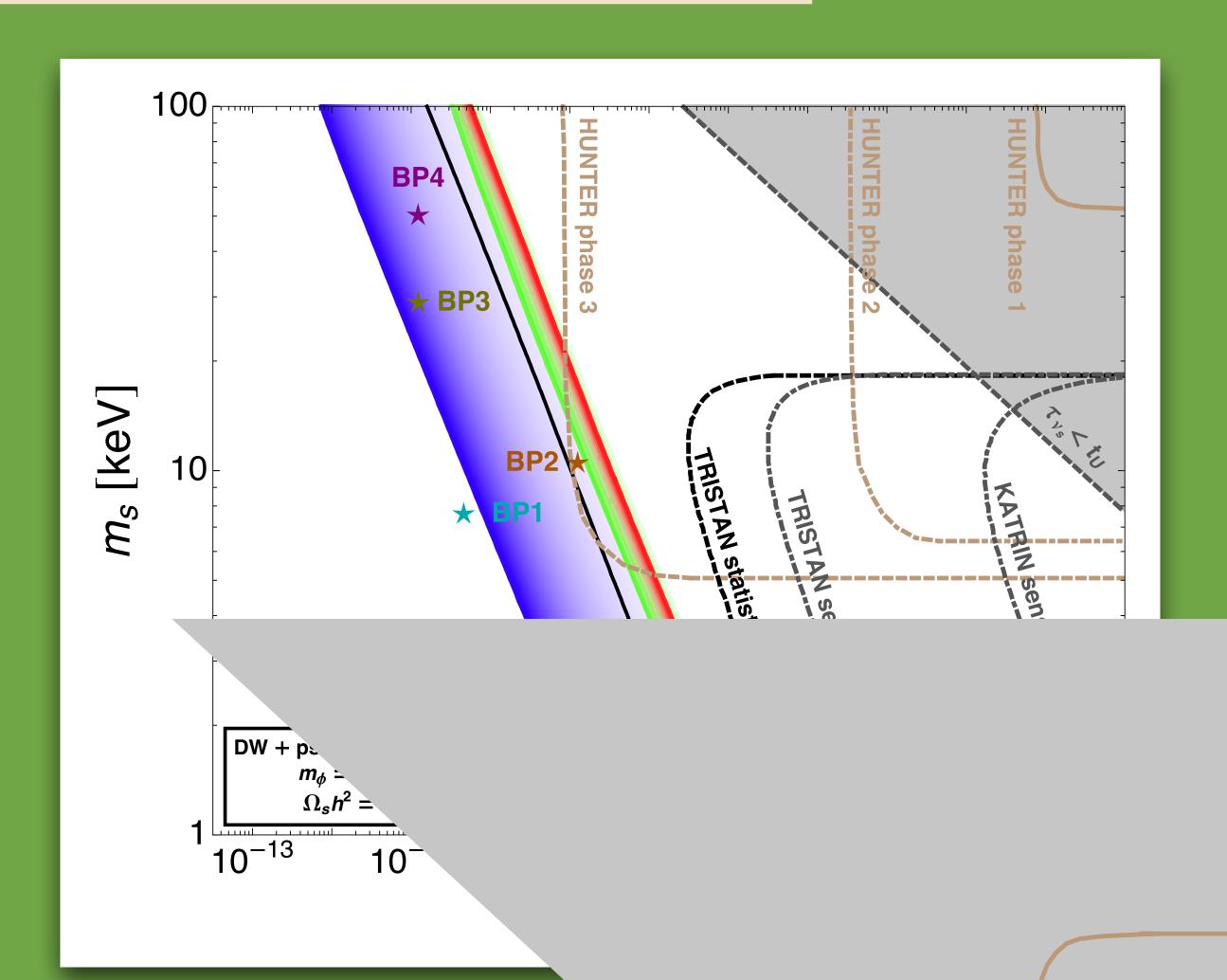


# D NON-STANDARD SELF-INTERACTIONS



## **INTRODUCTION - STERILE NEUTRINO DARK MATTER**

**Definition:** neutral fermions, singlets under the SM symmetries

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

## **INTRODUCTION - STERILE NEUTRINO DARK MATTER**

**Definition:** neutral fermions, singlets under the SM symmetries If neutrinos are Majorana particles:  $\nu_s = \nu_s = \nu_s + \sin \theta \nu_{\alpha}$ 

### sterile neutrino can play the role of DM:

- no em nor strong interaction, by definition
- massive: possibly with mass O(keV)

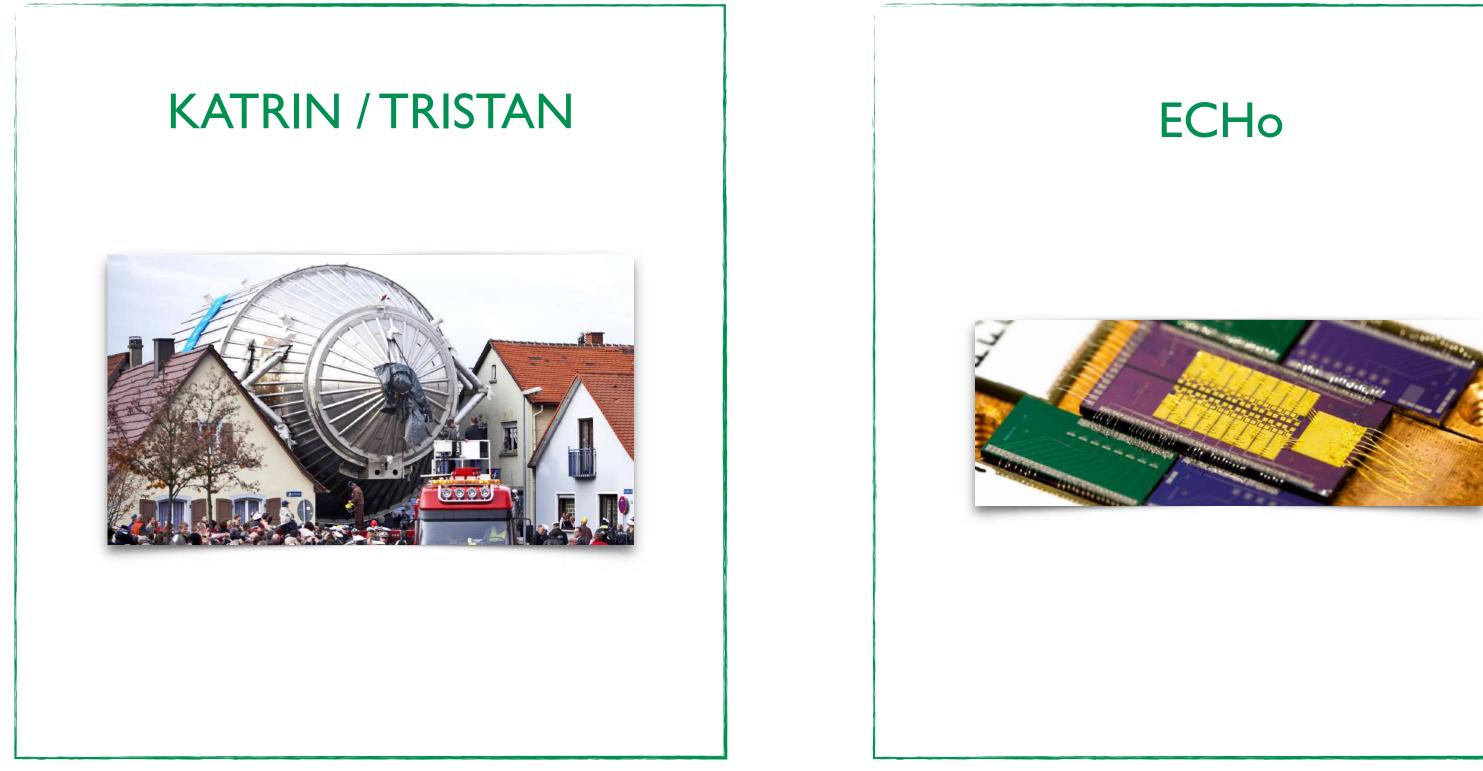
- compatible with large scale structures

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

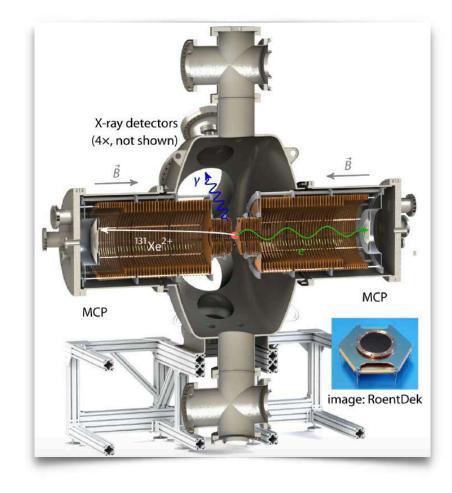
## SEARCHES IN TERRESTRIAL EXPERIMENTS

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











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,

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

### **Cristina Benso**



- the wave function has probability  $\propto \sin^2(2\theta_M)$  to collapse in the sterile state

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Mechanism: production through oscillation and collisions:

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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 
$$\Gamma_e(p) = c_e(p,T) G_F^2 p T^4$$
  
 $\langle P_m(\nu_e \to \nu_s; p,t) \rangle = \sin^2(2\theta_M) \sin^2\left(\frac{vt}{L}\right) \approx \frac{1}{2} \sin^2(2\theta_M)$ 

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- the wave function has probability  $\propto \sin^2(2\theta_M)$  to collapse in the sterile state

In the plasma, the mixing angle is

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

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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

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

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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

 $n(T) = \frac{g}{(2\pi)^3} \int_{-\infty}^{+\infty}$ sterile neutrino number density sterile neutrino yield  $Y = \frac{n}{s}$ 

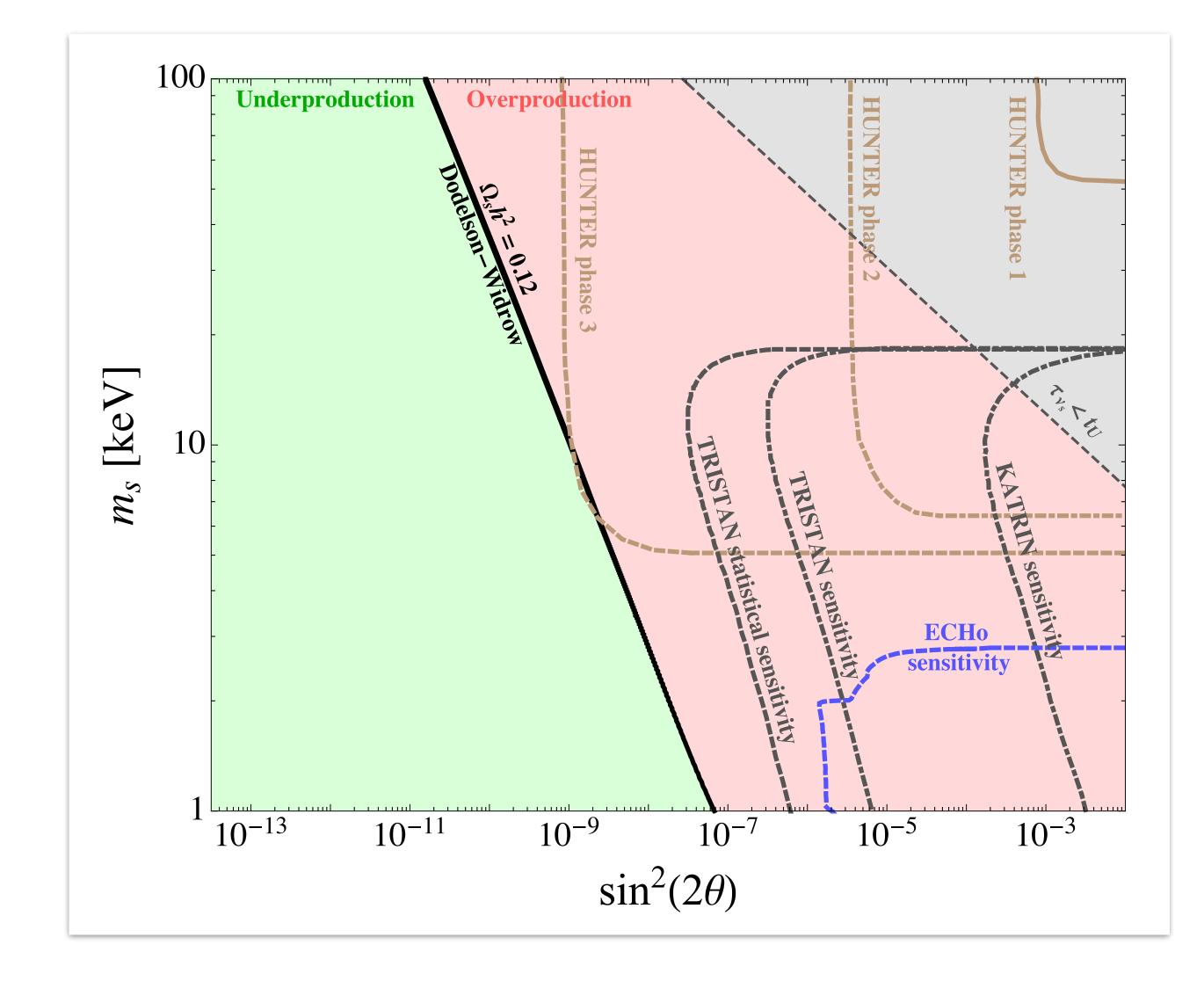
$$h^2 \Omega_s = \frac{s_0 m_s}{\rho_c / h^2} \frac{1}{g_{*s}} \left(\frac{45}{4\pi^4}\right) \int_0^\infty dr \, r^2 \left[f_{\nu_s}(r) + f_{\overline{\nu}_s}(r)\right]$$

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$$^{+\infty}_{\infty} d^3 p f(p,T)$$

## **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.

ere e indicates the NSS [is Grengi & kompared (to the standard weak interac an:

