Sterile neutrinos and implications for dark matter

Michele Lucente

GDR Neutrino, June 17th 2014

Based on:

A. Abada and M.L., *arXiv:1401.1507 [hep-ph]* (accepted on *Nucl.Phys.B.*)
A. Abada, G. Arcadi and M.L., *in preparation*

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:

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

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

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

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 (ν 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

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);

E.g.

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

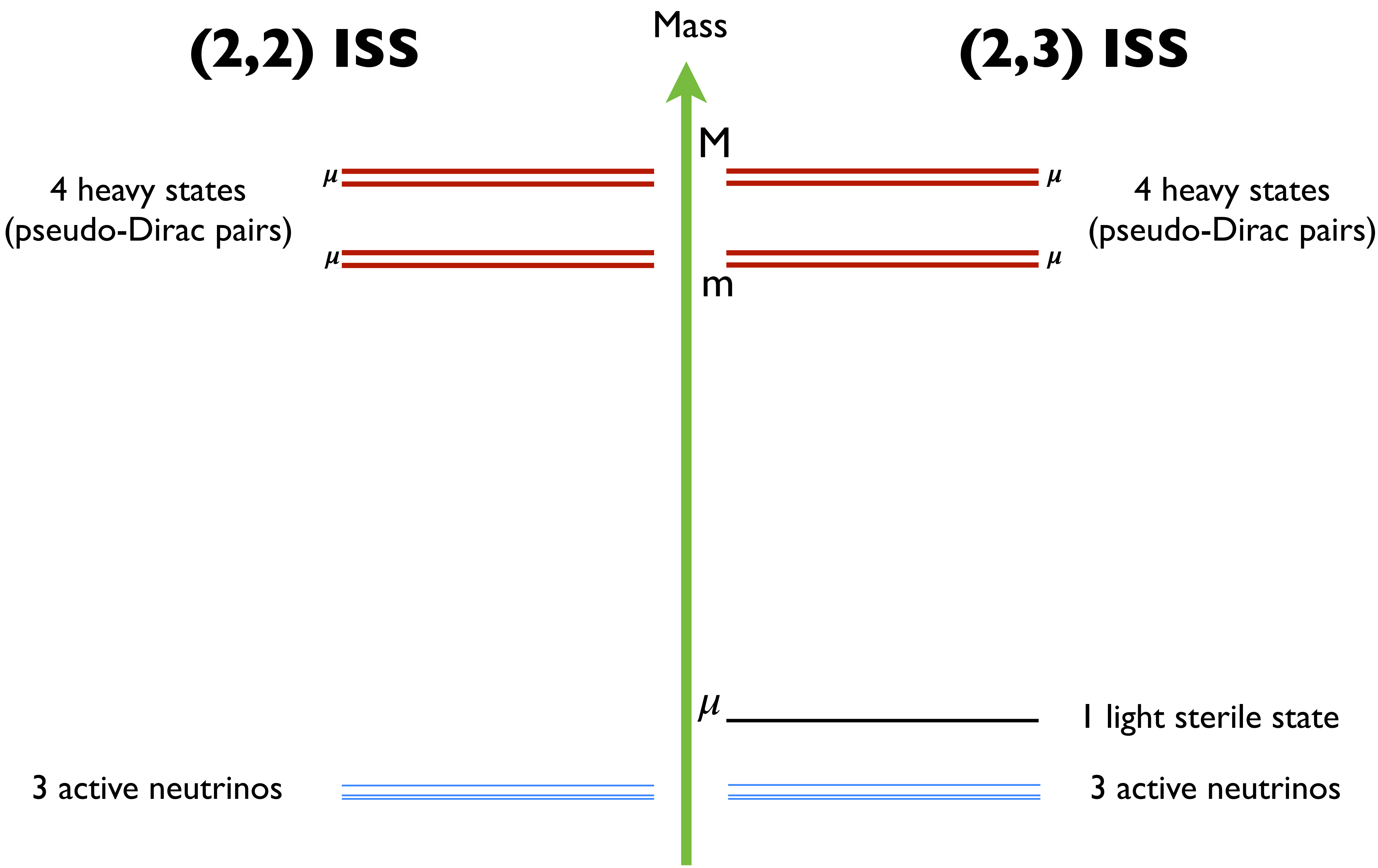
only if $\#s > \#\nu_R$

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

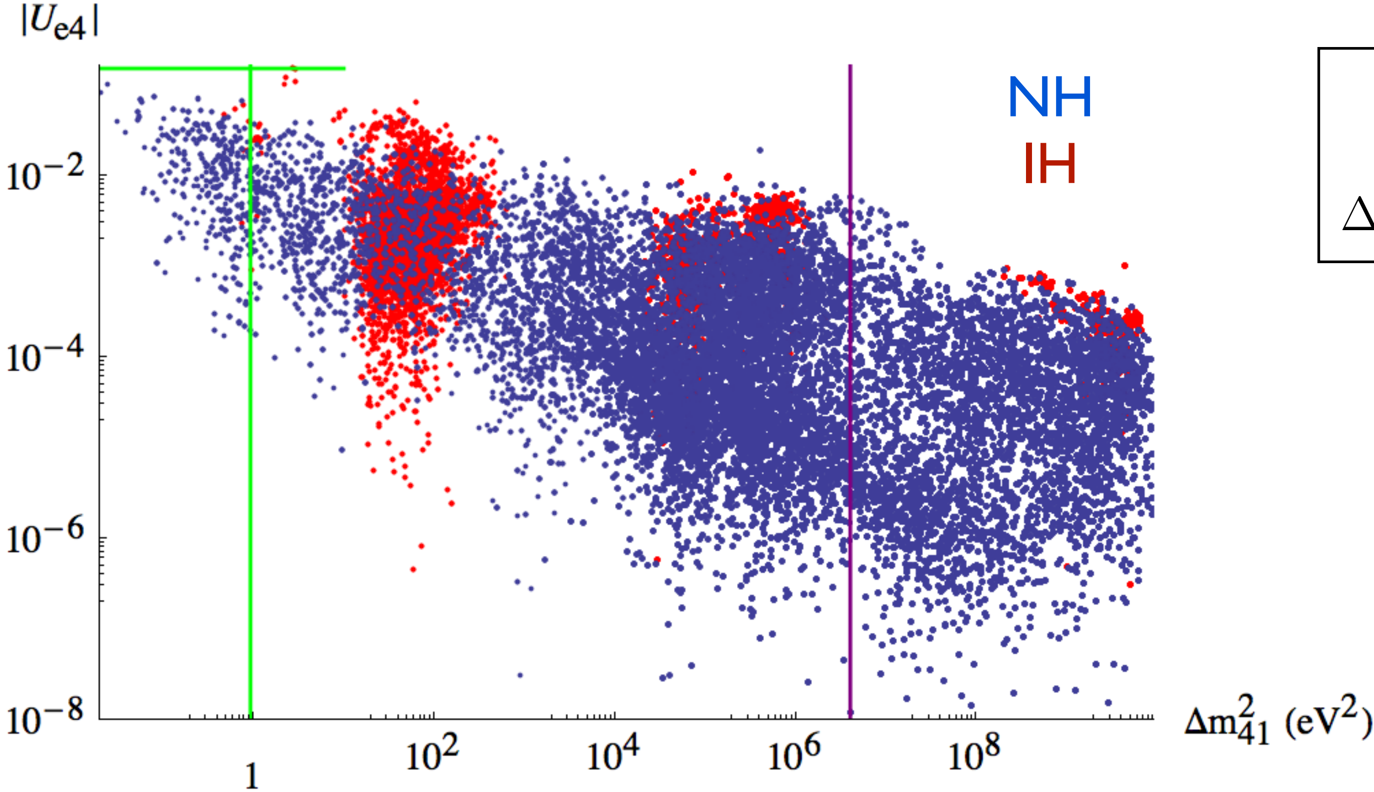
$\#\nu_L$ active neutrinos — $\sim \mathcal{O}(\mu)\,\mathcal{O}(k^2)$ — meV

