A detailed look at the GD-1 stream:

observed characteristics

Adrian Price-Whelan

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+ Ana Bonaca, Cecilia Mateu

A detailed look at the GD-1 stream:

a weather report from the Galactic halo

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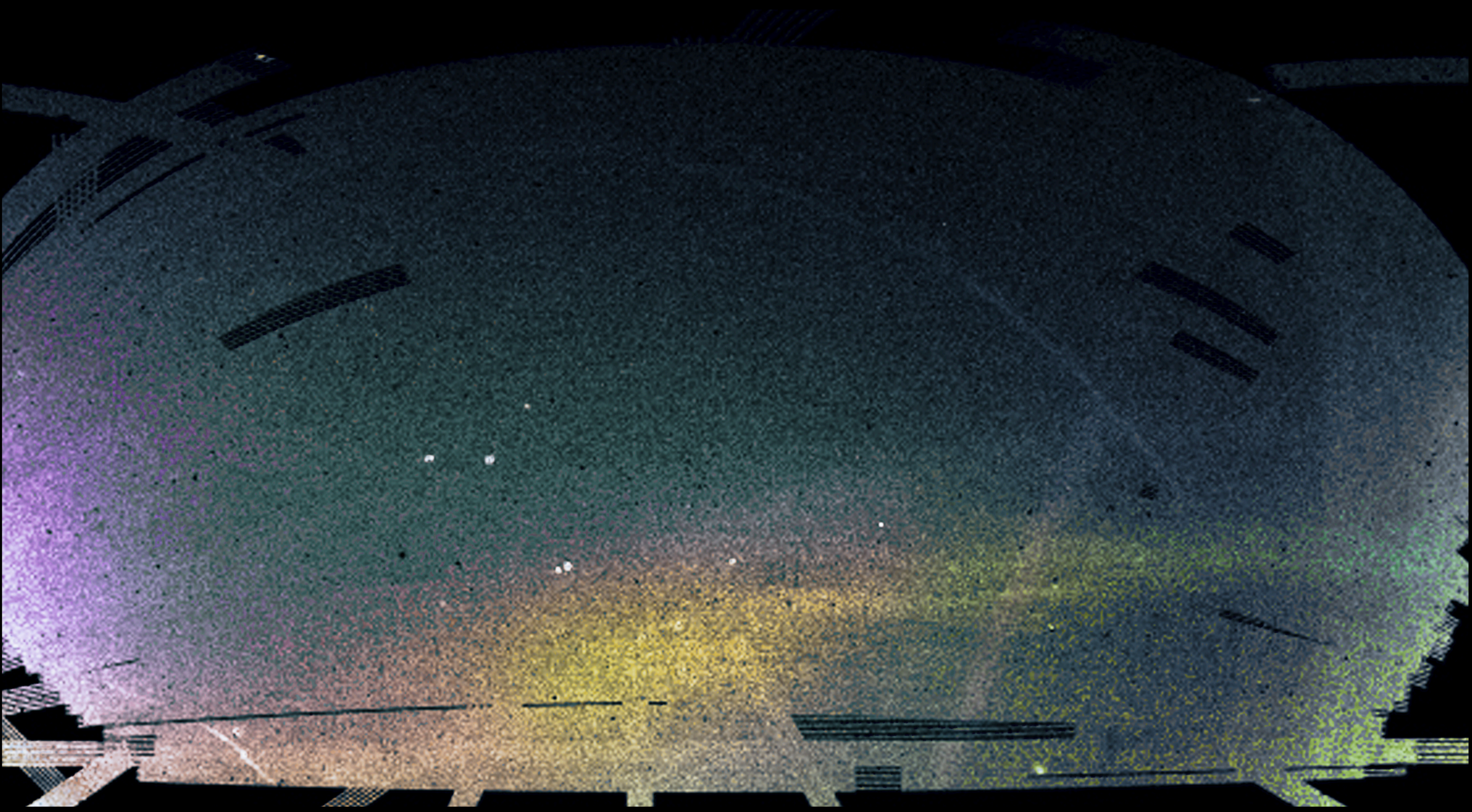
the field of streams



Data: SDSS

Bonaca et al. 2012

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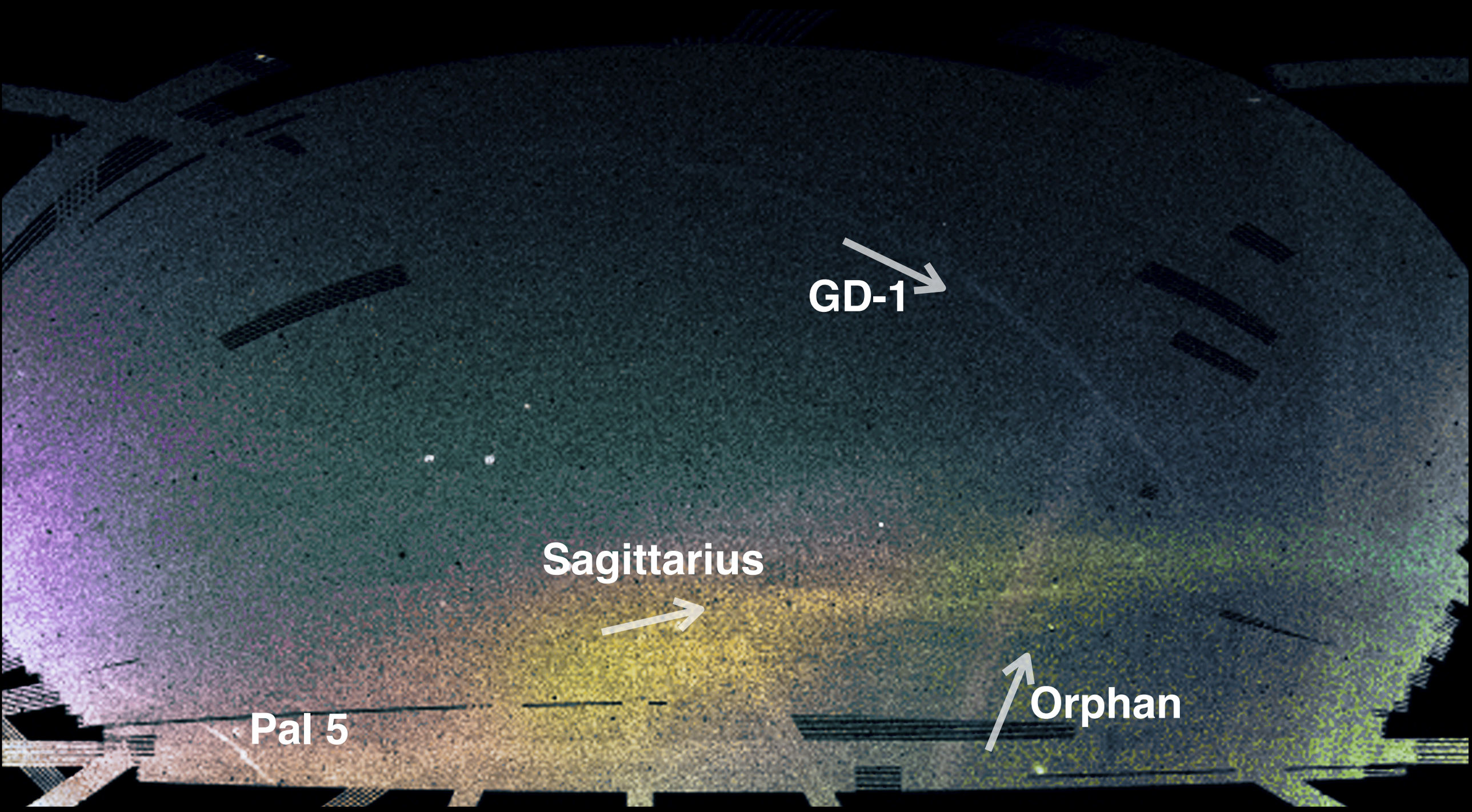


Data: SDSS

Bonaca et al. 2012

Properties of known streams

~30–60 known

Metal poor: [Fe/H] < -1

Width: ~50pc (globular cluster) to few kpc (Orphan / Sag)

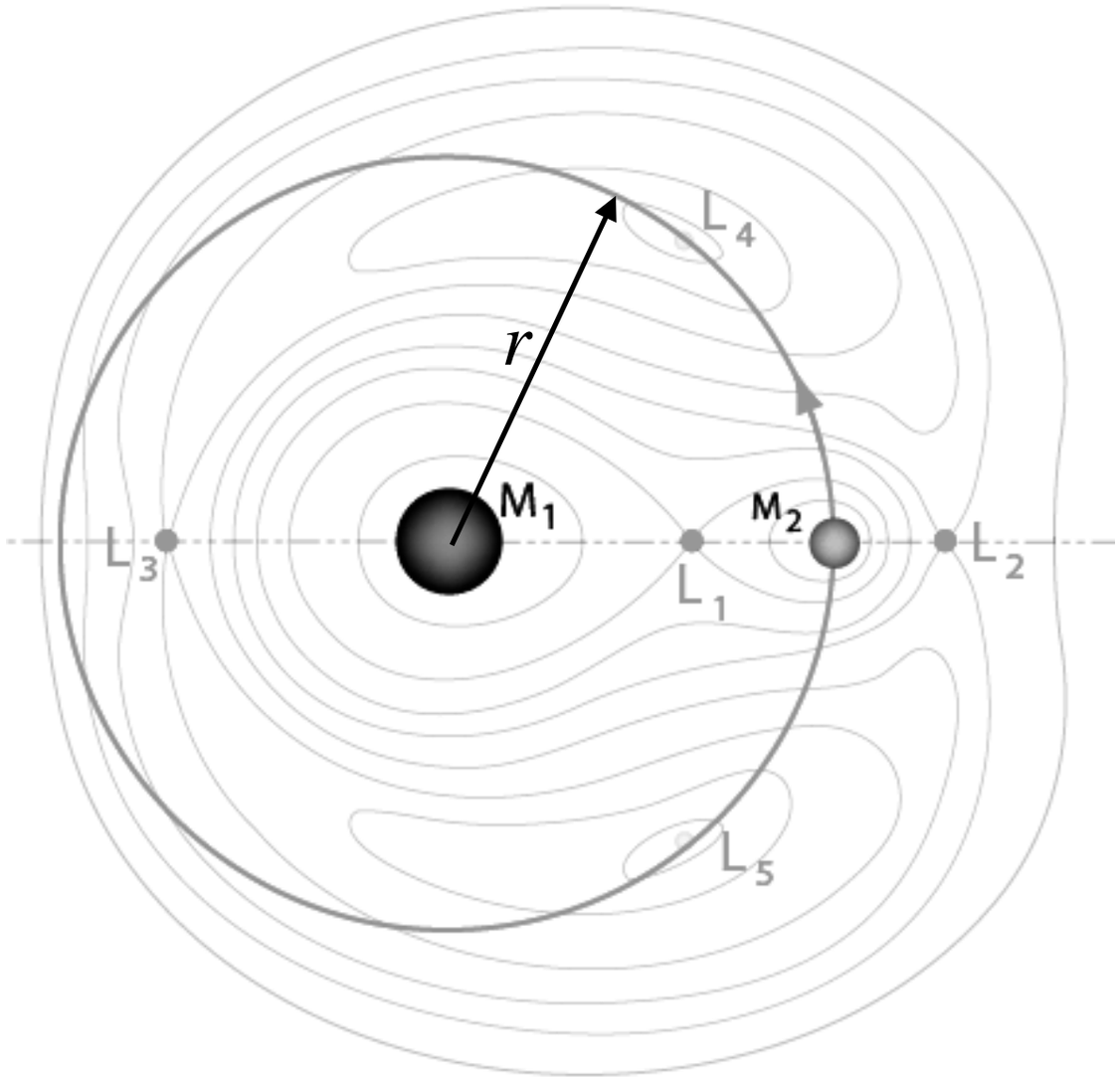
Length: ~kpc to 10 kpc (GD-1) to >100 kpc (Orphan / Sag)

Most found in the stellar halo (~5–100 kpc)

easier to find over foreground/background
where accreted things tend to disrupt
→ *dark matter dominates the force field!*

see, e.g., Grillmair & Carlin 2016, Shipp et al. 2018, Malhan/Ibata et al. 2018

Stream formation



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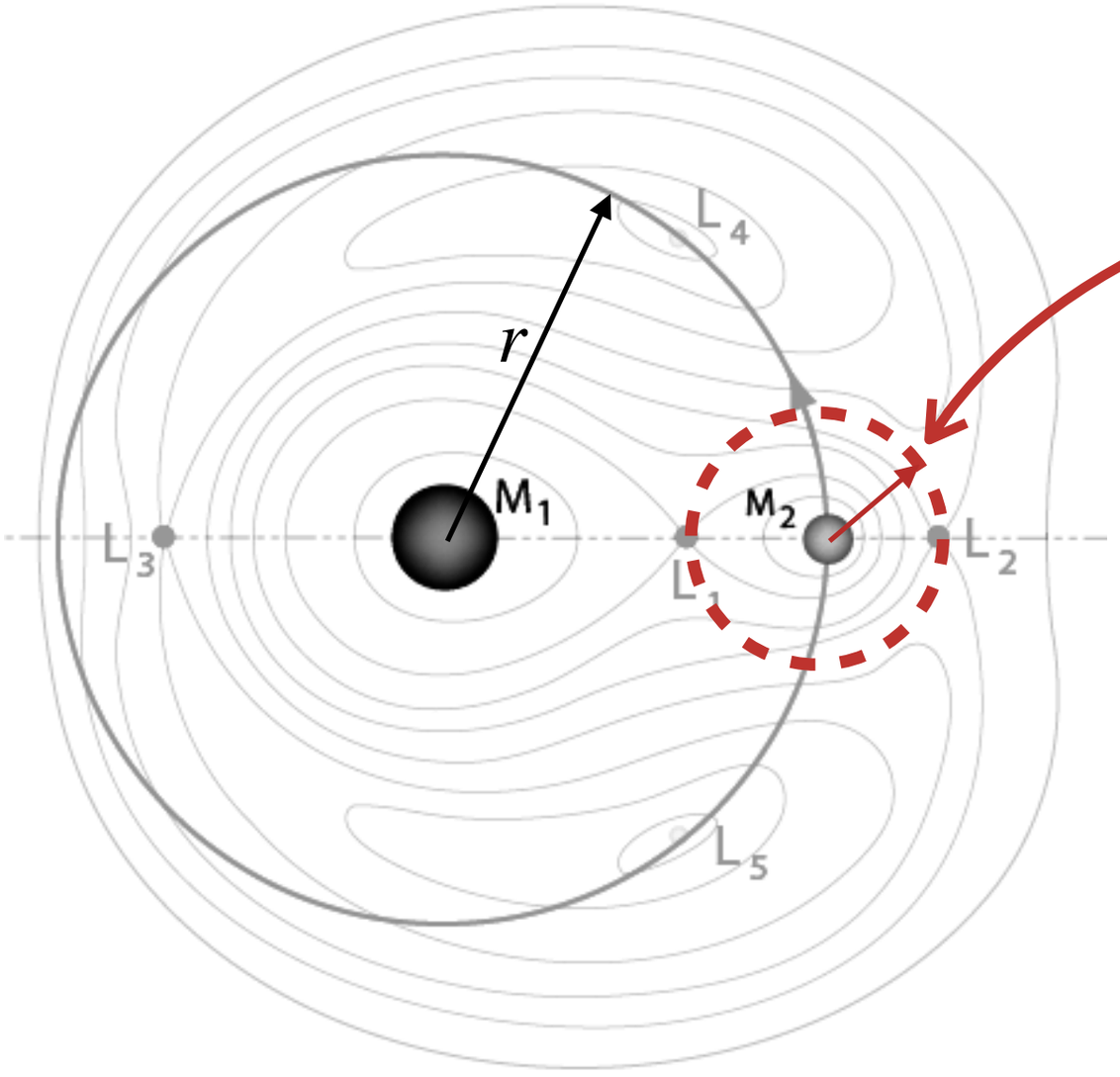

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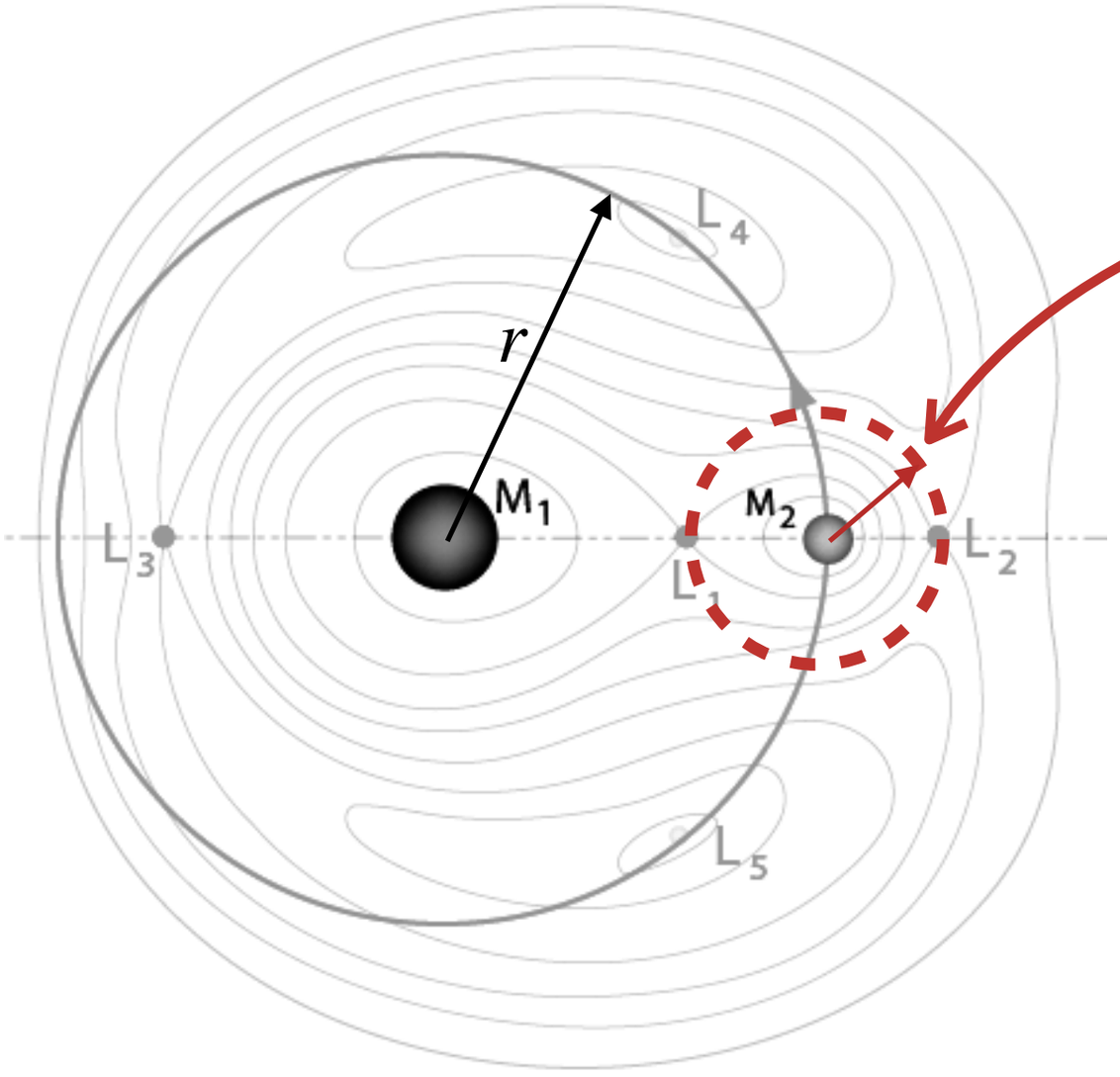
Stream formation



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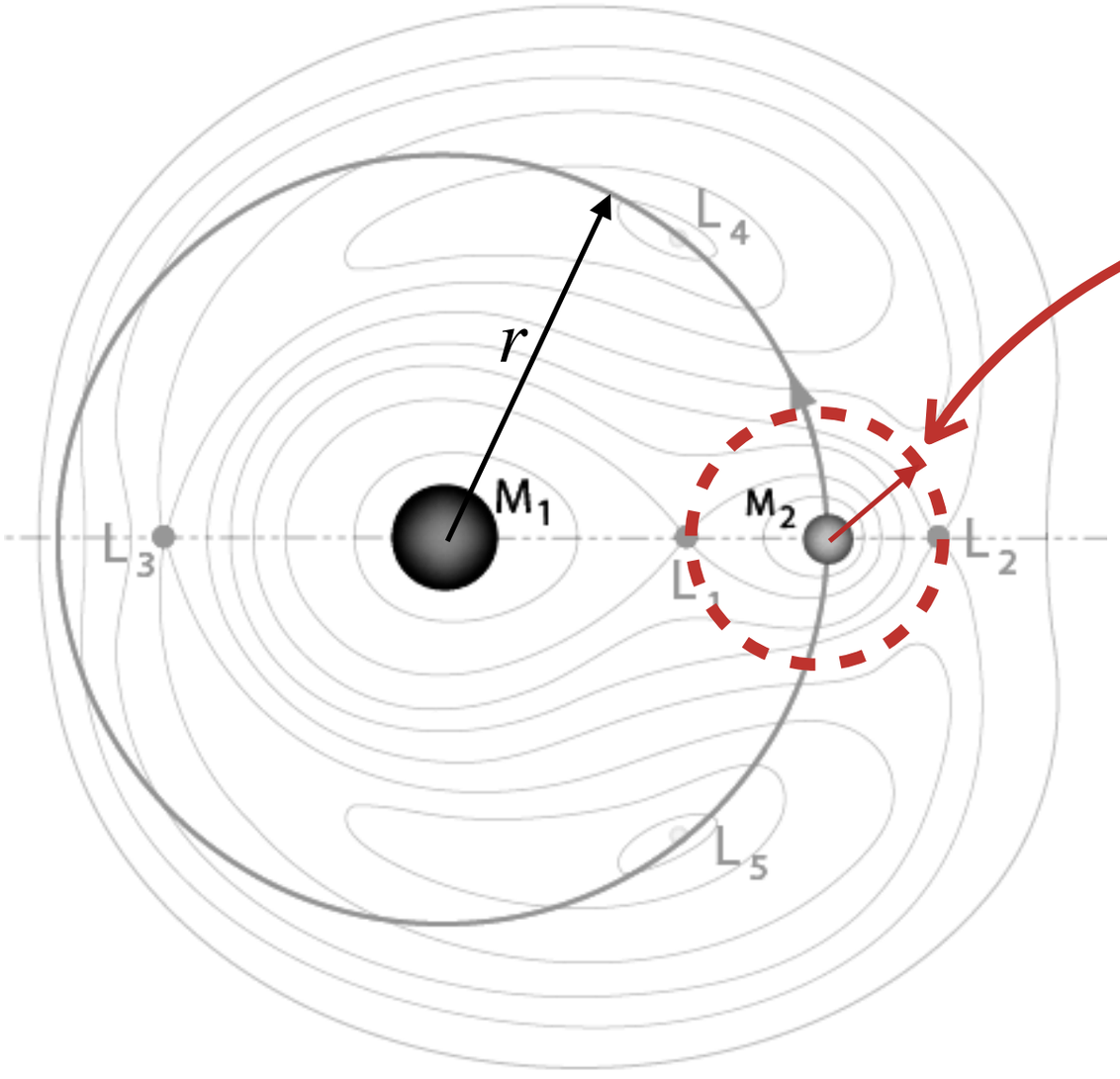

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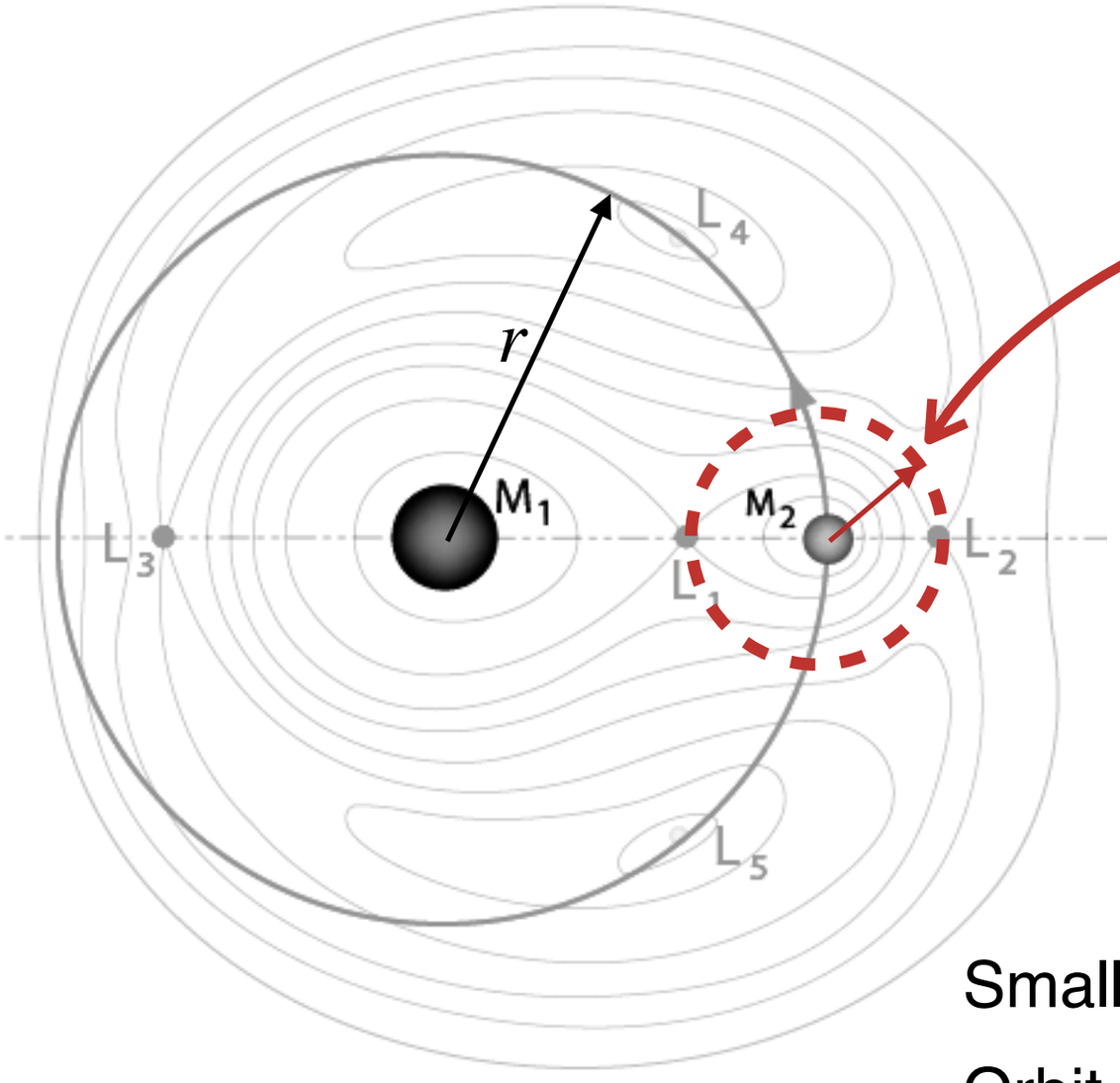

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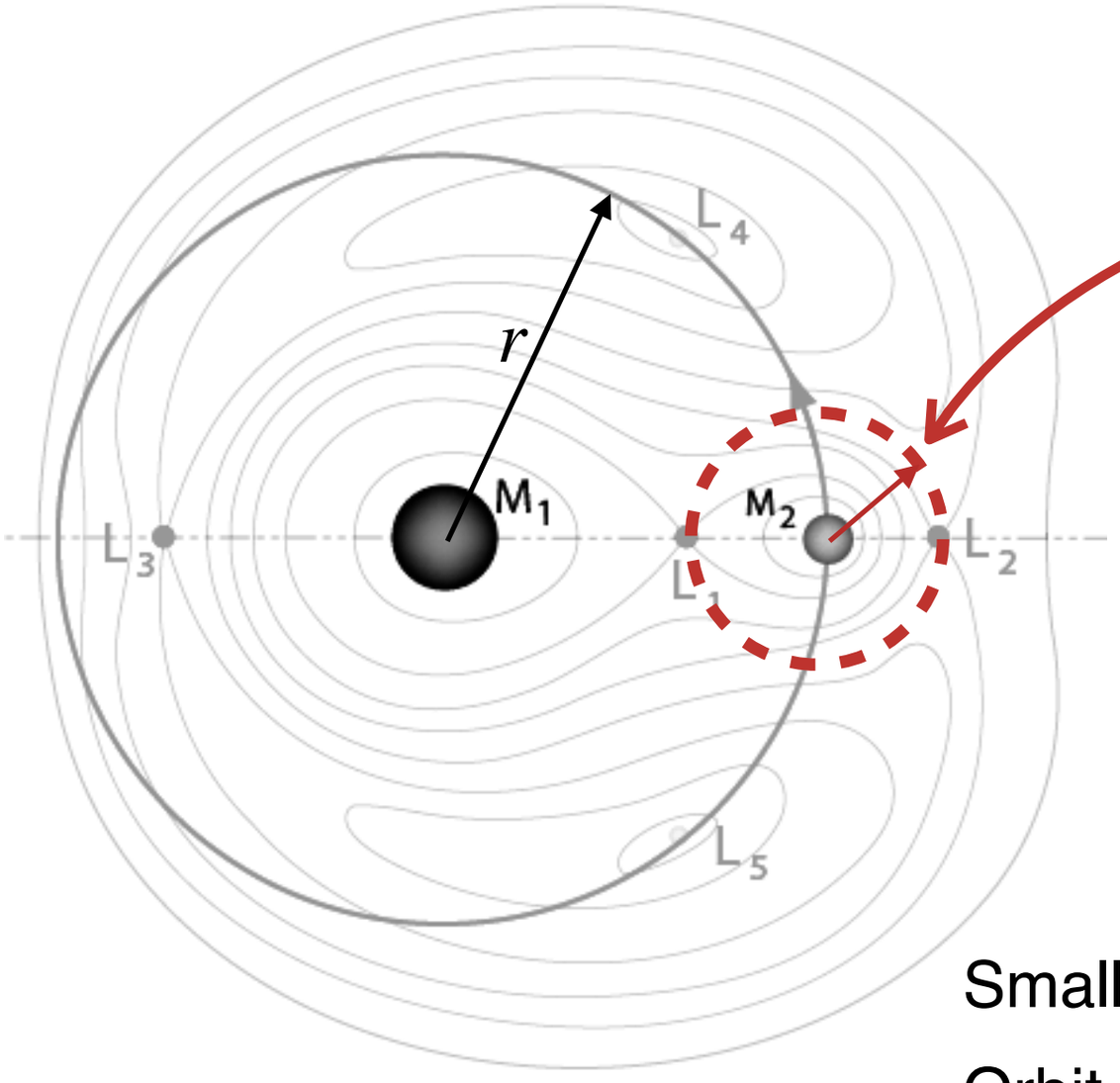
Small energy spread → stars almost trace an orbit

Orbit information → measure of acceleration

Infer the global dark matter distribution

Stream formation



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Small energy spread → stars almost trace an orbit

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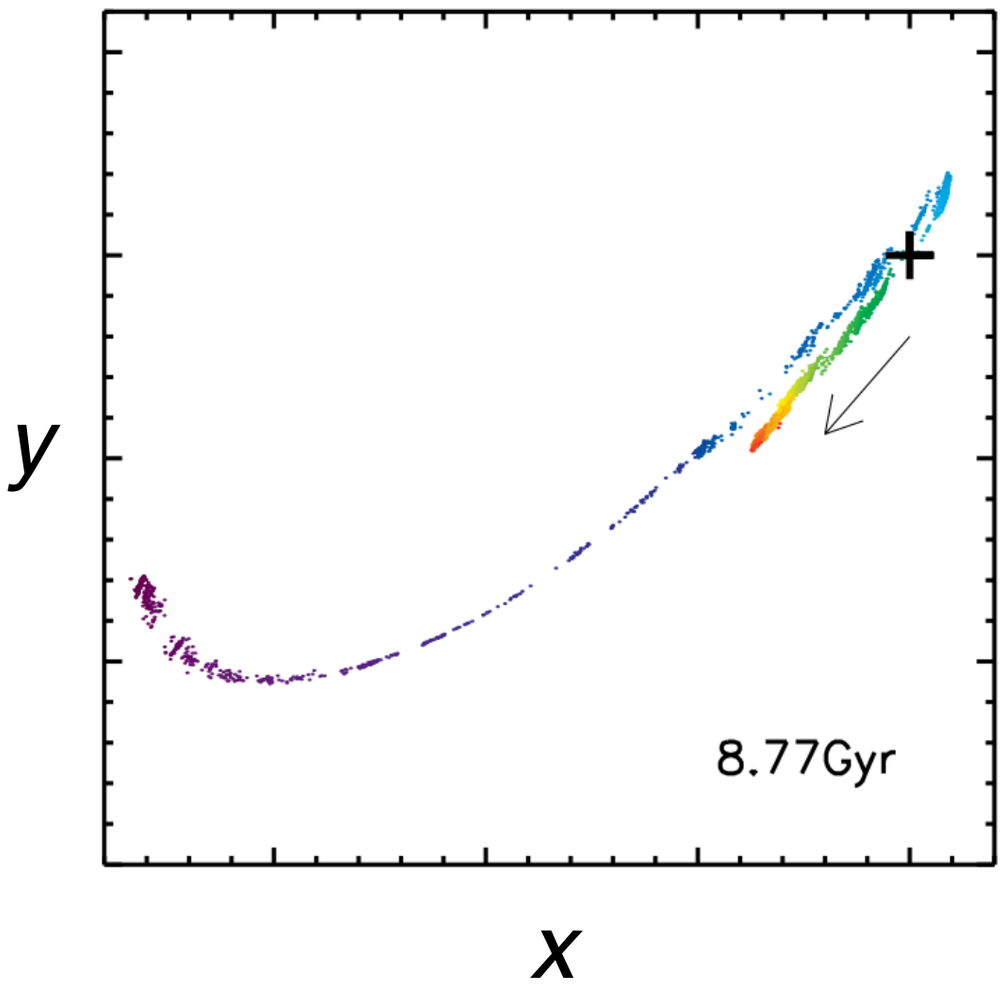
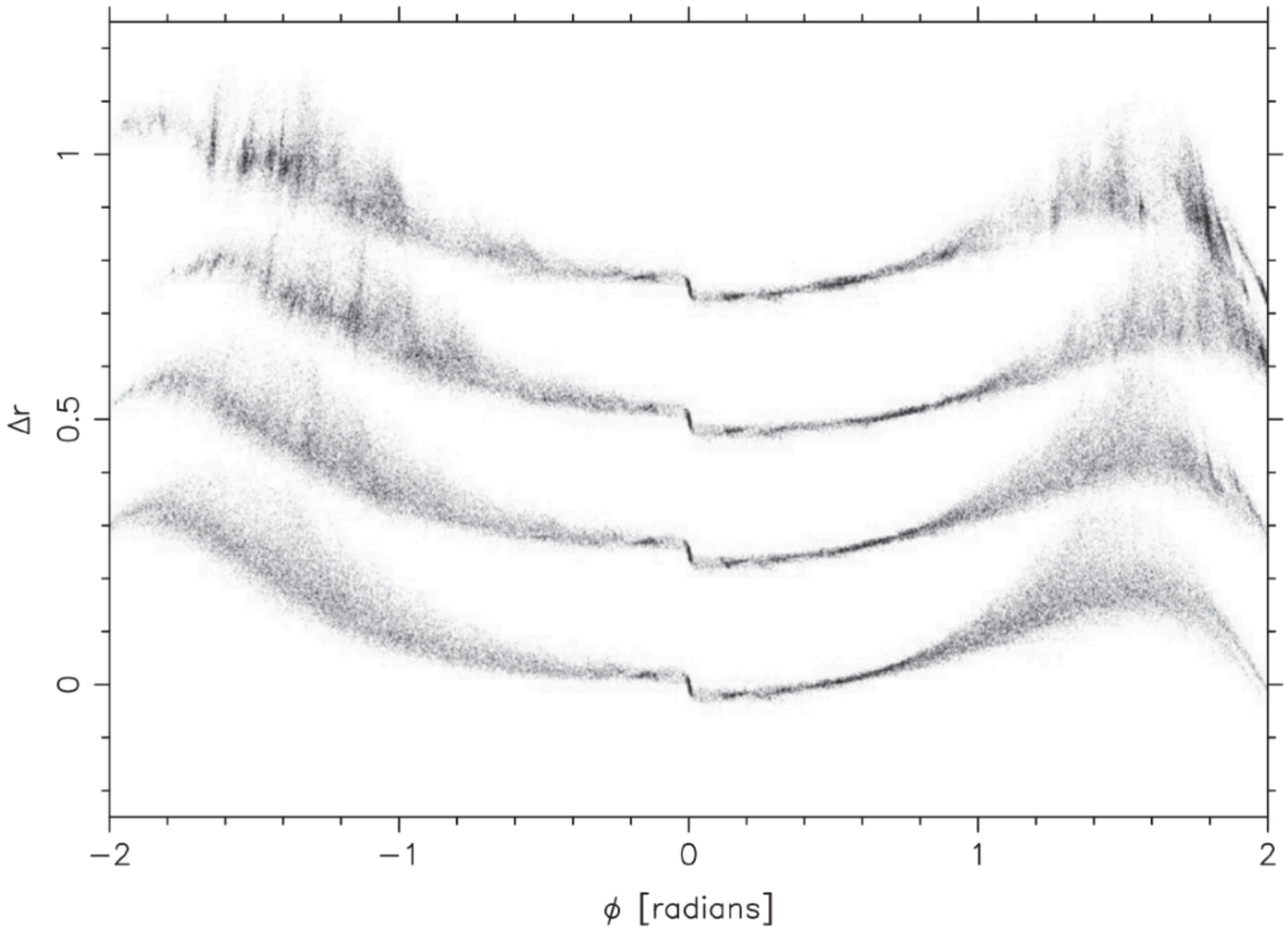
Infer the global dark matter distribution

e.g., Johnston et al. 1999, Binney 2008, Sanders & Binney 2013, Price-Whelan et al. 2014, etc…

Stream-subhalo interactions



Yoon et al. 2011



Carlberg 2015

streams simulated with subhalos

see also Siegel-Gaskins & Valluri 2008, Erkal, Sanders, Bovy work

Why care about streams?

They encode:

- Global dark matter distribution
- Interactions with dark matter substructure
- Accretion history

This talk

Briefly: some complexities in stream formation, and observed consequences

Why I think the GD-1 stream is worth our attention

What we do, don't, and should know about GD-1 (the post-*Gaia* perspective)

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Why I think the GD-1 stream is worth our attention

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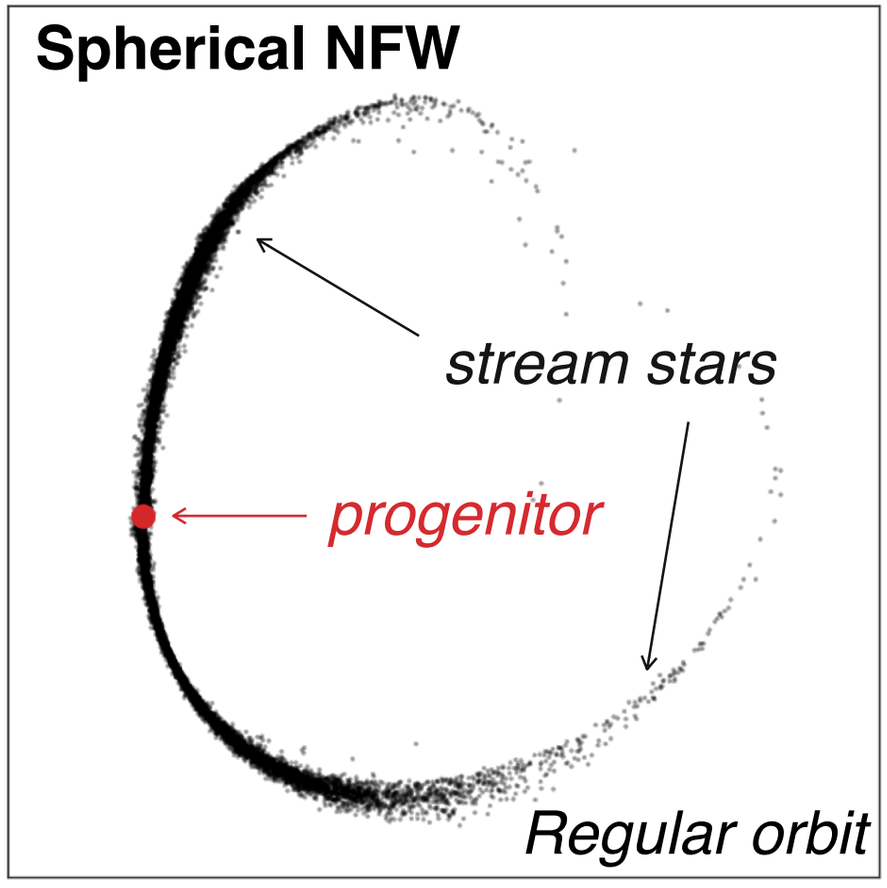
Ana's talk

Using the morphology of GD-1 features to constrain interaction / perturber models

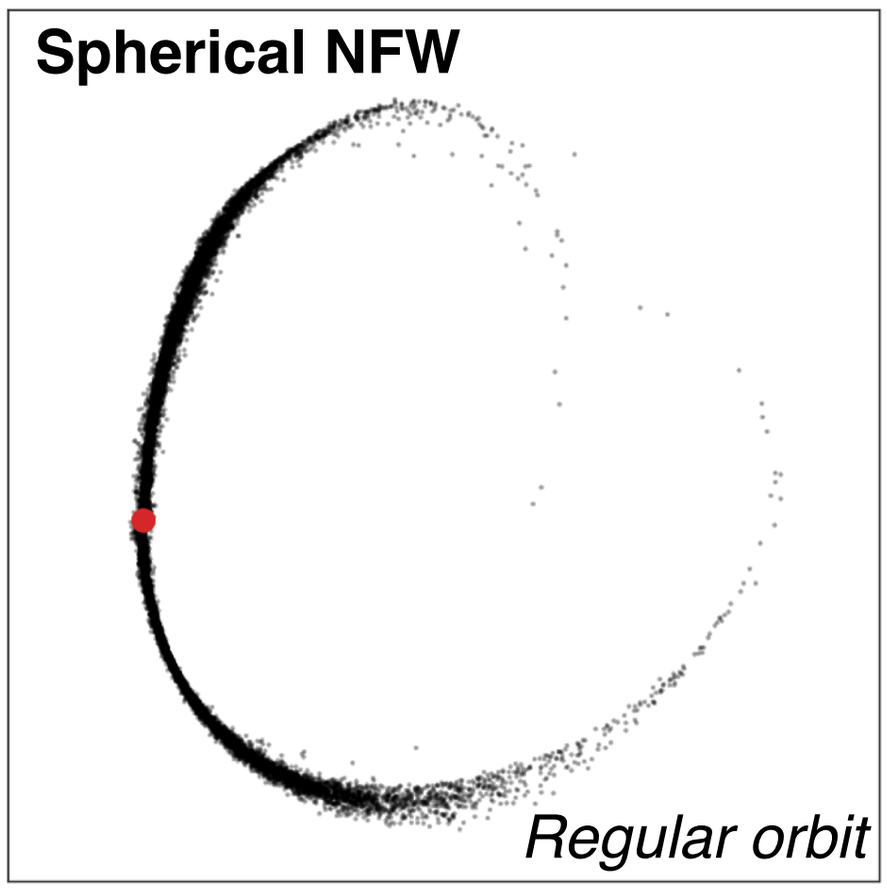
Spectroscopic follow-up

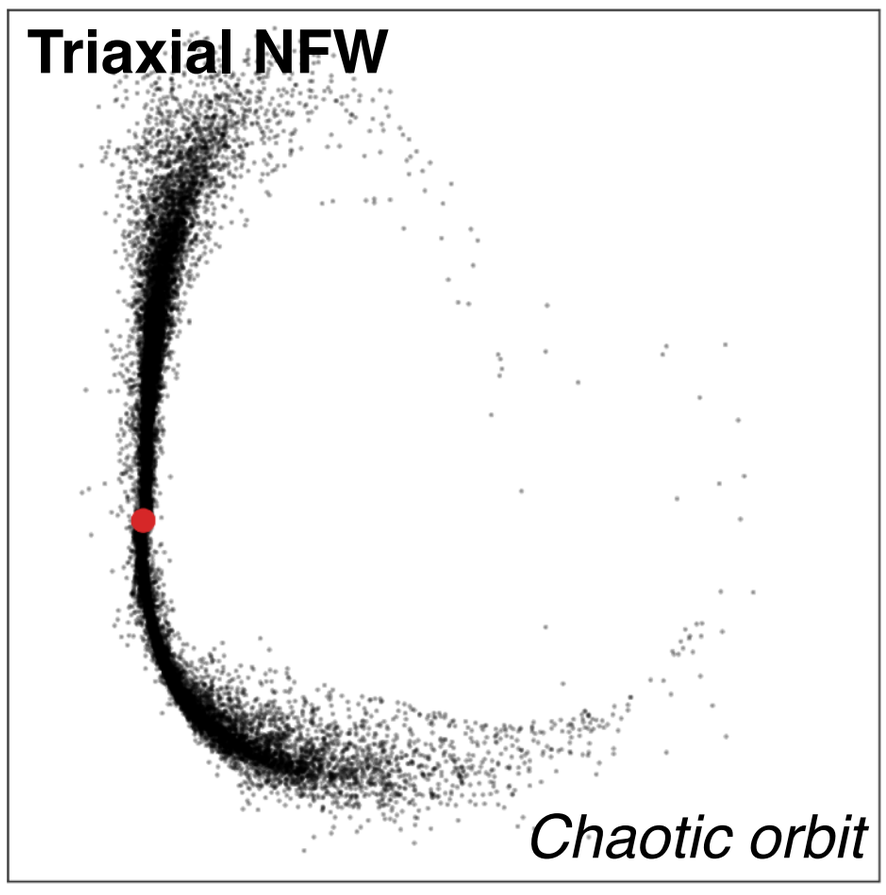
Constraints on dark matter physics?

