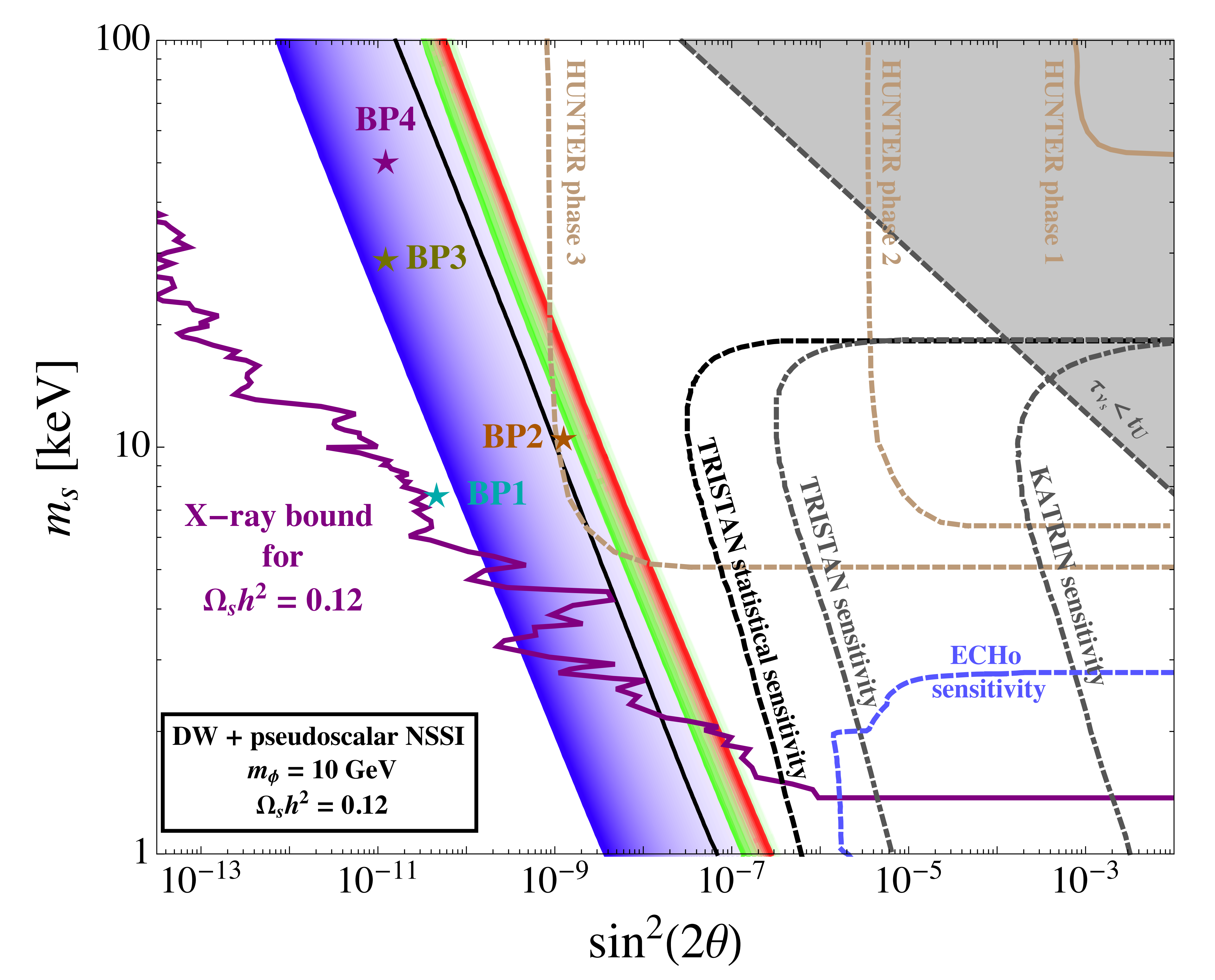
Impact of neutrino non-standard self-interactions on sterile neutrino dark matter

CRISTINA BENSO
Max-Planck Institut für Kernphysik (MPIK)



INTRODUCTION - STERILE NEUTRINO DARK MATTER

Definition: sterile neutrinos are neutral fermions, singlets under the SM symmetries.

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sterile neutrino can play the role of DM:

- ☑ no em nor strong interaction, by definition
- ☑ massive: possibly with mass O(keV)
- ☑ depending on mixing with active neutrinos: stable over time scales comparable with t_U
- ☑ depending on the production mechanism: produced in the early universe with velocities compatible with large scale structures

SEARCHES IN TERRESTRIAL EXPERIMENTS

- in the domain of direct detection
- rely on large mixing of $\nu_s \leftrightarrow \nu_e$ or $\overline{\nu}_s \leftrightarrow \overline{\nu}_e$

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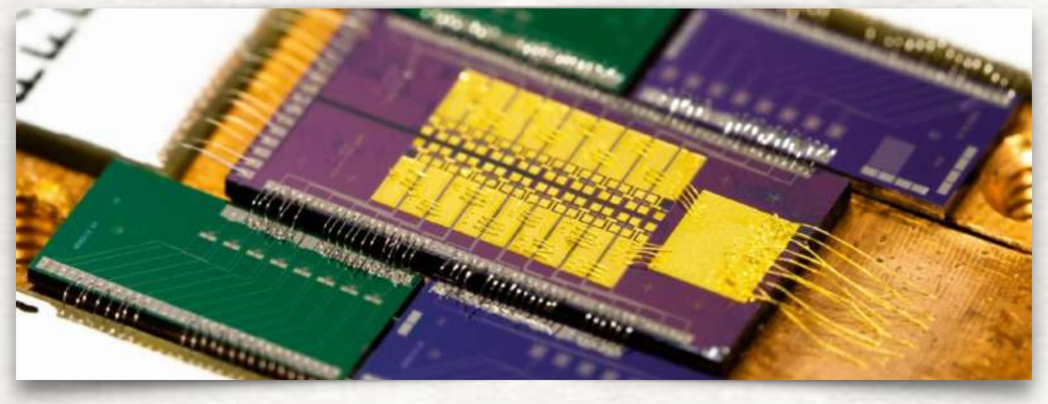
KATRIN

Tritium beta-decay

$m_s \lesssim 17.5$ keV

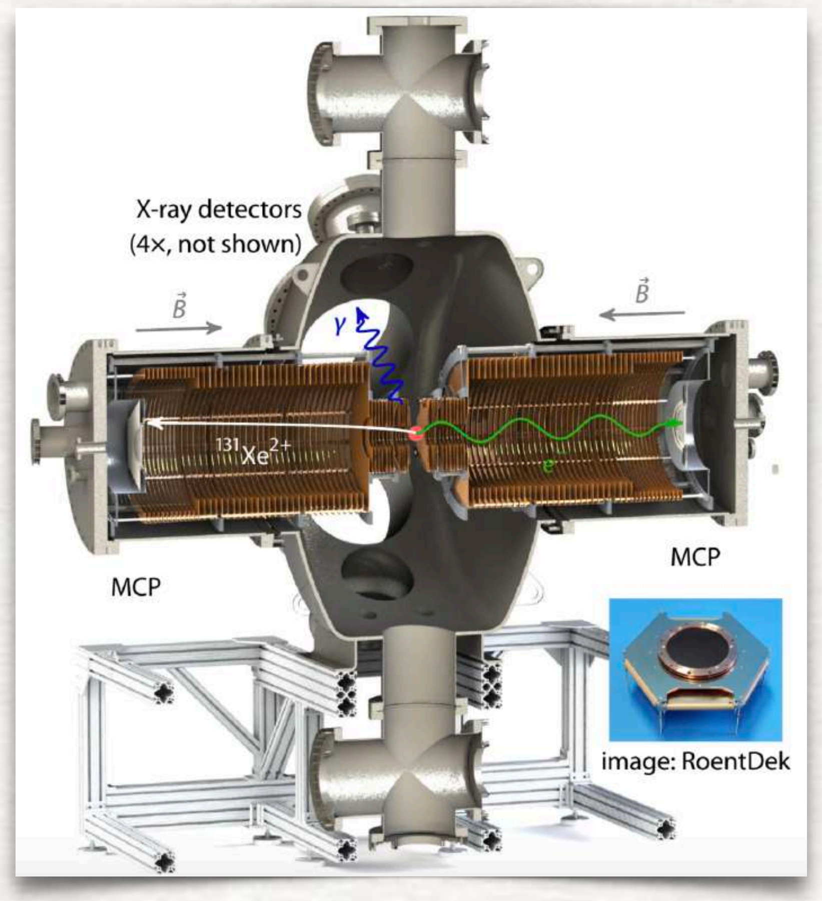
ECHo



Holmium EC

$m_s \lesssim 2.5$ keV

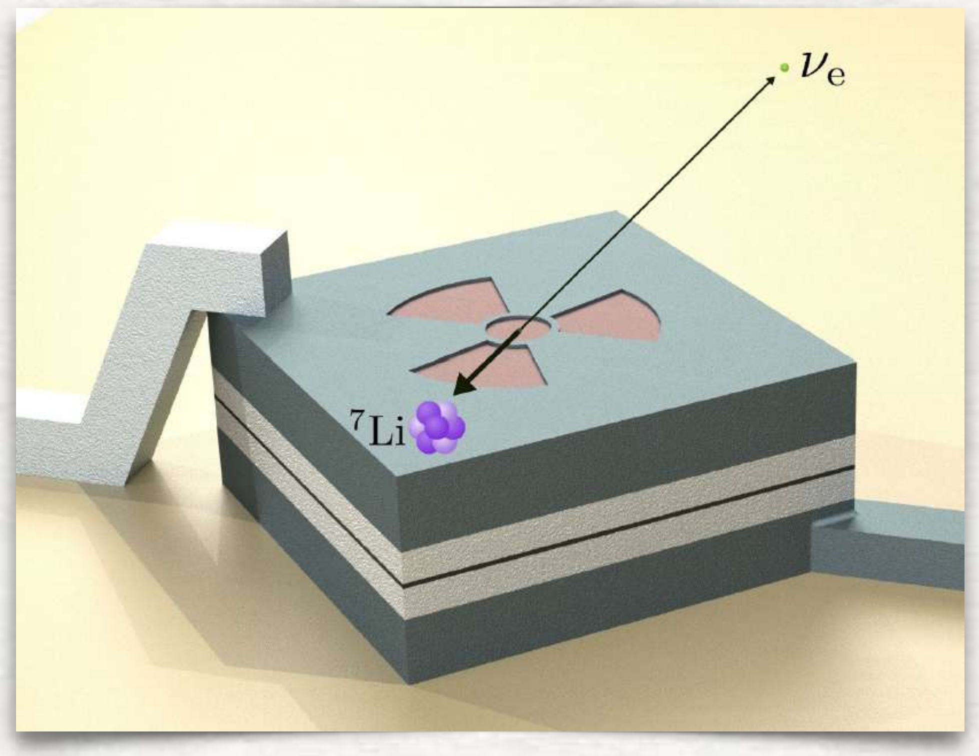
HUNTER



Caesium EC

$m_s \lesssim 350$ keV

BeEST



Beryllium EC

$10 \text{ keV} \lesssim m_s \lesssim 860$ keV

DODELSON-WIDROW PRODUCTION *

Assumption: $\nu_s \leftrightarrow \nu_e$ and $\overline{\nu}_s \leftrightarrow \overline{\nu}_e$ mixing

Mechanism: production through oscillation and collisions:

the neutrino fields, while propagating in the primordial plasma,
oscillate between the electron and the sterile state
when they interact with the other fields in the bath,
the wave function has probability $\propto \sin^2(2\theta_M)$ to collapse in the sterile state

* [Dodelson and Widrow, *Phys. Rev. Lett.* 72 (1994) 17-20]

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Evolution of the distribution function $f_s(p,t)$ described by the Boltzmann equation

$$\frac{\partial}{\partial t} f_s(p,t) - H\,p\,\frac{\partial}{\partial p} f_s(p,t) \approx \frac{\Gamma_e}{2} \langle P_m(\nu_e \to \nu_s; p,t)\rangle\, f_e(p,t)$$

where $\Gamma_e(p) = c_e(p,T)\, G_F^2\, p\, T^4$

$$\langle P_m(\nu_e \to \nu_s; p,t)\rangle = \sin^2(2\theta_M)\, \sin^2\left(\frac{v\,t}{L}\right) \approx \frac{1}{2} \sin^2(2\theta_M)$$

