Laboratories for rare event search experiments

-- Designing an Ideal WIMP experiment

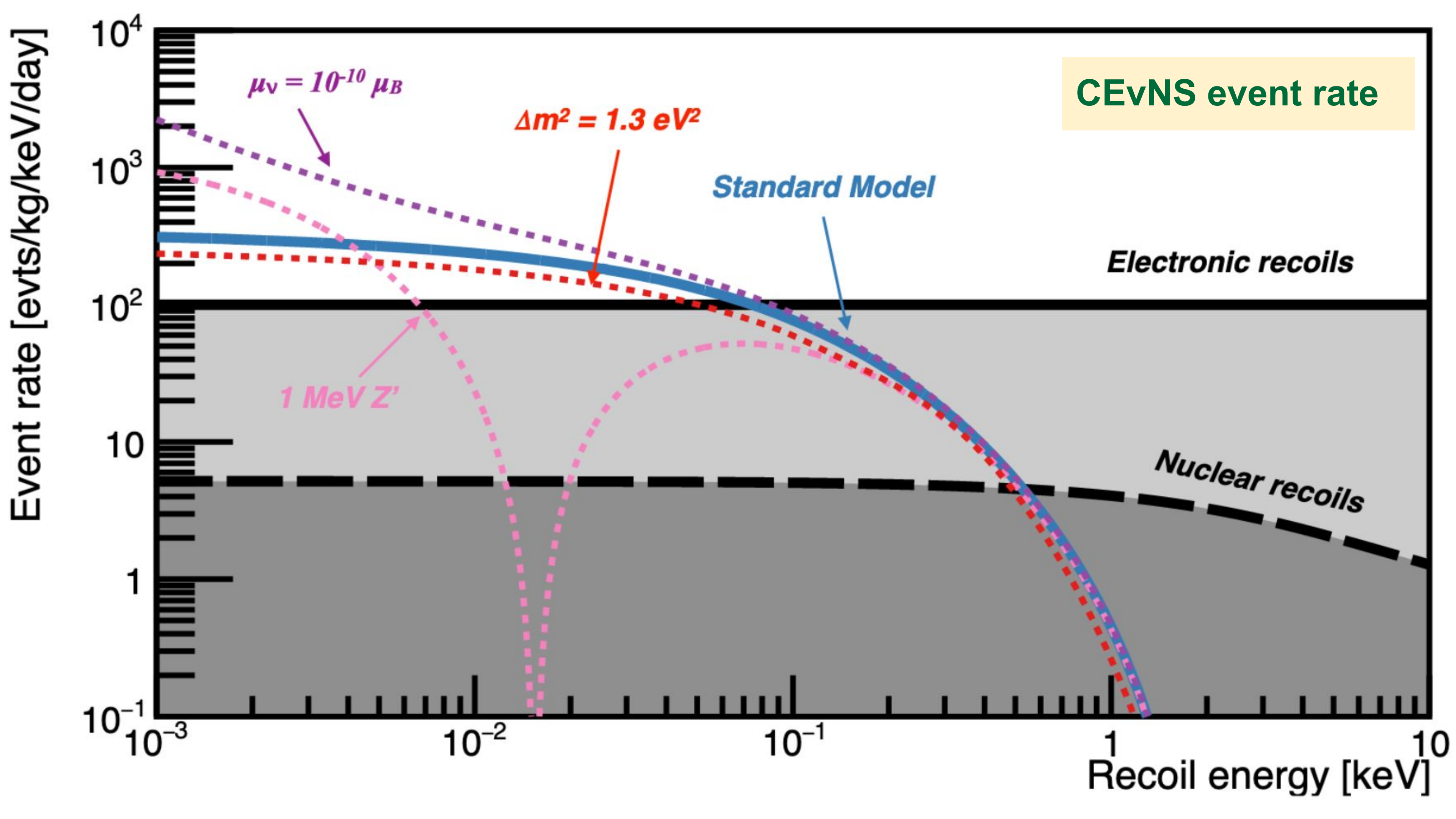
Rare event search experiments

- Finding a needle in a haystack…
- Examples:
- Direct detection of WIMP dark matter
  - <O(1) events/(30 kg years)
  - Signal region <10 keV
- Neutrinoless double beta decay (0vbb)
  - <O(1) events/(500 kg year)
  - Signal region ~ few MeV
- Neutrino coherent scattering (CEvNS)
  - ~O(1) events/(10 kg years)
  - Signal region <1 keV
- Numbers benchmarked for Xe-based experiments taken from Hyun Su Lee's presentation in CARLO 2016 here

Image obtained from internet

Background (haystack)

- Common unit used: DRU, Differential Rate Unit
    - 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 (ROI)
- Benchmark numbers stuck in my head
    - Unshielded lab: 10,000 DRU
        - Dominated by gammas from ^{40}K, ^{232}Th, ^{238}U from the wall
        - Muon rate: 1/(min * cm^2) at sea level
    - Useful environment: 100 DRU
    - Good environment: < (or <<) 10 DRU



CEvNS event rate
$\mu_\nu = 10^{-10}\,\mu_B$
$\Delta m^2 = 1.3\ eV^2$
Standard Model
Electronic recoils
1 MeV Z'
Nuclear recoils
Event rate [evts/kg/keV/day]
Recoil energy [keV]
10^4
10^3
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
10

Notes about noise vs background

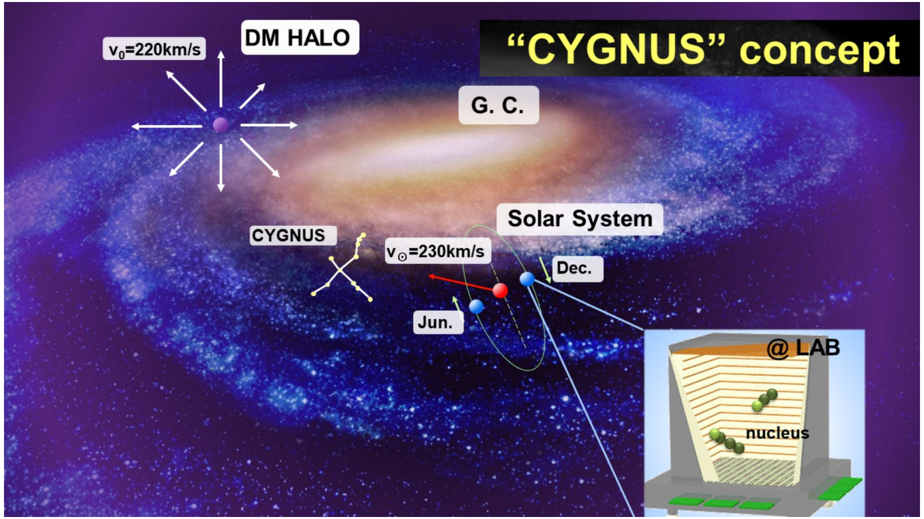
- Sometimes “noise” and “background” are used interchangeably
  - → Things that are not signal
- In some scenarios, we differentiate noise from background:
  - Noise is happening continuously
    - Due to physics, for sure… We’ll get into noise modeling in a later lecture
    - Often **not** coming from particle interactions
  - Background is mostly from particle interactions
    - Known or unknown
    - Give pulses in your detectors

