Sterile Neutrino Dark Matter

and

Possible Signals in Terrestrial Experiments

OUTLINE

- Introduction
- KATRIN experiment & sensitivity to Sterile Neutrinos
- Dodelson-Widrow production
- Critical Temperature
- X-ray constraint relaxation: Cocktail & Cancellation
- Shi-Fuller production
- CPT violation case
- Conclusions

INTRODUCTION - STERILE NEUTRINOS

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

- "sterile" because singlets with respect to any Standard Model interaction
  $\longrightarrow$ in principle, no limit on their number
- only relation with the SM through their mixing with ν_{LH}
- first and most natural portal to BSM physics

INTRODUCTION - STERILE NEUTRINOS

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

- "sterile" because singlets with respect to any Standard Model interaction
  $\longrightarrow$ in principle, no limit on their number
- only relation with the SM through their mixing with ν_{LH}
- first and most natural portal to BSM physics

Depending on their mass, eventual role in different puzzles :

- OSCILLATION EXPERIMENTS ANOMALIES (O(eV))
- DARK MATTER (O(keV))
- BARYON ASYMMETRY THROUGH LEPTOGENESIS (150 MeV - 100 GeV)
- NEUTRINO MASS GENERATION
  in the canonical minimal type-I seesaw (O(TeV))

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

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

INTRODUCTION - DARK MATTER

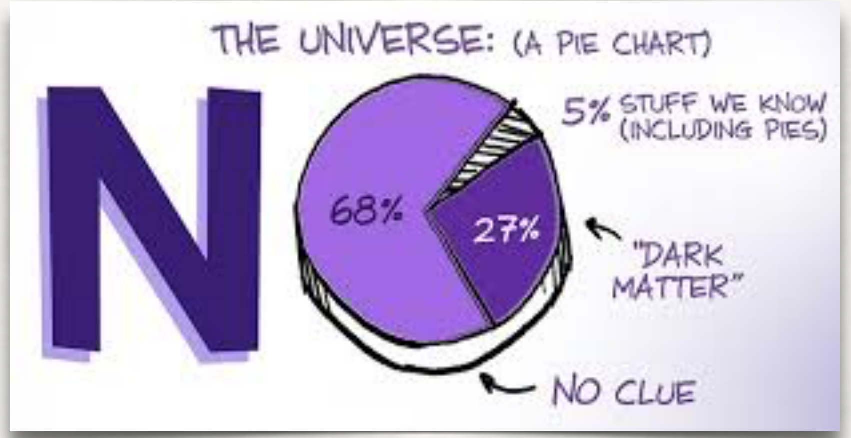
DARK MATTER represents
a PUZZLE historically arisen AT LARGE SCALES
but
likely requiring SOLUTION at very small scales,
coming FROM PARTICLE PHYSICS

ROTATION CURVES OF GALAXIES

VELOCITY DISPERSION IN GALAXIES

LARGE SCALE STRUCTURES FORMATION

GRAVITATIONAL LENSING



(Borrowed from J. Cham and Daniel Whiteson)

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

INTRODUCTION - DARK MATTER

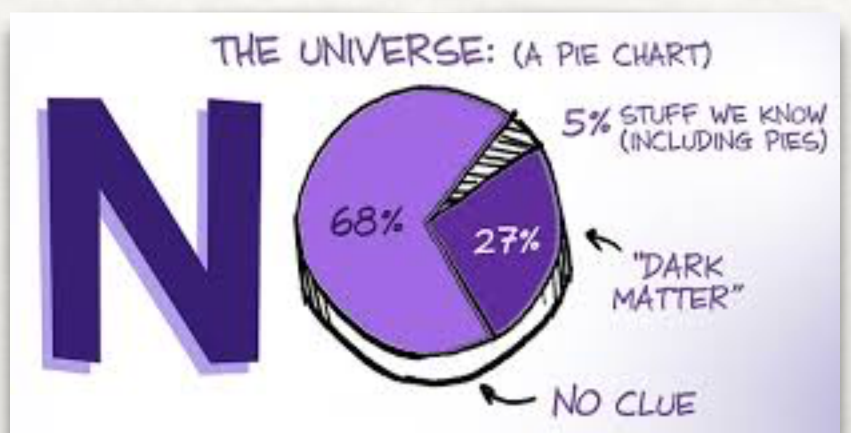
DARK MATTER represents
a PUZZLE historically arisen AT LARGE SCALES
but
likely requiring SOLUTION at very small scales,
coming FROM PARTICLE PHYSICS

ROTATION CURVES OF GALAXIES

VELOCITY DISPERSION IN GALAXIES

LARGE SCALE STRUCTURES FORMATION

GRAVITATIONAL LENSING



(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

GOOD DARK MATTER CANDIDATE

keV STERILE NEUTRINO

STERILE NEUTRINO DARK MATTER

GOOD DARK MATTER CANDIDATE	keV STERILE NEUTRINO
• NO EM nor STRONG INTERACTION	✓ by definition

STERILE NEUTRINO DARK MATTER

GOOD DARK MATTER CANDIDATE	keV STERILE NEUTRINO
NO EM nor STRONG INTERACTION	✓ by definition
MASSIVE	✓ $\mathcal{O}(\mathrm{keV})$

STERILE NEUTRINO DARK MATTER

GOOD DARK MATTER CANDIDATE

- NO EM nor STRONG INTERACTION
- MASSIVE
- STABLE on time scales comparable with the age of the universe

keV STERILE NEUTRINO

✓ by definition

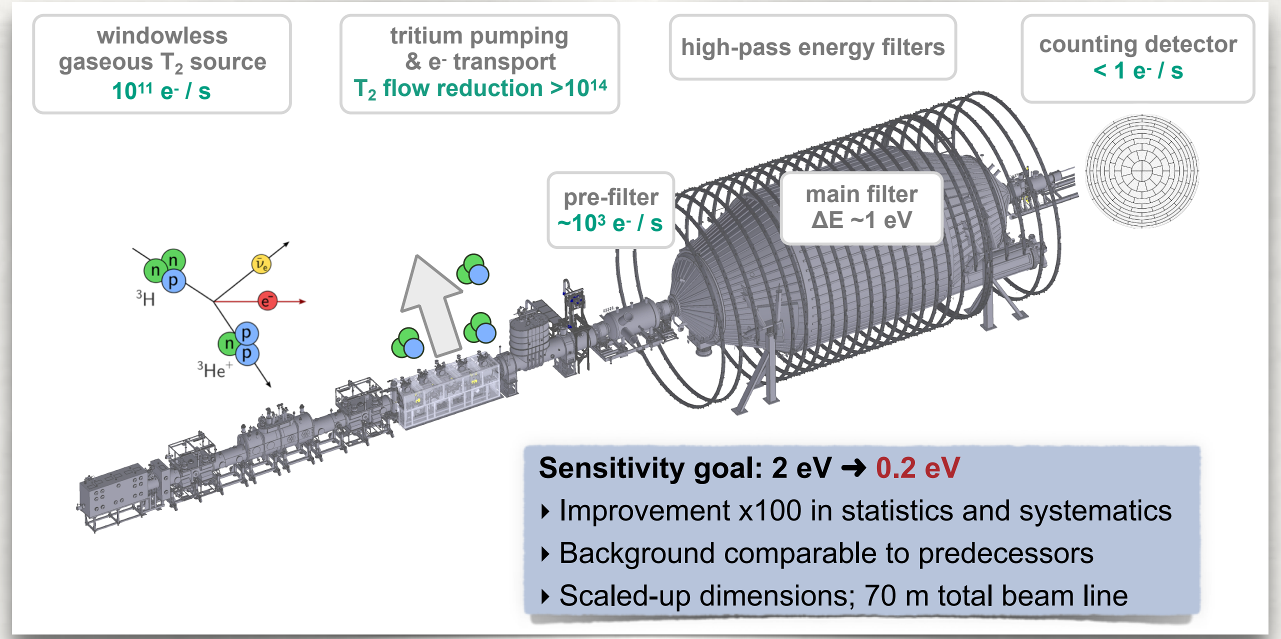
✓ $\mathcal{O}(\mathrm{keV})$

✓ depending on its mixing with the active species

STERILE NEUTRINO DARK MATTER

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

KATRIN EXPERIMENT



(Borrowed from K. Valerius lecture in Sinaia)

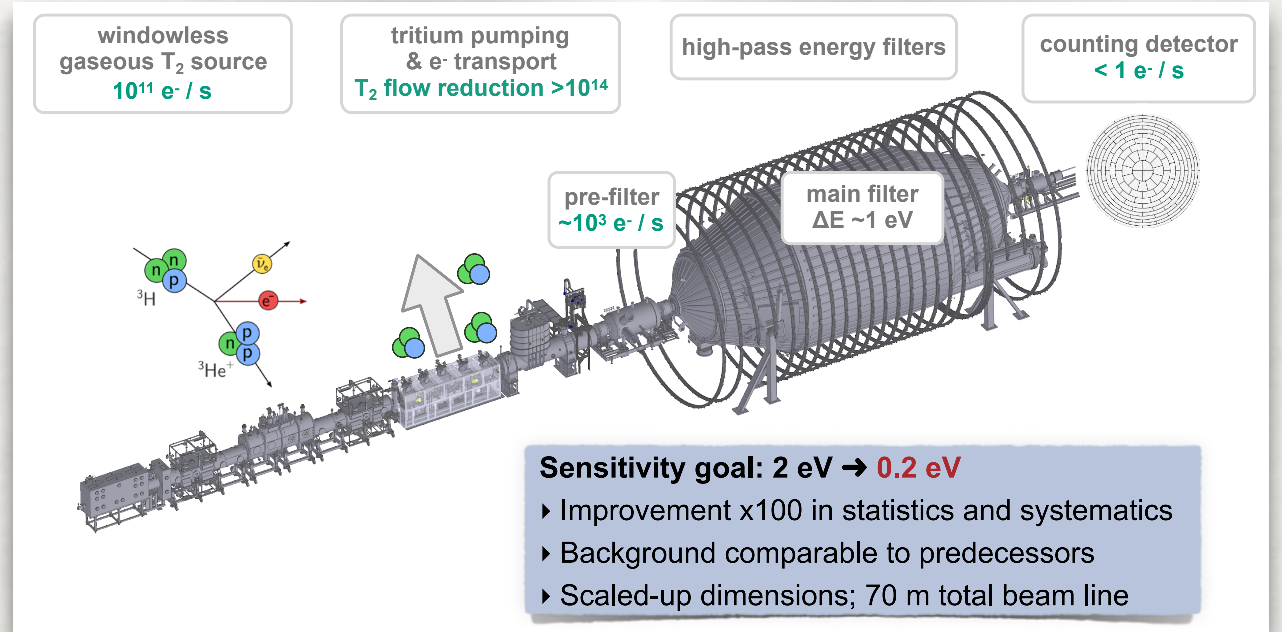
KATRIN EXPERIMENT

First goal:

measurement of $\boxed{m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2 \simeq m_1^2}$

hypothesis: $m_1 \simeq m_2 \simeq m_3 \gtrsim 0.2\,\text{eV}$

Process: $\boxed{\mathrm{T}_2 \rightarrow \mathrm{THe}^+ + e + \overline{\nu}_e}$



