Come To The Dark Side

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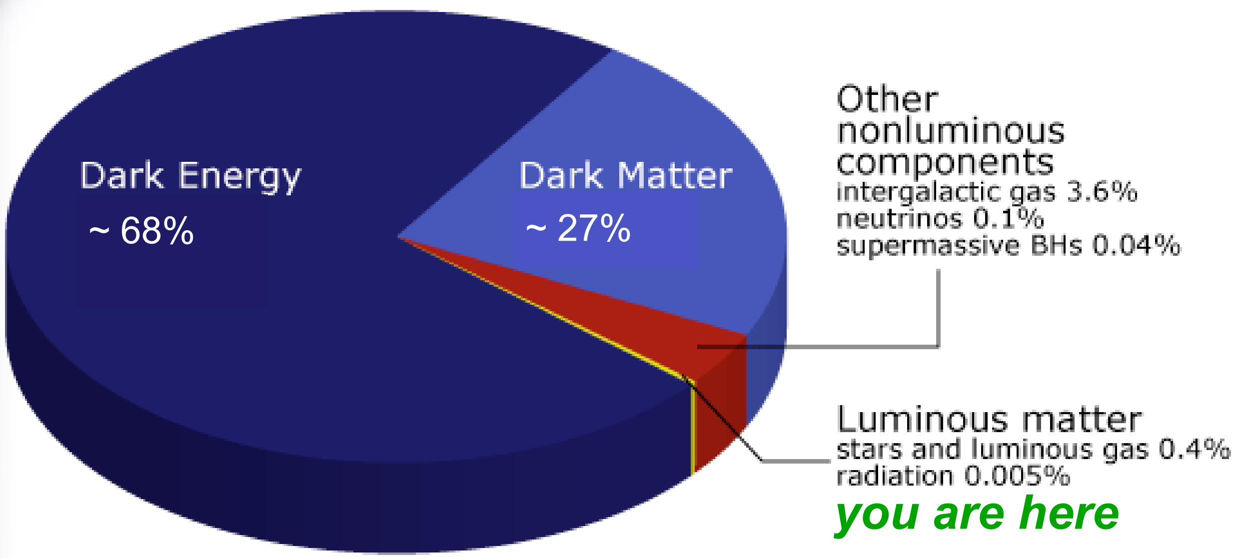
The Dark Matter Question



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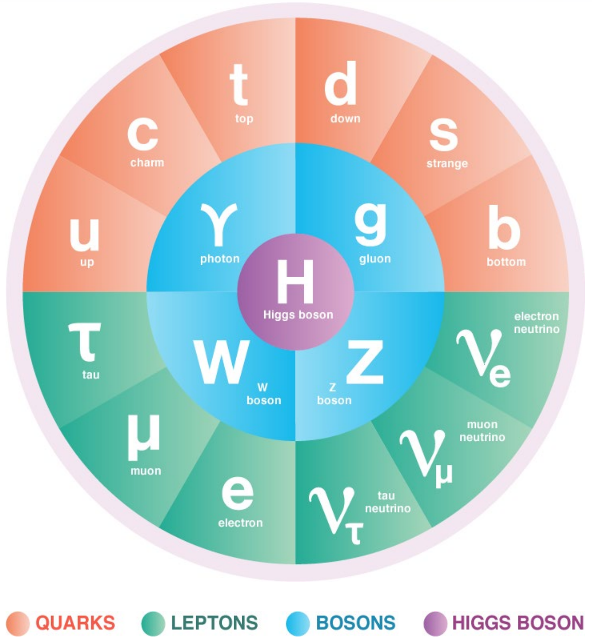

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So far, evidence for existence of DM comes from astrophysics

How to look for it in particle physics experiments?

Dark Outline

- **Review: DM Candidates**
- **Detection Strategies**
- **Direct: Current & Next-Gen Experiments**
  - **Recent Results**
  - **Backgrounds: “reducible” & ν fog**
  - **That weird DAMA thing**

DM Candidates

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Targeting "Beyond the Standard Model" Searches

DM searches → looking for BSM particle(s) with the following properties:

- Cold (non-relativistic)
- Stable on cosmological timescales
- Gravitationally interacting
- Feeble, if any, non-gravitational self-interactions
- Feeble, if any, non-gravitational interactions with luminous matter

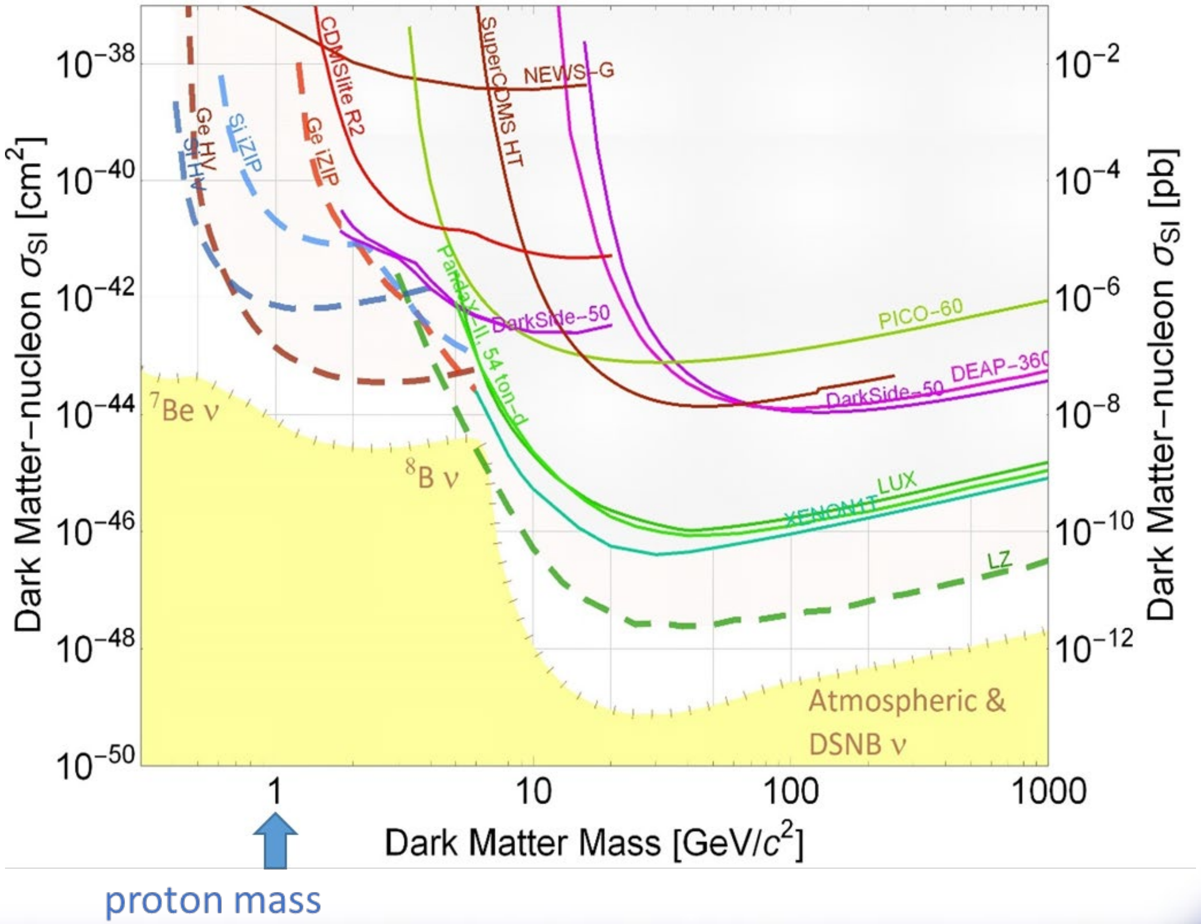
What mass scale?
What interactions with SM?
Are there "dark forces"?
How many new particle species?

WIMPing out?

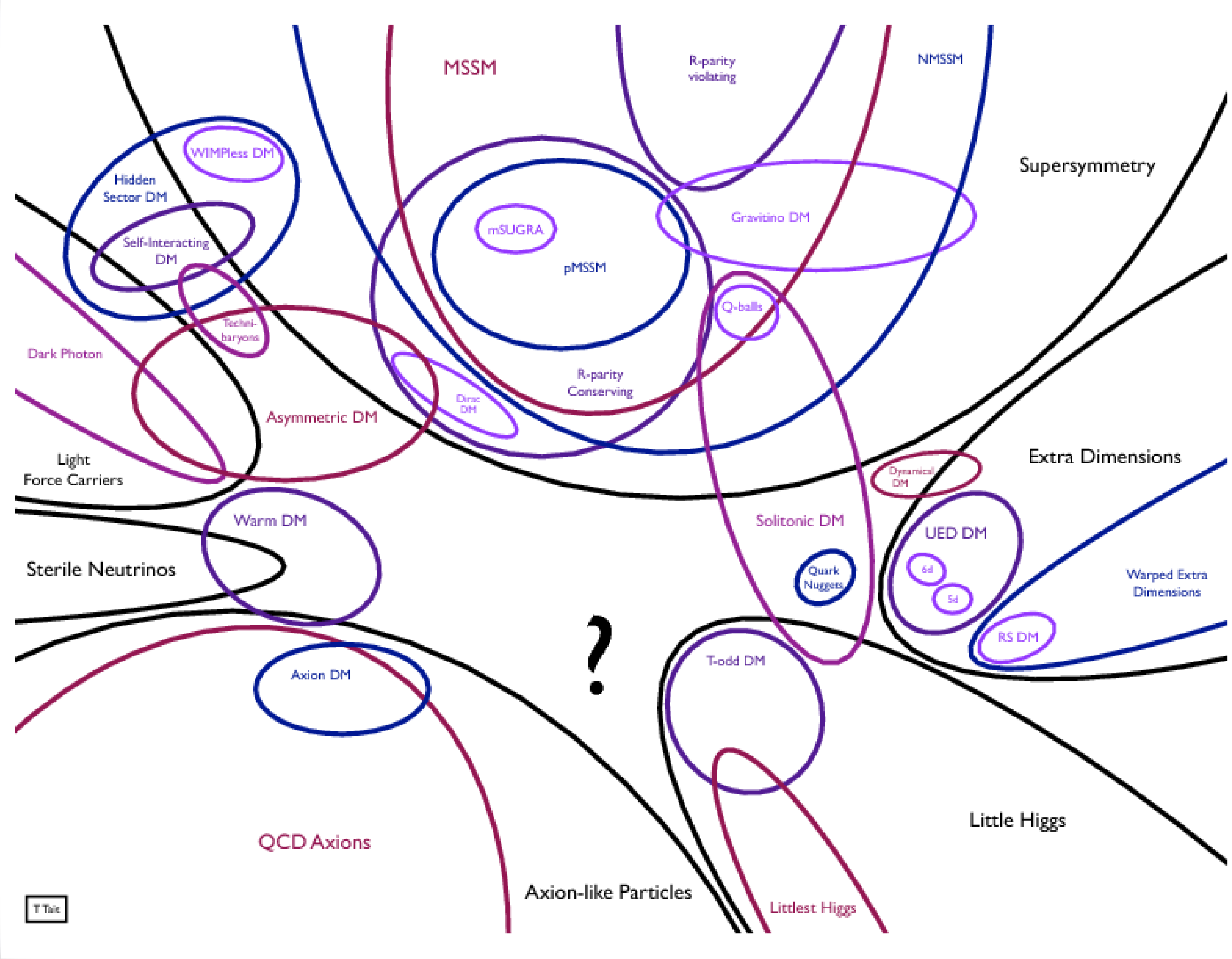
"Weakly Interacting Massive Particles" (WIMP) candidates:

- *Supersymmetric partners*
- *Additional Higgs bosons*
- *"Mirror universe" / "Hidden Valley" particles*
- *Kaluza-Klein particles*
- *Sterile neutrinos*
- *… etc*

But… searches *where we most expected to find WIMPs* haven't found them!



Particle Zoo!



"Zoo" of possibilities

Non-WIMP candidates

- FIMPs (Feebly Interacting), WIMPzillas (> 1000 TeV), SIMPs (Self-Interacting), ELDERs (Elastically Decoupling Relics), …
- Low-mass dark photons (sub-GeV)
- Lightly-ionizing / millicharged particles (sub-GeV)
- Axion-like particles (sub-eV)
- Massive gravitons
- Particles with only gravitational interactions and/or self-interactions
- MACHOs (Massive Compact Halo Objects), e.g. primordial black holes
- Modified [quantum / super-] gravity

Search Strategies

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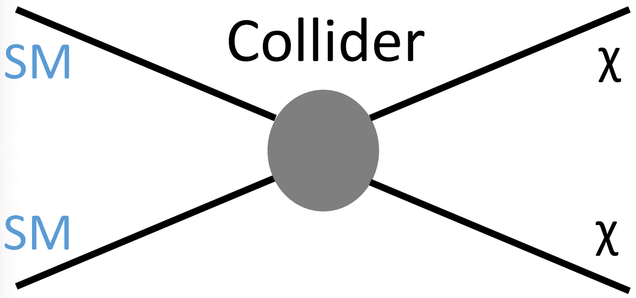
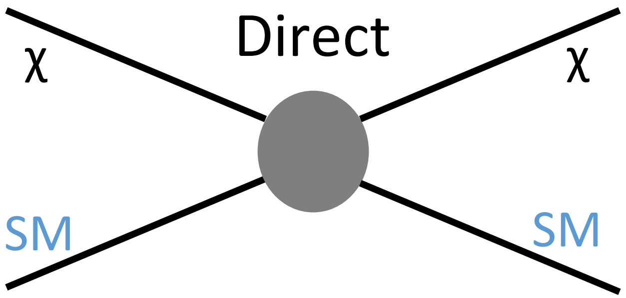
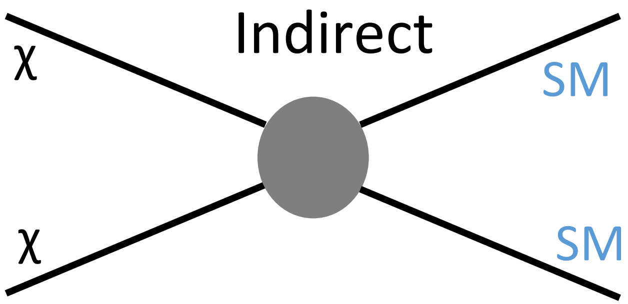
Search Strategies

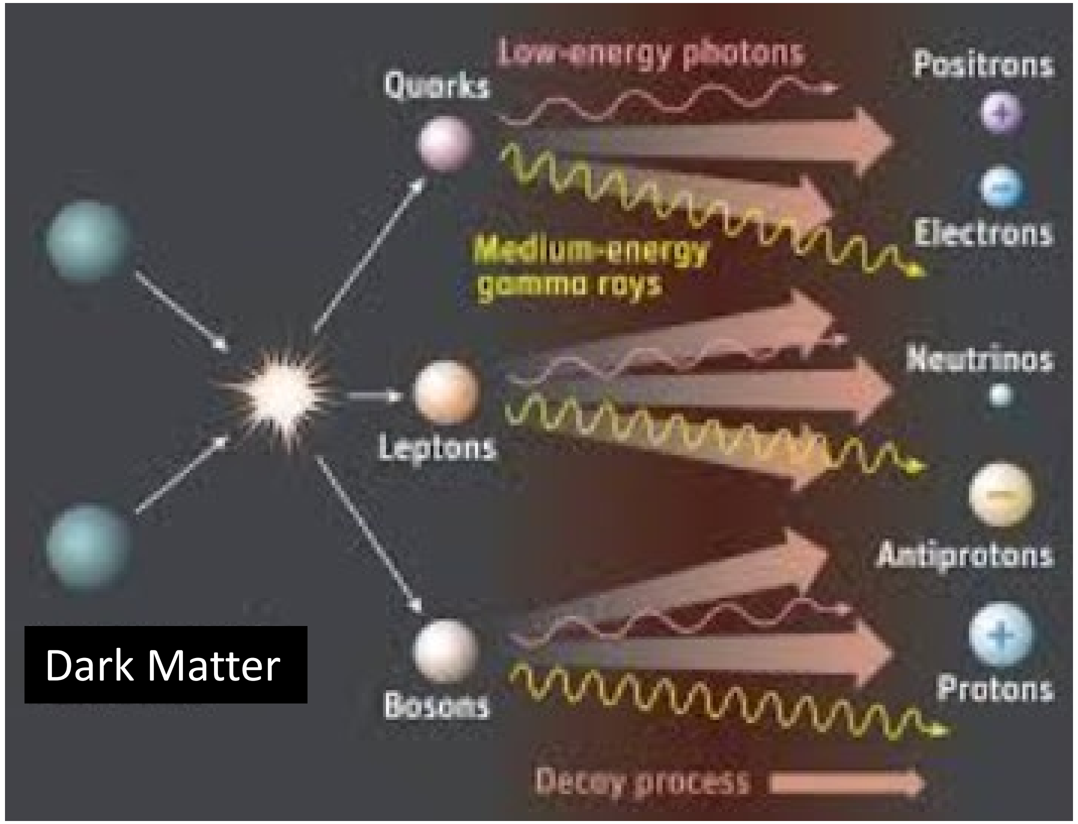
Complementarity between different types of experiments





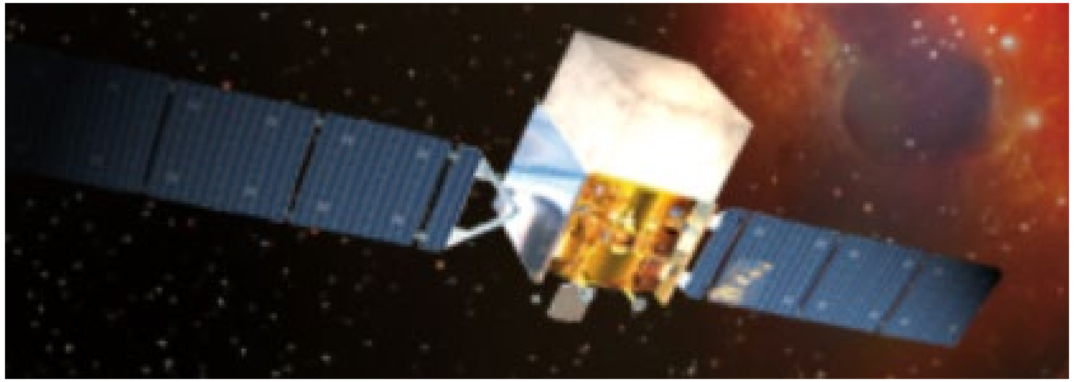


Indirect Detection

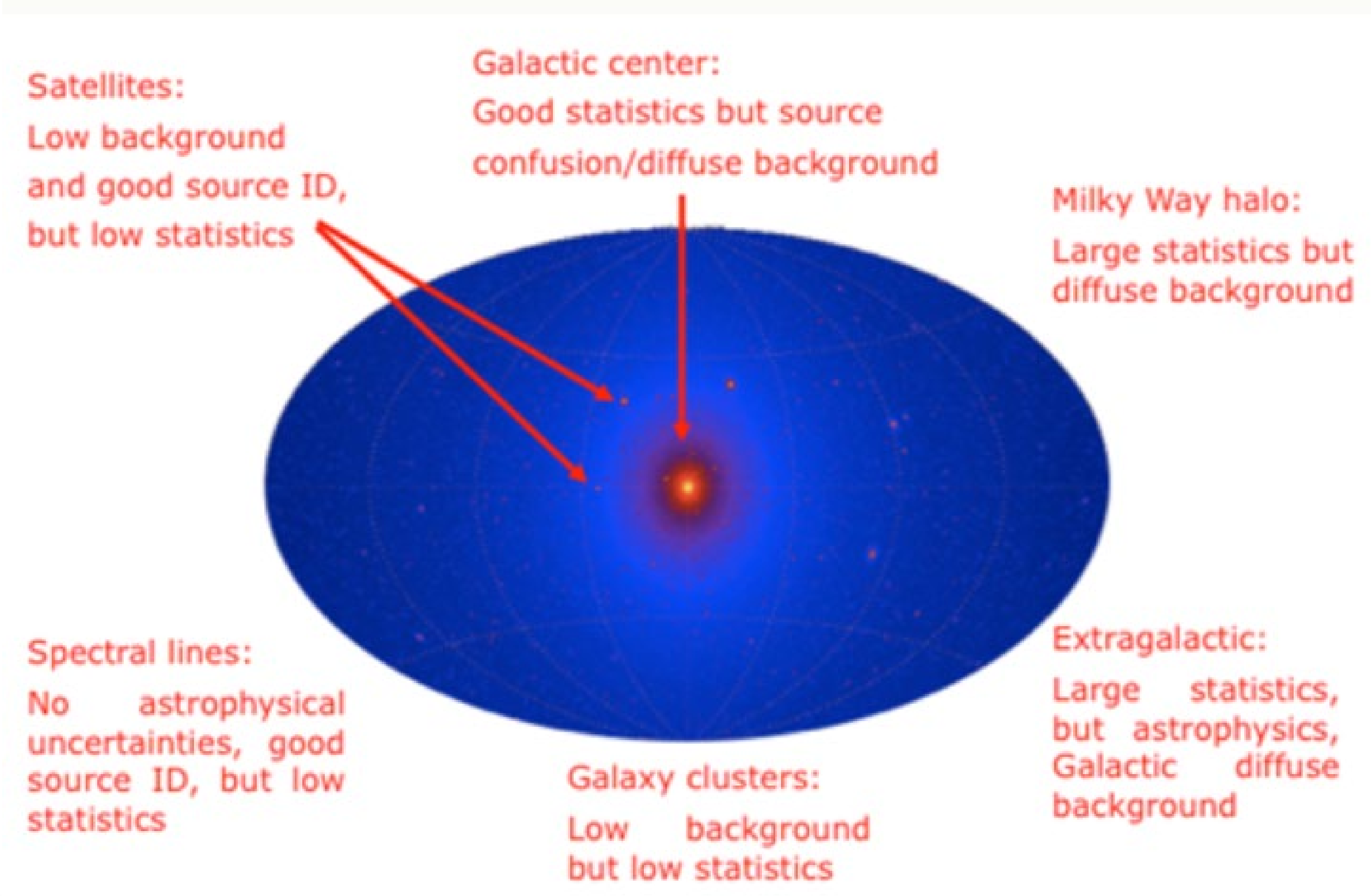


Collisions of WIMPs in outer space could produce SM particles that travel to Earth

"Signals" (e.g. excess photons of a certain frequency) detected by ground- or space-based telescopes



