Constraining Non-Standard Dark Matter - Nucleon Interactions

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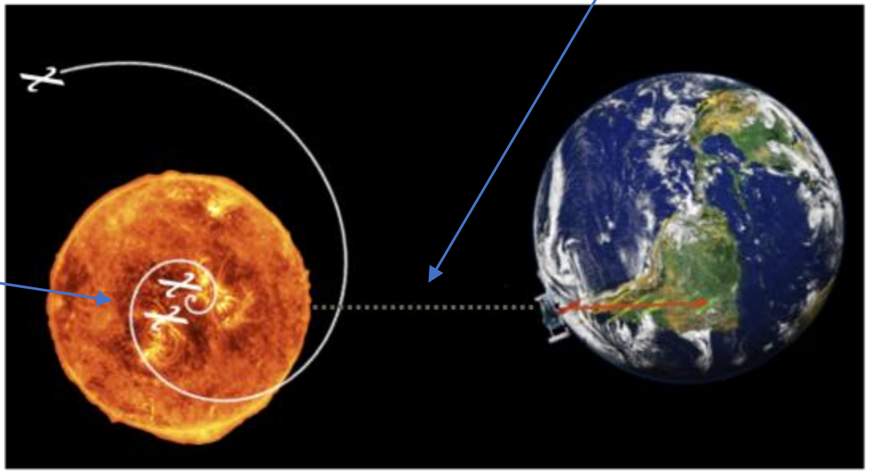
Dark Matter and Solar Capture

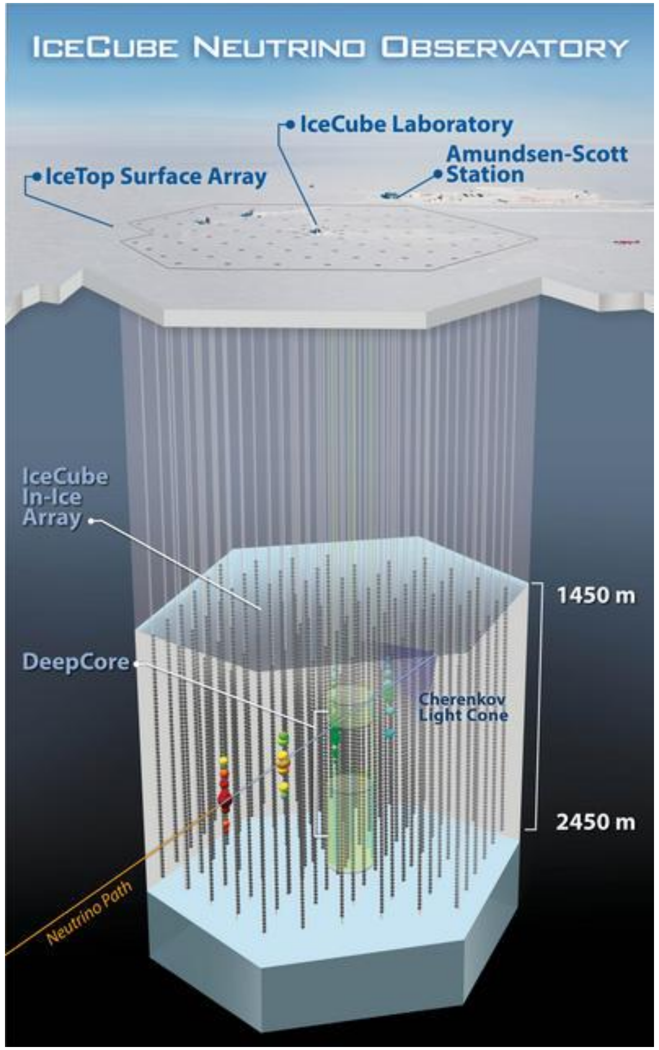
- Compelling observational evidence for dark matter (DM), but its nature remains unknown
- A variety of theories provide candidate particles



Neutrinos from DM annihilation

DM scattering off nuclei and accumulating in the Sun

- DM particles can be gravitationally **captured** by the Sun and can **annihilate** into SM particles
- **Neutrinos** originating from these annihilations can be detected by **IceCube**



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New Solar DM Search in IceCube

Likelihood analysis fitting for the number of signal neutrinos n_s produced as a result of DM annihilation in the Sun

$$\mathcal{L}(n_s) = \prod_{i=0}^{N} \frac{n_s}{N}\mathcal{S}(\psi_i) + (1 - \frac{n_s}{N})\mathcal{B}(\psi_i)$$

Publication under preparation

- WIMP masses: 5, 10, 20, 35, 50, 100, 300, 500 GeV
- Annihilation channels: $b\bar{b}, \tau\bar{\tau}, \nu\bar{\nu}$

- Seven years of IceCube DeepCore data

- Background pdf is generated by scrambling the data in azimuth
- Signal pdf uses weighted DM spectra obtained from WIMPSIM

No significant excess of neutrinos observed from the Sun, so upper limits on annihilation rate and spin-dependent cross section are placed.

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Publication under preparation

- WIMP masses: 5, 10, 2
- Annihilation channels:
- Seven years of IceCub

Usual assumption:
Spin-dependent (SD) and spin-independent (SI) interaction terms give leading order contribution

- Background pdf is generated by scrambling the data in azimuth
- Signal pdf uses weighted DM spectra obtained from WIMPSIM

No significant excess of neutrinos observed from the Sun, so upper limits on annihilation rate and spin-dependent cross section are placed.

