Terrestrial Searches of keV Sterile Neutrino Dark Matter: Alive and Well

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Sterile Neutrino Dark Matter

STERILE NEUTRINO

- def: $\nu_s = \nu_{RH} = P_R\,\psi_\nu = \frac{\mathbb{I}+\gamma^5}{2}\,\psi_\nu$;
- singlet under $SU(3)_C \times SU(2)_L \times U(1)_Y$
  $\rightarrow$ *sterile* and (almost at all) invisible to our searches;
- based on the value of m_s, ν_s can play a role in: the active ν_α masses generation, the baryonic asymmetry in the universe, and the existence and nature of dark matter (DM).

DARK MATTER

- one of the major components of our universe ($\sim$ 27%) together with ordinary matter ($\sim$ 5%) and dark energy ($\sim$ 68%) [1];
- currently observed only thanks to its large-scale gravitational effects, all we know about its particle nature are few necessary conditions that it must fulfill

General DM Candidate	Sterile Neutrino
no electromagnetic interaction	no electromagnetic interaction
no strong interaction	no strong interaction
massive	mass of $\mathcal{O}(\text{keV})$
perfectly stable or with $\tau_{\text{DM}} > t_{\text{U}}$	$\tau_{\nu_s} > t_{\text{U}}$ if mixing small enough

PRODUCTION THROUGH OSCILLATION AND COLLISIONS

If there is mixing $\boldsymbol{\nu_s \leftrightarrow \nu_e}$ and $\boldsymbol{\overline{\nu}_s \leftrightarrow \overline{\nu}_e}$,

$$h^2\,\Omega_s = h^2\,\Omega_{\nu_s} + h^2\,\Omega_{\overline{\nu}_s} = \frac{s_0\,m_s}{\rho_c/h^2}\frac{1}{g_{*s}(T_f)}\left(\frac{45}{4\pi^2}\right)\int_0^\infty dr\,r^2\left[f_{\nu_s}(r) + f_{\overline{\nu}_{s(r)}}\right],$$

where $r = p/T$, can be generated in the early universe through non resonant (**Dodelson-Widrow**) [2] or resonant (**Shi-Fuller**) [3] production.
f_{ν_s} ($f_{\overline{\nu}_s}$) is solution of the Boltzmann equation

