University of Southern Denmark

Probing Light Dark Matter

Chris Kouvaris

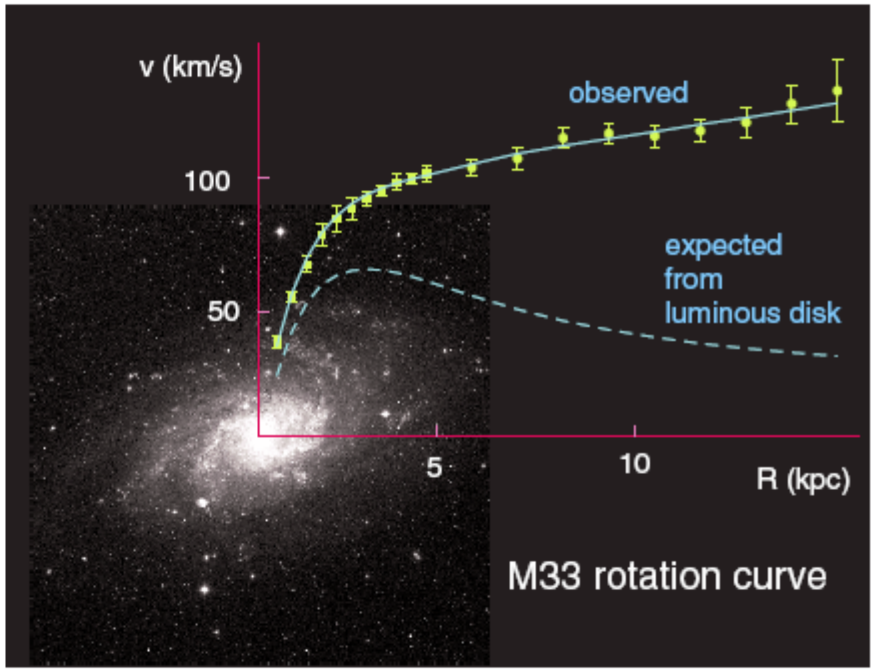
CP3 - Origins

Particle Physics & Origin of Mass

University of Coimbra, 13 December 2018

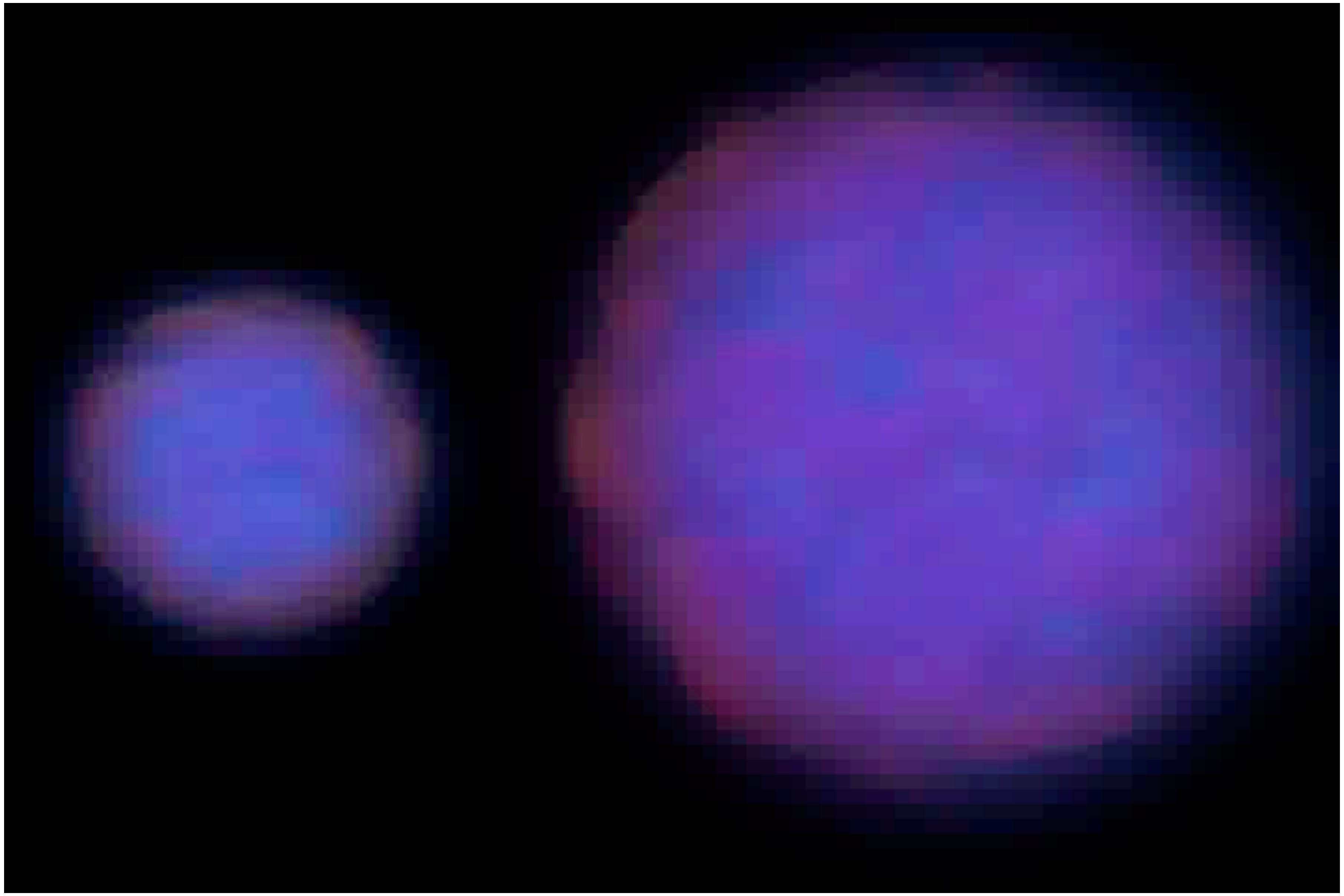
The Missing Mass of the Universe

A Mystery for 80 years!



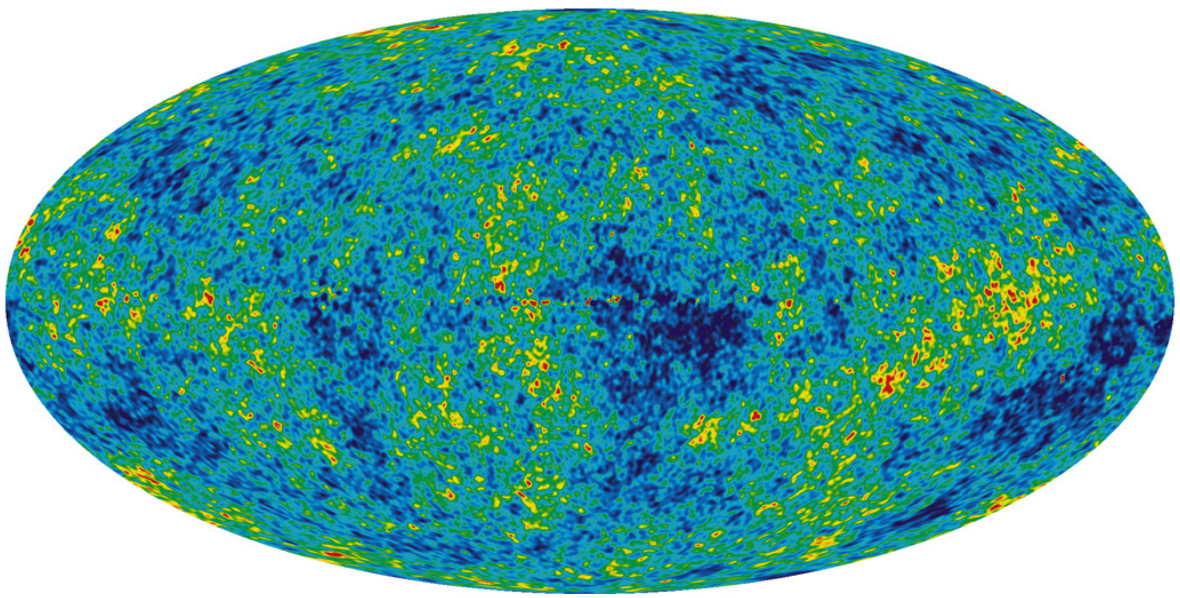
Rotation curves of Andromeda are not
falling according to Newton's law!

