# Extending the boundaries of Dark Matter Direct Detection experiments

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CP3 - Origins

Particle Physics & Origin of Mass

University of Southern Denmark

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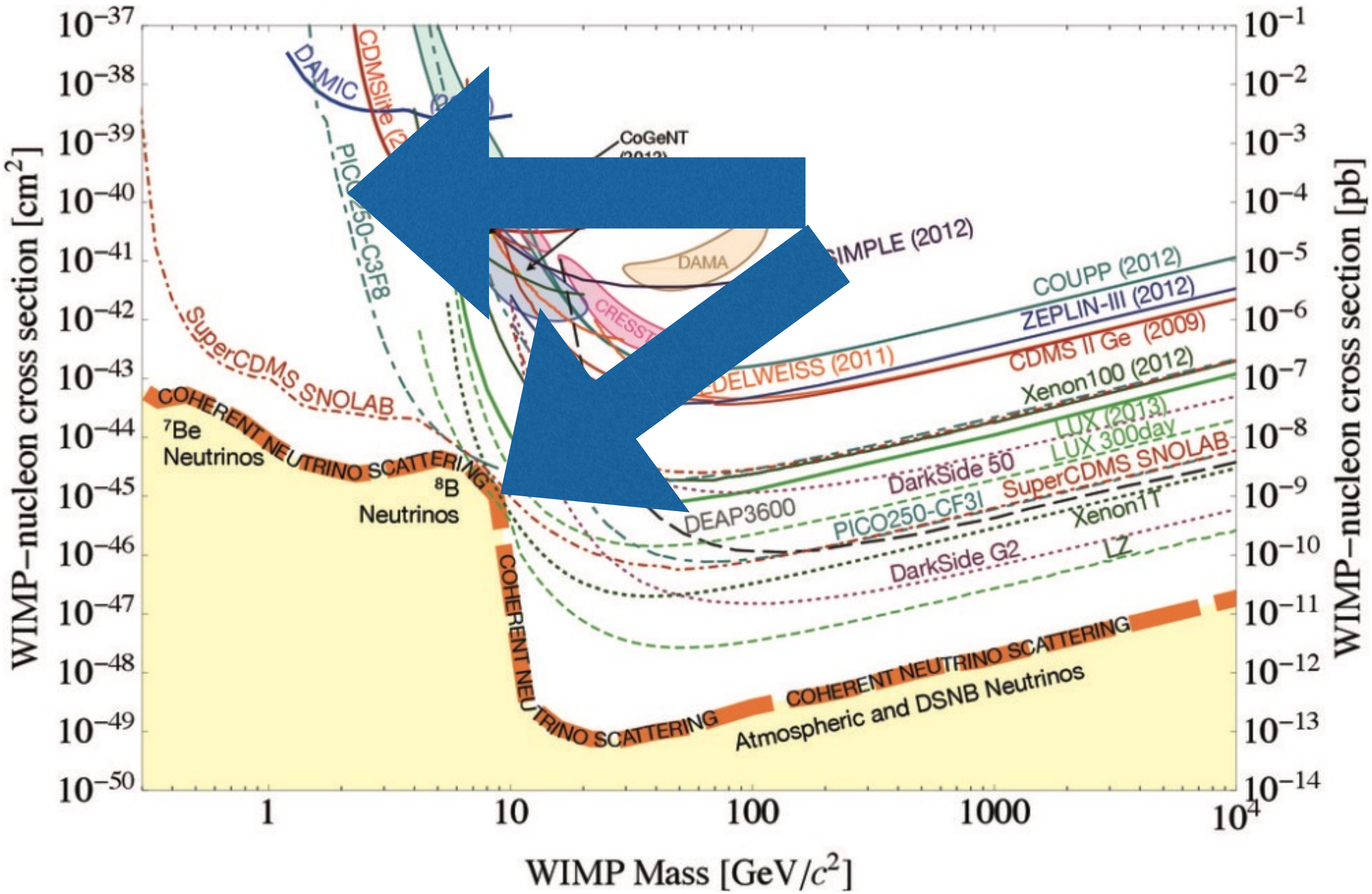
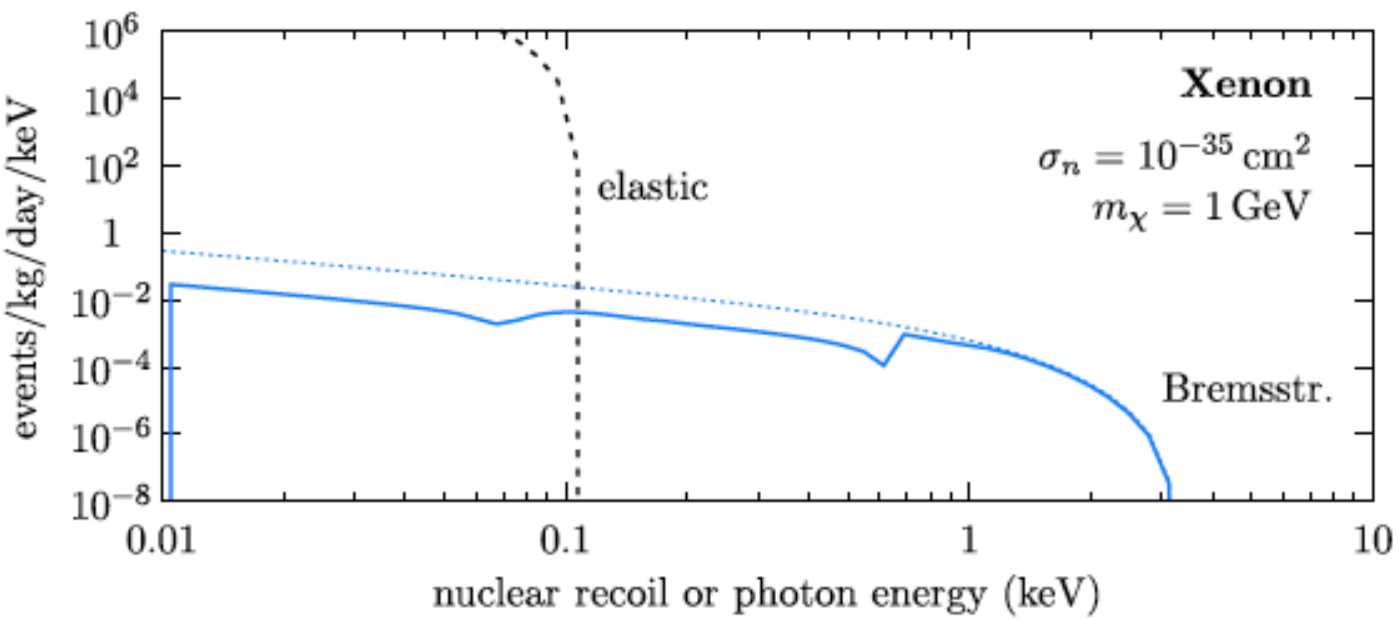
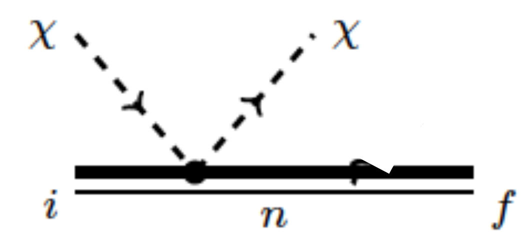
# Probing New Territory in Dark Matter Direct Detection