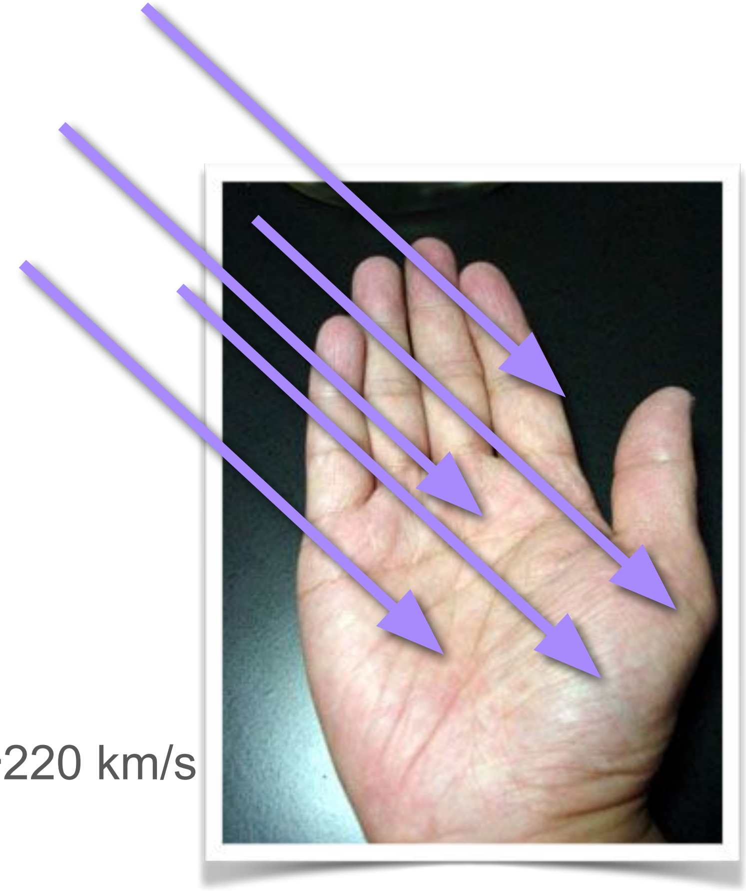
WIMP detection as an example

Theme: more signal, less background, then try to tell them apart…

Lecture adapted from Tali's slides
from TASI 2016

The Dark Matter Wind





- Dark matter apparently blows from Cygnus
- Our speed relative to the dark matter halo is ~220 km/s
- ~100,000 particles/cm^2/sec
- About 20 million/hand/sec
- Figure taken from the CYGNUS project

Principles of Particle Detection

Signal Interaction Rate
[events/(keV*kg*day)]

particle theory | nuclear structure | astrophysics properties

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

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

“reduced mass”

Principles of Particle Detection

Signal Interaction Rate [events/(keV*kg*day)]

astrophysics properties

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

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

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

Principles of Particle Detection

Signal Interaction Rate
[events/(keV*kg*day)]

nuclear structure

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

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

"Woods-Saxon Nuclear Form Factor"

J1 = Bessel function of the first kind, cylindrical harmonic

q = momentum transferred

s = "nuclear skin thickness", or the distance through which the charge density of the nucleus drops to zero (it is not a step function due to quantum mechanics)

Principles of Particle Detection

Signal Interaction Rate [events/(keV*kg*day)]

particle theory

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

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

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

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

A ← atomic mass

f ↑ coupling constant

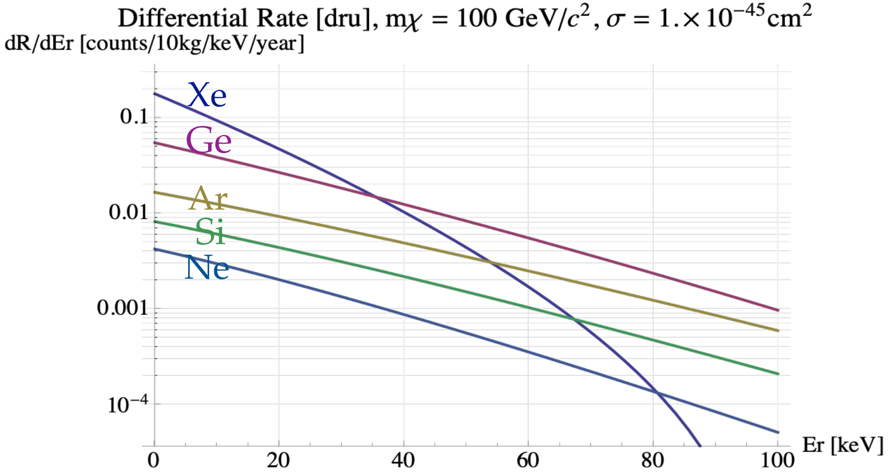
Enormous enhancement for heavy nuclei target!

Principles of Particle Detection

Signal
Interaction
Rate
[events/(keV*kg*day)]

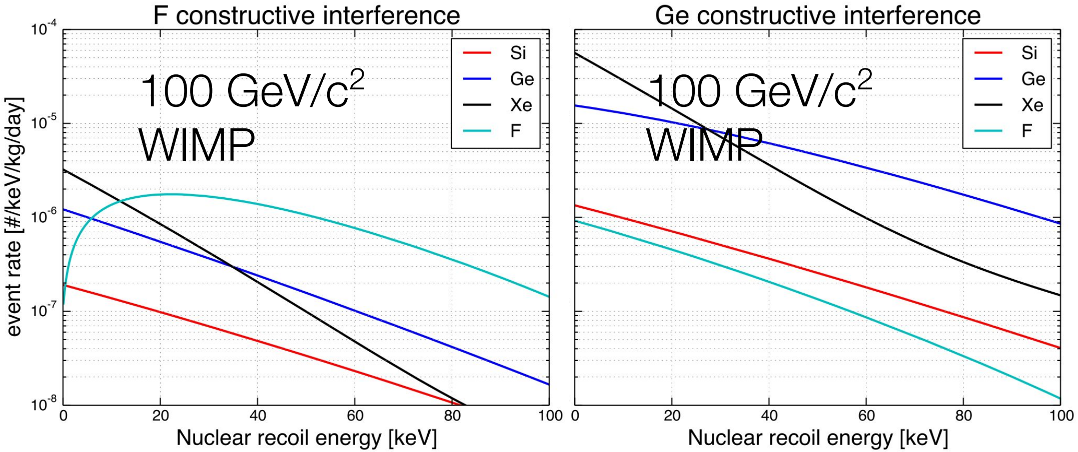
particle
theory

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



Dark Matter Could Look Different in Different Targets

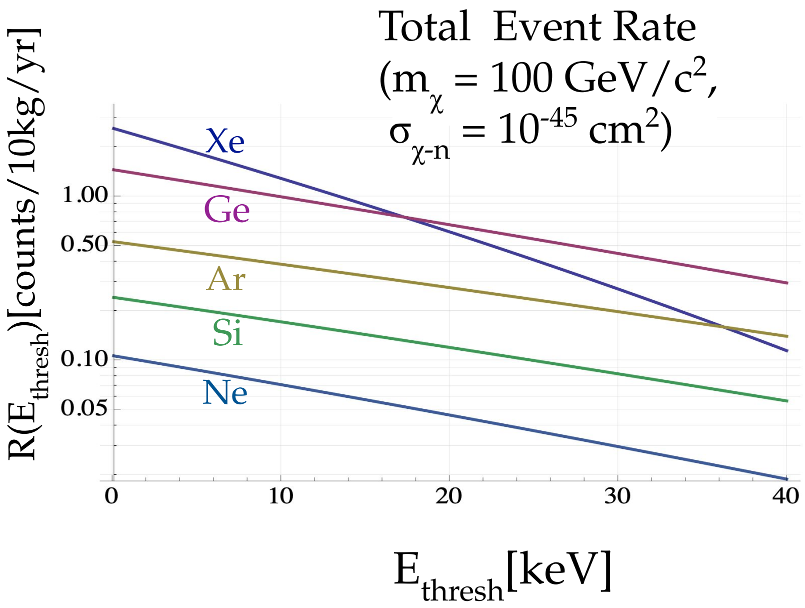
- More sophisticated interactions can exist, leading to not only different rates between targets, but different spectral shapes
- A robust dark matter direct detection program with different target materials will be needed to nail down which operators are contributing to any detected signal
- **We will need multiple targets to map out the physics of WIMP-nucleon interactions!**



Designing an Ideal WIMP Detector

The Event Rates are Extremely Low!

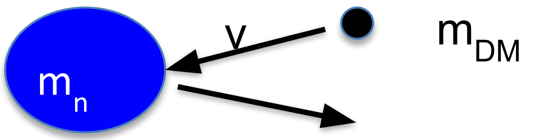
- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break…
- Event Rate is very, very low
- Radioactive background of most materials is higher than the event rate.



