Direct Dark Matter searches

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Outline
• Introduction
• Detection of WIMP
• Review of Direct Dark Matter Search Experiments
• Summary and Future prospects
Variety Observation

CMB
NASA/WMAP

Bullet clusters
D. Clowe et al., 2006

SDSS
M. Blanton and the SDSS

Rotation curve
dark matter

Masaki Yamashita
Weakly Interacting Massive Particle

**astrophysics**

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 ...

**particle physics**

SUSY
⇒ One of the favored scenario:

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

Linear combination of SUSY particles

\[
\chi^0_1 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}^0_u + \alpha_4 \tilde{H}^0_d
\]
Sensitivity and SUSY Parameter

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

near future
Super CDMS, XENON100, LUX, XMASS, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...
Sensitivity and SUSY Parameter

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near future
Super CDMS, XENON100, LUX, XMASS, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III, ...

Future experiments
SuperCDMS1t, XENON1t, LZ, Darwin, ArDM, XMASS 20T, ...

Roszkowski, Ruiz & Trotta (2007)

CMSSM, $\mu > 0$

ZEPLIN–I
EDELWEISS–I
CDMS–II
XENON100

$\sigma_p$ (pb)

Log $\sigma_p$ (pb)

$10^{-4.5}$

$1$ event/kg/yr

$1$ event/100kg/yr

$68\%$

$m_\chi$ (TeV)
How much DM around us?

Analysis of the kinematics of 412 stars at 1-4 kpc from the Galactic mid plane.

component is required to account for the observations. We extrapolate a dark matter (DM) density in the solar neighborhood of 0±1 mM⊙ pc⁻³, and all the current models of a spherical DM halo are excluded at a confidence level higher than 4σ. A detailed

Normally, we take ρ_{dm} ~0.3 GeV/cm³, v_{earth} ~230km/sec
We are here!

KLYPR

On the local dark matter density

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ABSTRACT

An analysis of the kinematics of 412 stars at 1–4 kpc from the Galactic mid-plane by Moni Bidin et al. (2012) has claimed to derive a local density of dark matter that is an order of magnitude below standard expectations. We show that this result is incorrect and that it arises from the invalid assumption that the mean azimuthal velocity of the stellar tracers is independent of Galactocentric radius at all heights; the correct assumption—that is, the one supported by data—is that the circular speed is independent of radius in the mid-plane. We demonstrate that the assumption of constant mean azimuthal velocity is physically implausible by showing that it requires the circular velocity to drop more steeply than allowed by any plausible mass model, with or without dark matter, at large heights above the mid-plane. Using the correct approximation that the circular velocity curve is flat in the mid-plane, we find that the data imply a local dark-matter density of $0.008 \pm 0.002 \, M_{\odot} \, pc^{-3} = 0.3 \pm 0.1 \, \text{Gev cm}^{-3}$, fully consistent with standard estimates of this quantity. This is the most robust direct measurement of the local dark-matter density to date.

Normally, we take $\rho_{\text{dm}} \sim 0.3 \, \text{GeV/cm}^3$, $v_{\text{earth}} \sim 230 \text{km/sec}$
Direct Detection Principle

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

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

For example, assuming

\[ M_w = 100 \text{ GeV/c}^2, \quad M_T = 100 \text{ GeV/c}^2, \quad r = 1 \]

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

\[ E_R = \frac{1}{2} M_W \beta^2 c^2 \]

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

\[ = 30 \text{ keV} \]
Differential Rate
Measuring the deposited energy due to elastic scattered nuclei by WIMP.

Expected spectrum:

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

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

Spin independent

\[
\sigma_0 = \frac{377}{M_\chi M_N} \left( \frac{\sigma_0}{1\text{pb}} \right) \left( \frac{\rho_D}{0.3\text{GeV}c^{-2}\text{cm}^{-3}} \right) \left( \frac{v_0}{230\text{km s}^{-1}} \right) \text{kg d}^{-1}
\]

Spin dependent

\[
\sigma_0 = \frac{(\lambda_{N,Z}^2 J(J+1))^{\text{Nuclear}}}{(\lambda_{p,Z}^2 J(J+1))^{\text{proton}}} \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}
\]
It should be consistent among same target material.
Energy spectrum (spin independent)

Low mass WIMP -> advantage for small Atomic Mass (Eth>6keVnr)

Energy threshold is very important.