# Probing sub-GeV Dark Matter with Inelastic Channels



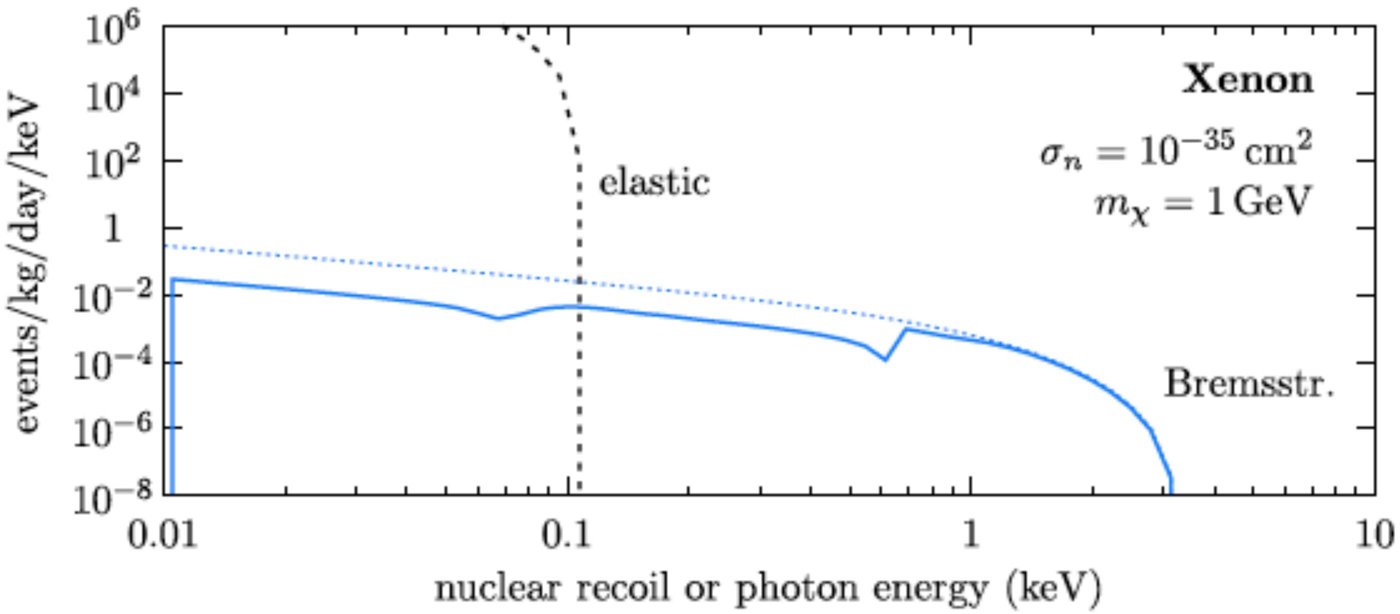

$$|V_{fi}|^2 = 2\pi\omega |M_{\mathrm{el}}|^2 \left| \sum_{n,n\neq i} \left[ \frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\,\langle n|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\,\langle f|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha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

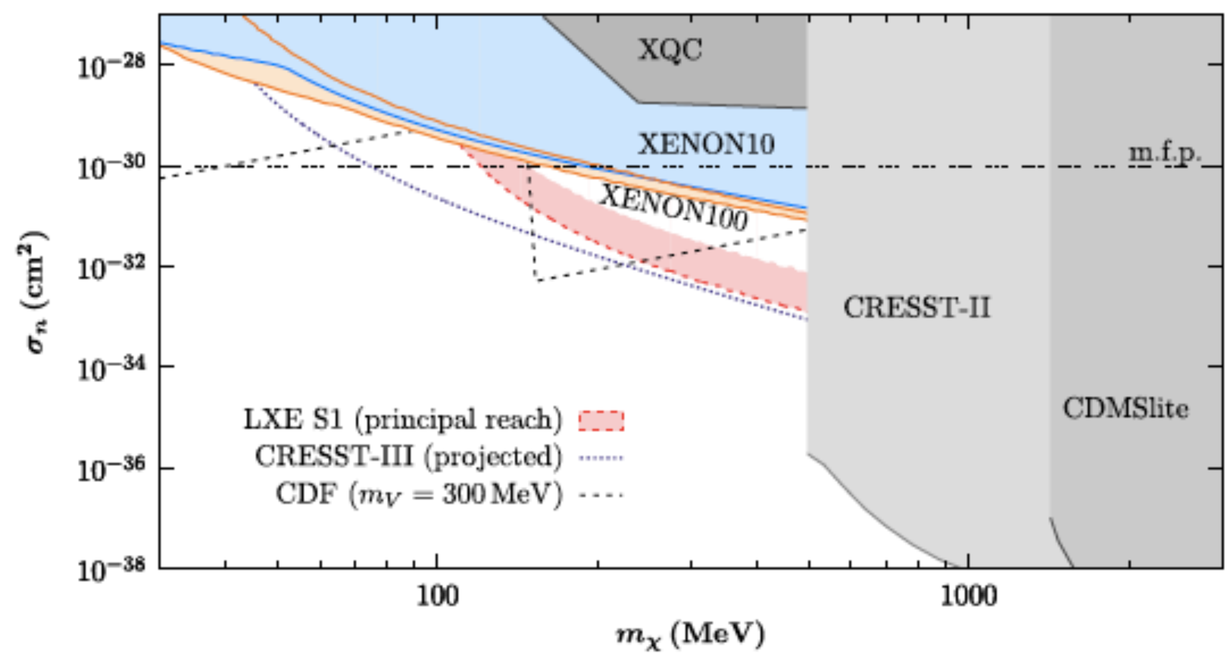
$$\frac{d\sigma}{d\omega dE_R} = \frac{4\omega^3}{3\pi}\frac{E_R}{m_N}\frac{m_e^2|\alpha(\omega)|^2}{\alpha} \times \frac{d\sigma}{dE_R}\Theta(\omega_{\max}-\omega)$$

CK, Pradler PRL '17

Majorana Experiment to test the formula using a neutron beam on a semiconductor target

# sub-GeV Limits on Dark Matter

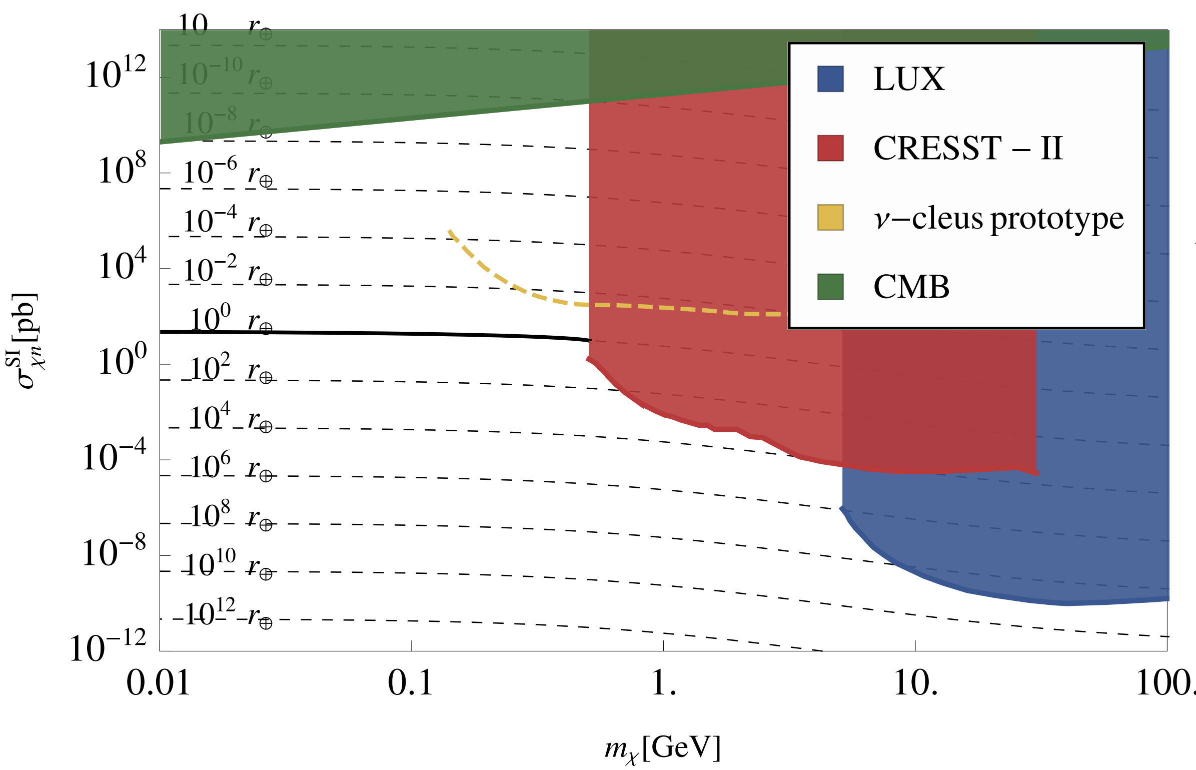



CK, Pradler PRL '17,
McCabe '17
Ibe, Nakano, Shoji, Suzuki '17
Dolan, Kahlhoefer, McCabe '17

- First time limits on sub-GeV DM with DM-nucleon interactions
- "Converting" a conventional detector to a directional one
- Generalize to final states that leave the atom excited
- Different DM-nucleon operators

# Dark Matter in the Shadow of the Earth




Emken, CK,'17

There is light dark matter phase space that might not be covered by underground experiments even if they lower their energy threshold due to effective stopping by the rock.

