Direct Dark Matter Searches: Part I

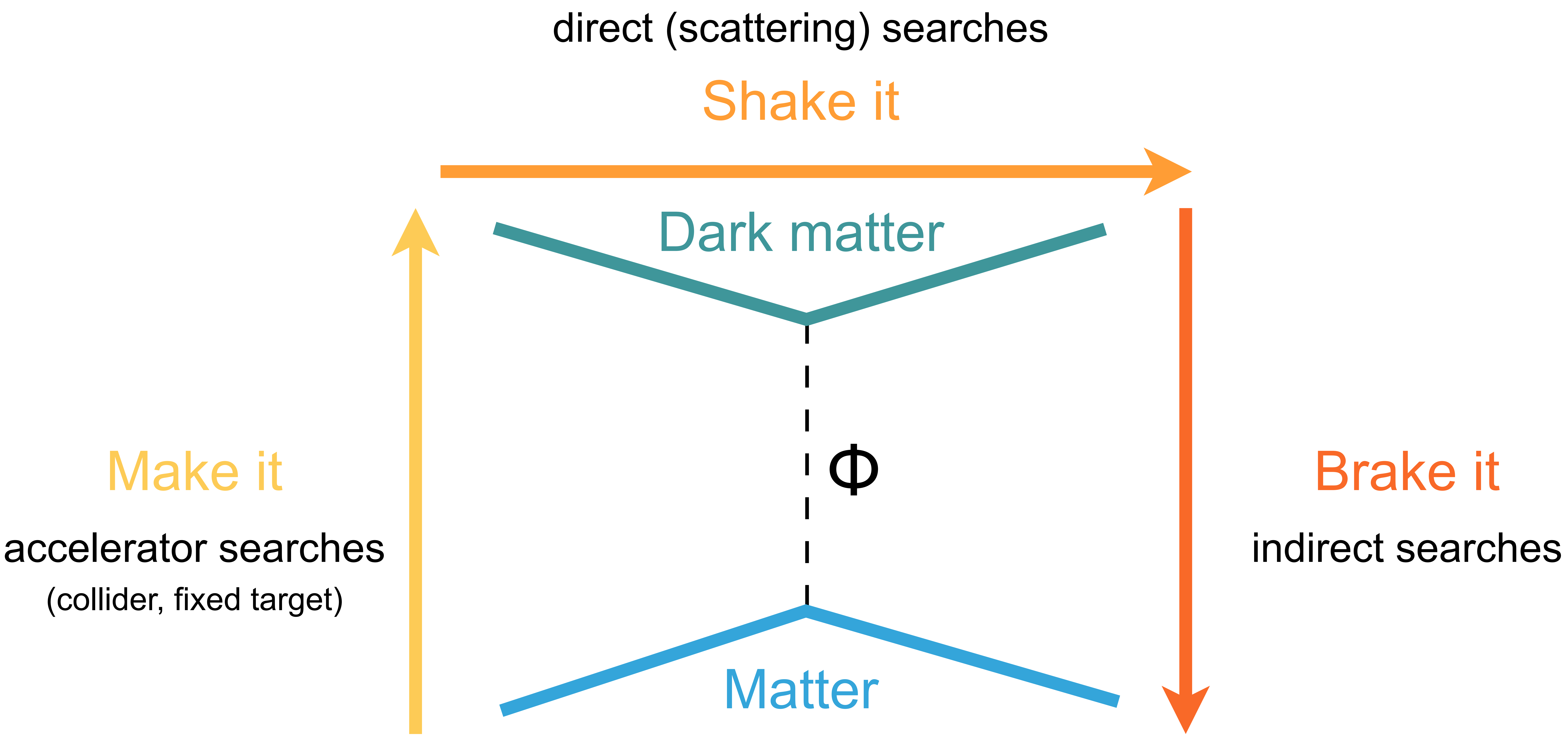
Principles of direct detection: nuclear recoil

ISAPP School „Neutrinos and Dark Matter – in the lab and in the Universe“, 24.09.2024

Belina VON KROSIGK (bkrosigk@kip.uni-heidelberg.de)

Credit: Swinburne Astronomy Productions - J. Josephides

Ways to detect dark matter particles



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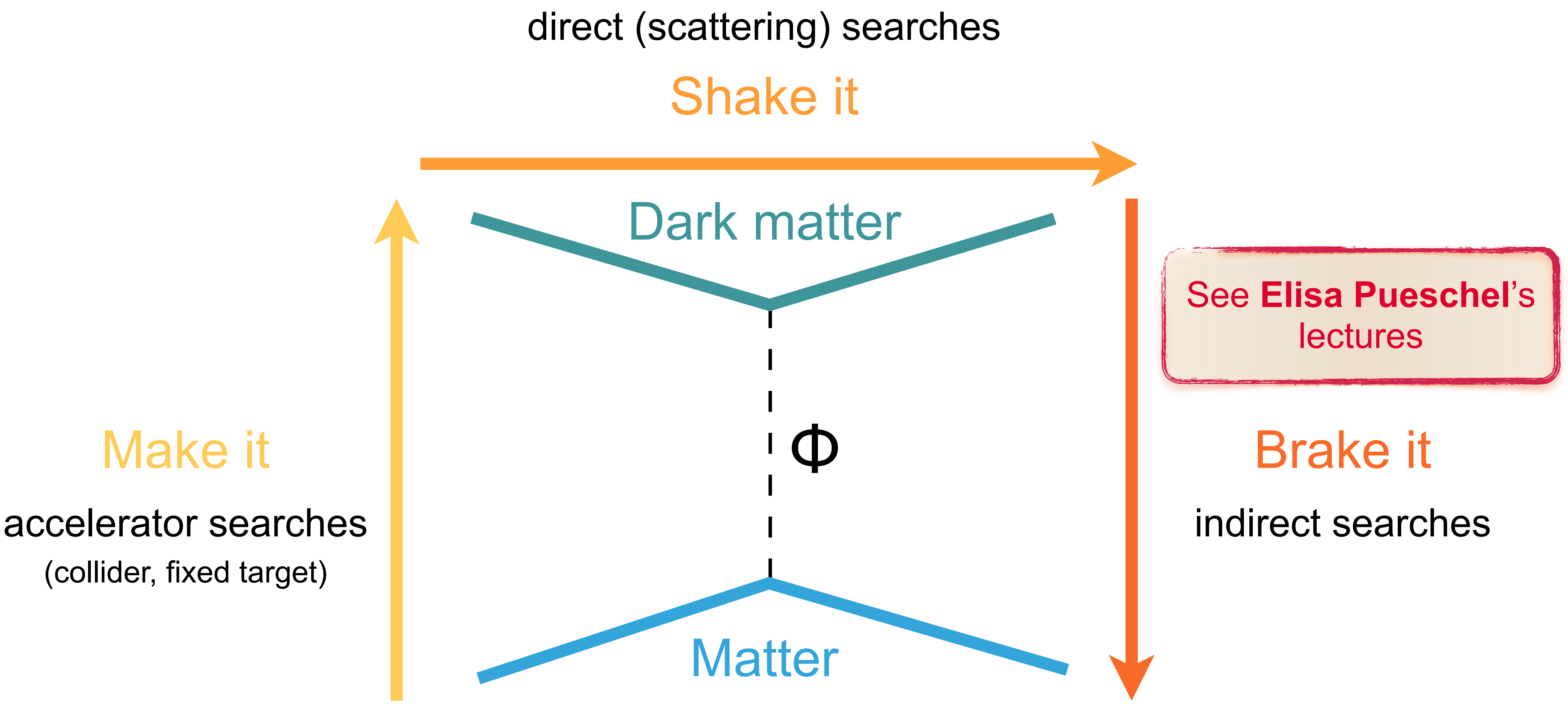

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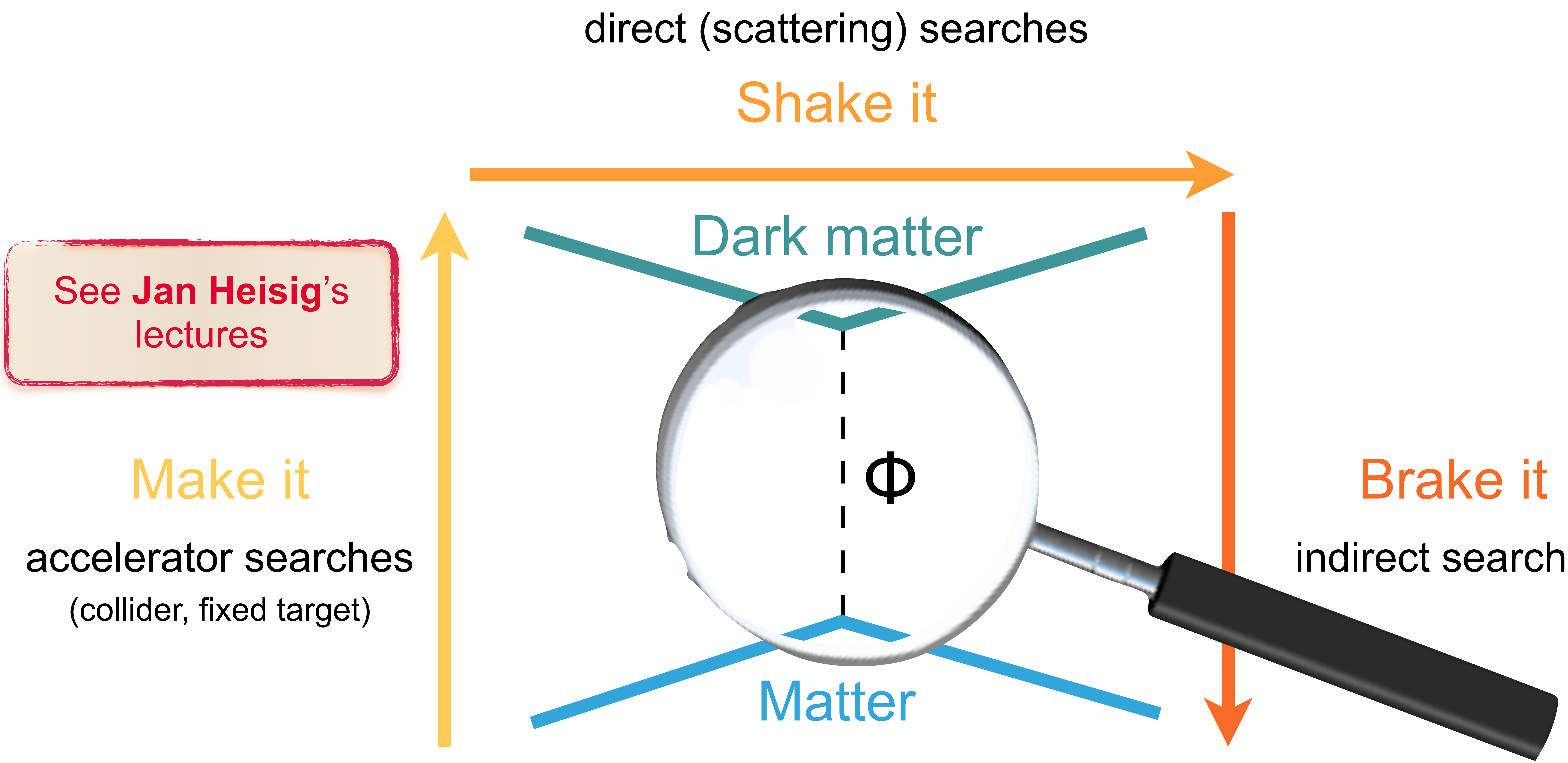
Ways to detect dark matter particles



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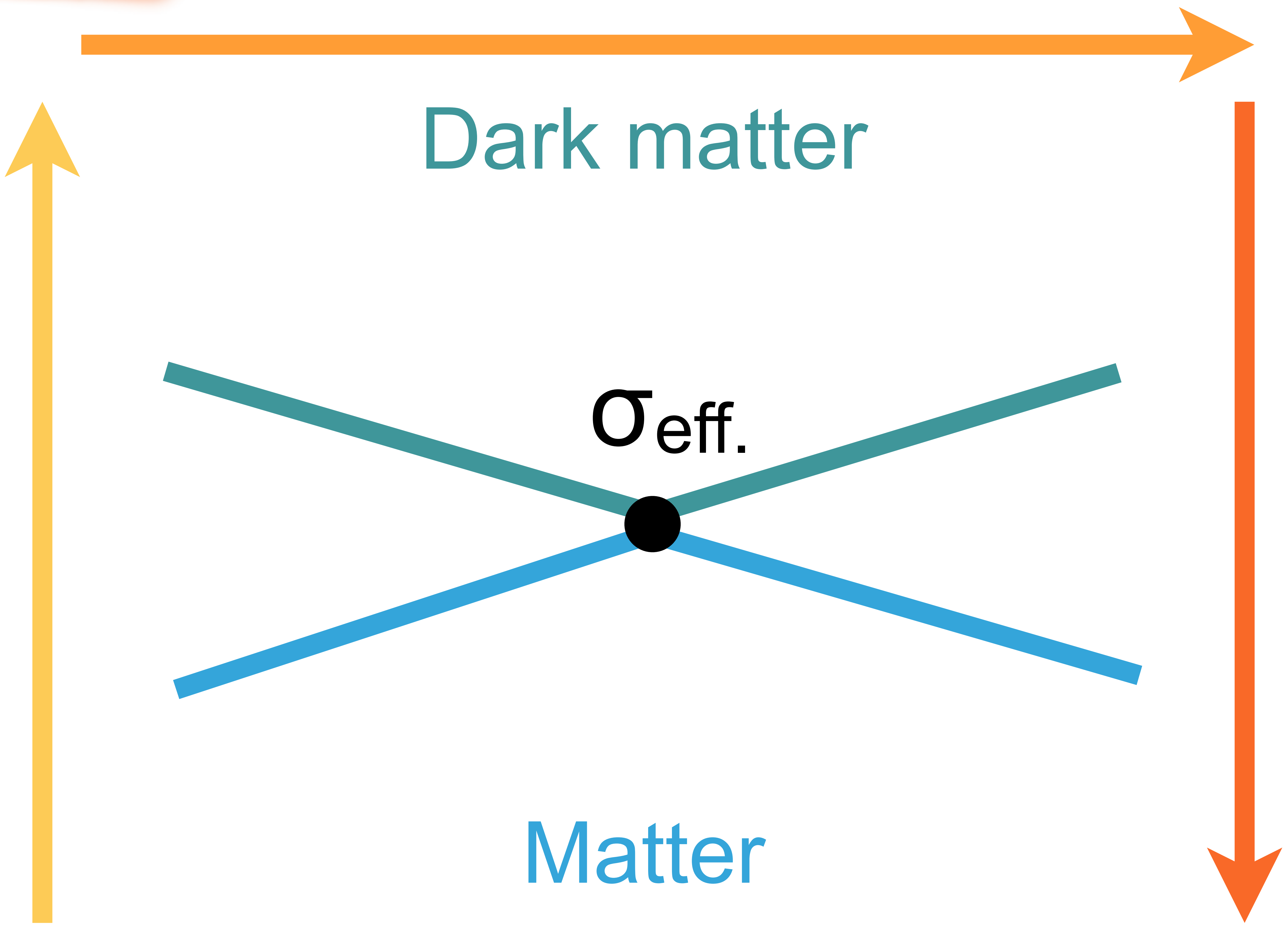
Ways to detect dark matter particles

Subject of these lectures

direct (scattering) searches

Shake it



Make it

accelerator searches

(collider, fixed target)

Brake it

indirect searches

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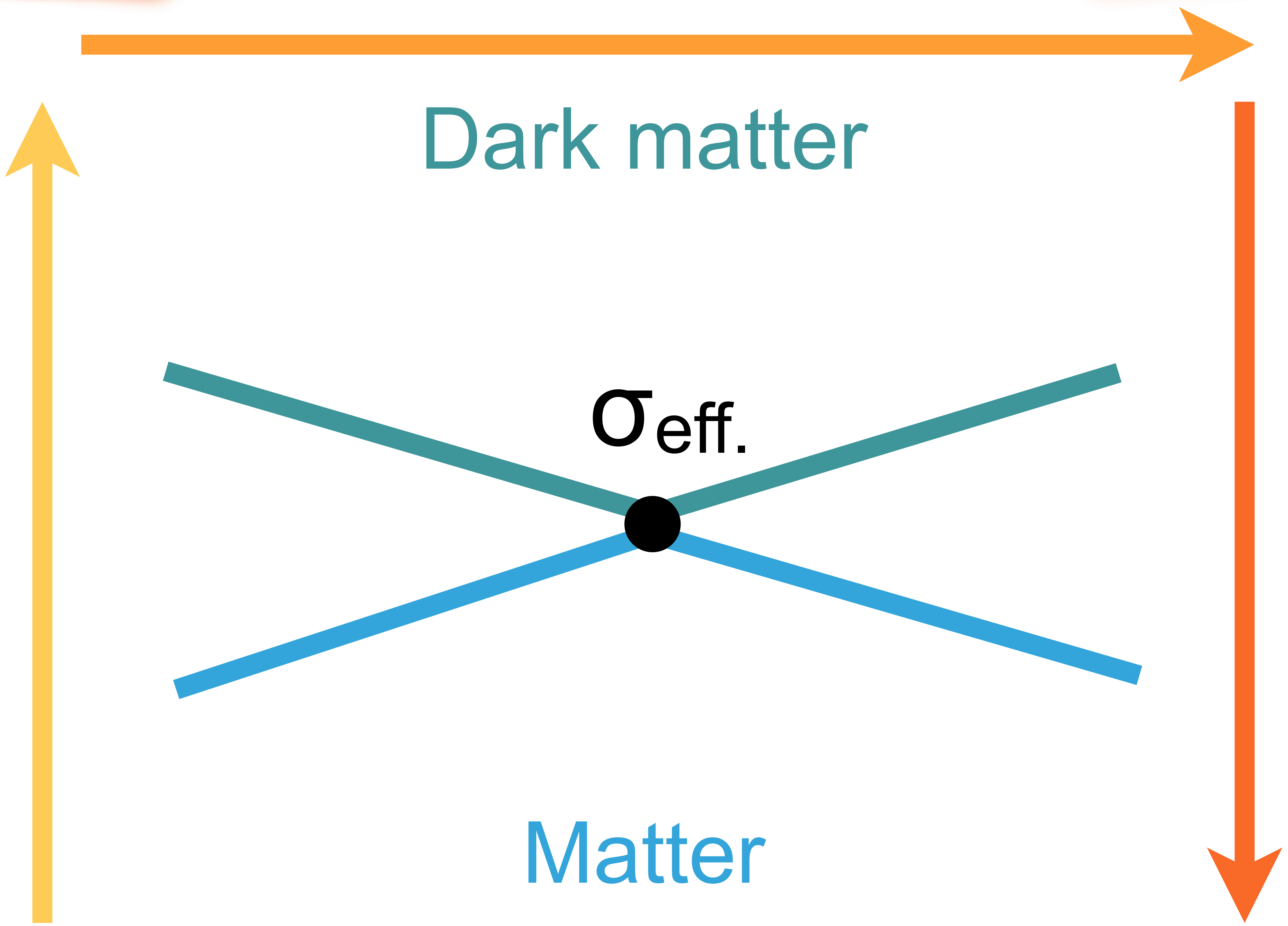
Non-scattering searches:
See **Béla Majorovits**' lectures



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Direct dark matter detection

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How to build a dark matter detector

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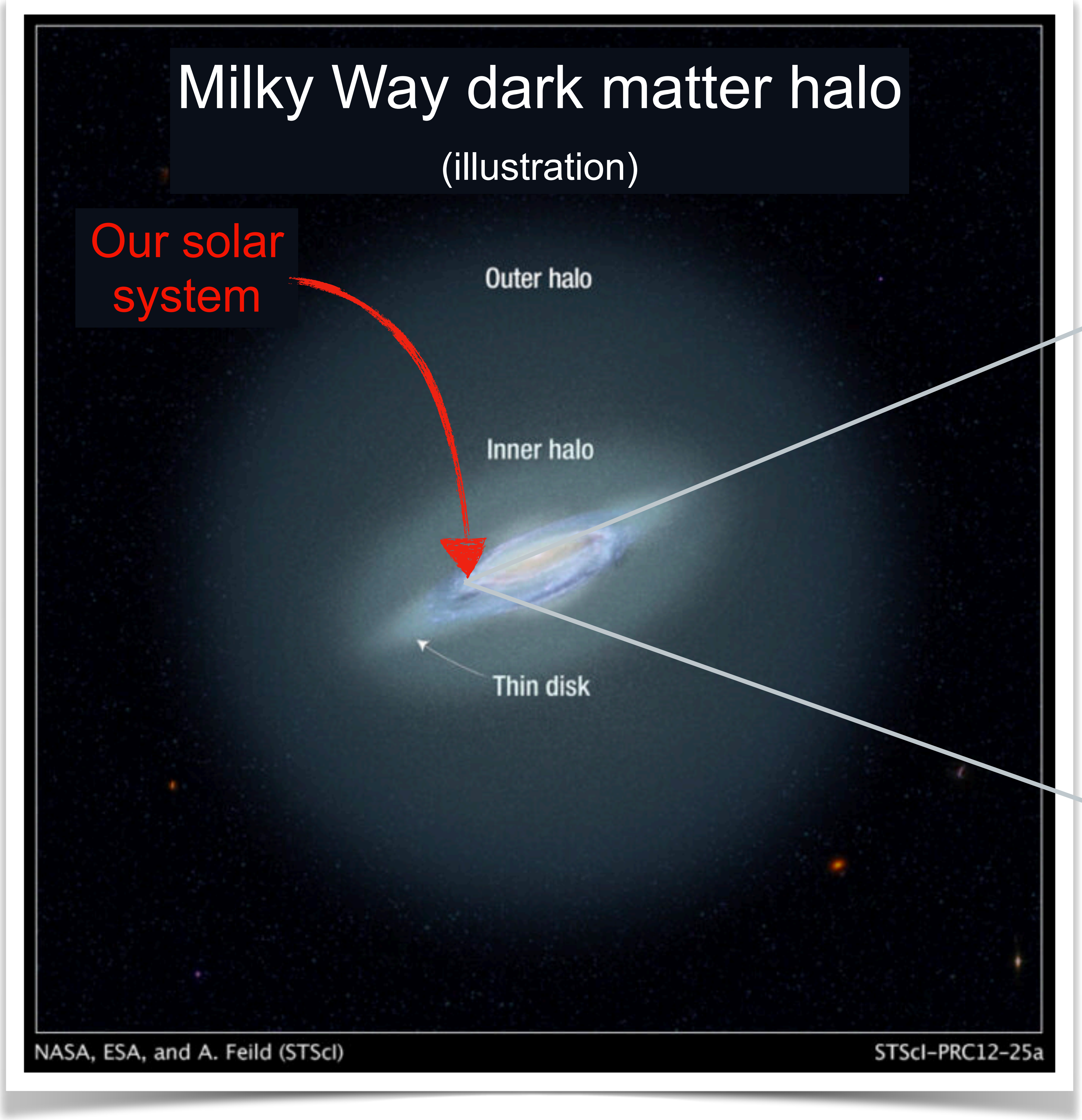
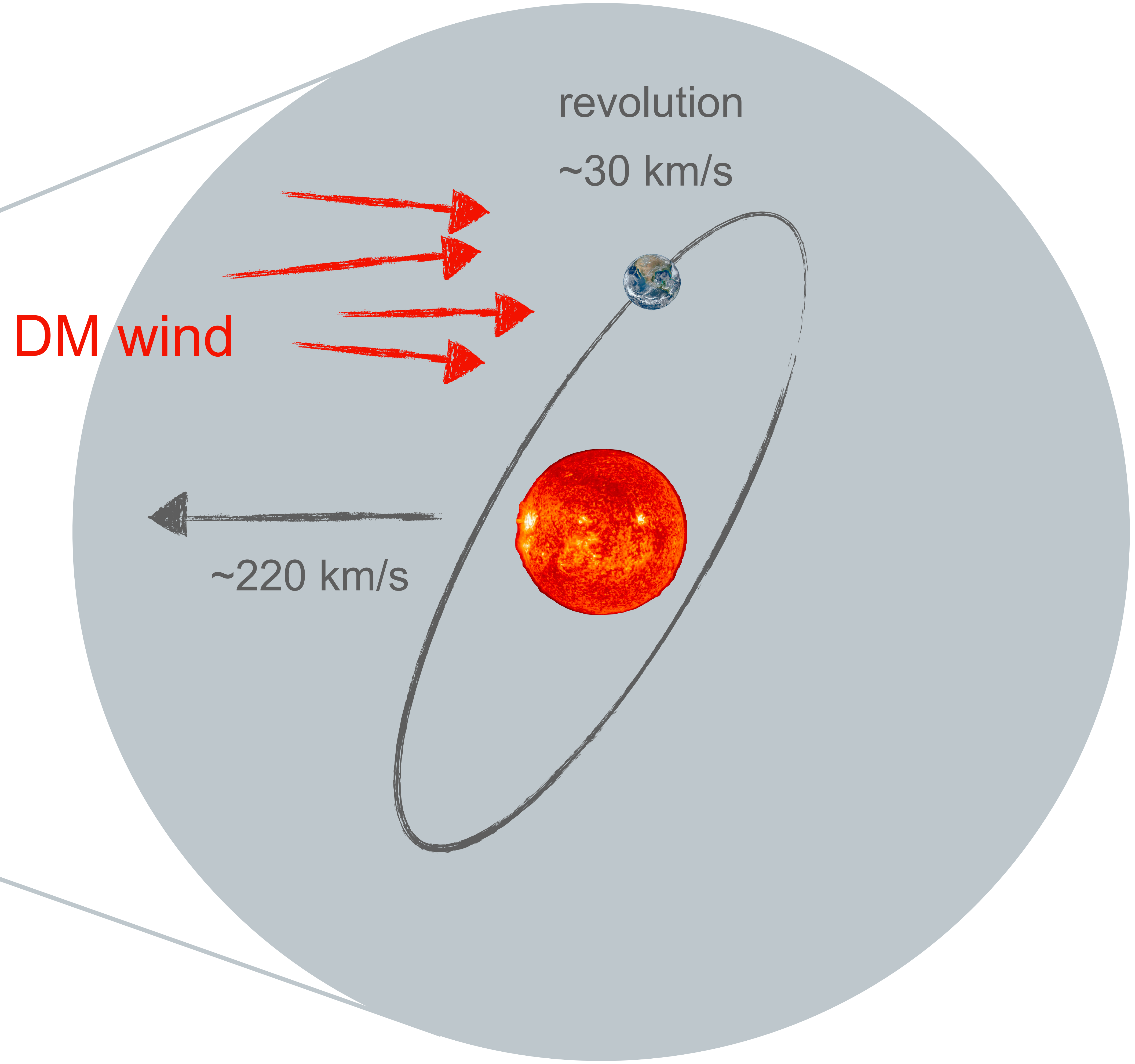
Direct dark matter detection

relic

How to build a
dark matter detector

Taking advantage of galactic dark matter halo





Taking advantage of galactic dark matter halo

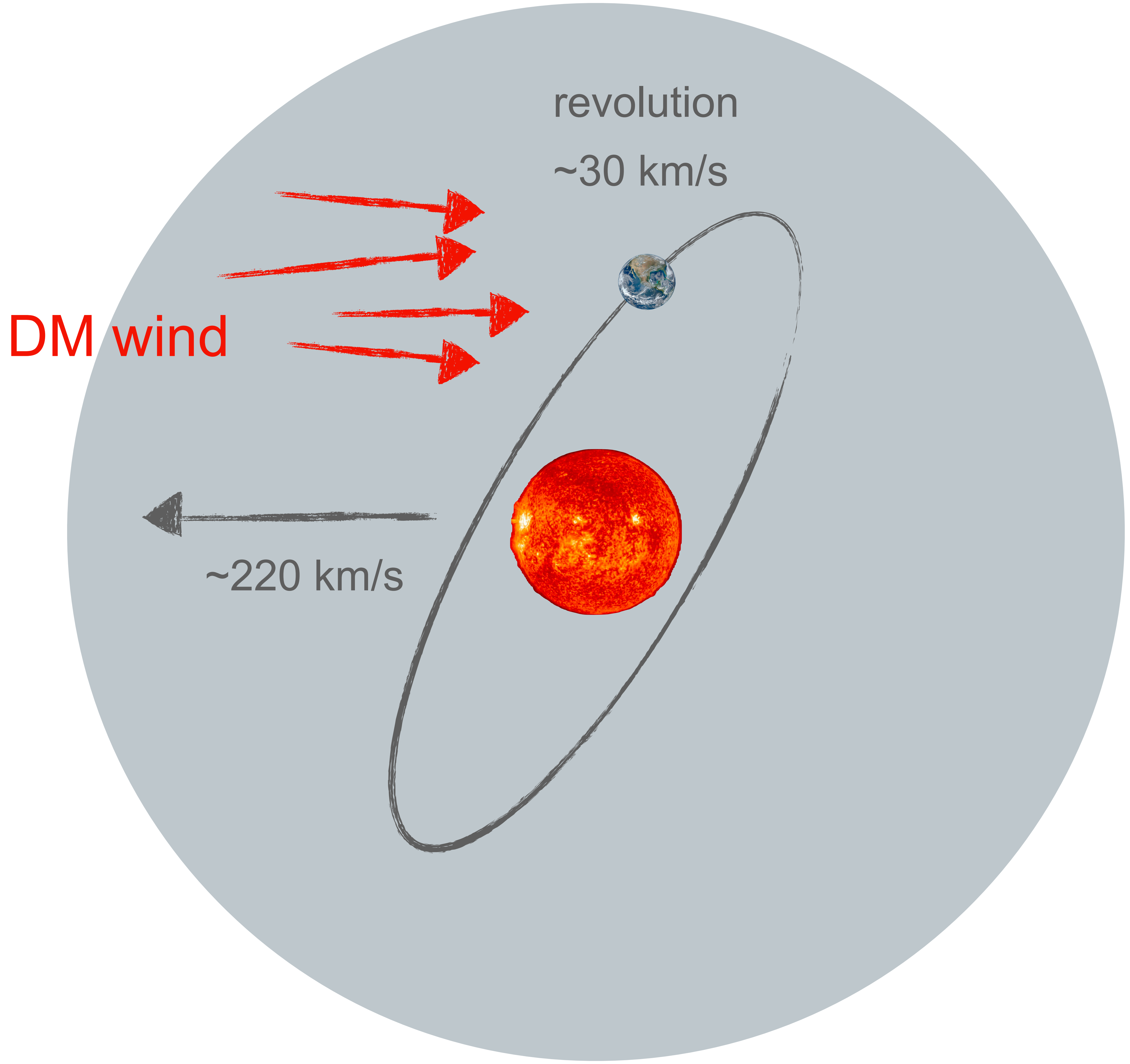
Place detector on Earth.

↓

DM particles will
permanently cross detector.

↓

Search for interactions of DM particles
with detector material.



How to design a dark matter detector

- Expected candidates, interactions, and rates
- Background considerations
- Experimental signatures

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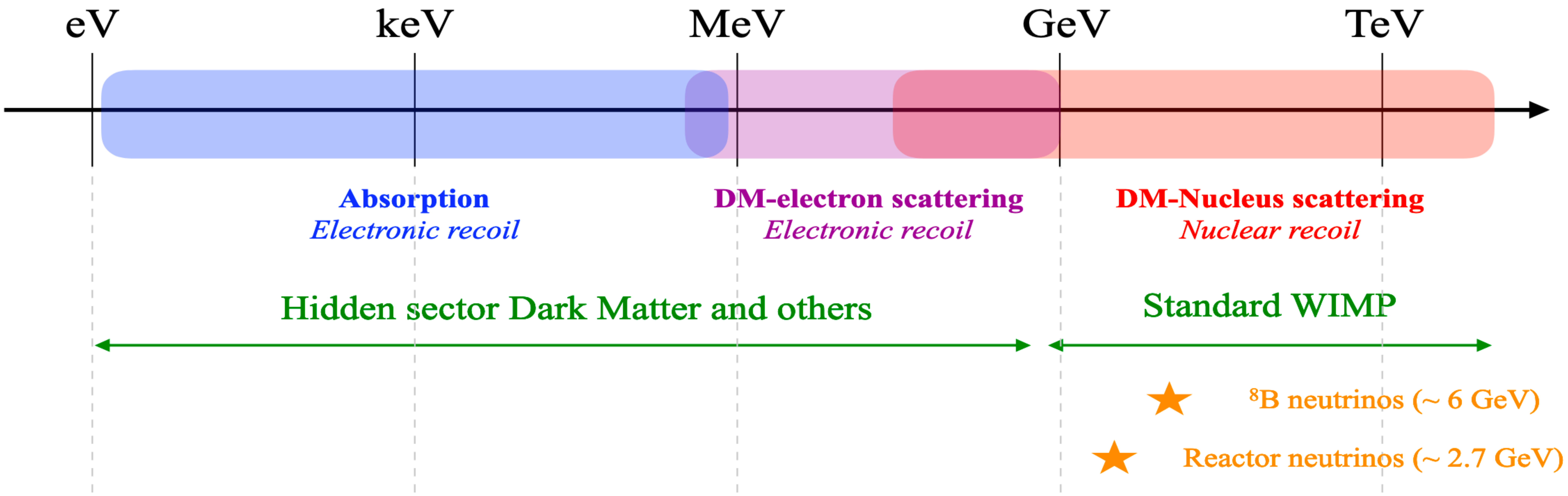

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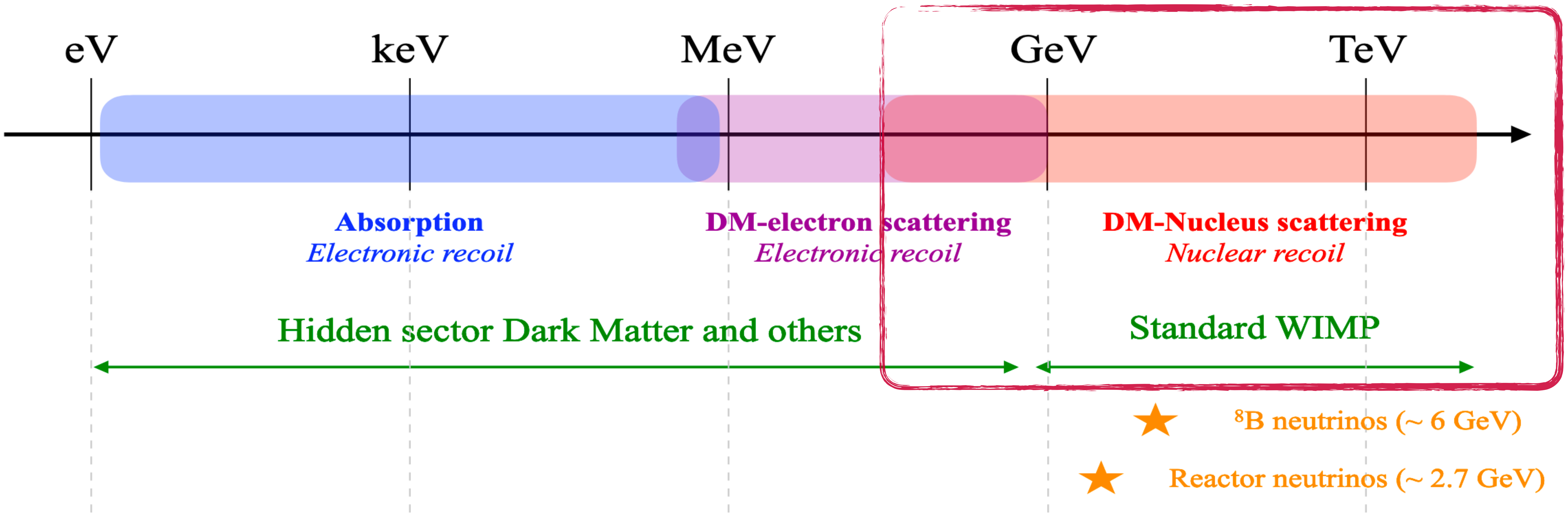

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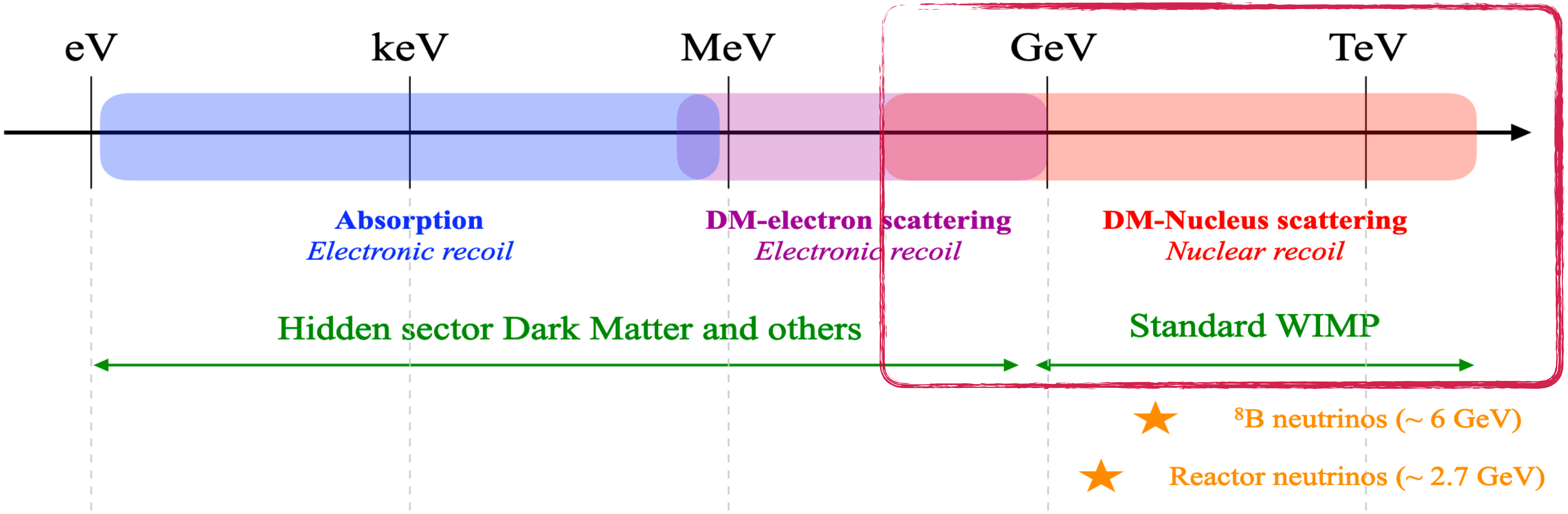

See **Marco Cirelli**'s lectures

How to design a dark matter detector

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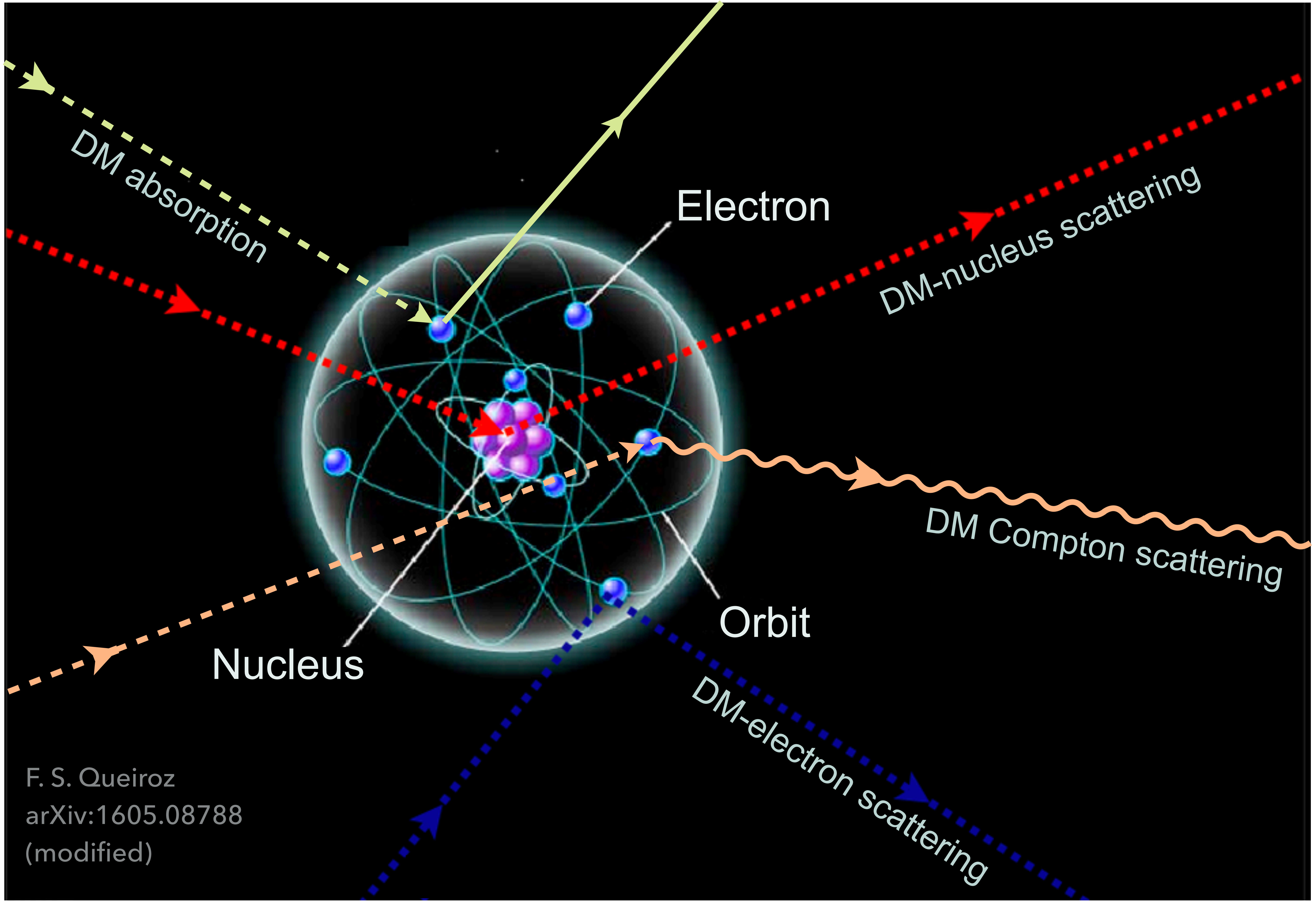