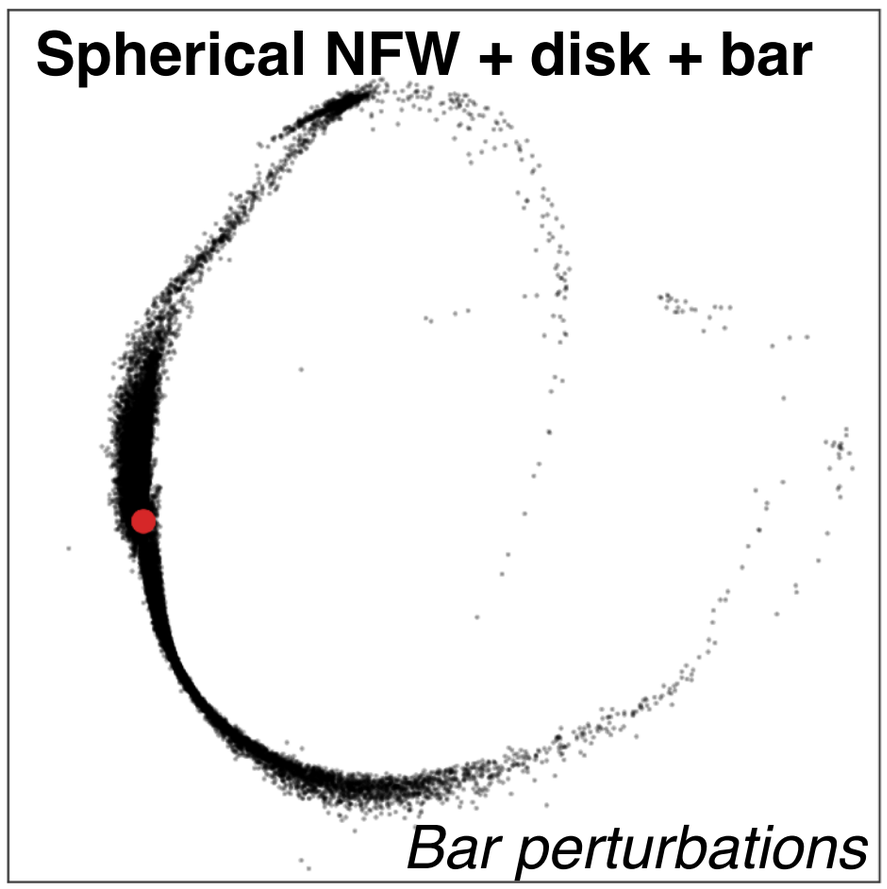
Streams around the Milky Way are complex

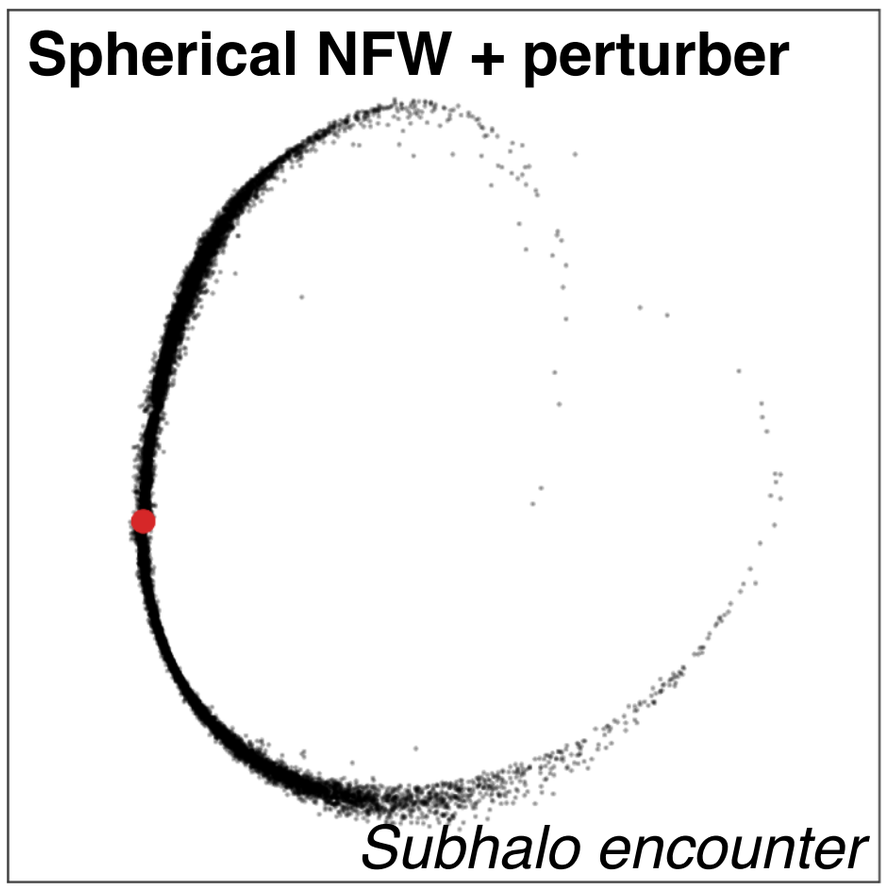


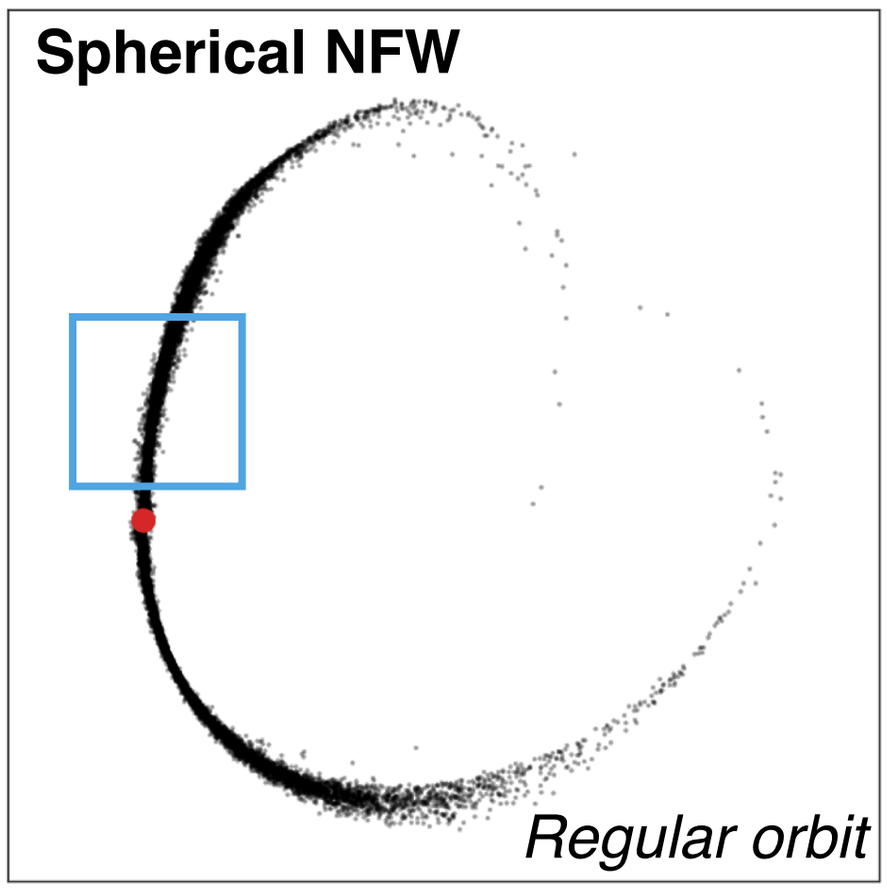
Spherical NFW model for the Milky Way


Spherical NFW
Regular orbit


Triaxial NFW
Chaotic orbit


Spherical NFW + disk + bar
Bar perturbations


Spherical NFW + perturber
Subhalo encounter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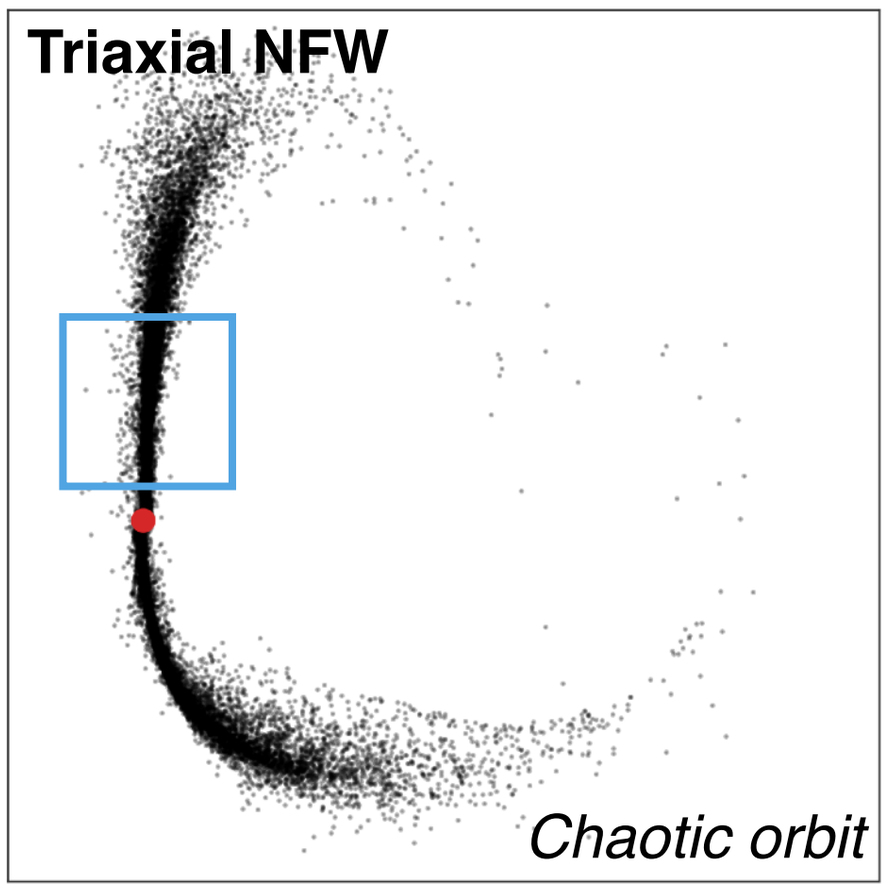
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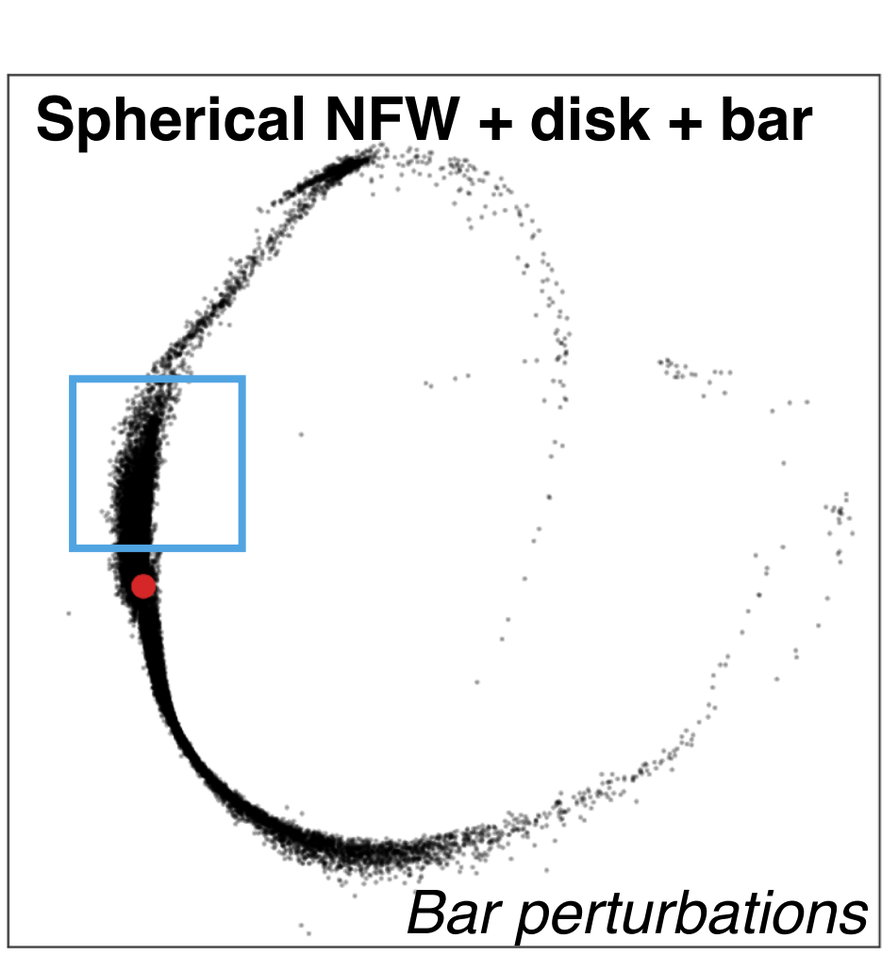
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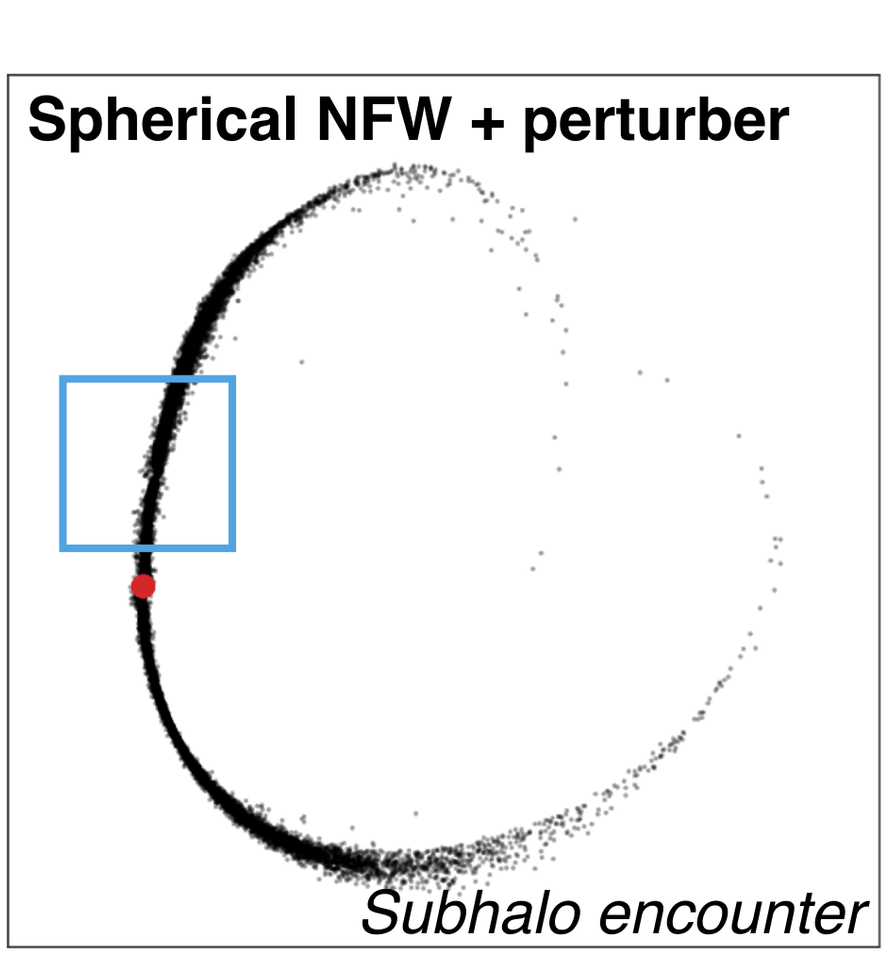
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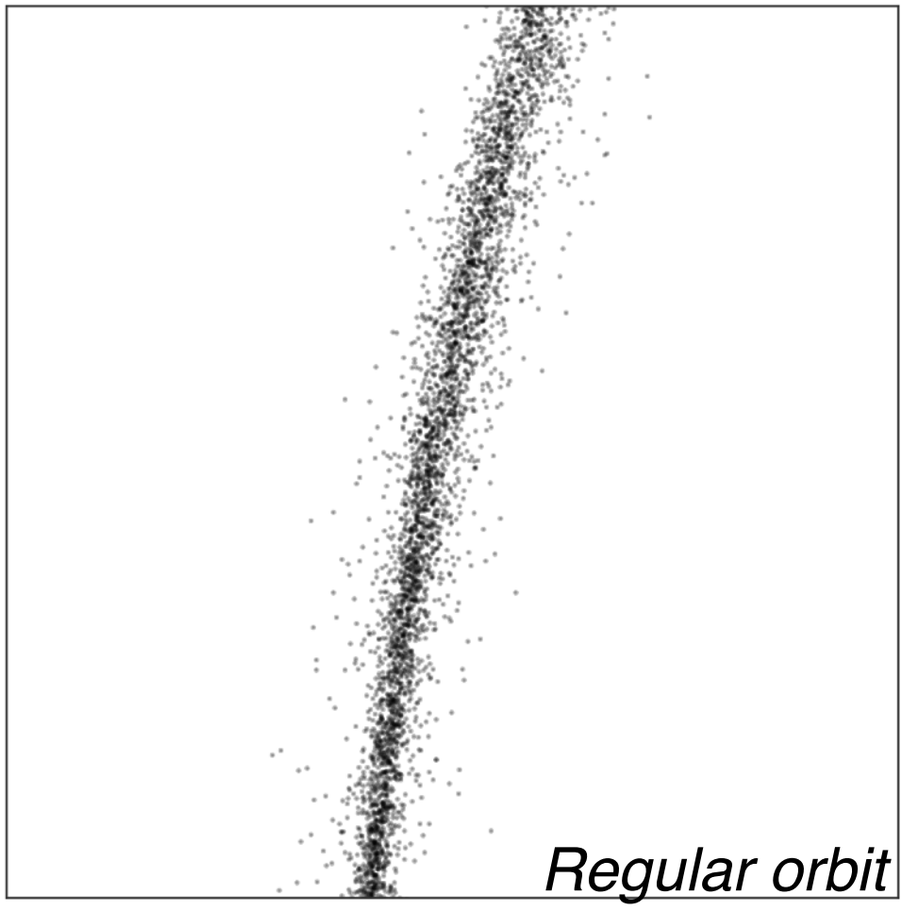
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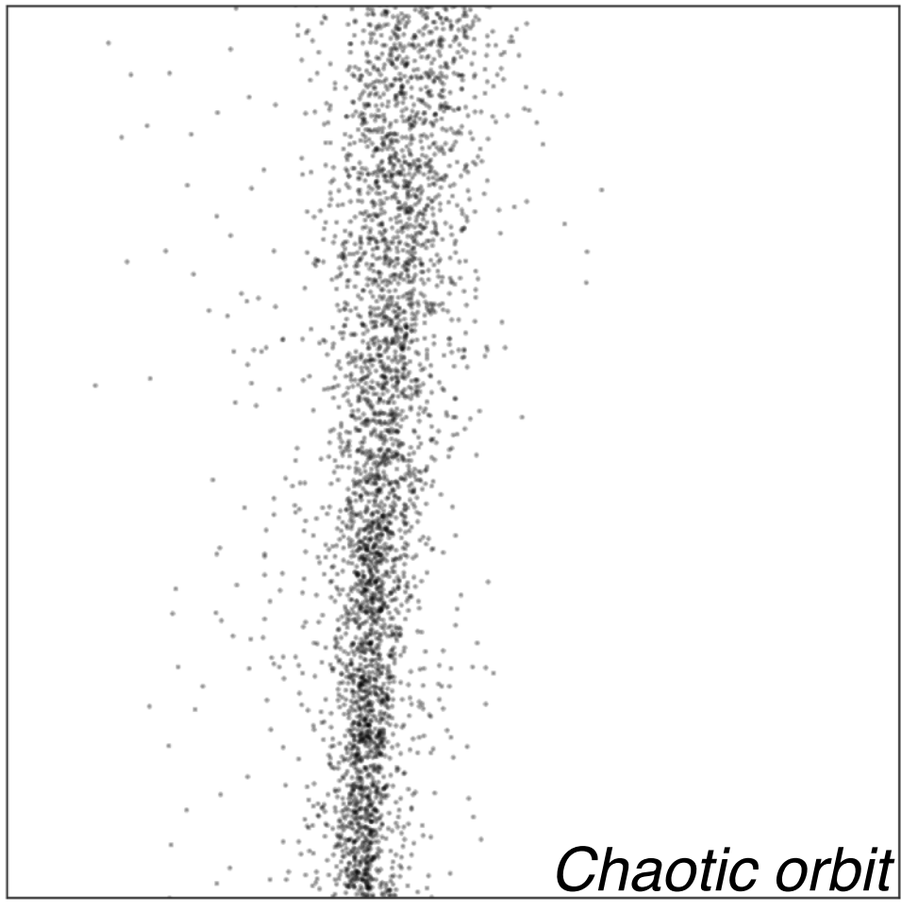
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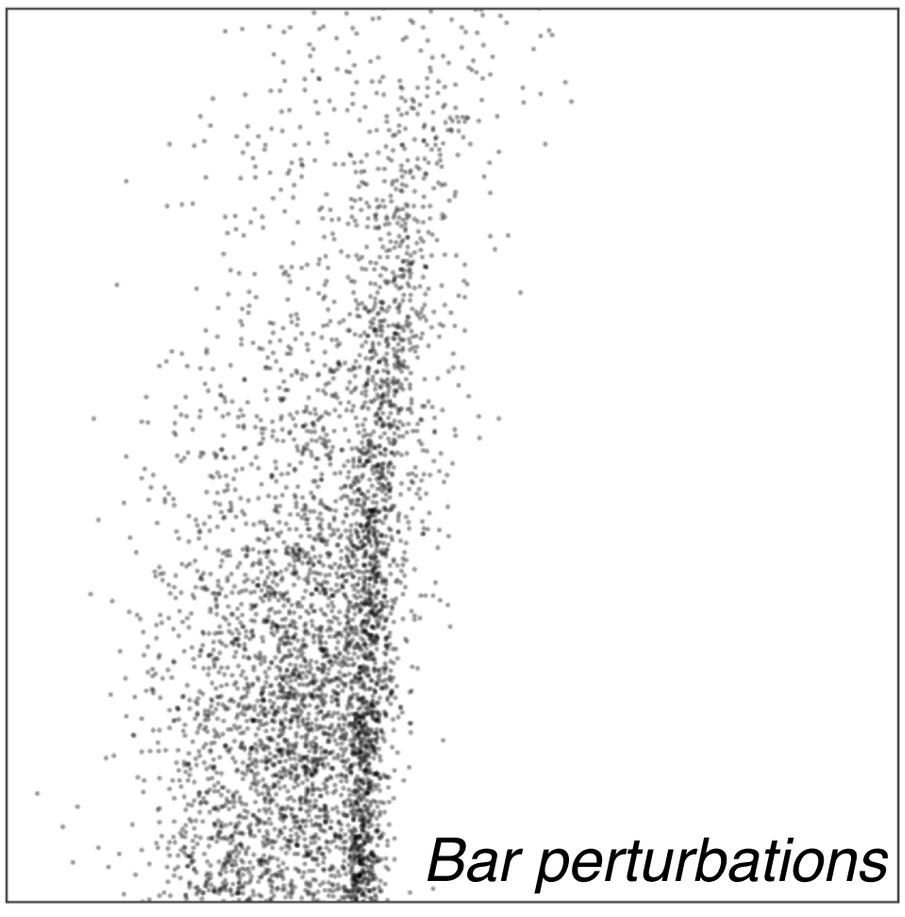
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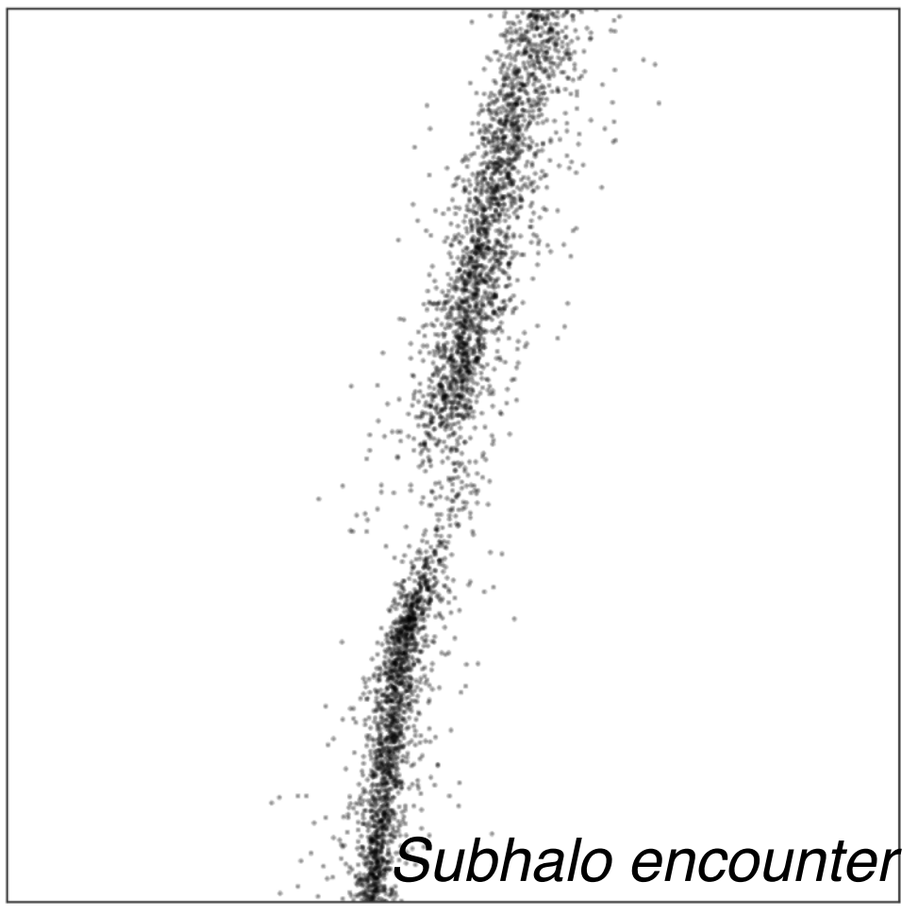
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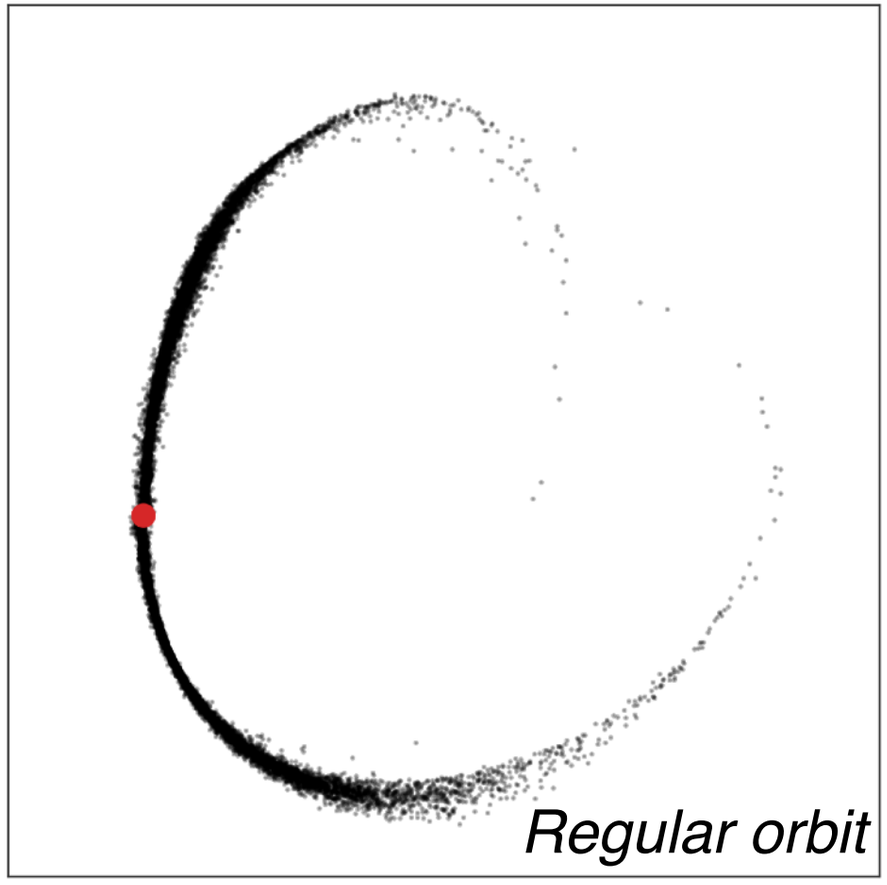
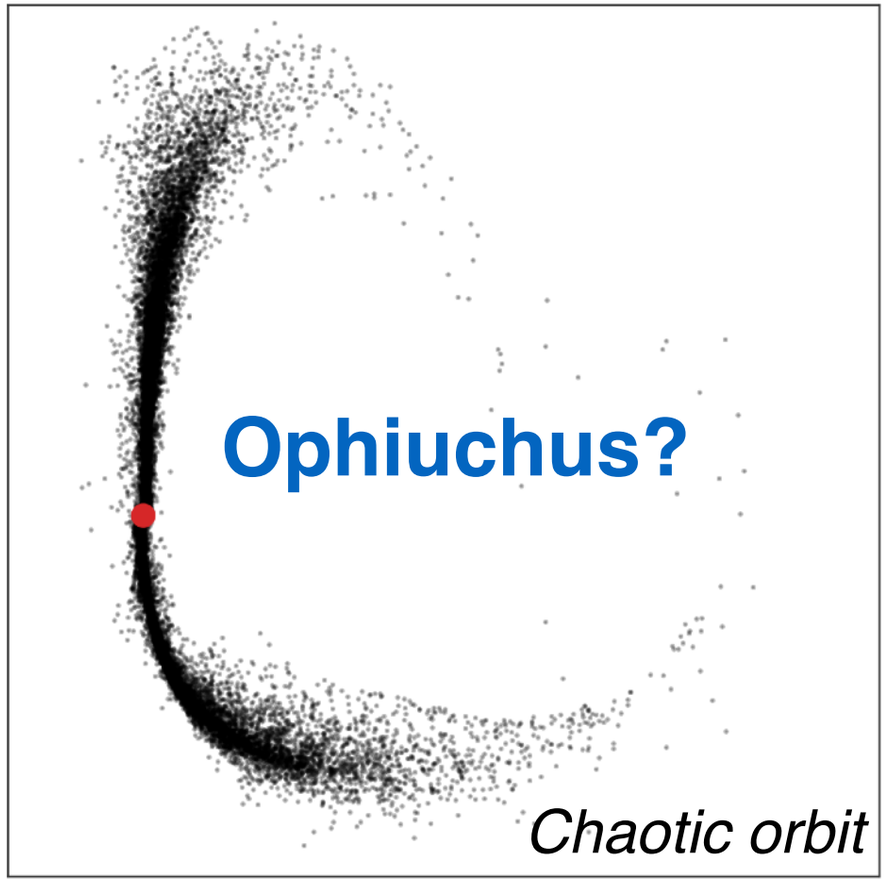
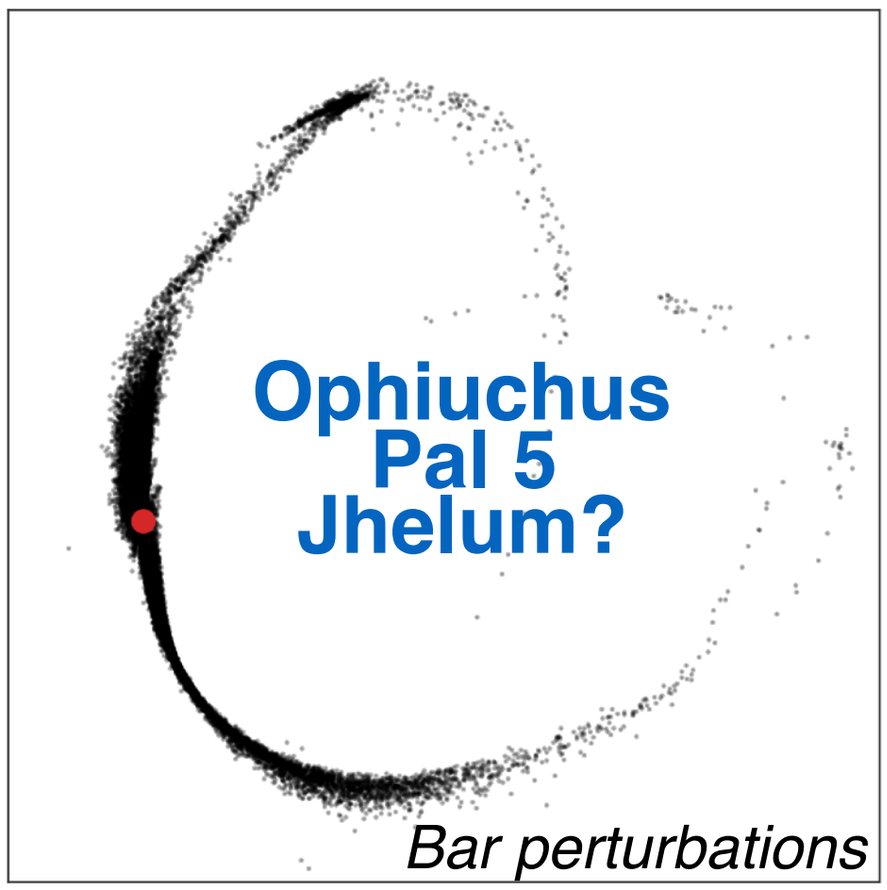




Pearson, *APW* **et al. 2015**
APW **et al. 2016a,b**



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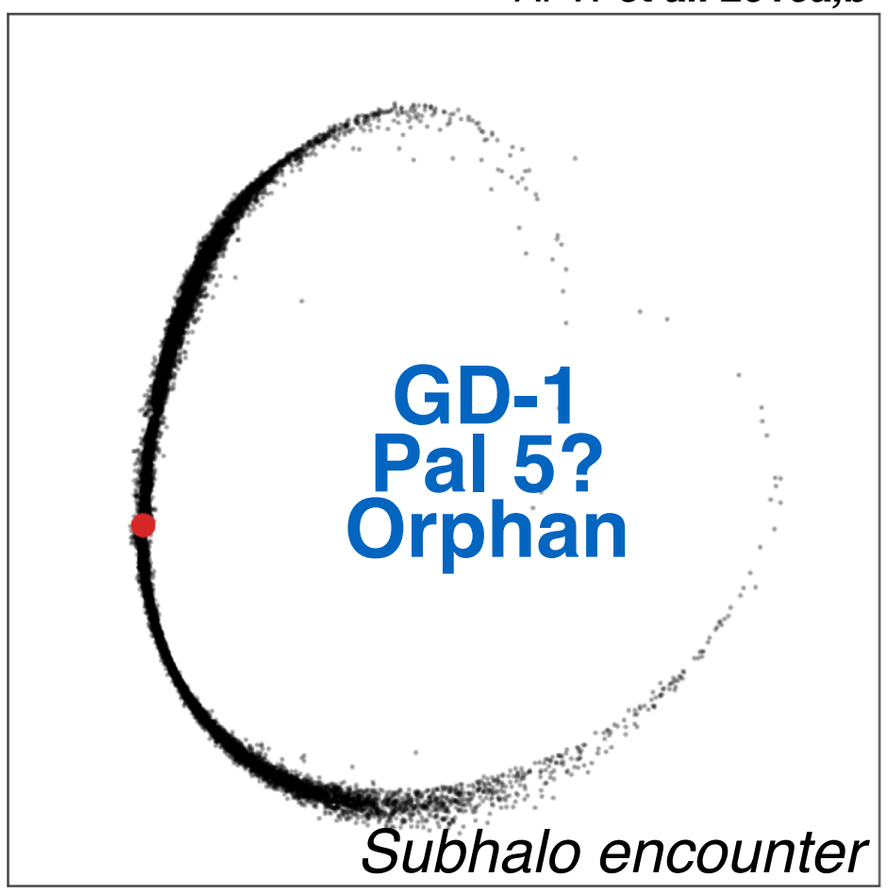
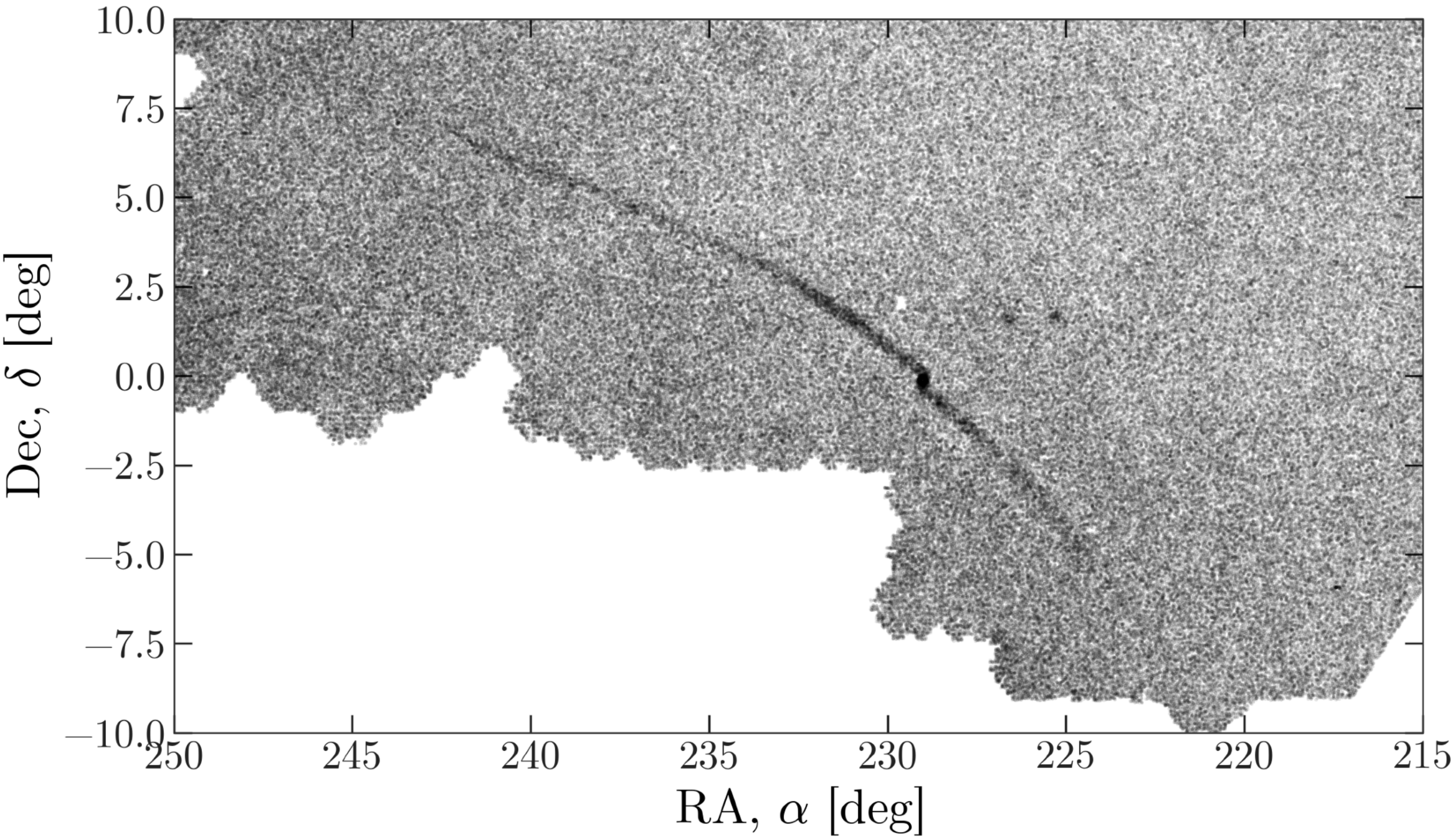
Bonaca, Pearson, *APW* **in prep.**



APW & Bonaca 2018
Bonaca, APW et al. 2019

e.g., Pal 5: asymmetric tails



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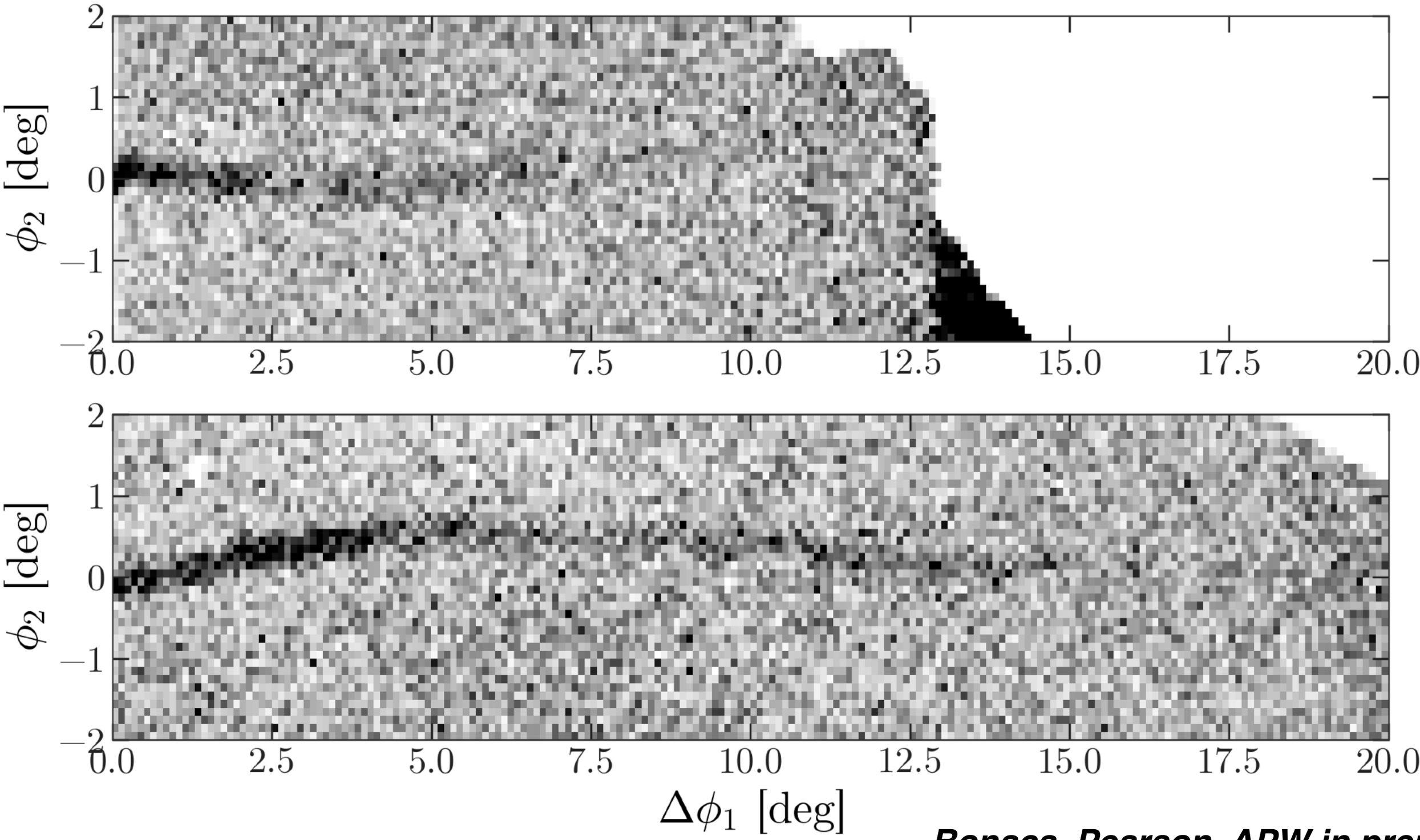

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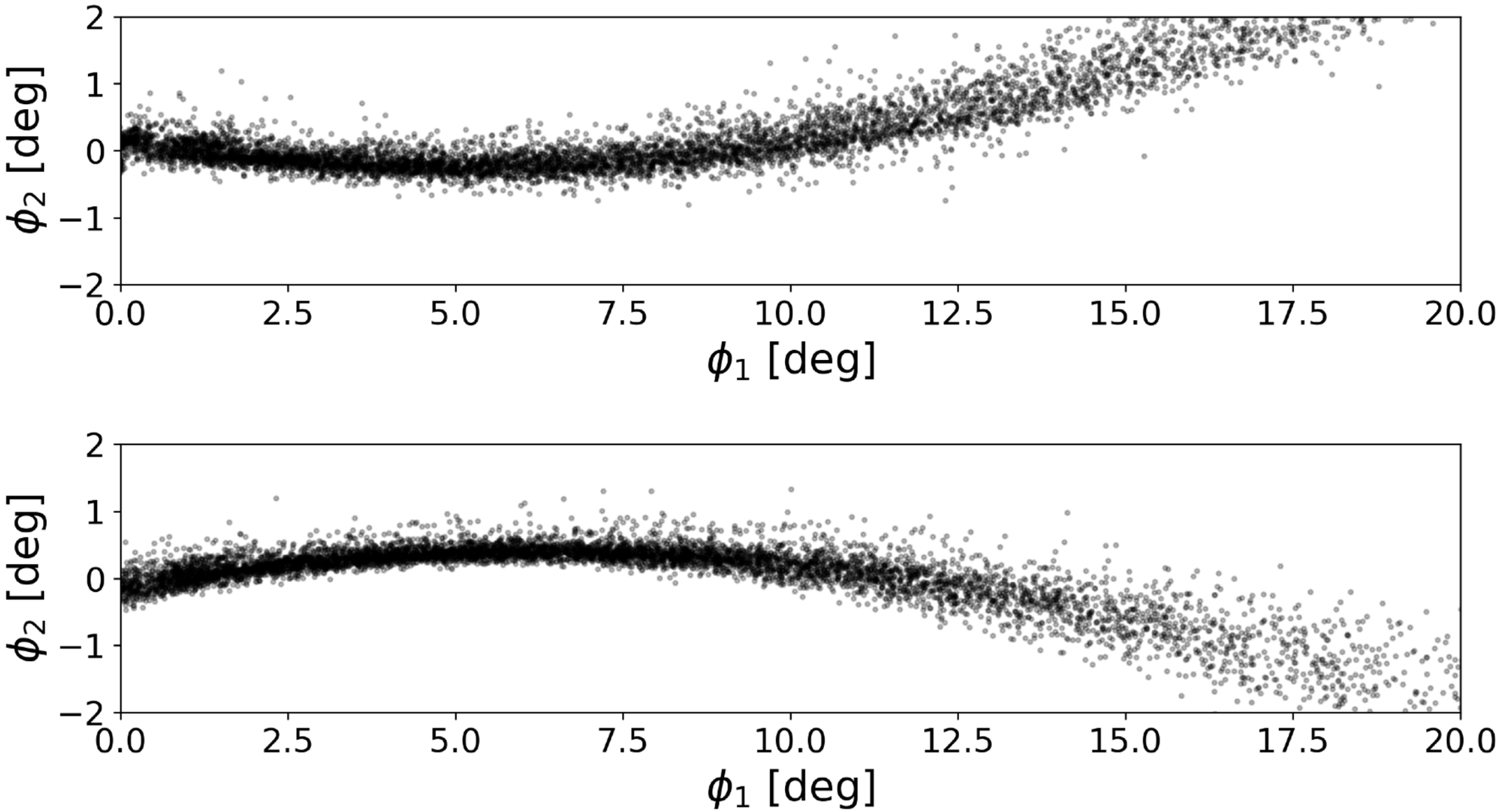
Stream model in a axisymmetric, static MW model

