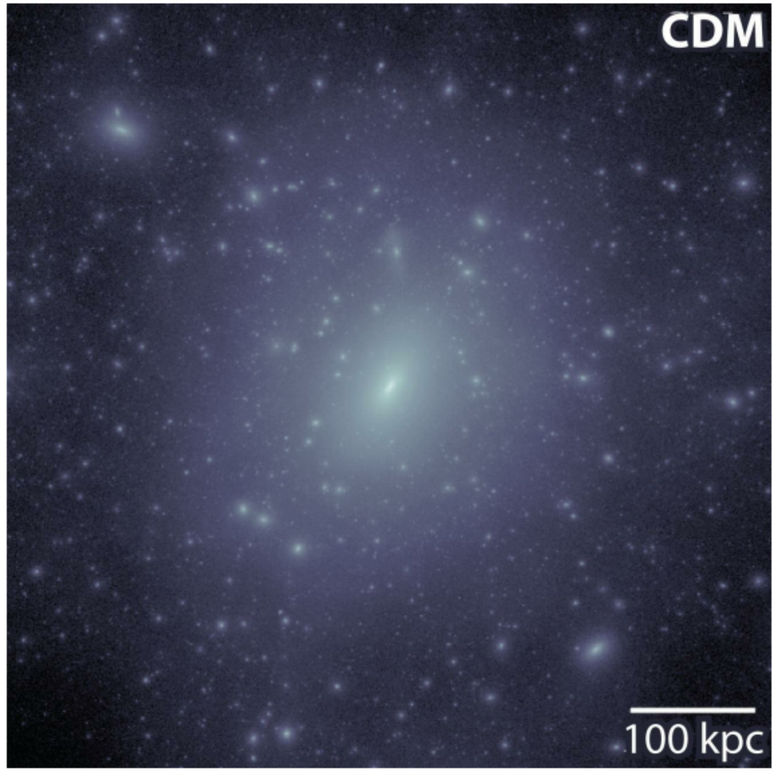
Ana Bonaca
ITC Fellow
Center for Astrophysics
Harvard & Smithsonian

Locating a dark dark-matter subhalo

The particle nature of dark matter is encoded on small scales

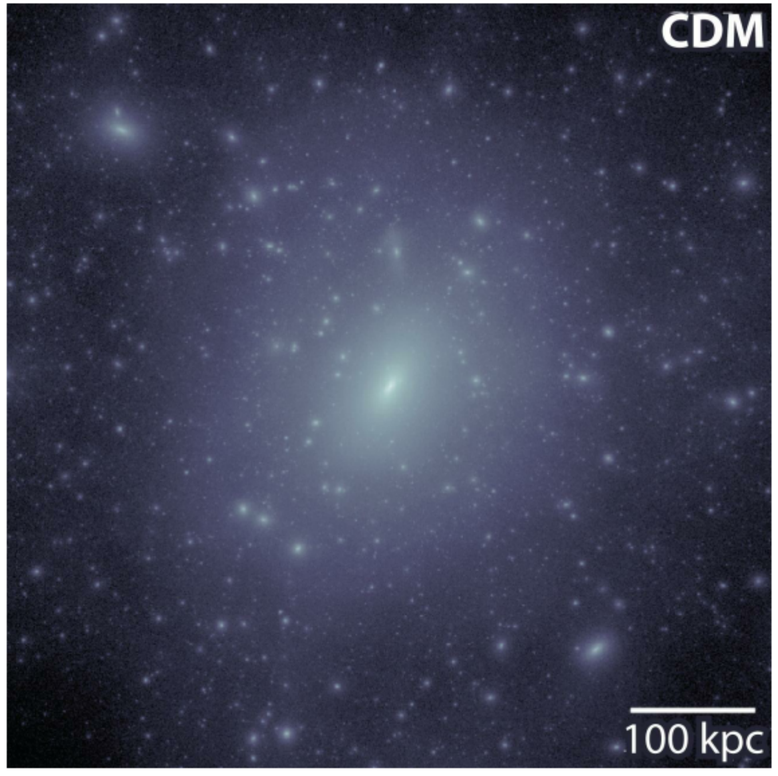
Particle mass ~ GeV



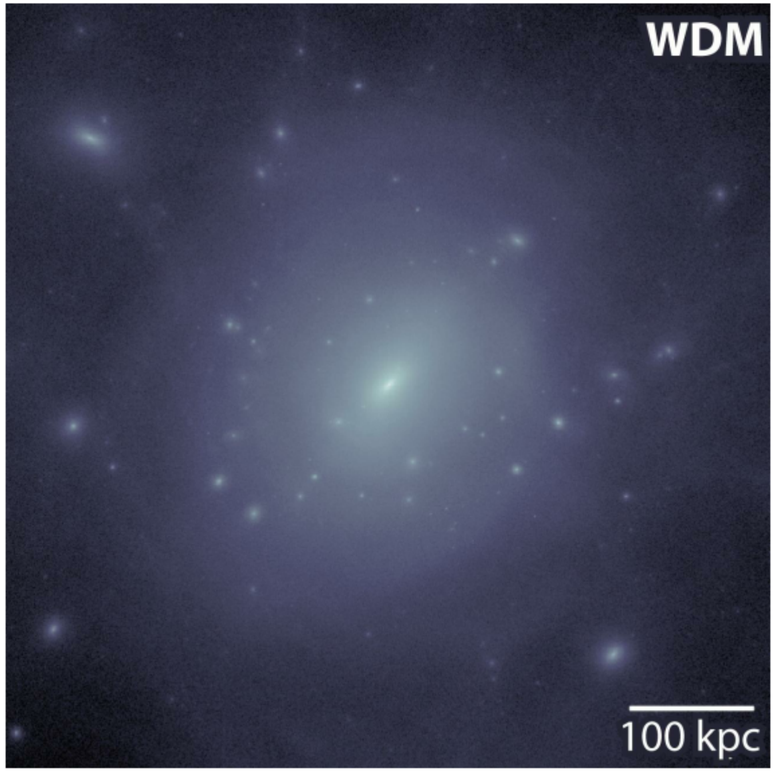
Bullock & Boylan-Kolchin (2017)

The particle nature of dark matter is encoded on small scales

Particle mass ~ GeV



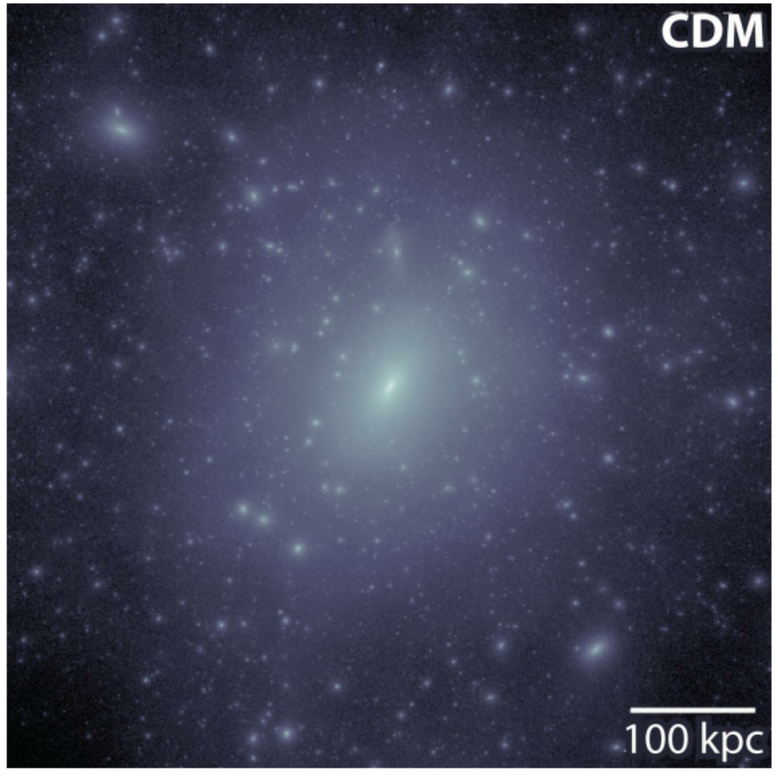
Particle mass ~ keV



Bullock & Boylan-Kolchin (2017)

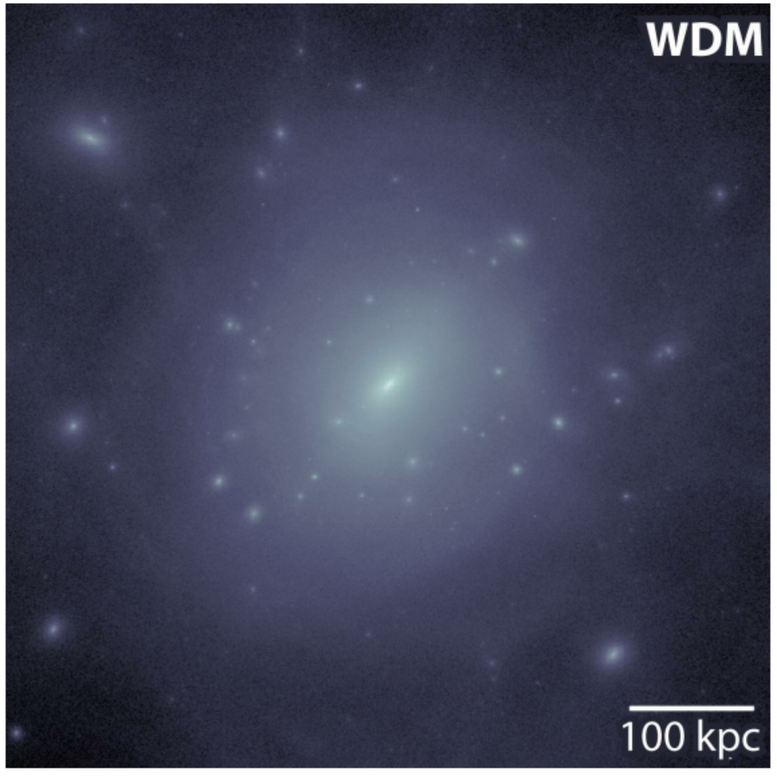
The particle nature of dark matter is encoded on small scales

Particle mass ~ GeV

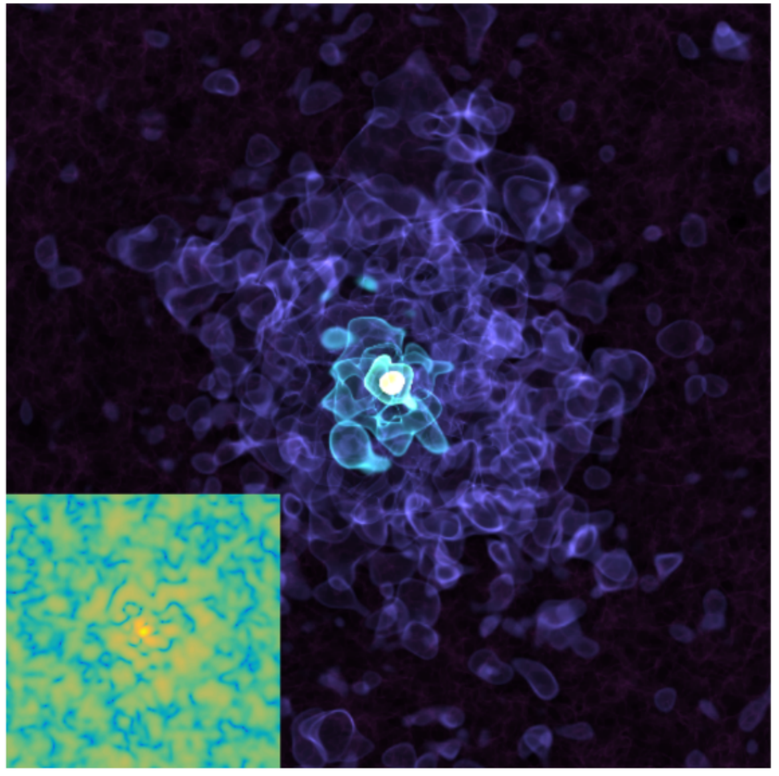


Bullock & Boylan-Kolchin (2017)

Particle mass ~ keV



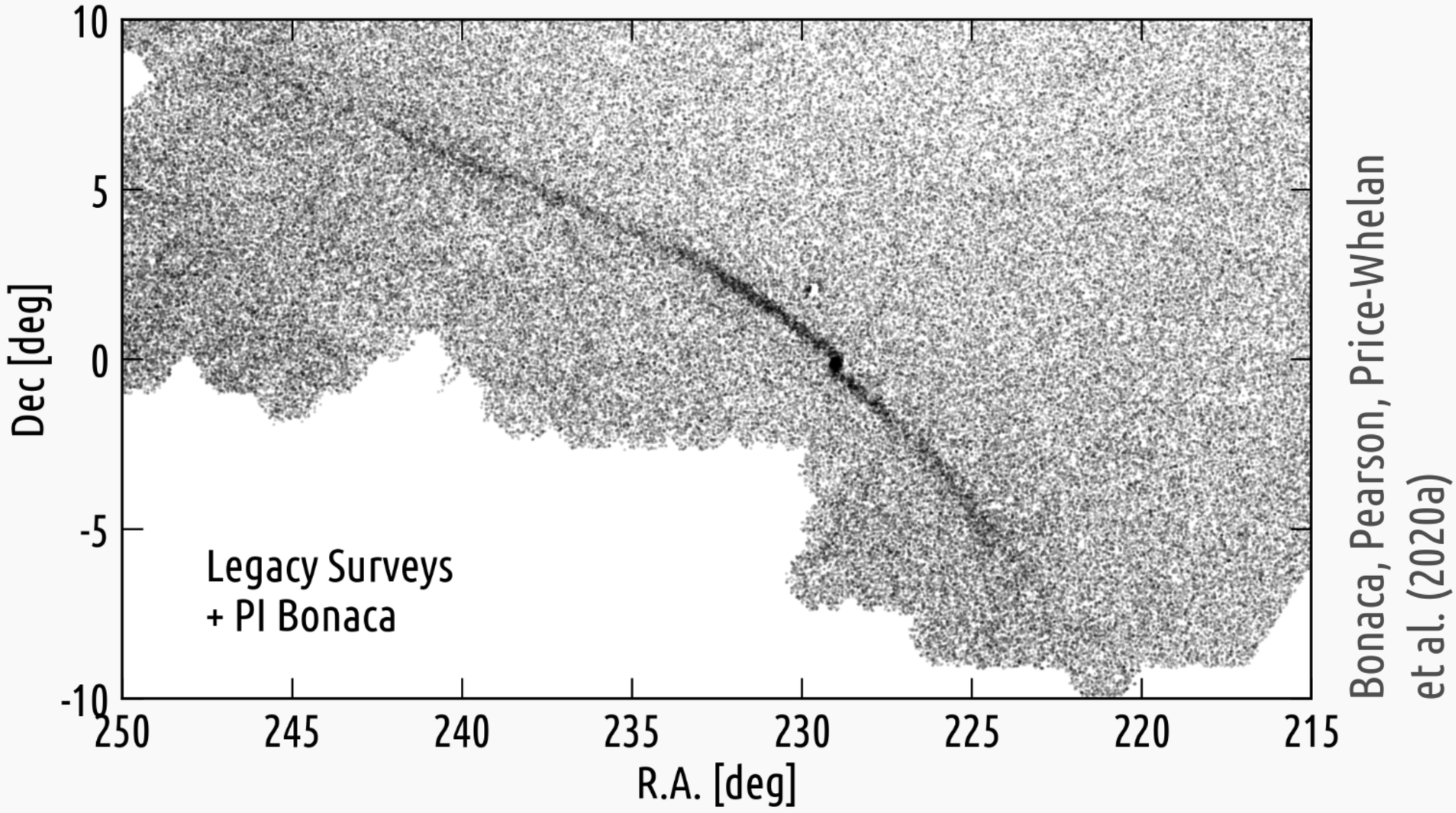
Particle mass ~ 10^{-22} eV



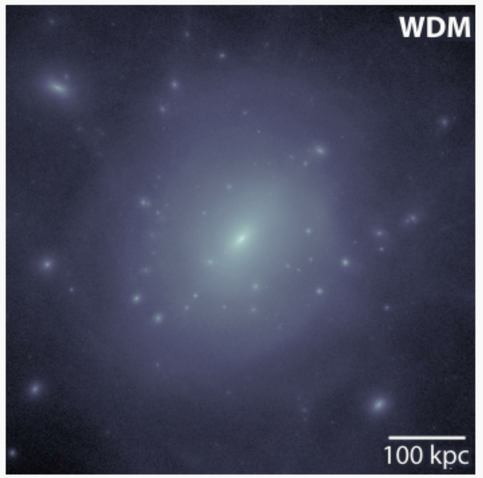
Mocz et al. (2017)

Goal: Find the minimum mass of a dark matter subhalo orbiting the Milky Way

Globular cluster Palomar 5 has a tidal stream of stars



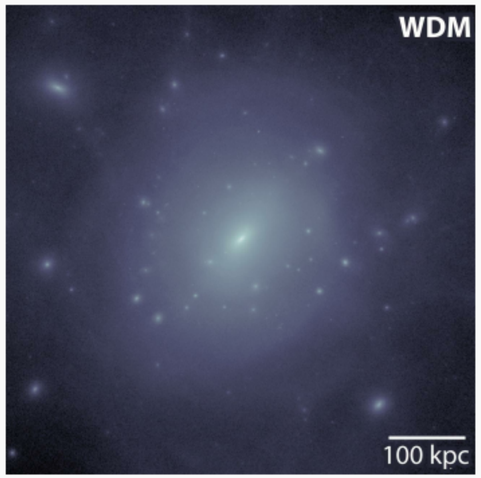
Stellar streams perturbed by dark matter subhalos have gaps

