A novel determination of the local dark matter density

Riccardo Catena

Institut für Theoretische Physik, Heidelberg

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R. Catena and P. Ullio, arXiv:0907.0018 [astro-ph.CO].

- Direct detection signals depend from dark halo properties.

- Example : Spin-independent dark matter-nucleus scattering.

- The expected event rate reads

$$\frac{dR}{dE_r} = \frac{\sigma_p \, \rho_{DM}(R_0)}{2\mu^2_{p,DM} m_{DM}} \langle \int_{v_{\min}}^{\infty} \frac{f_{DM}(v,t)}{v} dv \rangle A^2 F^2(E_r)$$

- It crucially depends on $\rho_{DM}(R_0)$ (this talk) and $f_{DM}(\vec{v},t)$.

1. The underlying Galactic Model
2. The experimental constraints
3. The method:Bayesian inference with Markov Chain Monte Carlo
4. Results and Conclusions

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Outline

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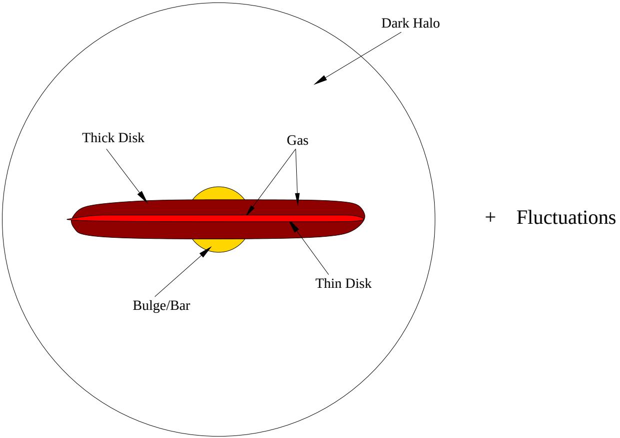


Figure: Schematic representation of the Galaxy

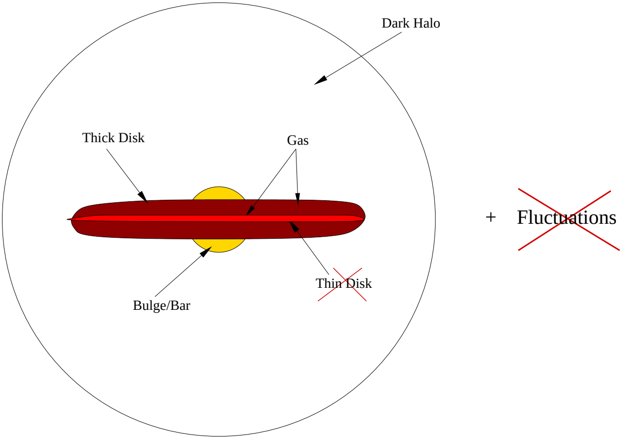


Figure: Schematic representation of the assumed Galactic model

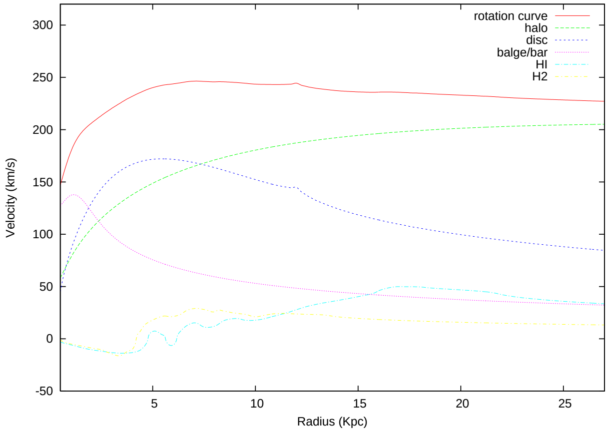


Figure: Rotation curve of the Galaxy

- The stellar disk:

$$\rho_d(R,z) = \frac{\Sigma_d}{2z_d}\, e^{-\frac{R}{R_d}}\, \mathrm{sech}^2\left(\frac{z}{z_d}\right) \text{ with } \qquad R < R_{\mathrm{dm}}$$

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

- The dust layer:

The distribution of the Interstellar Medium is assumed axisymmetric as well.
T. M. Dame, AIP Conference Proceedings **278** (1993) 267.

