Direct Dark Matter Searches

Context
Techniques
Status of current experiments
New results
Prospects

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DIRECT SEARCH: CONTEXT
Cold Dark Matter in the Universe

- Cold Dark Matter present at all scales in the Universe...

Essential part of a consistent picture

- Searched as a new particle at LHC
- Searched via the remains of its decay in cosmic rays (γ, ν, e+, antimatter)
- … Direct search: collision of WIMPs from our galactic halo on target nuclei in a laboratory on Earth
  - Proof that Dark Matter is present in our environment
  - After discovery: observatory for WIMP velocity distribution in our environment?
  - Sensitive to local WIMP density $\rho_{DM}$ (not to the cosmological density $\Omega_{DM}$)
(shortened) list of candidates

- **Axions**
  - Non-thermal relics ($\mu$eV-$\rightarrow$meV, CDM-$\rightarrow$HDM)
  
  - Recent results by XENON, Edelweiss, XMASS...
  
  - [arXiv:1404.1455;1307.1488;TeVPA2014]

- **WIMPs**
  - Stable thermal relics
  - Electroweak physics ($\sim$ prediction on annihilation/creation/scattering cross-sections)
  - Mass 10-100-1000 GeV/c$^2$ (atomic nucleus are interesting targets: maximal momentum transfer)

- **Other models**
  - Many are also covered by WIMP search (KK...)
  - Models without detectable particles are not excluded!
Direct search schematics

Observables: Event rate, $E_{\text{recoil}}$, $\theta_{\text{recoil}}$ (recoil range is related to $E_{\text{recoil}}$)

$$E_{\text{recoil}} = E_{\text{WIMP}} \frac{4M_{\text{nucleus}} M_{\text{WIMP}}}{(M_{\text{nucleus}} + M_{\text{WIMP}})^2} \cos^2 \theta_{\text{recoil}}$$
WIMP-nucleon collision

**Astrophysics**
(simplified - but standard - convention for detector comparison)

- $\rho_{\text{wimp}} = 0.3 \text{ GeV/cm}^3$
- $v_{\text{WIMP}} \sim v_{\text{SUN}} \sim 230 \text{ km/s}$

**Free parameters:** $M_{\text{WIMP}}, \sigma_{\text{WIMP-nucleon}}$

**Coherence factor**

- $\sim A^2$ for scalar coupling (spin-indep. interactions, *dominates for A \geq 20*)
- $\sim J(J+1)$ for axial coupling (spin-dep. interactions)

Nuclear Form factor (reduce $A^2$ enhancement at large A)
Historical notes

Method suggested in 1985 (28 years ago!) by Goodman + Witten

- Predict rates between 4 and 1400 events/kg/day for heavy \( \nu \).
  \[ M_\nu = 100 \text{ TeV} \leftrightarrow M_\nu = 100 \text{ GeV} \]

- As early as 1987, first significant constraints (exclusion of a heavy \( \nu \)) with ionization Ge and Si detectors: sensitivity to \( \sim \) few evts/kg/day

- To do better, need better rejection of radioactive backgrounds
Experimental progress vs time

Evolution of the WIMP–Nucleon $\sigma_{SI}$

Irregular, but systematic, improvement with time

Figure 4-3. Spin-independent limits for the major WIMP direct detection experiments (solid) and their projected sensitivity (open) for spin independent cross sections for a 50 GeV/c² mass WIMP. The shapes correspond to technologies: cryogenic solid state (blue circles), crystal detectors (purple squares), liquid argon (brown diamonds), liquid xenon (green triangles) and threshold detectors (orange inverted triangle).
Direct Dark Matter searches = simple experiment:

- look at a large number of nuclei and see if any of them recoils due to a hit-and-run collision caused by a WIMP... but:

- **Small event rate** per unit time and per number of target nuclei (as low as 1 per ton per year?)
- **Small kinetic energy** involved in such collisions
- **Need very strong rejection of radioactive backgrounds**
Dark Matter Searches around the world

- Underground sites (cosmic rays)
- Combine signals for ion/electron recoil identification
  - Heat (or thermalized phonons): “true” calorimetric energy
  - Ionization Yield
  - Scintillation Yield
  - Pulse shape discrimination: useful in some cases (Ne, Ar)
  - Also: dE/dx in superheated medium: COUPP, PICASSO
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Most recent detailed status talks:
- **TeVPA-IDM 2014, Amsterdam**
  - [http://indico.cern.ch/event/278032/](http://indico.cern.ch/event/278032/)
- **Dark Matter 2014, UCLA**
  - [https://hepconf.physics.ucla.edu/dm14/agenda.html](https://hepconf.physics.ucla.edu/dm14/agenda.html)
WIMP signatures