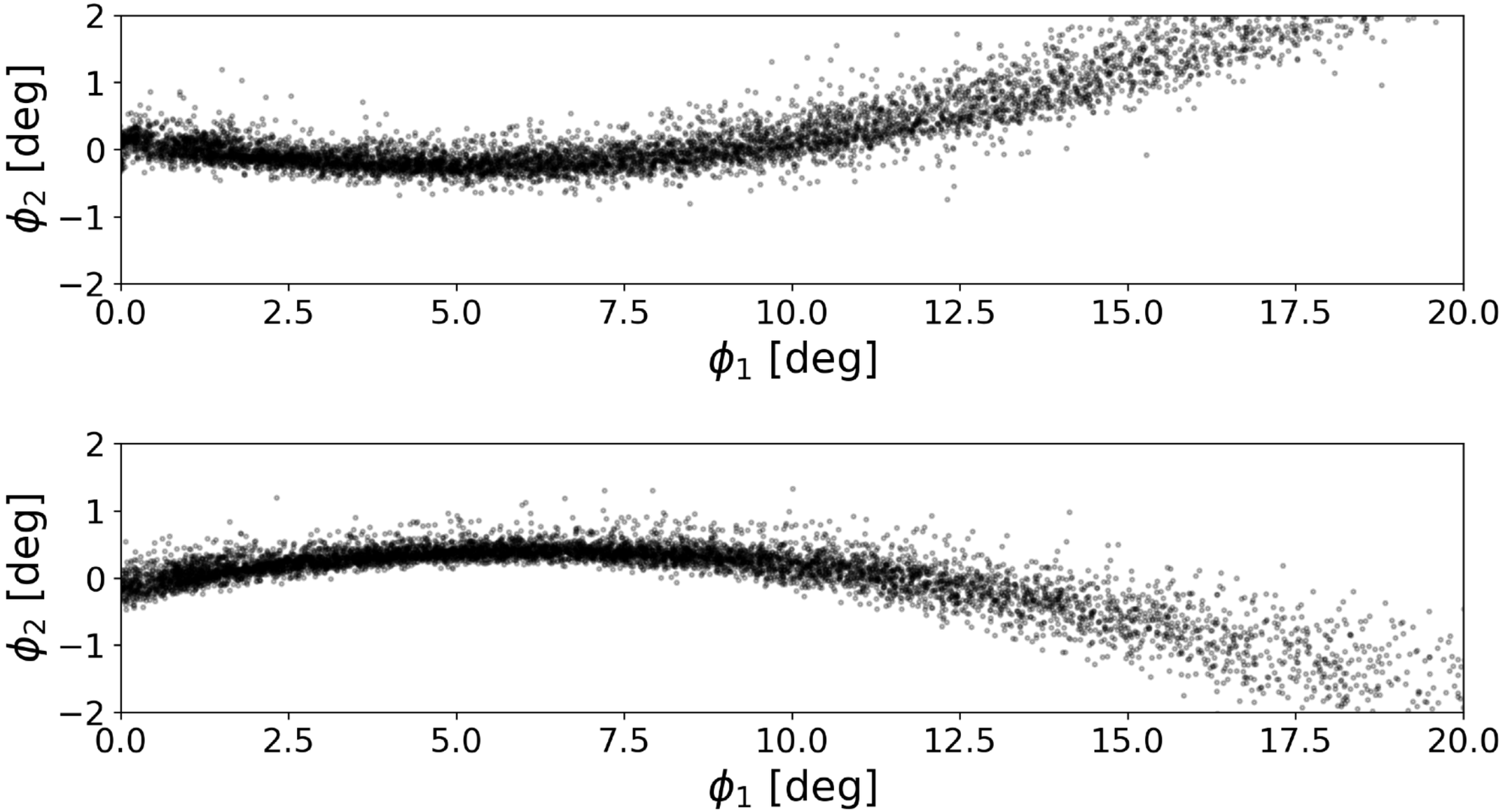


(from Sarah Pearson; see also Pearson et al. 2017

e.g., Pal 5

Stream model in a axisymmetric, static MW model

but: pericenter ~ 7–8 kpc



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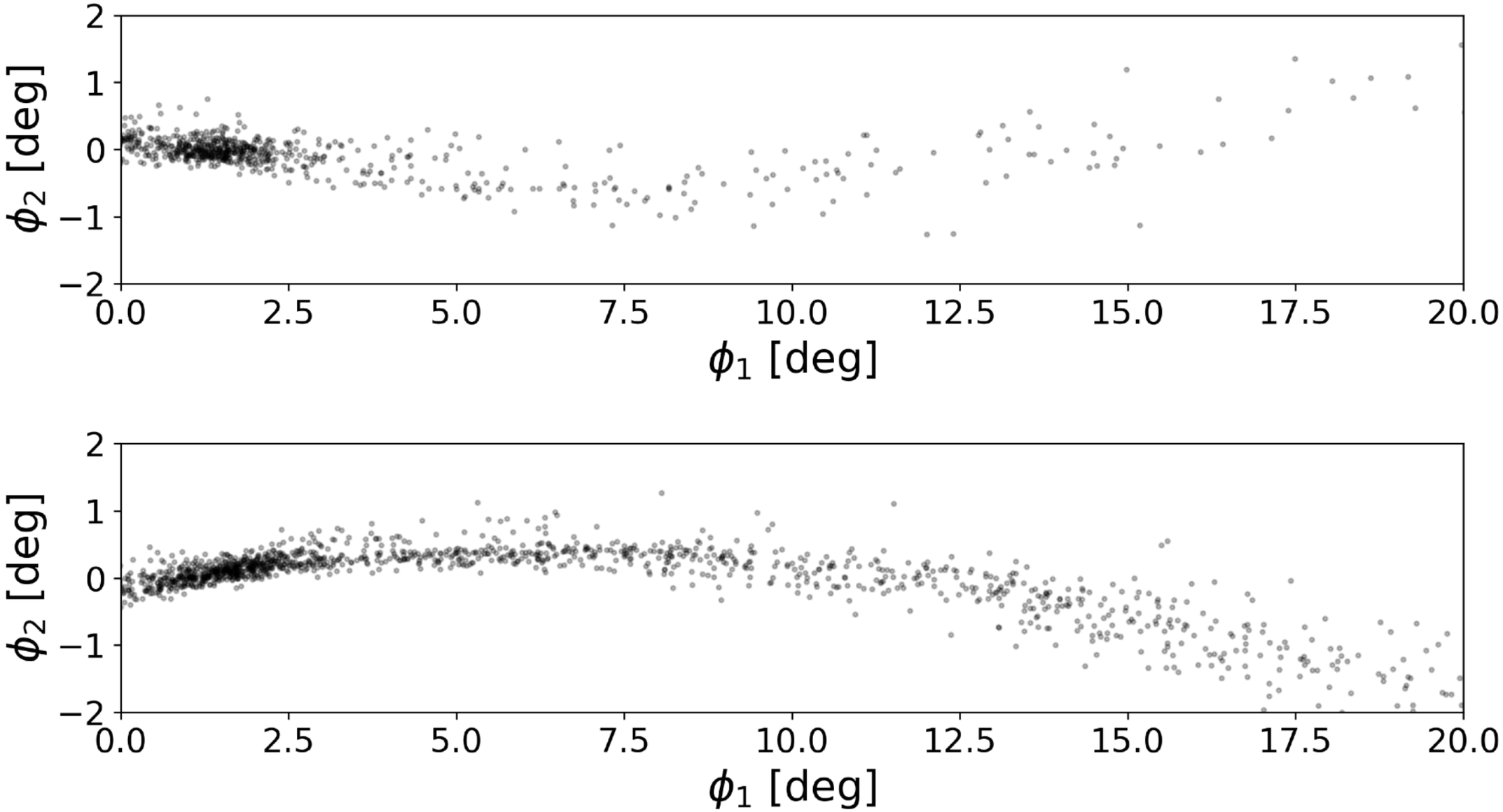
e.g., Pal 5: feeling the bar?

Stream model in a axisymmetric, static MW model
+ Dwek bar $10^{10}\ \mathrm{M}_\odot$ $\Omega = 38\ \mathrm{km\ s^{-1}\ kpc^{-1}} = 0.0389\ \mathrm{Myr^{-1}}$



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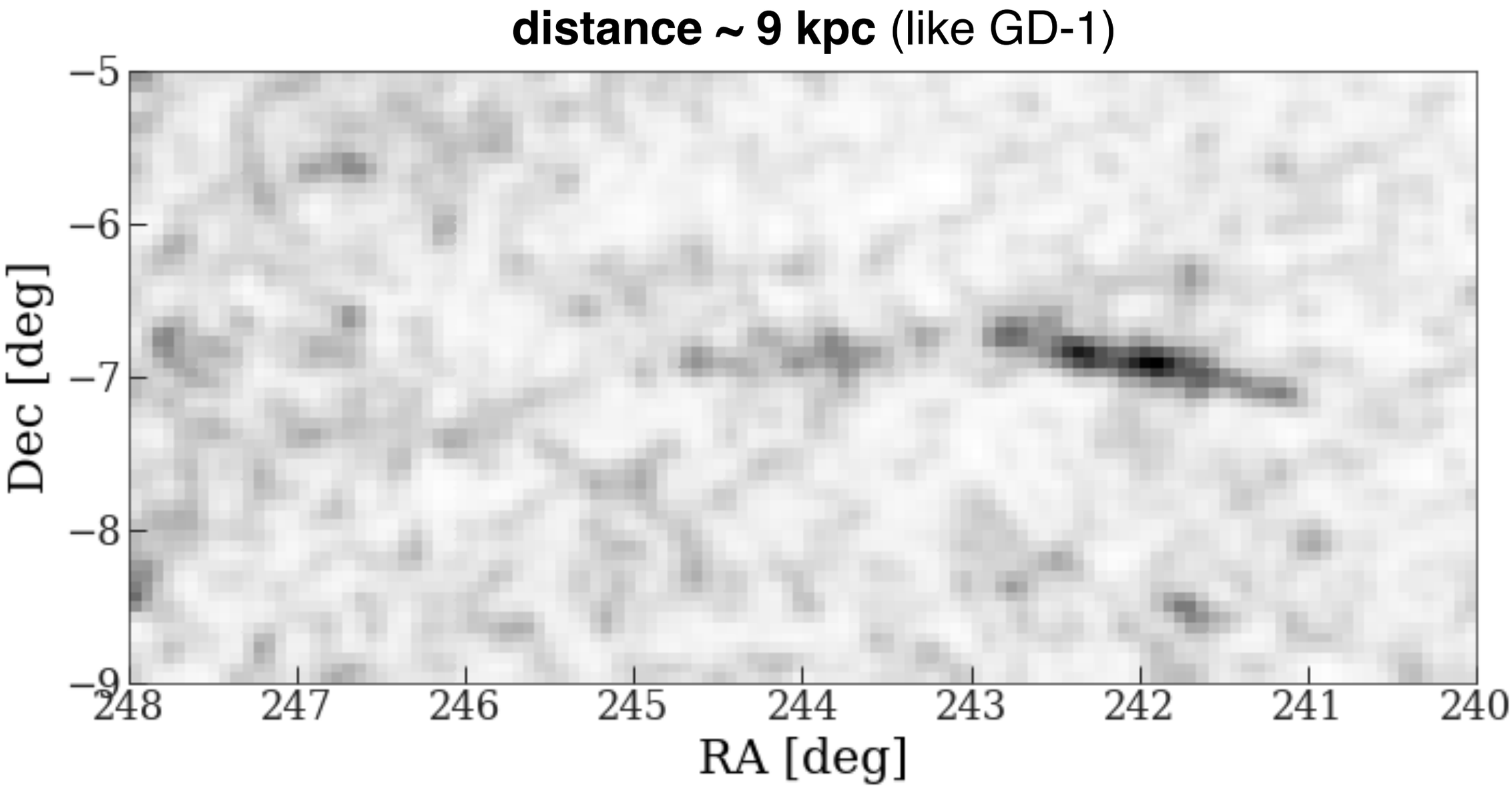
e.g., Ophiuchus: short stream + diffuse ‘fan’



Data: Pan-STARRS+*Gaia*

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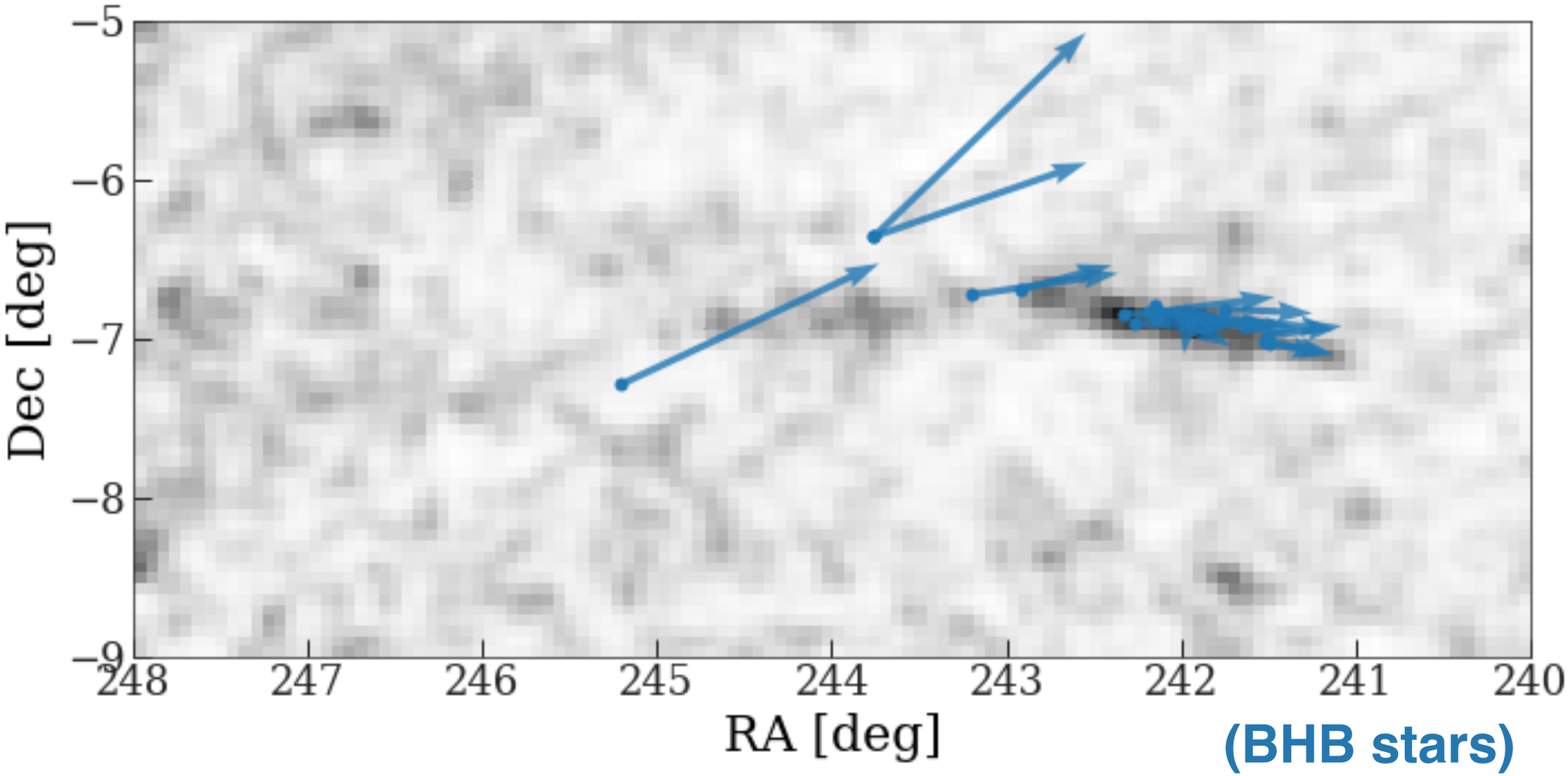

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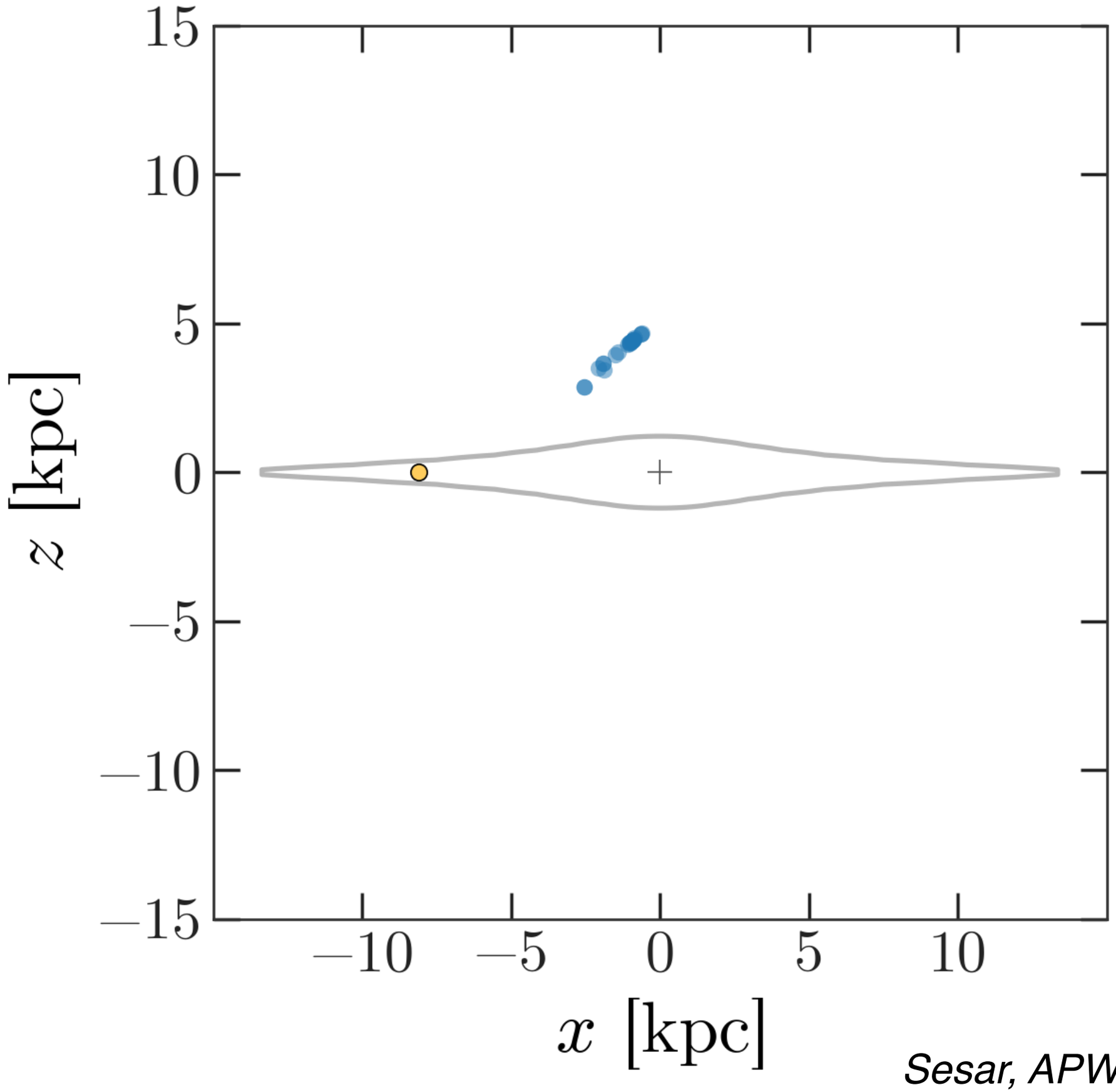
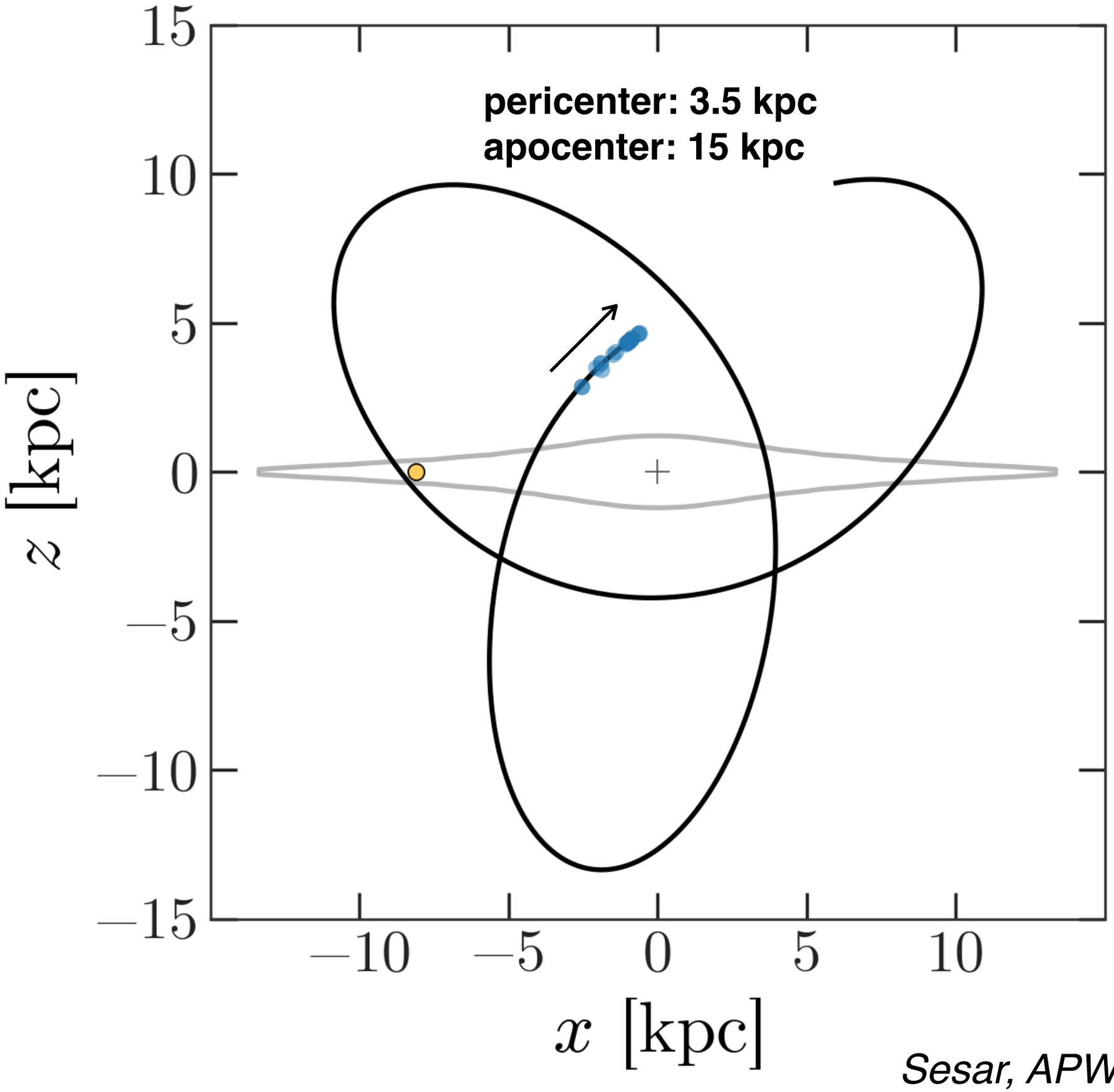


APW et al. 2016a
Sesar, APW et al. 2015, 2016



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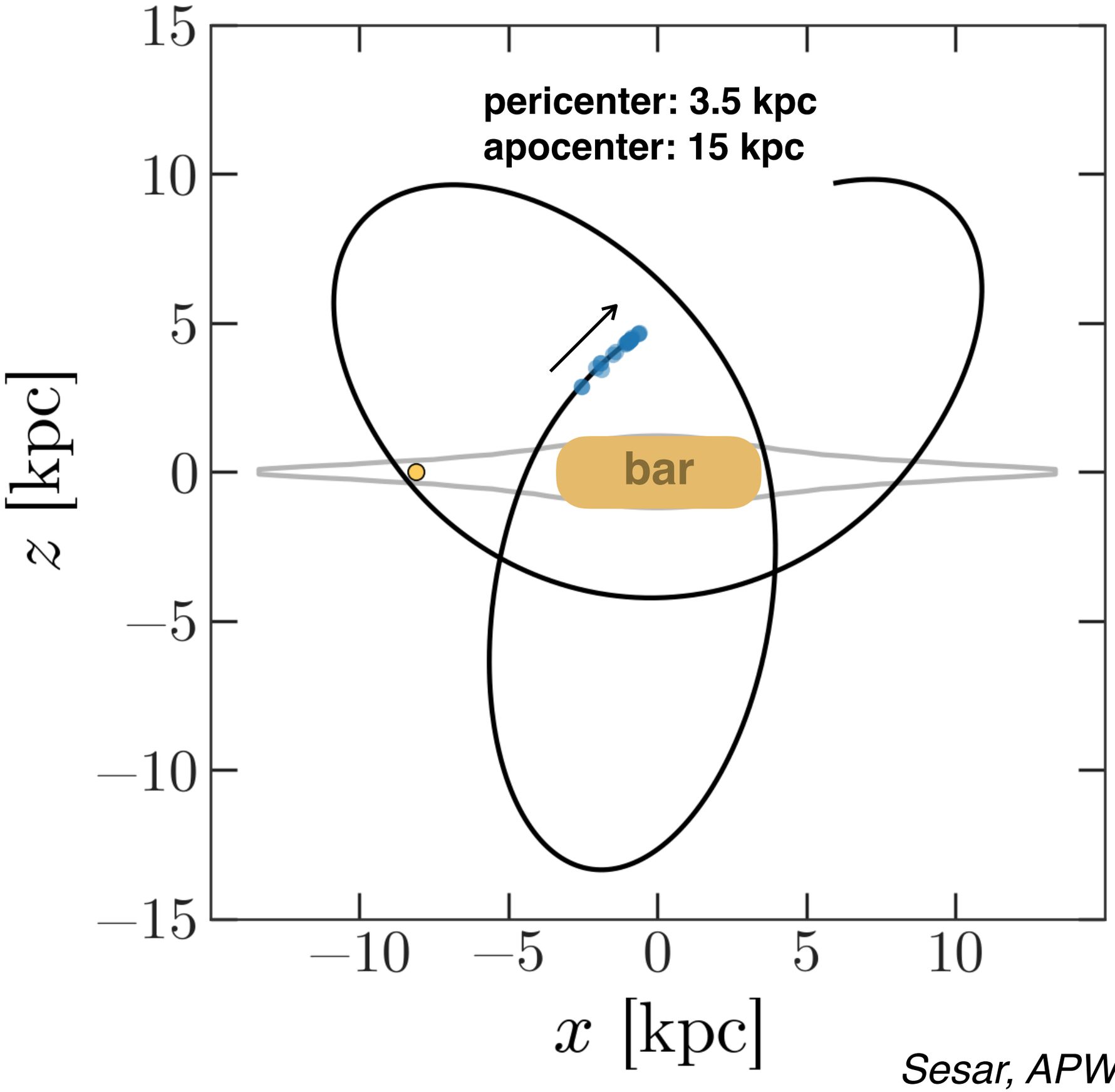

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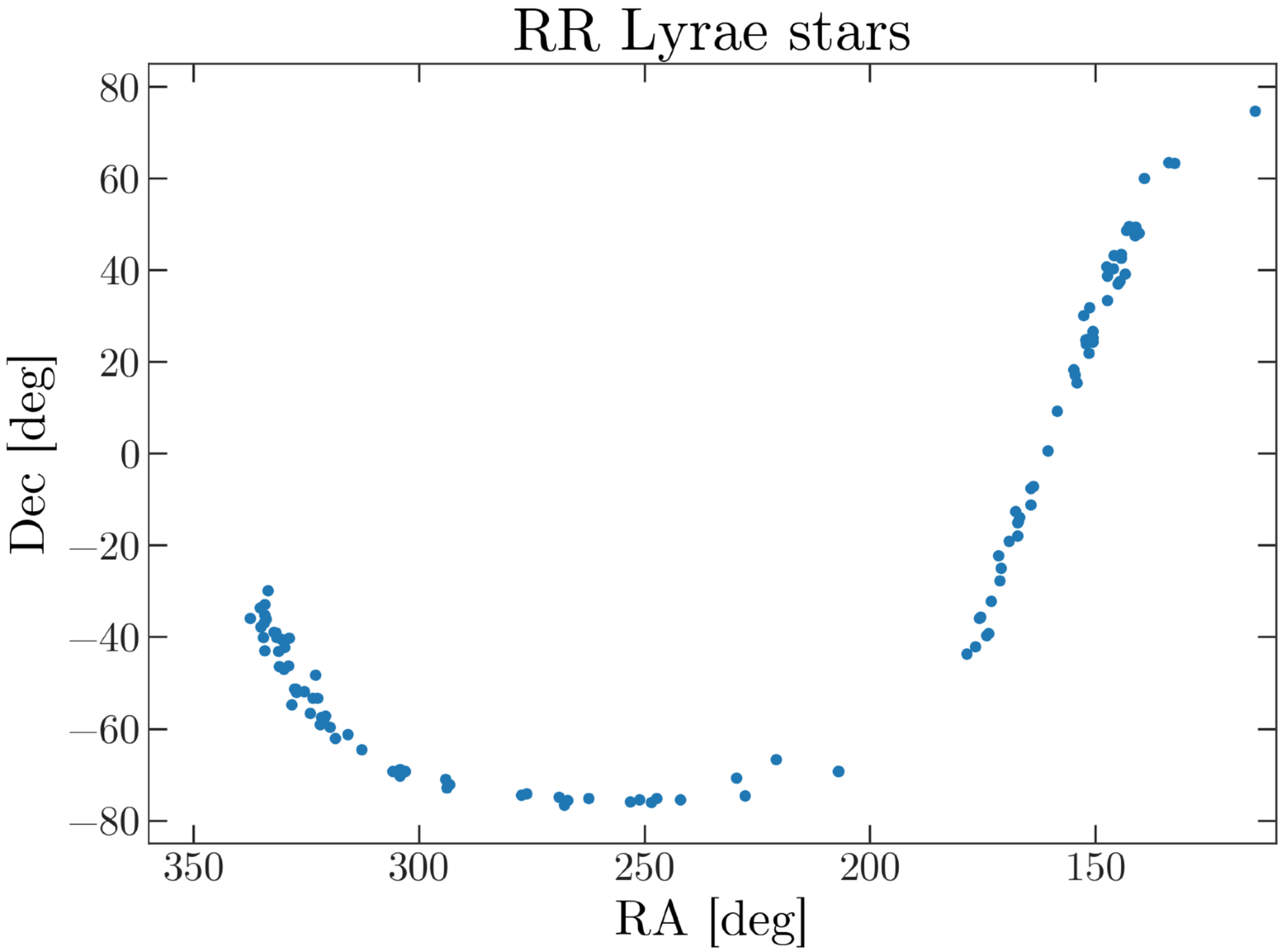
e.g., Orphan: feeling the LMC



Koposov, Belokurov, Li, Mateu, APW, Laporte, Evans et al. 2019

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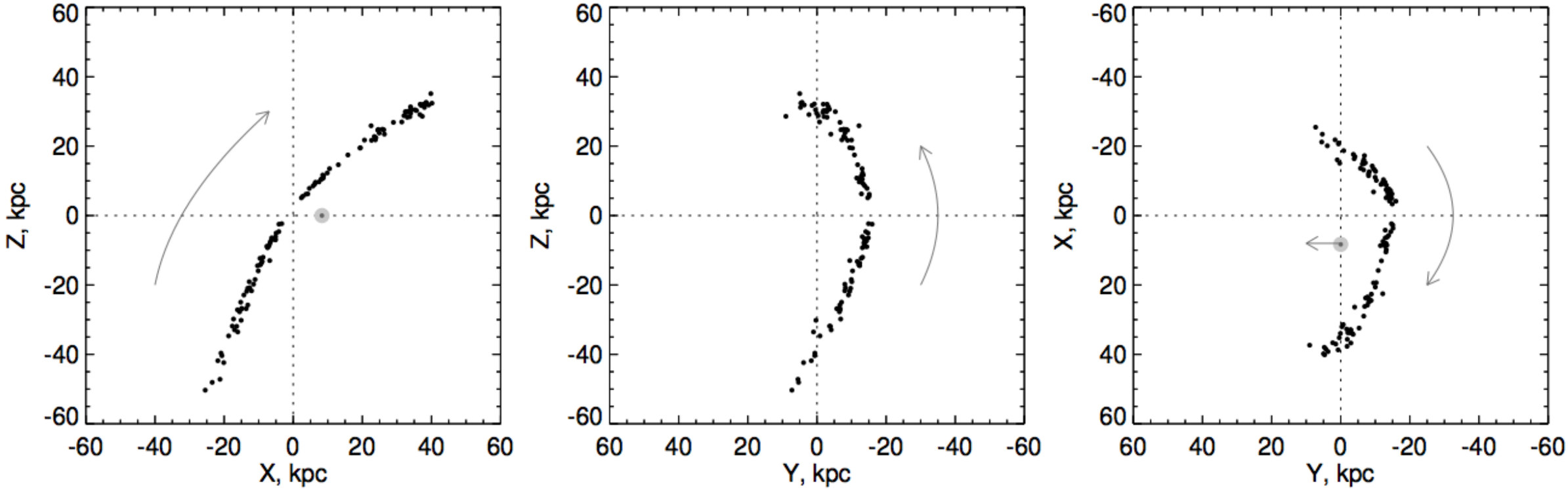

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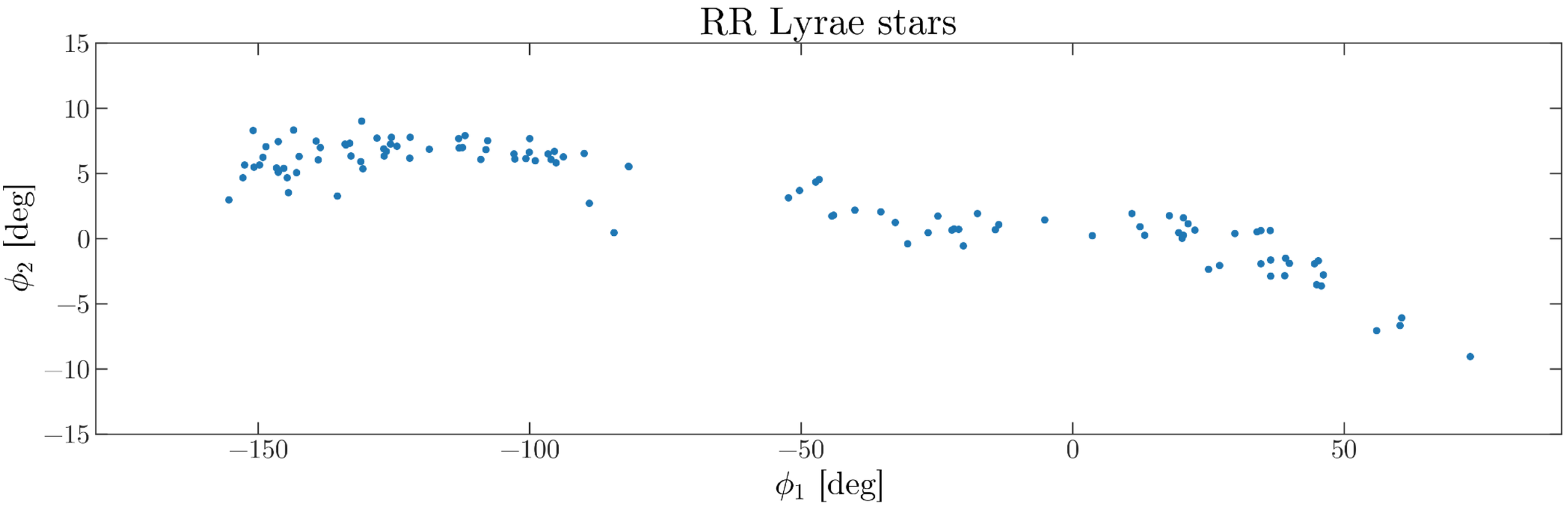

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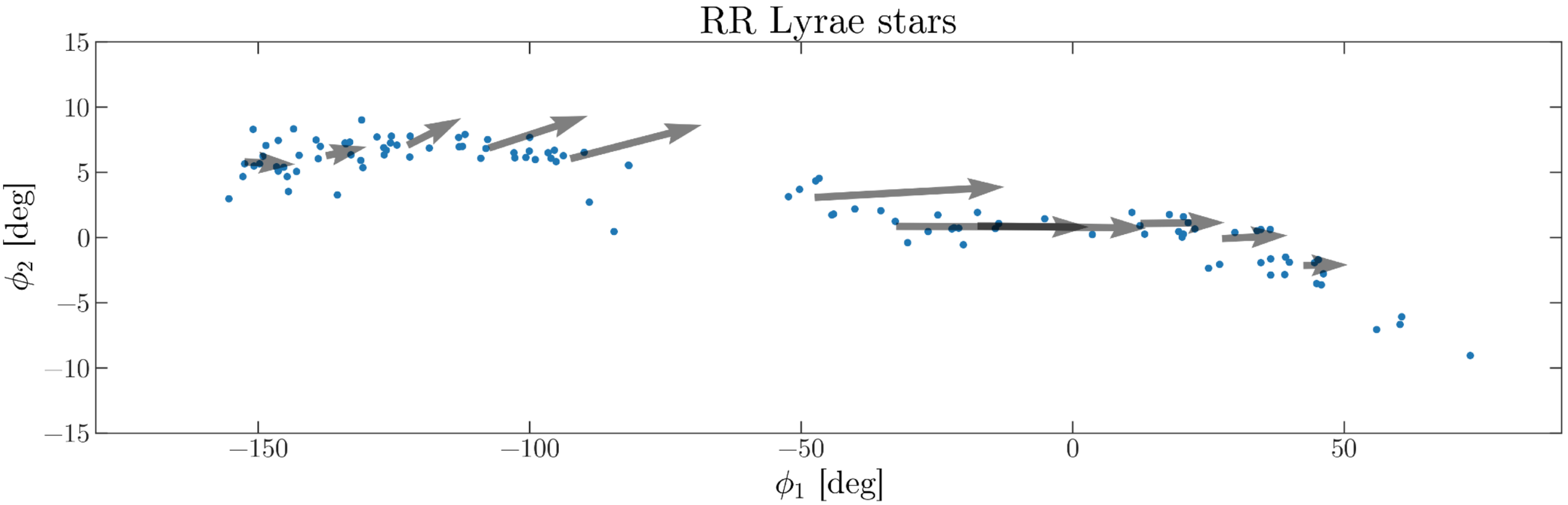

Proper motions don't point along the stream

Koposov, Belokurov, Li, Mateu, APW, Laporte, Evans et al. 2019

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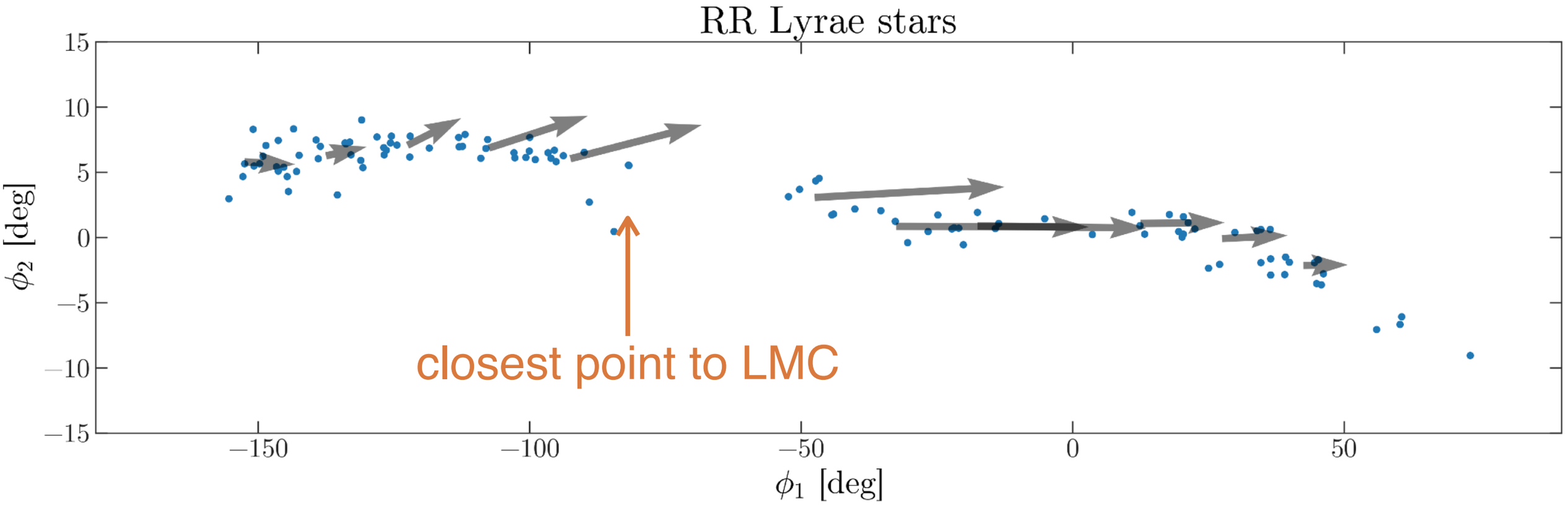

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Most of these are interesting in their own right

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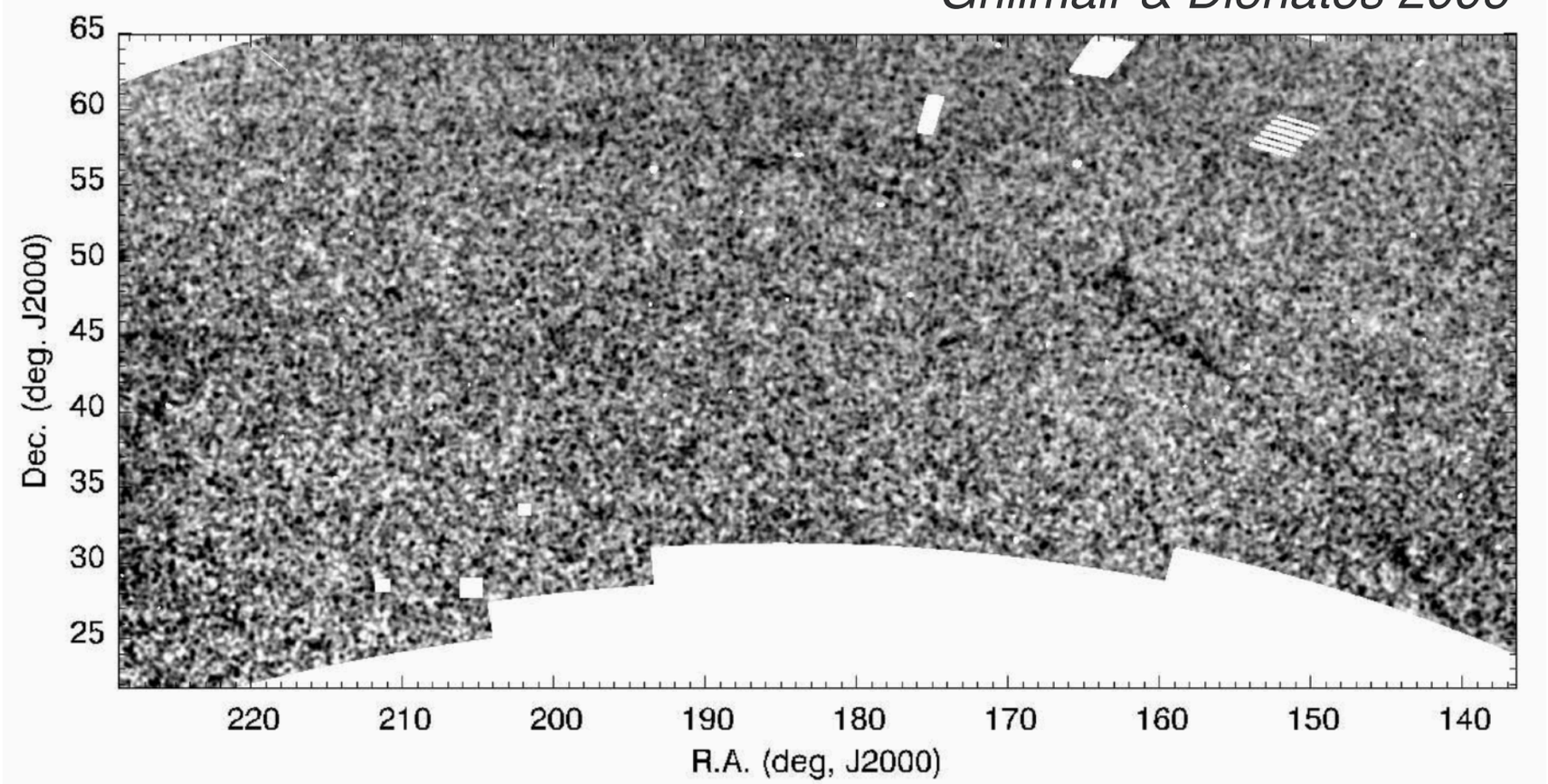
For what streams can we disentangle effects to study dark matter?