(Borrowed from K. Valerius lecture in Sinaia)

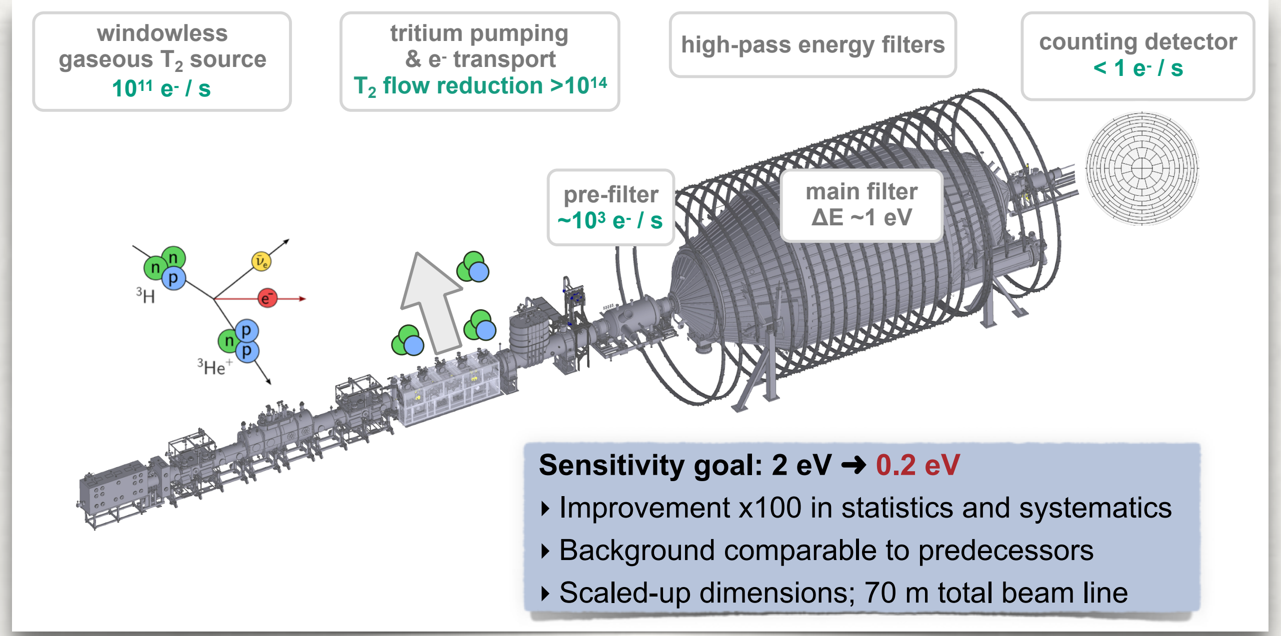
KATRIN EXPERIMENT

First goal:

measurement of $\boxed{m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2 \simeq m_1^2}$

hypothesis: $m_1 \simeq m_2 \simeq m_3 \gtrsim 0.2\,\mathrm{eV}$

Process: $\boxed{\mathrm{T}_2 \rightarrow \mathrm{THe}^+ + e + \overline{\nu}_e}$



(Borrowed from K. Valerius lecture in Sinaia)

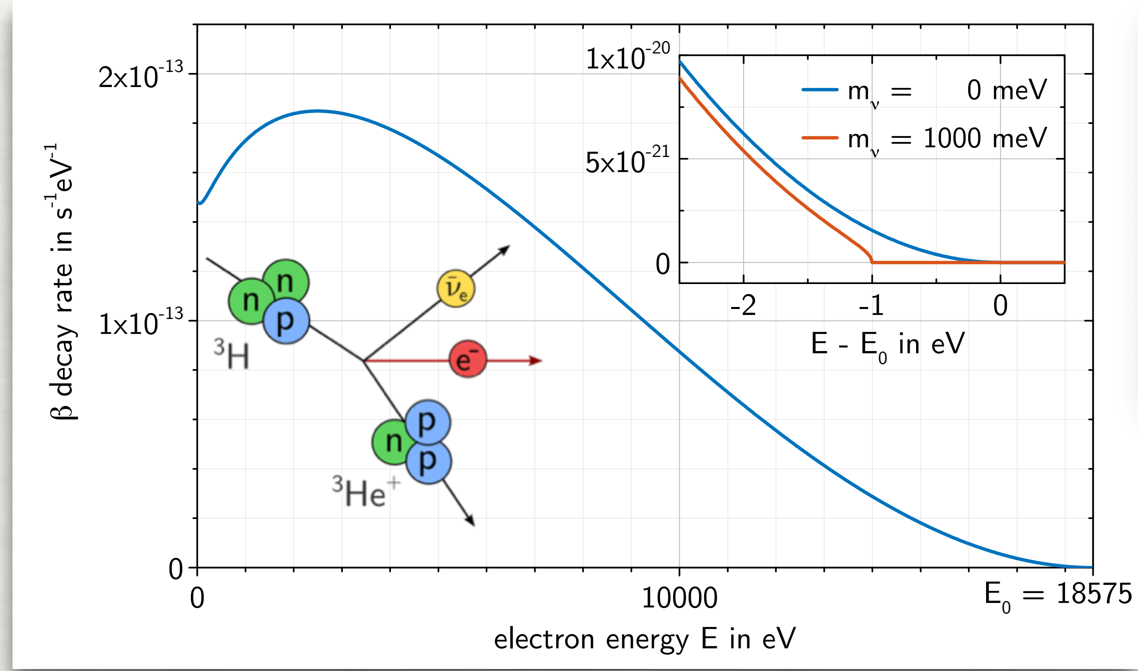
Observable: electron spectrum

$$\frac{d\Gamma}{dE} = C \cdot F(E, Z=2) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m(\nu_i)^2}.$$

Normalization factor

Fermi function

$$C = \frac{G_F^2}{2\pi^3} \cos^2 \Theta_C |M|^2$$



(Borrowed from K. Valerius lecture in Sinaia)

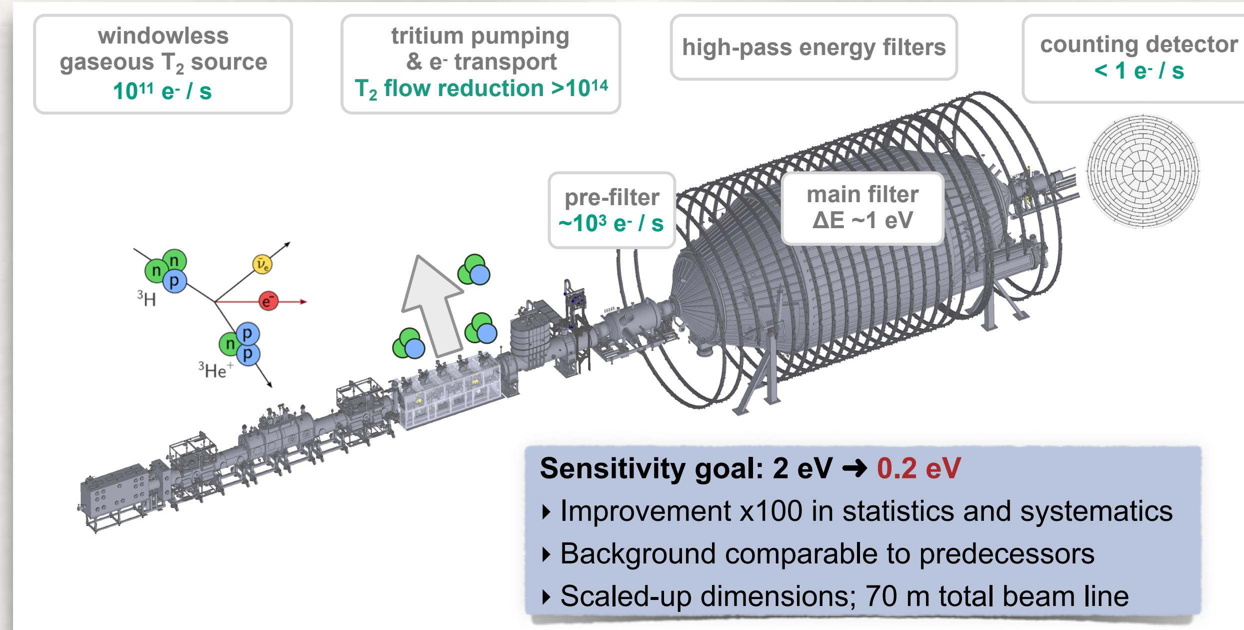
KATRIN EXPERIMENT

First goal:

measurement of $\boxed{m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2 \simeq m_1^2}$

hypothesis: $m_1 \simeq m_2 \simeq m_3 \gtrsim 0.2\,\text{eV}$

Process: $\boxed{\mathrm{T}_2 \to \mathrm{THe}^+ + e + \overline{\nu}_e}$



(Borrowed from K. Valerius lecture in Sinaia)

