Dark matter direct detection: a closer look at the astrophysical uncertainties

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R. C. and P. Ullio, JCAP **1008** (2010) 004
R. C. and P. Ullio, in preparation

- Expected signal at a dark matter direct detection experiment

$$\frac{dR}{dQ} = \frac{\rho^0_{\rm DM}}{M_\chi} \int_{|\vec{u}| \geq u_{\rm min}} d^3\vec{u}\, f(\vec{u})\, |\vec{u}|\, \frac{d\sigma}{dQ}$$

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Outline

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1. The Galactic Model
2. Datasets
3. Analysis: Bayesian approach
4. Results
   - Model parameters and local density
   - Local velocity distribution
   - Rate and exclusion limit
5. Conclusions

Outline

Galactic Model

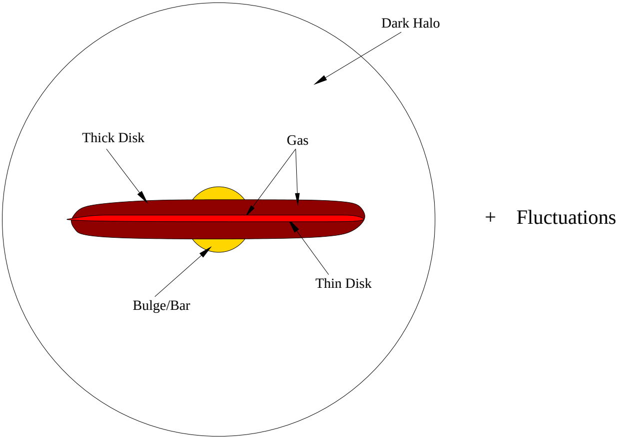


Figure: Schematic representation of the Galaxy

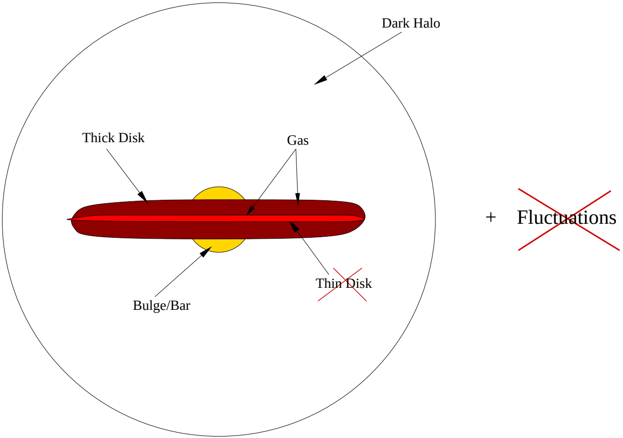


Figure: Schematic representation of the assumed Galactic model

- The stellar disk:

$$\rho_d(R,z) = \frac{\Sigma_d}{2z_d}\, e^{-\frac{R}{R_d}}\, \mathrm{sech}^2\left(\frac{z}{z_d}\right)$$

- The stellar bulge/bar:

$$\rho_{bb}(R,z) = \rho_{bb}^{(0)}\left[\exp\left(-\frac{s_b(R,z)^2}{2}\right) + s_a(R,z)^{-1.85}\,\exp(-s_a(R,z))\right]$$

- The Dark Matter halo:

$$\rho_h(R) = \rho' f\left(\frac{R}{a_h}\right),$$

where f is the Dark Matter profile.

- M_{vir}, and c_{vir} as halo parameters:

$$\rho' = \rho'(M_{\rm vir}, c_{\rm vir})$$

$$a_h = a_h(M_{\rm vir}, c_{\rm vir})$$

- The Dark Matter profile:

$$f_E(x) = \exp\left[-\frac{2}{\alpha_E}(x^{\alpha_E} - 1)\right]$$

J.F. Navarro et al., MNRAS **349** (2004) 1039.
A.W. Graham, D. Merritt, B. Moore, J. Diemand and B. Terzic, Astron. J. **132** (2006) 2701.

