511 keV constraints on feebly interacting particles

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Based on :

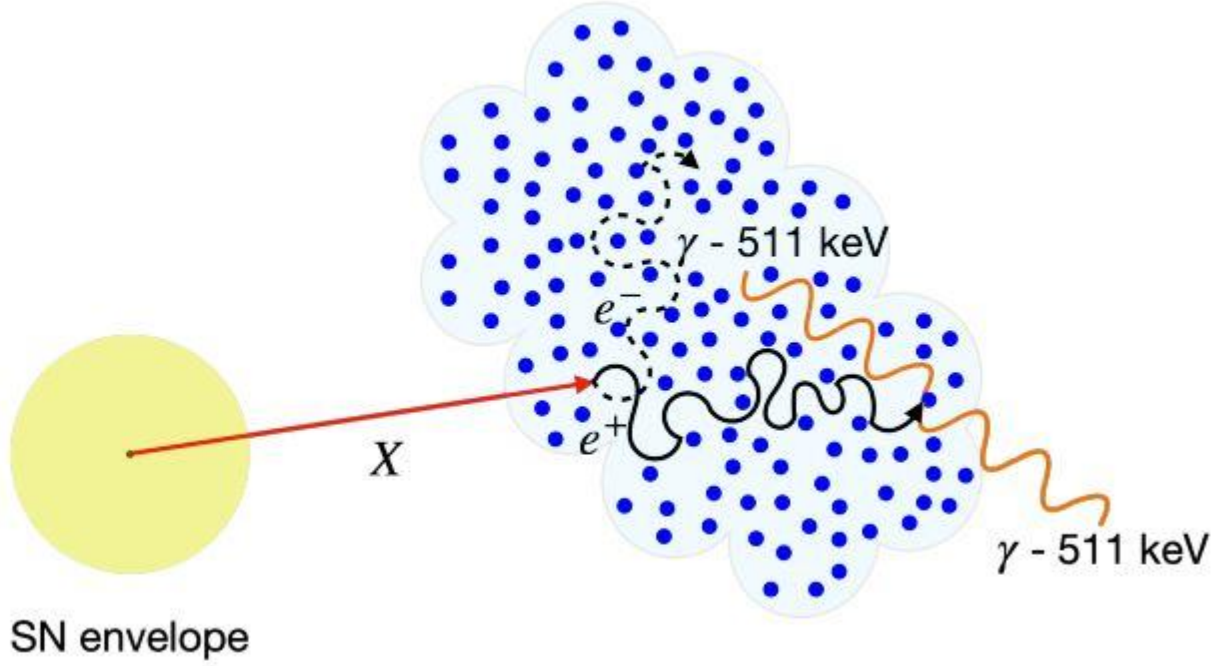
- F. Calore, P. Carenza, M. Giannotti, J. Jaeckel, G. Lucente, L. M. and A. Mirizzi, arXiv:2112.08382

OUTLINE

- Constraint strategy for the 511keV line
- Introduction to SN explosions
- Introduction to sterile neutrinos and dark photons
- Obtained bounds and discussion on the uncertainties
- Conclusions

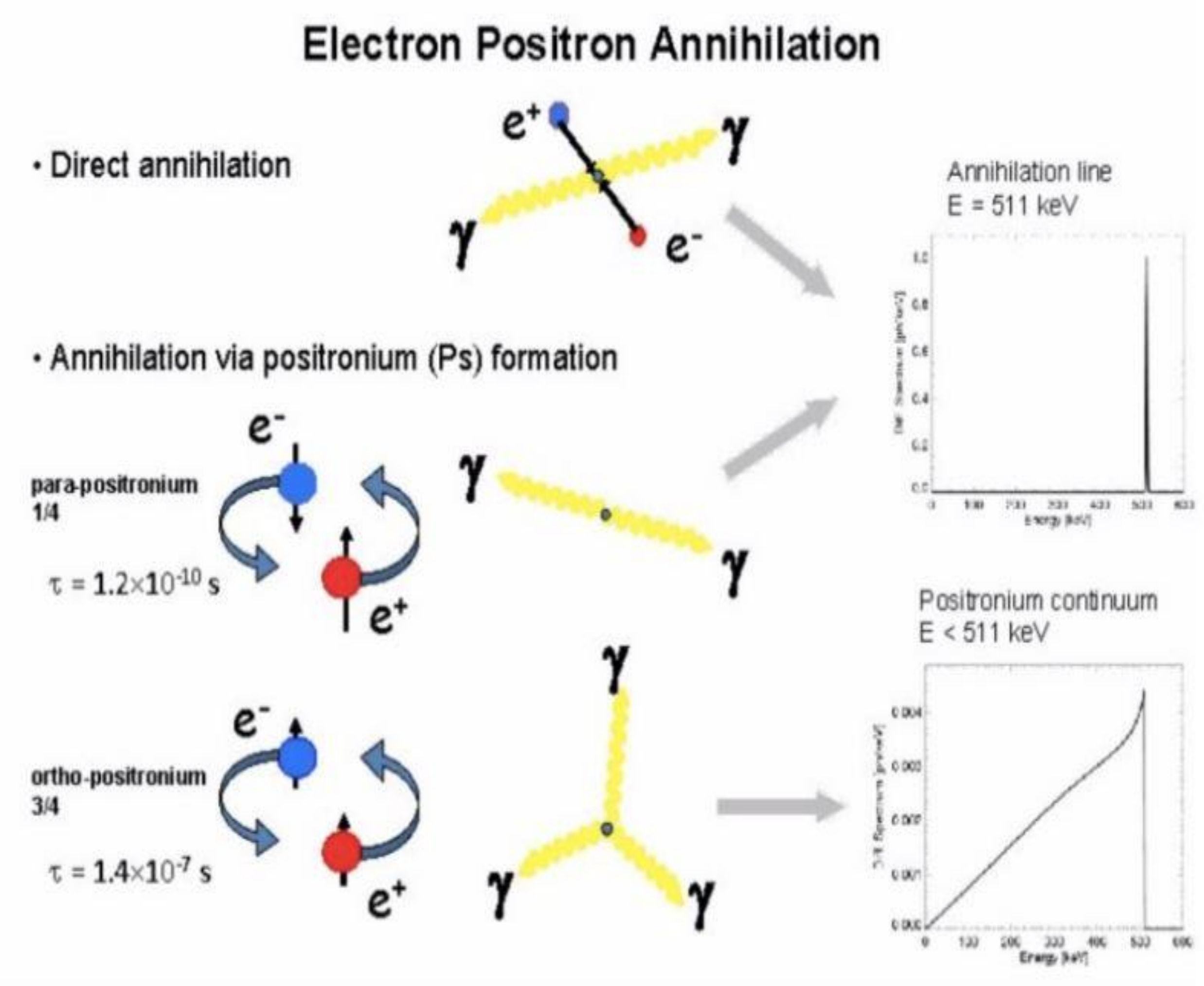
POSITRONS EMISSION FROM SN

- A schematic representation of the production mechanism of the 511 keV gamma-ray line by particle X decays in e^+e^- pairs.
- Positrons, before annihilate, are slowed down due to scattering.



