CYGNUS 2011

3rd Workshop on
Directional Detection of Dark Matter

Welcome

A short introduction to Directional detection of Dark Matter

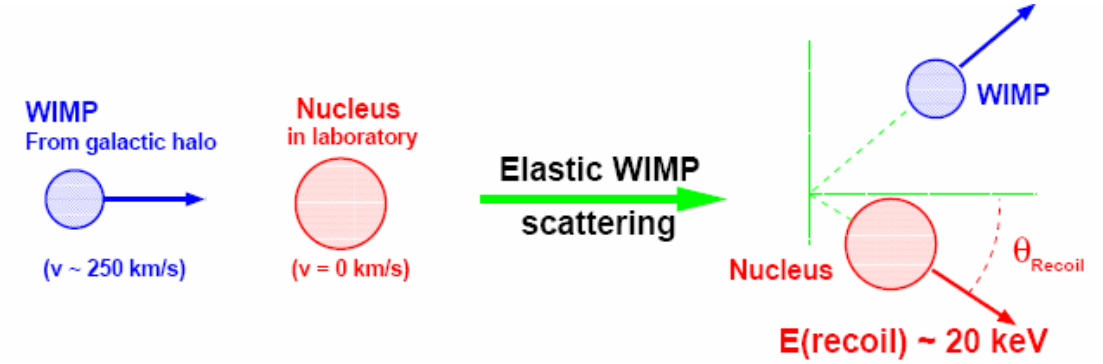
F. Mayet

with J. Billard and D. Santos

LPSC Grenoble

Université Joseph Fourier Grenoble

Directional DM detection



Direct → Directional

$$\frac{dR}{dE_R} \rightarrow \frac{d^2R}{dE_R d\Omega_R}$$

Directional detection requires to measure both

the recoil energy and the 3D track

Directional DM detection

D. N. Spergel, Phys. Rev. D **37** (1988) 1353

Motion of the Earth and the detection of weakly interacting massive particles

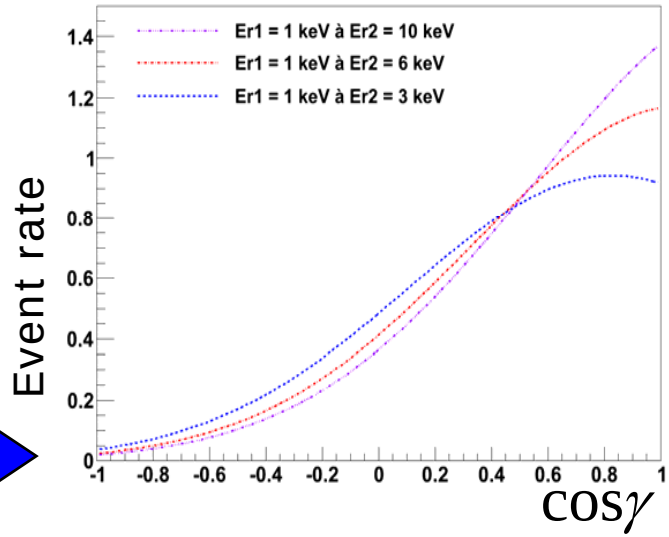
David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

a very strong angular dependence. The number of events in the forward direction will significantly exceed the number of events in the backward direction for any energy threshold E_{th}. This strong effect suggests that even weak angular resolution would be a powerful tool that could discriminate between the dark-matter signal and the background.

Early idea :

forward/backward asymmetry



Directional DM detection

From the pioneer work of David Spergel :

1. ”Powerful tool” :

   How to fully exploit these upcoming data ?

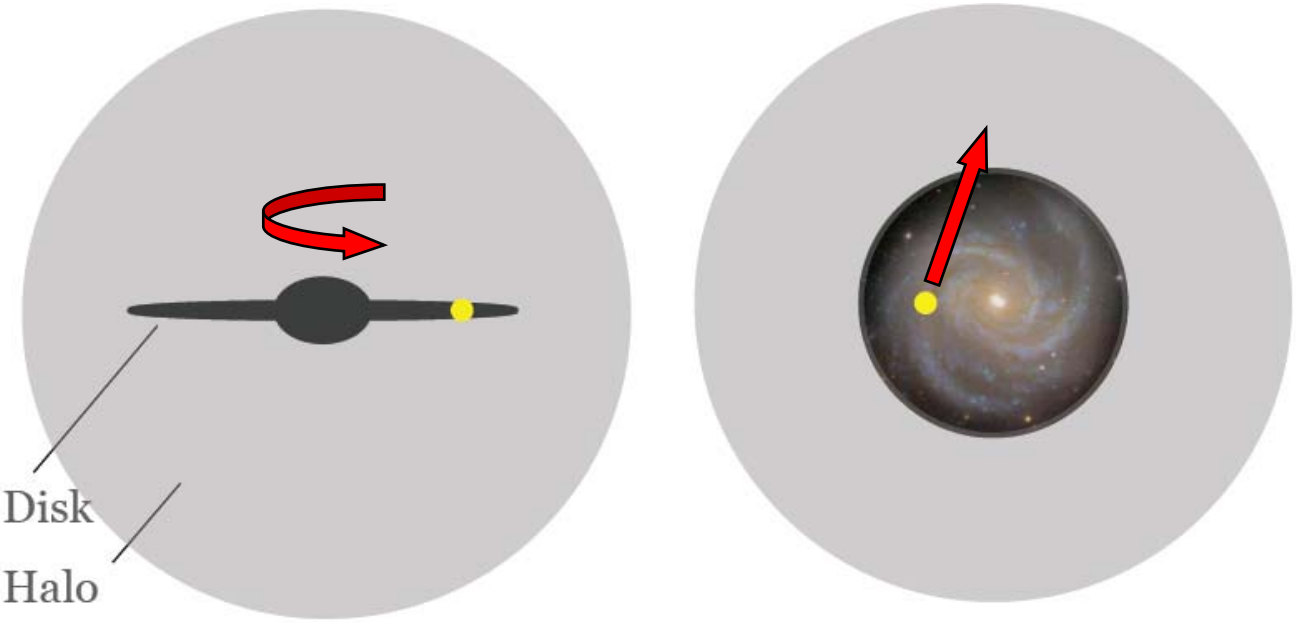
   Can directional detection bring something new ?