Need for detectors in shallow sites or on surface
However this would increase the background!

Observing a daily varying dark matter signal
Avignone Collar '93, CK, Shoemaker '14, Foot Vagnozzi '15

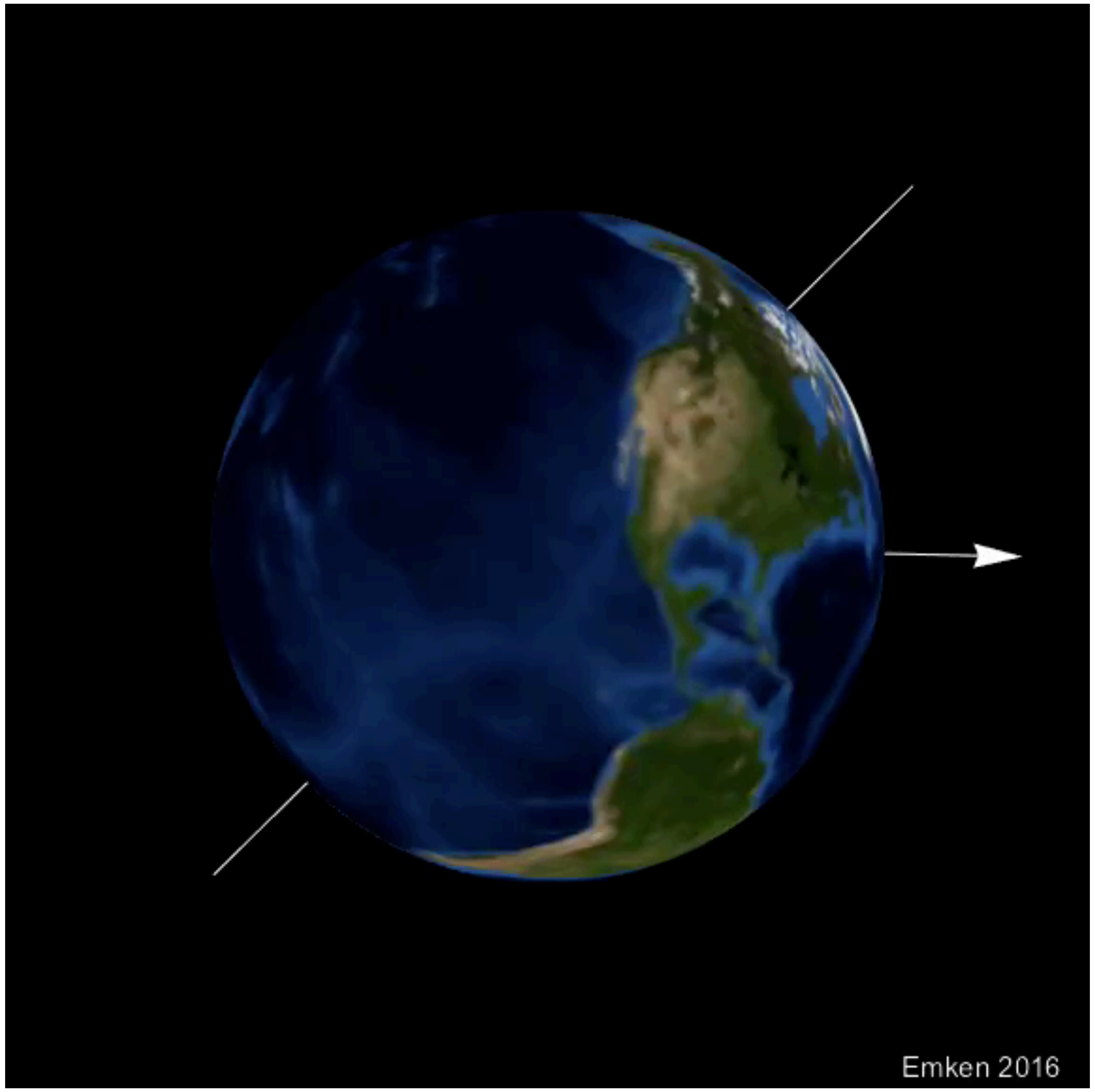
- Ideal for portable detectors like DAMIC can be placed either on the surface or in shallow sites
- Best latitude at the south hemisphere ~43 degrees. Chile, Argentina, Australia, New Zealand

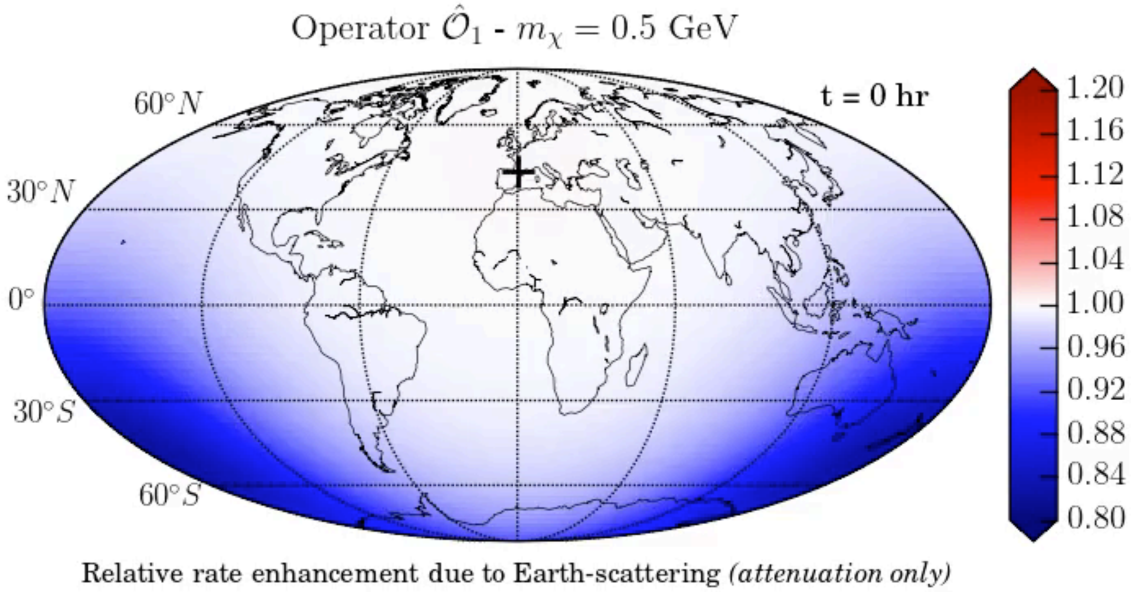
The effect can be probed also in directional detectors manifesting itself as a top-down asymmetry CK'15