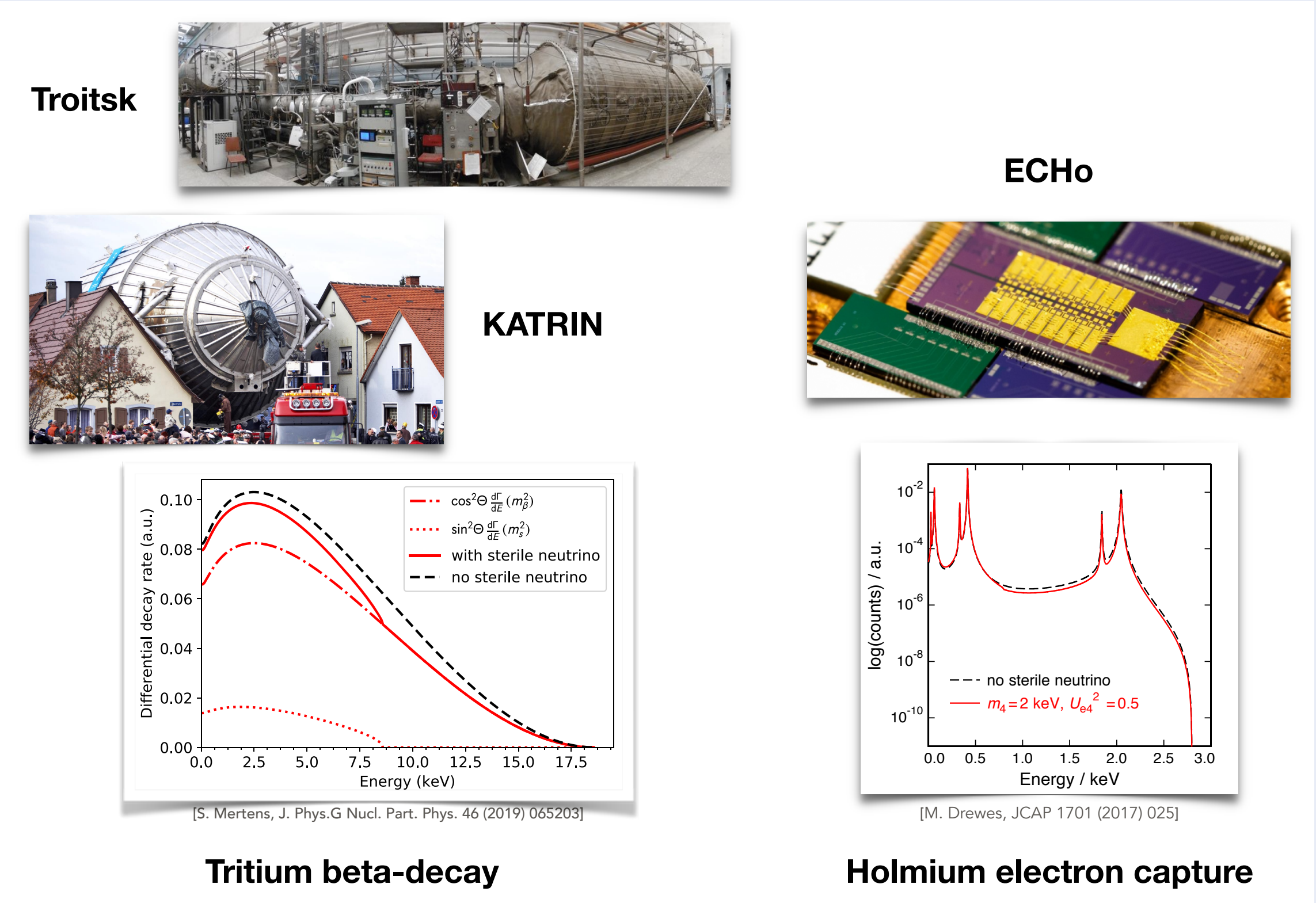
$$\frac{\partial T}{\partial t}\frac{\partial}{\partial T}f_{\nu_s}(p,T) - H\,p\,\frac{\partial}{\partial p}f_{\nu_s}(p,T) \approx \frac{\Gamma_e}{2}\langle P_m(\nu_e \to \nu_s; p, T)\rangle f_e(p,T)$$
$$\approx \frac{\Gamma_e}{4}\sin^2(2\theta_M)\,f_e(p,T)$$

where the ν_e interaction rate in the plasma is $\Gamma_e = c(p,T)\,G_F^2 T^4 p$,
the mixing angle in matter is

$$\sin^2(2\theta_M) = \frac{\left(\frac{m_s^2}{2p}\right)^2\sin^2(2\theta)}{\left(\frac{m_s^2}{2p}\right)^2\sin^2(2\theta) + \frac{\Gamma_e}{2} + \left[\frac{m_s^2}{2p}\cos(2\theta) - V_{\nu_s}\right]^2}$$

and the difference between non-resonant and resonant production is encoded in the definition of the **potential** $\boldsymbol{V_{\nu_s}}$ ($\boldsymbol{V_{\overline{\nu}_s}}$).

Overproduction and Critical Temprature



[S. Mertens, J. Phys.G Nucl. Part. Phys. 46 (2019) 065203]

Tritium beta-decay

[M. Drewes, JCAP 1701 (2017) 025]

Holmium electron capture

In the terrestrial experiments of the near future, **for the detection of a sterile neutrino DM signal**, recognizable in a kink in the electron or Holmium energy spectra, **a large value of the mixing angle is required**. In the standard scenario, where the production of sterile neutrinos starts at very high temperatures, this leads to **overproduction** ($\boldsymbol{\Omega_s > \Omega_{\text{DM}}}$). This problem does not affect scenarios in which sterile neutrinos are not produced until the universe reaches a critical temperature $T_c < T_{\max} \approx 133\left(\frac{m_s}{\text{keV}}\right)^{1/3}$, where $T_{\max}$ identifies the peak of the production through oscillation and collisions [2]. **If the production is delayed, the values of $\boldsymbol{m_s}$ and $\boldsymbol{\sin(2\theta)}$ needed for $\boldsymbol{\Omega_s = \Omega_{\text{DM}}}$ are larger, and the line that represents the latter condition in the parameter space shifts towards the sensitivity region of the experiments.**

CRITICAL TEMPERATURE

$\boldsymbol{T_c}$, at which the production of sterile neutrinos started, can be associated:

- to the **reheating temperature of the universe** $\boldsymbol{T}_{\text{RH}}$:
  if it was sufficiently low (lower bound $T_c = T_{\mathbf{RH}} \leq 4.7$ MeV [4]), the early production of sterile neutrinos was suppressed because the universe never reached $T_{\max}$;
- to the **scale of a dynamical change of** $\boldsymbol{m_s}$:
  due to the structure of $\sin^2(2\theta_M)$, both $m_s^{(T>T_c)} = 0$ (related to a phase transition) and $m_s^{(T>T_c)} \gg m_s^{\text{today}}$ (related to a misalignment mechanism) [5] suppress the early production at high temepratures.