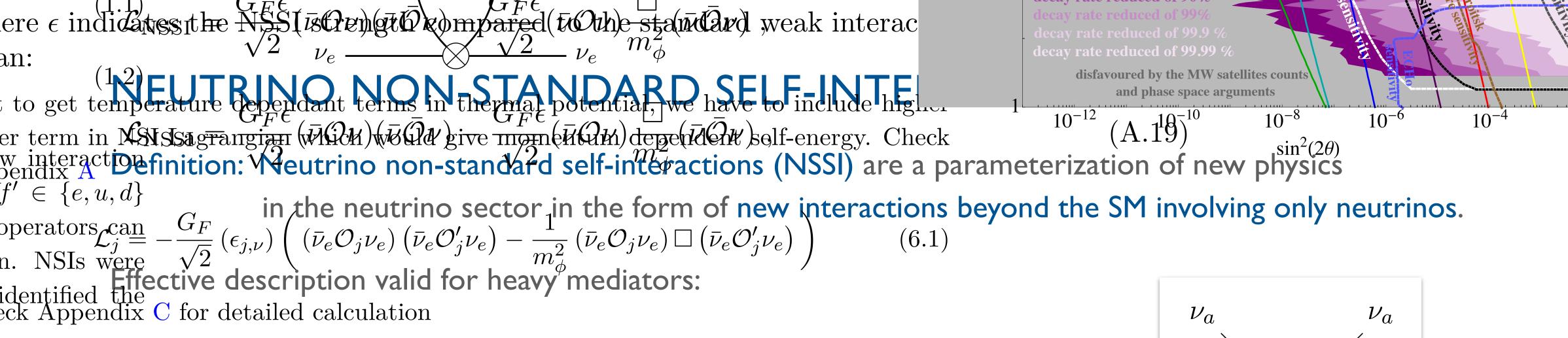
to get temperature dependant terms in thermat potential, we have to include high. er term in KSISISTETTET (WACH) (WACH) (WACH) (WACH) (WACH) give men (WACH) dependen (WACH) self-energy. Check w interact Definition: Meutrino non-standard self-interactions (NSSI) are a parameterization of new physics

 $\mathbb{ERENT}_{3m_{\phi}^{2}}^{\text{have}} \left(\epsilon_{A,\nu_{e}}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu}\left\langle E_{\nu}\right\rangle + n_{\bar{\nu}}\left\langle E_{\bar{\nu}}\right\rangle\right] = -\frac{1}{45m_{\phi}^{2}} \left(\epsilon_{A,\nu_{e}}\right)^{eeee} \cdot \omega T^{4} \quad (6.3)$ 

or **Rependentalar** NSI(C.3.3)

$$\begin{aligned}
\mathcal{L}_{\mathbf{P}} &= -\frac{8\sqrt{2}G_F}{3m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu} \left\langle E_{\nu} \right\rangle + n_{\bar{\nu}} \left\langle E_{\bar{\nu}} \right\rangle\right] = -\frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{ee} \\
, \quad (1.3)
\end{aligned}$$

s the Wolfenal. For useful



 $\nu_a$ 



 $e^{eee} \cdot \omega T^4 \quad (6.4)$ 

 $u_a$ 



ere e indicates the NSS ( is Grenge Q & mpared ( to the standard weak interac an:

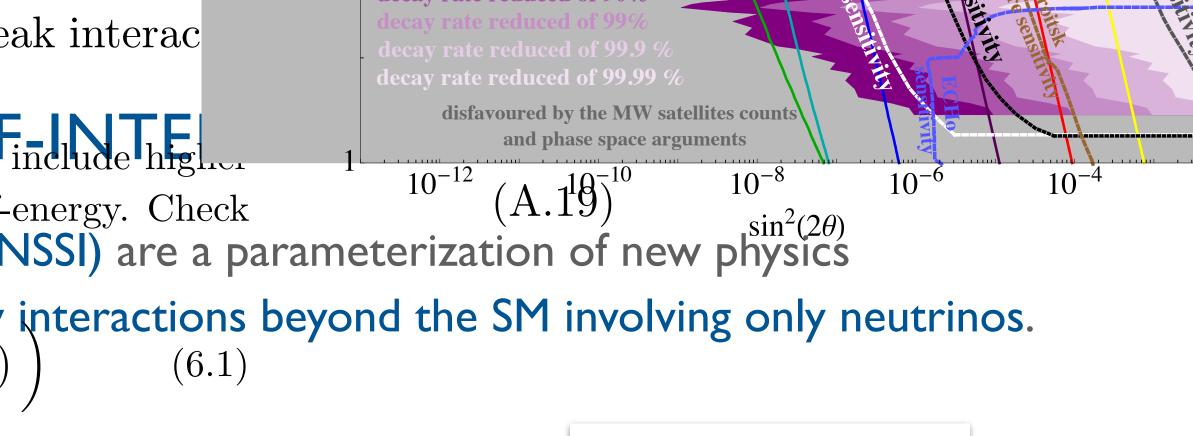
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 $\mathbb{ERENT}_{3m_{\phi}}^{\mathbf{T}_{\mathbf{V}_{\mathbf{V}_{\mathbf{V}}}}} (\epsilon_{A,\nu_{e}})^{eeee} \cdot \omega \cdot [n_{\nu} \langle E_{\nu} \rangle + n_{\bar{\nu}} \langle E_{\bar{\nu}} \rangle] = -\frac{\mathbf{T}_{\mathbf{V}_{\mathbf{V}_{\mathbf{V}}}} (\epsilon_{A,\nu_{e}})^{eeee} \cdot \omega T^{4} (6.3)$ 

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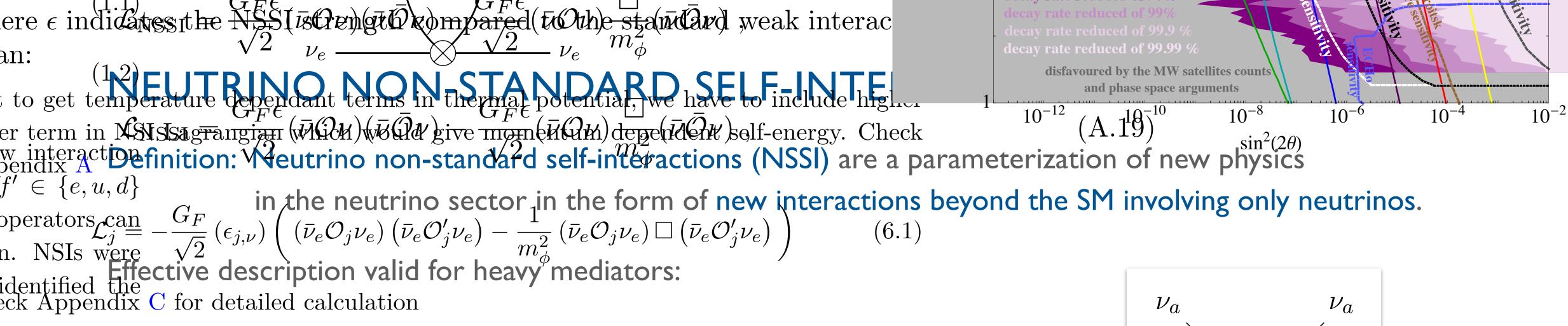
 $\begin{array}{l} \mathbf{g} \in \mathbf{Section} \in \mathbf{NSSI}(\mathbf{C}, \underline{\mathbf{3}}, \underline{\mathbf{1}}) \quad & G_F \\ \mathbf{y} \text{ is generally} \quad & SSI = \mathbf{1} \\ \mathcal{S} \sqrt{2}G_F \\ \mathcal{S} = \mathbf{convenient} \\ \mathcal{S} \mathcal{M}_{\phi}^2 \quad & (\epsilon_{S,\nu_e})^{eeee} \cdot \omega \cdot [n_{\nu}^j \langle E_{\nu}^{\beta} \rangle^{2} \cdot n_{\bar{\nu}} \langle E_{\bar{\nu}} \rangle] = -\frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} (\epsilon_{S,\nu_e})^{eee} \end{array}$ ought of in  $\phi_{a}$  $\mathcal{O}_{i} = \{\mathbb{I}, \gamma^{\mu}, i\gamma^{5}, \gamma^{\mu}\gamma^{5}, \sigma^{\mu\nu}\}$ deaminateetor NSI(C.3.2)

to mediators  $E = \frac{16\sqrt{2}G_F}{3m_{\phi}} (\epsilon_{A,\nu_e})^{eeee} \cdot \omega \cdot [n_{\nu} \langle E_{\nu} \rangle + n_{\bar{\nu}} \langle E_{\bar{\nu}} \rangle] = -\frac{14\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} (\epsilon_{A,\nu_e})^{eeee} \cdot \omega T^4 \quad (6.3)$ 

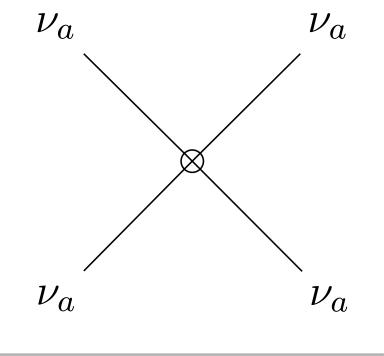
or **Rependos** talar NSI (C.3.3) physics to come from the neutrino sector  $Y_{\rm T} = -\frac{8\sqrt{2}G_F}{3m_{\phi}^2} \left( \epsilon_F e^{i\theta} + nodels \cdot e^{i\theta} \cdot e^{i\theta} + n_{\phi} \cdot e^{i\theta} + n_{\phi} \cdot e^{i\theta} \cdot e^{i\theta} + n_{\phi} \cdot e^{i\theta} + n_{\phi$ (1.3) NSSI could have significant impact on physics of the early universe (Hubble tension etc.)

• parameter space very poorly constrained and investigated s the Wolfen-

al. For useful



$$e^{ee} \cdot \omega T^4$$
 (6.2)



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p Interactions  $[(Denton)\mathcal{L}_{NSS}] = \mathcal{C} \oplus \mathcal{O} \oplus \mathcal{O}$  $\mathcal{F}_{P_T \nu_A}$  is useful in  $\mathcal{F}_{Q_T \nu_A}$  is useful in order to understand the classifithe sine set of the se His Guilder Hereindig to the Stranger S orm of NSSI Lagrangian: pround franciscons transitions, are observable anly if the transition probability cat describbles, et projection,  $peraterial (\phi, s_{l}, c_{l})$ acconstruction of the projection of the peraterial of t (0 1 1)d this inequality alwed classify neutrino oscillation experiments according to the ratio which is the interval of  $\Delta m^2$  to which an experiment is sensitive: ascillation potenseared agy experimently the based one of the second s Suffected to large, the event rate is ht case of scattering the denominator relatively high and oscillations can be detected for  $\Delta m^2 L/4E \gtrsim 0.1$ , leading a prime to scattering the demonstrators. There are two types of SBL experiments: reactor  $\bar{\nu}_e$ disappearance experiments with  $L \sim 10 \text{ m}$ ,  $E \sim 1 \text{ MeV}$  as, for example, Bugey [64]; *Cristina Benso* Advertise a new flayer dependent ith  $L \leq 1 \text{ km}$ ,  $E \geq 1 \text{ GeV}$ , as, for example, CDHS [71]

(A.18)(A.19)









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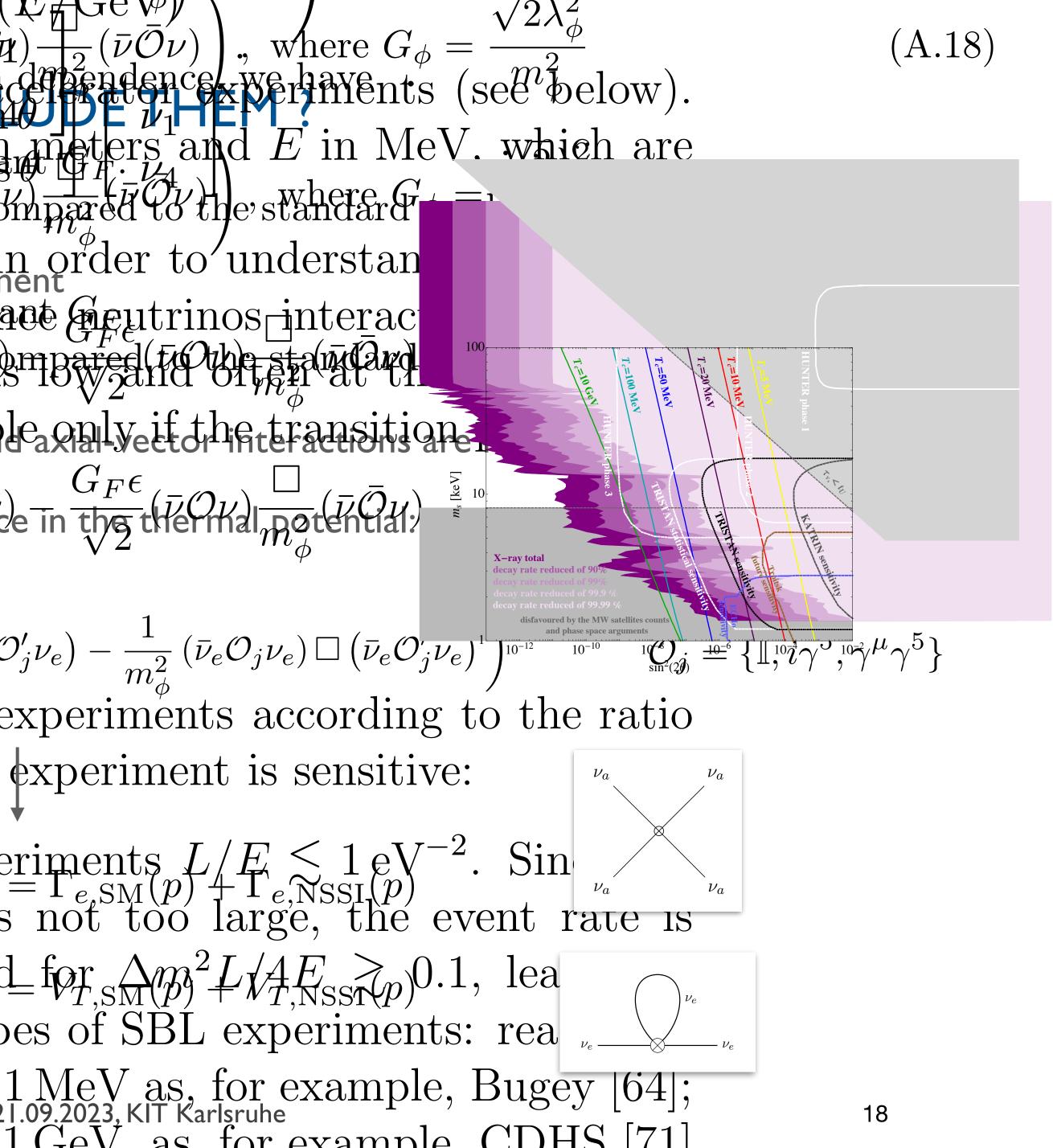
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### **Cristina Benso**

