Dark matter:
direct searches for WIMPs

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Direct Detection of WIMPs: Principle

- Elastic collisions with nuclei in ultra-low background detectors
- Energy of recoiling nucleus: *few keV to tens of keV*

\[
\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\text{min}}}^{v_{\text{max}}} d\mathbf{v} f(\mathbf{v}) v \frac{d\sigma}{dE_R}
\]

- \(N_N\) = number of target nuclei in a detector
- \(\rho_0\) = local density of the dark matter in the Milky Way
- \(f(\mathbf{v})\) = WIMP velocity distribution in lab frame
- \(m_W\) = WIMP-mass
- \(\sigma\) = cross section for WIMP-nucleus elastic scattering

\[v_{\text{min}} = \sqrt{\frac{m_N E_{\text{th}}}{2m_r^2}}\]
Astrophysics

High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$\rho_{\text{halo}} \sim 0.3 \text{ GeV} \cdot \text{cm}^{-3}$

$\Rightarrow$ WIMP flux on Earth:
$\sim 10^5 \text{ cm}^{-2}\text{s}^{-1} (M_W=100 \text{ GeV})$

- From cosmological simulations of galaxy formation: departures from the simplest case of a Maxwell-Boltzmann distribution
- However, a simple MB distribution is a good approximation, and yields conservative results
- SUSY: scattering cross sections on nucleons down to $\sim 10^{-48} \text{ cm}^2 (10^{-12} \text{ pb})$
- Here example in CMSSM, after LHC 1/fb

**Figure 14.** The 68% and 95% CL contours (red and blue, respectively) in the CMSSM (left) and the NUHM1 (right). The solid lines are for fits including the XENON100 [25] and LHC 1/fb data, whereas the dotted lines include only the pre-LHC data [5].

- Larger value of $\tan \beta$, but this may eventually lead to subsidiary tension with the LHC H/A constraints and the tightening experimental vise on $B(\ell^+\ell^-)$. In any case, it will be important to subject the $(g-2)$ constraint to closer scrutiny, and the upcoming Fermilab and J-PARC experiments on $(g-2)$ [66] are most welcome and timely in this regard. In parallel, refinements of the experimental inputs for the prediction of $(g-2)$ from both low-energy $e^+e^-$ and $\tau$ decay data would also be welcome. It will be also necessary to subject the theoretical calculations within the SM and the corresponding estimates of the remaining theoretical uncertainties to further scrutiny.

- The dark matter upper limit on the sparticle mass scale remains unchanged, and is responsible for the disfavoured region above $m_1/m_2 \sim 2500 \text{ GeV}$ visible in our figures for the CMSSM and the NUHM1. On the other hand, the dark matter constraint on $m_0$ is not so strong, as also seen in the figures, extending well beyond the range displayed. Considering the impact of direct jets + $\not{E_T}$ searches only, the regions of the CMSSM and NUHM1 ($m_0, m_1/m_2$) planes in Fig. 2 with $p$-values significantly non-zero extend beyond the likely reach even of the full-energy LHC in its high-luminosity incarnation.

- **A fortiori**, the same is true for the regions of these planes allowed at the current 95% CL ($\Delta \chi^2 = 5, 99$ relative to the global minima, bounded by the blue contours in Fig. 1). This is even more true of the full regions of the CMSSM and NUHM1 ($m_0, m_1/m_2$) planes that are allowed by the dark matter constraint.

- In light of this discussion, under what circumstances could one conclude that the CMSSM or NUHM1 is excluded? Currently, our best fits in both these models have $p$-values above 10%, comparable to that of SM fits to precision electroweak data from LEP and SLD, and the F-test shows that both the CMSSM and NUHM1 are warranted extensions of the SM, in the sense that introducing their parameters provides an improvement in $\chi^2$ that is valuable in both cases. Moreover, it seems unlikely that the LHC will soon be able to explore all the region of the ($m_0, m_1/m_2$) planes in Fig. 2 where the models' $p$-values exceed 5%, nor does the LHC seem likely soon to push $F_{\chi^2}$ (see Fig. 3) to uninterestingly low levels. This is not surprising, as in the high-mass limit the superpartners decouple and one is left essentially with the SM with a light Higgs.

