

Improved supernova bounds on CP-even scalars: cooling and decay constraints

Anirudhan A. Madathil

[arxiv:2603.04513](https://arxiv.org/abs/2603.04513)

Collaborators: Melissa Joseph, Samuel Liebersbach and Gustavo Marques-Tavares



Light Dark World 2026, Carleton University
July 28-31

DM-SM Interaction

- Does DM interact with SM particles?

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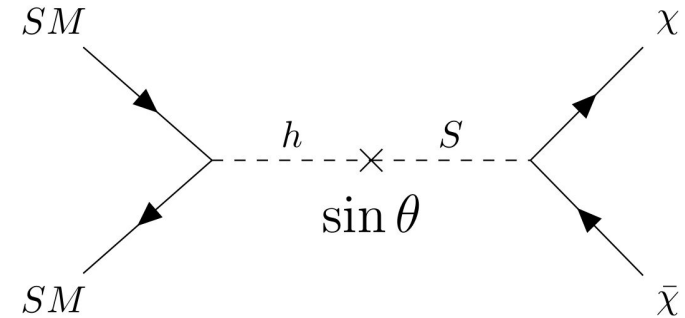
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Comparable energy density of DM and particles.

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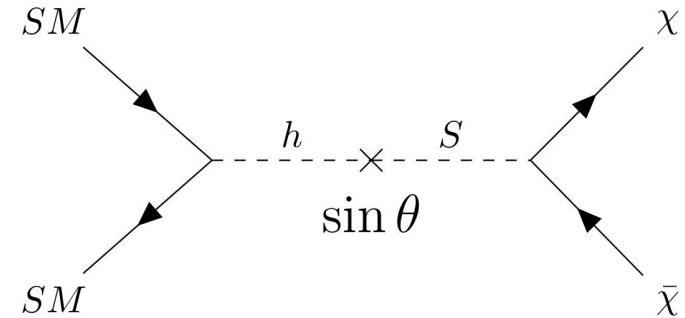
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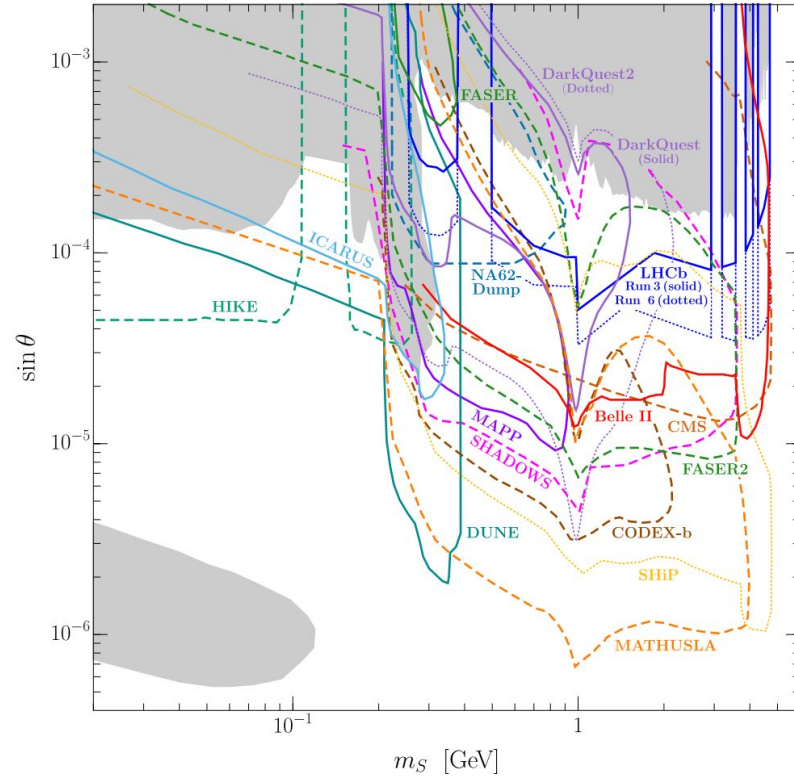
Could explain the production of DM in the early universe.
Comparable energy density of DM and particles.

- A scalar particle could mediate the interaction.
- As a result of mixing with the Higgs, the scalar has interactions similar to the Higgs except for an additional factor of $\sin\theta$.

$$\mathcal{L} \supset \frac{m_f}{v} h \bar{f} f \quad \Longrightarrow \quad \mathcal{L} \supset \sin\theta \frac{m_f}{v} S \bar{f} f$$