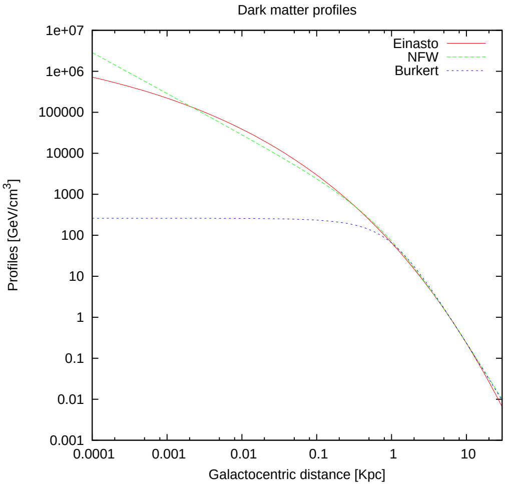
$$f_{NFW}(x) = \frac{1}{x(1+x)^2}$$

J.F. Navarro, C.S. Frenk and S.D.M. White, Astrophys. J. **462**, 563 (1996); Astrophys. J. **490**, 493 (1997).

$$f_B(x) = \frac{1}{(1+x)\,(1+x^2)}.$$

A. Burkert, Astrophys. J. **447** (1995) L25.

The underlying Galactic Model



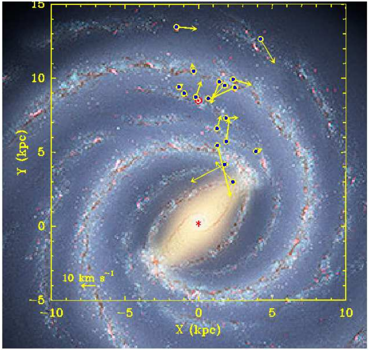
Parameters	Interpretation
f_b	fraction of collapsed baryons
Γ	bulge/disk masses ratio
R_d	disk radial scale
R_0	Sun's galactocentric distance
$M_{\rm vir}$	virial mass
$c_{\rm vir}$	concentration parameter
α_E	Einasto slope parameter
$\beta_\star$	halo stars anisotropy

Datasets

Constraints:

- proper motion of stars in the outer Galaxy

M. J. Reid *et al.* (2009)

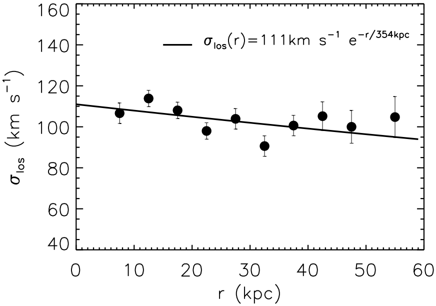


Constraints:

- proper motion of stars in the outer Galaxy

- radial velocity dispersion of halo stars

X. X. Xue *et al.* (2008)



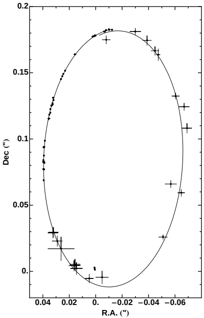
Constraints:

- proper motion of stars in the outer Galaxy

- radial velocity dispersion of halo stars

- stellar motions around the Galactic Center

S. Gilessen *et al.* (2009)



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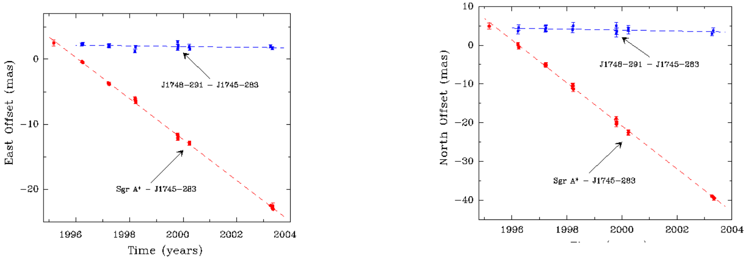
- peculiar motion of SgrA^*

M. J. Reid *et al.* (2004)



Constraints:

- proper motion of stars in the outer Galaxy

- radial velocity dispersion of halo stars

- stellar motions around the Galactic Center

- peculiar motion of SgrA^*

- Oort's constants

- terminal velocities

- total mean surface density within $|z| < 1.1\mathrm{kpc}$

- local disk surface mass density

- total mass inside 50 kpc and 100 kpc

Analysis

Parametric model of the Galaxy
- Frequentist approach $\Longrightarrow$ Maximum Likelihood
- Bayesian approach $\Longrightarrow$ Posterior probability density