- One way for the LHC to invalidate the models studied here would be to discover an SM-like ~ 1 event kg$^{-1}$ year$^{-1}$.
Particle physics

- SUSY: scattering cross sections on nucleons down to $\sim 10^{-48} \text{ cm}^2 (10^{-12} \text{ pb})$
- Here example in CMSSM, after LHC 5/fb, XENON100 and Bs-$\rightarrow \mu\mu$
Particle physics

- Many other possibilities for WIMPs: singlet (scalar, fermionic) dark matter, inert Higgs, minimal DM etc (see previous talk)
- can be probed by direct detection experiments

Singlet DM will be probed to $m_S \gtrsim 10$ TeV by LUX, XENON1T in the near future
Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[ \frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km s}^{-1}} \times \frac{\rho_0}{0.3 \text{ GeV cm}^{-3}} \right].$$

Recoil spectrum for different WIMP masses

- Lighter WIMPs
- Heavier WIMPs
Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution

\[
R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[ \frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km s}^{-1}} \times \frac{\rho_0}{0.3 \text{ GeV cm}^{-3}} \right].
\]

(Nuclear recoil spectrum for different target nuclei)

(Standard halo model with \( \rho = 0.3 \text{ GeV cm}^3 \))
The experimental challenge

- To observe a signal which is:
  - very small (few keV - tens of keV)
  - extremely rare (1 per ton per year?)
  - embedded in a background that is millions of times higher

- Specific dark matter signatures
  - rate and shape of recoil spectrum depend on target material
  - motion of the Earth cause a
    - temporal variation in the rate
    - directional dependence
The world wide wimp search

- SNOLab
- DEAP
- CLEAN
- Picasso
- COUPP
- DAMIC
- Soudan
- SuperCDMS
- CoGeNT
- Homestake
- LUX
- Boulby
- ZEPLIN
- DRIFT
- Modane
- EDELWEISS
- Canfranc
- ArDM
- Rosebud
- ANAIS
- Gran Sasso
- XENON
- CRESST
- DAMA/LIBRA
- DarkSide
- South Pole
- DM Ice
- Kamioka
- XMASS
- Newage
- YangYang
- KIMS
- Jinping
- Panda-X
- CDEX
Cryogenic Experiments at $T \sim \text{mK}$

- **Advantages**: high sensitivity to nuclear recoils (measure the full energy in the phonon channel); good energy resolution, low energy threshold (keV to sub-keV)

- **Ratio of light/phonon or charge/phonon:**
  - nuclear versus electronic recoils discrimination $\rightarrow$ separation of S and B

![Graph showing ratio of charge (or light) to phonon with peaks labeled $^{133}\text{Ba}$ and $^{252}\text{Cf}$, background and expected signal regions.]
Cryogenic Experiments at T~ mK

- Absorber masses from ~ 100 g to 1400 g

SuperCDMS
9 kg Ge running at Soudan (15 x 600 g)
proposed 200 kg Ge at SNOLab (1.4 kg crystals)

CRESST
18 detector modules (5 kg) installed at LNGS
low background run to start in 2013

EDELWEISS-III
commissioning run with 15 FID detectors in spring 2013 (12 kg Ge)
fall 2013: installation of 40 x 800 g (32 kg Ge)
New results from CDMS-Si


140 kg d exposure

3 events detected, 0.7 expected
likelihood analysis: 0.19% probability for known background-only hypothesis
best fit: 8.6 GeV, $1.9 \times 10^{-42}$ cm$^2$

Analysis ongoing of low-threshold run (CDMS-lite) at Soudan with one Ge detector
Projections: Cryogenic Experiments

Projected WIMP sensitivity for SuperCDMS Soudan after 3 calendar years (Spring 2015).

Cross-section [cm²] (normalised to nucleon)

Edelweiss

SuperCDMS Soudan projected

Texono: 1 kg Ge, E_{th}=500 eV

Results: spin-independent [arXiv:1303.0925, PRL13]

- New limits probed and excluded some of the low-mass WIMP allowed regions implied by other experiments.

