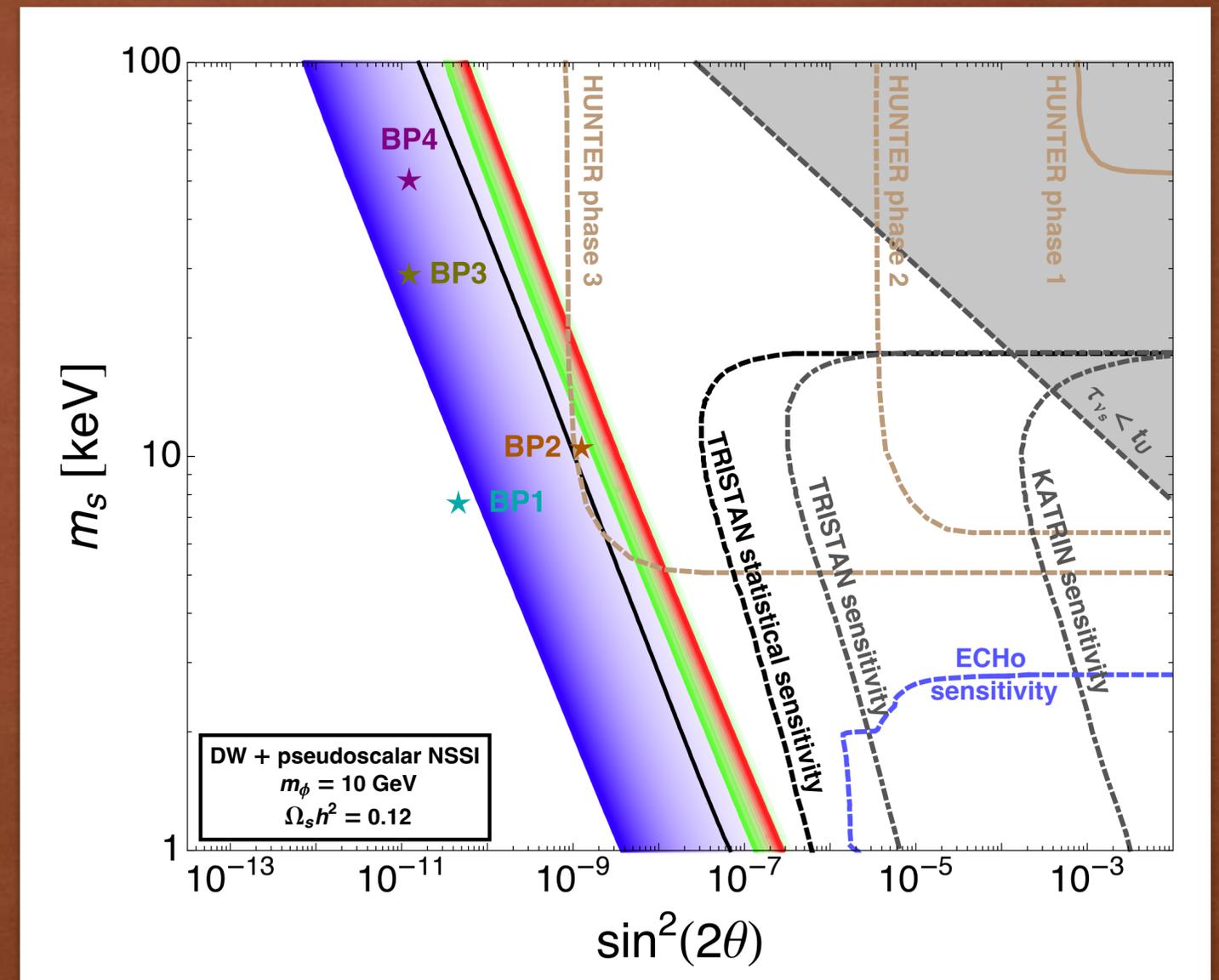


Impact of neutrino non-standard self-interactions on sterile neutrino dark matter production and detection

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OUTLINE

- ❖ Introduction about sterile neutrino dark matter
- ❖ Searches in terrestrial experiments & sensitivity to sterile neutrinos
- ❖ Dodelson-Widrow production of sterile neutrinos in the early universe
- ❖ Neutrino non-standard self-interactions (NSSI):
 - ★ what?
 - ★ why?
 - ★ how to include them?
 - ★ which impact on sterile neutrino dark matter?