Observable: electron spectrum

$$\frac{d\Gamma}{dE} = C \cdot F(E, Z=2) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m(\nu_i)^2}.$$

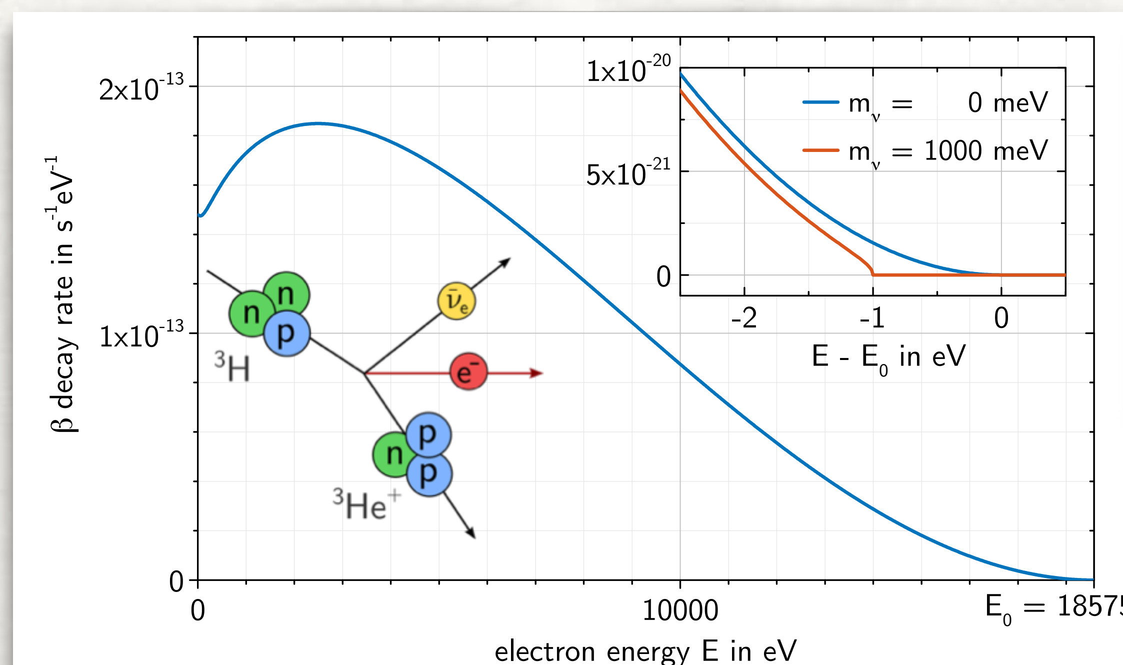
Normalization factor

Fermi function

$$C = \frac{G_F^2}{2\pi^3} \cos^2 \Theta_C |M|^2$$

Kurie function

$$K(E) \simeq (E_0 - E) \sqrt[4]{1 - \frac{m_\beta^2}{(E_0 - E)^2}}$$



(Borrowed from K. Valerius lecture in Sinaia)

KATRIN SEARCH FOR STERILE NEUTRINOS

If $|\nu_e\rangle$ admixture of $|\nu_i\rangle$ and $|\nu_s\rangle$ with $m_s \sim \mathcal{O}(\mathrm{keV})$,

$\longrightarrow$ due to the large mass splitting, THE SUPERPOSITION OF THE BETA-DECAY SPECTRA corresponding to the light effective mass term and the heavy mass eigenstate m_s , WILL BE DETECTABLE.

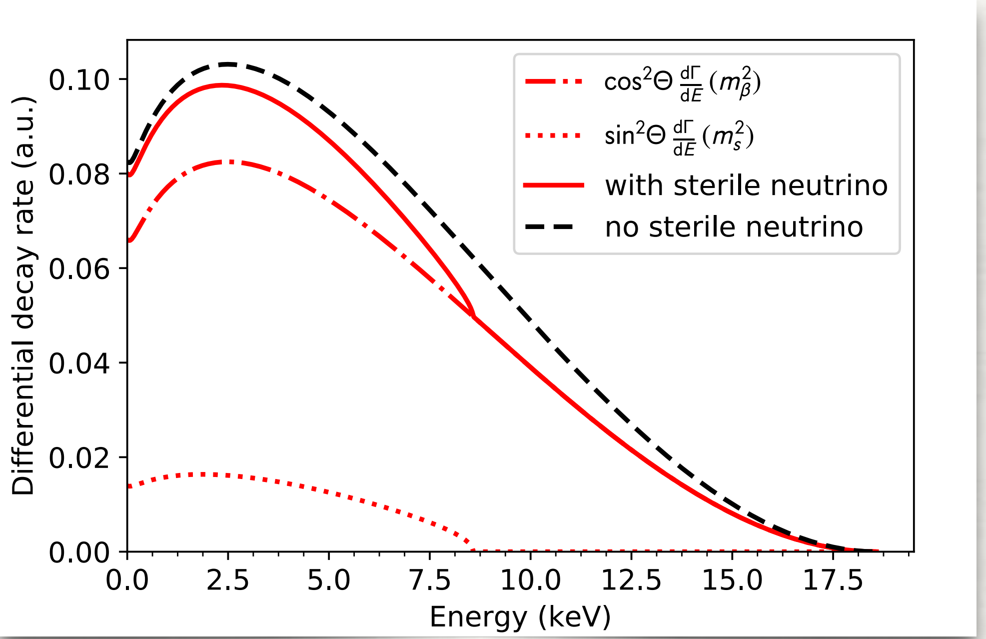
KATRIN SEARCH FOR STERILE NEUTRINOS

If $|\nu_e\rangle$ admixture of $|\nu_i\rangle$ and $|\nu_s\rangle$ with $m_s \sim \mathcal{O}(\mathrm{keV})$,

⟶ due to the large mass splitting, THE SUPERPOSITION OF THE BETA-DECAY SPECTRA corresponding to the light effective mass term and the heavy mass eigenstate m_s , WILL BE DETECTABLE.

Differential spectrum:

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



(Borrowed from S. Mertens lecture in Bad Honnef)

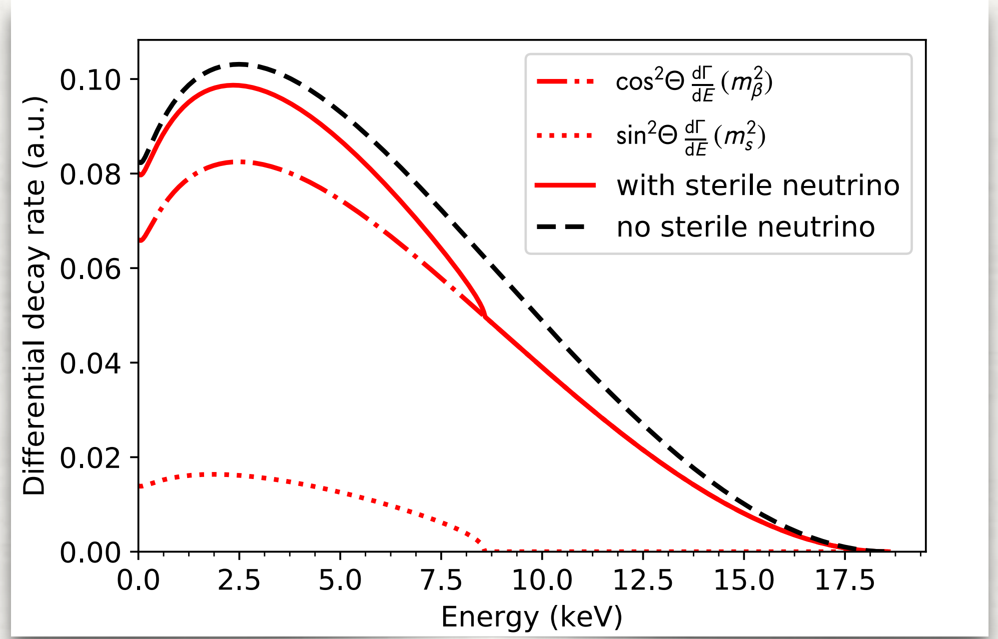
KATRIN SEARCH FOR STERILE NEUTRINOS

If $|\nu_e\rangle$ admixture of $|\nu_i\rangle$ and $|\nu_s\rangle$ with $m_s \sim \mathcal{O}(\mathrm{keV})$,

⟶ due to the large mass splitting, THE SUPERPOSITION OF THE BETA-DECAY SPECTRA corresponding to the light effective mass term and the heavy mass eigenstate m_s , WILL BE DETECTABLE.

