Direct Dark Matter Searches

Status and perspectives,
Impact of bolometer detectors

J. Gascon, IPNL / UCB Lyon

gascon@ipnl.in2p3.fr
Plan

- The experimental context of WIMP search

- Direct WIMP searches
  - Predicted scattering rates
  - Experimental signatures
  - Recoil energy detection

- Experiments: status and perspectives
  - Ge ionization
  - Scintillation
  - Bolometers
  - Others

- Detailed conclusion: see this morning session and many others!
Experimental context of WIMP searches
Dark Matter is here to stay

- Dark matter needed at astrophysical and cosmological scales
- Recent CMB measurements (Archeops, WMAP):
  \[ \Omega_{\text{matter}} \sim 0.3 \gg \Omega_{\text{baryon}} \sim 0.04 \]
- Most matter is non-baryonic, weakly interacting and decouples from ordinary matter early in Big Bang: WIMP!

Localy (in this room)\: \rho_{DM} \sim 0.3 \text{ GeV/cm}^3, \bar{v} = 250 \text{ km/s}
The neutralino, a natural WIMP candidate

> In supersymmetry, $\chi$ is naturally massive, neutral and has weak interactions.
> $\chi$ observable at LHC
> $\Omega_\chi$ 0.1 – 0.3 easily achieved in simplest Supersymmetry versions (MSSM)

- Predicts $45 \text{ GeV/c}^2 < M_{WIMP} < \sim 1 \text{ TeV/c}^2$ and $\sim 10^{-10} \sigma_{WIMP-\text{nucleon}} 10^{-6} \text{ pb}$
- Comparison of different experimental searches
  - *indirect*: WIMP annihilation products in cosmic rays
  - *direct*: WIMP scattering on a nucleus in the laboratory
Indirect searches

Search for WIMP annihilation products in cosmic rays: a complete and active program

- Annihilation $\rightarrow$ matter + antimatter:
  - Diffuse $\gamma$ halo around our galaxy?
  - $e^+/e^-$ excess? (HEAT, CAPRICE)
  - antiproton or antideuterium excess (AMS)

- WIMP accumulation at the center of
  - our Galaxy or nearby galaxies/clusters
  - the sun
  - the earth
  - directionnal probes: $\nu$, $\gamma$ and radiation.

- Difficult searches, but detectors already exists, motivated by astrophysics/cosmology studies
Big projects: ν telescopes

ANTARES (2.5 km under Mediterranean Sea)

AMANDA (2 km under Antartica)
Use MSSM framework to compare direct and indirect searches

“benchmark” studies, 

Direct-search detector competitive with large astronomical detectors

\( \sim \) kton SuperKamiokande water Cerenkov (sensitivity \( \sim 1000 \mu \text{y/km}^2 \)) compares with \( \sim \) kg of heat-and-ionization Ge bolometers (hep-ph/0106604)
Direct WIMP Search
Ingredients of Direct Searches

Elastic WIMP-nucleus scattering → measure recoil energy
Target = detector

- 5 ingredients $M_W$, $f(v)$, $\rho_W$, $\sigma_n$ and $\sigma_A/\sigma_n$
  - MSSM (or other theory) predicts WIMP mass ($M_W$) and WIMP-nucleon elastic scattering cross-section ($\sigma_n$)
  - Lewin et Smith’s prescriptions (Astropart. Phys. 6 (1996) 87) for:
    - local WIMP density ($\rho_W$)
    - WIMP velocity distribution ($f(v)$) and nucleon-to-nucleus scaling of cross-section ($\sigma_A/\sigma_n$)
  - Follow same prescriptions for comparison between experiments
- For $A > 30$, coherent scattering dominates ($\sigma_A/\sigma_n \propto \mu^2 A^2$)
- $A < 30$, non-MSSM: spin-dependent case, $\sigma_A/\sigma_n \propto$ nuclear spin.
- Nuclear form factor ($\sim 1/2$ for $A > \sim 100$)
Predicted rates

