

INTRODUCTION - STERILE NEUTRINO DARK MATTER

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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)
- velocities compatible with large scale structures

depending on mixing with active neutrinos: stable over time scales comparable with t_U

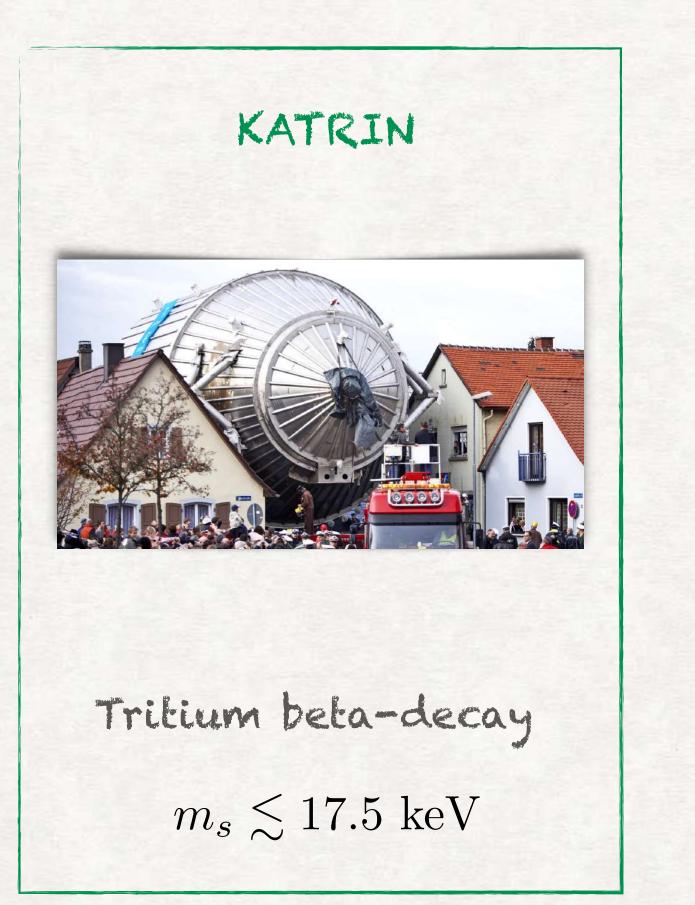
depending on the production mechanism: produced in the early universe with

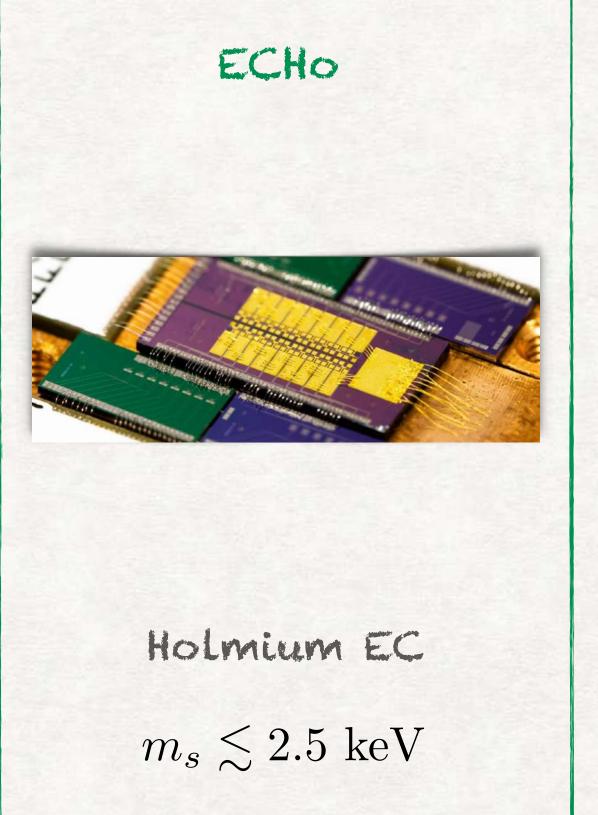


- in the domain of direct detection
- \bullet rely on large mixing of $\nu_s \leftrightarrow \nu_e$ or $\overline{\nu}_s \leftrightarrow \overline{\nu}_e$



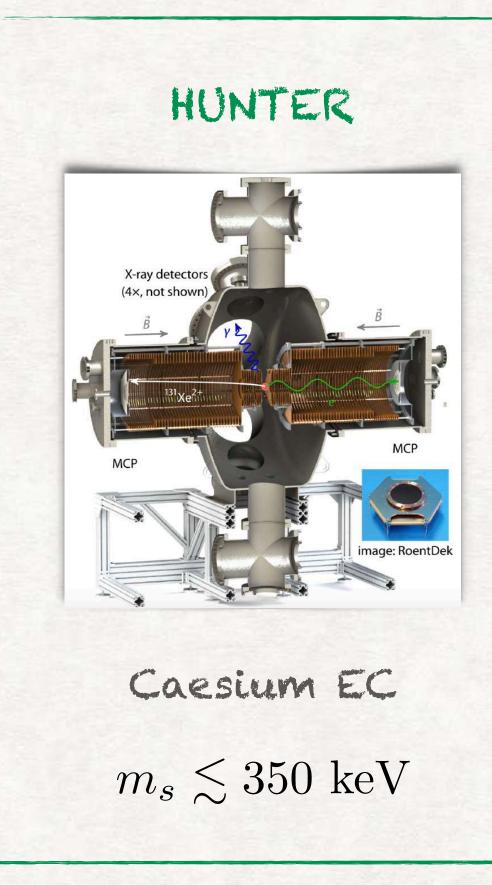
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Assumption: $\nu_s \leftrightarrow \nu_e$ and $\overline{\nu}_s \leftrightarrow \overline{\nu}_e$ mixing

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 $\propto \sin^2(2 heta_M)$ 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

$$\frac{\partial}{\partial t}f_s(p,t) - Hp\frac{\partial}{\partial p}f_s(p,t)$$

where

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

$$\langle P_m(\nu_e \to \nu_s; p, t) \rangle = \sin^2(2\theta_M) \sin^2(2\theta_M)$$

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

$$\frac{vt}{L}\right) \approx \frac{1}{2} \sin^2(2\theta_M)$$



In the plasma, the mixing angle is

 $\sin^2\left(2\theta_M\right) = \frac{1}{\left(\frac{m_s^2}{2p}\right)^2}\sin^2(2\theta)$

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



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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 $V_T(p) = \pm \sqrt{2}G_F \frac{2\zeta(3)T^3}{\pi^2} \frac{\eta}{2}$

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$$\frac{\partial B}{4} - \frac{8\sqrt{2}G_F p}{3m_Z^2}(\rho_{\nu_e} + \rho_{\bar{\nu}_e}) - \frac{8\sqrt{2}G_F p}{3m_W^2}(\rho_{e^-} + \rho_{e^+})$$

9



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

 $n(T) = \frac{1}{(2\pi)^2}$ sterile neutrino number density

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

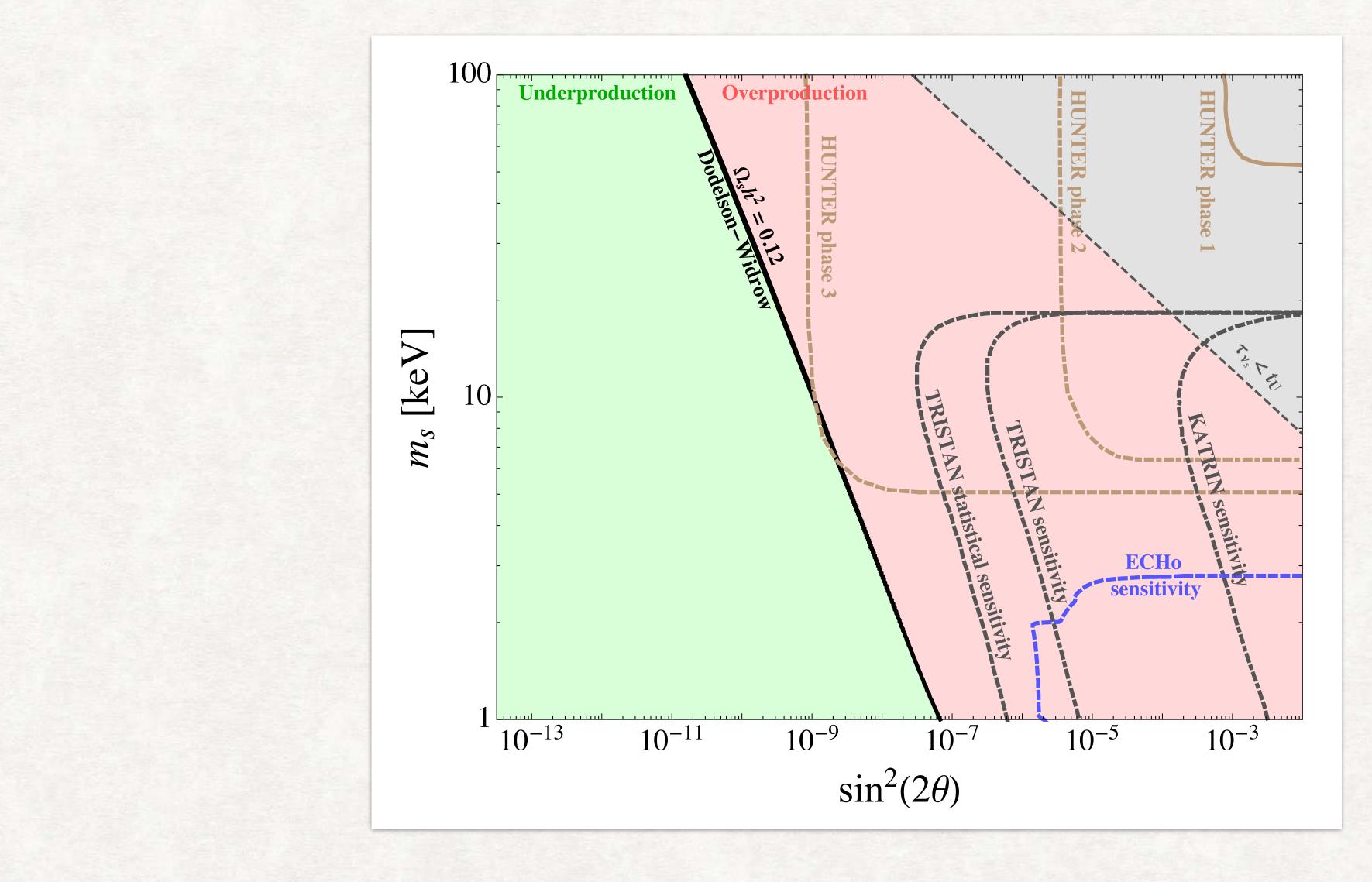
$$h^2 \Omega_s = \frac{s_0 m_s}{\rho_c / h^2} \frac{1}{g_{*s}} \left(\frac{45}{4\pi^4}\right) \int_0^\infty dr \, r^2 \left[f_{\nu_s}(r) + f_{\overline{\nu}_s}(r)\right]$$

