and closing

Opening Windows with Isospin-Violating Dark Matter

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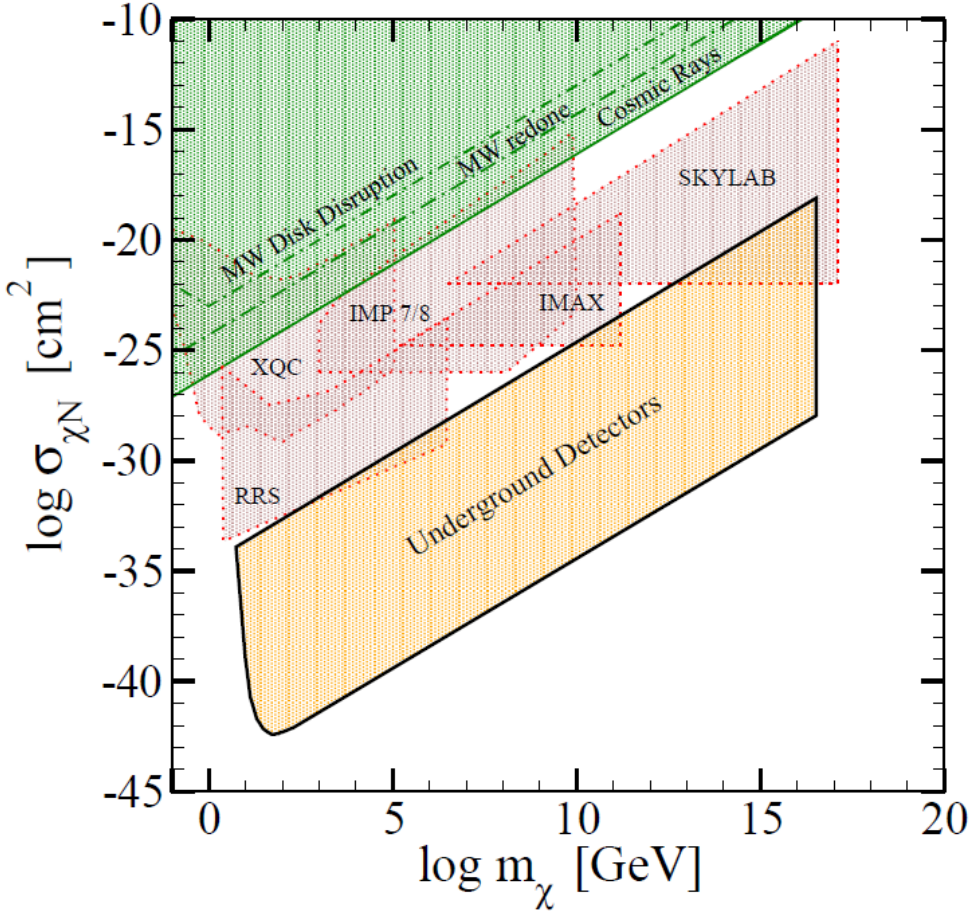
direct detection with large σ

- deep underground dir. detection exps. have a sensitivity ceiling
  - if σ is large enough, DM scatters multiple times in overburden
  - may lose a lot of energy
  - E deposited in detector below threshold
- to raise ceiling, use detectors with less overburden
  - surface runs
  - balloons, sounding rockets
  - impact on cosmology observables
- are there open windows?



Mack, Beacom, Bertone 0705.4298

isospin-violating dark matter

- we often assume DM couples equally to protons and neutrons
- simple, but need not be true
- couplings could be unequal, and could partially cancel

- can weaken sensitivity by reducing scattering in detector
- can strengthen sensitivity by reducing scattering in overburden

- can we open some windows, or close others?

