Identification of Dark Matter using Directional Detection

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(soon on the arXiv)

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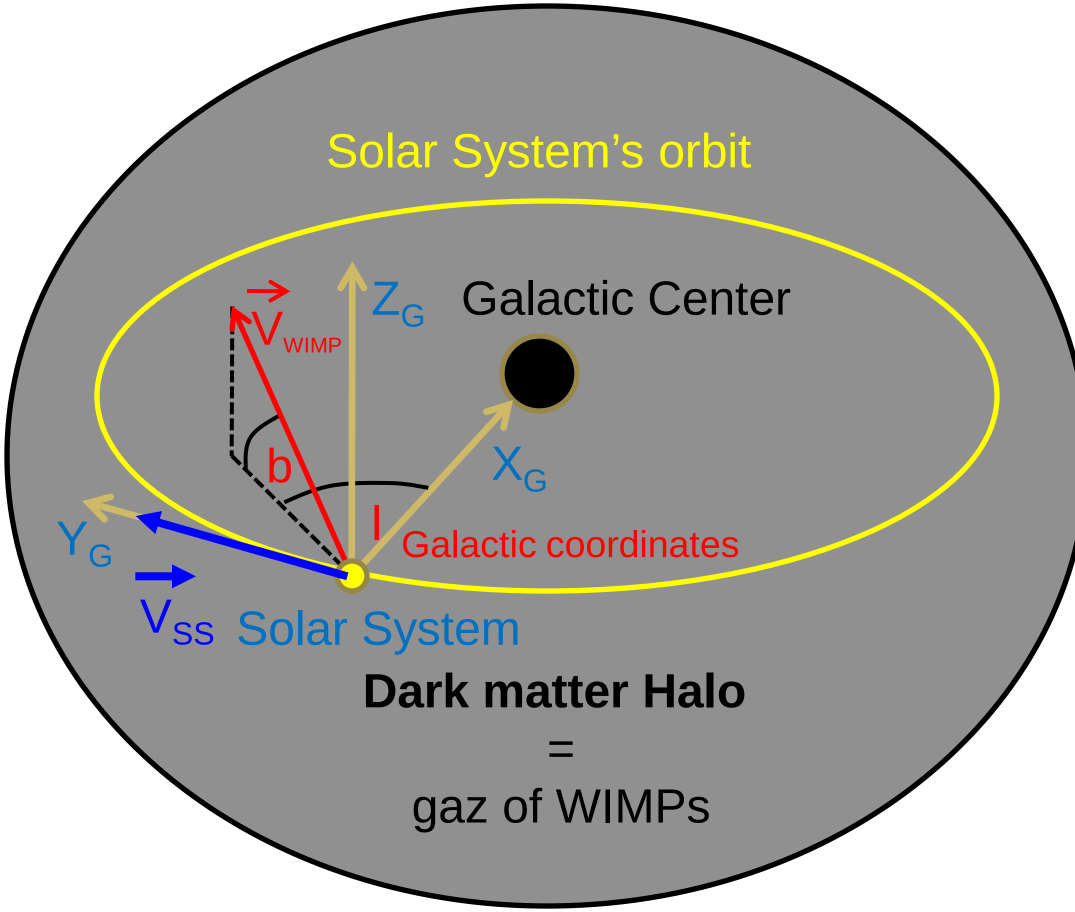
Outline

1. Directional detection & MIMAC prospects
2. Theoretical framework & a new MCMC analysis
3. Results from a simulated directional detection experiment
4. Effect of input parameters

Conclusions & discussion

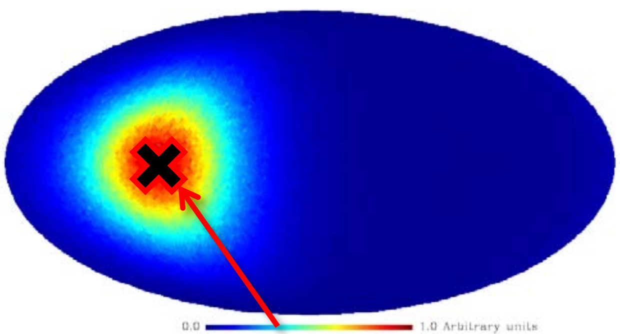
Directional detection & MIMAC prospects

I.a WIMP signal



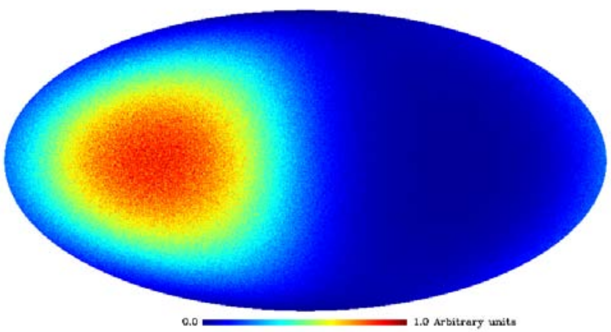
Considering the standard halo model, isothermal sphere:

WIMP flux entering a terrestrial detector represented in Galactic coordinates



After scaterring

WIMP induced recoil distribution



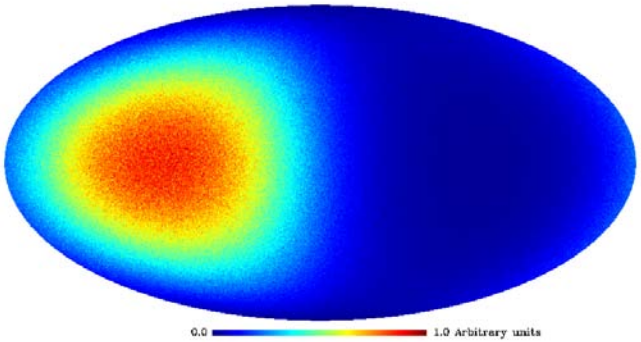
Cygnus Constellation (l = 90°,b = 0°)

Expected WIMP signal

I.b Interest of the directional detection

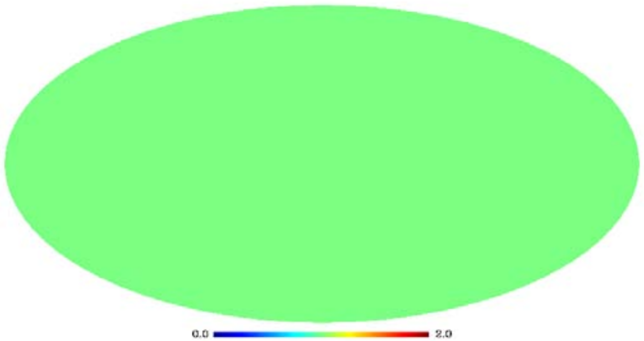
Background is supposed to be isotropic

WIMP signal



Vs

Background



Clear and unambiguous difference between WIMP signal and background

Directional detector :

- Need to measure : Recoil direction & Recoil energy
- Technology : Gazeous detector and TPC with low threshold
- Projects : **MIMAC**, DRIFT, DM-TPC, NEWAGE and Nuclear Emulsion

More details: S. Ahlen *et al., International Journal of Modern Physics A25 (2010)*

I.c MIMAC prospects

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

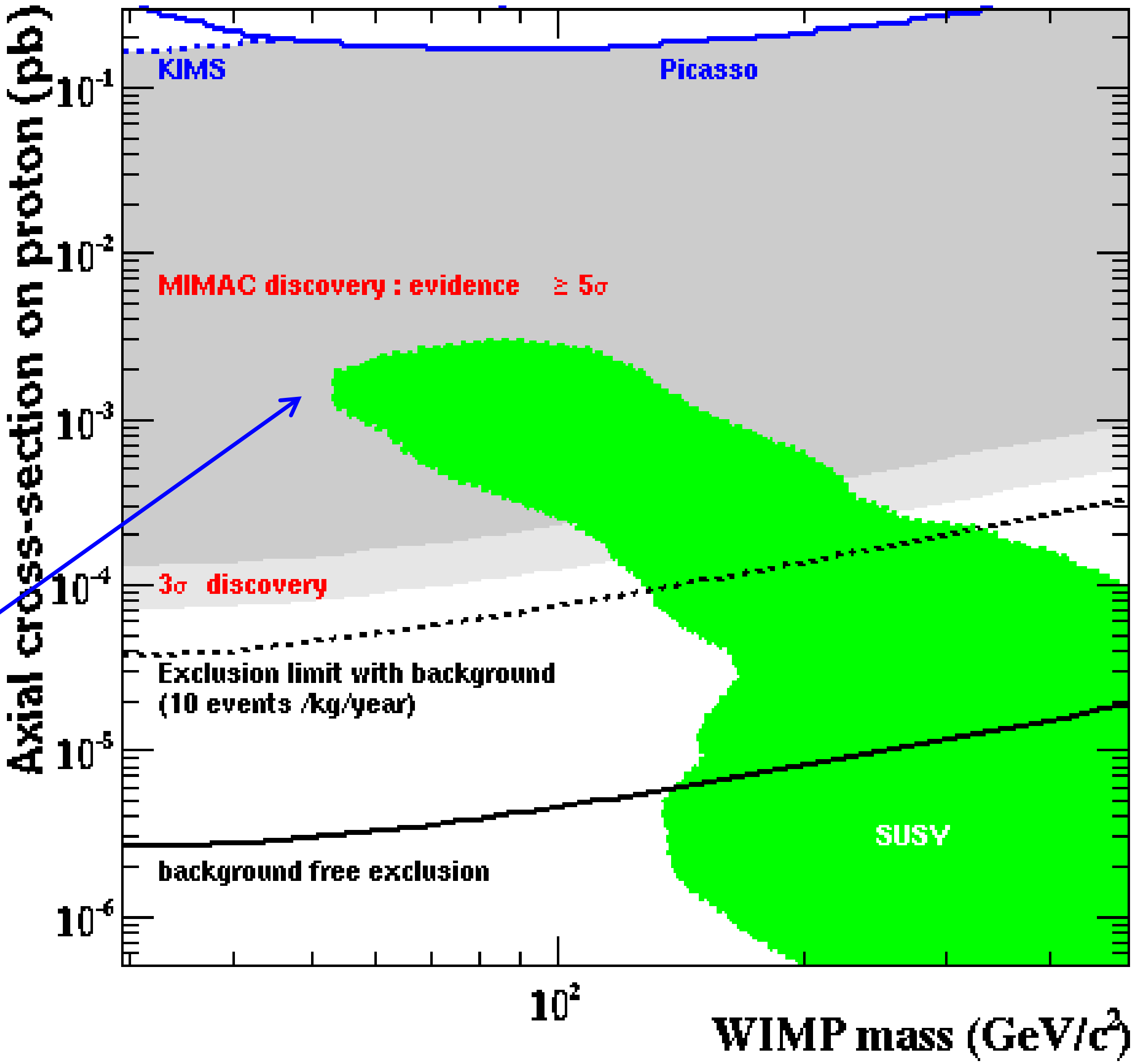
Down to 10^{-5} pb:

exclusion

Going further:

Characterization of Dark Matter

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



Theoretical framework
&
a new MCMC analysis

II.a Directional event rate

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

Form factor

- Particle physics
- Nuclear physics
- Astrophysics

Radon transform: [P. Gondolo 2002]

Kinematic relationship

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

Which expression of f(v) ?

II.b Velocity distribution

The multivariate gaussian velocity distribution function,

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

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

The velocity anisotropy parameter is defined as:

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

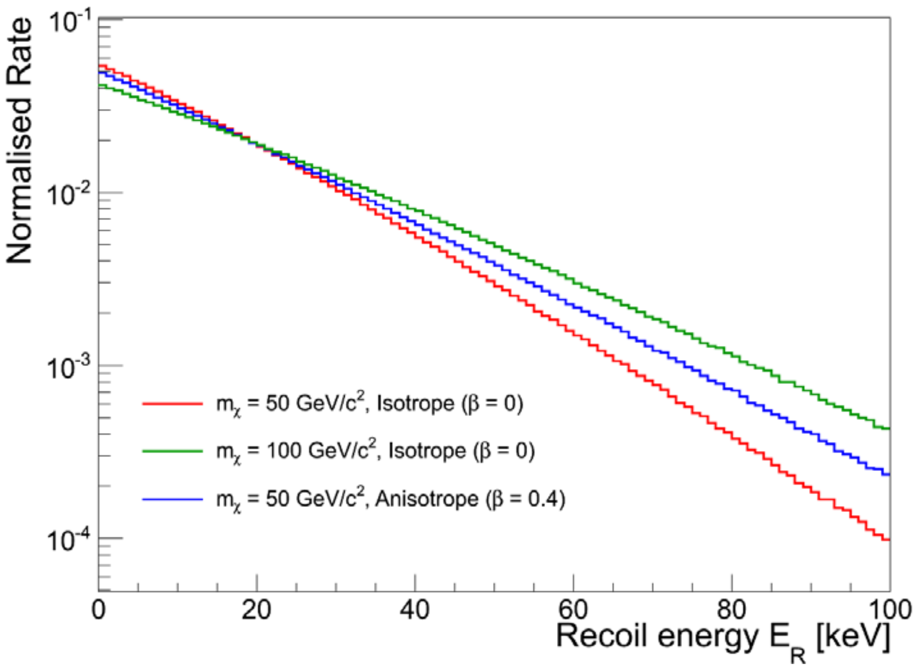
→

- if ß < 0: tangential anisotropy
- If ß > 0: radial anisotropy

According to N-Body simulations, 0 < ß < 0.4

II.c Effect of input parameters

dR/dE_r

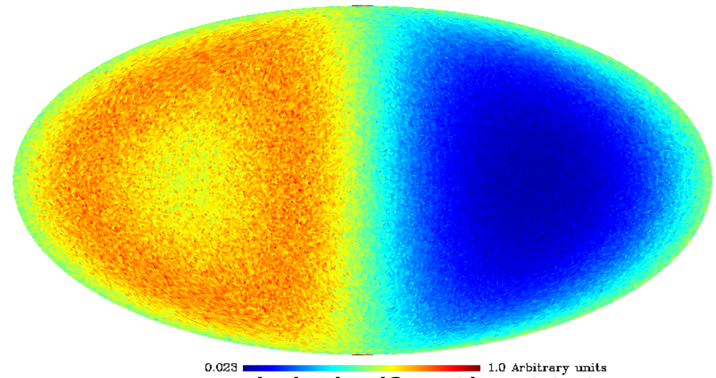


Directional detection: use of angular and energy information

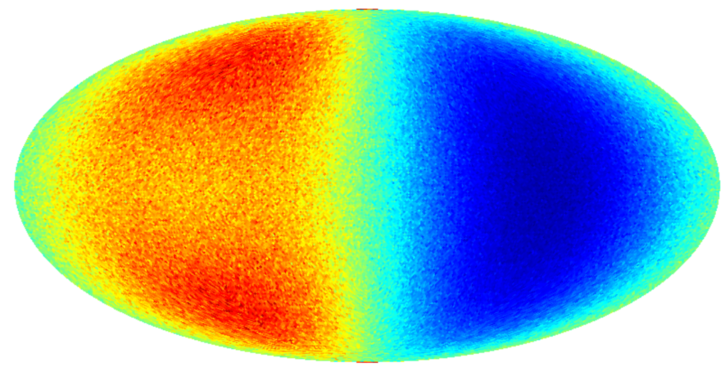
⇩

Offers the possibility to identify Dark Matter

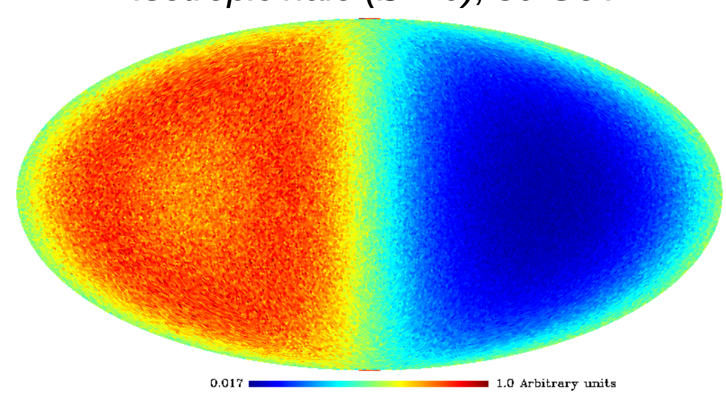
$dR/d\Omega_r$ at E_R = 5 keV



Isotropic halo (ß = 0); 100 GeV



Isotropic halo (ß = 0); 50 GeV



Anisotropic halo (ß = 0.4); 50 GeV

II.d 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 PDF of each parameter according to a single experiment?

$$\mathscr{L}(\vec{\theta}) = \frac{(\mu_s + \mu_b)^{N_{\rm event}}}{N_{\rm event}!} \times \prod_{n=1}^{N_{\rm event}} \left[\frac{\mu_s}{\mu_s + \mu_b} S(\vec{R}_n) + \frac{\mu_b}{\mu_s + \mu_b} B(\vec{R}_n) \right]$$

Where:

- N_{event} is the total number of recorded events
- μ_s and μ_b are the expected number of WIMP and background events
- S and B are the normalised directional rate for WIMP and background events

II.e The MCMC analysis

Interest of the Markov Chain Monte Carlo sampling:

• Size of the parameter space
• Reduced computational time compared to a grid calculation
• Precision on the estimation of the PDFs

Metroplis-Hastings algorithm with 2 different proposal functions:

• Multivariate gaussian
• Multivariate gaussian using the covariance matrix V

MCMC characteristics:

• 10-100 chains randomly started in the parameter space.
• Sub-sampling: « burn-in » and correlation lenghts => independant samples
• Chain convergence checked