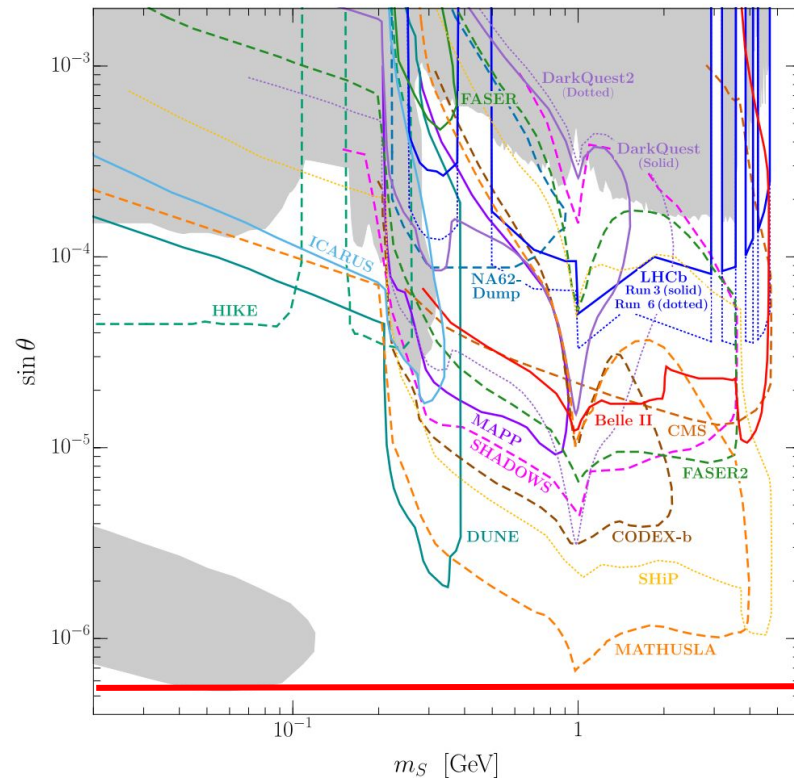


Current Status



B.Batell et.al, Snowmass 2021, arXiv:2207.06905

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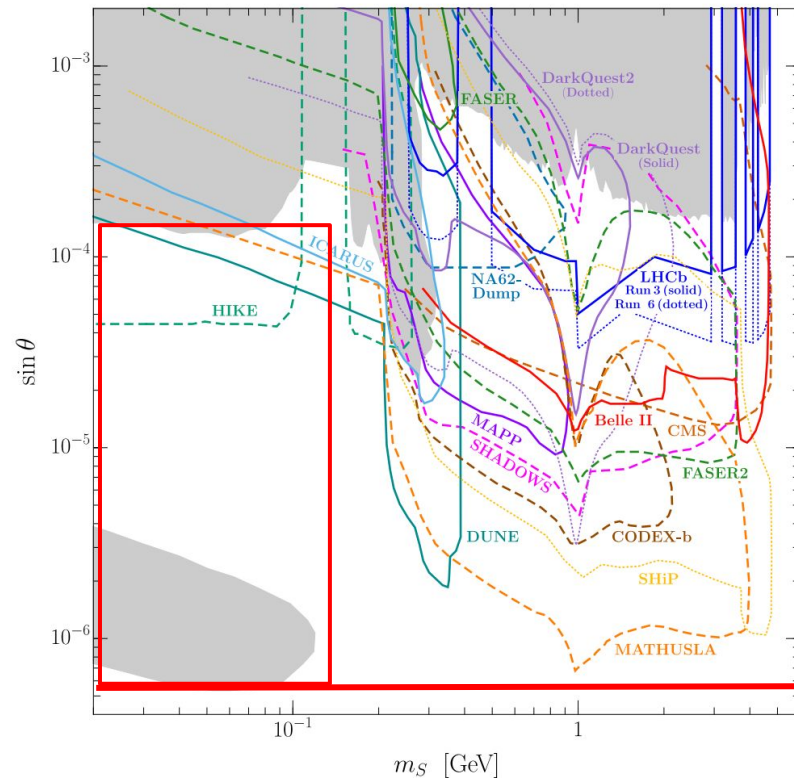


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Thermal production of DM

Gordan Kranjaic, arxiv:1512.04119

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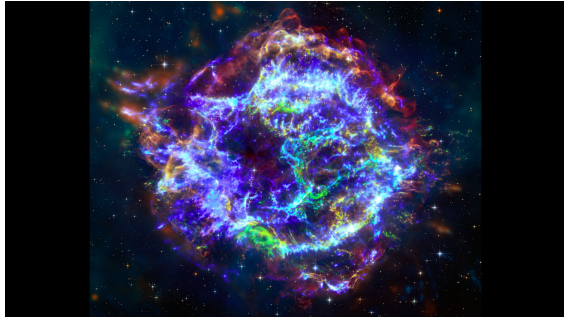


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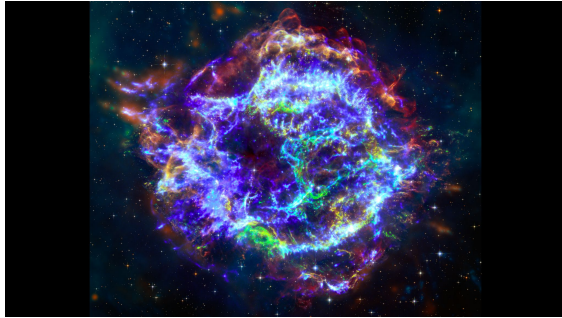
Supernova