# 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



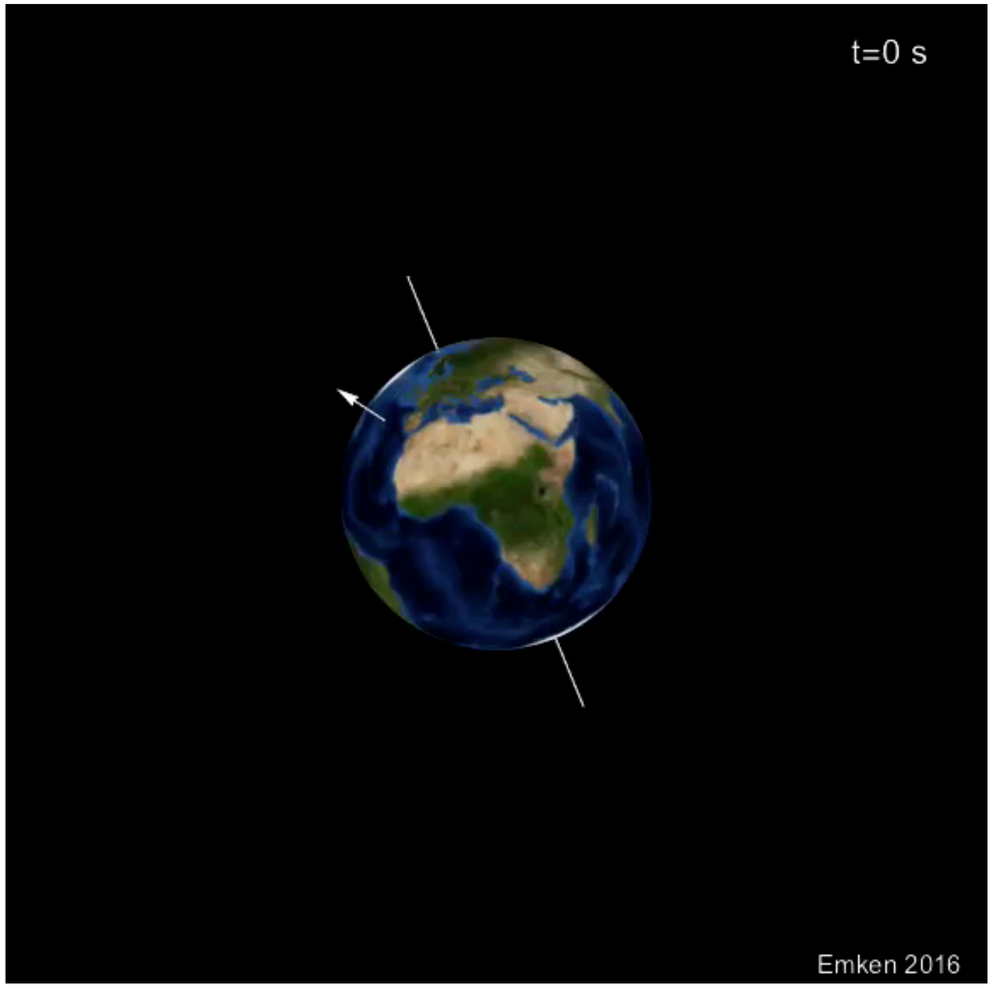



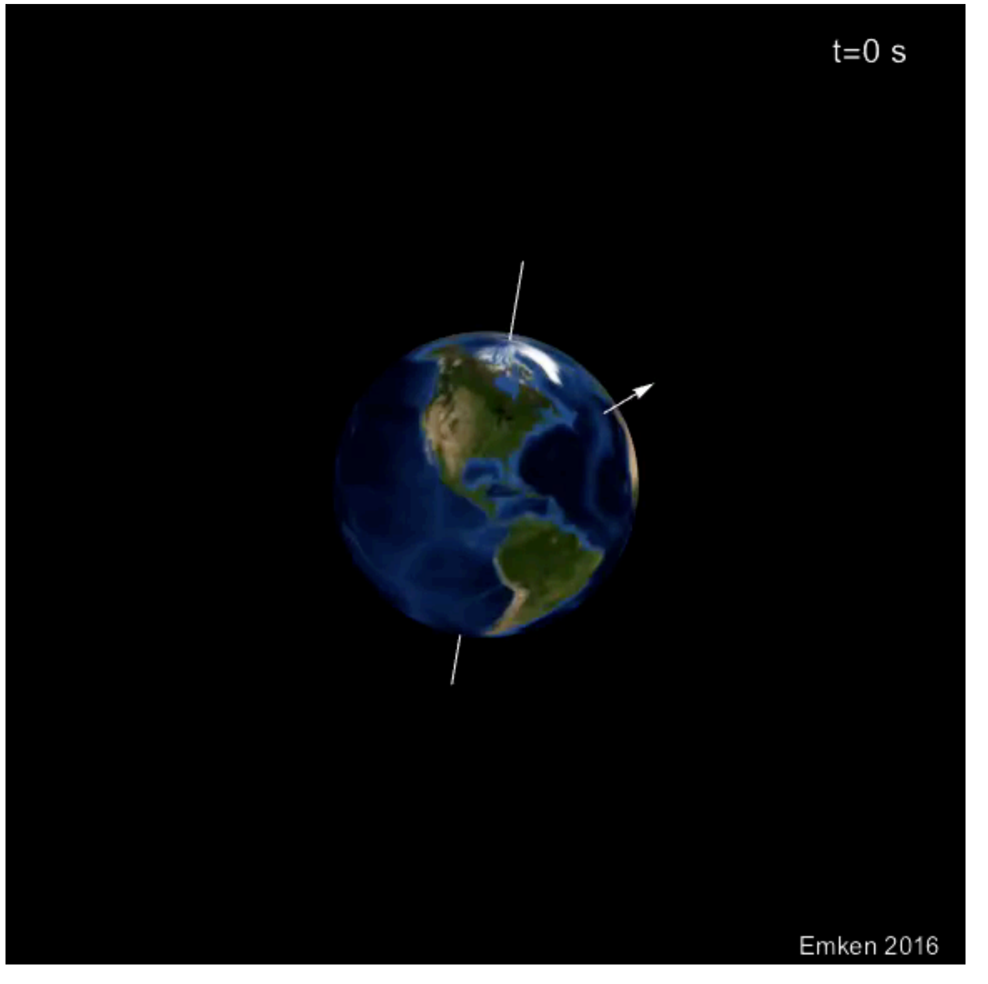

Kavanagh, Catena, CK '17

# DAMASCUS: Dark Matter on Supercomputers

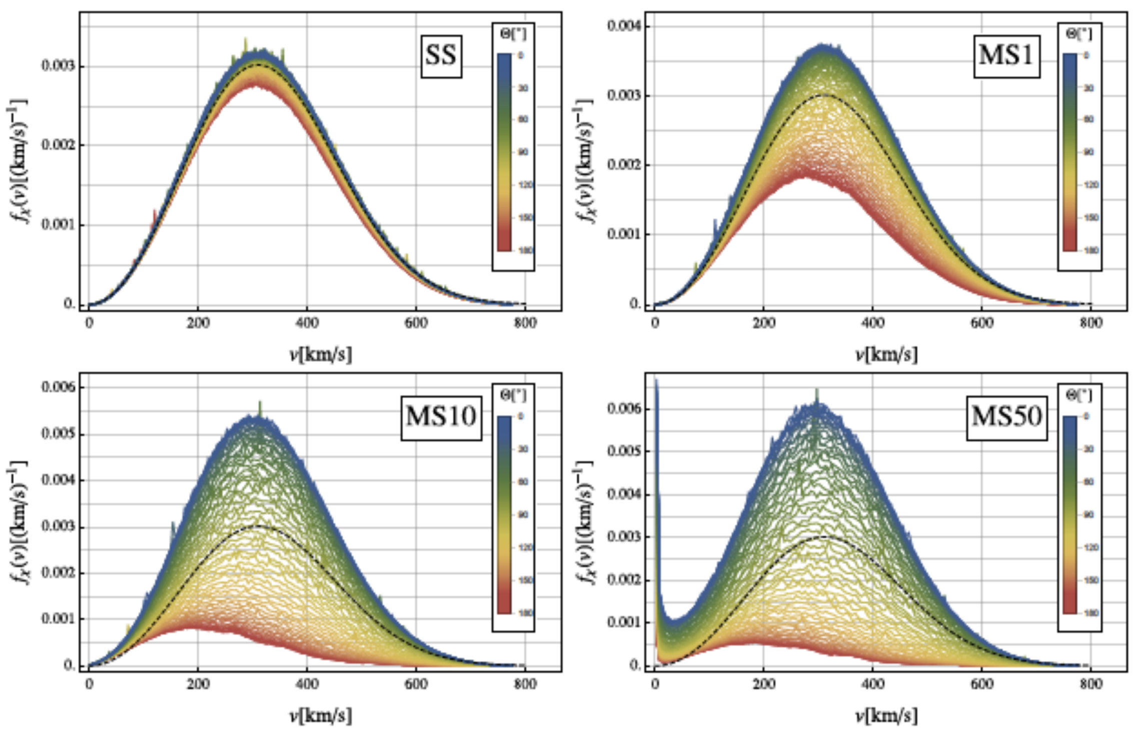
Performing a simulation of trillions of DM particles on ABACUS

