Title: Ugrnd Experiments

Speakers:

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Underground Science

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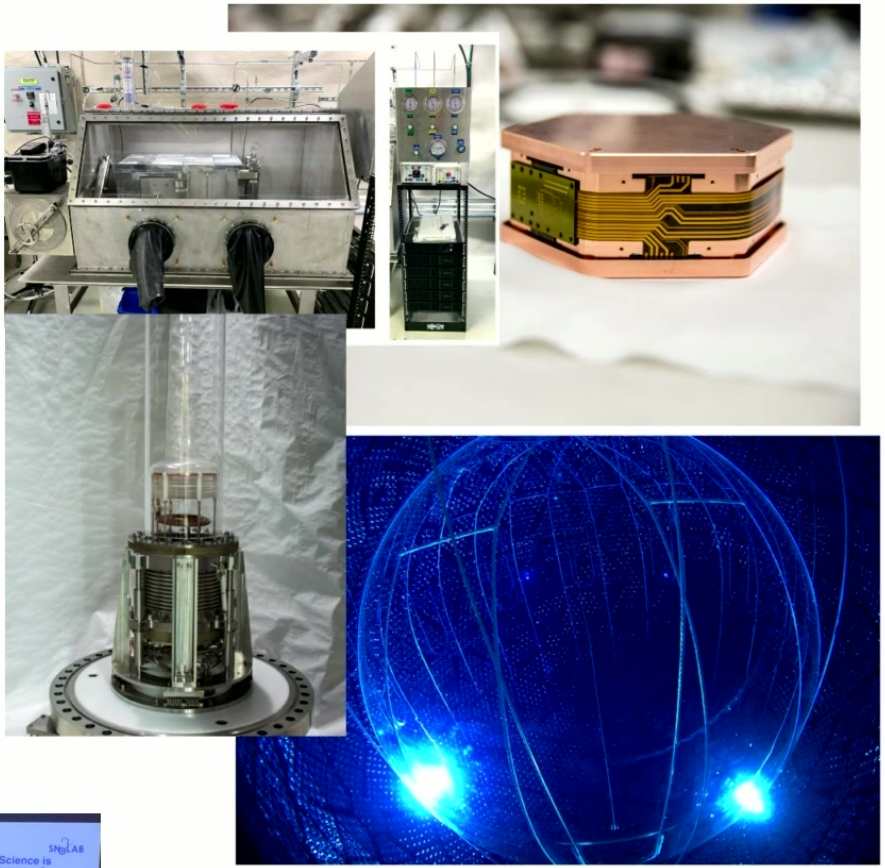
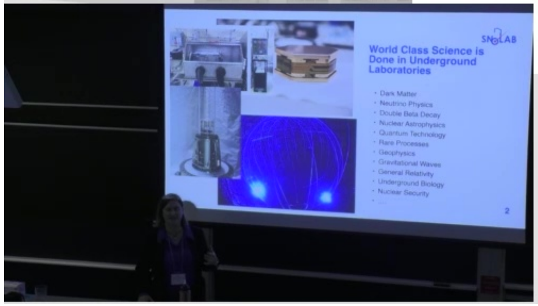
SNOLAB



World Class Science is Done in Underground Laboratories

- Dark Matter
- Neutrino Physics
- Double Beta Decay
- Nuclear Astrophysics
- Quantum Technology
- Rare Processes
- Geophysics
- Gravitational Waves
- General Relativity
- Underground Biology
- Nuclear Security
- ….



Dark Matter Direct Detection of Classical WIMPs

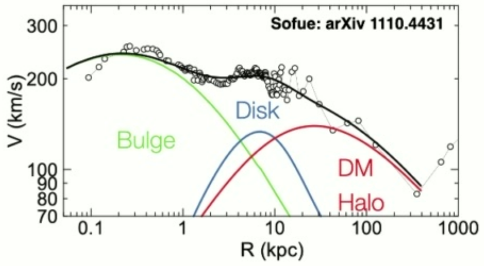
arXiv: 2110.02359

Dark Matter Direct Detection of Classical WIMPs

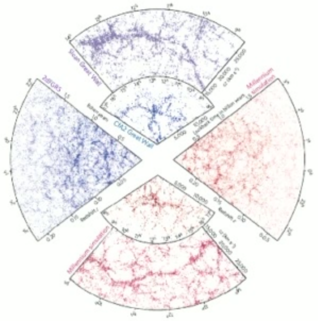
Abundance of Evidence for particle Dark Matter

- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gravitational lensing
  - Large Scale Structure formation

Rotation Curve of Milky Way

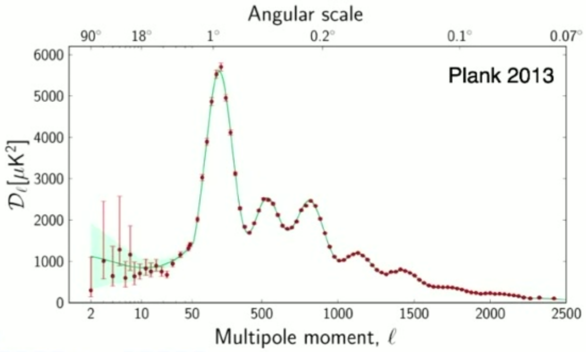


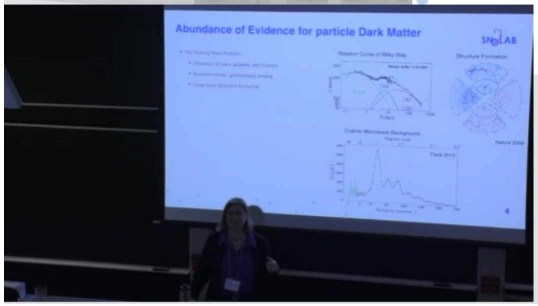
Structure Formation



Nature 2006

Cosmic Microwave Background

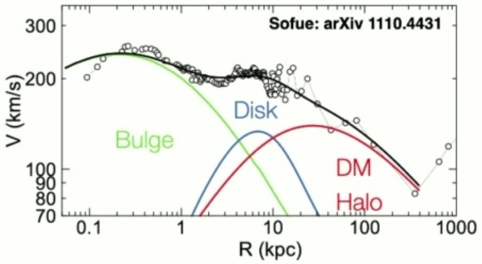




Abundance of Evidence for particle Dark Matter

- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gravitational lensing
  - Large Scale Structure formation
- Wealth of evidence for a particle solution
  - Microlensing (MACHOs) mostly ruled out
  - MOND has problems with Bullet Cluster
- Non-baryonic
  - Height of acoustic peaks in the CMB (Ω_b, Ω_m)
  - Power spectrum of density fluctuations (Ω_m)
  - Primordial Nucleosynthesis (Ω_b)
- And STILL HERE!
  - Stable, neutral, non-relativistic
  - Interacts via gravity and (maybe) a weak force

Rotation Curve of Milky Way



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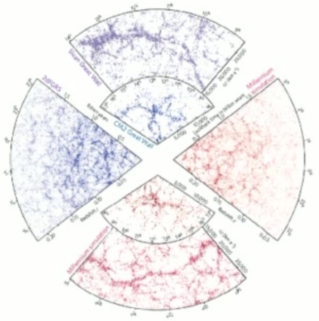

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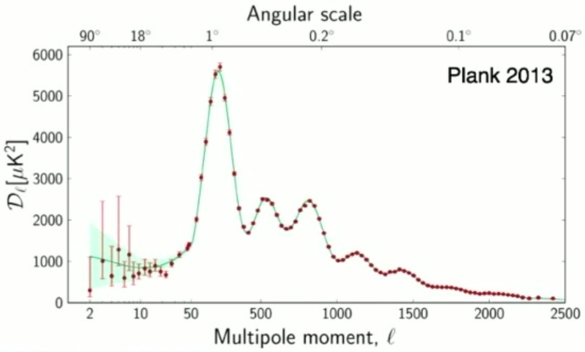
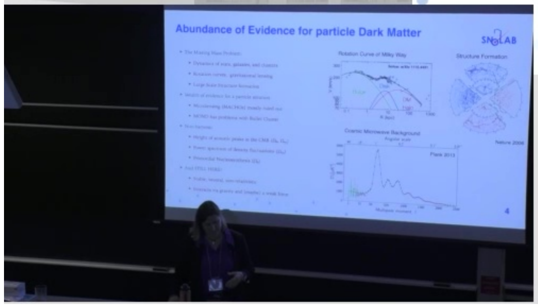
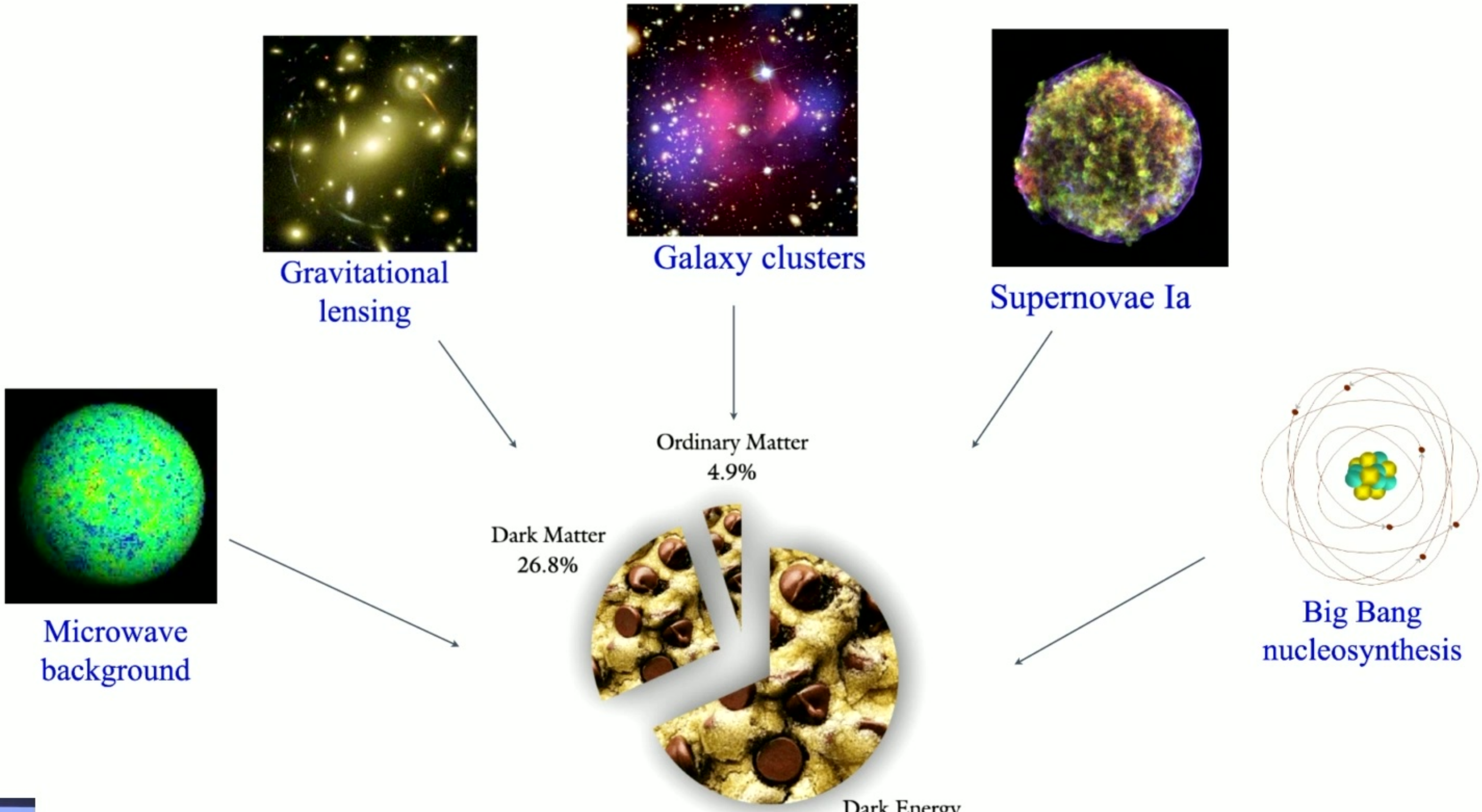






