Ana Bonaca

ITC Fellow

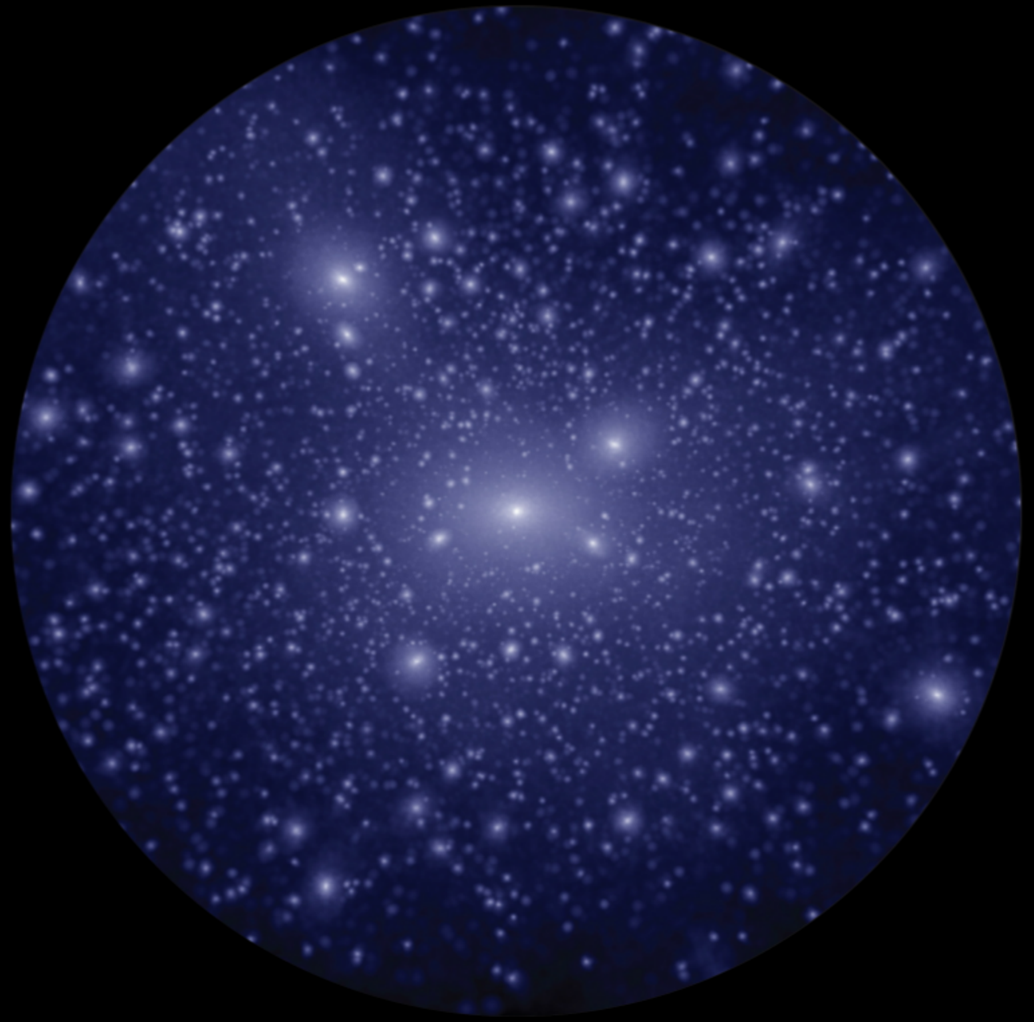
Harvard - Smithsonian
Center for Astrophysics

Uncovering the nature of dark matter with stellar streams in the Milky Way

CDM model matches the distribution of galaxies on large scales

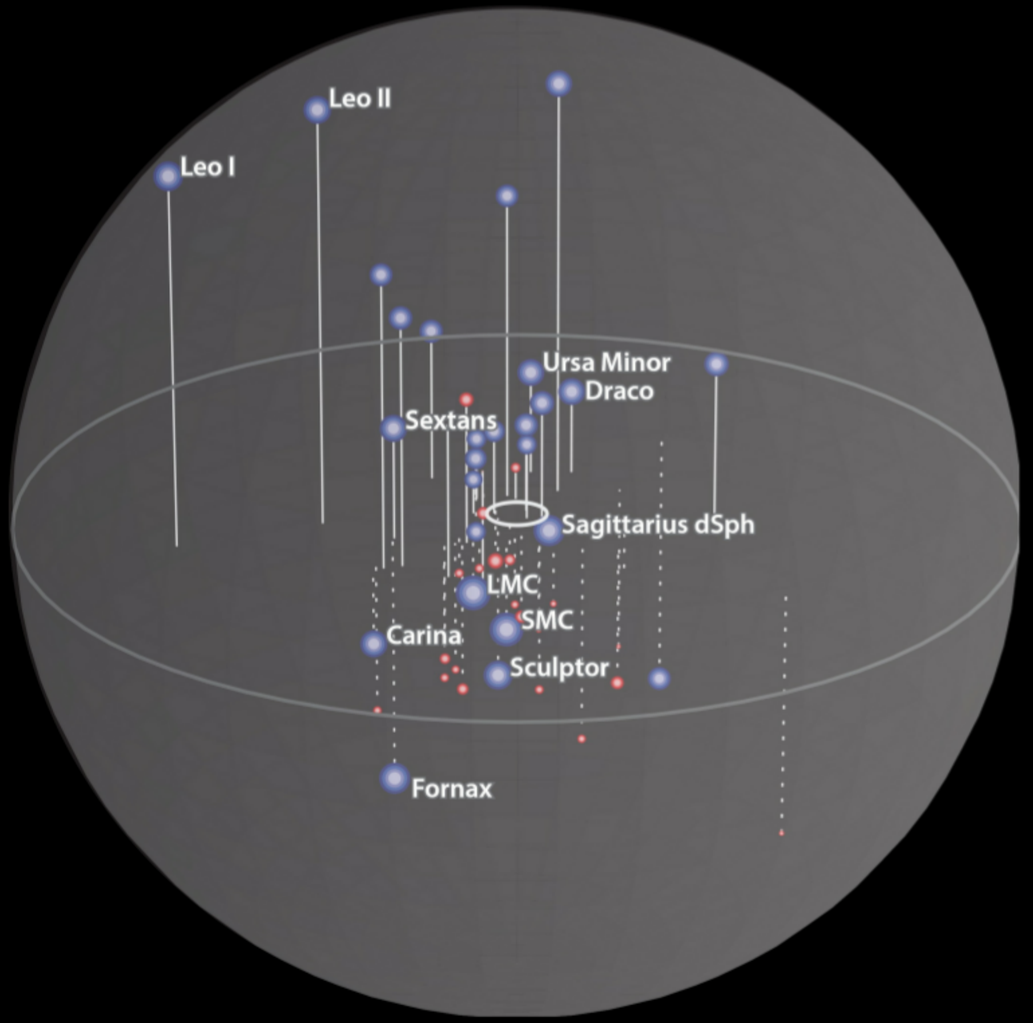
We don't see all the structure predicted by CDM on small scales

Dark matter in a simulated galaxy



Robles, Kelley, Bullock, Boylan-Kolchin

Satellite galaxies of the Milky Way



Pawlowski, Bullock, Boylan-Kolchin

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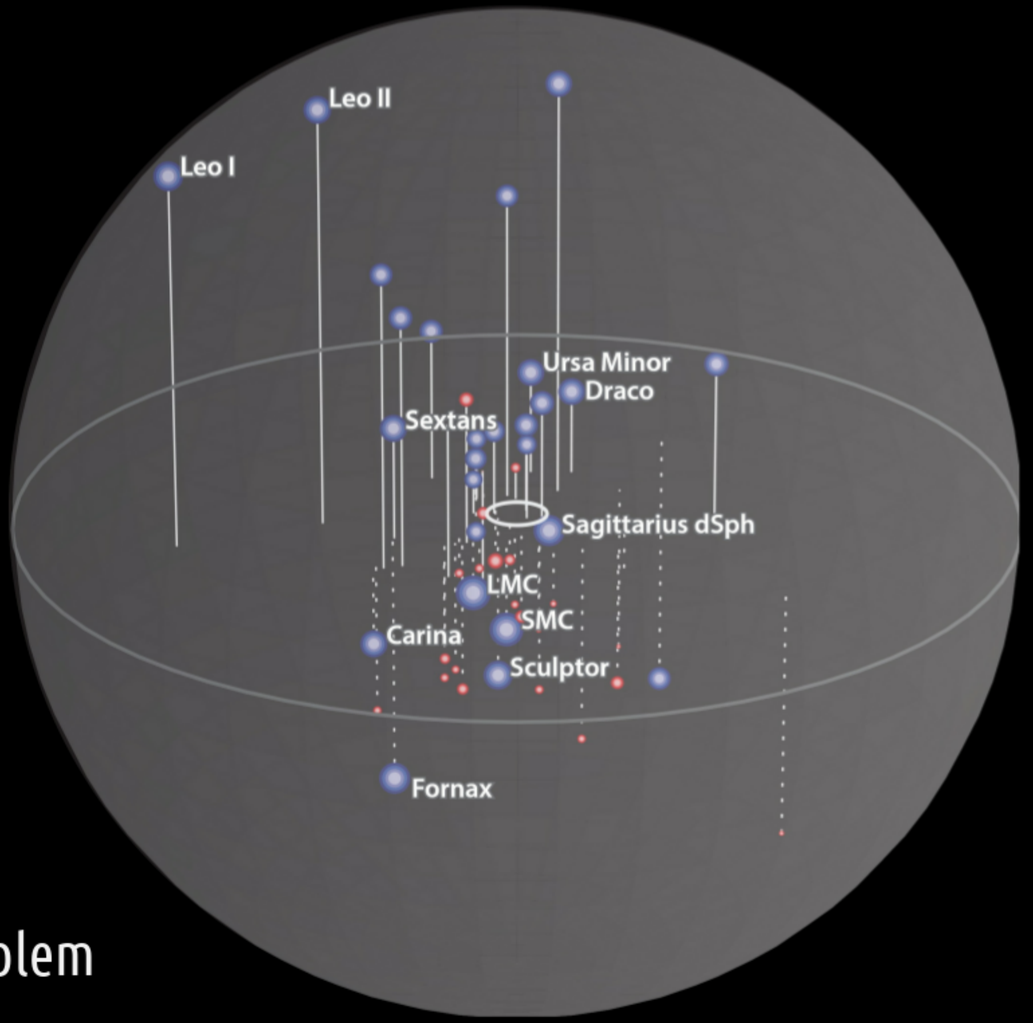
The
Missing
Satellites Problem

Satellite galaxies of the Milky Way



Pawlowski, Bullock, Boylan-Kolchin

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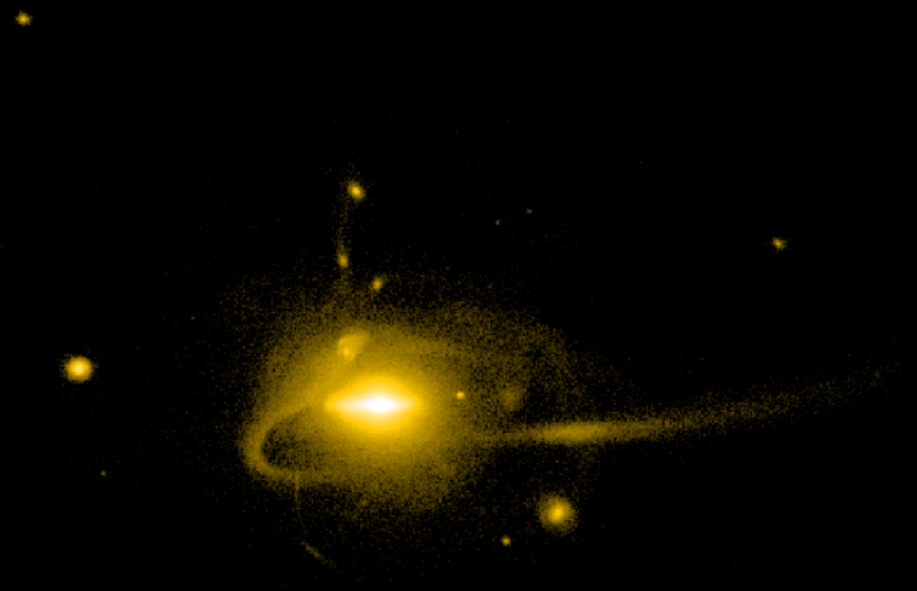
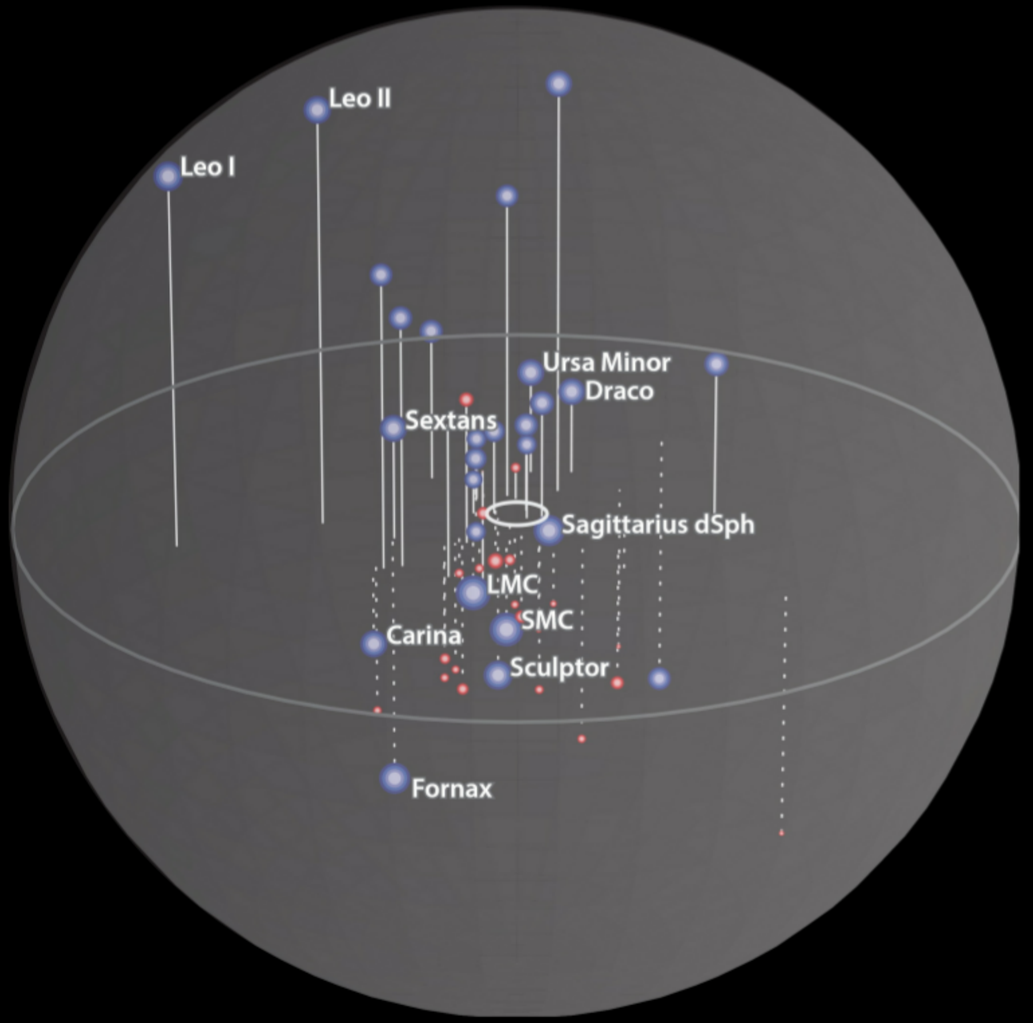
Stars in a simulated galaxy with baryons



Wetzel et al. (2016)

Satellite galaxies of the Milky Way



Pawlowski, Bullock, Boylan-Kolchin

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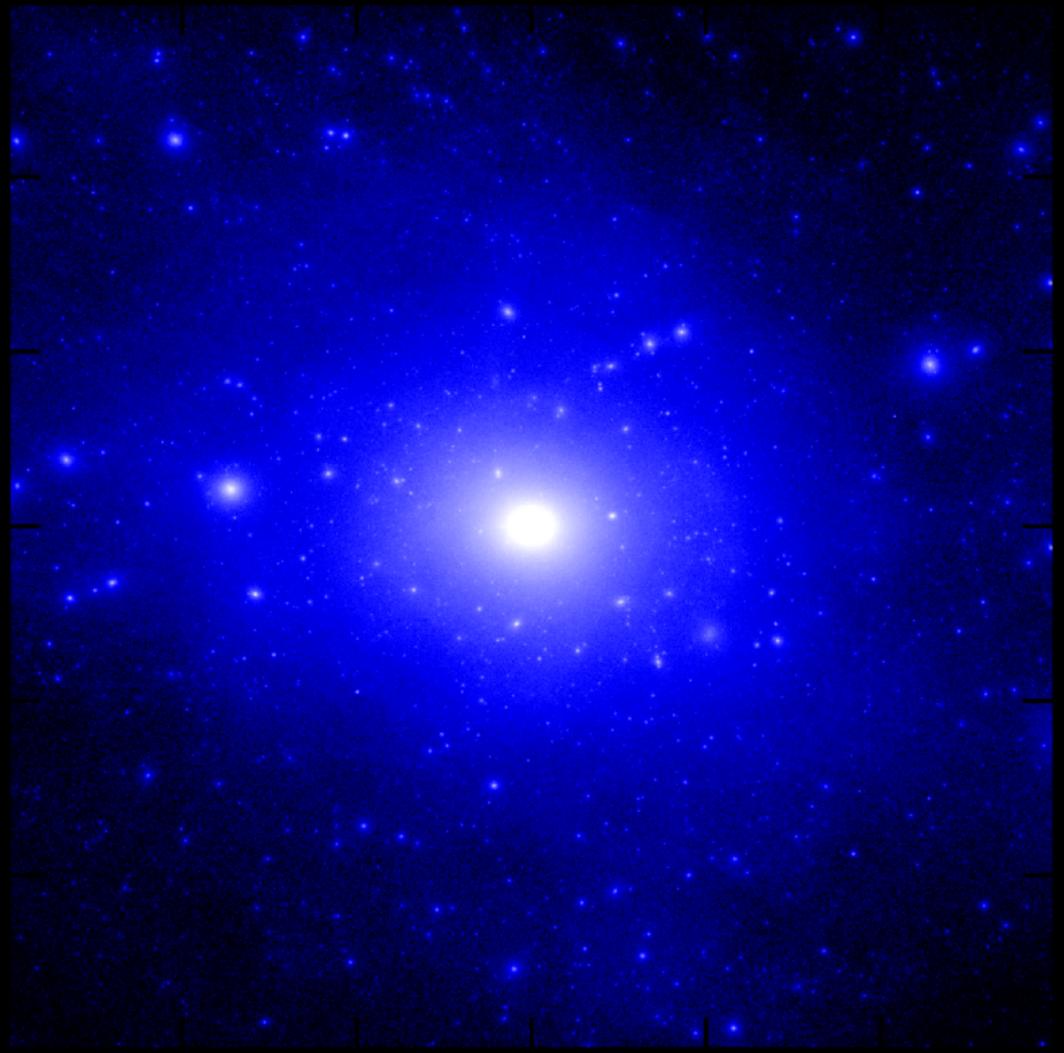

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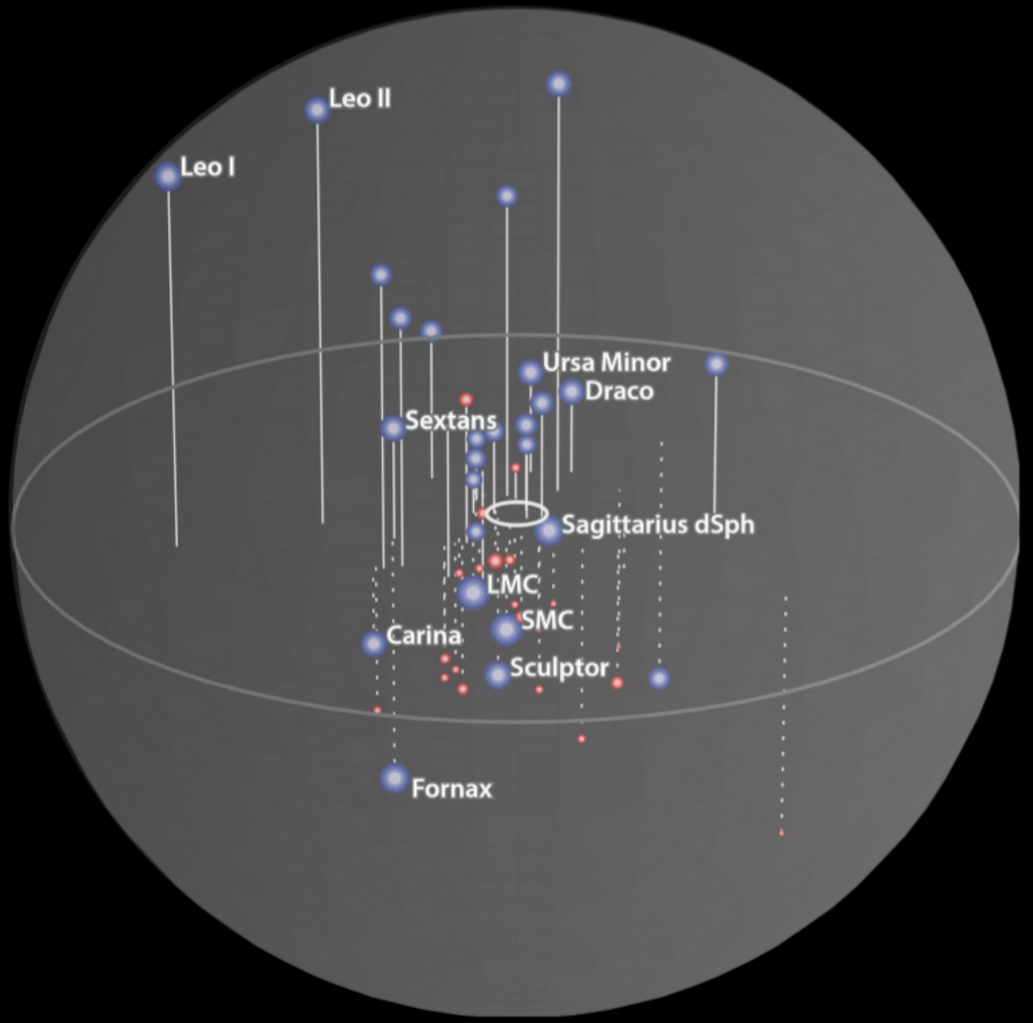
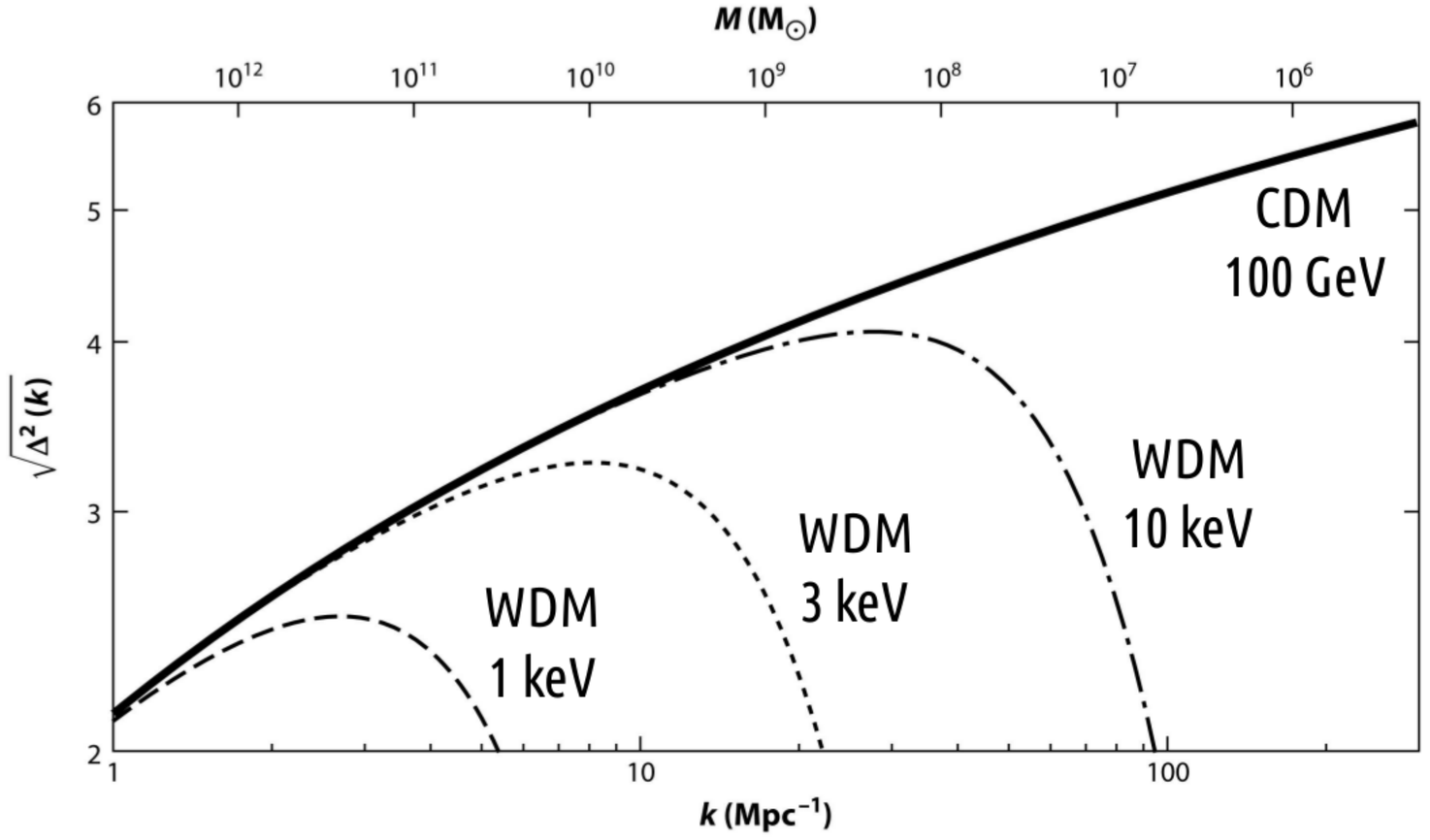


Pawlowski, Bullock, Boylan-Kolchin

Nature of dark matter is encoded in low-mass halos

... the search for abundant dark matter halos with inferred virial masses substantially lower than the expected threshold of galaxy formation ($M \sim 10^8\,\mathrm{M}_\odot$) is the most urgent calling ...



