UNIVERSITY OF SOUTHERN DENMARK

Probing Light Dark Matter

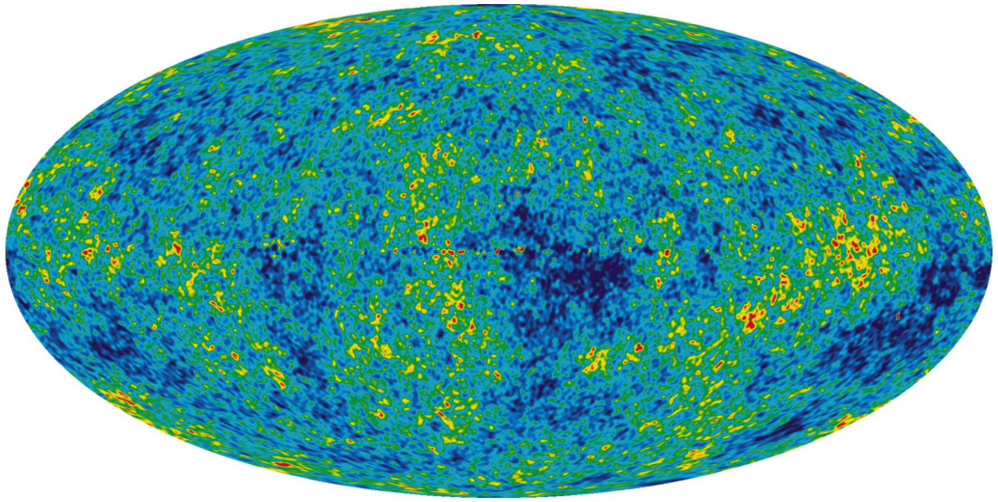
Chris Kouvaris

CP^3 - Origins

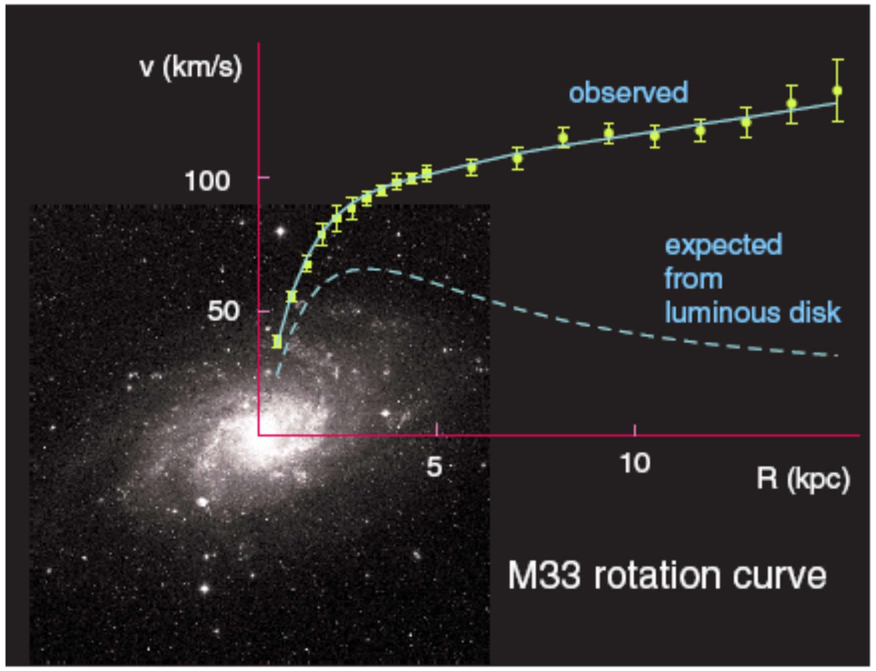
Particle Physics & Origin of Mass

DAMIC, 11 June 2018

Dark Matter

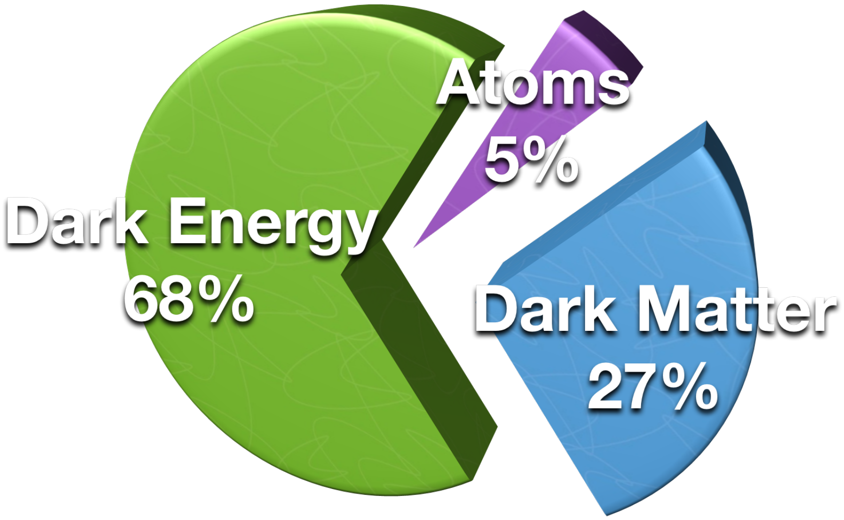


Microwave Background Radiation

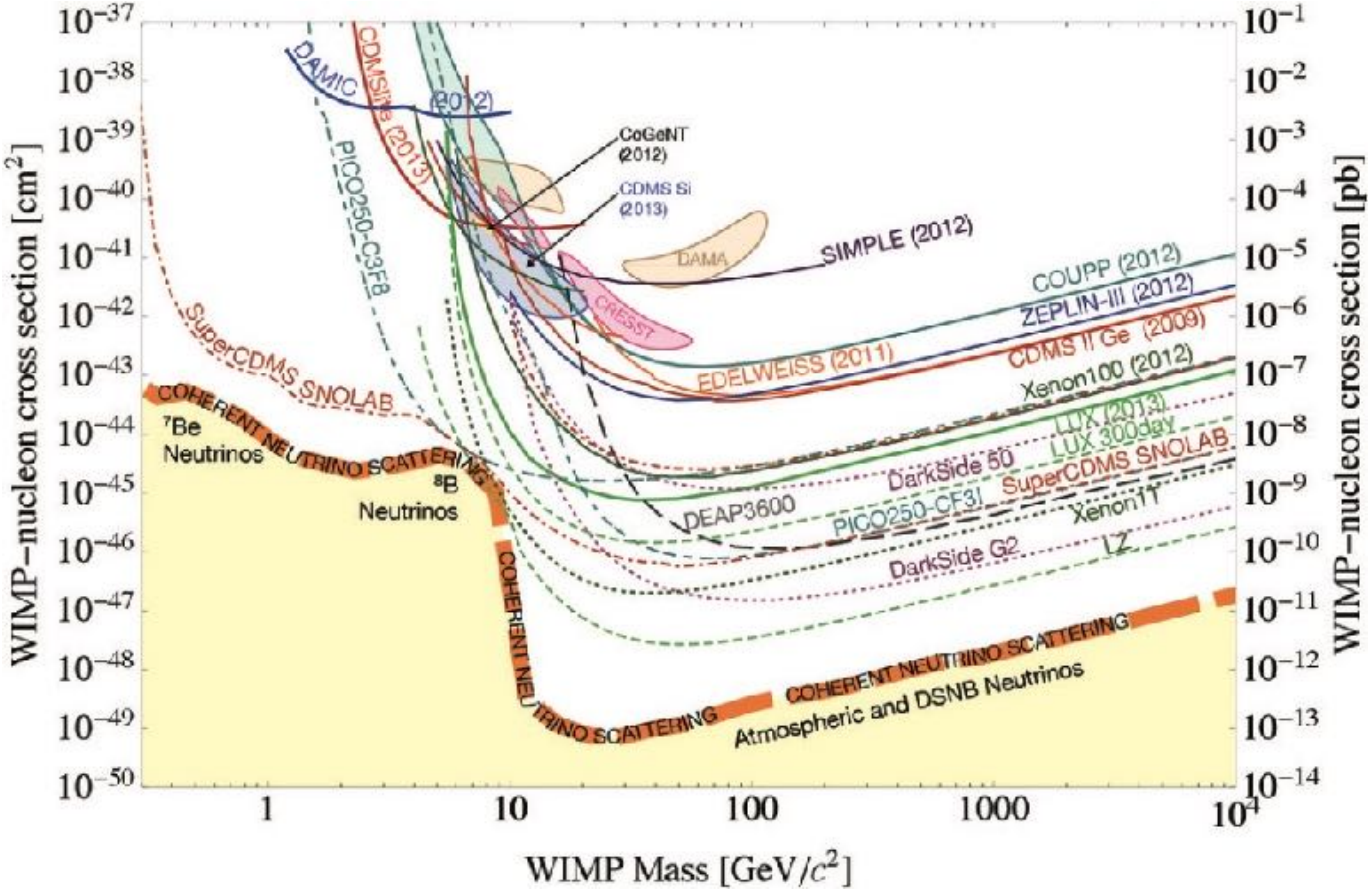


Rotational Curves

Bullet Cluster



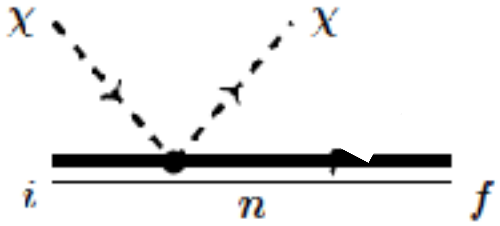
Probing New Territory in Dark Matter Direct Detection