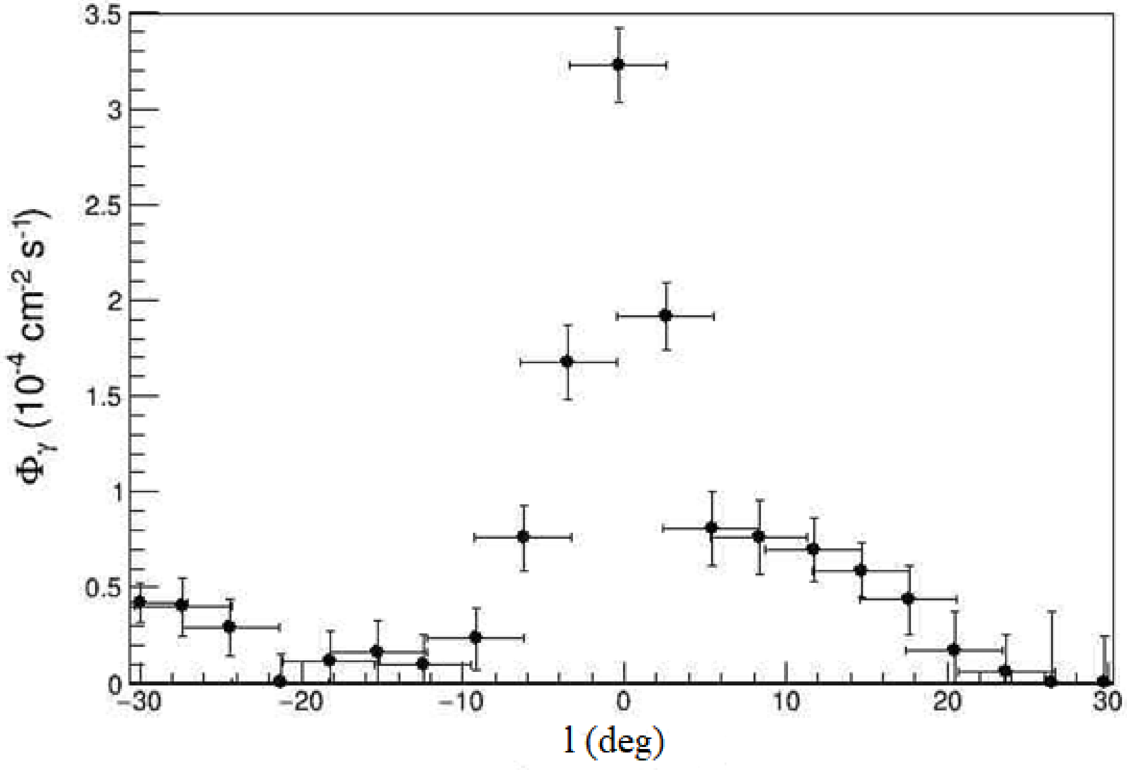
THE 511 keV LINE

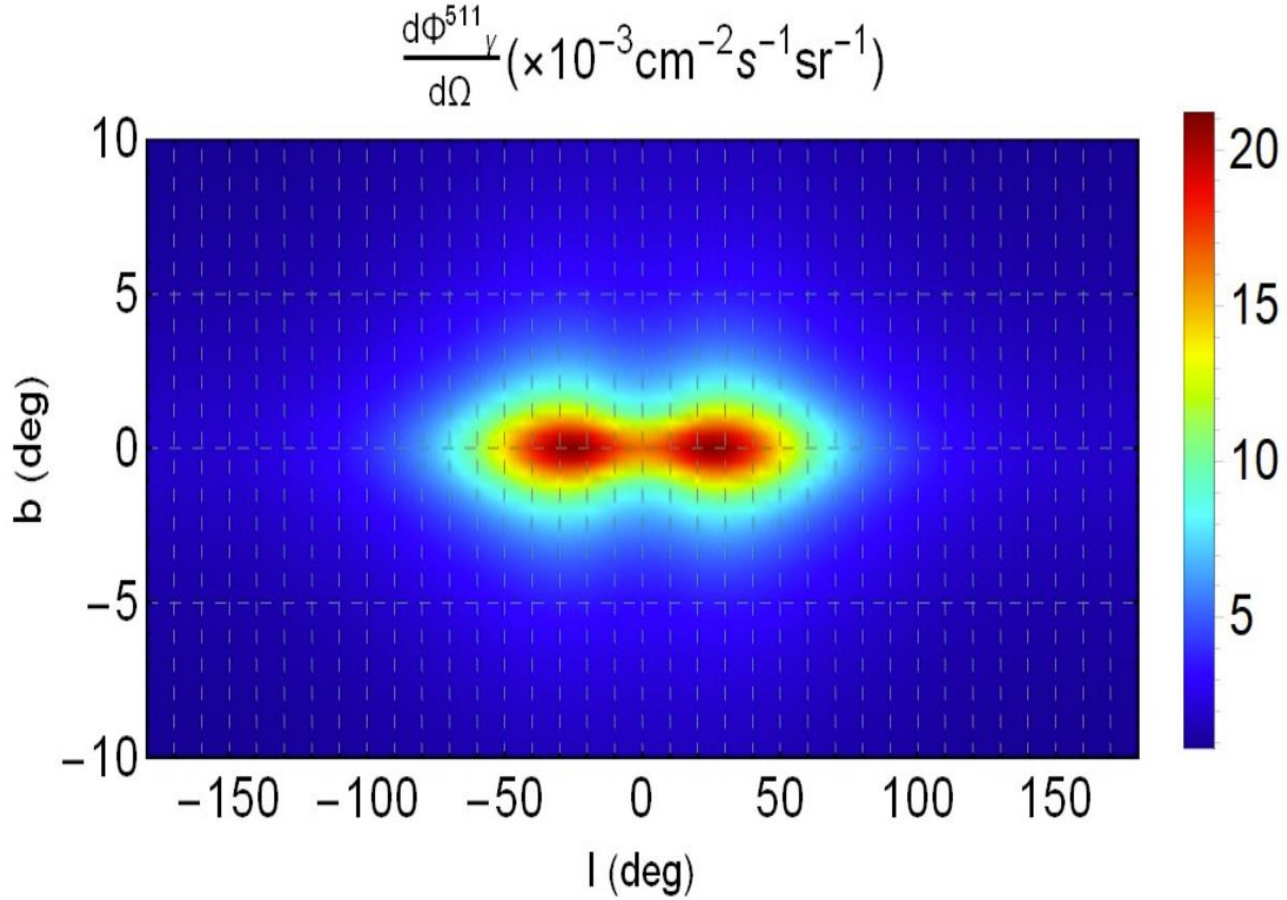
- Strong flux of 511 keV photons $\sim 10^{-3}$ ph cm^2 s^{-1} from the galactic bulge.
- SPI measurement positron annihilation (production) rate $\sim 10^{43}$ s^{-1}.
- Constraints on Dark Photons [De Rocco et al., JHEP 02 (2019)], Primordial Black Holes [Laha et al., PRD 101 (2020)], decaying Dark Matter [Cai et al., JCAP 03 (2021)] and Axions [F. Calore et al., PRD 104, 043016 (2021)].



