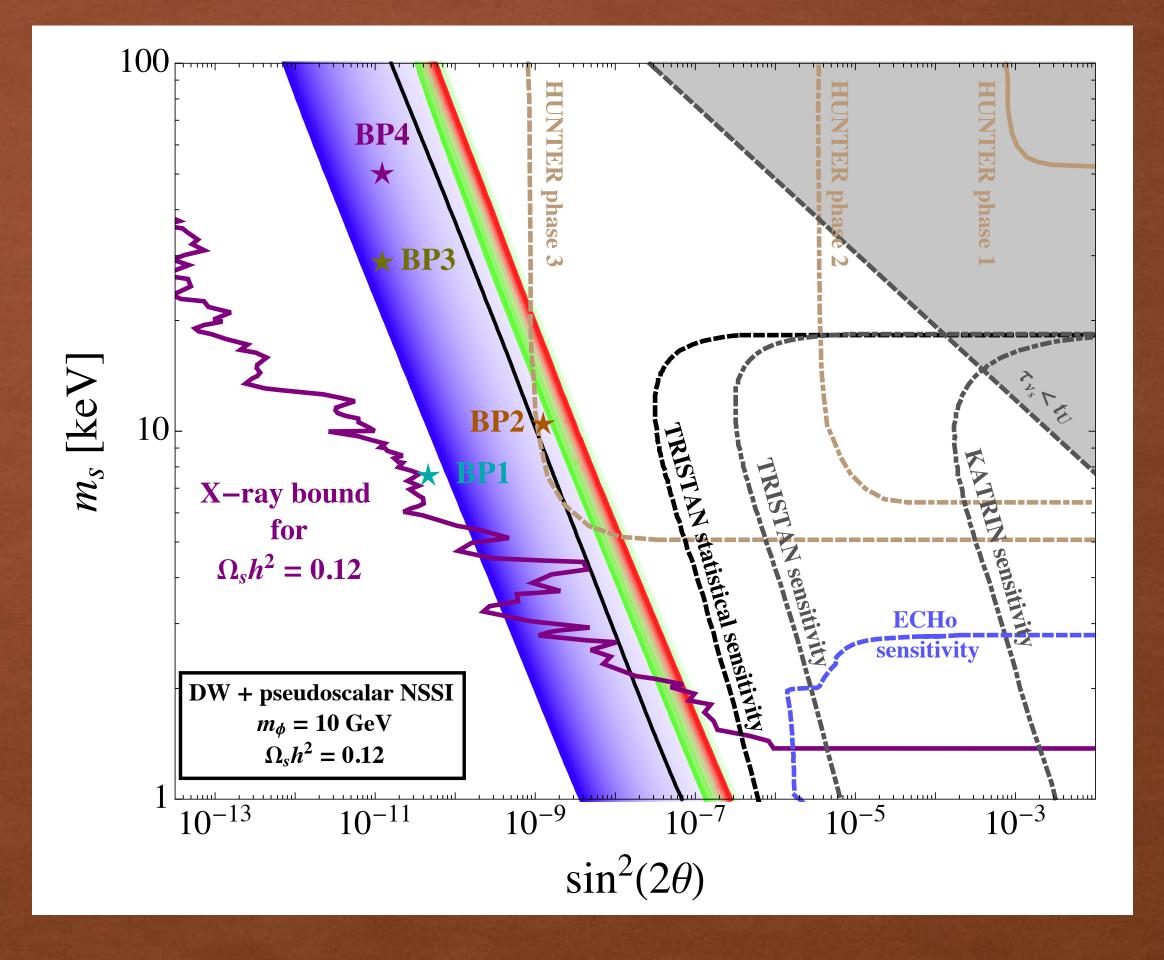


W + pseudoscalar NSSI

O h² = 0.12

Max-Planck Institut für Kernphysik (MPIK)





INTRODUCTION - STERILE NEUTRINO DARK MATTER

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

If neutrinos are Majorana particles: $u_s \mid
u_4 = \cos \theta \, \nu_s + \sin \theta \, \nu_{\alpha}$

INTRODUCTION - STERILE NEUTRINO DARK MATTER

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sterile neutrino can play the role of DM:

- o no em nor strong interaction, by definition
- massive: possibly with mass O(keV)
- $oldsymbol{arDelta}$ 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

- · in the domain of direct detection
- \bullet rely on large mixing of $u_s \leftrightarrow
 u_e$ or $\overline{
 u}_s \leftrightarrow \overline{
 u}_e$

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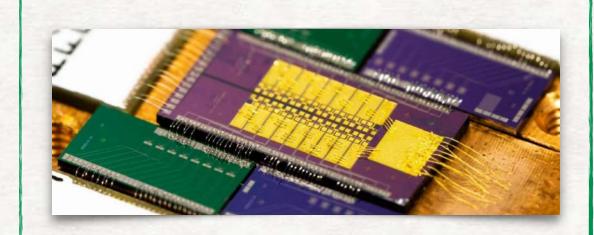
KATRIN



Tritium beta-decay

 $m_s \lesssim 17.5 \text{ keV}$

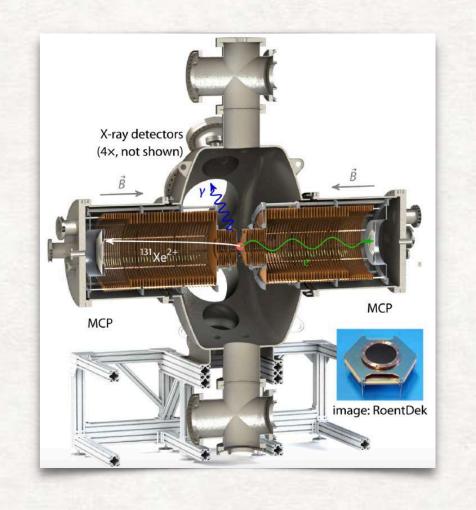




Holmium EC

 $m_s \lesssim 2.5 \text{ keV}$

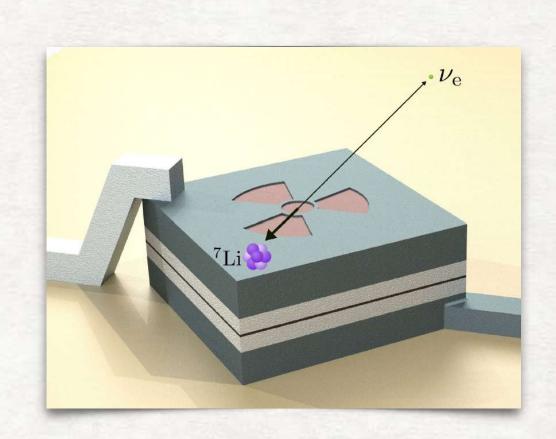
HUNTER



Caesium EC

 $m_s \lesssim 350 \text{ keV}$

BEEST



Beryllium EC

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

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

Mechanism: production through oscillation and collisions:

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

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

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

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

where
$$\Gamma_e(p) = c_e(p, T)$$

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

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

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

In the plasma, the mixing angle is

$$\sin^{2}(2\theta_{M}) = \frac{\left(\frac{m_{s}^{2}}{2p}\right)^{2} \sin^{2}(2\theta)}{\left(\frac{m_{s}^{2}}{2p}\right)^{2} \sin^{2}(2\theta) + \frac{\Gamma_{e}(p)}{2} + \left[\frac{m_{s}^{2}}{2p} \cos(2\theta) - V_{T}(p)\right]^{2}}$$

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

We solve the Boltzmann equation and find the distribution function

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

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and calculate the sterile neutrino dark matter abundance passing through