2. ”even a low angular resolution detector”

   What kind of detector is needed ?

   Which instrumental achievements are needed ?

A powerful tool ? : principle

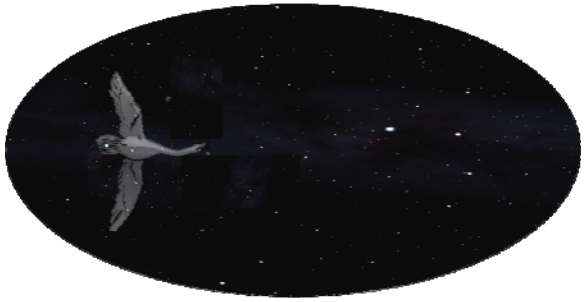


The Sun velocity vector ($\vec{v}_\odot$) is pointing towards ($\ell_\odot = 90°, b_\odot = 0°$) which happens to be roughly in the direction of the Cygnus constellation.

« A wind of WIMPs from Cygnus »

WIMP events = from Cygnus

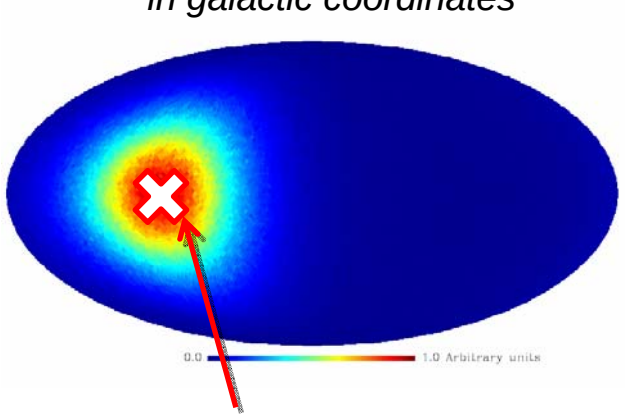
Background events = isotropic



Directional detection : expected signal

For a standard halo (isothermal and isotropic)

WIMP flux in a earth-based detector in galactic coordinates

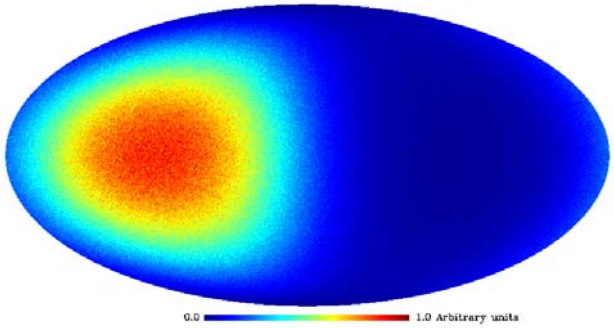


Cygnus Constellation (l = 90°,b = 0°)

After scattering

100 GeV/c² WIMP

Angular distribution of Fluorine recoils
Energy range : [5;50] keV



Expected WIMP-induced signal (recoil-map)

The recoil-map is still pointing toward Cygnus

also slightly broadenned

This will be the main result of directional detection.

Directional detection

”a Powerful tool ? ”

- How to get the most of upcoming directional data ?
- Can directional detection bring something new ?

Directional detection : which target ?

Need to measure low energy recoils

→ light target to maximize track length

→ low pressure → small mass

→ focus on SD interaction

to be competitive with ongoing experiments aiming at ton scale (or more)

- Ideal target : light with non-vanishing spin

→ candidates = H, ^{3}He, ^{19}F

→ most projects have chosen CF_4

- CS_2 is also an option

+ drift ion → suppress diffusion

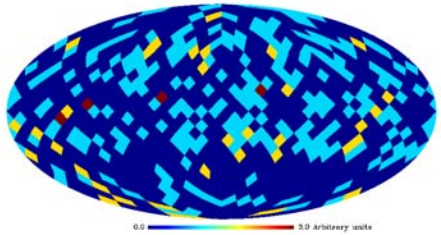
- SI interaction → must be competitive with ton-scale detectors

in the following : i will take the example of 30 kg.year CF_4 detector

Directional Detection : exclusion

First idea :

Directional detection may be used for exclusion



- **The Maximum Patch Method**

  S. Henderson, J. Monroe and P. Fisher, PRD 2008

A 2D generalization of the Maximum Gap method (S. Yellin PRD 2002) considering both directional and energy information

- **Directional Likelihood exclusion method**

  J. Billard, F. Mayet and D. Santos, PRD 2010

→*Considers the theoretical distributions of both WIMP and background events to set the most restrictive limits.*