OUR STRATEGY

- We compared the obtained results with the SPI data [Siegert et al., Astron. Astrophys. 627 (2019)]
- The most constraining bin is $l \in [28.25°, 31.25°]$





SNe CONSTRAINTS

- We are interested in the decay channel $X \to n_i e^+ + Y_i$
- We need to calculate the average number of positrons that decay outside the supernovae envelope

$$N_{pos} = n_{pos,X} \int dE \frac{dN_X^0}{dE} \left(\epsilon_{II} e^{-\frac{r_{II}}{l_X}} + \epsilon_I e^{-\frac{r_I}{l_X}} \right) \times \left[1 - e^{-\frac{r_G}{l_X}} \right]$$

$$n_{pos,X} = \sum_i n_i BR(X \to n_i e^+ + Y_i)$$

- We have considered $r_{II} = 10^{14}$cm, $r_I = 2 \times 10^{12}$cm, $\epsilon_{II} = 1 - \epsilon_I = 0.77$

- Positrons trapped by galactic magnetic field $O(\mu G)$: 511 keV photons generated not farther than 1 kpc from the X decay region. [Jean et al., Astron. Astrophys. 445 (2006)]
- Angular distribution of the 511 keV line photon signal from e^+e^- annihilation ($\tau_e \gtrsim 10^3$ yrs):

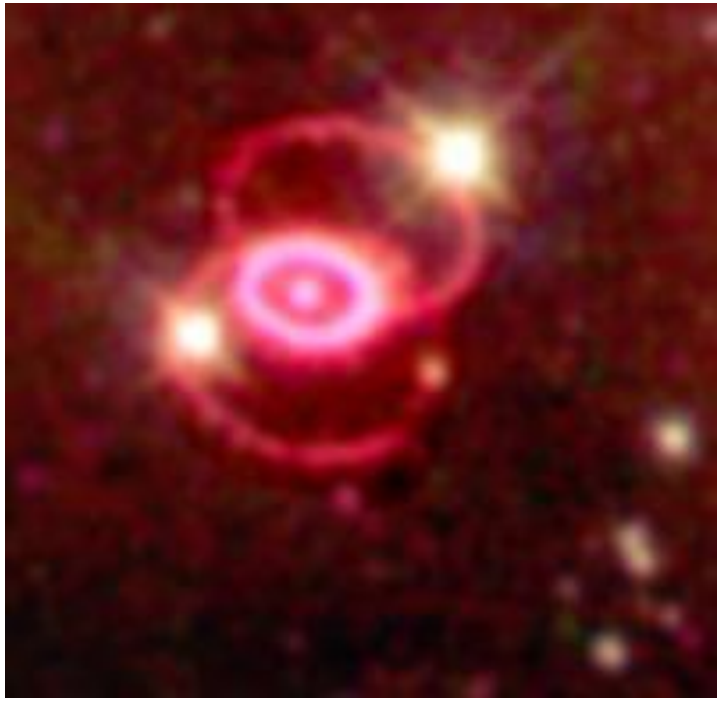
$$\frac{\mathrm{d}\Phi}{d\Omega} = 2k_{ps}N_{pos}\Gamma_{cc}\int ds\ s^2 \frac{n_{cc}}{4\pi s^2}$$

where:

- $k_{ps} = \frac{1}{4}$ parapositronium fraction
- $\Gamma_{cc} = 2\ \mathrm{SNe/century}$
- n_{cc} normalized SN volume distribution [Mirizzi et al., JCAP 0605 (2006)]

SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_{\odot}$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.



- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d $\approx O$ (10) kpc).

FEEBLY INTERACTING PARTICLES

- $m_X \leq O(1)$ GeV

- Extremely suppressed interaction between new particles and SM

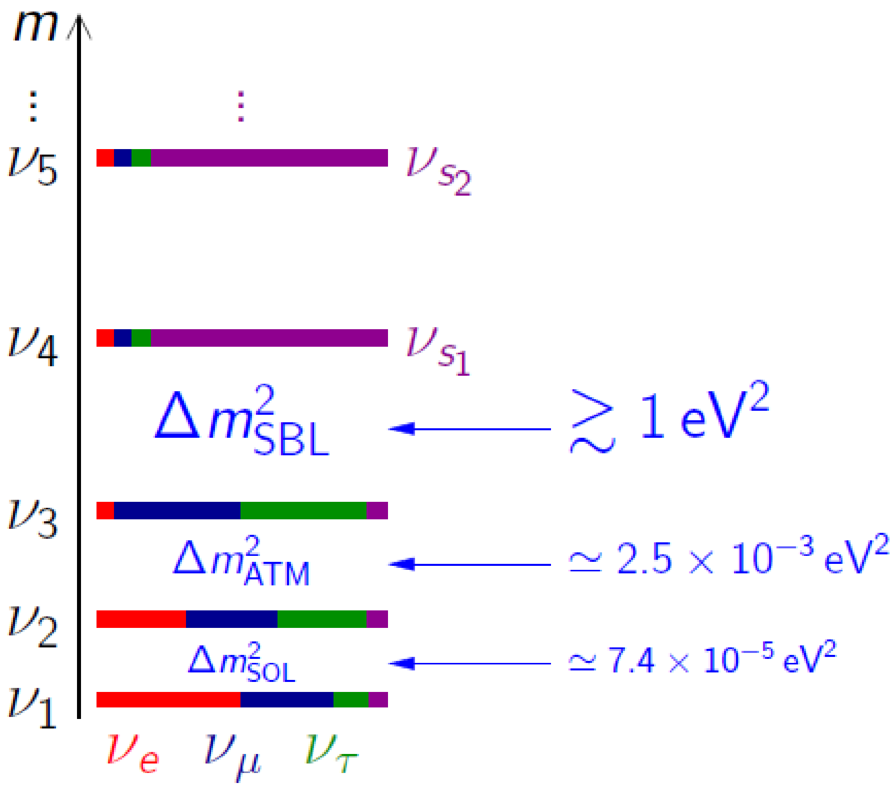
- They have been proposed to solve some SM open questions (neutrino mass, CP problem, dark matter, etc.)