Bullock & Boylan-Kolchin (2017)

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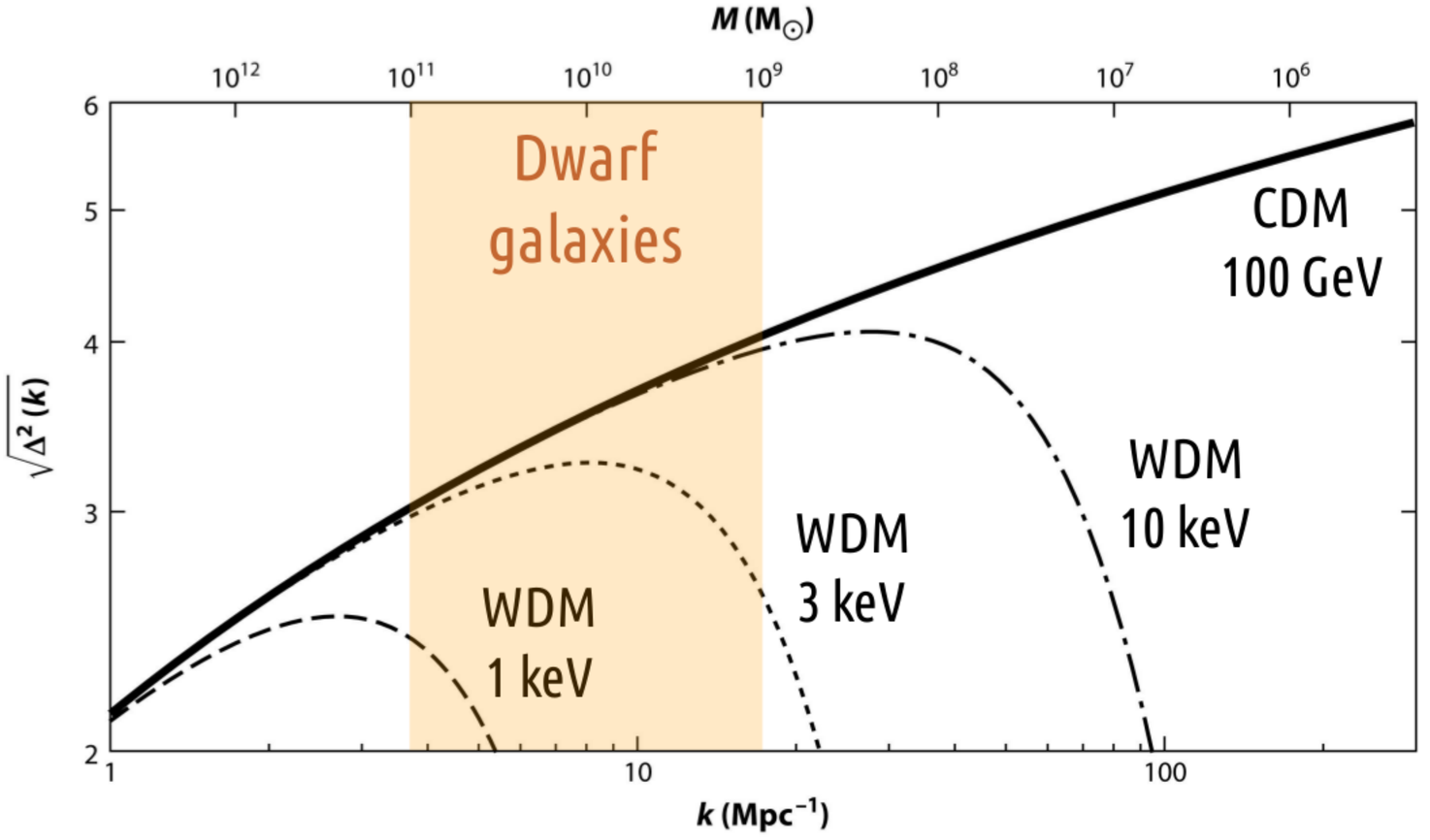
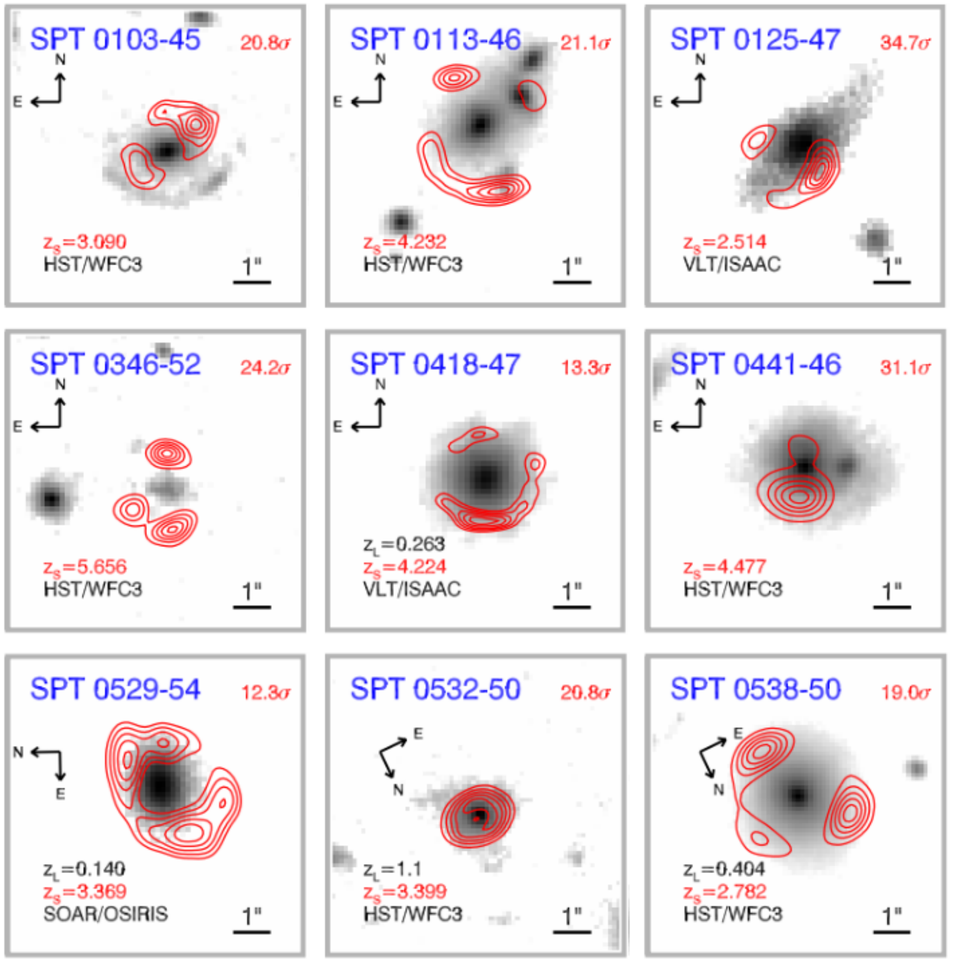


Bullock & Boylan-Kolchin (2017)

Extragalactic searches

can discover a large sample of subhalos



Hezaveh et al. (2016)

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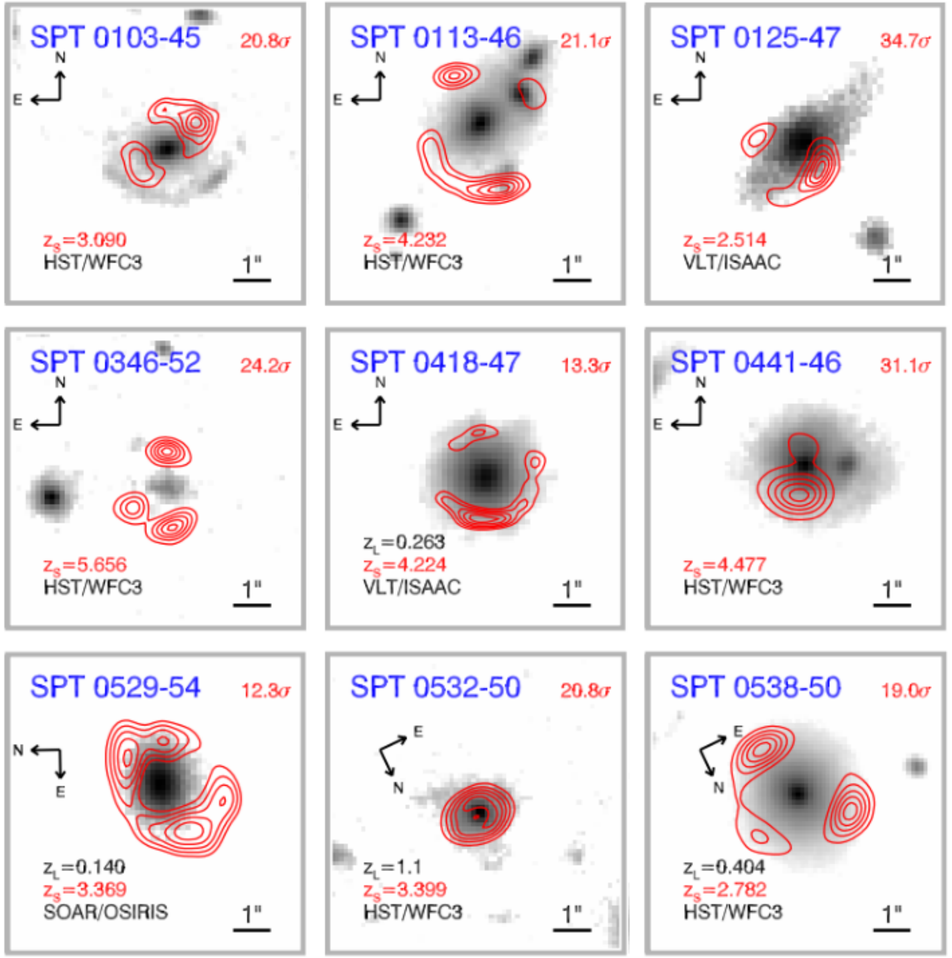

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Search in the Milky Way galaxy

would allow study of individual subhalos in a lot of detail

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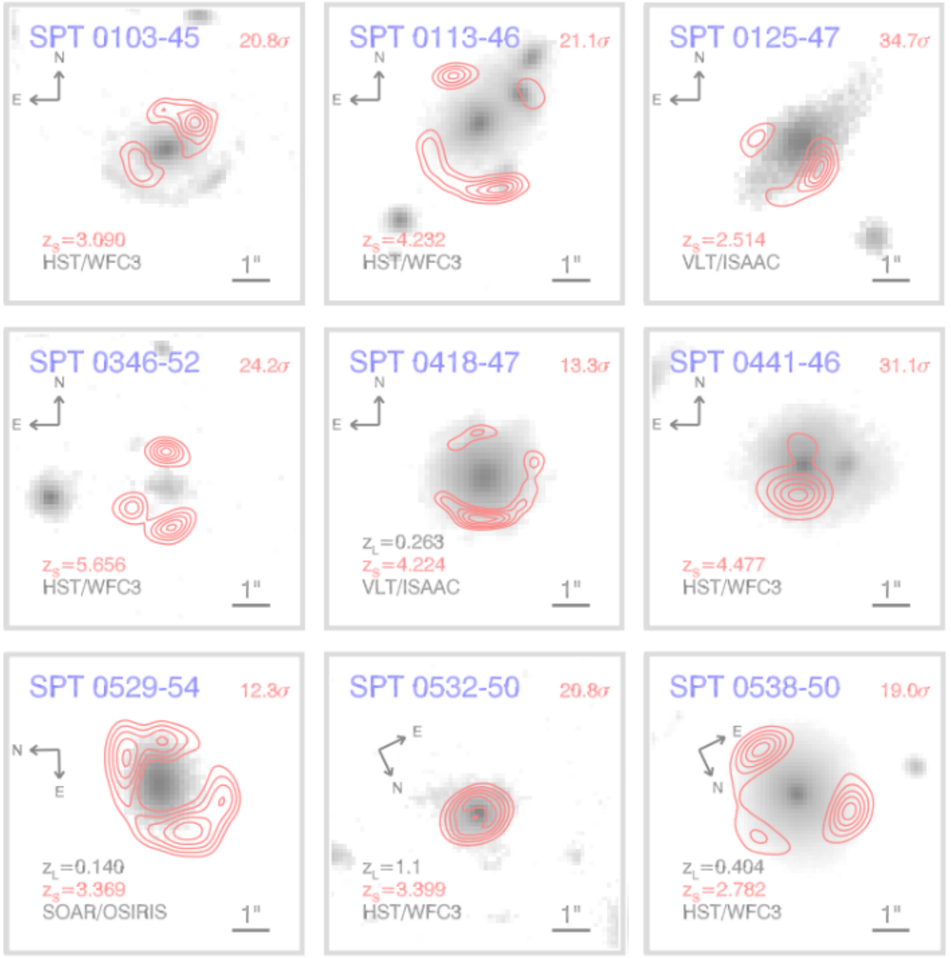


Hezaveh et al. (2016)

Search in the Milky Way galaxy

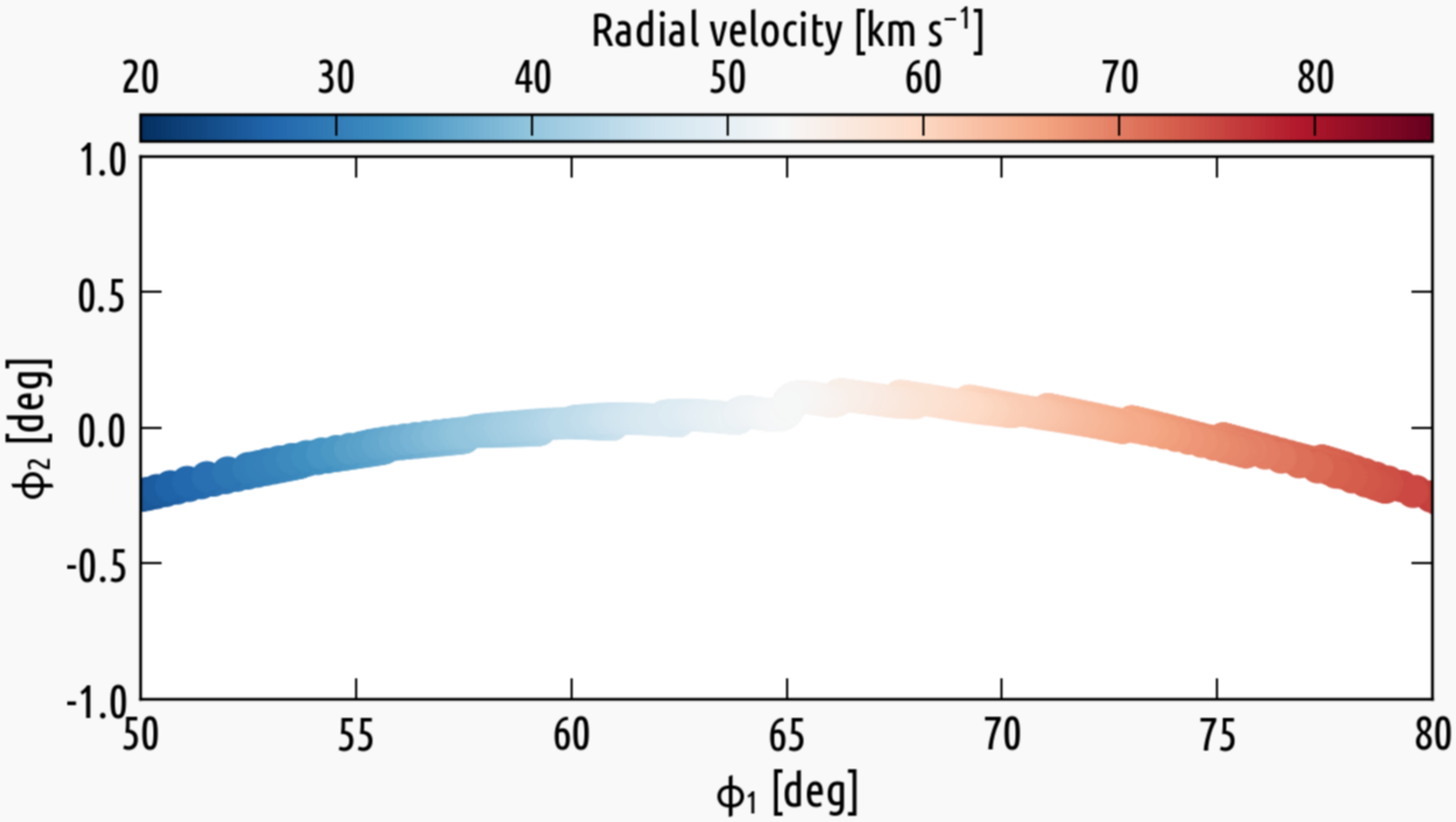
would allow study of individual subhalos in a lot of detail

Outline:

1) Find objects in the Milky Way halo that trace the gravitational potential

2) Search for signatures of deviations from the smooth distribution of matter

Stellar streams are shaped by the underlying matter distribution



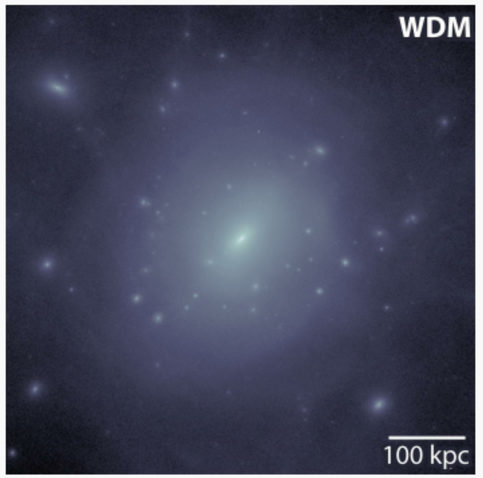
Bonaca et al. (2014)

$\log M_d / M_\odot = 10.833$

$V_h = 430$ km / s

$q_z = 1.000$

Stellar stream preserve a record of all gravitational interactions



Stellar stream in a smooth galaxy

Bonaca et al. (2014)

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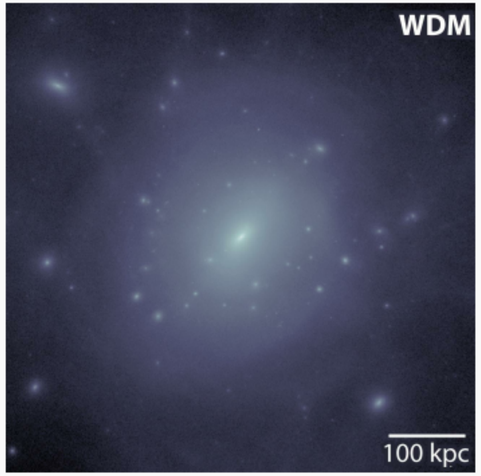

