Outline

• Lecture 1:
  • The dark matter problem
  • WIMP and WIMP-like DM detection

• Lecture 2:
  • WIMP detection technologies
  • Current and future limits

• Lecture 3:
  • More 1-10 GeV DM detection technologies
  • To the Neutrino Floor, and beyond!

• Lecture 4:
  • The SuperCDMS Experiment
  • meV - 1GeV direct detection

• Lecture 5:
  • Indirect sterile neutrino detection
The Dark Matter Problem
Galaxy Rotation Curves

expect slow orbits at high radius

speed

radius
Rotation Curve of the Milky Way

Bulge

Disk

DM Halo

Sofue 2012 & 2009

V (km/s)

R (kpc)

density of dark matter where we are: 0.3±0.1 GeV/cm³

R☉

MW     M31

Sofue 2012 & 2009

Enectali Figueroa-Feliciano \ ICTP-SAFIR \ July 2018
Galaxy Velocities in Clusters
Models of Structure Formation


Fits to Cosmic Microwave Background

Planck 2013
The $\Lambda$CDM Model of Cosmology

One model has emerged that fits all the observations with only 6 parameters.
The $\Lambda$CDM Model of Cosmology

We don’t know what 95% of the Universe is made of!

This model raises some truly fundamental physics questions:
- What is Dark Matter?
- What is Dark Energy?

**Components of the Universe:**
- Dark Energy: 68%
- Dark Matter: 27%
- Free H & He: 4%
- 0.03% of the Universe

Legend:
- Dark Energy
- Dark Matter
- Free H & He
- Stars and Gas
- Neutrinos
- Heavy Elements (Us)
We did not know the power of the dark side...
The Nature of Dark Matter

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

• Wealth of evidence for a particle solution
  • MOND has problems with weak lensing and CMB
  • Microlensing (MACHOs) mostly ruled out

• Non-baryonic
  • Height of acoustic peaks in the CMB ($\Omega_b$, $\Omega_m$)
  • Power spectrum of density fluctuations ($\Omega_m$)
  • Primordial Nucleosynthesis ($\Omega_b$)

• And STILL HERE!
  • Stable (or extremely long-lived), neutral, non-relativistic
  • Interacts via gravity and (maybe) some sub-weak scale force
Dark Matter may be a Rosetta Stone!

We know the Standard Model is incomplete.

Where does dark matter fit in?
We know the Standard Model is incomplete.

Where does dark matter fit in?

And how does it fit into a more general understanding?
A Beautiful Problem in Physics

40 Orders of Magnitude!
The Hunt for Dark Matter

Relic annihilation or decay in the cosmos
INDIRECT DETECTION

Relic Dark Matter Interacting in a Lab Experiment
DIRECT DETECTION

FERMI-GLAST

LHC man-made COLLIDER production
Theories of Dark Matter

- Supersymmetry
  - mSUGRA
  - R-parity Conserving
  - R-parity Violating
  - Gravitino DM
  - MSSM
  - pMSSM
  - NMSSM
- Extra Dimensions
  - UED DM
  - Warped Extra Dimensions
- Little Higgs
- Axion-like Particles
  - QCD Axions
  - Axion DM
  - Axion-like Particles
  - Sterile Neutrinos
  - Light Force Carriers
- Warm DM
- Asymmetric DM
- Hidden Sector DM
- Self-Interacting DM
- Dark Photon
- Extra Dimensions
- Solitonic DM
- Quark Nuggets
- T-odd DM
- RS DM
- Tait
- Techni-baryons
- Dynamical DM
- WIMPless DM
- Littlest Higgs
- Q-balls
- Warm DM
- Axion DM
- Axion-like Particles
- Little Higgs
- MSSM
- NMSSM
- Extra Dimensions
- Solitonic DM
Dark Matter Menu

- Axions
- Axion-like Particles
- Hidden Sector Particles
- Sterile Neutrinos
- WIMPs
- SuperWIMPs
- Solitons
- KK excitations
- Gravitinos
- And many more that can fit the bill...

no, we don’t serve quark soup!
Dark Matter Detection Channels

Hidden Sector Particles

ALPs | Axions | Sterile ν’s | WIMPs

Dark Matter Mass

<table>
<thead>
<tr>
<th>feV</th>
<th>peV</th>
<th>neV</th>
<th>μeV</th>
<th>meV</th>
<th>eV</th>
<th>keV</th>
<th>MeV</th>
<th>GeV</th>
<th>TeV</th>
<th>PeV</th>
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<tbody>
<tr>
<td>10^{-46}</td>
<td>10^{-40}</td>
<td>10^{-34}</td>
<td>10^{-28}</td>
<td>10^{-22}</td>
<td>10^{-16}</td>
<td>10^{-10}</td>
<td>10^{-4}</td>
<td>10^2</td>
<td>10^5</td>
<td>10^5</td>
</tr>
</tbody>
</table>