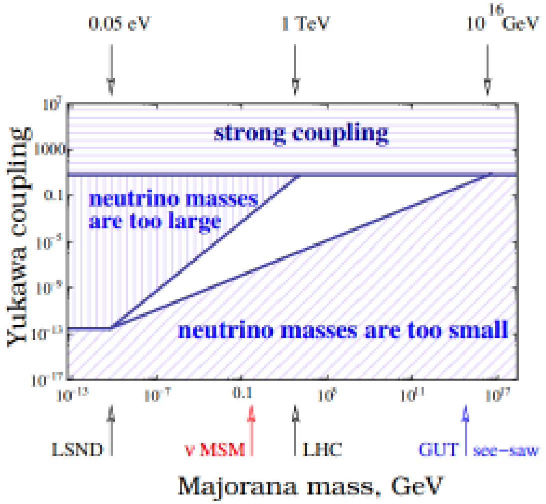
- Typical examples are axions, **sterile neutrinos and dark photons**.

- ALP constrained with the same strategy in [*F. Calore et al, Phys.Rev.D 104 (2021) 4, 043016*]

STERILE NEUTRINOS

[*Takehiko Asaka andMikhail Shaposhnikov, Phys.Lett.B620:17-26,2005*]





	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} .$$

Extra sterile neutrinos with masses $m_s \gg m_a$ and mixed with the active ones through a mixing angle θ_s are predicted in different extensions of the Standard Model

HEAVY STERILE ν FROM SNe

- We investigate the possibility also that heavy sterile neutrinos ($m \sim O(100)$ MeV) might be produced in supernovae explosion [*Fuller et al, Phys. Lett. B, 670, 4–5, 2009*]
- In the hot core ν_e, e, p, n are degenerate. The processes that will create sterile neutrino involve only ν_μ, ν_τ.
- We solved the Boltzmann equation for sterile neutrino population, following the technique developed by [*Hannestad et al, Phys. Rev. D 52, 1764*]

$$\frac{\partial f_s}{\partial t} = \frac{(2\pi)^4}{2E_1} \int d^3\widehat{p_2} d^3\widehat{p_3}\, d^3\widehat{p_4} \Lambda(f_s, f_2, f_3, f_4) S|M|^2 \delta^4(p_1 + p_2 - p_3 - p_4)$$

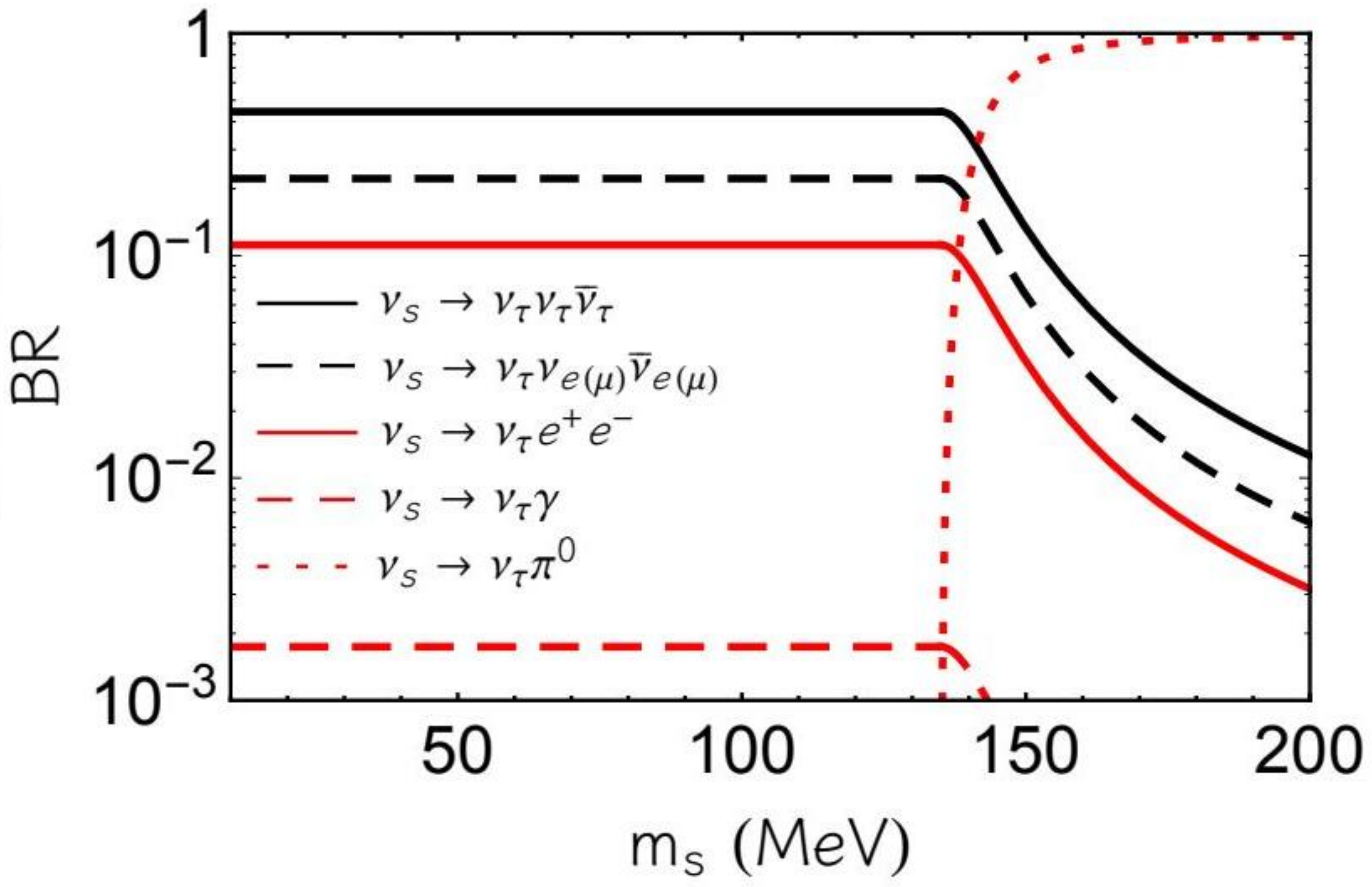
Process	$S\|M\|^2/(8G_F^2 \sin^2\theta_{\tau 4})$
$\nu_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$	$4u(u - m_4^2)$
$\nu_\mu + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$	$u(u - m_4^2)$
$\nu_\tau + \nu_\tau \to \nu_4 + \nu_\tau$	$2s(s - m_4^2)$
$\bar{\nu}_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau$	$2s(s - m_4^2)$
$\nu_\mu + \nu_\tau \to \nu_4 + \nu_\mu$	$s(s - m_4^2)$
$\bar{\nu}_\mu + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\mu$	$s(s - m_4^2)$
$\nu_\tau + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\mu$	$u(u - m_4^2)$
$\bar{\nu}_\tau + \nu_\mu \to \nu_4 + \nu_\mu$	$u(u - m_4^2)$