INTRODUCTION - STERILE NEUTRINO DARK MATTER

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

If neutrinos are Majorana particles: $\nu_s \quad | \quad \nu_4 = \cos \theta \nu_s + \sin \theta \nu_\alpha$

sterile neutrino can play the role of DM:

- ☑ no em nor strong interaction, by definition
- ☑ massive: possibly with mass $O(\text{keV})$
- ☑ 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 $\bar{\nu}_s \leftrightarrow \bar{\nu}_e$

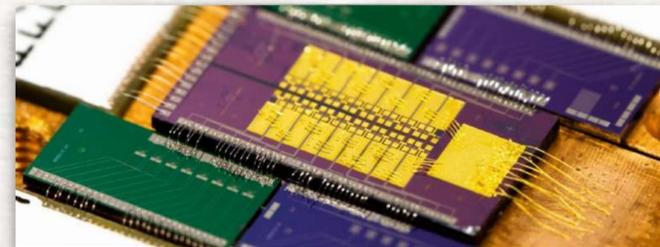
KATRIN/TRISTAN



Tritium beta-decay

$$m_s \lesssim 17.5 \text{ keV}$$

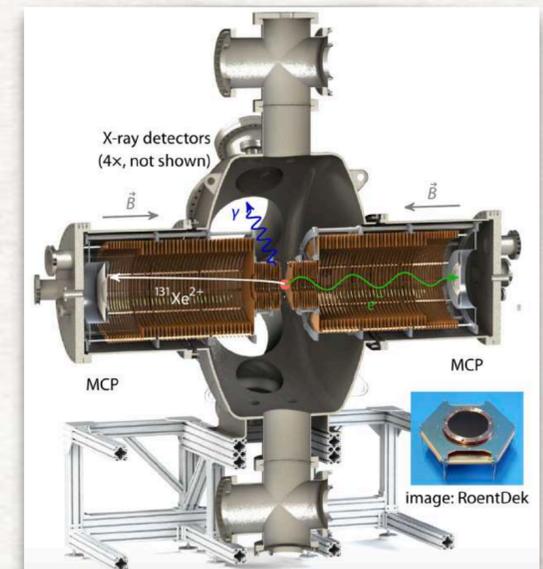
ECHO



Holmium EC

$$m_s \lesssim 2.5 \text{ keV}$$

HUNTER



Caesium EC

$$m_s \lesssim 350 \text{ keV}$$

DODELSON-WIDROW PRODUCTION *

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

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

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

where

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

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

* [S. Dodelson, L. M. Widrow, PRL 72 (1994) 17-20]

DODELSON-WIDROW PRODUCTION

In the plasma, the **mixing angle** is

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

where interactions of neutrinos with particles in the plasma impact on:

- **Interaction rate** $\Gamma_e(p) = c_e(p, T) G_F^2 p T^4$

- **Thermal potential** $V_T(p) = \pm \sqrt{2} G_F \frac{2\zeta(3) T^3 \eta_B}{\pi^2} \frac{1}{4} - \frac{8\sqrt{2} G_F p}{3m_Z^2} (\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2} G_F p}{3m_W^2} (\rho_{e^-} + \rho_{e^+})$

