keV Sterile Neutrino Dark Matter Terrestrial Searches:
Alive and Well

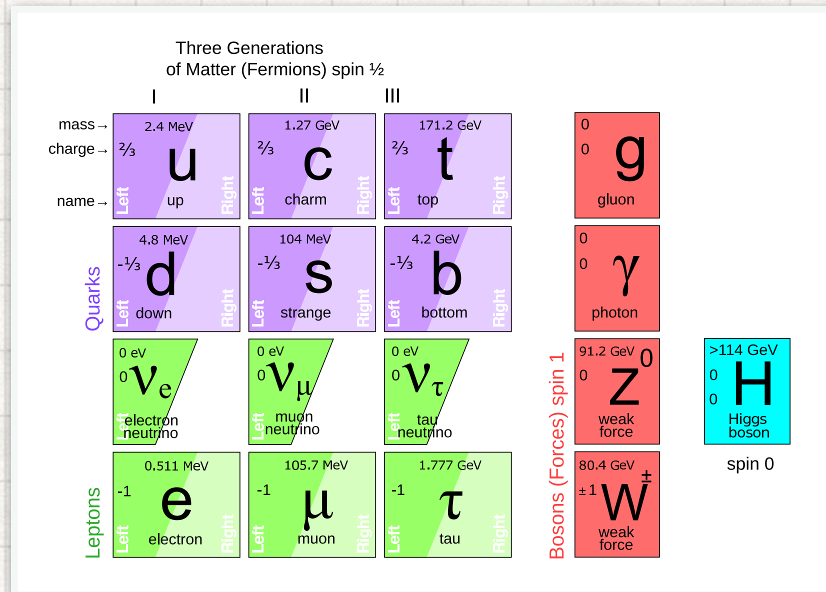
NeuTel2021

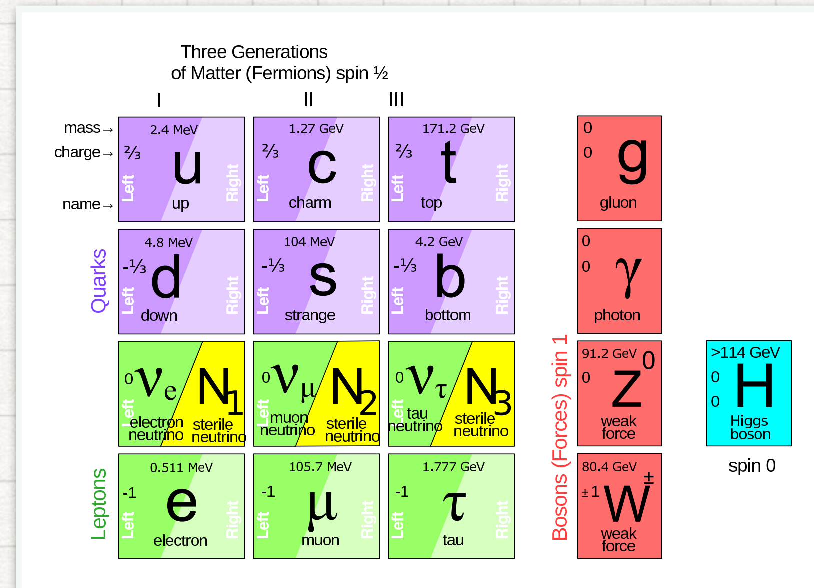
Cristina Benso
Max Planck Institute for Nuclear Physics - Heidelberg

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

IMPRS PTFS

STERILE NEUTRINO DARK MATTER





[M. Shaposhnikov, J. Phys. Conf. Ser. 408 (2013)]

SM

SM + sterile neutrinos

Only interacting (mixing) with the active neutrinos:

- good Dark Matter candidate ($m_s\ \mathcal{O}(\mathrm{keV})$)
- produced thanks to the mixing via oscillations and collisions
- detectable (hopefully) through the mixing

