Sterile Neutrino Dark Matter & Low Scale Leptogenesis from a Charged Scalar

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MF & Carlos E. Yaguna, arXiv:1409.0659 [hep-ph]

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Outline

- Sterile neutrinos for everything ?
- Multi-keV sterile neutrinos as dark matter:
  how to generate the correct abundance ?
- Multi-TeV or multi-GeV sterile neutrinos:
  can a sizable lepton (and baryon) asymmetry arise ?
- A charged scalar δ^+ may ease these tasks:
  motivations, implications, signatures

Sterile neutrinos: motivations

- Theory: gauged B-L, left-right symmetry, SO(10) unification, ...
  in general the symmetry breaking scale V should be high but the sterile mass scale $M_N = y_N V$ may be naturally suppressed
- Phenomenology:
  - non-zero ν masses, seesaw is operative for $M_N \gtrsim 10$ eV !
    (here I will neglect oscillation anomalies, that require $M_N \sim$ eV)
    talk by Carlo Giunti
  - baryogenesis via leptogenesis from N-decays ($T \sim M_N$)
    or from N-oscillations ($T >> M_N$)
    Fukugita-Yanagida, 86
    Akhmedov-Rubakov-Smirnov, 98
  - for M_N = multi-keV, N is stable enough and cold enough to be an automatic dark matter candidate
    Dodelson-Widrow, 93
  - pragmatical motivation: precision SM measurements allow only for gauge singlets below 100 GeV, with small Yukawa couplings

ν Minimal Standard Model

- By definition, SM + three sterile neutrinos below the EW scale: one multi-keV N_1 for DM, two multi-GeV $N_{2,3}$ for leptogenesis

Asaka-Blanchet-Shaposhnikov, 05
Asaka-Shaposhnikov, 05

- Main implications:
  - Lightest neutrino mass $m_\nu^{lightest} \lesssim 10^{-6}$ eV
  - DM production from ν_α - N_1 oscillations needs to be resonantly enhanced by a large primordial lepton asymmetry