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Effective Theory

- **Motivation:** standard SD and SI interactions can be suppressed or forbidden; non-standard interactions have driven theoretical research in DM direct detection in the past few years
- **Goal:** place limits on the coupling constants of the non-relativistic effective theory of dark matter- nucleon interactions

SI

$$\mathcal{O}_1 = \mathbb{1}_X \mathbb{1}_N$$

$$\mathcal{O}_3 = i\boldsymbol{S}_N \cdot \left(\frac{\boldsymbol{q}}{m_N} \times \boldsymbol{v}^\perp\right) \mathbb{1}_X$$

SD

$$\mathcal{O}_4 = \boldsymbol{S}_X \cdot \boldsymbol{S}_N$$

$$\mathcal{O}_5 = i\boldsymbol{S}_X \cdot \left(\frac{\boldsymbol{q}}{m_N} \times \boldsymbol{v}^\perp\right) \mathbb{1}_N$$

$$\mathcal{O}_6 = \left(\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N}\right)\left(\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \boldsymbol{S}_N \cdot \boldsymbol{v}^\perp \mathbb{1}_X$$

$$\mathcal{O}_8 = \boldsymbol{S}_X \cdot \boldsymbol{v}^\perp \mathbb{1}_N$$

$$\mathcal{O}_9 = i\boldsymbol{S}_X \cdot \left(\boldsymbol{S}_N \times \frac{\boldsymbol{q}}{m_N}\right)$$

$$\mathcal{O}_{10} = i\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N} \mathbb{1}_X$$

$$\mathcal{O}_{11} = i\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N} \mathbb{1}_N$$

$$\mathcal{O}_{12} = \boldsymbol{S}_X \cdot \left(\boldsymbol{S}_N \times \boldsymbol{v}^\perp\right)$$

$$\mathcal{O}_{13} = i\left(\boldsymbol{S}_X \cdot \boldsymbol{v}^\perp\right)\left(\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N}\right)$$

$$\mathcal{O}_{14} = i\left(\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N}\right)\left(\boldsymbol{S}_N \cdot \boldsymbol{v}^\perp\right)$$

$$\mathcal{O}_{15} = -\left(\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N}\right)\left[\left(\boldsymbol{S}_N \times \boldsymbol{v}^\perp\right) \cdot \frac{\boldsymbol{q}}{m_N}\right]$$

$$\mathcal{O}_{17} = i\frac{\boldsymbol{q}}{m_N} \cdot \mathcal{\boldsymbol{S}} \cdot \boldsymbol{v}^\perp \mathbb{1}_N$$

$$\mathcal{O}_{18} = i\frac{\boldsymbol{q}}{m_N} \cdot \mathcal{\boldsymbol{S}} \cdot \boldsymbol{S}_N$$

$$\mathcal{O}_{19} = \frac{\boldsymbol{q}}{m_N} \cdot \mathcal{\boldsymbol{S}} \cdot \frac{\boldsymbol{q}}{m_N}$$

$$\mathcal{O}_{20} = \left(\boldsymbol{S}_N \times \frac{\boldsymbol{q}}{m_N}\right) \cdot \mathcal{\boldsymbol{S}} \cdot \frac{\boldsymbol{q}}{m_N}$$

- Go beyond standard SD/SI framework → include **velocity and momentum dependent interactions**
- Two coupling constants per operator (isoscalar/isovector) → include isospin violating interaction models

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Method

→ Capture rate is **proportional** to coupling constant squared: $C_{cap} \propto c^2$
→ Use this proportionality to **convert limits**

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

$$c_0 = 10^{-3} m_v^{-2}$$

$$m_v = 246.2 \text{ GeV}$$

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Method

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

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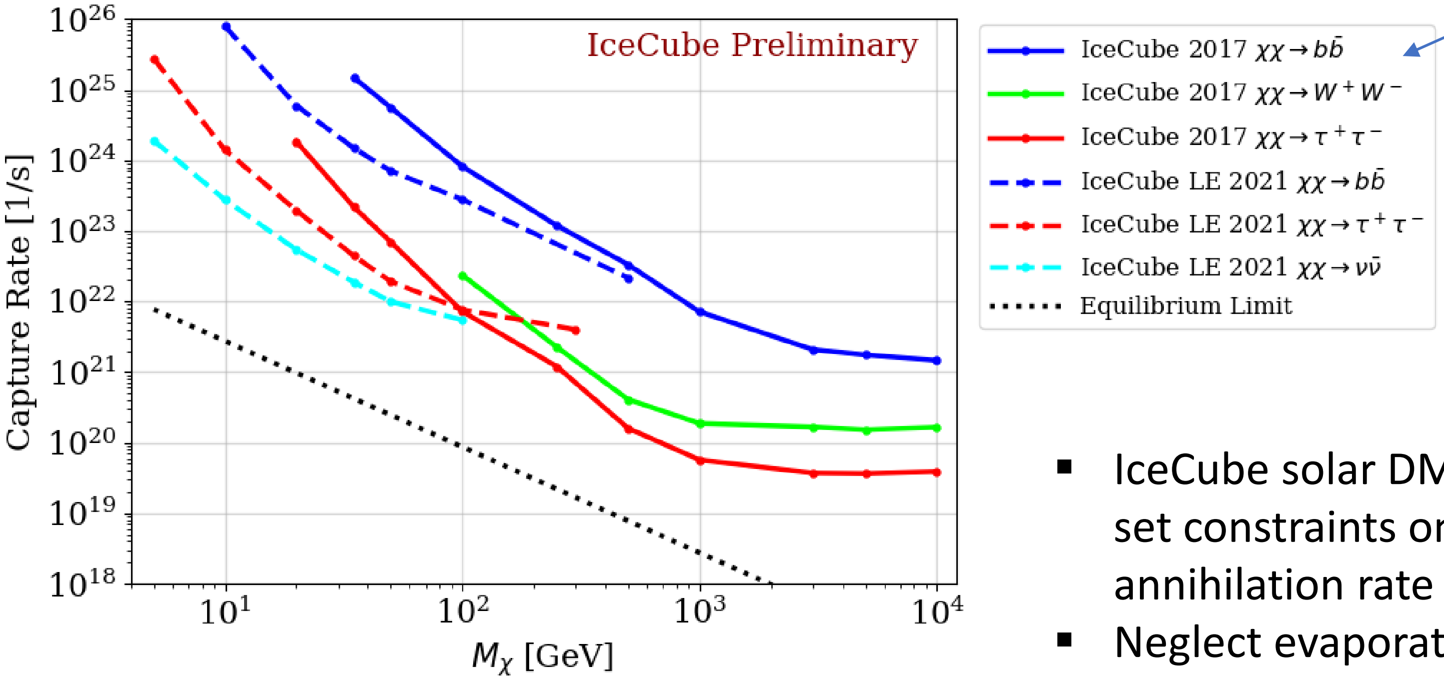
Results of two IceCube analyses