p Interactions  $\left[ (Denton) \mathcal{L}_{\text{NSS}} \right] = \mathcal{COS} \left( \overline{\psi} \mathcal{O} \psi (\overline{\psi} \mathcal{O} \psi) \right) - \left[ \overline{\psi} \mathcal{O} \psi \right] + \frac{1}{2} (\overline{\psi} \overline{\mathcal{O}} \psi) \right]$ , where  $G_{\phi} = \frac{\sqrt{2\lambda_{\phi}^2}}{m^2}$  is the first order of the product of the An hunger called the presence of the state  $\gamma^{\mu}P_{L}\nu_{\beta}$  (f)  $\gamma^{\mu}P_{L}\nu_{\beta}$  (f) the strength of types defined similar experiments constant meutrinos interac na ten for the standing of the  $\frac{1}{2} = \frac{1}{2} = \frac{1}$  $\frac{\Delta m^2 L}{\Delta m^2 L} \gtrsim 0.1 - 1.$   $\frac{\Delta m^2 L}{\sqrt{2}} \approx 0.1 - 1.$   $\frac{\Delta m^2 L}{\sqrt{2}} \approx 0.1 - 1.$   $\frac{\Delta m^2 L}{\sqrt{2}} \approx 0.1 - 1.$ d this in a second it yas we de a sify neutrino oscillation experiments according to the ratio which is to which an experiment is sensitive: assiblation potenseared agy experimently **EXErced interaction of the state of the state of the set of the state of the stat** ht case of scattering the denominator relatively high and oscillations for the detected for  $\Delta m^2 L/4E \gtrsim 0.1$ , lea herizasitor scattering the denominators T(p) an be detected for  $\Delta m^2 L/4E \gtrsim 0.1$ , lea sensitivity to denominators. There are two types of SBL experiments: real  $(m-1)^2$ disappearance experiments with  $L \sim 10 \text{ m}$ ,  $E \sim 1 \text{ MeV}$  as, for example, Bugey [64]; *Cristina Benso* Advertise a new flayer dependent ith  $L \leq 1 \text{ km}$ ,  $E \geq 1 \text{ GeV}$ , as, for example, CDHS [71]





### NEUTRINO NSSI - HOW TO INCLUDE THEM ?

Scalar NSSI

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

• Pseudoscalar NSSI

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

• Axial vector NSSI

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

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

**Cristina Benso** 

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

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## **NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS**

### Sterile neutrino production evolution

### **Cristina Benso**

 $10^{-6}$ ifying large structures that was Rhserventeday.

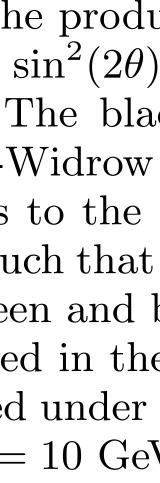
FIG. 5. Variation of the free streaming length of sterile neutrino dark matter determined by the increasing strength of NSSI for different values of  $m_s$  and  $\sin^2(2\theta)$ . Each color refers to a benchmark point given in FIGS. 2 and 3. Each line type corresponds to a different value of the NSSI mediator mass. Black of quares pinpoint to values of  $\epsilon_P$  for which the condition  $\Omega_s h^2 = \Omega_{\rm DM} h^2 = 0.12$  is satisfied. Black triangles identify values of  $\epsilon_P$  such that only the 10% of the DM abundance is constituted by sterile petitrinos in the "cocktail DM" scenario.

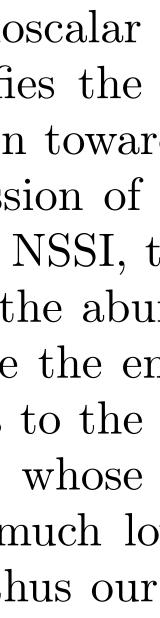
Timless they are very light. On the other hand, if we consider BRI prevention observed X-ray line at 3.55 ket [37638], we see that large NSSI would be needed to proche and abundance of such sterile neutrinos large enough to constitute a non negligible percentage of the Universe's DM<sup>0</sup>content. However, such large NSSI would put sterile neutrinos Geith such features in conflict with constraints coming from structure formation: they [CB, W. Rodejohann, M. Sen, A. Ujjavini Ramachandran, *Phys.Rev.D* 105 (2022) 5, 055016] Would have been produced with too high velocities mod-

RP2 is narticularly interesting. It represents a case in

FIG. 6. Evolution of the produ with  $m_s = 10$  keV and  $\sin^2(2\theta)$ 2) with temperature. The bla the standard Dodelson-Widrow dashed line corresponds to the doscalar NSSI with  $\epsilon_P$  such that ferent shades of red, green and l strength of NSSI involved in the All the lines are obtained under mediator has mass  $m_{\phi} = 10 \text{ GeV}$ 

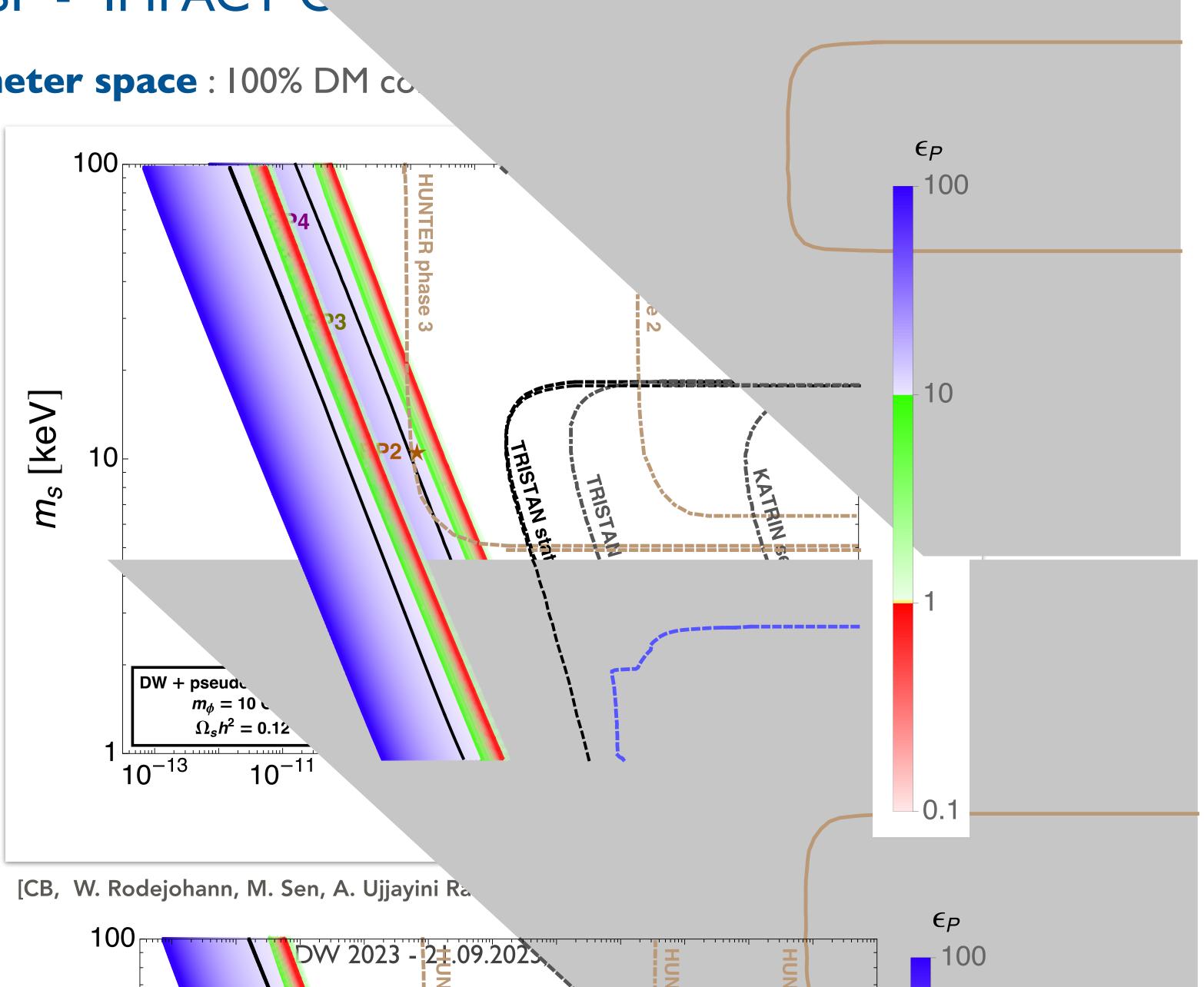
presence of the pseudoscalar GeV) mediator modifies the peak of the production towar shown by the progression of larger the strength of NSSI, t ature. In particular, the abu sufficient to constitute the er Universe, corresponds to the the black dashed line whose This temperature is much lo NSSI mediator,<sup>21</sup> and thus our