- Average $E_{Recoil} = 10 - 50$ keV

- Rates between $10^{-4}$ to 1 event/kg/day

- Germanium $\sim$ Iodine $\sim$ Xenon

- Reminder: natural radioactivity $\sim 10^6$ decays/kg/day, 100-1000 keV

- Requires low thresholds and extremely low backgrounds
Experimental Signatures

- Nuclear recoil, not electronic recoil (dominant bkg)
- $E_{recoil}$ spectrum shape (exponential, unfortunately)
- Coherence: $\mu^2 A^2$ dependence
- Directionnality ($\sim -\vec{v}_{SUN}$): R&D project DRIFT (tracks in solid $<< 1 \ \mu$m)
- Annual rate modulation ($\vec{v}_{SOLEIL} - \vec{v}_{TERRE}$): $\pm \sim 7\%$ (requires large WIMP samples)
- Absence of multiple interactions
- Uniform rate throughout volume (against surface radioactivity)
- Direct/indirect searches complementarity
- Compatibility with LHC (eventually)

Combination of signatures is essential
Recoil energy measurement

- Recoils produce ionization, scintillation and heat
- Combination of two signals to discriminate nuclear/electronic recoils
- Quenching effect: in detector calibrated using $\gamma$-ray source (keV electron-equivalent), reduced amplitudes of nuclear recoils signals

$$E_{ee} = Q \times E_{Recoil}$$

Examples:
- $Q \sim 0.3$ for ionization in Ge,
- $Q \sim 0.09$ for scintillation for I recoils in NaI,
- $Q' \sim 1$ for heat
- $(Q/Q') = Q$ in heat-and ionization Ge detectors
Comparison of expected signals

Response for $M_W=52$ GeV, $\sigma_n=7.2 \times 10^{-6}$ pb

**DAMA**
- Iodine, $Q=0.09$
- $0.7$ /kg/j
- $>2$ keV
- Bkg = ~1 /kg/j/keV$_{ee}$
- ~60000 kg·d

**HDM, IGEX**
- Ge, $Q=0.2-0.3$
- $1.3$ /kg/j
- $>4$ keV
- Bkg = ~0.2 /kg/d/keV$_{ee}$
- ~100 kg·d

**CDMS EDELWEISS**
- $2.0$ /kg/d
- $>10$ keV
- $1.1$ /kg/d
- $>20$ keV
- Bkg = 0-0.03 /kg/d/keV$_{ee}$
- ~10 kg·d
Strategy No 1: Big and Simple

- Ge ionization detectors (stemming from $0\nu 2\beta$ searches)
  - Low-radioactivity efforts: IGEX, Heidelberg-Moscou: $\sim 1$ evt/kg/d sensitivity
  - No electronic vs nuclear recoils discrimination.
  - Evolution: better environment radiopurity, $N_2$ shielding (GENIUS) self-shielding via segmentation (MAJORANA)

- Large scintillating detector mass
  - NaI: DAMA, ELEGANT, NAIAD, ANAIS,
  - Liquid Xe: ZEPLIN, Projects XENON, XMASS (100 kg in construction, aiming at $0\nu 2\beta$)

- Statistical rejection with pulse shape discrimination inexistant in Ge, inefficient at low energy in NaI

- DAMA (NaI): statistical discrimination using annual modulation $\rightarrow$ signal WIMP?

- ZEPLIN: PSD efficient down to a few photoelectrons?
- 100 kg NaI, 5 years
- 58,000 kilogram-days

Observed annual modulation for 2-6 keV\textsubscript{ee} (essentially 2-3 keV\textsubscript{ee})

Interpreted as
M\textsubscript{WIMP} = 52 GeV,
\(\sigma_n = 7.2 \times 10^{-6} \text{ pb}\)
(\(\sim 1 \text{ evt/kg/d}\))

Now incompatible with EDELWEISS, CDMS and ZEPLIN prel.
Preliminary ZEPLIN-I results: efficient PSD down to lowest energy
6 kg Xe, 230 kg.d, 1.5 p.e./keV

Now moving to two-phase with scintillation vs ionization event-by-event discrimination
Strategy No 2: Discrimination first

- First achieve event-by-event rejection of electron recoils
- ... then scale up detector mass and number (feasible: e.g. CUORICINO).

