The Dark Matter Distribution in our Galaxy

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P. Salucci, F.N., C.F. Martins, G. Gentile, A&A 2010
F.N., P. Salucci, JCAP 2013

The DM densities

All searches depend on the expected DM density:

- In the Solar System

  Direct laboratory searches at Earth:
  ...depend on the local density at earth $\rho_\odot$

  Indirect searches (annihilation in Sun, Earth)
  ...depend on accumulated DM which again is driven by $\rho_\odot$

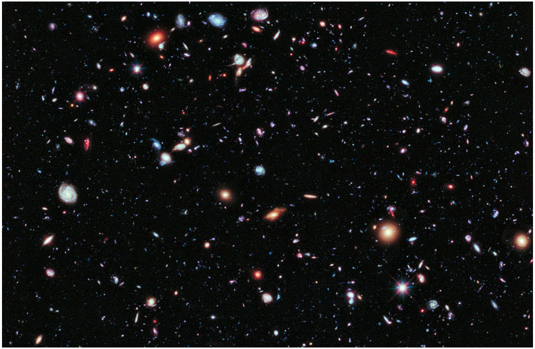
- In the Galaxy

  Looking for decay or annihilation
  ...depend on $\int \rho$ or ρ^2 along the l.o.s.

Both the Local and Galactic DM density are interesting.

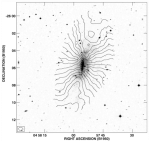
Our Galaxy is a typical Spiral, where the picture is clear...

Galaxies viewed from outside



DM in generic spiral galaxies: Observations

Rotation curve (optical, HI, etc)



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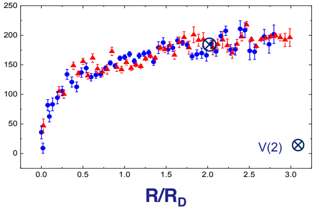
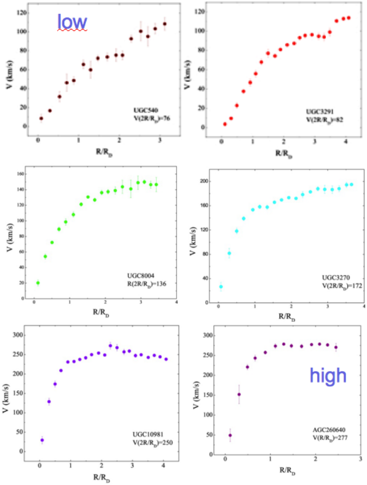


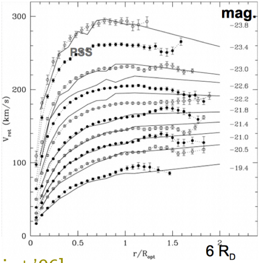
No "keplerian" fall of rotation

Different typical sizes

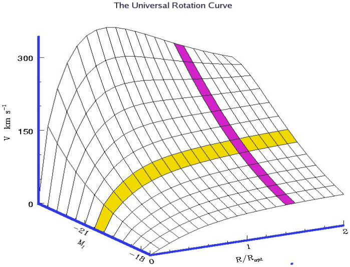


DM in generic spiral galaxies: Observations II

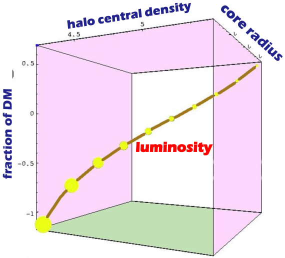
Coadding thousands of galaxies led to a coherent empirical picture



[Persic+'96]



Well modeled with a "cored" DM profile. . . with intriguiging relations:



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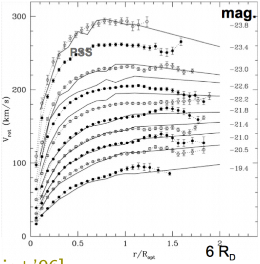

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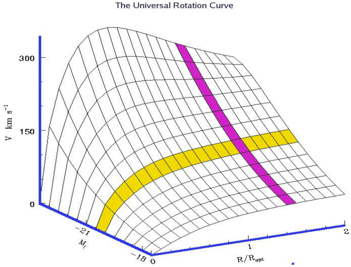

