The local dark matter phase-space density and impact on WIMP direct detection

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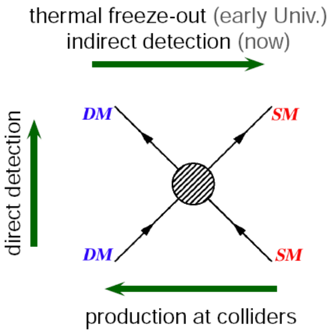
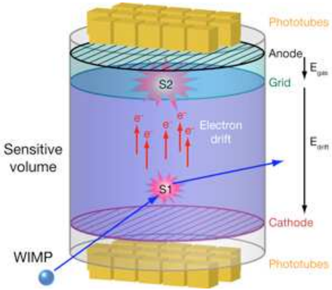
R. C. and P. Ullio, arXiv:1111.3556 [astro-ph.CO]

Overview

Dark Matter – Standard Model interactions:



Direct detection experimental setup:



- Dark matter direct detection: Computing the expected signal

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

- We will focus on the uncertainties on:

$$g(u) = \rho^0_{\rm DM} \int d\Omega \, |\vec{u}| \, f(\vec{u})$$

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Outline

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1. The Galactic Model
2. Datasets
3. Analysis: Bayesian approach
4. Results
   - Galactic model parameters and local density
   - Local phase-space density
   - Differential rate
5. Conclusions

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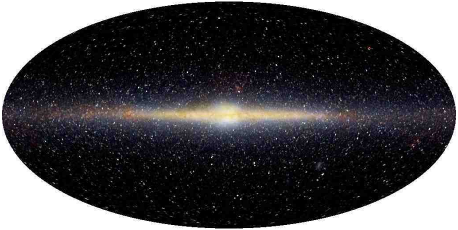
Galactic Model

The Milky Way



A three component mass model:

Stellar Disk + Bulge/Bar region + Dark Halo

- 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:

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

H. T. Freudenreich, Astrophys. J. **492**, 495 (1998)

- 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.

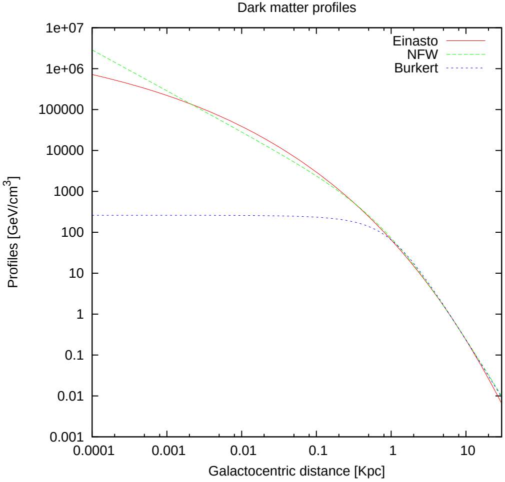
$$f_{NFW}(x) = \frac{1}{x(1+x)^2}$$

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



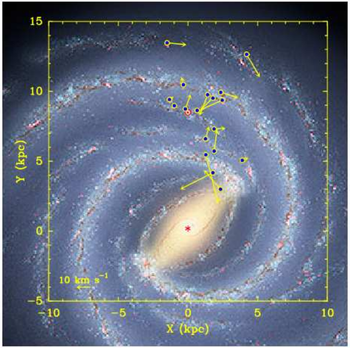
Parameter space

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)

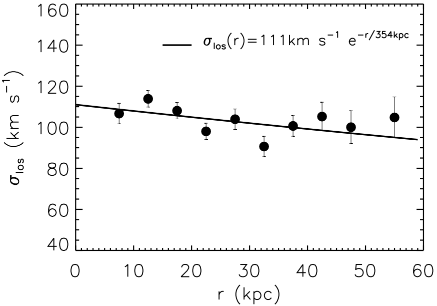


Constraints:

- proper motion of stars in the outer Galaxy

- radial velocity dispersion of halo stars

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

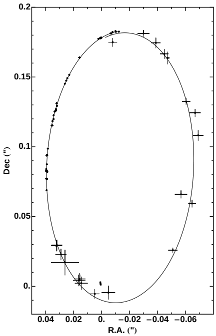


Constraints:

- 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)



The experimental constraints

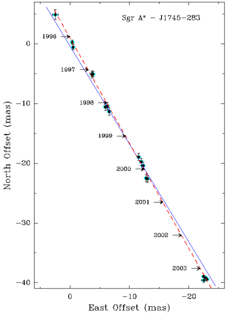
Constraints:

- proper motion of stars in the outer Galaxy

- radial velocity dispersion of halo stars

- stellar motions around the Galactic Center

- peculiar motion of SgrA^*
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

The method: 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: means and credible regions of functions $f(\vec{\eta})$, *e.g.* :