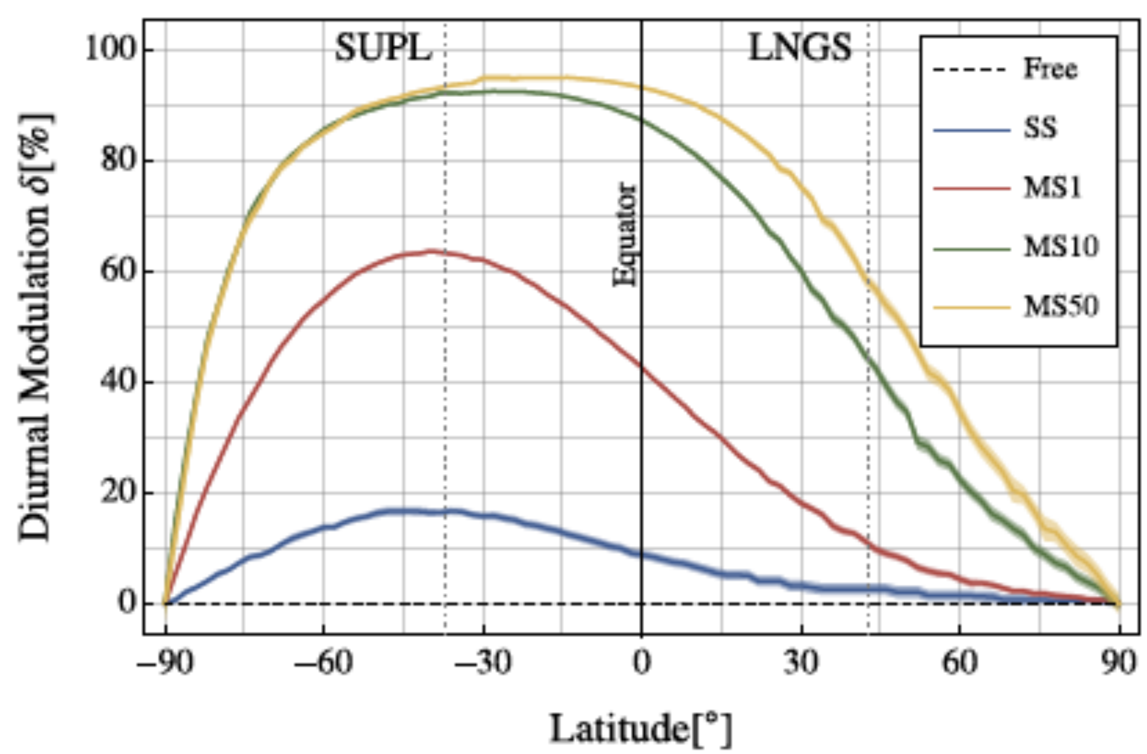
- fully parallelized code
- publicly available
- state-of-the-art composition and density profiles of the Earth
- Precise Recoil Spectrum
- Test self-consistency of experiments
- Probe Currently Elusive Dark Matter



# DAMASCUS running on high cross section



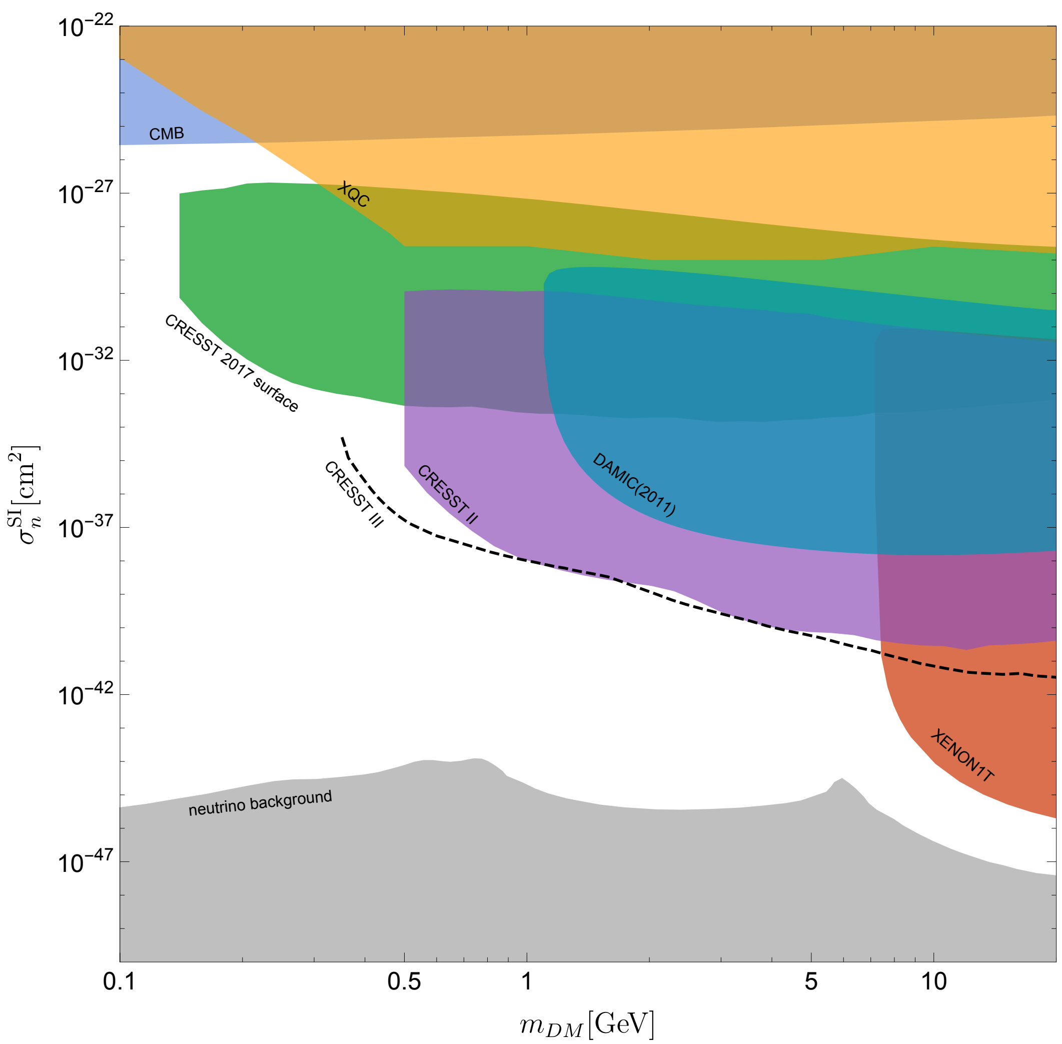



# How Blind are Underground Detectors to Strongly Interacting Dark Matter?

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.