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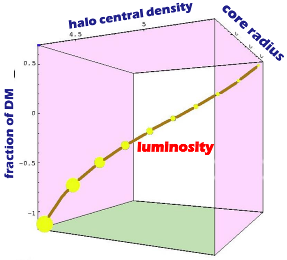
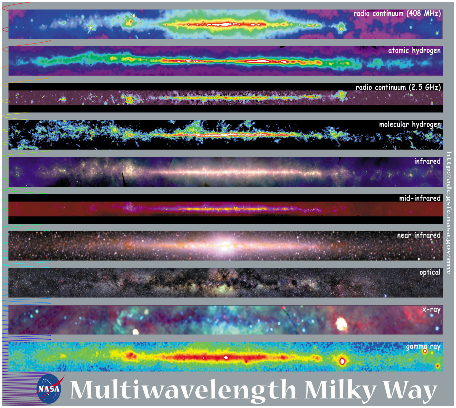


The Milky-Way conforms to this picture, but because we look from inside, life is not equally "easy". . .

The MW DM Density profile

Our galaxy

- Bulge
  ($10^{10}\ M_\odot$)
- Stellar disk
  (5–$7 \times 10^{10}\ M_\odot$)
- Dark Matter halo
  ($10^{11-12}\ M_\odot$)



and subleading

- Thick bulge/bar (up to $\sim$ 4kpc)
- Thick disk (older stars up to $z \sim$ kpc)
- Gas halo (few $10^{10}\ M_\odot$, to 100 kpc, new!)
- Stellar halo (globular clusters, old BHB, red, brown dwarfs, etc) (at least up to 80 kpc)

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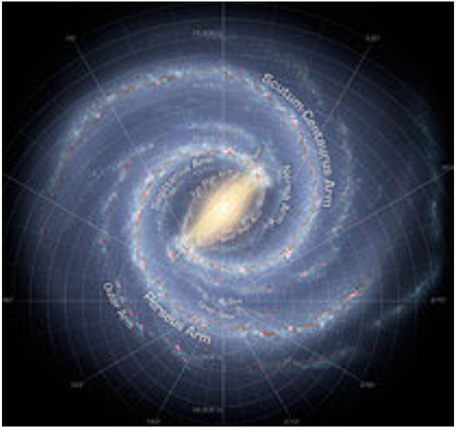

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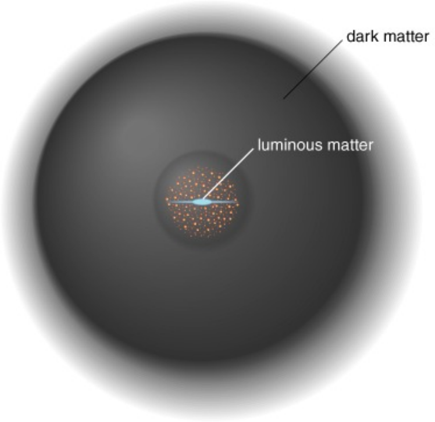

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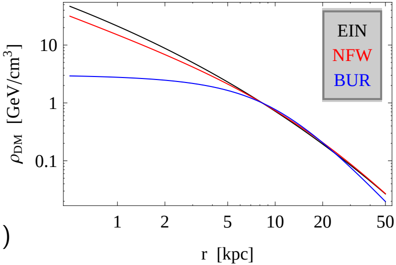
Component profiles

- DM profiles, Einasto, NFW, Burkert, cusped or cored

$$\rho_{EIN} = \rho_H \, e^{-(2/\alpha)(x^\alpha - 1)} \quad (\alpha = 0.17)$$

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

$$\rho_{BUR} = \frac{\rho_H}{(1+x)(1+x^2)}$$



(with $x = r/R_H$, scale radius R_H)

Triaxiality? (probably small [O'Brien+ '10]) Smooth? (who knows?)

- Bulge: pointlike (as seen from $r > 2\,$kpc)
  [Picaud+'04, Bissantz+'02, Robin+'11, ...] $M_B = 1.2\text{–}2 \times 10^{10}\, M_\odot$

- Disk: exponential, $\Sigma_D = (M_D/2\pi R_D^2) e^{-r/R_D}$ $\Delta z = 240$pc
  [PR'04,juric'08,robin'08,reyle'09,bovy'13] $M_D = 5\text{–}7 \times 10^{10}\, M_\odot$
  $R_D = 2.5 \pm 0.2\,$kpc

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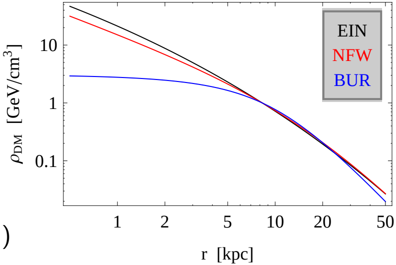