DODELSON - WIDROW* mechanism

SHI - FULLER** mechanism

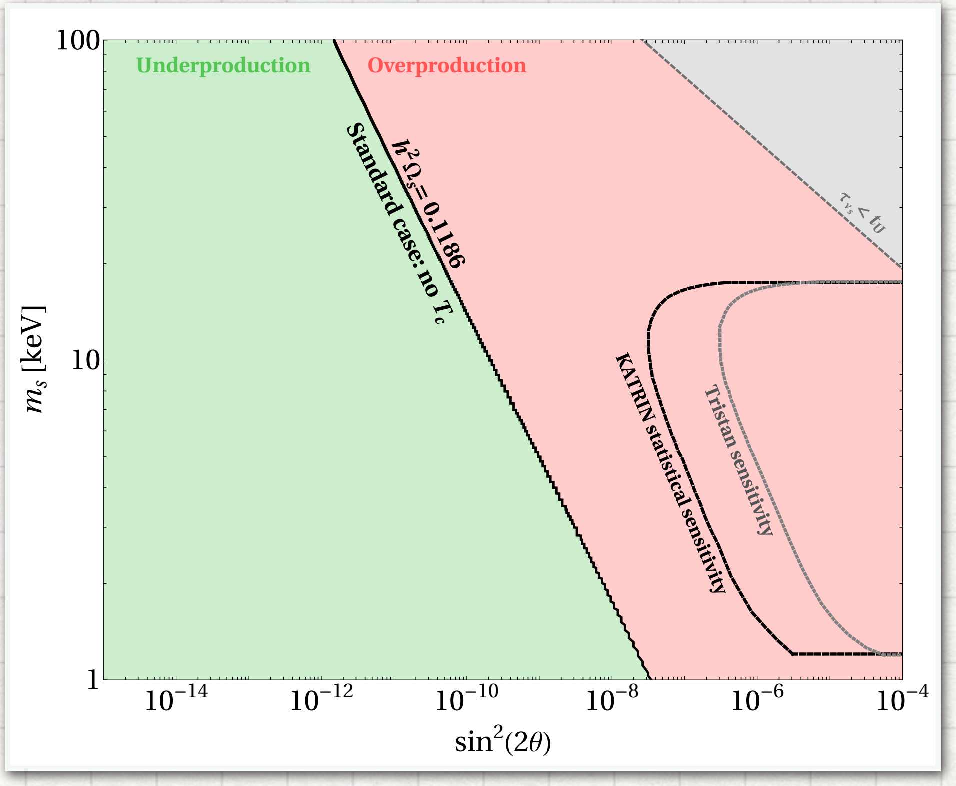
*[Dodelson and Widrow, Phys. Rev. Lett. 72 (1994) 17-20]

**[Shi and Fuller, Phys. Rev. Lett. 82 (1999) 2832-2835]

STERILE NEUTRINO ABUNDANCE CONSTRAINT

Problem with production through oscillation and collisions:

the line that represents the combination of mass and mixing that gives the right amount of DM today is too far from the region where we expect near future experiments to be sensitive

