Impact of low reheating temperature and X-ray bound relaxation on sterile neutrino dark matter searches in terrestrial experiments

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OUTLINE

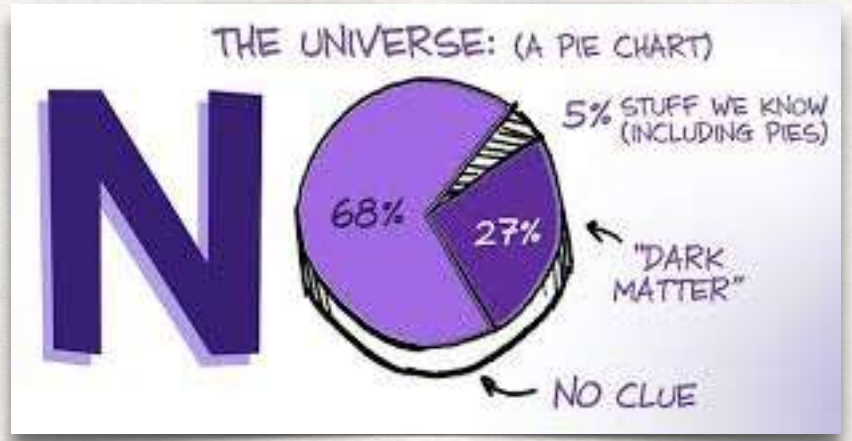
- Introduction on Dark Matter and Sterile Neutrinos
- Searches in terrestrial experiments & sensitivity to Sterile Neutrinos
- Dodelson-Widrow production
    - Overproduction and Critical Temperature
    - X-ray constraint relaxation: Cocktail & Cancellation
- Shi-Fuller production
- (CPT violation case)
- Conclusions

INTRODUCTION - DARK MATTER

DARK MATTER represents
a PUZZLE historically arisen AT LARGE SCALES
but
likely requiring SOLUTION at very small scales,
coming FROM PARTICLE PHYSICS

- ROTATION CURVES OF GALAXIES
- VELOCITY DISPERSION IN GALAXIES
- LARGE SCALE STRUCTURES FORMATION
- GRAVITATIONAL LENSING

[Bertone et al., hep-ph/0404175] [Clowe et al., astro-ph/0312273]



(Borrowed from J. Cham and Daniel Whiteson)

Combined cosmological and astrophysical observations made us aware of the content of the universe

Observations of galaxies, gravitational lensing phenomena and large scale structures provided hints about the features of a good DM candidate

STERILE NEUTRINO DARK MATTER

def: $\nu_s = \nu_{RH}$

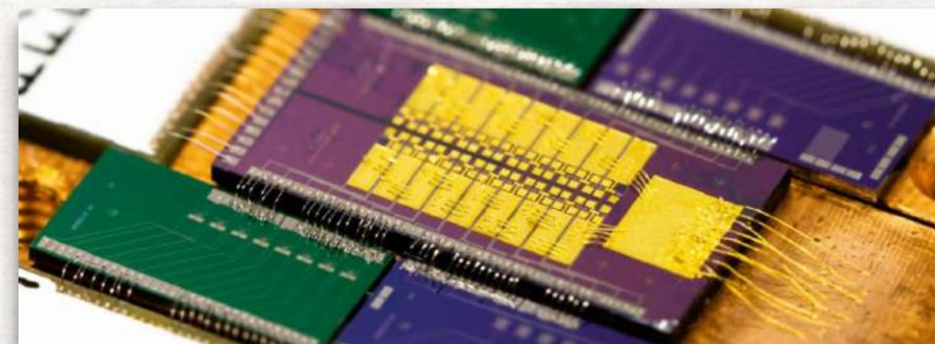
"sterile" because singlets with respect to any Standard Model interaction

GOOD DARK MATTER CANDIDATE	keV STERILE NEUTRINO
NO EM nor STRONG INTERACTION	√ by definition
MASSIVE	√ $\mathcal{O}(\mathrm{keV})$
STABLE on time scales comparable with the age of the universe	√ depending on its mixing with the active species
produced in the early universe with LOW ENOUGH VELOCITIES to be compatible with the l.s.s. formation	√ depending on the production mechanism

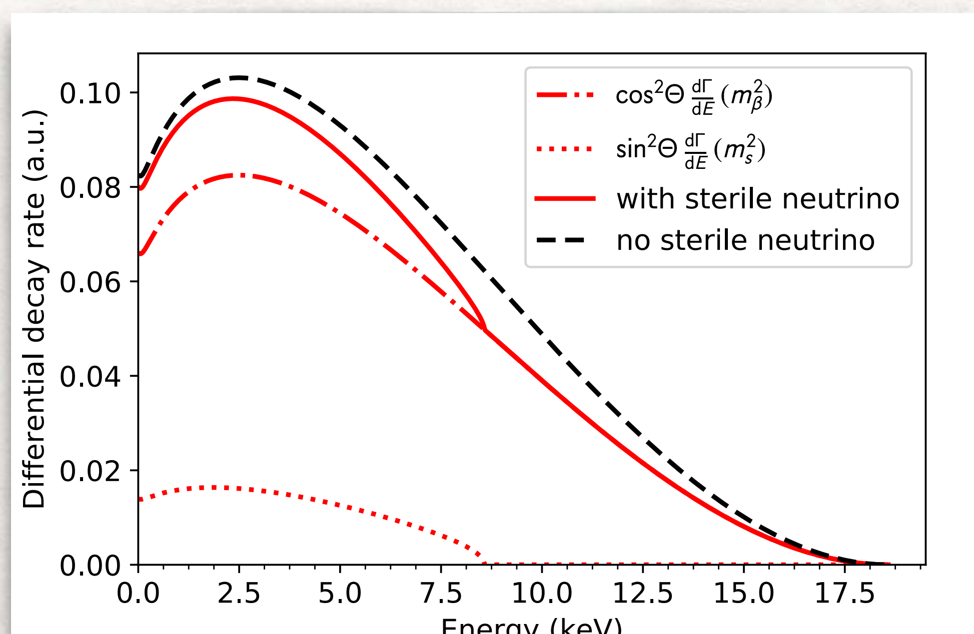
SEARCHES IN TERRESTRIAL EXPERIMENTS

Troitsk

ECHo



KATRIN



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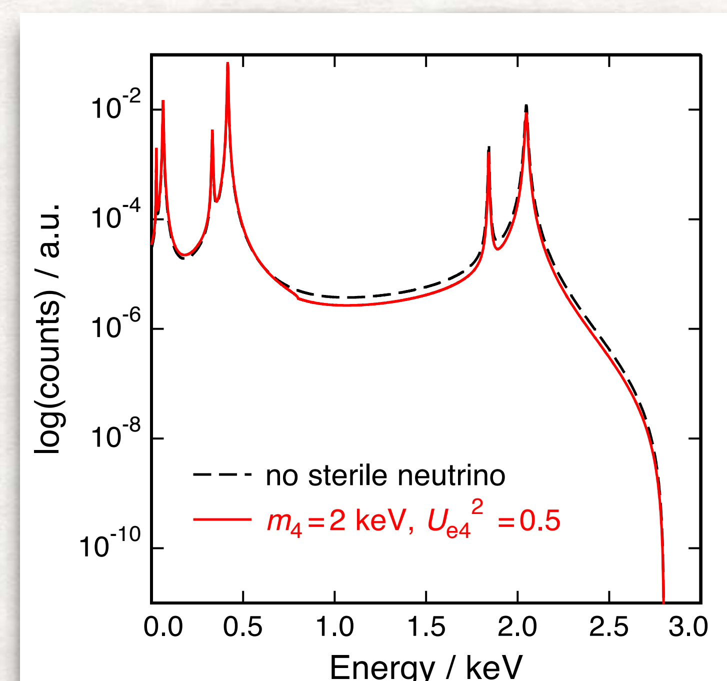

[M. Drewes, JCAP 1701 (2017) 025]