→ *Conservative method :*

By using **only the angular part of the event distribution**

to avoid *assumptions on the unknown energy spectrum of background*

In both cases : set an upper limit

Directional Detection : exclusion

Best limit in SD interaction (proton) : COUPP 2010

SUSY region

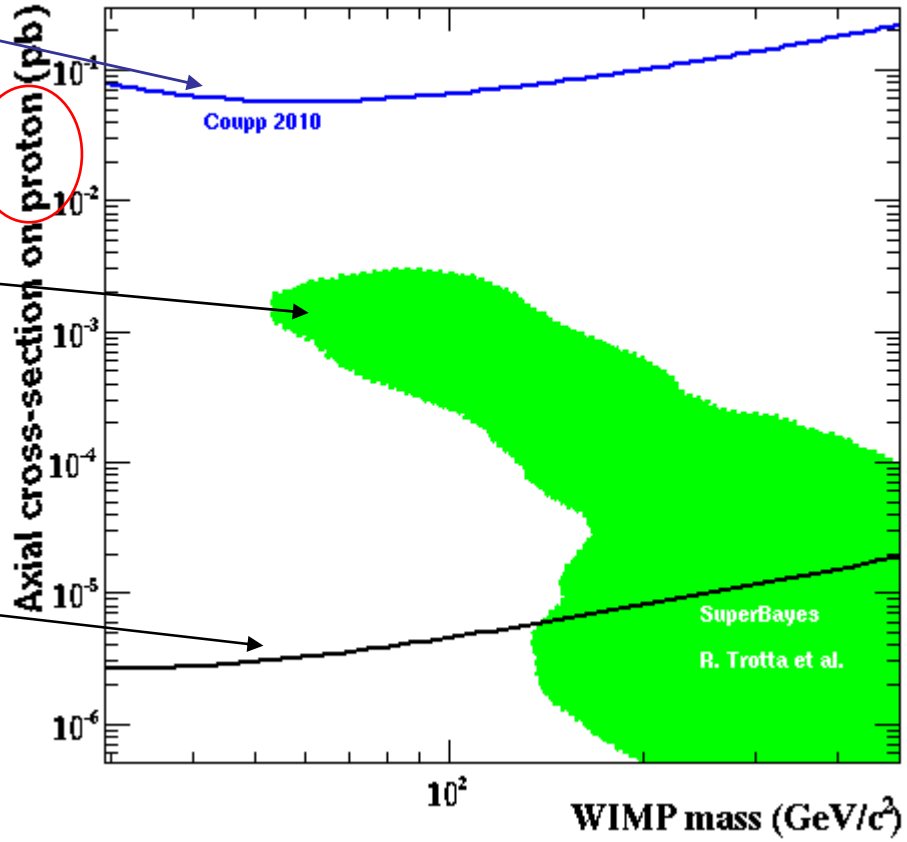
(from R. Trotta et al.)

Compatible with Cosmology & colliders

Your preferred detector

Result depends on

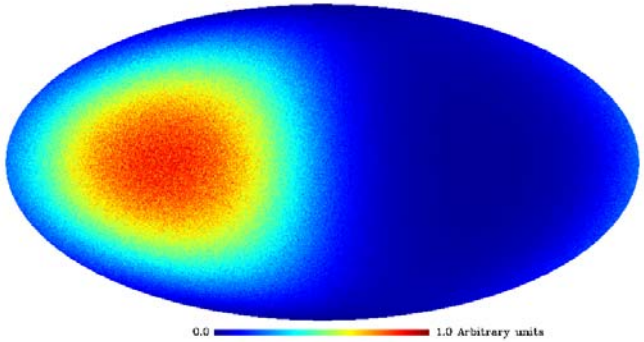
exposure,
residual background level,
threshold, …



Goal : try to be competitive with ongoing/planned direct experiments devoted to Spin-dependent interaction

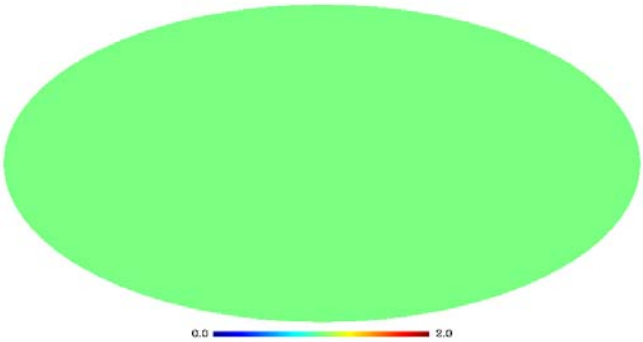
Directional detection : going further

WIMP signal



Vs

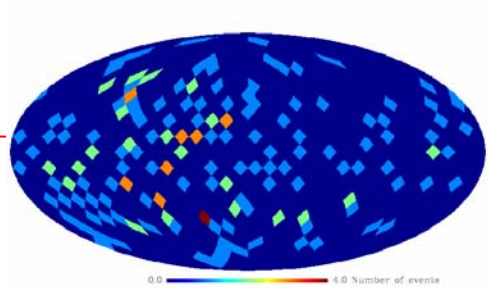
Background



Clear and unambiguous difference between WIMP signal and background

Directional detection : going further

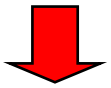
Second idea : ***prove the directional data are not compatible with background***



Several works on the subject : *(by publishing year)*

- C. J. Copi & L. M. Krauss, PLB 1999
- C. J. Copi & L. M. Krauss, PRD 2001
- B. Morgan & A. M. Green, PRD 2005
- C. J. Copi *et al.,* PRD 2007
- B. Morgan, A. M. Green and N. J. C. Spooner, PRD 2005
- A. M. Green & B. Morgan, Astropart. Phys. 2007
- O. Host & S. H. Hansen, JCAP 2007
- J. D. Vergados & A. Faessler, PRD 2007
- M. S. Alenazi & P. Gondolo, PRD 2008
- A. M. Green & B. Morgan, PRD 2008

Using these unbinned likelihood methods
or non-parametric statistical tests on unbinned data,