Differential spectrum:

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



(Borrowed from S. Mertens lecture in Bad Honnef)

To be able to look at the entire spectrum of the electrons, KATRIN WILL BE UPDATED (evolving into TRISTAN) being equipped with a NEW DETECTOR that is now under construction

DODELSON-WIDROW PRODUCTION

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

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

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:

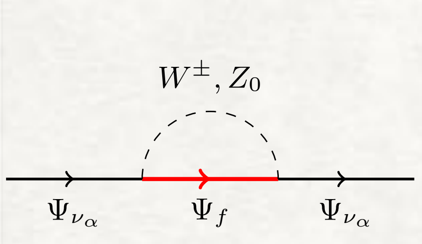
$$\boxed{\frac{\partial}{\partial t} f_s(p,t) - H\, p \frac{\partial}{\partial p} f_s(p,t) \approx \frac{\Gamma_e}{2} \langle P_m(\nu_e \to \nu_s; p, t)\rangle\, f_e(p,t)}$$

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

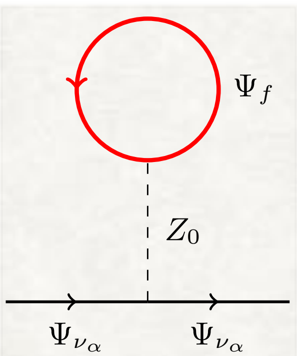
$$\langle P_m(\nu_e \to \nu_s; p, t)\rangle = \sin^2(2\theta_M)\, \sin^2\left(\frac{v\,t}{L}\right) \approx \frac{1}{2} \sin^2(2\theta_M)$$

DODELSON-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

THERMAL POTENTIAL

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

ASYMMETRY POTENTIAL

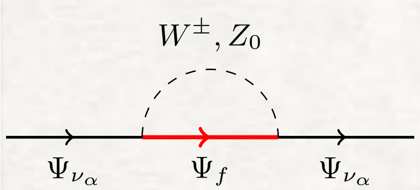
$$\boxed{V_L(p) = \frac{2\sqrt{2}\,\zeta(3)}{\pi^2}\,G_\mathrm{F} T^3\,\mathcal{L}^\alpha}$$

where

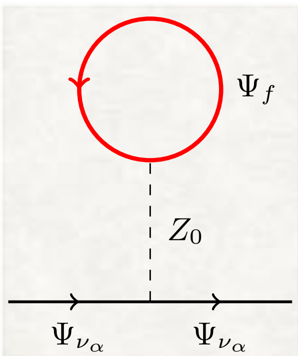
$$\mathcal{L}^\alpha \equiv 2L_{\nu_\alpha} + \sum_{\beta\neq\alpha} L_{\nu_\beta} \qquad \text{and} \qquad L_{\nu_\alpha} = \frac{(n_{\nu_\alpha} - n_{\overline{\nu}_\alpha})}{n_\gamma}$$

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

THERMAL POTENTIAL

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

ASYMMETRY POTENTIAL

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

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

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

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

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

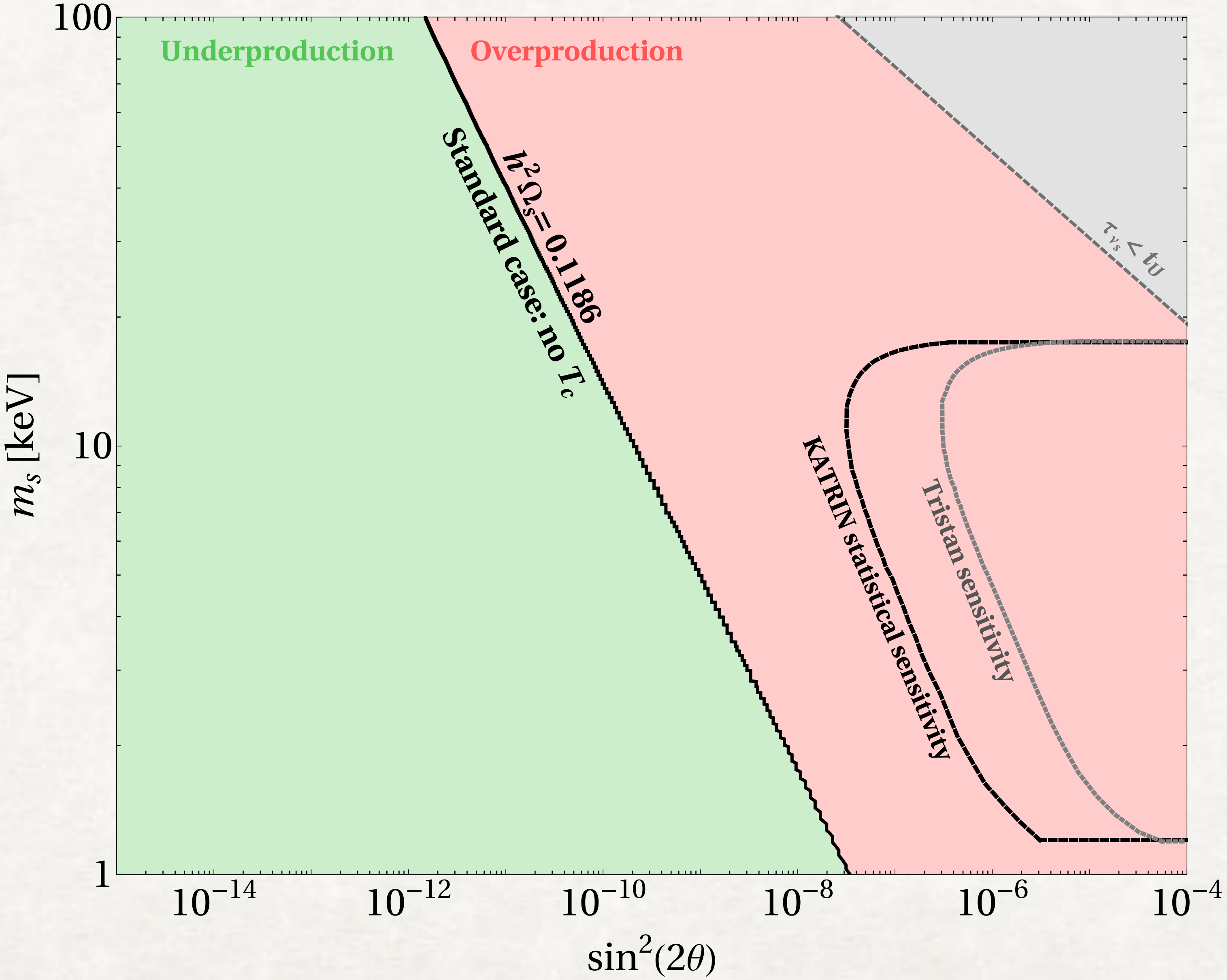
Critical Temperature

def: T_c is the temperature at which the sterile neutrinos started to be produced.

Critical Temperature

def: T_c is the temperature at which the sterile neutrinos started to be produced.

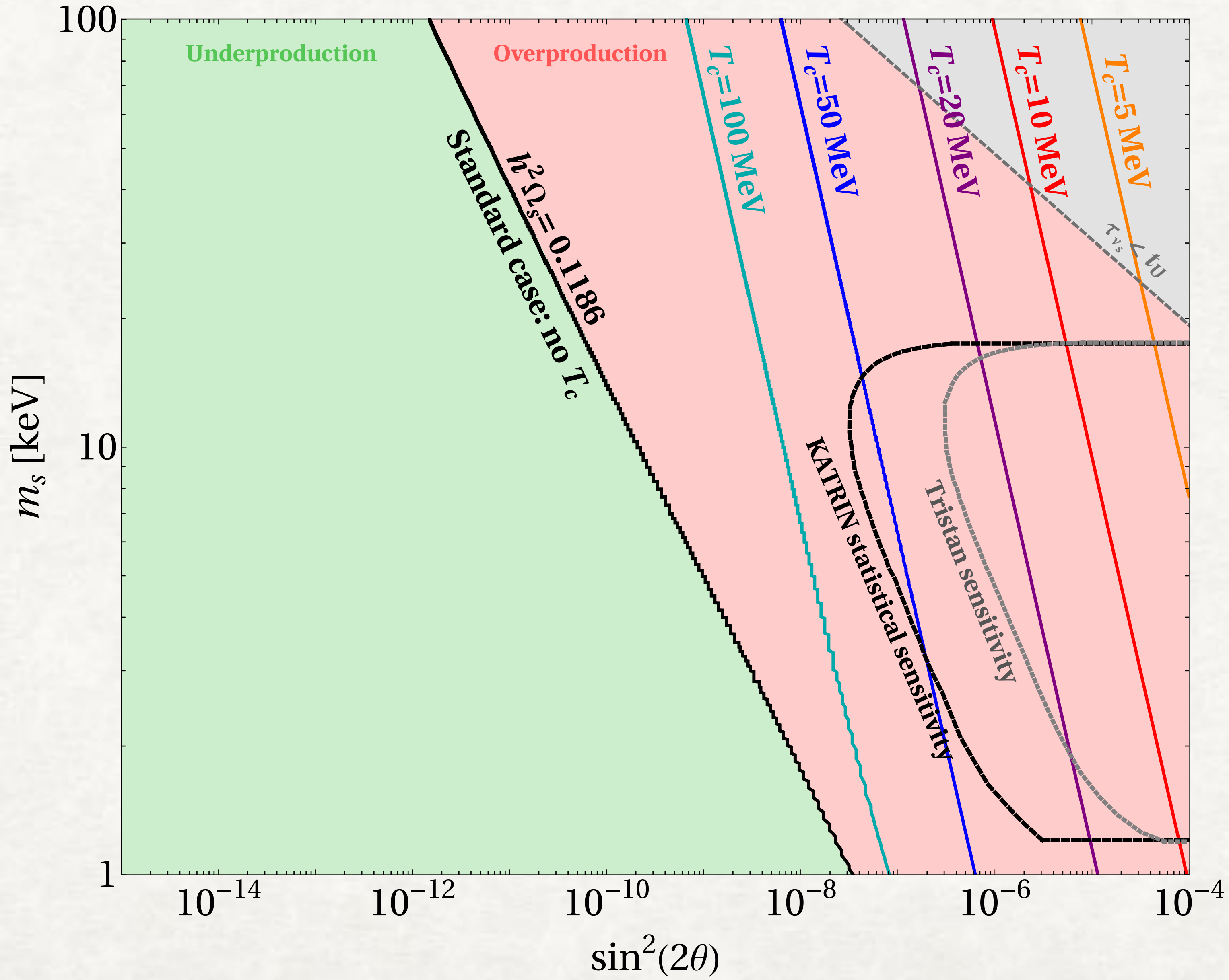
In the DW case the production peaks at $T = T_{max} \simeq 133 \left(\frac{m_s}{\mathrm{keV}}\right)^{1/3} \mathrm{MeV}$



Critical Temperature

def: T_c is the temperature at which the sterile neutrinos started to be produced.