for spin-independent, velocity-independent scattering

$$\frac{d\sigma}{dE_R} = \frac{m_A}{2\mu_N^2 v^2}\sigma_0\ f_{IV}^2\ F^2(E_R)$$

$$f_{IV} = f_p Z + f_n (A - Z)$$

$$\sigma_j \propto \frac{\mu_{A_j}^2}{\mu_N^2} f_{IV}^2\ \sigma_0$$

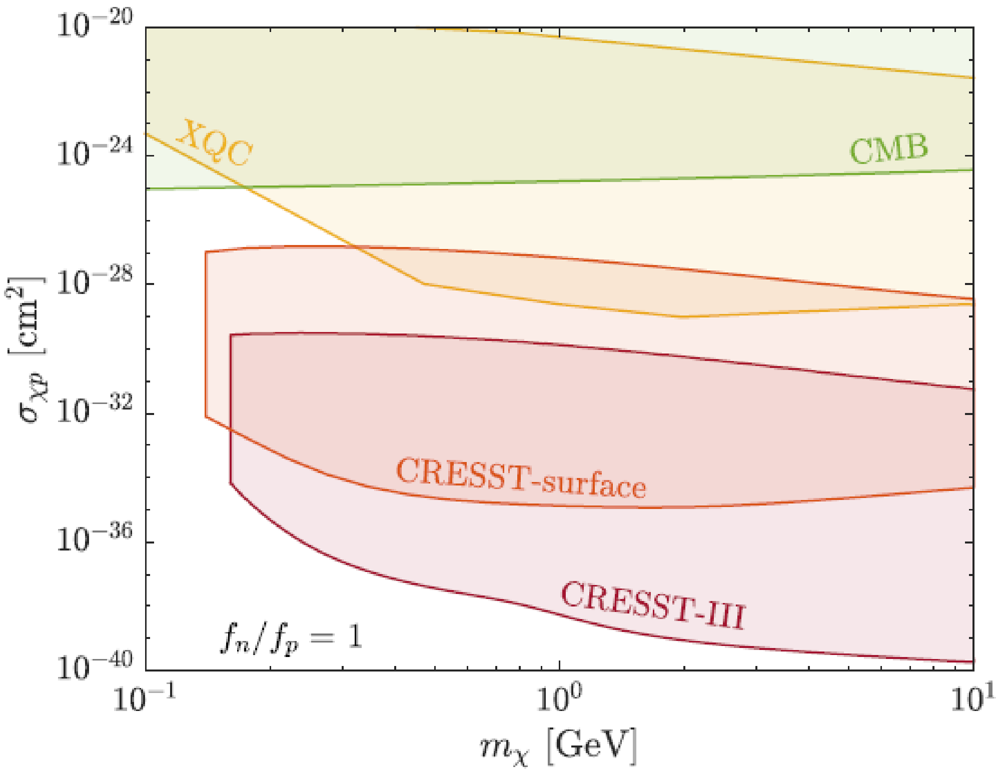
take

$f_p = 1$, $\sigma_0 = \sigma_p$, or
$f_n = 1$, $\sigma_0 = \sigma_n$

low-mass

- we focus on m_χ < 10 GeV
- direct detection experiments tend to have reduced sensitivity
- changes to sensitivity have a larger effect

- focus on
  - CRESST-surface (AL_2O_3)
  - CRESST-III ($CaWO_4$)
  - XQC – sounding rocket (Si)
  - CMB – DM scattering off baryons
    - couples DM to plasma



CRESST-surface → CRESST collaboration 1707.06749
CRESST-III → CRESST collaboration 1904.00498
XQC → Erickeck, Steinhard,McCammon, McGuire 0704.0794
CMB → Gluscevic, Boddy 1712.07133