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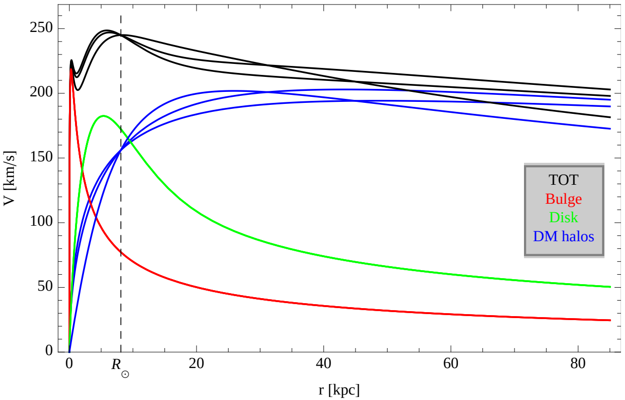
All together (illustration)



One would like to observe $V(r)$ to constrain ρ_{DM}.

But since we can not measure V(r) from outside...
...we need more elaborate observations.

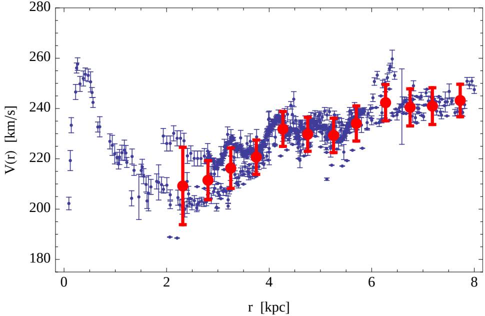
The Inner rotational velocities

Rotating hydrogen gas (HI) in the inner region

- Doppler gives relative speed along the l.o.s.
- Maximum at the tangential point, terminal velocities V_T:

$$V(r) = V_T(r/R_\odot) + V_\odot \; r/R_\odot$$

- Between 2 and 8 kpc a lot of measures of HI along the arms, with systematic variations. Need to define a binning:



- Inside ~ 2 kpc the bulge/bar structure prevents analysis.

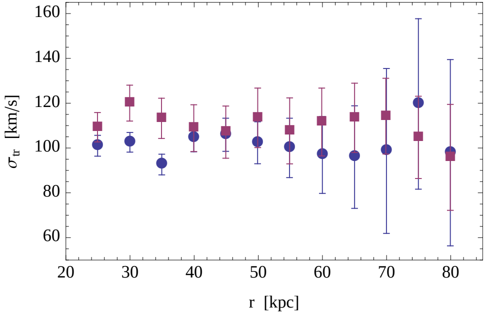
The Outer dispersion velocities

Out to $\sim 80\,\mathrm{kpc}$, survey of 'old' halo stars, moving randomly...

Only l.o.s. speed... need to rely on virial equilibrium

- $\sim$3000 Tracers
- Eliminate the outliers ($|v| > 500\,\mathrm{km/s}$, escape speed)
- Velocity dispersion $\sim 110\,\mathrm{km/s}$

Binned: [Gnedin+ '10, Xue+ '08, Xue+ '11] (SDSS DR6-DR8)



The Outer dispersion velocities cont'd

Each population of tracers has a measured density $\rho_i \propto r^{-\gamma_i}$,

- Consider virial equilibrium and use Jeans' Equation:

$$V^2 = \sigma_i^2 \left[\gamma_i - 2\beta_i - \frac{\partial \ln \sigma_i^2}{\partial \ln r} \right]$$

- Unknown velocity anisotropy β_i (maybe r dependent)
- Density power law: $\gamma_1 \simeq 4$, $\gamma_2 \simeq 3.5$
- More recently $\beta_2 \sim -0.5 \pm 0.5'$ (for $r > 25\,\text{kpc}$) [Kafle+ '12]

i.e. more tangential motion

Also a hint on β_1:
$(\gamma_1 - 2\beta_1) \simeq (\gamma_2 - 2\beta_2)$ implies $\beta_1 \sim 0$

($\partial \ln \sigma_i^2 / \partial \ln r$ is small)

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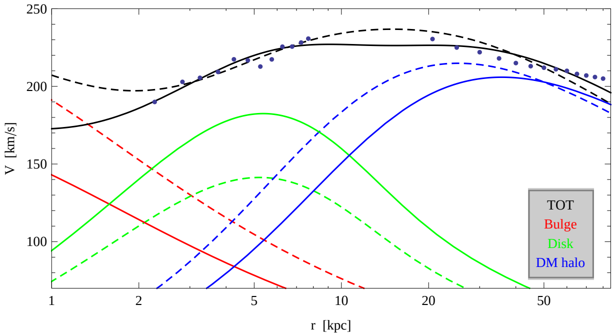
Method: We integrate Jeans' equation, for each choice of model parameters:

$$\{V^{model}(r), \beta_i\} \quad \rightarrow \quad \sigma_i^{model}(r)\,,$$

and compare σ_i^{model} with data for that population.