Probing New Territory in Dark Matter Direct Detection

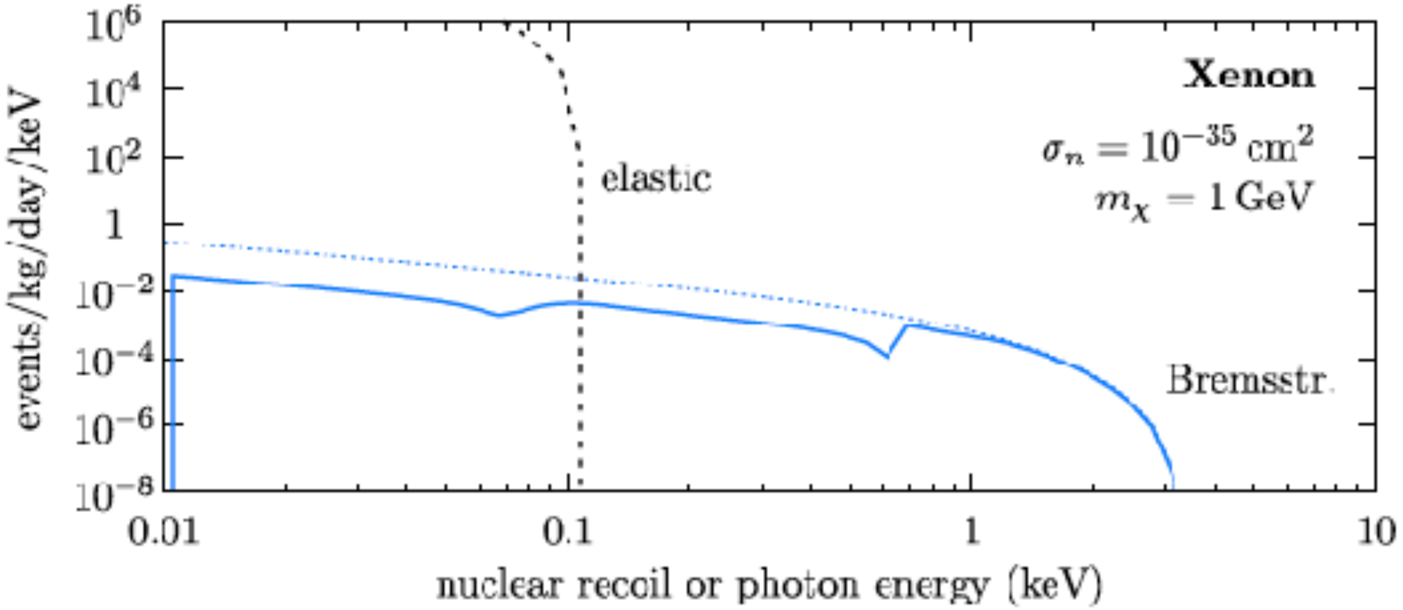
- Dark Matter via inelastic channels
- Shadowing Effect
- Dark Matter Reflecting off the Sun
- Bound Dark Matter

Probing sub-GeV Dark Matter



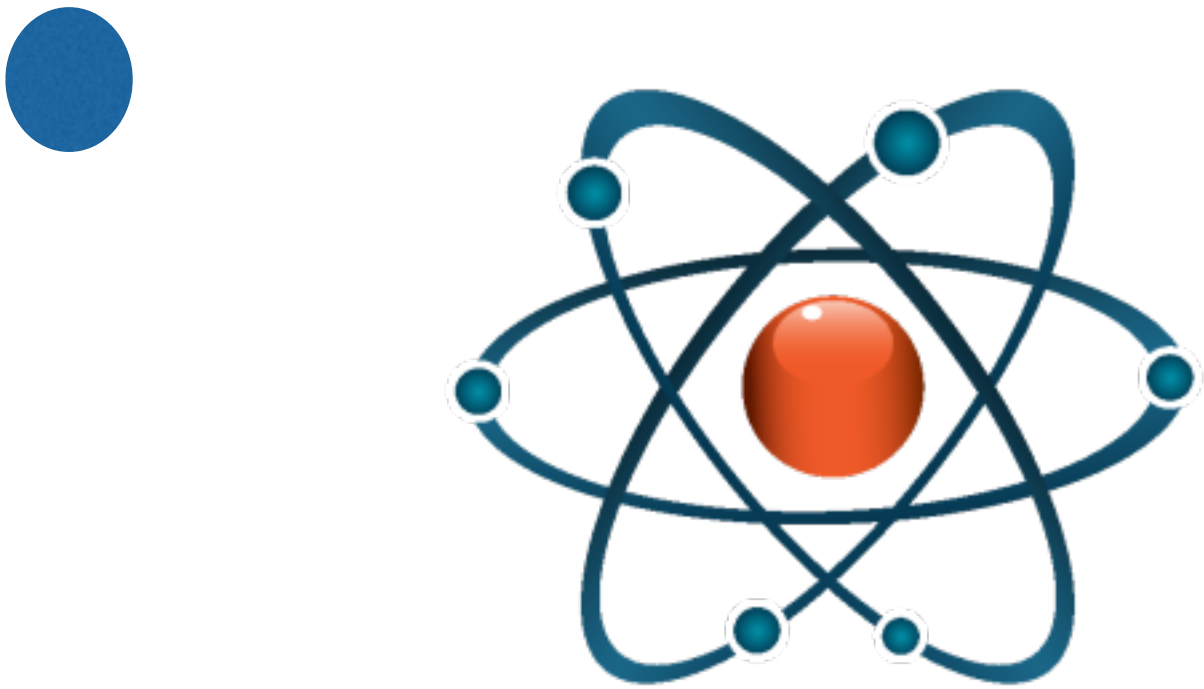
$$\mu_{N\mathrm{min}} = \sqrt{\frac{m_N E_{R\mathrm{th}}}{2}}\frac{1}{v_{\mathrm{max}}}$$