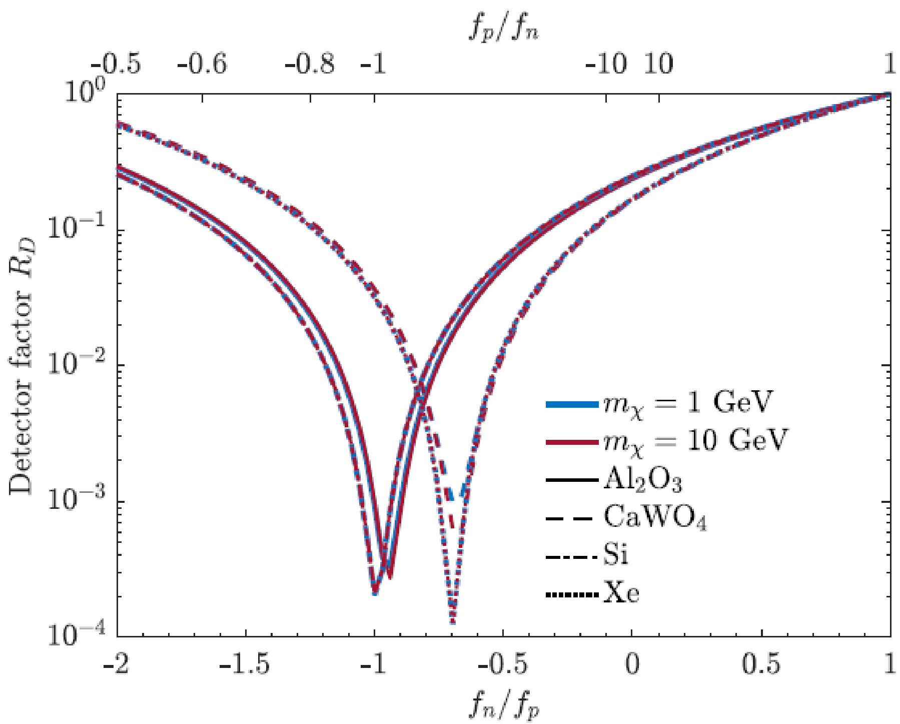
effect of IVDM - detector

- assume single scatter in detector
  - repurpose single scatter analysis
- low mass DM, so momentum transfer relatively small
- $F(E_R) \sim 1$

$$R_D \equiv \frac{\sum_j N_j \, \mu_{A_j}^2 \, f_{IV}^2}{\sum_j N_j \, \mu_{A_j}^2 \, A_j^2}$$

N = number of target nuclei

- R_D = roughly detector rate suppression, compared to $f_n = f_p$
- include isotope content
- for heavier target elements, trough at smaller $|f_n / f_p|$



effect of IVDM - overburden

- multiple scattering relevant
- simplify with SLA (qualitative)

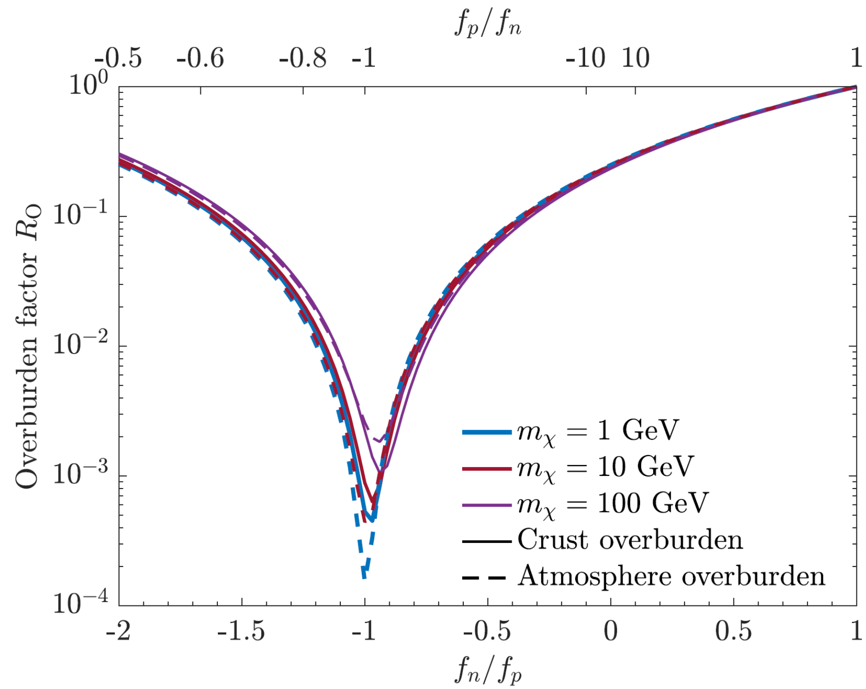
$$\Phi \equiv -\frac{1}{2E}\frac{dE}{dx} = \frac{n}{2E}\int_0^{E_{max}} dE_R \left(E_R \frac{d\sigma}{dE_R}\right)$$

$$= \sum_j \frac{n_j\, \mu_{A_j}^2}{m_\chi m_{A_j}} \sigma_j$$

$$R_O \equiv \frac{\sum_j n_j\, \mu_{A_j}^4\, f_{IV}^2 / m_{A_j}}{\sum_j n_j\, \mu_{A_j}^4 A_j^2 / m_{A_j}}$$

