The Local Dark Matter Density

New constraints on the Milky Way's dark disc and the shape of the halo

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Background

[What is $\rho_{dm}$? How do we measure it? Why is it interesting?]
Background | What is the local dark matter density?
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Background | What is the local dark matter density?

\[ \sim 200 \text{ pc} \]
How can we measure the local DM density?

1. Local measure:

\[ \rho_{dm} \]
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Background | **How can we measure the local DM density?**

I. Local measure:

\[ \rho_{dm} \]
Background | How can we measure the local DM density?

1. Local measure:

2. Global measure:
Background | How can we measure the local DM density?

1. Local measure:

2. Glc

\[ v^2 \sim GM(r)/r \]

Sofue et al. 2009

\[ \rho_{\text{dm}} \]
How can we measure the local DM density?

1. Local measure:

2. Global measure:
Why measure the local dark matter density?

1. Halo shape ...

\[ \rho_{dm} < \rho_{dm,\text{ext}} \quad \text{Prolate} \]

\[ \rho_{dm} > \rho_{dm,\text{ext}} \quad \text{Oblate/dark disc} \]
2. Detecting dark matter

- Big tub of inert material
- Deep underground
- Wait for rare event
- Need to know very local phase space distribution
Background | Why measure the local dark matter density?

2. Detecting dark matter

- Big tub of inert material
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$$\frac{dR}{dE} = \frac{\rho \sigma_{\text{wn}} |F(E)|^2}{2m\mu^2} \int_{v > \sqrt{ME/2\mu^2}}^{\nu_{\text{max}}} \frac{f(\mathbf{v}, \tau)}{v} d^3v$$
2. Detecting dark matter

- Big tub of *inert* material
- Deep underground
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\[
\frac{dR}{dE} = \frac{\rho \sigma_{\text{wn}} |F(E)|^2}{2m\mu^2} \int_{v > \sqrt{ME/2\mu^2}}^{v_{\text{max}}} f(v, t) \frac{d^3v}{v}
\]
2. Detecting dark matter

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\]
Background | The need for simulations

1. $\rho_{\text{lab}} \neq \rho_{\text{dm}}(<1\ \text{kpc})$
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The Milky Way disc

MW

~200pc
Background | **The need for simulations**

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Solar system is a million times smaller than this!

The Milky Way disc
Background | The need for simulations

1. \( \rho_{\text{lab}} \neq \rho_{\text{dm}} (\text{< 1 kpc}) \)

2. Need \( f(v, t) \)

Solar system is a million times smaller than this!
Simulations | “DM-only” simulations
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b) Local DM velocity PDF

- Maxwellian
- Aq-A-1
- Median
  - 68%; 95%

$\Delta \times 10^{-3}$

$v [\text{km s}^{-1}]$

$\times 10^{-3}$

Aq-A-1

Vogelsberger et al. 2009
Simulations | “DM-only” simulations | Fine structure

- **Unresolved substructure** | not likely important

- **Unresolved streams** | not likely important
  [Vogelsberger et al. 2011; Fantin et al. 2011]

- **Solar system** | not likely important
  [Peter 2009]
Simulations | “DM-only” simulations | Fine structure

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\[
\rho_{\text{dm}} \Rightarrow \rho_{\text{lab}}
\]

\~600 \text{ light years} \quad \~\text{metres}
Simulations | The importance of baryons
Simulations | The importance of baryons

Shape change

No baryons

With baryons

Figure 4: Including baryons in the cosmological simulations alters the predictions for $\rho_{dm}$. Left & Middle: Adding dissipative baryonic matter causes the dark matter halo to contract and change shape, becoming oblate and aligned with the disc at least out to $\sim 1$– disc scale length. The left plot shows projected density contours of a Milky Way mass dark matter halo from a cosmological simulation which is triaxial and has no symmetry. The middle plot shows the same simulation run including baryonic physics; the approximate size of the disc that is in the $x-y$ plane is marked by the red horizontal line. The dotted lines show density contours for the dark matter accreted from the four most massive satellites.

Right: The presence of a massive disc at high redshift biases the accretion of satellites causing their tidal debris – both stars and dark matter – to settle into a rotating disc. This plot shows the ratio of the density of this 'dark disc' to the halo density at the solar neighbourhood for a series of controlled simulations where a satellite of the mass of the Large Magellanic Cloud (LMC) or four times larger than this (LLMC) were merged with the Milky Way with different inclination angles. Notice that it is the low inclination mergers (LMC$1\sim$–$2^\circ$ and LLMC$1\sim$–$2^\circ$) that contribute most to the 'dark disc' as expected. Plot adapted from data presented in Read et al. (2009).

