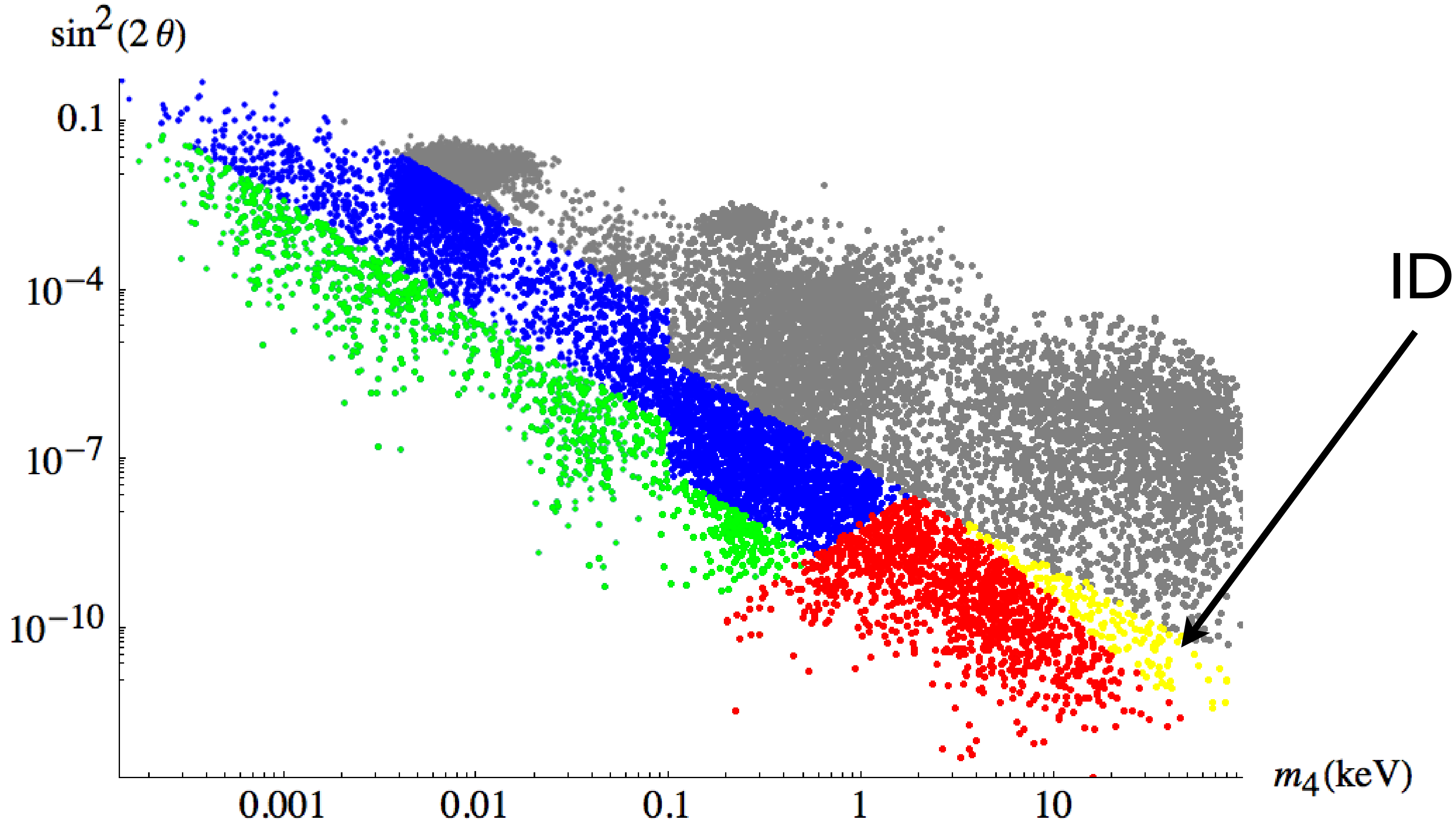


Massive ν can decay radiatively producing monochromatic γ

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

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

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



ID excluded

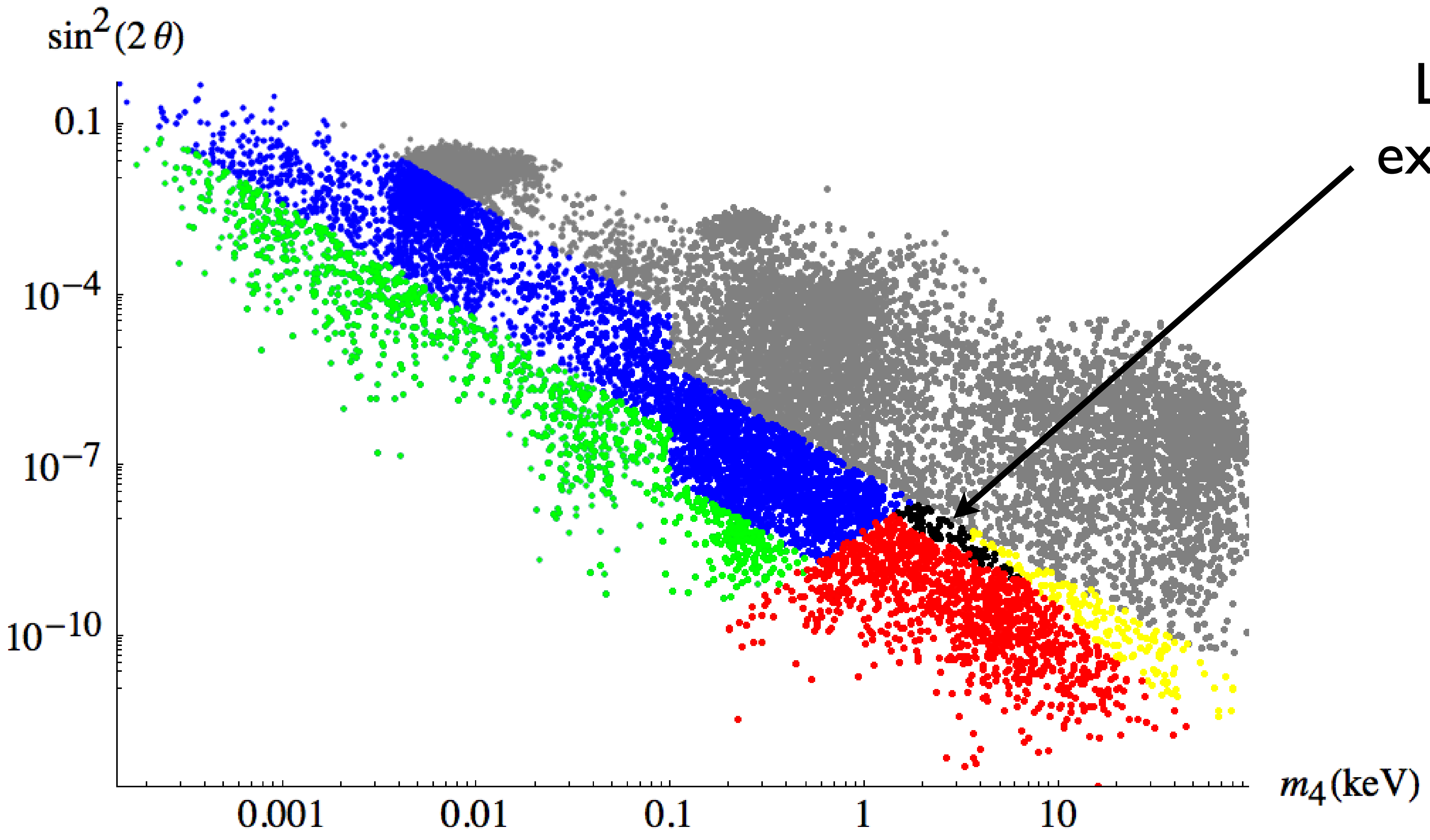
Constraints: Lyman-α