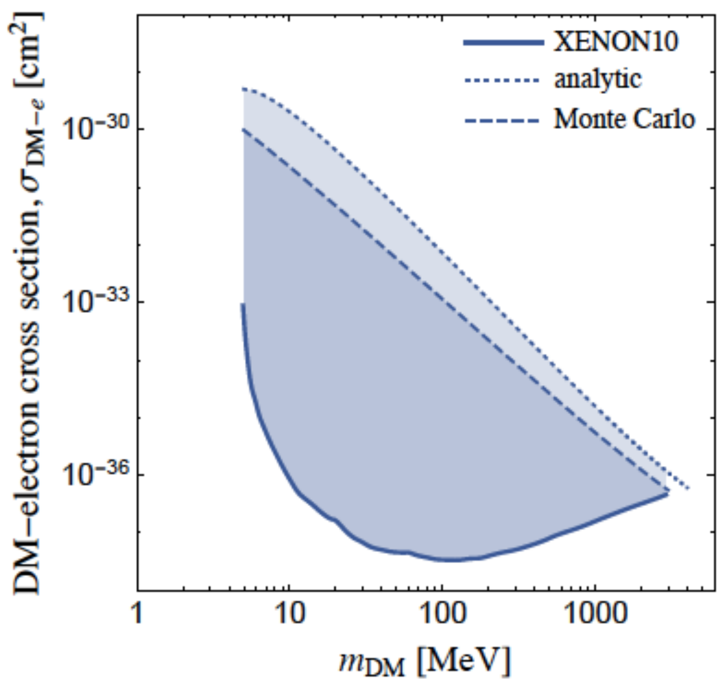
Monte Carlo simulations using DAMASCUS-Crust including atmosphere, shielding and crust

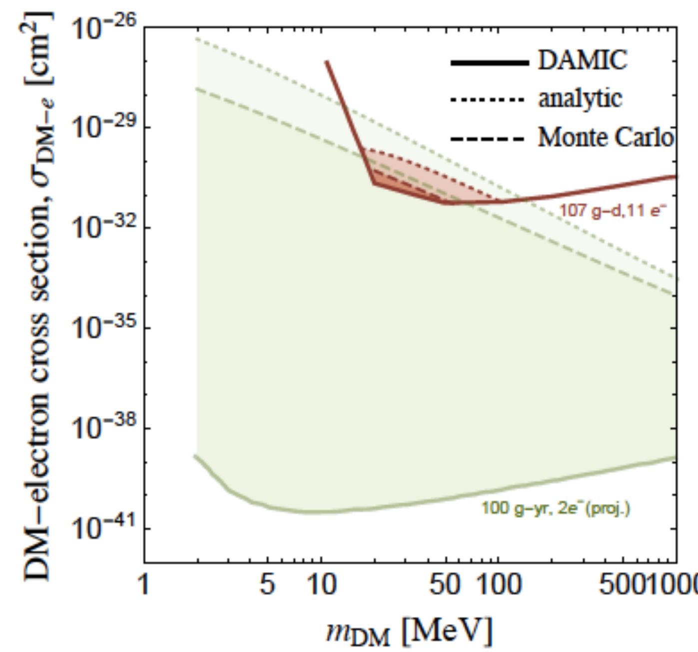



Emken, CK '18

# DM-Electron Scattering

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




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

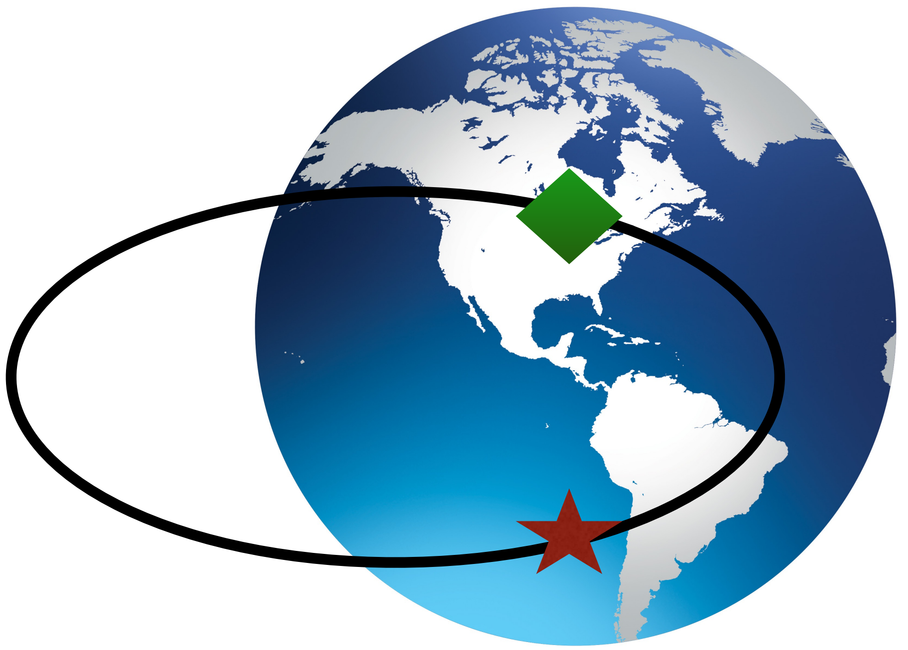
Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, '16, Emken, CK, Shoemaker '17

## What's the big deal?

EDGES has observed a larger than expected absorption in the 21cm line.
This is consistent with reduced baryon kinetic energy at z=17.
Loeb, Munoz '18 can explain this with a small fraction of millicharged DM

How is millicharged DM affected by stopping?
We can either exclude it or identify experimental blind spots
Could have been hidden within existing data due to stopping related abnormal spectrum?