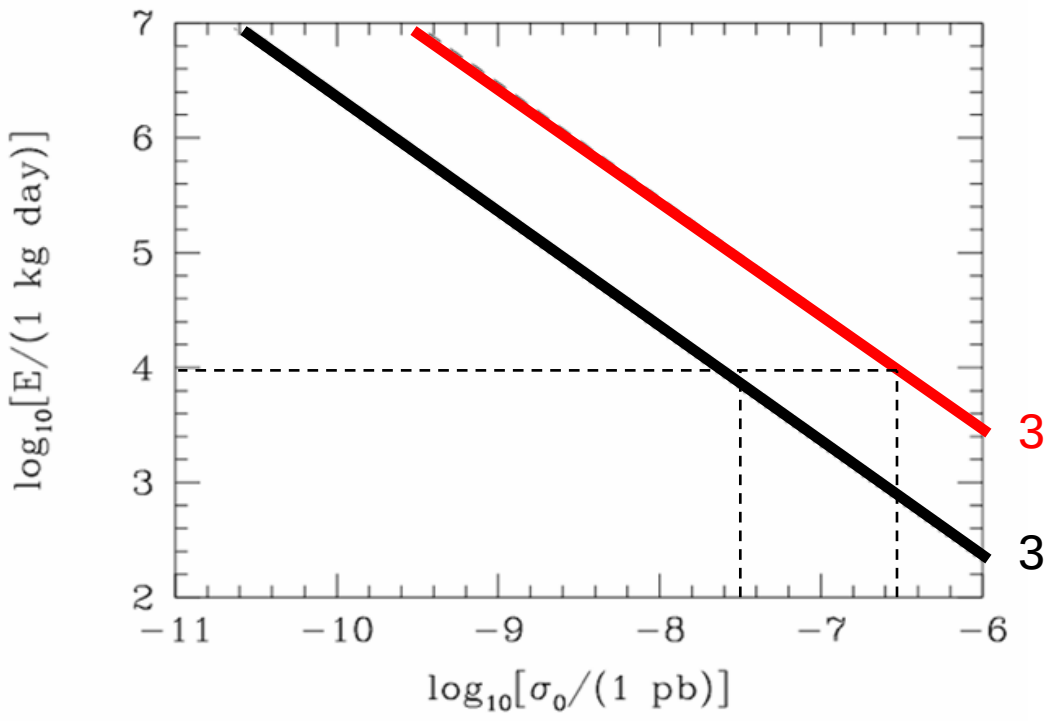


a few number of events O(10) is required to **reject the isotropy**

Directional detection : reject isotropy

A. M. Green and B. Morgan, Astropart. Phys 2007

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



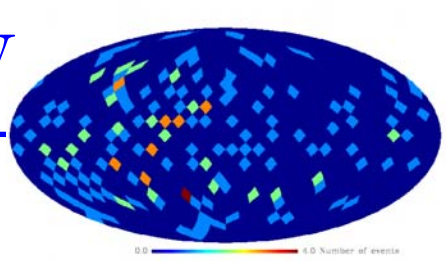
Study done for a CS_2 target

3D without sense recognition

3D with sense recognition

With ~10^4 kg.days (CS_2) reach ~10^{-7} pb (scalar)

Directional Detection : discovery



Third idea :

Directional detection may be used to discover Dark Matter

- **The median recoil direction as a WIMP directional detection signal**

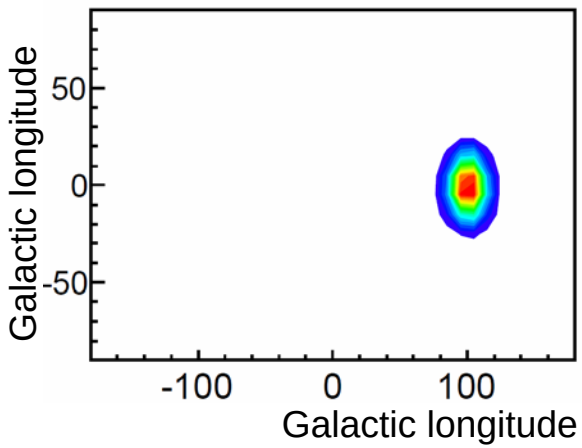
A. M. Green & B. Morgan, PRD 2010

Statistical test : model-independent but not blind. Search for a signal from Cygnus in the data.

- **Directional detection as a strategy to discover galactic Dark Matter.**

J. Billard et al., PLB 2010

→ **Blind Likelihood analysis**



- Proof of discovery : signal from Cygnus
- High significance even @ low exposure

From an Exclusion strategy
To a Discovery strategy

emphasizing differences with direct detection

Directional Detection : identification

Fourth idea :

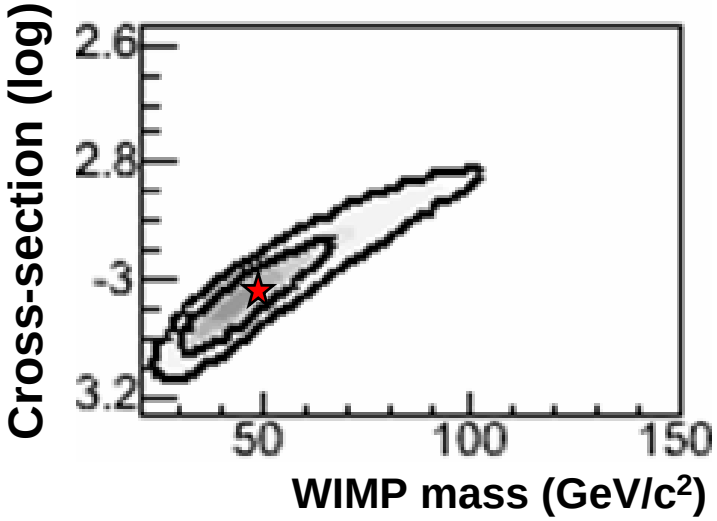
Directional detection may be used to identify Dark Matter

i.e. measure mass, cross –section and halo properties

by using the strong dependence of the WIMP signal with : the WIMP mass and the local velocity distribution.

