Direct Dark Matter Searches

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What is $\nu$? Invisibles12, GGI Florence, June 27th 2012

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Dark Matter: (indirect) Evidence

Particle Dark Matter Candidates:
- WIMP → „WIMP miracle“
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...

[Diagram showing various fractions of Dark Matter, Energy, and Atoms]
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
Direct WIMP Search

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WIMP

$v \sim 230 \text{ km/s}$
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

WIMP

$\nu \sim 230 \text{ km/s}$
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

→ nuclear recoil

WIMP

v ~ 230 km/s

Nuclear Recoil

Detectable Signal
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

\[ \rightarrow \text{nuclear recoil} \]

\[ v \sim 230 \text{ km/s} \]

Gamma- and beta-particles (background) interact with the atomic electrons

\[ \rightarrow \text{electronic recoil} \]
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei ➔ nuclear recoil

Recoil Energy:
\[ E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N} (1 - \cos \theta) \sim O(10 \text{ keV}) \]

Event Rate:
\[ R \propto N \frac{\rho_x}{m_x} \langle \sigma v \rangle \]
- \(N\) number of target nuclei
- \(\rho_x/m_x\) local WIMP density
- \(\langle \sigma \rangle\) velocity-averaged scatt. X-section

Detector
Local DM Density
Physics

Nuclear Recoil
\(E_R \sim O(10 \text{ keV})\)

\(v \sim 230 \text{ km/s}\)
Dark Matter around us?

How much is here?

canonical value: 0.3 GeV/cm³
Kinematical and chemical vertical structure of the Galactic thick disk II. A lack of dark matter in the solar neighborhood

C. Moni Bidin, G. Carraro, R. A. Mendez, R. Smith

We estimated the dynamical surface mass density Sigma at the solar position between Z=1.5 and 4 kpc from the Galactic plane, as inferred from the kinematics of thick disk stars.

We extrapolate a dark matter (DM) density in the solar neighborhood of $\sigma_{DM} \approx 0.3 \text{ GeV/cm}^3$. In particular, our results may indicate that any direct DM detection experiment is doomed to fail if the local density of the target particles is negligible.
Kinematical and chemical vertical structure of the Galactic thick disk II. A lack of dark matter in the solar neighborhood

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We estimated the dynamical surface mass density $\Sigma$ at the solar position between $Z=1.5$ and 4 kpc from the Galactic plane, as inferred from the kinematics of thick disk stars. We extrapolate a dark matter (DM) density in the solar neighborhood of $0.3 \pm 0.1 \text{ GeV/cm}^3$. In particular, our results may indicate that any direct DM detection experiment is doomed to fail, if the local density of the target particles is negligible.

On the local dark matter density

Jo Bovy, Scott Tremaine (IAS)

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 find that the data imply a local dark-matter density of $0.3 \pm 0.1 \text{ GeV/cm}^3$.

A new determination of the local dark matter density from the kinematics of K dwarfs

Silvia Garbari, Chao Liu, Justin I. Read, George Lake

We apply a new method to determine the local disc matter and dark halo matter density to kinematic and position data for $\sim 2000$ K dwarf stars taken from the literature. We perform a series of tests to demonstrate that our results are insensitive to plausible systematic errors in our distance calibration, and we show that our method recovers the correct answer from a dynamically evolved N-body simulation of the Milky Way. We find a local dark matter density of $(0.95 \pm 0.53-0.49 \text{ GeV/cm}^3)$ at 90% confidence assuming no correction for the non-flatness of the local rotation curve, and $(0.85 \pm 0.57-0.50 \text{ GeV/cm}^3)$ if the correction is included.
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei → nuclear recoil

Recoil Energy:

\[ E_r \sim \mathcal{O}(10 \text{ keV}) \]

Event Rate:

\[ R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_\chi-N \rangle \]

- Detector
- Local DM Density: \( \rho_\chi \sim 0.3 \text{ GeV}/c^2 \)
- Physics

WIMP Expectations
- scalar \( \chi-n \) interaction
- CMSSM: Trotta et al.
- CMSSM+LHC: Buchmueller et al.