GD-1 is the most promising!

Discovery of GD-1 (of 1)

Grillmair & Dionatos 2006



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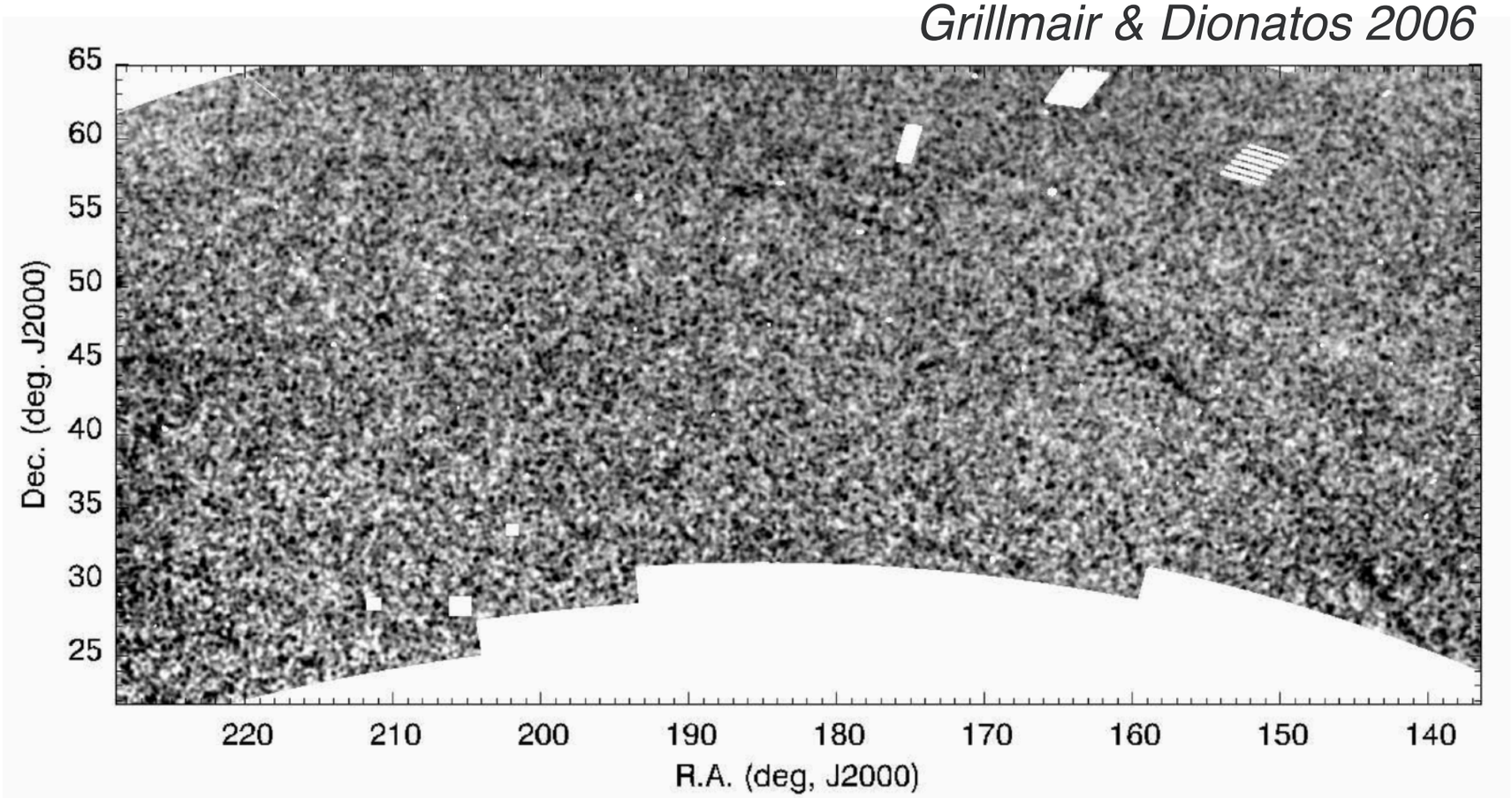

The longest thin stream: now known to be ~100º, 13–15 kpc

Metal-poor: [Fe/H] ~ -2

Old stellar population: ~12–13 Gyr

Relatively nearby: 8–10 kpc

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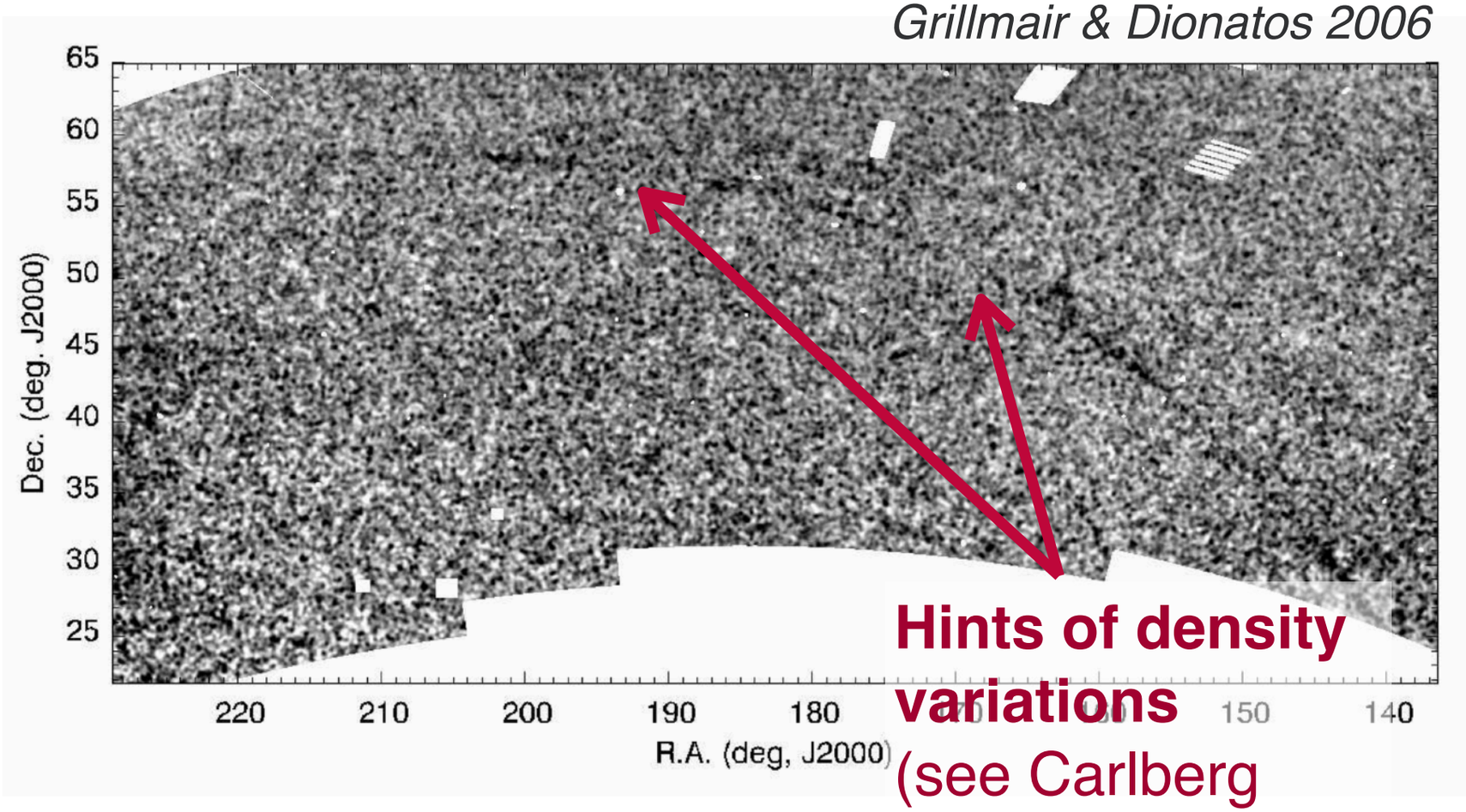

Hints of density variations (see Carlberg work 2013, 2016)

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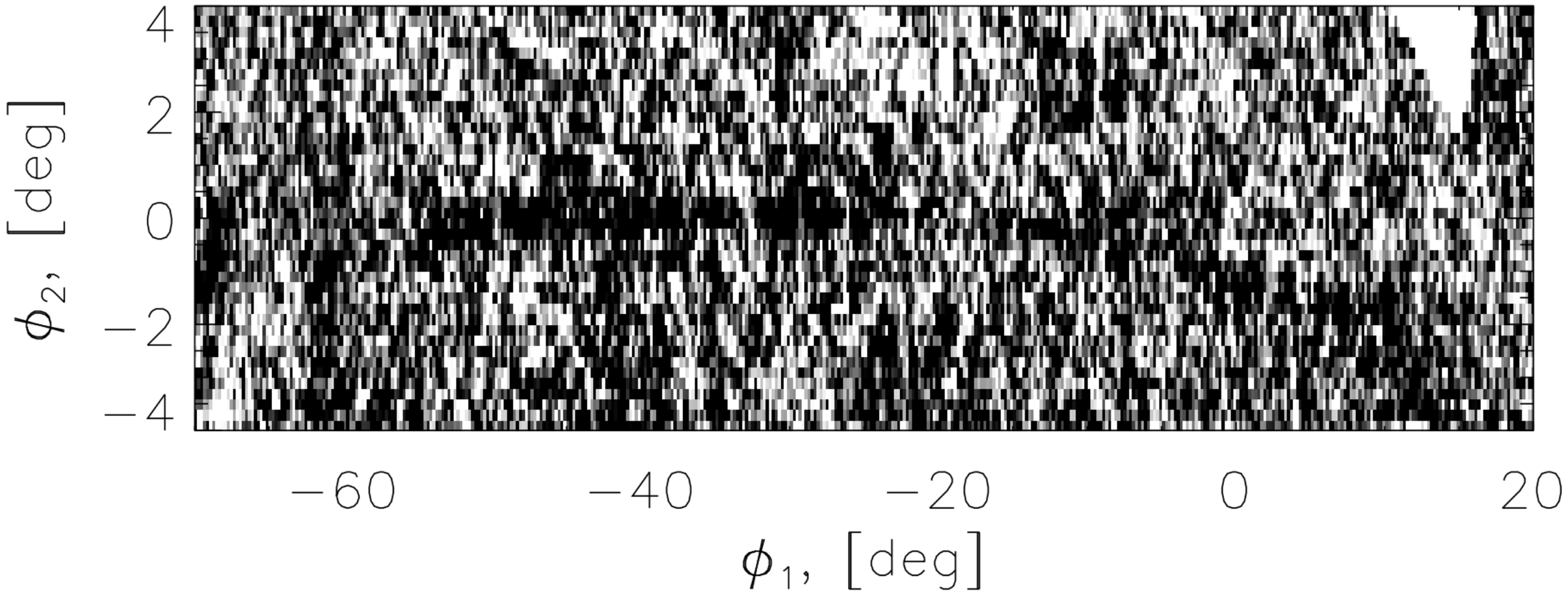
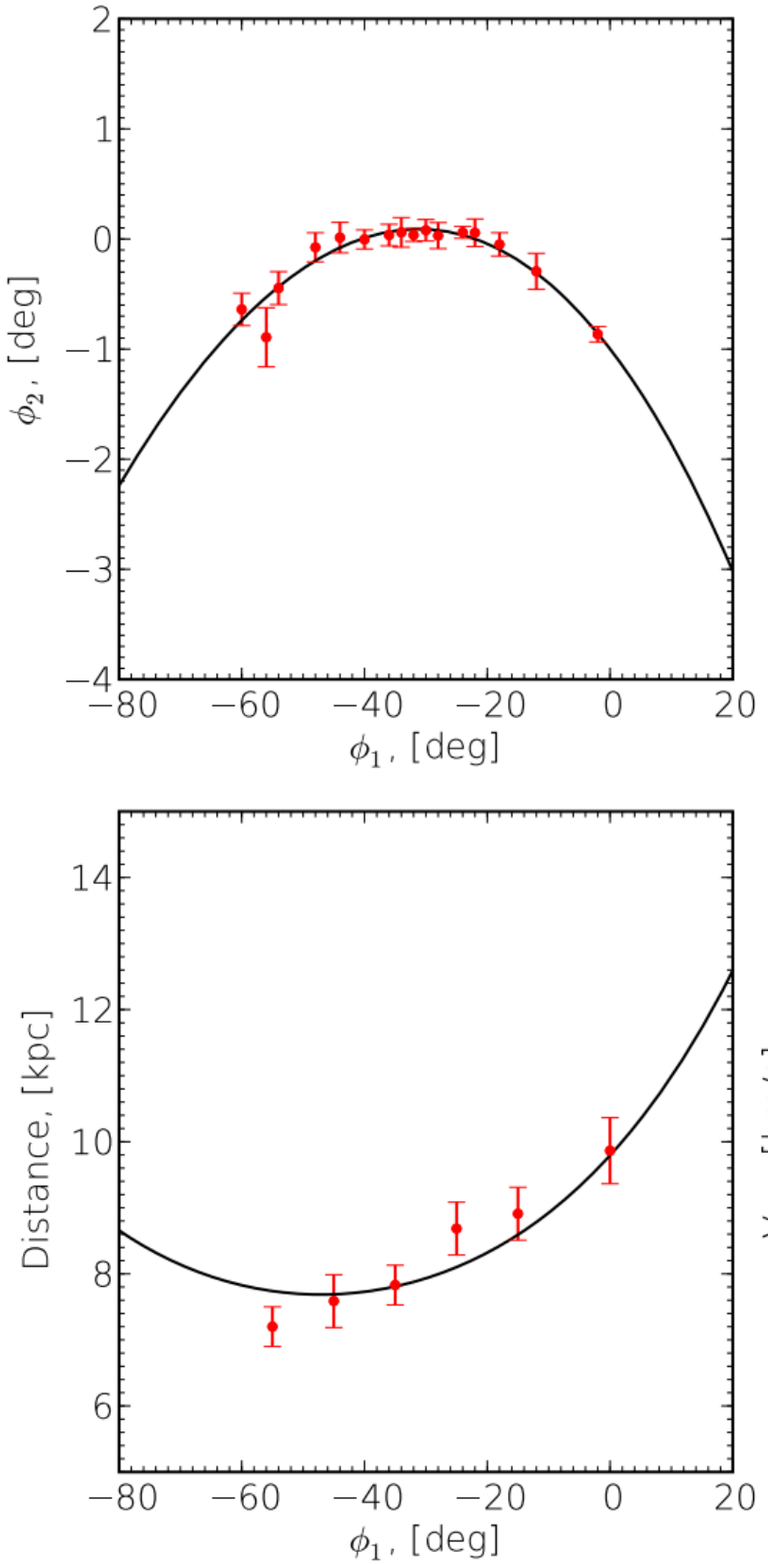
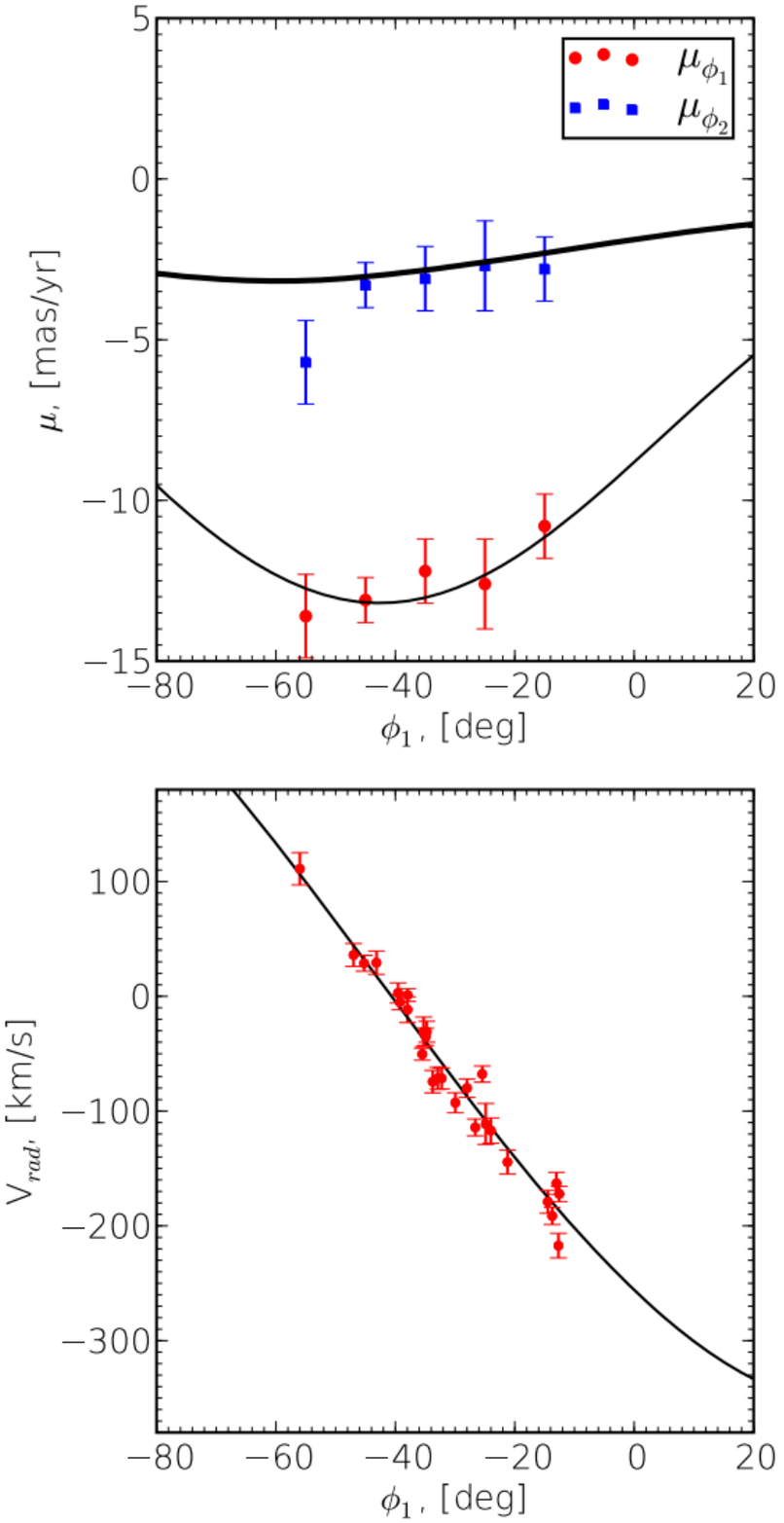


Koposov, Rix, Hogg 2010

the GD-1 stream

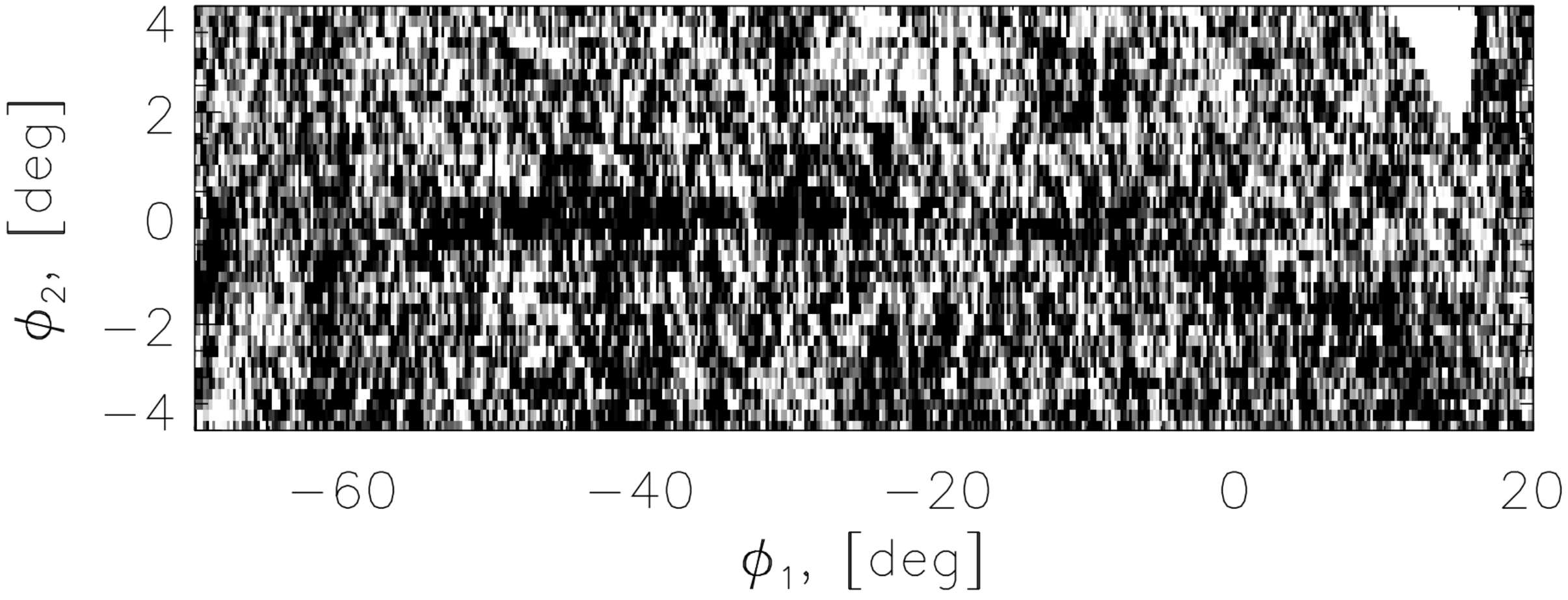




$$v_c(\mathrm{GD1}) \sim 220 \text{ km s}^{-1}$$

$$q_\Phi \sim 0.9$$

the GD-1 stream



density variations seen again

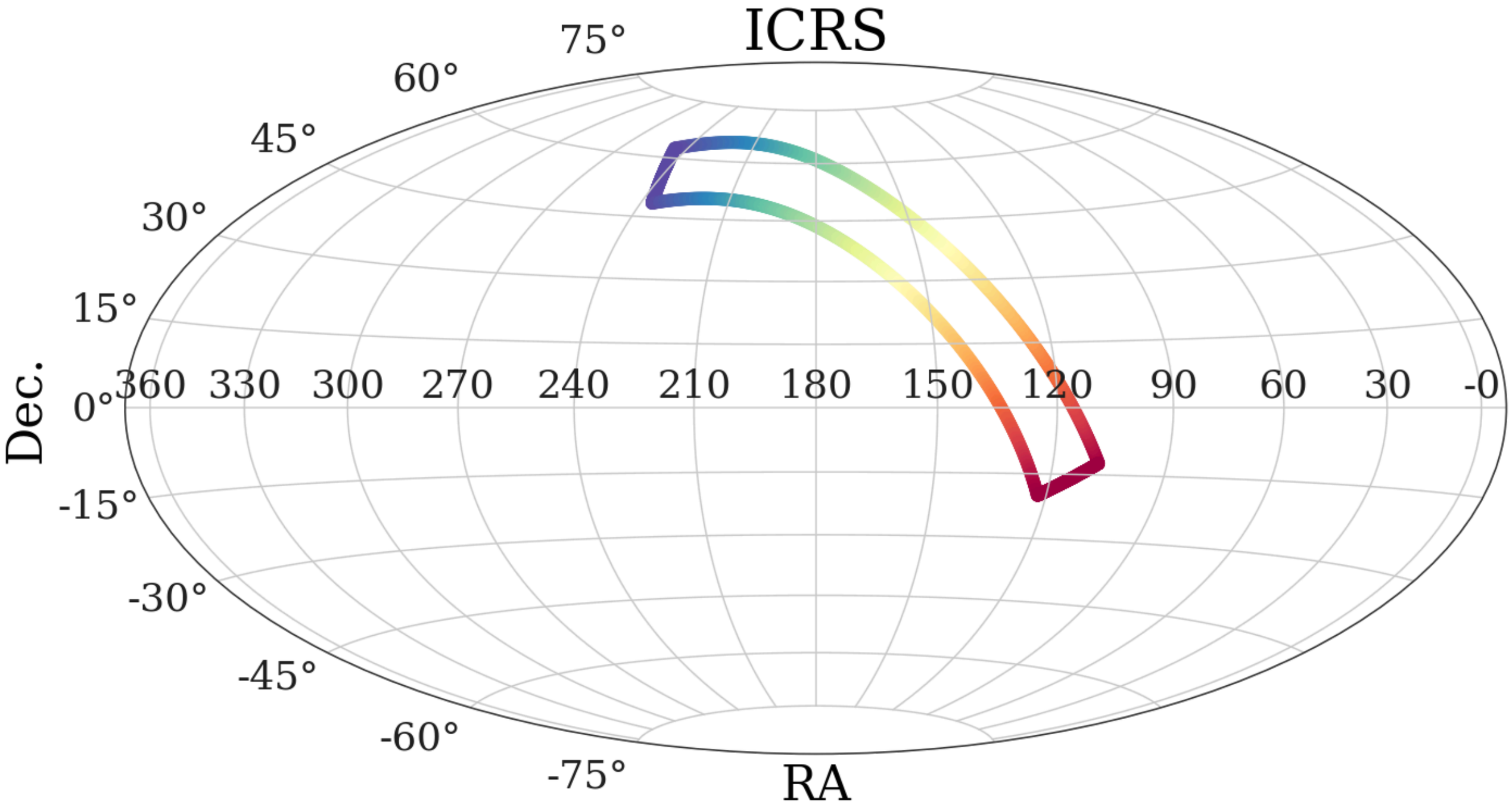
Koposov, Rix, Hogg 2010

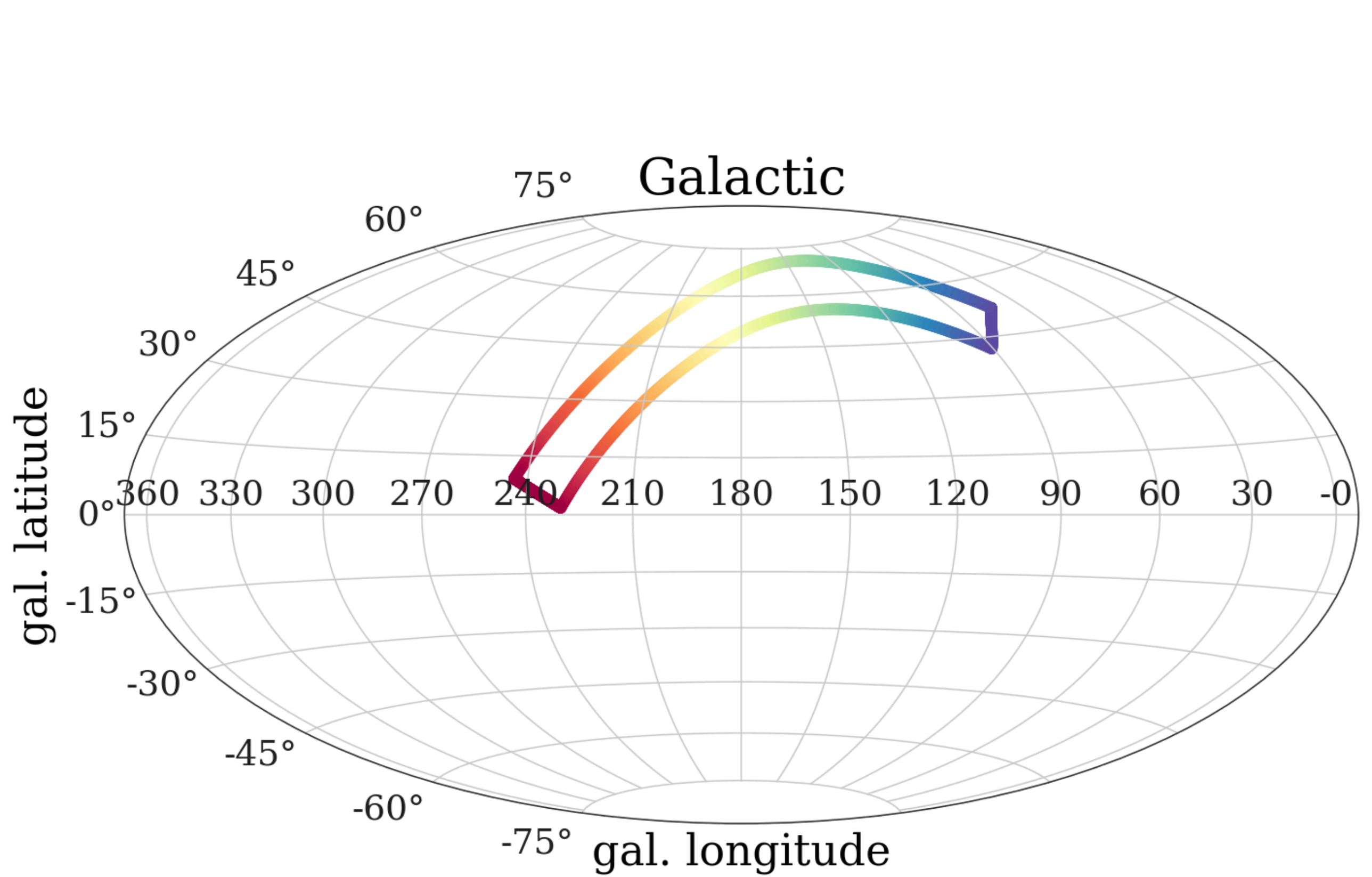
the GD-1 stream

It is interesting that the stream managed to evade possible destruction by interaction with DM subhalos orbiting around MW (Carlberg 2009). Although, the clumpiness observed in the stream may be attributed to these past interactions (S. E. Koposov et al. 2010, in preparation).

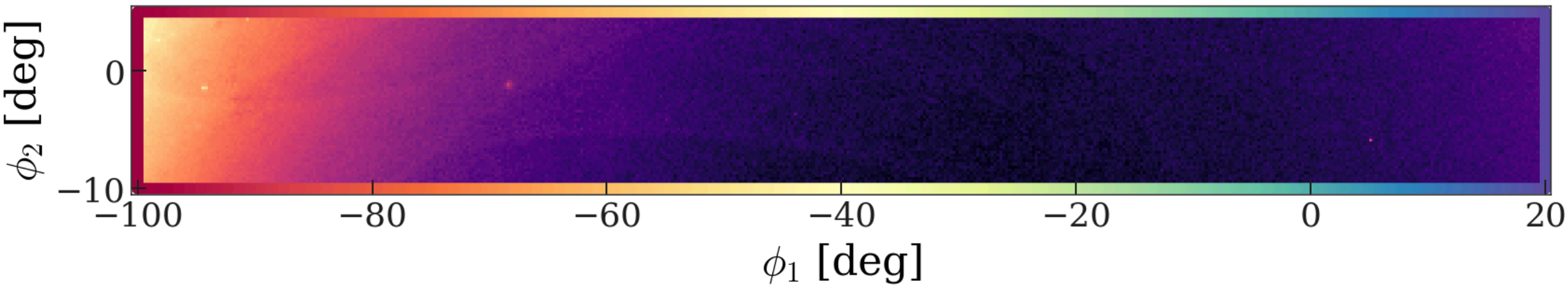
— Koposov, Rix, Hogg 2010

the GD-1 stream with Gaia+Pan-STARRS

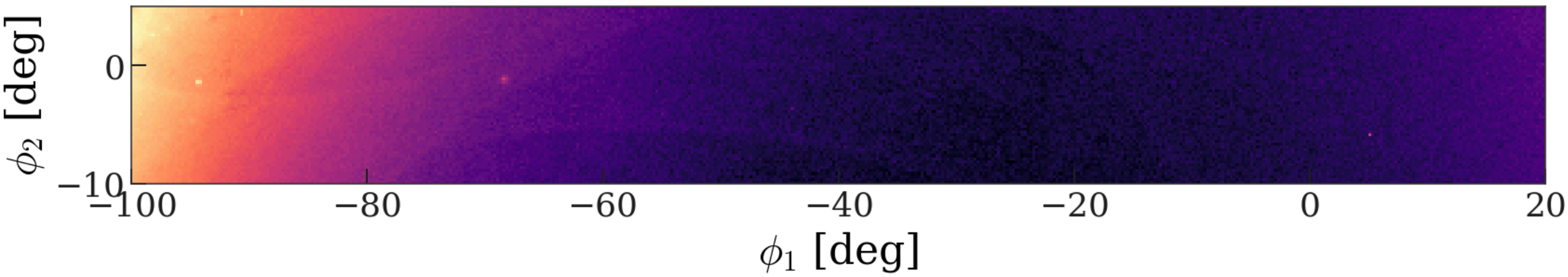

ICRS
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
360
330
300
270
240
210
180
150
120
90
60
30
-0
Dec.
RA


Galactic
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
360
330
300
270
240
210
180
150
120
90
60
30
-0
gal. latitude
gal. longitude

The GD-1 footprint in GD-1 coordinates

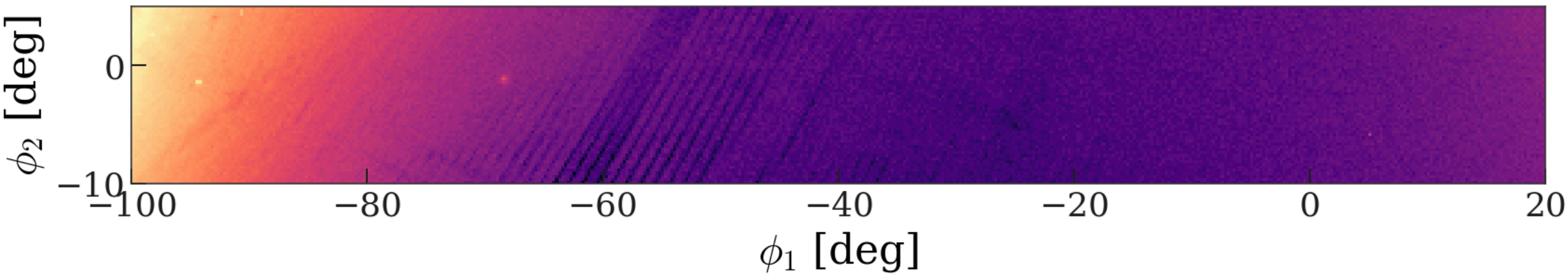


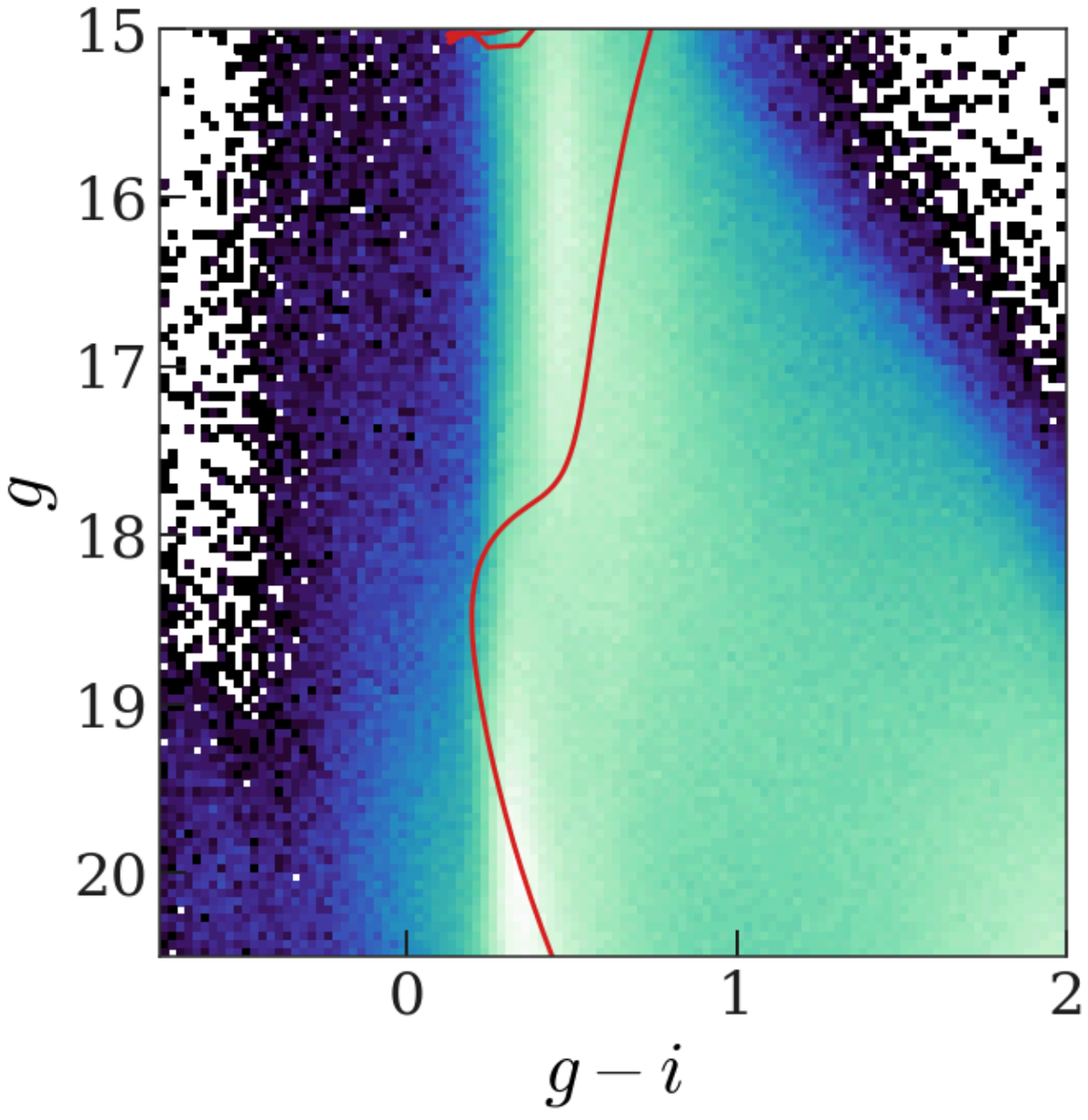
Density: all *Gaia* x Pan-STARRS

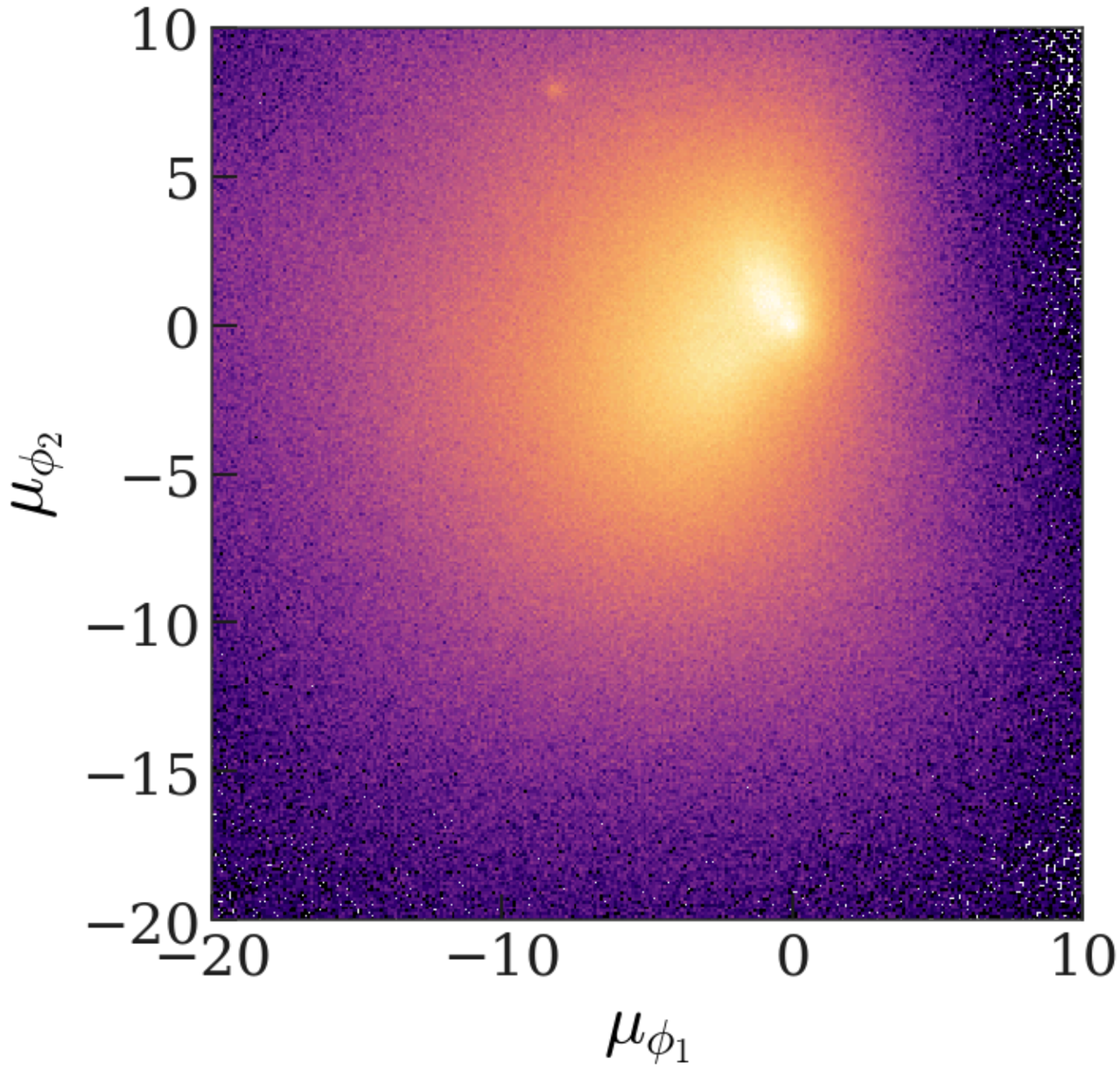


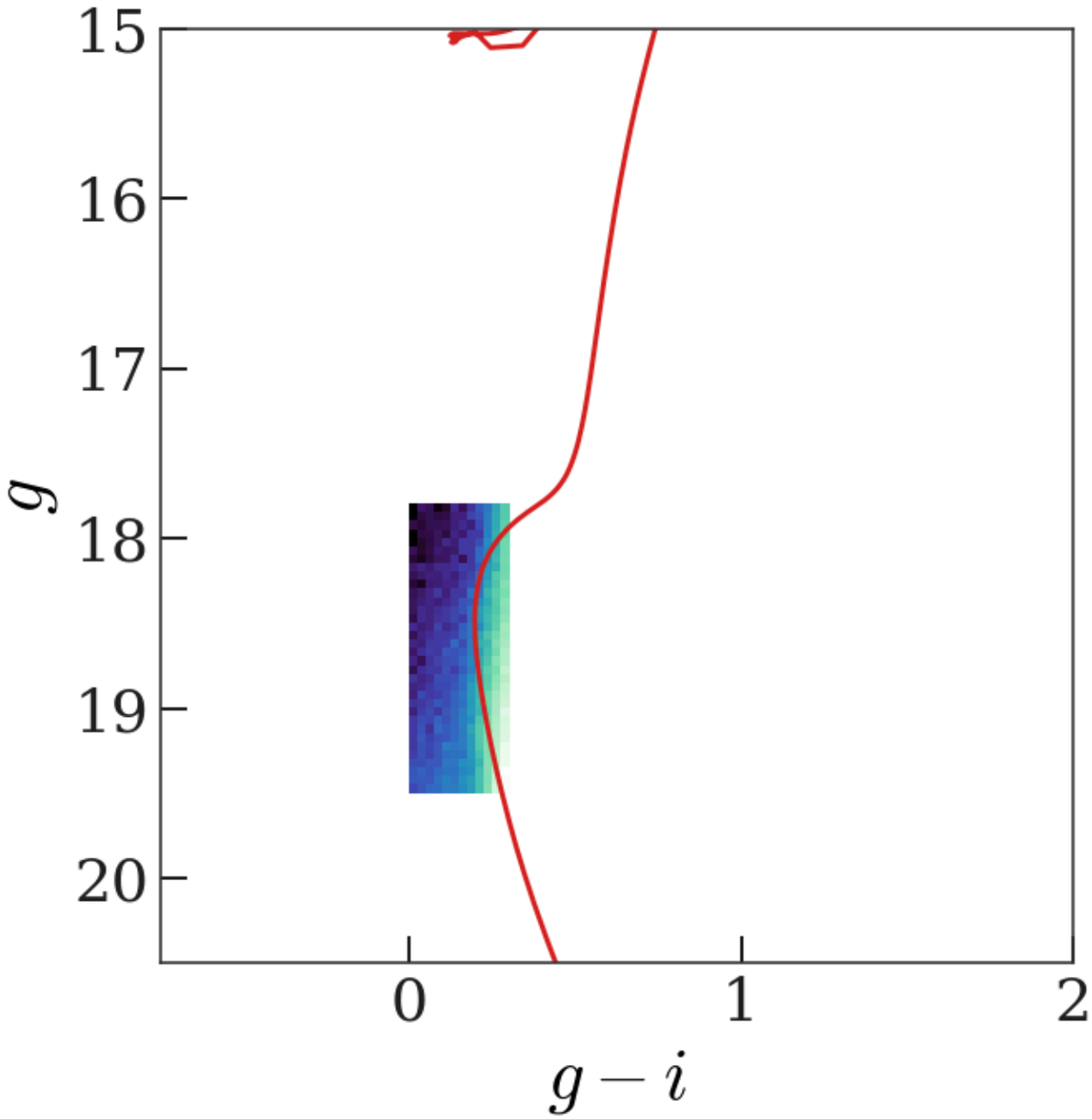
Density: all *Gaia* x Pan-STARRS, distant stars

