Direct detection of WIMPs
The dark matter puzzle

- The dark matter puzzle is fundamental: dark matter leads to the formation of structure and galaxies in the universe

- We have a so-called “standard model” of CDM, from “precision cosmology”: however, measurement ≠ understanding

- For 85% of matter in the universe is of unknown nature
What do we know about dark matter?

- So far, we mostly have “negative” information
- No color charge
- No electric charge
- No strong self-interaction
- Not a particle in the Standard Model of particle physics

Cold  Warm  Hot

Observation [e.g. rotation curves; lensing; galaxy counts etc.]

CMB Cold  Warm  Hot
What do we know about dark matter?

- The mass range spans merely 90 orders of magnitude

In this talk I will focus on the weak scale, and on direct detection.
How to directly detect it in the lab?

- By searching for collisions of invisibles particles with atomic nuclei $\Rightarrow E_{\text{vis}}$ ($q \sim$ tens of MeV)
- Need very low energy thresholds
- Need ultra-low backgrounds, good background understanding (no "beam off" data collection mode) and discrimination
- Need large detector masses (remember neutrino detectors)

$$E_R = \frac{q^2}{2m_N} < 100 \text{ keV}$$
What do we expect in a detector?

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

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

\[
\rho(R_0) = 0.2 - 0.56 \text{ GeV} \cdot \text{cm}^{-3}
\]

Justin Read, arXiv:1404.1938
WIMP scattering cross section

Scalar (S) \[ \mathcal{L} = \frac{G_S}{\sqrt{2}} \bar{\chi} \chi f f \]

Pseudoscalar (P) \[ \mathcal{L} = \frac{G_P}{\sqrt{2}} \bar{\chi} \gamma^5 \chi f \gamma_5 f \]

Vector (V) \[ \mathcal{L} = \frac{G_V}{\sqrt{2}} \bar{\chi} \gamma^\mu \chi f \gamma_\mu f \]

Axialvector (A) \[ \mathcal{L} = \frac{G_A}{\sqrt{2}} \bar{\chi} \gamma^\mu \gamma_5 \chi f \gamma_\mu \gamma^5 f \]

Tensor (T) \[ \mathcal{L} = \frac{G_T}{\sqrt{2}} \bar{\chi} \sigma^{\mu\nu} \gamma_5 \chi f \sigma_{\mu\nu} \gamma^5 f \]

Effective field theory approach, always valid for direct detection

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

see talk by Neal Weiner

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

see talk by R. J. Hill
The WIMP landscape in 2014

“Anomalies” at low WIMP masses

Sensitivity to masses up to 10 TeV and above!
Have we observed low-mass WIMPs?

CDMS-Si, DAMA/LIBRA, CoGeNT, CRESST: excess of events above the known backgrounds.
Have we observed low-mass WIMPs?

Or merely “thresholdinos”?

The Practical Matter of a Low Energy Rare Event Search

- Dark Matter signals will be expected to appear first in the lowest energy bins of an experiment that is still in search mode.
- Unfortunately, that is also where the first indications that systematics are starting to dominate.

Thresholdinos

- You should be ready to be skeptical of the results from your uppermost and lowermost bins of your histogram – Attributable, in spirit to Rutherford (I believe).
- It is difficult to control systematics that may cause events to be in edge bins/tails.
  - This is particularly important when a result is dependent on subtle effects.
- And we will need to push the detectors by another $10^4$ before we reach the irreducible coherent scattering atm. neutrino backgrounds.
Low-mass region: heavily constrained by CDMS-Ge, XENON10, XENON100, LUX, EDELWEISS, CRESST, CoGeNT, PandaX,...
How would a CDMS-Si like signal look like in XENON100 and LUX?

Assumption:

\[ m_W = 8.6 \text{ GeV} \text{ and WIMP-nucleon cross section of } 1.9 \times 10^{-41} \text{ cm}^2 \]

XENON100 Run10
expect: \(~ 220 \text{ events}\)

LUX first run
expect: \(~ 1550 \text{ events}\)

WIMP Mass 8 GeV
c-s \(2.0 \times 10^{-41} \text{ cm}^2\) (CDMSII Si favored)
Expect 1550 events
What is the origin of the DAMA signal?

