

Probing earth-bound dark matter with nuclear reactors

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CERN (\rightarrow U. Florida)

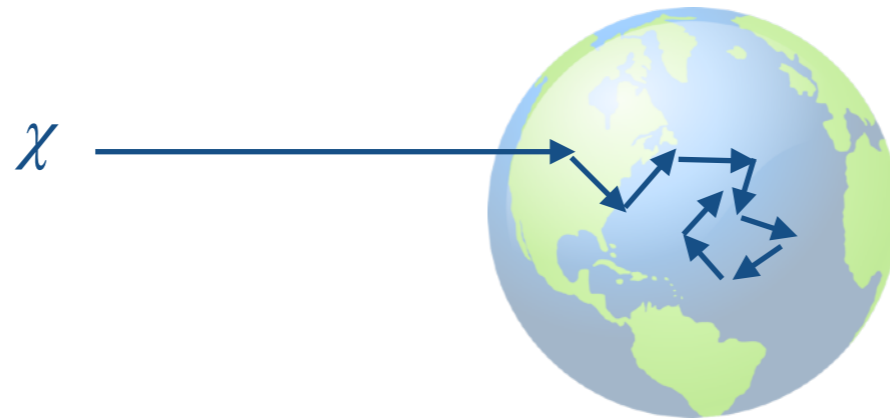
NDM 2025 @ IHP, Paris May.15.2025

Based on [2402.03431](#) with Maxim Pospelov and Anupam Ray



DM with large cross section

- DM flux can be captured by the Earth if $l_{\text{coll}} \lesssim R_{\oplus} \sim 6000 \text{ km}$.



- Thermalizes with the kinetic energy $K_{\chi} \sim T_{\oplus} \sim 0.03 \text{ eV}$.

➔ Hard to detect by DD, although abundant and strongly interacting.

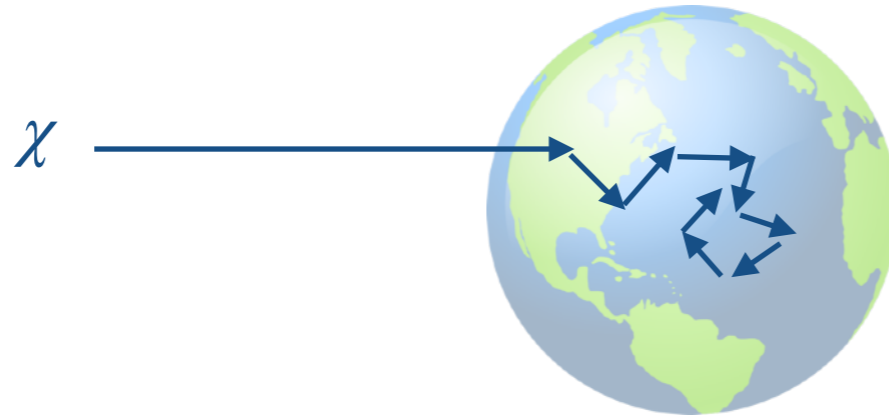
- Can we detect these strongly interacting DM?

➔ Nuclear reactor to accelerate DM and pass the threshold.

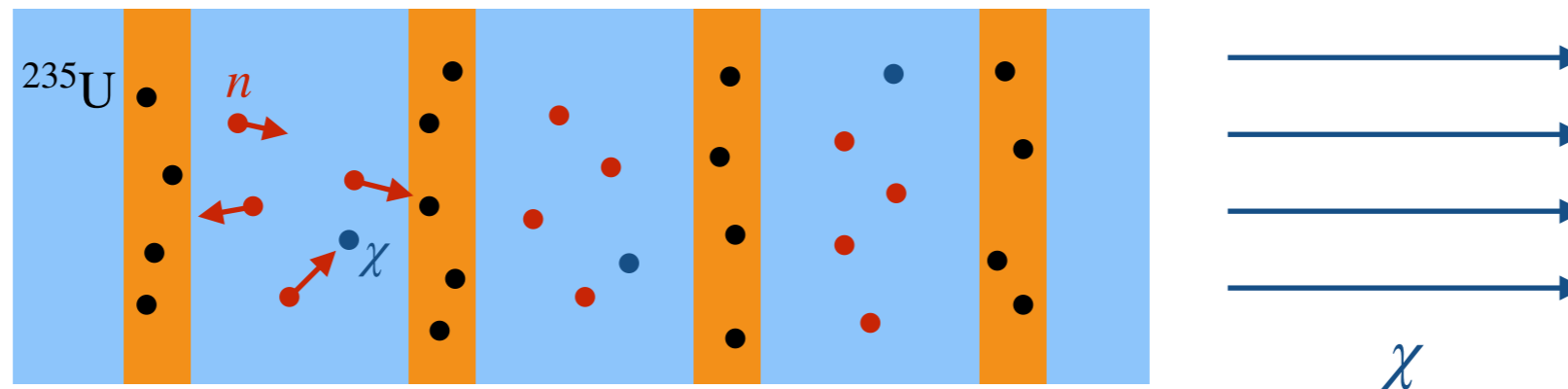
Many other interesting ideas exist: thermalized DM with collection of SM particles [Neufeld+18; Xu+21; Farrar22]; upscattering by cosmic ray [Bringmann+18; YE+18; Cappiello+19]; DM annihilation inside the Earth [McKeen+23; Pospelov+23]; nuclear isomer [Pospelov+19; Lehnert+19; MAJORANA23]; quantum devices [Das+22]; underground accelerators [McKeen+22]

Summary: three steps

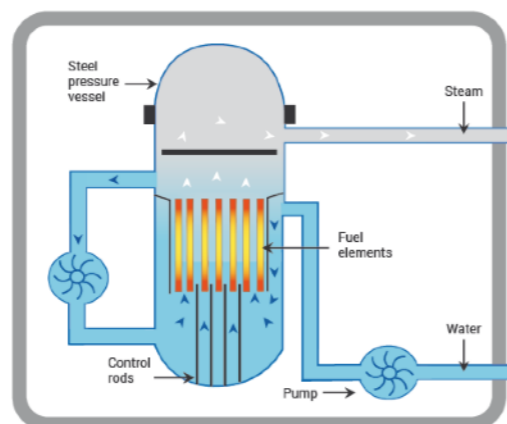
1st step: strongly interacting DM captured by Earth and thermalized.



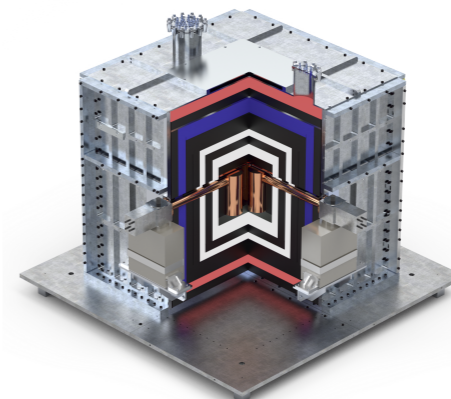
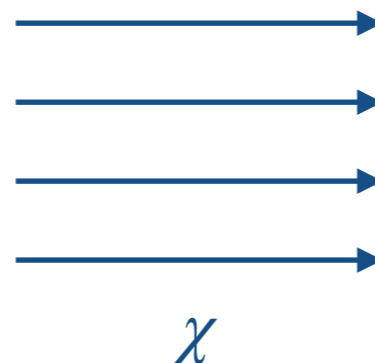
2nd step: DM accelerated by fast neutrons inside nuclear reactors.



3rd step: accelerated DM detected by CE ν NS detector.



