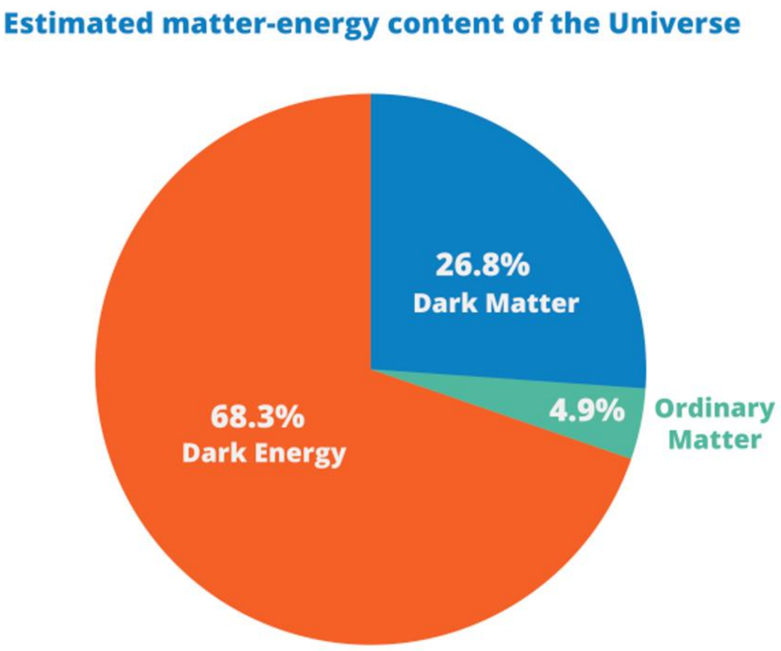
Constraining generalized Dark Matter-Nucleon Interactions based on Dark Matter Capture in the Sun with IceCube

Lilly Peters

Image: Yuya Makino, IceCube/NSF

Dark Matter



- Non-luminous
- Compelling observational evidence
- Its nature remains unknown

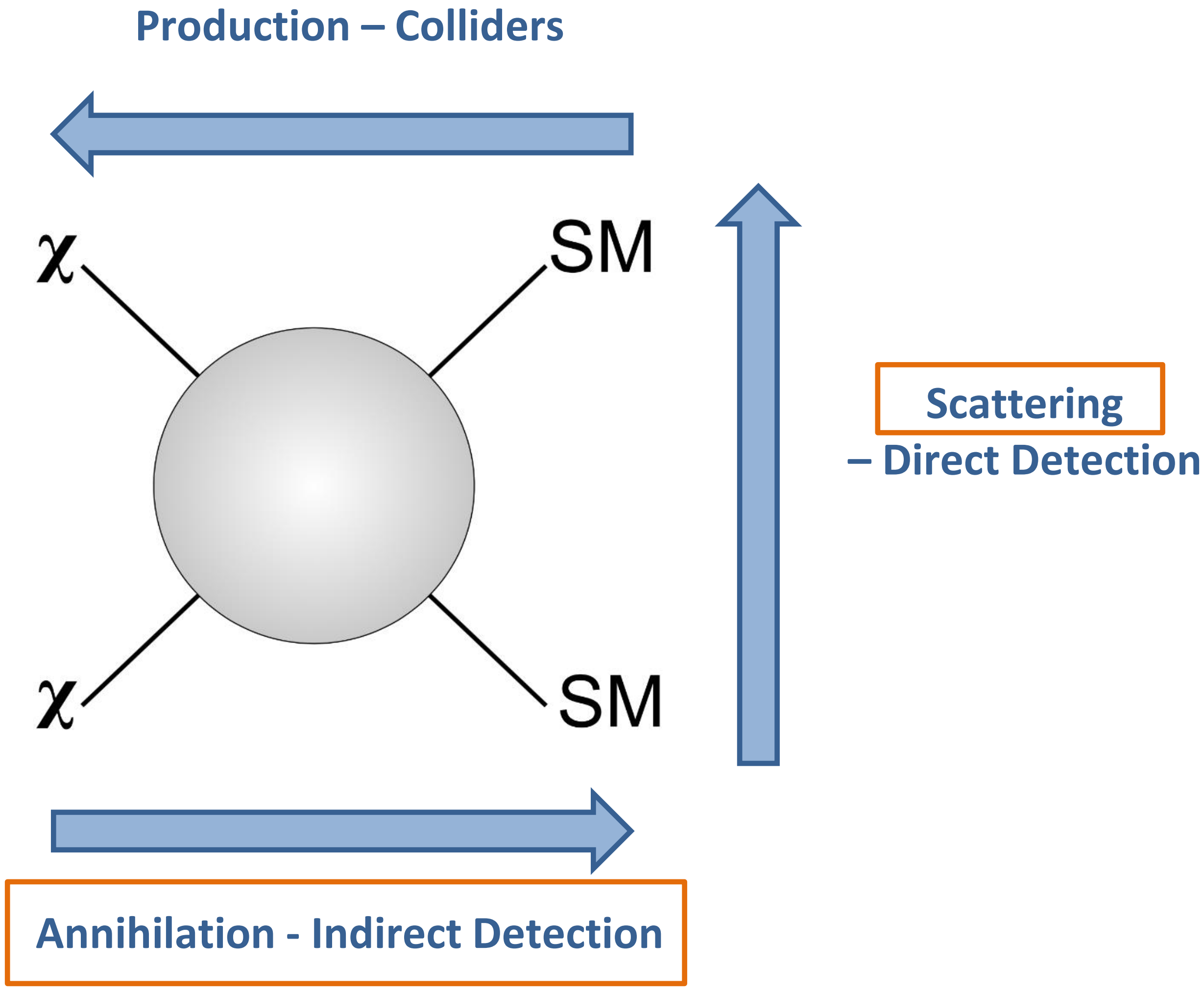
How to detect dark matter?

Dark Matter Detection

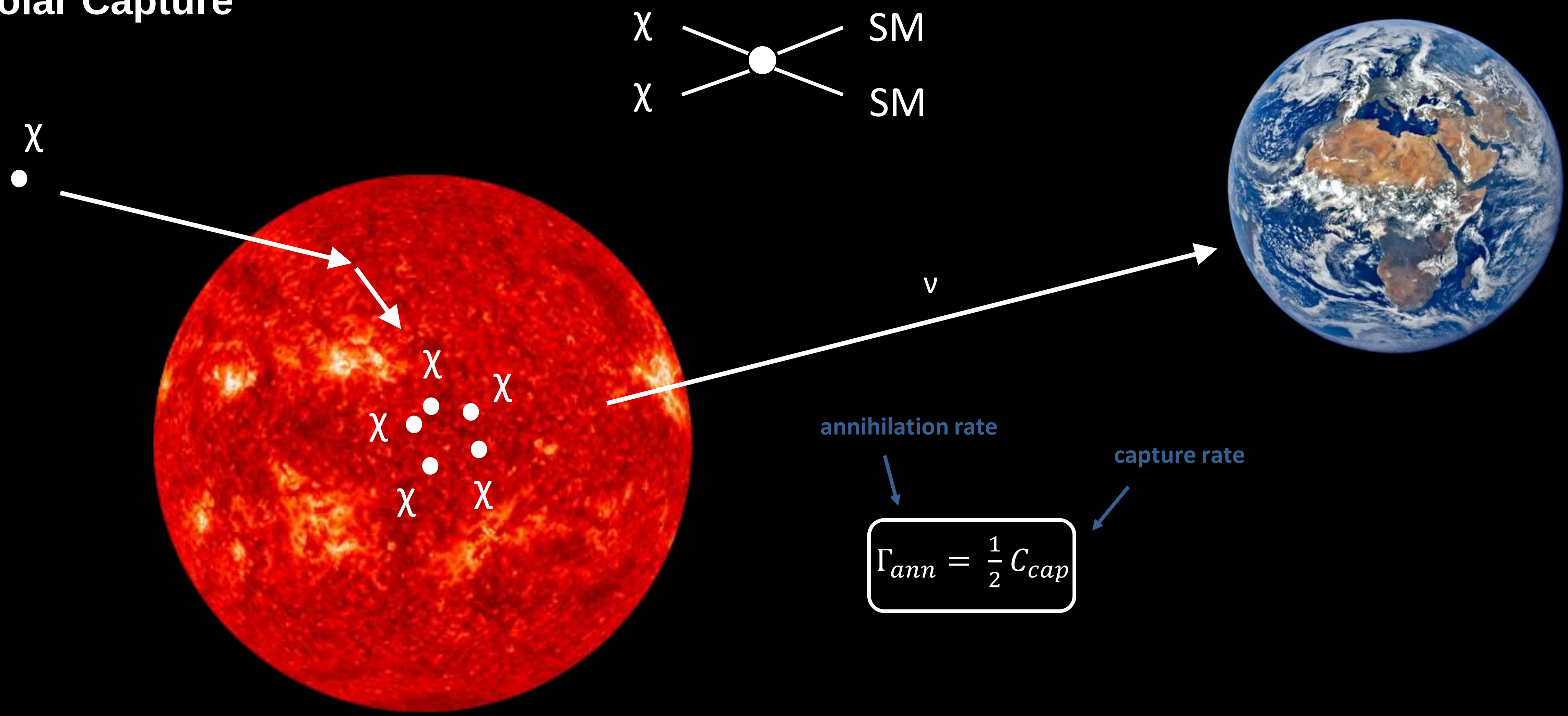
- Different interaction channels/search strategies for dark matter particles

- This work: **Solar capture**

→ special: **indirect** detection, but sensitive to **scattering** cross section



Solar Capture

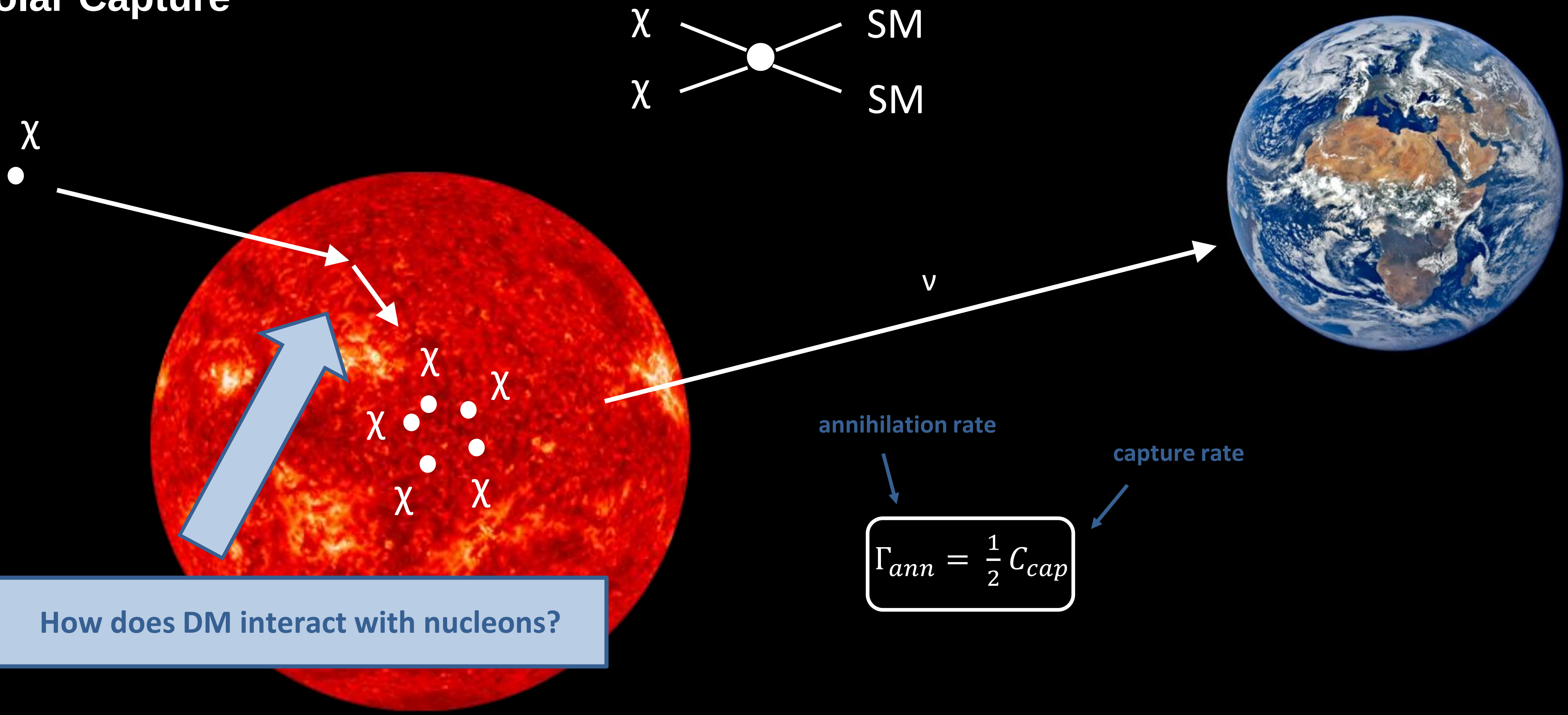


annihilation rate

capture rate

$$\boxed{\Gamma_{ann} = \frac{1}{2} C_{cap}}$$

Solar Capture



How does DM interact with nucleons?

annihilation rate

capture rate

$$\boxed{\Gamma_{ann} = \frac{1}{2} C_{cap}}$$

Effective Theory

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Motivation: standard spin-dependent (SD) and spin-independent (SI) interactions can be suppressed or forbidden
→ include **velocity** and **momentum dependent** interactions

„standard assumption“

SI → $\mathcal{O}_1$

SD → $\mathcal{O}_4$

$$
\begin{aligned}
\mathcal{O}_1 &= \mathbb{1}_{\chi N} & \mathcal{O}_{11} &= i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\mathbb{1}_N \\
\mathcal{O}_3 &= i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)\mathbb{1}_\chi & \mathcal{O}_{12} &= \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \\
\mathcal{O}_4 &= \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N & \mathcal{O}_{13} &= i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \\
\mathcal{O}_5 &= i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)\mathbb{1}_N & \mathcal{O}_{14} &= i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right) \\
\mathcal{O}_6 &= \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) & \mathcal{O}_{15} &= -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right] \\
\mathcal{O}_7 &= \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_\chi & \mathcal{O}_{17} &= i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N \\
\mathcal{O}_8 &= \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N & \mathcal{O}_{18} &= i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{S}}_N \\
\mathcal{O}_9 &= i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right) & \mathcal{O}_{19} &= \frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \frac{\hat{\mathbf{q}}}{m_N} \\
\mathcal{O}_{10} &= i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\mathbb{1}_\chi & \mathcal{O}_{20} &= \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right) \cdot \mathcal{S} \cdot \frac{\hat{\mathbf{q}}}{m_N}
\end{aligned}
$$

$$\mathcal{L}_{int} = \sum_{N=n,p} \sum_i c_i^N \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

isoscalar:

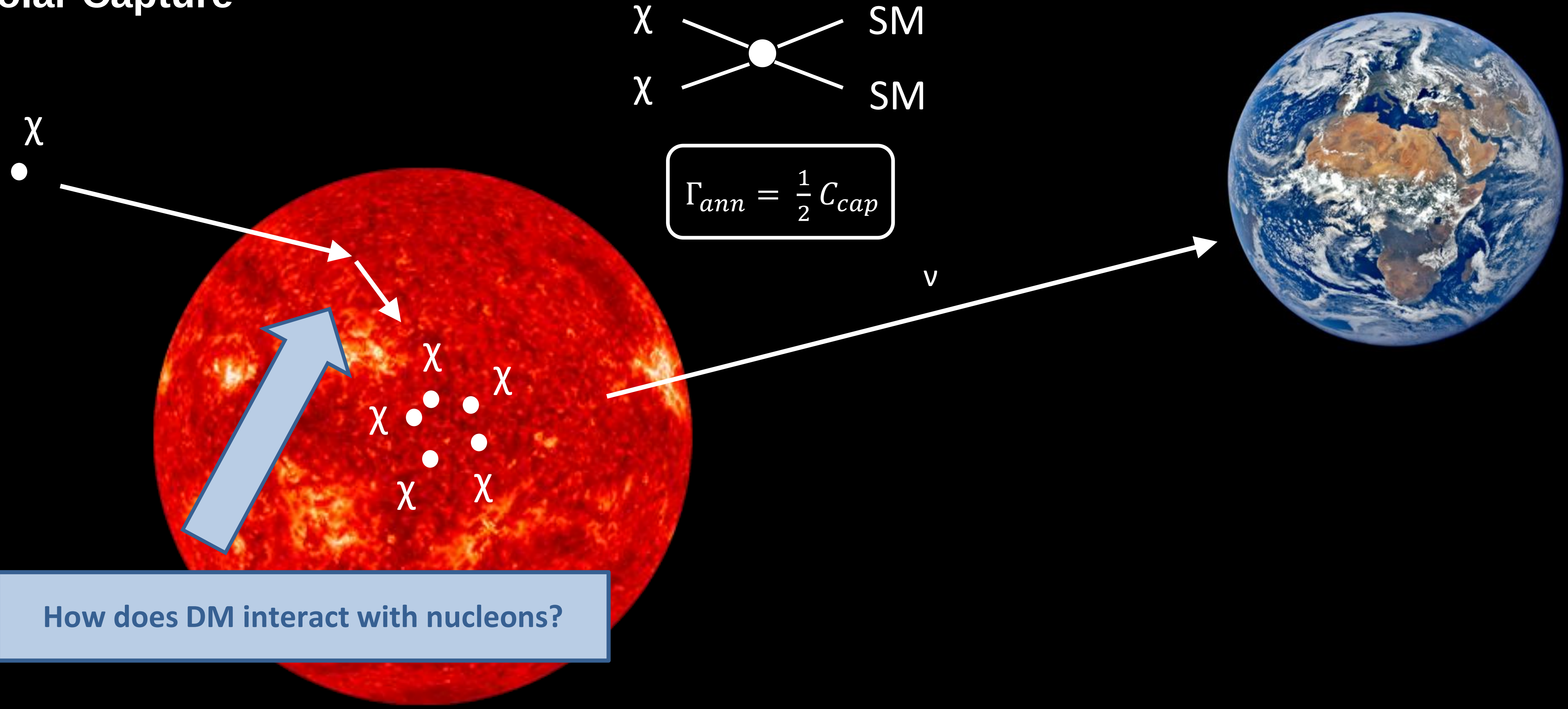
$$c^0 = c^p + c^n$$

isovector:

$$c^1 = c^p - c^n$$

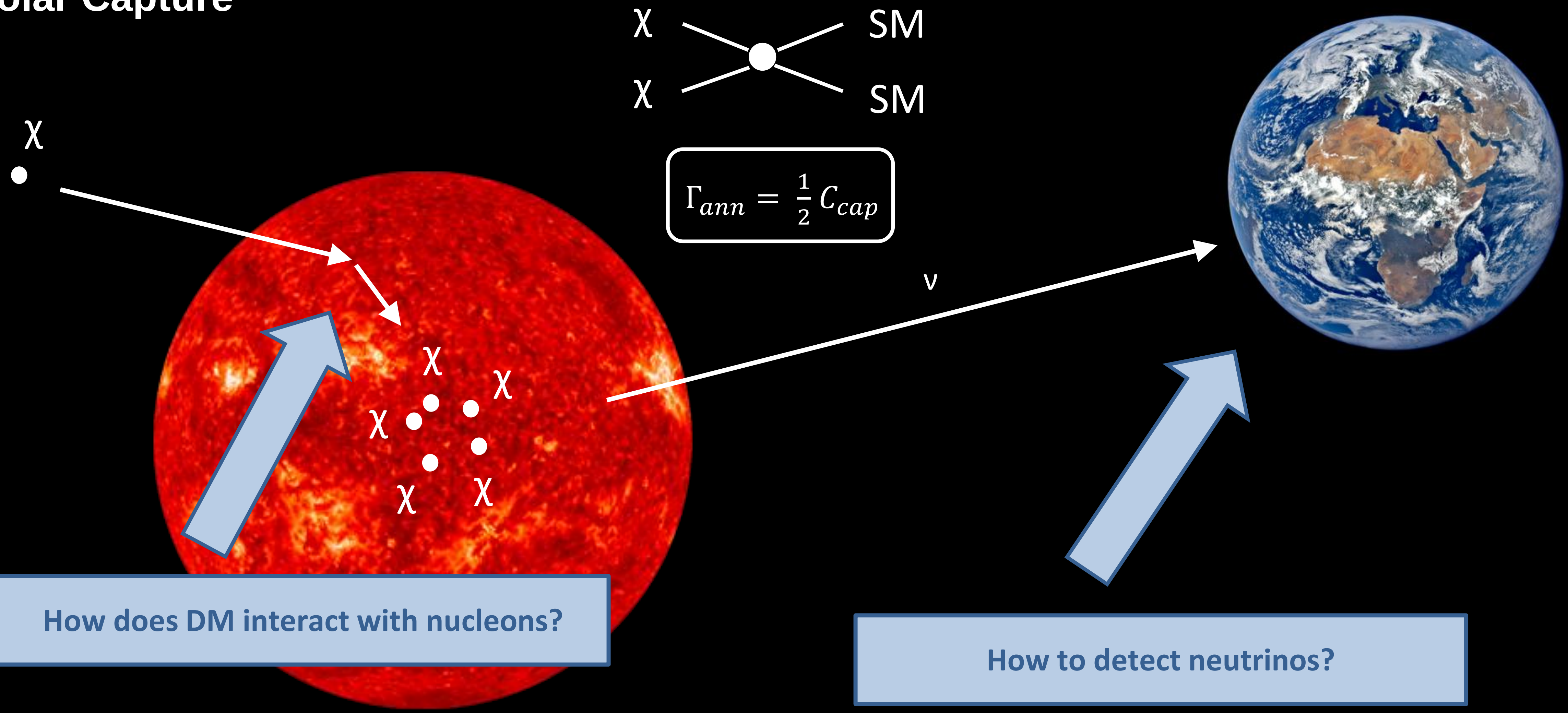
Goal: Constrain isoscalar and isovector **coupling constants** of all interaction operators (4, 14 and 18 for spin-0, spin-1/2 and spin-1 DM)

Solar Capture



$$\Gamma_{ann} = \frac{1}{2} C_{cap}$$

Solar Capture



$$\boxed{\Gamma_{ann} = \frac{1}{2} C_{cap}}$$

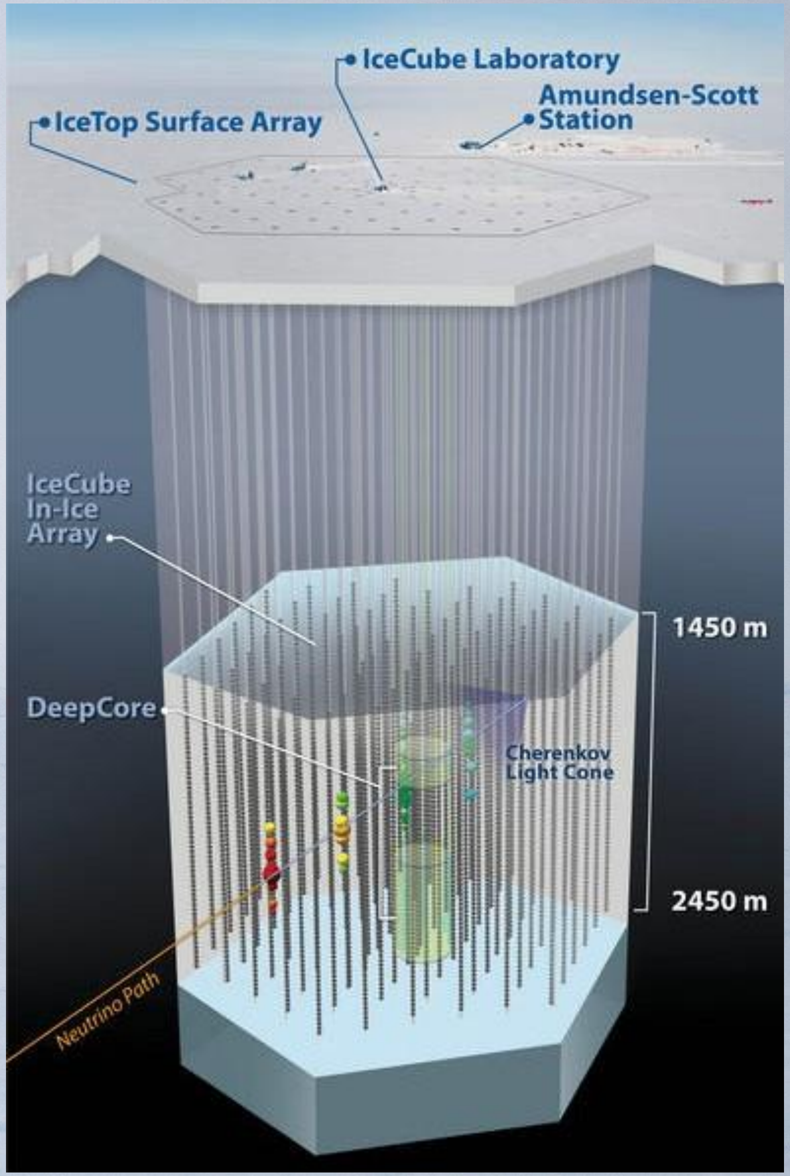
How does DM interact with nucleons?

How to detect neutrinos?

The IceCube Neutrino Observatory

Image: Yuya Makino, IceCube/NSF

- Neutrinos undergo **deep-inelastic scattering** in the Antarctic ice
- Optical detection of of **Cherenkov light** emitted by secondary charged particles



Method

Goal: Constrain isoscalar and isovector coupling constants of all interaction operators

- Capture rate is **proportional** to coupling constant squared: $C_{cap} \propto c^2$
- Use proportionality to **convert limits** from IceCube solar dark matter searches

$$(c_i^{limit})^2 = \frac{C_{cap}^{limit}}{C_{cap,i}} c_0^2$$

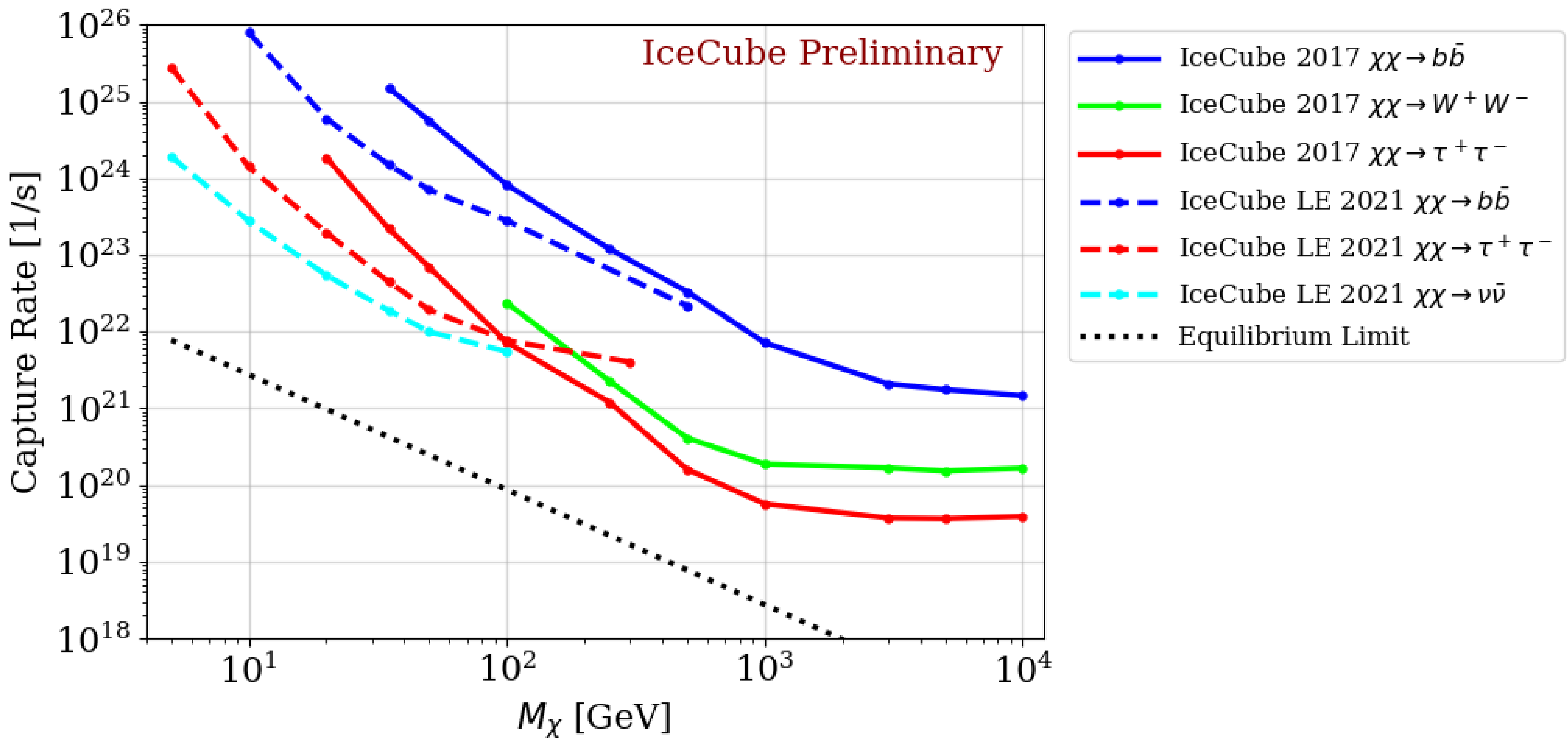
Calculate **capture rates** in the Sun for each interaction operator assuming $c_i = c_0$

(All other coupling constants are set to zero)

- Choose $c_0 = 10^{-3} m_v^{-2}$ $m_v = 246.2$ GeV

Capture Rate Limits

$$(c_i^{limit})^2 = \frac{\boxed{C_{cap}^{limit}}}{C_{cap,i}} c_0^2$$



2017:
- 3 years of data

LE 2021: new!
- 7 years of data
- low energy (DeepCore)
- also annihilation directly into neutrinos
- not published yet

Capture Rate Calculation

$$(c_i^{limit})^2 = \frac{C_{cap}^{limit}}{\boxed{C_{cap,i}}} c_0^2$$

Capture Rate Calculation

$$(c_i^{limit})^2 = \frac{C_{cap}^{limit}}{\boxed{C_{cap,i}}} c_0^2$$

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$$C_{cap}^{T} = n_{\chi} \int_0^{R_\odot} dr\, 4\pi r^2 n_T(r) \int_0^{\infty} du\, 4\pi u^2 f_\odot(u) \frac{u^2 + v_\odot^{esc}(r)^2}{u} \cdot \int_{E_{min}}^{E_{max}} dE_R \frac{d\sigma_T}{dE_R} \theta(\Delta E)$$