(Traditionally: derive pseudo-measures of V , w/ great uncertainties.)

Until 2010: the degeneration



- Inner: Bulge-Disk compensation
- Middle: Disk-DM Halo compensation
- Outer: DM Halo ρ_H-R_H flat direction
- and, $V_\odot$ not fixed $\rightarrow$ shift up/down.

Masers in Star forming regions

Parallax from ground based arrays: (angular precision 0.01 mas)

Able to constrain:

$V_\odot/R_\odot \simeq 30.2 \pm 0.3\,\mathrm{km/s\,kpc}$

$V_\odot \simeq 239 \pm 7\,\mathrm{km/s}$

[Brunthaler+ '11]

$V(r \simeq 10\mathrm{kpc}) \simeq 240 \pm 5\,\mathrm{km/s}$

$V(r \simeq 13\mathrm{kpc}) \simeq 244 \pm 4\,\mathrm{km/s}$

[Sanna+ '11]

$V(r \simeq 13\mathrm{kpc}) \simeq 250 \pm 2\,\mathrm{km/s}$

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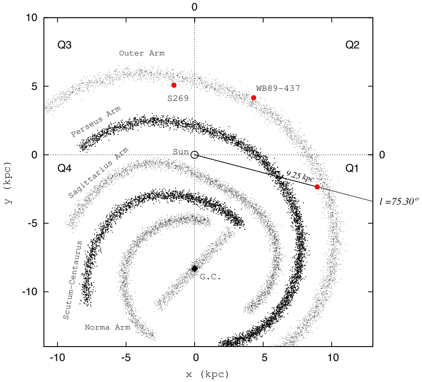

First results only.
In the near future more extensive surveys from BeSSeL and VERA.

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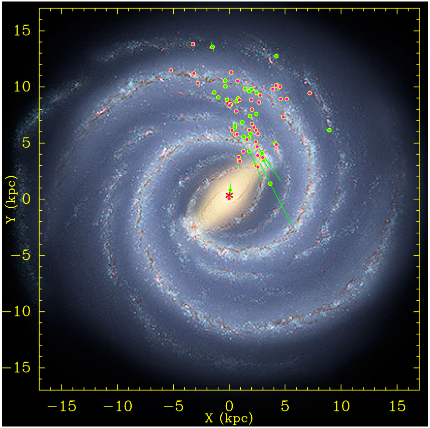

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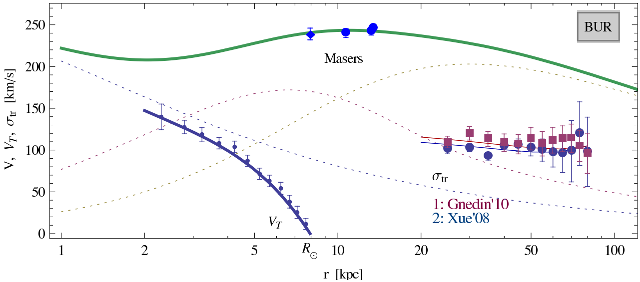
Fitting

- Model parameters, giving $V_{circ}(r)$ and integrated dispersion $\sigma(r)$: Sun ($R_\odot$, $V_\odot$, related); Bulge (M_B); Disk (M_D, R_D); DM Halo: (ρ_H, R_H) Anisotropy for tracers (β_1, β_2)
- Fitted against data: $V_T(x_i)$, $\sigma(r_i)$ and $V_{maser}(r_i)$.



- Not all parameters relevant, most important are ρ_H, R_H, β_2. Preference for Largest disk radius ($R_D \sim 3\,\text{kpc}$); Lightest bulge & disk ($M_B \simeq 10^{10}\,M_\odot$, $M_D \simeq 5\times10^{10}\,M_\odot$); (and see recent [Bovy Rix '13]!)