Indirect Detection

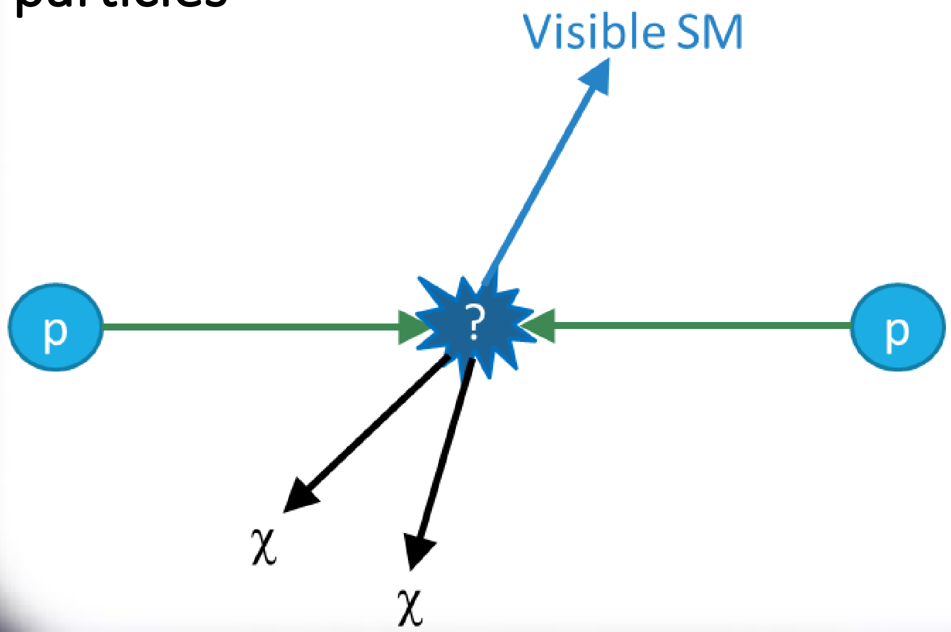


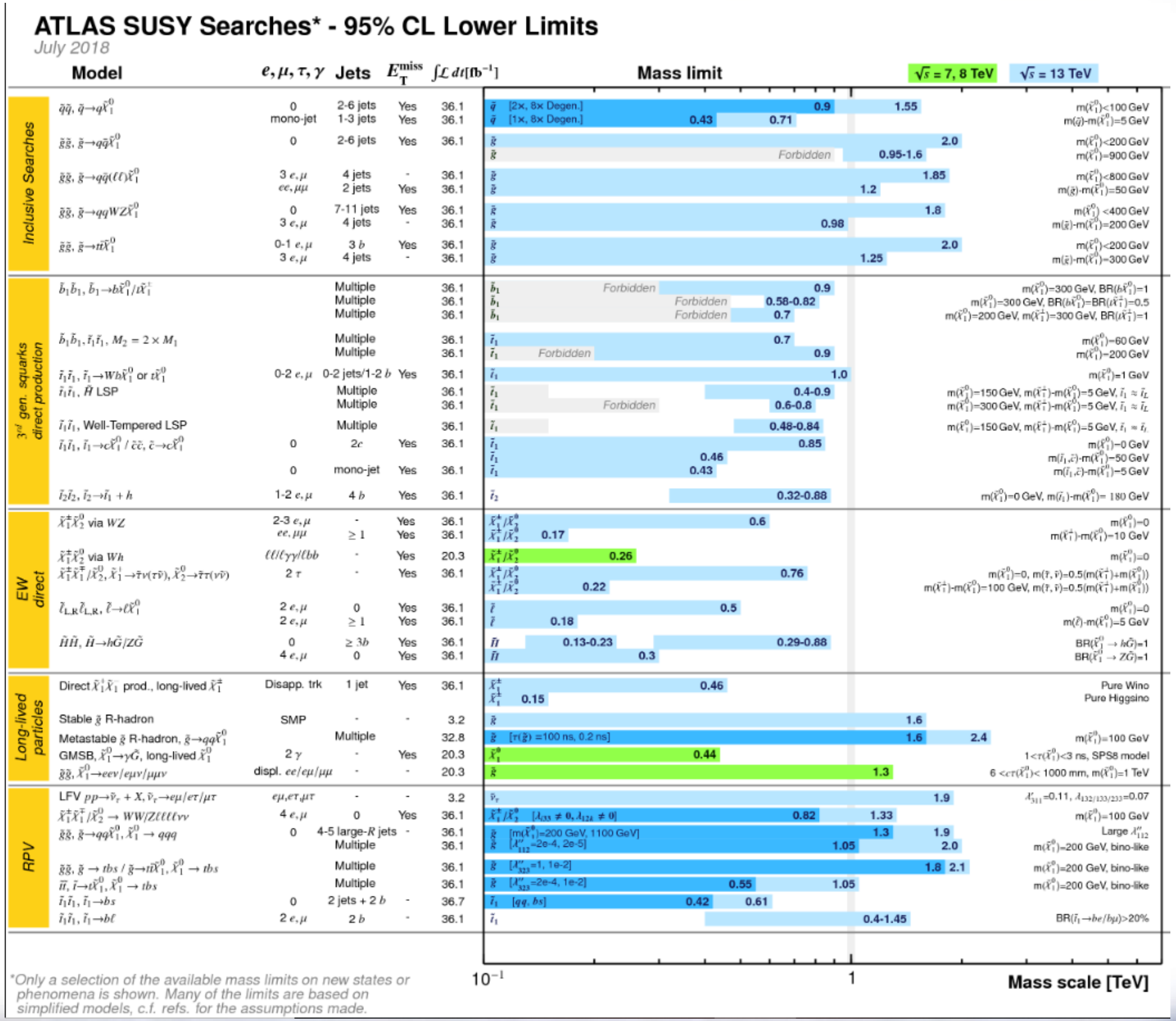
Expect some cosmic neighborhoods to have more DM than others

But some also give off more backgrounds

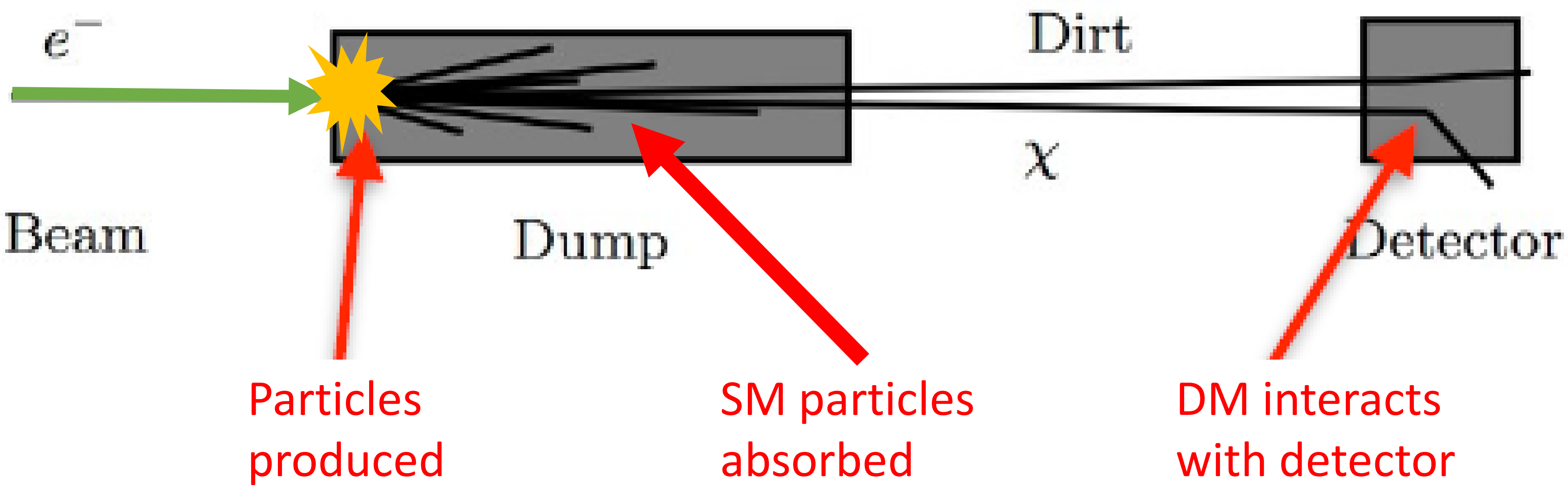
Collider Searches

- Most recent at Large Hadron Collider
- Often look for "missing transverse energy" carried off by DM produced in association with visible SM particles





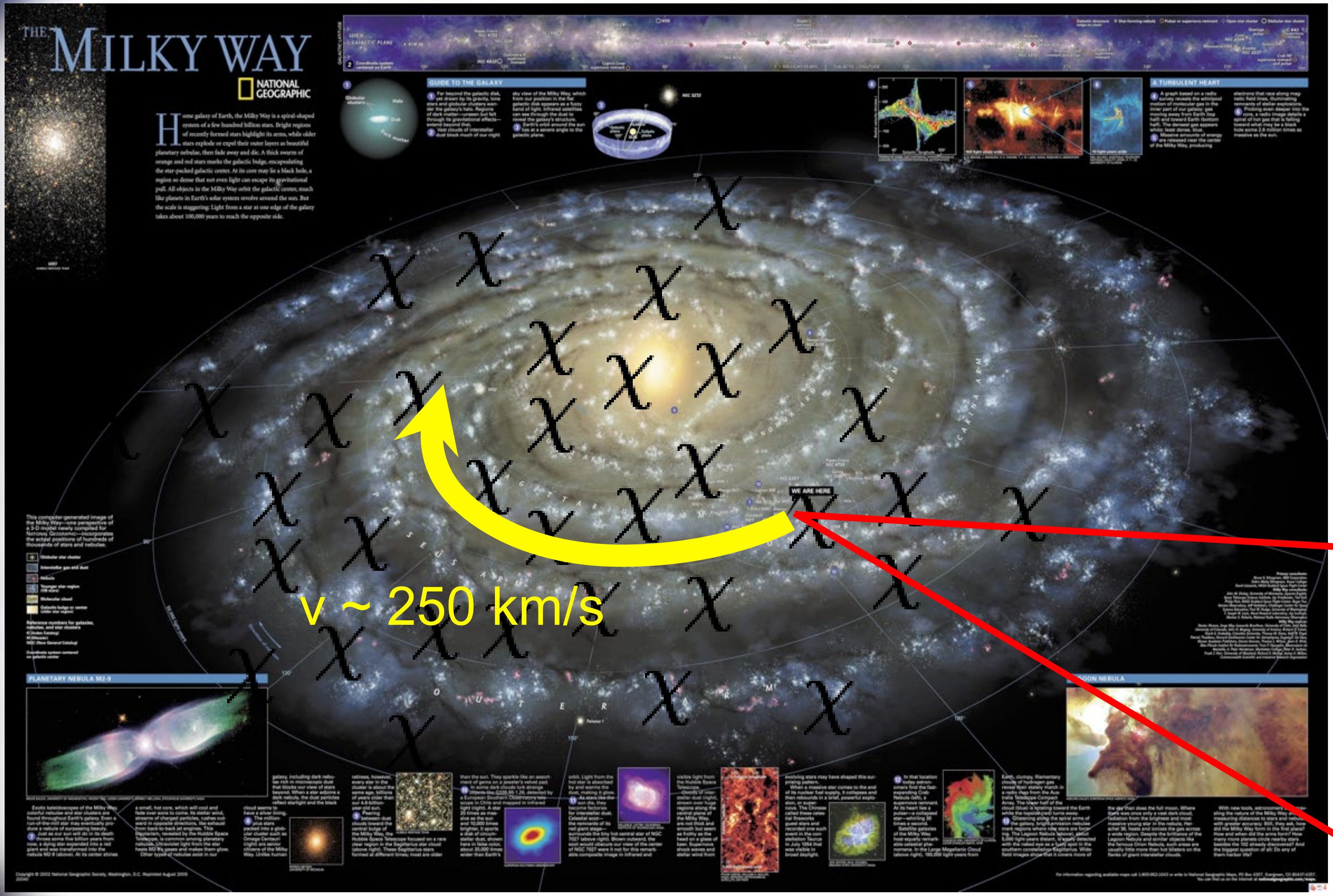
Fixed-Target Searches



When particle beam collides with fixed target, DM produced in association with visible SM particles

Only the DM reaches detector behind “beam dump” and dirt

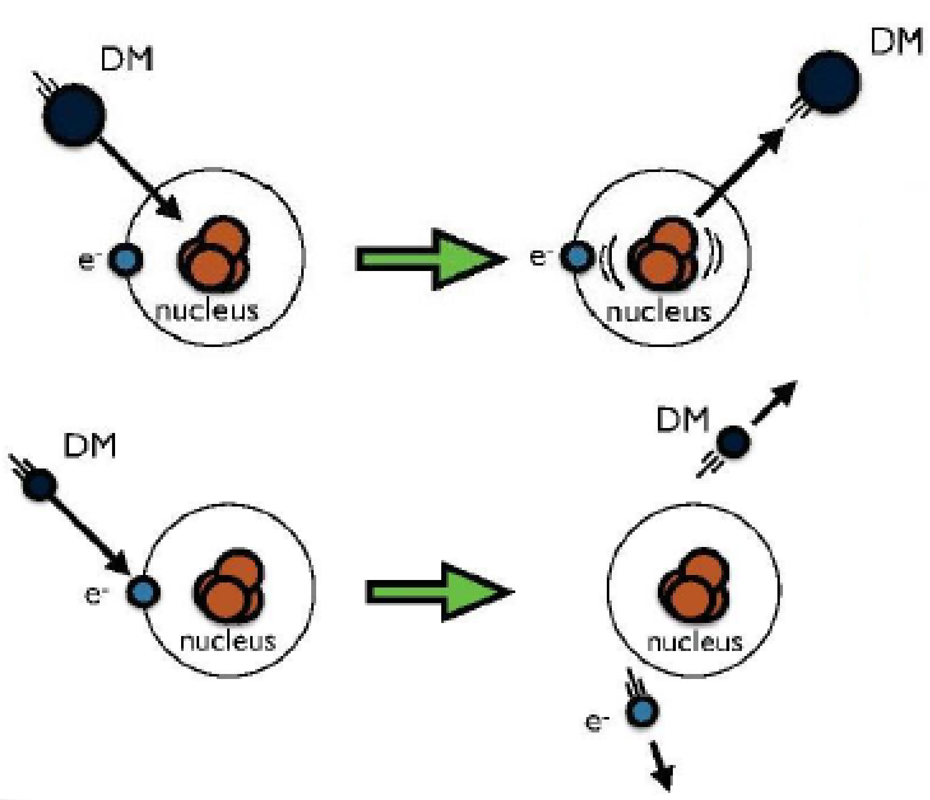
Direct Detection

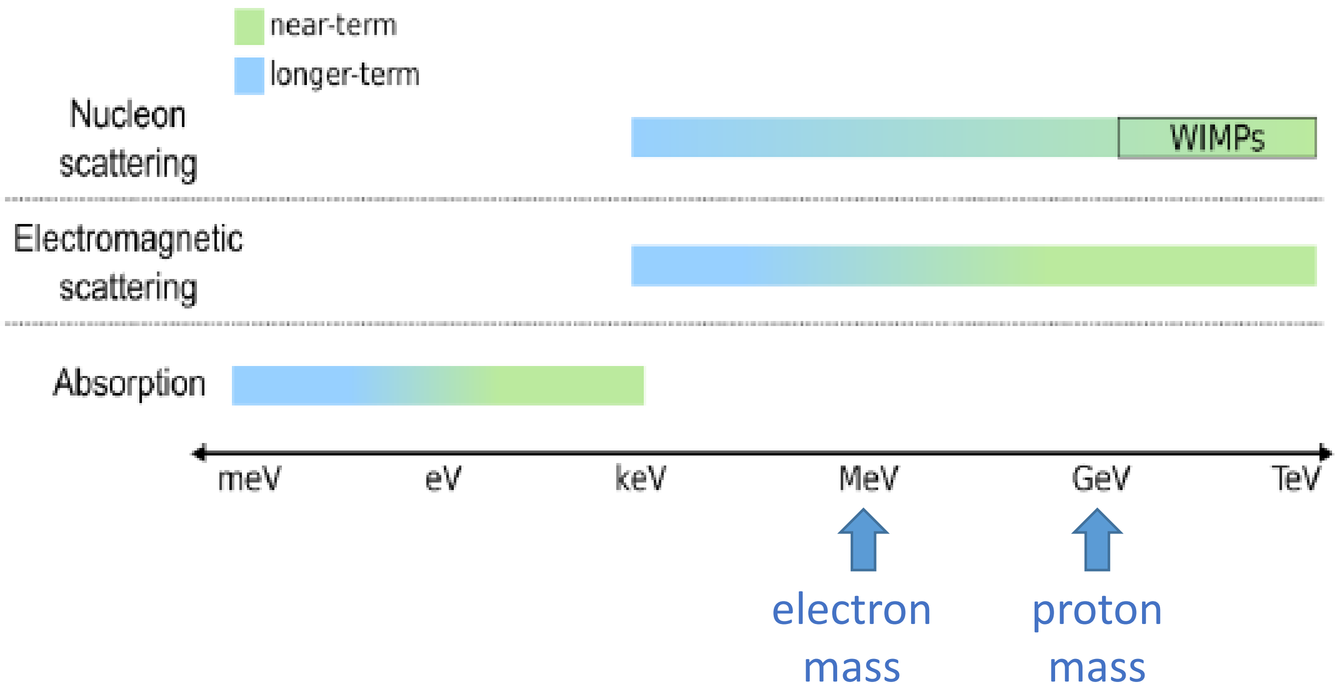


Collisions of galactic DM with SM particles in detector on Earth

Direct Detection

DM particles collide with SM particles in detector “target” and are absorbed, or cause nuclear and/or electronic recoils





Direct Detection Experiments

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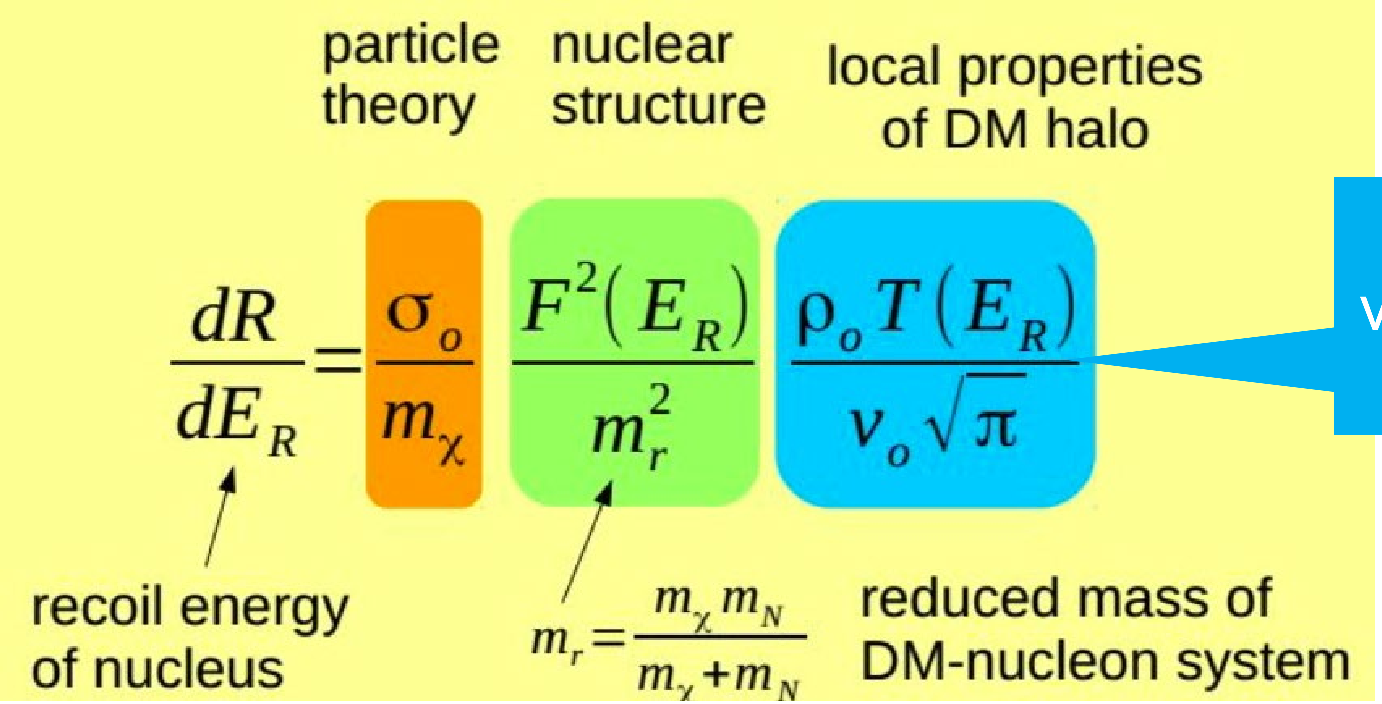
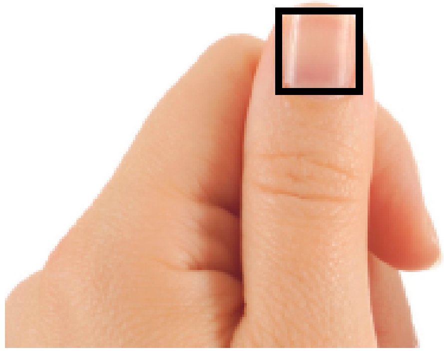
Direct Detection



Local $\rho_{DM} \approx 0.4$ GeV/cm^3
$v_{DM} \approx 250$ km/s (non-relativistic)

For $m_{DM} \approx 1$ GeV:
$flux_{DM} \approx 10$ million / cm^{2}s



Direct Detection

particle theory | nuclear structure | local properties of DM halo

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}$$

$$T(E_R) = \frac{\sqrt{\pi}}{2} v_o \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v} dv$$

integral over local WIMP velocity distribution

$$v_{\min} = \sqrt{E_R m_N / (2 m_r^2)}$$

minimum WIMP velocity for given E_R

$$T(E_R) \simeq \exp(-v_{\min}^2 / v_o^2)$$

for pure Maxwellian case

Slide credit: Enectali Figueroa-Feliciano

Direct Detection

particle theory | nuclear structure | local properties of DM halo

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o\sqrt{\pi}}$$

$$F(E_R) = \left[\frac{3J_1(qR_1)}{qR1}\right]^2 \exp\left(-(qs)^2\right)$$

"Woods-Saxon Nuclear Form Factor"

J_1 **= Bessel function of the first kind, cylindrical harmonic**
q **= momentum transferred**
s **= effective "nuclear skin thickness" (distance through which charge density of nucleus drops to 0, not a step function due to QM effects)**

Slide credit: Enectali Figueroa-Feliciano

Direct Detection

particle theory | nuclear structure | local properties of DM halo

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}$$

- Simplest case: Spin Independent interactions
- The scattering amplitudes from individual nucleons interfere.
- For zero momentum transfer collisions (extremely soft bumps) they add coherently:

$$\sigma_o = \frac{4m_r^2}{\pi}\left[Z f_p + (A - Z) f_n\right]^2$$

$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2$$

coupling constant

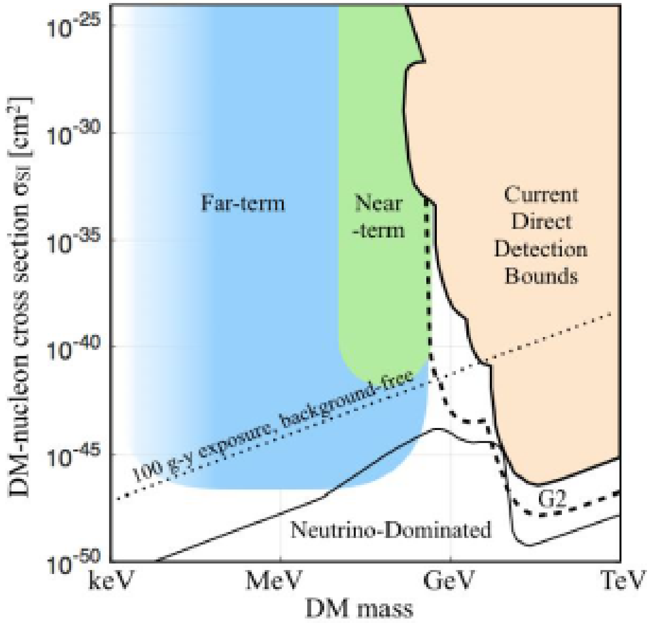
Enormous enhancement for heavy nuclei target!

