Title: Constraining a Thin Dark Matter Disk with Gaia

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Abstract: <p>If a component of the dark matter has dissipative interactions, it could collapse to form a thin dark disk in our Galaxy coincident with the baryonic disk. It has been suggested that dark disks could explain a variety of observed phenomena, including periodic comet impacts. Using the first data release from the Gaia mission, we search for a dark disk via its effect on stellar kinematics in the Milky Way. I will present new limits on the presence of a thin dark matter disk, as well as measurements on the matter density in the solar neighborhood.</p>
Constraining a thin dark matter disk with Gaia

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PI Seminar

1711.03103 with Katelin Schutz, Ben Safdi, and Chih-Liang Wu
Particle models for dark matter

Evidence for gravitation interactions

We can also use gravitational interactions to test gauge interactions of DM
Hidden Sectors

By analogy with the SM, a compelling possibility that dark matter has its own gauge interactions

Models containing new light mediators ($Z'$) could explain:
- small scale structure and SIDM
- large scale structure and $H_0$
- Galactic center GeV excess
- ...
where the interacting hidden sector may be a fraction of the total DM
Why dark disks?

By analogy with the Standard Model, if some of the dark matter interacts with "dark forces", this could also lead to cooling and flattening.

Very rough estimate:

\[ z_d \approx 2.5 \text{ pc} \left( \frac{\alpha_D}{0.02} \right)^2 \frac{m_C}{1 \text{ MeV}} \frac{100 \text{ GeV}}{m_X} \]

Thin dark matter disks?

Fan, Katz, Randall, and Reece 2013
Conditions for disk formation

- Disk formation: gas collisions produce radiation, which can escape, leading to cooling and collapse

- Fan et al. estimate dark disk scale height using the temperature at which cooling processes complete

- Note: Toomre instability was unaccounted for in estimates of thin dark disk formation

Thoul and Weinberg 94
Conditions for disk formation

- Disk formation: gas collisions produce radiation, which can escape, leading to cooling and collapse.

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Cooling rates

Thoul and Weinberg 94
Implications of dark disks

- Implications for (in)direct detection (McCullough & Randall, Fan, Katz & Shelton)
- Co-rotation of Andromeda satellites (Randall & Scholtz)
- Periodic disruption of comet trajectories causing mass extinction events (Randall & Reece, Shaviv, Kramer & Ramon)
- Collapsed dark matter objects can account for the point-like nature of the inner galaxy GeV excess (Agrawal & Randall)
- Massive black hole formation (D’Amico et al.)

High density dark disk considered for these!
Periodic Comet Impacts

Oscillation of sun about thin dark disk can perturb Oort cloud...

Randall and Reece 2014
Kramer and Rowan 2016
Shaviv 2016
Periodic Comet Impacts

Oscillation of sun about thin dark disk can perturb Oort cloud...

Leading to periodic comet impacts

Randall and Reece 2014
Kramer and Rowan 2016
Shaviv 2016
Bounds on a thin dark disk

Disk Surface Density

1604.01407 Eric Kramer and Lisa Randall
Using kinematics of ~2000 stars from Hipparcos.
Gaia satellite

- Full sky view of stellar positions, distances, and velocities
- Launched 2013
- First data release (DR1): September 2016 $\sim 10^6$ stars
- Next release (DR2): April 2018 $\sim 10^9$ stars
Gaia astrometry

With 15 μas resolution you can see a quarter on the surface of the moon
Gaia astrometry

TGAS: subsample of DR2
with parallaxes, vel's

Next data release:
astrometry for
~10^9 stars

number of stars

brightness

See also: MacMillan et al. 2017
Anderson et al. 2017
Dark matter applications

- Local dark matter density
  Read 2014, Silverwood et al. 2015

- Local velocity distribution
  Herzog-Arbeitman, Lisanti, Necib 2017

- Dark matter halo profile
  Bovy & Rix 2013 + followups

- Substructure — dark disks, thick dark matter disks, dark matter subhalos

  All important inputs for dark matter direct detection, indirect detection
Thick dark disk

a) $\rho_{\text{dm}} < \rho_{\text{dm, ext}}$

b) $\rho_{\text{dm}} > \rho_{\text{dm, ext}}$

Density profiles near $R = R_\odot$

- Baryons
- NFW DM halo
- Halo + thick dark disk

Read et al. 2009
Silverwood et al. 2015
Thin dark disk

Surface density

\[ \rho_{DD}(R_\odot, z) = \frac{\Sigma_D}{4h_D} \text{sech}^2 \left( \frac{z}{2h_D} \right) \]