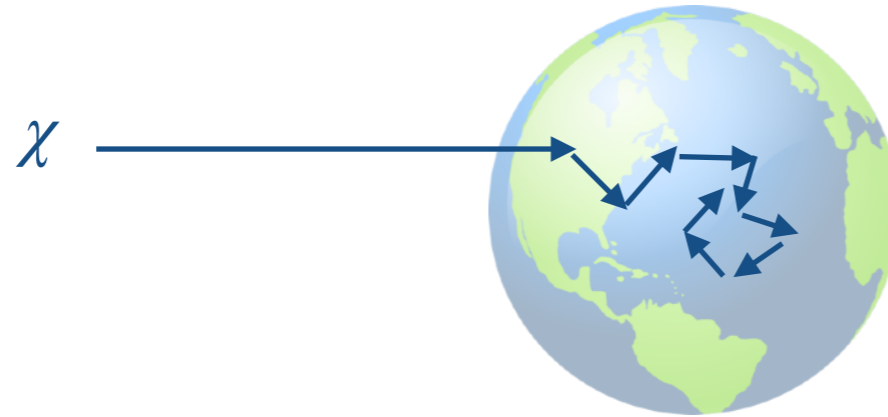
[Fig. from World Nuclear Association]



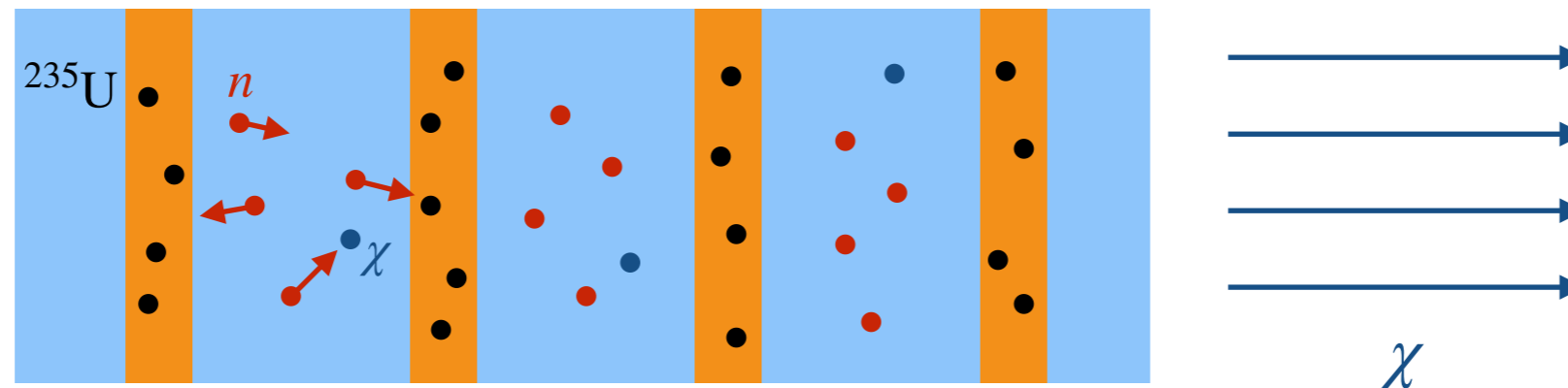
[CONUS]

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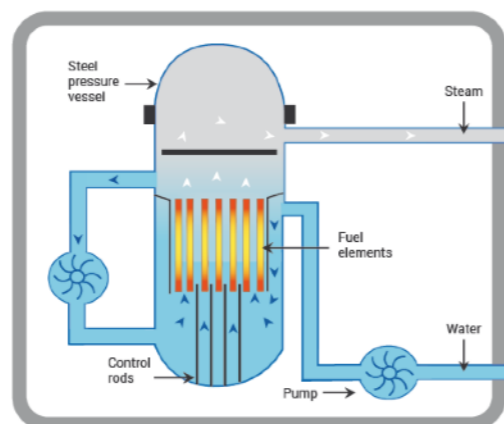
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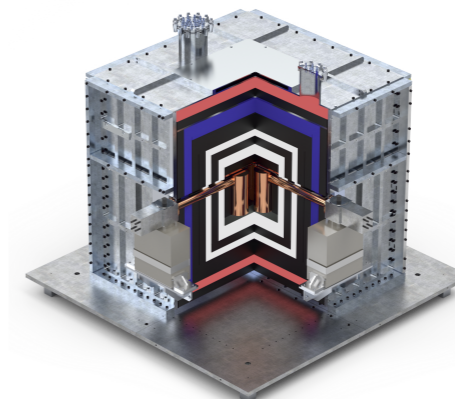
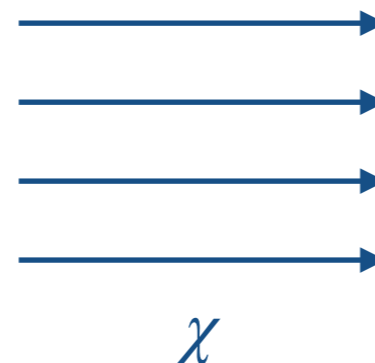
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[Fig. from World Nuclear Association]



[CONUS]

Earth-bound dark matter

- Time evolution DM number inside the Earth: [Neufeld+18; Bramante+22; ...]

$$\frac{dN_\chi}{dt} = \Gamma_{\text{cap}} - \Gamma_{\text{evap}} \times N_\chi \quad \longrightarrow \quad N_\chi = \frac{\Gamma_{\text{cap}}}{\Gamma_{\text{evap}}} \left(1 - e^{-t_\oplus \Gamma_{\text{evap}}} \right),$$

where Γ_{cap} : capture rate and Γ_{evap} : DM evaporation rate from Earth.

- Distribution inside the Earth crucial, computed by Boltzmann equation.

[Gould, Raffelt 90; Leane, Smirnov 22]

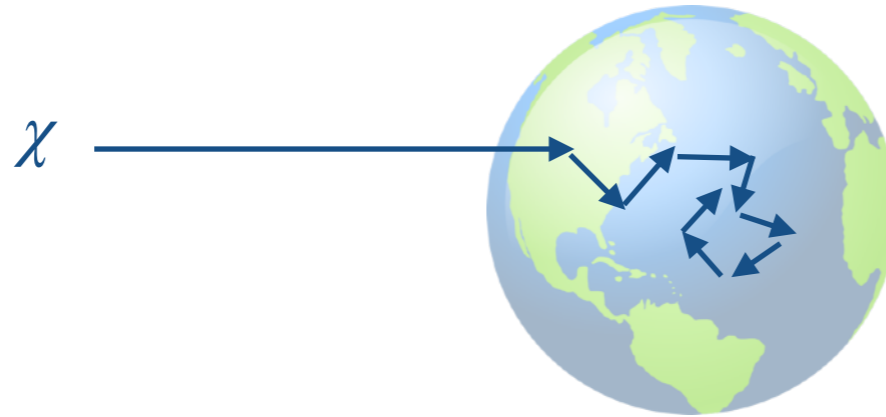
- GeV mass range most important for experiments close to surface.

$$\left\{ \begin{array}{l} - \text{Evaporates easily for } m_\chi \lesssim 1 \text{ GeV } (v_{\text{esc}} \sim 4 \times 10^{-5} \text{ for Earth}). \\ - \text{Sinks down to the Earth core for } m_\chi \gtrsim 3 \text{ GeV}. \end{array} \right.$$

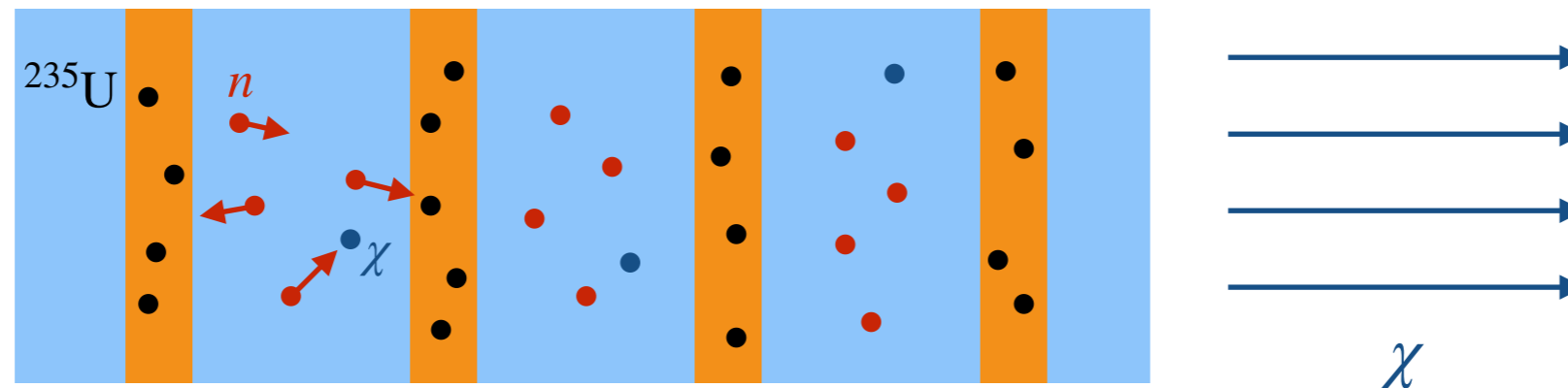
$\longrightarrow n_\chi(R_\oplus)/f_\chi \sim 10^{13} \text{ cm}^{-3}$ achievable for $m_\chi \sim 1 \text{ GeV}$.