Slide credit: Enectali Figueroa-Feliciano

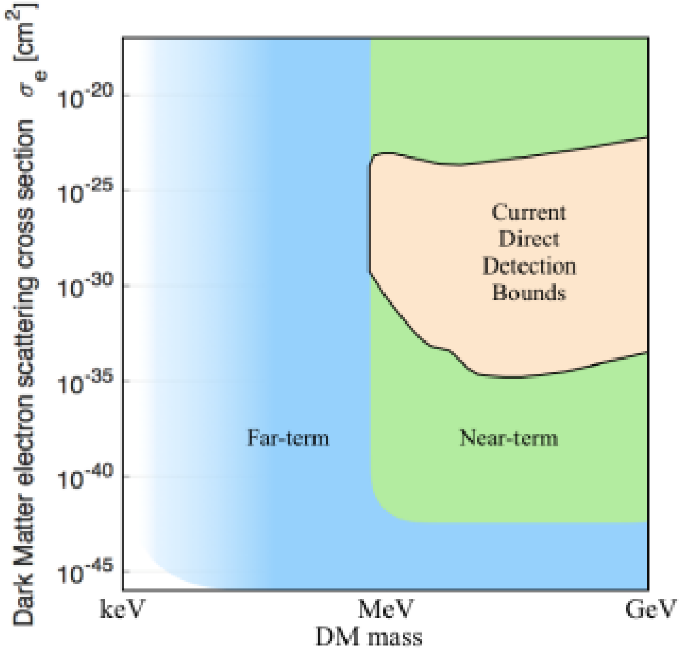
Moment of Truth

Next few years will either *find conventional WIMPs* or *rule them out.*

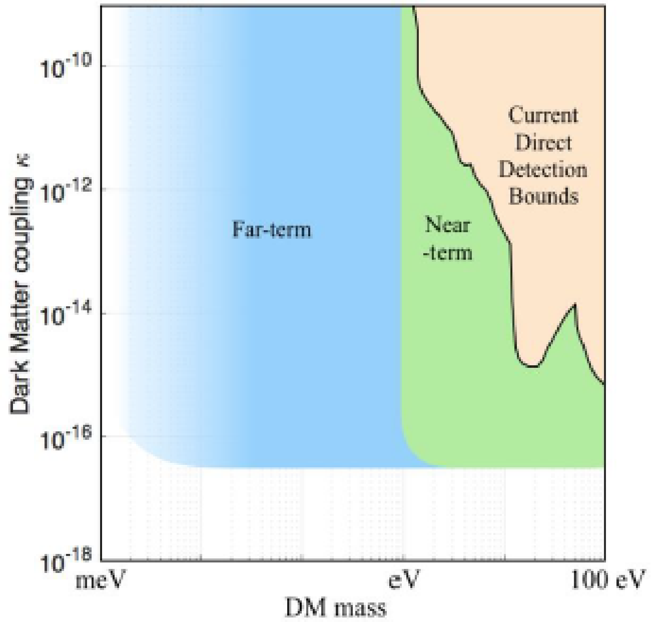
Lowering *mass* and/or *interaction* thresholds mean tougher backgrounds, and we will encounter "floor" where neutrinos drown out WIMP signal



Galactic dark matter scattering off nuclei



Galactic dark matter scattering off electrons

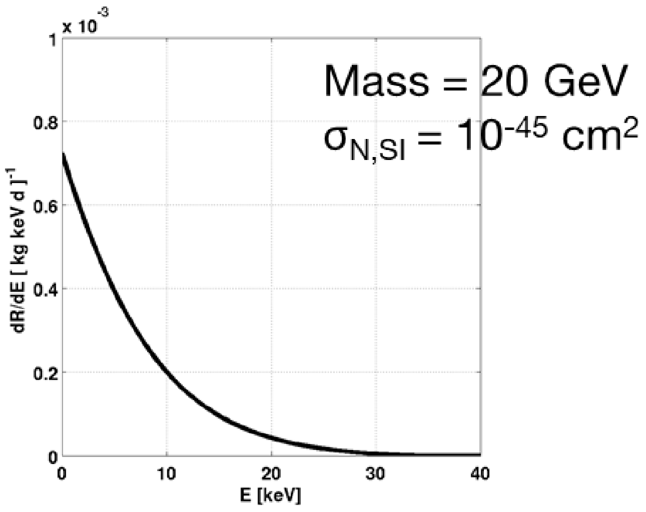


Galactic dark-photons absorbed by electrons

It's a "Rare Event Search"

- WIMP elastic scattering transfers only ~few 10s of keV to recoiling nucleus
- "Featureless" exponential spectrum
- Event Rate very, very low: easily swamped by backgrounds!

Expected WIMP Spectrum

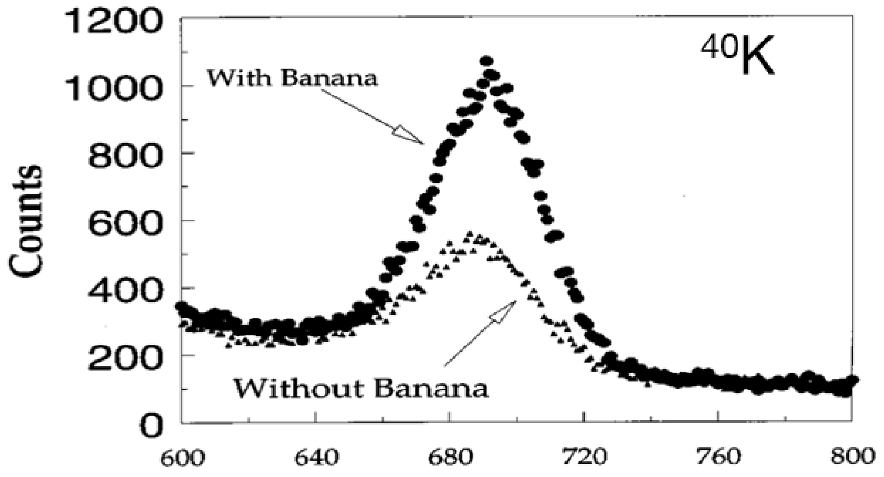


~1 event per kg per **year**

(Nuclear Recoils)

Measured Banana Spectrum

Hoeling *et al* Am.J.Phys. 1999, 67, 440.



~100 event per kg per **second**

(Electron Recoils)

Slide credit: Enectali Figueroa-Feliciano

(Generalized) Rare Event Search requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold, Good Energy Resolution

3: Low Backgrounds

4: Discrimination between Signal and Backgrounds

Slide credit: Enectali Figueroa-Feliciano

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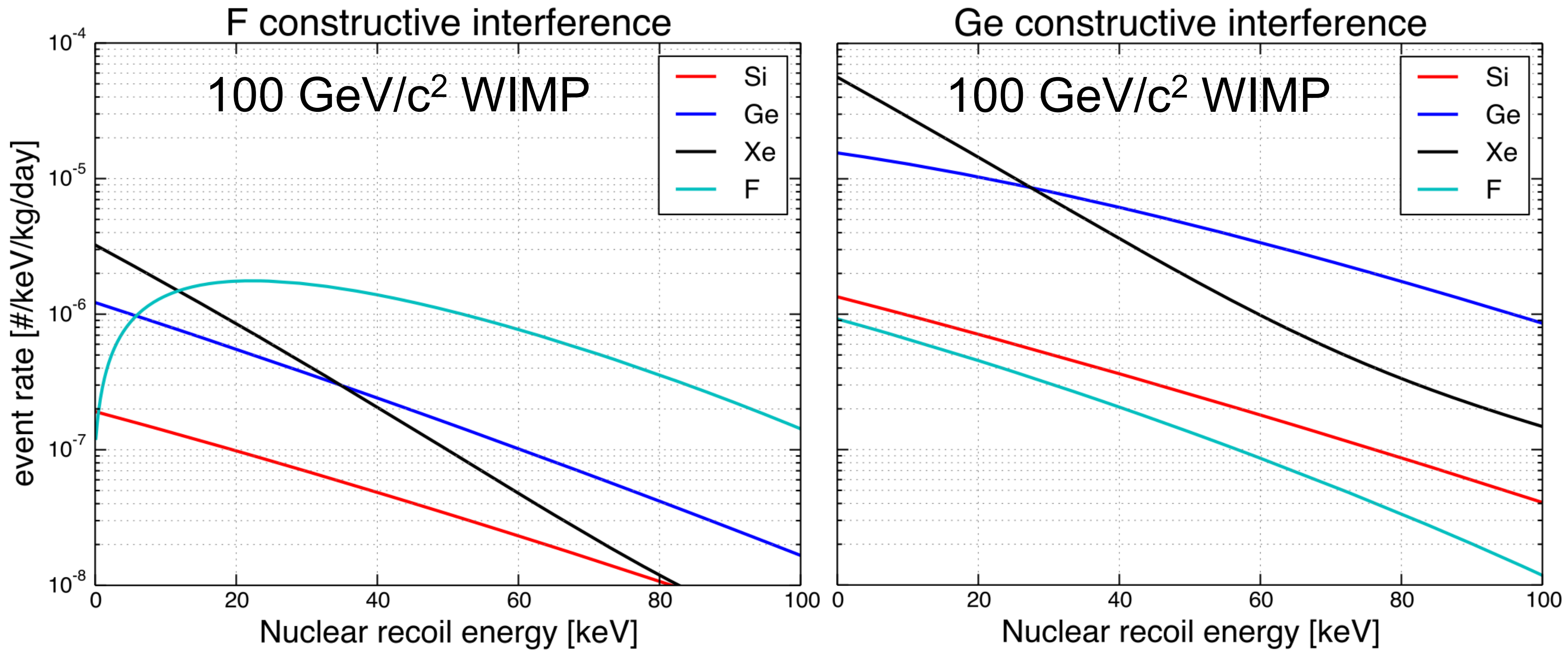
Dark Matter could look different in different targets

- More complicated interactions could lead to different rates (and different spectral shapes) in different target materials
- Robust program with multiple necessary to determine which (Effective Field Theory) operators are contributing to any detected signal



Slide credit: Enectali Figueroa-Feliciano

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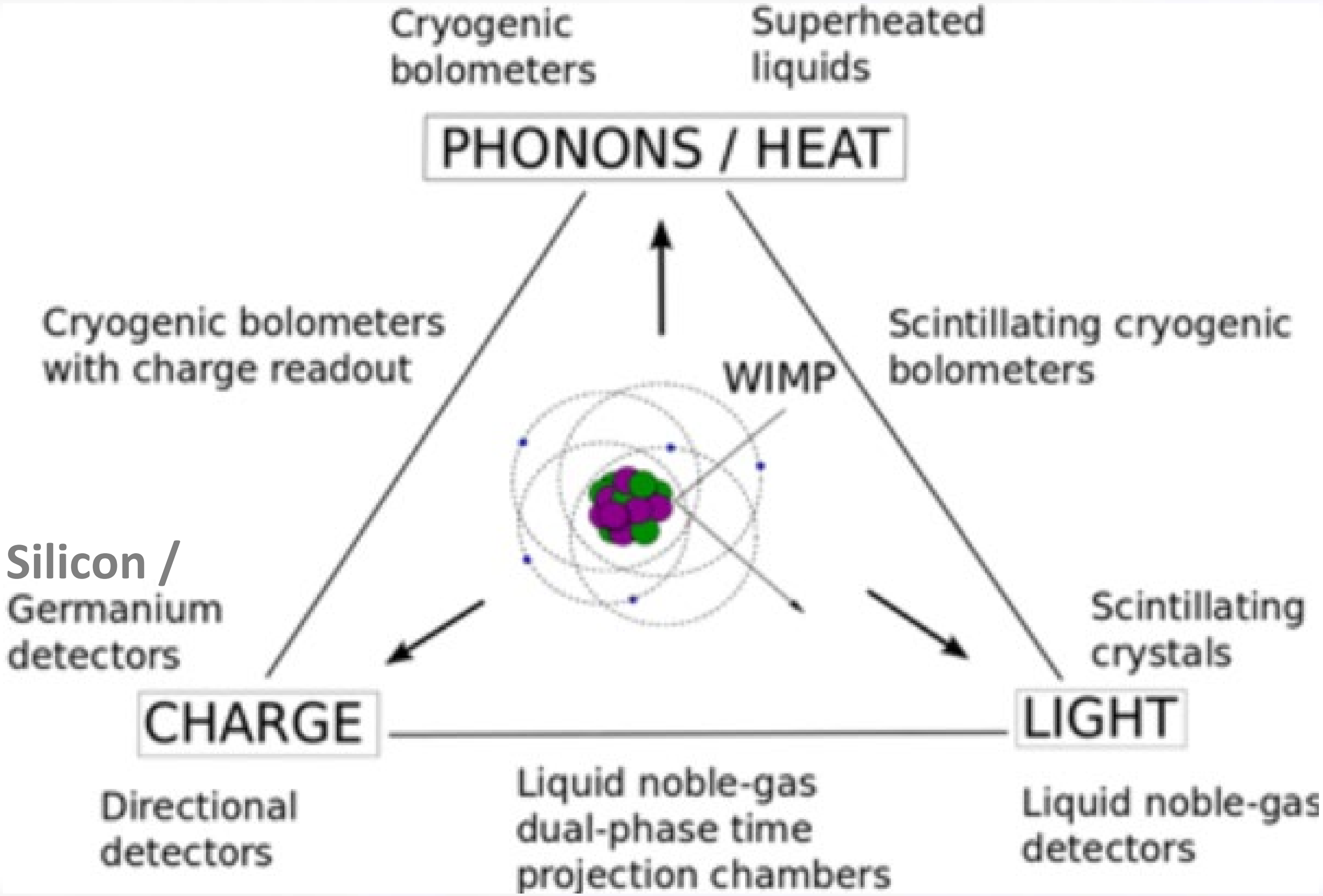
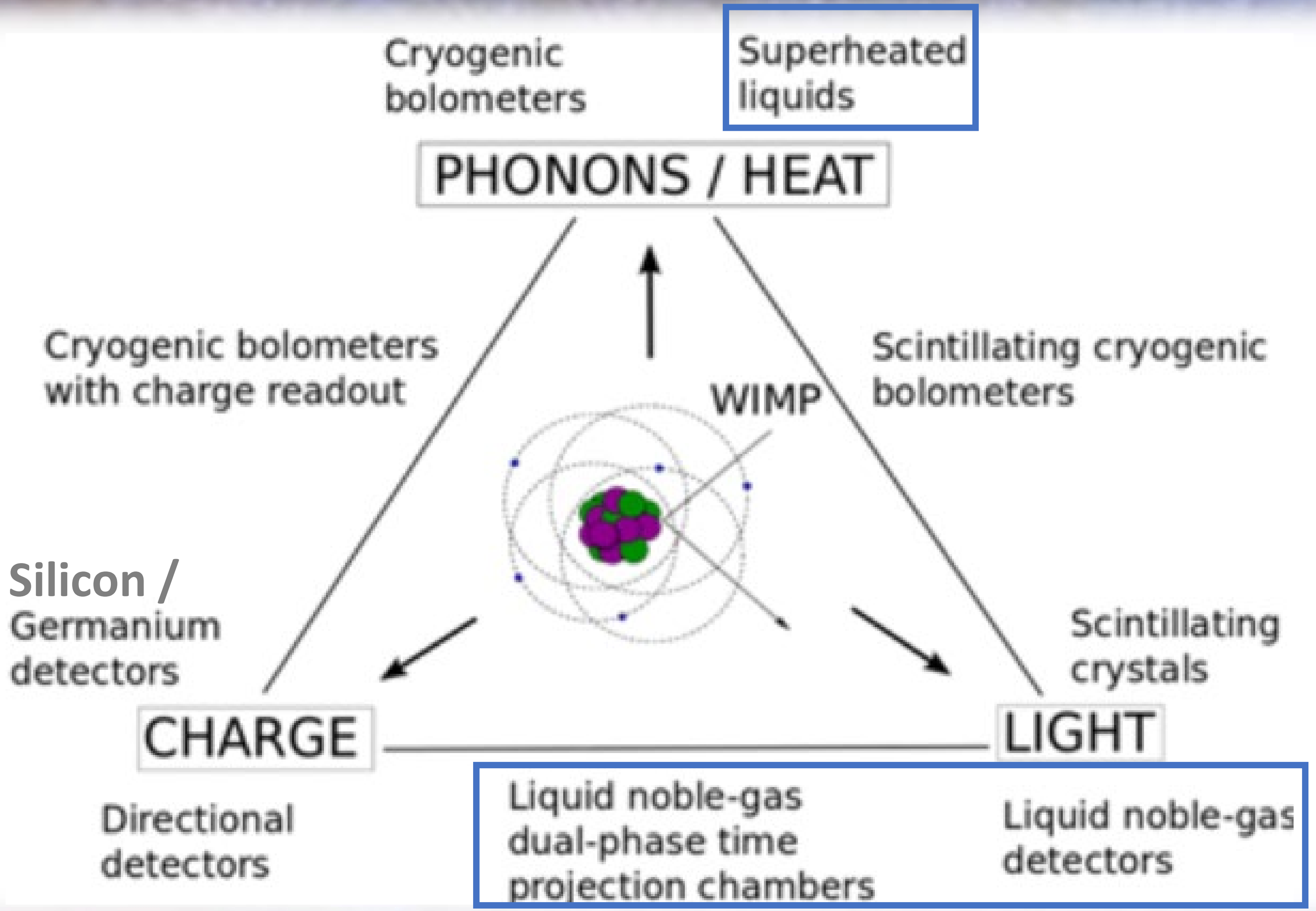
Next-Generation Direct Detection