Texono: 1 kg Ge, E_{th}=500 eV

- SuperCDMS Soudan projected

- CRESST projected

- Exposure of Run32 (~730 kg d) should be reached ~1 year ~2 years of data-taking

- Exposure of Run32 (Spring 2015) within 2 years of data-taking (~1 year cuts) within 2 years of data-taking

- CRESST projected

- DAMA/LOUD 2008

- CoGeNT

- CDMS-II SI 2013

- CRESST-II 2011

- CDMS-I 2011

- CDMS-II SI

- TEXONO

- TEXONO Projected

- M2

- M1

- CRESST 1a

- CRESST 2a

- CRESST projected

- XENON105 (best fit)

- XENON100 - 2012

- XENON100

- CDMS-II (GO)

- CDMS-II (SI)

- CDMS-I (Ge-Low)

- TEXONO 2007

- TEXONO 2013

- SuperCDMS Soudan (Proj.)

- EDELWEISS

- CDMS-II

- CRESST-I

- DAMA

- CRESST-II

- CoGeNT

- CoGeNT

- CoGeNT

- CDMS-II SI

- CDMS-I 2011

- CDMS-I 2011

- CDMS-I 2011

- CDMS-I 2011
Future Cryogenic Experiments at T~ mK

- SuperCDMS at SNOLab: proposed 200 kg Ge detectors, reach: $8 \times 10^{-47} \text{ cm}^2$
- EURECA at LSM extension (approved): phased approach 150 kg to 1 ton, multi-target (CaWO$_3$, Ge), reach $10^{-46} - 10^{-47} \text{ cm}^2$
- Potential collaboration between SuperCDMS and EURECA, at the 200 kg level

SuperCDMS at SNOLab

EURECA at DOMUS
Scintillation/Ionization: Noble Liquids

- High light and charge yield; transparent to their own light
- Large, scalable, homogeneous and self-shielding detectors -> fiducialization
- In air, by volume - Ar: 0.93%, Ne: 0.0018%, He: 0.00052%, Kr: 0.00011%, Xe: 0.0000087%

![Light and Charge Yield](image)
Two detector concepts

Single phase

Double phase (TPC)

PMT array

S1

S2

+HV

-HV

+ PSD

S1

S2

time

S1

S2

time
Single-phase detectors

- XMASS at Kamioka (LXe), DEAP and CLEAN at SNOLab (LAr)
- Challenge: ultra-low absolute background (materials, radon, alphas)

**XMASS at Kamioka:**
835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
unexpected background found
detector refurbished
new run this fall -> 2013

**CLEAN at SNOLab:**
500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014

**DEAP at SNOLab:**
3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014
Liquid xenon and liquid argon TPCs

<table>
<thead>
<tr>
<th>Detector</th>
<th>Notes</th>
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<tbody>
<tr>
<td>XENON100 at LNGS:</td>
<td>161 kg LXe (~50 kg fiducial)</td>
</tr>
<tr>
<td></td>
<td>242 1-inch PMTs taking new science data</td>
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<tr>
<td>LUX at SURF:</td>
<td>350 kg LXe (100 kg fiducial)</td>
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<td></td>
<td>122 2-inch PMTs physics run since spring 2013</td>
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<td></td>
<td>first result this fall</td>
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<td>PandaX at CJPL:</td>
<td>125 kg LXe (25 kg fiducial)</td>
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<td>143 1-inch PMTs</td>
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<tr>
<td></td>
<td>37 3-inch PMTs started in early 2013</td>
</tr>
<tr>
<td>ArDM at Canfranc:</td>
<td>850 kg LAr (100 kg fiducial)</td>
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<tr>
<td></td>
<td>28 3-inch PMTs in commissioning to run 2014</td>
</tr>
<tr>
<td>DarkSide at LNGS</td>
<td>50 kg LAr (dep in $^{39}$Ar) (33 kg fiducial)</td>
</tr>
<tr>
<td></td>
<td>38 3-inch PMTs in commissioning since May 2013 to run in fall 2013</td>
</tr>
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Noble liquid recent results: spin-independent cross section


XENON100 (2012)
- observed limit (90% CL)
- Expected limit of this run:
  - ± 1 σ expected
  - ± 2 σ expected