Summary: three steps

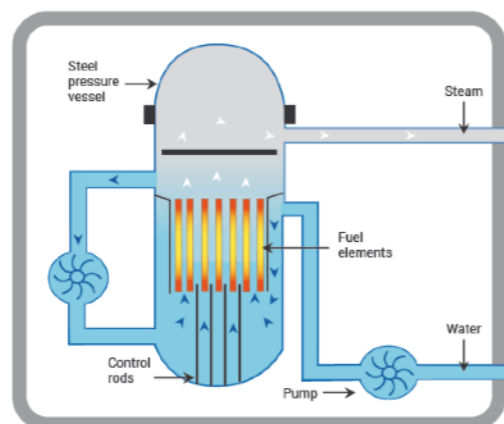
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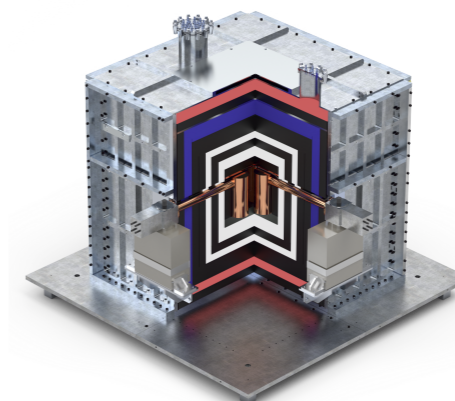
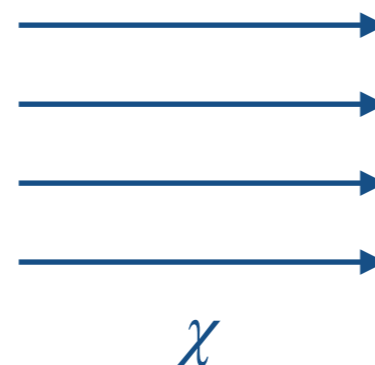
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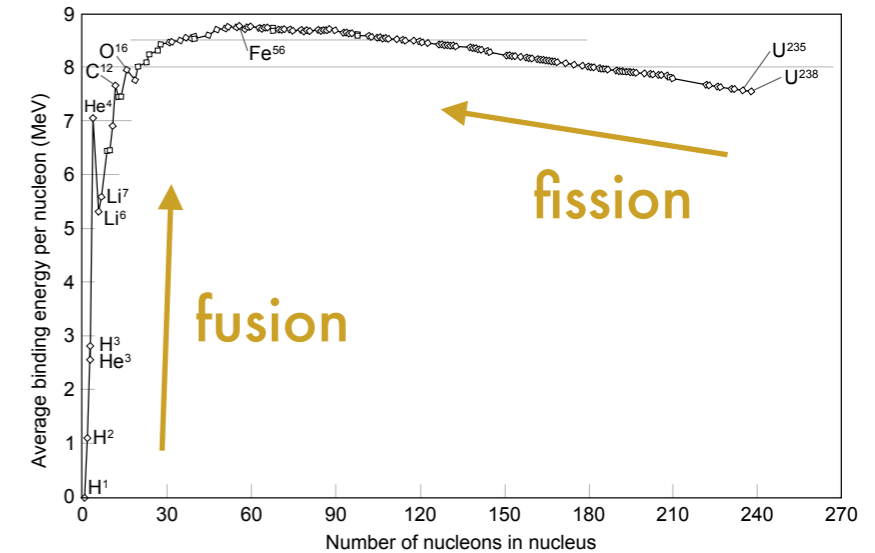
[CONUS]

Nuclear reactor

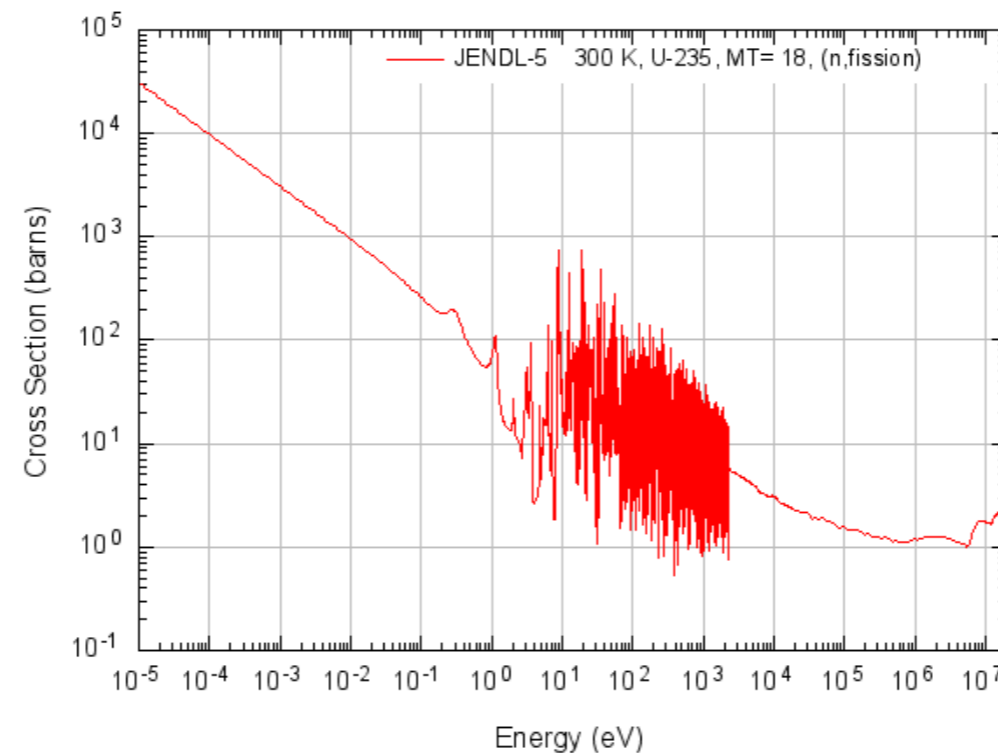
- Nuclear reactor = fission of ^{235}U etc. to produce energy.

➔ ~ 2.5 neutron per fission with $E_n \gtrsim 1 \text{ MeV}$.

$$\frac{dN_n}{dt} \simeq 7.8 \times 10^{19} \text{ sec}^{-1} \left(\frac{P}{1 \text{ GW}} \right).$$



- Fission cross section: increases at low energy.



JAEA Nuclear Data Center

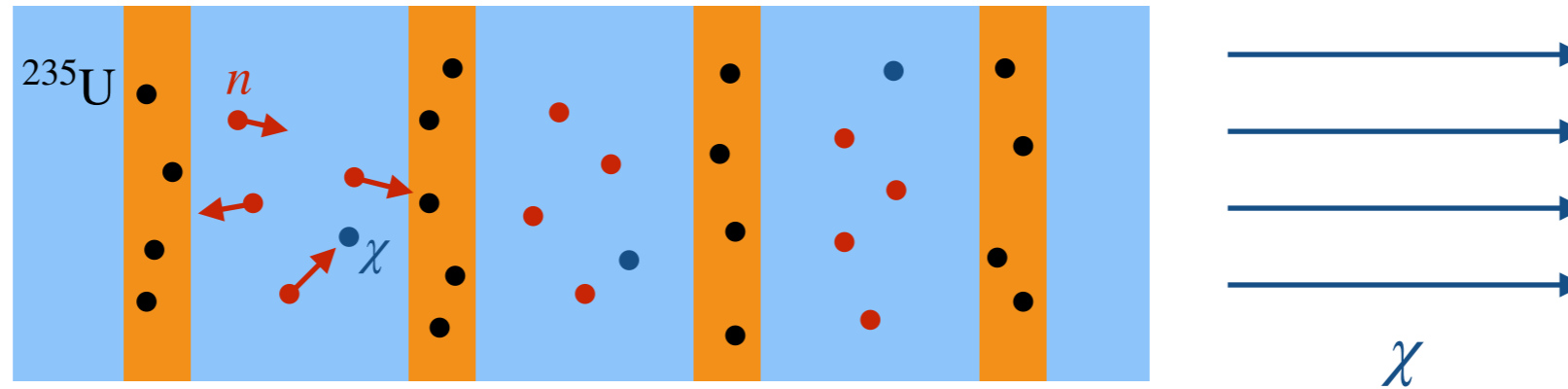
➔ Need to “moderate” fast neutrons by water, carbon, ...