Nuclear Recoil Direct Detection Requirements

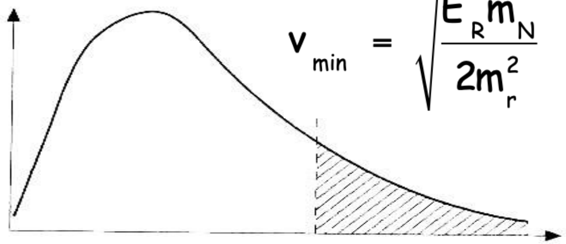
1: Large Exposure (Mass x Time)

The low-mass WIMP challenge

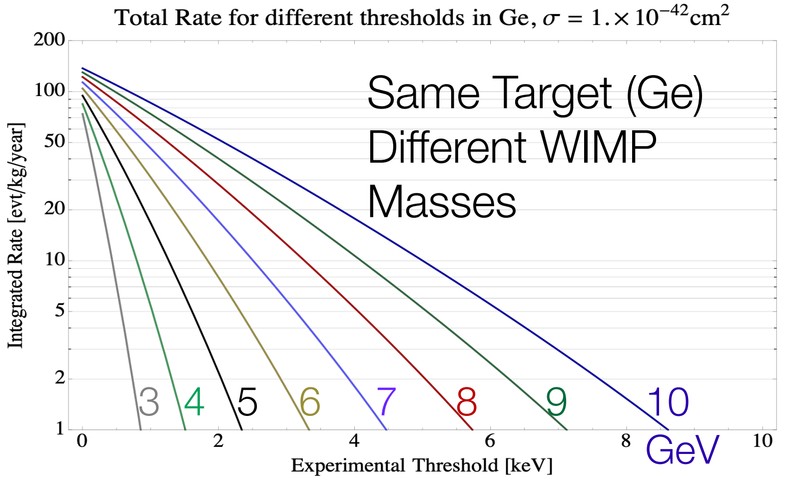


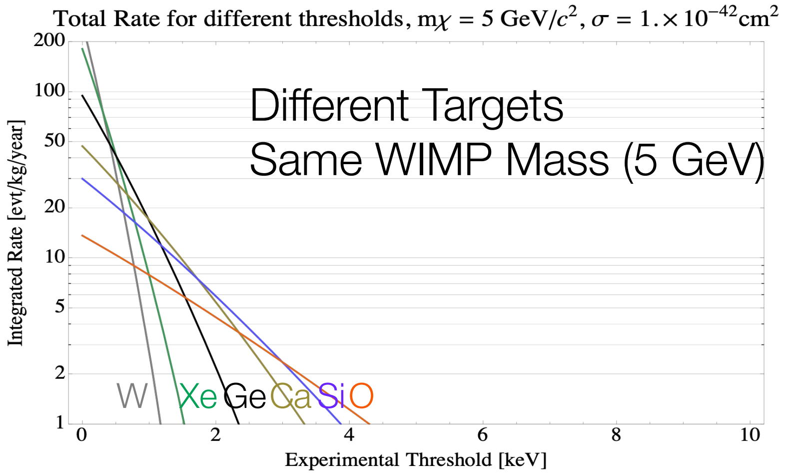
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

A WIMP must have a minimum velocity to produce a recoil of a specific energy



$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$





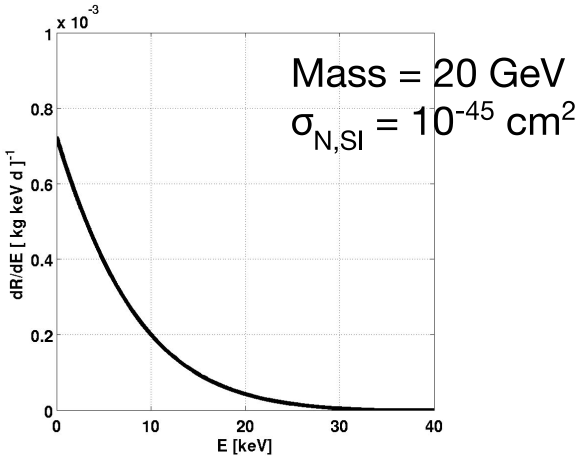
Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold

The (Signal) Event Rates are Extremely Low!

Expected WIMP Spectrum

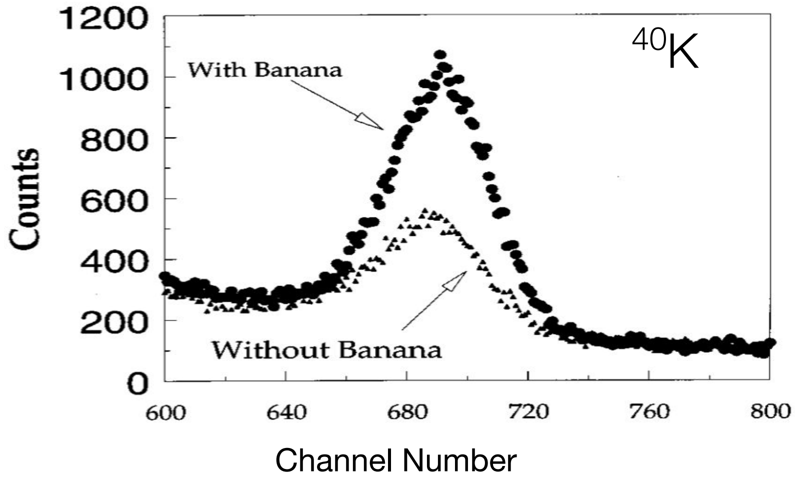


~1 event per kg per **year**

(Nuclear Recoils)

Measured Banana Spectrum

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

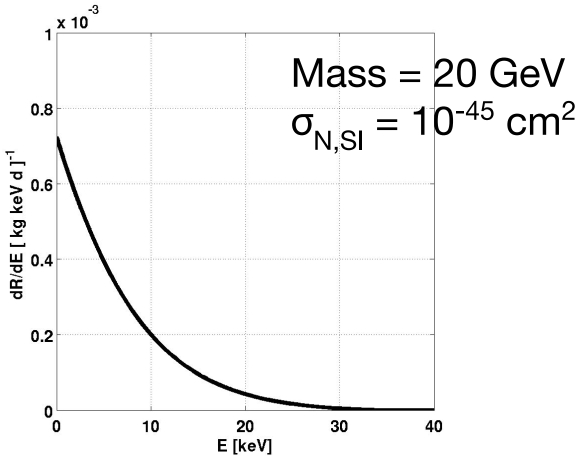


~100 event per kg per **second**

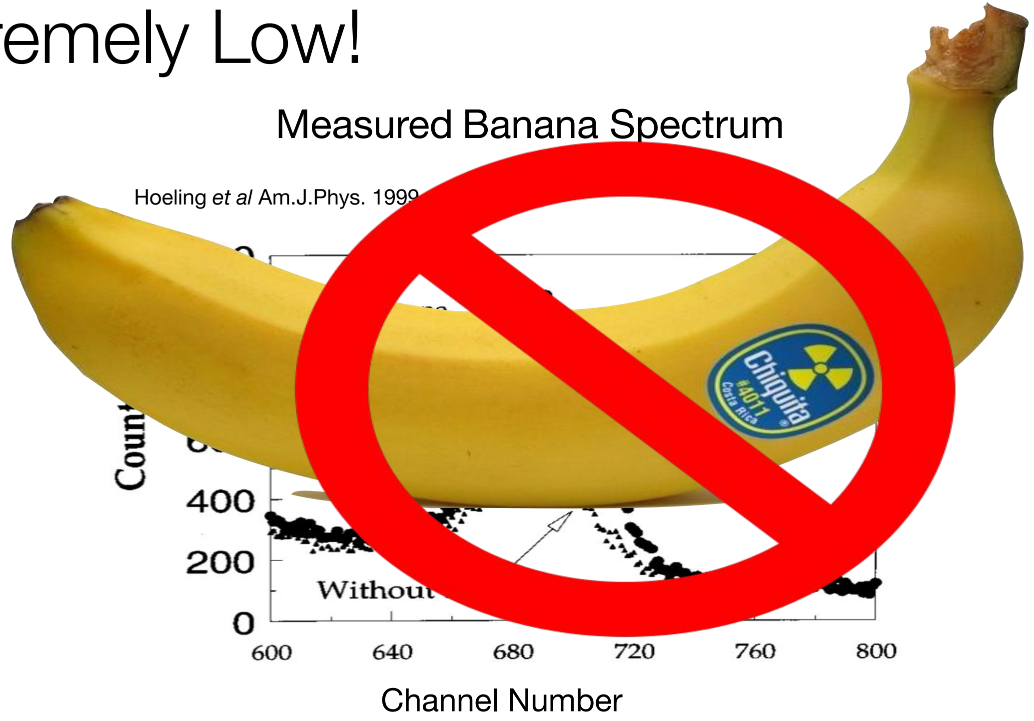
(Electron Recoils)

The Event Rates are Extremely Low!