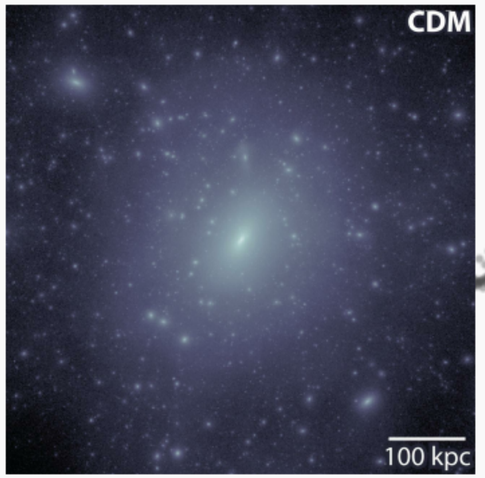


Stellar stream in a smooth galaxy

Bonaca et al. (2014)

Stellar streams perturbed by dark matter subhalos have gaps





Stellar stream in a smooth galaxy

Stellar stream in a clumpy galaxy

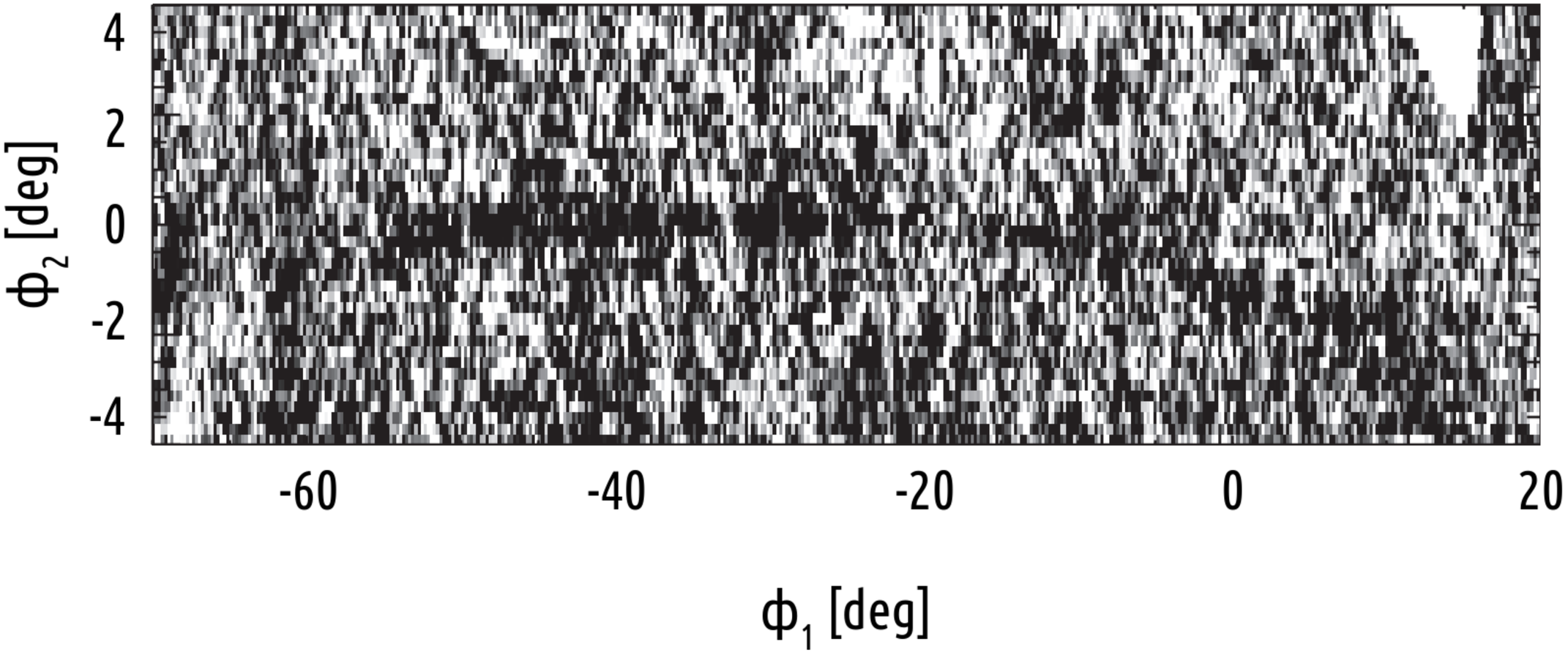
Bonaca et al. (2014)

Stellar halo of the Milky Way has plenty of tidal streams

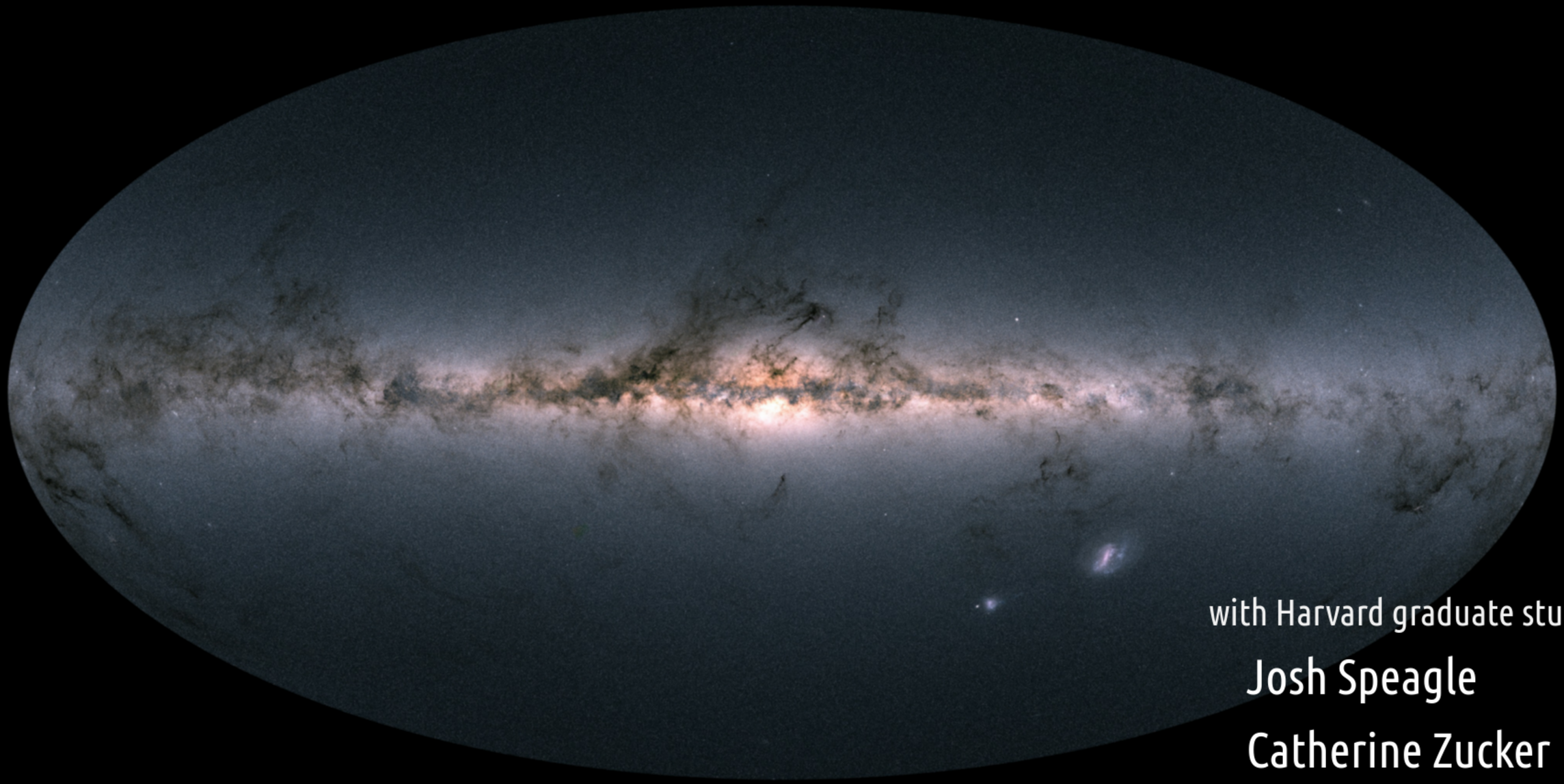
Bonaca et al. (2012)

Identifying members of stellar streams is challenging

GD-1 stream, Koposov et al. (2010)



In the Gaia era, both the positions and velocities of stars are known

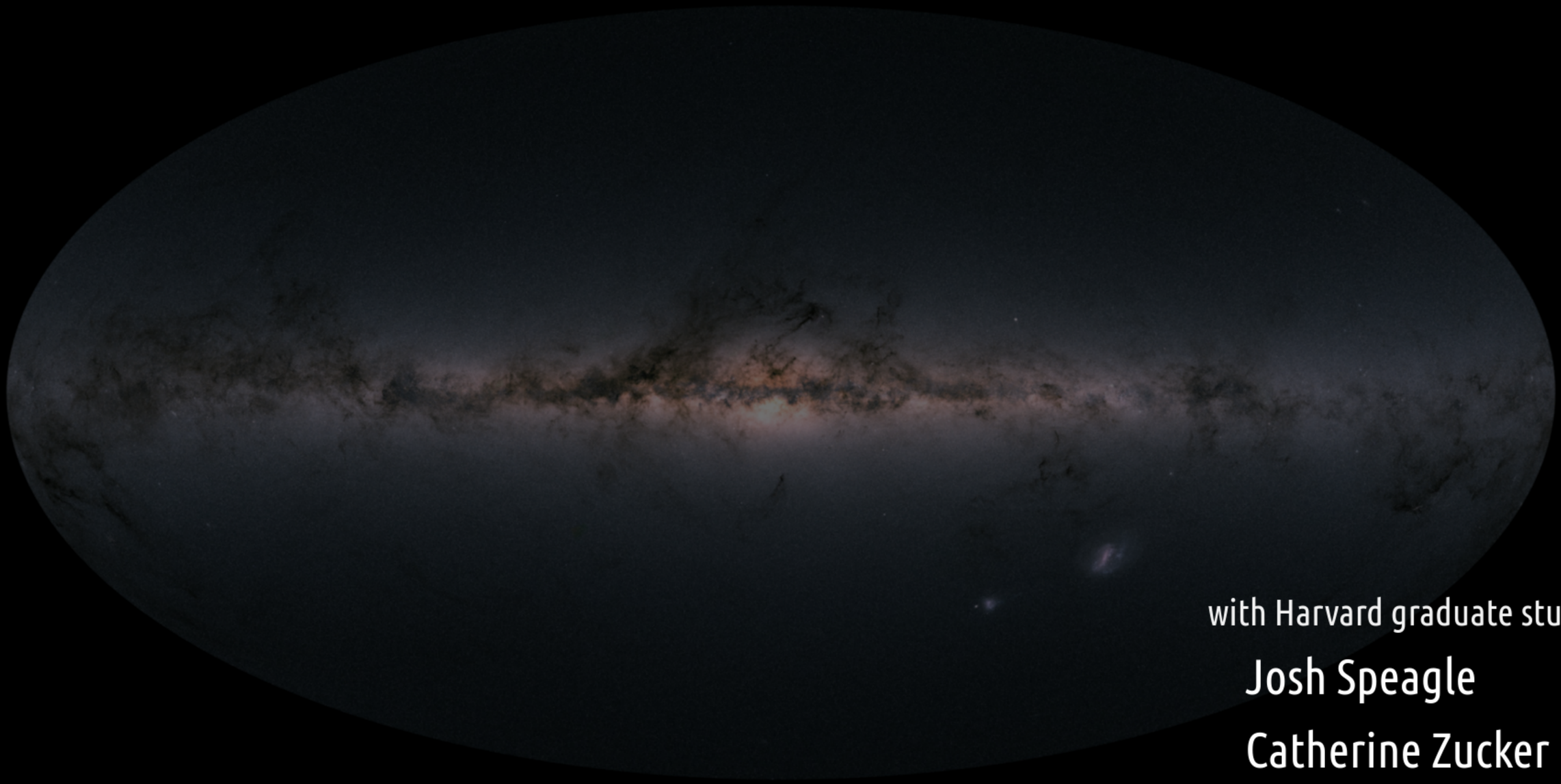


with Harvard graduate students

Josh Speagle

Catherine Zucker

In the Gaia era, both the positions and velocities of stars are known

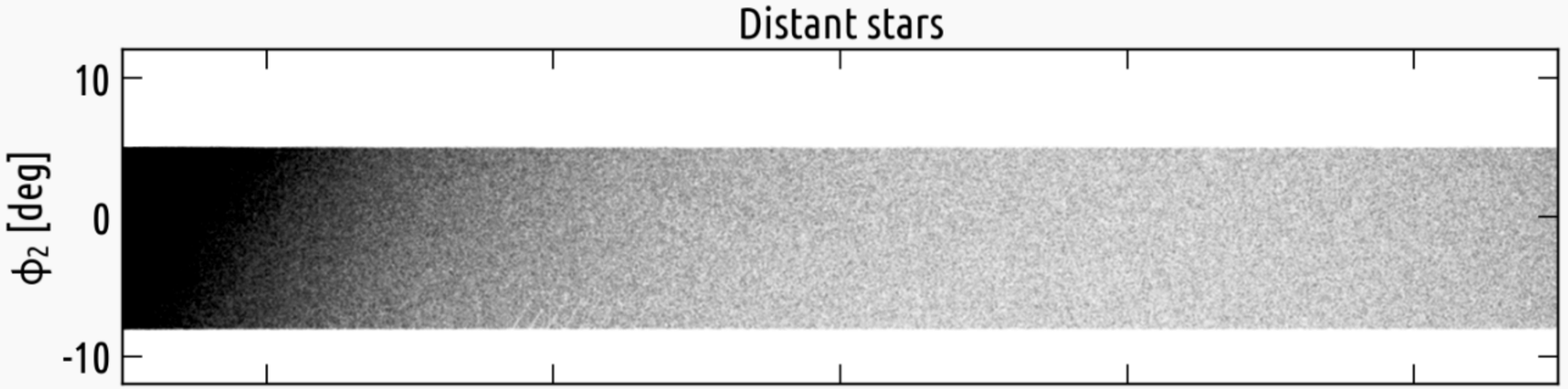


with Harvard graduate students

Josh Speagle

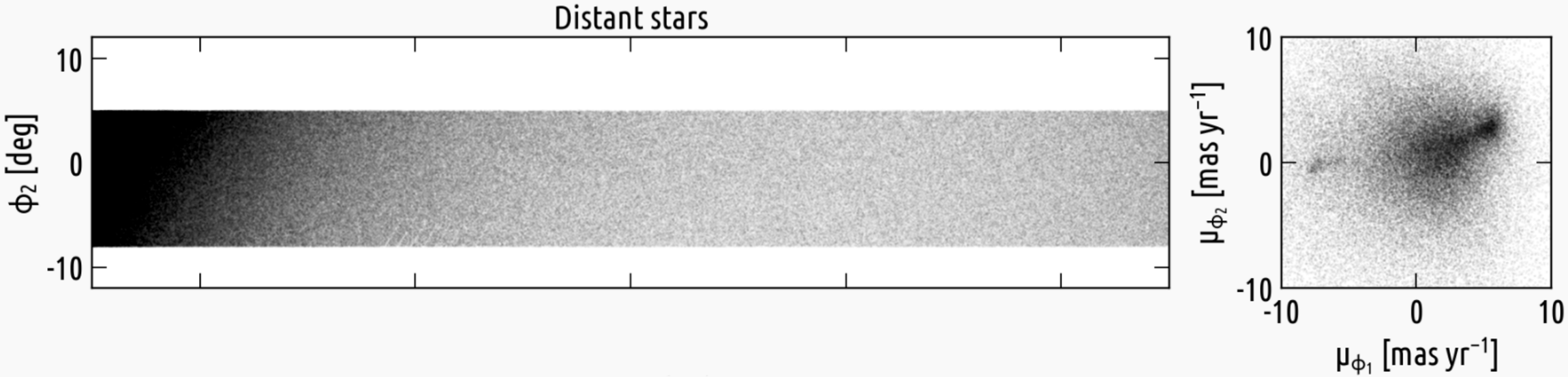
Catherine Zucker

Gaia's view of the GD-1 stellar stream



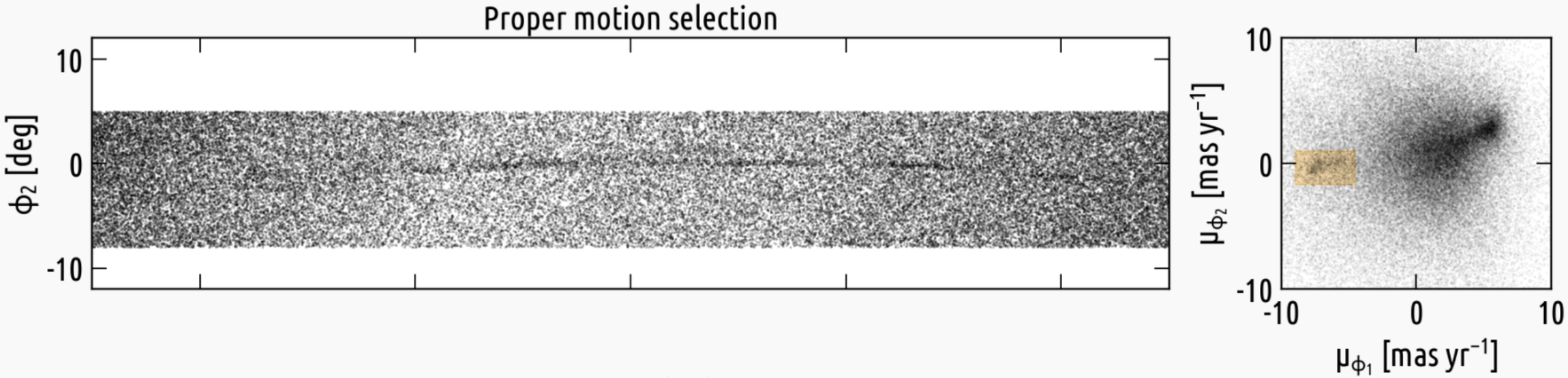
Price-Whelan & Bonaca (2018)

