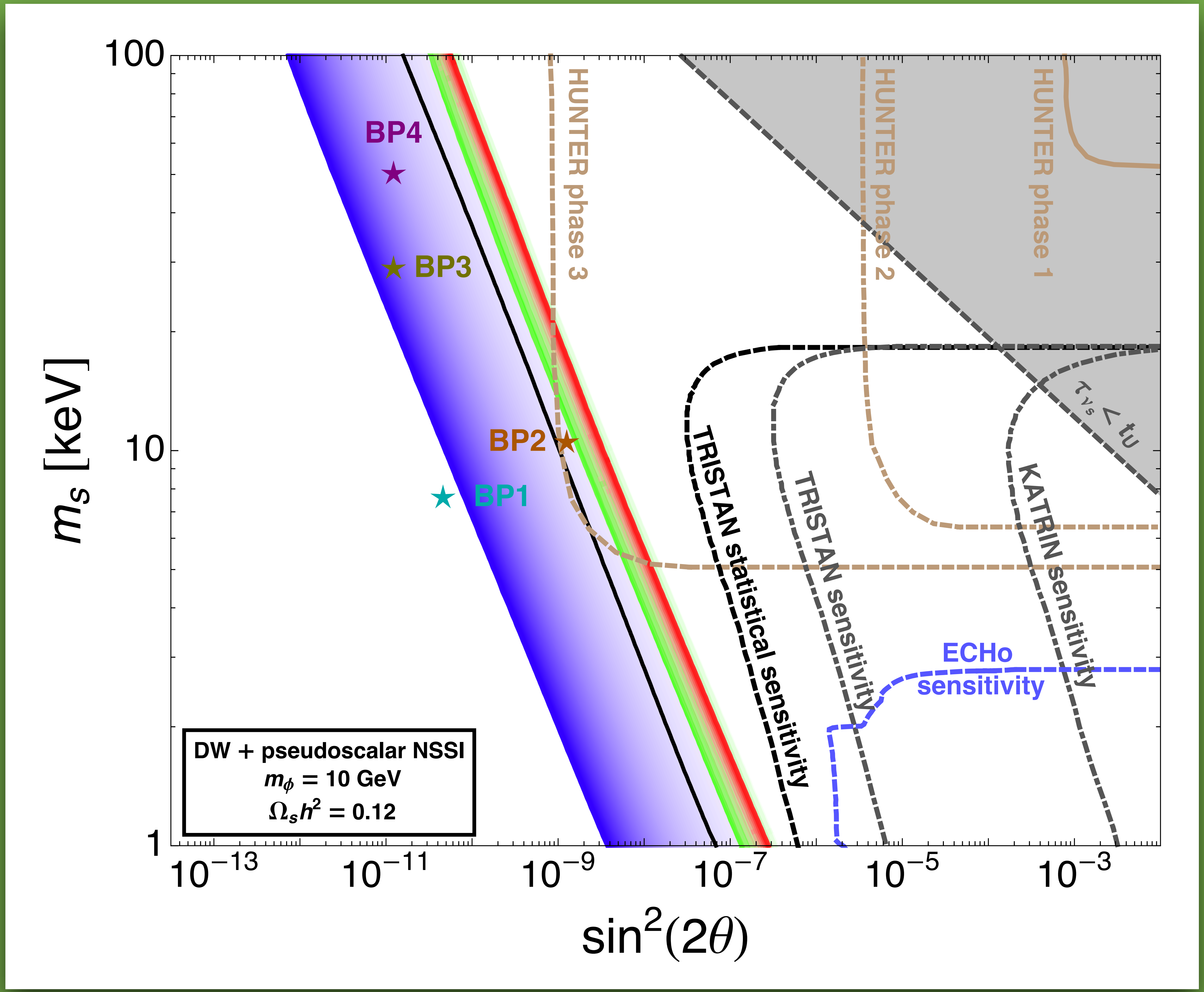
IMPACT OF NEUTRINO NON-STANDARD SELF-INTERACTIONS ON STERILE NEUTRINO DARK MATTER

Cristina Benso

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



INTRODUCTION - STERILE NEUTRINO DARK MATTER

Definition: neutral fermions, singlets under the SM symmetries

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

INTRODUCTION - STERILE NEUTRINO DARK MATTER

Definition: neutral fermions, singlets under the SM symmetries

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

sterile neutrino can play the role of DM:

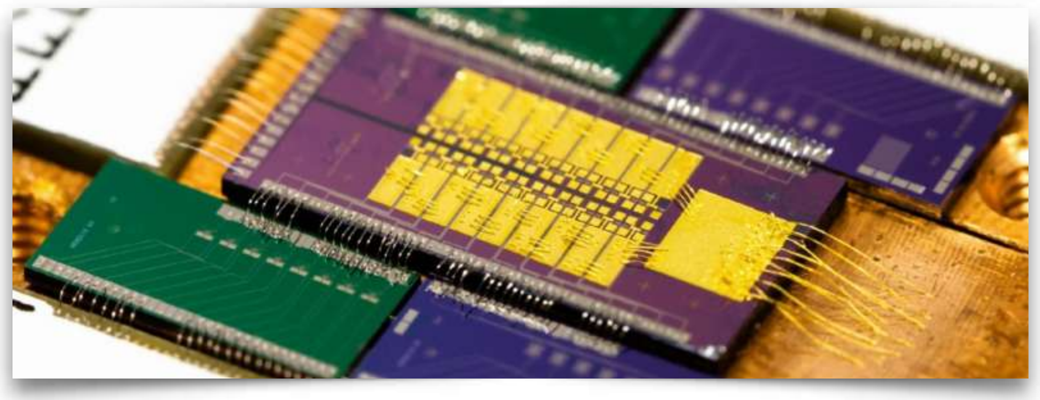
- ☑ no em nor strong interaction, by definition
- ☑ massive: possibly with mass O(keV)
- ☑ depending on mixing with active neutrinos: stable over time scales comparable with t_U
- ☑ depending on the production mechanism: produced in the early universe with velocities compatible with large scale structures

SEARCHES IN TERRESTRIAL EXPERIMENTS

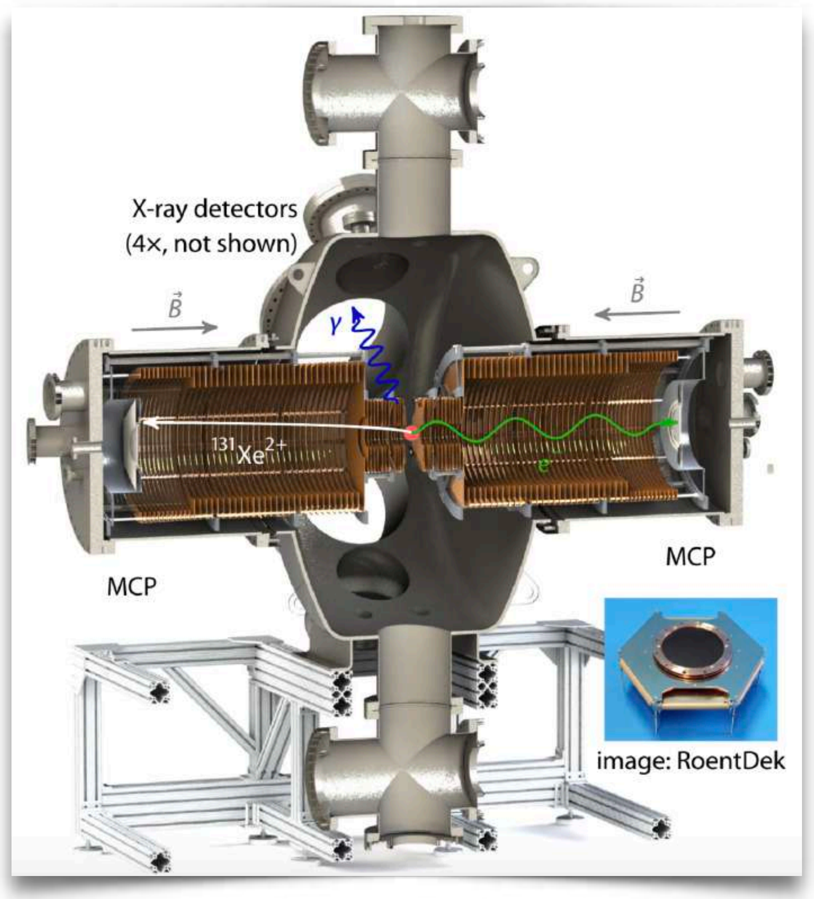
- in the domain of direct detection
- rely on large mixing of $\nu_s \leftrightarrow \nu_e$ or $\overline{\nu}_s \leftrightarrow \overline{\nu}_e$

KATRIN / TRISTAN

ECHo



HUNTER



DODELSON-WIDROW PRODUCTION *

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

Mechanism: production through oscillation and collisions:

while the neutrino fields propagate in the primordial plasma,
they oscillate between the electron and the sterile state and
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

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

DODELSON-WIDROW PRODUCTION *

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

Mechanism: production through oscillation and collisions:

while the neutrino fields propagate in the primordial plasma,
they oscillate between the electron and the sterile state and
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

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

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

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

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

DODELSON-WIDROW PRODUCTION

In the plasma, the mixing angle is

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

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

DODELSON-WIDROW PRODUCTION

We solve the Boltzmann equation and find the distribution function

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

DODELSON-WIDROW PRODUCTION

We solve the Boltzmann equation and find the distribution function

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

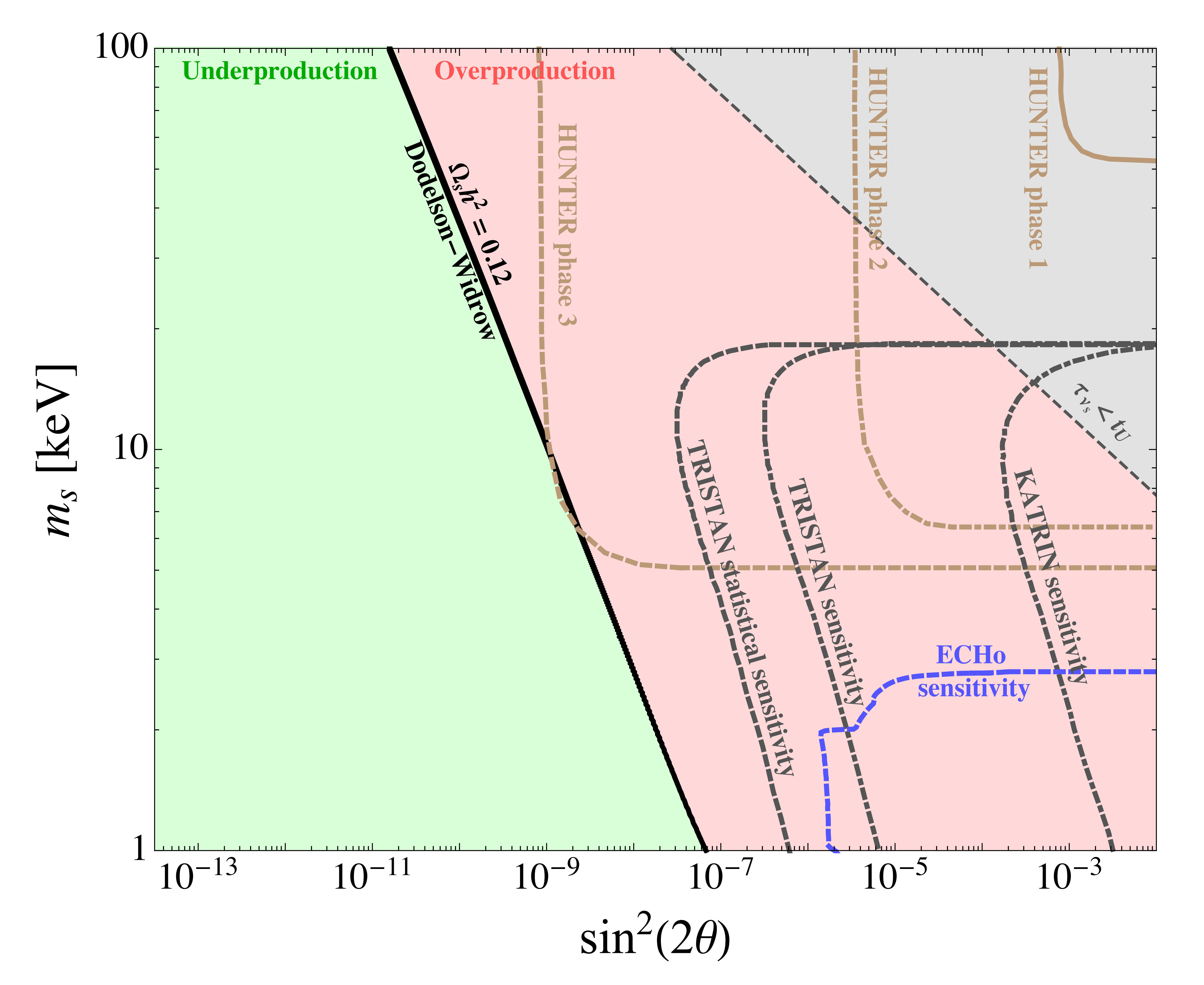
and calculate the sterile neutrino dark matter abundance passing through