Expected WIMP Spectrum



Measured Banana Spectrum



~1 event per kg per **year**

(Nuclear Recoils)

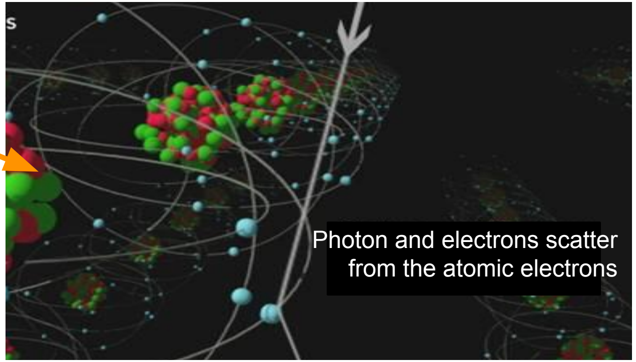
~100 event per kg per **second**

(Electron Recoils)

Discrimination between electron and nuclear recoils really helps!

Typical backgrounds

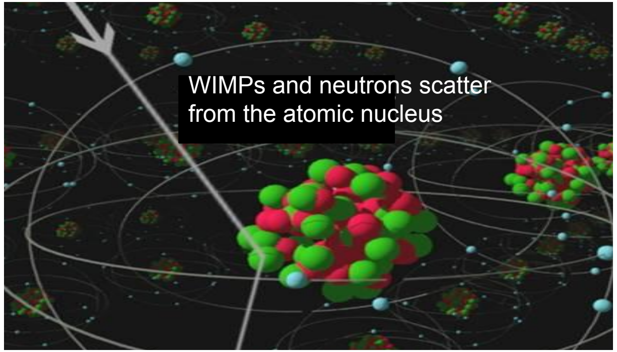
Most backgrounds are from trace radioactivity (U, Th, K contamination) or induced by cosmic rays (cosmogenic background)



ELECTRON RECOILS (ER)

Gamma: Most prevalent background

Beta: on the surface or in the bulk



NUCLEAR RECOILS (NR)

Neutron: NOT distinguishable from WIMP

Alphas: almost always a surface event

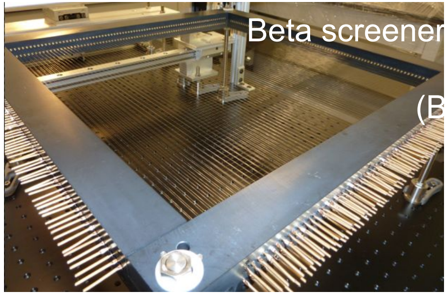
Recoiling parent nucleus: yet another surface event

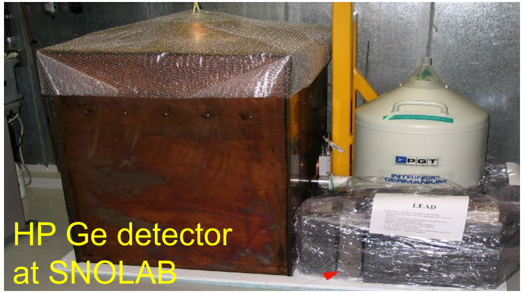
Managing backgrounds (in 5-steps)

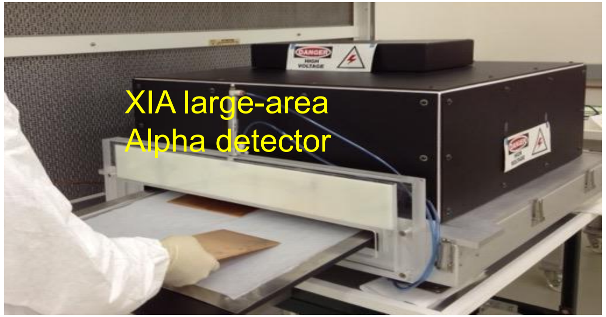
1) Choose highly radiopure materials for your detector and experimental setup. Build it in a state-of-the art clean lab (class ~1000 or better is often used).

1a) Screening and material assay

Materials used for dark matter (and some neutrino) experiments must be thoroughly screened for radioactivity before use.







In many cases one is looking for isotope contamination at the level of parts per billion (ppb).

The demands on radiopurity are so high that one needs a detector that is almost as well shielded and low in background as the dark matter detector itself!

www.radiopurity.org

radiopurity.org

documentation

GitHub

about | search | advanced search | insert | update

Query Assistant

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

Search for records containing the term...

include synonyms

search

advanced search

RESULTS

num records: 139

Units:

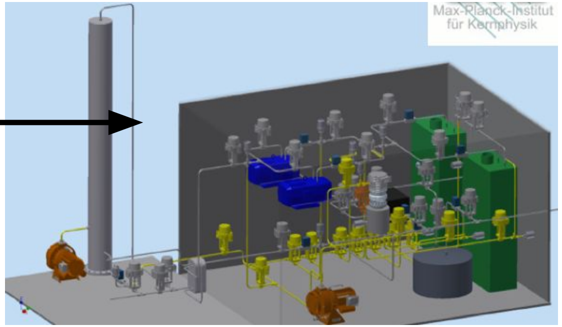
Units Convert

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

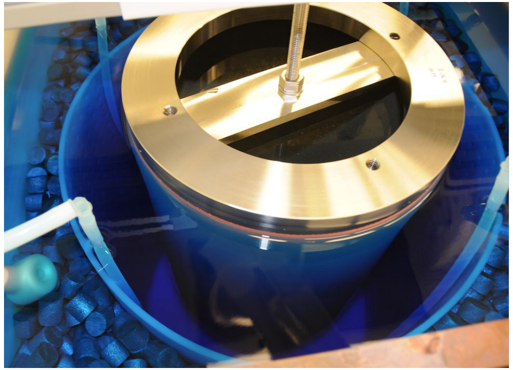
1b) If you can't find it build it

If the materials you come across aren't clean enough then build, extract or purify it yourself

Kr and Rn purification schematic for Xenon 1T



Distillation tower (at Fermilab) for extracting Ar depleted in 39Ar from natural gas wells