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

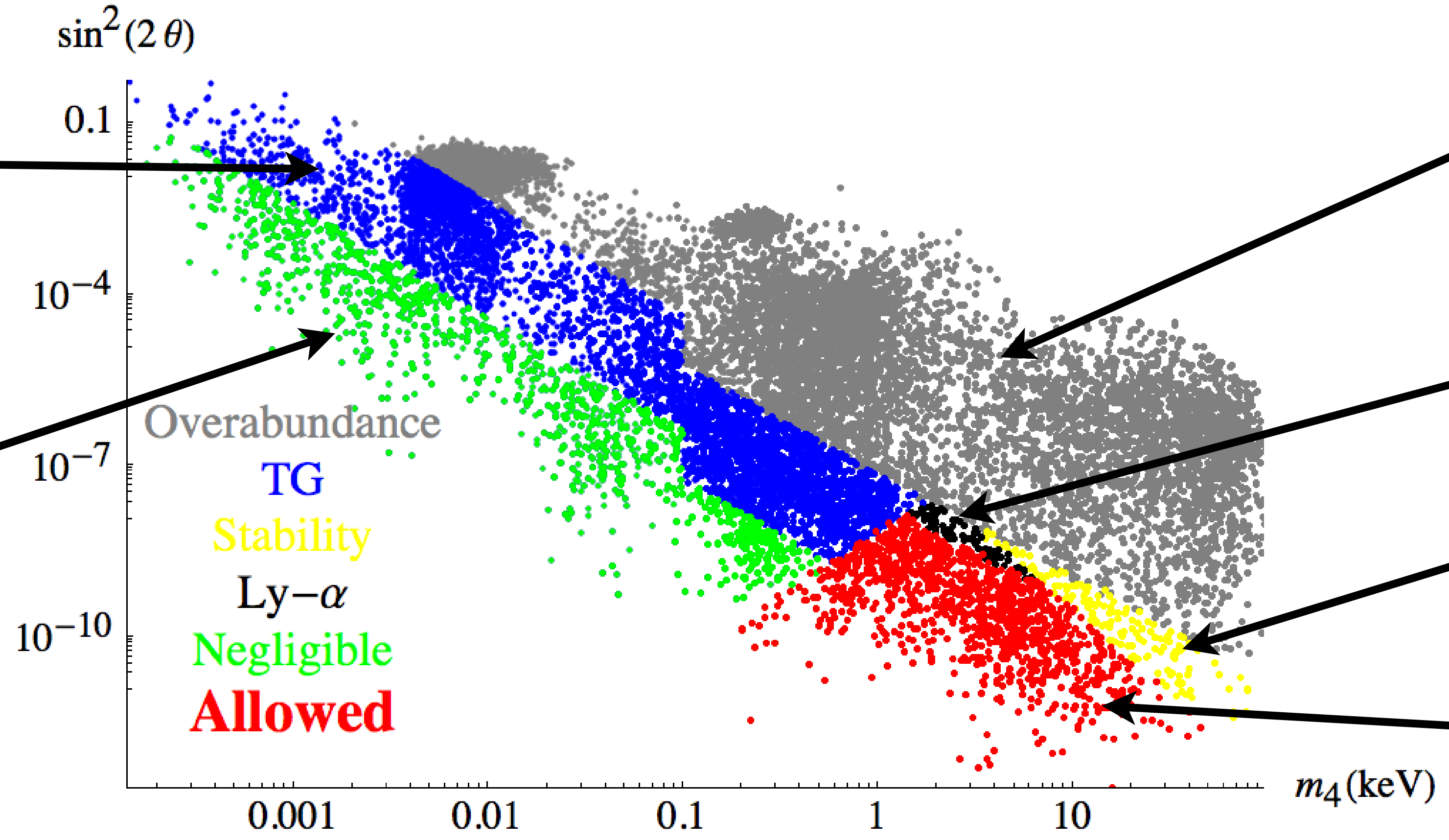
A. Boyarsky, J. Lesgourgues, O. Ruchayskiy and M. Viel, 0812.0010 [astro-ph]



Ly-α exluded

WDM constraints

DW produced sterile ν are warm dark matter



Too dense phase-space

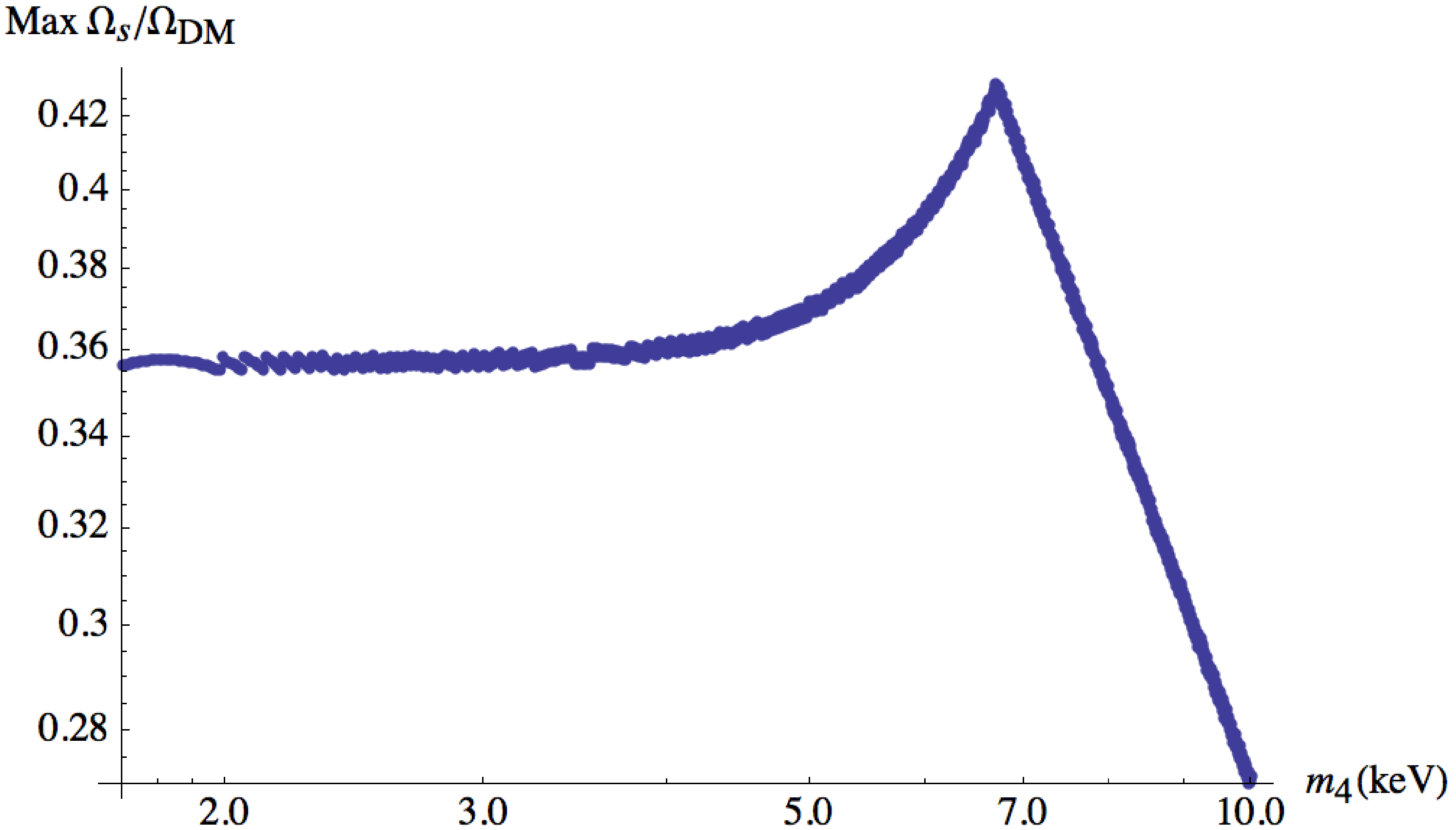
Negligible abundance (< 1%)