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DODELSON-WIDROW PRODUCTION

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

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DODELSON-WIDROW PRODUCTION

We solve the Boltzmann equation and find the distribution function

$$f_s(r) = \int_{T_{\rm fin}}^{T_{\rm in}} dT \left(\frac{M_{\rm Pl}}{1.66\,\sqrt{g_*}\,T^3}\right)\left[\frac{1}{4}\,\frac{\Gamma_e(r,T)\left(\frac{m_s^2}{2\,r\,T}\right)^2\,\sin^2(2\theta)}{\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)+\left(\frac{\Gamma_e}{2}\right)^2+\left(\frac{m_s^2}{2\,r\,T}-V\right)^2}\right]\frac{1}{e^r+1}$$

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and calculate the sterile neutrino dark matter abundance passing through

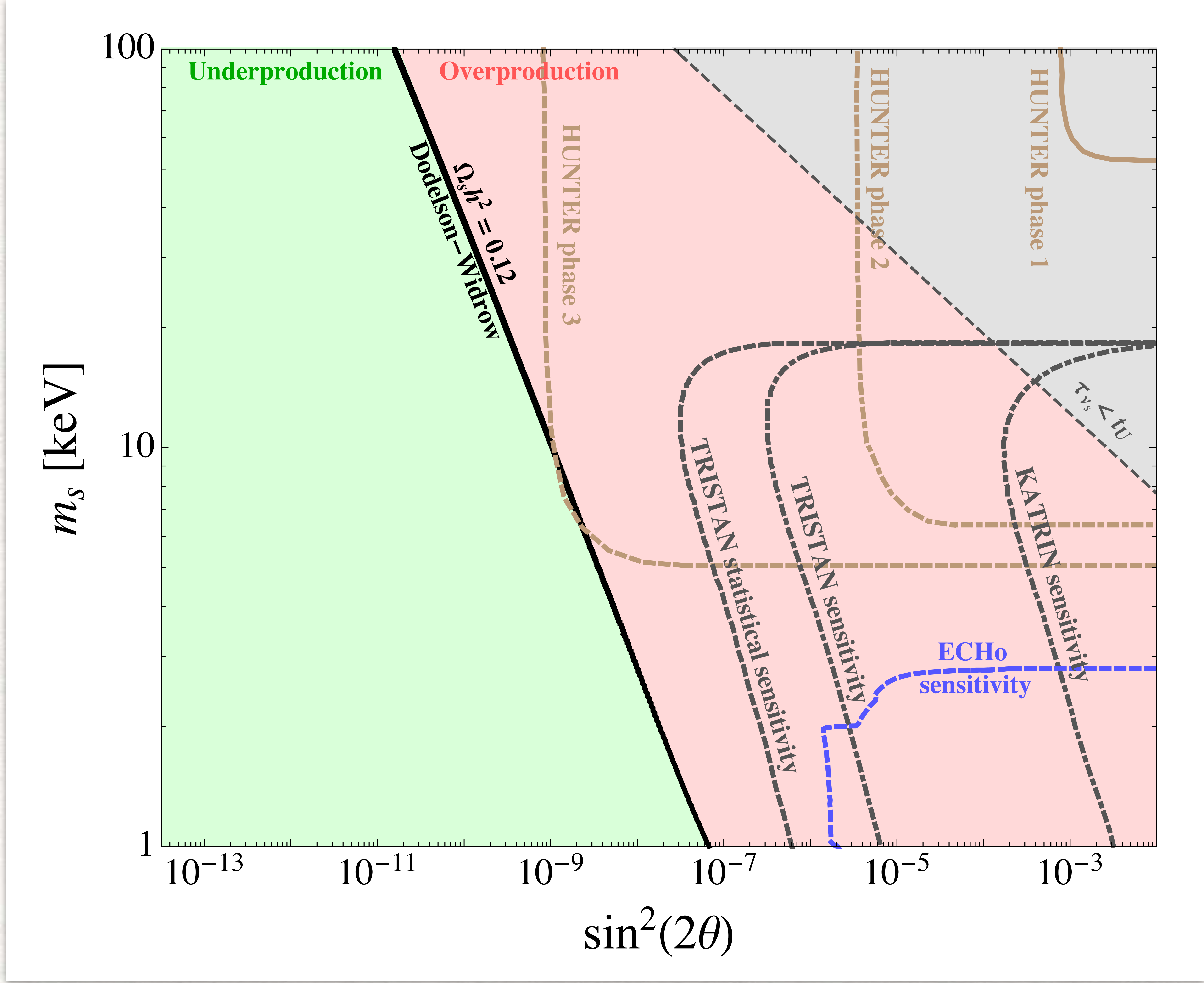
sterile neutrino number density $\quad n(T) = \dfrac{g}{(2\pi)^3}\displaystyle\int_{-\infty}^{+\infty} d^3p\, f(p,T)$

sterile neutrino yield $\quad Y = \dfrac{n}{s}$

⟶

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

DODELSON-WIDROW PRODUCTION - CHALLENGE FOR DETECTION



NEUTRINO NON-STANDARD SELF-INTERACTIONS - WHAT? WHY?

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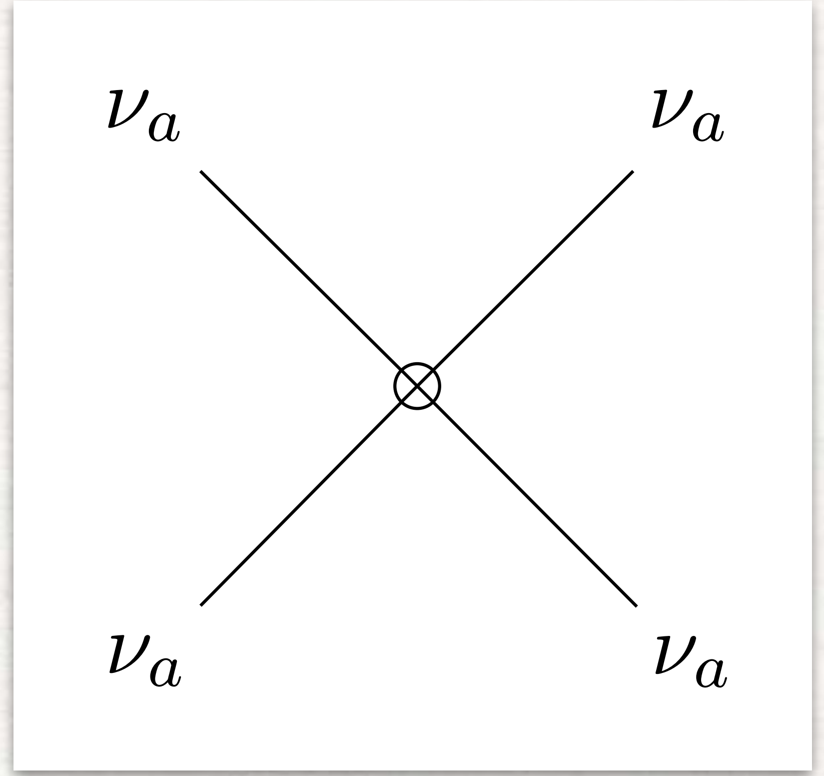
Effective description valid for heavy mediators

$$\mathcal{L}_{\rm NSSI} = -\frac{G_F}{\sqrt{2}} \sum_j \sum_{\alpha,\beta,\gamma,\delta} \varepsilon_j^{\alpha\beta\gamma\delta} \left(\bar{\nu}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{\nu}_\gamma \bar{\mathcal{O}}_j \nu_\delta\right)$$

$$\mathcal{O}_j = \{\mathbb{I}, \gamma^\mu, i\gamma^5, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$



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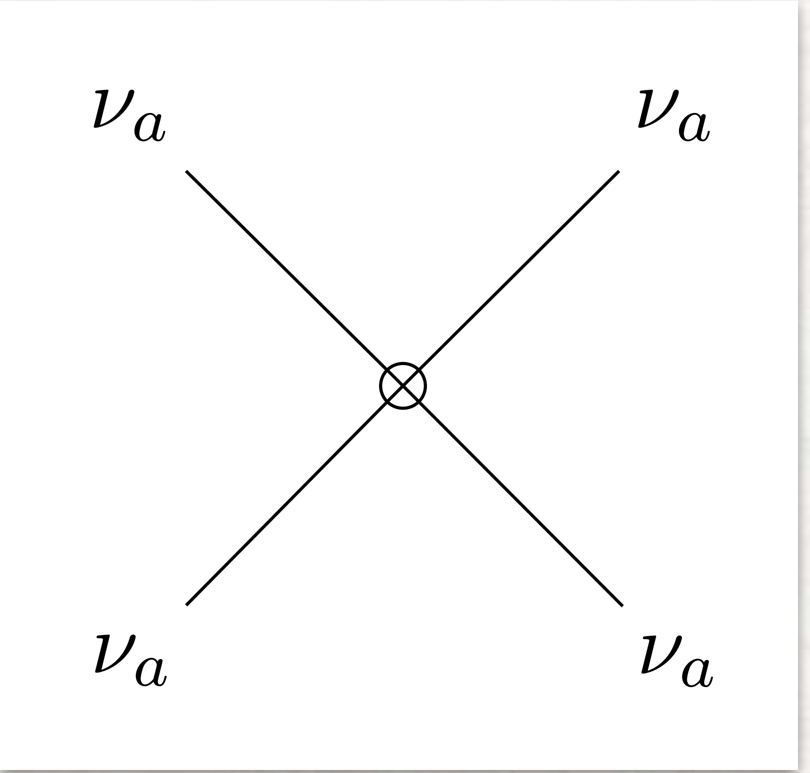

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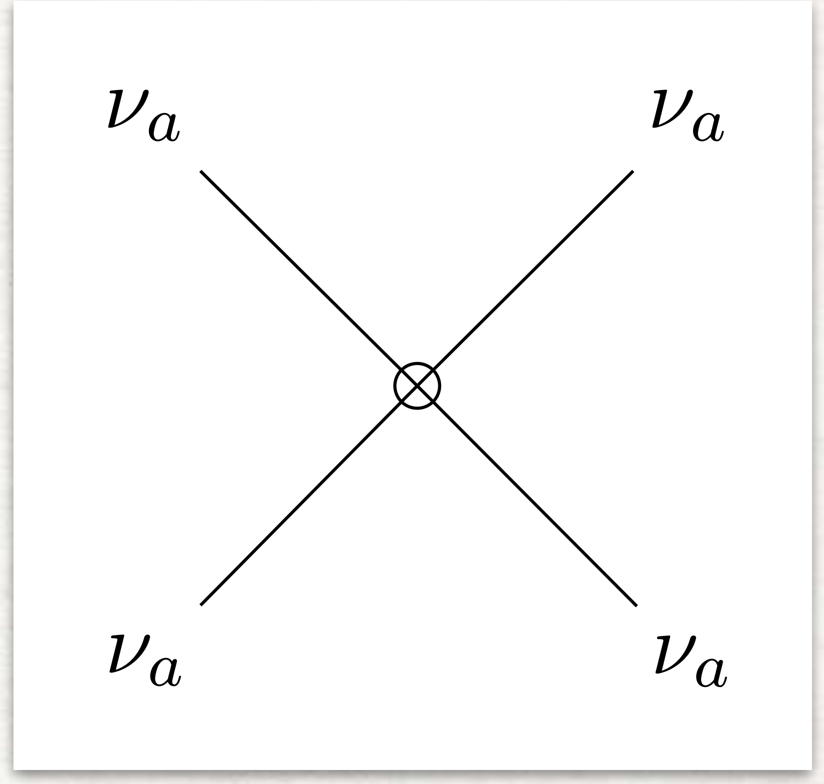

Why are NSSI interesting?

- we expect new physics to come from the neutrino sector
- some models describing neutrino mass generation naturally include NSSI
- NSSI could have significant impact on physics of the early universe (Hubble tension etc.)
- parameter space very poorly constrained and investigated

(See [arXiv: 2203.01955 [hep-ph]] for more information)

NEUTRINO NSSI - HOW TO INCLUDE THEM?

