Direct Dark Matter Search Experiments

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2011/12/18 Particle Cosmology at Nagoya University
Outline

• Introduction
• Detection of WIMP
• Review of Direct Dark Matter Search Experiments
• XMASS Experiment at Kamioka
• Summary
Those results encourage the direct detection of dark matter.
Weakly Interacting Massive Particle

Dark Matter is required to be
- Neutral
  - can not see ...
- Non-baryonic
  - weakly interacting
- Cold (non-relativistic)
  - large scale structure
- New Particle?
  - neutralino, Kaluza-Klein particle, axion gravitino ...

SUSY particle physics
⇒ One of the favored scenario:

The lightest SUSY particle is stable and likely becomes a dark matter candidate

Linear combination of SUSY particles

\[
\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0
\]
Sensitivity and SUSY Parameter

CMSSM in 2007
hep-ph 0705.2012v1
Roszkowski et al.

Focus Point region
near future
CDMS-II, XENON100, XMASS, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

coannihilation region

Future experiments

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Cold Thermal Relics

Goal is to detect the undiscovered particles in our galaxy.

- $H$: expansion rate
- $\Gamma$: interaction rate
  - when $T > m_x$
    - $\chi \chi \leftrightarrow ff'$ (f: SM particle)
  - $T < m_x$
    - $\chi \chi \rightarrow ff'$
    - $H > \Gamma$
    - freeze out

Production = Annihilation ($T > m_x$)

Production suppressed ($T < m_x$)

Freeze out ($H > \Gamma$)

E.W. Kolb and M.S. Turner.

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Approaches to Dark Matter Detection

- Direct detection
  - SK, PAMELA...

- Indirect detection
  - LHC, ILC ...

- Colliders
WIMP in the Galactic Halo

Deposit energy in the detector on the earth

We need ...
- local density and velocity of dark matter
- characteristic of target nuclei (Xe, Na, Ge, I ...)

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The Milky Way

Normally, we take $\rho_{dm} \sim 0.3 \text{ GeV/cm}^3$, $v_{\text{earth}} \sim 230 \text{ km/sec}$
WIMPs around us

$$\rho_{dm} = 0.3 \text{ GeV/cm}^3$$

- A few WIMPs in 1 Liter of volume around us if we assume 100 GeV mass.
- $10^8$ through your hand every second.
- only < 1 event/day will interact with your body.

How can we detect them?
Direct Detection Principle

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

\[ \chi + N \rightarrow \chi + N \]

Deposit Energy

\[ E_{\text{recoil}} \sim <100 \text{ keV} \]
For example, assuming

\( M_{\text{W}} = 100 \text{ GeV/c}^2 \), \( M_{\text{T}} = 100 \text{ GeV/c}^2 \), \( r = 1 \)

WIMP velocity: \( v \approx 0.75 \times 10^{-3} = 220 \text{ km/sec} \)

\[
E_R = r \frac{(1 - \cos \theta)}{2} E_W \quad \text{(center of mass)}
\]

\[
r = \frac{4 M_{\text{W}} M_{\text{N}}}{(M_{\text{W}} + M_{\text{N}})^2}
\]

\[
E_R = \frac{1}{2} M_{\text{W}} \beta^2 c^2
\]

\[
= \frac{1}{2} \times 100 \times \text{GeV/c}^2 \times (0.75 \times 10^{-3}) c^2
\]

\[
= 30 \text{ keV}
\]
Differential Rate

Measuring the deposited energy due to elastic scattered nuclei by WIMP.

Expected spectrum:

\[
\frac{dR}{dE_R} = R_0 \frac{F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(v, v_E) d^3v
\]

- \( R_0 \): Event rate (depends on atomic nuclei)
- \( F \): Form Factor
- motion dynamics
  - Maxwellian distribution for DM velocity is assumed.
  - \( v \): velocity onto target,
  - \( v_E \): Earth’s motion around the Sun

Spin independent

\[
\sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}
\]

Spin dependent

\[
\sigma_0 = \frac{(\lambda_{N,Z}^2 J(J+1))^{\text{Nuclear}}}{(\lambda_{p,Z}^2 J(J+1))^{\text{proton}}} \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}
\]
Energy spectrum