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

Ly-α exluded

ID excluded

Allowed region

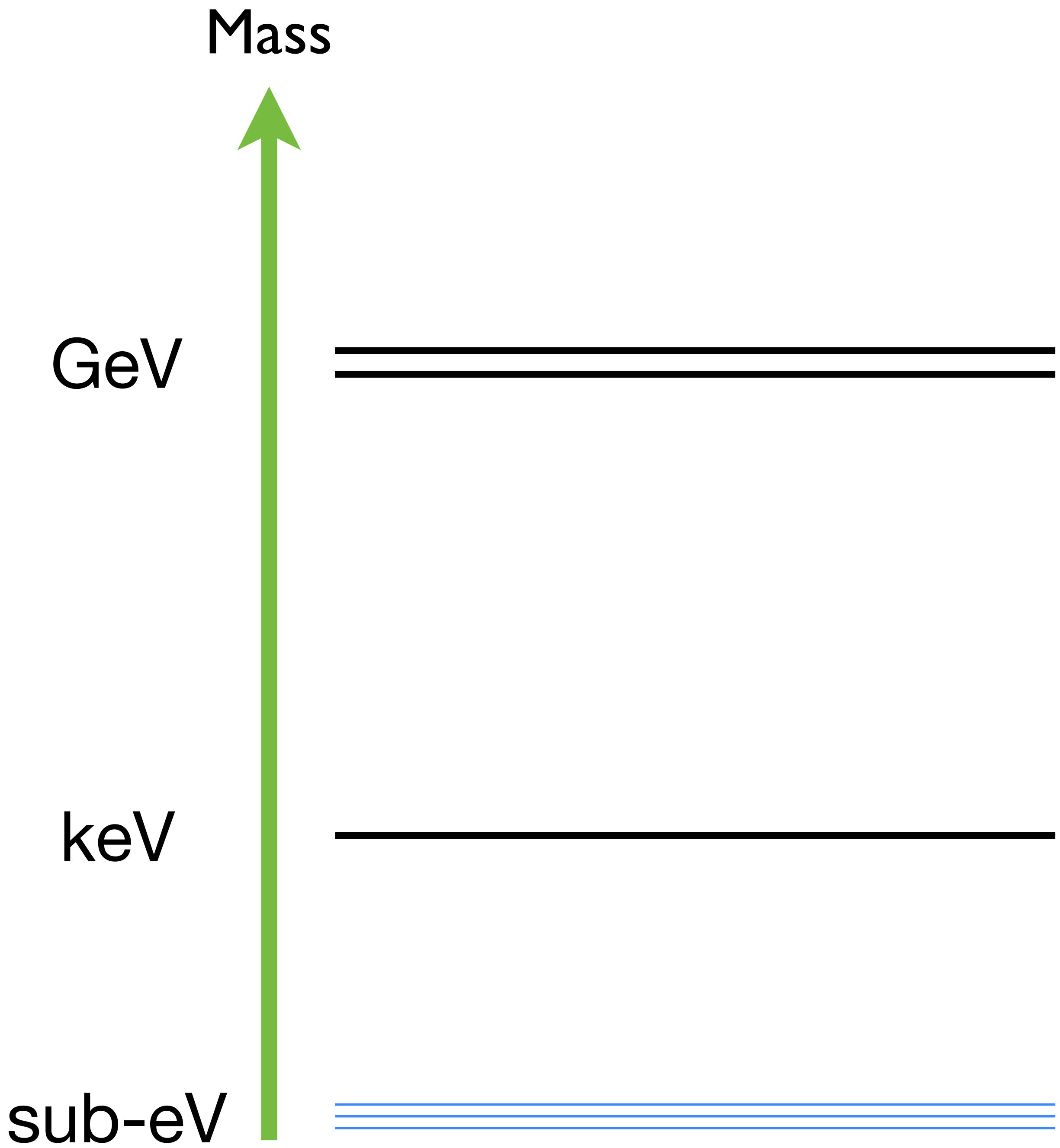


Sterile ν produced via **DW cannot** account for the 100% of the **observed DM abundance**

The νMSM

T. Asaka, S. Blanchet and M. Shaposhnikov, hep-ph/0503065
T. Asaka and M. Shaposhnikov, hep-ph/0505013
M. Shaposhnikov and I. Tkachev, hep-ph/0604236

Type-I Seesaw with a phenomenologically motivated mass spectrum



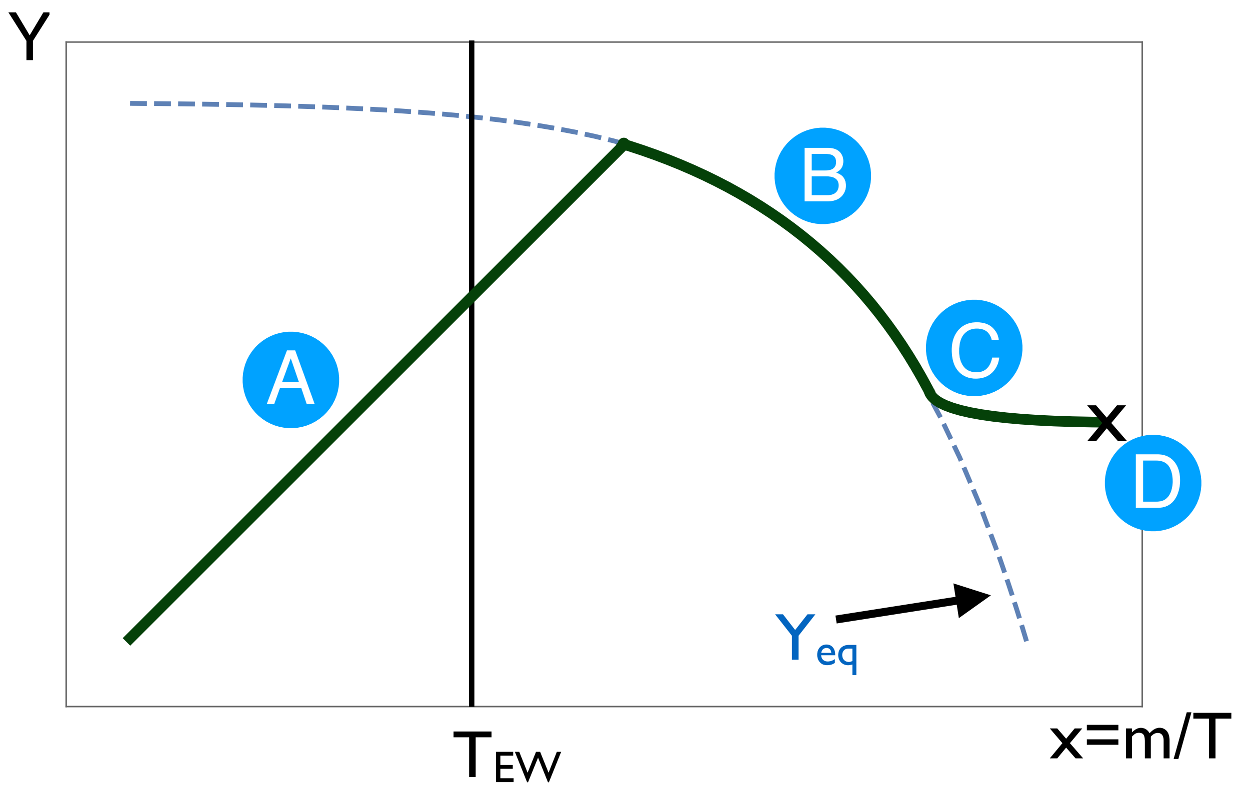
At the origin of the lepton **asymmetries** of the Universe and of **neutrino masses**

Dark matter candidate
(does not significantly contribute to ν masses)

Active neutrinos

νMSM thermal history

L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]



