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

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arxiv:2603.04513

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THE UNIVERSITY of UTAH

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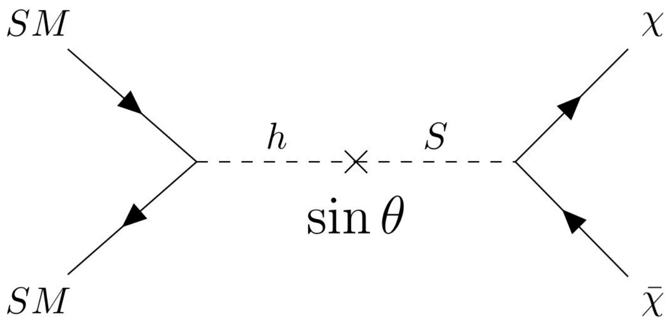
DM-SM Interaction

- Does DM interact with SM particles?
  Could explain the production of DM in the early universe.
  Comparable energy density of DM and particles.

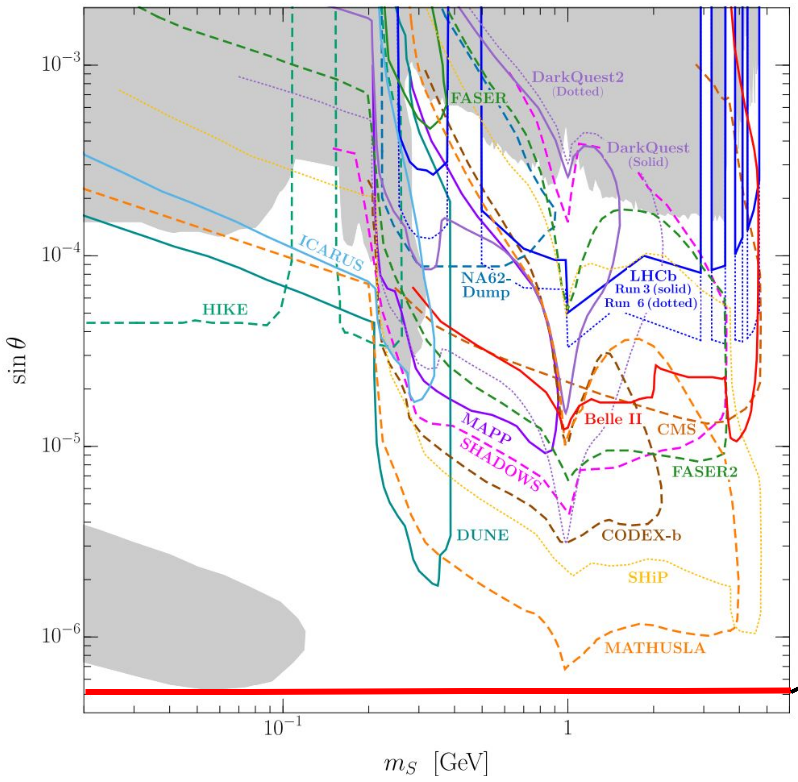
- A scalar particle could mediate the interaction.

- As a result of mixing with the Higgs, the scalar has interactions similar to the Higgs except for an additional factor of sinθ.

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



Current Status



Thermal production of DM

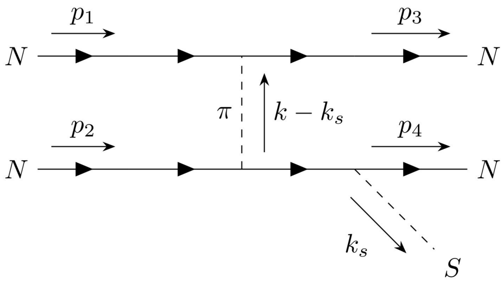
B.Batell et.al, Snowmass 2021, arXiv:2207.06905

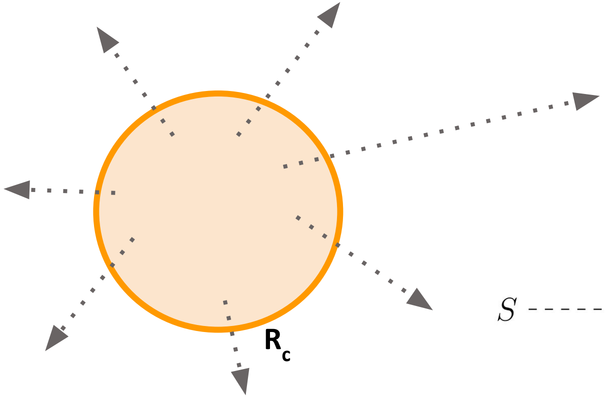
Supernova

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

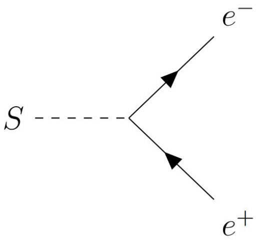
$$T \sim 30\ \mathrm{MeV}$$

Dominant production channel:





Cooling



Decay into SM

Positron Bound

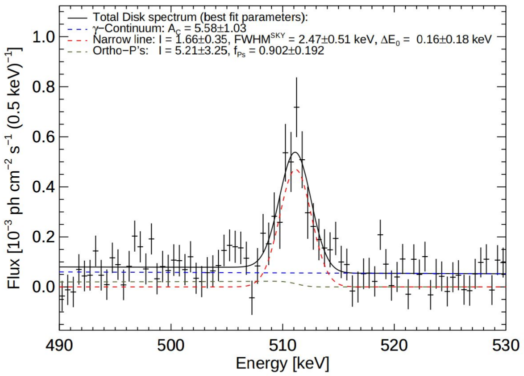
- SPI gamma ray spectrometer on the INTEGRAL satellite has measured 511 keV gamma ray flux from the galactic center region.

- Based on the measurement, positron annihilation rate should not be greater than 4×10^{43} s^{-1}.

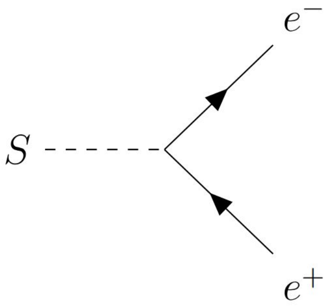
- Scalar decay into positron, which can contribute to the galactic 511 keV gamma ray flux.

- SN occur in our galaxy with an average rate of 2 SN/century.

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



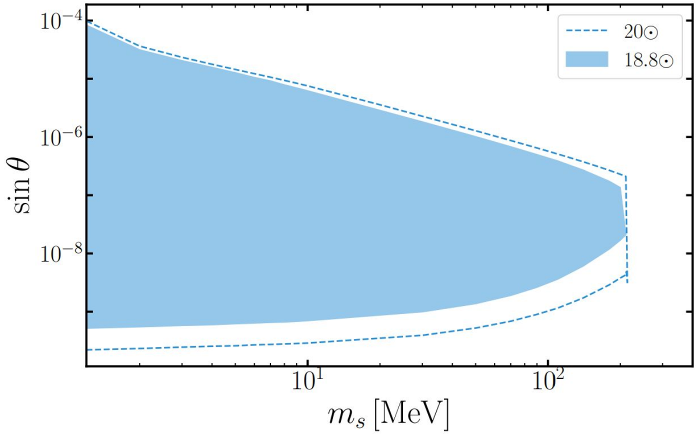
T. Siegert et.al, Astron. Astrophys. 586 (2016) A84 [1512.00325]