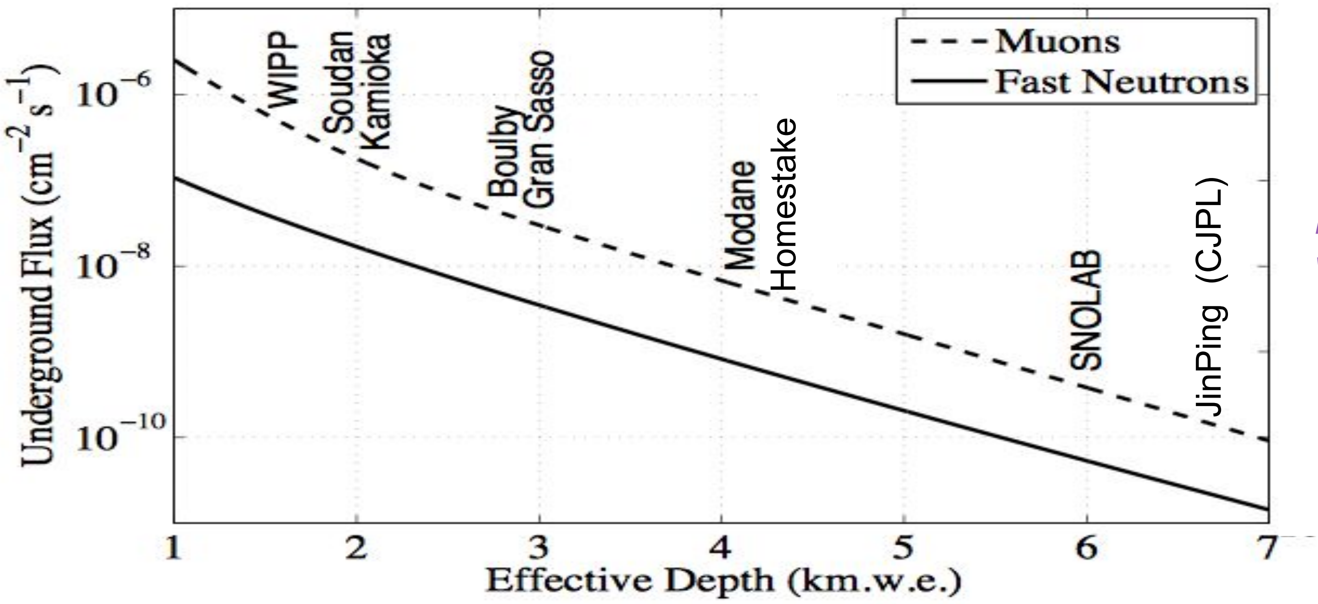
Copper electroforming setup at PNNL

Managing backgrounds (in 5-steps)

1) Choose highly radiopure materials for your detector and experimental setup. Build it in a state-of-the art clean lab (class ~1000 or better is often used).

2) Cosmic muons produce fast neutrons via spallation. These are difficult to shield against and are a source of irreducible background. Go deep underground where the fast neutron flux is reduced.

2) Where to locate your experiment



m.w.e. = meters water equivalent

Most experiments use the earth as shielding from muons. The lower the muon rate, the lower the fast neutron rate.

Managing backgrounds (in 5-steps)

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3) Unless you bury your detector 2 km deep in pristine glacial ice, you will have significant background from radioactivity. Surround your radiopure experiment with several tons of radiopure shielding

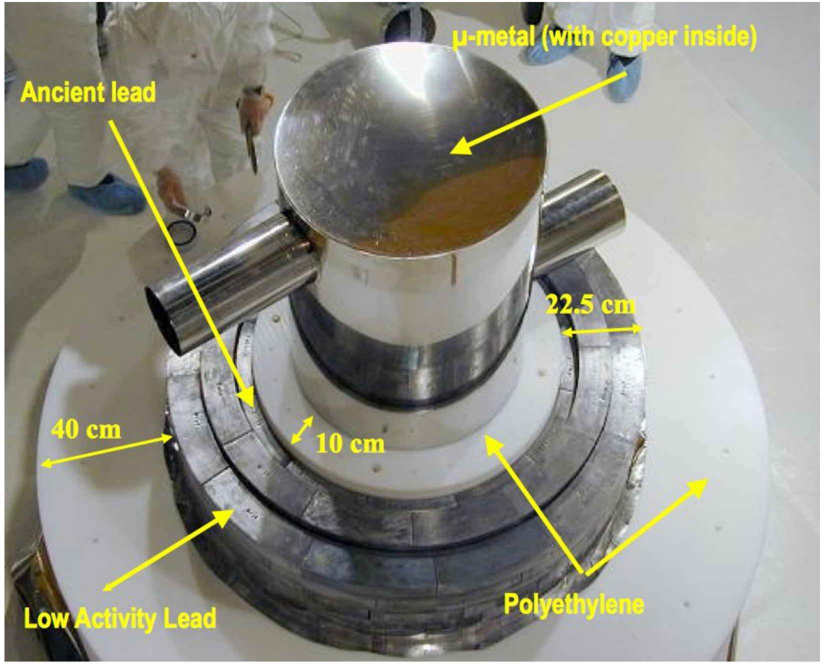
3a) Passive Shielding

Trace U/Th/K and other isotopes in cavern walls and surroundings produce a constant flux of gammas and neutrons (via spontaneous fission or α,n)

Lead shields against gammas; *~22 cm drops the gamma rate by ~10^6*

Ancient lead or copper shields against ^{210}Pb, and its daughters, found in standard lead

Polyethylene or water moderates radiogenic and cosmogenic neutrons so that they produce recoils below the experimental threshold; *0.5 m of poly reduces the neutron scattering rate by ~10^4*

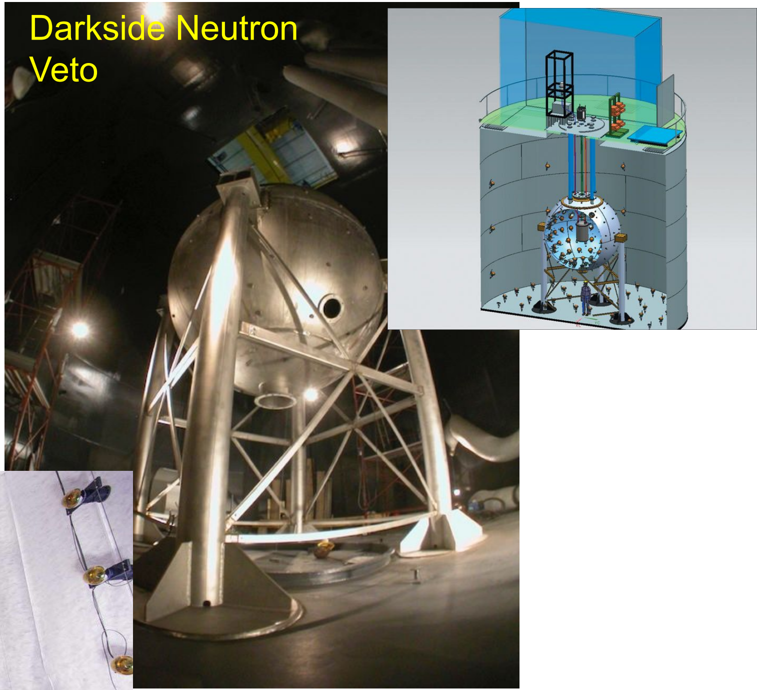


SuperCDMS Soudan passive shielding

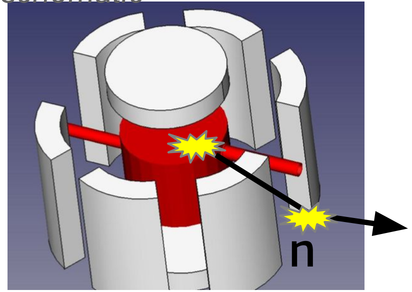
3b) Active Shielding

Muon Veto: water cherenkov or scintillator; rejects muons passing through or near experiment (and the fast neutrons that come with them)

Neutron Veto: liquid scintillator doped with isotope w/ high neutron capture cross-section; tags radiogenic neutrons that originate on contaminated material close to or within the experiment.



SuperCDMS neutron veto schematic



Managing backgrounds (in 5-steps)

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3) Unless you bury your detector 2 km deep in pristine glacial ice, you will have significant background from radioactivity. Surround your radiopure experiment with several tons of radiopure shielding

4) You will likely still have O(106) more ER than expected WIMP scatters in your detector, so make sure your experiment has some ability to distinguish ER from NR - at the level of one part in 106 or 107 if you can manage it.

Managing backgrounds (in 5-steps)

1) Choose highly radiopure materials for your detector and experimental setup. Build it in a state-of-the art clean lab (class ~1000 or better is often used).

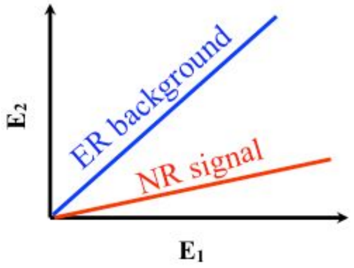
2) Cosmic muons produce fast neutrons via spallation. These are difficult to shield against and are a source of irreducible background. Go deep underground where the fast neutron flux is reduced.