Bullet Cluster

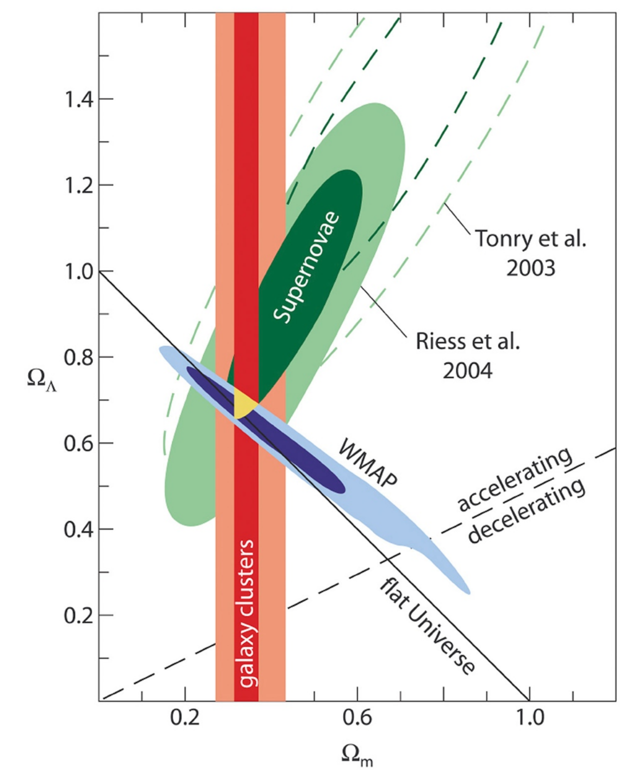


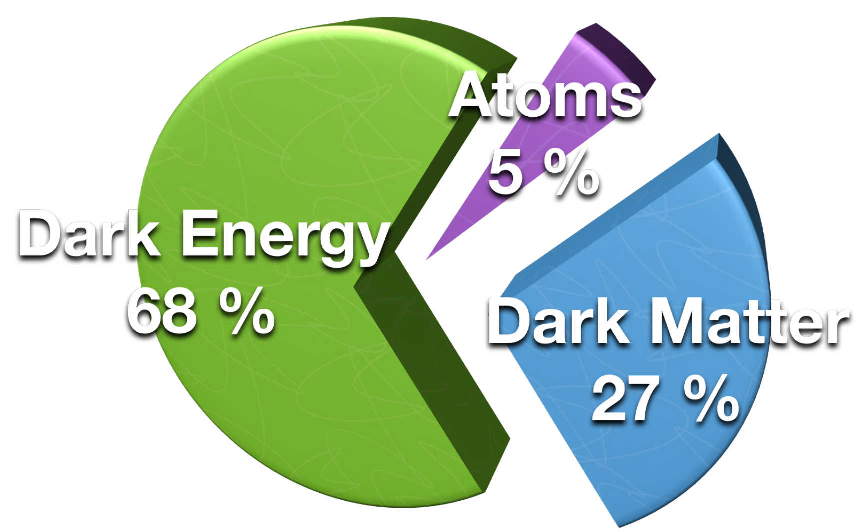
Bullet Cluster

Dark Matter

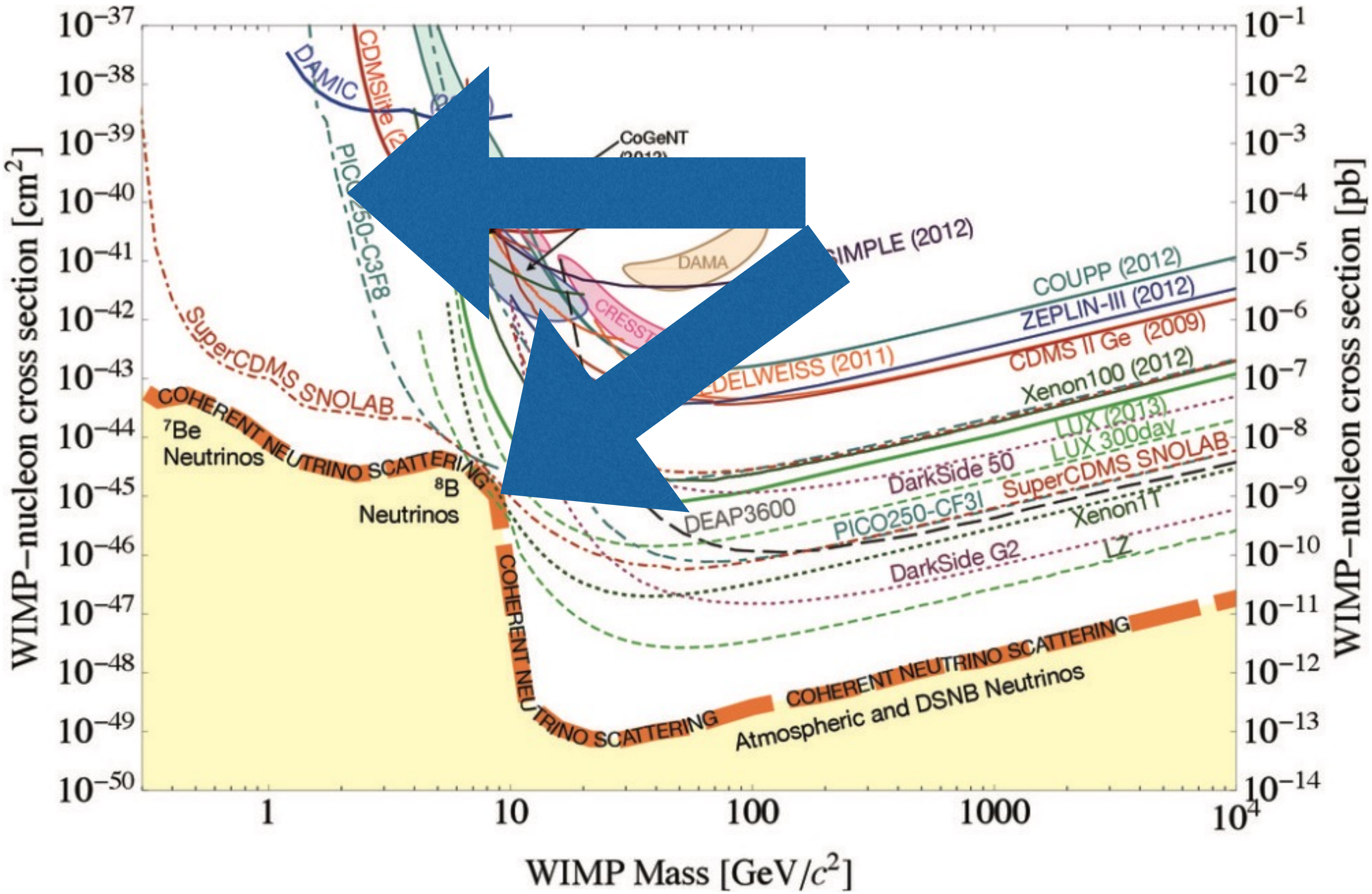


Microwave Background Radiation





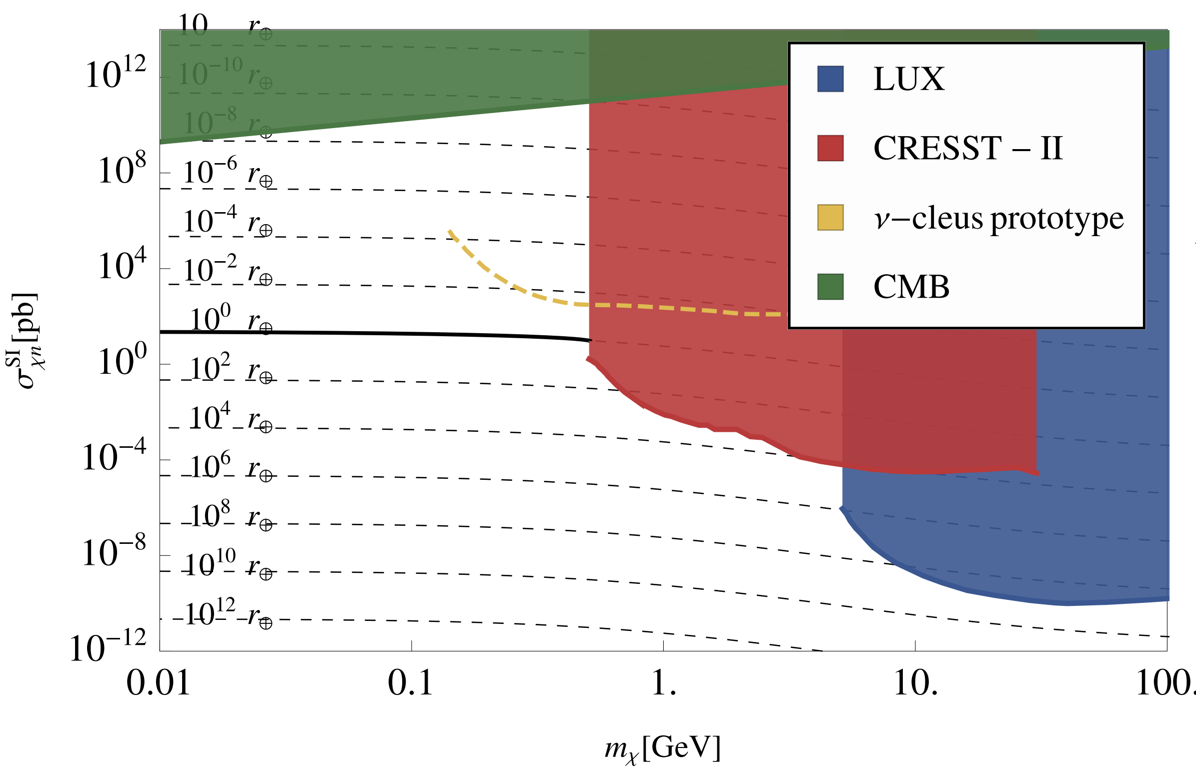
Probing New Territory in Dark Matter Direct Detection



Probing New Territory in Dark Matter Direct Detection

- Terrestrial Effects on Direct Detection
- Dark Matter via inelastic channels
- Dark Matter Reflected off the Sun
- Bound Dark Matter to the Earth

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!

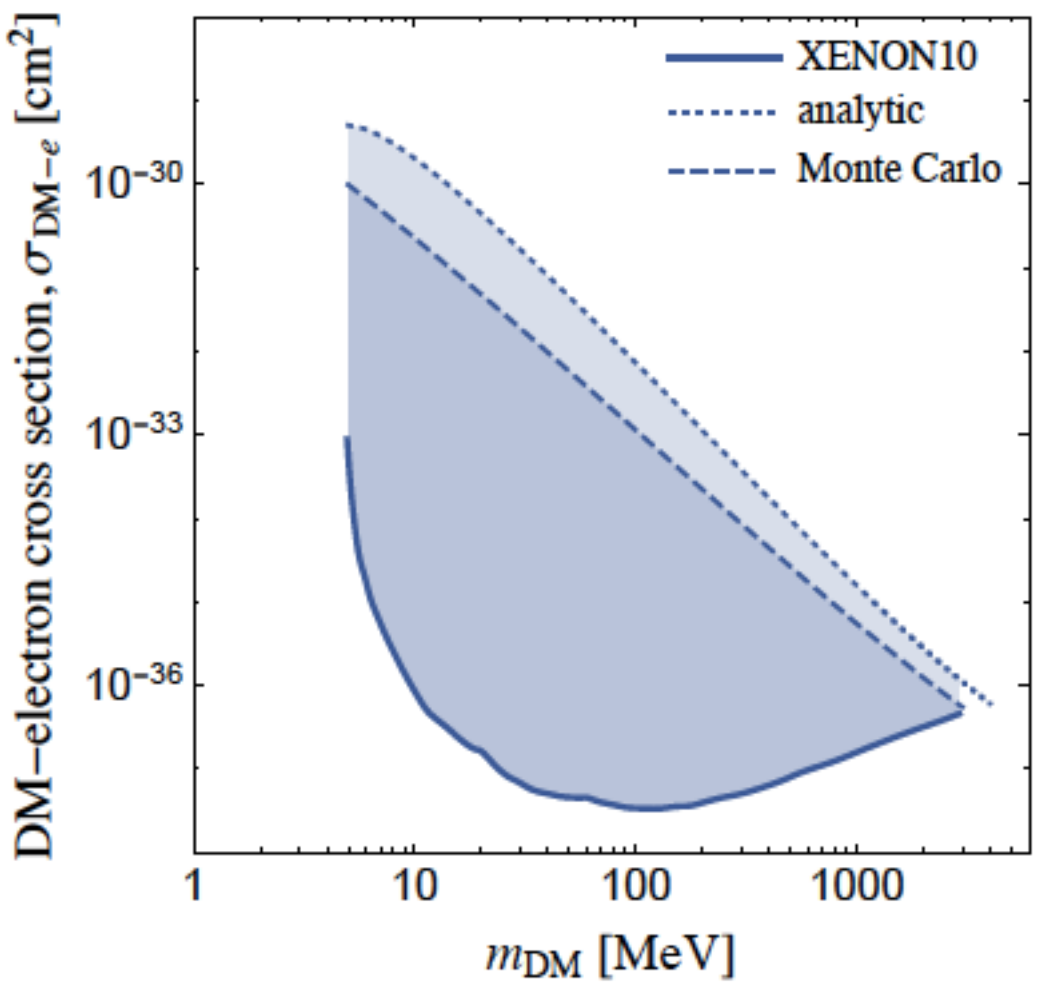
Observing a daily varying dark matter signal
Avignone Collar '93, CK, Shoemaker '14, Foot Vagnozzi '15