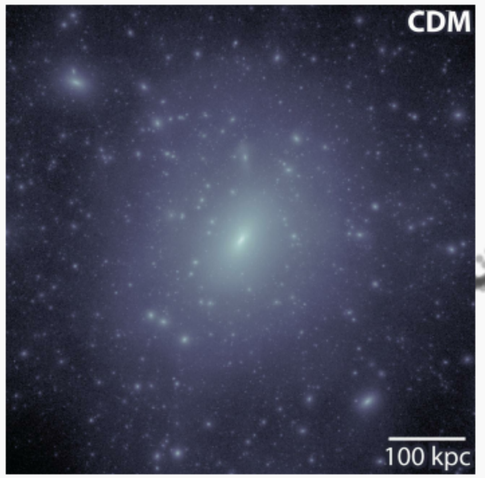

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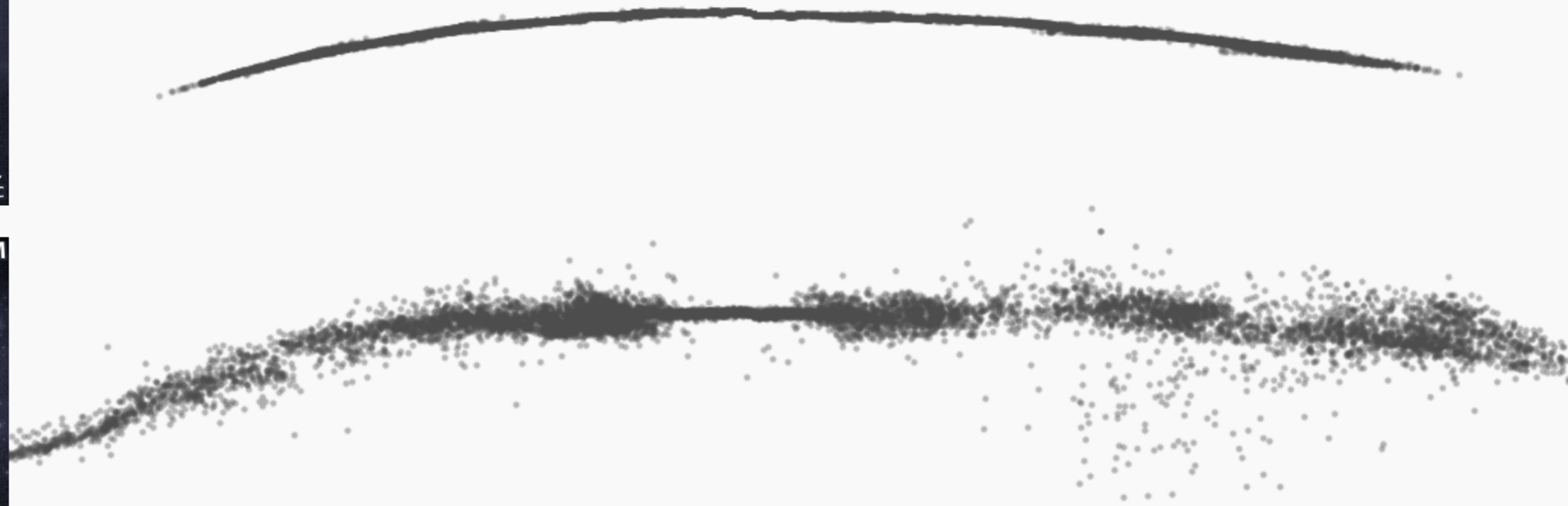
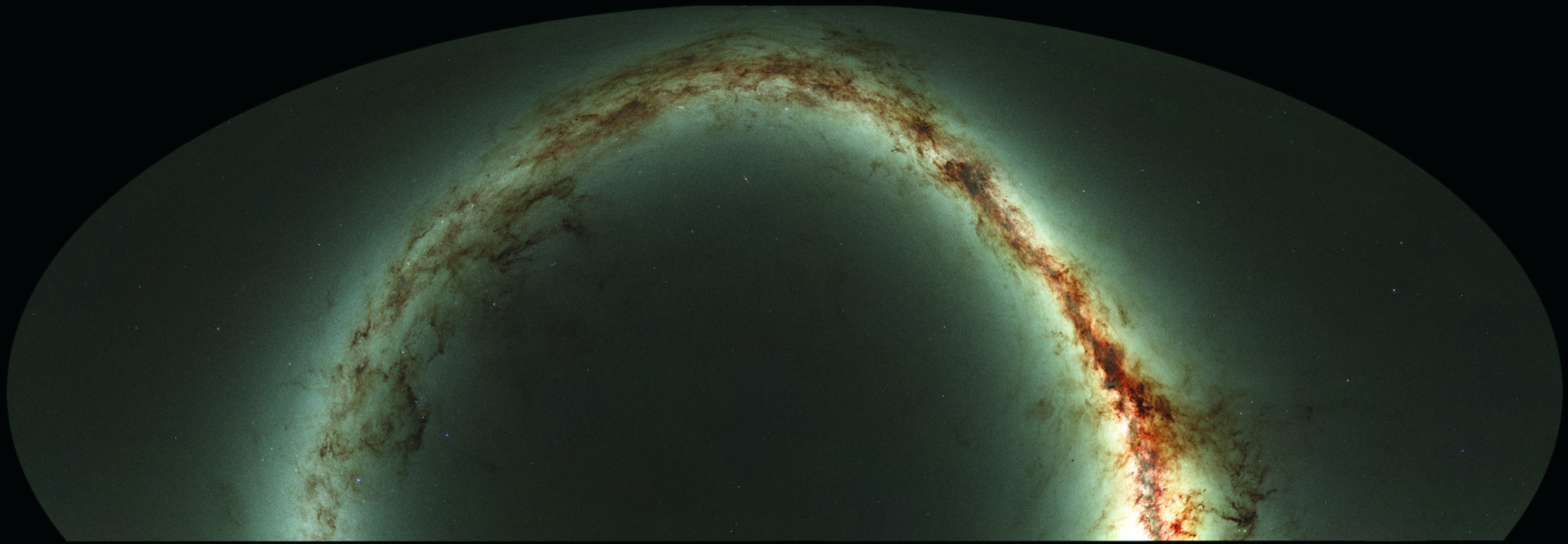
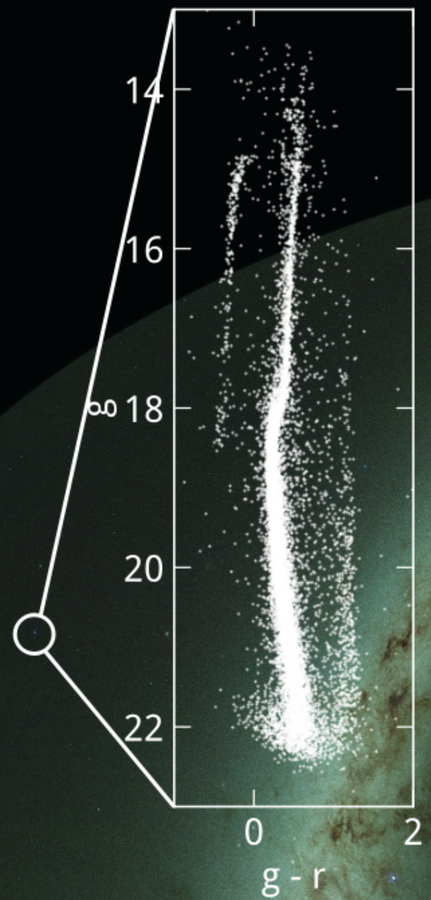


Bonaca et al. (2014)

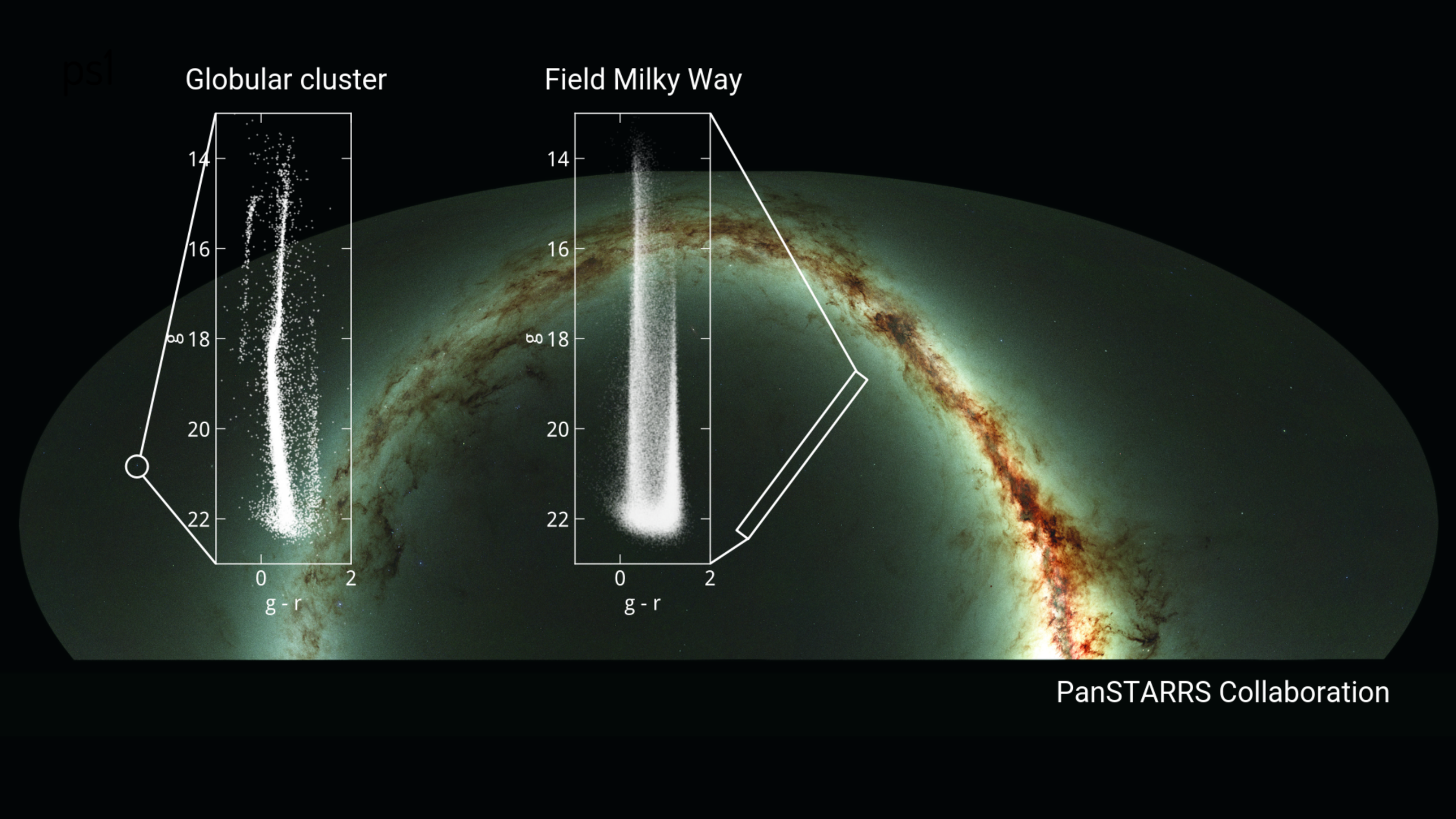

ps1
PanSTARRS Collaboration

ps1

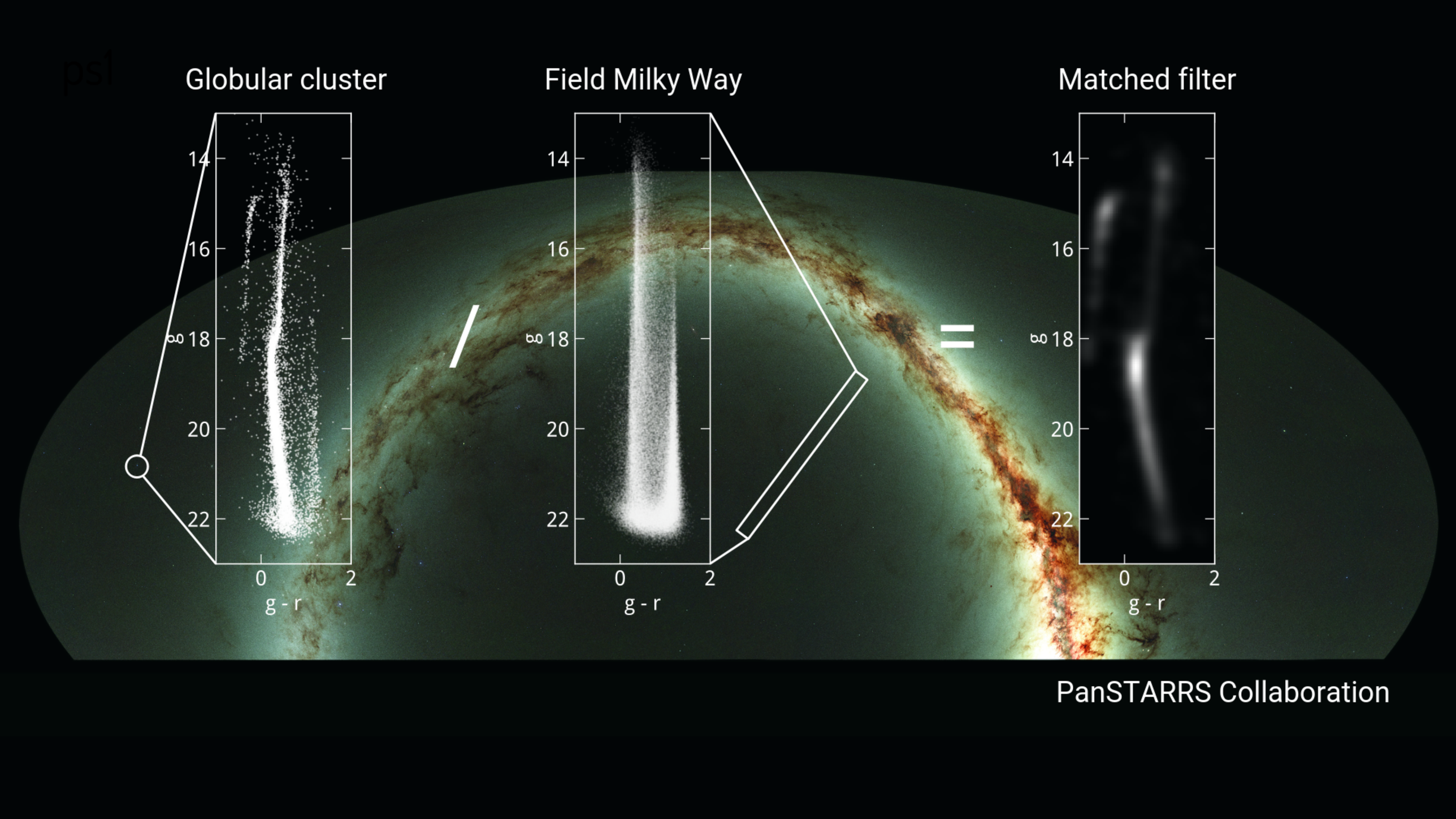
Globular cluster



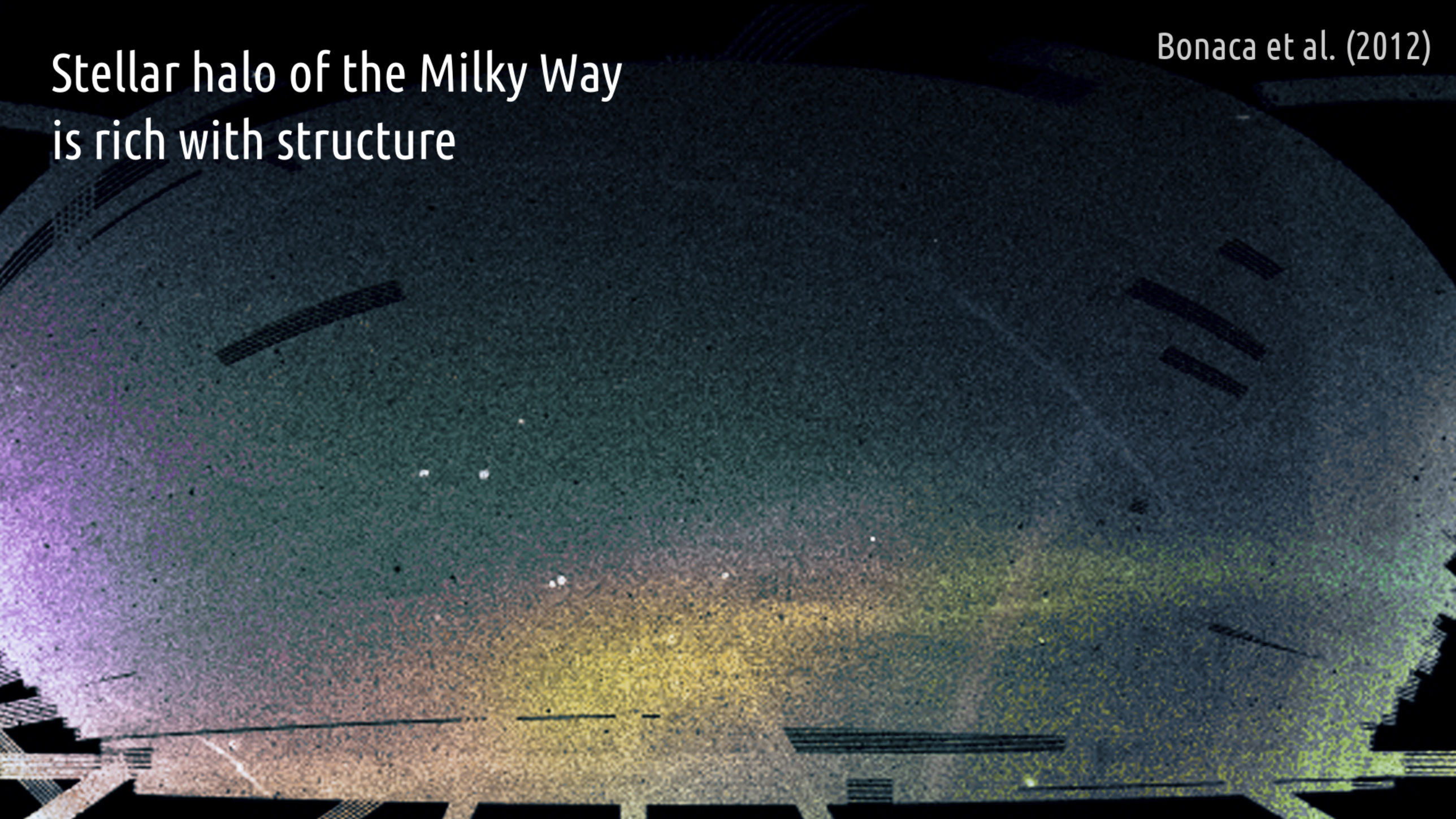
PanSTARRS Collaboration



PanSTARRS Collaboration


ps1
Globular cluster
Field Milky Way
Matched filter
14
16
18
20
22
g
0
2
g - r
PanSTARRS Collaboration

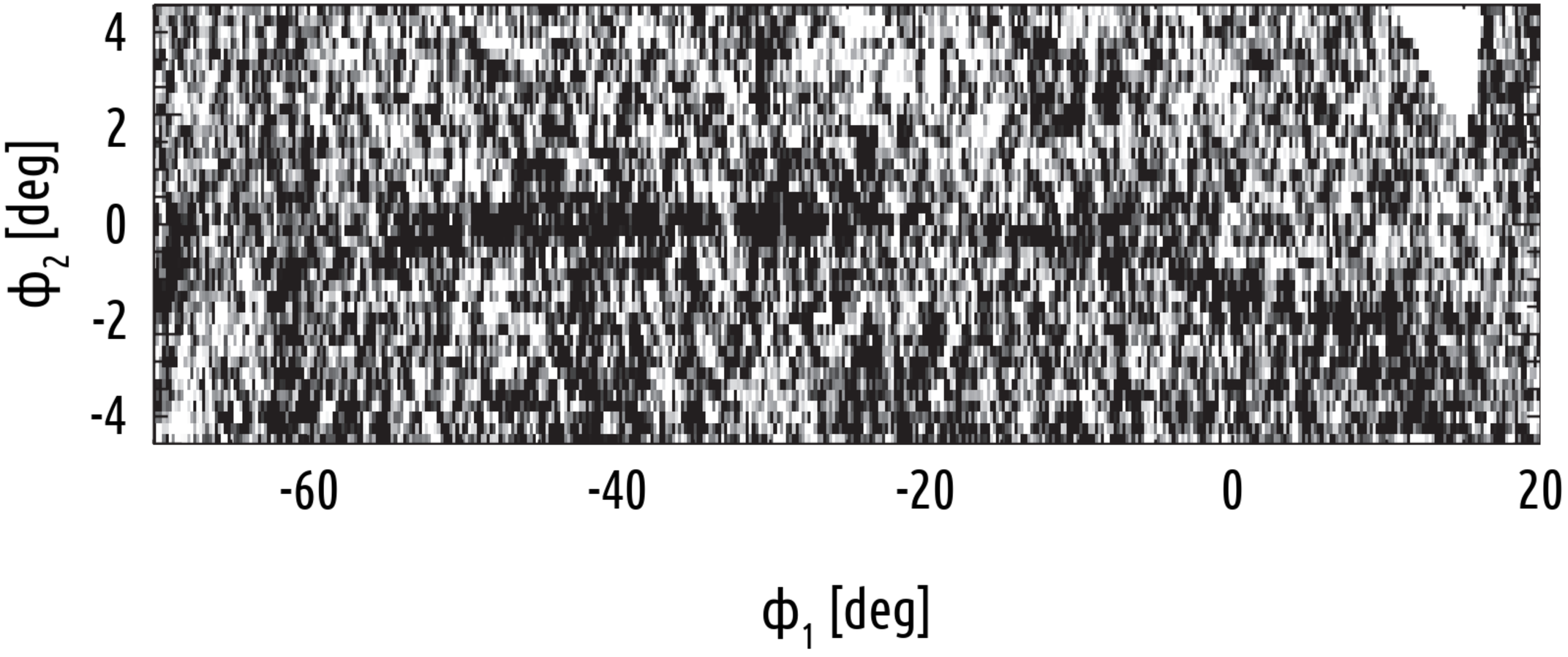
Stellar halo of the Milky Way is rich with structure



Bonaca et al. (2012)

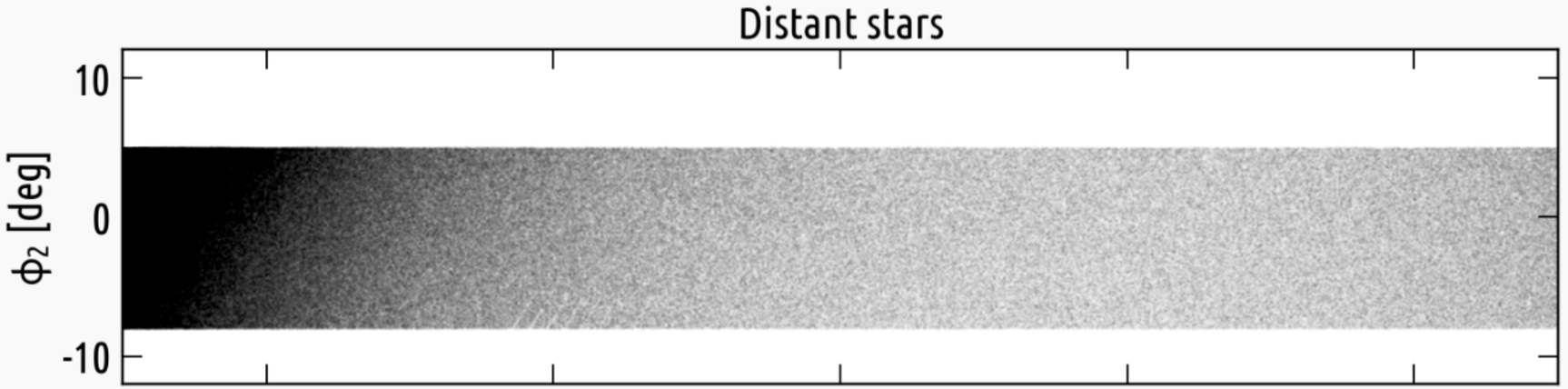
Identifying members of stellar streams is challenging

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



Gaia Data Release 2

Gaia's view of the GD-1 stellar stream



Price-Whelan & Bonaca (2018)

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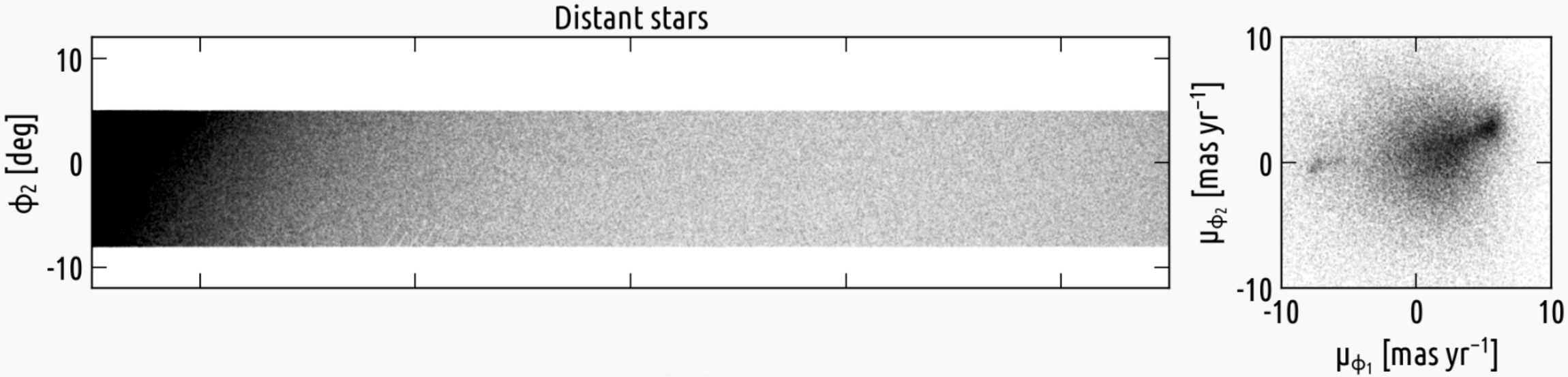

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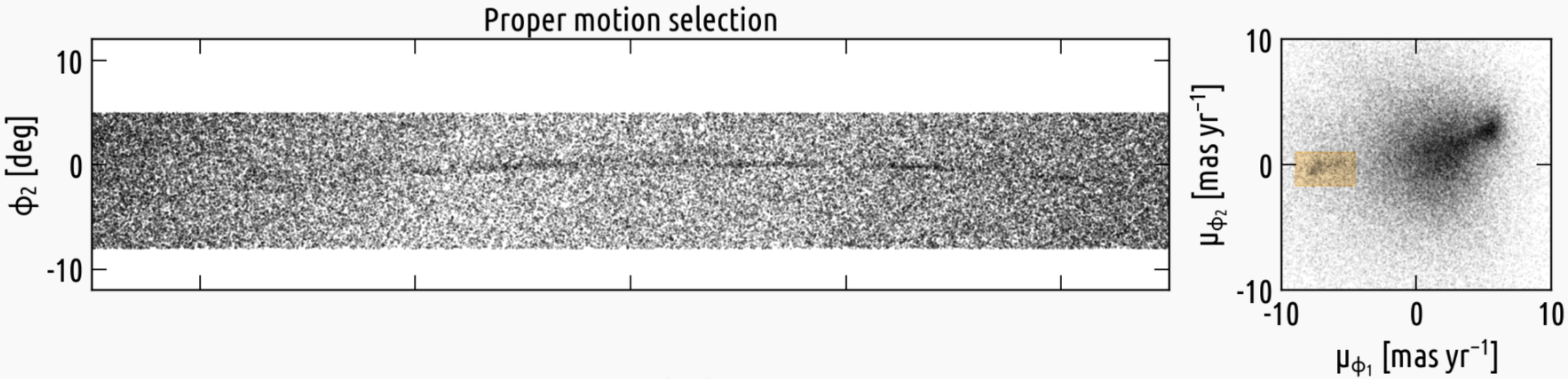