Results from a simulated directional detection experiment

MIMAC characteristics

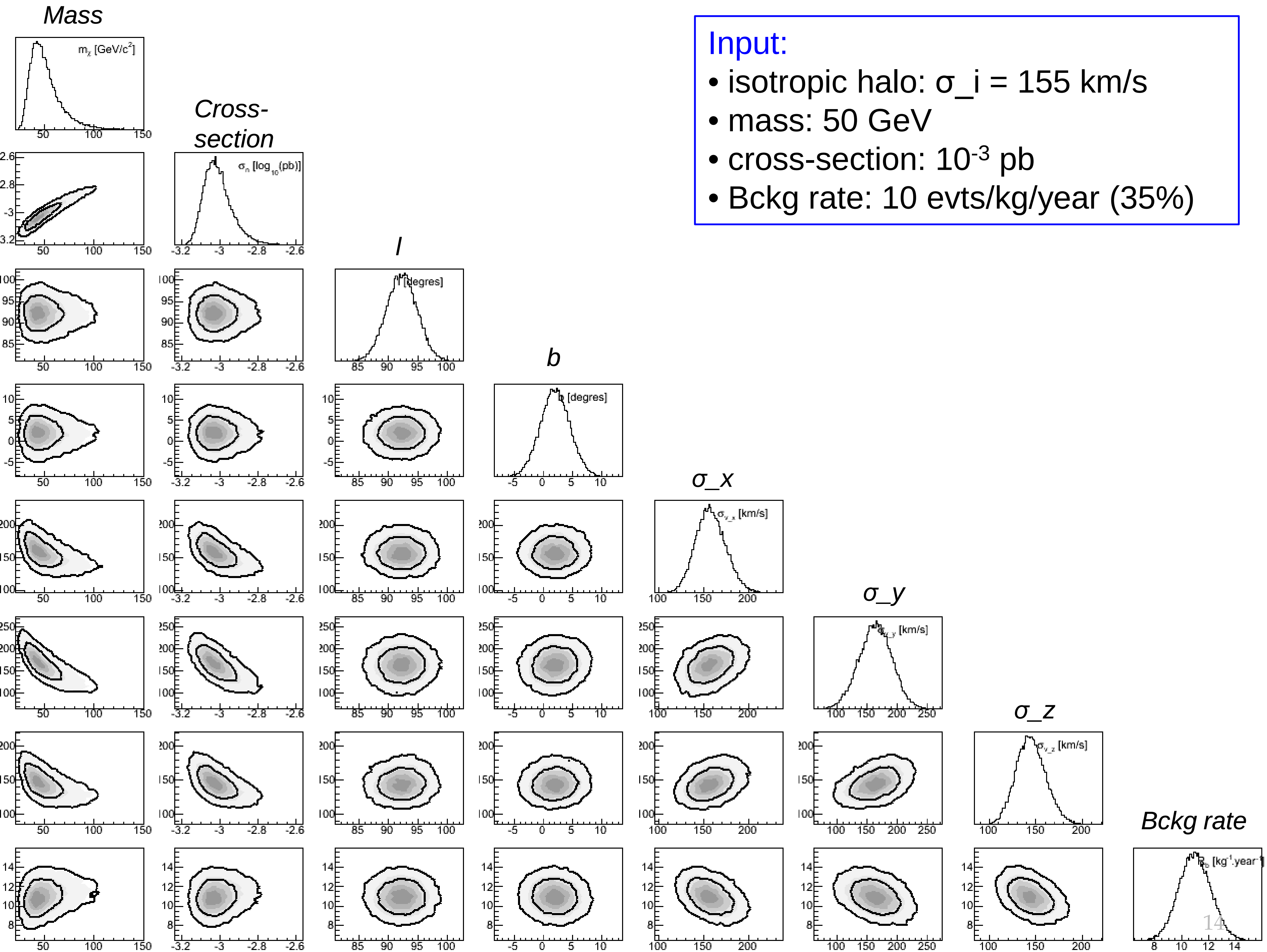
-10 kg CF_4 => 50 m^3 @ 50 mbar

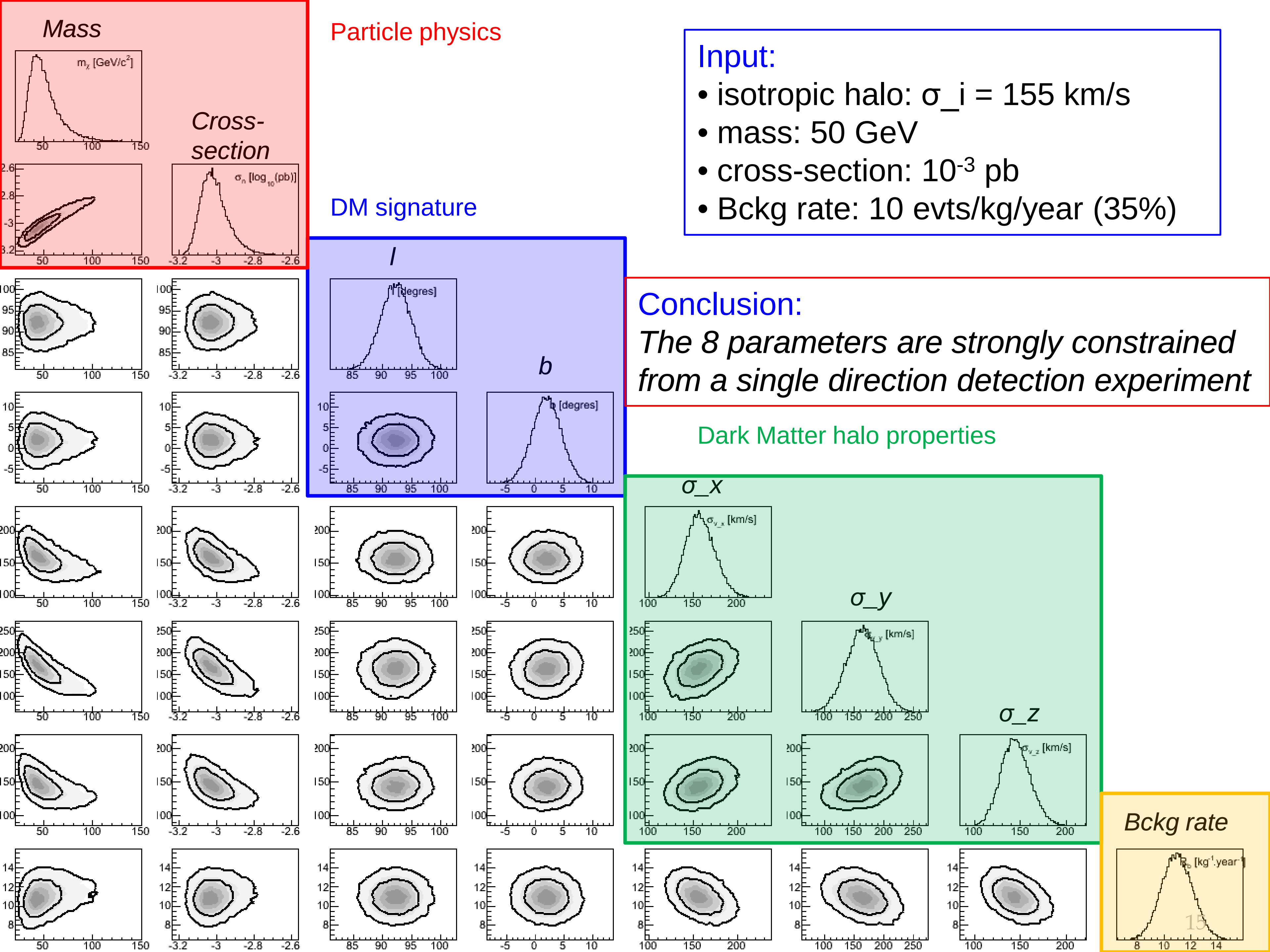
- DAQ : 3 years

- Recoil energy [5, 50] keV

Input:

- isotropic halo: σ_i = 155 km/s
- mass: 50 GeV
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)





Input:

- isotropic halo: σ_i = 155 km/s
- mass: 50 GeV
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)

Conclusion:

The 8 parameters are strongly constrained from a single direction detection experiment

