Estimating the local DM content using Gaia

J. Buch, J. Leung, and J. Fan, JCAP 2019 no. 04, 026
• Local density and morphology of DM is an important ingredient in both direct and indirect DM searches.

• From a theoretical perspective, DM with dissipative self-interactions, for instance $U(1)_D$, can cool down like baryons and form compact objects (substructure). Depending on the specifics of astrophysical modeling (need better simulations!!), various signatures have been proposed recently: [Fan et al. ’13; Ghalasi & McQuinn ’17; Buckley & DiFranzo ’17, Chacko et al. ’18, Chang et al. ’18 (parallel talk today)]

• $\sim$1% of the total DM density $\Rightarrow O(1)$ fraction of the baryons in the solar neighborhood.
Central question: Can we set realistic constraints on the density in DM substructure in the solar neighborhood using current dynamical methods?
**Not shown:** Dark matter (DM) halo; MW $R_{\text{vir}} \sim 200$ kpc
Early G stars

F stars

A stars

R = 150 pc

z = 200 pc

Reviews: L. Strigari, '12, J. Read, '14

Image Credit: ESA
Overview

• Motivation

• *Gaia* DR2 and data selection

• Dynamical analysis

• Results and outlook

*Not an acronym anymore*
Gaia DR2 and Data Selection

Lia Halloran, Globular Cluster after Cecilia Payne
Gaia DR2 by numbers
[also see plenary by D. Hogg tomorrow]

- **Gaia DR2 provides:**
  - photometry in 3 bands \((G, G_{RP}, G_{BP})\) for ~1.7 billion sources between \(3 < G < 21\).
  - \((\alpha, \delta, \mu_{\alpha}, \mu_{\delta}, \varpi)\) astrometric solution for ~1.3 billion sources.
  - radial velocity spectra (RVS) for ~7 million sources with \(G < 12.5\)

- ~70 scans/source by end of survey!

Lindgren et al., 2018 Aug 27  Gaia DR2 astrometry, slide 51 of 54
Selection function (or lack thereof!)

- The DR2 catalog has a limiting magnitude $G \approx 21$, bright limit $G \approx 2$, and is essentially complete between $G \approx 12$ and $G \approx 17$. While this is definitely an improvement over TGAS, we still need to use an external catalog for constructing a volume complete number density of stars.

- We query the Gaia archive for stars in DR2 (full data is \~550 GB*) cross-matched with 2MASS and apparent magnitude $J < 14$, and calculate the effective completeness using the gaia_tools package [Bovy '17].

- 2MASS also provides color information ($J$, $K_s$) for DR2 stars, which we use for classifying stars into different spectral types: A, F, early G. An advantage of using $(J-K_s)$ instead of Gaia colors ($G_{BP} - G_{RP}$) is that these are in the infrared spectrum and only weakly affected by scattering due to interstellar dust.

* If you’re interested in working with DR2, I’d be happy to share ideas about handling data.
Vertical Number Density

- We define the local solar neighborhood as a heliocentric cylinder of radius $R=150$ pc and half-height $z=200$ pc.

- There’s $\sim 2.5x$ improvement in statistics in the local neighborhood using DR2.

\[ z (\text{kpc}) = \frac{\sin b}{\varpi \text{(mas)}} \]

<table>
<thead>
<tr>
<th>Data set</th>
<th>Gaia DR2</th>
<th>TGAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Subtype</td>
<td>Total</td>
<td>Midplane</td>
</tr>
<tr>
<td>A A0-A9</td>
<td>4445</td>
<td>321</td>
</tr>
<tr>
<td>F F0-F9</td>
<td>37707</td>
<td>2253</td>
</tr>
<tr>
<td>Early G G0-G3</td>
<td>43332</td>
<td>2188</td>
</tr>
</tbody>
</table>
Midplane velocity distribution