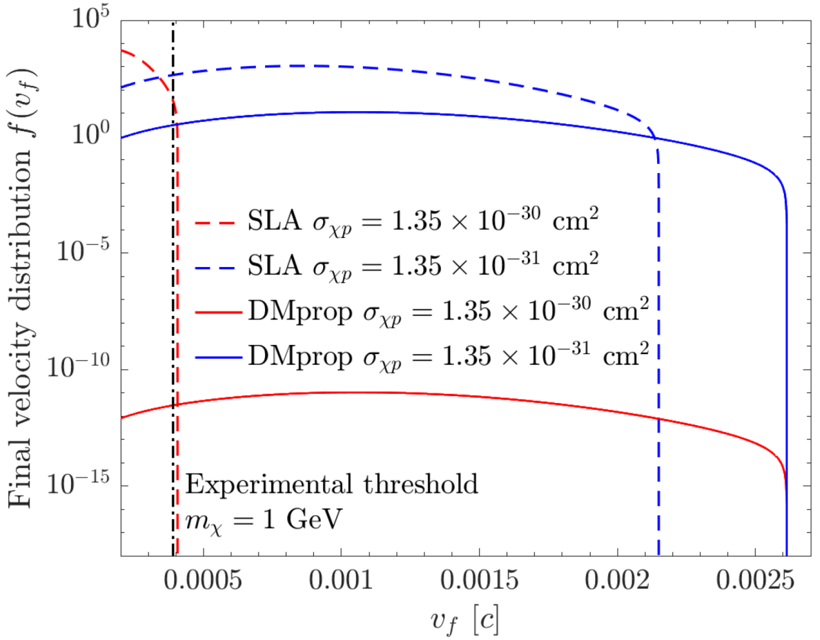
- $\Phi \propto$ fractional energy loss per length
- R_O = suppression of Φ from IVDM
- roughly, keeping $R_O\, \sigma_0$ fixed keeps impact of overburden fixed

- experiments dominated by crust or atmosphere
- overburden dominated by lighter elements (trough near $f_n / f_p = -1$)



DM velocity distribution

- SLA (straight line approx.) may not be great for low mass DM
  - DM changes direction during scattering
- use DMprop (Cappiello 2301.07728)
  - "flat-earth" approx.
  - DM can change direction (isotropic in Earth frame)
  - include probability for scattering
  - modified to include IVDM
- compared to SLA
  - reduced flux
  - but tail of high-v particles from fluctuations in scattering



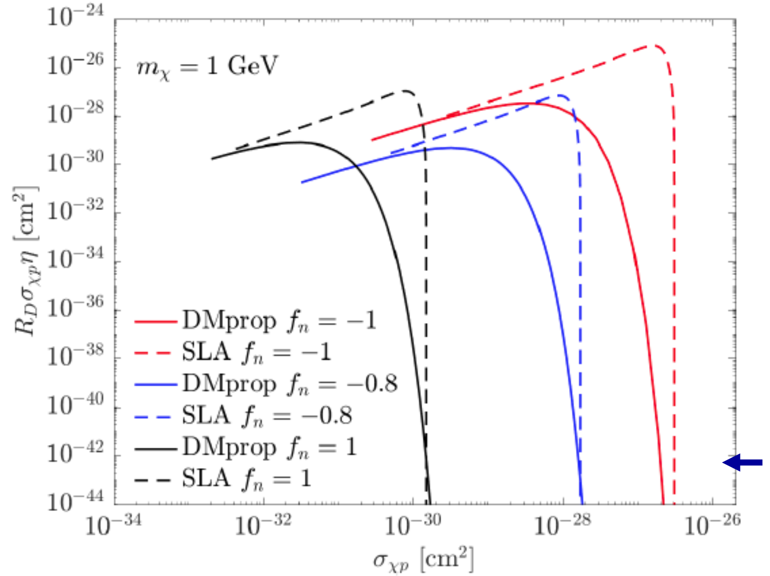
velocity distribution at CRESST-III (1.4km underground , f_n / f_p = 1)