3) Unless you bury your detector 2 km deep in pristine glacial ice, you will have significant background from radioactivity. Surround your radiopure experiment with several tons of radiopure shielding

4) You will likely still have $O(10^6)$ more ER than expected WIMP scatters in your detector, so make sure your experiment has some ability to distinguish ER from NR - at the level of one part in 10^6 or 10^7 if you can manage it.

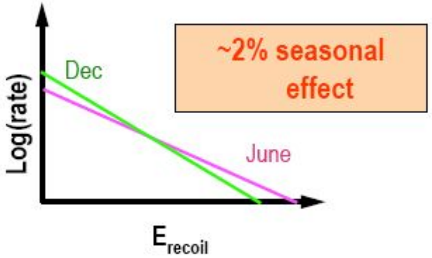
5) A team of talented students and postdocs who fine-tune rejection of background and maximize signal acceptance will extract the most out of the data.

Separating Signal from Background…



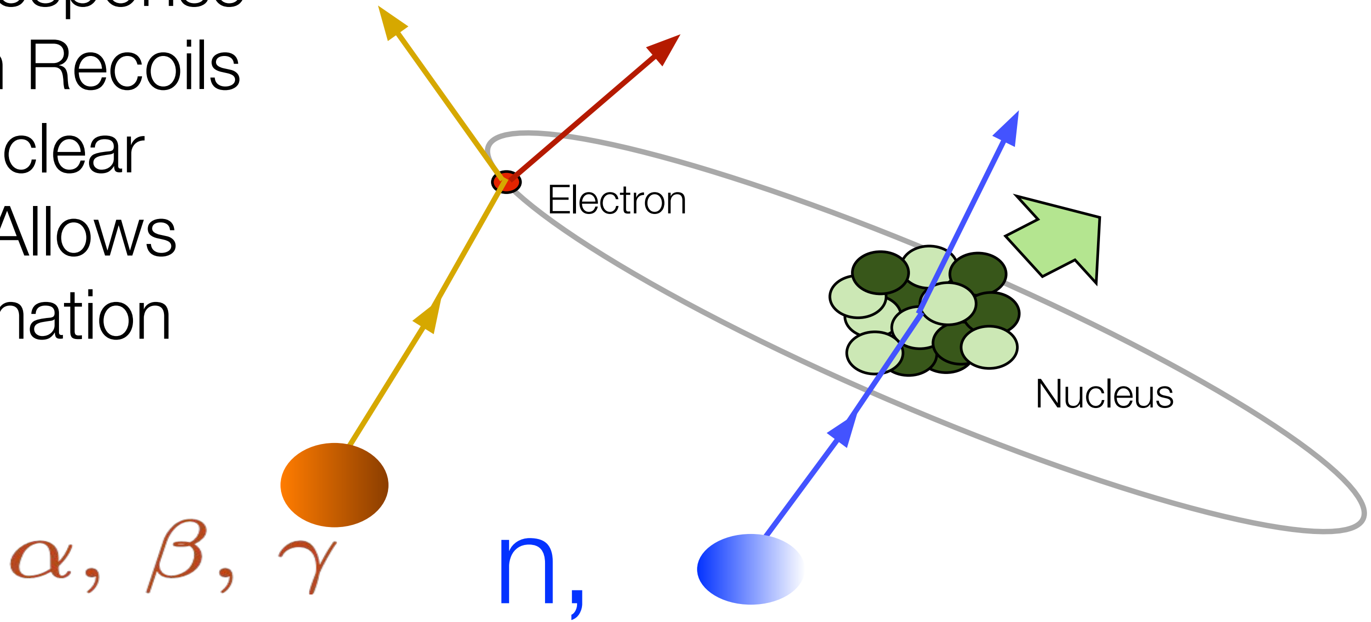
- By Detector Response
  - Obtain particle identification from the physics of the detector response to different types of particle interactions.

- By Astrophysical Modulation
  - Annual Modulation in the WIMP recoil spectrum. Earth's velocity through the galactic halo is max in June, min in December (DAMA/LIBRA).
  - Daily modulation of the incident WIMP direction. Measure the direction of the short track produced by nuclear recoil. (DM-TPC)
- Can be Event-by-Event or Statistical



Particle ID through Detector Response

Different Response to Electron Recoils and Nuclear Recoils Allows Discrimination



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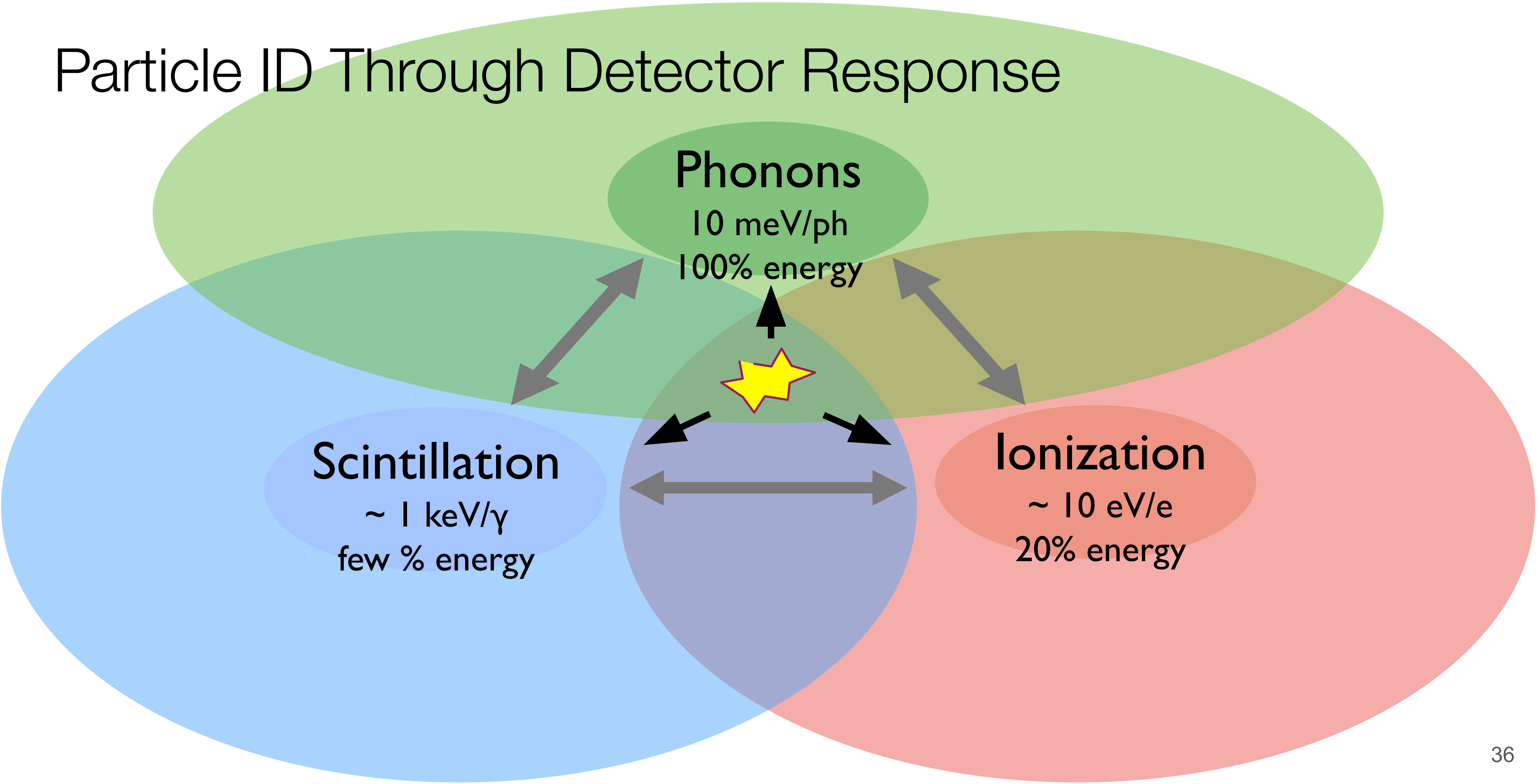
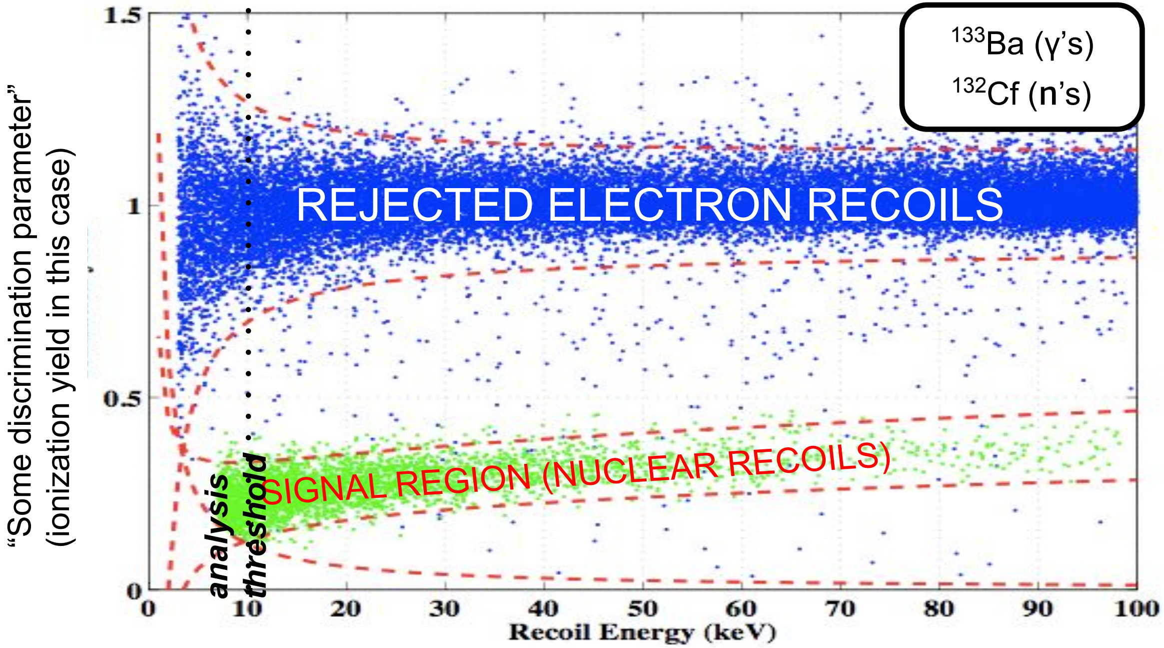
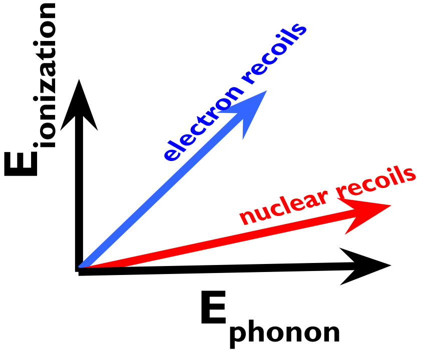


