A New Method for Determining the Local Dark Matter Density

Hamish Silverwood
GRAPPA, University of Amsterdam

Co-authors:
Sofia Sivertsson
Pascal Steger
Justin Read
Gianfranco Bertone

TeVPA15, 27 October 2015
Kashiwa, Japan
Density of dark matter right here
Why do we measure local DM density?

Density of dark matter right here
Why do we measure local DM density?

**Direct Detection** (e.g. Xenon1T, XMASS, DAMIC, LUX...)

\[
\frac{dR}{dE} = \frac{\rho_\odot}{m_{DM} m_N} \int_{v > v_{\text{min}}} d^3v \frac{d\sigma}{dE} (E, v) v f(\bar{\nu}(t))
\]

**Indirect Detection** through Solar Capture and annihilation to neutrinos (IceCube, Antares)

\[
C^\odot \approx 1.3 \times 10^{21} s^{-1} \left( \frac{\rho_{\text{local}}}{0.3 \text{GeV cm}^{-3}} \right) \left( \frac{270 \text{km s}^{-1}}{v_{\text{local}}} \right) \times \left( \frac{100 \text{GeV}}{m_\chi} \right) \sum_i \left( \frac{A_i (\sigma_{X_i,SD} + \sigma_{X_i,SI}) S(m_\chi/m_i)}{10^{-6} \text{pb}} \right)
\]

Density of dark matter right here

Scans of theoretical parameter space, eg **Supersymmetry**
How do we measure local DM density?

• **Global measurements (rotation curves):**
  powerful, but have to assume global properties of the halo,
  see Miguel Pato’s talk on Friday morning
  e.g. Dehnen & Binney 1998; Weber & de Boer 2010; Catena & Ullio 2010; Salucci et al. 2010; McMillan 2011; Nesti & Salucci 2013; Piffl et al. 2014; Pato & Iocco 2015; Pato et al. 2015

• **Local measurements:**
  larger uncertainties but fewer assumptions
Our Method

• Local measurements in $z$-direction
• Data points are **positions** and **velocities** for a set of tracer stars

- bin the data to get **tracer density** $\nu$ and **velocity dispersion**
  \[ \sigma_{ij}^2(x) = \overline{v_i v_j} - \overline{v_i} \overline{v_j} \]

• Focus on making as **few assumptions** as possible
Link kinematic data to mass density via Jeans Equations

- Tracer stars follow the Collisionless Boltzmann Equation:
  \[
  \frac{df}{dt} = \frac{\partial f}{\partial t} + \nabla_x f \cdot v - \nabla_v f \cdot \nabla_x \Phi = 0
  \]

- \( f(x,v) \) - stellar distribution function, positions \( x \), velocities \( v \), gravitational potential \( \Phi \)

- Integrate over velocities, switch to spherical-polar co-ordinates, and get the Jeans Equation in \( z \).
Integrate

\[
\frac{1}{R\nu} \frac{\partial}{\partial R} (R\nu \sigma_{Rz}) + \frac{1}{R\nu} \frac{\partial}{\partial \phi} (\nu \sigma_{\phi z}) + \frac{1}{\nu} \frac{d}{dz} (\nu \sigma_z^2) = -\frac{d\Phi}{dz} \quad K_z
\]

Construct model for tracer density \( \nu \), Dark Matter + Baryon density \( \rightarrow K_z \), tilt term \( T(z) \). Calculate velocity dispersion \( \sigma_z \), then fit the model to velocity dispersion, tracer density & tilt term to data. Use Multinest to derive posterior distribution on DM.

Key equation assumes only dynamical equilibrium. Can use almost any model to describe tracer density, mass density and tilt term. We can in principle have more parameters than data points, hence we call it Non-Parametric Method.
Modelling the Components:

**Tracer Density with the \( k_z \) parameterization**

We want to **discard the assumption of exponential tracer density** \( \nu \).

\( k_z \) allows for sufficient freedom to yield good fit to data. Integration of \( k_z \) yields smoother \( \nu \) profile. Priors on \( k_z \) can further limit fitting to noise in data.
Modelling the Components:

**Tracer Density with the $k_z$ parameterization**

We want to **discard the assumption of exponential tracer density**. $k_z$ allows for sufficient freedom to yield good fit to data. Integration of $k_z$ yields smoother $\nu$ profile. Priors on $k_z$ can further limit fitting to noise in data.

