the ESA ***Gaia*** Mission and dark matter

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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?

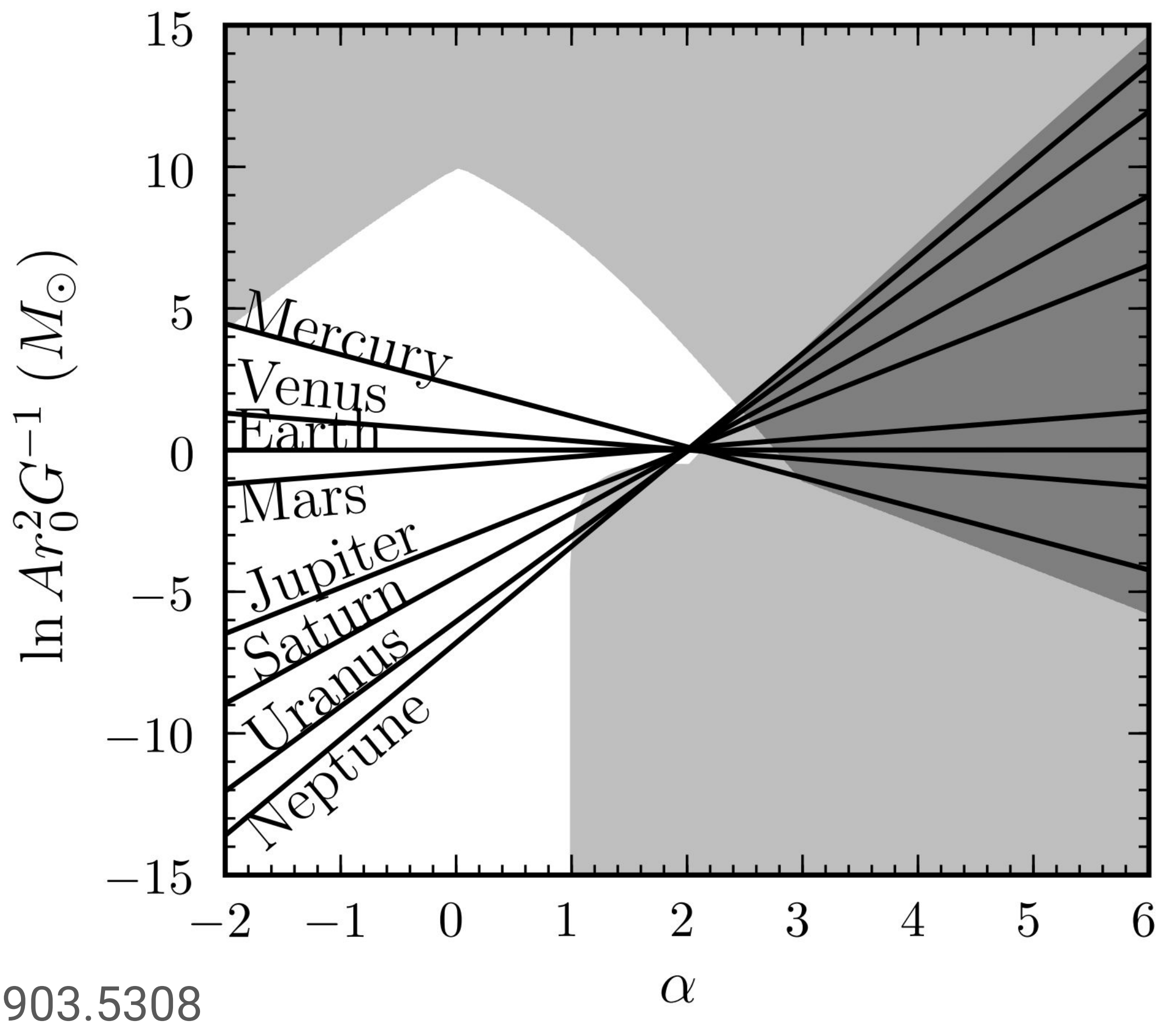
- Interactions with SM particles
- Self-interactions and dark radiation
- Exceedingly low masses (like axions)
- Exceedingly high masses (like black holes)
- Power spectrum, clustering, substructure, and so on