Max Recoil Energy in Silicon [eV]

| 10^{26} | 10^{23} | 10^{20} | 10^{17} | 10^{14} | 10^{11} | 10^8 | 10^5 | 10^2 | 10^{-1} | 10^{-4} |

Dark Matter Particle Density per Liter

Nuclear Recoils

Sterile ν’s

板材中子

暗物质探测通道
Dark Matter Detection Channels

Hidden Sector Particles

<table>
<thead>
<tr>
<th>ALPs</th>
<th>Axions</th>
<th>Sterile ν’s</th>
<th>WIMPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>feV</td>
<td>peV</td>
<td>neV</td>
<td></td>
</tr>
</tbody>
</table>

Dark Matter Mass

- $10^{-41}$
- $10^{-35}$
- $10^{-29}$
- $10^{-23}$
- $10^{-17}$
- $10^{-11}$
- $10^{-5}$
- $10^0$
- $10^1$
- $10^1$
- $10^1$

Max Electron Recoil Energy [eV]

- $10^{26}$
- $10^{23}$
- $10^{20}$
- $10^{17}$
- $10^{14}$
- $10^{11}$
- $10^8$
- $10^5$
- $10^2$
- $10^{-1}$
- $10^{-4}$

Dark Matter Particle Density per Liter

- Electron Recoils
- Nuclear Recoils
# Dark Matter Detection Channels

## Hidden Sector Particles

<table>
<thead>
<tr>
<th>ALPs</th>
<th>Axions</th>
<th>Sterile $\nu$'s</th>
<th>WIMPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>feV</td>
<td>peV</td>
<td>neV</td>
<td>$\mu$eV</td>
</tr>
<tr>
<td>$10^{-41}$</td>
<td>$10^{-35}$</td>
<td>$10^{-29}$</td>
<td>$10^{-23}$</td>
</tr>
</tbody>
</table>
| Dark Matter Mass | Max Electron Recoil Energy [eV] | Mean Distance Between Particles [m] | \[
\text{Coherent/Resonant Detection} & \text{Electron Recoils} & \text{Nuclear Recoils} \\
10^{12} & 10^9 & 10^6 & 10^3 & 10^0 & 10^{-3} & 10^{-6} & 10^{-9} & 10^{-12} & 10^{-15} & 10^{-18} |
\]
Nuclear Recoils
The WIMP “Miracle”

\[ \Omega_{\text{DM}} \approx \frac{m_{\text{DM}}}{T_f} \rho_c M_{\text{Pl}} T_o^3 \langle \sigma_{\text{ann}} v \rangle \]

\[ m_{\text{DM}} \sim 0.1 - 1 \text{ TeV} \]

\[ \sigma_{\text{ann}} = \frac{k \alpha^2}{m_{\text{DM}}^2} \]

\[ \sigma_{\text{ann}} \sim 1 \text{ pb} \]

Cosmology Predicts the Weak Scale!
Dark Matter Astrophysics

\[ f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{|\vec{v}|^2}{2\sigma^2}\right) \]

\[ \sigma = \sigma_{rms} = \sqrt{\frac{3}{2}}v_0 = 270 \text{ km/s} \]

and \( v_0 = 220 \text{ km/s} \)

- The dark matter density falls off as \( r^{-2} \)
- Particles with speed greater than the local escape velocity are not gravitationally bound. The standard halo extends out to infinite radii and thus the speed distribution in this model must be truncated “by hand”. We take \( v_{esc} = 650 \text{ km/s} \).
Density of Dark Matter in this Room

- Local dark matter density:
  - \( \rho_0 = 0.3 \text{ GeV} / \text{cm}^3 \)
  - Assume mass = 60 GeV/c^2
  - Density = 5000 particles/m^3

10 WIMPs on average, inside a 2 liter bottle (if mass=60 x proton)
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/cm²/sec

• About 20 million/hand/sec
Principles of Particle Detection

Interaction Rate  \[ \frac{dR}{dE_R} \]

[events/keV/kg/day]

\[
\sigma_o \frac{F^2(E_R)}{m^2_r} \rho_o \frac{T(E_R)}{v_o \sqrt{\pi}}
\]

\[ m_r = \frac{m_\chi m_N}{m_\chi + m_N} \]