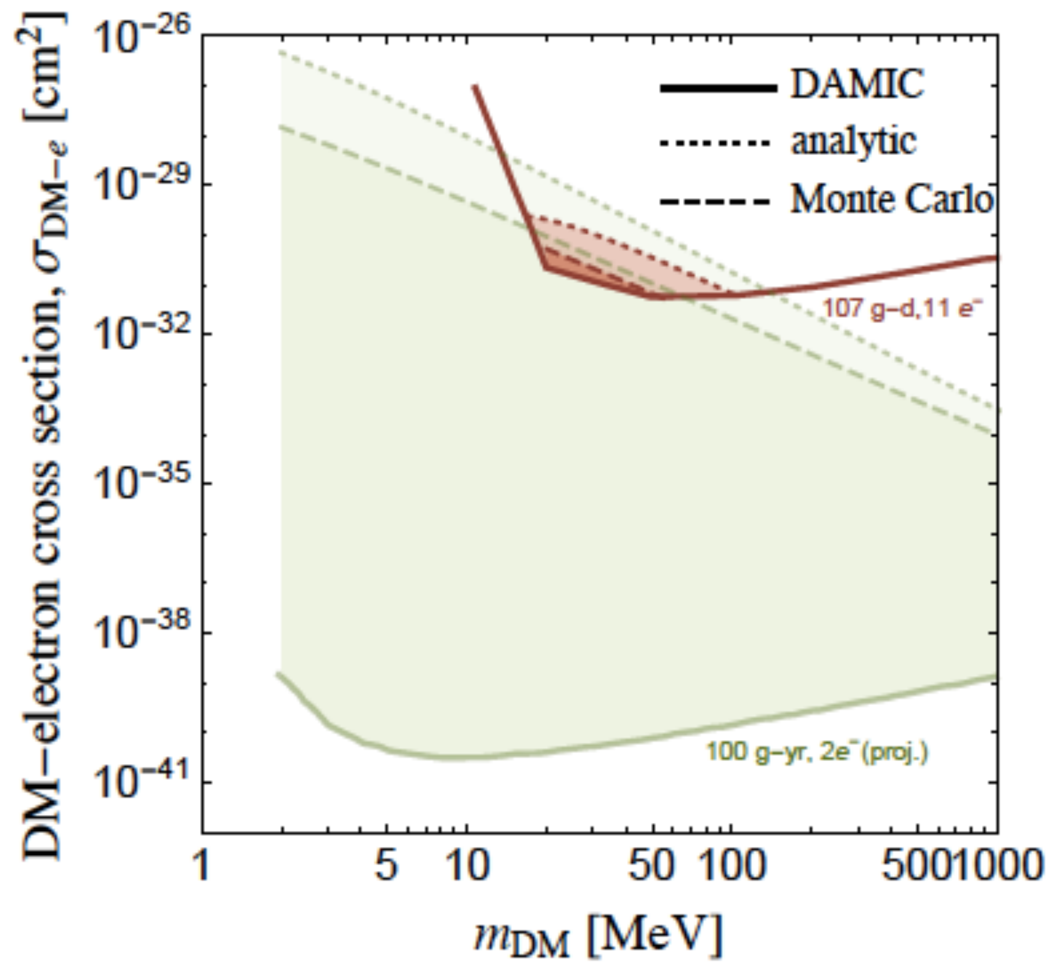
- Ideal for portable detectors like DAMIC can be placed either on the surface or in shallow sites
- Best latitude at the southern hemisphere ~43 degrees. Chile, Argentina, Australia, New Zealand

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

Re-visiting Direct Detection Limits

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





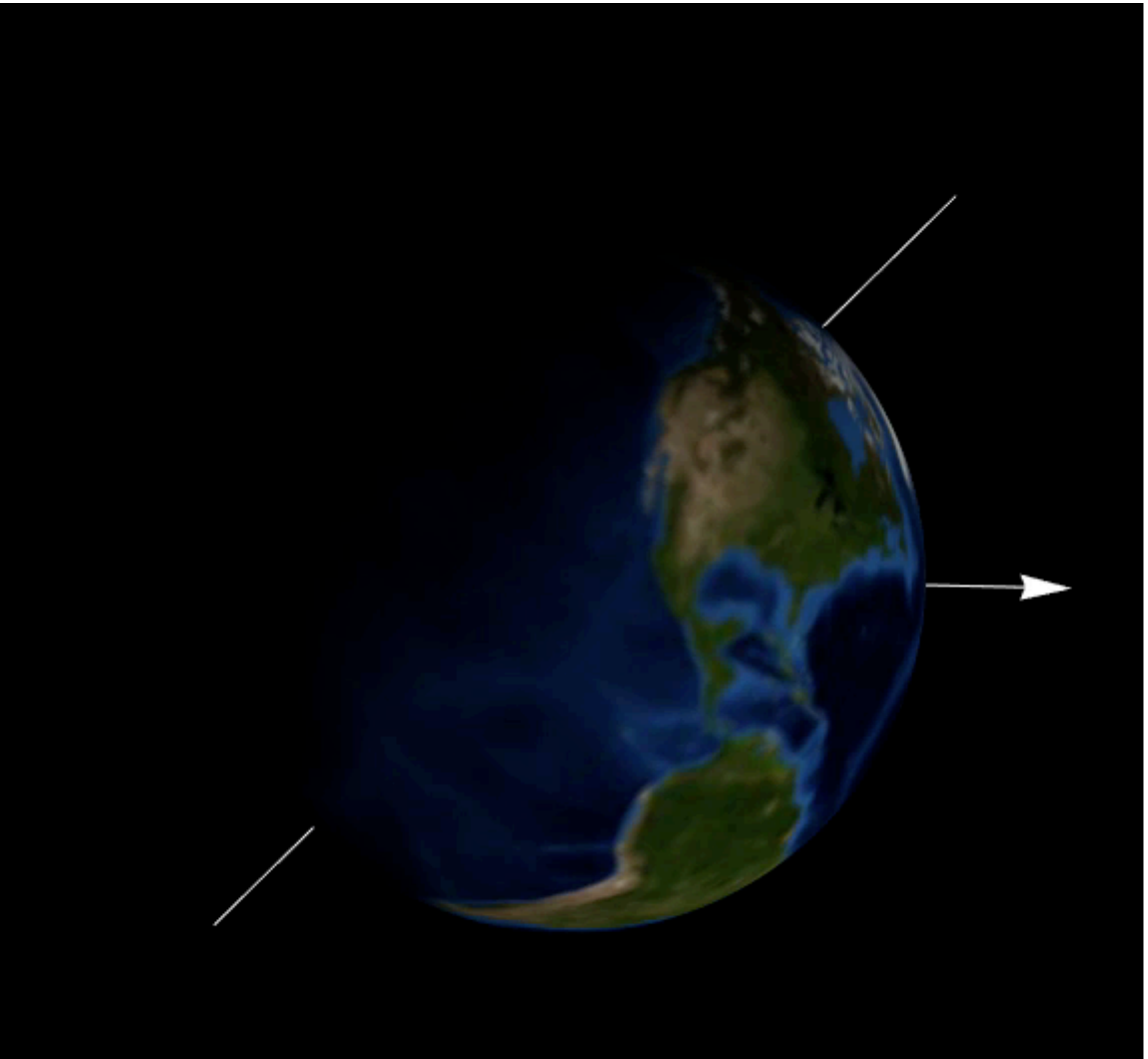
Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, '16, Emken, CK, Shoemaker '17

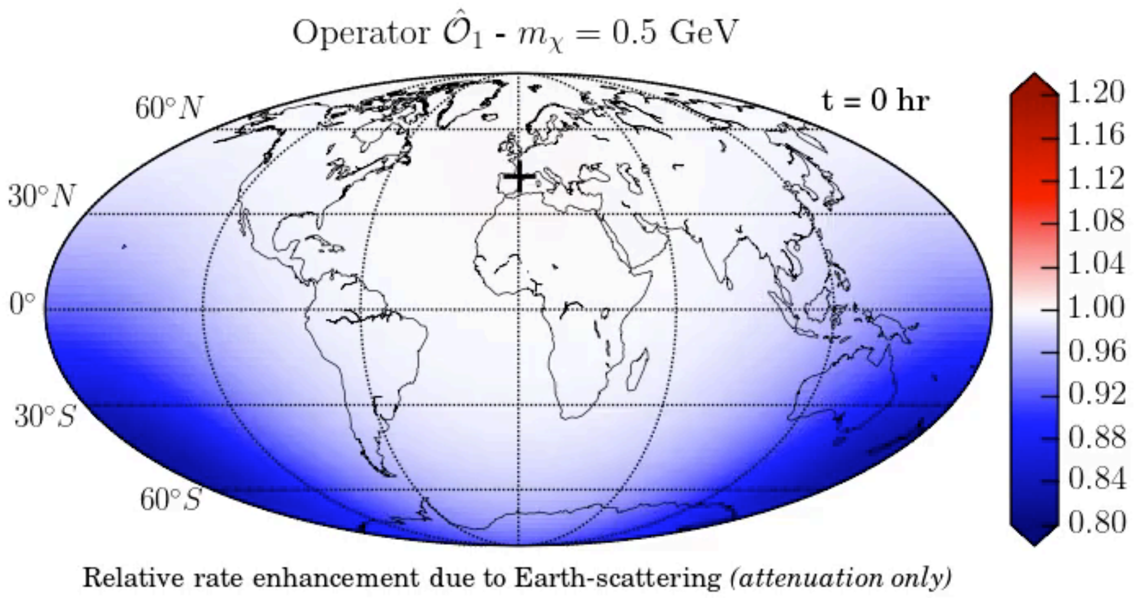
Experiment	Depth [m]	$E_{\rm thr}$[eV]
XENON10	1400	12.4
DAMIC	100	40
DAMIC (proj.)	100	$\sim 1-2$