[*L.M., A. Mirizzi, P. D. Serpico and A. Esmaili, JCAP01(2020)010*]

HEAVY STERILE DECAY

- The produced sterile neutrinos decay into different channels depending on their mass.

Process	$\Gamma/G_F^2 m_s^3 \lvert U_{\tau s}\rvert^2$	Threshold (MeV)
$\nu_s \to \nu_\tau \gamma$	$9\alpha m_s^2/2048\pi^4$	0
$\nu_s \to \nu_\tau \nu_\tau \bar{\nu}_\tau$	$m_s^2/384\pi^3$	0
$\nu_s \to \nu_\tau \nu_{e(\mu)} \bar{\nu}_{e(\mu)}$	$m_s^2/768\pi^3$	0
$\nu_s \to \nu_\tau e^+ e^-$	$(\tilde{g}_L^2 + g_R^2) m_s^2/192\pi^3$	1
$\nu_s \to \nu_\tau \pi^0$	$f_\pi^2/32\pi\,(1 - m_s^2/m_\pi^2)^2$	135



DARK PHOTONS

- The Lagrangian describing dark photons is *[B. Holdom, Phys. Lett. B 166 (1986) 196–198.]*

$$L = \frac{1}{2} m_{A'} A'_{\mu} A'^{\mu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

- The dark photon is a $U(1)$ gauge boson mixed with the SM photon.

- After being produced in the SN core, the dark photons can decay into e^+e^-

$$\Gamma = \frac{1}{3} \alpha \epsilon^2 m_{A'} \sqrt{1 - \frac{4m_e^2}{m_{A'}^2}} \left(1 + \frac{2m_e^2}{m_{A'}^2}\right)$$

DARK PHOTONS PRODUCTION

- The dominant process is the Bremsstrahlung $\Gamma_{ibr} \propto \epsilon_m^2$ with

$$\epsilon_m = \frac{\epsilon}{\left(1 - \frac{\mathrm{Re}\Pi}{m_{A'}^2}\right)^2 + \left(\frac{\mathrm{Im}\Pi}{m_{A'}^2}\right)^2}$$

- In the SN core $\mathrm{Im}\Pi \ll \mathrm{Re}\Pi$ → Resonant production if $\mathrm{Re}\Pi = m_{A'}^2$