$$\rho \sim 10^{14} \text{ g/cm}^3$$

$$T \sim 30 \text{ MeV}$$

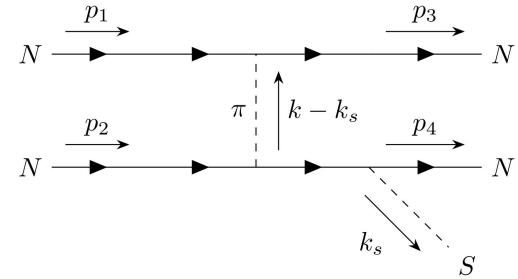
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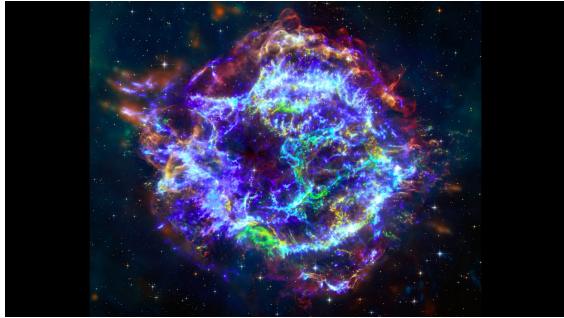
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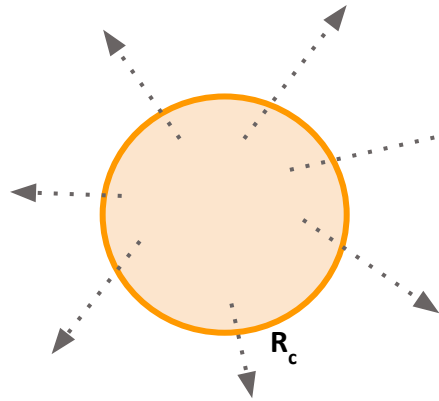
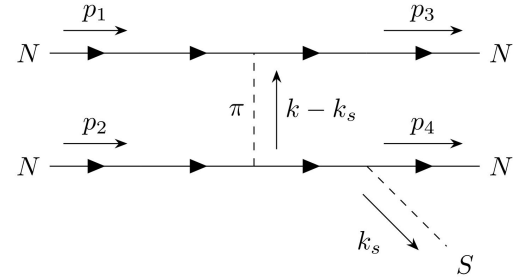
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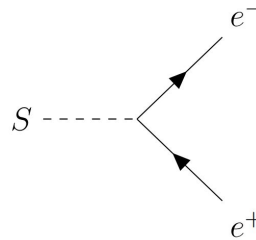
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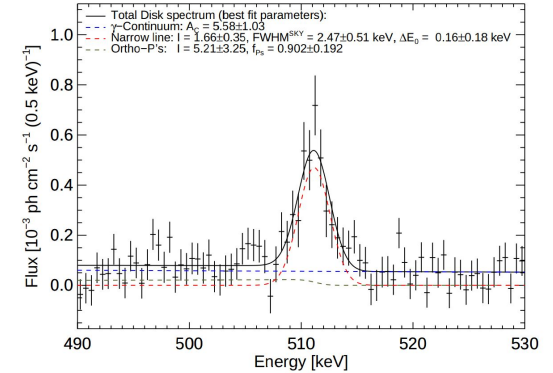
Cooling



Decay into SM

Positron Bound

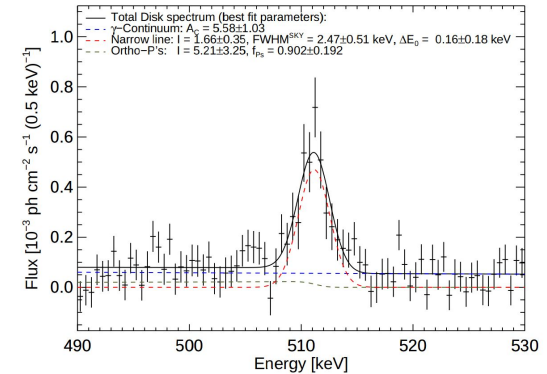
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T. Siegert et.al, Astron. Astrophys. 586 (2016) A84 [1512.00325]

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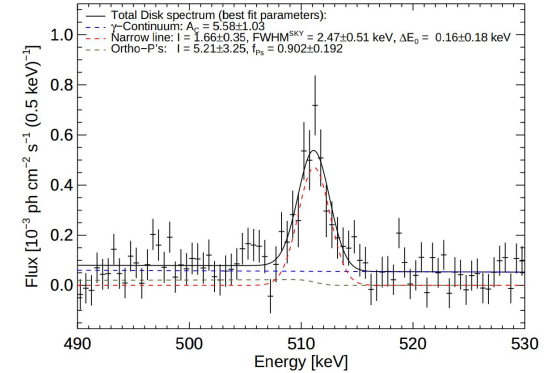
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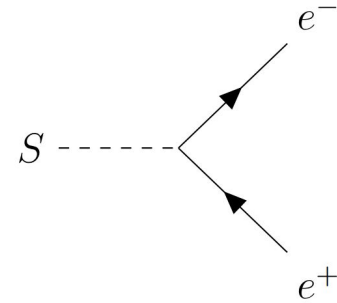
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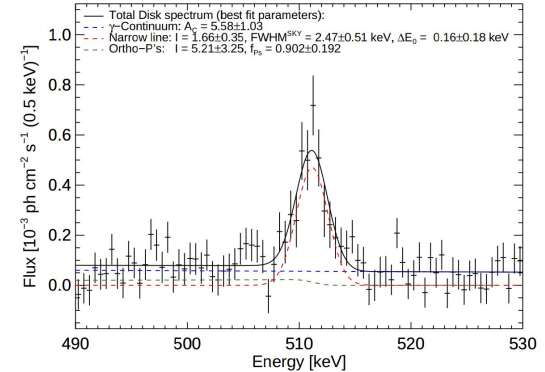
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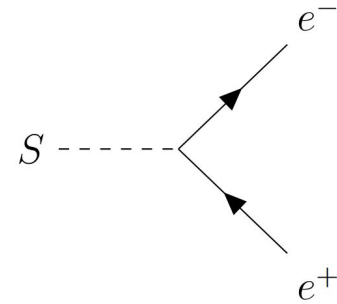
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- Based on the measurement, positron annihilation rate should not be greater than $4 \times 10^{43} \text{ s}^{-1}$.
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- SN occur in our galaxy with an average rate of 2 SN/century.