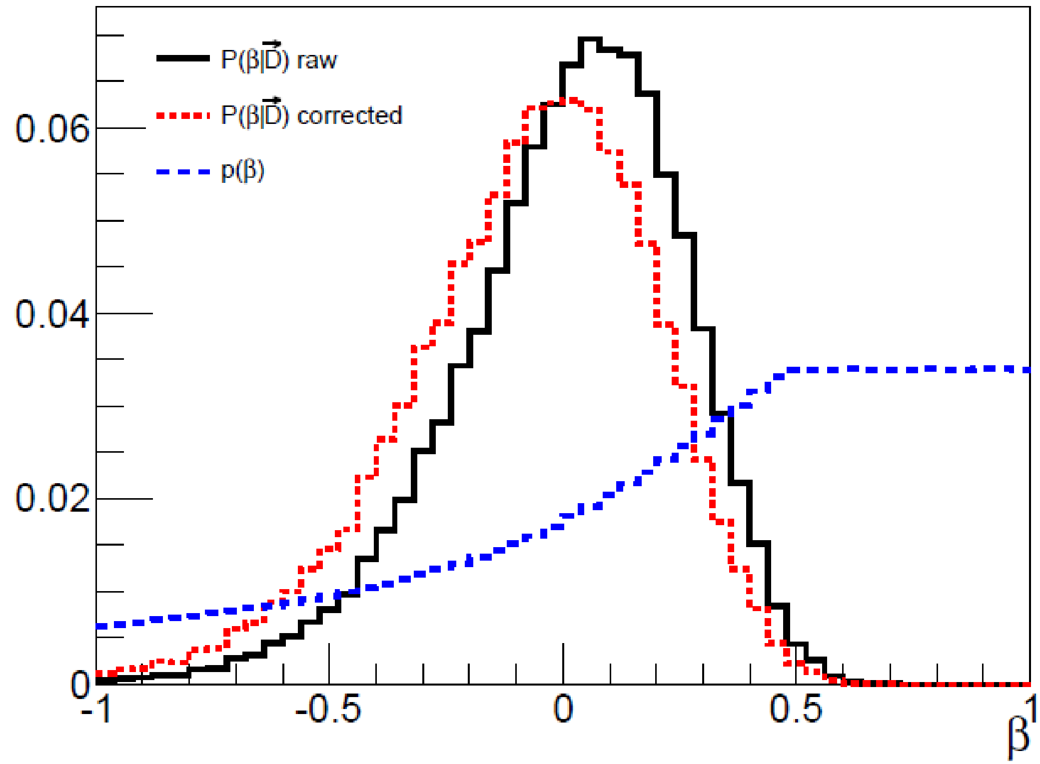
III.e Constraint on the velocity anisotropy

The PDF of the ß parameter can be deduced from: $$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$$

With a flat prior on the σ_i

Induced prior

With a flat prior on ß



Excellent constraint on the ß parameter from a single directional detection experiment:

$$\beta = -0.073^{+0.29}_{-0.18} \; (68\% \; CL)$$

Effect of input parameters

MIMAC characteristics

-10 kg CF_4 => 50 m^3 @ 50 mbar

- DAQ : 3 years

- Recoil energy [5, 50] keV

III.e Input WIMP mass

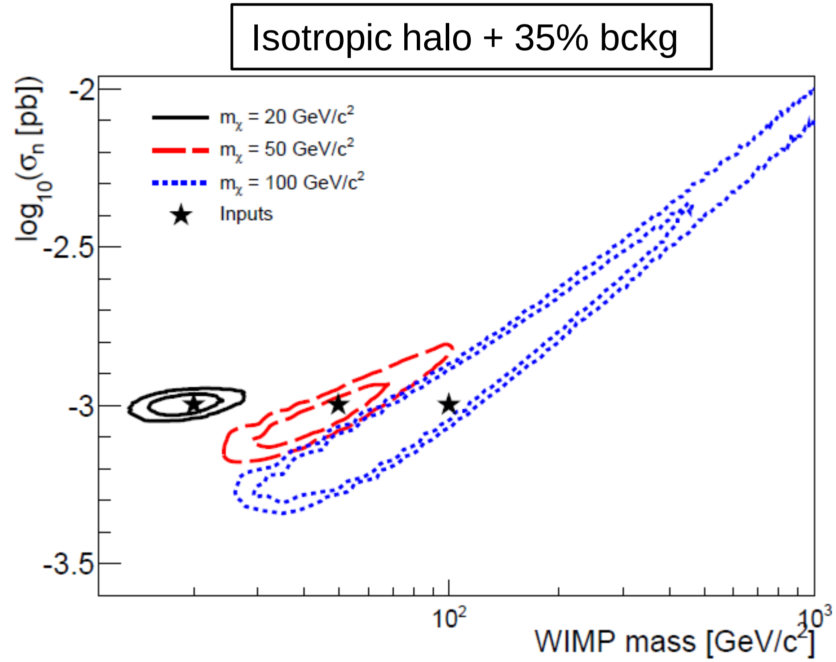
Isotropic halo (ß = 0) with three different masses:

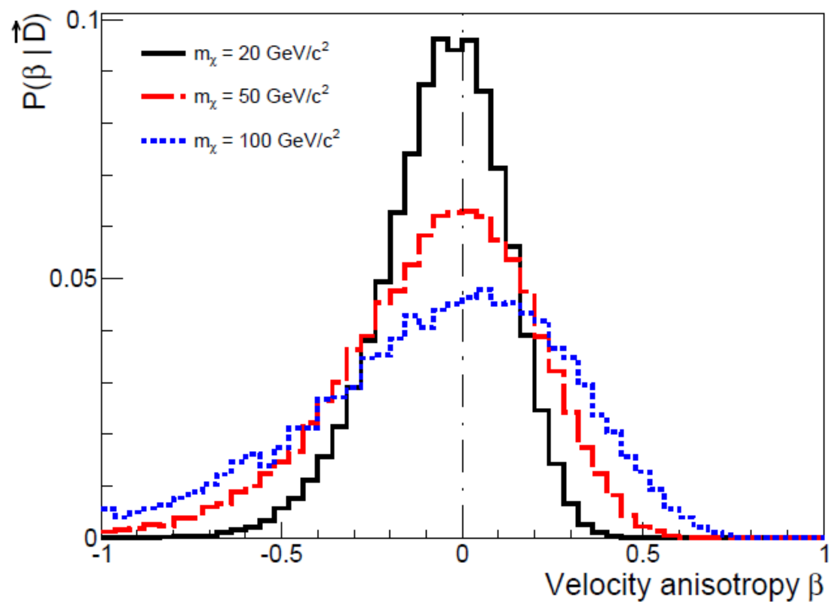
- 20 GeV
- 50 GeV
- 100 GeV

The ß parameter is always constrained:

- 20 GeV ⟶ $\beta = -0.056^{+0.19}_{-0.12}$
- 50 GeV ⟶ $\beta = -0.073^{+0.29}_{-0.18}$
- 100 GeV ⟶ $\beta = -0.105^{+0.41}_{-0.24}$

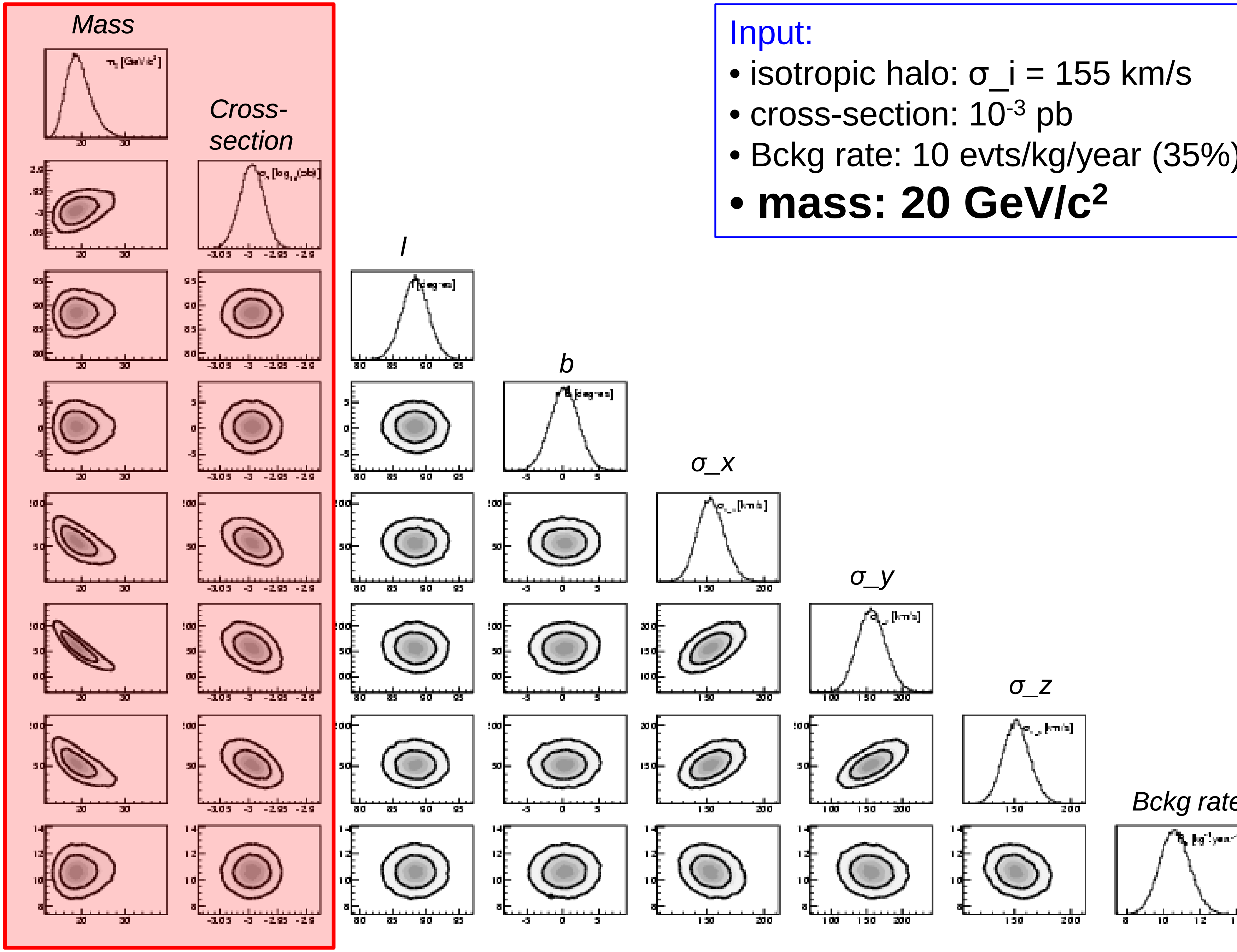
Heavy WIMP implies less stringent constraints

