A review on the discovery reach of directional detection

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Outline

1. Review of the discovery reach of directional detection
   - Exclusion
   - Discovery
   - Identification

2. Interplay with latest LHC results
   - Heavy squarks
   - monophoton/monojet
Directional detection: expected signal

Constellation Cygnus (l = 90°; b = 0°)

**WIMP flux** in galactic coordinates
for a standard halo (isothermal and isotropic)

**WIMP signal** (recoil map)
Angular distribution of Fluorine recoils [5;50] keV

**Elastic scattering**
100 GeV/c² WIMP

**Background**

**Unambiguous difference** between WIMP and background

- low number of WIMPs (low exposure)
- large residual background
- poor angular resolution
1. Review of the discovery reach of directional detection

- **Exclusion**
- **Discovery**
- **Identification**

Can we exclude a Dark Matter signal?

- J. Billard *et al.*, PRD 2010
- S. Henderson *et al.*, PRD 2008

0 WIMP + 300 Bckg
Exclusion

**Goal**: try to be competitive with ongoing/planned direct experiments devoted to Spin-dependent interaction (on proton)

**Best limit on SD interaction (proton)**

- Your preferred SUSY model
- Your preferred detector

Result depends on exposure, residual background level, threshold, …
Isotropy rejection

The exposure required to reject isotropy (and hence detect a WIMP signal) at 95% CL in 95% of exp.

Study done for a CS$_2$ target

With $\sim 10^4$ kg.days (CS$_2$) reach $\sim 10^{-7}$ pb (SI)
1. Review of the discovery reach of directional detection

| Exclusion | Discovery | Identification |

Can we claim a Dark Matter discovery?

A.M. Green & B. Morgan, PRD 2010

100 WIMPs + 100 Bckg
Directional detection may be used to discover Dark Matter

Blind likelihood analysis

Proof of discovery: signal from Cygnus

Exclusion strategy

Discovery strategy

Estimation of the statistical significance…

F. Mayet - Cygnus 2013, Toyama, Japan
Discovery

Estimation of the discovery potential considering astrophysical uncertainties => Profile likelihood method

Detector characteristics
- 10 kg CF$_4$
- DAQ: 3 years
- Recoil energy range [5, 50] keV

Discovery at 3σ

- With BKG (300)
- Without BKG

→ Even with a large number of background events, discovery is still possible

→ Only low number of WIMP events are required at low masses

→ A discovery (>3σ@90%CL) with BKG is possible down to $10^{-3}$-$10^{-4}$ pb
Discovery

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=> *Profile likelihood method*

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Directional reach in SUSY space

- (N)MSSM with 11(12) parameters defined at the weak scale
- Cosmology and Colliders constraints included (before Higgs discovery)

→ low $\mu$ and $M_1$ models would not escape a discovery with a large directional detector (30 kg.year).
N-body simulations favor a co-rotating Dark Disk (10%-50% of local DM density)

\[ \Rightarrow \text{for a null velocity, Dark Disk Wimps have an isotropic velocity distribution} \]

\[ \Rightarrow \text{only extreme Dark Disk parameters may affect the directional signal} \]

\[ \Rightarrow \text{not a threat for directional detection} \]
1. Review of the discovery reach of directional detection

   Exclusion

   Discovery

   Identification

Can we infer Dark Matter properties from directional detection?

J. Billard et al., PRD 2011
Dark Matter identification

Directional detection may be used to identify Dark Matter

i.e. measure WIMP and halo properties

A Markov Chain Monte Carlo analysis dedicated to directional detection (10^{-3} pb)

- Multivariate gaussian (triaxial halo)
- Simulated data: CF4 detector (30 kg.year) + 35% background

- Eight free parameters constrain with the same set of directional data
  - The WIMP mass m_X
  - The WIMP-nucleon cross section \( \sigma_n \)
  - The main direction of the signal (l_o, b_o)
  - The three velocity dispersions \( \sigma_x, \sigma_y, \sigma_z \)
  - The background rate R_b

WIMP properties

Halo properties
Dark Matter identification

**Mass**

**Cross section**

**Input parameters**

- Isotropic halo: \( \sigma_x = \sigma_y = \sigma_z = 155 \) km/s
- WIMP mass: 50 GeV/c^2
- Cross section: \( 10^{-3} \) pb
- Background rate (R_b): 10 evts/Kg/an (35%)

The eight fitting parameters are simultaneously and consistently constrained according to the input values.
The eight parameters are strongly constrained with only one directional data set.
Going further: Dark Matter 3D

Post-discovery era: the WIMP mass and cross section are supposed to be known. Hence, after LHC discovery and/or other DM exp.