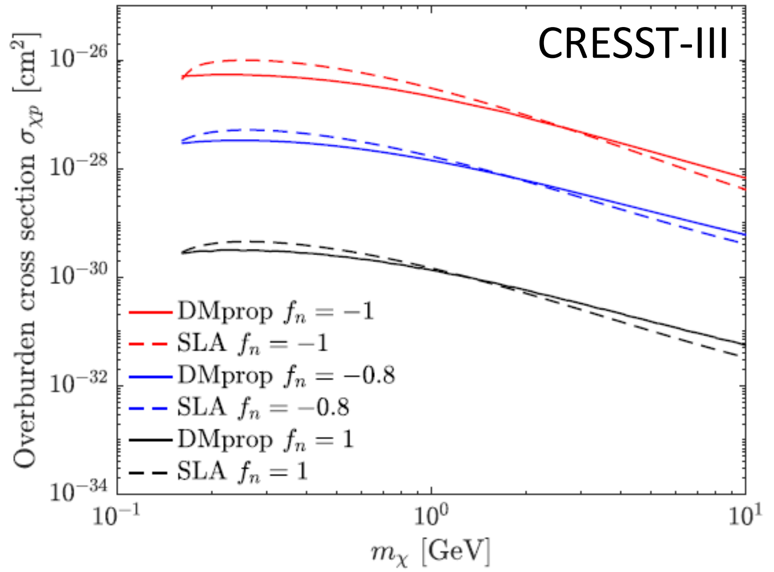
direct detection sensitivity

- only care about the ceiling and floor of sensitivity
  - don’t need velocity distribution in interior
- at floor, overburden irrelevant
  - almost all events come from particles scattering only in detector
- at ceiling, can assume DM is downward going
  - increasing path length gives an exponential suppression
  - so “flat-earth” approximation will be reasonable
  - for low-mass DM, scattering close to isotropic in Earth frame
- DMprop should give a good approximation