In the DW case the production peaks at $T = T_{max} \simeq 133 \left(\frac{m_s}{\mathrm{keV}}\right)^{1/3} \mathrm{MeV}$



Critical Temperature

<u>NEW SCALE</u> in the primeval universe

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

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 $m_D \simeq \theta\, m_s$

$c \approx 63$

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

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 $m_D \simeq \theta\, m_s$

$c \approx 63$

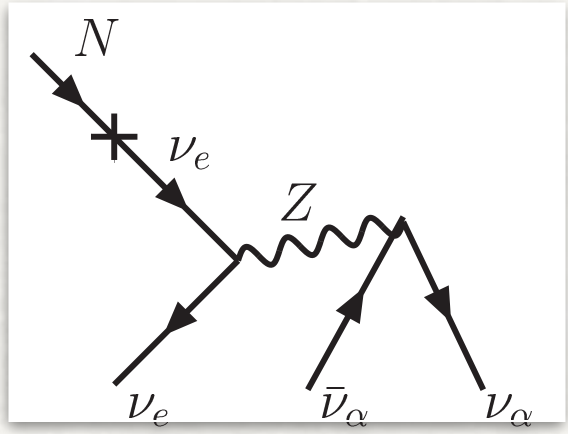
$\Gamma_\alpha(p) = c_\alpha(T) G_F^2 T^4 p$

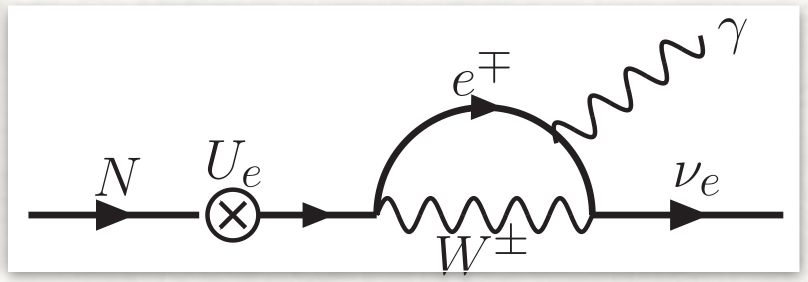
- PHASE TRANSITION CASE: $\boxed{m_s^{(T>T_c)} = 0}$

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

X-RAY CONSTRAINT

Decay channels for sterile neutrinos



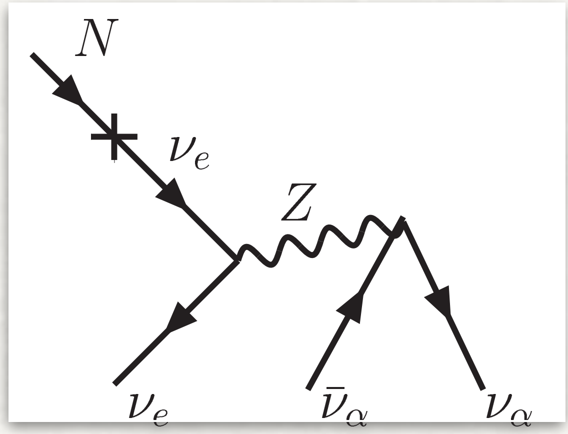


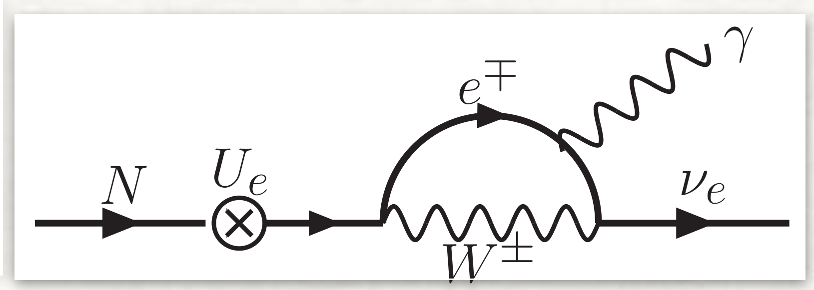
$$\Gamma_{\nu_s \to 3\nu} = \frac{G_F^2\, m_s^5}{96\,\pi^3} \sin^2(2\theta)$$
$$= \frac{1}{4.7 \times 10^{10}\ \mathrm{s}} \left(\frac{m_s}{50\ \mathrm{keV}}\right)^5 \sin^2(2\theta)$$

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

X-RAY CONSTRAINT

Decay channels for sterile neutrinos





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

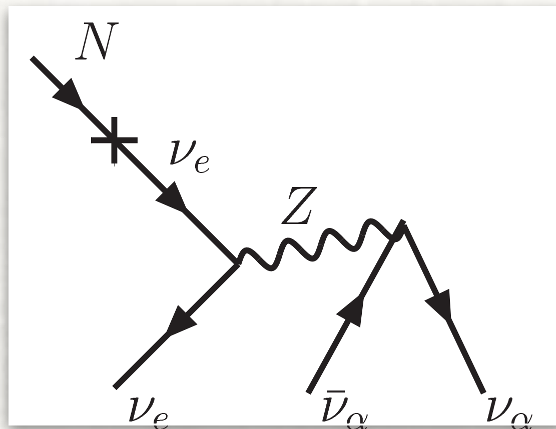
$$\Gamma_{\nu_s \to \nu\gamma} = \frac{9\,\alpha\, G_F^2}{1024\,\pi^4} \sin^2(2\theta)\, m_s^5$$
$$\simeq 5.5 \times 10^{-22}\, \theta^2 \left(\frac{m_s}{\mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

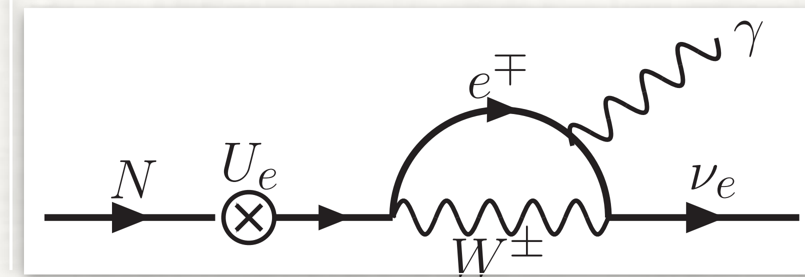
$$\Downarrow$$

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

X-RAY CONSTRAINT

Decay channels for sterile neutrinos





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

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

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

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

X-ray Constraint Relaxation - DM Cocktail

OBSERVABLE : Flux of photons

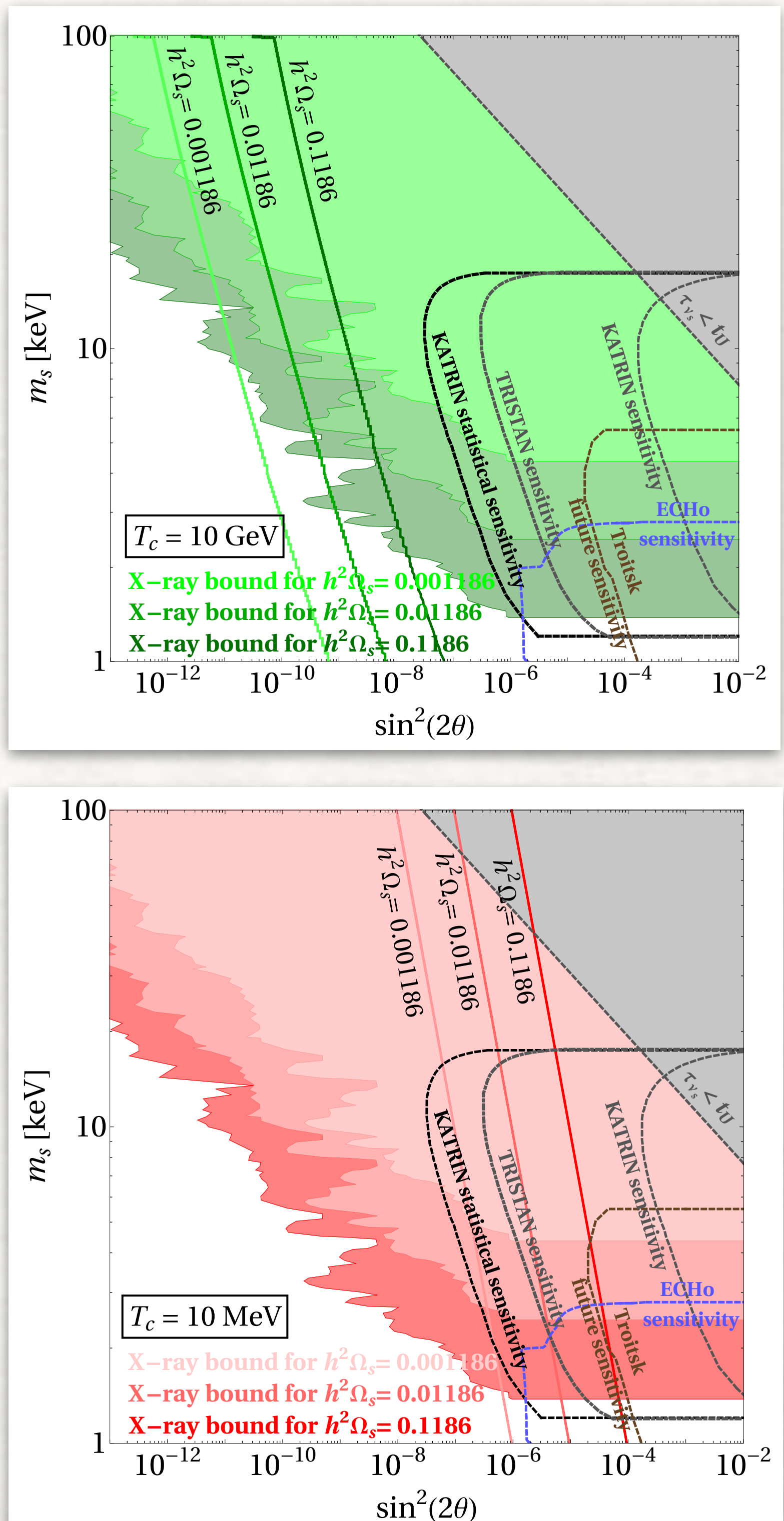
$$F = \frac{\Gamma_{\nu_s \to \nu\gamma}}{4\pi m_s} \int dl\, d\Omega\, \rho_{\rm DM}(l, \Omega)$$