Assumptions for concreteness:

- heavy mediators ⟶ effective field theory treatment
- only electron flavor-diagonal NSSI considered
- for Majorana neutrinos: only scalar, pseudoscalar and axial-vector interactions are non-zero
- to capture temperature and momentum dependence in the thermal potential:

$$\mathcal{L}_j = -\frac{G_F}{\sqrt{2}}\left(\epsilon_{j,\nu}\right)\left(\left(\bar{\nu}_e\mathcal{O}_j\nu_e\right)\left(\bar{\nu}_e\mathcal{O}'_j\nu_e\right) - \frac{1}{m_\phi^2}\left(\bar{\nu}_e\mathcal{O}_j\nu_e\right)\Box\left(\bar{\nu}_e\mathcal{O}'_j\nu_e\right)\right)$$

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$\downarrow$

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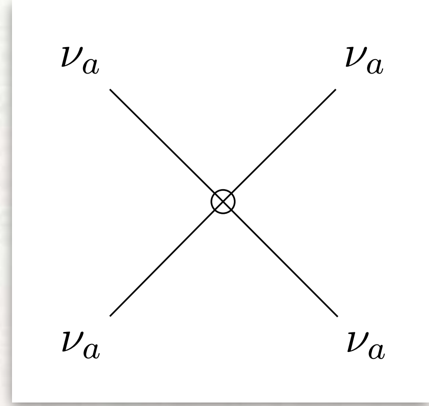

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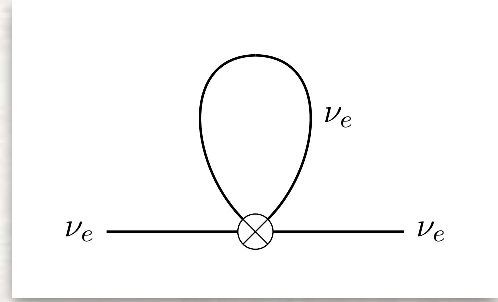

NEUTRINO NSSI - HOW TO INCLUDE THEM?

- Scalar NSSI

$$\Gamma_{e,\mathrm{NSSI}}(p) = \frac{7\pi}{180}\epsilon_S^2\, G_F^2\, p\, T^4 \qquad V_{T,\mathrm{NSSI}}(p) = -\frac{7\sqrt{2}\pi^2}{45\, m_\phi^2}\epsilon_S\, G_F\, p\, T^4$$

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- Axial vector NSSI

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following [M. Paraskevas, 1802.02657] [P. B. Pal, *AJP* 79 (2011), 485498] [J. C. D'Olivo et al., *PRD* 46 (1992) 1172]

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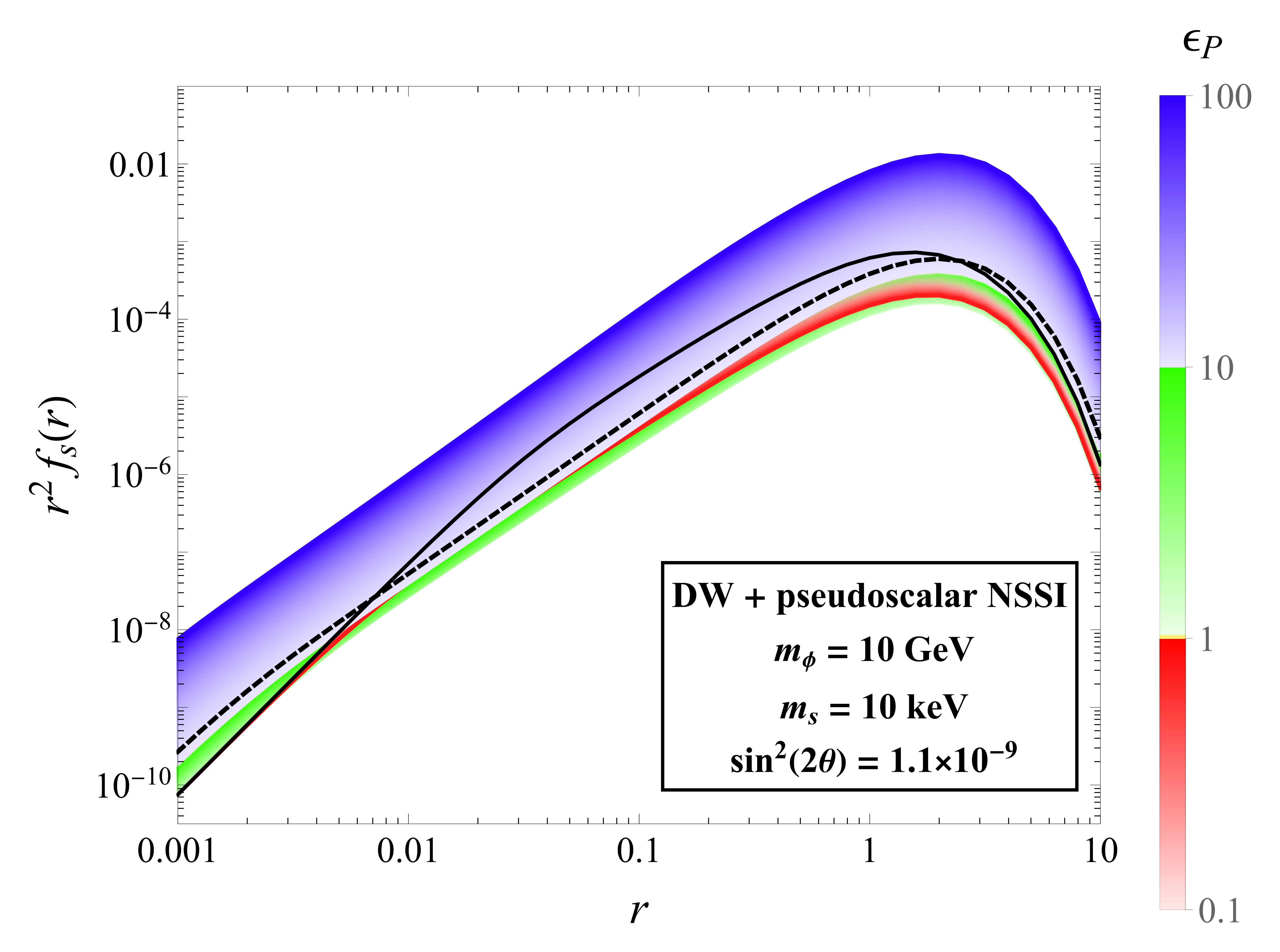
NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

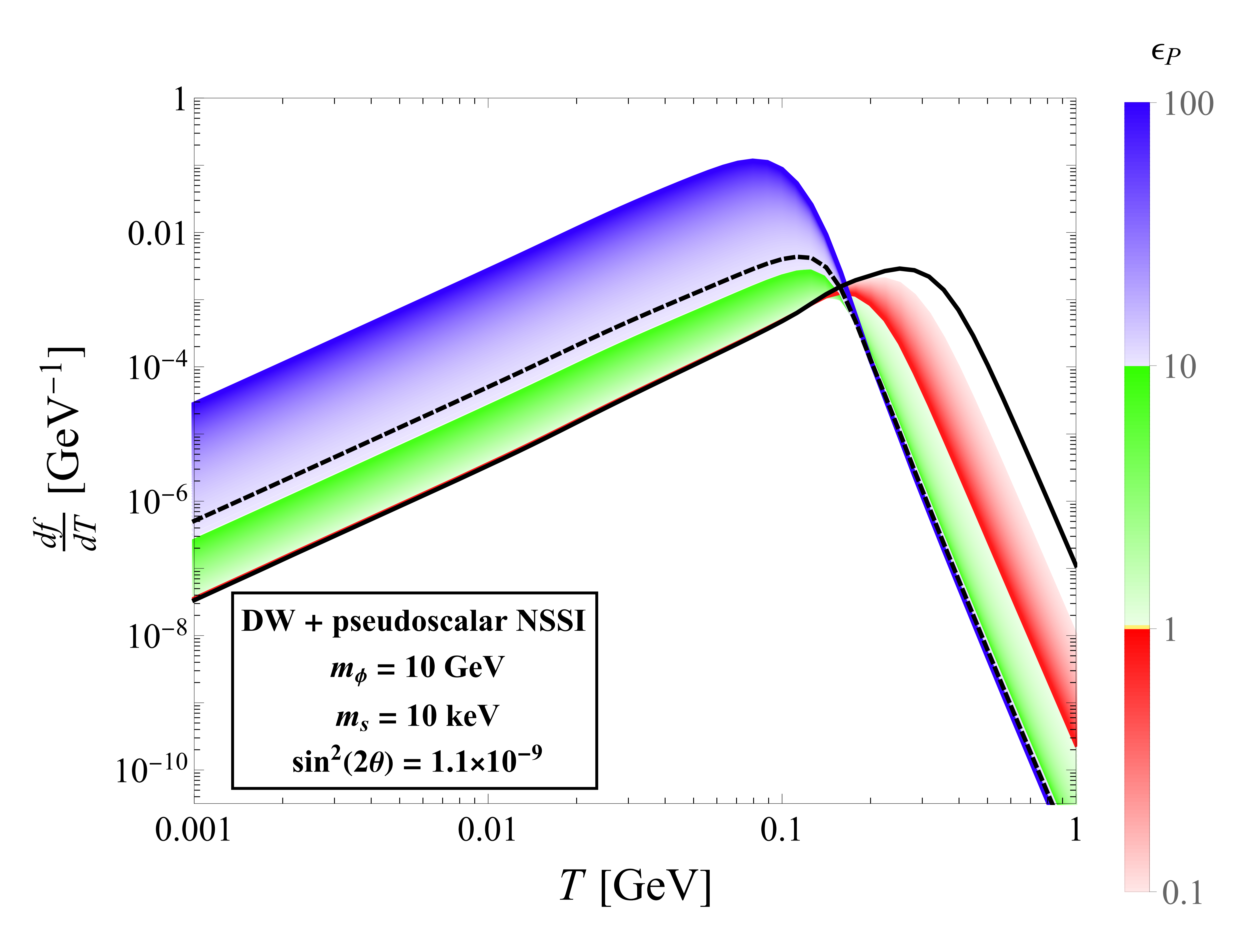
Sterile neutrino distribution function



[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *PRD* 105 (2022) 5, 055016]

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

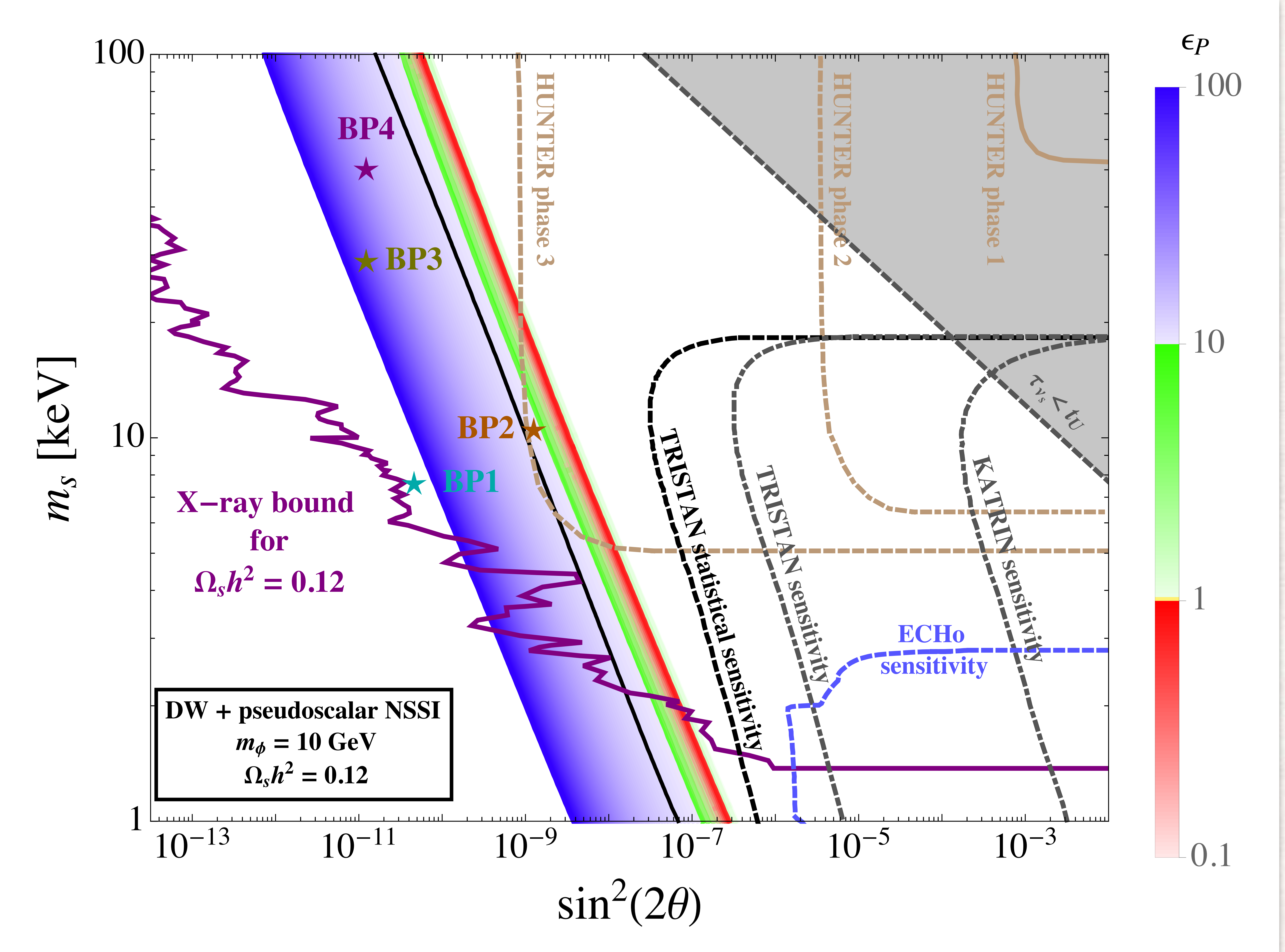
Sterile neutrino production evolution



[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *PRD* 105 (2022) 5, 055016]