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

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

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

DODELSON-WIDROW PRODUCTION - CHALLENGES FOR DETECTION



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.

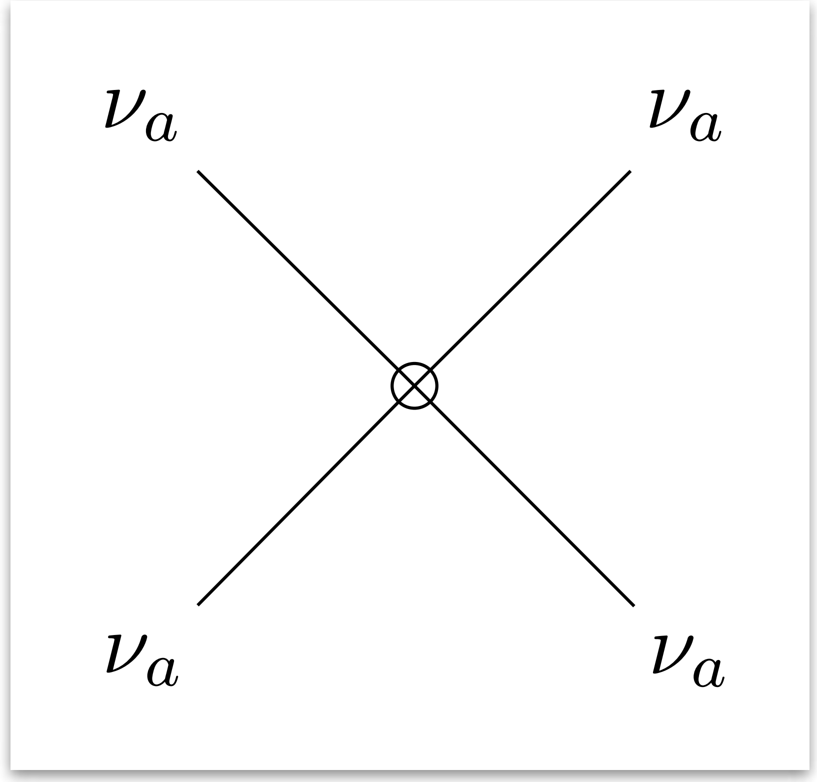
NEUTRINO NON-STANDARD SELF-INTERACTIONS - WHAT ? WHY ?

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:

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

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



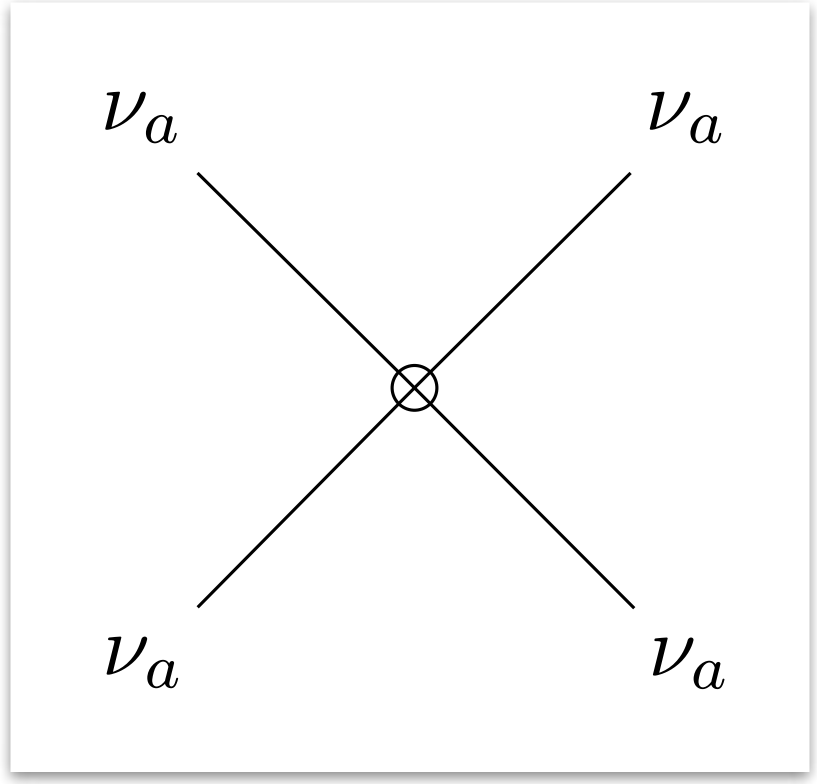
NEUTRINO NON-STANDARD SELF-INTERACTIONS - WHAT ? WHY ?

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:

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

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



Why are NSSI interesting?

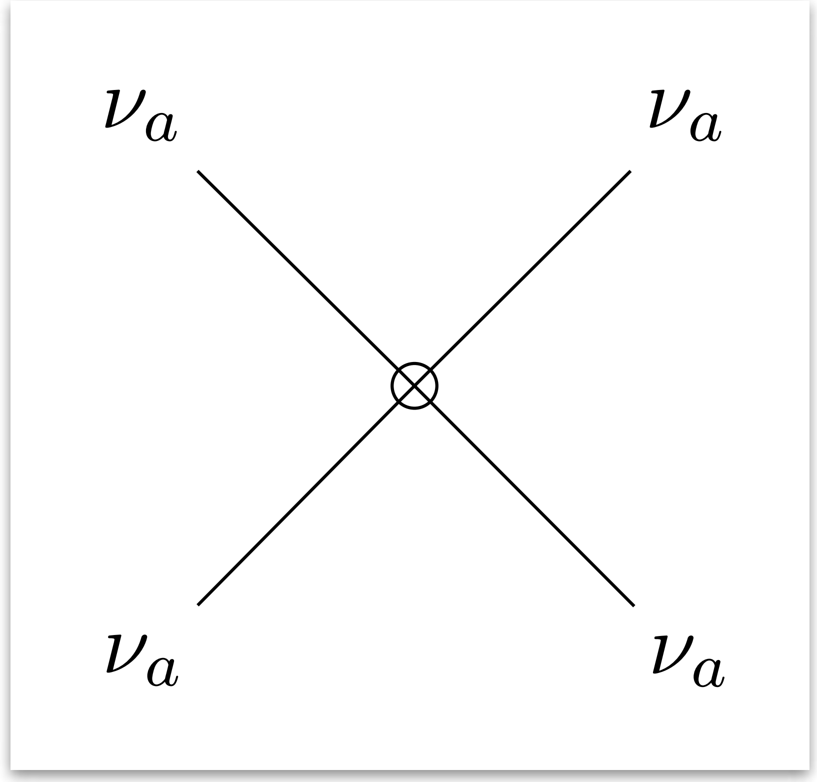
NEUTRINO NON-STANDARD SELF-INTERACTIONS - WHAT ? WHY ?

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:

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

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



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

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:

$$\mathcal{L}_j = -\frac{G_F}{\sqrt{2}} \left(\epsilon_{j,\nu}\right) \left(\left(\bar{\nu}_e \mathcal{O}_j \nu_e\right) \left(\bar{\nu}_e \mathcal{O}'_j \nu_e\right) - \frac{1}{m_\phi^2} \left(\bar{\nu}_e \mathcal{O}_j \nu_e\right) \Box \left(\bar{\nu}_e \mathcal{O}'_j \nu_e\right) \right) \qquad \mathcal{O}_j = \{\mathbb{I}, i\gamma^5, \gamma^\mu \gamma^5\}$$

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

NEUTRINO NSSI - HOW TO INCLUDE THEM ?

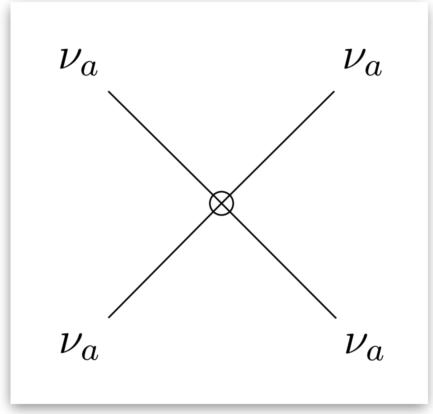
Assumptions for concreteness:

- 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:

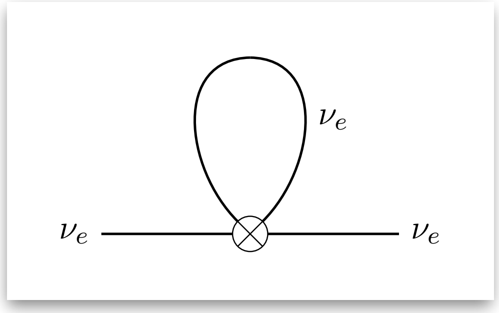
$$\mathcal{L}_j = -\frac{G_F}{\sqrt{2}}(\epsilon_{j,\nu})\left((\bar{\nu}_e\mathcal{O}_j\nu_e)(\bar{\nu}_e\mathcal{O}'_j\nu_e) - \frac{1}{m_\phi^2}(\bar{\nu}_e\mathcal{O}_j\nu_e)\Box(\bar{\nu}_e\mathcal{O}'_j\nu_e)\right) \qquad \mathcal{O}_j = \{\mathbb{I}, i\gamma^5, \gamma^\mu\gamma^5\}$$

$$\downarrow$$

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



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



NEUTRINO NSSI - HOW TO INCLUDE THEM ?

- Scalar NSSI

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

- Pseudoscalar NSSI

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

- Axial vector NSSI

$$\Gamma_{e,\mathrm{NSSI}}(p) = \frac{7\pi}{135}\epsilon_A^2\, G_F^2\, p\, T^4 \qquad V_{T,\mathrm{NSSI}}(p) = -\frac{14\sqrt{2}\pi^2}{45\, m_\phi^2}\epsilon_A\, G_F\, p\, T^4$$

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

NEUTRINO NSSI - HOW TO INCLUDE THEM ?