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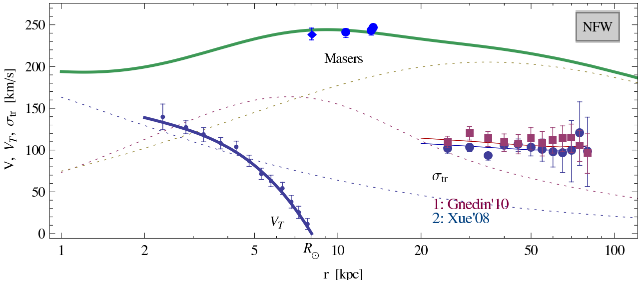

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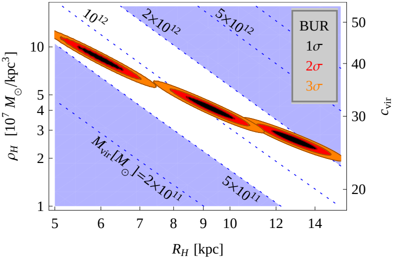
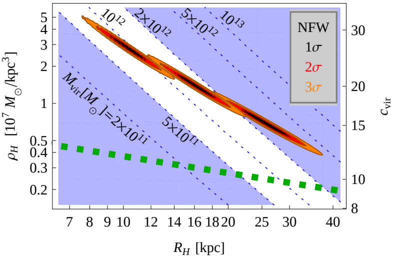
Fits: three cases, with $\beta_2 = 0, -0.5, -1$

Best: $\chi^2/40dof = 0.59, 0.41, 0.35$ (BUR) and 0.9, 0.46, 0.35 (NFW)



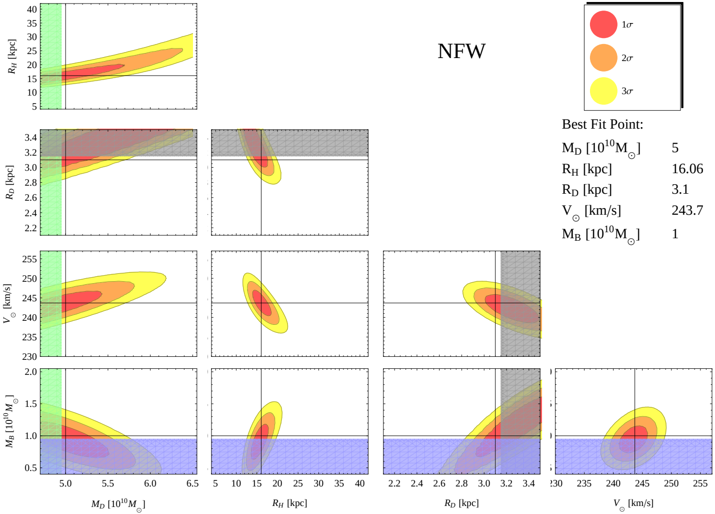


Blue regions mark $M_{vir}[10^{12}\,M_\odot]$. Green dots mark predictions of simulations.

[from Dehnen+'96, to Deason+'12]

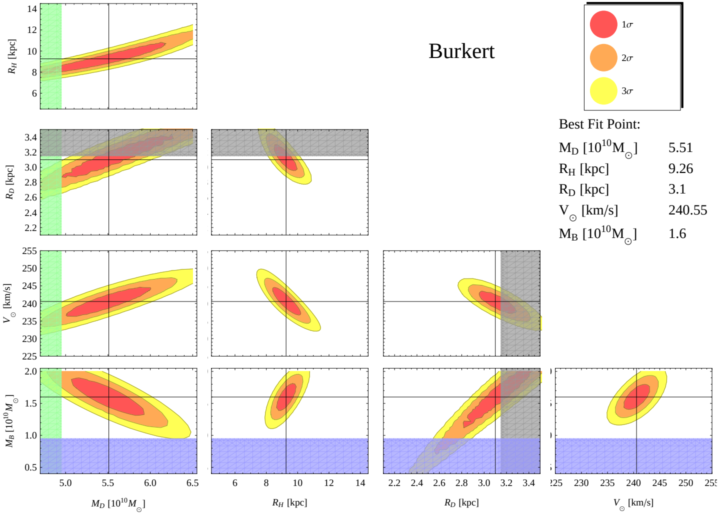
- Uncertainty in ρ_H, R_H due to the anisotropy β_2.
- c_{vir} is too large wrt to predictions of ΛCDM simulations.
- So: the "cusp-problem" also in our Galaxy.

Correlations



NFW fit required widest/lightest Disk, Bulge → cored..