**Non-parametric model for tracer density.**

**Discard usual assumption of exponential tracer density.**
Modelling the Components:

**Tilt Term**

\[
\frac{1}{R \nu} \frac{\partial}{\partial R} \left( R \nu \sigma_{Rz} \right) \]

('tilt' term: \( \mathcal{T} \))

\[
\nu(R, z) = \nu(z) \exp(-R/R_0)
\]

\[
\sigma_{Rz}(R, z) = \sigma_{Rz}(z) \exp(-R/R_1)
\]

\[
\mathcal{T}(R_\odot, z) = \sigma_{Rz}(R_\odot, z) \left[ \frac{1}{R_\odot} - \frac{1}{R_0} - \frac{1}{R_1} \right]
\]

Tilt term links vertical and radial motion.

\( T \sim 0 \) at low \( z \), becomes larger at higher \( z \) where DM becomes dominant part of total density profile.

Would normally require moving to 2D Jeans equations, but with a few simplifying assumptions we can model the Tilt Term and remain in 1D.

\[
\sigma_{Rz}(R_\odot, z) = A z^n \bigg|_{R_\odot}
\]

Parameters:
- \( A \)
- \( n \)
- \( R_0 = R_1 \)
Modelling the Components:

**Dark Matter Density profile**

**Constant $\rho_{DM}$**
Within 10% of correct spherical halo density up to $z \sim 3\text{kpc}$

**Constant $\rho_{DM} + \text{Dark Disc}$**
Dark Discs from e.g. accretion of subhalos, Partially Interacting DM.

Similar vertical profile from flattened, oblate halo.
Results:

- Initial testing on **Mock Data** sets generated from distribution functions
- Varying numbers of tracer stars
- With & without effects of **tilt** (radial-vertical motion coupling)
- With & without **dark discs**
Results: Sampling

More data points = better result.

Mock Data

86% Credible Region

95% Credible Region

Posterior Median

10^4 tracer stars

10^5 tracer stars

10^6 tracer stars
Results: The Importance of Tilt

Neglecting tilt leads to a systematic bias of the dark matter density, given fixed baryon density profile.
Method is able to reconstruct a Dark Disc structure.
Ongoing Work:
- Testing on mock data sets generated from N-body simulations.
- Updating baryon model
- Working with G-dwarf measurements from the Sloan Digital Sky Survey (SDSS)

Future Work
- 2016: Tycho-Gaia Astrometric Solution:
  combine data from Tycho catalogue (from Hipparcos, 1993) with first Gaia data, leverage 24 year time difference.
- Incorporate axial term and expand method to two and three dimensions
- 2016-2022: Gaia data releases

arXiv:1507:08581
Conclusions

- **New method** to reconstruct vertical Dark Matter density profile and Local Dark Matter Density

- **Enormous freedom** in describing the input models: we can move beyond constant Dark Matter density profile and exponential tracer density profile

- **Tilt term** is very important for local Dark Matter measurements - ignoring it will yield systematic bias. Our method can deal with tilt term within a 1D approach.

Thank you.
Modelling the Components:

**Tracer Density with the $k_z$ parameterization**

---

**PARAMETERS**

- **Tracer Density**
- **Tilt Term**
- **DM mass density**
- **Baryonic mass density (multiple pops)**

We want to *discard the assumption of exponential tracer density $\nu$.*

$k_z$ allows for sufficient freedom to yield good fit to data. Integration of $k_z$ yields smoother $\nu$ profile. Priors on $k_z$ can further limit fitting to noise in data.
Modelling the Components:

**Tilt Term**

\[
\frac{1}{R\nu} \frac{\partial}{\partial R} (R\nu \sigma_{Rz})
\]

'Tilt' term: \( T \)

Tilt term links vertical and radial motion.

Important at higher \( z \), where DM contribution becomes higher.

Would normally require moving to 2D Jeans equations, but with a few simplifying assumptions we can model the Tilt Term and remain in 1D.

\[
\nu(R, z) = \nu(z) \exp(-R/R_0)
\]

\[
\sigma_{Rz}(R, z) = \sigma_{Rz}(z) \exp(-R/R_1)
\]

\[
T(R_\odot, z) = \sigma_{Rz}(R_\odot, z) \left[ \frac{1}{R_\odot} - \frac{1}{R_0} - \frac{1}{R_1} \right]
\]

\[
\sigma_{Rz}(R_\odot, z) = A \pi^n |_{R_\odot}
\]

Parameters:
- \( A \),
- \( n \),
- \( R_0 = R_1 \)
Modelling the Components:

**Dark Matter Density profile**

**Constant $\rho_{DM}$**
Within 10% of correct spherical halo density up to $z \sim 3kpc$

**Constant $\rho_{DM} +$ Dark Disc**
Dark Discs from e.g. accretion of subhalos, Partially Interacting DM.

Similar vertical profile from flattened, oblate halo.