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



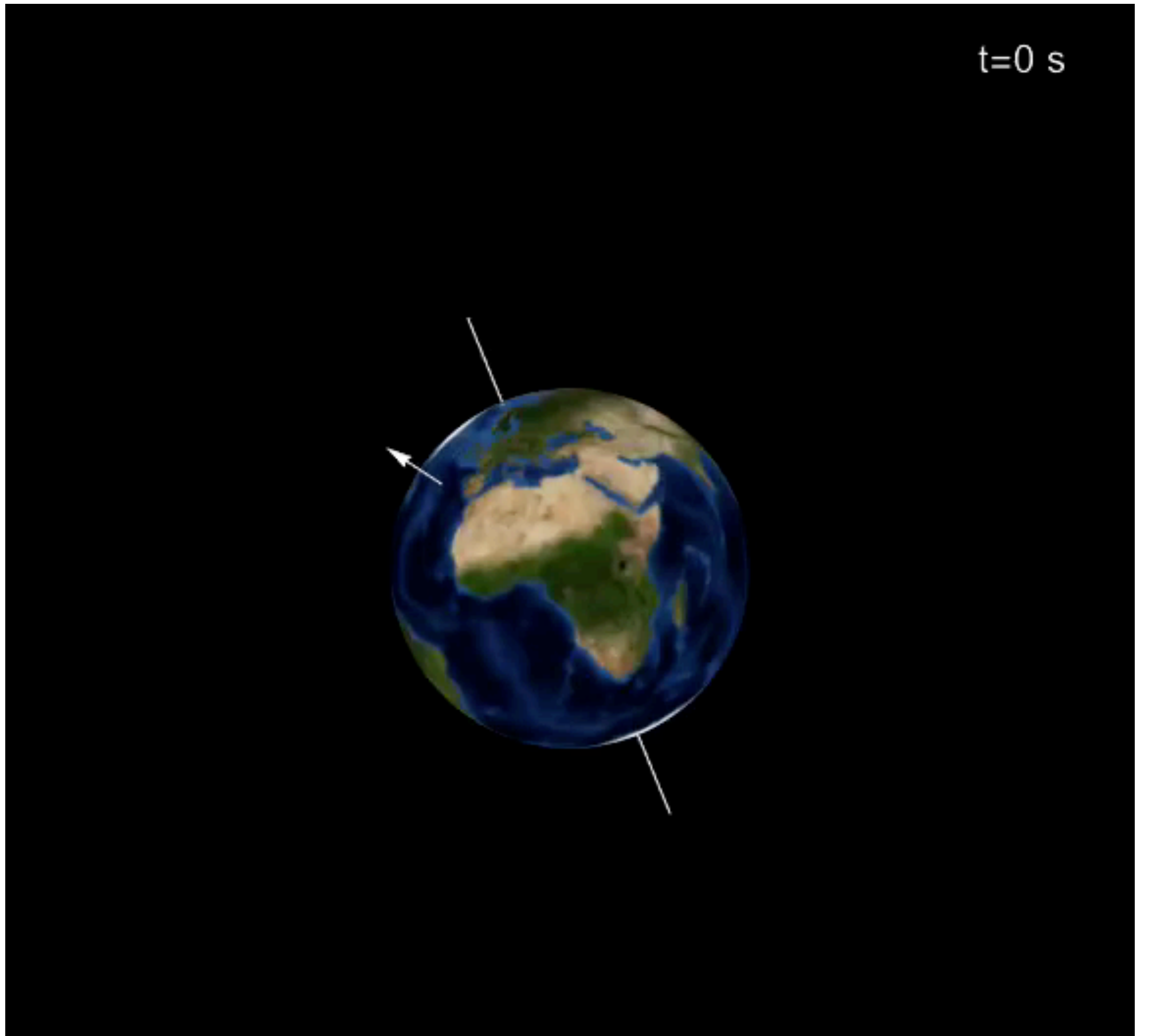


Kavanagh, Catena, CK '17

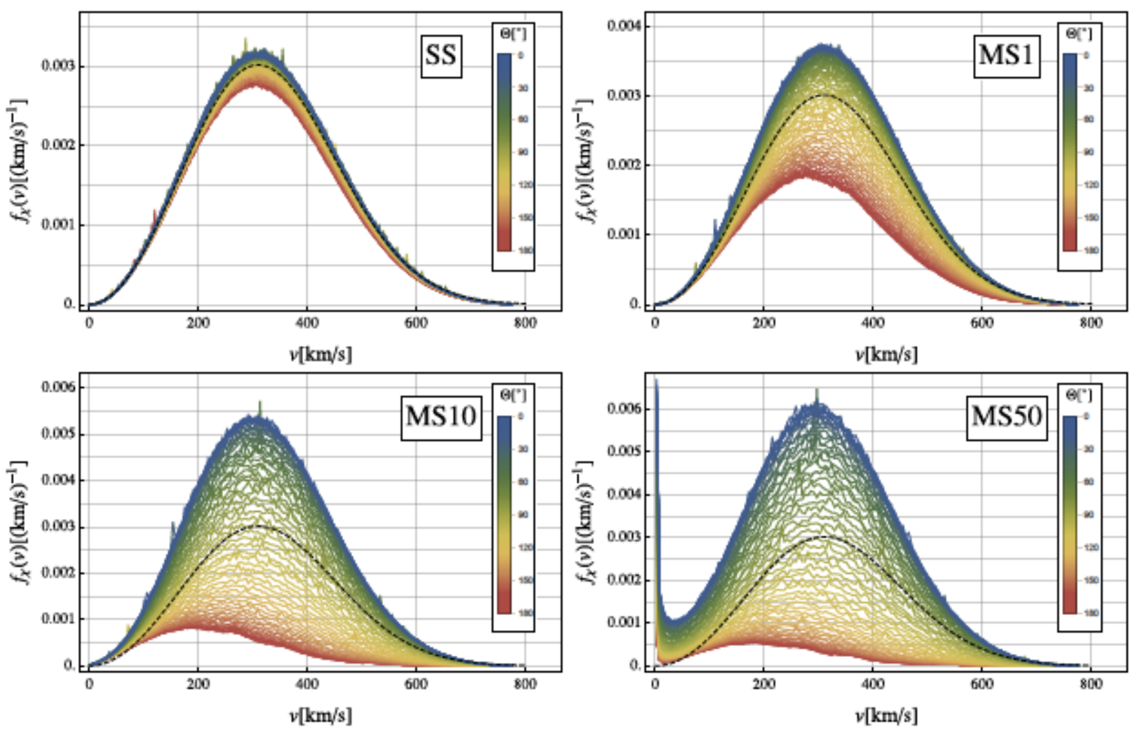
DAMASCUS: Dark Matter on Supercomputers

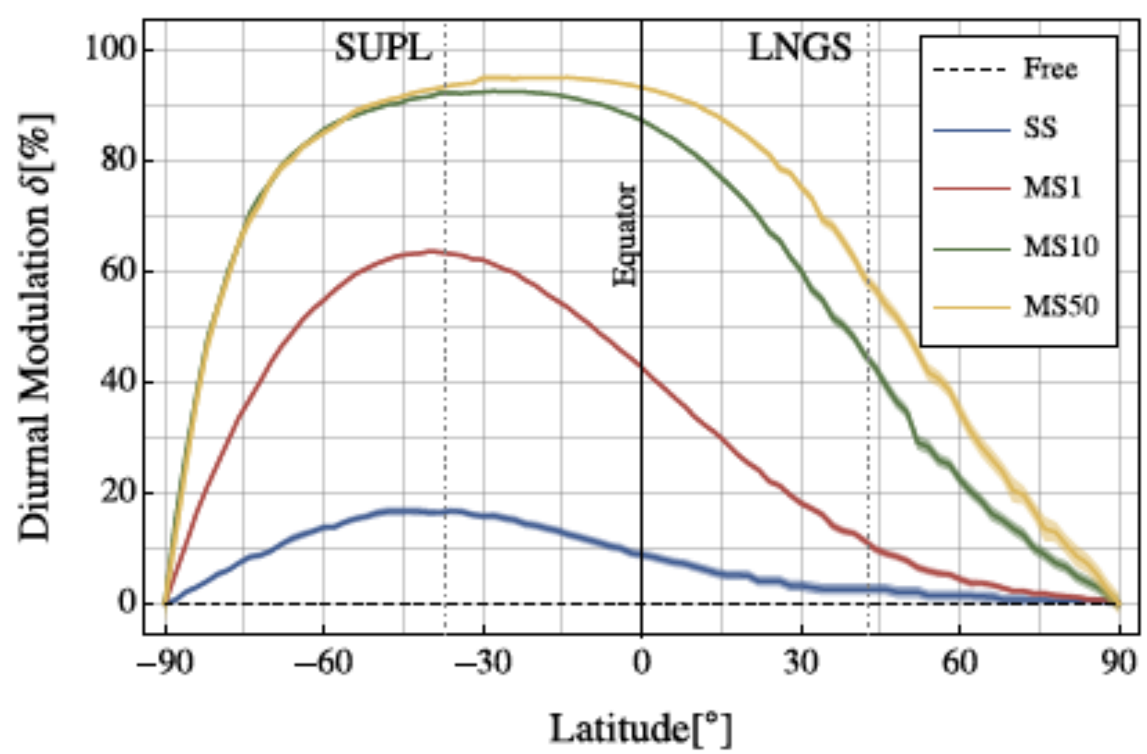
Performing a simulation of trillions of DM particles on ABACUS