SEARCHES IN TERRESTRIAL EXPERIMENTS

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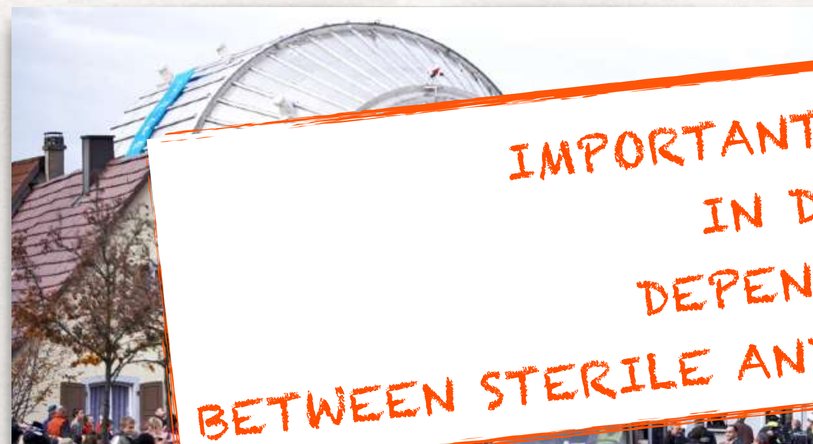
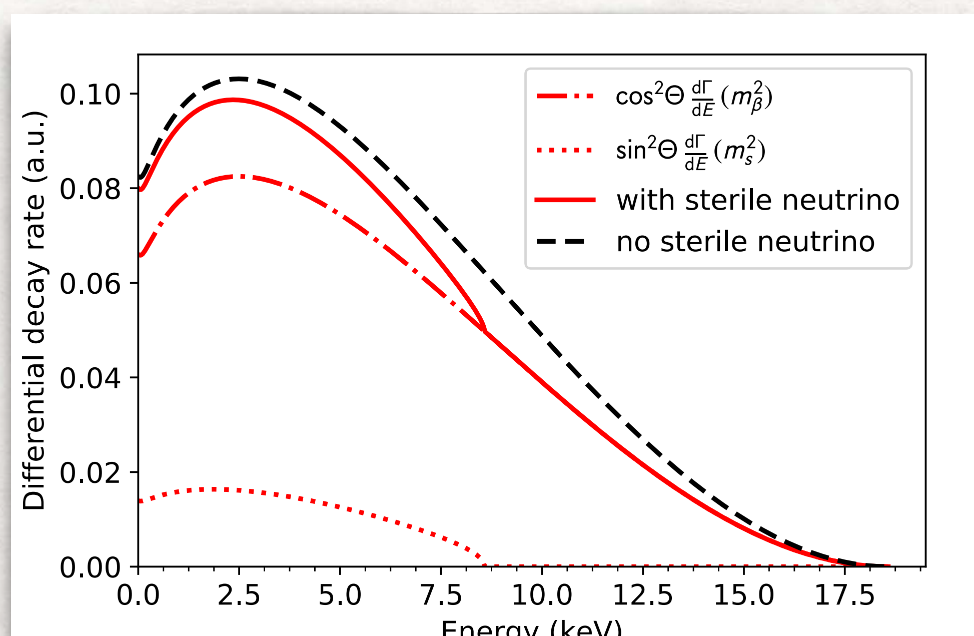


IMPORTANT: THE SUCCESS OF ALL THESE EXPERIMENTS
IN DETECTING KEV STERILE NEUTRINOS
DEPENDS ON THE MAGNITUDE OF THE MIXING
BETWEEN STERILE AND ACTIVE NEUTRINOS, THAT NEEDS TO BE QUITE LARGE



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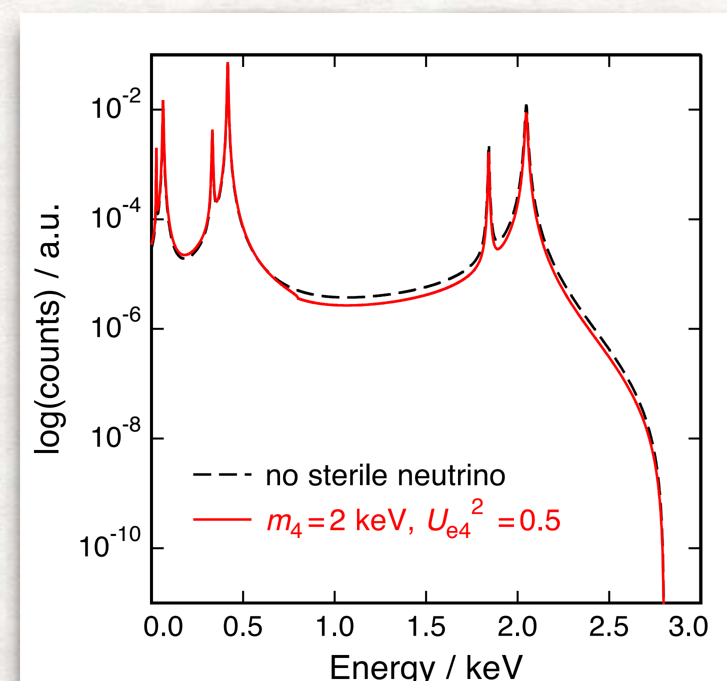


[M. Drewes, JCAP 1701 (2017) 025]

DODELSON-WIDROW PRODUCTION*

Hp: $\nu_s \leftrightarrow \nu_e$ (and $\overline{\nu}_s \leftrightarrow \overline{\nu}_e$) mixing

Hp: Production through oscillation and collisions:

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

Evolution of the distribution function $f_s(p,t)$ described by the BOLTZMANN EQUATION:

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

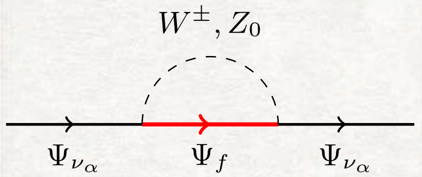
where $\Gamma_e(p) = c_e(p,T)\, G_F^2\, p\, T^4$

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

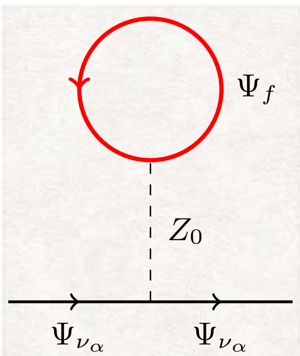
*[Dodelson and Widrow, Phys. Rev. Lett. 72 (1994) 17-20]

DODELSON-WIDROW PRODUCTION

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



(a) bubble diagram



(b) tadpole diagram

[Abazajian et al., Phys. Rev. D 64 (2001) 023501]

THERMAL POTENTIAL

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

ASYMMETRY POTENTIAL

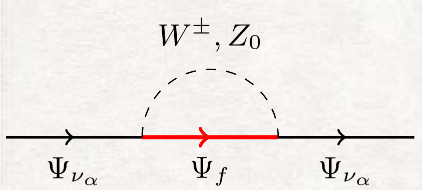
$$V_L(p) = \frac{2\sqrt{2}\,\zeta(3)}{\pi^2}\,G_{\mathrm{F}}T^3\,\mathcal{L}^\alpha$$

where

$$\mathcal{L}^\alpha \equiv 2L_{\nu_\alpha} + \sum_{\beta\neq\alpha} L_{\nu_\beta}$$ and $$L_{\nu_\alpha} = \frac{(n_{\nu_\alpha} - n_{\overline{\nu}_\alpha})}{n_\gamma}$$

DODELSON-WIDROW PRODUCTION

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



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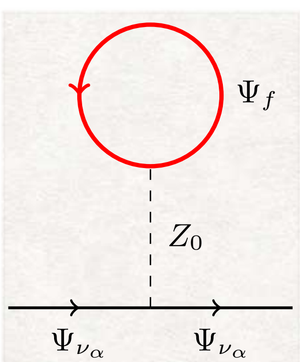