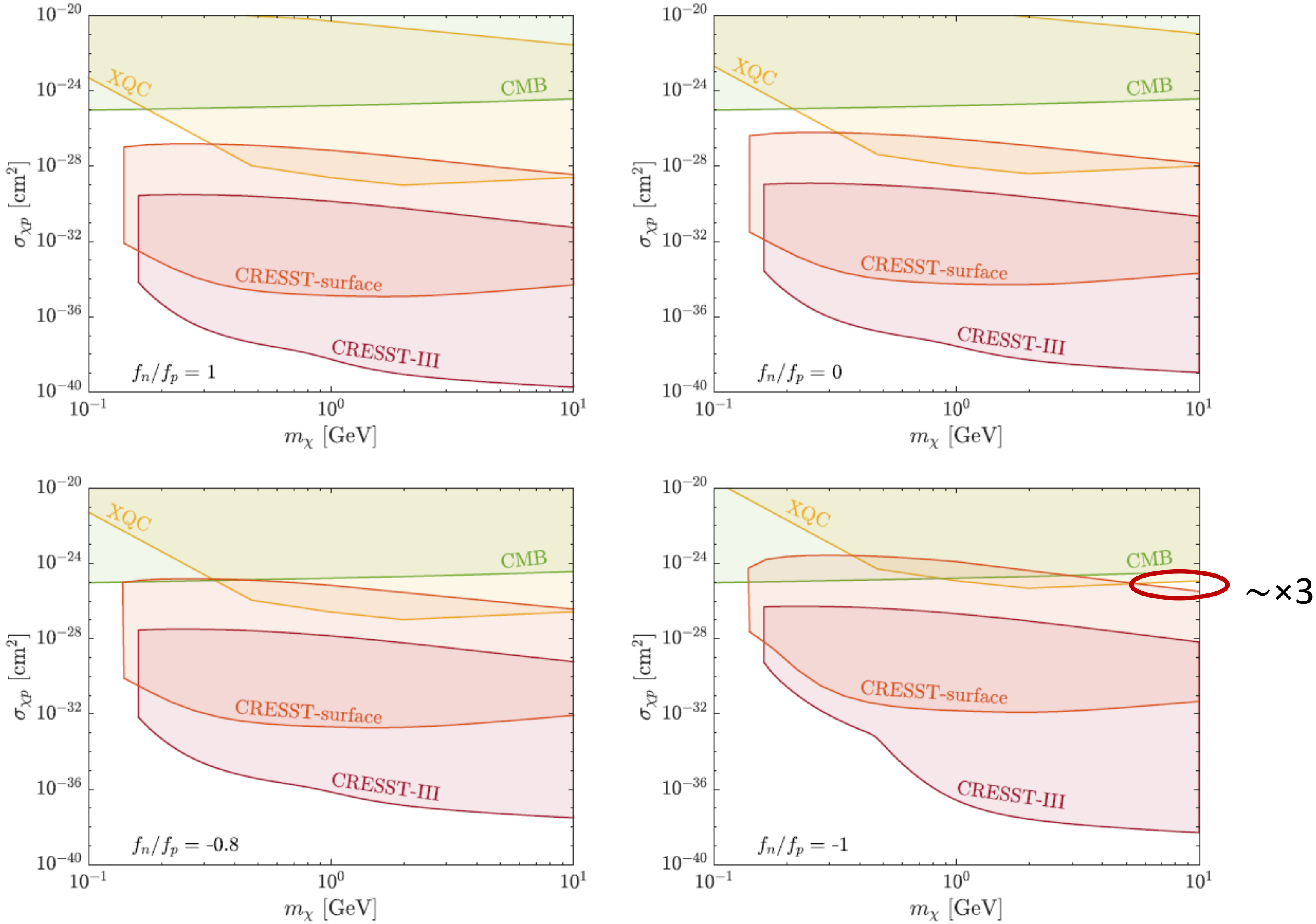
direct detection event rate

- $N_{events} \propto R_D \times \sigma_0 \times \eta$
- $\eta = \int dv_f\, f(v_f) / v_f$
  - weighted flux of detectable events
- at small σ_0, rate $\propto \sigma_0$
- drops because of overburden
  - get ceiling and floor
- DMprop shows suppression of flux due to reflection
- but for small detection rate, SLA and DMprop match up
  - basically, find σ_0 where almost nothing gets through
- won't match if rate higher, so we use DMprop





results



XQC
CMB
CRESST-surface
CRESST-III
$f_n/f_p = 1$
$f_n/f_p = 0$
$f_n/f_p =$ -0.8
$f_n/f_p =$ -1
$\sigma_{\chi p}$ [cm^2]
m_χ [GeV]
10^{-20}
10^{-24}
10^{-28}
10^{-32}
10^{-36}
10^{-40}
10^{-1}
10^{0}
10^{1}
~×3

future directions

- so far, we have only been interested in sensitivity for detection
  - only need the ceiling and floor
- with a future detector, might have enough events to be in the interior of sensitivity region

- could explore daily modulation with a directional detector
- but sensitive to how the velocity distribution is distorted by the overburden

- if you need to go beyond flat-Earth approximation, much more computationally intensive

conclusion

- dark matter direct detection exps. have a sensitivity ceiling and floor
- isospin-violation can open some sensitivity windows, while closing others
- competing effects from reduction of scattering in the detector, and reduction of scattering in overburden

- interesting effects, especially at low mass

Mahalo!

Backup Slides

DMprop algorithm

- flux of particles at detector: start with
  - incoming flux
  - $P_0(z)$ → probability of reaching depth z without scattering
  - $P(z-z')$ → probability of reaching z from z' without scattering
- successively convolve to get $P_n(z)$ → probability of reaching depth z after n scatters
- sum on n
- energy distribution at detector: start with
  - initial energy distribution
  - energy distribution after one scatter (assuming isotropic scattering in Earth frame)
  - successively convolve to get energy distribution after n scatters
  - sum over n, weighting energy distribution by $P_n(z)$
- doesn't account for correlation of energy with depth