- The stellar bulge/bar:

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

where

$$s_a^2 = \frac{q_a^2(x^2+y^2)+z^2}{z_b^2} \qquad s_b^2 = \left[\left(\frac{x}{x_b}\right)^2 + \left(\frac{y}{y_b}\right)^2\right]^2 + \left(\frac{z}{z_b}\right)^4 .$$

H. Zhao, arXiv:astro-ph/9512064.

- 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:

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

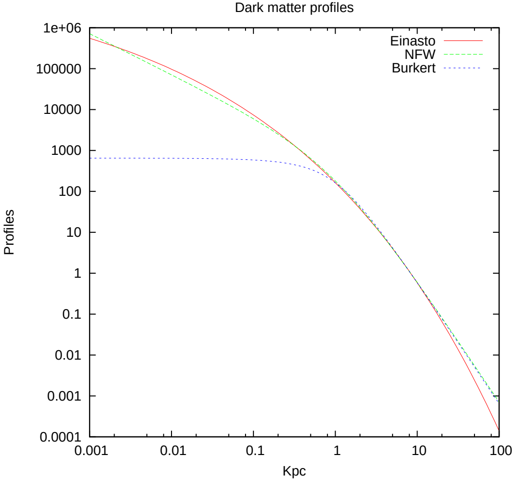
J.F. Navarro et al., MNRAS **349** (2004) 1039.
A.W. Graham, D. Merritt, B. Moore, J. Diemand and B. Terzic, Astron. J. **132** (2006) 2701.

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

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.


Dark matter profiles
Profiles
Kpc
1e+06
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.001
0.01
0.1
1
10
100
Einasto
NFW
Burkert

Galactic components	Parameters
Disk	Σ_d
Disk	R_d
Bulge/bar	$\rho_{bb}(0)$
Halo	α_E
Halo	$M_{\rm vir}$
Halo	$c_{\rm vir}$
All components	R_0
All components	$\beta_\star$

Constraints:

- Oort's constants: $A - B = \frac{\Theta_0}{R_0}$; $A + B = -\frac{\partial\Theta(R_0)}{\partial R}$

- 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

- l.s.r. velocity, proper motion and parallaxes distance of high mass star forming regions in the outer Galaxy

- radial velocity dispersion of tracers from the SDSS

- stellar motions around the massive black hole in the GC

- peculiar motion of SgrA^*

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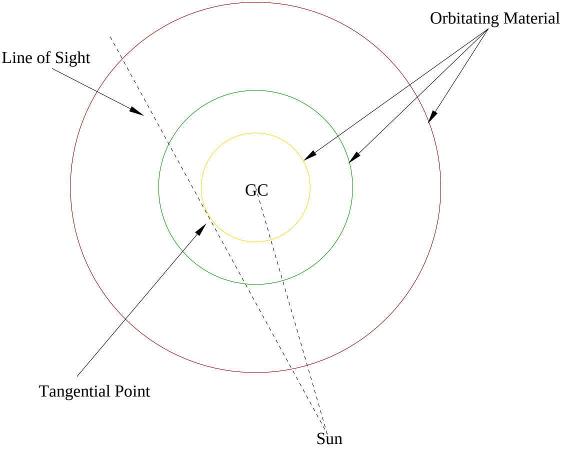


The terminal velocity is the l.o.s. velocity of the material at the tangential point

- How to measure a terminal velocity?

From the Doppler shift of a reference absorption line.

- How to calculate a terminal velocity?

$v_{\mathrm{term}} = \Theta(R) - \Theta(R_0)\frac{R}{R_0}$

- It is a strong constraint in the range $3\,\mathrm{kpc} \lesssim R < R_0$

-The dataset: population of stars with distances up to $\sim 60\,\mathrm{kpc}$ from the Galactic center. The distances are accurate to $\sim 10\%$ and the radial velocity errors are less than $30\,\mathrm{km\,s^{-1}}$.

-It is a strong constraint in the range $10\,\mathrm{kpc} \lesssim R \lesssim 60\,\mathrm{kpc}$

-To compare the data to the predictions: Jeans Equation

$$\sigma_r^2(r) = \frac{1}{r^{2\beta_\star}\,\rho_\star(r)} \int_r^\infty d\tilde{r}\;\tilde{r}^{2\beta_\star - 1} \rho_\star(\tilde{r}) \Theta^2(\tilde{r})$$

- where $\beta_\star$ is the anisotropy parameter: $\beta_\star \equiv 1 - \sigma_t^2/\sigma_r^2$.