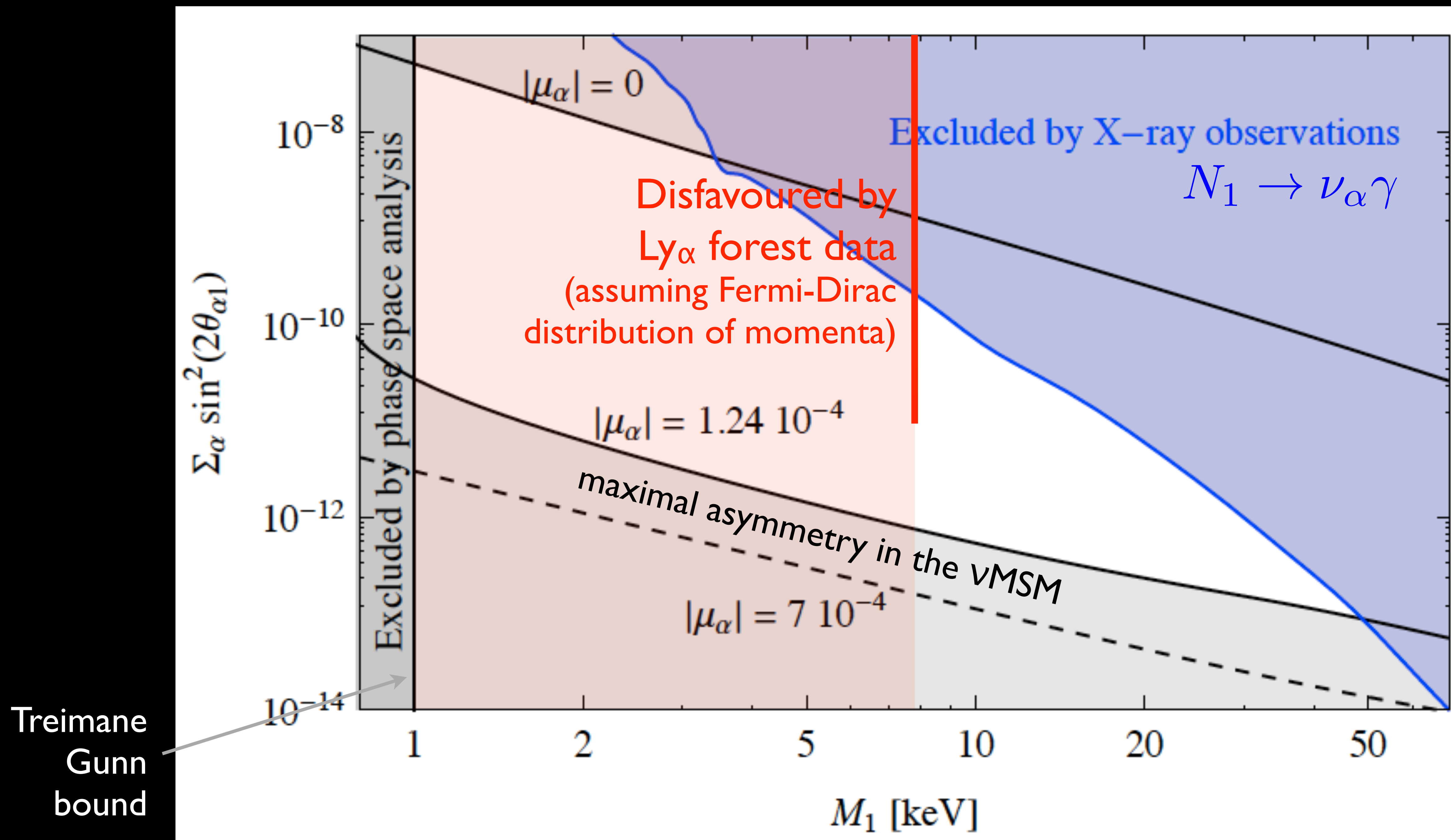
    Shi-Fuller, 98
    Laine-Shaposhnikov, 08
  - Leptogenesis from ν_α - $N_{2,3}$ oscillations can be successful for a specific flavour structure of $(y_\nu)_{\alpha 2,3}$ and $M_2-M_3 \lesssim 10^{-5}\, M_2$

    Canetti-Shaposhnikov, 10
    Shuve-Yavin, 14
- Detailed analyses of this model led to important progress on the theoretical and phenomenological side
- However, minimality is scarcely motivated and, once it is relaxed, several strict predictions drop