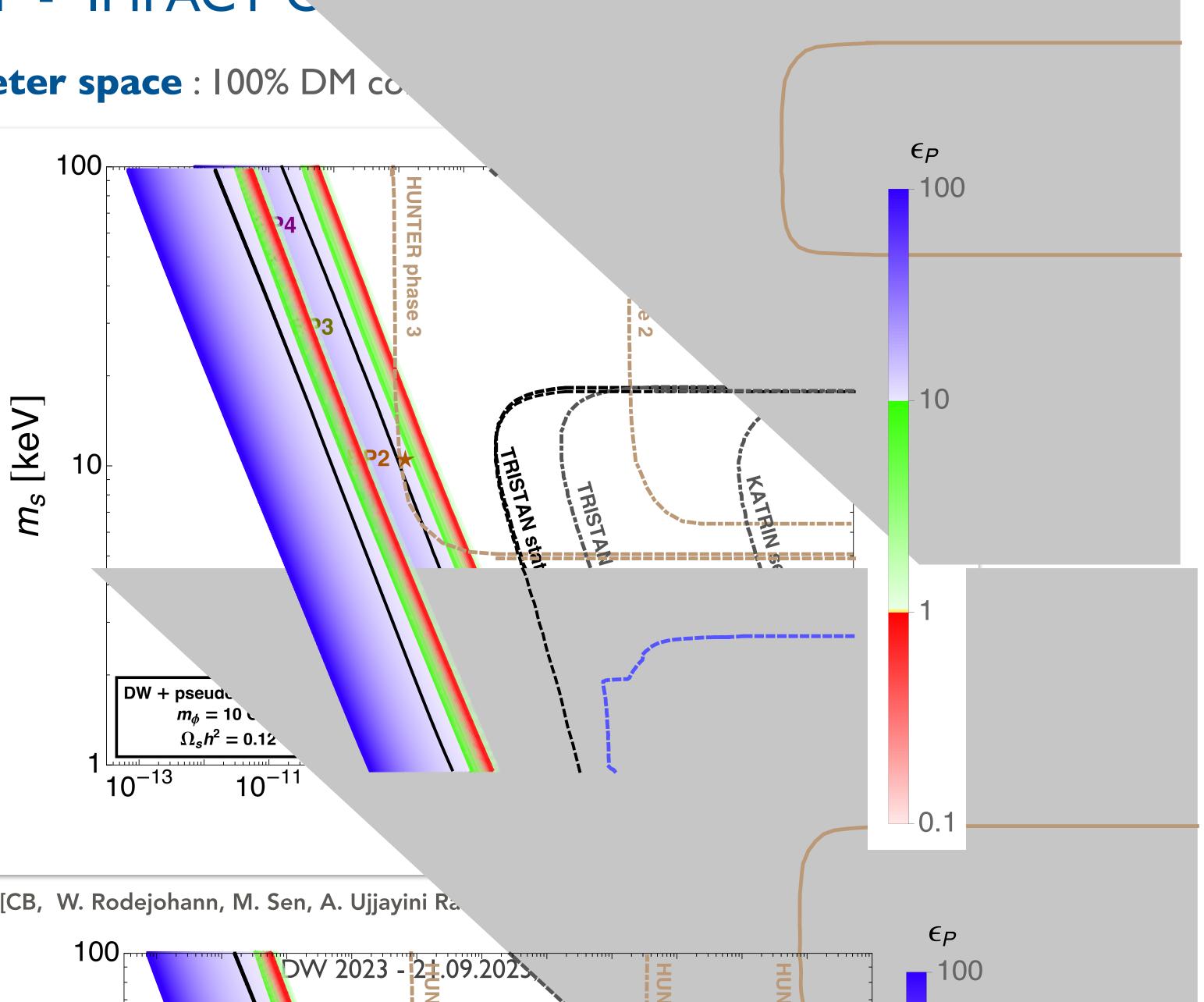






### Sterile neutrino parameter space : 100% DM cc.



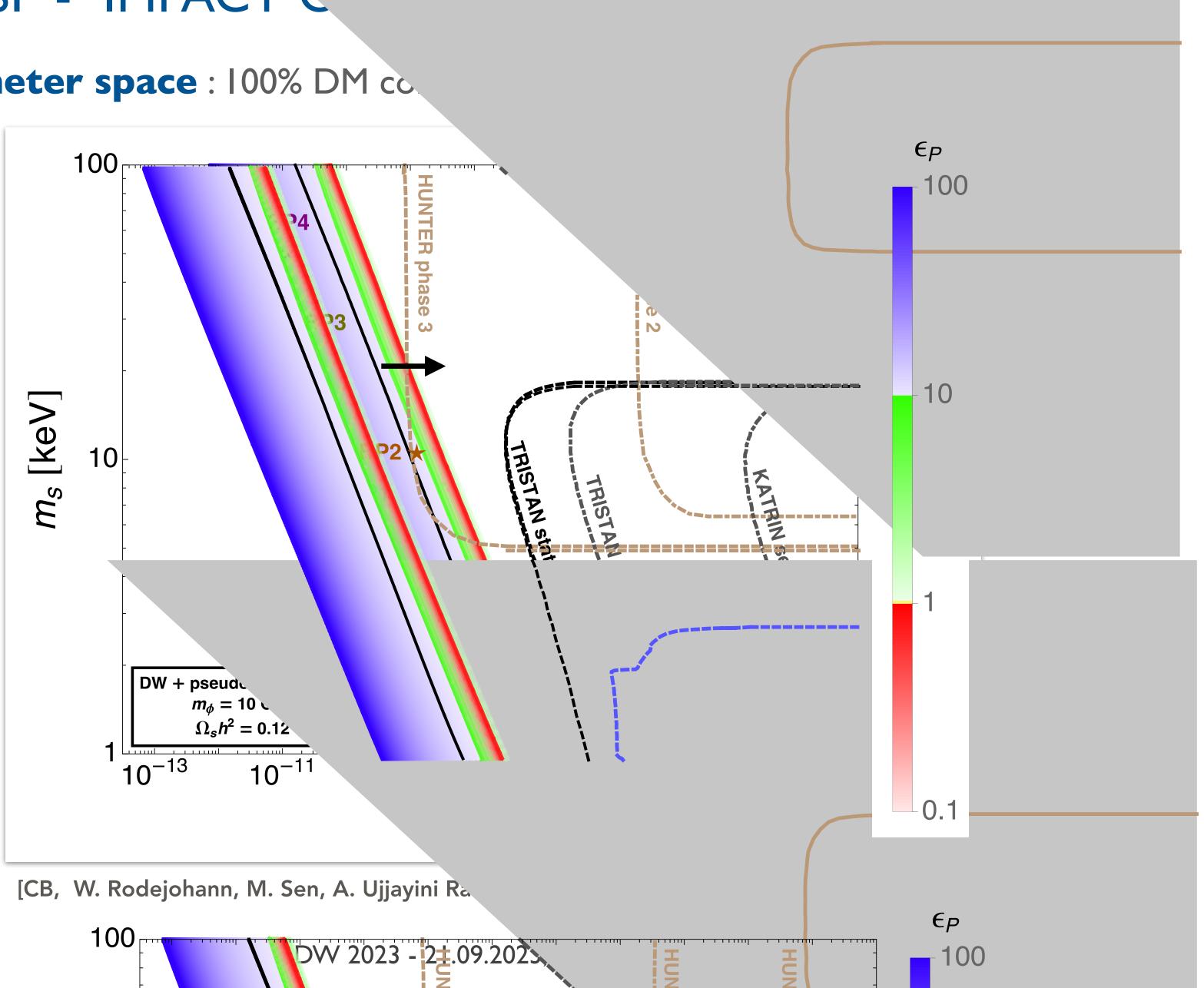


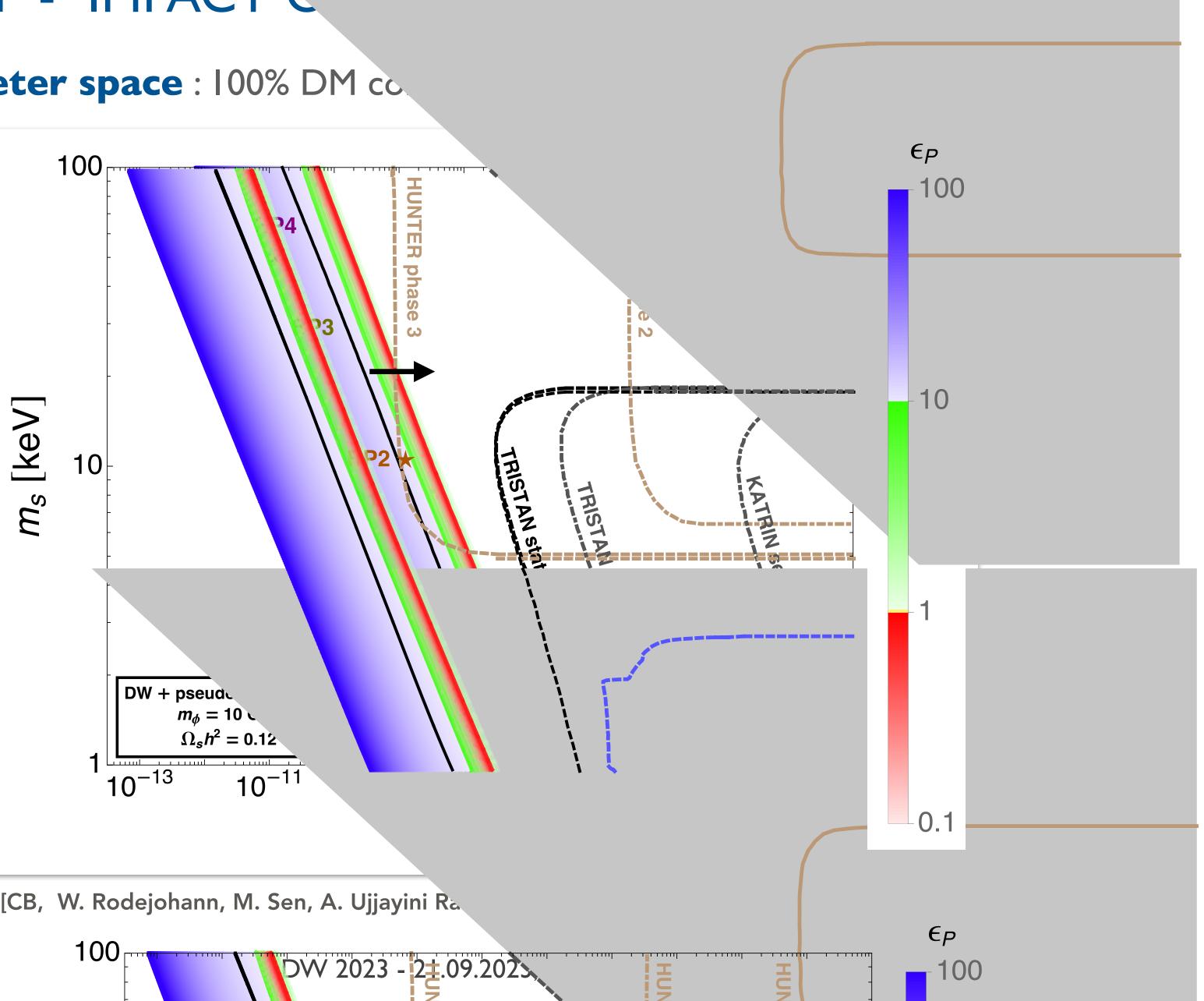
Cristina Benso

22



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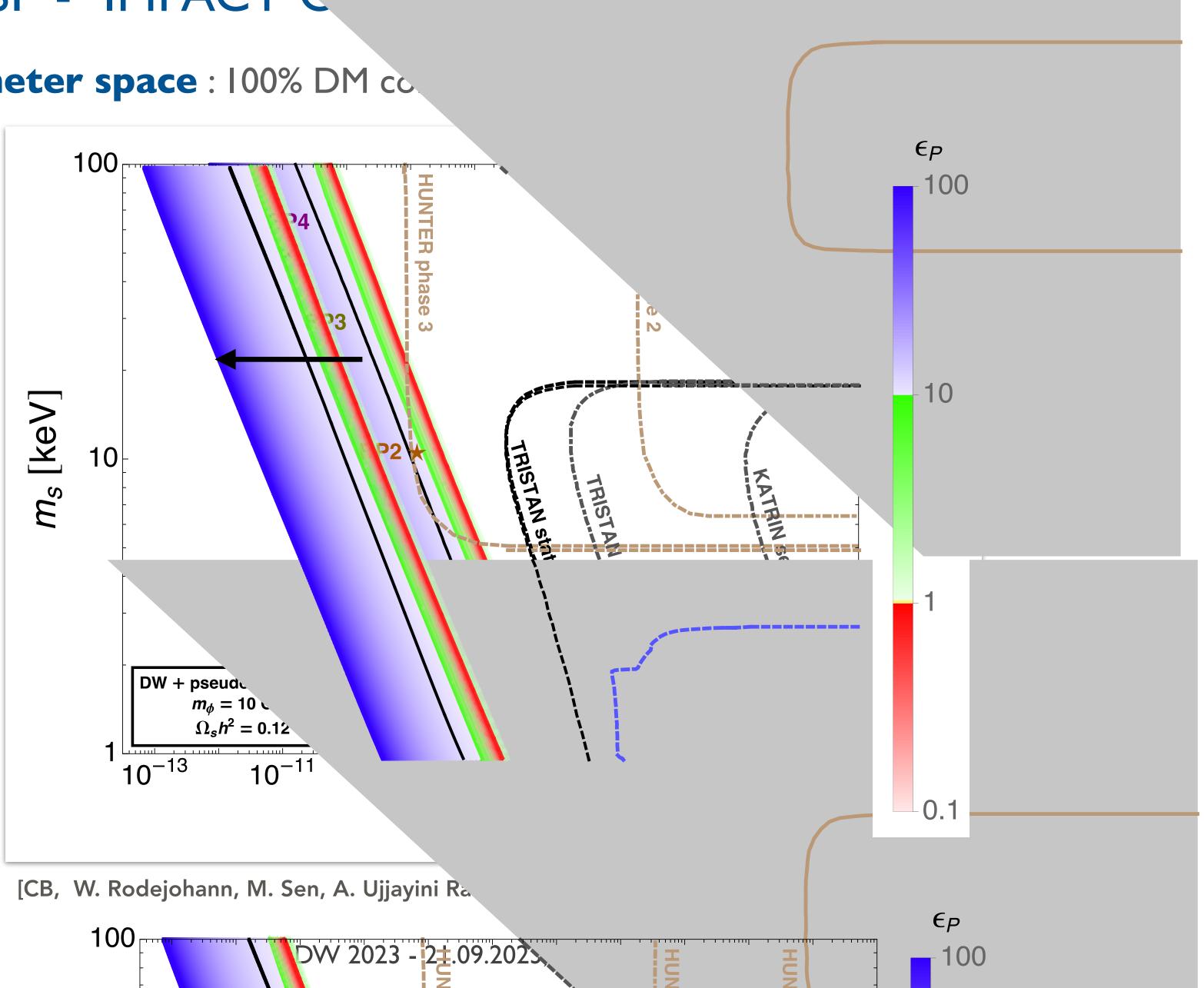


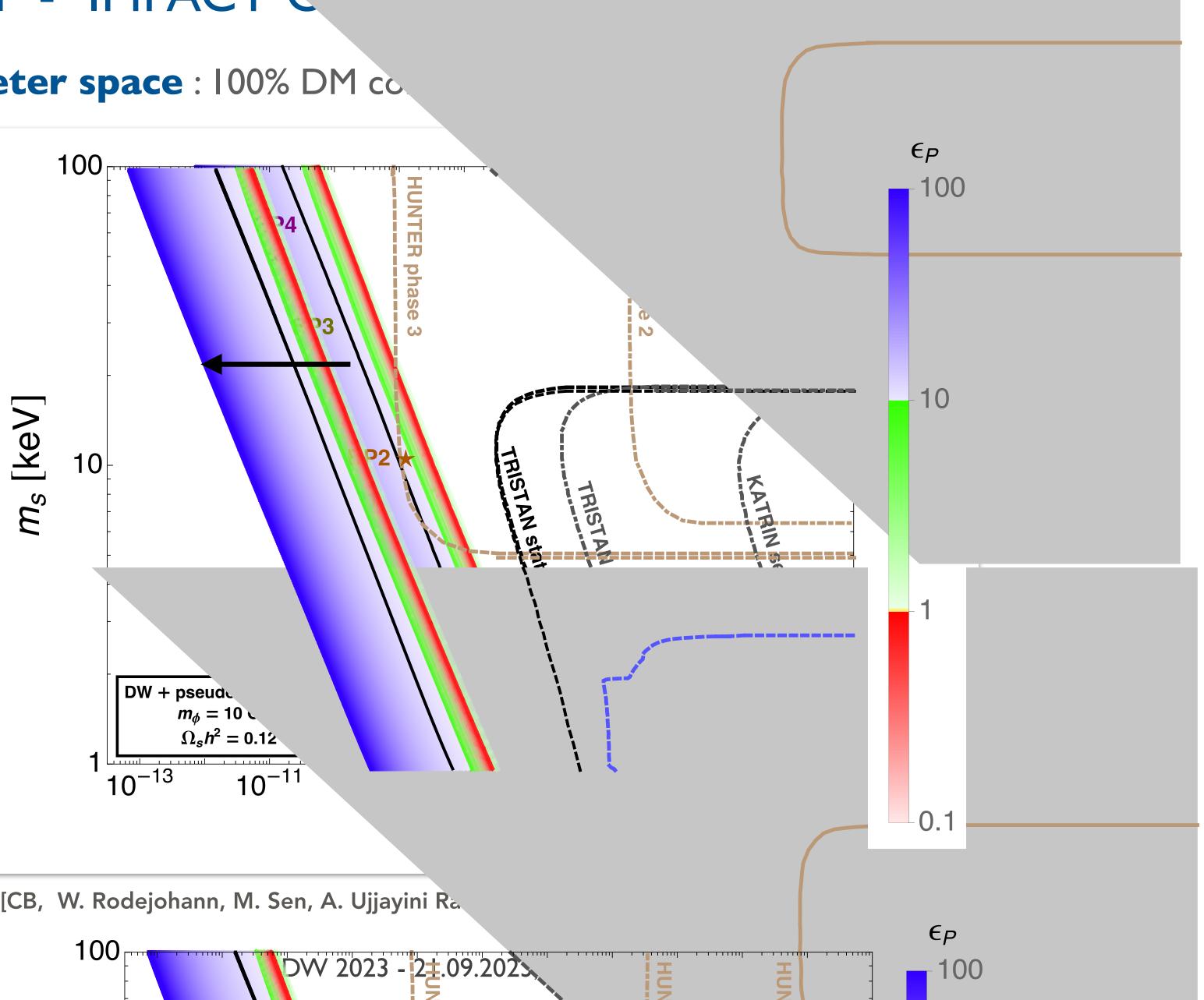
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23