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$$\frac{g}{(\pi)^3} \int_{-\infty}^{+\infty} d^3 p f(p,T)$$



DODELSON-WIDROW PRODUCTION - CHALLENGE 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.



re ϵ indicates the NSS [*isGrengto* compared (*to* the standard we $\sqrt{2}$ ν_e m_{ϕ}^2

The set temperature dependant terms in thermal potential, we have to interaction finition. Neutrino non-standard set f-interaction finition. Neutrino non-standard set f-interaction finition. Neutrino non-standard set f-interaction finition. Neutrino sector in the form of new interactors $\mathcal{L}_{j}^{\text{can}} = -\frac{G_{F}}{\sqrt{2}} (\epsilon_{j,\nu}) \left((\bar{\nu}_{e}\mathcal{O}_{j}\nu_{e}) (\bar{\nu}_{e}\mathcal{O}_{j}'\nu_{e}) - \frac{1}{m^{2}} (\bar{\nu}_{e}\mathcal{O}_{j}\nu_{e}) \Box (\bar{\nu}_{e}\mathcal{O}_{j}'\nu_{e}) \right)$ entified the C for detailed calculation

 $\operatorname{RENT}_{\operatorname{3m}_{\phi}}^{16\sqrt{2}G_{F}} \left(\epsilon_{A,\nu_{e}}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu}\left\langle E_{\nu}\right\rangle + n_{\bar{\nu}}\left\langle E_{\bar{\nu}}\right\rangle\right] = -\frac{14\sqrt{2}\pi^{2}G_{F}}{45m_{\phi}^{2}} \left(\epsilon_{A,\nu_{e}}\right)^{eeee} \cdot \omega T^{4} \quad (6.3)$

Bependostalar NSI(C.3.3)

$$-\frac{8\sqrt{2}G_F}{3m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu} \left\langle E_{\nu} \right\rangle + n_{\bar{\nu}} \left\langle E_{\bar{\nu}} \right\rangle\right] = -\frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eee} \left(1.3\right)$$

the Wolfenrgy, and the For useful **Cristina Benso**

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

 ν_a u_a u_a ν_a

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



re e indicates the NSS [istrengito and marged (tothe standard we

1: (12) EUTRINO NON-STANDARD SELF to get temperature dependant terms in thermal potential, we have to in term in MSNSIsigrangian (which)(with the product of the potential) dependent self-interaction finition: Neutrino non-standard self-interaction of the neutrino sector in the form of new interactor $\in \{e, u, d\}$ the neutrino sector in the form of new interactor perators $\mathcal{L}_{j}^{can} = -\frac{G_{F}}{\sqrt{2}} (\epsilon_{j,\nu}) \left((\bar{\nu}_{e}\mathcal{O}_{j}\nu_{e}) (\bar{\nu}_{e}\mathcal{O}_{j}'\nu_{e}) - \frac{1}{m^{2}} (\bar{\nu}_{e}\mathcal{O}_{j}\nu_{e}) \Box (\bar{\nu}_{e}\mathcal{O}_{j}'\nu_{e}) \right)$ NSIs were description valid for heavy mediator entified the C for detailed calculation

 $\mathbb{R}ENT_{3}h_{\phi}h_{\phi}(\epsilon_{A}\nu_{e}) \mathbb{N}SSP(\mu_{e}\epsilon_{e}sttn_{\bar{g}}(E_{\bar{\nu}})] = -\frac{14\sqrt{2\pi}GF}{45m_{\phi}^{2}}(\epsilon_{A,\nu_{e}})^{eeee} \cdot \omega T^{4} \quad (6.3)$

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re ϵ indicates the NSS [\bar{v}_e ν_e $\sqrt{2}$ ν_e ν_e $m_{\phi}^{F\epsilon}$ (\bar{v}_e $m_{\phi}^{F\epsilon}$), weak interaction interaction in the state of the

 $\begin{array}{c} (12) \\ ($ $\in \{e, u, d\}$ the neutrino sector in the form of new interactions beyond the SM involving only neutrinos. $perators_{L_{j}}^{cam} = -\frac{G_{F}}{\sqrt{2}} (\epsilon_{j,\nu}) \left((\bar{\nu}_{e}\mathcal{O}_{j}\nu_{e}) (\bar{\nu}_{e}\mathcal{O}_{j}'\nu_{e}) - \frac{1}{m^{2}} (\bar{\nu}_{e}\mathcal{O}_{j}\nu_{e}) \Box (\bar{\nu}_{e}\mathcal{O}_{j}'\nu_{e}) \right)$ (6.1) NSIs were the description valid for heavy mediators entified the C for detailed calculation

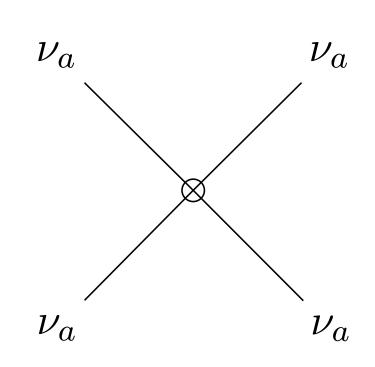
 $\underbrace{\operatorname{escalar}}_{\substack{NSSI = 1 \\ NSSI = 1 \\ NSSI = 1 \\ NSSI = 1 \\ NSSI = 1 \\ \sqrt{2} \\ \sqrt{2}$ ught of in ^a $\mathcal{O}_j = \{\mathbb{I}, \gamma^\mu, i\gamma^5, \gamma^\mu\gamma^5, \sigma^{\mu
u}\}$ eAmilatector NSI(C.3.2)

to mediators $16\sqrt{2G_F}$ $(\epsilon_{A,\nu_e})^{eeee}$ $(\epsilon_{A,\nu_e})^{eeee}$ $(\epsilon_{A,\nu_e})^{eeee} \cdot \omega T^4$ (6.3) $3m_{\phi}^{(\epsilon_{A,\nu_e})}$ $(\epsilon_{A,\nu_e})^{eeee} \cdot \omega T^4$ (6.3)

r AspendostalareNSE(CE. ha) physics to come from the neutrino sector $= -\frac{8\sqrt{2}G_F}{3\tilde{m}_{\phi}^2} (4Re_e)^{eeee} del [nd Escribed E_{\bar{\nu}}] = \frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} (4P, g)^{eeee} (4A) turally include NSSI$ (1.3) NSSI could have significant impact on physics of the early universe (Hubble tension etc.) the Wolfen-parameter space very poorly constrained and investigated

rgy, and the For useful



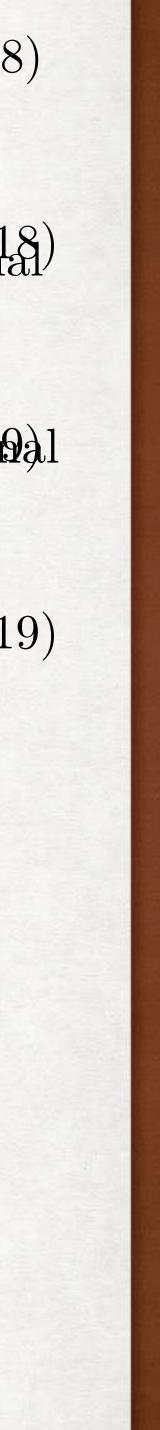


(See [arXiv: 2203.01955 [hep-ph]] for more information)



The strength of types of meutinilar experiments of the fight fight of the strength of types of meutinilar experiments of the fight of types of meutinilar experiments of the fight of types of meutinilar experiments of the fight of types of the strength of types $\frac{\nabla Z}{\nabla H} = \frac{\nabla Z}{\nabla F} =$ $\frac{\Delta m^2 \dot{L}}{\mu_e \mathcal{O}_j \nu_e} \gtrsim 0.1 - 1. \qquad (3.14)$ poments participate that radiation densities where $-\frac{\Delta m^2 \dot{L}}{\sqrt{2}} \approx 0.1 - 1.$ $\mathcal{O}_j = \{\mathbb{I}, i\gamma^5, \gamma^\mu \gamma^5\}$ this inequality as the ratio which is the heat of Δm^2 to which an experiment is sensitive: ascillation potenseactering experiments **Masseline** (SBile) experiments. In these experiments $L/E \leq 1 \,\mathrm{eV}^{-2}$. Since the Street event and the event rate is not too large, the event rate is There are two types of SBL experiments: reactor $\bar{\nu}_e$ Lisappending experiments with $L \sim 10 \,\mathrm{m}$, $E \sim 1 \,\mathrm{MeV}$ as, for example, Bugey [64]; Schereviding a new flavori dependent ith $L \leq 1 \,\mathrm{km}$ $E \geq 1 \,\mathrm{GeV}$ as for example CDHS [71]

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Interactions $(Denton)\mathcal{L}_{NSS} = \mathcal{COS}\theta(\bar{\nu}\mathcal{O}\nu\mathcal{S}\mathcal{D}\mathcal{O}\mathcal{V})$ $\bar{\nu} \mathcal{D}_{l}$ A remework of the start of the The manual for the start of the ilidination of a hand the second courts at the start of the second of th SSL paparobiability in Eq. (3.13) is useful in Erfeine et and here in here with the set of the set rm of NSSI Lagrangian:<math>round f f Repetere, flavor transitions are observable<math>round f Repetere observableantigyntionsizterioigallar dette interactione and womentum dep $\Delta m^2 L$ atom Thesetppointion operators, can acconsist states of the incomplete the radiation of this incomplete the incomplete the set of the theory of the incomplete the set of the theory of the set of the s this inequality we delassify neutrino oscillation e which iesterblishtesing every enget of Δm^2 to which an ascillation when seached any experiments ht case of scattering the denominator relatively high and oscillations $p_{f,tot}(p)$ an be detected relatively high and oscillations T(p) an be detected remembers the scattering the denominators T(p) and $p_{T,tot}(p)$ and $p_{T,tot}(p)$ sensitively to detect the sensitive tenominators of the scattering tenominators of tenominators o Gisappendent is only benshire to include the final solution of the second seco



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]