N_1 dark matter from oscillations

Along the black lines $\Omega_{N1} = \Omega_{DM}$

$$\mu_\alpha = \frac{\Delta n_\alpha}{s}$$



adapted from Canetti-Drewes-Frossard-Shaposhnikov, 12

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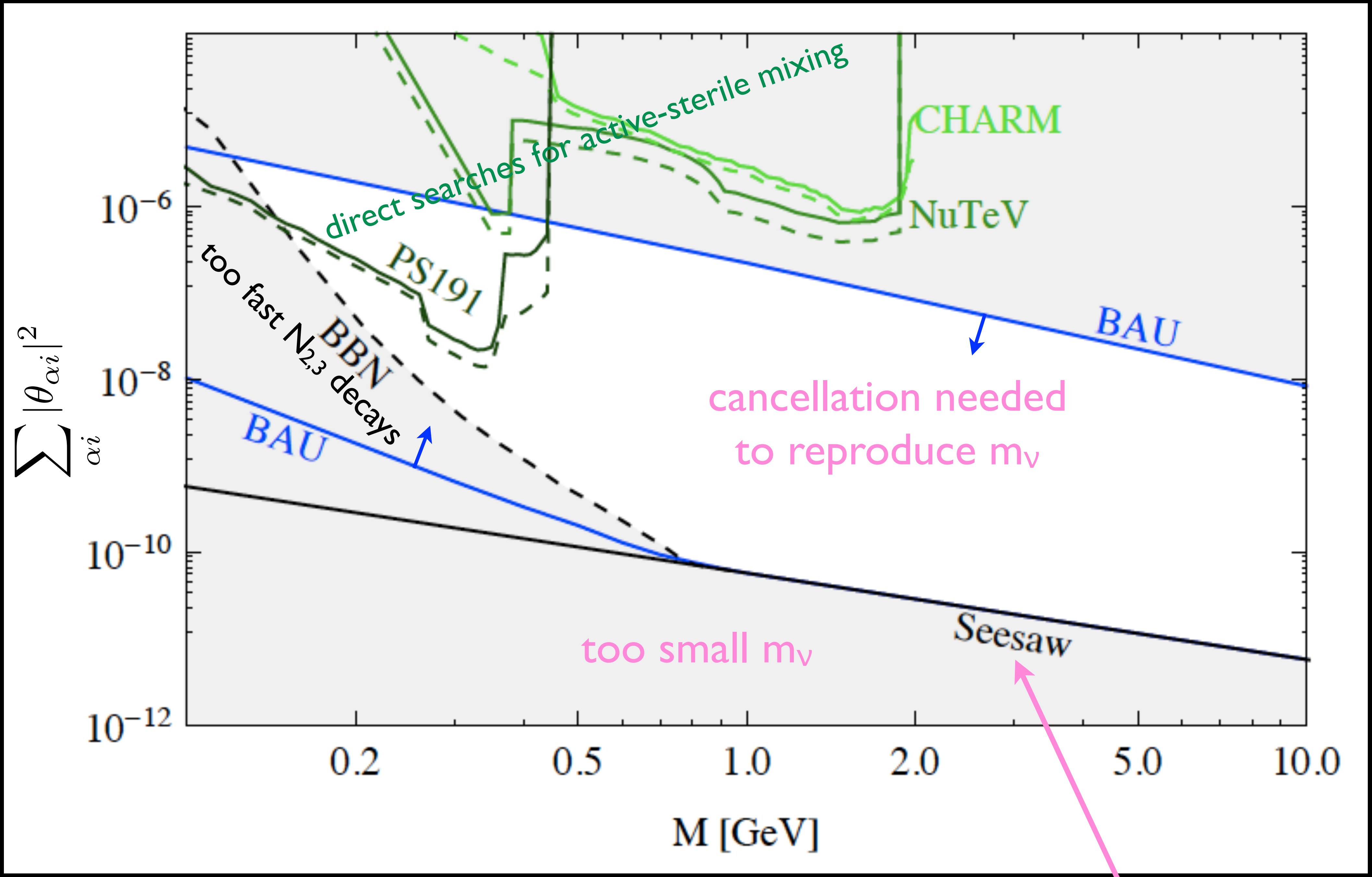
Caveat: strong flavour dependence



$$(m_\nu)_{\alpha\beta} = \theta_{\alpha i}\theta_{\beta i} M_i \lesssim 0.1 eV$$

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The role of a charged scalar

- In most, well-motivated SM extensions, sterile neutrinos come with several other fields
- A scalar δ^+, weak singlet of charge one, is very much special for its couplings to leptons

$$\mathcal{L}_N \supset -\frac{1}{2}\overline{(N_{Ri})^c}(M_N)_{ij}N_{Rj} - \overline{l_{L\alpha}}(y_\nu)_{\alpha i}N_{Ri}\tilde{H}$$

$$\mathcal{L}_\delta \supset -M_\delta^2\delta^+\delta^- - \overline{l_{L\alpha}}(y_L)_{\alpha\beta}(i\sigma_2)(l_{L\beta})^c\delta^+ - \overline{(e_{R\alpha})^c}(y_R)_{\alpha i}N_{Ri}\delta^+$$