$$\mu_{N\mathrm{min}} = \frac{2\omega_{\mathrm{th}}}{v_{\mathrm{max}}^2}$$

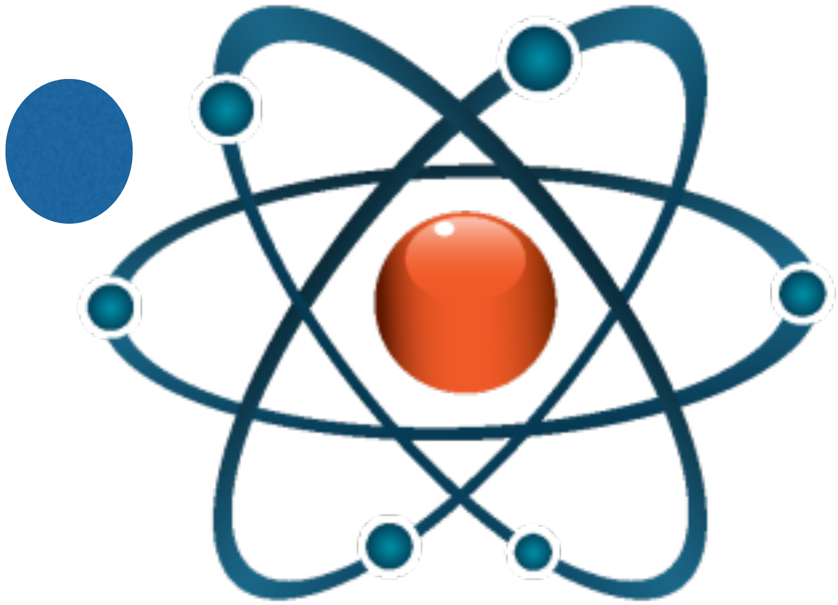


CK, Pradler Phys. Rev. Lett '17

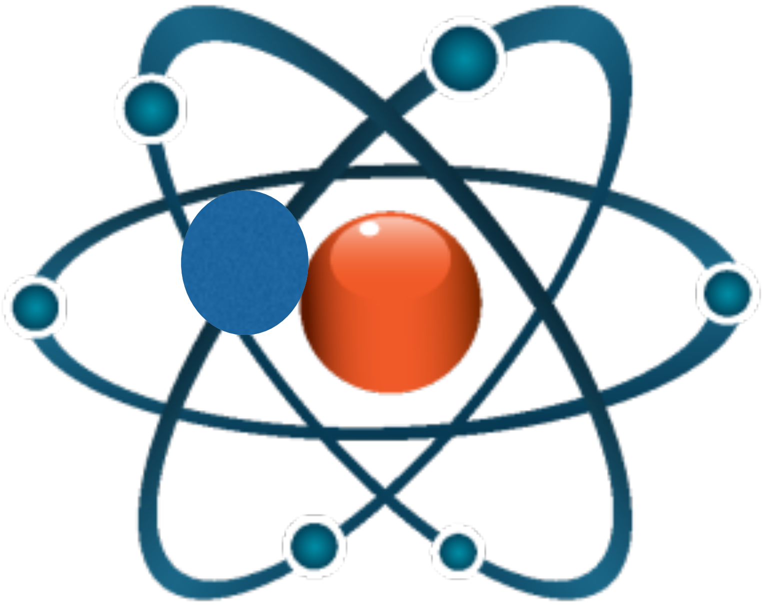
Probing sub-GeV Dark Matter



Probing sub-GeV Dark Matter



Probing sub-GeV Dark Matter



Probing sub-GeV Dark Matter

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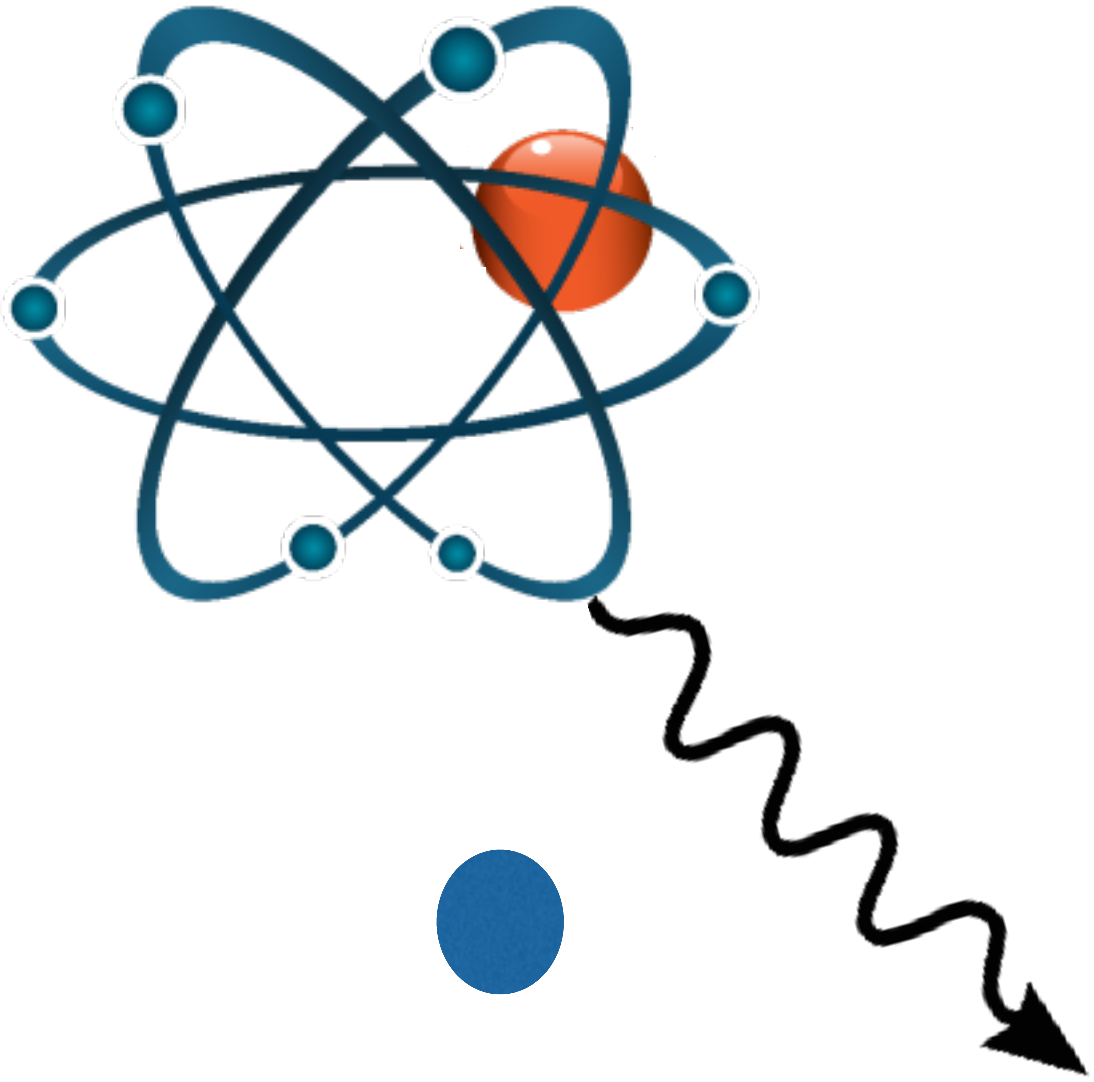
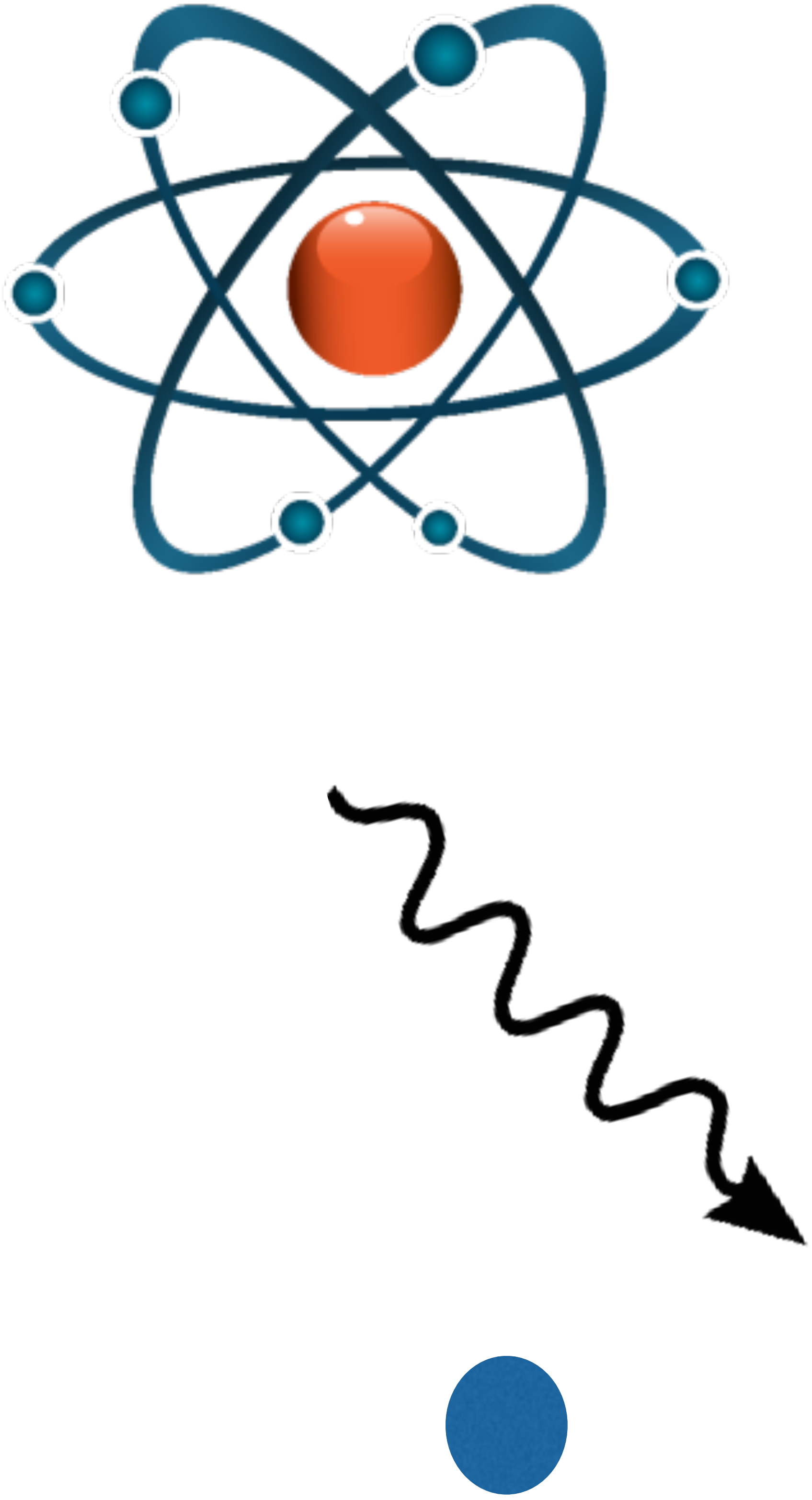
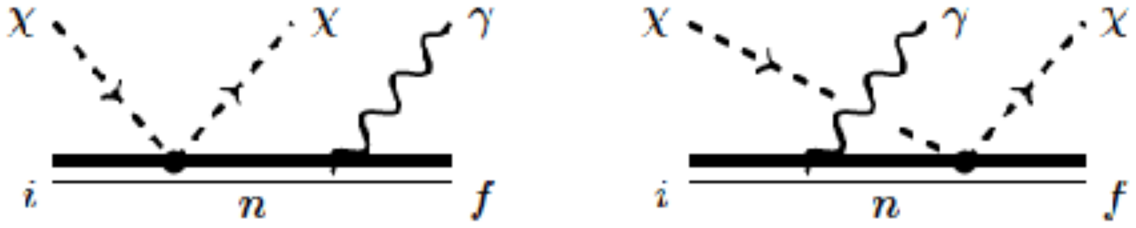