- Possible explanation: **a combination of neutrinos and muons**
- Solar $^8$B neutrino- and atmospheric muon-induced neutrons
- **Combined phase of muon and neutrino components***: good fit to the data

Jonathan Davis, PRL 113, 081302 (2014)

*Muons: flux correlated with T of atmosphere; period is ok but phase is 30 d too late
*Neutrinos: flux varies with the Sun-Earth distance; period is ok but phase peaks in early Jan
What next? We need a variety of techniques to convincingly discover and constrain WIMPs!
Cryogenic Experiments at T~ mK

- High sensitivity to nuclear recoils, good energy resolution, **low energy threshold** (keV to sub-keV) => **low-mass WIMPs**
- Ratio of light/phonon or charge/phonon:
  - nuclear versus electronic recoils discrimination => **separation of S and B**

Ratio of charge (or light) to phonon

Background region

Expected signal region

\[
\begin{align*}
133\text{Ba} & \\
252\text{Cf} &
\end{align*}
\]
New data from cryogenic experiments

- Absorber masses from ~ 100 g to 1400 g

SuperCDMS
new, leading results at low masses
proposed for SNOLAB:
Std: ~92 kg Ge, 11 kg Si
Lite: 5 kg Ge, 1.2 kg Si

CRESST
18 CaWO₃ detector modules (5 kg) installed at LNGS in 2013
low-background run in 2014, recent results and taking more data

EDELWEISS-III
new run with 36 Ge FID800 (~30 kg) detectors since June 2014
End 2014/early 2015: reach 3000 kg x d (125 live days)
2016: reach 1.2 ton x days (500 live days)
Future Cryogenic Experiments at T~ mK

- SuperCDMS at SNOLab: approved by NSF&DoE
- Collaboration between SuperCDMS and EURECA, at the ~100 kg level (cryostat can house up to 400 kg target material)
- Multi-target approach (CaWO₃, Ge), start data taking in 2018
- Reach for SI cross sections: $8 \times 10^{-47}$ cm²

The diagram shows the reach for WIMP-nucleon cross sections, with a focus on projected performance improvements and future potential in the field. The text highlights advancements in detection technologies, collaborations, and the potential for reaching SI cross sections at a level of $8 \times 10^{-47}$ cm².

See talks by B. Loer, A.J. Anderson.
CCDs for low-mass WIMPs: DAMIC

- Particle identification
- Fiducialisation to reject surface events (X-rays)
- DAMIC100 (100 g Si active mass) under construction at SNOLAB; results in 2015

2012 DAMIC limit 107 g–days with 0.04 keV energy threshold
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 2 L
- Future: PICO (PICASSO + COUPP) -> 250 l detector detector at SNOLAB, C3F8 with 3 keV threshold

COUPP 60 kg CF$_3$I detector installed at SNOLAB; physics run until May 2014

PICASSO at SNOLAB

PICO 2L

Spin-dependent limits

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

see talk by O. Harris

n-induced event (multiple scatter)

WIMP: single scatter
Noble liquid detector concepts

Single phase

PMT array

S1

+ PSD

time

Double phase (TPC)

PMT array

S1

e

S2

e

time

+ HV

-HV
New data from Xe and Ar single-phase

- XMASS at Kamioka (LXe), DEAP and CLEAN at SNOLab (LAr)

**XMASS at Kamioka:**
- 835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
- Unexpected background found
- Detector refurbished, new run since Nov 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
- First data expected in fall 2014
New data from Ar and Xe TPCs

**XENON100 at LNGS:**
- 161 kg LXe (~50 kg fiducial)
- 242 1-inch PMTs
- close to unblinding of new data set
- 161 kg LXe (~50 kg fiducial)
- New run in 2014

**LUX at SURF:**
- 370 kg LXe (100 kg fiducial)
- 122 2-inch PMTs
- physics run and first results in 2013
- new run in 2014

**PandaX at CJPL:**
- 125 kg LXe (37 kg fiducial)
- 143 1-inch PMTs
- 37 3-inch PMTs
- first results in August 2014

**ArDM at Canfranc:**
- 850 kg LAr (100 kg fiducial)
- 28 3-inch PMTs
- first results in 2014

**DarkSide at LNGS:**
- 50 kg LAr (dep in $^{39}$Ar) (33 kg fiducial)
- 38 3-inch PMTs
- first data with non-depl Ar in 2014

see talk Y. Guardincerri
Example: LUX dark matter data

- First run: 85.3 live-days, 118 kg fiducial mass
- No sign of dark matter, observed distribution consistent with backgrounds
- New run of 300 live-days planned for 2014/15, sensitivity increase by a factor of 5