- **Markov Chain Monte Carlo analysis to constrain Dark Matter properties with directional detection.**

J. Billard, F. Mayet and D. Santos, PRD 2011



	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb)
Input	50	-3
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$

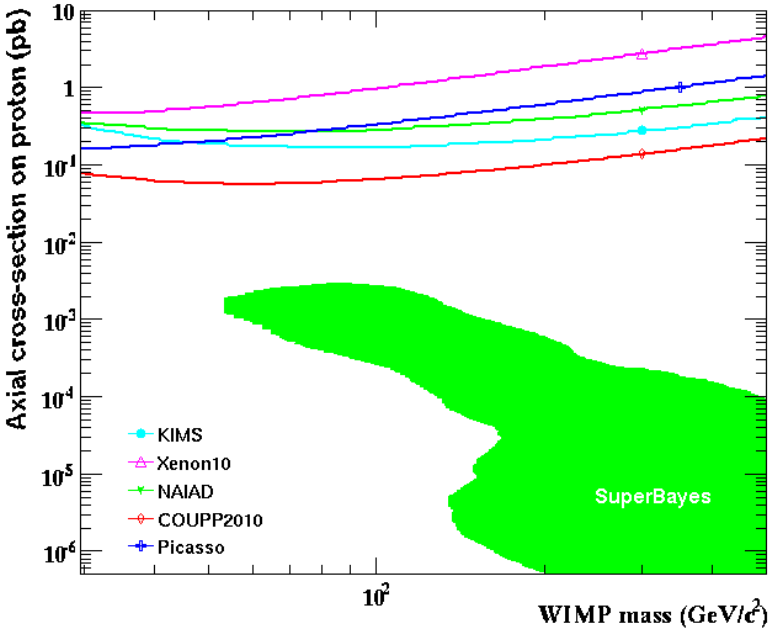
- This could be the outcome of a 30 kg.year CF4 directional detector
- This cannot be achieved with non-directional detectors

Directional Detection : SD interaction

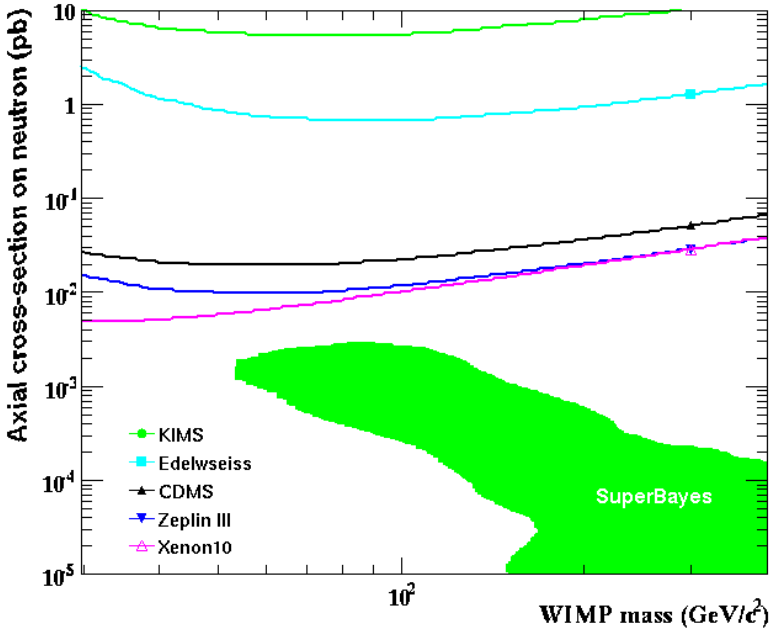
SD cross-section on nucleus : $\sigma^{SD}(^{A}\mathrm{X}) = \frac{32}{\pi} G_F^2 \times \mu_A^2 \times \frac{J+1}{J}\left(a_p < S_p > + a_n < S_n >\right)^2$

- **Xenon100** : ^{129}Xe, ^{131}Xe : **neutron-SD**
- **Directional detection** : CF_4 : **proton-SD**

Proton SD interaction



Neutron SD interaction



looks safe on proton-SD side …

SD interaction

D. R. Tovey *et al.*, PLB 2000
E. Moulin *et al.*, PLB 2005

However, results on SD interaction should be treated « à la Tovey », *i.e.* model-independent formalism

$$\left(\langle S_p\rangle\sqrt{\sigma_p} \pm \langle S_n\rangle\sqrt{\sigma_n}\right)^2 < \frac{3}{4} \times \frac{\mu_p^2}{\mu_A^2} \times \frac{J}{J+1} \times \sigma_A^{lim}(m_\chi)$$