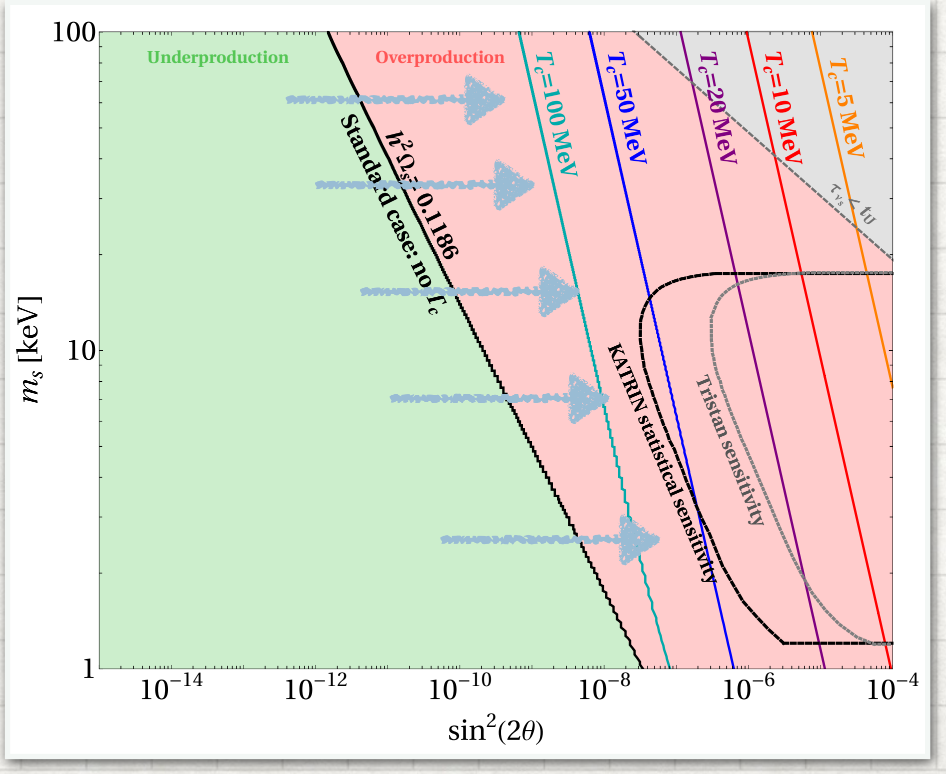


Remember peak in the production at

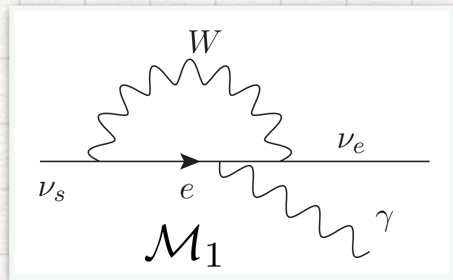
$$T = T_{max} \simeq 133 \left(\frac{m_s}{\text{keV}}\right)^{1/3} \text{MeV}$$

Solution: consider non standard scenario where sterile neutrino dark matter production started at CRITICAL TEMPERATURE $T_c < T_{max}$

→ SHIFT TOWARDS THE SENSITIVITY REGION



X-RAYS CONSTRAINT



$$\Gamma_{\nu_s \to \nu\gamma} = \frac{9\,\alpha\,G_F^2}{1024\,\pi^4}\sin^2(2\theta)\,m_s^5$$

→ Constraint on $\sin^2(2\theta_M)$ and m_s from the non observation of the monochromatic line in the x-ray band

OBSERVABLE : Flux of photons

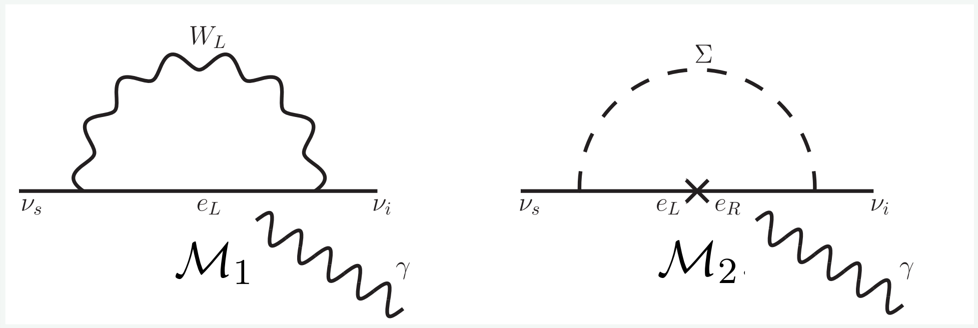
$$F = \frac{\Gamma_{\nu_s\to\nu\gamma}}{4\pi m_s}\int dl\,d\Omega\,\rho_{\rm DM}(l,\Omega)$$

← The constraint is relaxed if the decay rate is reduced: if $|\mathcal{M}|^2$ is reduced.

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

$$\mathcal{M}_1 \to \mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 \quad \text{and} \quad |\mathcal{M}|^2 = |\mathcal{M}_1+\mathcal{M}_2|^2 < |\mathcal{M}_1|^2$$

Particular realization:

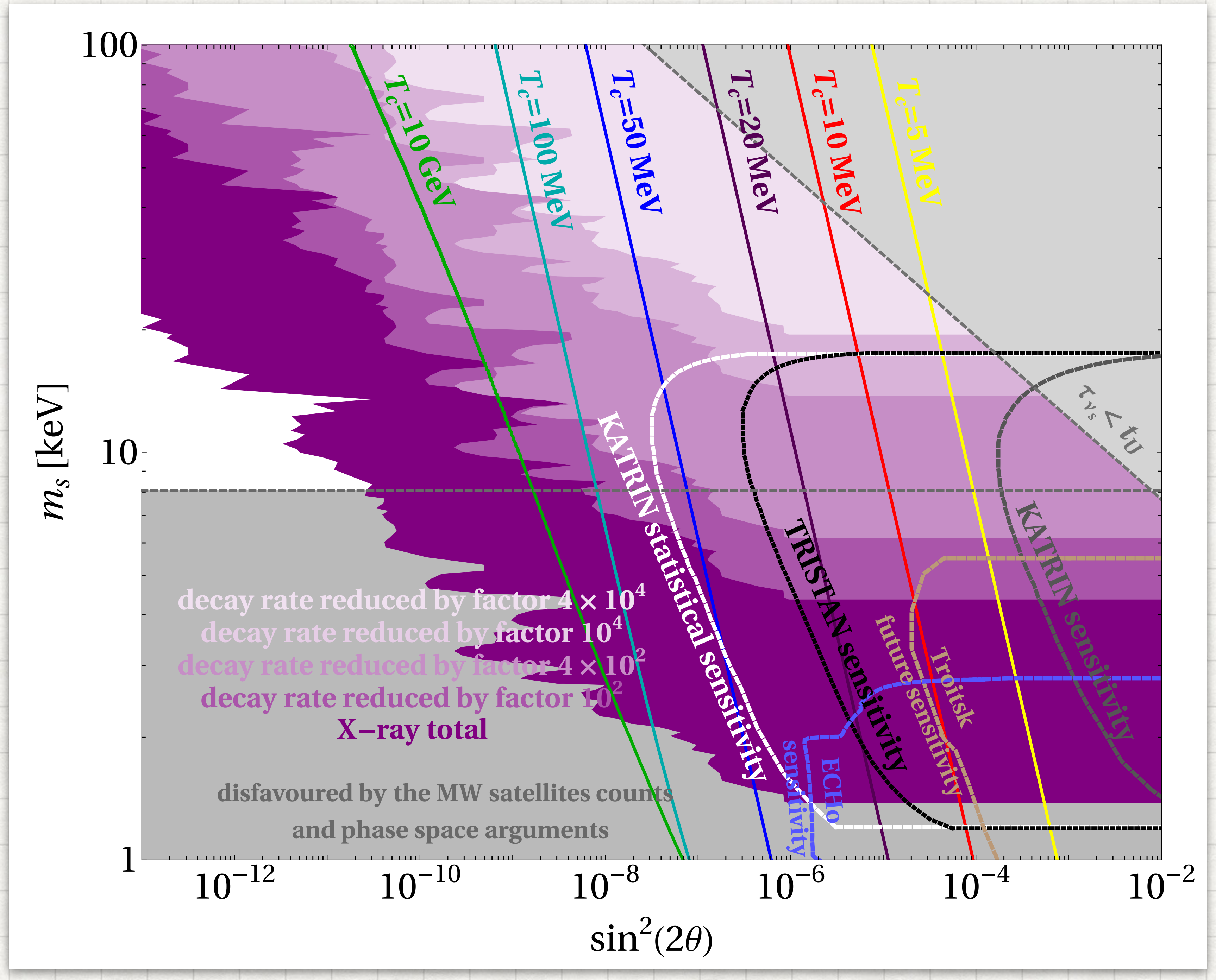


Adding a heavy scalar and 3 new parameters $\lambda, \lambda', m_\Sigma$

→ PARTIAL OR EVEN COMPLETE CANCELLATION

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