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ASYMMETRY POTENTIAL

$$V_L(p) = \frac{2\sqrt{2}\,\zeta(3)}{\pi^2} G_F T^3 \mathcal{L}^\alpha = 0$$

in the non resonant production

since $$L_{\nu_\alpha} = \frac{(n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})}{n_\gamma} = 0$$

DODELSON-WIDROW PRODUCTION

We are able to solve the Boltzmann equation and get

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

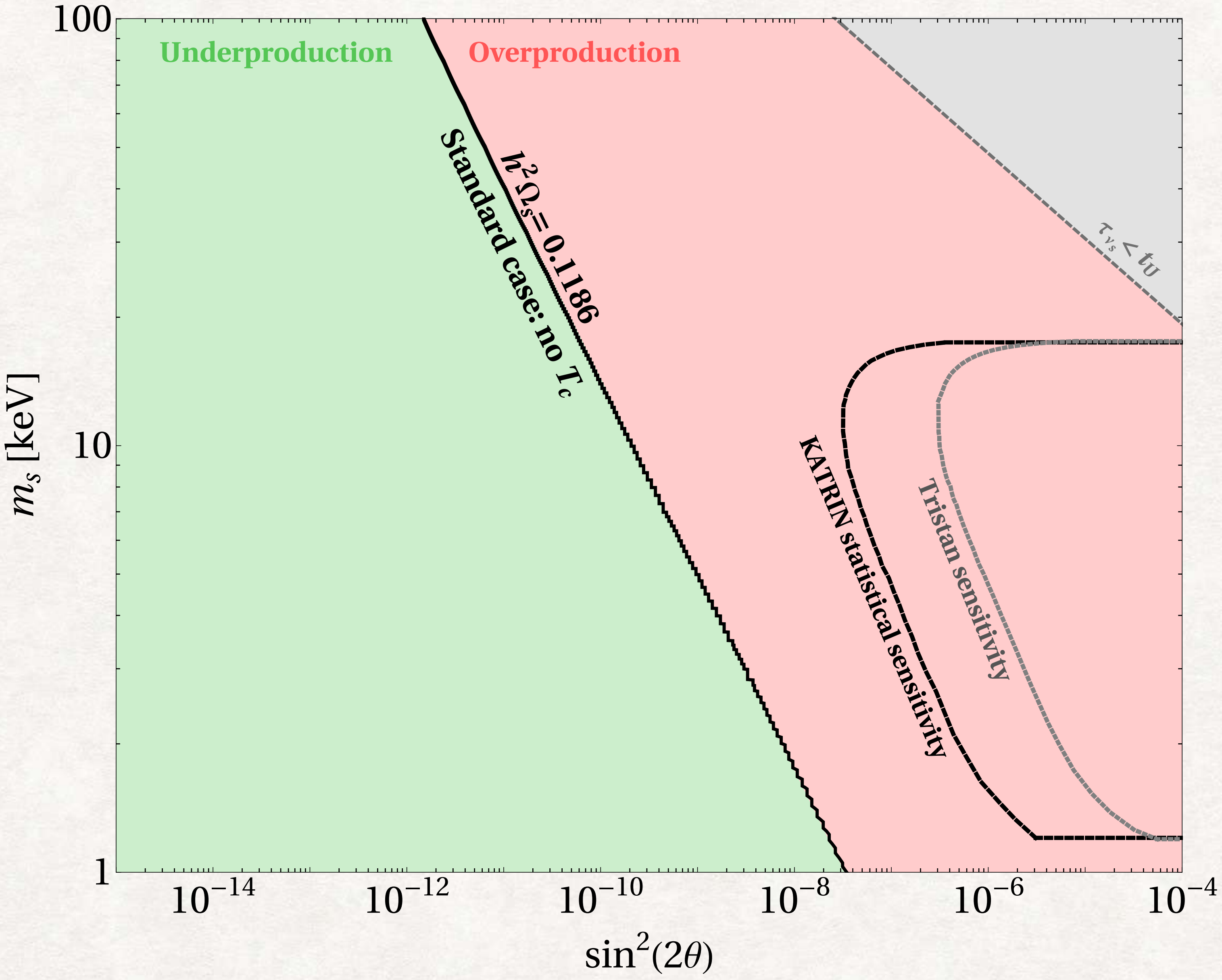
For non relativistic relic $h^2\,\Omega = \dfrac{s_0\,m}{\rho_c/h^2} Y_0$

where the yield is $Y = \dfrac{n}{s}$ and $n(T) = \dfrac{g}{(2\pi)^3}\displaystyle\int_{-\infty}^{+\infty} d^3p\, f(p,T)$