Sum over 16 most abundant elements

DM density

Solar Model

DM velocity distribution

Capture Rate Calculation

$$(c_i^{limit})^2 = \frac{C_{cap}^{limit}}{\boxed{C_{cap,i}}} c_0^2$$

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$$C_{cap}^T = n_\chi \int_0^{R_\odot} dr\, 4\pi r^2 n_T(r) \int_0^\infty du\, 4\pi u^2 f_\odot(u) \frac{u^2 + v_\odot^{esc}(r)^2}{u} \cdot \int_{E_{min}}^{E_{max}} dE_R \boxed{\frac{d\sigma_T}{dE_R}} \theta(\Delta E)$$

Sum over 16 most abundant elements

DM density

Solar Model

DM velocity distribution

DM response functions → **Contain the coupling constants**

$$\boxed{\begin{aligned}\frac{d\sigma_T}{dE_R}(\omega^2, q^2) = \frac{2m_T}{\omega^2}\frac{1}{2J+1}\sum_{\tau,\tau'}\Bigg[\sum_{k=M,\Sigma',\Sigma''} R_k^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_k^{\tau\tau'}(q^2) \\ + \frac{q^2}{m_N^2}\sum_{k=\Phi'',\Phi''M,\tilde{\Phi}',\Delta,\Delta\Sigma'} R_k^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_k^{\tau\tau'}(q^2)\Bigg]\end{aligned}}$$

Nuclear response functions

Nuclear response operators

→ **Multipole expansion of nuclear charges and currents gives six nuclear response operators: M, Σ',Σ'',Δ, Φ', Φ''**
→ **Measure different quantities (spin, mass, …)**
→ **Favor different elements**

Results

- Capture Rates
- Systematic Uncertainties
- Limits on the Coupling Constants

Image: Yuya Makino, IceCube/NSF

Capture Rates

spin ½ isoscalar

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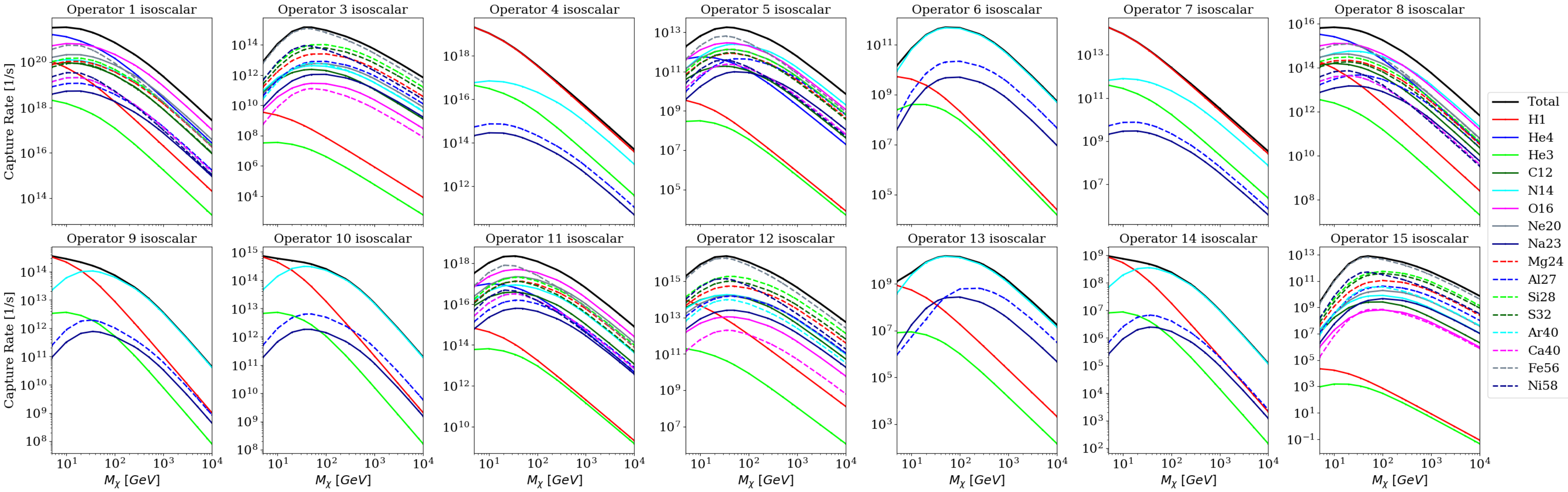

- Most relevant elements can be **H1, He4, N14, O16, Al27 or Fe56**
- Dependence on **momentum transfer** → suppression of lighter elements

Systematics

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$$C_{cap}^{T} = \underbrace{n_{\chi}}_{\text{DM density}} \int_0^{R_\odot} dr\, 4\pi r^2 \underbrace{n_T(r)}_{\text{Solar Model}} \int_0^{\infty} du\, 4\pi u^2 \underbrace{f_\odot(u)}_{\text{DM velocity distribution}} \frac{u^2 + v_\odot^{esc}(r)^2}{u} \cdot \int_{E_{min}}^{E_{max}} dE_R \frac{d\sigma_T}{dE_R} \theta(\Delta E)$$

Solar Model

DM velocity distribution

DM density

Systematics – Velocity Distribution

spin ½ isoscalar

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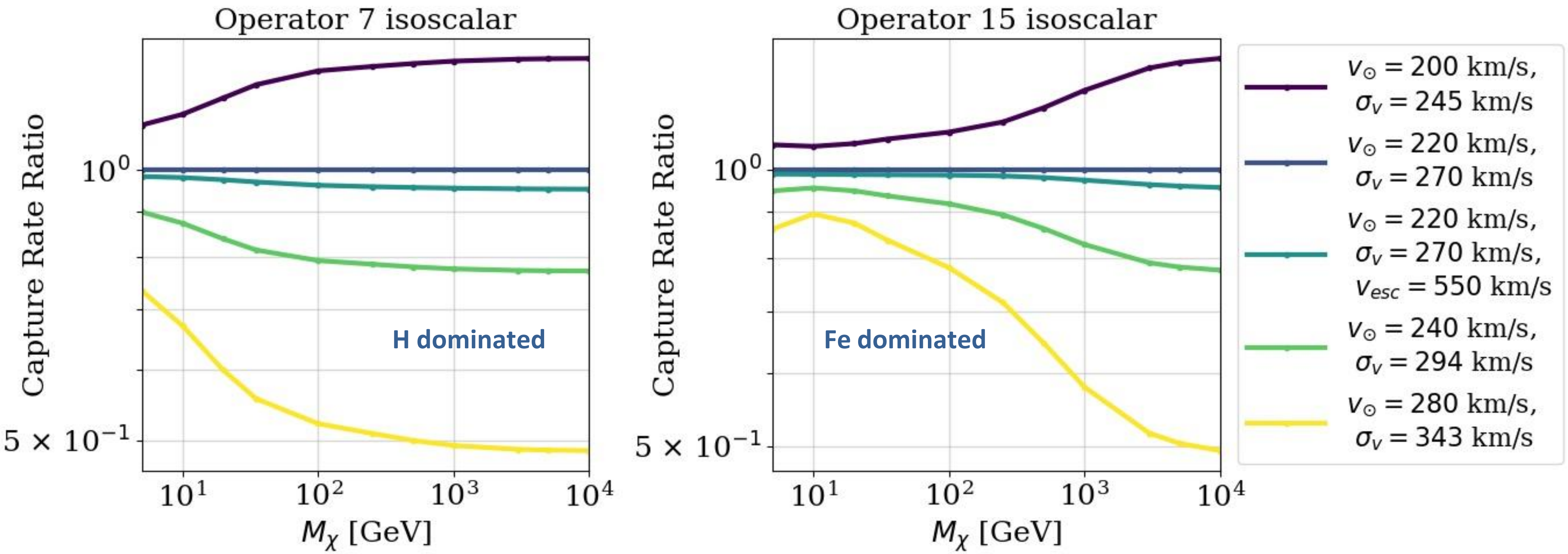
- Standard Assumptions: **Maxwellian** distribution with rotational velocity of 220 km/s, dispersion of 270 km/s and no galactic escape velocity

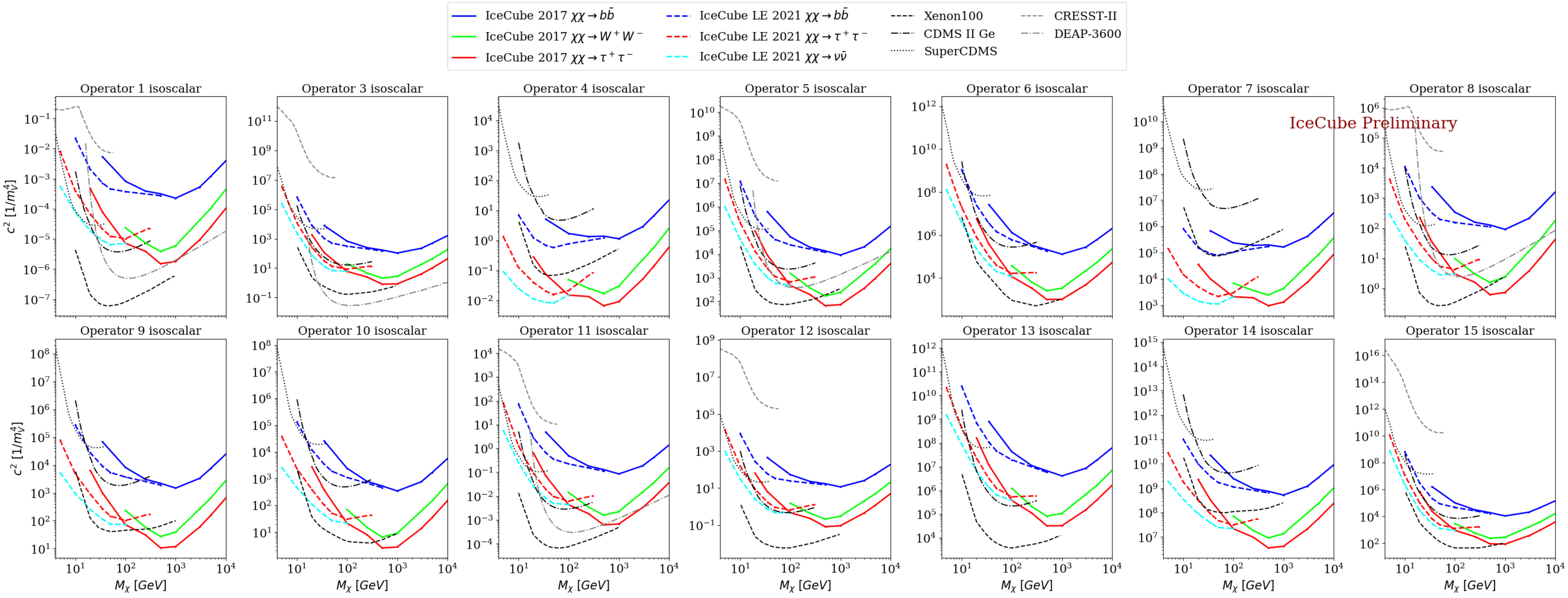


→Operators which are dominated by **hydrogen** are affected at **smaller dark matter masses**

Limits

$$(c_i^{limit})^2 = \frac{C_{cap}^{limit}}{C_{cap,i}} c_0^2$$

spin ½ isoscalar



Summary

- Calculated **capture rates** of dark matter in the Sun within the **general effective theory** of isoscalar and isovector **dark matter-nucleon interactions** in the non-relativistic regime
- The theory predicts **four, 14 or 18 interaction operators** for dark matter particles with **spin 0, spin 1/2 or spin 1** with a non-trivial **dependence on velocity and momentum transfer**
- Studied impact of **systematic uncertainties** on the capture rate, in particular the **velocity distribution** of dark matter particles in the Galaxy and the **elemental composition** of the Sun
- Used the computed capture rates **to convert exclusion limits** on the capture rate by IceCube into **limits on the coupling constants** of the theory
- Leading limits for various interaction types, dark matter masses and annihilation channels

Thank you for your attention!

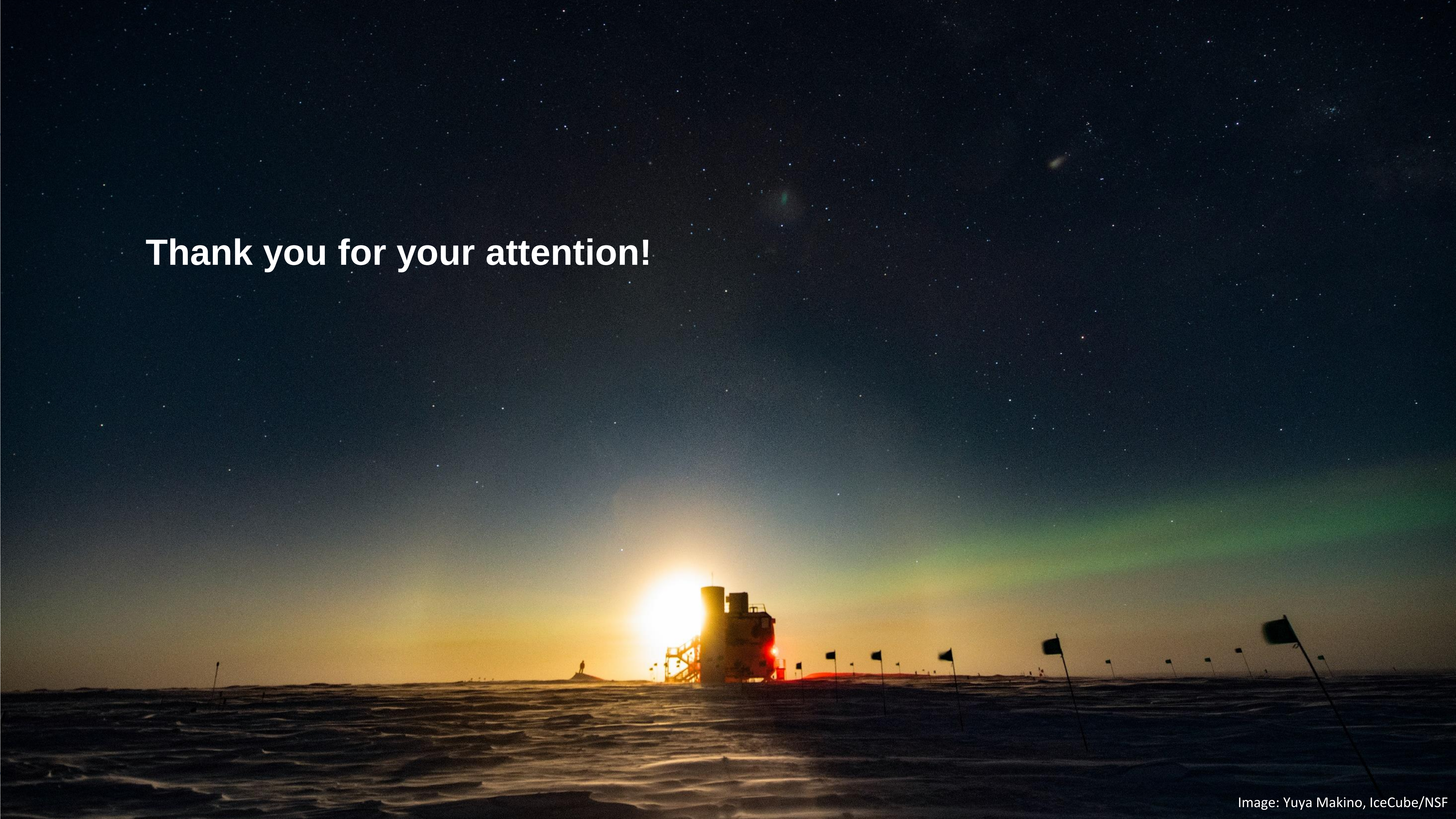
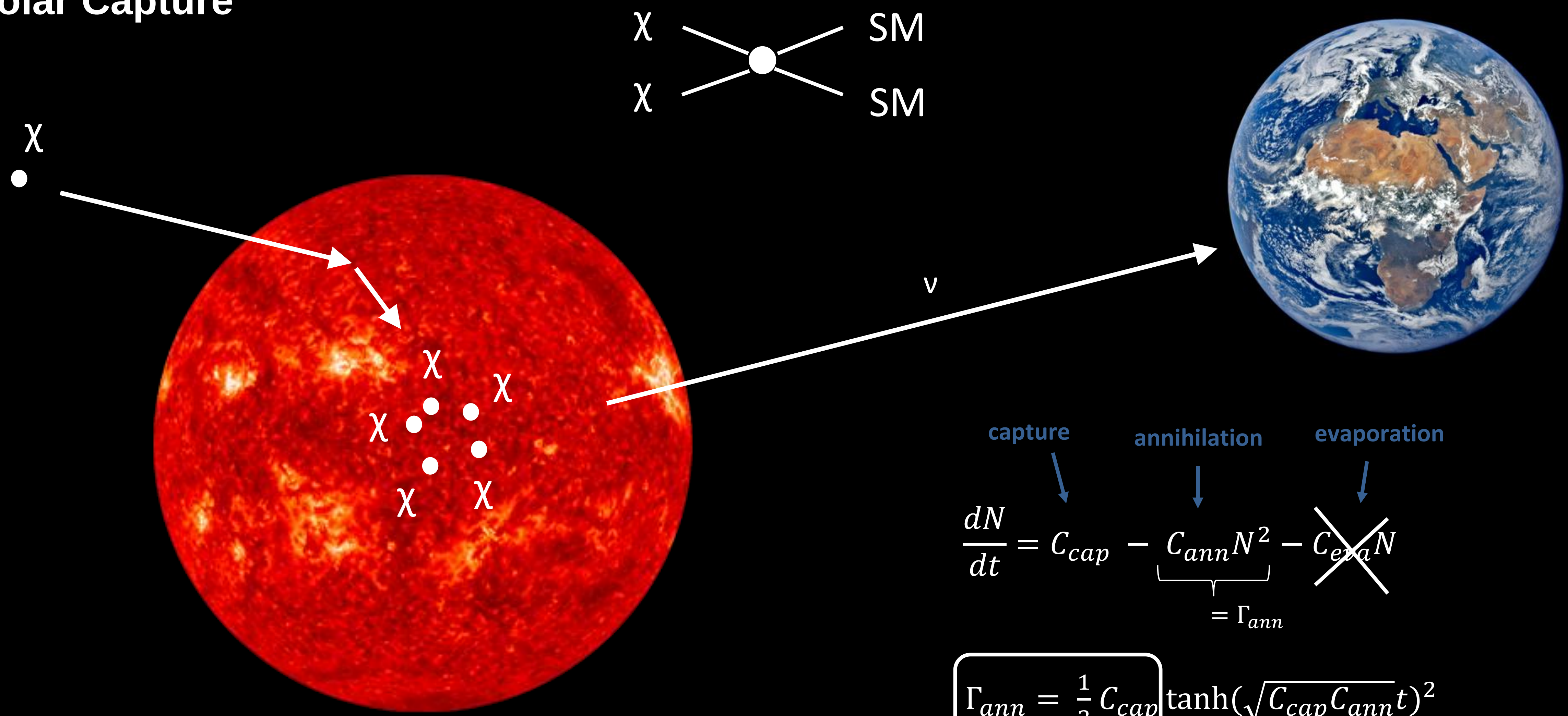


