A Solar System Test of Self-Interacting Dark Matter

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arXiv:1811.00557 (CG and Jessie Shelton)

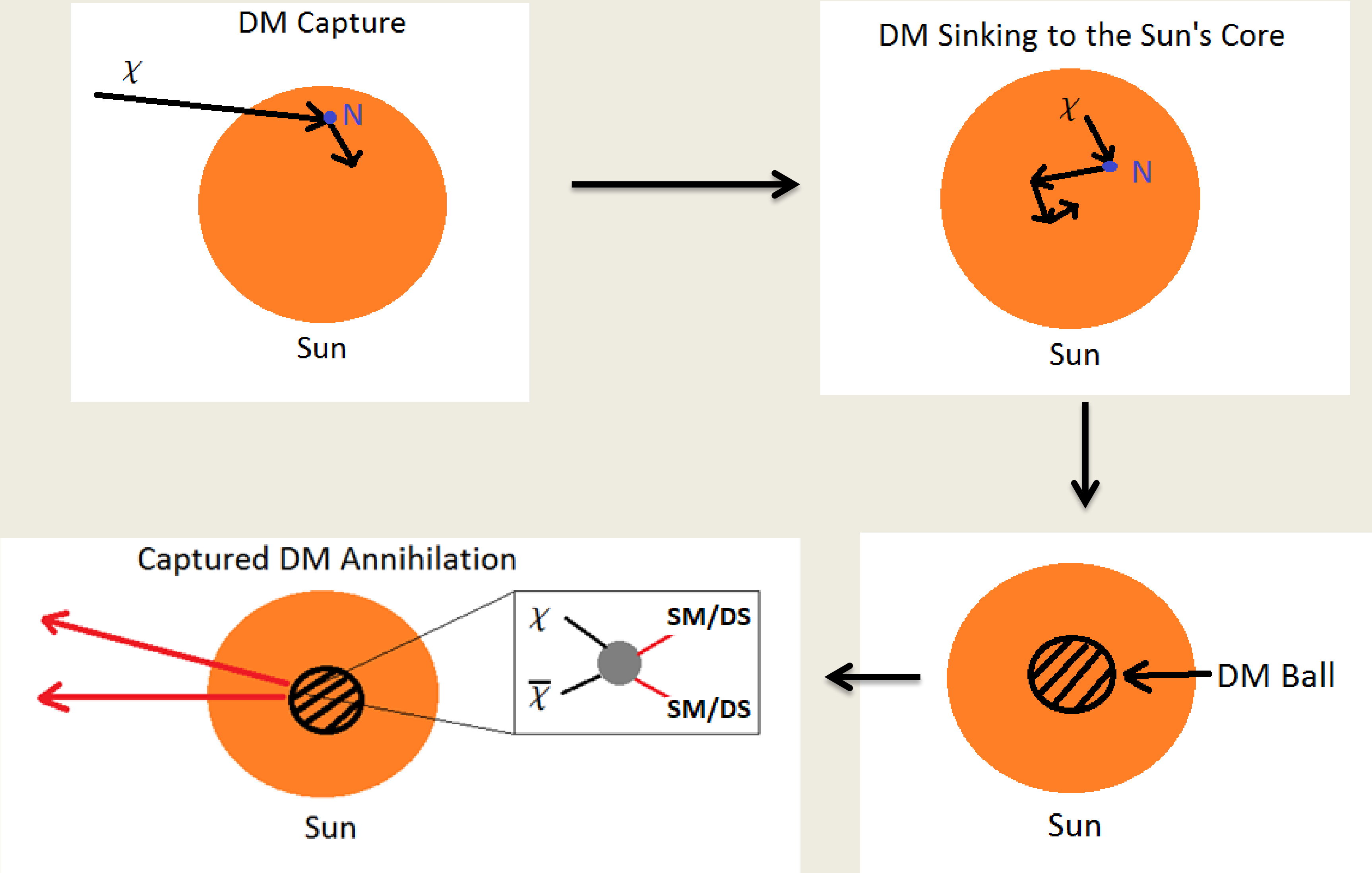
Outline

- Indirect Detection of Dark Matter (DM) in the Solar System: DM capture by the Sun/Earth.

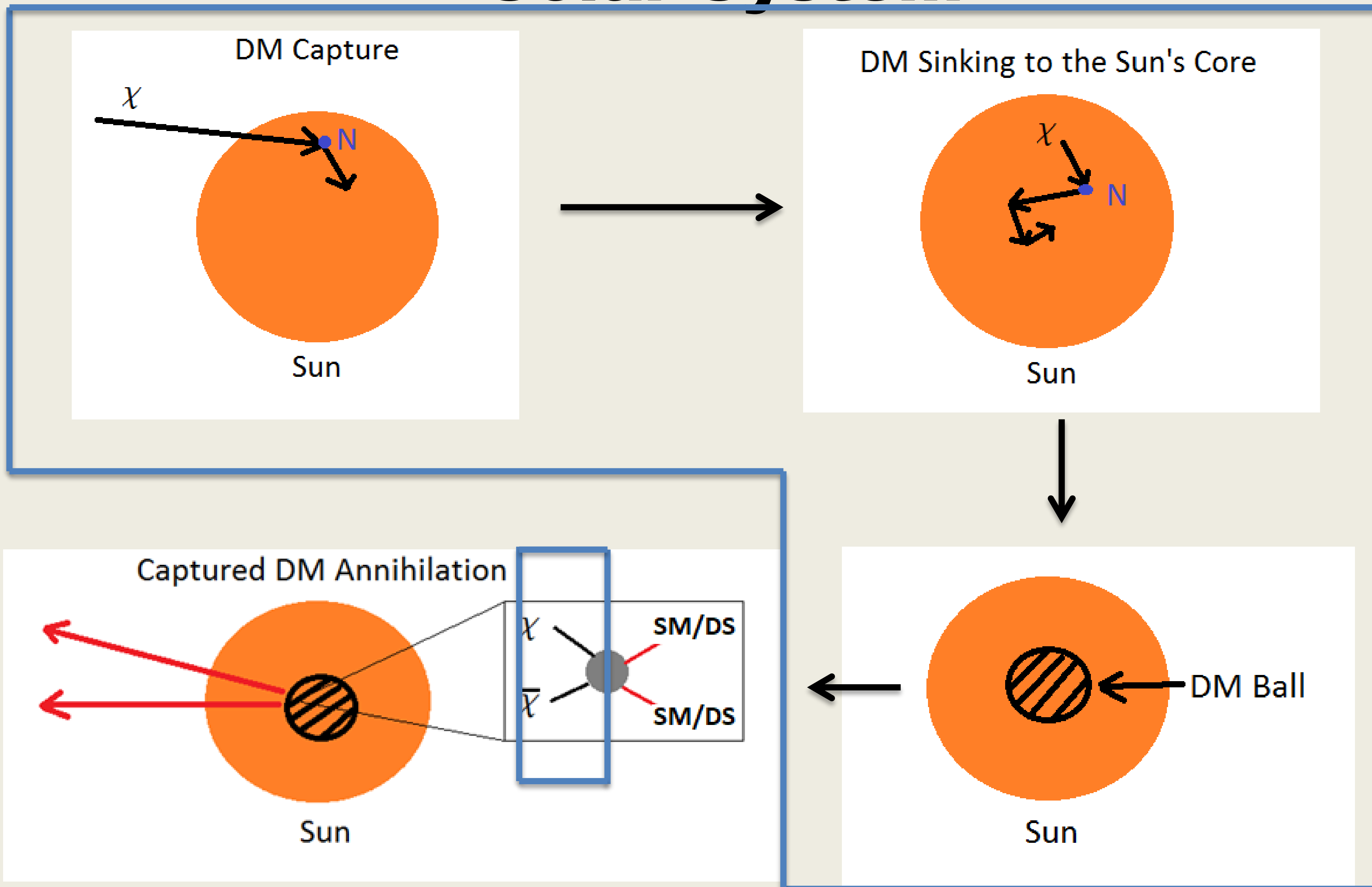
- Modifications to Sun/Earth-captured DM due to DM Self-Interactions (SI).

- Construct and describe an observational probe of SIDM based on Sun/Earth-captured DM.

Indirect Detection of DM in the Solar System



Indirect Detection of DM in the Solar System



Modelling Captured DM Population

- Simplest model: $$\dot{N} = C_c - C_a N^2(t), \quad N(0) = 0.$$

Rate of DM capture by nuclei
$C_c = C_c(M_{DM}, \sigma_p)$

DM annihilation coefficient
$C_a = C_a(M_{DM}, \langle \sigma_{\rm ann} v \rangle)$

- Annihilation rate of (Sun-captured) DM: $$\Gamma_{\rm a} = \frac{1}{2} C_{\rm a} N^2(\tau_{\rm Sun})$$

- σ_p: Assume a spin independent DM-nucleon interaction.