• Meanwhile, the vertical velocity of a star is given by,

\[
w = w_\odot + \frac{\kappa \mu_b}{\sigma} \cos b + v_R \sin b,
\]

• We define the midplane using a latitude cut, \(|b| < 5^0\), and use an approximation for the mean RV when a star has no RV data in DR2,

\[
\langle v_R \rangle = -u_\odot \cos l \cos b - v_\odot \sin l \sin b - w_\odot \sin b,
\]
Dynamical Analysis

Lia Halloran, Globular Cluster after Cecilia Payne
The procedure for obtaining the tracer density is straightforward:

a) choose a mass model for baryons (gas, stars, and stellar remnants), DM contribution from the halo, and other exotic DM component,

b) calculate the local galactic potential of these ingredients, and

c) compute the tracer density as a function of the potential.

Dynamical analysis

[Flynn & Fuchs ‘92; Holmberg & Flynn ‘98; Kramer & Randall ‘16; Schutz et al. ‘17]
Local mass content

- The total mass density is given by,

\[ \rho_{\text{tot}} = \sum_{i=1}^{N_b} \rho_i(0)e^{-\Phi/\sigma_{z;i}^2} + \rho_{\text{DM}} + \rho_{\text{substructure}}(z) \]

where the sum is over \( N_b \) components of the Bahcall model that consists of a set of isothermal components of baryons characterized by their midplane densities \( \rho_i(0) \) and vertical velocity dispersion \( \sigma_{z;i}^2 \).

\[ \rho_{DD}(z) = \frac{\Sigma_{DD}}{4h_{DD}} \text{sech}^2\left(\frac{z}{2h_{DD}}\right) \]

\[ \Sigma_{DD}(R_\odot) = \frac{\epsilon M_{\text{DM}}^\text{gal}}{2\pi R_{DD}^2} \exp(-R_\odot/R_{DD}) \]

<table>
<thead>
<tr>
<th>Baryonic components</th>
<th>( \rho(0) ) [M(_\odot)/pc(^3)]</th>
<th>( \sigma_z ) [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 ± 1.6</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 ± 0.0011</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>
</tbody>
</table>
• To obtain the potential in part $b)$, we solve the Poisson eq.

\[ \nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \Phi}{\partial r} \right) = 4\pi G \rho_{\text{tot}}, \]

with,

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \Phi}{\partial r} \right) \approx (3.4 \pm 0.6) \times 10^{-3} \, M_\odot/\text{pc}^3 \]

[Bovy '16]
Equilibrium density modeling

- A self-gravitating stellar population with phase space distribution function (DF), $f(x, v)$, satisfies the *collisionless* Boltzmann equation (CBE) [Jeans (1922)],

$$\frac{Df}{Dt} \equiv \frac{\partial f}{\partial t} + (\nabla_x f) \cdot v - (\nabla_x \Phi) \cdot (\nabla_v f) = 0$$

- Assuming equilibrium and time-independence of the potential, we obtain the Boltzmann equation in the $z$ direction for each tracer population,

$$w \frac{\partial f_i}{\partial z} - \frac{\partial \Phi}{\partial z} \frac{\partial f_i}{\partial w} = 0.$$

where $f_i(z, w)$ is the distribution function. Integrating over the velocity, we obtain the normalized tracer density [Flynn & Fuchs (1992)],

$$\frac{\nu_i(z)}{\nu_i(0)} = 2 \int_0^\infty dw f_{i,z=0}(\sqrt{w^2 + 2\Phi(z)})$$
Toy model

Effect of thin DD

- No dark disk
- $\Sigma_{DD} = 20 \, M_\odot/pc^2$, $h_{DD} = 10 \, pc$
Results and Outlook
Data analysis

• We constrain the total matter density by including with the Bahcall model:
  a) Local DM density $\rho_{\text{DM}}$,

  b) Local DM content: $\rho_{\text{DM}} + \text{thin DD}$

• Our model $\mathcal{M}$ is characterized by $\theta = \{\psi, \xi\}$, where $\psi = \{\rho_{\text{DM}}, \Sigma_{\text{DD}}, h_{\text{DD}}\}$ are the parameters of interest, and $\xi$ are the nuisance parameters, including height of the sun, baryonic uncertainties etc.