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

Minimal ISS spectra



(2,3) ISS: light sterile state



(3+1) best-fit points

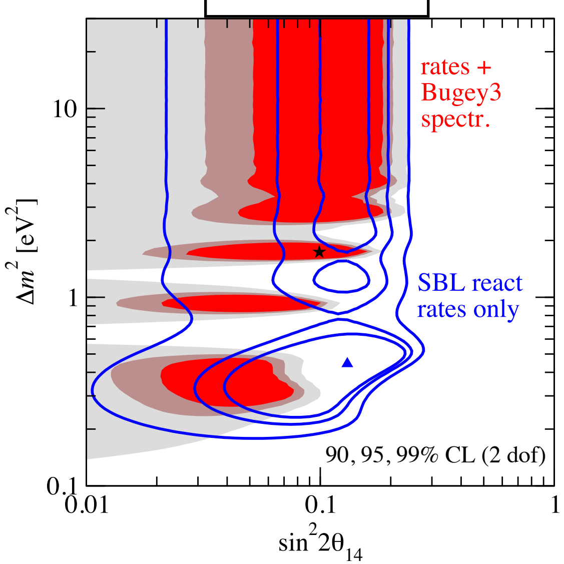
hep-ph:1303.3011

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

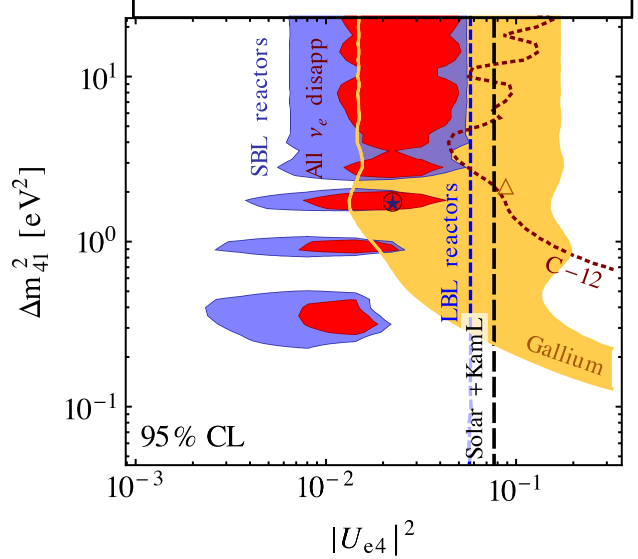
de Vega, Sanchez: astro-ph.CO:1304.0759

$m_{DM} \approx 2$ KeV

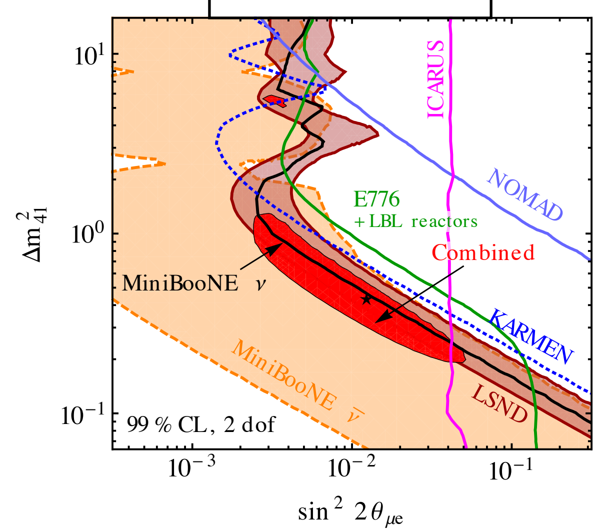
SBL reactors



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



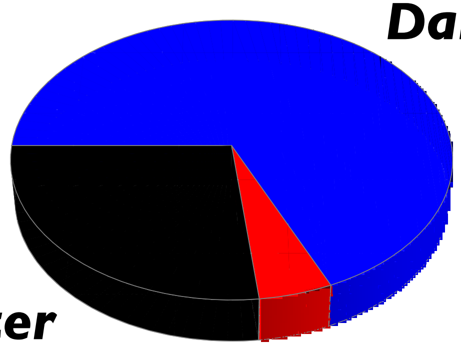
SBL accelerators



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

Sterile ν as Dark Matter

The Cosmic Pie:



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

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

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

$$h = 0.673 \pm 0.012 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

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

Sterile neutrinos could be viable DM candidates

Constraints: abundance

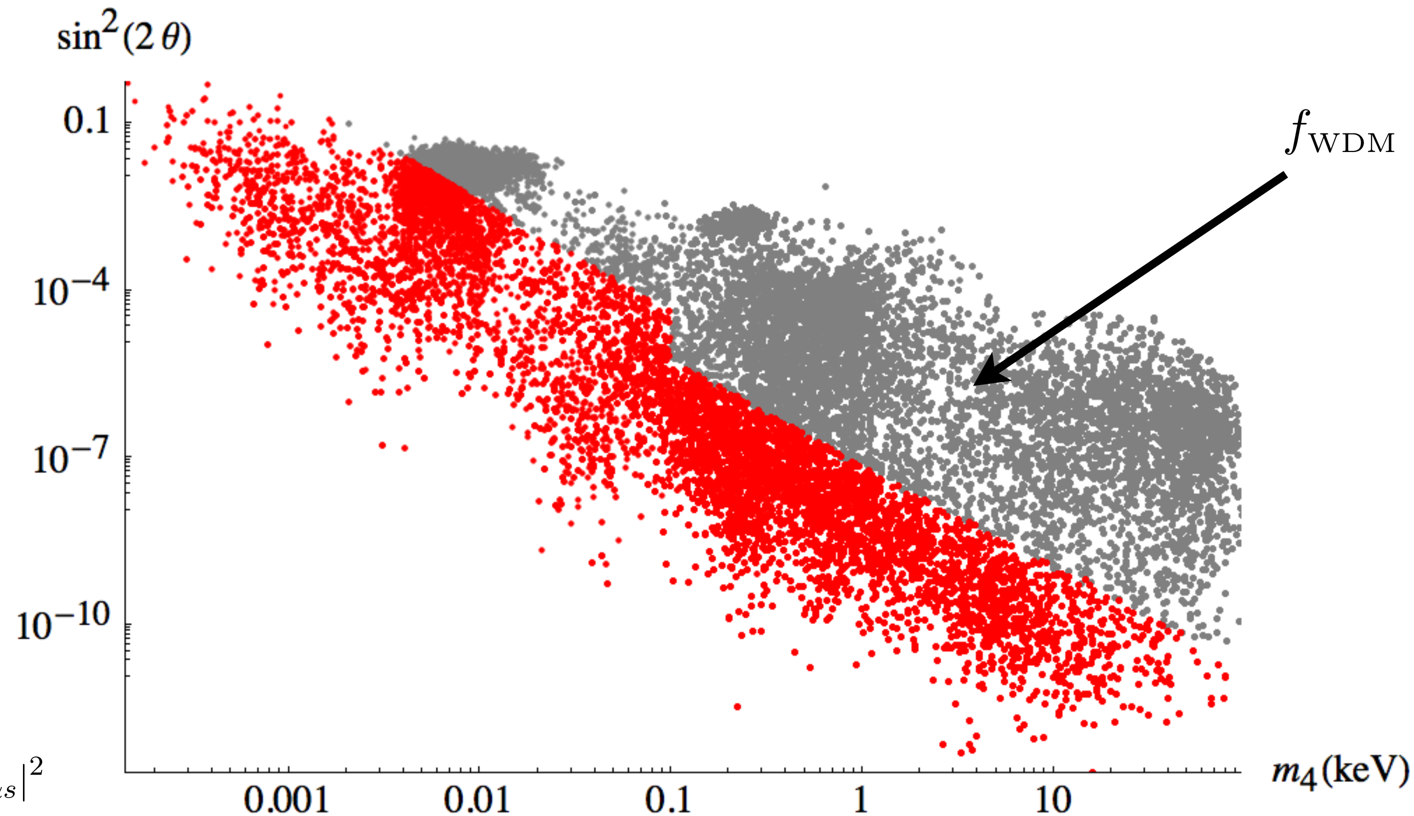
DW: as long as an active-sterile mixing is present, a population of sterile ν is produced by oscillations in the primordial plasma

