New channels of indirect detection for gauged sterile neutrino dark matter

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- Freeze in production of DM
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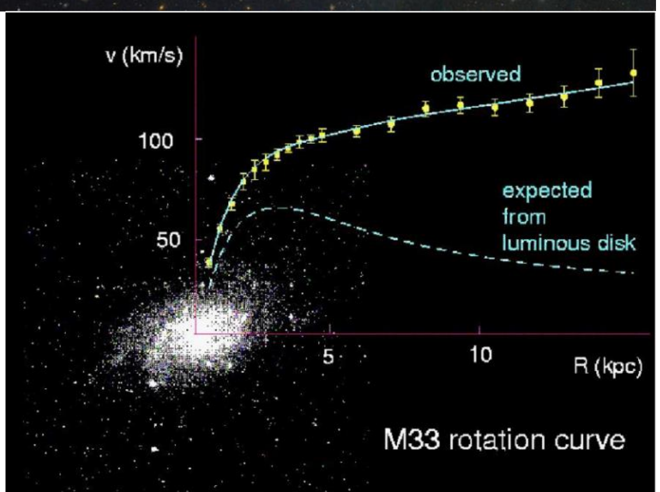
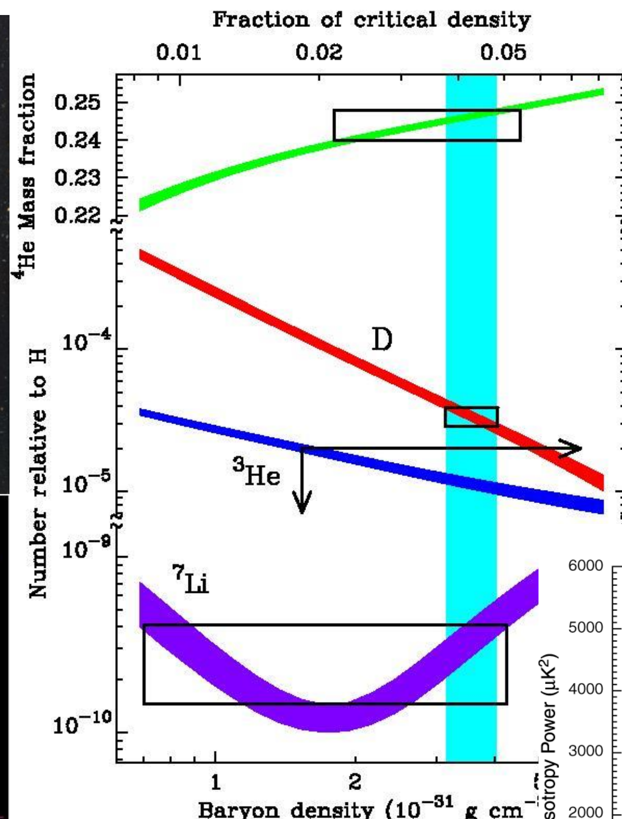
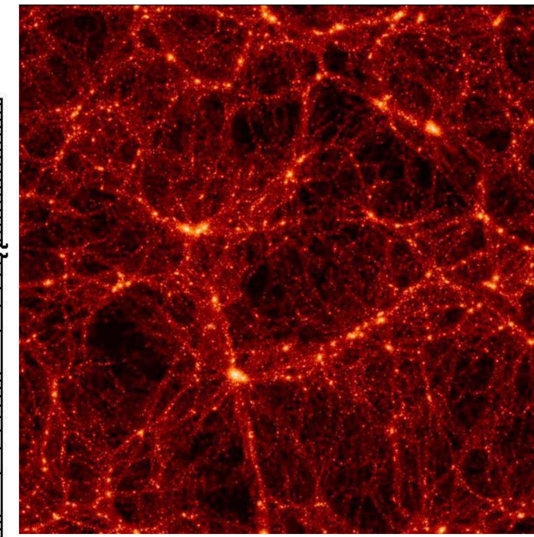
§ Introduction