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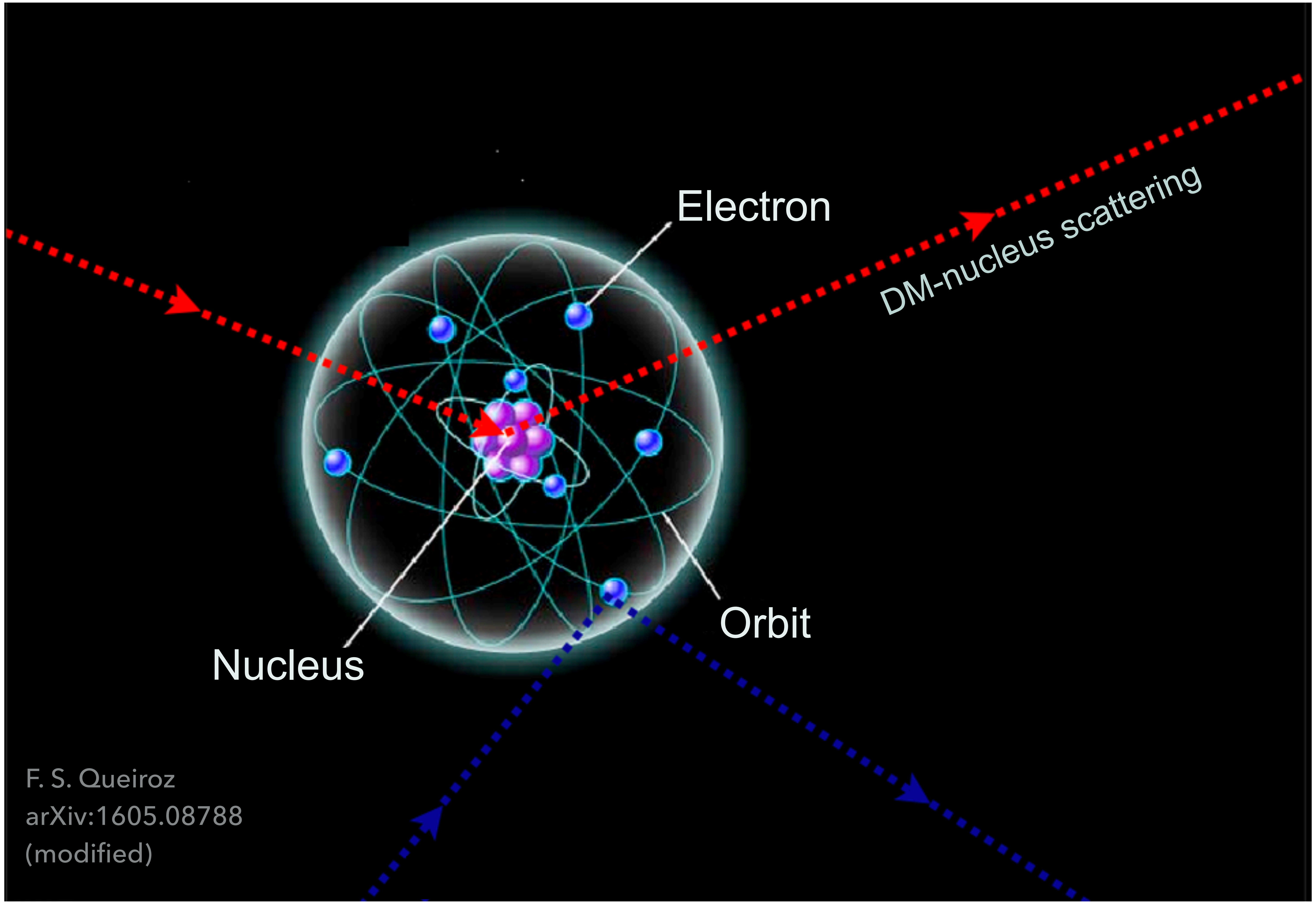
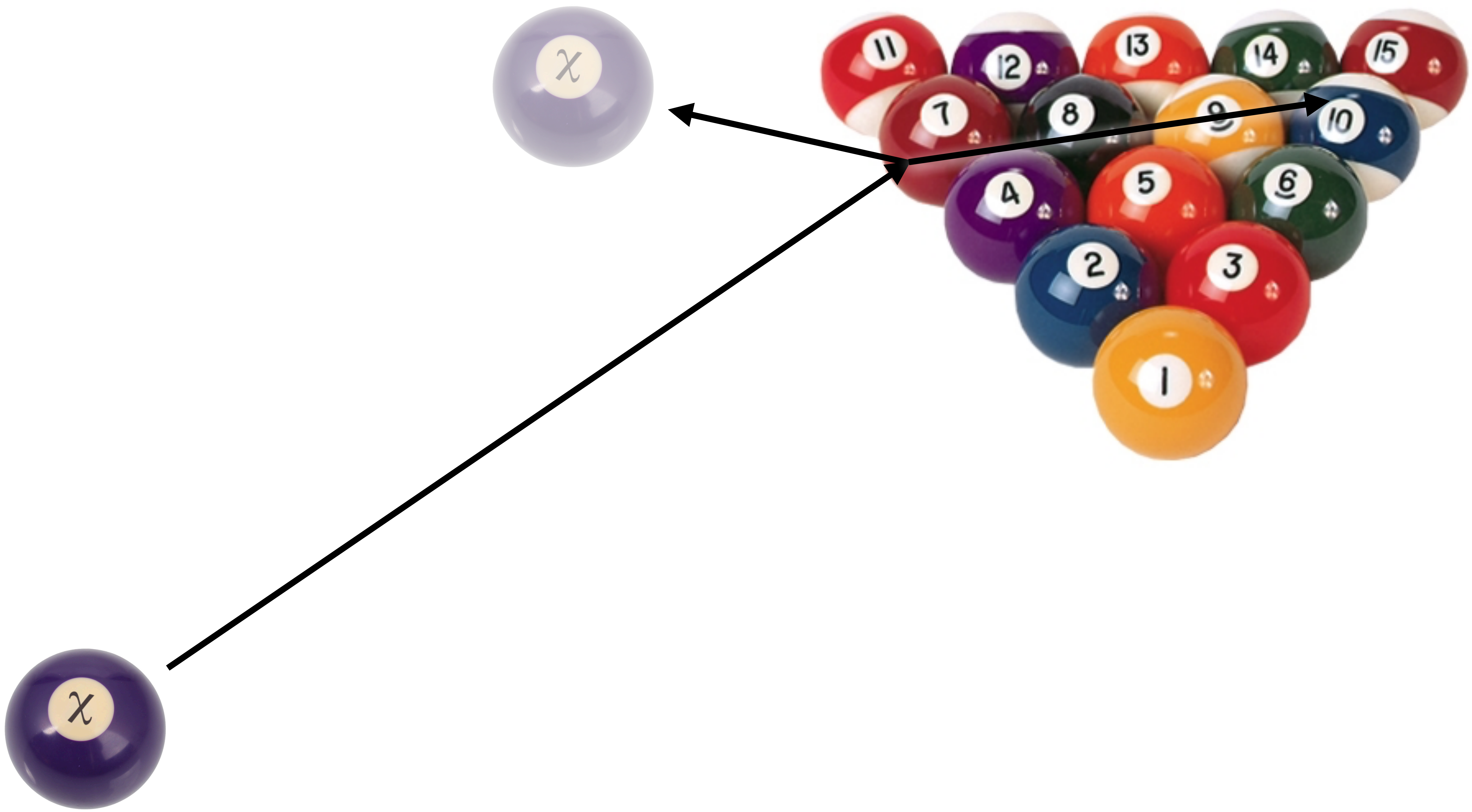


Elastic dark matter-nucleus scattering



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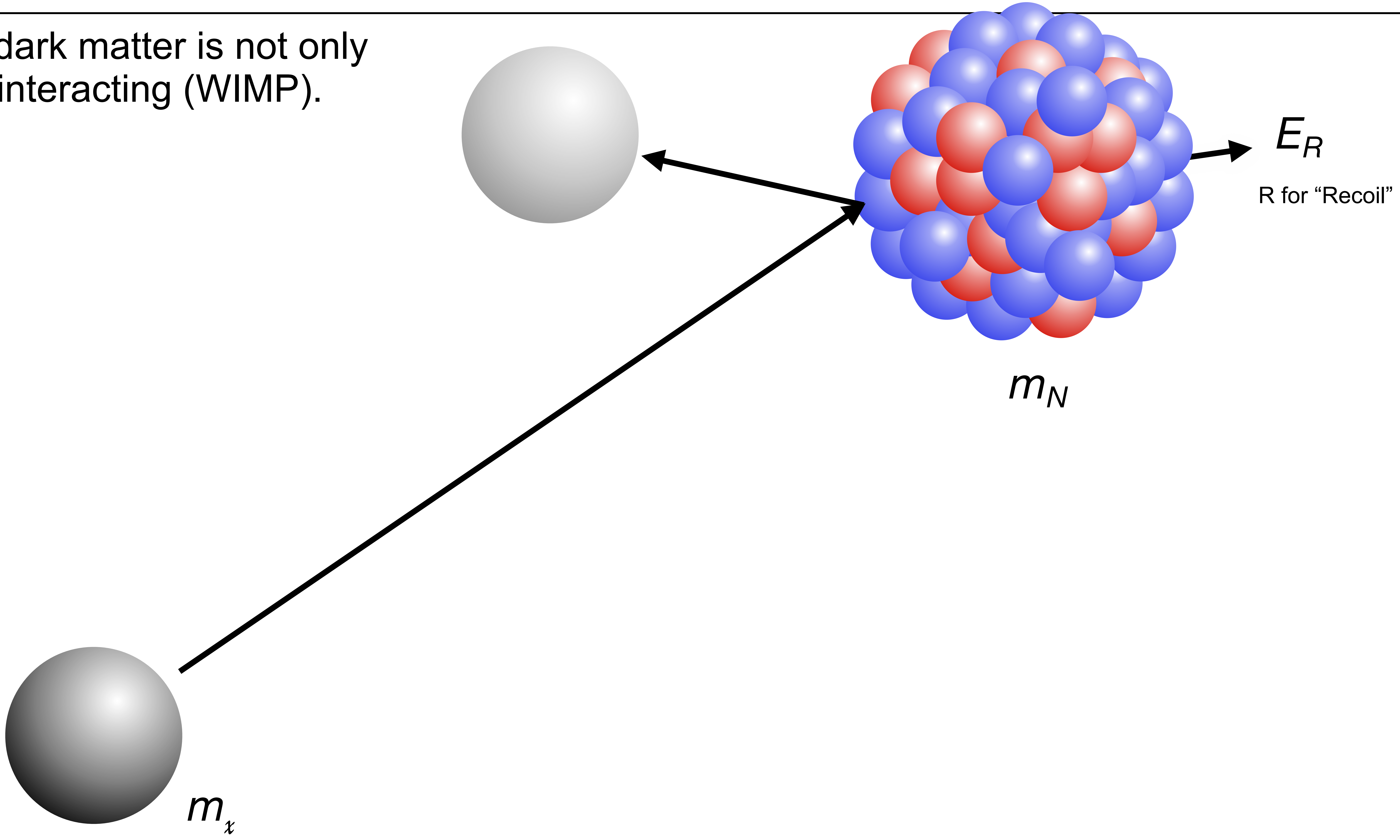
Assume that the dark matter is not only gravitationally interacting (WIMP).



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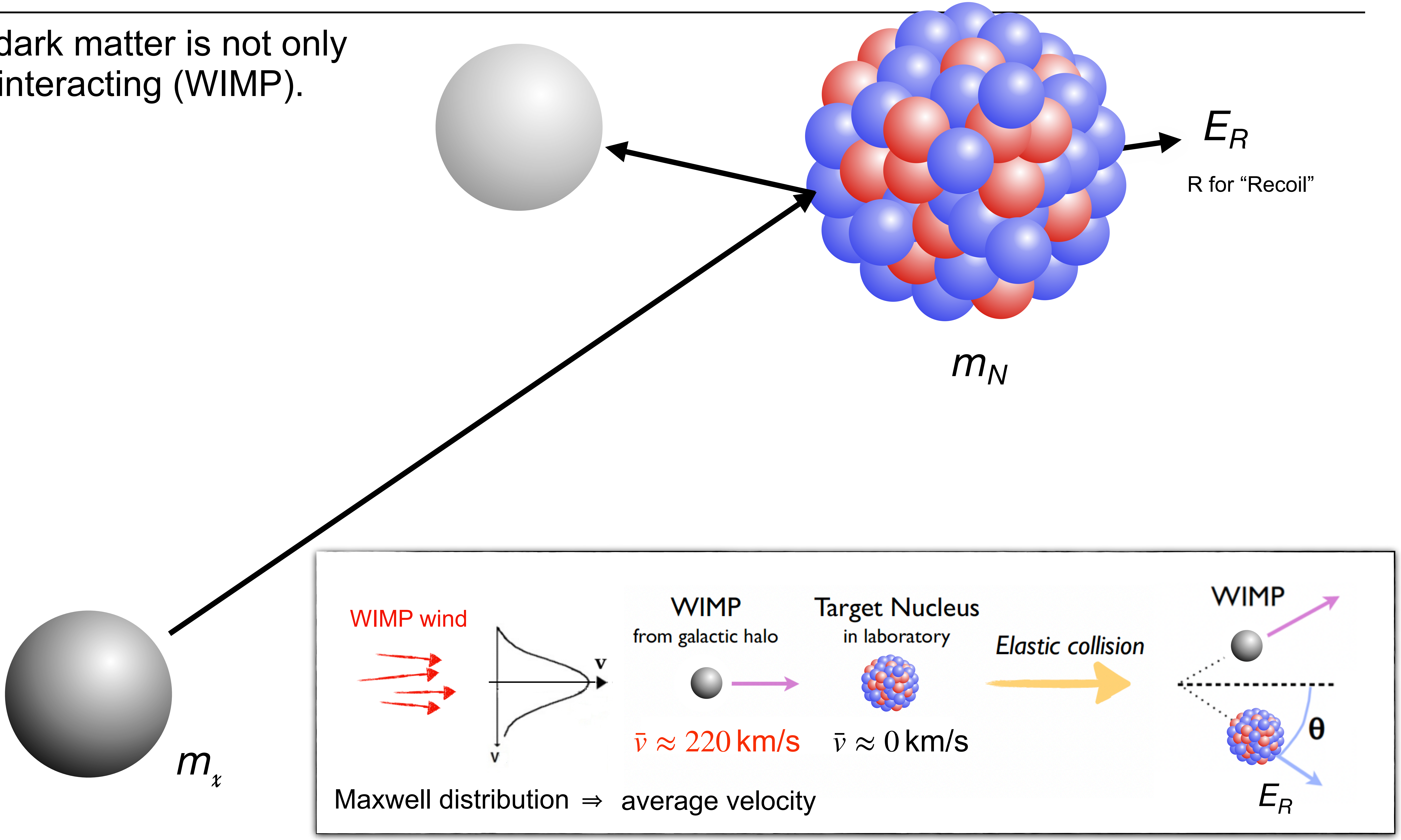
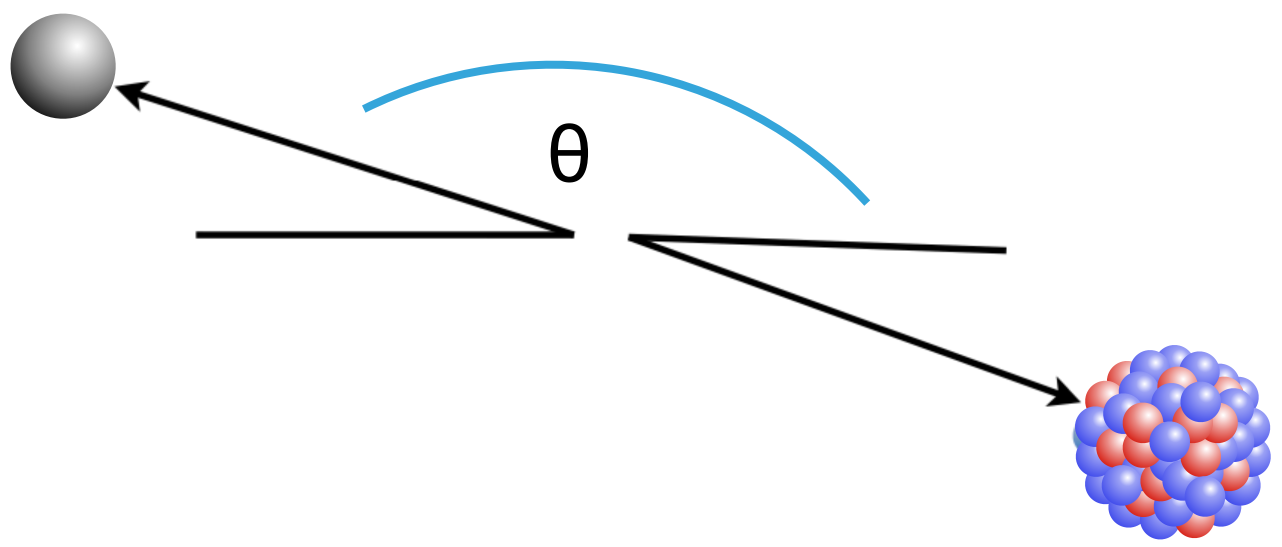


Dive-in: kinematics

Calculate E_R, i.e. the recoil energy of a nucleus, in the center of mass frame:



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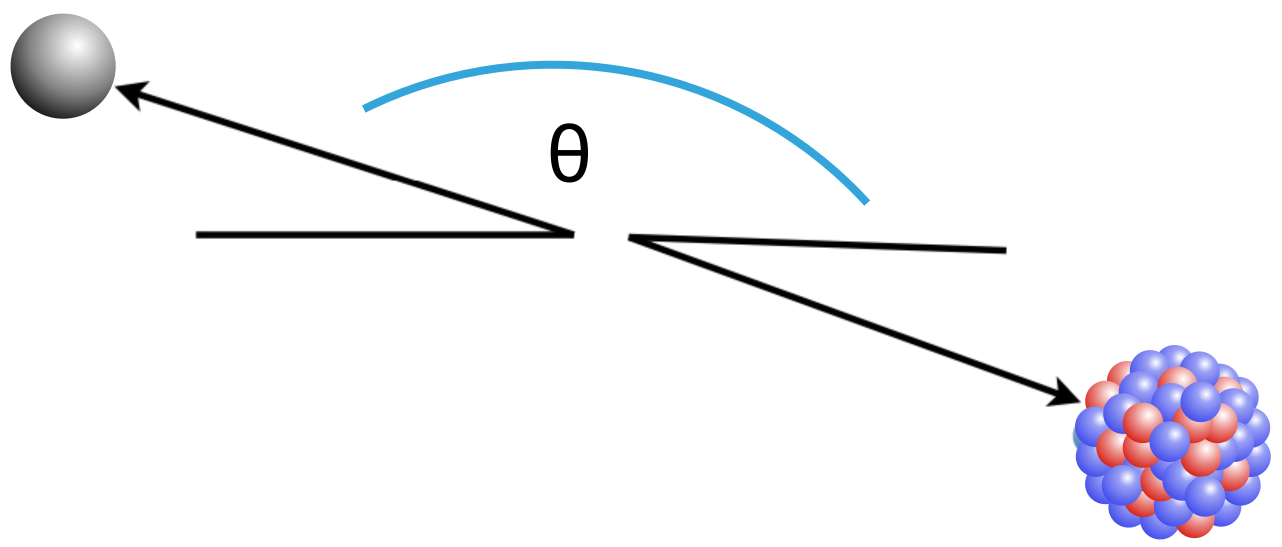

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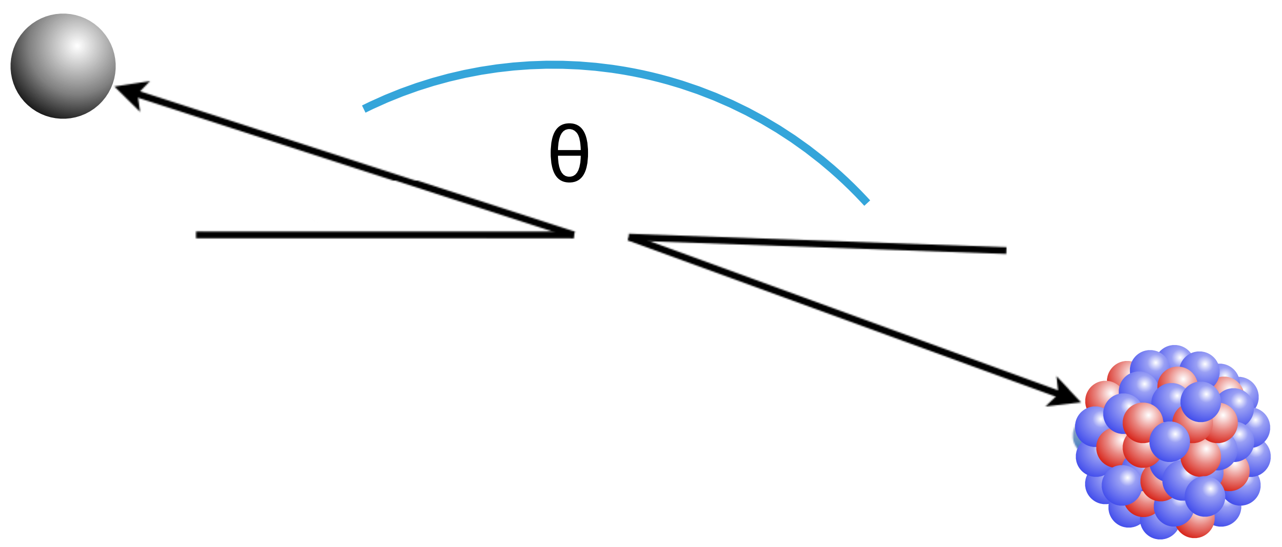

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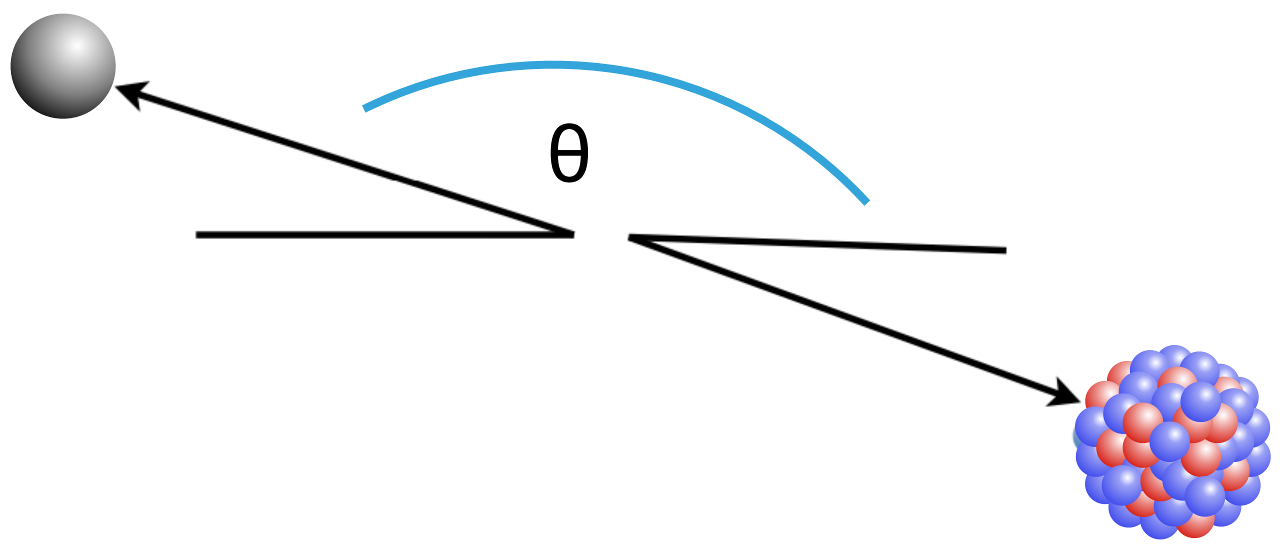

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$\bar{v}$: mean DM speed relative to target

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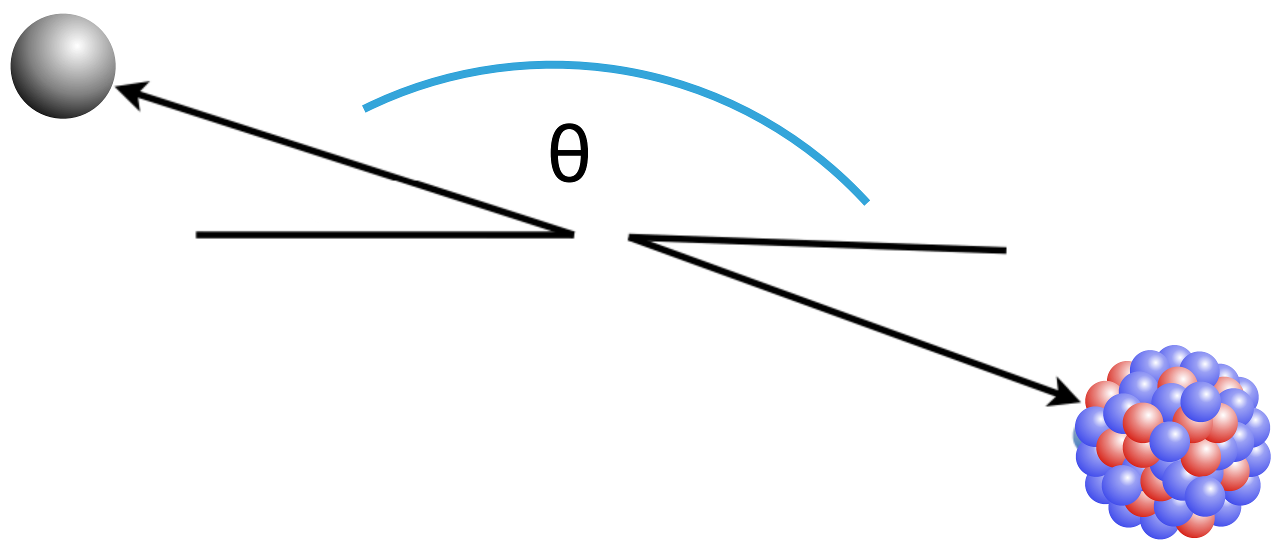

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Minimum DM particle speed v_{min}
for which we can reach a certain recoil:

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- Implications
  - Lighter dark matter particles ($m_\chi << m_N$) require a larger minimum speed for a given E_R
  - Inelastic scattering can further increase the minimum speed needed

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What recoil energies do we expect?

$$E_R^{\max} = 2\frac{\mu^2 \bar{v}^2}{m_N} = \left(\frac{1}{2} m_\chi \bar{v}^2\right)\left(\frac{4 m_\chi m_N}{(m_\chi + m_N)^2}\right)$$

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But what about rates?

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Expected rates in a detector

number of observed DM particles

DM number density • DM velocity

$$N = t \cdot \overbrace{n \cdot v} \cdot \underbrace{N_T \cdot \sigma}$$

observation time

number of targets • scattering cross section

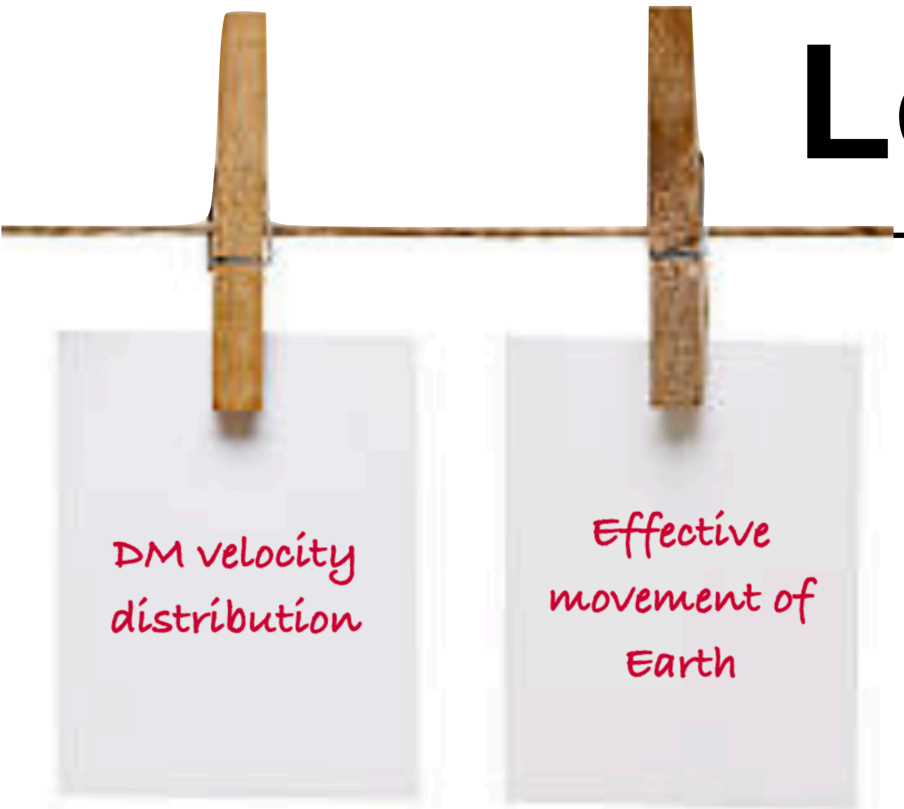
Spectrum of DM recoils, i.e. the energy dependence of the number of detected DM particles:

$$\frac{dN}{dE_R} = t \cdot n \cdot v \cdot N_T \cdot \frac{d\sigma}{dE_R}$$

Expected rates in a detector - the laundry list

Both theoretical and experimental aspects need to be carefully evaluated for a sound rate prediction.

Local velocity distribution



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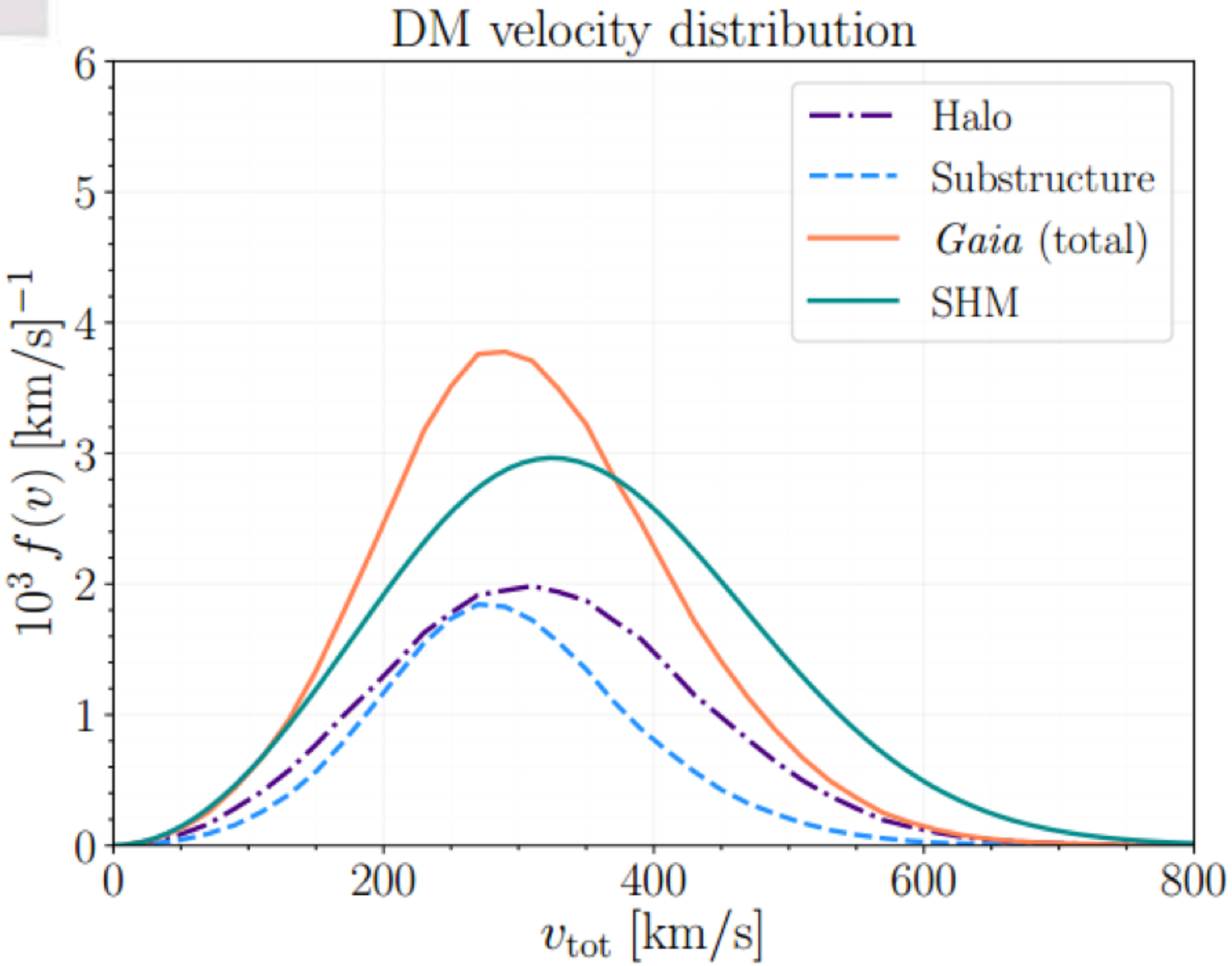
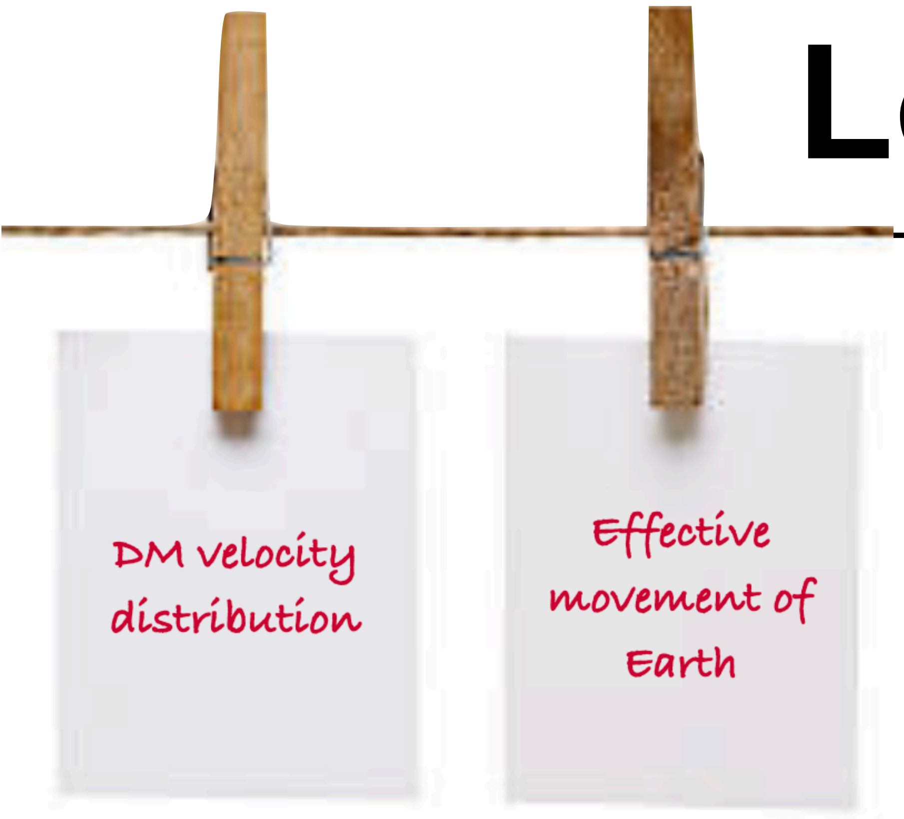


SHM: Standard Halo model (truncated Maxwell distribution)

$$f(\vec{v}) = \frac{1}{N_{\rm esc.}} \frac{1}{(2\pi\sigma^2)^{3/2}} e^{-\frac{|\vec{v}|^2}{2\sigma^2}} \Theta(v_{\rm esc.} - v)$$

J. Buch, J. Fan, J. Shing Chau Leung, PRD 101, 063026 (2020)



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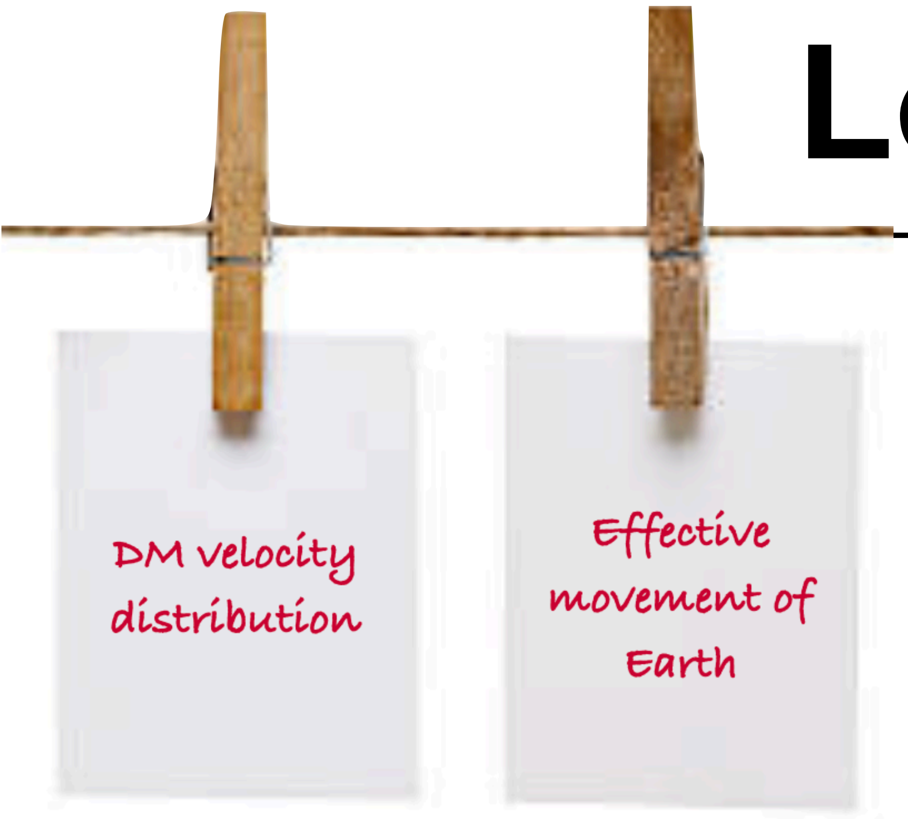

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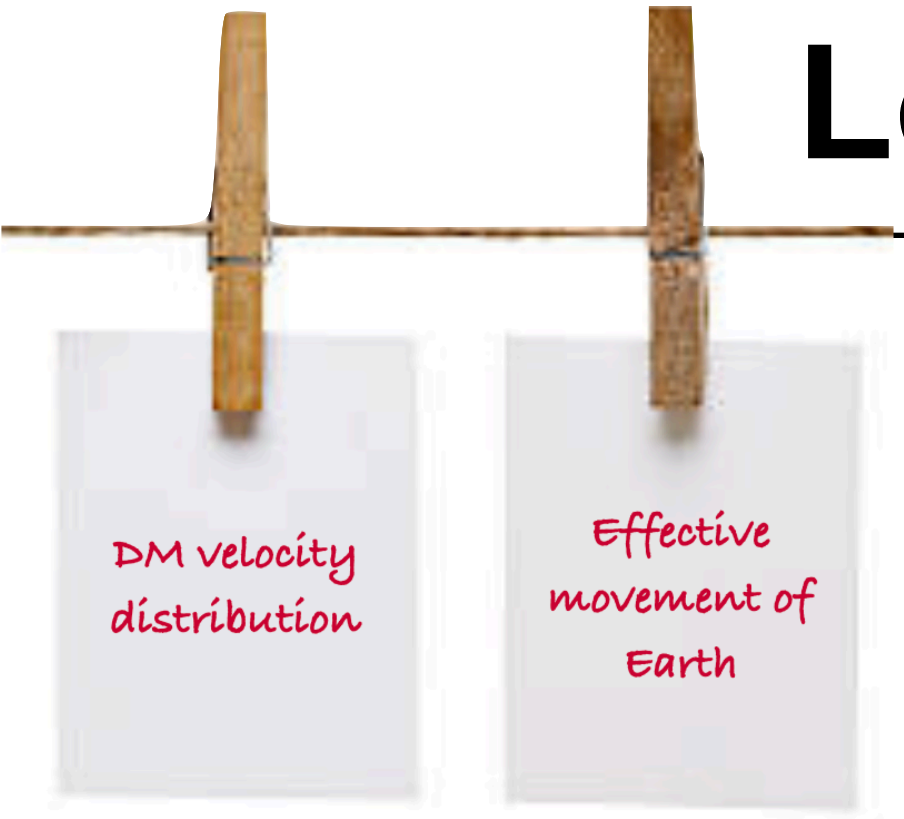
local DM mass density

exposure

Note that: $n = \frac{\rho_0}{m_\chi}$, $N_T = \frac{M_T}{m_N}$, $\varepsilon = t \cdot M_T$



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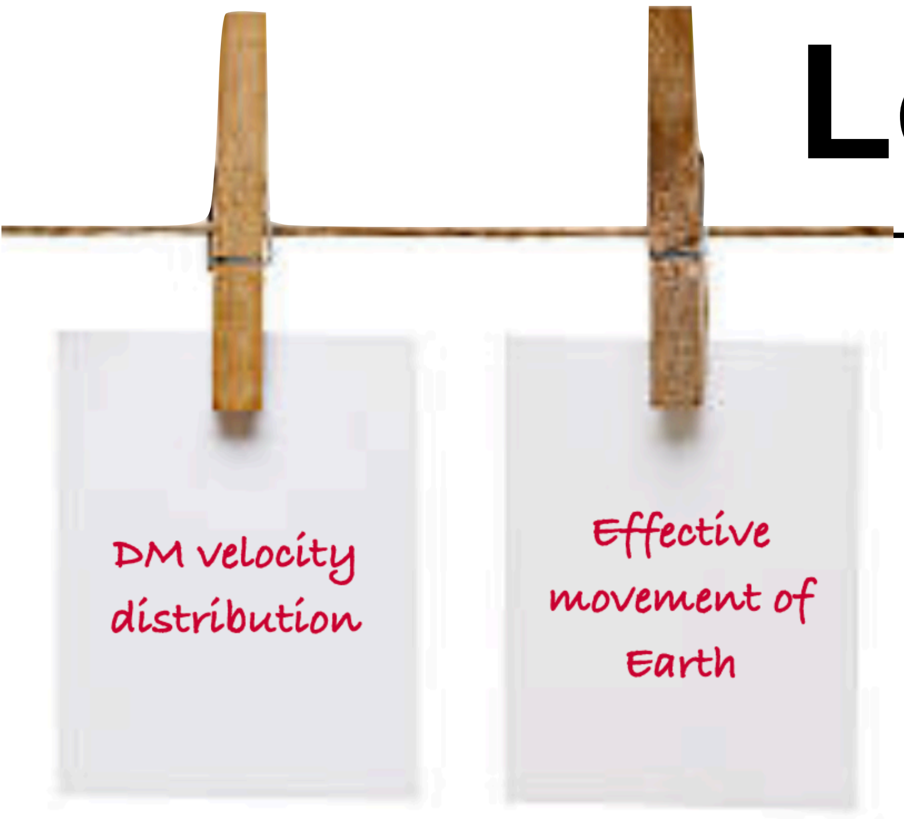

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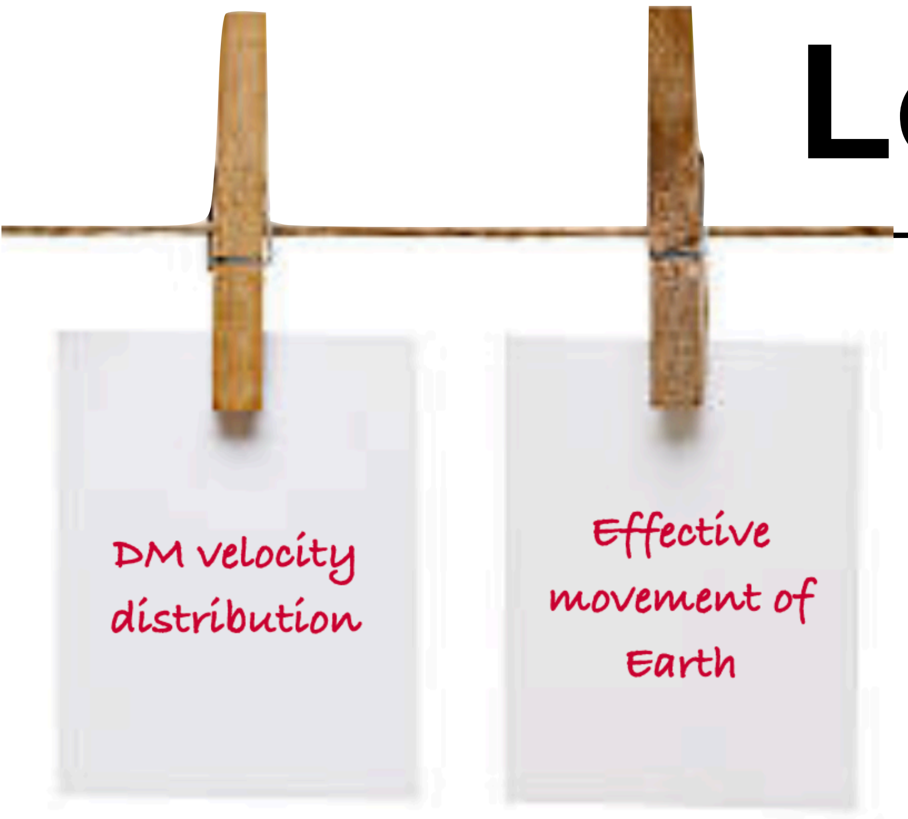