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

Recent evaluation give

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

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



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

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

Constraints: phase-space density

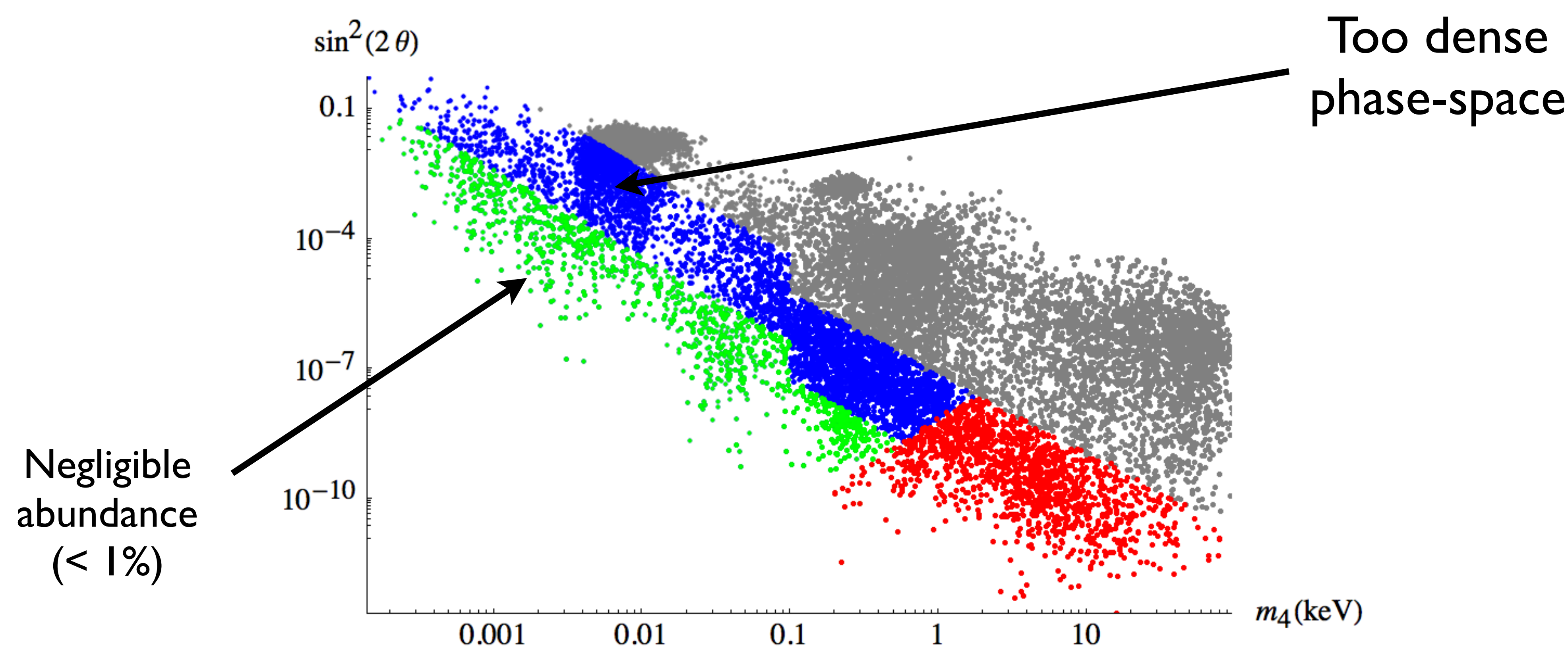
For fermionic DM Pauli exclusion principle impose a maximum on its distribution function (degenerate Fermi gas). Imposing that inferred phase-space density do not excess this bound it is possible to extract a lower bound on the DM mass

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

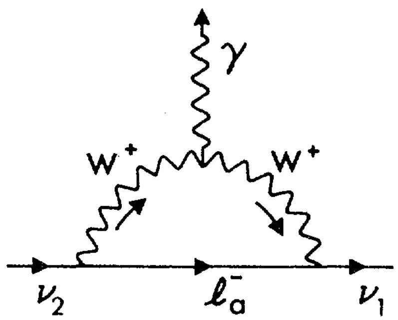
$$f_{max,\mathrm{NRP}} = \frac{94\ \omega_{\mathrm{DM}}}{2\,(2\pi\hbar)^3}\frac{m_{\mathrm{NRP}}^3}{\mathrm{eV}^3} \quad \Rightarrow \quad m_{\mathrm{NRP}} > 1.77\,\mathrm{keV}$$

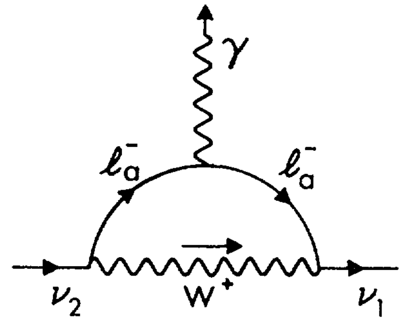
from dSphs observations

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



Constraints: stability and indirect detection (ID)