2017: three years of data

2021: seven years of data, IceCube DeepCore, not published yet

- IceCube solar DM searches set constraints on annihilation rate
- Neglect evaporation, assume equilibrium between capture and annihilation

Method

Results of two IceCube analyses

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

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

$$c_0 = 10^{-3} m_v^{-2}$$

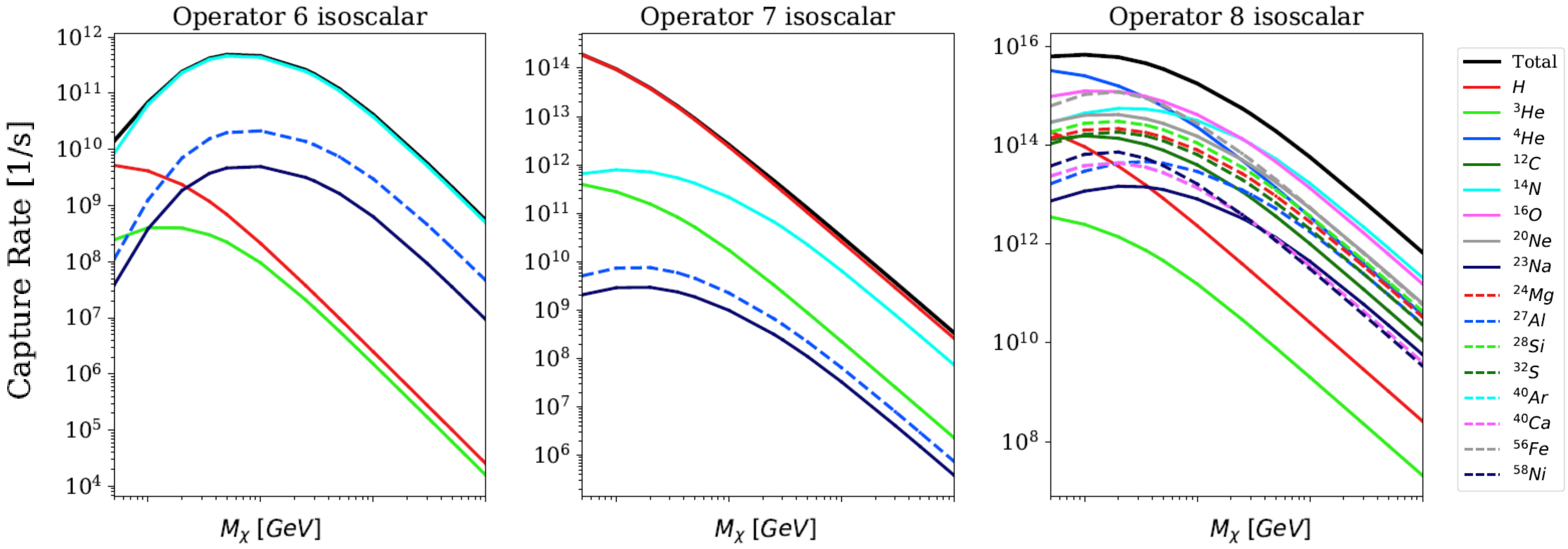
$$m_v = 246.2 \text{ GeV}$$

Differential cross section in EFT framework:

DM response functions

Nuclear response functions

$$\frac{d\sigma_{T\chi}(E_r,w^2)}{dE_r} = \alpha(v^2)\sum_{\tau,\tau',k}\left(\frac{q^2}{m_N^2}\right)^{\ell(k)} R_k^{\tau\tau'}\left(v_T^{\perp 2},\frac{q^2}{m_N^2}\right) W_k^{\tau\tau'}(q^2)$$