Gravitational lensing

Galaxy clusters

Supernovae Ia

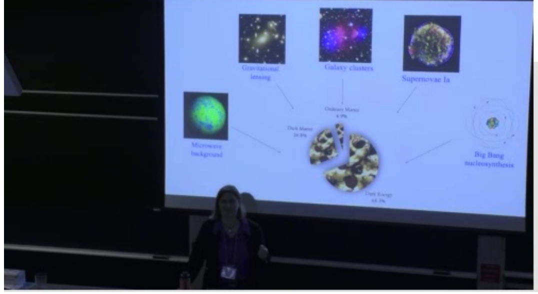
Microwave background

Ordinary Matter
4.9%

Dark Matter
26.8%

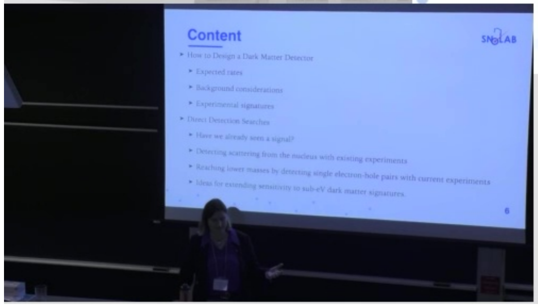
Big Bang nucleosynthesis

Dark Energy
68.3%

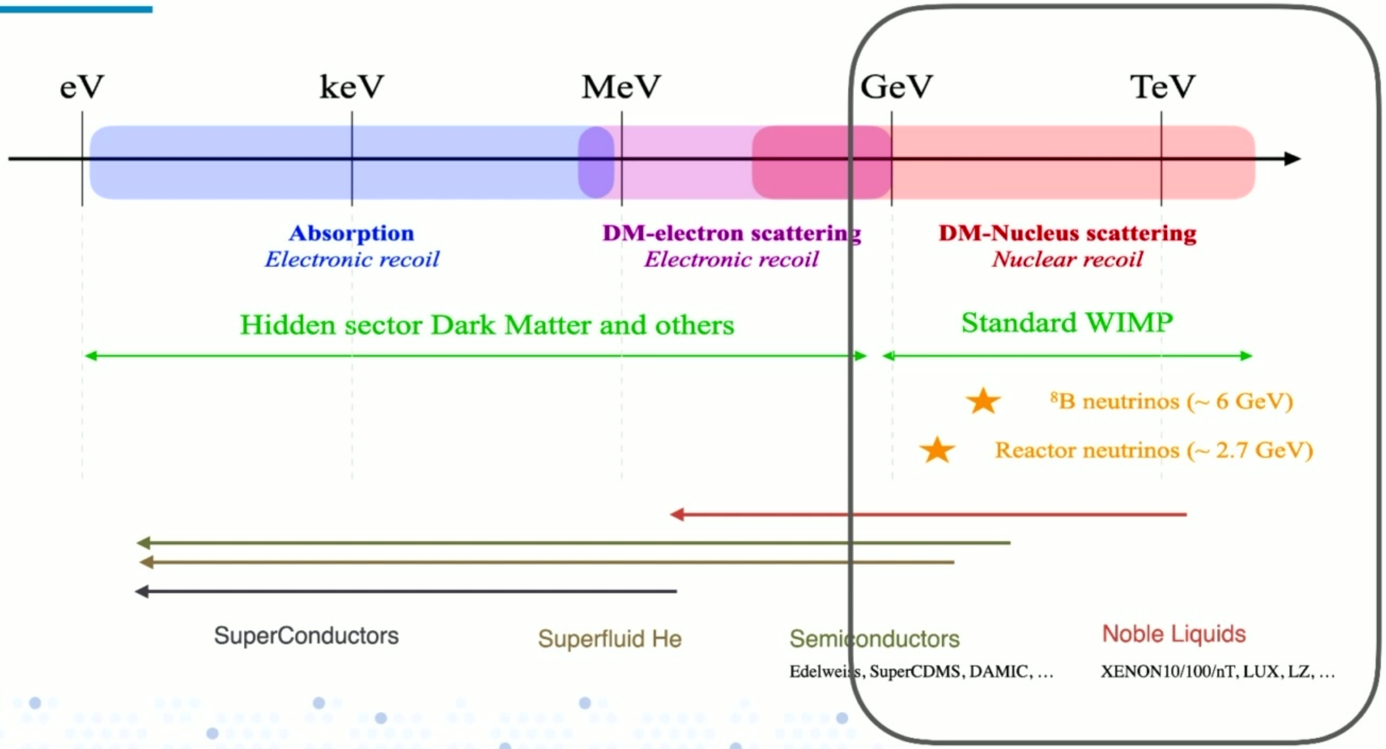


Content

- How to Design a Dark Matter Detector
    - Expected rates
    - Background considerations
    - Experimental signatures
- Direct Detection Searches
    - Have we already seen a signal?
    - Detecting scattering from the nucleus with existing experiments
    - Reaching lower masses by detecting single electron-hole pairs with current experiments
    - Ideas for extending sensitivity to sub-eV dark matter signatures.



Direct Detection Energy Ranges



Absorption
Electronic recoil

DM-electron scattering
Electronic recoil

DM-Nucleus scattering
Nuclear recoil

Hidden sector Dark Matter and others

Standard WIMP

^{8}B neutrinos (~ 6 GeV)

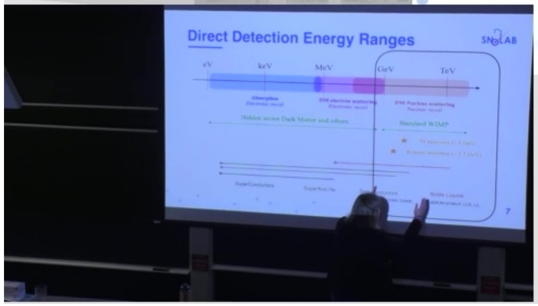
Reactor neutrinos (~ 2.7 GeV)

SuperConductors

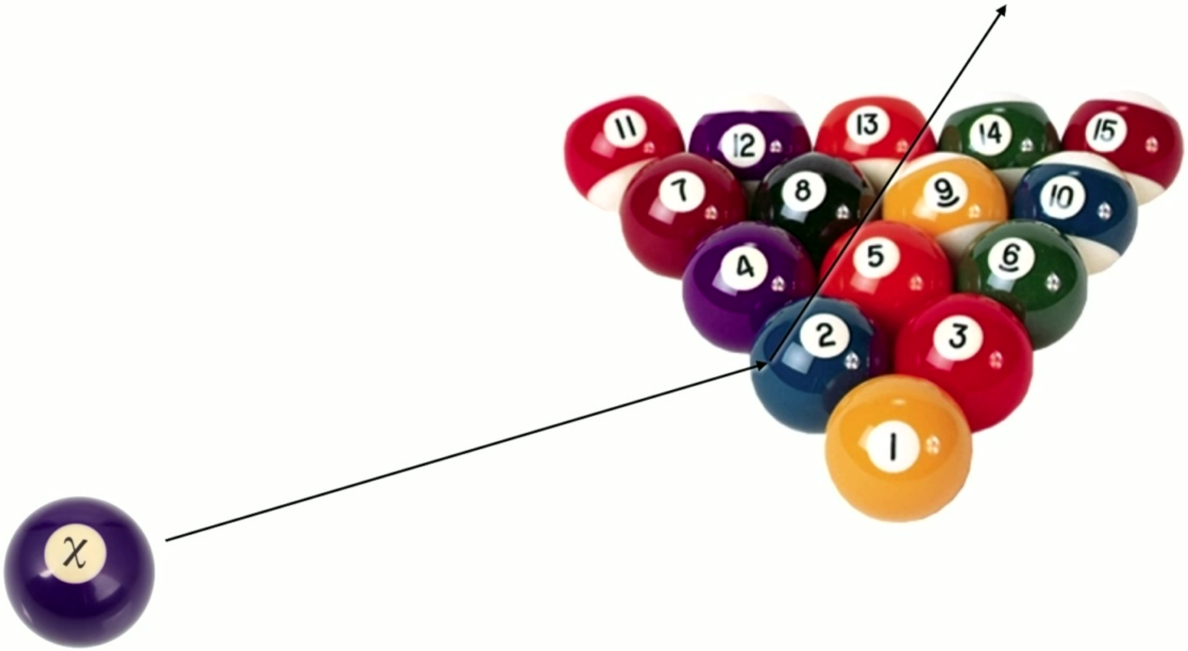
Superfluid He

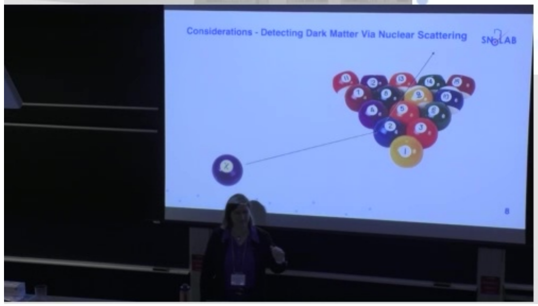
Semiconductors
Edelweiss, SuperCDMS, DAMIC, …

Noble Liquids
XENON10/100/nT, LUX, LZ, …



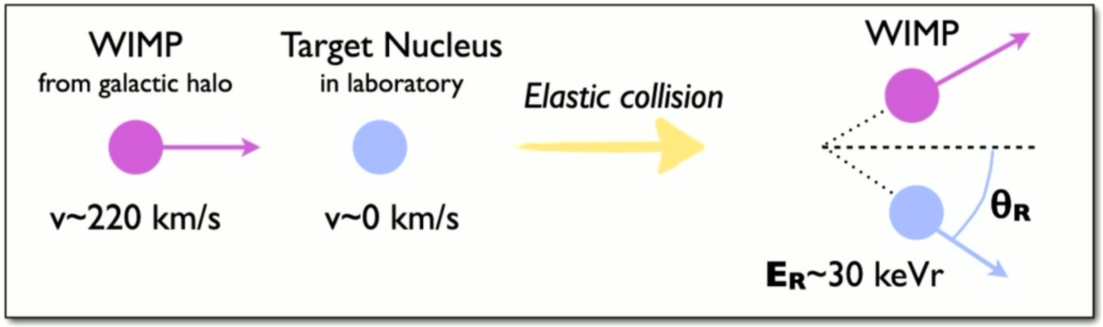
Considerations - Detecting Dark Matter Via Nuclear Scattering