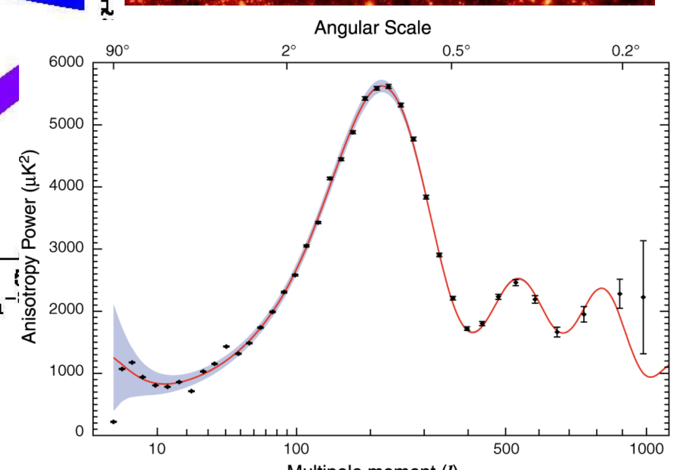
Evidences for dark matter

Dark matter: convincing evidences









Dark matter candidates

Baryonic dark matter

- BBN, structure formation constraints
-

Known particle candidate

- Only one
- Neutrino

Hypothetical particle

Dark matter candidates

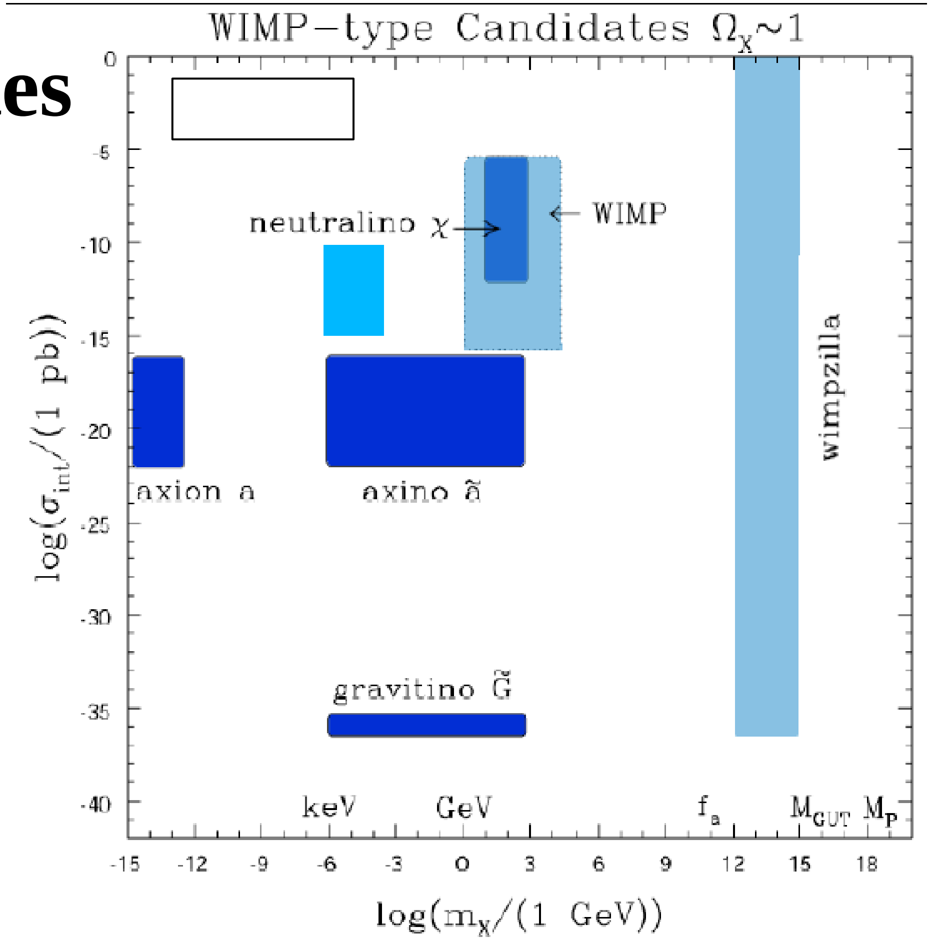
Hypothetical candidates

Sterile neutrino

Axion

WIMP

Others



modified L. Roszkowski's diagram

Dark matter candidates

Hypothetical candidates

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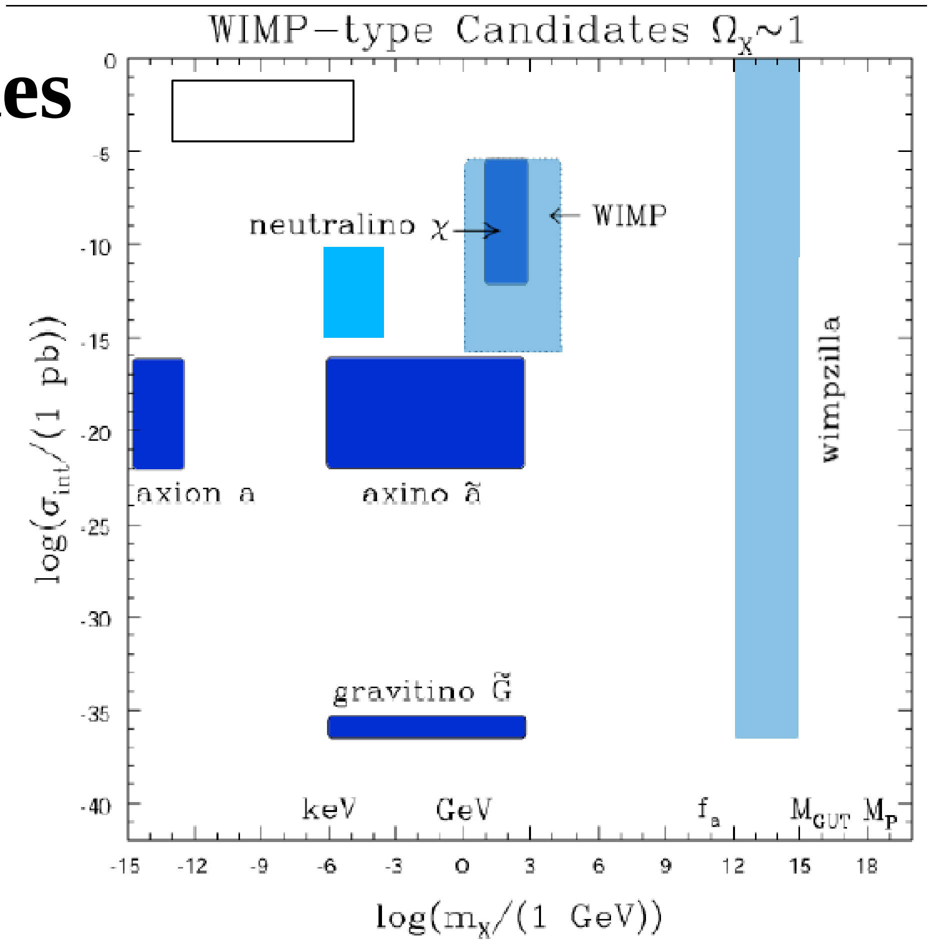
WIMP

Others



modified L. Roszkowski's diagram

- SM + RH neutrinos

Adding RH neutrinos

- Adding RH neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{i}{2}\overline{\nu_R}\not{\partial}\nu_R - y\,\bar{L}\Phi\nu_R - \frac{1}{2}\overline{\nu_R}M_M\nu_R + h.c.$$

- If Dirac masses ≪ Majorana masses, seesaw mechanism works [Minkowski (1977), Yanagida (1979), Gell-Mann et al (1979)]
  - $\begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \rightarrow \begin{pmatrix} -m_D^T \frac{1}{M_M} m_D & 0 \\ 0 & M_M \end{pmatrix}$
  - $\nu_a \cong U_{MNS}\nu_L + \theta\nu_R^C$ Neutrino oscillation
  - $\nu_s \cong \theta\,\nu_L + \nu_R^C$ Sterile neutrino, almost RH
  - $\theta = {}^{m_D}/_{M_M} \ll 1$: active-sterile mixing

Adding RH neutrinos

- Neutrino oscillations
  - Two mass squared differences: solar and atm.
  - Two RH neutrino is enough to generate those.
- If num. of RH neutrinos ≥ 3, the leftover may be a DM candidate.

☑ Electrically neutral

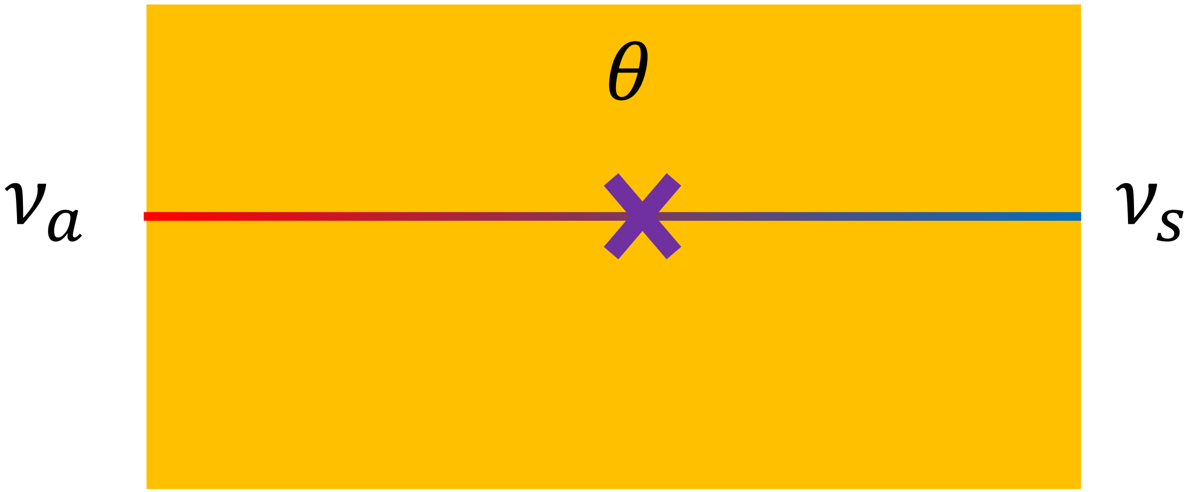
☑ Cold/Warm ness : mass m_{ν_s}

☑ Longevity : Lifetime $\tau \propto \theta^2$

  - Abundance?
  - Other cosmological/Astrophysical constraints?

Production of sterile neutrino

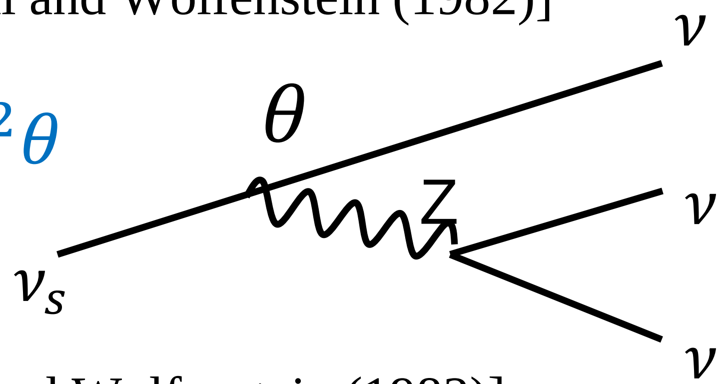
- Via active-sterile neutrino oscillation a.k.a Dodelson-Widrow mechanism [Dodelson and Widrow (1994)]