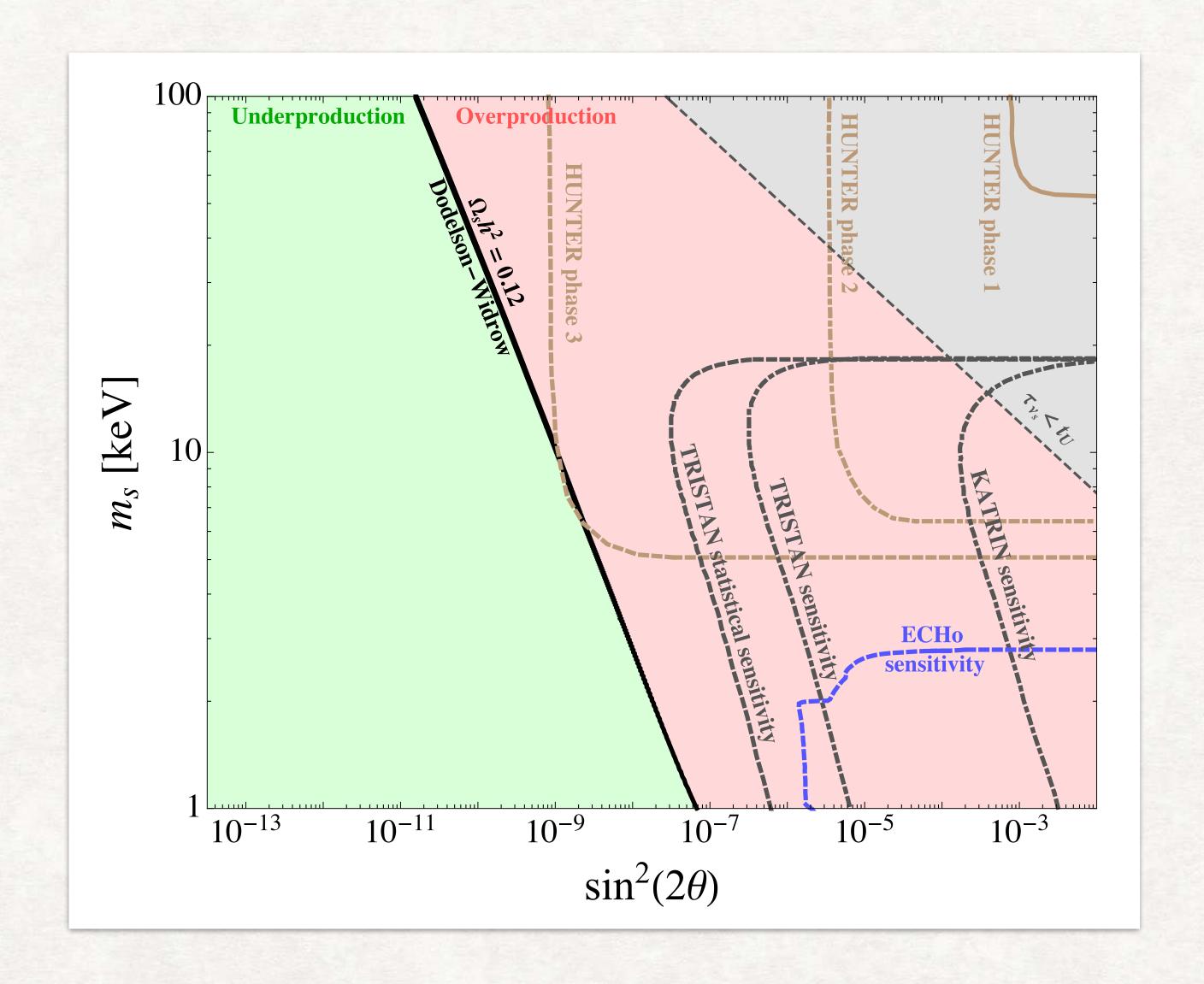
sterile neutrino number density

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

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

$$h^{2} \Omega_{s} = \frac{s_{0} m_{s}}{\rho_{c}/h^{2}} \frac{1}{g_{*s}} \left(\frac{45}{4\pi^{4}}\right) \int_{0}^{\infty} dr \, r^{2} \left[f_{\nu_{s}}(r) + f_{\overline{\nu}_{s}}(r)\right]$$

DODELSON-WIDROW PRODUCTION - CHALLENGE FOR DETECTION



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

<u>Definition</u>: 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.

to get temperature dependant terms in the mal potential; we have to include higher term in MSNS agrangian (\bar{w}) ($\bar{$

w interaction finition: Neutrino non-standard self-interactions (NSSI) are a parameterization of new physics $v\in\{e,u,d\}$ the neutrino sector in the form of new interactions beyond the SM involving only neutrinos. Perators $\mathcal{L}_{j}^{\mathrm{cap}} = -\frac{G_F}{\sqrt{2}}(\epsilon_{j,\nu})\left(\bar{\nu}_e\mathcal{O}_j^{\prime}\nu_e\right) - \frac{1}{m^2}(\bar{\nu}_e\mathcal{O}_j^{\prime}\nu_e) \square\left(\bar{\nu}_e\mathcal{O}_j^{\prime}\nu_e\right)\right)$ (6.1)

NSIs were the content of the content of the sector of the sector

entified the C for detailed calculation

The experimental (C.3.1)
$$G_F = \frac{G_F}{\sqrt{2}} \sum_{\substack{S \ \text{convenient} \ \text{ought of in }^{\dot{\alpha}}}} \sum_{\substack{S \ \text{convenient} \ \text{cos}, \nu_e \ \text{ought of in }^{\dot{\alpha}}}} \sum_{\substack{S \ \text{convenient} \ \text{cos}, \nu_e \ \text{convenient} \ \text{cos}}} \sum_{\substack{S \ \text{convenient} \ \text{cos}, \nu_e \ \text{convenient} \ \text{cos}}} \sum_{\substack{S \ \text{convenient} \ \text{cos}}} \sum_{\substack{S \ \text{convenient} \ \text{cos}}}} \sum_{\substack{S \ \text{convenient} \ \text{cos}}} \sum_{\substack{S \ \text{convenient}$$

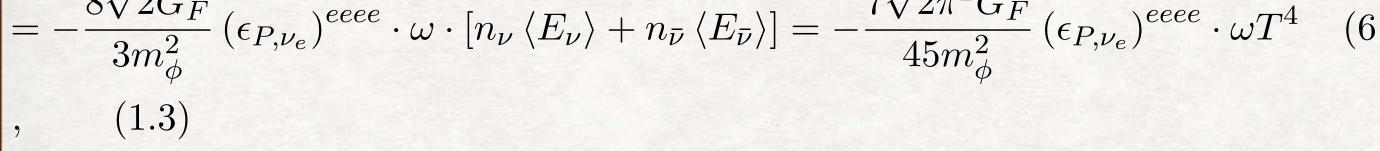
eachipatector NSI(C.3.2)

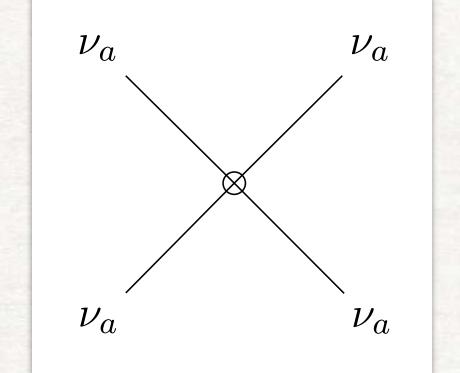
to mediators
$$15\sqrt{2G_F} \left(\epsilon_{A,\nu_e}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu} \left\langle E_{\nu} \right\rangle + n_{\bar{\nu}} \left\langle E_{\bar{\nu}} \right\rangle\right] = -\frac{14\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} \left(\epsilon_{A,\nu_e}\right)^{eeee} \cdot \omega T^4 \quad (6.3)$$

r Pspendostalar NSI(C.3.3)

$$= -\frac{8\sqrt{2}G_F}{3m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu} \left\langle E_{\nu} \right\rangle + n_{\bar{\nu}} \left\langle E_{\bar{\nu}} \right\rangle\right] = -\frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eeee} \cdot \omega T^4$$

$$(6.4)$$





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to get temperature dependant terms in the mal potential; we have to include higher term in MSNS agrangian (\bar{w}) ($\bar{$

interaction $\frac{1}{2}$ Neutrino non-standard self-interactions (NSSI) are a parameterization of new physics

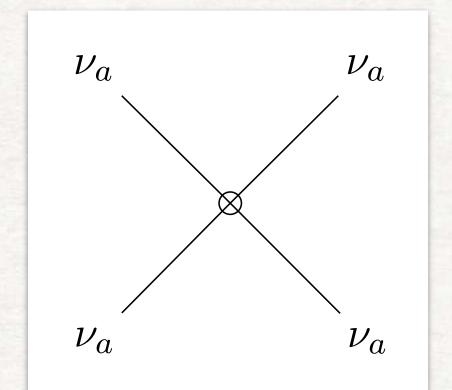
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to mediators
$$16\sqrt{2G_F}$$
 (care) respectively the $\langle E_{\nu} \rangle$ the $\langle E_{\nu} \rangle$ $| = -\frac{14\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} \left(\epsilon_{A,\nu_e}\right)^{eeee} \cdot \omega T^4$ (6.3)

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$$= -\frac{8\sqrt{2}G_F}{3m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eeee} \cdot \omega \cdot \left[n_{\nu} \left\langle E_{\nu} \right\rangle + n_{\bar{\nu}} \left\langle E_{\bar{\nu}} \right\rangle\right] = -\frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} \left(\epsilon_{P,\nu_e}\right)^{eeee} \cdot \omega T^4$$

$$, \qquad (1.3)$$



the Wolfen-

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For useful Cristina Benso

re ϵ indicates the NSS istrement by compared two the standard weak interaction.

 $10^{-12} (A.19^{-10})$

to get temperature dependant terms in thermal potential, we have to include higher $A = 10^{-12}$ (A $= 10^{-10}$)

term in KSNSIsagrangian (FIGM) (FIGM) give man (FIGM) dependent self-energy. Check interaction (NSSI) are a parameterization of new physics

Hulk A $e \in \{e, u, d\}$ the neutrino sector in the form of new interactions beyond the SM involving only neutrinos. Perators $\mathcal{L}_{j}^{\text{cap}} = -\frac{G_{F}}{\sqrt{2}} (\epsilon_{j,\nu}) \left((\bar{\nu}_{e} \mathcal{O}_{j} \nu_{e}) - \frac{1}{m_{\phi}^{2}} (\bar{\nu}_{e} \mathcal{O}_{j} \nu_{e}) \square \left((\bar{\nu}_{e} \mathcal{O}_{j}^{\prime} \nu_{e}) - \frac{1}{m_{\phi}^{2}} (\bar{\nu}_{e} \mathcal{O}_{j}^{\prime} \nu_{e}) \right)$ NSIs were the sective description valid for heavy mediators entified the

entified the C for detailed calculation

to mediators
$$[6\sqrt{2}G_F]_{\text{NSSW}} (\epsilon_{\text{Appe}})^{\text{eeee}}_{\text{NSSW}} [me\langle F_{\nu}\rangle \text{th} n_{\bar{\sigma}}\langle E_{\bar{\nu}}\rangle] = -\frac{14\sqrt{2}\pi^2 G_F}{45m_{\phi}^2} (\epsilon_{A,\nu_e})^{\text{eeee}} \cdot \omega T^4 \quad (6.3)$$

r AspendiostalareNSI(C.348) physics to come from the neutrino sector

$$=-\frac{8\sqrt{2}G_F}{3m_{\phi}^{25}}(\kappa_{Re_e})^{eeee}_{model} m_{des} E_{sc} + i\beta_{\bar{\nu}} (E_{\bar{\nu}}) = \frac{7\sqrt{2}\pi^2 G_F}{45m_{\phi}^{2}} (E_{sc})^{eeee}_{model} m_{des} =$$