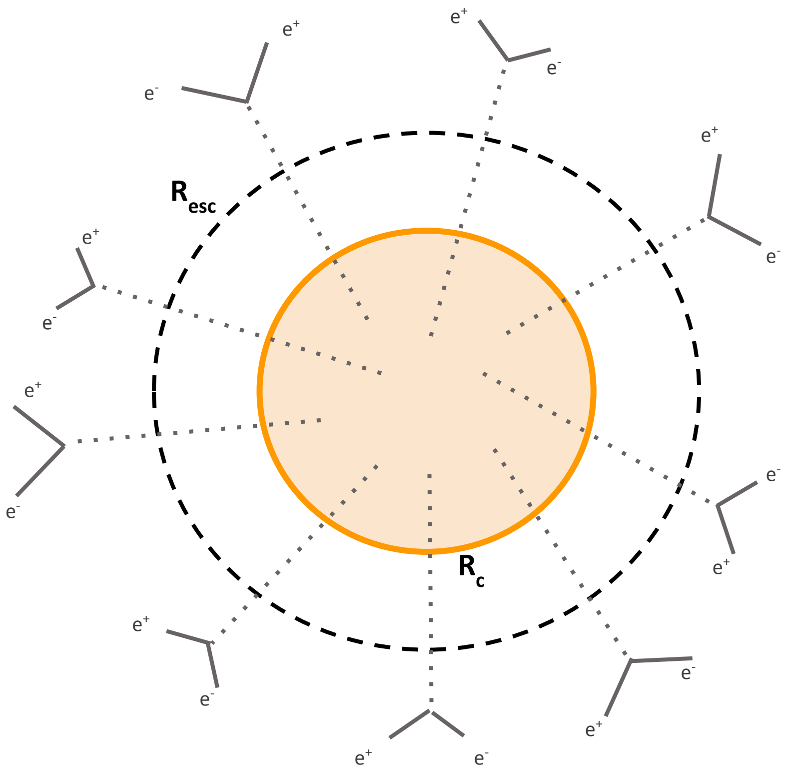


Positron Bound

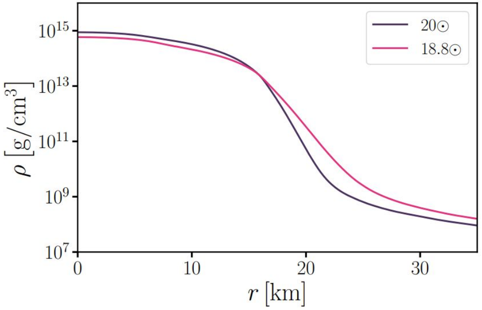
- Lower bound

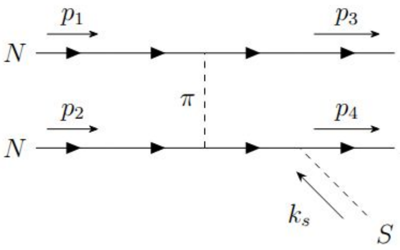
$$N_{e^+\text{lower}} = \int dt \int_0^{R_c} 4\pi r^2 \frac{dN}{dt dV} dr = 10^{53}.$$