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

Sterile neutrino parameter space : 100% DM constituted by sterile neutrinos



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CONCLUSIONS

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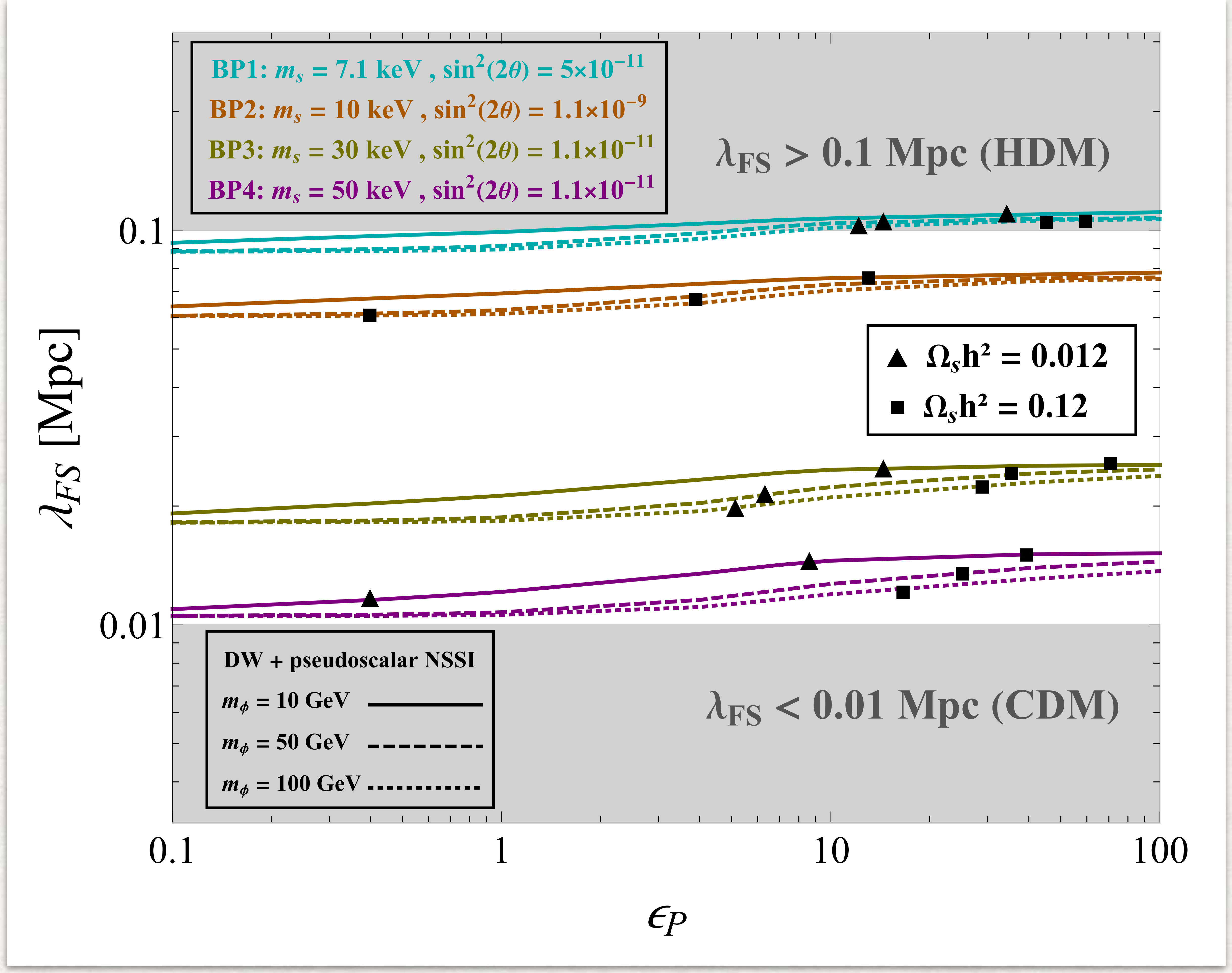
- The parameter space region in which $\Omega_{\rm DM} = \Omega_s$ is enlarged by such NSSI and they enhance the possibility to detect sterile neutrino dark matter in HUNTER phase 3.

NEUTRINO NSSI - IMPACT ON STRUCTURE FORMATION

Relevant observable: free streaming length

$$\lambda_{\rm FS} = \int_0^{t_0} \frac{\langle v(t)\rangle}{a(t)} dt \simeq 1.2 \text{ Mpc} \left(\frac{\text{keV}}{m_s}\right) \frac{\langle p/T\rangle}{3.15}$$

- Depends on the features of the production through the distribution function needed to calculate <p/T>
- Structures cannot form on scales < $\lambda_{\rm FS}$
- Neither NSSI strength nor mediator mass affect significantly $\lambda_{\rm FS}$
- What makes the major difference is still the sterile neutrino mass



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- Active neutrino NSSI considered are not in conflict with large scale structures.

BACKUP

SEARCHES IN TERRESTRIAL EXPERIMENTS

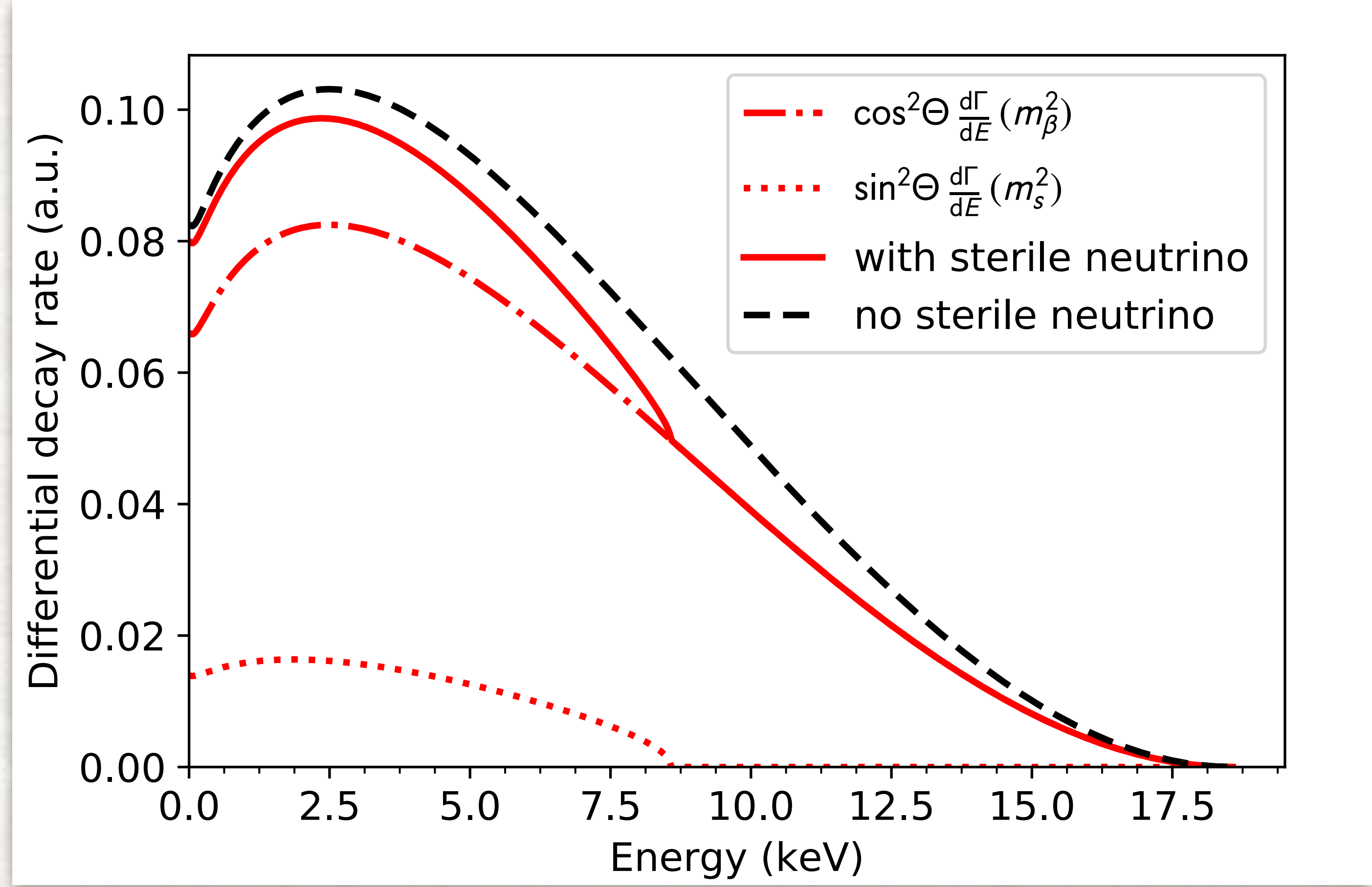
KATRIN

[Troitsk experiment based on the same process but less sensitive]

Based on **tritium beta-decay**:

- ★ Short half-life of 12.3 yrs ⟶ high decay rate
- ★ Endpoint of $E_0 = 18.6\,\mathrm{keV}$ ⟶ allows search of sterile neutrinos with mass up to several keV

Signature: kink in the electron spectrum at energy $E_0 - m_s$ with magnitude governed by the mixing amplitude $\sin^2\theta$

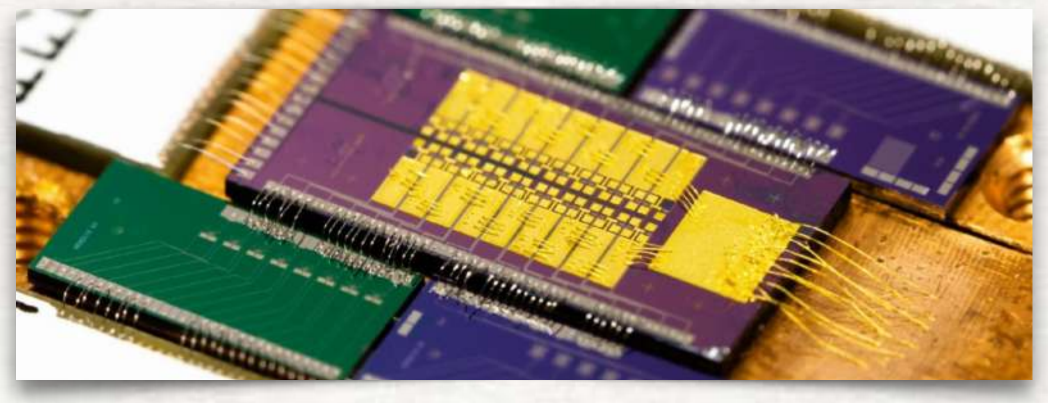


(Borrowed from S. Mertens lecture in Bad Honnef)