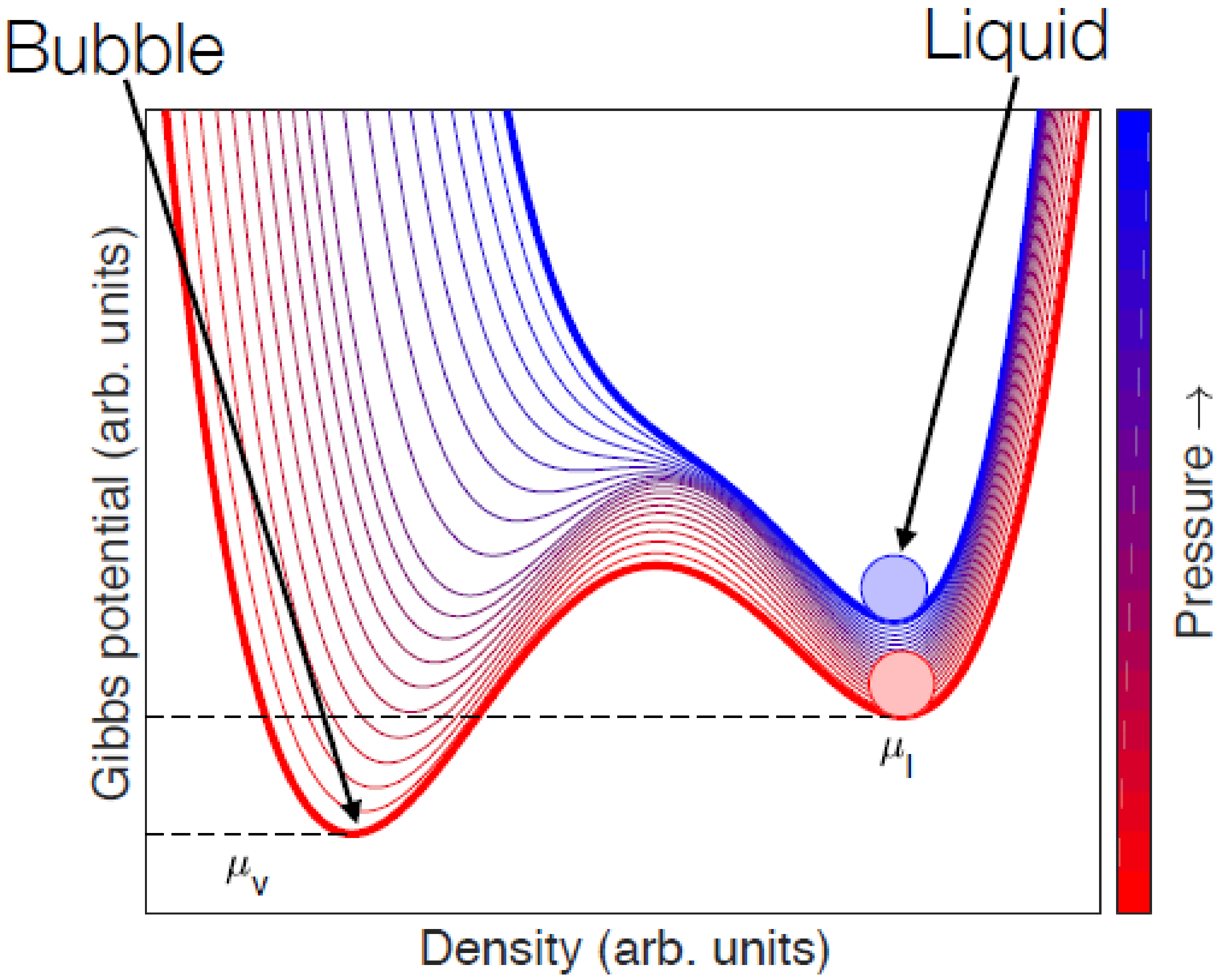
Next-Generation Direct Detection



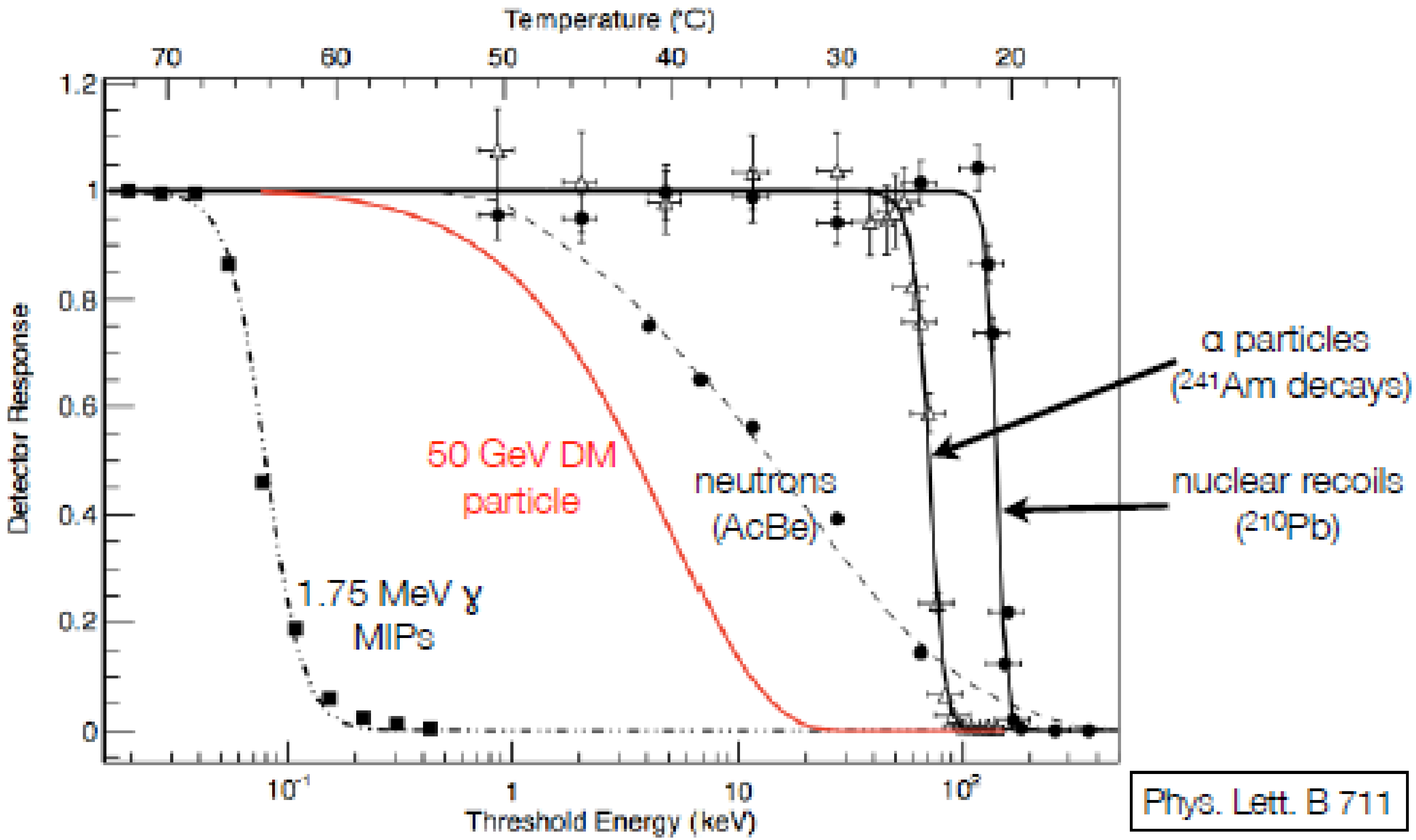
arXiv:1509.08767

Bubble Chambers

- Jar of superheated liquid
- Incoming particle deposits energy, causing bubbles to nucleate
- Minimum deposition required to overcome surface tension: a few keV
- Cameras and/or acoustic sensors trigger on bubbles, then re-set chamber by pressurizing it
- e.g. PICO



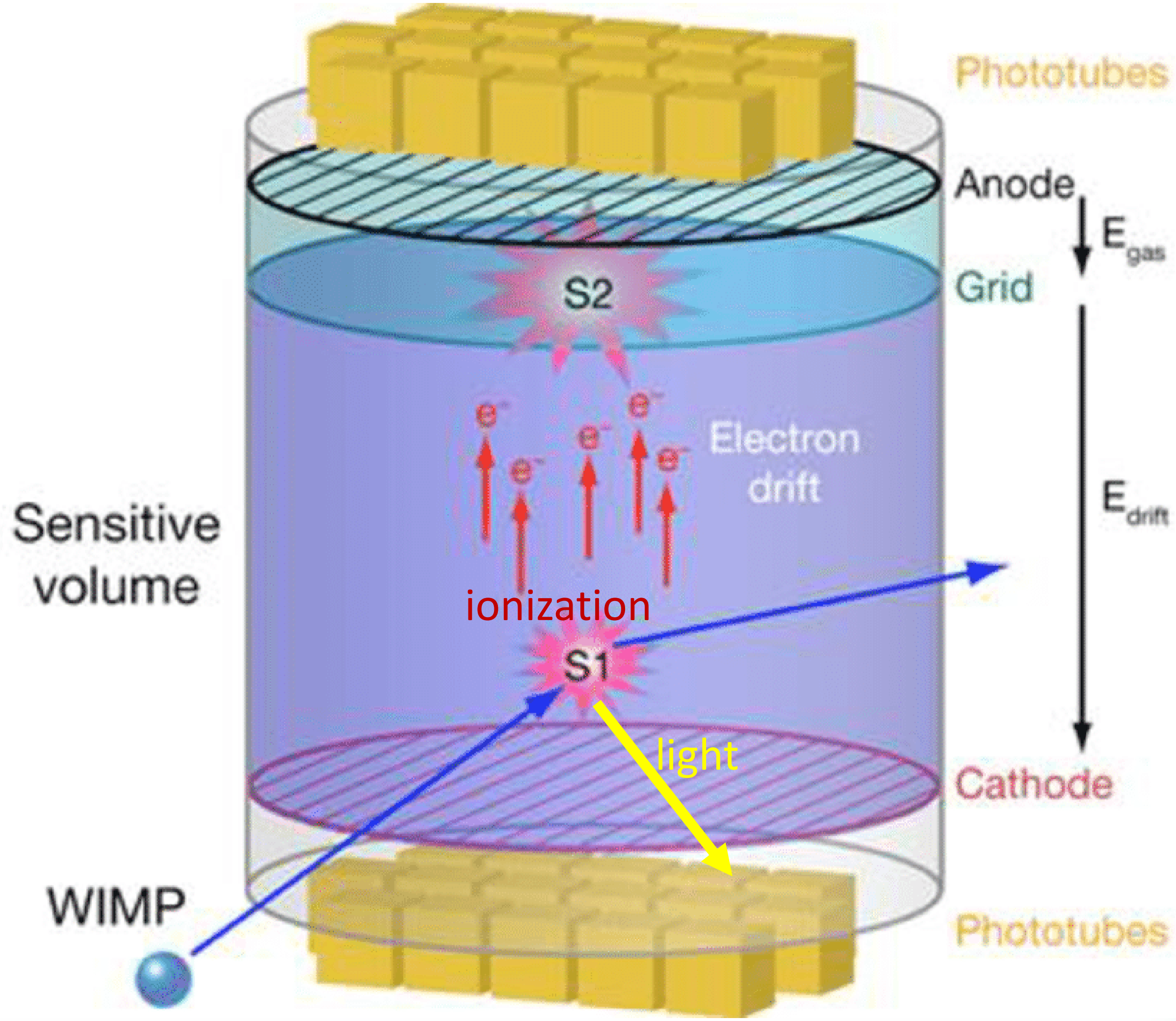
Bubble Chambers



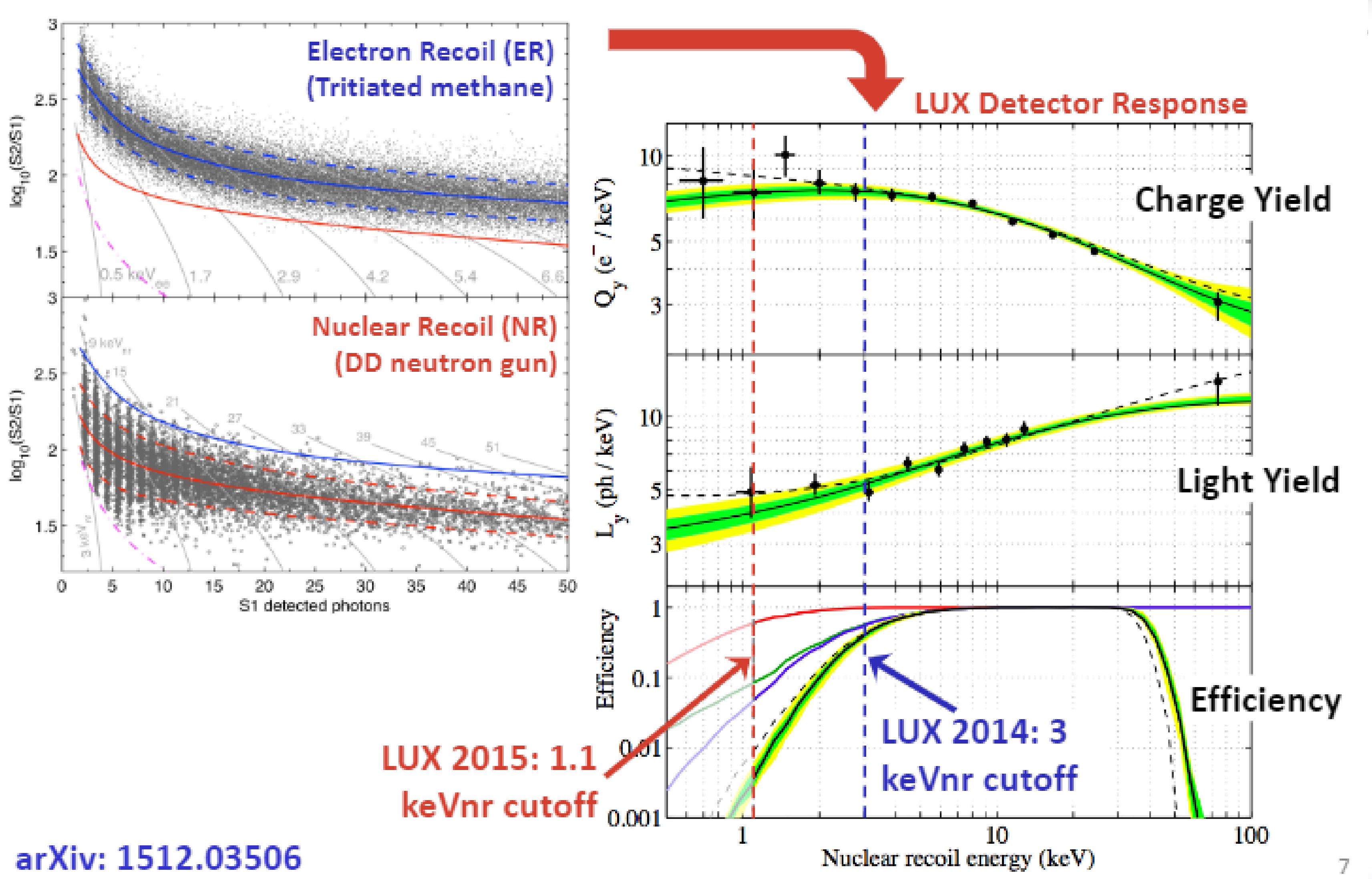
Phys. Lett. B 711

Noble Liquid/Gas Detectors

- Large tank of liquid noble element (xenon or argon) attached to sensors for light and ionization energy of particle interactions
- May also have gaseous layer
- Shielded, and often underground, to avoid interference from cosmic rays and ambient radiation
- e.g. XENON, LUX, LZ, PandaX, DarkSide, DEAP



Noble Liquid/Gas Detectors

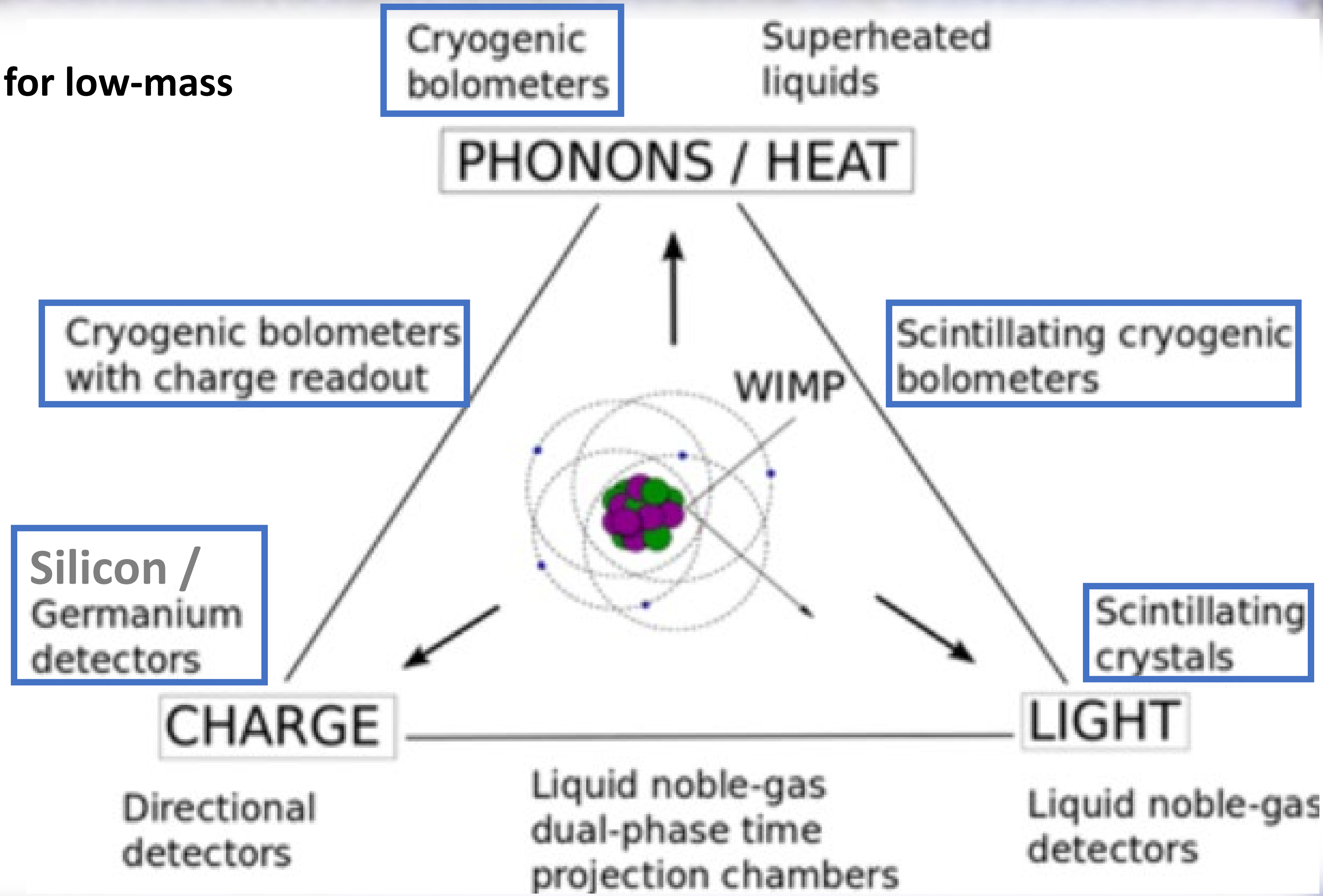


[May also use "pulse shape discrimination" for Particle ID, won't get into this here]

Solid-State Detectors

Low thresholds: well-suited for low-mass DM searches
See Ziqing Hong's lectures!

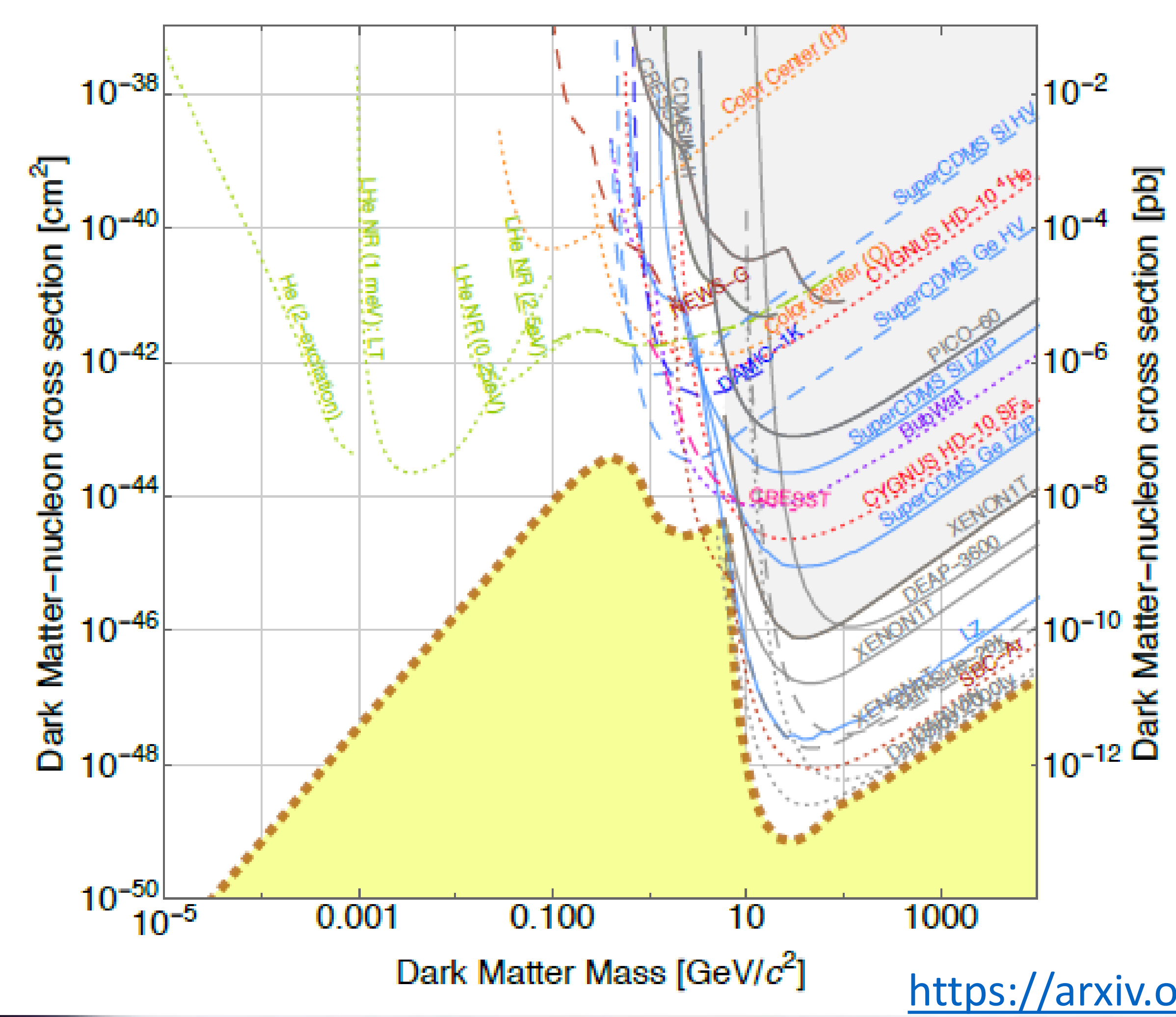
Phonon signal independent of particle interaction type, while ionization / scintillation can provide ER vs NR discrimination



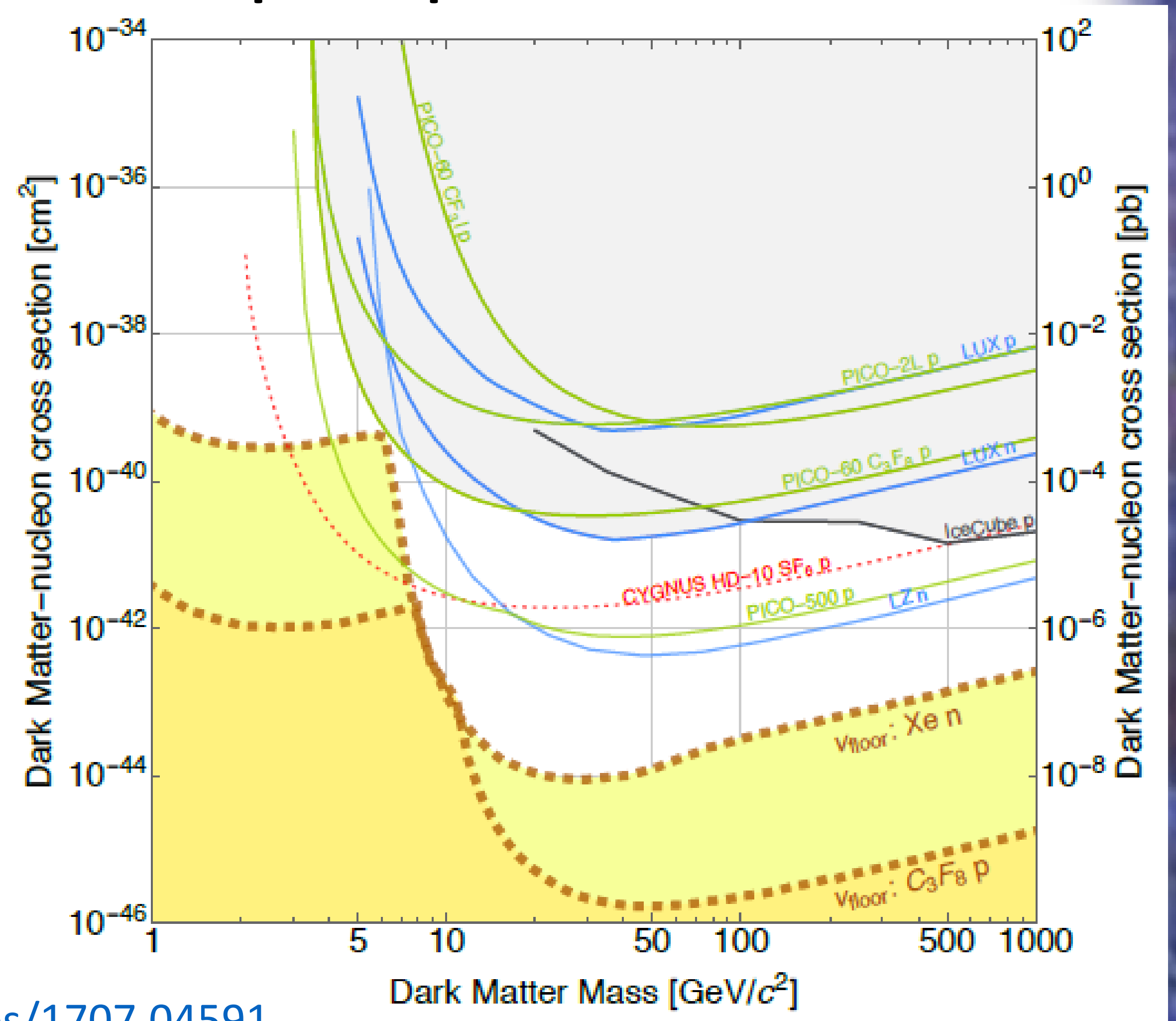
Direct Detection:
Recent Experimental Results & Near-Future Outlook