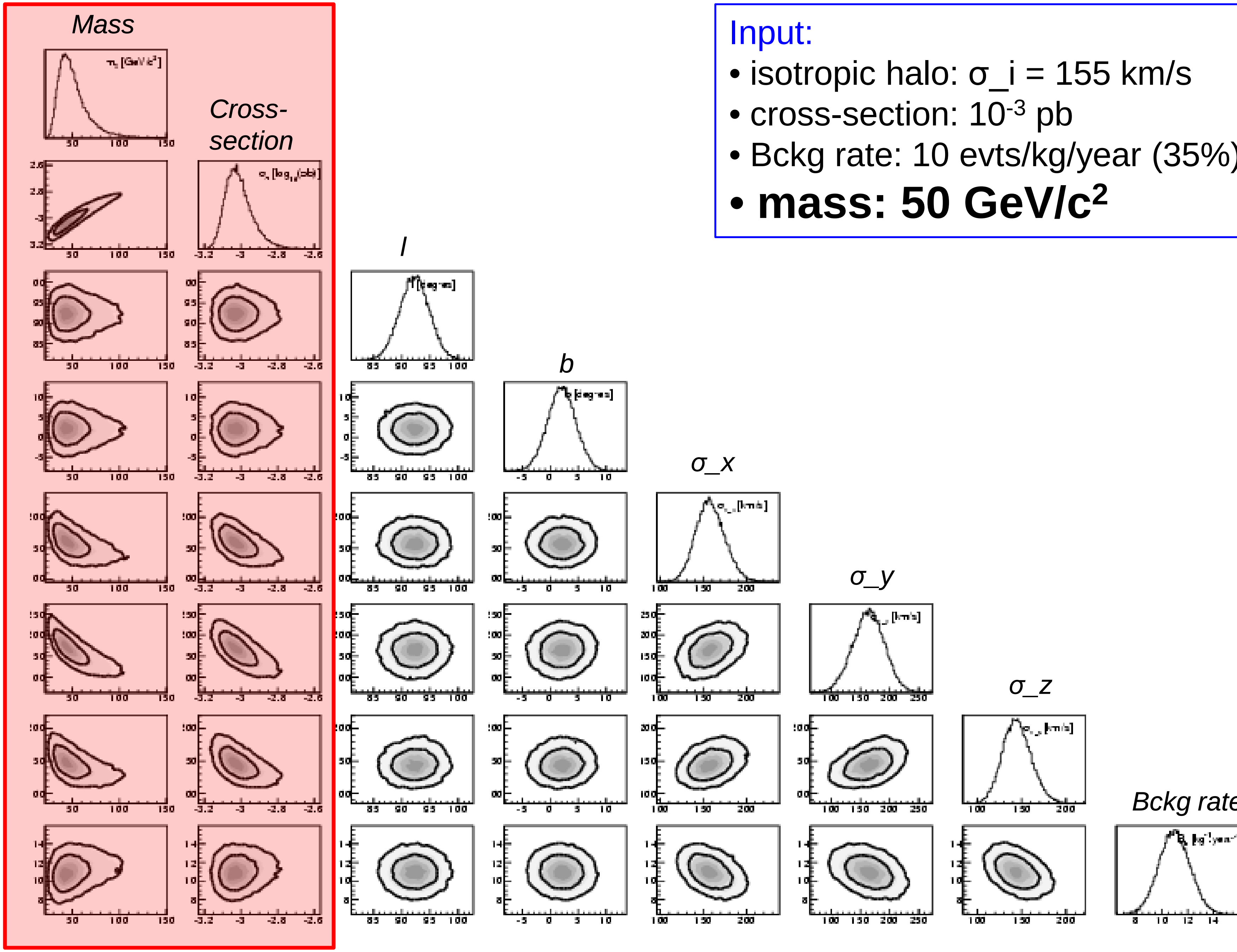




Input:

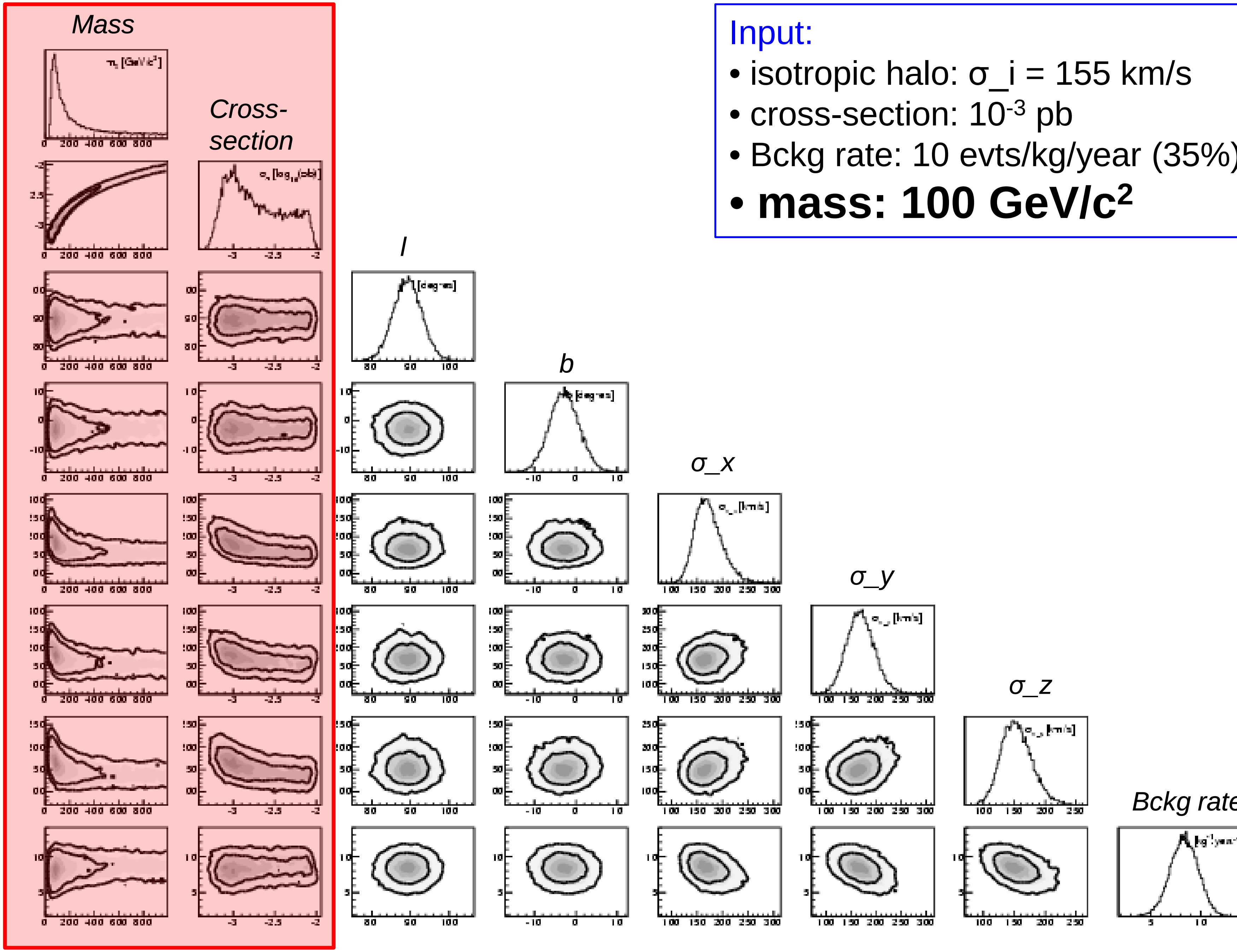
- isotropic halo: σ_i = 155 km/s
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)
- **mass: 20 GeV/c²**





Input:

- isotropic halo: σ_i = 155 km/s
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)
- **mass: 50 GeV/c²**



Input:

- isotropic halo: σ_i = 155 km/s
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)
- **mass: 100 GeV/c^2**

III.e Input halo model

2 input halo models:

Isotropic (ß = 0)
Anisotropic (ß = 0.4)

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

The ß parameter is well constrained:

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

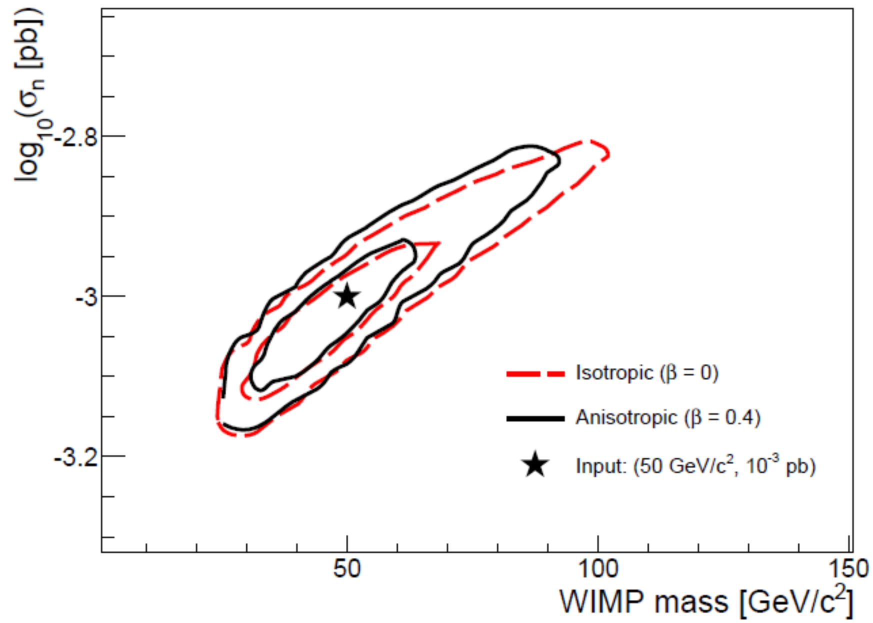
Anisotropic ⟶ $\beta = 0.38^{+0.18}_{-0.10}$

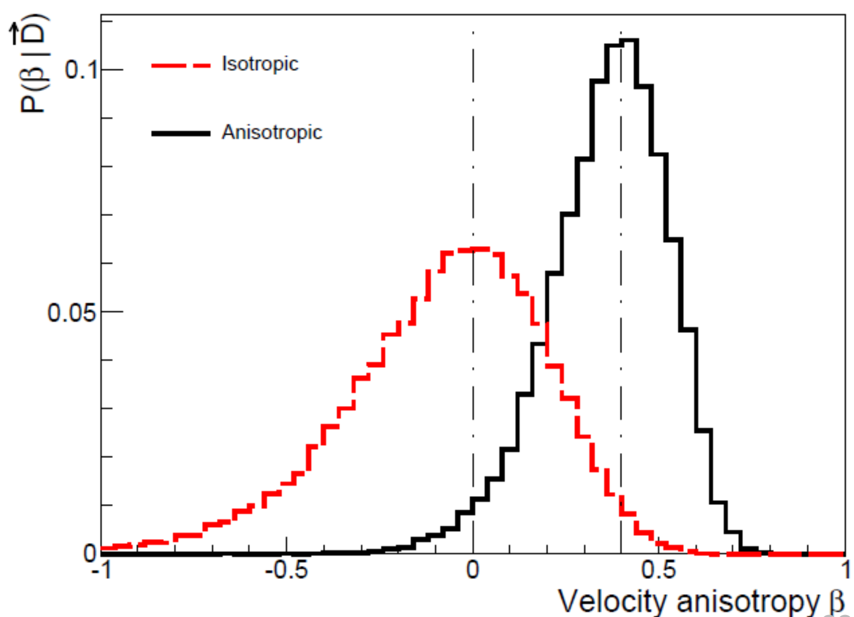
This method allows to:

- Constrain the Dark Matter halo properties

- Constrain the WIMP properties in a « quasi model-independent » analysis

35% of bckg + 50 GeV/c²





III.e Input Background model

We used 3 input background models:

- No background (optimistic)
- Flat background
- Exponential background (pessimistic)

Similar to the expected WIMP spectrum

The ß parameter is well constrained:

No background → $\beta = 0.049^{+0.26}_{-0.10}$

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

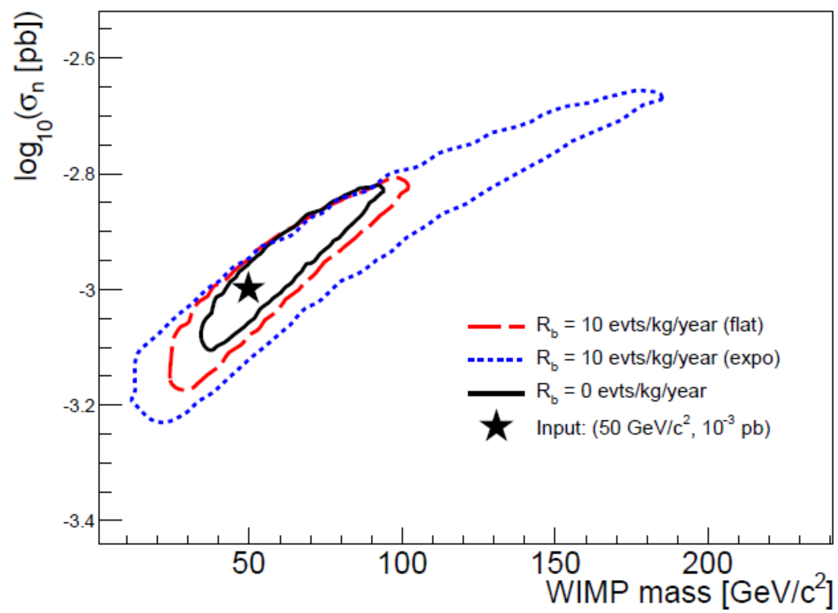
Exponential → $\beta = -0.20^{+0.26}_{-0.21}$

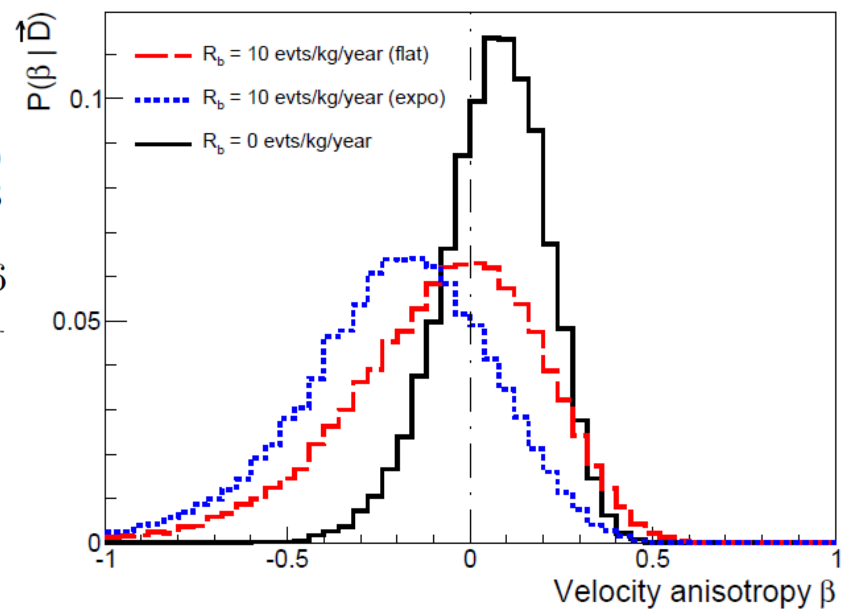
For each background model we have:

- Constraints on the Dark Matter halo

- Constraints on the WIMP properties

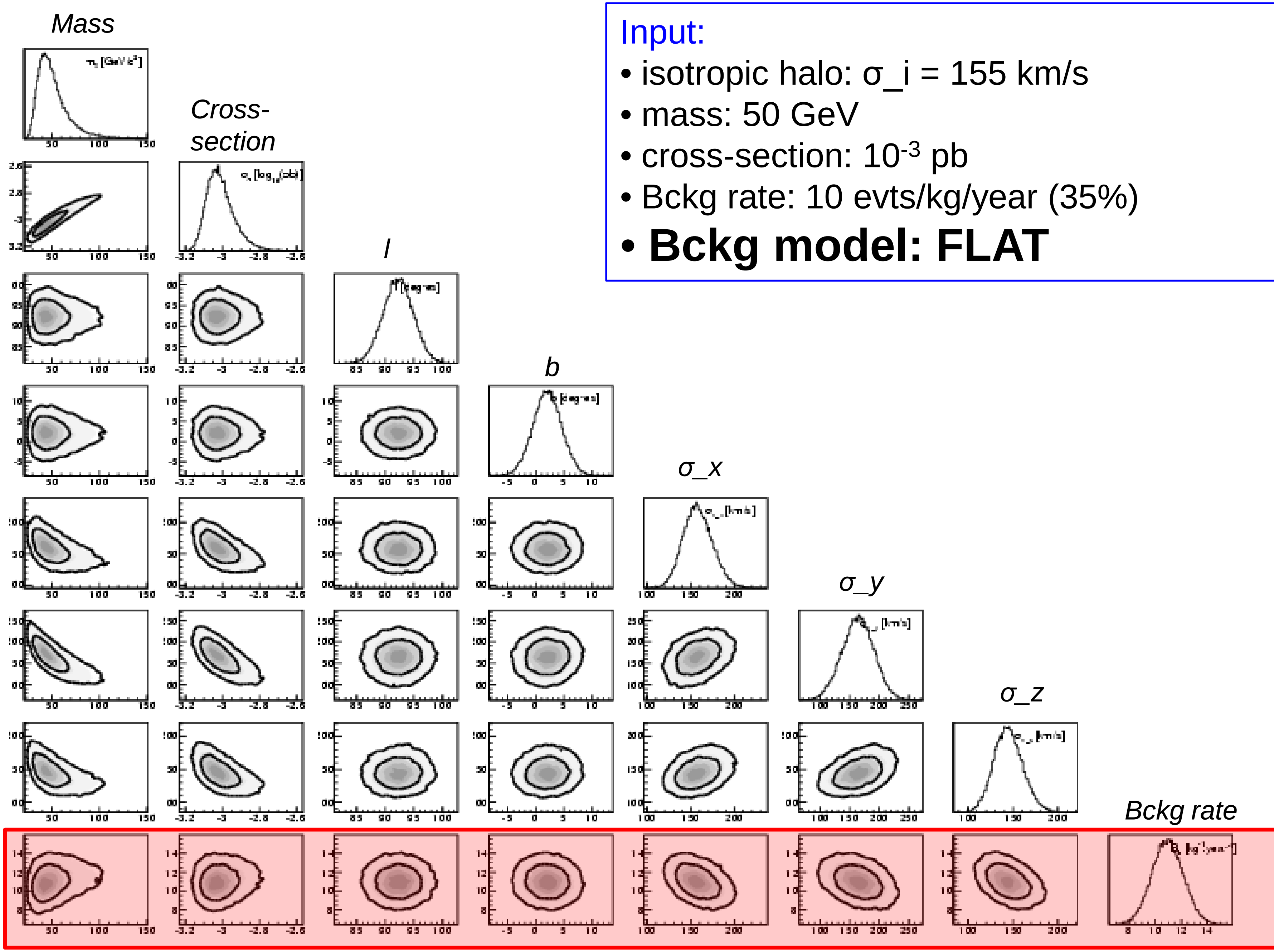
Isotropic halo + 50 GeV/c^2





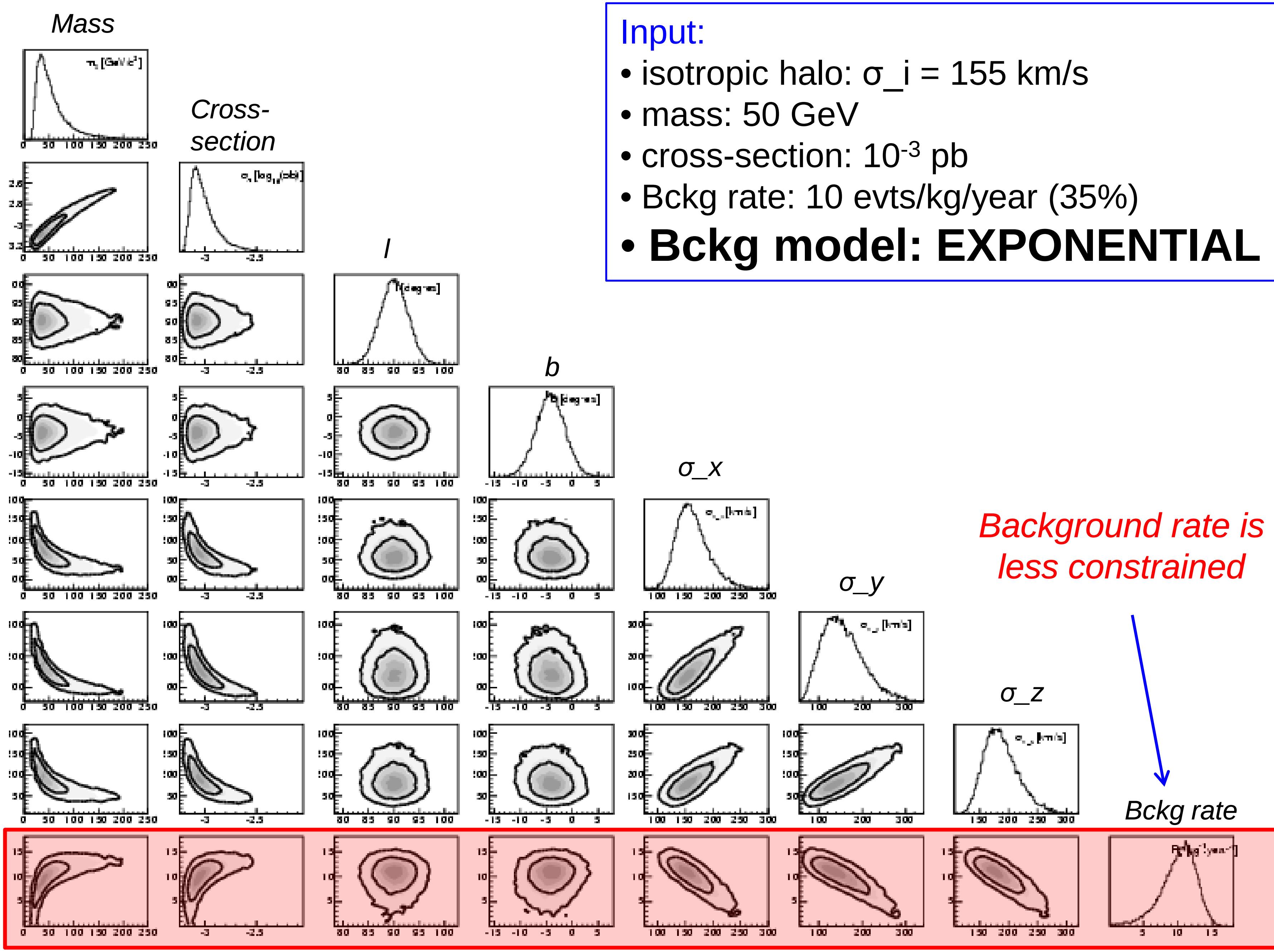
Input:

- isotropic halo: σ_i = 155 km/s
- mass: 50 GeV
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)
- **Bckg model: FLAT**



Input:

- isotropic halo: σ_i = 155 km/s
- mass: 50 GeV
- cross-section: 10^{-3} pb
- Bckg rate: 10 evts/kg/year (35%)
- **Bckg model: EXPONENTIAL**



Conclusions & discussion

Developement of a « quasi model-independent » MCMC analysis dedicated to directional detection (MIMAC)

The main assumption is: *WIMP velocities are Gaussian distributed*

Main results:

- Constraints on the WIMP velocity distribution
- Constraints on the WIMP properties
- Identification of a genuine WIMP positive detection

works for any input

Going further:

Use of N-Body generated Dark Matter haloes to evaluate effects of substructures: dark-disk, clumps, streams,…

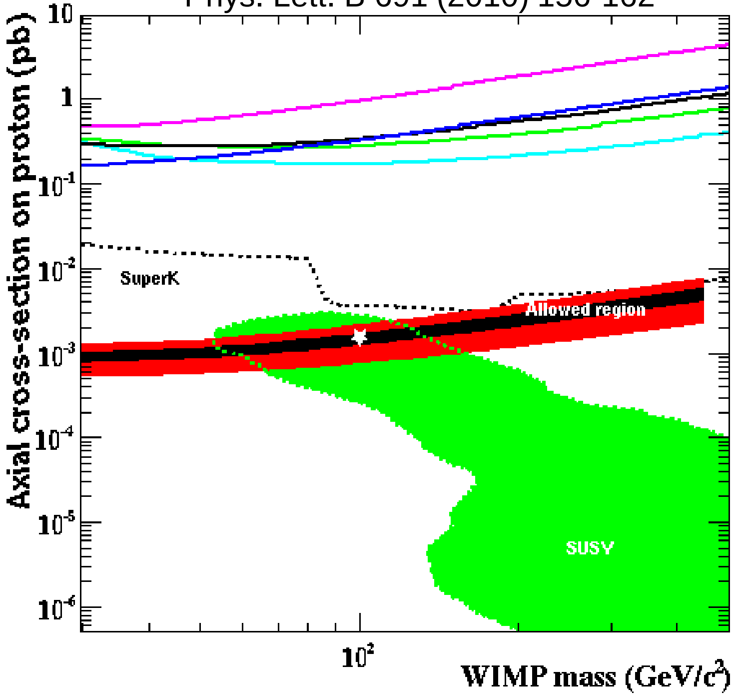
I.c Directional analysis

Using a dedicated statistical methods applied to directional data

2 possible scenarios

Discovery of Dark Matter

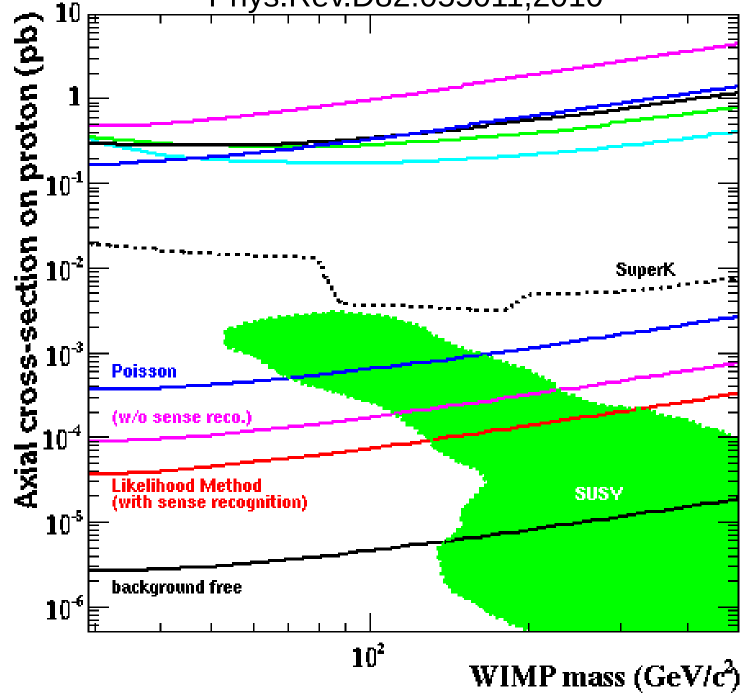
Phys. Lett. B 691 (2010) 156-162



High SD WIMP-proton cross-section
(down to ~10^{-4} pb)
High significance discovery of DM

