Exclusion, Discovery and Identification of Dark Matter with directional detection

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Outline

1. Characteristics of directional detection data

2. Case of a null detection: Exclusion limits

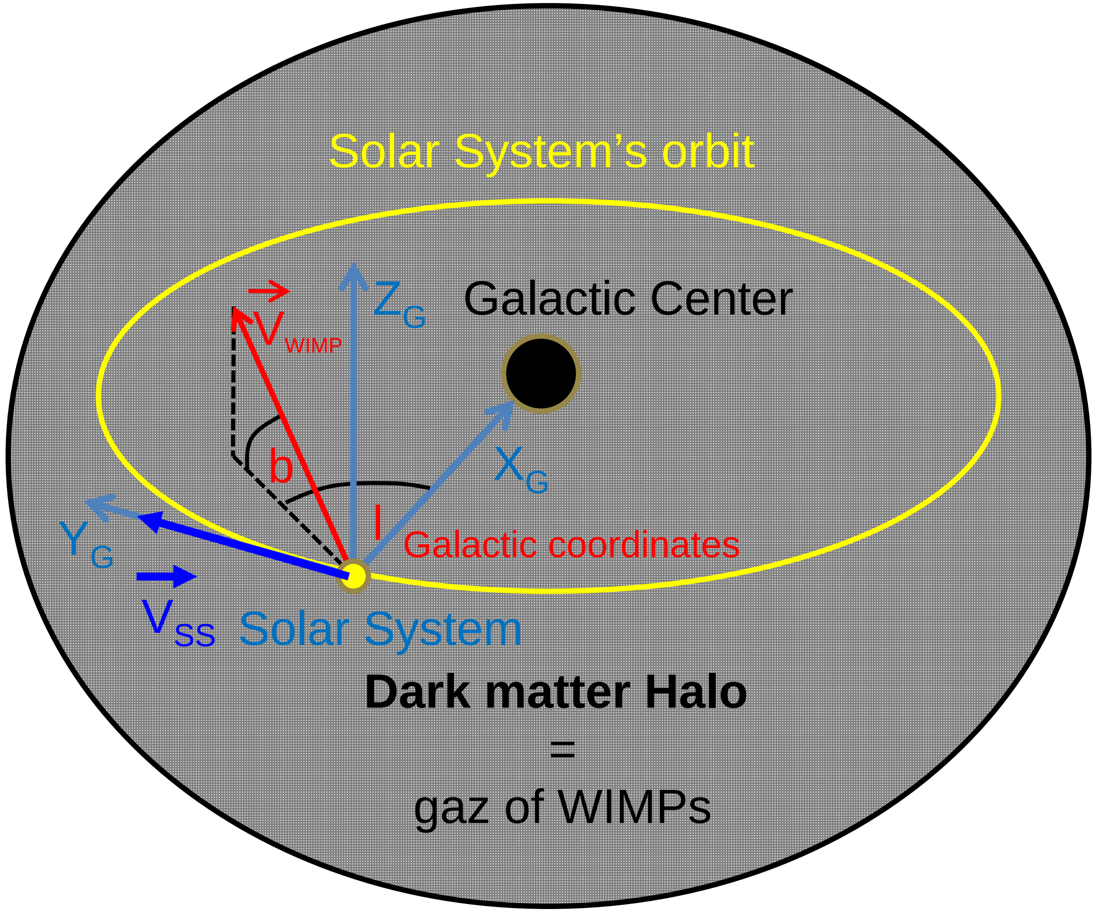
3. Case of positive detection: Claim a discovery

4. Case of a high significance detection: Constraints on WIMP properties

Conclusions & discussion

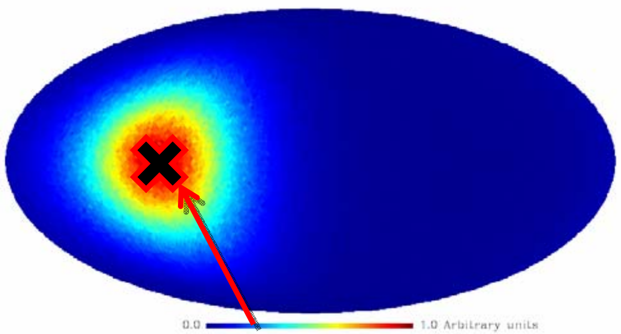
Directional detection signal

I.a WIMP signal



Considering the standard halo model, isothermal sphere:

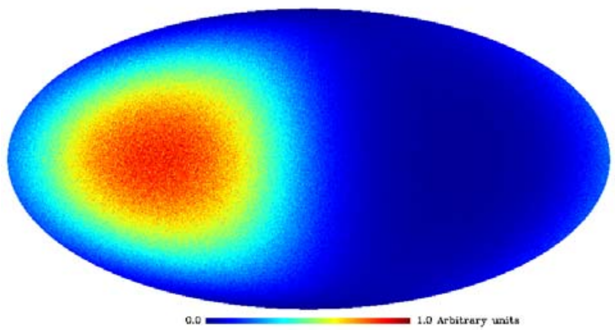
WIMP flux entering a terrestrial detector represented in Galactic coordinates



Cygnus Constellation (l = 90°,b = 0°)

After scaterring

WIMP induced recoil distribution



Expected WIMP signal

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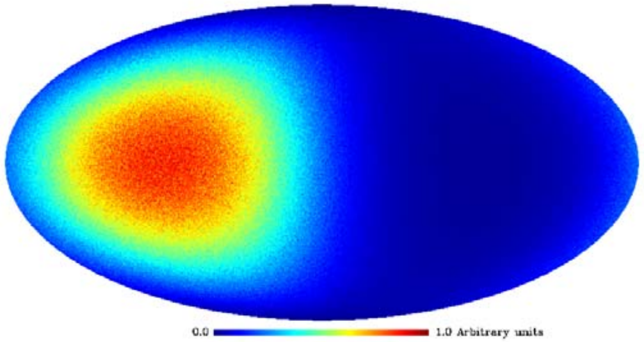
I.b Interest of the directional detection

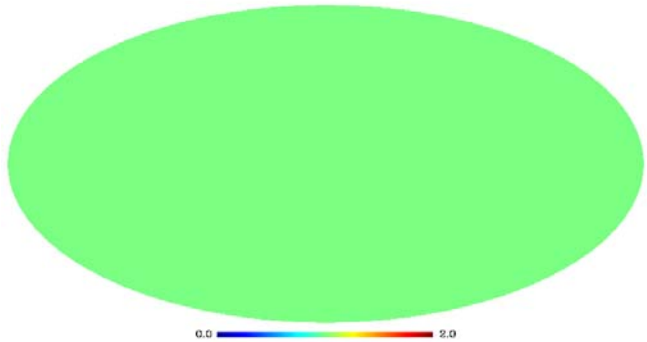
Background is supposed to be **isotropic**

WIMP signal



Vs

Background



Clear and unambiguous difference between WIMP signal and background

<u>How to take the most advantage of this difference to:</u>

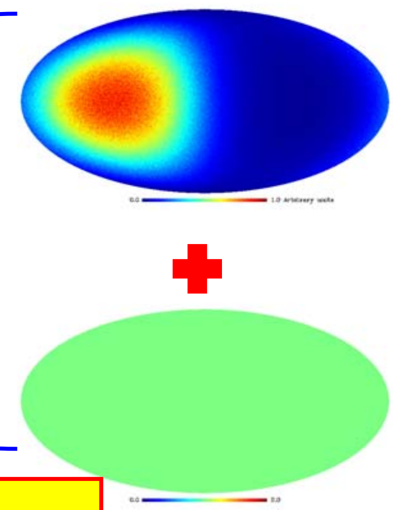
- Set exclusion limits
- Claim a discovery with a sufficient significance
- Identify Dark Matter (particle and galactic physics)

Depending on the WIMP nucleon cross-section

I.c Expected signal

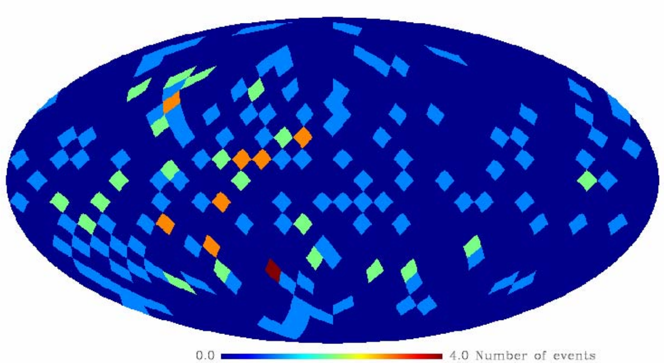
Characteristics of directional data

- Low number of WIMP events
- A large background fraction
- Rather low angular resolution

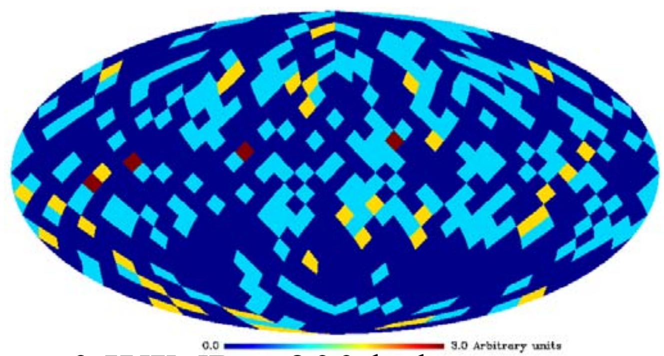


Pseudo data

- 10 kg CF_4
- Livetime : 3 years
- Recoil energy range : [5, 50] keV
- Background event rate R_b = 10 evts/kg/year