Nuclear Recoil Limits

Spin-Independent



Spin-Dependent



https://arxiv.org/abs/1707.04591

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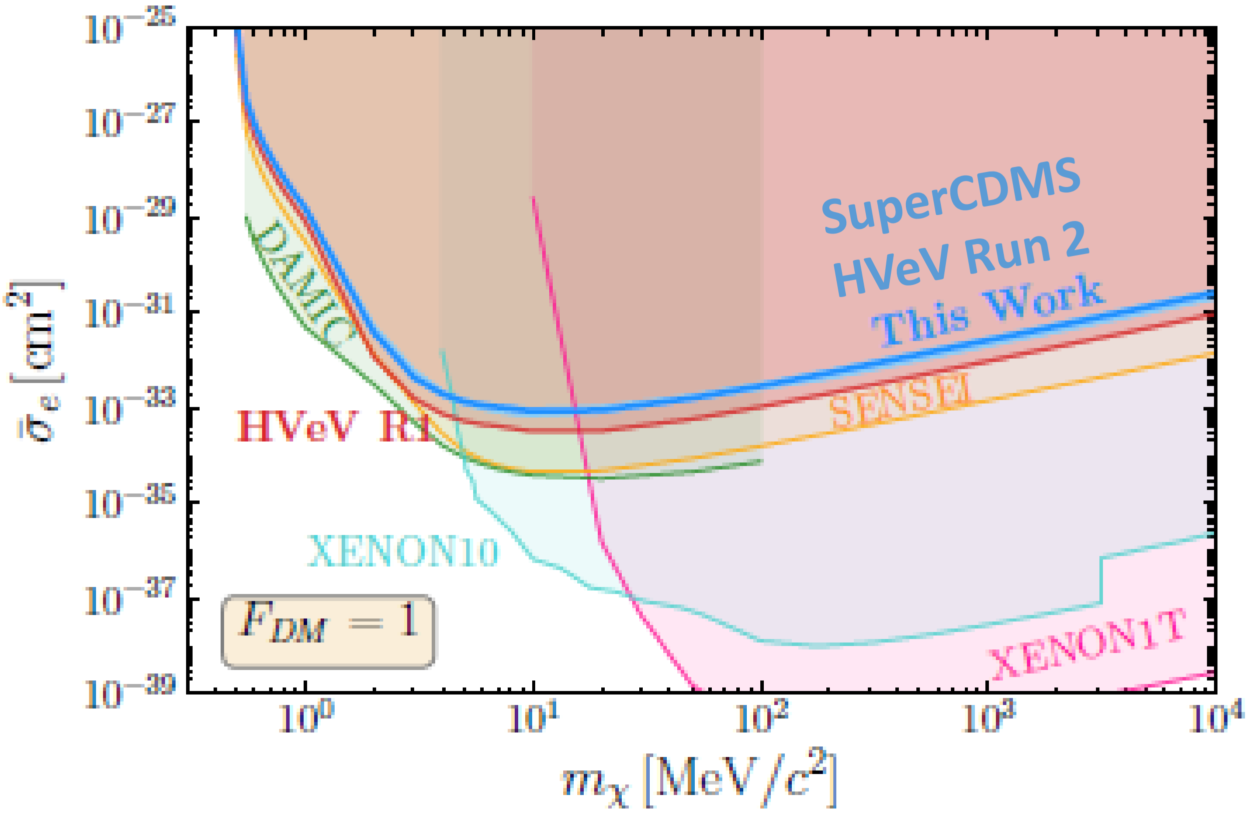
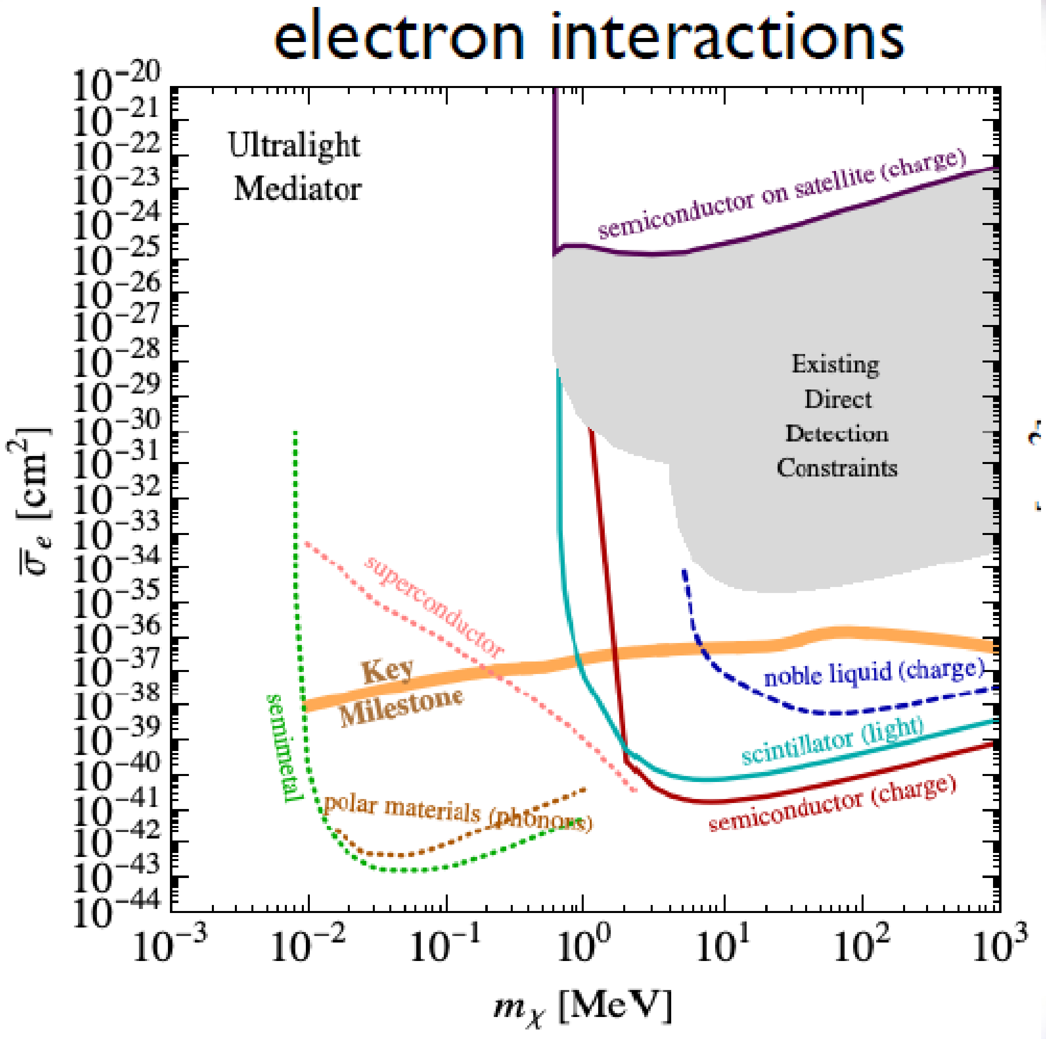
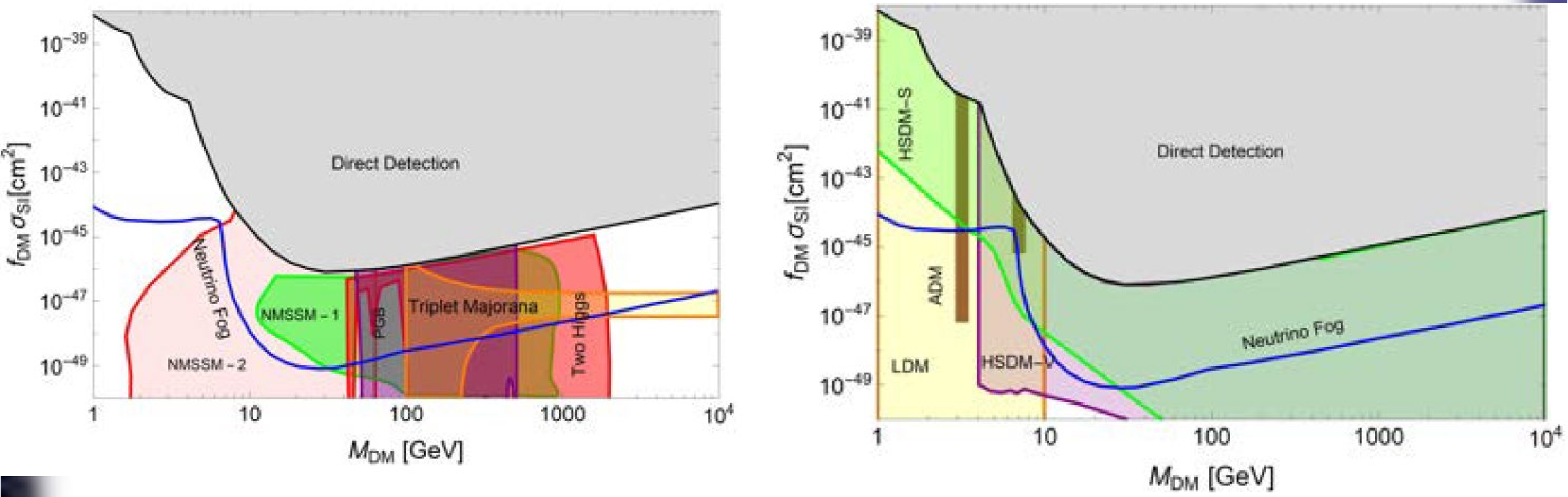
Electron Recoil Limits



https://arxiv.org/abs/2005.14067



Lots of DM models we haven't ruled out



arXiv:2203.08084

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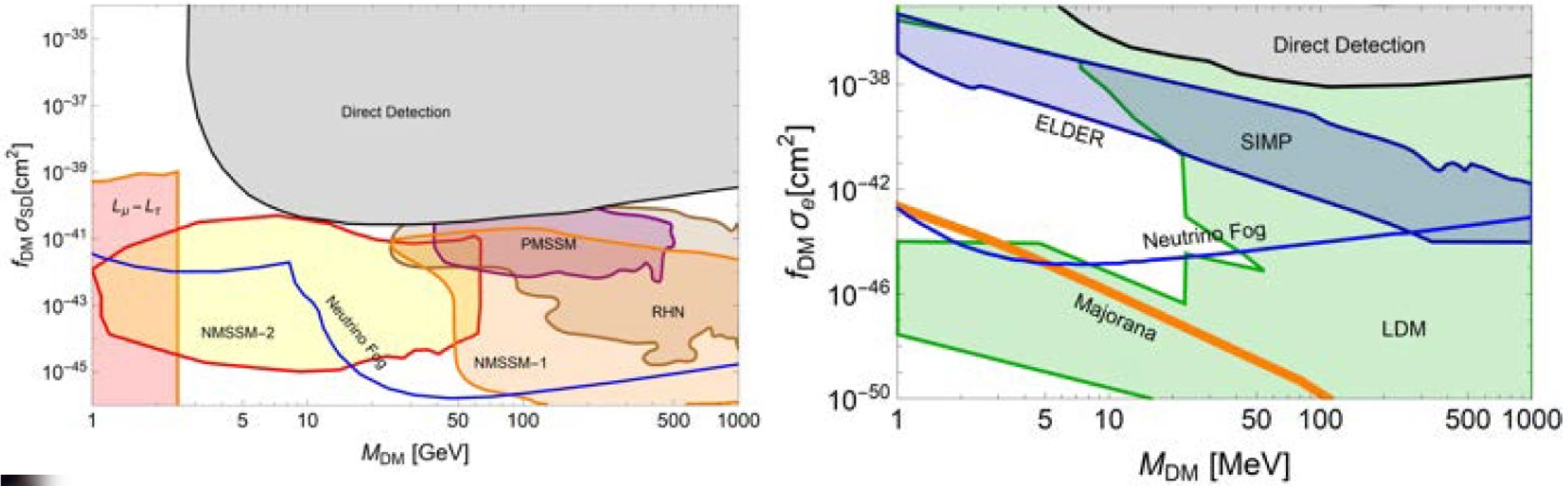
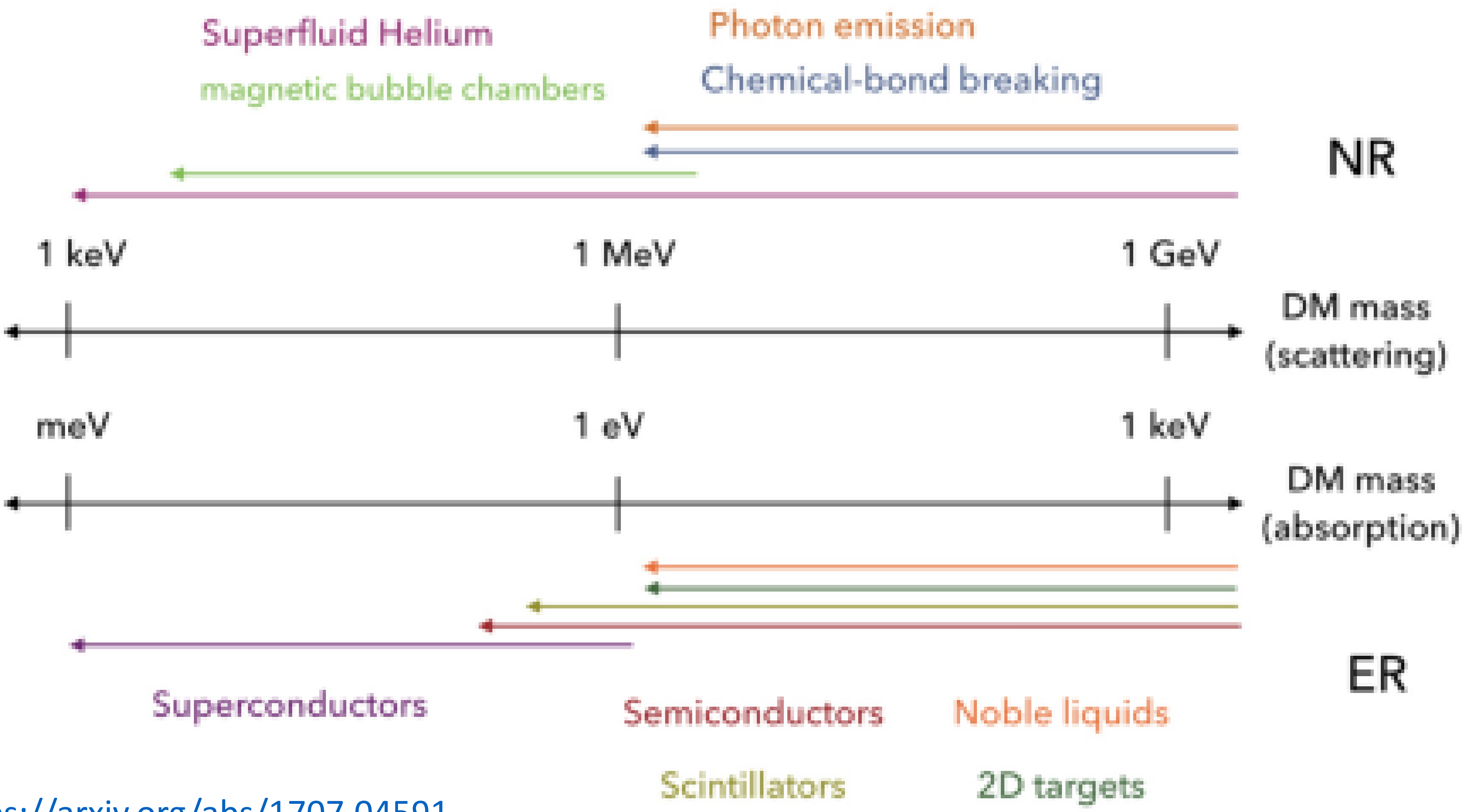


arXiv:2203.08084

“Cosmic Visions” for Direct Detection



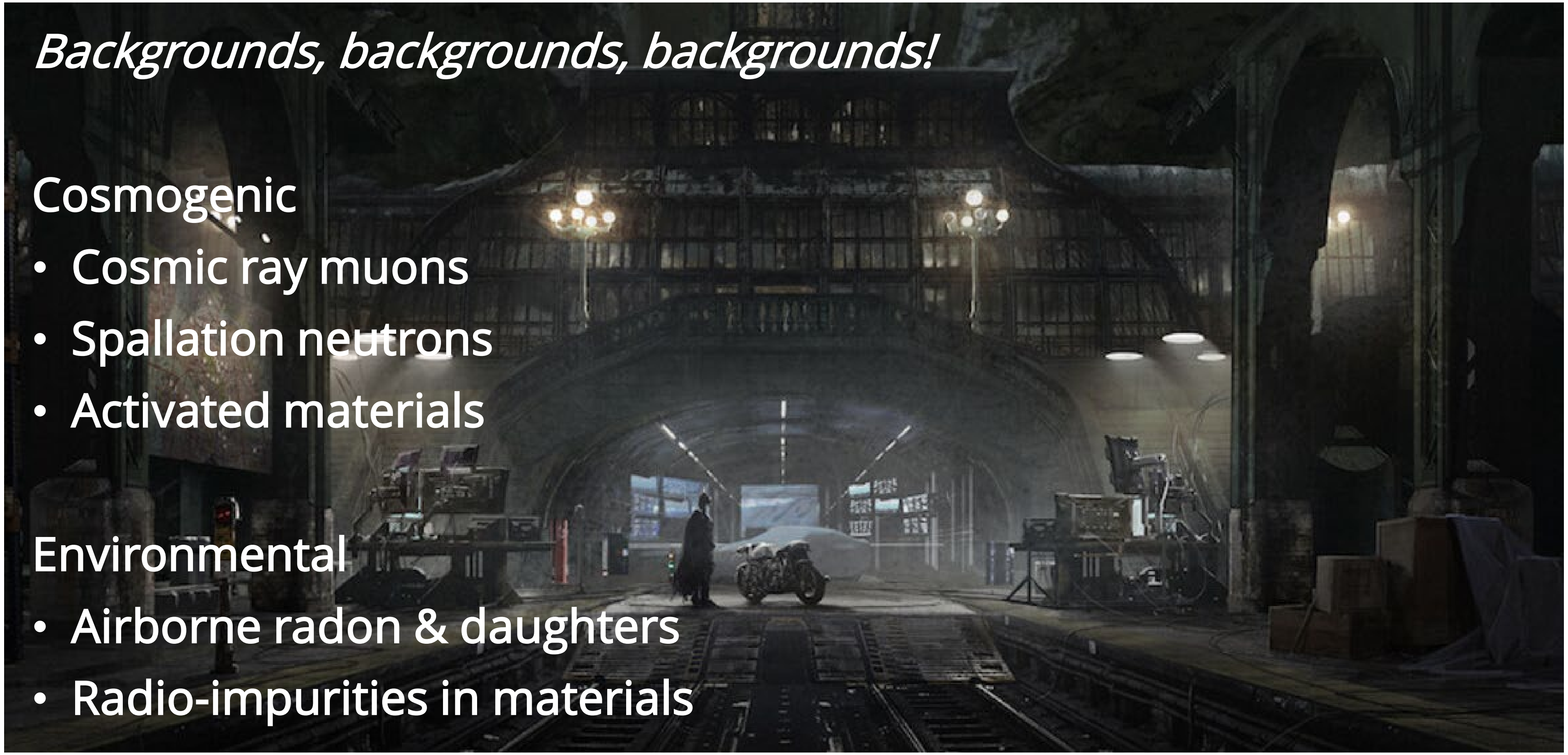
https://arxiv.org/abs/1707.04591

Backgrounds!

Underground dark secret lairs

Hide the detectors in shielding and bury them in an underground clean-room.

Why?



Backgrounds, backgrounds, backgrounds!

