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 ($\gamma$, $\nu$, 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 $\Omega_{DM}$)

July 30, 2014
ICNFP14: Direct Dark Matter Searches
Cosmology: $\Omega_{\text{DarkMatter}} \sim 0.268 \pm 0.02 \left(1.3 \, \text{M}_{\text{proton}} / \text{m}^3 \right)$

Astrophysics: Locally, $\rho_{\text{DM}} \sim 0.4 \, \text{GeV/cm}^3 \left(0.3 \, \text{M}_{\text{proton}} / \text{cm}^3 \right)$

**Hypothesis: thermal production in the Big Bang**

- **Particle physics**: pair production (and annihilation)
- **Big Bang Thermodynamics**: $\Omega_{\text{DarkMatter}}$ proportional to $\sigma_{\text{annihilation}}$:
  
  \[
  \frac{\langle \sigma_{\text{annihilation}} v \rangle}{(\Omega_{\text{DM}} h^2)} \sim 0.3 \times 10^{-27} \, \text{cm}^3/\text{s}
  \]
- **Miracle WIMP**: For $\Omega = 0.27$, $\sigma_{\text{annihilation}} \sim$ Weak Nuclear Force.
- **Big Bang Thermodynamics + Weak Force**: $M_{\text{WIMP}} \sim 10 - 10,000 \, \text{GeV/c}^2$

**Predictions are possible for identifying WIMPs in 3 channels:**

1. **Creation at LHC** ($\sigma_{\text{creation}}$)
2. **Annihilation products in cosmic rays** ($\sigma_{\text{annihilation}}$)
3. **Elastic Scattering on target nuclei** ($\sigma_{\text{scattering}}$)
(shortened) list of candidates

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

- **WIMPs**
  - Stable thermal relics
  - Electroweak physics (~ prediction on annihilation/creation/scattering cross-sections)
  - Mass 10-100-1000 GeV/c² (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

Possible observables: Event rates, Recoil Energy and Range, Scattering angle...

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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 \( A > \sim 20 \))

\[ \sim J(J+1) \] for axial coupling (spin-dep. interactions)

Nuclear Form factor (reduce \( A^2 \) enhancement at large \( A \))

Particle + Nuclear Physics

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

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

- As early as 1987, first significant constraints (exclusion of a heavy $\nu$) with ionization Ge and Si detectors: sensitivity to ~ 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/c$^2$ 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)

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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
Neutralino-nucleon scattering cross-section can be calculated within SUSY

Separation spin dependent (SD) / independent (SI): general expression for most types of interactions, even beyond SUSY

Quark/nucleon spin mostly cancel out, but quark/mass add coherently: scattering rate enhancement
Spin-dependent interactions

- 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.

See AMS, IceCube talks this week
Absence of “minimal” SUSY at LHC opens SUSY phase space

- Less predictive in terms of $M_{WIMP}$
- Two (opposing?) biases:
  - heavy SUSY suggests heavy WIMPs
  - absence of SUSY calls for something new
  - ... lighter than conventional SUSY?

Roszkowski, Moriond QCD2013

Wang, Aspen2013

Light DM spin-1 mediator.

SUSY, typically Higgs mediated.
The experimental search domain

Increasing kg * day

WIMP–nucleon cross section [cm$^2$]

WIMP Mass [GeV/$c^2$]

Figuerol-Feliciano, TeVPA2014
The experimental search domain
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 [cm$^2$]

WIMP Mass [GeV$/c^2$]
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 $v_E$
  \[ \theta_{\text{RECOIL}} \neq \theta_{\text{WIMP}} \]
  \[ \text{but } \langle \theta_{\text{RECOIL}} \rangle = \langle \theta_{\text{WIMP}} \rangle \]

- 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)

  - **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>
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<th>Expt</th>
<th>Target (bar)</th>
<th>F mass (g)</th>
<th>Vol. (L)</th>
<th>Thresh. (keV)</th>
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<td>DRIFT</td>
<td>CS$_2$ (0.04) CF$_4$ (0.01)</td>
<td>33</td>
<td>800</td>
<td>50</td>
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<tr>
<td>NEWAGE</td>
<td>CF$_4$ (0.2)</td>
<td>9</td>
<td>15</td>
<td>140</td>
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<tr>
<td>MIMAC</td>
<td>F</td>
<td>1</td>
<td>5</td>
<td>20</td>
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<tr>
<td>DM-TPC</td>
<td>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 $\sim \pm 3\%$, 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 (KIMS).