T

zero abundance of N_I

thermal production of N_2, N_3 **A**
→ lepton asymmetry generated

200 GeV T_{EW} **Electroweak Symmetry Breaking**
→ lepton Asymmetry converted to baryon asymmetry

T_+ N_2, N_3 reach equilibrium **B**
→ lepton asymmetry washed out

few GeV T_- N_2, N_3 freeze out **C**
→ lepton asymmetry generated

T_d N_2, N_3 decay **D**
→ lepton asymmetry generated

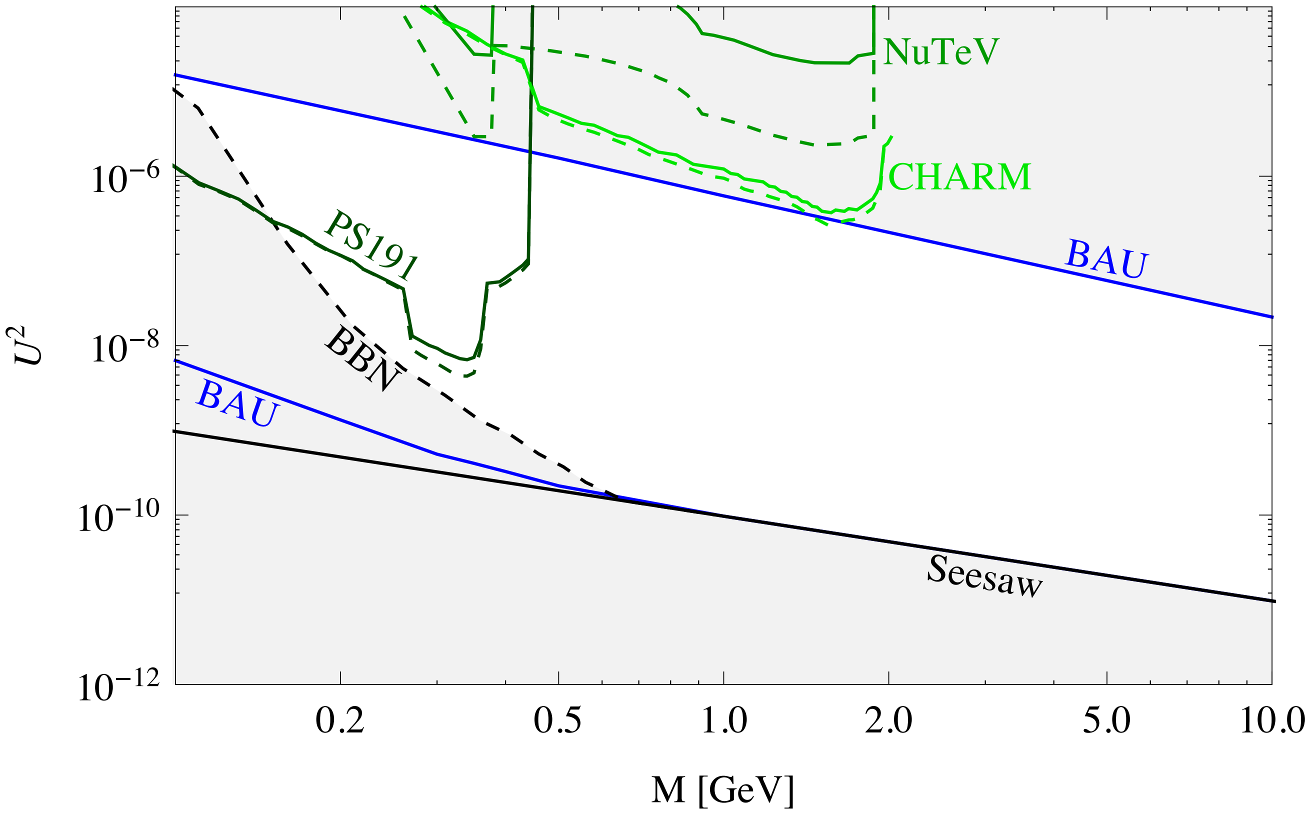
100 MeV T_{DM} **resonant N_1 Dark Matter production**

t

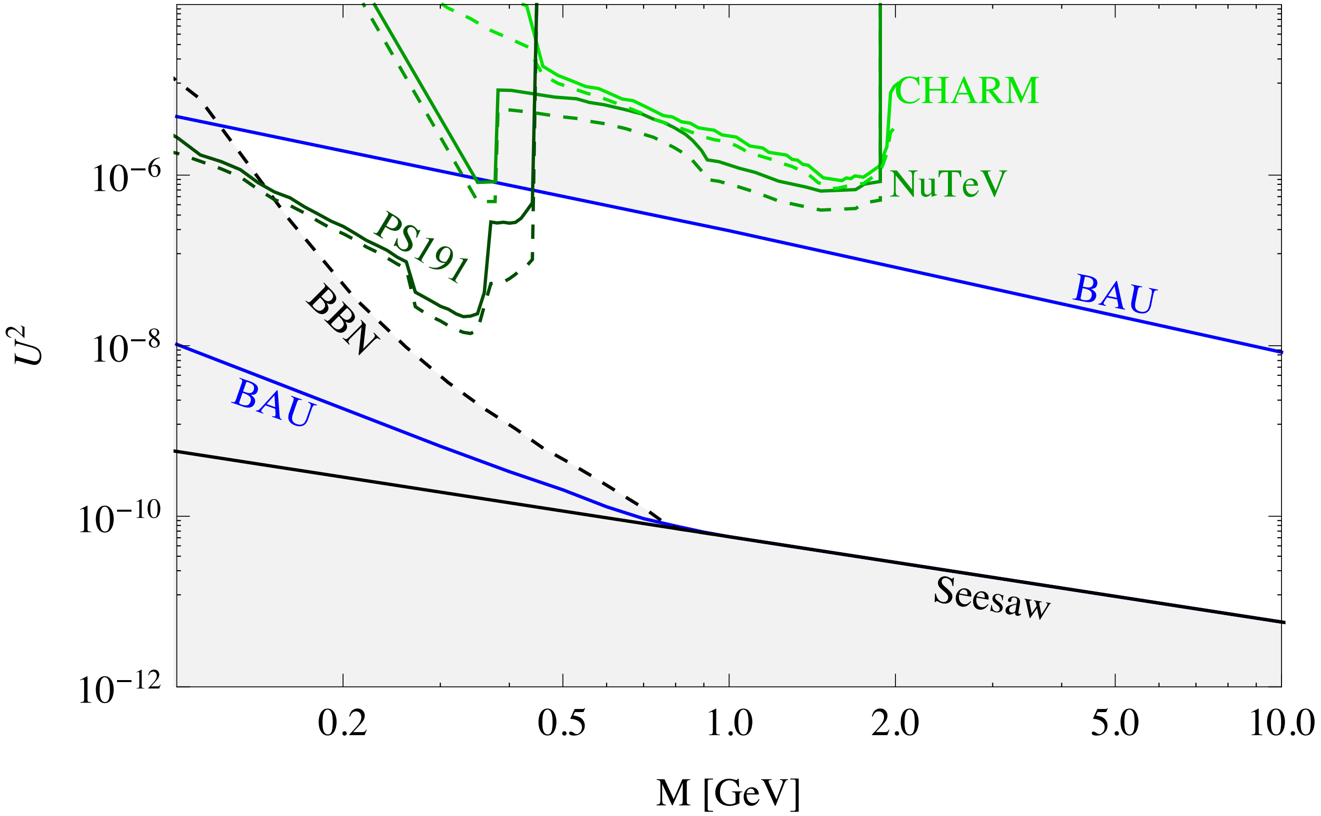
νMSM baryogenesis solution

L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]

Normal hierarchy



Inverted hierarchy



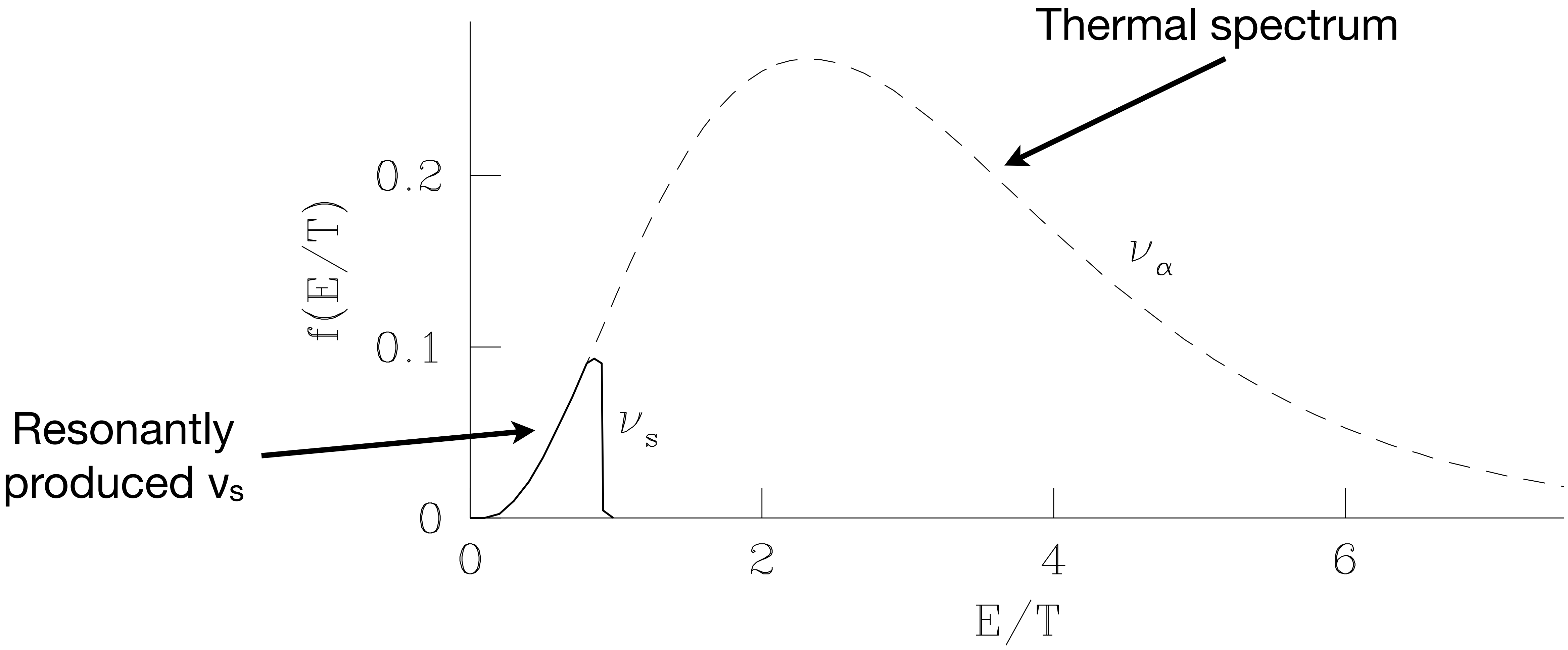
Required mass degeneracy

$$\frac{\delta M}{M} \lesssim 10^{-3}$$

νMSM dark matter solution

Shi-Fuller mechanism: **lepton number-driven resonant** MSW conversion of active neutrinos

X. D. Shi and G. M. Fuller, astro-ph/9810076



Required lepton asymmetry

$$\mu_\alpha = \frac{n_\alpha}{s} \gtrsim 8 \cdot 10^{-6}$$

Required mass degeneracy

$$\frac{\delta M}{M} \lesssim 10^{-14}$$

The Inverse Seesaw (ISS)

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:
- #ν_L + (#s - #ν_R) light states
- #ν_R pseudo-Dirac couples

Mass

E.g.