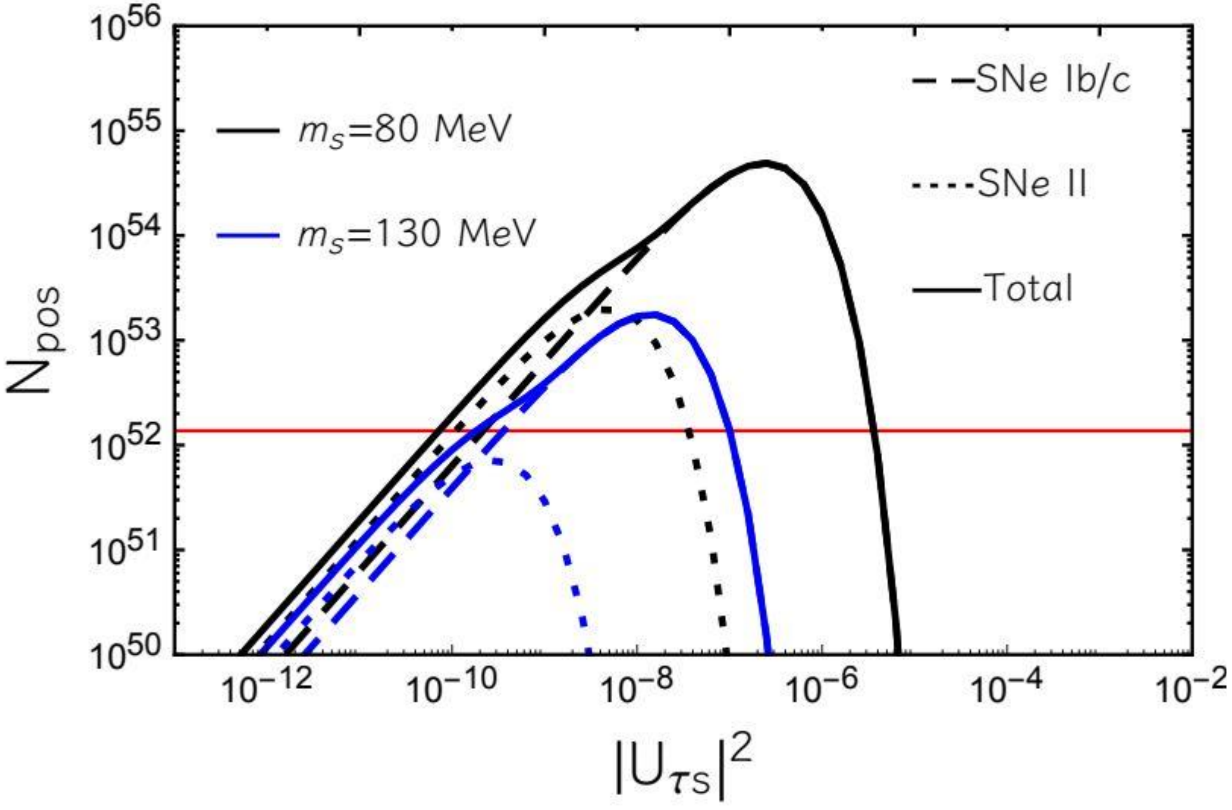
↓

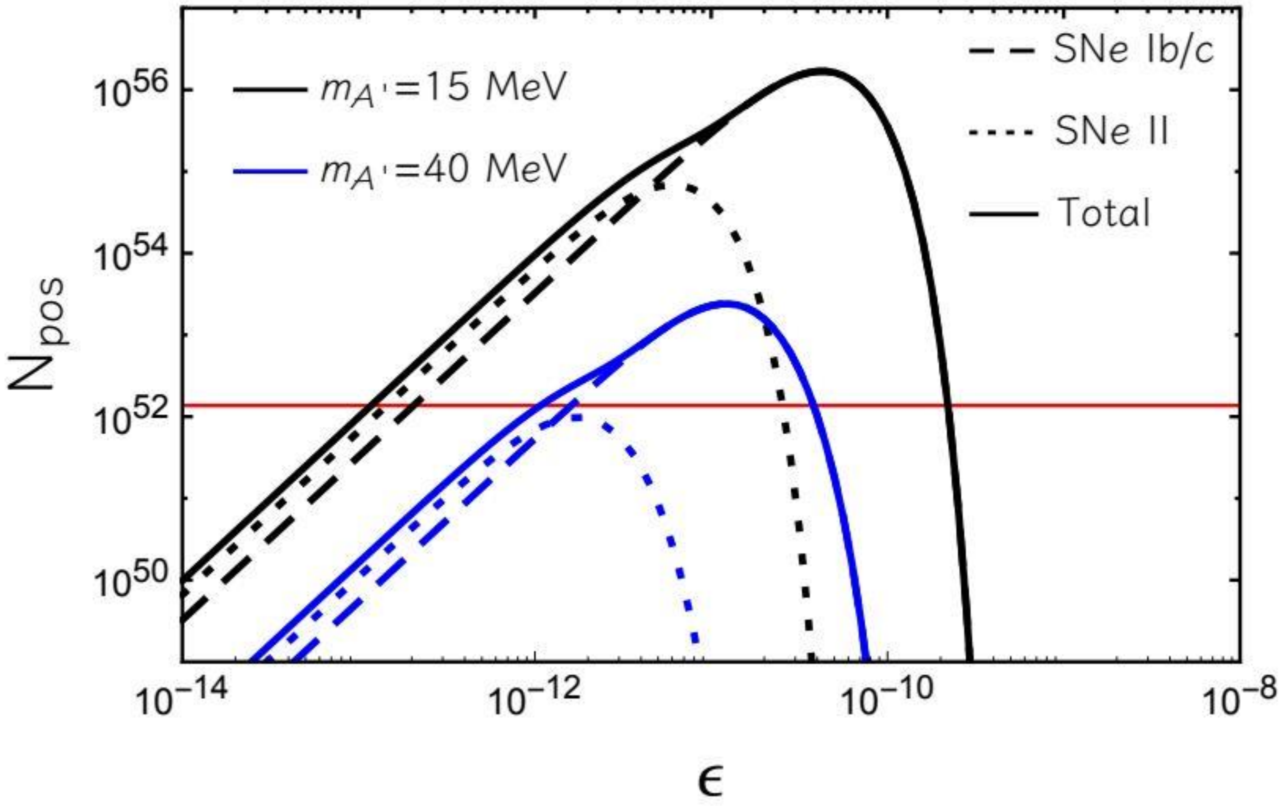
$$\omega_p \simeq m_{A'}$$

with ω_p the plasma frequency

POSITRONS PRODUCTION

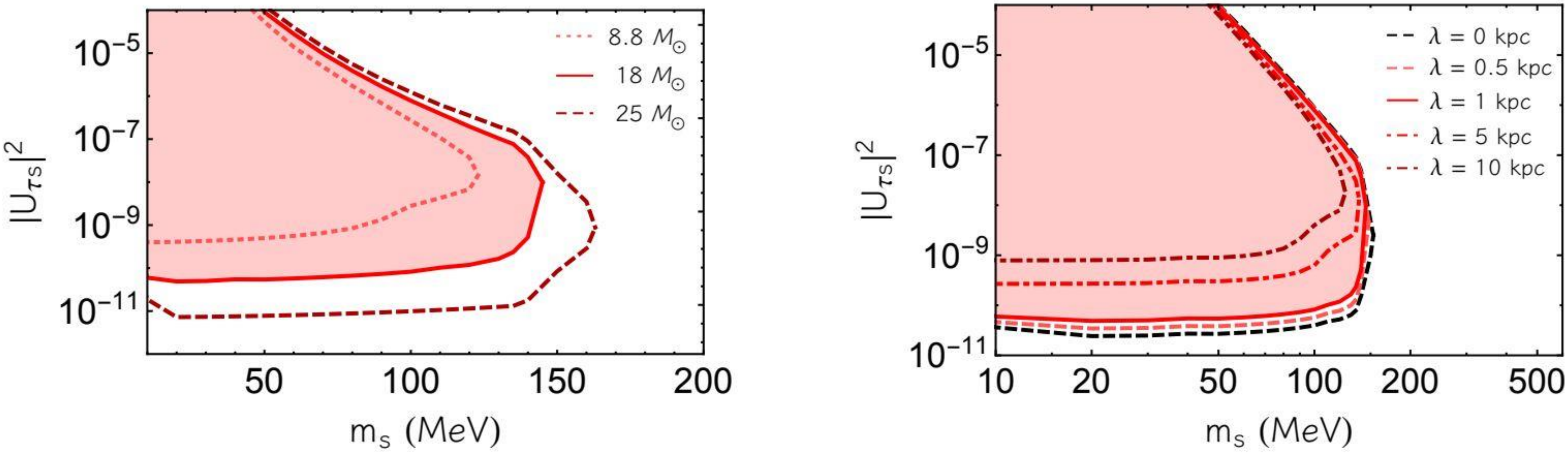
- The number of positrons obtained from sterile neutrinos and dark photons decay.
- In red we show the maximum value of N_{pos} allowed from the observations.



