Dark Matter - Direct Searches

Rencontres de Blois 2011
02-May-2011

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XENON100 TPC
Outline

- Dark Matter Evidence & Models
- Direct Detection Technique
- Status of DM Direct Detection and discussion of selected experiments
- Future
- Summary
Dark Matter Detection Methods

- **Astrophysics / Cosmology:**
  - Measurement of Gravitational Effects.
    - Rotation curves of spiral galaxies
    - Orbital velocities of galaxies in clusters (Zwicky 1933)
    - Colliding clusters (Bullet cluster)
    - Large scale structure, lensing

- **Direct Detection:**
  - WIMP scattering
  - Axion searches, ...

- **Indirect Detection:** from annihilation or decay
  - Cosmic rays
    - PAMELA positrons?
    - Fermi, ATIC, HESS electrons? Anti-deuterons?
  - Neutrinos
  - Gamma-rays

- **Accelerator-based Creation and Measurement:**
  - Missing energy / momentum (+ jets + lepton(s))
  - Search for (possibly) DM-related particles
    - SUSY, extra dimensions, dark photon
Evidence for Dark Matter at Different Astrophysics Scales

**Spiral Galaxies**  
Scale: \( \sim 10^{21} \) m  
Rotation curves remain flat far beyond the edge of the visible disk.

\[
\begin{align*}
\nu(R) &= \sqrt{G M(R)/R} \\
\nu(R) &\approx \text{const}
\end{align*}
\]

\[
\Rightarrow \left\{ \begin{array}{l}
M(R) \propto R \\
\rho(R) \propto R^{-2}
\end{array} \right.
\]

**Galaxy Clusters**  
Scale: \( \sim 10^{22} \) m  
- Orbital velocities of galaxies (Zwicky's discovery in 1933)  
- X-ray gas  
- Gravitational lensing

**The Dark Universe**  
Scale: \( \sim 10^{26} \) m  
- CMB: \( \Omega_{\text{tot}} = 1.0 \)  
- CMB, BBN: \( \Omega_b = 0.045 \)  
- Galaxy clusters: \( \Omega_m = 0.27 \)  
- Supernovae Ia: \( \Omega_m - \Omega_\Lambda \)  
- Structure formation: cold DM
What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not hot (relativistic)
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big Bang nucleosynthesis
- Electrically neutral
  - Dark Matter

Dark Matter requires physics beyond the Standard Model.
What do we know about Dark Matter?

- Gravitationally interacting
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  - Dark Matter
- Additional constraints from accelerator searches, direct and indirect searches.

This still leaves many options.

Where to start? Look for “well motivated” candidates.
The Appeal of Weakly Interacting Massive Particles (WIMPs): A Thermal Relic at just the Right Density

\[ \frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v \rangle \left( n_\chi^2 - n_{\chi, \text{eq}}^2 \right) \]

Decrease due to universe expansion

Boltzmann equation

1. \( kT \gg m_\chi c^2 \): equilibrium of WIMP pair creation and annihilation

2. \( kT < m_\chi c^2 \): WIMP creation suppressed by factor \( \exp(-kT/m_\chi c^2) \).

Weakly Interacting: freeze out when annihilation rate drops below expansion rate:

\[ H > \Gamma_{\text{ann}} \sim n_\chi \langle \sigma_a v \rangle \]

results in relic density:

\[ \Omega_\chi h^2 \approx 10^{-27} \text{ cm}^3 \text{ s}^{-1} \langle \sigma_a v \rangle \]

If \( m_\chi \) and \( \sigma_a \) related to the electroweak scale

\[ \Rightarrow \Omega_\chi h^2 \sim O(0.1) \]

“WIMP miracle”

Massive particles: average WIMP velocity is non-relativistic.
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WIMP Dark Matter Direct Detection

- Scattering of WIMPs $\chi$ off of nuclei $A$.
  - elastic or inelastic?
  - spin-independent ($\sim A^2$) or spin-dependent?
- Energy spectrum:
  \[
  \frac{dR}{dE} = \frac{\rho_\chi \sigma_s}{2 m_\chi \mu^2} |F(E)|^2 \int_{v_{\text{min}}}^{v_{\text{esc}}} f\left(\frac{\mathbf{v}}{v}, t\right) d^3\mathbf{v}
  \]
  \[
  f\left(\mathbf{v}, t\right) \propto \exp\left(-\frac{(\mathbf{v} + \mathbf{v}_E(t))^2}{2 \sigma_v^2}\right)
  \]
  - $m_\chi \sim 10 - 10^4$ GeV/c$^2$, $\mu = (m_\chi m_n)/(m_\chi + m_n)$
  - $v_\chi \sim 230$ km/s
  - “Standard” spherical halo:
    Featureless recoil spectrum $\langle E \rangle \sim O(10 \text{ keV})$
  - $\rho_\chi/m_\chi$: local number density of WIMPs
  - $\rho_\chi \sim 0.3$ GeV/c$^2$/cm$^3$, $\rho_\chi/m_\chi \leq 10 / L$
  - $\sigma_s$ cross section per nucleus.