Detectable Signal

- 1 event/kg/yr
- 1 event/ton/yr
Direct WIMP Search

**Summary:** Tiny Rates

\[ R < 0.01 \text{ evt/kg/day} \]

\[ E_R < 100 \text{ keV} \]

Recoil Energy:

\[ E_r \sim \mathcal{O}(10 \text{ keV}) \]

Event Rate:

\[ R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_\chi n \rangle \]

Detector  
Local DM Density  
Physics

\[ \rho_\chi \sim 0.3 \text{ GeV/c}^2 \]
Summary: Tiny Rates
\[ R < 0.01 \text{evt/kg/day} \]
\[ E_R < 100 \text{keV} \]

How to build a WIMP detector?
- large total mass, high \( A \)
- low energy threshold
- ultra low background
- good background discrimination
Background Sources

**Environment:** U, Th chains, K

- $\gamma$ and $\beta$ decays (electronic recoil)
- Alphas can pose a problem (technology dependent)
- Neutrons from ($\alpha, n$) and sf in rocks and detector parts
- Neutrons from cosmic ray muons

### Background Sensitivity

**Without background:** $\propto (mt)^{-1}$

**With background:** $\propto (mt)^{-1/2}$
Laboratori Nazionali del Gran Sasso

XENON100
XENON1T
DarkSide
CRESST
DAMA

LNGS: 1.4km rock
(3700 mwe)

Other laboratories:
Boulby (UK), LSM (F),
Canfranc (E), Soudan (US),
Sanford (US), SNOLab (CA),
Kamioka (JP), Jinping (CN), ...

XENON100
World-wide Efforts

- Homestake/SURF
- LUX
- SNOLAB
  - DEAP/CLEAN
  - PICASSO
  - COUPP
- Soudan
  - CDMS-II
  - CoGeNT
- Boulby
  - DRIFT
  - (ZEPLIN)
  - (NaIAD)
- Canfranc
  - ArDM
- LSM
  - EDELWEISS
- LNGS
  - XENON
  - DAMA/Libra
  - CRESST
  - DarkSide
  - (WArP)
- JINPING
- Panda-X
- CDEX
- YangYang
- KIMS
- Oto
- PICOLOM
- WIPP
  - DMTPC
- South Pole
  - DM-Ice

1. Homestake
   - Depth, m.w.e.: 4160
2. Soudan
   - Depth, m.w.e.: 2040
3. WIPP
   - Depth, m.w.e.: 1580
4. SNOLAB
   - Depth, m.w.e.: 5990
5. Baskan
   - Depth, m.w.e.: 4700
6. South Pole
   - DM-Ice
7. Canfranc
   - Depth, m.w.e.: 2450
8. Fréjus/Modane
   - Depth, m.w.e.: 4150
9. Boulby
   - Depth, m.w.e.: 2805
10. Kamioka
    - Depth, m.w.e.: 2050
Direct WIMP Detection

Phonons

COUPP
PICASSO
SIMPLE

CDMS
EDELWEISS

Charge

Tracking:
DRIFT, DMTPC,
MIMAC, NEWAGE

CRESST
ROSEBUD

Light

XENON, ZEPLIN
LUX, Panda-X
ArDM, Darkside,
MAX, DARWIN, LZ

DAMA, KIMS
DM-Ice, XMASS
DEAP/CLEAN

CoGeNT
CDEX/Texono
Background Suppression

A  Avoid Backgrounds
   Use of radiopure materials
   Shielding
      deep underground location
      large shield (Pb, water, poly)
      active veto (\(\mu, \gamma\) coincidence)
      self shielding \(\rightarrow\) fiducialization

B  Use knowledge about expected WIMP signal
   WIMPs interact only once
      \(\rightarrow\) single scatter selection
      require some position resolution
   WIMPs interact with target nuclei
      \(\rightarrow\) nuclear recoils
      exploit different \(dE/dx\) from signal and background