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

(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 Cristina Benso rentoansistoperrobiability in Eq. (3.13) is useful in order to understand the classifi-This Get enwhere indicates the Issurfactory and the boundard weak interactions, we get the final The of NSSI Lagrangian:

Pour of NSSI Lagra (A.19)The state of the this inequality we dela sify neutrino oscillation experiments according to the ratio which iesterblishtesing experiment of Δm^2 to which an experiment is sensitive: escillation phonomenology experiments Whatson income (SBile) responsing ents. In these experiments $L/E \lesssim 1\,\mathrm{eV}^{-2}$. Since the

Shifted the conditions these experiments $L/E \lesssim 1\,\mathrm{eV}^2$. Since the shifted the conditions these experiment is not too large, the event rate is relatively high and oscillations can be detected for $\Delta m^2 L/4E \gtrsim 0.1$, leading a remaining the temperature. There are two types of SBL experiments: reactor $\bar{\nu}_e$

is appearance experiments with $L \sim 10\,\mathrm{m}$, $E \sim 1\,\mathrm{MeV}$ as, for example, Bugey [64]; by the residence of the property of

17

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Interactions [Denton $\mathcal{L}_{\text{NSS}} = \cos \theta(\bar{\nu}\mathcal{O}\nu)$] $-\left[\bar{\nu}\mathcal{O}\eta\right] + \left[\bar{\nu}\mathcal{O}\eta\right]$, where $G_{\phi} = \frac{\sqrt{2}}{2}$ (E The W) (A.18)ceping terms up to first order in 2 tourstain moment up de readence verbayents (see below). The number construction of the expressed in meters and E in MeV. which are itumide of a land the series in the series of the series o Tentohnsistopaprobiability in Eq. (3.13) is useful in order to understant $P_{L\nu_{\beta}}(f) = P_{L\nu_{\beta}}(f) = P_$ This Grant here indicates the Experimental compared to the standard The of NSSI Lagrangian: V^2 representations are observable only if the transition property of the personal neutrinos: only scalar, pseudoscalar and axial-vector in the property low six bichemeans ethat it is necessary that V^2 and V^2 are neutrinos; only scalar, pseudoscalar and axial-vector in the property of the property of the property of the property of the person of the property of the p The transfer project in the set of the set this inequality we delassify neutrino oscillation experiments according to the ratio which iesterblishtesing experiment of Δm^2 to which an experiment is sensitive: escillation phonomenology experiments Suffer were considered in these experiments $L/E \lesssim 1 \, \mathrm{eV}^{-2}$. Sin the experiment is not too large, the event rate is relatively high and oscillations pan be detected for $\Delta m^2 L/4E \gtrsim 0.1$, leasensitivity to $\Delta m_{\rm p} = 0.1$. There are two types of SBL experiments: reasons the relative of the sensitivity of $\Delta m_{\rm p} = 0.1$. Lisappearance experiments with $L \sim 10 \, \text{m}$, $E \sim 1 \, \text{MeV}$ as, for example, Bugey [64]; PASCOS 2022, 26.07.22 - MPIK Heidelberg [71] as the example of the property of the second state of the example of the exa 19

NEUTRINO NSSI - HOW TO INCLUDE THEM?

Scalar NSSI

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

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

· Pseudoscalar NSSI

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· Axial vector NSSI

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

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

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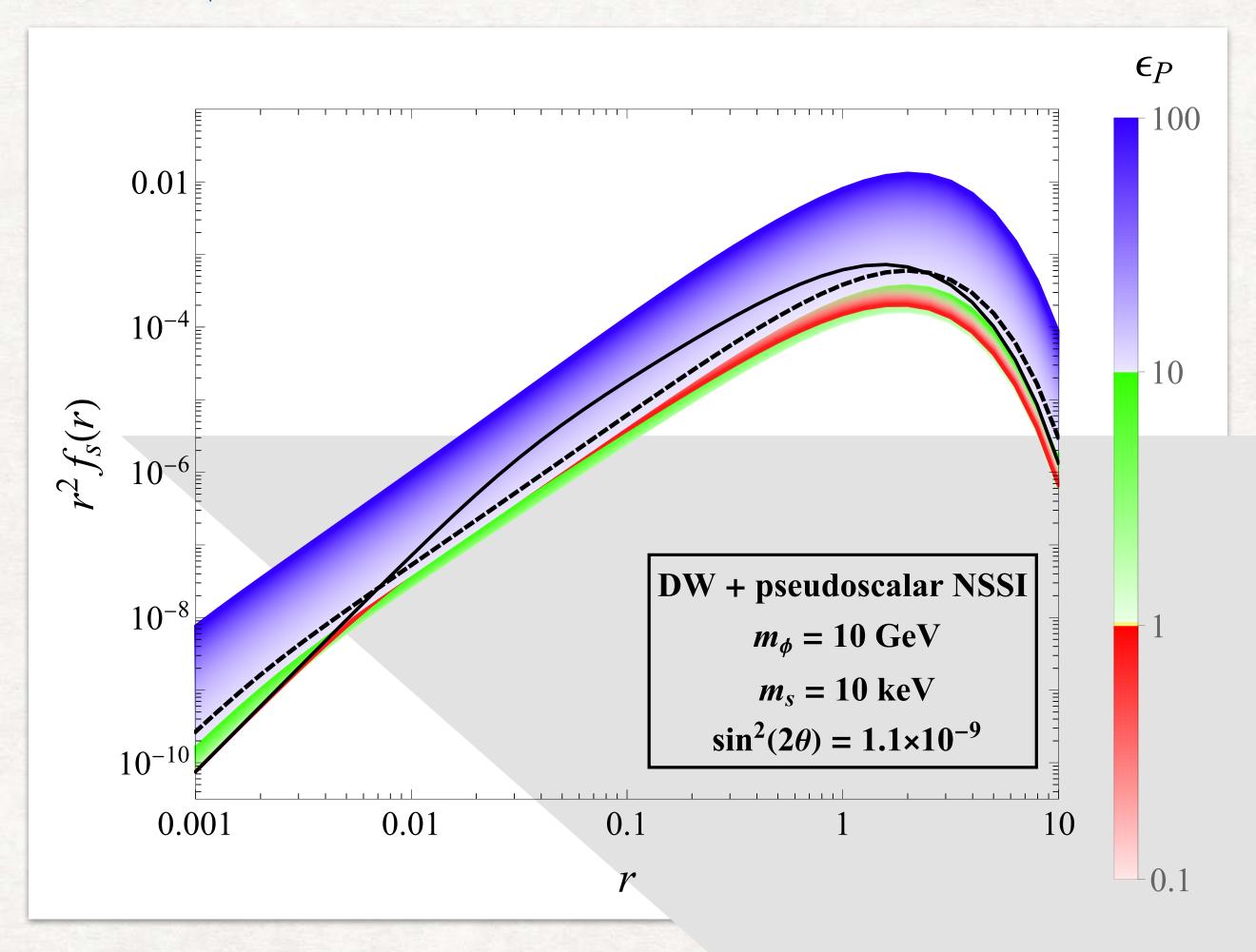
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NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

Sterile neutrino distribution function



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

NEUTRINO NSSI - IMPACT ON STERILE NEUTRINOS

Sterile neutrino production evolution 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 guares 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.

> they are very light. On the other hand, if we consider BVI production of the famous observed X-ray line at 3.55 keW = 37688, we see that large NSSI would be needed to produce an abundance of such sterile neutrinos large enough to constitute a non negligible percentage of the Universe's DM others. However, such large NSSI would put sterile neutrinos With such features in conflict with constraints coming from structure formation: they [CB, W. Rodejohann, M. Sen, A. Ujjayini Ramachandran, PRD 105 (2022) 5, 055016] Would have been produced with too high velocities mod-