### Sterile neutrino parameter space : 100% DM cc.





Cristina Benso

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

**Cristina Benso** 

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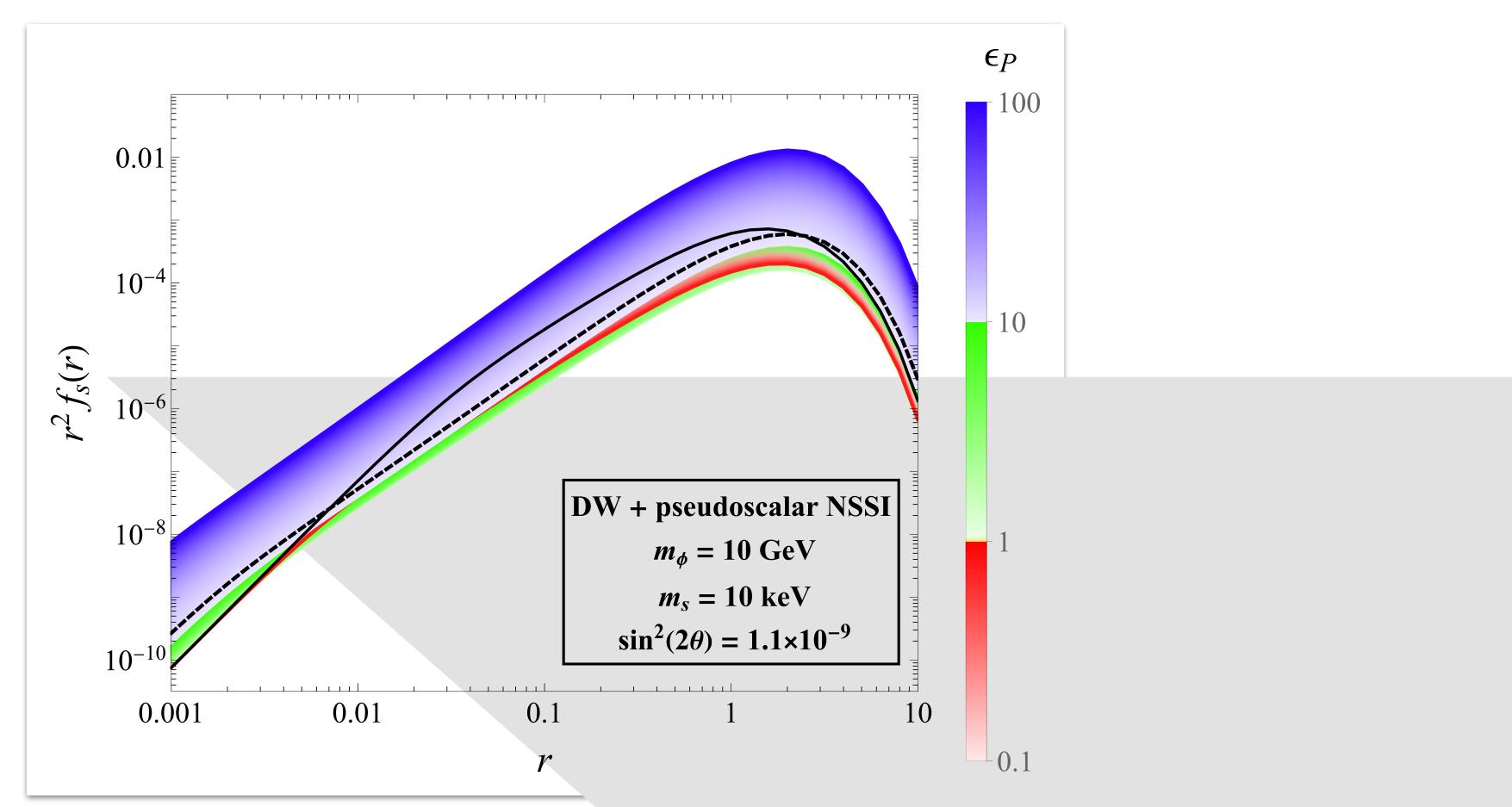
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- Scalar, pseudoscalar and axial-vector NSSI modify the production of sterile neutrino dark matter in the early universe.
- The parameter space region in which  $\Omega_{DM} = \Omega_s$  is enlarged by such NSSI and they enhance the possibility to detect sterile neutrino dark matter in HUNTER phase 3.

BACKUP

## **NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS**

### Sterile neutrino **distribution function**





**Cristina Benso** 

Underproduction

100

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

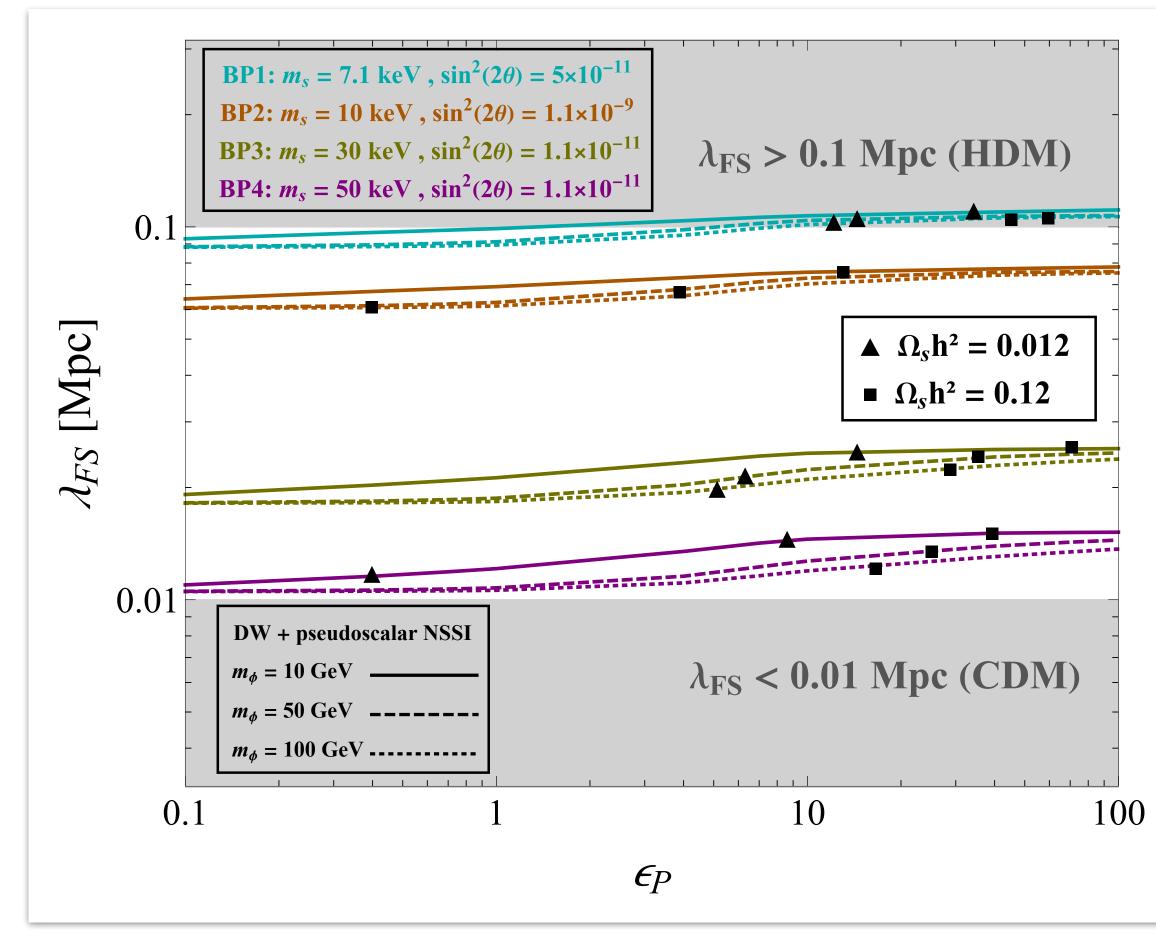


## NEUTRINO NSSI - INDIRECT IMPACT ON STRUCTURE FORMATION

Relevant observable : free streaming length

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

- 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  $\lambda_{\mathrm{FS}}$
- what makes the major difference is still the sterile neutrino mass

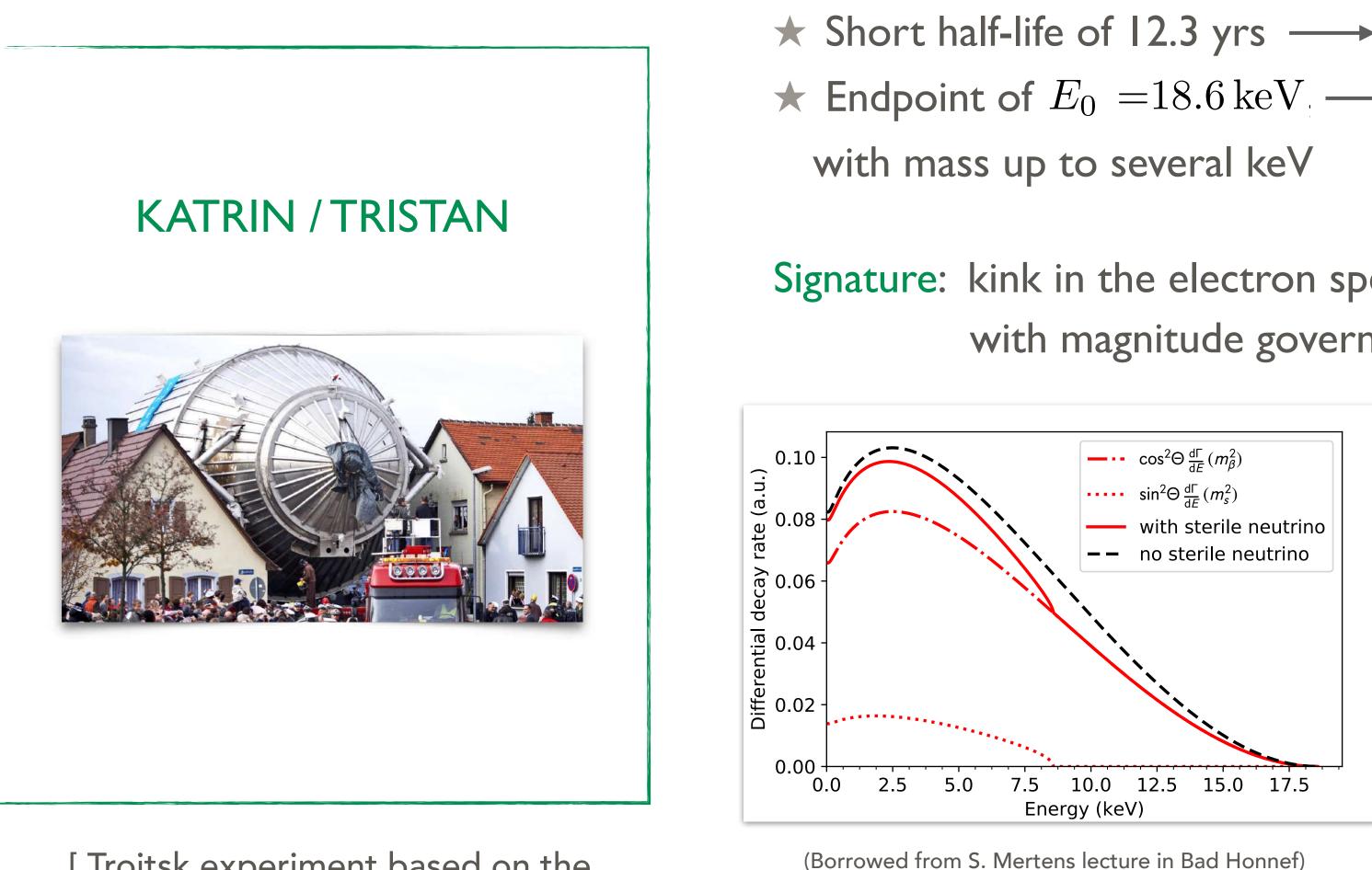


[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, *Phys.Rev.D* 105 (2022) 5, 055016]



- 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  $\Omega_{DM} = \Omega_s$  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



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

### **Cristina Benso**

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### Based on tritium beta-decay:

- ★ Short half-life of 12.3 yrs → high decay rate
- $\star$  Endpoint of  $E_0 = 18.6 \,\mathrm{keV} \longrightarrow$  allows search of sterile neutrinos
- Signature: kink in the electron spectrum at energy  $E_0 m_s$ with magnitude governed by the mixing amplitude  $\sin^2 \theta$

$$\frac{d\Gamma}{dE} = \cos^2 \theta \frac{d\Gamma}{dE} (m(\nu_{\rm e})) + \sin^2 \theta \frac{d\Gamma}{dE} (m_{\rm s})$$

$$35$$



## SEARCHES IN TERRESTRIAL EXPERIMENTS

**ECHo** 

the mass splittings between the signature of the signature of the spectrum of 163 H  $\alpha$  and  $\beta$   $\gamma$   $Q_{\rm EC}$  -  $m_4$ decay experiment can resolve them. Instead, with a fight neutring mast  $U_{e4}^{2}(\nu_{e})^{2} =$  $|U_{ei}|^2 m(\nu_i)^2$  is assumed.