Examples
   Scintillation Pulse Shape
   Charge/Light Ratio
   Charge/Phonon Ratio
2 Observables for Discrimination

Ionization yield and Charge/Light ratio depend on \(dE/dx \rightarrow \) discrimination

**CDMS-II**
Discrimination \(O(10^{-5})\), large acceptance

BUT: „surface events“ → timing cut

**XENON100**
~99.5% rejection @ 50% acceptance
WIMP Searches – Evolution

Plot adapted from R. Gaitskell
WIMP Searches – Evolution

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WIMP Searches – Evolution

[Graph showing evolution of WIMP searches over time, with various detectors marked at different cross-section limits.]
WIMP Searches – Evolution

Plot adapted from R. Galluskell

- Crystals Ge/Nal
- Cryogenic Detectors
- Liquid Noble Gases Xe/Ar
WIMP Searches – Evolution

![Graph showing the evolution of WIMP searches from 1985 to 2020. The graph plots spin-independent cross sections at a scale of \(10^{-40} \text{ GeV}^2/\text{cm}^2\) on the y-axis and year on the x-axis. Different detectors are represented by markers, with some experiments marked as missing. The graph includes detectors such as EDELWEISS, CDMS, DAMA, XENON, and others. The x-axis is labeled with years from 1985 to 2020.]

- **Crystals Ge/Nal**
- **Cryogenic Detectors**
- **Liquid Noble Gases Xe/Ar**

Some experiments are missing!
The WIMP Landscape today

→ this talk: focus only on spin-independent, elastic interactions

some results are missing!
For higher $E_{\text{rec}}$, sensitivity to low mass WIMPs is higher for light targets
→ need low threshold
→ lower sensitivity can be (to some extent) compensated by target mass

(CoGeNT: 0.33 kg, XENON100: 48.0 kg → factor ~150)
The WIMP Landscape today

![Graph showing the WIMP-Nucleon Cross Section vs. WIMP Mass with various experimental results and limits.]

- DAMA/Na
- CoGeNT
- CDMS (2011)
- CDMS (2010)
- CRESST (2011)
- XENON10 (S2 only, 2011)
- EDELWEISS (2011)
- CRESST (2007, reanalysis)
- ZEPLIN-III (2011)
- COUPP (2012)
- XENON100 (2011)

Observed limit (90% CL)

Expected limit of this run:
- ± 1 σ expected
- ± 2 σ expected

Some results are missing!
M. Schumann (U Zürich) – Direct Dark Matter Searches

Annual Modulation: DAMA/Libra

- PMTs coupled to NaI(Tl) Scintillators @ LNGS → extremely clean background necessary
- looks for annual modulation (~3% effect)
- large mass and exposure: 1.17 ton years

DAMA finds annual modulation @ 8.8σ C.L.

BUT: no ER/NR discrimination!


what is here?

no modulation above 6 keV
Annual Modulation: DAMA/Libra

Nal quenching factor at low E?
→ relevant for comparison with other experiments

Collar, TAUP2011

Phase of muon background
→ seems to be different from DAMA modulation

arXiv:1202.4179

what is here?
no modulation above 6 keV

S_m (cpd/kg/keV)

= 8 keVr (Na: QF~0.25)
= 22 keVr (I: QF~0.09)
@ Soudan Lab, Minnesota (USA)
measure charge and heat (phonons):
\[ E \text{ deposition} \rightarrow \text{temperature rise } \Delta T \]

Crystals: \textbf{Ge, Si} cooled to few mK
\[ \Delta T \sim \mu K \]