Image: Yuya Makino, IceCube/NSF

Solar Capture



capture annihilation evaporation

$$\frac{dN}{dt} = C_{cap} - \underbrace{C_{ann}N^2}_{=\Gamma_{ann}} - \cancel{C_{eva}N}$$

$$\boxed{\Gamma_{ann} = \frac{1}{2}C_{cap}}\underbrace{\tanh\left(\sqrt{C_{cap}C_{ann}}\,t\right)^2}_{=1 \text{ for } t \gg 1/\sqrt{C_{cap}C_{ann}}}$$

DM Response Functions

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$$R_M^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(\frac{q^2}{m_N^2} v_T^{\perp 2} c_5^\tau c_5^{\tau'} + v_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{q^2}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right) \tag{4.3}$$

$$R_{\Phi''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{q^2}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right) \cdot \left(c_{12}^{\tau'} - \frac{q^2}{m_N^2} c_{15}^{\tau'}\right) \tag{4.4}$$

$$R_{\tilde{\Phi}'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau c_{12}^{\tau'} + \frac{q^2}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right) \tag{4.5}$$

$$R_{\Sigma''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{q^2}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{q^2}{m_N^2}\left(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}\right) + \frac{q^4}{m_N^4} c_6^\tau c_6^{\tau'} + v_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{q^2}{m_N^2} v_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right] \tag{4.6}$$

$$R_{\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{1}{8}\left(\frac{q^2}{m_N^2} v_T^{\perp 2} c_3^\tau c_3^{\tau'} + v_T^{\perp 2} c_7^\tau c_7^{\tau'}\right) + \frac{j_\chi(j_\chi+1)}{12} \cdot \left[c_4^\tau c_4^{\tau'} + \frac{q^2}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{v_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right) \cdot \left(c_{12}^{\tau'} - \frac{q^2}{m_N^2} c_{15}^{\tau'}\right) + \frac{q^2}{2m_N^2} v_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right] \tag{4.7}$$

$$R_{\Delta}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{3}\left(\frac{q^2}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right). \tag{4.8}$$

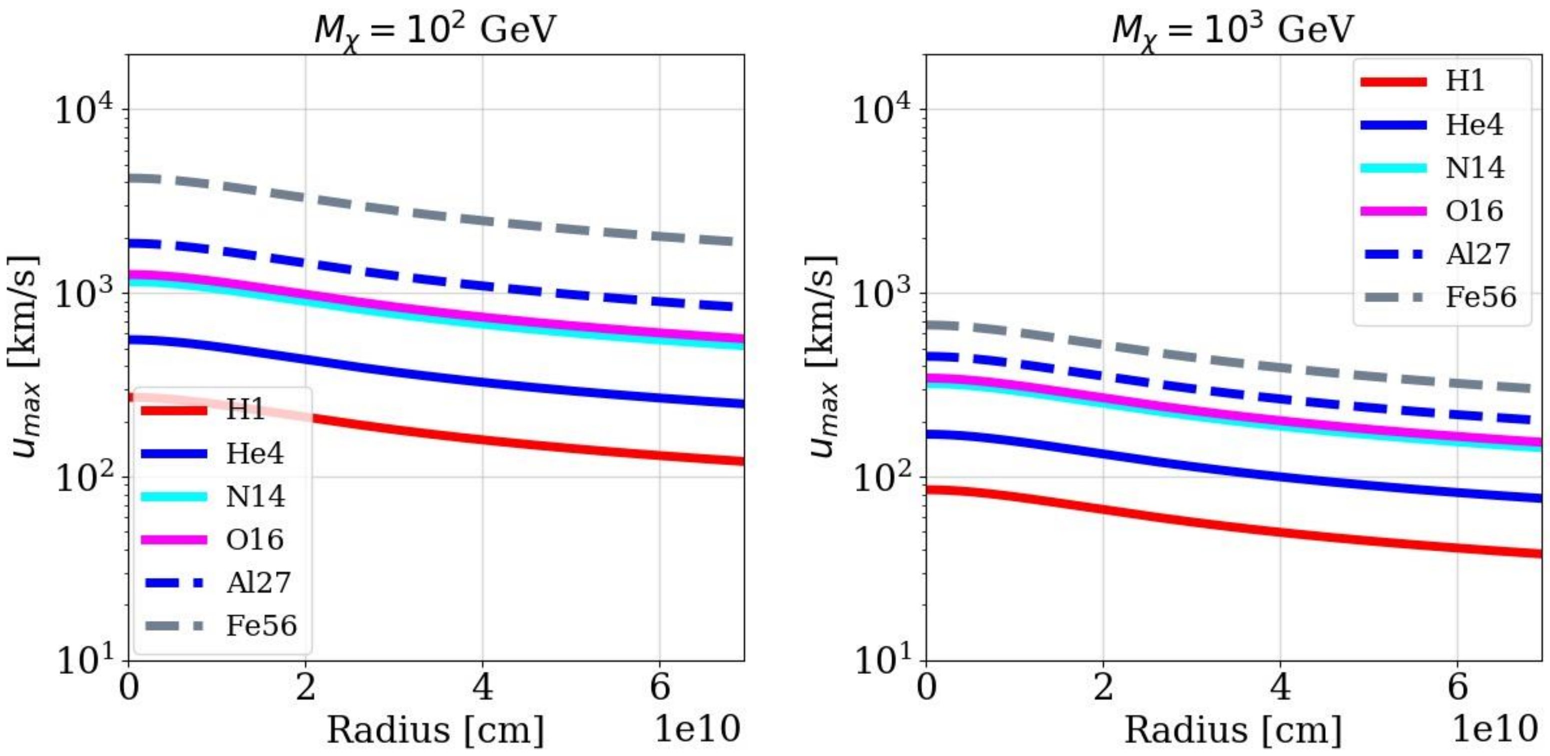
Capture Rate Calculation

$$C_{cap}^{T} = n_\chi \int_0^{R_\odot} dr\, 4\pi r^2 n_T(r) \int_0^\infty du\, 4\pi u^2 f_\odot(u) \frac{u^2 + v_\odot^{esc}(r)^2}{u} \cdot \int_{E_{min}}^{E_{max}} dE_R \frac{d\sigma_T}{dE_R} \boxed{\theta(\Delta E)}$$

$$\boxed{E_{min} = \frac{1}{2} M_\chi u^2 , \qquad E_{max} = \frac{2\mu_T^2}{m_T}\left(u^2 + v_\odot^{esc}(r)^2\right) , \qquad \Delta E = E_{max} - E_{min}}$$

→ Integration over u has effectively an **upper bound** u_{max} where $E_{min} = E_{max}$
→ u_{max} is **smaller** for **heavier** dark matter masses and **lighter** target elements

Capture Rate Calculation



→ Integration over u has effectively an **upper bound** u_{max} where $E_{min} = E_{max}$

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Capture Rates

spin ½ isoscalar

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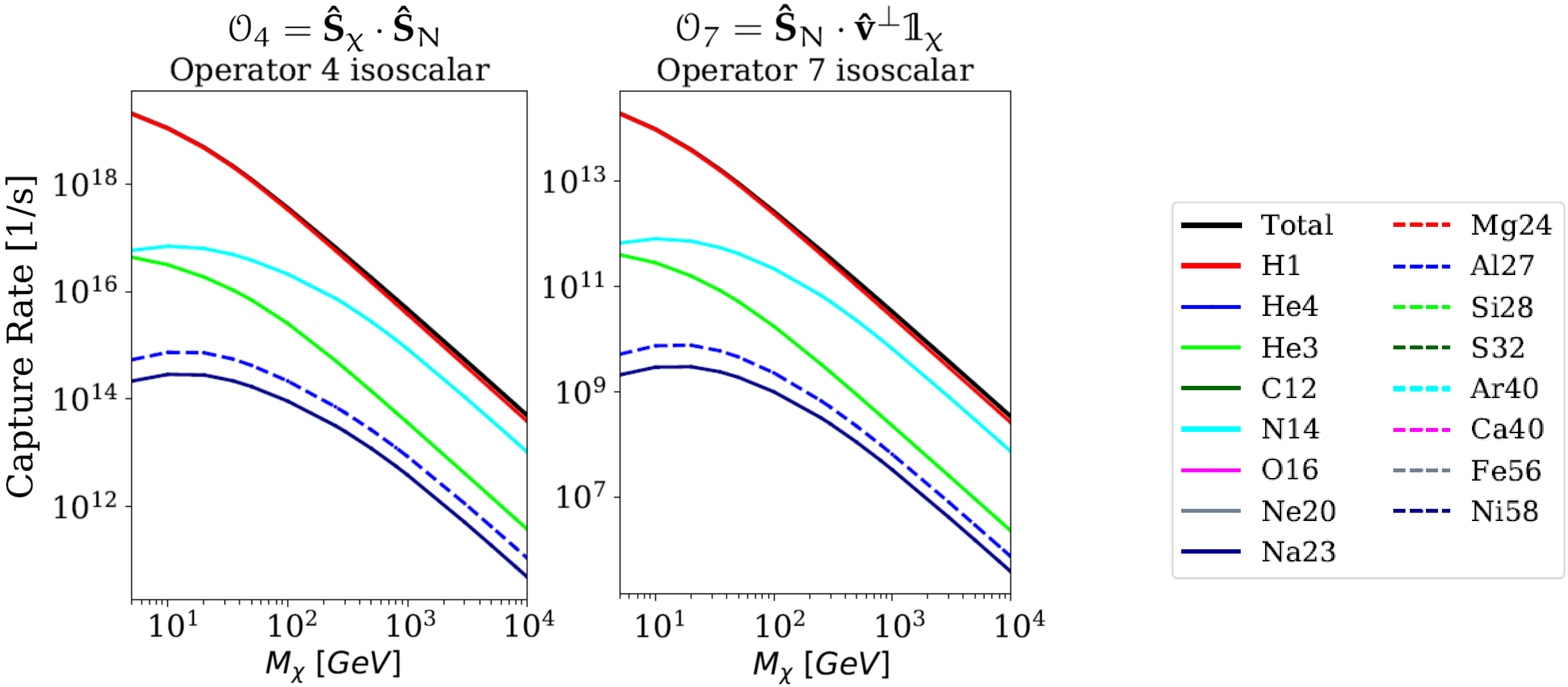

- Two **hydrogen** dominated operators
- They contain the **spin dependent** nuclear response operators **Σ‘** and **Σ“**
- Capture rate generated by operator 7 is smaller due to **velocity suppression**

Capture Rates

spin ½ isoscalar

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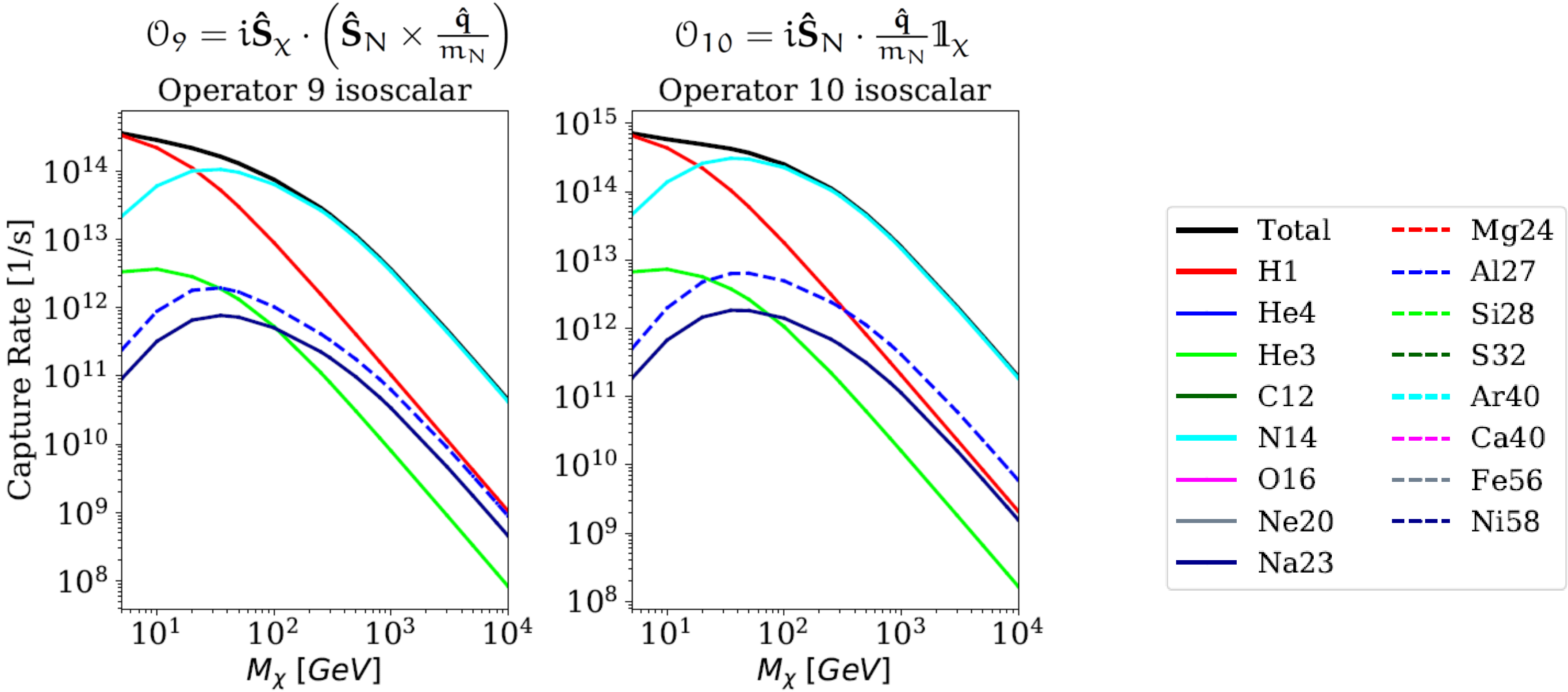