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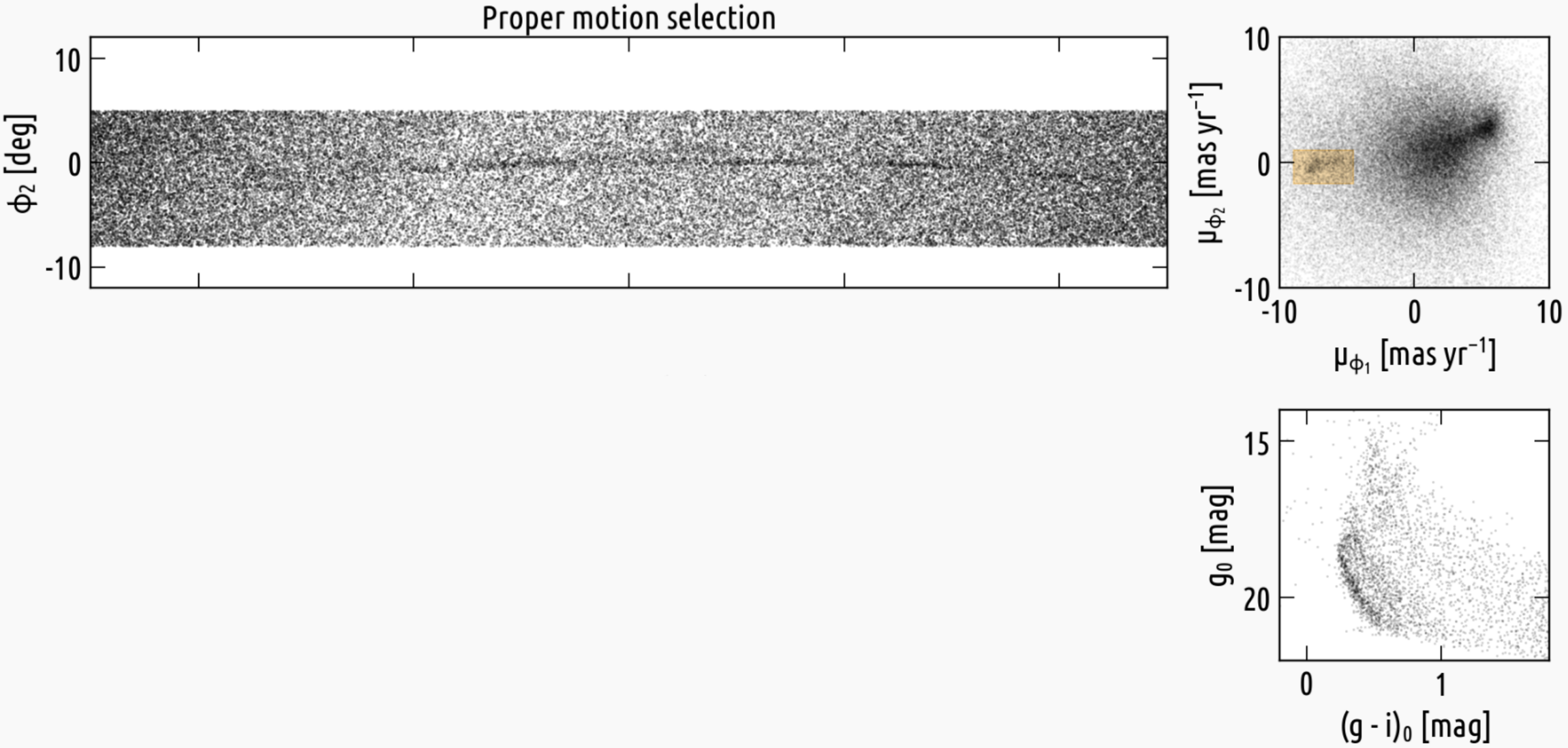

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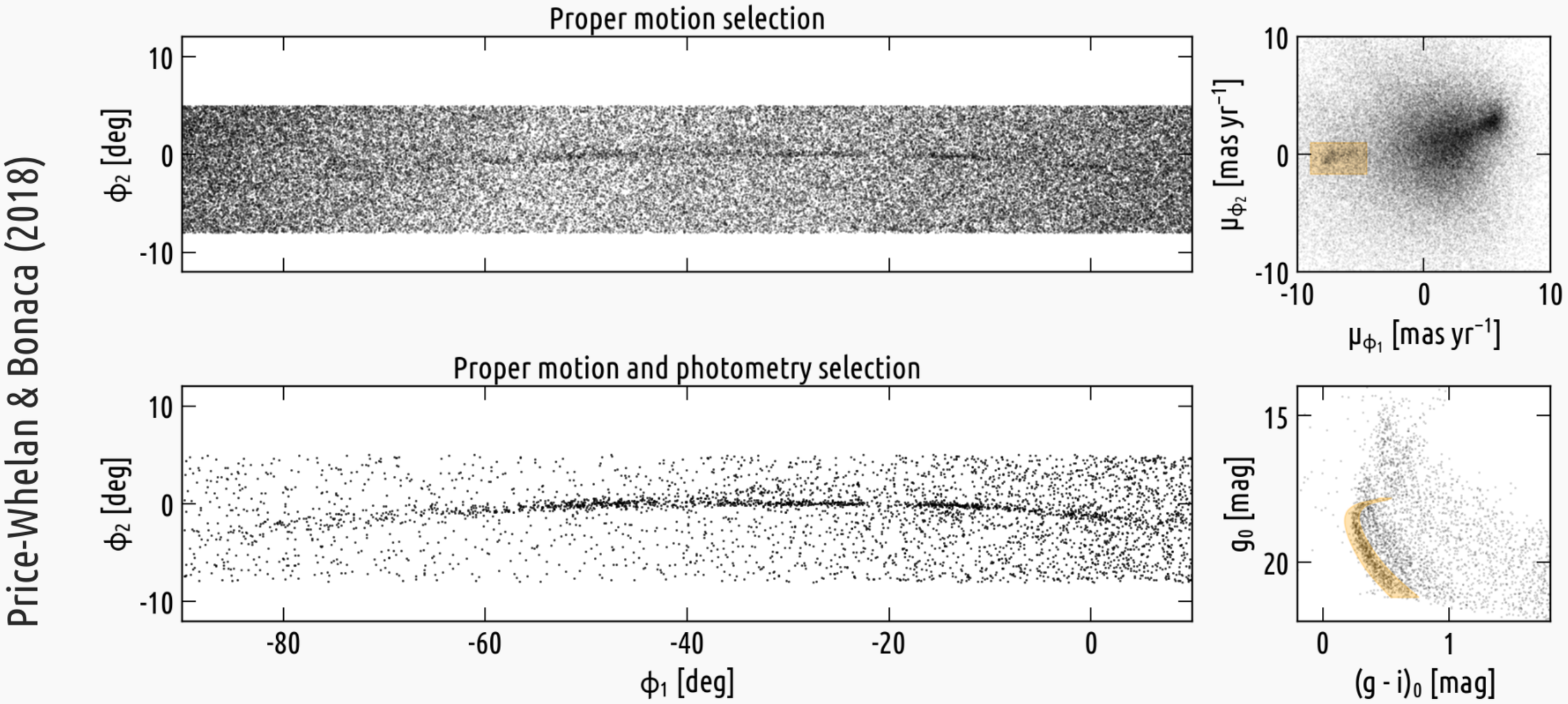

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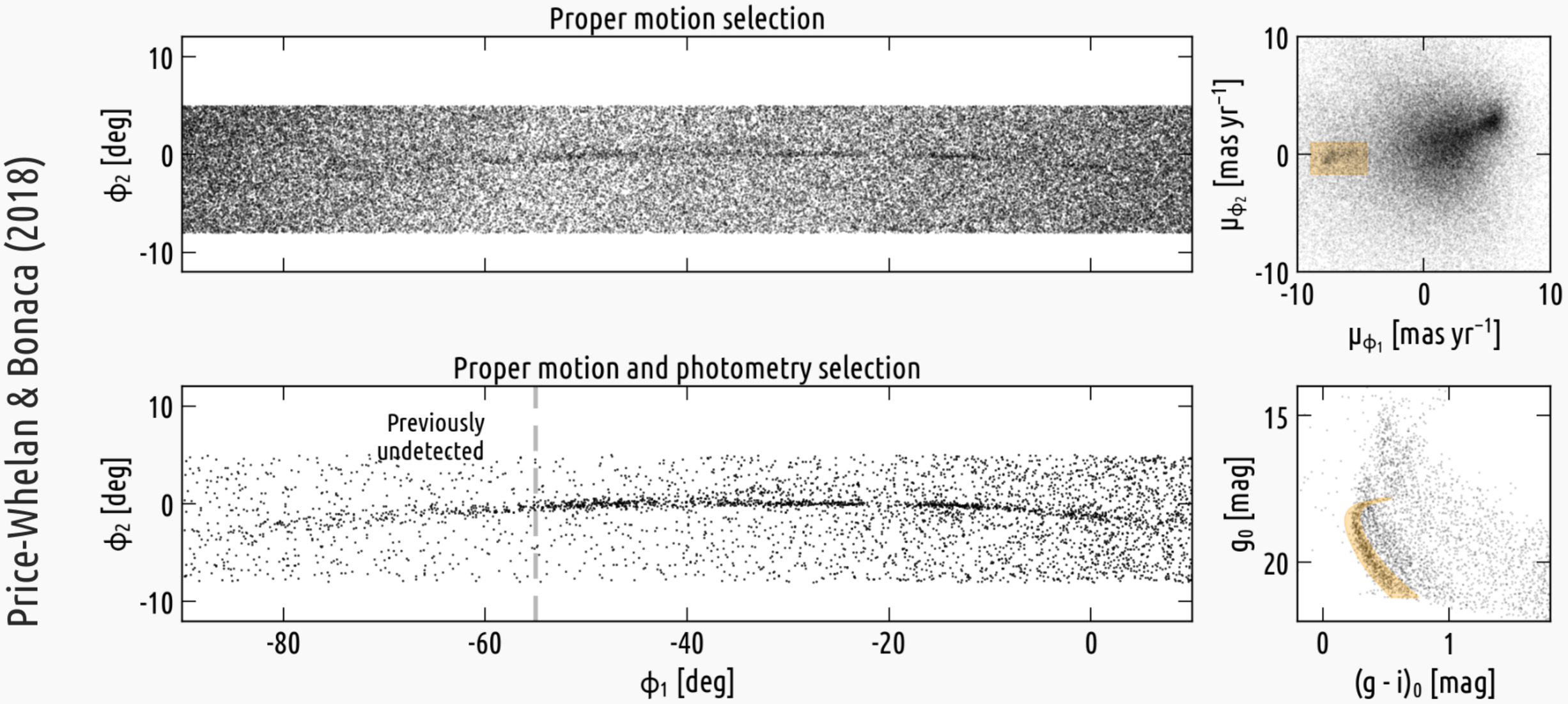

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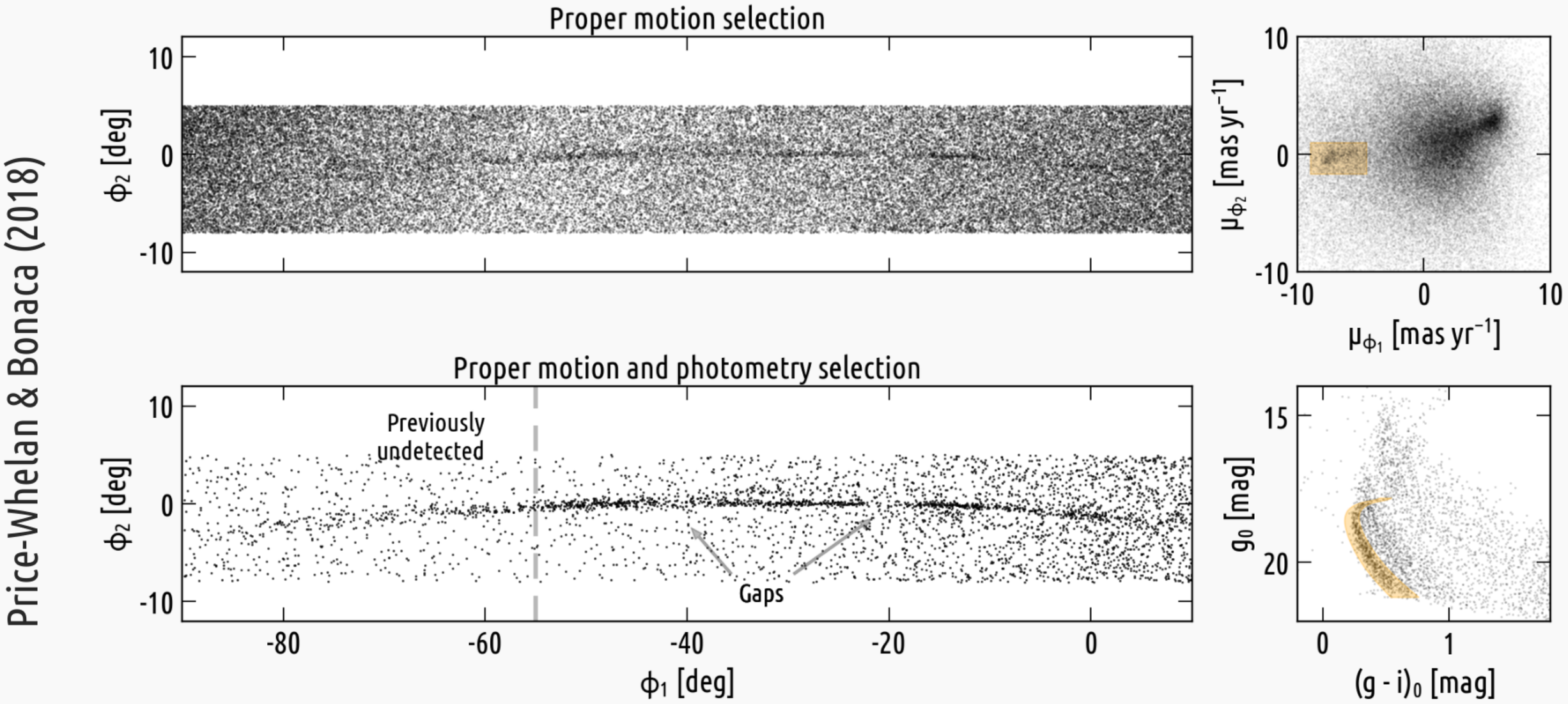

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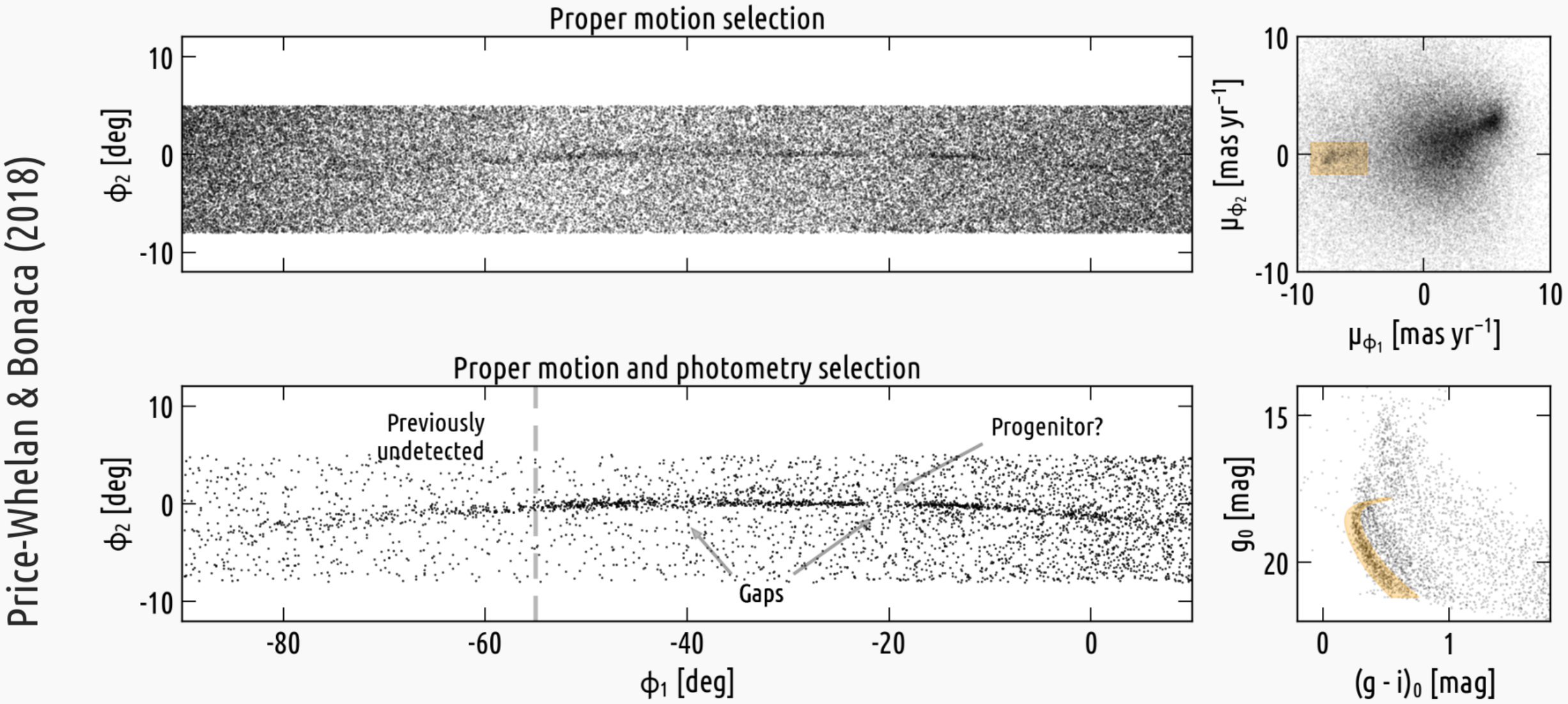

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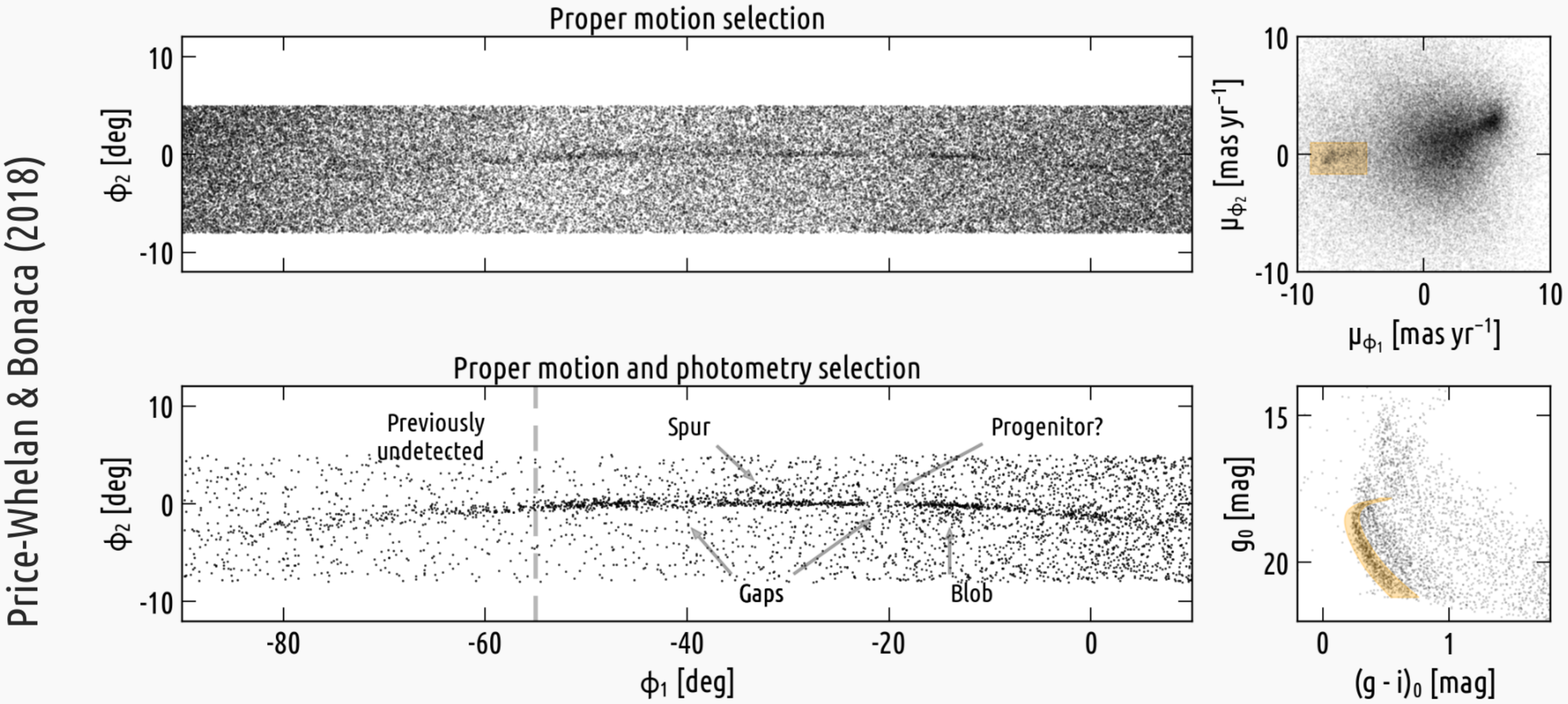
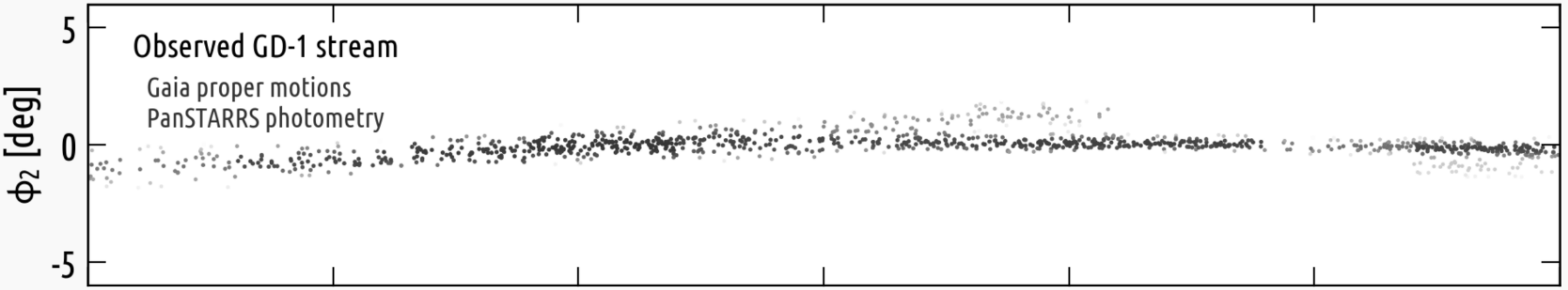