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):

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

- Output: the mean and the variance with respect to $p(\eta|d)$ of functions $f(\eta)$.

- We will focus on $f = \eta$ and $f = \rho_{DM}(R_0)$.

- Monte Carlo expectation values:

$$\langle f(\eta)\rangle = \int d\eta\, f(\eta)p(\eta|d) \approx \frac{1}{N}\sum_{t=0}^{N-1} f(\eta^{(t)}) \ ,$$

where $\eta^{(t)}$ was sampled from $p(\eta|d)$.

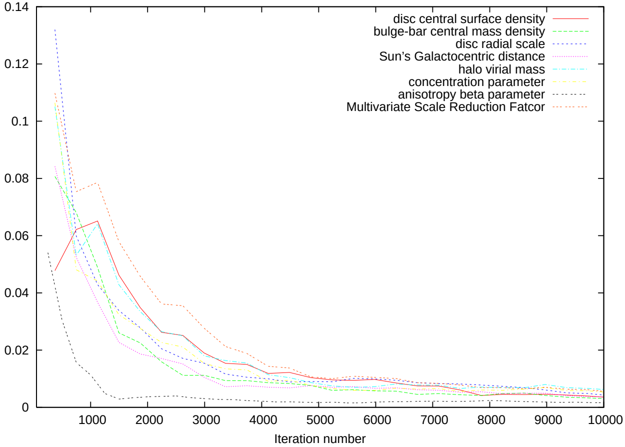
- Monte Carlo technics require a method to sample $\eta^{(t)} \Longrightarrow$ Markov chains.

- Markov chains :

$$\left.\begin{array}{r} p(\eta^{(0)}) \\ T(\eta^{(t)}, \eta^{(t+1)}) \end{array}\right\} \Longrightarrow \eta^{(t)} \text{distributed according to}\, p(\eta|d).$$

R≡ (Scale reduction factor).
Convergence: $R < 1.1$ and roughly constant.

1-R as a function of the iteration number:



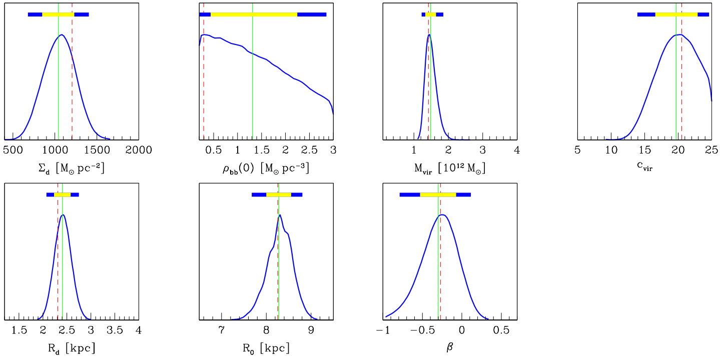


Figure: Marginal posterior pdf of the Galactic model parameters (NFW profile).

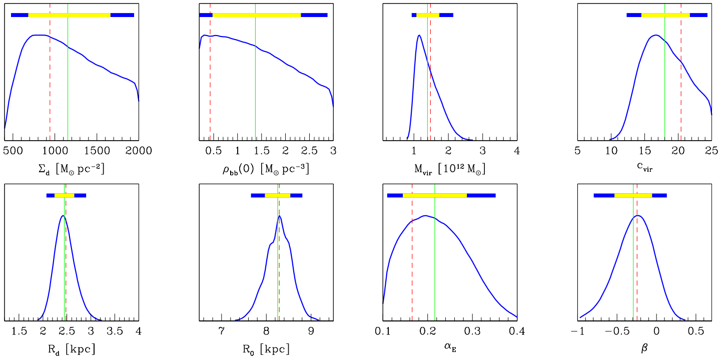


Figure: Marginal posterior pdf of the Galactic model parameters (Einasto profile).