DODELSON-WIDROW PRODUCTION

We solve the Boltzmann equation and find the distribution function

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

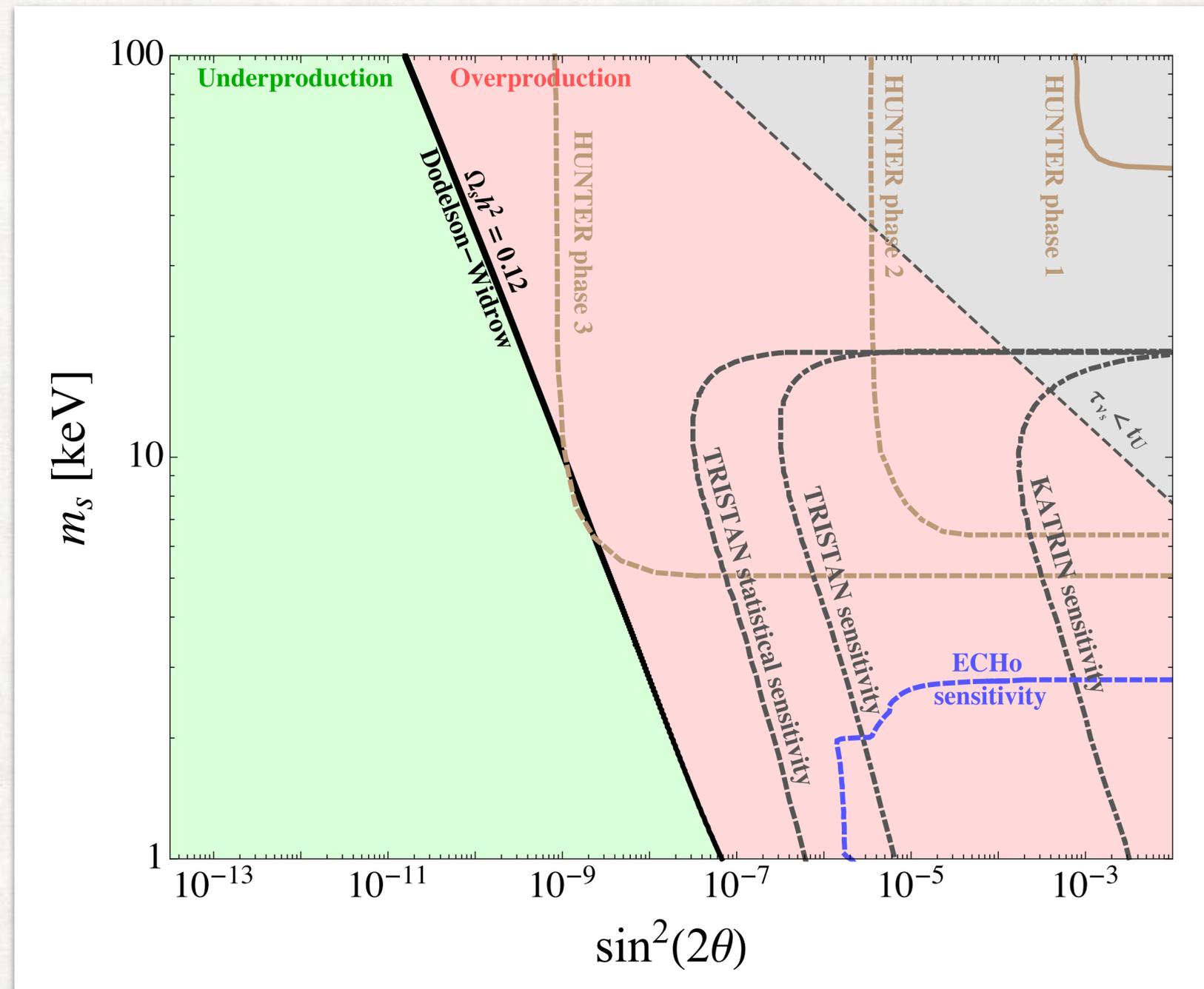
and calculate the **sterile neutrino dark matter abundance** passing through

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

sterile neutrino yield $Y = \frac{n}{s}$

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

DODELSON-WIDROW PRODUCTION - CHALLENGES FOR DETECTION



- **X-ray bound :**
disfavors large values of θ and m_s
[CB, V. Brdar, M. Lindner, W. Rodejohann, *PRD* 100 (2019), 115035]
[J. Barry, J. Heeck, W. Rodejohann, *JHEP* 07 (2014), 081]
- **Limits from structure formation :**
disfavor small values of m_s
[R. An, V. Gluscevic, E. O. Nadler, Y. Zhang, arXiv: 2301.08299]
[I. A. Zelko, T. Treu, K. N. Abazajian, D. Gilman, A. J. Benson, *PRL* 129 (2022) 19, 191301]
- **Limit from DM abundance :**
rules out large values of θ