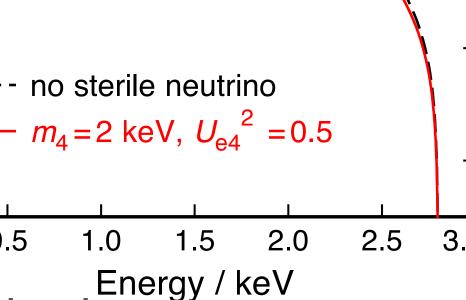
the electron neutrino contains an admixture of a neutrino mass eigenstate with a mass he key range, the different mass eigenstates will no longer form one effective neutrino term. In this case, due to the large mass splitting, the superposition of the  $\beta - \frac{1}{m_4} = 2 \text{ keV}, U_{e4}^2 = 0.5$ spectra corresponding to the light effective mass term  $m(\nu_{e})$  and the heavy mass eigenstate log(counts) / a 10-3 10-4  $m_{\rm s}$ , can be detectable. The differential spectrum can be written as  $=\cos^2\theta \frac{d \log}{dE}(m(\nu_{\rm e}))$ (8.1)10<sup>-5</sup> 1.0 1.2 scale sterile neutrino. First, tritium  $\beta$ -decay is of super-allowed type, and therefore a precise

[HOLMES and predominantly determines the active-sterile neutrino mixing, and predominantly determines the size based of the effect process spectral shape [127]. Figure 35 shows a dualitative example with perfect keV energy resolution and no energy smeafing hift of halatomic, thermal or scattering effects. Cristina Benso Tritium  $\beta$  decay provides distingto advantages when keeps the signature of a keV-

10<sup>-10</sup> Based on holmium electron capture: 0.5 2.0 0.0 1.5 1.0 Energy / keV  $\star$  calorimetric measurement  $\longrightarrow$  all events occurring in the detector give a measurable signal (entire spectrum "for free") endpoint of  $Q_{\rm EC} = 2.833 \text{ keV} \longrightarrow \text{ allows search of sterile neutrinos}$ only with mass < 2.5 keV

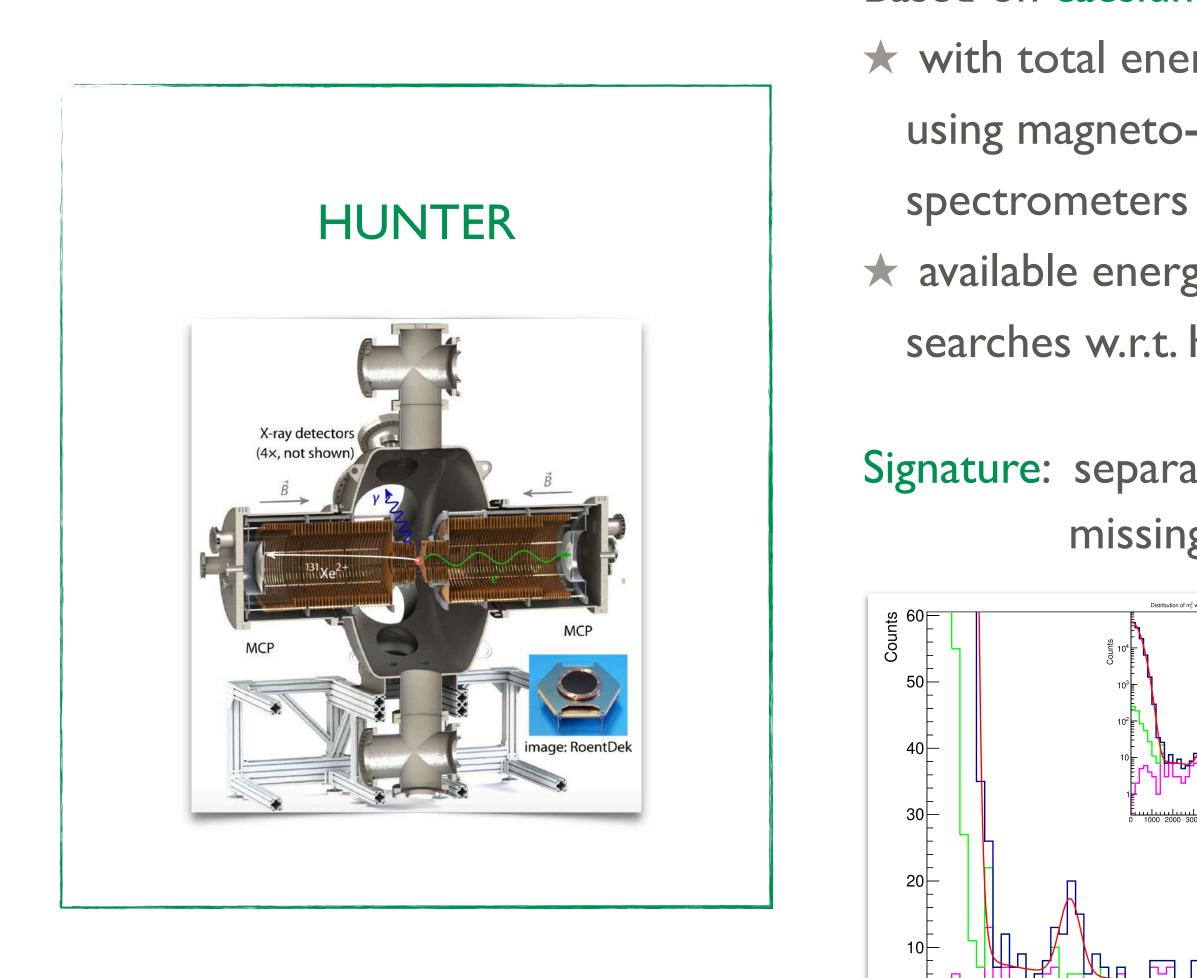
log(d

10<sup>-8</sup>



-- no sterile neutrino

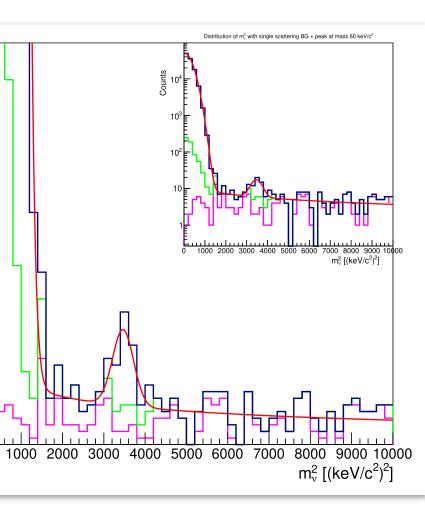
# SEARCHES IN TERRESTRIAL EXPERIMENTS



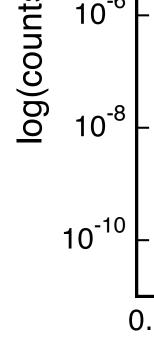
#### **Cristina Benso**

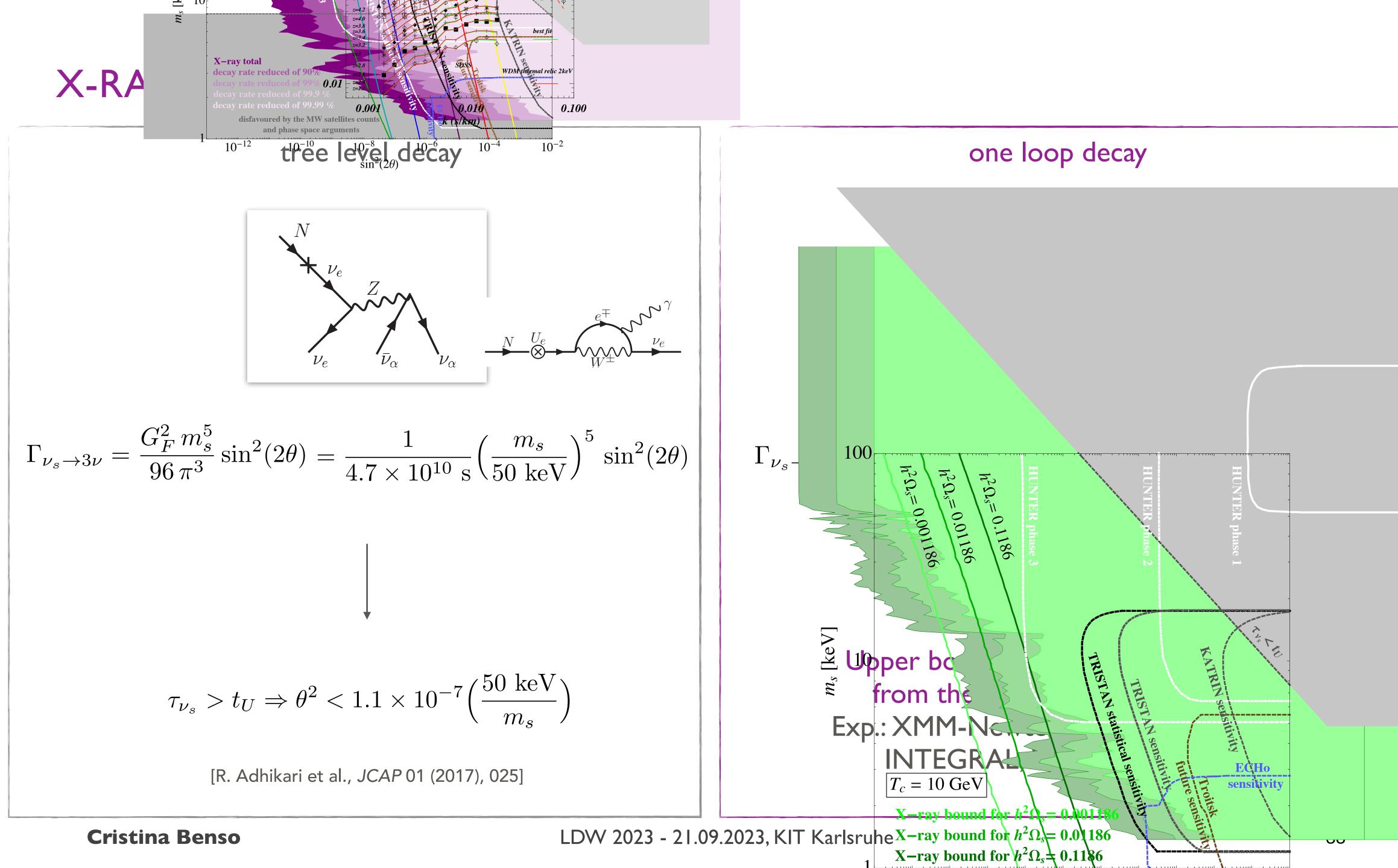
### Based on caesium electron (K-) capture:

- **★** with total energy-momentum reconstruction
  - using magneto-optical atom trap (MOT) and reaction ion momentum
- $\star$  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  $|U_{e4}^2|$

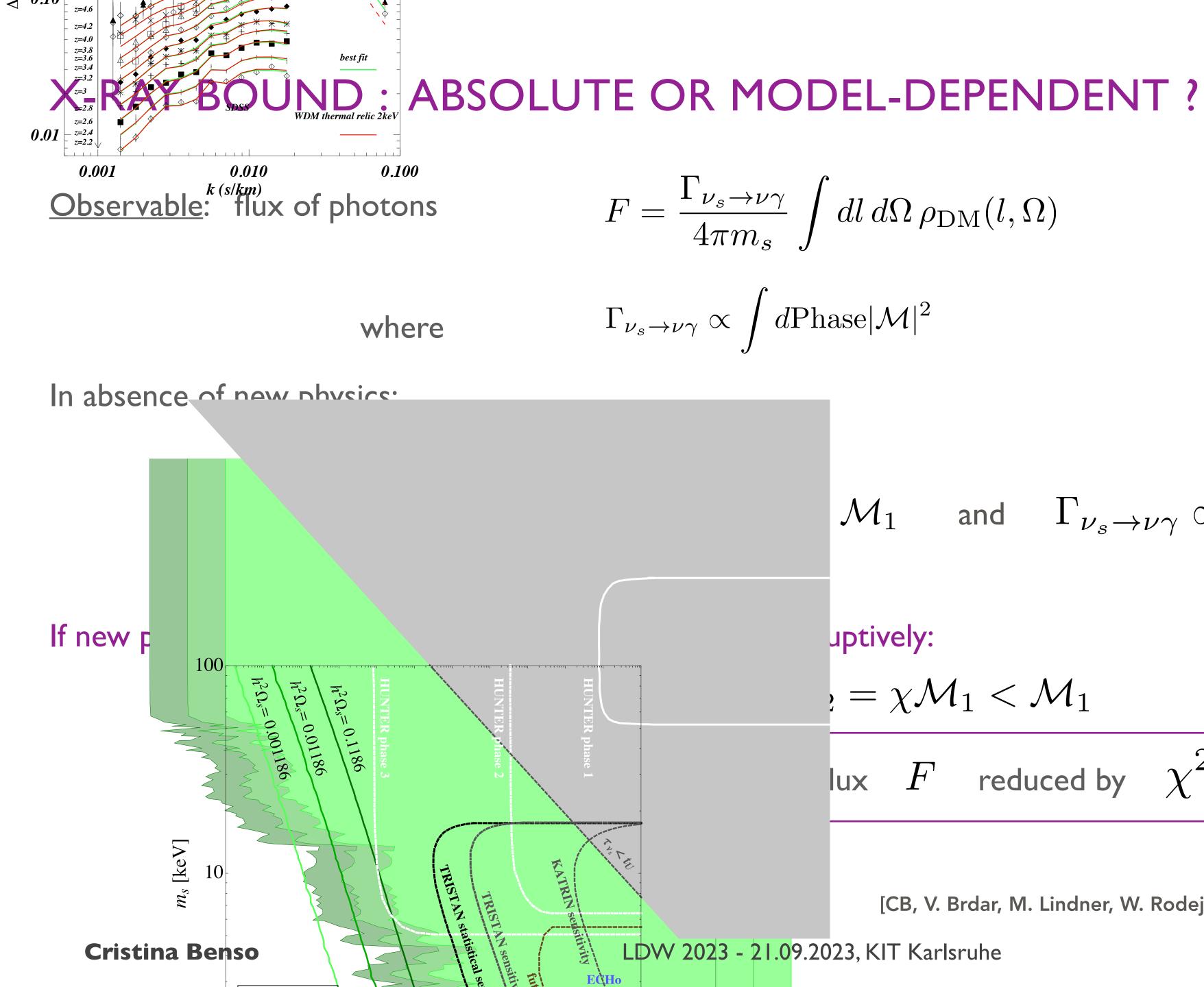


[C. J. Martoff et al., Quantum Sci. Technol. 6 (2021) 024008]