$$N_{e^+} \lesssim 10^{53}$$



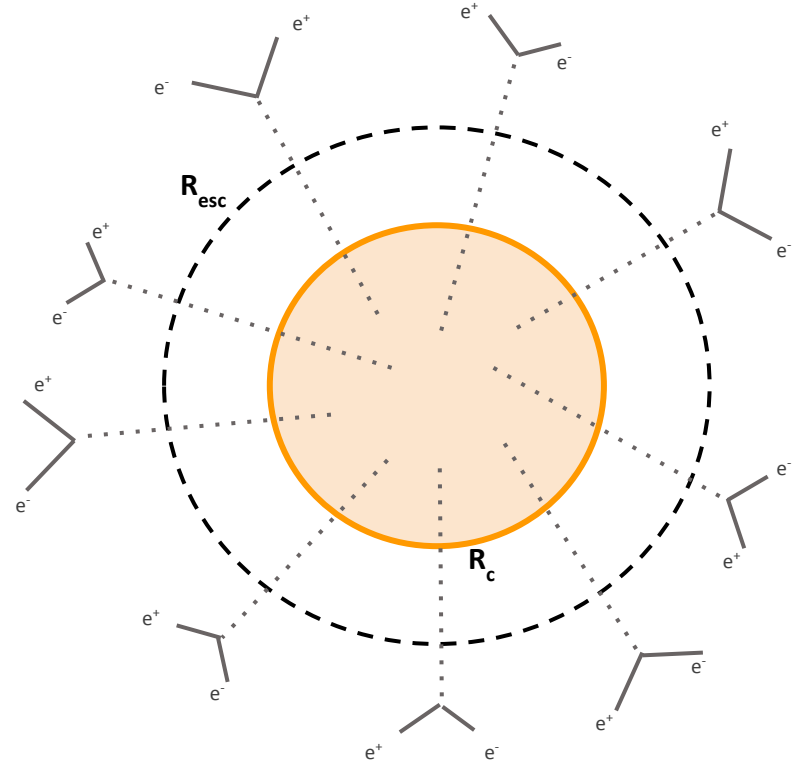
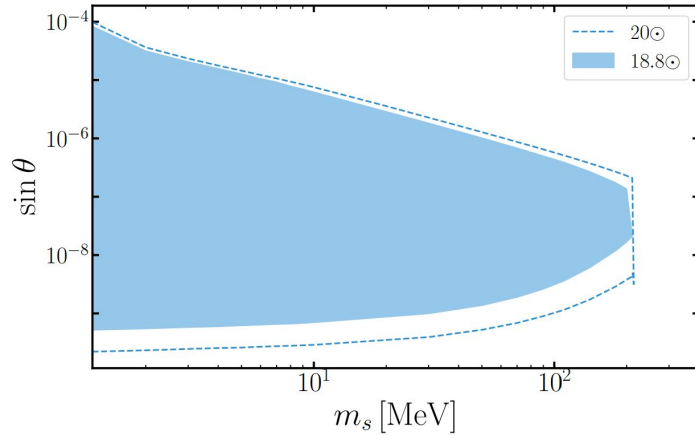
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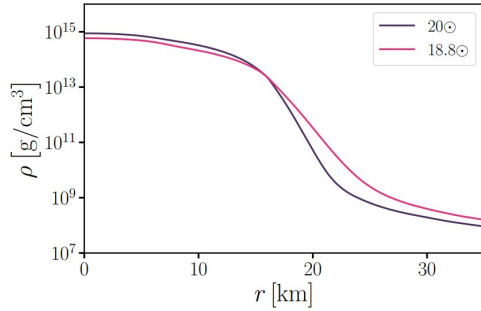
Positron Bound

- Lower bound

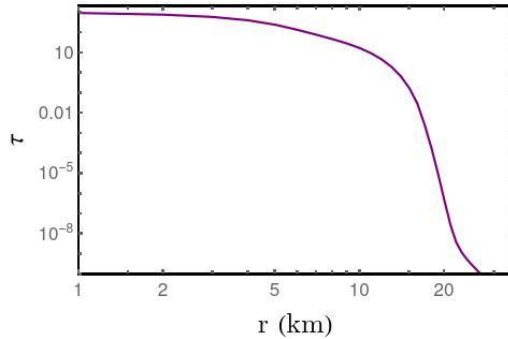
$$N_{e^+ \text{lower}} = \int dt \int_0^{R_c} 4\pi r^2 \frac{dN}{dt dV} dr = 10^{53}.$$