$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m(\nu_e)) + \sin^2\theta \frac{d\Gamma}{dE}(m_s)$$

SEARCHES IN TERRESTRIAL EXPERIMENTS

ECHo

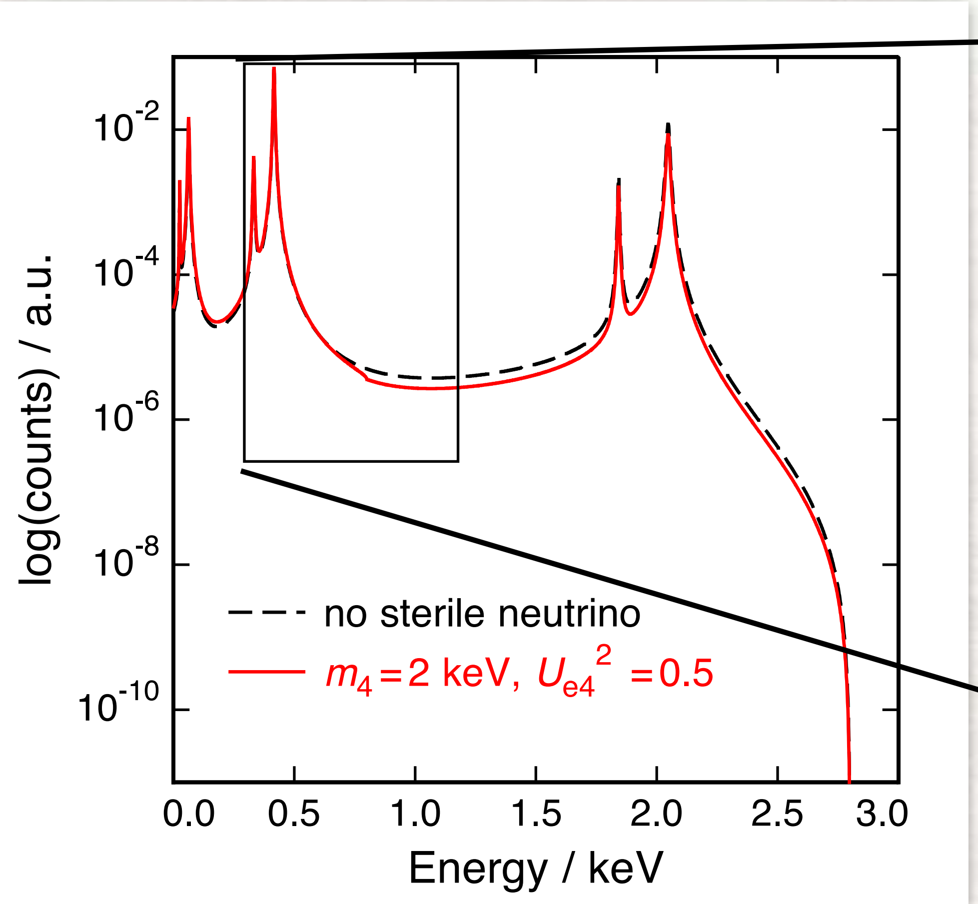


[HOLMES and NuMECS experiments based on the same process]

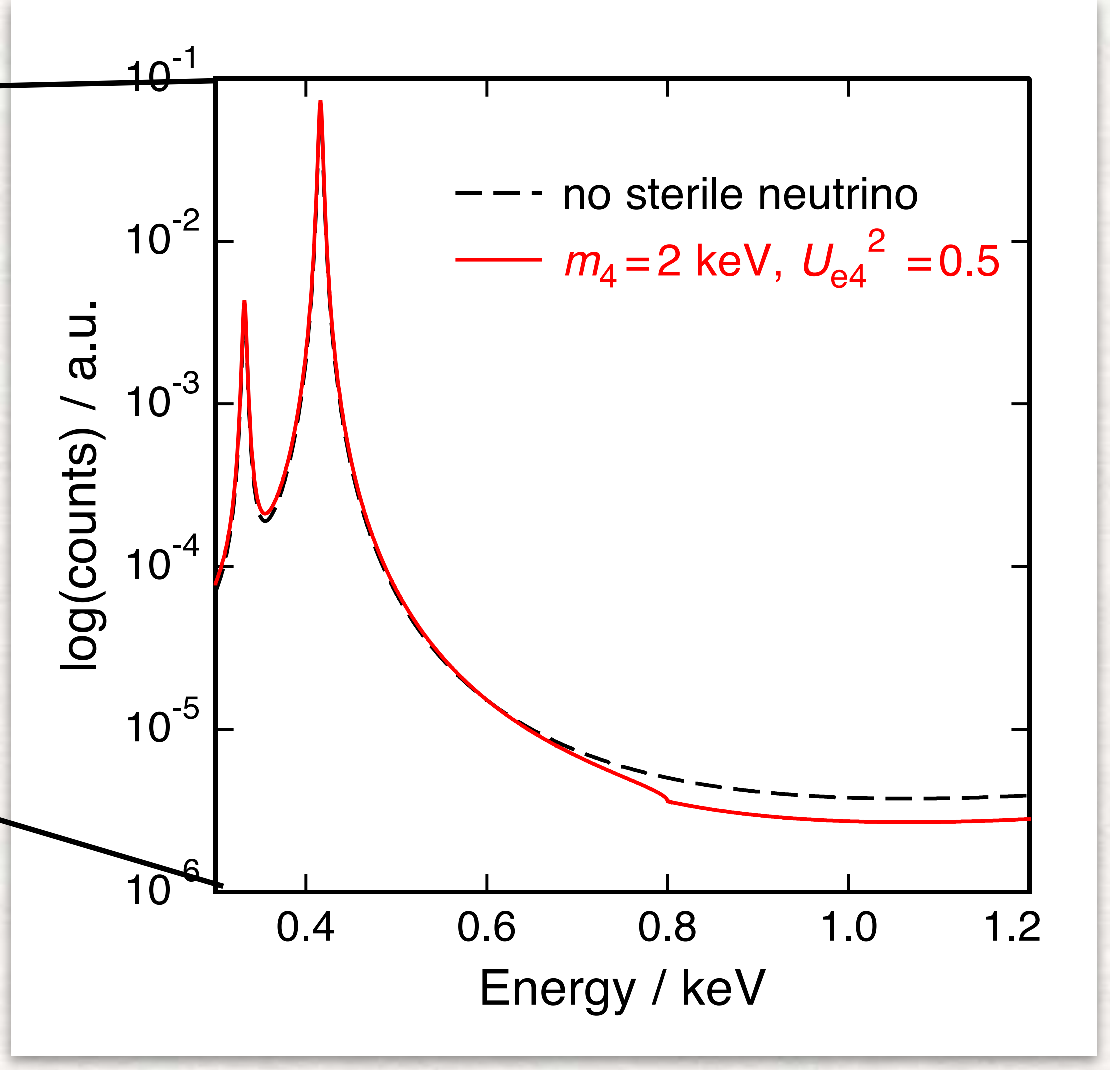
Based on holmium electron capture:

- ★ calorimetric measurement ⟶ all events occurring in the detector give a measurable signal (entire spectrum "for free")
- endpoint of $Q_{\mathrm{EC}} = 2.833$ keV ⟶ allows search of sterile neutrinos only with mass < 2.5 keV

Signature: kink in the EC spectrum of $^{163}\mathrm{Ho}$ at energy $Q_{\mathrm{EC}} - m_4$ with amplitude proportional to $|U_{e4}^2|$

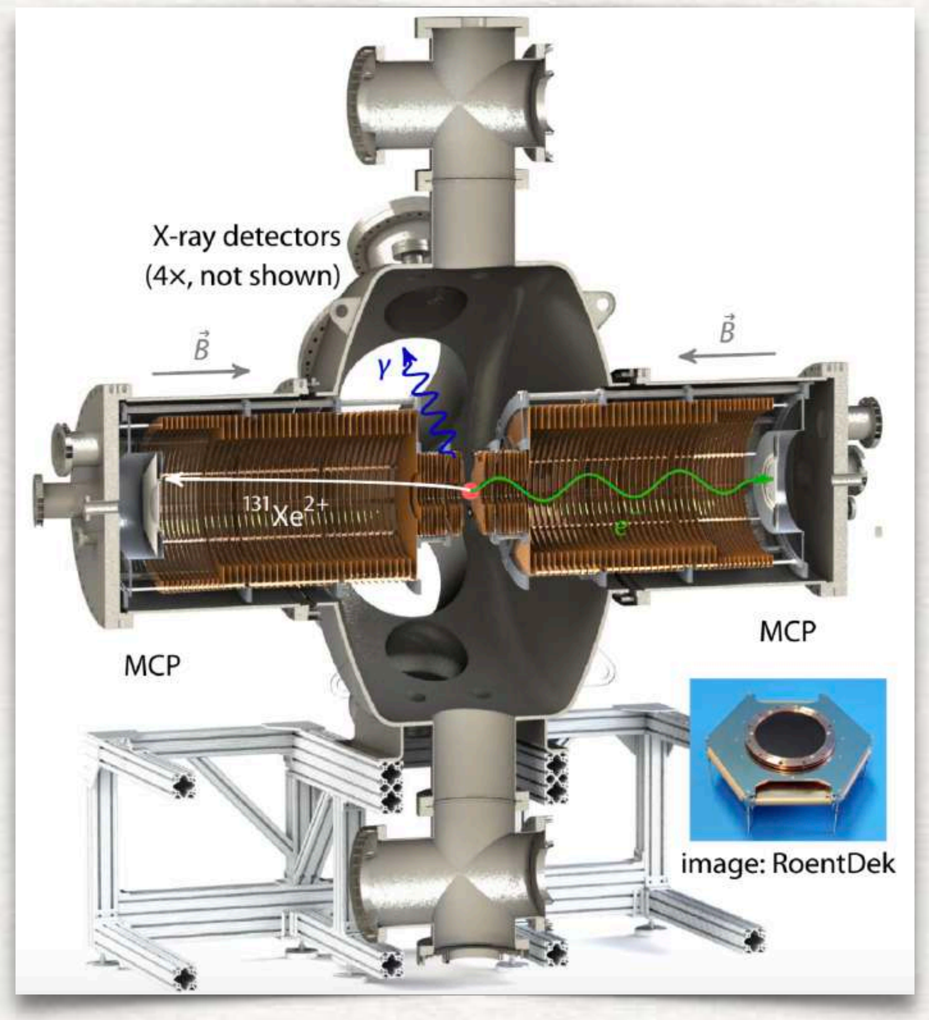


[M. Drewes, *JCAP* 1701 (2017) 025]



SEARCHES IN TERRESTRIAL EXPERIMENTS

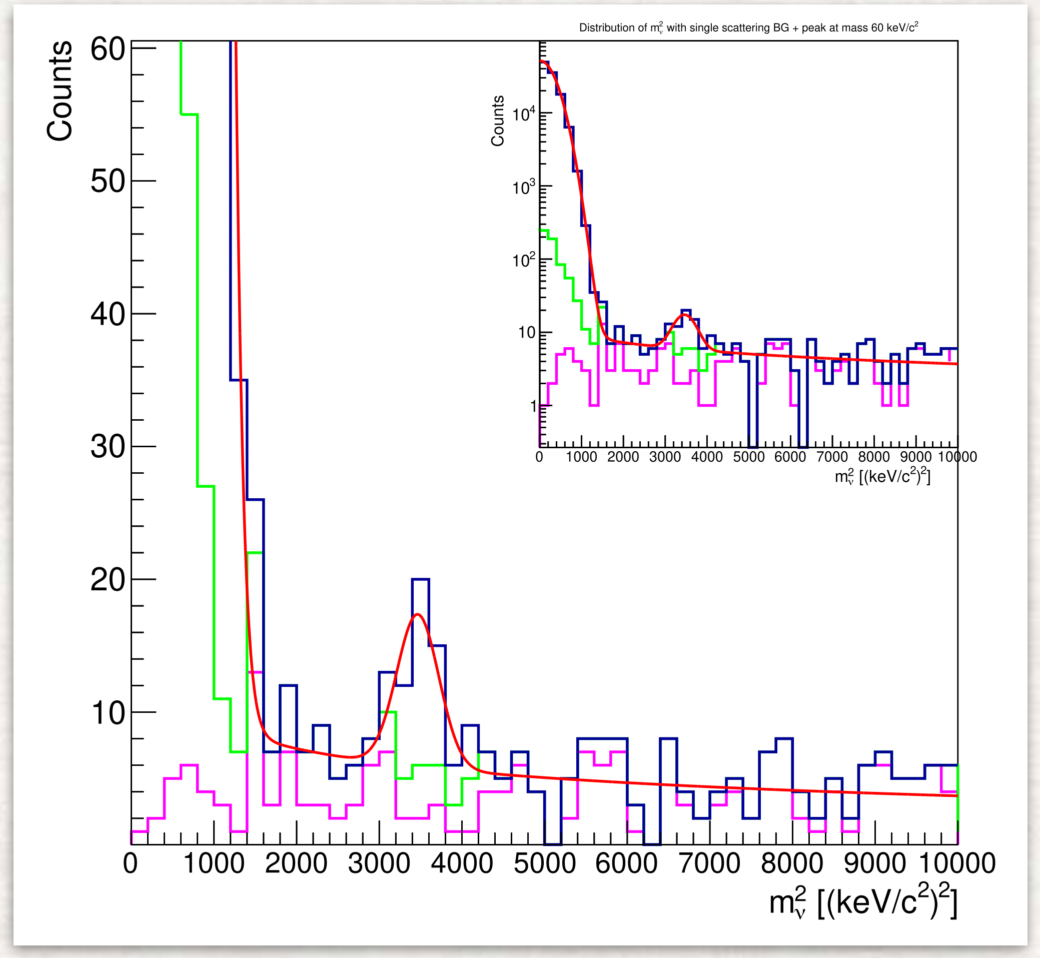
HUNTER



Based on caesium electron (K-) capture:

- ★ with total energy-momentum reconstruction using magneto-optical atom trap (MOT) and reaction ion momentum spectrometers
- ★ available energy of the reaction $Q = 352\,\mathrm{keV}$ allows complementary searches w.r.t. KATRIN & ECHo

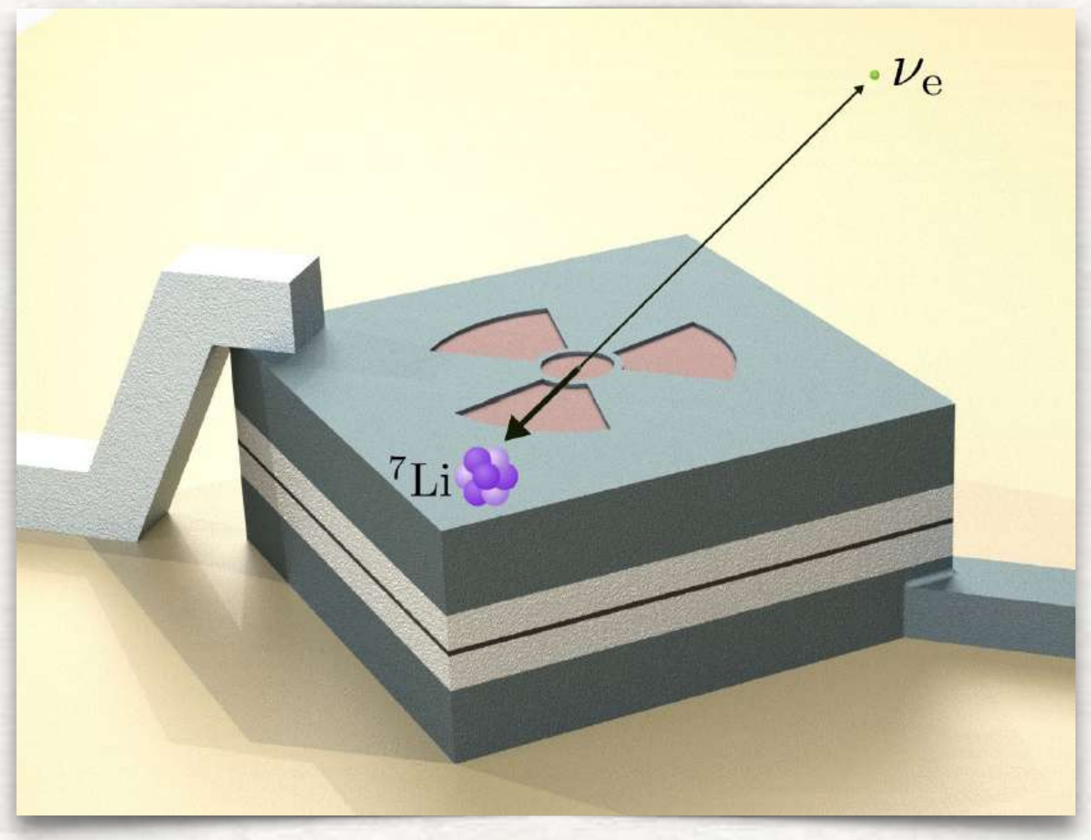
Signature: separated population of events with non-zero reconstructed missing mass up to 352 keV



[C. J. Martoff et al, *Quantum Sci. Technol.* 6 (2021) 024008]

SEARCHES IN TERRESTRIAL EXPERIMENTS

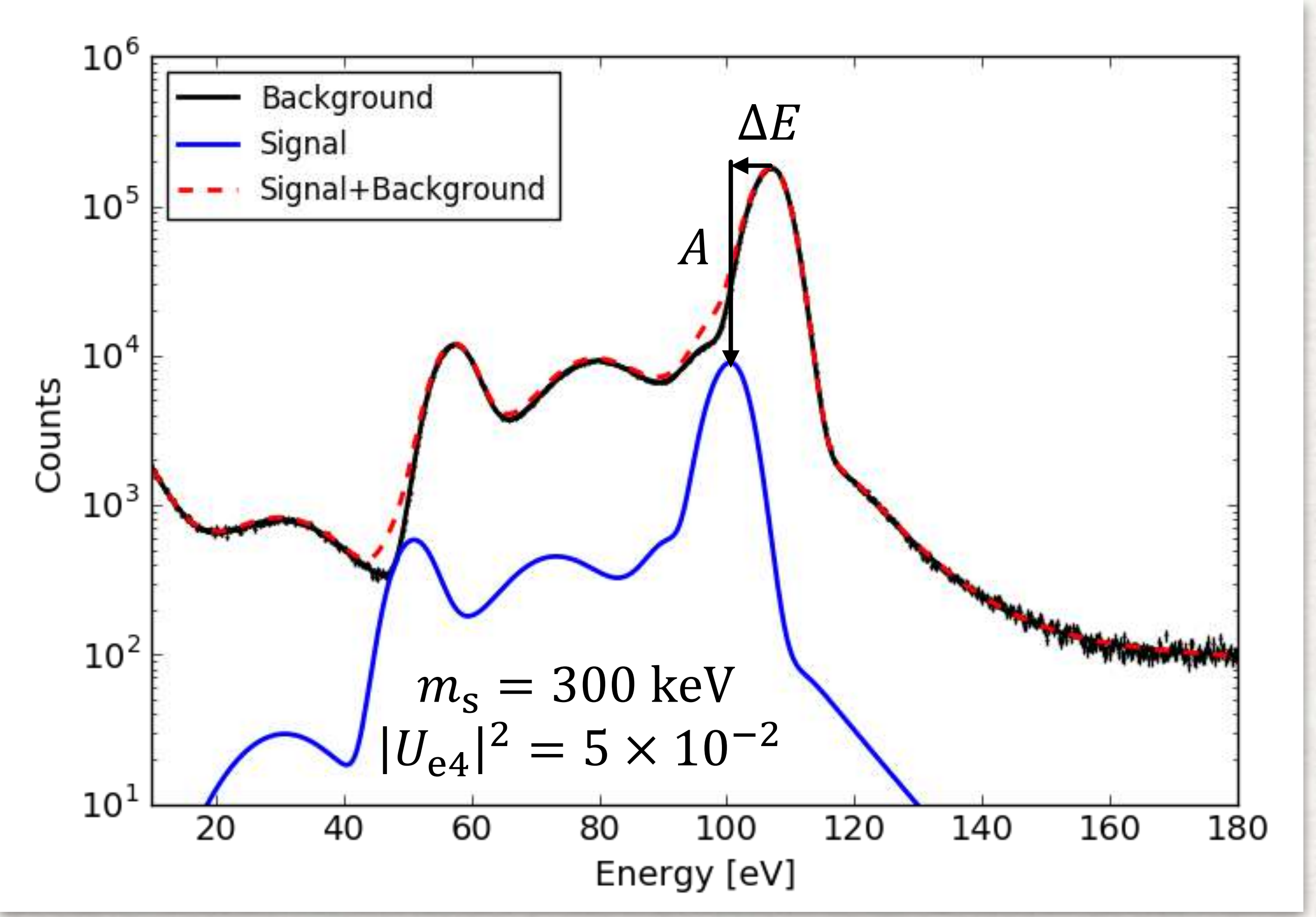
BeEST



Based on beryllium electron capture:

- ★ with decay momentum reconstruction using superconducting tunnel junction (STJ) quantum sensing technology
- ★ available energy of the reaction $Q = 862\ \mathrm{keV}$ allows complementary searches w.r.t. KATRIN & ECHo

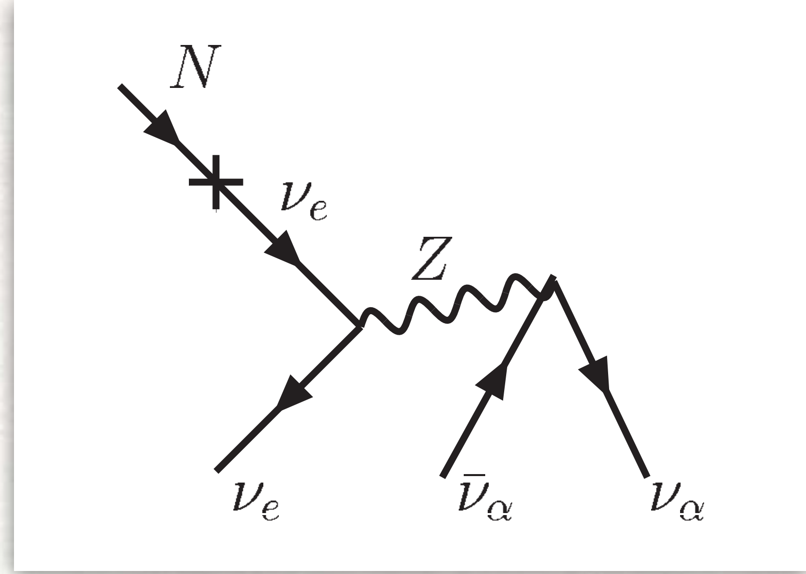
Signature: spectrum similar to the one of the standard case (no sterile neutrinos) but shifted in energy and with smaller amplitude



(Borrowed from G, Kim, APS-DNP Meeting 2020)

X-RAY BOUND

tree level decay

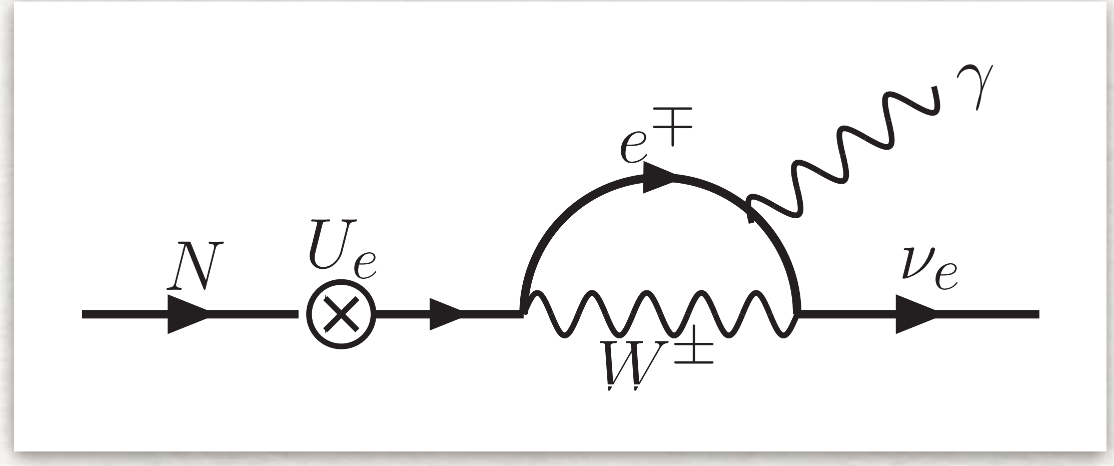


$$\Gamma_{\nu_s \to 3\nu} = \frac{G_F^2\, m_s^5}{96\,\pi^3} \sin^2(2\theta) = \frac{1}{4.7 \times 10^{10}\ \mathrm{s}} \left(\frac{m_s}{50\ \mathrm{keV}}\right)^5 \sin^2(2\theta)$$

$$\tau_{\nu_s} > t_U \Rightarrow \theta^2 < 1.1 \times 10^{-7} \left(\frac{50\ \mathrm{keV}}{m_s}\right)$$