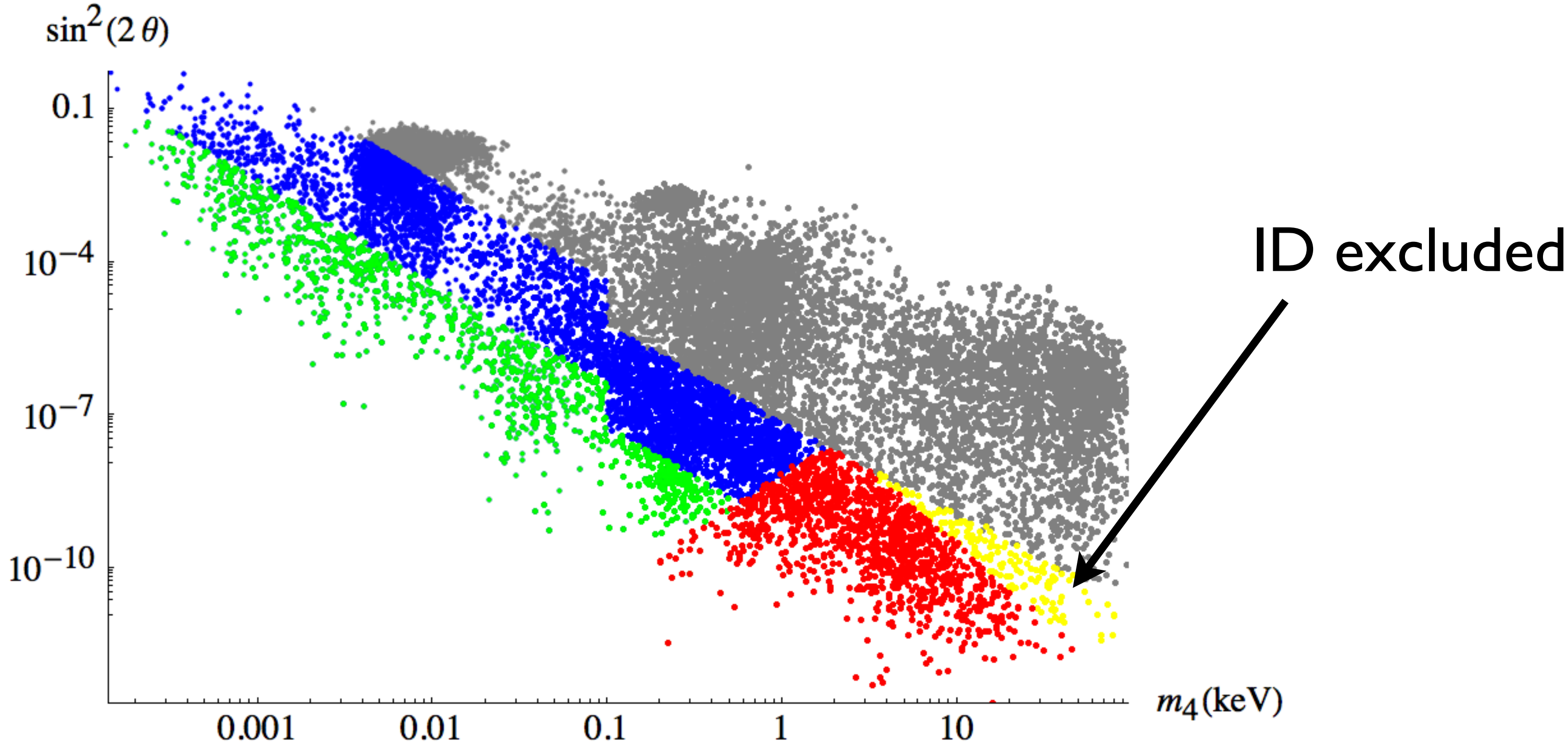


A massive ν can radiatively decay producing monochromatic γ

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

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

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



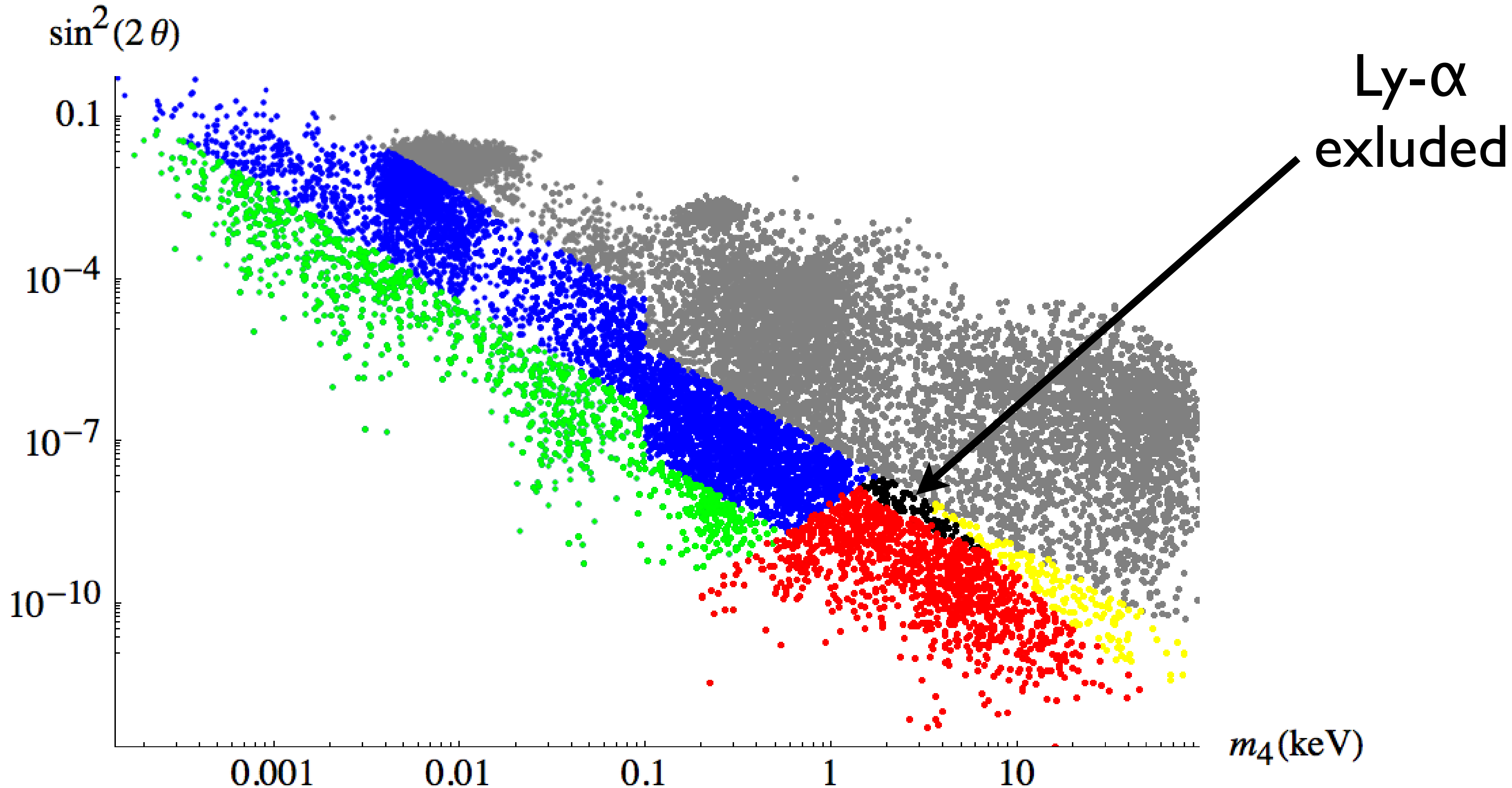
Constraints: Lyman-α

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

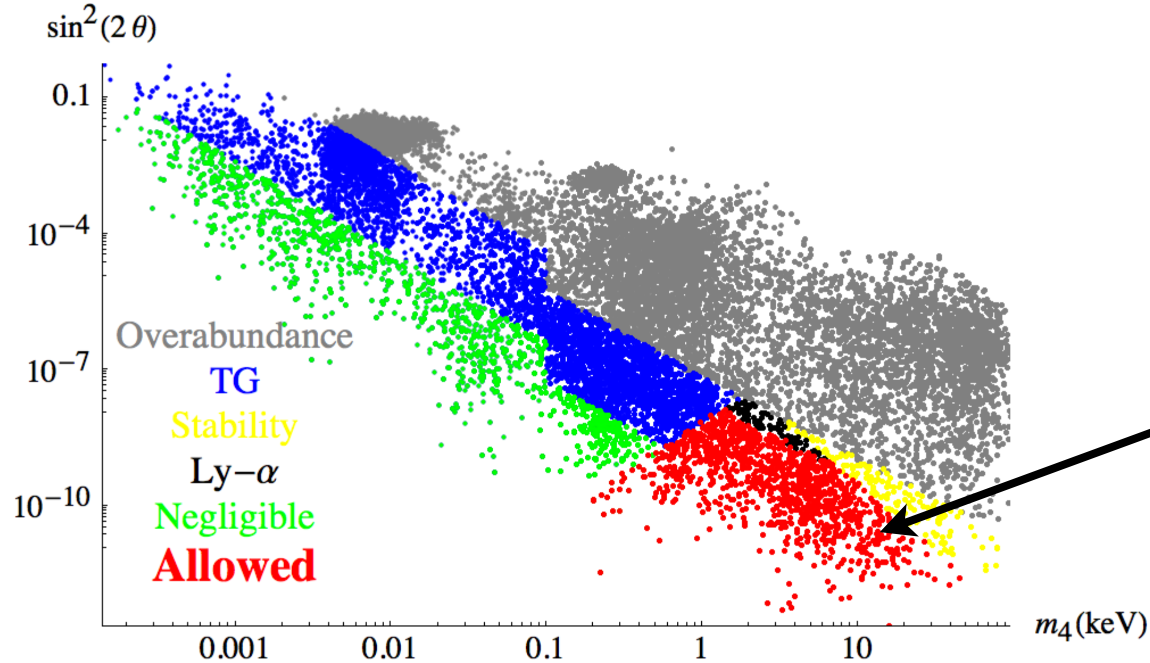
Narayanan, Vijay K.; Spergel, David N.; Davé, Romeel; Ma, Chung-Pei, Astrophys. J. 543, 103 (2000)