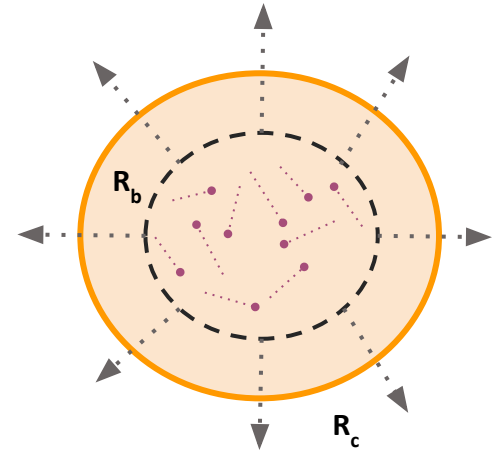
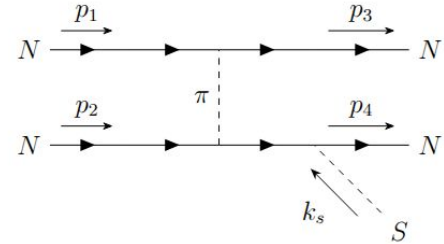
Trapping: Black-body Approximation



Inverse MFP $\lambda^{-1} \propto n_b^2$



Optical depth $\tau = \int \langle \lambda^{-1} \rangle dr$

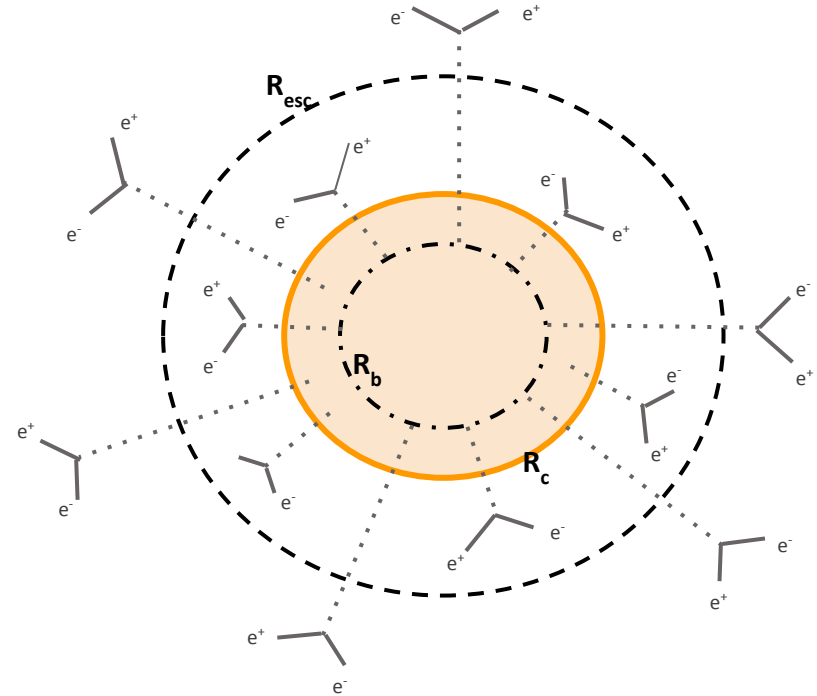
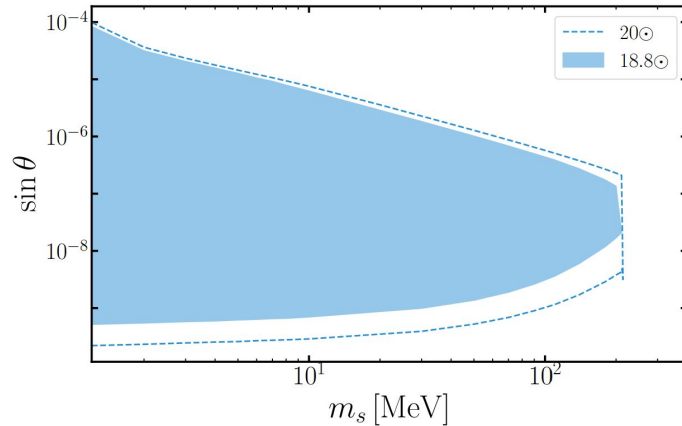


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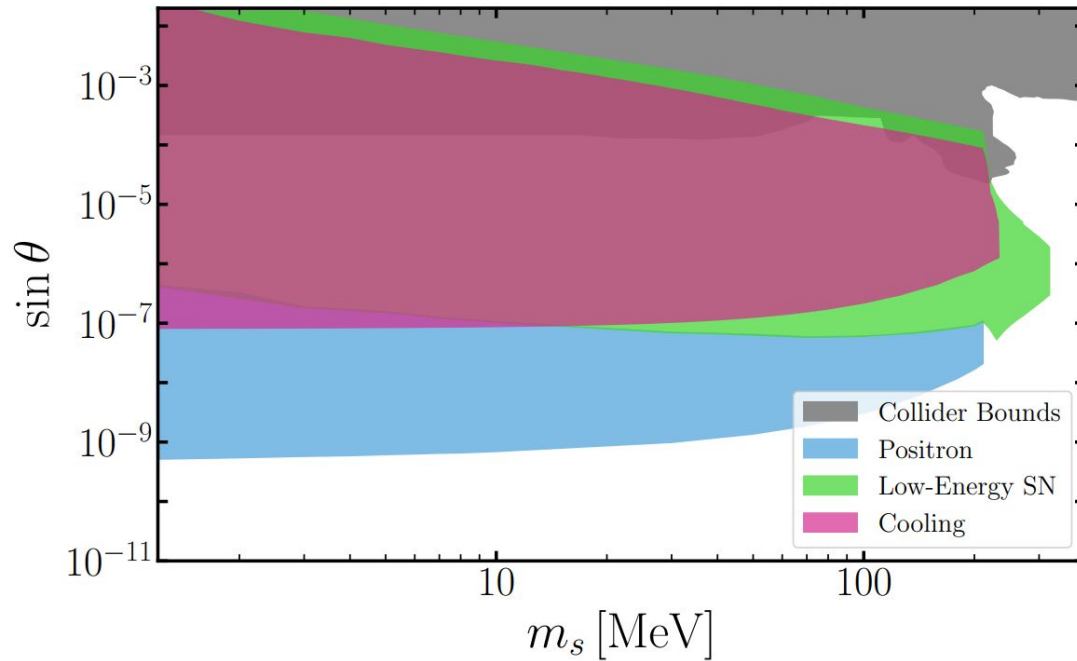
- Upper bound