Nuclear reactor = neutron beam dump experiment

[wikipedia]

Reactor as DM accelerator

- Fast neutron can up-scatter DM while slowed down by moderator.



- DM spectrum per neutron:

$$\frac{d\bar{N}_\chi}{dE_\chi}(E_n, E_\chi) = n_\chi \int_{E_{\text{th}}}^{E_n} \frac{dE}{-dE/dx} \frac{d\sigma_{\chi n}}{dE_\chi}(E, E_\chi).$$

- Neutron loses energy via elastic scattering with protons: $-\frac{dE}{dx} \simeq \frac{E}{2} n_p \sigma_{pn}(E).$

- Assume isotropic scattering: $\frac{d\sigma_{\chi n}}{dE_\chi}(E, E_\chi) = \frac{\sigma_{\chi n}}{\beta_{\chi n} E} \Theta(\beta_{\chi n} E - E_\chi), \quad \beta_{\chi n} = \frac{4m_\chi m_n}{(m_\chi + m_n)^2}.$

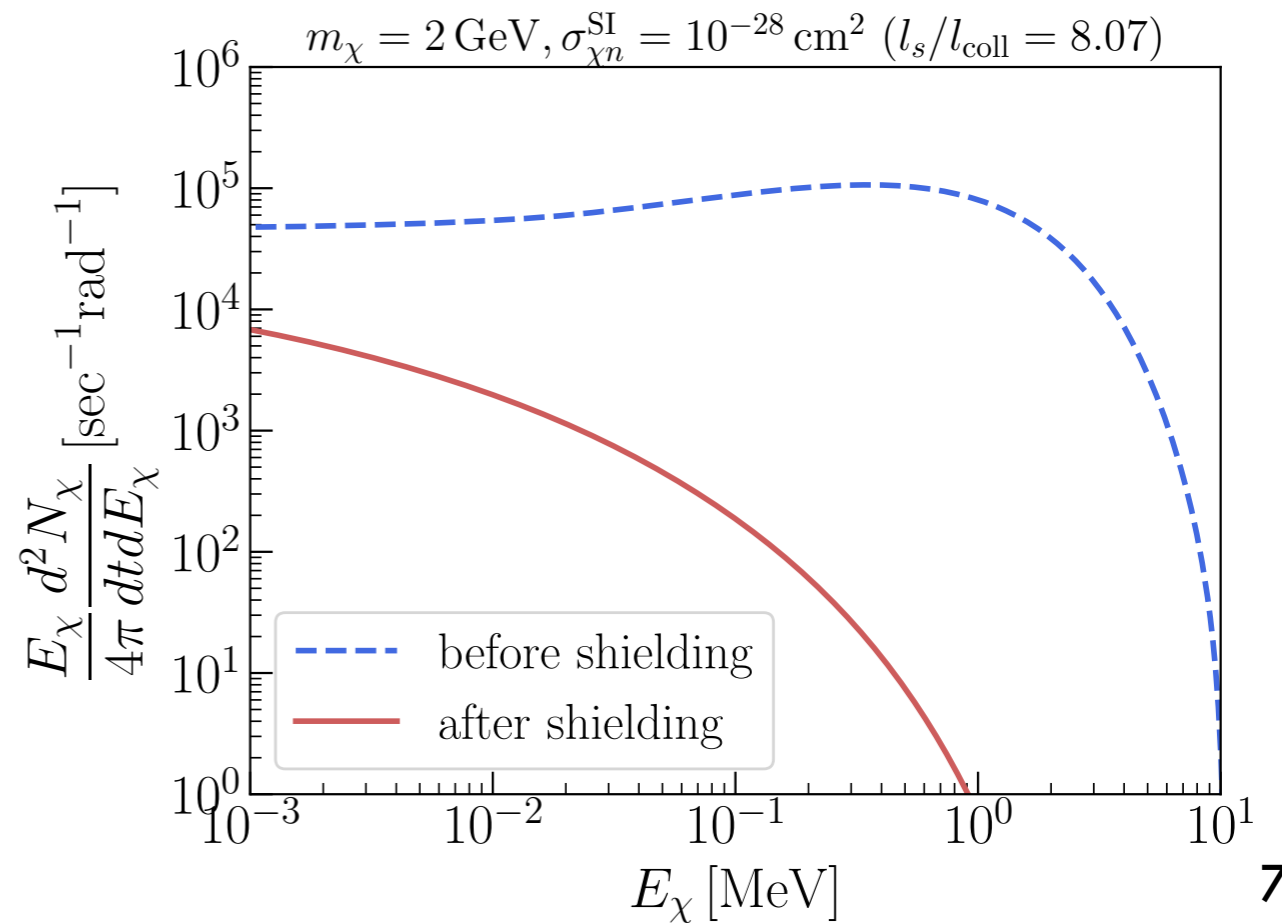
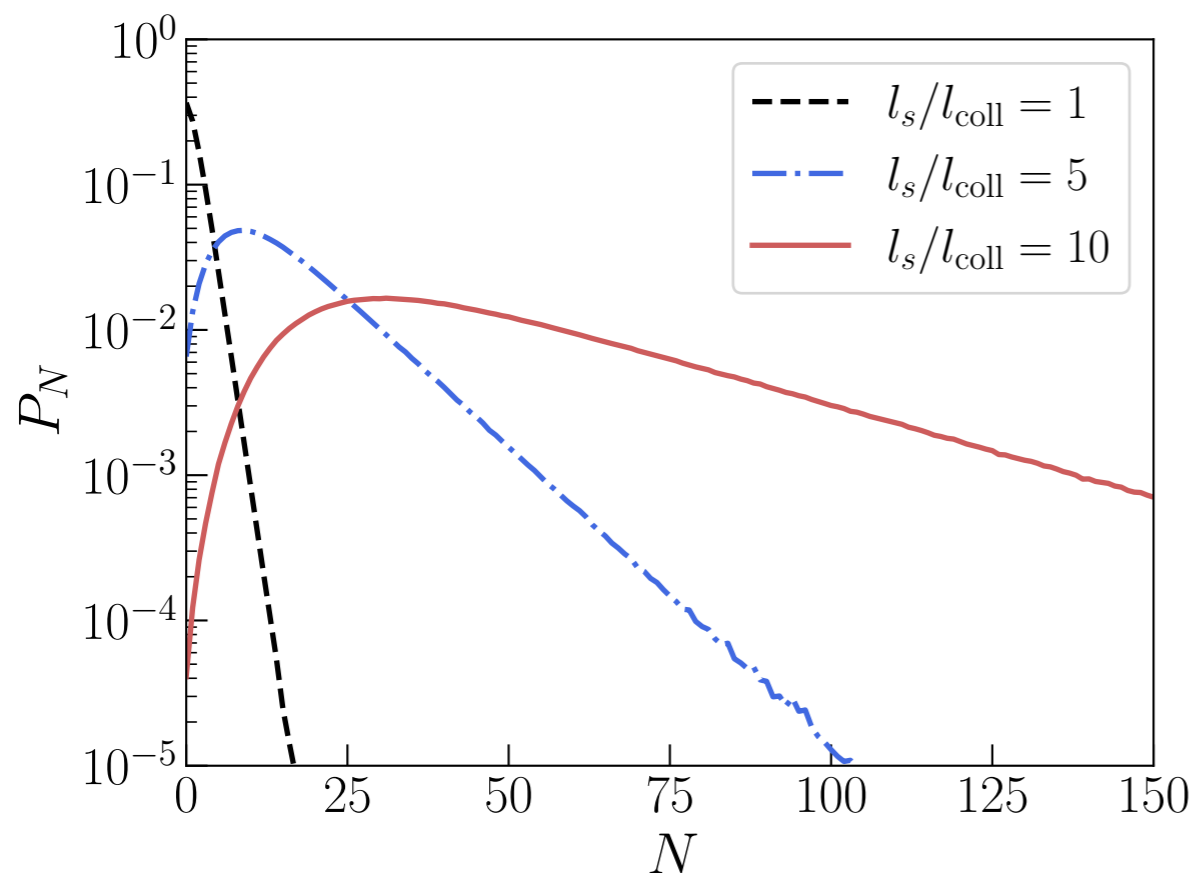
$$\Rightarrow \frac{dN_\chi}{dE_\chi} = \frac{2}{\beta_{\chi n}} \int_{E_\chi/\beta_{\chi n}}^{\infty} dE_n \frac{dN_n}{dE_n} \int_{E_\chi/\beta_{\chi n}}^{E_n} \frac{dE}{E^2} \frac{n_\chi \sigma_{\chi n}}{n_p \sigma_{pn}(E)}.$$