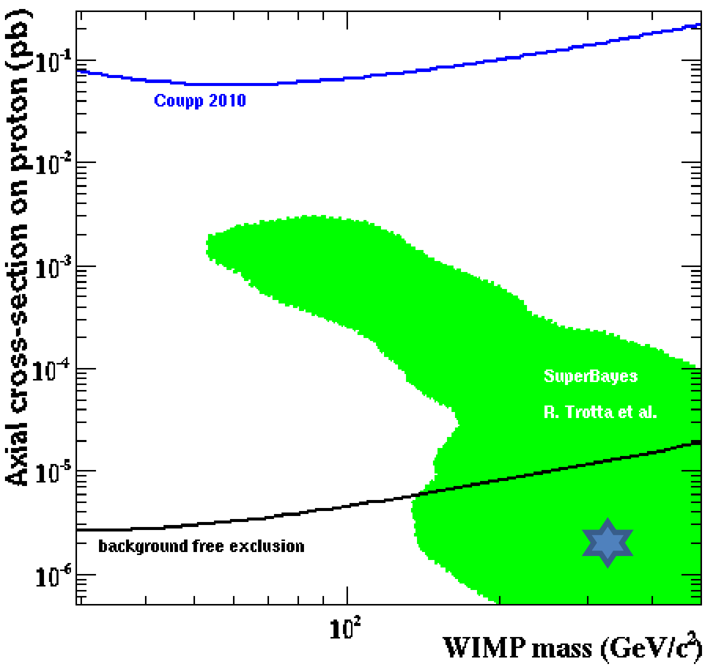


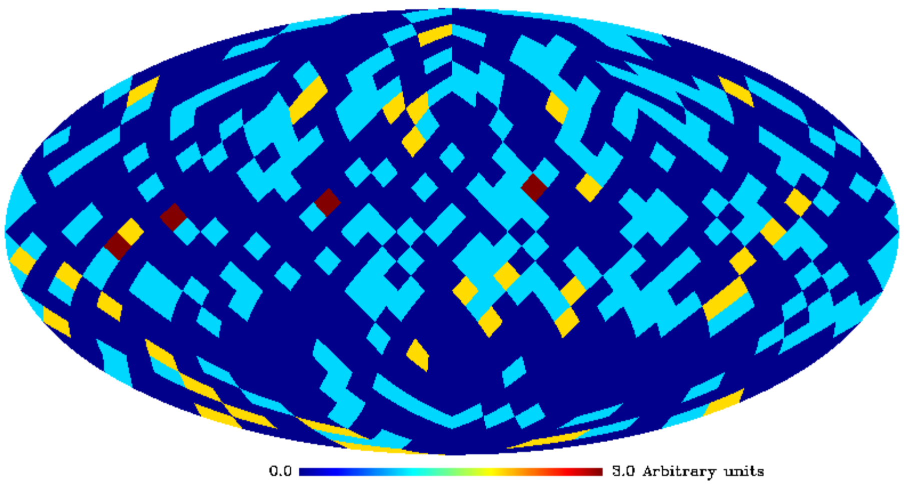
100 WIMP + 100 bck events



0 WIMP + 300 bck events

What can we conclude from such skymaps ?





300 background events. No WIMP

Case of a null detection

Setting upper limits using directional data…

II.a Directional exclusion limit methods

Several methods can be used for directional detection:

➢ **Poisson method**

No assumptions on the origin of events

➢ **1D Directional Maximum Gap method** (*S. Yellin, Phys.Rev. D66 (2002) 032005*)

Uses only the theoretical WIMP event angular distribution to set limits

➢**The Maximum Patch Method** *(S. Henderson et .al,* Phys.Rev.D78:015020,2008*)*

A 2D generalization of the Maximum Gap method considering both directional and energy informations

➢ **Directional Likelihood method** (*J. Billard et .al,* Phys.Rev.D82:055011,2010**)**

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

Considering only the angular part of the event distribution

⬇

No assumptions on the energy spectrum of background: ***conservative***

II.b Directional likelihood Method

Goal = Estimate, from an observed recoil map M, the expected number of :

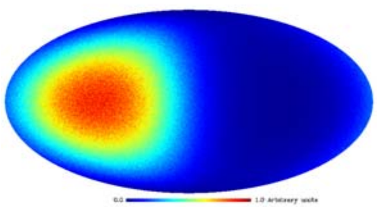
- WIMP events : μ_s
- Background events : μ_b

Consider flat priors and an extended likelihood function

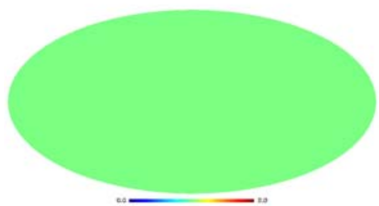
$$\mathscr{L}(\mu_s, \mu_b) = \underbrace{\frac{(\mu_s + \mu_b)^N}{N!} e^{-(\mu_s + \mu_b)}}_{\text{Poisson distribution}} \times \underbrace{L(\mu_s, \mu_b)}_{\text{Likelihood}}$$

Poisson distribution *Likelihood*

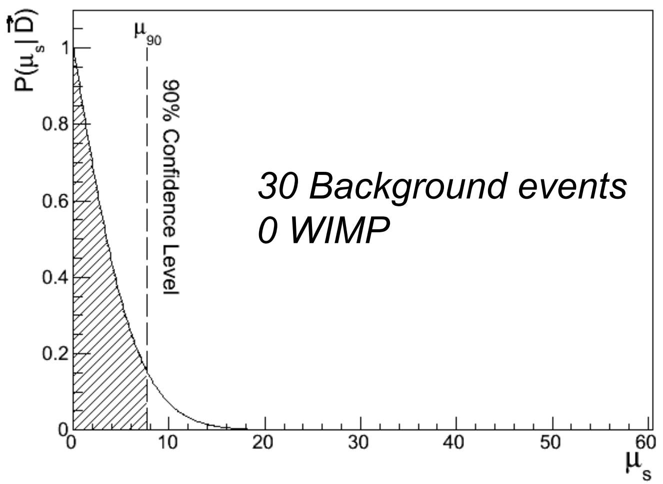
$$L(\mu_s, \mu_b) = \prod_{i=1}^{N_{\text{pixels}}} P\left(\frac{\mu_s}{\mu_s + \mu_b} S_i + \frac{\mu_b}{\mu_s + \mu_b} B_i | M_i\right)$$



S: Signal



B: Background

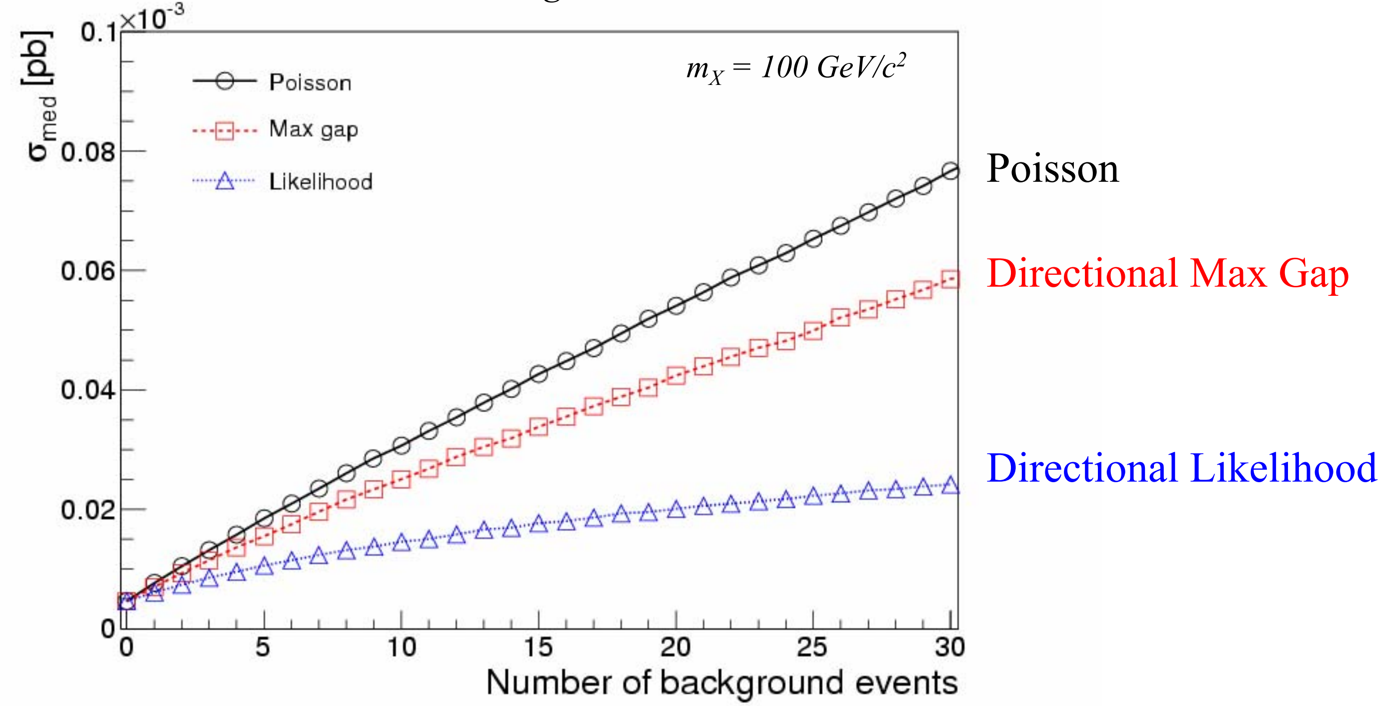


Marginalize over μ_b to get: $P(\mu_s | D)$

II.c Comparison of the three methods

- For each input and each method : 10,000 toy Monte Carlo experiments.
- From each experiment, we can estimate the median value of the upper limit σ_{med}.