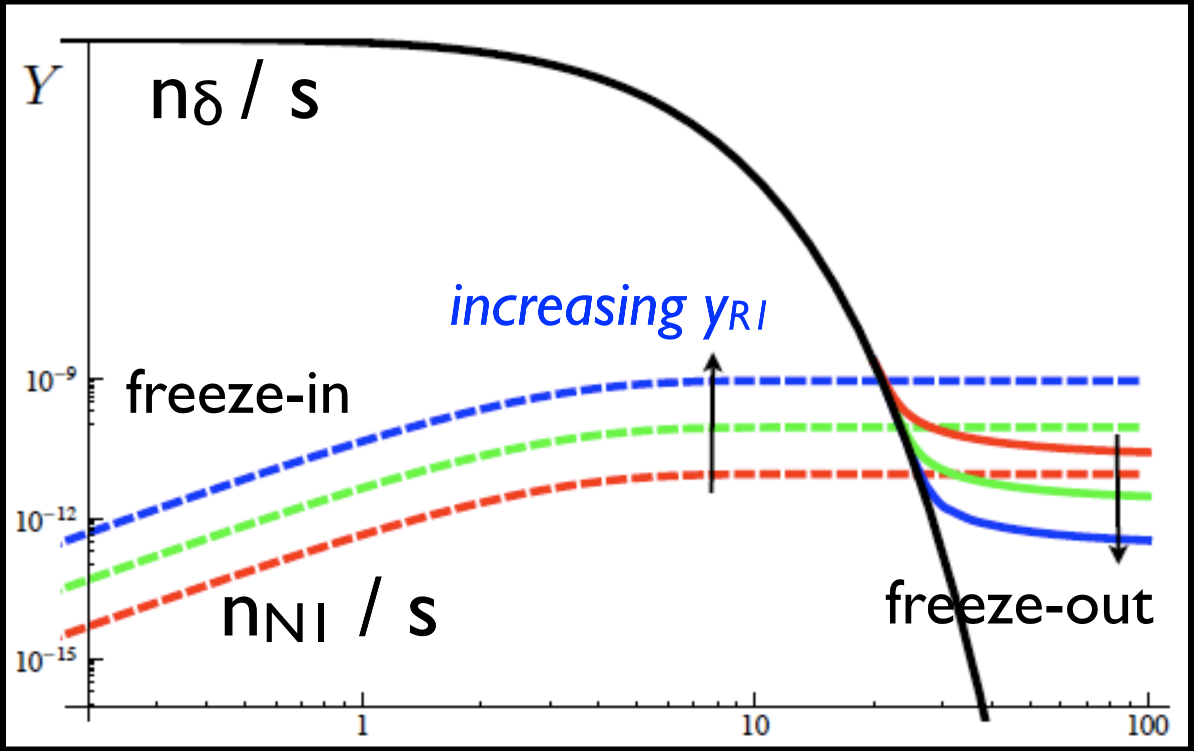
$$l_L \leftrightarrow e_R \qquad H \leftrightarrow \delta^+$$

Dark matter from δ^+ decays

$\overline{(e_{R\alpha})^c}(y_R)_{\alpha 1} N_{R1} \delta^+ \Rightarrow \delta^+ \rightarrow N_1 e^+_\alpha$

Hall-Jedamzik-MarchRussell-West, 09

Freeze-in: a less-than-thermal population of N_1 is produced by the δ^+ decays; the N_1 number density reaches a plateau at $T \approx M_\delta$:



$z = M_\delta / T$

The Boltzmann equation can be solved analytically:

$$\Omega_{N_1} h^2 \approx 0.11 \left(\frac{M_1}{10 \text{ keV}}\right) \left(\frac{y_{R1}}{1.5 \times 10^{-7}}\right)^2 \left(\frac{1 \text{ TeV}}{M_\delta}\right)$$

Frigerio-Yaguna, 14

This is independent from active-sterile mixing angles $\theta_{\alpha 1}$ (y_R versus y_ν)
This production mechanism dominates over oscillations for $\theta_{\alpha 1} < 10^{-5}$
X-ray bounds can be evaded reducing $\theta_{\alpha 1}$, even for $M_1 >> 10$ keV !