→ Sterile neutrino dark matter abundance

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

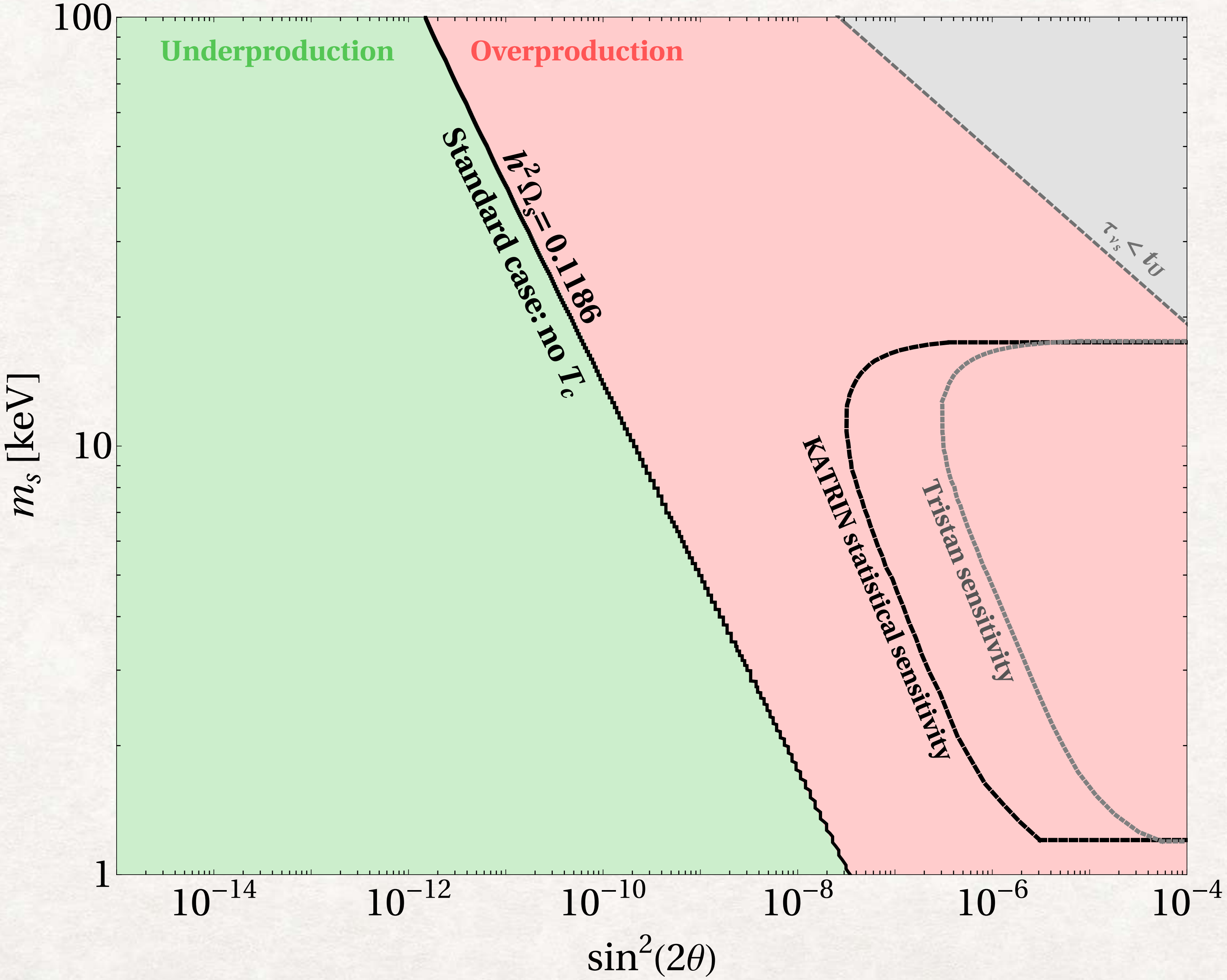
Critical Temperature



Critical Temperature

In the Dodelson-Widrow case the production peaks at

$$T = T_{max} \simeq 133 \left(\frac{m_s}{\text{keV}}\right)^{1/3} \text{MeV}$$



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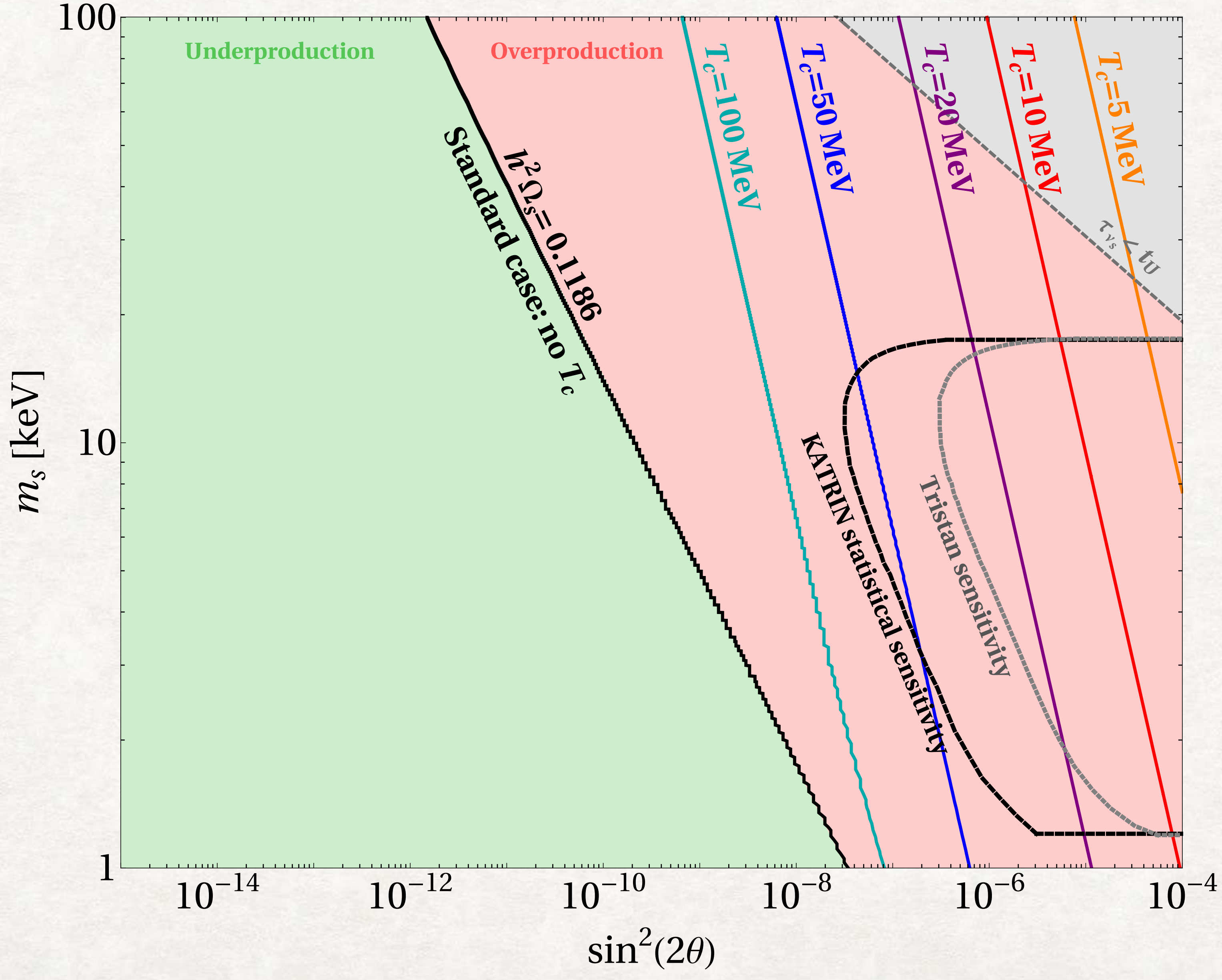


Critical Temperature

NEW SCALE in the primeval universe

- LOW REHEATING TEMPERATURE

The production of sterile neutrinos started at lower temperatures than the peak one because the universe never reached T_max

- SCALE OF THE DYNAMICAL CHANGE OF m_s

$$\sin^2(2\theta_M) = \frac{m_D^2}{m_D^2 + [c\,\Gamma_\alpha\, E/m_s \,+\, m_s/2]^2}$$

with

$$m_D \simeq \theta\, m_s$$

$$c \approx 63$$

$$\Gamma_\alpha(p) = c_\alpha(T) G_F^2 T^4 p$$

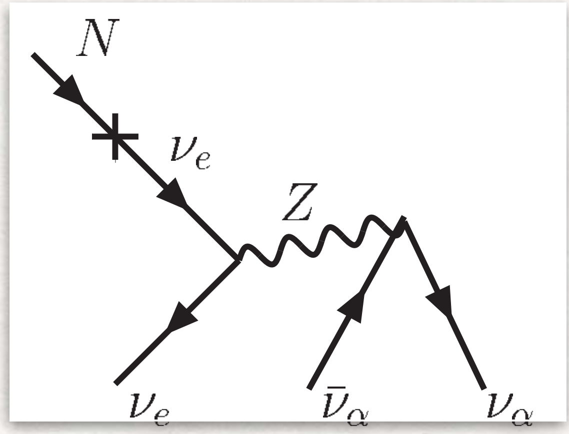
- PHASE TRANSITION CASE : $m_s^{(T>T_c)} = 0$

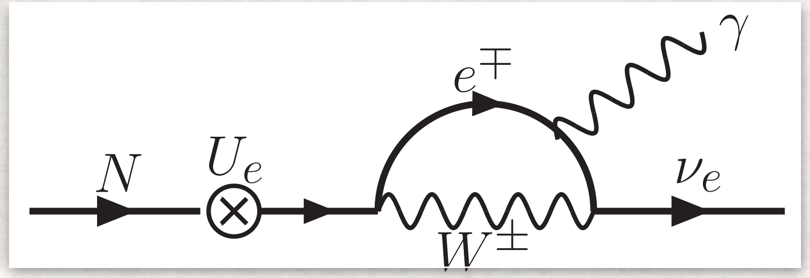
- MISALIGNMENT MECHANISM CASE : $m_s^{(T>T_c)} \gg m_s^{\text{today}}$

[Bezrukov et al., JCAP 06, 051 (2017)]

X-RAY CONSTRAINT

Decay channels for sterile neutrinos





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

$$\Gamma_{\nu_s \to \nu\gamma} = \frac{9\,\alpha\, G_F^2}{1024\,\pi^4} \sin^2(2\theta)\, m_s^5 \simeq 5.5 \times 10^{-22}\, \theta^2 \left(\frac{m_s}{\mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

