the ESA **Gaia** Mission and dark matter

David W Hogg
(NYU) (Flatiron) (MPIA)
Disclaimers

I am not a member of the ESA Gaia Consortium.

I am not going to try to be fair or comprehensive in this presentation.
How do we know there is dark matter?

- **Observed velocity dispersions** (second moments of velocity) are too large in gravitationally bound systems to be explicable by stars and gas alone.
  - True for galaxies of all masses, and clusters of galaxies.
  - Also true locally in the Milky Way.
- **Big-bang nucleosynthesis** is observationally inconsistent with the high baryon density that would be needed to explain the expansion history.
- The **growth of large-scale structure** is too rapid to be explained by the observed baryon density.
- The observed **orbit structure in the Milky Way** requires an immense quasi-spherical halo of unseen mass.
How is astronomy sensitive to dark matter?

- Dynamics of (near) equilibrium systems
- Kinematics of non-equilibrium sub-structures in the Milky Way
- Growth of large-scale structure
- Gravitational lensing
- Scattering of, annihilation into, or mixing with, photons
- Scattering from baryons or dissipation in stars, etc
What does astronomy constrain?

- Interactions with SM particles
- Self-interactions and dark radiation
- Exceedingly low masses (like axions)
- Exceedingly high masses (like black holes)
- Power spectrum, clustering, substructure, and so on
What does Gaia provide?

- Micro-arcsecond to sub-milli-arcsecond measurements of 2 billion stars.
  - Hence: Parallaxes and proper motions; hence distances and transverse velocities.
- Radial velocities for millions.
- Low-resolution spectrophotometry for a billion.
- All with no moving parts!
  - The engineering behind the mission, both hardware and software, is incredible.
  - All measurements saturate information-theoretic bounds, given the telemetry.
We don’t get to see stars move along their orbits

- For our purposes, *Gaia* sees only a snapshot in time.
- We only see **position and velocity at a single moment** on the past light cone.
  - Imagine if Brahe, Kepler, Hooke, and Newton had only had *that* information?
Near-equilibrium dynamical systems

- Virial theorem
- Jeans Equation
- Full forward modeling
  - These are all, essentially, based on second moments of the velocity distribution.
  - See, eg, Binney & Tremaine.
Schutz et al. arXiv:1711.03103
Combining spectroscopy and photometry with Gaia

- Spectroscopy provides a radial velocity for each star.
- Also detailed element abundances.
- Spectroscopy and photometry can deliver dust attenuation information.
- And additional distance information when parallaxes are near zero.
  - See papers by Anders, Hogg, Leung, and others.
Non-equilibrium dynamical structures

- Stars form in clusters (and clusters of clusters).
- As clusters disrupt tidally, they form streams that illuminate the orbits in a neighborhood in orbit space.
  - Streams can be very “cold” or very informative in phase space.
- These streams reveal the acceleration field of the Galaxy
  - See papers by Bonaca, Bovy, Johnston, Price-Whelan, Sanders, etc.
Substructure interactions and streams

- Because stellar streams are thin in phase space, they act like gravitational antennae.
  - They record past gravitational interactions.
- An interaction with any compact structure will leave a scar.
  - Any non-trivial time variation in the force law leaves a trace (eg, Erkal).
- These features can be used to dynamically “image” dark-matter substructure.
  - See papers by Bonaca, Carlberg, Erkal, Johnston, Yoon, etc.
Observed GD-1 stream

Gaia proper motions
PanSTARRS photometry

Model of a perturbed GD-1

t = 495 Myr
M = 5 \times 10^6 M_\odot
r_s = 10 pc
b = 15 pc
V = 250 km s^{-1}
Other things to watch for

- Wide-separation binary stars are sensitive to dark-matter granularity and substructure.
- Gravitational lensing can imprint anomalous velocities and accelerations into the Gaia data.
  - See Van Tilburg et al arXiv:1804.01991
- Gaia may improve the Solar-System constraints on some parameters.
- Gaia is very strongly testing stellar astrophysics; this will strengthen, eg, constraints on dark matter trapped in stars, and other anomalies.
Fig. 6. Solar neighbourhood *Gaia* HRDs for a) $\sigma > 40$ mas (25 pc, 3,724 stars), b) $\sigma > 20$ mas (50 pc, 29,683 stars), and c) $\sigma > 10$ mas (100 pc, 212,728 stars).
Take-home messages

- The ESA Gaia Mission is measuring the dark matter in the Milky Way.
  - Especially in concert with huge spectroscopic and photometric surveys.
- Methods for looking at the dark matter with Gaia fall into categories:
  - Near-equilibrium methods (virial, Jeans, and so on)
  - Out-of-equilibrium methods (streams, Snail, and so on)
  - Other (gravitational lensing, stellar physics, eg)
- We might have good evidence for a dark substructure in the Milky Way halo.
- Now is the time to bring particle physicists and astronomers closer together to design new measurements, and new missions.
- All relevant data are completely public!