For 100 GeV WIMPs

Event Rate

Recoil Energy (keV)

Energy threshold

100GeV: 10^{-44} cm^2

Xe, I, Ge, Ar, Na, O

Energy threshold

Recoil Energy (keV)
Energy spectrum

Energy threshold

For 10 GeV WIMPs

Event Rate

Recoil Energy (keV)

Energy threshold

10GeV: $10^{-44}$ cm$^2$

- Xe
- I
- Na
- Ge
- Ar
- O

10 GeV WIMPs
Direct Detection
At the surface, a few cosmic rays go through your hand every second. It reduced to $1/10^5$ if you are in Kamioka mine.
Direct Dark Matter Search in the World
Techniques for Detector

Various Targets: Ge, Xe, Ar, Ne and so on.
Two Signals are used to particle identification to distinguish btw Nuclear Recoil and gamma or beta.

CDMS
EDELWEISS

CRESST

Ionization

Phonon

Light

XMASS, CLEAN

ZEPLIN, XENON
WARP, LUX, ArDM
Current status

Results from 730 kg days of the CRESST-II Dark Matter Search

Federica Petricca on behalf of the CRESST collaboration
XENON at Gran Sasso, Italy

**XENON100**

**Goal** (compared to XENON10):
- increase target $\times 10$
- reduce gamma background $\times 100$
- material selection & screening
- detector design

**Quick Facts:**
- 161 kg LXe TPC (mass: $10 \times \text{Xe10}$)
- 62 kg in target volume
- active LXe veto ($\geq 4$ cm)
- 242 PMTs (Hamamatsu R8520)
- passive shield
  (Pb, Poly, Cu, H$_2$O, N$_2$ purge)

M. Schumann (U Zürich) – XENON100

E. Aprile

arXiv:1107.2155
Event Discrimination: Electron or Nuclear Recoil

\[ \mathcal{L}_{\text{eff}} (E_{\text{nr}}) = \frac{L_{y,\text{nr}} (E_{\text{nr}})}{L_{y,\text{ee}} (E_{\text{ee}} = 122 \text{ keV})} \]

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Result of XENON100

- Data taken in first half of 2010
- 100.9 life days
- 48 kg fiducial volume out of 62 kg
- Data blinded in ROI

Expected Background
Gaussian Leakage: 1.14 ± 0.48
Anomalous Leakage: 0.56 ± 0.25
Neutron Background: 0.11 ± 0.08
Total: 1.8 ± 0.6 events

Observe 3 events
- Likelihood for 3 or more events is 28%
- Profile Likelihood analysis also does not yield significant signal -> calculate limit

arXiv:1104.2549
DAMA/LIBRA

- Gran Sasso in Italy
- DAMA (~100 kg) + LIBRA (~250 kg) of NaI
- Annual Modulation (DAMA 7 yrs + LIBRA 4yrs)

- $v_{\text{sun}} \sim 232 \text{ km/s}$ (Sun velocity in the halo)
- $v_{\text{orb}} = 30 \text{ km/s}$ (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ \quad $T = 1$ year
- $t_0 = 2^{\text{nd}}$ June (when $v_\oplus$ is maximum)

\[ v_\oplus(t) = v_{\text{sun}} + v_{\text{orb}} \cos \gamma \cos[\omega(t-t_0)] \]

\[ S_k[\eta(t)] = \int_{A_E} \frac{dR}{dE_R} dE_R \equiv S_{0,k} + S_{m,k} \cos[\omega(t-t_0)] \]
Dark Matter investigation by model-independent annual modulation signature

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature.

Comparison between single hit residual rate (red points) and multiple hit residual rate (green points) for (DAMA/LIBRA 1-6): Clear modulation in the single hit events $A=(0.0091\pm 0.0014)$ cpd/kg/keV; No modulation in the residual rate of the multiple hit events $A=(-0.0006\pm 0.0004)$ cpd/kg/keV.

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about $9\sigma$ C.L.

A.Incicchi
What is the background?