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The DM-nucleon scattering cross section

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$$E_R = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) = \frac{E_R^{\mathrm{max}}}{2}(1 - \cos\theta)$$

The DM-nucleon cross section can be separated:

$$\frac{d\sigma}{dE_R} = \left[\left(\frac{d\sigma}{dE_R}\right)_{\mathrm{SI}} + \left(\frac{d\sigma}{dE_R}\right)_{\mathrm{SD}}\right]$$

Spin Independent — arises from scalar or vector couplings to quarks

Spin Dependent — arises from axial-vector coupling to quarks

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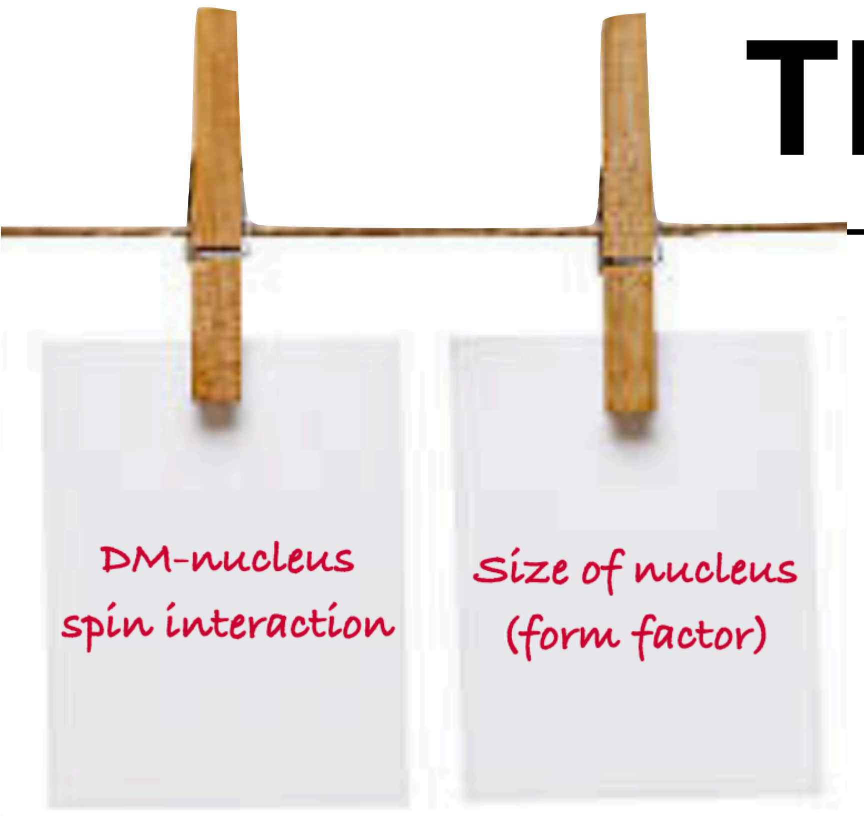

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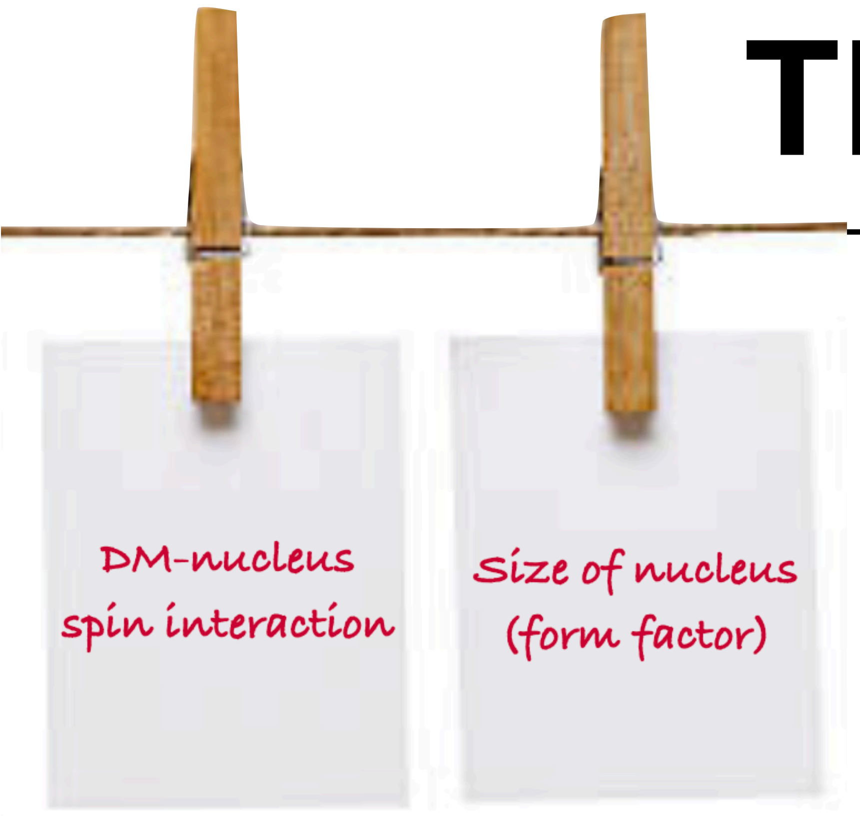
$$= \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{\text{SI}} F_{\text{SI}}^2(E_R) + \sigma_0^{\text{SD}} F_{\text{SD}}^2(E_R)\right]$$

F: nuclear form factor

The DM-nucleon scattering cross section



particle theory

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{\mathrm{SI}} F_{\mathrm{SI}}^2(E_R) + \sigma_0^{\mathrm{SD}} F_{\mathrm{SD}}^2(E_R)\right]$$

nuclear form factors:
quantum mechanics of interaction with nucleus

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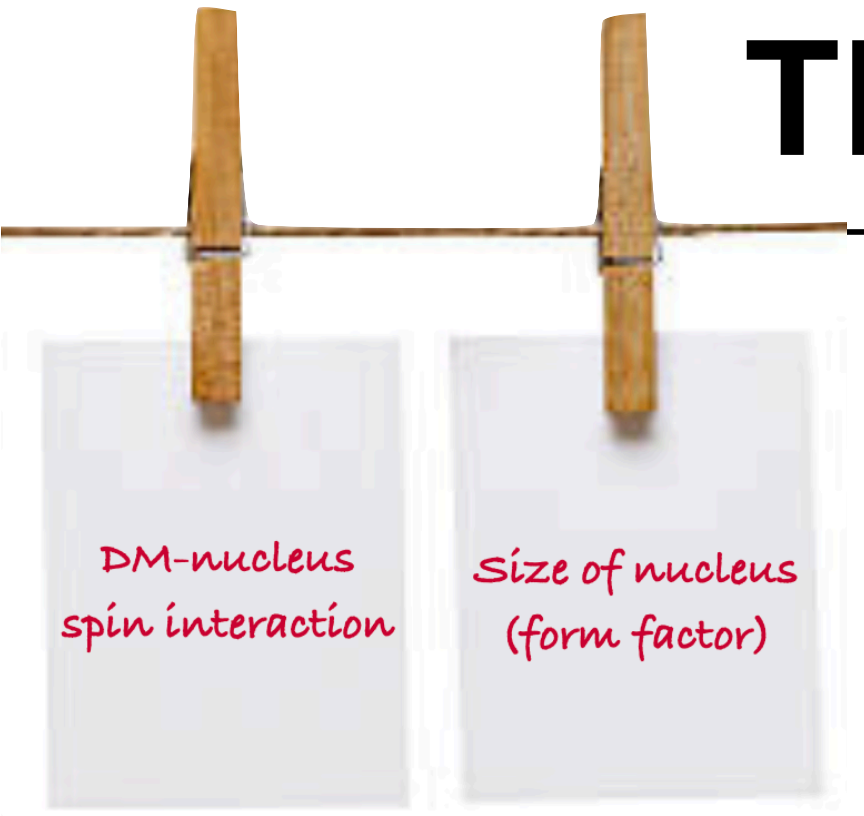

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nuclear form factors:
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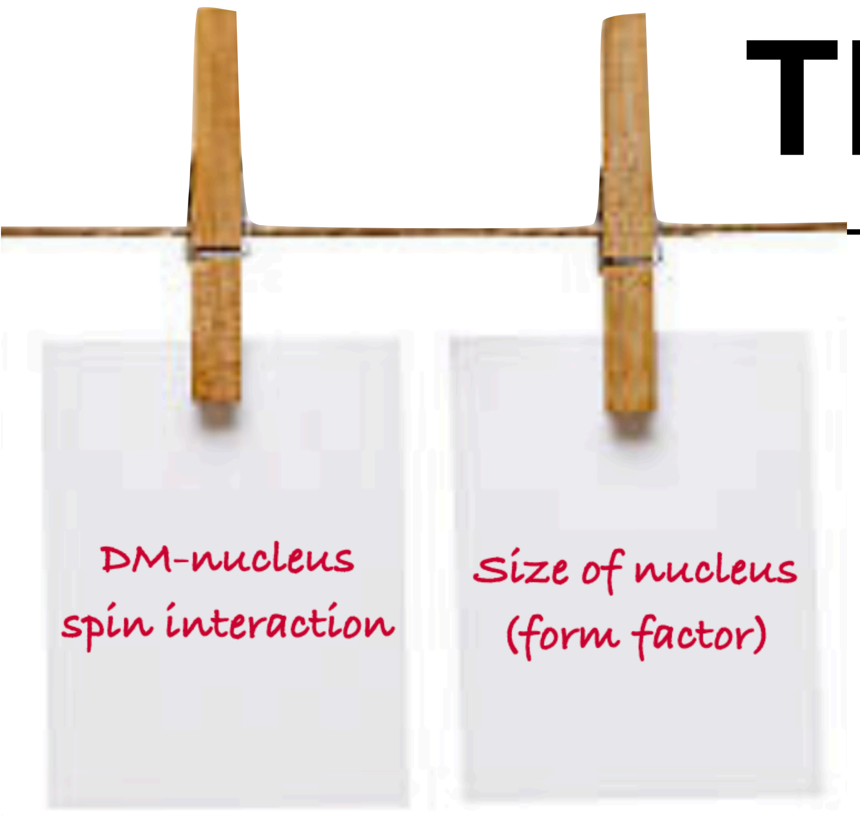
Spin-Independent (SI)

Spin-Dependent (SD)



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nuclear form factors:
quantum mechanics of interaction with nucleus

Spin-Independent (SI)

Spin-Dependent (SD)

Fermi constant

expectation value of proton/neutron spin within nucleus

$$\sigma_0^{\mathrm{SD}} = \frac{32 G_F^2 \mu^2}{\pi} \frac{J+1}{J} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2$$

nuclear angular momentum

effective couplings to protons and neutrons

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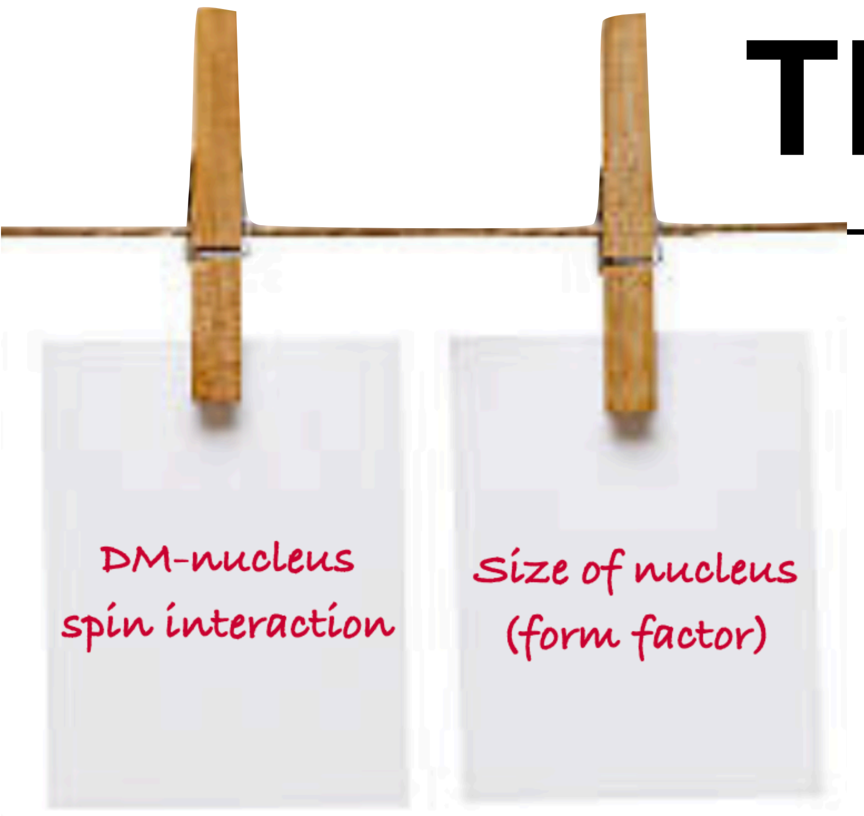
The DM-nucleon scattering cross section



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nuclear form factors:
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Spin-Independent (SI)

$$\sigma_0^{\mathrm{SI}} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

scalar couplings to protons and neutrons

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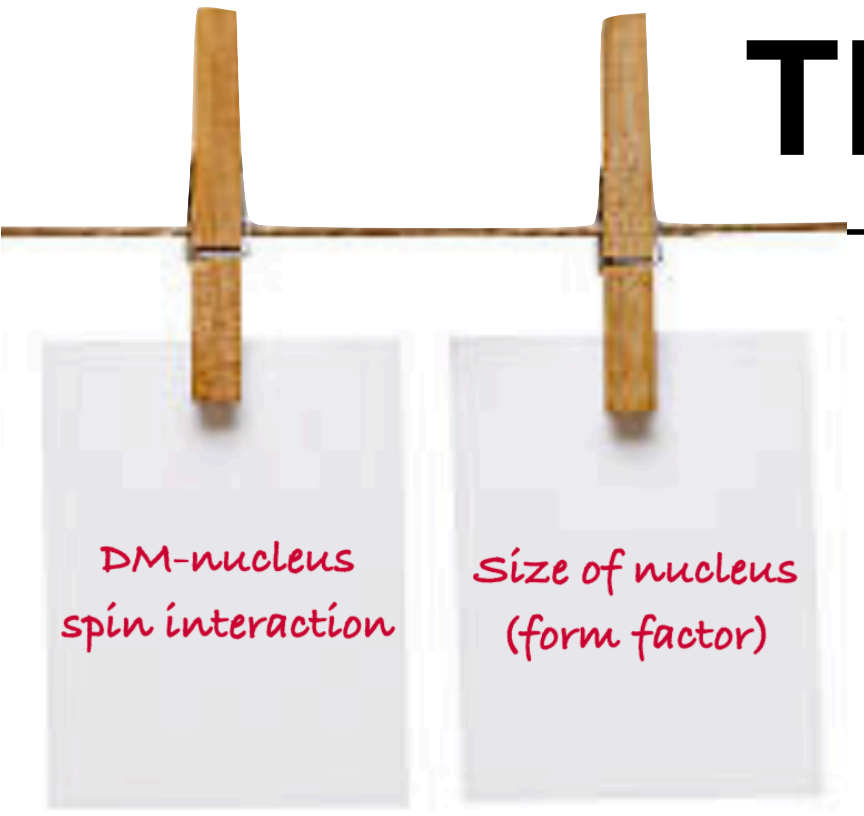

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nuclear form factors:
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$$\sigma_0^{\mathrm{SI}} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$

scalar couplings to protons and neutrons

In most models $f_p \approx f_n$.

⇒ Scattering adds coherently with A^2 enhancement.

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effective couplings to protons and neutrons

Nuclei with non-zero angular momentum required.

No coherence effect!

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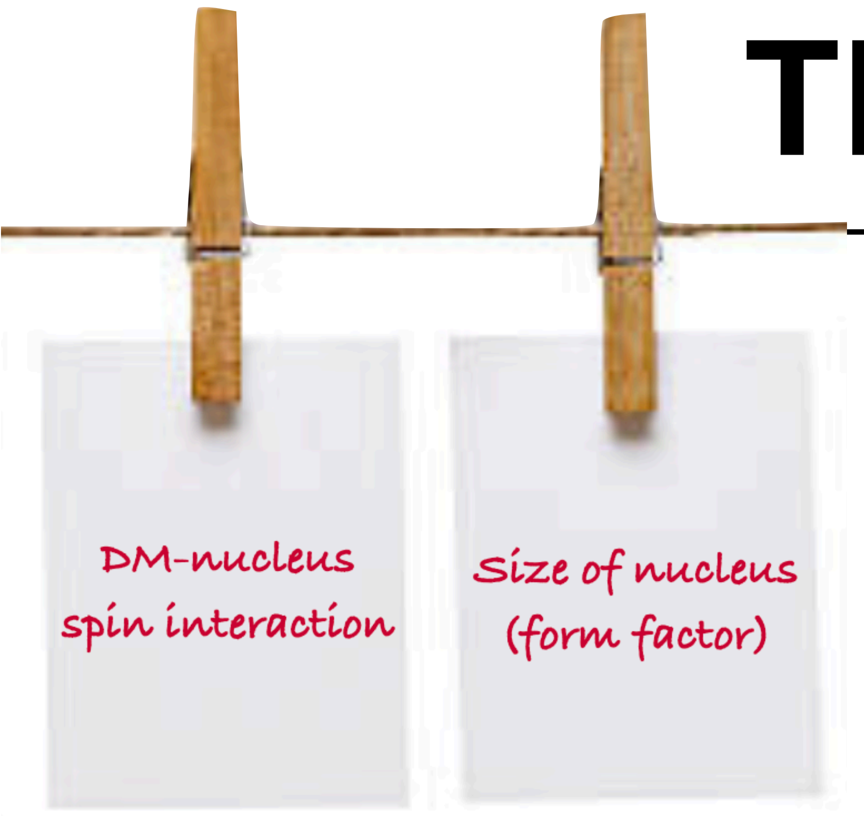
The DM-nucleon scattering cross section



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Finally… the dark matter direct detection master formula

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{\text{min.}}}^{\infty} v f(\vec{v}) \frac{d\sigma}{dE_R} d\vec{v}$$

$$\frac{d\sigma^{\text{SI}}}{dE_R} = \frac{m_N}{2\mu^2 v^2} \sigma_0^{\text{SI}} F_{\text{SI}}^2(E_R)$$

$$f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|\vec{v}|^2}{2\sigma^2}}$$

$\rho(r) \propto r^{-2}$ and $\rho_0 \approx 0.3\,\text{GeV}\,\text{cm}^{-3}$

$$\left(\frac{dR}{dE_R}\right)_{\chi N}^{\text{SI}} = \frac{\sigma_0^{\text{SI}}}{m_\chi} \cdot \frac{\rho_0 T(\vec{v})}{v\sqrt{\pi}} \cdot \frac{F_{\text{SI}}^2(E_R)}{\mu^2}$$

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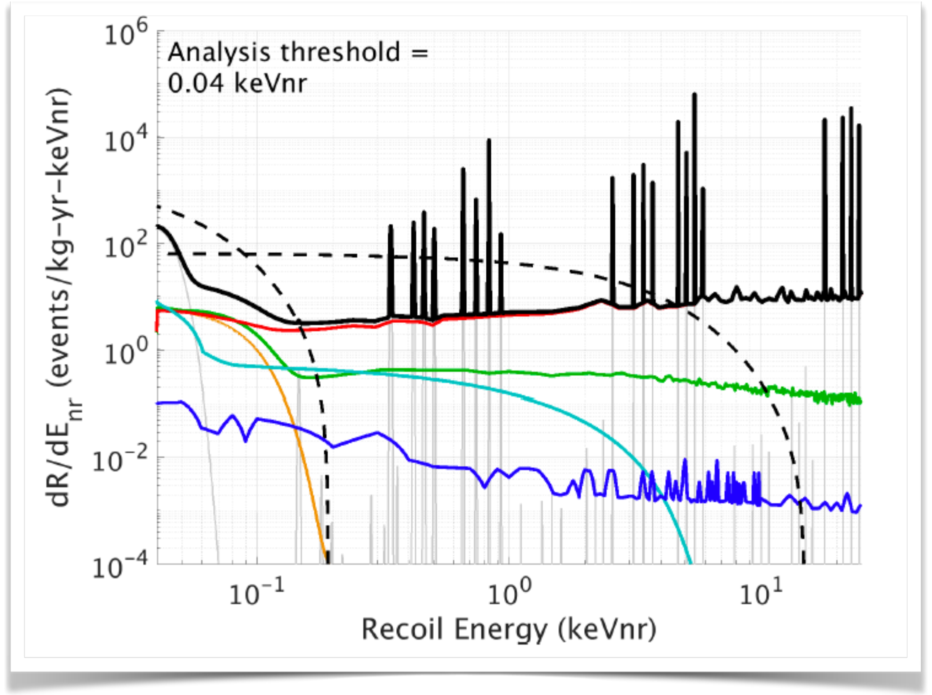

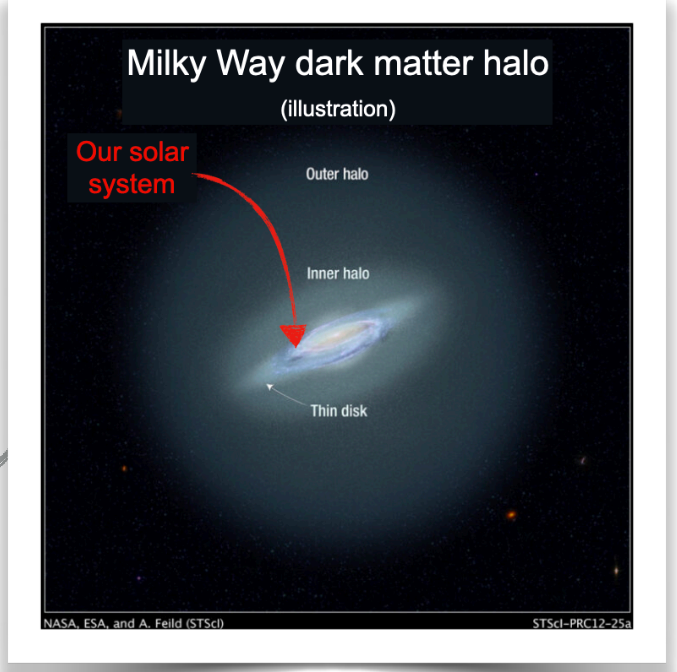

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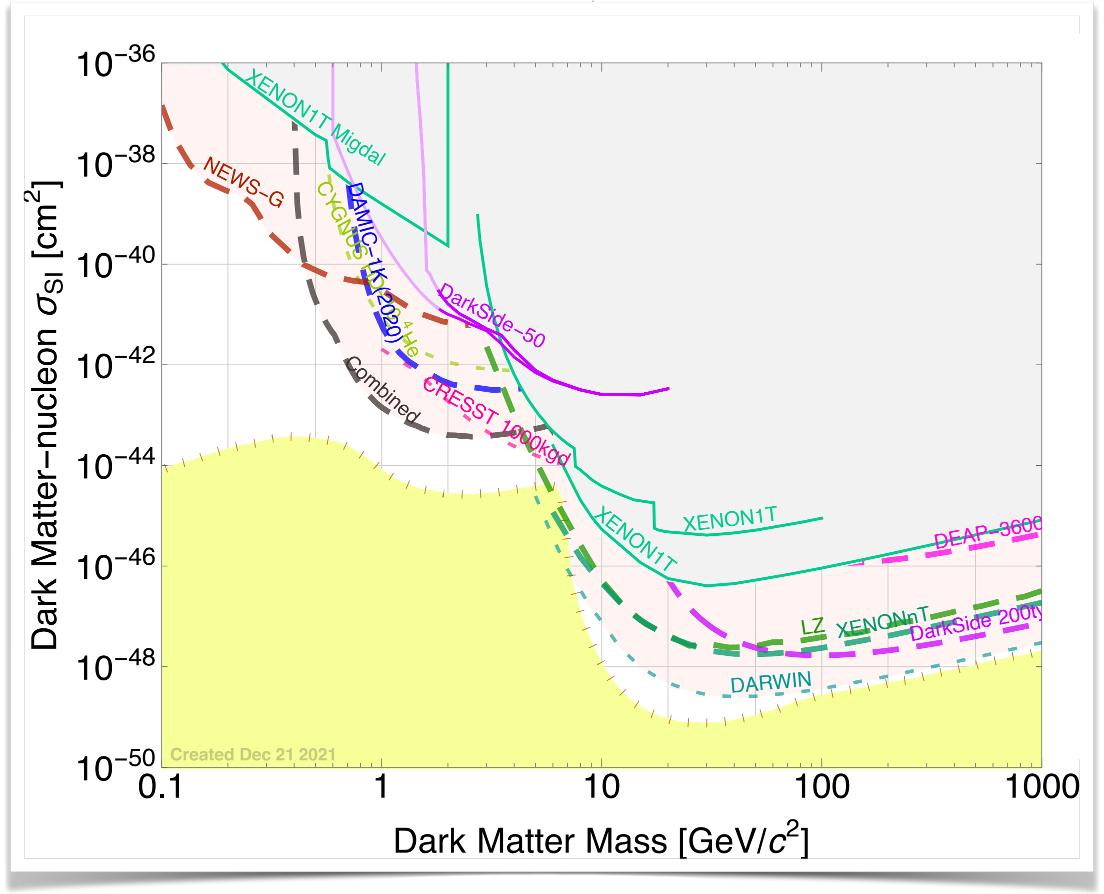

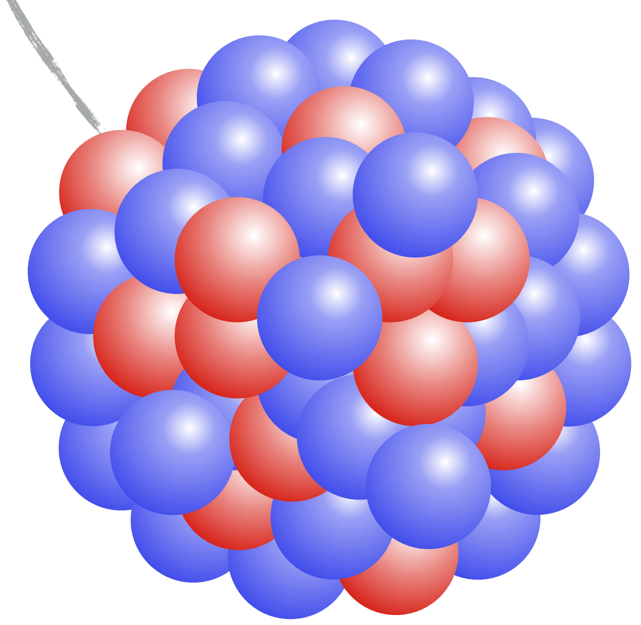

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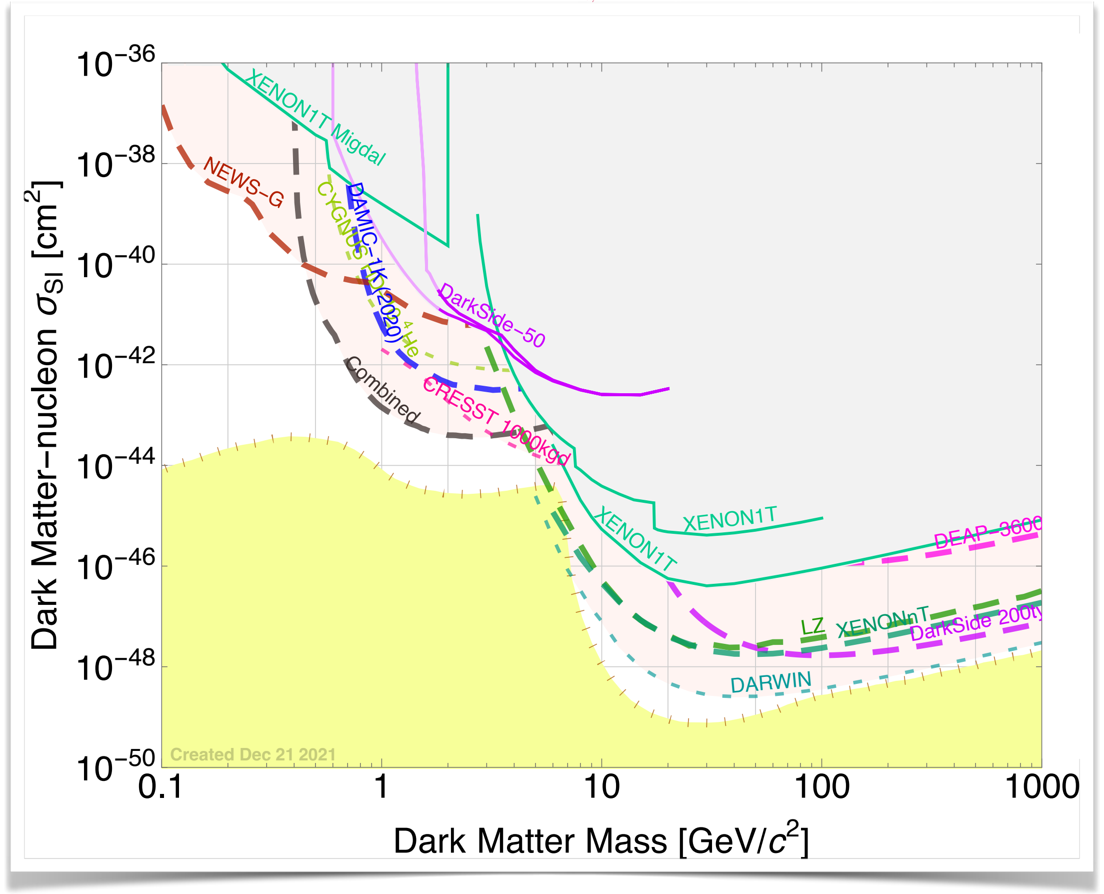

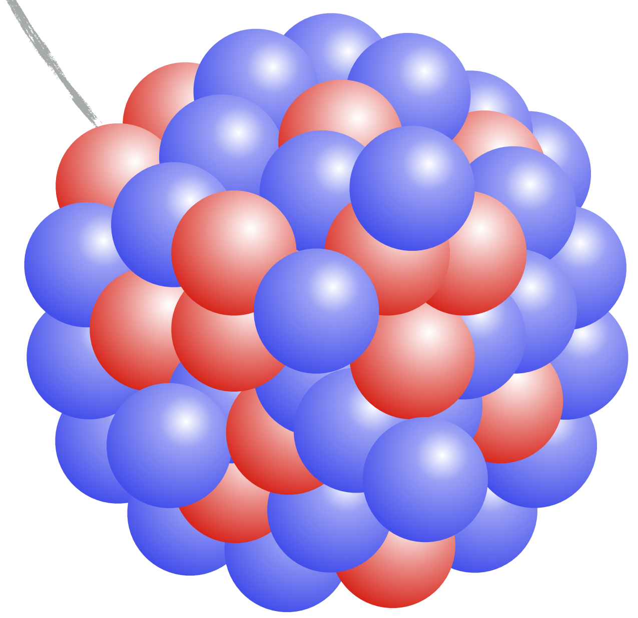

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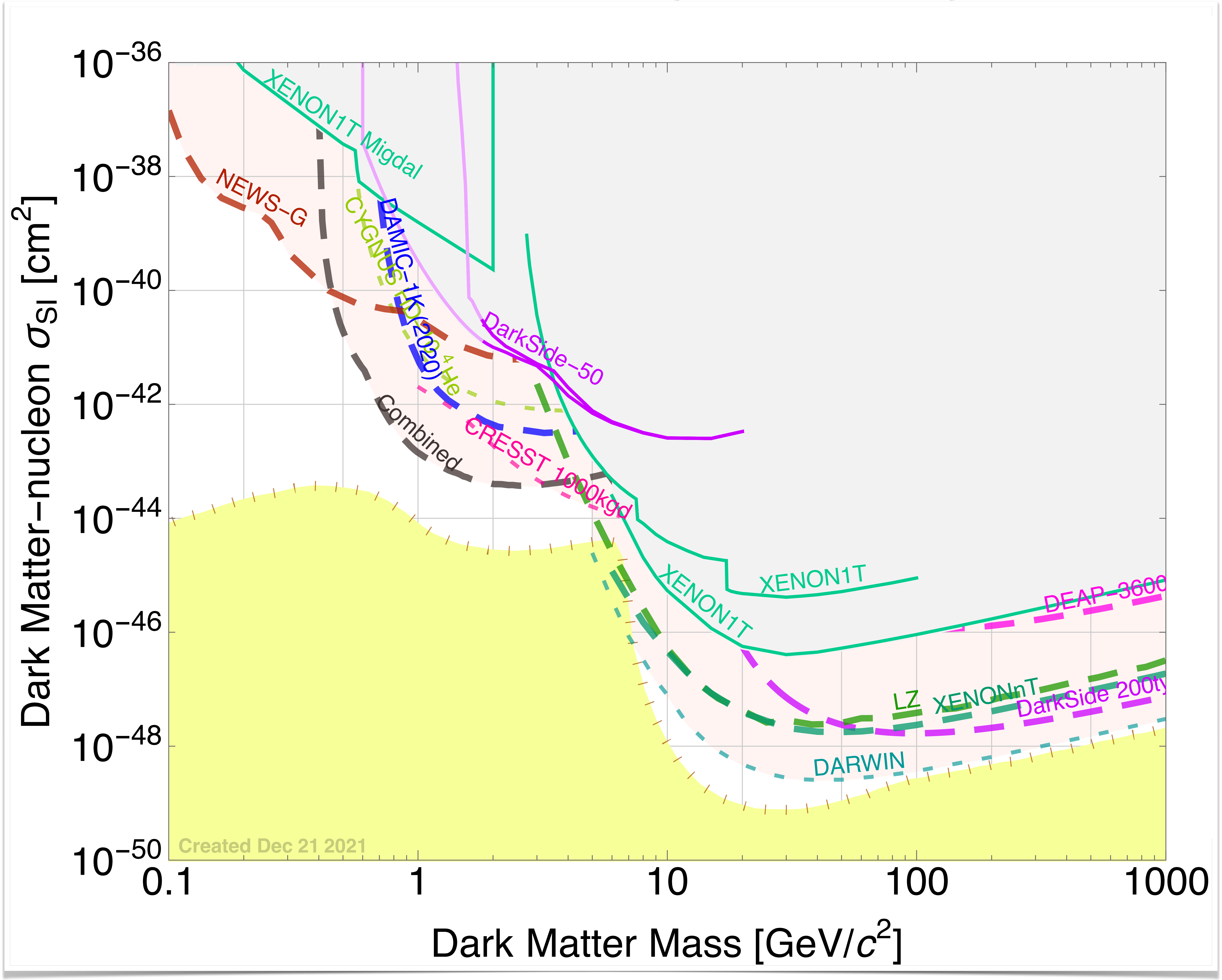
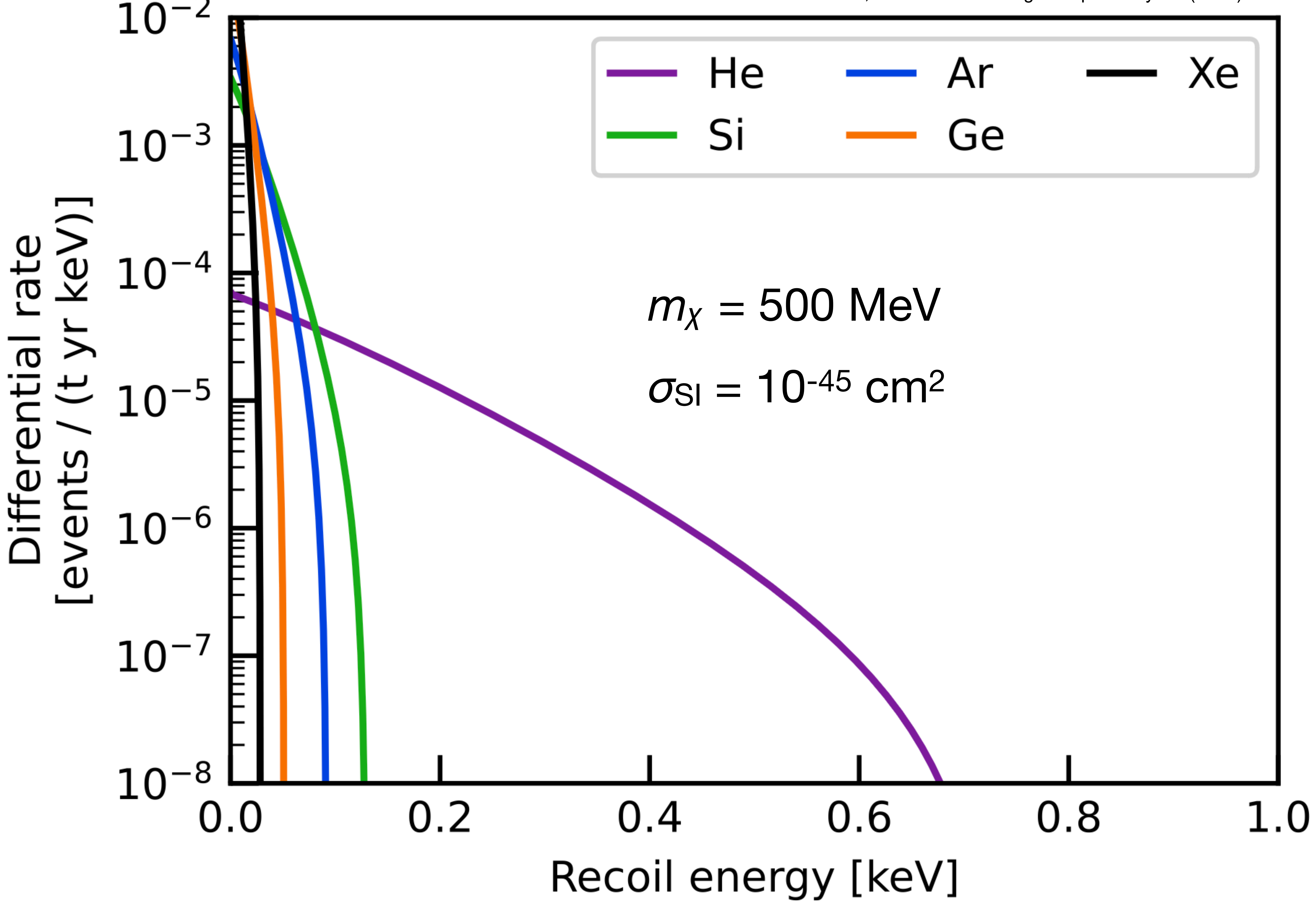
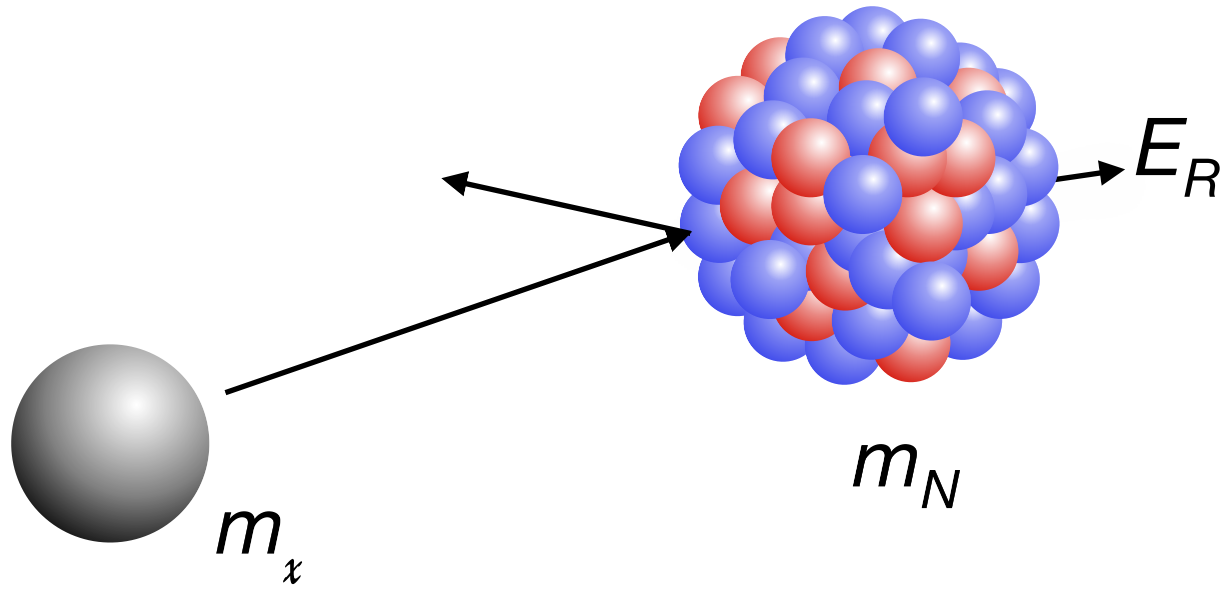


What nucleus (i.e. target) to pick?