For 10 GeV WIMPs

Event Rate [events/day/kg/keVnr]

Recoil Energy (keV)

Energy threshold by xe100

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

- Xe
- I
- Ge
- Na
- Ar
- O
Energy spectrum (spin independent)

heavier WIMP -> advantage for Large Atomic Mass
Detector mass is important. (> 100 kg)
Direct Dark Matter Search in the World

- **CanFranc**
  - IGEX
  - ROSEBUD
  - ANAIS
  - ArDM

- **Boulby**
  - NaIAD
  - ZEPLIN I/II/III
  - DRIFT I/II

- **Gran Sasso**
  - DAMA/LIBRA
  - CRESST I/II
  - XENON
  - WARP
  - Dark Side
  - NIT

- **SNOLAB**
  - DEAP-CLEAN
  - Picasso
  - COUPP

- **Homestake**
  - LUX

- **Soudan**
  - CDMS II
  - CoGENT

- **Frejus**
  - EDELWEISS I/II

- **Kamioka**
  - XMASS
  - NEWAGE

- **YangYang**
  - KIMS

- **JINPING**
  - PANDA-X
  - CDEX

- **Oto**
  - PICOLON

- **Kamioka**
  - XMASS
  - NEWAGE

- **South Pole**
  - DM-ICE
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.

$\gamma/\beta$

WIMP or Neutron

CDMS
EDELWEISS

Phonon

CRESST

Ercoil

CoGENT
Ionization

ZEPLIN, XENON
WARP, LUX, ArDM, DarkSide

DAMA, NAIAD, XMASS, DEEP-CLEAN
XENON program roadmap: growing in target size...

- **XENON10**
  - Achieved (2007)
  - $\sigma_{SI} = 8.8 \cdot 10^{-44} \text{ cm}^2$

- **XENON100**
  - Achieved (2011)
  - $\sigma_{SI} = 7.0 \cdot 10^{-45} \text{ cm}^2$
  - Projected (2012)
  - $\sigma_{SI} \sim 2 \cdot 10^{-45} \text{ cm}^2$

- **XENON1T**
  - Projected (2017)
  - $\sigma_{SI} = \sim 10^{-47} \text{ cm}^2$

- In advanced design phase
  - Construction in the end of 2012

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Results

- No background subtraction, i.e., assume all events could be WIMPs

- For spin-independent, elastic scattering, 90% CL limits incompatible with DAMA/LIBRA entire excess

- The parameter space for CoGeNT remains if majority of excess events not due to WIMPs

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**EDELWEISS detector**

- Cryogenic set-up (18 mK):
  - Host Germanium bolometers
  - Up to 40kg

- Shieldings:
  - Clean room + deradonized air $10 \text{ mBq/m}^3$
  - Ac+ve muon veto (>98% coverage)
  - $50 \text{ cm PE}$ shield + $20 \text{ cm lead}$ shield

- Monitoring detector:
  - Radon detector sensitive down to few mBq/m$^3$
  - $^3\text{He}$ neutron detector (thermal neutron monitoring inside shields)
  - Liquid scintillator neutron counter (study of muon induced neutrons)
Xe Target Experiments
XENON at Gran Sasso, Italy

XENON100

Goal (compared to XENON10):
• increase target ×10
• reduce gamma background ×100
→ material selection & screening
→ detector design

Quick Facts:
• 161 kg LXe TPC (mass: 10 × Xe10)
• 62 kg in target volume
• active LXe veto (≥4 cm)
• 242 PMTs (Hamamatsu R8520)
• passive shield (Pb, Poly, Cu, H₂O, N₂ purge)