Cosmogenic

- Cosmic ray muons
- Spallation neutrons
- Activated materials

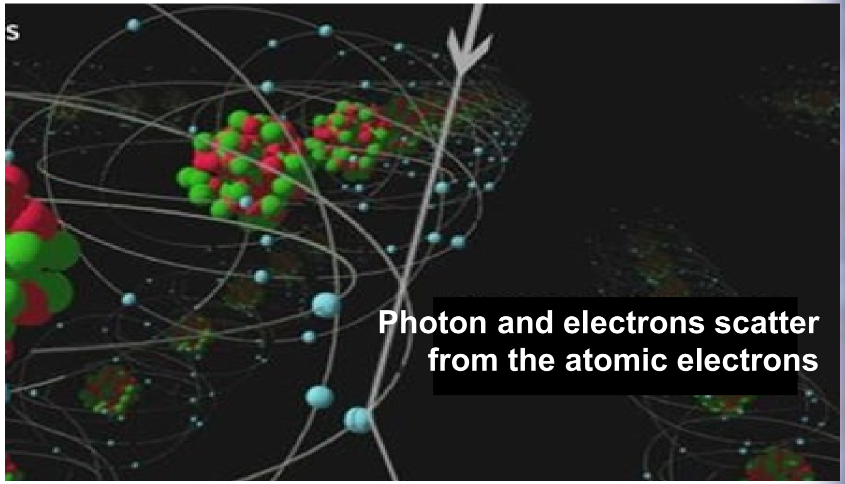
Environmental

- Airborne radon & daughters
- Radio-impurities in materials

The most troublesome backgrounds

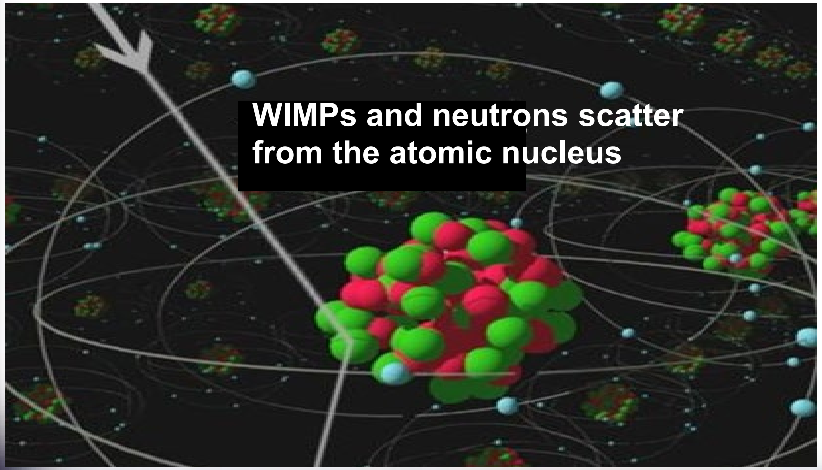
Most from trace radioactivity (U, Th, K) or cosmogenic (cosmic ray muons produce fast neutrons via spallation, difficult to shield against)

ER



γ: Most prevalent

β: on surfaces or in the bulk



NR

n: often indistinguishable from WIMP

α: on surfaces

Recoiling nucleus: another surface event

 Slide credit: Enectali Figueroa-Feliciano

Managing backgrounds (in 6 not-so-easy steps)

1) Build detector out of highly radiopure materials in state-of-the art clean lab (generally Class1000 or better)
2) Go deep underground where fast neutron flux (from cosmic ray muon spallation) is reduced.
3) Surround experiment with several tons of radiopure shielding
4) For WIMP NR search: distinguish ER vs NR (detector will see ~10^6 more ER than WIMP NR events)
5) “Fiducialize” target volume to reject surface events (requires detector to reconstruct some event position info as well as event energy)
6) Fine-tune background rejection “cuts” and maximize signal acceptance to extract the most out of the data (use event simulations, and advanced statistical analysis techniques)

Quantifying backgrounds

- Often measured in Differential Rate Units (DRU)
  - Events/(keV * kg * day)
  - Rationale: for a low cross-section process, event rate scales with exposure (kg * day), and the signal spectrum is often flat within a certain energy Region Of Interest
- Commonly-used “benchmark” numbers:
  - Unshielded lab: 10,000 DRU, cosmic muon rate 1/(min * cm^2) at sea level
  - Useful environment: 100 DRU
  - Good environment: < (or <<) 10 DRU
- Note: “noise” rate depends on detector instruments (electronics etc), and is not technically a background!
  - Backgrounds are due to particle interactions, noise is not
  - Noise happens continuously

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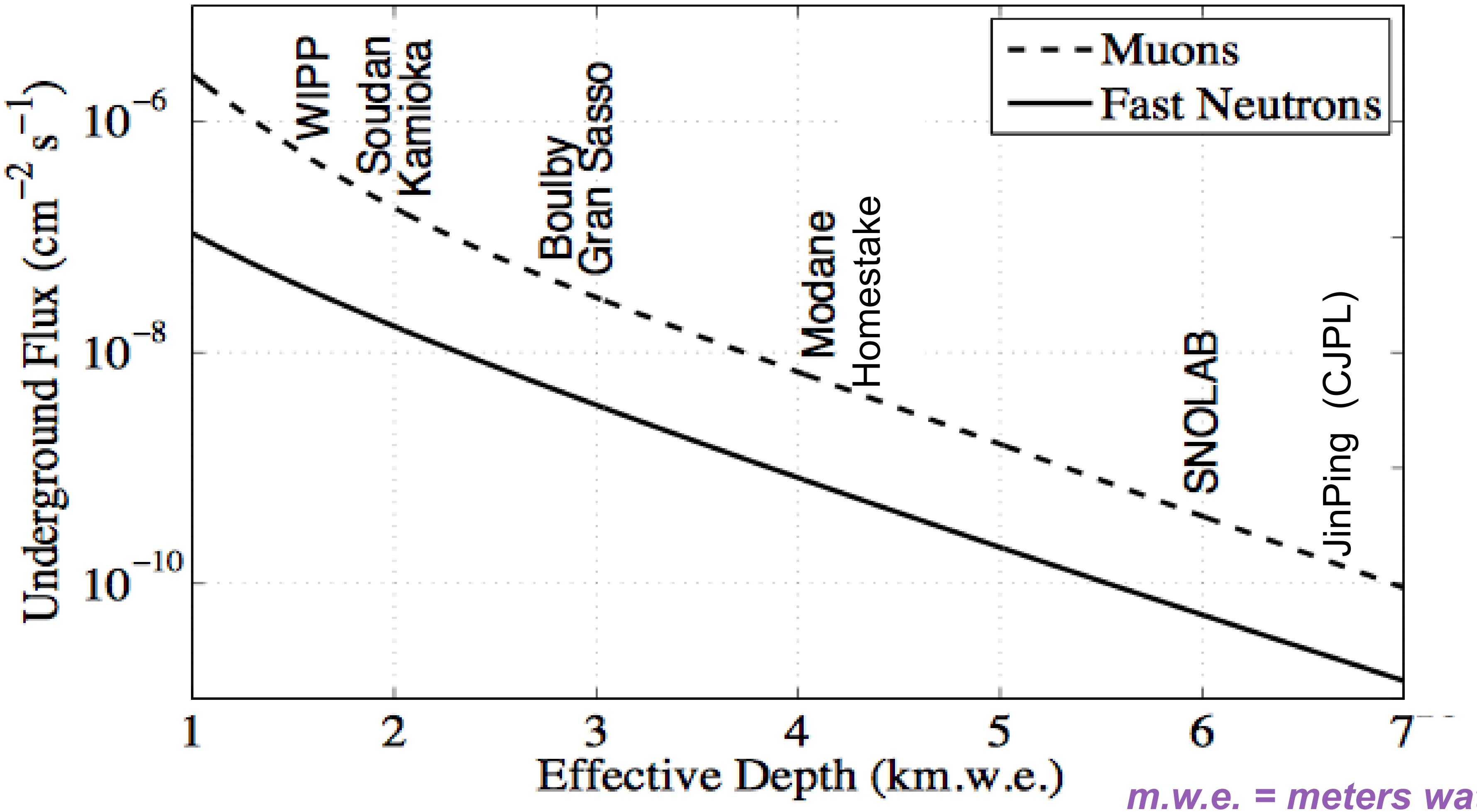
Natural shielding to help reduce backgrounds

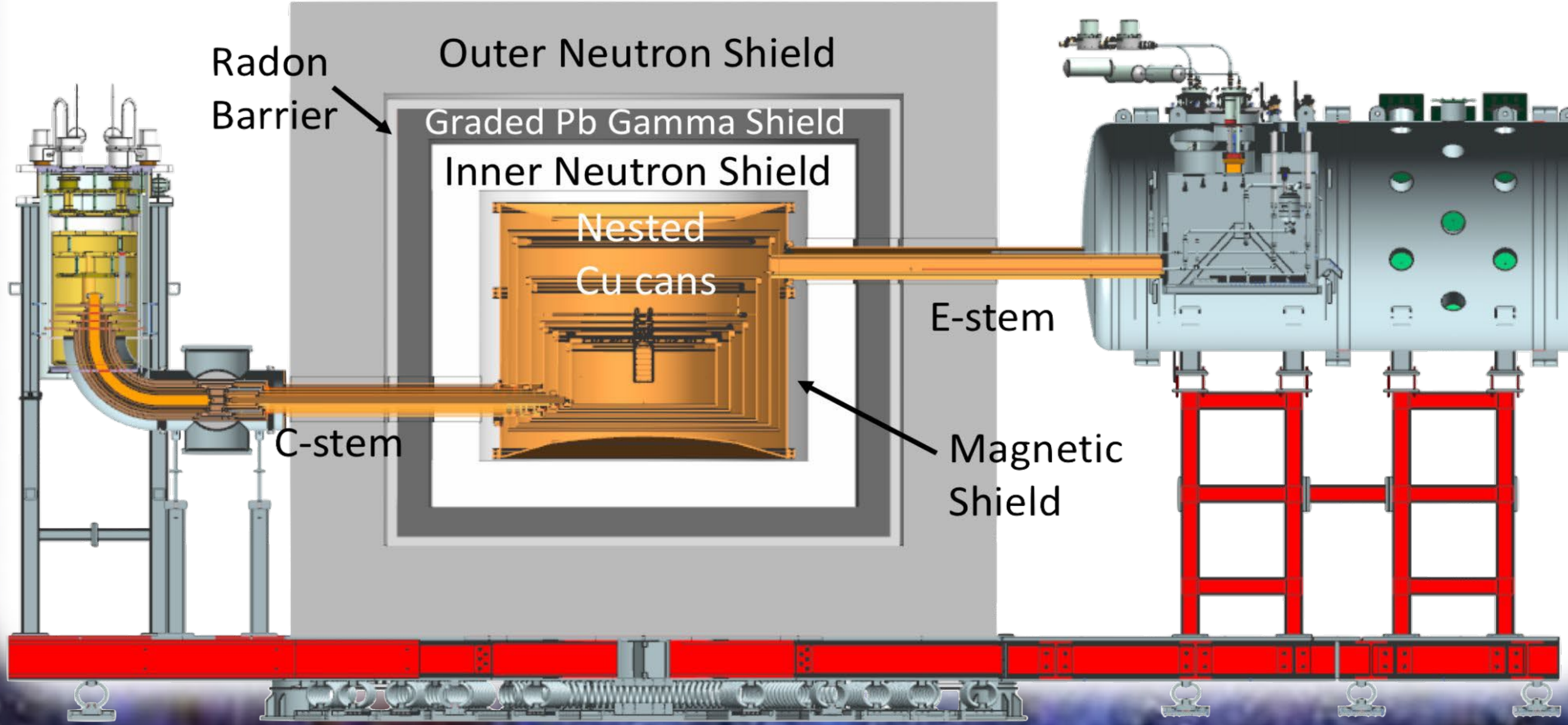
Go underground, use the earth as free shielding from cosmic ray muons



m.w.e. = meters water equivalent

Artificial shielding to help reduce backgrounds

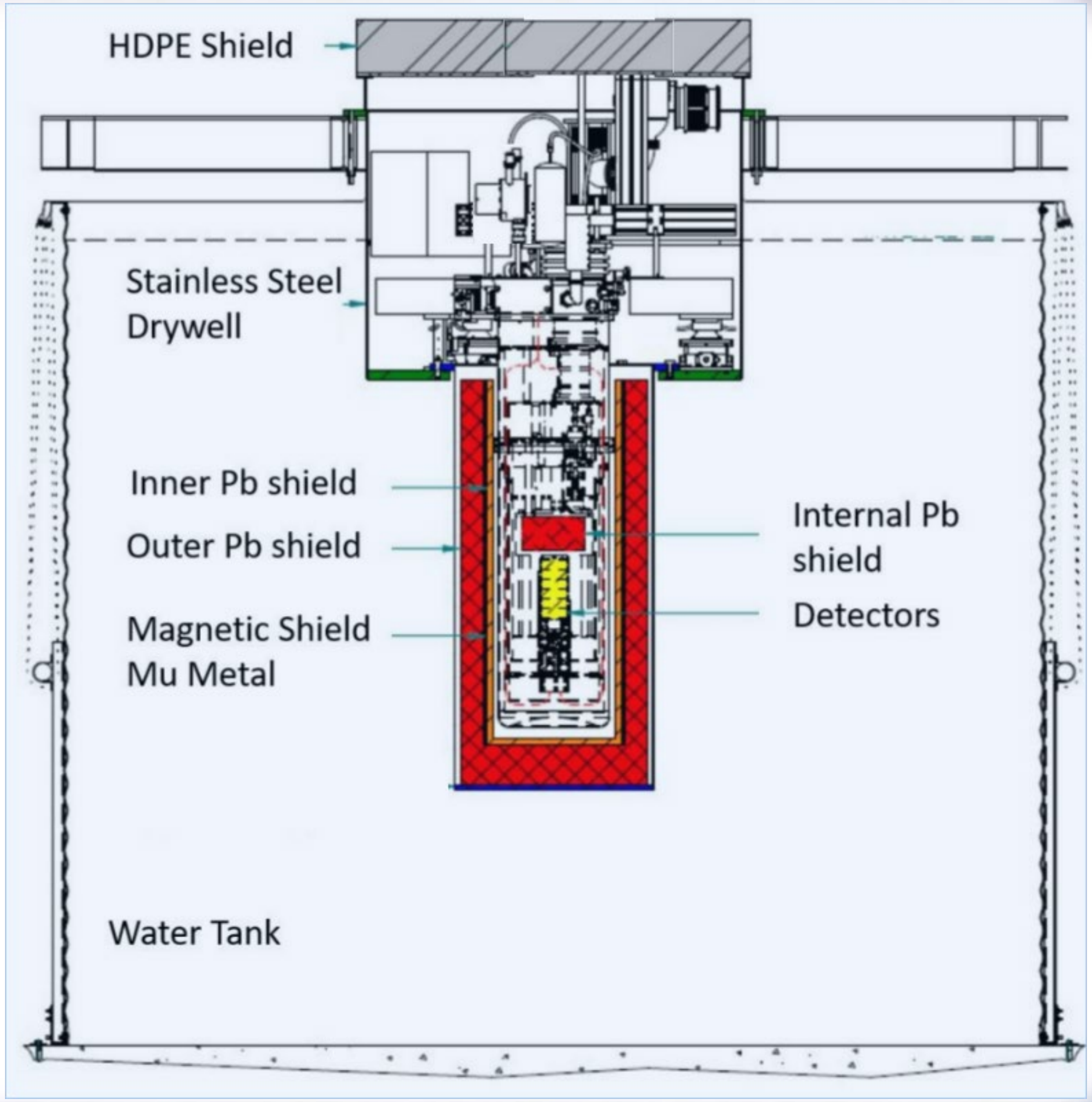
e.g. SuperCDMS: Note the multiple layers!



Artificial shielding to help reduce backgrounds

e.g. CUTE (Cryogenic Underground Test) facility @SNOLAB:

- ~ 10 cm low activity Lead in drywell
- Mu-metal reduces external B-field ~x50
- ~1.5 m water, 20 cm Polyethylene lid
- 15 cm Lead "plug" inside cryostat
- Active low Ra air purge in drywell



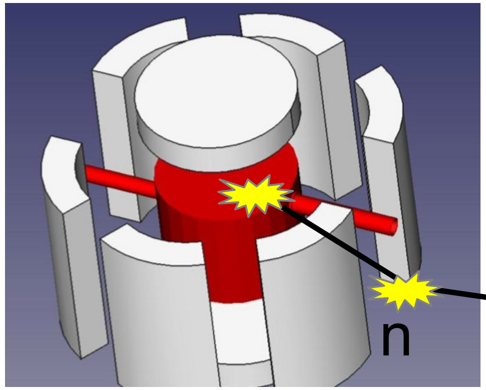
Slide credit: Andrew Kubik

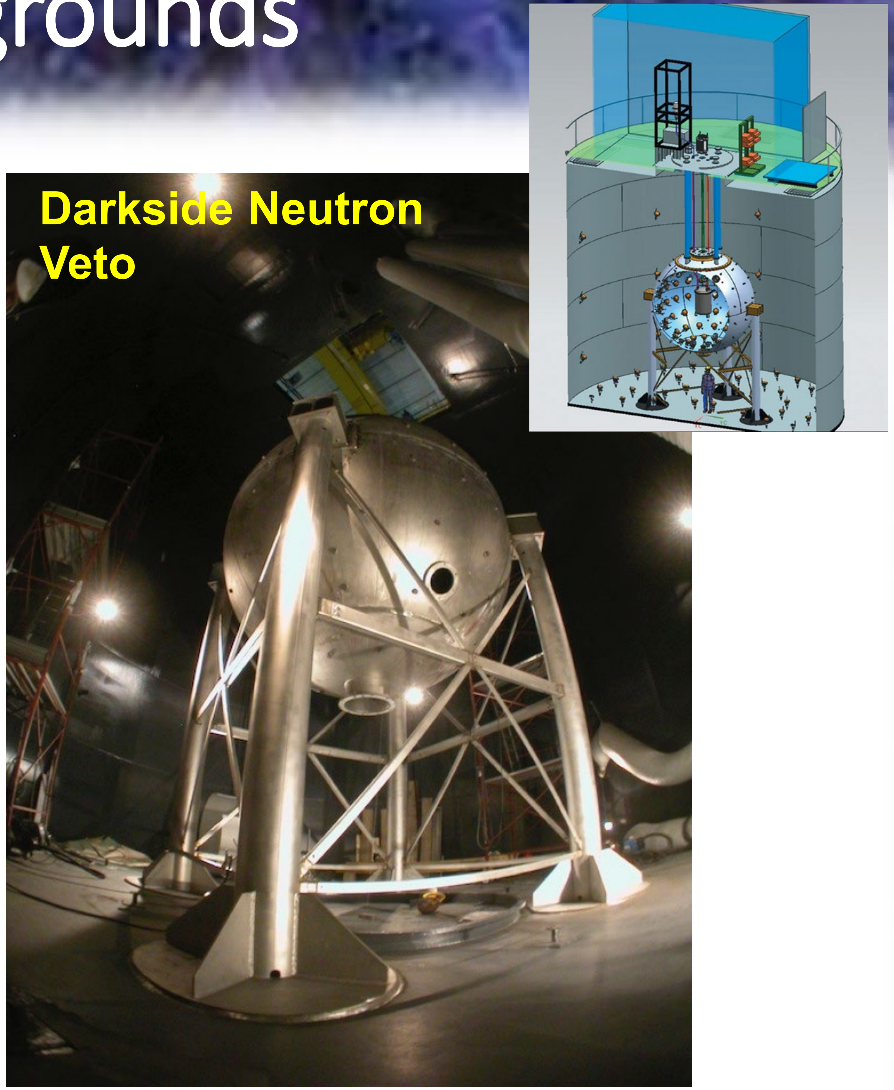
Active shielding to help reject backgrounds

Muon Veto: water Cherenkov or scintillator, tags muons passing through/near experiment

Neutron Veto: liquid scintillator doped with isotope w/ high neutron capture cross-section; tags radiogenic neutrons originating from contaminated material

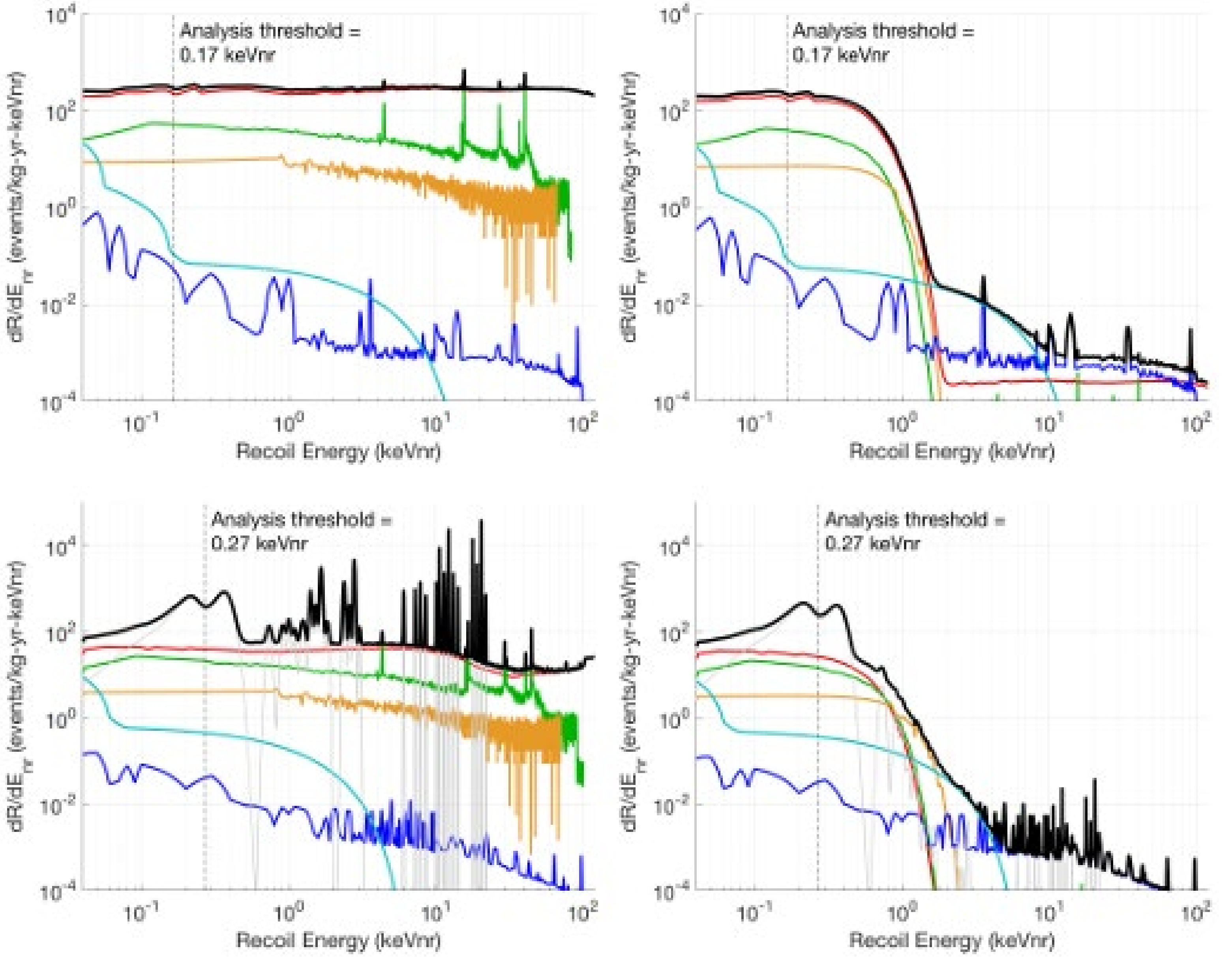
Proposed SuperCDMS neutron veto





Slide credit: Enectali Figueroa-Feliciano

Background modelling examples



e.g. SuperCDMS:

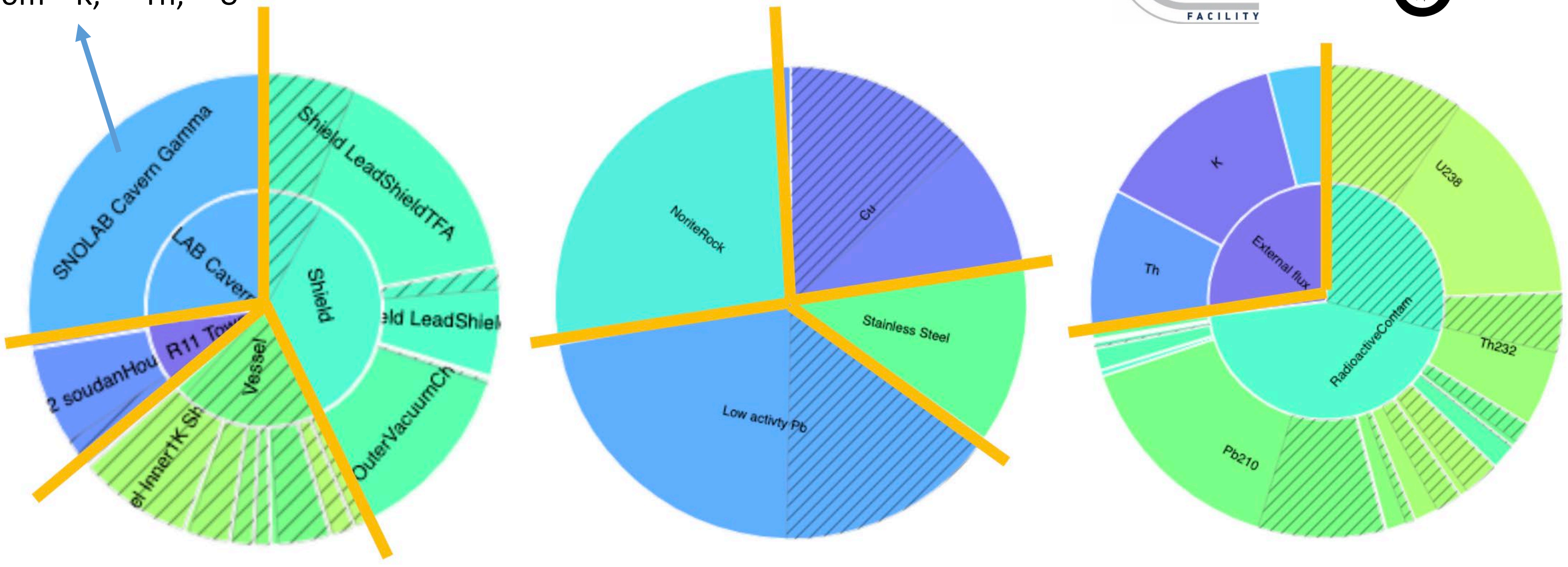
Background spectra, before (left) and after (right) analysis cuts in Si (top) and Ge (bottom) iZIP detectors, as a function of nuclear recoil energy (keVnr)

Thick black: total background
Red: electron recoils from Compton gamma-rays, H, Si
Grey: Ge activation lines, convolved with 10 eV r.m.s. resolution (for an actual detector, expect more smeared-out reconstruction in pre-cut spectrum)
Green: surface betas
Orange: surface Pb recoils
Blue: neutrons
Cyan: CEvNS

Background modelling examples

e.g. CUTE:

from ^{40}K, ^{232}Th, ^{238}U



Component Material Contaminant

Slide credit: Silvia Scorza

Background assay examples

Radioactive Contamination

- Long-lived radioactive isotopes are contained in traces in all materials.
- Screen each component/material to get the specific activity of the contained radioactive isotopes.