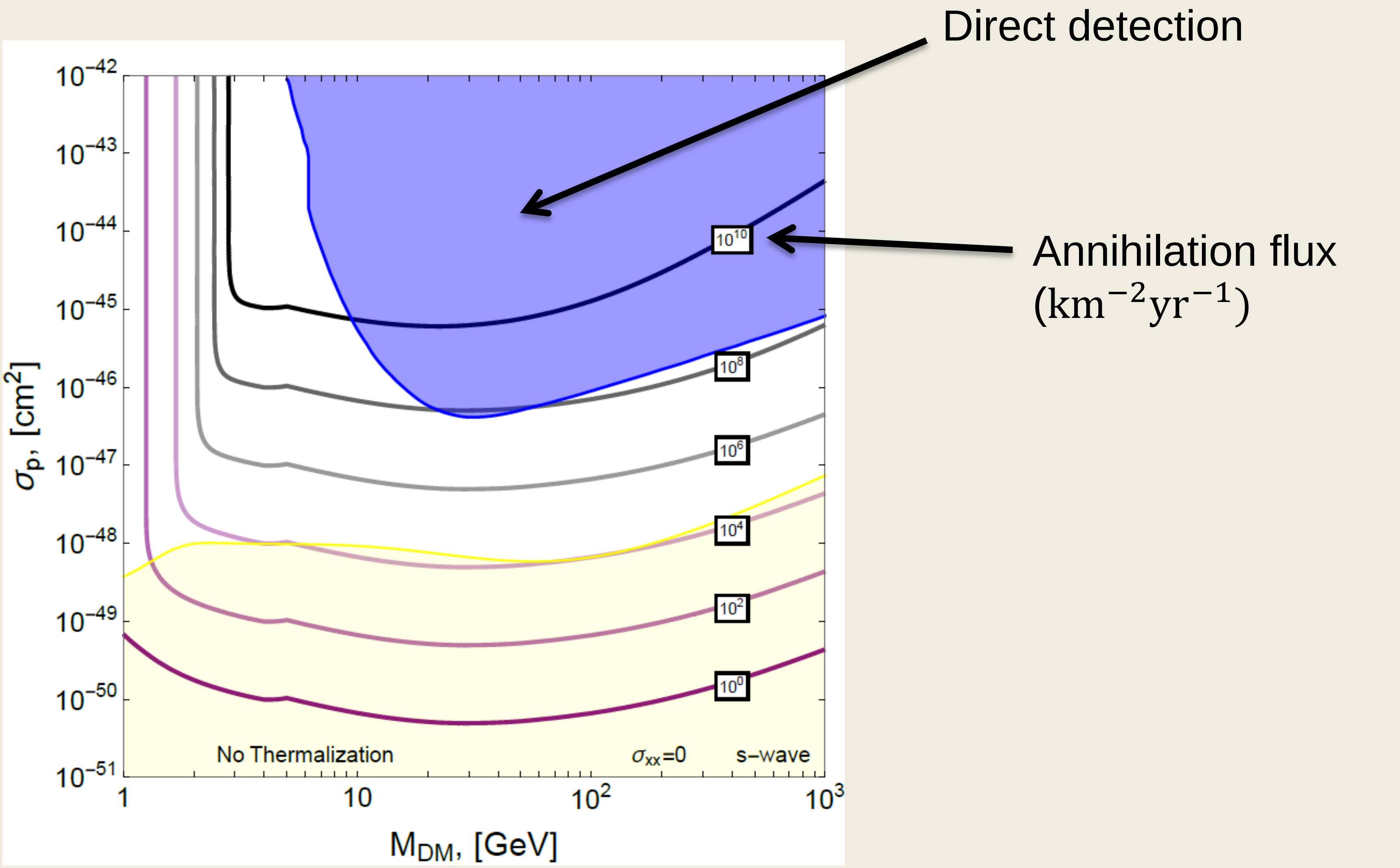
- $\langle \sigma_{\rm ann} v \rangle$: s-wave. Fixed by relic abundance constraint.

Simplest DM Population Model

$$\dot{N} = C_c - C_a N^2$$

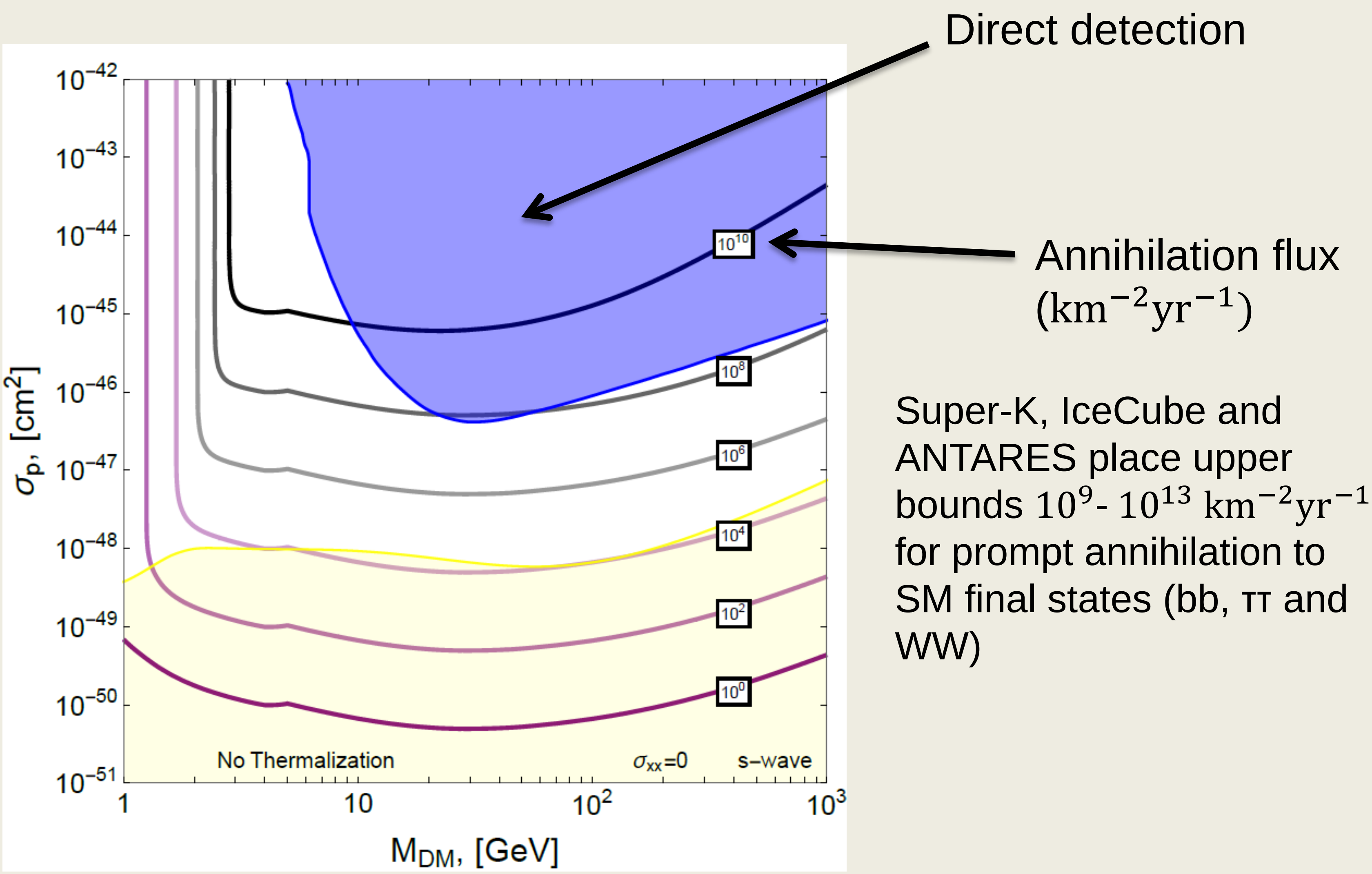
- General solution: $N(t) = N_{0,eq} \tanh\left(\frac{t}{\tau}\right)$ $N_{0,eq} = \sqrt{\frac{C_c}{C_a}}$
- Equilibrium is reached if $t_{Sun} \gtrsim \tau = \frac{1}{\sqrt{C_c C_a}}$
- At equilibrium: $\Gamma_a = \frac{1}{2} C_c$
- Annihilation flux: $\Phi_{\text{ann}} = \frac{\Gamma_{\text{a}}}{4\pi R^2}$

Annihilation Flux in the Sun



[CG, Shelton]

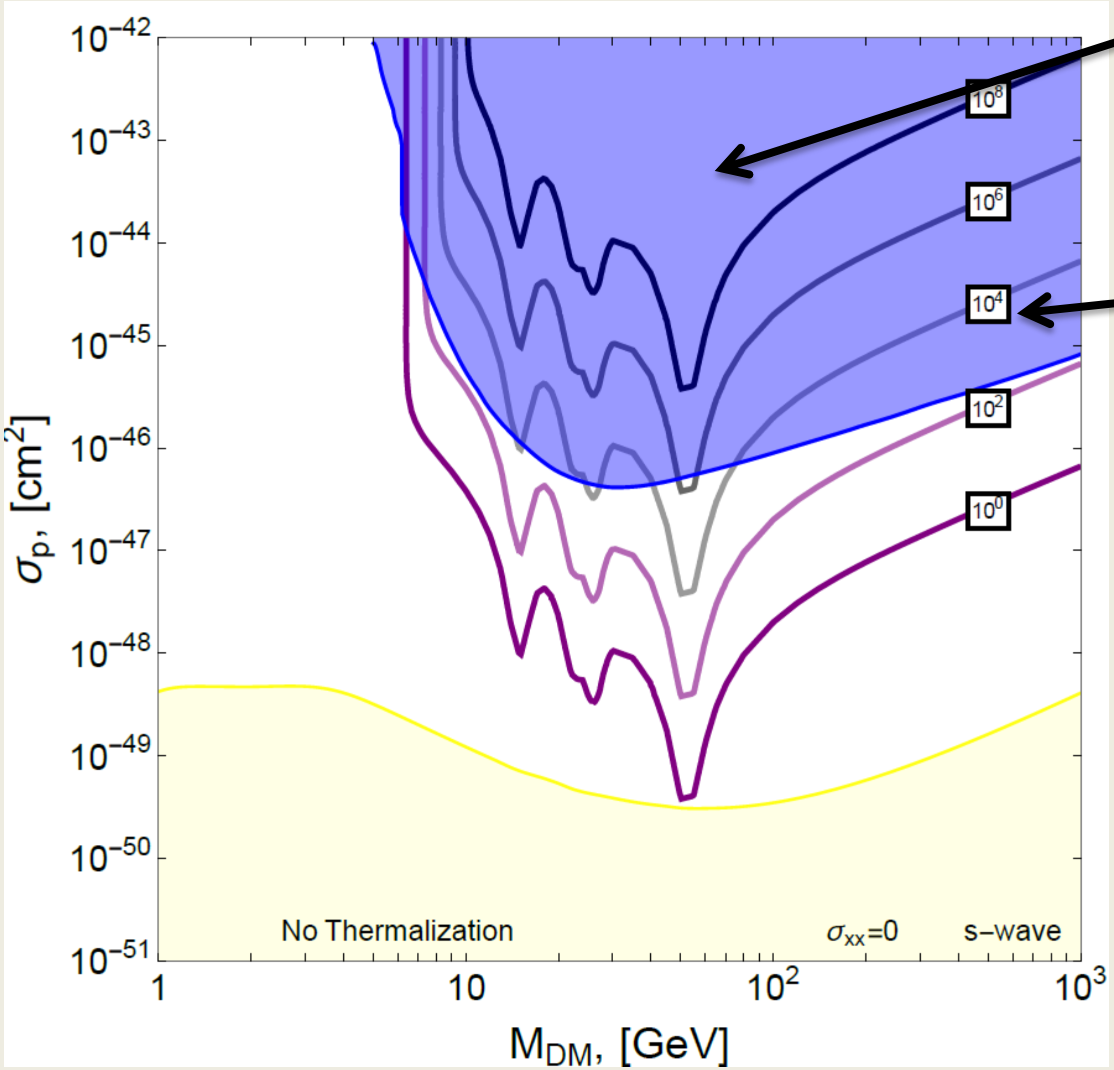
Annihilation Flux in the Sun



[CG, Shelton]