• We also account for the uncertainties in the midplane velocity distribution through: bootstrap (statistical), asymmetry possibly due to effects of disequilibria (systematic).
Data analysis

• Assuming a Gaussian likelihood function for our number density,

\[ p_{\nu}(d | \mathcal{M}, \theta) = \prod_{i=1}^{N_z} \frac{1}{\sqrt{2\pi \sigma_{\ln \nu_i}^2}} \exp \left( -\frac{(\ln(N_{\nu} \nu_{i}^{\text{mod}}(\theta)) - \ln \nu_{i}^{\text{data}})^2}{2 \sigma_{\ln \nu_i}^2(\theta)} \right) \]

we perform parameter estimation in a Bayesian framework by sampling the posterior,

\[ p(\theta | d) = \frac{p(d | \mathcal{M}, \theta) p(\theta | \mathcal{M})}{Z} \]

using the Markov Chain Monte Carlo (MCMC) sampler \texttt{emcee} [D. Foreman-Mackey et al. ’13]

• Note that MCMC methods are samplers and not optimizers, so there is no one ‘true’ value for each parameter. Instead, results are quoted using marginalized posteriors of parameters.
Local DM density

<table>
<thead>
<tr>
<th>Stellar type</th>
<th>$\rho_{\text{DM}}$ [M$_{\odot}$/pc$^3$]</th>
<th>$\rho_{\text{DM}}$ [GeV/cm$^3$]</th>
<th>$\rho_b$ [M$_{\odot}$/pc$^3$]</th>
<th>$z_{\odot}$ [pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A stars</td>
<td>0.016$^{+0.010}_{-0.010}$</td>
<td>0.608$^{+0.380}_{-0.380}$</td>
<td>0.088$^{+0.007}_{-0.007}$</td>
<td>8.80$^{+3.74}_{-4.23}$</td>
</tr>
<tr>
<td>F stars</td>
<td>0.039$^{+0.008}_{-0.008}$</td>
<td>1.482$^{+0.304}_{-0.304}$</td>
<td>0.089$^{+0.007}_{-0.007}$</td>
<td>2.04$^{+2.84}_{-3.13}$</td>
</tr>
<tr>
<td>G stars</td>
<td>0.009$^{+0.011}_{-0.008}$</td>
<td>0.342$^{+0.418}_{-0.304}$</td>
<td>0.088$^{+0.007}_{-0.007}$</td>
<td>2.79$^{+3.48}_{-2.04}$</td>
</tr>
</tbody>
</table>
Local DM density

• Our results are consistent with previous measurements:

\[ \rho_{\text{DM}} = 0.012^{+0.001}_{-0.002} \text{ M}_\odot/\text{pc}^3 \text{ (within 1}\sigma) \]  
[Sivertsson et al. ‘17]

\[ \rho_{\text{DM}} = 0.008^{+0.003}_{-0.003} \text{ M}_\odot/\text{pc}^3 \text{ (within 2}\sigma) \]  
[Bovy & Tremaine ‘12]

• Notice that the error bars are fairly large in our case. While poorly modeled systematics can be a culprit, the posteriors indicate a high level of degeneracy between baryons and DM.

• Indeed, as first pointed out by (Bahcall, 1992) and shown via detailed N-body simulations by (Garbari et al., 2011), this degeneracy can only be broken by including the density falloff at \( z > 1 \text{ kpc} \).