Radon exposure

- Air above surface and underground contains traces of ^{222}Rn, whose decays can implant ^{210}Pb into the surface of exposed materials.
- Need to know the radon level and exposure time to mine air to estimate the decay rate.

Cosmogenic Activation

- Neutrons originating from cosmic showers can activate materials residing on Earth's surface.
- Monitor component's time on Earth's surface and cooldown time until the experiment starts.

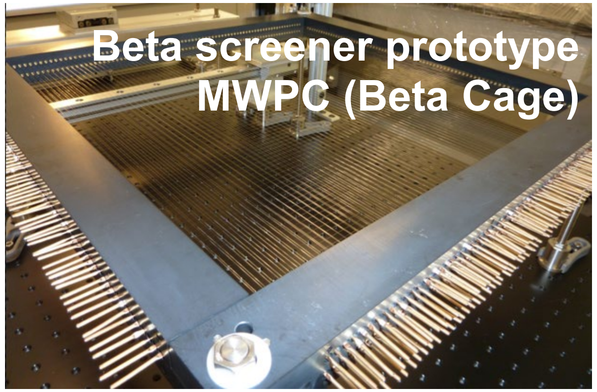
Dust on surfaces

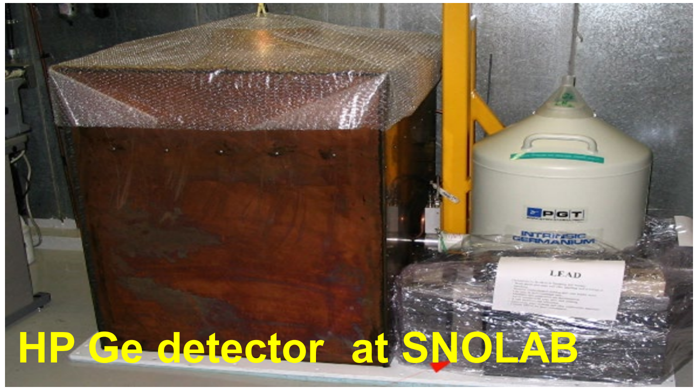
- Dust can accumulate on surfaces and can contain radioactive contaminants.
- Need to know the type and concentration of radioactive contaminants, accumulation rate and mass of the dust.

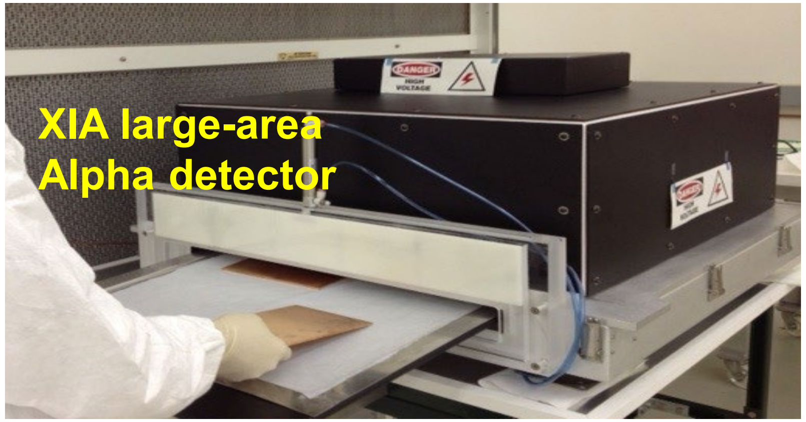
Slide credit: Birgit Zatschler

Background assay examples

Radiopurity requirements are so high, assay detector apparatus must be almost as well-shielded and low-background as the DM detector itself!



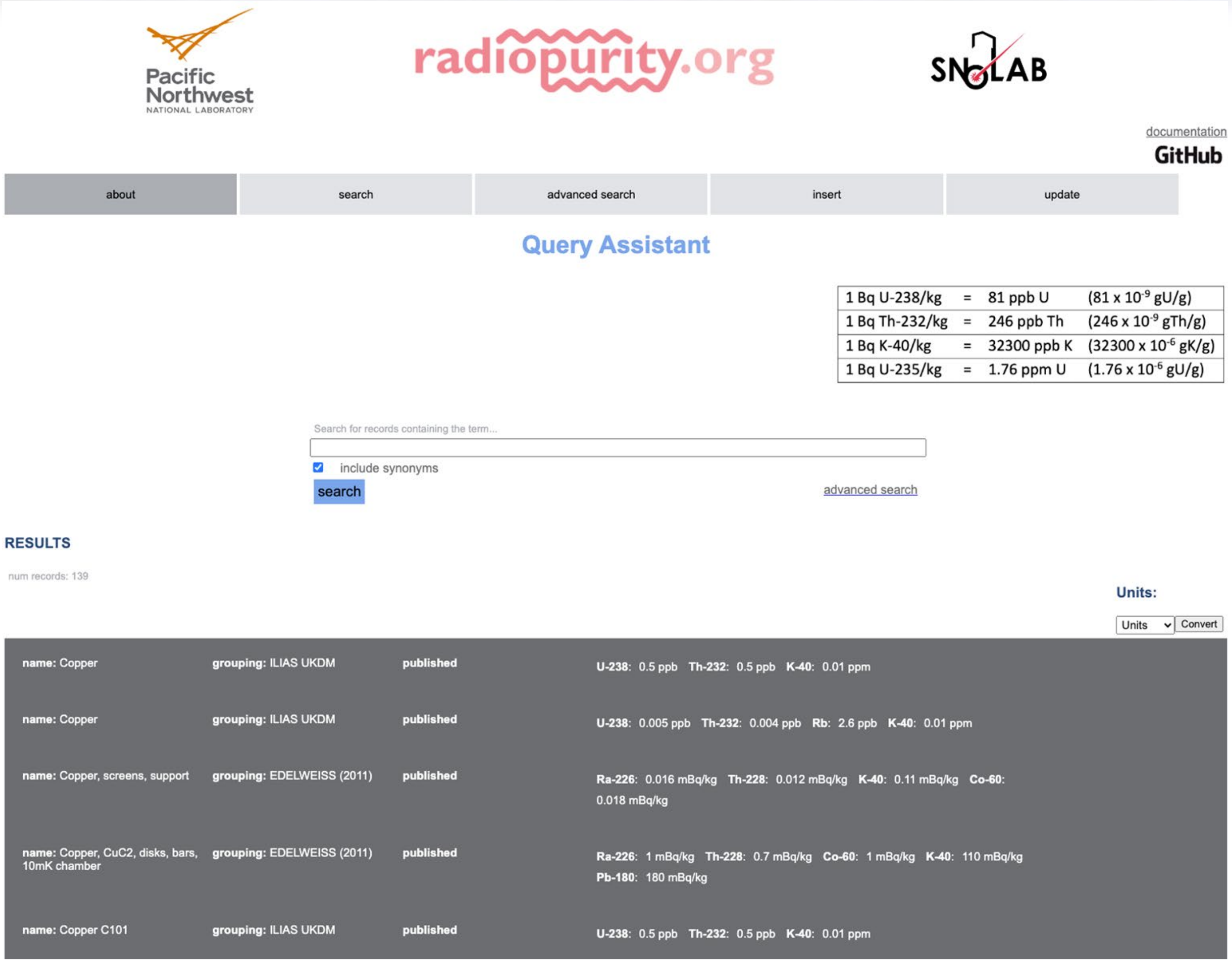




Quantifying isotope contamination at the level of parts per billion (ppb) is challenging!

Slide credit: Enectali Figueroa-Feliciano

Radiopurity database!



Pacific Northwest NATIONAL LABORATORY

radiopurity.org

SNOLAB

documentation

GitHub

about | search | advanced search | insert | update

Query Assistant

1 Bq U-238/kg	=	81 ppb U	(81 x 10^{-9} gU/g)
1 Bq Th-232/kg	=	246 ppb Th	(246 x 10^{-9} gTh/g)
1 Bq K-40/kg	=	32300 ppb K	(32300 x 10^{-6} gK/g)
1 Bq U-235/kg	=	1.76 ppm U	(1.76 x 10^{-6} gU/g)

Search for records containing the term...

include synonyms

search

advanced search

RESULTS

num records: 139

Units:

Units Convert

name: Copper	**grouping:** ILIAS UKDM	**published**	**U-238:** 0.5 ppb **Th-232:** 0.5 ppb **K-40:** 0.01 ppm
name: Copper	**grouping:** ILIAS UKDM	**published**	**U-238:** 0.005 ppb **Th-232:** 0.004 ppb **Rb:** 2.6 ppb **K-40:** 0.01 ppm
name: Copper, screens, support	**grouping:** EDELWEISS (2011)	**published**	**Ra-226:** 0.016 mBq/kg **Th-228:** 0.012 mBq/kg **K-40:** 0.11 mBq/kg **Co-60:** 0.018 mBq/kg
name: Copper, CuC2, disks, bars, 10mK chamber	**grouping:** EDELWEISS (2011)	**published**	**Ra-226:** 1 mBq/kg **Th-228:** 0.7 mBq/kg **Co-60:** 1 mBq/kg **K-40:** 110 mBq/kg **Pb-180:** 180 mBq/kg
name: Copper C101	**grouping:** ILIAS UKDM	**published**	**U-238:** 0.5 ppb **Th-232:** 0.5 ppb **K-40:** 0.01 ppm

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Simulation example

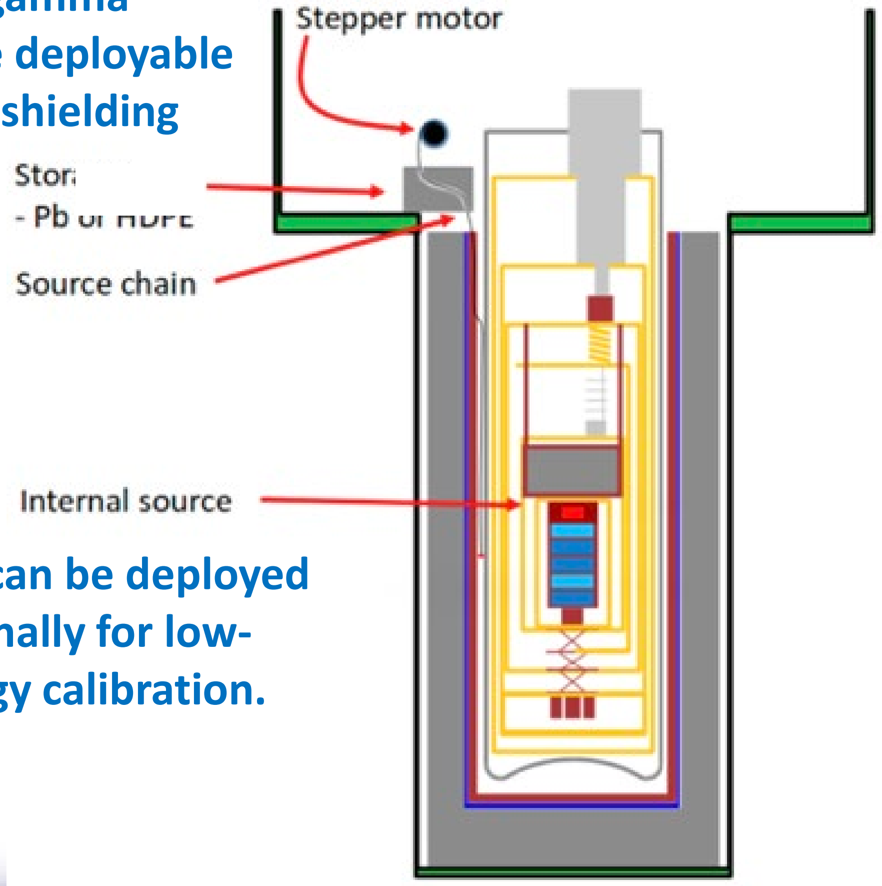
- What **GEANT4** does: Particle transport through materials, interactions of particles with atoms ("EM processes") or nuclei ("hadronic processes")
  - Processes implemented for energies ~100 eV to ~10 TeV
  - Particles (including secondaries!) tracked individually, until they lose all their energy (dE/dx) or decay
  - Transport assumes simple relativistic kinematics
- User defines full apparatus geometry and EM fields in GEANT4
- User also defines "sources" (natural or artificial)
- User chooses physics processes from pre-defined lists
- GEANT4 generates events: particles emitted from sources, incident on apparatus
  - Monte Carlo method
- Interactions lead to energy deposits (**hits**) at specific locations in detector; energy transferred between nuclei and/or electrons (ionization, dE/dx)

Another thing: Calibrations

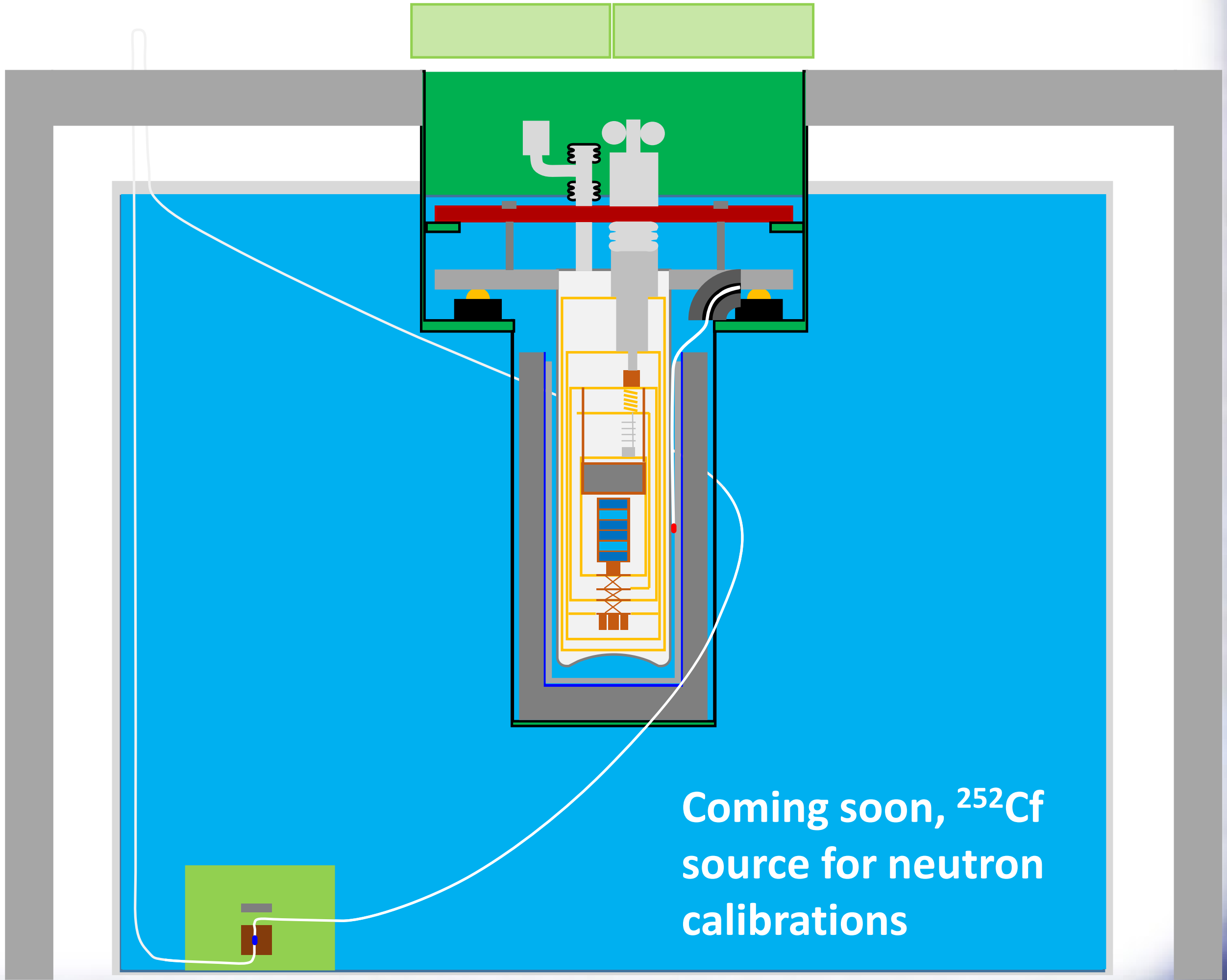
To get accurate background spectra, need to get the energy scale right!

e.g. CUTE:

^{133}Ba gamma source deployable inside shielding

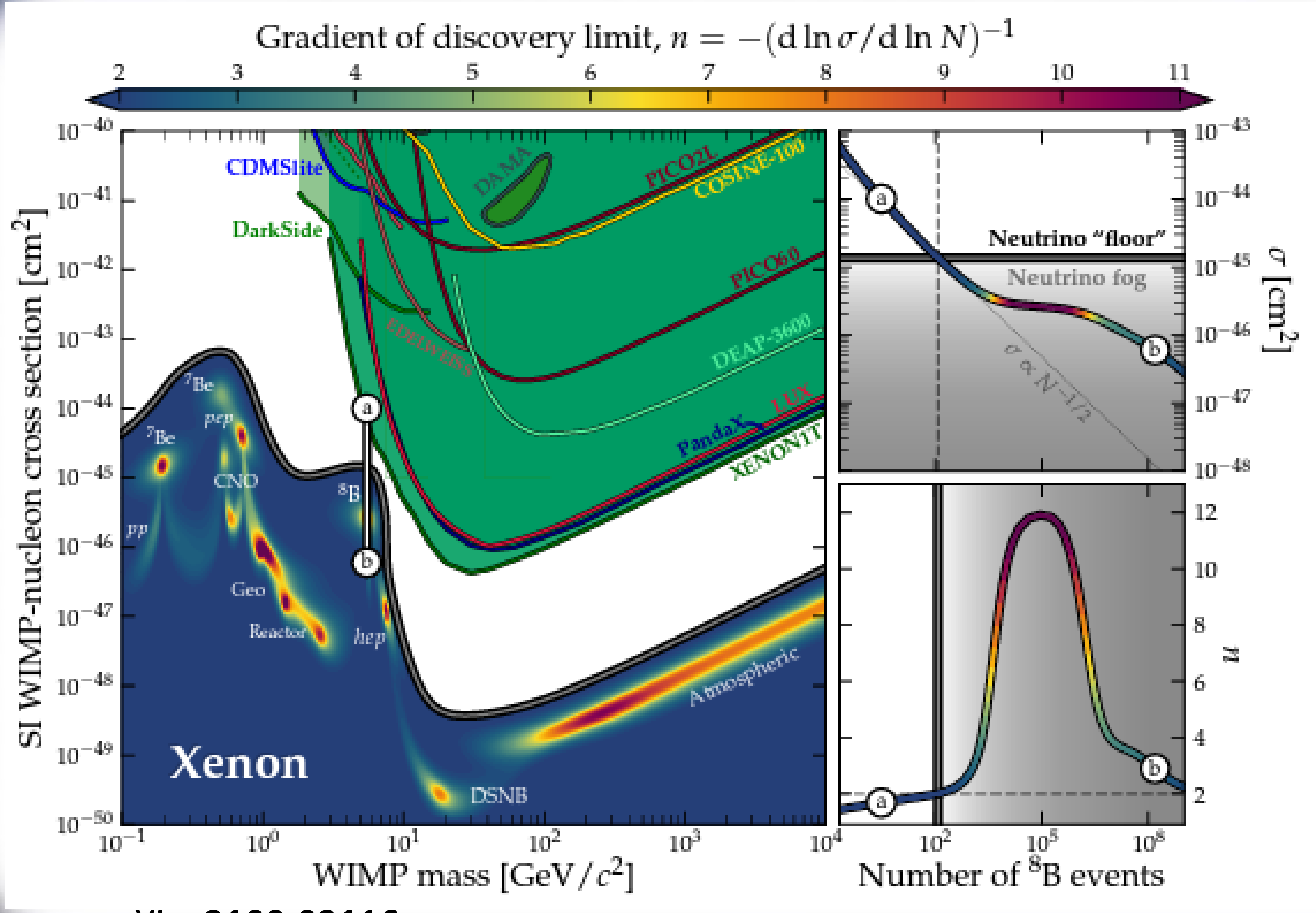


^{55}Fe can be deployed internally for low-energy calibration.