Typical rate $< 10^{-2}$ events / kg / day
Backgrounds in Direct DM Search

Cross-sections are very small: \(<10^{-43} \text{ cm}^2\) or \(10^{-7} \text{ pb}\) (spin-independent)

Without background, sensitivity \(\propto (\text{mass} \times \text{exposure time})^{-1}\)

With background subtraction \(\propto (M_t)^{-1/2}\)
until limited by systematics.

Backgrounds:

Gamma-rays & beta decays:
\~100 events/kg/day
Need very good \(\beta\) and \(\gamma\) background discrimination.
Shielding: low-activity lead, water, noble liquids (active), liquid \(\text{N}_2\), ...

Neutrons from \((\alpha, n)\) and spontaneous fission (concrete, rock, etc.):
\~1 event/kg/day (LNGS)
Neutron moderator (polyethylene, paraffin, ...)

Neutrons from CR muons:
Rate depending on depth.
\(\mu\)-veto, \(n\)-veto, shielding

\(\alpha\) decays from Rn daughters, ...
DM Detector Overview
Detection Principles

Bubble Formation
COUPP, PICASSO

Tracking
Drift, DM-TPC, NIT

Ionization
CoGeNT

CDMS-II, Super-CDMS
EDELWEISS-II

LAr: WARP, ArDM
LXe: XENON, LUX, Zeplin

Phonons
CRESST-II, ROSEBUD, EURECA

Scintillation
DAMA/LIBRA
KIMS, XMASS, DEAP/CLEAN
Looking for Dark Matter at Underground Labs

Techniques:
- Cryogenic (Ge, Si etc.)
- Solid Scintillator (NaI, CsI)
- Noble Liquids (LXe, LAr)
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Part 1: Signals?
DAMA/LIBRA Annual Modulation
R. Bernabei et al. arxiv:0804.2741, arxiv:1002.1028

- Modulation in 2-6 keV single hits: 8.9 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (statistics?)
- **DM detection?**
- Conflict with other experiments in standard scenarios that test the larger steady state effect!

Drukier, Freese, Spergel PRD 86
Freese et al. PRD 88

~250 kg of NaI counters
1.17 ton-year exposure (2010)
Low Mass WIMPs?  
Inelastic Dark Matter?  
Luminous DM?  

... or some yet to be understood detector or background effect?
CoGeNT: What are these excess events?

- Single P-type point contact (PPC) Germanium detector:
  - 440 g mass, 330 g fiducial (CDMS: 250 g per detector)
  - Low electronic noise, hence low threshold (0.4 keVee)
- Located in Soudan mine (2100 mwe)
- Passive shield + Muon veto
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- Exposure: 18.5 kg d
  - Data meanwhile available: 145 kg d
  (evidence for annual modulation?)

CoGeNT favored parameter space
if excess is interpreted as SI WIMP scattering

Aalseth et al.
PRL 106 (2011) 131301

Background
Low Mass WIMPs?

... or some yet to be understood detector or background effect?
CRESST II: Phonons + Scintillation

CRESST
Cryogenic Rare Event Search with Superconducting Thermometers

light + phonons (scintillating crystals)

Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso

Transition Edge Sensors (TES)
superconducting phase-transition-thermometer tungsten $T_c \approx 15 \text{mK}$

Phonon detector ($\text{CaWO}_4$)
Light detector (SOS)
CRESST II: What are these excess counts?

- Data from 9 CaWO$_4$ detectors
- Exposure: 730 kg d
- 57 events observed in O-band (in allen Detektoren)
- Acceptance region (detector specific): O-band in $\sim$10-40 keV

- Background estimated from sidebands:
  - $\alpha$-events: 9.3
  - neutrons (generate mostly O-recoils): 17.3
  - e/$\gamma$ leakage: 9.0

- Excess events not explained by modeled background: 4.6 $\sigma$ (?)

- Hint of low-mass WIMPs?
  - best fit: $M_\chi \sim 13$ GeV/$c^2$
  - $\sigma \sim 3 \times 10^{-5}$ pb = $3 \times 10^{-41}$ cm$^2$
  - confidence region?

- Systematic background uncertainty?