A simple model of GD-1 fails to match the observed density profile



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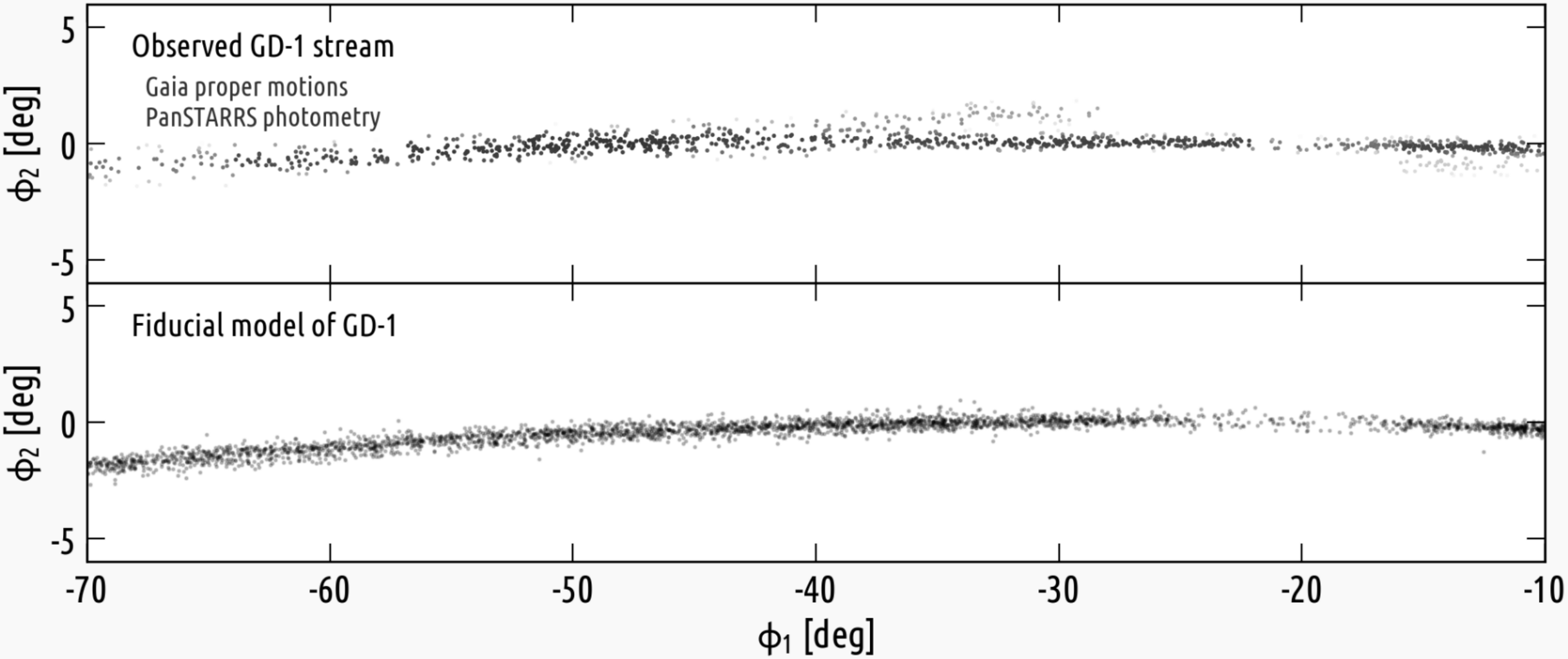
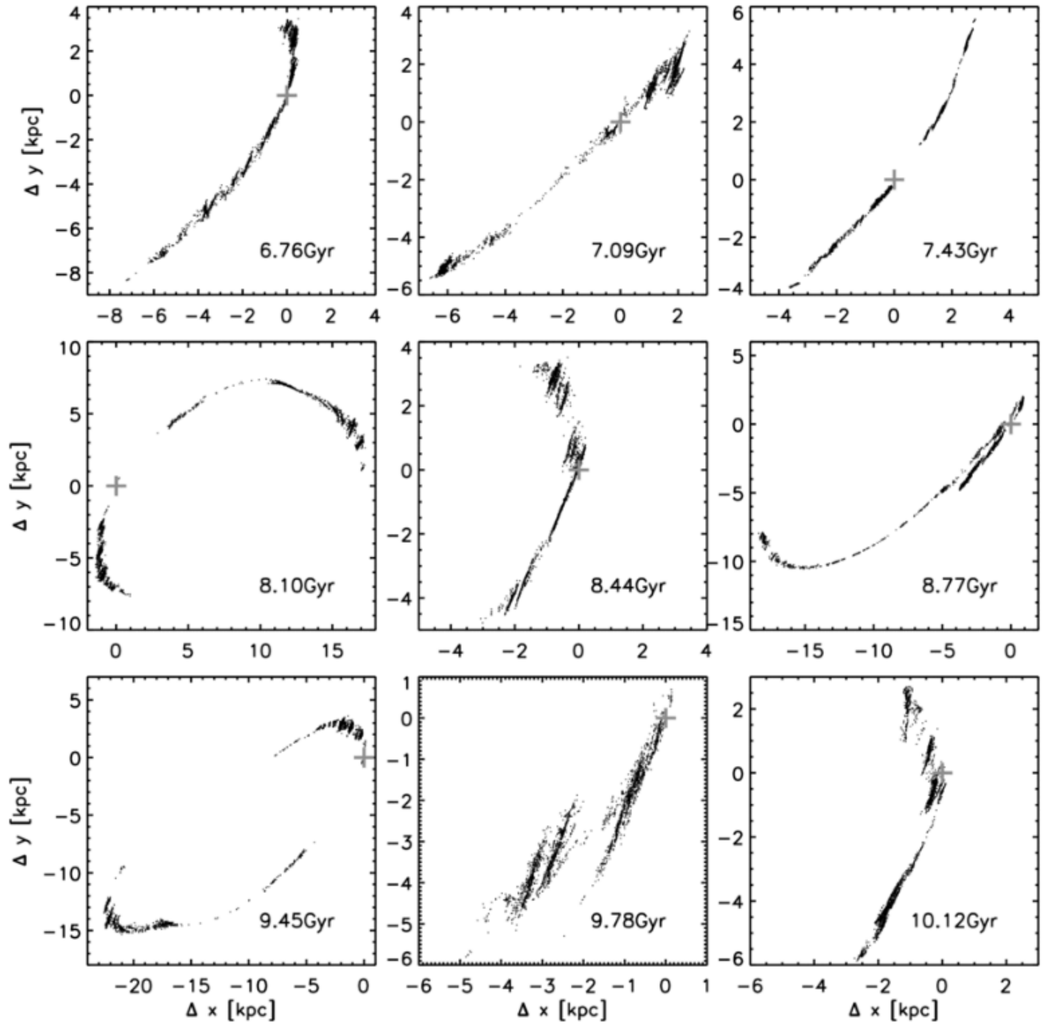


Subhalo encounters produce gaps in streams

Yoon et al. (2011)



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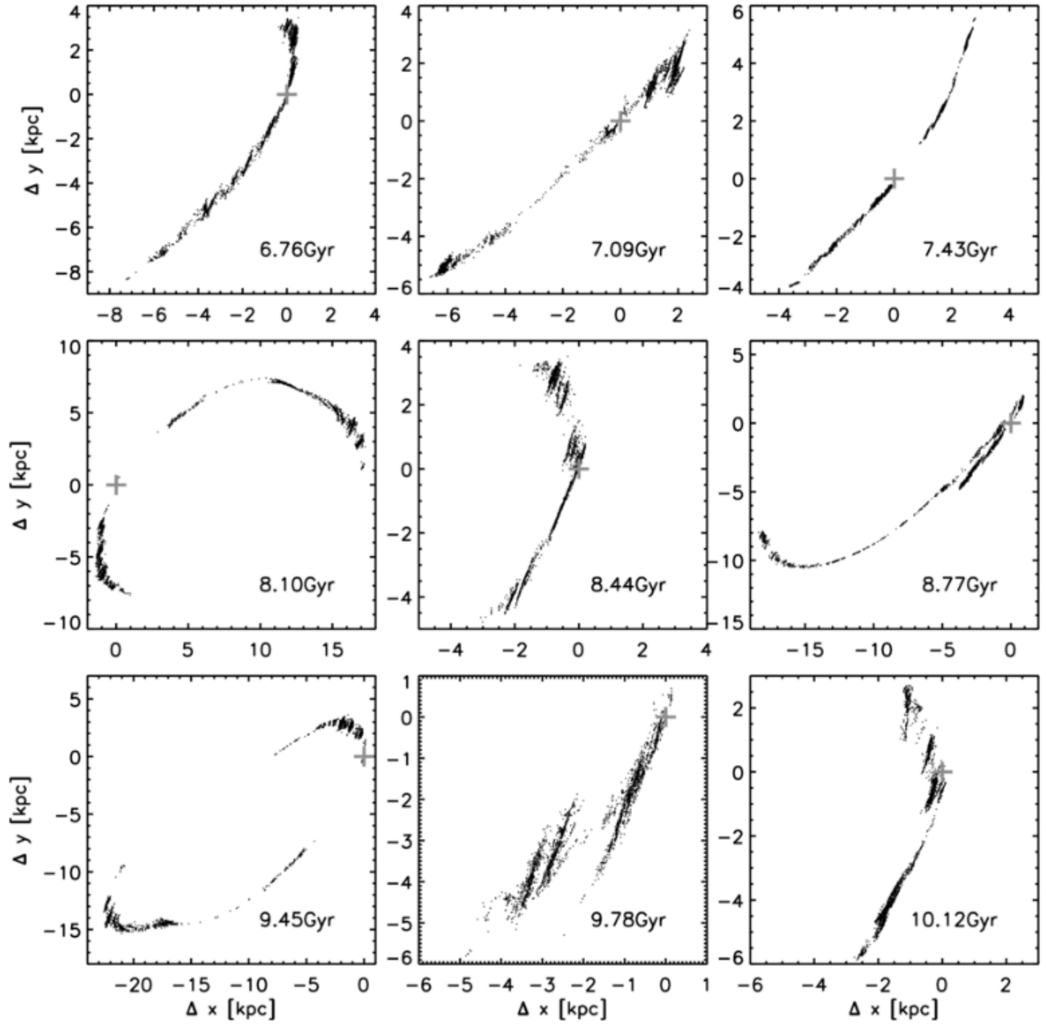
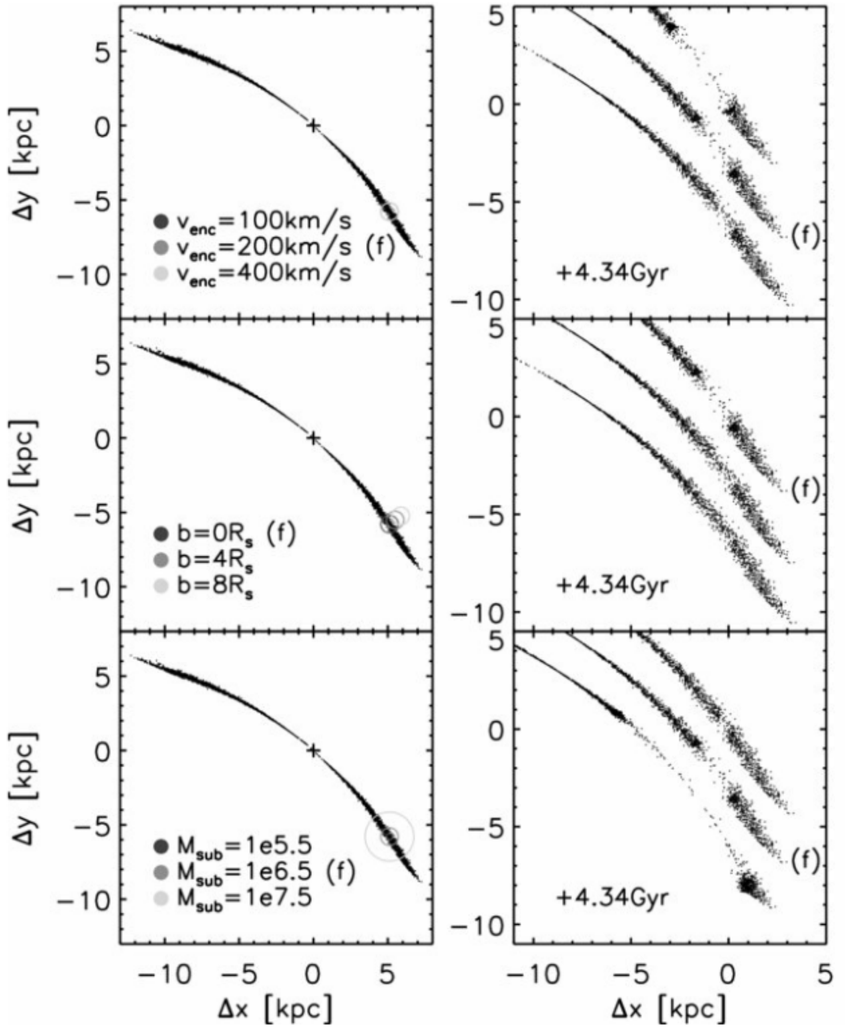
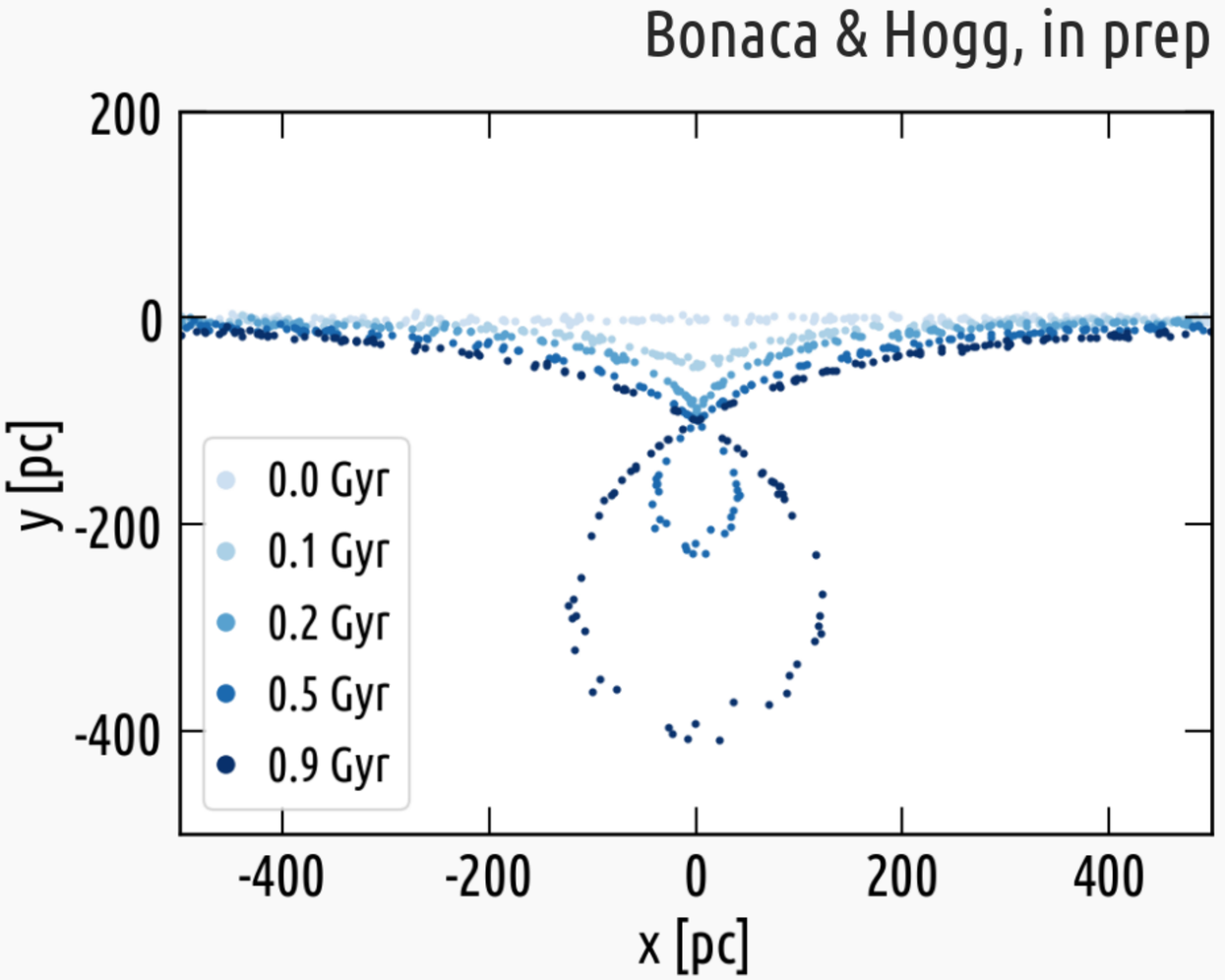




Carlberg (2009) | Carlberg (2012)
Ngan & Carlberg (2014) | Ngan et al. (2015)
Erkal & Belokurov (2015) | Ngan et al. (2016)
Erkal et al. (2016)

A massive perturber can pull stars from the stream



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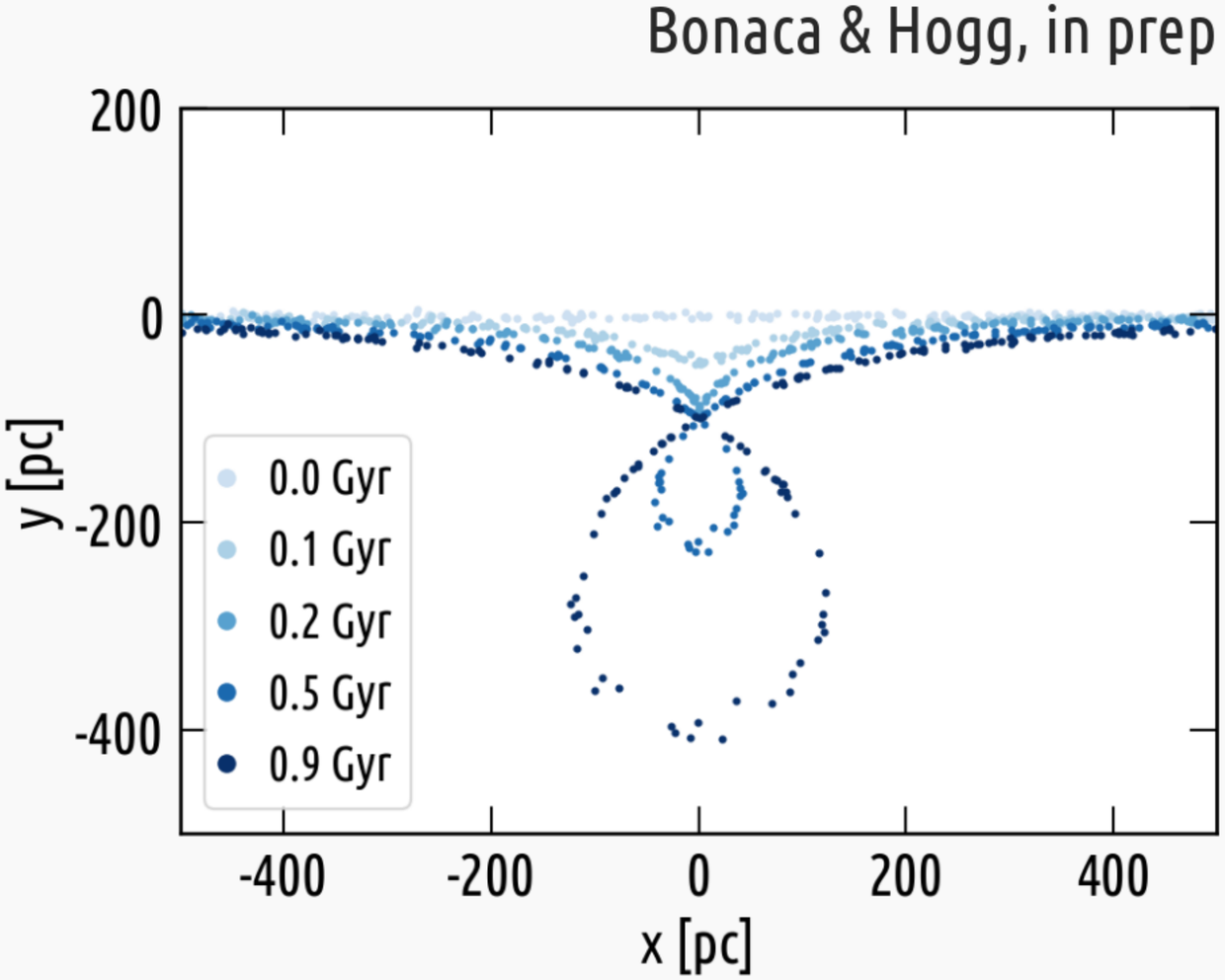