→ constructive and destructive cases

→ results of a SD-neutron detector

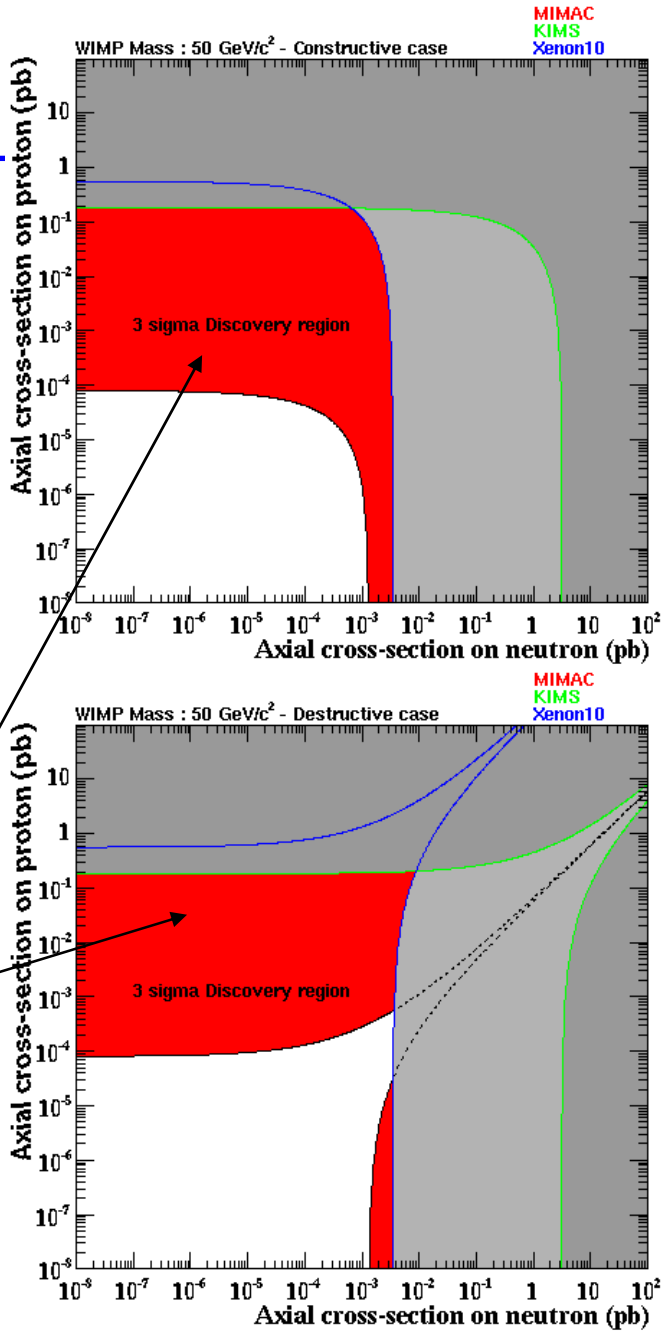
does contrain SD-proton interaction

Discovery region expected

for a 30 kg.year CF_4 directional detector

already partly excluded by Xenon10…

waiting for Xenon100 result on SD…



CYGNUS 2011

During the workshop, we will have several talks related to this topic :

(Thursday morning)

- Exclusion, Discovery and Identification of Dark Matter with Directional Detection
Julien BILLARD (LPSC Grenoble)

- AMIDAS for Direct Dark Matter Detection Experiments
Chung-Lin SHAN (National Cheng Kung University)

- MIMAC potential discovery and exclusion of Supersymmetric neutralinos
Daniel ALBORNOZ VASQUEZ (LAPTH)

- Principal properties of the velocity distribution of dark matter particles on the outskirts of the Solar System
Anton BAUSHEV (DESY Zeuthen)

Directional detector

”even a low angular resolution detector”

→ *Not so easy !*

- Experimental issues
- State of the art
- …

Pioneer works on directional detection

• **Dark matter detection with hydrogen proportional counters**
G. Gerbier, J. Rich, M. Spiro and C. Tao,
Nuclear Physics B – Proc. Sup. 1990

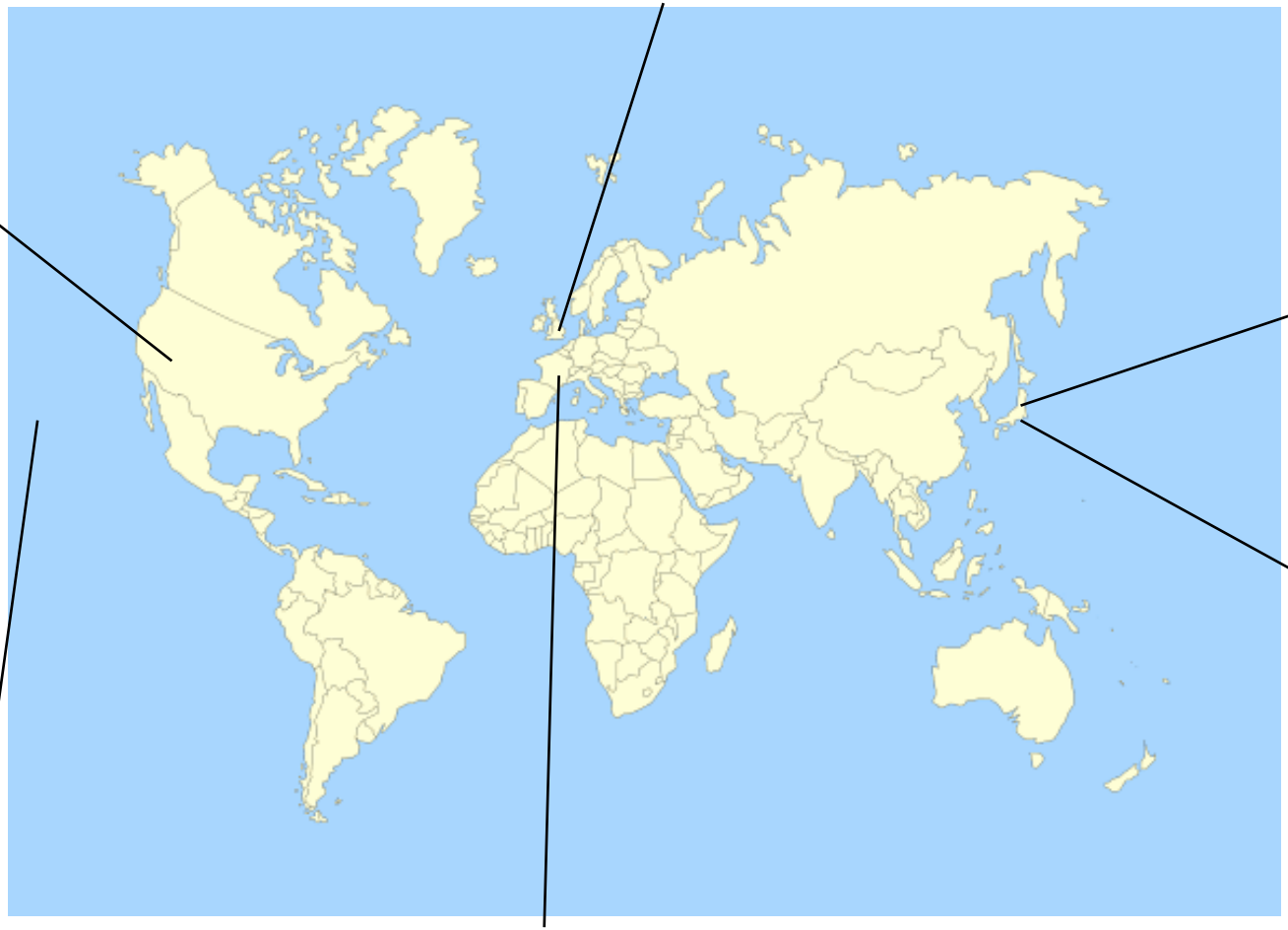
• **Low pressure gaseous detector for particle dark matter**
K. N. Buckland et al.,
Phys. Rev. Letter 1994