- Further background reduction planned.
Part 2: Limits
CDMS-II: Phonons + Charge
(Cryogenic Germanium)

- Located at Soudan mine (Minnesota)
- Ge crystals operated at ~40 mK
- Fast phonon read-out with Tungsten Transition-edge sensors (TES)
  - direct measurement of nuclear recoil energy
  - SQUID Readout
- Low-voltage drift for charge read-out
  - e.m. background suppression with charge / phonon ratio
- Suppression of surface events with phonon timing signal
CDMS-II
Spin-Independent Limit

- 2 events observed after all cuts.
- Pre-opening background estimate: 0.6 events
- Revised estimate: 0.8 +/- 0.1 events
- 23% chance for background.
- CDMS-II completed.
- Next phase: Super-CDMS (15 kg) at Soudan mine construction and first operation in parallel

CDMS Low Threshold Limit

- Strong tension with low mass WIMP interpretation of CoGeNT & DAMA/LIBRA results
- Discussion about background subtraction
Edelweiss-2
(Phonons + Charge: Cryogenic Ge)

- Simultaneous measurement
  - Heat @ 18 mK with Ge/NTD (neutron transmutation doped) thermometer
  - Ionization @ few V/cm with Al electrodes
- Event by event identification of recoil type by ratio Ionization / E_{recoil}

Shielding: ~ 4800 mwe
μ-flux: ~ 5 / m² / day
Edelweiss-2 – Interleaved Electrodes

- Modification of E field near the surfaces with interleaved electrodes
- Use ‘b’ and ‘d’ signals as vetos against surface events
- Separation of surface and volume events.
- Beta rejection ~ $10^{-5}$
- Substantial improvement over discrimination based on phonon timing (CDMS)
Edelweiss-2 WIMP Search
Result 2009-2010 data

- total exposure of 427 kg.d
  - 384kg.d in 90% NR band (WIMP RoI)
- 5 events observed
  - 4 with E<22.5keV
  - 1 with E=172keV
- Expected background: ~ 3 events

$\sigma_{SI} < 4.4 \times 10^{-8}$ pb (90% CL) for $M_\chi = 85$ GeV/c$^2$
The XENON Program

Collaboration: US (3)+ Switzerland (1) + Italy (2) + Portugal (1) + Germany (3) + France (1) + Netherlands (1) + Israel (1) + China (1)

GOAL: Explore WIMP Dark Matter with a sensitivity of $\sigma_{SI} \sim 10^{-47}$ cm$^2$.
  - Requires ton-scale fiducial volume with extremely low background.

CONCEPT:
  - Target LXe: excellent for DM WIMPs scattering.
    - Sensitive to both axial and scalar coupling.
  - Detector: two-phase XeTPC: 3D position sensitive, self-shielding.
  - Background discrimination: simultaneous charge & light detection (>99.5%).
  - PMT readout with >3 pe/keV. Low energy threshold for nuclear recoils (~5 keV).

PHASES:

<table>
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<tr>
<th>R&amp;D</th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
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- Proof of concept.
  - Total mass: 14 kg
  - 15 cm drift.
  - Best limit in '07: $\sigma_{SI} \sim 10^{-43}$ cm$^2$
- Dark Matter run ongoing.
  - Total mass: 170 kg
  - 30 cm drift.
  - 2011: $\sigma_{SI} \sim 7 \times 10^{-45}$ cm$^2$
  - Goal: $\sigma_{SI} \sim 2 \times 10^{-45}$ cm$^2$
- Technical design studies.
  - Total mass: ~2.5 t
  - 90 cm drift.
  - Goal: $\sigma_{SI} \sim 3 \times 10^{-47}$ cm$^2$
**XENON100 (2008-2011+)**

- 100 times lower background than XENON10
  - Material screening
  - Active LXe Veto
  - Upgrade of XENON10 shield (Cu, water)
  - Cryocooler/Feedthroughs outside shield
  - Low activity stainless steel
  - LXe self-shielding
- ~7 times larger target mass
  - 62 kg in target volume, 165 kg total LXe
- New PMTs with lower activity and high QE
- Improved electronics, grids, ...
- Gamma & neutron calibrations.
**XENON100:**
The Lowest Background Dark Matter Detector

Rate [events/keV/kg/day]

- **CRESST**
  - arXiv:0809.1829
- **CoGeNT**
  - arXiv:1002.4703
- **CDMS**
  - arXiv:0912.3592
- **DAMA**
  - arXiv:1002.1028

**Factor 100 lower**

XENON10 (before fid.)

XENON10 (after fid.)

XENON100 (before fid.)

XENON100 (after fid.)