Probing sub-GeV Dark Matter



Probing sub-GeV Dark Matter

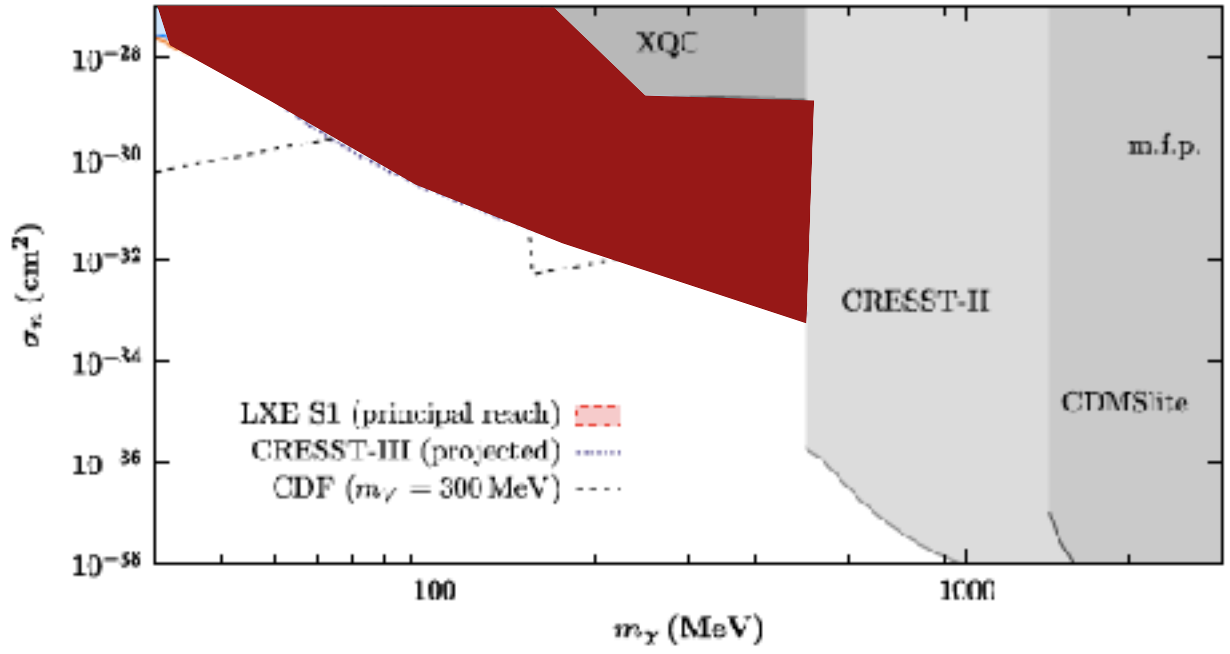


$$|V_{fi}|^2 = 2\pi\omega|M_{\mathrm{el}}|^2 \left| \sum_{n,n\neq i} \left[\frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\,\langle n|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\,\langle f|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|n\rangle}{\omega_{ni}+\omega} \right] \right|^2$$

$$\frac{d\sigma}{d\omega dE_R} = \frac{4\omega^3}{3\pi}\frac{E_R}{m_N}\frac{m_e^2|\alpha(\omega)|^2}{\alpha} \times \frac{d\sigma}{dE_R}\Theta(\omega_{\mathrm{max}}-\omega)$$

CK, Pradler PRL ’17

Probing New Parameter Space



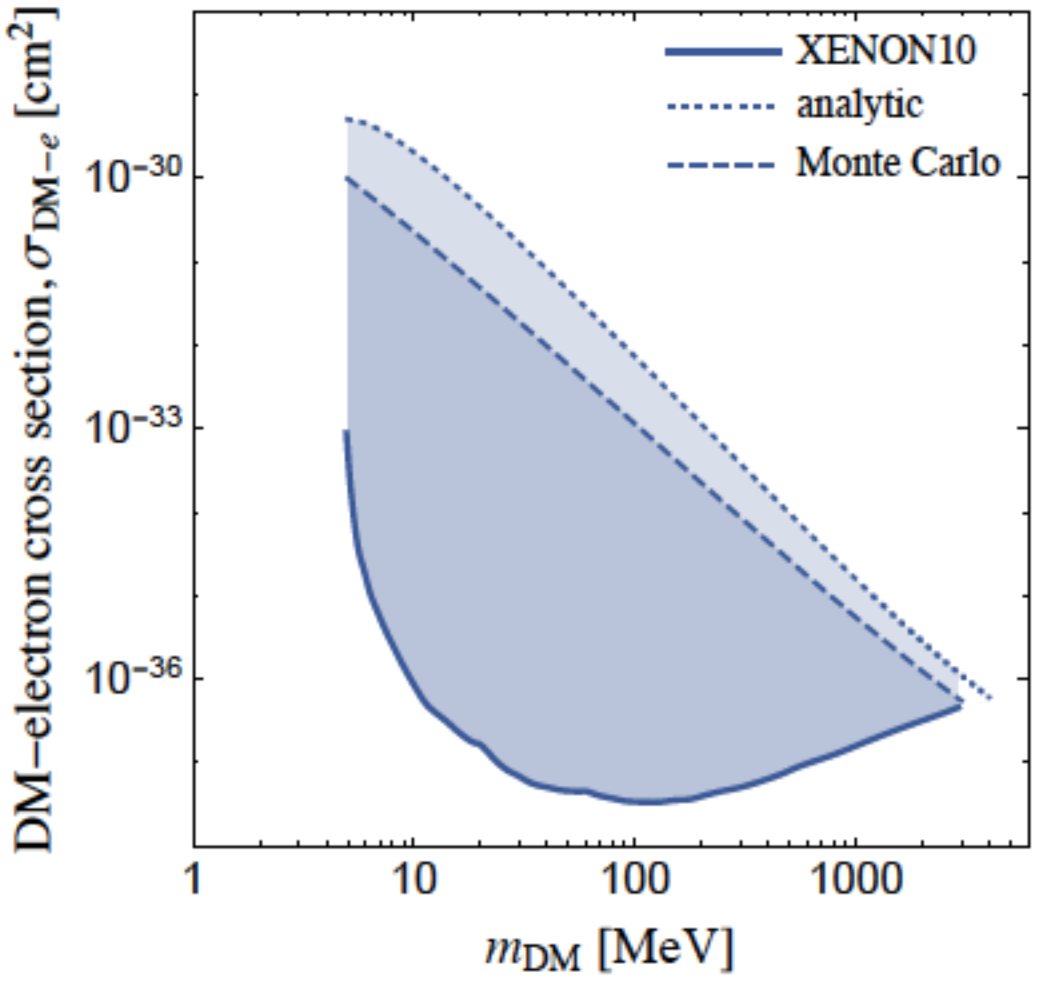
CK, Pradler Phys. Rev. Lett '17,
McCabe '17

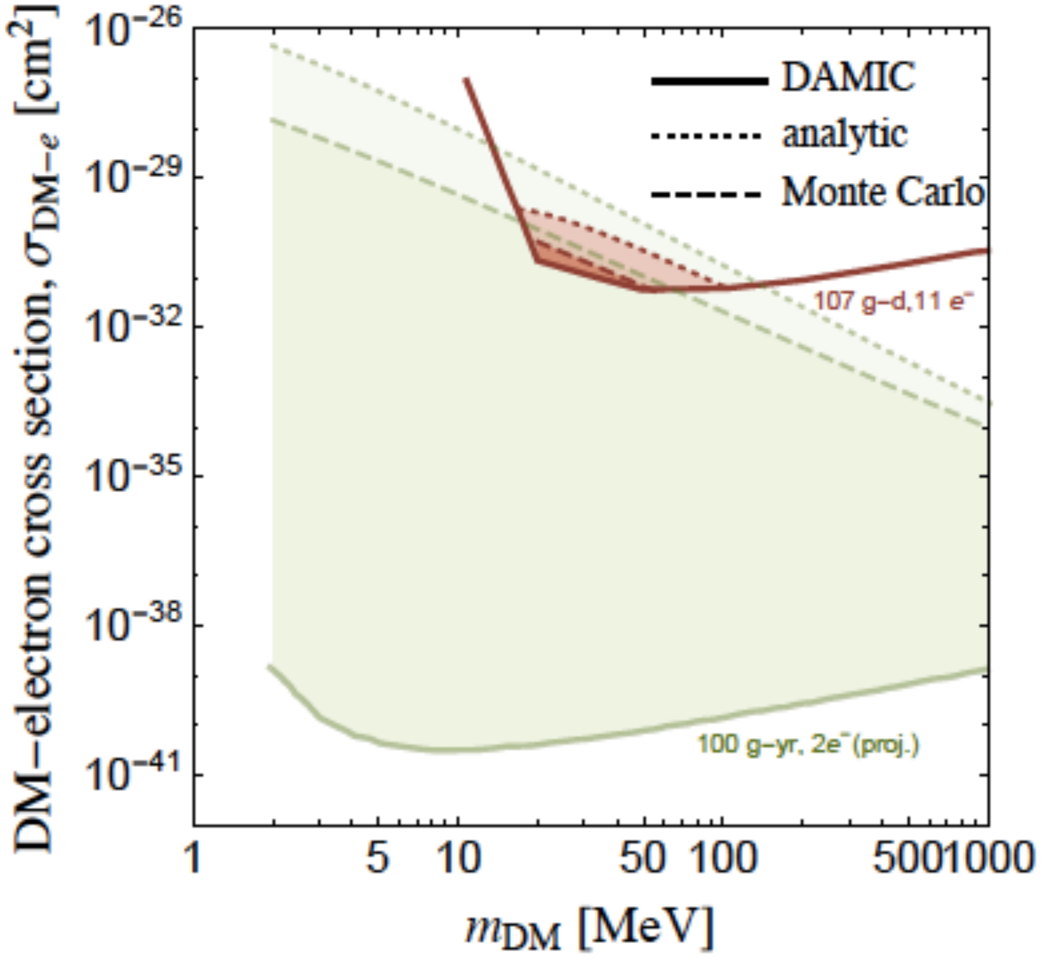
This is the tip of the iceberg of what inelastic channels can offer

- "Converting" a conventional detector to a directional one
- Address the neutrino floor problem
- Resonant Scattering
- Generalize to final states that leave the atom excited: Simultaneous double photon production that bears zero background
- Majorana Experiment will test our formula with a neutron beam on a semiconductor target

Re-visiting Direct Detection Limits

$$\mathscr{L} \supset g_X \bar{X} \gamma^\mu X A'_\mu + \varepsilon F_{\mu\nu} F'^{\mu\nu} + m_\phi^2 A'_\mu A'^\mu$$