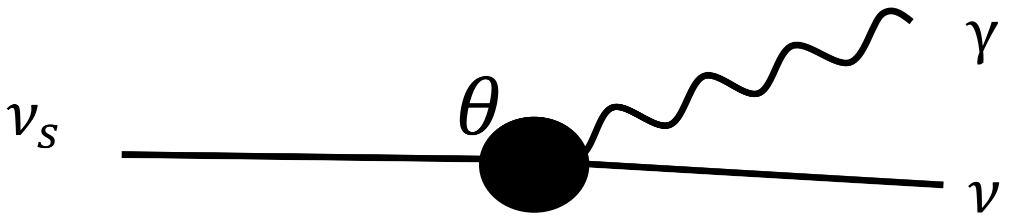
- Mixing in medium
- Production rate $\sim G_F^2\, T^5 \sin^2 2\theta$

Sterile neutrino is decaying DM

- Not completely stable [Pal and Wolfenstein (1982)]
  - $\Gamma(\nu_s \to 3\nu) = \frac{G_F^2\, m_{\nu_s}^5}{96\, \pi^3} \sin^2\theta$



- Not completely dark [Pal and Wolfenstein (1982)]
  - $\Gamma(\nu_s \to \gamma\nu) = \frac{9\, \alpha_{em} G_F^2\, m_{\nu_s}^5}{256\, \pi^4} \sin^2\theta$
  - Powerful tool for hunting sterile neutrino DM
  - Severely constrained by X-ray background



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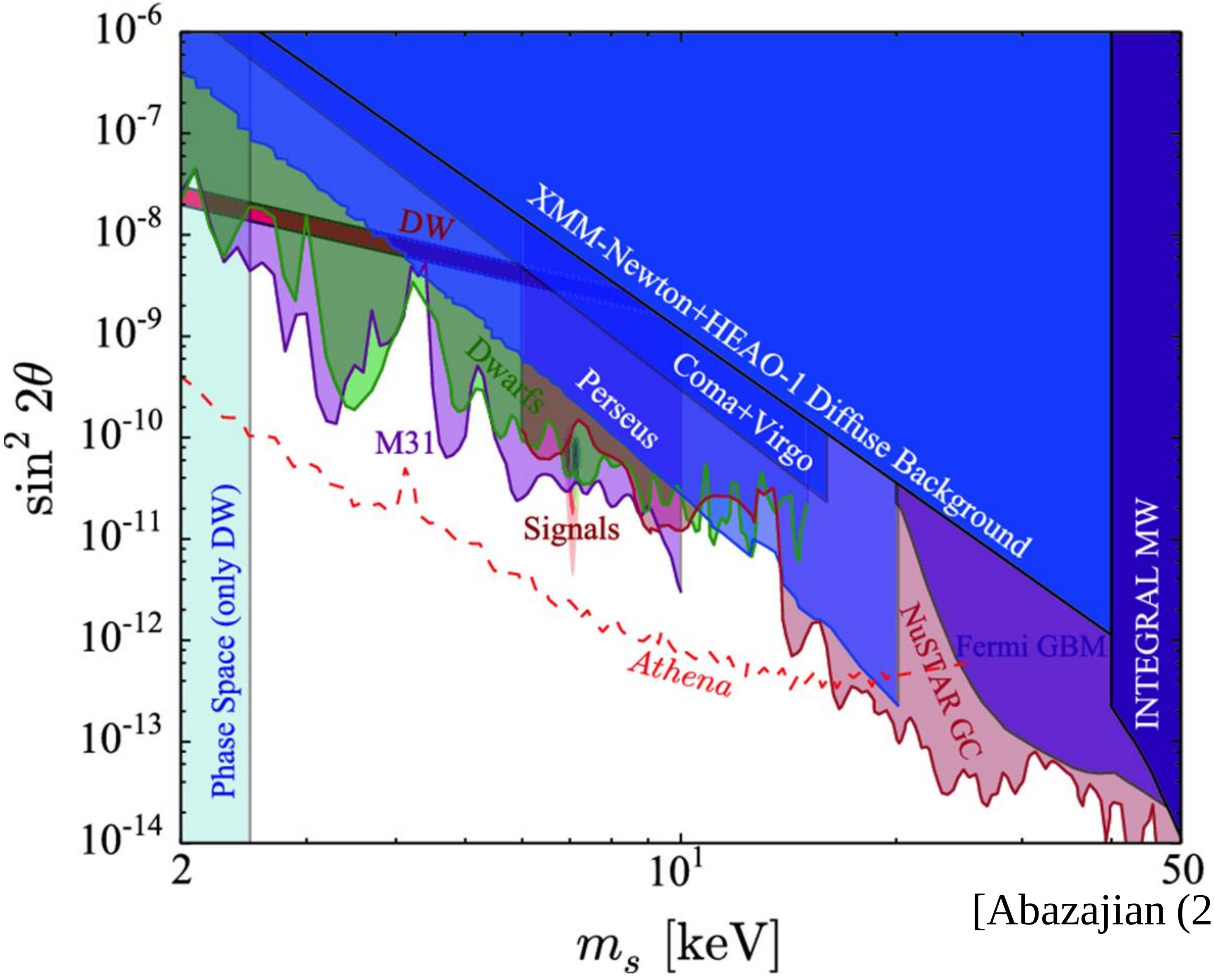

[Abazajian (2019)]

Production of sterile neutrino - revisit

- Dodelson-Widrow mechanism
  - Confront with X-ray bound
- Resonant oscillation [Shi and Fuller (1999)]
  - Large lepton asymmetry
- Nonthermal with or from new states
  - Beyond SM + RH neutrinos
  - From an extra scalar decay [Shaposhnikov and Tkachev (2006), Kusenko (2006)]
  - Z' mediated scattering [Khalil and Seto (2008), Kaneta, Kang and Lee (2017), …]

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- Freeze-in production of DM

Freeze in Production

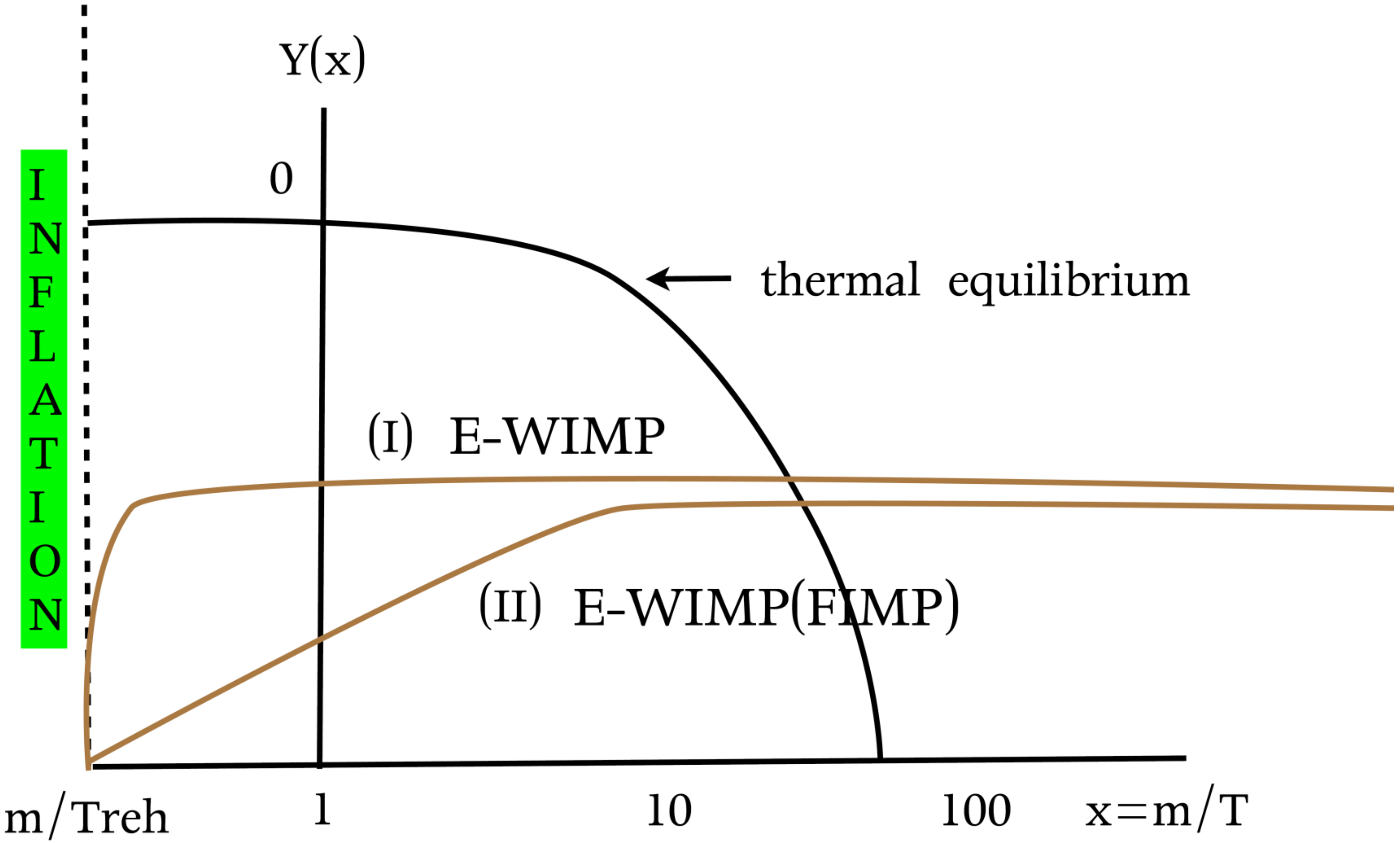
- A kind of non-thermal production
- but called "Thermal production"
    - Never be in thermal equilibrium
    - Produced through thermal scatterings