DD9 is nonticularly interesting. It nonnegants a case

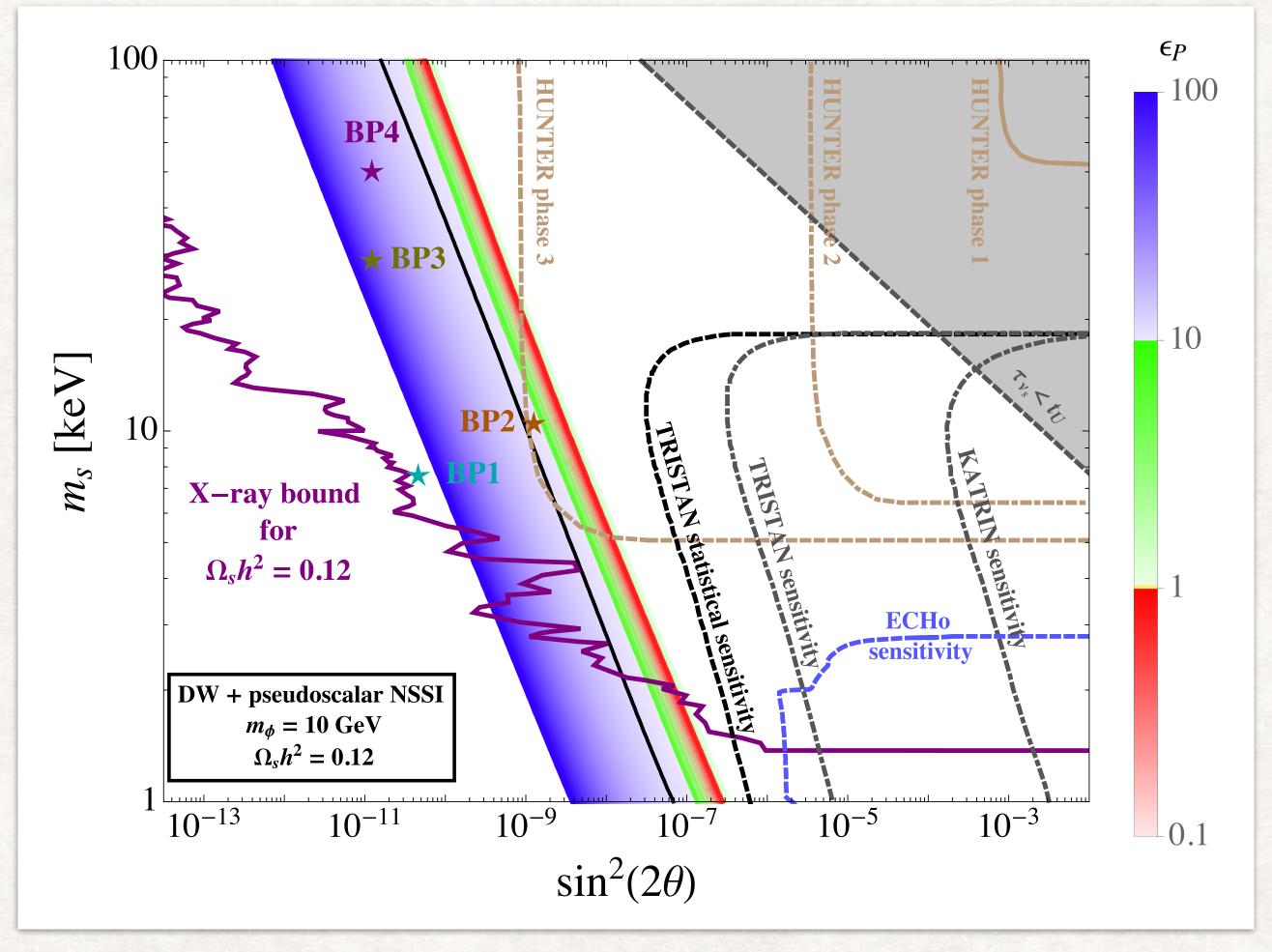
ifying large structures, that we preserve today.

FIG. 6. Evolution of the prowith $m_s = 10 \text{ keV}$ and $\sin^2($ 2) with temperature. The the standard Dodelson-Widr dashed line corresponds to doscalar NSSI with ϵ_P such t ferent shades of red, green ar strength of NSSI involved in All the lines are obtained und mediator has mass $m_{\phi} = 10$

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

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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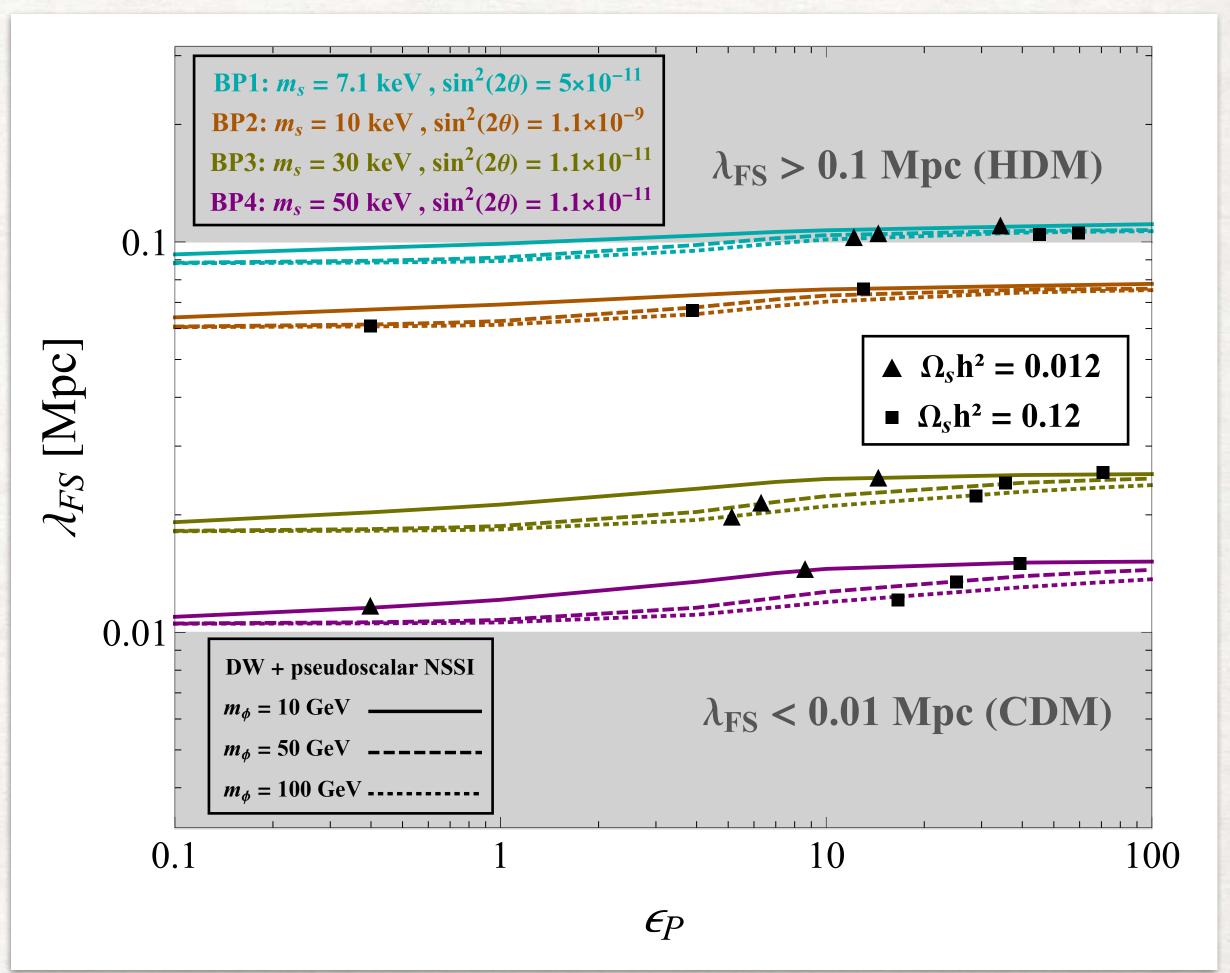
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NEUTRINO NSSI - IMPACT ON STRUCTURE FORMATION

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>
- \circ 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, PRD 105 (2022) 5, 055016]

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

BACKUP

KATRIN



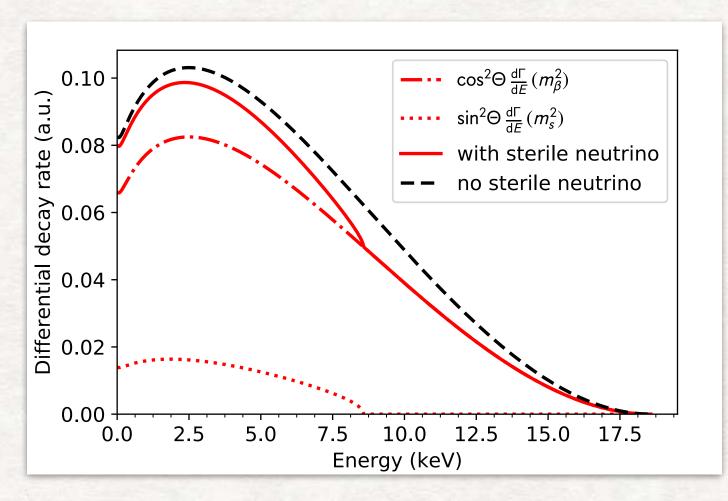
[Troitsk experiment based on the same process but less sensitive]

Cristina Benso

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 $E_0-m_{
m s}$ with magnitude governed by the mixing amplitude $\sin^2\theta$

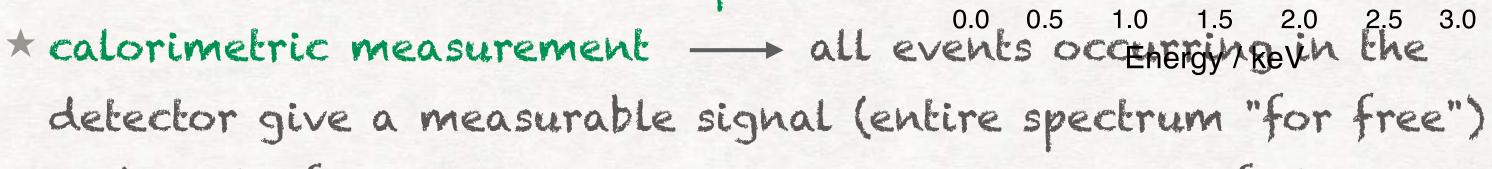


(Borrowed from S. Mertens lecture in Bad Honnef)

PASCOS 2022, 26.07.22 - MPIK Heidelberg

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

Based on holmium electron capture:



-- no sterile neutrino

 $-m_4 = 2 \text{ keV}, \ U_{e4}^{2} = 0.5$

• endpoint of $Q_{\rm EC}=2.833~{
m keV}$ \longrightarrow allows search of sterile neutrinos only with mass < 2.5 keV



the mass splittings between theithree light mass eigenstates are spesifially modulified bat every $Q_{\rm EC}$ - m_4 decay experiment can resolve them. Instead a single effective light neutring $m_{\rm e4}$ as $m(\nu_{\rm e})^2 = \sum_{i=1}^3 |U_{ei}|^2 m(\nu_i)^2$ is assumed.