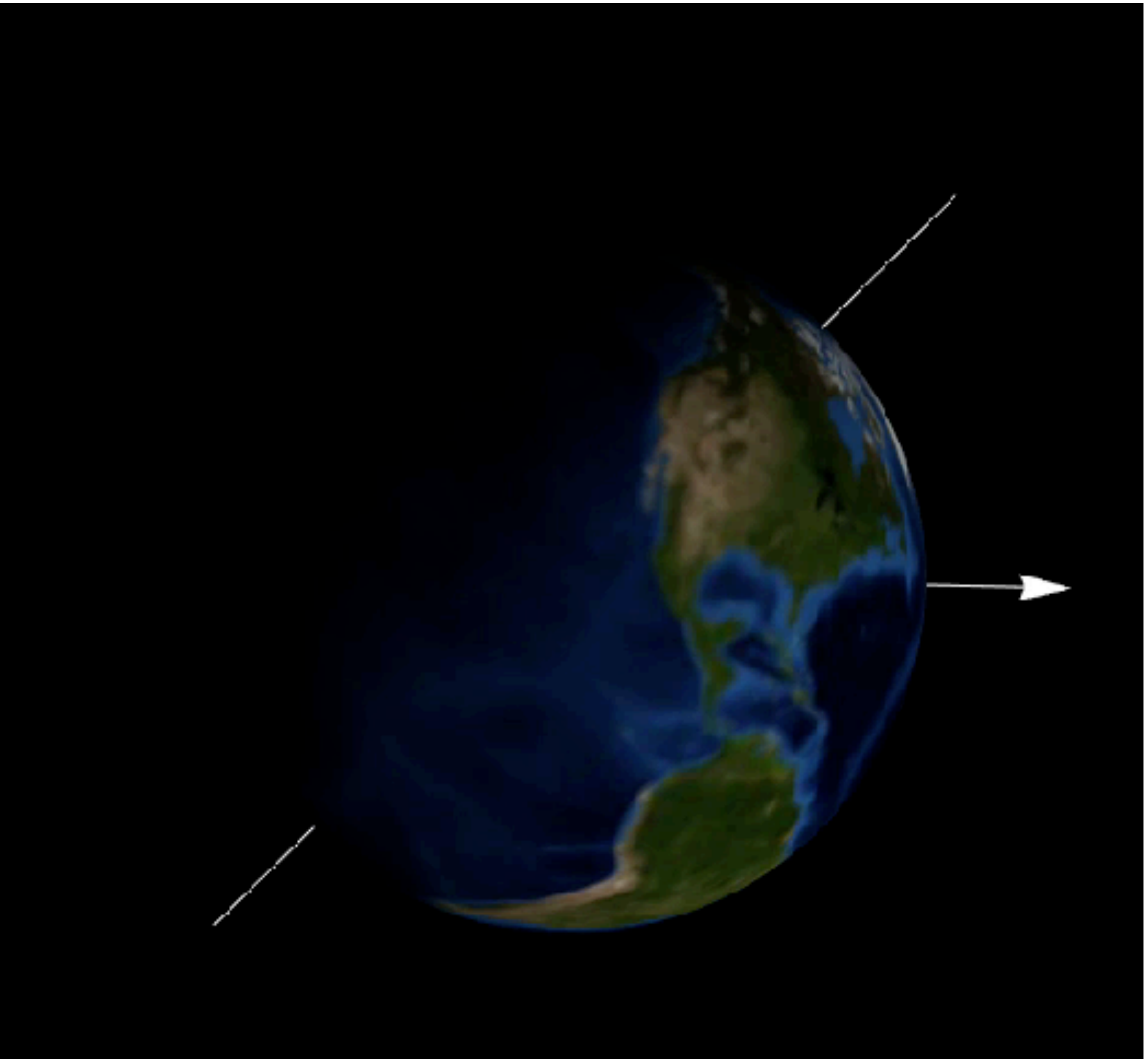
Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, '16, Emken, CK, Shoemaker '17

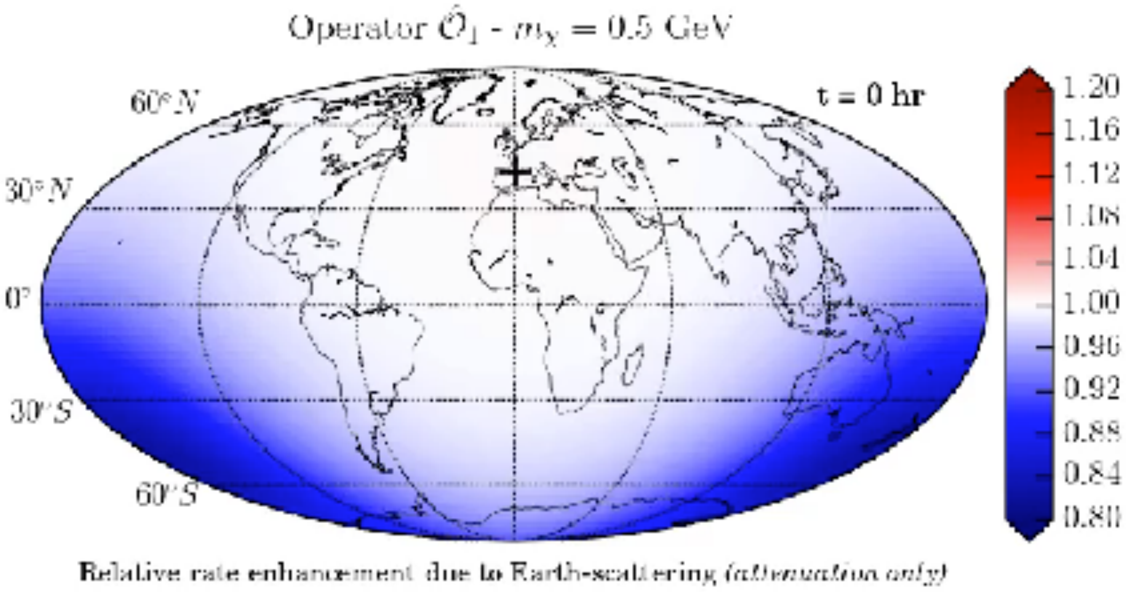
Experiment	Depth [m]	E_{thr}[eV]
XENON10	1400	12.4
DAMIC	100	40
DAMIC (proj.)	100	$\sim 1-2$

Daily Modulation in the Dark Matter Signal

The dark matter signal in underground detectors has three types of diurnal modulation:

- Shadowing effect
- Gravitational focusing Sikivie, Wick '02, Alenazi Gondolo '06, CK, Nielsen '15
- Rotational velocity of the Earth



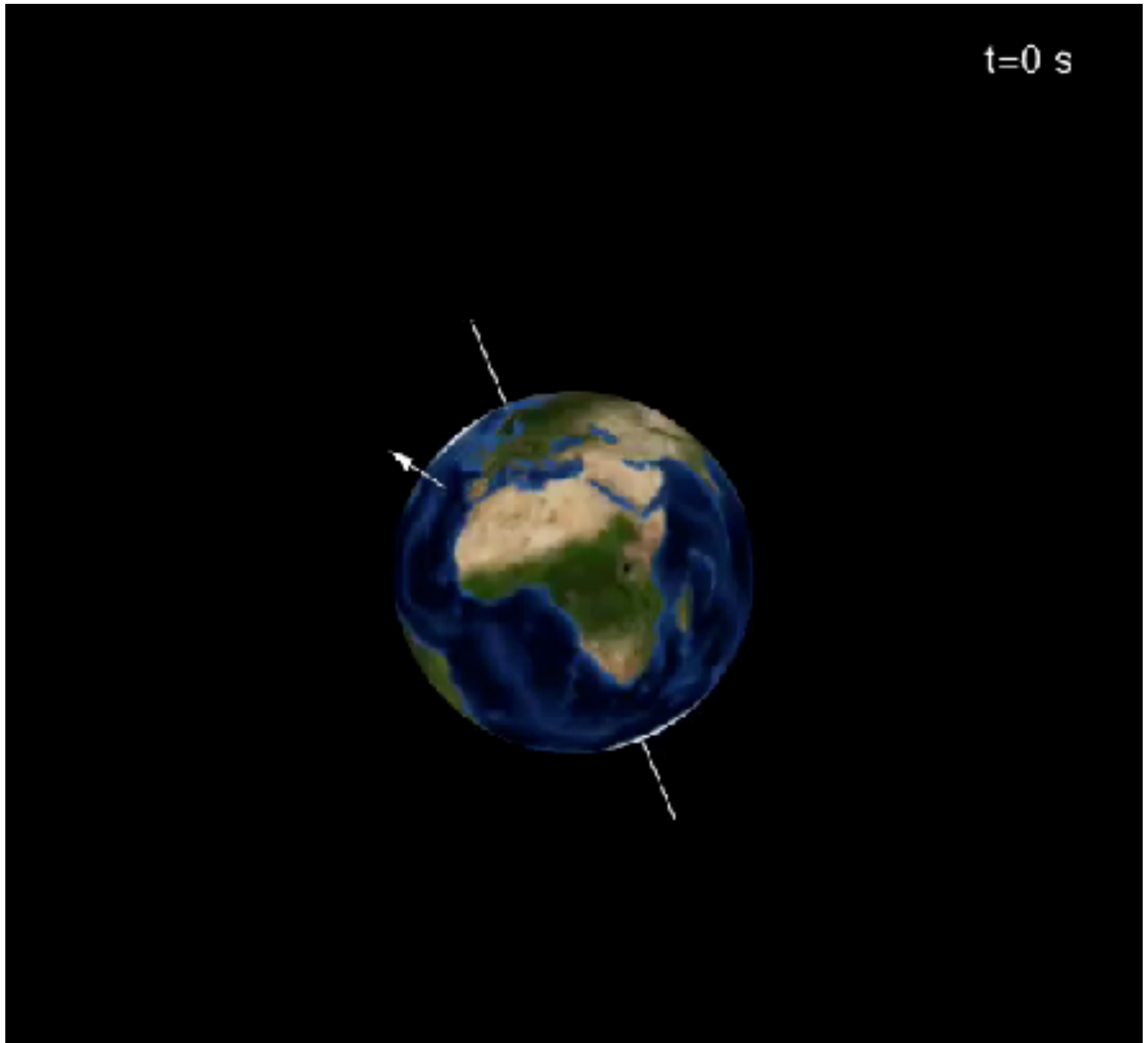


Kavanagh, Catena, CK '17

DAMASCUS: Dark Matter on Supercomputers

Performing a simulation of trillions of DM particles on ABACUS

- fully parallelized code
- publicly available
- state-of-the-art composition and density profiles of the Earth
- Precise Recoil Spectrum
- Test self-consistency of experiments
- Probe Currently Elusive Dark Matter