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

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

Upper bounds on mass and mixing angle from the X-rays observations

Exp: XMM-Newton, Chandra, Suzaku, Swift, INTEGRAL, HEAO-1, Fermi/GBM

X-ray Constraint Relaxation - DM Cocktail

OBSERVABLE : Flux of photons

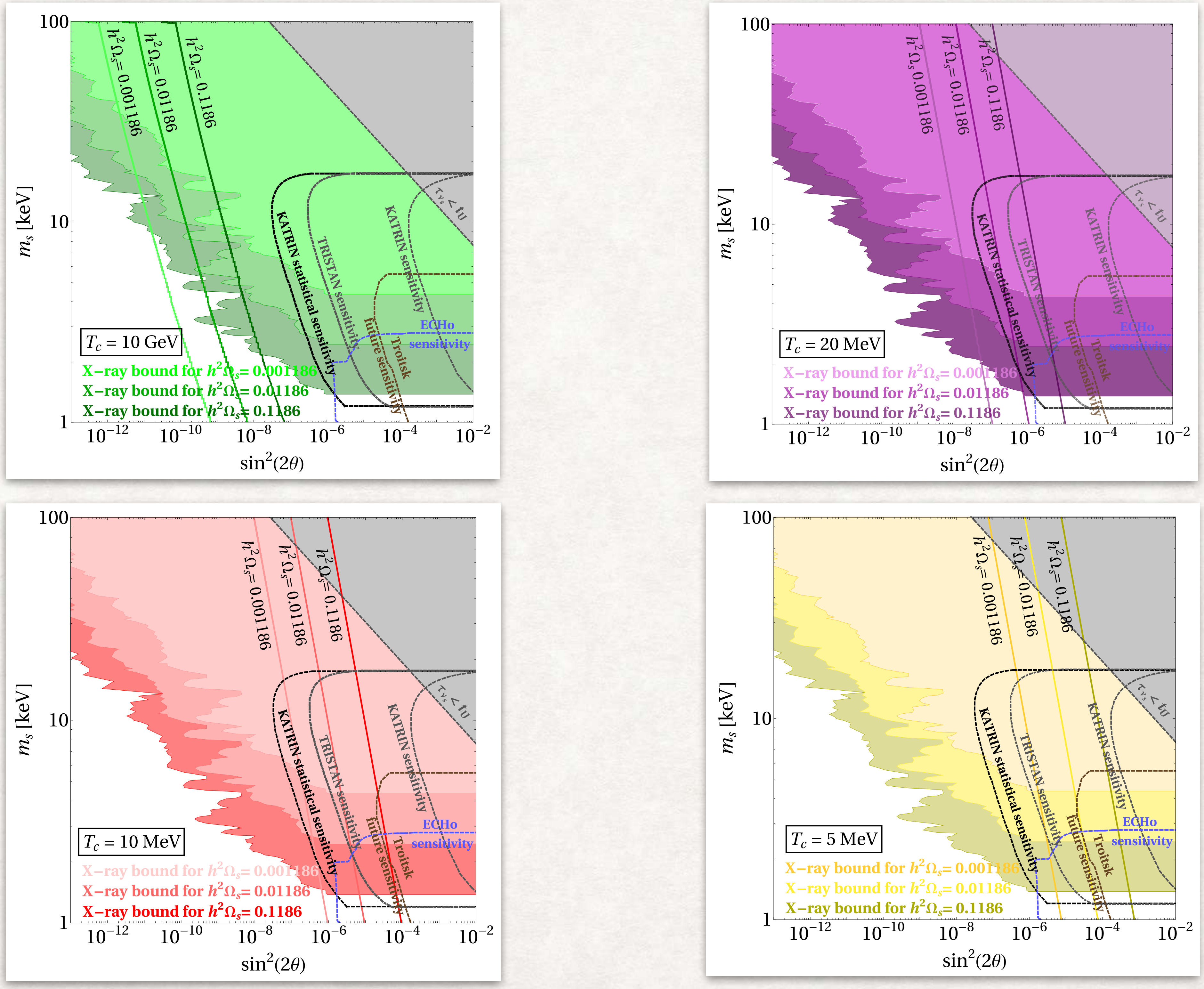
$$F = \frac{\Gamma_{\nu_s \to \nu\gamma}}{4\pi m_s} \int dl\, d\Omega\, \rho_{\rm DM}(l,\Omega)$$

The first possibility to get a relaxed constraint from the X-rays observations is to hypothesize that ONLY A FRACTION OF THE DARK MATTER content of the universe is CONSTITUTED BY STERILE NEUTRINOS

$\rho_s < \rho_{DM}$ allows larger $\sin^2(2\theta)$ and m_s

Secondary advantage:
multicomponent dark matter allows in principle more freedom also from other constraint coming for example from large scale structures