Super-K, IceCube and ANTARES place upper bounds 10^9- 10^{13} $\mathrm{km}^{-2}\mathrm{yr}^{-1}$ for prompt annihilation to SM final states (bb, ττ and WW)

Annihilation Flux in the Earth



Direct detection

Annihilation flux $(\mathrm{km}^{-2}\mathrm{yr}^{-1})$

[CG, Shelton]

What if DM self-interacts?

- New kinematic channels appear.

Self-Capture:

Halo DM + Captured DM $\rightarrow$ Captured DM + Captured DM

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- New kinematic channels appear.

Self-Capture:

Halo DM + Captured DM → Captured DM + Captured DM

Self-Ejection:

Halo DM + Captured DM → Halo DM + Halo DM

SIDM Population Dynamics

$$\dot{N} = C_c + (C_{sc} - C_{se})N(t) - C_a N^2(t).$$

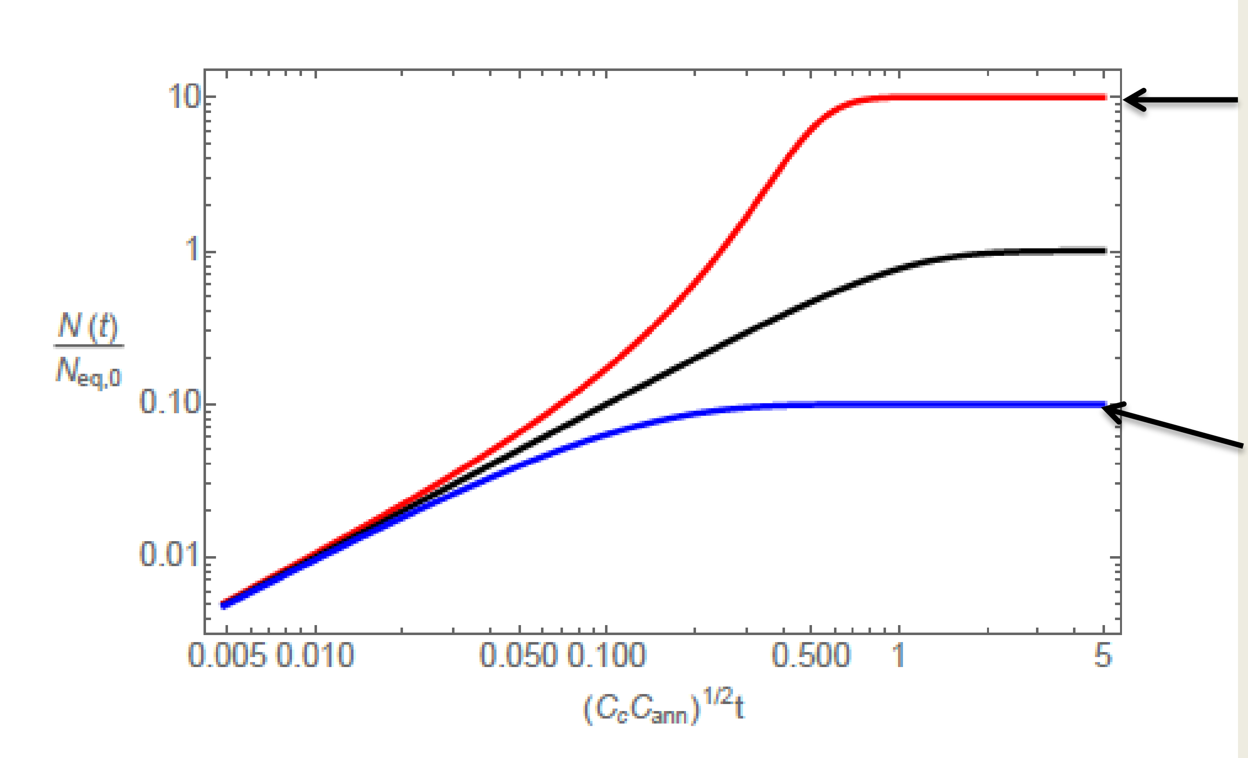
Self-capture **Self-ejection**

$$C_{sc/se} = C_{sc/se}\,(M_{DM}, \sigma_{xx})$$

σ_{xx} - self-interaction cross-section. Our modelling assumes a constant σ_{xx} (no velocity or angular dependence).

SIDM Population Dynamics

$$\dot{N} = C_c + (C_{sc} - C_{se})N(t) - C_a N^2(t).$$

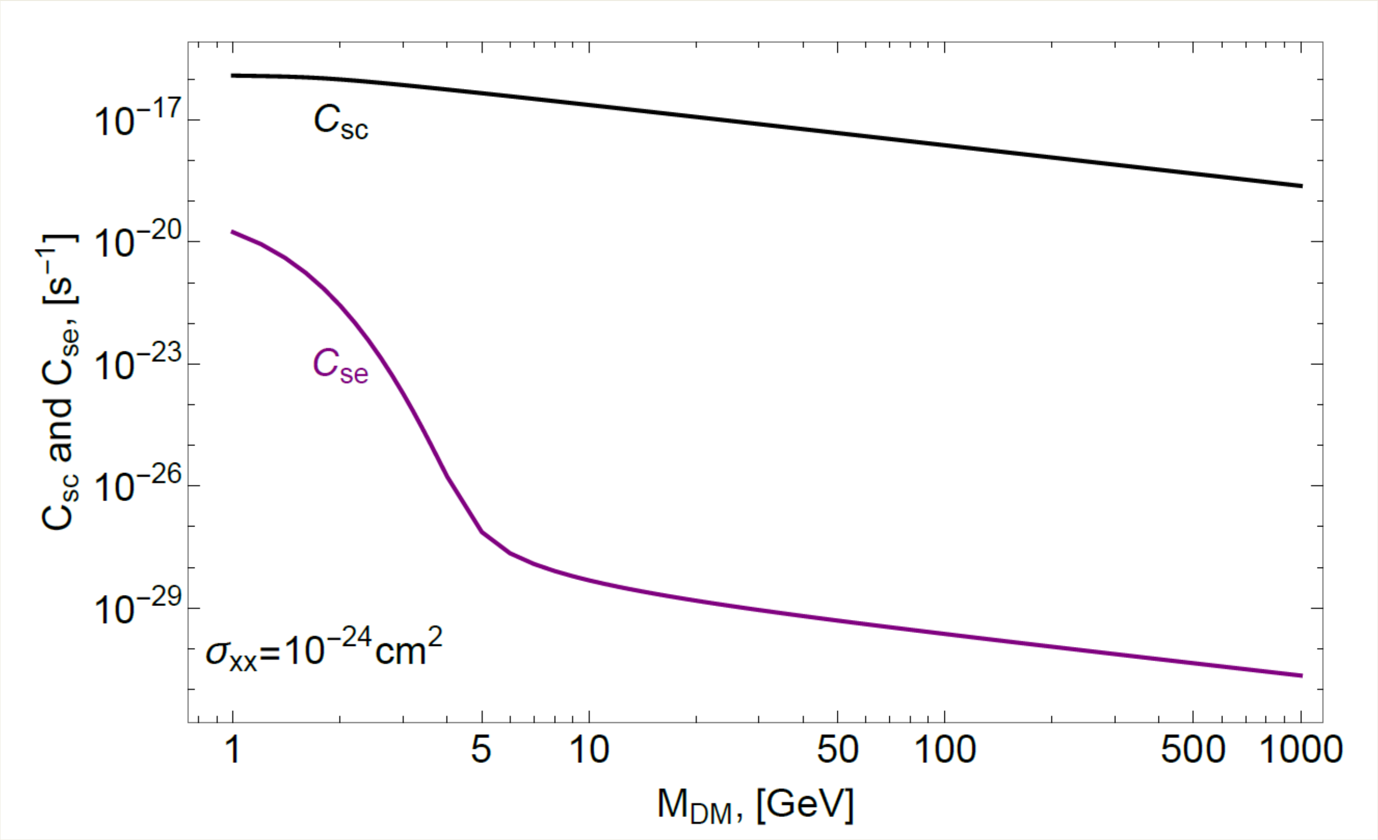


$C_{sc} > C_{se}$

$C_{sc} < C_{se}$

Zentner, Andrew R. "High-energy neutrinos from dark matter particle self-capture within the Sun." *Physical Review D* 80.6 (2009): 063501.