- Scalar NSSI

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

- Pseudoscalar NSSI

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

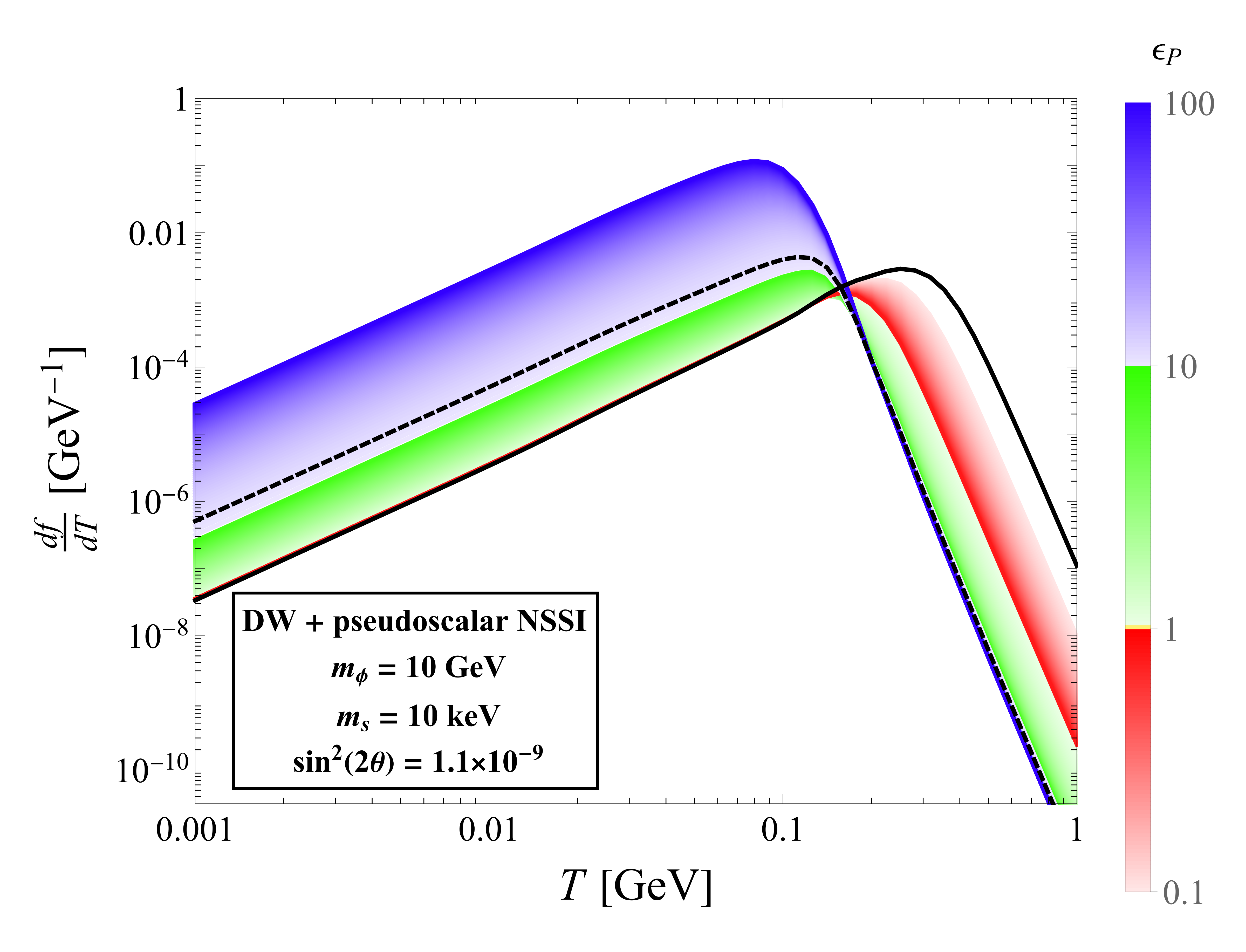
- Axial vector NSSI

$$\Gamma_{e,\mathrm{NSSI}}(p) = \frac{7\pi}{135}\epsilon_A^2\, G_F^2\, p\, T^4 \qquad V_{T,\mathrm{NSSI}}(p) = -\frac{14\sqrt{2}\pi^2}{45\, m_\phi^2}\epsilon_A\, G_F\, p\, T^4$$

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

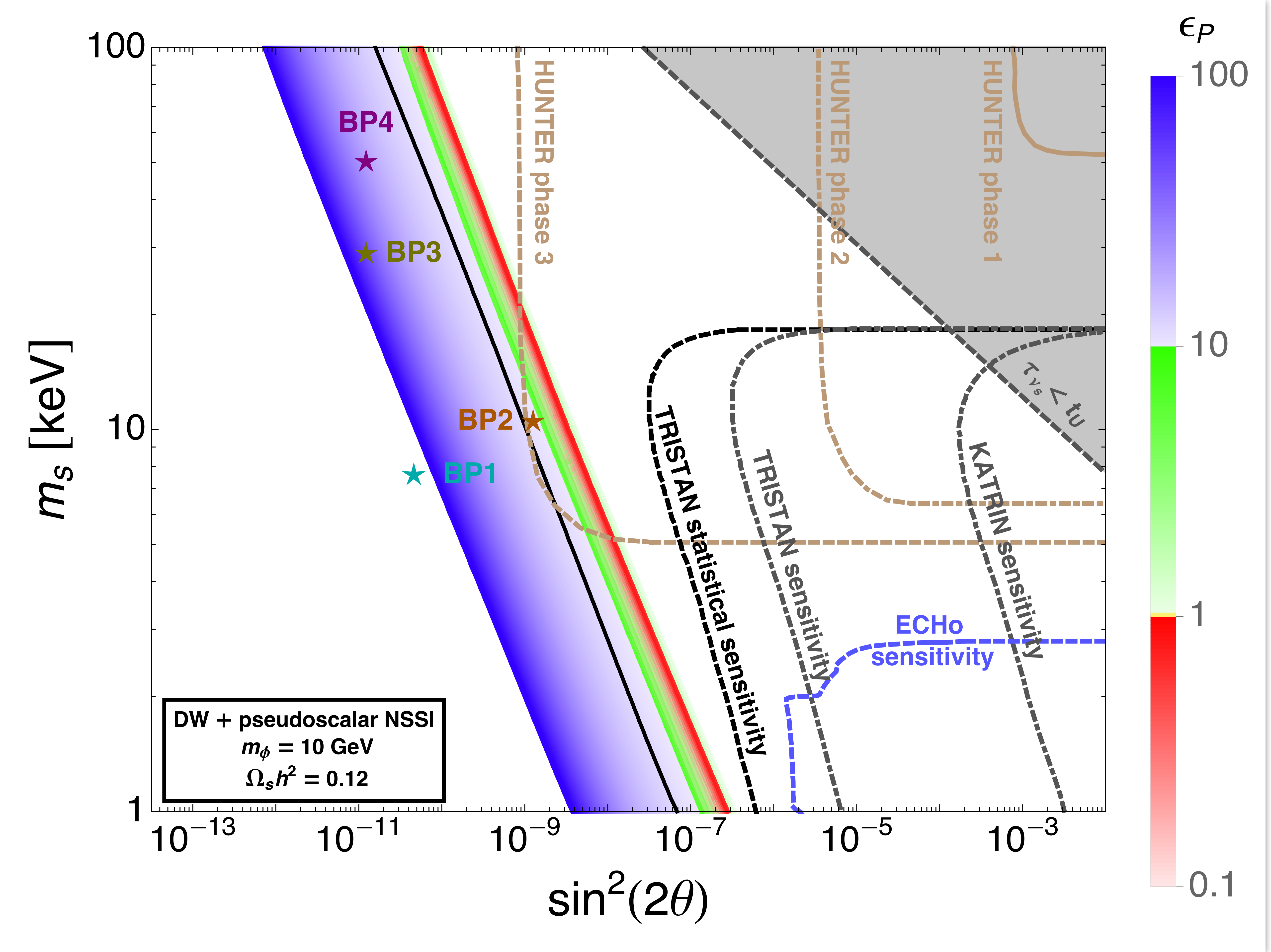
Sterile neutrino **production evolution**



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

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

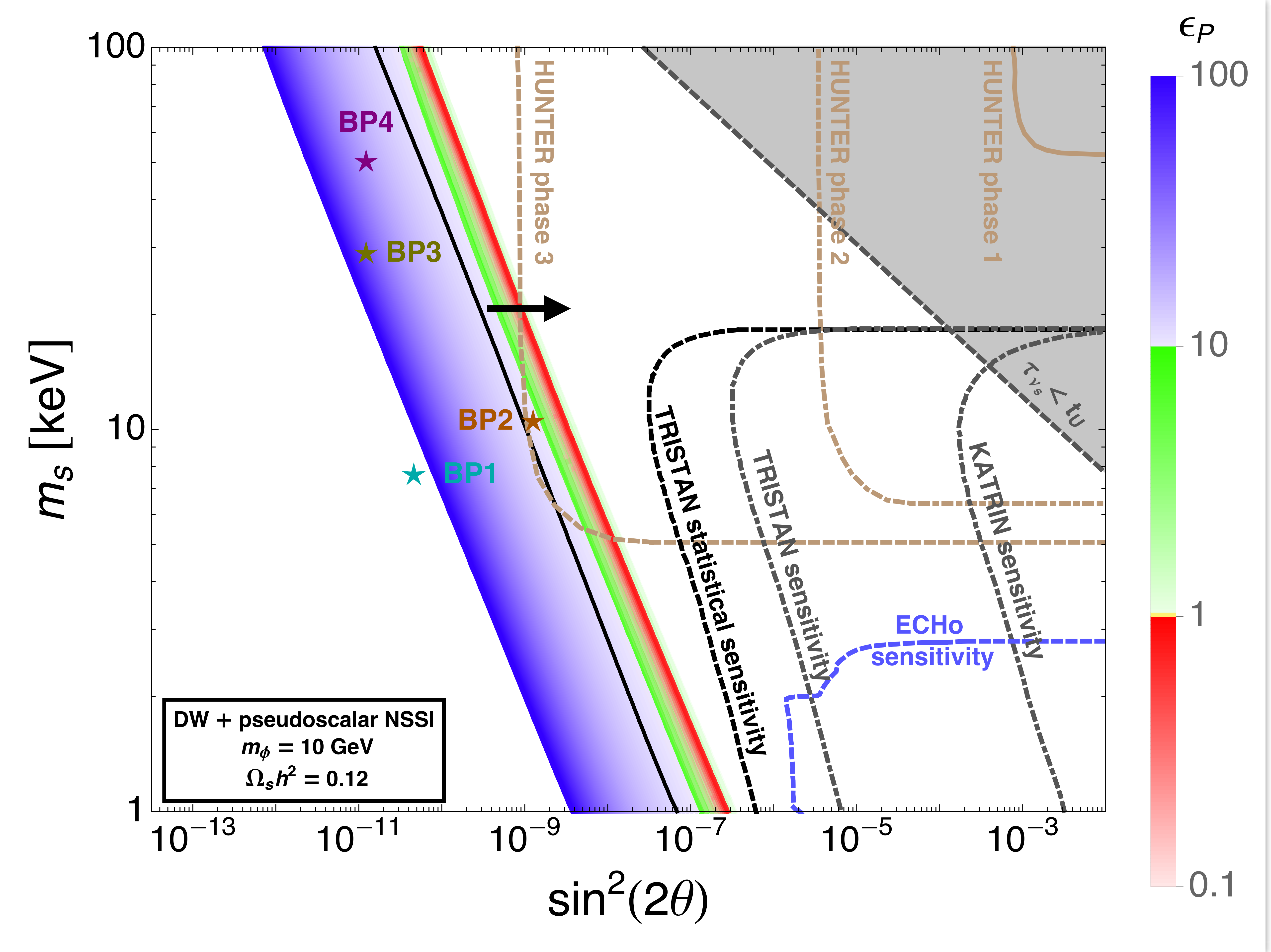
Sterile neutrino **parameter space** : 100% DM constituted by sterile neutrinos



