Introduction to **DM** direct detection

**WIMPs**
1-1000GeV
In our Milky Way

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The lab experiment

1. Concept of keV particle detection with a NaI(Tl) detector and a SiPM LySO detector
2. Energy calibration with radioactive sources
3. Energy resolution

4. Background measurements: rates and identification of background observed
5. Comparison with measurements underground with a Germanium detector
6. Design your ideal detector!
CDEX: reaching best present Ge limits in 5 years!

10 kg Ge crystal

Y. Qian et al., arxiv 1404.4946

Cosmogenics Ge-68 has 270.8 days half-life!
Usual assumptions of DM distribution in our Galaxy

Usual assumptions:

- $\rho_{DM} = 0.3$ GeV/cm$^3$, $\beta = 10^{-3}$
- Maxwellian distribution of velocities, $v_{rms} = 270$ km/s

« Simplified Model » of Matter in our Galaxy: SMMG

Used for most comparisons...

But is it the reality? Clumps? Corotation?
WIMP searches: Direct detection

- **Principle**: (Goodman and Witten, 1985, Drukier and Stodolsky 1984)

  Elastic scattering of **galactic DM** off detector nuclei

  Nuclear recoils of a few keV

  Ge, Si, NaI, LXe, …
WIMP searches: Direct detection

- **Principle**: (Goodman and Witten, 1985, Drukier and Stodolsky 1984)

  Elastic scattering of galactic DM off detector nuclei
  Nuclear recoils of a few keV

- **Exponential recoil energy distribution**

  \[
  \frac{dR}{dE_R} = \frac{R_o}{E_{o,r}^r} e^{-E_R/E_{o,r}}
  \]

  event rate per unit mass

  total event rate (point like nucleus)

  recoil energy

  incident energy

  kinematic factor

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

- **Rates**: Weak interactions or smaller
Differential rate for WIMP elastic scattering

\[
\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_W} \int_{v_{\text{min}}}^{v_{\text{max}}} dv f(v) v \frac{d\sigma}{dE_R}
\]

\[
v_{\text{min}} = \sqrt{\frac{m_N E_{\text{th}}}{2 m_r^2}}, v_{\text{max}} = v_{\text{esc}}
\]

\[
f(v) dv = 4\pi \left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2} v^2 \exp\left(-\frac{3v^2}{2\bar{v}^2}\right) dv, \bar{v} = 270 \text{ km/s}
\]

\[
E_R = \frac{m_r^2 v^2 (1 - \cos \vartheta)}{m_N}
\]

\[
\frac{d\sigma}{dE_R} = \frac{\sigma_0}{E_R^{\text{max}}} F^2(E_R), \quad \sigma_0 = \frac{1 + m_W / m_p}{1 + m_W / m_N} A^2 \sigma_{\text{scalar}}^{\text{nucleon}}
\]
Direct detection: Interaction rates

Depend on several parameters

- **Astrophysical hypothesis**: model of DM in Galaxy (SMMG)
  \[ \rho_{\text{DM}}, f(v) \]

- **Nuclear form factors** \( F^2 \) important for heavy nuclei

- **Detector response** Quenching factors, resolutions, thresholds,....

- **Particle physics** Nature of WIMP and cross-sections

\[ \sigma \]

- **Coherent**
  - **Spin Independent (SI)**
    - eg, Dirac \( v \)

- **Axial**
  - **Spin Dependent (SD)**
    - eg, Majorana \( v \)

**Neutralinos** are a linear combination of higgsinos and gauginos

with cross-sections \(< 0.1 \sigma_v\)
WIMP direct detection with and w/o background rejection

Elastic scattering off nuclei

Ionization

Scintillation

Liquid Xe

NaI, CaF$_2$, LXe, ...

CaWO$_4$, BGO, ...

Ge, Si

WIMP target

Phonons

mixed detections

Ge, Si

Al$_2$O$_3$, LiF, ...

He 3 detector

Superconducting granules

Freon aerogel
Need mountain coverage

Comparison of main ULs in the world
Chinese Underground Laboratory in Jinping CJPL

Road and Tunnel

Yue Qian 岳骞，2009
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Pandax: inauguration end march 2014 – First results 2016

- Ton scale liquid Xenon two phase (liquid and gas) TPC
- Project lead by SJTU

No events found in the DM search region!
WIMP searches: Direct detection: a summary

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**Nuclear recoils of a few keV**

**Exponential recoil energy distribution**

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- **Event rate per unit mass**
- **Total event rate** (point like nucleus)
- **Recoil energy**
- **Incident energy**
- **Kinematic factor**
  \[= 4M_\chi M_N/(M_\chi + M_N)^2\]

**Rates:** Weak interactions or smaller

**Need of signatures** for identifying galactic origin

- Annual modulation with MASSIVE detectors
- Directionality: low pressure TPC?
- Dependence on nucleus
Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin)
- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction
Wealth of evidence for DM is astrophysical.

More Complexity!
Rotation curves: what is often said [incorrectly] to be expected

Galaxy at the top has no halo. Its surface brightness decreases rapidly, orbital velocities outside the nucleus decrease in Keplerian fashion.

Keplerian behaviour just outside the nucleus can NOT be expected

A. Bosma
For NGC 300 and M33, the 21-cm data give turnover points near the photometric outer edges of these systems. These data have relatively low spatial resolution; if they are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different.

**M31 – Need for dark matter based on radio data**

![Graph showing rotation velocity vs. radius for M31 with various data points and curves representing data from different sources.](image)

- Babcock (1939)
- van de Hulst et al. (1958)
- Rubin & Ford (1970)
- Roberts & Whitehurst (1975)
Wealth of Evidence for DM

- Galaxy rotation curves (V. Rubin, Bosma (HI))
- Dynamics of galaxy clusters (Zwicky)
- Gravitational lensing mass reconstruction

- Bullet cluster (Clowe+, 2006)
N-Body simulations: CDM

- Preferred paradigm: CDM
- Most N-Body simulations use stable CDM halos as seed for structures:
  - structures evolve, merge and cluster
- Properties of CDM halos
  - cuspy density profiles,
  - Triaxial halos
  - central density depends on the mass of the halo.
Very different DM candidates

1. Neutrino
2. WIMPs (Weakly interacting massive particles) 10-1000 GeV
3. Light axions

Modified Gravity

SIMPs

MACHOs

Black holes

Cold Molecular Hydrogen

Dust
Theories of Dark Matter

Snowmass 2013
Why WIMPs?

“WIMP” = “Weakly Interacting” Massive Particles

• Arguments in the 1980’s:

  • Need for Cold Dark Matter from Large Scale Structures
  • Very good Particle physics candidate: SUSY LSP
  • Weak neutrino size cross sections expected which our detectors Ge, NaI were sensitive to…
A natural particle physics solution
Stable linear combination gauginos and higgsinos (LSP)
$\text{SUSY} > 7$ parameters MSSM $\Rightarrow$ no predictive power
Experimental Constraints LEP, pp, $b \rightarrow s\gamma$, + LHC ...

Look everywhere possible!
Direct and Indirect
Detections
WIMP searches

Direct detection
Ge, Si, NaI, LXe, ...

Indirect detection
Accelerator particle production, eg, LHC
ν, γ, p, e+

+ Galactic, cluster, Universe scales...