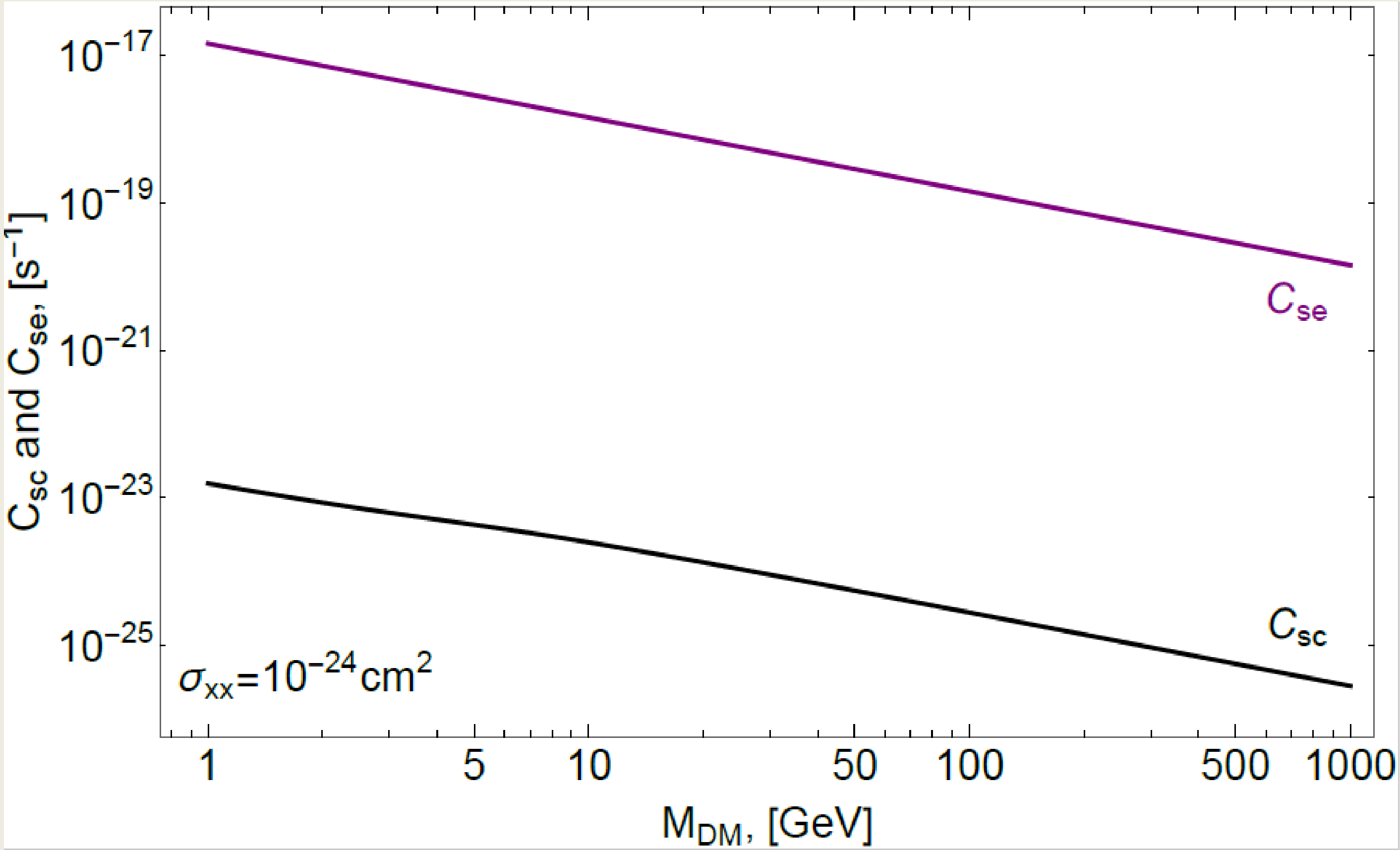
Sun-Captured SIDM



[CG, Shelton]

- Self-Interactions <u>enhance</u> the Sun-captured DM population. <u>Enhanced</u> DM annihilation rate and flux of SM annihilation products.

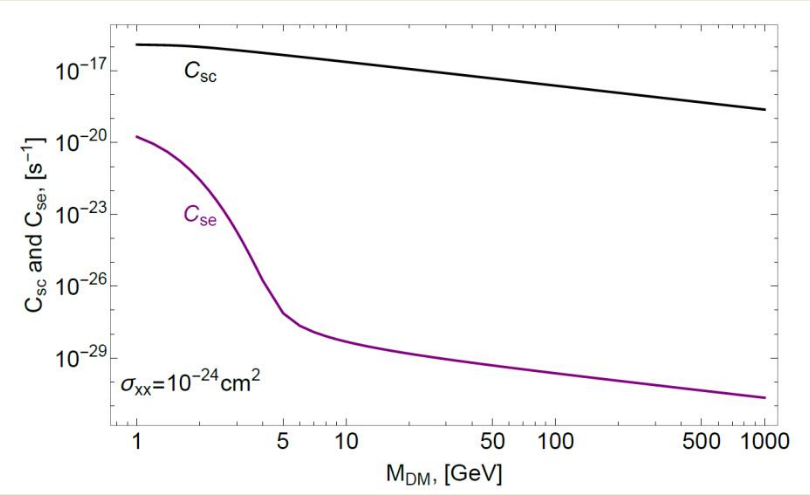
Earth-Captured SIDM



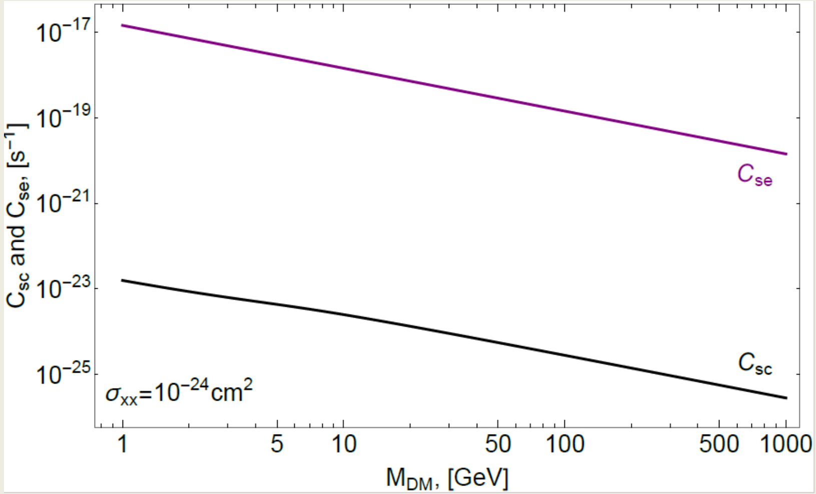
[CG, Shelton]

- Self-Interactions <u>deplete</u> the Earth-captured DM population. <u>Suppression</u> of the DM annihilation rate and flux of SM annihilation products.

Sun/Earth-Captured SIDM



Sun



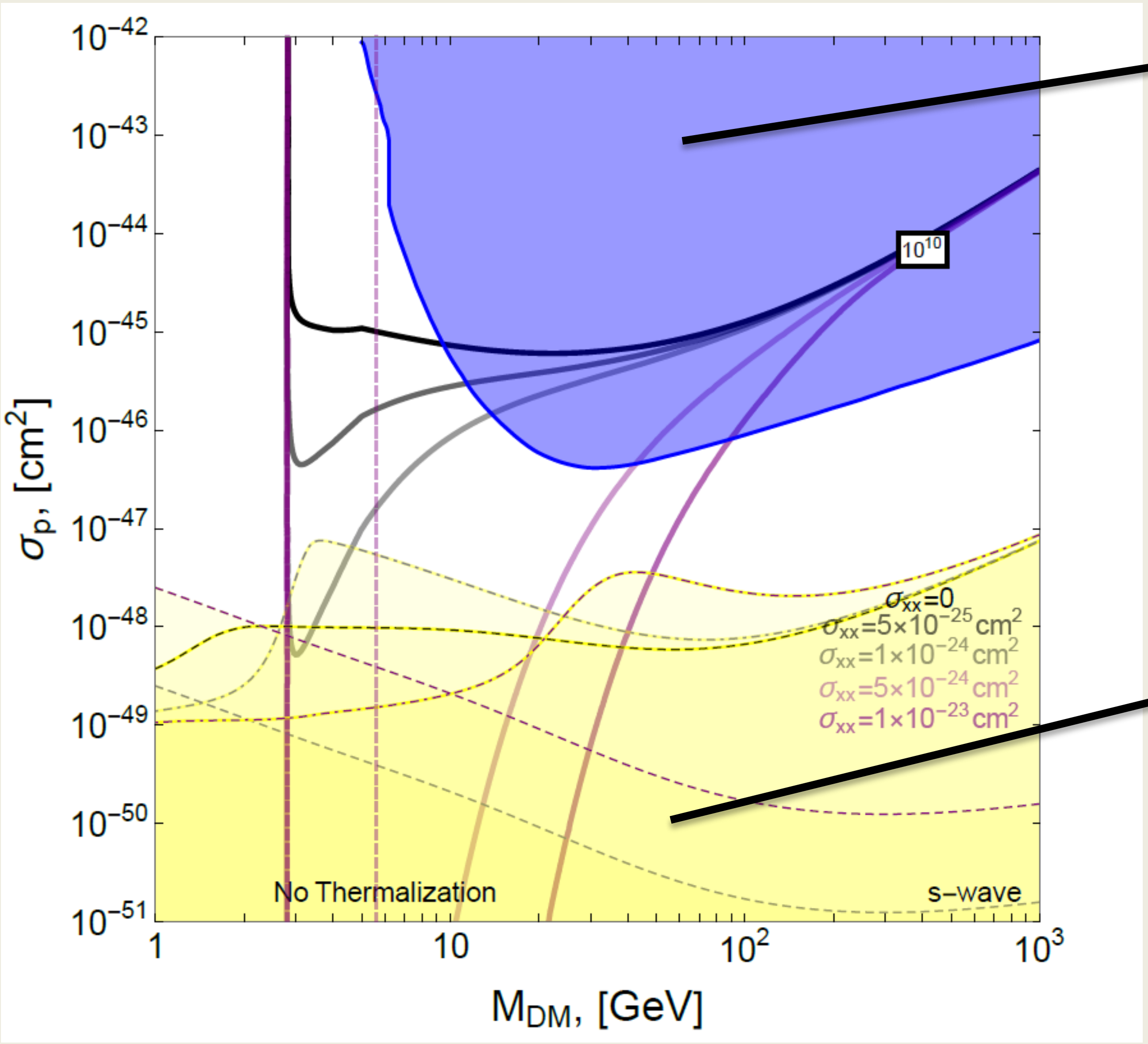
Earth

DM speed in the Halo: $\sim 300 \frac{km}{s}$, while:

Sun: $v_{esc} \sim 600 \frac{km}{s} \rightarrow$ self-capture more likely

Earth: $v_{esc} \sim 12 \frac{km}{s} \rightarrow$ self-ejection more likely

Self-Interactions modify the constraints from flux measurements

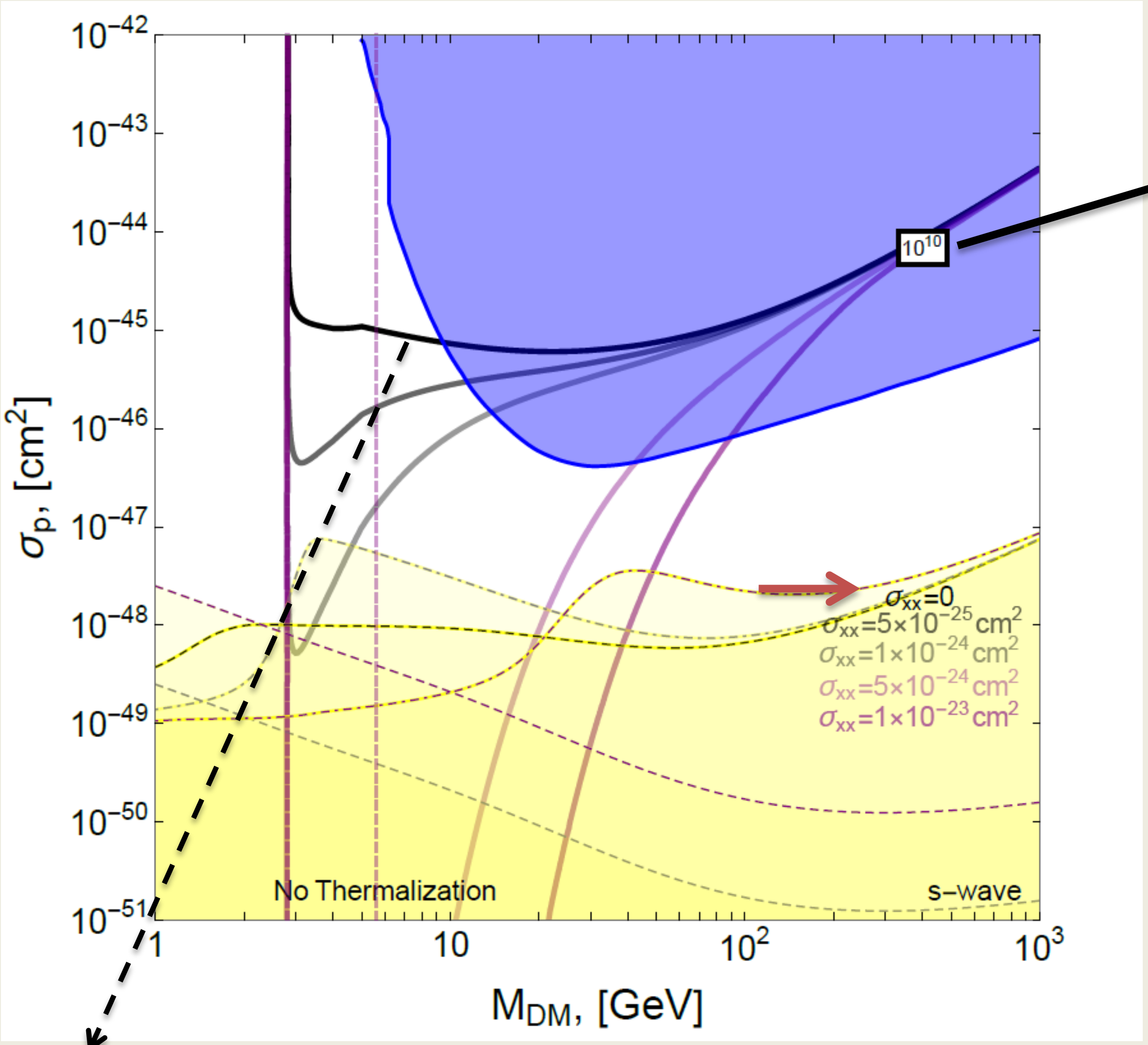


Excluded by direct detection experiments

Captured DM does not thermalize

[CG, Shelton]

Self-Interactions modify the constraints from flux measurements

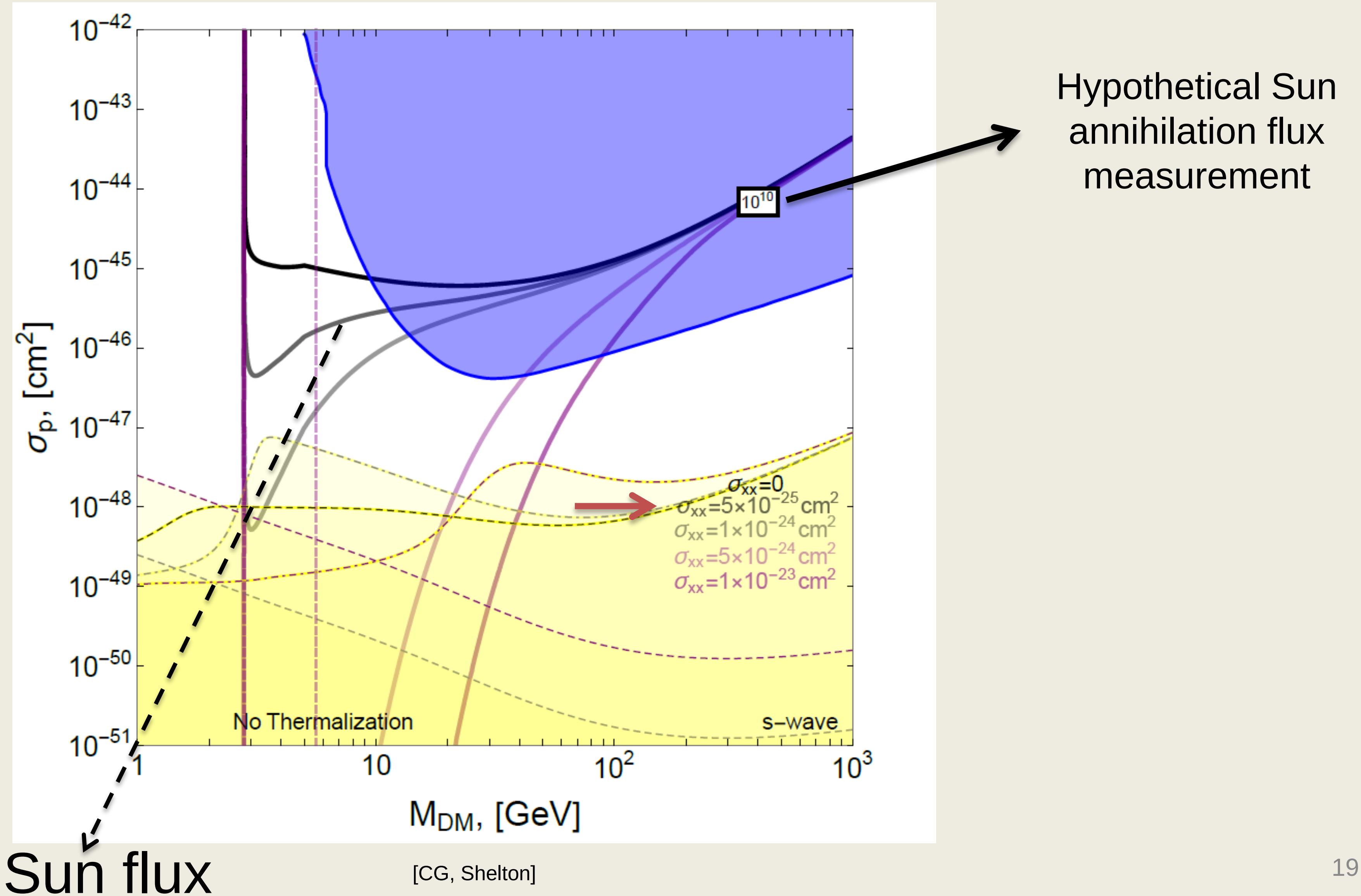


Hypothetical Sun annihilation flux measurement

Sun flux

[CG, Shelton]

Self-Interactions modify the constraints from flux measurements



[CG, Shelton]