Shielding effect

- Reactor core: shielded by e.g. concrete such as $^{28/29}\text{Si}$.
- Crude approximation: core surrounded by spherical shield with thickness l_s .
- Multiple scattering important for $l_s/l_{\text{coll}} \gtrsim 1$ with $l_{\text{coll}} = 1/n_s\sigma_{\chi s}$.

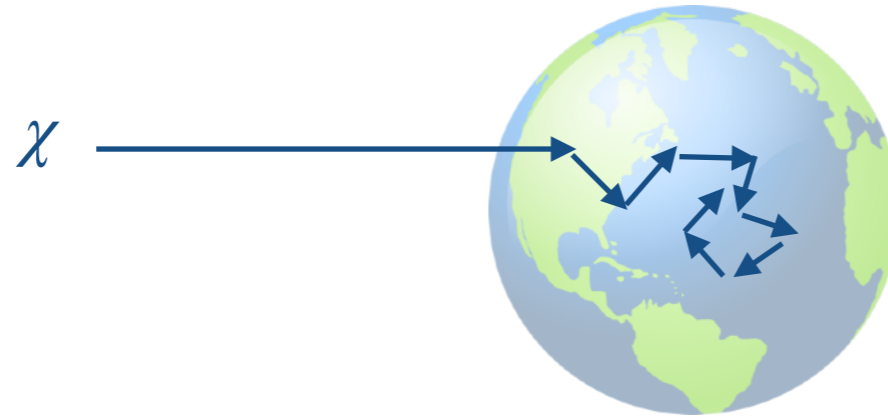
$$\Rightarrow \left. \frac{dN_\chi}{dE_\chi} \right|_{\text{shield}} = \int dE \frac{dN_\chi}{dE_\chi}(E) \times \sum_{N=0}^{\infty} P_N \times f_N(E, E_\chi).$$

P_N : prob. exiting shield after N scattering, $f_N(E, E_\chi)$: energy dist. with initial energy E after N scatterings.

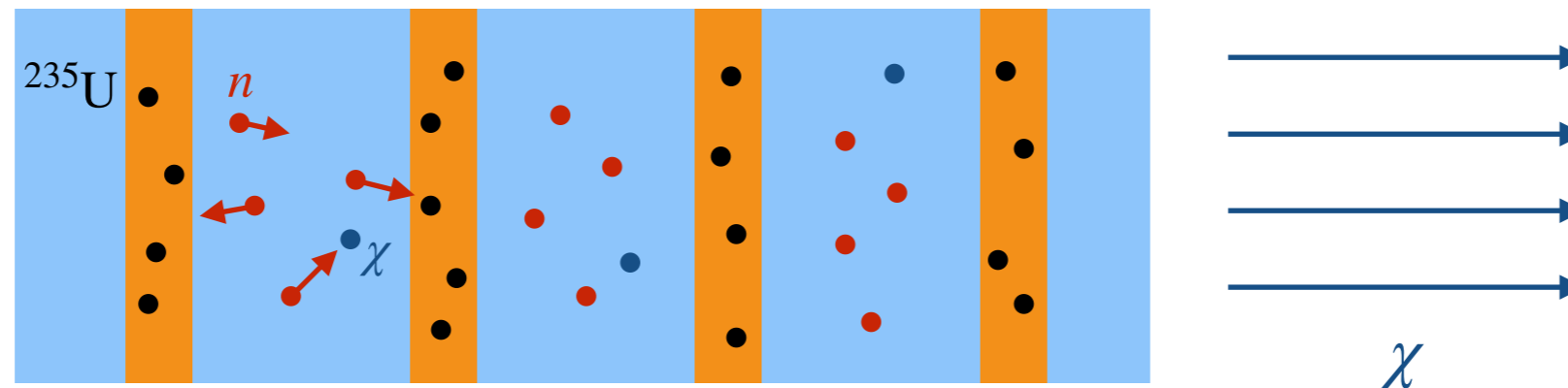


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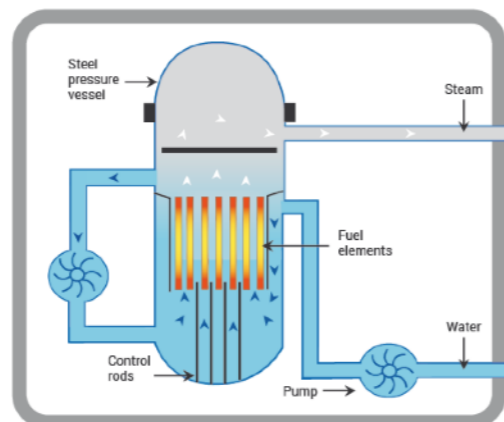
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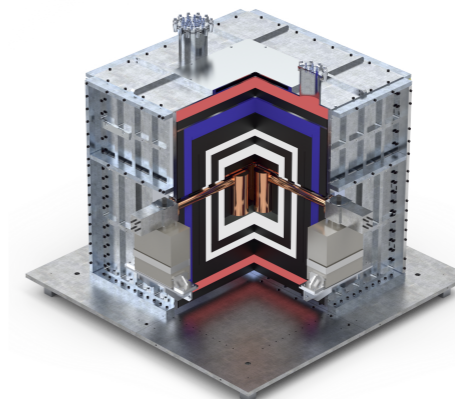
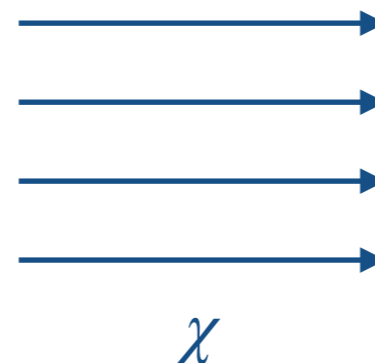
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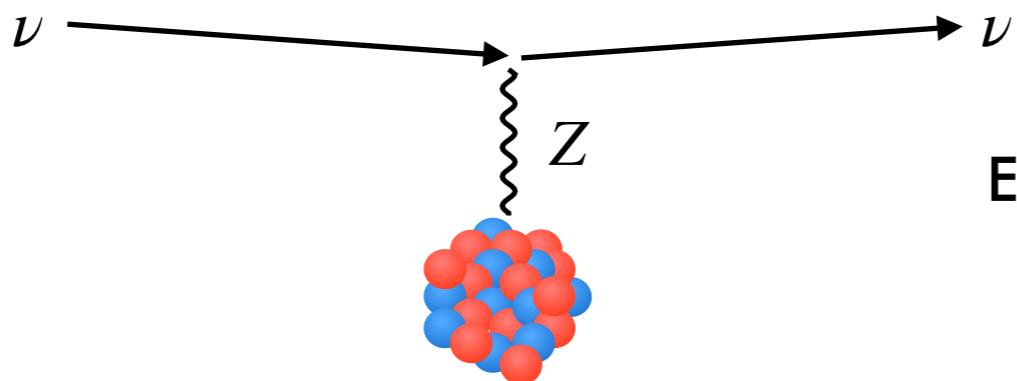