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

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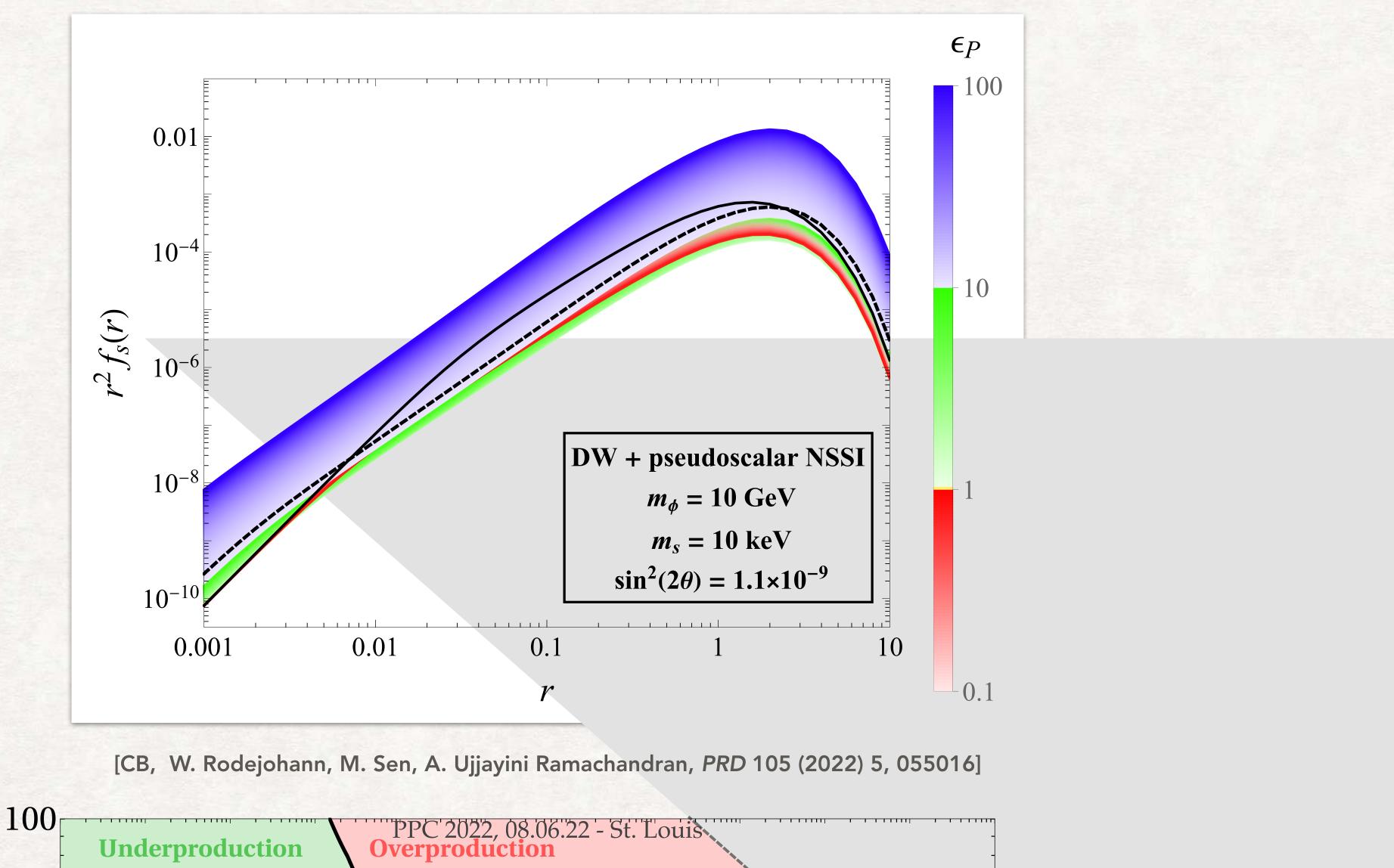
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NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

Sterile neutrino distribution function





NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

Sterile neutrino production evolution of the free streaming length of sterile neu-

[GeV 10⁻⁶

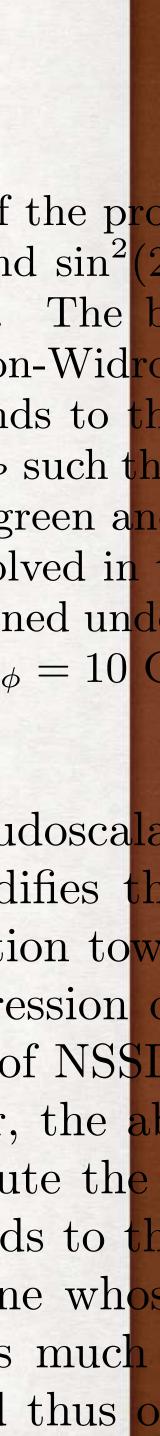
Unless they are very light. On the other hand, if we consider $BW1_{ptehatscide N551}$ less the famous observed X-ray line at 3.55 keV [37638], we see that large NSSI would be needed to produce a such sterile neutrinos large enough to constitute a non negligible percentage of the Universe's DM content. However, such large NSSI would put sterile neutrinos Gwith such features in conflict with constraints coming from structure formation: they would have been produced with too high velocities mod-ifying large structure a that we observe today.

DD9 is norticularly interesting. It represents a case in

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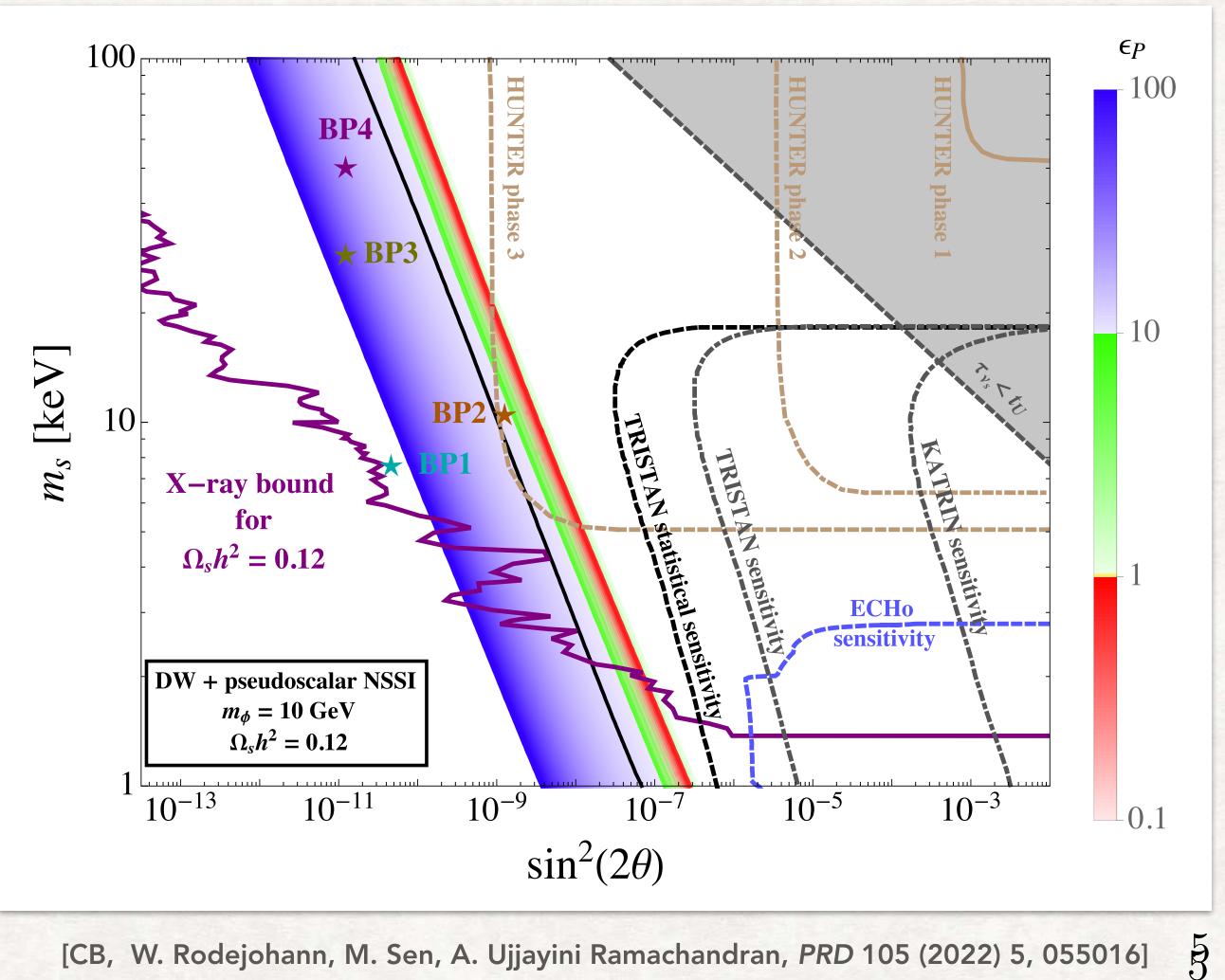
FIG. 5. Variation of the free streaming length of sterile neutrino dark matter determined by the increasing strength of NSSI for different values of m_s and $\sin^2(2\theta)$. Each color refers to a benchmark point given in FIGS. 2 and 3. Each line type corresponds to a different value of the NSSI mediator mass. Blackosquares pinpoint to values of ϵ_P for which the condition $\Omega_s h^2 = \Omega_{\rm DM} h^2 = 0.12$ is satisfied. Black triangles identify values of ϵ_P such that only the 10% of the DM abundance is constituted by sterile neutrinos in the "cocktail DM" scenario. FIG. 6. Evolution of the prowith $m_s = 10$ keV and $\sin^2(22)$ with temperature. The k the standard Dodelson-Widro dashed line corresponds to th doscalar NSSI with ϵ_P such th ferent shades of red, green an strength of NSSI involved in All the lines are obtained und mediator has mass $m_{\phi} = 10$ (

presence of the pseudoscala GeV) mediator modifies the peak of the production town shown by the progression of larger the strength of NSSI ature. In particular, the all sufficient to constitute the Universe, corresponds to the the black dashed line whom This temperature is much NSSI mediator, and thus o



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]

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

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- They can have been produced in the early universe via oscillation and collisions through *** Dodelson-Widrow mechanism.

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This vanilla scenario is hardly detectable in terrestrial experiments in the near future.



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Active neutrino non-standard self-interactions (NSSI) are well motivated extension of the SM.



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



- * 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.

- matter in the early universe.
- * The parameter space region in which $\Omega_{\mathrm{DM}}=\Omega_s$ is enlarged by such NSSI

This vanilla scenario is hardly detectable in terrestrial experiments in the near future.