  - Heat-and-ionization CDMS, EDELWEISS
  - Heat-and-scintillation CRESST (300 g CaWO$_4$) and ROSEBUD (BGO)
  - Two phase Xe liquide: project ZEPLIN-II

- Bolometers achieving best published sensitivities, despite much smaller masses and exposures.
  - Edelweiss, CDMS (0.3-0.2 kg with $\sim$ 10 kg·j)
  - DAMA, IGEX+HDM, ZEPLIN-I (prelim.) (6-100 kg with 100–50000 kg·j)

→ discrimination pays!
Heat-and-scintillation detectors

- One target material can’t test signatures
  - in $A^2$ dependence
  - in spin-dependence

Heat-Scintillation
larger choice of targets
CRESST CaWO$_4$ (300 g)
ROSEBUD BGO

![Diagram](Diagram.png)
Simultaneous heat and ionization measurement
→ More direct measurement of $E_{\text{recoil}}$
Phonon trigger: High efficiency even for “quenched” events

However, low $\theta T$ and weak $\vec{E}$ field... good charge collection?
\( \gamma \) calibration:
\[ Q_{\gamma} = \text{Ion.}/\text{Recoil} = 1 \]

\(^{252}\text{Cf} \) neutron calib.
\[ Q_{\text{nucl}} = 0.16 \left( E_R \right)^{0.18} \]

\( \text{Résolutions (ion. + heat)} \rightarrow \text{width of } \gamma \text{ and } n \text{ bands} \)

Separation \( n/\gamma \)
\[ > 99.9\% \]
for \( E_R > \sim 15 \text{ keV} \)

Green: ionization thresh.

Magenta: \(^{73}\text{Ge}(n,n'\gamma)\)
Similar kg.d exposure, CDMS better resolution and threshold.

- Edelweiss deep underground (Fréjus LSM), CDMS shallow site.

- Gains to come: Edelweiss-I (statistics, resolution), Edelweiss-II with >21 detectors and improved shielding and muon veto (2004) CDMS at SOUDAN Mine, CRYOARRAY (1 ton) studies.
**Spin-independent limits**

Incompatibility with DAMA resists to halo model variations (Copi et Krauss, astro-ph/0208010).
Evolution of Direct Searches

Scalar Cross-section (pb) [60 GeV WIMP]

Year


Based on Gaitskell, astro-ph/0106200

~1 event kg$^{-1}$ day$^{-1}$

~1 event kg$^{-1}$ yr$^{-1}$

~1 event 100 kg$^{-1}$ yr$^{-1}$

Homestake

Oroville

UKDMC

HDM, IGEX

EDELWEISS

DAMA

CDMS SUF

GENINO 100 kg Ge

Majorana–1

NOW

ZEPLIN–I

CDMS Soudan

EDELWEISS II

ZEPLIN–II

GENIUS 1t Ge

LHC

XENON, ZEPLIN 1t

CryoArray ~1t

Based on Gaitskell, astro-ph/0106200

Ge Diode

Nal

Ge Cryogenic

Liquid Xe

Signal

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Other Discrimination Strategies

- Other R&D for detectors only sensitive to nuclear recoils

- Superconducting detector (see this morning)

- Superheated droplets detectors (SIMPLE, PICASSO)
  low-\(A\), high-spin target (\(^{19}\)F)
  PICASSO: New excavation in Sudbury - SNOLab.

- Superfluid He\(^3\) project (MACHe3)
  low-\(A\), high-spin target (\(^{3}\)He)
Conclusions

- WIMP direct searches are stimulating an intense detector R&D program aiming at the lowest possible background down to very low energy

- Bolometer-based techniques (heat-and-ionization) provide present best published results, with further improvements incoming

- Essential complementarity of signatures: more room left for other developments and new ideas

- From now to LHC, develop tools capable of observing dark matter particles