Energy distribution of the modulation amplitudes

\[ R(t) = S_0 + S_m \cos(\omega(t - t_0)) \]

where \( T = 2\pi/\omega = 1 \text{ yr} \) and \( t_0 = 152.5 \text{ day} \)

\[ \Delta E = 0.5 \text{ keV bins} \]

A clear modulation is present in the (2-6) keV energy interval, while \( S_m \) values compatible with zero are present just above.

The \( S_m \) values in the (6–20) keV energy interval have random fluctuations around zero with \( \chi^2 \) equal to 27.5 for 28 degrees of freedom.


DAMA recently upgrade to Higher QE PMTs.
CoGENT at Soudan
(Coherent Germanium Neutrino Telescope)

**CoGeNT Dark Matter Experiment**
*(in brief…)*

- 440-gram high purity germanium ionization spectrometer
- ~0.5 keV energy threshold
- In low-background shield at Soudan Underground Lab
- Operated for dark matter direct-detection search

**Installed:** Aug. 2009
**Data start:** Dec. 2009
**Offline:** Mar. 2011
*(Soudan Lab mine fire)*
**Data Restart:** July 2011
CoGENT (surface event cut)

Surface events -> external gamma, poor charge collection but ...

C.E. Aalseth et al. PRL 106, 131301
CoGENT result

- Energy threshold 0.5 keV
- 0.33 kg x 442 days
- modulation hypothesis 2.8 sigma
- 16.6±3.8% amplitude
- 347±29 days period
- minimum in Oct 16±12 d

to increase statistic: 440g -> C4 (1 kg x 4 modules)
Target crystals operated as *cryogenic calorimeters* (~10mK)
- energy deposition in the crystal:
  - mainly phonons
    - temperature rise detected with W-thermometers
    - measurement of deposited energy (sub keV resolution at low energy)
  - small fraction into scintillation light

Separate *cryogenic light detector* to detect the light signal

**Detector module:**
- Simultaneous measurement of:
  - deposited energy \( E \) in the crystal (independent of the type of particle)
  - scintillation light \( L \) (characteristic of the type of particle)

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300gx8 modules for analysis

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Estimate the contribution of the backgrounds and investigate a possible excess by using likelihood.

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>e / γ events</td>
<td>8.00 ± 0.05</td>
<td>8.00 ± 0.05</td>
</tr>
<tr>
<td>α events</td>
<td>11.5±2.6</td>
<td>11.2±2.5</td>
</tr>
<tr>
<td>neutron events</td>
<td>7.5±6.3</td>
<td>9.7±6.1</td>
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<tr>
<td>Pb recoils</td>
<td>15.0±5.2</td>
<td>18.7±4.9</td>
</tr>
<tr>
<td>signal events</td>
<td>29.4±8.6</td>
<td>24.2±8.1</td>
</tr>
<tr>
<td>$m_{\chi}$ [GeV]</td>
<td>25.3</td>
<td>11.6</td>
</tr>
<tr>
<td>$\sigma_{WN}$ [pb]</td>
<td>1.6·10⁻⁶</td>
<td>3.7·10⁻⁵</td>
</tr>
</tbody>
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WIMP acceptance region
67 events accepted
Results from 730 kg days of the CRESST-II Dark Matter Search
Federica Petricca on behalf of the CRESST collaboration

Conclusions and Outlook

- Long successful physics run of CRESST
- Observed events difficult to explain with known backgrounds compatible with light WIMPs
- "Results from 730 kg days of the CRESST-II Dark Matter Search" submitted to European Physical Journal C currently available on arXiv:1109.0702
- New physics run in preparation with several improvements aimed at background reduction:
  - Modification of the clamps holding the crystals to reduce $\alpha$ and Pb-recoils backgrounds
  - Installation of an additional internal neutron shielding to complement the present one
- Expected to start this year
Activity In Japan

- NEWAGE (Kobe)
- Kamioka
- CF4(TPC)
- NIT (Nagoya)
- R&D
- Emulsion
- PICOLON (Tokushima) NaI
- CANDLES (Osaka) CaF
- XMASS
  - Kamioka
  - LXe
XMASS Experiment at Kamioka
Location

Kamioka

Tokyo
Kamioka Observatory

- 1000m under a mountain = 2700m water equiv.
- 360m above the sea
- Horizontal access
- Super-K for $\nu$ physics and other experiments in deep underground
- KamLAND (Tohoku U.)