- 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



DAMASCUS running on high cross section



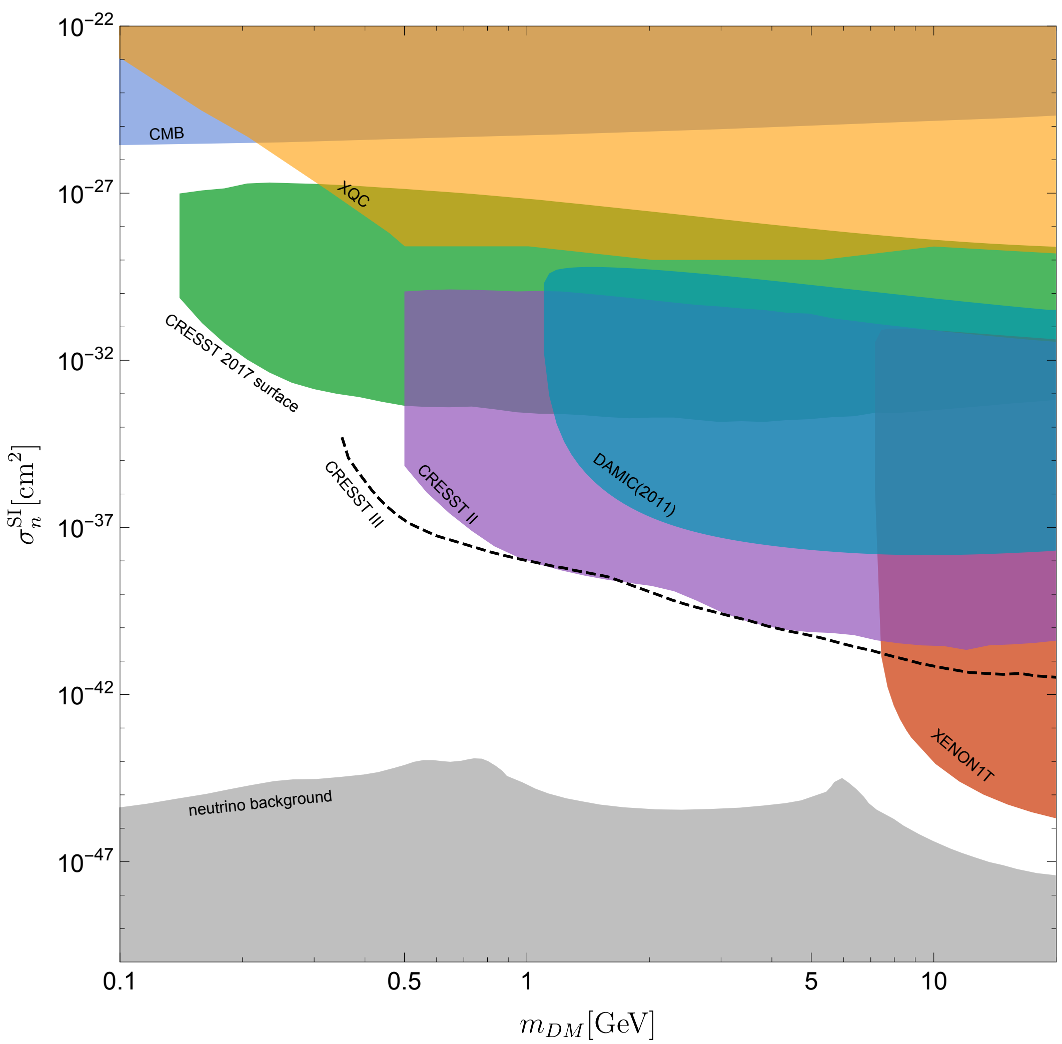


How Blind are Underground Detectors to Strongly Interacting Dark Matter?

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

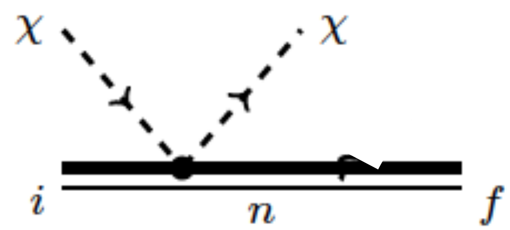
The critical cross section is independent of the exposure, so detectors can be blind for part of the parameter space regardless of how long they accumulate data.

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



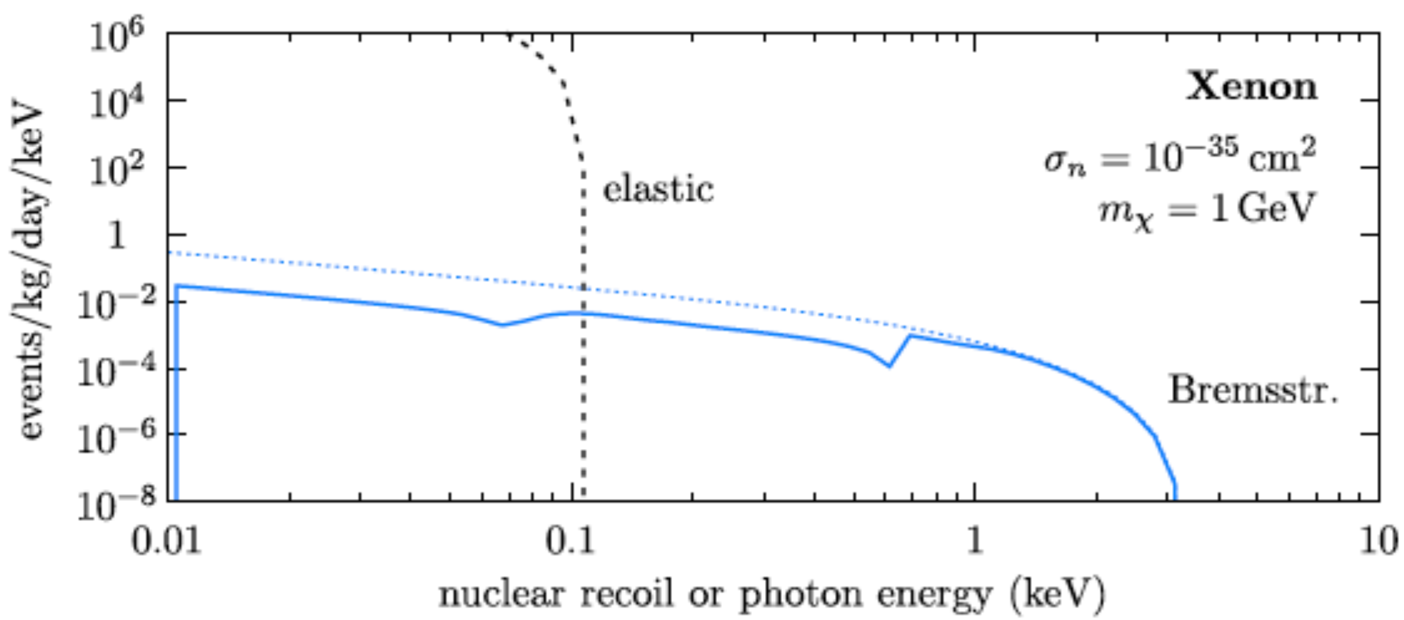
Emken, CK ’18

Probing sub-GeV Dark Matter



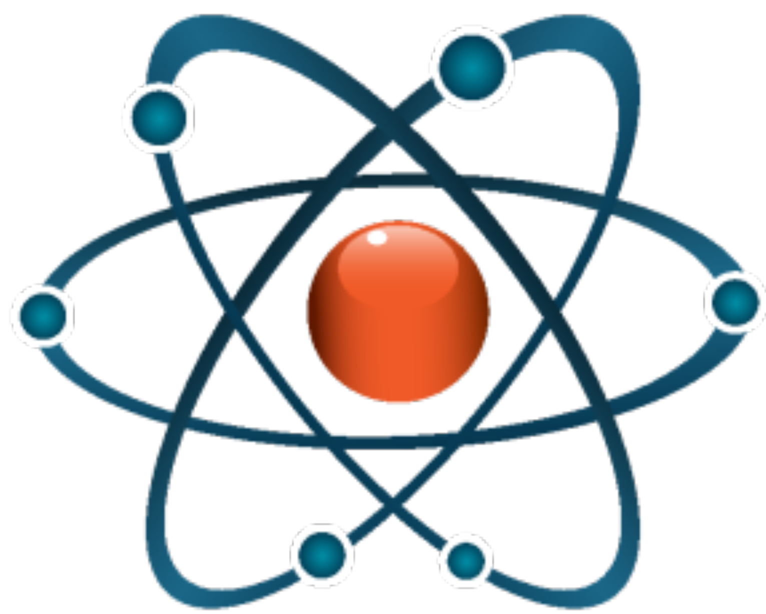
$$\mu_{N\min} = \sqrt{\frac{m_N E_{R\mathrm{th}}}{2}} \frac{1}{v_{\max}}$$