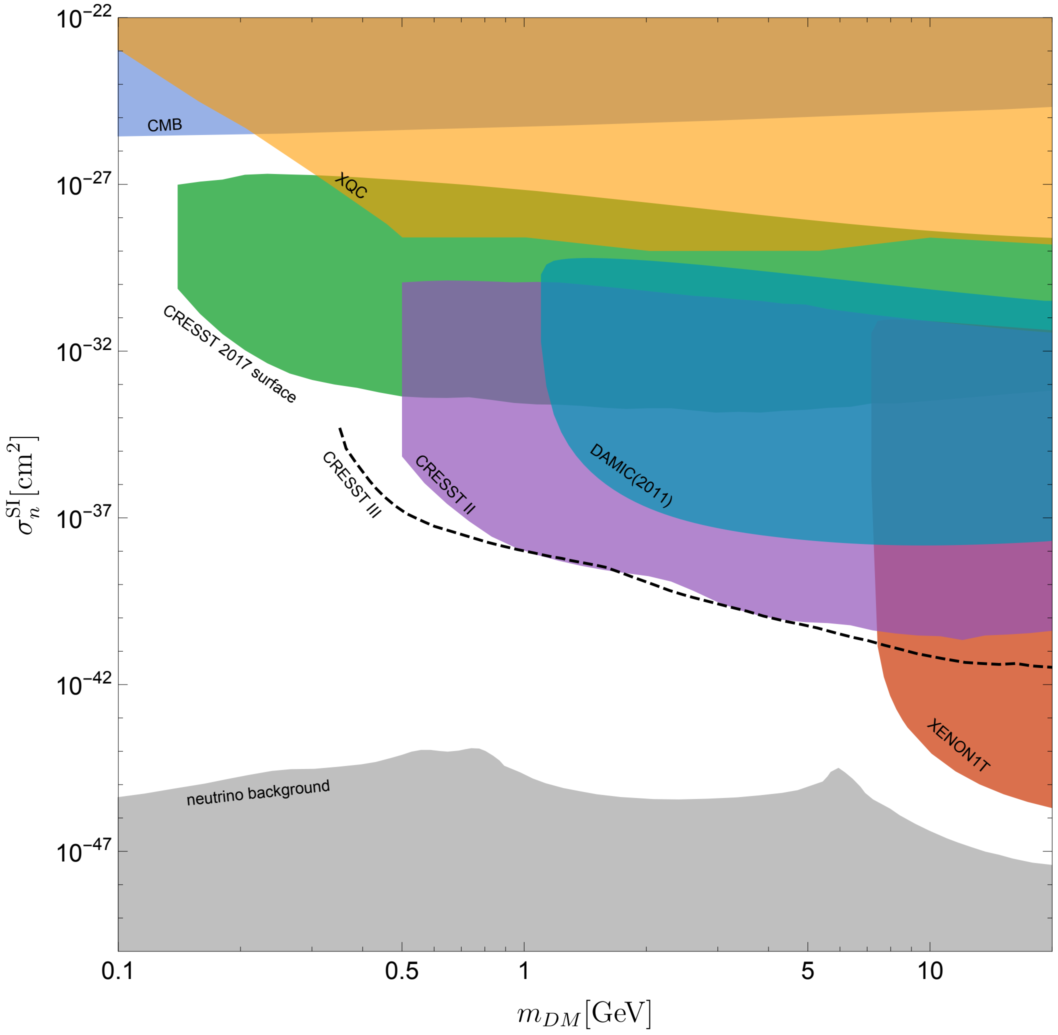


How Blind are Underground Detectors to Strongly Interacting Dark Matter?

There is a critical cross section above which no detection is possible for a given depth.

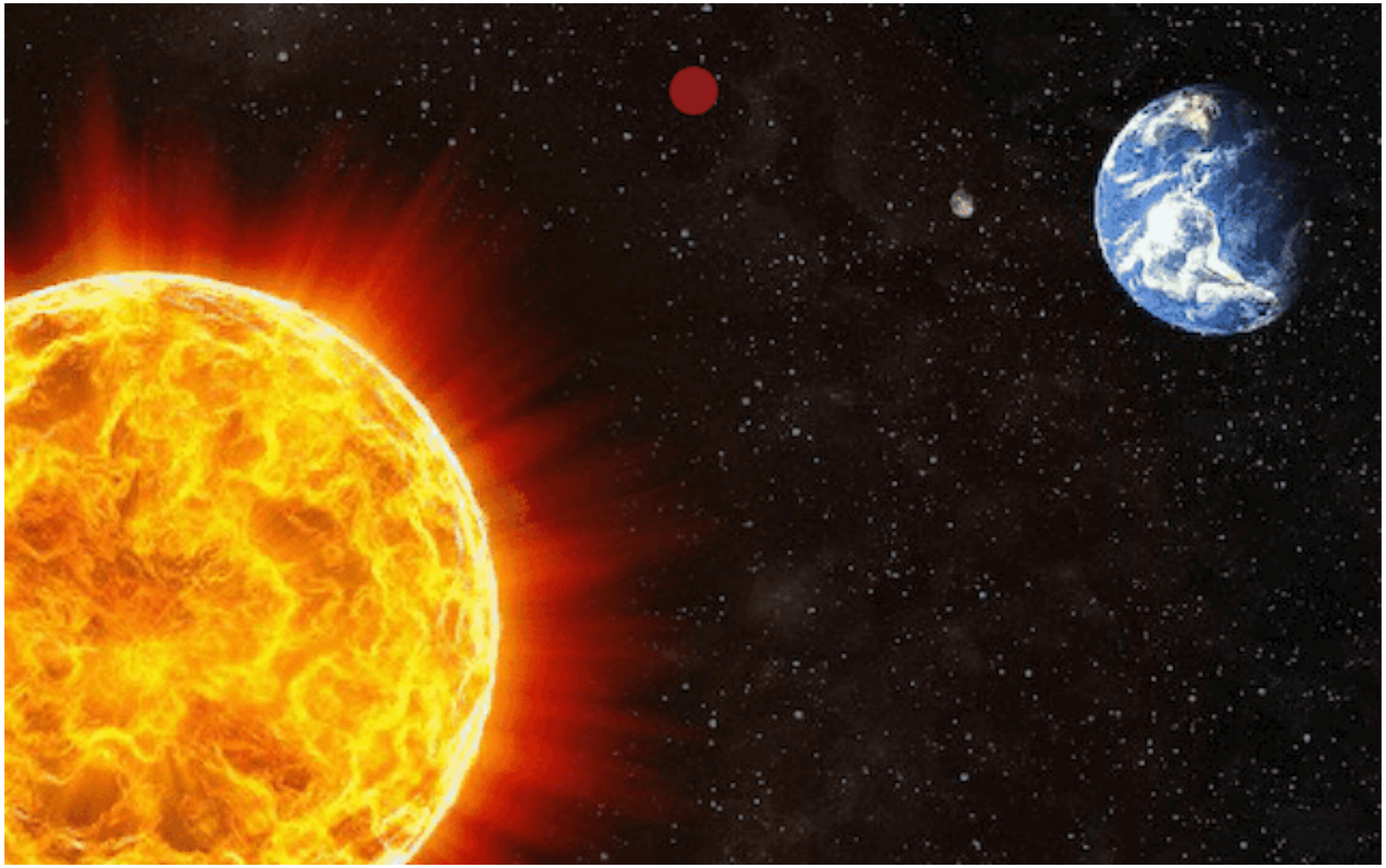
The critical cross section is independent of the exposure, so detectors can be blind for part of the parameter space regardless of how long they accumulate data.