Very good discrimination
\[ \rightarrow \text{BUT: reject surface events via timing} \]

similar: \textit{EDELWEISS} (F)
The WIMP Landscape today

M. Schumann (U Zürich) – Direct Dark Matter Searches

some results are missing!
p-type point contact Ge-detector, ultra low noise, very low threshold: 0.4 keVee underground @ Soudan
no ER/NR discrimination, reduce surface events by risetime cut excess at lowest energies
p-type point contact **Ge-detector**, ultra low noise, very low threshold: 0.4 keVee underground @ Soudan

no ER/NR discrimination, reduce surface events by risetime cut

excess at lowest energies

\[ \sigma = 10^{-40} \text{ cm}^2 \]

low leakage

high leakage
CoGeNT

Recent CoGeNT news:

- old "signal"
- new "background"
- remaining "signal"

J. Collar @ TAUP

Kopp, Schwetz, Zupan, arXiv:1110.2721
Kelso, Hooper, Buckley, arXiv:1110.5338

p-type point contact Ge-detector, ultra low noise, very low threshold: 0.4 keVee underground @ Soudan
no ER/NR discrimination, reduce surface events by risetime cut excess at lowest energies
CoGeNT annual modulation

PRL 107, 141301 (2011)

Spectrum:

Rate vs Time:

Stability:

- Clear modulation in 15 months data
- Modulation up to 3 keVee (~10 keVr)
- CoGeNT stability not yet demonstrated with DAMA standards
CoGeNT annual modulation

*Spectrum:*

- Clear modulation in 15 months data
- Modulation up to 3 keVee (~10 keVr)
- CoGeNT stability not yet demonstrated with DAMA standards

*Rate vs Time:*

- Observation regarding the modulation, e.g. Fox et al, arXiv:1107.0717, also others...
- There is a modulation
- There is a significant component >1.5 keV
- Modulation not well explained by standard Maxwellian DM halo

*XENON100 should have seen 10-30 events
- CDMS-II should see O(1) modulation

*Stability:*

- Electronic noise
- Trigger threshold

*Observations regarding the modulation*

*PRL 107, 141301 (2011)*
CDMS Annual Modulation

annual modulation analysis on NR data (with discrimination!)

No modulation is found:
<0.06 evt/keVnr kg day in 5-11.9 keVnr at 99% CL
Inconsistent with CoGeNT in 1.2-3.2 keVee range at 98% CL

A recent re-assessment of the low $E$ quenching factor of Ge suggests that the whole CoGeNT region is covered by CDMS-II.

Barker, Mei: arXiv: 1203.4620
The WIMP Landscape today

Some results are missing!
scintillating \textbf{CaWO}_4 \textbf{crystals} detect light (silicon on sapphire+TES) and phonons (TES)
multi-target approach
excellent n-$\gamma$ discrimination
730 kg $\times$ d exposure published in 2011
$\rightarrow$ rather large background
$\rightarrow$ new run in 2012 to reduce bg

\begin{tabular}{|c|c|c|}
\hline
 & M1 & M2 \\
\hline
$e/\gamma$-events & 8.00 $\pm$ 0.05 & 8.00 $\pm$ 0.05 \\
$\alpha$-events & 11.5$^{+2.6}_{-2.3}$ & 11.2$^{+2.5}_{-2.3}$ \\
neutron events & 7.5$^{+6.3}_{-5.5}$ & 9.7$^{+6.1}_{-5.1}$ \\
Pb recoils & 15.0$^{+5.2}_{-5.1}$ & 18.7$^{+4.9}_{-4.7}$ \\
\hline
signal events & & \\
\hline
$m_\chi$ [GeV] & 25.3 & 11.6 \\
$\sigma_{WN}$ [pb] & 1.6 $\cdot$ 10$^{-6}$ & 3.7 $\cdot$ 10$^{-5}$ \\
\hline
\end{tabular}
The WIMP Landscape today

![Graph showing the WIMP landscape with various experiments listed.]