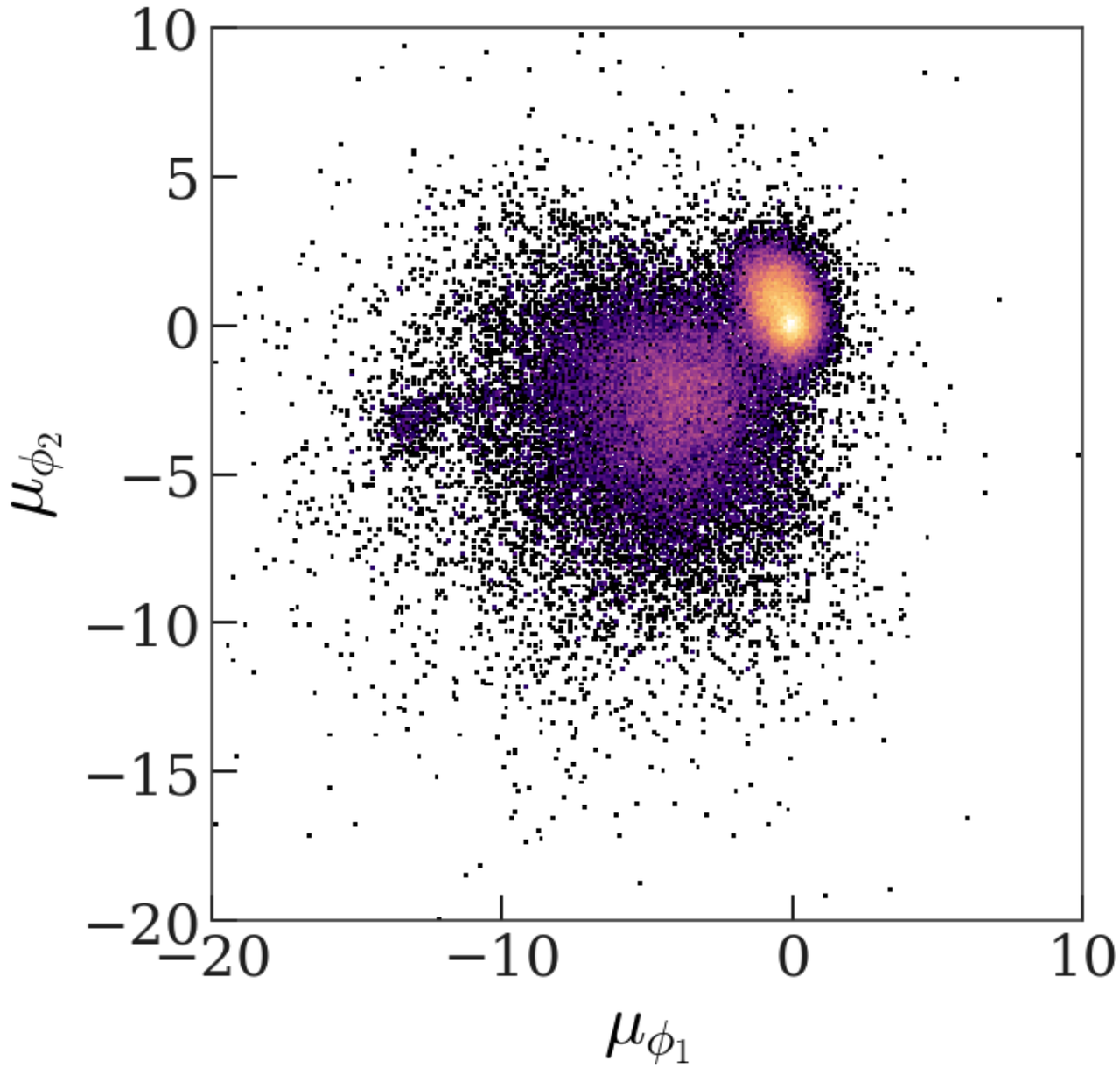
parallax < 1 mas

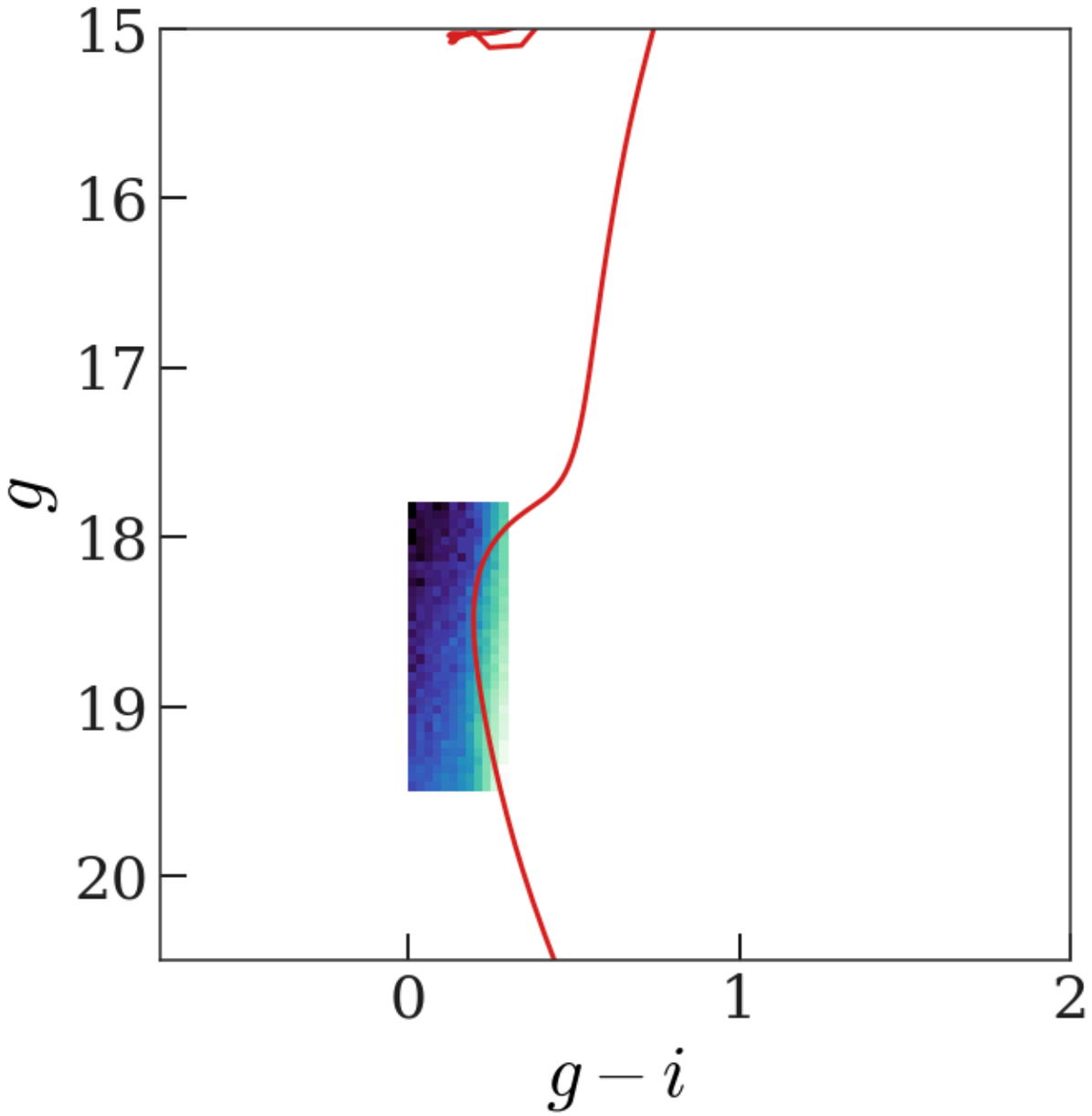


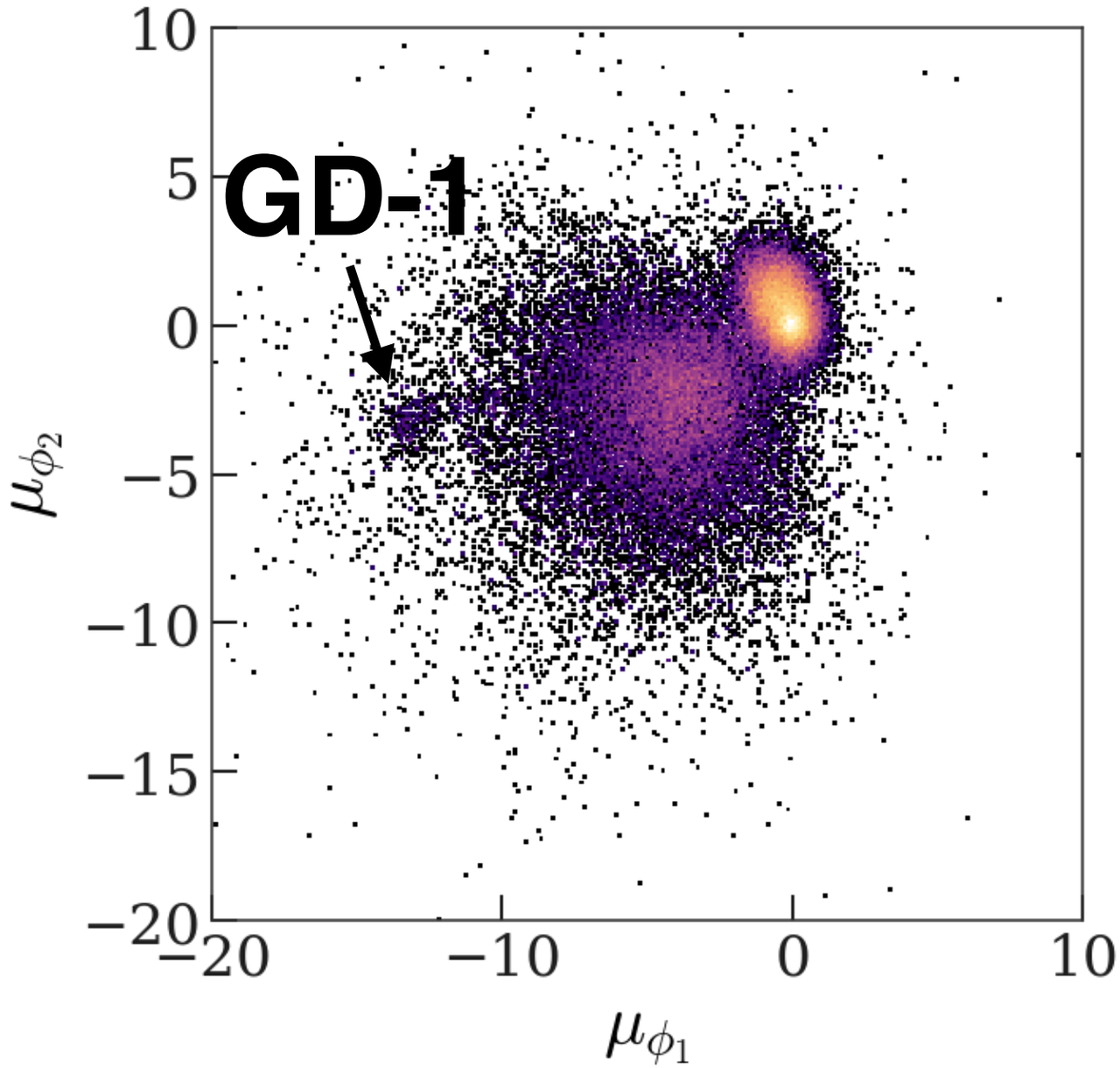

15
16
17
18
19
20
g
0
1
2
$g-i$

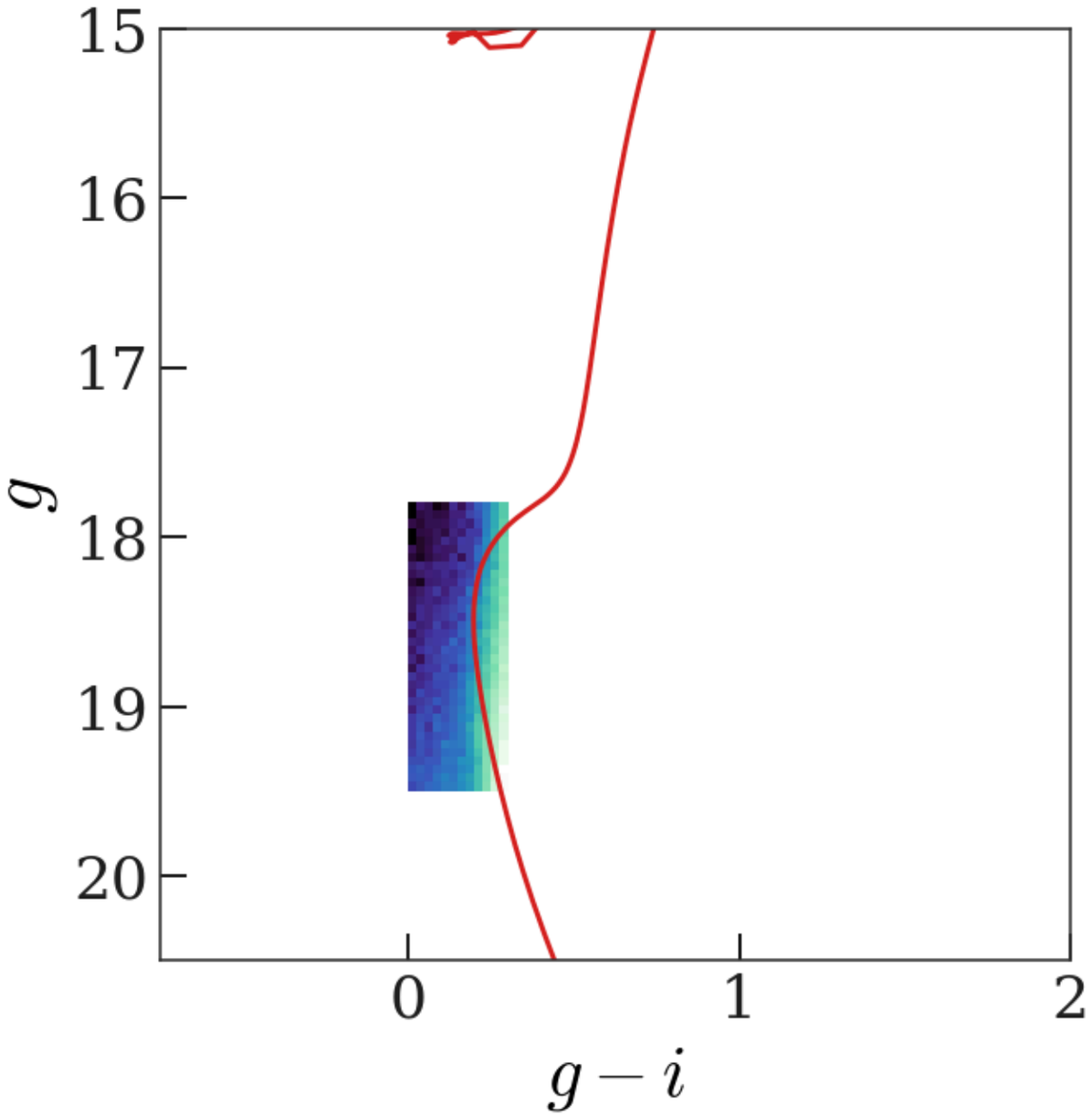

10
5
0
−5
−10
−15
−20
μ_{ϕ_2}
−20
−10
0
10
μ_{ϕ_1}

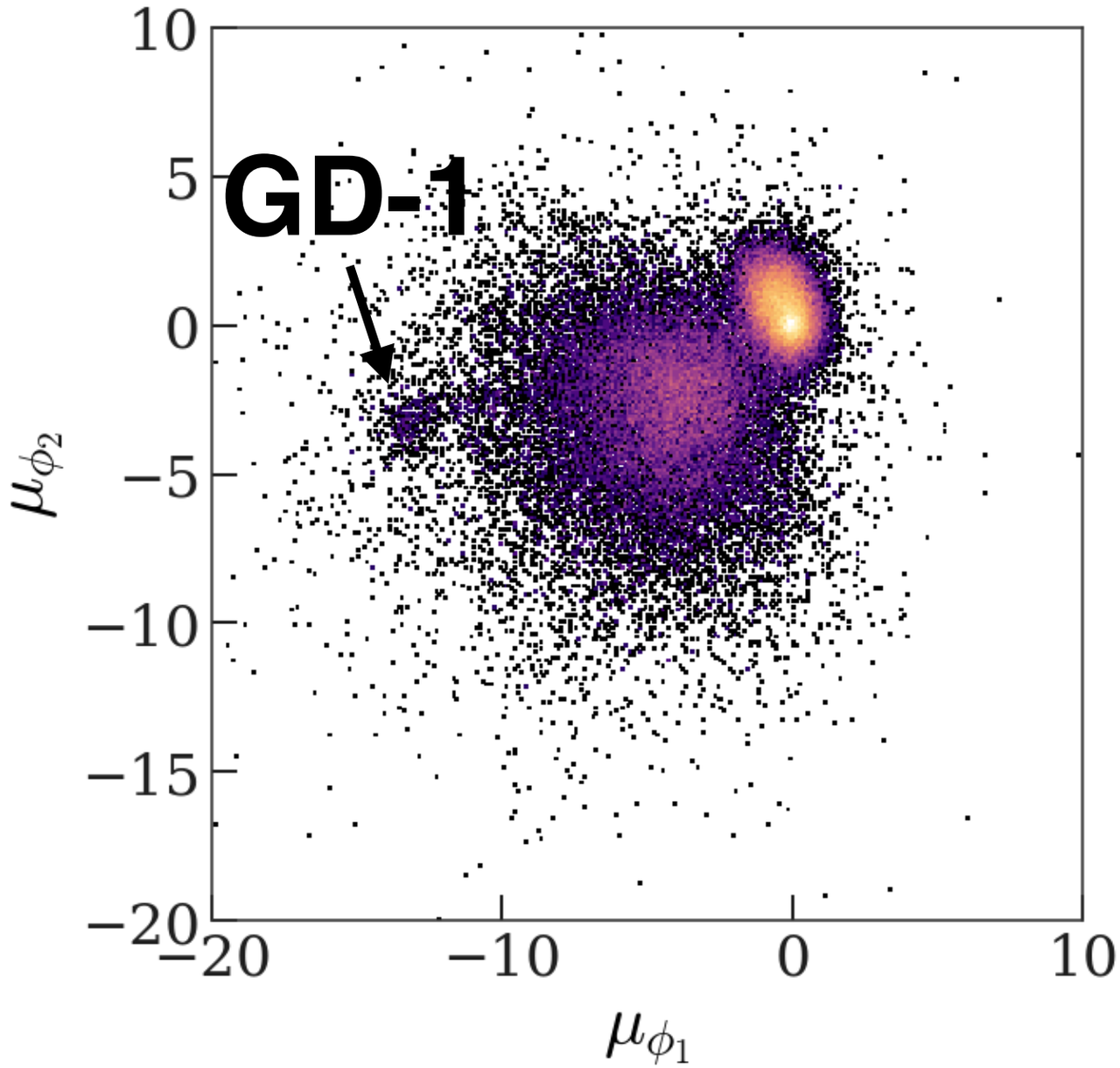

15
16
17
18
19
20
g
0
1
2
g − i


10
5
0
−5
−10
−15
−20
μϕ2
−20
−10
0
10
μϕ1

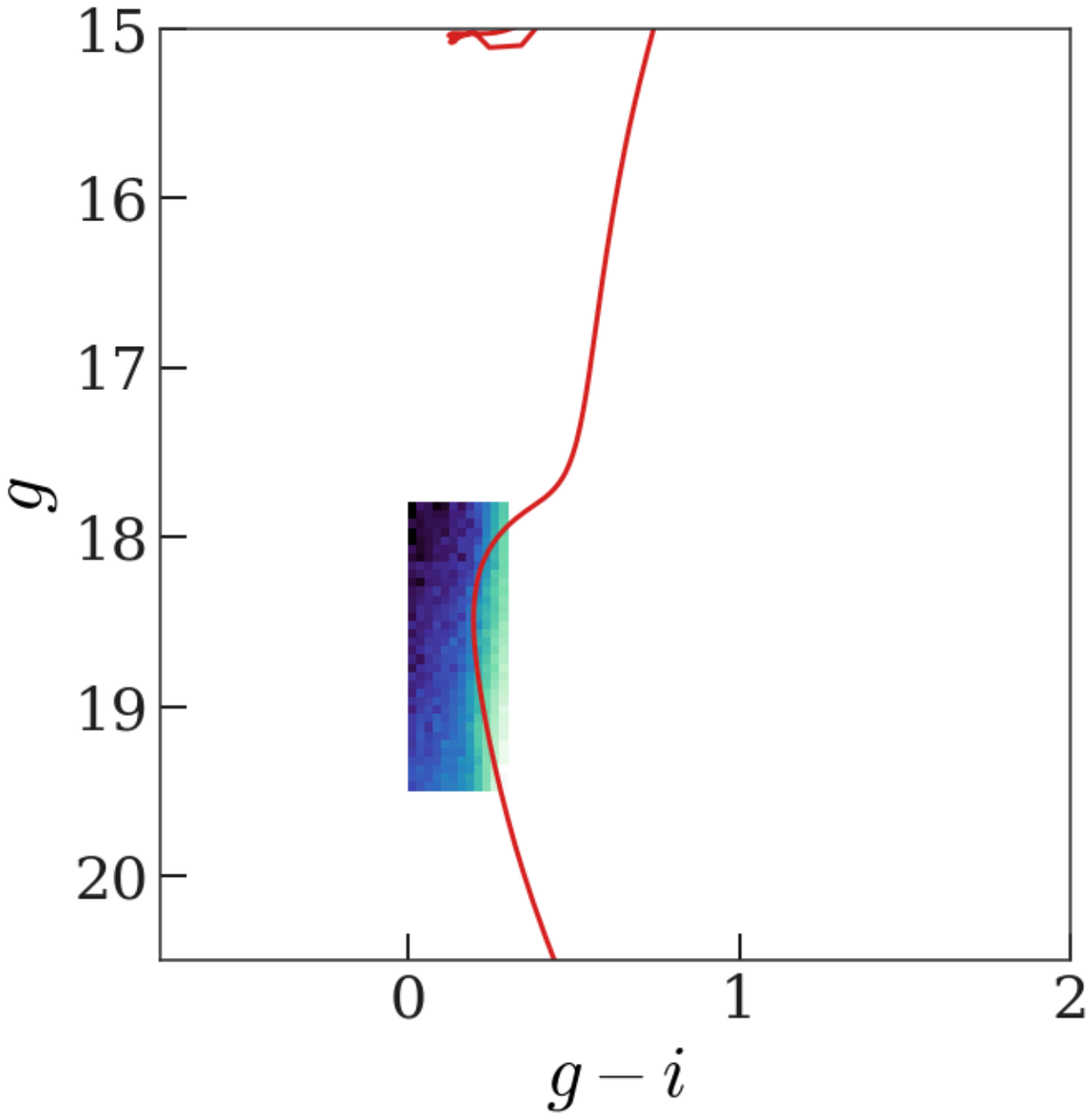

15
16
17
18
19
20
g
0
1
2
$g-i$

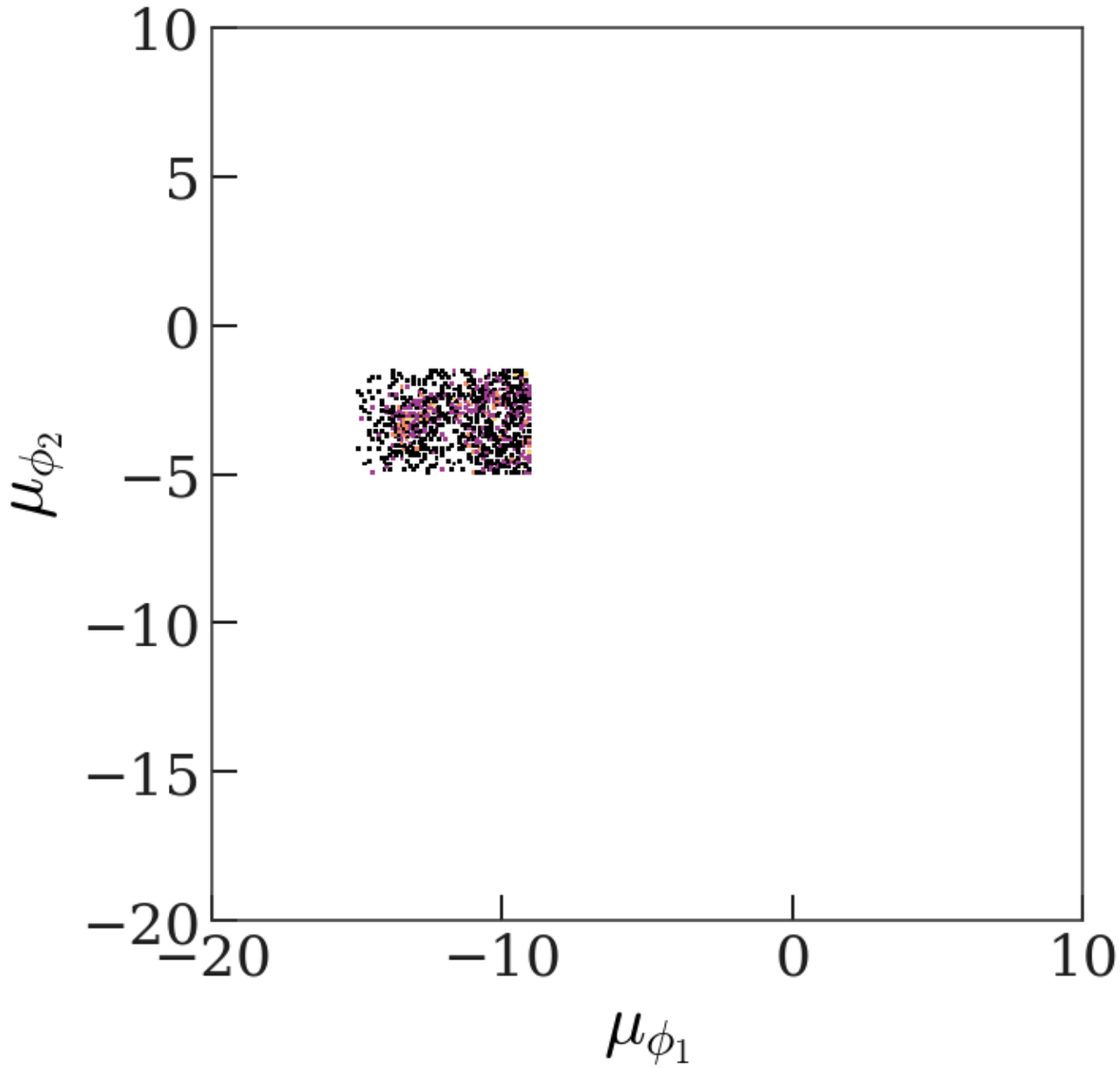

GD-1
10
5
0
−5
−10
−15
−20
μ_{ϕ_2}
−20
−10
0
10
μ_{ϕ_1}





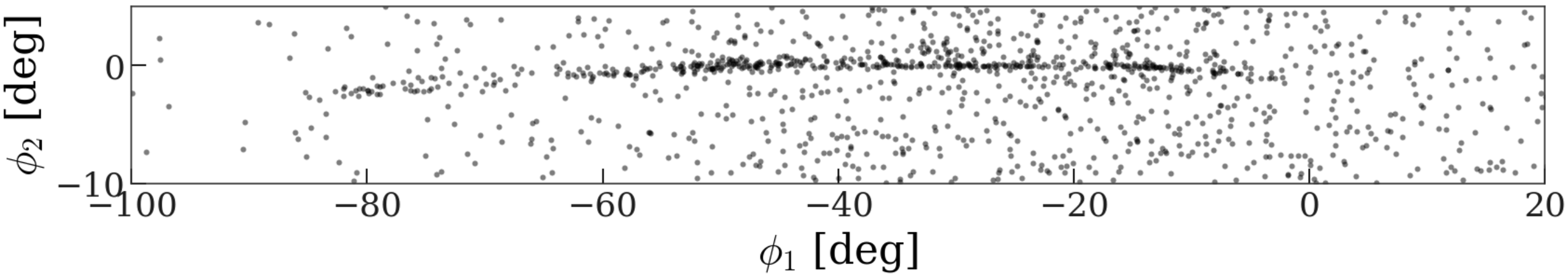
Note: GD-1 is kinematically distinct from the disk!

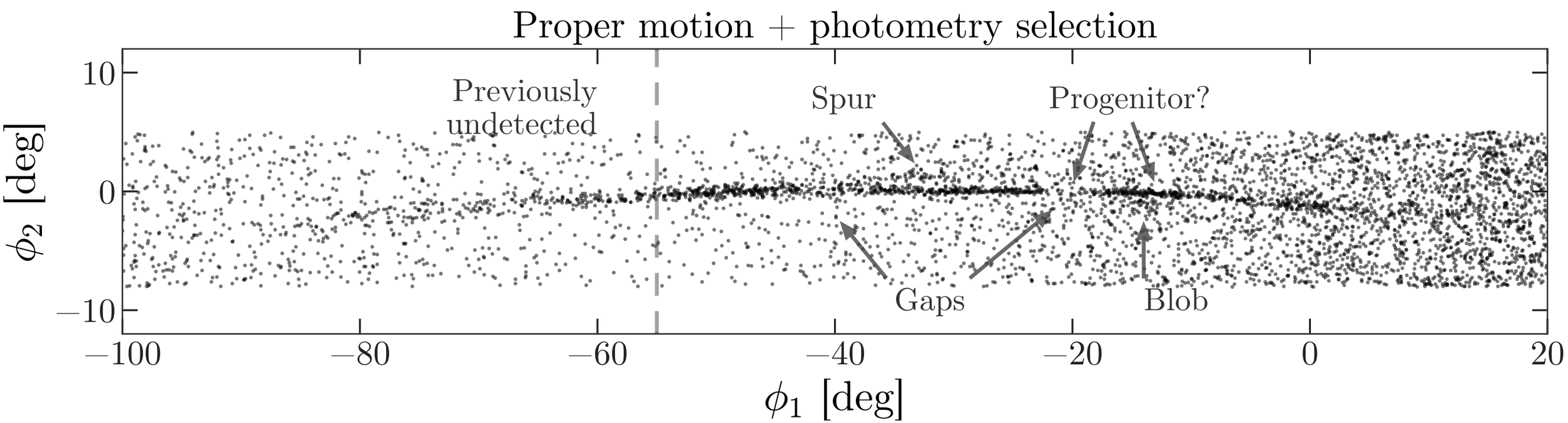

15
16
17
18
19
20
g
0
1
2
$g-i$


10
5
0
−5
−10
−15
−20
μ_{ϕ_2}
−20
−10
0
10
μ_{ϕ_1}

“fish in a barrel”

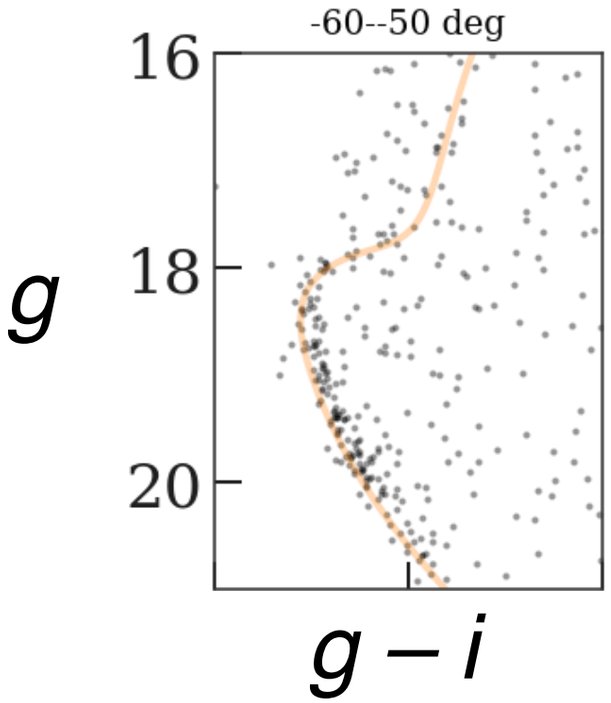
Very simple MSTO CMD + proper motion selection



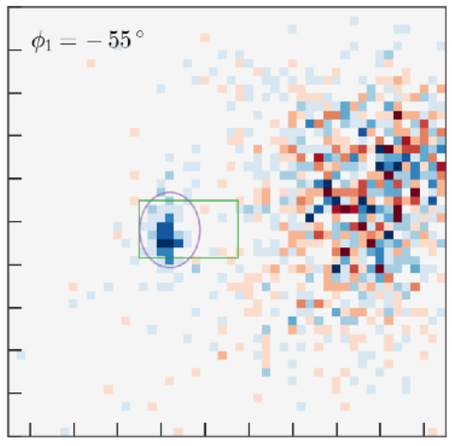


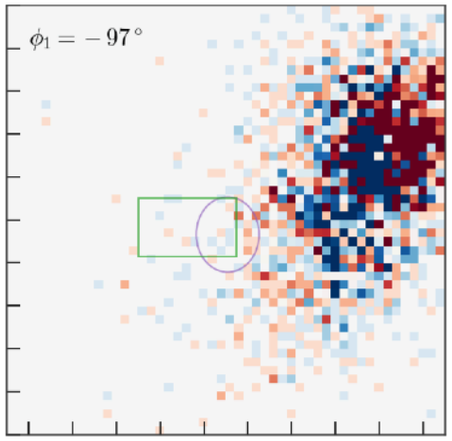
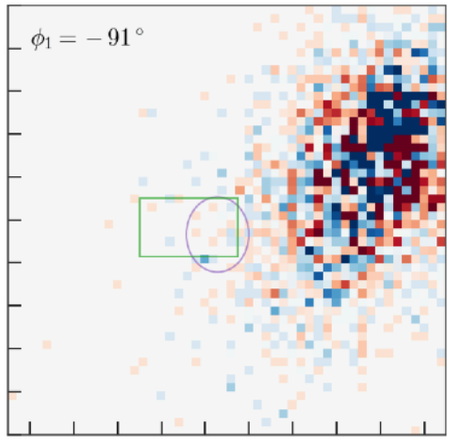
Data: Pan-STARRS+*Gaia*

***APW** & Bonaca 2018*


-60--50 deg
16
18
20
g
g – i

-100--90 deg
-90--80 deg
-80--70 deg
-70--60 deg
-60--50 deg
-50--40 deg
-40--30 deg
-30--20 deg
-20--10 deg
-10-0 deg
0-10 deg
10-20 deg
16
18
20
g


$\phi_1 = -55^\circ$


$\phi_1 = -97^\circ$

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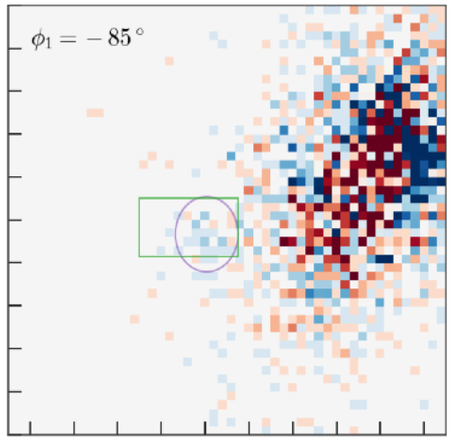
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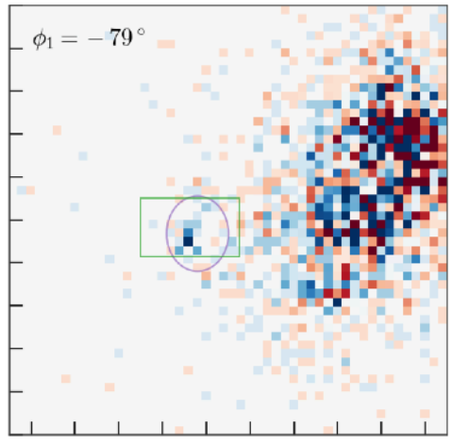
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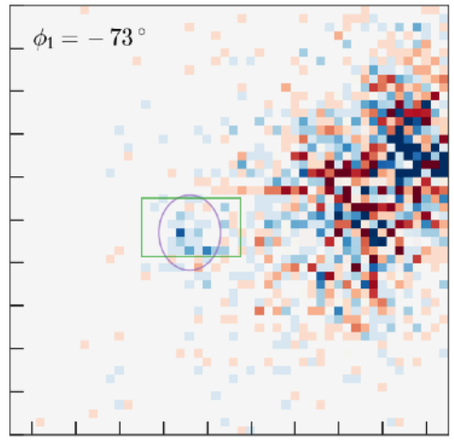
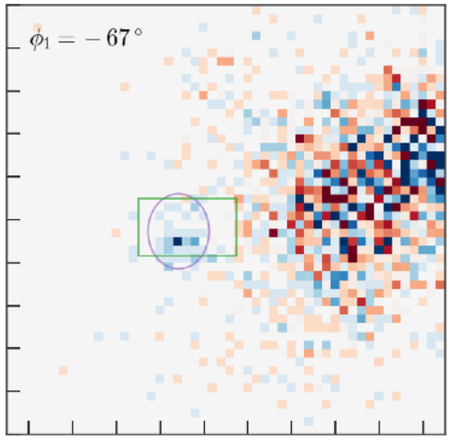

$\phi_1 = -73^\circ$

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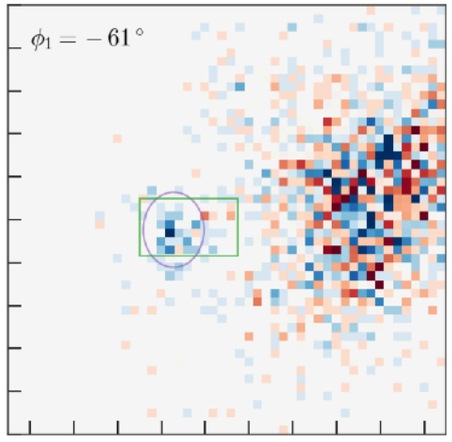
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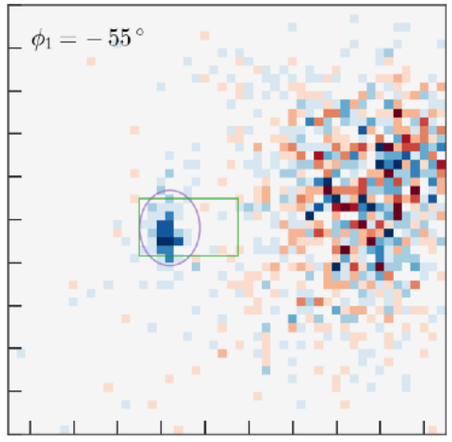
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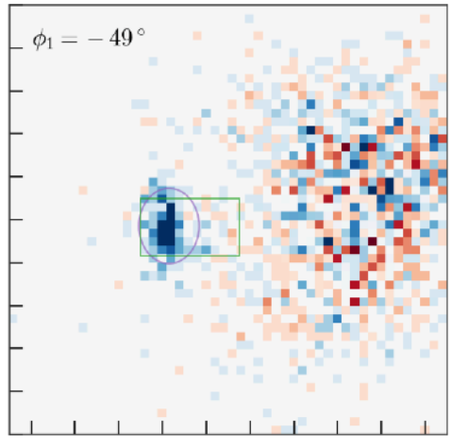
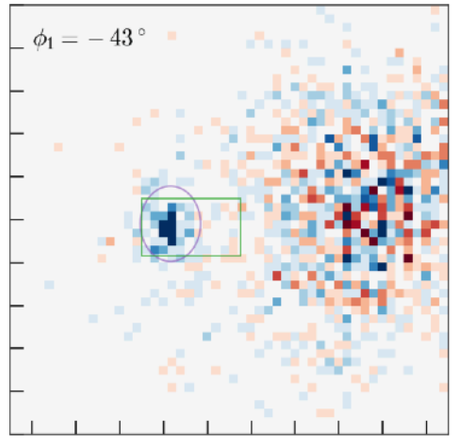

$\phi_1 = -49^\circ$

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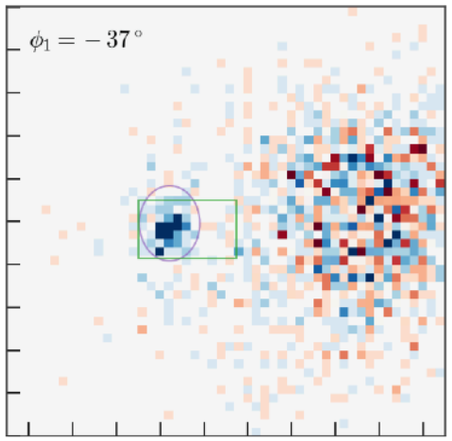
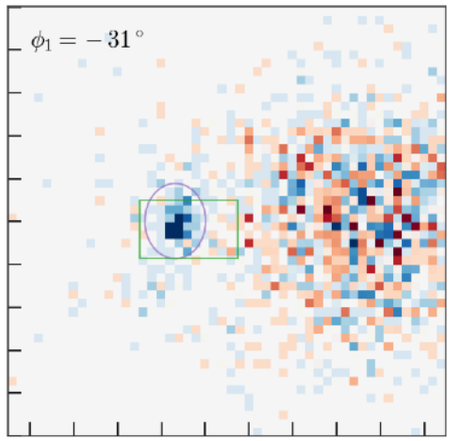

$\phi_1 = -37^\circ$

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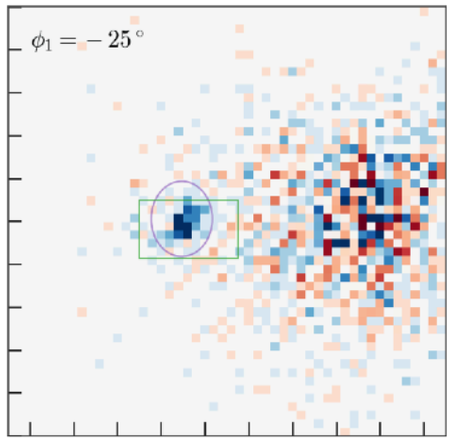
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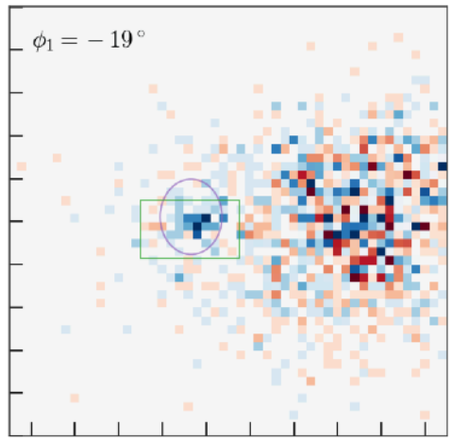
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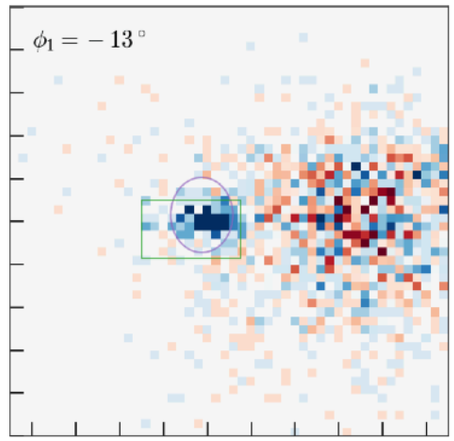
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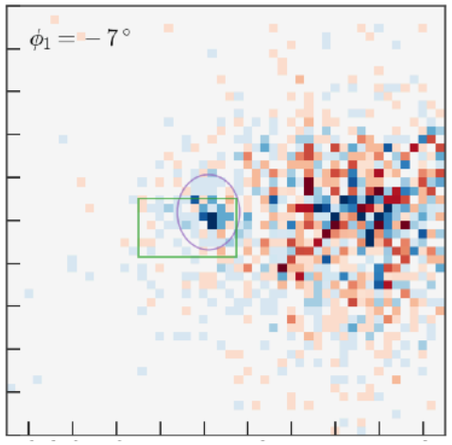
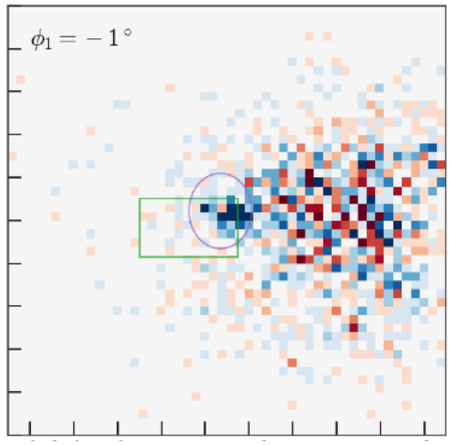
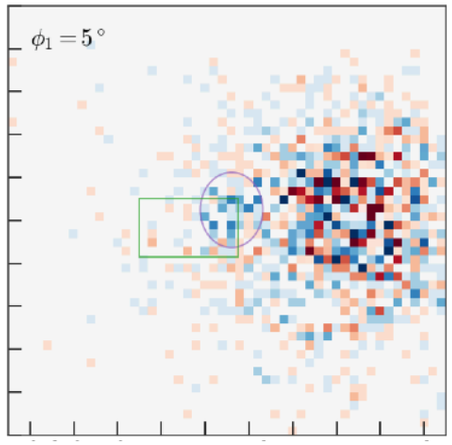
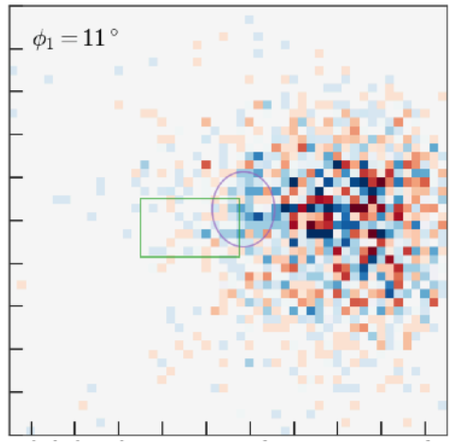