Direct Detection Event Rates

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

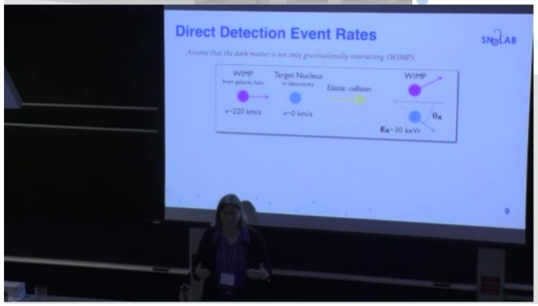


WIMP
from galactic halo
v~220 km/s

Target Nucleus
in laboratory
v~0 km/s

Elastic collision

WIMP
θ_R
E_R~30 keVr



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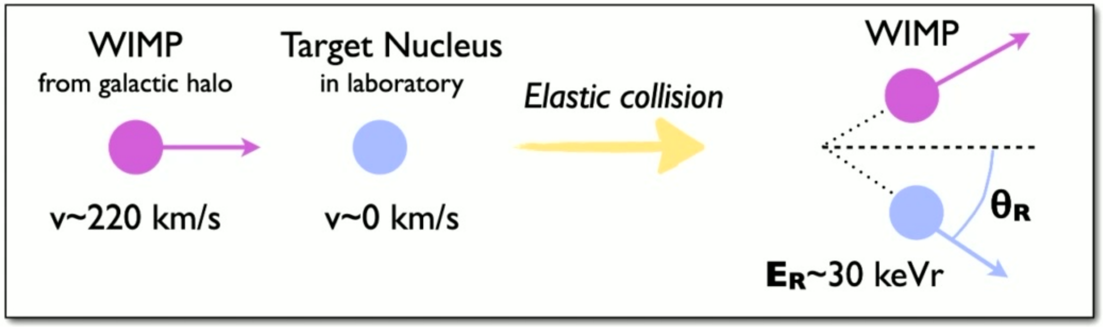
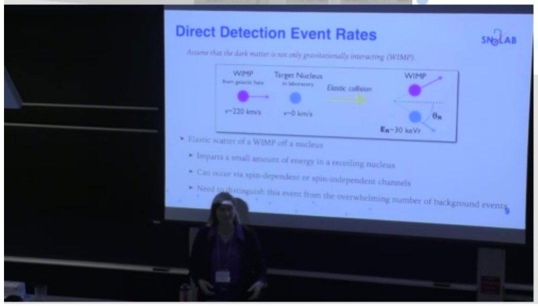


- Elastic scatter of a WIMP off a nucleus
  - Imparts a small amount of energy in a recoiling nucleus
  - Can occur via spin-dependent or spin-independent channels
  - Need to distinguish this event from the overwhelming number of background events

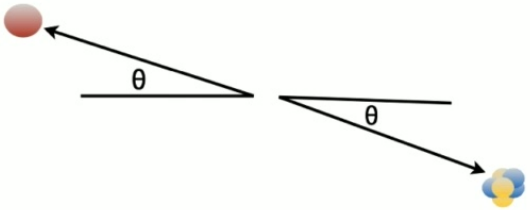


Kinematics

- Calculate the recoil energy of a nucleus in the center of mass frame.

initial momentum: $\vec{p} = -\overrightarrow{E_k}$

final momentum: $\vec{p}' = -\overrightarrow{E_k}' = \vec{q} + \mu\vec{v}_\chi$



where

WIMP-nucleus reduced mass: $\mu = \dfrac{m_\chi m_N}{m_\chi + m_N}$

q = *momentum transfer*

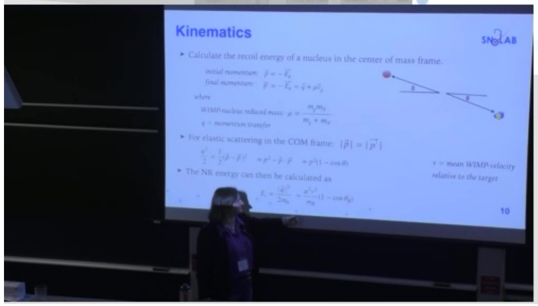
- For elastic scattering in the COM frame: $|\vec{p}| = |\overrightarrow{p'}|$

$$\frac{q^2}{2} = \frac{1}{2}(\vec{p} - \vec{p}')^2 \quad = p^2 - \vec{p}\cdot\vec{p}' \quad = p^2(1 - \cos\theta)$$

v = *mean WIMP-velocity relative to the target*

- The NR energy can then be calculated as

$$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta_R)$$



Kinematics

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

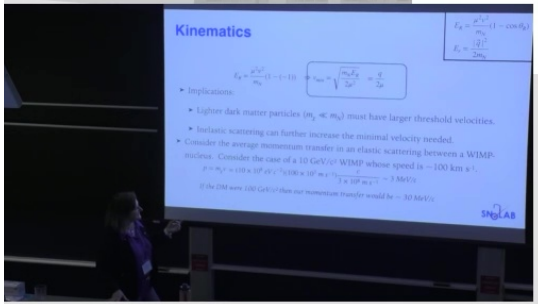
$$E_r = \frac{|\vec{q}\,|^2}{2m_N}$$

$$E_R = \frac{\mu^2 v^2}{m_N}(1-(-1)) \Rightarrow \boxed{v_{min} = \sqrt{\frac{m_N E_R}{2\mu^2}} = \frac{q}{2\mu}}$$

- Implications:
  - Lighter dark matter particles ($m_\chi \ll m_N$) must have larger threshold velocities.
  - Inelastic scattering can further increase the minimal velocity needed.
- Consider the average momentum transfer in an elastic scattering between a WIMP-nucleus. Consider the case of a 10 GeV/c^2 WIMP whose speed is ∼100 km s^{-1}.

$$p = m_\chi v = (10\times 10^8\ eV\, c^{-2})(100\times 10^3\ m\, s^{-1})\frac{c}{3\times 10^8\ m\, s^{-1}} \sim 3\ MeV/c$$

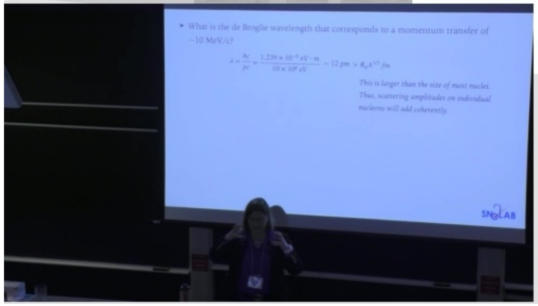
If the DM were 100 GeV/c^2 then our momentum transfer would be ∼ 30 MeV/c

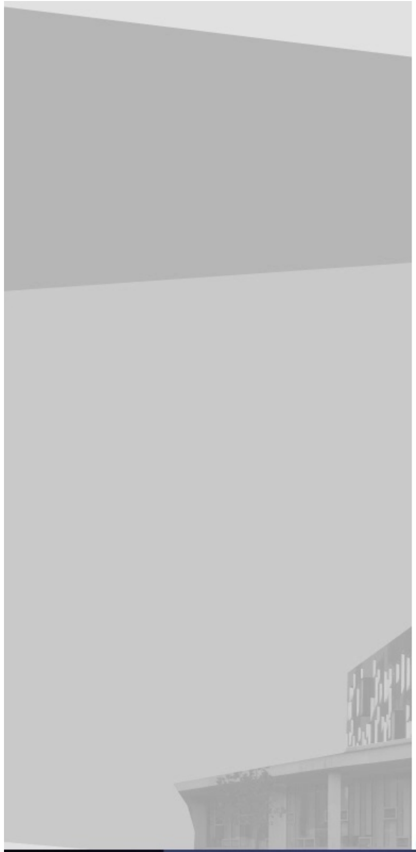


- What is the de Broglie wavelength that corresponds to a momentum transfer of ~10 MeV/c?

$$\lambda = \frac{hc}{pc} = \frac{1.239 \times 10^{-6}\ eV \cdot m}{10 \times 10^{6}\ eV} \sim 12\ pm > R_0 A^{1/3}\ fm$$

This is larger than the size of most nuclei. Thus, scattering amplitudes on individual nucleons will add coherently.





Expected Rates in a Detector - Simplified.

- The differential event rate for simplified WIMP interaction (a detector stationary in the galaxy) is given by:

event rate

total event rate

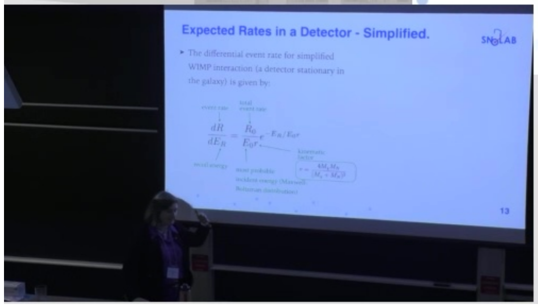
$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

kinematic factor

$$r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2}$$

recoil energy

most probable incident energy (Maxwell-Boltzman distribution)



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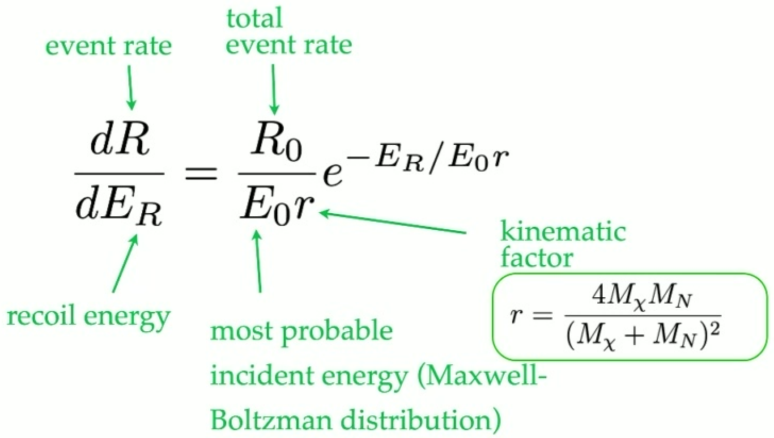

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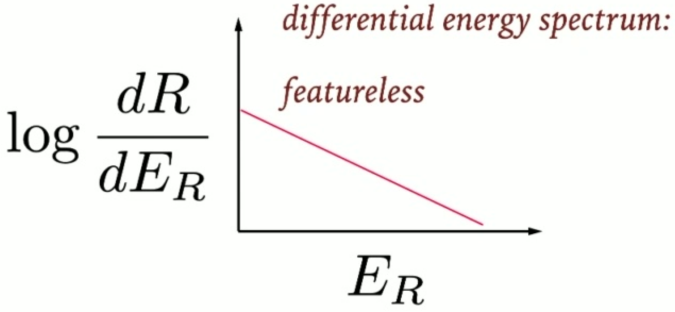
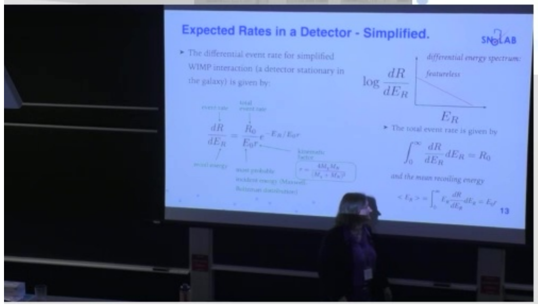


- The total event rate is given by

$$\int_0^\infty \frac{dR}{dE_R} dE_R = R_0$$

and the mean recoiling energy

$$< E_R > = \int_0^\infty E_R \frac{dR}{dE_R} dE_R = E_0 r$$



Example: Calculate the Mean NR Deposited in a Detector

- Assume that the DM mass and the nucleus mass are identical:

$$m_\chi = m_N = 100\ GeV/c^2$$

- Our formula is

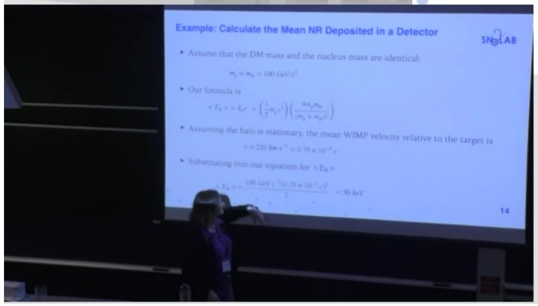
$$< E_R > = E_0 r\ = \left(\frac{1}{2} m_\chi v^2\right)\left(\frac{4 m_\chi m_N}{(m_\chi + m_N)^2}\right)$$