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

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

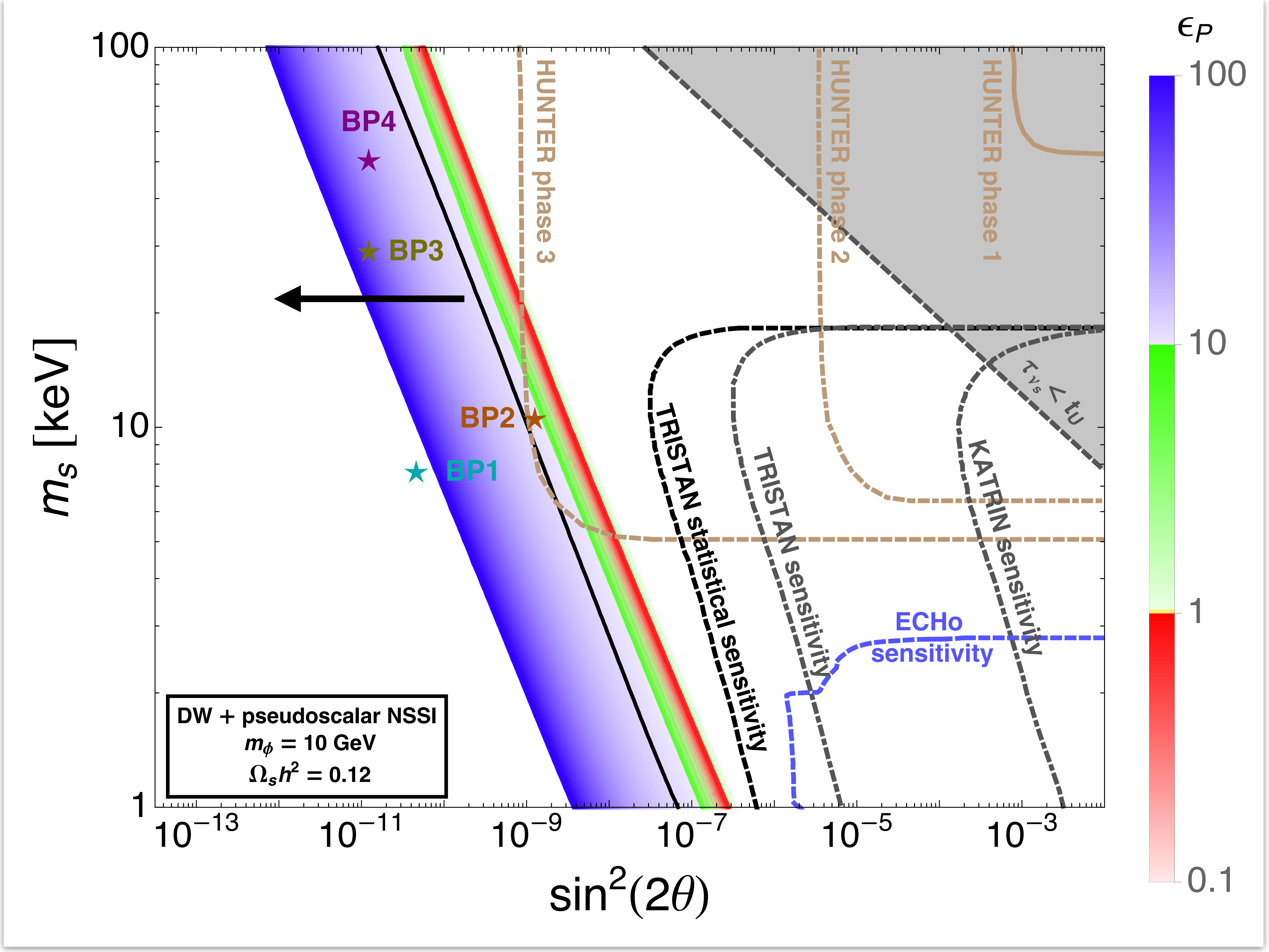
Sterile neutrino **parameter space** : 100% DM constituted by sterile neutrinos



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

CONCLUSIONS

- Sterile neutrinos that mix with active neutrinos are good dark matter candidates.

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.

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 testable in in terrestrial experiments in the near future.

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 testable in in terrestrial experiments in the near future.
- Active neutrino non-standard self-interactions (NSSI) are well motivated extension of the SM.

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 testable in 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.

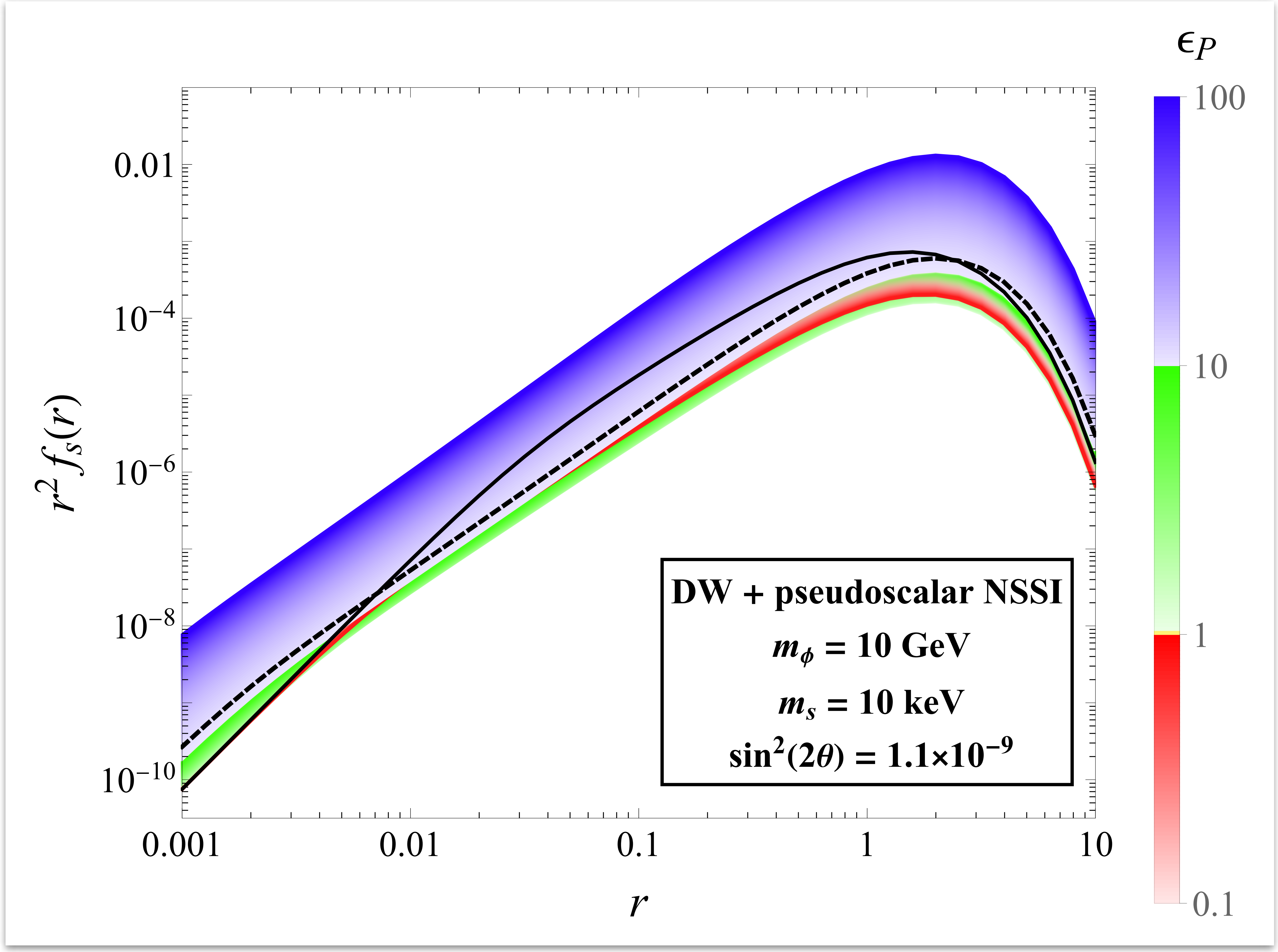
CONCLUSIONS

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

BACKUP

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

Sterile neutrino **distribution function**



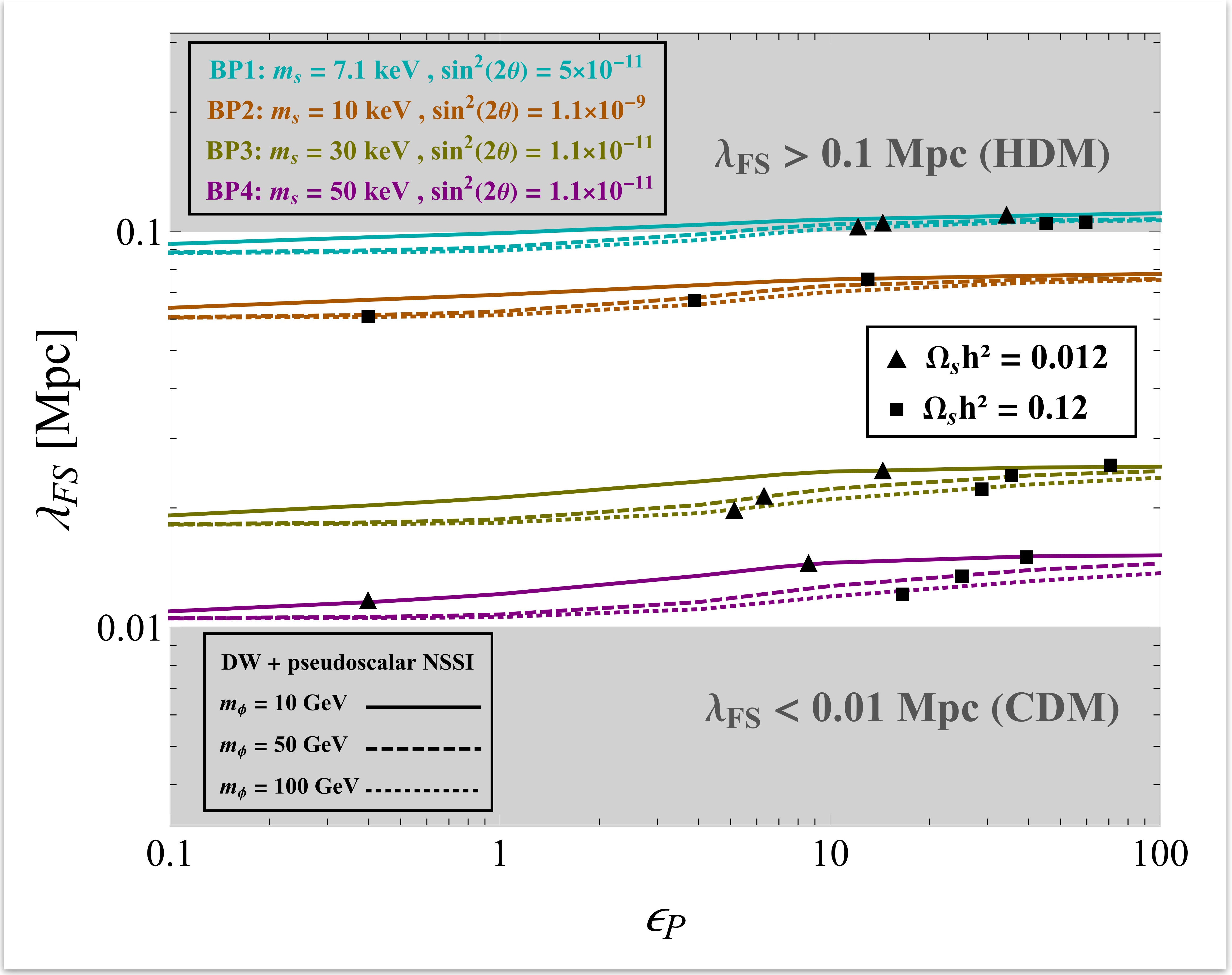
[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *Phys.Rev.D* 105 (2022) 5, 055016]

NEUTRINO NSSI - INDIRECT 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



[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *Phys.Rev.D* 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 testable in 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 $\Omega_{\rm DM} = \Omega_s$ is enlarged by such NSSI and they enhance the possibility to detect sterile neutrino dark matter in HUNTER phase 3.
- Active neutrino NSSI considered are not in conflict with large scale structures.