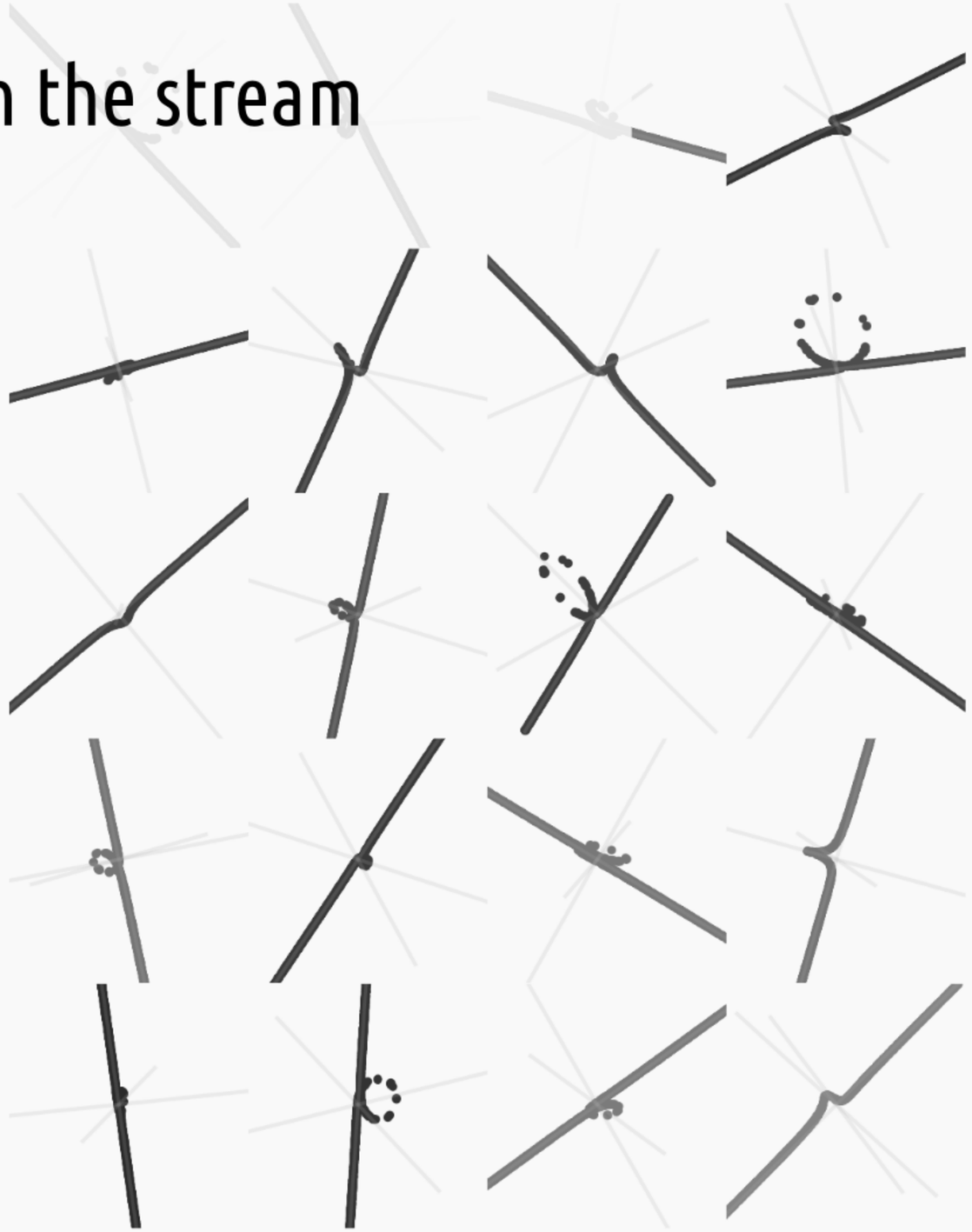

A massive perturber creates a gap in a stream orbiting the Galaxy

Subhalo perturbation
in a logarithmic potential

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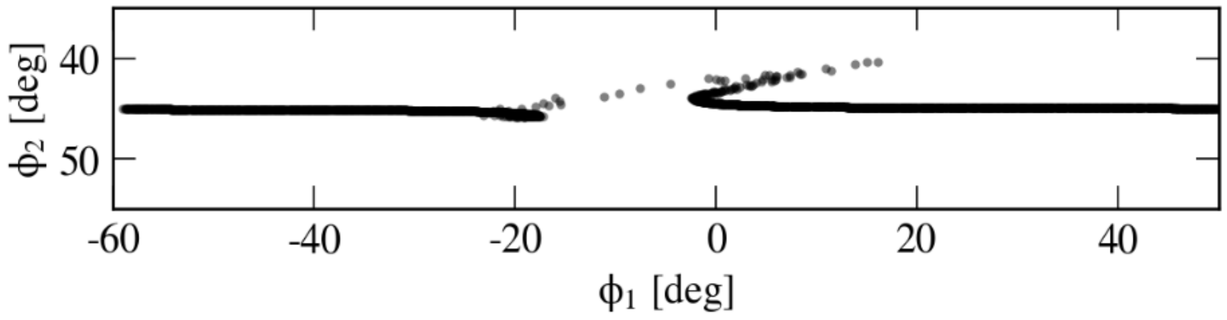
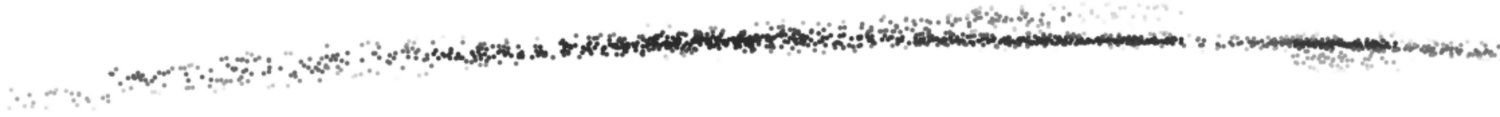
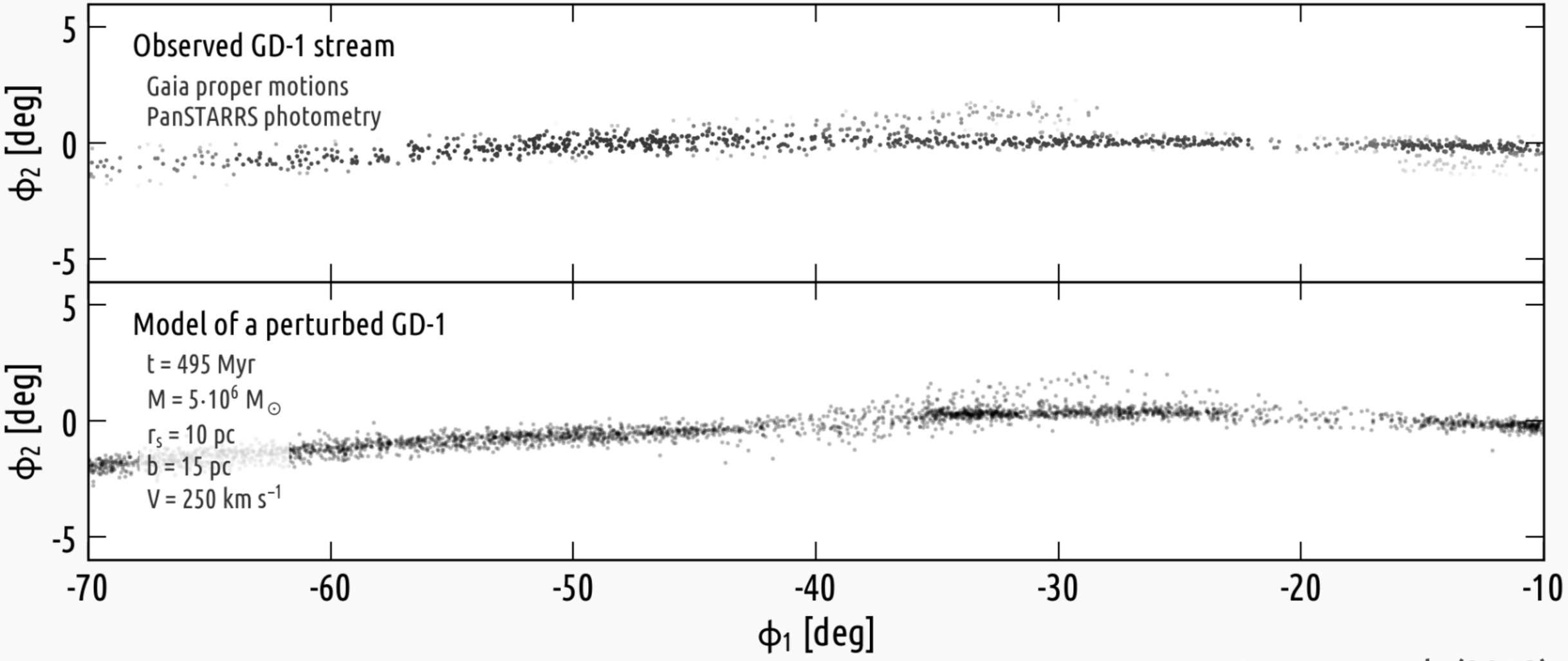


Most probable GD-1 members



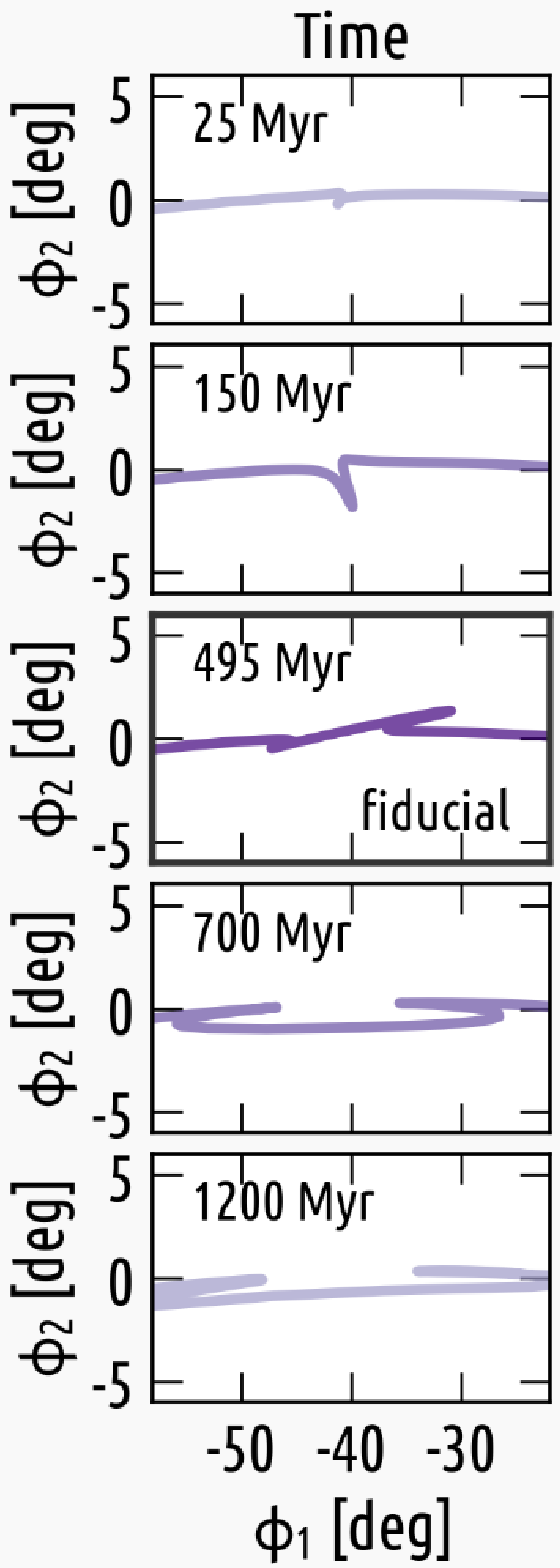
Realistic GD-1 encounter scenario

Encounter qualitatively accounts for all features observed in GD-1



Bonaca et al. (2019)

Stream morphology constrains the encounter parameters



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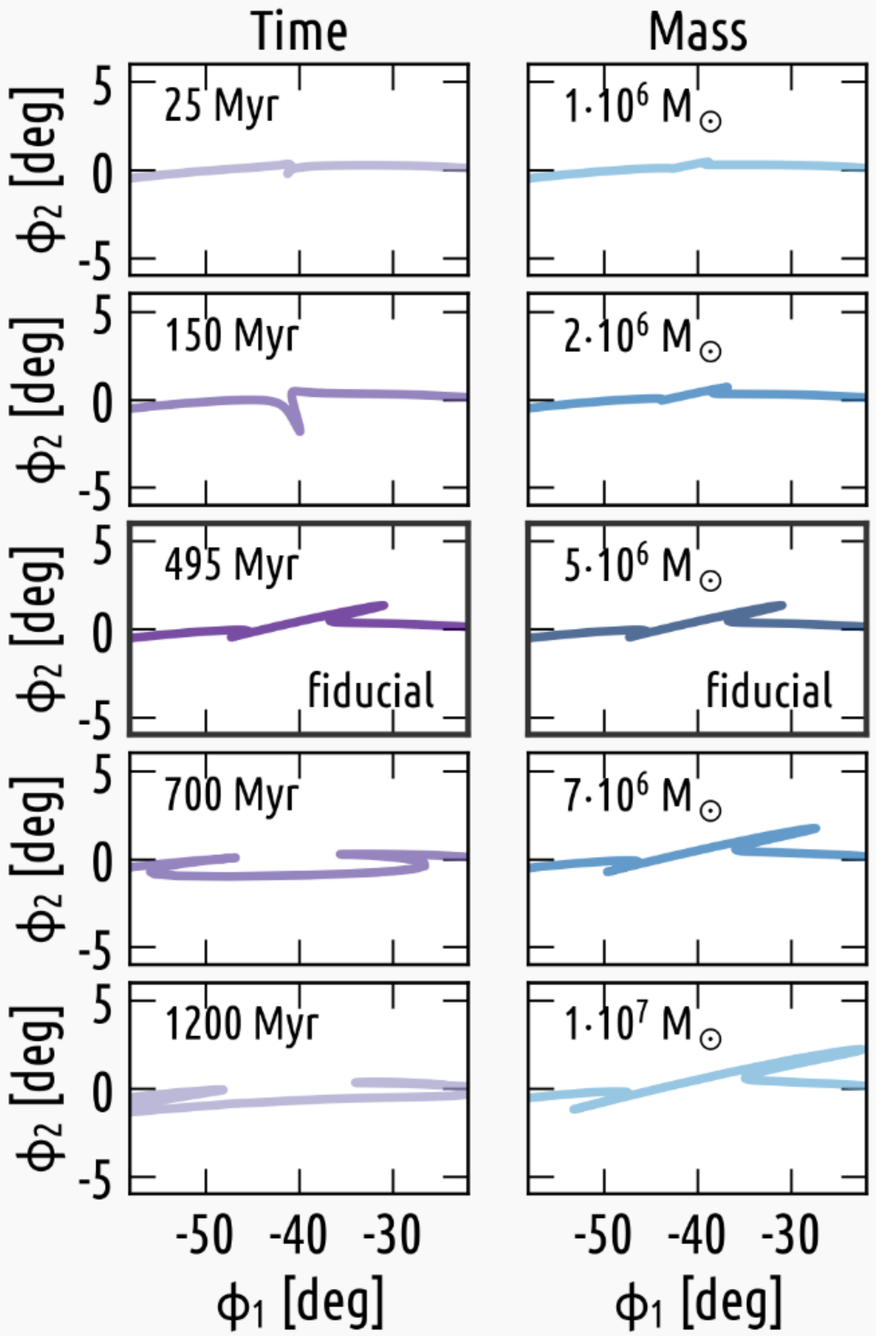

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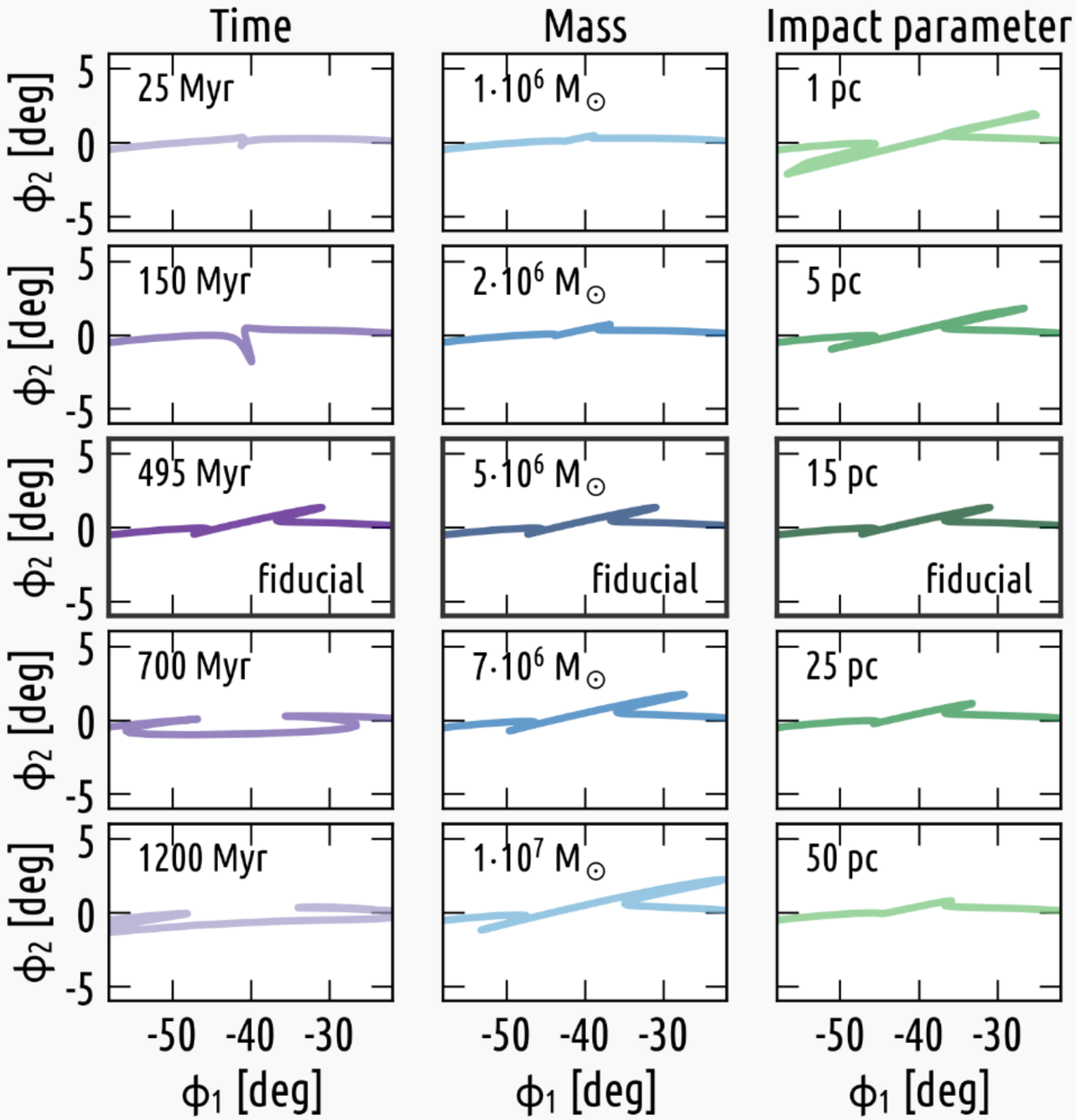

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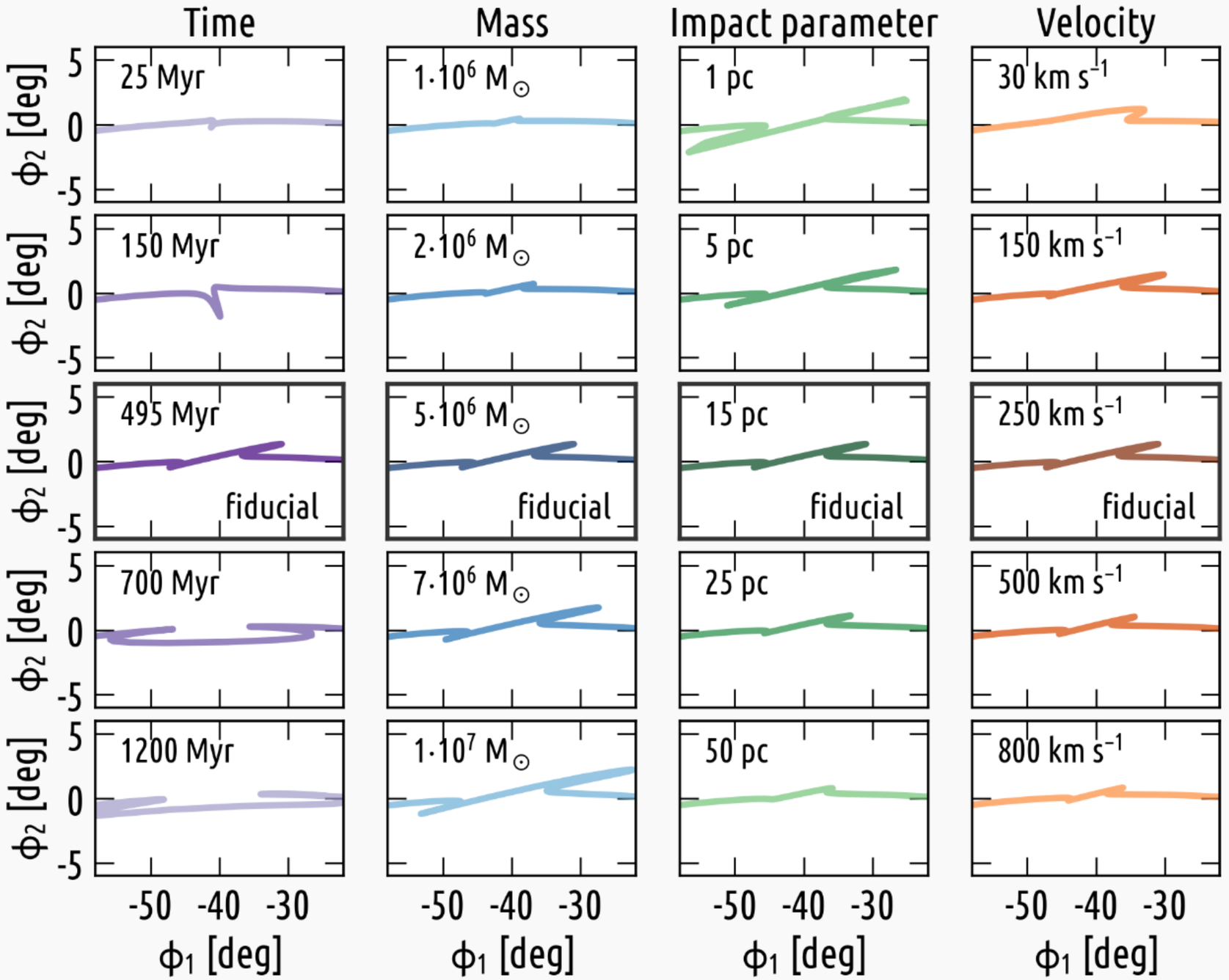

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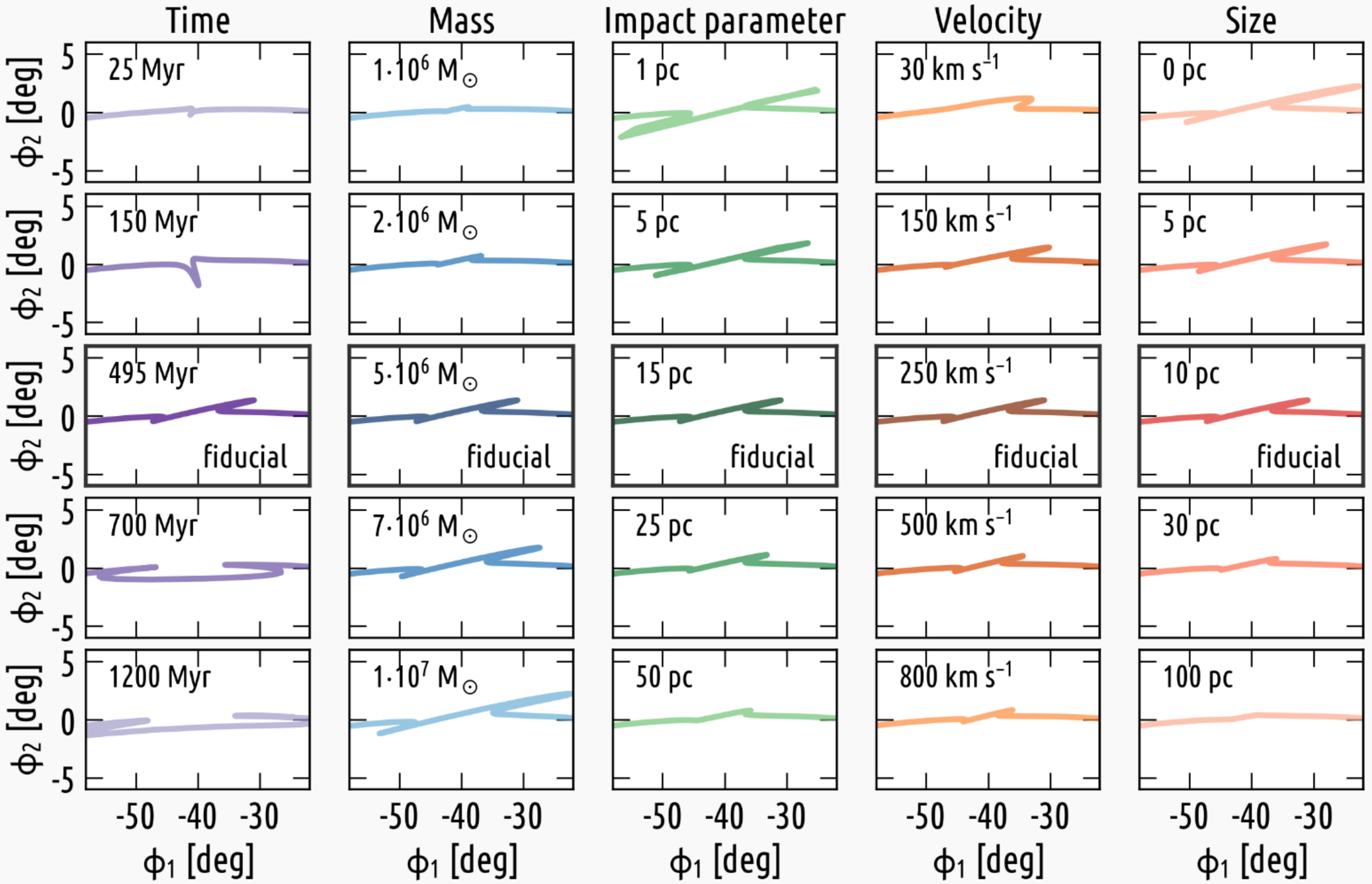
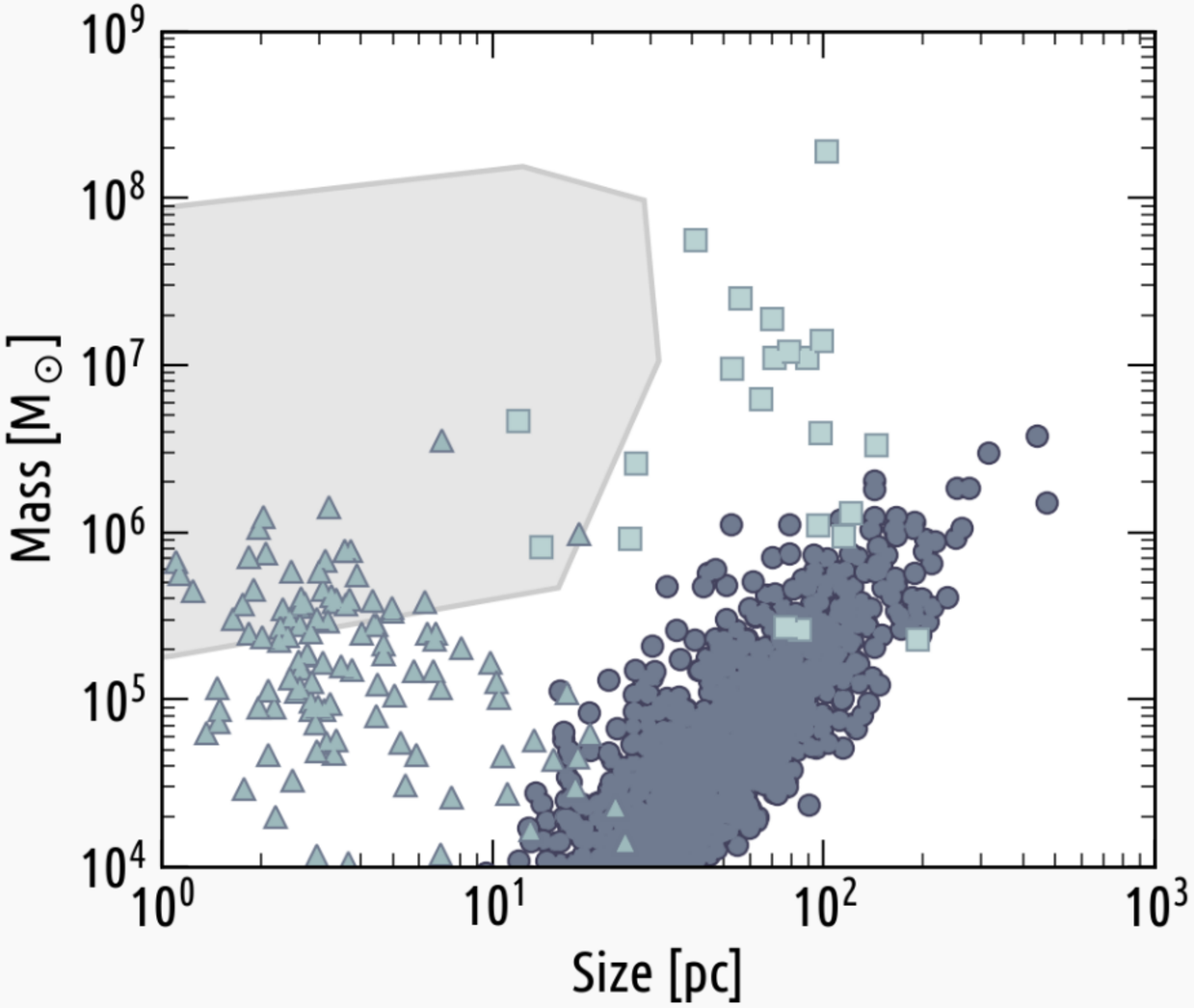