Scale height

Density profiles near \( R = R_\odot \)

- Baryons
- NFW DM halo
- Halo + thick dark disk
- Thin dark disk
  - \( \Sigma_D = 5M_\odot/\text{pc}^2 \)
  - \( h_D = 50 \text{ pc} \)
I. Constraining a dark disk and the local DM density
Basic idea

Tracer populations (of stars) are sensitive to the total gravitating mass.

Familiar example:
Basic idea

Tracer populations (of stars) are sensitive to the total gravitating mass.

\[ \frac{d f_A}{dt} = \partial_t f_A + \partial_x f_A \cdot \mathbf{v} - \partial_v f_A \cdot \partial_x \Phi = 0 \]

Under assumptions of separability, equilibrium:

\[ v_z \partial_z f_A - \partial_z \Phi \partial_{v_z} f_A = 0 \]

For tests of these assumptions, see Garbari et al. 2011
Basic idea

Tracer populations (of stars) are sensitive to the total gravitating mass.

\[ \frac{d f_A}{d t} = \partial_t f_A + \partial_x f_A \cdot \mathbf{v} - \partial_v f_A \cdot \partial_x \Phi = 0 \]

Under assumptions of separability, equilibrium:

\[ v_z \partial_z f_A - \partial_z \Phi \partial_{v_z} f_A = 0 \]

The stellar density is determined by gravitational potential and distribution of mid-plane z-velocities

\[ \nu_A(z) = \nu_{A,0} \int dv_z f_{A,0} \left( \sqrt{v_z^2 + 2\Phi(z)} \right) \]

Number density of tracer population

\[ f(v_z) = \text{Distribution of vertical velocities in the plane of the MW.} \]

Used as input data.

For tests of these assumptions, see Garbari et al. 2011
Tracer stars

Midplane velocity distribution $f(v)$

Density fall-off $v(z)$

Density of tracer stars, Gaia-DR1

- No dark disk
- $\Sigma_D = 10 M_\odot/\text{pc}^2$, $h_D = 50 \text{pc}$
Gravitational Potential

Determining the gravitational potential requires a mass model

Model baryonic mass as a number of isothermal* components $v_A$

Vertical Jeans equation:

$$\frac{\sigma_A^2}{v_A} \frac{\partial}{\partial z} v_A + \frac{\partial}{\partial z} \Phi = 0 \quad \rightarrow \quad \nu_A(z) = \nu_A(0) e^{-\Phi(z)/\sigma_A^2}$$