If the electron neutrino contains an admixture of a neutrino mass eigenstate with a mass in the keV range, the different mass eigenstates will no longer form one effective neutrino mass term in this case, due to the large mass splitting, the superposition of the β -decay representate spectra corresponding to the light effective mass term $m(\nu_e)$ and the heavy mass eigenstate m_s , can be detectable. The differential spectrum can be written as

$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m^{\rm e}(\nu_{\rm e})) + \sin^2\theta \frac{d\Gamma}{dE}(m_{\rm s}), \qquad \frac{g_{\rm e}}{g_{\rm e}} = 0.5$$

$$--- \text{ no sterile neutrino mixing, and predominantly determines the size}$$

$$(8.1)$$

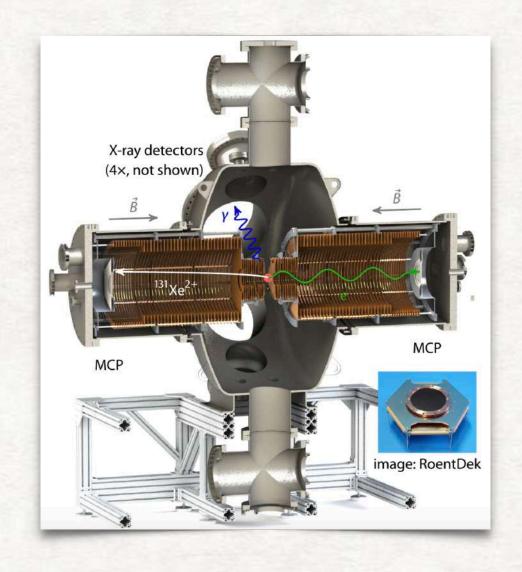
[HOLMES aware Messribes the active-sterile neutrino mixing, and predominantly determines the size based of the effect on the spectral shape [127]. Figure 35 shows a chalifative example with perfect.

based on the same process pectral shape [127]. Figure 35 shows a chalifative example with perfect.

energy resolution and no energy smearify from atomic, thermal or scattering effects.

Cristina Benso Tritium β decay provides distingt advantages when search for the signature of a keV-scale sterile neutrino. First, tritium β -decay is of super-allowed type, and therefore a precise

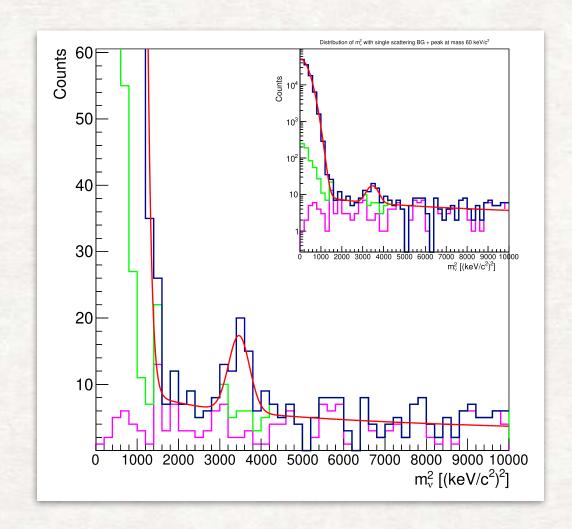
HUNTER



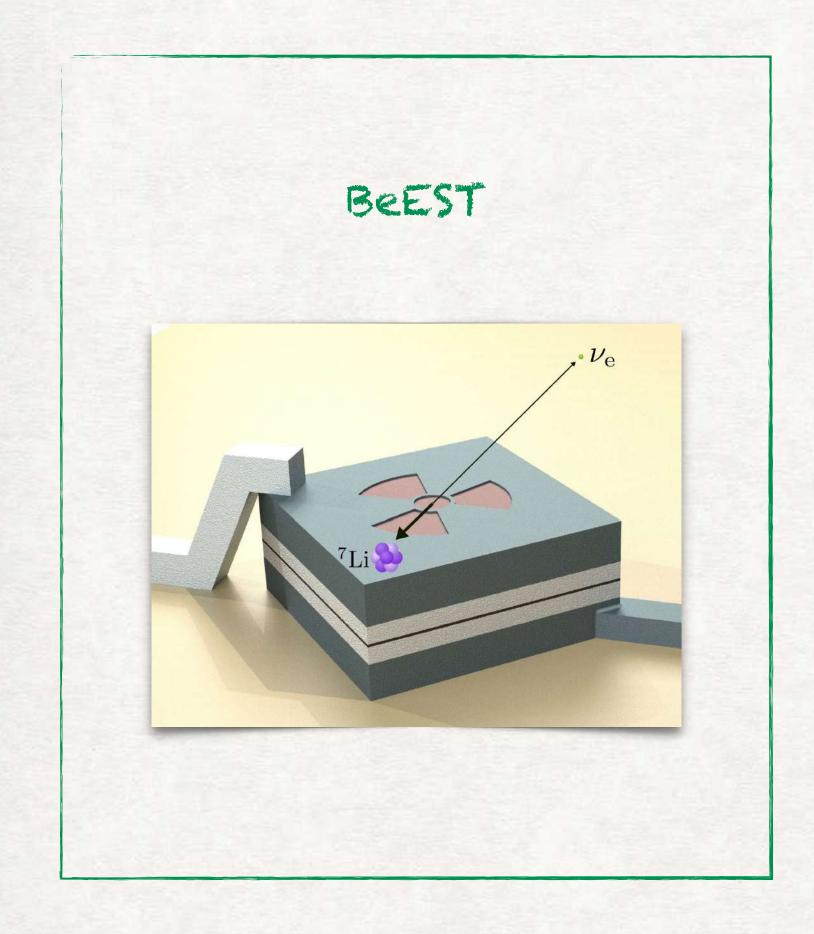
Based on caesium electron (K-) capture:

- * 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

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



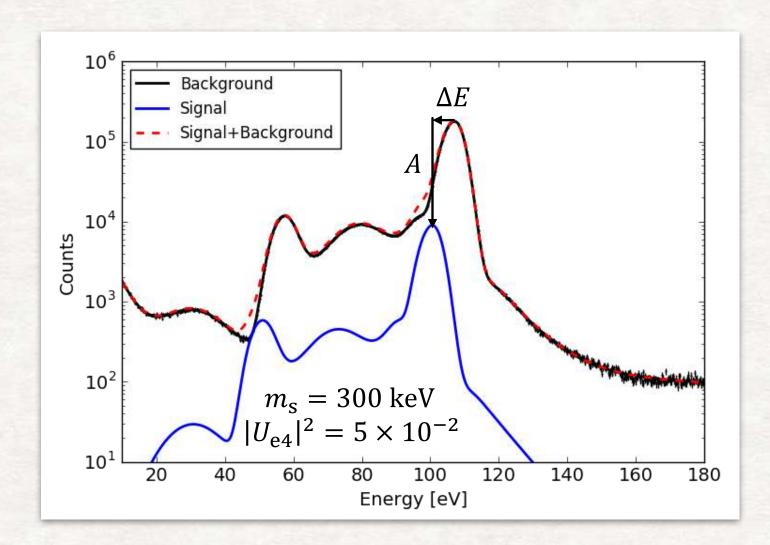
[C. J. Martoff et al, Quantum Sci. Technol. 6 (2021) 024008]



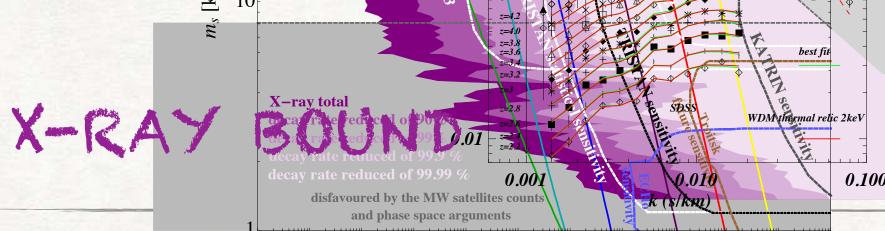
Based on beryllium electron capture:

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

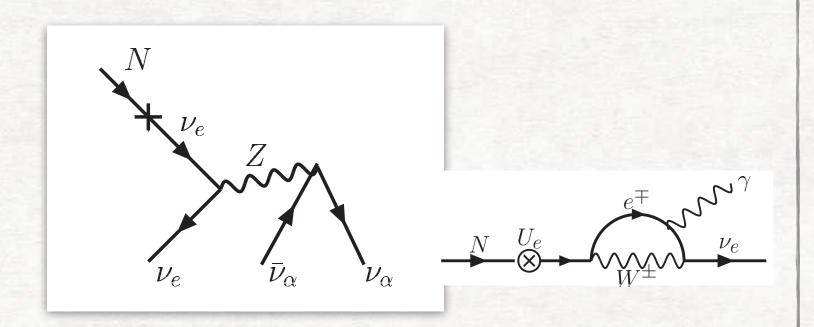
Signature: spectrum similar to the one of the standard case (no sterile neutrinos) but shifted in energy and with smaller amplitude