Dark matter indirect detection

$$N_1 \to \nu_\alpha \gamma \quad \Rightarrow \quad E_\gamma \simeq M_1/2$$

The X-ray rate is proportional to $M_1^5\ \theta_{\alpha 1}^2$
The N_1 relic density from δ^+ decays is independent from M_1 and $\theta_{\alpha 1}$

As a case study, consider the unidentified spectral line at 3.5 keV observed from some galaxy clusters and from Andromeda

Bulbul et al., 14
Boyarsky-Ruchayskiy-Iakubovskyi-Franse, 14

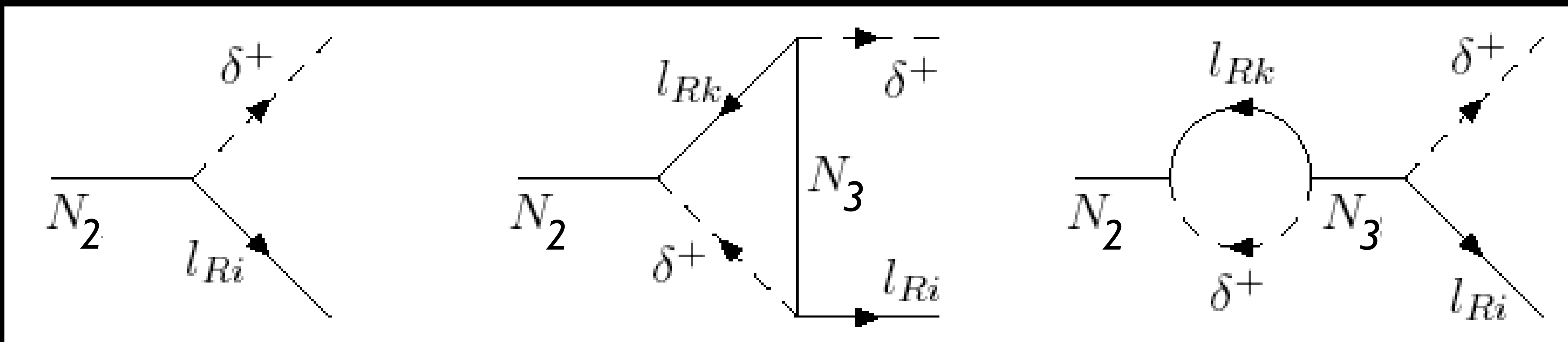
(the signal significance was questioned, and no signal was observed from other clusters/galaxies, in several recent papers)

One can fit such observation with $M_1 \approx 7$ keV and $\theta_{\alpha 1} \approx 3 \cdot 10^{-6}$
N_1 relic density from oscillations is tiny and slightly too warm (barring large primordial lepton asymmetry): δ^+ decays can cure these problems

Weaker rates are compatible with this scenario too ...

Leptogenesis close to TeV scale

For $M_{2,3} > T_{EW}, M_\delta$ lepton asymmetry can be produced in $N_{2,3}$ decays through y_R in complete analogy with decays through y_ν



Frigerio-Hambye-Ma, 06

Large enough CP asymmetry:

$$\frac{|\mathrm{Im}[\sum_\alpha (y_R)_{\alpha 2}(y_R)^*_{\alpha 3}]^2|}{\sum_\alpha (y_R)_{\alpha 2}(y_R)^*_{\alpha 2}} \gtrsim 2\cdot 10^{-6}\,\frac{M_3}{M_2}$$

Small enough washout:

$$\sum_\alpha (y_R)_{\alpha 2}(y_R)^*_{\alpha 2} \lesssim 10^{-13}\,\frac{M_2}{1\ \mathrm{TeV}}$$

Leptogenesis from y_R can be successful for M_2 as small as a few TeVs contrary to leptogenesis from y_ν that requires $M_2 > 10^8$ GeV (barring resonances) because m_ν is tiny

for TeV scale washout effects see Racker, 13

Leptogenesis from N-oscillations (y_ν)

$$\overline{l_{L\alpha}}(y_\nu)_{\alpha i} N_{Ri}\tilde{H} = y_\nu^\alpha \overline{l_{L\alpha}} N_{R\alpha}\tilde{H}$$