Gaia's view of the GD-1 stellar stream



Price-Whelan & Bonaca (2018)

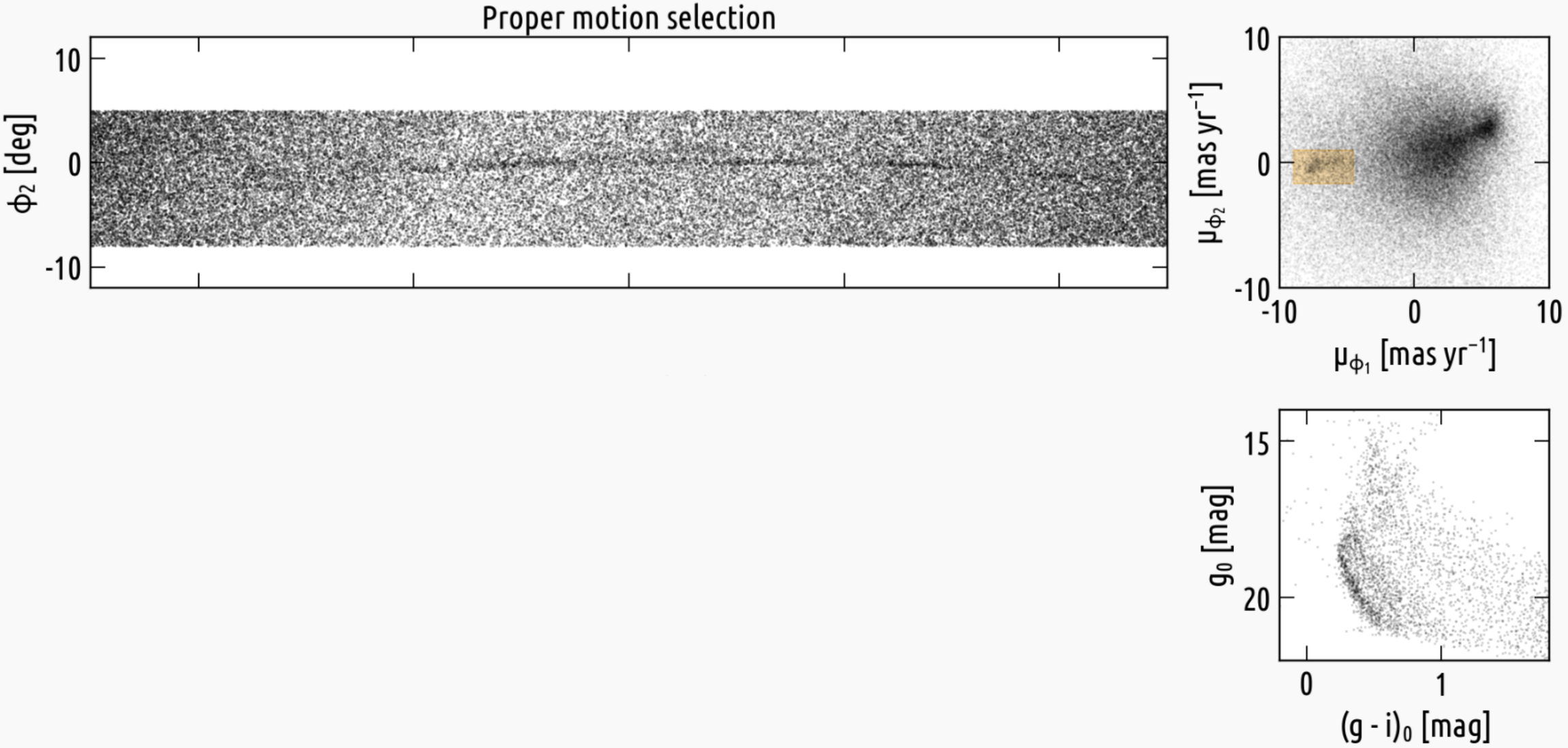
Gaia's view of the GD-1 stellar stream



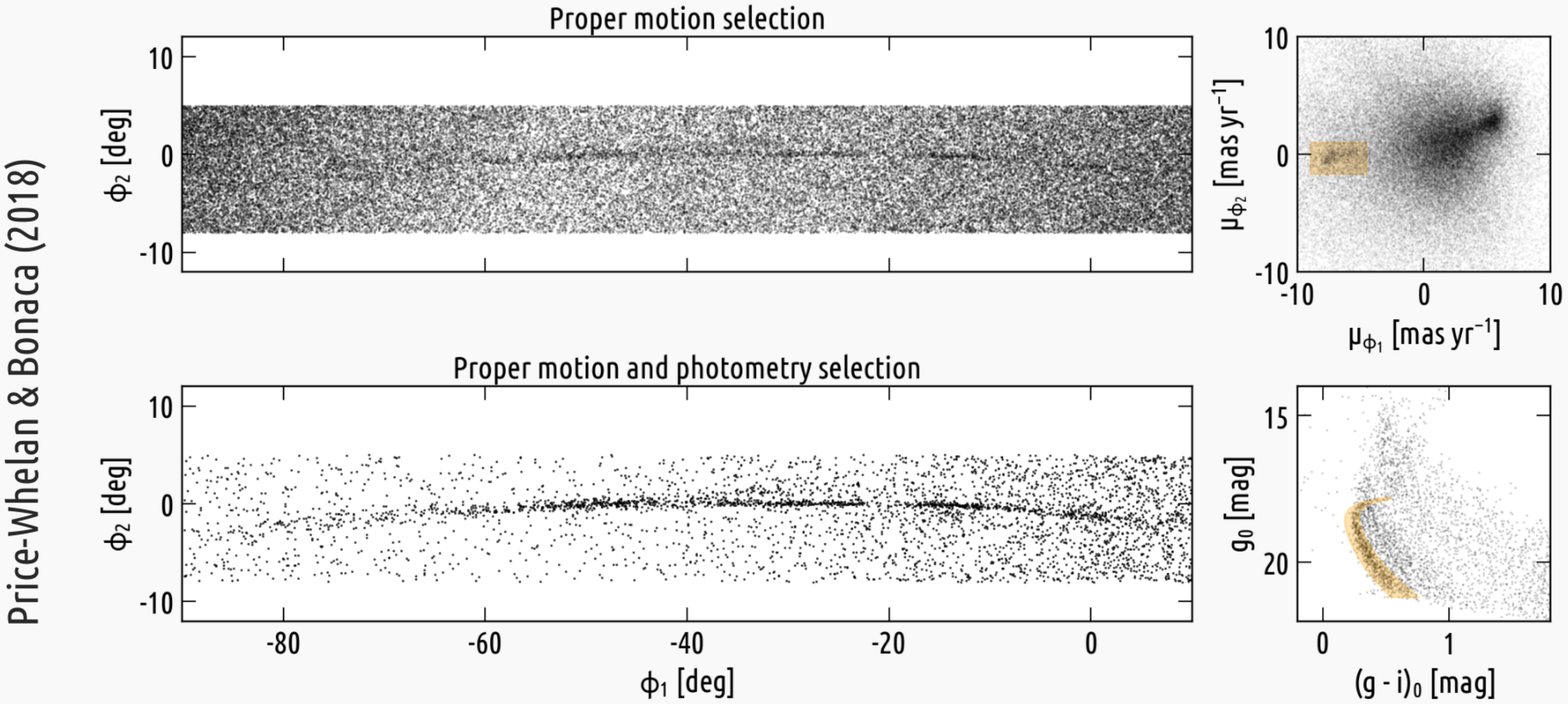
Price-Whelan & Bonaca (2018)

Gaia's view of the GD-1 stellar stream

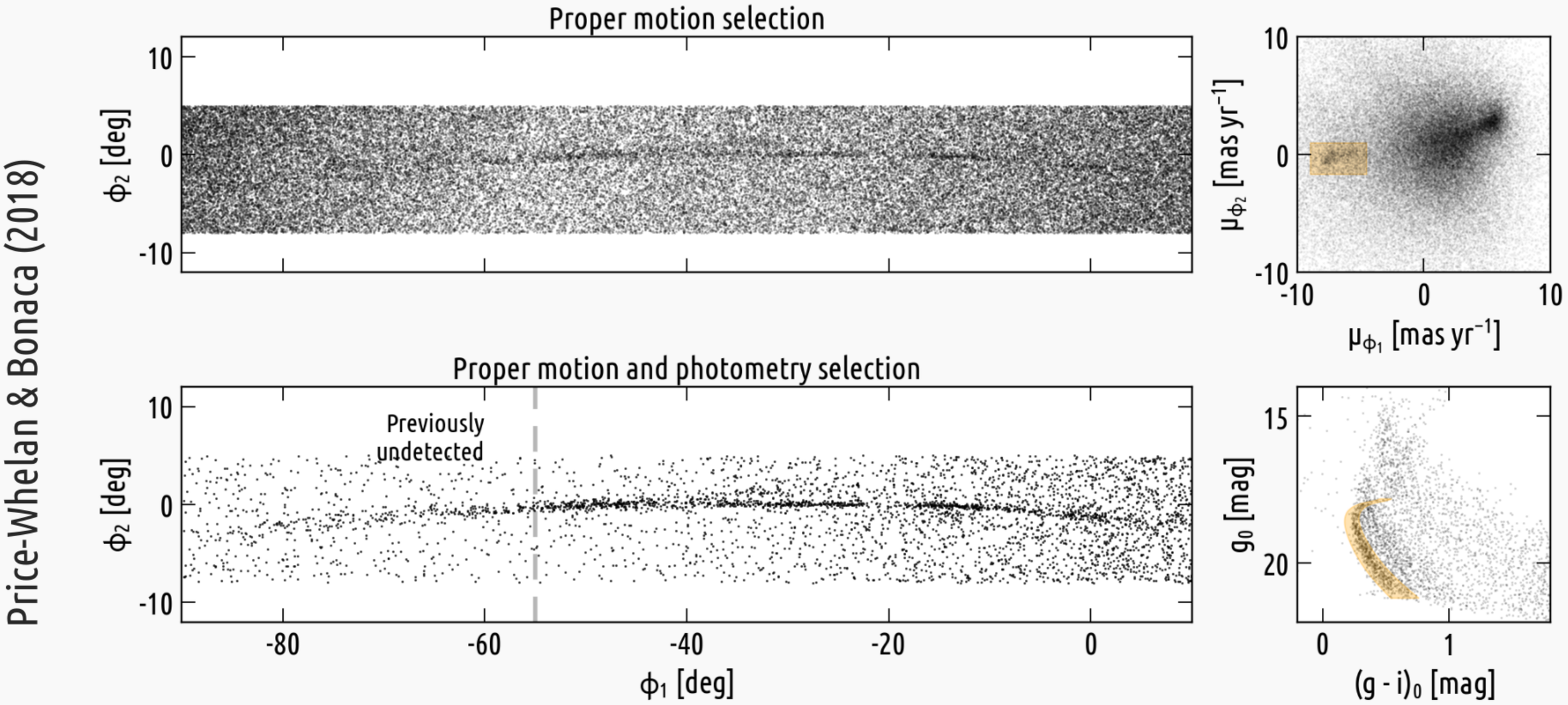
Price-Whelan & Bonaca (2018)