• A generic parametrization of DM distribution
• 3 integrals of motion decomposed on the basis of special functions

\[ f_1(\mathcal{E}) = \sum_k c_{\mathcal{E}} P_k \left( \frac{\mathcal{E}}{E_{\text{lim}}} \right), \]
\[ f_2(L_t) = \sum_{n} c_{L_t}^n \cos \left( n\pi \frac{L_t}{L_{\text{max}}} \right), \]
\[ f_3(L_z) = \sum_{m} c_{L_z}^m \cos \left( m\pi \frac{L_z}{L_{\text{max}}} \right). \]

~1000 events are required for a good measurement of the underlying DM distribution.
2. Interplay with latest LHC results

Heavy squarks
monophoton/monojet

Is Xenon100 a threat to directional detection?
A priori: no! SD-neutron versus SD-proton, but...

D. Albornoz-Vasquez et al., PRD 2012

Is LHC a threat to directional detection?

G. Bélanger et al., in preparation
SD interaction

\[
\sigma^{SD}(AX) = \frac{32}{\pi} G_F^2 \times \mu_A^2 \times \frac{J + 1}{J} \left( a_p < S_p > + a_n < S_n > \right)^2
\]

Proton SD interaction ($a_n=0$)

CF4 detectors

Neutron SD interaction ($a_p=0$)

Xenon100, CDMS, Edelweis, ..

First caveat: model independent treatment requires to consider both cross-sections

D. R. Tovey et al., PLB 2010
Recent results from LHC

- LHC => Heavy squarks (>TeV)
- Squark exchange diagram: suppressed
- SD cross section:
  - does not depend on quark flavor
  - only on the Z-neutralino coupling

SD cross section should be close (and should not depend on SUSY parameters)
Consequences for Dark Matter

MSSM + collider & cosmology constraints

- SD cross-section on p and n can no longer be considered as independent
- All SD results apply to directional detection
  - e.g. large exposure experiments (Xenon, SuperCDMS, ...)

D. Albornoz-Vasquez et al., PRD 2012

\( \frac{\sigma_p}{\sigma_n} = 1.3 \)
SD interaction on Nucleon

We need to consider SD-nucleon cross section

- All SI experiments have a not so small odd-nuclei fraction ($^{129,131}$Xe, $^{73}$Ge, $^{29}$Si)
  - 3% in Si, 7% in Ge, 50% in Xe
- Upcoming SI results may close the directional window
Other searches: monophoton/monojet @LHC

DM pair production

\[ q \rightarrow \chi \rightarrow q \]

**s-channel**

Elastic scattering

\[ \chi \rightarrow q \rightarrow \chi \]

**t-channel**

**golden channel ... no signal**

make it visible...

→ consider ISR

→ one photon/jet and missing energy

F. Mayet - Cygnus 2013, Toyama, Japan
ATLAS \( \sqrt{s}=7 \text{ TeV}, \int L \, dt = 4.6 \text{ fb}^{-1} \)

- **Effective theory**

4-fermion interaction *a la Fermi*

Point like interaction = heavy propagator

**Question:**

Is it really model independent?
Conclusion

1) A large directional detector (30 kg.year) could lead either to a:
   - constraint on DM properties (halo and particle), $\sim 10^{-3}$ pb
   - conclusive discovery (with a high significance), $10^{-4}$-$10^{-5}$ pb
   - competitive exclusion, $10^{-5}$-$10^{-6}$ pb

   cannot be achieved by non-directional detectors

2) Most other Dark Matter searches seem to be relevant to the SD-neutron space
   - Large exposure SI detectors
   - LHC
   - Neutrino telescope