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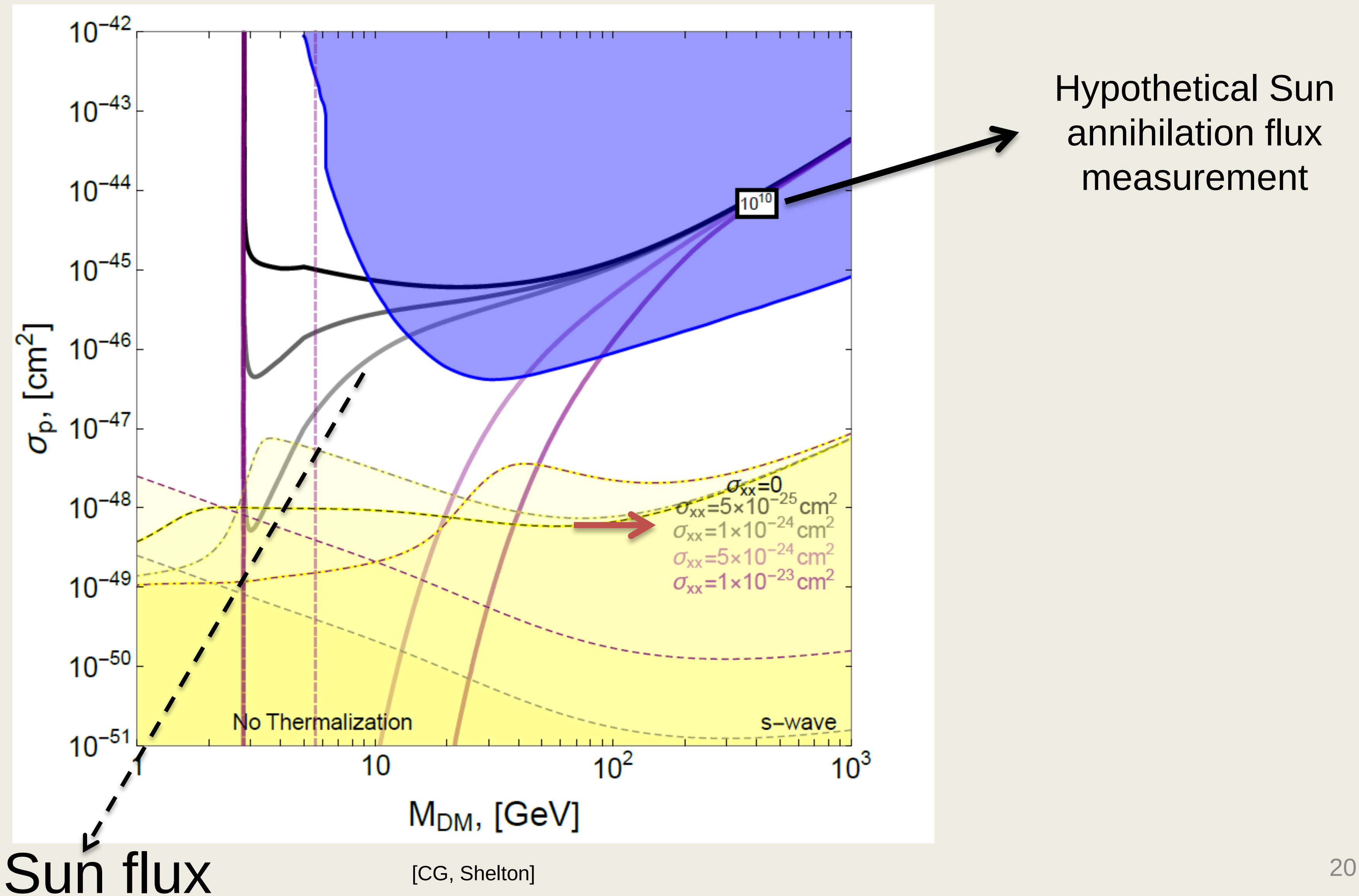

[CG, Shelton]

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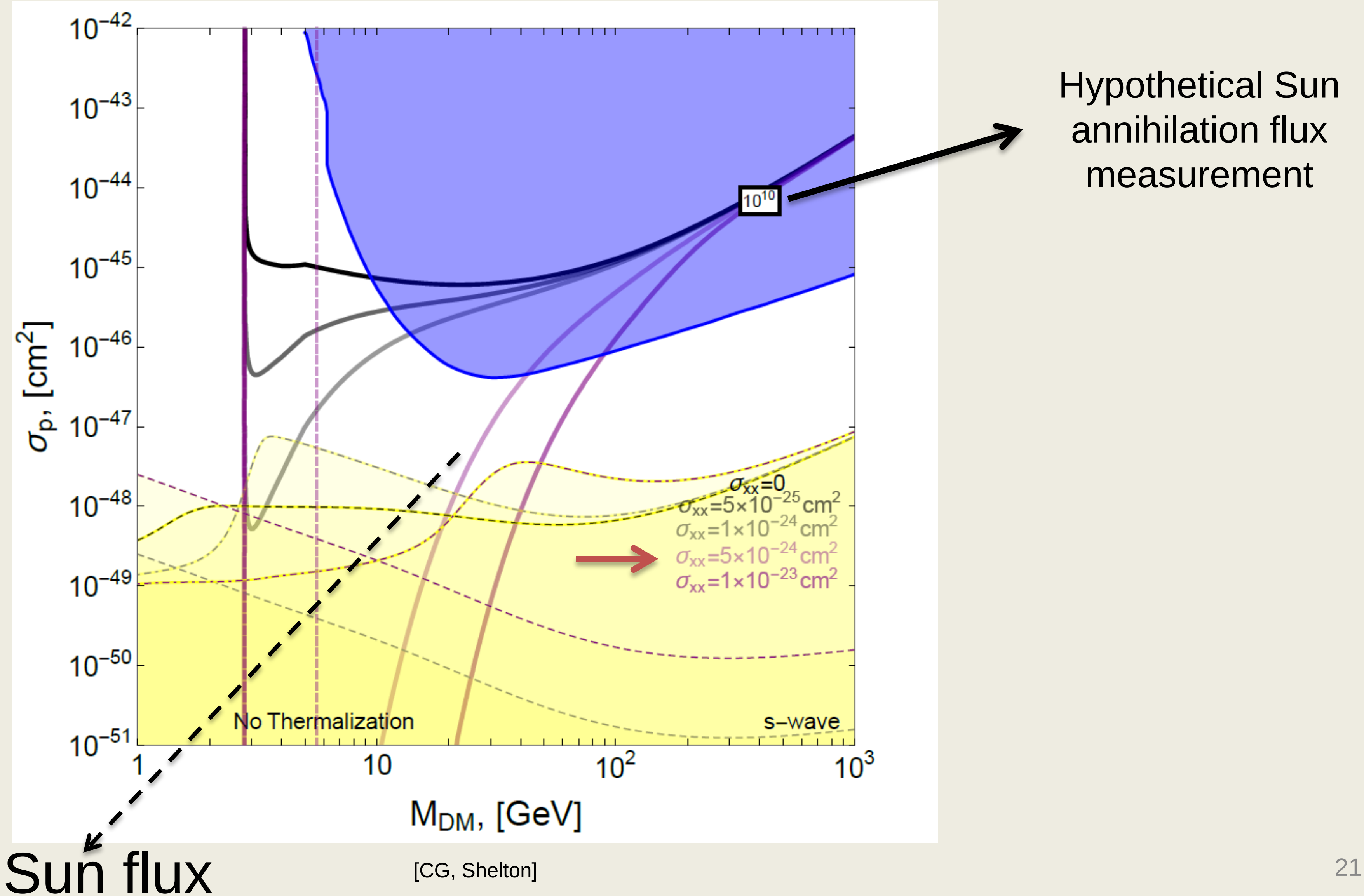


[CG, Shelton]

Can we exploit the fact that Self-Interactions affect the Sun and Earth-captured DM populations differently?

Sun and Earth fluxes depend on the same DM inputs

$$\Phi^{Sun} = \Phi^{Sun}(M_{DM}, \sigma_p, \sigma_{xx}, <\sigma v>)$$

$$\Phi^{Earth} = \Phi^{Earth}(M_{DM}, \sigma_p, \sigma_{xx}, <\sigma v>)$$

Fixed by the relic density constraint

If σ_{xx}=0, a measurement of the Sun flux Φ_m^{Sun} would predict a unique Earth-flux:

$$\Phi_p^{Earth} = \Phi^{Earth}(M_{DM}, \Phi_m^{Sun}).$$

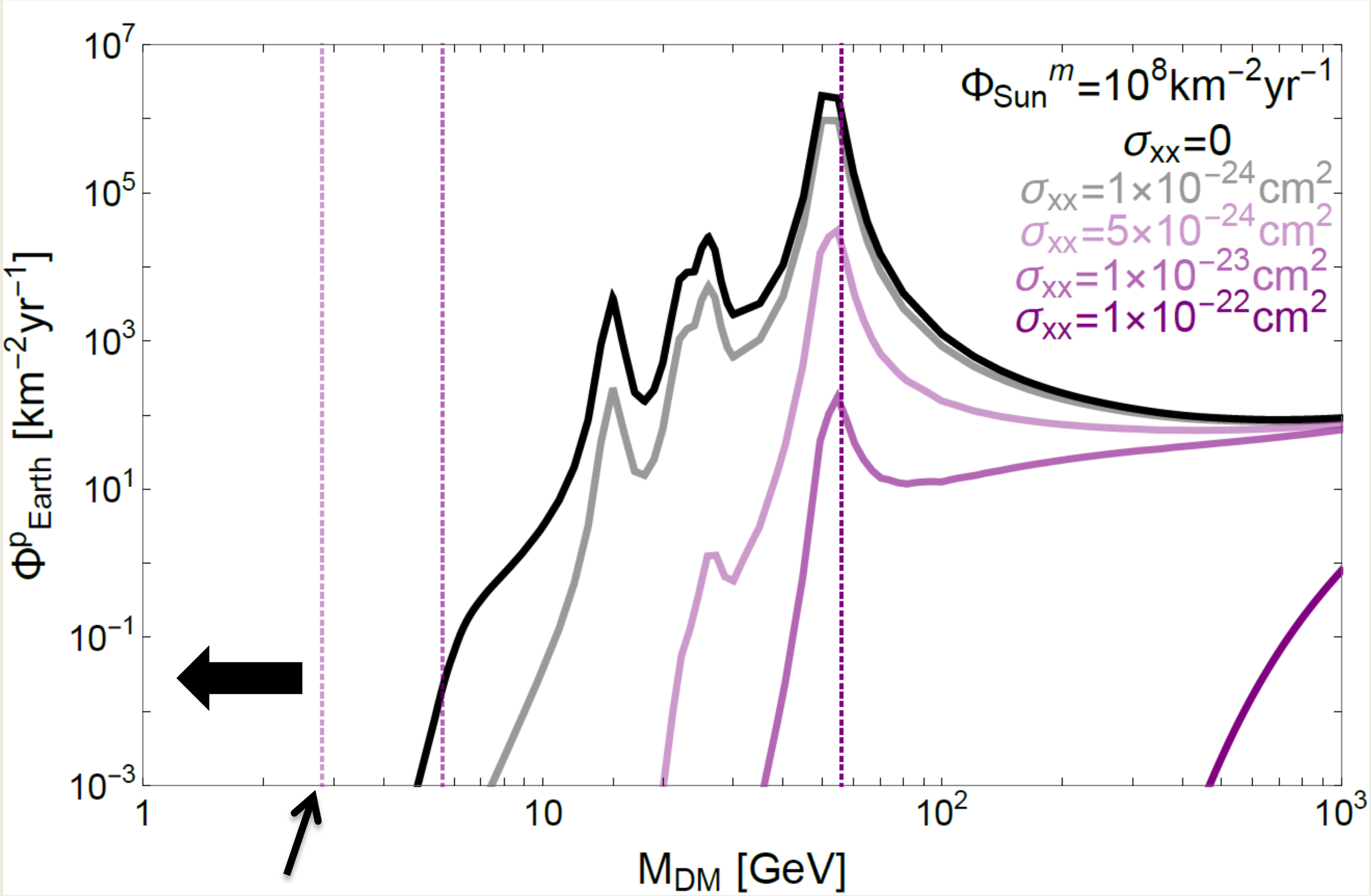
We call this the “null” prediction.