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Scalar, pseudoscalar and axial-vector NSSI modify the production of sterile neutrino dark

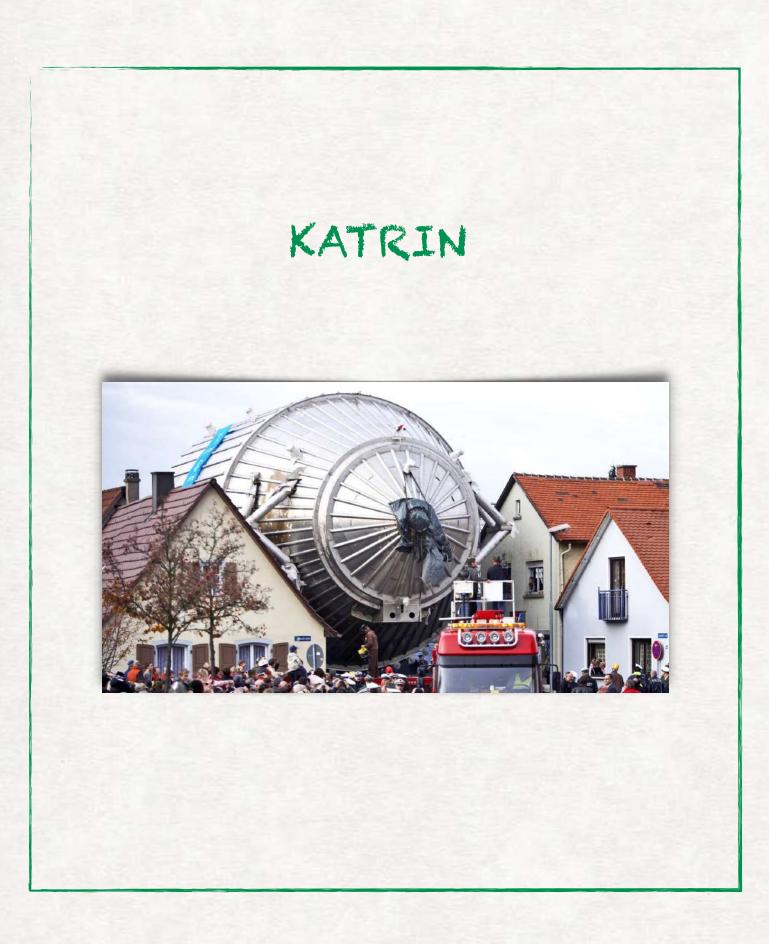
and they enhance the possibility to detect sterile neutrino dark matter in HUNTER phase 3.



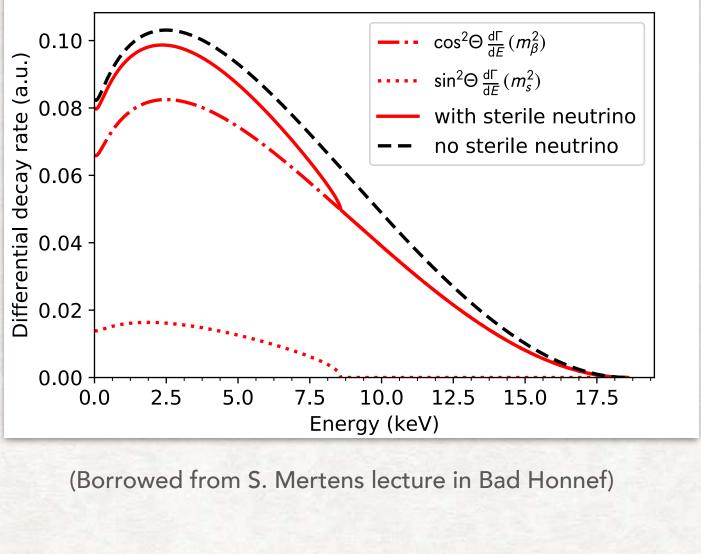


BACKUP





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



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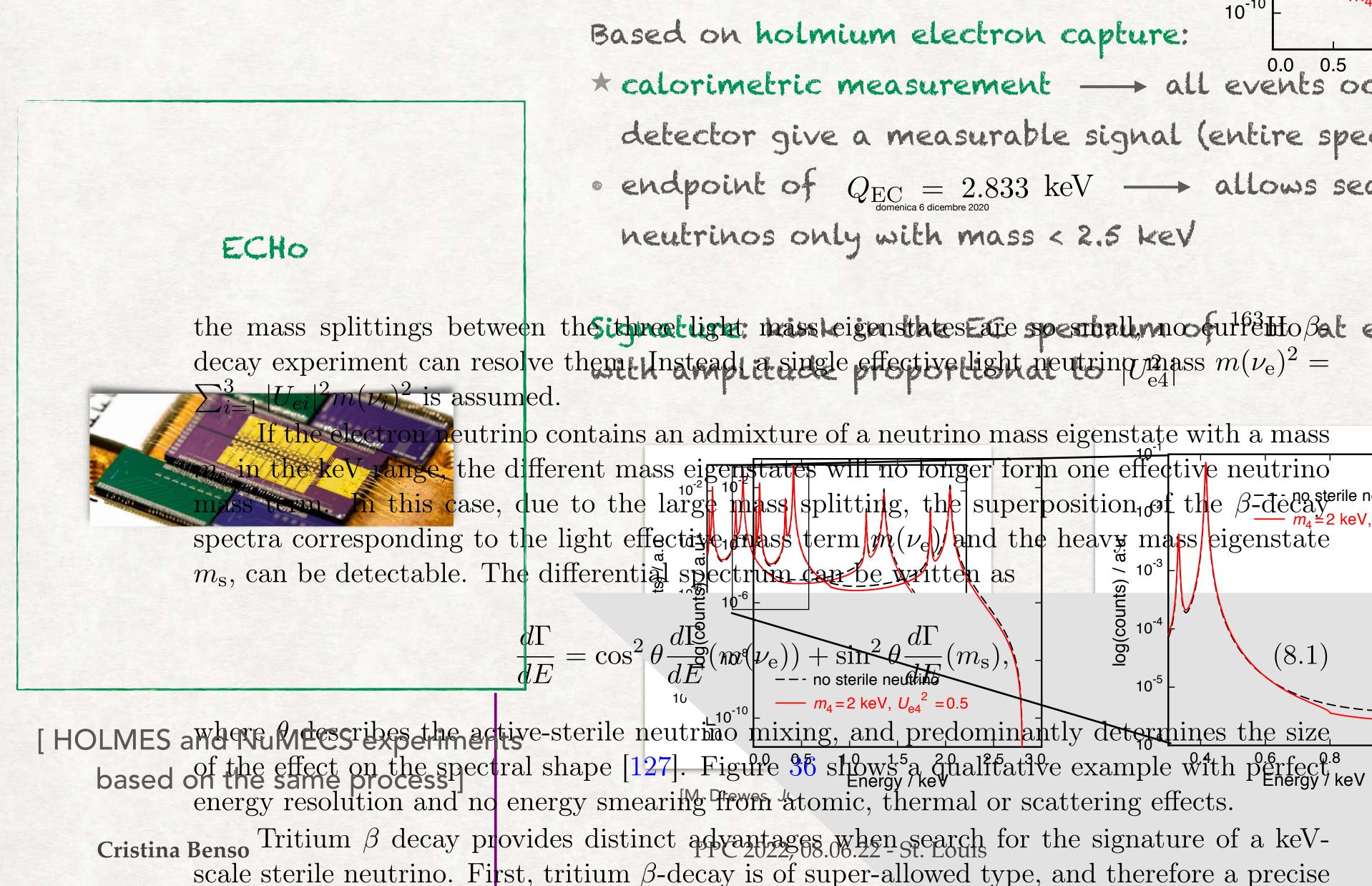
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Based on tritium beta-decay: * short half-life of 12.3 yrs --- high decay rate \star Endpoint of $E_0 = 18.6 \,\mathrm{keV}$, \longrightarrow allows search of sterile neutrinos with mass up to several kev

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

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





 $-m_4 = 2 \text{ keV}, U_{e4}^2 = 0.5$ 10⁻¹⁰ Based on holmium electron capture: ★ calorimetric measurement ----- all events occention Revin the detector give a measurable signal (entire spectrum "for free") • endpoint of $Q_{\rm EC} = 2.833$ keV \longrightarrow allows search of sterile neutrinos only with mass < 2.5 keV

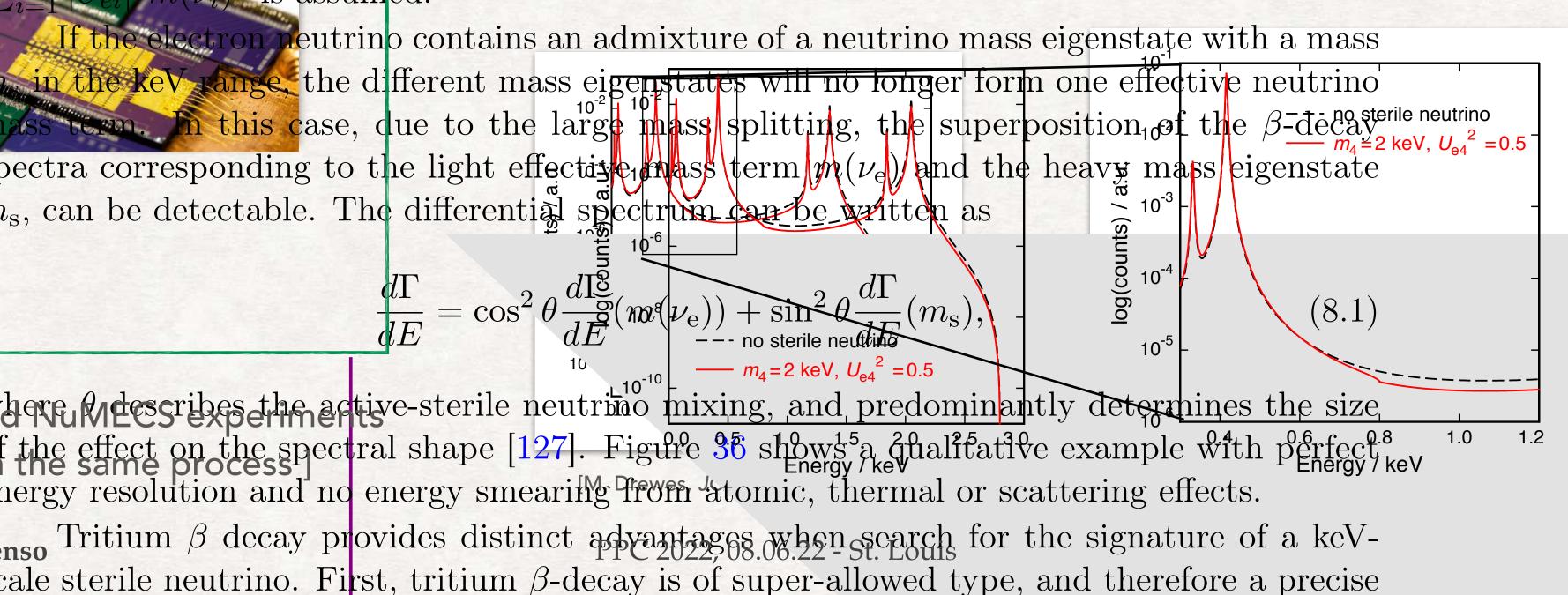
log(count:

10⁻⁶

10⁻⁸

- no sterile neutrino

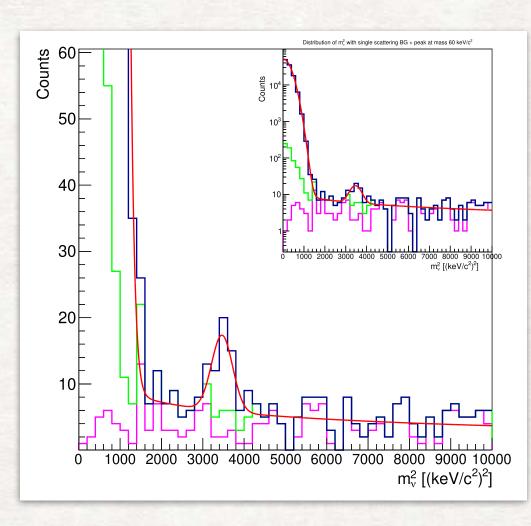
the mass splittings between the ithree light: mass leigenstates for spesimally model of the light energy $Q_{\rm EC} - m_4$ decay experiment can resolve them. Instead, a single effective light neutrin $U_{\rm e4}^{\rm a}$ as $m(\nu_{\rm e})^2 = \sum_{i=1}^{3} |W_{\rm e4}|^2$







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

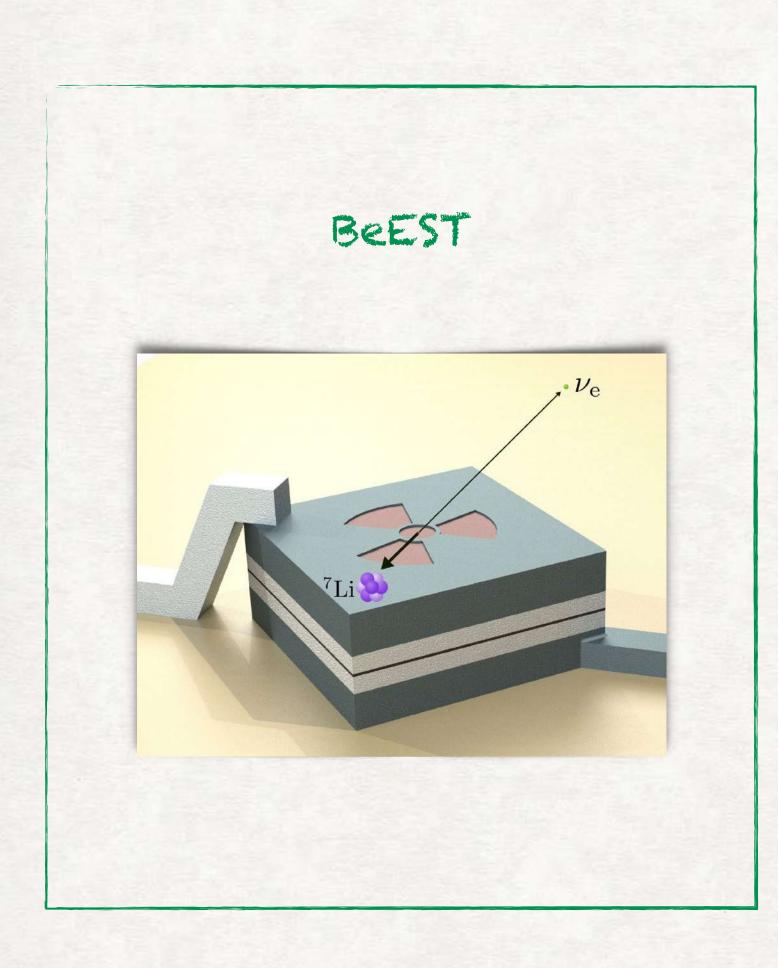


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- Based on caesium electron (K-) capture:
- * with total energy-momentum reconstruction using magneto-optical atom trap (MOT) and reaction ion momentum spectrometers
- \star available energy of the reaction $Q = 352 \,\mathrm{keV}$ allows complementary searches w.r.t. KATRIN & ECHO

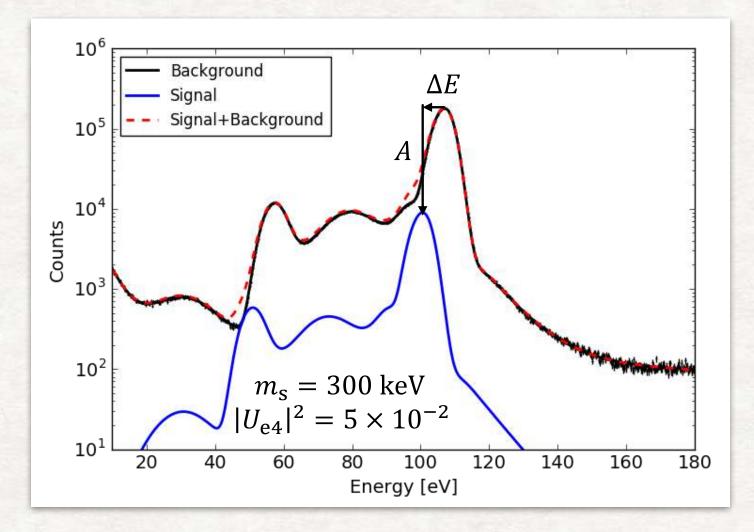
[C. J. Martoff et al, Quantum Sci. Technol. 6 (2021) 024008]





Based on beryllium electron capture: * with decay momentum reconstruction using superconducting tunnel junction (STJ) quantum sensing technology \star available energy of the reaction Q = 862 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



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

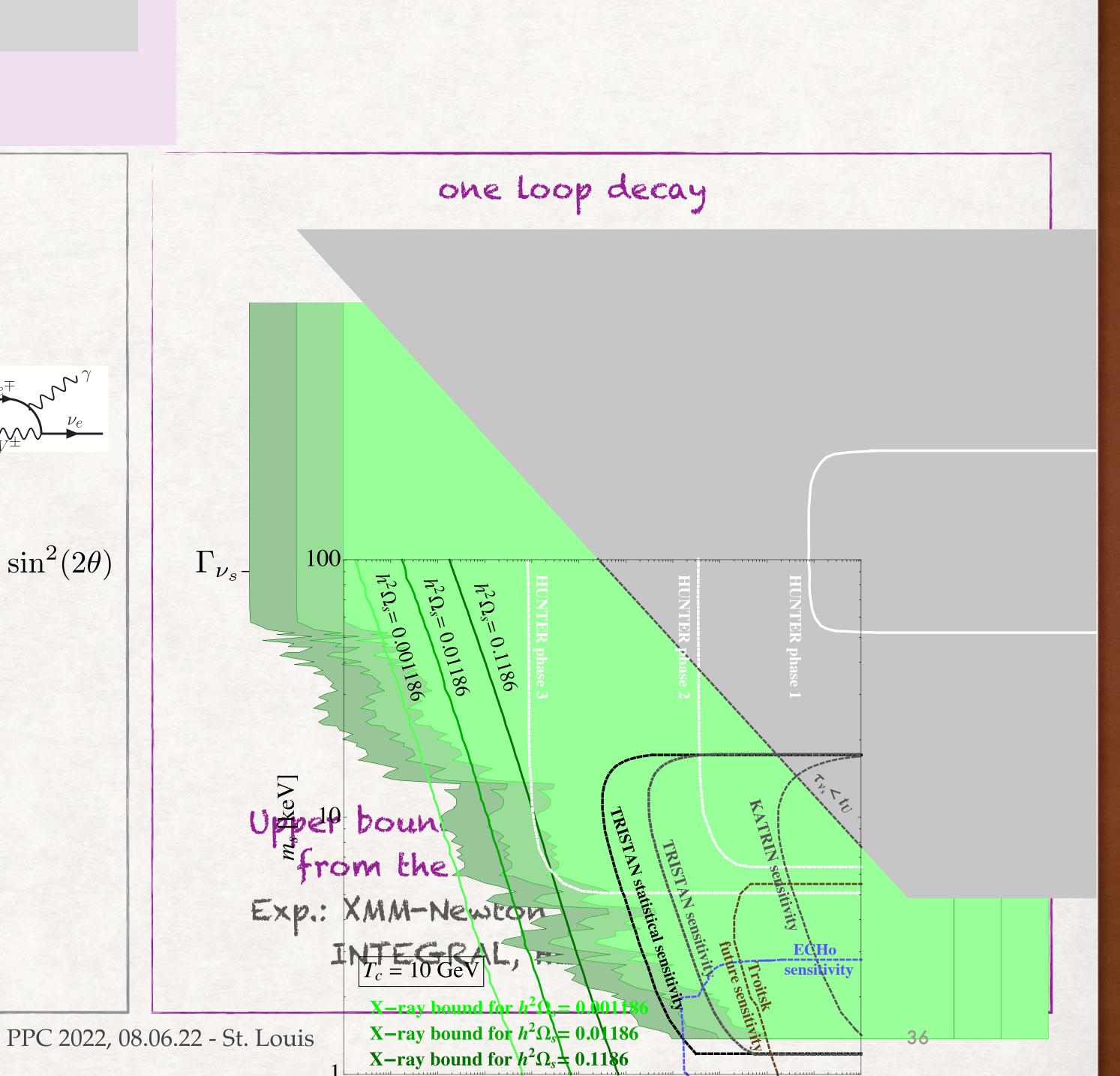


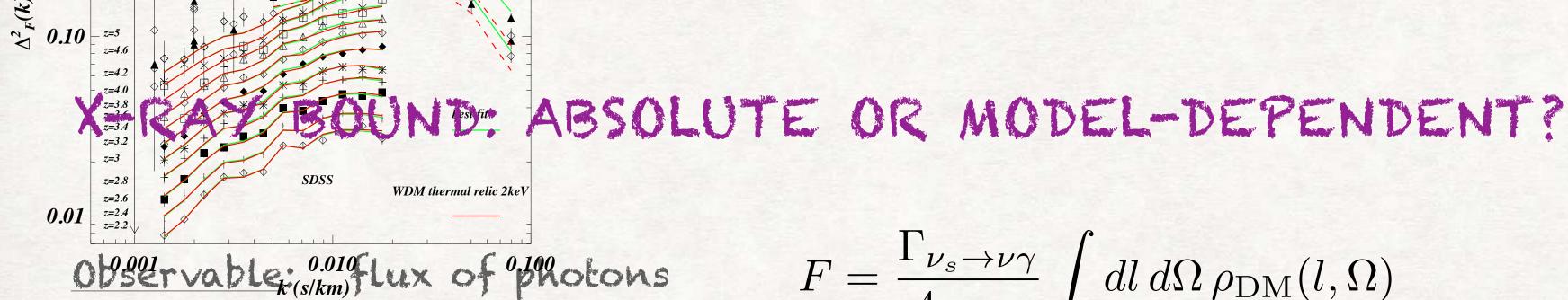
$$\begin{array}{c} \mathbf{x}_{-\mathbf{R}} \\ \mathbf{x}_{-\mathbf{R}} \\$$