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



 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{-2}



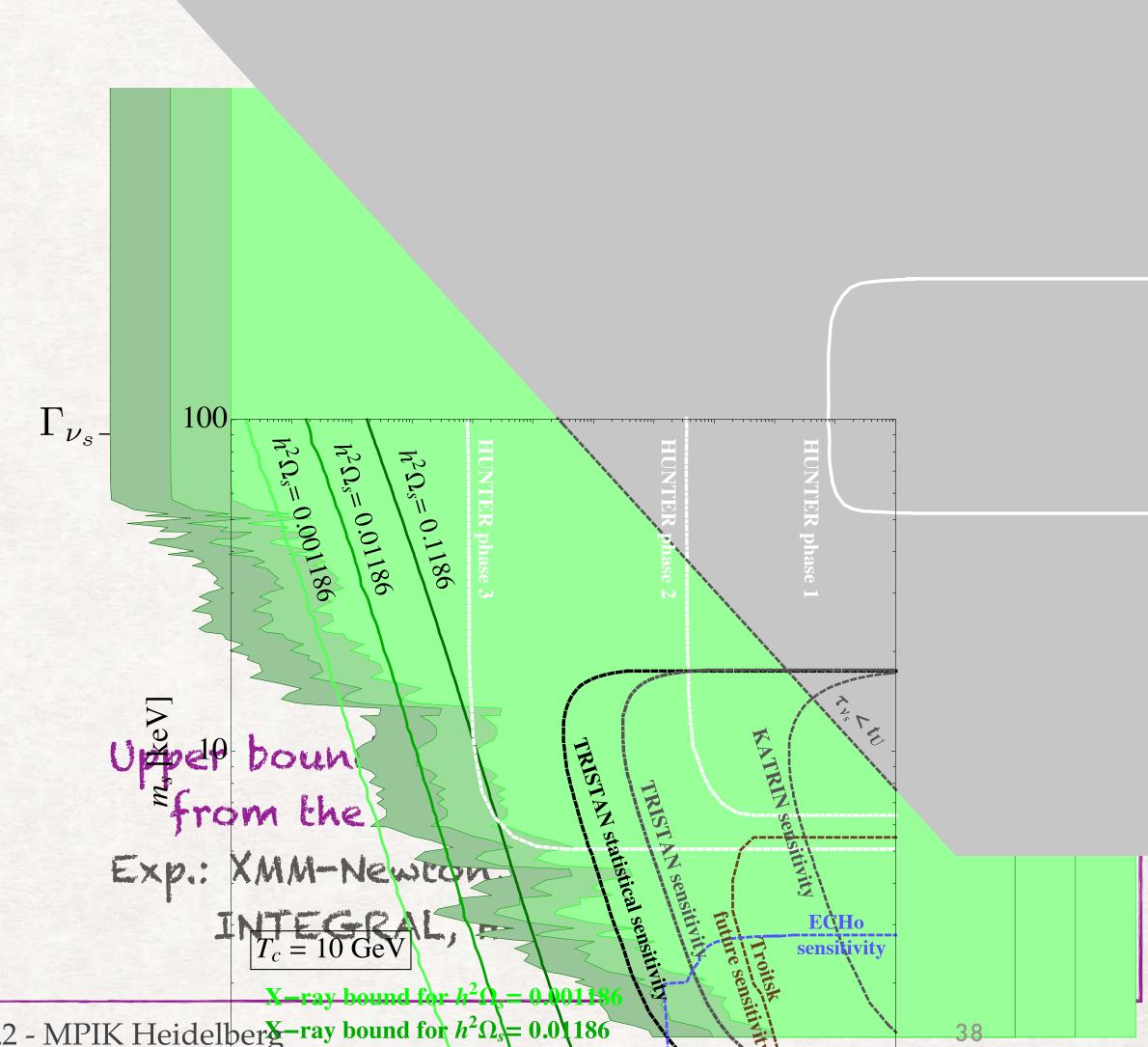
$$\Gamma_{\nu_s \to 3\nu} = \frac{G_F^2 m_s^5}{96 \pi^3} \sin^2(2\theta) = \frac{1}{4.7 \times 10^{10} \text{ s}} \left(\frac{m_s}{50 \text{ keV}}\right)^5 \sin^2(2\theta)$$



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

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

one loop decay



BOUND: ABSOLUTE OR MODEL-DEPENDENT?

Observable: 0.010 flux of photons

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

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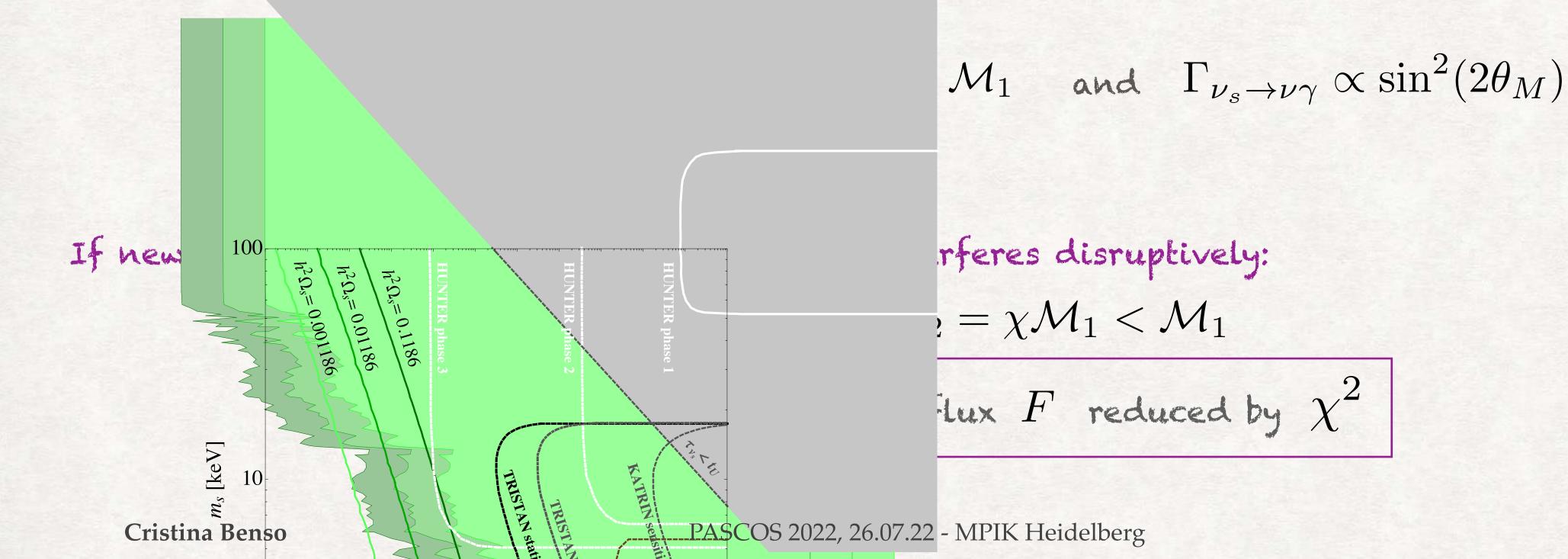
where

TRIST

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

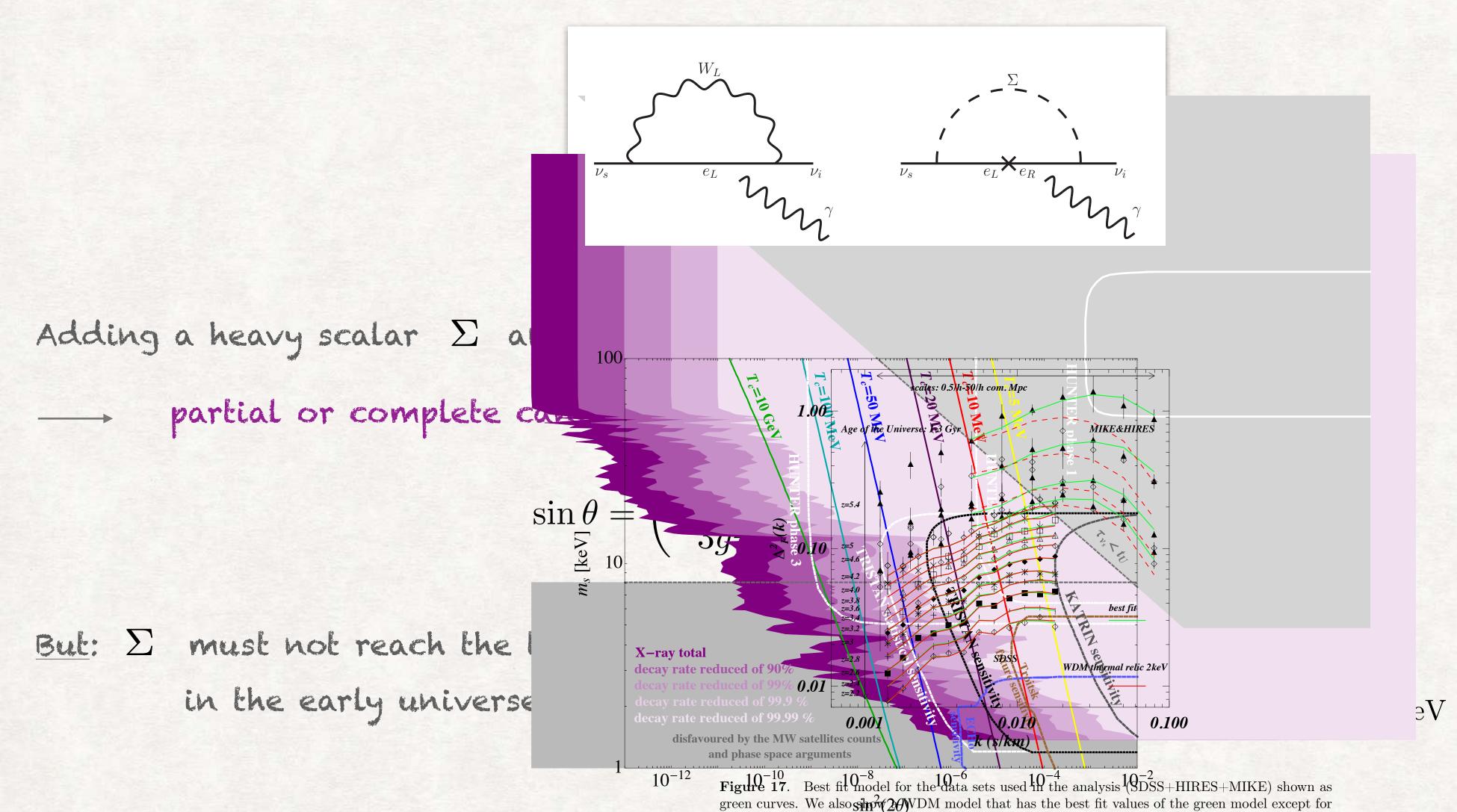
In absence of new physics:

Cristina Benso



X-RAY BOUND: ABSOLUTE OR MODEL-DEPENDENT?