- **Directionality** (correlation with $v_{\text{sun}}$)
  - Challenge: $\sim 20$ nm recoil in solid, $\sim 30$ $\mu$m in gas
  - Low-pressure TPC? -> Still in R&D [DRIFT, DMTPC, MIMAC...]
  - *Small annual modulation* of flux ($\sim 2\%$) requires *large statistics* + *depends more on velocity distribution details*.

- Nuclear (and not electron = dominant bkg) recoils
  - **Particle identification**

- A$^3$ dependence of coherent scattering rate/kg
  - Motivates *diversity of target materials*

- Large scattering length
  - **Self-shielding** [*Xenon, Argon*] or
    *segmentation+multiplicity* [*Ge, Scintillators*]

- Control of systematics also favours target/expt. diversity
In many models (like SUSY) axial, spin-dependent (SD) interaction are either already excluded, or mixed with spin-independent (SI) component. (... but this statement is model-dependent)

- SI component amplified by \(A^2\) coherence tends to dominate.
- SD most efficiently probed by indirect searches (\(\nu\) detectors) or even LHC, as SD searches don’t benefit from \(A^2\) coherence factor.

Spin-dependent interactions
Absence of “minimal” SUSY at LHC opens SUSY phase space

Less predictive in terms of $M_{\text{WIMP}}$

Two (opposing?) biases:
- heavy SUSY suggests heavy WIMPs
- absence of SUSY calls for something new
- ... lighter than conventional SUSY?
The experimental search domain

![Graph showing the experimental search domain for WIMP-nucleon cross section versus WIMP mass, with various experiments and limits depicted.](image-url)
The experimental search domain

[Graph showing the experimental search domain for WIMP-nucleon cross section vs. WIMP mass with various experimental results and trends indicated, such as DAMIC, CoGeNT, CDMS Si (2013), SIMPLE (2012), DAMA, COUPP (2012), ZEPLIN-III (2012), CDMS II Ge (2009), Xenon100 (2012), EDELWEISS (2011), CRESST, and a trend line indicating increasing kg/day.]
The experimental search domain

The figure shows a plot of the WIMP–nucleon cross section versus WIMP mass, with different experimental results and theoretical predictions highlighted. The axes are labeled as follows:

- Y-axis: WIMP–nucleon cross section [cm²]
- X-axis: WIMP Mass [GeV/c²]

Key features include:
- The green region represents the range of experimental results from various experiments.
- The red line with arrows indicates the decreasing threshold for WIMP–nucleon cross section as the WIMP mass increases.
- The plot also includes theoretical predictions and constraints from various experiments and analyses.

The figure is credited to Figueroa-Feliciano, TeVPA2014.
The experimental search domain

Cf concept of "WIMP safe" limits, (PDG)
The experimental search domain

Dedicated low-mass searches with relaxed background suppression

WIMP–nucleon cross section [cm²]

WIMP Mass [GeV/c²]

Figueroa-Feliciano, TeVPA2014

July 15, 2014
FFP14: Direct Dark Matter Searches
2- DETECTION TECHNIQUES
Signals in direct searches

- Exponential recoil spectrum
- \( A^3 \) dependence of rate

\[ \text{It’s not a neutron-induced nuclear recoil } (\sigma = \pi R^2 \propto A^{2/3}) \]

- No coincidence between adjacent detectors (detector array)
- Uniform rate within the fiducial volume (large detectors)

- Directionality (correlation with \( \vec{v}_{\text{SUN}} \) direction): need to measure nuclear recoil trajectory
- Annual modulation (large statistics needed)

- Identification of nuclear recoils (vs electron recoils)
**Directionality: use $v_{\text{Earth}}$ to detect WIMP wind**

- Average WIMP wind direction due to $v_E$

- $\theta_{\text{RECOIL}} \neq \theta_{\text{WIMP}}$
  - but $<\theta_{\text{RECOIL}}> = <\theta_{\text{WIMP}}>$

- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil

- Astrophysics bonus: measure of $f(v)$
Range of nuclear recoils in matter

20 keV Ge recoils in crystal Ge:
Range ~20 nm

20 keV Kr recoils in gaseous Kr:
Range ~30 µm

- Molecular Dynamic Simulations of « hot » atoms produced by a 10 keV Si or Ge recoil (Nordlund, 1998)

SRIM

Range: <10 nm

Range: <20 nm
R&D on direction-sensitive techniques

- Idea: check for recoil tracks in ancient mica, $\theta_{\text{recoil}} \sim -v_{\text{sun}}$
  - *Problem: direction of $v_{\text{sun}}$, $v_{\text{earth}}$ changes constantly, continental drift…*

- Idea: low-pressure gas TPC detector

<table>
<thead>
<tr>
<th>Expt</th>
<th>Target (bar)</th>
<th>F mass (g)</th>
<th>Vol. (L)</th>
<th>Thresh. (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRIFT</td>
<td>UK CS$_2$ (0.04) CF$_4$ (0.01)</td>
<td>33</td>
<td>800</td>
<td>50</td>
</tr>
<tr>
<td>NEWAGE</td>
<td>JPN CF$_4$ (0.2)</td>
<td>9</td>
<td>15</td>
<td>140</td>
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<tr>
<td>MIMAC</td>
<td>F CF$_4$+CHF$_3$ (0.05)</td>
<td>1</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>DM-TPC</td>
<td>US CF$_4$ (0.1)</td>
<td>3</td>
<td>9</td>
<td>80</td>
</tr>
</tbody>
</table>

  - *Problems: low-density target to expand track length to ~cm, reduce diffusion of e$^-$/ion (negative CS$_2$ ions instead of e$^-$)*

- Idea: scan tracks in emulsions
  - ~100 nm resolution; ~200 keV threshold for Br recoils (200 nm)
Annual modulation in DAMA

- Need large statistics: flux modulation is $\sim \frac{1}{2} \left( \pm \frac{15}{235} \right) = \pm 3\%$, or less when considering experimental thresholds.

- Claimed to be observed ($\sim \pm 2\%$) at low-energy in NaI (DAMA).

- Non-modulating component ($\sim 1 \text{ evt/kg/day}$) is $\sim$total rate in NaI, but not observed in Ge, Xenon, CaWO$_4$ and CsI.

- Signal in low-efficiency, near-threshold region.

- No “source off” expt. possible.
CoGeNT Modulation

- 440 g Ge diode, point-contact electrode
- Arxiv:1002.4703 (Risetime discr. of surface evts)
- Arxiv:1106.0650 (Annual modulation)
- Arxiv:1208.5737 (Revised evaluation of surface rejection, reduction of annual modulation)

8 GeV WIMP?
Effect of a nuclear recoil in matter

Two type of energy losses:

- Ion-ion collisions (producing displacements and vibrations in the crystal: athermal phonons): nuclear dE/dx.
- Ionization (electronic dE/dx)
- Cascade of collisions and mix of nuclear & electronic dE/dx well described by Lindhard’s theory + measured dE/dx
- In a closed system, after a while, all excitation decays into thermal energy -> rise in temperature

(+ Permanent crystalline defects? )
Effect of an electron recoil in matter

- Most common (long range) radioactive background: $\gamma$-rays, producing electron recoils (photoelectron, Compton)
- No ion-ion collisions only electronic $dE/dx$
- Comparing ionization and scintillation yields is a powerful tool to separate nuclear and electron recoils
- Other effects due to difference in $dE/dx$: density of energy deposit are not the same. This may also affect the risetime of the scintillation signal (pulse shape discrimination)

Initial recoil energy

Ionization (100%)

Thermal phonons (Heat)

('+ No permanent crystalline defects? ')

July 15, 2014

FFP14: Direct Dark Matter Searches
Detection techniques

$\gamma$, $\beta$ discrimination:

- Two simultaneous signals
  - Heat/Phonon
  - Ionisation
  - Scintillation
- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal
- Other “dE/dx” related ideas

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**Discrimination « dE/dx»: COUPP+Picasso (PICO)**

Bubble formation in metastable system triggered by large+localized dE/dx

**Spin-dependent:**
Light target ($^{19}$F) with spin

2 kg CF$_3$I

A CCD camera takes pictures at 50 Hz. Chamber triggers on appearance of bubble in the frame.
Low-threshold semiconductors