F. Toschi, calculated following Astropart. Phys. 6 (1996) 87





$$E_R = \frac{1}{2}\frac{q^2}{m_N} \lesssim \frac{2\,m_\chi^2 v^2}{m_N}$$

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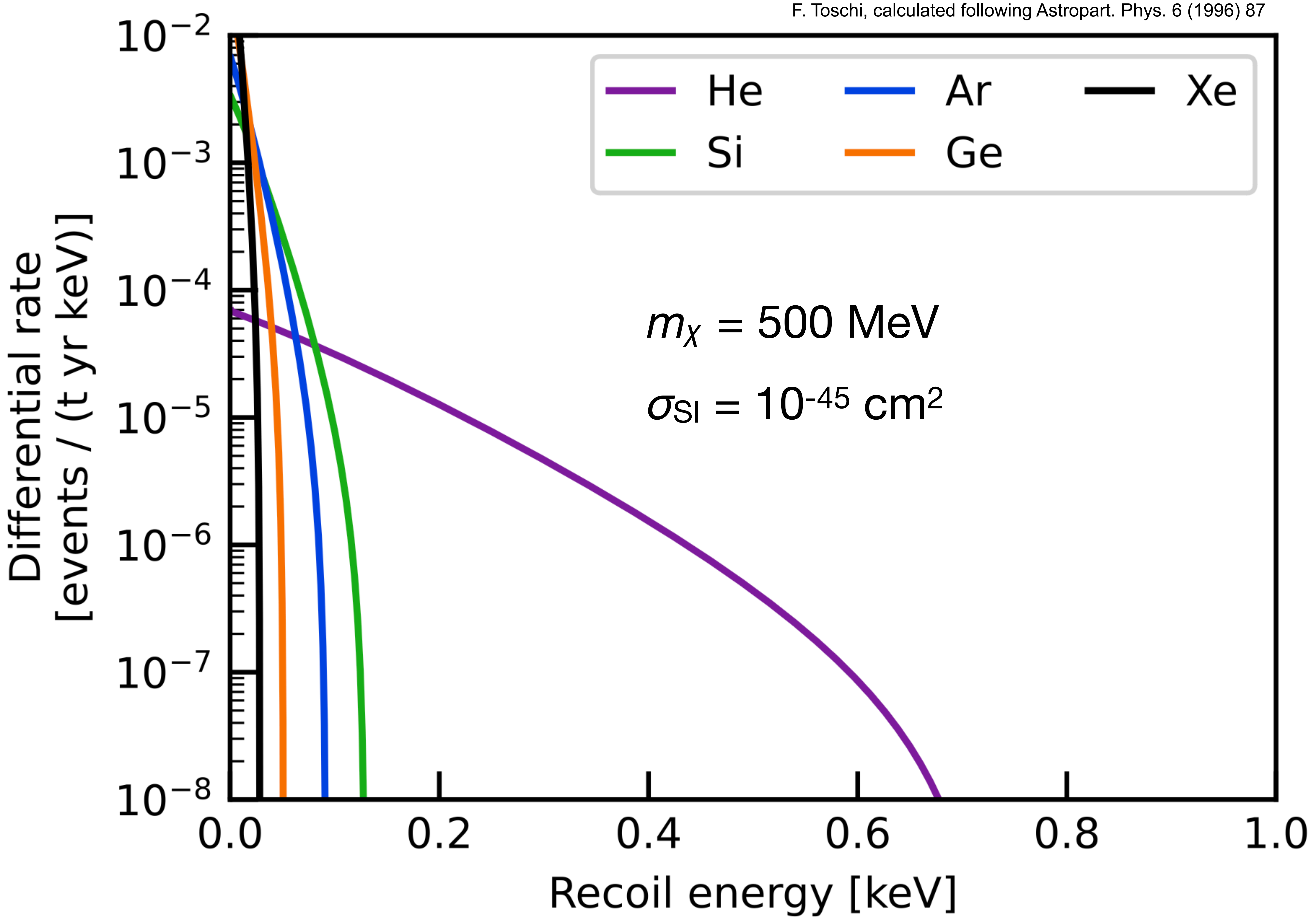

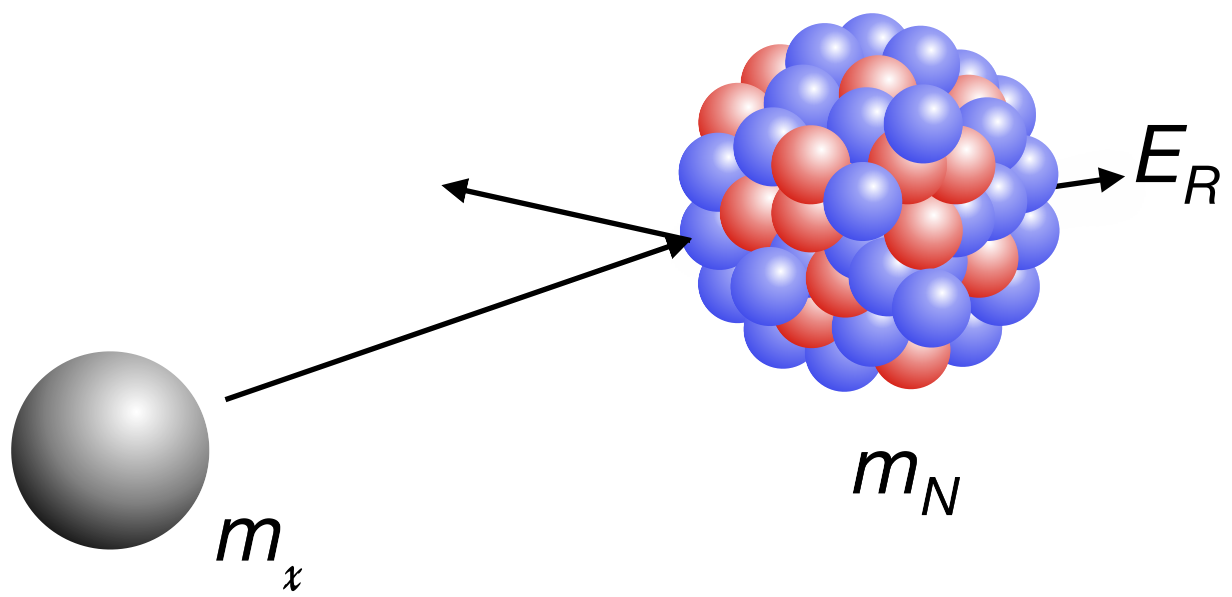

$$E_R = \frac{1}{2}\frac{q^2}{m_N} \lesssim \frac{2\, m_\chi^2 v^2}{m_N}$$

Light target nuclei are favorable!

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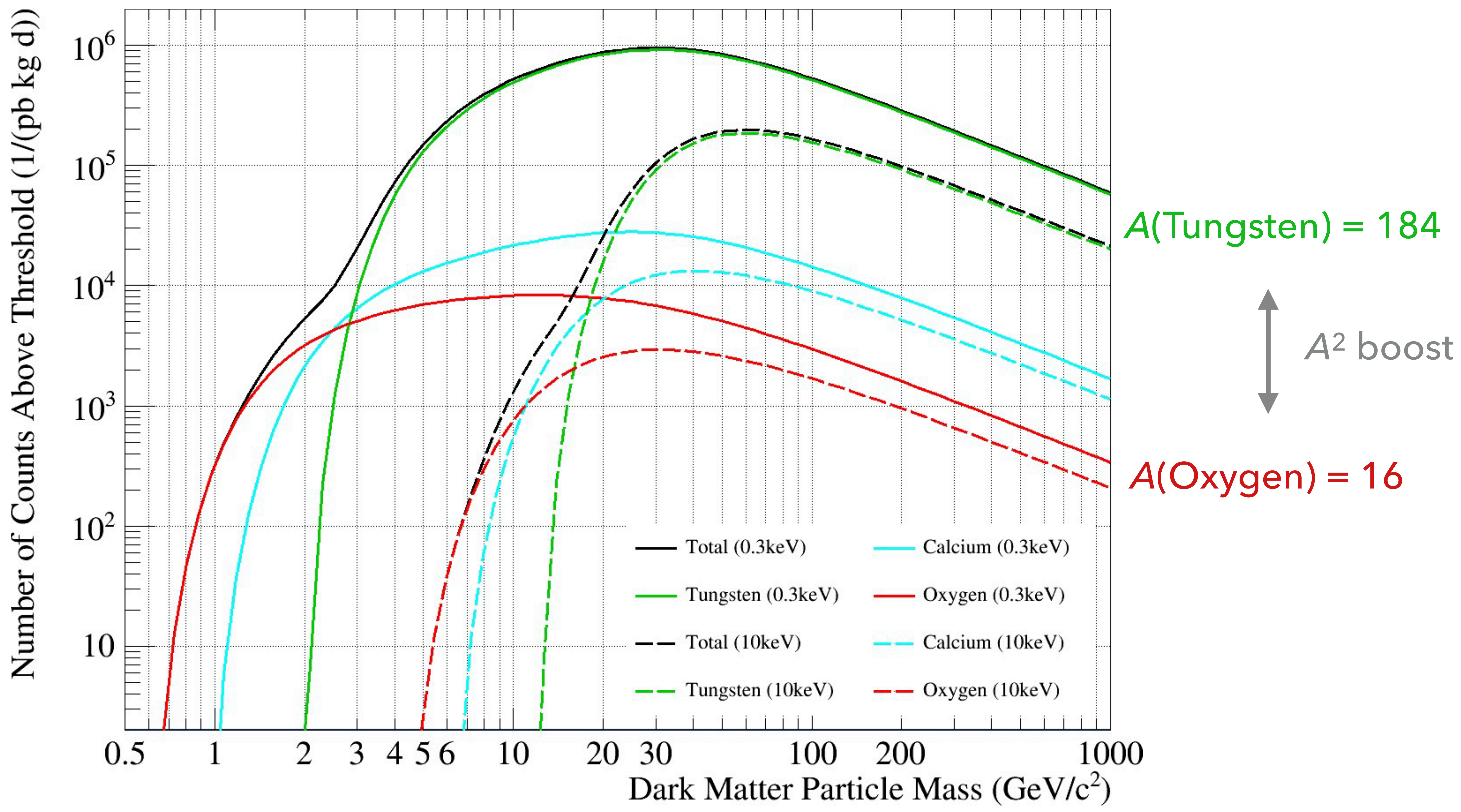

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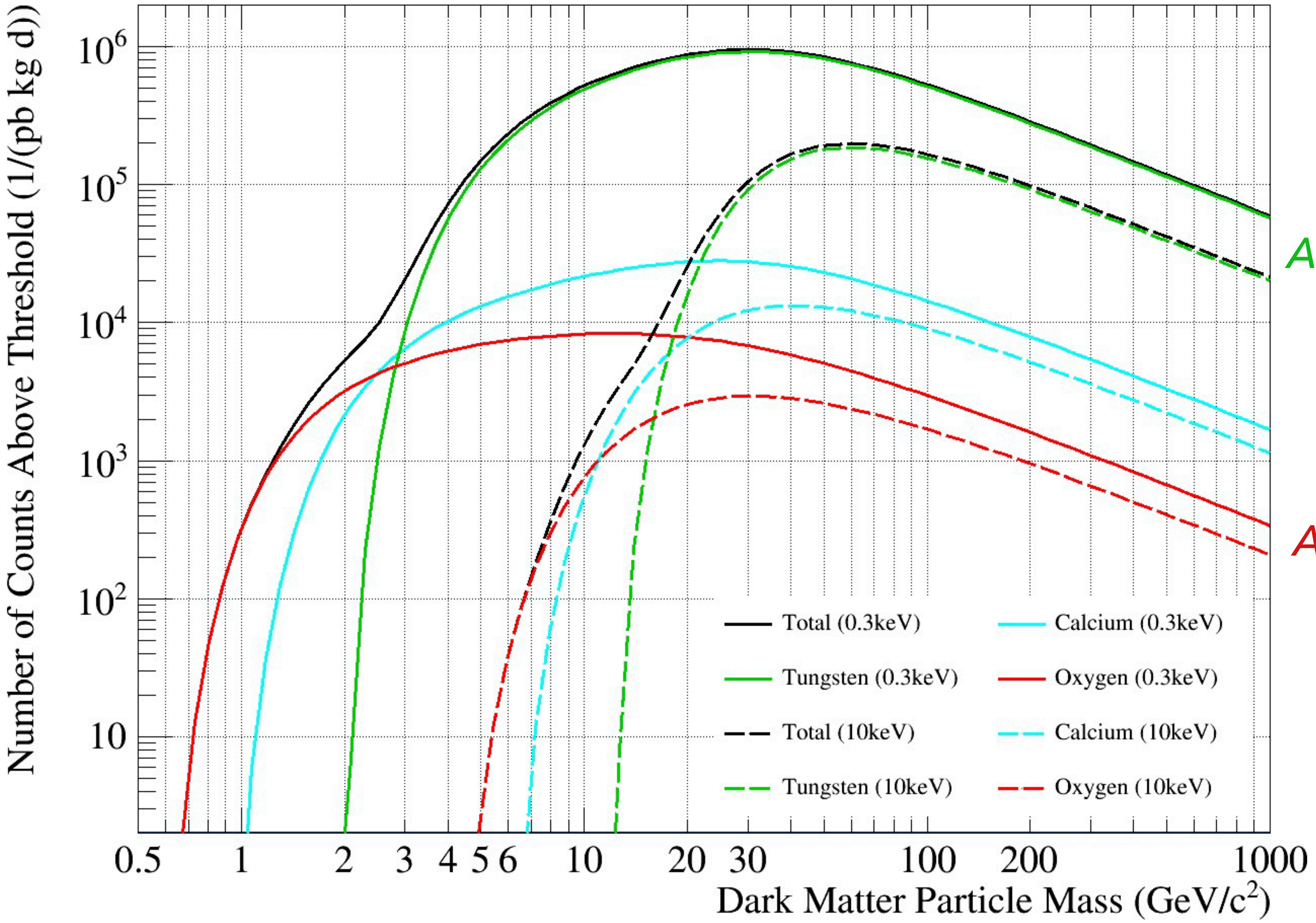

A(Tungsten) = 184

A^2 boost

A(Oxygen) = 16

Heavy target nuclei are favorable!

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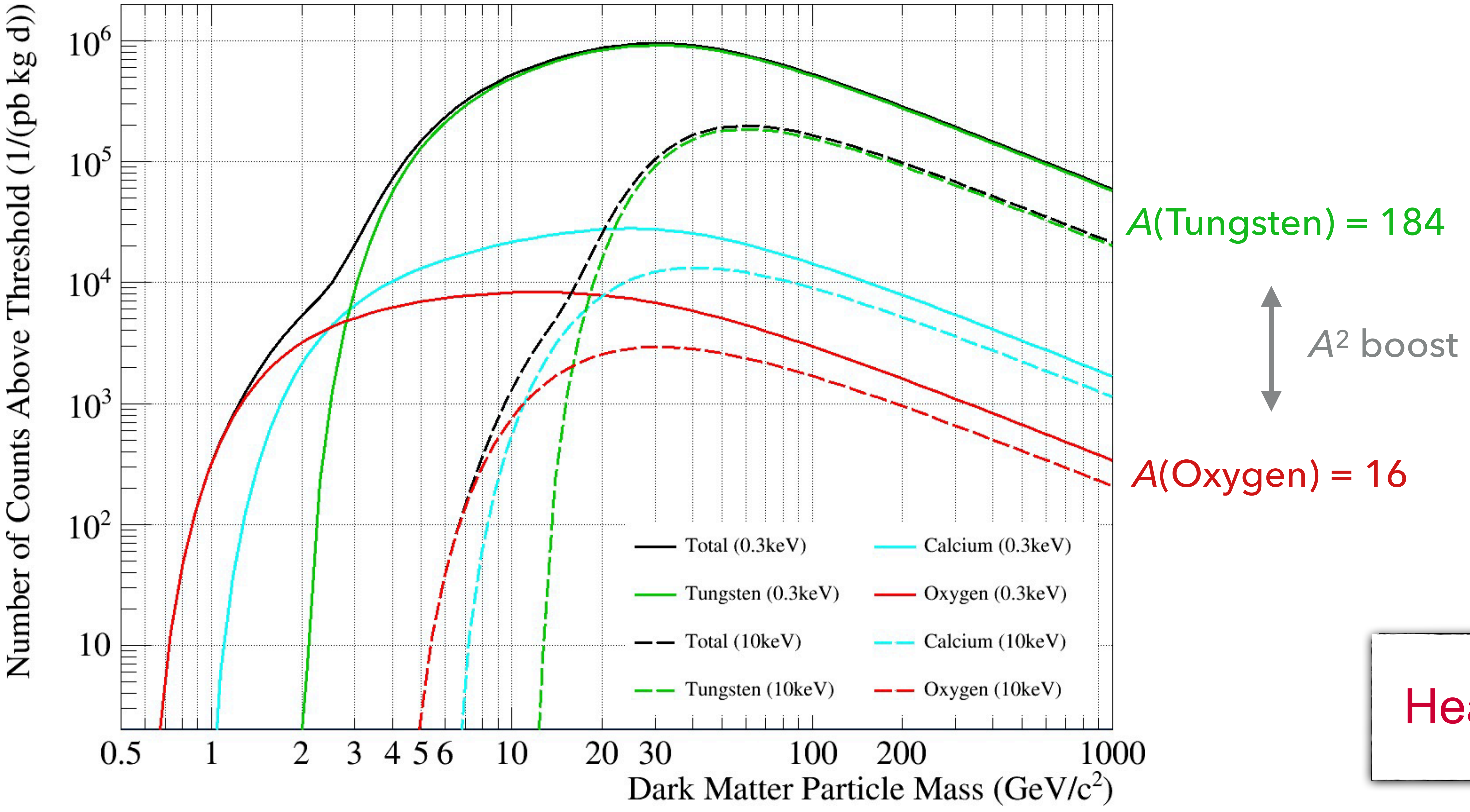
What nucleus (i.e. target) to pick?



Heavy target nuclei are favorable!

Wait…what?

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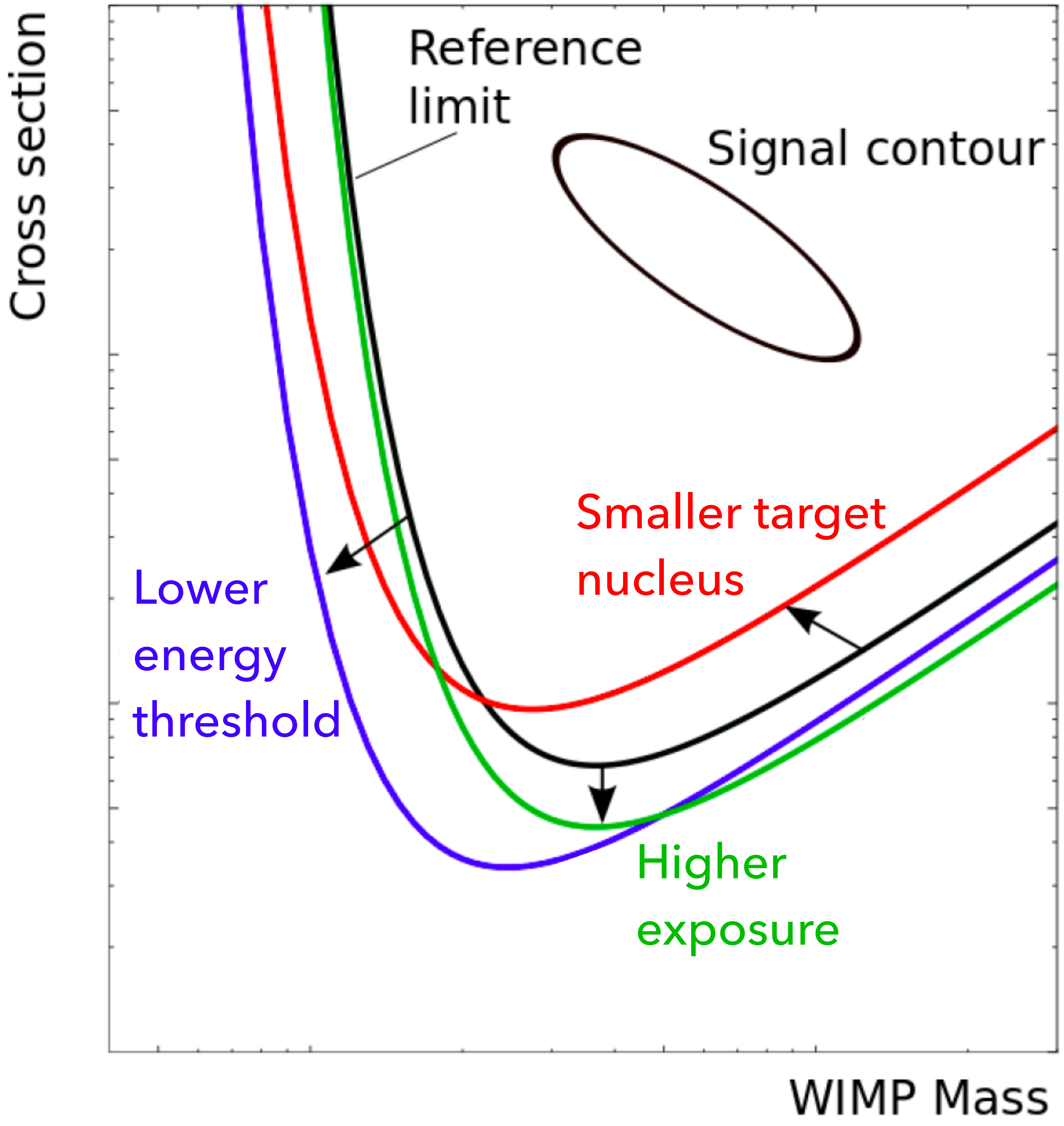
What nucleus (i.e. target) to pick?

J. Phys. G43 (2016) 1, 013001



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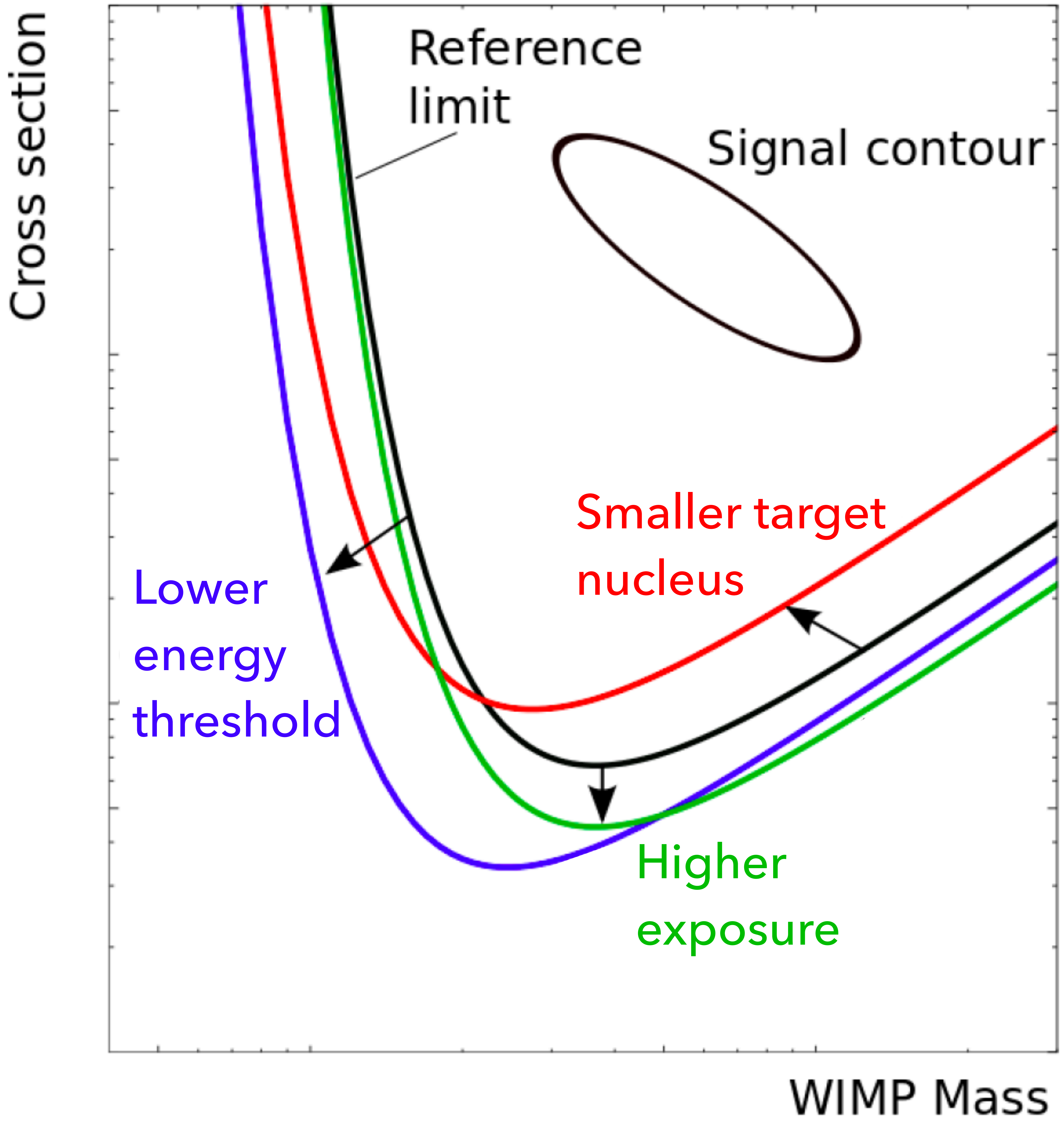
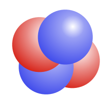
What nucleus (i.e. target) to pick?

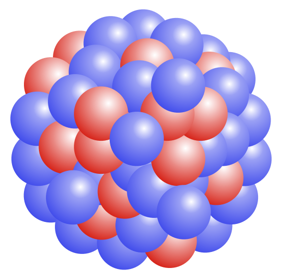
J. Phys. G43 (2016) 1, 013001



Group

13	14	15	16	17	18
					He Helium
B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon
Al Aluminium	Si Silicon	P Phosphorus	S Sulfur	Cl Chlorine	Ar Argon
Ga Gallium	Ge Germanium	As Arsenic	Se Selenium	Br Bromine	Kr Krypton
In Indium	Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon



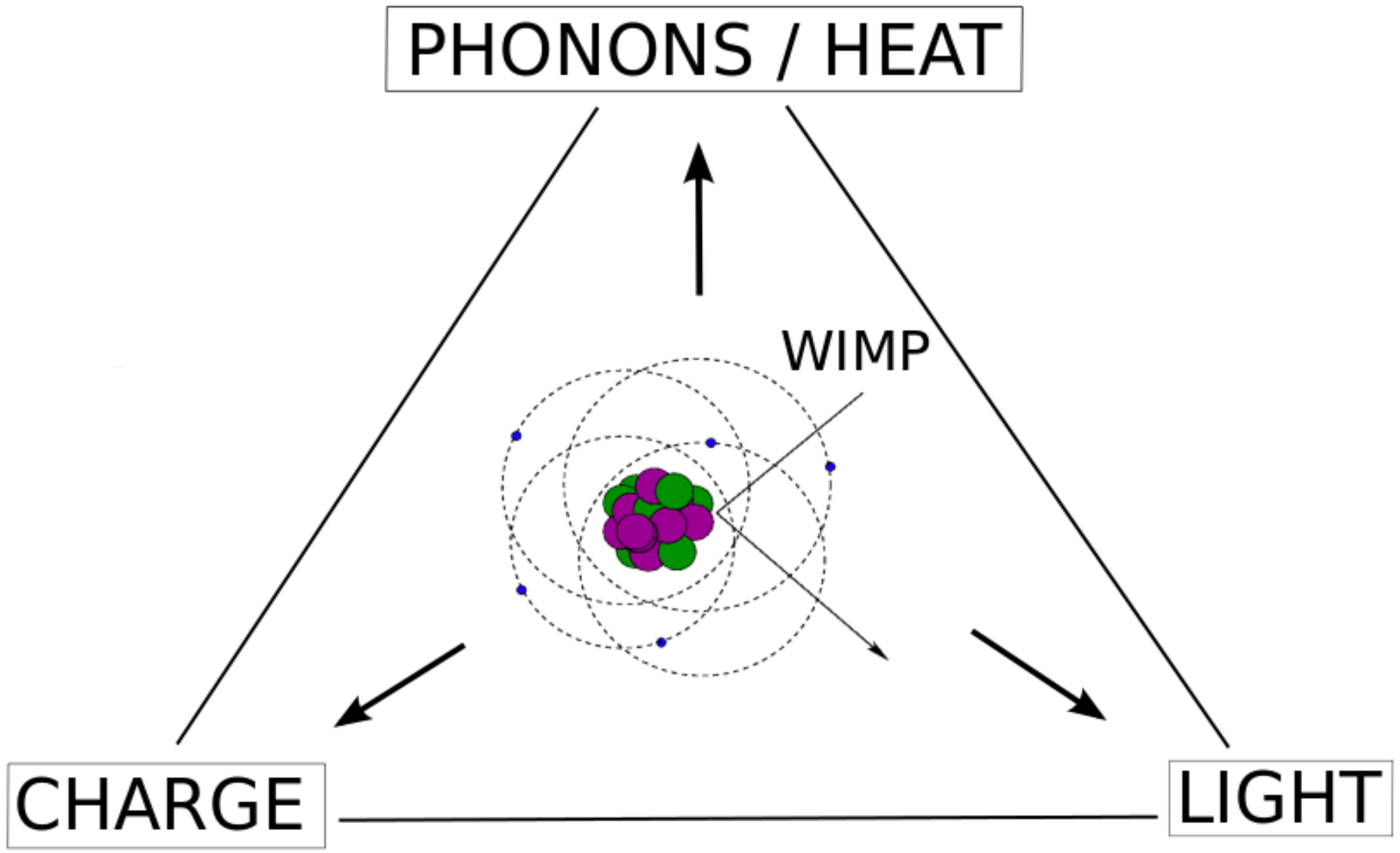


It depends on the parameter space you are interested in!

Direct dark matter detection

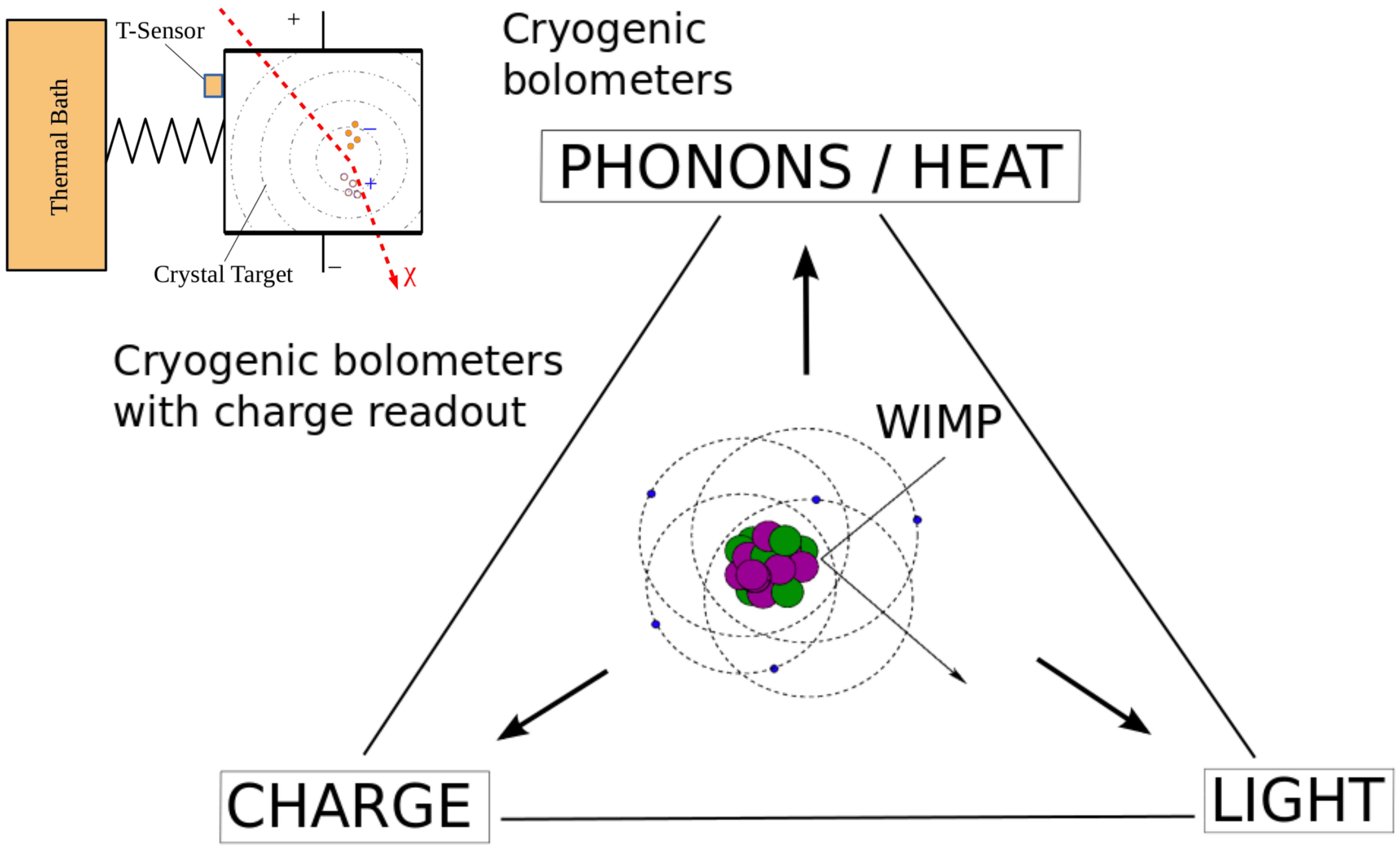
Detector concepts

How to design a dark matter detector



T. Marrodán Undagoitia, L Rauch, J. Phys. G43 (2016) no.1, 013001

How to design a dark matter detector



APPEC Committee Report 2021, arXiv:2104.07634 [hep-ex]
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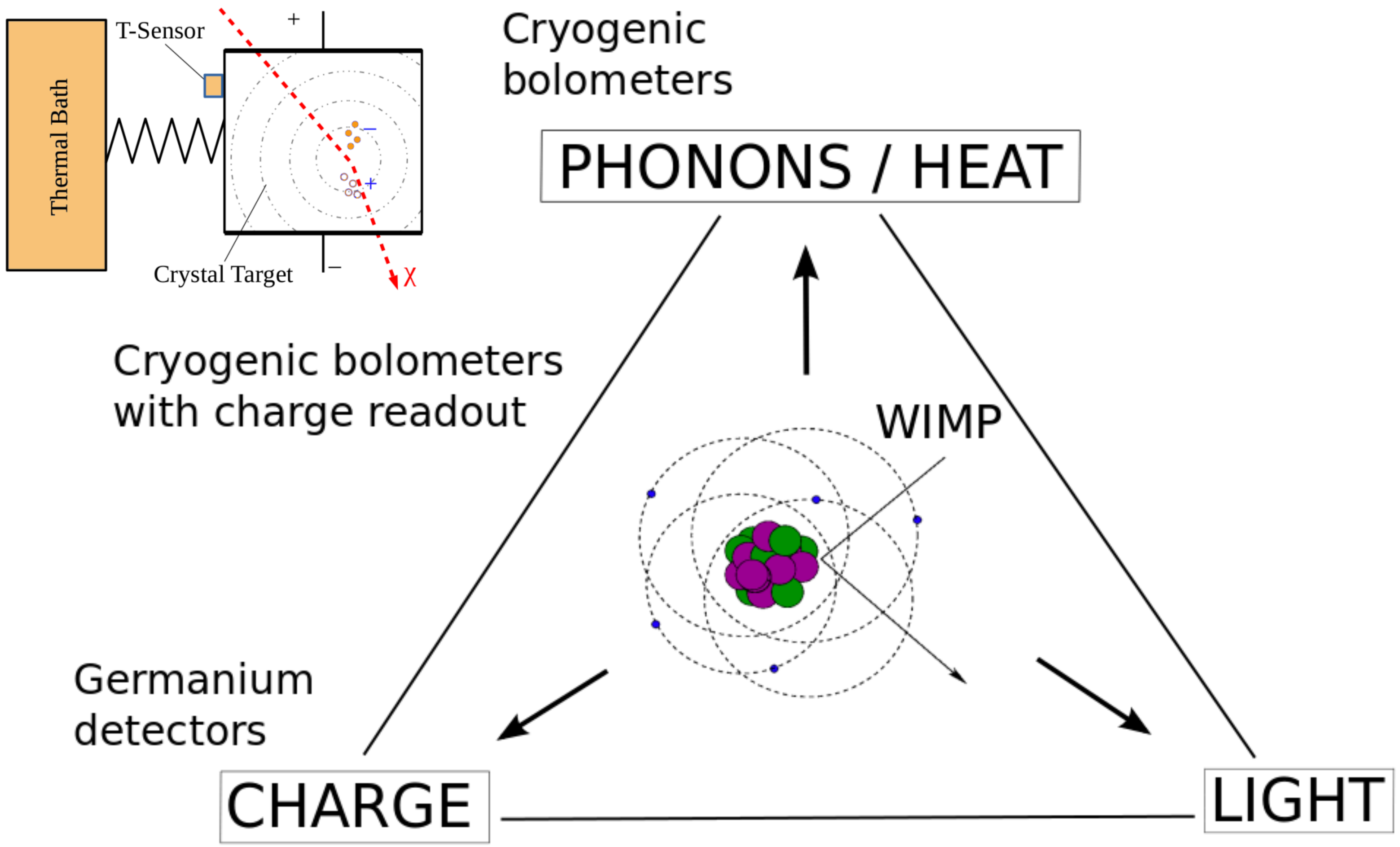

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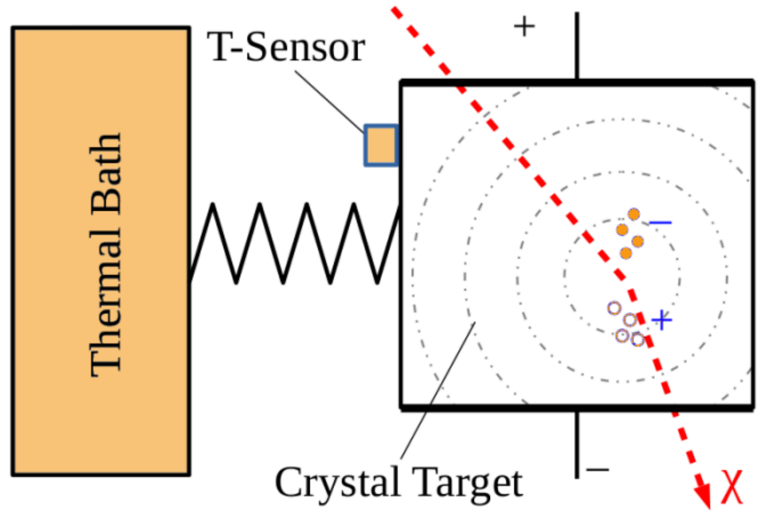
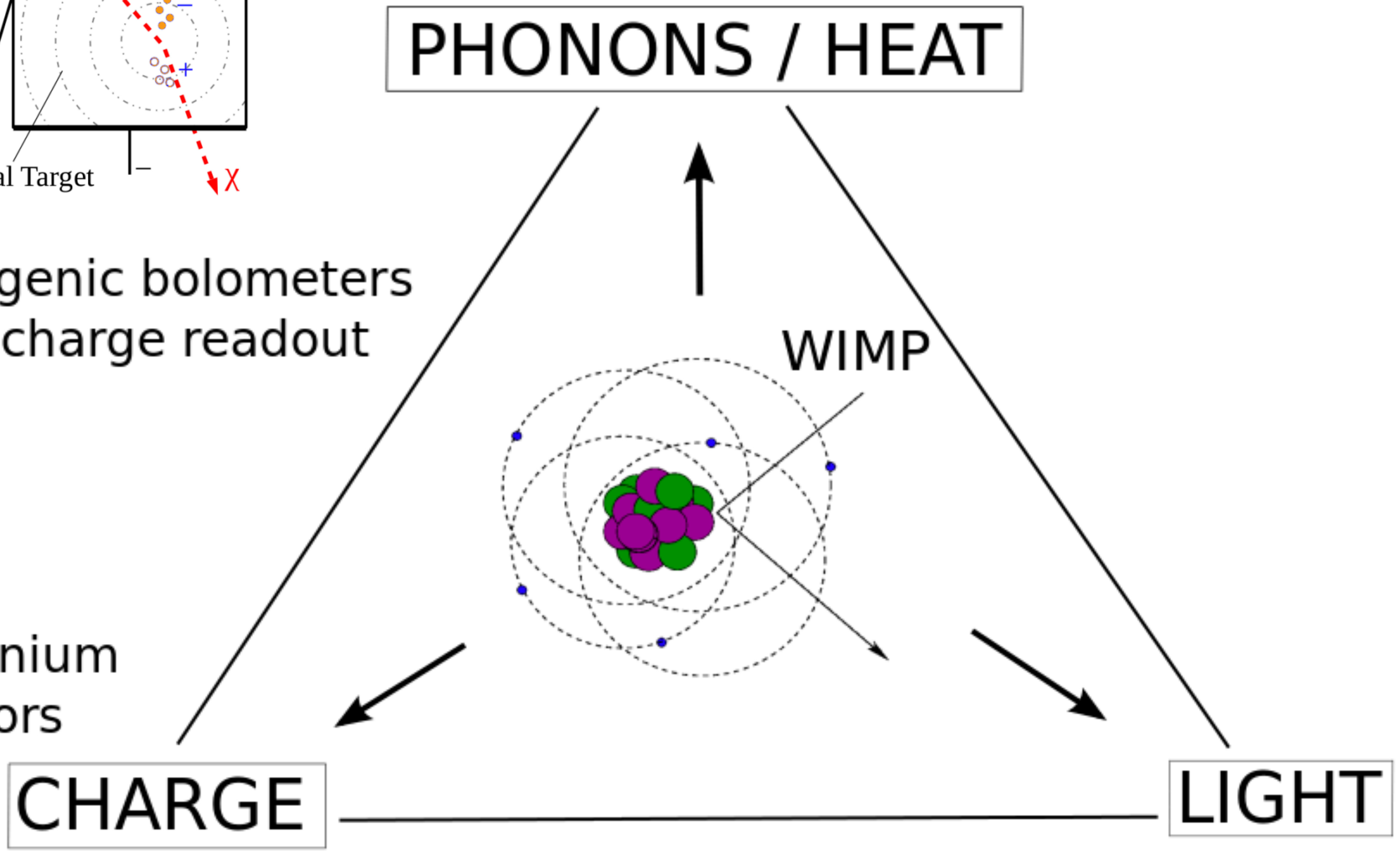


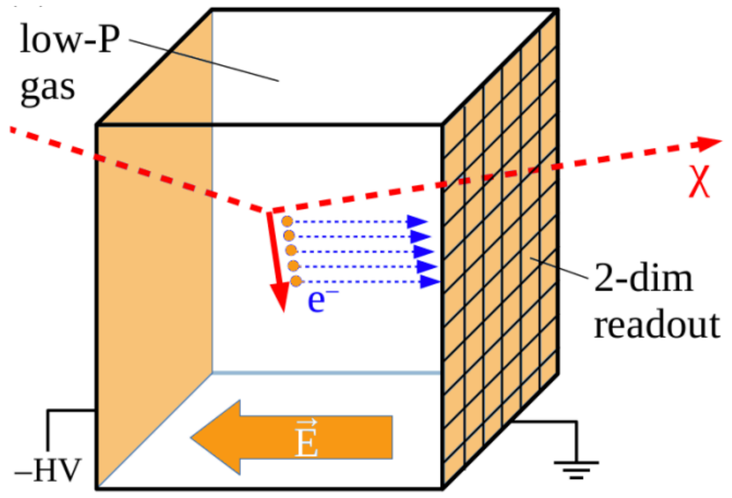
Cryogenic bolometers

Cryogenic bolometers with charge readout



Germanium detectors

Directional detectors



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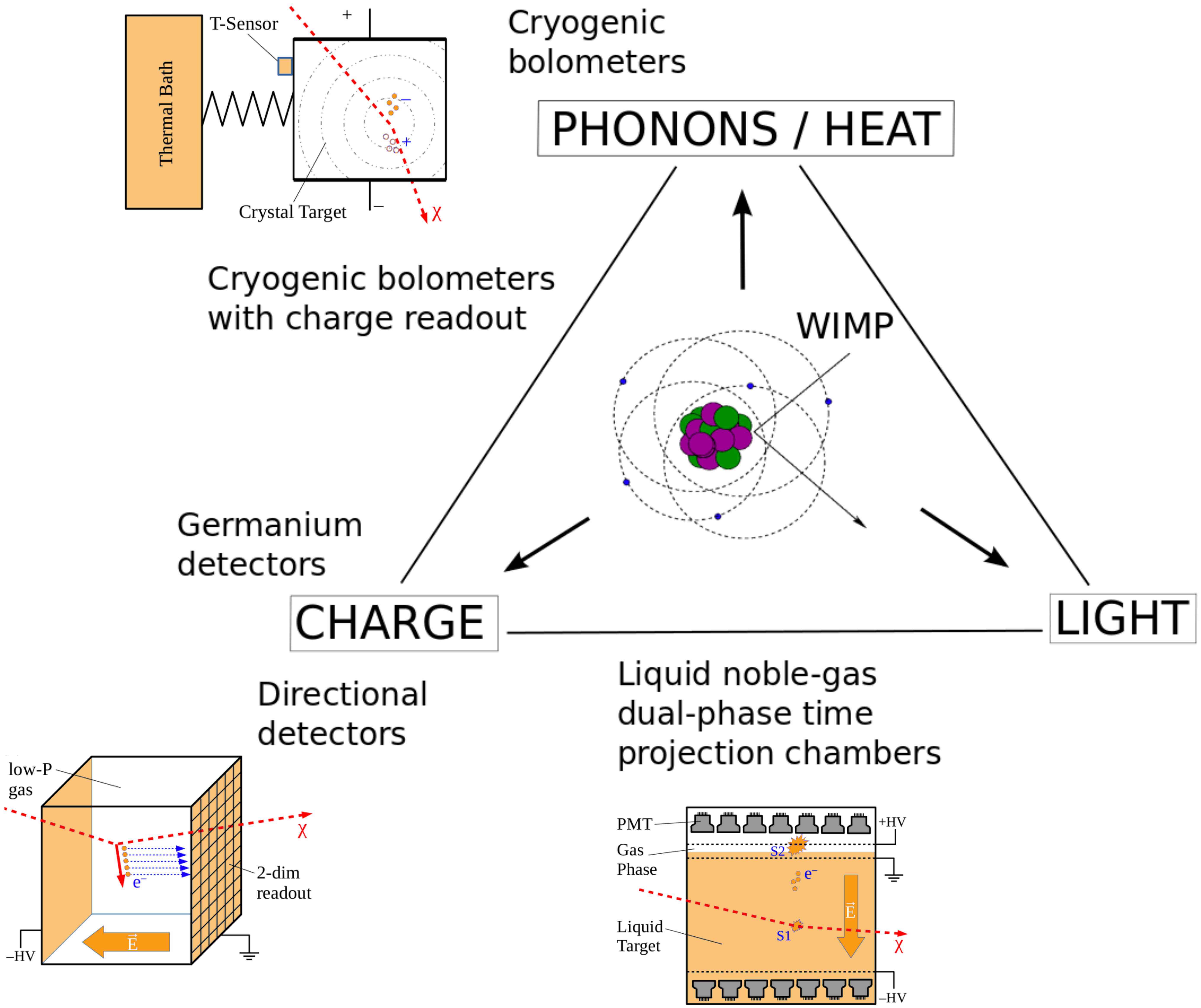