The effect of the presence of such critical temperature is evident in the shift of the coloured lines towards smaller $\sin^2(2\theta)$, in the first plot on the right.

X-ray Bound and Cancellation

Sterile neutrinos with $m_s < 2m_e$ and mixed with active ν_α, can decay

- at tree-level through $\boldsymbol{\nu_s \to \nu_\alpha\,\overline{\nu}_\beta\,\nu_\beta}$:
  this process determines the lifetime of ν_s [6];
- at one-loop level through $\boldsymbol{\nu_s \to \nu_\alpha\,\gamma}$ with decay rate

$$\Gamma_{\nu_s \to \nu_\alpha\gamma} = \frac{9\,\alpha\,G_F^2}{1024\,\pi^4}\sin^2(2\theta)\,m_s^5 \simeq 5.5 \times 10^{-22}\,\theta^2\left(\frac{m_s}{\text{keV}}\right)^5\ \text{s}^{-1}.$$

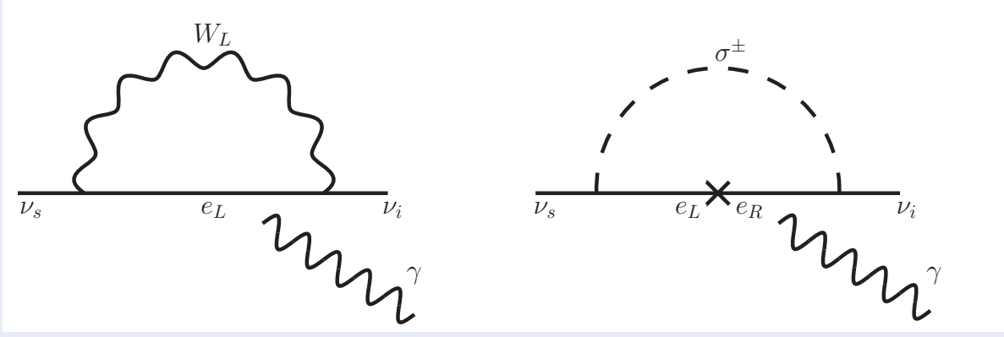
The non-observation, in the spectra of DM dominated objects, of monochromatic photons in the X-ray band expected from the latter process sets a strong upper bound on m_s and θ: $\theta^2 \leq 1.8 \times 10^{-5}\left(\frac{\text{keV}}{m_s}\right)^5$ [7].
The observable related to the latter process is the flux of photons

$$F_{\text{X-rays}} = \frac{\Gamma_{\nu_s \to \nu\gamma}}{4\,\pi\,m_s}\int dl\,d\Omega\,\rho_s(l,\Omega),$$

where ρ_s is the sterile neutrino DM energy density, l the distance along the line of sight and Ω the solid angle, and its expression suggests that this constraint has not to be considered in the full glory, but rather relaxed, both in the case of $\Omega_s < \Omega_{\text{DM}}$ and in the case of reduced decay rate [8].

REDUCED DECAY RATE

Being $\Gamma_{\nu_s \to \nu\gamma} \propto \int dP_{phase\,space}|\mathcal{M}_1|^2 \propto \sin^2 2\theta\,m_s^5$, where $\mathcal{M}_1$ comes from the contribution of the usual diagram in the left panel of the figure below, **larger values of $\boldsymbol{m_s}$ and $\boldsymbol{\theta}$** are allowed by the same value of the flux, **if $\boldsymbol{|\mathcal{M}_1|^2}$ is reduced by replacing $\boldsymbol{\mathcal{M}_1 \to \mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2}$**, where $\mathcal{M}_2$ gives a contribution related to the diagram represented in the right panel, in disruptive interference, so that $|\mathcal{M}|^2 < |\mathcal{M}_1|^2$.