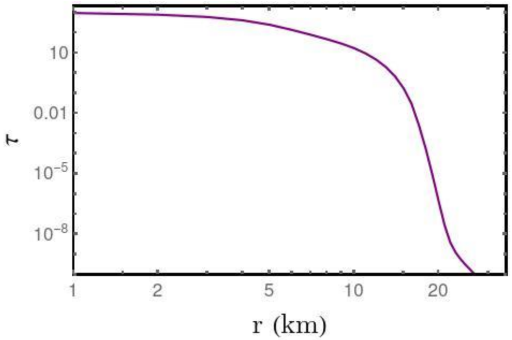


Trapping: Black-body Approximation

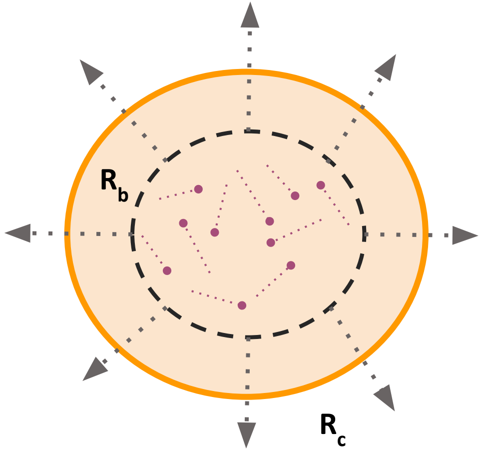




Inverse MFP $\lambda^{-1} \propto n_b^2$



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

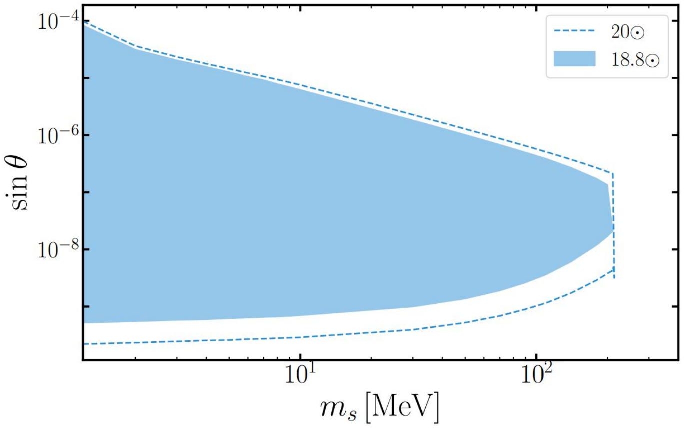


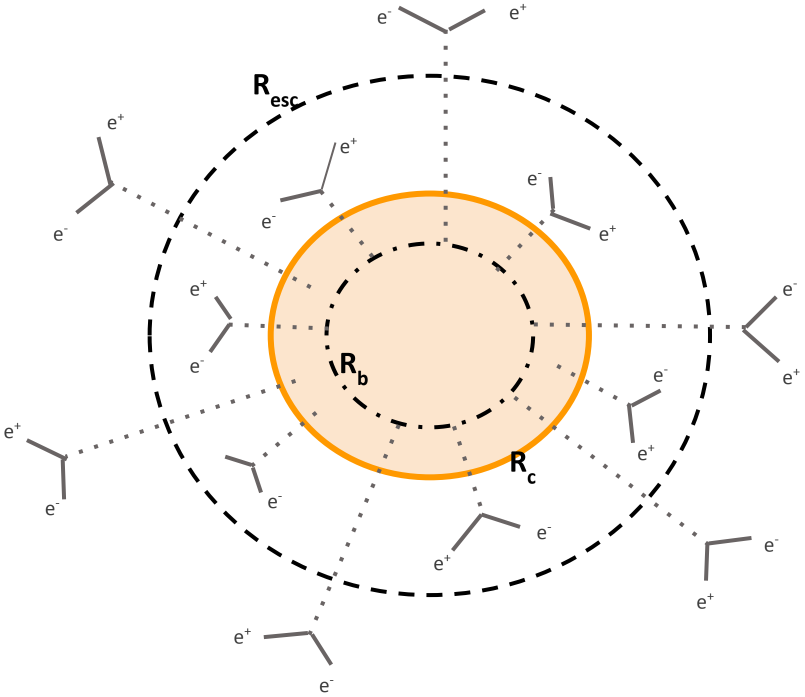
Trapping

- Upper bound

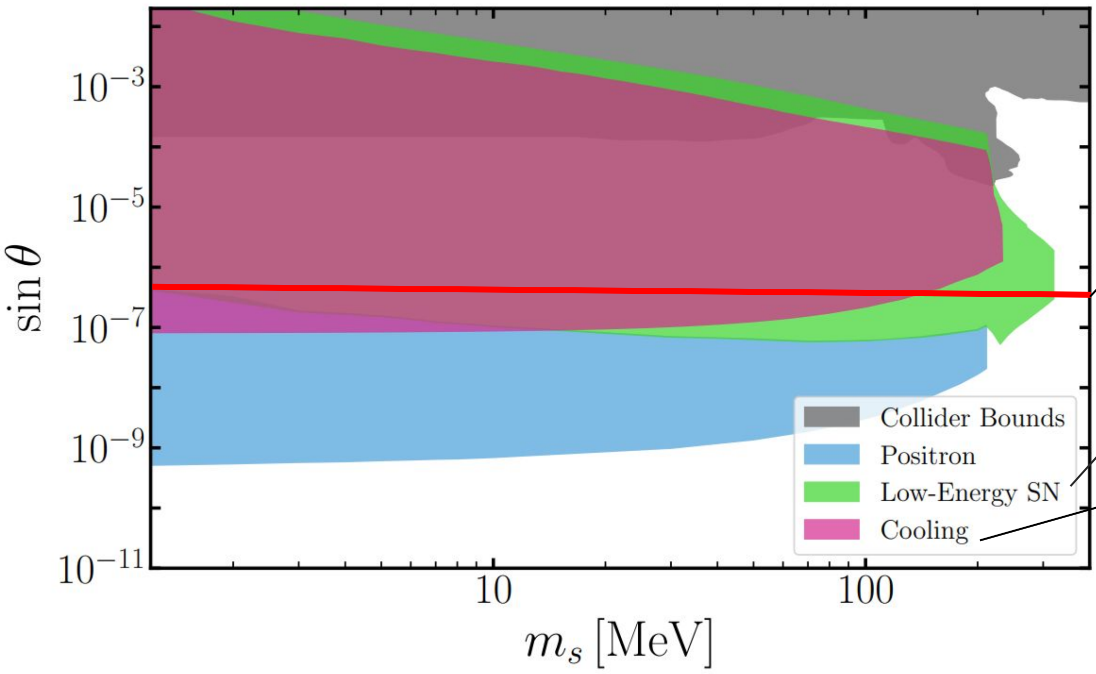
$$N_{e^+\text{trap}} = \int \frac{dN_b}{dt} e^{-\tau_{dec}(R_b, R_{esc})} dt$$