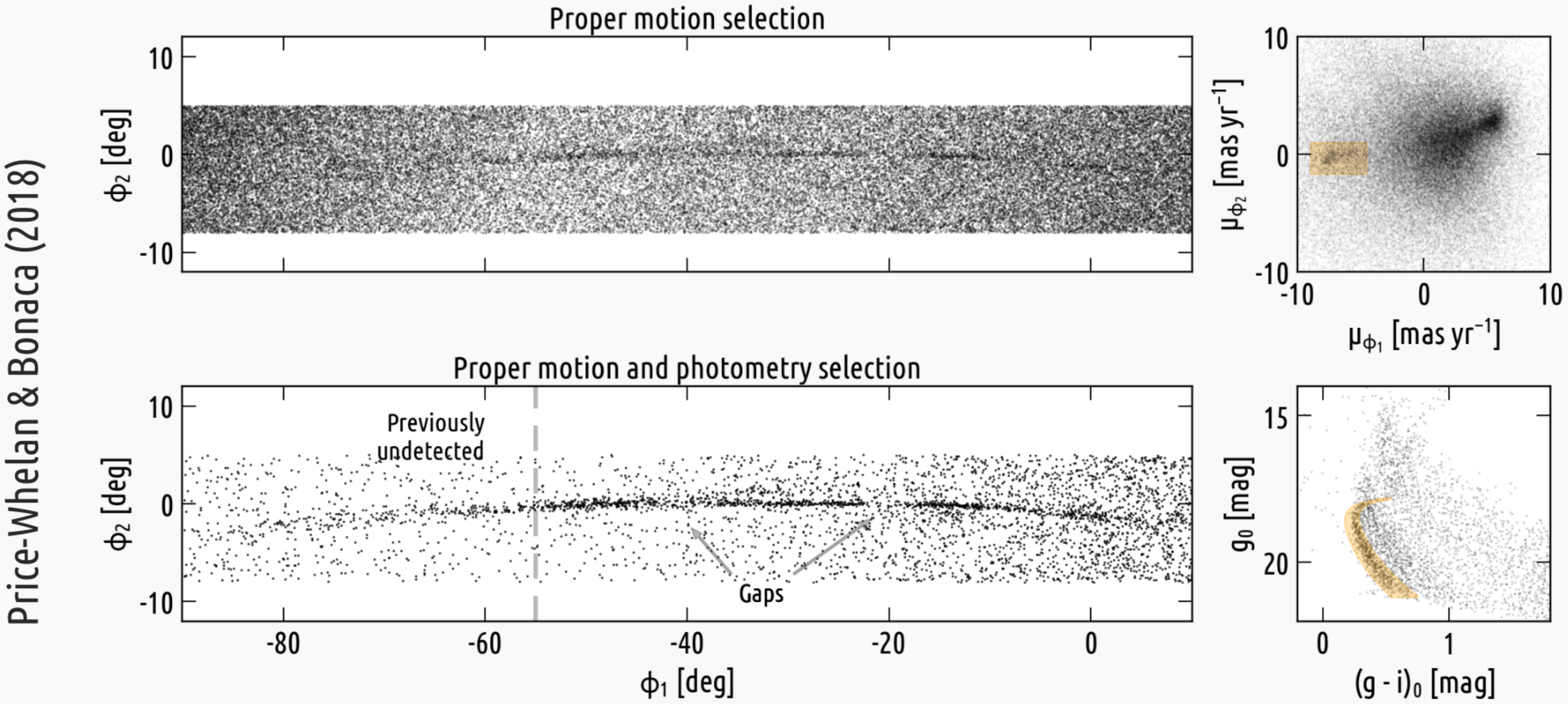
Gaia's view of the GD-1 stellar stream



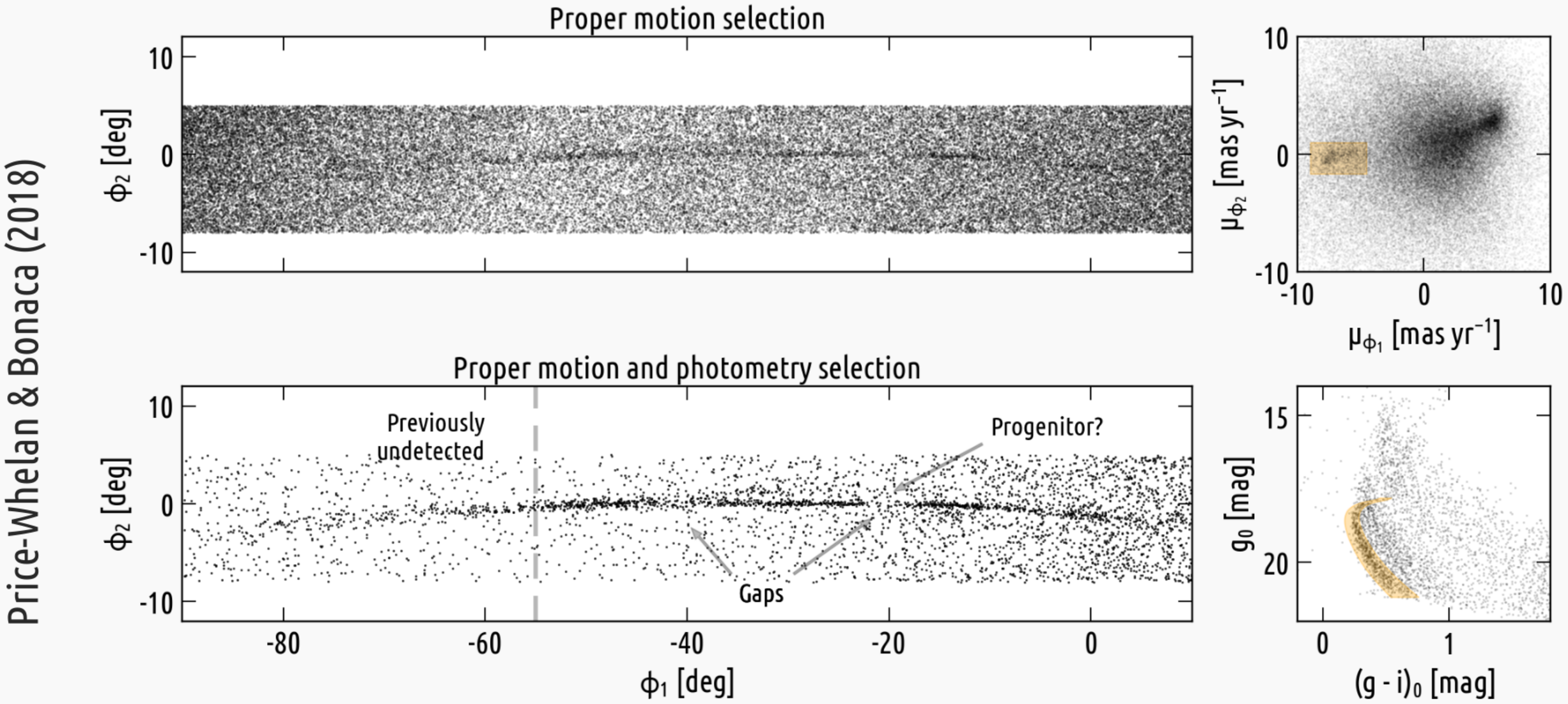
Gaia's view of the GD-1 stellar stream



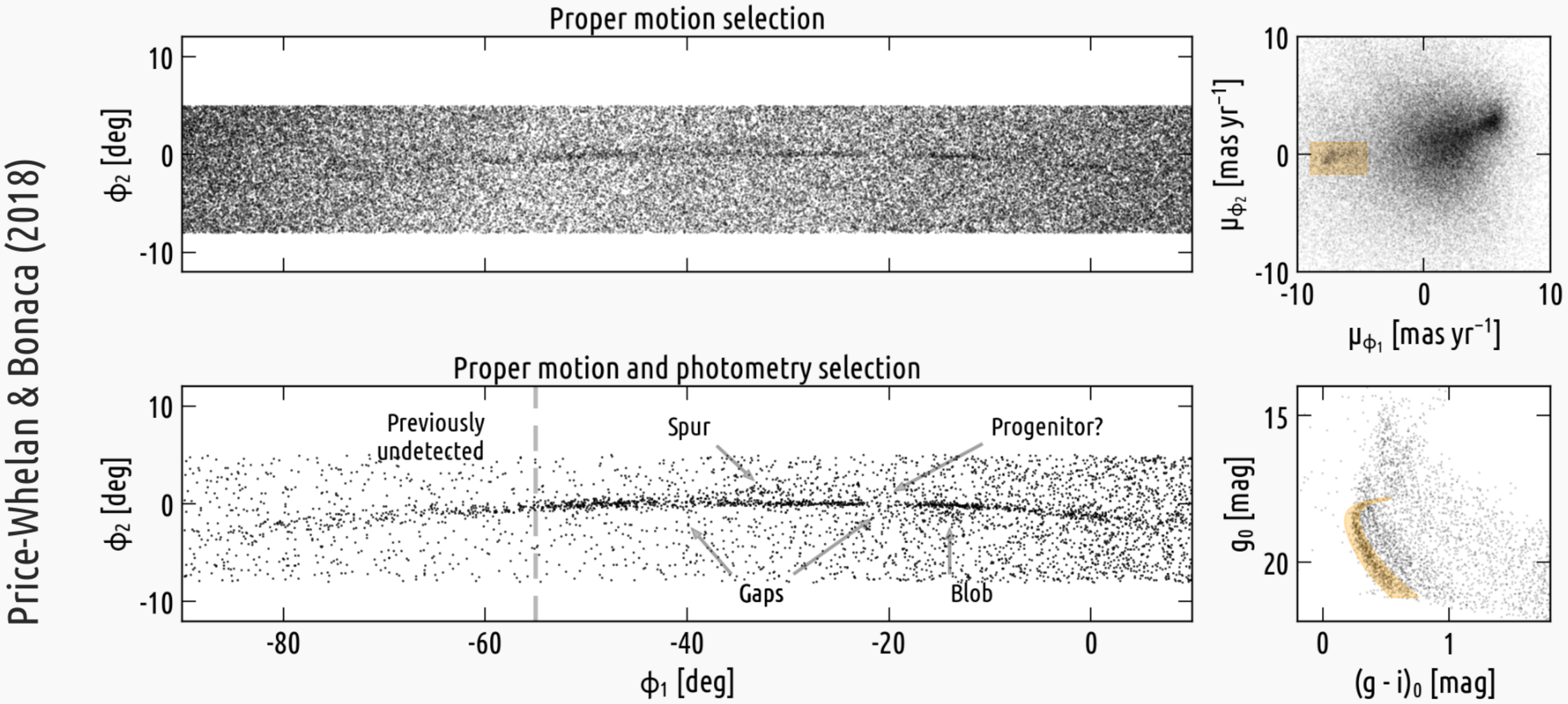
Gaia's view of the GD-1 stellar stream



Gaia's view of the GD-1 stellar stream



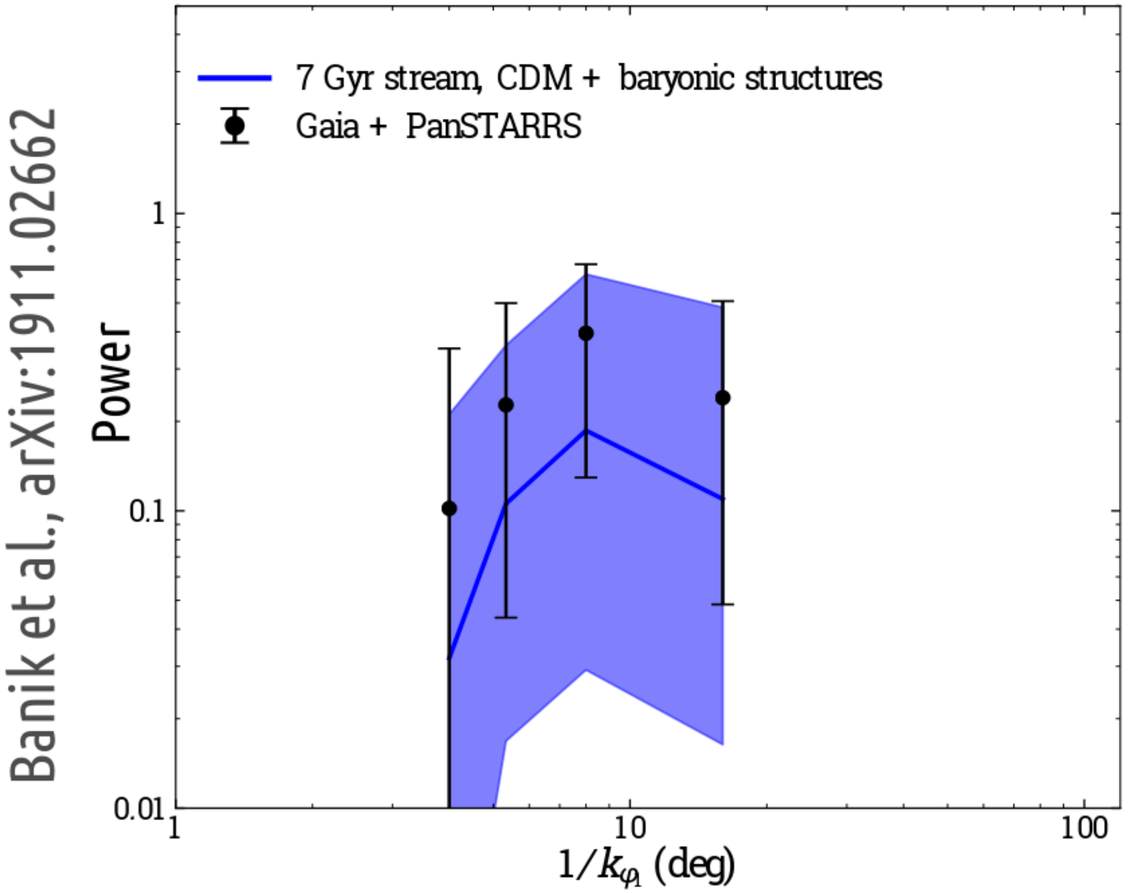
Gaia's view of the GD-1 stellar stream



Price-Whelan & Bonaca (2018)

Stream gaps are a signature of dark matter subhalos

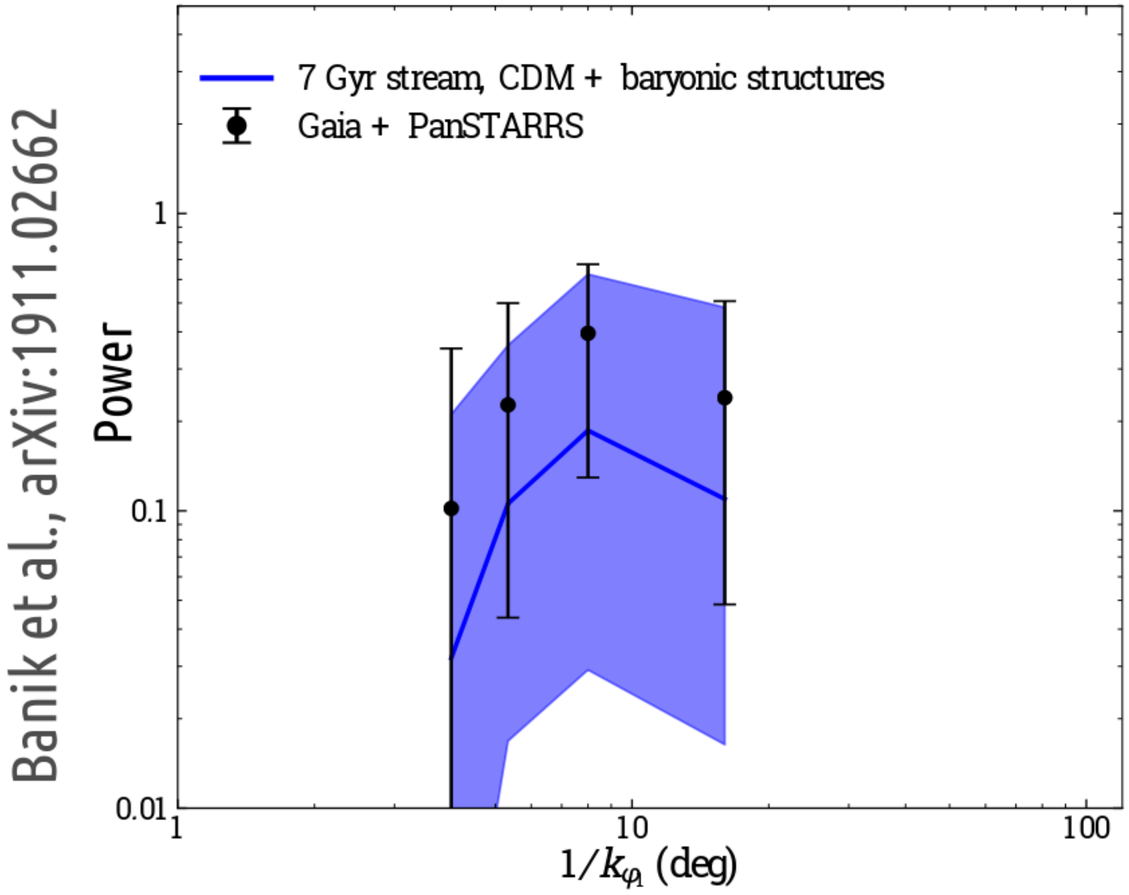
"Evidence of a population of dark subhalos from Gaia and Pan-STARRS observations of the GD-1 stream"



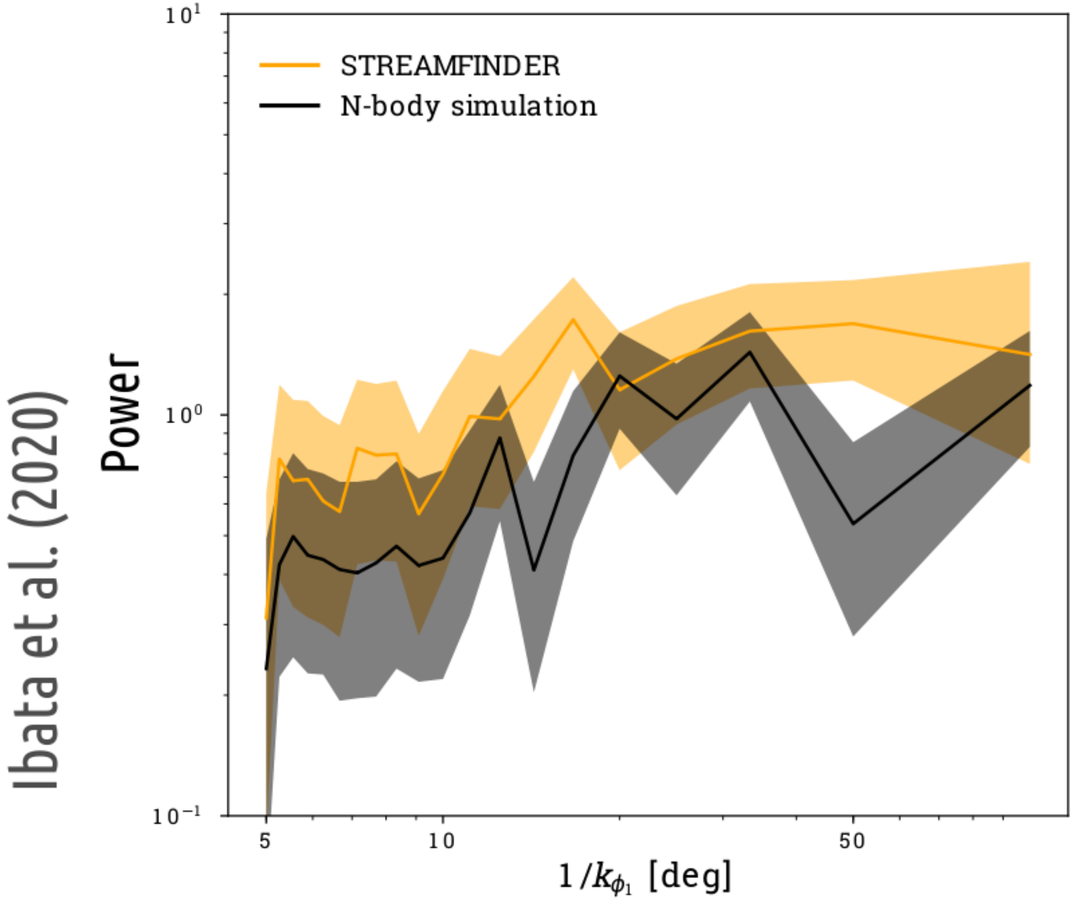
Banik et al., arXiv:1911.02662

Stream gaps are not a unique signature of dark matter subhalos

"Evidence of a population of dark subhalos from Gaia and Pan-STARRS observations of the GD-1 stream"

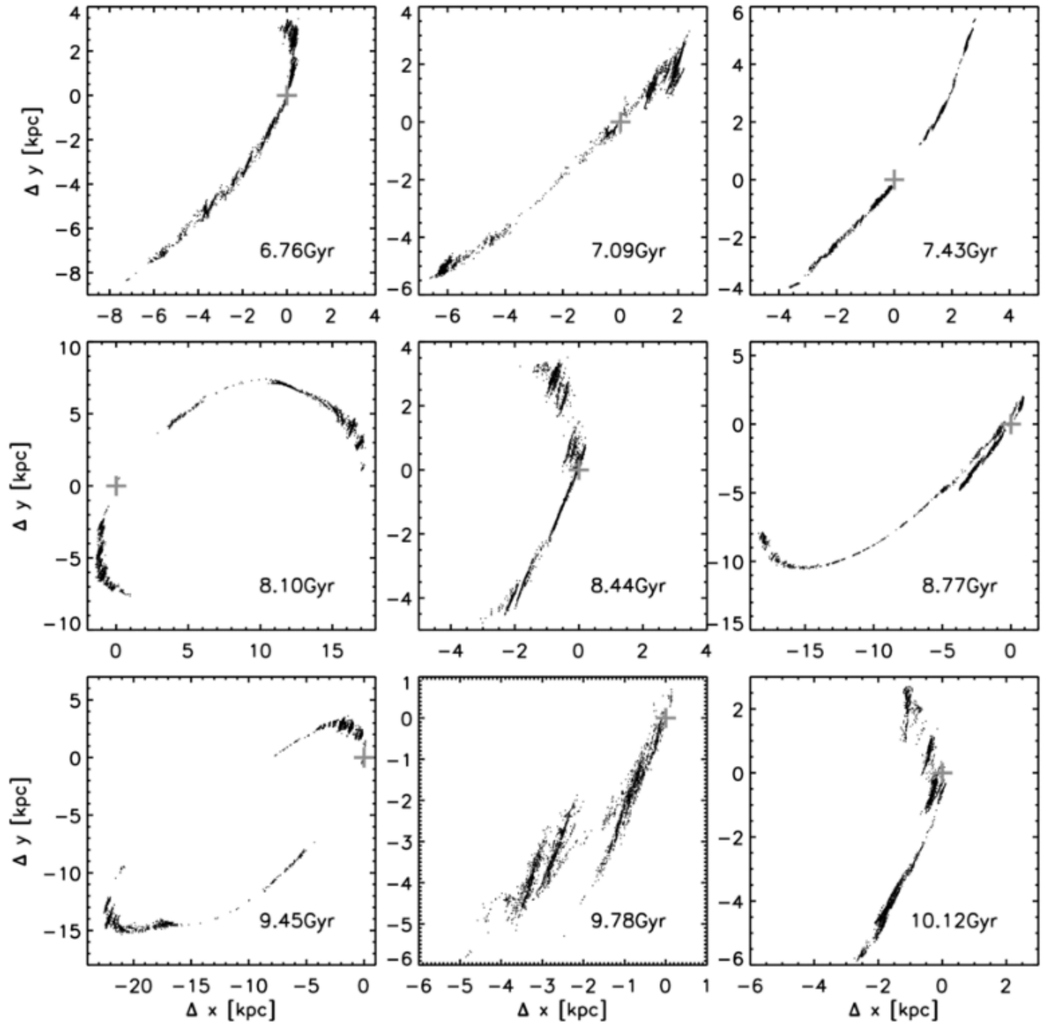


"Detection of Strong Epicyclic Density Spikes in the GD-1 Stellar Stream: An Absence of Evidence for the Influence of Dark Matter Subhalos?"