- Assuming the halo is stationary, the mean WIMP velocity relative to the target is

$$v \approx 220\ km\ s^{-1} = 0.75 \times 10^{-3}\ c$$

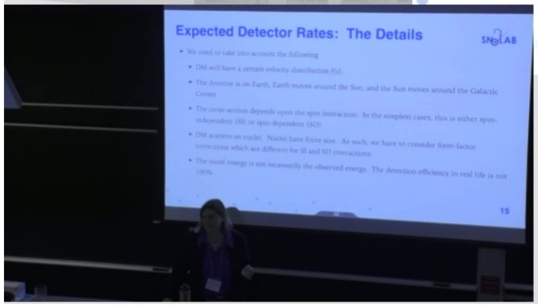
- Substituting into our equation for <E$_R$>

$$< E_R > = \frac{100\ GeV\, c^{-2} (0.75 \times 10^{-3}\ c)^2}{2} \quad \sim 30\ keV$$



Expected Detector Rates: The Details

- We need to take into account the following
  - DM will have a certain velocity distribution $f(v)$.
  - The detector is on Earth, Earth moves around the Sun, and the Sun moves around the Galactic Center.
  - The cross-section depends upon the spin interaction. In the simplest cases, this is either spin-independent (SI) or spin-dependent (SD)
  - DM scatters on nuclei. Nuclei have finite size. As such, we have to consider form-factor corrections which are different for SI and SD interactions.
  - The recoil energy is not necessarily the observed energy. The detection efficiency in real life is not 100%.



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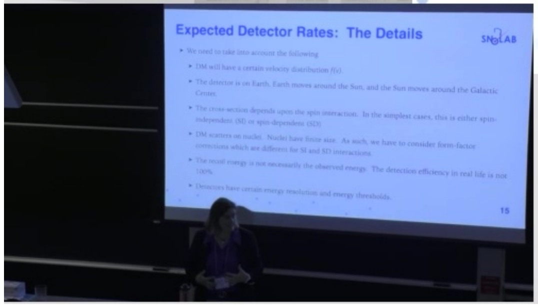
  - DM scatters on nuclei. Nuclei have finite size. As such, we have to consider form-factor corrections which are different for SI and SD interactions.
  - The recoil energy is not necessarily the observed energy. The detection efficiency in real life is not 100%.
  - Detectors have certain energy resolution and energy thresholds.



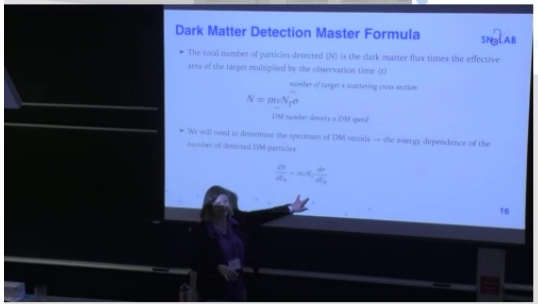
Dark Matter Detection Master Formula

- The total number of particles detected (N) is the dark matter flux times the effective area of the target multiplied by the observation time (t)

$$N = t\underbrace{nv}_{\textit{DM number density x DM speed}}\overbrace{N_T\sigma}^{\textit{number of target x scattering cross section}}$$

- We will need to determine the spectrum of DM recoils → the energy dependence of the number of detected DM particles

$$\frac{dN}{dE_R} = tnvN_T\frac{d\sigma}{dE_R}$$



$$\frac{dN}{dE_R} = tnvN_T\frac{d\sigma}{dE_R}$$

- We need to consider the DM particles are described by their local velocity distribution, $f(\vec{v})$, were $\vec{v}$ is the DM velocity in the reference frame of the detector.

$$\frac{dN}{dE_R} = tnN_T\int_{v_{min}} vf(\vec{v})\frac{d\sigma}{dE_R}d\vec{v}$$

We need to integrate all possible DM velocities with their corresponding probability density and

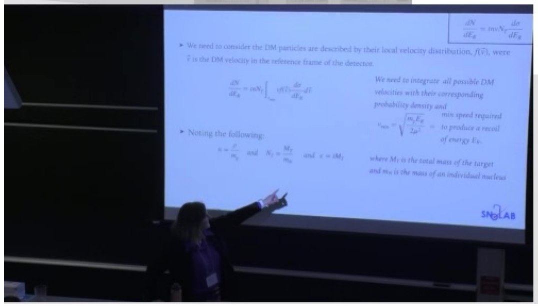
$$v_{min} = \sqrt{\frac{m_\chi E_R}{2\mu^2}} =$$

min speed required to produce a recoil of energy E_R.

- Noting the following:

$$n = \frac{\rho}{m_\chi} \quad and \quad N_T = \frac{M_T}{m_N} \quad and \quad \epsilon = tM_T$$

where M_T is the total mass of the target and m_N is the mass of an individual nucleus



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where M_T *is the total mass of the target and* m_N *is the mass of an individual nucleus*

- We can write

$$\frac{dN}{dE_R} = \epsilon\frac{\rho}{m_\chi m_N}\int_{v_{min}} vf(\vec{v})\frac{d\sigma}{dE_R}d\vec{v}$$

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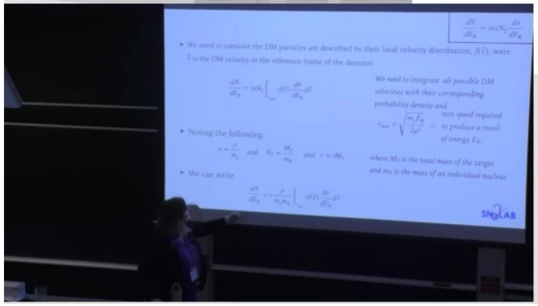


Elements of Ideal Event Rate in Direct Detection:

Differential Event Rate:
[events/keV/kg/day]

local WIMP density

WIMP-nucleon scattering cross section

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi}\int_{v_{min}}^{\infty} v f(v)\frac{d\sigma_{\chi N}}{dE_R}dv}$$

nucleus mass

WIMP mass

WIMP speed distribution in detector frame

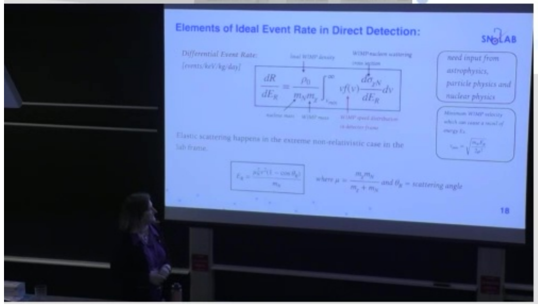
need input from astrophysics, particle physics and nuclear physics

Minimum WIMP velocity which can cause a recoil of energy E_R.

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

Elastic scattering happens in the extreme non-relativistic case in the lab frame.

$$\boxed{E_R = \frac{\mu_N^2 v^2(1-\cos\theta_R)}{m_N}} \qquad where\ \mu = \frac{m_\chi m_N}{m_\chi + m_N}\ and\ \theta_R = scattering\ angle$$



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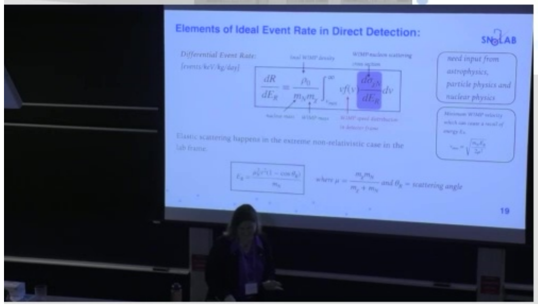


The Scattering Cross Section

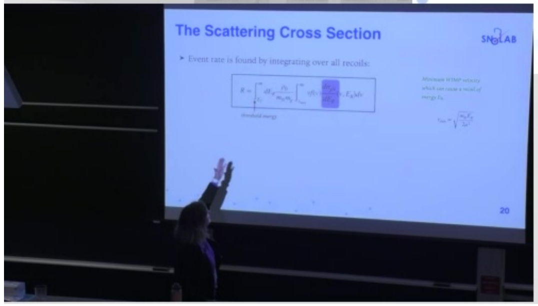
- Event rate is found by integrating over all recoils:

$$\boxed{R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) dv}$$

threshold energy

Minimum WIMP velocity which can cause a recoil of energy E_R.

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



The Scattering Cross Section

- Event rate is found by integrating over all recoils:

$$\boxed{R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) dv}$$

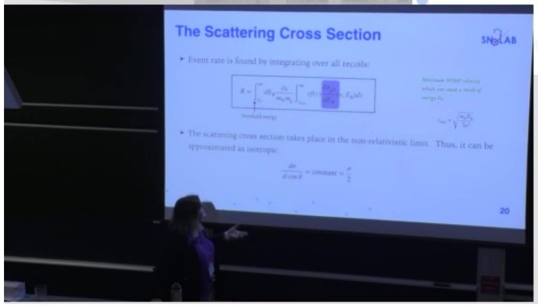
threshold energy

Minimum WIMP velocity which can cause a recoil of energy E_R.

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

- The scattering cross section takes place in the non-relativistic limit. Thus, it can be approximated as isotropic.

$$\frac{d\sigma}{d\cos\theta} = constant = \frac{\sigma}{2}$$



$$\frac{d\sigma}{d\cos\theta} = \frac{\sigma}{2}$$

- Recall, $E_R^{max} = 2\mu^2 v^2 / m_N$. That means we can write …

$$E_R = E_R^{max} \frac{1+\cos\theta}{2} \quad \longrightarrow \frac{dE_R}{d\cos\theta} = \frac{E_R^{max}}{2}$$

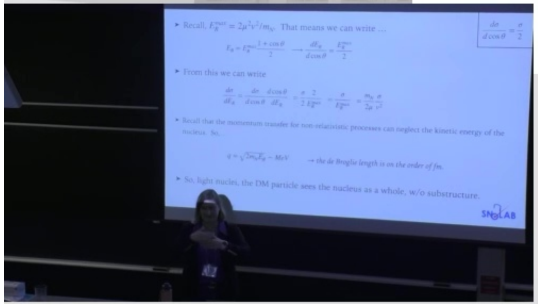
- From this we can write

$$\frac{d\sigma}{dE_R} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dE_R} = \frac{\sigma}{2}\frac{2}{E_R^{max}} = \frac{\sigma}{E_R^{max}} = \frac{m_N}{2\mu}\frac{\sigma}{v^2}$$

- Recall that the momentum transfer for non-relativistic processes can neglect the kinetic energy of the nucleus. So,…

$$q = \sqrt{2m_N E_R} \sim MeV \qquad \rightarrow \textit{the de Broglie length is on the order of fm.}$$

- So, light nuclei, the DM particle sees the nucleus as a whole, w/o substructure.



- Heavier nuclei require inclusion of the nuclear form factor to account for the loss of coherence.

- The WIMP-nucleon cross section can be separated:

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

Spin-Independent + Spin-Dependent

SI arise from scalar or vector couplings to quarks.

SD arise from axial-vector couplings to quarks.