**XENON100 (2011)**
- Observed limit (90% CL)
- Expected limit of this run:
  - ± 1 σ expected
  - ± 2 σ expected

**Some results are missing!**
**Liquid Noble Gases: Detector Concepts**

**Single Phase Detector**
- PMT
- Liquid target
- Time

**Time Projection Chamber**
- PMT
- Gas
- Pos HV
- Neg HV
- Energy (E)

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M. Schumann (U Zürich) – Direct Dark Matter Searches
• **LXe** dual phase detector
• was operated at Boulby mine (UK)
• science run 2011:
  1344 kg x days raw exposure
  8 events observed in the ROI (7-29 keVr)
  → compatible with background expectation
• ZEPLIN program has come to an end

12kg LXe target  5.1 kg fiducial mass
XENON100

Quick Facts
- 62 kg LXe target
- Dual phase TPC
- active LXe veto
- 242 PMTs
- running @ LNGS (IT)

Last science run:
4800 kg x d raw exposure
1471 kg x d acpt. corrected (100 GeV/c²)
3 events observed
→ fully compatible with background
→ best WIMP limit over large mass range

lowest published background of all running DM experiments
PRD 83, 082001 (2011)
Quick Facts
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PRD 83, 082001 (2011)
Nuclear Recoil Energy Scale

- WIMPs interact with target nucleus → nuclear recoil (nr) scintillation
  \(\text{\(\beta\) and \(\gamma\)'s produce electronic recoils)}

- absolute measurement is difficult → measure relative to \(^{57}\text{Co}\) (122keV)

- relative scintillation efficiency \(L_{\text{eff}}\):
  \[
  L_{\text{eff}}(E_{\text{nr}}) = \frac{LY(E_{\text{nr}})}{LY(E_{\text{ee}} = 122 \text{ keV})}
  \]

measurement principle:

Most precise measurement with Values down to 3 keVr by CU:

- take average of all existing measurements
- take into account uncertainty in PL analysis
→ get real 90% CL contour (stat AND syst)
Current Science Run

- decreased background
- lower threshold
- more than 2x of 2010 dark matter data
- much more calibration data

→ data analysis is almost done
→ expect new results very soon
XMASS

- single phase LXe detector
- 800kg total, 100kg fiducial mass
- 60% of surface covered with 642 hexagonal PMTs
- very high LY (~7x higher than Xe100)

- located in Kamioka (JP)
- running since end of 2010; ultra low Kr85 background

XMASS announced background problems (surface events on Cu and from Al ring on PMTs) in March 2012
→ needs more investigation

M. Schumann (U Zürich) – Direct Dark Matter Searches
XENON1T

- dual phase LXe TPC
- 2.4t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background than Xe100
  (self shielding, low radioactivity components)
- Timeline: 2010 – 2015
- start construction at LNGS this year
The Future...

Note: plot contains only experiments using noble liquids
Summary

- **CRESST (2011)**
- **SIMPLE (2011)**
- **CRESST (2007, reanalysis)**
- **ZEPLIN-III**
Backup
XENON10 „S2 only“ Analysis

*PRL 107, 051301 (2011)*

trade z-position+discrimination for lower threshold

Fig. adapted from *Astro. Part. Phys.* 34, 679 (2011)
XENON10 „S2 only“ Analysis

- 12.5d data from 2006
- trigger threshold at single electron level; data not used before
- require S2>5 e⁻ (~1.4 keV)
- radial cut r<3 cm, basically no z-cut → 1.2 kg
- choosing Qy 40% higher (lower) would yield a 2x stronger (weaker) limit @ 7 GeV/c²

Models:
- Sorensen/Dahl, PRD83, 063501 (2011)
"Predictions" are due to a mistake. Xenon is not Germanium! One has to consider the electron-ion recombination and the exciton to ion ratio, which vary with E.

Conclusion: only if Q_y is incompatible with data and theoretical understanding one can avoid the XENON10 constraints.
Criticism or Confusion?

Conclusion: only if $Q_y$ is incompatible with data and theoretical understanding one can avoid the XENON10 constraints.

ZEPLIN work on single electrons:
- arXiv:1110.3056

$\sim 130 \, e^-$