Freeze in Production

- UV (in)dependence
  - Depends on Reheating temperature T_R
    - E.g., Gravitino, Axino, …
  - Does not depends on T_R
    - Renormalizable Op, very weak (feeble) interaction, light mediators
    - Most effective at $T \sim$ DM mass
    - Depends on the cross section only   c.f., WIMP
    - E.g., Single scalar DM [McDonald (2002)] RH sneutrino DM [Asaka, Ishiwata and Moroi (2006)]
    - Catchy name "Feebly Interacting massive Particle, FIMP" came later [Hall et al (2010)]

Freeze in Production

Extremely (Super-) weakly interacting massive particles



By courtesy of K.Y. Choi

Freeze in Production

- With equations
- $\frac{d\, n_{\nu_s}}{dt} + 3Hn_{\nu_s} = \langle \sigma v(i\bar{\imath} \to \nu_s \nu_s)\rangle n_i n_{\bar{\imath}}$
- $\langle \sigma v(i\bar{\imath} \to \nu_s \nu_s)\rangle \sim \frac{g^4}{T^2}$
- $Y := \frac{n_{\nu_s}}{s} =$

$$\int_{T_0}^{T_R} \frac{\langle \sigma v(i\bar{\imath} \to \nu_s \nu_s)\rangle n_i n_{\bar{\imath}}}{s\ H\ T} \sim \int_{T_0}^{T_R} \frac{M_P\ {}^{g^4}\!/_{T^2}\ T^3 T^3}{s\ T^2\ T} \sim \frac{M_P g^4}{m_{\nu_s}}$$

- $\Omega_{\nu_s} h^2 \propto m_{\nu_s} Y \sim M_P g^4$

§ Sterile neutrino DM in feeble gauged U(1) extended model

Extension of the model

- SM+ RH neutrinos
  - Difficulty in Sterile neutrino DM production
  - The number of generation of RH neutrinos?
- Gauged U(1) extension
  - New gauge interactions provide DM production
  - Anomaly free condition
    - $U(1)_{B-L}$: +1 for baryon, -1 for lepton [Davidson (1979), Mohapatra and Marshak (1980), …]
    - $U(1)_R$: +1(-1) for RH, 0 for left-handed [Jung et al (2010), Ko, Omura and Yu (2014), …]
  - Various dark photon search in "lifetime frontier"

Model

- Content

	Q	u_R	d_R	L	e_R	ν_R	H	S
$SU(3)$	3	3	3	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	0
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	-1	0	$+2$
$U(1)_R$	0	$\frac{1}{2}$	$-\frac{1}{2}$	0	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	-1

TABLE I: Matter contents and charge assignm… ds.

The VEV of S generates the mass of the extra geuge boson X :
$m_X^2 = q_X^2\, g_X^2\, v_S^2$ and
Majorana masses for RH neutrinos
$m_{\nu_R} = \frac{y_R}{\sqrt{2}}\, v_S$

Model

- States $\nu_s = \nu_{R_1} + \sin\theta U_{1\alpha}\nu^c_{L\alpha}$
- Interactions
  - Fermion-gauge $\mathcal{L}_{\text{int.}} = ie\overline{f}\gamma^\mu(\epsilon^V_f + \epsilon^A_f\gamma_5)fX_\mu,$

    where ϵ^V_f and ϵ^A_f are the vector and axial vector coupling defined by

$$\epsilon^V_f = \frac{1}{2}(x_{f_R} + x_{f_L})\epsilon_X \cos\chi - \left(\frac{1}{2}T_f - Q_f \sin^2\theta_W\right)\epsilon_{\text{NC}},$$

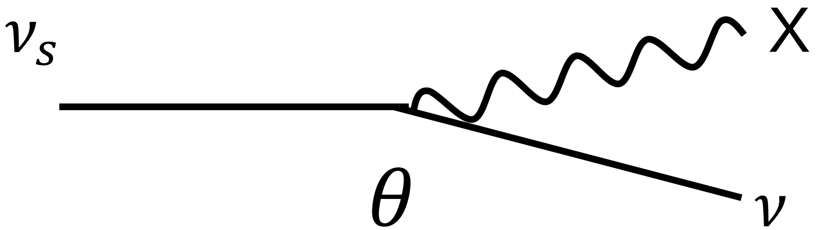
$$\epsilon^A_f = \frac{1}{2}(x_{f_R} - x_{f_L})\epsilon_X \cos\chi + \frac{1}{2}T_f\epsilon_{\text{NC}}.$$

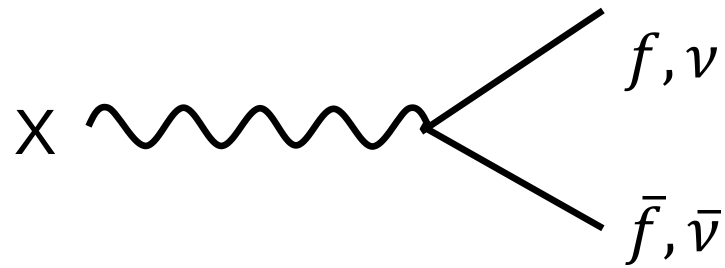
    - *Z*-*X* mixing χ $\epsilon_{\text{NC}} = \frac{\sin\chi}{\sin\theta_W \cos\theta_W}$
  - Active-sterile-gauge

$$\mathcal{L} = ie\sin\theta U_{1\alpha}\delta_{\alpha i}\overline{\nu^c_s}\gamma^\mu(\epsilon^V + \epsilon^A\gamma_5)\nu_i X_\mu + h.c.,$$

Decay of gauged sterile neutrino DM

- $\nu_s \to X\nu$
  - New main decay mode
  - Followed by $X \to 2\nu, f\bar{f}$