- Operator 6, 9, 10, 13 and 14 also contain only **Σ'** and **Σ''**
- Depend on **momentum transfer** → suppression of lighter elements
- In addition to the suppression of lighter elements due to a lower maximum accessible velocity u_{max} this leads to a **domination of nitrogen** at large DM masses

Capture Rates

spin ½ isoscalar

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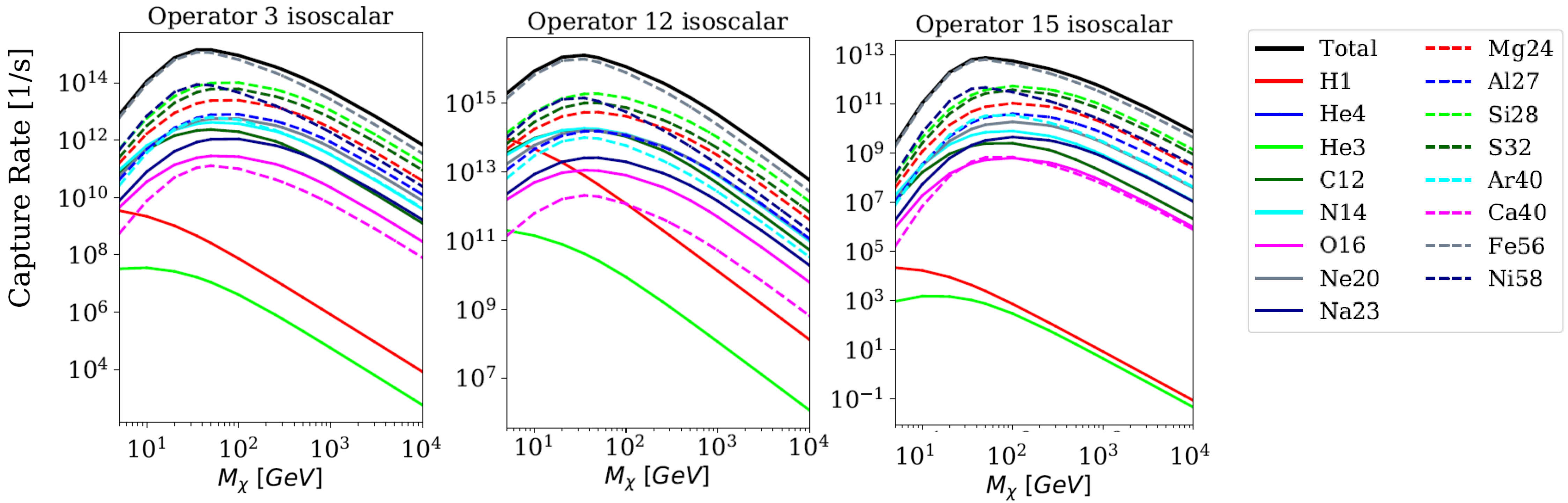
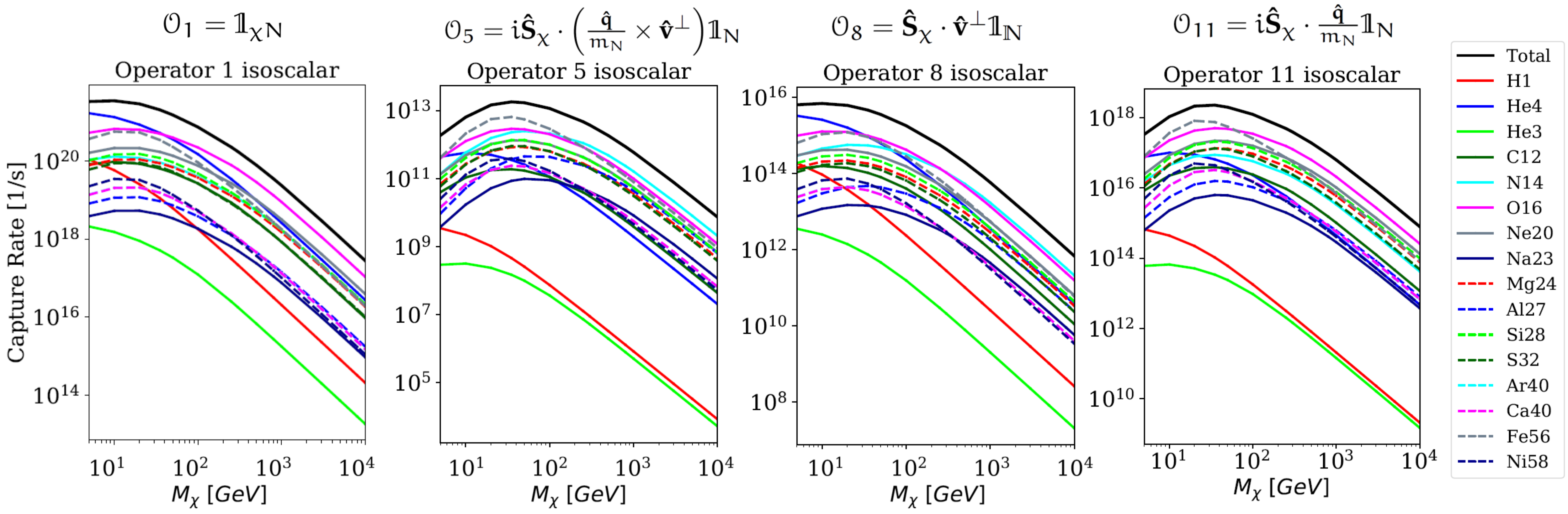
$$\mathcal{O}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^{\perp}\right)\mathbb{1}_\chi \qquad \mathcal{O}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^{\perp}\right) \qquad \mathcal{O}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^{\perp}\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$



- **Iron** dominated operators
- Dominant response **Φ''** that favors **heavy elements** with orbits of **large angular momentum**

Capture Rates

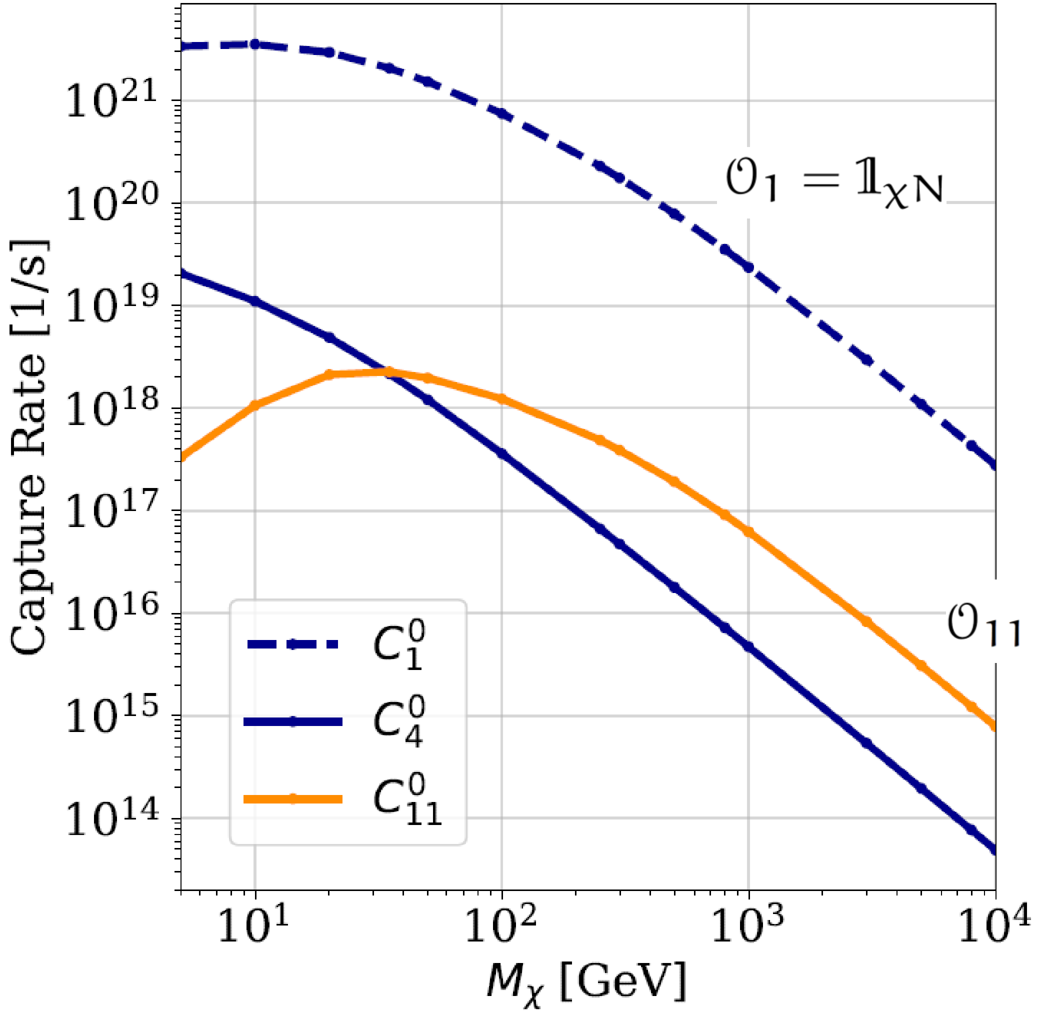
spin ½ isoscalar



- The standard SI response **M** favors heavy elements
- For Operator 5 and 8 additionally **Δ** contributes (→ Nitrogen)

Capture Rates

spin ½ isoscalar



$$\mathcal{O}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\mathbb{1}_N$$

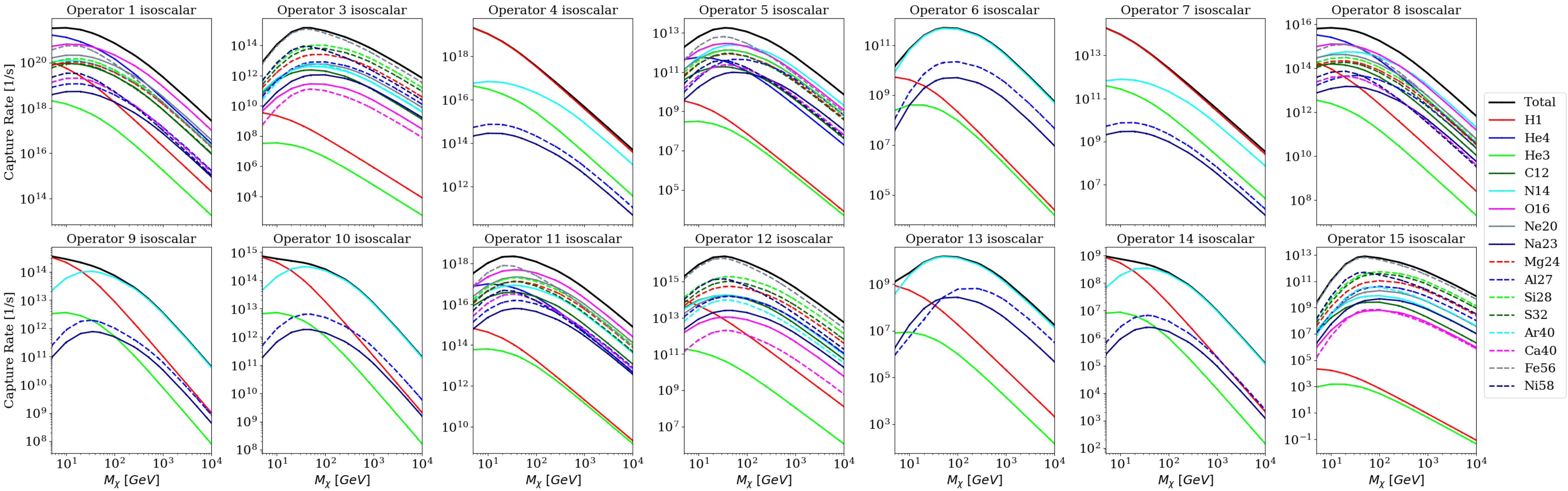
$$\mathcal{O}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

- Operator 1 and 4 are the ‚standard' SI and SD interactions
- Operator 11 generates a **larger capture rate** for DM masses > 35 GeV for isoscalar couplings

→ Should be **included** in ‚standard analyses'