$$N_{e^+\text{trap}} = \int \frac{dN_b}{dt} e^{-\tau_{dec}(R_b, R_{esc})} dt$$

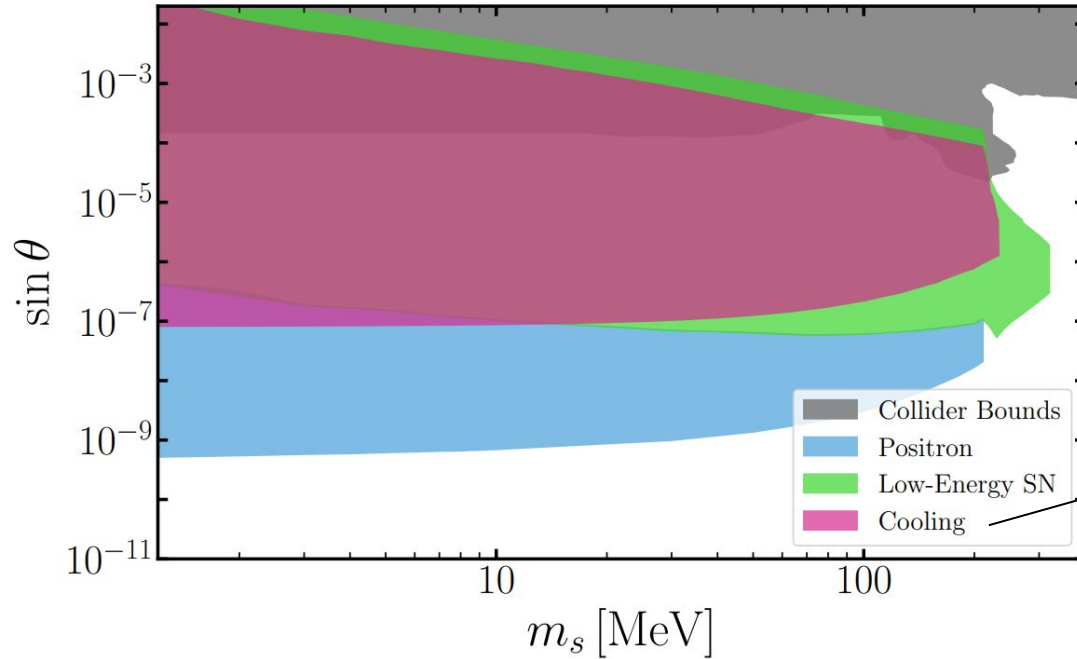
$$+ \int dt 2\pi \int_{R_b}^{R_c} r^2 dr \int_{m_s}^{\infty} d\omega e^{-\tau_{dec}(r, R_{esc}, \omega)} \frac{dN}{dt dV d\omega}$$