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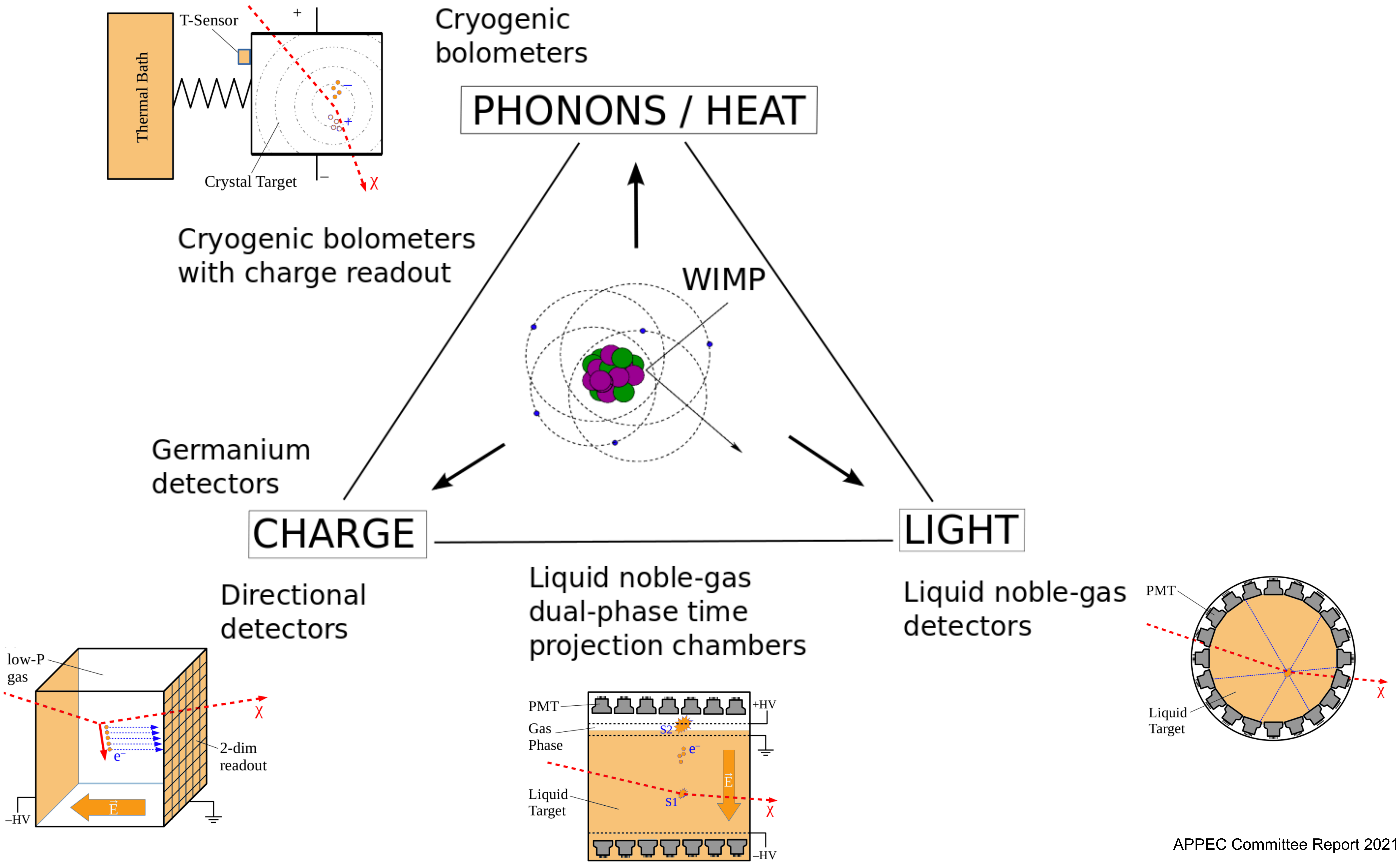

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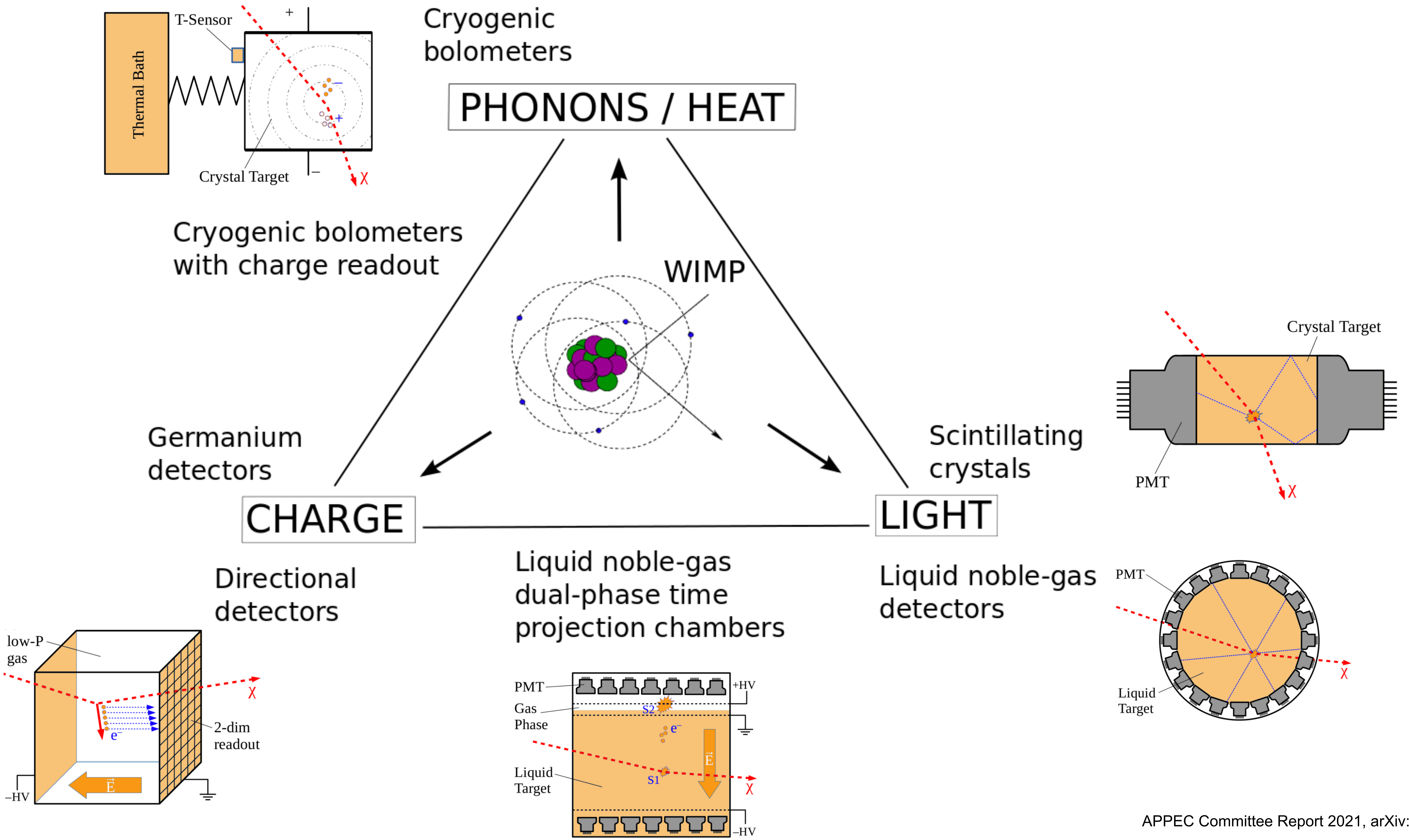

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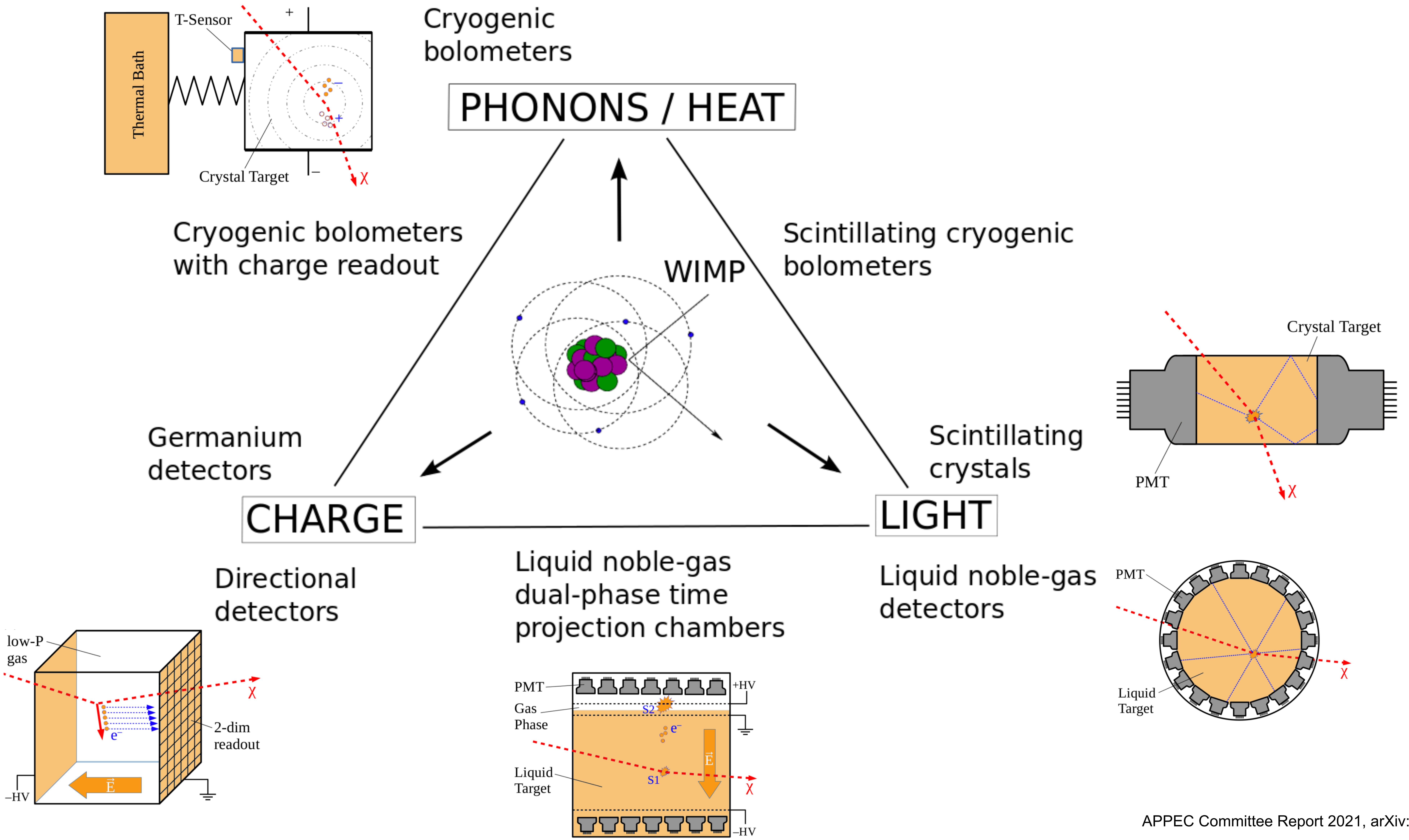

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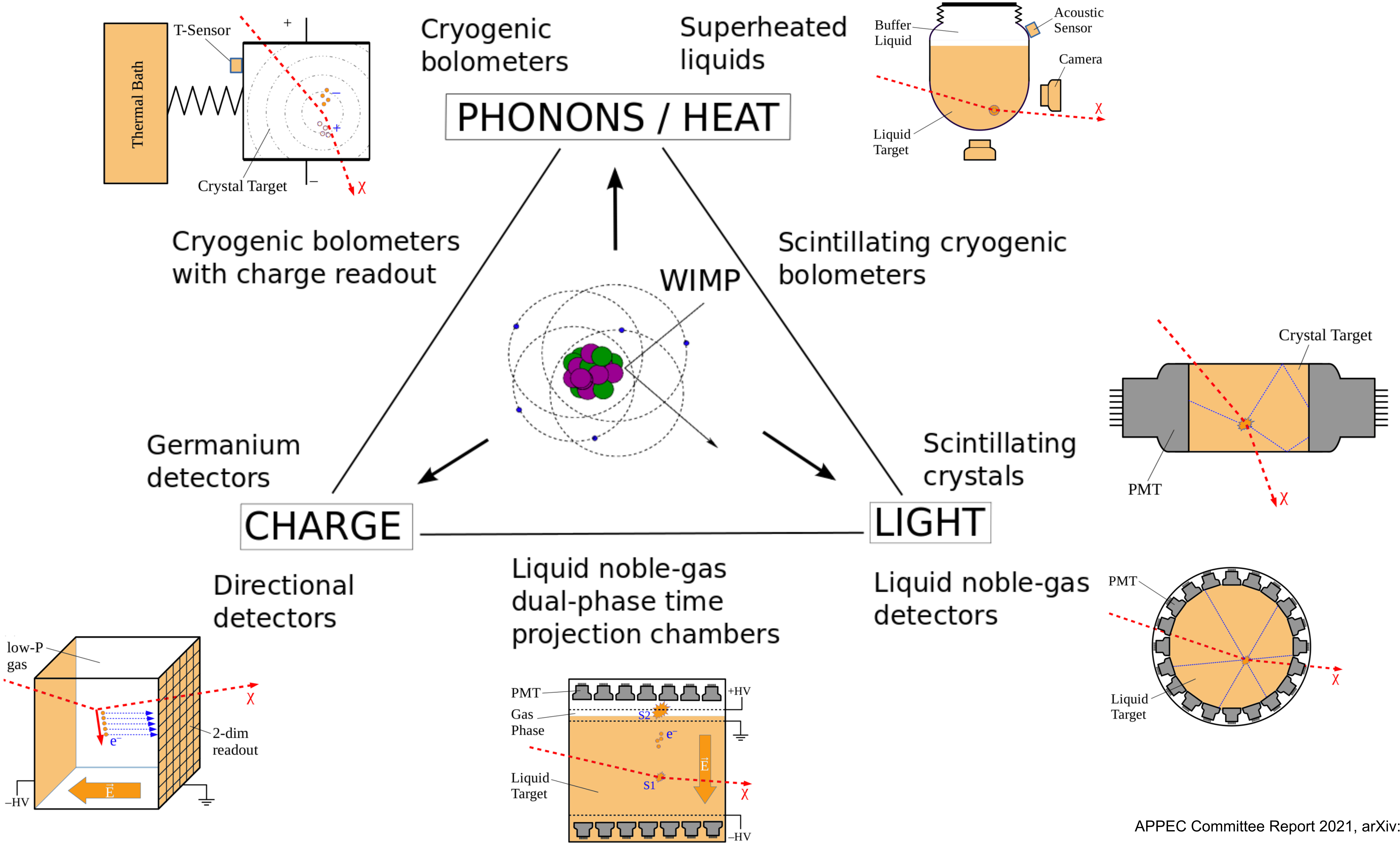

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Direct dark matter detection

Why combining two signals?

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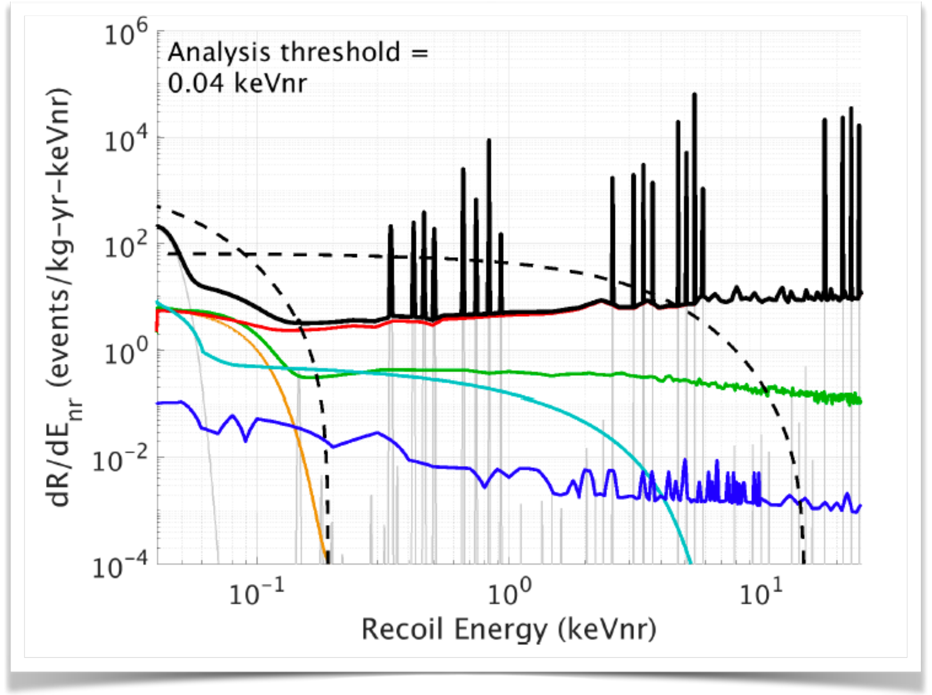
Direct dark matter detection

Backgrounds…

The dark matter direct detection master formula



$$\left(\frac{dR}{dE_R}\right)^{\mathrm{SI}}_{\chi N} = \frac{\sigma_0^{\mathrm{SI}}}{m_\chi} \cdot \frac{\rho_0 T(\vec{v})}{v\sqrt{\pi}} \cdot \frac{F_{\mathrm{SI}}^2(E_R)}{\mu^2}$$

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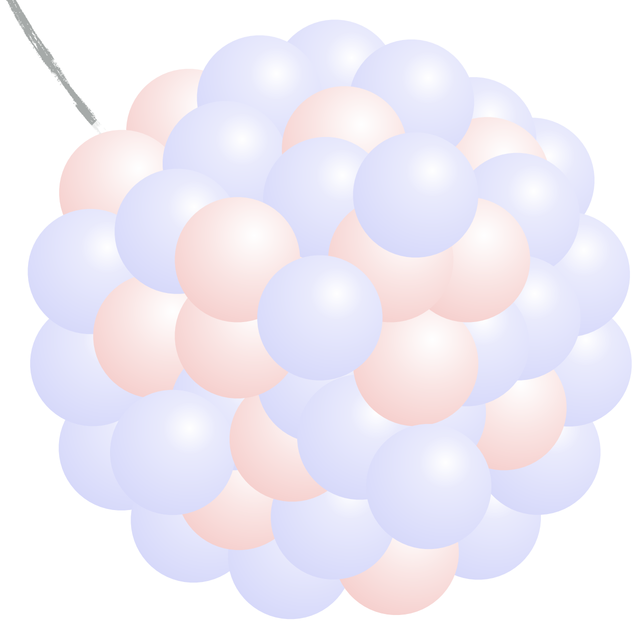
$\rho(r) \propto r^{-2}$ and $\rho_0 \approx 0.3\,\mathrm{GeV\,cm^{-3}}$



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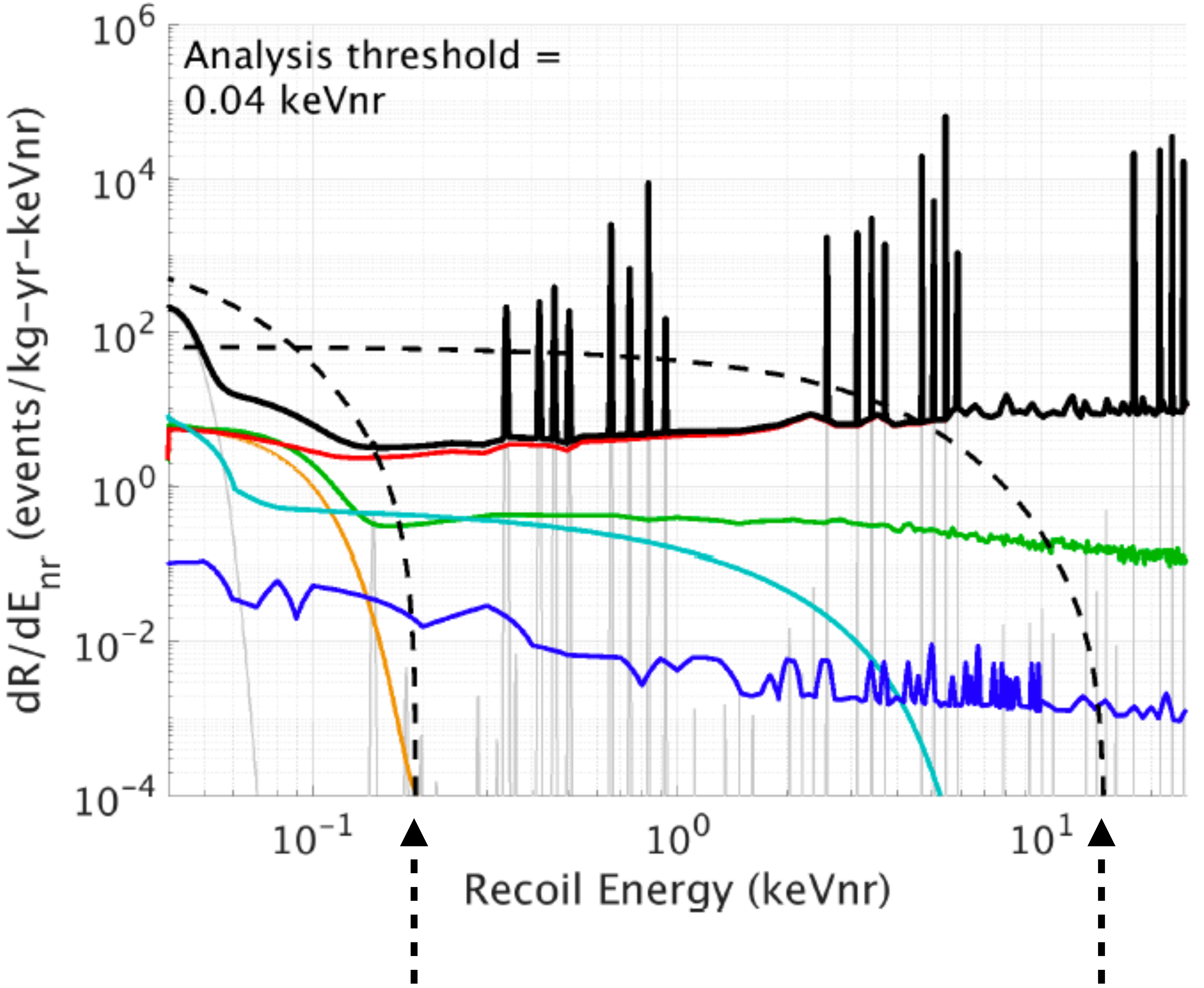
DM-nucleus scattering spectrum and backgrounds

Example:

Prediction for SuperCDMS SNOLAB (Ge HV detectors)



1 GeV/c² WIMP 10 GeV/c² WIMP with $\sigma = 10^{-42}$ cm²

SuperCDMS Collaboration, Phys. Rev. D 95, 082002 (2017)

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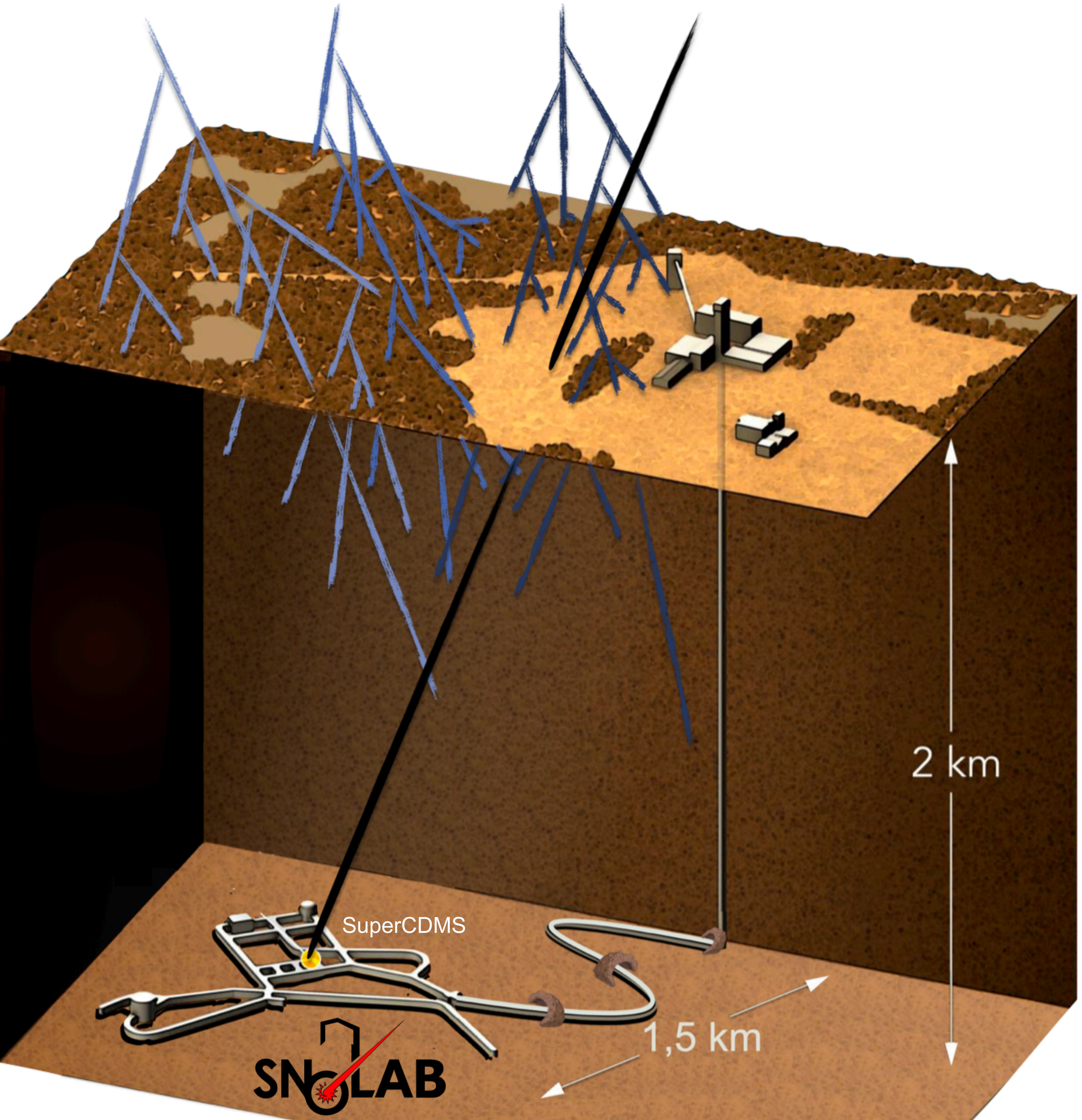
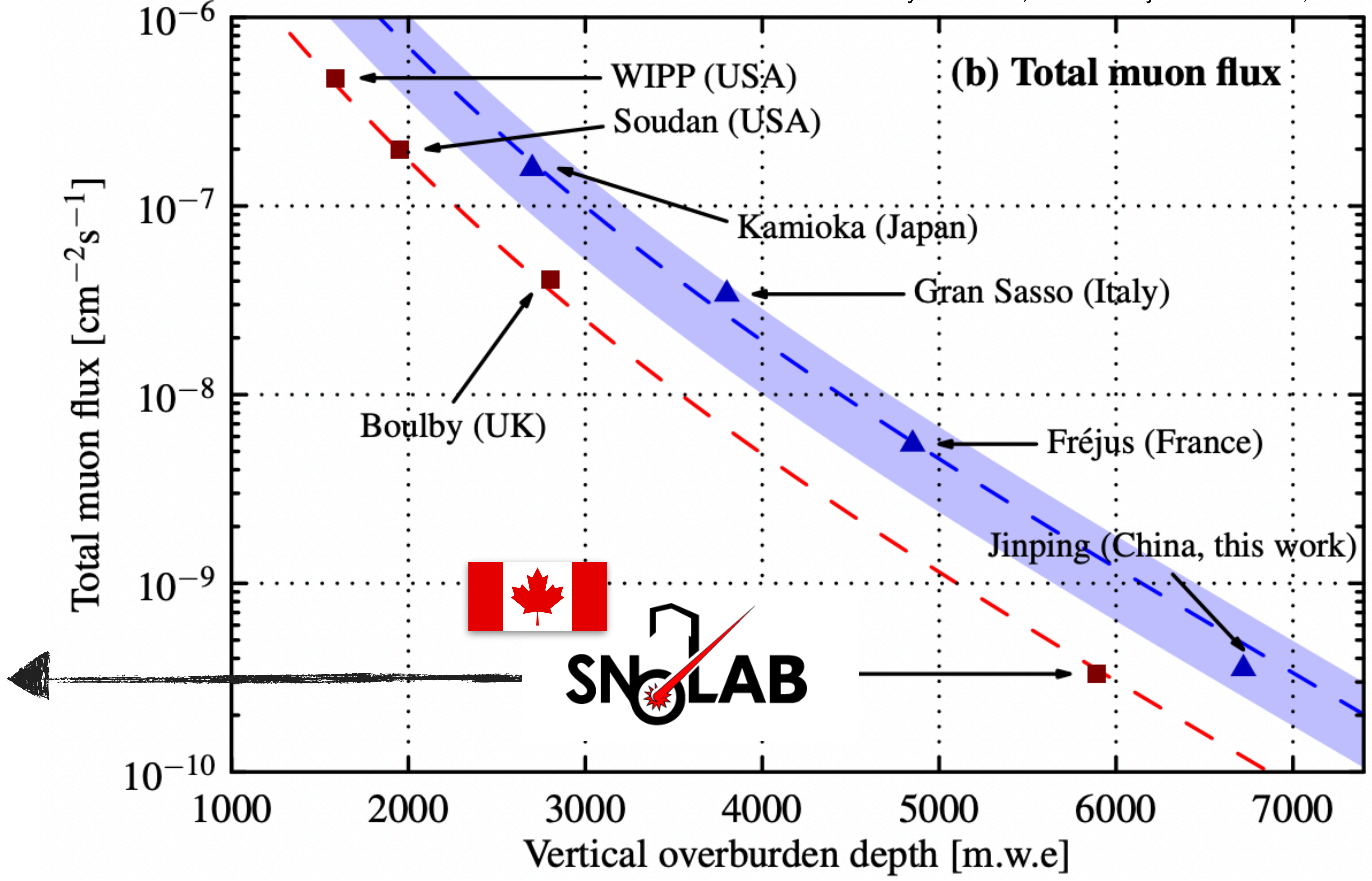
Backgrounds: cosmic rays



Credit: SuperCDMS Collaboration / SNOLAB / M. Wilson

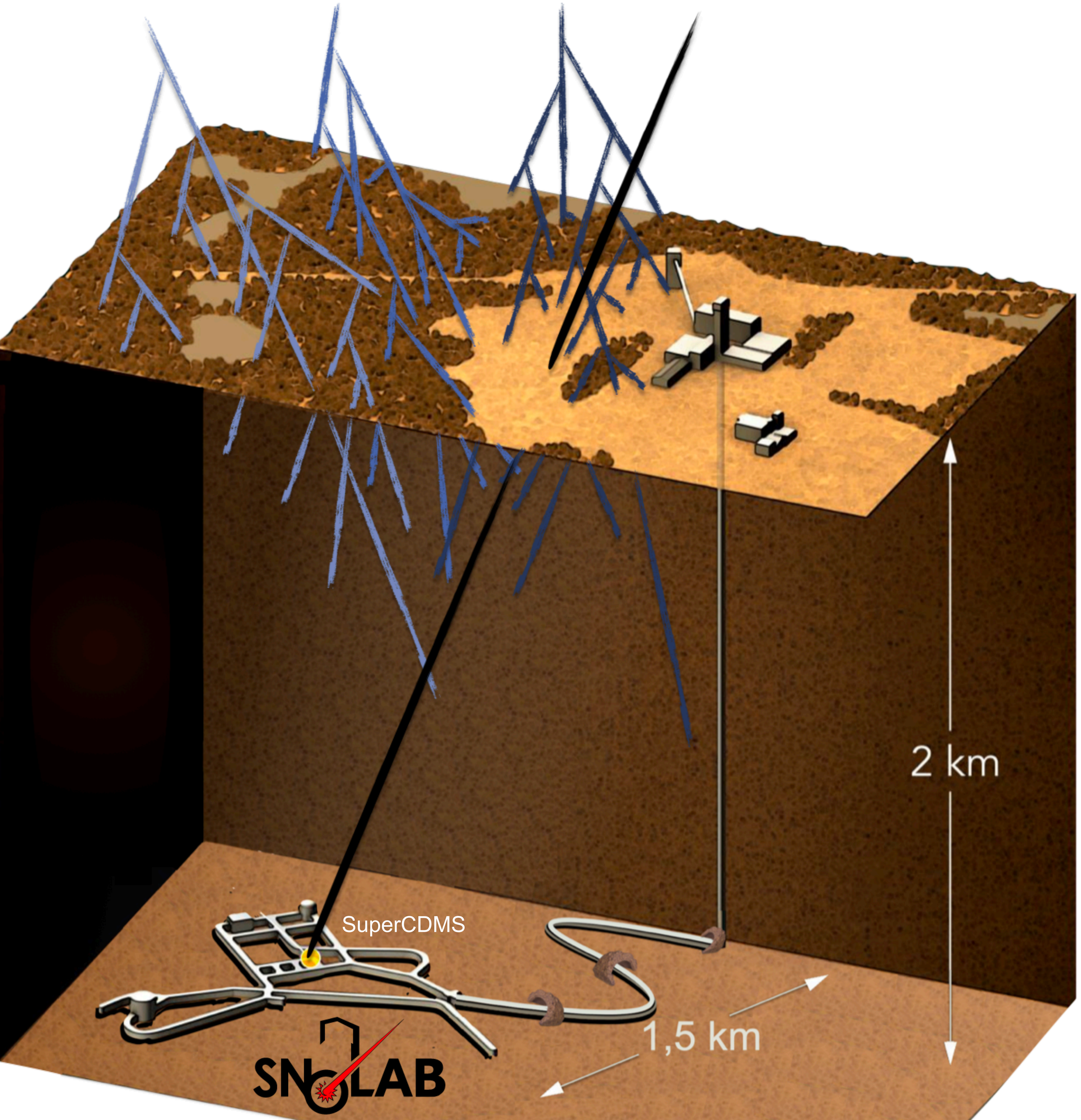
Going underground to mitigate cosmic and cosmogenic backgrounds

Zi-yi Guo et al., Chinese Phys. C 45 025001, 2021



At SNOLAB: ~0.3 muons per m^2 per day.

Backgrounds: cosmic rays



Credit: SuperCDMS Collaboration / SNOLAB / M. Wilson

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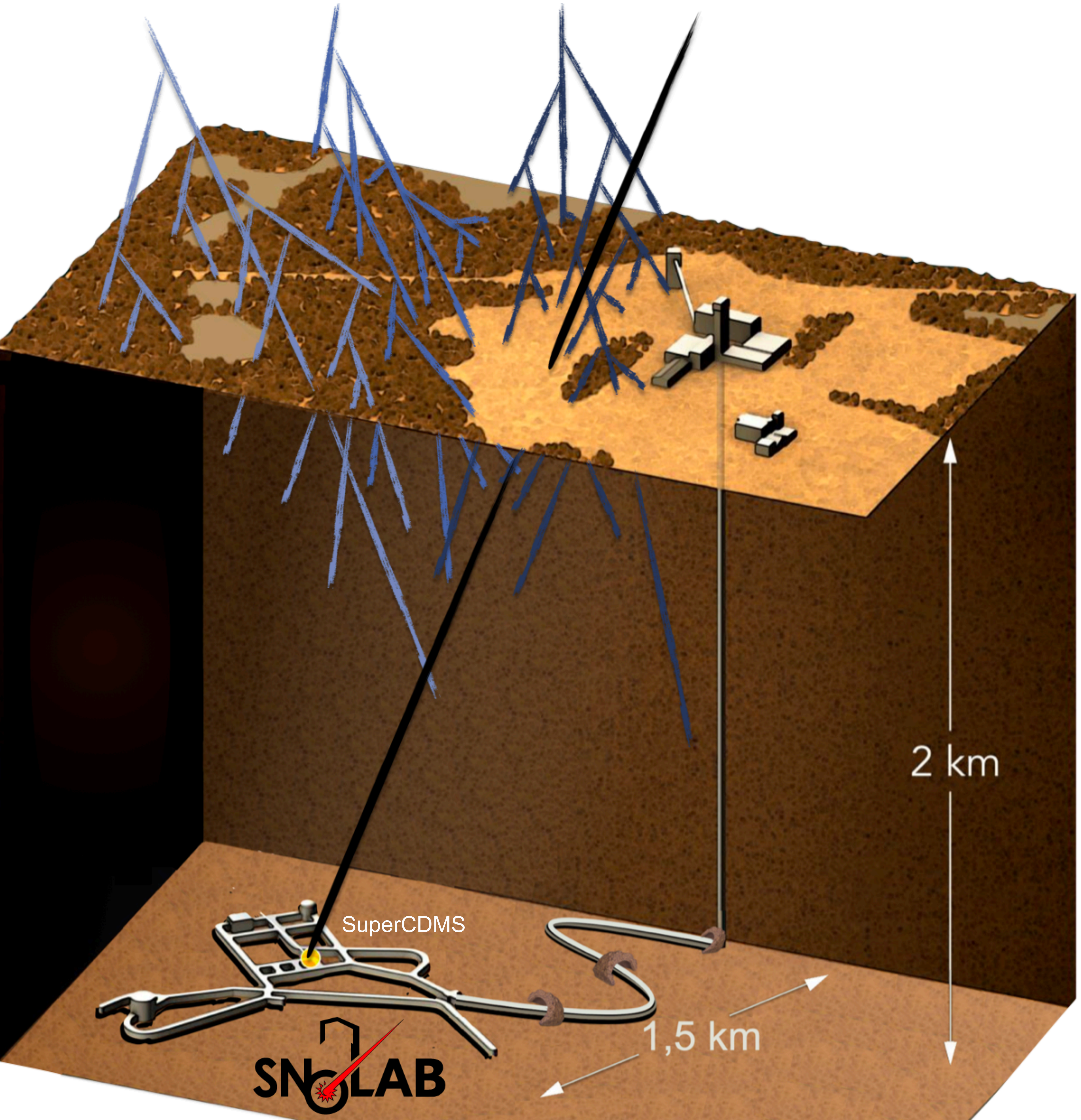