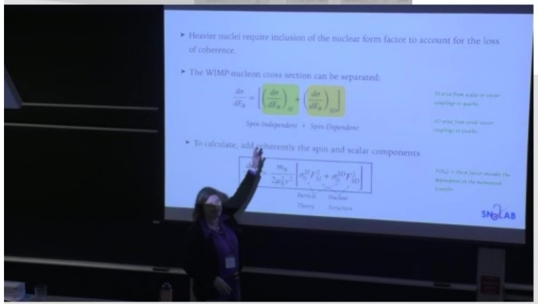
- To calculate, add coherently the spin and scalar components

$$\boxed{\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu_N^2 v^2} \left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right]}$$

Particle Theory

Nuclear Structure

$F(E_R)$ = Form factor encodes the dependence on the momentum transfer.



$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}\left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right]$$

- Spin Independent: Woods-Saxon Form Factor

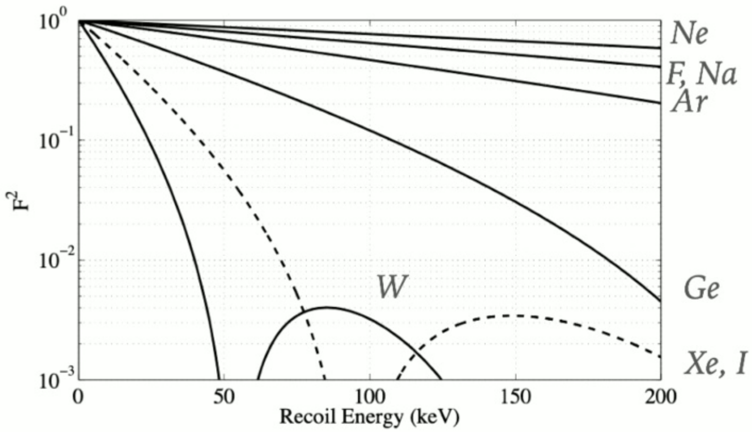
$$F(q) = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 e^{-q^2s^2/2}$$

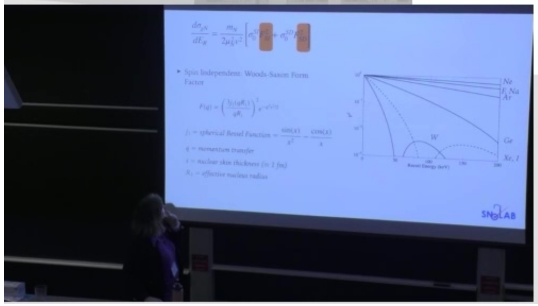
j_1 = *spherical Bessel Function* $= \frac{\sin(x)}{x^2} - \frac{\cos(x)}{x}$

q = *momentum transfer*

s = *nuclear skin thickness* ($\simeq$ 1 fm)

R_1 = *effective nucleus radius*





$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}\left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right]$$

- Spin Dependent Interactions

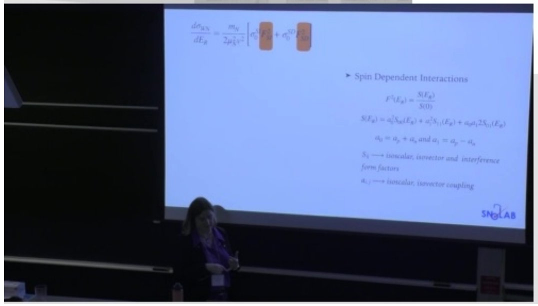
$$F^2(E_R) = \frac{S(E_R)}{S(0)}$$

$$S(E_R) = a_0^2 S_{00}(E_R) + a_1^2 S_{11}(E_R) + a_0 a_1 2 S_{01}(E_R)$$

$$a_0 = a_p + a_n \text{ and } a_1 = a_p - a_n$$

$S_{ij} \longrightarrow$ *isoscalar, isovector and interference form factors*

$a_{i,j} \longrightarrow$ *isoscalar, isovector coupling*



$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}\left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right]$$

- **Spin-Independent**

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

coupling to proton

coupling to neutron

Assume low momentum transfer:

- In most models $f_n \sim f_p$ (scalar four-fermion coupling constants)
  - Scattering adds coherently with A^2 enhancement

- **Spin-Dependent**

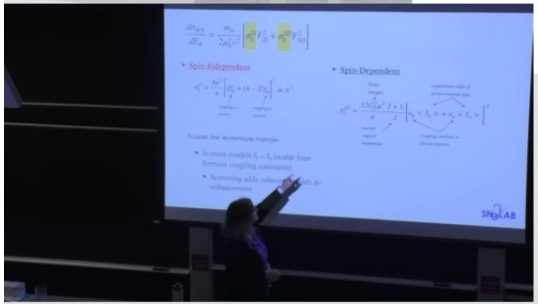
Fermi constant

expectation value of proton/neutron spin

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

nuclear angular momentum

coupling constant to proton/neutron



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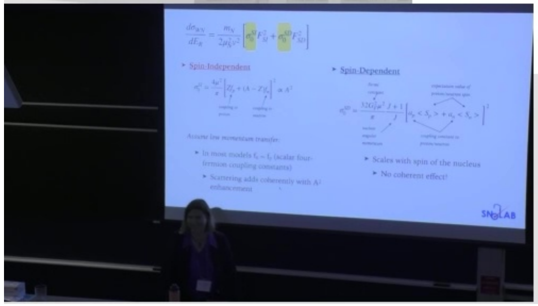
nuclear angular momentum

coupling constant to proton/neutron

- Scales with spin of the nucleus
  - No coherent effect!



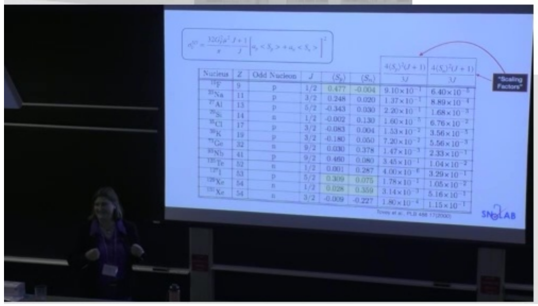
$$\sigma_0^{SD} = \frac{32G_F^2\mu^2}{\pi}\frac{J+1}{J}\left[a_p < S_p > + a_n < S_n >\right]^2$$

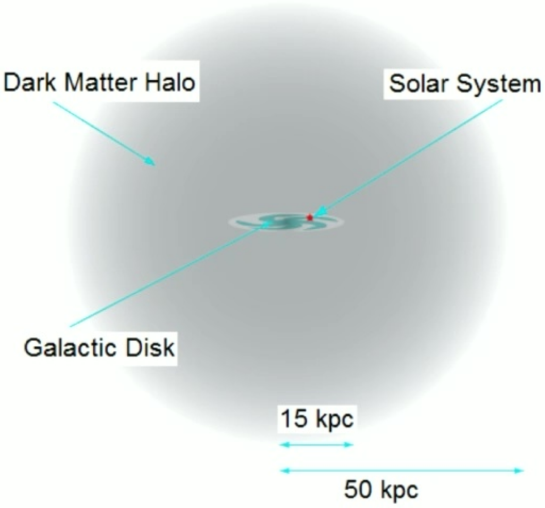
“Scaling Factors”

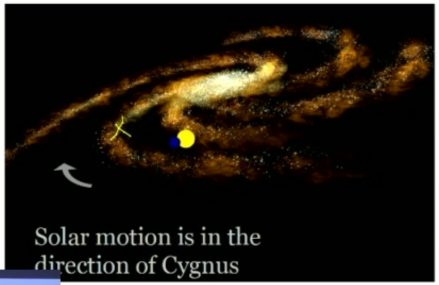
Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	$\frac{4\langle S_p\rangle^2(J+1)}{3J}$	$\frac{4\langle S_n\rangle^2(J+1)}{3J}$
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

Tovey et al., PLB 488 17(2000)

SNOLAB







Relic WIMP Distribution: Simplified Model

- WIMPs are distributed in isothermal spherical halos with Gaussian velocity distribution (Maxwellian)

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

- The speed dispersion is related to the local circular speed by

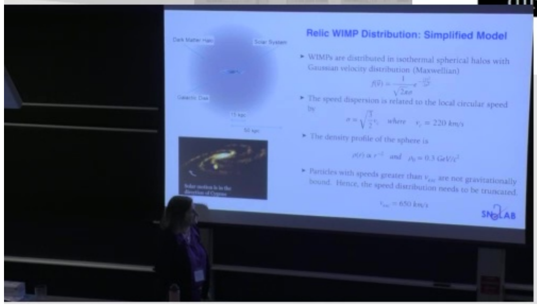
$$\sigma = \sqrt{\frac{3}{2}} v_c \quad where \quad v_c = 220\ km/s$$

- The density profile of the sphere is

$$\rho(r) \propto r^{-2} \quad and \quad \rho_0 = 0.3\ GeV/c^2$$

- Particles with speeds greater than v_{esc} are not gravitationally bound. Hence, the speed distribution needs to be truncated.

$$v_{esc} = 650\ km/s$$



Density of WIMPs in Your Work area

- The local dark matter density is

$$\rho_0 = 0.3\ GeV/cm^3$$

- Pick your favored mass for the dark matter particle

$$m = 5\ GeV/c^2$$

$$m = 60\ GeV/c^2$$

- What is the number density?

$$60{,}000\ particles/m^3 \longrightarrow for\ 5\ GeV/c^2$$

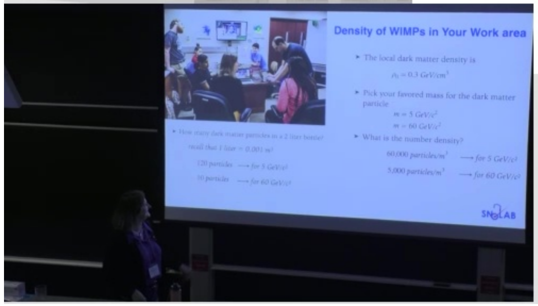
$$5{,}000\ particles/m^3 \longrightarrow for\ 60\ GeV/c^2$$

- How many dark matter particles in a 2 liter bottle?

recall that 1 liter = 0.001 m^3

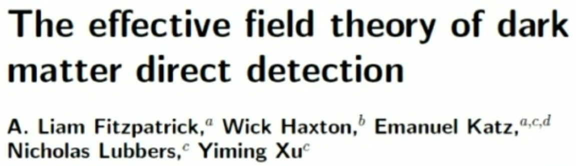
$$120\ particles \longrightarrow for\ 5\ GeV/c^2$$

$$10\ particles \longrightarrow for\ 60\ GeV/c^2$$



Maybe Not that Simple?

- Effective Field Theory considers leading order and NLO operators that can occur in the effective Lagrangian that describes the WIMP-nucleon interactions.
- Contains 14 operators, that rely on a range of nuclear properties in addition to the SI and SD cases. They combine such that the WIMP-nucleon cross section depends on six independent nuclear response functions:
  - One "Spin independent"
  - Two "Spin Dependent"
  - Three "Velocity-Dependent"
- Two pairs of these interfere, resulting in eight independent parameters that can be probed



The effective field theory of dark matter direct detection

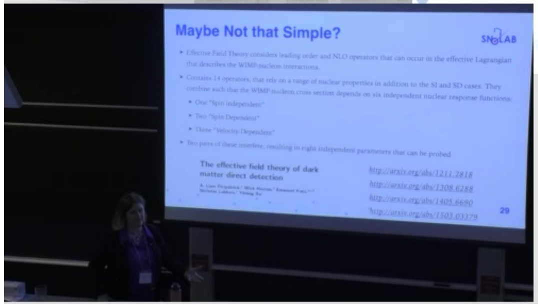
A. Liam Fitzpatrick,[a] Wick Haxton,[b] Emanuel Katz,[a,c,d] Nicholas Lubbers,[c] Yiming Xu[c]

http://arxiv.org/abs/1211.2818

http://arxiv.org/abs/1308.6288

http://arxiv.org/abs/1405.6690

http://arxiv.org/abs/1503.03379



$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

- The EFT framework parameterizes the WIMP-nucleus interaction in terms of the 14 operators listed to the left.