Monte Carlo simulations using DAMASCUS-Crust including atmosphere, shielding and crust



Emken, CK '18

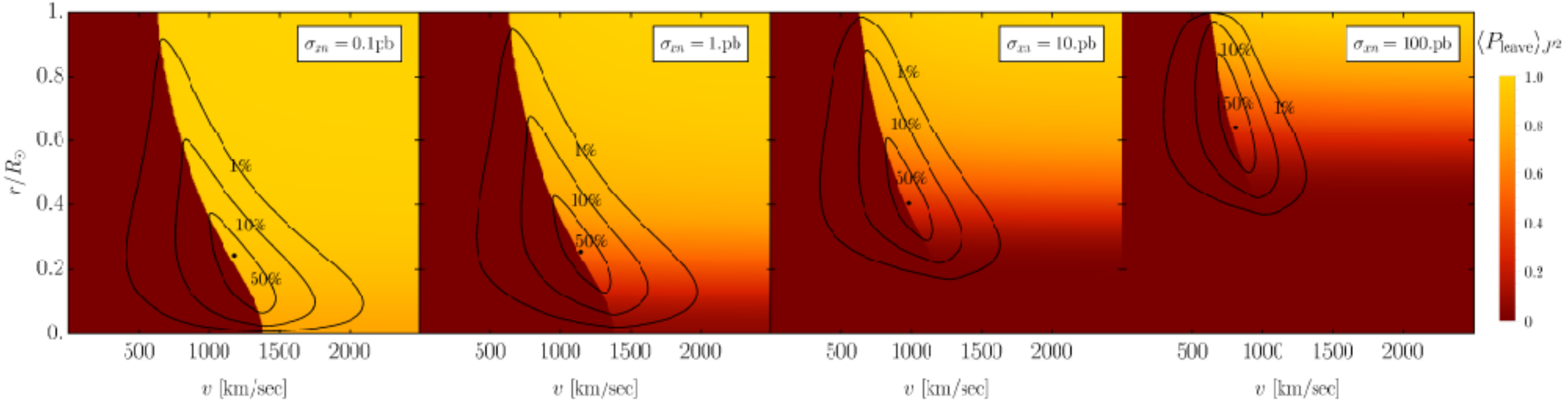
Reflecting off the Sun



Light Particles crossing the Sun can scatter off hot nuclei and ejected out with higher velocity than the one they entered, thus becoming potentially detectable

Reflecting off the Sun

$$\frac{\mathrm{d}S}{\mathrm{d}v\mathrm{d}r} = \pi n_x \int_0^\infty \mathrm{d}u \int_0^{w^2(u,r)r^2} \mathrm{d}J^2 \frac{f_{\mathrm{halo}}(u)}{u} P_{\mathrm{surv}}(r, R_\odot)\left[1 + P^2_{\mathrm{surv}}(r_{\mathrm{peri}}, r)\right] \frac{\mathrm{d}\Omega}{\mathrm{d}v}\left[w(u,r) \to v\right]\left[w(u,r)^2 - \frac{J^2}{r^2}\right]^{-1/2}$$



Emken,CK, Nielsen '17

Similar Ideas:
- Evaporating Dark Matter CK'15
- DM-electron scattering An, Pospelov, Pradler '17

Reflecting off the Sun

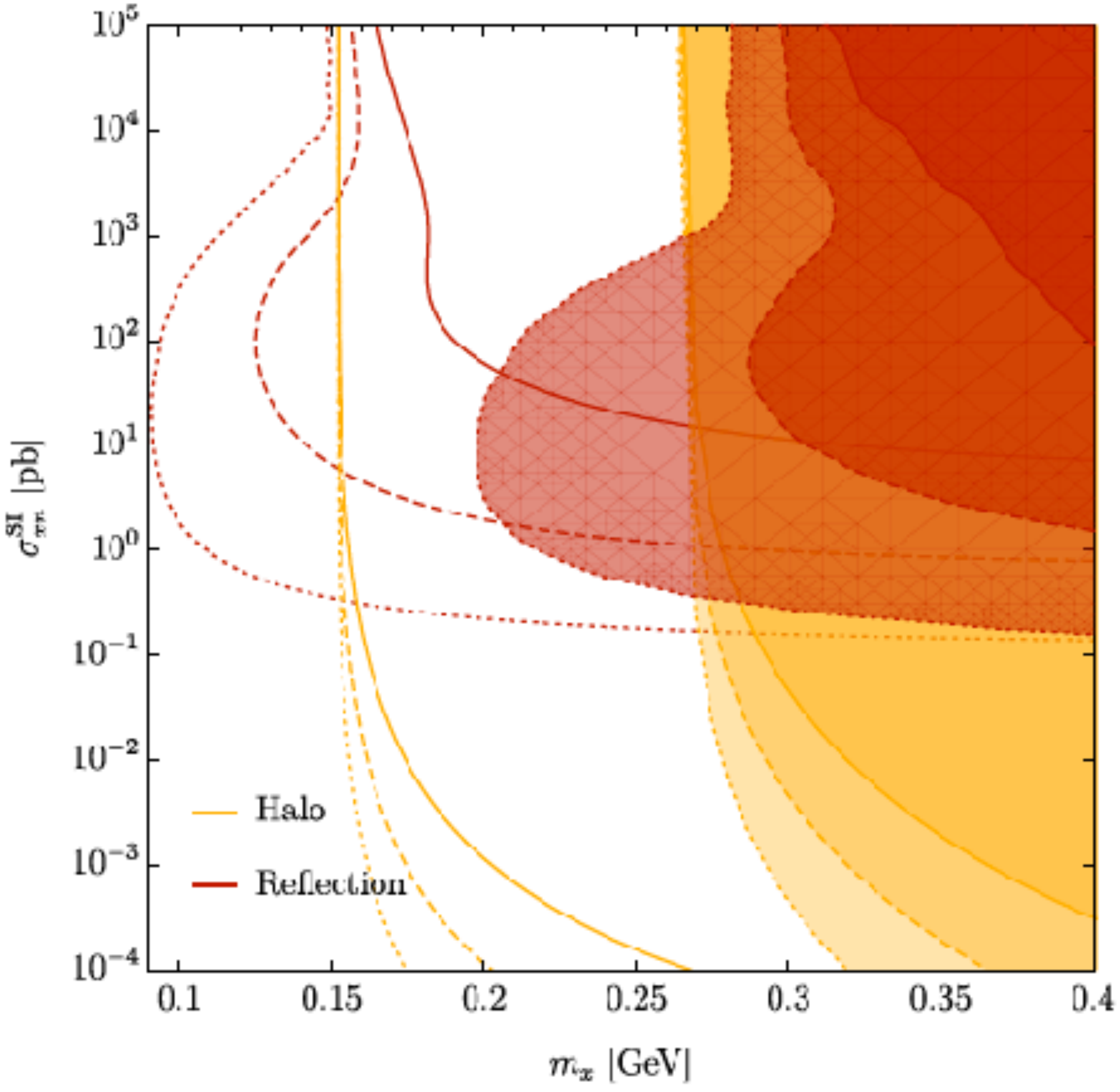
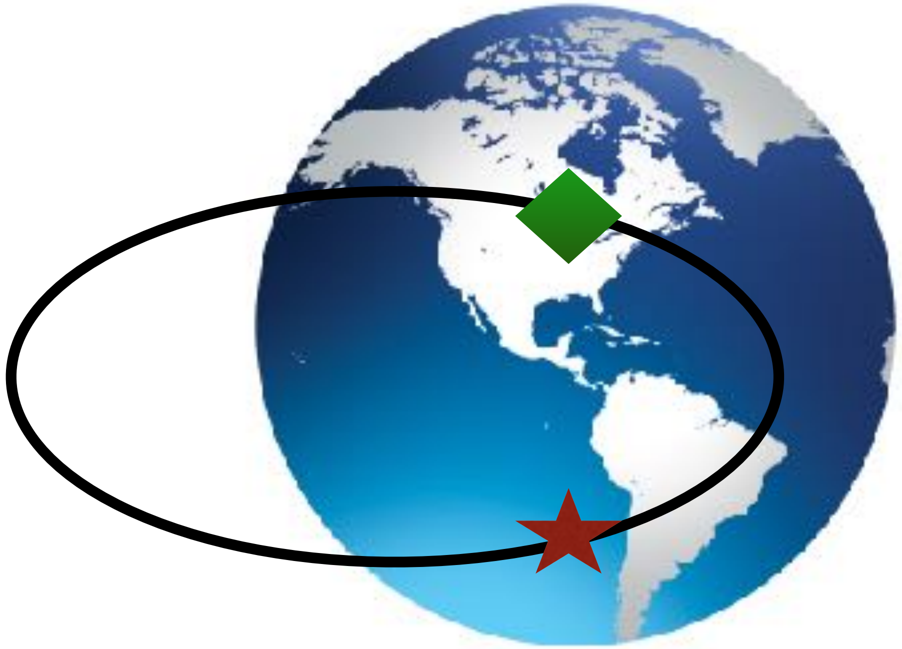


FIG. 2. Solar reflected DM in red and halo DM in yellow. The filled contours project constraints for a CRESST-III type detector with exposures of 1/10/100 ton·days (solid/dashed/dotted). The free lines project constraints for an idealized sapphire detector (perfect energy resolution and no background) with 20 eV threshold and exposures of 10/100/1000 kg·days (solid/dashed/dotted). As the exposure increases, halo constraints improve towards lower cross sections only. In contrast, reflection increases the sensitivity to lower masses.