$\phi_1 = -7^\circ$

$\phi_1 = -1^\circ$

$\phi_1 = 5^\circ$

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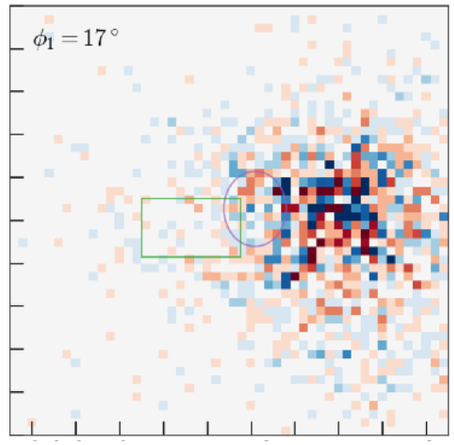
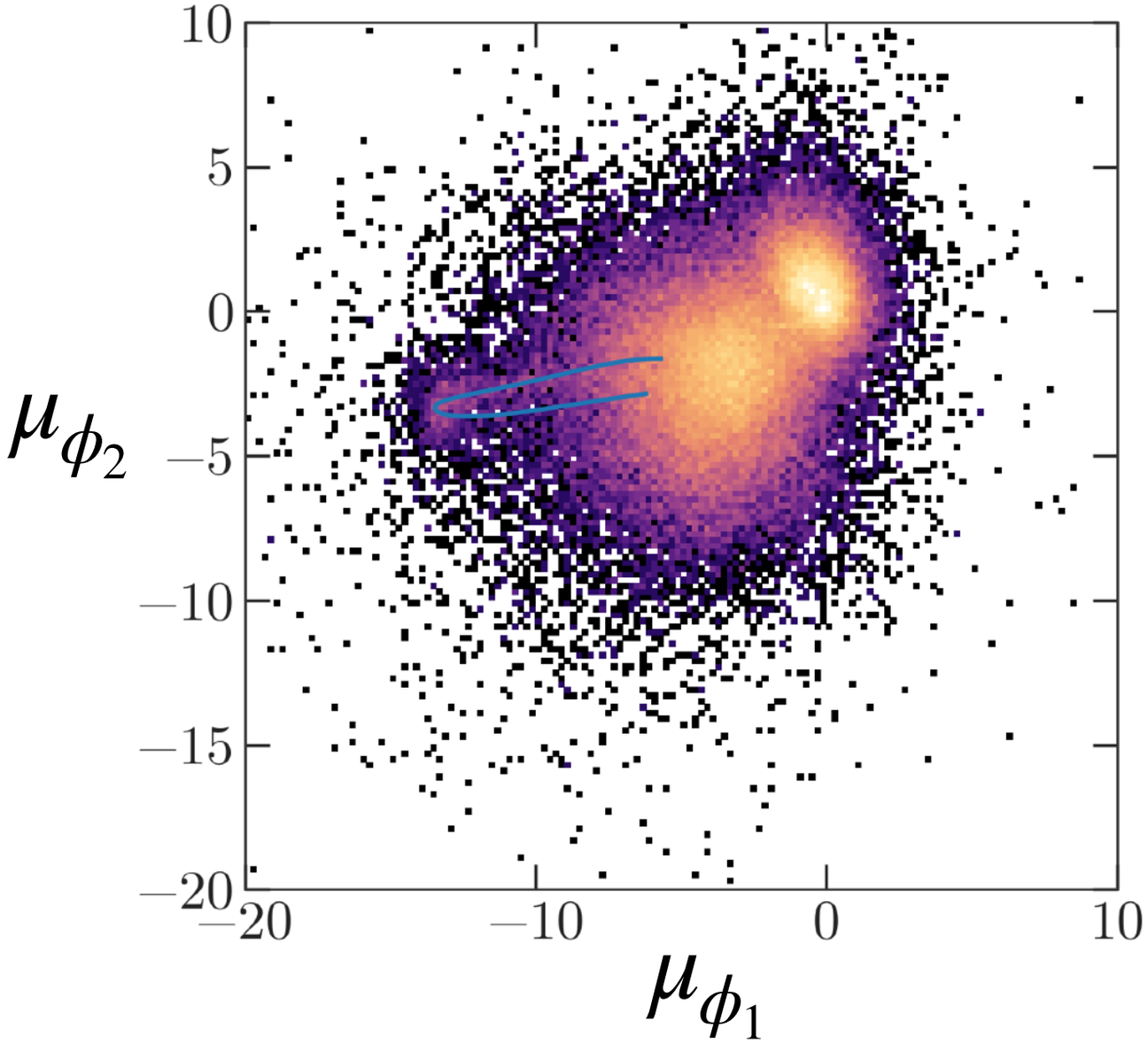

$\phi_1 = 17^\circ$

the GD-1 stream: improved selection

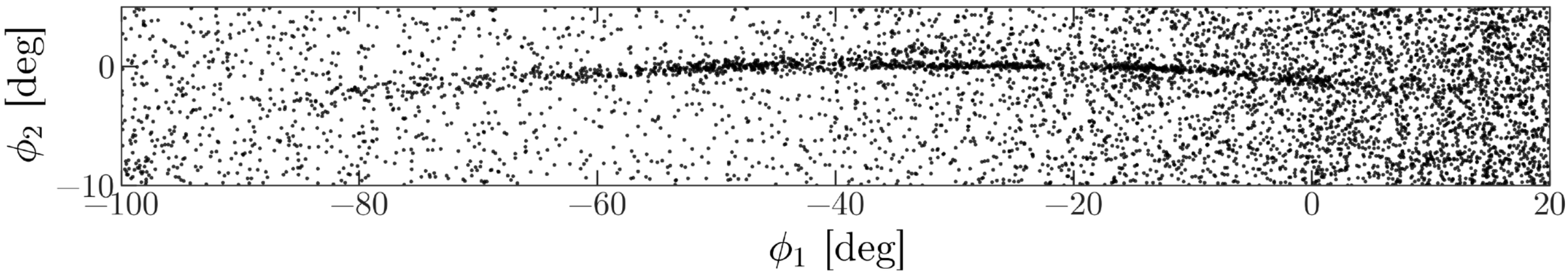
Simultaneously model the variation of the background (disk, halo) proper motion distribution + the stream (Gaussian mixture models for both)

Properly handle *Gaia* covariant astrometric errors



the GD-1 stream

initial *Gaia* DR2 (photometric + proper motion selection)

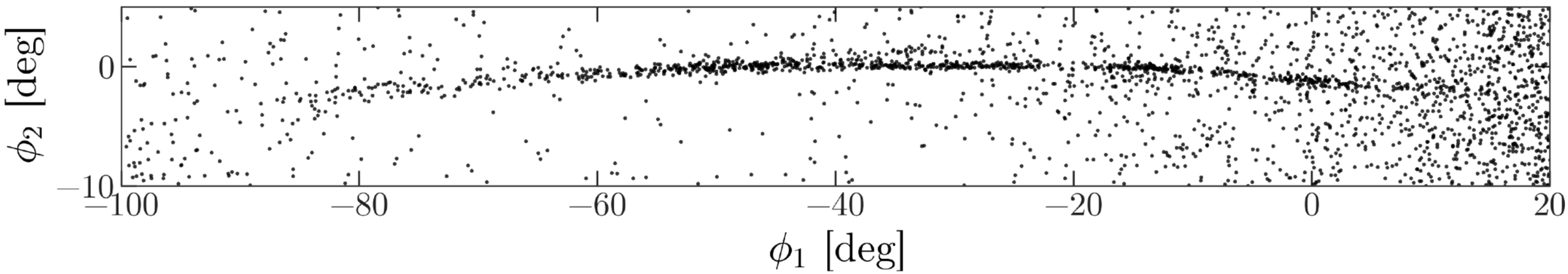


Data: Pan-STARRS+*Gaia*

***APW** & Bonaca 2018*

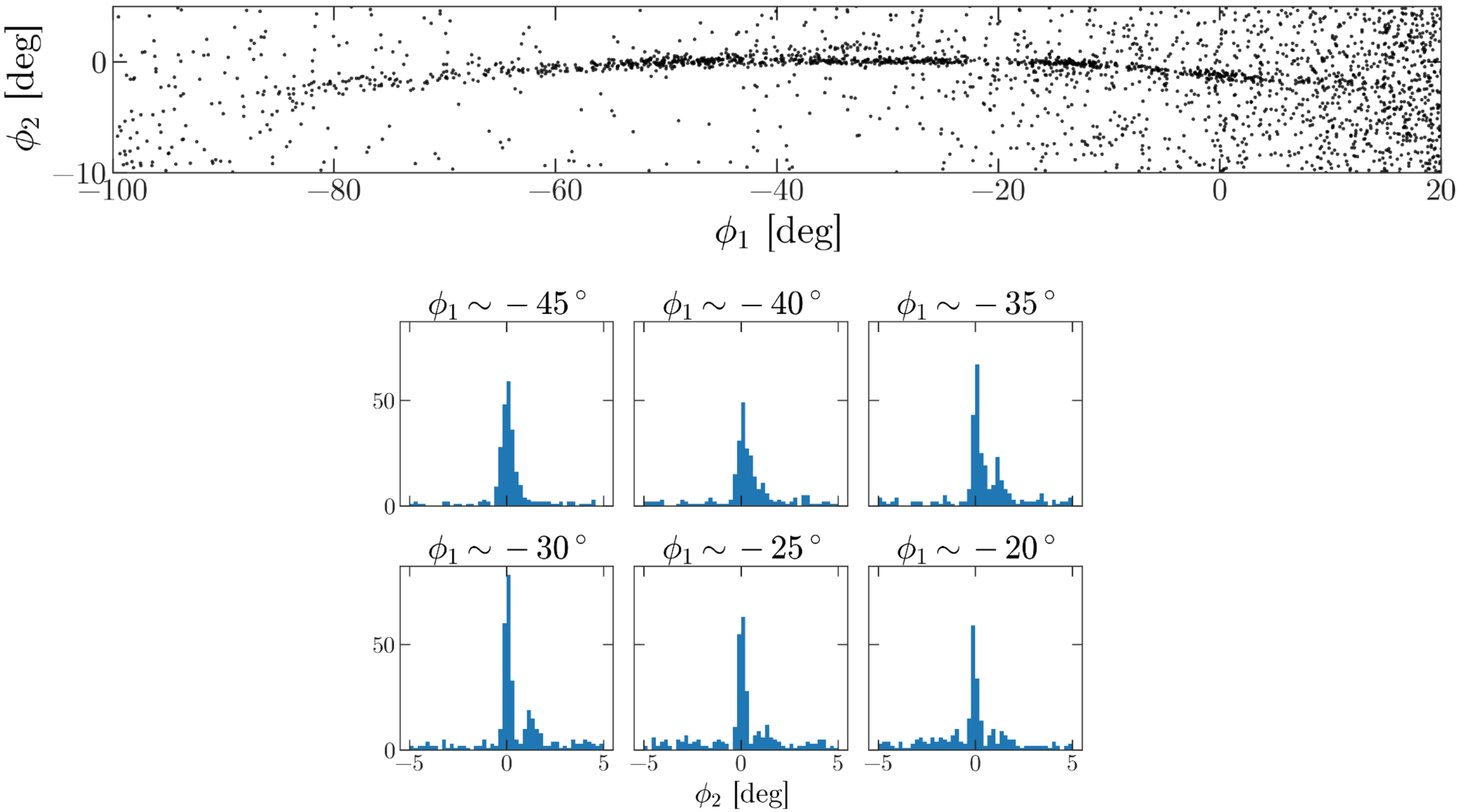
the GD-1 stream

simultaneously infer distance, proper motion vs. longitude



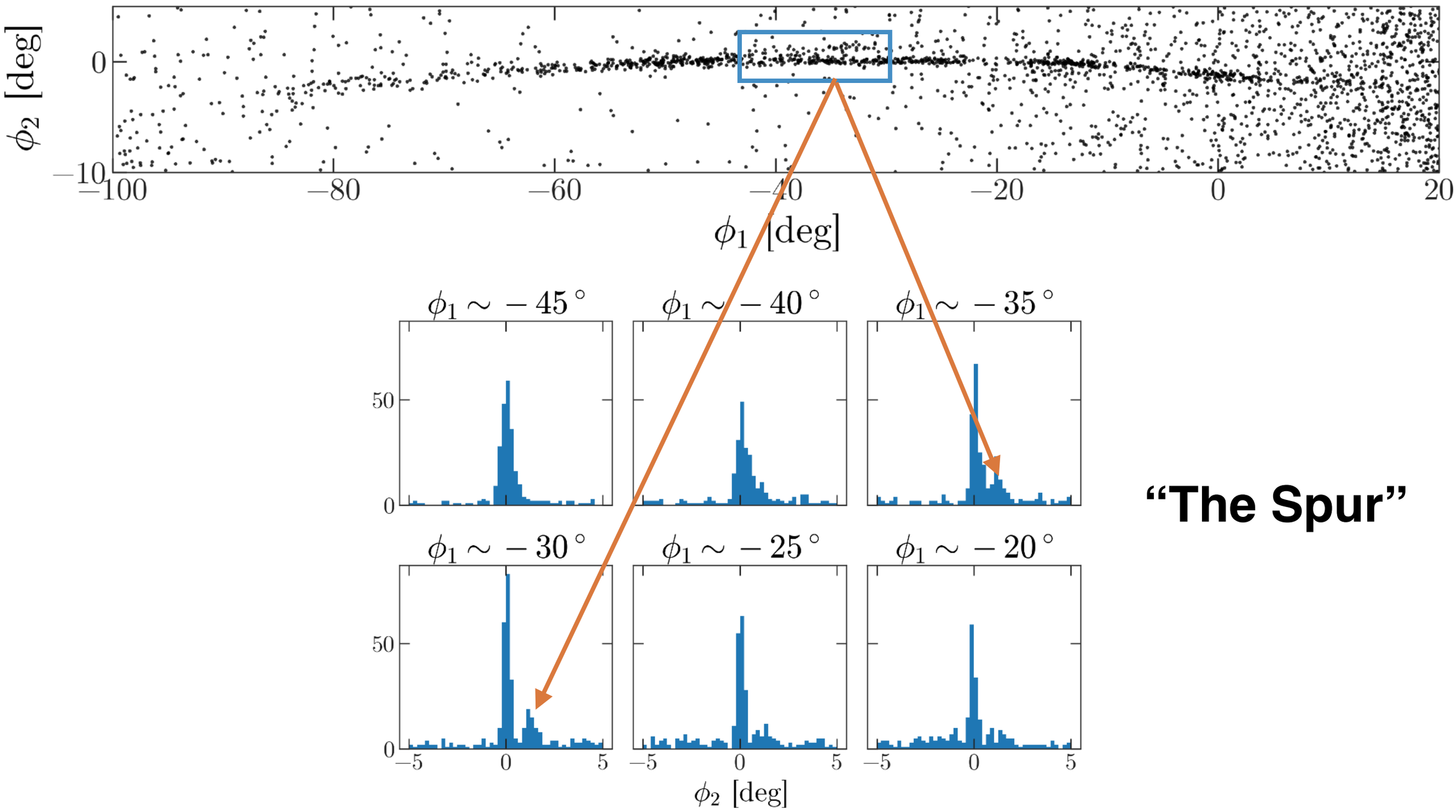
the GD-1 stream

simultaneously infer distance, proper motion vs. longitude



the GD-1 stream

simultaneously infer distance, proper motion vs. longitude



“The Spur”

Now, with an empirical model for the kinematics of GD-1, we are:

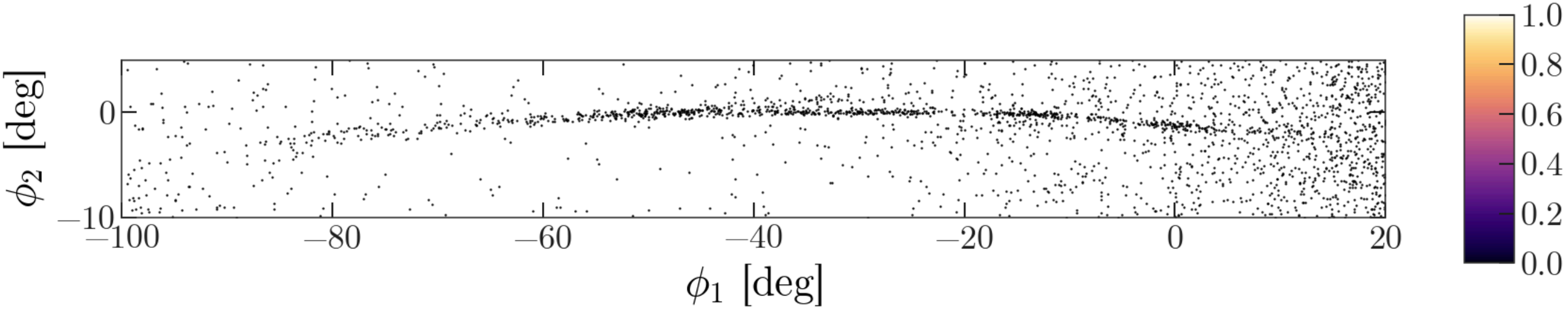
1) Quantifying density variations

2) Characterizing its stellar population / other tracers

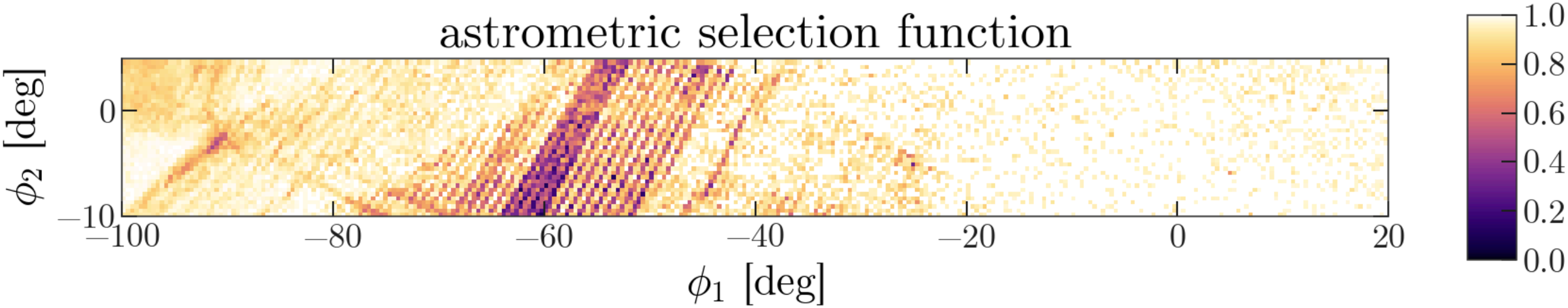
3) Attempting to fit model streams

the density variations and gaps in GD-1

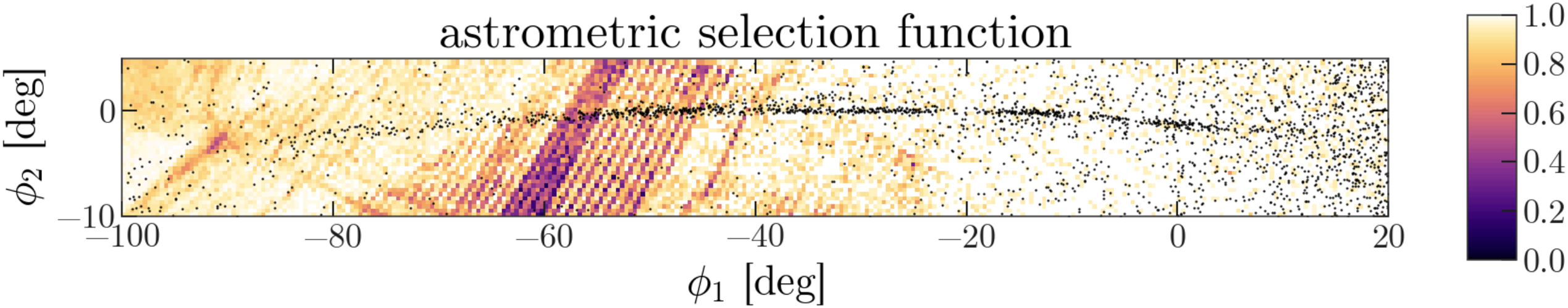
Density structure of GD-1



Density structure of GD-1



Density structure of GD-1

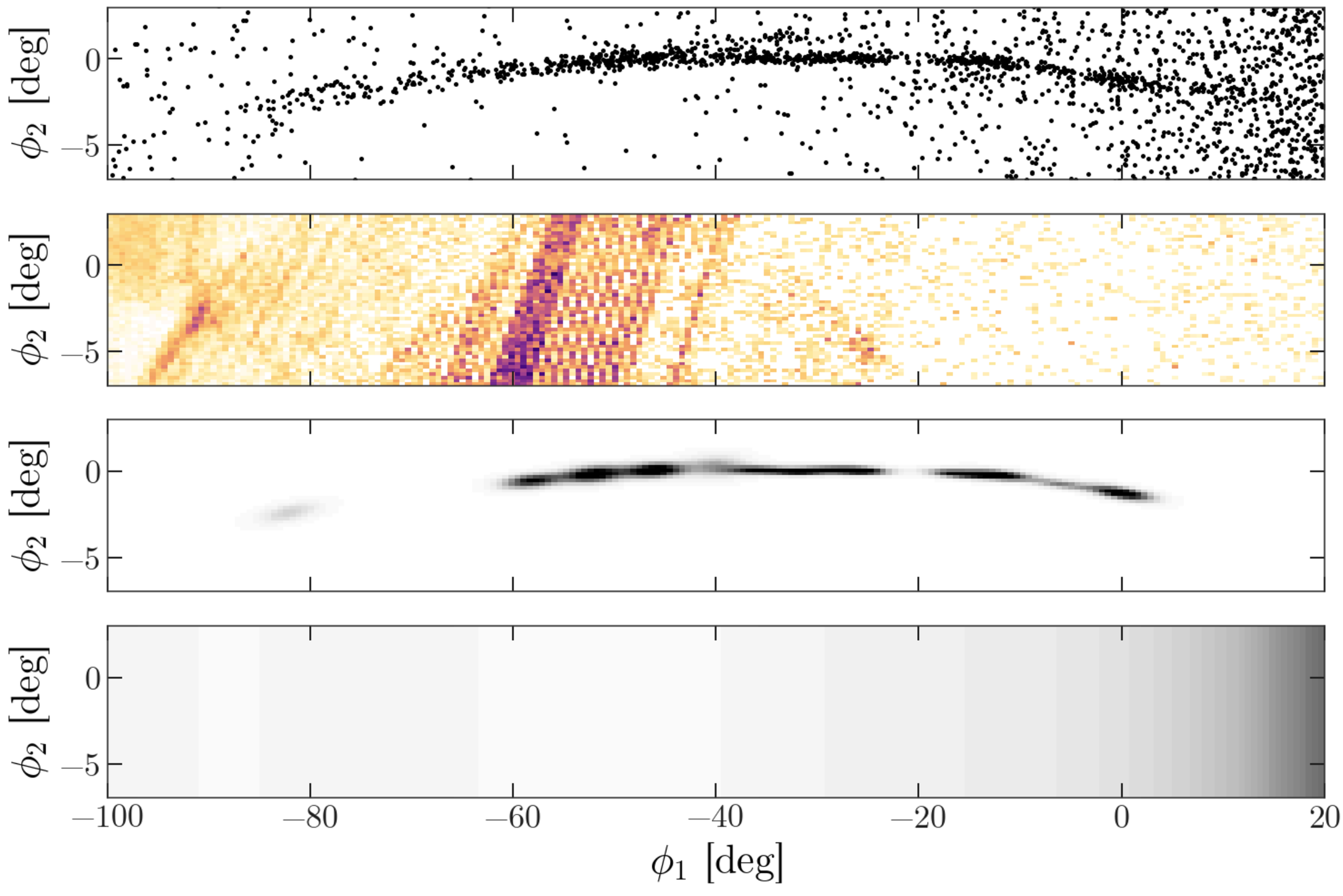


Note: spur appears unaffected by selection function

But density variations on left are strongly affected

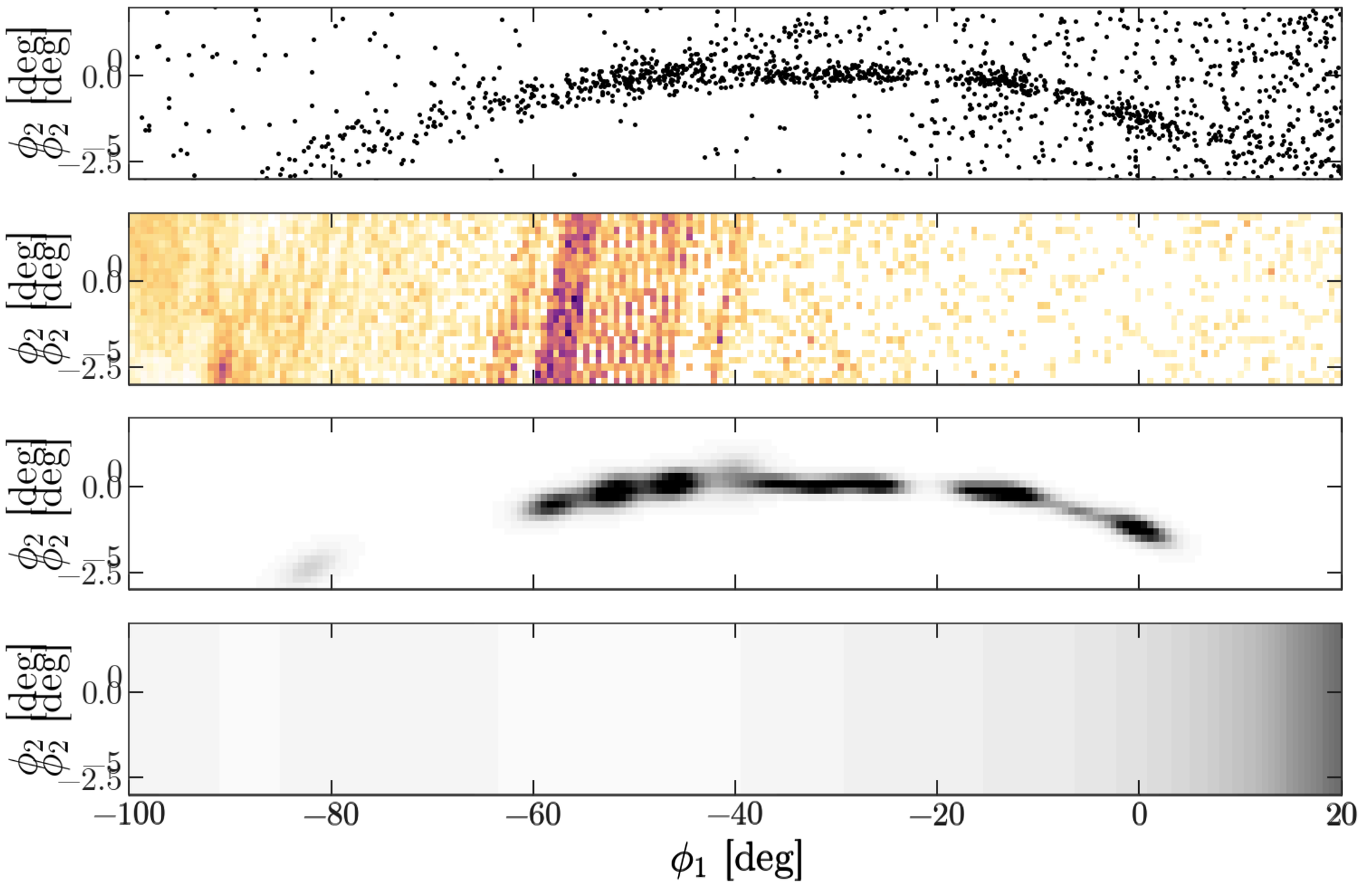
In progress: quantifying the density variations

(see also de Boer et al. 2018 for a pre-DR2 view)



In progress: quantifying the density variations

(see also de Boer et al. 2018 for a pre-DR2 view)



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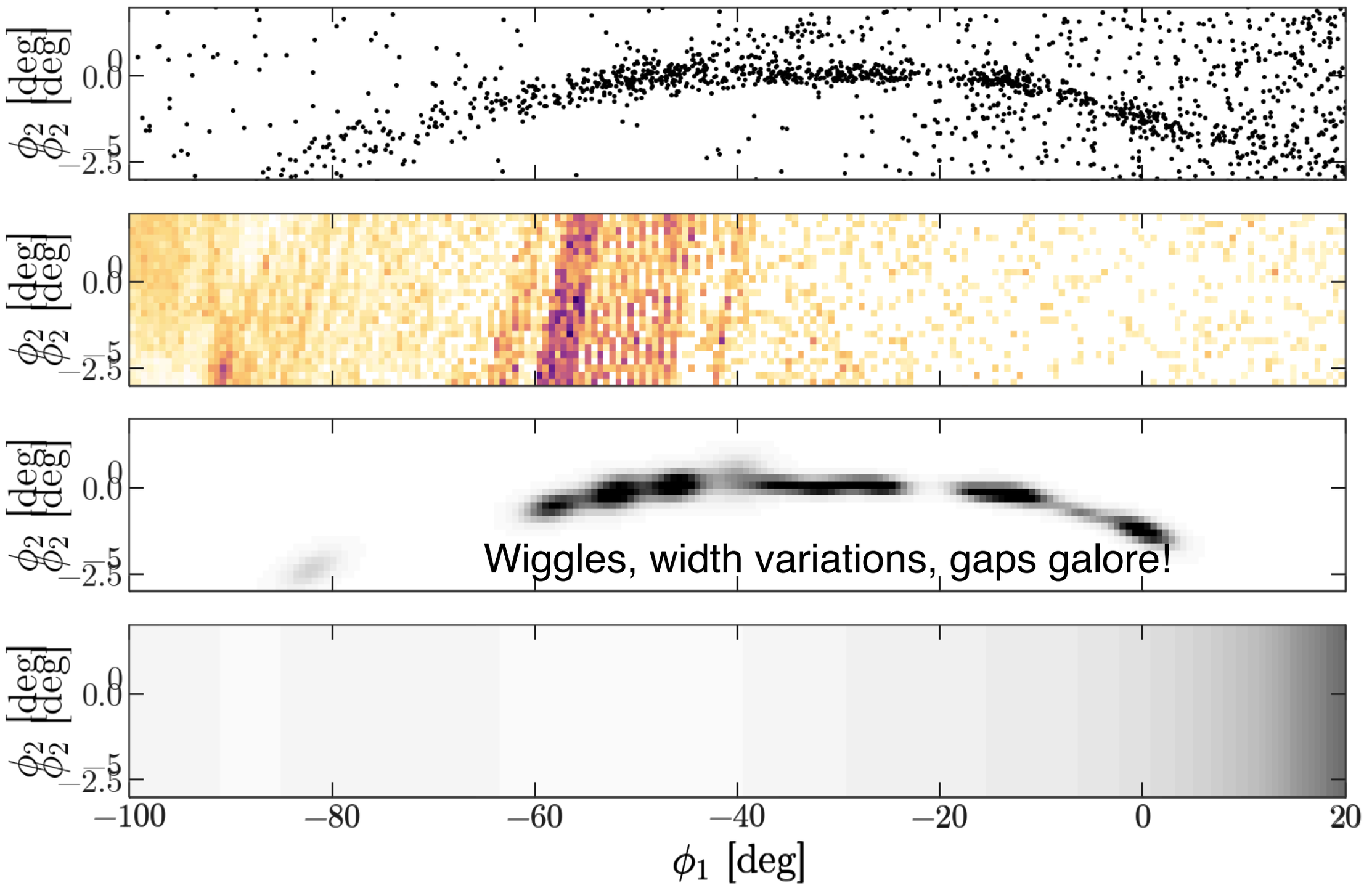


Preliminary findings

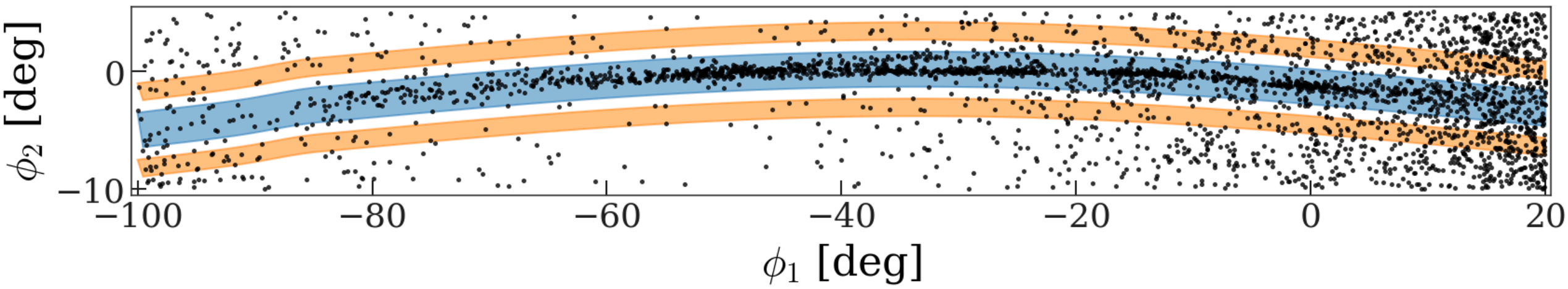
Even using the astrometric selection function, there are 3–4 significant under-densities in GD-1

The “spur” and “blob” features are highly significant and unaffected by *Gaia* selection function

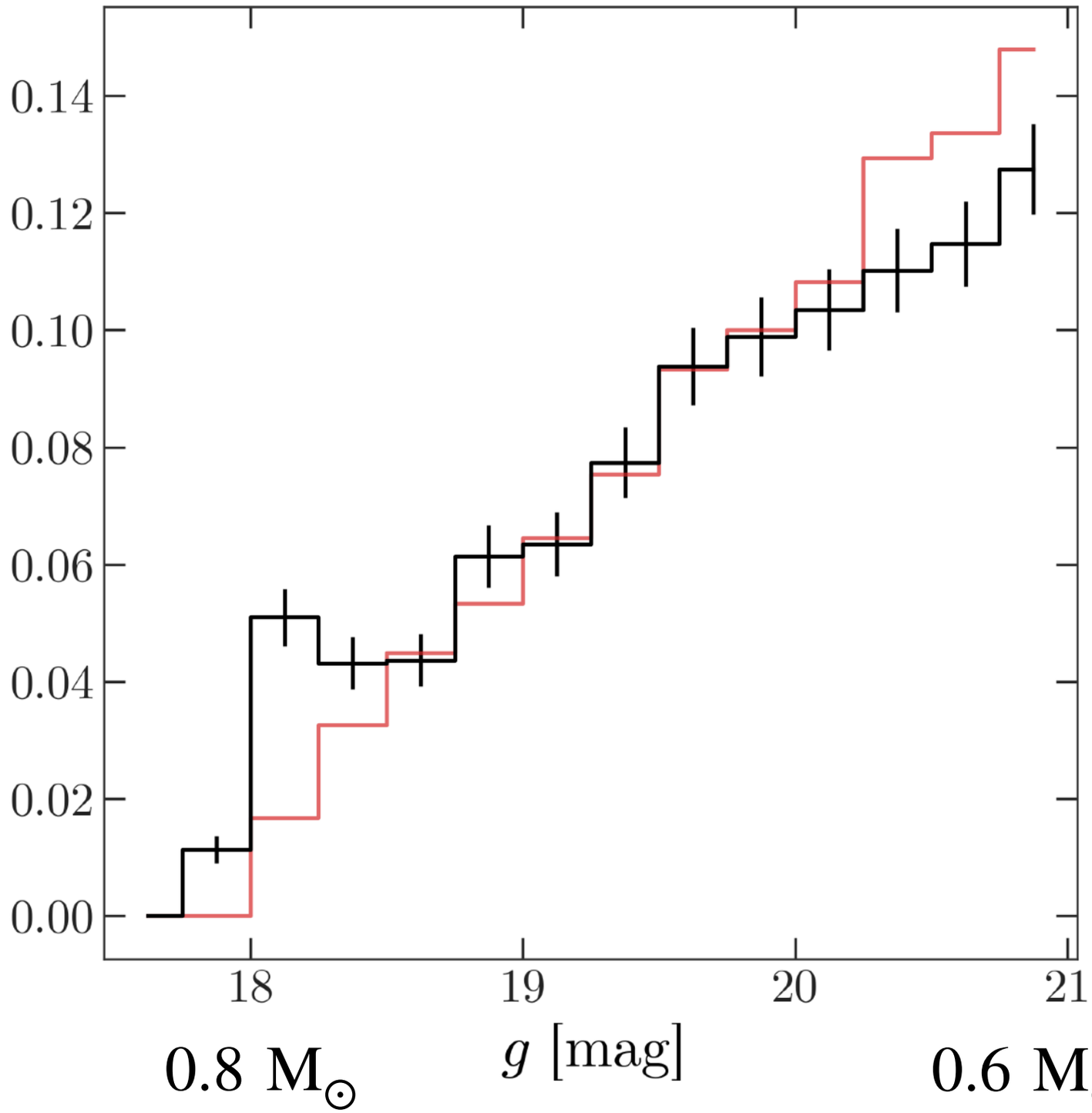
We see significant deviations and “wiggles” of the stream track

the stellar population of GD-1

GD-1: stellar population



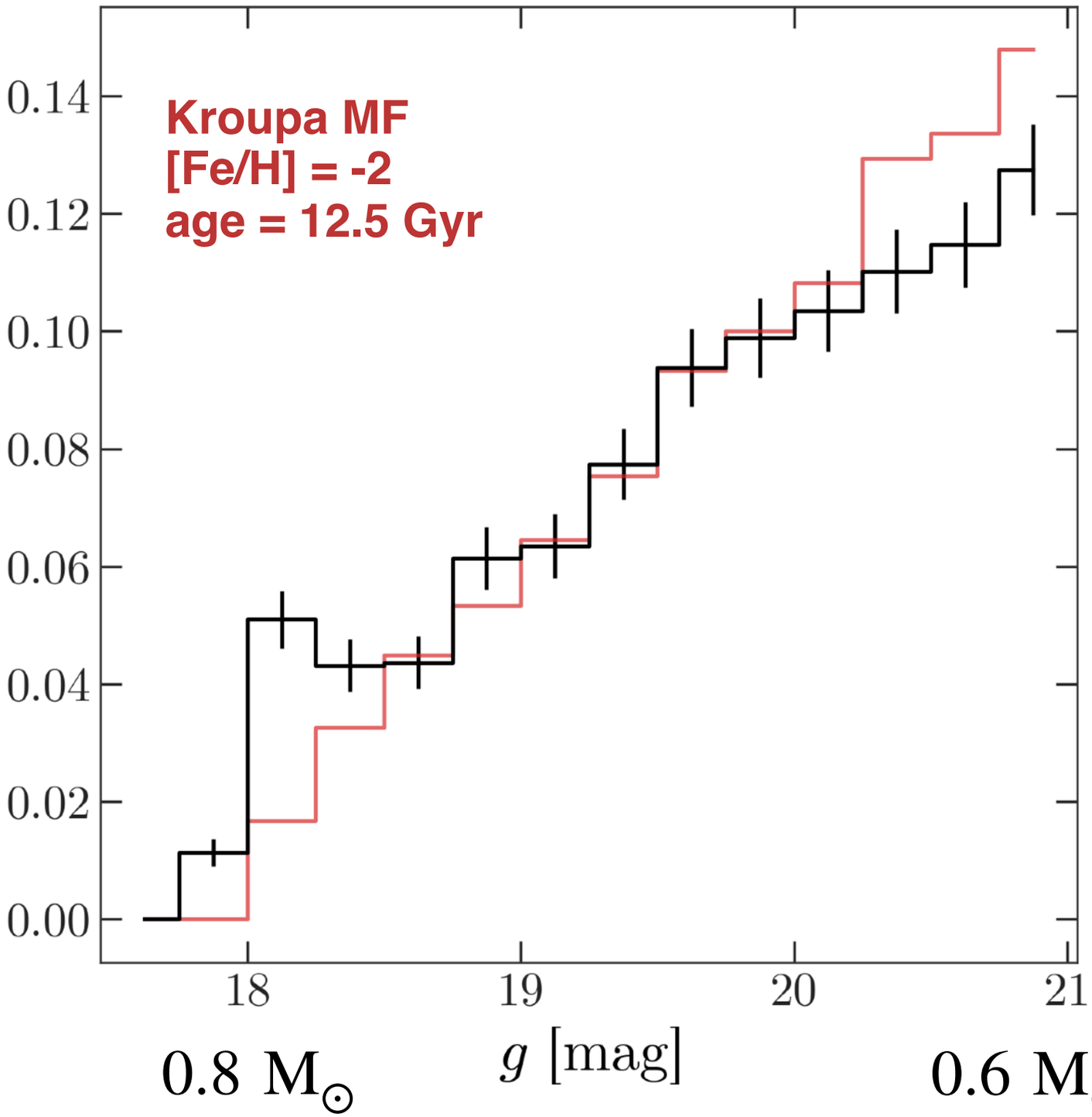
GD-1 luminosity function



$M \sim 4 \times 10^4$ M$_\odot$

(total)

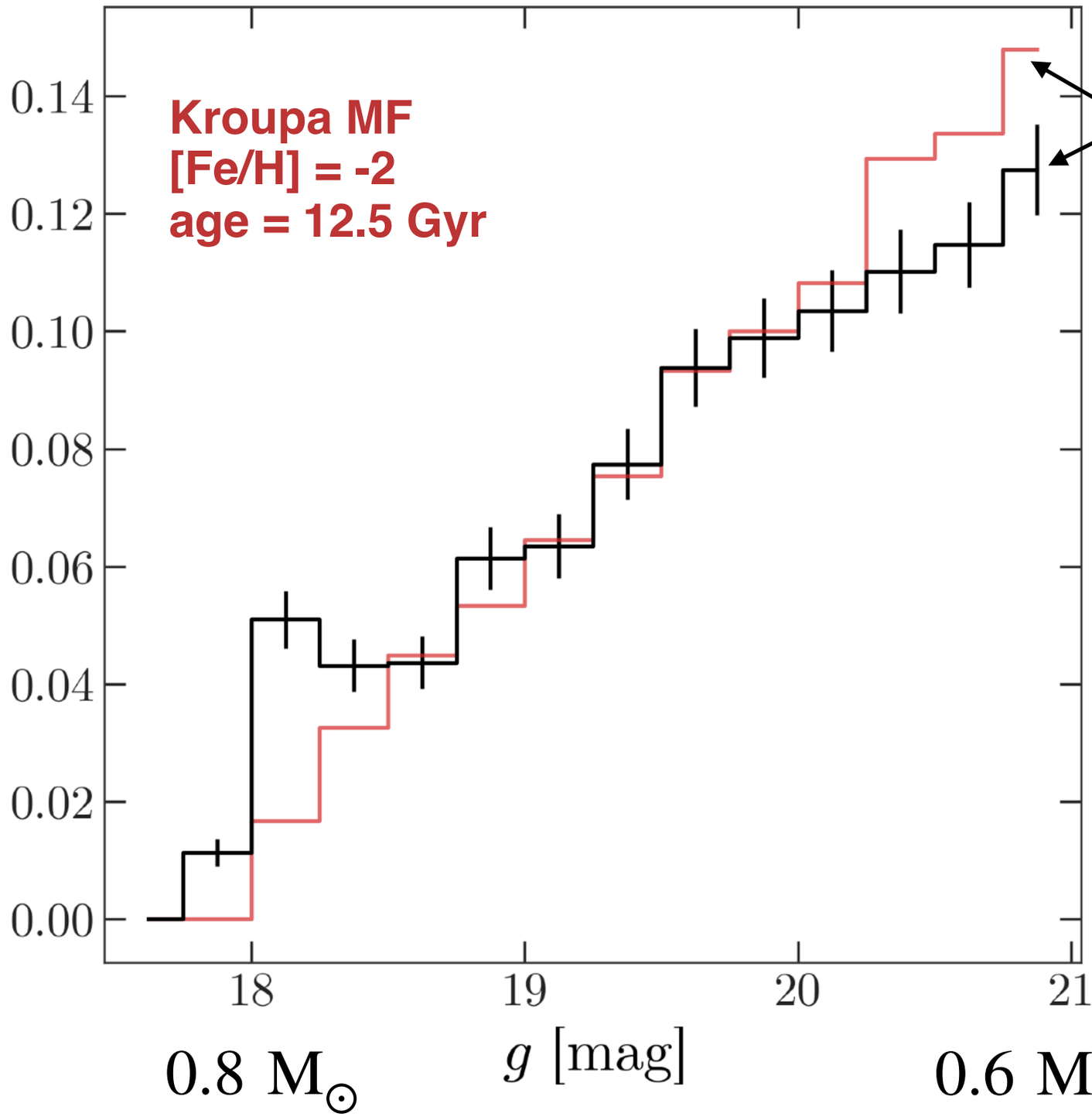
GD-1 luminosity function



$M \sim 4 \times 10^4$ M$_\odot$

(total)

GD-1 luminosity function

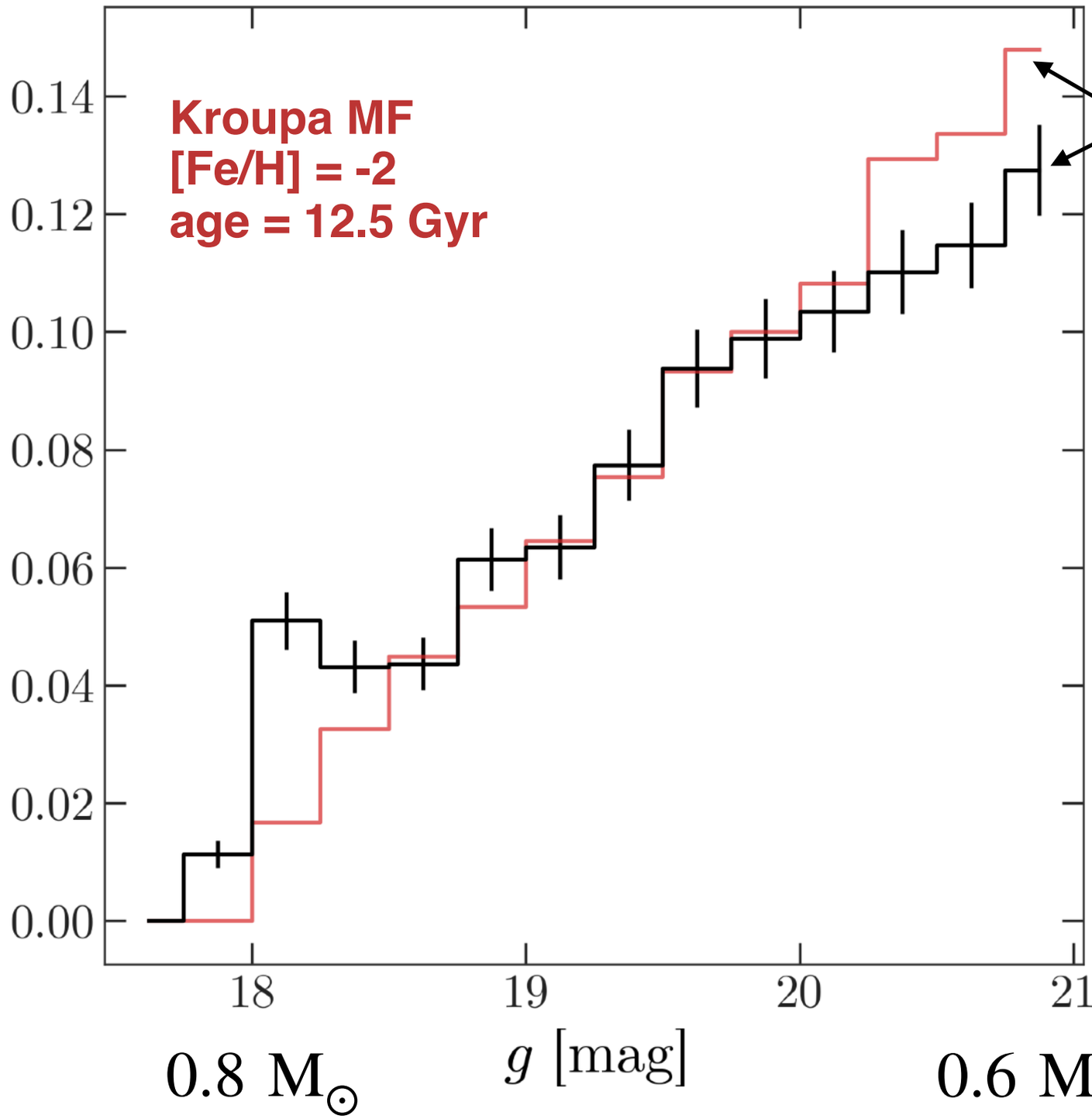


Mass segregation?