Supernova Bounds

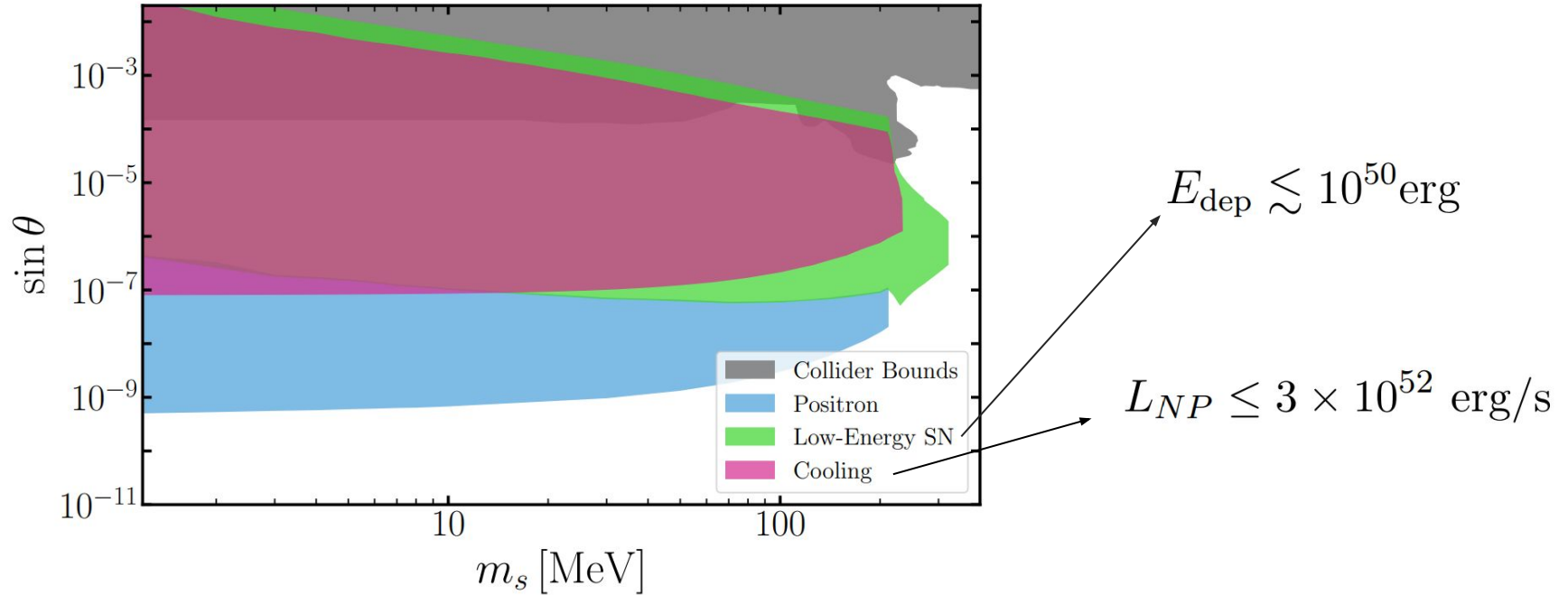


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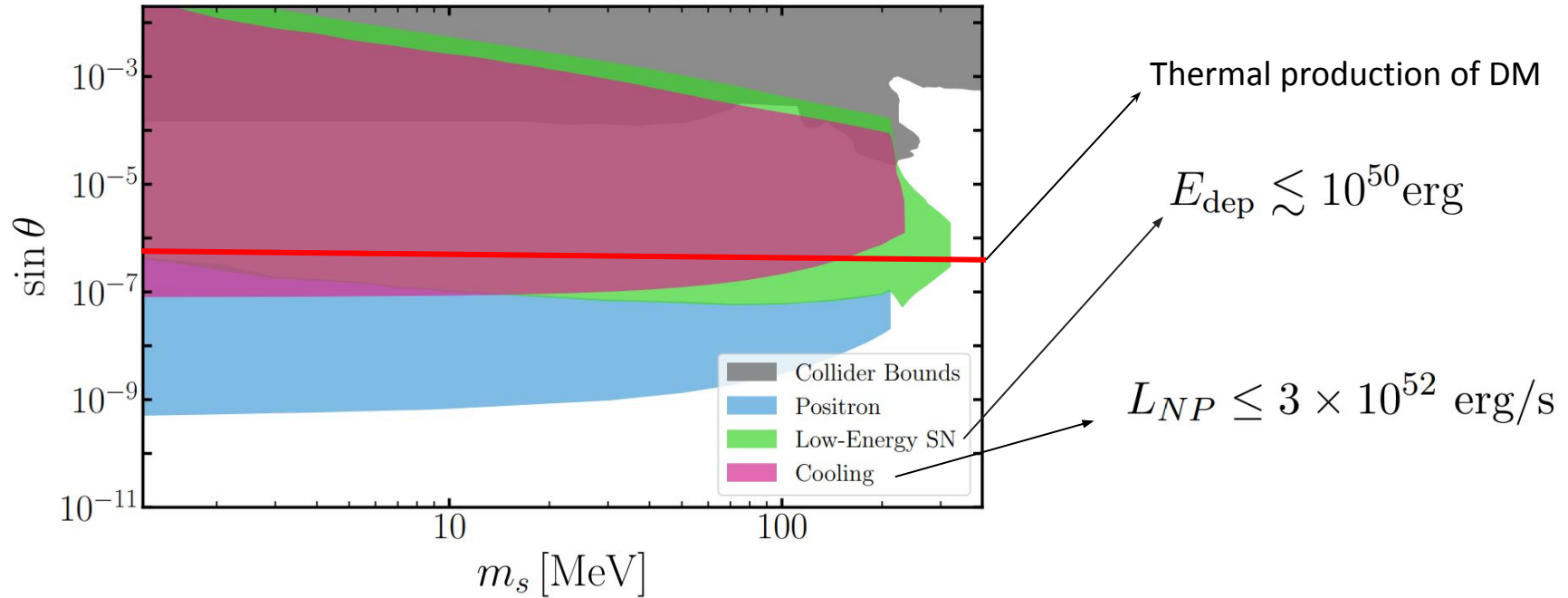