The Liquid Xenon Dual Phase TPC
Ionization + Scintillation

- Wimp recoil on Xe nucleus in dense liquid (2.9 g/cm$^3$) → Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs.
- Charge drift towards liquid/gas interface.
- Charge extraction liquid/gas at high field between ground mesh (liquid) and anode (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (10 kV/cm)

- 3D position measurement:
  - X/Y from S2 signal. Resolution few mm.
  - Z from electron drift time (~1 mm).
Background Discrimination in Dual Phase Liquid Xenon TPC's

Ionization/Scintillation Ratio $S2/S1$

3D Position Resolution: fiducial cut, singles/multiples

XENON100

gamma-rays ($^{60}$Co)

neutrons (AmBe)

$S1=4 \text{ pe}$

$S2=15 \text{ e}$

Radius$^2$ [cm$^2$]
XENON100 – 2010 Run

- 100.9 live days, exposure: 1471 kg×d
- Energy window: 4 – 30 PE S1 / 8.4 – 44.6 keVnr
- Observed after all cuts: 3 events. Expected background: (1.8 ± 0.6) events (25% probability)
- Profile Likelihood limit based on side-bands from calibration
XENON100 – 2010 Run

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- Energy window: 4 – 30 PE S1 / 8.4 – 44.6 keVnr
- Observed after all cuts: 3 events. Expected background: (1.8 ± 0.6) events (25% probability)
- Profile Likelihood limit based on side-bands from calibration
- Best SI limit. Minimum \( \sigma_s = 7.0 \times 10^{-45} \text{ cm}^2 \) @ 50 GeV/c^2
- SUSY (CMSSM) parameter space further constrained in updated models incl. LHC limits.
- Strong tension with low mass WIMP interpretation for DAMA, CoGeNT, CRESST
- Inelastic DM as explanation for DAMA annual modulation ~ ruled out.

![Graph showing WIMP-Nucleon Cross Section vs. WIMP Mass](image-url)
Inelastic Dark Matter –
dead for DAMA interpretation?

- Model: Elastic scattering is suppressed.
  DM scatters preferentially in a low-lying excited state.
- Motivation: make DAMA/LIBRA annual modulation
  compatible with SI limits at energy splitting
  \(~90 – 140\) keV and WIMP masses \(50 – 140\) GeV/c\(^2\).
- XENON100 rules this scenario out (for Na, I).
- Caveat: WIMP scattering off heavy Tl (A=204)
  \(10^{-3}\) abundance in NaI(Tl) – fine-tuned parameters
  survive for Xe target. Use W in CRESST?
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Future Developments

Noble Liquids

- **LXe:**
  - XENON100 (taking data)
  - XMASS (LXe scint., construction completed)
  - LUX (LXe, under construction)
  - XENON1T (start construction 2011)

- **LAr:**
  - WARP (commissioning phase)
  - ArDM (moving underground)
  - Mini-Clean (scint., under construction)
  - DEAP-3600 (under construction)

Cryogenic Germanium

- **USA:**
  - Super-CDMS (under construction)
  - GeoDM (R&D)

- **Europe:**
  - Edelweiss-3 (under construction)
  - EURECA (R&D)
    - possible combination of cryogenic crystals and Ge

Superheated liquids

- COUPP (60 kg under construction)
- PICASSO
The Future of Direct Dark Matter Searches (next ~5 years)

Spin-independent sensitivity
measured: solid
expectations: dashed
COUPP may enter the picture if acoustic background suppression works very well
Summary & Outlook

• Progress in Dark Matter direct searches:
  ▶ Sensitivity advanced by 2-3 orders of magnitude in the last decade, increasing pace.
  ▶ Noble liquid detectors are starting to set the pace in sensitivity.

• Exciting new results in the last year:
  ▶ CoGeNT, CRESST excess events & DAMA/LIBRA annual modulation:
    Low mass WIMPs with $\sigma_s \sim 10^{-40} \text{ cm}^2$ @ ~7 GeV/c$^2$? Or poorly understood backgrounds?

• New XENON100 result April 2011:
  ▶ Upper limit on (spin-independent) WIMP-nucleon cross-section
    $\sigma_s = 7.0 \times 10^{-45} \text{ cm}^2$ @ 50 GeV/c$^2$
    ~ Factor 5 improvement over previous limits.
  ▶ XENON100 challenges the low mass WIMP interpretation. (+ low threshold CDMS)
  ▶ Inelastic DM (nearly) ruled out as explanation for annual modulation in DAMA/LIBRA.

• The future looks exciting:
  ▶ Rapid progress at the LHC:
    Limits on new physics improving fast. Will we see SUSY soon?
  ▶ New results in indirect searches:
    but fundamental problems of background subtraction remain (so far).
  ▶ Direct + indirect searches + LHC:
    We will know much more about DM within the next 5 years.
    *If DM consists of WIMPs we will likely have found signs of them.*

Thank you for your attention!