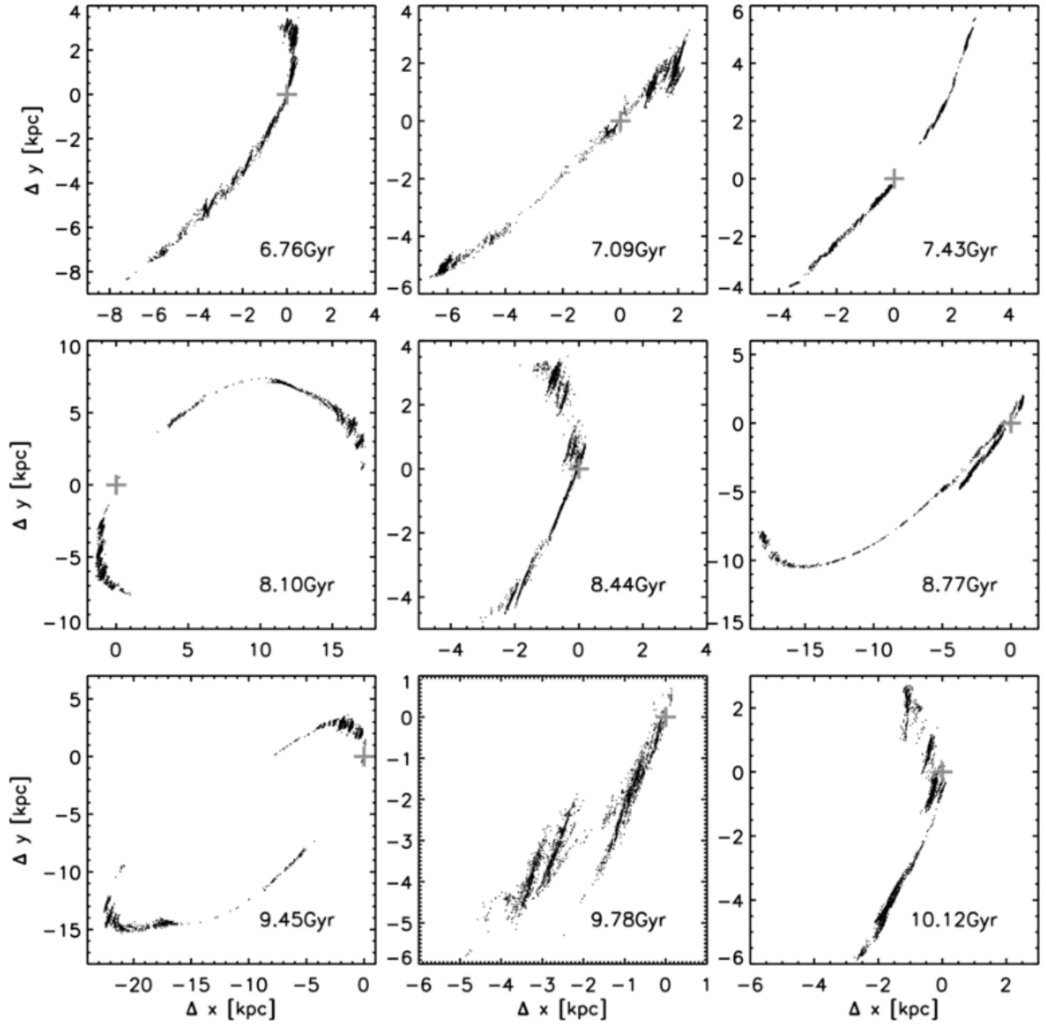
Subhalo encounters produce both gaps and spurs in streams

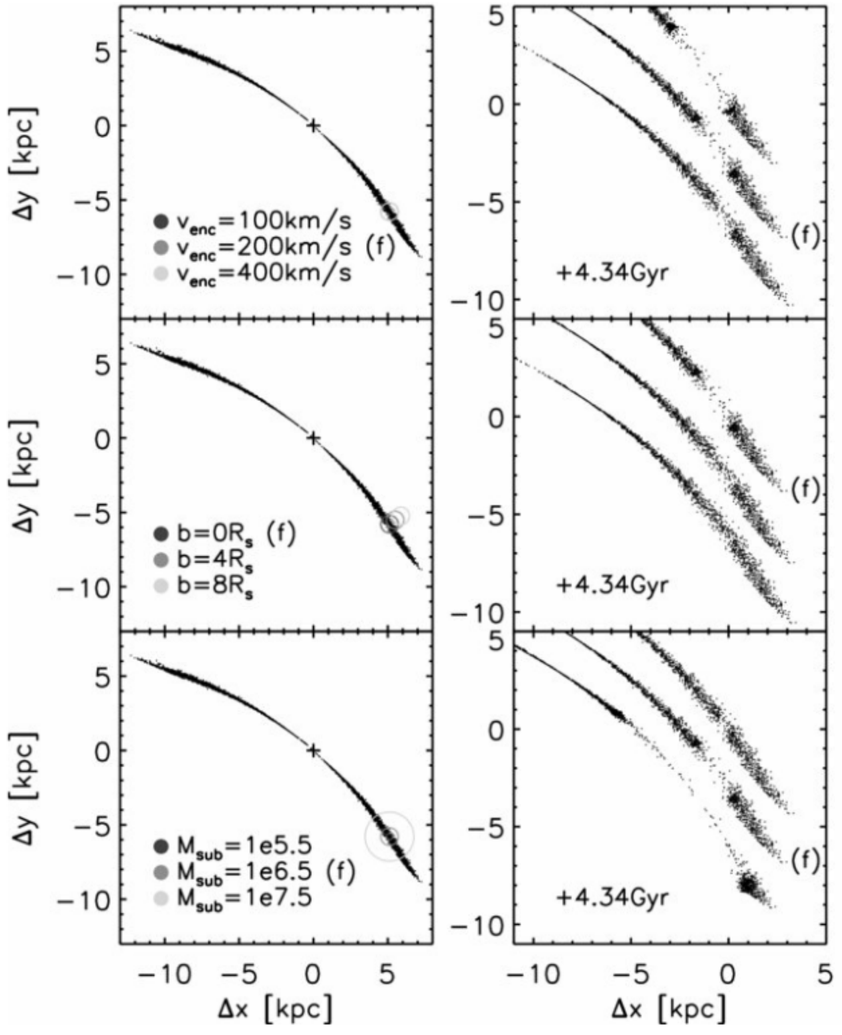
Yoon et al. (2011)



Subhalo encounters produce both gaps and spurs in streams

Yoon et al. (2011)

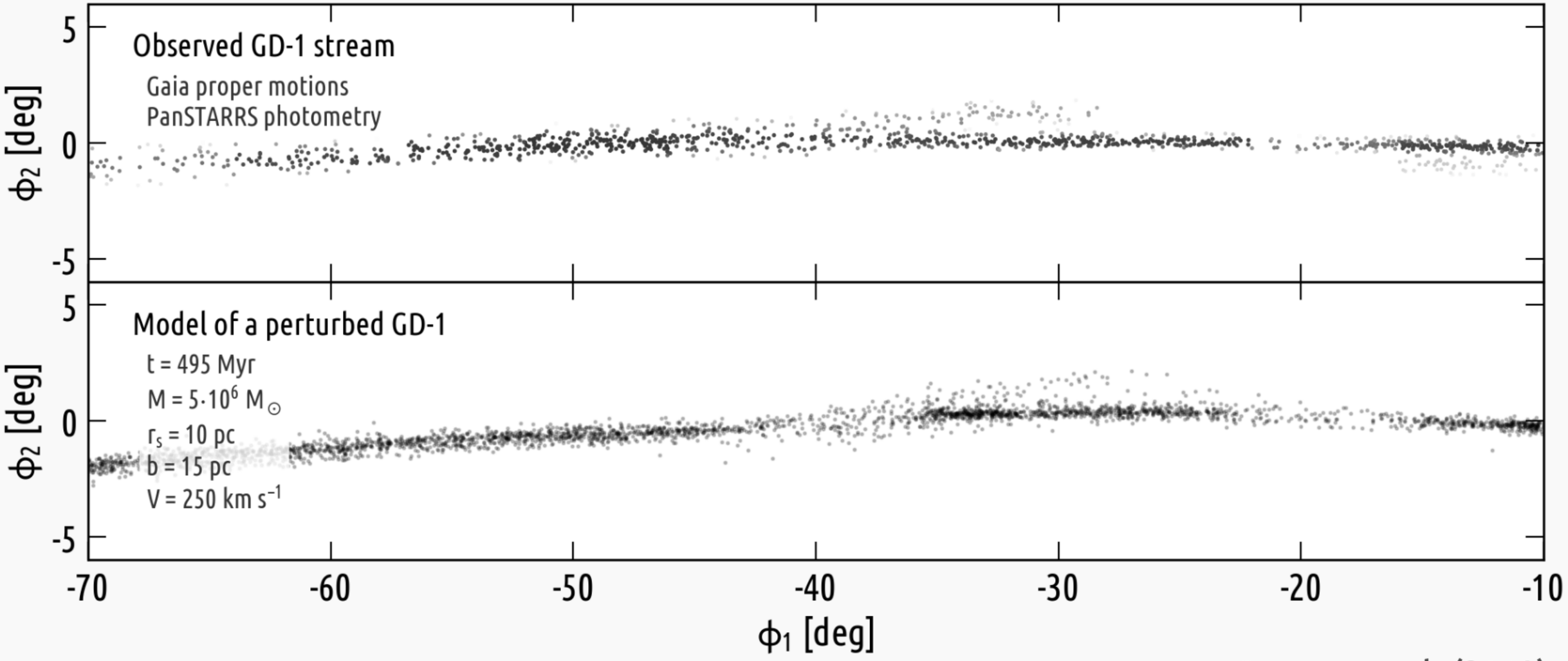




Carlberg (2009) | Carlberg (2012)
Ngan & Carlberg (2014) | Ngan et al. (2015)
Erkal & Belokurov (2015) | Ngan et al. (2016)
Erkal et al. (2016)

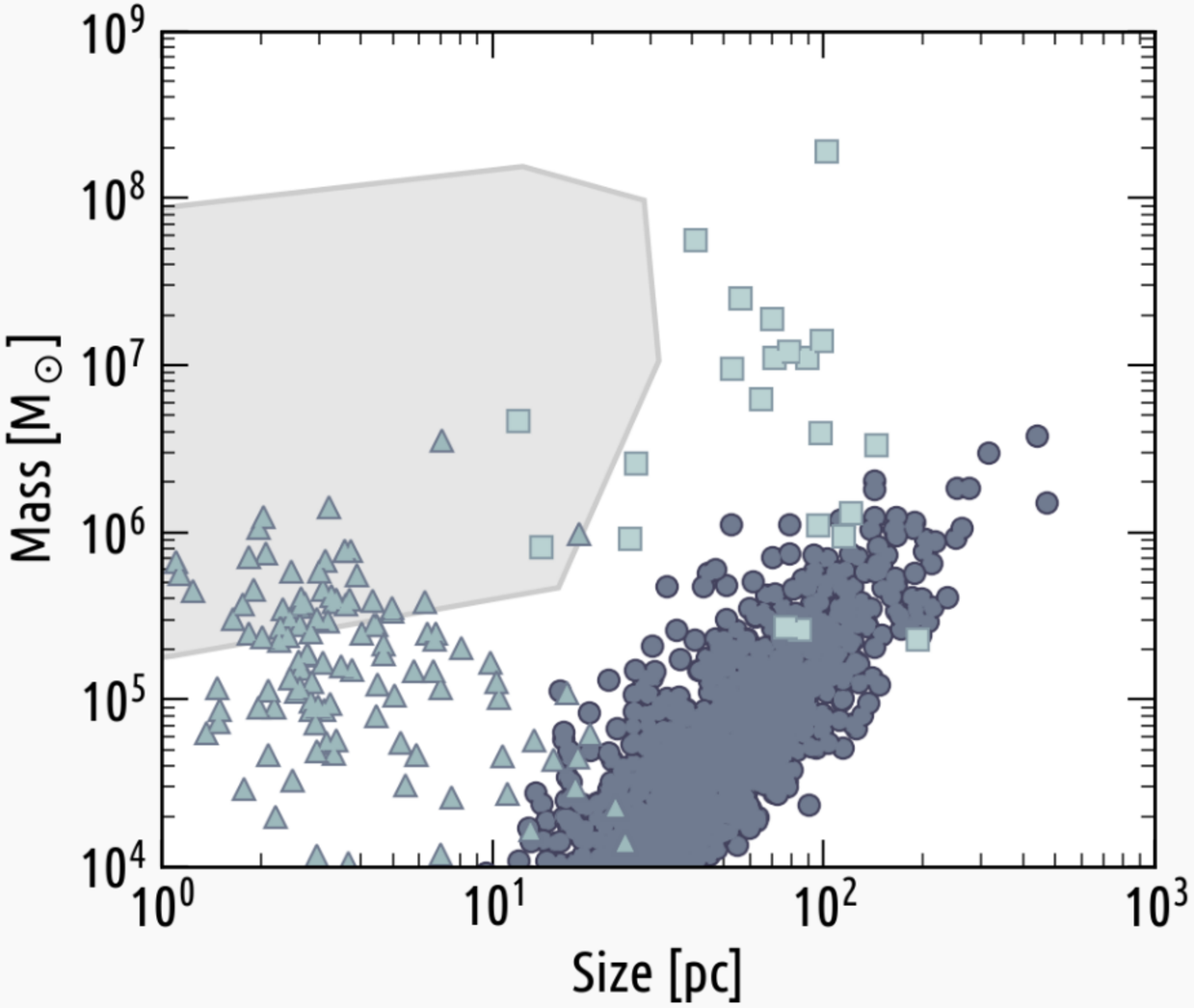
Realistic GD-1 encounter scenario

Encounter qualitatively accounts for all features observed in GD-1



Bonaca et al. (2019)

Dark matter subhalo is a plausible perturber of GD-1



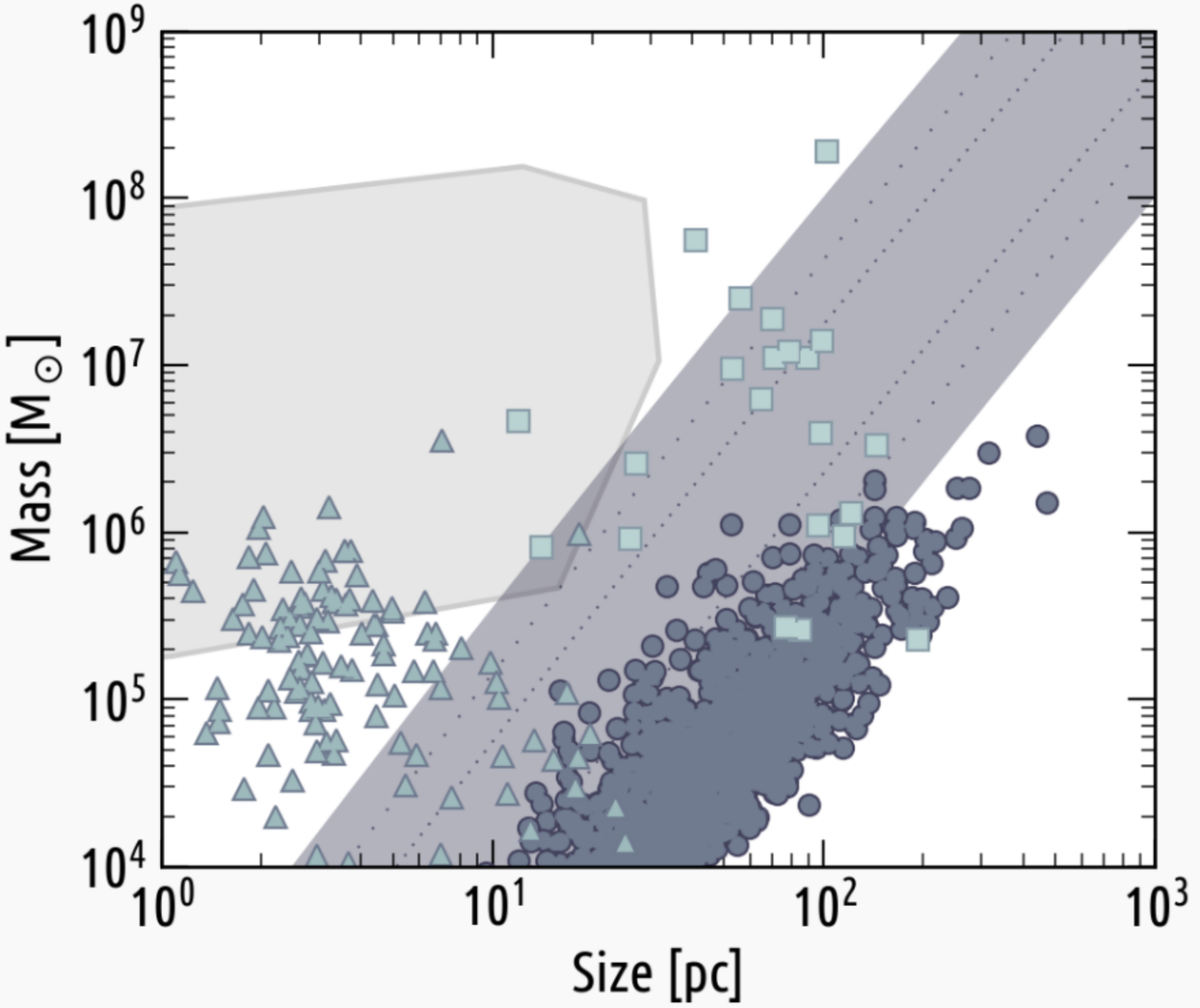
GD-1 perturber
(Bonaca et al. 2018)