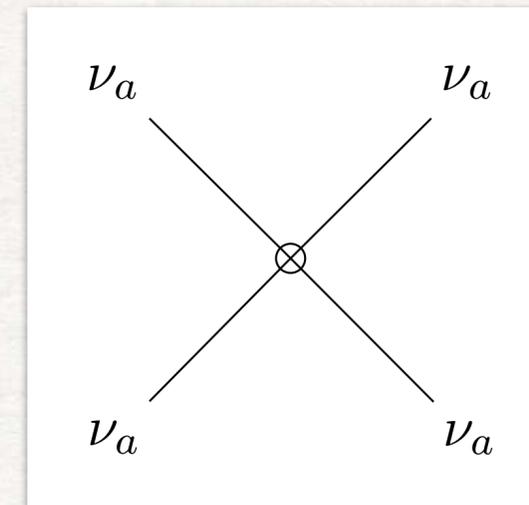
NEUTRINO NON-STANDARD SELF-INTERACTIONS - WHAT? WHY?

Definition: Neutrino non-standard self-interactions (NSSI) are a parameterization of new physics in the neutrino sector in the form of new interactions beyond the SM involving only neutrinos.

Effective description valid for heavy mediators

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

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



Why are NSSI interesting?

- we expect new physics to come from the neutrino sector
- some models describing neutrino mass generation naturally include NSSI [J. M. Berryman et al., arXiv: 2203.01955]
- NSSI could have significant impact on physics of the early universe (Hubble tension etc.)

NEUTRINO NSSI - HOW TO INCLUDE THEM?

Assumptions for concreteness:

- heavy mediators \longrightarrow 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:

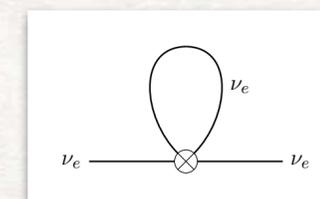
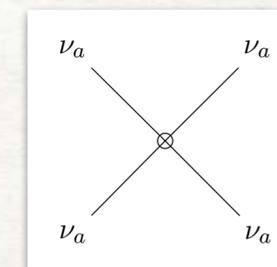
$$\mathcal{L}_j = -\frac{G_F}{\sqrt{2}} (\epsilon_{j,\nu}) \left((\bar{\nu}_e \mathcal{O}_j \nu_e) (\bar{\nu}_e \mathcal{O}'_j \nu_e) - \frac{1}{m_\phi^2} (\bar{\nu}_e \mathcal{O}_j \nu_e) \square (\bar{\nu}_e \mathcal{O}'_j \nu_e) \right)$$

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



$$\Gamma_e(p) \quad \rightarrow \quad \Gamma_{e,\text{tot}}(p) = \Gamma_{e,\text{SM}}(p) + \Gamma_{e,\text{NSSI}}(p)$$

$$V_T(p) \quad \rightarrow \quad V_{T,\text{tot}}(p) = V_{T,\text{SM}}(p) + V_{T,\text{NSSI}}(p)$$



NEUTRINO NSSI - HOW TO INCLUDE THEM?

- Scalar NSSI

$$\Gamma_{e,\text{NSSI}}(p) = \frac{7\pi}{180} \epsilon_S^2 G_F^2 p T^4$$

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

- Pseudoscalar NSSI

$$\Gamma_{e,\text{NSSI}}(p) = \frac{7\pi}{180} \epsilon_P^2 G_F^2 p T^4$$

$$V_{T,\text{NSSI}}(p) = -\frac{7\sqrt{2}\pi^2}{45 m_\phi^2} \epsilon_P G_F p T^4$$

