Searching for Dark Matter at the Deep Underground Laboratories

Kaixuan Ni
University of California, San Diego
nikx@ucsd.edu

REV20 Seminar  Oct.18, 2016
First evidence of dark matter came from the Coma Cluster (Fritz Zwicky, 1933)

400 times invisible matter compared to the visible matter!

Coma Cluster, 0.3 billion light years away
Dark matter evidence from the Galactic rotational curves (Vera Rubin, 1976)

https://youtu.be/sI23cwbbNqs
measure dark matter with "gravitational lensing" effect.
“Bullet clusters” colliding with each other and separating the dark matter and normal matter parts.
All Matter and Energy

- All Other Visible Atoms: 0.01%
- Hydrogen and Helium: 0.5%
- Invisible Atoms: 4%
- Cold Dark Matter: 25%
- Dark Energy: 70%

New Order of the Universe
The Milky Way Surrounded by a Dark Matter Halo
What we know about normal matter?
What is Dark Matter?

- Known through gravitational effect, but no EM interactions
- Any interaction with normal matter besides gravity?
- Baryonic dark matter (brown dwarfs, black holes etc.)
- Non-baryonic dark matter (BSM of particle physics)

Is dark matter the **Weakly Interacting Massive Particle (WIMP)** from the Beyond Standard Model physics, such as Supersymmetry?
Three ways to probe the nature of dark matter

1. **Produce dark matter**: using high energy colliders

2. **Indirect detection**: detect the annihilation/decay products

3. **Direct detection**: via collisions with standard model particles
Detect Dark Matter in Our Galaxy

direct detection

indirect detection

Dark Matter Halo

Extent of Survey around the Sun

Milky Way

WIMPs and Neutrons scatter from the Atomic Nuclei

Photons and Electrons scatter from the Atomic Electrons

WIMP Dark Matter Particles $E_{CM} \approx 100 \text{GeV}$

$\chi$ Neutrons $\nu$ $\mu$$e$ $\pi$$\gamma$

Gamma-rays

Neutrinos

+$a few p/\bar{p}, d/\bar{d}$

Anti-matter
Detect DM via Scattering
Detect DM via Scattering

smaller cross-section, lower detectability
Direct Detection of Dark Matter: Basic Facts

- WIMP mass: GeV~100 TeV
- Local WIMP density: 0.3 GeV/cm$^3$
- Isothermal Maxwellian velocity distribution with $v_0$~220 km/s
- WIMP escape velocity ~544 km/s
- Local circular velocity ~230 km/s
- Standard assumption: elastic scattering with target nucleus, coupling to mass (SI) or spin (SD)

$$\frac{d\sigma}{d|q|^2} = \frac{C}{v^2} G_F^2 F |q|^2$$

$$C_{SI} = \frac{1}{\pi G_F^2} \left[ n \left( A-Z \right) f_n \right]^2$$

$$C_{SD} = \frac{8}{\pi} \left[ a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \frac{J+1}{J}$$

$\sim 1000,000$ particles/cm$^2$/sec

$<1$ detection/100-kg/year
Expected Signatures in Detectors: Spin-Independent case

\[ \frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2m_\chi \mu_A^2} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3v \]

\[ M_\chi = 50 \text{ GeV/c}^2, \quad \sigma_{\chi-n} = 1 \times 10^{-46} \text{ cm}^2 \]

Signals to look for:
1) Low Energy Excess
2) Nuclear Recoils
3) Annual Modulation

**Low Rate**
- Xe (A=131)
- Ge (A=73)
- Ar (A=40)

**Low Energy**

![Graph showing expected rates for different elements with threshold energy on the x-axis and rate on the y-axis.]

- June 2
- Dec 2
Challenge #1: how to achieve ultra-low background

- Avoid cosmic rays
- Go deep underground
- Avoid natural radiation
- Use ultra-pure materials
More than 20 experiments world-wide are searching for DM at underground labs.
The muon induced background is greatly reduced by going to a deep underground laboratory.
Experiments detect charge, light or phonon (heat) from the recoil nucleus produced by DM collision.

The most common background (gamma and beta decays) is reduced with careful material selection, shielding (Pb, Cu, Xe, water), and scintillation and ionization methods for a given energy.

Nuclear recoils (WIMPs and neutrons) interact via a nuclear recoil mechanism. Neutrons are therefore the most dangerous source of background, coming from rocks (use shields) or muons induced (go deep underground).