2 #ν_R heavy states
(pseudo-Dirac pairs)

$\approx \mathcal{O}(n)$

TeV
(testable)

only if #s > #ν_R
(#s - #ν_R) light sterile states

$\sim \mathcal{O}(\mu)$

eV

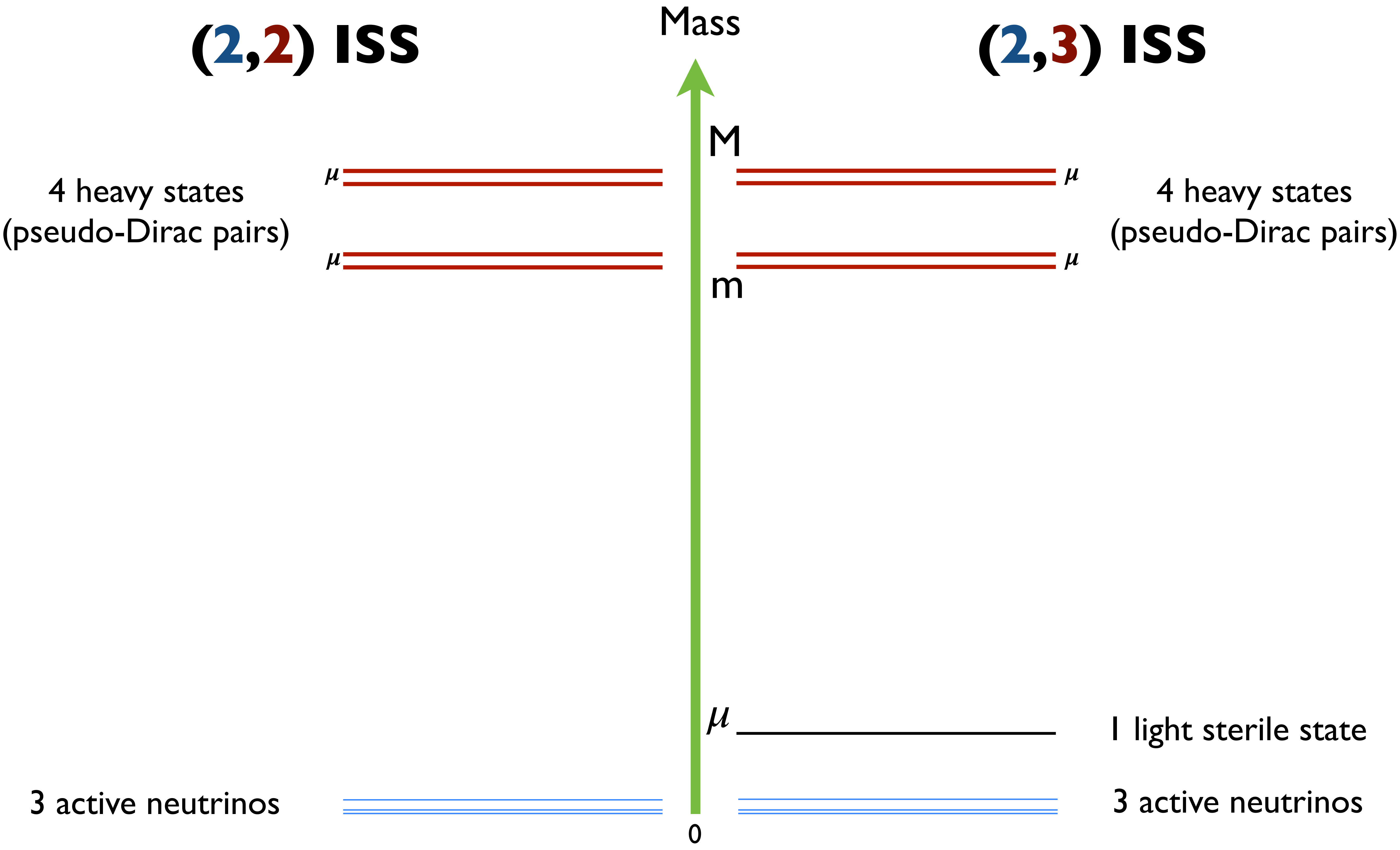
#ν_L active neutrinos

$\sim \mathcal{O}(\mu)\mathcal{O}(k)$

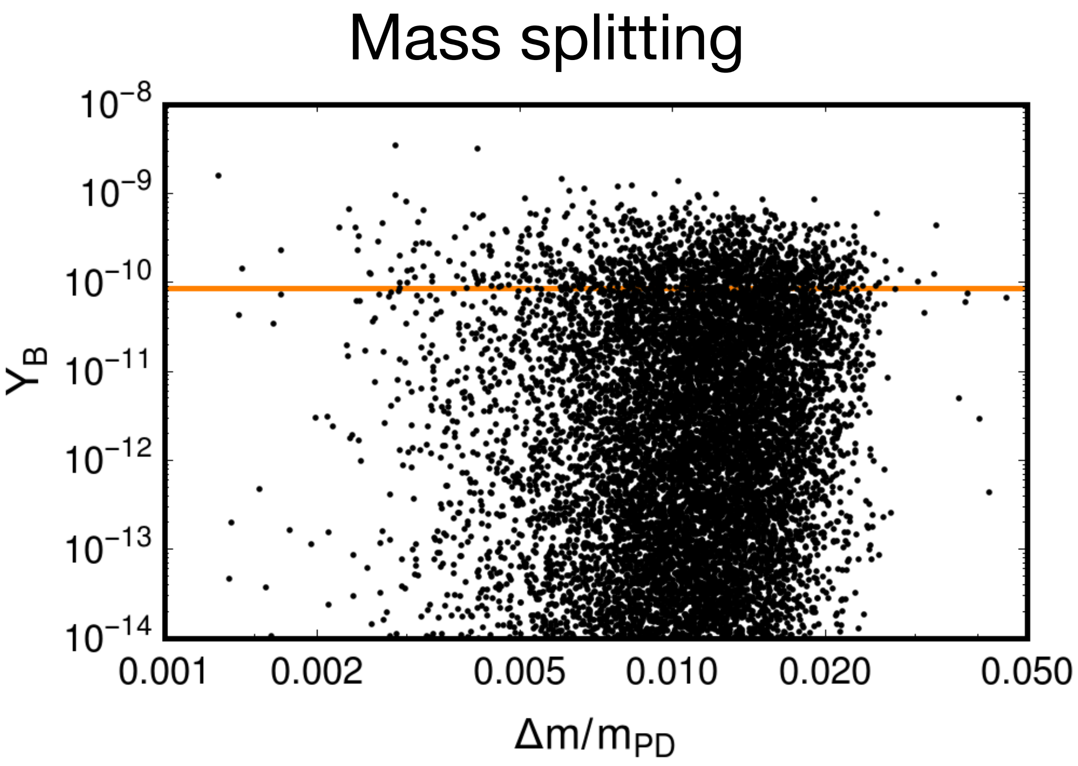
meV

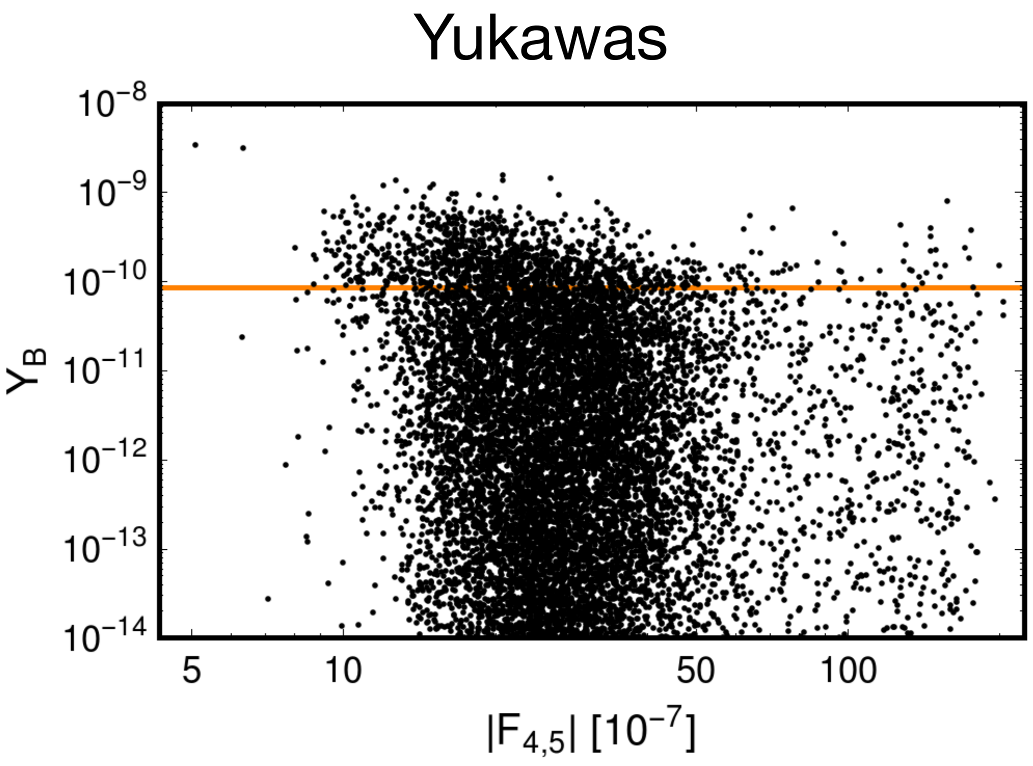
$$k = \frac{|d|}{|n|}$$