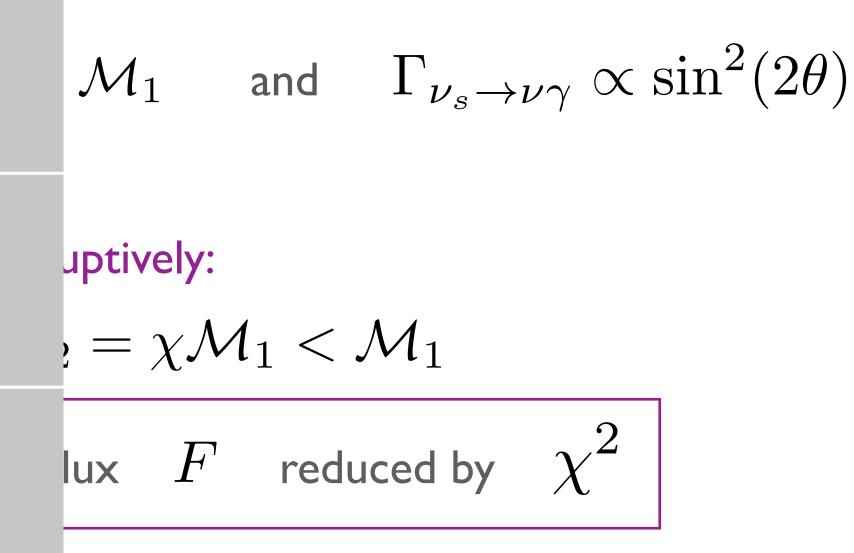




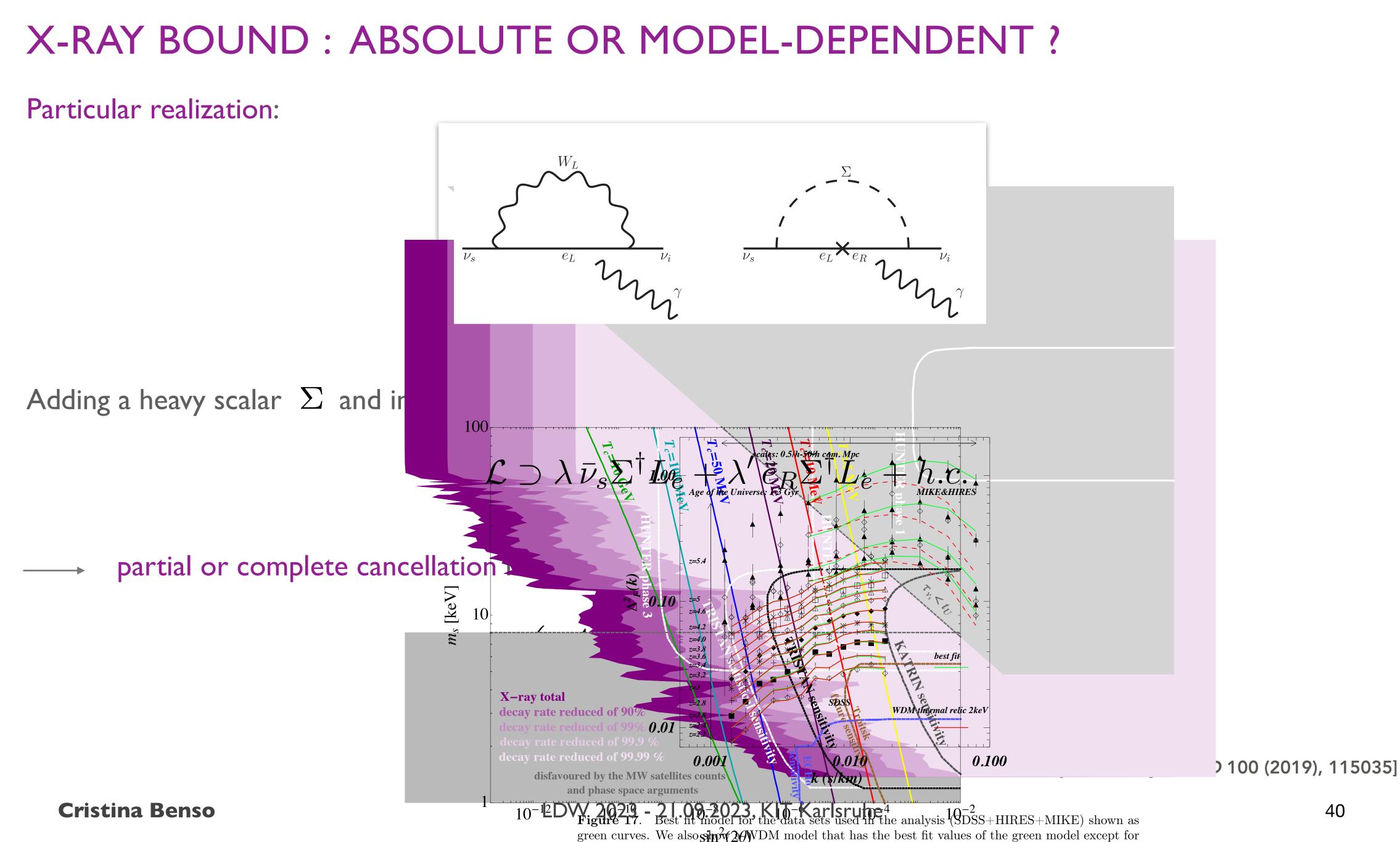




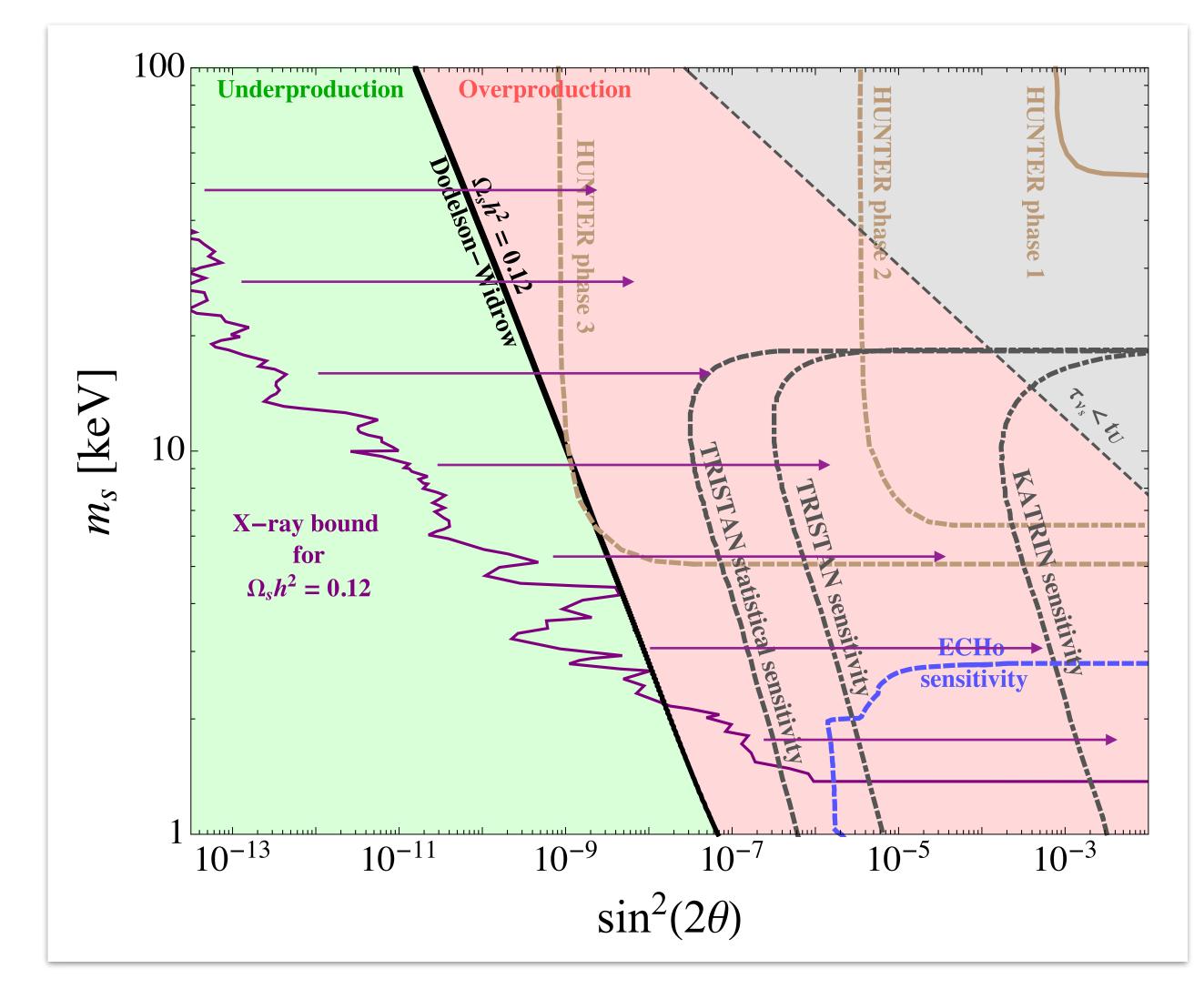
$$\frac{\nu\gamma}{ds}\int dl\,d\Omega\,\rho_{\rm DM}(l,\Omega)$$



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



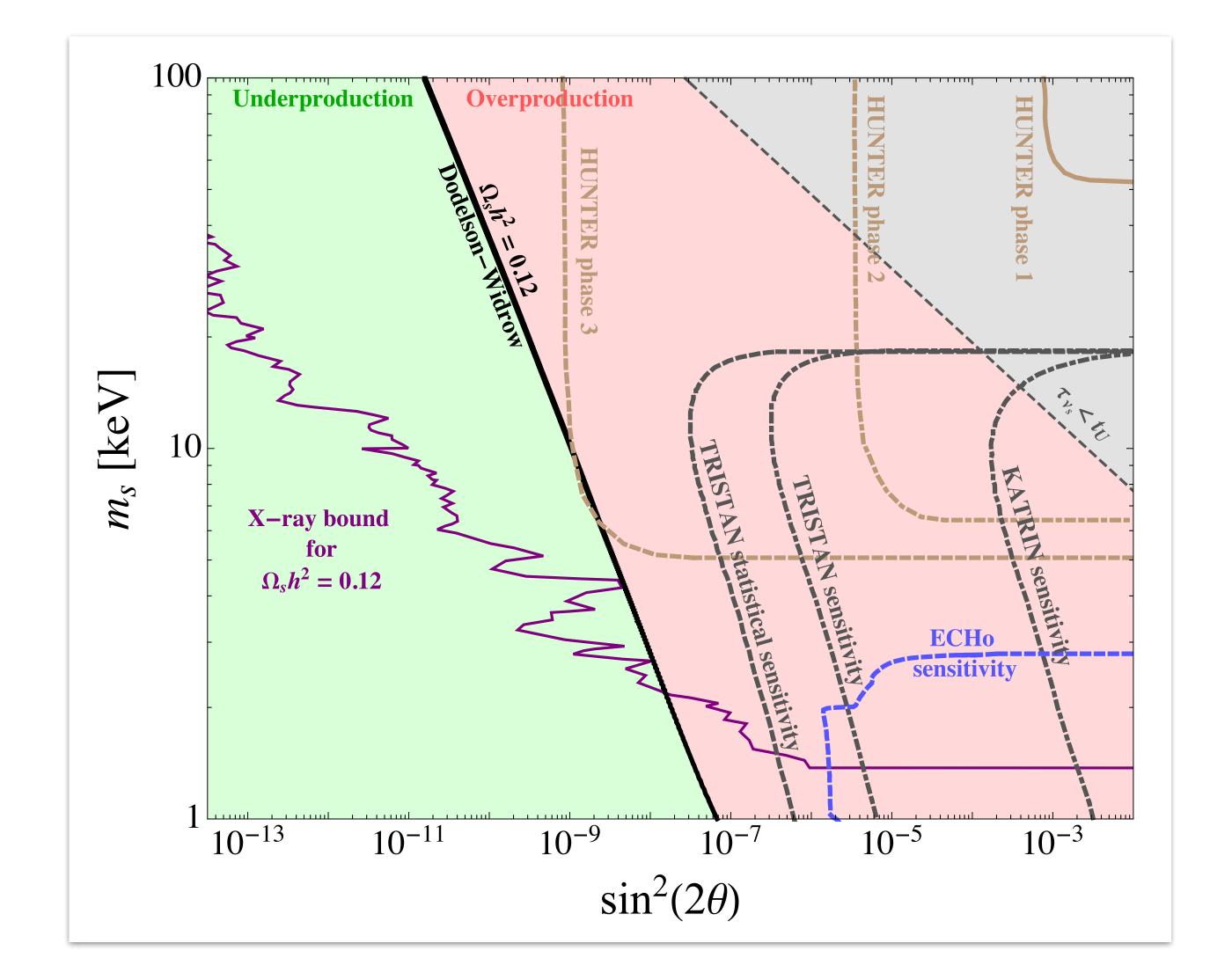
## X-RAY BOUND : ABSOLUTE OR MODEL-DEPENDENT ?



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

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## X-RAY BOUND : ABSOLUTE OR MODEL-DEPENDENT ?