  $\vec{v}^\perp$ = relative velocity between incoming WIMP and nucleon

  q = momentum transfer

  $\vec{S}_\chi$ = WIMP spin

  $\vec{S}_N$ = nucleon spin

- In addition, each operator can independently couple to protons or neutrons.

  Note $\mathcal{O}_2$ is not considered as it cannot arise from the non-relativistic limit.

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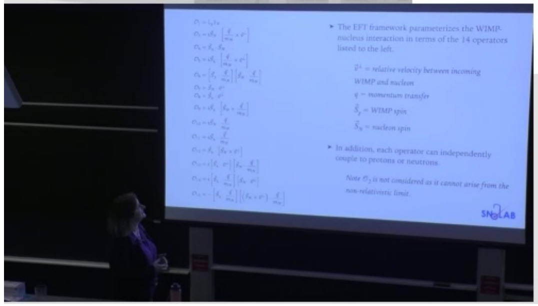
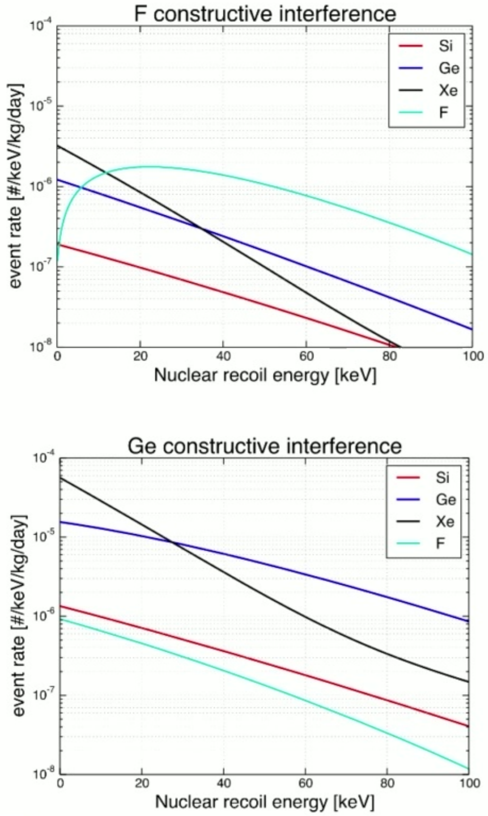


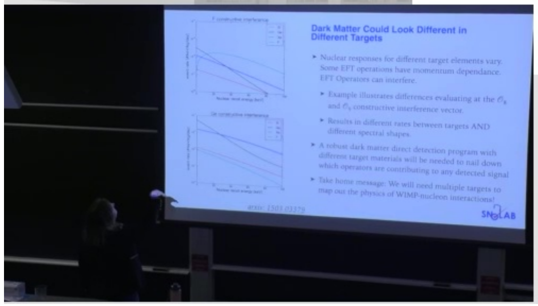


arxiv: 1503.03379

Dark Matter Could Look Different in Different Targets

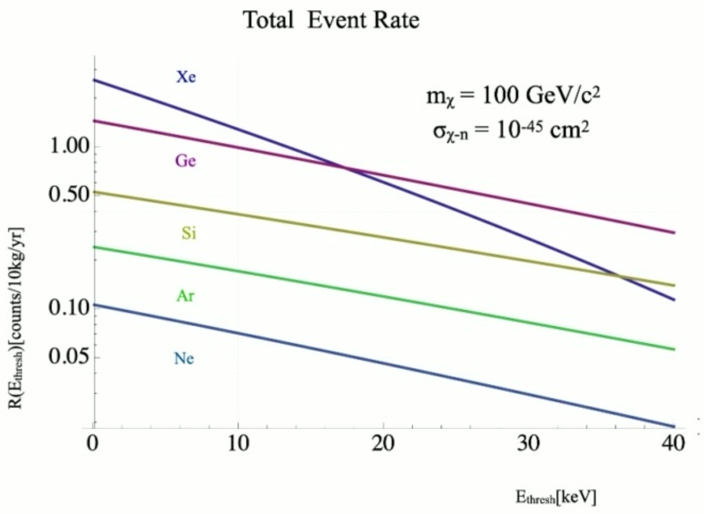
- Nuclear responses for different target elements vary. Some EFT operations have momentum dependance. EFT Operators can interfere.
  - Example illustrates differences evaluating at the $\mathcal{O}_8$ and $\mathcal{O}_9$ constructive interference vector.
  - Results in different rates between targets AND 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
- Take home message: We will need multiple targets to map out the physics of WIMP-nucleon interactions!

SNOLAB

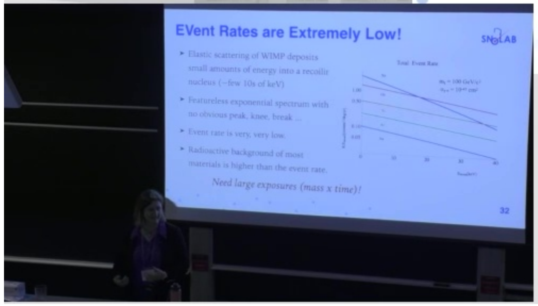


EVent Rates are Extremely Low!

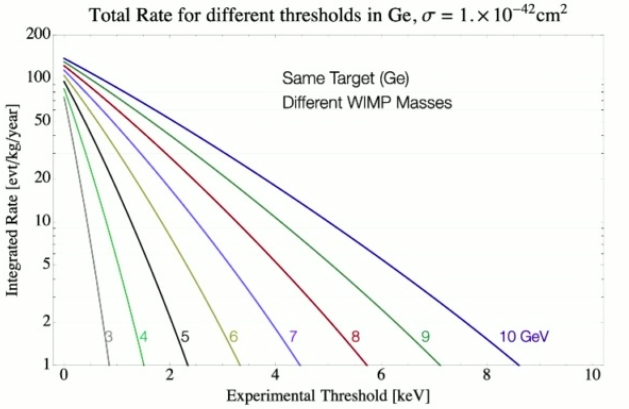
- Elastic scattering of WIMP deposits small amounts of energy into a recoilin nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.
- Radioactive background of most materials is higher than the event rate.

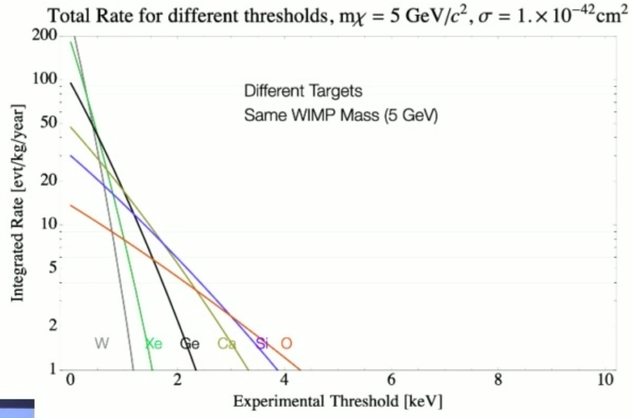


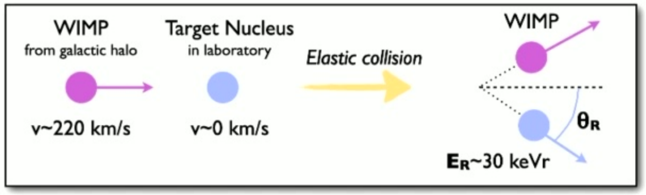
Need large exposures (mass x time)!



The Low-Mass WIMP Challenge

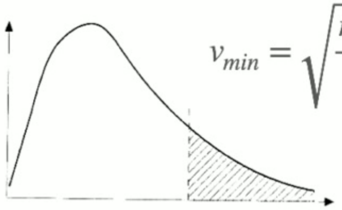

Total Rate for different thresholds in Ge, $\sigma = 1.\times10^{-42}\text{cm}^2$


Total Rate for different thresholds, $m_\chi = 5\ \text{GeV}/c^2$, $\sigma = 1.\times10^{-42}\text{cm}^2$



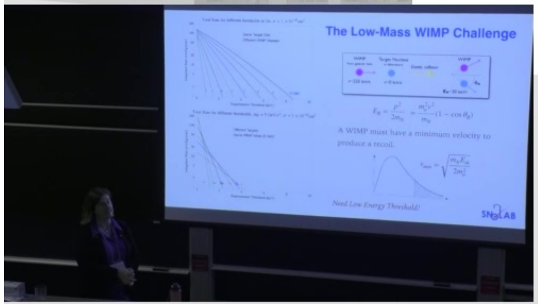
$$E_R = \frac{p^2}{2m_N} = \frac{m_\mu^2 v^2}{m_N}(1 - \cos\theta_R)$$

A WIMP must have a minimum velocity to produce a recoil.



$$v_{min} = \sqrt{\frac{m_N E_{th}}{2m_\mu^2}}$$

Need Low Energy Threshold!



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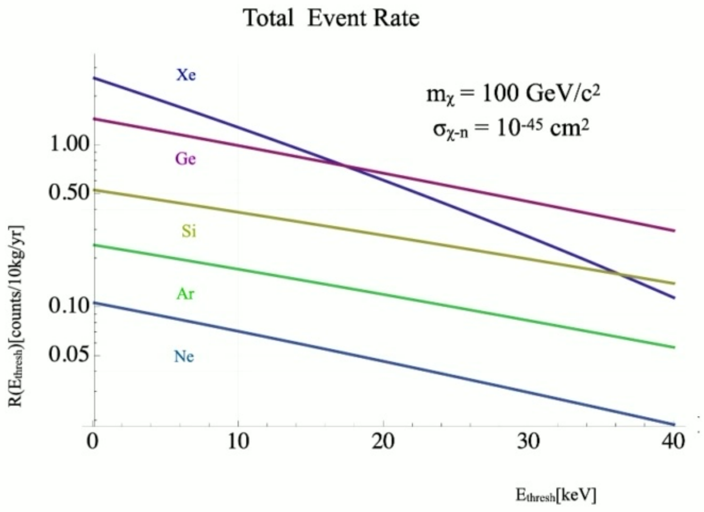