• Interestingly, (A. Widmark 2018), also finds an excess surface mass density \( \sim 5-9 \text{ M}_\odot/\text{pc}^2 \) for \( |d| < 50\text{pc} \).
Central question: Can we set realistic constraints on the density in DM substructure in the solar neighborhood using current dynamical methods?
Local DM content (w thin DD)

Highly diagonal posterior in the DM-DD plane

Flat posteriors in the baryon-DM, baryon-DD plane

Highly diagonal posterior in the DM-DD plane

Answer: Maybe, but ...
Local DM content (w thin DD)

- Better understanding and modeling of how disequilibria affects dynamics in the solar neighborhood.

- Need physical observable(s) to break the degeneracy between DM and substructure; ratios, hierarchical modeling?
Conclusions

• We estimate, using A stars as tracers: a) the value of local DM density (with no DD) to be $\rho_{DM} = 0.016 \pm 0.01 \ M_\odot/pc^3$, and b) exclude a thin DD with $\Sigma_{DD}$ greater than $(5 - 12) \ M_\odot/pc^2$ at the 95% confidence level.

• Due to the latent degeneracy between baryons and DM (substructure or otherwise) in the solar neighborhood, hard to match the precision (given unknown systematics) of DM density measurements at high z.

• Inference using current dynamical methods will not scale linearly with precision in Gaia data (high bias, not high variance!); biggest challenge to detecting DM substructure is modeling the effects of disequilibria on stellar motions.

• We’ve only begun to tap the potential of Gaia; there’s much more data than theory can keep up with at this point!
Thank you.

Comments & criticisms welcome!
Extra slides
• Consider a minimal model: a heavy fermion $X$ and a light fermion $C$ charged under a $U(1)_D$ symmetry.

• We can treat this setup as a dark sector that constitutes a fraction, $\varepsilon$, of the total DM content, i.e: most of the DM is still cold and collisionless.

• Further, like the baryons, we assume that we only have an asymmetric population of $X$ and $C$ particles today, along with the dark photon $\gamma_D$.

• Phenomenology applicable to several ideas discussed by many authors over the years [Mohapatra+ ’96, Foot ’04, Feng+ ’08, Kaplan+ ’09]

![Image Credit: J. Leung](image_url)
• Schematically, the dissipative dark component cools while falling into the halo losing its kinetic energy through the dark photons escaping the galaxy without reabsorption.

• However, the conservation of the initial angular momentum results in the shrinkage of the halo, which ultimately flattens to form a disk.

• At the first order, we can estimate the fraction $\epsilon$ of such a component by subtracting the contribution of the baryonic components from the total matter surface density (Oort limit),

$$\epsilon \lesssim 0.05$$

• Exploring the effect of dissipative DM interactions using cooling prescriptions [Fan & Rosenberg ‘17] in simulations is still lacking. For constraining many dissipative DM scenarios, their input will be key!
To achieve a cooling timescale faster than the age of the Universe, we require the light particles Cs to dissipate energy similar to that of the baryonic gas through bremsstrahlung and Compton scattering.

The heavy particles Xs can also cool simultaneously due to the thermal coupling between the two species as a result of Rutherford scattering.
The exponential dependence on the potential is due to the vertical Jeans equation, derived by integrating the Boltzmann equation assuming each population is in equilibrium,

\[
\frac{1}{r \nu_i} \frac{\partial}{\partial r} \left( r \nu_i \sigma_{rz;i} \right) + \frac{1}{r \nu_i} \frac{\partial}{\partial \phi} \left( \nu_i \sigma_{\phi z;i} \right) + \frac{1}{\nu_i} \frac{d}{dz} \left( \nu_i \sigma_{z;i}^2 \right) = - \frac{d \Phi}{dz}
\]

"Tilt" term

"Axial" term
The DR2 midplane velocity distribution has a more gradual falloff as compared to TGAS that results in a broader predicted density. Raises issues regarding the robustness of the method!

Broader prediction → accommodates more matter → weaker constraints
• DR2 catalog should be treated as independent from DR1! In particular, there may be significant differences between observations in DR2 and the Tycho-Gaia Astrometric Solution (TGAS) subset of DR1 for some sources.