- **Majorana**: plans for 40 kg Ge detectors by end 2014 (primarily for $0\nu\beta\beta$)
- Bkg goal of $\sim 0.001$ event/kg/day/keV
- 0.6 keV threshold achieved with MALBEK single-detector test
- **TEXONO/CDEX**: PC Ge with pulse shape discrimination down to $\sim 0.4$ keV
- **DAMIC**: 1-g Si CCDs with $< 50$ eV$_{ee}$ thresholds
- “dEdx” discrimination (15 $\mu$m x 15$\mu$m pixels)
- Best limits presently for WIMP masses 1.5-3 GeV ($\sim 4 \times 10^{-39}$ cm$^2$)
NOBLE LIQUID & GAS
Xenon S1/S2 discrimination

- Different scintillation (S1) and ionisation (S2) yields for nuclear / electronic recoils
- PMT array for (x,y), drift time for z : 3-D fiducial volume
Xenon and LUX S1/S2 discrimination

- **Xenon 100**: 170 kg LXe, 34 kg fiducial, 30 cm drift, 98(top)+80(bottom) PM’s
- Trigger on 3 PM coincidence: poor energy resolution, excellent noise suppression
- **10 keV nuclear recoil**: $S_1 \sim 5 \text{ P.E.}$ $S_2 \sim 800 \text{ P.E.}$ (from $\sim 30 \text{ ionization } e^-$)

- **LUX**: 370 kg LXe, 118 kg fiducial, 59 cm drift, 122 PM’s + active water veto
- Trigger on 2 PM coincidence: excellent noise suppression + 3 keV threshold
- **10 keV nuclear recoil**: $S_1 \sim 7 \text{ P.E.}$ $S_2 \sim 800 \text{ P.E.}$
XENON and LUX fiducialization

- **XENON-100 2012**: 34kg Xe fiducial, 225 day exposure
- Low $\gamma$ background (19 ppt $^{85}\text{Kr}$)
- Observe 2 evts, compatible with expected bkg = 1.0±0.2 evt (0.2 n + 0.8 Compton)
- **LUX 2013** [PRL 112 091303]: 118kg Xe fiducial, 85 day exposure
XENON and LUX data

- XENON-100 2012: 34kg Xe fiducial, 225 day exposure
  - Observe 2 evts, compatible with expected bkg = 1.0±0.2 evt (0.2 n + 0.8 Compton)
- LUX 2013 [PR1 112 091303]: 118kg Xe fiducial, 85 day exposure
  - Observed rate compatible with $\gamma$-background estimates
XENON and LUX limits

- LUX first experiment to reach $10^{-45} \text{ cm}^2$ ($10^{-9} \text{ pb}$) sensitivity (~10 kg-year)
- Incompatible with some “hints” seen for low WIMP mass
Xe/Ar low radioactive background

- Backgrounds in fiducial (center) volume, before rejection of $e^-$ recoils: benefits from large self-shielded volume
Some LXe and LAr projects

- LZ: next generation project for LUX and ZEPLIN
- XMASS (Kamioka): 100 kg + 642 PMs. Monophase, rejection based on fiducialization. Need to study and reduce internal radioactive background.
- DEAP-CLEAN (SNOLAB): 100 kg Ar, *need $10^8$ rejection of radioactive $^{39}$Ar* (pulse shape discr., $\tau = 1.6 \, \mu s$)
- DarkSide-50: 33 kg fiducial Ar, *depleted in $^{39}$Kr* (underground source, depletion $10^{-2}$ to $10^{-3}$)
- PANDA: 125 kg Xe in Jinping tunnel, China
GE IONIZATION + PHONON
Nuclear recoil / gamma discrimination

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for nuclear recoils (WIMP or neutron scattering) and electronic recoils ($\beta, \gamma$ decays)
  - discrimination of dominant background
  - Stable and reliable rejection performances
Limitation: poor ionization yield for surface events

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for nuclear recoils (WIMP or neutron scattering) and electronic recoils ($\beta, \gamma$ decays)

- Limitation: deficient charge collection near surface (trapping, dead layer)

  => different surface rejection strategy for CDMS & EDELWEISS

![Graph showing ionization/recoil vs recoil energy for different sources](image)
Interleaved electrodes with alternate potential, to separate surface and bulk events