- If $\sigma_{xx} \neq 0$, must account for the enhancement of the Sun-captured population and depletion of the Earth-captured DM population:

$$\Phi_p^{Earth} = \Phi^{Earth}(M_{DM}, \sigma_{xx}, \Phi_m^{Sun})$$

- A subsequent measurement of Φ^{Earth} can reveal the strength of self-interactions if this measured flux is different from the null prediction.

Self-Interactions “distort” the Earth flux predictions

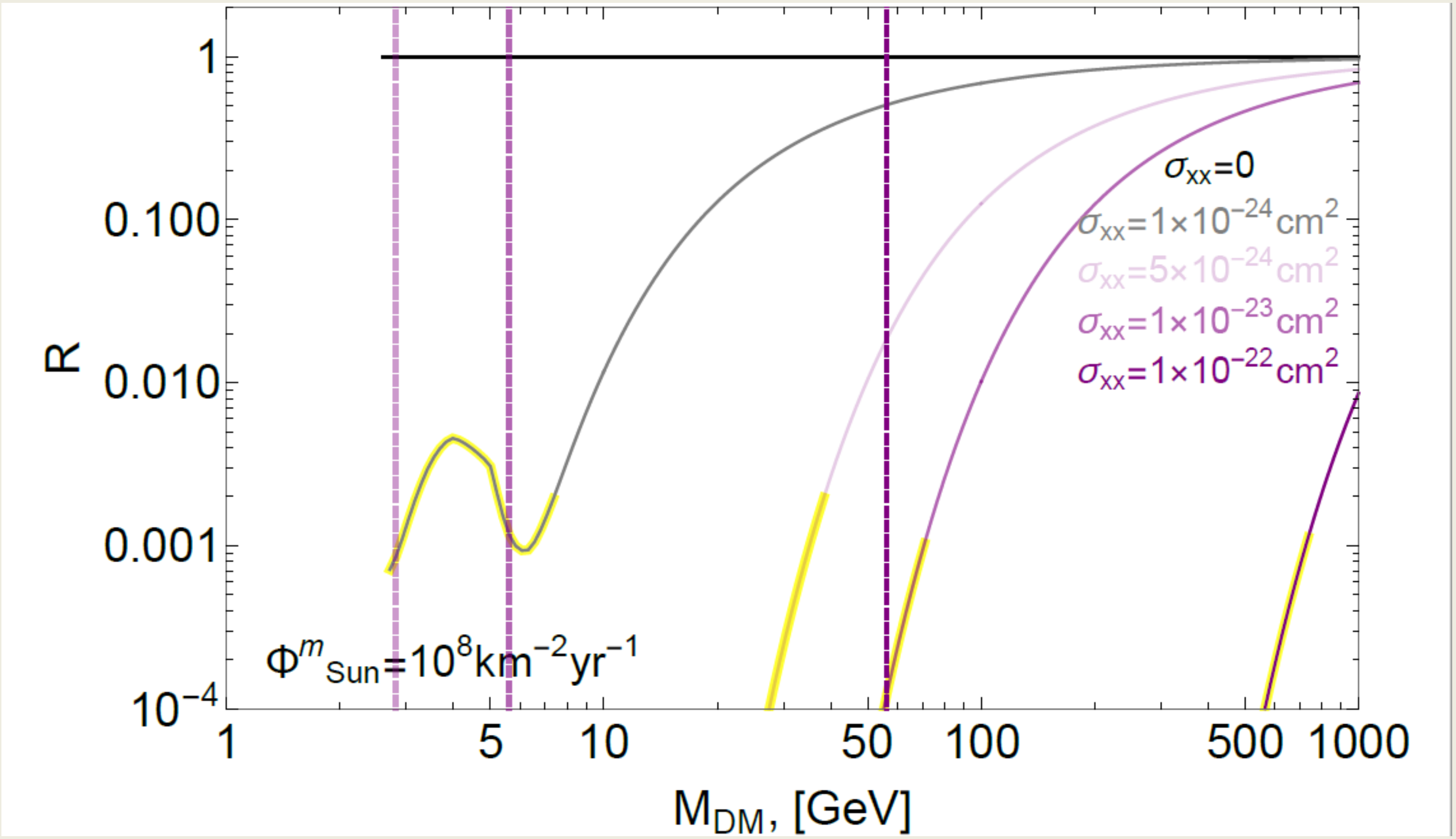


In tension with Bullet Cluster bounds at corresponding σ_{xx}.

[CG, Shelton]

Isolating Impact of SI's:

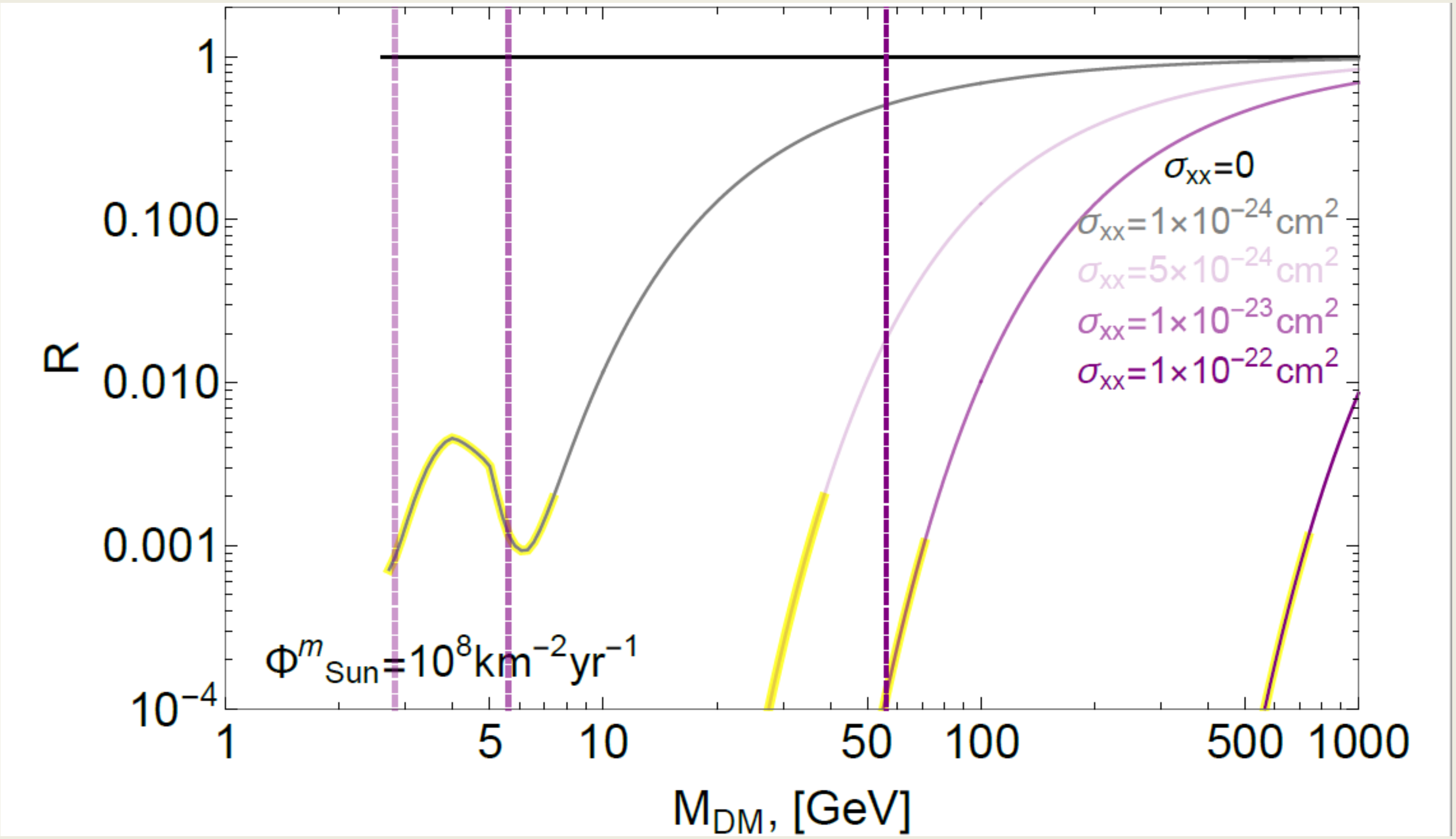
$$R \equiv \frac{\Phi_{\oplus}^{(\mathrm{p})}(M_{\mathrm{DM}}, \sigma_{\mathrm{xx}}; \Phi_{\odot}^{\mathrm{m}})}{\Phi_{\oplus}^{(0)}(M_{\mathrm{DM}}; \Phi_{\odot}^{\mathrm{m}})}$$



[CG, Shelton]

Isolating Impact of SI's:

$$R \approx \left(\frac{1 - \frac{C_{\odot sc}}{2} \tau_{\odot}}{1 + \frac{C_{\oplus se}}{2} \tau_{\oplus}} \right)^2$$



[CG, Shelton]

Conclusions

- DM Self-Interactions affect the Sun and Earth-captured DM populations in “opposite” ways – enhancement in the former and depletion in the latter case.