Simplest realization

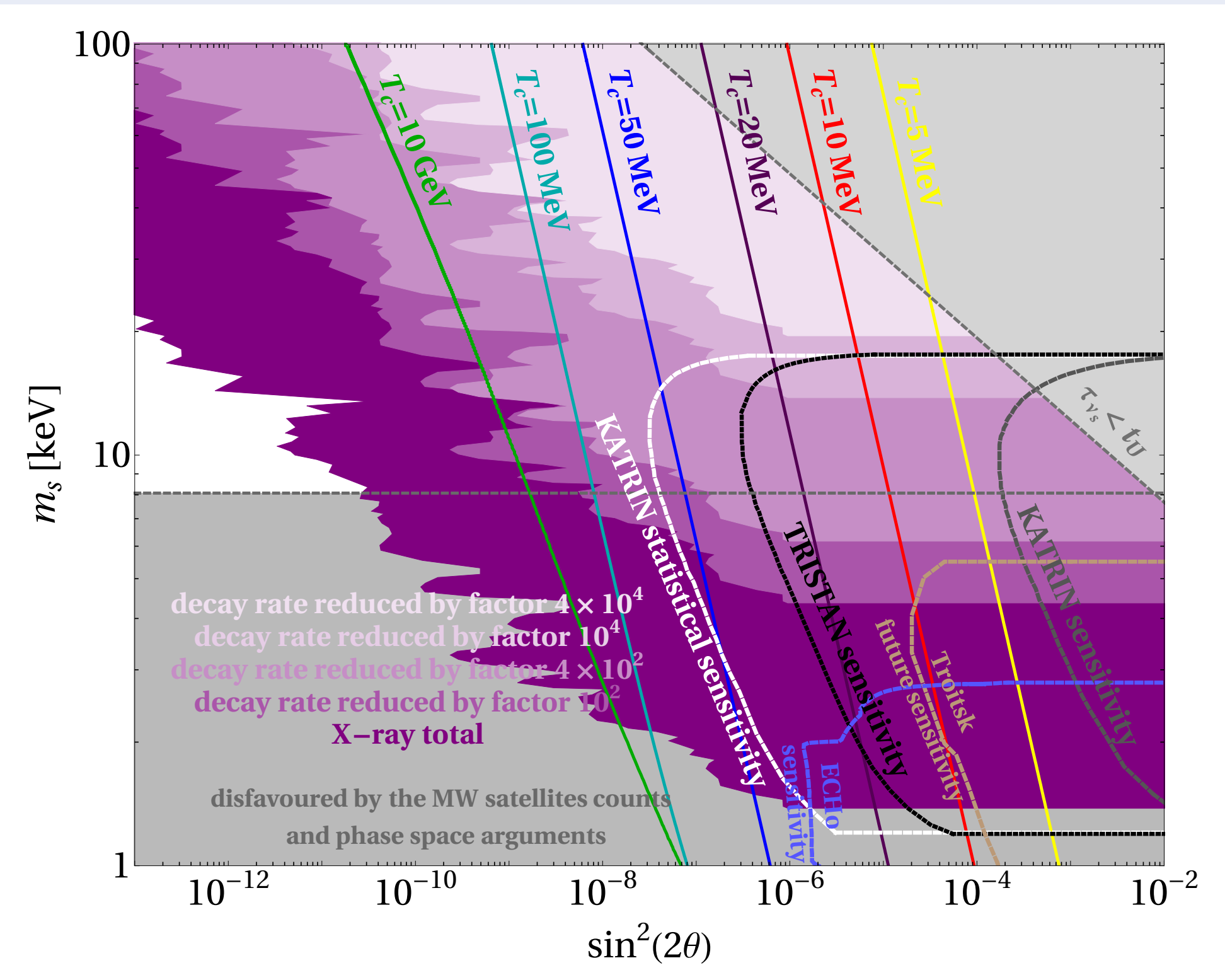
With the introduction of a new scalar particle $\Sigma = (\sigma^0, \sigma^-)$, with quantic numbers (1, 2, -1) under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as the mediator of the decay process interacting with the leptonic sector according to

$$\mathcal{L} \supset \lambda\,\bar{\nu}_s\Sigma^\dagger L_e + \lambda'\,\bar{e}_R, \tilde{\Sigma}^\dagger L_e + h.c.$$

the suppression of the signal can be partial (as shown in the plots on the right in different shades of purple) or even complete, if the parameters introduced together with the new scalar (λ, λ' and m_Σ) satisfy the relation

$$\sin\theta = \left(\frac{-4\lambda\lambda'}{3g^2}\right)\frac{m_e}{m_s}\frac{m_W^2}{m_\Sigma^2}\left[\text{Log}\left(\frac{m_e^2}{m_\Sigma^2}\right) + 1\right].$$