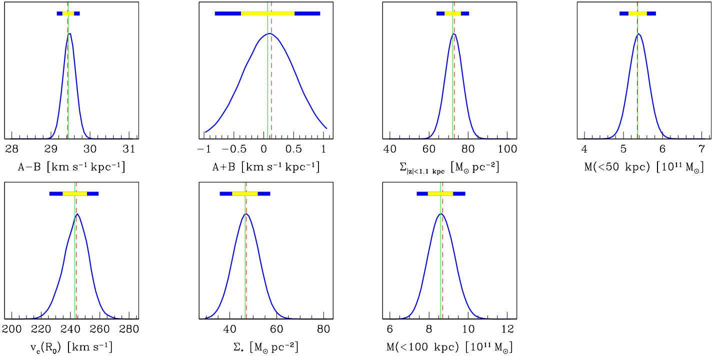


Figure: Marginal posterior pdf of a set of derived quantities (Einasto profile).

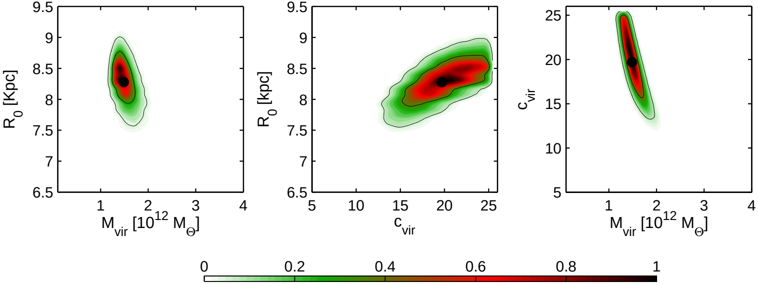
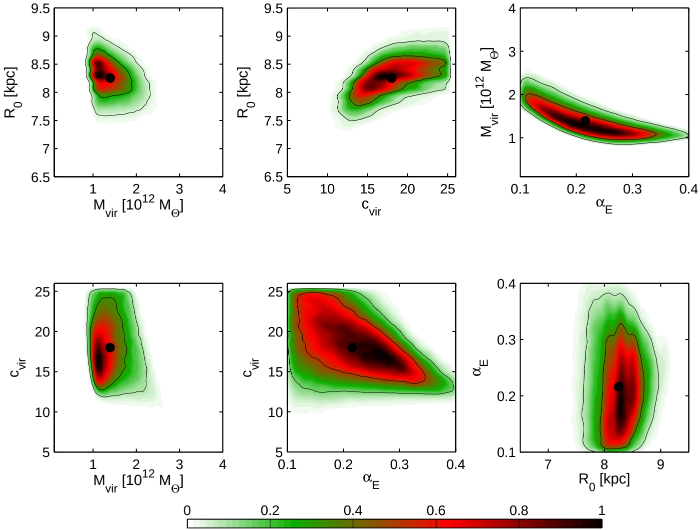


Figure: Two dimensional marginal posterior pdf in the planes spanned by combinations of the Galactic model parameters (NFW profile).



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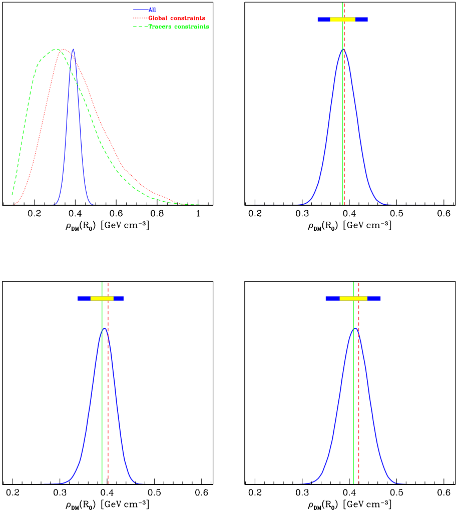

Figure: Marginal posterior pdf for the local Dark Matter density. Top left panel: Einasto profile, applying different subsets of constraints. Top right panel: Einasto profile. Bottom left panel: NFW profile. Bottom right panel: Burkert profile.

- Numerically we find:

$$\rho_{DM}(R_0) = (0.385 \pm 0.027)\,\mathrm{GeV\,cm^{-3}} \qquad \text{(Einasto)}$$

$$\rho_{DM}(R_0) = (0.389 \pm 0.025)\,\mathrm{GeV\,cm^{-3}} \qquad \text{(NFW)}$$

$$\rho_{DM}(R_0) = (0.409 \pm 0.029)\,\mathrm{GeV\,cm^{-3}} \qquad \text{(Burkert)}$$

- No strong dependences from the assumed halo profile.