Pure background

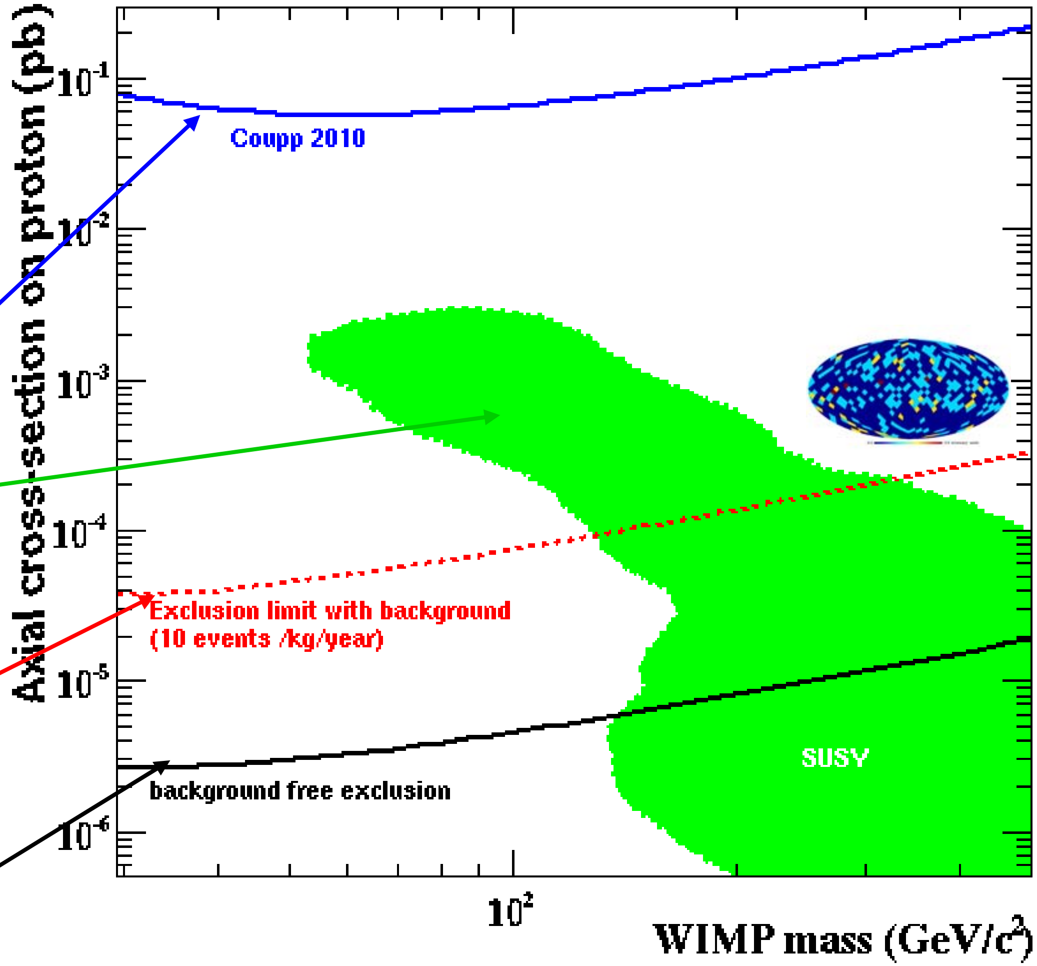


Directional Likelihood Method overcomes the others
... especially at high background contamination

II.c MIMAC expected limits

MIMAC characteristics
- 10 kg CF_4
- DAQ : 3 years
- Recoil energy [5, 50] keV
- Background rate:
  10 evts/kg/year

J. Billard *et al.*, Phys.Rev.D82:055011,2010



Most restrictive limit: COUPP

Supersymmetry: SuperBayes

Expected limit: 300 bckg events

Down to ~ 10^{-5} pb

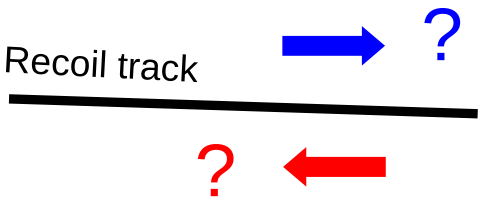
Expected sensitivity: 0 event

Down to ~ 10^{-6} pb

What about the effect of experimental uncertainties on these limits?

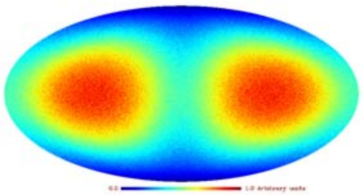
II.d Experimental effects: Sense Recognition (SR)

Sense of the recoiling nuclei?



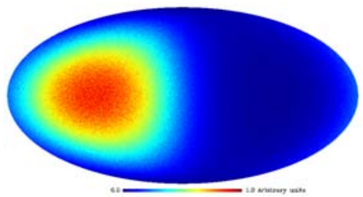
Effect on expected performance of MIMAC:

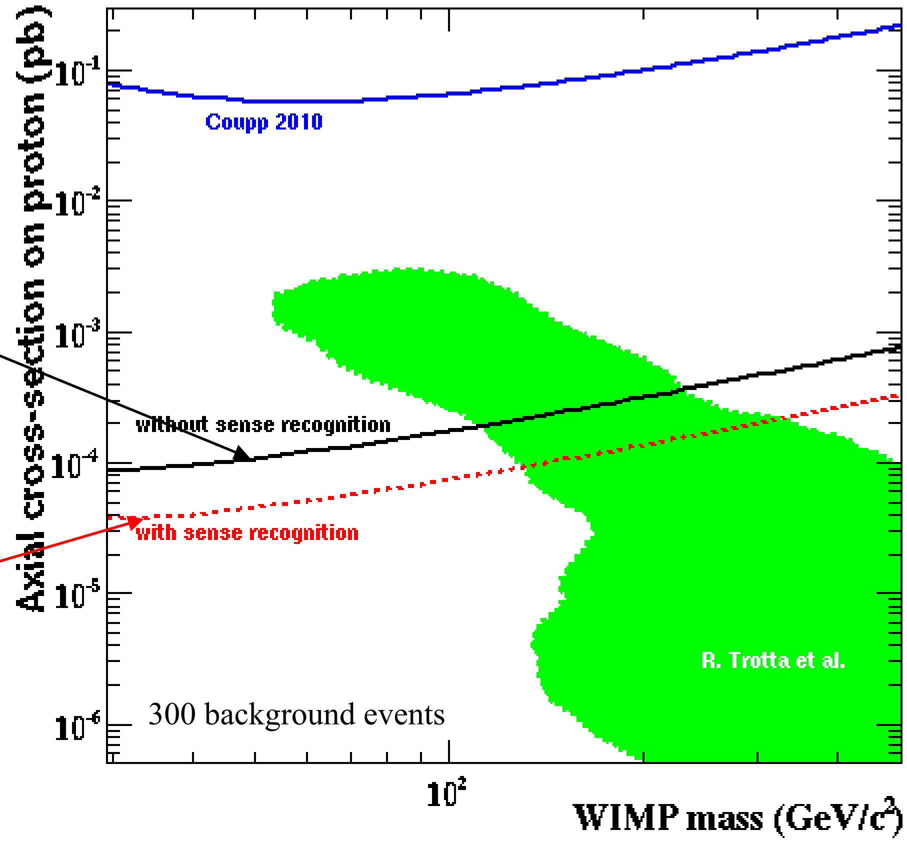
Without Sense Recognition



The WIMP distribution tends to isotropy

With Sense Recognition





Loose about a factor of 2-3

Very important experimental issue

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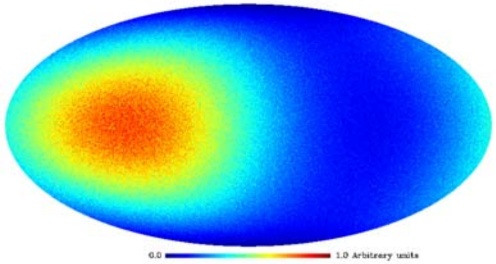
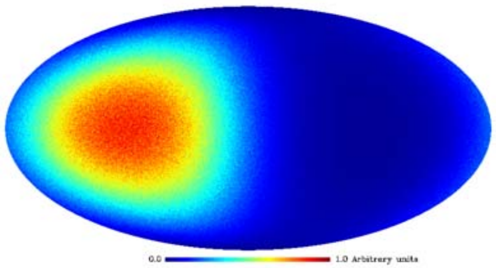
II.e Experimental effects: angular resolution

Key issue for directional detection

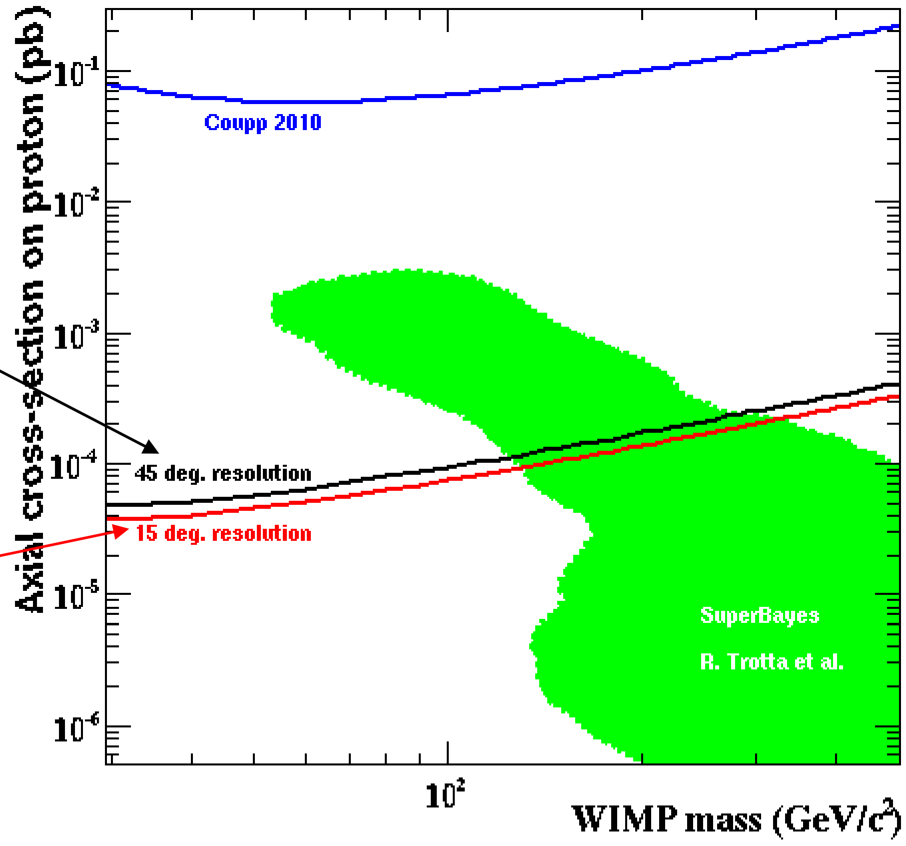
$\sigma_\Theta = 45\,°$



$\sigma_\Theta = 15\,°$



Effect on expected performance of MIMAC:

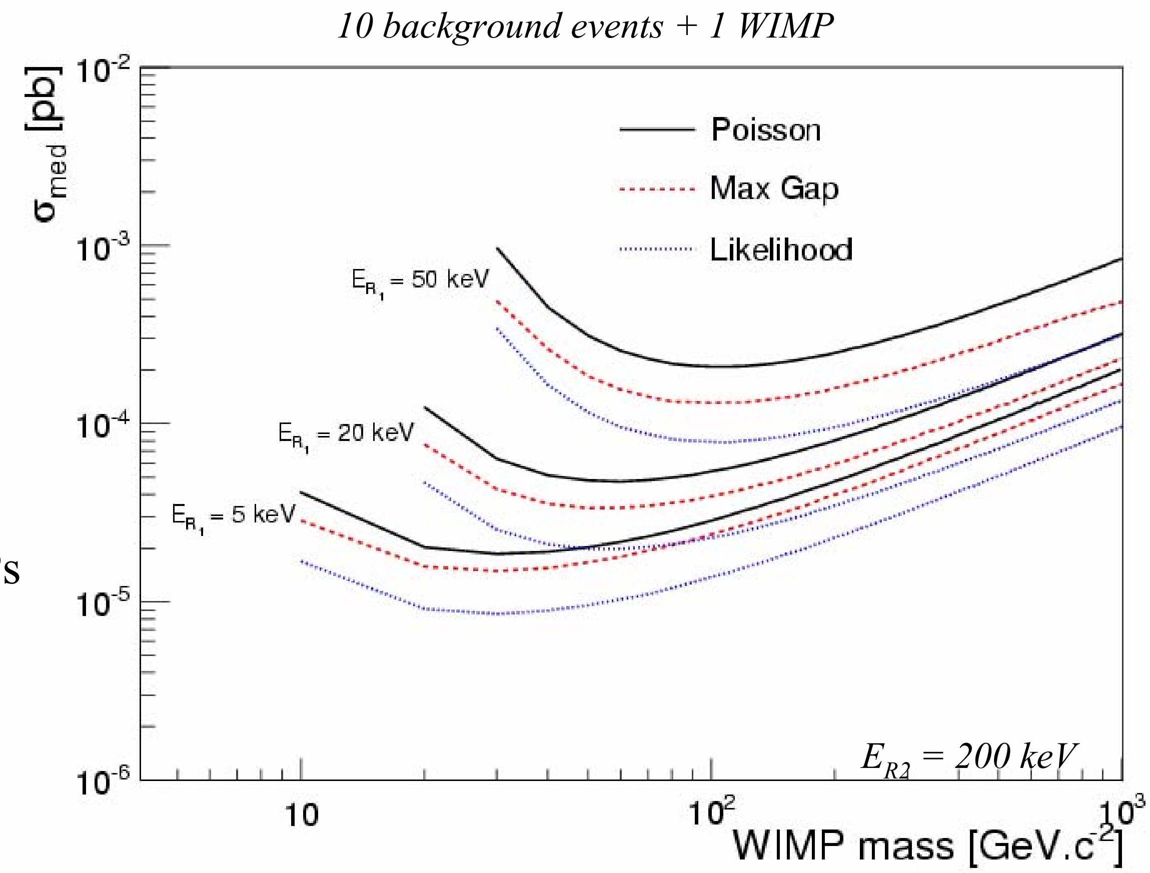


Minor experimental issue

II.f Effect of the energy threshold E_{R1}

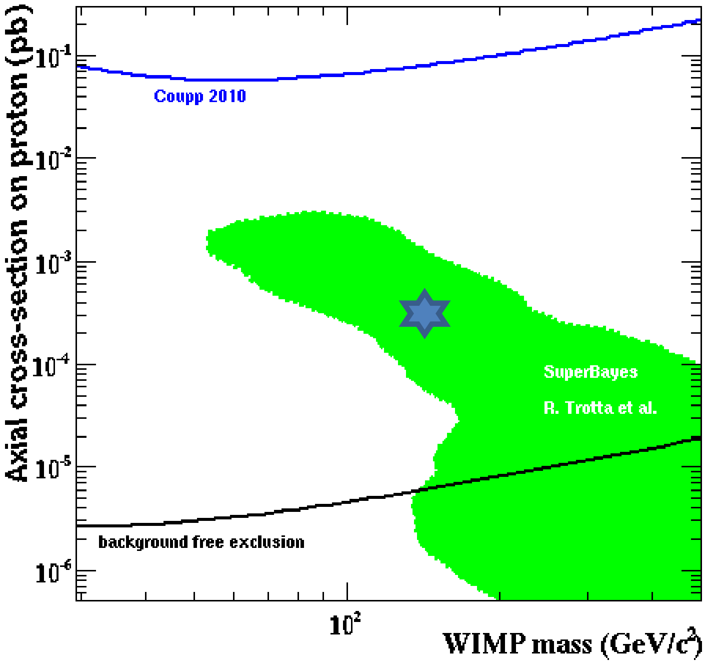
A lower energy threshold leads to:

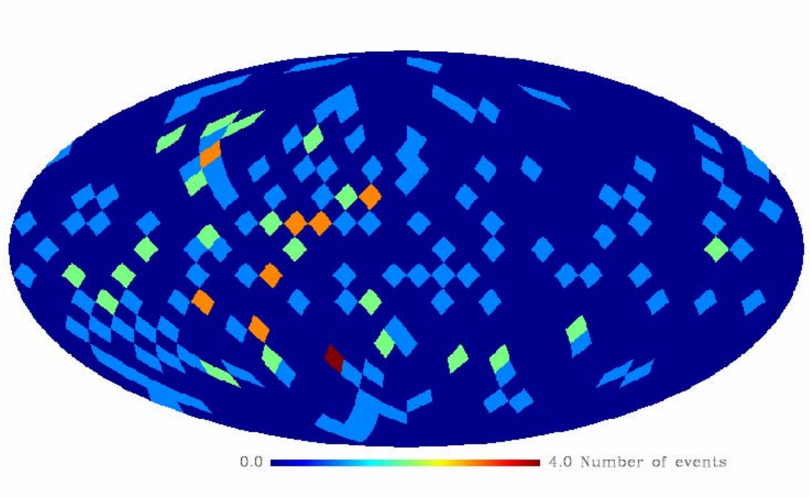
- More restrictive limits
- A higher sensitivity to light WIMPs



One order of magnitude between 5 and 50 keV threshold

Most important experimental effect



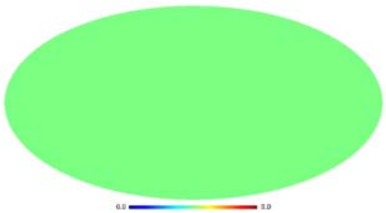


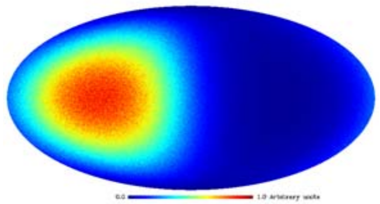
Observed recoil map
(100 WIMPs + 100 bckg)

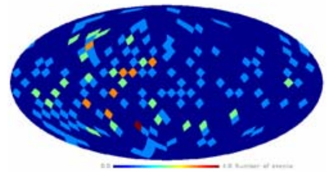
Case of a positive detection

...Is there any WIMP events in this observed recoil map?

III.b Likelihood definition







B: Background **S: Theoretical WIMP signal** **M: Measurement**

$$\mathscr{L}(m_\chi, \lambda, \ell, b) = \prod_{i=1}^{N_{\rm bins}} P([(1-\lambda)\underline{B_i} + \lambda \underline{S_i(m_\chi; \ell, b)}]|\underline{M_i})$$

A four parameter likelihood:

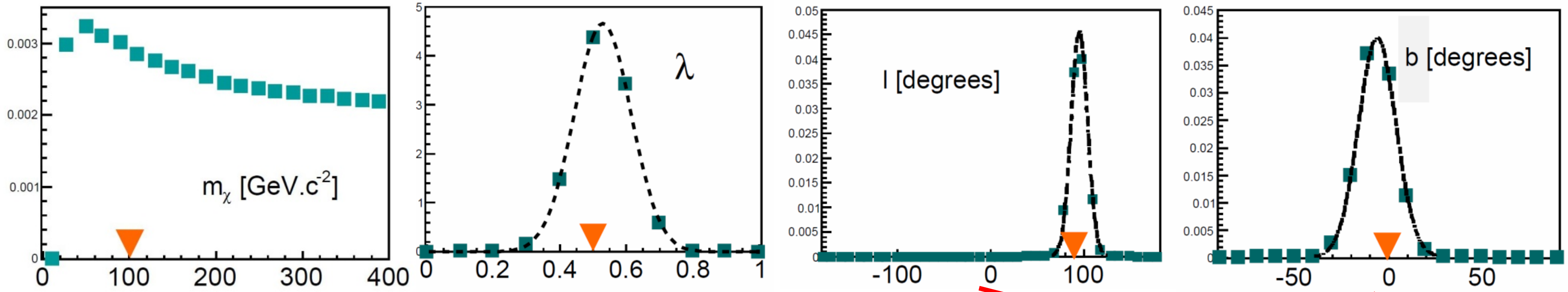
- WIMP mass m_X
- The WIMP fraction: $\lambda = S/(B+S)$
- l and b refers to the main incoming direction

Blind analysis
Prove that the signal comes from Cygnus

III.c A map based likelihood analysis

J. Billard *et al.*, Phys. Lett. B 691 (2010) 156-162

$$\lambda = S/(B+S)$$



Probability density functions

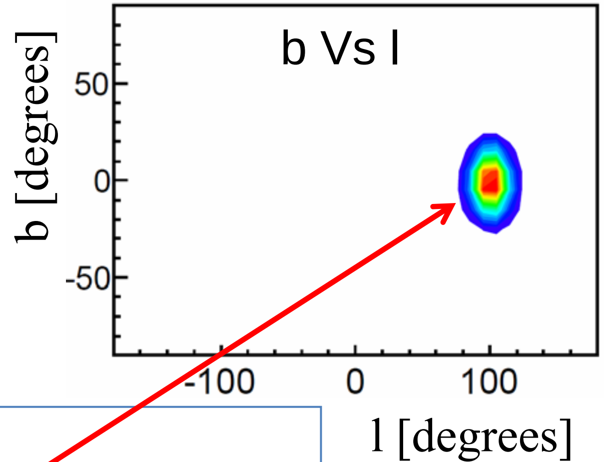
Likelihood analysis

WIMP mass: $m_\chi > 10$ GeV.c^{-2}

WIMP fraction: $\lambda = 0.53 \pm 0.085$ (1σ CL)