160 events observed (1.9 evts/d)
Expect 0.64±0.16 leakage below NR mean
Distribution consistent with ER backgrounds

Spin Independent Sensitivity

$m_{\text{WIMP}}$ (GeV/c$^2$)

10$^{-1}$ 10$^0$ 10$^1$ 10$^2$ 10$^3$

$\sigma_{\text{WIMP-nucleon}}$ (cm$^2$)

10$^{-46}$ 10$^{-45}$ 10$^{-44}$ 10$^{-43}$ 10$^{-42}$

LUX (2013)-85 live days
XENON100(2011)-100 live days
XENON100(2012)-225 live days
ZEPLIN III
CDMS II Ge
Edelweiss II

LUX is the most sensitive experiment in the world!

Accepted in PRL, arXiv: 1310.8214
Future noble liquid detectors

- **Under construction**: XENON1T at LNGS, 3.1 t LXe in total
- **Future**: LUX-ZEPLIN (7 t LXe) (approved by NSF&DoE), XENONnT (n=6-7 t LXe) (to be proposed), XMASS (5 t LXe), DarkSide (5 t LAr) (R&D funds)
- **Design and R&D**: “ultimate detector” DARWIN (~20 t LXe and/or 50 t LAr)
The XENON1T Experiment

- Under construction at LNGS since fall 2013
- Total LXe mass: 3.1 t, 1 m charge drift; 248 3-inch PMTs; background goal: 100 x lower than XENON100, ~5 x 10^{-2} events/(t-d-keV)
- Commissioning and science run: mid and late 2015
- Goal: 2 x 10^{-47} cm^2 at a WIMP mass of ~ 50 GeV
XENON1T construction at LNGS

- Water tank completed, service building ready
- Integration of several subsystems (cryostat, cryogenics, storage, purification, cable pipe etc) accomplished by August 2014
- PMTs screened and tested in cold gas and LXe; TPC under prototyping
XENONnT: 2018 - 2020

- Double the amount of LXe (~7 tons), double the number of PMTs
- XENON1T is designed such that many sub-systems will be reused for the upgrade:
  - Water tank + muon veto
  - Outer cryostat and support structure
  - Cryogenics and purification system
  - LXe storage system
  - Cables installed for XENONnT as well
  - More LXe, PMTs, electronics will be needed
DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector for $m_W > 6$ GeV
- Physics goal: build the “ultimate WIMP detector”, before the possibly irreducible neutrino background takes over; probe WIMP cross sections down to $\sim 10^{-49}$ cm$^2$

DARWIN: 25 groups from 9 countries

Darwin.physik.uzh.ch

~20 t LXe (and/or 50 t LAr) cryostat in large water Cherenkov shield
What can we say about the dark matter?

Newstead et al., PHYSICAL REVIEW D 88, 076011 (2013)

Xe 10 t yr, Xe 20 t yr
Xe 10 t yr + Ar 20 t yr

Xe 10 t yr + Ar 20 t yr for XS of:
3 \times 10^{-46} \text{ cm}^2, 3 \times 10^{-47} \text{ cm}^2, 3 \times 10^{-48} \text{ cm}^2

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

$$\nu_{esc} = 544 \pm 40 \text{ km/s}$$

$$v_0 = 220 \pm 20 \text{ km/s}$$
Will we turn into neutrino physicists?

- Electronic recoils from solar neutrinos: neutrino - electron scattering
- Nuclear recoils from $^8$B solar neutrinos: neutrino - nucleus coherent scattering
- Nuclear recoils from atmospheric + DSNB: neutrino - nucleus coherent scattering

![Graphs showing neutrino fluxes and event rates](image-url)

Will we turn into neutrino physicists?

- Electronic recoils from pp solar neutrinos: $\sim 10^{-48}$ cm$^2$ (depending on ER vs NR discr.)
- Nuclear recoils from $^8$B solar neutrinos: below $\sim 4 \times 10^{-45}$ cm$^2$ for low-mass WIMPs
- Nuclear recoils from atmospheric + DSNB: below $10^{-49}$ cm$^2$

$$\nu + e^- \rightarrow \nu + e^-$$

$$\nu + N \rightarrow \nu + N$$

LB et al., JCAP01 (2014) 044
Will directional information help?