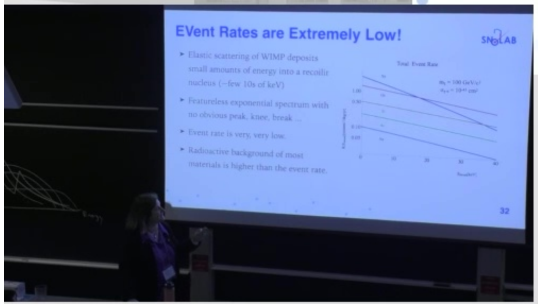

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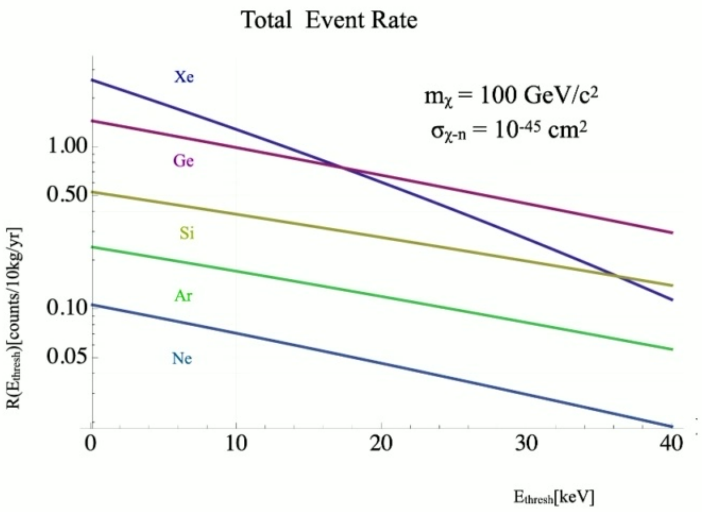

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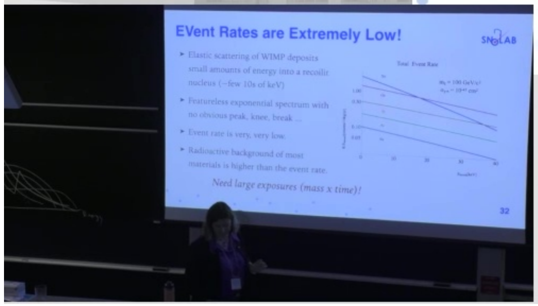

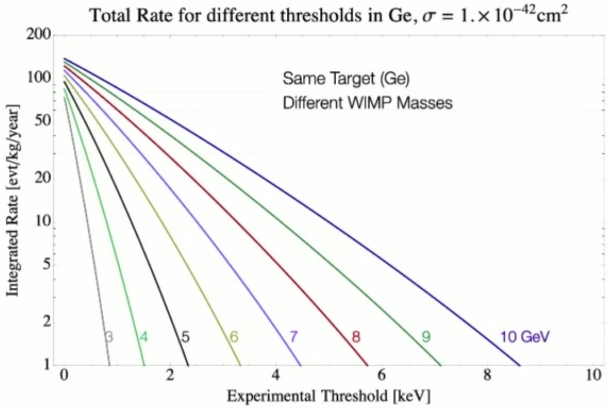
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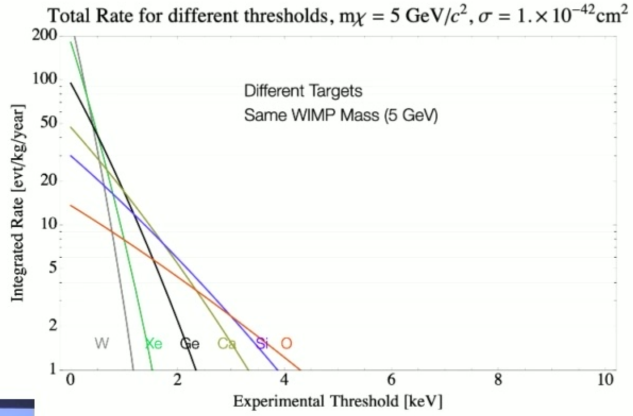
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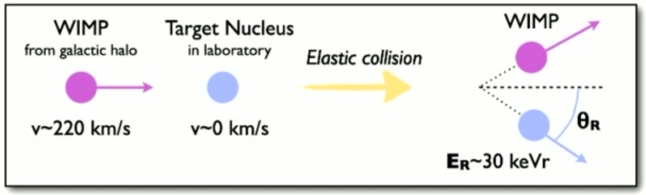

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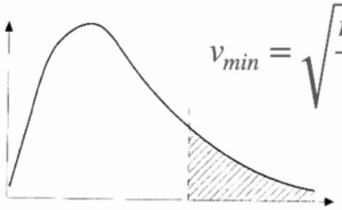
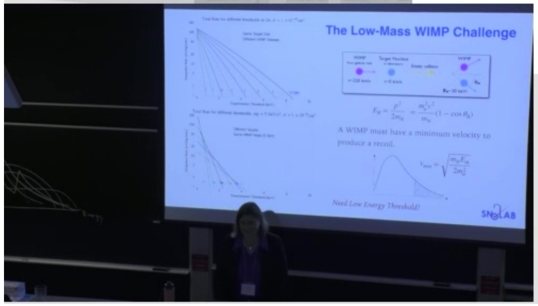


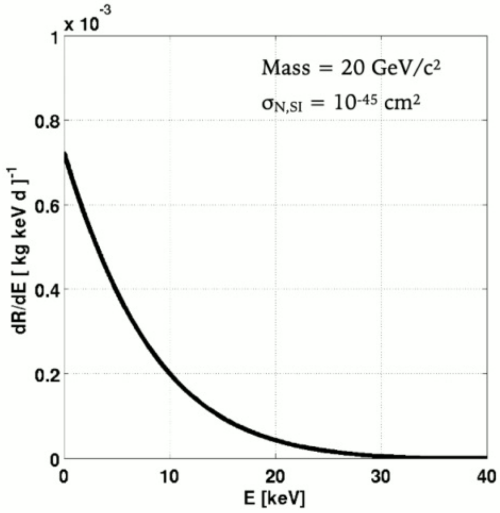
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2m_\mu^2}}$$

Need Low Energy Threshold!



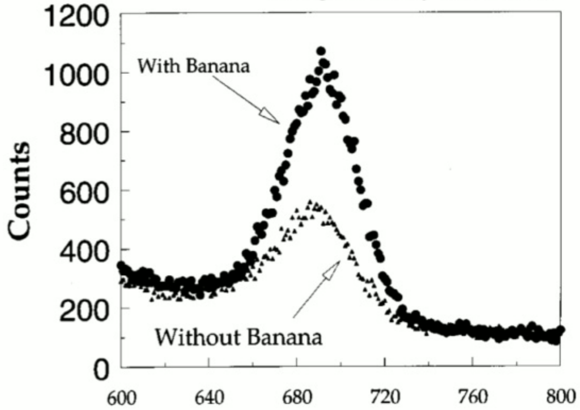
The Event Rates Are Extremely Low!

- Expected WIMP Spectrum



- Measured Banana Spectrum

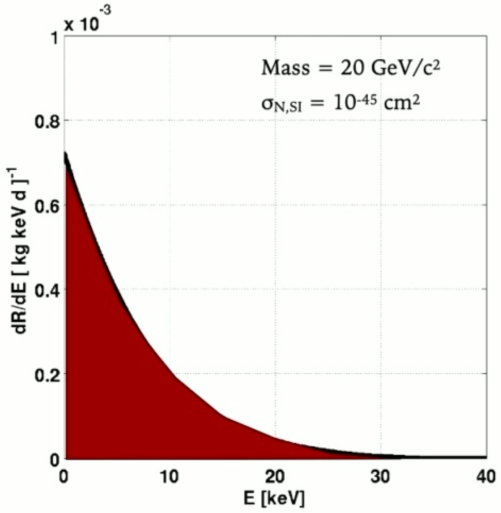
Hoeling et al Am.J.Phys. 1999, 67, 440.



Gamma measurements with a 3-inch NaI detector

The Event Rates Are Extremely Low!

- Expected WIMP Spectrum

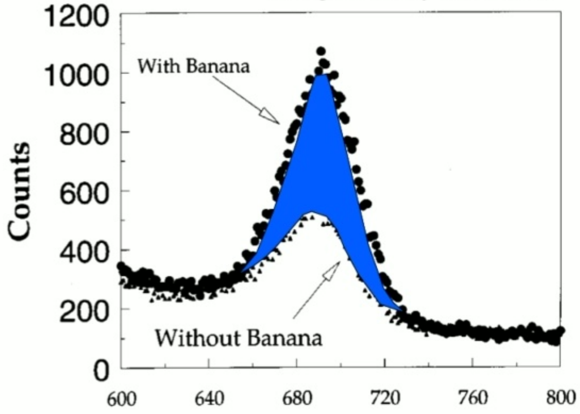


~1 event per kg per year

(*nuclear recoils*)

- Measured Banana Spectrum

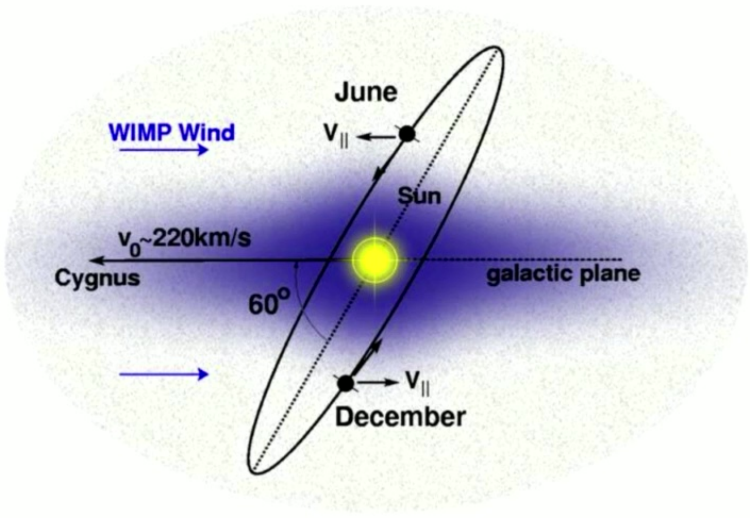
Hoeling et al Am.J.Phys. 1999, 67, 440.

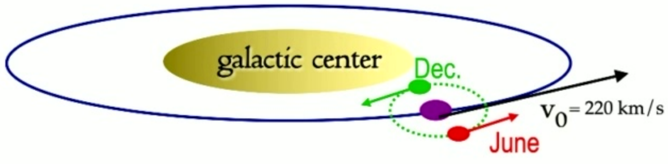


~100 events per kg per year

(*electron recoils*)

Signals

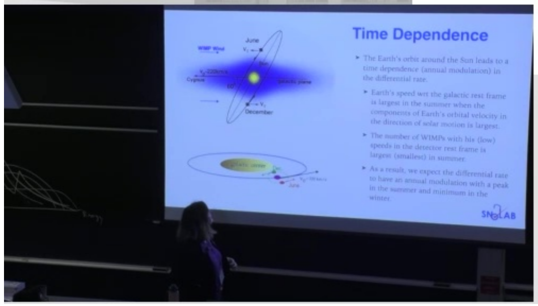




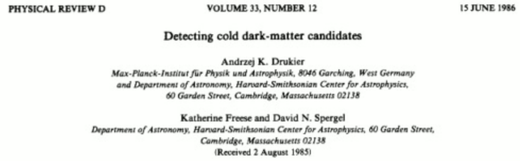
Time Dependence

- The Earth's orbit around the Sun leads to a time dependence (annual modulation) in the differential rate.
  - Earth's speed wrt the galactic rest frame is largest in the summer when the components of Earth's orbital velocity in the direction of solar motion is largest.
  - The number of WIMPs with his (low) speeds in the detector rest frame is largest (smallest) in summer.
  - As a result, we expect the differential rate to have an annual modulation with a peak in the summer and minimum in the winter.

SNOLAB



Time Dependence of the Signal



PHYSICAL REVIEW D VOLUME 33, NUMBER 12 15 JUNE 1986

Detecting cold dark-matter candidates

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and Department of Astronomy, Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, Massachusetts 02138

Katherine Freese and David N. Spergel
Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street,
Cambridge, Massachusetts 02138
(Received 2 August 1985)

- Earth's orbital speed is much smaller than Sun's circular speed ($\frac{v_{orb}}{v_c} \simeq 0.07$). We can Taylor expand the differential rate to a first approximation.