X-ray Constraint Relaxation - DM Cocktail



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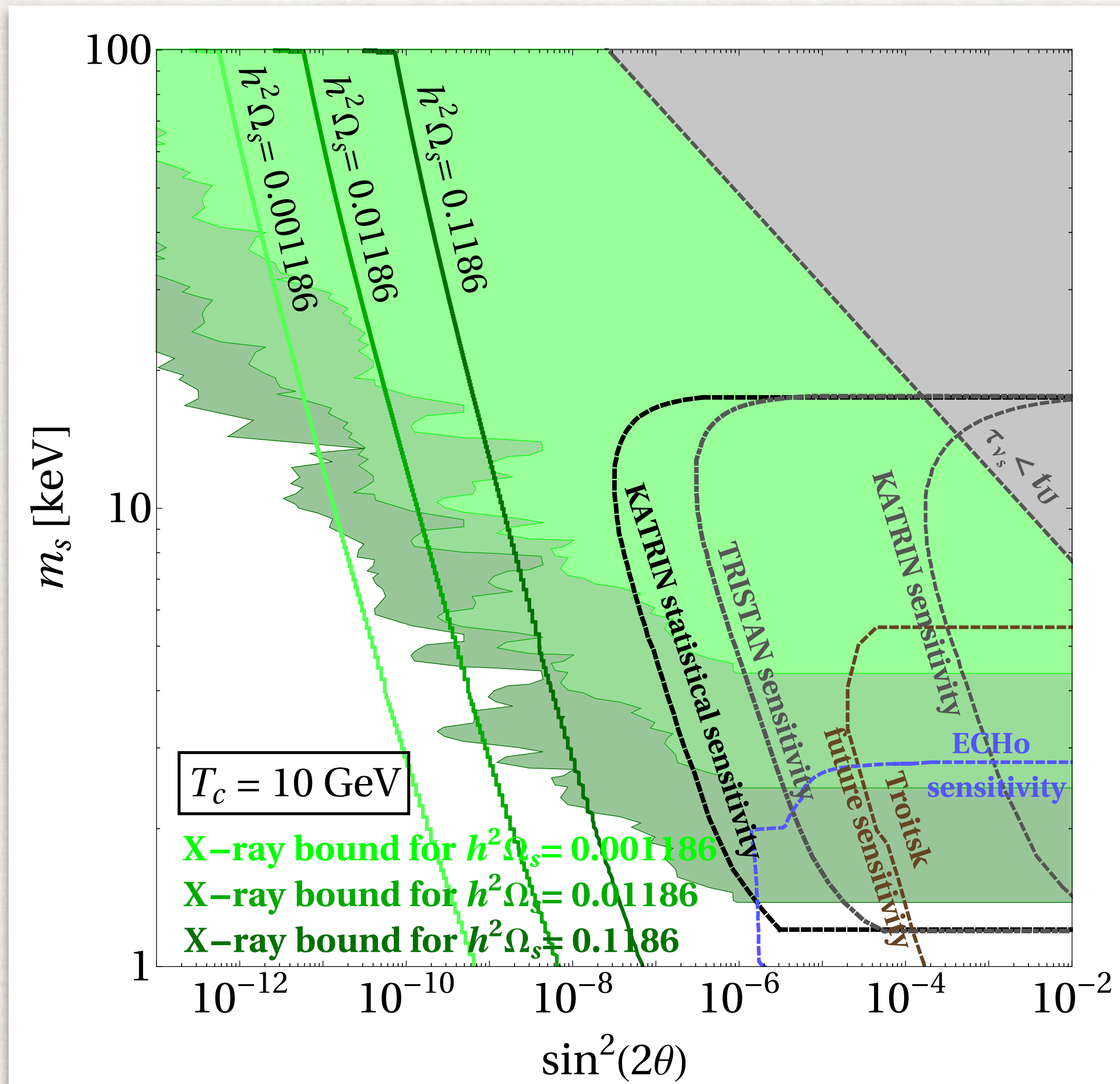
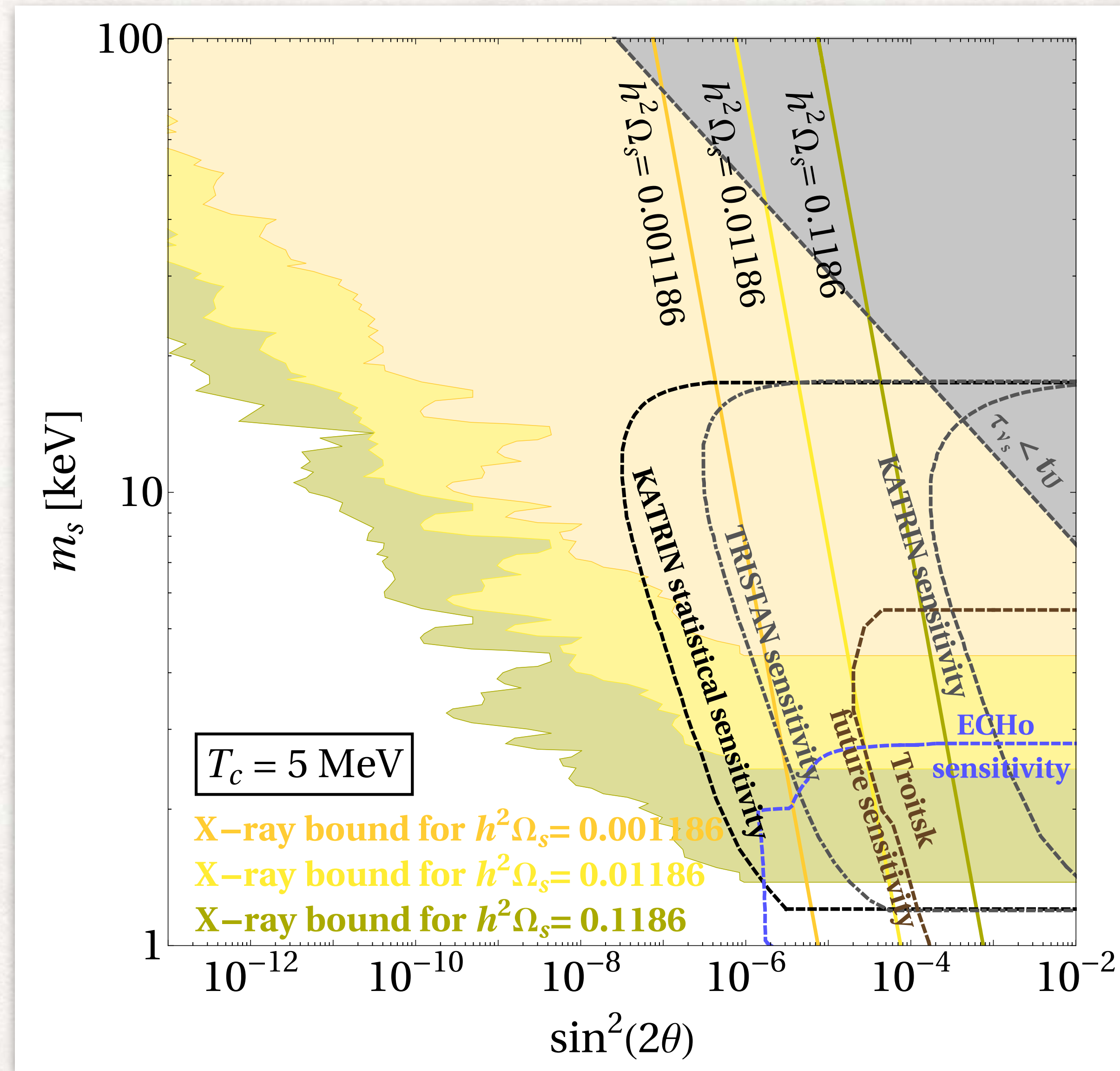




[CB, V. Brdar, M. Lindner, W. Rodejohann, Phys. Rev. D 100 (2019) 11, 115035]

X-ray Constraint Relaxation - Reduced Decay Rate

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

The second possibility to get a relaxed constraint from the X-rays observations is to hypothesize that the DECAY RATE determined by the mixing angle and the mass IS REDUCED

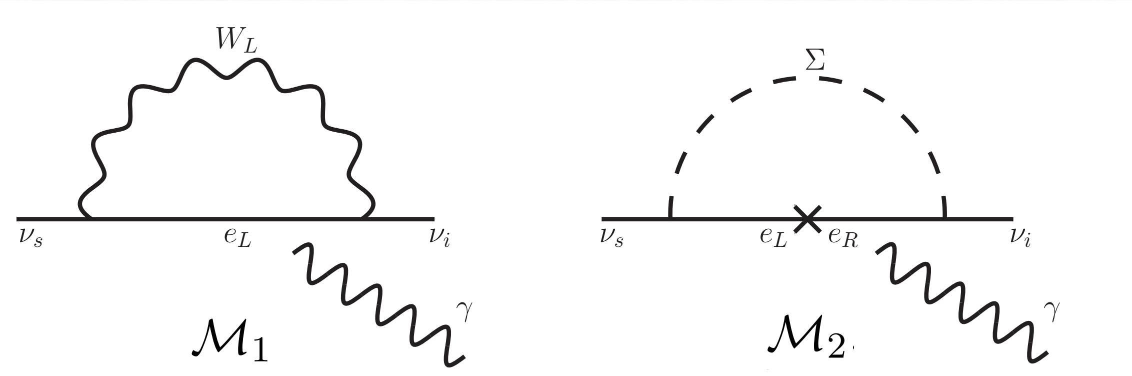
$\Gamma \propto \int d\mathrm{Phase}\, |\mathcal{M}|^2$ reduced if $|\mathcal{M}|^2$ reduced

This can be achieved if we consider the contribution of two diagrams with the same initial and final state and such that

$\mathcal{M} \to \mathcal{M}_1 + \mathcal{M}_2$ where $|\mathcal{M}|^2 < |\mathcal{M}_1 + \mathcal{M}_2|^2$

X-ray Constraint Relaxation - Reduced Decay Rate

Particular realization:



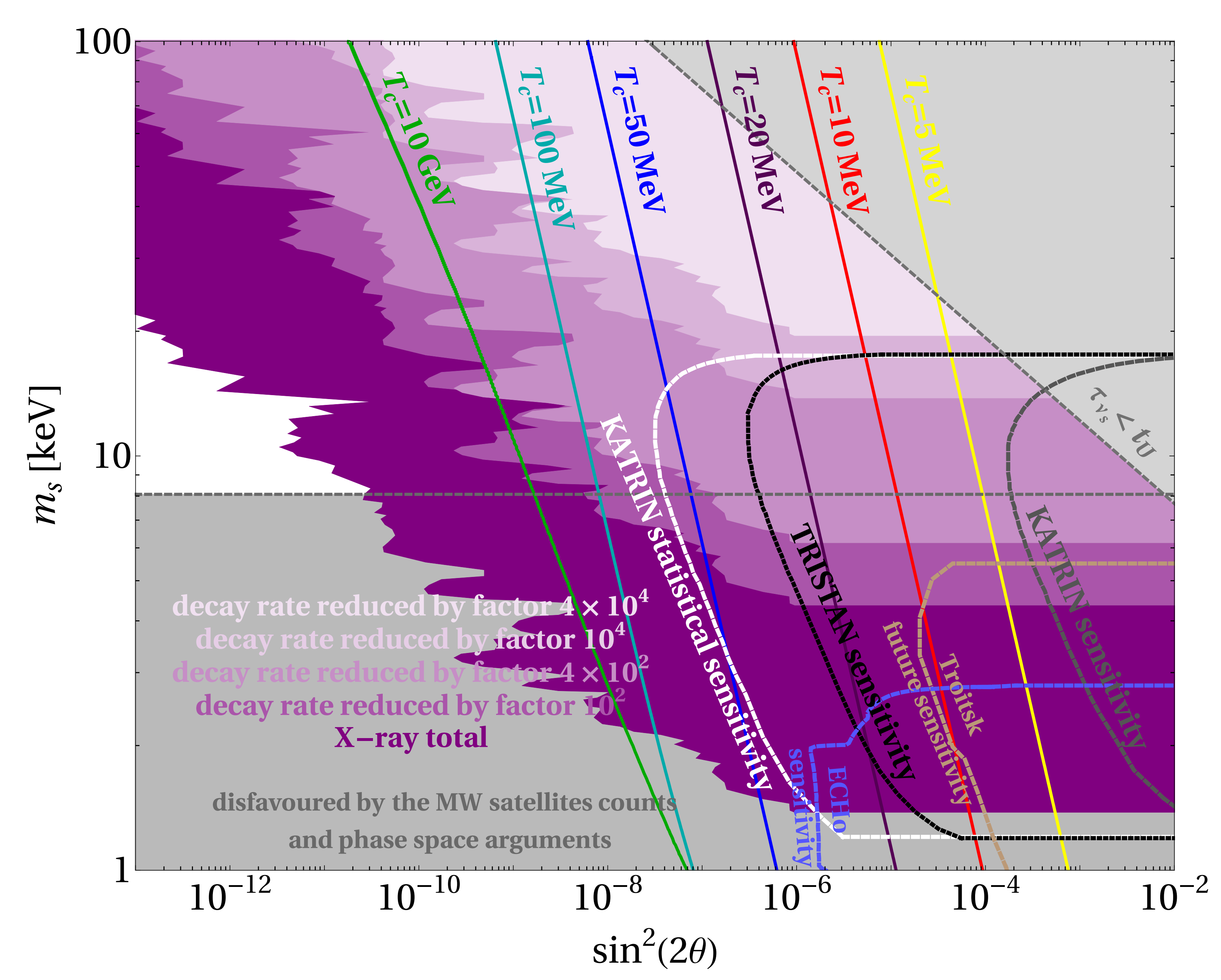
Adding a heavy scalar Σ and 3 new parameters $\lambda, \lambda', m_\Sigma$

It is possible to have partial or even complete cancellation if

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

Warning: Σ must not reach the thermal equilibrium in the early universe $\leftrightarrow$ $\begin{cases} \lambda \lesssim 10^{-7} \\ \text{or} \\ T_{RH} < m_\Sigma \sim 1 \text{ TeV} \end{cases}$

X-ray Constraint Relaxation - Reduced Decay Rate



[CB, V. Brdar, M. Lindner, W. Rodejohann, Phys. Rev. D 100 (2019) 11, 115035]

RESONANT PRODUCTION - SHI-FULLER CASE*

Hp: $L_{\nu_e} \neq 0$

⟶ depending on the sign of the asymmetry, the production of sterile neutrinos or antineutrinos was enhanced for specific values of p and T as a consequence of the resonance in the denominator of $\sin^2(2\theta_M)$

$$h^2\,\Omega_s = \frac{s_0\,m_s}{\rho_c/h^2}\frac{45}{(2\pi)^4}\frac{M_{\rm Pl}}{1.66\,g_{*s}\sqrt{g_*}}\int_0^\infty dr\,r^2\int_{T_{\rm fin}}^{T_{\rm in}}\frac{dT}{T^3}\times$$

$$\left[\frac{\Gamma_e(r,T)\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)}{\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)+\left(\frac{\Gamma_e}{2}\right)^2+\left(\frac{m_s^2}{2\,r\,T}-V_{\nu_s}\right)^2}+\frac{\Gamma_e(r,T)\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)}{\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)+\left(\frac{\Gamma_e}{2}\right)^2+\left(\frac{m_s^2}{2\,r\,T}-V_{\bar\nu_s}\right)^2}\right]$$

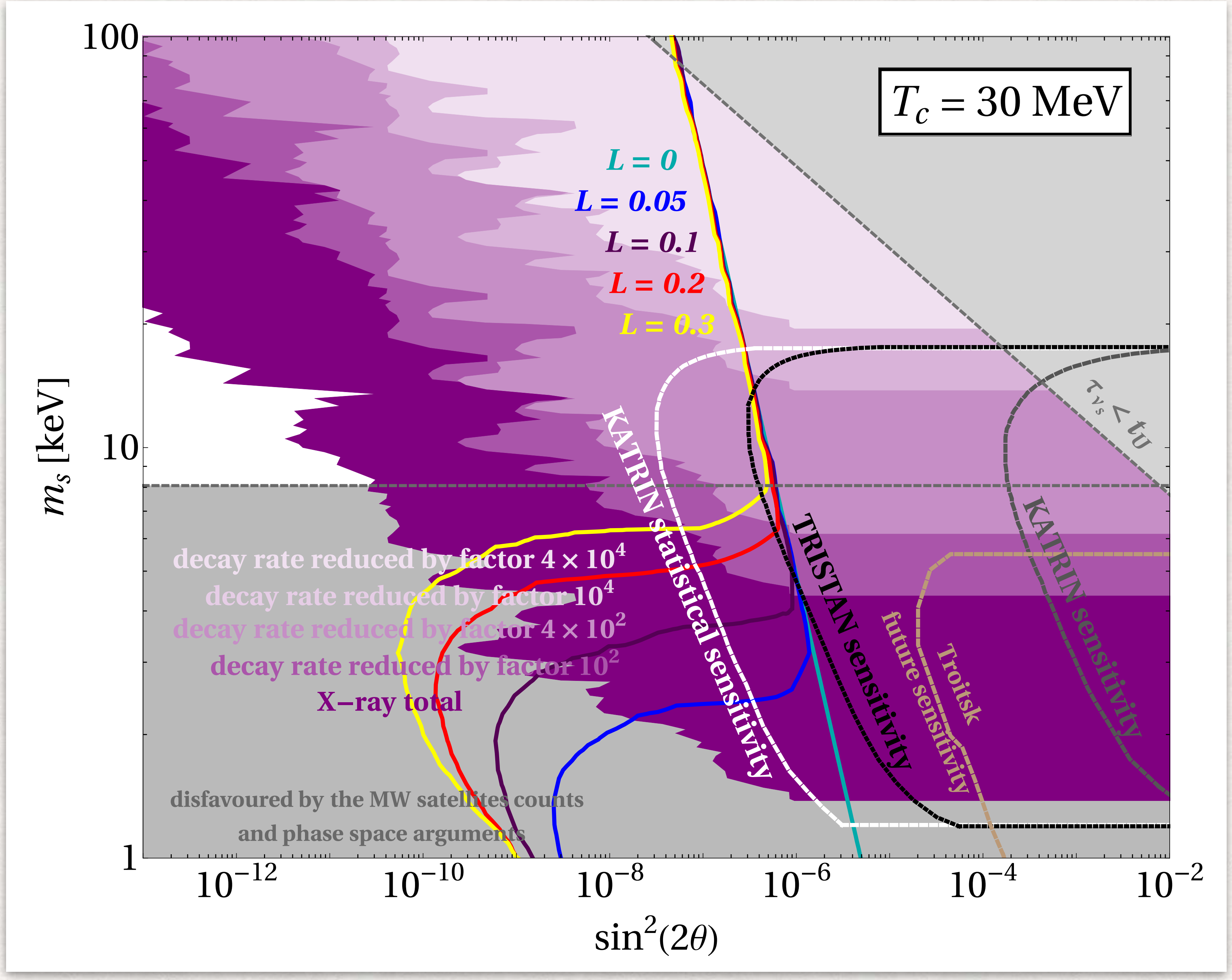
where

$$V_{\nu_s}(p) = +\sqrt{2}G_F\frac{2\,\zeta(3)\,T^3}{\pi^2}\frac{\eta_B}{4}-\frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e}+\rho_{\bar\nu_e})-\frac{8\sqrt{2}\,G_F\,p}{3m_W^2}(\rho_{e^-}+\rho_{e^+})+\frac{2\sqrt{2}\,\zeta(3)}{\pi^2}\,G_{\rm F}T^3\times L_e$$

$$V_{\bar\nu_s}(p) = -\sqrt{2}G_F\frac{2\,\zeta(3)\,T^3}{\pi^2}\frac{\eta_B}{4}-\frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e}+\rho_{\bar\nu_e})-\frac{8\sqrt{2}\,G_F\,p}{3m_W^2}(\rho_{e^-}+\rho_{e^+})-\frac{2\sqrt{2}\,\zeta(3)}{\pi^2}\,G_{\rm F}T^3\times L_e$$