DODELSON-WIDROW PRODUCTION SCENARIO



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

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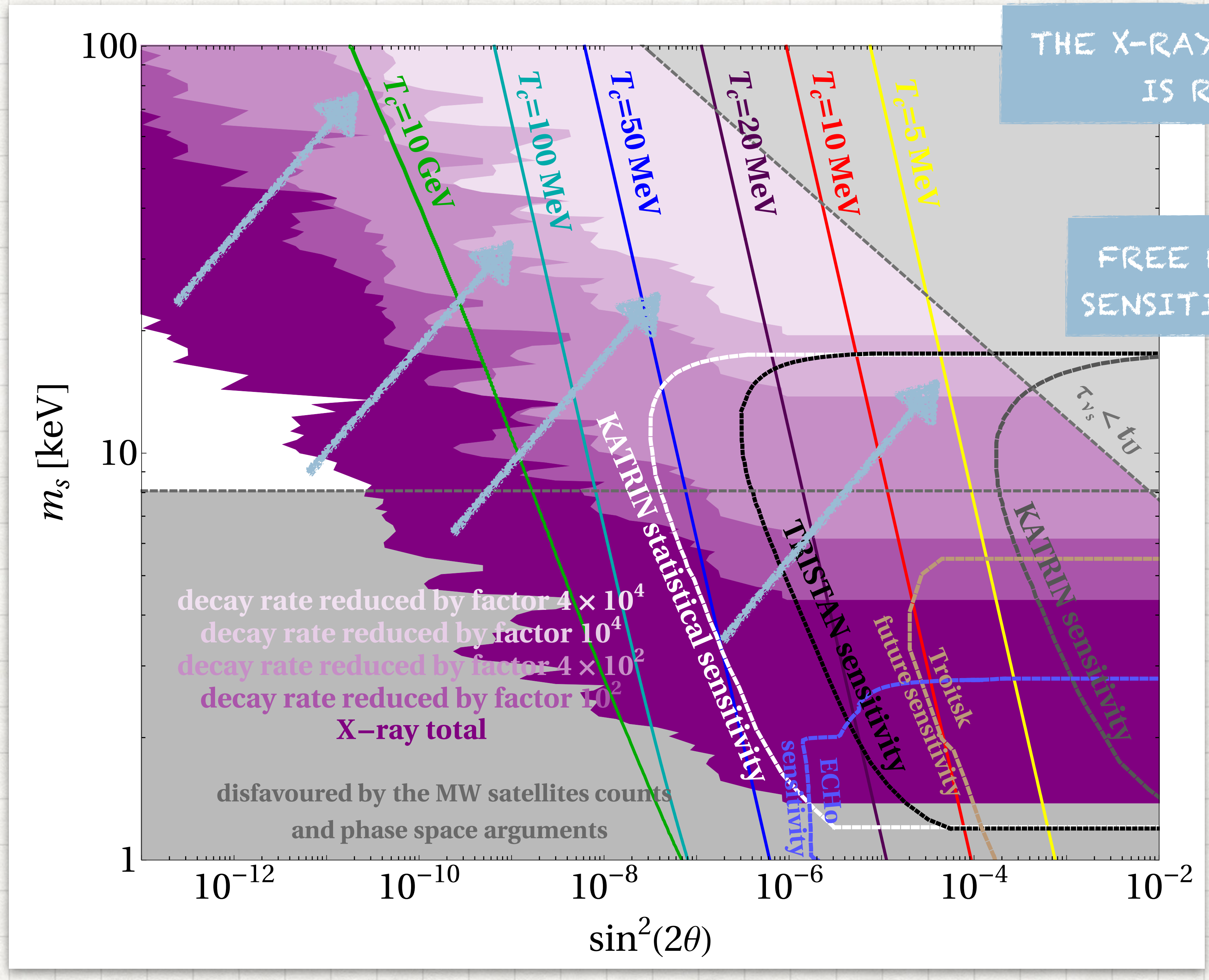