Coming soon, ^{252}Cf source for neutron calibrations

What about the neutrinos?!



arXiv: **2109.03116**

ν "floor" traditionally defines region of parameter space where DM signals get hidden under "irreducible" ν bg

- under arbitrary choices of exposure, threshold

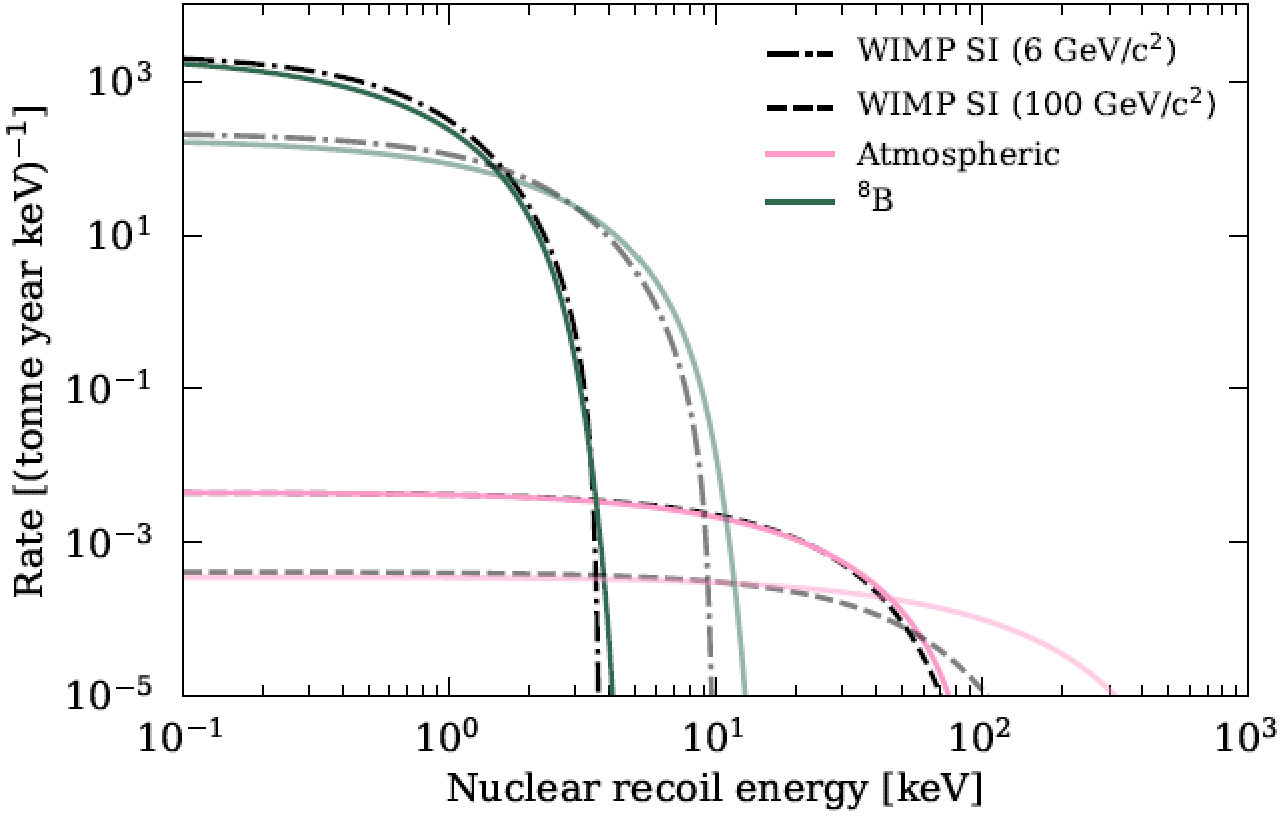
New definitions proposed, e.g. :
n = index in scaling of *discovery limit* σ with *#bg events N ,*
fog = n>2 regime

Still:

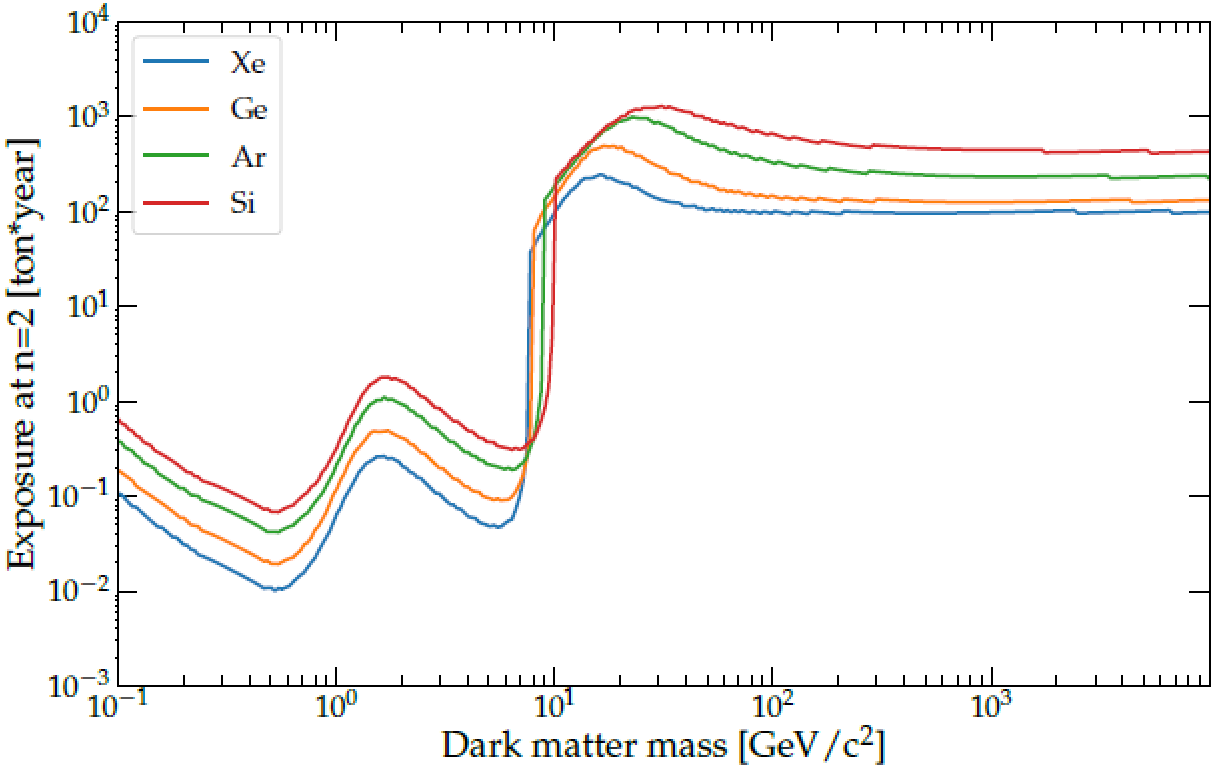
- Depends on target material
- Influenced by systematic uncertainties on ν flux normalization

Neutrino backgrounds making you foggy-headed?

ν NRs on Xe (darker colour) and Ar (lighter)

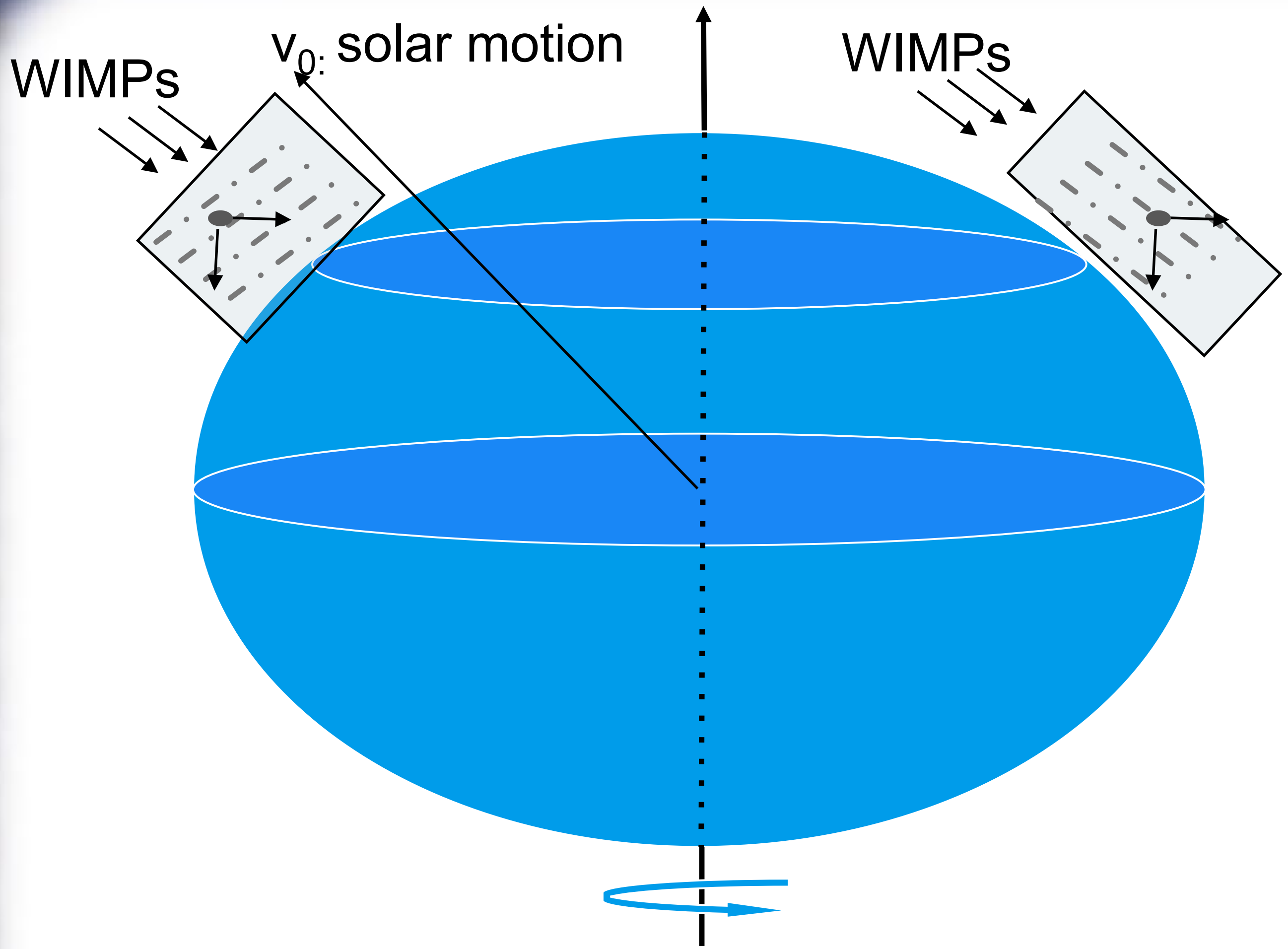


Exposure required to reach *n*=2 (systematic-limited) SI ν fog

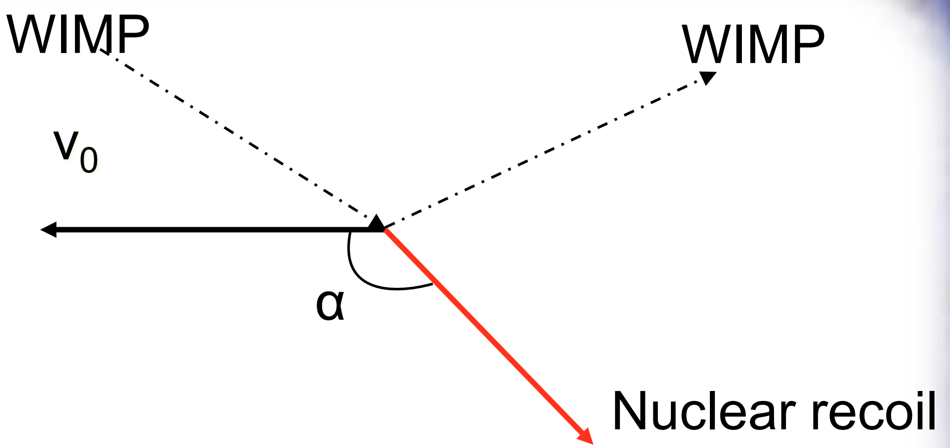


arXiv: **2109.03116**

Directional Detection to penetrate fog?



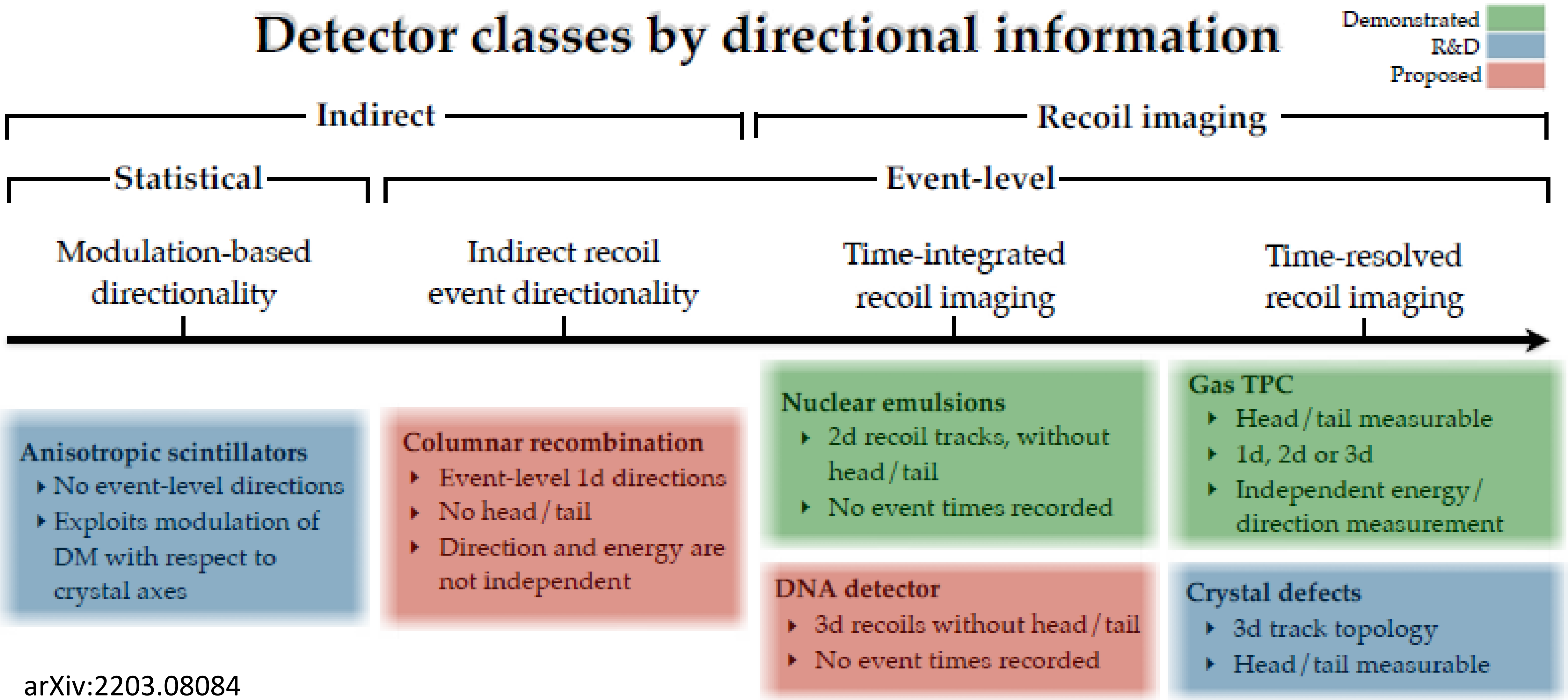
Diurnal modulation: mean recoil direction rotates over one sidereal day



Distribution of angle between solar motion and recoil direction: peaks at α=180°

Slide credit: Enectali Figueroa-Feliciano

Directional Detection to penetrate fog?



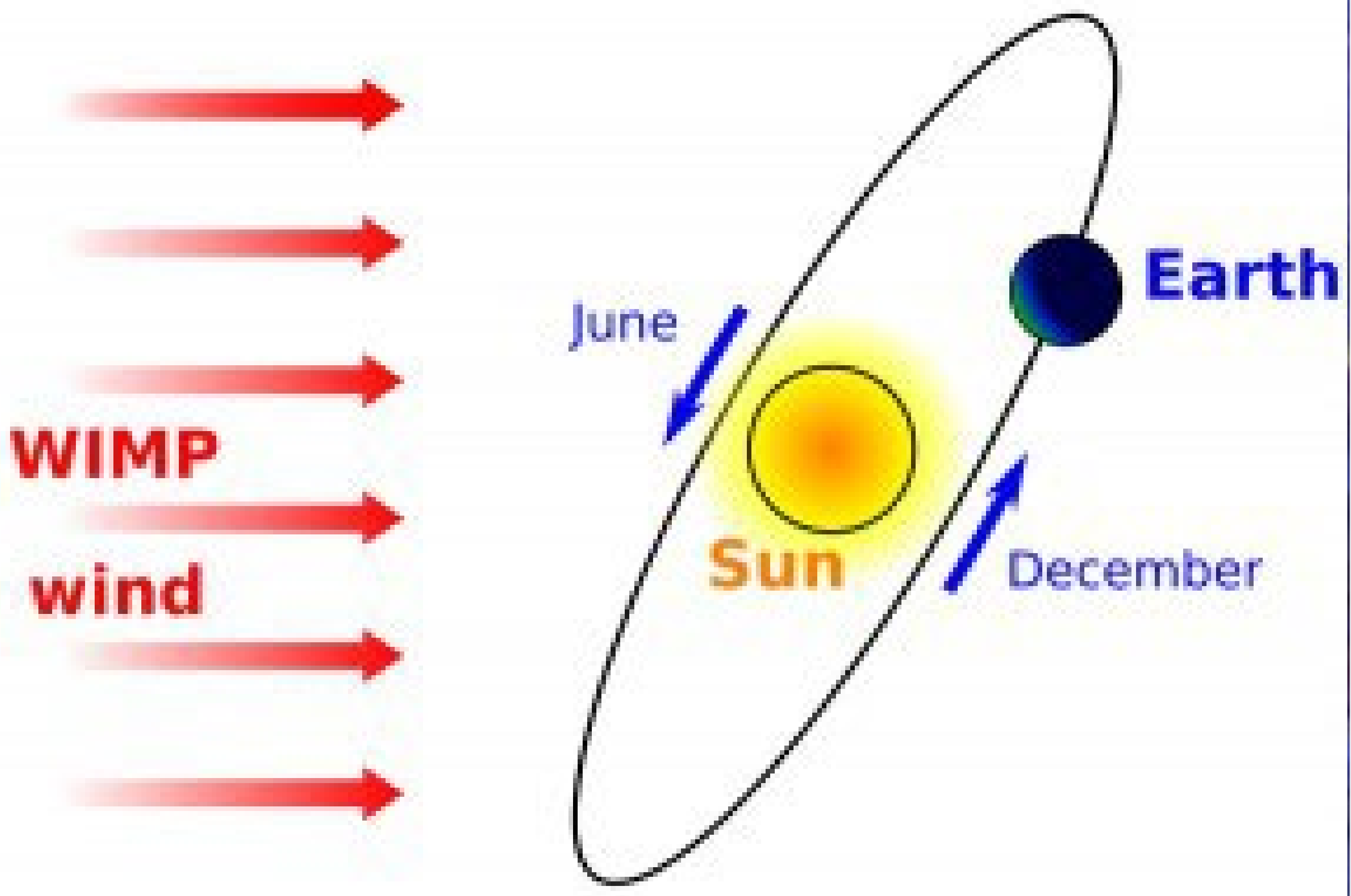
arXiv:2203.08084

That Weird DAMA Thing… ?!

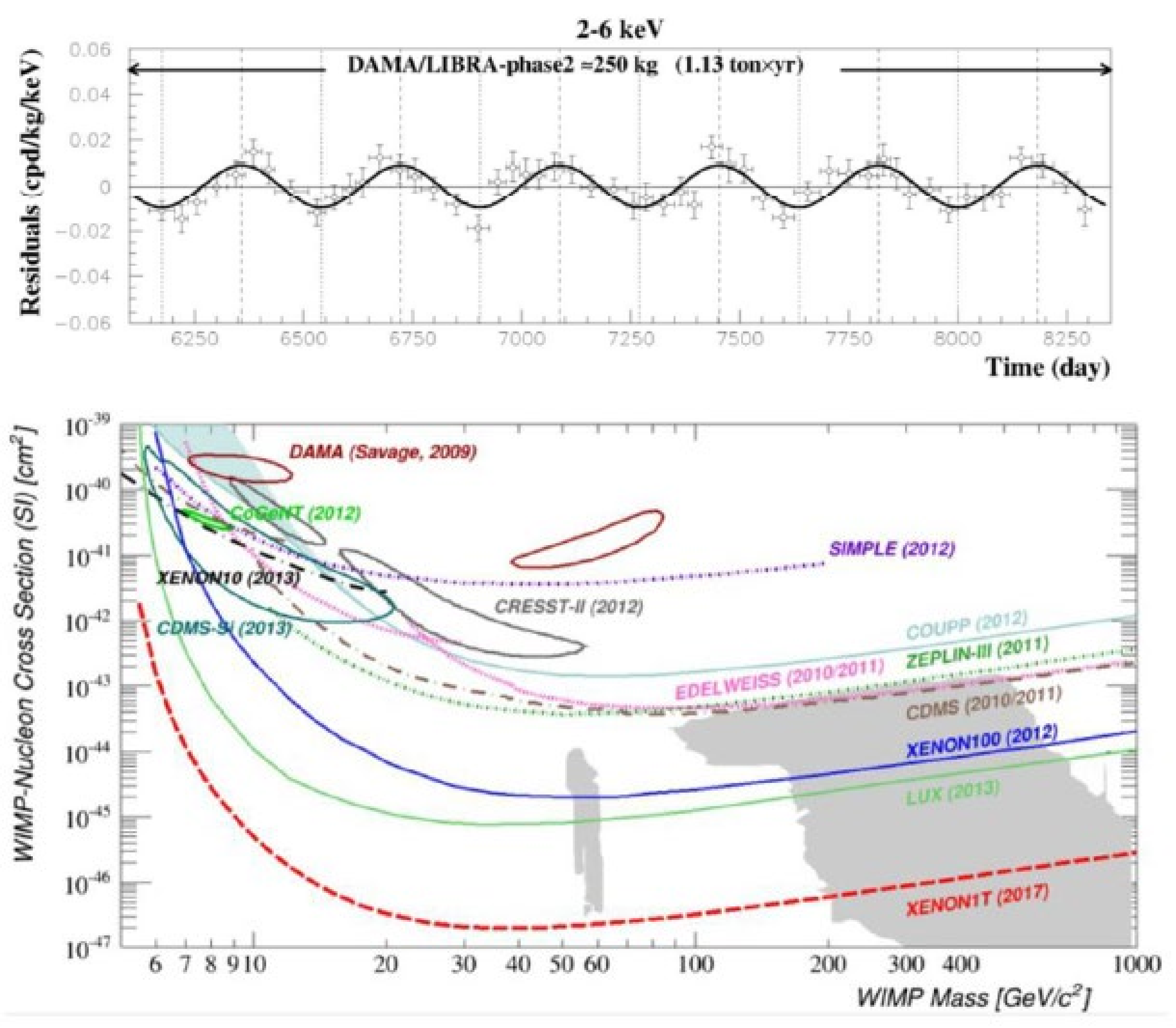
Annual Modulation

Basic concept: <u>absolute</u> #events in detector doesn't matter, only <u>relative</u> # at different times of year.

So, backgrounds that are constant in time don't matter … right?



And Now For Something Confusing…



DAMA/LIBRA sees 12-sigma “annual modulation” signal, incompatible with null-results from direct detection experiments that use background subtraction / modelling!

And Now For Something Confusing…

Is the "DAMA signal" ruled-out? Probably.

https://www.forbes.com/sites/startswithabang/2021/03/04/goodbye-damalibra-worlds-most-controversial-dark-matter-experiment-fails-replication-test/ , https://www.nature.com/articles/d41586-022-02222-9

- COSINE: https://arxiv.org/abs/1906.01791
- ANAIS: https://arxiv.org/abs/2103.01175 , https://pos.sissa.it/441/041/pdf