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





Supernova Bounds



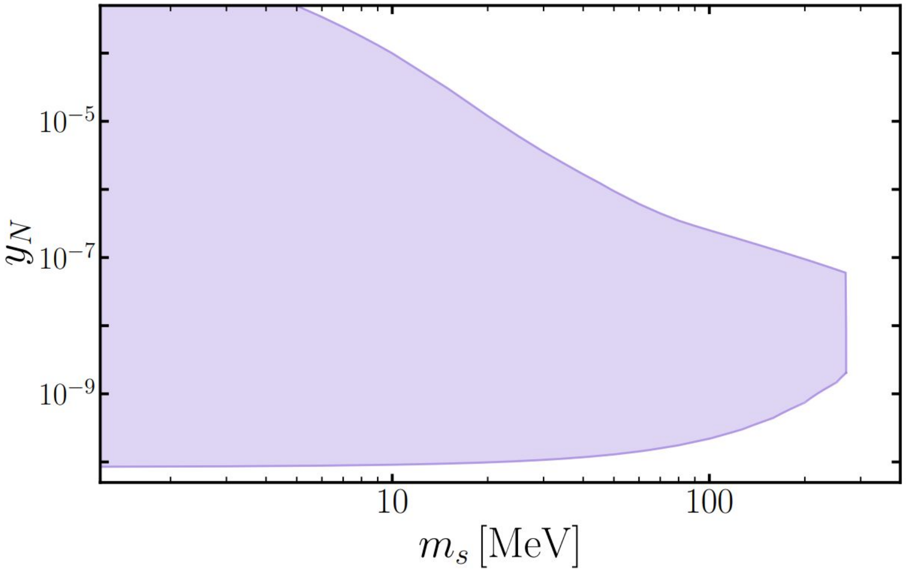
Thermal production of DM

$$E_{\rm dep} \lesssim 10^{50}\text{erg}$$

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

Hadrophilic scalar

- CP-even scalar motivated from DM direct detection.

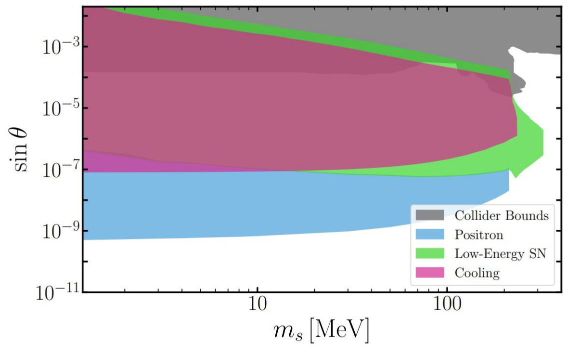


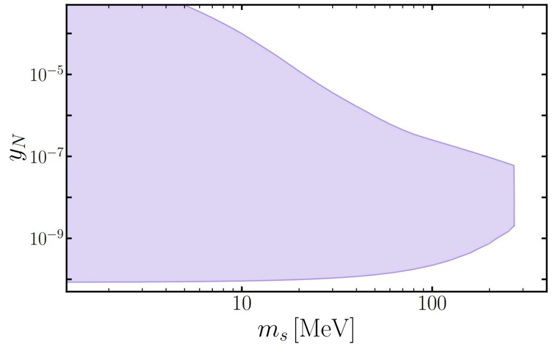
$$\mathcal{L} = -y_N S_N \bar{N} N$$

Cooling bounds

Summary

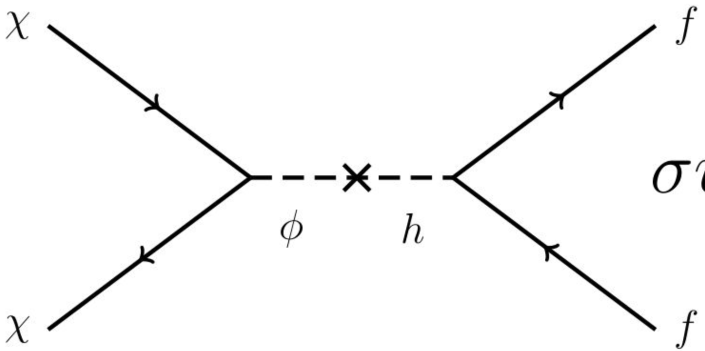
- Supernovae provide among the most powerful probes of weakly-coupled scalars in the MeV mass range, where laboratory experiments lose sensitivity.
- Placed new decay-based constraints from the galactic 511 keV positron flux and energy deposition in low-energy Type II-P supernovae.
- Constrain the mixing angle sinθ 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~10^{-10}.





Backup slides

Thermal DM Production



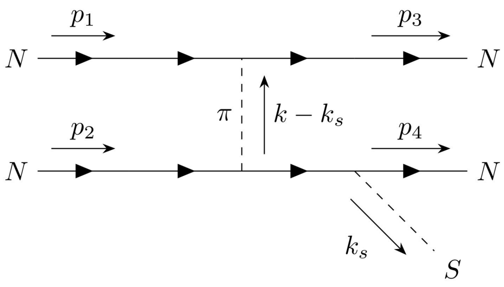
$$\sigma v \propto g_\chi^2 g_f^2$$

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

Gordan Kranjaic, arxiv:1512.04119

Amplitude calculation

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



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