Full Inter-Digitized 800 g HP-Ge Detector

Height: 4 cm

Width: 7 cm
Test of rejection of $10^5 \beta$ from $^{210}$Bi, $10^5 \beta$ from $^{210}$Pb and $10^5$ $^{206}$Pb recoils from $^{210}$Po $\alpha$ decays ($>>$ years of WIMP searches)
**EDELWEISS 2014 status**

- 36x800 g detectors installed
- Facility able to collect 3000 kgd per 6 months, expect $10^{-9}$ pb sensitivity in coming 2 years
CDMS iZIP detectors

- Large area: sensitivity to athermal phonons
- **Phonon time distribution**
- Photolithographic patterns of W-TES + Al collector
- **Use partition (outer/inner, top/bottom) to fiducialize**
Phonon time discrimination

- Phonon risetime < 50 µs
- Ionization risetime < 1 µs
- « Timing parameter » combines rise time and phonon-ionization delay
- Nuclear/electronic recoil discrimination!

Sensitivity to « z »? (no, works even if sensors on only one side)
Due instead to a difference between the phonons produced in the primary interaction and in the Luke-Neganov process.
SuperCDMS Soudan: 650g iZIPs

- Data started in 2012 with 9 kg (6 kg fiducial)
- Recent results: 577 kdg WIMP search with low thresholds
Dedicated low mass WIMPs

- Using Luke-Neganov amplification, can lower the threshold
- Price to pay: no nuclear recoil discrimination (but can test it by varying $V_{\text{polar}}$)
- Current threshold on $E_{\text{electron-equivalent}} \sim 1 \text{keV}_{\text{ee}}$ with $V_{\text{polar}} = 3.2\text{V}$
- Biasing at 70V reduces threshold by $(1+3.2/3)/(1+70/3) = 12$
- $840 \text{eV}_{\text{NuclRecoil}}$ threshold on (standard iZIP) Ge detector
Future projects: USA

- SuperCDMS at SNOLab: improved cosmic protection
  - 10 cm radius: double iZIP detector mass to 1.38 kg

- Goal: ~200 kg Ge 140 000 kgd (4 year run) $10^{-10}$ pb in ~2017

Cushman, IDM2012
Future cryogenic project EU

- European priority: completion of EDELWEISS-III (physics 2014-2015) and present CRESST runs
- EURECA: ~1 t combining Ge and CaWO$_4$ targets (see later)
- EURECA CDR recently completed
- 2013: EURECA discussions with SuperCDMS-SNOLAB: discussion on common strategy, collaboration for the cryogenics underway.
SCINTILLATION+HEAT
Heat-scintillation: CRESST

- 18x300 g CaWO$_4$ Crystals with Tungsten film thermometer
- Light detector = thin Si wafer + same type of thermometer
- 3 targets in same detector
  \[ A = 16, \ 40 \ \text{and} \ 184 \]
  \[ Q = 0.10, \ 0.06 \ \text{and} \ 0.04 \]

New: 6 detectors with radiopure clamps & fully reflecting scintillating housing to increase light yield

BONUS: tags $^{210}$Po $\rightarrow$ $^{\alpha}$+$^{206}$Pb
two body decay
$^{206}$Pb recoil $\sim$ W recoil
New CRESST limits at low mass

- 29.35 kgd of low-threshold data (0.6 keV), 1x250g detectors with support in CaWO$_4$
- Sensitivity from W recoils at high mass, and from O recoils at low mass
- Successful reduction of previous background of light-only events + neutrons
CONCLUSIONS
Conclusions

- Direct Dark Matter Searches: crucial experiments to attest the presence of WIMPs in our galaxy; complementary to LHC and indirect searches
- Apparently simple, but the required extreme low-backgrounds are challenging and they foster constant technological innovations.
- Need variety of targets (essential to validate possible discovery)
- Intense world-wide competition of R&D efforts to reduce backgrounds and increase the mass of the arrays
Future experiments (recent news)

The DOE Office of High Energy Physics and the NSF Physics Division have jointly selected a portfolio of projects for the “second generation” of direct detection dark matter experiments. We are pleased to announce that the joint DOE/NSF second-generation program will include the LZ and SuperCDMS-SNOLAB experiments with their collective sensitivity to both low and high mass WIMPs, and ADMX-Gen2 to search for axions. It will also include a program of R&D to test and develop technologies for future experiments, consistent with the recent P5 recommendations. The agencies will work with the proponents to develop project plans that can achieve their compelling science goals as expeditiously as possible.