Akhmedov-Rubakov-Smirnov, 98
Asaka-Shaposhnikov, 05

- At $T \gg M_N$ the states N_α are produced coherently and oscillate among different α
- With two or more steriles, CP violation is possible: a flavour asymmetry Δ_α appears between N_α of opposite helicities
- $\Sigma_\alpha \Delta_\alpha = 0$ (no lepton number violation), but a net lepton asymmetry is transferred to baryons, if only some flavour α goes in equilibrium above T_{EW}: $y_\nu^\alpha > 10^{-7}$ for some α only
- Here M_N acts as washout, since it equilibrates the opposite helicities of N_α: to avoid strong washout $M_N < 100$ GeV
- Large y_ν^α tends to spoil coherence, as active-sterile transitions become faster than the oscillation time: $y_\nu^\alpha < 10^{-5}$
- $N_{2,3}$ should decay through y_ν before BBN: this implies $M_N > 0.1$ GeV

Leptogenesis from $N_{2,3}$ oscillations

adapted from Canetti-Drewes-Frossard-Shaposhnikov, 12

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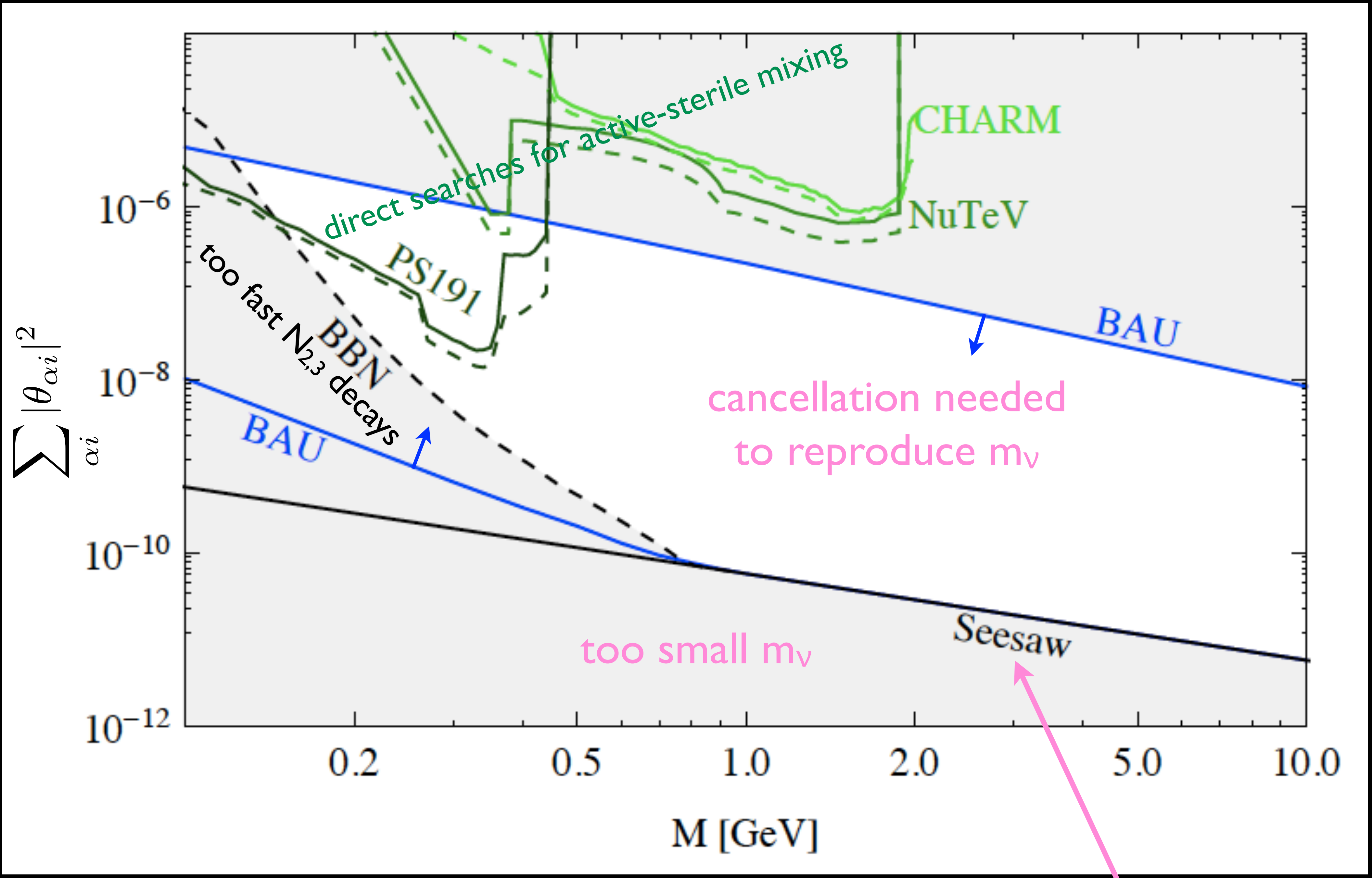