Acknowledgment:
We gratefully acknowledge the cooperation...
Liquid xenon and liquid argon detectors

- Under construction: XENON1T at LNGS, 3.5 t LXe in total
  - commissioning in 2014, first run in 2015; goal $2 \times 10^{-47} \text{ cm}^2$
- Near future: XMASS (5 t LXe), DarkSide-5000 (5 t LAr)
- Design and R&D: LZ (7 t LXe), DARWIN (20 t LXe/LAr)
Argon/xenon complementarity


\[ \sigma_{\chi p} [\text{cm}^2] \]

\[ m_\chi [\text{GeV}] \]

\[ \rho_\chi = 0.3 \pm 0.1 \text{ GeV cm}^{-3} \]

\[ v_0 = 220 \pm 20 \text{ km/s} \]

\[ v_{\text{esc}} = 544 \pm 40 \text{ km/s} \]
Room temperature scintillators

- **NaI**: DAMA/LIBRA 250 kg at LNGS; time variation in the event rate with: $T = 1$ yr, phase = June 2±7 days, $A = 0.018$ events/(kg keV day)
- **CsI**: KIMS 103.4 kg at Yangyang laboratory; ER vs. NR discrimination based on time structure of events; does not confirm DAMA/LIBRA in an annual modulation search
- **NaI**: ANAIS, 250 kg, under construction at LSC; DM-Ice, proposed 250 kg at the South Pole

![DAMA/LIBRA](image1.png)  ![KIMS](image2.png)  ![ANAIS](image3.png)  ![DM-Ice](image4.png)
Bubble chambers

- Detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)
- Large rejection factor for MIPs ($10^{10}$), scalable to large masses, high spatial granularity
- Existing detectors: SIMPLE, COUPP, PICASSO (→ PICO)
- Future: COUPP-500 → ton-scale detector

Example:

- n-induced event (multiple scatter)
- WIMP: single scatter

COUPP 4 kg CF$_3$I detector at SNOLAB

COUPP 60 kg CF$_3$I detector installed at SNOLAB; physics run since March 2013

Recoil range $<< 1 \mu m$ in a liquid - very high dE/dx

PICASSO at SNOLAB
Spin-dependent results

\[
\frac{d\sigma_{SD}(q)}{dq^2} = \frac{8G_F^2}{(2J + 1)v^2} S_A(q)
\]

\[
S_A(0) = \frac{(2J + 1)(J + 1)}{\pi J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2
\]

WIMP-neutron coupling

WIMP-proton coupling

Directional detectors

- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- MicroTPCs: MIMAC (CF₄, CHF₃, H gas), NEWAGE (CF₄ gas)
- TPC: DRIFT (negative ion, CS₂), DM-TPC (CF₄ gas)
Neutrinos as backgrounds

- Electronic recoils from pp solar neutrinos: $\sim 10^{-48} \text{ cm}^2$
- Nuclear recoils from $^8\text{B}$ solar neutrinos: below $10^{-44} \text{ cm}^2$ for low-mass WIMPs
- Nuclear recoils from atmospheric + DSNB: below $10^{-48} \text{ cm}^2$

\[ \nu + e^- \rightarrow \nu + e^- \]

\[ \nu + N \rightarrow \nu + N \]


LB, Physics of the Dark Universe 1, 94 (2012)
WIMP search evolution in time

About a factor of 10 every 2 years!
Can we keep this rate of progress?

L. B., Physics of the Dark Universe 1, 94 (2012)
Summary and Prospects

- Cold dark matter is still here with us
- It could be made of a new, heavy, neutral, stable and weakly interacting particle
- *We have entered the era of data: direct detection, the LHC, indirect detection*
- Direct detection experiments have reached unprecedented sensitivity (cross sections down to $10^{-8}$ pb) and can probe WIMP with masses from a few GeV to a few TeV
- “Ultimate” WIMP detectors might be able to prove or disprove the WIMP hypothesis and provide complementary information to *indirect searches and the LHC*
- However, we should be prepared for surprises!
End
XENON100 predictions for light WIMPs

- How would the CDMS-Si signal look like in XENON100’s Run10 data?