Outer disk molecular clouds
(Miville-Deschênes et al. 2017)

Globular clusters
(Baumgardt & Hilker 2018)

Dwarf galaxies
(McConnachie 2012)

Dark matter subhalo is a plausible perturber of GD-1



GD-1 perturber
(Bonaca et al. 2018)

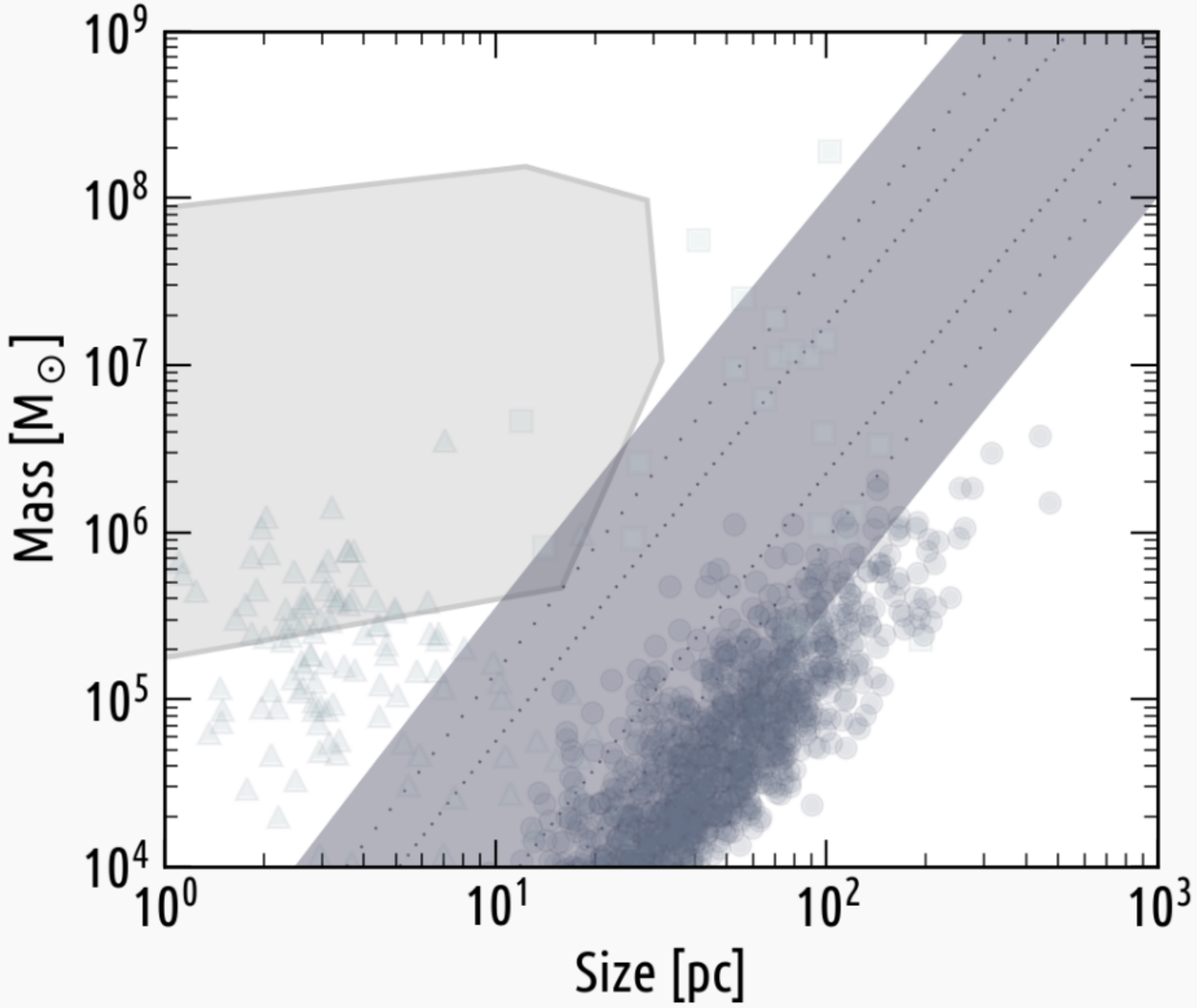
Outer disk molecular clouds
(Miville-Deschênes et al. 2017)

Globular clusters
(Baumgardt & Hilker 2018)

Dwarf galaxies
(McConnachie 2012)

ΛCDM subhalos (3 σ scatter)
(Moliné et al. 2017)

Dark matter subhalo is a plausible perturber of GD-1



GD-1 perturber
(Bonaca et al. 2018)

Outer disk molecular clouds
(Miville-Deschênes et al. 2017)

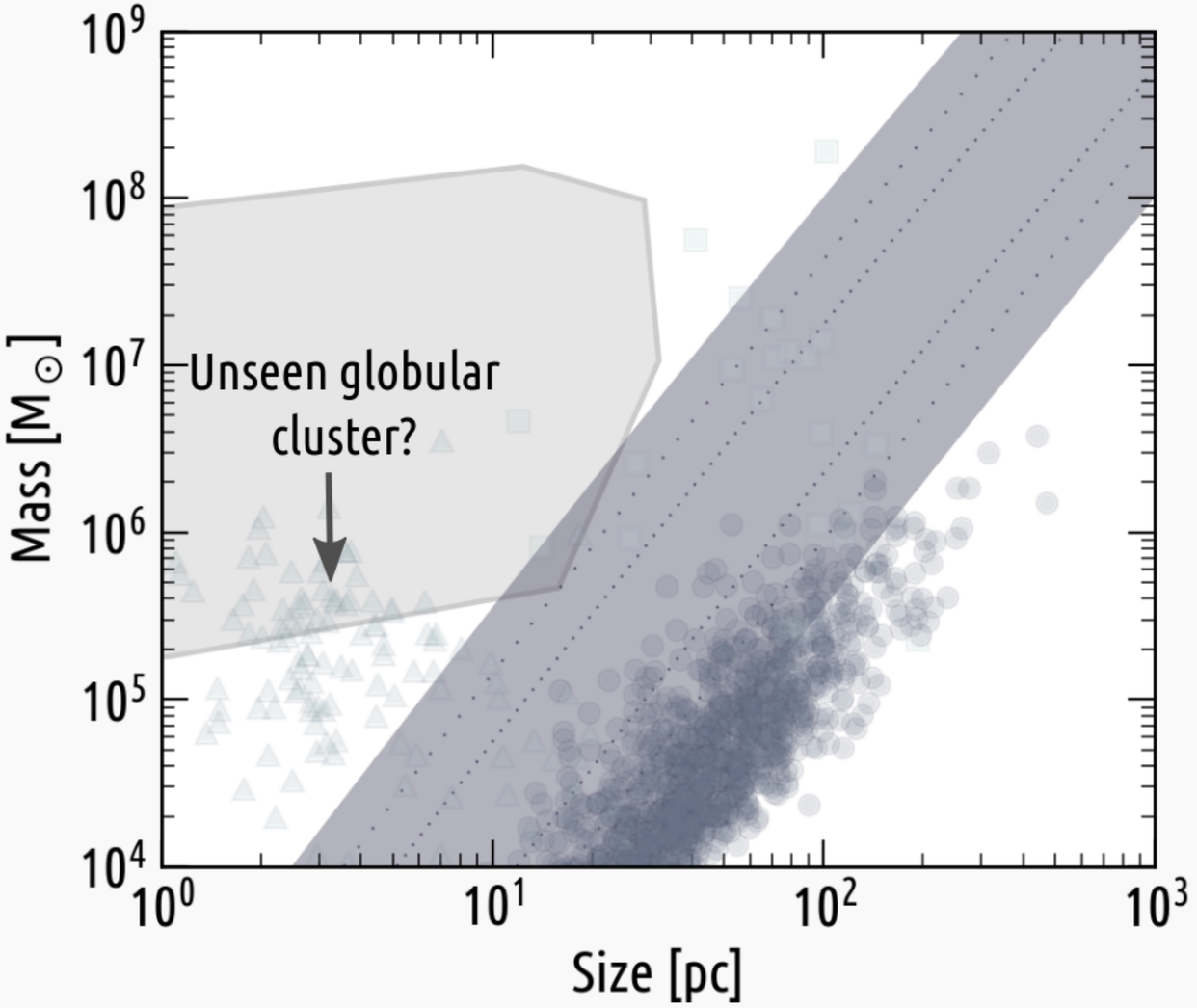
Globular clusters
(Baumgardt & Hilker 2018)

Dwarf galaxies
(McConnachie 2012)

Inconsistent orbits

ΛCDM subhalos (3 σ scatter)
(Moliné et al. 2017)

Dark matter subhalo is a plausible perturber of GD-1



GD-1 perturber (Bonaca et al. 2018)

Outer disk molecular clouds (Miville-Deschênes et al. 2017)

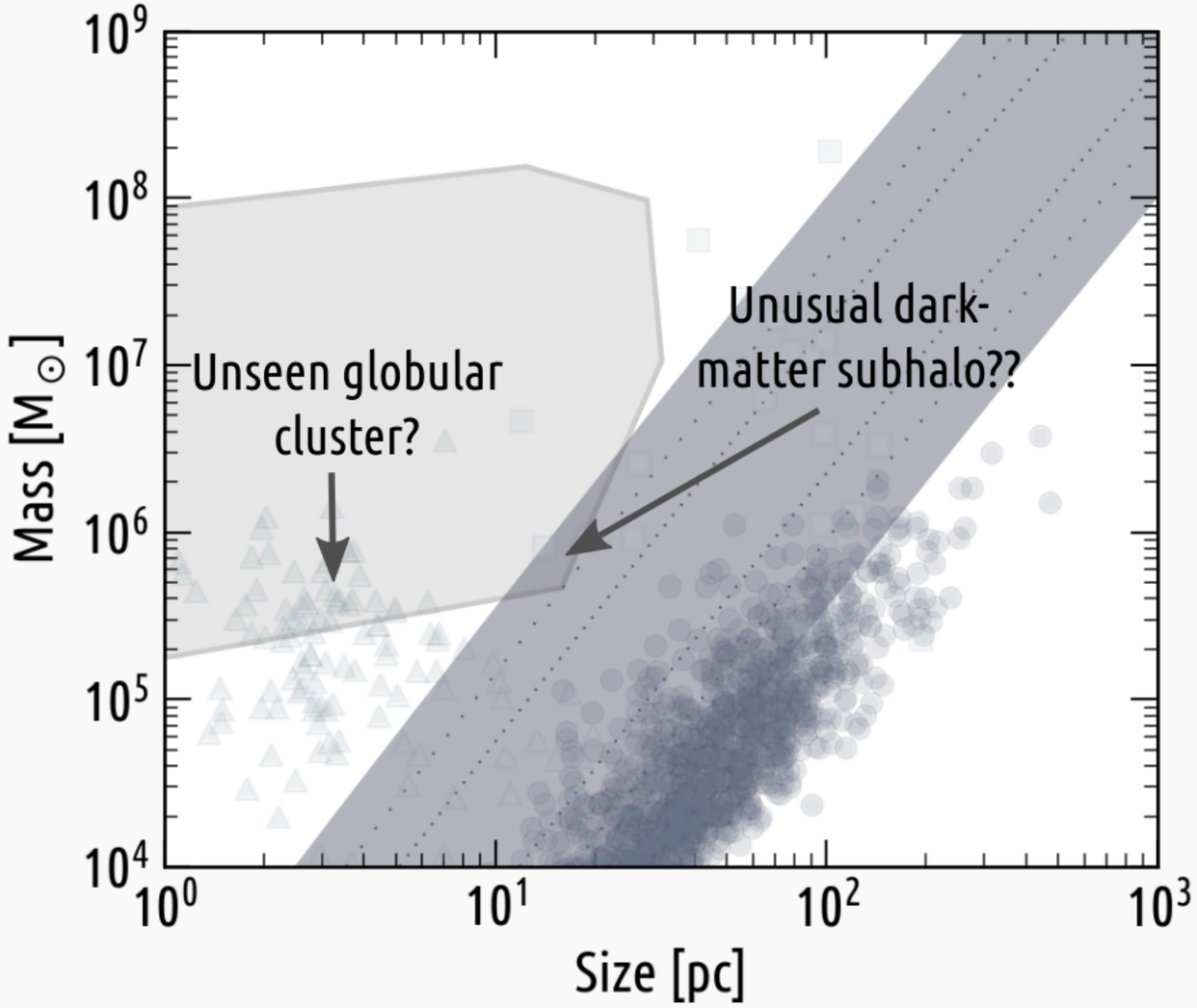
Globular clusters (Baumgardt & Hilker 2018)

Dwarf galaxies (McConnachie 2012)

Inconsistent orbits

ΛCDM subhalos (3 σ scatter) (Moliné et al. 2017)

Dark matter subhalo is a plausible perturber of GD-1



GD-1 perturber (Bonaca et al. 2018)

Outer disk molecular clouds (Miville-Deschênes et al. 2017)

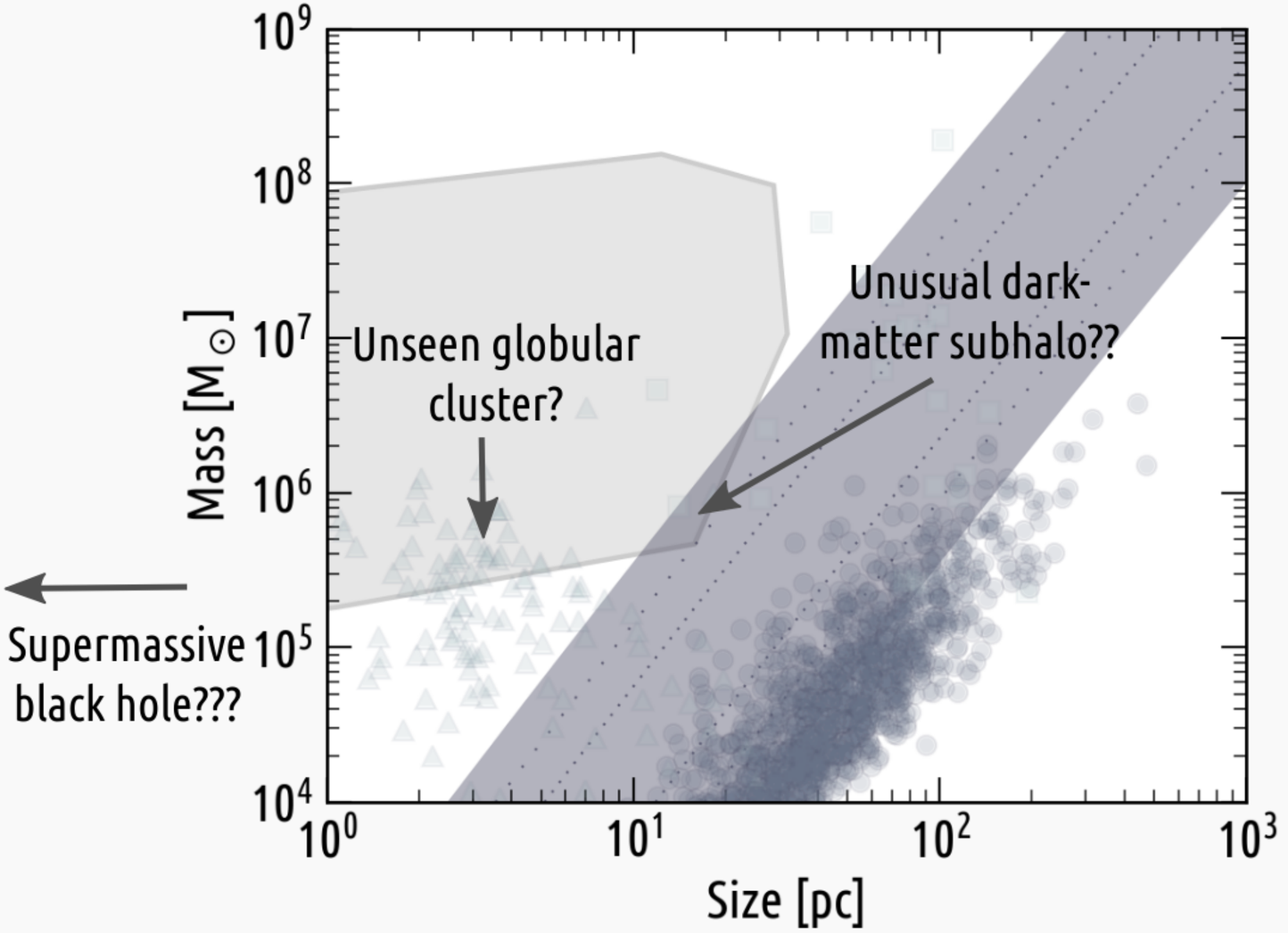
Globular clusters (Baumgardt & Hilker 2018)