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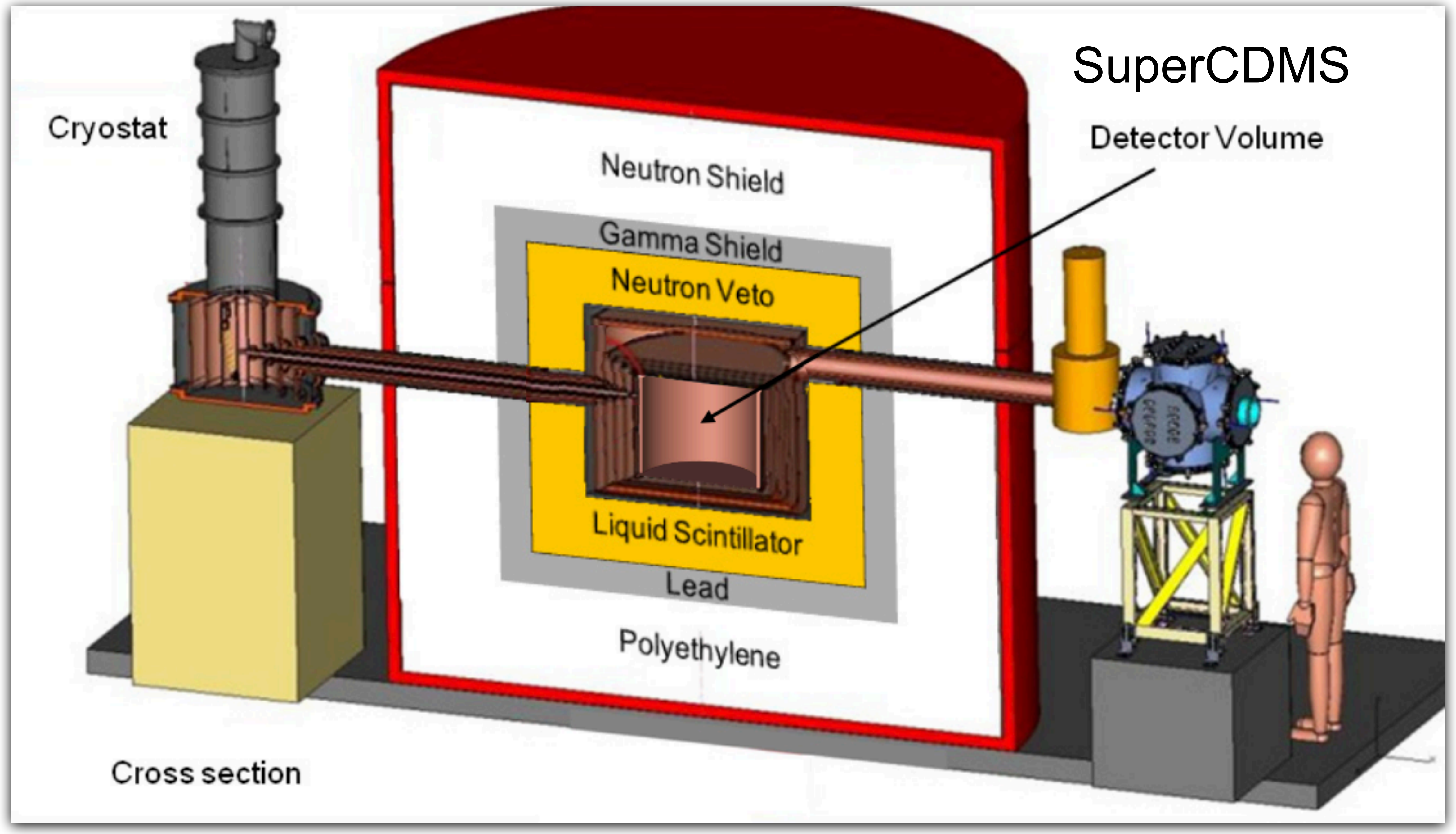
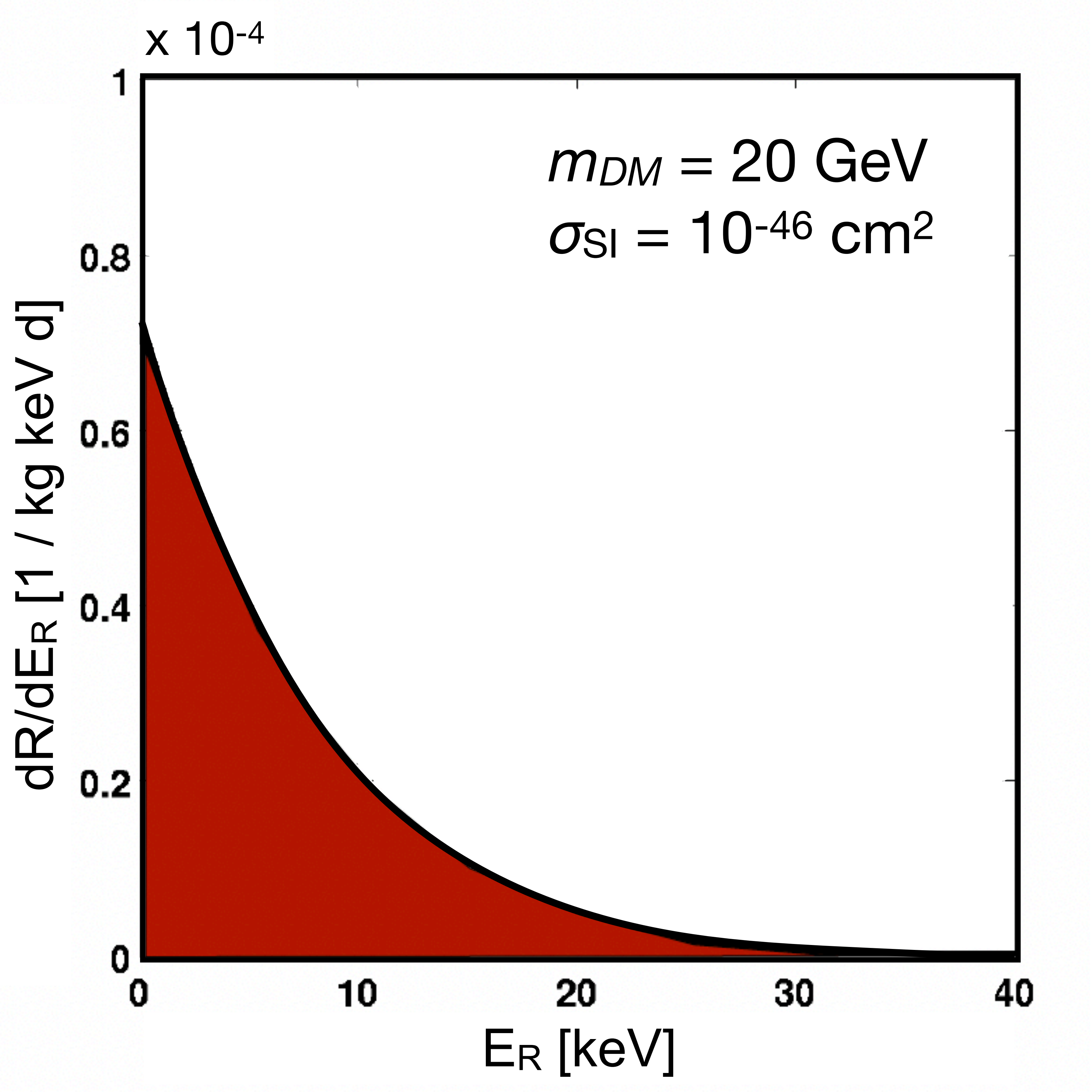


Additional active and passive shielding against cosmogenic secondaries

Backgrounds: radioactive decays

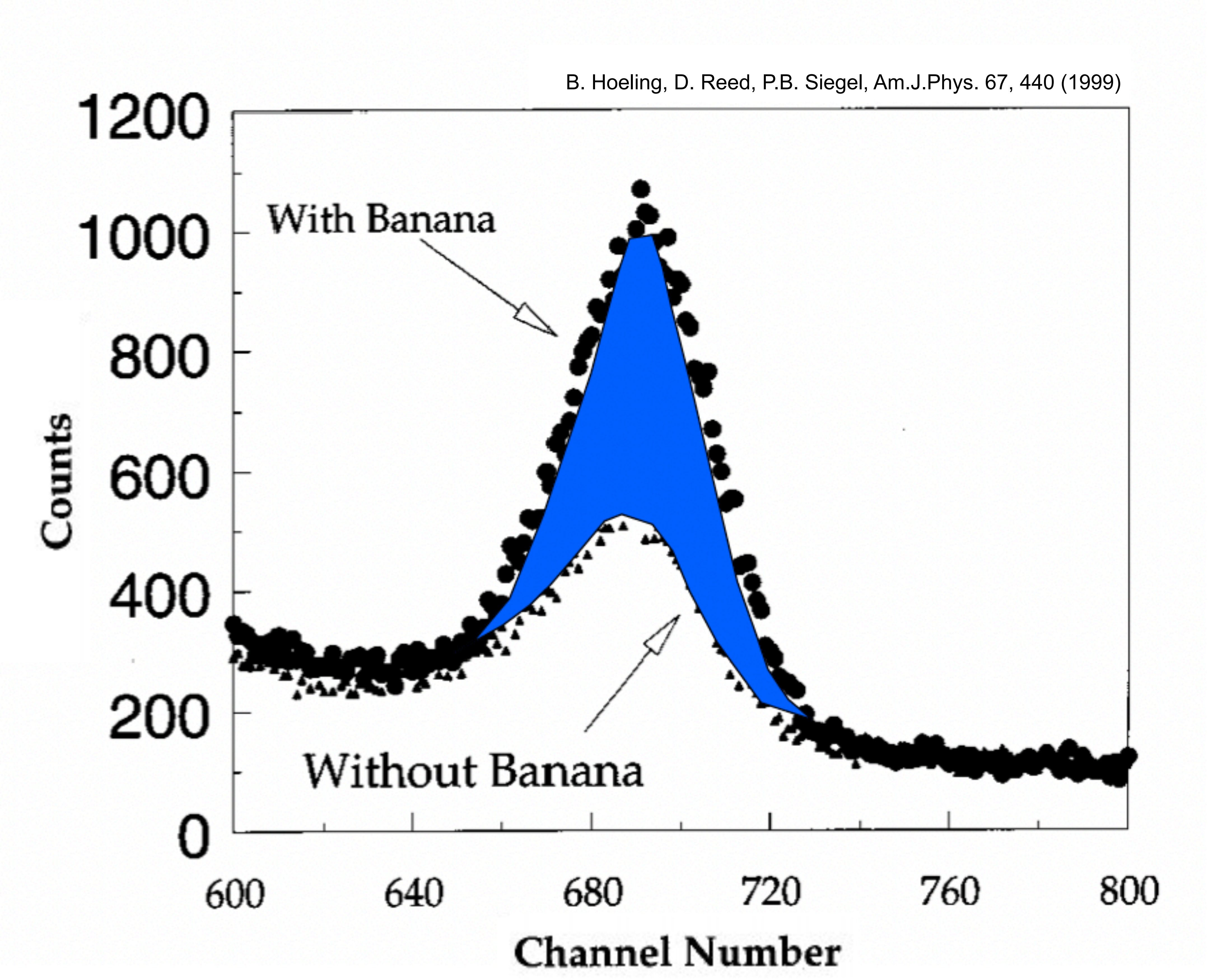
Expected DM spectrum



<0.1 event per kg per year

→ nuclear recoils

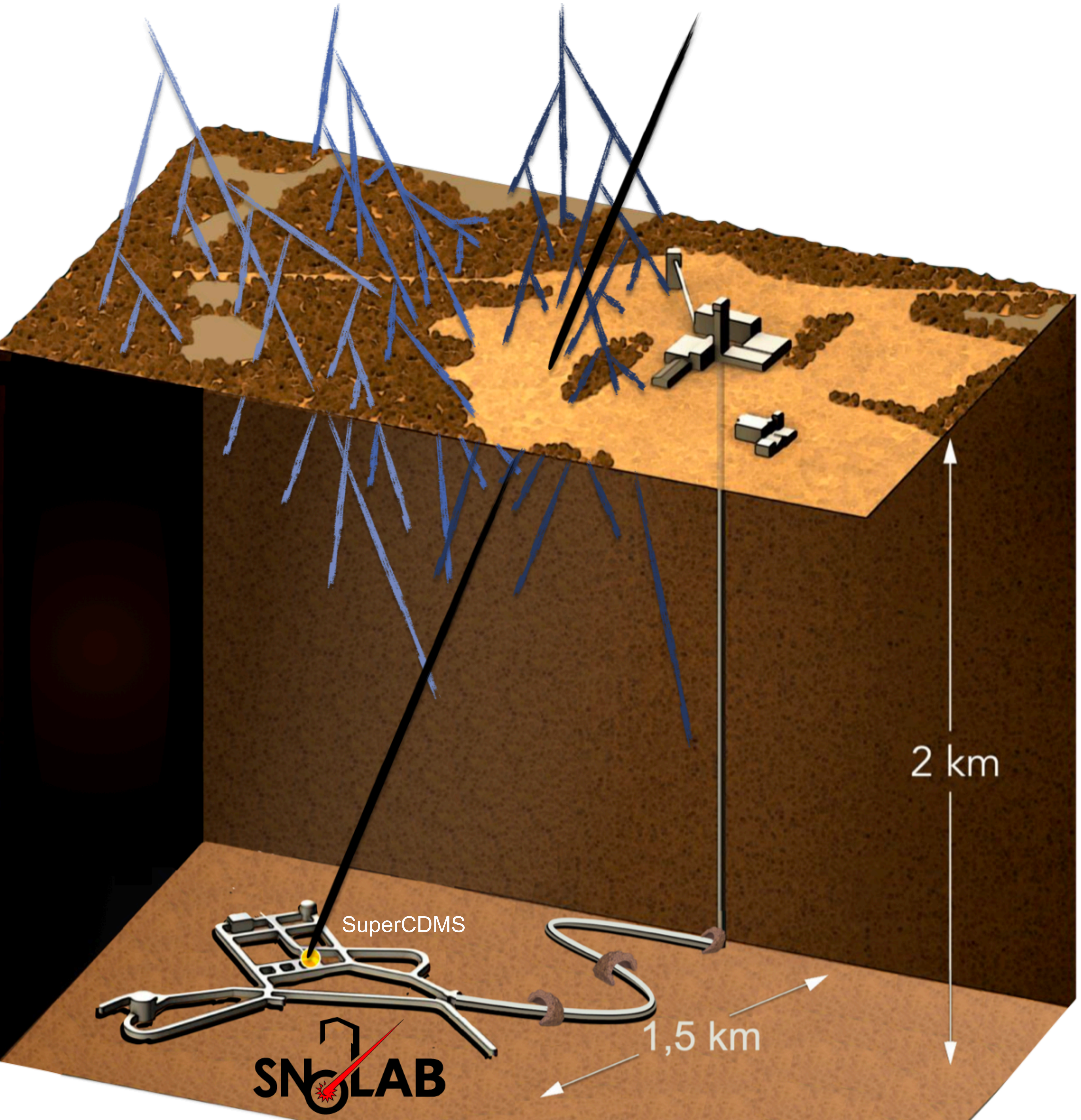
Measured banana spectrum



>100 000 events per banana per year

→ electron recoils

Backgrounds: cosmic rays and radioactive decays



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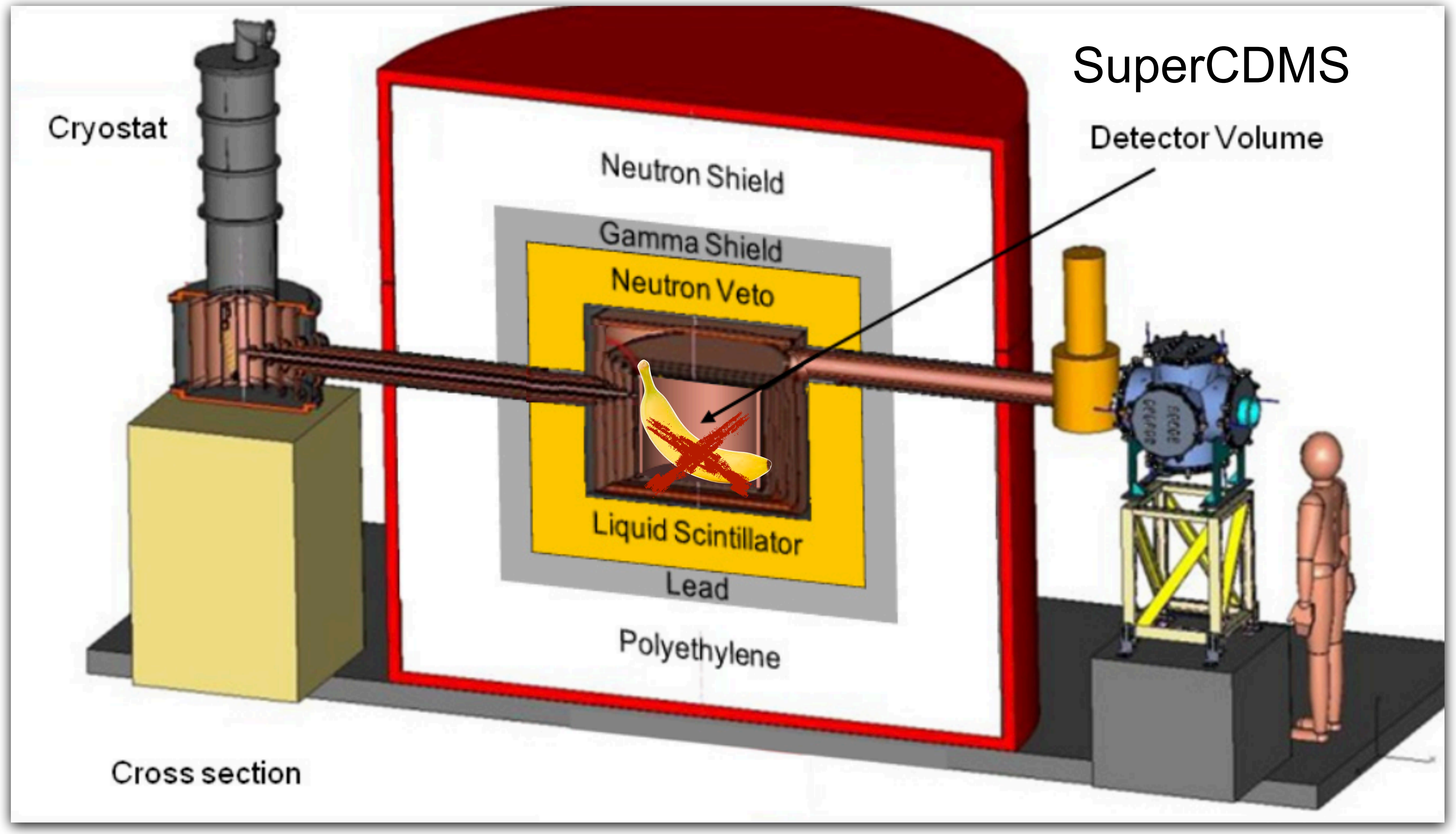

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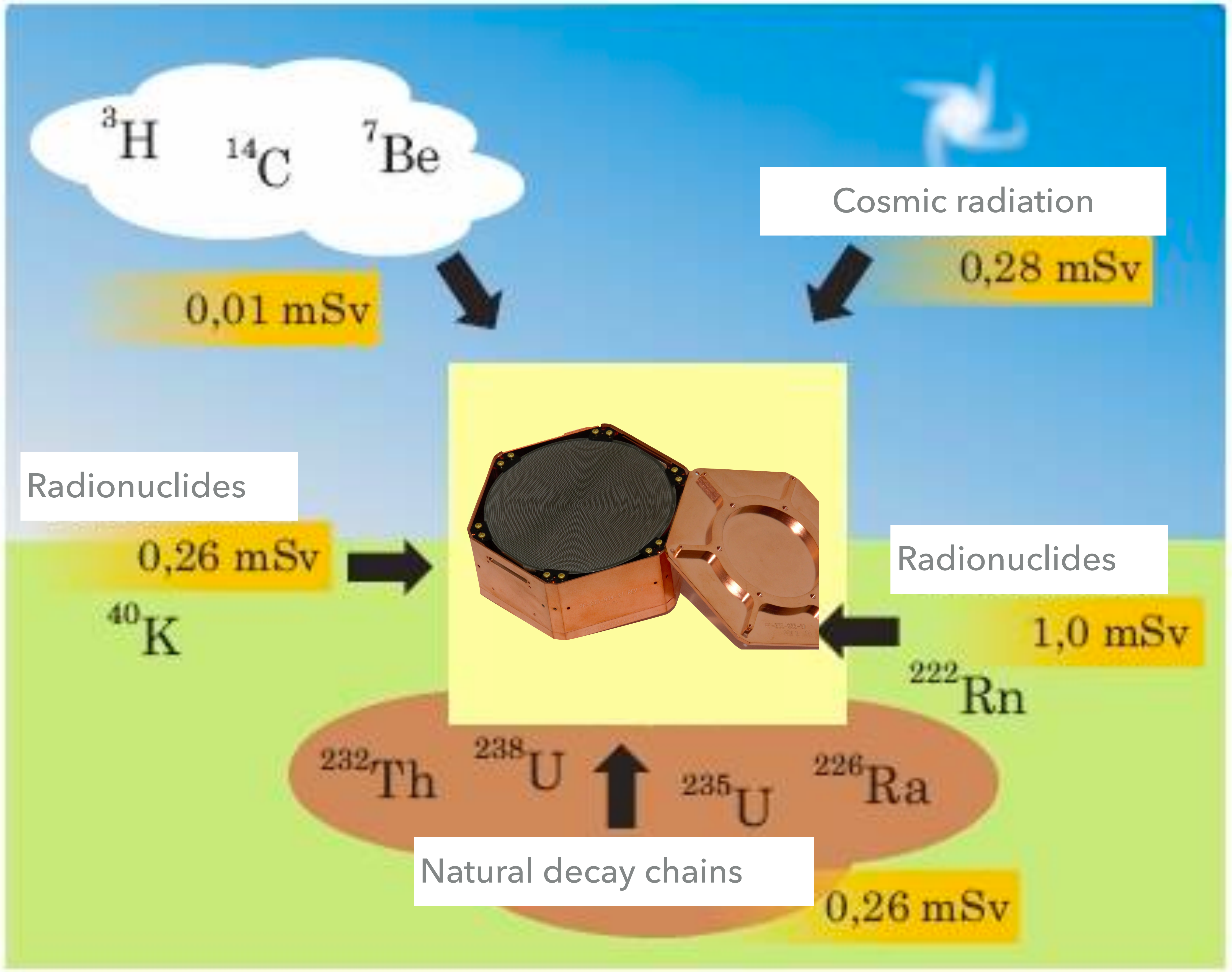


http://www.goerudio.com/izpratnes-lapa/radioaktivitate (modified)

Mitigation strategies

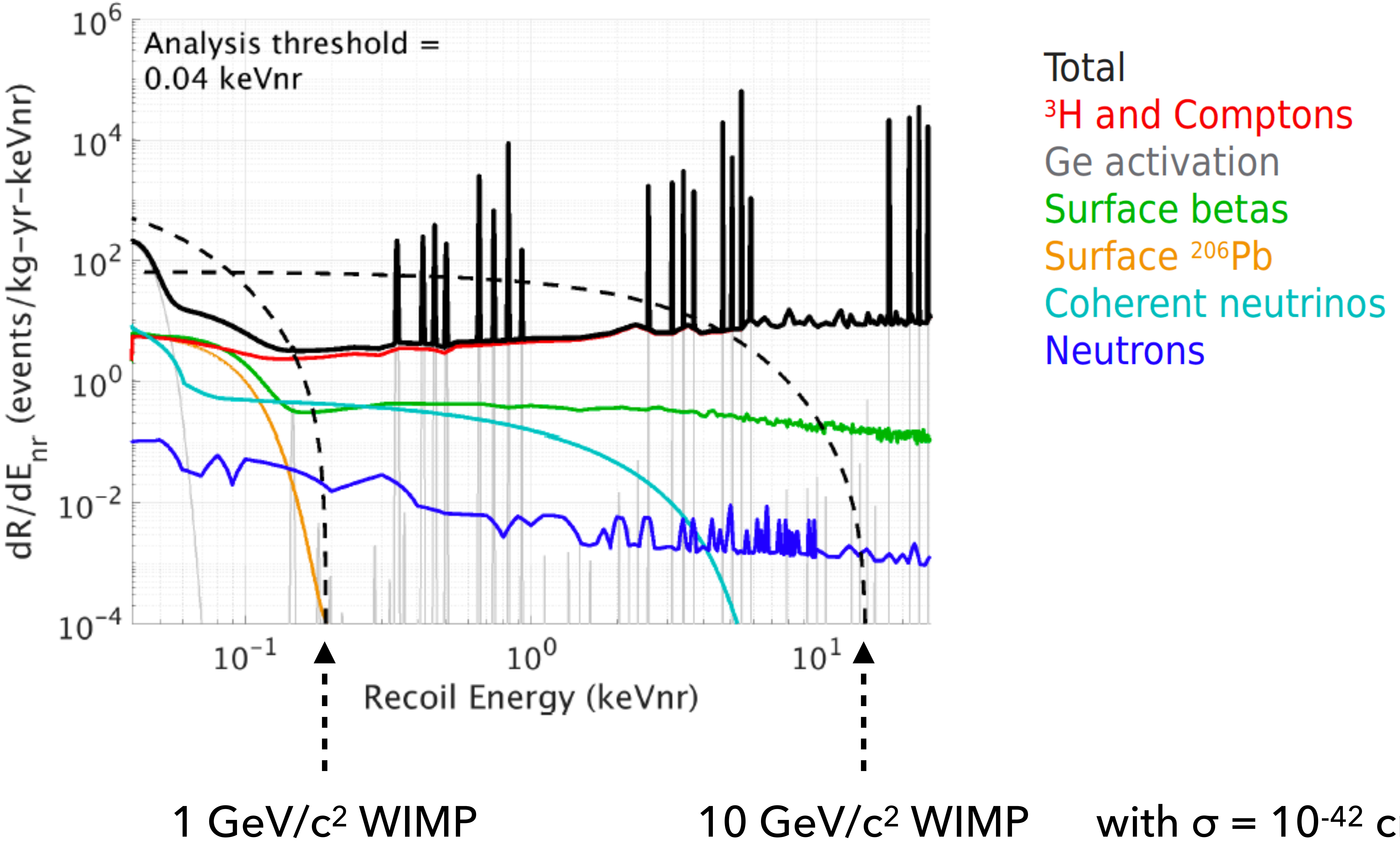
- going underground
- storing materials underground
- passive and active shielding
- Radon mitigation
- use of materials with high purity
- characterize the background
- …

DM-nucleus scattering spectrum and backgrounds

Example:

Prediction for SuperCDMS SNOLAB (Ge HV detectors)

Still not background free!



with $\sigma = 10^{-42}$ cm^2

SuperCDMS Collaboration, Phys. Rev. D 95, 082002 (2017)

DM-nucleus scattering spectrum and backgrounds

Example:

Prediction for SuperCDMS SNOLAB (Ge HV detectors)

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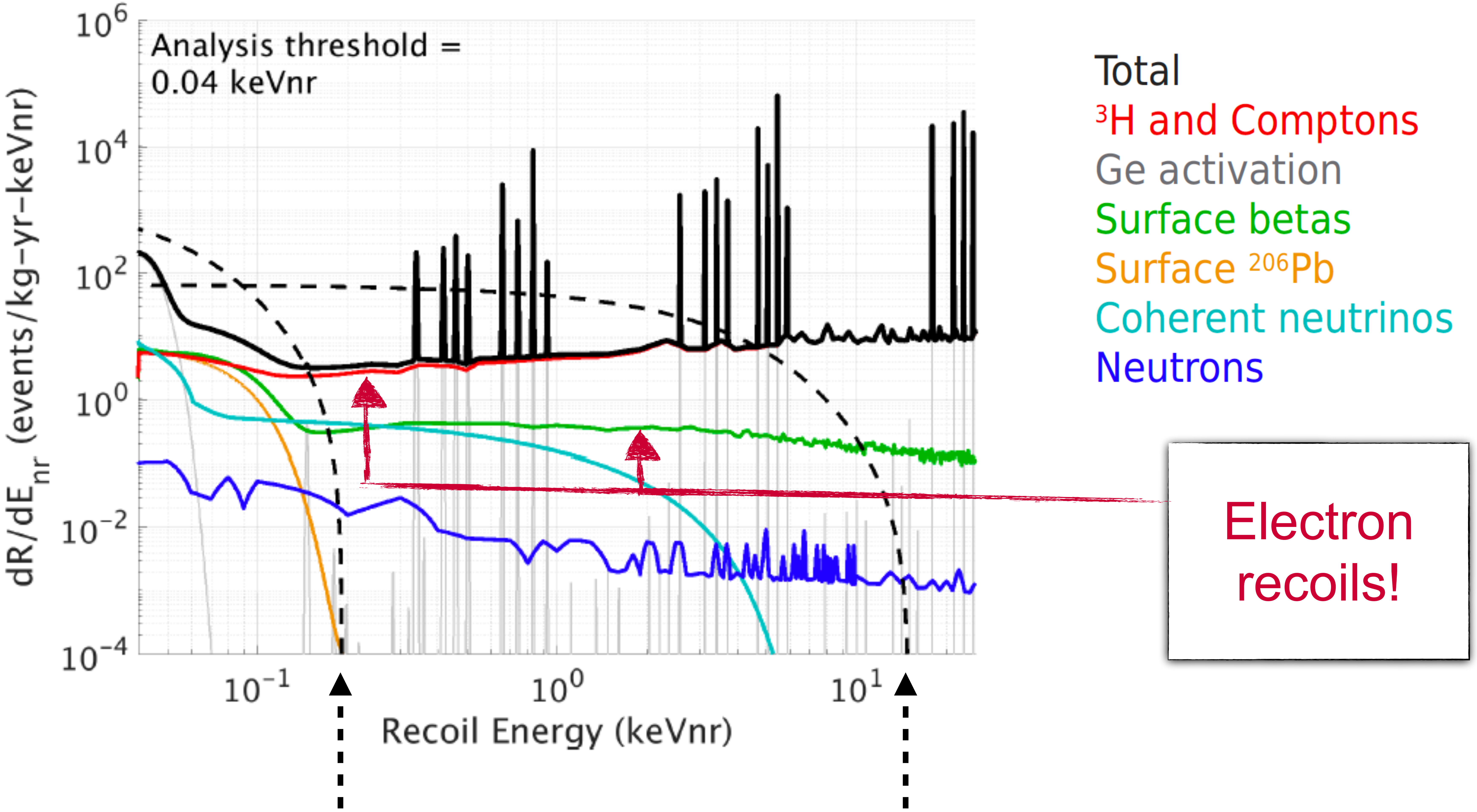


1 GeV/c^2 WIMP

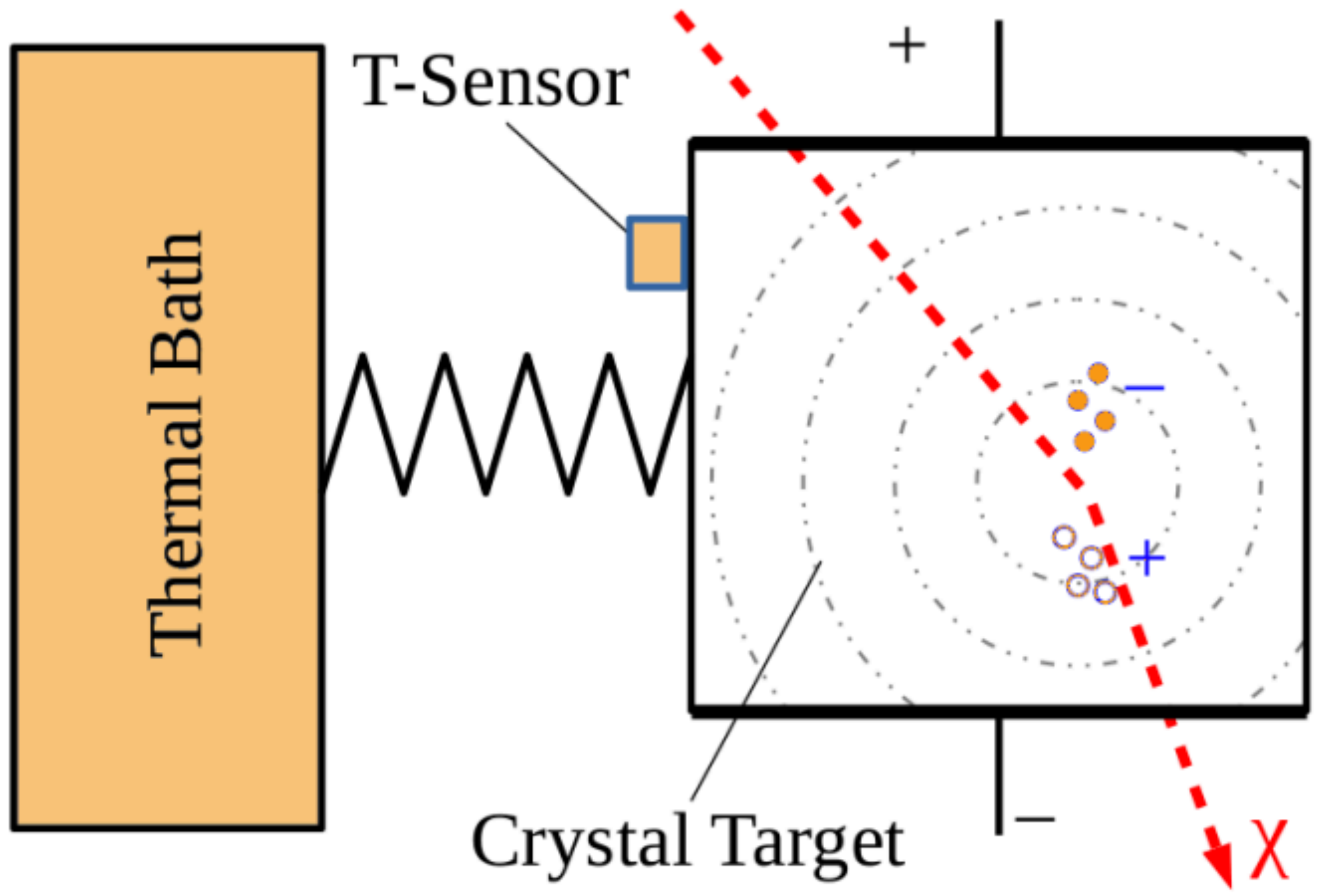
10 GeV/c^2 WIMP

with $\sigma = 10^{-42}$ cm^2

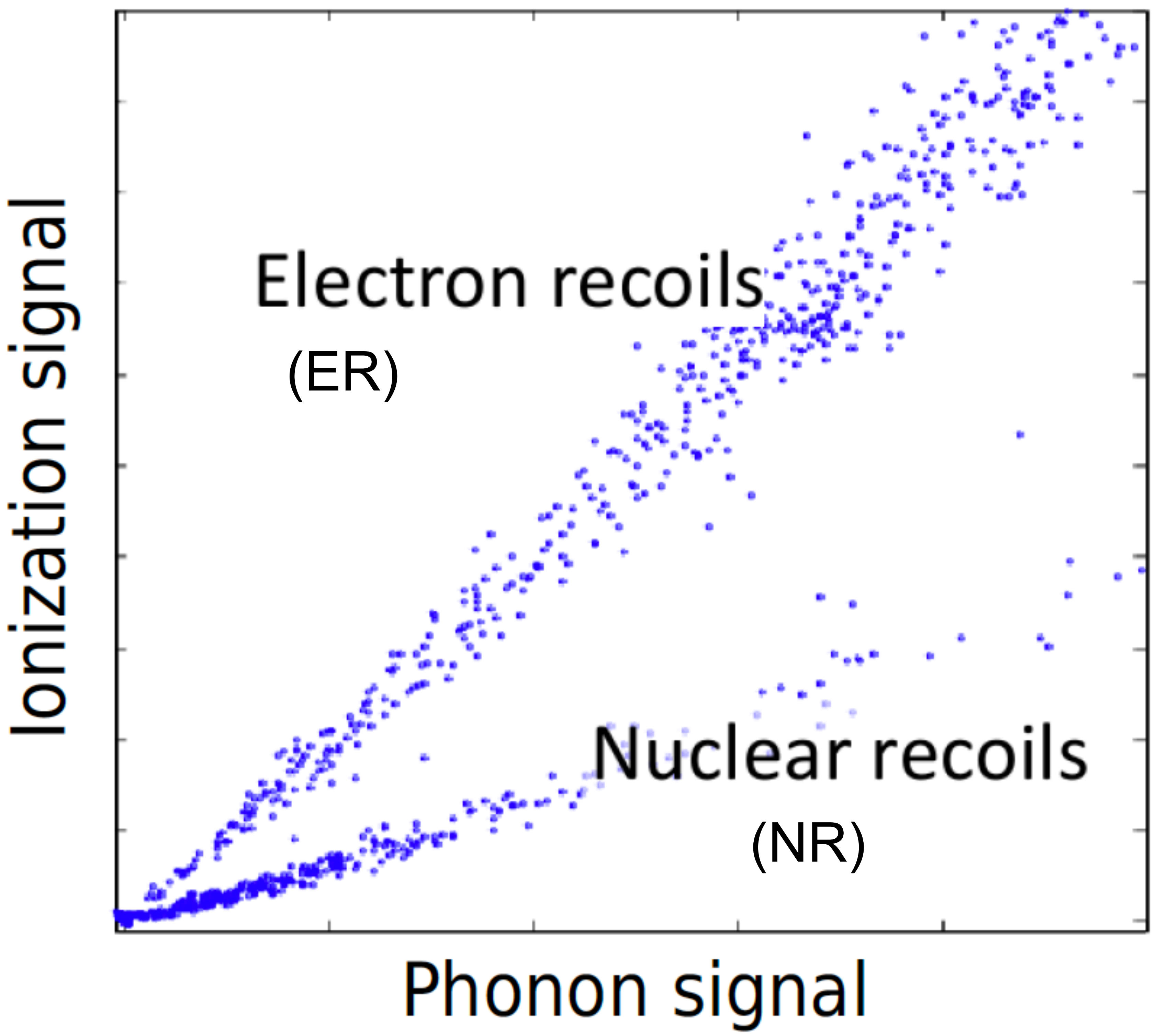
SuperCDMS Collaboration, Phys. Rev. D 95, 082002 (2017)

Background discrimination using two signals

Example: measurement of PHONON/HEAT and IONIZATION signals



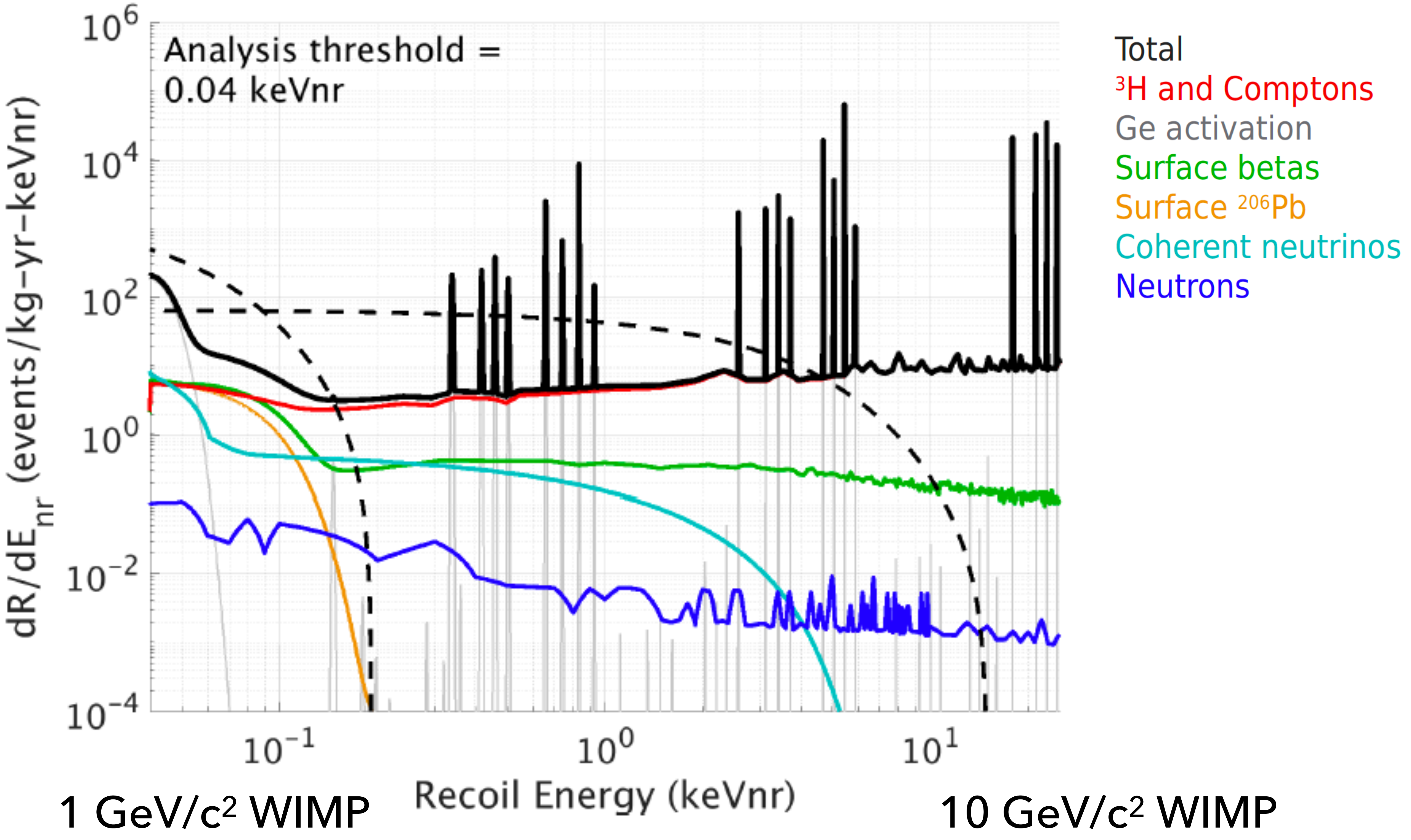
Cryogenic bolometers with charge readout

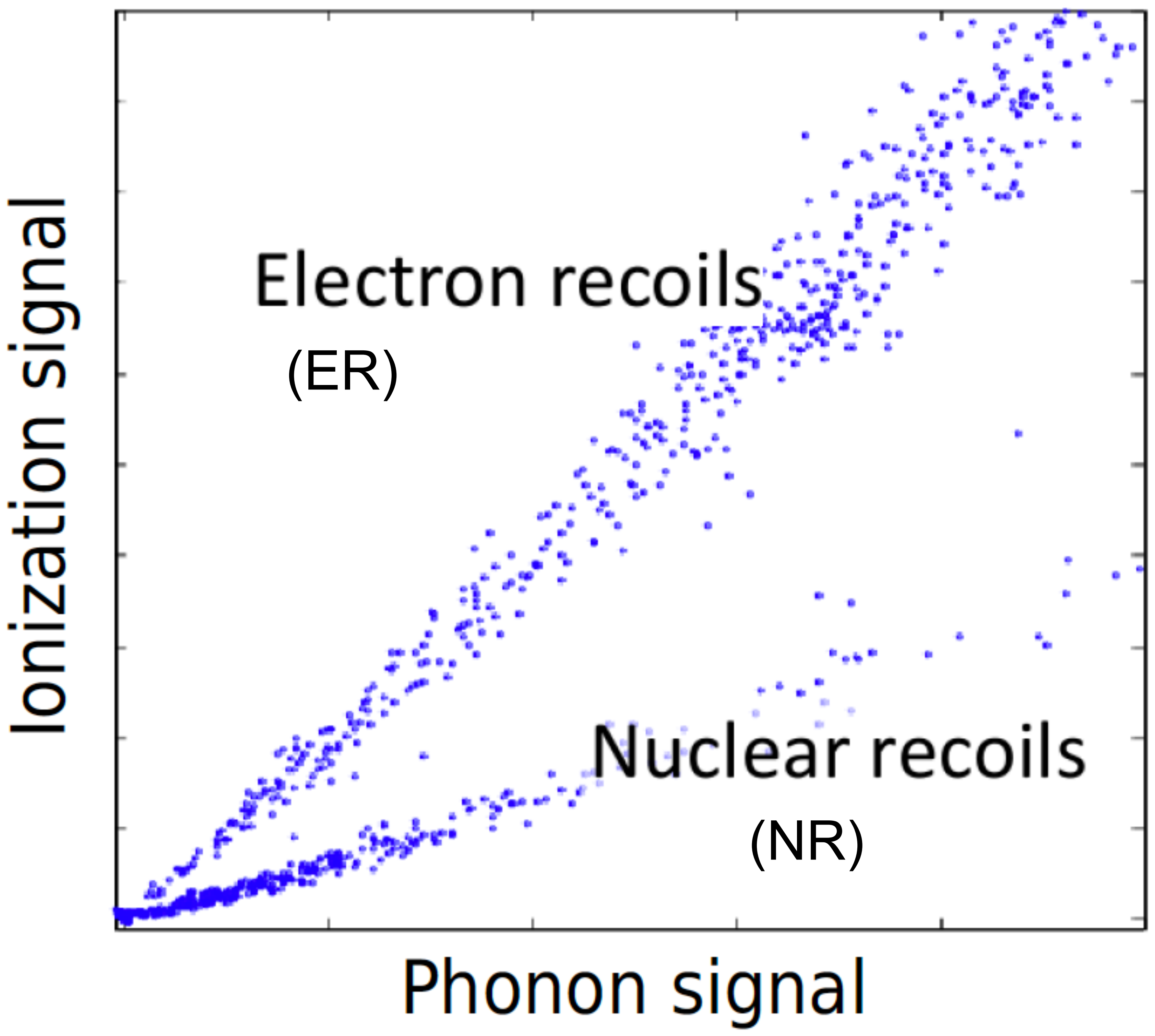


Two signals offer strong discrimination power between WIMP NR signals and backgrounds with ER signatures!