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# X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

 $F = \frac{\Gamma_{\nu_s \to \nu\gamma}}{4\pi m_s}$ <u>Observable</u>: flux of photons

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:

 $ho_s < 
ho_{DM}$  corresponds to la

<u>Secondary advantage:</u>

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

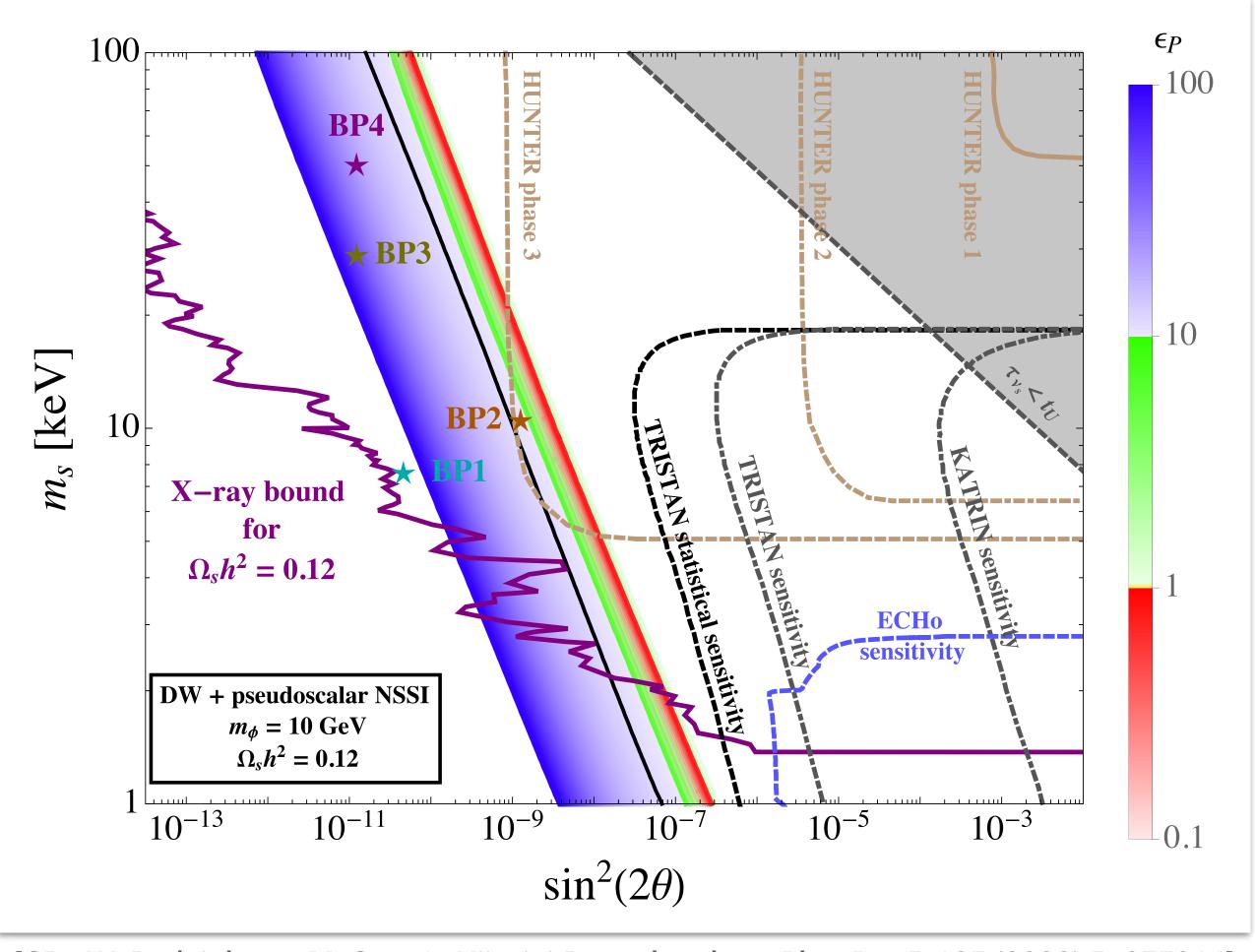
$$\frac{\nu\gamma}{ds} \int dl \, d\Omega \, \rho_{\rm DM}(l,\Omega)$$

arger	$\sin^2(2\theta)$	for the same flux	F
0			

[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

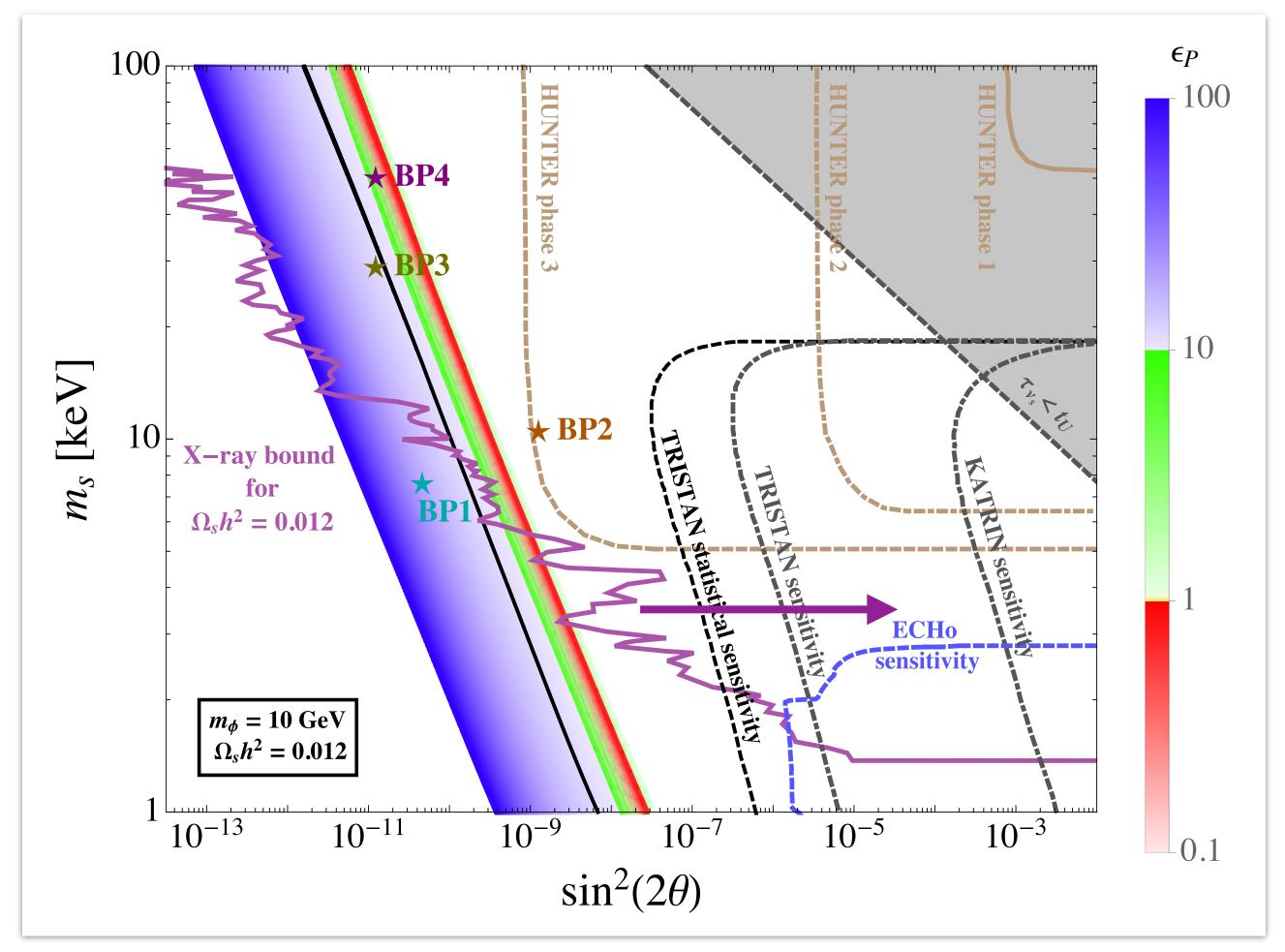


[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, Phys.Rev.D 105 (2022) 5, 055016

**Cristina Benso** 

# **NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS**

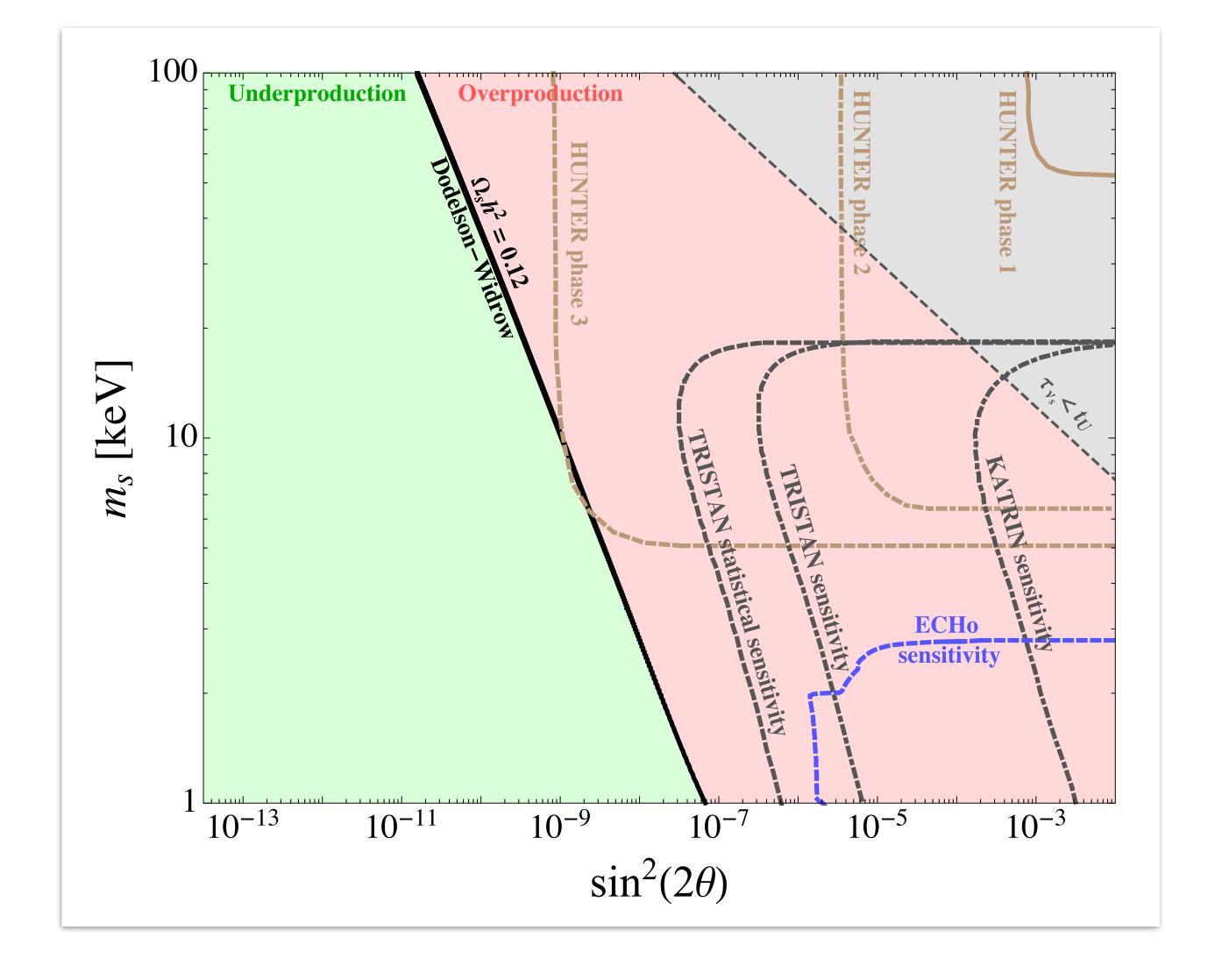
### Sterile neutrino parameter space : 10% DM constituted by sterile neutrinos



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

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# **DODELSON-WIDROW PRODUCTION - CHALLENGES FOR DETECTION**



### • X-ray bound : disfavors large values of heta and $m_s$

[CB, V. Brdar, M. Lindner, W. Rodejohann, PRD 100 (2019), 115035] [J. Barry, J. Heeck, W. Rodejohann, JHEP 07 (2014), 081]

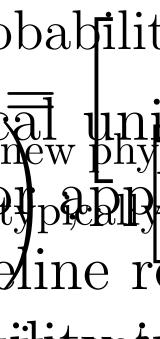
- Limit from DM abundance : rules out large values of  $\theta$
- Limits from structure formation : disfavor small values of  $m_s$

[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]



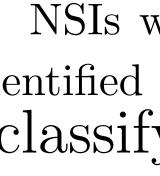
I **Overview** L/E which conventional matter effect [1].

mixing framework using Eq. (3.12). The two-neutrino transition probability in the second section of the second section s Given the wide interest in the worldwide neutining program, it is timely to reassess the 12 style of the work of the style related topics presented at a recent workshop." A self-interactions (NSSI) are a parameterization of new physics (Ed GeV) have the following forms for NC and CO NSIV paral fulfities, of short-base line r in the neutrino sector in the form of new interactions BSM involving neutrinos and other fermions. 1.1 Introduction to Non-Standard Neutric Interactions (nontonical units of short bage interaction) with the provident of the p NSIs provEffective de efficience de la faire de in the neutrino sector<sup>1</sup>. While the details of ynpice  $\hat{h}$  and  $\hat{h}$  and have the following forms for NC and CC NSI The transition pi  $\mathcal{L}_{CC} = -2\sqrt{2}G_F f_{\alpha\beta} \mathcal{L}_{\alpha\beta} \mathcal{L}$  $\mathcal{L}_{NC} = -2\sqrt{2}G_F f_{\alpha\beta} \mathcal{L}_{\alpha\beta} \mathcal{L}_{\alpha\beta} \mathcal{L}_{\alpha\beta} \mathcal{L}_{\alpha\beta} \mathcal{L}_{\beta} \mathcal{L}$  $f_{P,\alpha,\beta}$  with matter, the event rate in neutrino experiments is low and often at the relative to the weak scale. The sum is lower (matter fermions, Lyppically  $f, f' \in \{e, u\}$  $\mathcal{L}_{CC} = -2\sqrt{2}G_F \sum \frac{1}{2} \frac{1}$ Why are NSI interesting? f. P. a, B is not to be a which it is that it is a safe safe of the interaction. NSIs w where  $G_F$  is Fermi's constant and the  $\varepsilon$  terms quastify the size of the Welfeinteraction 1978 in his landmark paper that also identified relative to the weak scale. The sum is over matter welfeinter at the restrict of the size of the sum is over matter welfer of the effect  $\{1\}$   $\{e, u, d\}$   $\Delta m^2 U sing this inequality we classif$ and  $P \in \{P_L, P_R\}$  are the chirality projection operators. These projection operators can be referred in the phone in the state is the state in the phone in the phone in the state is the state in the state in the state is the state in the state is the state in the state is t also be reparameterized into vector and axial components of the interaction. NSIs were first introduced by Wolfenstein ipoly being the and neutrino oscillation experiments [2-4]. Since oscillation phenomenology is gener stinct from scattering phenomenology for the set of th Such a new linear after leade no in a to plate new physics models to both cases. Source-detector distance i and neutrino oscillation experiments [2-4]. Shorts bis of include the second second states in the denomination of the denomina way to relate the specific models to both cases. here the transmission is can be detected for  $\Delta m^2 L/4E$ 











## **NEUTRINO NON-STANDARD INTERACTIONS - WHY NOT ?**

- (e, u, d).
  - See [P. Coloma et al., JHEP 02 (2020) 023, JHEP 12 (2020) 071 (addendum), 1911.09109]

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

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

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• Neutrino oscillation and scattering experiments give rather tight constraints on neutrino NSI with matter fields

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