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

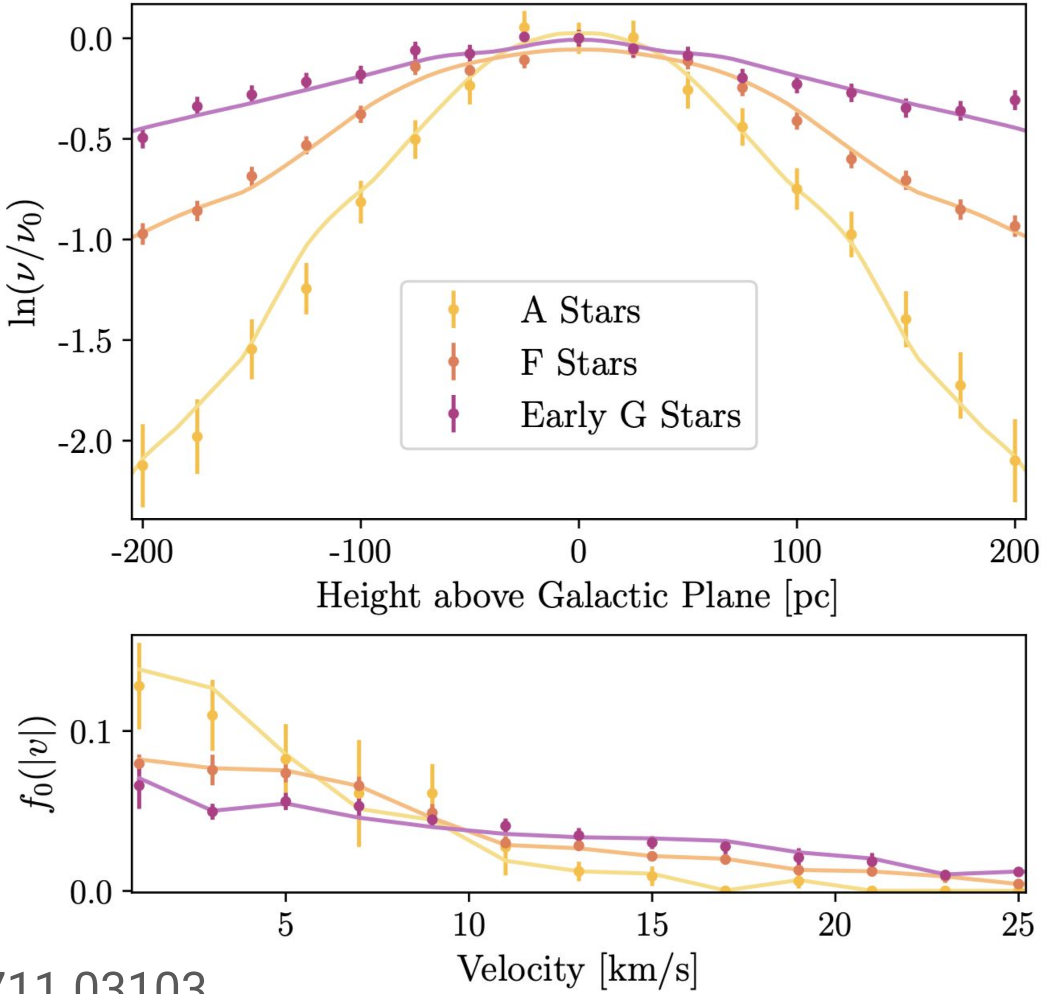
- For our purposes, *Gaia* sees only a snapshot in time.
- We only see **position and velocity at a single moment** on the past light cone.
    - Imagine if Brahe, Kepler, Hooke, and Newton had only had *that* information?