Background discrimination using two signals

Example: measurement of PHONON/HEAT and IONIZATION signals



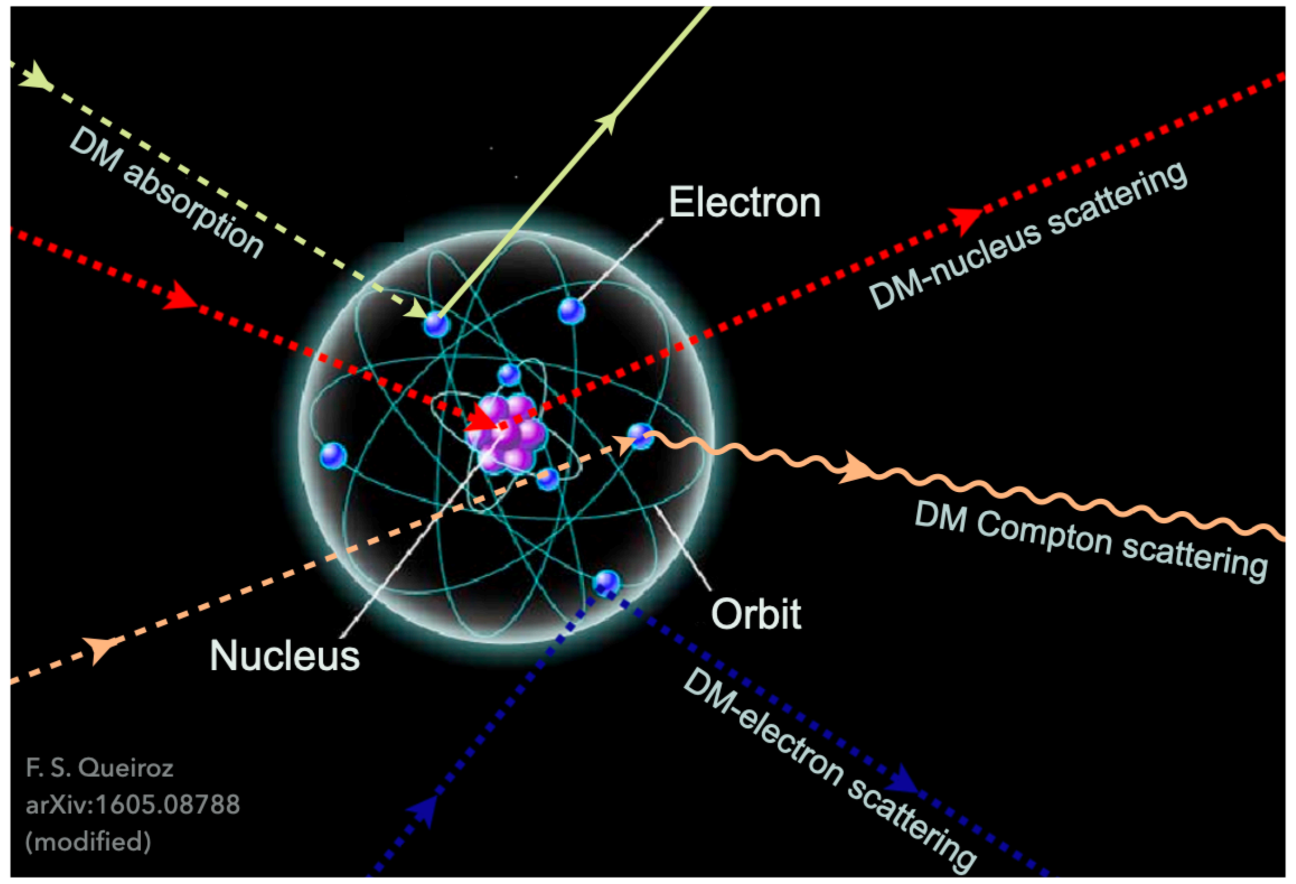


Two signals offer strong discrimination power between WIMP NR signals and backgrounds with ER signatures!

Summary

How to build a dark matter detector

1. pick your interaction



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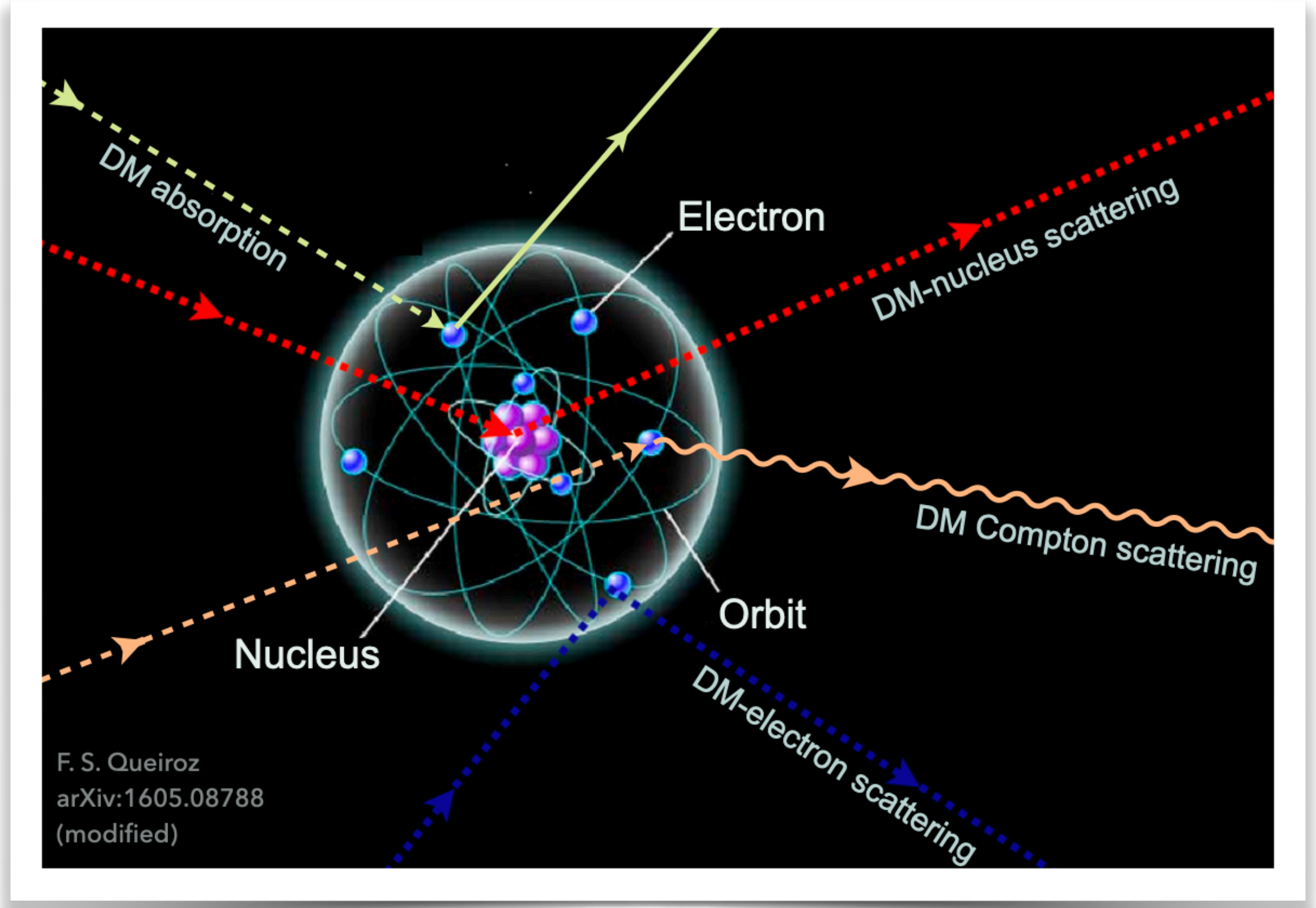

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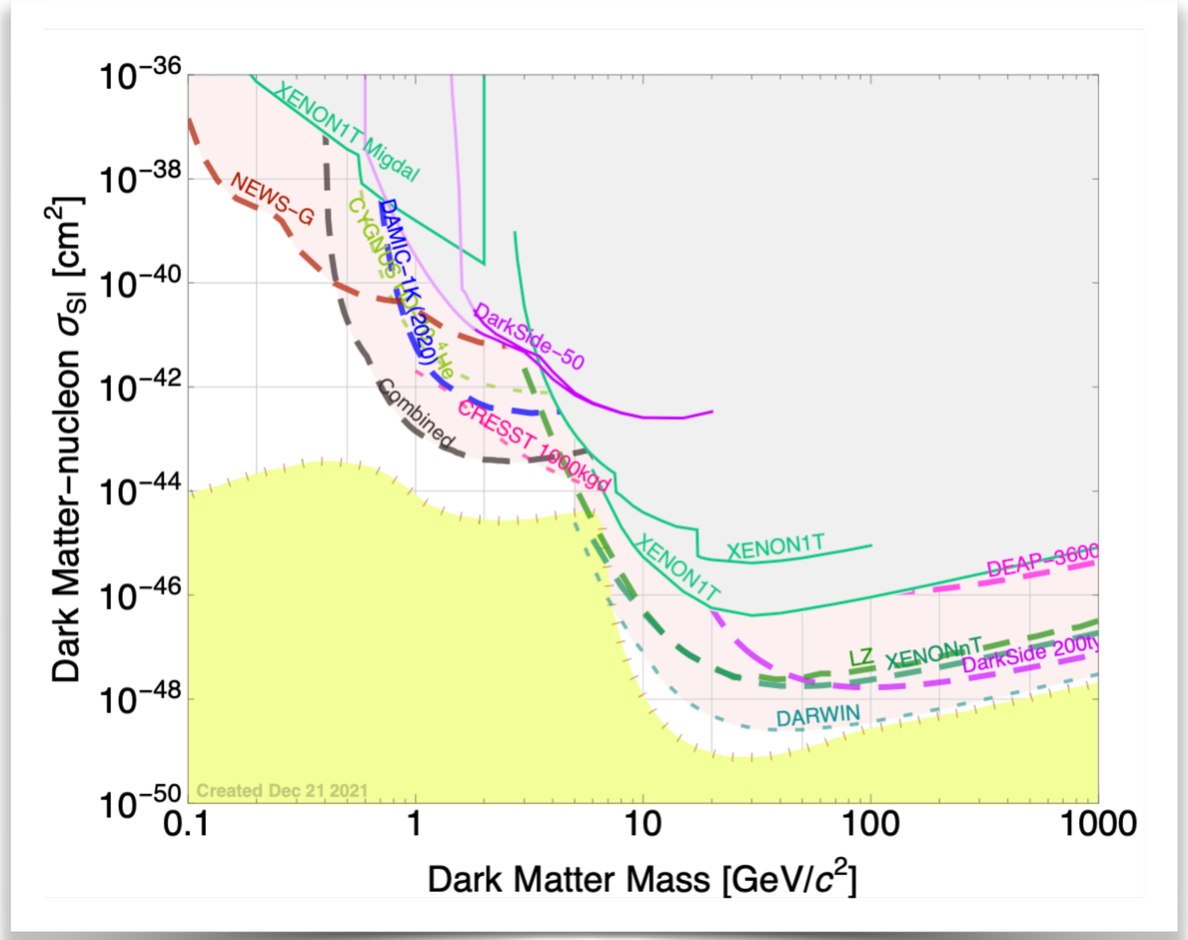

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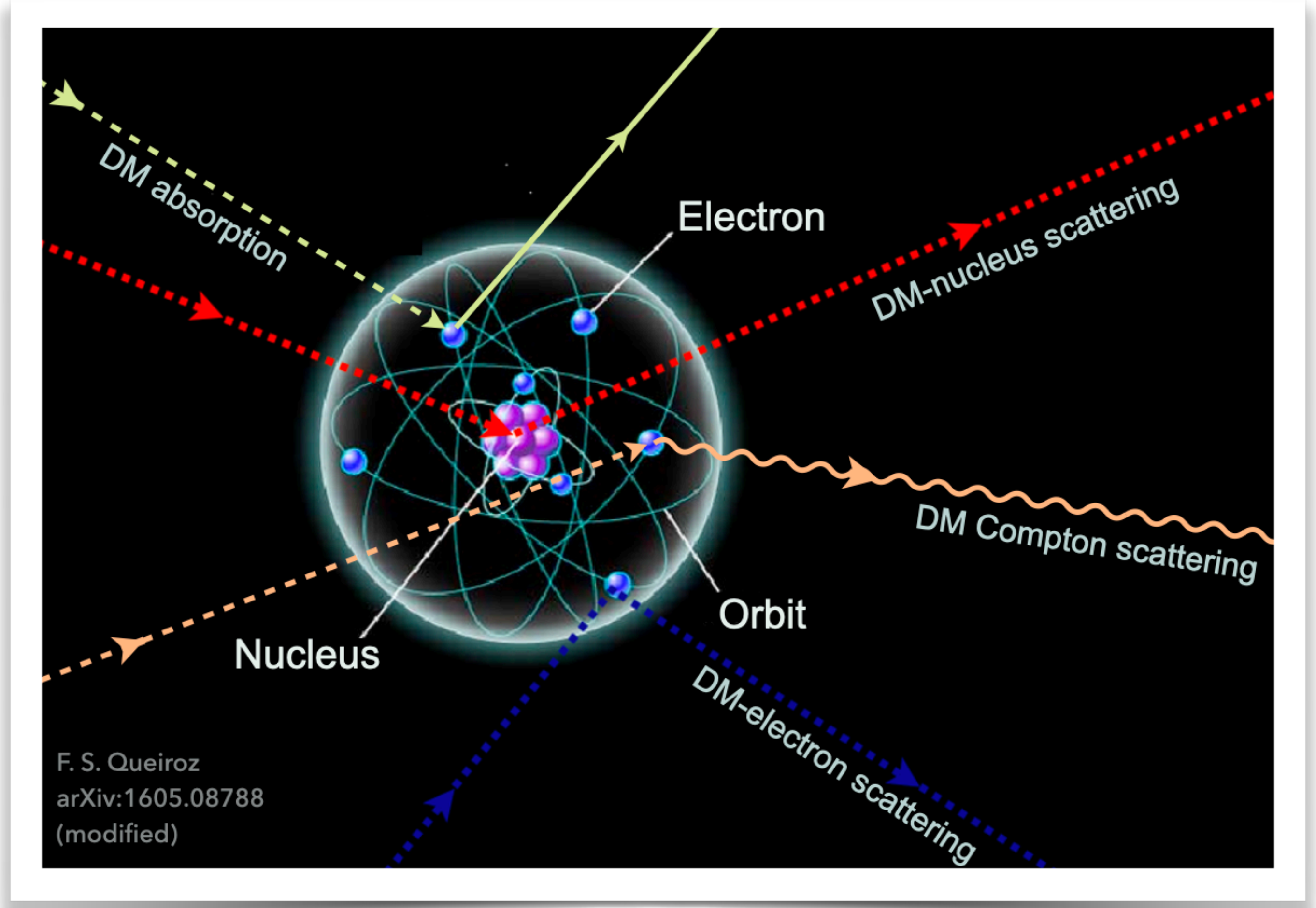

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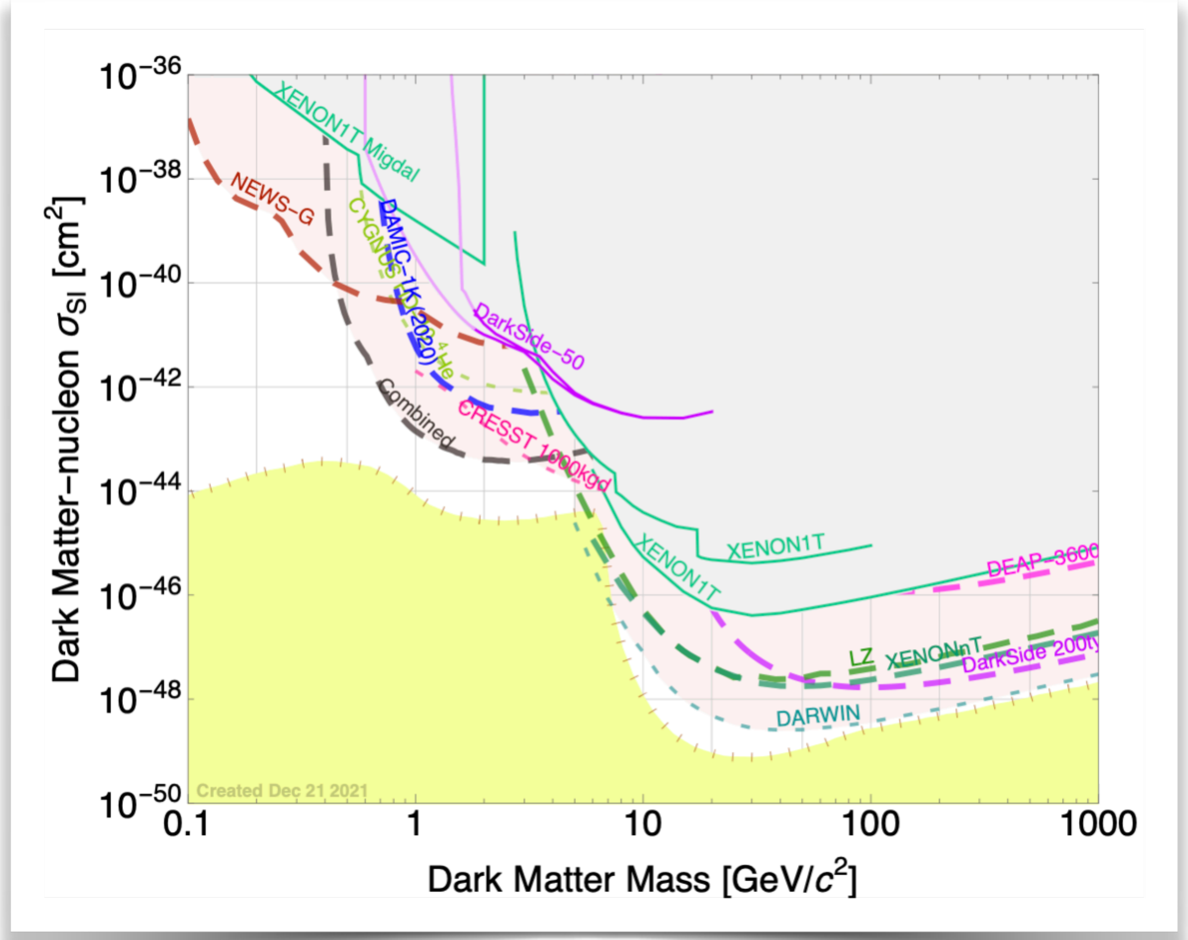
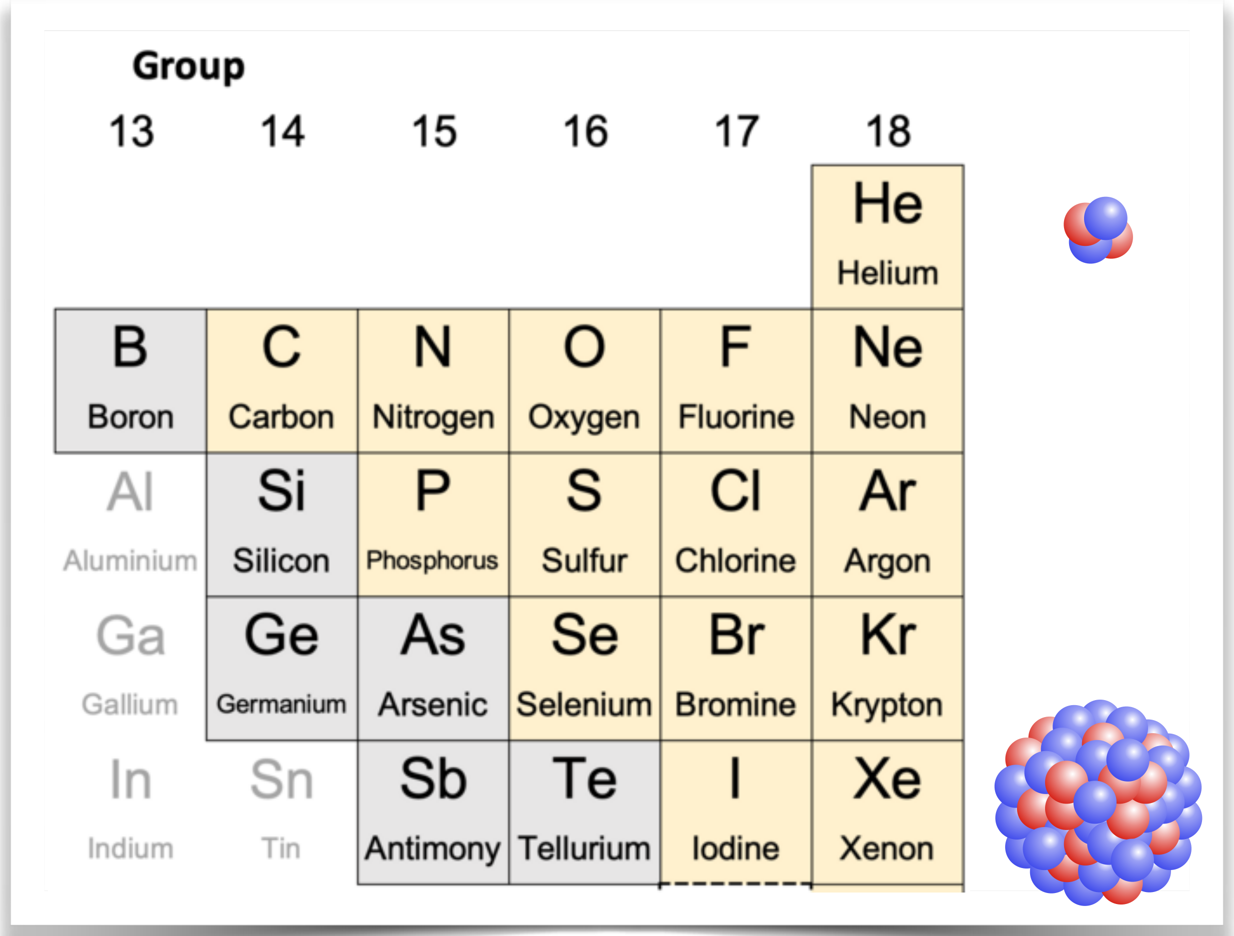


3. pick your target material



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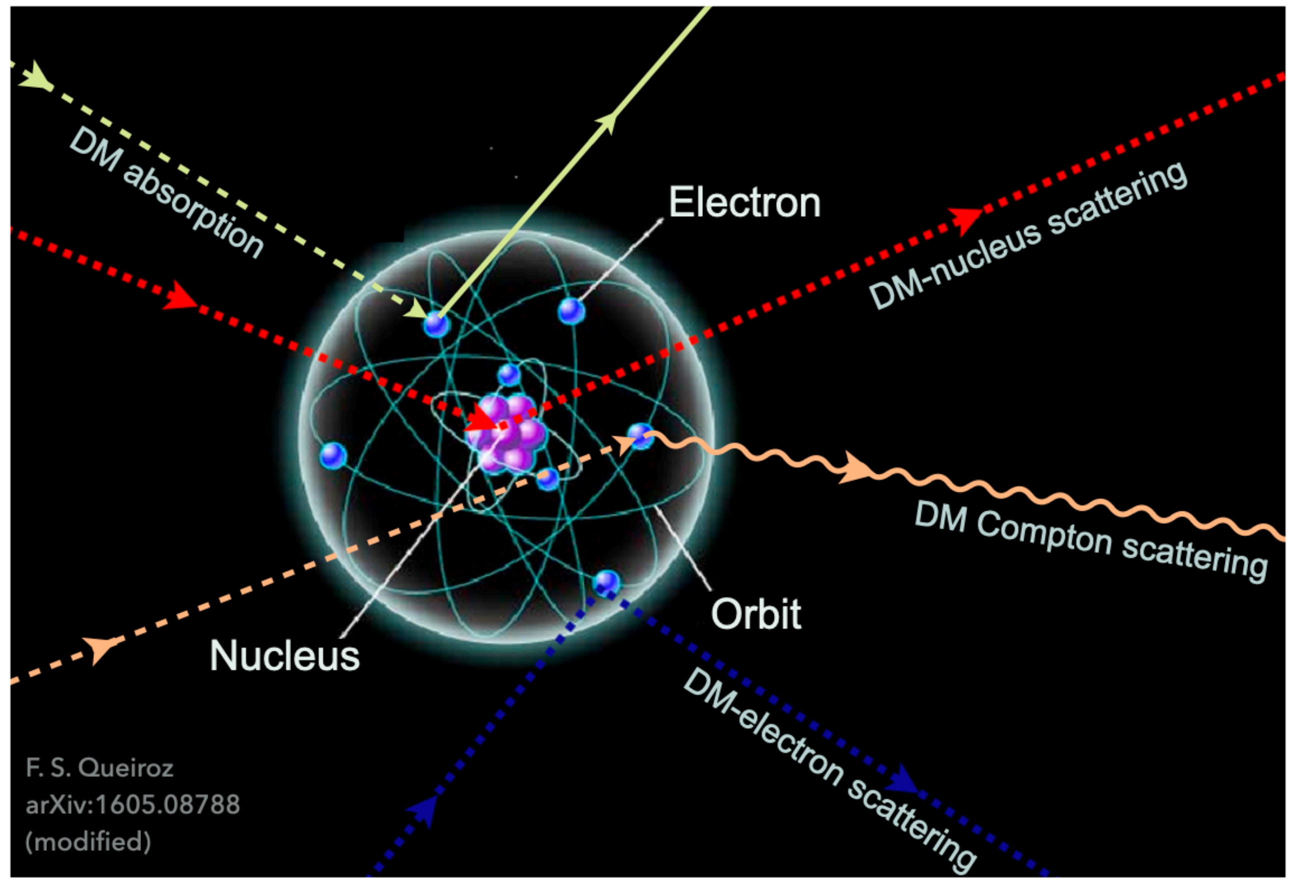

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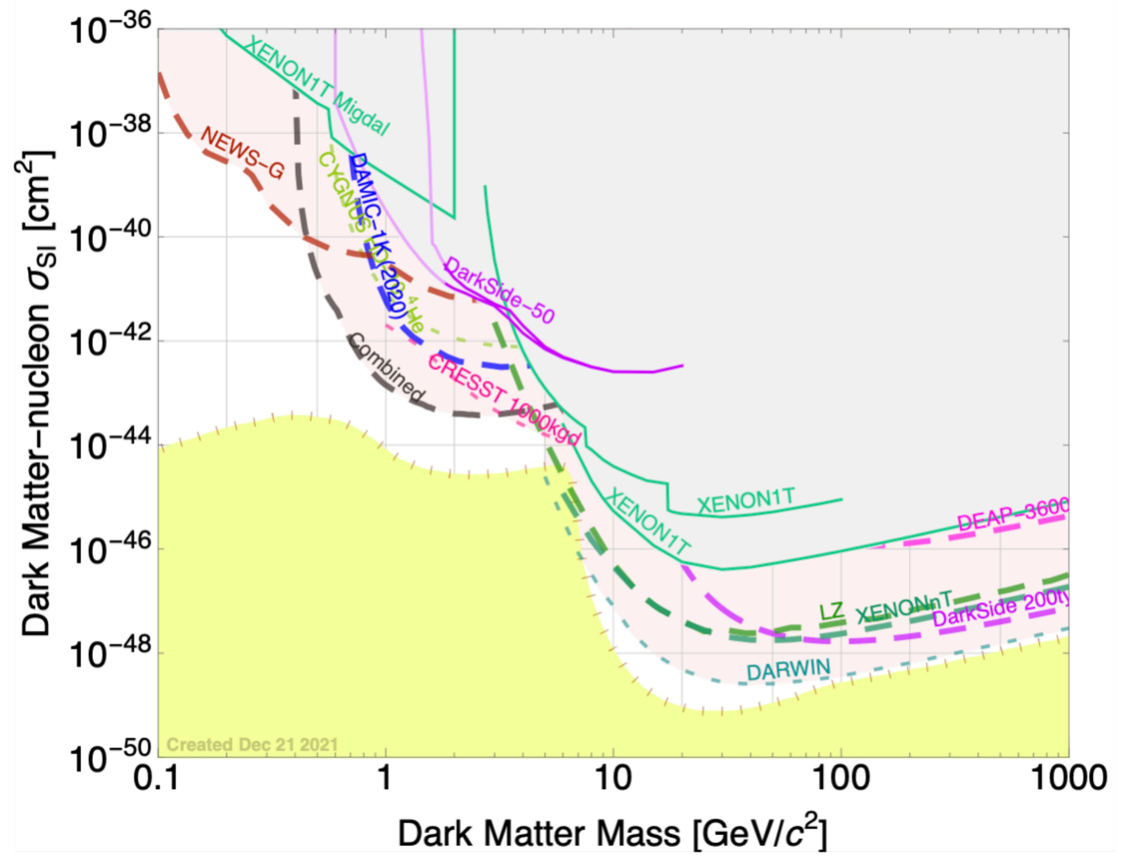

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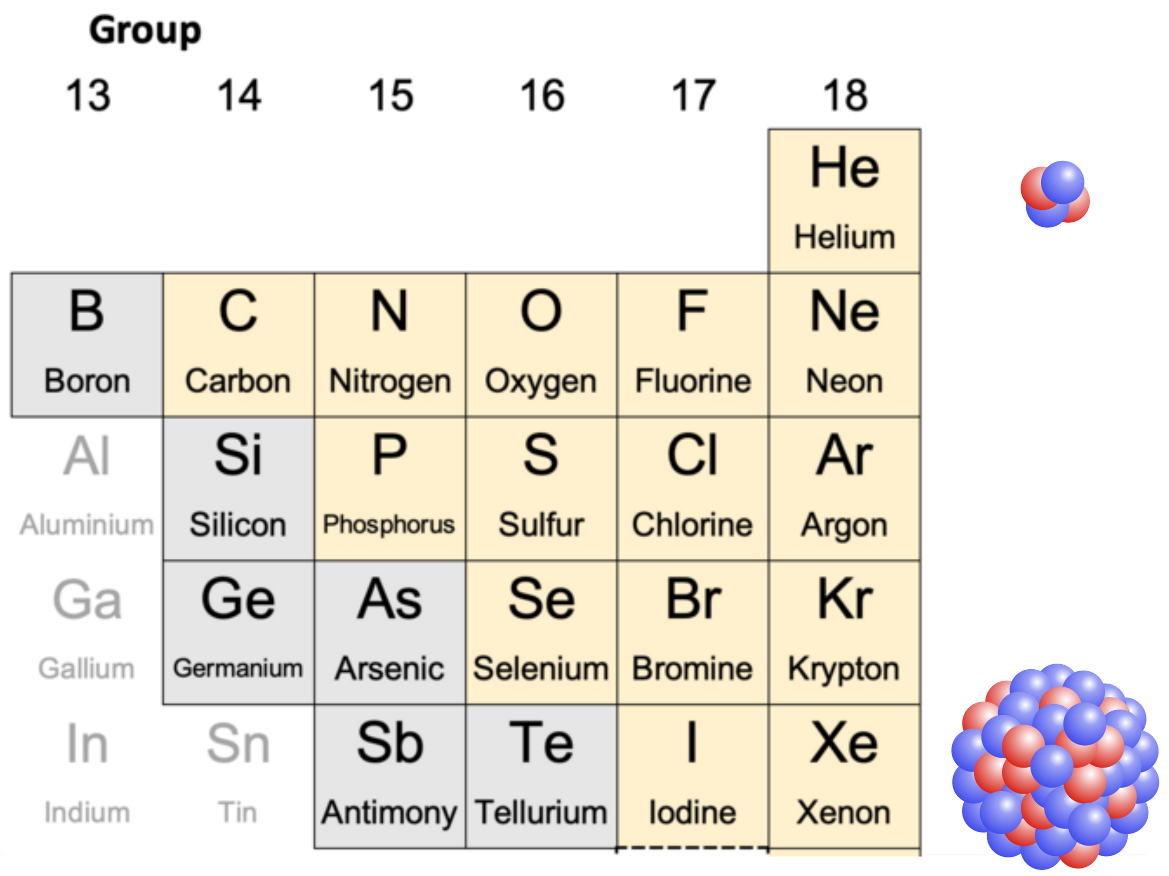
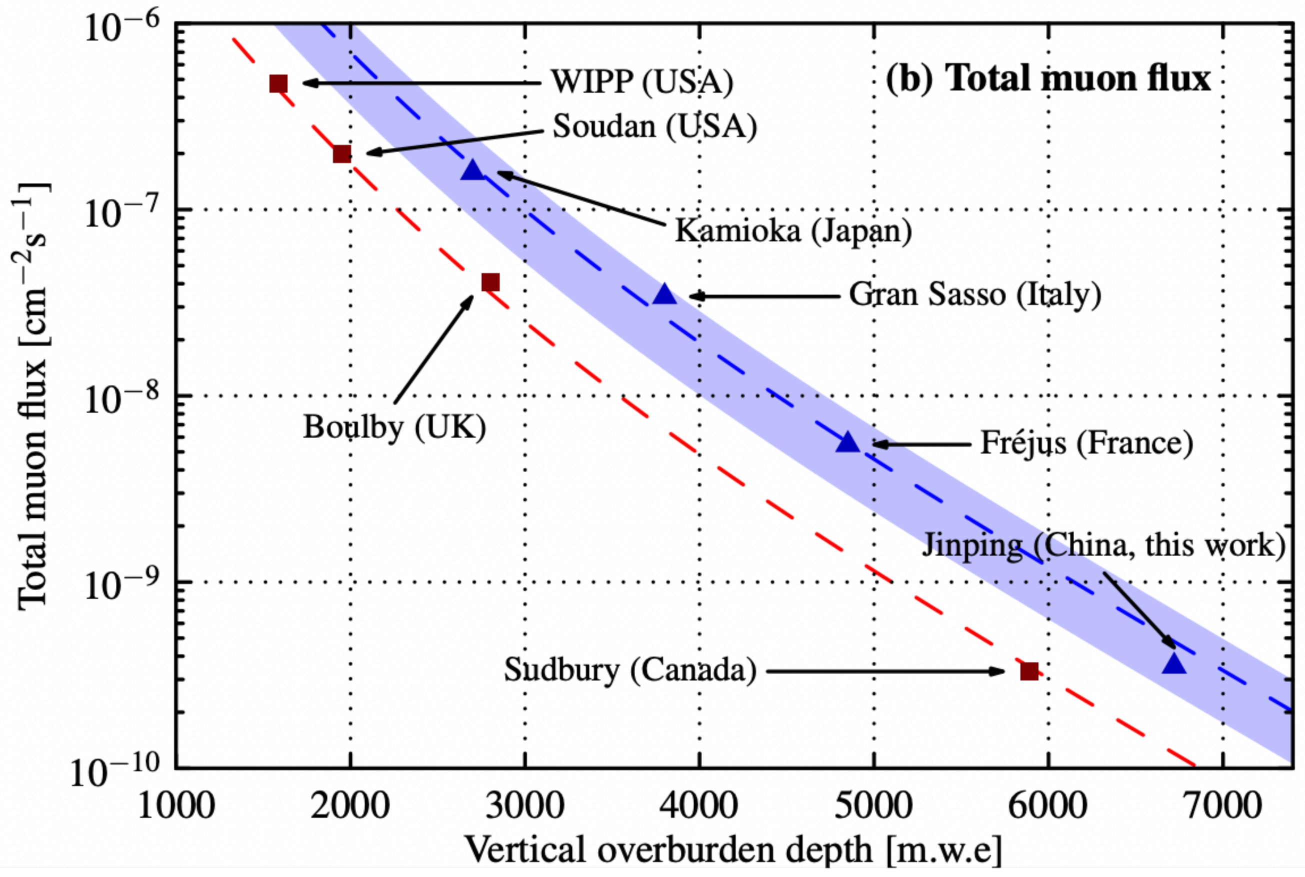


4. pick your underground lab



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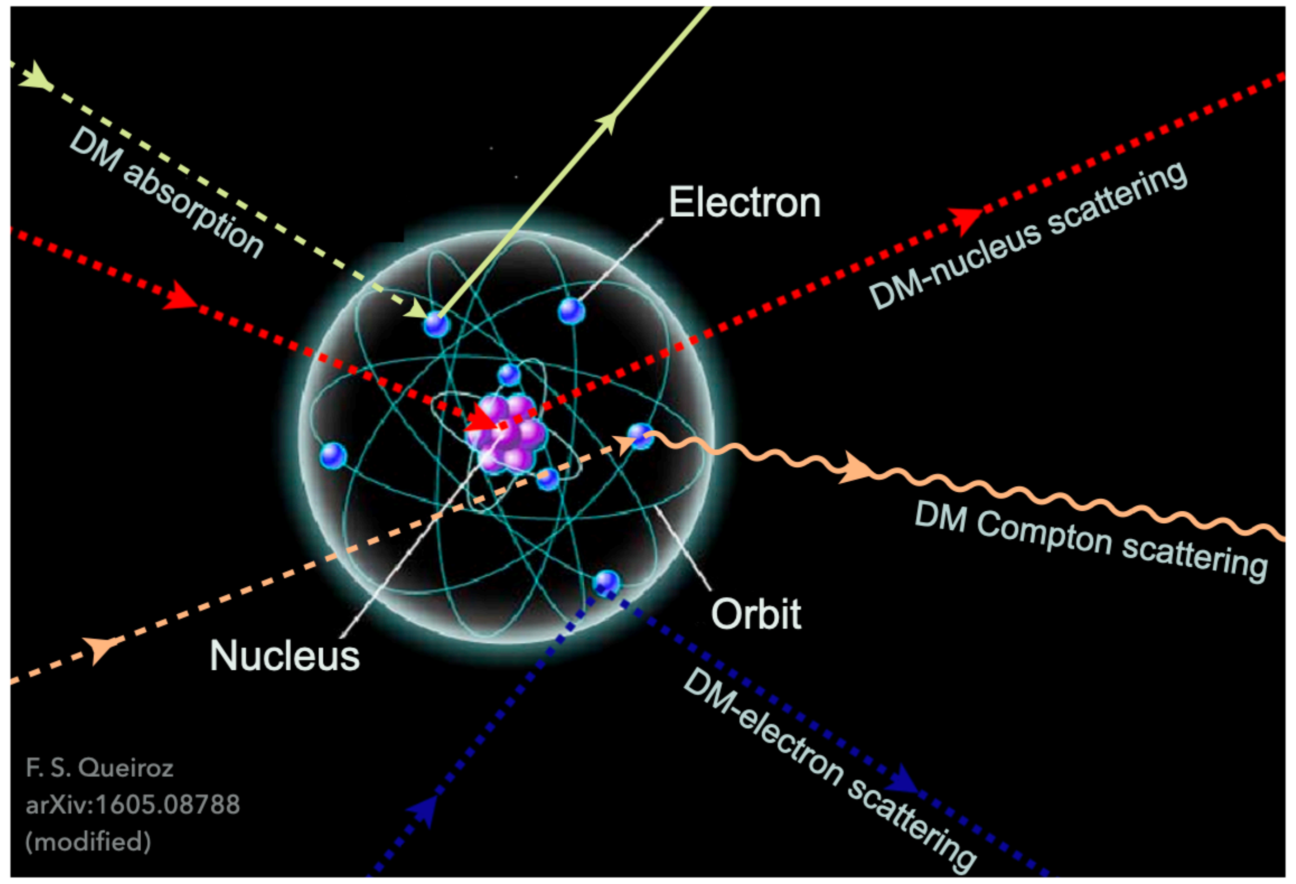

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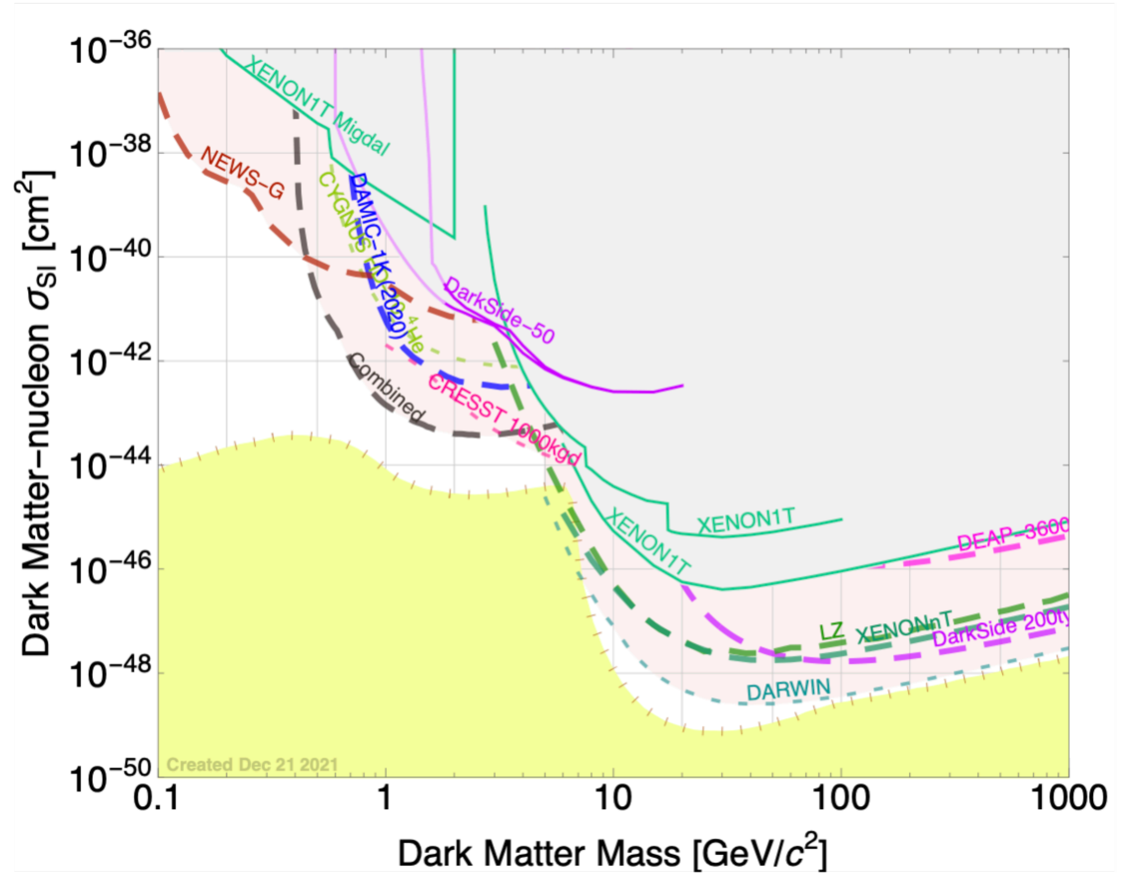

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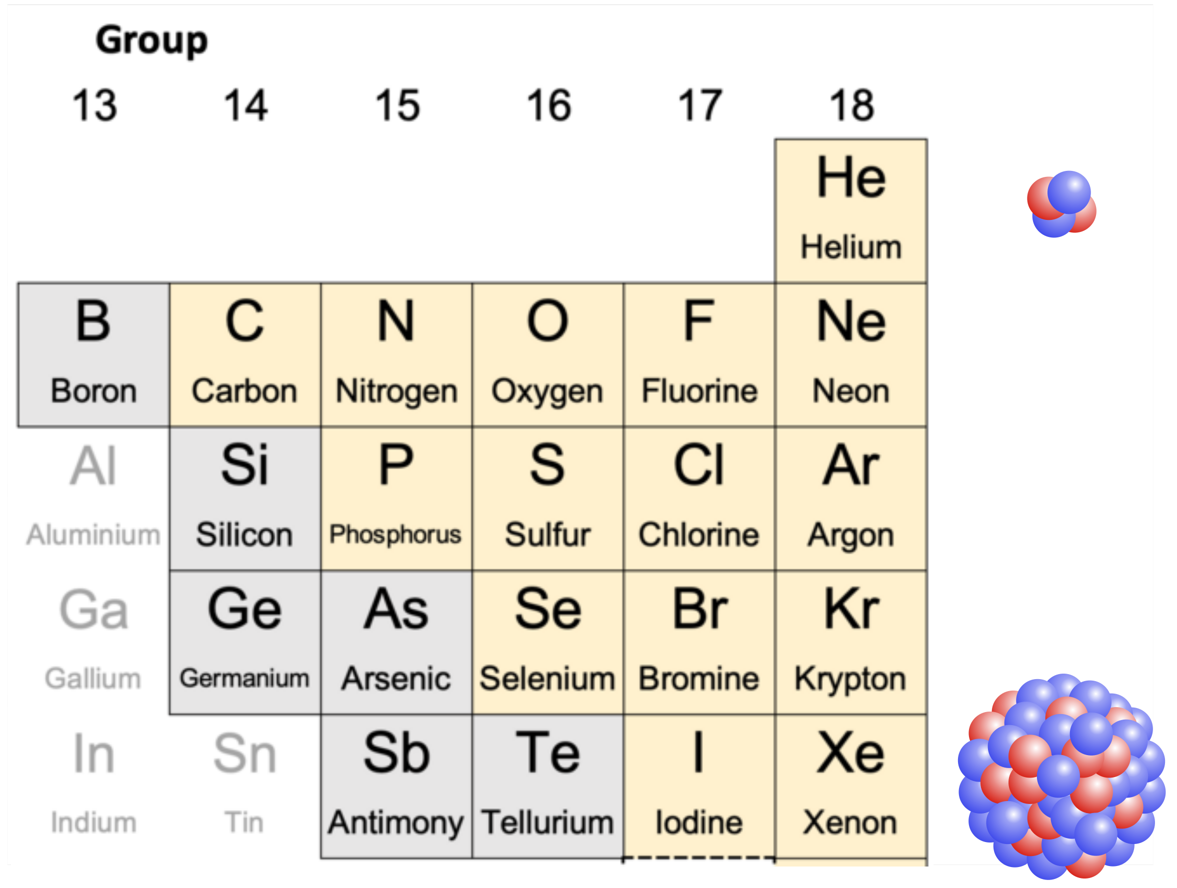