-easy to scale up the detector
-light(S1) + Charge(S2)
particle ID (n-recoil vs gamma)
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: $1.14 \pm 0.48$
Anomalous Leakage: $0.56 \pm 0.25$
Neutron Background: $0.11 \pm 0.08$
Total: $1.8 \pm 0.6$ events

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

- Data taking for Dark Matter search is terminated!
- From March 1st 2011 up to now. More than one year of continuous operation
- More than 220 live days of data collected Excellent Detector Performance and Stability
- Blind analysis in advanced state
- XENON1T phase: construction in Fall 2012. in a few weeks.

arXiv:1104.2549

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The LUX Detector will be deployed in the Sanford Lab at the Homestake Mine (South Dakota, USA), 1.5 km deep (4300 m.w.e., flux reduced x10^-7 compared to sea level)

- Two phase Xe TPC
- Homestake: 1.5 km deep
- 350 kg Liquid Xe Detector (59 cm height, 49 cm diameter)
- 122 Hamamatsu R8778 PMTs (d = 5 cm)
- 61 on top, 61 on bottom
- Low-background Ti Cryostat

Expected to have lower background than XENON100

### Underground Science Timeline

- Start dismantling surface March 2012
- Start installation underground May 21, 2012
- Finish installation September 2012
- Finish commissioning November 2012
- First data before the end of 2012
- First result in first quarter of 2013
- 300 days result by end 2013
XMASS at Kamioka in Japan

- Sensitive volume 835 kg LXe out of 1100 kg
  (DAMA 7 yrs + LIBRA 4 yrs -> 1.17 ton x yr)
- Scintillation only, self-shielding (Fiducial ~ 100 kg)
- Total: 642 Hex PMTs
  (low radioactive PMT R10789)
- High Photo coverage: 62%
- 15 Photoelectron/keV
  (best among DM scintillator)
- Under investigating surface events (Al seal of PMT, Cu surface)

Total photo electron distribution

15PE/keV
Ge Target Experiments
CDMS (Low threshold analysis)

- Soudan in US.
- Powerful particle ID by Phone + Charge signal
- 241 kg-days with lowest noise 8 Ge detectors (~230 g each)
- Data: Oct 2006 - Sep 2008
- Energy threshold (1.5-2.5 keV)

-No background subtraction, ie assume all events could be WIMPs

- For spin-independent, elastic scattering, 90% CL limits incompatible with DAMA/LIBRA and entire CoGeNT excess

- Some parameter space for CoGeNT remains if majority of excess events not due to WIMPs

CDMS Collaboration, PRL 106, 131302 (2011)
Cryogenic set-up (18 mK):  
- Host Germanium bolometers (Heat + Charge)  
- Up to 40kg  
- Low Threshold Analysis (< 5keV)

1. Exposure: 113 kg.d  
2. Estimated background:  
   1. Neutron < 1.7  
   2. Gamma: 1.2  
   3. Heat-only << 1  
   4. Surface events are negligible background.

3. Limit derived from simple Poisson statistics in the «WIMP box»

[Graph showing WIMP box for MW=10GeV]
Others (NaI, CaWO4)
**DAMA/LIBRA in Gran Sasso**

- DAMA (~100 kg) + LIBRA (~250 kg) of NaI
- Annual Modulation $8.8\sigma$ (DAMA 7 yrs + LIBRA 4yrs -> 1.17ton x yr)
- Muon rate in Gran Sasso ? (arXiv:1202.4179v2) phase is different.
- Other experiment can do same thing ? Especially by NaI ? (->DM-ICE program)

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

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

\[ S_k[\eta(t)] = \int \frac{dR}{dE_R} dE_R \equiv S_{0,k} + S_{m,k} \cos[\omega(t-t_0)] \]
DAMA/LIBRA upgrade in Nov/Dec 2010

- high QE 35% at 420nm
- Energy threshold 2keV -> 1keV
- a better energy resolution
- a better noise/scintillation discrimination
- less radioactivity

Typical residual contaminations of the new PMTs with high Q.E. produced by HAMAMATSU for the range 5.5–7.5 ph.e./keV, depending on the detector.