*Velocity dispersion doesn’t depend on $z$

Connect this to the mass density profile with Poisson equation

$$\frac{\partial^2 \Phi}{\partial z^2} = 4\pi G \rho$$

Inject: baryons, smooth dark matter halo, and dark disk

For tests of these assumptions, see Garbari et al. 2011
Baryons

Isothermal components of Baryonic mass

<table>
<thead>
<tr>
<th>Baryonic Component</th>
<th>( \rho(0) ) [( \text{M}_\odot / \text{pc}^3 )]</th>
<th>( \sigma ) [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Gas (H(_2))</td>
<td>0.0104 ± 0.00312</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>Cold Atomic Gas (H(_1)(1))</td>
<td>0.0277 ± 0.00554</td>
<td>7.1 ± 0.5</td>
</tr>
<tr>
<td>Warm Atomic Gas (H(_1)(2))</td>
<td>0.0073 ± 0.0007</td>
<td>22.1 ± 2.4</td>
</tr>
<tr>
<td>Hot Ionized Gas (H(_II))</td>
<td>0.0005 ± 0.00003</td>
<td>39.0 ± 4.0</td>
</tr>
<tr>
<td>Giant Stars</td>
<td>0.0006 ± 0.00006</td>
<td>15.5 ± 1.0</td>
</tr>
<tr>
<td>( M_V &lt; 3 )</td>
<td>0.0018 ± 0.00018</td>
<td>7.5 ± 2.0</td>
</tr>
<tr>
<td>( 3 &lt; M_V &lt; 4 )</td>
<td>0.0018 ± 0.00018</td>
<td>12.0 ± 2.4</td>
</tr>
<tr>
<td>( 4 &lt; M_V &lt; 5 )</td>
<td>0.0029 ± 0.00029</td>
<td>18.0 ± 1.8</td>
</tr>
<tr>
<td>( 5 &lt; M_V &lt; 8 )</td>
<td>0.0072 ± 0.00072</td>
<td>18.5 ± 1.9</td>
</tr>
<tr>
<td>( M_V &gt; 8 ) (M Dwarfs)</td>
<td>0.0216 ± 0.0028</td>
<td>18.5 ± 4.0</td>
</tr>
<tr>
<td>White Dwarfs</td>
<td>0.0056 ± 0.001</td>
<td>20.0 ± 5.0</td>
</tr>
<tr>
<td>Brown Dwarfs</td>
<td>0.0015 ± 0.0005</td>
<td>20.0 ± 5.0</td>
</tr>
<tr>
<td>Total</td>
<td>0.0889 ± 0.0071</td>
<td>—</td>
</tr>
</tbody>
</table>

Biggest uncertainties are in the gas density

Stellar midplane densities are improving with Gaia (Bovy 2017)

collected from: Flynn et al. 2006, Read 2014, McKee et al. 2015, Kramer+Randall 2015, Bovy 2017
Density profiles

![Graph showing density profiles for different types of stars and gas over height above the Galactic Plane.]

- Molecular Hydrogen
- Atomic Gas
- A and F Stars
- G Stars
- K Stars
- M Stars
- White Dwarfs

Density [M\_\odot/pc\(^3\)]

0 50 100 150 200
Height above Galactic Plane [pc]
Density profiles

$$
\rho_{DD}(z) = \frac{\Sigma}{4h} \text{sech}^2 \left( \frac{z}{2h} \right)
$$

- **Molecular Hydrogen**
- **Atomic Gas**
- **A and F Stars**
- **G Stars**
- **K Stars**
- **M Stars**
- **White Dwarfs**
- **Dark Disk**
Analysis

1. Model the baryons at the plane

2. Solve Poisson-Jeans equations for the gravitational potential $\Phi$, including dark matter and dark disks

3. Selecting a tracer population of stars, determine the vertical fall-off of stars (using $\Phi$ and f(v))

4. Fit to data, marginalizing over many nuisance parameters

see also: Kramer and Randall, Holmberg and Flynn 2000
Tracer stars

Gaia measures fainter stars out to larger distances

- Hipparcos survey (~1990)
- Our cuts for Gaia DR1

We divide up tracers into three populations: A, F, and Early G stars

Bovy 2017
Equilibrium?

- The basis of our analysis is that the stellar populations and mass components are close to equilibrium near the mid-plane.

- Stellar populations have different lifetimes, and display different departures from equilibrium.

- To be conservative, we also include a systematic from asymmetries in $f(v)$.

Data from Widrow et al. 2012
Figure from Gomez et al. 2013
Velocity distributions

- Best fit $v_{z,\text{sun}} = 6.8 \pm 0.2$ km/s consistent with independent determinations
- Good fit to Gaussians
- Final systematics are: ~15%, 5%, 7% for AFG stars
Number density of tracers

![Graph showing number density of tracers vs height above Galactic Plane.]

Best fit assuming no dark disk.