Exclusion of Dark Matter

Phys.Rev.D82:055011,2010



Low SD WIMP-proton cross-section
(down to ~10^{-4} ,10^{-6} pb)
Competitive exclusion limits

III.c Analyse d'une chaine de Markov

Il y a trois critères très important à prendre en compte:

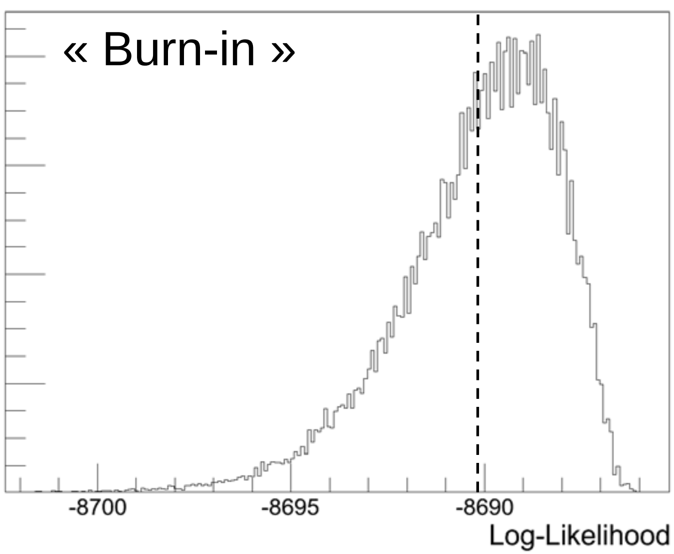
1. La longueur de « Burn-in » *b* définie telle que: $p(\vec{\theta}_b) > E[p(\vec{\theta})]$

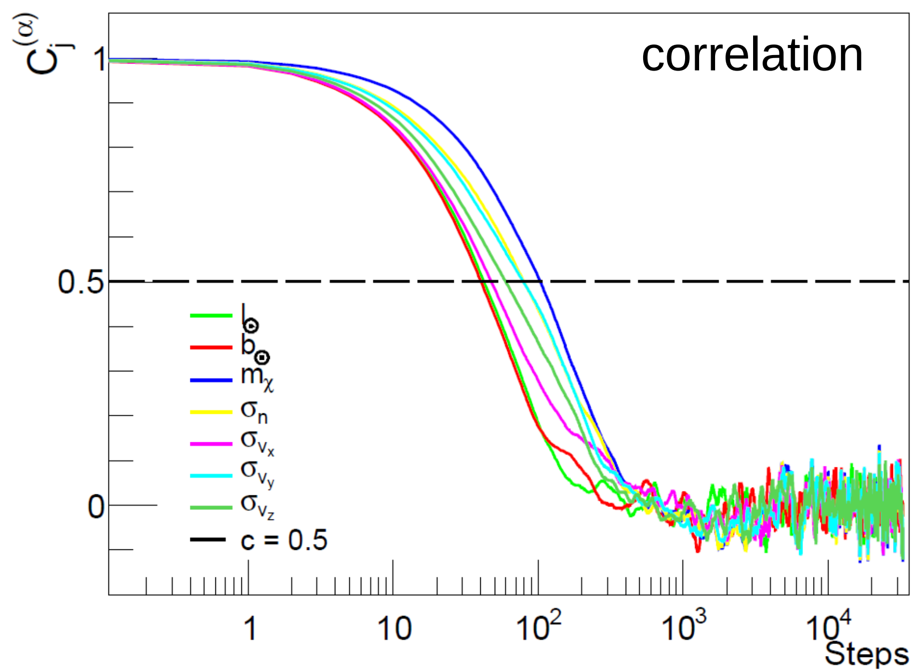
2. La longueur de corrélation *l* définie telle que: $l = \max[l^{(1)}, ..., l^{(\alpha)}, ..., l^{(m)}]$

Chaque $l^{(\alpha)}$ est défini comme étant égal au plus petit indice j tel que:

$$c_j^{(\alpha)} < 1/2$$

Avec $c_j^{(\alpha)}$ la fonction d'autocorrélation (FFT) du paramètre α



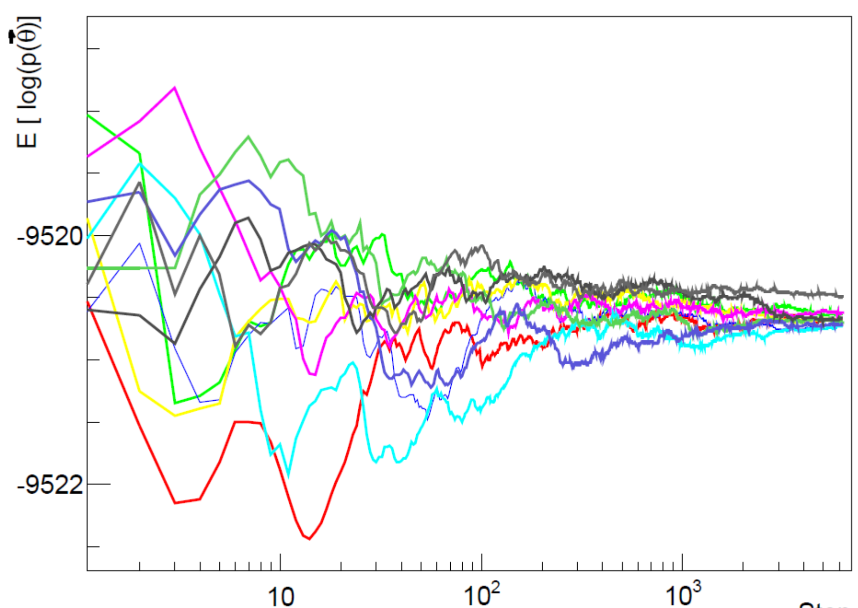


III.c Analyse d'une chaine de Markov

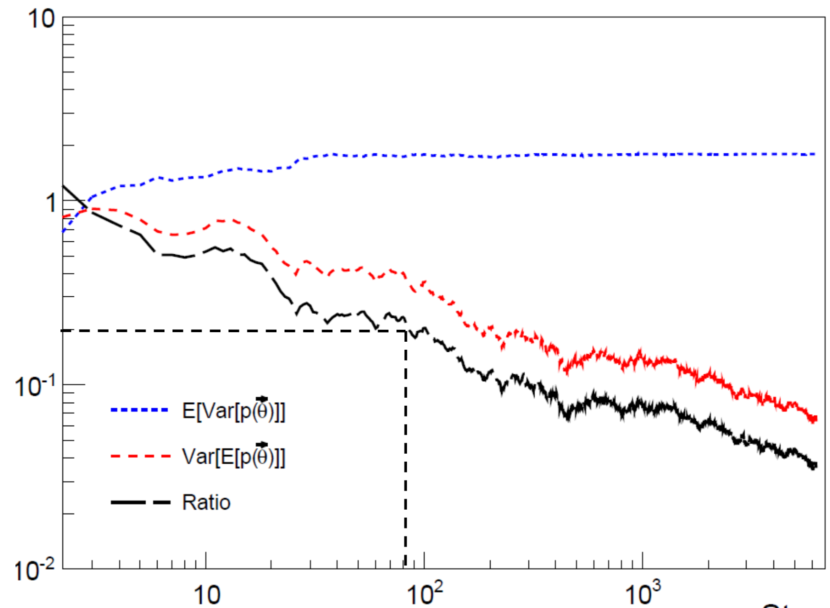
On effectue donc du *sub-sampling* pour ne récupérer que les échantillons indépendants tel que: $\vec{\theta}_{i=b+kl}$

3. Critère de convergence: Il est défini par le ratio qui doit être inférieur à une limite r_c

$$r = \frac{\mathrm{Var}\left[\mathrm{E}(p(\vec{\theta}))\right]}{\mathrm{E}\left[\mathrm{Var}(p(\vec{\theta}))\right]}$$



Moyenne du Log-Likelihood en fonction du nombre d'échantillons indépendants



Evolution du ratio r en fonction du nombre d'échantillons indépendants