[Adhikari et al., *JCAP* 01 (2017), 025]

one loop decay



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

Upper bounds on mass and mixing angle from the X-rays (non-)observations

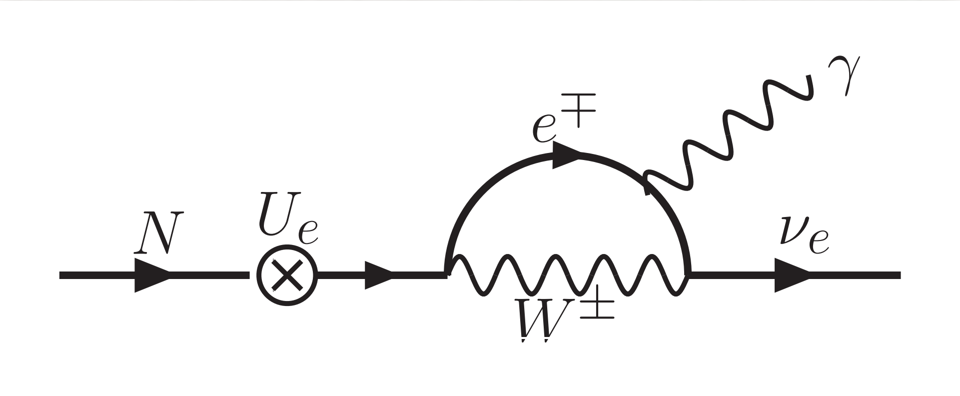
Exp.: XMM-Newton, Chandra, Suzaku, Swift, INTEGRAL, HEAO-1, Fermi/GBM

X-RAY BOUND: ABSOLUTE OR MODEL-DEPENDENT?

Observable: flux of photons
$$F = \frac{\Gamma_{\nu_s \to \nu\gamma}}{4\pi m_s} \int dl\, d\Omega\, \rho_{\rm DM}(l,\Omega)$$

where
$$\Gamma_{\nu_s \to \nu\gamma} \propto \int d\text{Phase}|\mathcal{M}|^2$$

In absence of new physics:



⟷ $\mathcal{M} = \mathcal{M}_1$ and $\Gamma_{\nu_s \to \nu\gamma} \propto \sin^2(2\theta_M)$

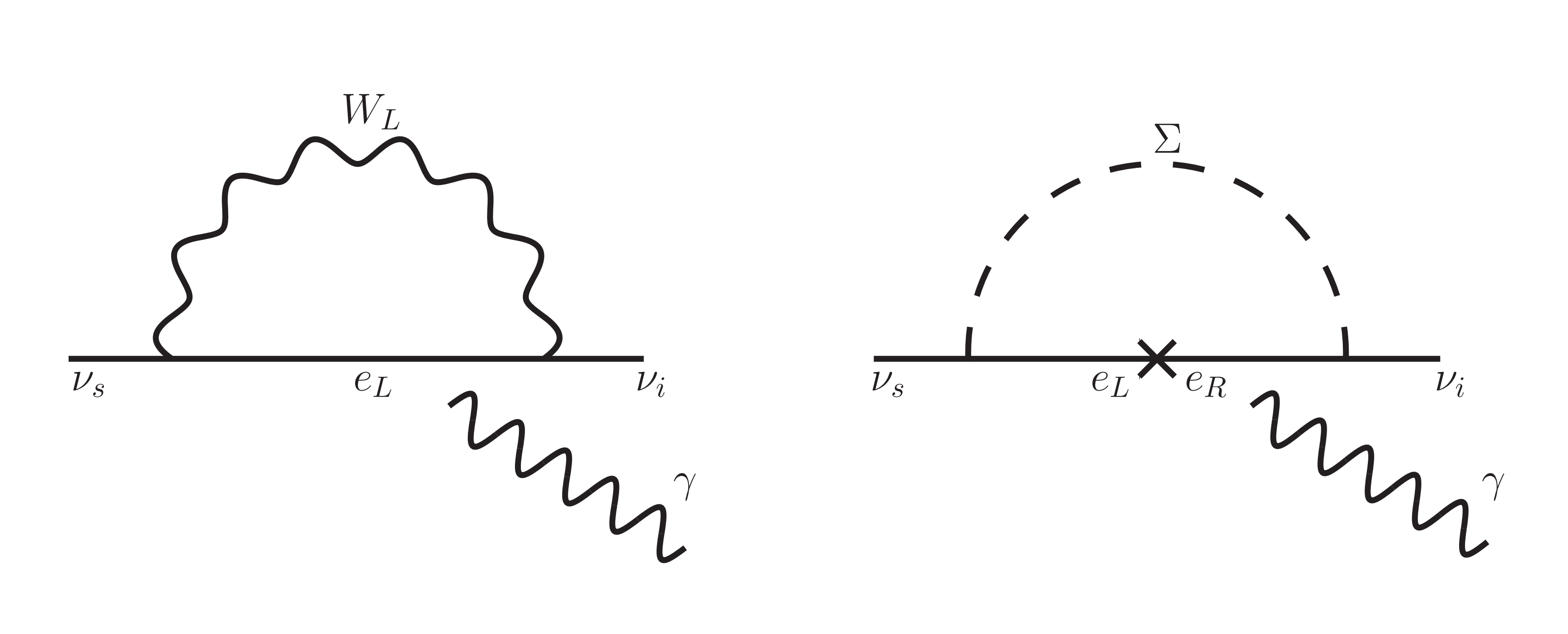
If new physics mediates the same decay and interferes disruptively:

$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 = \chi\mathcal{M}_1 < \mathcal{M}_1$$

decay rate $\Gamma_{\nu_s \to \nu\gamma}$ and flux F reduced by χ^2

X-RAY BOUND: ABSOLUTE OR MODEL-DEPENDENT?

Particular realization:



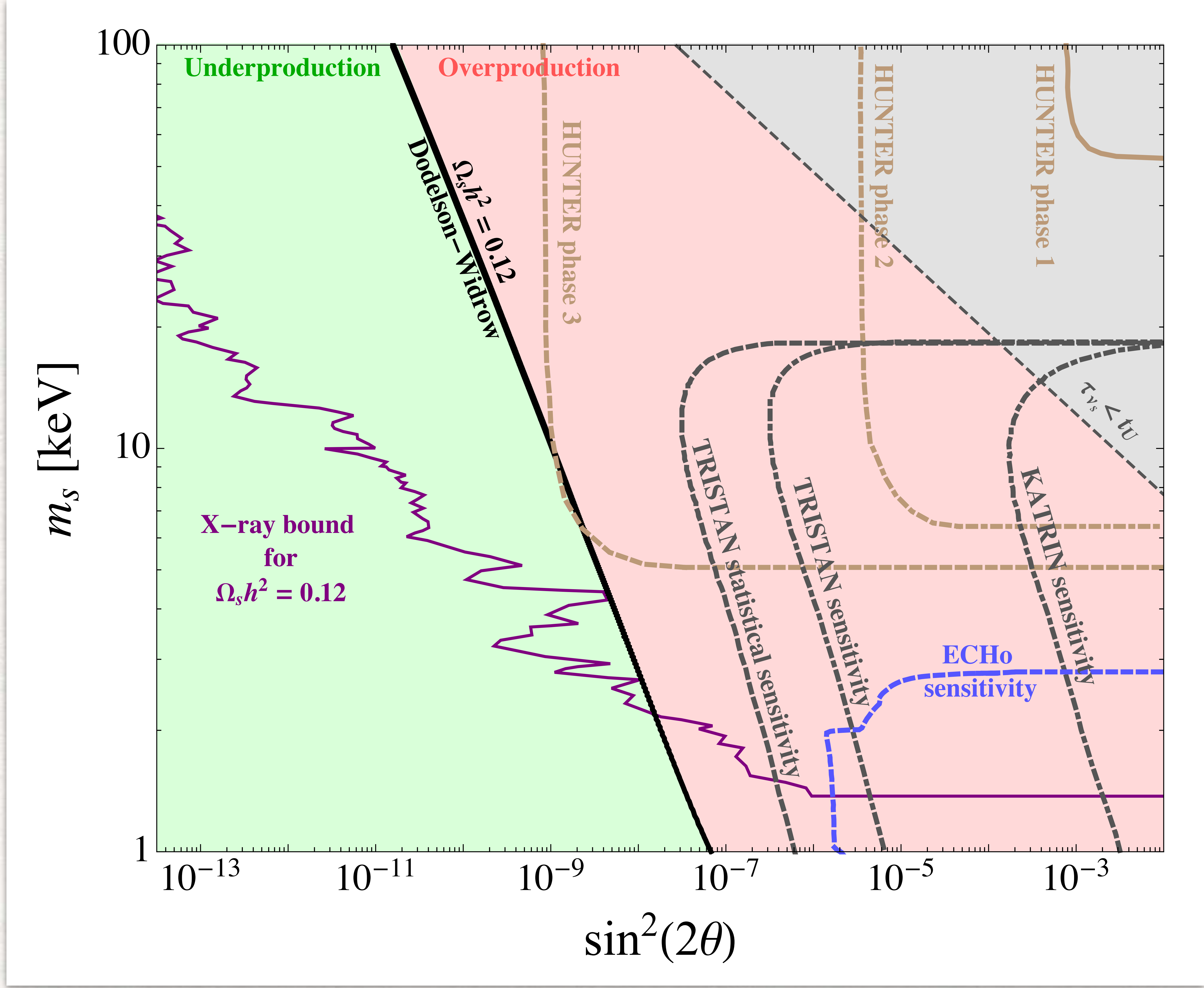
Adding a heavy scalar Σ and introducing 3 new parameters $\lambda, \lambda', m_\Sigma$

$\longrightarrow$ partial or complete cancellation if the following condition is satisfied

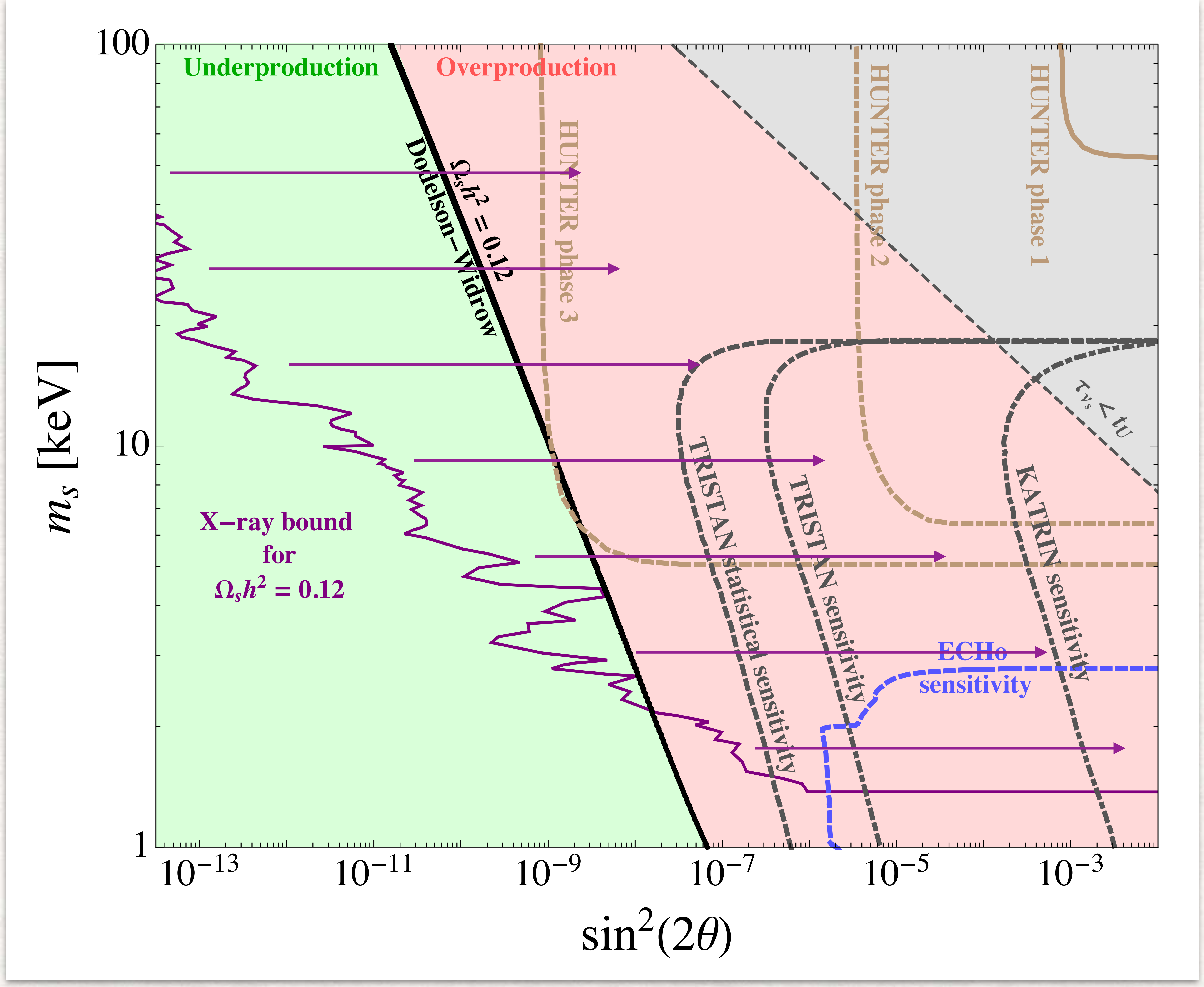
$$\sin\theta = \left(\frac{-4\lambda\lambda'}{3g^2}\right)\frac{m_e}{m_s}\frac{m_W^2}{m_\Sigma^2}\left[\mathrm{Log}\left(\frac{m_e^2}{m_\Sigma^2}\right)+1\right]$$