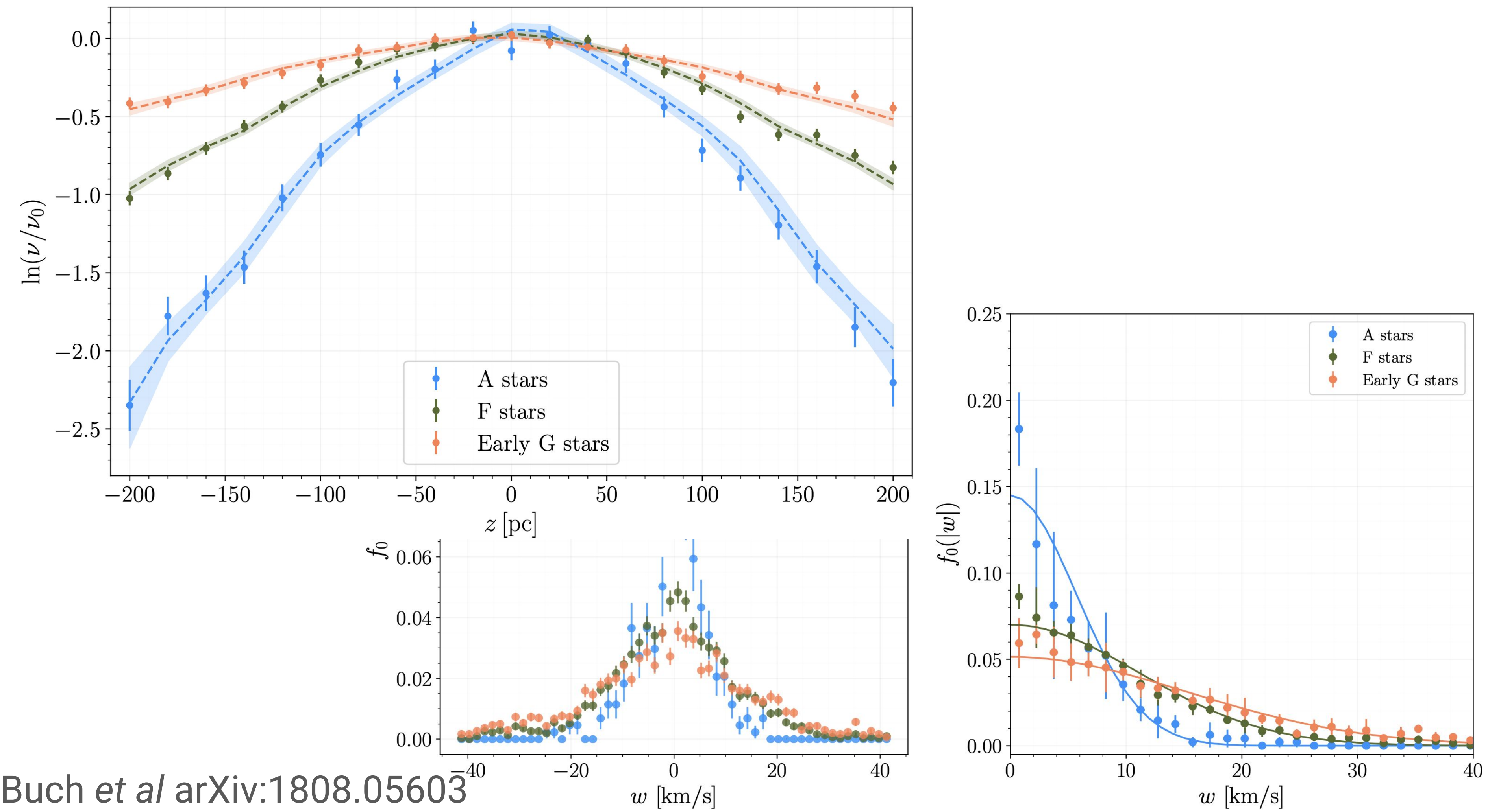
Bovy *et al* arXiv:0903.5308

Near-equilibrium dynamical systems

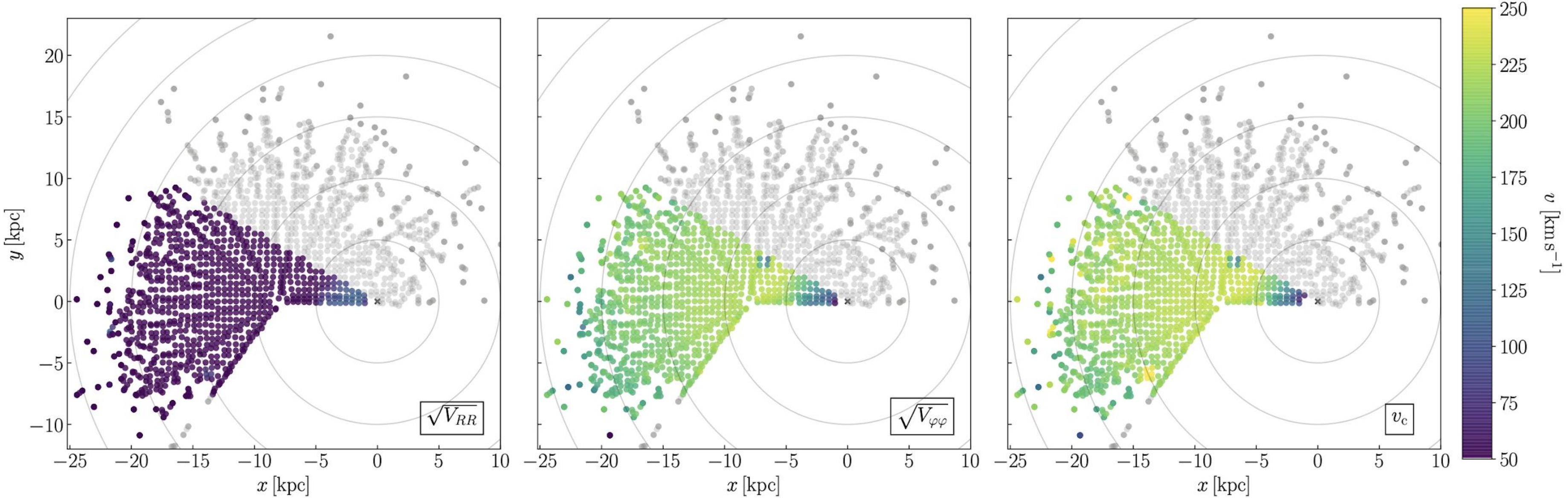
- Virial theorem
- Jeans Equation
- Full forward modeling
  - These are all, essentially, based on **second moments of the velocity distribution**.
  - See, *eg*, Binney & Tremaine.