"reduced mass"
Principles of Particle Detection

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

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

\[
v_{\text{min}} = \sqrt{E_R m_N / (2m_r^2)}
\]

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

integral over local WIMP velocity distribution

minimum WIMP velocity for given \(E_R\)

for pure Maxwellian case

astrophysics properties

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Principles of Particle Detection

Interaction Rate
[events/keV/kg/day]
\[ \frac{dR}{dE_R} = \frac{\sigma_o}{m_{\chi}} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}} \]

These two depend on the interaction type.
Let’s look at the standard assumptions, that the interaction is either spin-independent or spin-dependent
Principles of Particle Detection: Spin Independent

Interaction Rate

\[ \frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \rho_o T(E_R) \frac{m^2}{\nu_o \sqrt{\pi}} \]

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

“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: Spin Independent

Interaction Rate

\[
\frac{dR}{dE_R} = \sigma_o \frac{F^2(E_R)}{m_r^2} \rho_o \frac{T(E_R)}{\sqrt{\pi}}
\]

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

\[
\sigma_o \approx \frac{4m_r^2}{\pi} f A^2
\]

Enormous enhancement for heavy nuclei target!
Interaction Rate
(events/keV/kg/day)

\[
\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \cdot \frac{F^2(E_R)}{m^2_f} \cdot \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}
\]

Differential Rate [dru], \(m_\chi = 100 \text{ GeV}/c^2\), \(\sigma = 1 \times 10^{-45} \text{ cm}^2\)

\(dR/dE_r [\text{counts/10kg/keV/year}]\)

**Spin-Independent Recoil Spectrum**

- Xe
- Ge
- Ar
- Si
- Ne
**Principles of Particle Detection: Spin Dependent**

Interaction Rate

\[ \frac{dR}{dE_R} = \sigma_o \frac{F^2(E_R)}{m^2_r} \rho_o T(E_R) \]

Where:

- \( \sigma_o \) is the nuclear structure function
- \( F^2(E_R) = S(E_R)/S(0) \)
- \( S(E_R) = a_0^2 S_{00}(E_R) + a_1^2 S_{11}(E_R) + a_0 a_1 S_{01}(E_R) \)

“Spin-dependent Form Factor”

- \( a_0 = \) isoscalar matrix element
- \( a_1 = \) isovector matrix element

\( S_{ii} \) are obtained from detailed nuclear calculations.
**Principles of Particle Detection: Spin Dependent**

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

- Dominated by unpaired nucleons
- For spinless nuclides, SD cross section = 0
- For zero momentum transfer collisions (extremely soft bumps) the cross section is approximately:

\[
\sigma_o = \frac{32(J + 1)}{\pi J} G_F^2 m_r^2 (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2
\]

- Nuclear Angular Momentum
- Fermi constant
- Coupling constant
- Spin
Principles of Particle Detection: Spin Dependent

\[ \sigma_o = \frac{32(J + 1)}{\pi J} G_F^2 m_r^2 \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2 \]

Nuclear Angular Momentum  Fermi constant  Coupling constant  Spin

---


<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Z</th>
<th>Odd Nucleon</th>
<th>J</th>
<th>( \langle S_p \rangle )</th>
<th>( \langle S_n \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{19})F</td>
<td>9</td>
<td>p</td>
<td>1/2</td>
<td>0.441</td>
<td>-0.109</td>
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<tr>
<td>(^{23})Na</td>
<td>11</td>
<td>p</td>
<td>3/2</td>
<td>0.248</td>
<td>0.020</td>
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<tr>
<td>(^{27})Al</td>
<td>13</td>
<td>p</td>
<td>5/2</td>
<td>-0.343</td>
<td>0.030</td>
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<tr>
<td>(^{29})Si</td>
<td>14</td>
<td>n</td>
<td>1/2</td>
<td>-0.002</td>
<td>0.130</td>
</tr>
<tr>
<td>(^{35})Cl</td>
<td>17</td>
<td>p</td>
<td>3/2</td>
<td>-0.083</td>
<td>0.004</td>
</tr>
<tr>
<td>(^{39})K</td>
<td>19</td>
<td>p</td>
<td>3/2</td>
<td>-0.180</td>
<td>0.050</td>
</tr>
<tr>
<td>(^{73})Ge</td>
<td>32</td>
<td>n</td>
<td>9/2</td>
<td>0.030</td>
<td>0.378</td>
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<tr>
<td>(^{93})Nb</td>
<td>41</td>
<td>p</td>
<td>9/2</td>
<td>0.460</td>
<td>0.080</td>
</tr>
<tr>
<td>(^{125})Te</td>
<td>52</td>
<td>n</td>
<td>1/2</td>
<td>0.001</td>
<td>0.287</td>
</tr>
<tr>
<td>(^{127})I</td>
<td>53</td>
<td>p</td>
<td>5/2</td>
<td>0.309</td>
<td>0.075</td>
</tr>
<tr>
<td>(^{129})Xe</td>
<td>54</td>
<td>n</td>
<td>1/2</td>
<td>0.028</td>
<td>0.359</td>
</tr>
<tr>
<td>(^{131})Xe</td>
<td>54</td>
<td>n</td>
<td>3/2</td>
<td>-0.009</td>
<td>-0.227</td>
</tr>
</tbody>
</table>
Effective Field Theory contains 14 operators, which 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, so there are eight independent parameters that can be probed.