Challenge#2: how to detect low energy nuclear recoils?
Current Limits

WIMP–nucleon cross section [cm$^2$]

WIMP–nucleon cross section [pb]

WIMP Mass [GeV/$c^2$]

two-phase xenon experiments

Atmospheric and DSNB $\nu$

$^7$Be $\nu$

$^8$B $\nu$
The most sensitive technology

Two-phase xenon for dark matter searches

WIMPs/Neutrons

nuclear recoil

Gammas

electron recoil

\( (S2/S1)_{\text{wimp}} < (S2/S1)_{\text{gamma}} \)
Merits of **Two-Phase Xenon** for Dark Matter Searches

**Scientifically Attractive**
- Sensitive to both **heavy** and **light** dark matter
- Sensitive to both **Spin-independent** and **Spin-dependent** (Xe129, Xe131)
- Sensitive to both **nuclear recoils** and **electron recoils**

**Technically Achievable**
- **Ultra-low background** with self-shielding, 3D fiducialization, ER/NR discrimination
- **Ultra-pure Xe target**: sub-ppb ($O_2$ etc.) and sub-ppt (Kr) contamination
- **Multi-ton target achievable**: with reasonable cost ($1\sim2$M/ton) and relative simpler cryogenics (165K)
Liquid xenon detectors pushing the sensitivity of dark matter direct detection.

Update from Physics of the Dark Universe 1, 94 (2012)
XENON100 (2012): $2 \times 10^{-45}$ cm$^2$ at 55 GeV (SI) with 34 kg x 225 days (PRL, 2012)
LUX (2013-2015): 6.0x10^{-46} cm^2 at 33 GeV with 118 kg x 85 days (arXiv:1512.03506, PRL)
LUX (2016): final limit $2.2 \times 10^{-46}$ cm$^2$ at 50 GeV with 100 kg x 332 live-days (arXiv:1608.07648)
PandaX-II in China - first dark matter search result (2016):
no WIMPs in 367 kg x 99 live-days

- Drift time [µs] vs. Radius² [cm²]
- WIMP-nucleon cross section (cm²)

- 367 kg
- 2.5 \times 10^{-46} \text{ cm}^2 \text{ at } 40 \text{ GeV} / c^2
- keep running now

The next biggest detector **XENON1T** is coming online at Gran Sasso Underground Laboratory, Italy.
The XENON Collaboration
10 countries
21 institutions
130 scientists
XENON1T: the largest running dark matter detector

- Dual phase Xe TPC
- 2 ton of LXe in active volume
- 3.5 tons in total
- Active muon veto
- Water tank
- Cryogenics
- Xe purification
- DAQ electronics
- Xe storage & analytics
- Kr distillation column
XENON1T/nT Xenon Handling Systems

Built and Commissioned for XENON1T and XENONnT
XENON1T/nT Xenon Handling Systems

Built and Commissioned for XENON1T and XENONnT
XENON1T/nT Xenon Handling Systems

Built and Commissioned for XENON1T and XENONnT
XENON1T/nT Xenon Handling Systems

Built and Commissioned for XENON1T and XENONnT
XENON1T/nT Xenon Handling Systems

Built and Commissioned for XENON1T and XENONnT
XENON1T TPC: the largest two-phase xenon TPC ever built

- 2-ton active liquid xenon target
- 96 cm drift x 96 cm diameter TPC
- 248 low radioactivity, high QE (~35%) R11410-21 PMTs
- Detector fully filled and functional in May
- Signals keep improving with better liquid purity

![XENON1T TPC](image)

- TOP ARRAY: 127 PMTs
- BOTTOM ARRAY: 121 PMTs

One early event in the top part of TPC:

![Event](image)
XENON1T: liquid xenon purity keeps improving

- Electron lifetime reaching a few hundred us
- TPC is now fully transparent to all events, a milestone towards science data taking

160710_0624 one recent event in the middle of TPC
Recent status: reducing the background with water shielding

- Zero-field background spectrum before filling the water shield
- Active Shielding
  - 700 m of demineralized water
  - Lined with reflective foil
  - 84 high-QE PMTs → 99.5% detection efficiency
- Background from muon-induced neutrons ~0
- First fill and commissioning as a detector: March 2016
- First muons!

E. Aprile et al. (XENON Collaboration), JINST 9, P11006 (2014)

Background studies started towards the first dark matter data taking now!
XENON1T Background Studies

Background Simulation and Expected Performance (JCAP 1604 (2016) no.04, 027)

ER Background from detector materials (1-12 keVee)

Overall ER Background (1-12 keVee)

Optimal fiducial volumes will be chosen at different stages of the dark matter search.

Less than 0.5 electronic recoil bkg event in 1800 kg x 20 live-days (with 99.75% ER rejection)
Continue to probe two orders of magnitude in the WIMP parameter space with the XENON1T/νT program in the next five years!
Summary

- Liquid Xenon is now the most sensitive technology for direct Dark Matter detection
- Three orders of magnitude improvement in sensitivity in the last decade by XE100/LUX/PandaX experiments
- XENON1T, the largest running dark matter detector, is starting to explore new territories of the Dark Matter parameter space now!

Roszkowski, Sessolo, Williams, arXiv:1405.4289