Particular realization:

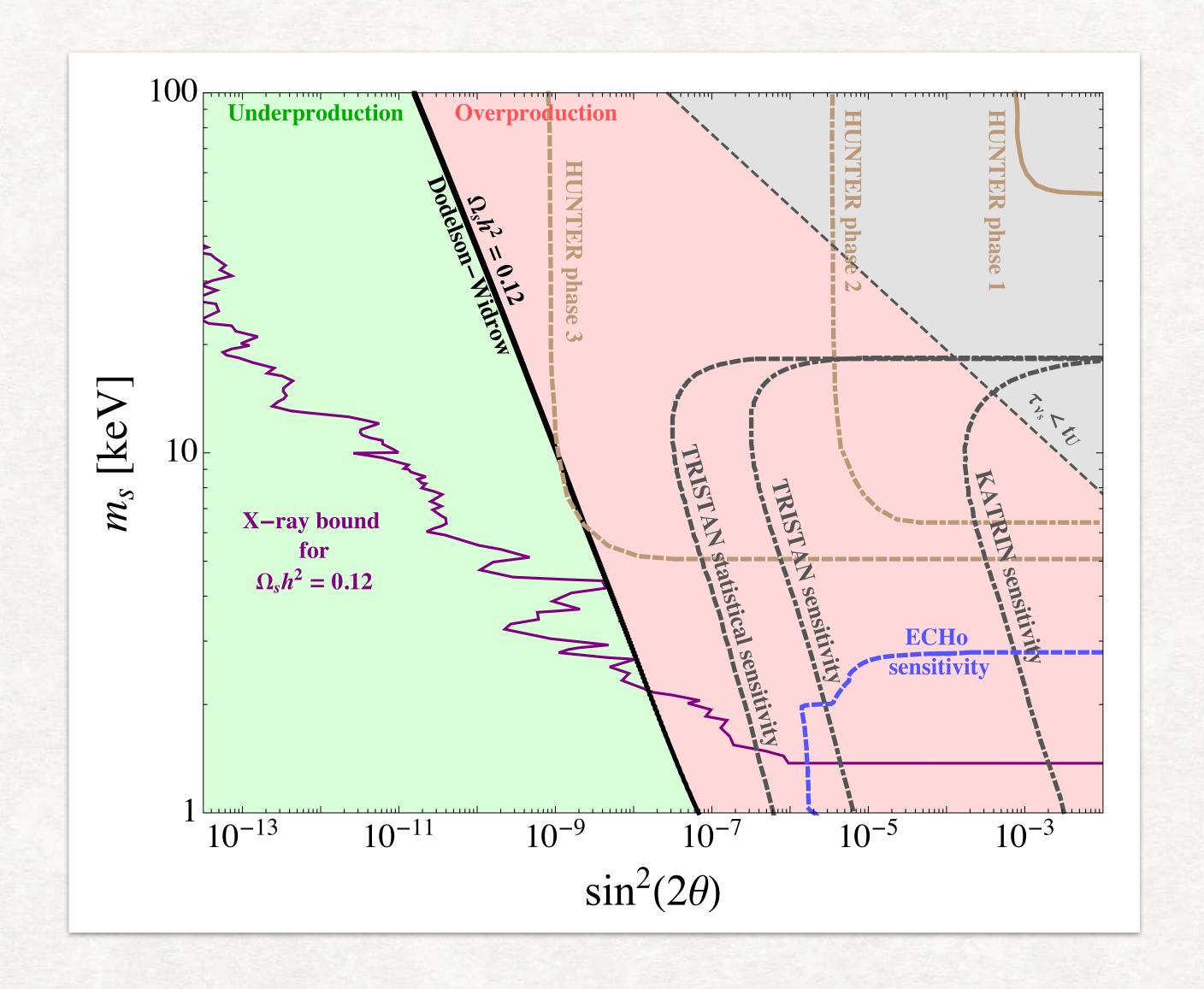


the WDM (thermal relic) mass of 2 keV (red dashed curves). These data span about two orders of PASCOS 2012 in 2614 212 period 212 pe

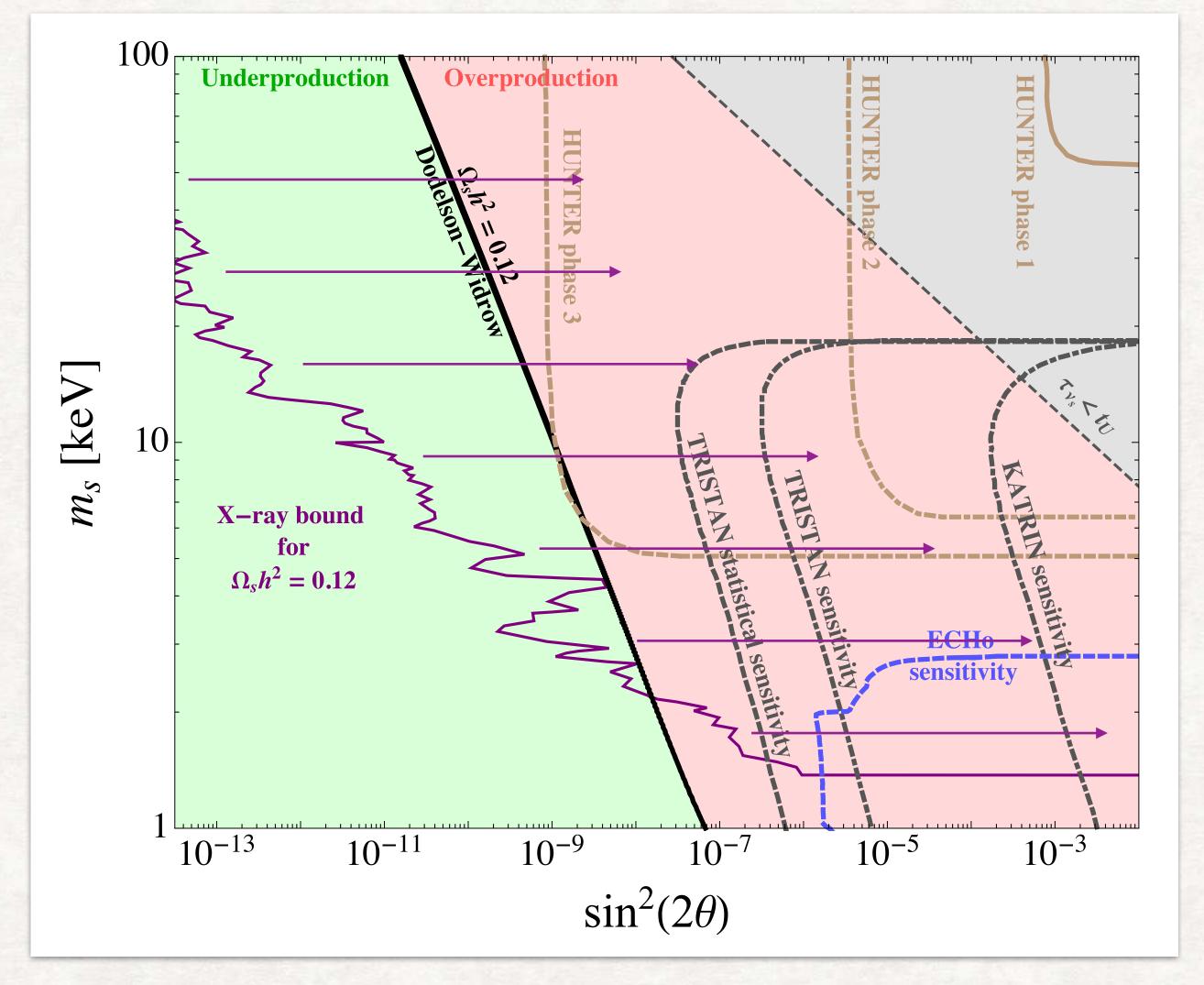
the WDM model does not fit the data at small scales and high redshift.