These constraints are highly-model dependent, we applied the limits for DW produced sterile ν

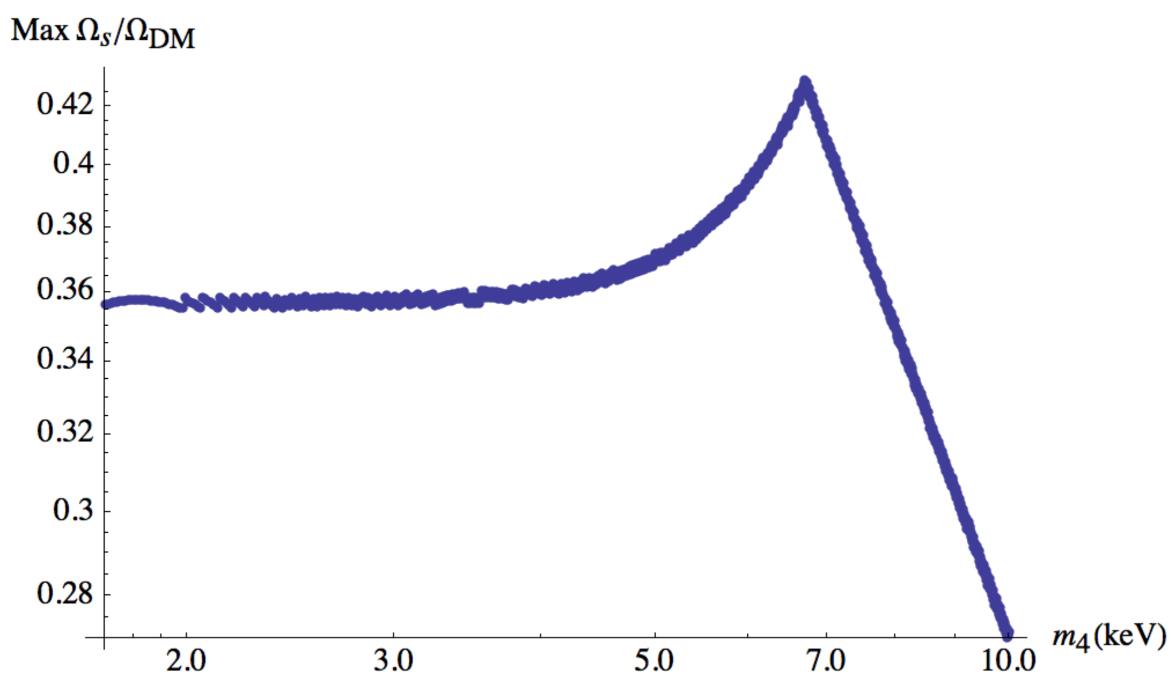
A. Boyarsky, J. Lesgourgues, O. Ruchayskiy and M. Viel, 0812.0010 [astro-ph]