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Leptogenesis from N-oscillations (y_R)

$$\overline{(e_{R\alpha})^c}(y_R)_{\alpha i}N_{Ri}\delta^+ = y_R^\alpha \overline{(e_{R\alpha})^c}N_{R\alpha}\delta^+$$

Frigerio-Yaguna, 14

- The very same mechanism is operative producing N_α from $e_{R\alpha}$ instead of $l_{L\alpha}$, through the coupling y_R instead of y_ν
- Charged lepton Yukawas equilibrate $e_{R\alpha}$ and $l_{L\alpha}$ // one needs M_δ (instead of M_H) smaller than T_{oscill} // y_R provides extra CP violation
- With y_ν only one needs $M_2-M_3 \lesssim 10^{-5} M_2$ (large oscillation time enhances Δ_α): tuning can be relaxed when y_R is added (as indicated by related numerical studies)

  Drewes-Garbrecht, 12
  Shuve-Yavin, 14
- y_R is not constrained by the seesaw relation, nor by $N_{2,3}$ decays via active-sterile mixing: larger window open in the y_R-M_N plane

$N_{2,3}$ and δ^+ detection

talk by Nicola Serra

- $N_{2,3}$ are feebly coupled to the SM, still active-sterile mixing could be observable in various neutrino experiments: looking forward to SHiP
- Charged scalars could be produced at LHC through q qbar → γ/Z → $\delta^+\delta^-$ followed by $\delta^+ \to e_\alpha^+ + \nu$
- The best way to constrain M_δ is to use the SUSY search of right-handed sleptons (same gauge charges as δ^+) directly pair-produced and decaying into lepton + light neutralino: $M_\delta > 240$ GeV at 95% C.L.