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The effective field theory of dark matter direct detection

A. Liam Fitzpatrick, Wick Haxton, Emanuel Katz, Nicholas Lubbers, Yiming Xu

http://arxiv.org/abs/1308.6288
http://arxiv.org/abs/1405.6690
Dark Matter Could Look Different in Different Targets

• EFT Operators can interfere, generating 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.

• Take home message: *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.

![Graph showing event rates as a function of threshold energy](image-url)

**Total Event Rate**

\( m_\chi = 100 \text{ GeV/c}^2, \sigma_{\chi-n} = 10^{-45} \text{ cm}^2 \)
Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)
The low-mass WIMP challenge

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

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

$$v_{\text{min}} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$
The low-mass WIMP challenge below 5 GeV

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

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

\[ v_{\text{min}} = \sqrt{\frac{E_R m_N}{2m_r^2}} \]

Differential Interaction Rate as a function WIMP Mass

Ge target
\[ \sigma = 1. \times 10^{-42} \text{cm}^2 \]

Recoil Energy [keV]

Differential Interaction Rate [evt/kg/day]

0.3 GeV
0.5 GeV
0.7 GeV
1 GeV
3 GeV
5 GeV
Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold
The Event Rates are Extremely Low!

Expected WIMP Spectrum

Mass = 20 GeV
\( \sigma_{N,SI} = 10^{-45} \text{ cm}^2 \)

Measured Banana Spectrum

The Event Rates are Extremely Low!

Discrimination between electron and nuclear recoils really helps!

Expected
WIMP Spectrum

Mass = 20 GeV
\( \sigma_{N,SI} = 10^{-45} \text{ cm}^2 \)

- ~1 event per kg per year
  - (Nuclear Recoils)

- ~100 events per kg per second
  - (Electron Recoils)

Measured
Banana Spectrum
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 WIMPS
- Alphas: almost always a surface event
- Recoiling parent nucleus: yet another surface event

Most backgrounds are from trace radioactivity (U, Th, K contamination) or induced by cosmic rays (cosmogenic background).
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!
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.
Most experiments use the earth as shielding from muons. The lower the muon rate, the lower the fast neutron rate.

m.w.e. = meters water equivalent
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.
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 ~10⁶

**Ancient lead or copper** shields against ²¹⁰Pb, 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 ~10⁴
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.
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).

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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 $O(10^6)$ 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.
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).

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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.
Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold

3: Low Backgrounds
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
Different Response to Electron Recoils and Nuclear Recoils Allows Discrimination

$v/c \approx 0.3$

$E_r \approx 10's \text{ KeV}$

$v/c \approx 7 \times 10^{-4} = 210 \text{ km/s}$

Particle ID through Detector Response
Particle ID Through Detector Response

**Phonons**
- 10 meV/ph
- 100% energy

**Scintillation**
- ~ 1 keV/γ
- few % energy

**Ionization**
- ~ 10 eV/e
- 20% energy

**ArDM**
- DarkSide
- LUX
- WARp
- XENON
- ZEPLIN II, III
- Xe, Ar, Ne

**ArDM-TPC**
- DRIFT
- IGEX

**CRESST I**
- CUORE
- TeO₂, Al₂O₃, LiF

**CRESST ROSEBUD**
- CaWO₄, BGO
- ZnWO₄, Al₂O₃...

**IONIZATION**
- Ge, Si

**CDMS EDELWEISS**
- Ge, Si

**CLEAN**
- DAMA
- DEAP
- NAIAD
- ZEPLIN I
- XMASS

**Xe, Ar, Ne**
- NaI(Tl)

**ANALIS**
- CoGeNT
- COSME
- COUPP
- DM-TPC
- DRIFT
- IGEX

**Ge, CS₂, C₃F₈**
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.
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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.

"Some discrimination parameter (ionization yield in this case)"

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