WDM summary



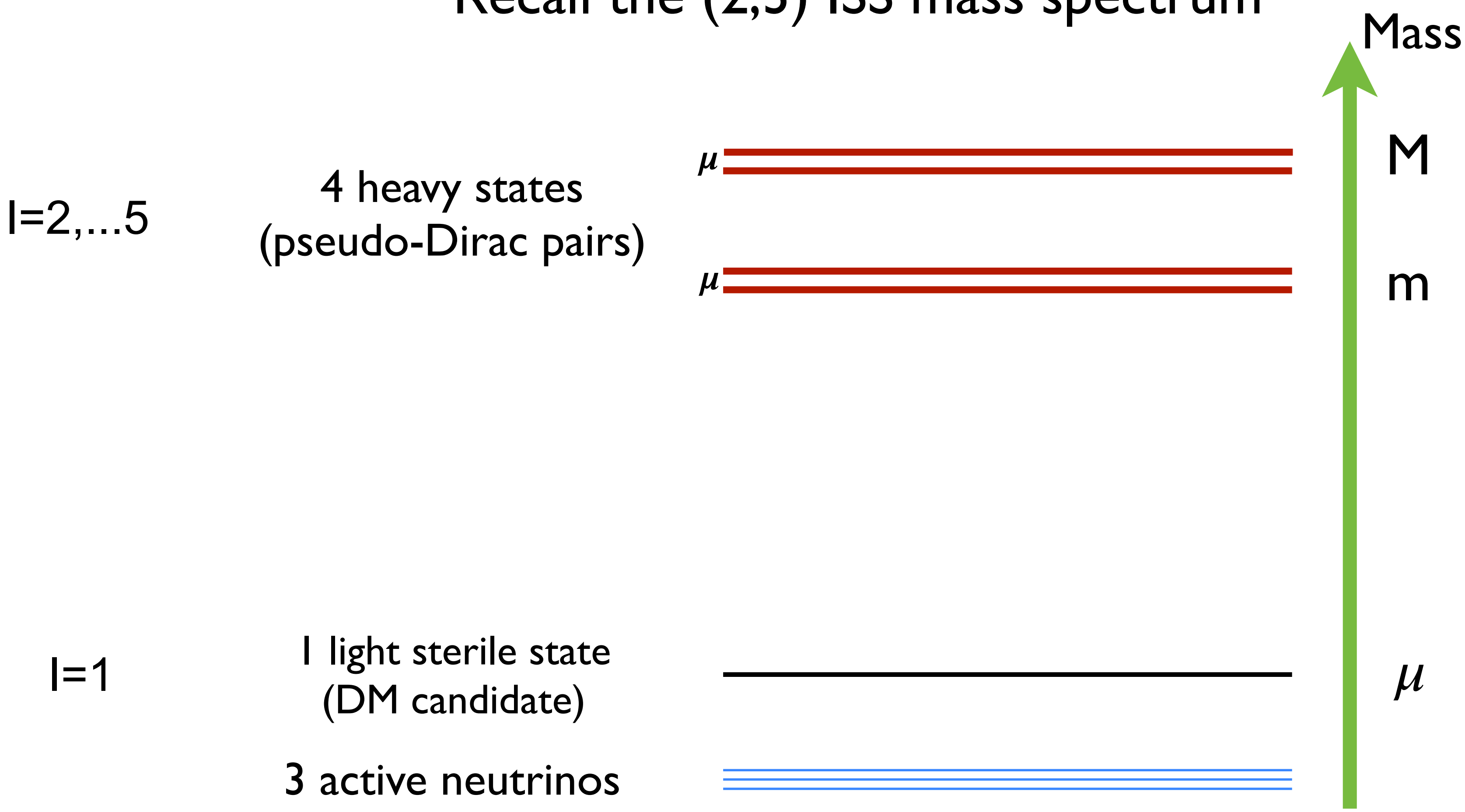
Allowed region



Ly-α
and
x-ray
constraints

Effects of heavy sterile states

Recall the (2,3) ISS mass spectrum

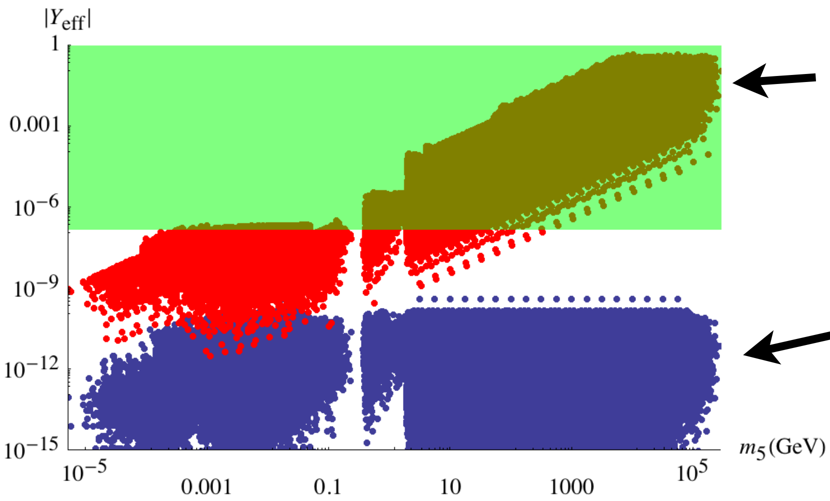


ISS can accommodate tiny ν masses with large O(1) Yukawas

Heavy states can thermalize in the early Universe

Thermalization of the heavy sterile states

- Unbroken EW phase: efficient interactions via Higgs scattering



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

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

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

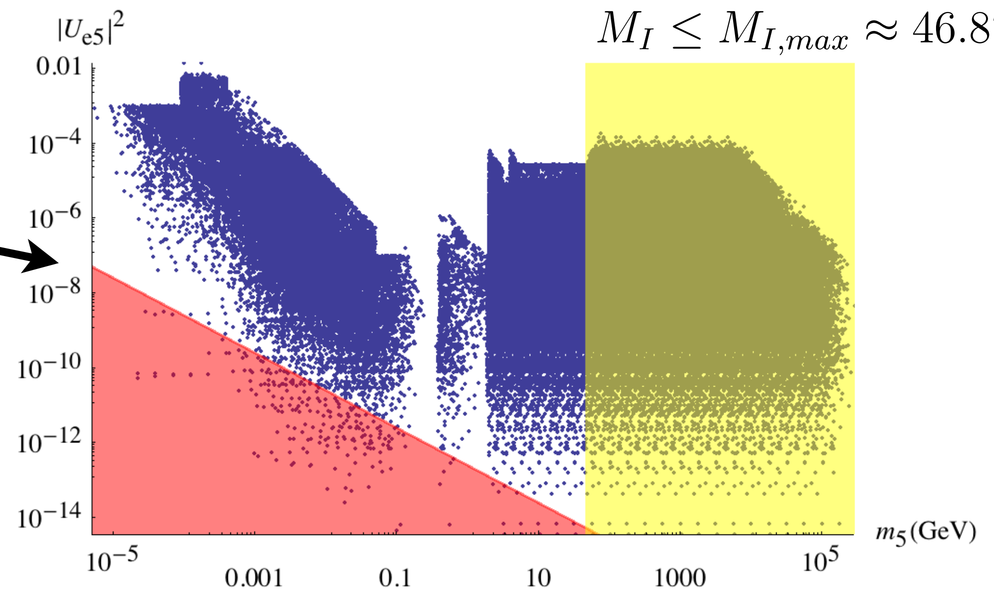
Thermalization if

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

Peak production at

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

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



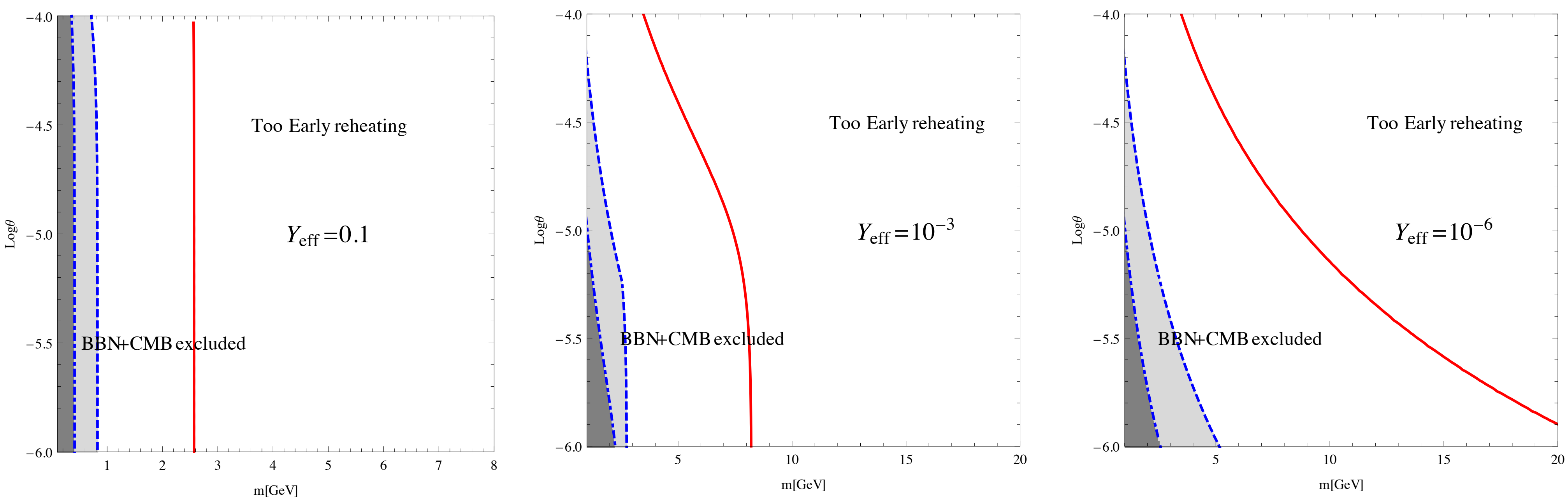
Entropy injection

If the heavy states thermalize 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 $\qquad Y^{eff}_{\alpha i} \equiv Y_{\alpha\beta} U_{\beta i}$

Entropy dilution

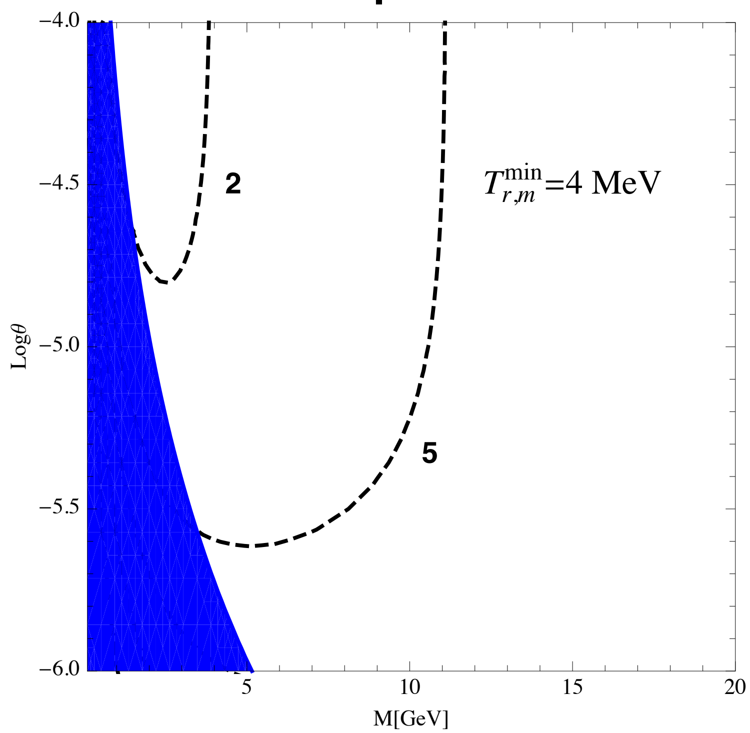
Consider the pseudo-Dirac couples to be degenerate with masses *M* > *m*