WIMP with $m_W = 8.6$ GeV

WIMP-nucleon cross section: $1.9 \times 10^{-41}$ cm$^2$

~ 220 (+300, -85) events in the ROI (high, and low contours of $L_{\text{eff}}$ and $Q_y$ error bands)
WIMP Scattering Cross Sections

- In the extreme NR limit relevant for galactic WIMPs ($10^{-3}$ c) the interactions leading to WIMP-nuclei scattering are classified as (Goodman and Witten, 1985):

  - scalar interactions (WIMPs couple to nuclear mass, from the scalar, vector, tensor part of L)
    \[
    \sigma_{SI} \sim \frac{\mu^2}{m_X^2} \left[ Z f_p + (A - Z) f_n \right]^2
    \]
    $f_p, f_n$: effective couplings to protons and neutrons

  - spin-spin interactions (WIMPs couple to the nuclear spin, from the axial part of L)
    \[
    \sigma_{SD} \sim \mu^2 \frac{J_N}{J_N + 1} \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2
    \]
    $a_p, a_n$: effective couplings to protons and neutrons
    $\langle S_p \rangle$ and $\langle S_n \rangle$
    expectation values of the p and n spins within the nucleus
WIMP scattering cross section

\[ \sigma_0 \sim 10^{-39} \text{ cm}^2 \]

\[ \sigma_0 \sim 10^{-45} \text{ cm}^2 \]

See DarkSusy for detailed predictions
http://www.physto.se/~edsjo/darksusy/
The background noise

- **Electromagnetic radiation**
  - natural radioactivity in detector and shield materials
  - airborne radon \(^{222}\text{Rn}\)
  - cosmic activation of materials during storage/transportation at the Earth’s surface

- **Neutrons**
  - radiogenic from \((\alpha, n)\) and fission reactions
  - cosmogenic from spallation of nuclei in materials by cosmic muons

- **Alpha particles**
  - \(^{210}\text{Pb}\) decays at the detector surfaces
  - nuclear recoils from the Rn daughters

Cosmic rays: operate deep underground

Muon flux vs overburden

- WIPP
- Soudan
- Kamioka
- Gran Sasso
- Homestake (Chlorine)
- Baksan
- Mont Blanc
- Sudbury

Proposed NUSL Homestake

Current Laboratories

Cosmic rays operate deep underground.
CoGeNT: low-mass WIMPs?

- Point-contact, 330 g Ge detector at Soudan
- Energy threshold: ~ 0.5 keV ionization (~ 2 keV NR energy)
- 2011: claim of an annual modulation at 2.8-σ level (0.5 - 3 keVee), ~ 450 days

arXiv: 1002.4703; C. E. Aalseth et al., PRL106
Modulation: DAMA/LIBRA, CoGeNT

- DAMA/LIBRA (250 kg NaI, 0.82 tons-year): 8.9-σ effect
- CoGeNT (330 g HPGe, 450 d): 2.8-σ effect

- Origin of the time variation in the observed rate - unclear!
- Movement of the Earth-Sun system through the dark matter halo?
- Environmental?
Origin of the time variation in the observed rate:

- motion of the Earth-Sun system through the WIMP halo?
- environmental effects?
- unclear!

see also David Nygren, arXiv:1102.0815

Muon rate variation at LNGS: Amplitude: ~ 0.015; T = 1 year, $\phi = July \ 15\pm15\ days$

* M.Selvi et al., Proc. 31st ICRC, ŁÓDŹ 2009
Detect a \textit{temperature increase} after a particle interacts in an absorber

\[ \Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}} \]

\[ \tau = \frac{C(T)}{G(T)} \]

\[ C(T) \propto \frac{m}{M} \left( \frac{T}{\Theta_D} \right)^3 JK^{-1} \]

- \( m = \) absorber mass
- \( M = \) molecular weight of absorber
- \( \Theta_D = \) Debye temperature (at which the highest frequency gets excited)
Transition Edge Sensors

- The substrate is cooled well below the SC transition temperature \( T_c \).
- The temperature rise (~ µK) is measured with TES.

Example: TES for CDMS detectors.