THE X-RAY CONSTRAINT IS RELAXED

FREE EXPERIMENTS' SENSITIVITY REGION

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

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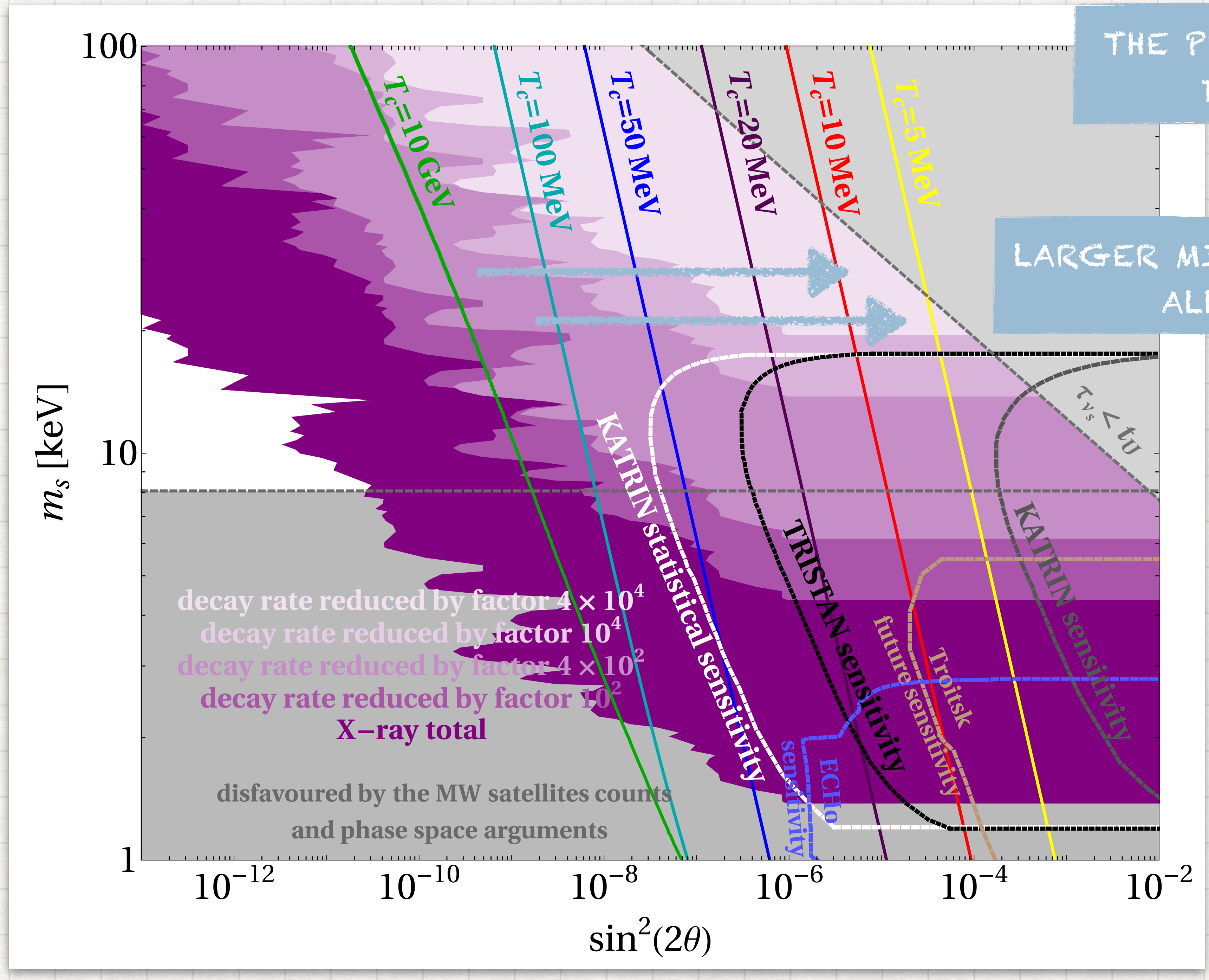
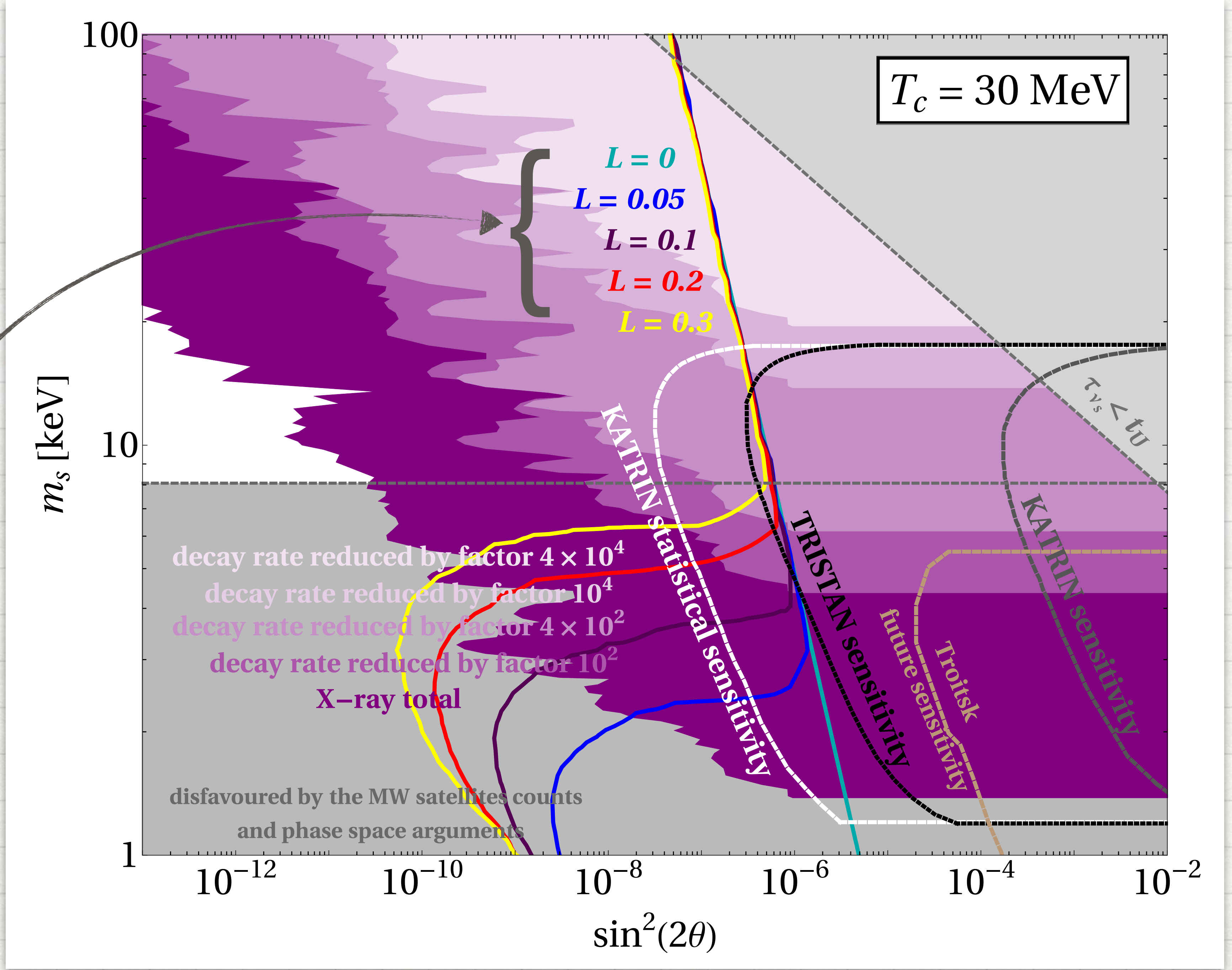