SEARCHES IN TERRESTRIAL EXPERIMENTS

KATRIN / TRISTAN

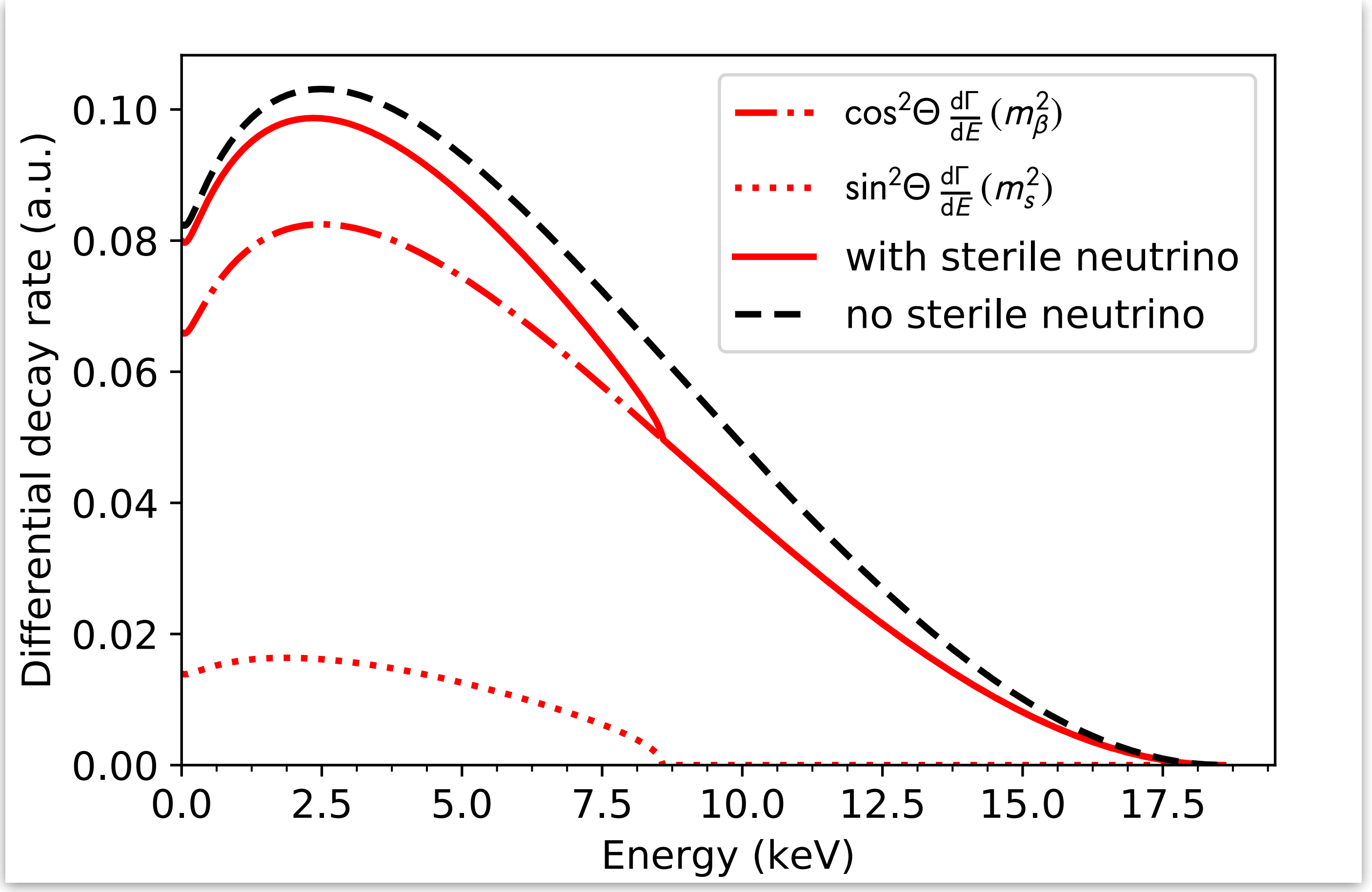
[Troitsk experiment based on the same process but less sensitive]

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 $\sin^2\theta$

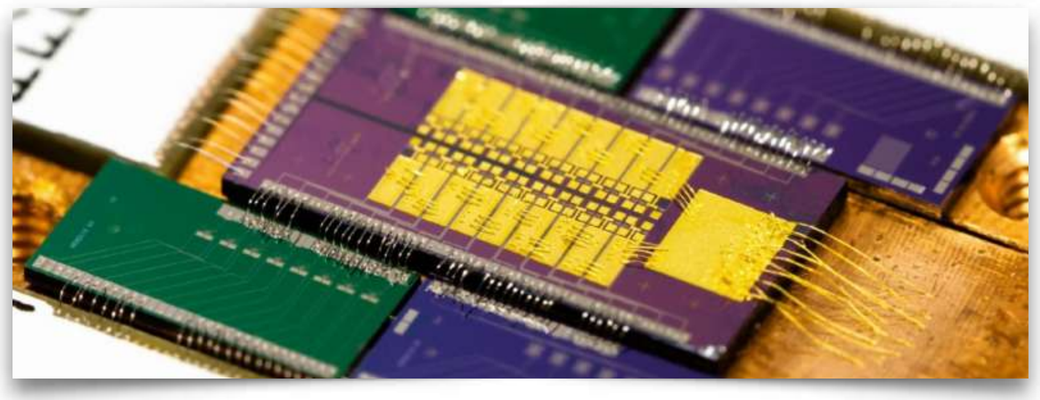


(Borrowed from S. Mertens lecture in Bad Honnef)

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

SEARCHES IN TERRESTRIAL EXPERIMENTS

ECHo



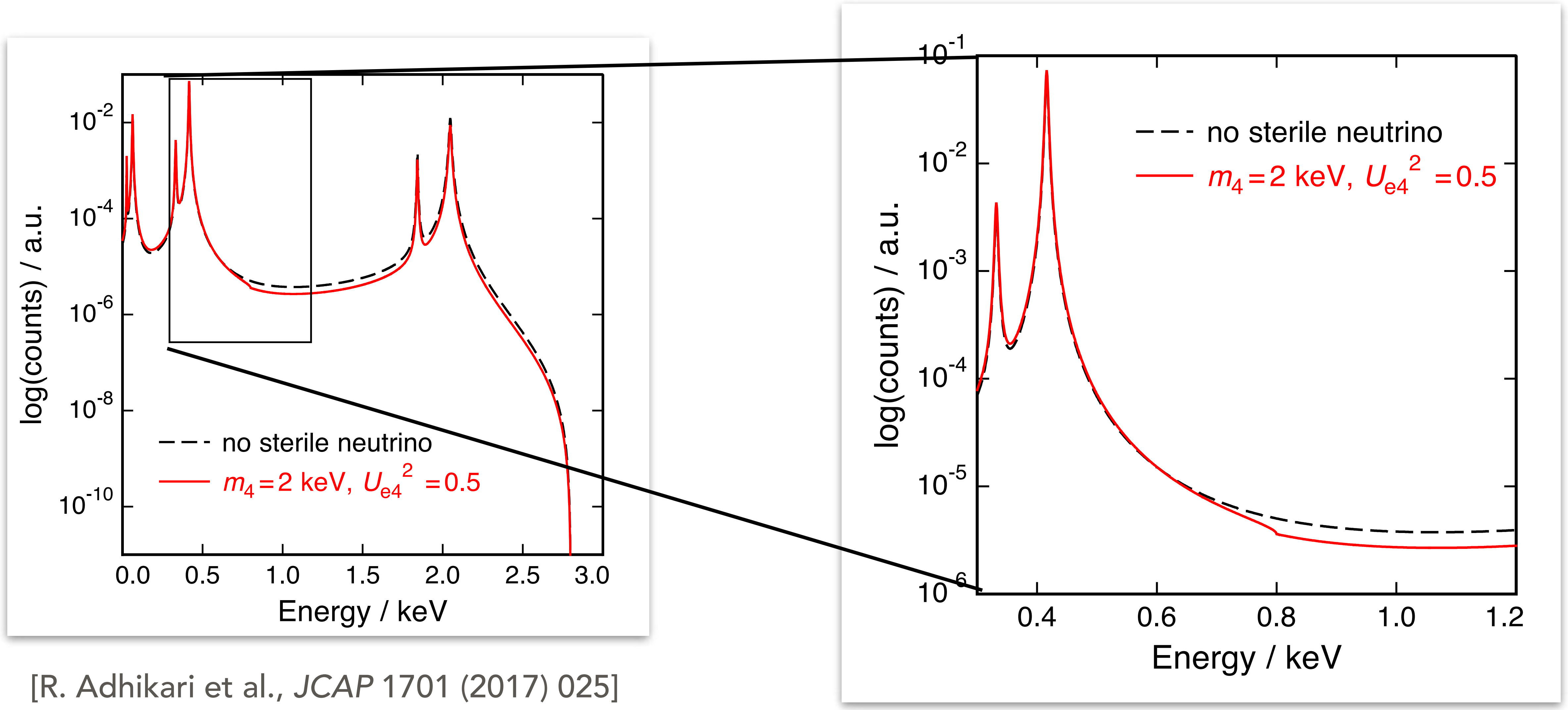
[HOLMES and NuMECS experiments based on the same process]

Based on holmium electron capture:

★ calorimetric measurement ⟶ all events occurring in the detector give a measurable signal (entire spectrum "for free")

- endpoint of $Q_{\mathrm{EC}} = 2.833\ \mathrm{keV}$ ⟶ allows search of sterile neutrinos only with mass < 2.5 keV