[CONUS]

CE ν NS experiment

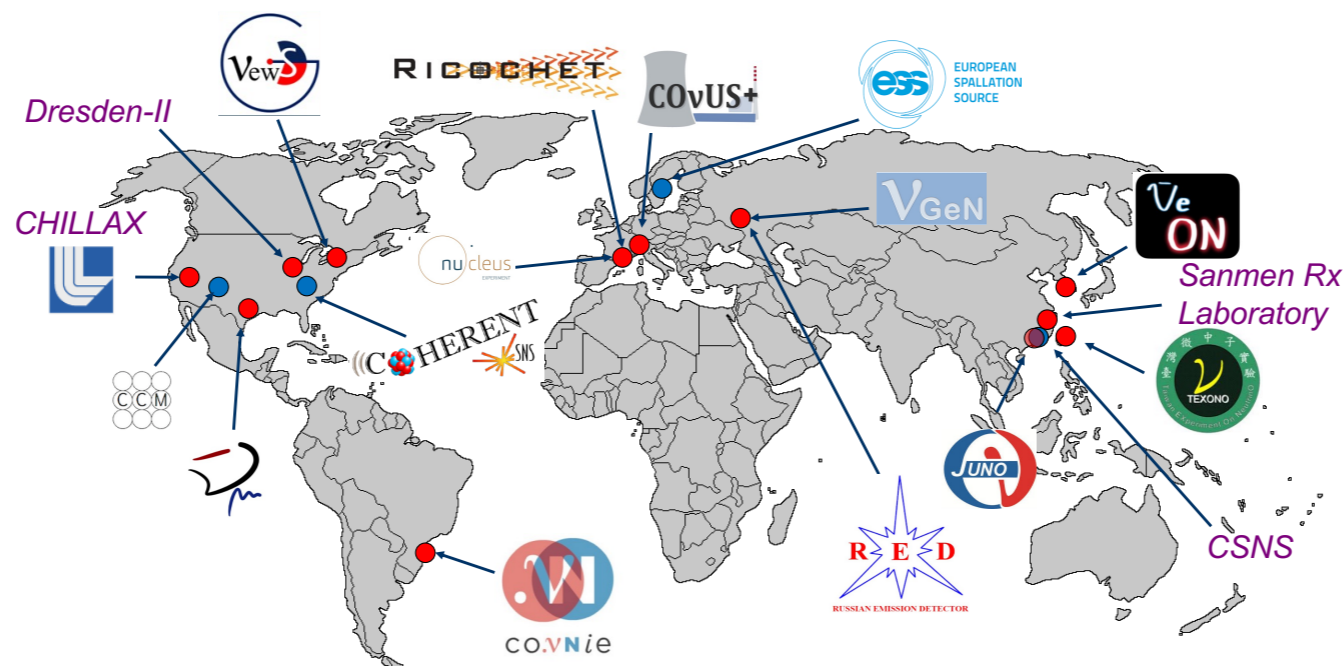
- Coherent elastic neutrino-nucleus scattering (CE ν NS)

[Freedman 74]



Enhanced at low energy: $\sigma_{\nu A} \propto A^2$.

- Recent interest in CE ν NS measurements:



[https://indico.global/event/6083/contributions/49995/attachments/24972/42738/2024_06_Mag7s_Exp_Summary.pdf]

- Detection from stopped pion by COHERENT and reactor by CONUS+.
- Detectors next to nuclear reactors.

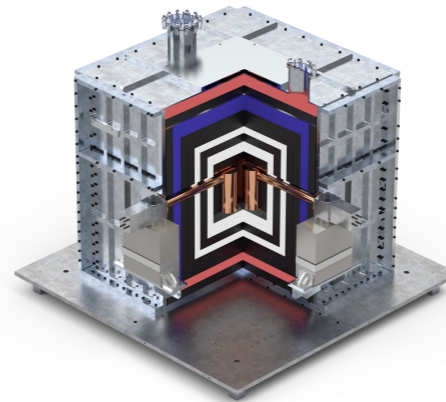
➔ Can detect reactor-accelerated DM.

CONUS

- CONUS experiment at Brokdorf, Germany, to look for $CE\nu NS$.



[Photo from Wikipedia]




[CONUS]

- Experimental configuration:

P	l_{det}	l_s	Detector material
3.9 GW	17.1 m	5 m	^{74}Ge (92 %), ^{73}Ge (8 %)

- We use CONUS data of $248.7 \text{ kg} \times \text{day}$ [CONUS 20]

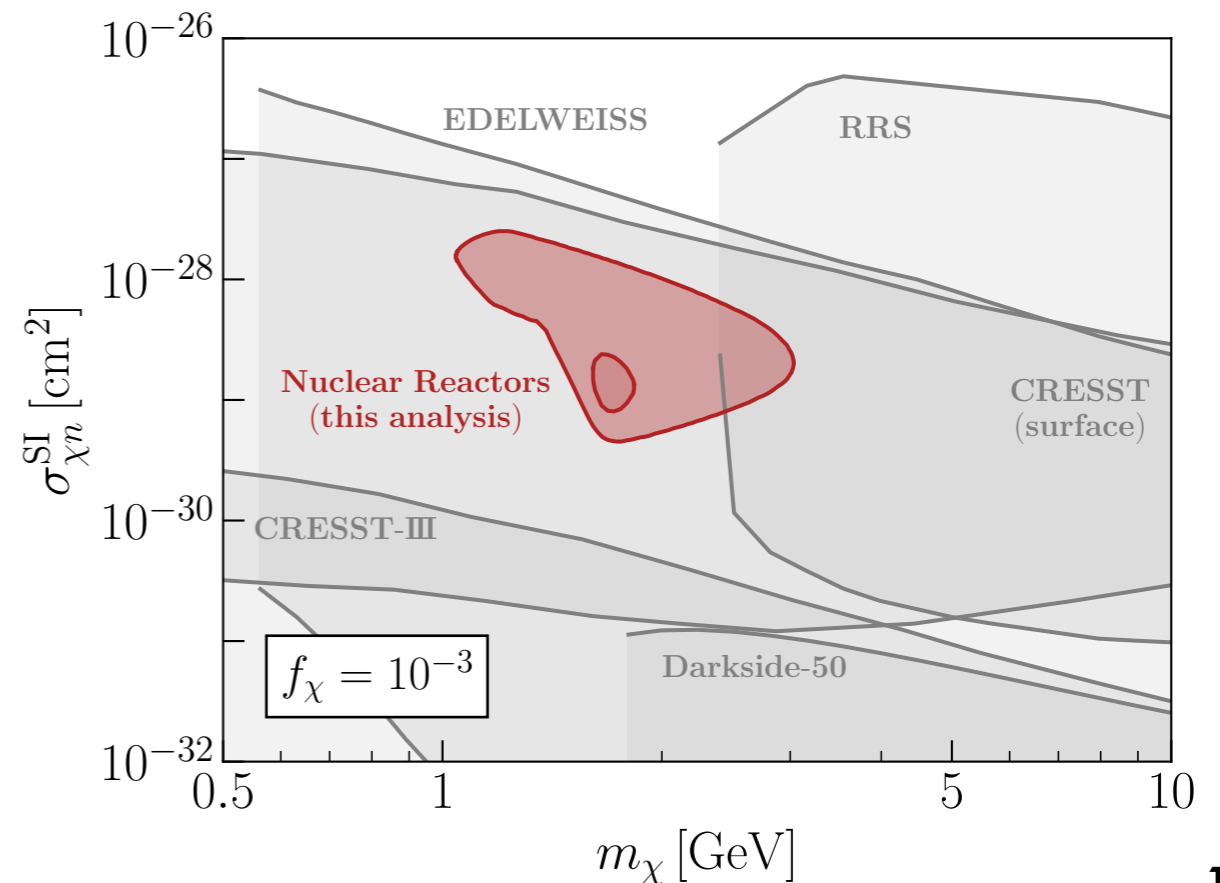
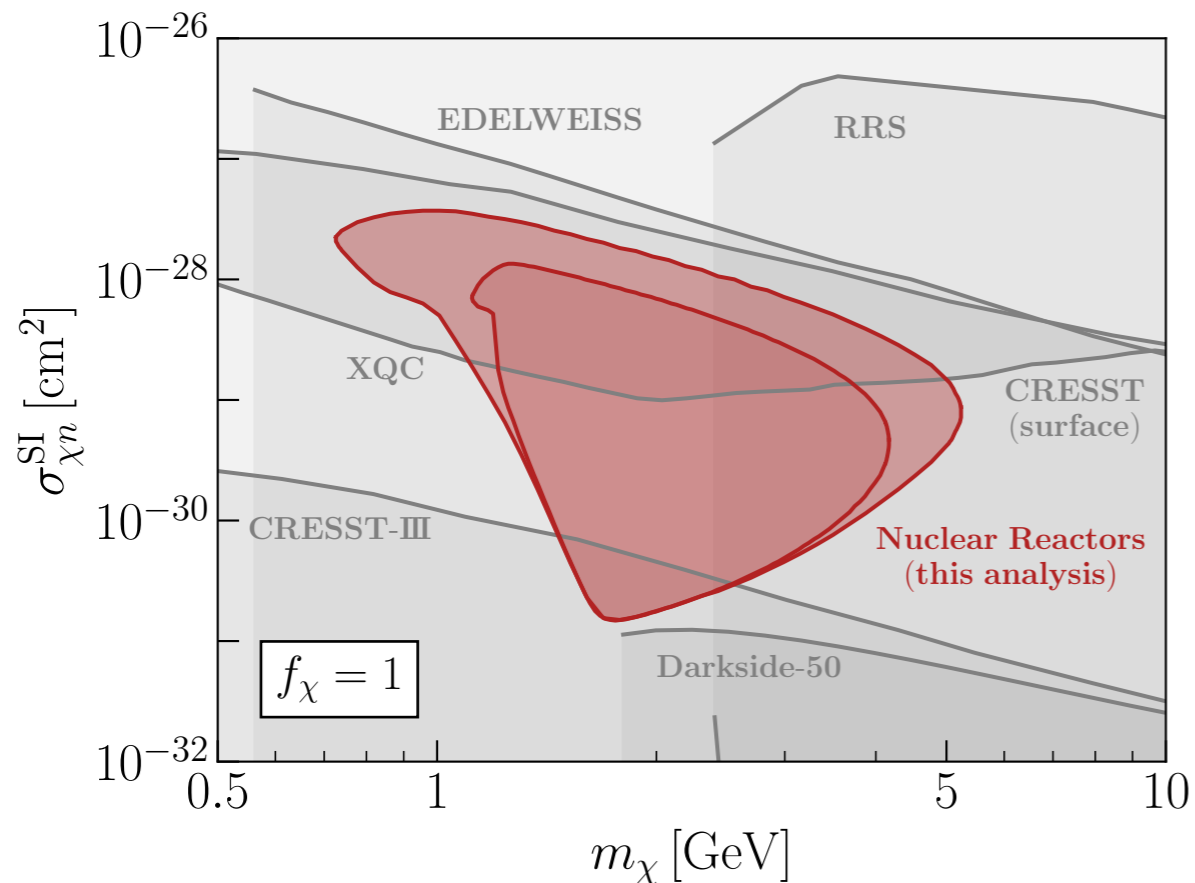