Dark matter subhalo is a plausible perturber of GD-1



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)

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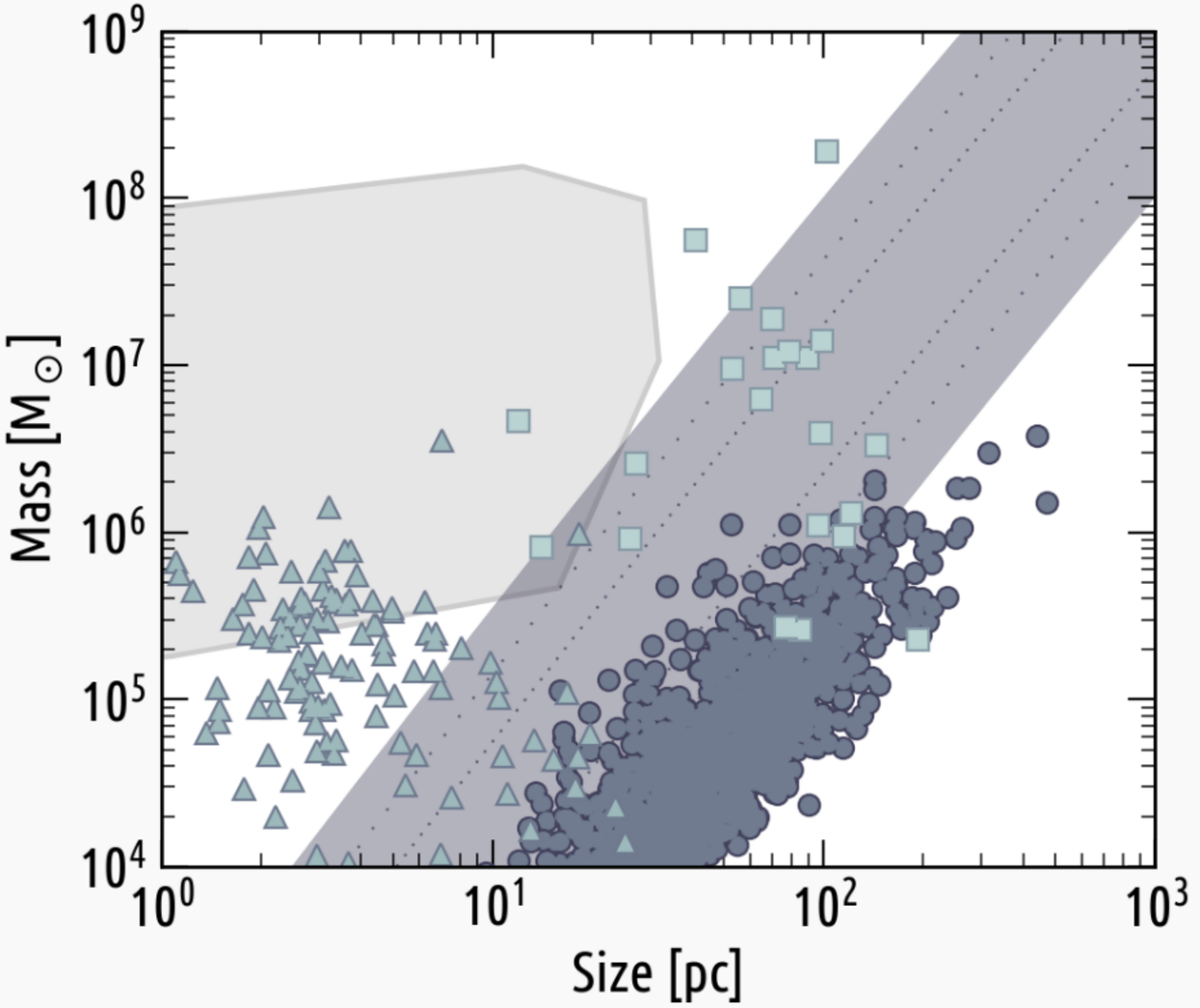

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ΛCDM subhalos (3 σ scatter)
(Moliné et al. 2017)

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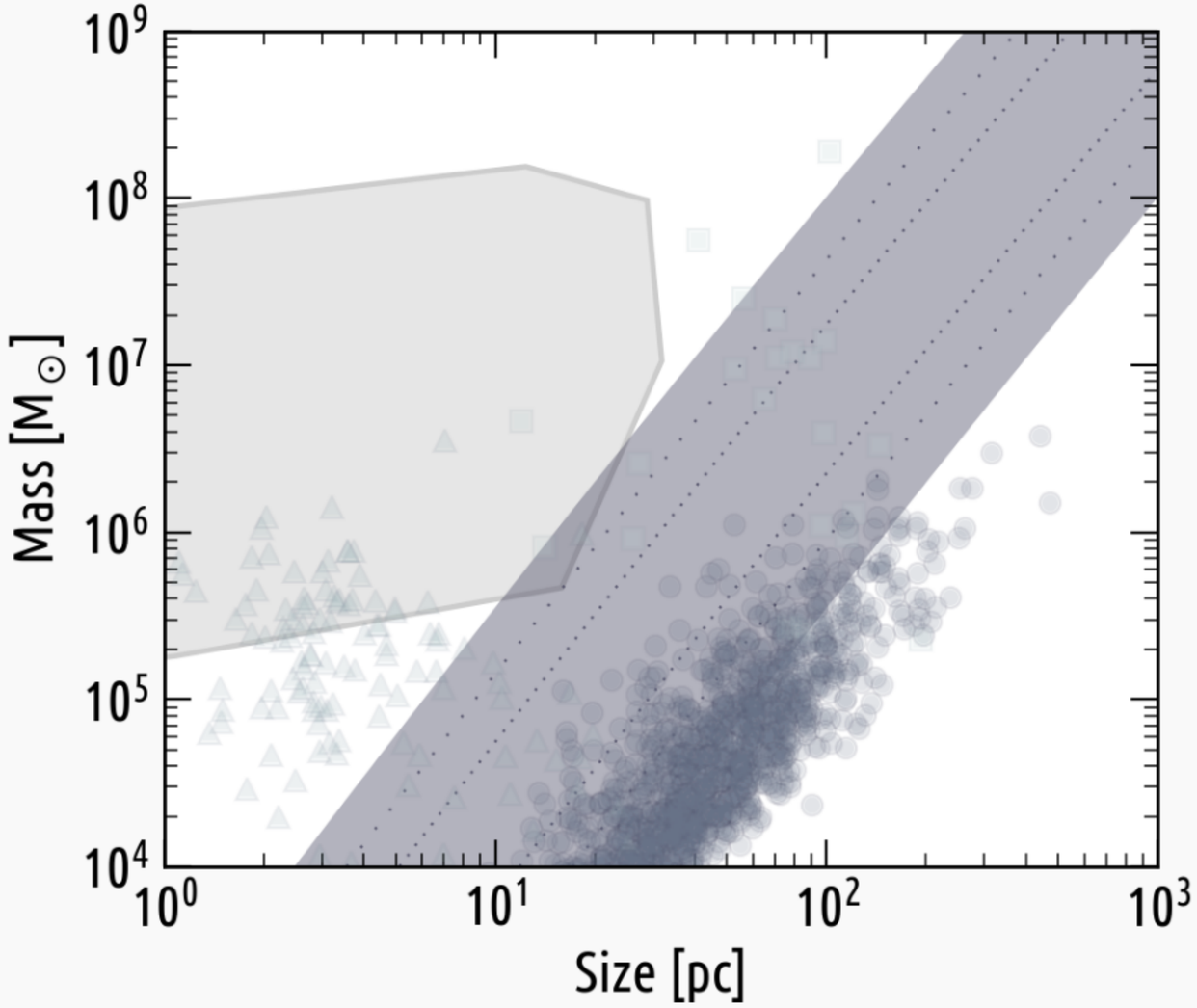

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(Miville-Deschênes et al. 2017)

Globular clusters
(Baumgardt & Hilker 2018)

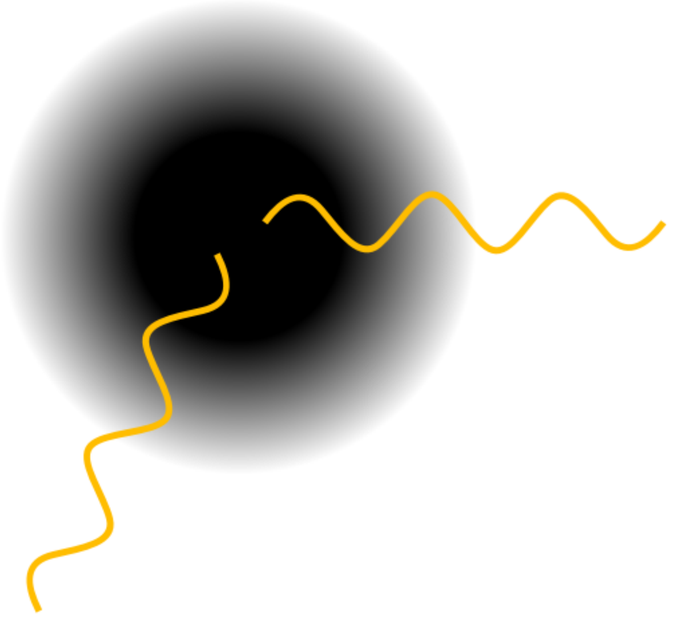
Dwarf galaxies
(McConnachie 2012)

Inconsistent orbits

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

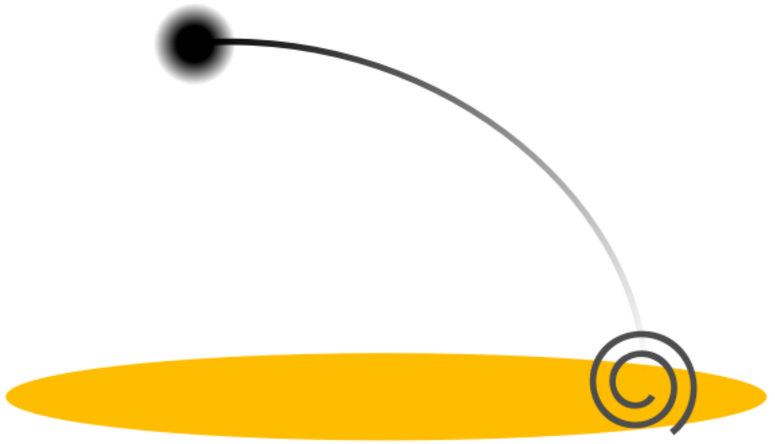
Additional signatures of the hypothetical perturber:

Annihilation



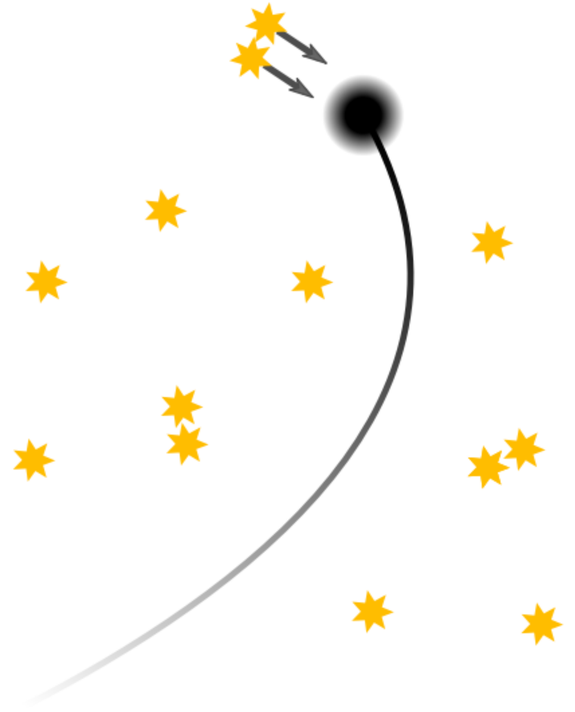
(e.g., Albert et al. 2017)

Disk disturbances



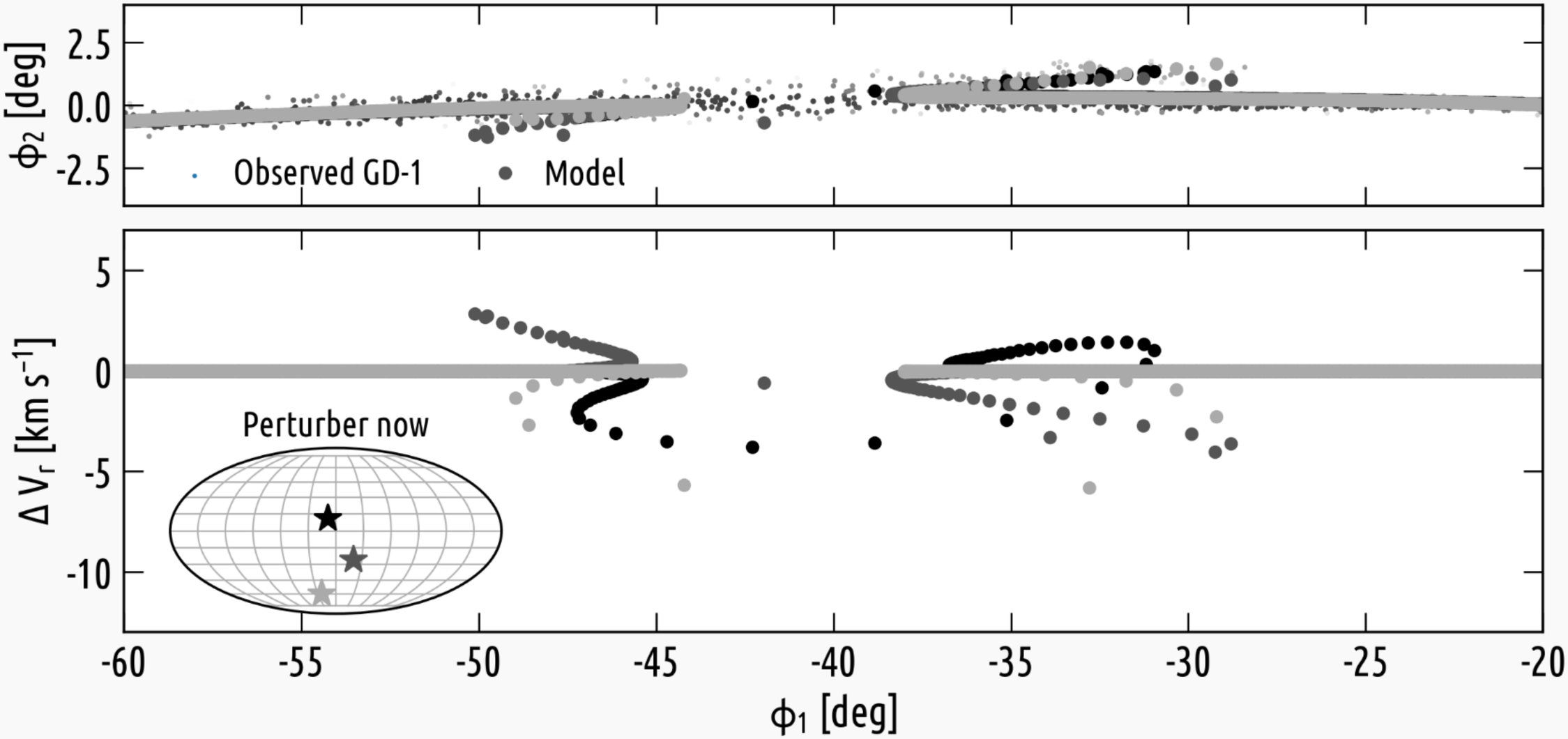
(e.g., Antoja et al. 2018)

Perturbations of halo stars



(e.g., van Tilburg et al. 2018)

Radial velocities can constrain the orbit of the GD-1 perturber



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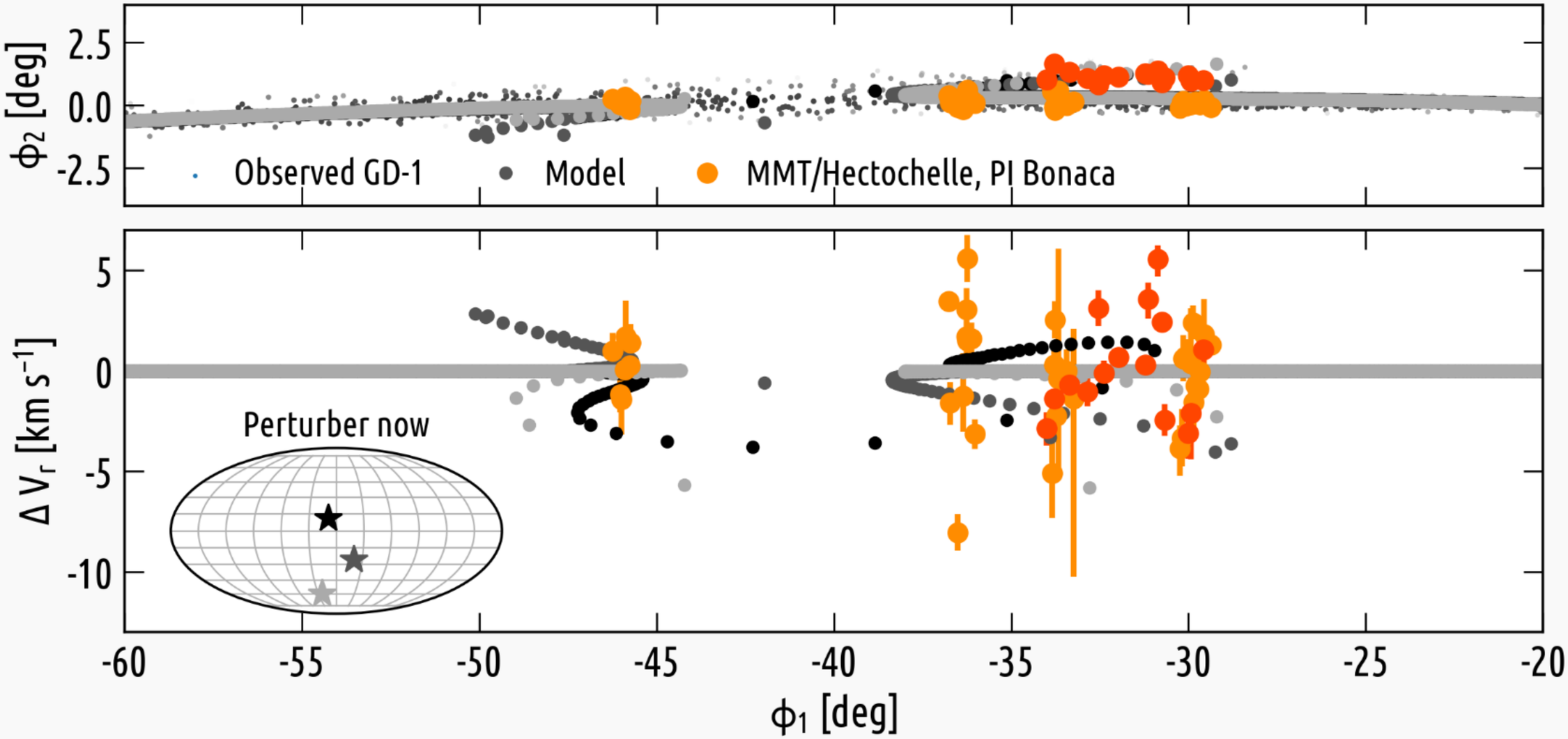
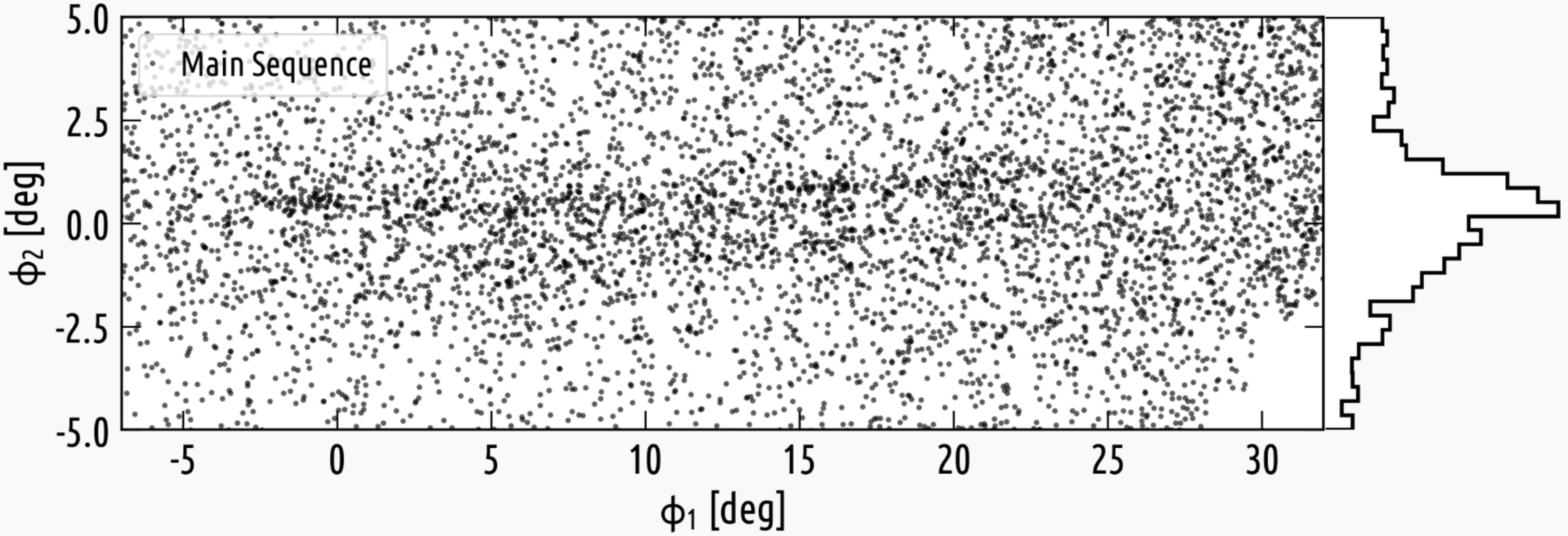