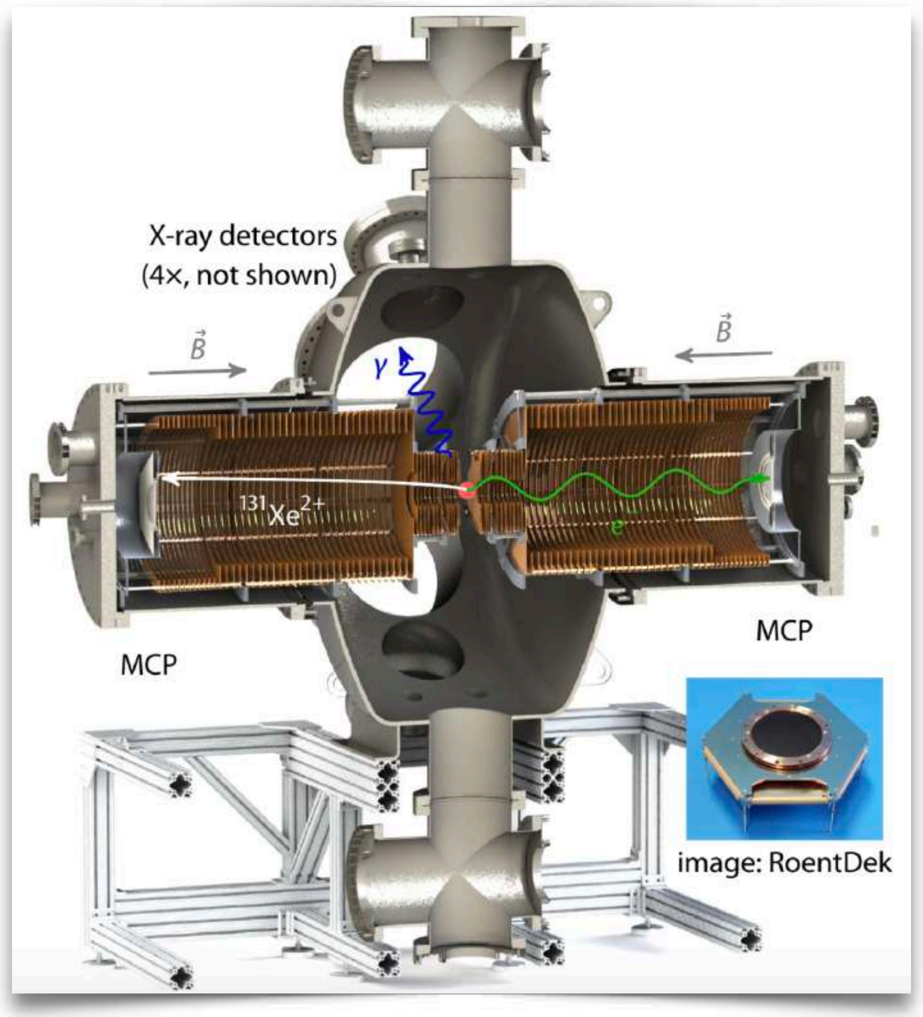
Signature: kink in the EC spectrum of $^{163}\mathrm{Ho}$ at energy Q_{EC} - m_4 with amplitude proportional to $|U_{e4}^2|$



[R. Adhikari et al., *JCAP* 1701 (2017) 025]

SEARCHES IN TERRESTRIAL EXPERIMENTS

HUNTER

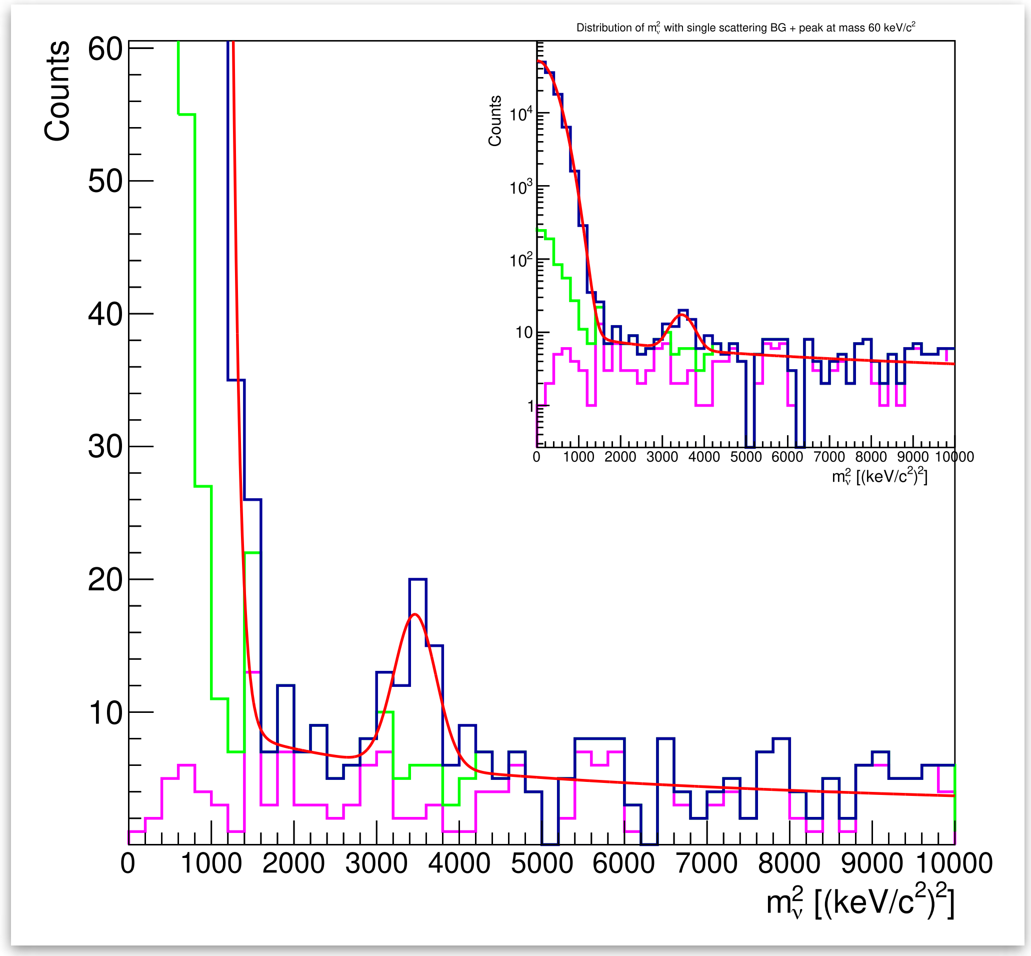


Based on caesium electron (K-) capture:

★ 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

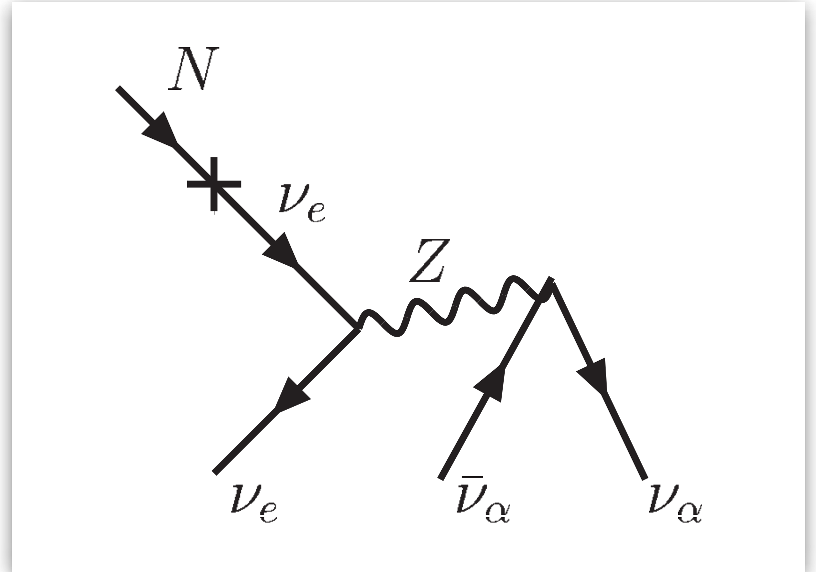
Signature: separated population of events with non-zero reconstructed missing mass up to 352 keV and height of the peak prop. to $|U_{e4}^2|$



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

X-RAY BOUND

tree level decay

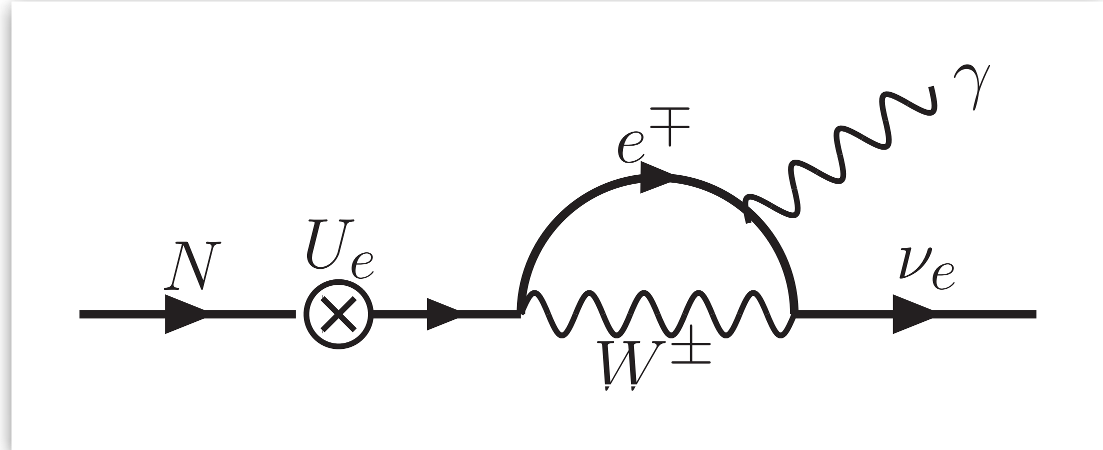


$$\Gamma_{\nu_s \to 3\nu} = \frac{G_F^2\, m_s^5}{96\,\pi^3} \sin^2(2\theta) = \frac{1}{4.7 \times 10^{10}\ \mathrm{s}} \left(\frac{m_s}{50\ \mathrm{keV}}\right)^5 \sin^2(2\theta)$$

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

[R. 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 ?

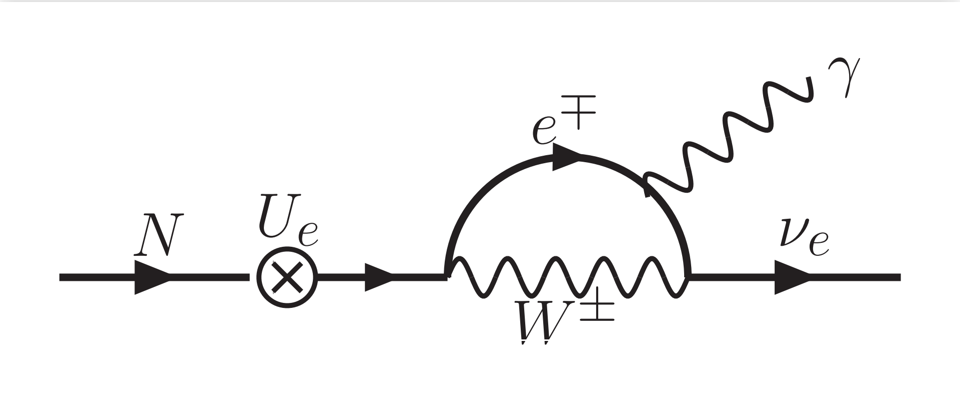
Observable: flux of photons

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

where

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

In absence of new physics:



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

If new physics mediates the same decay and interferes disruptively:

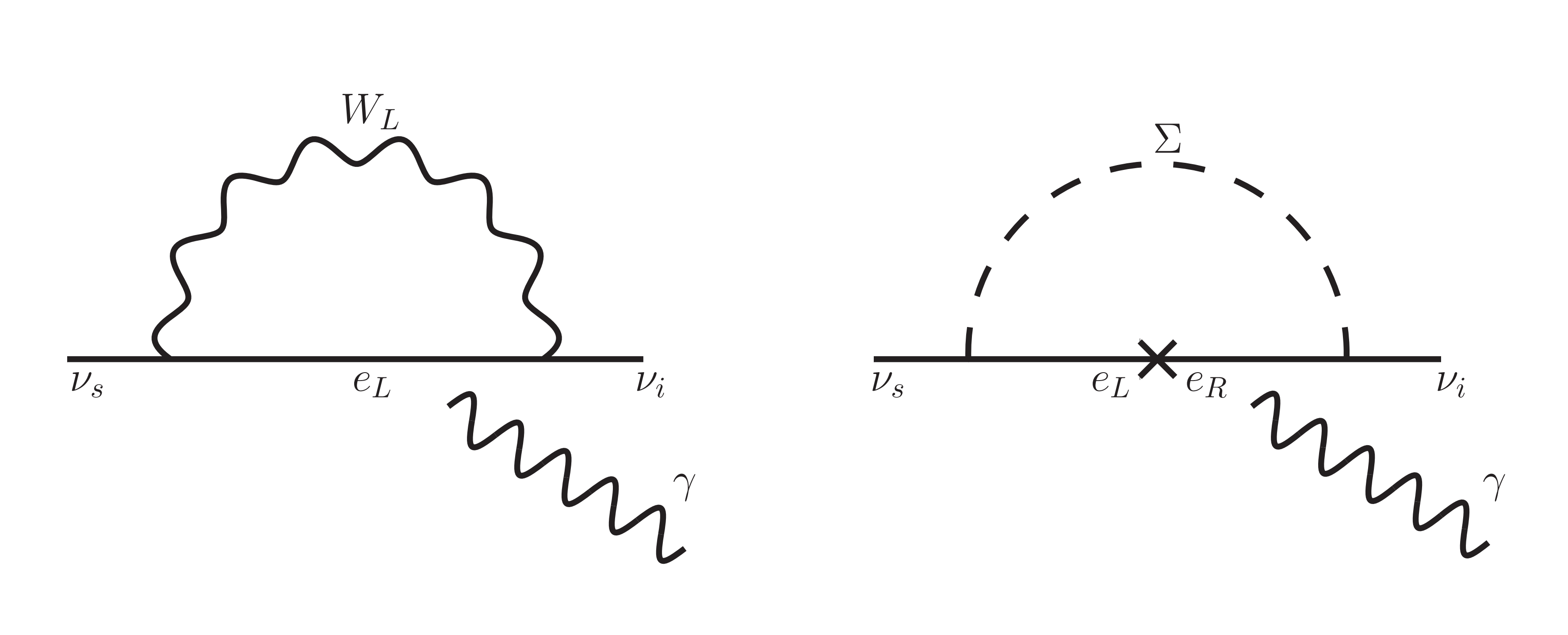
$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 = \chi \mathcal{M}_1 < \mathcal{M}_1$$

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

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

X-RAY BOUND : ABSOLUTE OR MODEL-DEPENDENT ?

Particular realization:



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

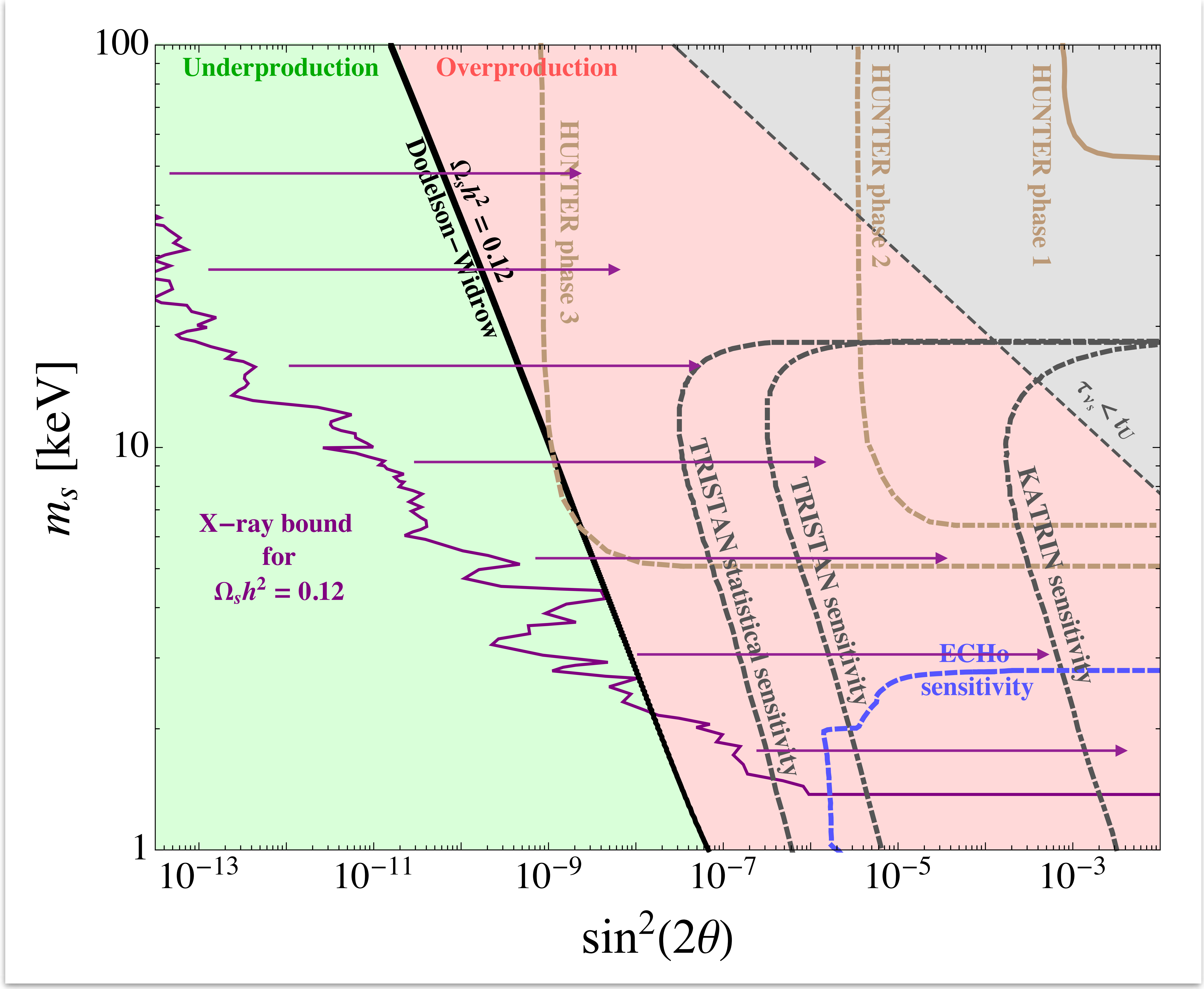
$$\mathcal{L} \supset \lambda\, \bar{\nu}_s \Sigma^\dagger L_e + \lambda'\, \bar{e}_R \tilde{\Sigma}^\dagger L_e + h.c.$$

⟶ partial or complete cancellation if the following condition is satisfied

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

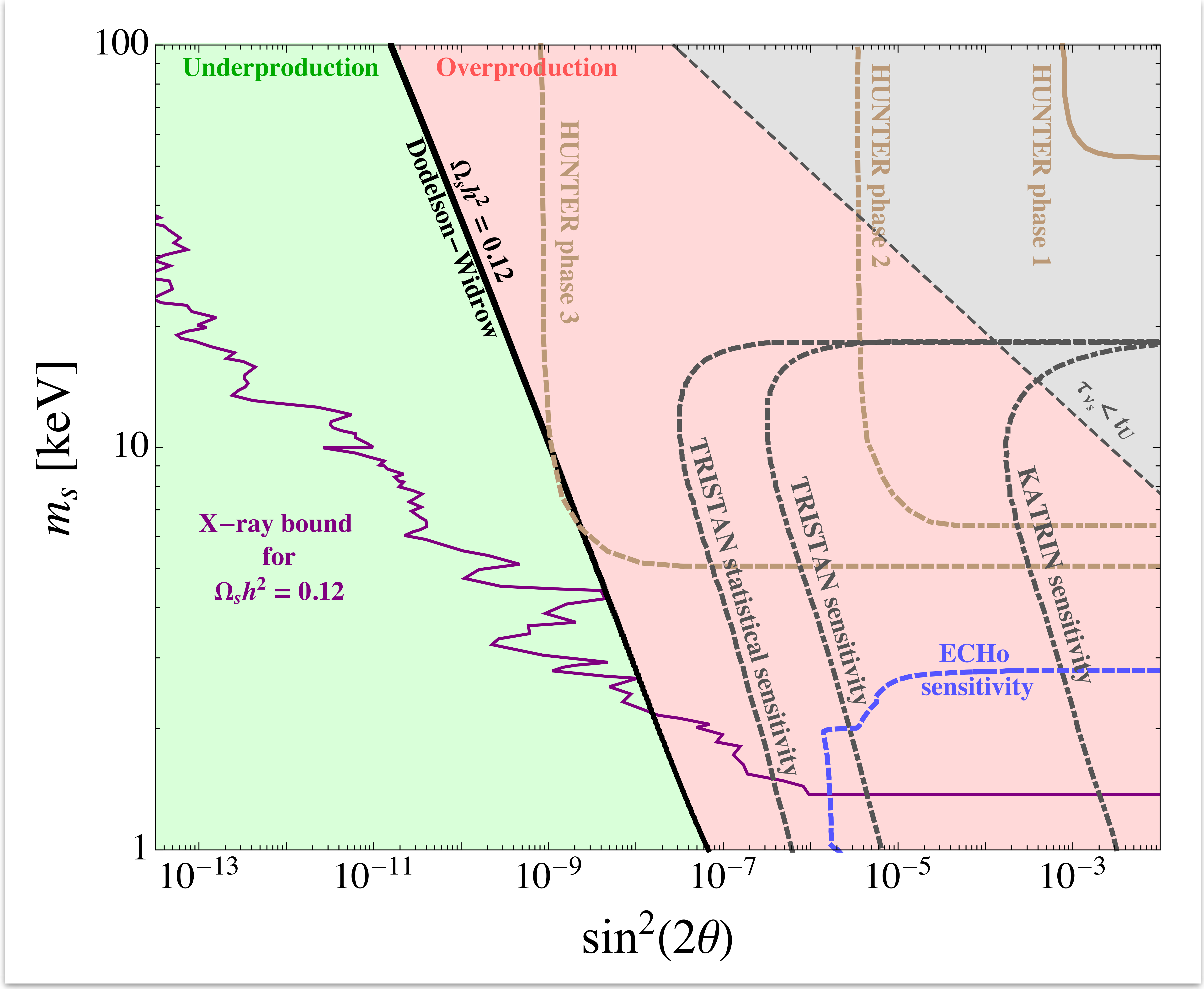
[CB, V. Brdar, M. Lindner, W. Rodejohann, *Phys.Rev.D* 100 (2019), 115035]

X-RAY BOUND : ABSOLUTE OR MODEL-DEPENDENT ?



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

X-RAY BOUND : ABSOLUTE OR MODEL-DEPENDENT ?