Require $\int_{1.7 \text{ keV}}^{5.6 \text{ keV}} dE_{\text{eve}} \frac{dN_{\text{eve}}}{dE_{\text{eve}}} < 85.$

Result: spin-independent

Spin-independent cross section

[YE, Pospelov, Ray 24]

- DM fraction: $f_\chi = 1$ (left) and $f_\chi = 10^{-3}$ (right), scaling is $\sigma \propto f_\chi^{-1/2}$ (we use σ twice).
- Small (large) region: DM without (with) multiple scatterings.
- The parameter region covered by other direct detection experiments.
- An idealistic research reactor, e.g. $P = 1$ MW, $l_{\text{det}} = 3$ m, $l_s = 1$ m, extends ceiling.

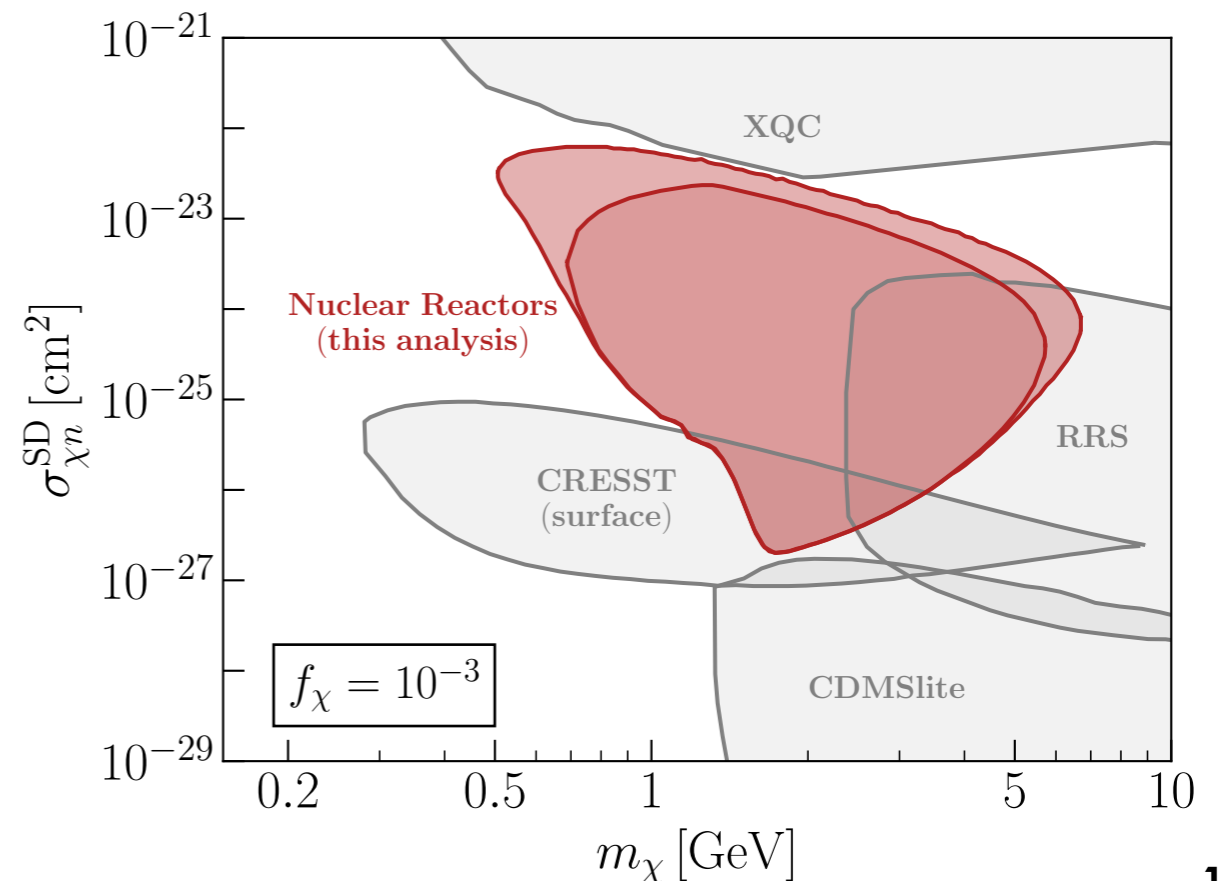
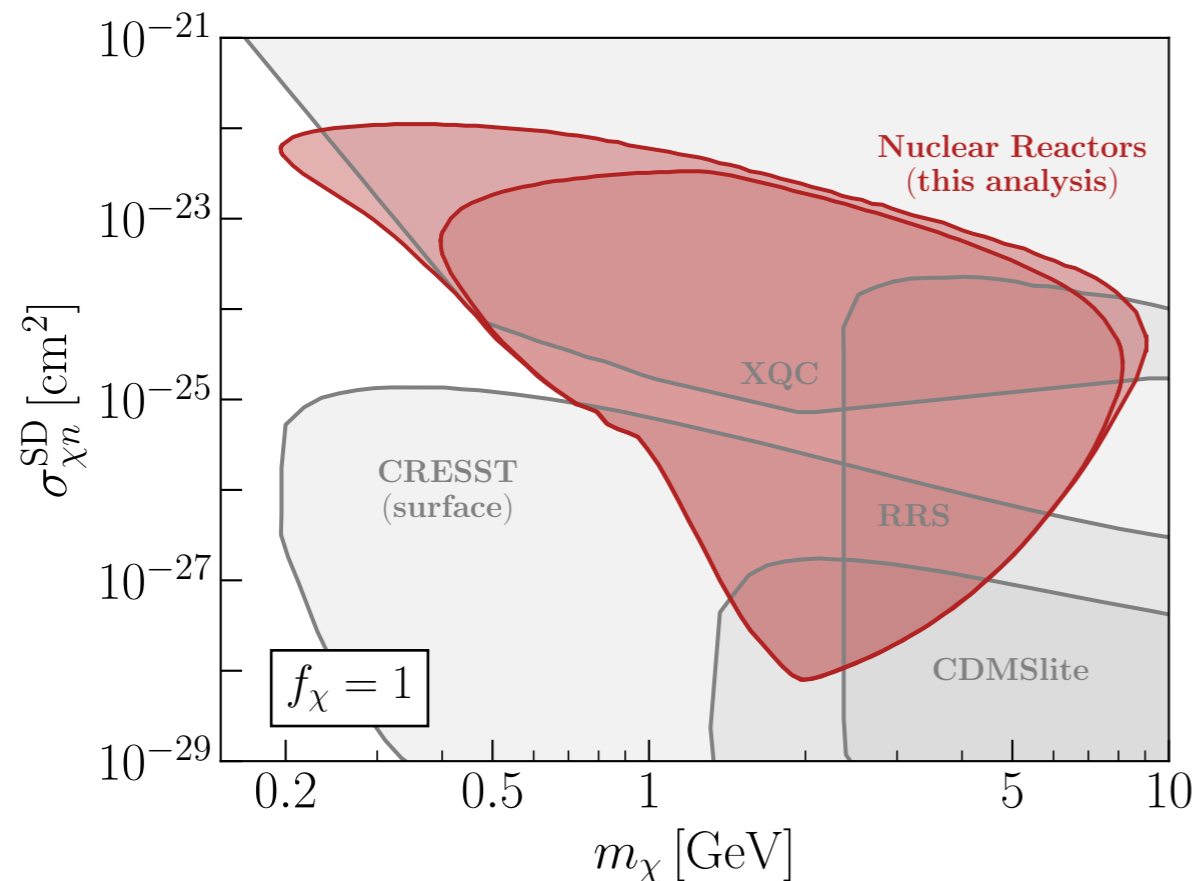