THE PRODUCTION IS DELAYED

LARGER MIXING ANGLES ALLOWED

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

SHI-FULLER PRODUCTION SCENARIO

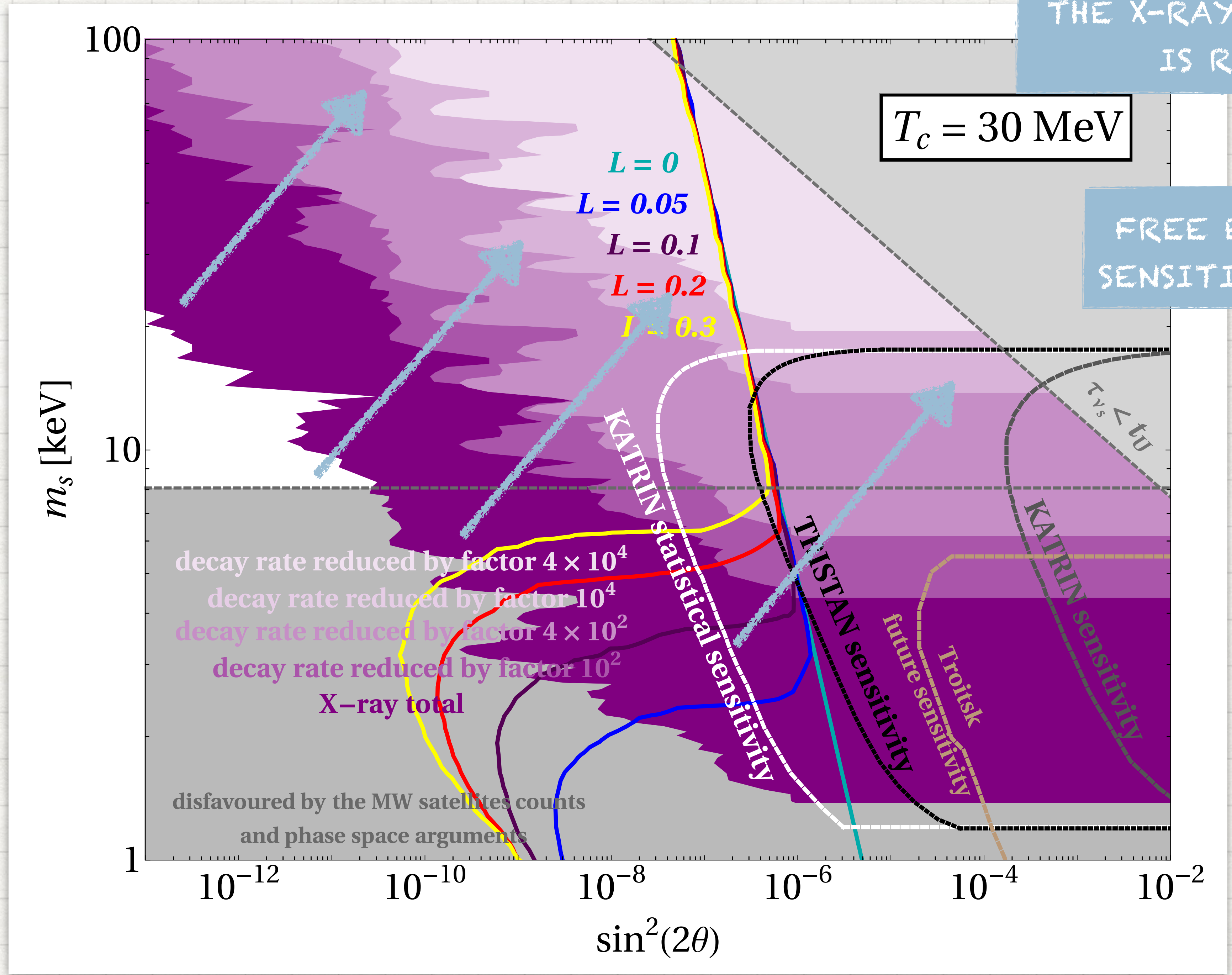


Primordial asymmetry in the lepton sector

$$L = \frac{(n_\nu - n_{\overline{\nu}})}{n_\gamma}$$

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

SHI-FULLER PRODUCTION SCENARIO



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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.

BACKUP SLIDES

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:

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

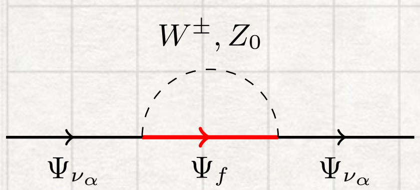
where $\Gamma_e(p) = c_e(p,T)\, G_F^2\, p\, T^4$

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

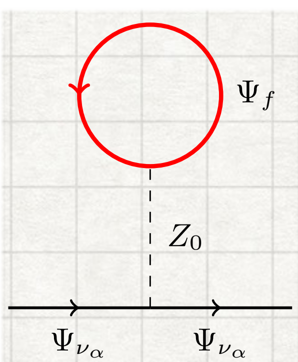
*[Dodelson and Widrow, Phys. Rev. Lett. 72 (1994) 17-20]

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

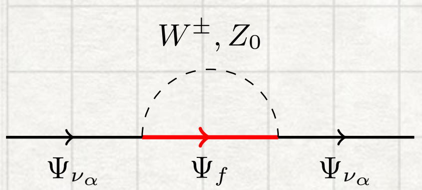
$$V_L(p) = \frac{2\sqrt{2}\,\zeta(3)}{\pi^2}\,G_\mathrm{F}T^3\,\mathcal{L}^\alpha$$

where

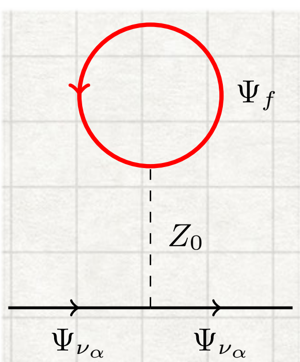
$$\mathcal{L}^\alpha \equiv 2L_{\nu_\alpha} + \sum_{\beta\neq\alpha} L_{\nu_\beta}$$ and $$L_{\nu_\alpha} = \frac{(n_{\nu_\alpha} - n_{\overline{\nu}_\alpha})}{n_\gamma}$$

DODELSON-WIDROW PRODUCTION

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



(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

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

in the non resonant production

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

DODELSON-WIDROW PRODUCTION

We are able to solve the Boltzmann equation and get

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

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

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

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 $\sin^2(2\theta_M)$

$$h^2\,\Omega_s = \frac{s_0\, m_s}{\rho_c/h^2}\frac{45}{(2\pi)^4}\frac{M_{\rm Pl}}{1.66\, g_{*s}\sqrt{g_*}}\int_0^\infty dr\, r^2 \int_{T_{\rm fin}}^{T_{\rm in}} \frac{dT}{T^3} \times \frac{1}{e^r+1}$$

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

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]

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)]