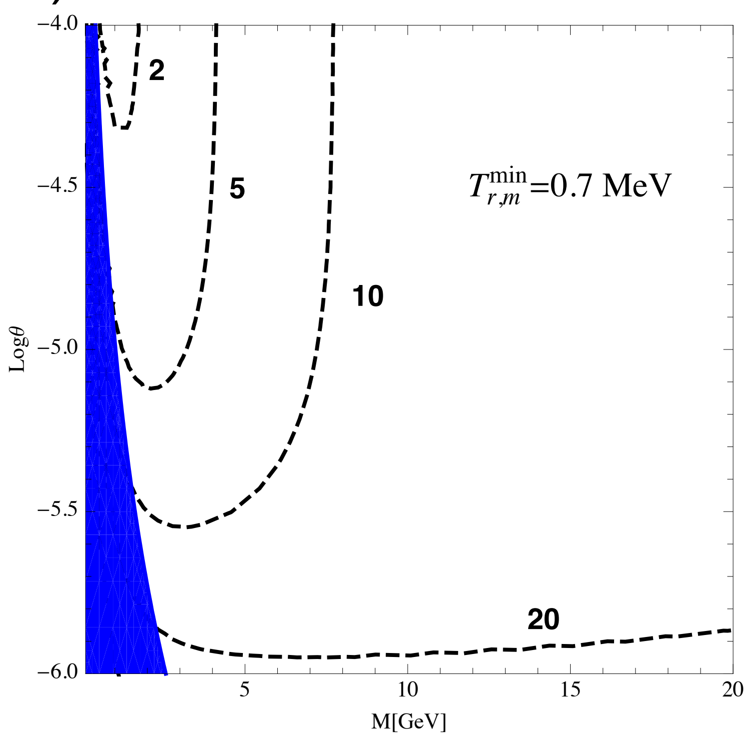
$$S_M = \left[1 + 2.95\left(\frac{2\pi^2}{45} g_*(T_{r,M})\right)^{1/3} \left(\frac{\sum_\alpha m_\alpha Y_\alpha}{M\ Y_M}\right)^{1/3} \frac{(M\ Y_M)^{4/3}}{(\Gamma M_{\rm PL})^{2/3}}\right]^{3/4}$$

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

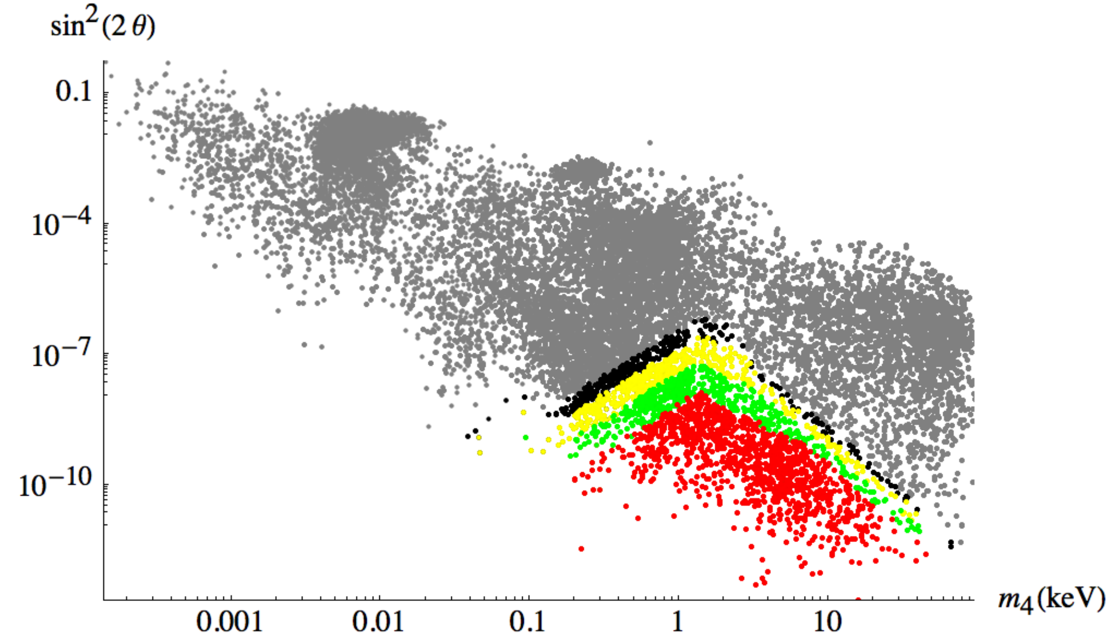
$$S = S_m \times S_M$$

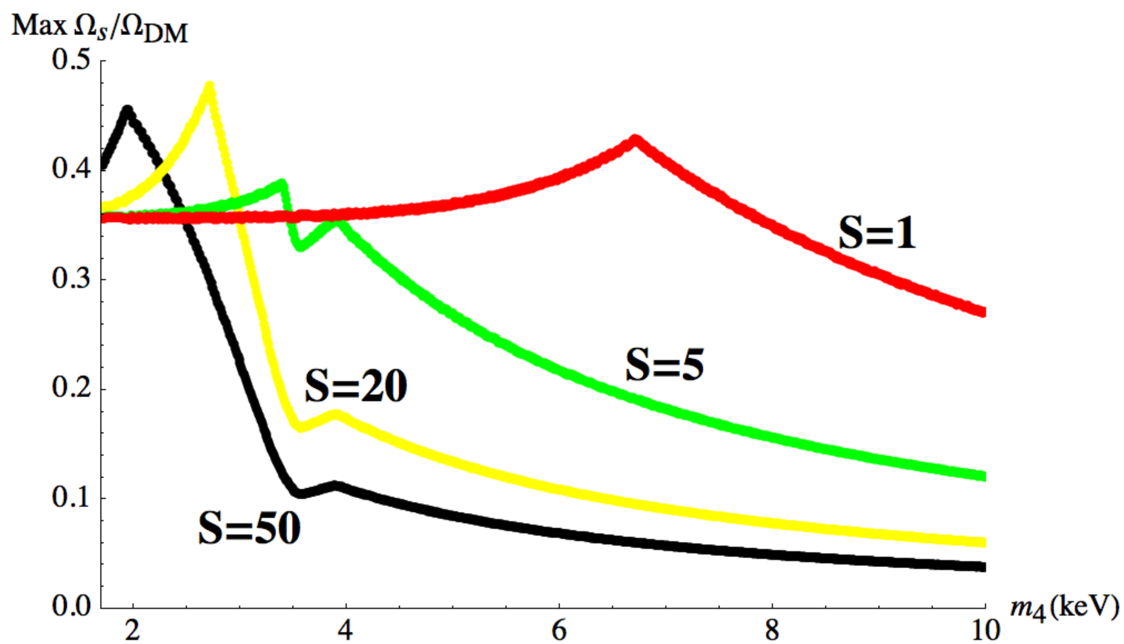
Examples of S with (m, $\theta_{\rm m}$) chosen to fix $T_{\rm r,m}$





WDM summary with entropy injection





The entropy injection enlarges the allowed parameter space but it is not effective to make Ω_s=1viable

Is Ω_s=1 viable?

Cosmological constraints on the (2,3) ISS parameter space makes impossible to produce the whole DM abundance via DW mechanism

$$\max f_{WDM} \approx 0.48$$

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

Effective if $Y_{eff} > 10^{-7}$ and $Y_{eff}\, \sin\theta < 10^{-7}$ and $m_h < M_I < 160$ GeV

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

$$\Gamma\left(N_I \to hDM\right) = \frac{m_I}{16\pi} Y^2_{\rm eff,I} \sin^2\theta \left(1 - \frac{m_h^2}{m_I^2}\right)$$