- Signal in low-efficiency, near-threshold region

- NaI modulation expt. checks: SABRE (use DarkSide veto) DM-ICE (Antarctic site, deep in ice)

See DAMA-LIBRA talk on Saturday
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)

735x54
CoGeNT 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 \( \frac{dE}{dx} \).
- Ionization (electronic \( \frac{dE}{dx} \))
- Cascade of collisions and mix of nuclear & electronic \( \frac{dE}{dx} \) well described by Lindhard’s theory + measured \( \frac{dE}{dx} \)
- In a closed system, after a while, all excitation decays into thermal energy -> rise in temperature

Initial recoil energy

Displacements, Vibrations

Athermal Phonons

Ionization (~30 %)

Thermal phonons (Heat)

Scintillation (~2 %)

(+ 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?)
\( \gamma, \beta \) discrimination:

- Two simultaneous signals
  - Heat/Phonon
  - Ionisation
  - Scintillation

- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal

- Other “dE/dx” related ideas

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**Detection techniques**

- Heat
  - CDMS
  - EDELWEISS
  - SuperCDMS

- Heat/Phonon
- Ionisation
- Scintillation

- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal

- Other “dE/dx” related ideas

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Metastable
- PICASSO
- SIMPLE
- COUPP

Pulse Shape timing
- DEAP
- CLEAN

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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

See PICASSO-COUPP-PICO talk on Saturday

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$^2$)

Projections with 0.3-0.5 keV threshold

Izraelevitch, TeVPA-IDM2014
See XENON-100 talk on Saturday, and noble liquid review on Monday
Example setup: LUX

- 300 tonnes water tank
  - 3.5 m thickness on the sides
- Cherenkov muon veto
  - 20 PMTs (10" diameter)
- All external backgrounds subdominant
**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: $S1 \sim 5$ P.E. $S2 \sim 800$ P.E. (from $\sim$30 ionization e$^-$)

- **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: $S1 \sim 7$ P.E. $S2 \sim 800$ P.E.
XENON and LUX fiducialization

- XENON-100 2012: 34kg Xe fiducial, 225 day exposure
- Low $\gamma$ background (19 ppt $^{85}$Kr)
- Observe 2 evts, compatible with expected bkg = $1.0\pm0.2$ 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 [PRL 112 091303]: 118kg Xe fiducial, 85 day exposure
  - Observed rate compatible with γ-background estimates
XENON and LUX limits

- LUX first experiment to reach $10^{-45}$ cm$^2$ ($10^{-9}$ 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

- **XENON 1t**: in construction.
  Reduction of radioactive background (cryostat, PM, purification).

  XENON-1t in Gran Sasso

- **LZ**: next generation LUX+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 descr., $\tau = 1.6 \mu s$)

- **DarkSide-50**: 33 kg fiducial Ar, *depleted in $^{39}$Kr* (underground source, depletion $10^{-2}$ to $10^{-3}$)

- **PandaX**: 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

![Graph showing ionization/recoil vs. recoil energy for nuclear recoils and electronic recoils](image)
**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](image-url)
EDELWEISS Interleaved detectors

- Interleaved electrodes with alternate potential, to separate surface and bulk events
EDELWEISS Interleaved detectors

- 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

- Photolithographic patterns of W-TES + Al collector
- Large area: sensitivity to athermal phonons
- Use phonon partition (outer/inner, top/bottom) and ionization partition to fiducialize
Data started in 2012 with 9 kg (6 kg fiducial)

Recent results: 577 kdg WIMP search with low thresholds: record sensitivity despite smaller target mass than Xe expts.
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 $V_{polar}$)
- Current threshold on $E_{\text{electron-equivalent}} \sim 1 \text{ keV}_{ee}$ with $V_{polar} = 3.2V$
- 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.
SCINTILLATION + HEAT
Heat-scintillation: CRESST

- 18x300 g CaWO₄ 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 \( ^{210}\text{Po} \rightarrow \alpha + ^{206}\text{Pb} \)
2-body decays
\( ^{206}\text{Pb} \) 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 CaWO₄
- 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
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.

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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) and broaden mass range sensitivity
- Intense world-wide competition of R&D efforts to *reduce backgrounds* and *increase the mass of the arrays*