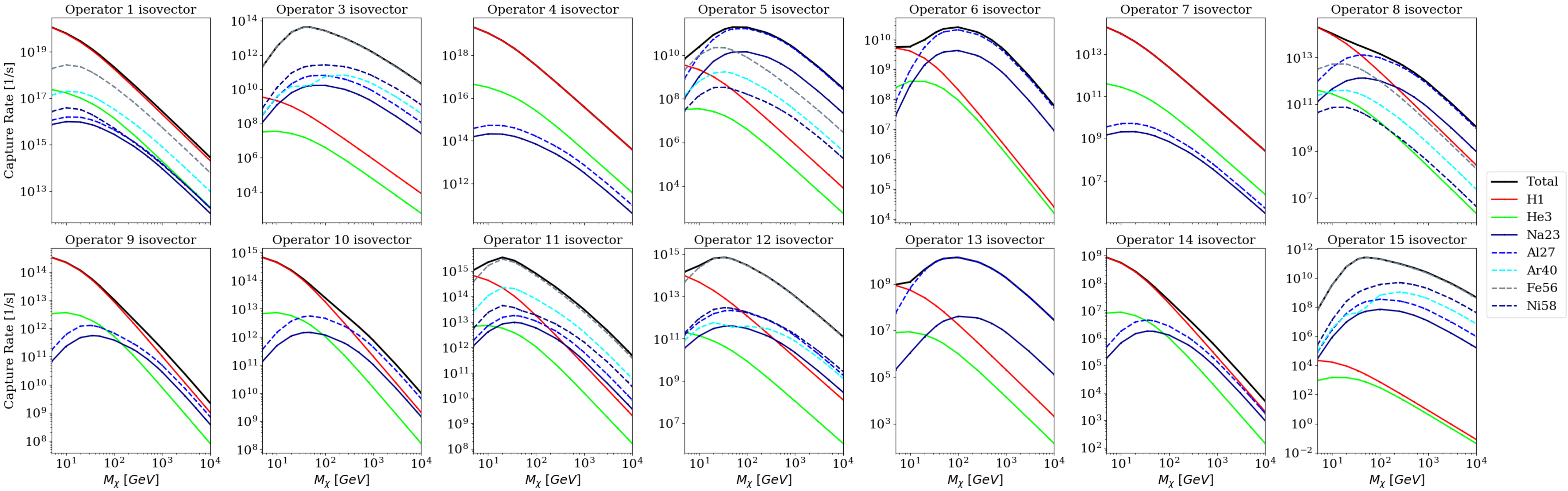
Capture Rates

spin ½ isoscalar



Capture Rates

spin ½ isovector



Capture Rates

spin 1 isoscalar

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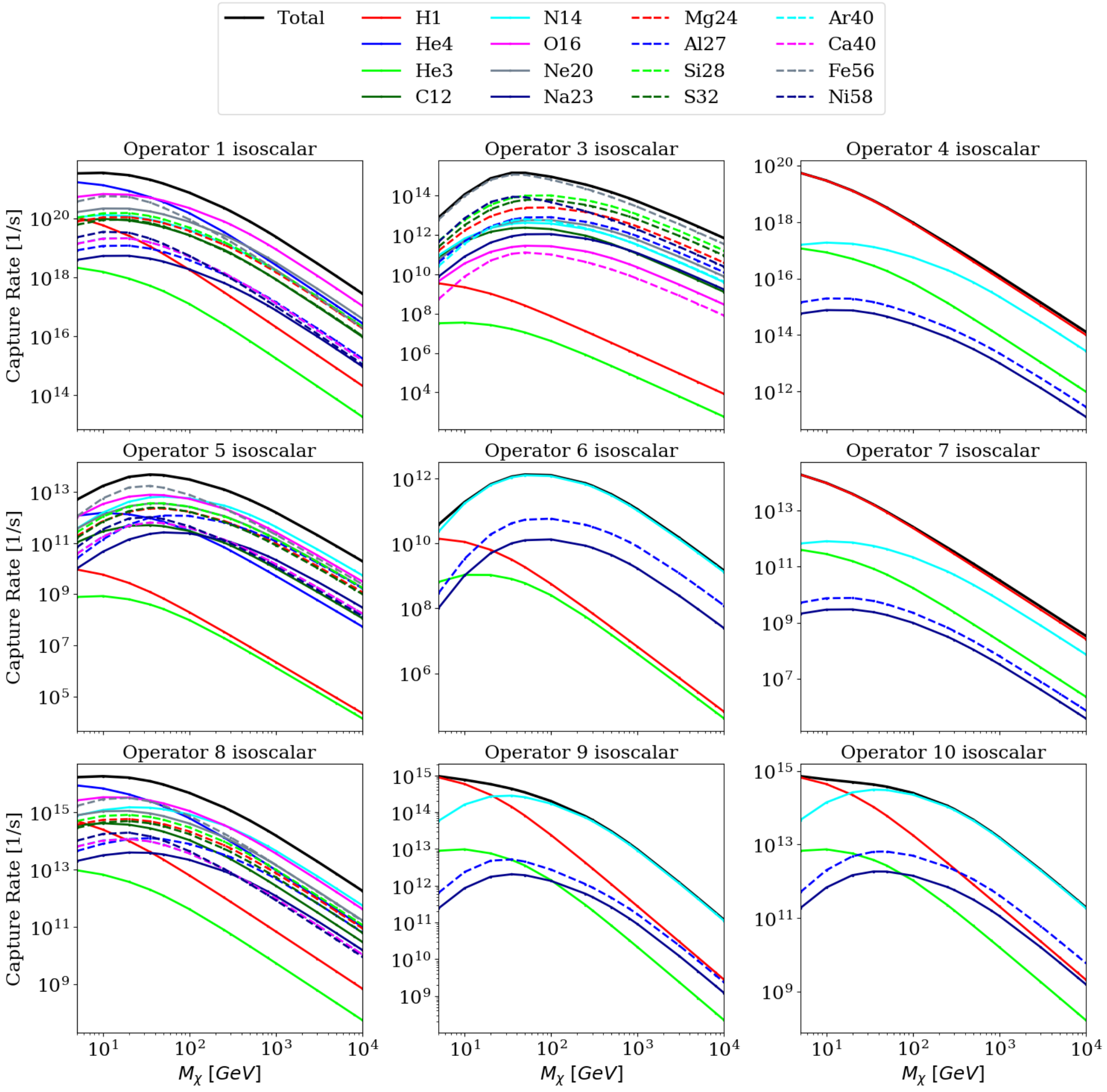
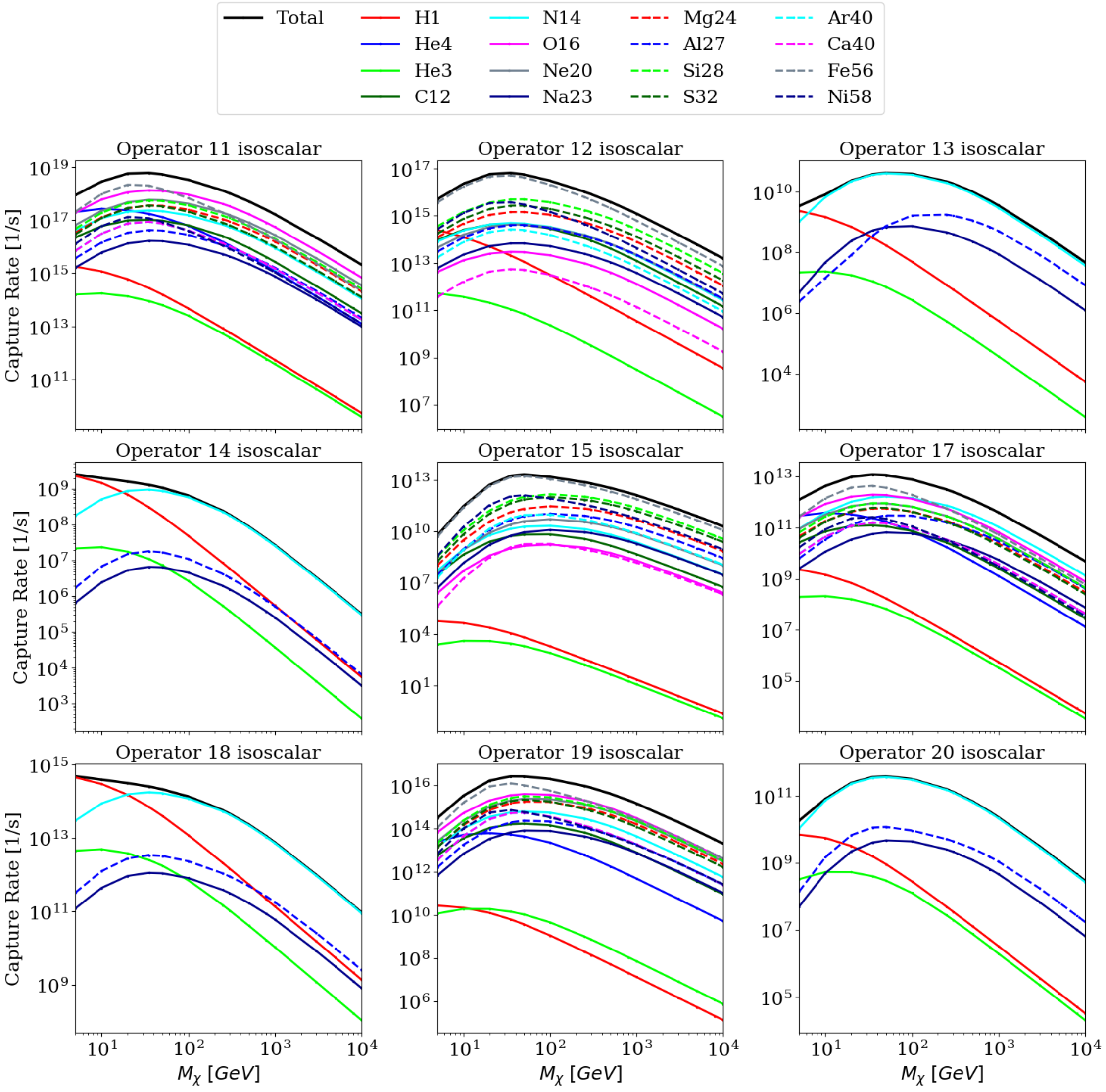
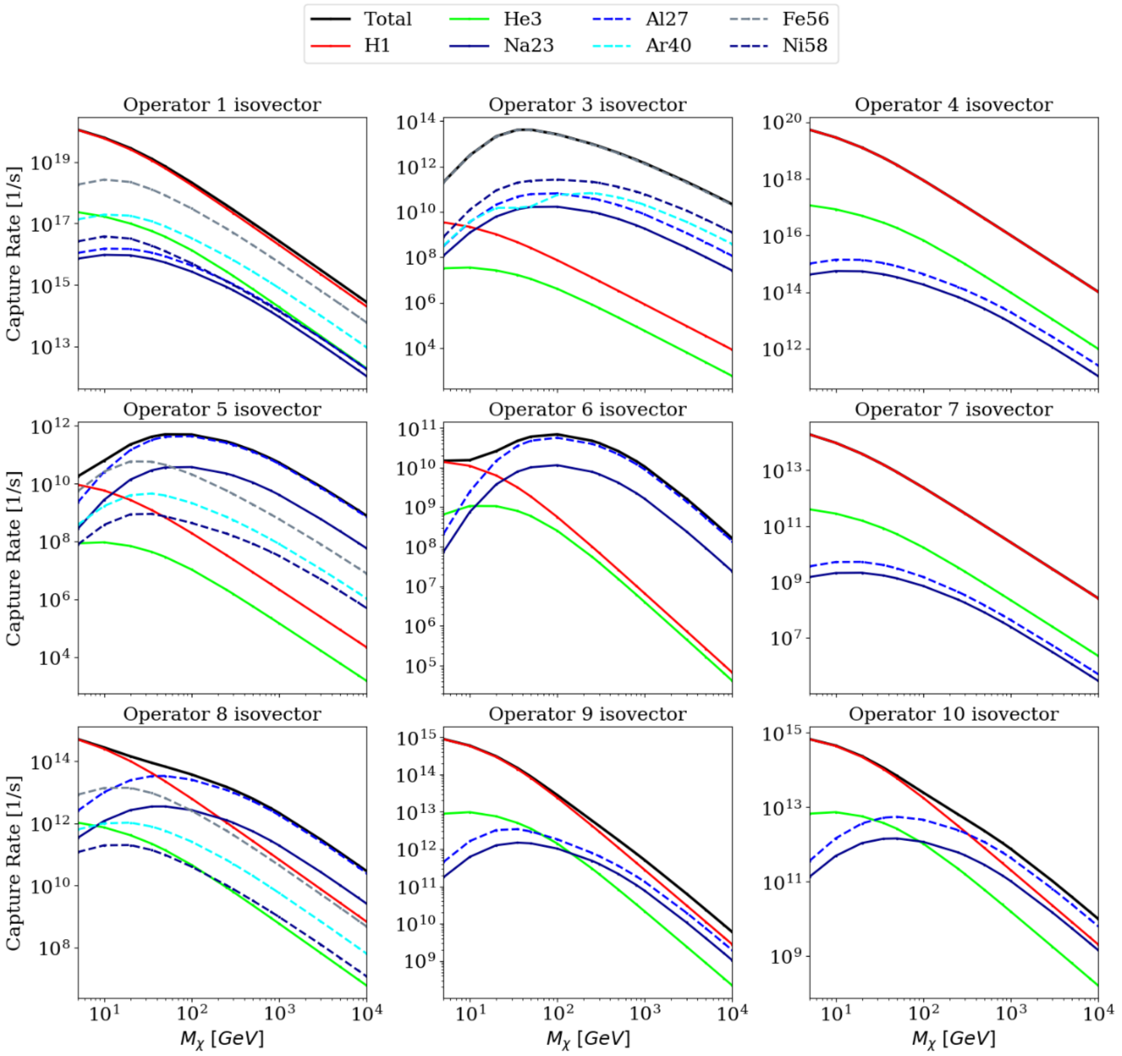
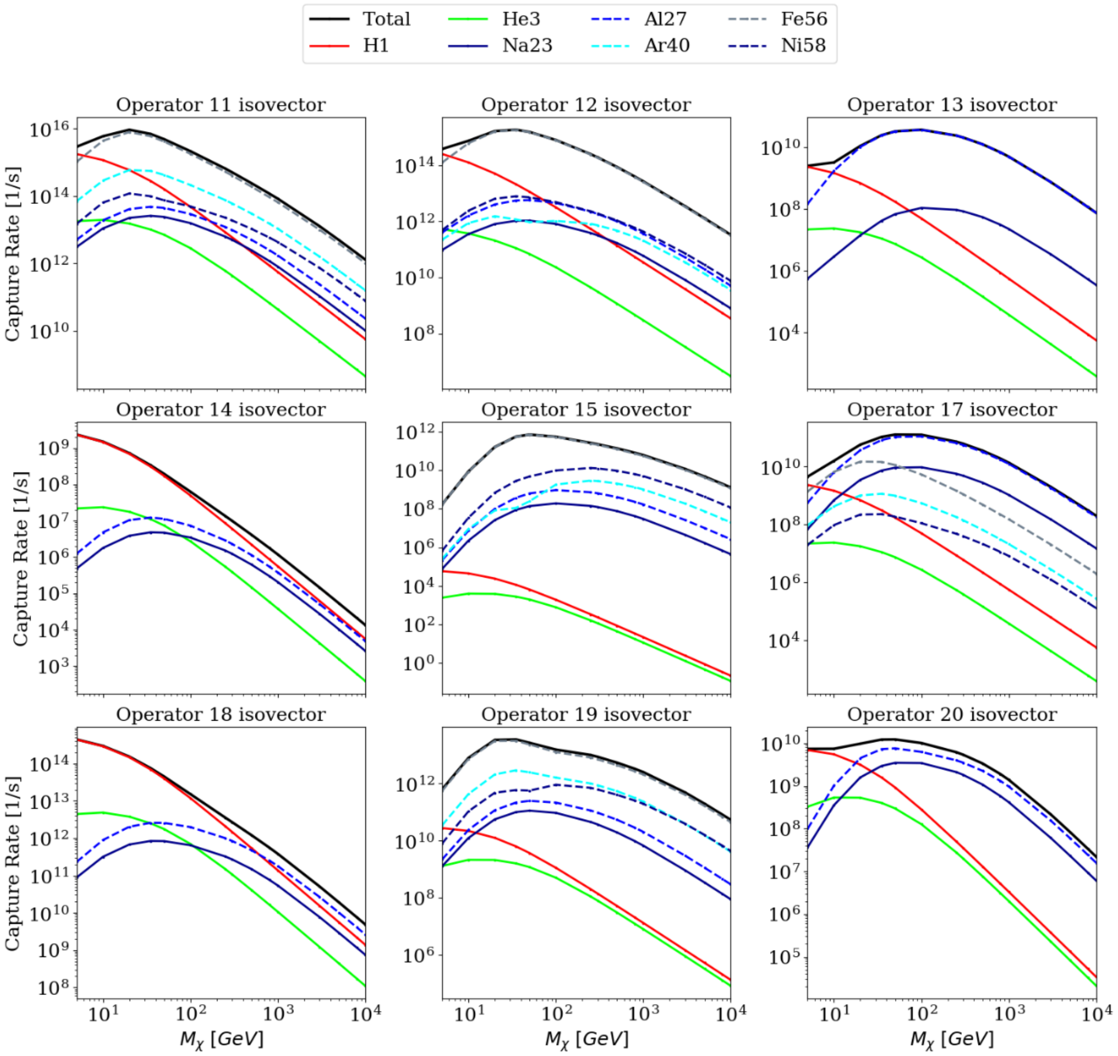