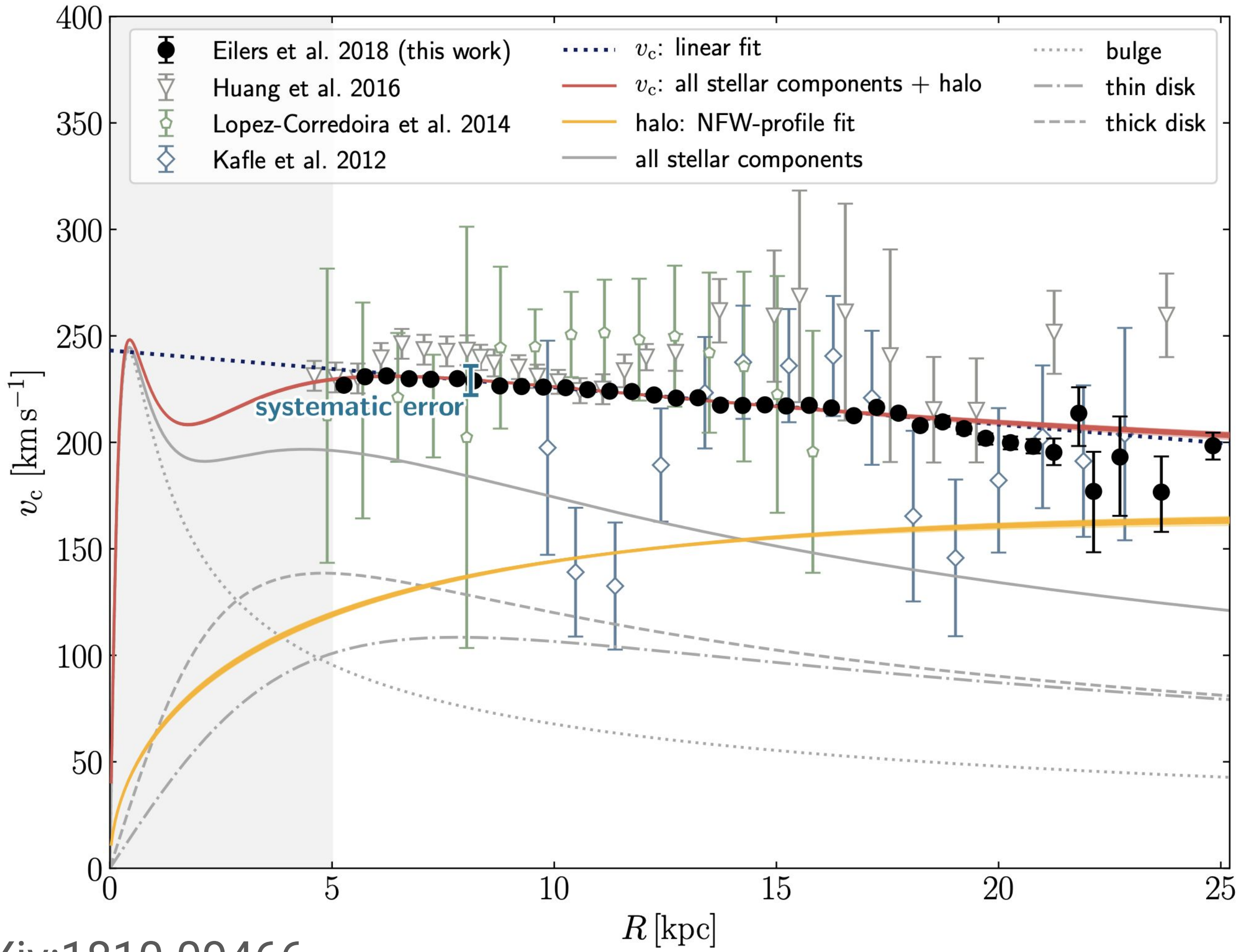
Schutz *et al* arXiv:1711.03103



Buch *et al* arXiv:1808.05603



Eilers *et al* arXiv:1810.09466



Eilers *et al* arXiv:1810.09466

Combining spectroscopy and photometry with *Gaia*

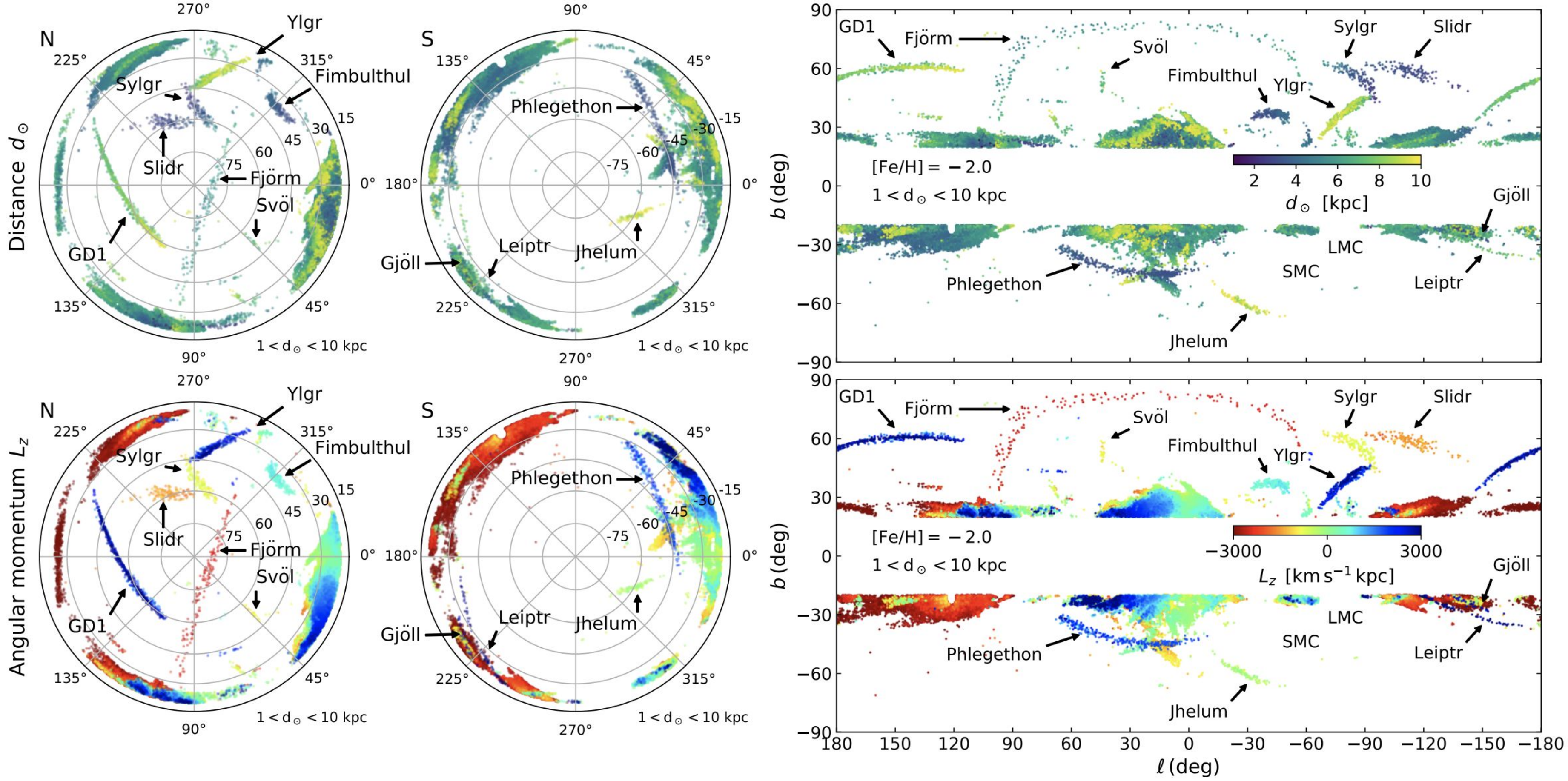
- Spectroscopy provides a radial velocity for each star.
- Also detailed element abundances.
- Spectroscopy and photometry can deliver dust attenuation information.
- And additional distance information when parallaxes are near zero.
  - See papers by Anders, Hogg, Leung, and others.