→ Most relevant elements can be H1, He4, N14, O16, Al27 or Fe56

Method

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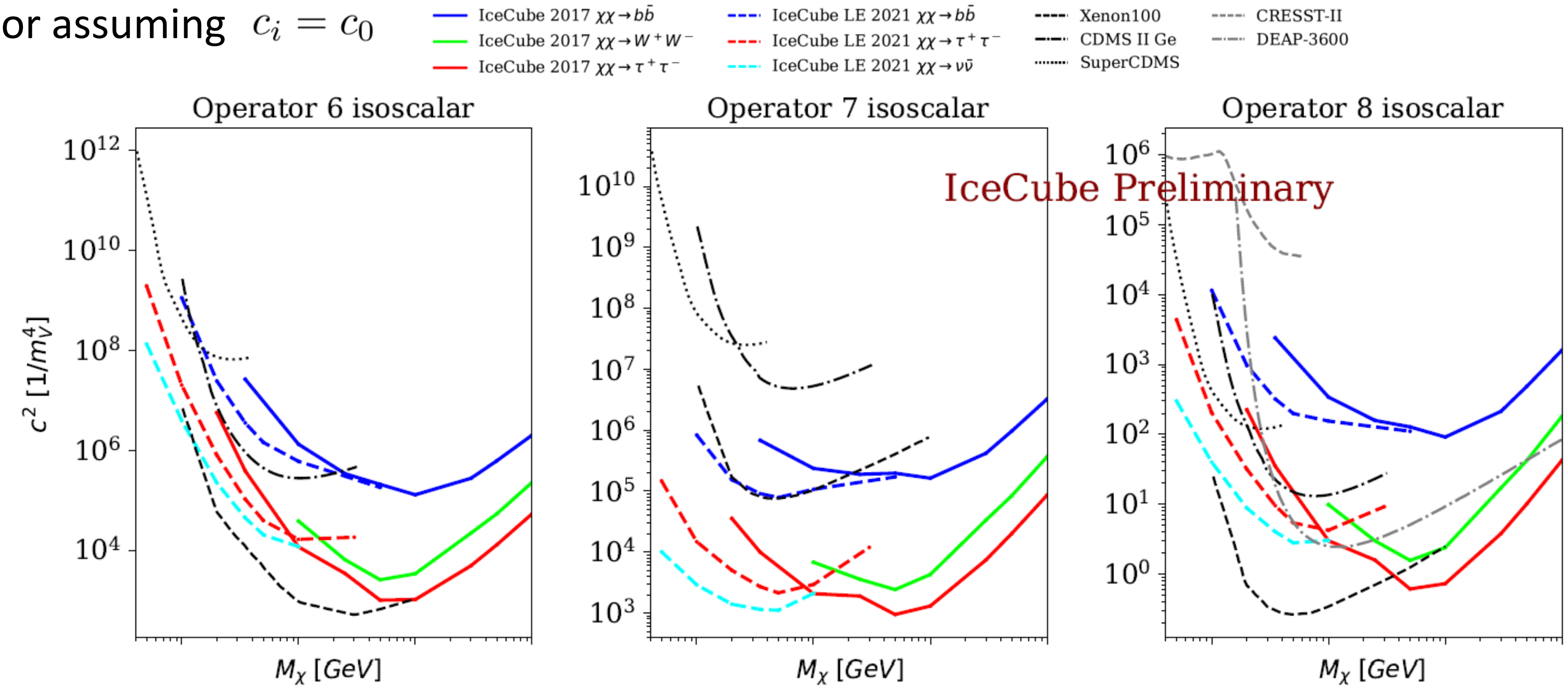
Results of two IceCube analyses

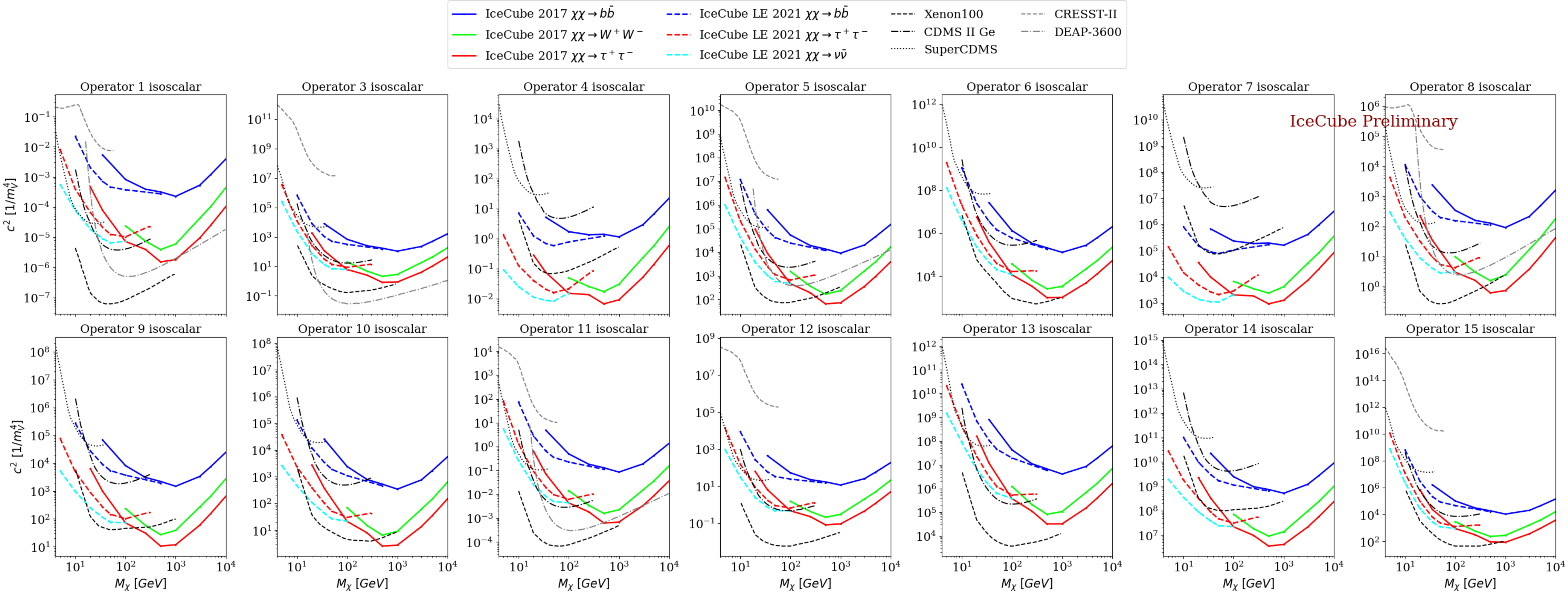
Calculated capture rates in the Sun for each interaction operator assuming $c_i = c_0$