Dwarf galaxies (McConnachie 2012)

Inconsistent orbits

ΛCDM subhalos (3 σ scatter) (Moliné et al. 2017)

Dark matter subhalo is a plausible perturber of GD-1



GD-1 perturber (Bonaca et al. 2018)

Outer disk molecular clouds (Miville-Deschênes et al. 2017)

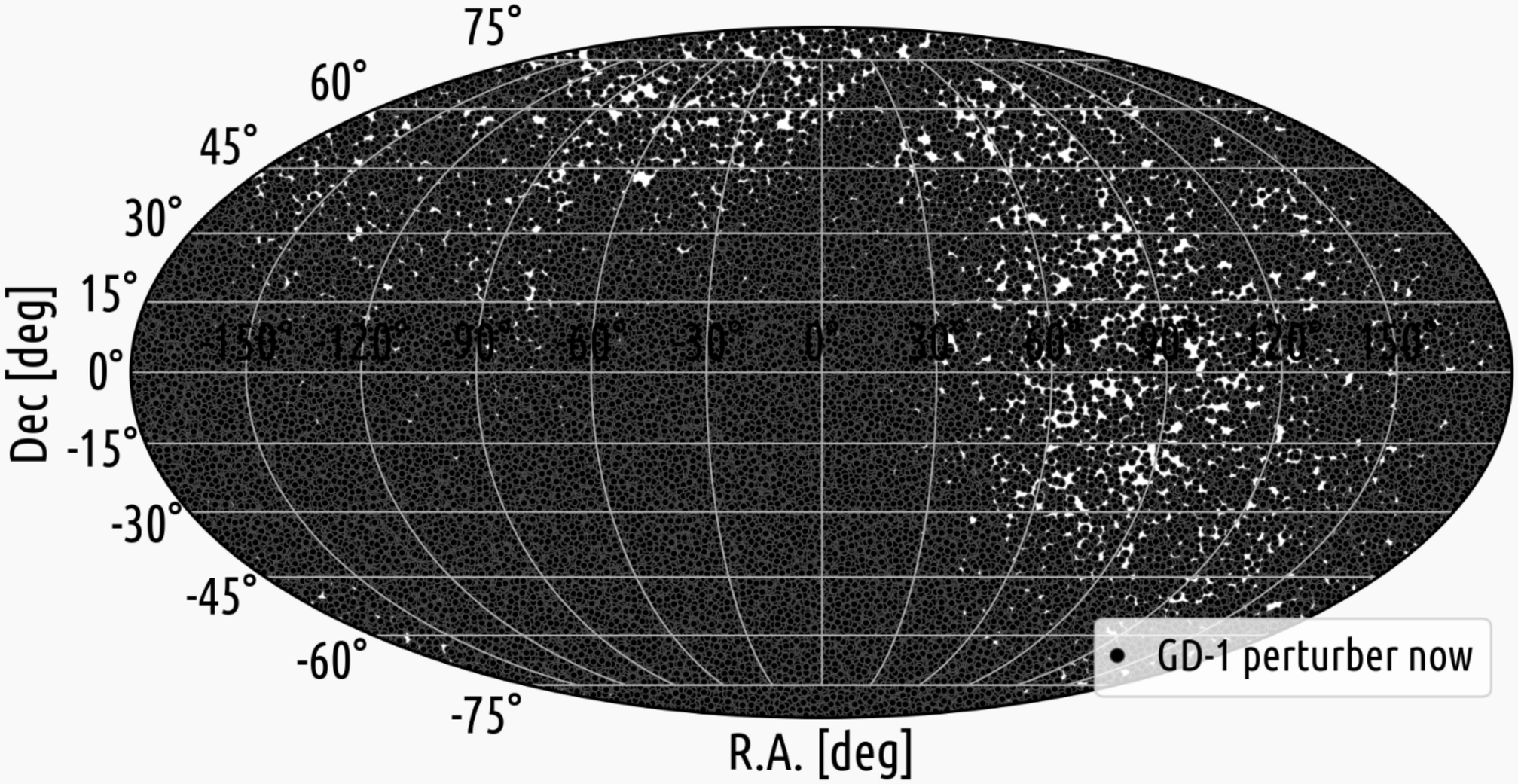
Globular clusters (Baumgardt & Hilker 2018)

Dwarf galaxies (McConnachie 2012)

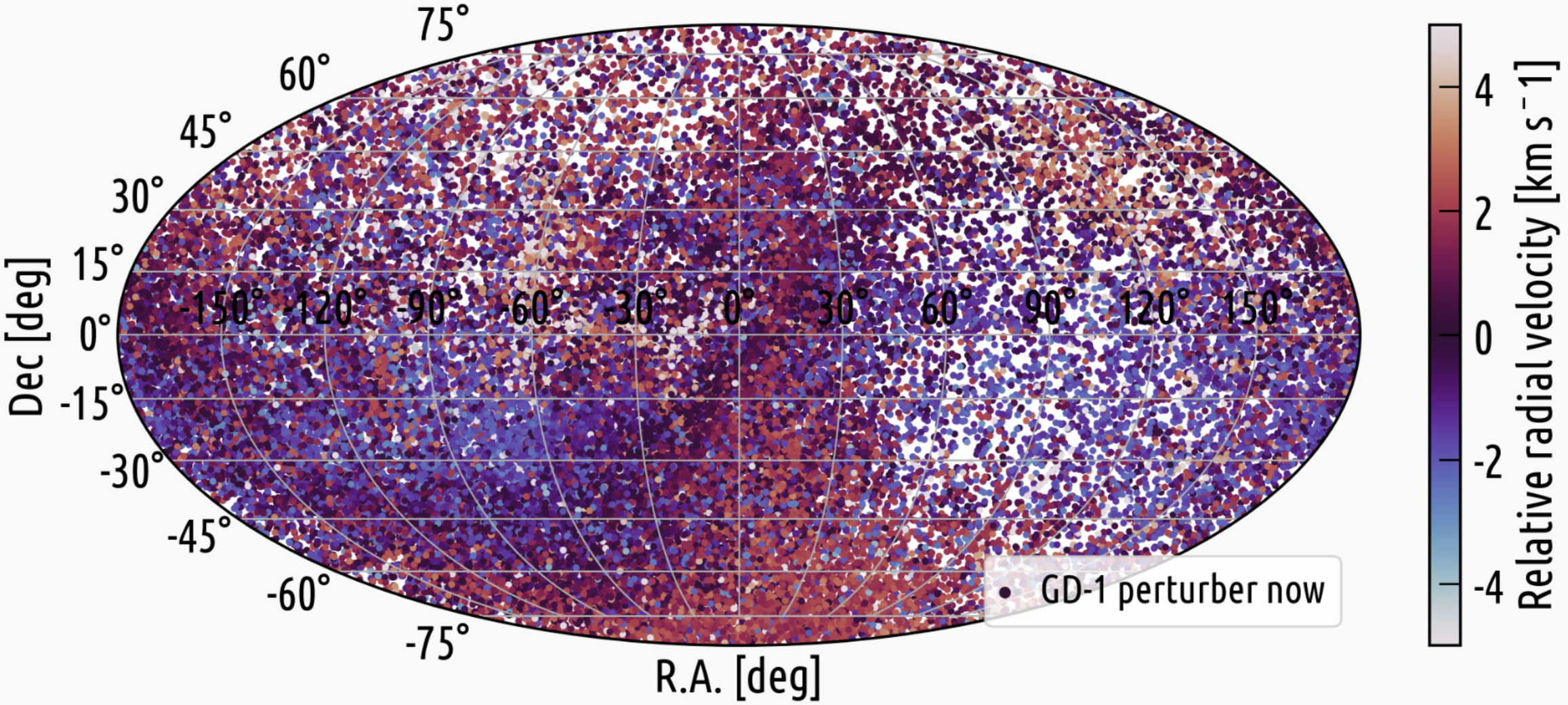
Inconsistent orbits

ΛCDM subhalos (3 σ scatter) (Moliné et al. 2017)

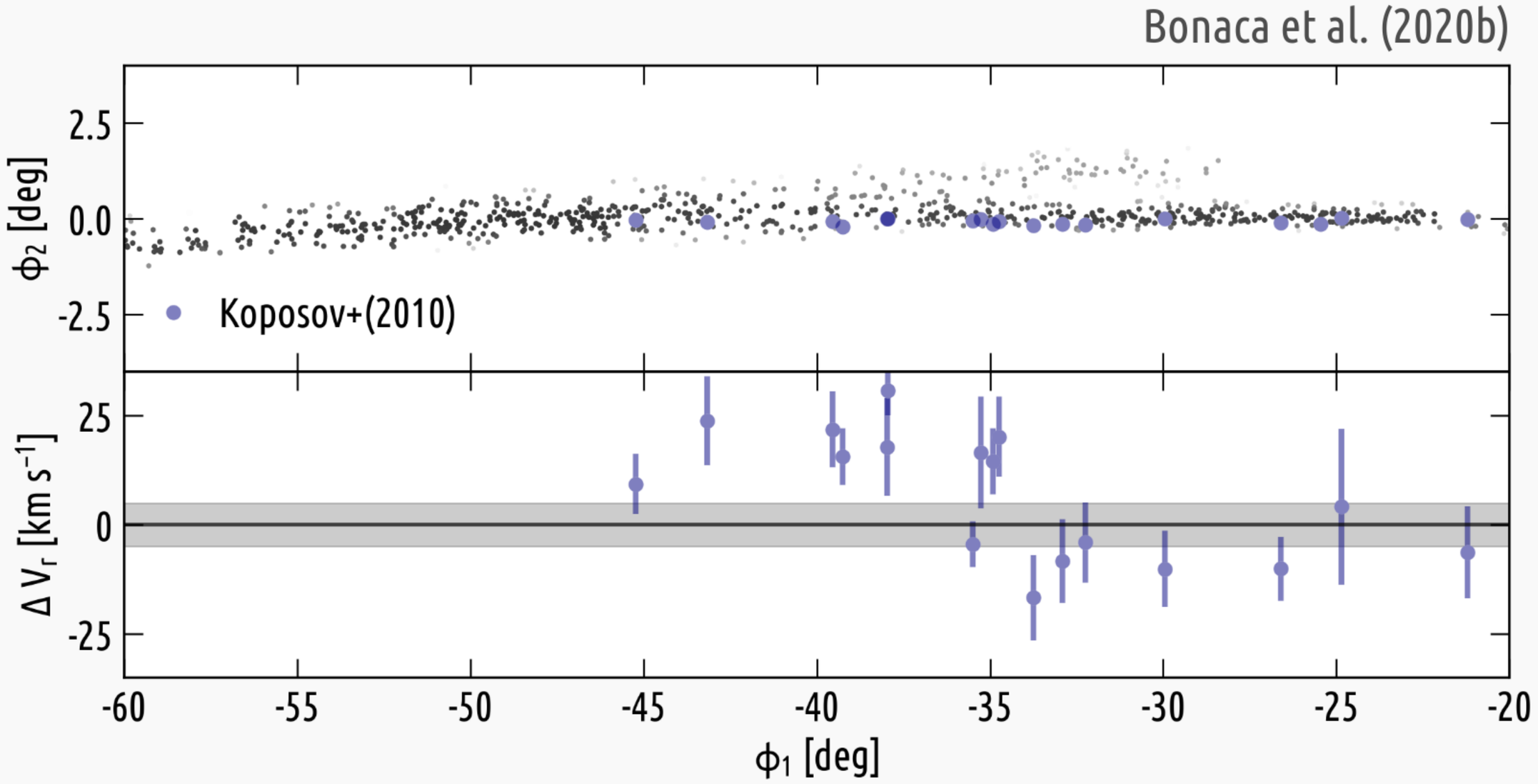
Stream morphology allows for a wide range of perturber orbits



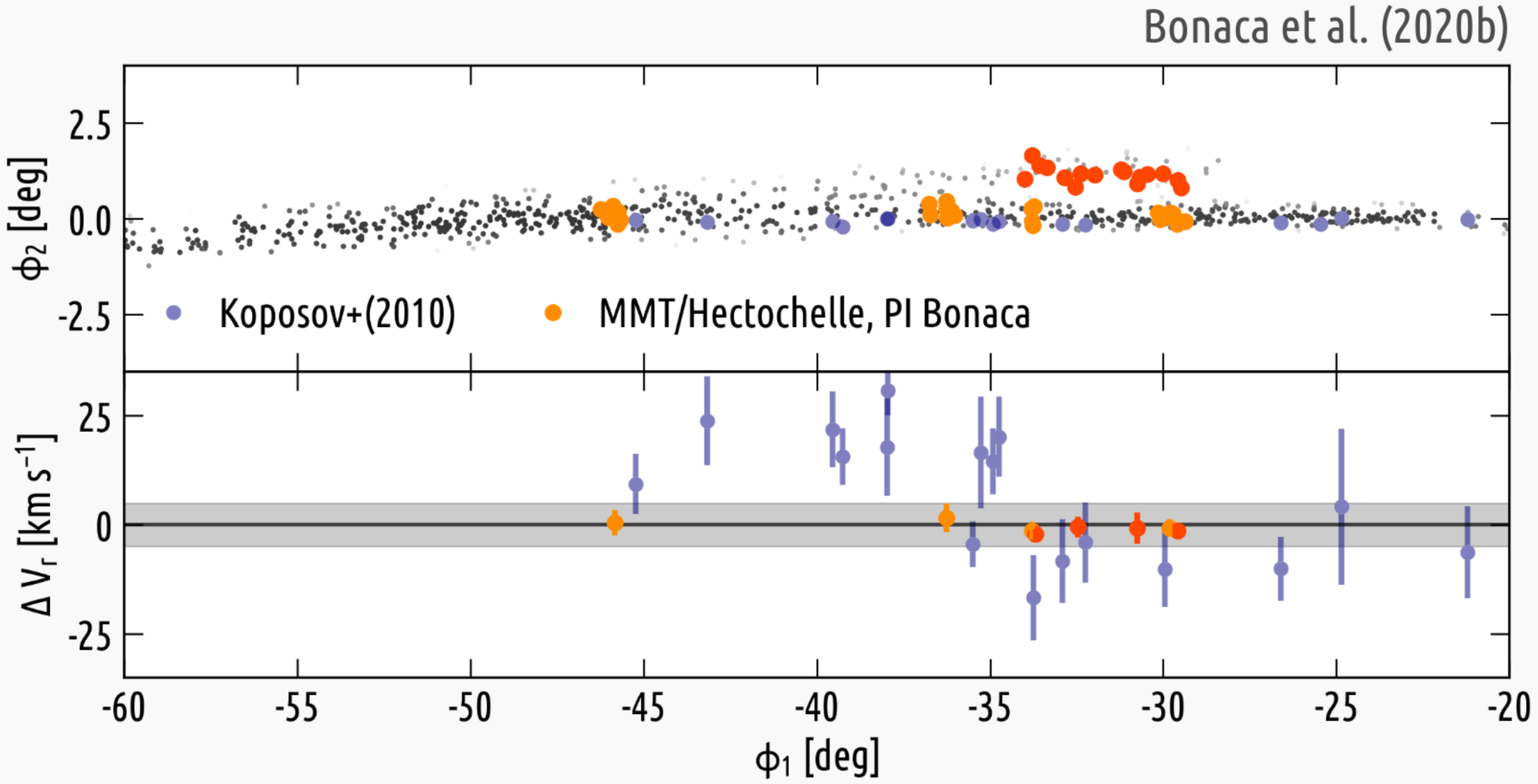
Stream morphology allows for a wide range of perturber orbits