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:

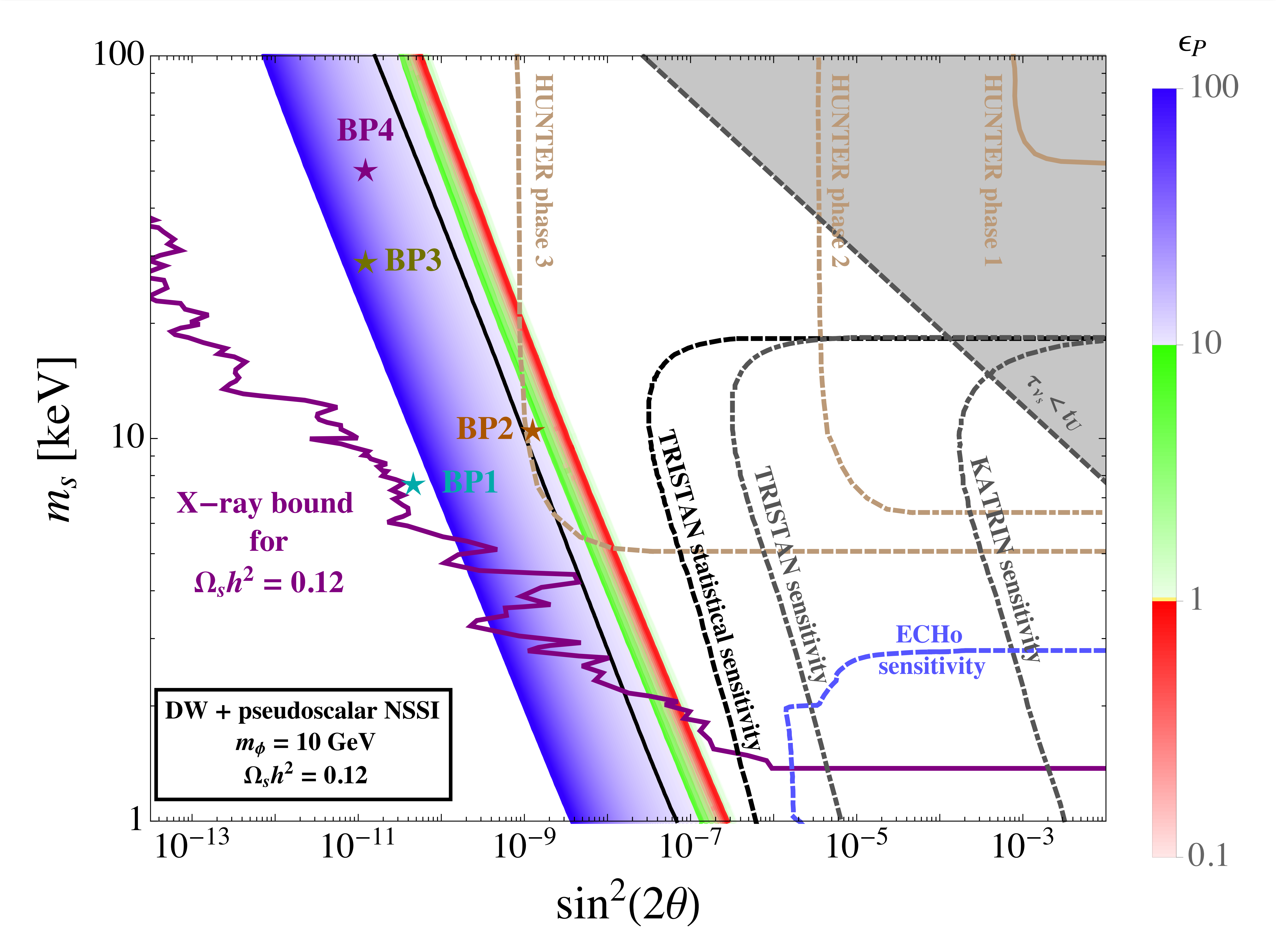
$\rho_s < \rho_{DM}$ corresponds to larger $\sin^2(2\theta)$ for the same flux F

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

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

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

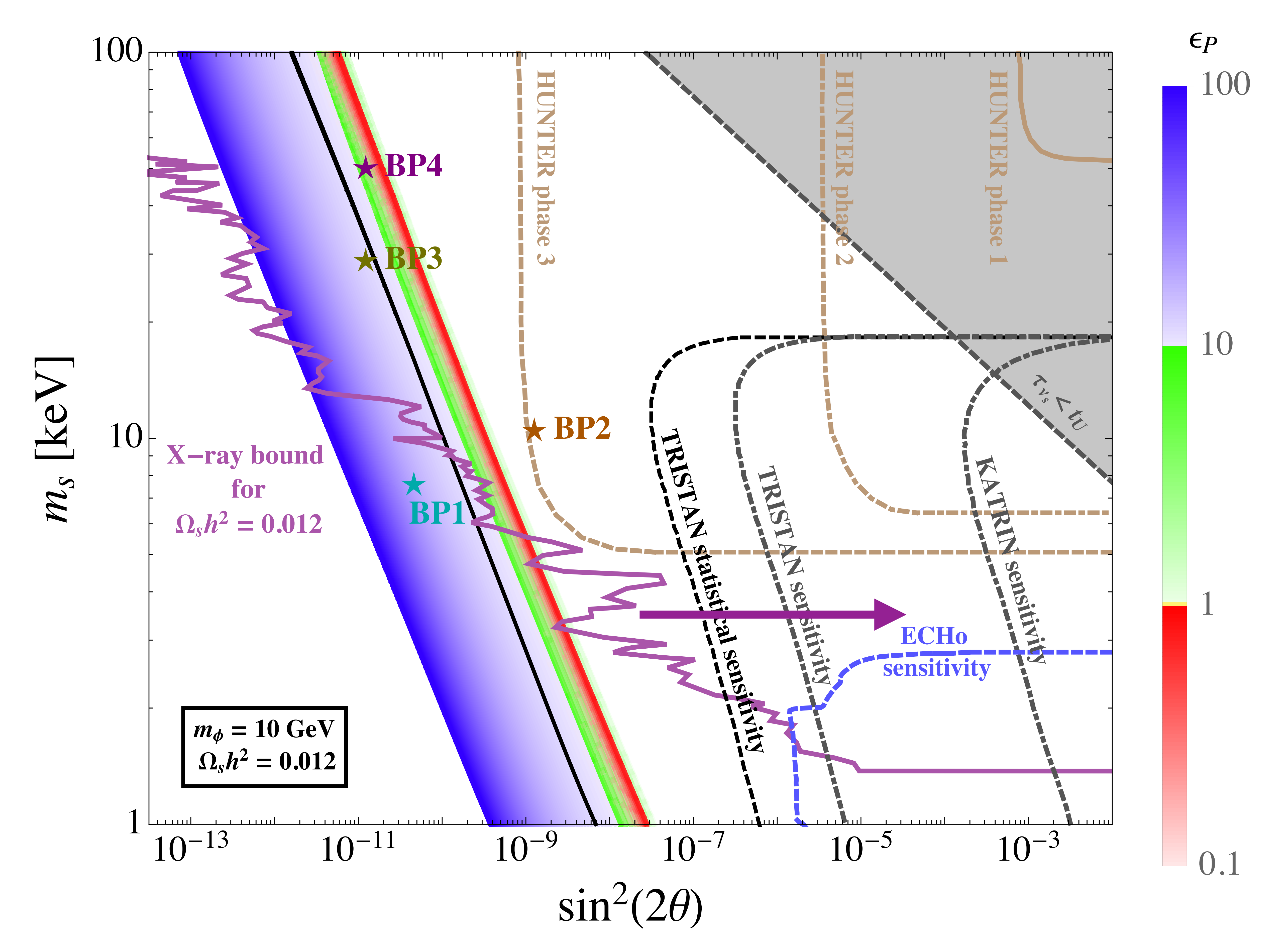
Sterile neutrino **parameter space** : 100% DM constituted by sterile neutrinos



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

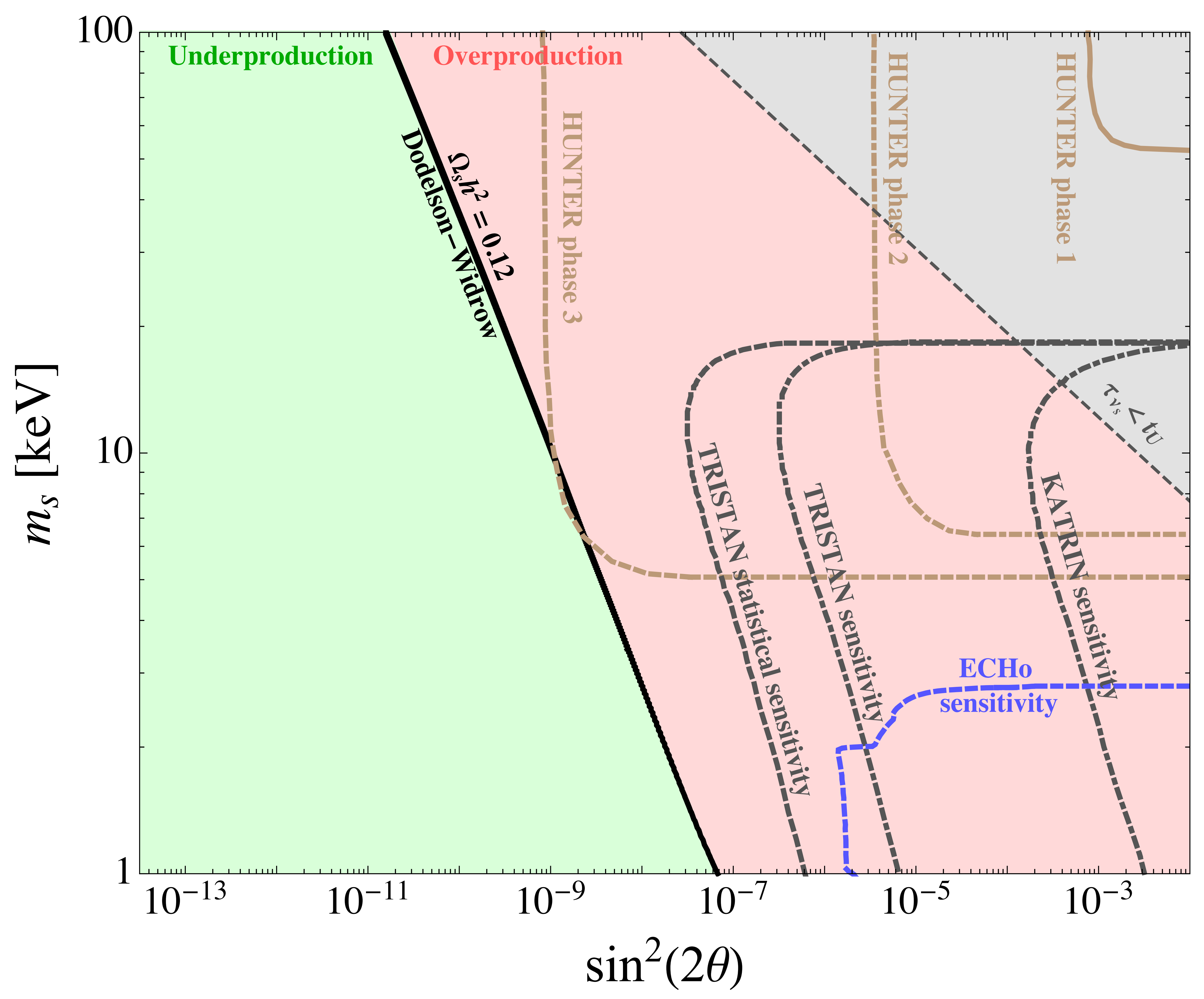
NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

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



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

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]

- Limit from DM abundance :
  rules out large values of θ

- 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]

NEUTRINO NON-STANDARD 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 BSM involving neutrinos and other fermions.

Effective description valid for heavy mediators

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

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

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

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