Correlations

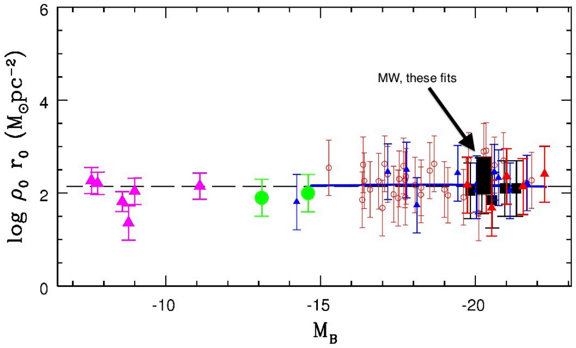


Best Fit Point:

M_D [$10^{10}M_\odot$]	5.51
R_H [kpc]	9.26
R_D [kpc]	3.1
$V_\odot$ [km/s]	240.55
M_B [$10^{10}M_\odot$]	1.6

Comparing, for cored profile

Comparing the best (Burkert) fits with the other galaxies



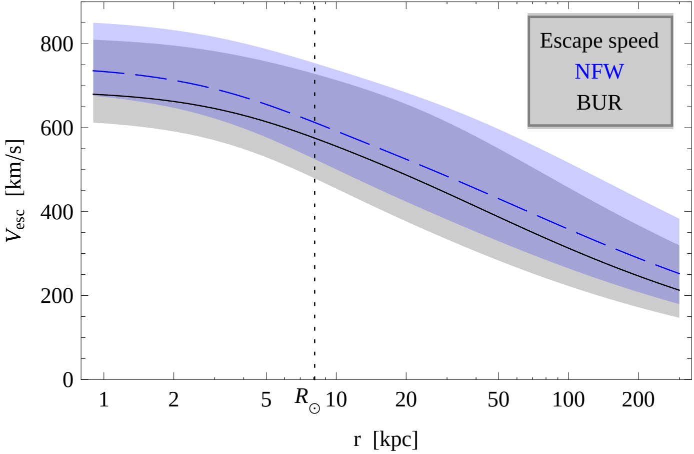
Intriguing property: same central surface density $\rho_H r_H$ [Donato+ '09]

MW fits well, despite the large uncertainties.

What about the impact for DM searches...

The DM escape velocity profile

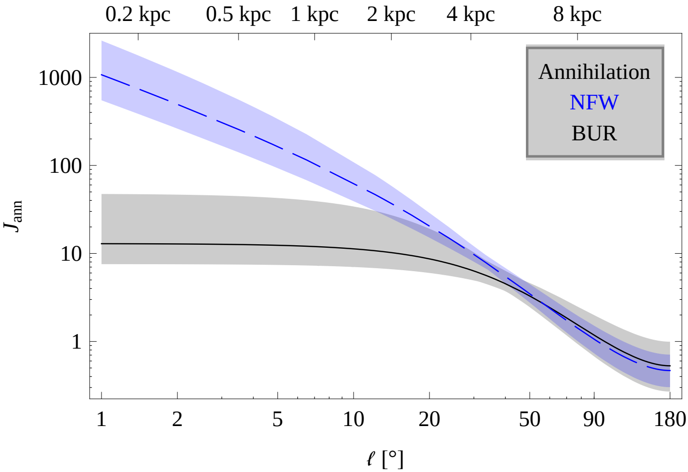
At 2σ CL:



...mildly relevant for direct detection, especially at low DM mass.

The DM annihilation angular profile

At 2σ CL:



…hard to discriminate, need to mess with the Galactic Center.

The DM Density at the Sun location

The Local DM density

Early vertical motion studies gave $\rho_\odot \simeq 0.3\,\mathrm{GeV/cm^3}$. [Kuijken+ '89]
Other using early profile modeling (unreliable) or simulations.
No uncertainty given before 2009...

- Global profile modeling: in 2009 first estimate

  $$\rho_\odot = 0.389 \pm 0.02\,\mathrm{GeV/cm^3}$$ [Catena+ '09]

  too precise (see [Weber+ '10, Pato+ '11, McMillan '11] still modeling).

- Vertical force: Recent ESO survey claimed no DM!?

  $$\rho_\odot = 0 \pm 0.05\,,\mathrm{GeV/cm^3}$$ [Mona-Bidin+ '12]

  Criticized first by [Bovy+ '12], on the velocity assumptions.
  Other criticisms may be advanced. Method still uncertain (see GAIA).