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

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

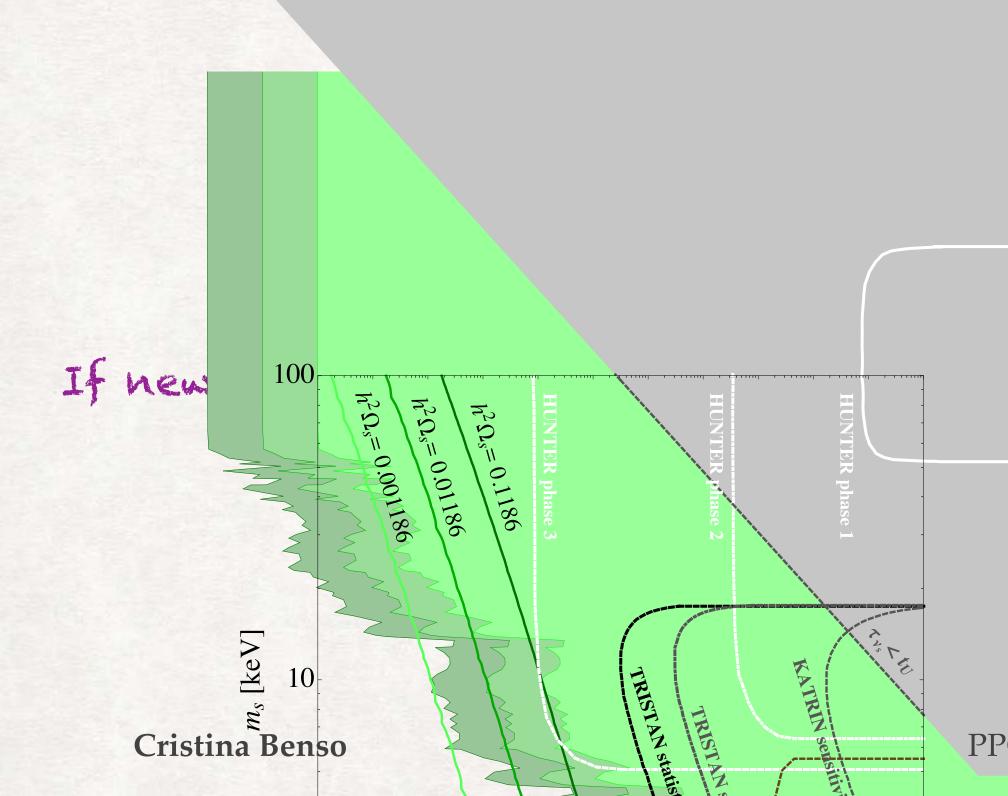
[Adhikari et al., JCAP 01 (2017), 025]





where

In absence of new physics:



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

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

 \mathcal{M}_1 and $\Gamma_{\nu_s
ightarrow
u_\gamma} \propto \sin^2(2\theta_M)$

rferes disruptively:

 $q = \chi \mathcal{M}_1 < \mathcal{M}_1$

2 Flux F reduced by χ^2



X-RAY BOUND: ABSOLUTE OR MODEL-DEPENDENT?

100

10

 $\sin \theta_{\rm [kev]}$

 e_L

Particular realization:

Adding a heavy scalar Σ a

partial or complete can

must not reach the But: Σ in the early universe

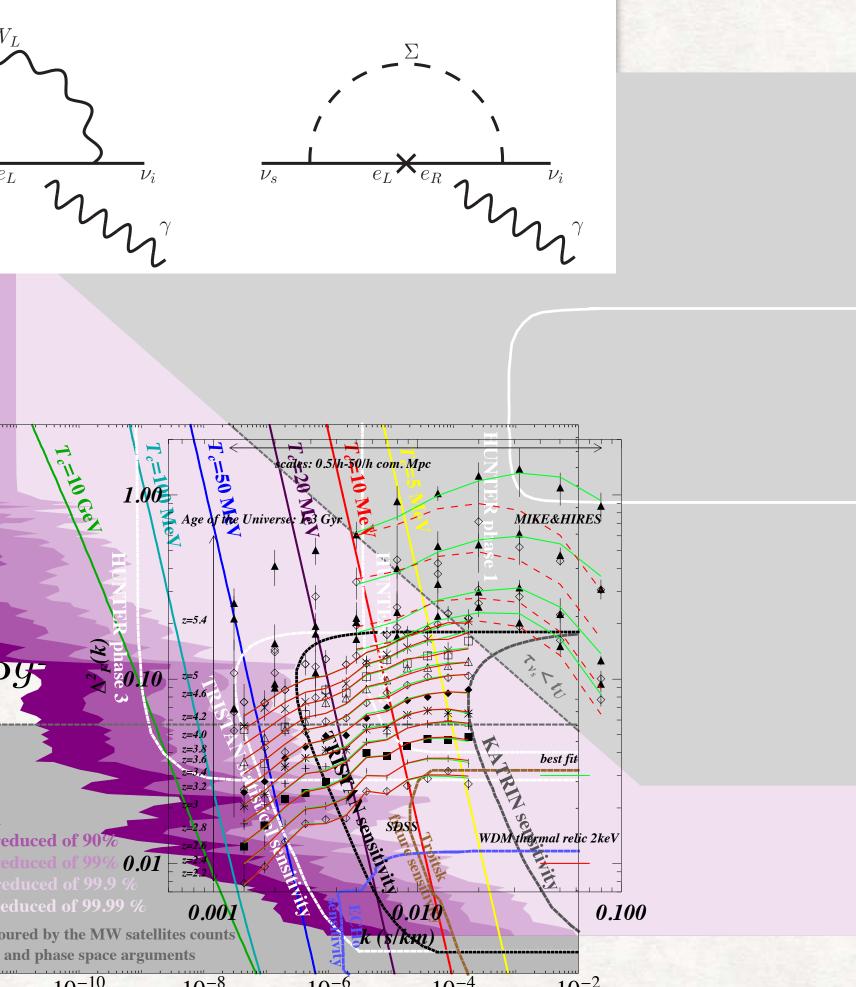
X–ray total decay rate reduced of disfavoured by the MW satellites counts

JG

 10^{-12}

Figure 17. Best fit model for the data sets used in the analysis 10^{-4} analysis 10^{-2} HIRES+MIKE) shown as green curves. We also since 20 WDM model that has the best fit values of the green model except for the WDM (thermal relic) mass of 2 keV (red dashed curves). These data span about two orders of Imagaitud 22 cale and the 22 iod St-3. LOVELST the Big Bang. From this plot is is apparent how the WDM model does not fit the data at small scales and high redshift.

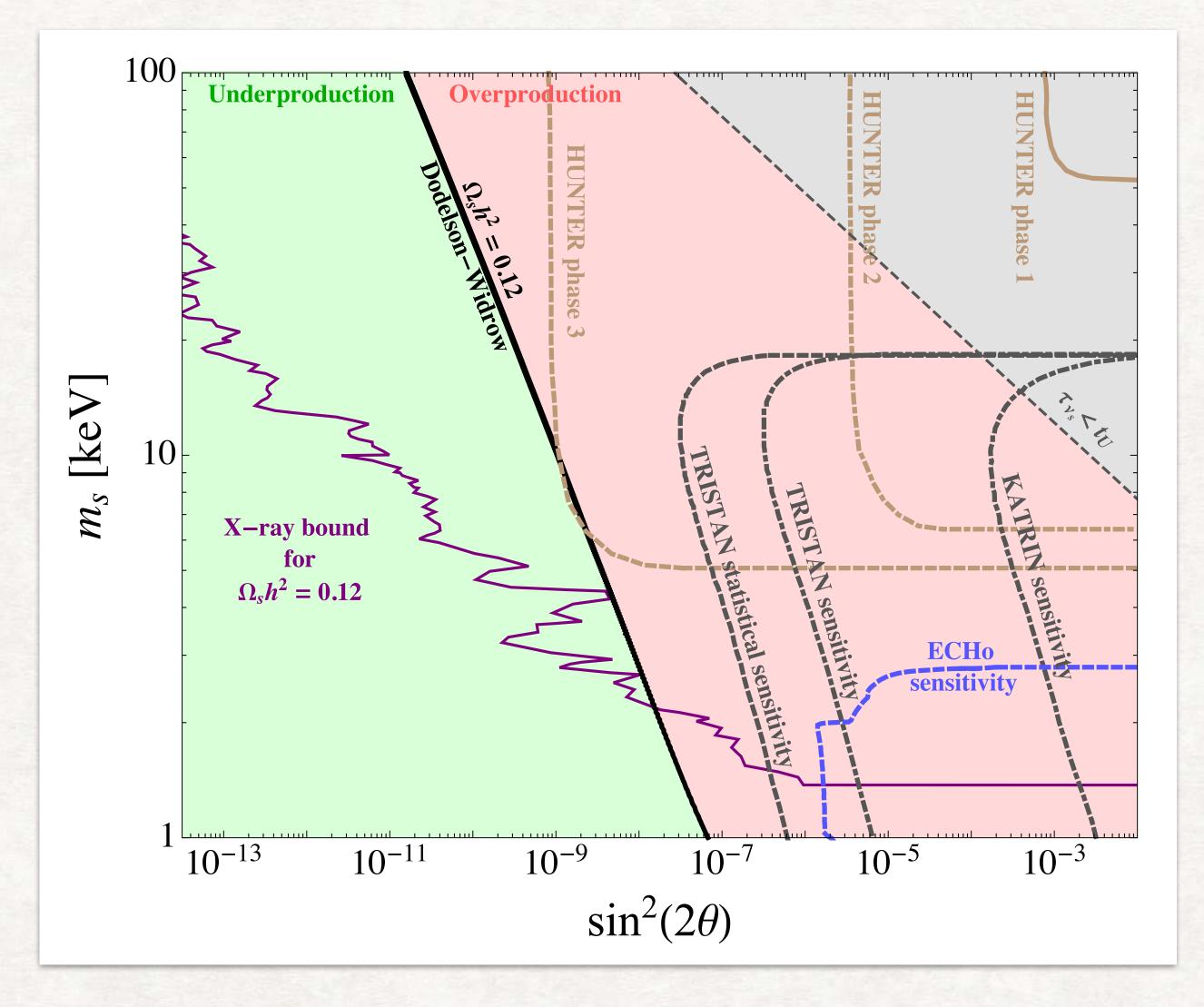
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эV