But: Σ must not reach the thermal equilibrium in the early universe $\leftrightarrow$ $\begin{cases}\lambda \lesssim 10^{-7} \\ \text{or} \\ T_{RH} < m_\Sigma \sim 1 \text{ TeV}\end{cases}$

X-RAY BOUND: RELAXATION



X-RAY BOUND: RELAXATION



[CB, V. Brdar, M. Lindner, W. Rodejohann, *Phys.Rev.D* 100 (2019), 115035]

X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

Observable: flux of photons $F = \frac{\Gamma_{\nu_s \to \nu\gamma}}{4\pi m_s} \int dl\, d\Omega\, \rho_{\rm DM}(l, \Omega)$

where $\rho_{\rm DM}$ is the entire dark matter energy density in the universe

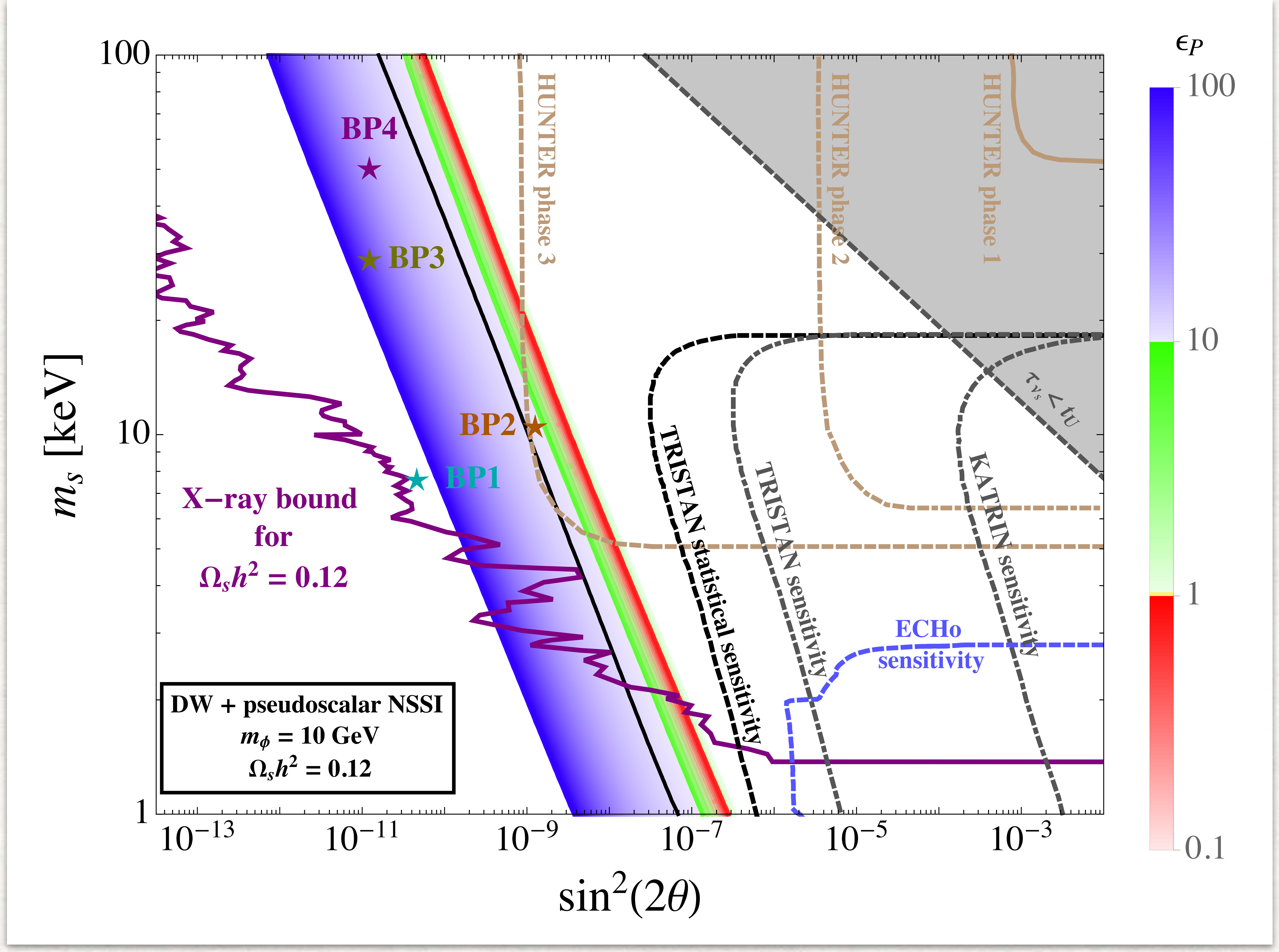
If DM is a "cocktail" of different species of DM candidates:

> $\rho_s < \rho_{DM}$ corresponds to larger $\sin^2(2\theta)$ for the same flux F

Secondary advantage: multicomponent dark matter leaves in principle more freedom also from other constraints coming for example from structure Formation.

X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

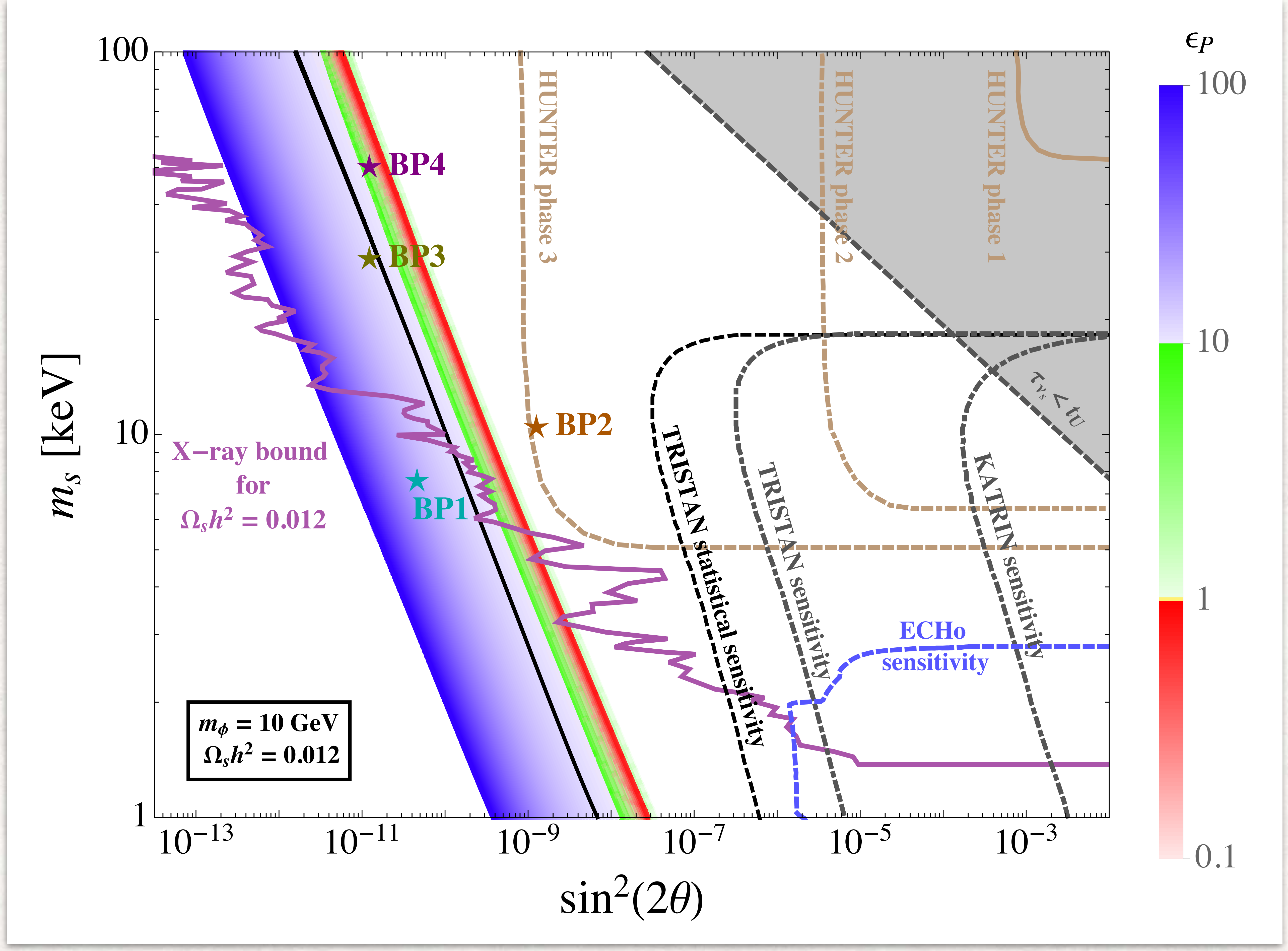
Sterile neutrino parameter space : 100% DM constituted by sterile neutrinos



[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *PRD* 105 (2022) 5, 055016]

X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

Sterile neutrino parameter space : 10% DM constituted by sterile neutrinos



[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *PRD* 105 (2022) 5, 055016]

NEUTRINO NON-STANDARD INTERACTIONS - WHAT? WHY?

Definition: Neutrino non-standard interactions (NSI) are a parameterization of new physics in the neutrino sector in the form of new interactions beyond the SM involving neutrinos and other fermions.

Effective description valid for heavy mediators

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

$$f, f' \in \{e, u, d\} \quad P \in \{P_L, P_R\}$$

Why are NSI interesting?

- we expect new physics to come from the neutrino sector
- some models describing neutrino mass generation naturally include NSI
- initially considered possible solution to the solar and atmospheric neutrino anomalies
- NSI can affect determination of neutrino parameters in the standard picture

NEUTRINO NON-STANDARD INTERACTIONS - WHY NOT?

- Neutrino oscillation and scattering experiments give rather tight constraints on neutrino NSI with matter fields (e, u, d).

  See [P. Coloma et al., *JHEP* 02 (2020) 023, *JHEP* 12 (2020) 071 (addendum), 1911.09109]

  However, such small couplings may anyway be relevant in modifying sterile neutrino dark matter production.

- Neutrino non-standard interactions with quarks and leptons of the 2nd and 3rd generation are much less constrained.

  However, only muons and strange quarks are still relativistic in the plasma at the time of maximal production of sterile neutrinos.
  For the other non-relativistic particles the number density is suppressed like

$$n_i(T) = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$