Non-equilibrium dynamical structures

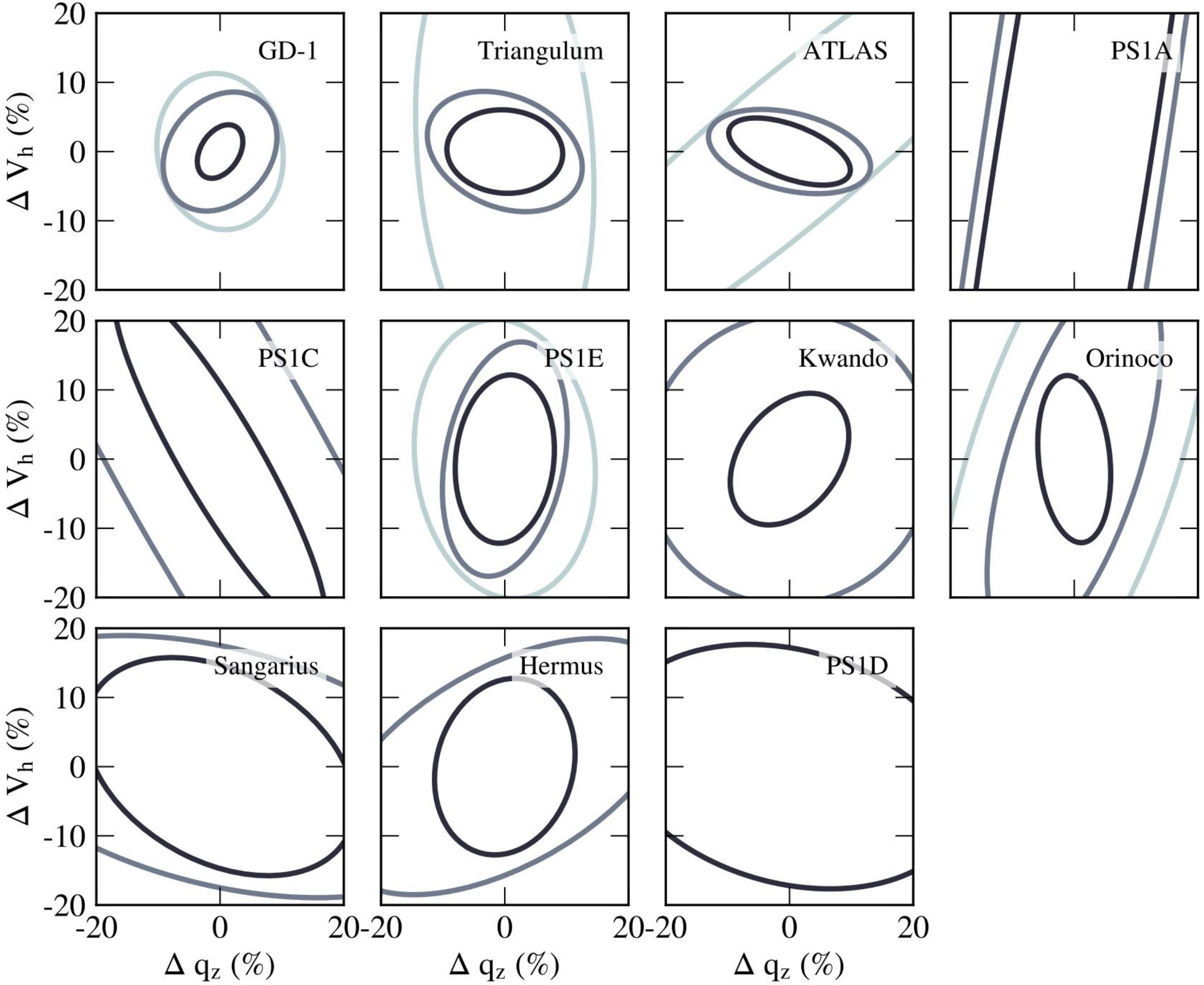
- Stars form in clusters (and clusters of clusters).
- As clusters disrupt tidally, they form streams that illuminate the orbits in a neighborhood in orbit space.
    - Streams can be very “cold” or very informative in phase space.
- These streams reveal the acceleration field of the Galaxy
    - See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