$$L_{NP} \leq 3 \times 10^{52} \text{ erg/s}$$

Supernova Bounds

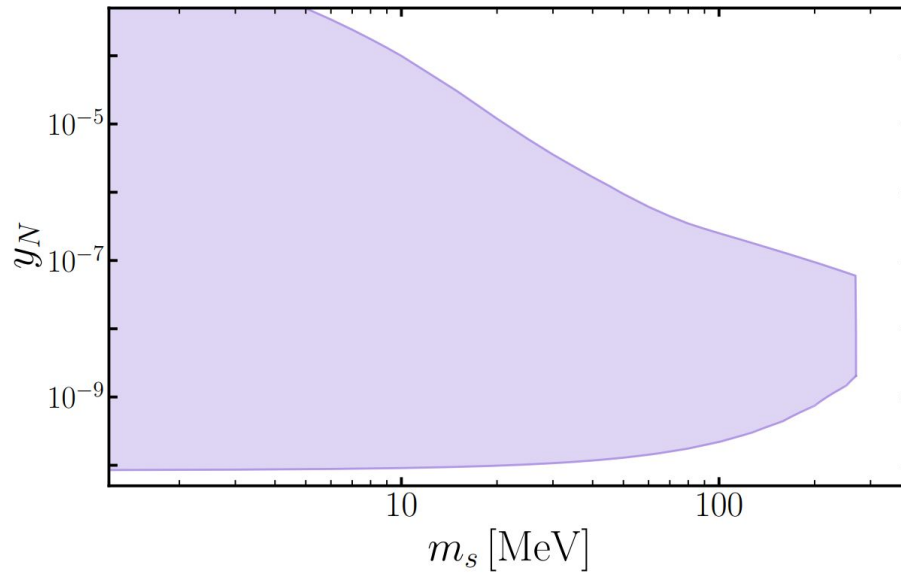


Supernova Bounds



Hadrophilic scalar

- CP-even scalar motivated from DM direct detection.

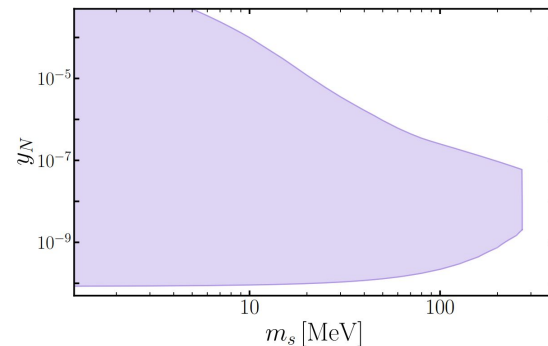
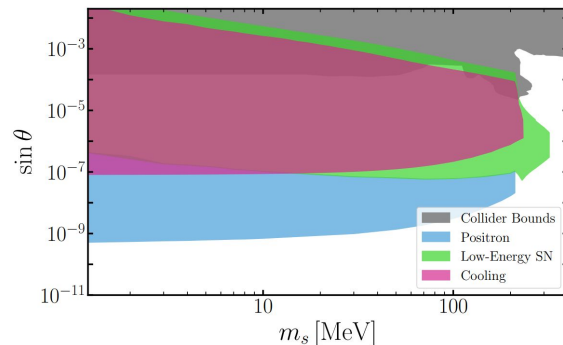


Cooling bounds

$$\mathcal{L} = -y_N S_N \bar{N} N$$

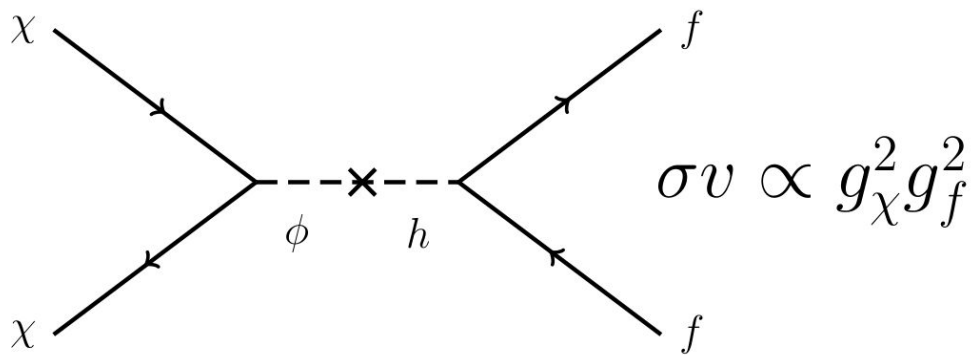
Summary

- Supernovae provide among the most powerful probes of weakly-coupled scalars in the MeV mass range, where laboratory experiments lose sensitivity.
- Placed new decay-based constraints from the galactic 511 keV positron flux and energy deposition in low-energy Type II-P supernovae.
- Constrain the mixing angle $\sin\theta$ to five orders of magnitude below the existing collider bounds.
- We also extend our analysis to a hadrophilic scalar model, constraining Yukawa couplings down to $y_N \sim 10^{-10}$.



Backup slides

Thermal DM Production



$$g_\chi^2 \sin^2 \theta \gtrsim \frac{53\pi^3 \sqrt{g_*(m_t)} m_t}{\zeta(3) m_{Pl}} \approx 2 \times 10^{-13}$$

Gordan Kranjaic, arxiv:1512.04119

Amplitude calculation

$$\mathcal{M}_b = g_{pp\pi}^2 \frac{\sin \theta_{hNN}}{(k - k_s)^2 - m_\pi^2} \frac{\bar{u}(p_4)(\not{p}_4 + \not{k}_s + m_N)\gamma^5 u(p_2)\bar{u}(p_3)\gamma^5 u(p_1)}{(p_4 + k_s)^2 - m_N^2}$$

$$\frac{1}{(p_i \pm k_s) - m_N^2} \approx \pm \frac{1}{2m_N\omega} \left(1 - \frac{\mathbf{p}_i^2}{2m_N^2} + \frac{\mathbf{p}_i \cdot \mathbf{k}_s}{m_N\omega} + \frac{(\mathbf{p}_i \cdot \mathbf{k}_s)^2}{m_N^2\omega^2} \mp \frac{m_s^2}{2m_N\omega} \right)$$