This above makes hunting for the gravitational effect of dark matter near the Sun rather like looking for the proverbial needle in the haystack. This is one motivation for using extrapolations from larger scales where the dark matter dominates the potential. It leads to a trade-off between moving away from the Solar neighbourhood to see more dark matter, and minimising the number of assumptions that must go in to the method. I discuss this further in §3.
The importance of baryons

Shape change

No baryons

With baryons

Katz & Gunn 1991; Dubinski 1994; Debattista et al. 2008; Read et al. 2009

Dark discs

Lake 1989; Read et al. 2008/9
Simulations | The importance of baryons

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Lake 1989; Read et al. 2008/9
Simulations | Dark discs

Late Planar Merger [LPM]

$v_{\phi}$(km/s)

Read et al., 2008/9; Bruch et al. 2009a/b.
Simulations | Dark discs

Late Planar Merger [LPM]

$\mathbf{v}_\phi$ (km/s)

Read et al., 2008/9; Bruch et al. 2009a/b.
Simulations | Dark discs

Late Mergers [LM]

Read et al., 2008/9; Bruch et al. 2009a/b.
Simulations | Dark discs

Read et al., 2008/9; Bruch et al. 2009a/b.
Measurement

$[\rho_{dm}; \text{the local halo shape; and the MW's dark disc}]$
\[ \frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} \]
Measurement | Theory

\[ \frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} \]

Steady state

Bahcall 1989; Garbari et al. 2011/12
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Steady state But! hard to measure \( f(\mathbf{r}, \mathbf{v}) \)

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But! hard to measure \( f(\mathbf{r}, \mathbf{v}) \)

Moments \( \Rightarrow \)

Jeans equations

Bahcall 1989; Garbari et al. 2011/12
Measurement \textbf{Theory}

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\]

\begin{align*}
\text{Steady state} & \quad \text{But! hard to measure } f(r, \mathbf{v}) \\
\text{Moments} \Rightarrow & \quad \text{Jeans equations}
\end{align*}

\[
\frac{1}{R} \frac{\partial}{\partial R} \left( R \nu_i \overline{v_R v_z} \right) + \frac{\partial}{\partial z} \left( \nu_i \overline{v_z^2} \right) + \nu_i \frac{\partial \Phi}{\partial z} = 0
\]

Bahcall 1989; Garbari et al. 2011/12
Measurement | Theory

\[ \frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} \]

Steady state \hspace{1cm} But! hard to measure \( f(r, \mathbf{v}) \)

Moments ⇒ Jeans equations

\[ \frac{1}{R} \frac{\partial}{\partial R} \left( R \nu_i \bar{v} R \nu_z \right) + \frac{\partial}{\partial z} \left( \nu_i \bar{v}^2 \right) + \nu_i \frac{\partial \Phi}{\partial z} = 0 \]

"tilt term"

\( h \ll R_d \)

Bahcall 1989; Garbari et al. 2011/12
Measurement | Theory

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Steady state

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Moments \( \Rightarrow \)

Jeans equations

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"tilt term"

\( h \ll R_d \)

Bahcall 1989; Garbari et al. 2011/12
Measurement | Mock data

The graphs show the relationship between $\nu$ and $z_{(kpc)}$ on the left, and $\sigma_z$ versus $z_{(kpc)}$ on the right. The text $n_* = 10^3$ is also included on the right graph.

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Mock data
1D simple mock data

\[ n^* = 10^3 \]

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$\Delta \rho_{dm} \sim 0.375 \text{ GeV cm}^{-3}$

$n_\ast = 10^3$
\[ n \ast = 1 \]

\[ \Delta \rho_{dm} \sim 0.1 \text{ GeV cm}^{-3} \]

\[ n_\ast = 10^4 \]
Measurement | Real data

Need a good tracer:
Need a good tracer:

- Well mixed $\Rightarrow$ equilibrium
- Well populated $\Rightarrow$ good statistics (at high $z$!)
- Volume complete (helpful)
- Velocity data ($v_z$)
- Good distances

Measurement | Real data
Need a good tracer:

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\textbf{a)} 2000 stars

Volume Complete

[Kuijken & Gilmore 1989]
Need a good tracer:

- Well mixed $\Rightarrow$ equilibrium
- Well populated $\Rightarrow$ good statistics (at high $z$!)
- Volume complete (helpful)
- Velocity data ($v_z$)
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**a)** 2000 stars
Volume Complete
[Kuijken & Gilmore 1989]