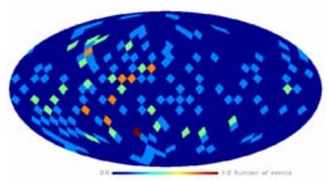
Galactic latitude: $l = 95^\circ \pm 10^\circ$ (1σ CL)

Galactic Longitude: $b = -6^\circ \pm 10^\circ$ (1σ CL)



Conclusions of the map analysis:

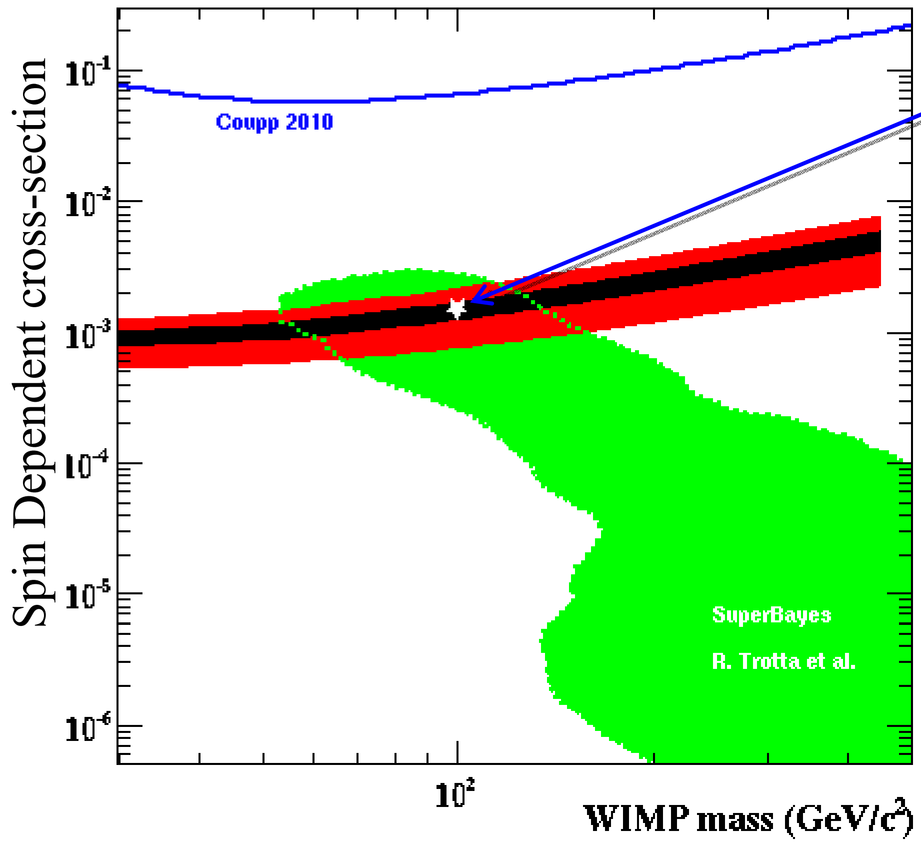
- The signal is pointing toward the Cygnus Constellation within 10° (68% CL)
- $N_{WIMP} = 106 \pm 15$ (68% CL) ~ 7σ signigicance

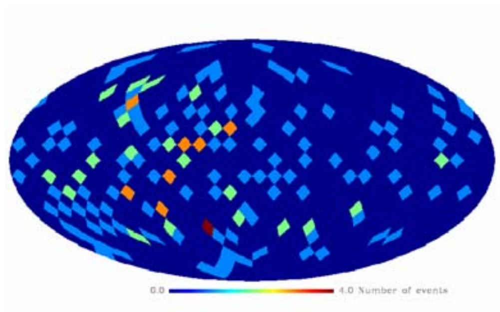


III.d Constraining the WIMP mass and cross-section

Constraint on λ implies a constraint on the WIMP-nucleon cross-section:

Allowed regions deduced from the likelihood analysis,
NOT exclusion!





Realistic simulated data

- -10 Kg CF_4
- - DAQ : 5 months
- - Bckg rate = 25 evts/kg/year
- - Angular resolution: 15° (FWHM)

From: Exclusion strategy

↓

To: Discovery strategy

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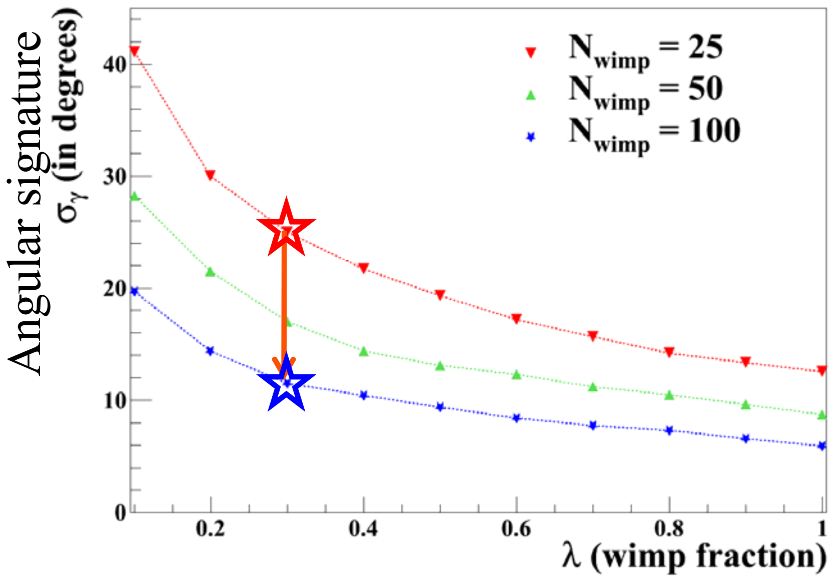
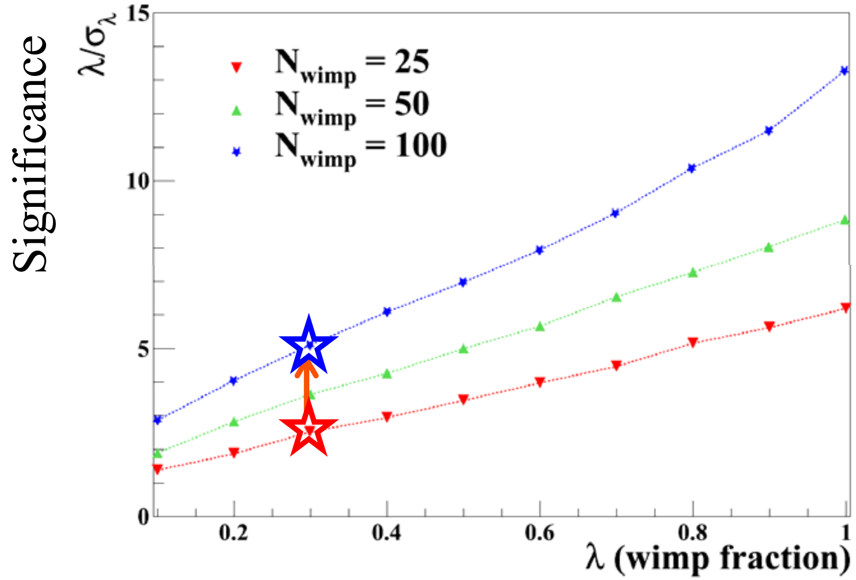
III.e Systematical studies

Angular signature: $\sigma_\gamma = \sqrt{\sigma_\ell \sigma_b}$

Significance: λ/σ_λ

Satisfactory results on a large range of exposure (N_{WIMP}) and background fraction (λ)





☆ Low exposure results: *1.25 kg.year CF4 detector = 25 WIMPs and 50 background*
WIMP from Cygnus within 25° but… poor significance (HINT of DM detection)

☆ High exposure results: *5 kg.year CF4 detector = 100 WIMPs and 200 background*
WIMP from Cygnus within 10° High significance (5σ) ! (DISCOVERY of DM)

J. Billard et *al.*, Phys. Lett. B 691 (2010) 156-162

IIIf: MIMAC « road map »

MIMAC characteristics
- 10 kg CF_4
- DAQ : 3 years
- Recoil energy [5, 50] keV
- Background rate:
  10 evts/kg/year

Down to 10^{-4} pb:

discovery

Down to 10^{-5} pb:

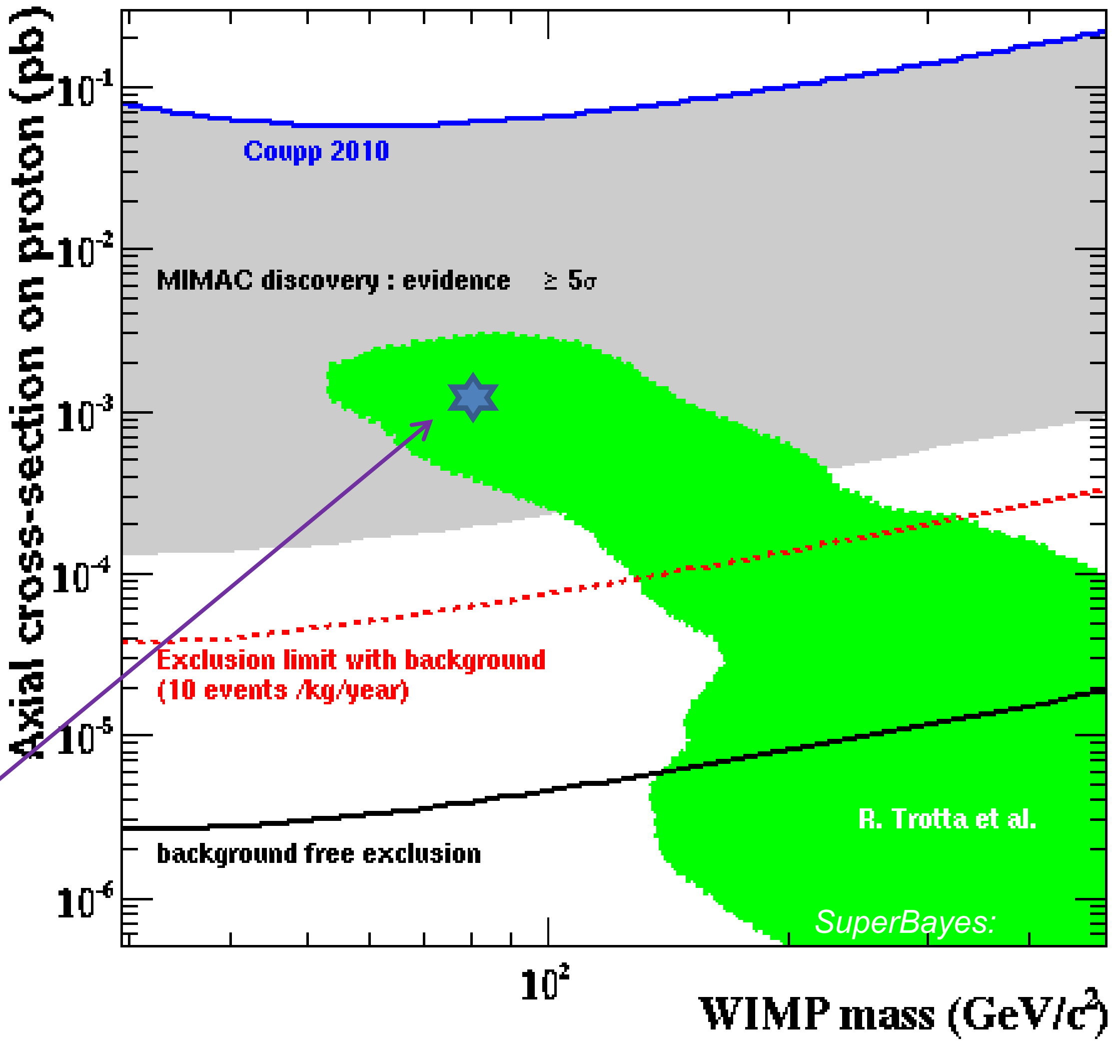
exclusion

Going further… = 10^{-3} pb:

Identification of DM

« Contraints on the mass, the cross-section and the halo properties »

J. Billard *et al.*:
Phys.Rev.D82:055011,2010 **&** Phys. Lett. B 691 (2010) 156-162



A Markov Chain Monte Carlo analysis to identify Dark Matter

IV.a Directional event rate

Form factor

$$\frac{d^2R}{dE_R d\Omega} = \frac{\rho_0 \sigma_0}{4\pi m_\chi m_r^2} F^2(E_R) \hat{f}(v_{\min}, \hat{q})$$

- Astrophysics
- Particle physics
- Nuclear physics

$$F(E_R) = \frac{\sin(\sqrt{2m_N E_R} r_n)}{\sqrt{2m_N E_R} r_n}$$

In the case of an axial coupling

Radon transform: [P. Gondolo 2002]

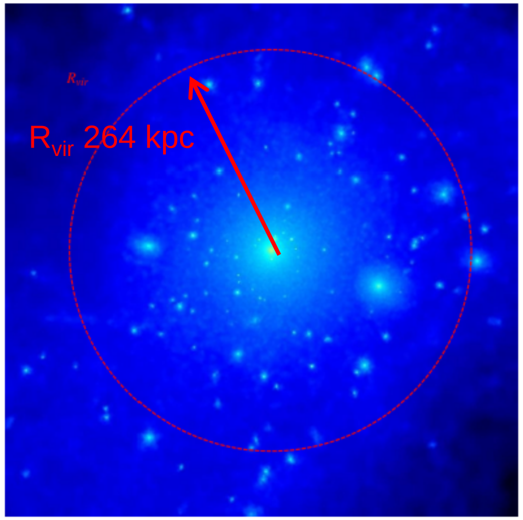
Kinematic relationship

$$\hat{f}(v_{\min}, \hat{q}) = \int d^3v \, \delta(\vec{v}.\hat{q} - v_{\min}) f(\vec{v}) \quad ?$$

« Geometrically, the Radon transform is the integral of the velocity distribution on a plane orthogonal to the recoil direction and at a distance v_{min} from the origin »

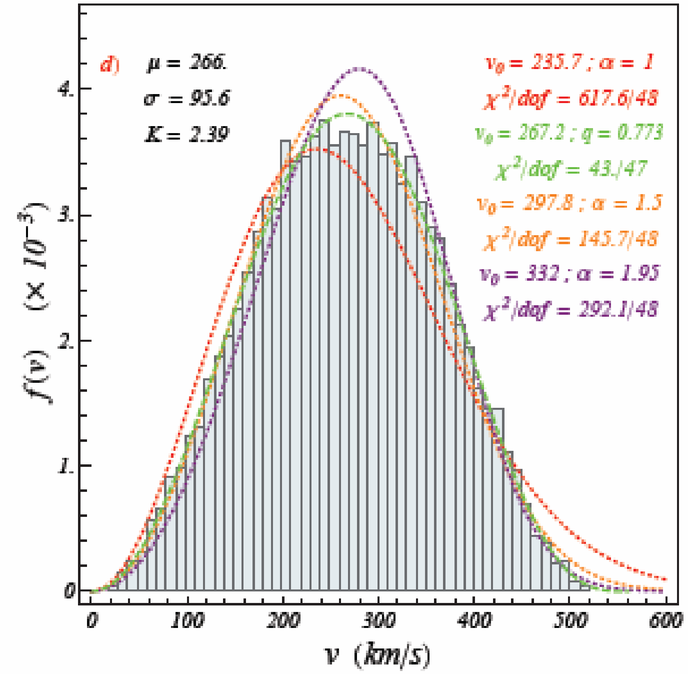
IV.b The velocity distribution

N-Body simulation with baryons (F. S. Ling et al. 2009)



Dark Matter halo from cosmological N-Body simulations (RAMSES code from R.Teyssier)

Velocity distribution of the WIMP particle within a radius of 9 kpc in the Galactic frame



- No evidence against a smooth velocity distribution
- Standard isotropic halo model disfavoured in this case: ß = 0.06

Anisotropy parameter: $$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$$

- ß < 0: Tangential anisotropy
- ß > 0: Radial anisotropy
- ß = 0: isotropic

Compatible with a multivariate gaussian distribution…

IV.b The velocity distribution: Multivariate Gaussian

From the Jeans equation: the velocity tensor is symetric

« One can find an orthogonal basis where the velocity tensor is diagonal »

$$f(\vec{v}) = \frac{1}{(8\pi^3 \det \boldsymbol{\sigma}_v^2)^{1/2}} \exp\left[-\frac{1}{2}(\vec{v} - \vec{v}_\odot)^T \boldsymbol{\sigma}_v^{-2}(\vec{v} - \vec{v}_\odot)\right]$$

The multivariate gaussian velocity distribution function, naturally arises from the fact that:

- It is the triaxial generalization of the standard isothermal sphere [Binney and Tremaine]
- It reproduces flat rotation curves ($\rho(r) = 1/r^2$) [N. W. Evans et al. 2000]
- It is quite consistent with recent numerical N-body simulations

  [M. Vogelsberger et al. 2009, M. Khulen et al. 2010, F. S. Ling et al. 2010]

The multivariate Gaussian is then used as a fitting model

J. Billard et *al.*, Phys.Rev.D83:075002,2011

IV.c Free parameters

The 8 free parameters of the fitting model are:

- The WIMP mass m_X
- The WIMP-nucleon cross- section σ_n
- The main incoming direction of the signal (l_O, b_O)
- The 3 velocity dispersions σ_x, σ_y et σ_z
- The background rate R_b

What are the posterior Probability Density Functions of each parameter according to a single experiment?

We developed a Markov Chain Monte Carlo sampling based on the Metropolis-Hastings algorithm for the following reasons:

- Size of the parameter space: 8 dimensions!
- The estimation of the PDFs are very accurate

Sub-sampling: « burn-in » and correlation lenghts => independant samples

Full Markov Chain Monte Carlo result

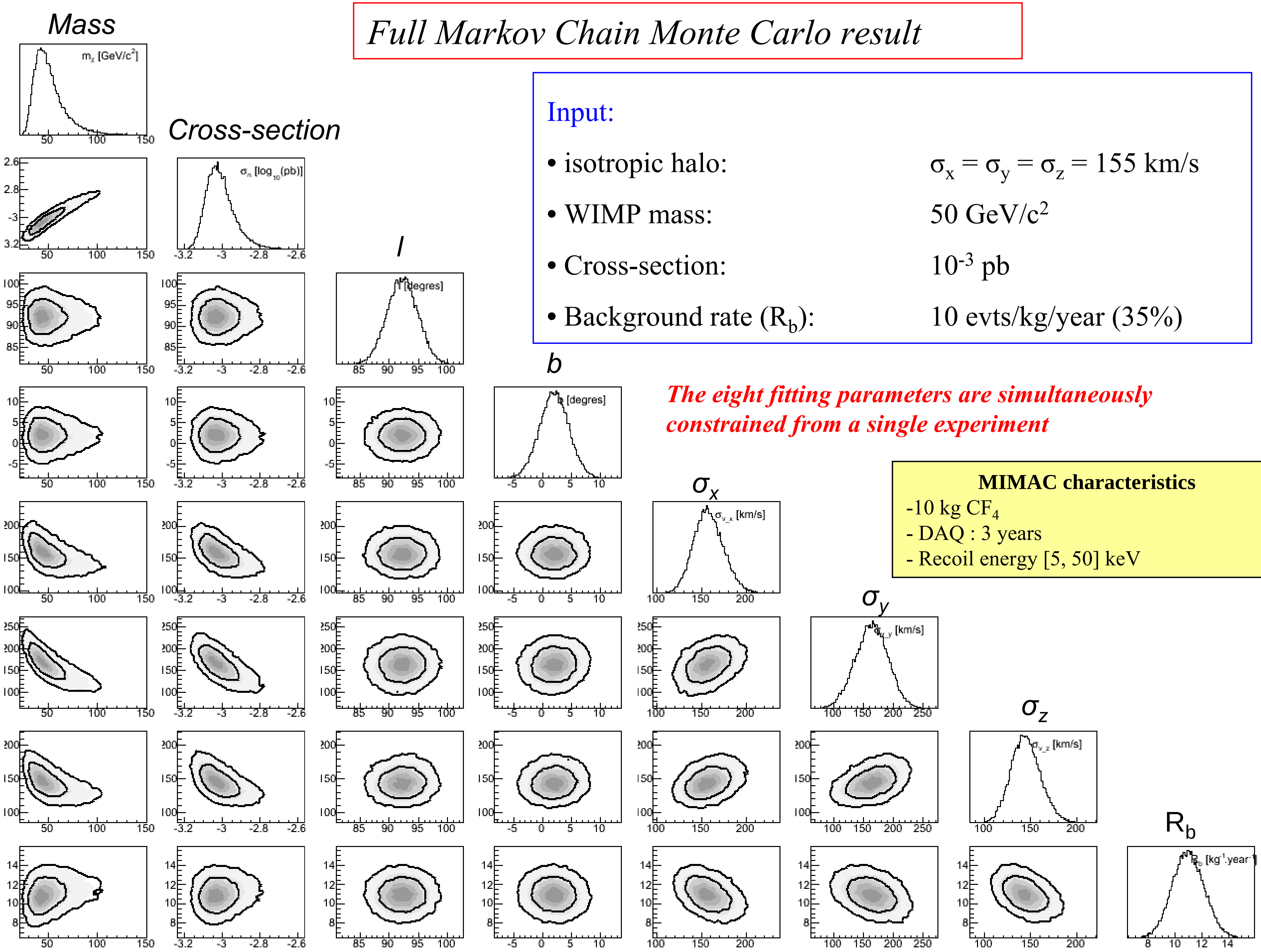
Input:

- 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/year (35%)

The eight fitting parameters are simultaneously constrained from a single experiment

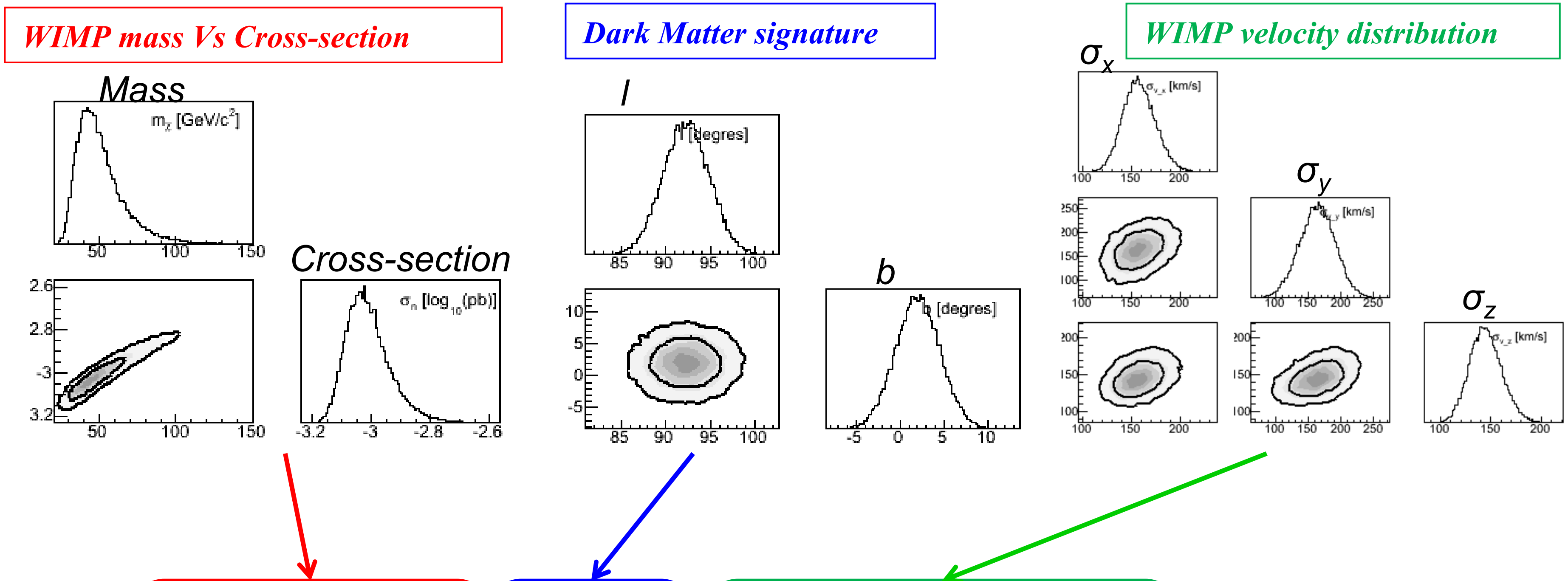
MIMAC characteristics

-10 kg CF_4
- DAQ : 3 years
- Recoil energy [5, 50] keV



IV.d Deduced constraints

The 8 fitting parameters are strongly constrained from a single directional detection experiment:



	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb))	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}	145^{+14}_{-17}	$-0.073^{+0.29}_{-0.18}$	10.97 ± 1.2

J. Billard et *al.*, Phys.Rev.D83:075002,2011

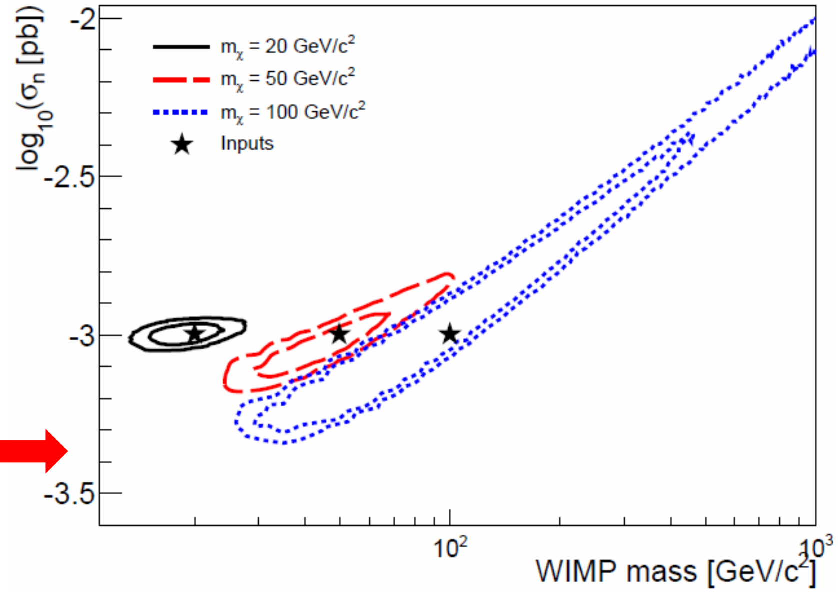
IV.e Input WIMP mass

Standard halo with three different masses:

- **20 GeV**
- **50 GeV**
- **100 GeV**

Consistent constraints on (m_X, $log_{10}(\sigma_n)$)

Isotropic halo + 35% bckg

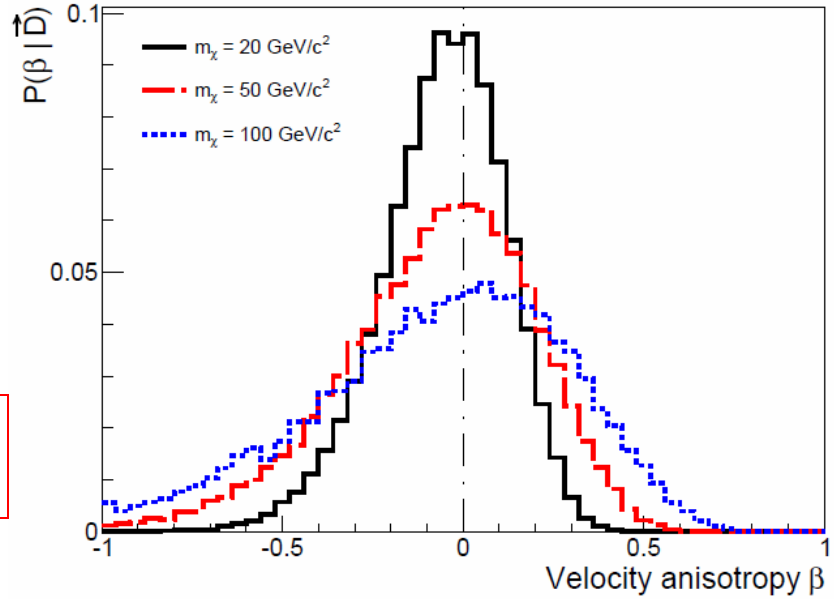


Constraints on the ß parameter:

$$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$$

(Deduced from the full MCMC analysis)

Isotropic halo: ß = 0



Constraints on the WIMP parameters and Dark Matter halo are consistents for all WIMP masses

J. Billard et *al.*, Phys.Rev.D83:075002,2011

35% of bckg + 50 GeV/c^2

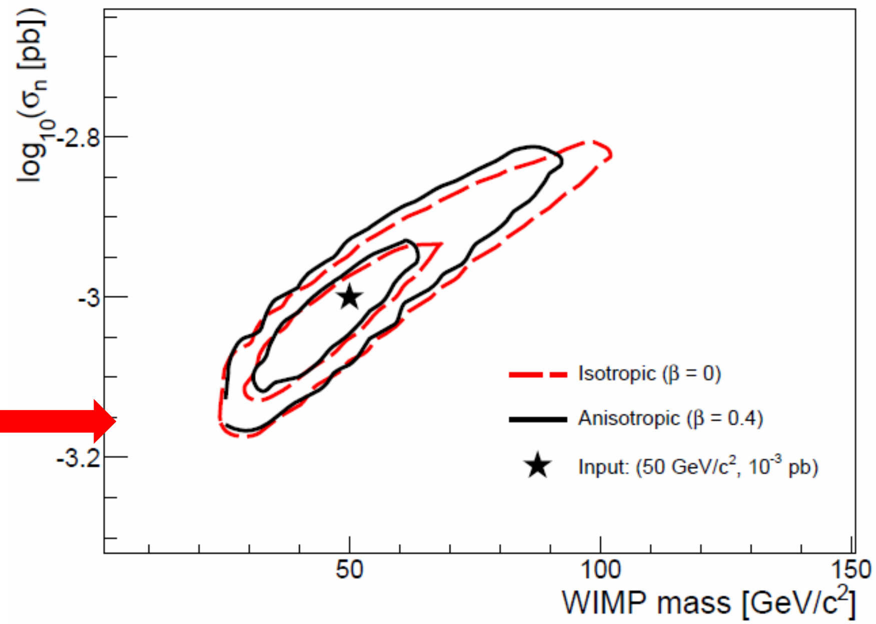
IV.f Input halo model

2 input halo models to generate pseudo-data:

Isotropic (ß = 0)

Extremely Anisotropic (ß = 0.4)

Similar constraints on (m_X, $log_{10}(\sigma_n)$)

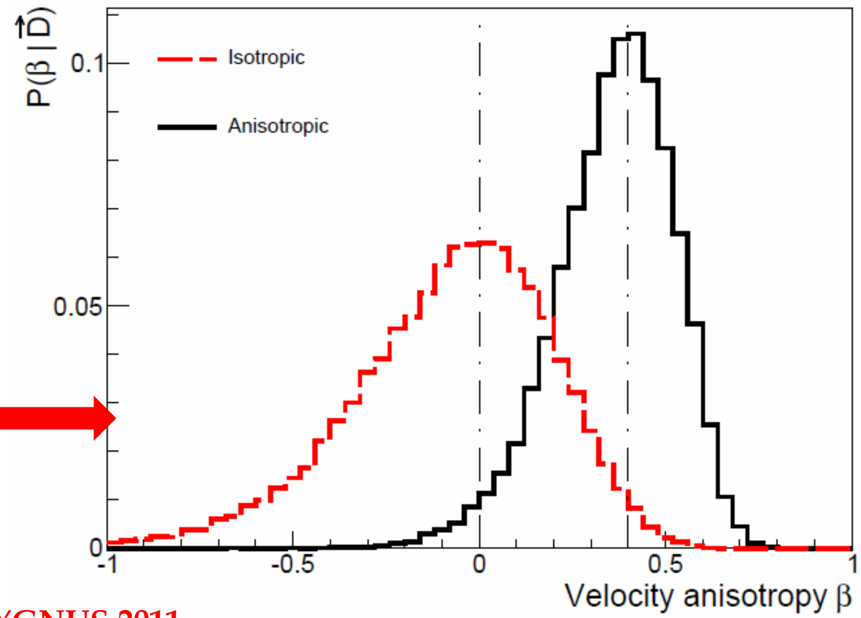


Constraints on the ß parameter:

Isotropic → $\beta = -0.073^{+0.29}_{-0.18}$

Anisotropic → $\beta = 0.38^{+0.18}_{-0.10}$

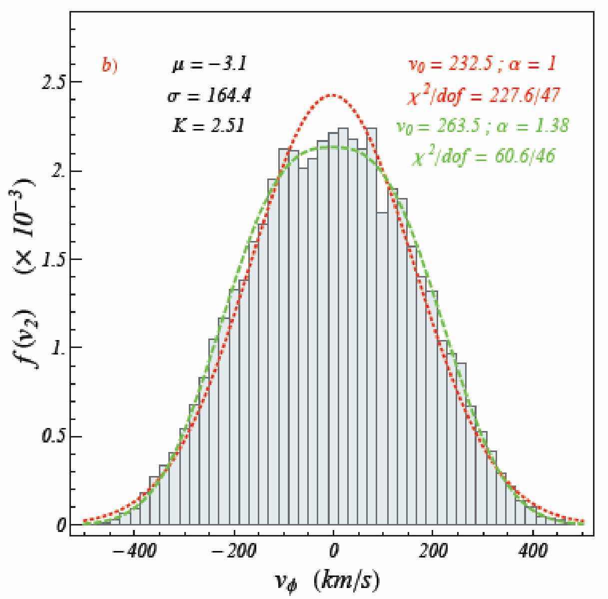
Discrimination between various halo model could be achieved with directional detection



IV.h Effect of refined halo model from Nbody simulations

RAMSES [R. Teyssier et al.]: Cosmological N-Body simulations

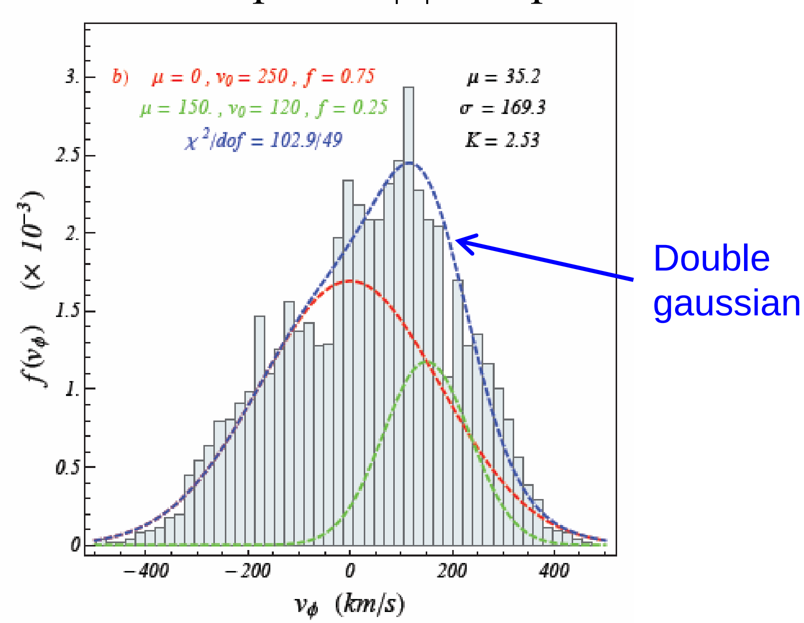
Shell distribution:
7<R<9 kpc (16545 particles)



➢ Gaussian distribution disfavoured
Kurtosis = 2.51

ß ~ 0,06
Smooth, weakly anisotropic and non-gaussian

Ring distribution:
7<R<9 kpc and |z|< 1 kpc (2662 particles)



➢ Presence of a co-rotating (**150 km/s**) **Dark Disk** with a **25%** contribution to the local WIMP velocity distribution

ß ~ 0,12
With a corotating Dark Disk

IV.h Effect of refined halo model from Nbody simulations

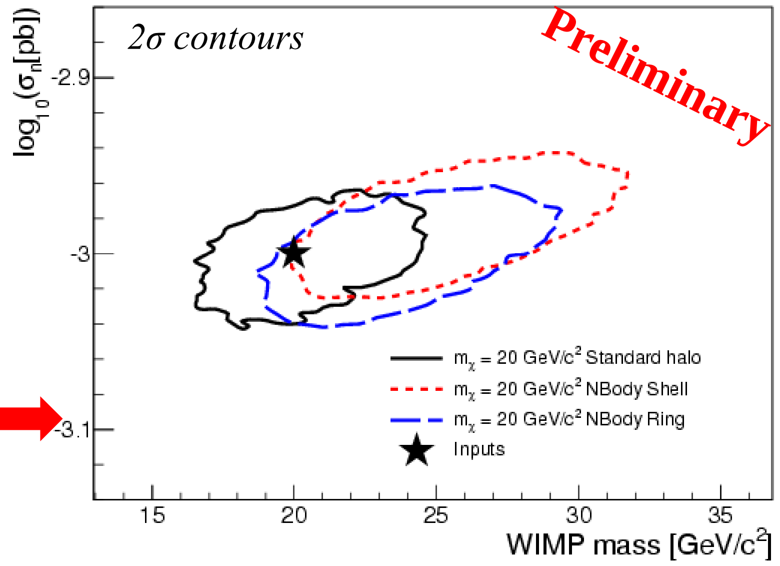
3 input halo models to generate pseudo-data:

Standard halo

Smooth

Dark Disk

Bias ~2σ in the (m_X, $log_{10}(\sigma_n)$)



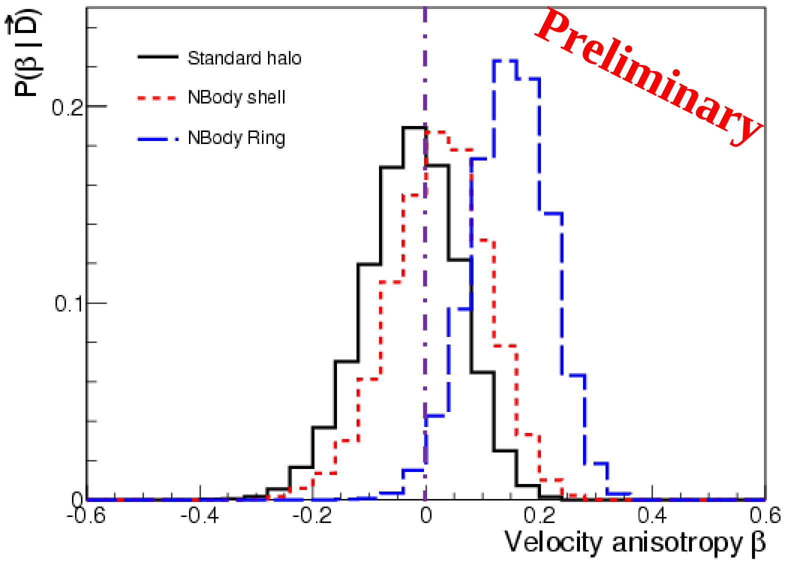
Constraints on the ß parameter:

Standard halo → $\beta = -0.01^{+0.09}_{-0.06}$

Smooth → $\beta = 0.02^{+0.09}_{-0.07}$

Dark Disk → $\beta = 0.15^{+0.06}_{-0.06}$

Robustness of the multivariate gaussian WIMP velocity distribution



Conclusion

Directional detection presents a lot of advantages in comparison with the classical direct detection of Dark Matter:

- **The WIMP induced signal is different from the expected background one**
- **Exclusion, discovery or identification (Particle physics and astrophysics)**

The study of the impact of Dark Matter halo from Nbody simulations on directional detection
(J. Billard et al., in preparation)

<u>However, these results require:</u>

- **3D Reconstruction of tracks with good resolutions**
- **Sense recognition**
- **An accurate measurement of the recoil energy**

→ *Requires a highly performant detector with a carefull analysis…*