Textbook example with CDMS





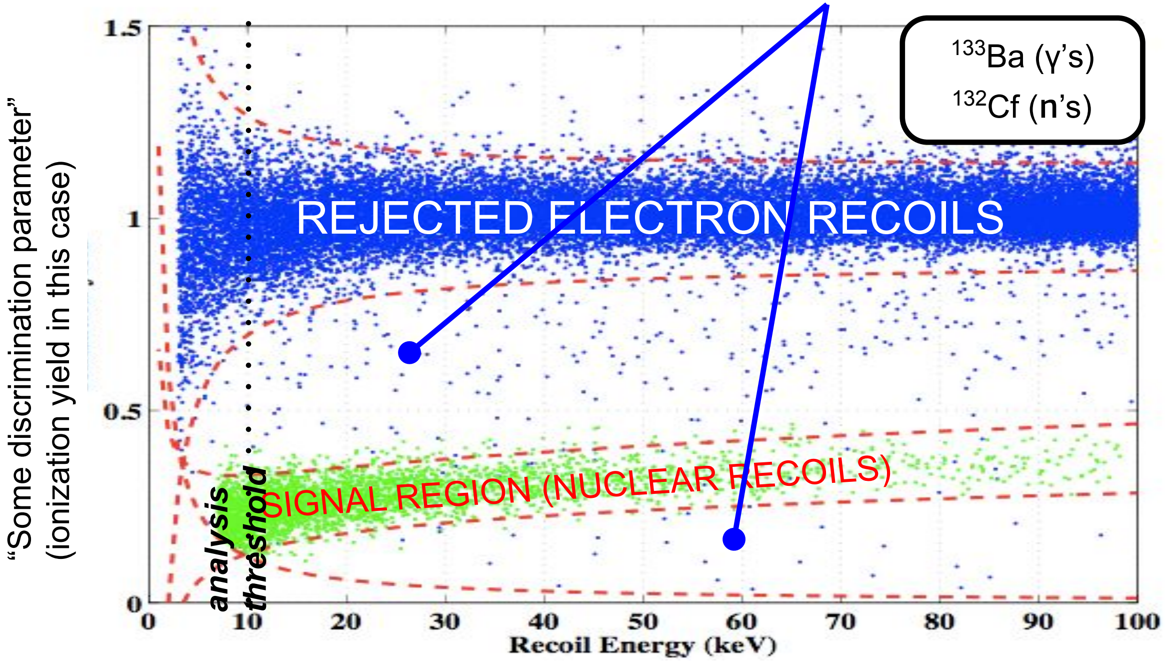
$$\text{ionization yield} = \frac{E_{ionization}}{E_{phonon}}$$

1:10^4 rejection of gammas based on ionization yield alone

Experiments that measure more than one of the products of a recoil exploit the fact that ER's and NR's deposit different fractions of the recoil energy in the form of HEAT, IONIZATION and SCINTILLATION.

Surface Events

1:10^4 sounds great, BUT wait! What are these events?



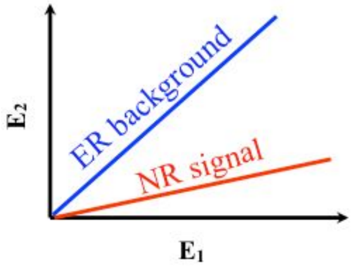
SURFACE EVENTS (betas, alphas, recoiling parent nuclei and x-rays) are a near-universal problem in direct detection.

FIDUCIALIZATION of the target volume is necessary to reject these events. So ideally, your detector needs to be able to determine the position of an event as well as its energy.

Other ways of attaining Particle Identification

- Pulse-Shape Discrimination
    - e.g., scintillation timing (DEAP/CLEAN, DarkSide, etc…)
- Nuclear-recoil-only trigger mechanism
    - (a la COUPP, PICASSO, PICO…)
- Self-Shielding (XMASS)
- Others...