- $\nu_s \to 3\nu$
- $\nu_s \to \gamma\nu$

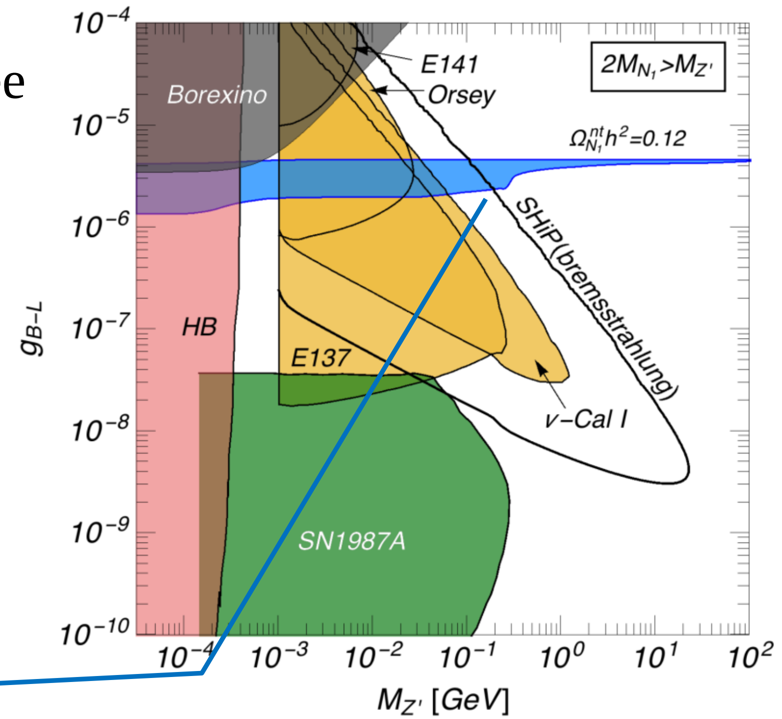
Sterile neutrino DM abundance

- Spectrum range $2m_{\nu_s} > \ m_X$
- Equation

$$\frac{dn_{\nu_s}}{dt} + 3Hn_{\nu_s} = \sum_f \langle \sigma v(f\bar{f} \to \nu_s\nu_s)\rangle n_f n_{\bar{f}}$$

- Abundance [Kaneta, Kang and Lee (2017)]

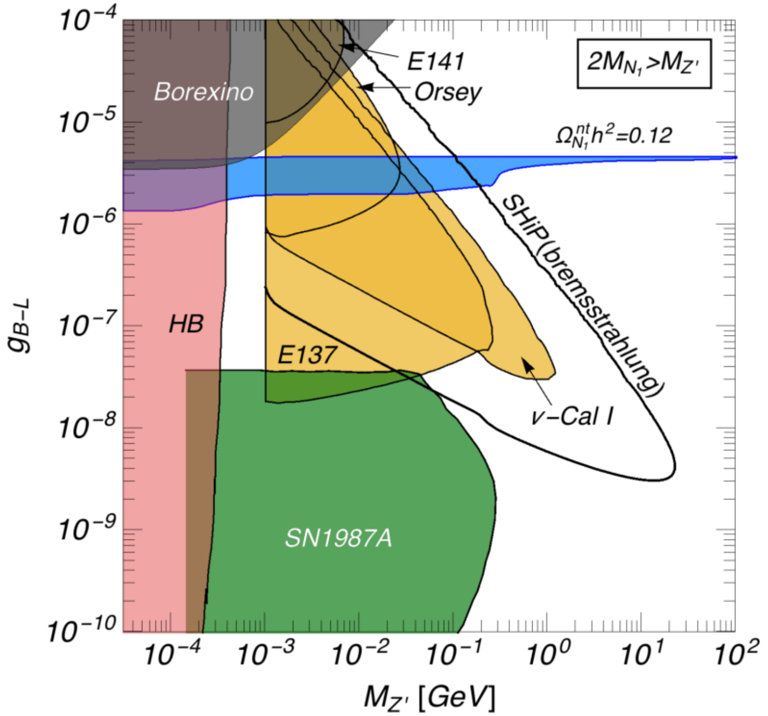
$$\Omega_{\nu_s} h^2 \simeq 0.12 \left(\frac{g_X}{4.5 \times 10^{-6}} \right)^4$$



$2m_{\nu_s} \cong \ m_X$

Constraints on X boson

- Various constraints [Kaneta, Kang and Lee (2017)]
    - Borexino
    - Astrophysical
        - HB stars
        - SN1987A
    - Beam dump experiments
        - $m_X > 2\, m_e$



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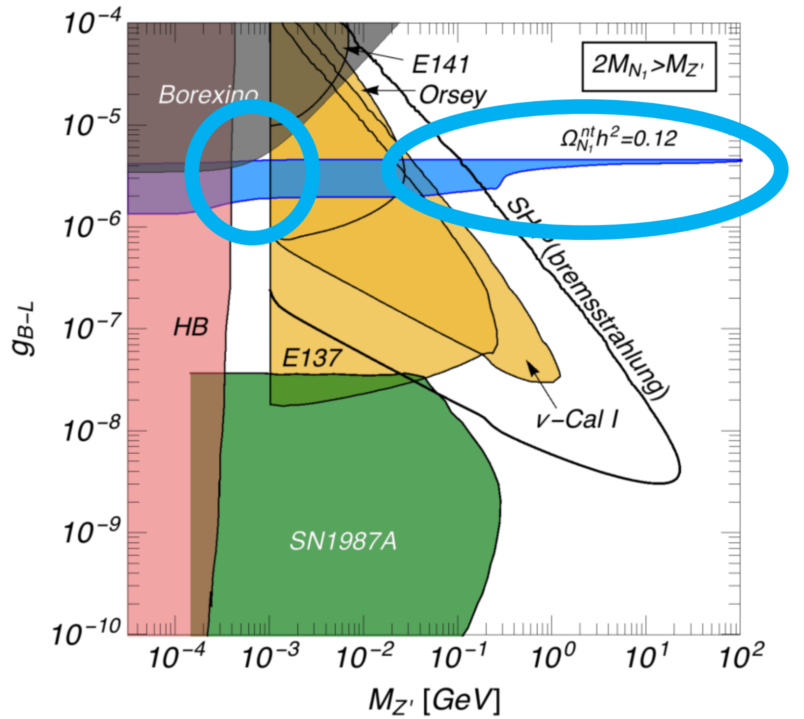