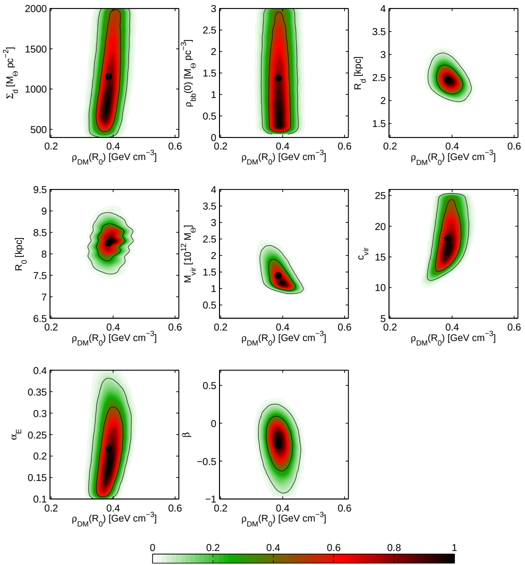

Figure: Two dimensional marginal posterior pdf in the planes spanned by the local Dark Matter energy density and the Galactic model parameters for the Einasto case.

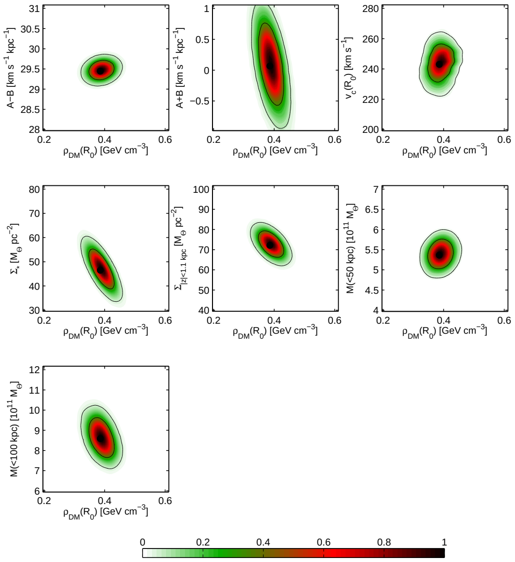

Figure: Two dimensional marginal posterior pdf in the planes spanned by the local Dark Matter energy density and the derived quantities for the Einasto case.

- **Maximum Likelihood approach:**

M. Weber and W. de Boer, arXiv:0910.4272 [astro-ph.CO].

* Only three free parameters (many fixed a priori)
* For some choice of the fixed parameters (with reasonable M_{vir}):
  $\rho_{DM}(R_0) = (0.39 \pm 0.05)\,\mathrm{GeV\,cm}^{-3}$

- **Poisson equation approach:**

P. Salucci, F. Nesti, G. Gentile and C. F. Martins, arXiv:1003.3101 [astro-ph.GA].

* Strategy: $\rho_{DM}(R_0) = \frac{1}{4\pi G R_0^2} \frac{\partial}{\partial R}\left(R\Theta^2\right)_{R=R_0} - K$,
  $\rho_{DM}(R_0) = (0.43 \pm 0.11 \pm 0.10)\,\mathrm{GeV\,cm}^{-3}$

- **Fisher matrix forecasts:**

L. E. Strigari and R. Trotta, JCAP **0911** (2009) 019 [arXiv:0906.5361 [astro-ph.HE]].

* Assumed a reference point in parameter space it tests the reconstruction capabilities of a future direct detection experiment accounting for astrophysical uncertainties.

Conclusions

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

- Assuming a Einasto Dark Matter profile, we find

$$\rho_{DM}(R_0) = (0.385 \pm 0.027)\,\mathrm{GeV\,cm}^{-3}\,.$$

- Assuming an NFW Dark Matter profile, we find

$$\rho_{DM}(R_0) = (0.389 \pm 0.025)\,\mathrm{GeV\,cm}^{-3}\,.$$

- Assuming an Burkert Dark Matter profile, we find

$$\rho_{DM}(R_0) = (0.409 \pm 0.029)\,\mathrm{GeV\,cm}^{-3}\,.$$

- For a given dark matter profile, we can therefore estimate the local value of the Dark Matter density with an accuracy of roughly the 7%.
- This result alleviate the astrophysical uncertainties on the theoretical predictions for the direct detection dark matter signals.