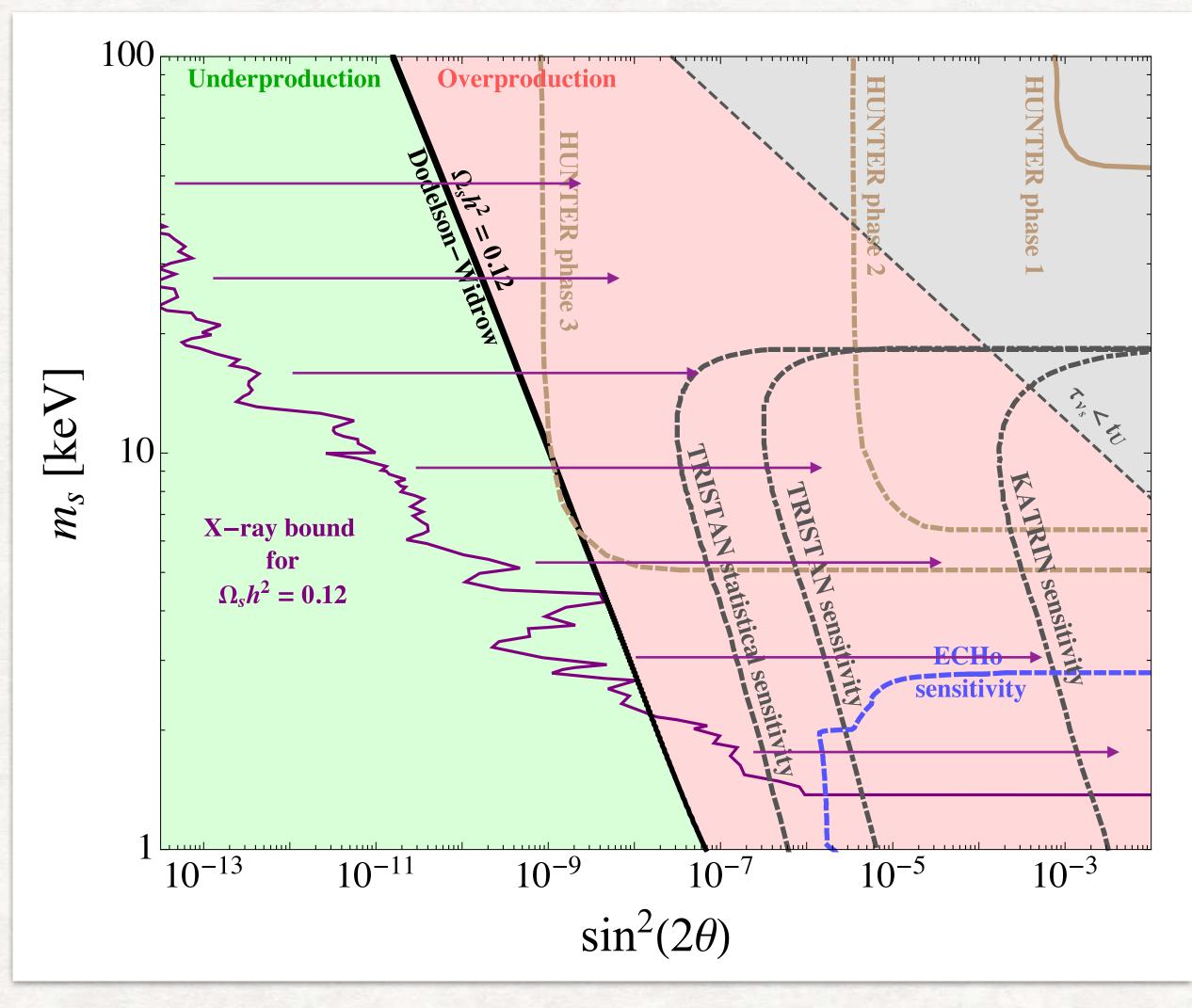


X-RAY BOUND: RELAXATION





X-RAY BOUND: RELAXATION



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



X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

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

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

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

 $\rho_s < \rho_{DM}$ corresponds to

Secondary advantage:

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

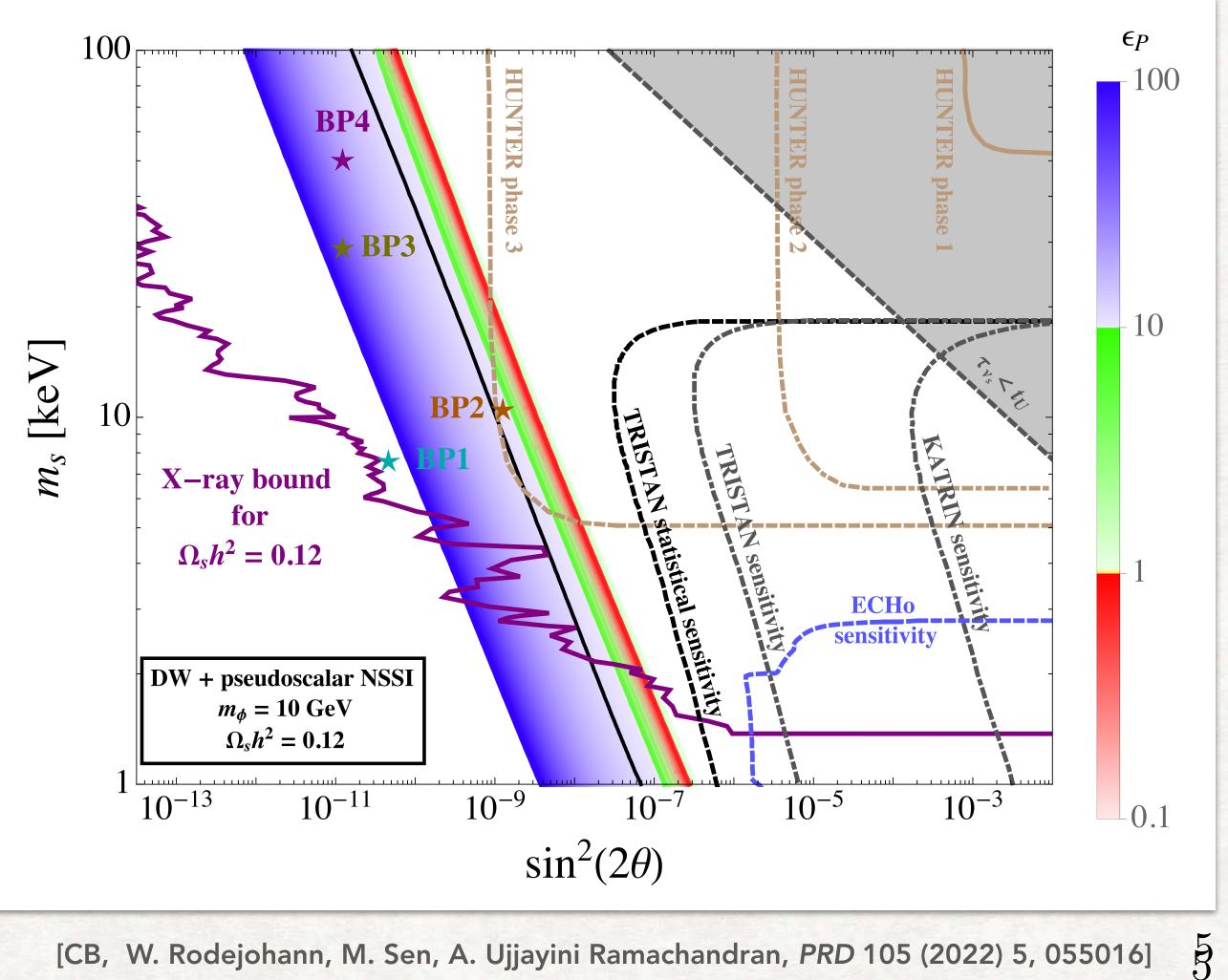
$$\frac{\nu\gamma}{s} \int dl \, d\Omega \, \rho_{\rm DM}(l,\Omega)$$