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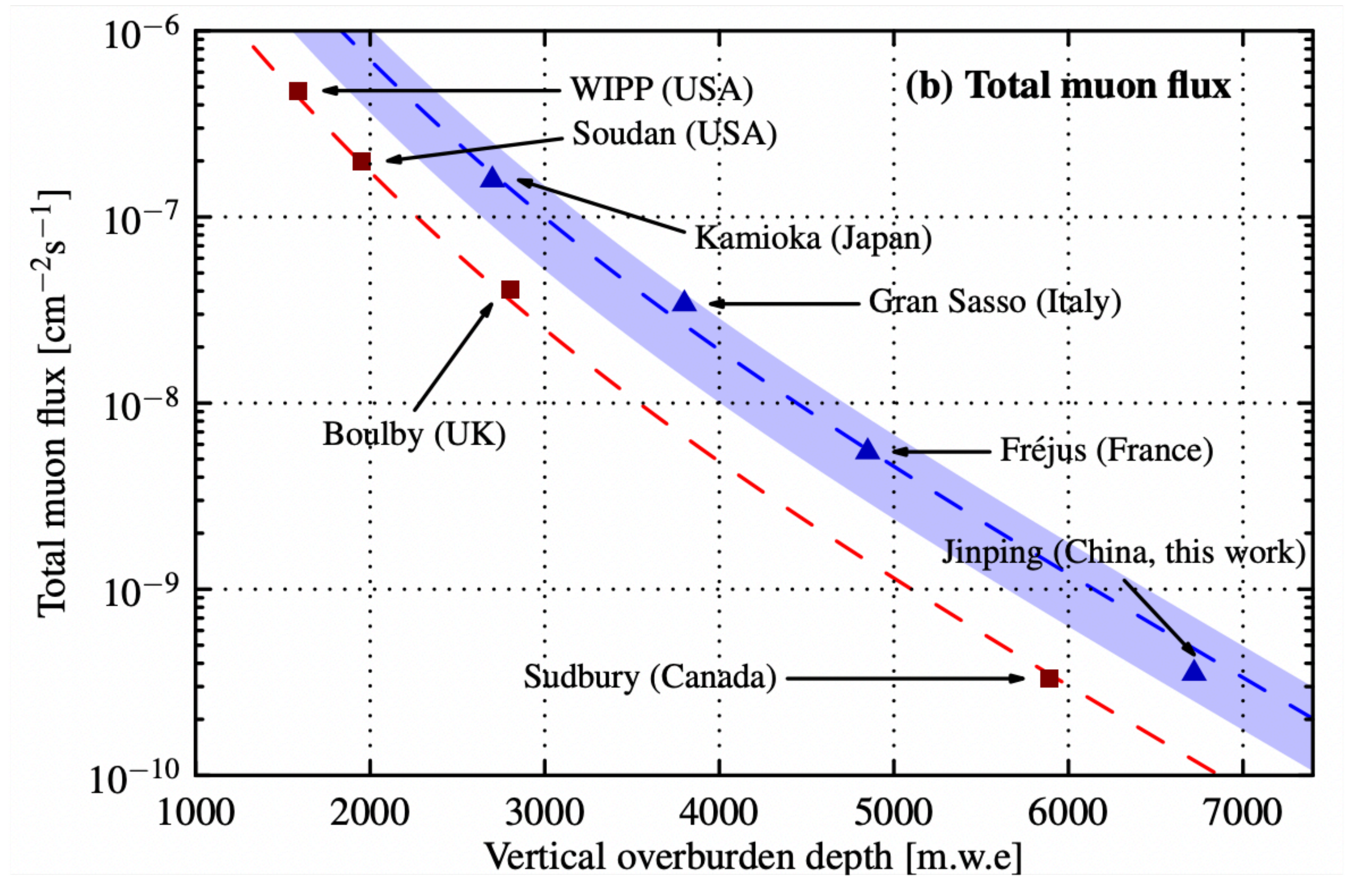
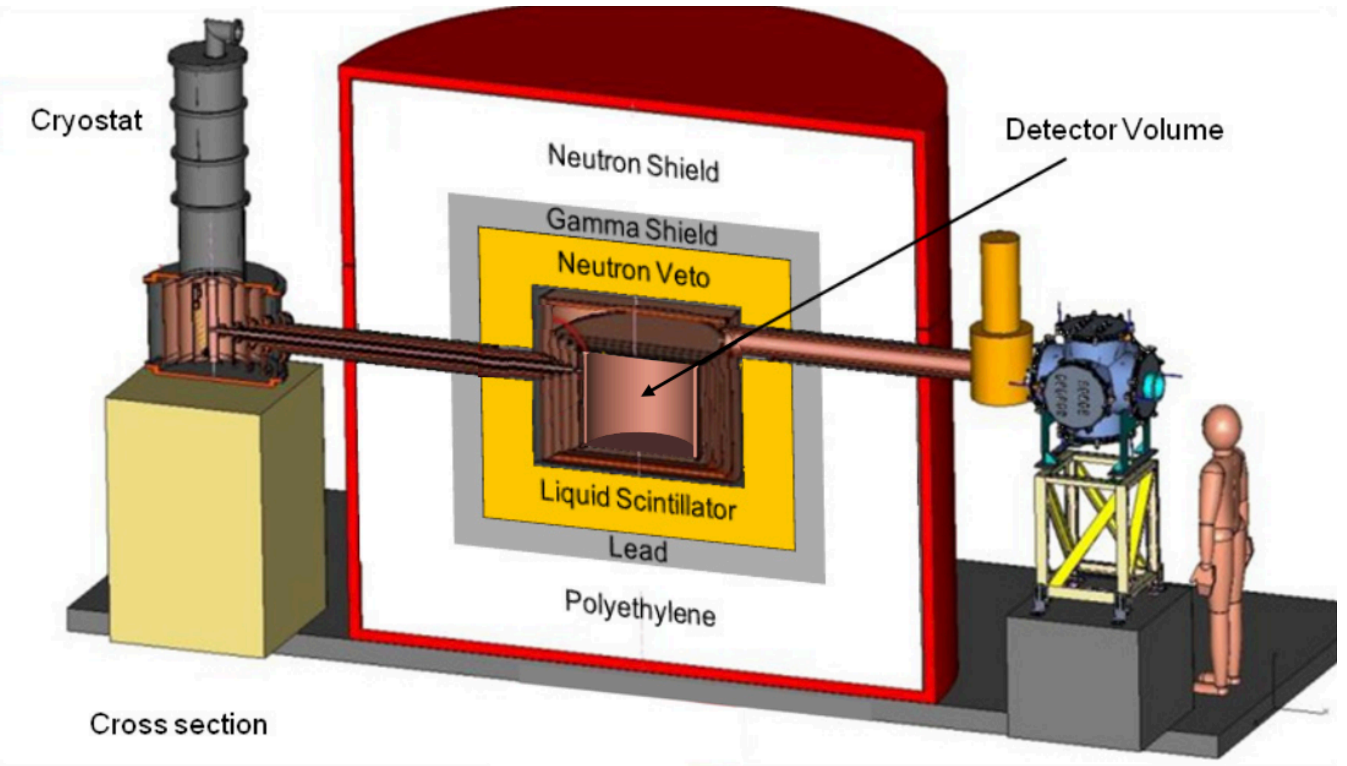


5. design your shielding



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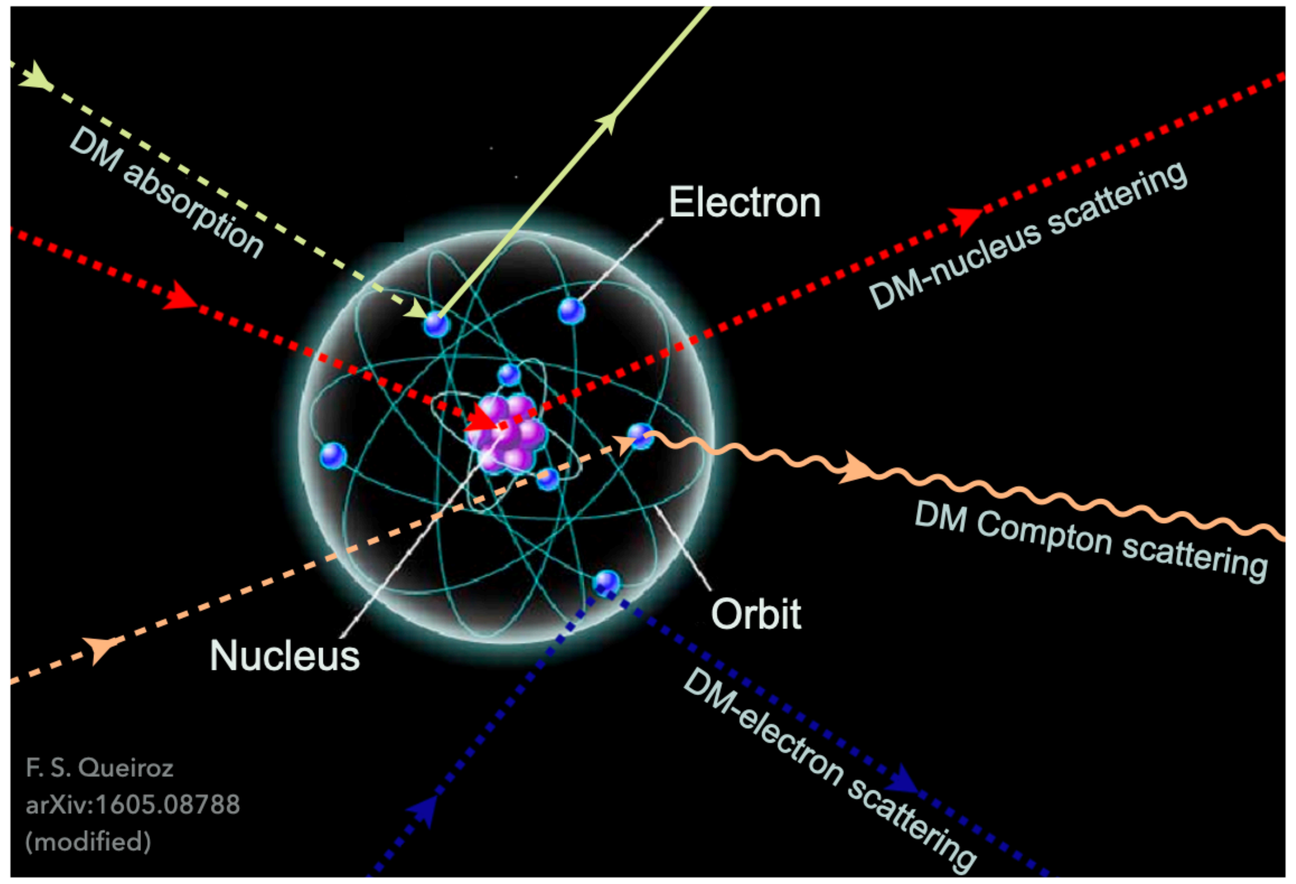

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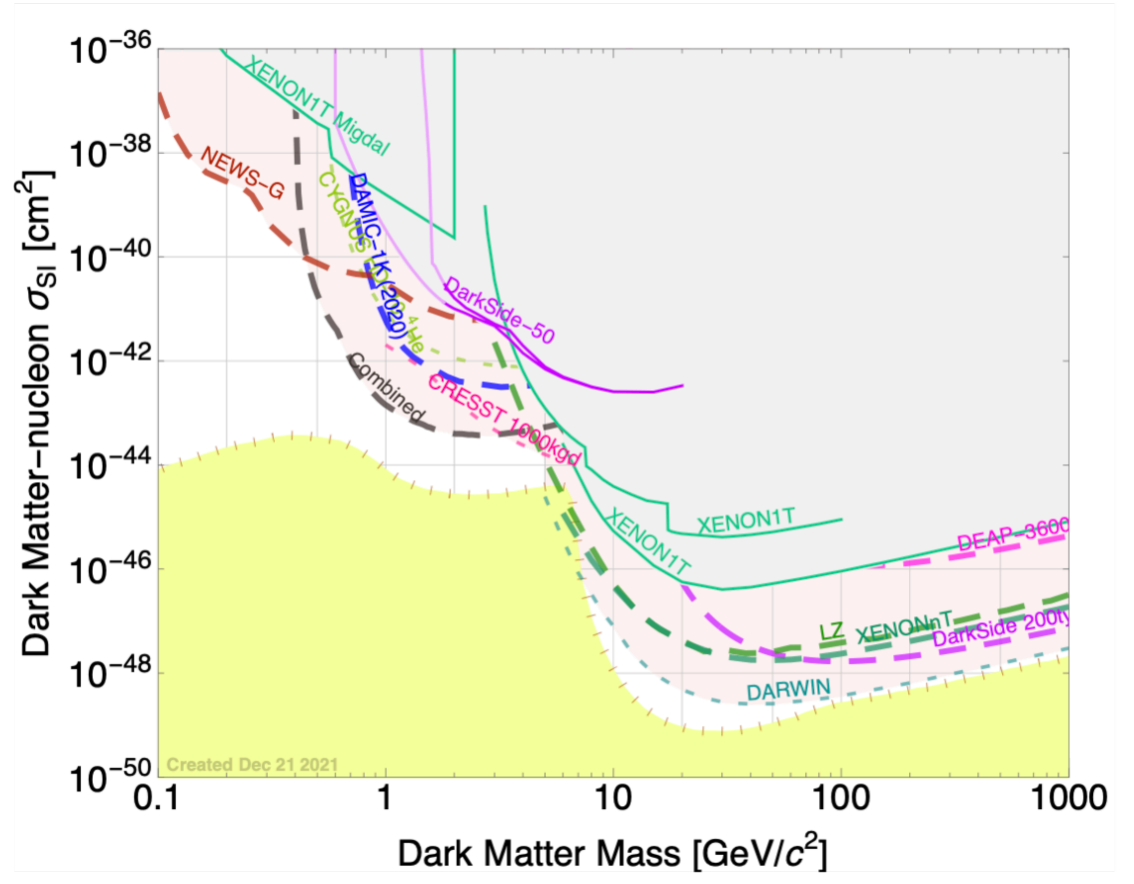

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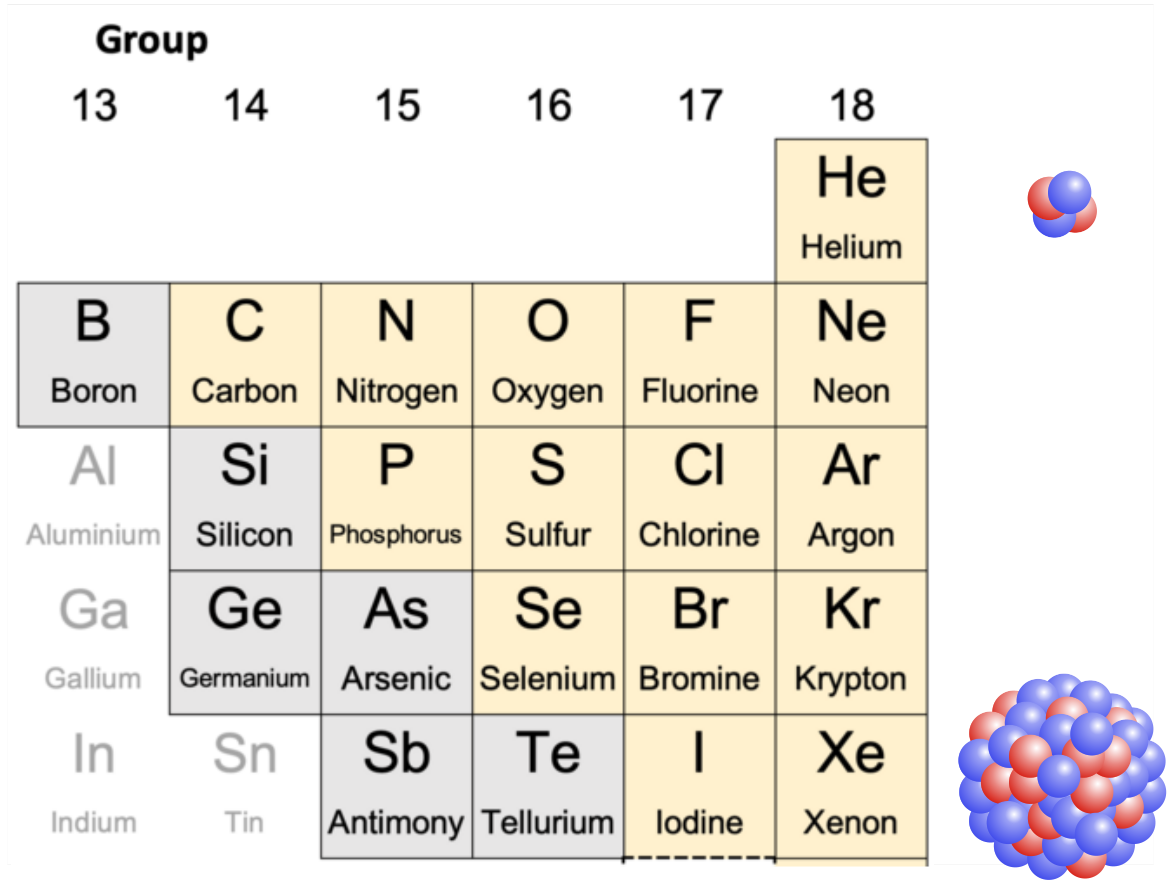

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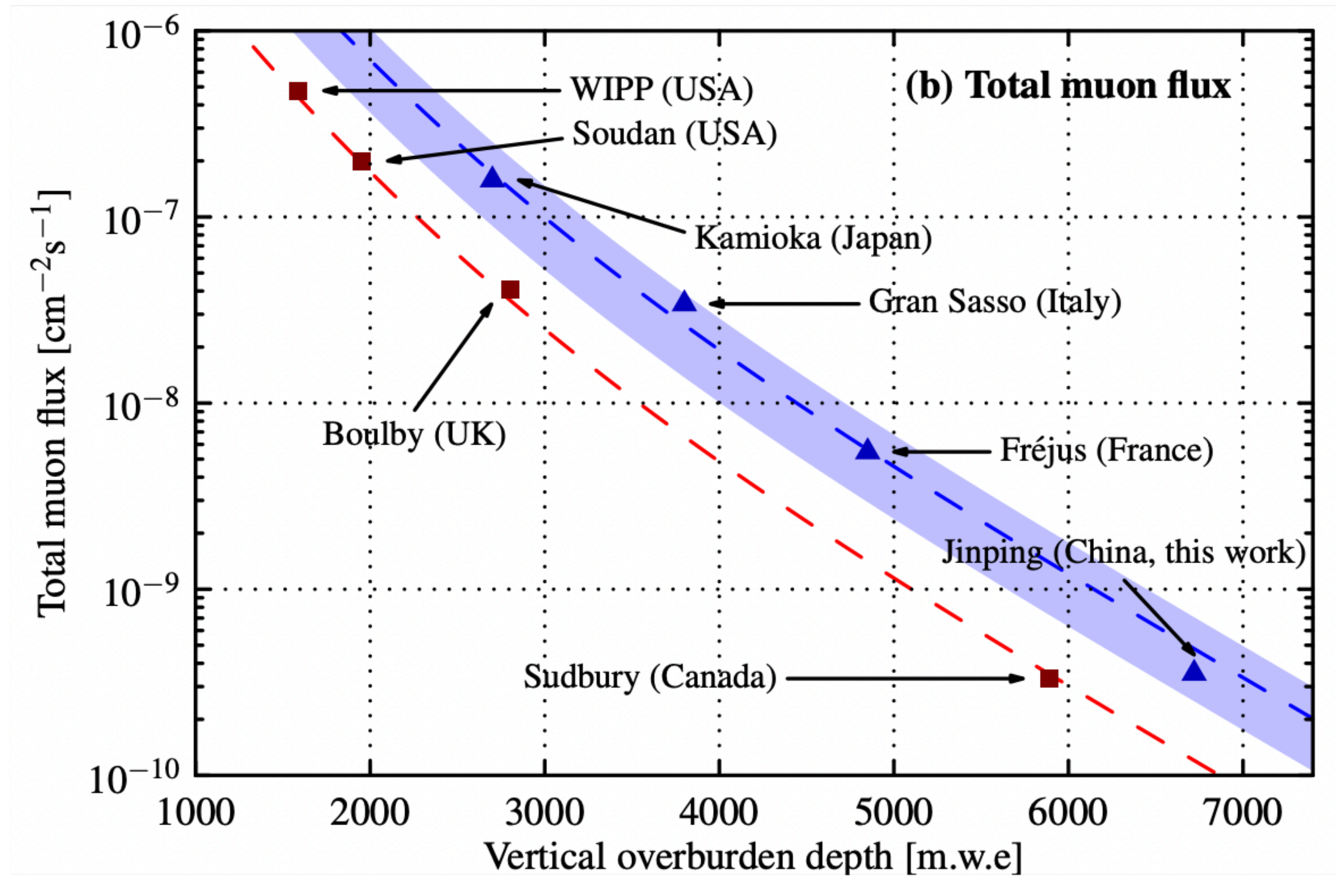

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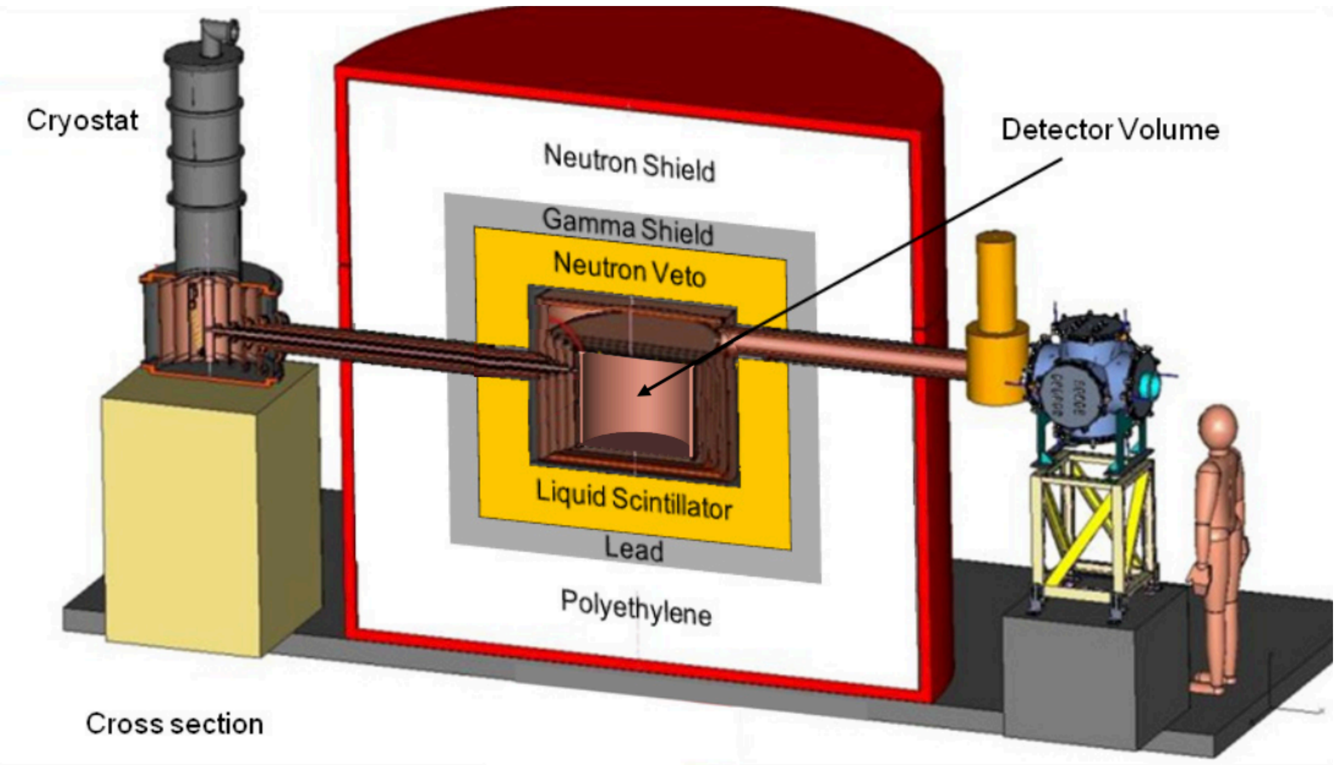

6. select and characterize your material

How to build a dark matter detector

And last but not least…

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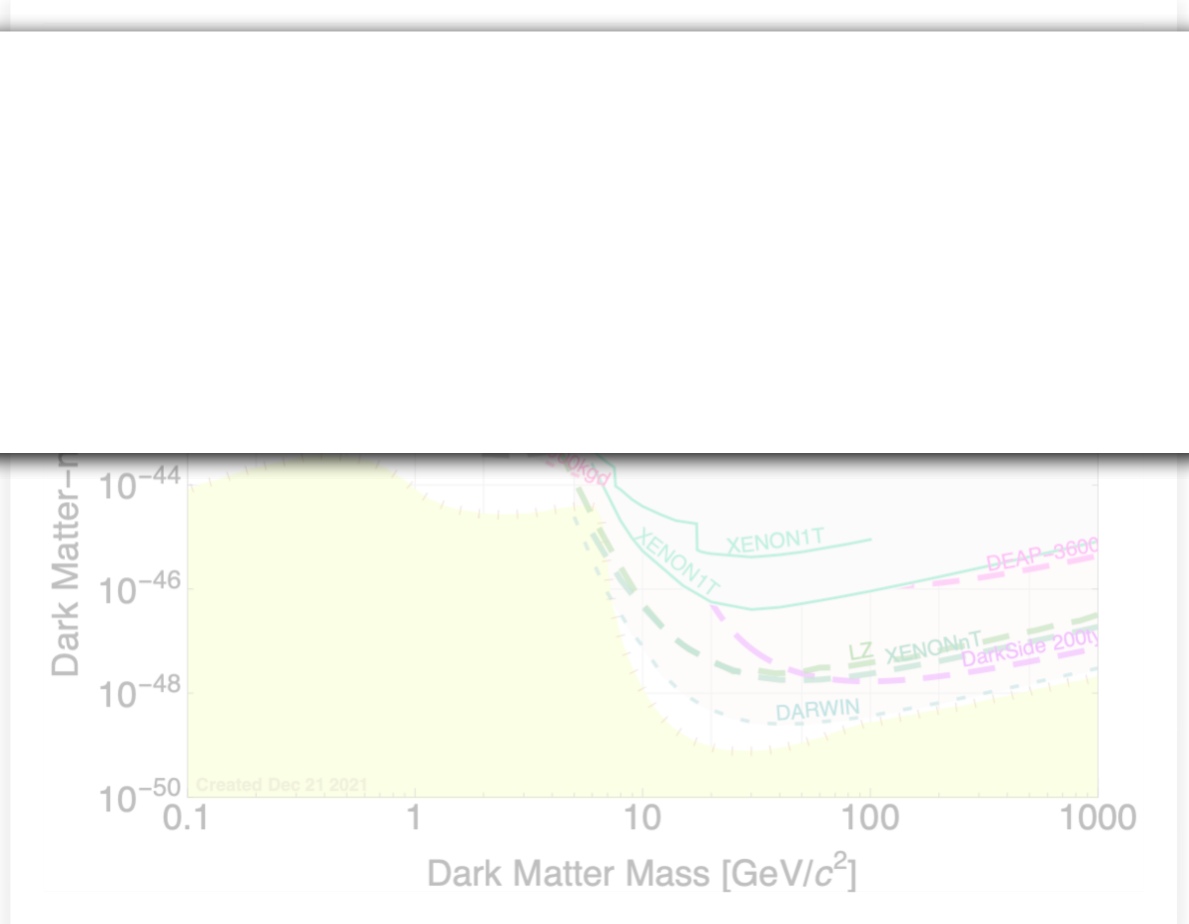
2. pick your parameter space



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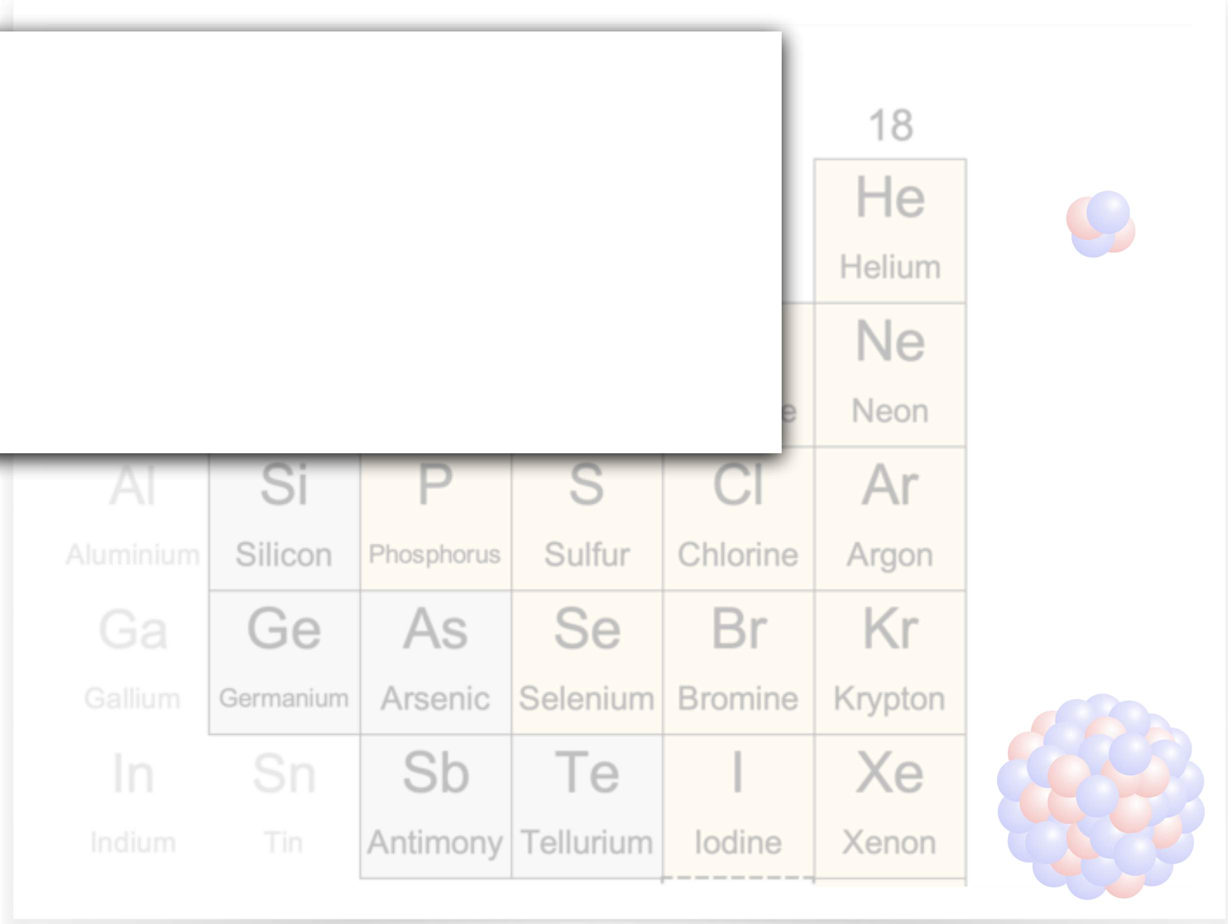

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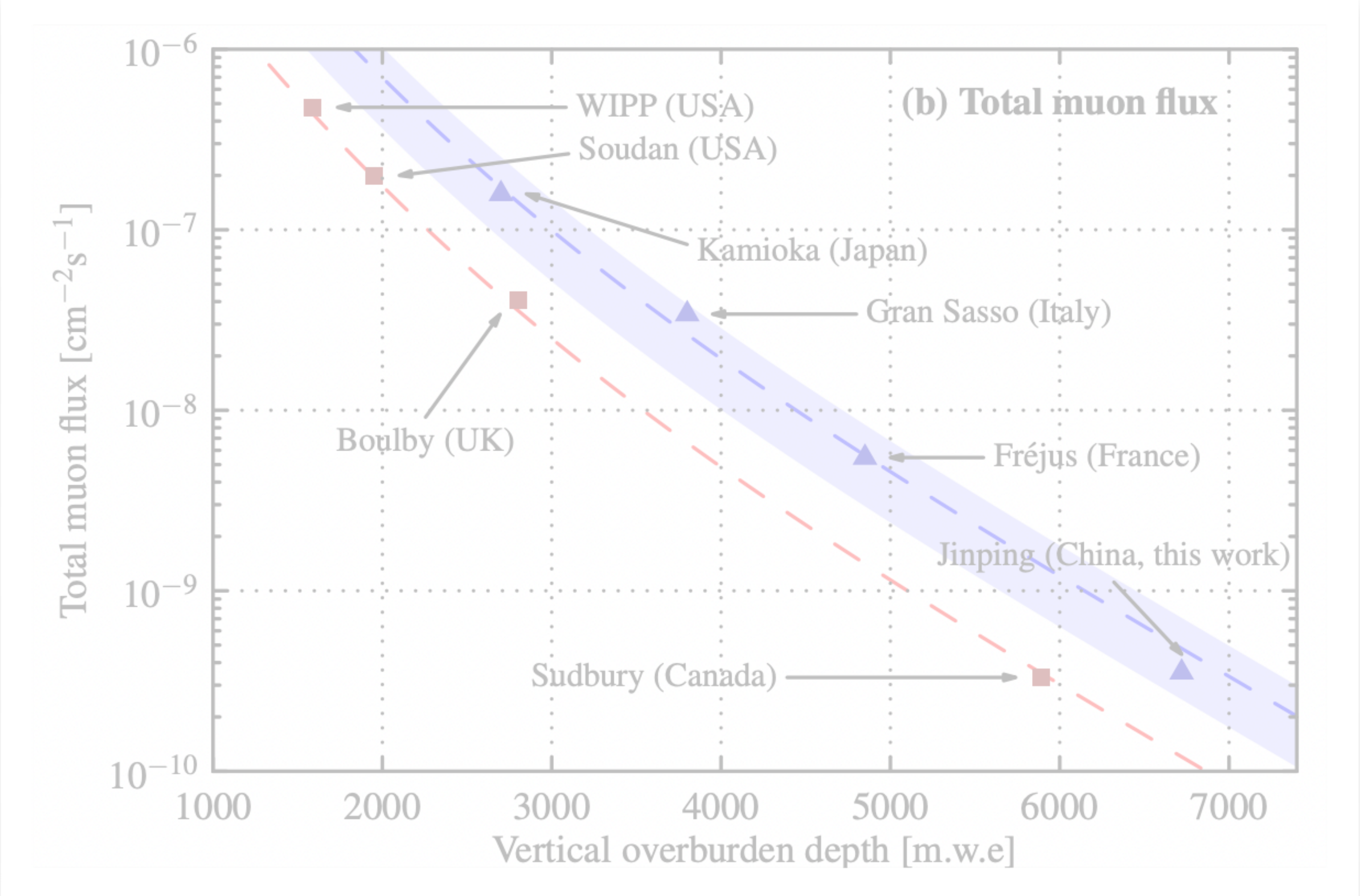

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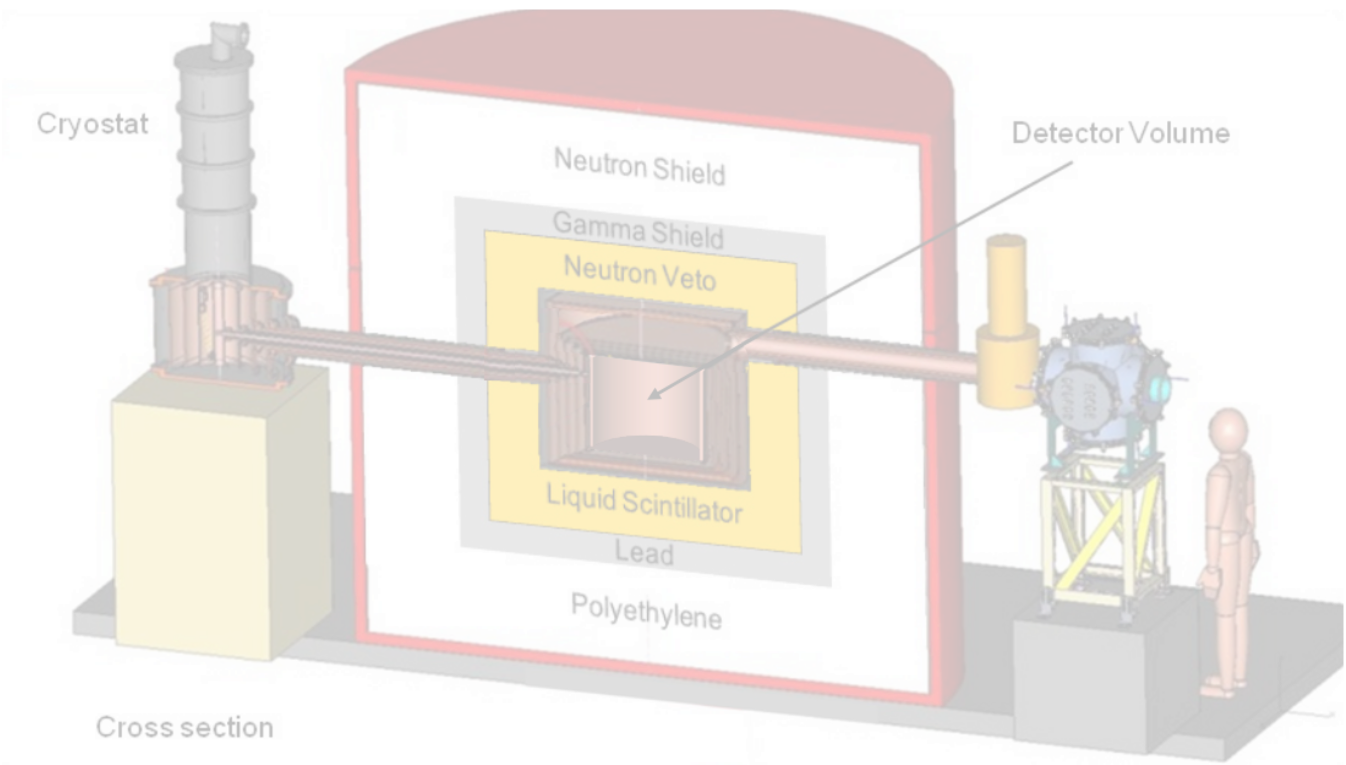

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How to build a dark matter detector

1. pick your interaction

2. pick your parameter space

3. pick your target material

And last but not least…

… pick your team - it's a team effort!

4. pick your undergrou

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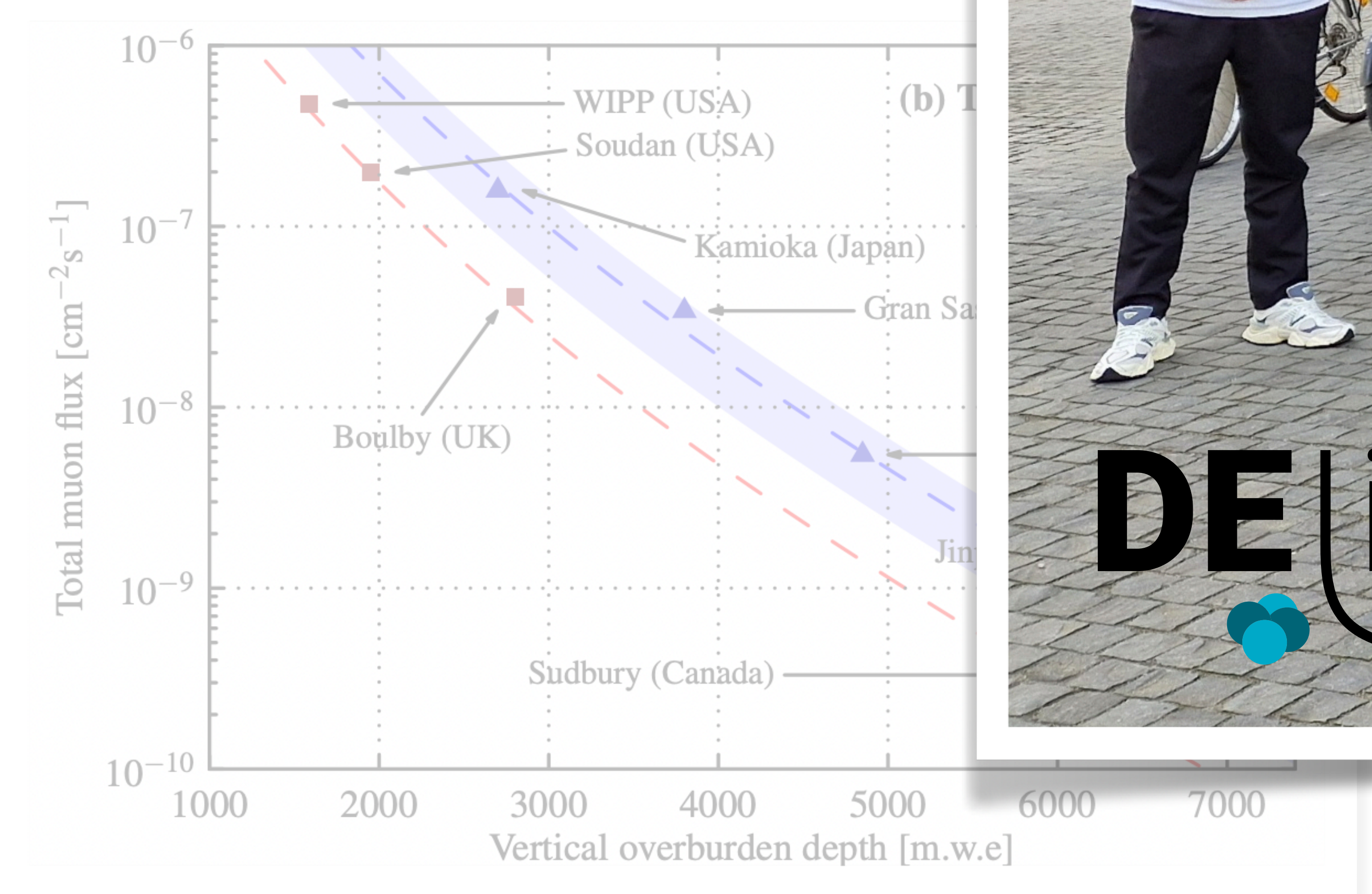

Cross section