Capture Rates

spin 1 isovector





Systematics – Solar Model

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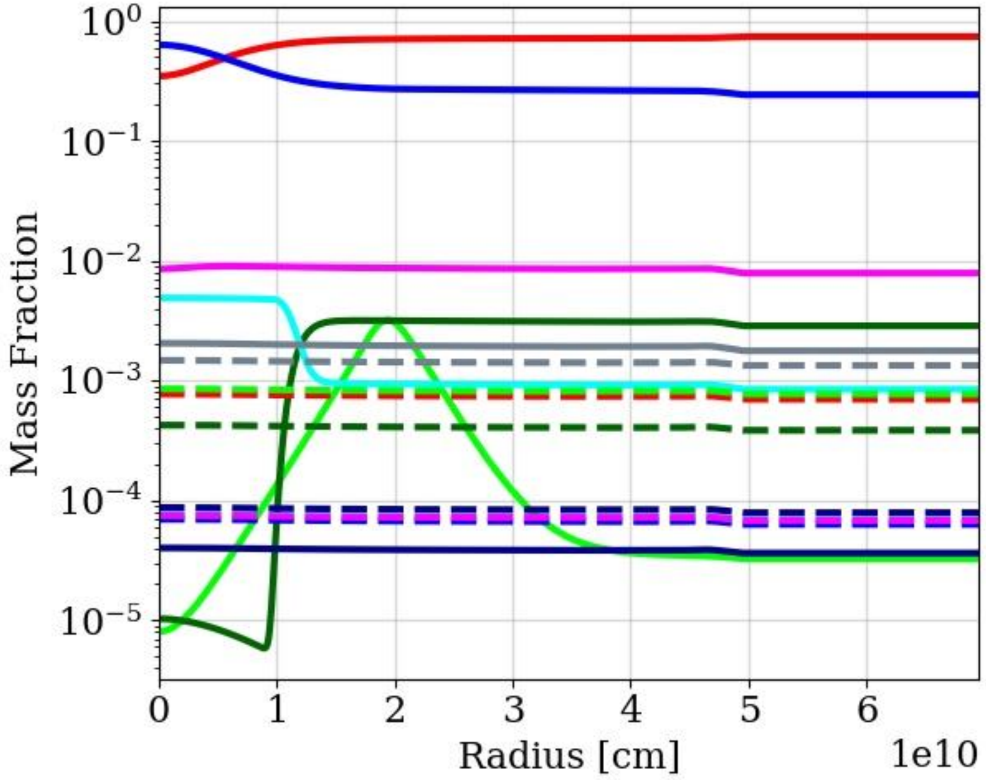
B16 GS98



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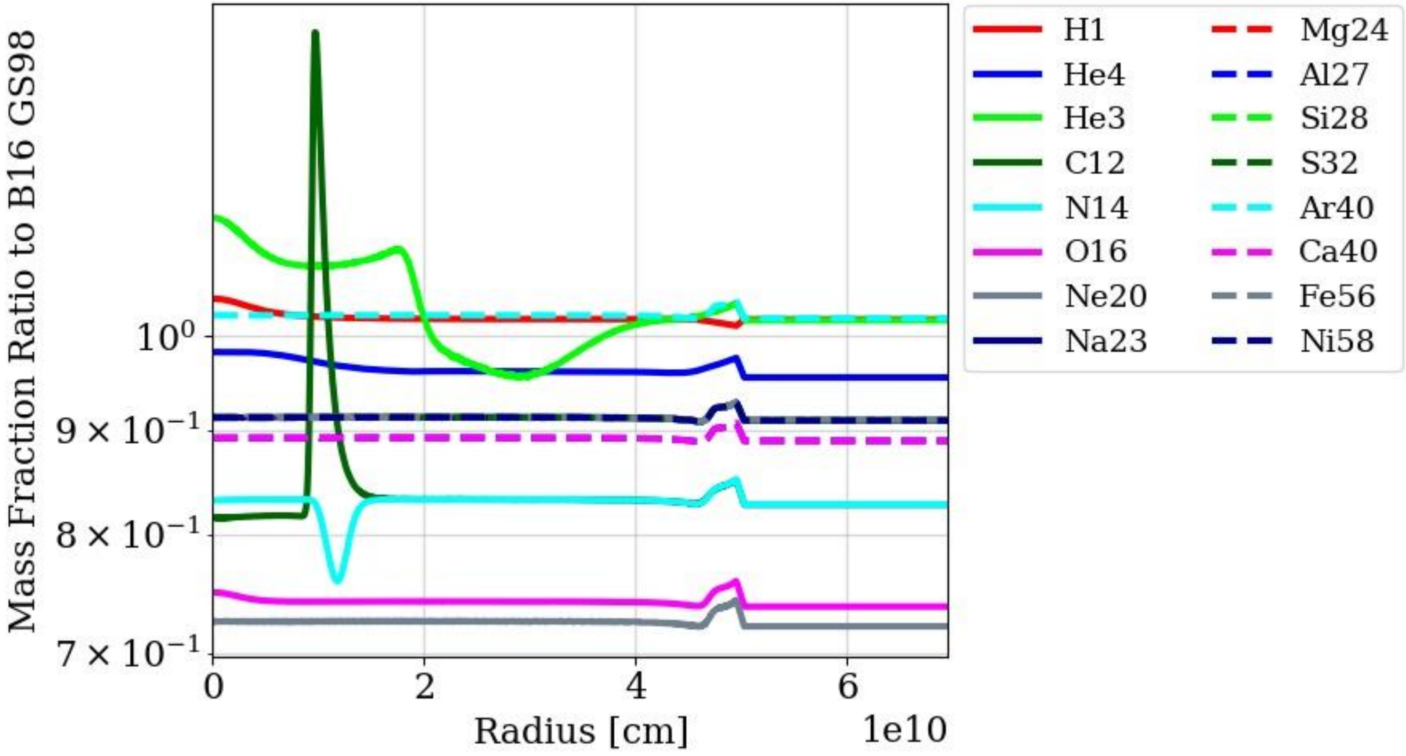
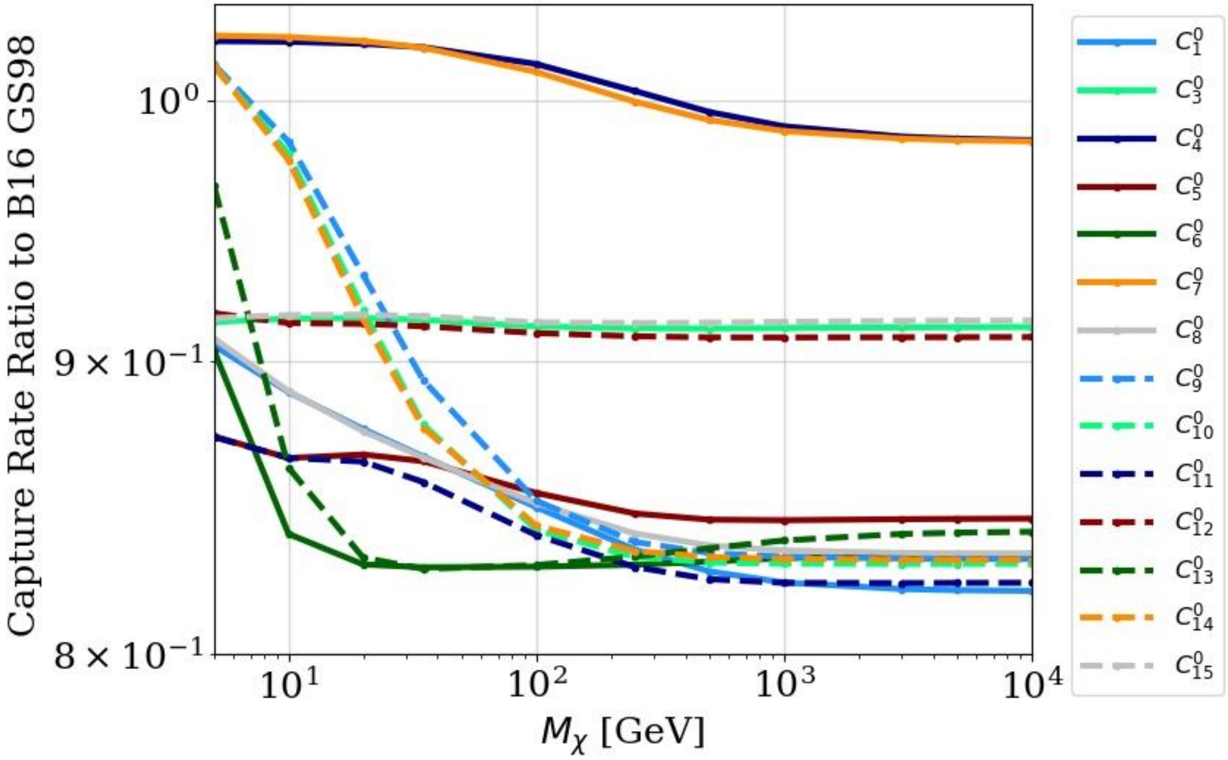


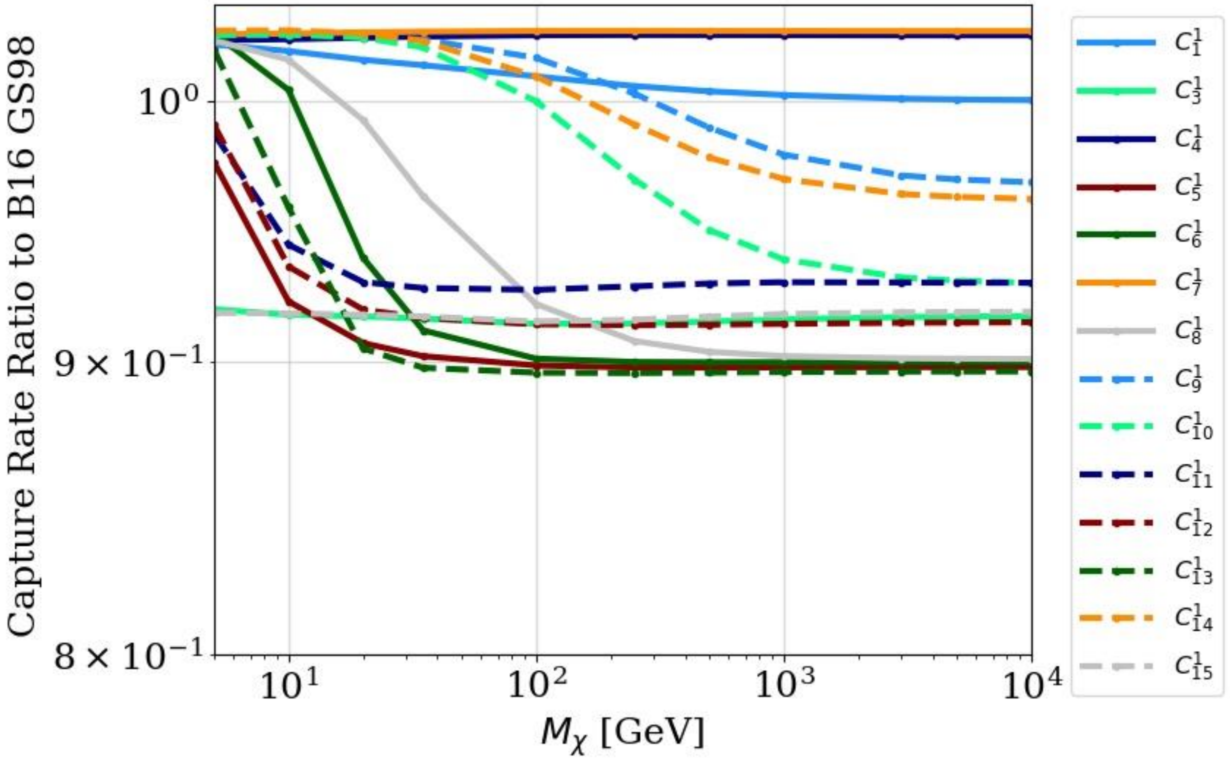
Systematics – Solar Model

spin ½

B16 AGSS09 - isoscalar



B16 AGSS09 - isovector



→ Hydrogen dominated O4 and O7 least affected
→ Largest effect for O16 dominated interaction types (up to 18%)
→ Less deviation for isovector interactions because N14 and O16 do not contribute

Systematics – Velocity Distribution

spin ½ isoscalar

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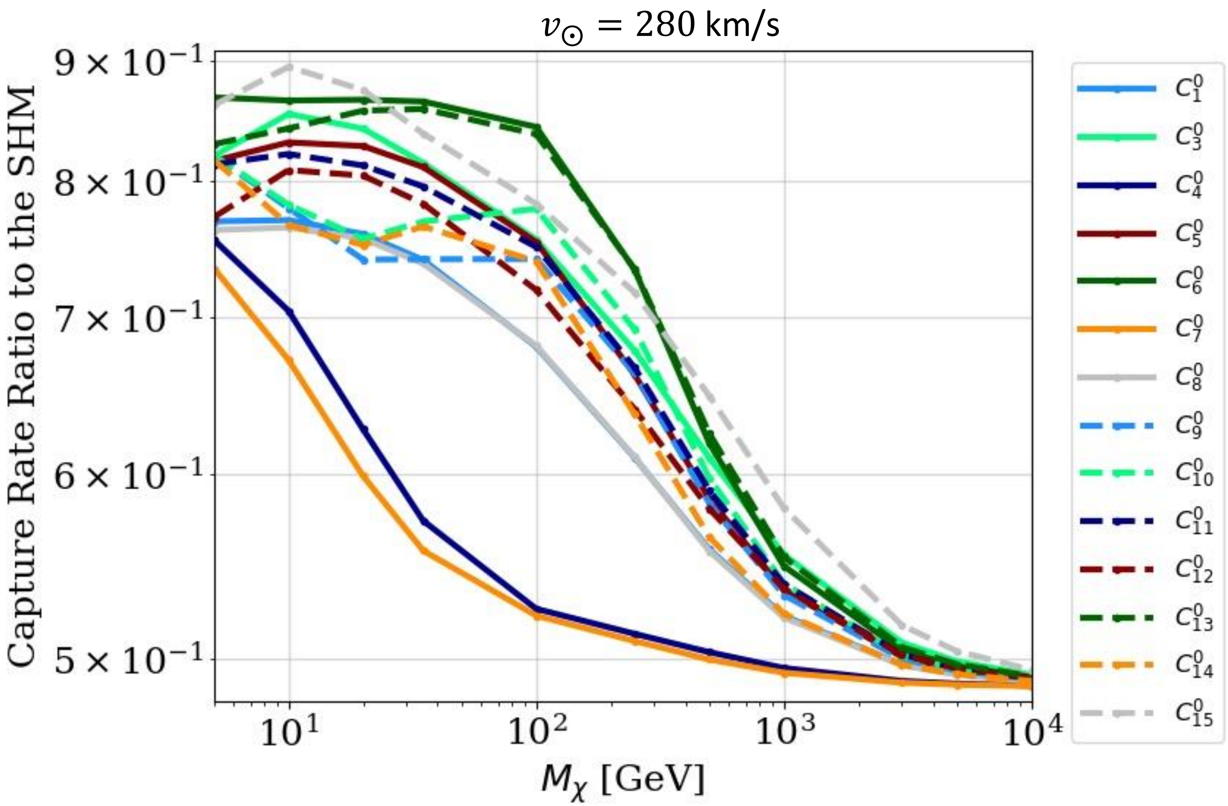
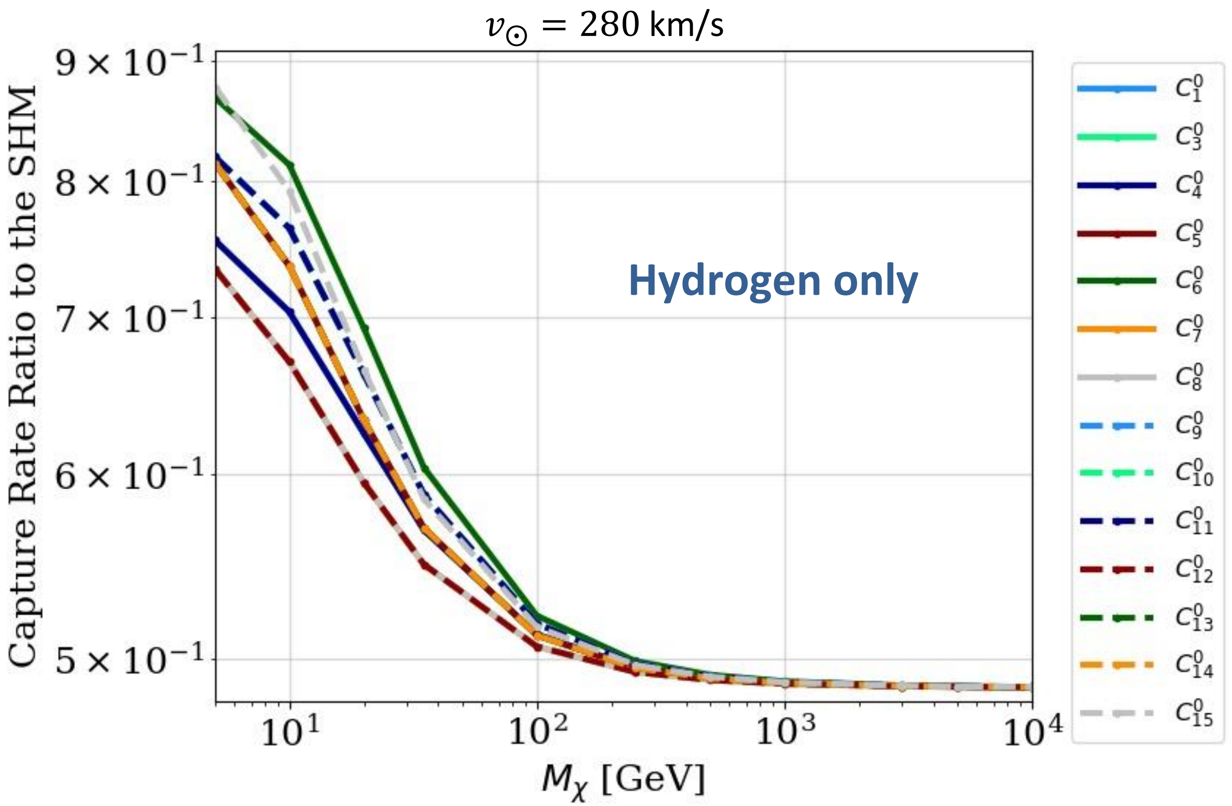