Get limits on coupling constants



Isoscalar Coupling Constants

Spin ½



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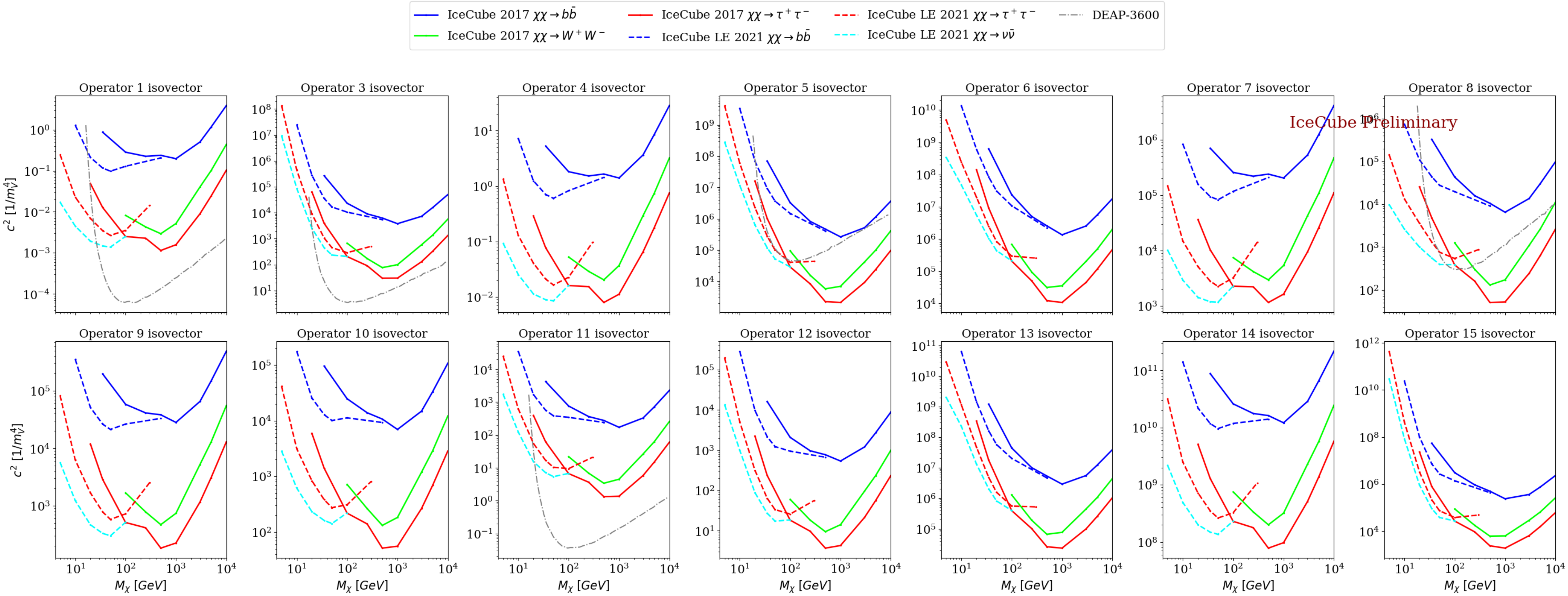
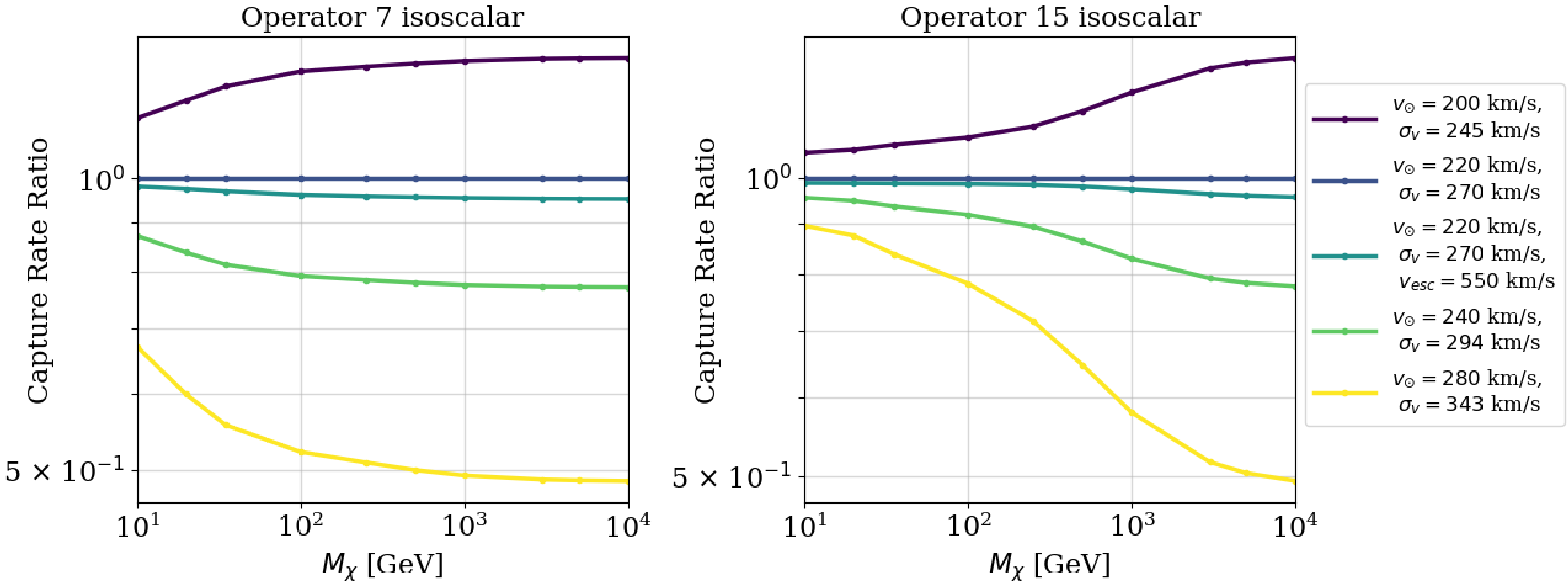
Isovector Coupling Constants