# Detecting Bound Dark Matter



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

Damour, Krauss '98,
CK, Catena '16

capture $\sigma$

accumulation time $1/\sigma$

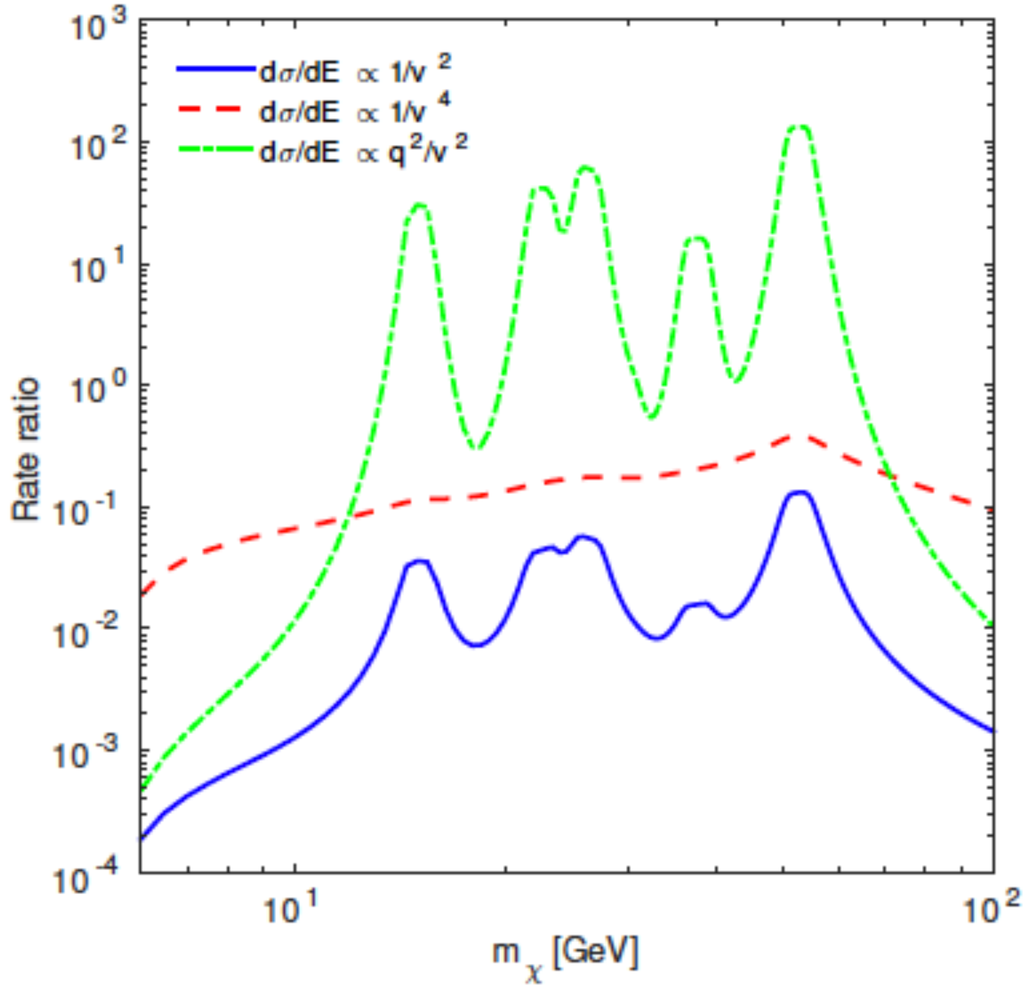
rate of events: nondirectional $\sigma$

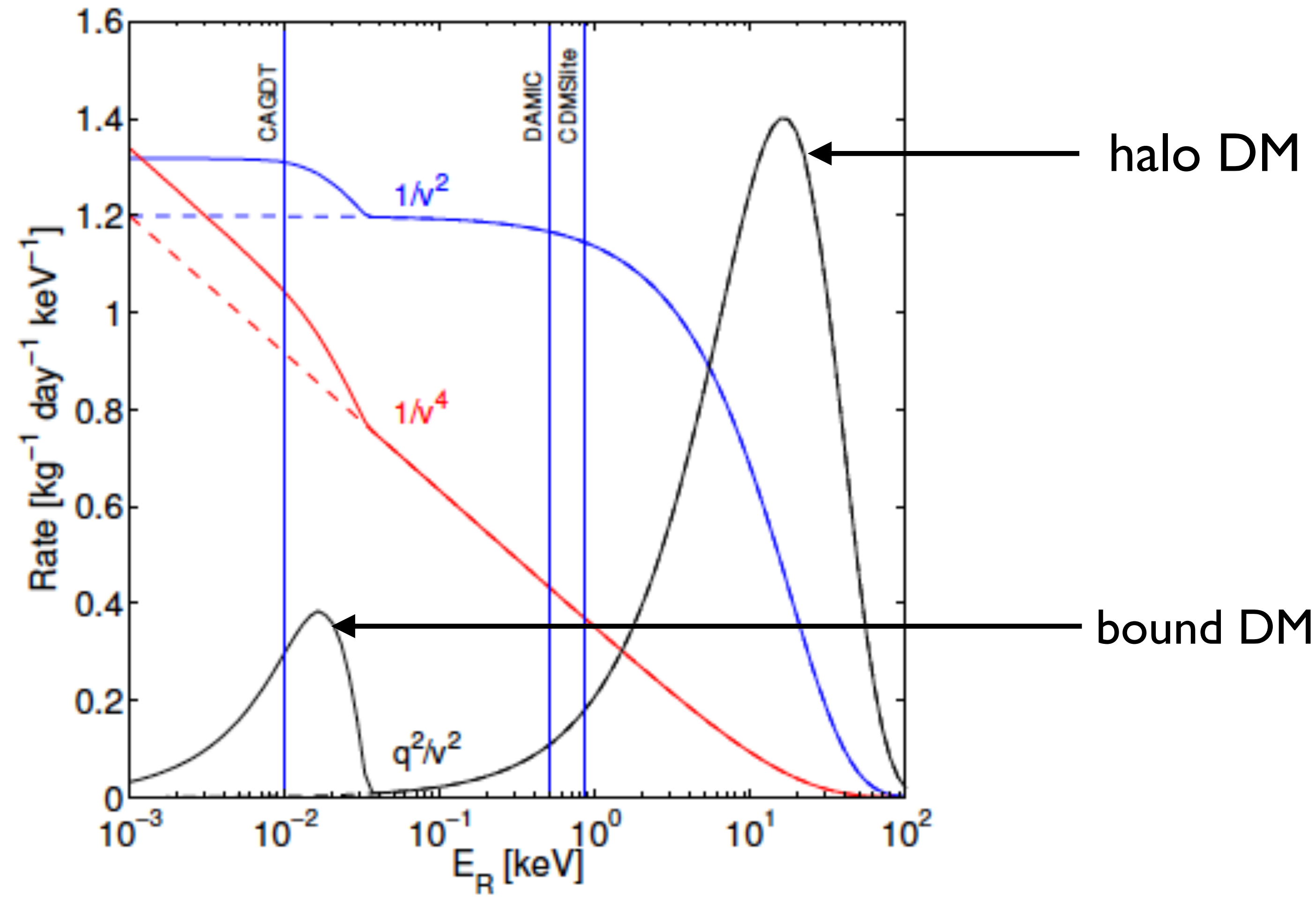
directional

# Dark Matter-Nucleus effective interactions

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

# A “smoking gun” for direct detection




CK, Catena ‘16

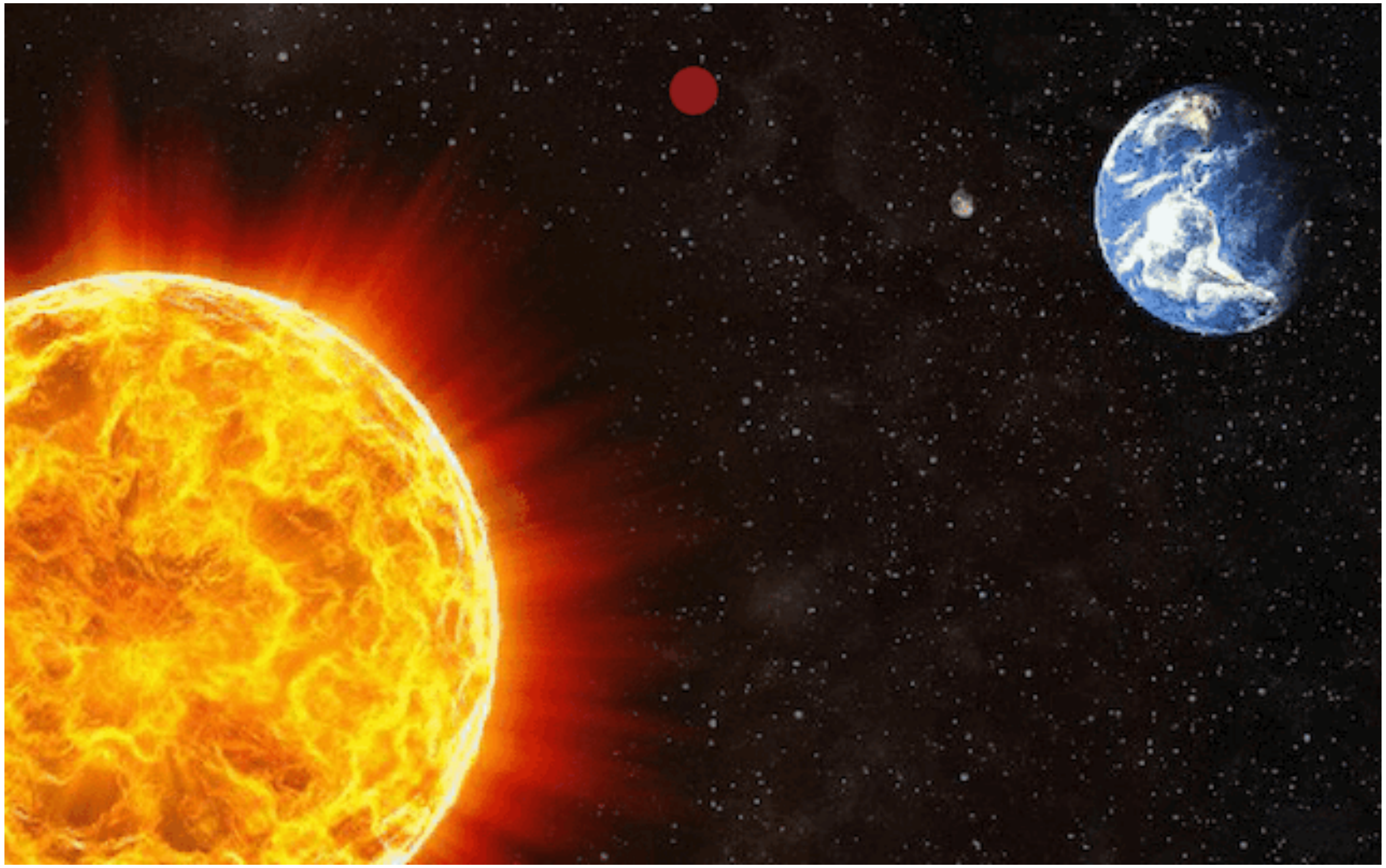
Low experimental energy threshold is essential