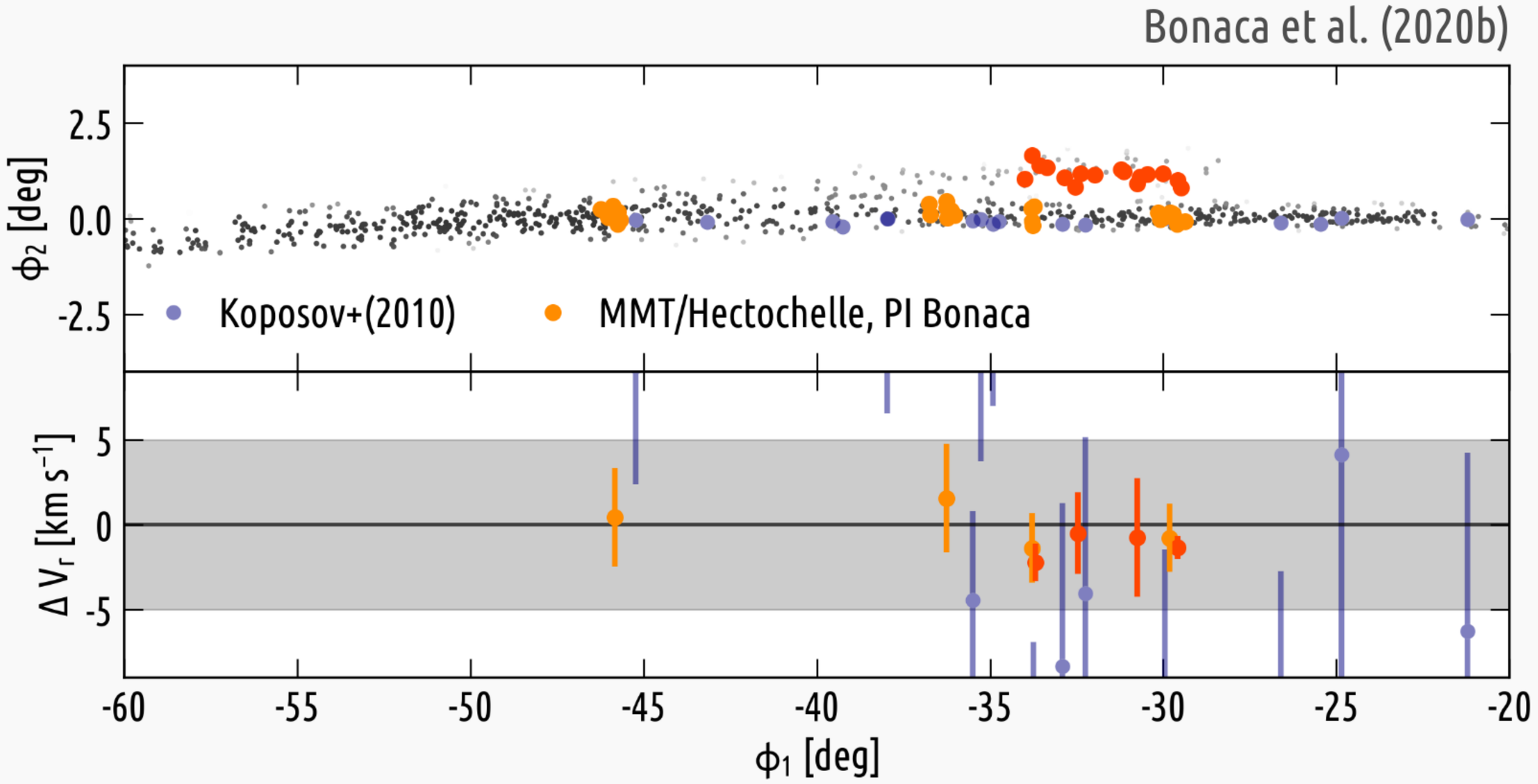
There is no radial velocity offset between the GD-1 stream and spur



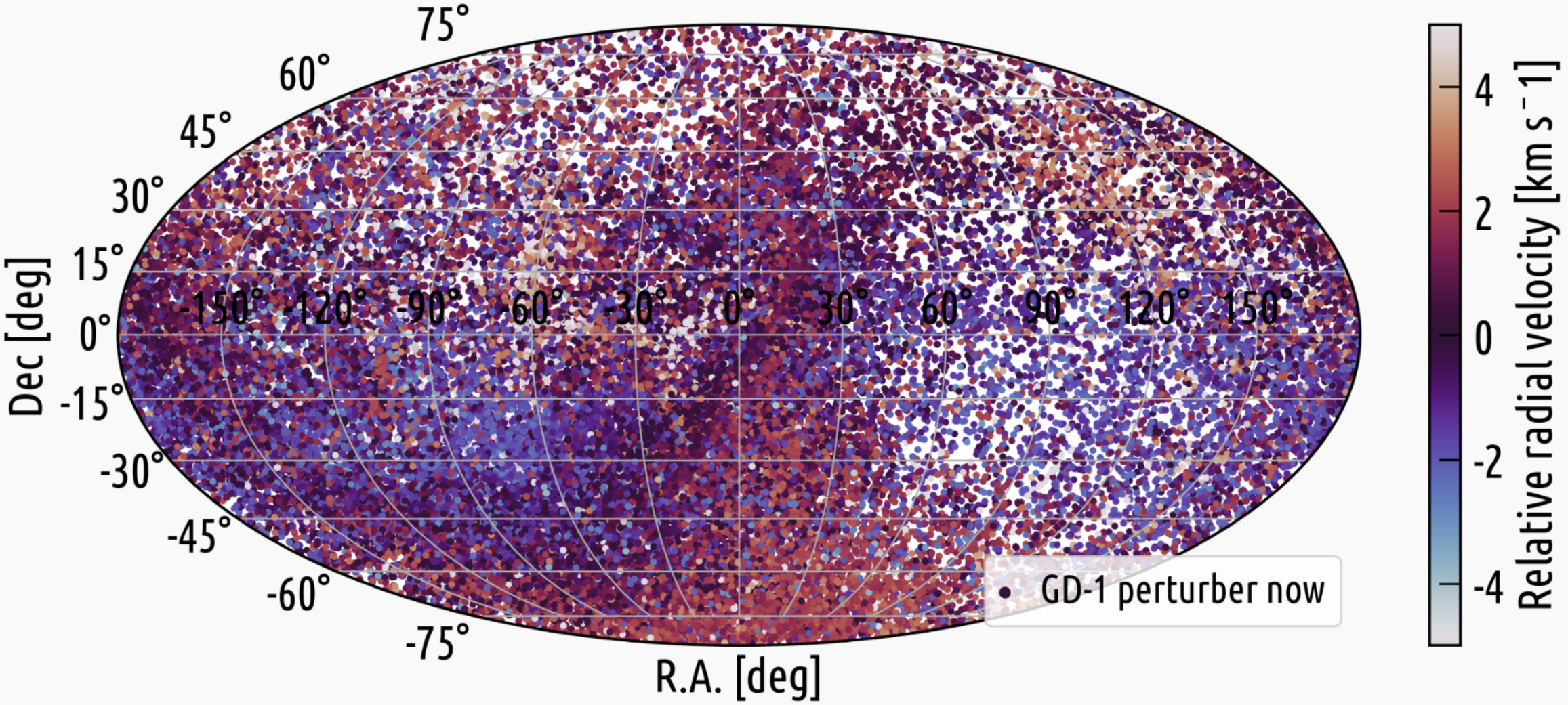
There is no radial velocity offset between the GD-1 stream and spur



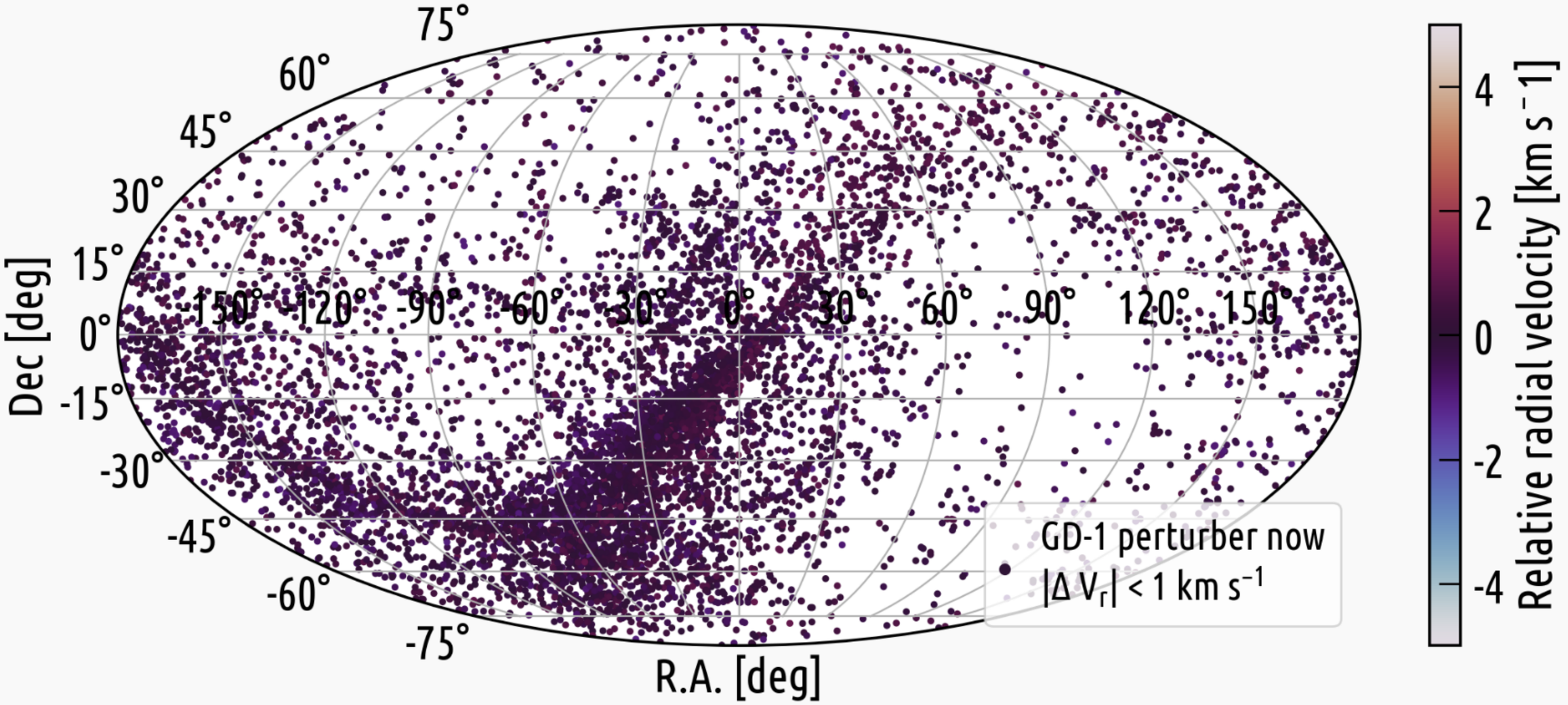
There is no radial velocity offset between the GD-1 stream and spur



With kinematics, the GD-1 perturber is localized on the sky

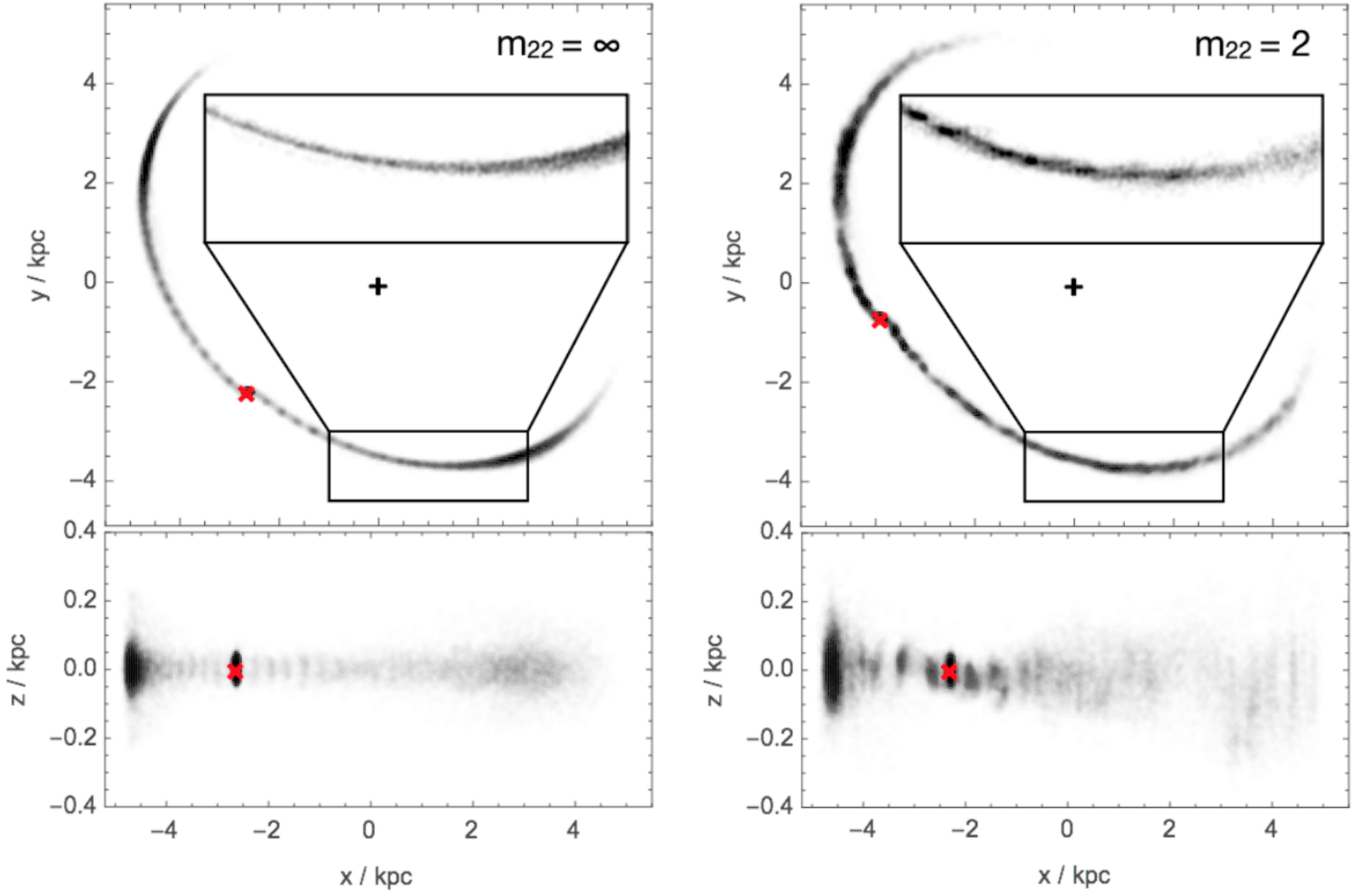


With kinematics, the GD-1 perturber is localized on the sky



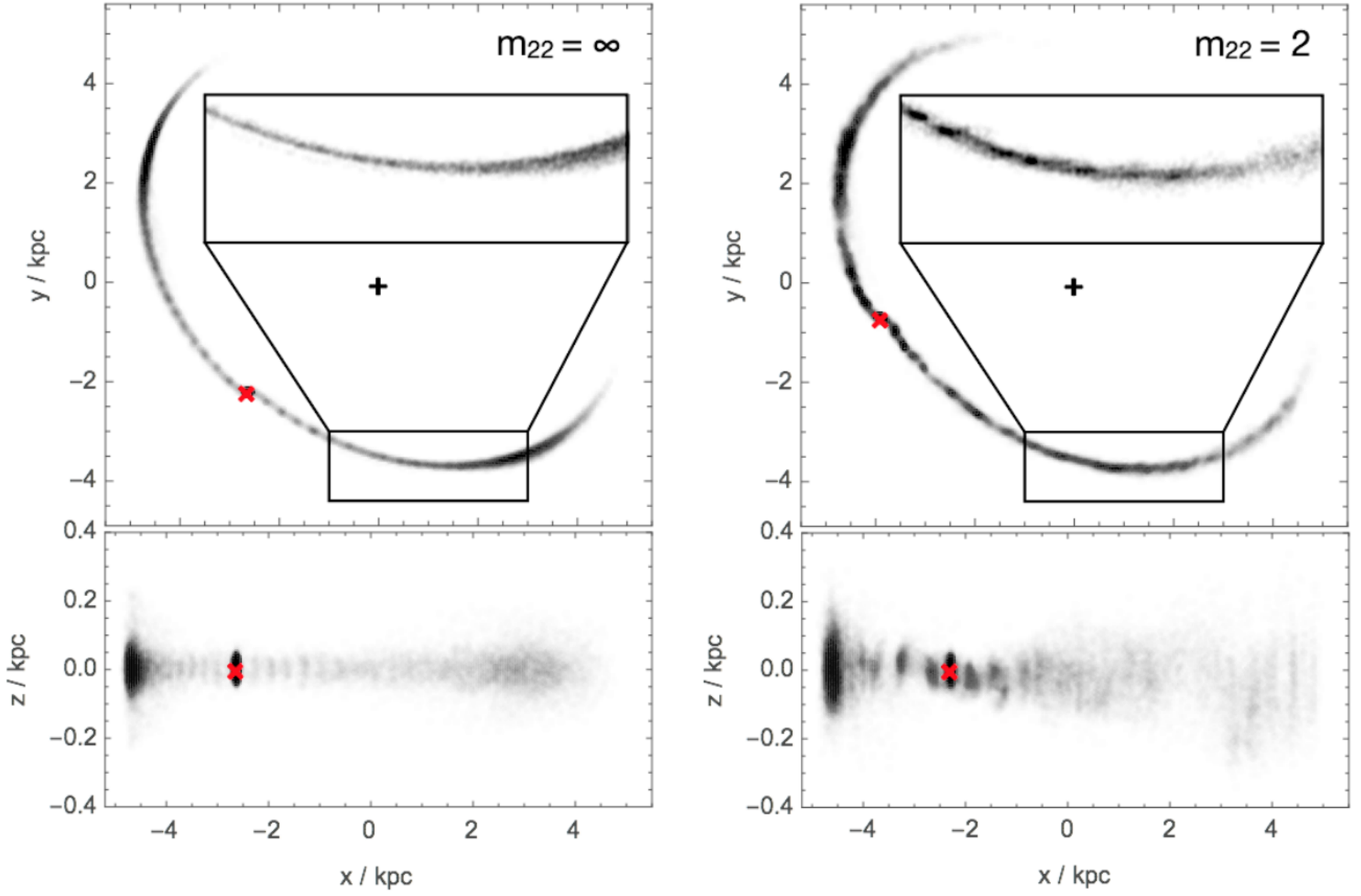
Fuzzy Dark Matter dynamically heats stellar streams

Amorisco & Loeb, arXiv:1808.00464



Fuzzy Dark Matter dynamically heats stellar streams

Amorisco & Loeb, arXiv:1808.00464



with NAU undergrad
Megan Gialluca

measured radial velocity dispersion in the GD-1 stream:

$$\sigma_{V_r} \approx 2\,\mathrm{km\,s^{-1}}$$

expectation in a smooth Milky Way:

$$\sigma_{V_r} \lesssim 1\,\mathrm{km\,s^{-1}}$$

An entire web of stellar streams awaits to be confidently revealed with the next generation of photometric surveys