$M \sim 4 \times 10^4$ M$_\odot$

(total)

GD-1 luminosity function



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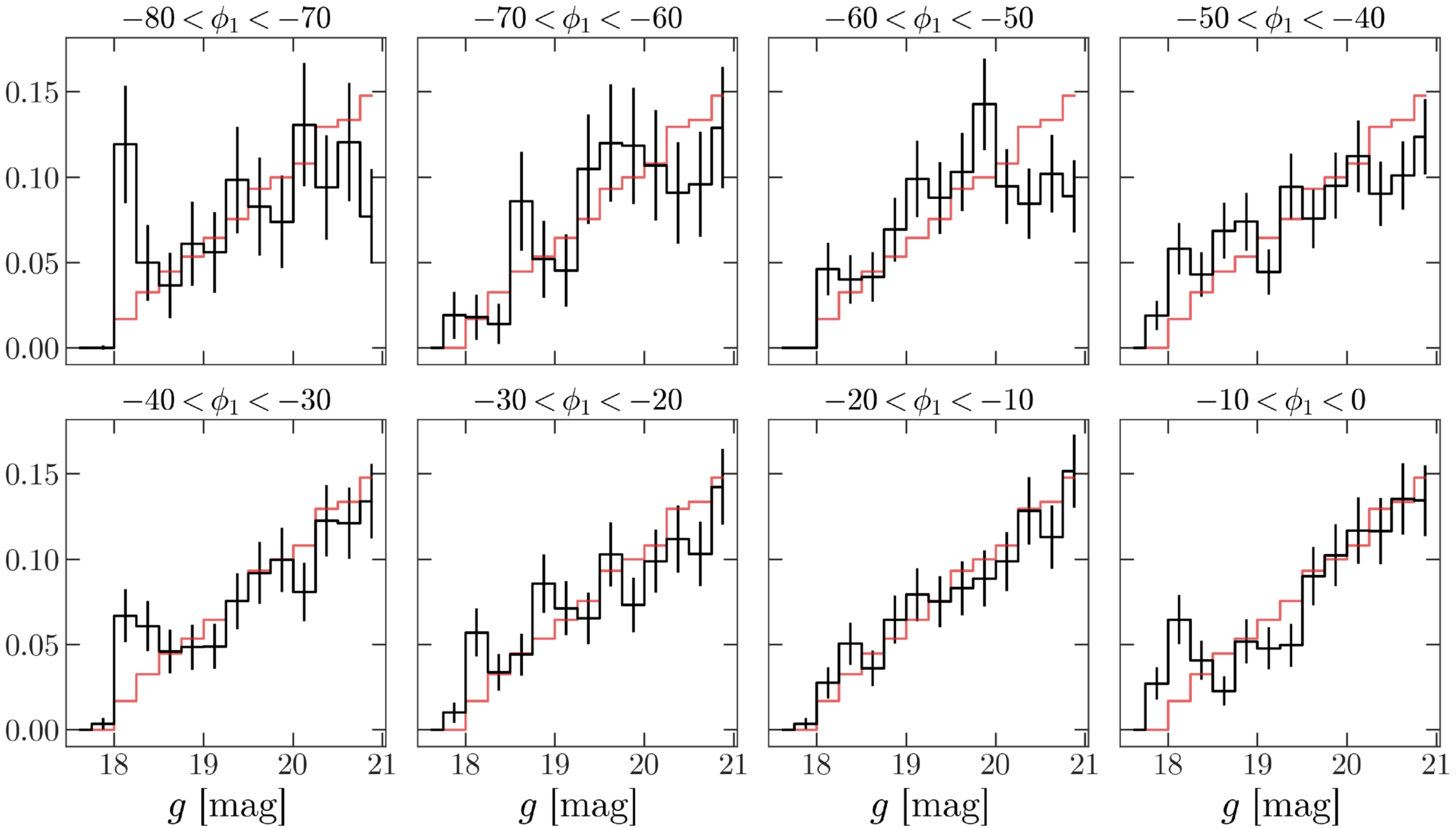
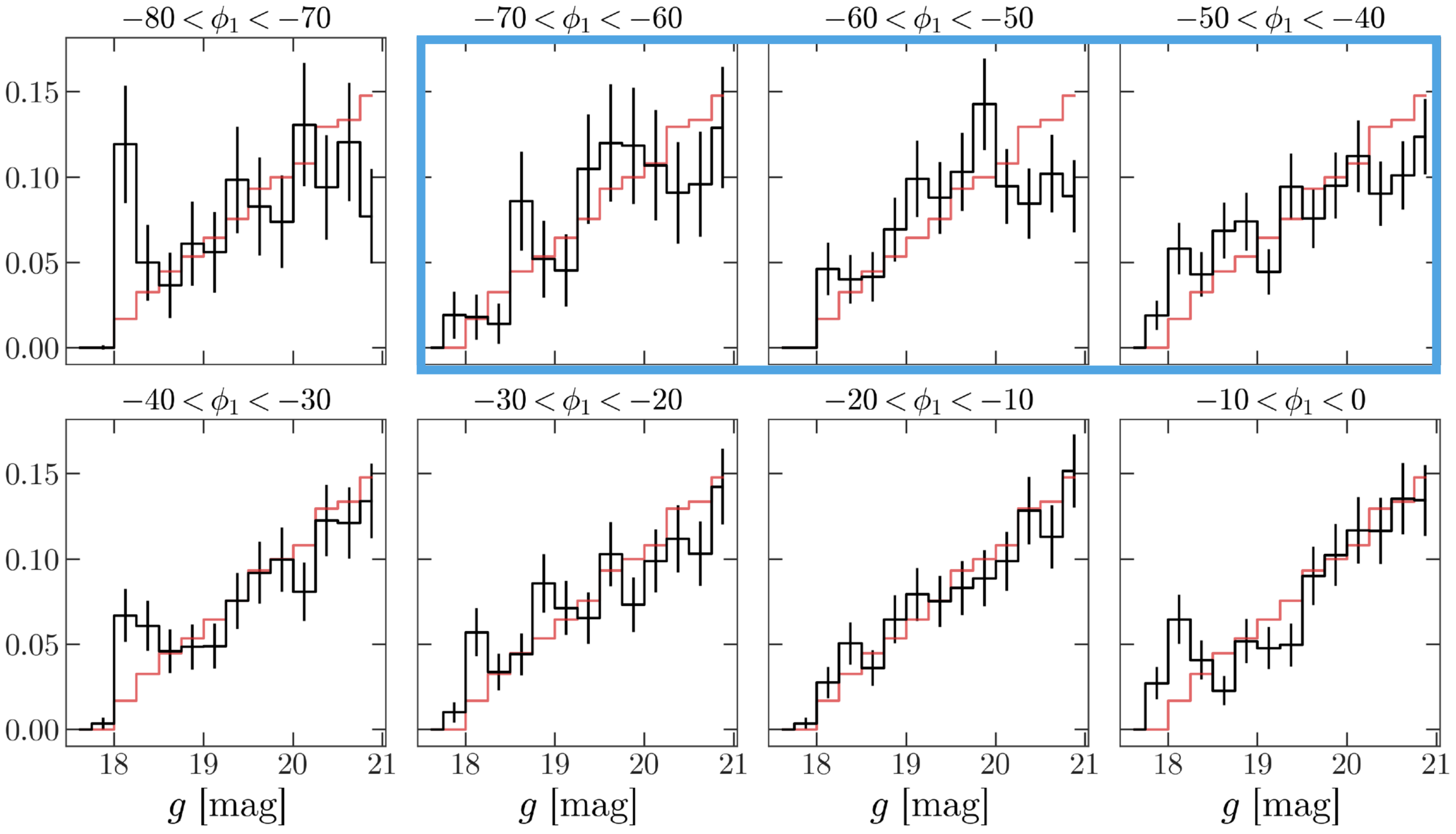
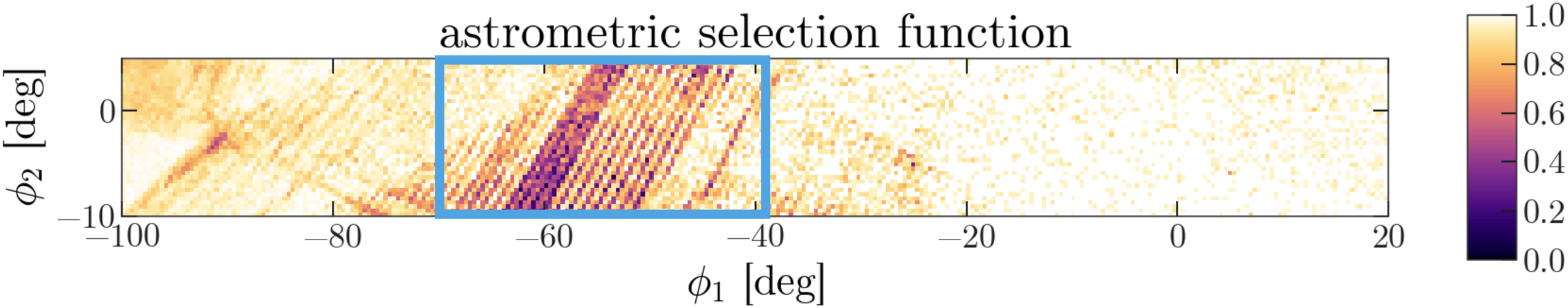


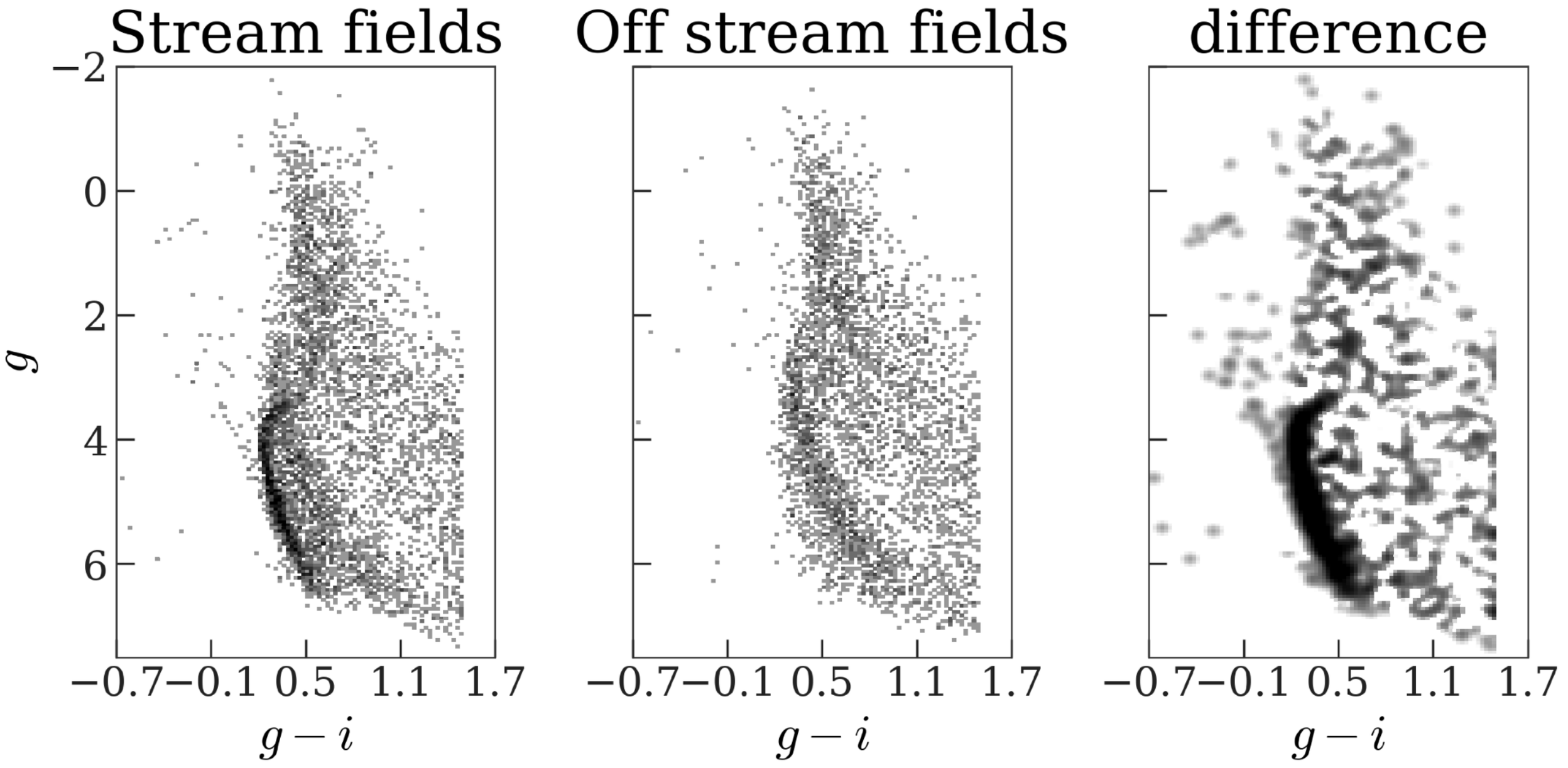
GD-1 luminosity function



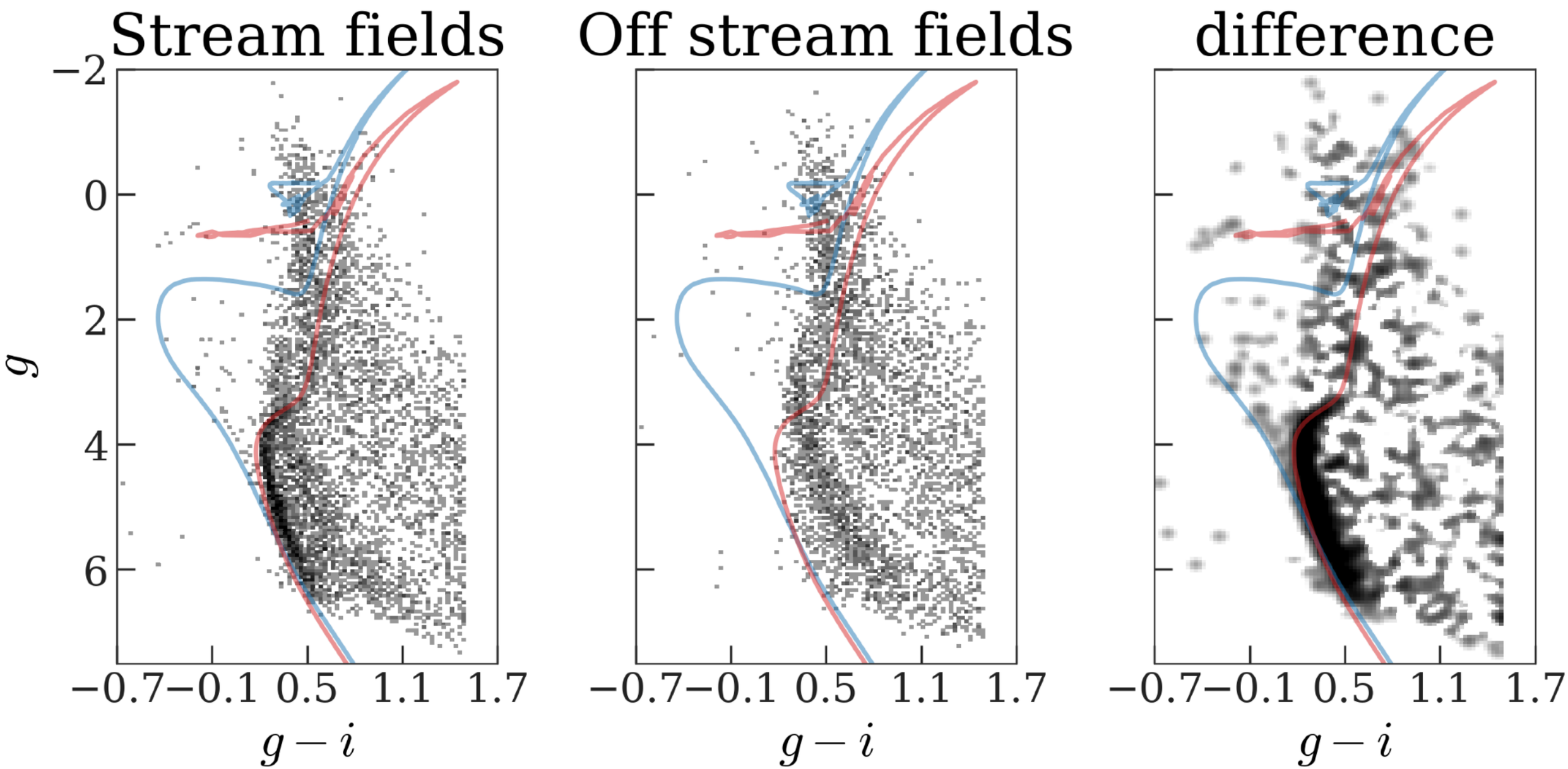
Density structure of GD-1



GD-1 stellar population



[Fe/H] = -2.0
age = 2.5 Gyr
age = 12.5 Gyr



Stream fields

Off stream fields

difference

BHB

RHB&RRL

BS

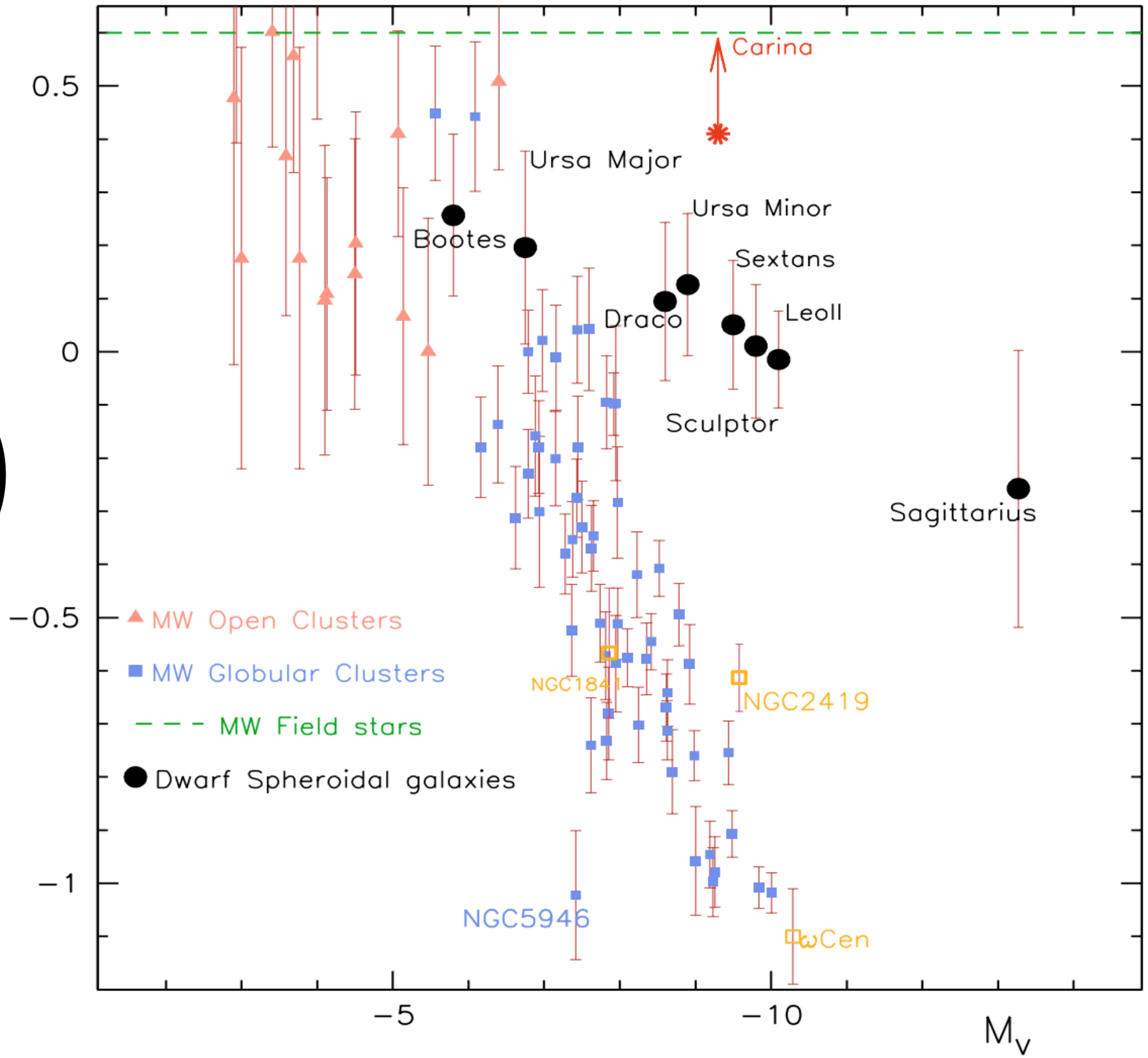
g

$g-i$

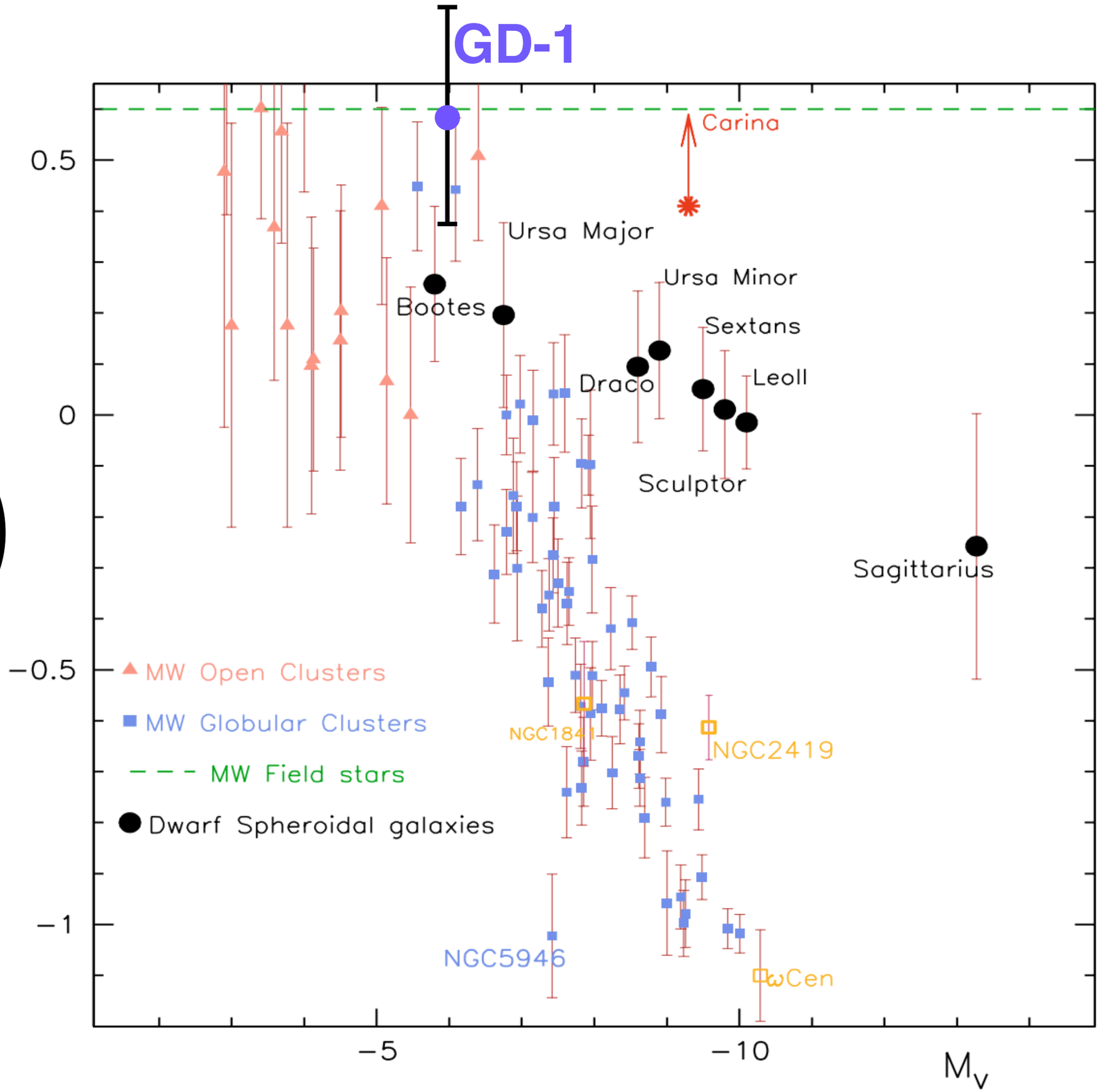
−2
0
2
4
6

−0.7 −0.1 0.5 1.1 1.7

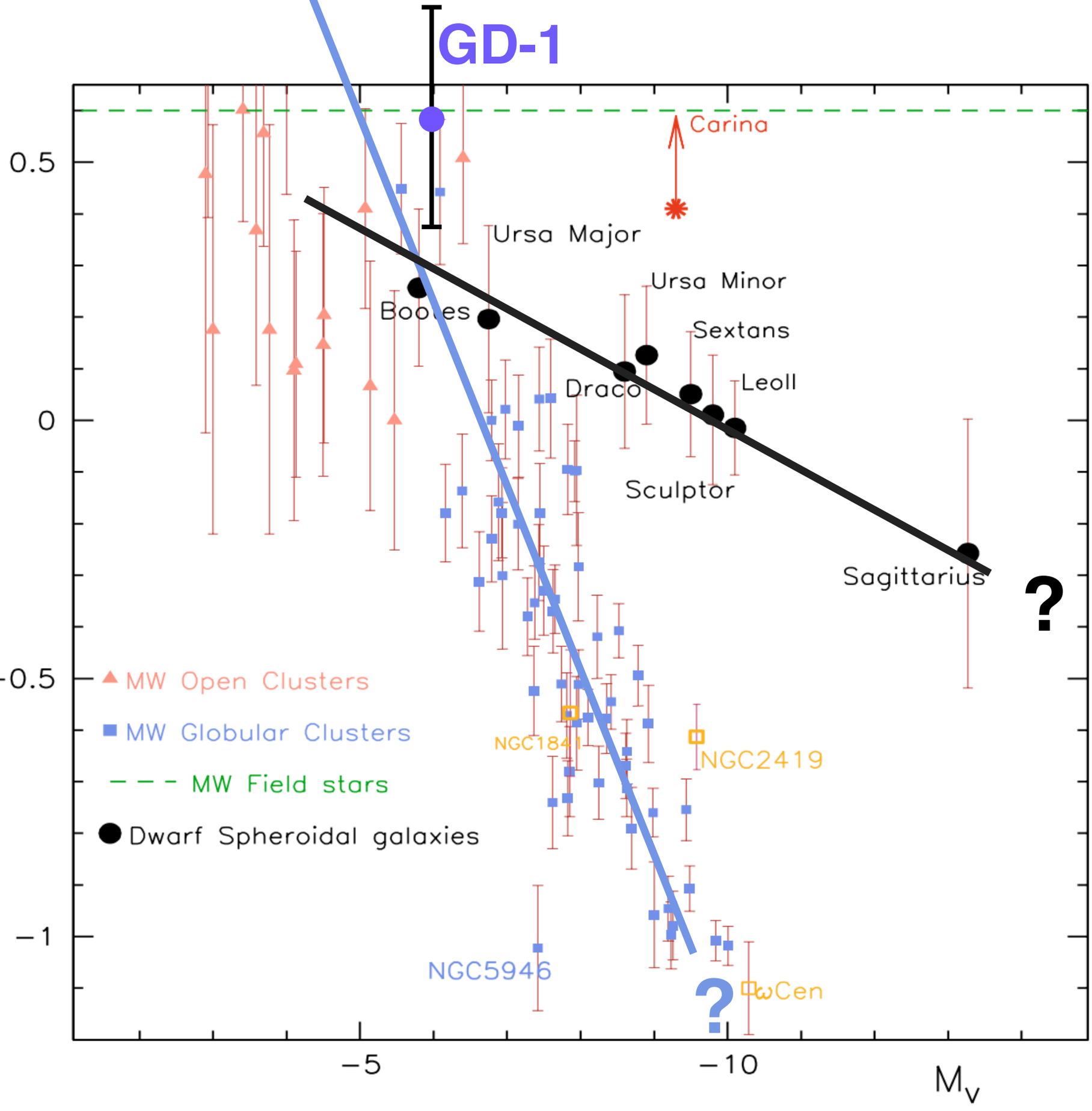
$$\log_{10}\left(\frac{N_{BS}}{N_{HB}}\right)$$



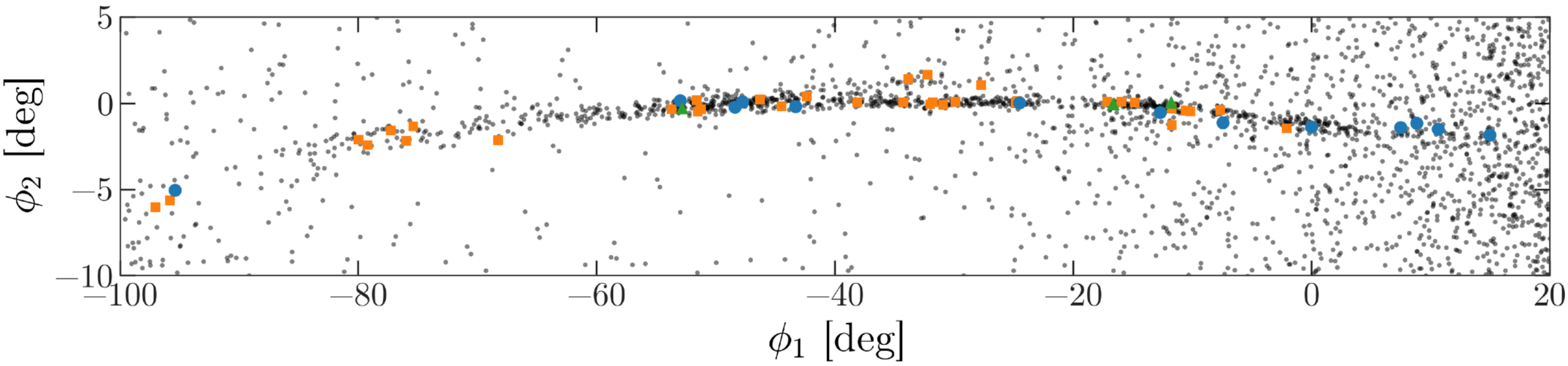
$$\log_{10}\left(\frac{N_{BS}}{N_{HB}}\right)$$



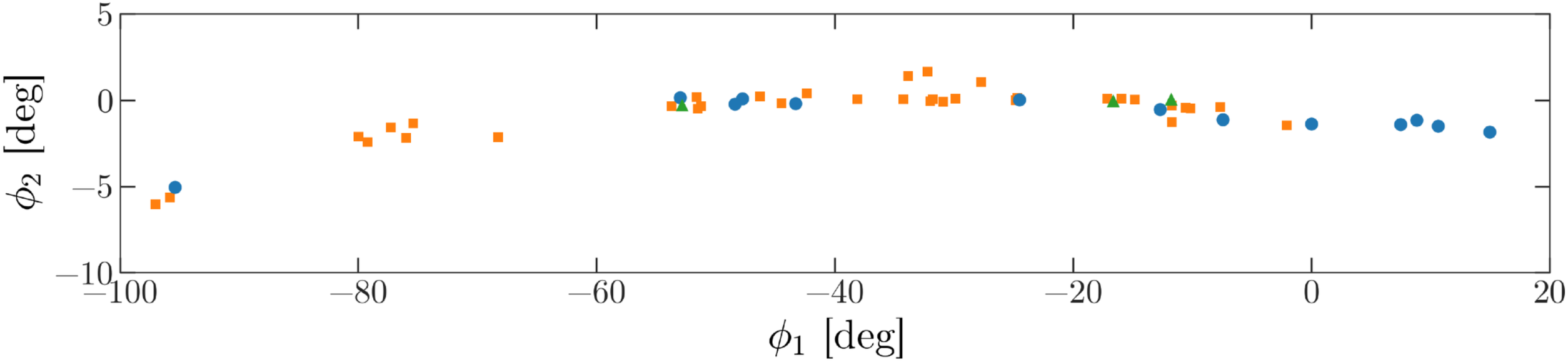
$$\log_{10}\left(\frac{N_{BS}}{N_{HB}}\right)$$

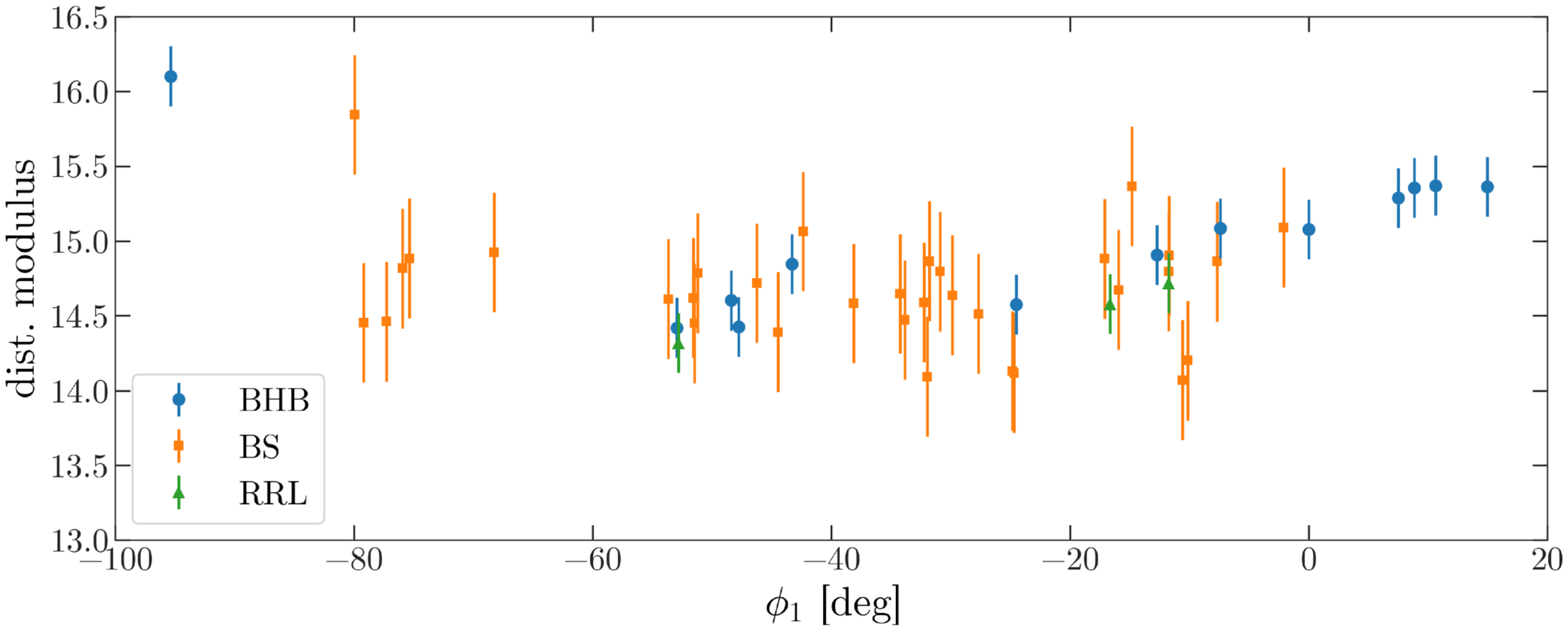


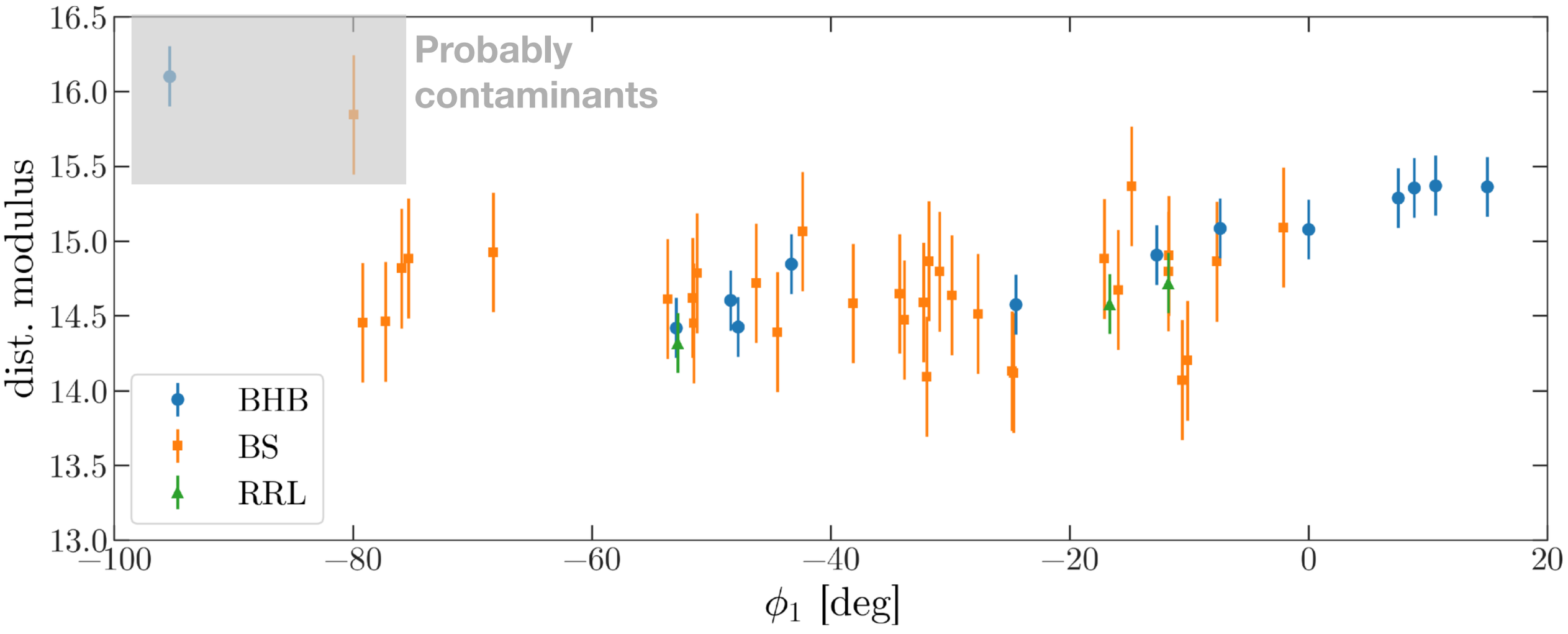
BHB RRL BS

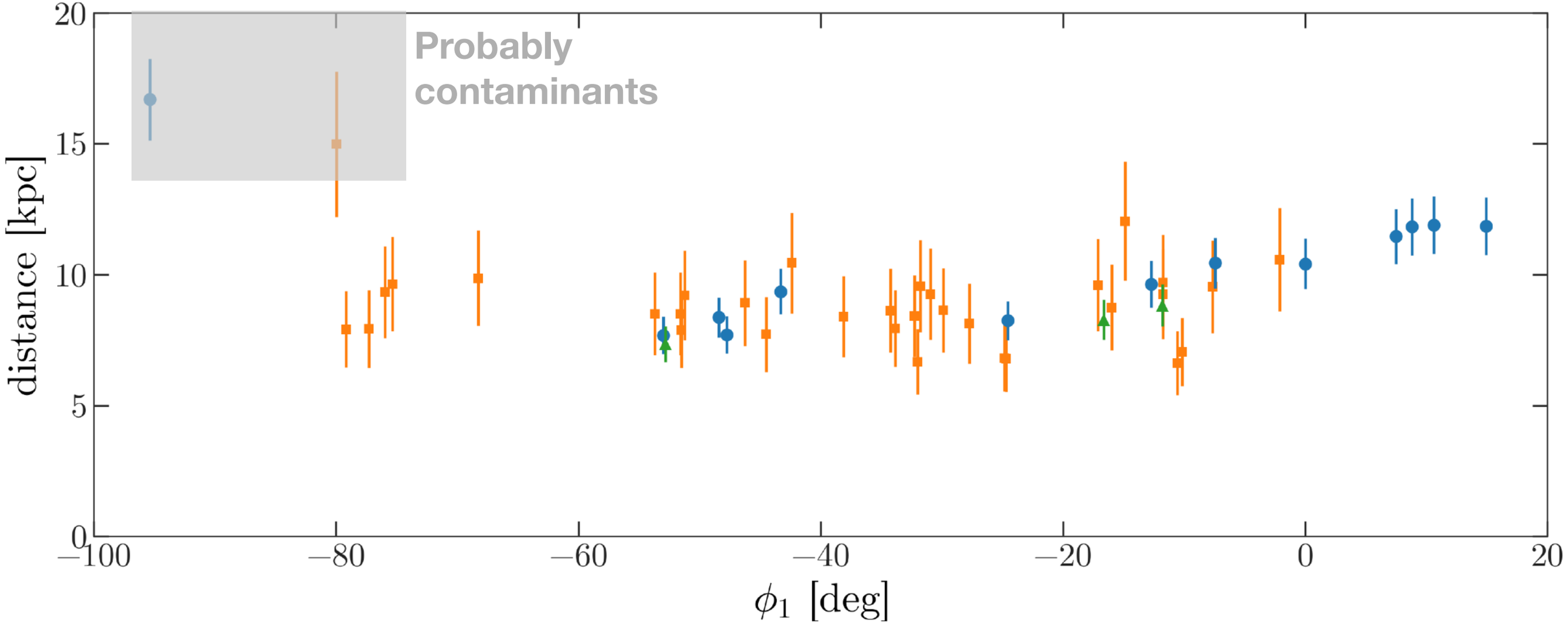


BHB RRL BS

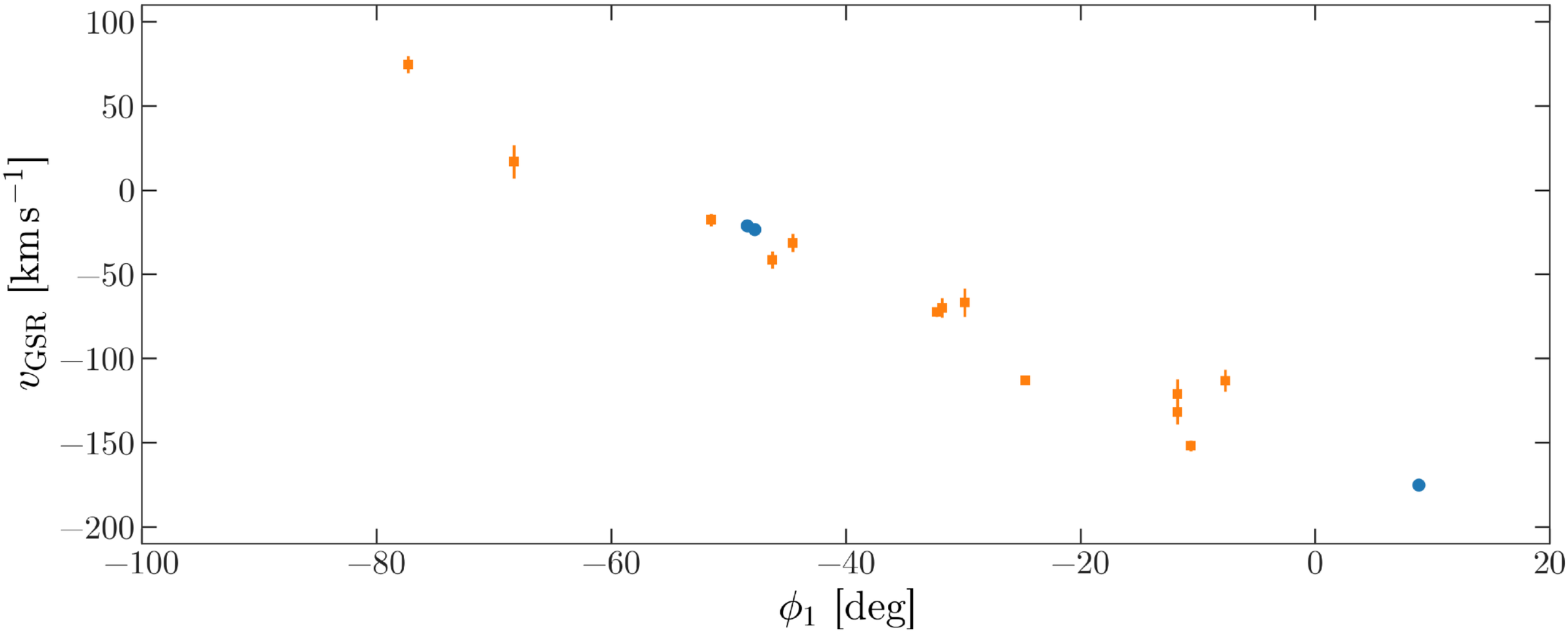



16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
dist. modulus
BHB
BS
RRL
−100
−80
−60
−40
−20
0
20
ϕ_1 [deg]