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

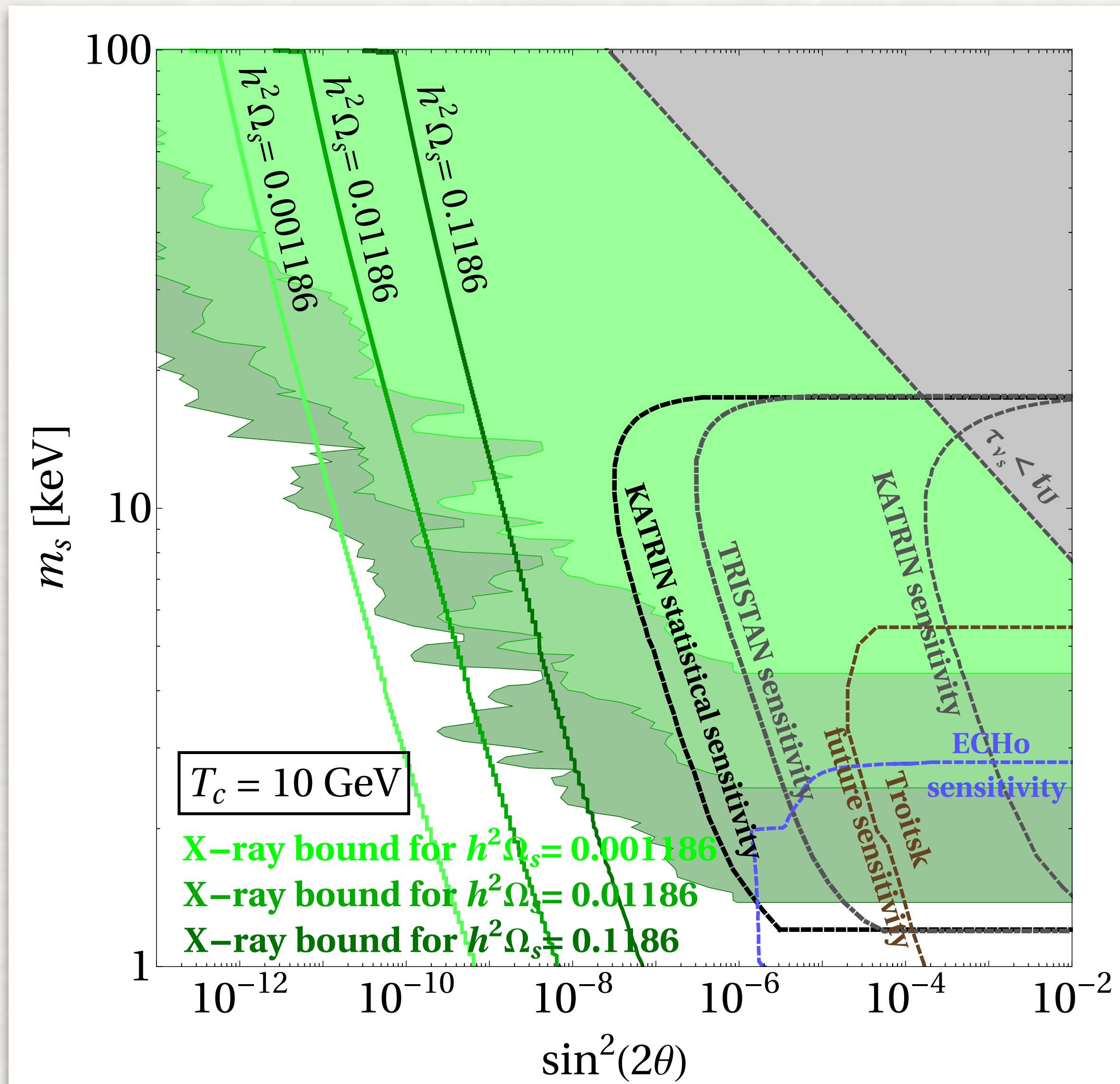
$\rho_s < \rho_{DM}$ allows larger $\sin^2(2\theta)$ and m_s

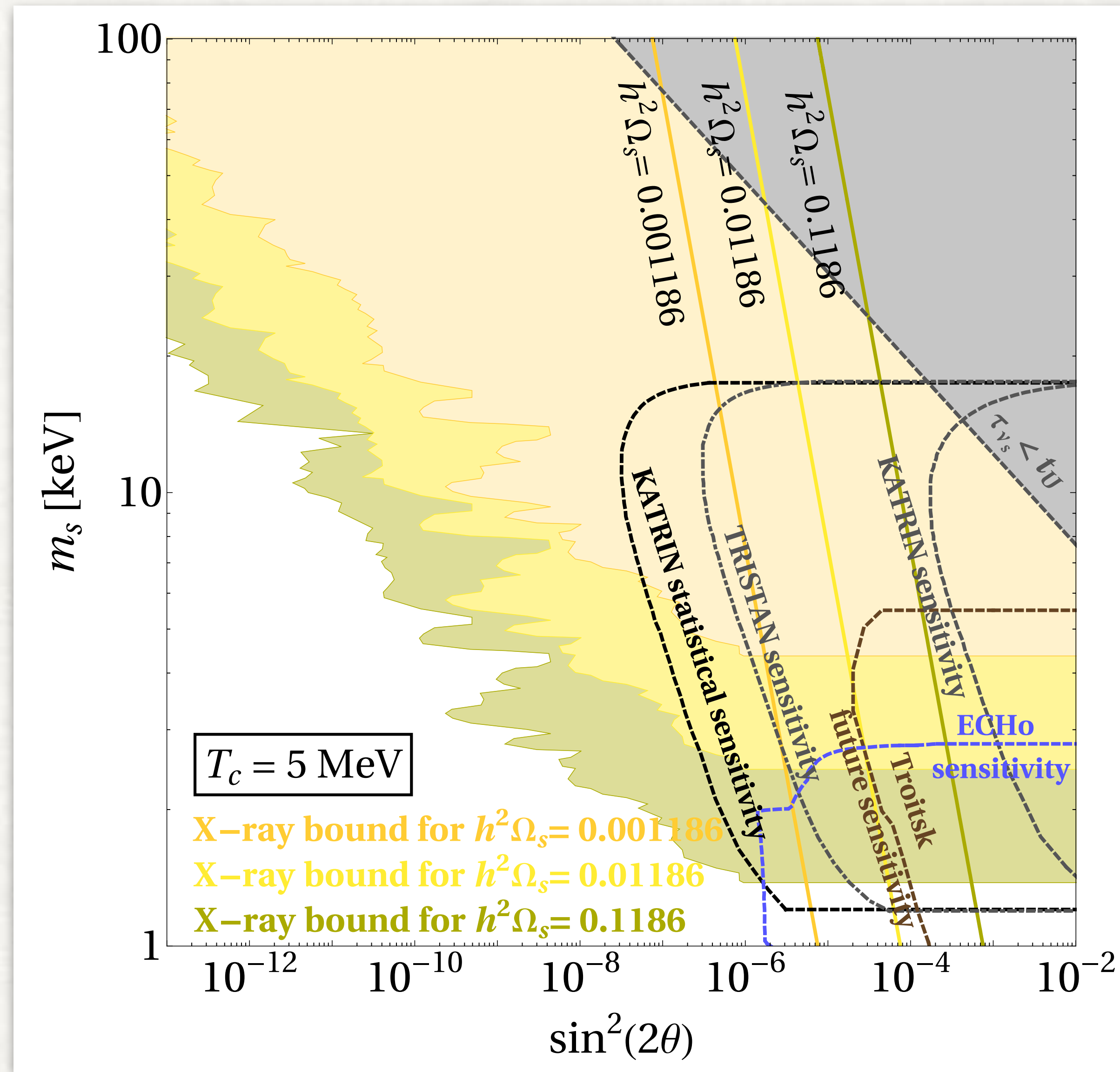
Secondary advantage:
multicomponent dark matter allows in principle more freedom also from other constraint coming, for example, from large scale structures

X-ray Constraint Relaxation - DM Cocktail



X-ray Constraint Relaxation - DM Cocktail





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

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

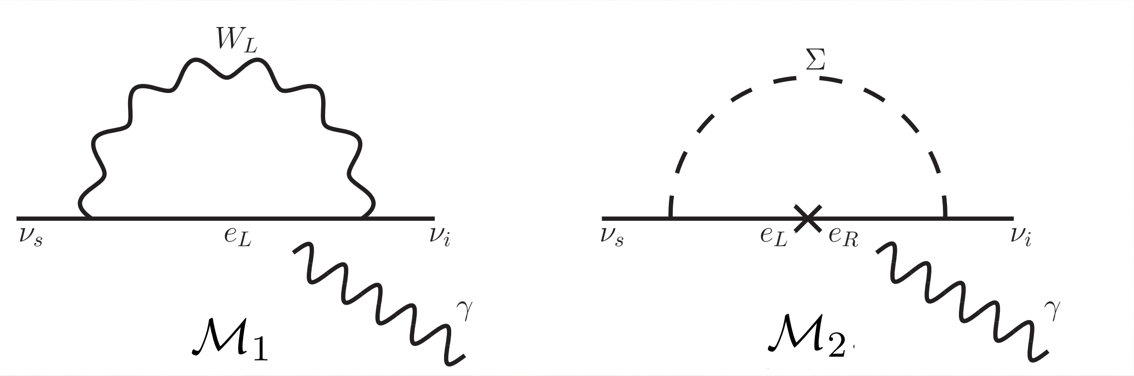
$$\Gamma \;\propto\; \int d\text{Phase}\, |\mathcal{M}|^2 \;\text{ reduced } \quad \text{if} \quad |\mathcal{M}|^2 \;\text{ reduced}$$