Cristina Benso

X-RAY BOUND: RELAXATION



X-RAY BOUND: RELAXATION



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

X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

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

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

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

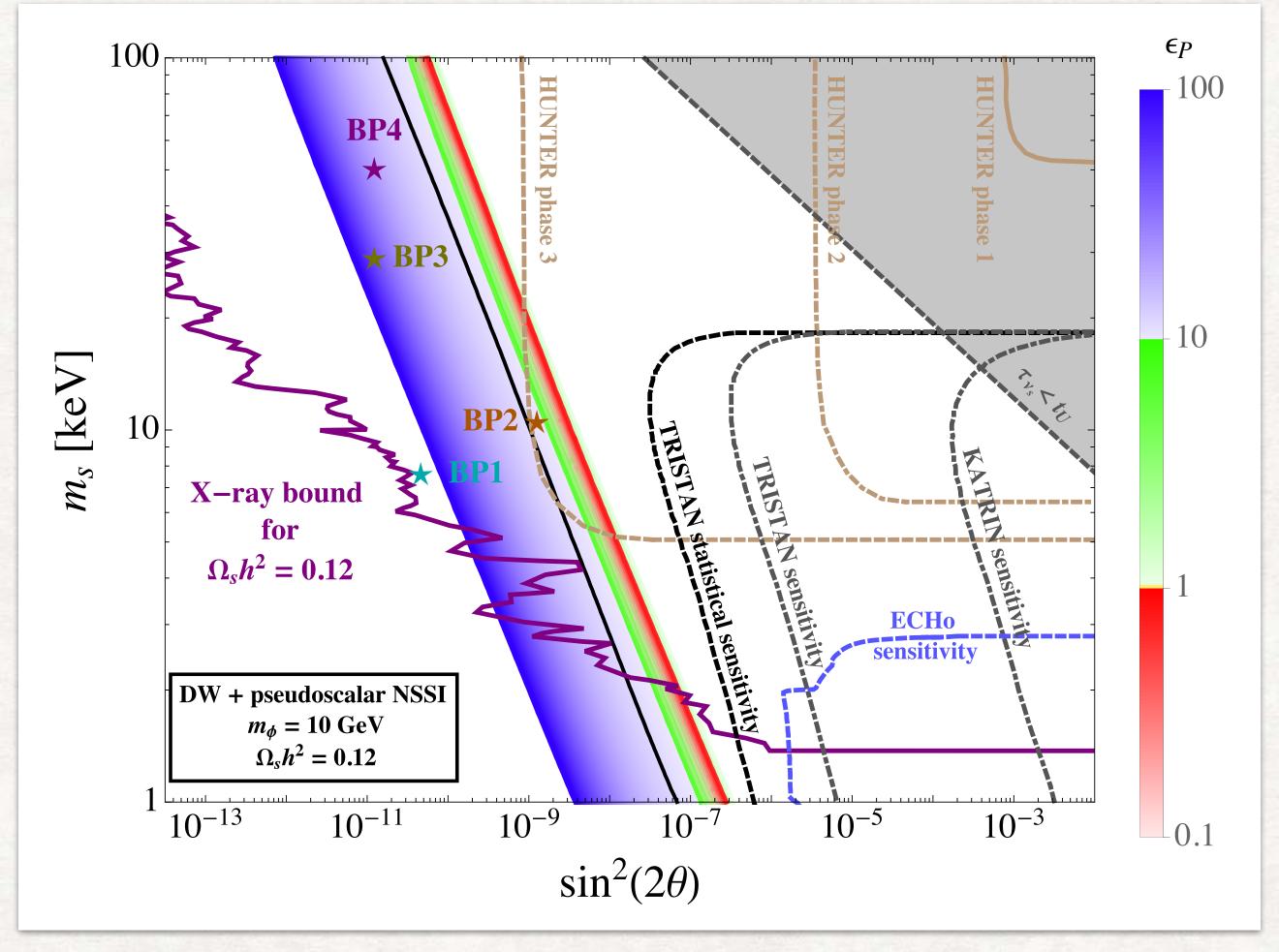
$$ho_s <
ho_{DM}$$
 corresponds to larger $\sin^2(2\theta)$ for the same flux F

Secondary advantage:

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

X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

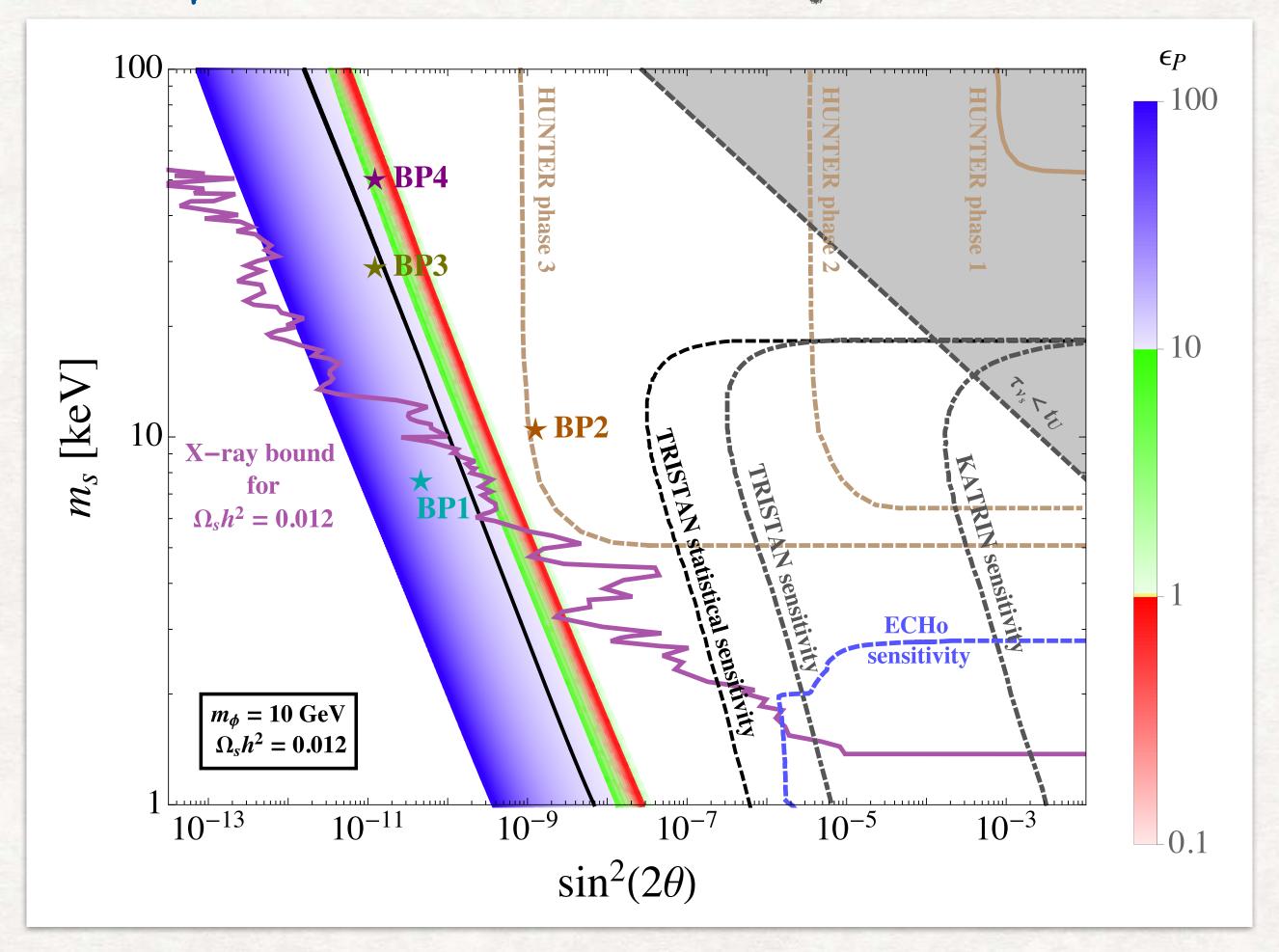
Sterile neutrino parameter space: 100% DM constituted by sterile neutrinos



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

X-RAY BOUND: RELAXATION IN THE DM COCKTAIL SCENARIO

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



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

Overview mixing framework using For. (3.12). The two-neutrino transition probabiling 11.1 Introduction to Non-Standard Neutrino Interactions (Denton) iven the wide interest in the worldwide mysitic pragram, it is timely to reassess they by the they have used typic at the art topics related to non-standard new particular government the art topics related to non-standard new particular government topics related to non-standard new particular government topics related to non-standard new particular government. resents an overview of NSIs and a number of in depth medgen analysis and a number of indepth medgen and a number of indepth medgen analysis and a number of indepth medgen analysis and a number of indepth medgen analysi lated topics presented at a recent workshop. have the following forms for NC and CO NSIVING HELF BUENCY the hold the neutrino sector in the form of new interactions beyond the SM intelling heuttings and Introduction to wear scalar a verband wheehavious coentratical units of short pareint ansition to repain typical units of \mathcal{L} and \mathcal{L} are an expectation of \mathcal{L} and \mathcal ave the following forms for NC and CC $\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}}\stackrel{\text{NSI}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}}\stackrel{\text{NSI}}}{\stackrel{\text{NSI}}}\stackrel{\text{NSI}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}\stackrel{\text{NSI}}}\stackrel{\text{NSI}}}$ $\mathcal{L}_{\text{NC}} = -2\sqrt{2}G_F f_{\lambda,\lambda}^{\text{F}} \mathcal{L}_{\alpha\beta}^{\text{F}} \mathcal{L}_{\alpha\beta}^{\text{F}} \mathcal{L}_{\alpha\beta}^{\text{F}} \mathcal{L}_{\beta}^{\text{F}} \mathcal$ Why are $\frac{1}{\sqrt{2}} = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}}$ here G_F is Fermi's constant and the ε terms quantify the directive of the work in the land of the t also identified elative to the weak scale. The sum is over mattern termional typically effect $\{1\}\{e,u,d\}$ $\frac{\Delta m^2 U \sin g}{u \cos g}$ this inequality we classify and $P \in \{P_L, P_R\}$ are the chirality projection operators uch a new interaction leads to a right phenomenology instablish testimentary. uso be reparameterized into vector and axial components of the interaction. NSIs were initially considered sostilling the interaction experiments income according to the initially considered sostilling the during the light of the interaction. NSIs were initially considered sostilling the interaction. NSIs were initially considered sostilling the interaction. NSIs were initially considered sostilling the interaction. NSIs were initially since of the interaction. NSIs were initially since of the initial way in the interaction. NSIs were initially since of the initial way in the conventional matter effect [1]. L/E which establishes the range of Δm to which an experiment is sensitive. Such a new interaction leads to a rich phenomenology in both scattering experiments and neutrino oscillation experiments [2–4]. Shortsubased inches selection experiments [2–4]. Shortsubased inches selection experiments [2–4]. The distinct from scattering phenomenology, the scaling that a fresh the experiment is only sensitive to mentary that a fresh experiment is only sensitive to mentary that a fresh experiment is only sensitive to mentary that the experiment is only sensitive to mentary the experiment in the experiment is only sensitive to mentary the experiment in the experiment is only sensitive to mentary the experiment in the experiment is only sensitive to mentary the experiment in the experiment is only sensitive to mentary the experiment in the experiment is only sensitive to mentary the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in the experiment is only sensitive to the experiment in

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

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