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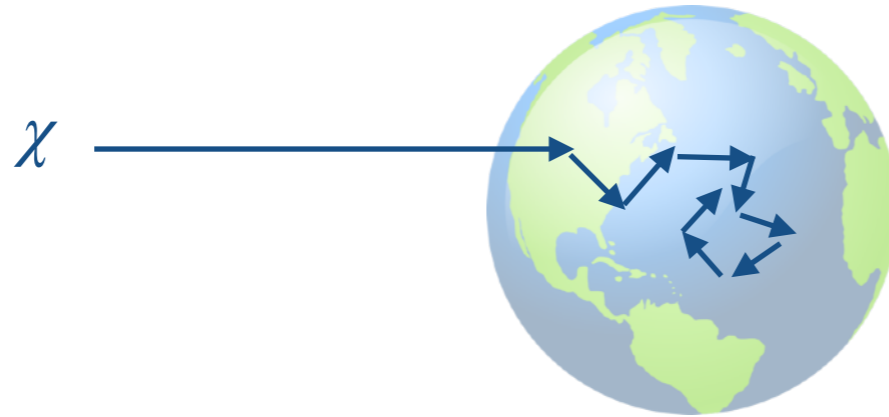
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- Small (large) region: DM without (with) multiple scatterings.
- CE ν NS experiment covers new parameter regions.
- Atmosphere shielding is relatively thicker for SD since ^{14}N : $I = 1$.

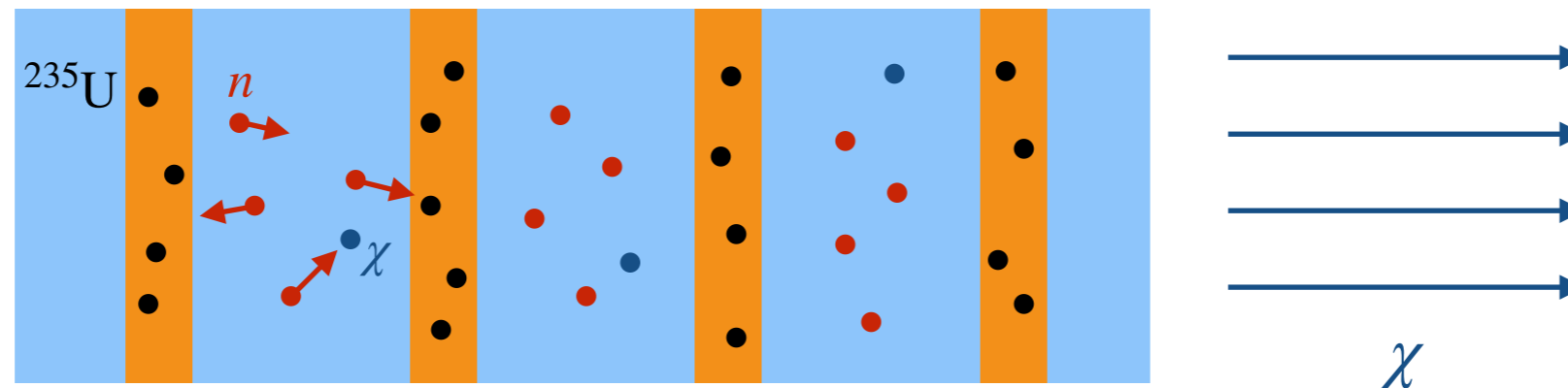


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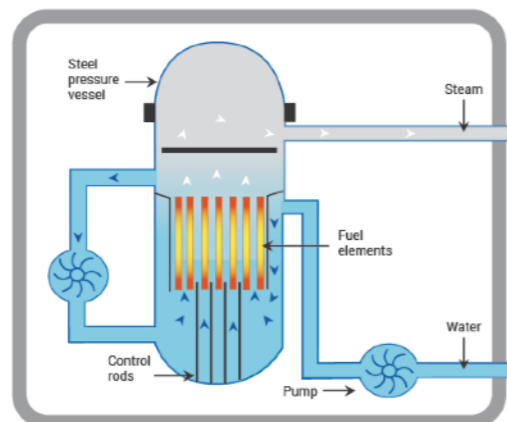
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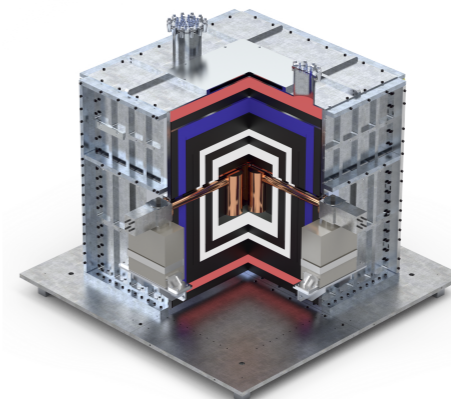
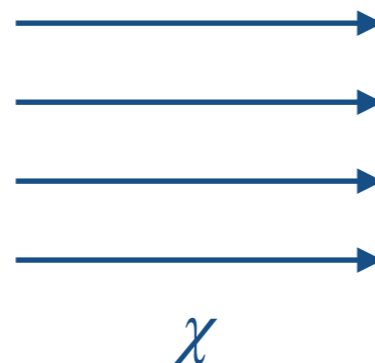
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[Fig. from World Nuclear Association]



[CONUS]

Summary

- Earth-bound DM up-scattered by nuclear reactors.
 - ➔ $\text{CE}\nu\text{NS}$ experiments ideal for “accelerated” DM detection.
- Research reactor with less shielding potentially improves the SI case.
- Interesting bounds obtained for the SD case.