- This work $\rightarrow$ Bayesian approach

- Target: posterior pdf (Bayes' theorem):

$$p(\vec{\eta}|\vec{d}) = \frac{\mathcal{L}(\vec{d}|\vec{\eta})\pi(\vec{\eta})}{p(\vec{d})} \, ; \qquad \vec{d} = \mathrm{data}\, ; \qquad \vec{\eta} = \mathrm{parameters}$$

- Output: the mean and the variance of functions $f(\vec{\eta})$, *e.g.* :

$$\langle f(\vec{\eta}) \rangle = \int d\vec{\eta} f(\vec{\eta}) p(\vec{\eta}|\vec{d})$$

- We will focus on:

1) $f = \eta^i$

2) $f =$ local density

3) $f =$ velocity distribution

1) Calculate the phase space density ($E \equiv E(v)$)

$$F_{DM}(E) = \frac{1}{\sqrt{8}\pi^2} \int_0^E \frac{d^2 \rho_{DM}}{d\psi^2} \frac{d\psi}{\sqrt{E - \psi}}$$

2) Derive the dark matter velocity distribution function in the Galactic rest frame

$$f(v, \vec{\eta}) = \frac{F_{DM}(\vec{\eta}, v)}{\rho^0_{DM}(\vec{\eta})}$$

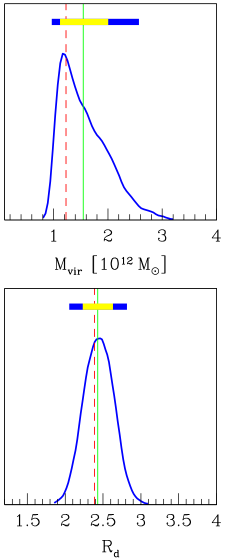
3) Analyze separately N velocity bins u_i with $i = 1, ..., N$ in the detector rest frame

$$g_i(\vec{\eta}) = \int d\Omega \, u_i f(v_i(u_i), \vec{\eta})$$

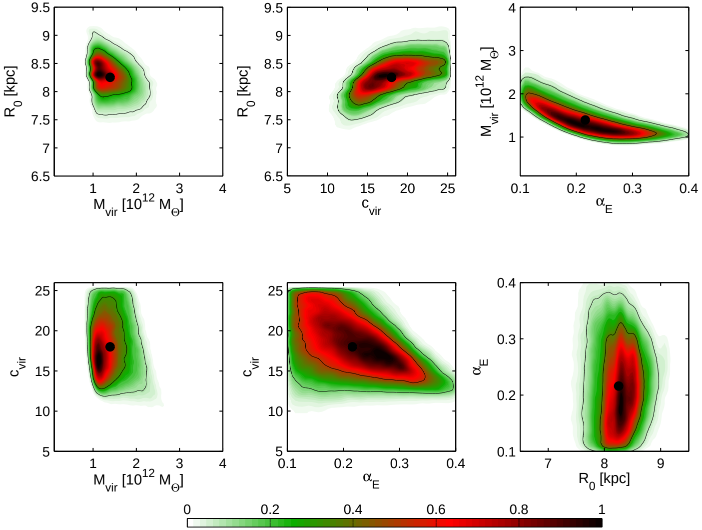
Results:

Model parameters and local density

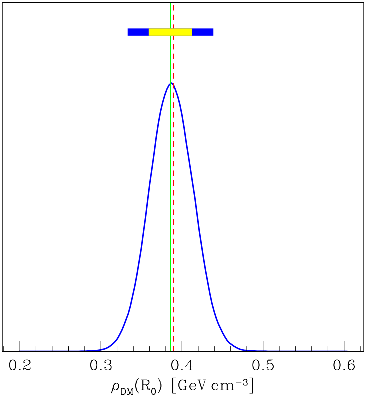
1D marginal posterior pdf: model parameters (Einasto)



2D marginal posterior pdf: model parameters (Einasto)