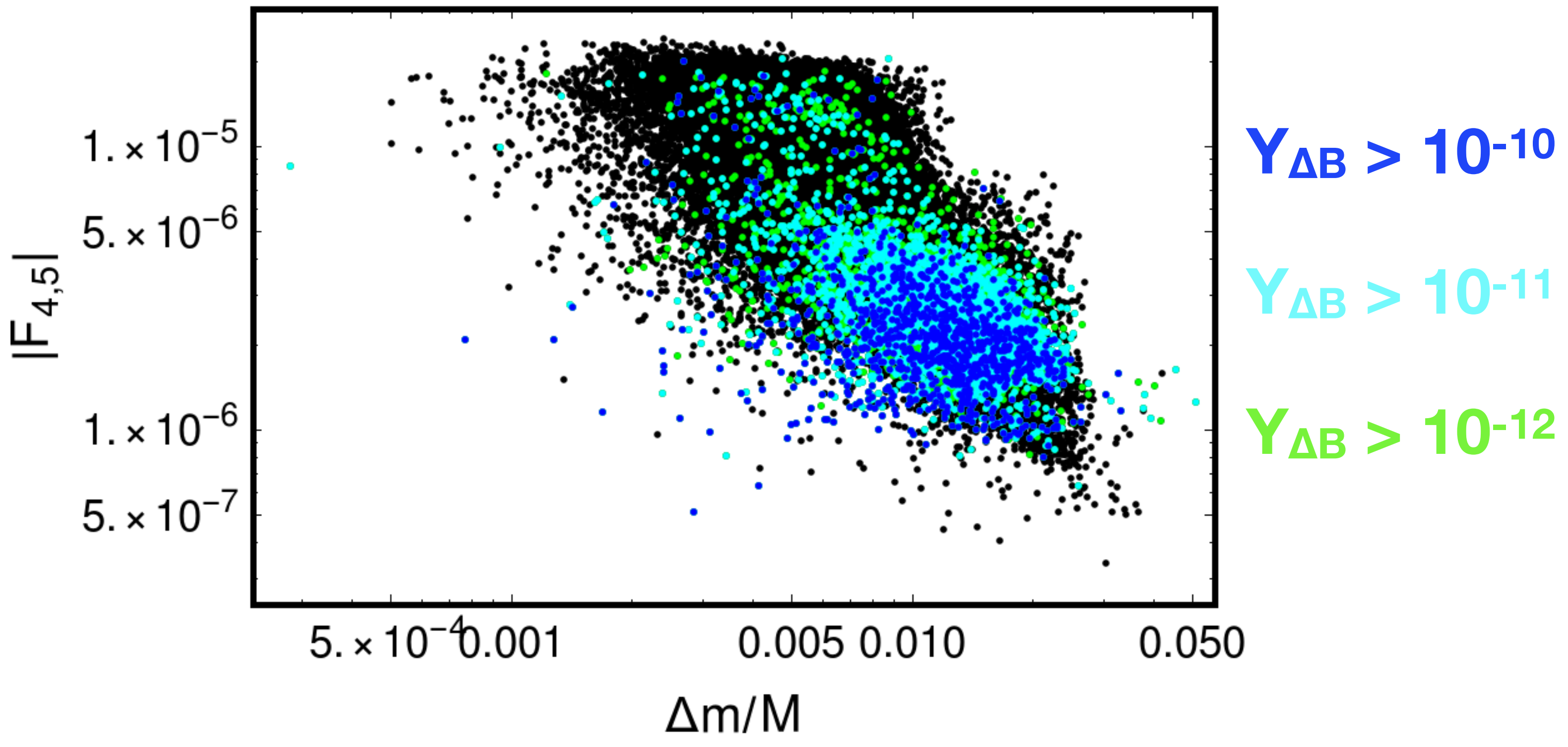
Minimal ISS spectra



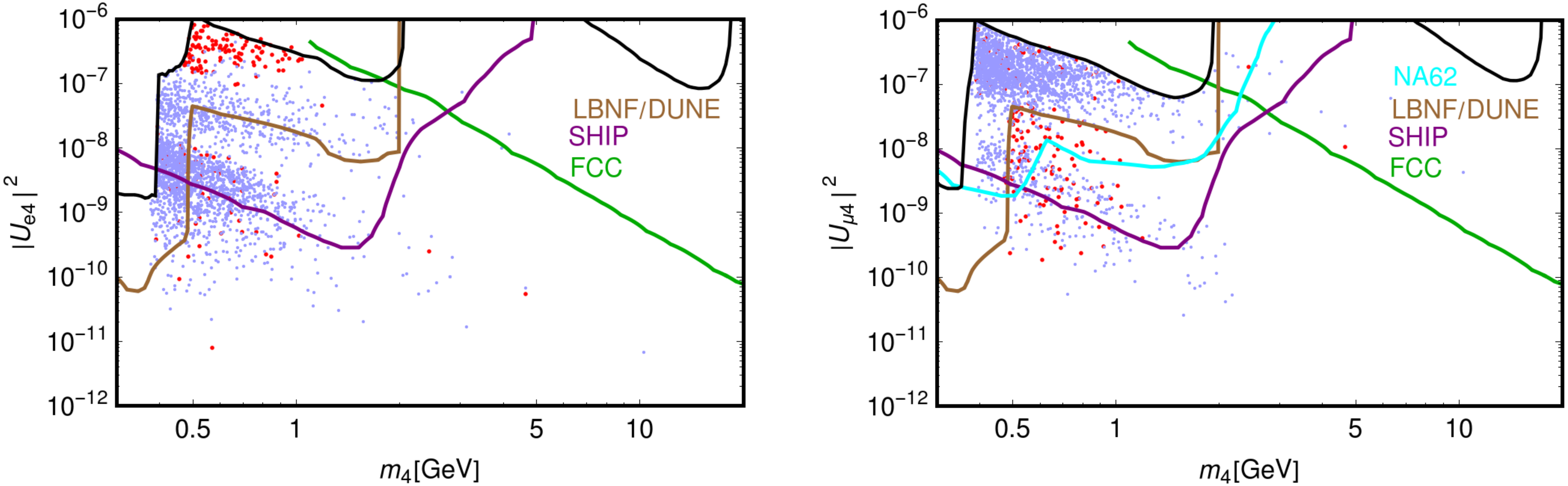
ARS leptogenesis in the (2,2) ISS


Mass splitting


Yukawas



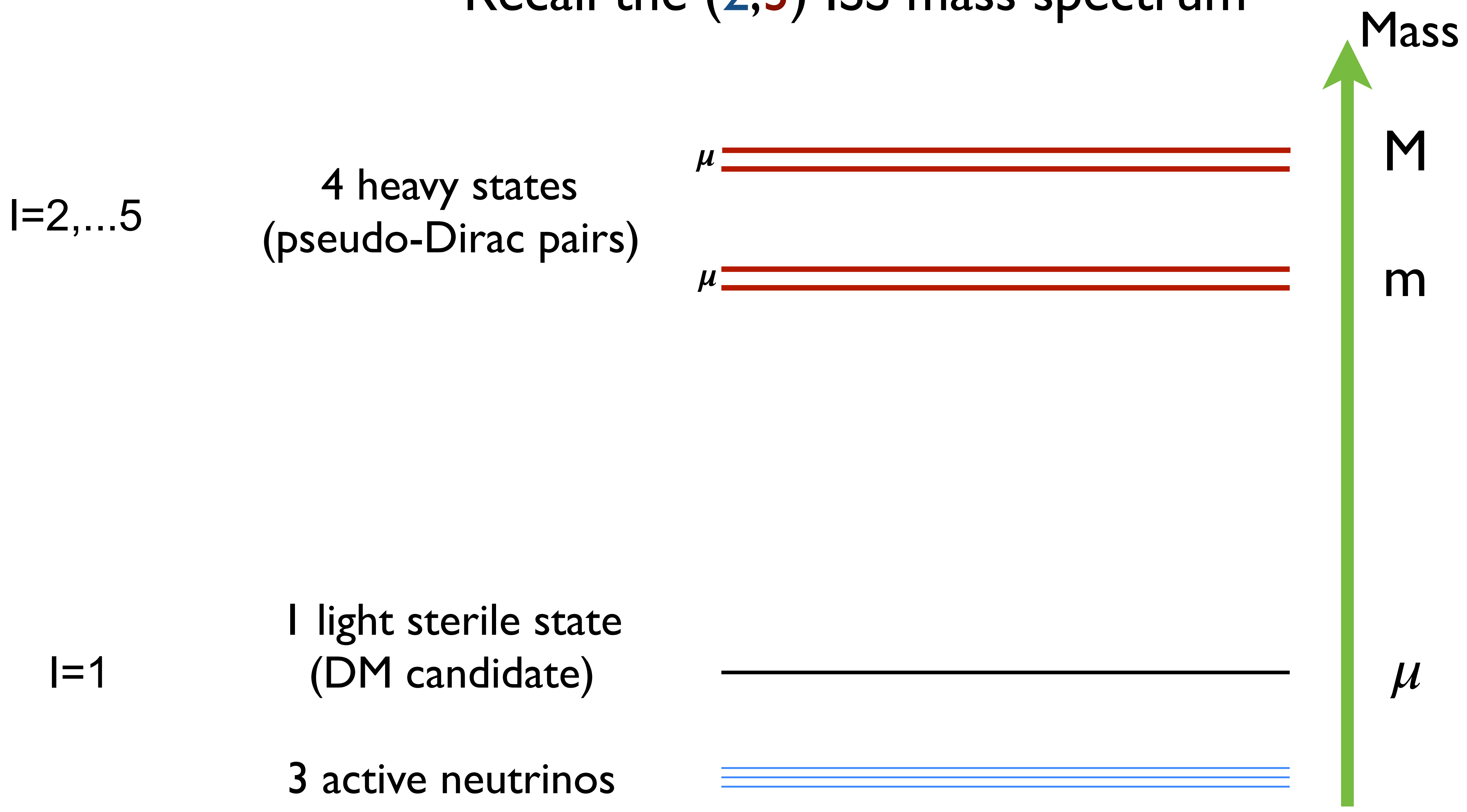
Testability



A large fraction of solutions is testable in future experiments

Towards a dark matter solution

Recall the (2,3) ISS mass spectrum



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