Spin ½



Dependency on the Velocity Distribution



- Dominated by hydrogen
- Dominated by iron

→ Operators which are dominated by heavier elements are affected at larger dark matter masses

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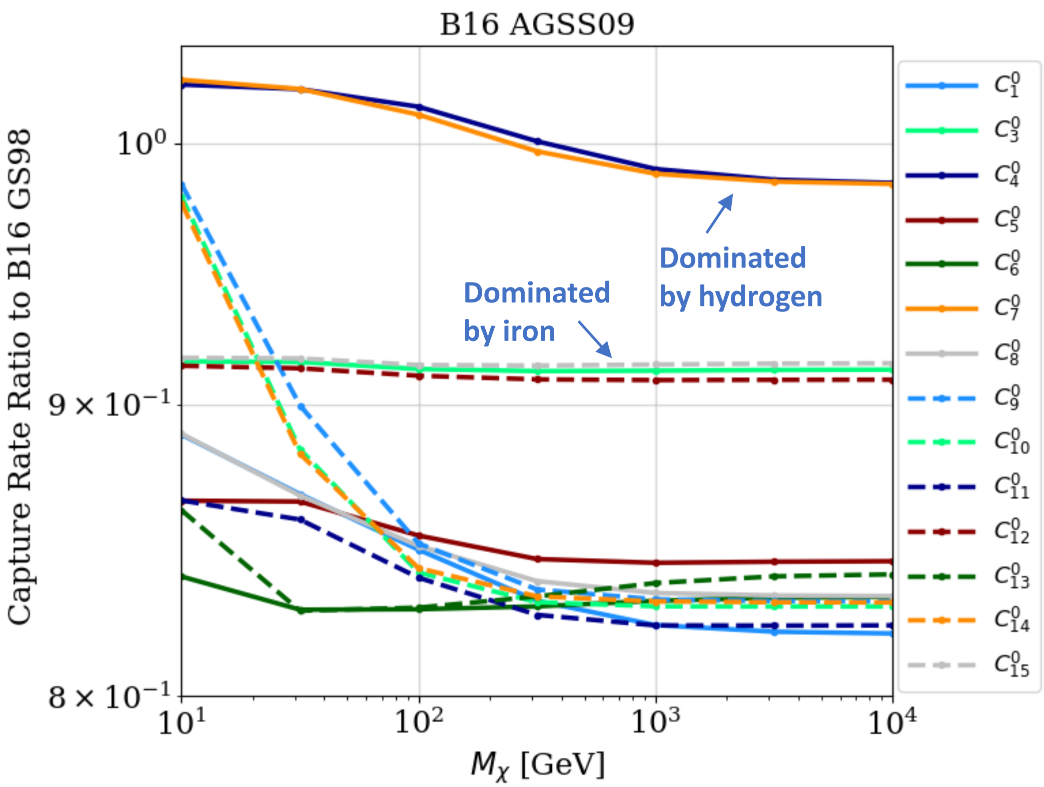
Dependency on the Solar Model



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Dominated by iron

Dominated by hydrogen

→ Capture rate depends linearly on nuclear abundance

→ Abundance of the respective dominating element in the considered solar model has a large impact

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Conclusions

- We have reported upper limits on the isoscalar and isovector coupling constants of the non-relativistic effective theory of dark matter-nucleon interactions for dark matter particles with spin ½
- The theoretical framework is also valid for other spins
- The results are based on annihilation rate limits from two IceCube analyses and can be updated with future analyses

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Thank you for your attention!

Backup

Dark Matter Response Functions

$$
\begin{aligned}
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] \\
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)\left(c_{12}^{\tau'} - \frac{q^2}{m_N^2} c_{15}^{\tau'}\right) \\
R_{\Phi'' M}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) &= c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'} \\
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] \\
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'} + \right. \\
&\quad \left. \frac{q^2}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \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] \\
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}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\quad \left. \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)\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] \\
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] \\
R_{\Delta\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right]. \qquad \text{(B.1)}
\end{aligned}
$$

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Capture Rate Calculation

$$C_{\mathrm{cap}}^{N} = n_X \int_0^{R_\oplus} dr\, 4\pi r^2 n_N(r) \int_0^{v_{\mathrm{gal}}} du\, 4\pi u^2 f_\oplus(u) \frac{u^2 + v_\oplus^2(r)}{u} \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} dE_R \boxed{\frac{d\sigma_N}{dE_R}} \Theta(\Delta E)$$

R prop to c^2

EFT part:

$$\boxed{\frac{\mathrm{d}\sigma_{T\chi}\left(E_r, w^2\right)}{\mathrm{d}E_r}} = \alpha\left(v^2\right) \sum_{\tau,\tau',k} \underline{\left(\frac{q^2}{m_N^2}\right)^{\ell(k)} R_k^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_k^{\tau\tau'}\left(q^2\right)}$$