Probably
contaminants
BHB
BS
RRL
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
dist. modulus
−100
−80
−60
−40
−20
0
20
ϕ_1 [deg]


Probably
contaminants
20
15
10
5
0
−100
−80
−60
−40
−20
0
20
distance [kpc]
ϕ_1 [deg]

Radial velocities from BOSS



Preliminary findings

GD-1 has a total stellar mass comparable to a low-mass globular cluster or ultra-faint (e.g., Bootes I)

No clear evidence for LF variations over the stream, but the MSTO has a small range in stellar masses

GD-1 has many (~32) blue stragglers and fewer (~9) BHB stars, but at its total mass this is inconclusive

GD-1 stream fitting

GD-1: stream fitting

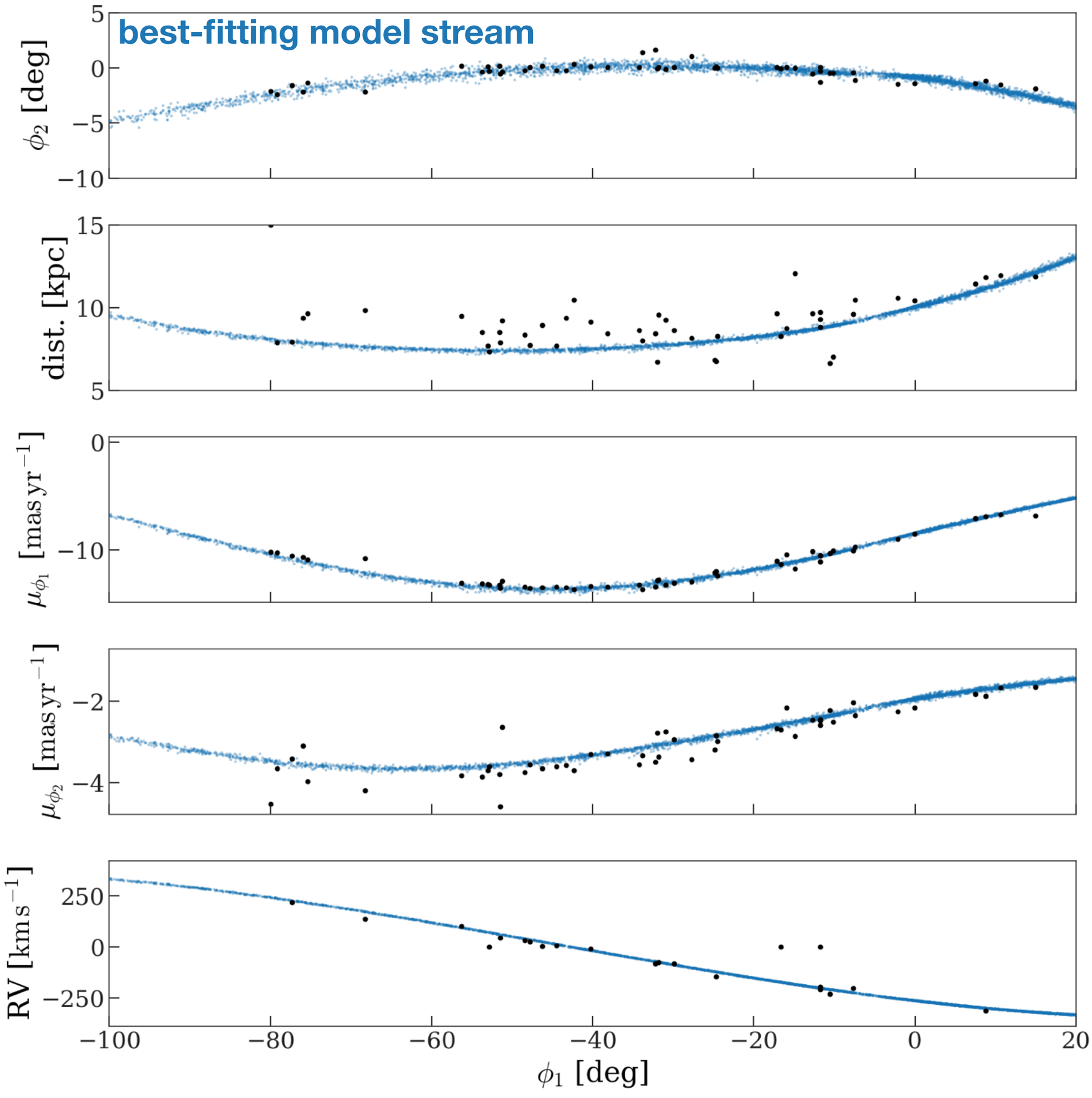
Using mock stream / particle spray / Lagrange point stripping method to generate a model stream in a given Milky Way model

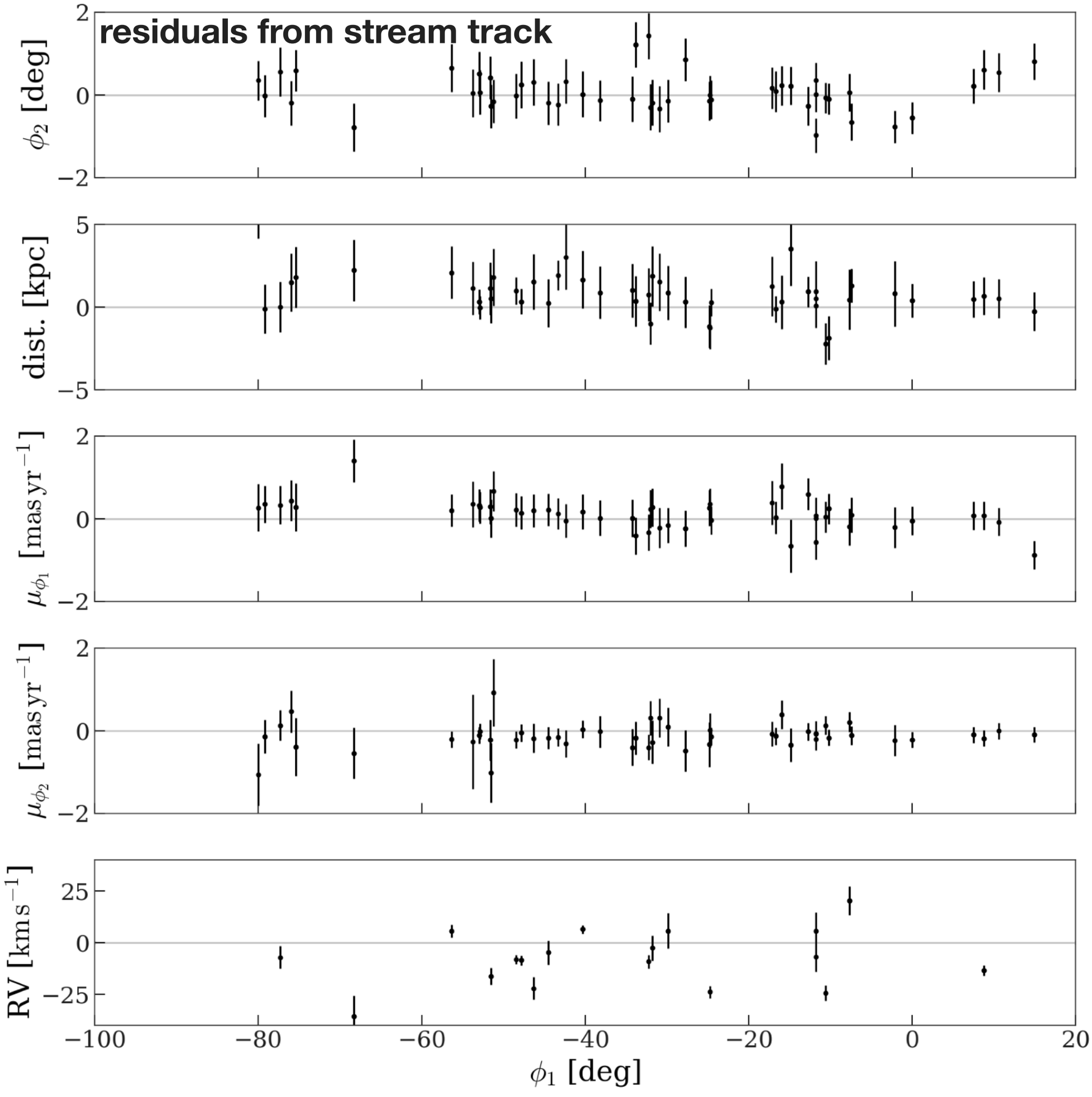
Extract stream “track” (density ridgeline), compare to data to compute the likelihood

Vary: progenitor orbit, solar motion, mass model parameters

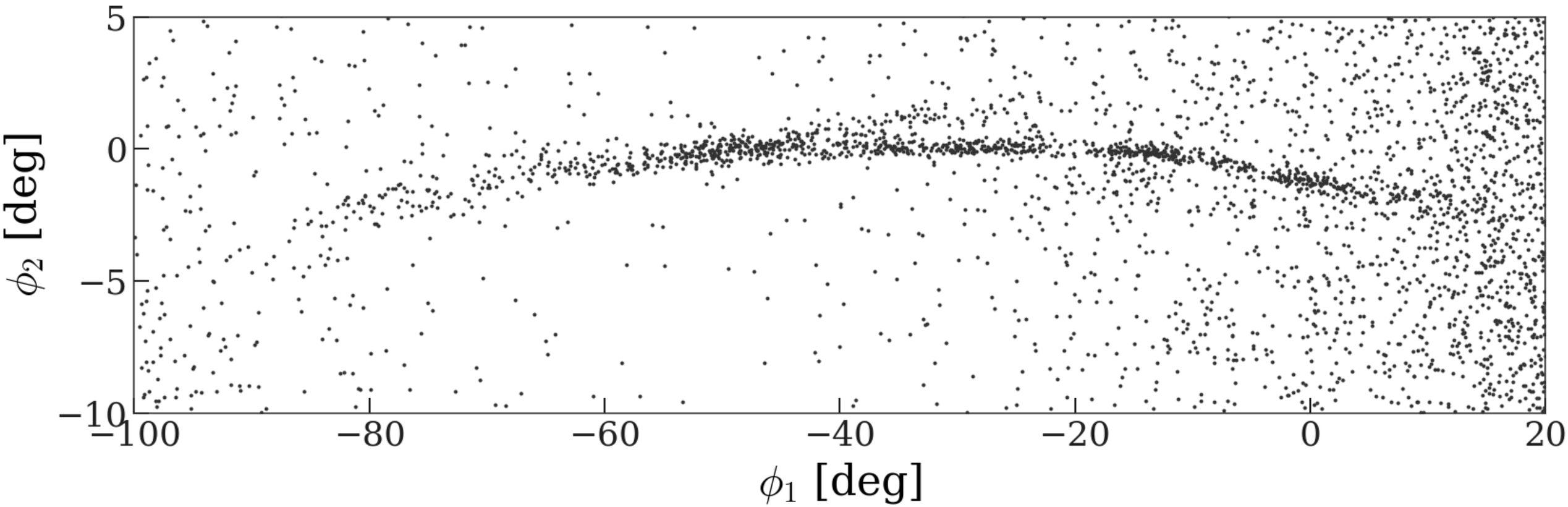
Ignoring the spur! We hope we can first build a better “fiducial” model for the stream, then try perturbing it (see Ana’s talk)

Currently using compiled 6D information for BHB, BS, RRL stars


best-fitting model stream
ϕ_2 [deg]
dist. [kpc]
μ_{ϕ_1} [mas yr^{-1}]
μ_{ϕ_2} [mas yr^{-1}]
RV [km s^{-1}]
ϕ_1 [deg]


residuals from stream track
ϕ_2 [deg]
dist. [kpc]
μ_{ϕ_1} [mas yr^{-1}]
μ_{ϕ_2} [mas yr^{-1}]
RV [km s^{-1}]
ϕ_1 [deg]

clearly this model sucks



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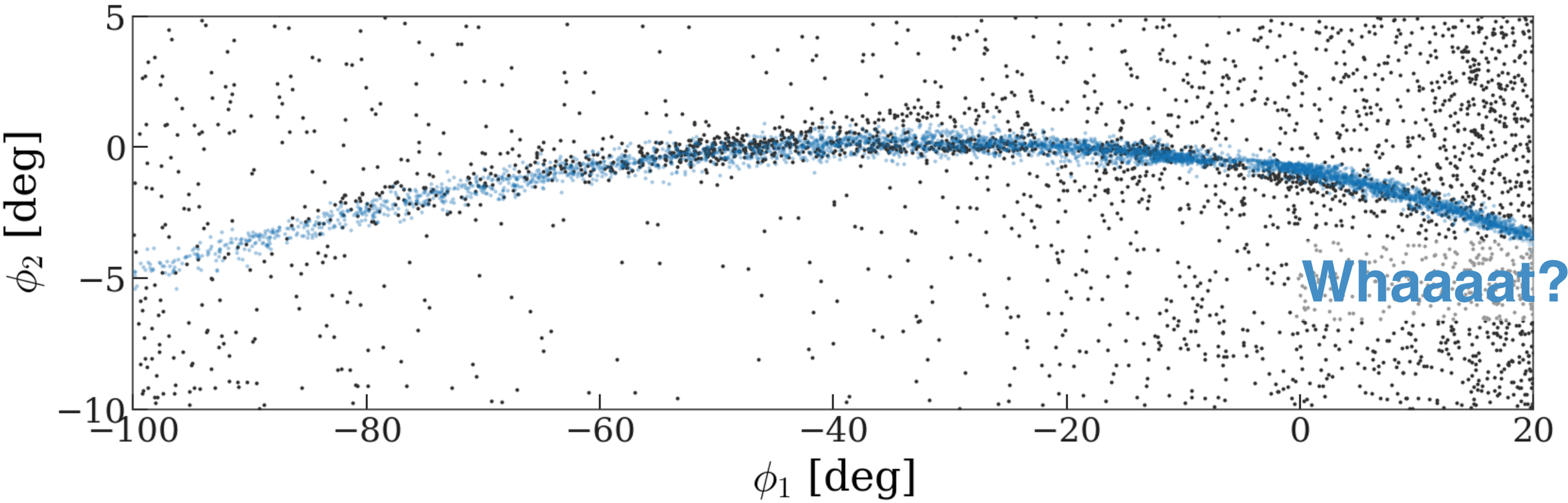


GD-1: stream fitting

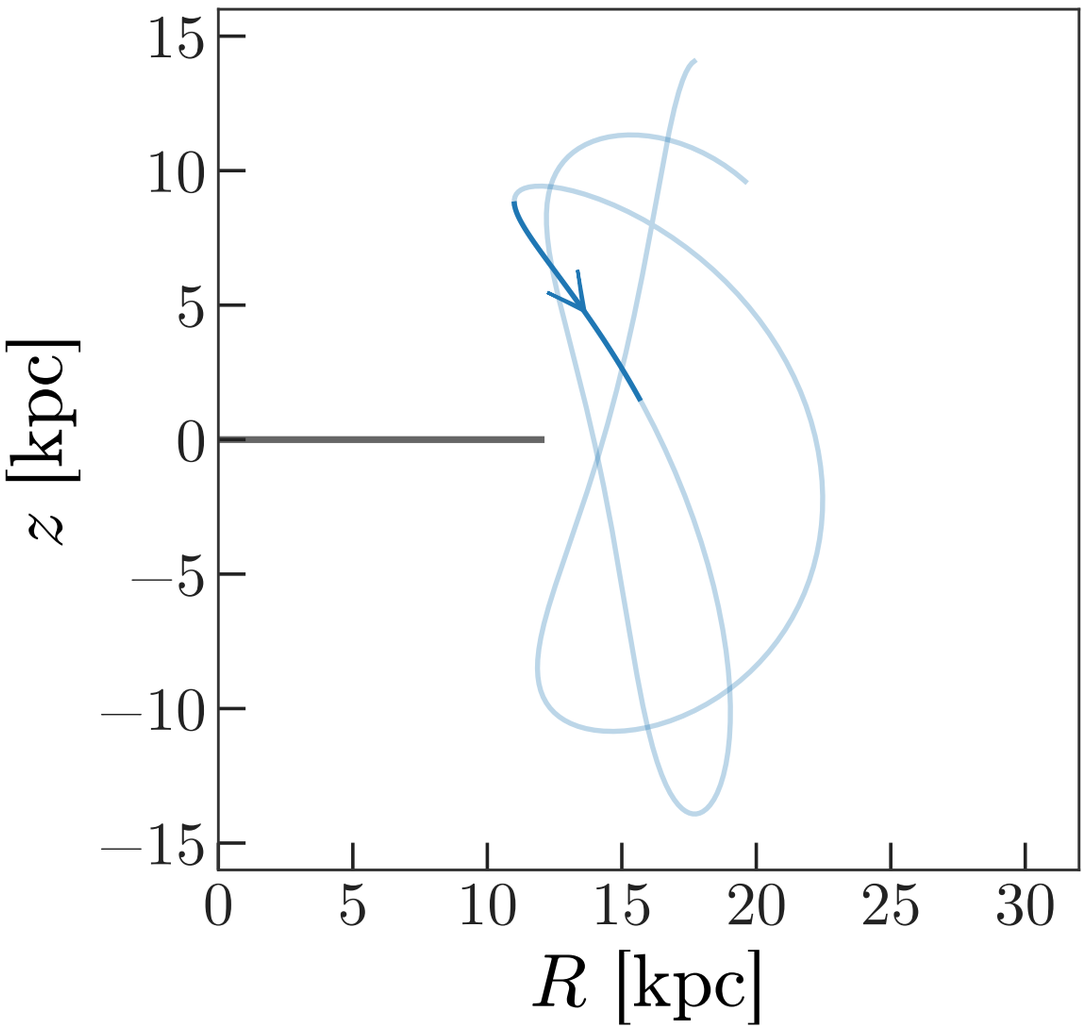
From this, with a simple (logarithmic) axisymmetric mass model, we recover the Koposov et al. 2010 result:

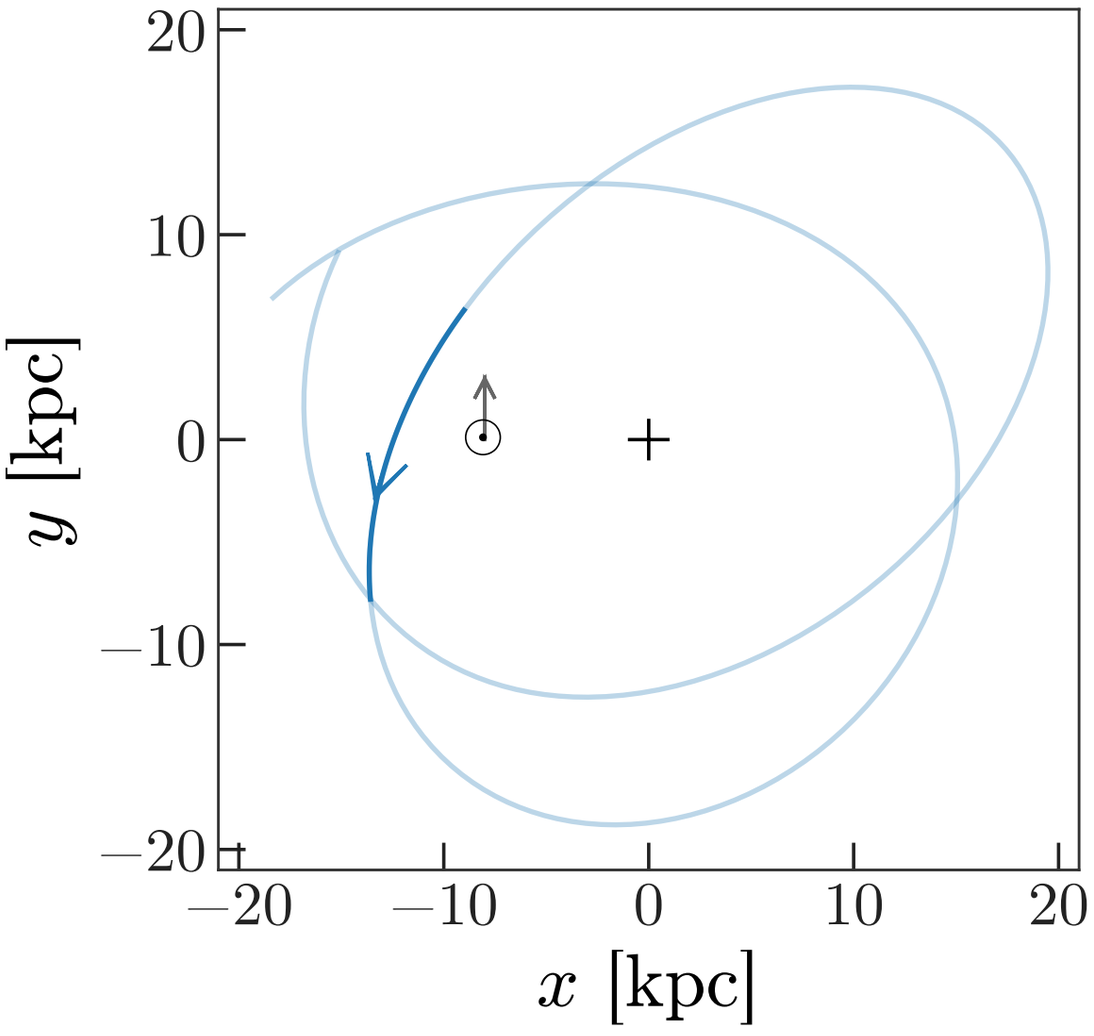
$$v_c(\mathrm{GD1}) \sim 220 \ \mathrm{km\ s^{-1}}$$

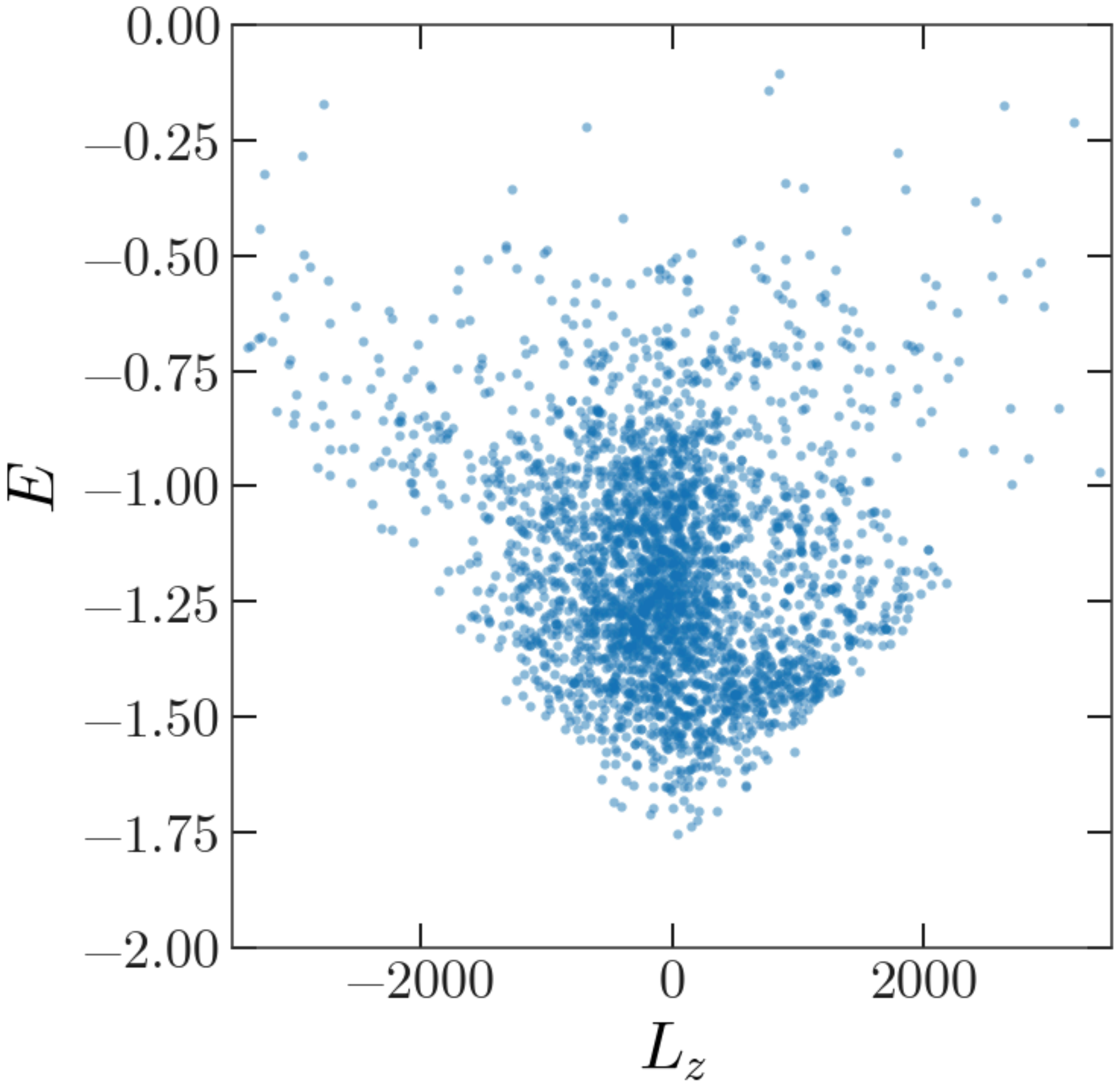
$$q_\Phi \sim 0.9$$

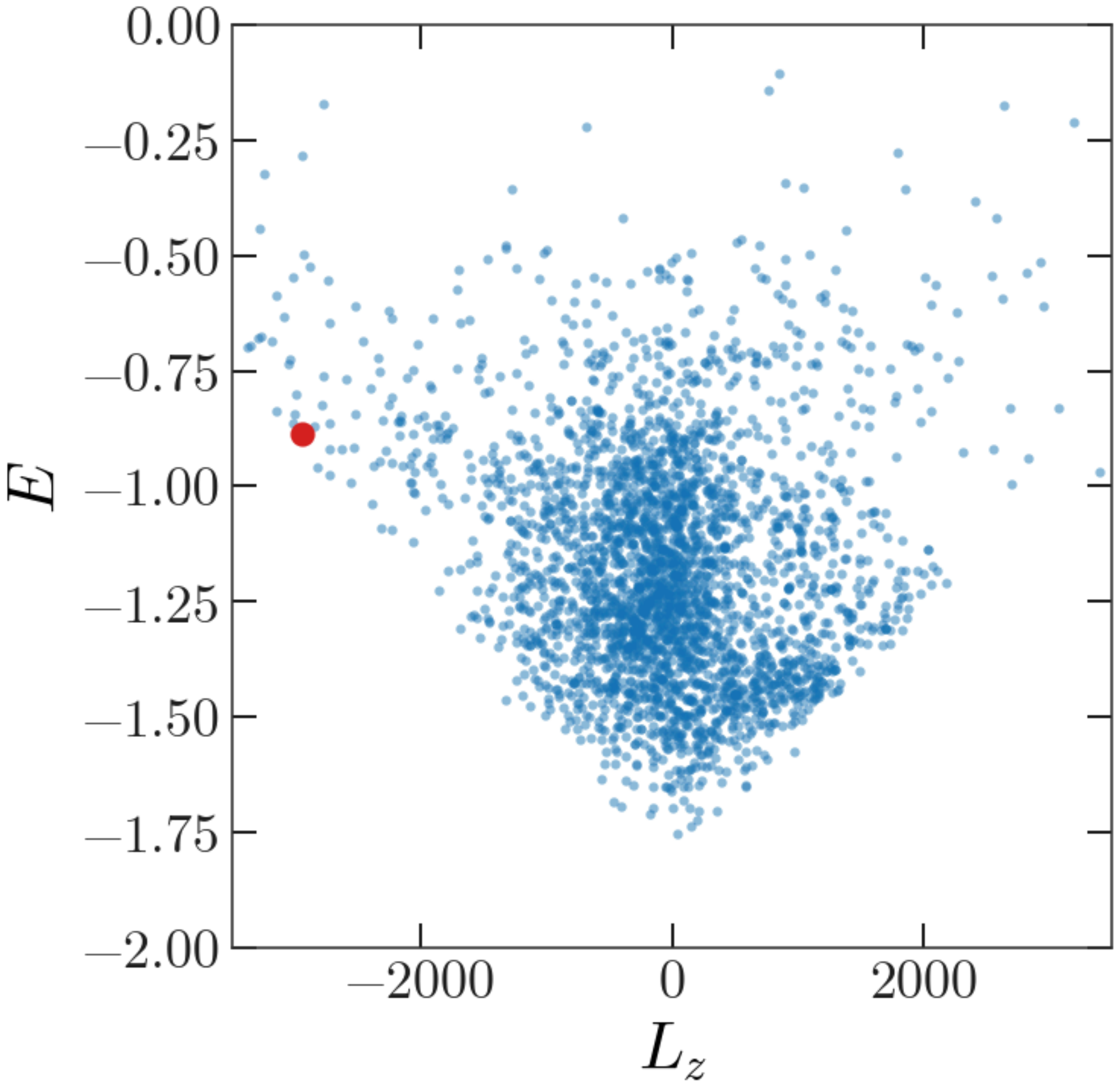
But: the detailed sky track of the stream is clearly off, the dispersions (spatial and velocity) are wrong, location of the progenitor is unknown, Milky Way model is way too simple, mass-loss history of the progenitor unknown, etc…

the orbit of the GD-1 progenitor






0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
−1.75
−2.00
E
−2000
0
2000
L_z


0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
−1.75
−2.00
E
−2000
0
2000
L_z

What we know about GD-1:

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Retrograde w.r.t. disk and kinematically distinct from halo

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Mostly at high Galactic latitude

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Relatively near the Sun (~8 kpc)

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Given all of this, it should be incredibly useful for constraining small-scale dark matter!

What we don't know:

What has caused the "wiggles" and density variations along the stream?

What is the "blob" and is it related to the "spur"?

Where did the progenitor end up / disrupt?

Detailed chemical abundances of the stream stars?

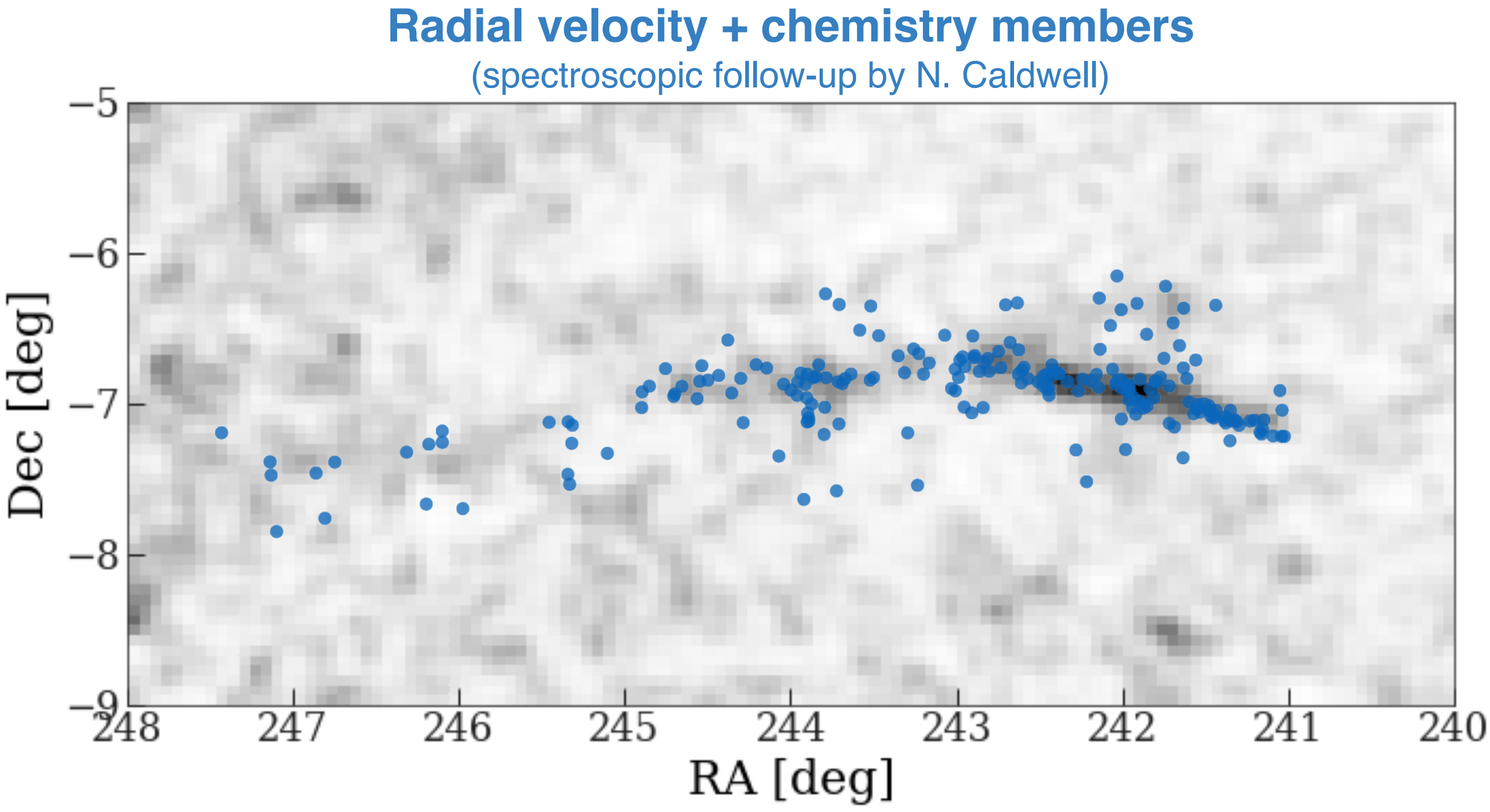
What was the GD-1 progenitor?

Where did the GD-1 progenitor come from? (don't say the Sausage / Enceladus / Sequoia!)

To get a sense of the geometry of GD-1 and other streams:

http://bit.ly/streamviz

e.g., Ophiuchus: short stream + diffuse ‘fan’

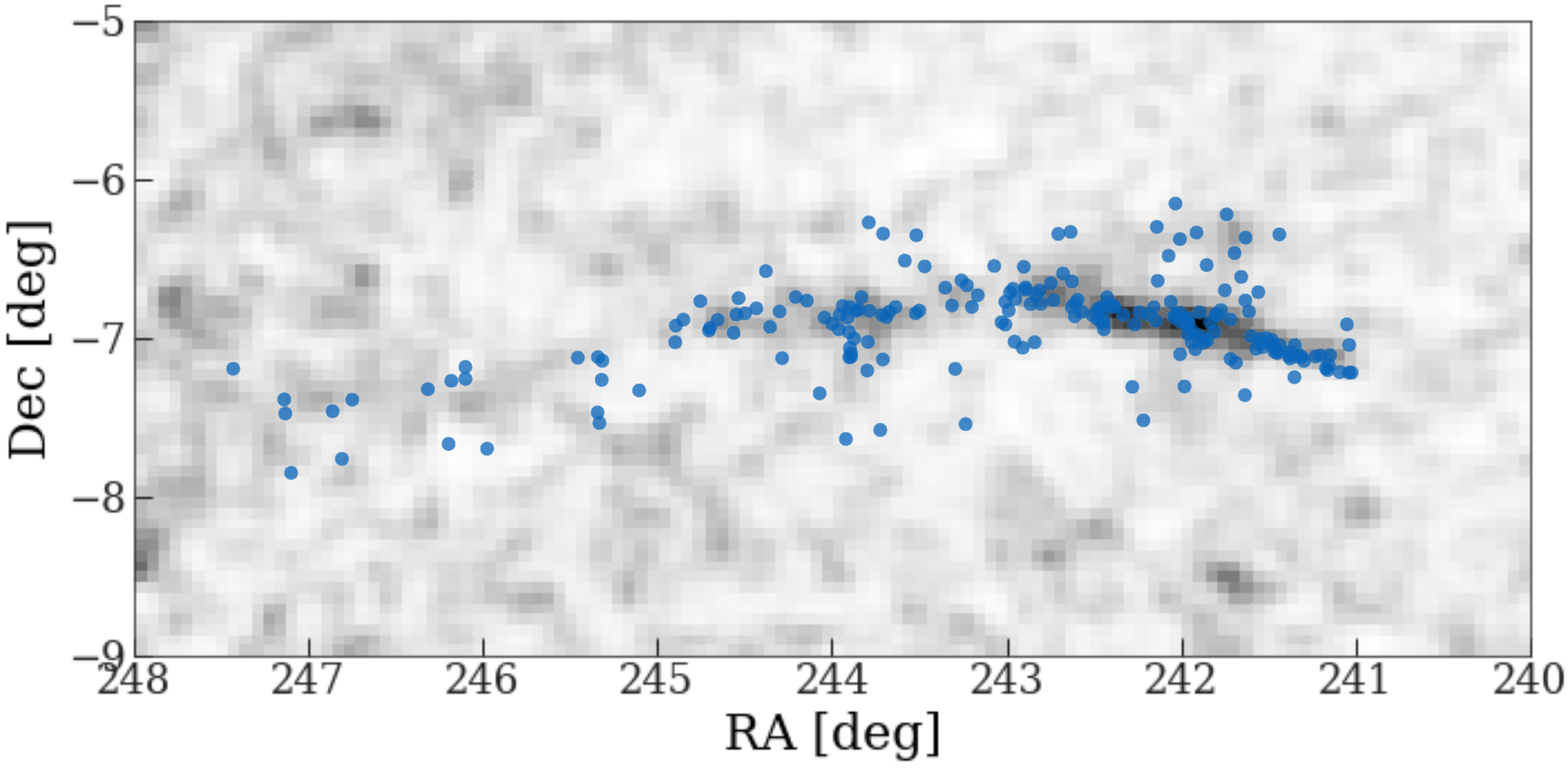


Data: Pan-STARRS+*Gaia,*
Hectochelle

Caldwell, *APW in prep.*

e.g., Ophiuchus: short stream + diffuse ‘fan’

Short, low-density, and diffuse / spread out stream stars?



Data: Pan-STARRS+*Gaia,*
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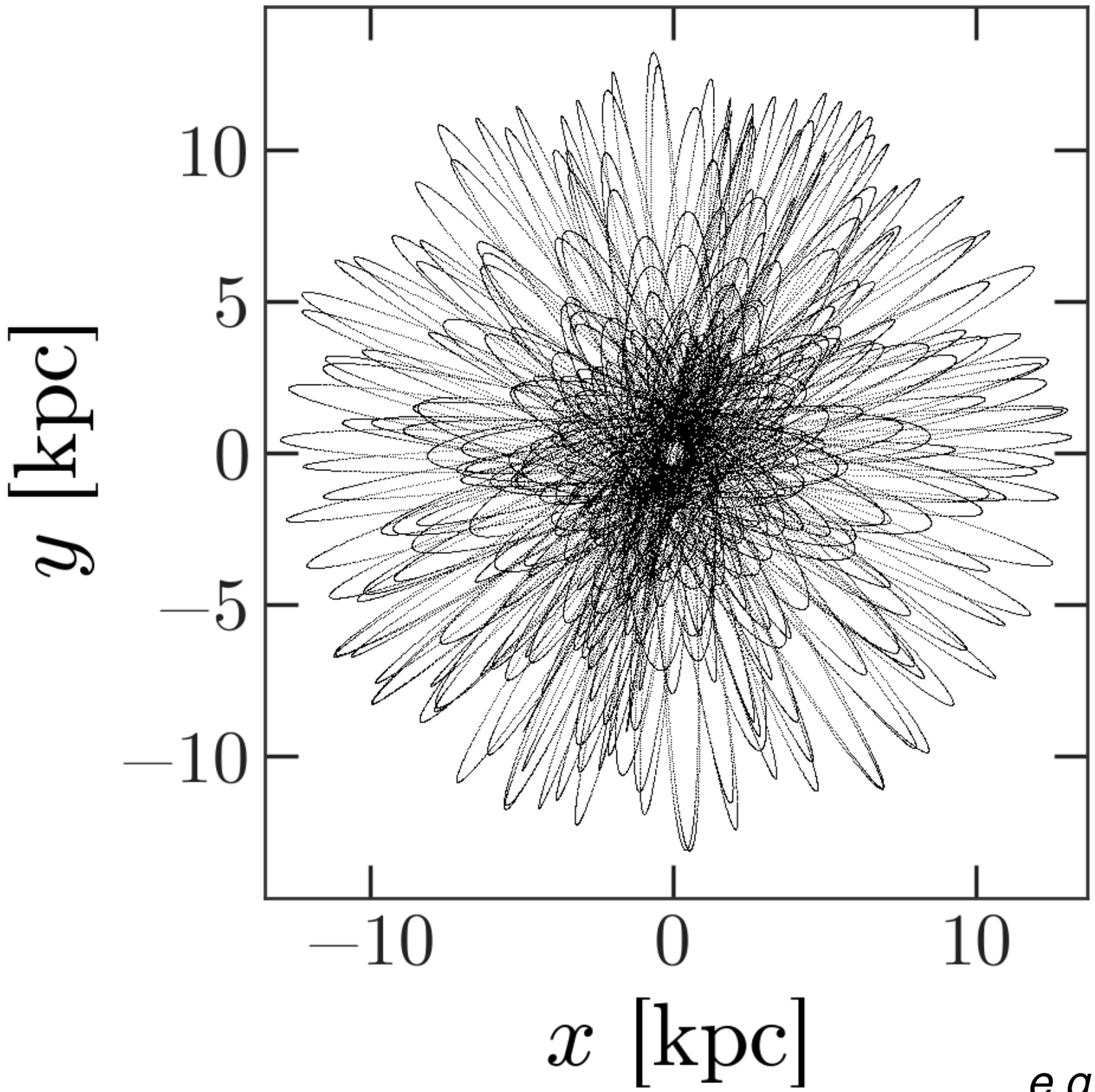
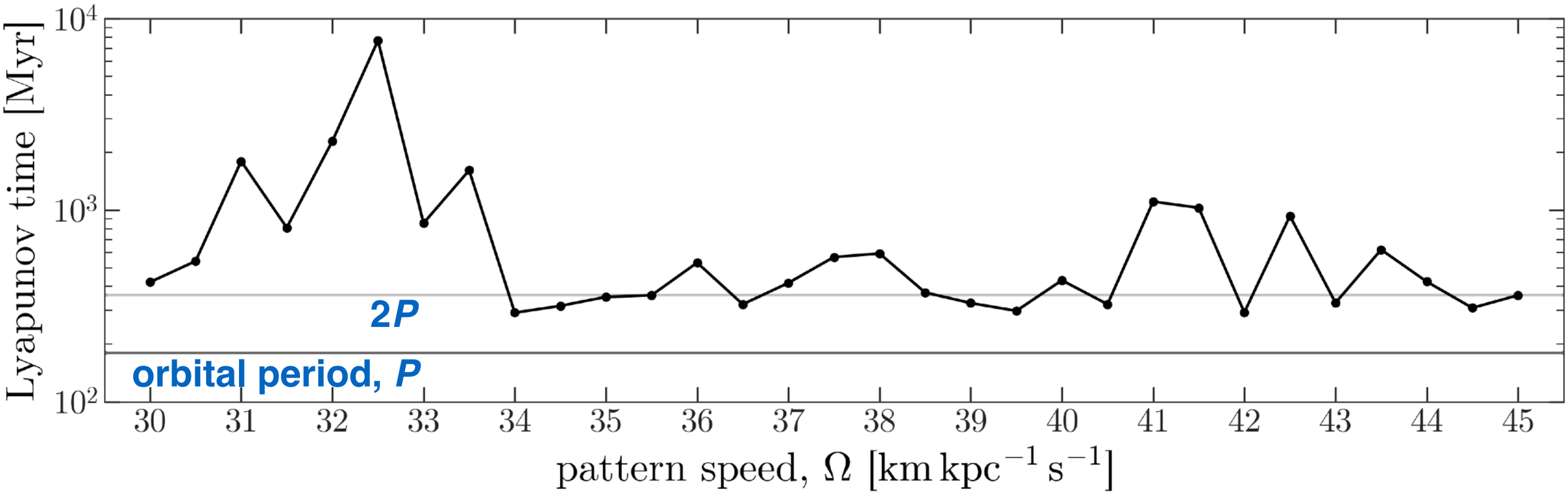
bar-induced chaos



*e.g., **APW** et al. 2016a,b*

bar-induced chaos



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PS1-E