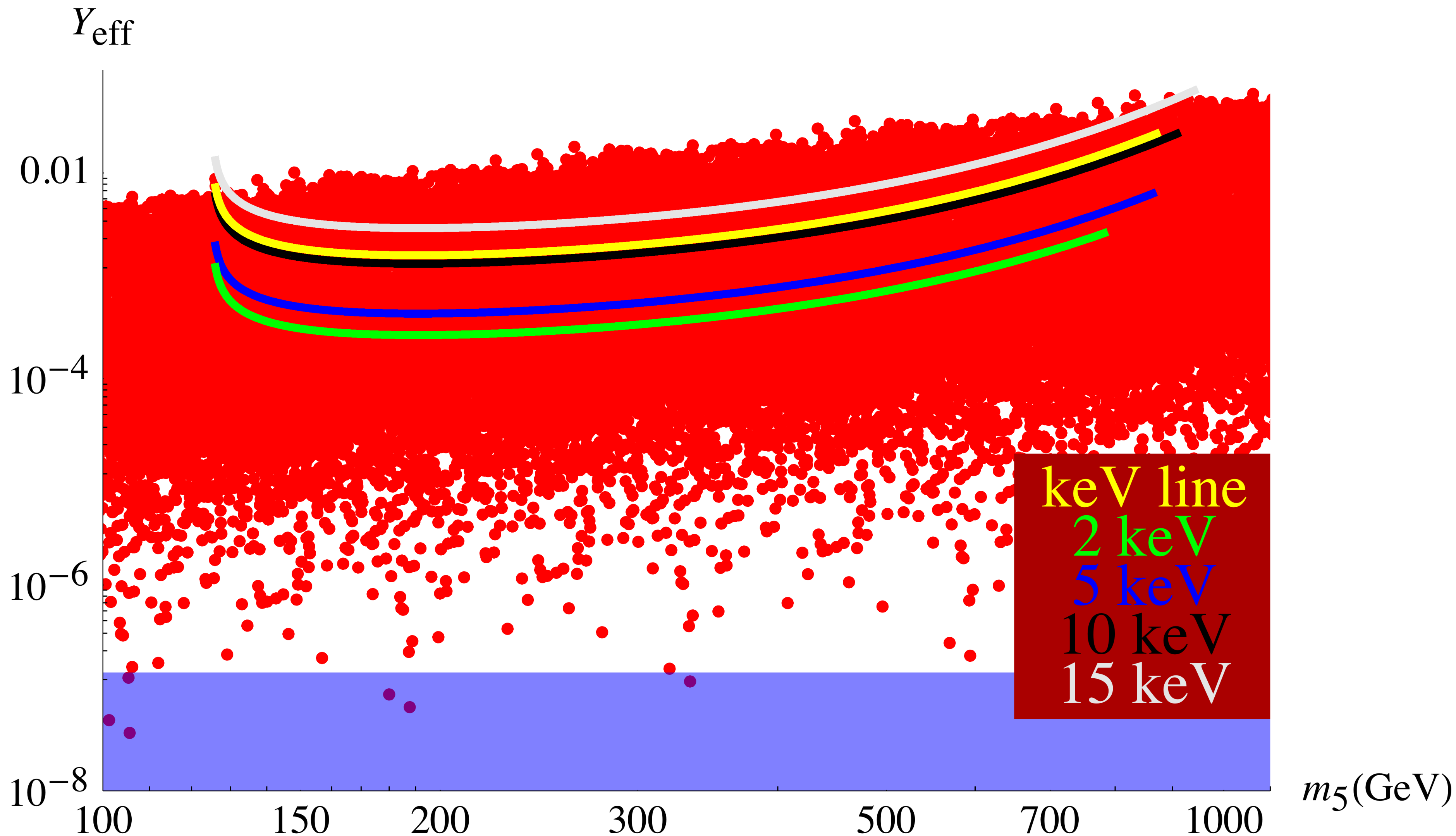
$$\Omega h^2 \approx 2.16\times 10^{-1} \left(\frac{\sin\theta}{10^{-6}}\right)^2 \left(\frac{m_{\rm DM}}{1\ {\rm keV}}\right) \sum_I g_I \left(\frac{Y_{\rm eff,I}}{0.1}\right)^2 \left(\frac{m_I}{1{\rm TeV}}\right)^{-1} \left(1 - \frac{m_h^2}{m_I^2}\right) \chi\left(m_I\right)$$

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

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

Examples for different neutrino masses

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



sinθ close to the maximum allowed value for each mass

3.5 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]

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 $f_{WDM} \approx 0.4$)

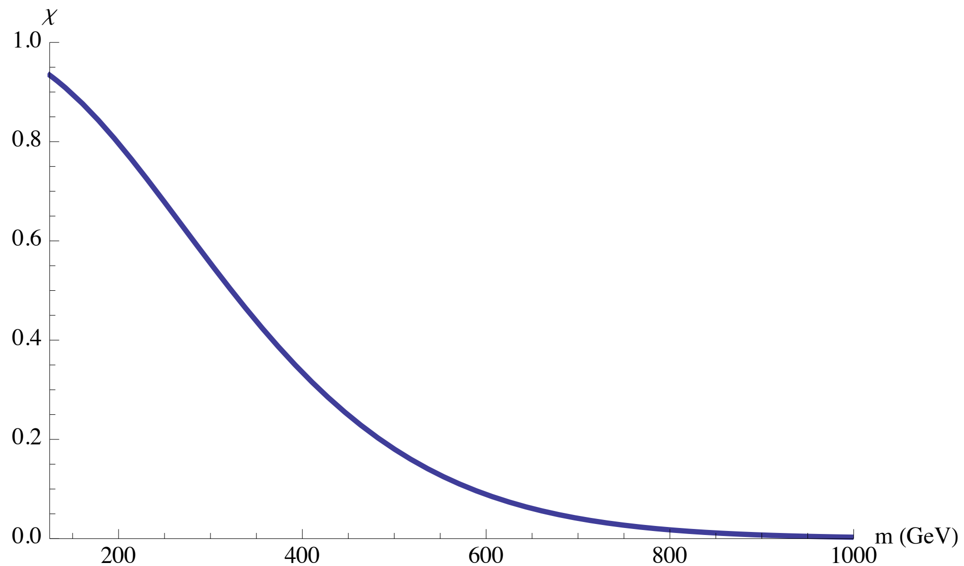
Backup

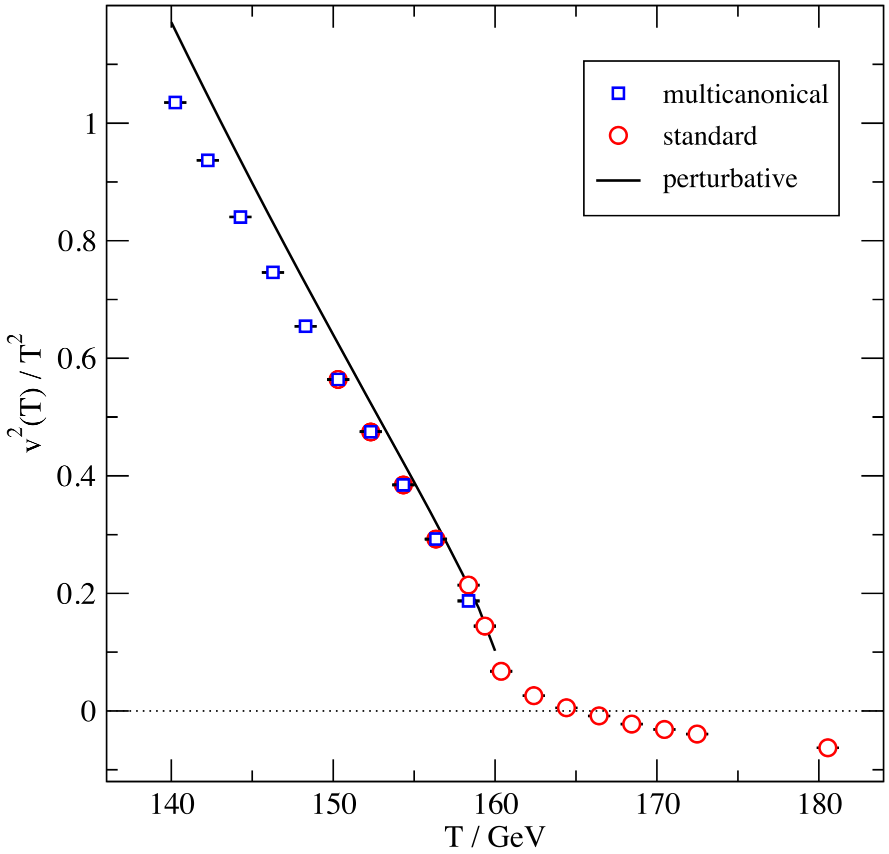
Mixing temperature dependance

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]

Sterile ν in CMB