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

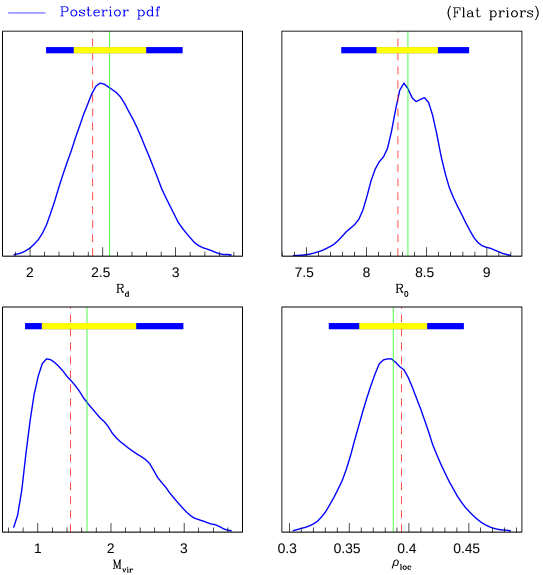
- Examples:

1) $f = \eta^i$
2) $f = \rho^0_{\mathrm{DM}}$
3) $f = g(u)$
4) $f = \frac{dR}{dQ}$

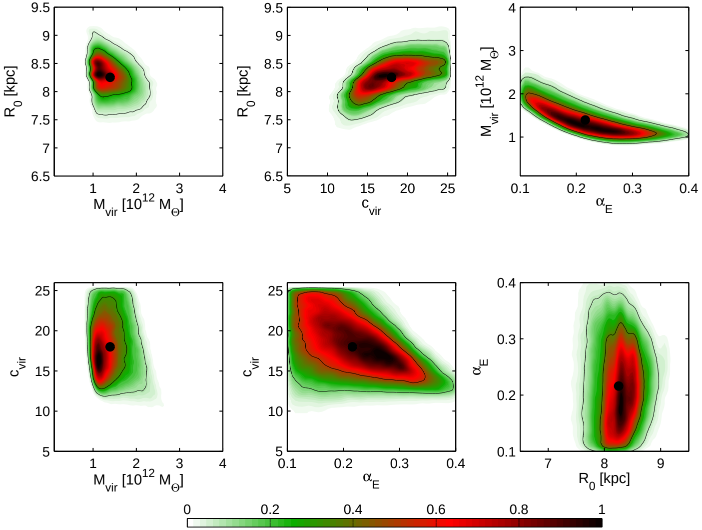
Results:

model parameters and local density

1D marginal posterior pdf (Einasto)



2D marginal posterior pdf: model parameters (Einasto)



Results:

local phase-space density

Phase-space density via Eddington's inversion formula

1) Invert the relation $\rho_{\rm DM} = \int d^3v\, F_{DM}(v)$:

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

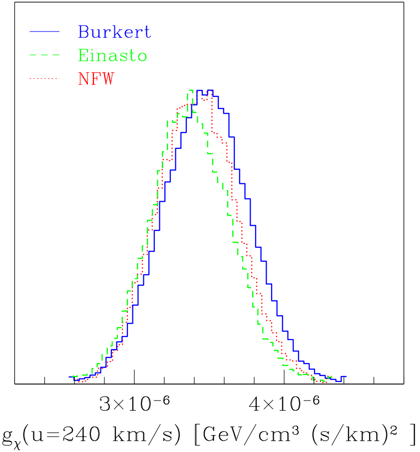
ψ is the *total* gravitational potential.

2) Velocity transformation from the Galactic frame (v) to the detector rest frame (u):

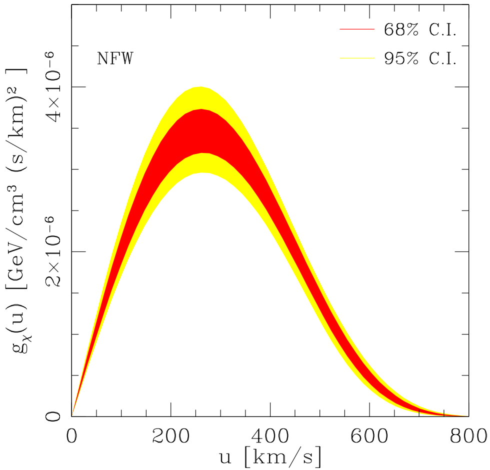
$$g(u;\vec{\eta}) = \int d\Omega\, u F_{DM}(v(u);\vec{\eta})$$

Posterior pdf for the phase-space density (one bin)

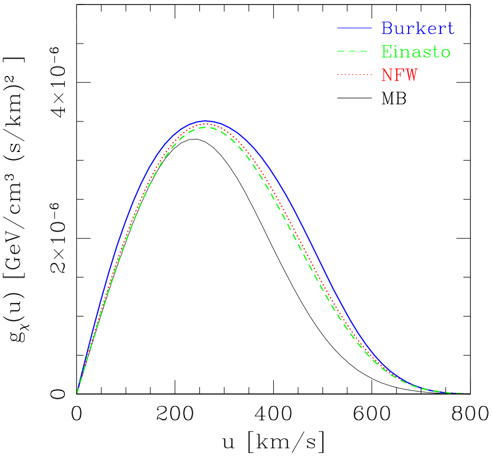
$$f(\vec{\eta}) = g(\bar{u}, \vec{\eta}); \qquad \bar{u} = 240\,\mathrm{km\,s}^{-1}$$