Detecting Bound Dark Matter

DM that get captured by the Earth, can later on recoil in detectors



Damour, Krauss ’98,
CK, Catena ‘16

capture σ

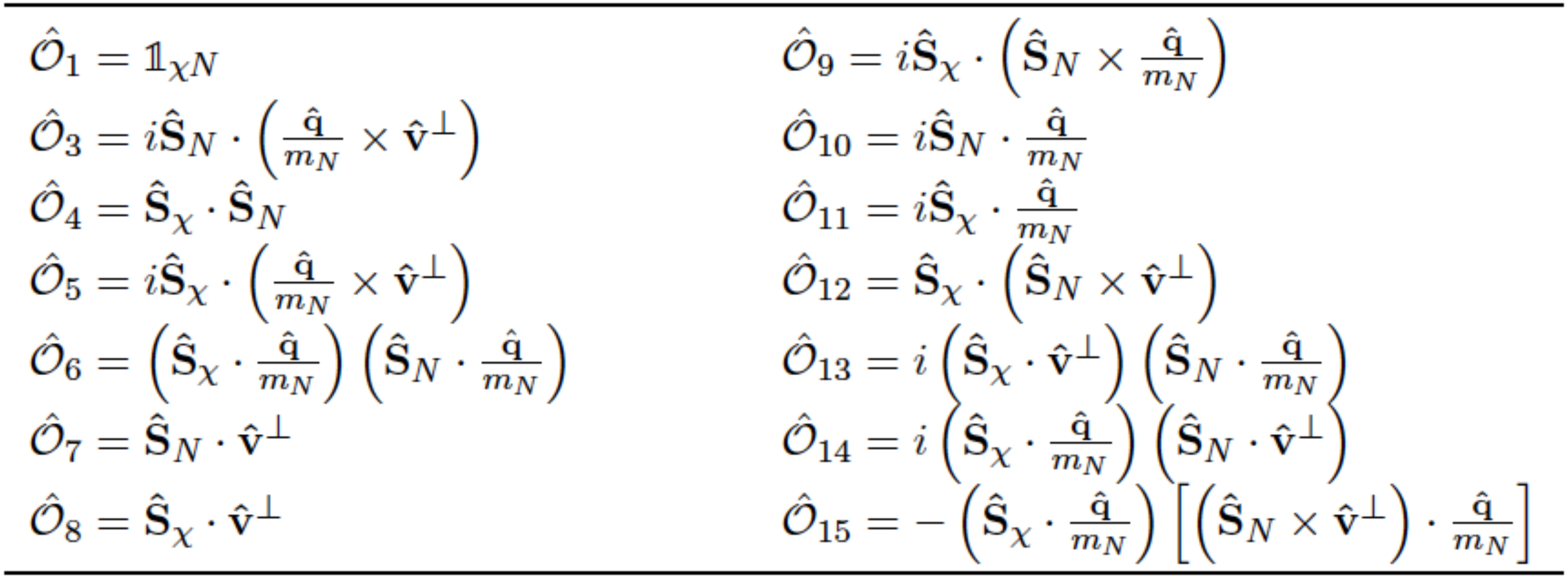
accumulation time $1/\sigma$

rate of events: nondirectional

σ

directional

Dark Matter-Nucleus effective interactions



$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

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

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

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

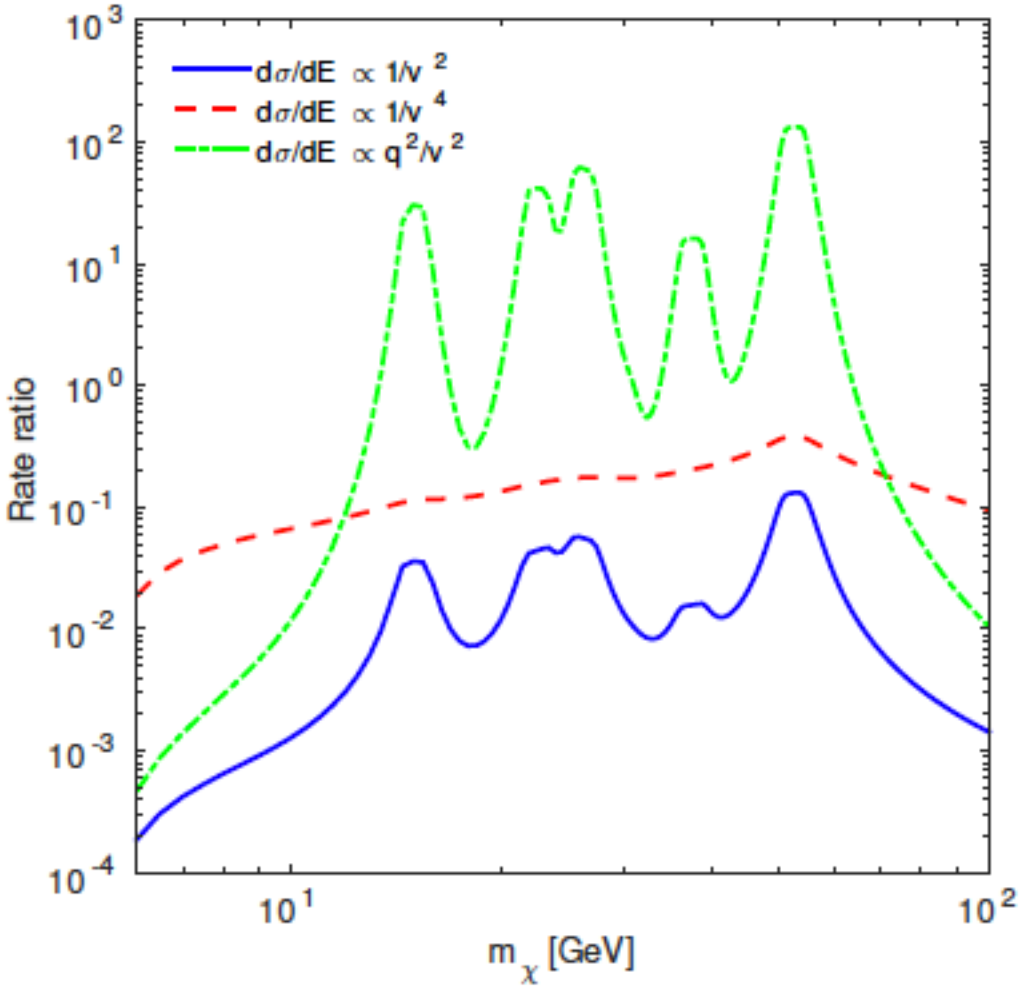
$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

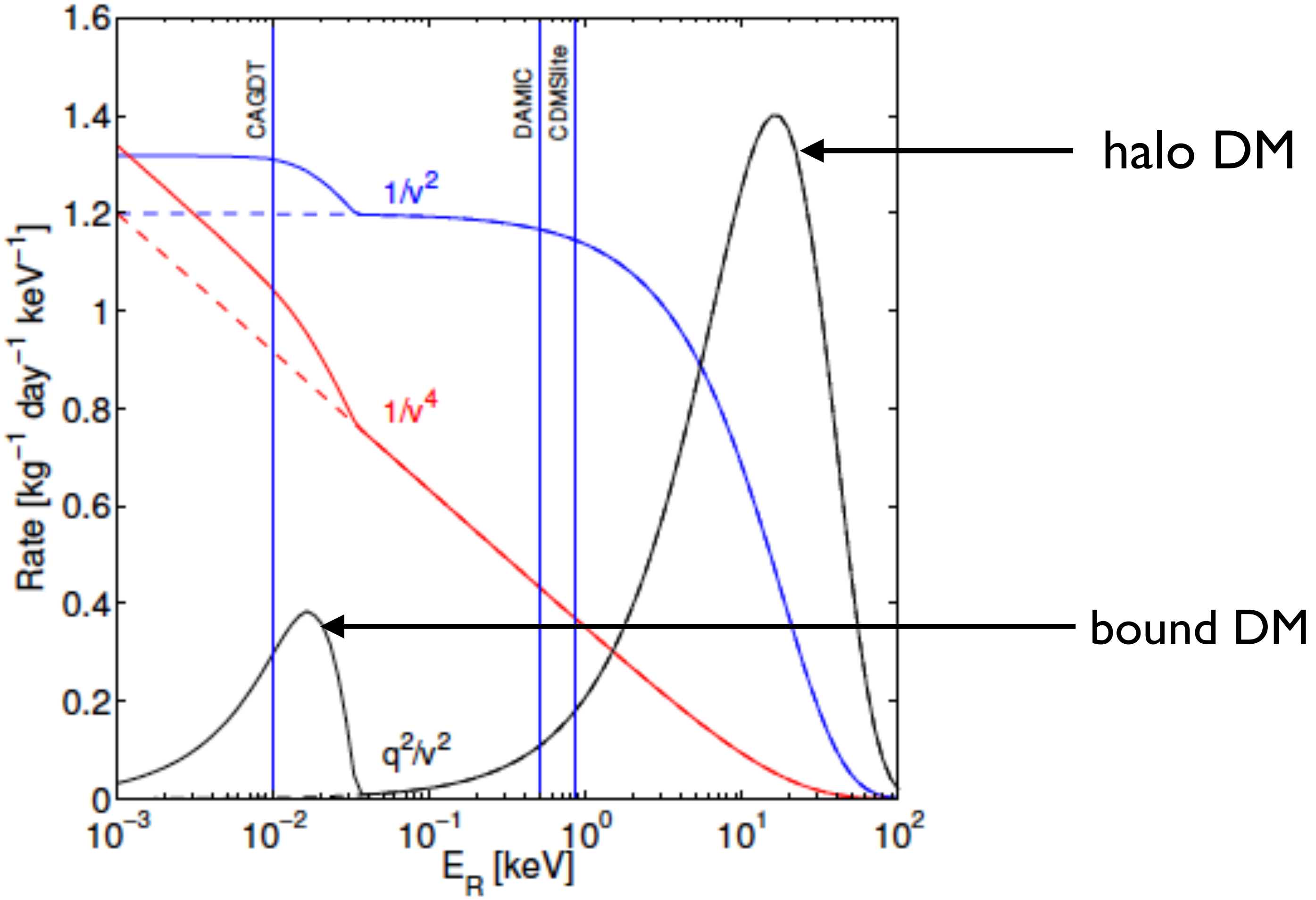
$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

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

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

A “smoking gun” for direct detection





CK, Catena ‘16

Low experimental energy threshold is essential

Go beyond the neutrino floor

Ratio bound/halo independent of cross section

The signal can be used for identifying the type of interaction

Conclusions

Inelastic Channels

- New Limits
- Reducing effectively the energy threshold of current detectors
- “Converting” non-directional detectors to directional ones

Shadow Effect

- probing elusive DM with shallow detectors
- precise recoil spectrum

Reflected Dark Matter

- Probing low masses

Bound Dark Matter

- Smoking Gun Signal for Dark Matter Discovery
- Identifying the type of interaction