Operators that contribute to transition probability:

$$M_{LM;\tau}(q) = \sum_{i=1}^{A} M_{LM}(q\mathbf{r}_i) t_{(i)}^{\tau} \qquad \Sigma'_{LM;\tau}(q) = -i \sum_{i=1}^{A} \left[\frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i} \times \mathbf{M}_{LL}^{M}(q\mathbf{r}_i)\right] \cdot \vec{\sigma}(i) t_{(i)}^{\tau}$$

$$\Delta_{LM;\tau}(q) = \sum_{i=1}^{A} \mathbf{M}_{LL}^{M}(q\mathbf{r}_i) \cdot \frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i} t_{(i)}^{\tau} \qquad \Sigma''_{LM;\tau}(q) = \sum_{i=1}^{A} \left[\frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i} M_{LM}(q\mathbf{r}_i)\right] \cdot \vec{\sigma}(i) t_{(i)}^{\tau}$$

$$\tilde{\Phi}'_{LM;\tau}(q) = \sum_{i=1}^{A} \left[\left(\frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i} \times \mathbf{M}_{LL}^{M}(q\mathbf{r}_i)\right) \cdot \left(\vec{\sigma}(i) \times \frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i}\right) + \frac{1}{2} \mathbf{M}_{LL}^{M}(q\mathbf{r}_i) \cdot \vec{\sigma}(i)\right] t_{(i)}^{\tau}$$

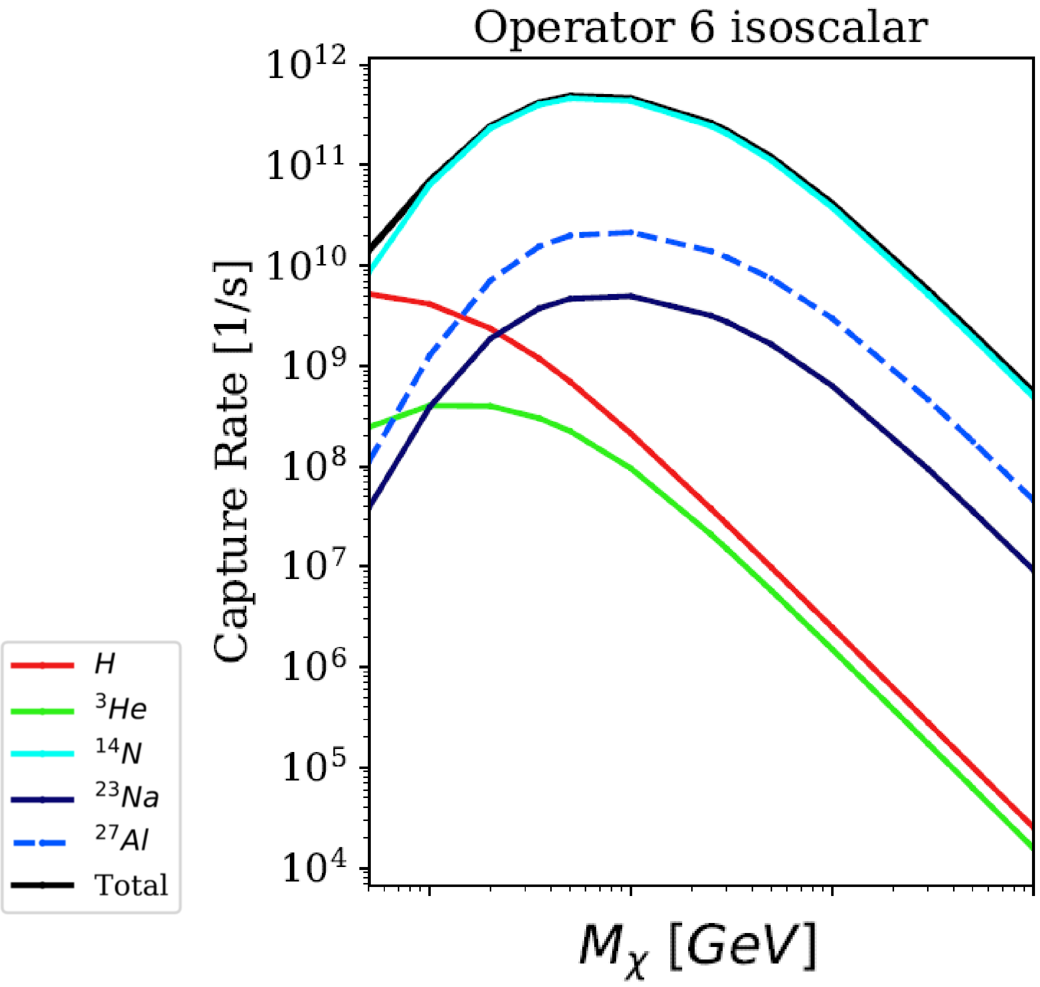
$$\Phi''_{LM;\tau}(q) = i \sum_{i=1}^{A} \left(\frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i} M_{LM}(q\mathbf{r}_i)\right) \cdot \left(\vec{\sigma}(i) \times \frac{1}{q} \overrightarrow{\nabla}_{\mathbf{r}_i}\right) t_{(i)}^{\tau} .$$

→ Complex dependency on dark matter mass and nucleon mass

→ Different operators measure different quantities and therefore favor different elements

→ Most relevant elements are not only determined by nuclear abundance but by a compromise between these different effects

Example: Capture Rate for Operator 6



- Depends on operator $\Sigma''_{LM;\tau}$ which measures spin
- Dominated by N14
  - Larger mass fraction than Na23, Al27
  - Larger spin than H, He3
- In addition H and He3 contributions are suppressed by kinematic limits