Gaia reveals two distinct components in the thin Jhelum stream

Bonaca et al. arXiv:1906.02748



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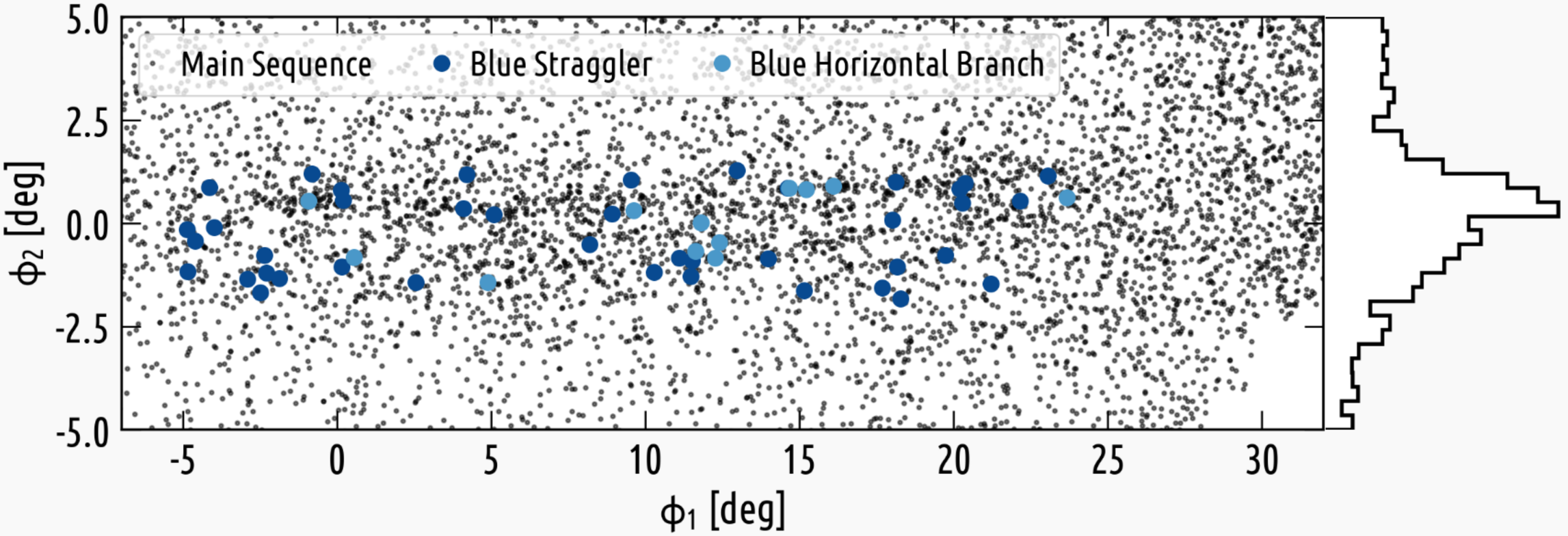
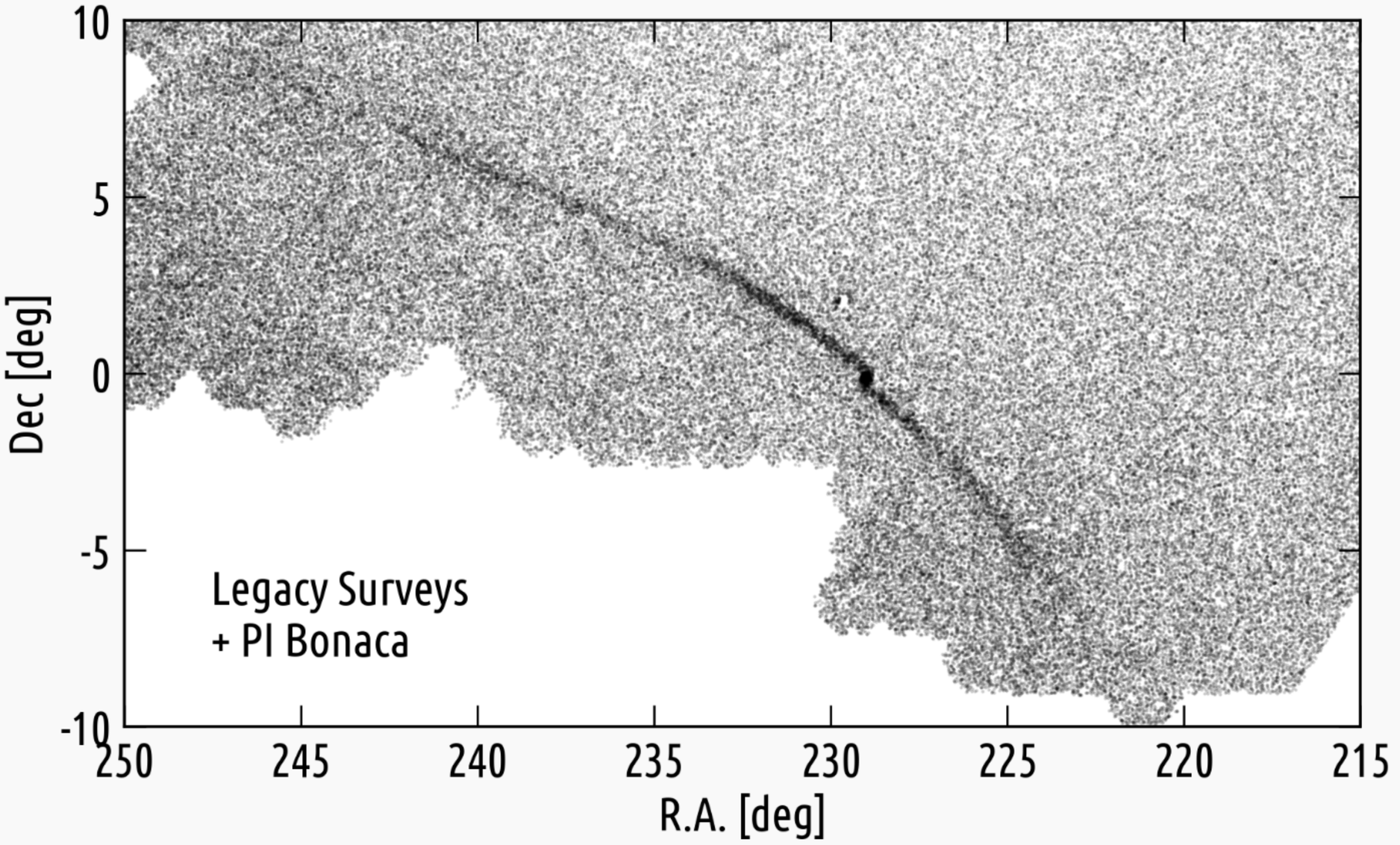


Signature of a globular disruption in a dark matter subhalo?
(Penarrubia et al. 2017, Carlberg 2018)

Deep photometry highlights the asymmetry in Palomar 5 tails



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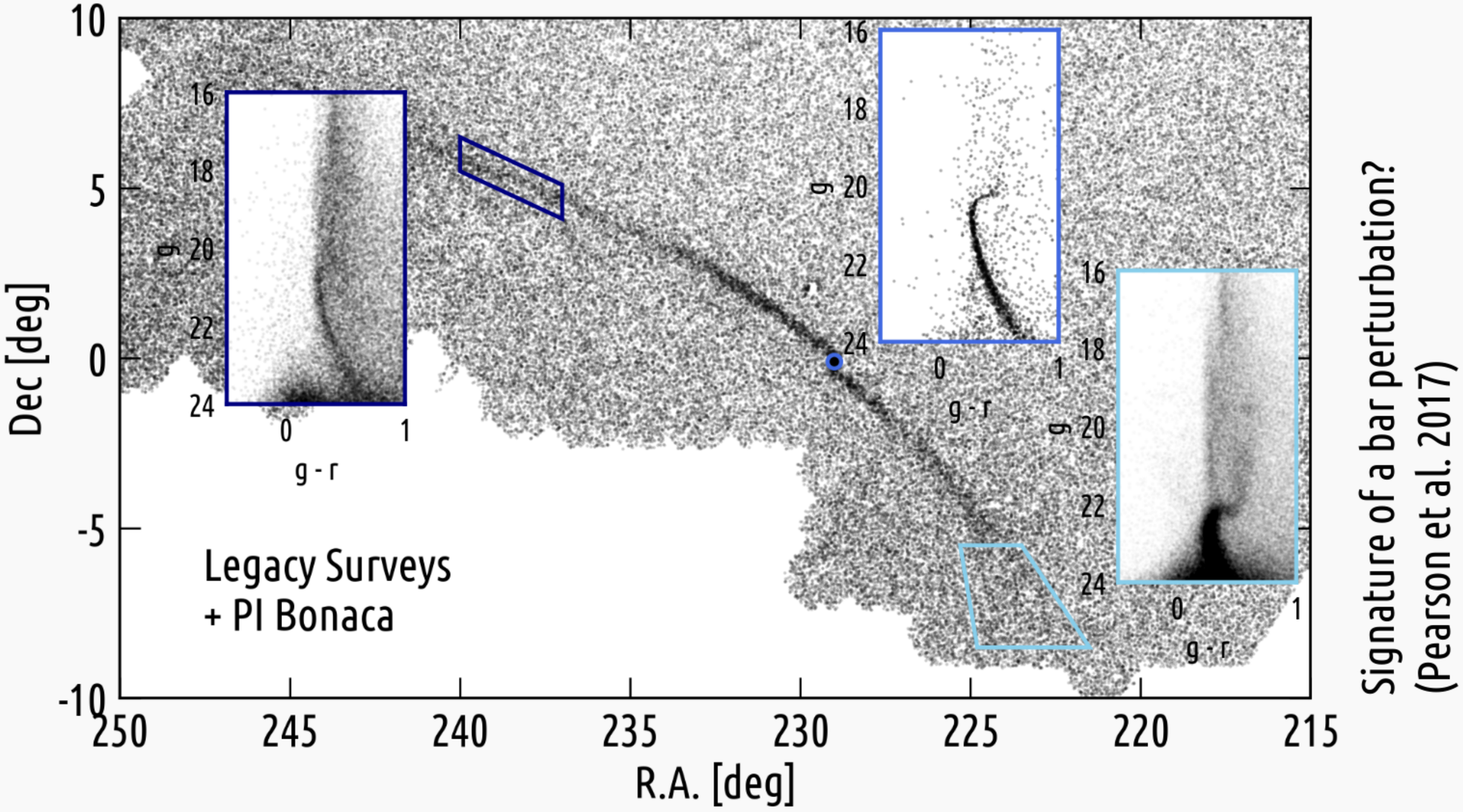
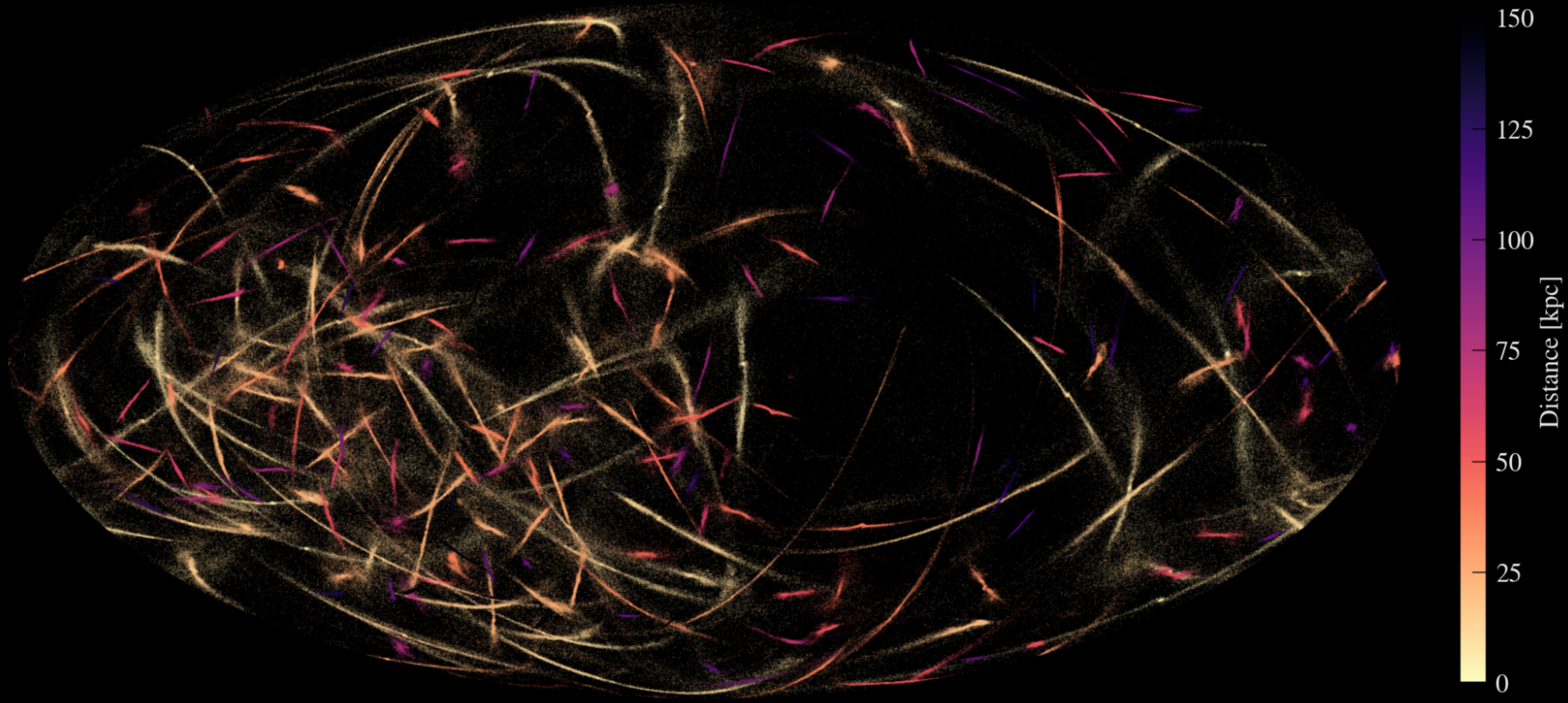


The next generation of photometric surveys will confidently reveal streams throughout the Milky Way



$g_{lim} = 27.4$

Nature of dark matter with tidal streams in the Milky Way

GD-1

#1 Stream gap and members observed beyond the main GD-1 stream can be explained by a recent encounter with a massive, dense perturber.

Price-Whelan & Bonaca (2018)
Bonaca et al. (2019)

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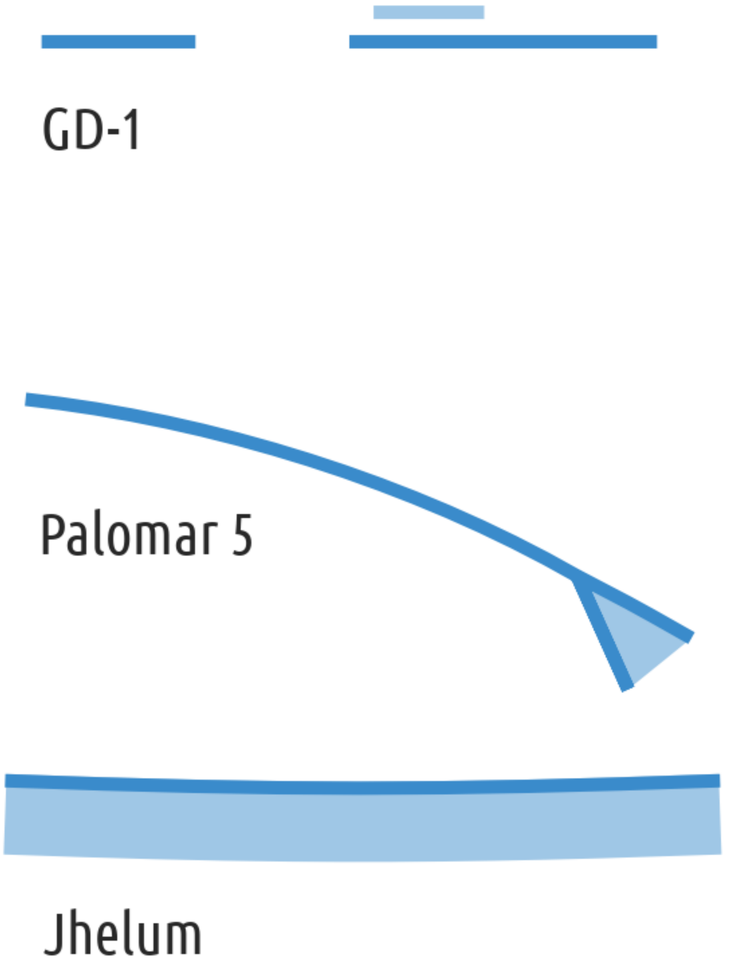

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Bonaca et al. (2019)

#2 Detailed modeling of all stellar streams in the Milky Way will constrain the amount of sub-structure in our dark matter halo.

Bonaca et al. 1906.02748

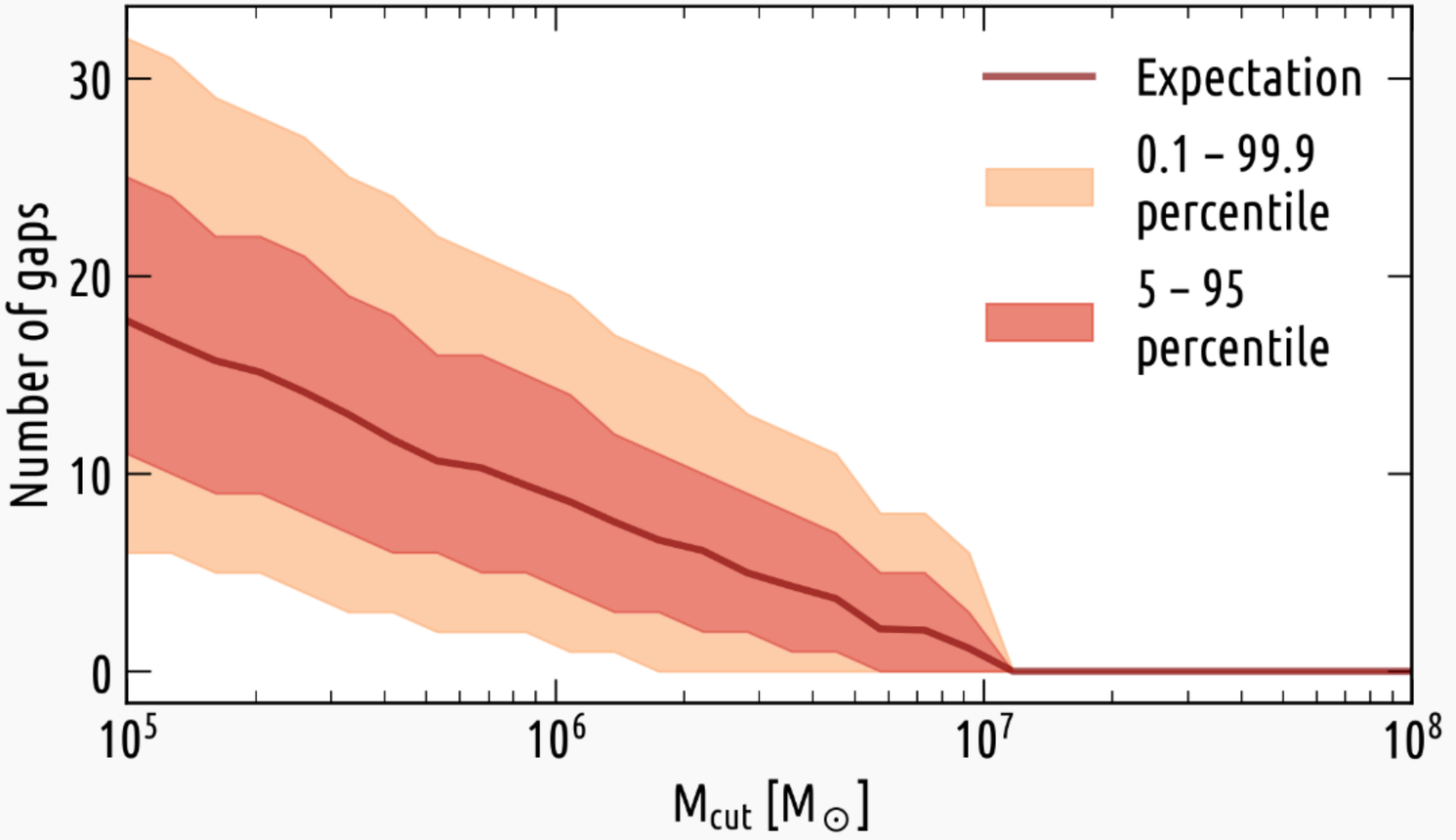
Gap counts in the LSST era will constrain the nature of dark matter

streams in the LSST footprint:
13 known (Shipp et al. 2018)

dynamical age: 8 Gyr

subhalo encounter rates:
N-body (Erkal et al. 2016)

minimum detectable subhalo:
$\gtrsim 10^5\,\mathrm{M}_\odot$



Drlica-Wagner, Mao, ..., Bonaca, ... arXiv:1902.01055

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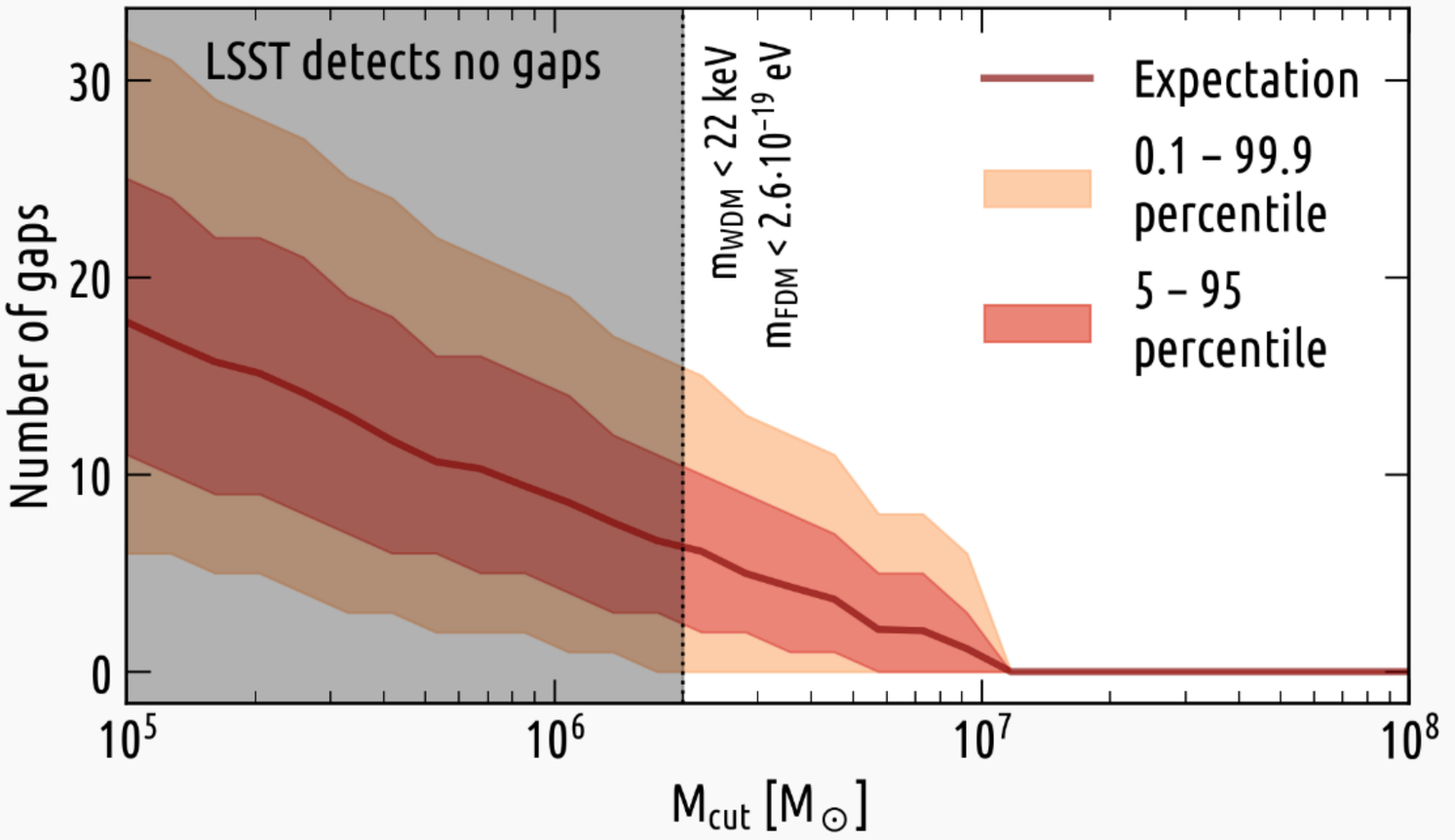

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