**b)** 10,000 stars
Complex SF
[Zhang et al. 2013]
Measurement | Historic measures

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM

By J. C. Kapteyn

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) Distribution of stars. Observations are fairly well represented, at least up to galactic lat. $70^\circ$, if we assume that the equidensity surfaces are similar ellipsoids of revolution, with axial ratio 5.1, and this enables us to compute quite readily (2) the gravitational acceleration at various points due to such a system, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The total number of stars is taken as $47.4 \times 10^9$. (3) Random and rotational velocities. The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration ($G\eta$) decreasing with the distance $\rho$. Therefore the density $\Delta$ is assumed to obey the barometric law: $G\eta = -\bar{u}^2 (\delta \Delta / \delta \rho) / \Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) the mean mass of the stars decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2 (\delta \Delta / \delta \rho) / \Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where
FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT
AND MOTION OF THE STARS

By J. C. KAPTEYN

ABSTRACT

First attempt at a general theory of the distribution of the stellar system.—(1) Distribution of stars. Observations at least up to galactic lat. 70°, if we assume the stellar system to be an ellipsoid of revolution, with axial ratio 5.1, show readily (2) the gravitational acceleration at various points by summing up the effects of each of ten ellipsoidal shells surrounding the average star at a distance of a parsec, 47.4 \times 10^9. (3) Random and rotational velocities of surfaces is such that the stellar system cannot have a general rotational motion around the galactic axis, however, there is no rotation, and the bulk of gas at uniform temperature, but with a gradual increase with the distance \( \rho \). Therefore the density \( \Delta \), \( G \eta = -\bar{u}^2(\Delta/\rho\Delta)/\Delta \); and taking the mean radius of the sun, the author finds that (4) the mean mass of the stars is close to \( r \), with the value of \( \rho \) the value independently found for the average mass of a shell at the distance \( \rho \). Whatever the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to \( -\bar{u}^2(\Delta/\rho\Delta)/\Delta \), \( \bar{u} \) is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where...
with the distance $p$. Therefore the density $\Delta$ is assumed to obey the barometric law: $G_n = -\bar{u}^2(\delta\Delta/\delta p)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author found that (5) the relative mass of the stars decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2(\delta\Delta/\delta p)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine the amount of dark matter from its gravitational effect. (6) The chief defects of the theory are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the position of the center of the system is not the sun, as assumed, but is probably some 650 parsecs away in the direction galactic long. 77°, lat. -28°. The average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G_n$ with $p$ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were concluded. Hence either the assumption or the conclusions are wrong; and that no further use has been made between stars of different types.

1. Equidensity surfaces supposed to be similar.

Mount Wilson Contribution No. 1883 a provisional derivation was given of the star-density in the stellar system. The question was...
incidentally suggested that when the theory is perfected it may be possible to determine the amount of dark matter from its gravitational effect.
It is incidentally suggested that when the theory is perfected it may be possible to determine the amount of dark matter from its gravitational effect.
Measurement | Comparison of recent measures

\[ \rho_{dm, ext} (\text{Jogco et al. 2011}) \]

\[ \rho_{dm} \text{ [Msun pc}^{-3}] \]

\[ \nu \text{ [GeV cm}^{-3}] \]

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Measurement | Comparison of recent measures

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\[ \Sigma_s = 55 \text{M}_\odot \text{pc}^{-3} \]
Measurement | The dark disc

![Graph showing the ratio of dark matter densities for different models.](image)

- **Oblate**
  - LPM
  - LM
  - Q

- **Prolate**
  - -1.8

Models: G12, G12*, Z13, BR13

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The dark disc | The hunt for accreted stars

1. A chemical template ...

Ruchti, Read et al. 2014, submitted
1. A chemical template ...

Born in dwarf or outer disc
2. A kinematic template ...

Ruchti, Read et al. 2014, submitted
2. A kinematic template ...
Real data [Ruchti et al. 2014 submitted]

Measurement | The dark disc | The hunt for accreted stars

Ruchti, Read et al. 2014, submitted
Measurement | The dark disc | The hunt for accreted stars

Real data [Ruchti et al. 2014 submitted]
The dark disc | The hunt for accreted stars

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Conclusions

• The latest constraints on the local dark matter density give:

\[ \rho_{\text{dm}} = 0.33^{+0.26}_{-0.075} \text{ GeV cm}^{-3} \]

\[ \rho_{\text{dm}} = 0.25 \pm 0.09 \text{ GeV cm}^{-3} \]

[volume complete; G12*, R14]

[SDSS; Z13]

• Comparing these with the rotation curve implies a near-spherical MW halo at \(~8\text{kpc}\), little dark disc, and a quiescent merger history.

• We have searched for stars accreted along with the dark disc, finding none so far; this supports the “quiescent MW” scenario.

• Gaia will move us into the realm of truly precise measurements of the Local Dark Matter Density.

Garbari et al. 2012; Zhang et al. 2013; Read 2014; Ruchti, Read et al. 2014, submitted