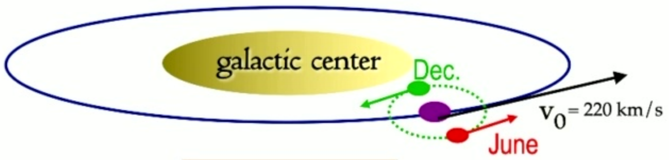
$$\frac{dR}{dE_R}(E_R, t) \approx \frac{dR}{dE_R}\left[1 + \Delta(E_R)\cos\frac{2\pi(t - t_0)}{T}\right]$$

period *phase*

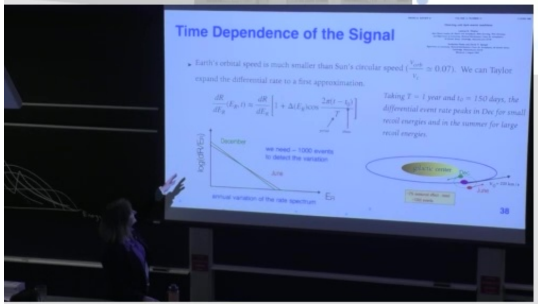
Taking $T = 1$ year and $t_0 = 150$ days, the differential event rate peaks in Dec for small recoil energies and in the summer for large recoil energies.

we need ~ 1000 events to detect the variation

annual variation of the rate spectrum



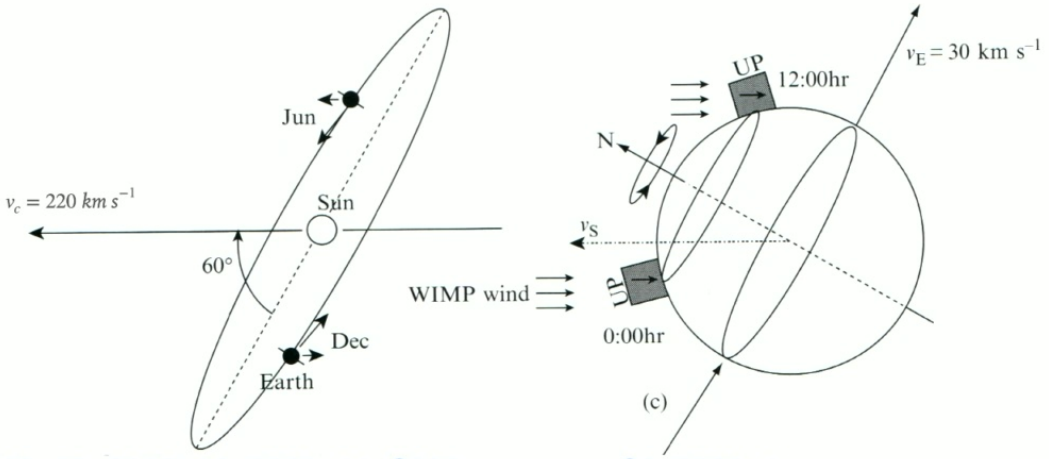
~2% seasonal effect - need ~1000 events

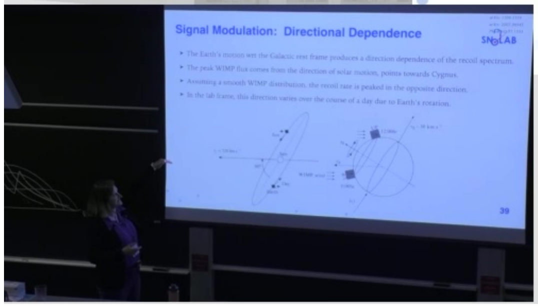


arXiv: 1209.3339
arXiv: 2003.04545
PhysRevD 37.1353

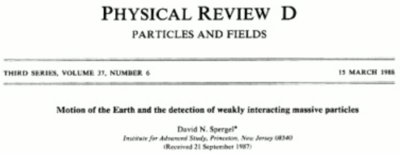
Signal Modulation: Directional Dependence

- The Earth's motion wrt the Galactic rest frame produces a direction dependence of the recoil spectrum.
- The peak WIMP flux comes from the direction of solar motion, points towards Cygnus.
- Assuming a smooth WIMP distribution, the recoil rate is peaked in the opposite direction.
- In the lab frame, this direction varies over the course of a day due to Earth's rotation.





Signal Modulation: Directional Dependence



PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 37, NUMBER 6 15 MARCH 1988

Motion of the Earth and the detection of weakly interacting massive particles

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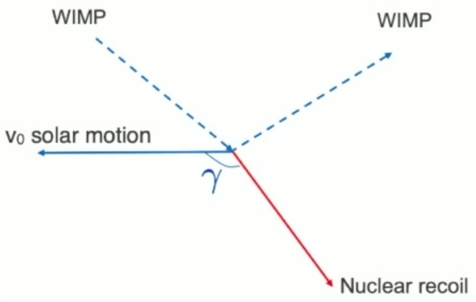
(Received 21 September 1987)

- The number of NR along a particular direction in the lab frame will change over the course of a day.
- Assuming a Standard Halo model, the dependence is given by

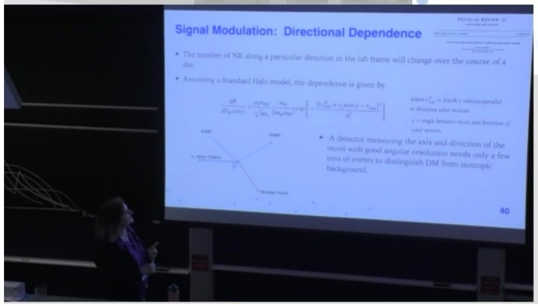
$$\frac{dR}{dE_R \cos\gamma} = \frac{\rho_0 \sigma_{WN}}{\sqrt{\pi}\sigma_v} \frac{m_N}{2m_W m\mu^2} exp\left[-\frac{[(v^E_{orb} + v_c)\cos\gamma - v_{min}]^2}{\sigma_v^2}\right]$$

where v^E_{orb} = *Earth's velocity parallel to direction solar motion*

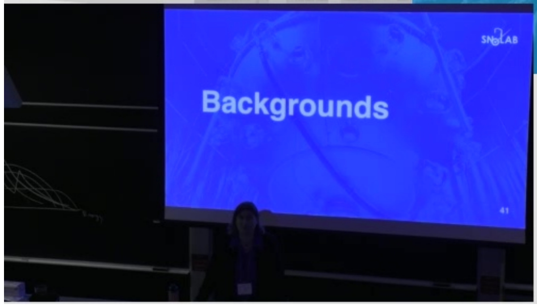
γ = *angle between recoil and direction of solar motion*



- A detector measuring the axis and direction of the recoil with good angular resolution needs only a few tens of events to distinguish DM from isotropic background.

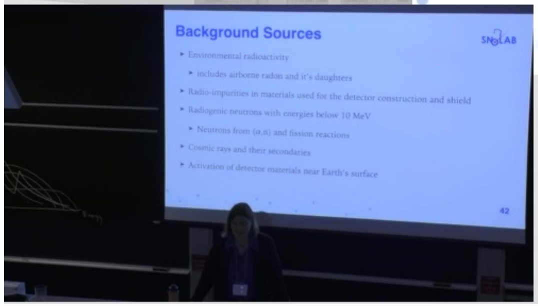


Backgrounds



Background Sources

- Environmental radioactivity
  - includes airborne radon and it's daughters
- Radio-impurities in materials used for the detector construction and shield
- Radiogenic neutrons with energies below 10 MeV
  - Neutrons from (α,n) and fission reactions
- Cosmic rays and their secondaries
- Activation of detector materials near Earth's surface



Background Sources

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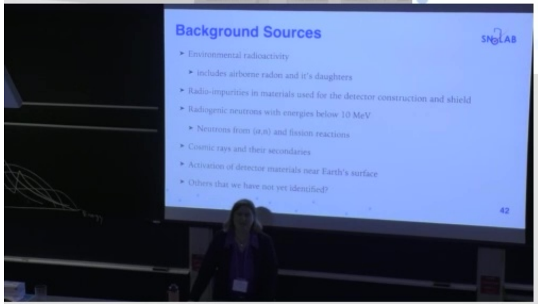
- Cosmic rays and their secondaries
- Activation of detector materials near Earth’s surface
- Others that we have not yet identified?



Aside: Reminder of Radioactive Decay

- Activity [decays/time] is a measure of the decay rate of a radionuclide.

$$A = \frac{dN}{dt} = \lambda N \qquad \begin{aligned} \lambda &= decay\ constant \\ N &= total\ number\ of\ radioactive\ atoms \end{aligned}$$

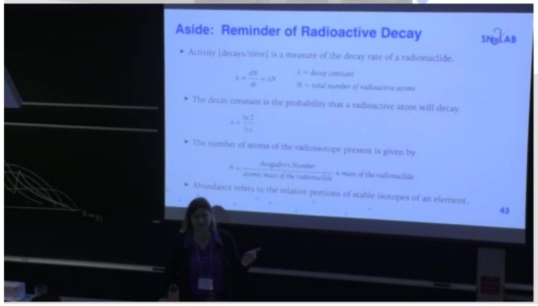
- The decay constant is the probability that a radioactive atom will decay.

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

- The number of atoms of the radioisotope present is given by

$$N = \frac{Avogadro's\ Number}{atomic\ mass\ of\ the\ radionuclide} \times mass\ of\ the\ radionuclide$$

- Abundance refers to the relative portions of stable isotopes of an element.



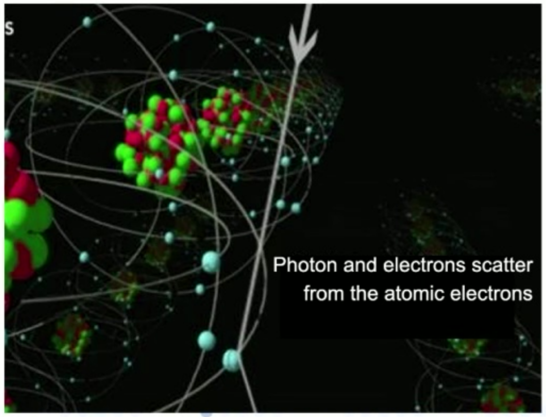
Event Signatures

The most problematic backgrounds are interactions from neutrons that result from (α,n) and fission reactions from ^{238}U and ^{232}Th decays in detector components and in close vicinity of target materials.

Electron Recoils (ER)

Gamma: Most prevalent background

Beta: on surface or in bulk



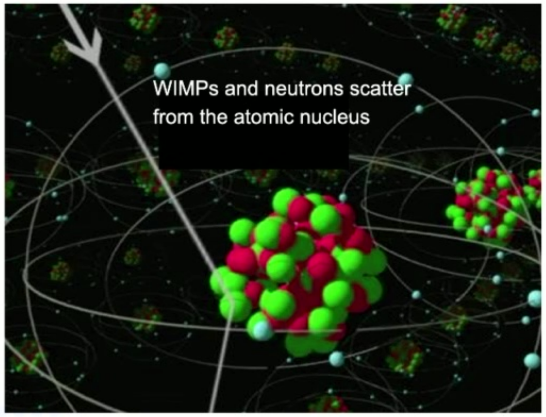
Photon and electrons scatter from the atomic electrons

NUCLEAR Recoils (NR)

Neutron: NOT distinguishable from WIMP

Alpha: almost always a surface event

Recoiling Parent Nucleus: surface event



WIMPs and neutrons scatter from the atomic nucleus