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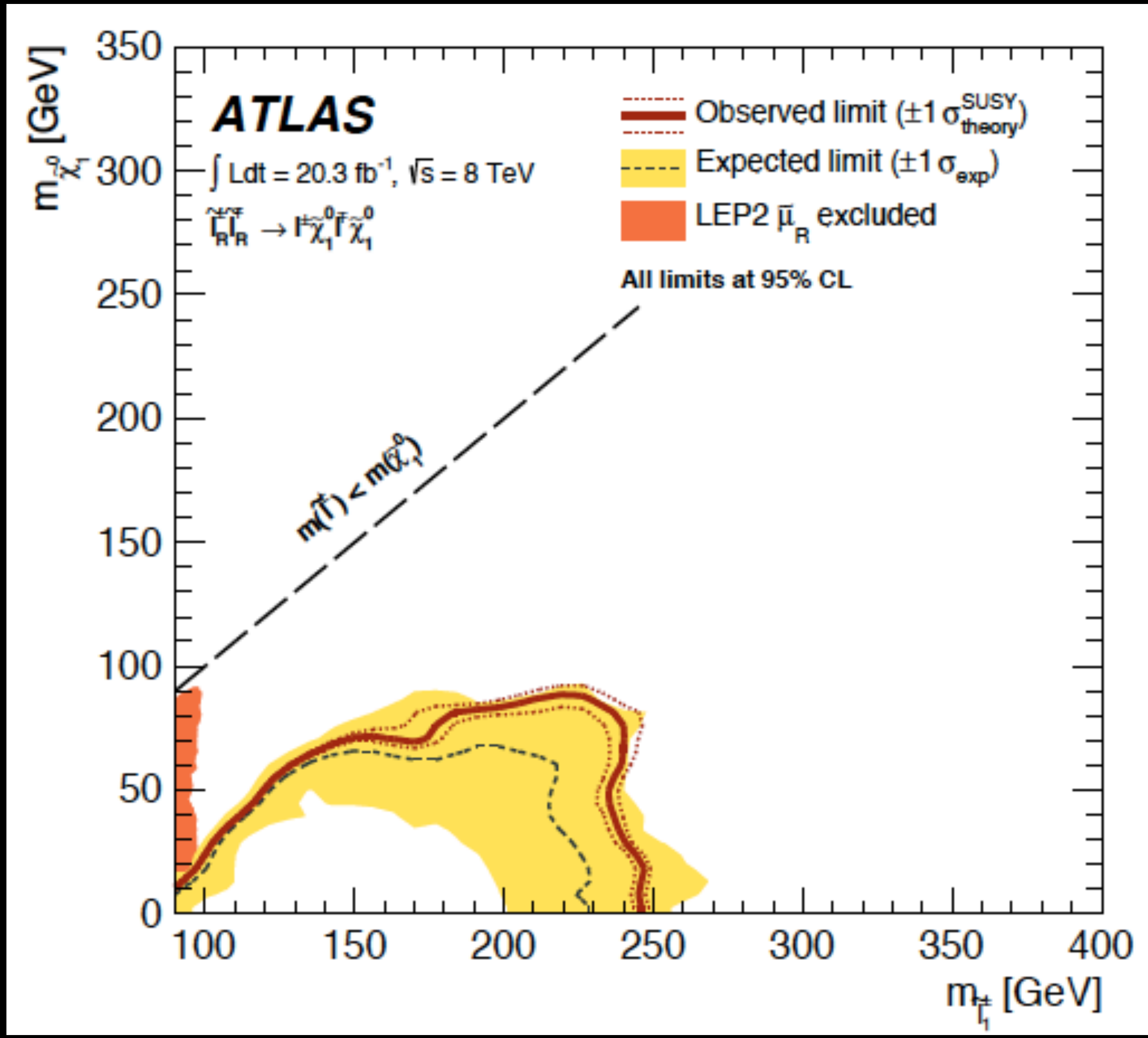

Flavour structure of the model

Recap or required masses and couplings (order of magnitude)

(they may be interpreted in terms of a flavour symmetry, broken by a small parameter $\varepsilon = \langle \Phi \rangle / \Lambda \sim 0.1$)

$$M_N = diag(10 \text{ keV}, 10 \text{ GeV}, 10 \text{ GeV}) = diag(\epsilon^{16}, \epsilon^{10}, \epsilon^{10}) 10^{11} \text{ GeV}$$

$$M_\delta = 1 \text{ TeV}$$

$$y_\nu = \begin{pmatrix} \epsilon^{13} & \epsilon^7 & \epsilon^7 \\ \epsilon^{12} & \epsilon^6 & \epsilon^6 \\ \epsilon^{12} & \epsilon^6 & \epsilon^6 \end{pmatrix} \qquad y_R = \begin{pmatrix} \epsilon^{11} & \epsilon^8 & \epsilon^8 \\ \epsilon^{10} & \epsilon^7 & \epsilon^7 \\ \epsilon^9 & \epsilon^6 & \epsilon^6 \end{pmatrix}$$

This fits (i) neutrino mass (ii) dark matter relic density (iii) baryon asymmetry from $N_{2,3}$ oscillations

A well-defined hierarchy of masses and couplings is required (specific flavour structure), but no fine-tuning is needed

Conclusions

- Sterile neutrinos N may play a role in the generation of the baryon asymmetry and of the dark matter relic density, in various ranges of masses and couplings
- Freeze-in is generic: light, feebly coupled states can be populated by heavy particle decays/annihilations;
  a charged scalar δ^+ does the job to produce N dark matter
- Leptogenesis knows many ways: N out-of-equilibrium decays or N flavour oscillations, in connection with m_ν (coupling $N_L l_L H$) or not (coupling $N_R e_R \delta^+$)
- These mechanisms involve states at accessible energies, TeV or even much below, with the opportunity for a number of direct tests