By courtesy of Dr. Miyoki
XMASS Experiment
Multi purpose low-background experiment with LXe.

- Xenon MASSive detector for Solar neutrino ($pp/^{7}\text{Be}$)
- Xenon neutrino MASS detector (double beta decay)
- Xenon detector for Weakly Interacting MASSive Particles (DM)

Solar Neutrino

Double Beta Decay

Dark Matter
100kg Prototype (FV: 30kg, ~30cm)

800kg Detector (FV: 100kg, 80cm)

20ton Detector (FV: 10ton, ~2.5m)

R&D

Completed

2007: Project was funded.

Dark Matter

Solar Neutrino Dark Matter
Why Liquid Xenon?

- High Atomic mass Xe (A~131) good for SI case (cross section $\propto A^2$)
- Odd Isotope (Nat. abun: 48%, 129,131) with large SD enhancement factors
- High atomic number (Z=54) and density ($\rho=3\text{ g/cc}$):
  - compact, flexible and large mass detector.
- High photon yield (~ 46000 UV photons/MeV at zero field)
- Easy to purify for both electro-negative and radioactive purity
  - by recirculating Xe with getter for electro-negative
  - Distillation for Kr removal

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Self Shielding by LXe

Blue : $\gamma$ tracking
Pink : whole liquid xenon
Deep pink : fiducial volume

$\gamma$ into LXe sphere

Goal is to achieve $10^{-4}$ keV

MC simulation

Counts/keV/day/kg

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Design of 800 kg Detector

- 60 triangle in total
- About 10 PMT/triangle × 60
- Total: 642 PMTs
- Photo coverage: 62%

Hexagonal PMT
Hamamatsu R10789
QE 28-39%

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Assembly of PMT holder and installation of PMTs

OFHC: brought into the mine <1 month after electrorefining.
to avoid activation by cosmic rays.
Joining two halves
In the Water Shield

20 inch PMT x 70

gas/liquid line
Radioactivity

e.g. $^{40}$K case

4000 Bq/human

15 Bq/Banana

0.01 Bq/PMT

6.42 Bq/642 PMTs
The goal is to achieve 1/10 reduction of radioactivity level of R8778 (except $^{60}\text{Co}$).

- The background is $<1.2\times10^{-5}/\text{keV/d/kg} @ 5-10\text{keV}$

Based on V.Tomasello, et al., NIMA595(2008)431
Demonstration of the detector performance

• Calibration system
  – Introduction of radioactive sources into the detector.
  – <1mm accuracy along the Z axis.
  – Thin wire source for some low energy $\gamma$ rays to avoid shadowing effect.
  – $^{57}$Co, $^{241}$Am, $^{109}$Cd, $^{55}$Fe, $^{137}$Cs..

Source rod with a dummy source

Stepping Motor
Linear Motion Feed-through
Gate valve
~5m
Top photo tube
Photoelectron dist. at the center of the detector

- $^{57}$Co source at the center of the detector gives a typical response of the detector.
- High p.e. yield 15.1+/-1.2 p.e./keV was obtained.
- The photo electron yield distribution was reproduced by a simulation.
Performance of the vertex reconstruction

- Reconstructed vertices for various positioning of the source overlayid.
- Position resolution was as expected by a simulation:
  1.4cm RMS (0cm) 1cm RMS (+/-20cm) for 122keV $\gamma$ rays
Sensitivity for SI case

$10^{-4}$ dru, 100 kg fiducial (flat bg assumed)

1 keV, 2 keV, 5 keV

$\sigma_{\chi p} = 10^{-44}$ cm$^2$

50 GeV WIMP

Black: signal + BG
Red: BG
Summary

XENON100:
  continuing to running and preparing XENON1T
DAMA/LIBRA:
  Upgrade to higher QE.
CoGENT:
  0.4 kg -> 1kg Upgrade. (C4)
CRESST:
  Upgrade to reduce background from crystal holder and will add more shield for neutron.
XMASS:
  Commissioning mode. Hopefully, we say something in Mach 2012.