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

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

X-ray Constraint Relaxation - Reduced Decay Rate

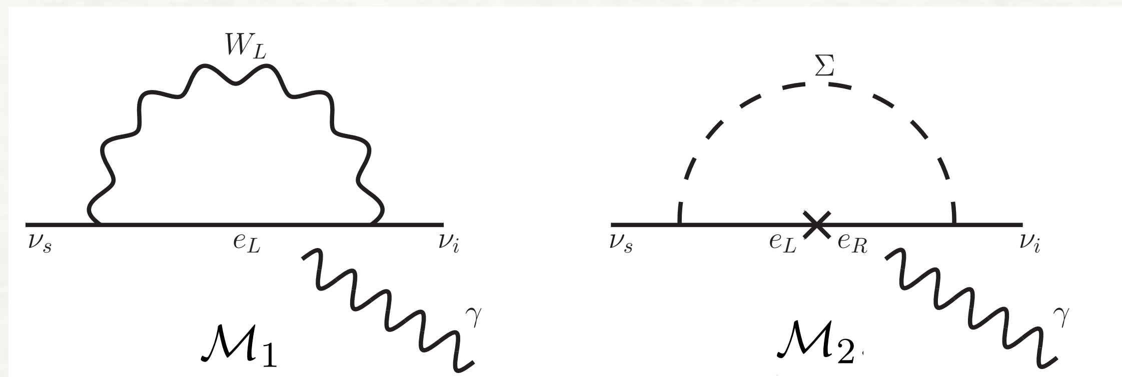
Particular realization:



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

X-ray Constraint Relaxation - Reduced Decay Rate

Particular realization:



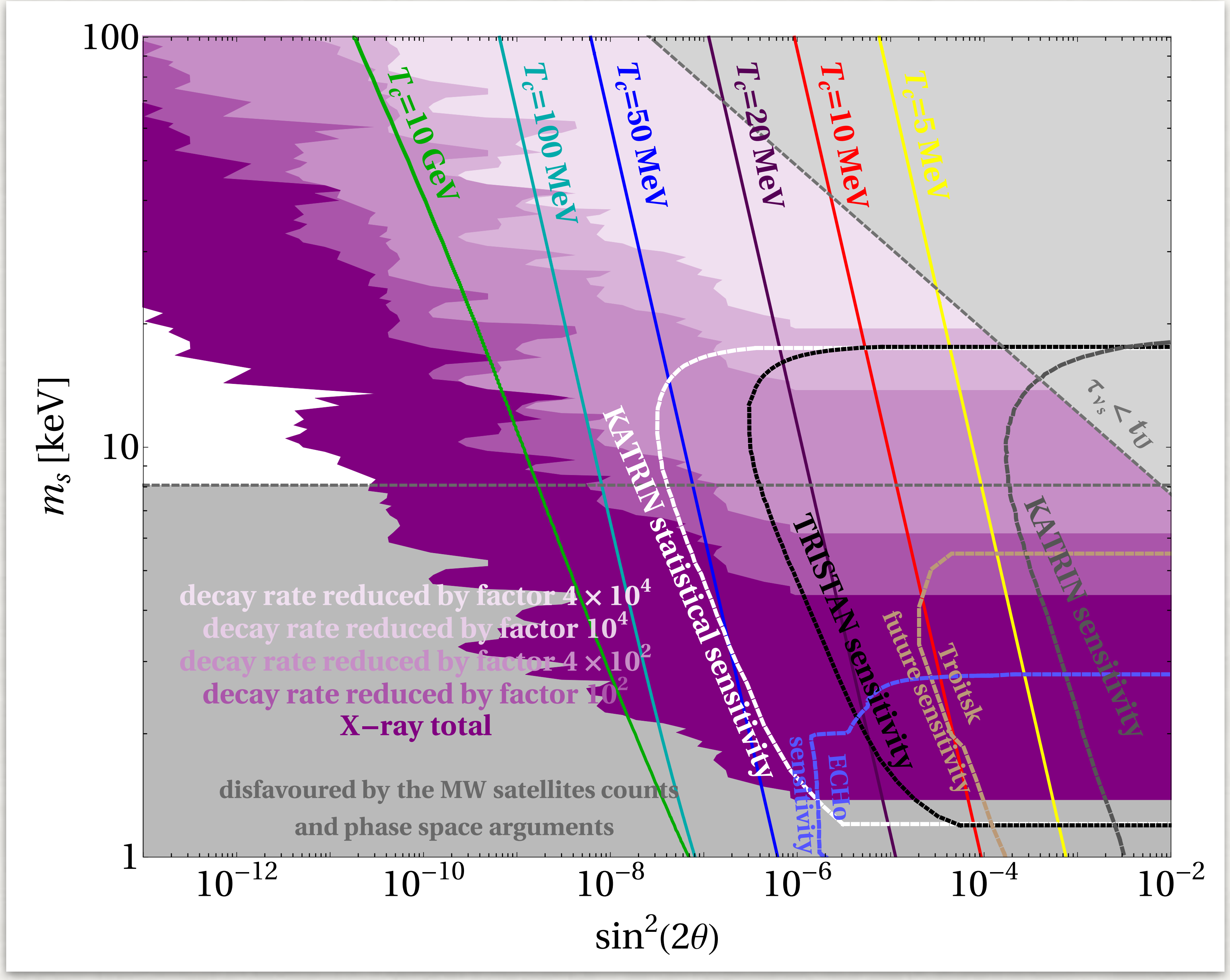
Adding a heavy scalar Σ and 3 new parameters $\lambda, \lambda', m_\Sigma$

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



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 $\sin^2(2\theta_M)$

RESONANT PRODUCTION - SHI-FULLER CASE

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

$\longrightarrow$ 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 $\sin^2(2\theta_M)$

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

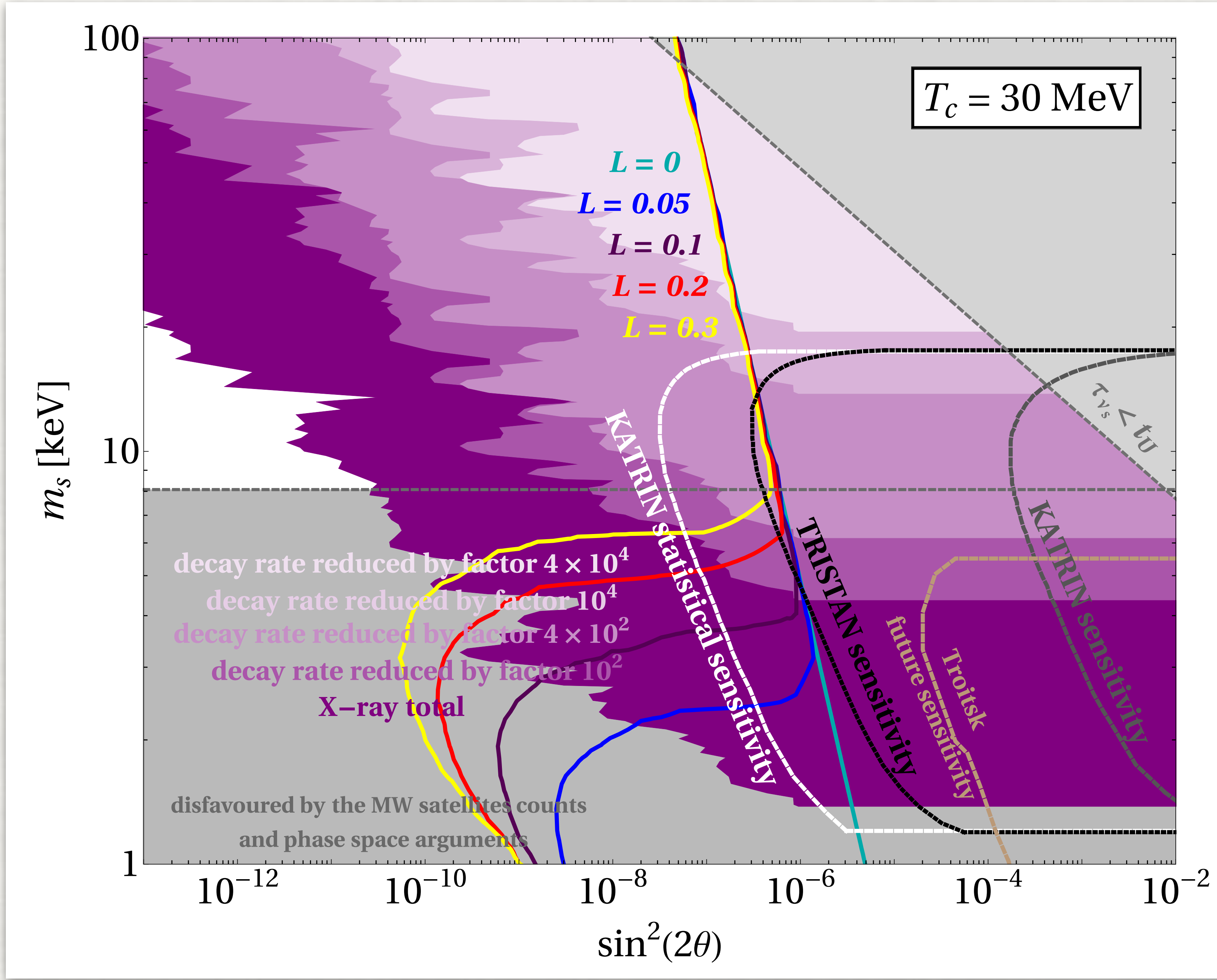
$$\left[\frac{\Gamma_e(r,T)\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)}{\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)+\left(\frac{\Gamma_e}{2}\right)^2+\left(\frac{m_s^2}{2\,r\,T}-V_{\nu_s}\right)^2}+\frac{\Gamma_e(r,T)\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)}{\left(\frac{m_s^2}{2\,r\,T}\right)^2\sin^2(2\theta)+\left(\frac{\Gamma_e}{2}\r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

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-FULLER CASE



CPT VIOLATION CASE

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

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

$\longrightarrow$ 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.