- Our work to assess analytically the uncertainties found

  $$\rho_\odot = 0.43 \pm 0.1 \pm 0.1\,\mathrm{GeV/cm^3}$$ [Salucci, FN+ '10]

  still the most conservative, halo model independent.

Analytical method for the Local DM density

Decompose radial acceleration as due to Bulge + Disk + DM Halo

$$V^2/r = a_B + a_D + a_H\,.$$

Use Gauss law for the DM Halo, $\partial_r(r^2 a_H) \propto \rho_H r^2$

$$\begin{aligned}
\rho_H(r) &= \frac{1}{4\pi G}\frac{1}{r^2}\frac{d}{dr}\left[r^2\left(\frac{V^2(r)}{r} - a_D(r) - a_B(r)\right)\right] X_q\,,\\
&= \frac{1}{4\pi G}\frac{V^2}{r^2}\left[\left(1+2\frac{d\ln V}{d\ln r}\right) - \frac{V_D^2}{V^2} f\left(\frac{r}{R_D}\right) X_{z_0}\right] X_q\,.\\
&\to 0.65\,\frac{\text{GeV}}{\text{cm}^3}\left(\frac{\omega_\odot}{\text{km/s kpc}}\right)^2 X_q\left[(1+2\alpha_\odot) - \beta\, f(r_{\odot D})\, X_{z_0}\right],
\end{aligned}$$

with f a known analytic function, for thin disk. Notes

- At $R_\odot$ the contribution of Bulge is negligible
- $\omega_\odot \equiv (V_\odot/R_\odot) \simeq 30$, angular speed (very well known)
- $\alpha_\odot \equiv d\ln V/d\ln r|_\odot = 0 \pm 0.1$, RC slope (uncertain)
- $\beta \equiv (V_D/V_\odot)^2 = 0.65$–$0.77$ "disk to total" ratio (constrained)
- $\rho_{\odot D} \equiv R_\odot/R_D = 3.4 \pm 0.5$ (constrained).
- $X_q \simeq 1$ corrects spherical Gauss law, for oblateness.
- $X_{z_0} \simeq 1$ corrects for nonzero disk thickness.

Result

- An analytical formula:

$$\rho_\odot = 0.43 \frac{\text{GeV}}{\text{cm}^3}\Bigg[1 + 2.9\,\alpha_\odot - 0.64\left(\beta - 0.72\right) + 0.45\left(r_{\odot D} - 3.4\right) - 0.1\left(\frac{z_0}{\text{kpc}} - 0.25\right) + 0.10\left(q - 0.95\right) + 0.07\left(\frac{\omega}{\text{km/s kpc}} - 30.3\right)\Bigg].$$

  Good also for the future.

- Today, using central values and present uncertainties:

$$\rho_\odot = \left(0.43 \pm 0.094_{(\alpha_\odot)} \mp 0.016_{(\beta)} \pm 0.096_{(r_{\odot D})}\right)\frac{\text{GeV}}{\text{cm}^3},$$

Conclusions

Dark Matter in our Galaxy:

- MW modeling starting to be reliable.
- Main uncertainty due to stellar halo velocity anisotropy.
- The model appears consistent with similar galaxies, and starts to give hints on the nature of DM.
- Preference for cored profile, down to 2 kpc.
- Large c_{vir} at odds with ΛCDM simulations.
- Hard to discriminate profiles, need to look inside 1 kpc.

Dark matter near the sun:

- $\rho_\odot = 0.4 \pm 0.2$ is still a good proper estimate.
- Uncertainties can not be reduced, at present.

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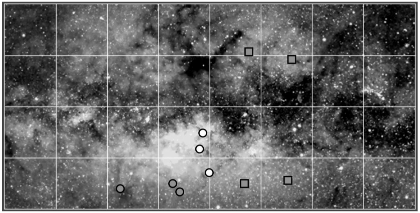
Dark matter near the sun:

- $\rho_\odot = 0.4 \pm 0.2$ is still a good proper estimate.
- Uncertainties can not be reduced, at present.

Thanks!

The Bulge mass



Measures are very uncertain:

- 2MASS survey (star count) yields [Robin+ '11]
  a boxy bulge $\sim 0.61 \times 10^{10}\, M_\odot$ $(1.5 \times 0.4 \times 0.4)$ kpc
  a thick bulge $\sim 0.026 \times 10^{10}\, M_\odot$ $(4.4 \times 1.3 \times 0.8)$ kpc

- Microlensing [Bissantz Gerard '02]
  $M_B = 0.9 \times 10^{10}\, M_\odot$ (probably underestimated)

- Infrared survey (star count) [Picaud Robin '04]
  a boxy bulge $\sim 2.4 \pm 0.6 \times 10^{10}\, M_\odot$, including Disk.
  subtracting disk $\rightarrow 1.7\text{–}1.9 \pm 0.6 \times 10^{10}\, M_\odot$
  or lower limit $M_B > 1.1\text{–}1.3 \times 10^{10}\, M_\odot$

Some improvement w/ APOGEE, or even VERA (?)