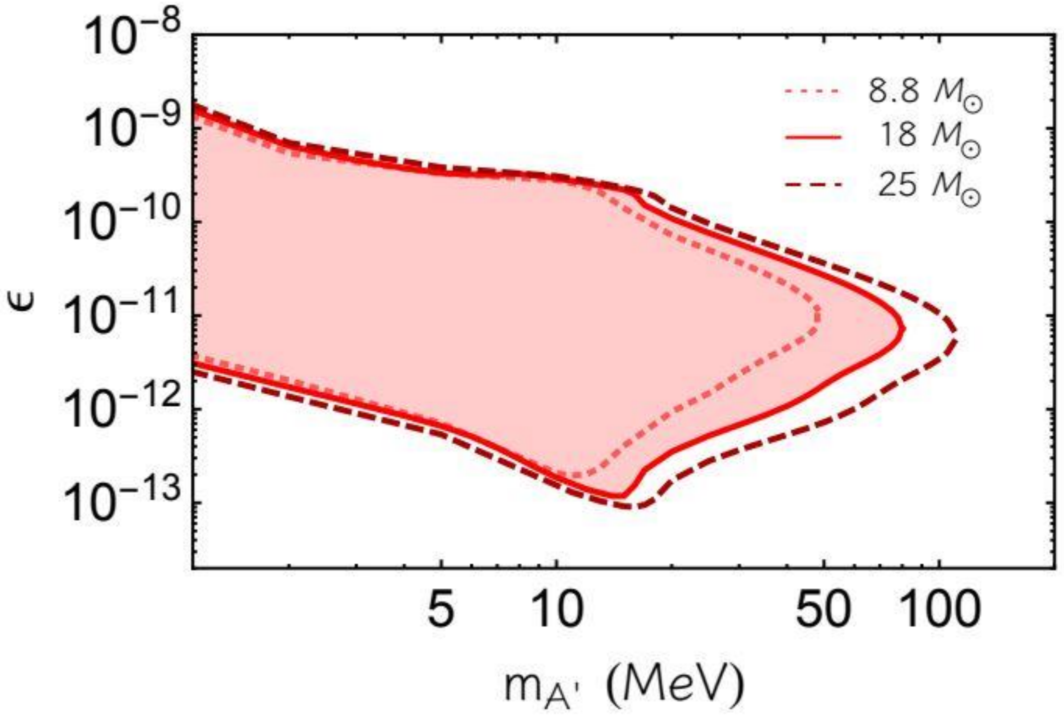


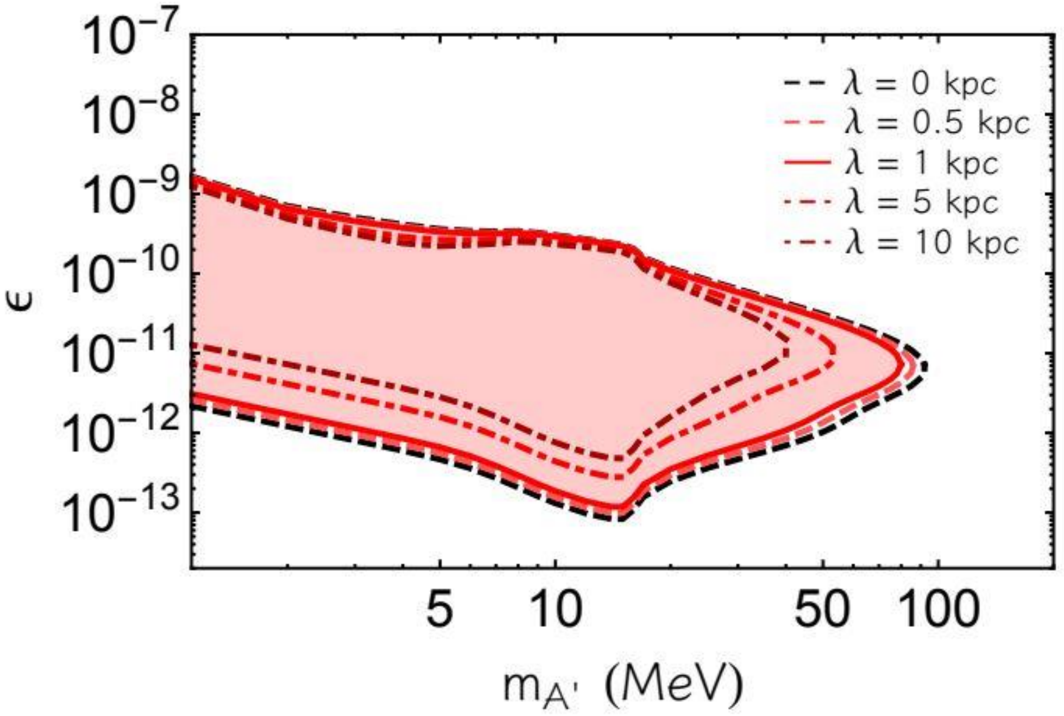
UNCERTANTIES OF THE MODEL

- Finally, we have considered the uncertainties on these bounds:
  - the progenitor supernova mass
  - the smearing scale λ, coming from the non negligible l_X