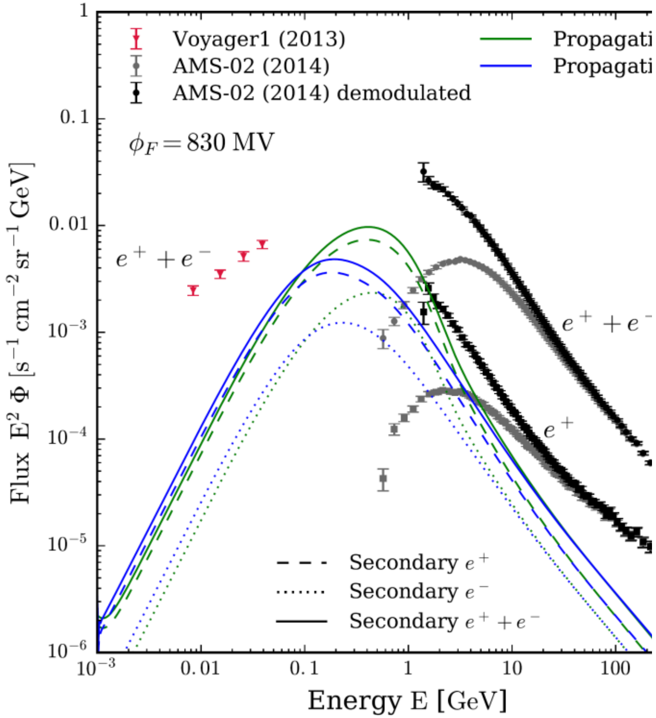
- Two windows

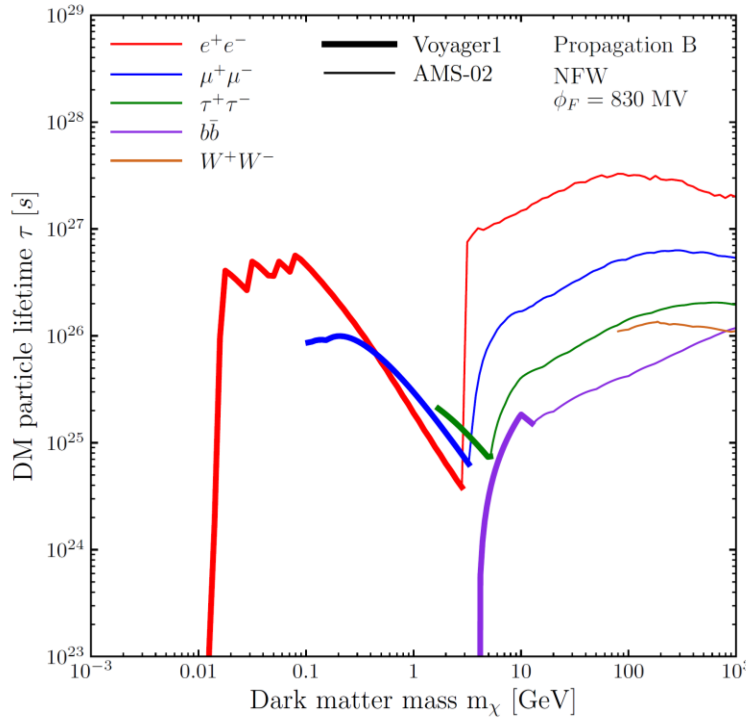
$$0.3\,\text{MeV} \lesssim m_X < 1\,\text{MeV},$$

$$100\,\text{MeV} \lesssim m_X,$$

e^-e^+ cosmic ray constraints

- For $m_X > 2\,m_e$, $\nu_s \to \nu X, X \to e^-e^+$
- Hard to find Sub-GeV e by magnetic field
- $\tau(\mathrm{DM} \to e^-e^+) \gtrsim 10^{27}$ **sec.** [Boudaud, Lavalle and Salati (2017)] based on Voyager I data [Cumming et al (2016)]





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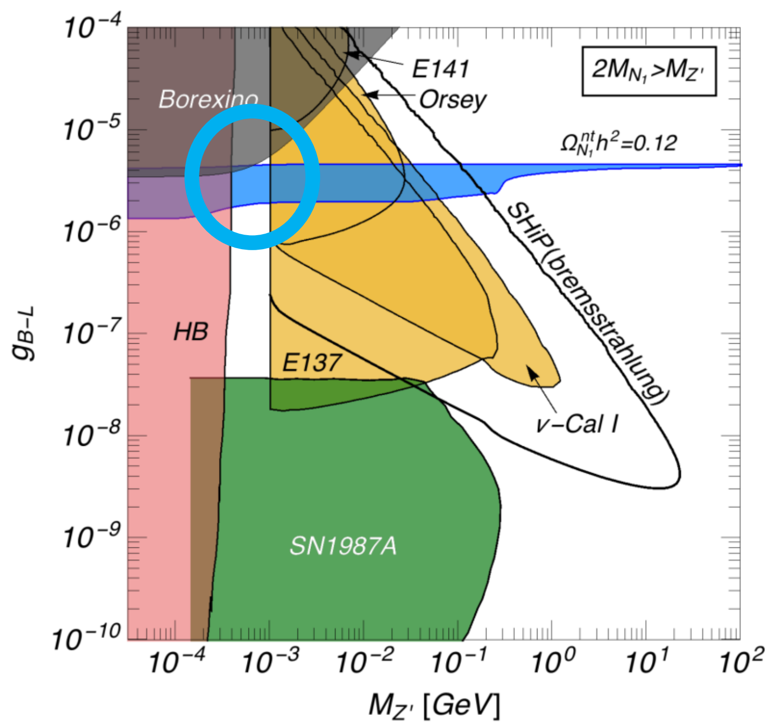


- Two windows

$$0.3\,\mathrm{MeV} \lesssim m_X < 1\,\mathrm{MeV},$$

$$100\,\mathrm{MeV} \lesssim m_X,$$

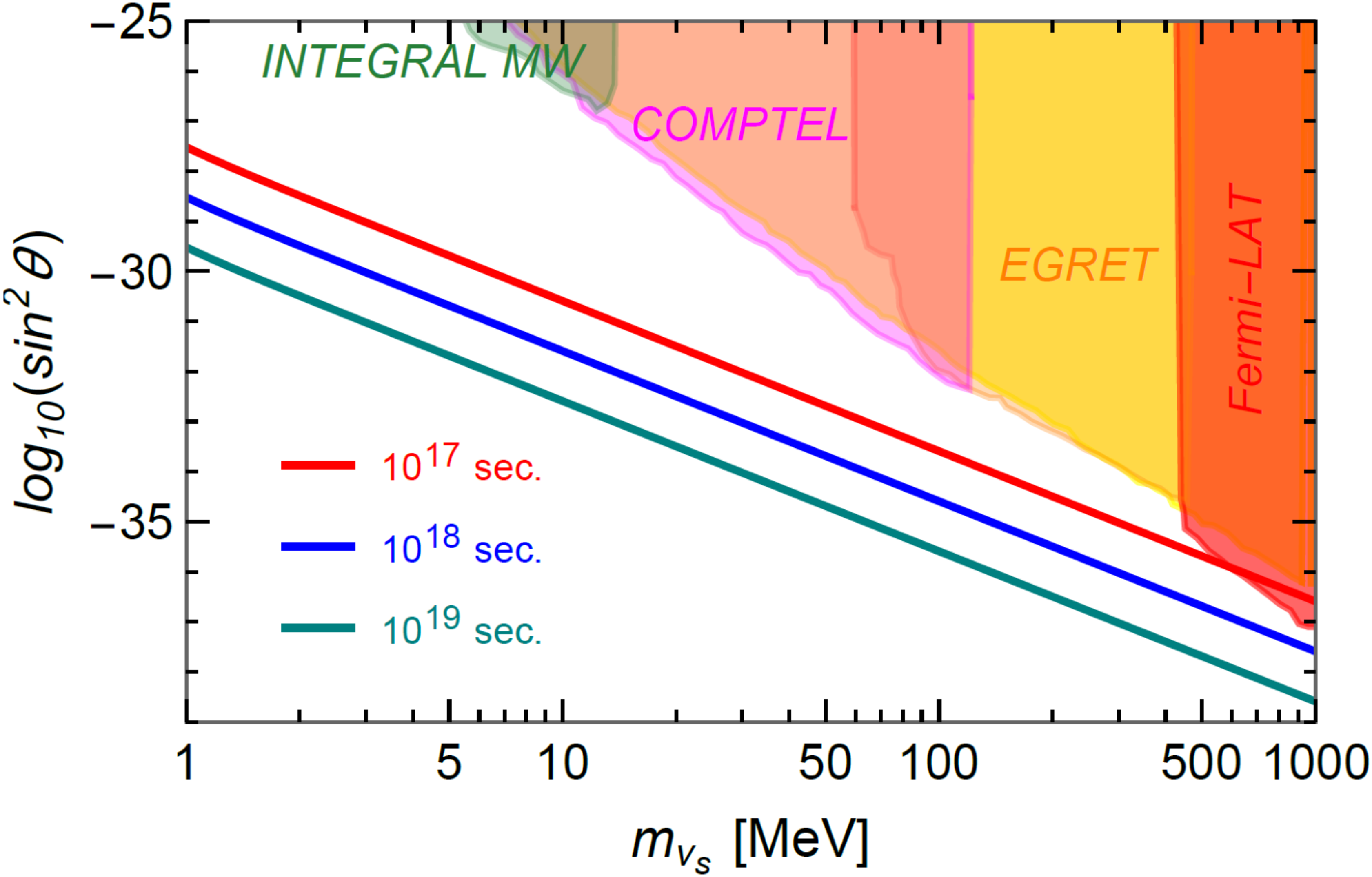
Parameters

- Parameters fixed so far, in other words prediction
  - Gauge coupling $g_X \simeq 10^{-6}$ by DM abundance
  - $m_X =$ several $\times 10^{-1}$ MeV
  - $v_S \simeq 10^2$ GeV from above two