image credit: Bonaca *et al*

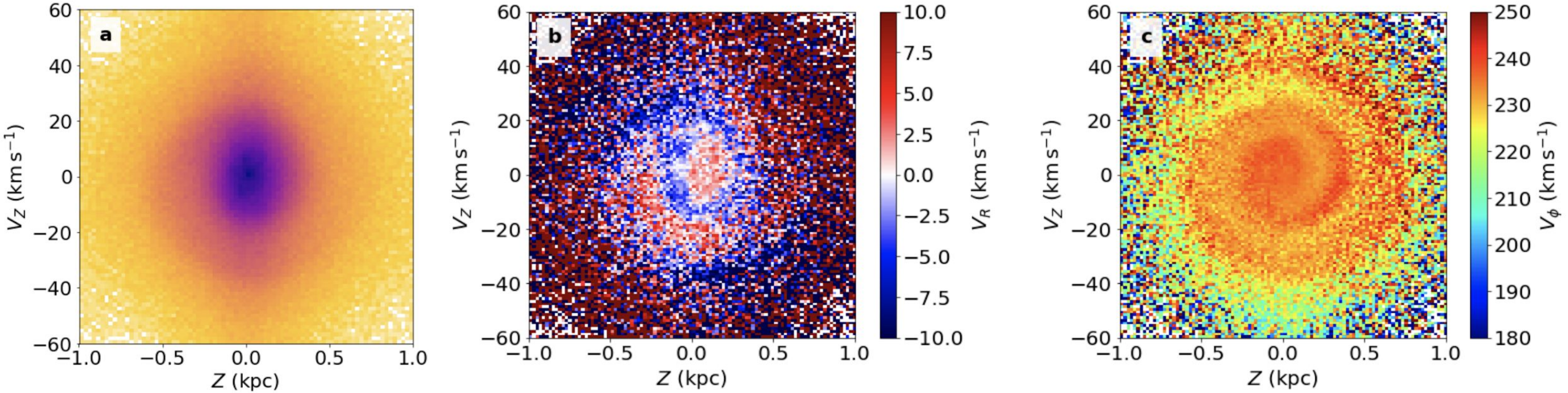
Northern Sky



Ibata *et al* arXiv:1901.07566



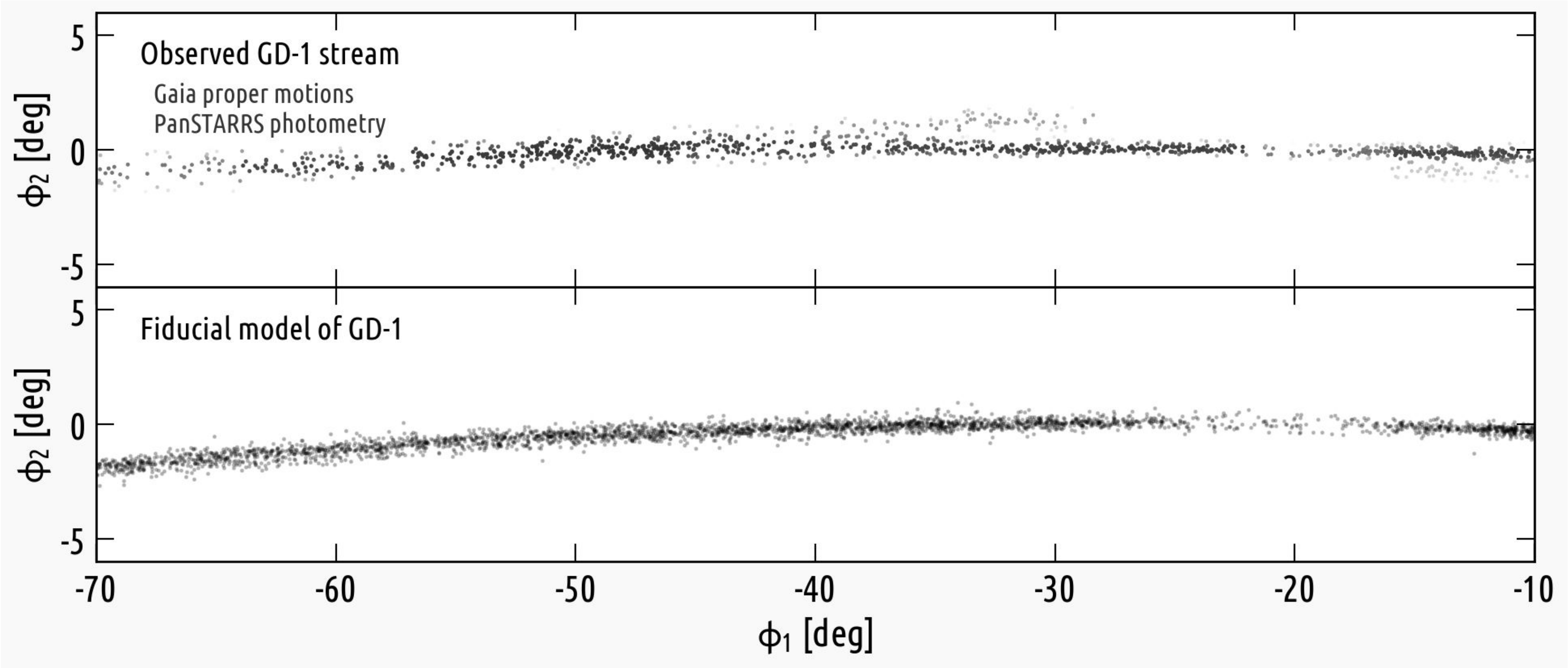
Bonaca & Hogg arXiv:1804.06854



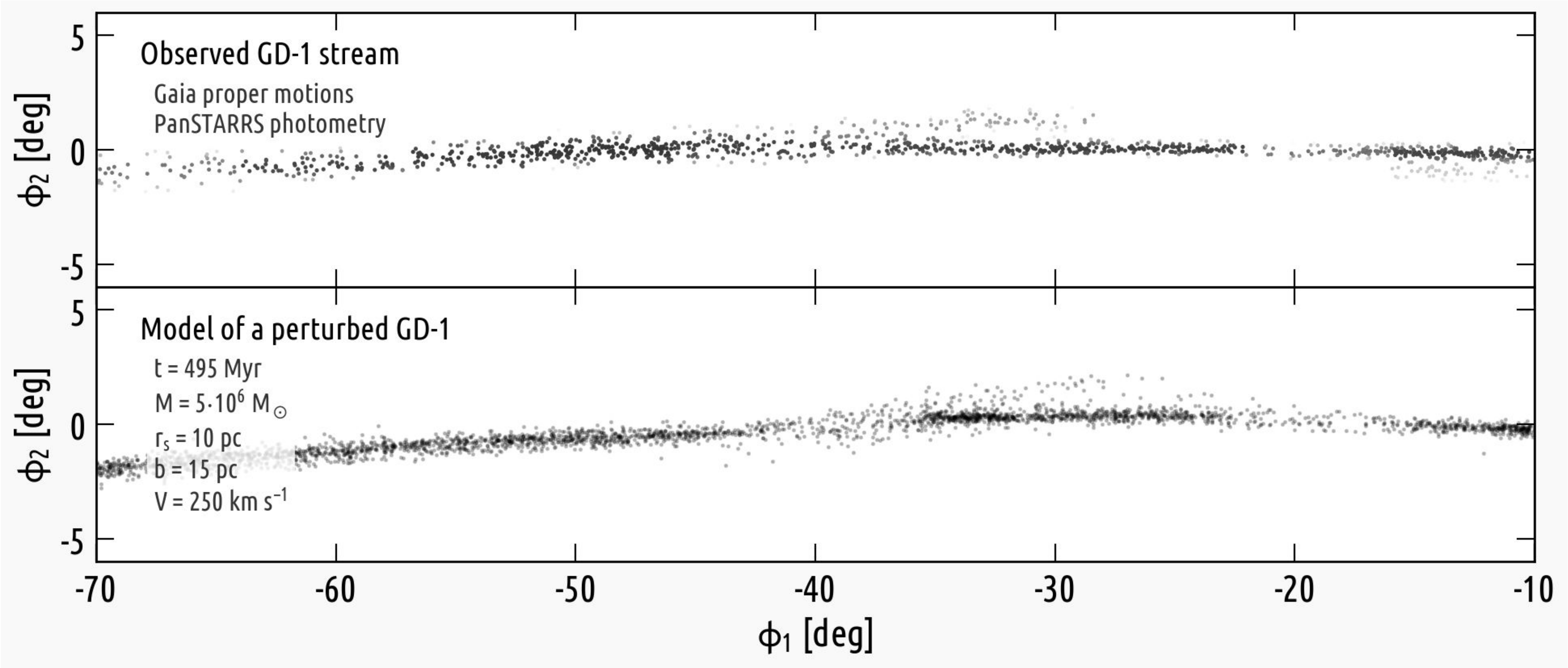
Antoja *et al* arXiv:1804.10196

Substructure interactions and streams

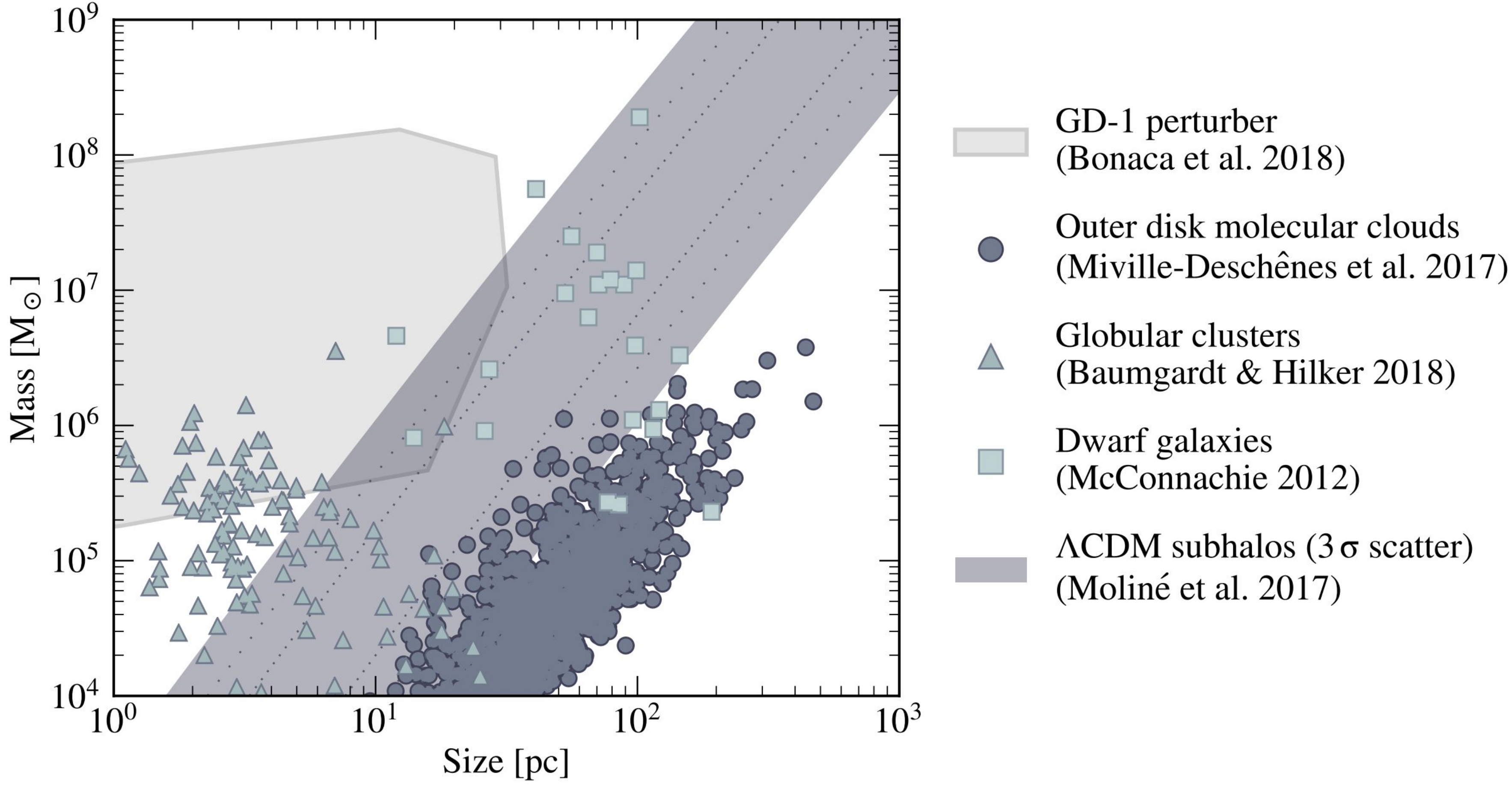
- Because stellar streams are thin in phase space, they act like gravitational antennae.
  - They record past gravitational interactions.
- An interaction with any compact structure will leave a scar.
  - Any non-trivial time variation in the force law leaves a trace (*eg*, Erkal).
- These features can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