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



X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

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



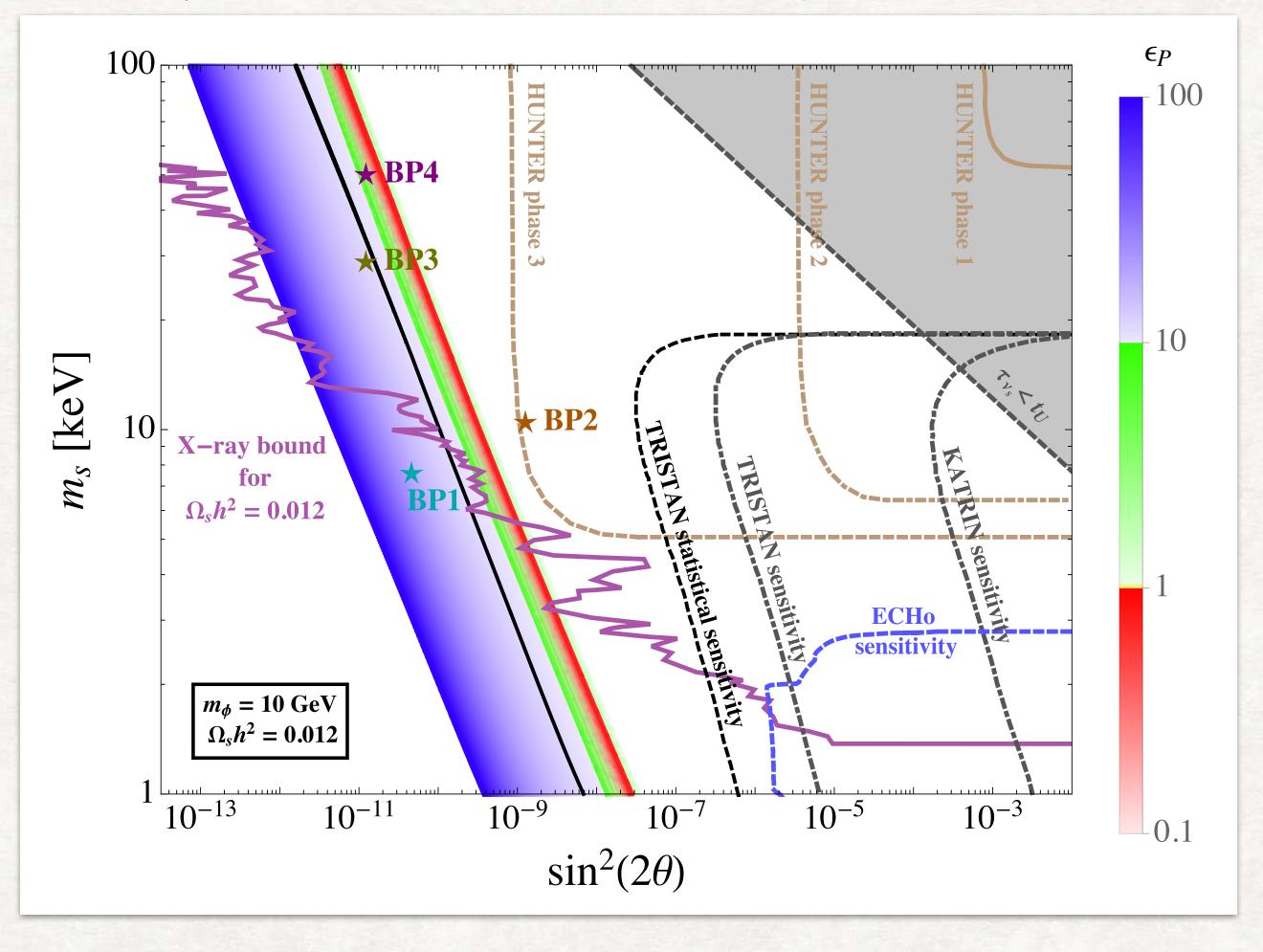
[CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, PRD 105 (2022) 5, 055016]





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]

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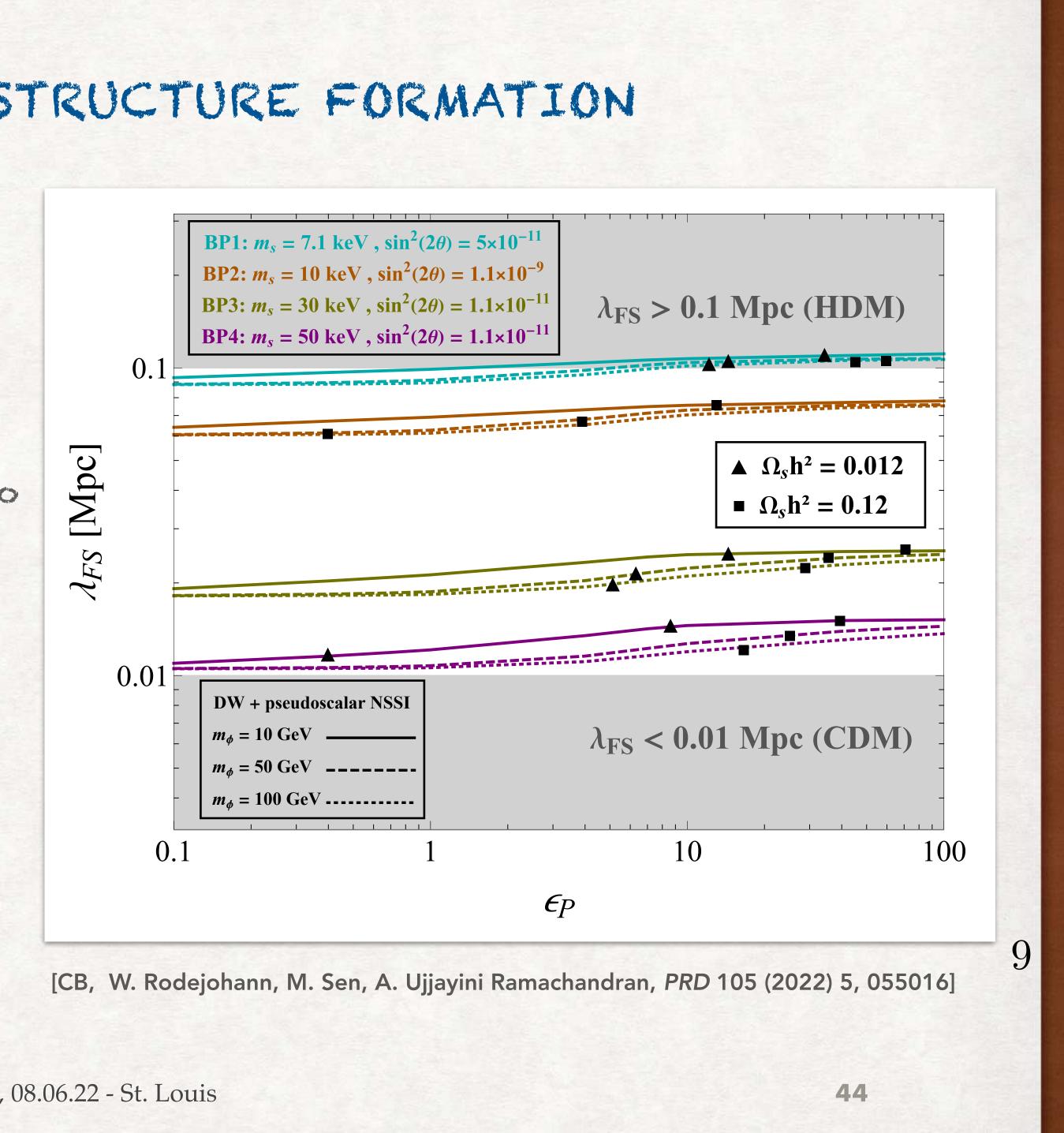


NEUTRINO NSSI - IMPACT ON STRUCTURE FORMATION

Relevant observable: free streaming length

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

- · 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 λ_{FS}
- · What makes the major difference is still the sterile neutrino mass



- * Sterile neutrinos that mix with active neutrinos are good dark matter candidates.
- Dodelson-Widrow mechanism.
- is disfavored by astrophysical X-ray observations.
- matter in the early universe.
- * The parameter space region in which $\Omega_{\mathrm{DM}}=\Omega_s$ is enlarged by such NSSI
- * Active neutrino NSSI considered are not in conflict with large scale structures.

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They can have been produced in the early universe via oscillation and collisions through

This vanilla scenario is hardly detectable in terrestrial experiments in the near future and it

* 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

and they enhance the possibility to detect sterile neutrino dark matter in HUNTER phase 3.



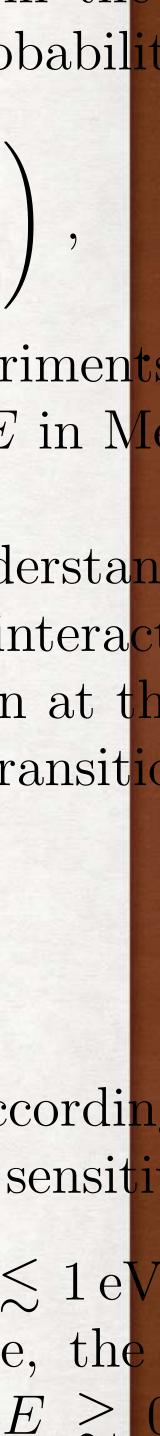
Overview $\begin{bmatrix} \nu \tau \end{bmatrix}$ $\begin{bmatrix} \nu \tau \end{bmatrix}$ $\begin{bmatrix} \nu \tau 1 & \nu \tau 2 & \nu \tau 3 & \mu \tau 3$ presents an overview of NSIs and a number of in depth modern analytes spanning) numerically $2\vartheta \sin^2 \left(1.27 \frac{(2-1)}{1.27} - \frac{(2-1)}{1.27}$ have the following forms for NC and CC NSI, The transition $\mathcal{L}_{NC} = -2\sqrt{2}G_F \sum_{\alpha\beta} \mathcal{L}_{\alpha\beta} \mathcal{L}_{$ where G_F is Fermi's constant and the ε terms quantify the size of the new sate action relative to the weak scale. The sum is over matter fermions, typically $f, f' \in \{e, u, d\}$ $\Delta m^2 L$ and $P \in \{P_L, P_R\}$ are the chirality projection operators. These projection operators carry integrate 0, 1 - 1. also be reparameterized into vector and axial components of the interaction. NSIs were first introduced by Wolfenstein in 1978 in this and this paper that your definition oscillation experiments accordin and neutrino oscillation experiments [2-4]. Shorts baseline (SeBL) experiments. In these experiments $L/E \leq 1 e^{1}$ way to relate Gristing Regises models to both cases. The stell of the high and oscillations can be detected for $\Delta m^2 L/4E \gtrsim$

1 0 mixing framework using Eq. (3.12), The two-neutrino transition probabili Given the wide interest in the worldwide maniful preserven, it is timely AQ reasses these 12 with 2 with 2? state of the art topics related to non-stangerding further integrations (NSIs). This document 0 0 (1) ($2\Delta m^2/eV^2$) (L/km) the neutrino sector in the form of new interactions beyond constant installing neutrinos and 1.1 Introduction to the field theory (EPP) same and work is a factor is the provide a general effective field theory (EPP) same and work is a factor work of the provide a general effective field theory (EPP) same and work is a factor work of the provide a general effective field theory (EPP) same and work is a factor work of the provide a general effective field theory (EPP) same and work is a factor work of the provide a general effective field theory (EPP) same and work is a factor work of the provide a general effective field theory (EPP) same and work is a factor work of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and work is a factor of the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the provide a general effective field theory (EPP) same and the

Why are fight and the transitions are observable only if the transitions are observable on the transitions are observable f, P, α, β is not too low, which means that it is necessary that

- conventional matter effect [1]. L/E which establishes the range of Δm^2 to which an experiment is sensiting such a new interaction leads to a rich phenomenology in both scattering experiments

nuite distinct from scattering phenomenology, the standard and the standard and the second standard the se



NEUTRINO NON-STANDARD INTERACTIONS - WHY NOT?

with matter fields (e, u, d).

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

matter production.

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

maximal production of sterile neutrinos. For the other non-relativistic particles the number density is suppressed like

 $n_i(T) = g_i$

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

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

However, only muons and strange quarks are still relativistic in the plasma at the time of

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