*[Shi and Fuller, astro-ph/9810076]

SHI-FULLER CASE



[CB, V. Brdar, M. Lindner, W. Rodejohann, Phys. Rev. D 100 (2019) 11, 115035]

CPT VIOLATION CASE

Hp: $L_{\nu_e} \neq 0$

Hp: because of CPT symmetry violation,
$\overline{\nu}_s \leftrightarrow \overline{\nu}_e$ mixing but $\nu_s \not\leftrightarrow \nu_e$

→ DARK MATTER composed by ONLY STERILE ANTINEUTRINOS that experienced a suppression of the production in presence of a lepton asymmetry that on the contrary would enhance the production of sterile neutrinos.

$$h^2\,\Omega_s = \frac{s_0\,m_s}{\rho_c/h^2}\,\frac{45}{(2\pi)^4}\,\frac{M_{\rm Pl}}{1.66\,g_{*s}\sqrt{g_*}}\int_0^\infty dr\,r^2\int_{T_{\rm fin}}^{T_{\rm in}}\frac{dT}{T^3}\left[\frac{\Gamma_e(r,T)\left(\frac{m_s^2}{2\,r\,T}\right)^2\,\sin^2(2\theta)}{\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)+\left(\frac{\Gamma_e}{2}\right)^2+\left(\frac{m_s^2}{2\,r\,T}-V_{\overline{\nu}_s}\right)^2}\right]$$

with

$$V_{\overline{\nu}_s}(p) = -\sqrt{2}G_F\,\frac{2\,\zeta(3)\,T^3}{\pi^2}\,\frac{\eta_B}{4} - \frac{8\sqrt{2}\,G_F\,p}{3m_Z^2}(\rho_{\nu_e}+\rho_{\overline{\nu}_e}) - \frac{8\sqrt{2}\,G_F\,p}{3m_W^2}(\rho_{e^-}+\rho_{e^+}) - \frac{2\sqrt{2}\,\zeta(3)}{\pi^2}\,G_{\rm F}T^3\times L_e$$

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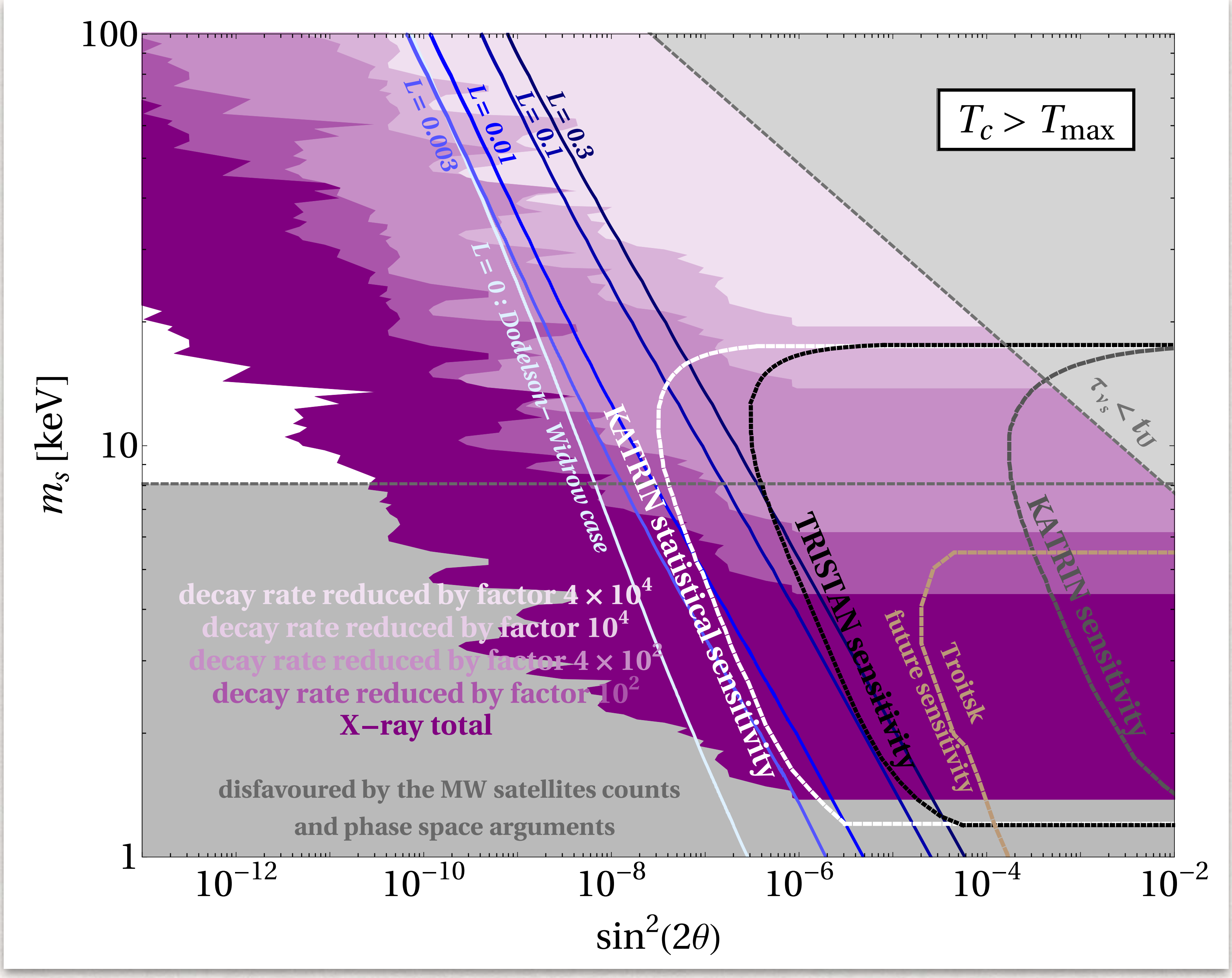
CPT VIOLATION CASE



[CB, V. Brdar, M. Lindner, W. Rodejohann, Phys. Rev. D 100 (2019) 11, 115035]

CONCLUSIONS

- Constraints coming from the X-ray observations and measured Ω_{DM} can cause problems in the detection at TERRESTRIAL EXPERIMENTS of keV sterile neutrino dark matter produced through oscillation and collisions
- It is possible to efficiently RELAX THE X-RAY BOUND both in the Dark Matter Cocktail scenario and in the case of two (or more) decay channels for the keV sterile neutrino
- The introduction of a CRITICAL TEMPERATURE, in a non standard cosmological scenario or related to a new scale concerning the sterile neutrino mass, allows to have larger values of mixing angles
- The combination of these two methods sets available again the region of the parameter space in which we expect the TERRESTRIAL EXPERIMENTS to become sensitive in the near future to signals of keV sterile neutrino dark matter produced through both the Dodelson-Widrow and the Shi-Fuller mechanism.

THANK YOU FOR THE ATTENTION!