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

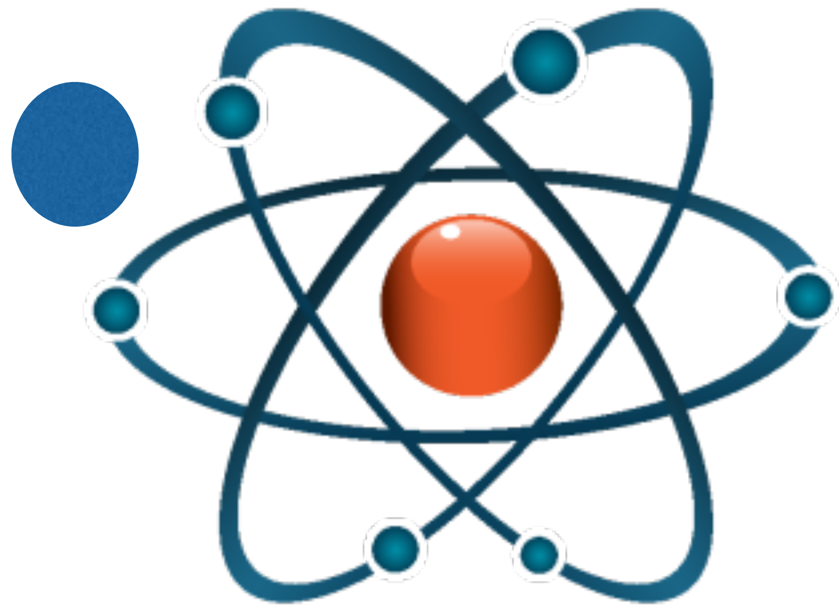


CK, Pradler Phys. Rev. Lett '17

Probing sub-GeV Dark Matter



Probing sub-GeV Dark Matter



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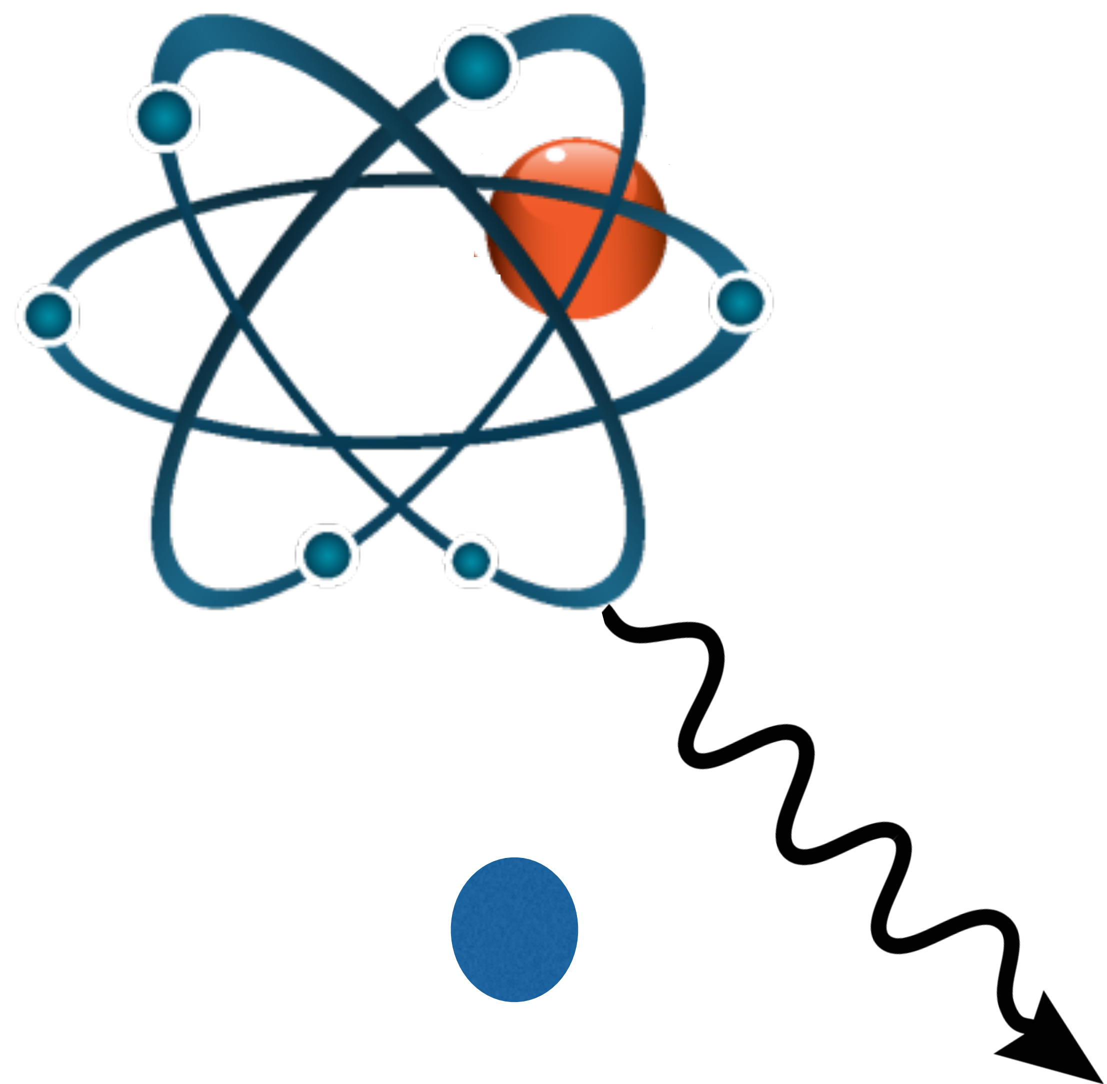

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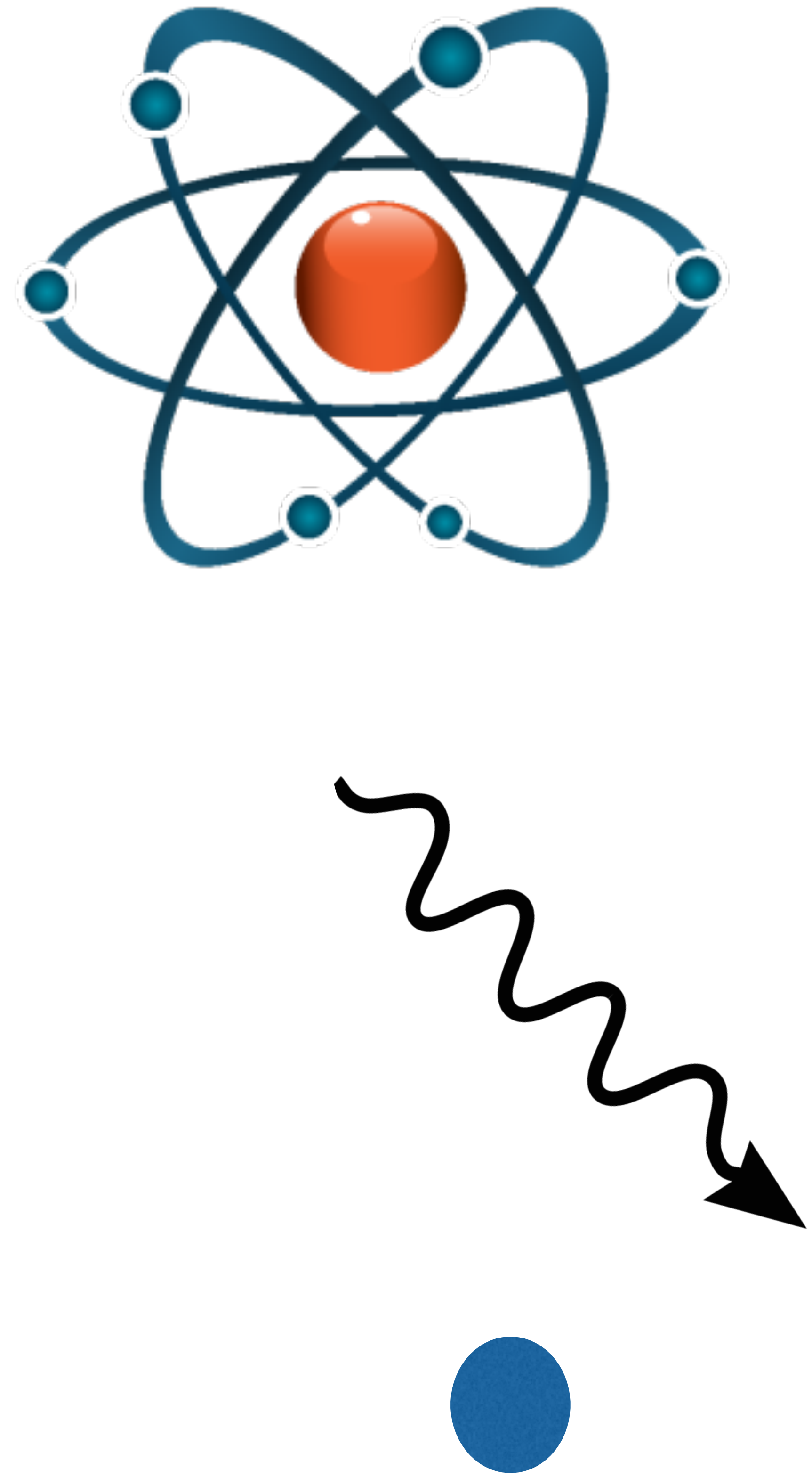
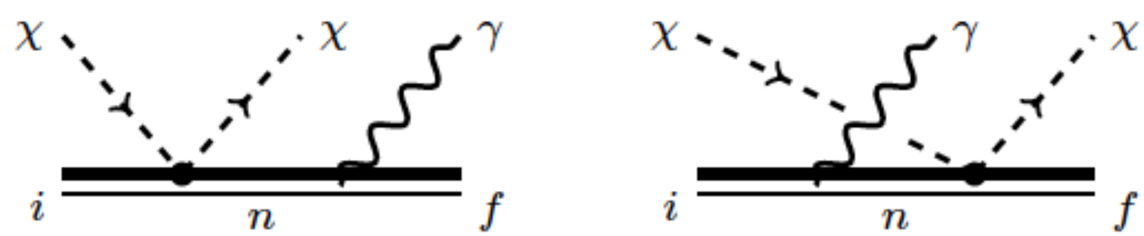


Probing sub-GeV Dark Matter

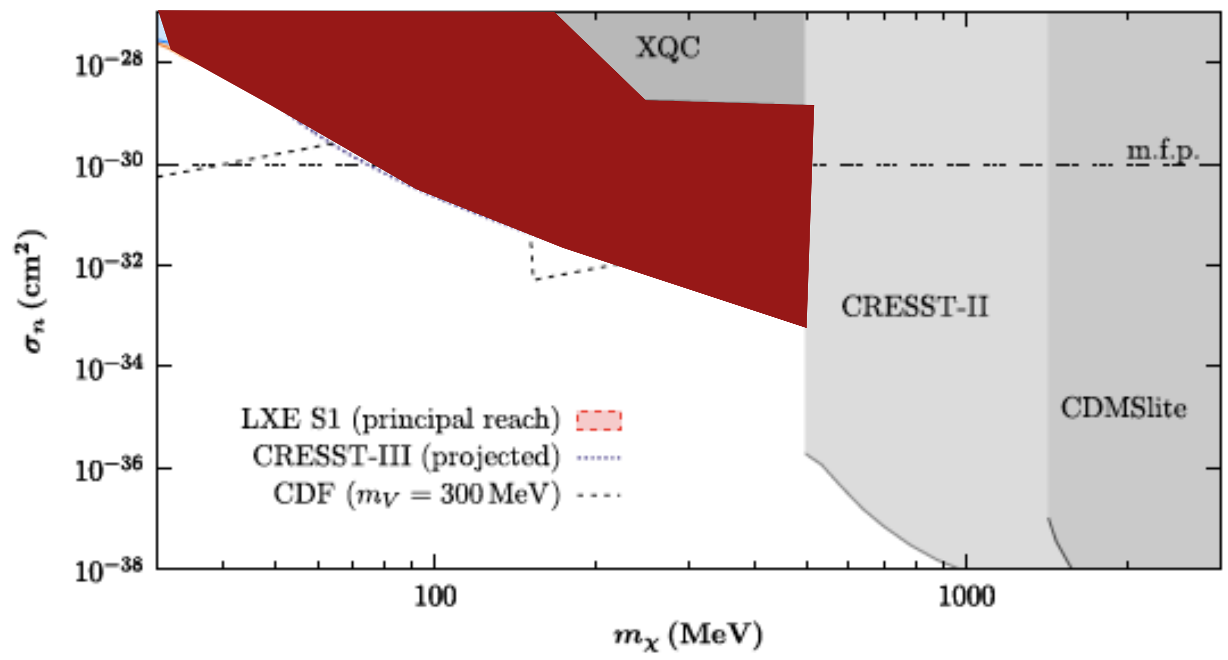


$$|V_{fi}|^2 = 2\pi\omega |M_{\rm el}|^2 \left| \sum_{n,n\neq i} \left[\frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\,\langle n| e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\,\langle f| e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha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