Go beyond the neutrino floor

Ratio bound/halo independent of cross section

The signal can be used for identifying the type of interaction

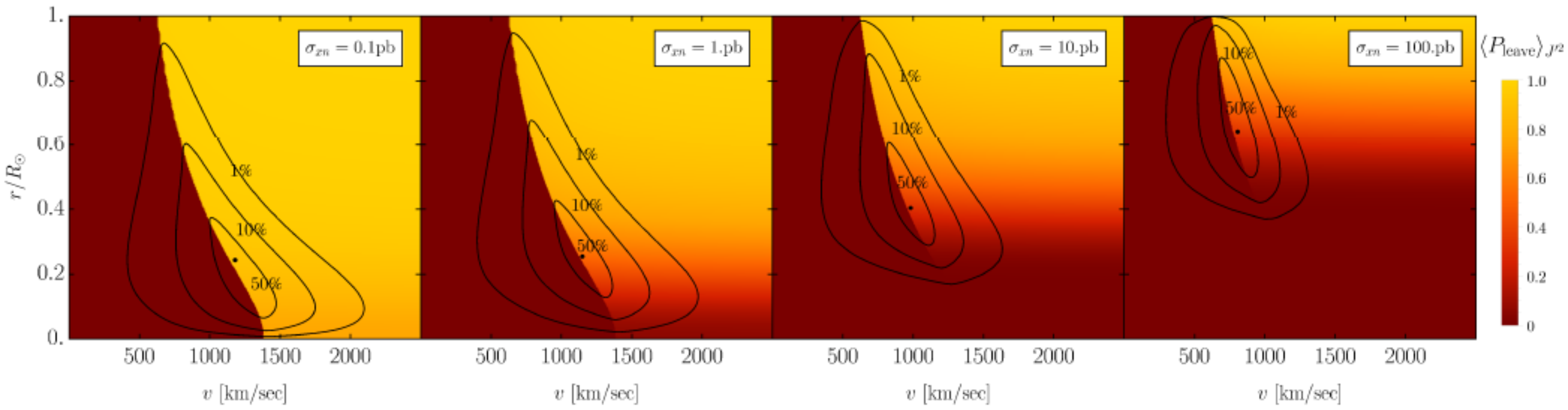
# Reflecting off the Sun



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

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




Emken,CK, Nielsen '17

Similar Ideas:

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

# Reflecting off the Sun

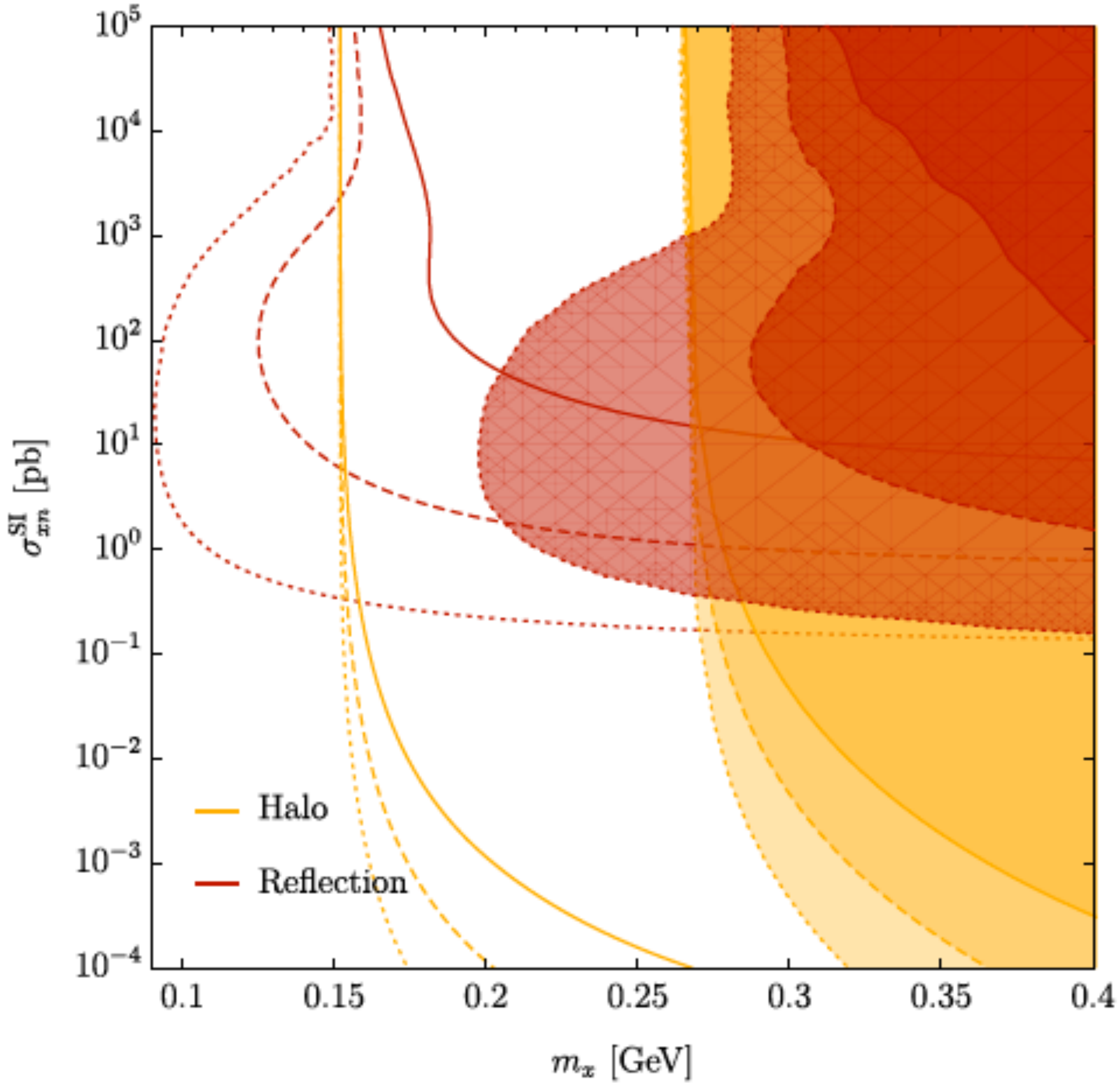



FIG. 2. Solar reflected DM in red and halo DM in yellow. The filled contours project constraints for a CRESST-III type detector with exposures of 1/10/100 ton·days (solid/dashed/dotted). The free lines project constraints for an idealized sapphire detector (perfect energy resolution and no background) 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.

# 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
- test the DM explanation of the 21cm line

## Bound Dark Matter

- Independent of cross section
- Unique "Smoking Gun" Signal in Low Recoil
- Could alleviate the neutrino floor problem

## Dark Matter Reflected off the Sun

- Boost limits in the MeV region
- Independent of Halo Velocity Distribution