Here $\rho_{DM} = 0.014 \, M_\odot/pc^3 = 0.5 \, GeV/cm^3$
Setting limits

\( \ln L (\chi^2) \) function includes measurements of vertical density profiles; \( f(v) \) for 3 tracer pops; baryons

Sample over:
- \( \rho_{DM} \)
- \( \rho_b \) baryon densities + velocity dispersions
- \( f(v) \) in 20 bins for each tracer
- height of sun \( z_{sun} \)
- overall normalization for density profiles

= 89 parameters

Condition for 95\% one-sided limit:
\[ \lambda(\Sigma_{DD}) = -2.71 \]

Cowan, Cranmer, Gross, Vitells 2011
Dark disk bounds

New limit from Gaia

Expectation from mock data catalogs, assuming default baryon mass model and $\rho_{DM} = 0.015 \, M_\odot/pc^3$
Dark disk bounds

New limit from Gaia

Kramer & Bandell (2016)

This Work

Improvements

Statistics:
~38,000 vs. 2000 stars

Longer lever arm:
max z = 200 pc vs. 150 pc

Nuisance parameters:
marginalize over many
nuisance parameters vs.
“non-equilibrium” method
Robustness of bounds

Alternate Binning

Alternate Gas Densities

<table>
<thead>
<tr>
<th>Gas Component</th>
<th>Kramer &amp; Randall $\rho(0)$ [M$_\odot$/pc$^2$]</th>
<th>McKee et al. $\rho(0)$ [M$_\odot$/pc$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Gas (H$_2$)</td>
<td>0.014 ± 0.005</td>
<td>0.01 ± 0.003</td>
</tr>
<tr>
<td>Cold Atomic Gas (H$_1$)</td>
<td>0.015 ± 0.003</td>
<td>0.028 ± 0.006</td>
</tr>
<tr>
<td>Warm Atomic Gas (H$_2$(1))</td>
<td>0.005 ± 0.001</td>
<td>0.007 ± 0.001</td>
</tr>
<tr>
<td>Hot Ionized Gas (H$_\text{II}$)</td>
<td>0.00011 ± 0.0003</td>
<td>0.0005 ± 0.0002</td>
</tr>
</tbody>
</table>

Kramer & Randall gas densities lower by ~25%
Bounds by population

F and Early G stars have similar statistics: differences may be due to statistical fluctuations, measurement error, different dynamical densities seen by older stars, effect of non-equilibrium perturbations?
Dark disk parameters

Bayesian analysis gives similar results on the dark disk posterior distributions for 3 tracer populations
Local dark matter density

Measurements of midplane density in $M_\odot$/pc$^3$

<table>
<thead>
<tr>
<th>Component</th>
<th>A Stars</th>
<th>F Stars</th>
<th>Early G Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>baryons</td>
<td>$0.088 \pm 0.006$</td>
<td>$0.088 \pm 0.007$</td>
<td>$0.085 \pm 0.007$</td>
</tr>
<tr>
<td>DM</td>
<td>$0.038 \pm 0.012$</td>
<td>$0.019 \pm 0.011$</td>
<td>$0.004 \pm 0.004$</td>
</tr>
</tbody>
</table>

First measurements of *local* DM density (usually obtained at 1.1 kpc).
Dark disk implications, revisited

- Dynamical influence on local stars in the Milky Way (Kramer/Randall non-equilibrium method):
  \[ \Sigma \sim 12 \, \text{M}_\odot/\text{pc}^2 , \, h \sim 10 \, \text{pc} \]
- Enhanced direct detection signal: \( O(1) \) level
- Periodic disruption of comet trajectories causing mass extinction events:
  \[ \Sigma \sim 10-20 \, \text{M}_\odot/\text{pc}^2 , \, h \sim 10-30 \, \text{pc} \]
- Collapsed dark matter objects can account for the point-like nature of the inner galaxy GeV excess:
  \[ \Sigma \sim 10 \, \text{M}_\odot/\text{pc}^2 , \, h \sim 10 \, \text{pc} \]
- Co-rotation of Andromeda satellites
  \[ \Sigma \sim 10 \, \text{M}_\odot/\text{pc}^2 , \, h \sim 50 \, \text{pc} \]

Important to note that dissipative DM is not ruled out!
Conclusions

- Dark disks can arise in models of dissipative dark matter

- Using Gaia TGAS data, we obtain + new bounds on the presence of thin dark matter disks + measurements of midplane densities and first local dark matter density

- Exciting time to better understand dark matter in the Milky Way with Gaia data!

Thanks!