• **Pioneering work by the DRIFT Collaboration @ Boulby mine**
Negative ion drift (CS2) to suppress diffusion

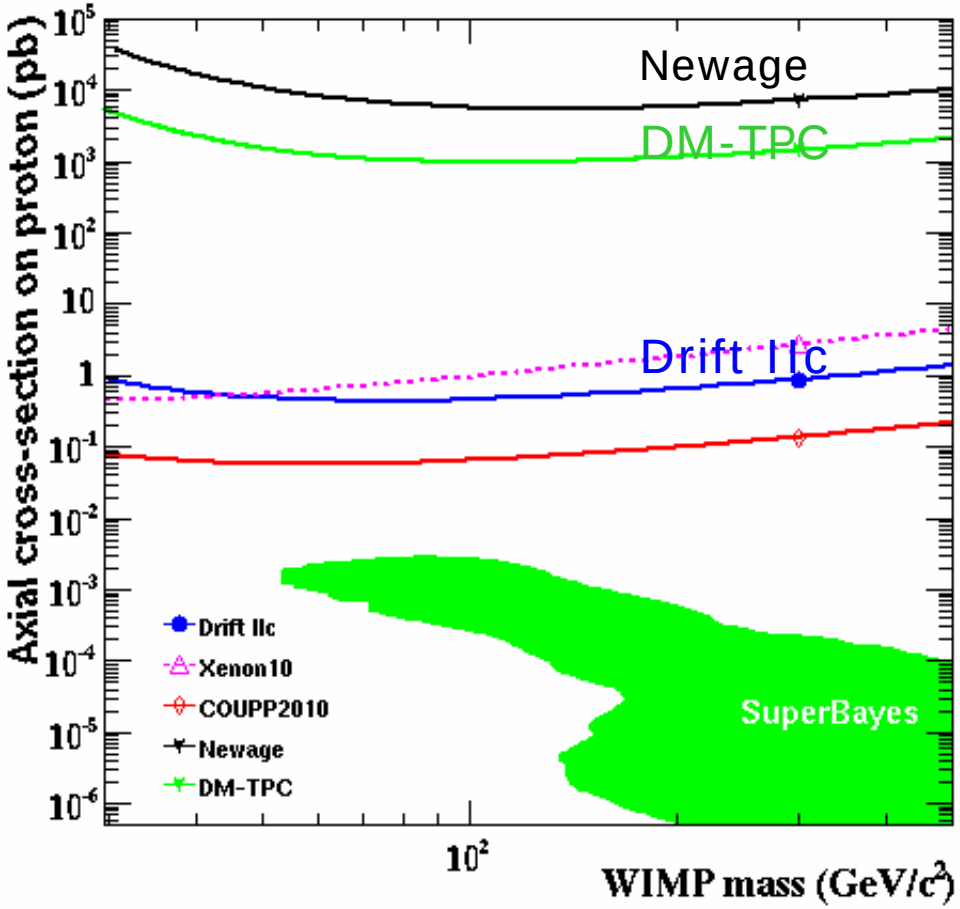
→ Recently add Fluorine target (SD interaction)
→ see talk by Neil Spooner

since then directional detection has grown …

Directional detection : a worldwide effort



State of the art : early directional results



S. Ahlen *et al.*, PLB 2011
K. Miuchi *et al.*, PLB 2010
E. Daw *et al.*, arxiv:1010.3027

Up to now, all current directional results suffers from low exposure and/or large background events

CYGNUS 2011

All today talks are devoted to the status report

of current directional projects (and non-directional ones) :

- Progress with DRIFT II and DRIFT III
Neil SPOONER (University of Sheffield)

- Status of the DMTPC Experiment
Jocelyn MONROE (MIT)

- Status of the MIMAC project for directional detection of Dark Matter
Daniel SANTOS (LPSC Grenoble)

- NEWAGE
Kentaro MIUCHI (Kyoto University)

- The Directional Dark Matter Detector (D^3)
Sven VAHSEN (University of Hawaii)

- R&D Status of Nuclear Emulsion for Directional Dark Matter Search
Tatsuhiro NAKA (Nagoya University)

- Review on non-directional detection
Benjamin CENSIER (IPN Lyon)