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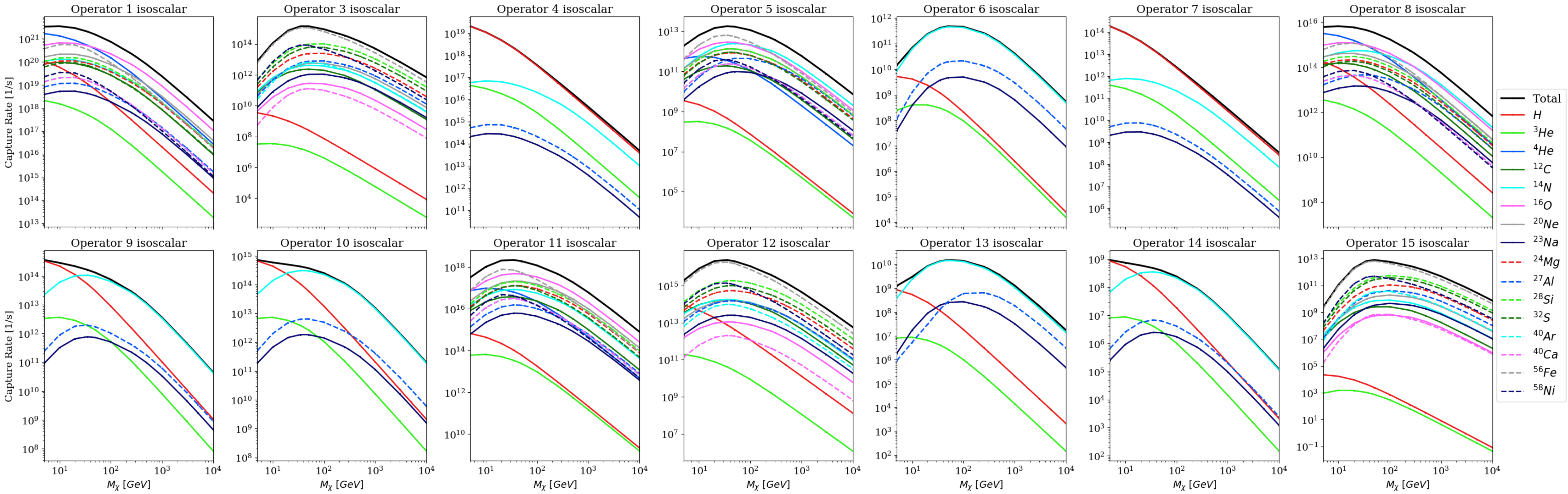
Capture Rates for all Operators

Spin ½ isoscalar



→ Most relevant elements can be H1, He4, N14, O16, Al27 or Fe56

→ Capture rate depends linearly on nuclear abundance, so the mass fraction of these elements in the considered solar model has a large impact

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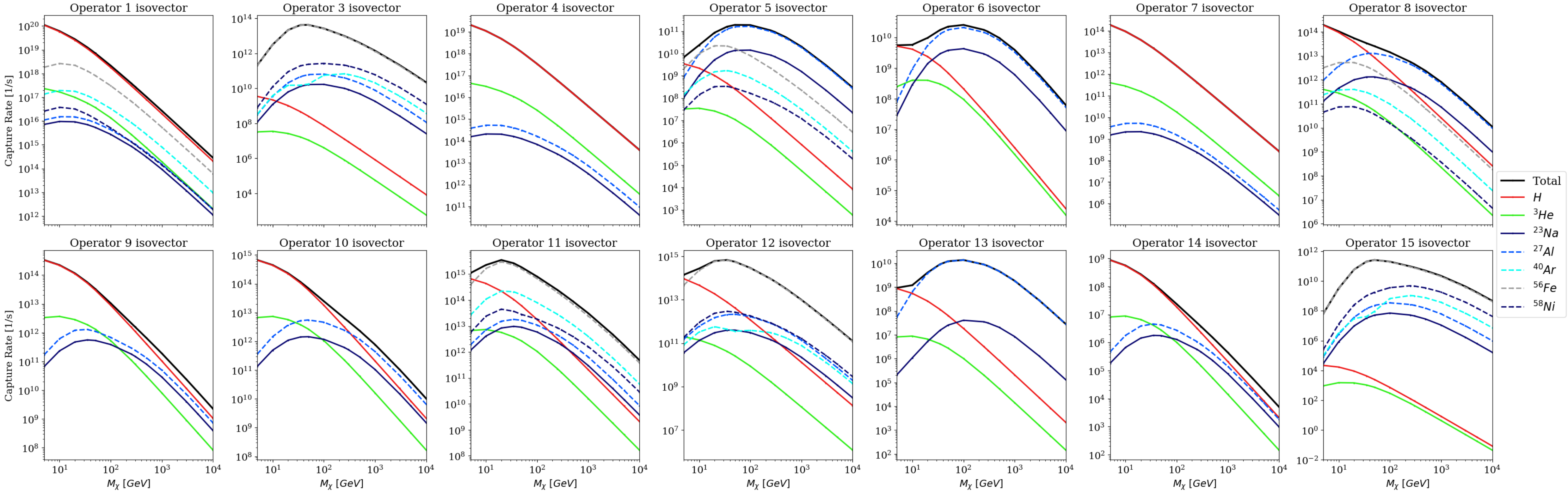
Capture Rates for all Operators

Spin ½ isovector



→ Most relevant elements can be H1, He4, N14, O16, Al27 or Fe56

→ Capture rate depends linearly on nuclear abundance, so the mass fraction of these elements in the considered solar model has a large impact