Specific features were asked for by DAMA coll. to the company in order to fit the requirements of the project: 1) the Q.E. at 6.1 keV should be 2.1 ± 0.03%, 2) the dark current should be less than 0.15 ± 0.02 Bq/kg, 3) the dead time should be less than 500 cps, 4) the peak/valley ratio should be at least 40%; 5) a multiplication factor of less than 0.35; 6) a peak/valley ratio at peak and dark current 3% @ peak and dark current.

Typical values of residual contaminations are shown in table 1; the averaged values are also given.

We remind that the only data treatment which is performed on the analyzed data of DAMA/LIBRA is to eliminate obvious noise events (whose number sharply decreases when increasing the number of available photoelectrons) near the edges of the batches: 1) 40 PMTs with photocathode, ten dynodes, high Q.E., high gain, low level of dark current and a lower level of radioactivity; 2) 25 PMTs with eight dynodes, high Q.E., high gain and a lower level of radioactivity; 3) 20 PMTs with eight dynodes, high Q.E., high gain, a lower level of radioactivity and of less than 0.15 ± 0.02 Bq/kg; 4) 10 PMTs with six dynodes, high Q.E., high gain, a lower level of radioactivity and of less than 0.15 ± 0.02 Bq/kg; 5) a multiplication factor of less than 0.35; 6) a peak/valley ratio at peak and dark current 3% @ peak and dark current.

Figure 5: The results have shown some improvement in the PMTs production is well limited.
CoGENT at Soudan

- 440-gram high purity germanium ionization spectrometer
  - p-type Point Contact
  - ~0.5 keV energy threshold
  - In low-background shield at Soudan Underground Lab


- 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

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to increase statistic: 440g
-> C4 (1 kg x 4 modules)
CaWO₄ target (~300g)
- Measuring both scintillation light and phonon.
- 8 CaWO₄ was used for analysis out of fully operated 18 modules.
- Total exposure 730 kg days

Background Reduction:
- Modification of the clamps holding the crystals to reduce α and Pb-recoils backgrounds
- Installation of an additional internal neutron shielding

Table 3.

<table>
<thead>
<tr>
<th>Event Type</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>
</tr>
<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>
</table>

Fig. 8 displays the data set of a different neutron background. The only exception to this arrangement is the surrounding material which moderates an incoming neutron. The spectrum can be parametrized by a rather long tail extending down to the accepted energy range, where a possible population of Pb recoils below the tungsten band is visible, with a rather long tail extending down to the acceptance region, where a possible Pb recoil is set at 90 keV so that it covers the low energy tail. An example of the resulting reference region is highlighted.

Two maximum in Likelihood

For an estimate of this background, we follow a similar procedure as discussed above. The spectrum can be parametrized by a rather long tail extending down to the accepted energy range, where a possible population of Pb recoils below the tungsten band is visible, with a rather long tail extending down to the acceptance region, where a possible Pb recoil is set at 90 keV so that it covers the low energy tail. An example of the resulting reference region is highlighted.
## Summary

| **XENON100:** |  
| XE100 operation was terminated. 200 days data will be open soon. preparing XENON1T -> DARWIN program (multi ton Xe+Ar target) |

| **LUX:** |  
| Moving the detector from surface to underground lab. |

| **XMASS:** |  
| High light yield (15 PE/keV). Analysis and identifying of the background is on going. |

| **EDELWEISS:** |  
| <5keV threshold analysis. Move to Phase EDELLWEISS III |

| **CDMS:** |  
| Low threshold analysis. Super CDMS (iZIP) 10kg is on going. |

| **CoGENT:** |  
| statistical improve 0.4 kg -> 1kg Upgrade. (C4) |

| **DAMA/LIBRA:** |  
| Upgrade to higher QE in Nov/Dec 2010. |

| **CRESST:** |  
| Upgrade to reduce background from crystal holder and will add more shield for neutron. |

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I apologize for the experiments which could not be covered in this talk.

Masaki Yamashita
Thank you.