- Axial vector NSSI

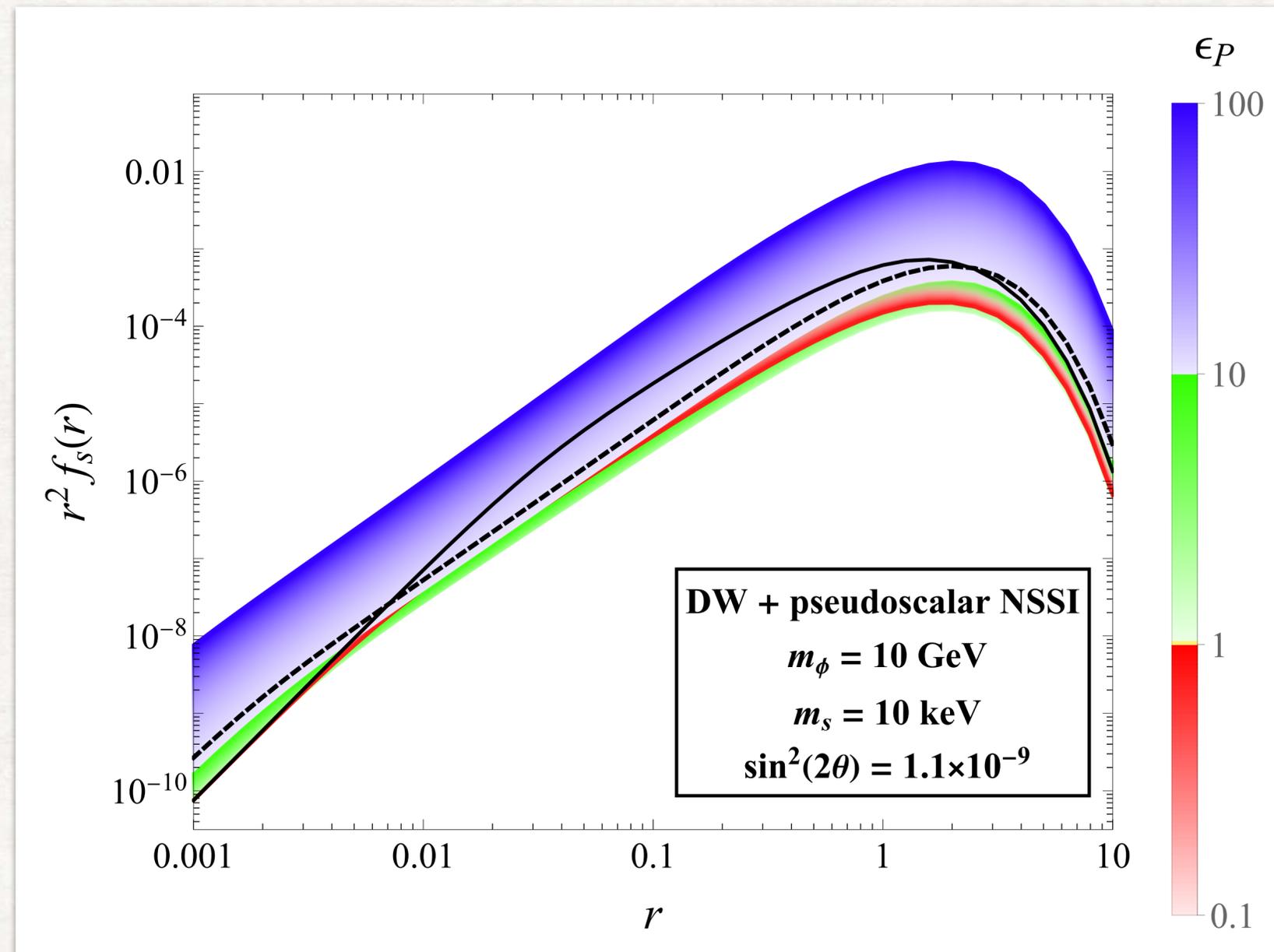
$$\Gamma_{e,\text{NSSI}}(p) = \frac{7\pi}{135} \epsilon_A^2 G_F^2 p T^4$$

$$V_{T,\text{NSSI}}(p) = -\frac{14\sqrt{2}\pi^2}{45 m_\phi^2} \epsilon_A G_F p T^4$$