Separating Signal from Background…



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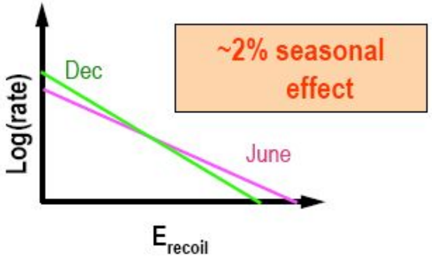
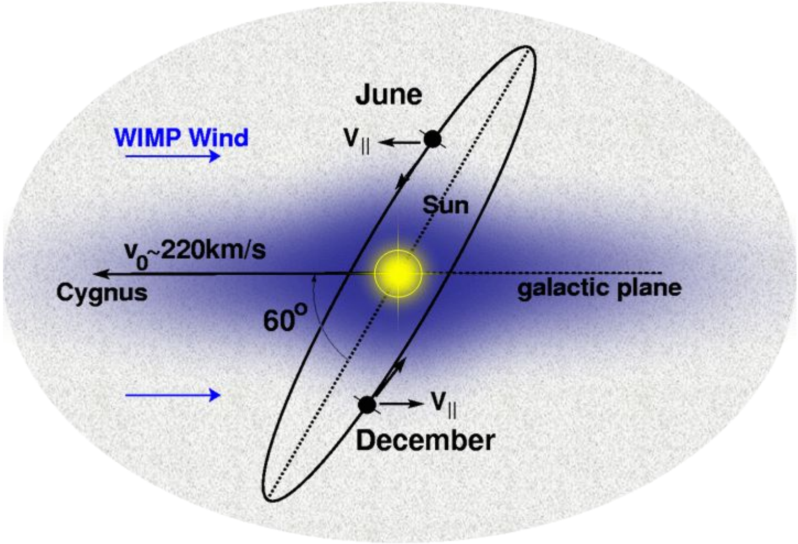


Annual Modulation

Earth's motion about the Sun produces small changes in velocity relative to the dark halo

→ Modulates expected rate of dark matter interactions detected on Earth



If you see a signal, check for an annual modulation

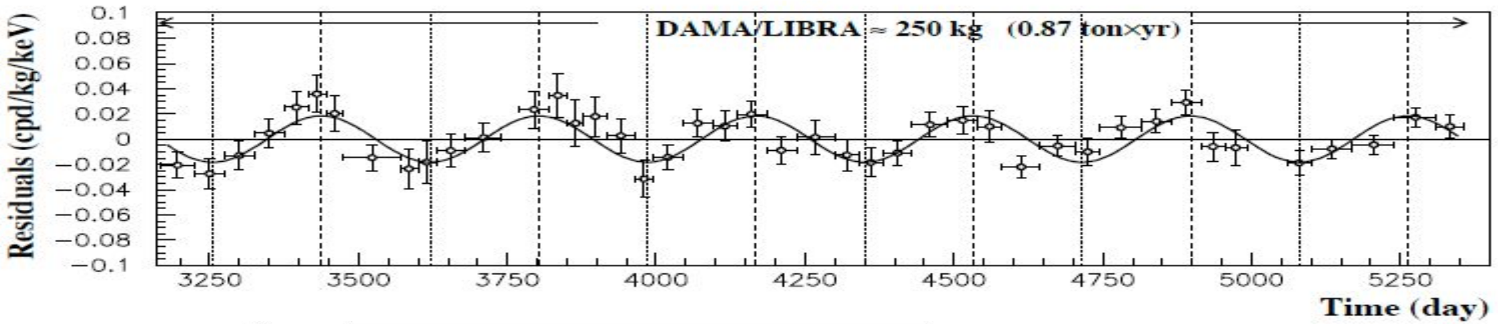
OR

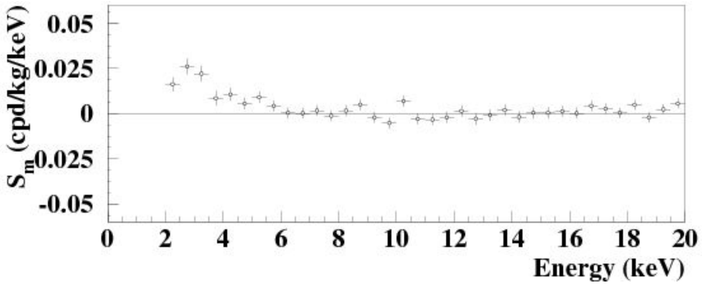
If you have irreducible backgrounds, use the modulation to pick out a signal

A dark-matter-induced modulation will have extrema in June and December (whether it's max or min depends on target and threshold)

Annual Modulation

For example, you might see a signal like this…

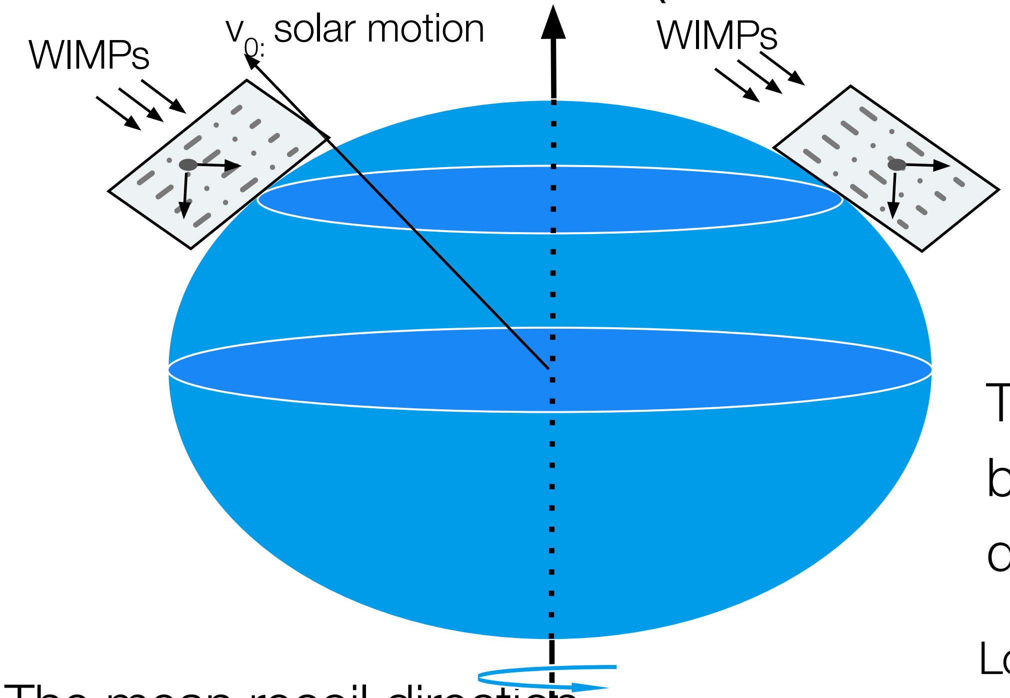


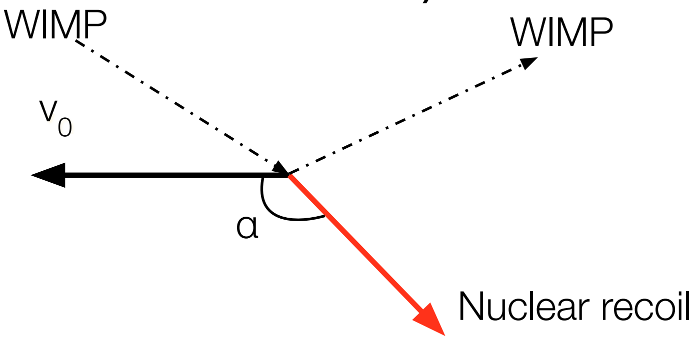


This statement was written in 2016, and is still true to date.

DAMA/NaI and successor DAMA/LIBRA operate large arrays of NaI detectors. Their combined data yield a 9σ modulation consistent with dark matter. It has never been verified by another experiment, yet no one has a really good alternative explanation.

Diurnal Modulation (a.k.a. Directional Detection)

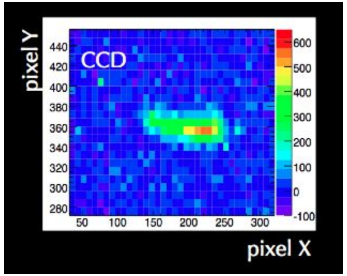




The distribution of the angle α between the solar motion and recoil directions: peaks at α=180°

The mean recoil direction rotates over one sidereal day

Low pressure TPC's preserve dE/dx profile such that "head to tail" measurement can be made



Summary of (generalized) Rare Event Search Experiment Requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold/ Good Energy Resolution

3: Low Backgrounds

4: Discrimination between Signal and Backgrounds

Additional reading

- An example of determining the background level of a working experiment: Characterization of the background spectrum in DAMIC at SNOLAB https://arxiv.org/abs/2110.13133
- An example of the design of an underground cryogenic experiment/lab: The Cryogenic Underground TEst (CUTE) Facility at SNOLAB https://arxiv.org/abs/2310.07930