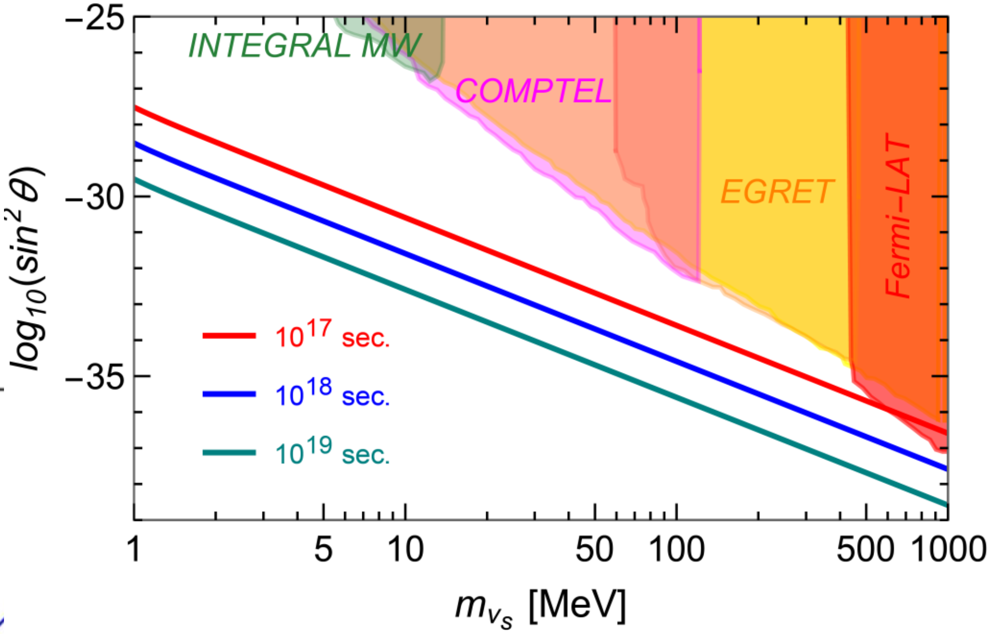
- Remaining
  - DM mass m_{ν_s}
  - Lifetime $\tau_{\nu_s} \leftrightarrow \theta$ active-sterile mixing

X/gamma constraints

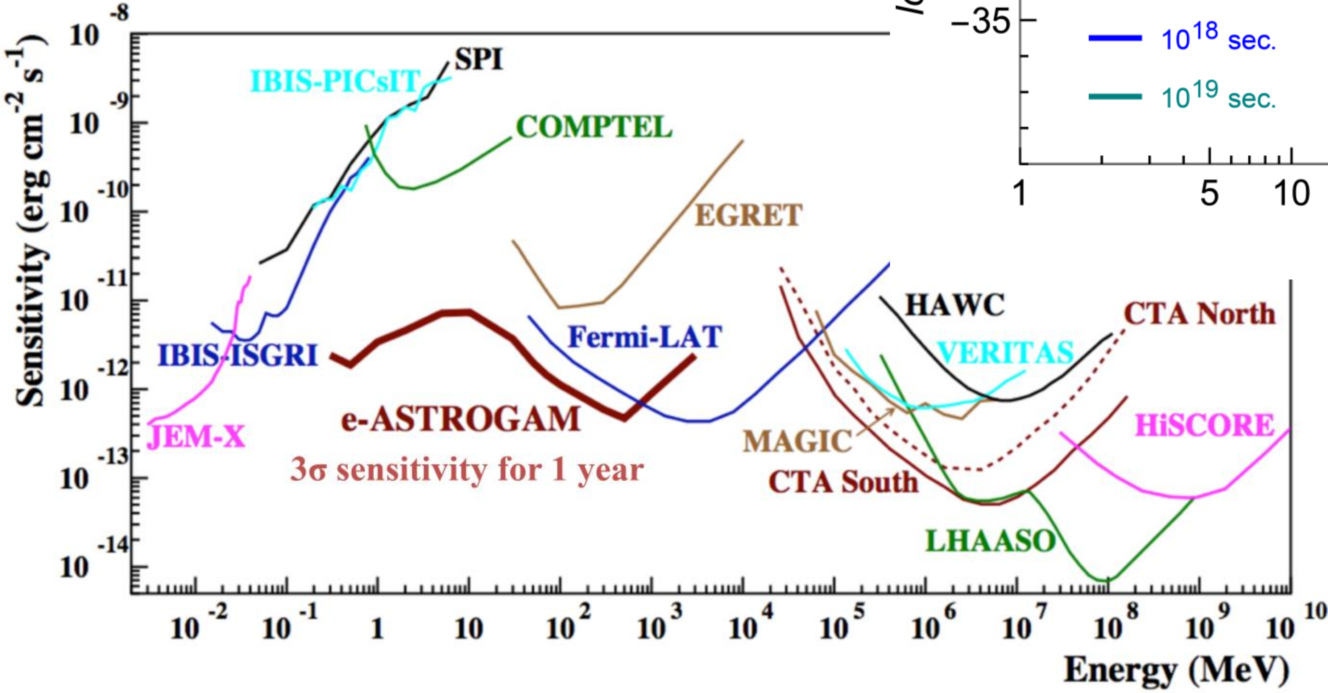
Constraints data [De Romeri et al (2020)]



X/gamma constraints



[e-ASTROGAM's Slide]



Good target for next MeV gamma astronomy!?

Decay of gauged sterile neutrino DM

- $\nu_s \rightarrow X\nu$
  - New main decay mode
  - Followed by $X \rightarrow 2\nu, \cancel{f\bar{f}}$
  - Spectrum

    $$\frac{dN}{dE} \cong \delta\left(E - {}^{m_{\nu_s}}/_{2}\right) + 2\delta\left(E - {}^{m_{\nu_s}}/_{4}\right)$$

  - **Can those νs be detected?**
- $\nu_s \rightarrow 3\nu$
- $\nu_s \rightarrow \gamma\nu$