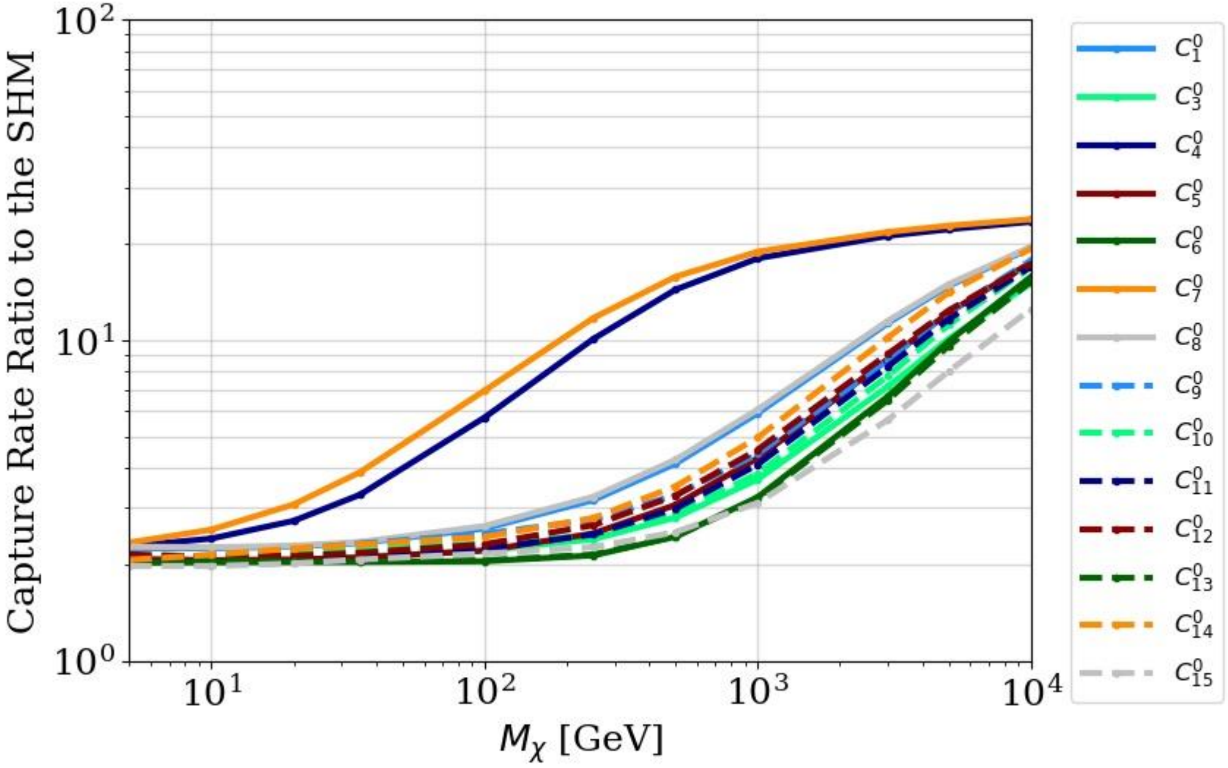
→ Velocity and momentum dependence in operators is **subdominant**

→ Capture rate is **less sensitive** to changes in the velocity distribution with **increasing** order of **q** and **decreasing** order of **v**

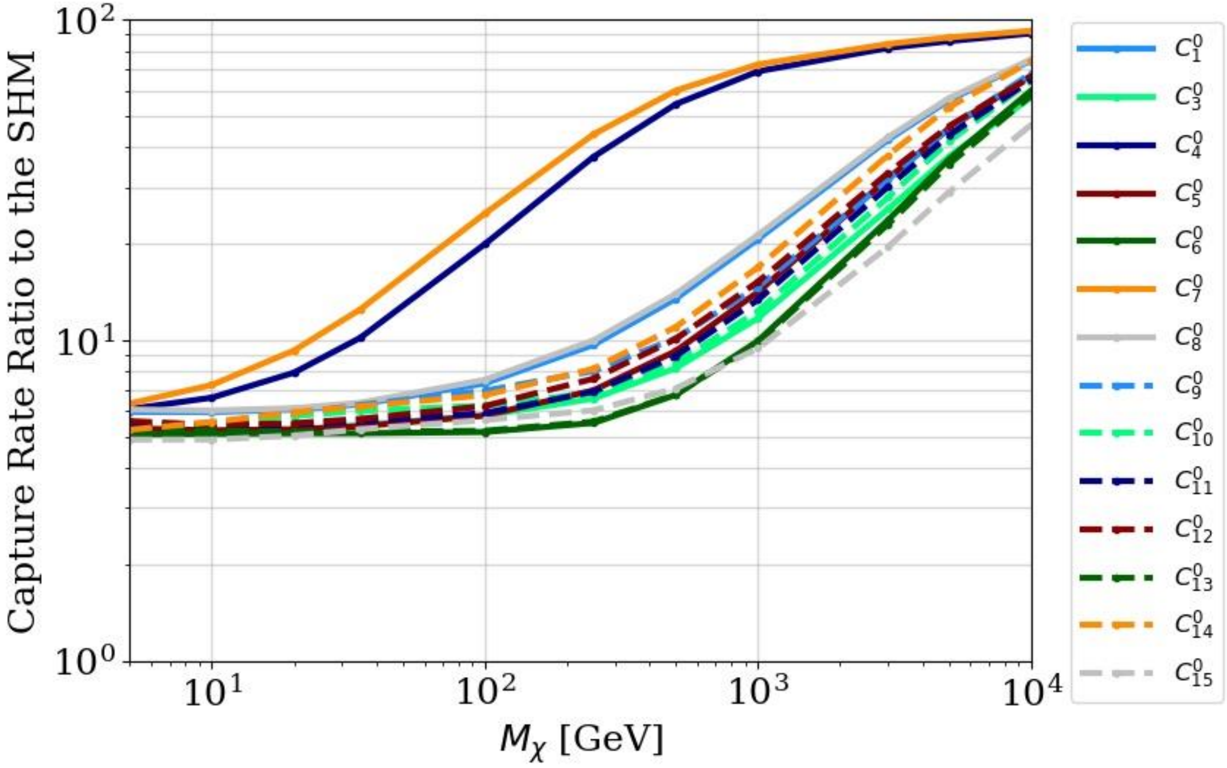
Systematics – Dark Disk

spin ½ isoscalar

$\rho_{dd}/\rho_h = 0.25$



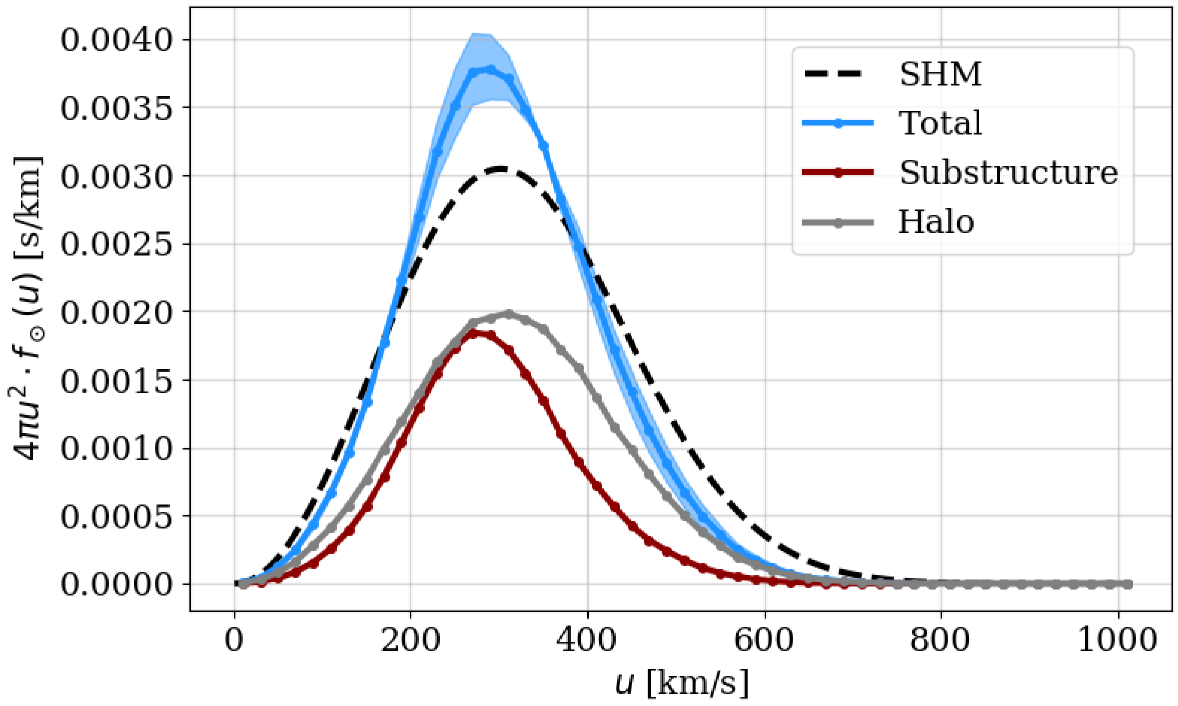
$\rho_{dd}/\rho_h = 1$

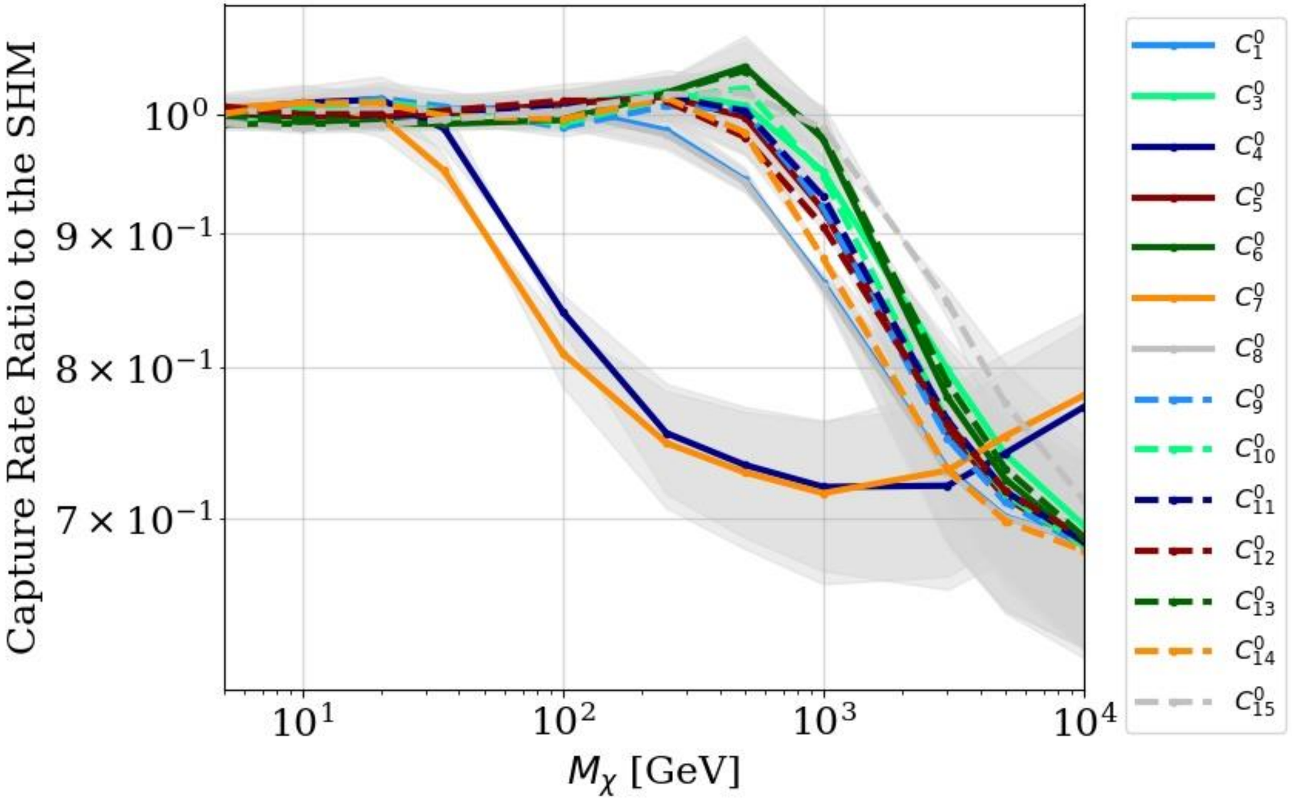


Systematics – Gaia Sausage

spin ½ isoscalar

Necib et al





$$f(u) = (1 - \eta_{sub}) f_{halo}(u) + \eta_{sub} f_{sub}(u).$$

Limits

spin ½ isovector