Posterior pdf for the phase-space density (all bins)



Posterior pdf for the phase-space density: all bins, three profiles



Results:

differential rate

Differentail Rate as functions of the GM parameters

- Event rate evaluated at N energy bins Q_i

$$R_i(\vec{\eta}) = \frac{dR}{dQ}(\vec{\eta}, Q_i) = \frac{1}{M_N M_\chi} \int_{|\vec{u}| \geq u_{\min(Q_i)}} du\, u^2\, g(u, \vec{\eta})\, \frac{d\sigma}{dQ}(Q_i)$$

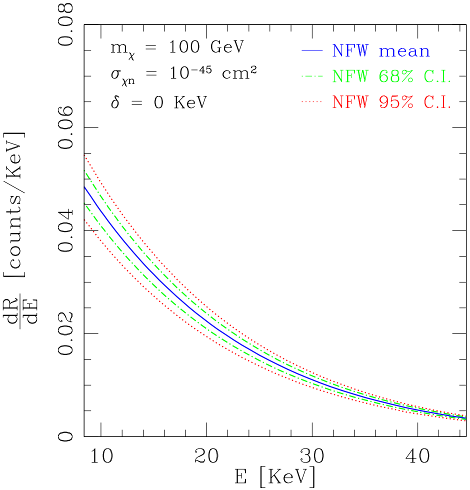
Elastic Scattering

$$u_{\min} = \sqrt{\frac{M_N Q_i}{2\mu^2}}$$

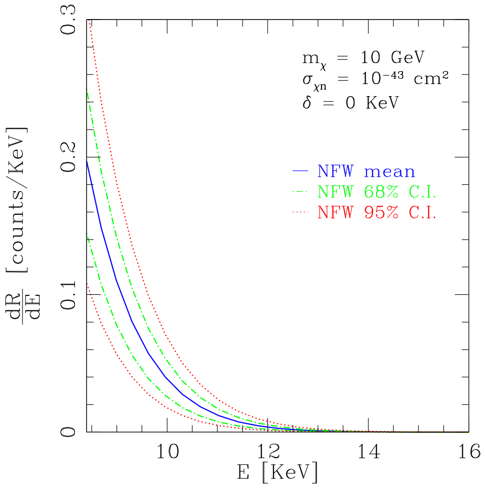
Inelastic Scattering

$$u_{\min} = \sqrt{\frac{1}{2 M_N Q_i}} \left(\frac{M_N Q_i}{\mu} + \delta \right)$$

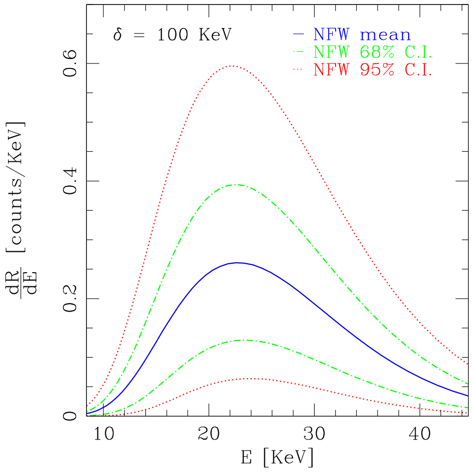
Posterior pdf for the differential rate: elastic case



Posterior pdf for the differential rate: elastic case

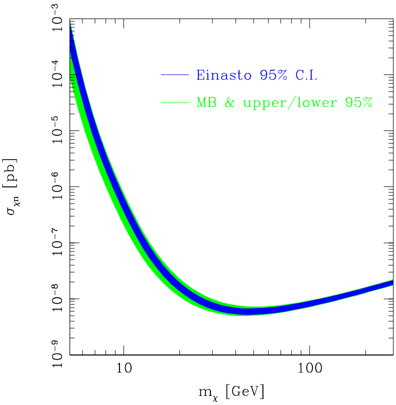


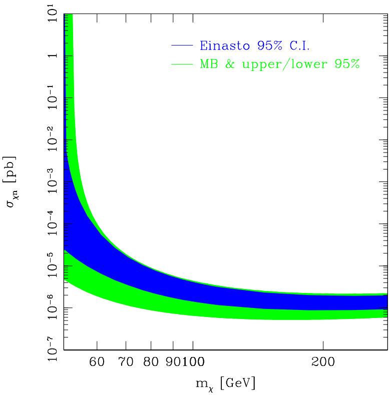
Posterior pdf for the differential rate: inelastic case



Posterior pdf for the exclusion limit

Left: elastic case. Right: inelastic case.





Conclusion

- We proved that Bayesian probabilistic inference is a good method to constrain the local dark matter density and phase-space density.
- 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%.
- The local dark matter phase-space density can be also determined with this method.
- Concerning the signals, astrophysical uncertainties are more relevant for the case of inelastic scattering.
- These results do 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.