Production through Dodelson-Widrow Mechanism



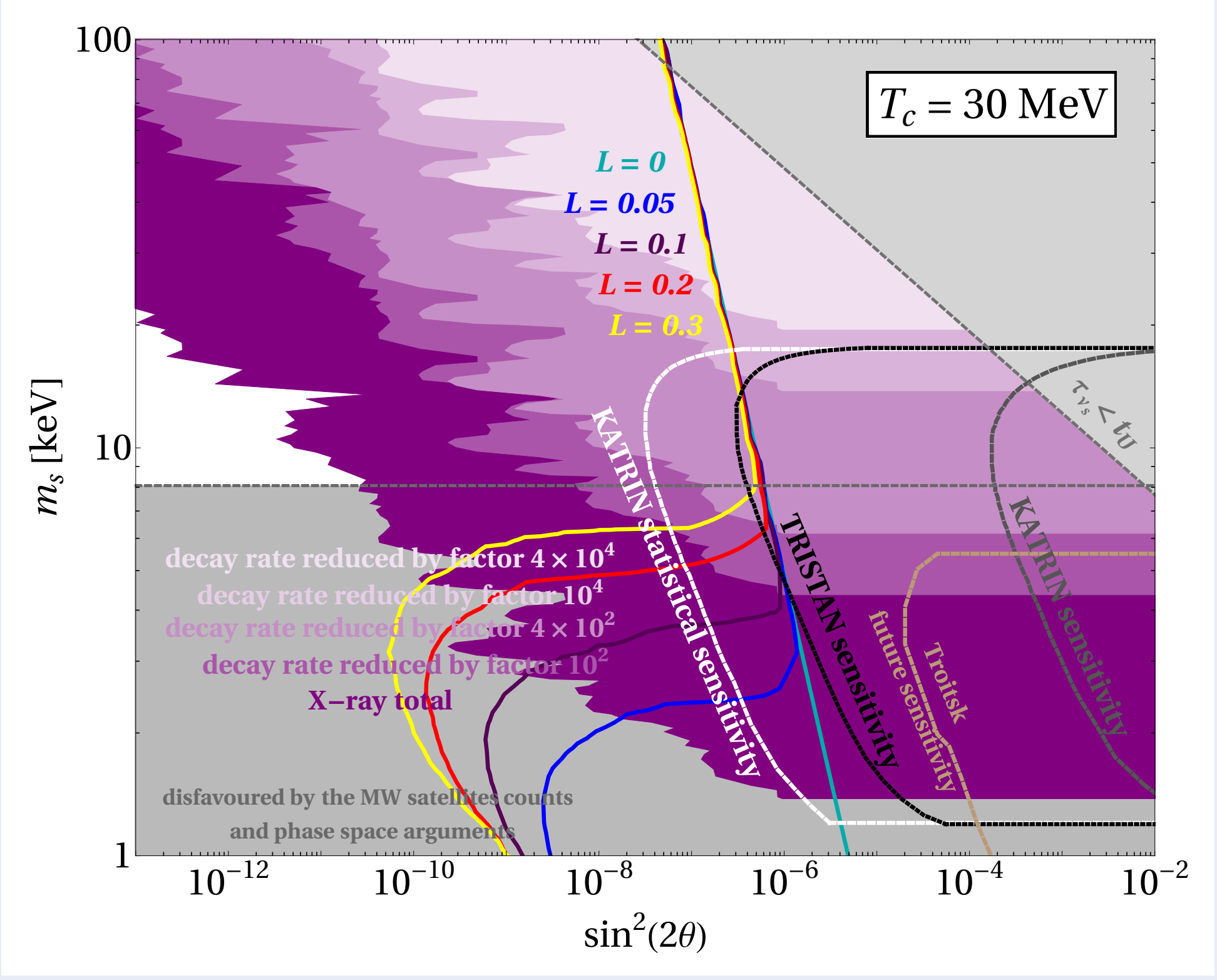
ASSUMPTIONS:

- $\boldsymbol{\nu_s \leftrightarrow \nu_e}$ and $\boldsymbol{\overline{\nu}_s \leftrightarrow \overline{\nu}_e}$ mixing
- primordial $\boldsymbol{L_e = \frac{n_{\nu_e} - n_{\overline{\nu}_e}}{n_\gamma} = 0}$
- $V_{\nu_s} = +\sqrt{2}\,G_F\,\frac{2\,\zeta(3)\,T^3}{\pi^2}\,\frac{\eta_B}{4} - \frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2}\,G_F\,p}{3m_{W_L}^2}(\rho_{e^-} + \rho_{e^+})$,
  $V_{\overline{\nu}_s} = -\sqrt{2}\,G_F\,\frac{2\,\zeta(3)\,T^3}{\pi^2}\,\frac{\eta_B}{4} - \frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2}\,G_F\,p}{3m_{W_L}^2}(\rho_{e^-} + \rho_{e^+})$

RESULTS:

- **an eventual signal of sterile neutrino DM can be found at KATRIN, if the production of sterile neutrinos started at temperatures around 50 MeV or lower**, thanks to the shift related to T_c of the line representing the condition $\boldsymbol{\Omega_s = \Omega_{\text{DM}}}$ towards larger $\sin^2(2\theta)$, and thanks to the relaxation of the X-ray bound (in different shades of purple) due to reduced decay rate;
- also the Troitsk experiment would be sentitive to sterile neutrino DM in the future, in case of very large values of the mixing angle and very low critical temperatures, in a less conservative consideration of Milky Way satellite counts constraint.

Production through Shi-Fuller Mechanism



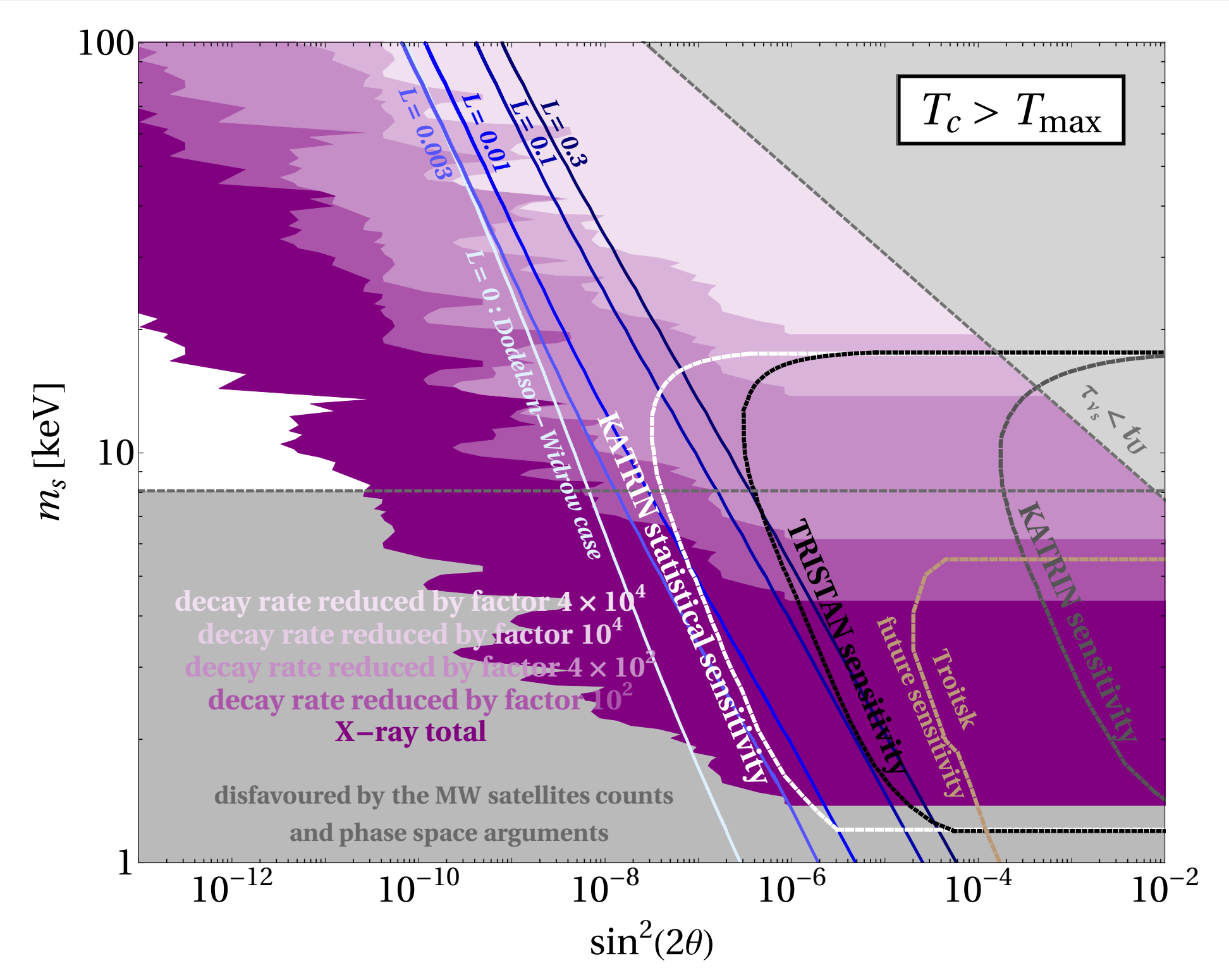
ASSUMPTIONS:

- $\boldsymbol{\nu_s \leftrightarrow \nu_e}$ and $\boldsymbol{\overline{\nu}_s \leftrightarrow \overline{\nu}_e}$ mixing
- primordial $\boldsymbol{L_e = \frac{n_{\nu_e} - n_{\overline{\nu}_e}}{n_\gamma} < 0}$ and $\boldsymbol{L = |L_e|}$
- $V_{\nu_s} = +\sqrt{2}\,G_F\,\frac{2\,\zeta(3)\,T^3}{\pi^2}\,\frac{\eta_B}{4} - \frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2}\,G_F\,p}{3m_{W_L}^2}(\rho_{e^-} + \rho_{e^+}) + \boldsymbol{\frac{4\sqrt{2}\zeta(3)}{\pi^2}G_F\,T^3\,L_e}$,
  $V_{\overline{\nu}_s} = -\sqrt{2}\,G_F\,\frac{2\,\zeta(3)\,T^3}{\pi^2}\,\frac{\eta_B}{4} - \frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2}\,G_F\,p}{3m_{W_L}^2}(\rho_{e^-} + \rho_{e^+}) - \boldsymbol{\frac{4\sqrt{2}\zeta(3)}{\pi^2}G_F\,T^3\,L_e}$

RESULTS:

- due to $\boldsymbol{L_e < 0}$, the primordial lepton asymmetry, the production of **sterile antineutrino dark matter** is **enhanced**, **requiring smaller mixing angles**;
- due to $\boldsymbol{L_e < 0}$, the production of **sterile neutrino dark matter** is **suppressed**, therefore we do not consider the possibility to detect these DM candidates in ECHo
- **in case of detection**, a **further cross-check on** the value of $\boldsymbol{T_c}$ will be **required** to discriminate between the resonant production case and the non-resonant one.

Production in presence of CPT violation



ASSUMPTIONS:

- **only** $\boldsymbol{\overline{\nu}_s \leftrightarrow \overline{\nu}_e}$ mixing ($\nu_s \leftrightarrow \nu_e$ suppressed due to CPT violation)
- primordial $\boldsymbol{L_e = \frac{n_{\nu_e} - n_{\overline{\nu}_e}}{n_\gamma} > 0}$ and $\boldsymbol{L = |L_e|}$
- V_{ν_s} does not contribute becuse ν_s are not produced,
  $V_{\overline{\nu}_s} = -\sqrt{2}\,G_F\,\frac{2\,\zeta(3)\,T^3}{\pi^2}\,\frac{\eta_B}{4} - \frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2}\,G_F\,p}{3m_{W_L}^2}(\rho_{e^-} + \rho_{e^+}) - \boldsymbol{\frac{4\sqrt{2}\zeta(3)}{\pi^2}G_F\,T^3\,L_e}$

RESULTS:

- the production of sterile neutrino dark matter is suppressed because, due to CPT violation, ν_s does not mix with ν_e;
- the production of sterile antineutrino dark matter is also suppressed due to the primordial lepton asymmetry;
- **the overproduction is avoided for large mixings even without invoking a delay in the beginning of the production.**

Main References

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[2] *S. Dodelson, L. M. Widrow*, Phys. Rev. Lett. 72, (1994), [hep-ph/9303287];
[3] *X. Shi, G. M. Fuller*, Phys. Rev. Lett. 82, (1999), [hep-ph/9810076];
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