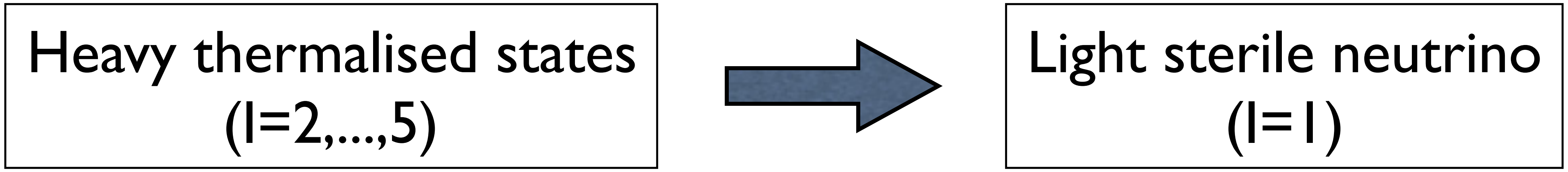
⬇

Heavy states can thermalise in the early Universe

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

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

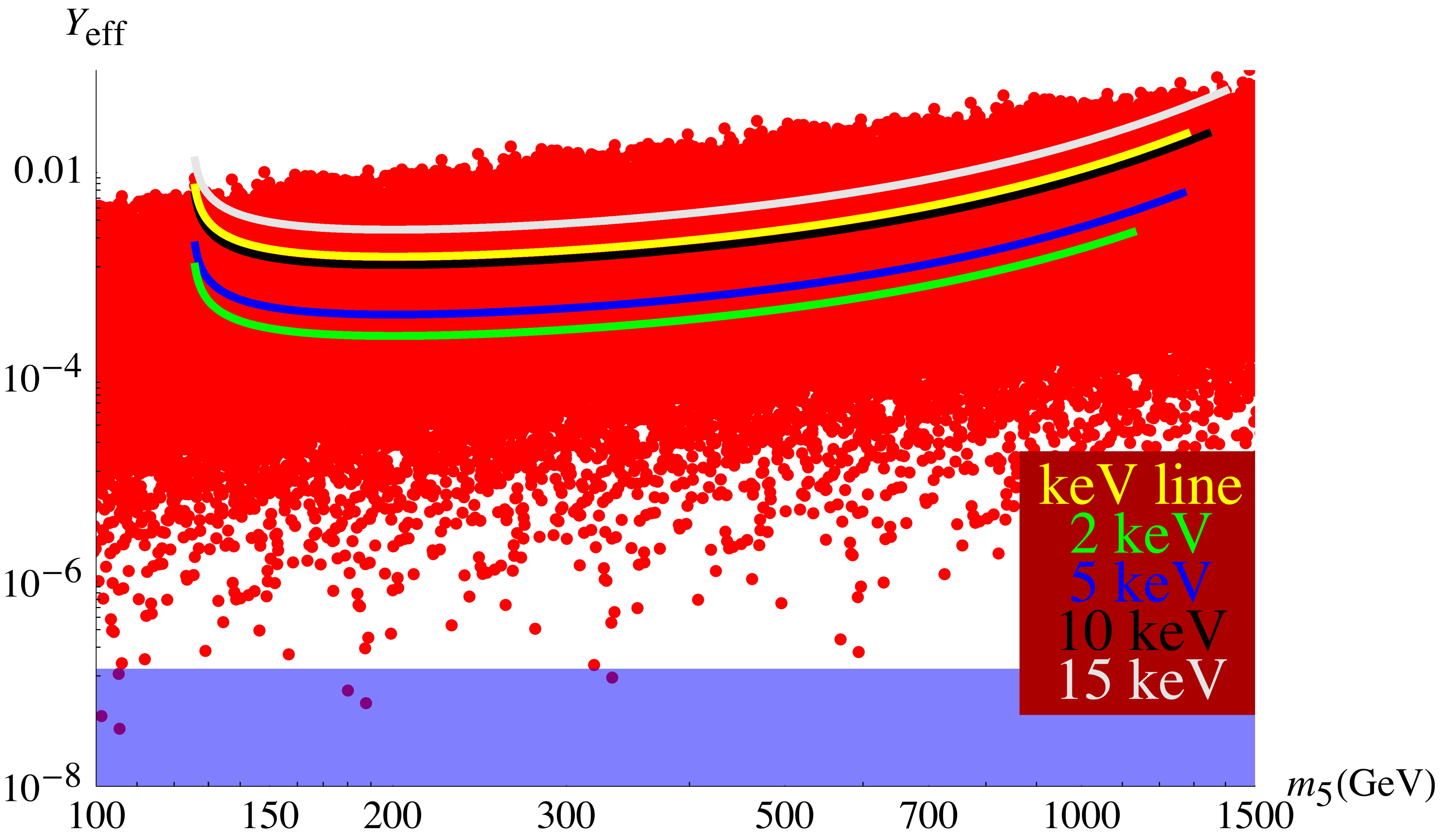
$$\Gamma \left(N_I \to h \ + \ {\rm DM}\right) = \frac{m_I}{16\pi} Y_{\rm eff,I}^2 \sin^2\theta \left(1 - \frac{m_h^2}{m_I^2}\right)$$