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

CK, Pradler PRL '17

Probing New Parameter Space

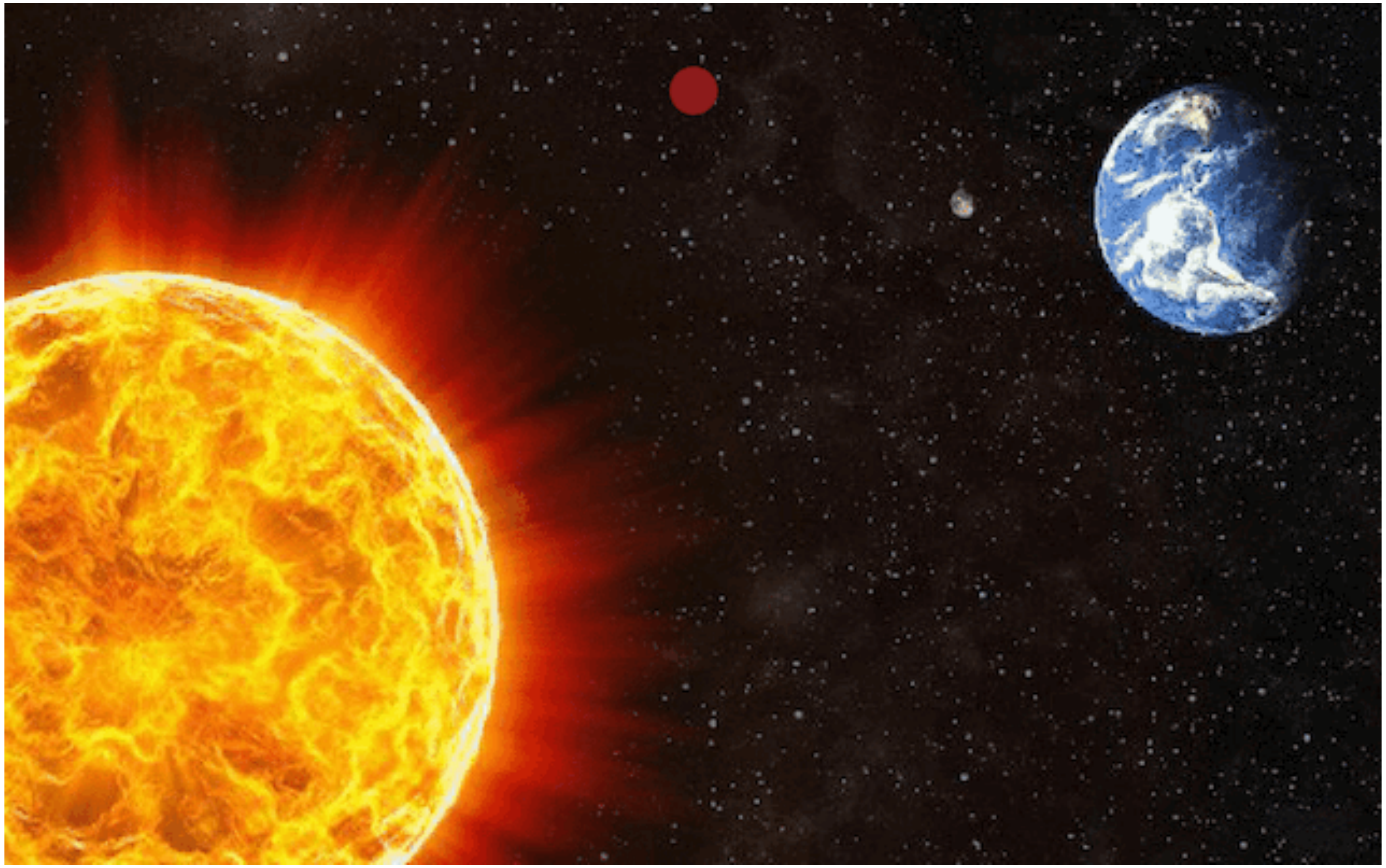


CK, Pradler Phys. Rev. Lett '17,
McCabe '17

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

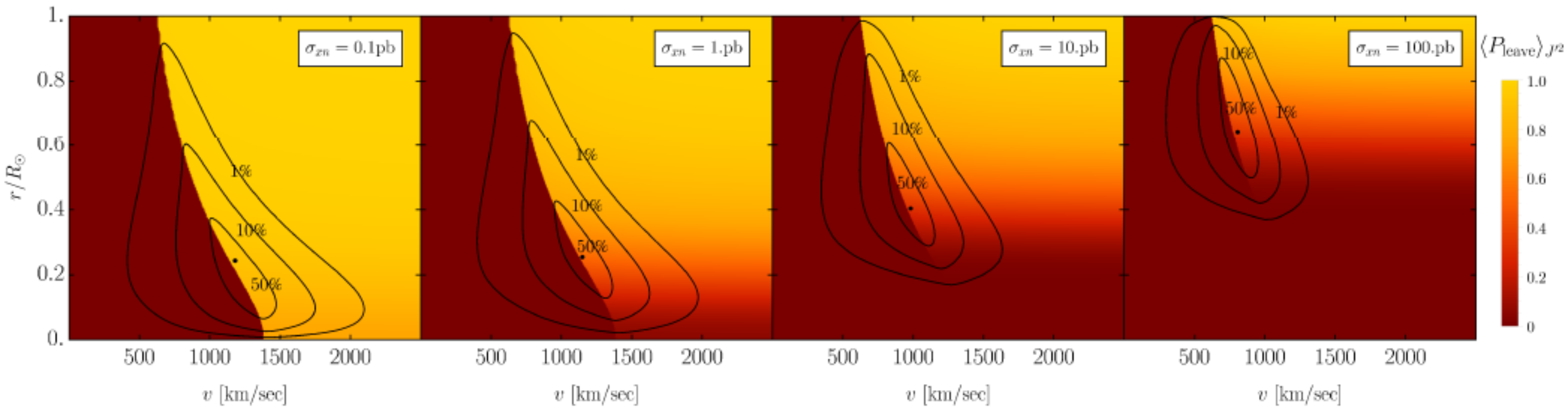
3. Reflecting off the Sun



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

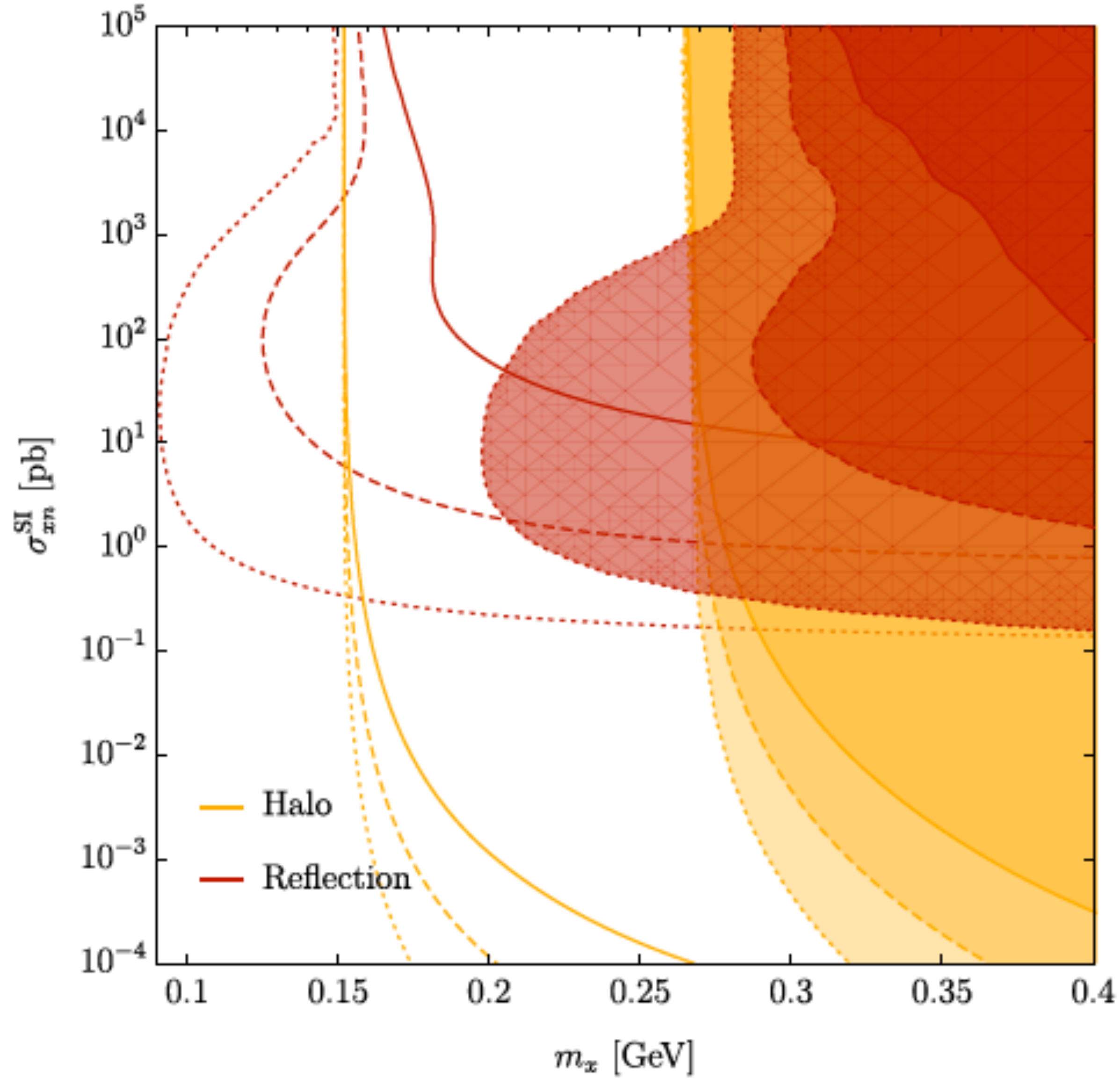
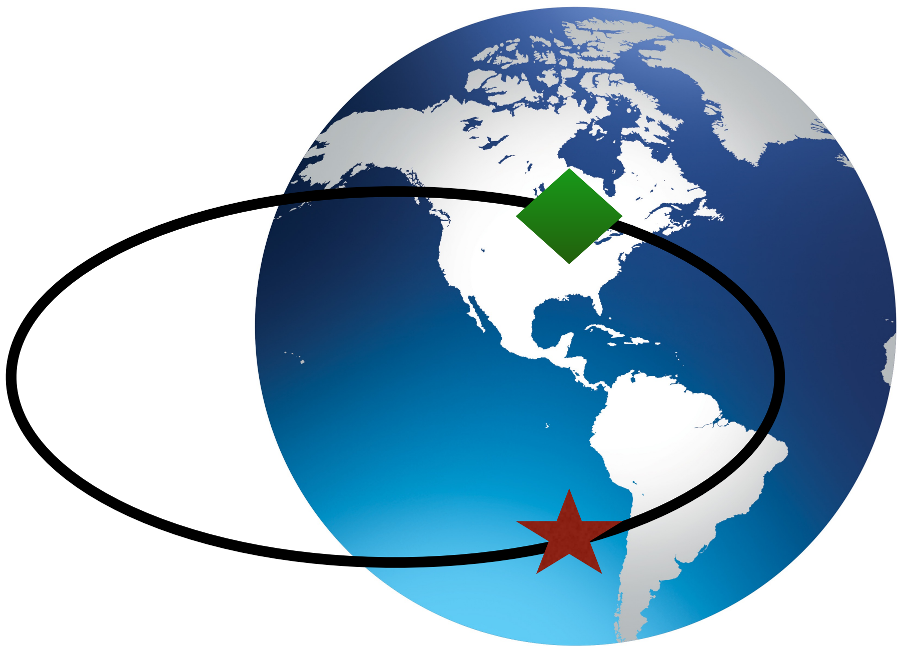