Directional Detector : experimental issues

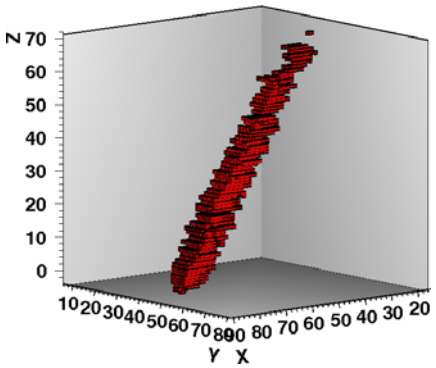
Basic idea : retrieve from data the **energy** and **3D track** of the recoiling nucleus

i.e. measure tracks of a few mm and a few keV

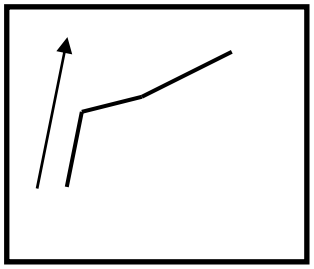
- **Energy** : three issues
  - → Calibration (at low energy)
  - → Quenching (must be known to convert ionisation energy to recoil energy)
  - → Low energy threshold
    *Nota Bene : it means measuring **both** energy and track…*
    Of course : the lower the better

- **3D Track** : several issues
  - → **Initial direction (angular resolution)**
  - → Full Track (e/recoil discrimination)

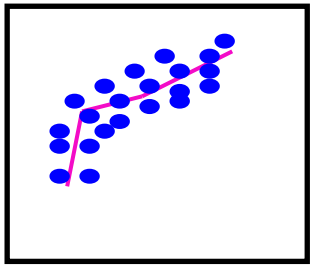
  Difficulties : straggling, electron drift, …



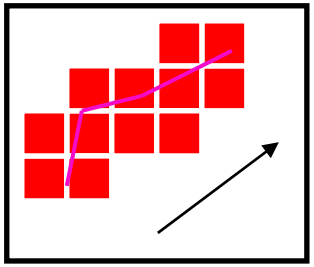
Directional Detector : 3D track



Recoil nucleus



Electron drift



as seen in a directional detector

Observables :

- Initial direction
- Full Track (e/recoil discrimination)

Inputs :

- electron drift properties

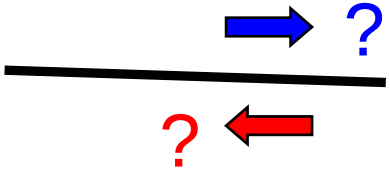
(velocity & dispersions)

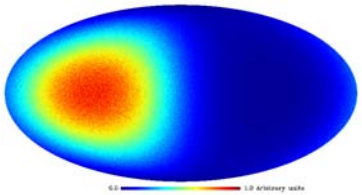
Requirements:

- track reconstruction analysis
- dedicated electronics
- high-performance readout (GEM, Micromegas,…)

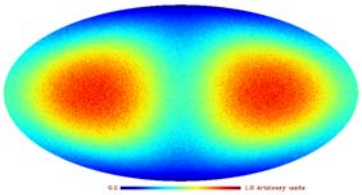
Directional Detector : other experimental issues

- Sense recognition (SR)





With Sense Recognition



Without Sense Recognition

Main question :

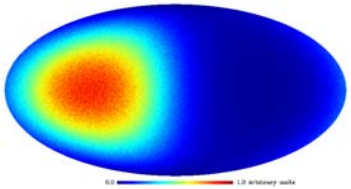
not : **yes or no**

but : **How much SR**

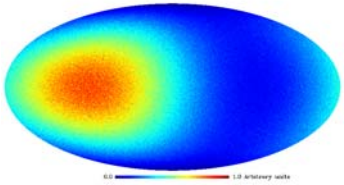
→Need to be measured

$$SR = f(E,z,\ldots)$$

- Angular resolution



$\sigma_\Theta = 15°$



$\sigma_\Theta = 45°$

Must be measured

$$\sigma = f(E,z,\ldots)$$

→ Need for detector commissioning, using e.g. an ion/neutron beam

→ Once known, maybe included in Likelihood data analysis

CYGNUS 2011

Thursday & Friday

- DMTPC R&D
James BATTAT (MIT)

- Simulation of the Directional Dark Matter Detector (D3)
Igal JAEGLE (University of Hawaii)

- Quenching factor measurement for Dark Matter Search.
Olivier GUILLAUDIN (LPSC Grenoble)

- Dedicated front-end and readout electronics developments for real time 3D
Olivier BOURRION (LPSC Grenoble)

- Track reconstruction: expected performance for the MIMAC detector
Julien BILLARD (LPSC Grenoble)

- Status of R&D on microbulk Micromegas for low background applications
Igor IRASTORZA (Universidad de Zaragoza)

- Low X-ray background measurements at the Underground Canfranc Lab.
Javier GALAN (University of Zaragoza)

- Micromegas detector developments for MIMAC
Esther FERRER RIBAS (IRFU/CEA)

Directional Detector : other applications

Low pressure gazeous Directional detectors

allow for an accurate measurement of nuclear recoils

→ might lead to other applications with the same technology :
neutron detection system (Energy and flux)

• Production and measurement of neutron reference fields: the AMANDE facility
Lena LEBRETON (IRSN)

• Directional Neutron Observer (DiNO)
Igal JAEGLE (University of Hawaii)

CYGNUS 2011

Friday afternoon

• The Modane underground laboratory

Pia LOAIZA (LSM)

Friday afternoon is devoted to

a guided-tour of the Modane underground laboratory

• Departure : 1pm15

• Return to Aussois : 4pm30

CYGNUS 2011 acknowledges financial support from :

- **IN2P3**
- **Physical instruments**

Physical Instruments