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

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

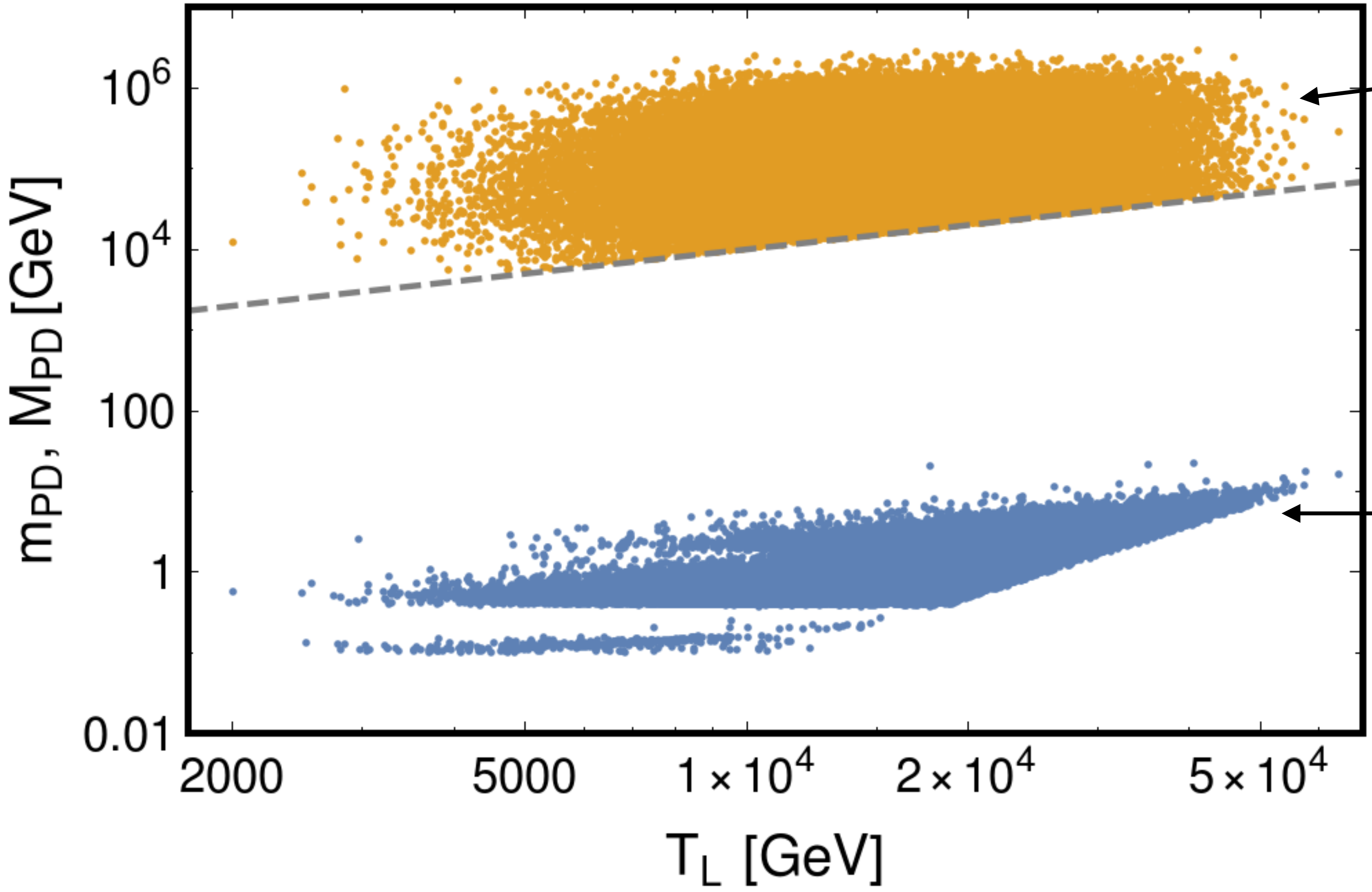
The spectrum of the produced DM is “colder” than the DW one, evading the Ly-α bounds

Dark Matter Production in the (2,3) ISS



Split ISS

One **heavier** pseudo-Dirac pair at the origin of **DM**,
one **lighter** other accounting for **leptogenesis**?



Freeze-in DM?

Leptogenesis?

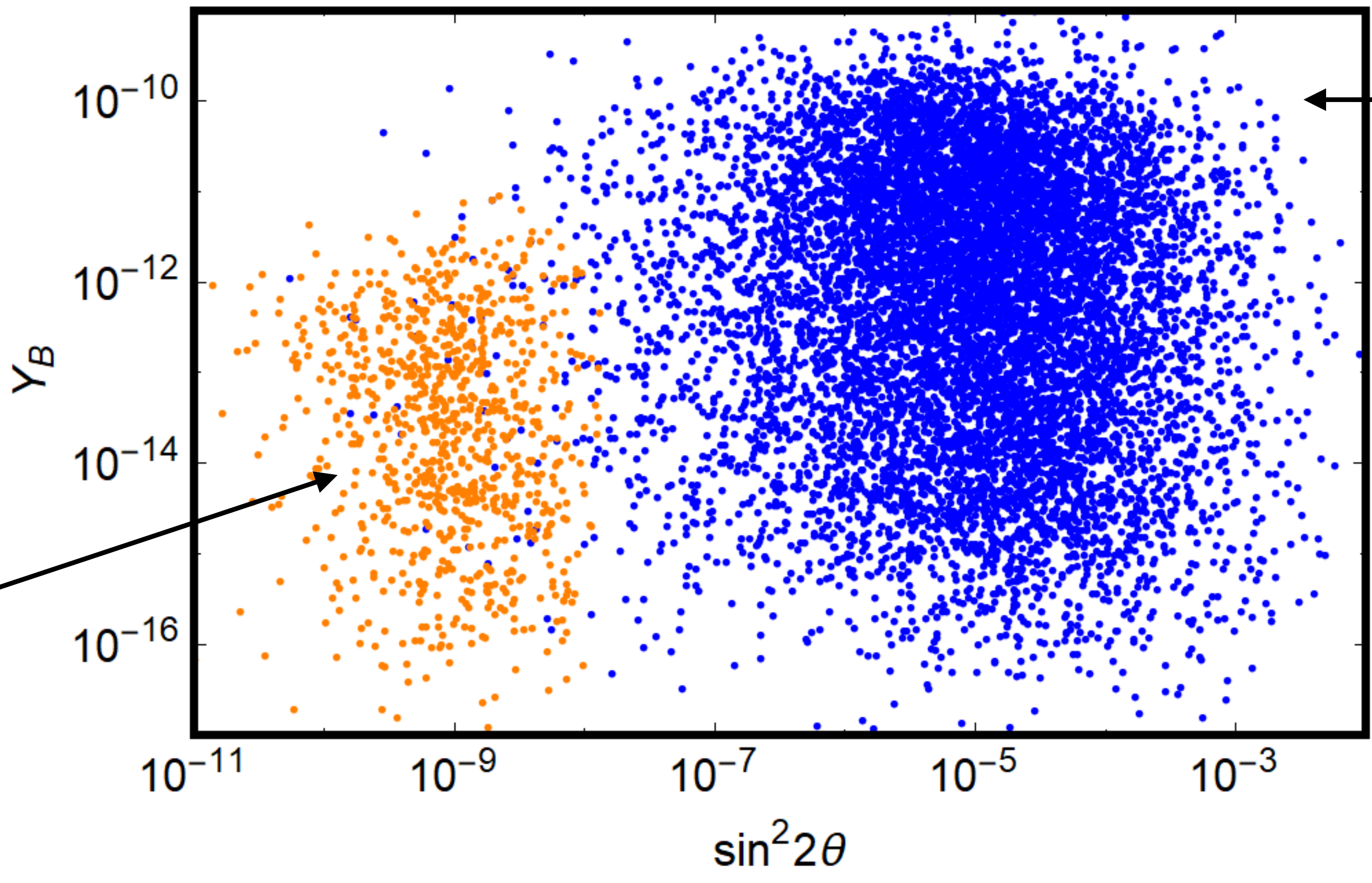
In the Inverse Seesaw

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

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

Sterile fermions can provide a common
solution to the SM observational problems:

- **neutrino masses**
- **dark matter**
- **baryogenesis**

The **νMSM** provides a **minimal common solution** for the three problems, but results to be quite **fine-tuned**

The **ISS** provides **simultaneous** solutions for **neutrino** physics and **DM or** for **neutrino** physics and **BAU**, but **BAU** and **DM solutions** appear in **different regions of the parameter space**

Backup

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