Neutrino flux and detection

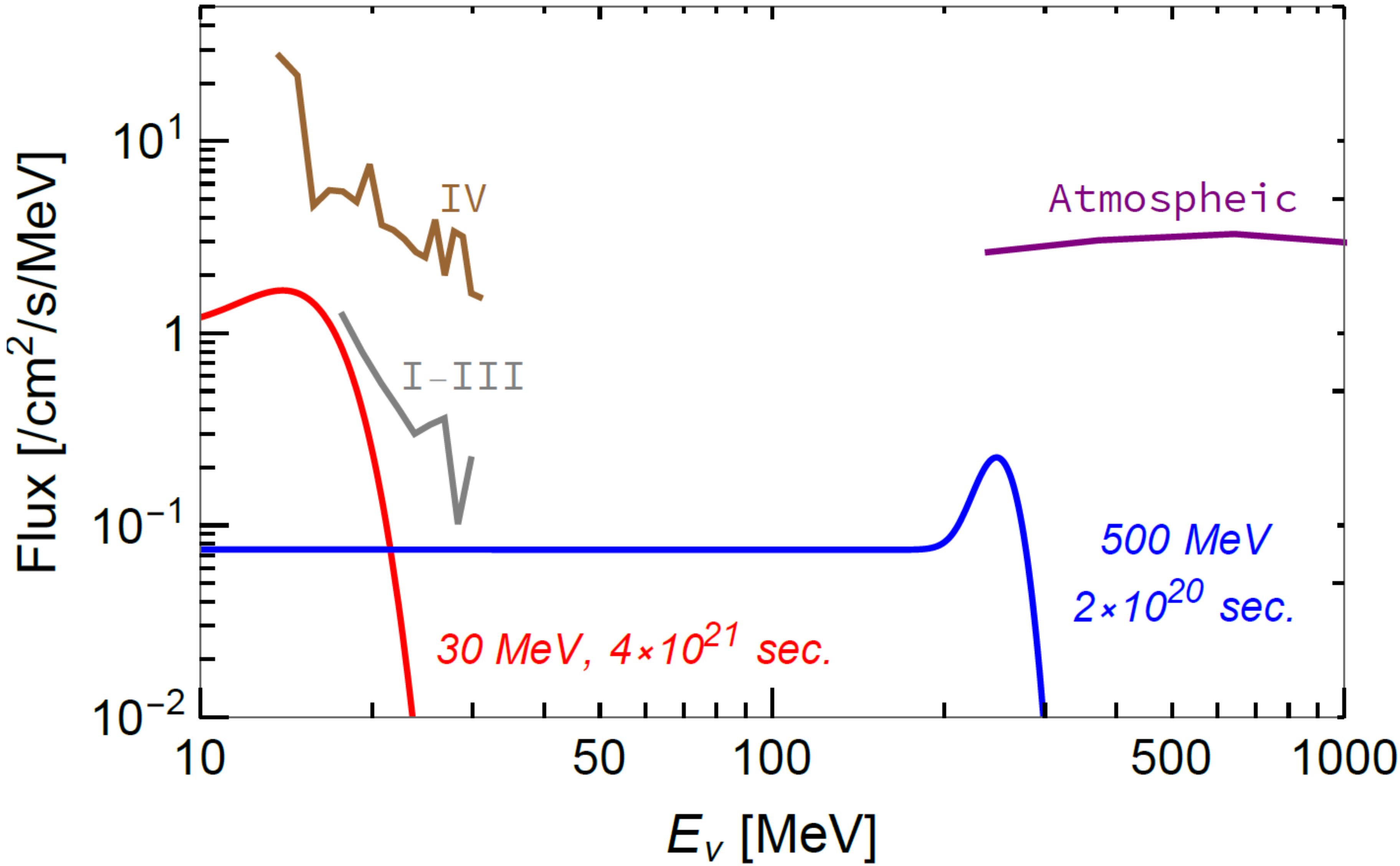
- Flux from sterile neutrino decay
  - $\frac{d\,\phi^{\nu_s}}{d\,E_\nu} = \frac{d\,N}{d\,E_\nu}\frac{J}{4\,\pi\,\tau_{\nu_s}\,m_{\nu_s}}$, $J = \int_{\mathrm{l.o.s}} ds\,\rho_{DM}\,d\Omega$
  - $J = 7 \times 10^{22}$ GeV/cm^2 for MW halo [Buch et al (2020)]
- Detection
  - ν + water $\rightarrow$ Chelenkov light in SK
  - ν + nuclei $\rightarrow$ ν + nuclei + recoil energy in DD

$$\left(\frac{d\sigma}{dE_r}\right)(\nu N \to \nu N) = \frac{G_F^2}{8\pi E_\nu^2}((A-Z)-(1-4s_W^2)Z)^2 m_N(2E_\nu^2 - m_N E_r)$$

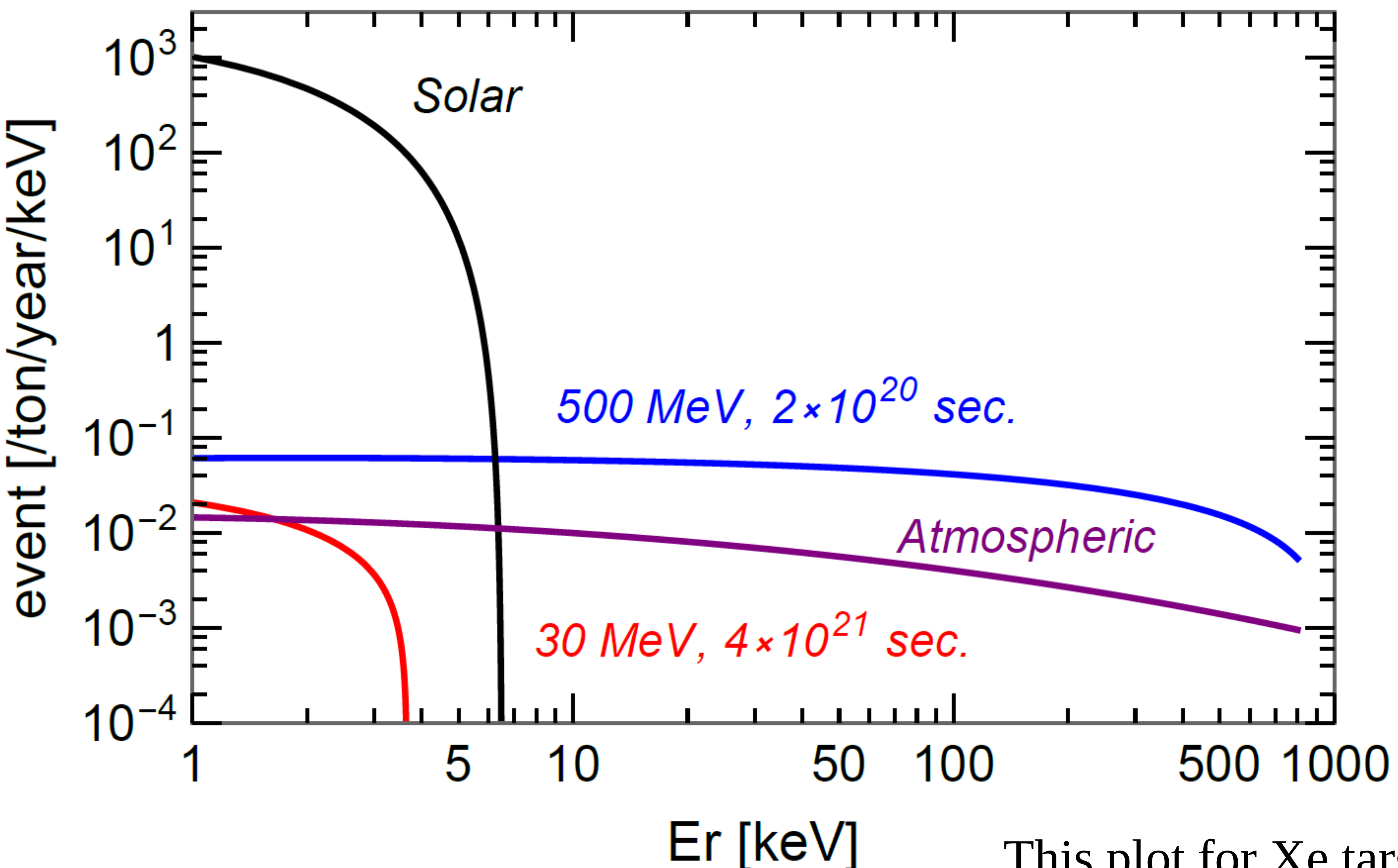
[Freedman (1974)]

  - X boson exchange is negligible for $g_X < 10^{-4}$
    [Boehm et al (2019)]

Super-Kamiokande :
Bound and Implication



Prospect for DM Direct Detection experiments



This plot for Xe target

§ Summary (1/2)

- An extra U(1) extension
  - neutrino masses
  - gauge symmetry, neutrino generation
  - sterile neutrino as dark matter
- Sterile neutrino production
  - Freeze in mechanism
  - No T_R dependence, g_X determined

§ Summary (2/2)

- Search for sterile neutrino dark matter
  - X/gamma ray
  - Neutrino ray hitting water and nucleus
  - Complementary and multi-searches in sky and underground
  - Double-check or consistency check

    as WIMP