- The fractional suppression of the captured DM annihilation flux can be orders of magnitude, providing a striking signature of self-interactions.

- A measurement of the annihilation fluxes of Sun and Earth-captured DM constitutes a diagnostic test of DM Self-Interactions. (Caveat: Observationally viable only for spin-independent DM-nucleon cross-section.)

Back-Up Slides

Construction of C_c

$$C_c = \int_0^R d^3\vec{r} \sum_i \frac{dC_{c,i}}{dV}$$

$$\frac{dC_{c,i}}{dV} = \int d^3u f(u) \frac{\sqrt{u^2 + v_{esc}^2(r)}}{u} n_i(r) n_{\mathrm{DM}} \sqrt{u^2 + v_{esc}^2(r)} \sigma_{cap}$$

Construction of C_c

$$C_c = \int_0^R d^3\vec{r} \sum_i \frac{dC_{c,i}}{dV}$$

Nuclear species in the Sun/Earth

$$\frac{dC_{c,i}}{dV} = \int d^3u f(u) \frac{\sqrt{u^2 + v_{esc}^2(r)}}{u} n_i(r) n_{\mathrm{DM}} \sqrt{u^2 + v_{esc}^2(r)} \sigma_{cap}$$

Velocity distribution of Halo DM

Differential capture rate

Construction of C_c

$$C_c = \int_0^R d^3\vec{r} \sum_i \frac{dC_{c,i}}{dV}$$

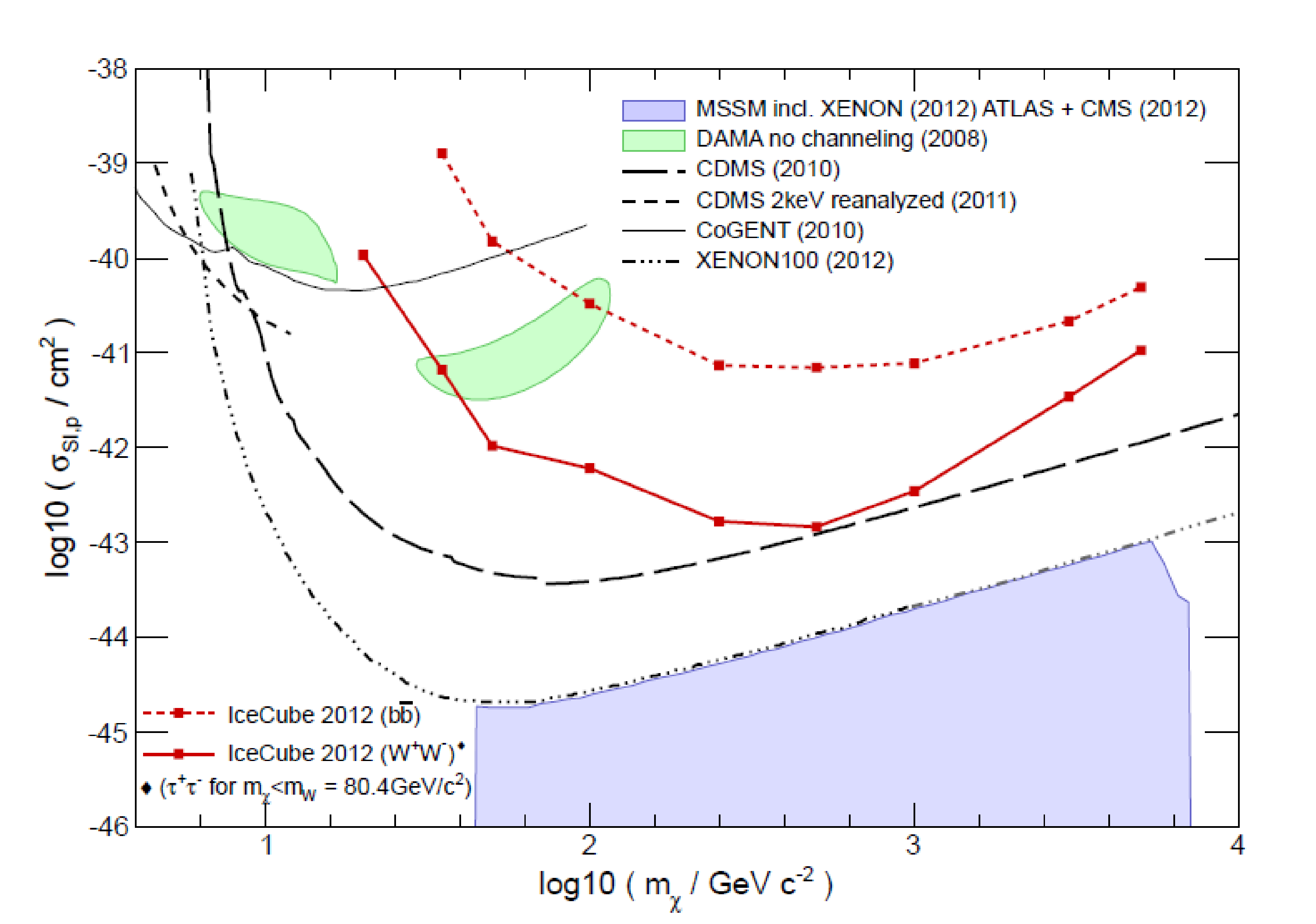
$$\frac{dC_{c,i}}{dV} = \int d^3u f(u) \frac{\sqrt{u^2 + v_{esc}^2(r)}}{u} n_i(r) n_{\mathrm{DM}} \sqrt{u^2 + v_{esc}^2(r)} \sigma_{cap}$$

Kinematic constraint on energy transfer

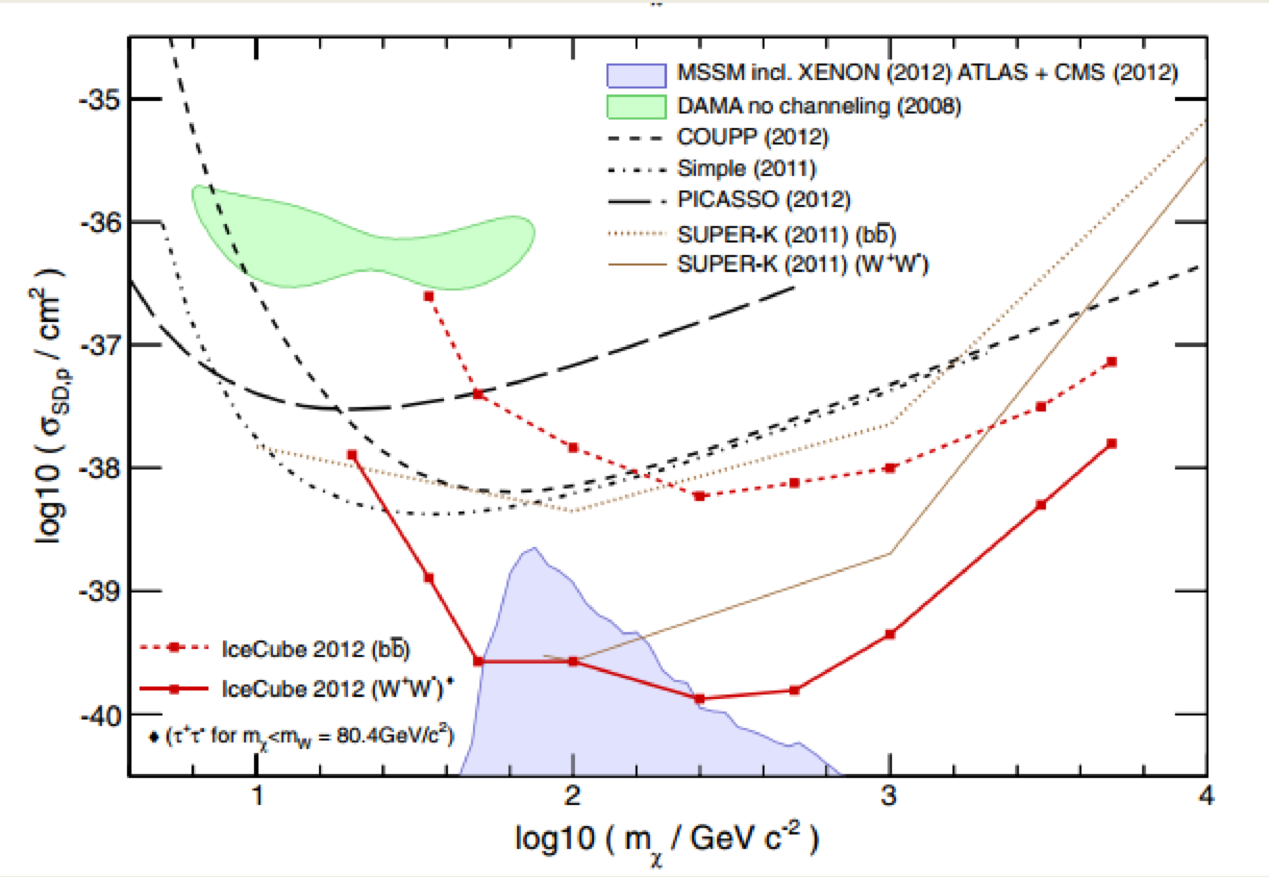
$$\sigma_{cap} = \int_{\Delta E_{min}}^{\Delta E_{max}} \frac{d\sigma}{d\Delta E} d\Delta E$$

Energy transfer in collision

$$\frac{\Delta E}{E} \geq \frac{u^2}{u^2 + v_{esc}^2(r)}$$



IceCube Collaboration.
arXiv:1212.4097v2 [astro-ph.HE]



90% CL upper limits on σ_p as a function of WIMP mass

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