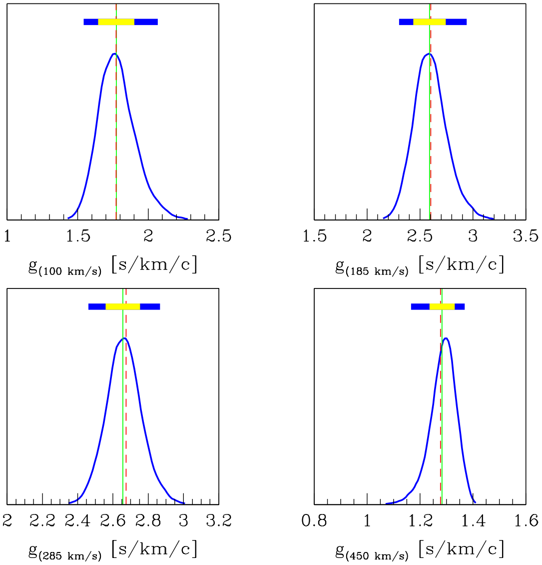
1D marginal posterior pdf: the dark matter local density (Einasto)



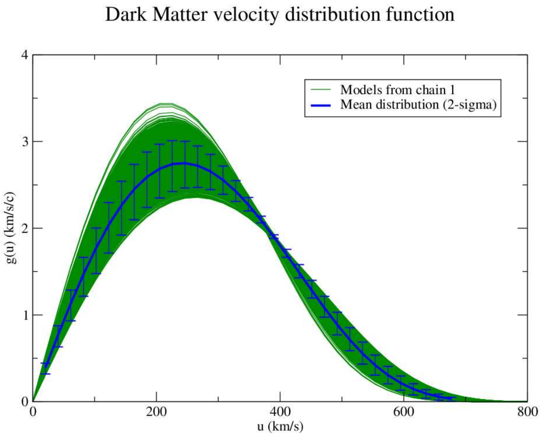
Results:

local velocity distribution

Posterior pdf for the velocity distribution at some velocity bins



Galactic model parameters → velocity distribution



Results:

rate and exclusion limit

We can now analyze:

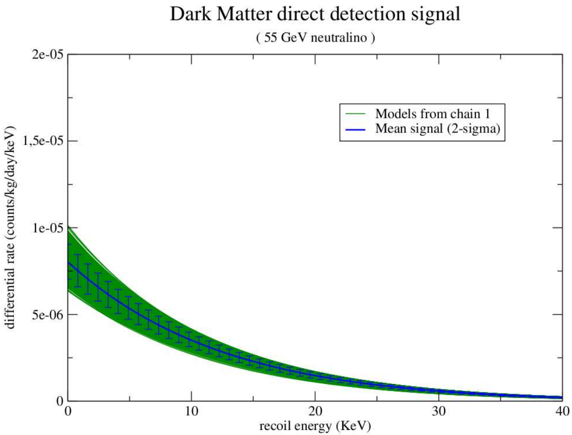
- Events rate evaluated at N energy bins Q_i

$$R_i(\vec{\eta}) = \frac{dR}{dQ}(\vec{\eta}, Q_i)$$

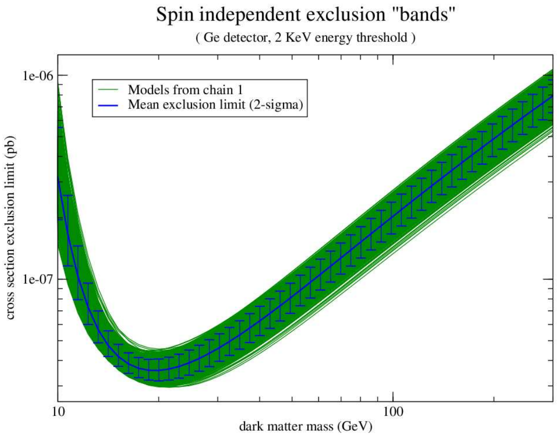
- Exclusion limit evaluated at M mass bins m_i

$$\sigma_i(\vec{\eta}) = \text{cross section} \times \frac{\text{background events}}{\text{signal at threshold}(m_i)}$$

Velocity distribution → signal



Signal → exclusion limit



Conclusion

- We proved that Bayesian probabilistic inference is a good method to constrain the local dark matter density and velocity distribution function.

- For a given dark matter profile, and assuming spherical symmetry, we can therefore estimate the local dark matter density with an accuracy of roughly the 10%.

- This result does not include a number of systematic uncertainties which are related to the galactic model, *e.g.*:
  - baryonic compression
  - non spherical dark matter halos
- The method can however account for such systematics.