CPT VIOLATION CASE

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

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

$\longrightarrow$ 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

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

CPT VIOLATION CASE

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

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

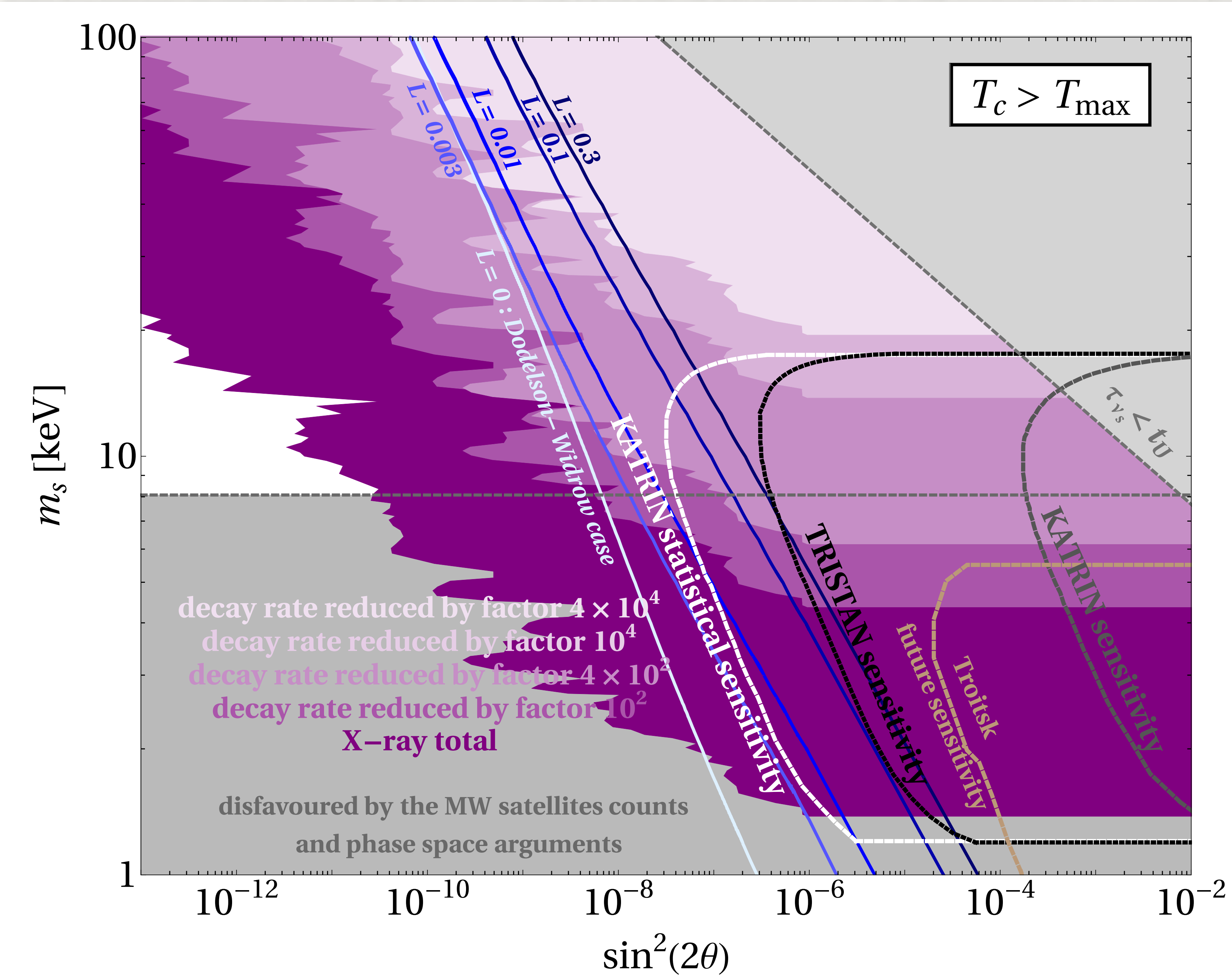
$\longrightarrow$ DARK MATTER composed by ONLY STERILE ANTINEUTRINOS that experienced a suppression of the production in presence of a lepton asymmetry that on the contrary would enhance the production of sterile neutrinos.

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

with

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

CPT VIOLATION CASE



CONCLUSIONS

- Constraints coming from the X-ray observations and measured Ω_{DM} can cause problems in the detection at KATRIN 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

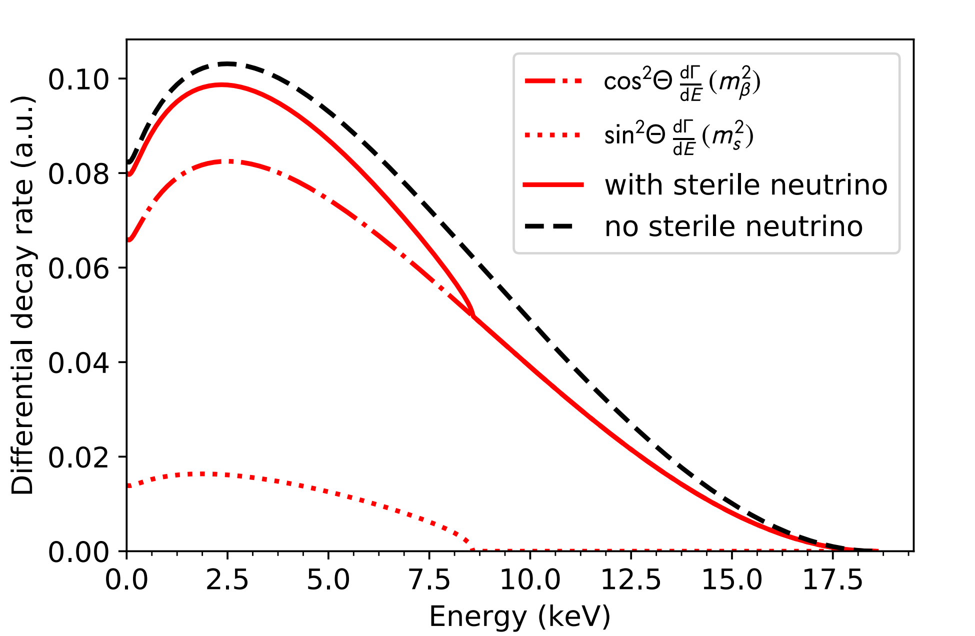
- The combination of these two methods sets available again the region of the parameter space in which we expect KATRIN to become sensitive in the near future to signals of keV sterile neutrino dark matter produced through both the Dodelson-Widrow and the Shi-Fuller mechanism.

THANK YOU FOR THE ATTENTION!

KATRIN SEARCH FOR STERILE NEUTRINOS

If $|\nu_e\rangle$ admixture of $|\nu_i\rangle$ and $|\nu_s\rangle$ with $m_s \sim \mathcal{O}(\mathrm{keV})$,

→ due to the large mass splitting, THE SUPERPOSITION OF THE BETA-DECAY SPECTRA corresponding to the light effective mass term and the heavy mass eigenstate m_s , WILL BE DETECTABLE.



(Borrowed from S. Mertens lecture in Bad Honnef)

Differential spectrum:

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

Advantages in KATRIN searches:

- Short half-life (12.3 yrs)

→ high signal rates with low source densities

- Endpoint energy of $E_0 = 18.575\ \mathrm{keV}$

→ search for sterile neutrinos in a mass range of astrophysical interest

- Ultra luminous tritium source

→ high statistic search for keV-sterile neutrinos

DODELSON-WIDROW PRODUCTION

Assuming $g_*(T) = \text{const}$ in the plasma during the sterile neutrinos production and making use of the relation valid for fixed $r = p/T$

$$-H\,T\left(\frac{\partial f_s(p,T)}{\partial T}\right)_p - H\,p\left(\frac{\partial f_s(p,T)}{\partial p}\right)_T = -H\,T\left(\frac{\partial f_s(p,T)}{\partial T}\right)_{p/T} = -H\,T\left(\frac{\partial f_s(r)}{\partial T}\right)_r$$

We are able to solve the Boltzmann equation and get

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

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

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

$\longrightarrow$ Sterile neutrino dark matter abundance

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

Critical Temperature

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: $\boxed{m_s^{(T>T_c)} = 0}$

  if $m_s = f\langle\phi\rangle$, where ϕ is a new scalar field belonging to a hidden sector that develops a non-zero VEV after a phase transition at $T = T_c$

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

  if $m_s^{(T>T_c)} = m_s^{\text{today}} + M$, where $M = f\Phi$ depends on the value of the Scalar field Φ , that can be very large at $T = T_c$

X-RAY CONSTRAINT

X-RAY SIGNALS

- Contribution to the diffuse X-ray Background in the whole universe
- Milky Way halo
- Overdense regions: galaxy clusters and dwarf spheroidal galaxies

Example: 3.5 keV line

(in stacked spectrum of galaxy clusters, individual spectra of nearby galaxy clusters, Andromeda galaxy, Galactic Center region)

$$\text{line at E} = 3.55\ \text{keV} \qquad \leftrightarrow \qquad \begin{cases} m_s \simeq 7.1\,\text{keV}, \\ \tau_{\nu_s} \sim 10^{27.8\pm 0.3} \\ \sin^2(2\theta) \simeq (2-20)\times 10^{-11} \end{cases}$$

But uncertainty on its origin
(DM decay? instrumental origin? astrophysical origin?)