The Sun Galactic Radius and Angular Velocity

- $R_\odot$
  Gillessen 2009:
  $8.33 \pm 0.3\,\mathrm{kpc}$

  Ghez et al 2009 (using orbits):
  $8.0 \pm 0.6\,\mathrm{kpc}$
  $8.4 \pm 0.4\,\mathrm{kpc}$(assuming stationary BH)

  Bovy et al 2009 (a global average) [0907.5423v2]

$$R_\odot = (8.2 \pm 0.5)\,\mathrm{kpc}$$

- $V_\odot/R_\odot$ measured with a high accuracy, much better than $V_\odot$ and $R_\odot$ separately:

$$V_\odot/R_\odot = (30.3 \pm 0.3)\,\mathrm{km/s/kpc}$$

[MB+09,reid+09,Brunthaler+11]

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The Slope and Disk contribution $R_\odot$

- Circular velocity slope $\alpha(r) = \frac{d \ln V(r)}{d \ln r}$
  It is uncertain but limited, inside the solar circle:

$$\alpha(2\,\text{kpc} < r < 8\,\text{kpc}) \simeq 0.1\text{–}0$$

(also slightly correlated with $R_\odot$ through the terminal velocities)
At $R_\odot$ we can take the broad range

$$\alpha_\odot = 0. \pm 0.1$$

(confirmed by the global profile fits, above)

- Contribution of disk to sun's rotation, $\beta = V_D/V_\odot$
  The disk can neither contribute totally, nor negligibly.
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The Local DM density, cont'd

$$\rho_\odot = 0.65\,\frac{\text{GeV}}{\text{cm}^3}\left(\frac{\omega_\odot}{\text{km/s kpc}}\right)^2 X_q\left[(1+2\alpha_\odot) - \beta\, f(r_{\odot D})\, X_{z_0}\right],$$

Result depends on

- $\omega_\odot \equiv (V_\odot/R_\odot)$, angular speed (very well known)
- $\alpha_\odot \equiv d\ln V/d\ln r|_\odot$, RC slope (uncertain)
- $\beta \equiv (V_D/V_\odot)^2$ "disk to total" ratio (constrained)
- $\rho_{\odot D} \equiv R_\odot/R_D$ (constrained).

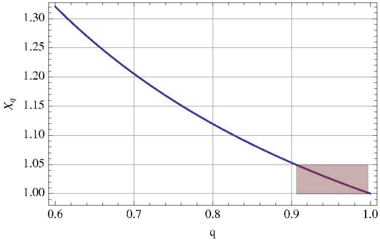


Fig. A.1. Effect of the DM halo oblateness q.

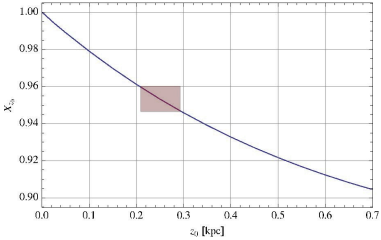
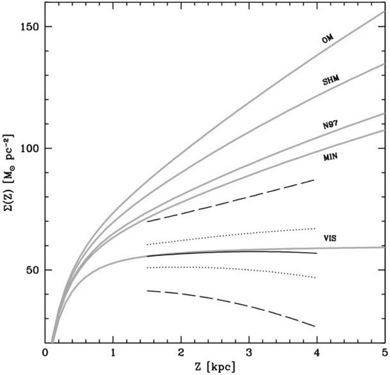


Fig. B.1. Effect of the disk thickness z_0.

Claim of no local DM!?

- ESO claim [Mona-Bidin+'12]
  using thick disk stars, with $|z| < 4\,\mathrm{kpc}$
  (This is a lot above or below the disk.)
  Measures l.o.s. velocity dispersion
  Assume 'circular' velocity is z and R independent
  Use vertical Jeans equation to find the gravitational potential
  $\rightarrow$ local DM surface density =0



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  But using simulation of the z dynamics and MCMC.
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- More generally,
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  Waiting for GAIA - increasing statistics and precision.

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