- Yes, but mostly for low WIMP masses
- Many directional techniques currently in R&D phase
- Might be difficult to reach the $10^{-48}$ - $10^{-49}$ cm$^2$ cross section with this technique

36.6 t yr exposure, 500 (solar) nu events

367 t yr exposure, 500 nu events

Directional detectors

- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- Challenge: good angular resolution + head-tail at $E_{\text{thr}}$ (~30-50 keV)

**DMTPCino TPC at MIT**
- CCD readout
- 1 m$^3$ prototype, CF$_4$ gas
- Commissioning fall 2014

**MIMAC**
- 100x100 mm$^2$ 51 chamber at Modane
- CF$_4$, CHF$_3$, H gas
- Goal: achieve similar or better S:N per pixel, for $35^\circ$ resolution at 50 keV$_{\text{r}}$ in 1 m$^3$ module, ideally: 1 camera+lens/side (~0.005$/\text{channel}$ now)

**NEWAGE, Kamioka**
- CF$_4$ gas at 0.1 atm
- 50 keV threshold

**DRIFT, Boulby Mine**
- 1 m$^3$, negative ion drift
- CS$_2$, CF$_4$, O$_2$ gas
- DRIFTIII plans:
  - 24 m$^3$ (3 x 8 m$^3$ cells)
  - at Boulby
  - 4 kg target mass
Will we detect WIMP dark matter soon?

About a factor of 10 increase in sensitivity every 2 years

Who knows! Perhaps (hopefully?!?) by 2026…
The End
Direct-detection experiments can also search for solar axions, ALPs, vector... 

- Limits on axions and ALPs from CDMS, DAMA, CoGeNT, XMASS, EDELWEISS, XENON100

Solar axions

Galactic ALPs

---

Laura Baudis, University of Zurich, COSMO2014, Chicago
Particle physics

- SUSY: scattering cross sections on nucleons down to \(10^{-48} \text{ cm}^2 (10^{-12} \text{ pb})\)

\[10^{-44} \text{ cm}^2: \sim 1 \text{ event kg}^{-1} \text{ year}^{-1}\]

\[10^{-47} \text{ cm}^2: \sim 1 \text{ event t}^{-1} \text{ year}^{-1}\]
Recent results from CDMS-Si

- Data from 11 x 0.106 kg Si crystals, for 140 kg-days exposure
- Energy region: 7-100 keV$_{nr}$ analyzed
- 3 events observed upon unblinding, 0.7 events expected
- Likelihood analysis: 0.19% probability for known background-only hypothesis
- **best fit: 8.6 GeV, 1.9 x 10^{-42} cm^2**
New results from SuperCDMS

- Data from 15 x 0.6 kg Ge crystals, for 577 kg-days exposure
- Low energy region: 1.6 - 10 keV$_{nr}$ analyzed
- 11 events observed upon unblinding, consistent with background model
- **New upper limit inconsistent with previous “excesses”, including CDMS-Si**

![Graph showing data and background models](image-url)

*Source: Laura Baudis, University of Zurich, COSMO2014, Chicago*
Example of a 9 keV nuclear recoil event

S1: 4 photoelectrons detected from about 100 S1 photons

S2: 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

XENON100 top PMT array

XENON100 bottom PMT array

drift time of electrons
Example: XENON100 dark matter data

- Exposure: ~ 225 days x 34 kg fiducial liquid xenon mass

**Fiducial mass region:**
34 kg of liquid xenon
406 events in total

**Signal region:**
2 events are observed
0.79 ± 0.16 gamma leakage events expected
0.17 +0.12-0.7 neutron events expected
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

Expected Scattering Cross Sections

- The WMP-nucleus scattering is NR for galactic WIMPs ($v/c \sim 10^{-3}$) -> simple NR effective theory, $q \sim O(10-100 \text{ MeV})$

- Interactions leading to **WIMP-nuclei scattering** are parameterized as:
  - **scalar interactions** (coupling to nuclear mass, from scalar, vector, tensor part of L)
    \[
    \sigma_{SI} \sim \frac{\mu^2}{m^2} \left[ Z f_p + (A - Z) f_n \right]^2
    \]
    $f_p, f_n$: scalar 4-fermion couplings to protons and neutrons
  - **spin-spin interactions** (coupling to the nuclear spin $J_N$, from axial-vector part of L)
    \[
    \sigma_{SD} \sim \mu^2 \frac{J_N + 1}{J_N} \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2
    \]
    $a_p, a_n$: 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