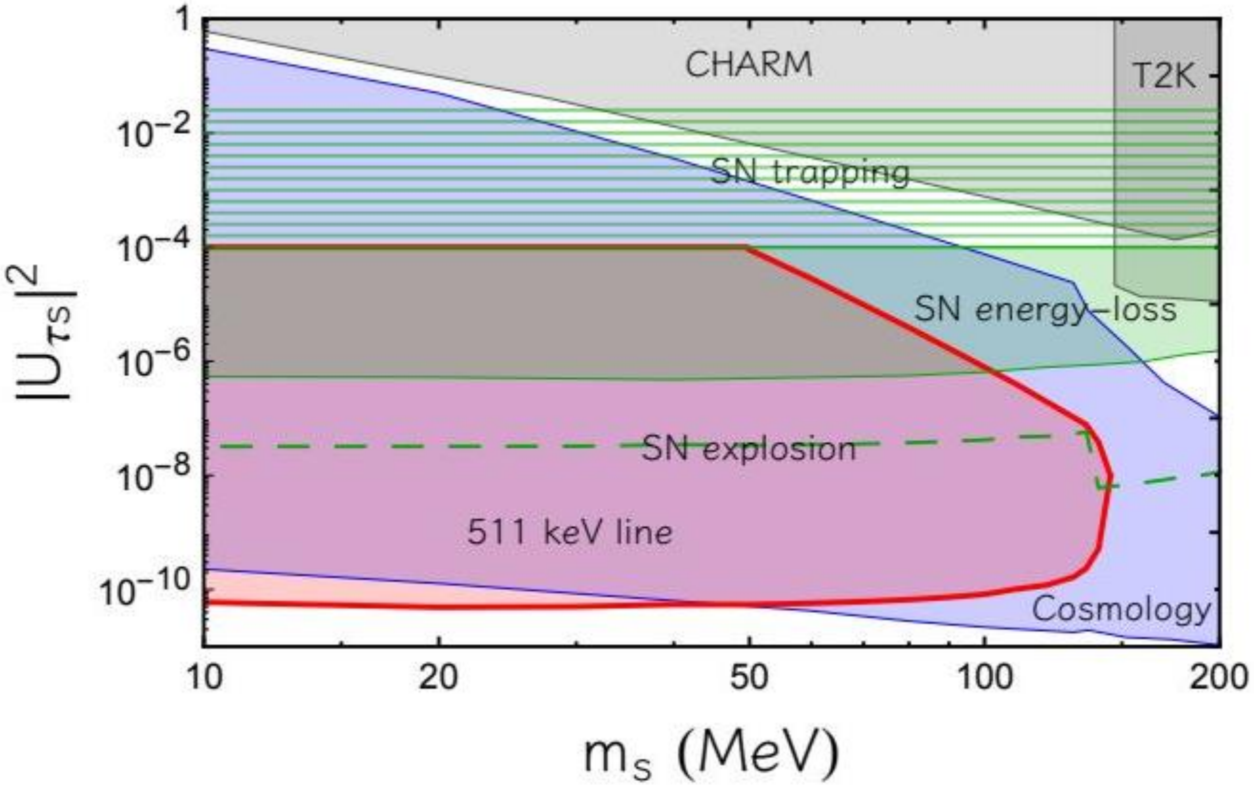
- The uncertainties can reach two orders of magnitude of difference.
- The uncertainties on the fraction of SN II and SN I b/c have really small effects.

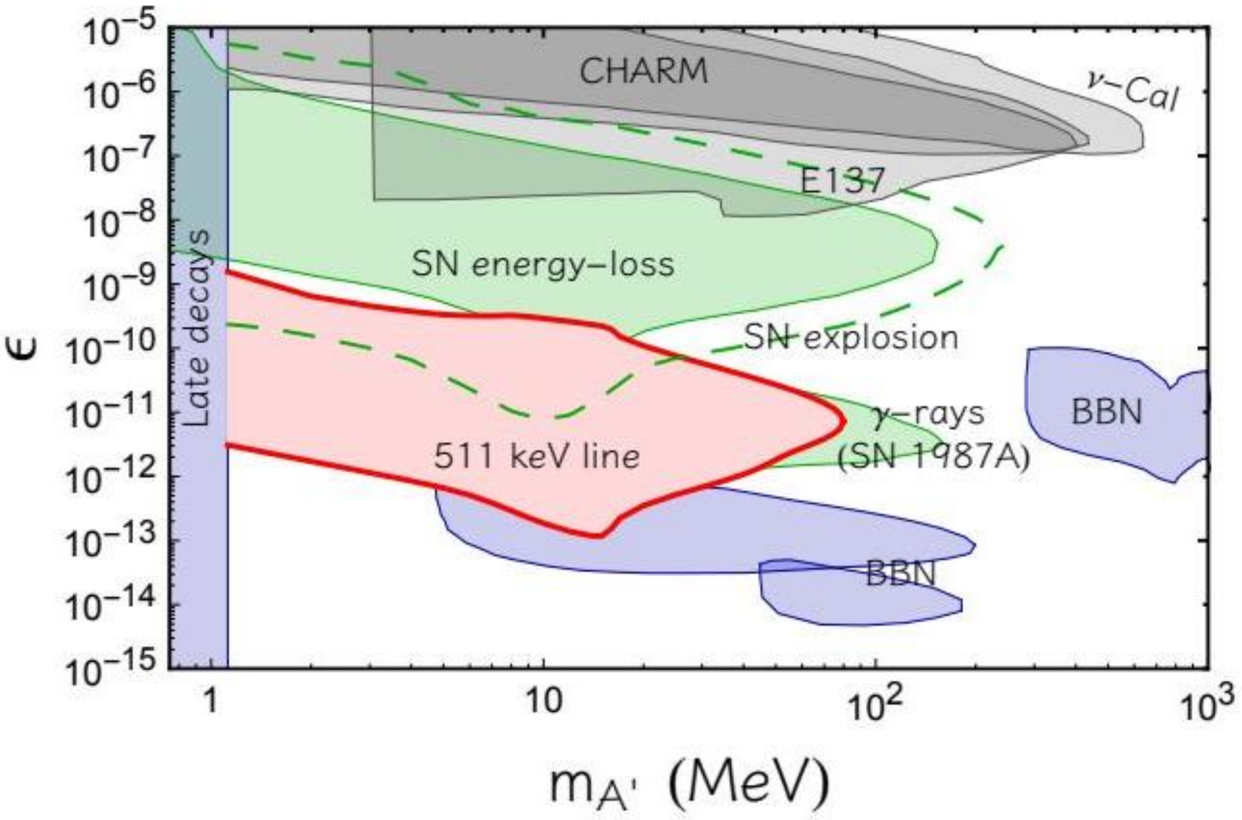




CONSTRAINTS OVERVIEW

- Results from the 511 keV constraints for the ν_s mixed only with active tauonic and for dark photons.





[F. Calore, P. Carenza, M. Giannotti, J. Jaeckel, G. Lucente, L. M. and A. Mirizzi, arXiv:2112.08382]

CONCLUSIONS

- Heavy sterile ν_s with masses $O(100)$ MeV and dark photons are two possible candidates of dark matter
- We analyzed the phenomenology of these particles emitted by a core-collapse SN
- We constraint the sterile neutrinos and dark photons parameter space using the photon flux observed and the 511 keV line.
- We finally discuss the possible uncertainties in this method of constraints.
- Further improvement from future observations and more accurate analysis.

Thanks for the attention

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