FIG. 2. Solar reflected DM in red and halo DM in yellow. The filled contours project constraints for a CRESST-III type detector with exposures of 1/10/100 ton·days (solid/dashed/dotted). The free lines project constraints for an idealized sapphire detector (perfect energy resolution and no background)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

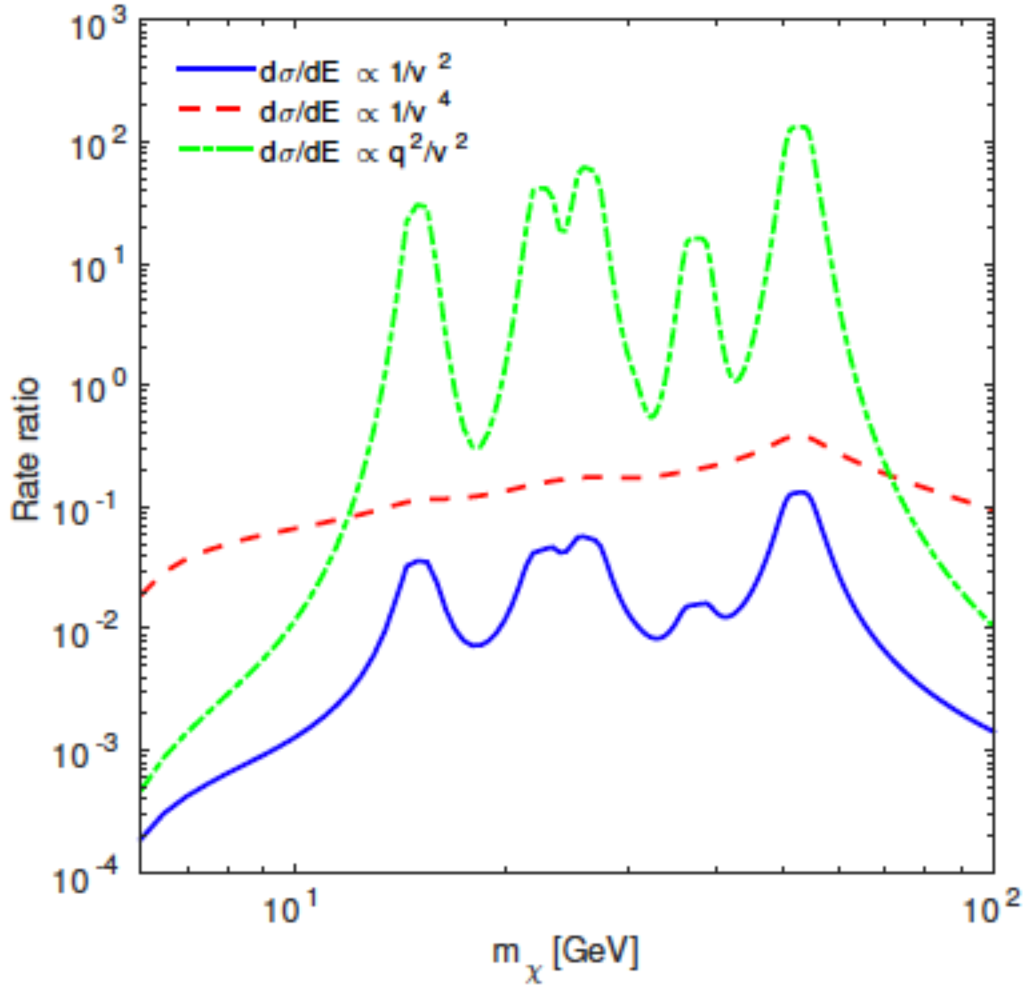
rate of events: nondirectional σ

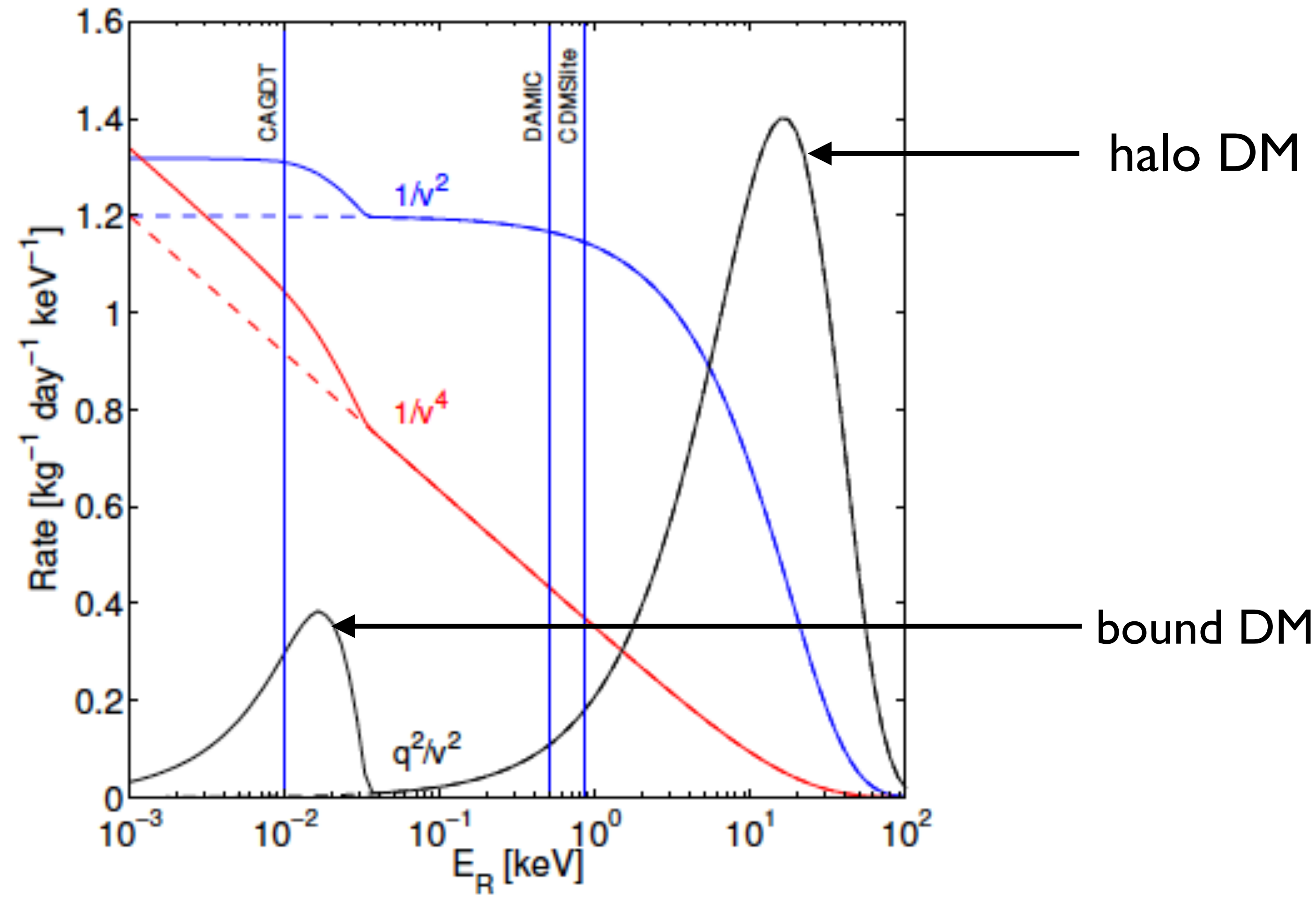
directional

Dark Matter-Nucleus effective interactions

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

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

Conclusions

Shadow Effect

- probing elusive DM with shallow detectors
- precise recoil spectrum

Inelastic Channels

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

Reflected Dark Matter

- Probing low masses

Bound Dark Matter

- “Smoking Gun” Spectral features
- cross section independent ratio