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

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

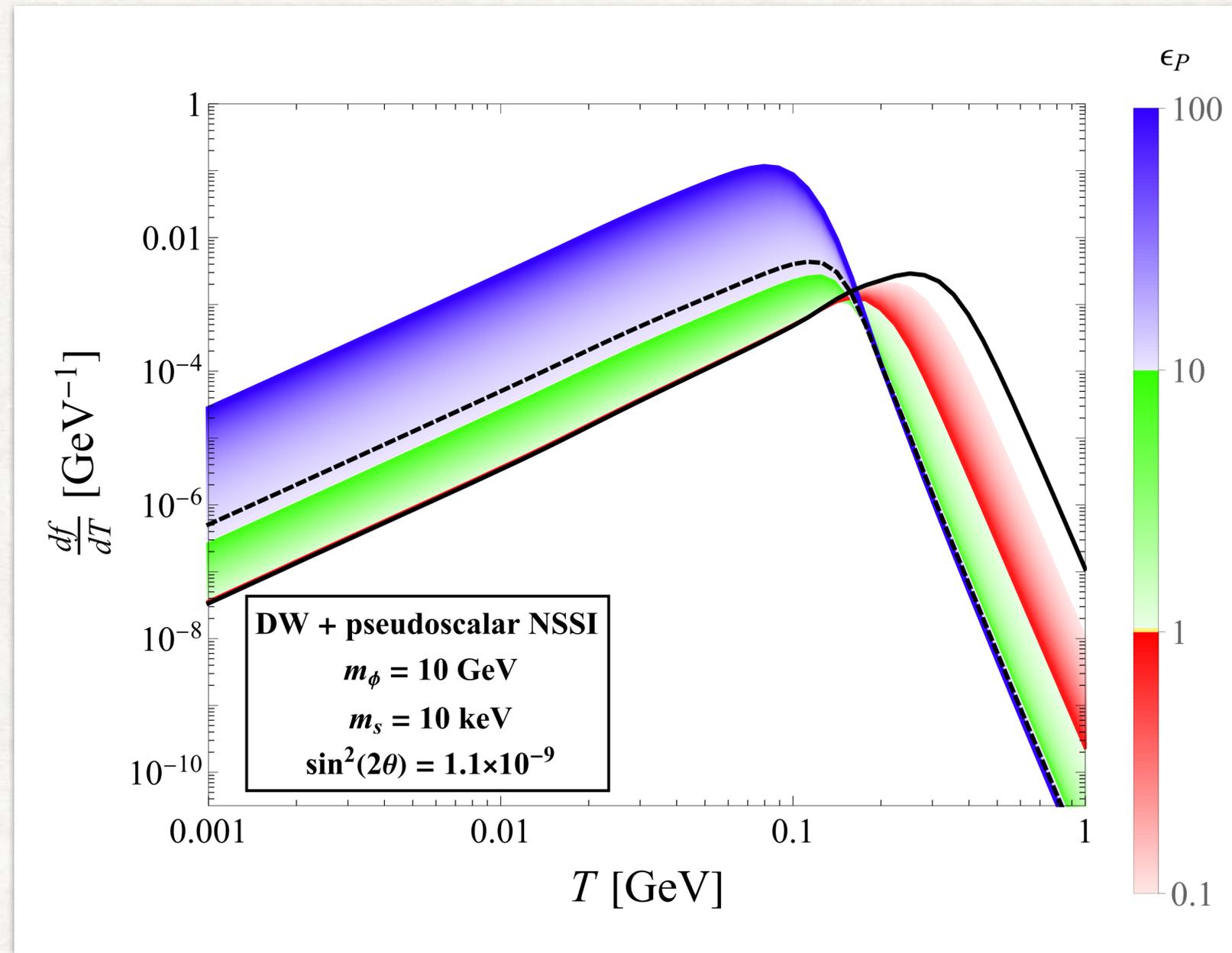
Sterile neutrino distribution function



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

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

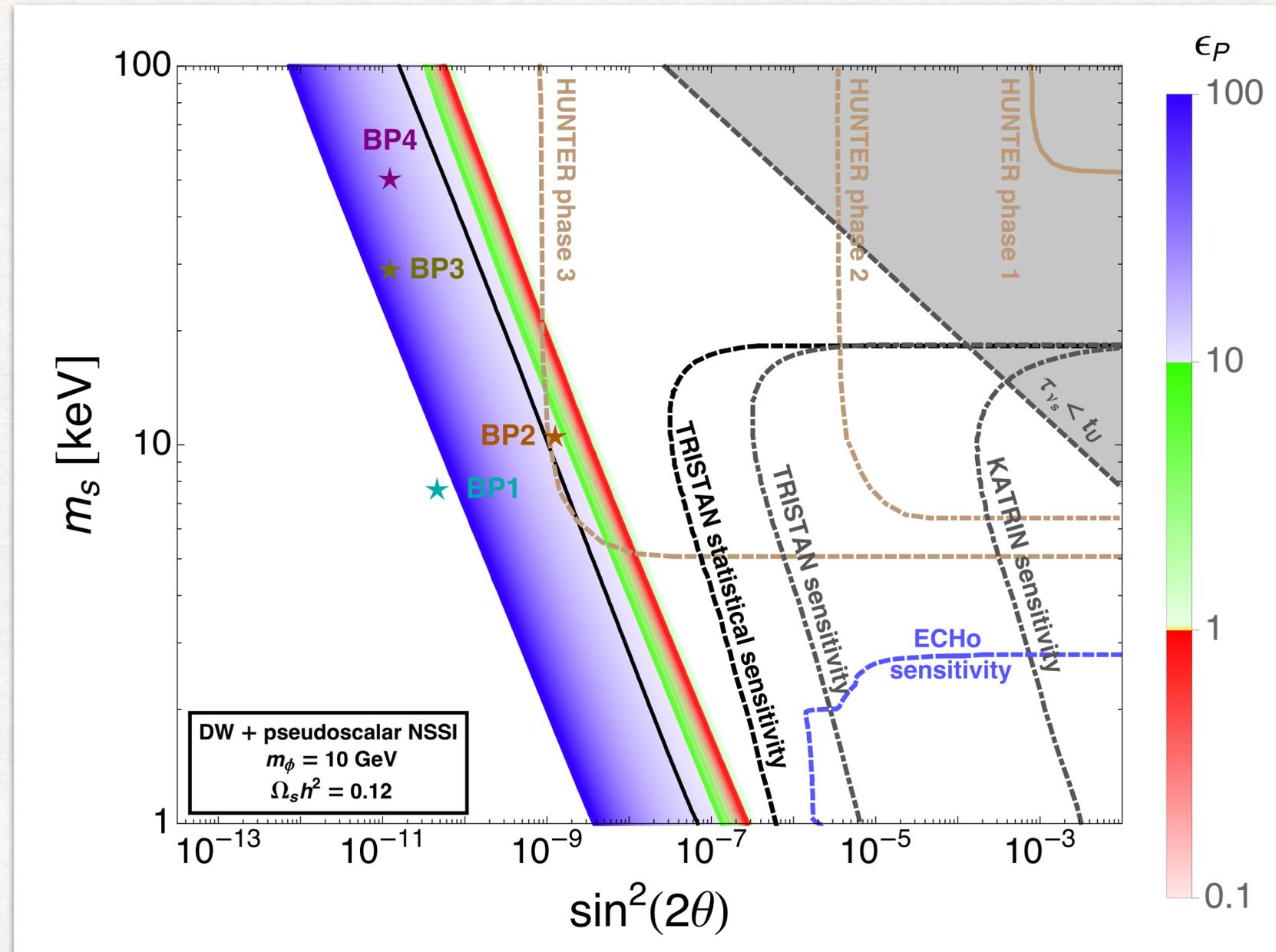
Sterile neutrino production evolution



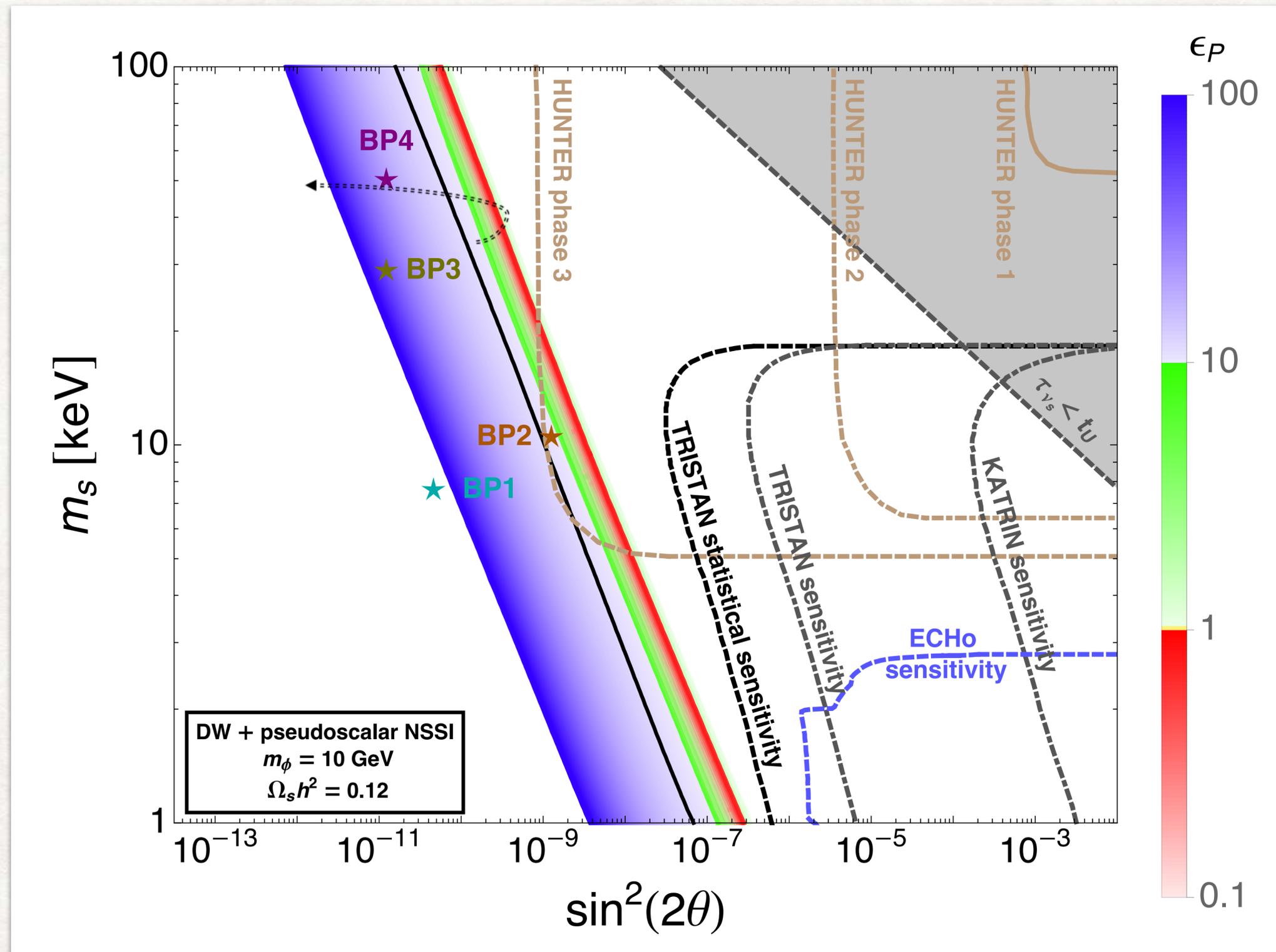
[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *PRD* 105 (2022) 5, 055016]

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

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



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



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

CONCLUSIONS

- ❖ Sterile neutrinos that mix with active neutrinos are good dark matter candidates.
- ❖ They can have been produced in the early universe via oscillation and collisions through Dodelson-Widrow mechanism.
- ❖ This vanilla scenario is hardly detectable in terrestrial experiments in the near future.
- ❖ Active neutrino non-standard self-interactions (NSSI) are well motivated extension of the SM.
- ❖ Scalar, pseudoscalar and axial-vector NSSI modify the production of sterile neutrino dark matter in the early universe.
- ❖ The parameter space region in which $\Omega_{\text{DM}} = \Omega_s$ is enlarged by such NSSI and they enhance the possibility to detect sterile neutrino dark matter in HUNTER phase 3.