Bonaca *et al* arXiv:1811.03631



Bonaca *et al* arXiv:1811.03631



Bonaca *et al* arXiv:1811.03631

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.

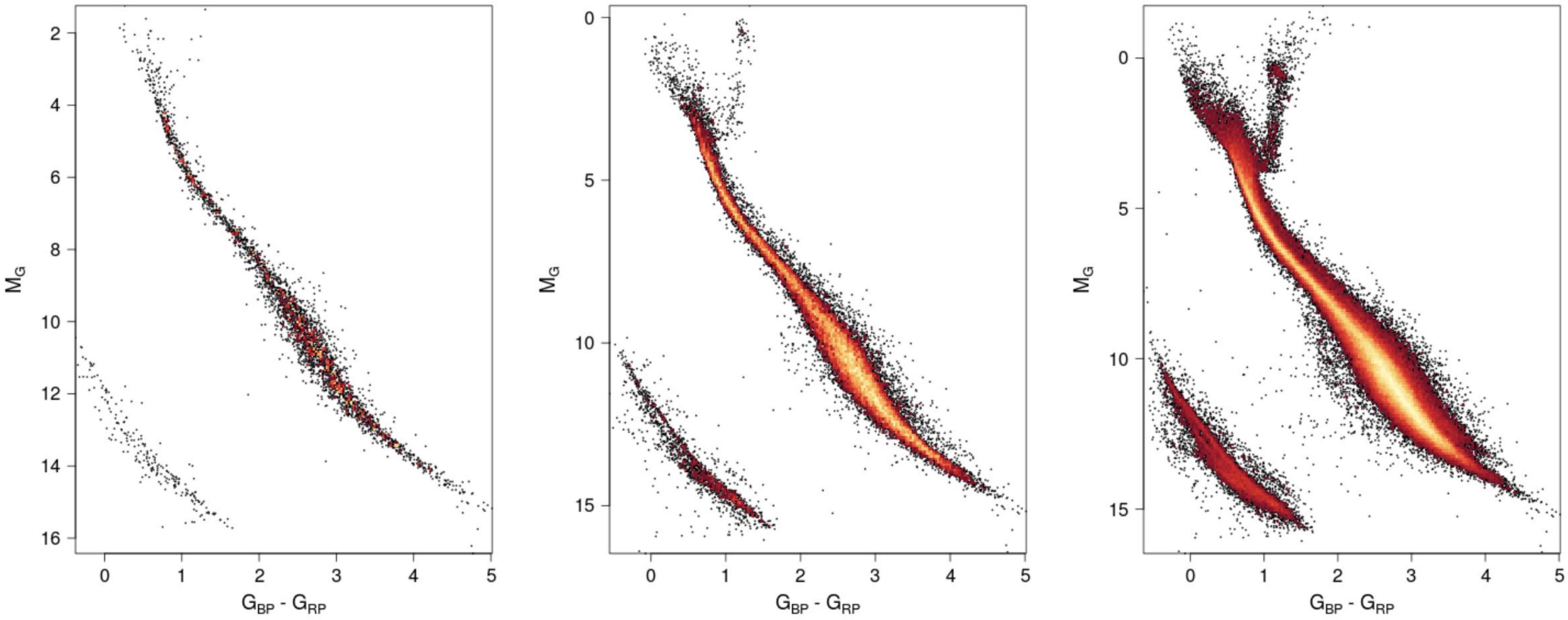


Fig. 6. Solar neighbourhood *Gaia* HRDs for a) $\varpi > 40$ mas (25 pc, 3,724 stars), b) $\varpi > 20$ mas (50 pc, 29,683 stars), and c) $\varpi > 10$ mas (100 pc, 212,728 stars).

Gaia Collaboration arXiv:1804.09378

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!**