The Galactic stellar halo

Robyn Sanderson

ISSS, Summer 2019

Outline

- What is the “halo”?
- What is in it?
- How do we think stars get there?
- What do we know about their properties?
- How do we make & test predictions for this part of the Galaxy?
- What have we learned so far from Gaia?
- What will we learn in the future?

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What is the “halo” ? [for purposes of this lecture]

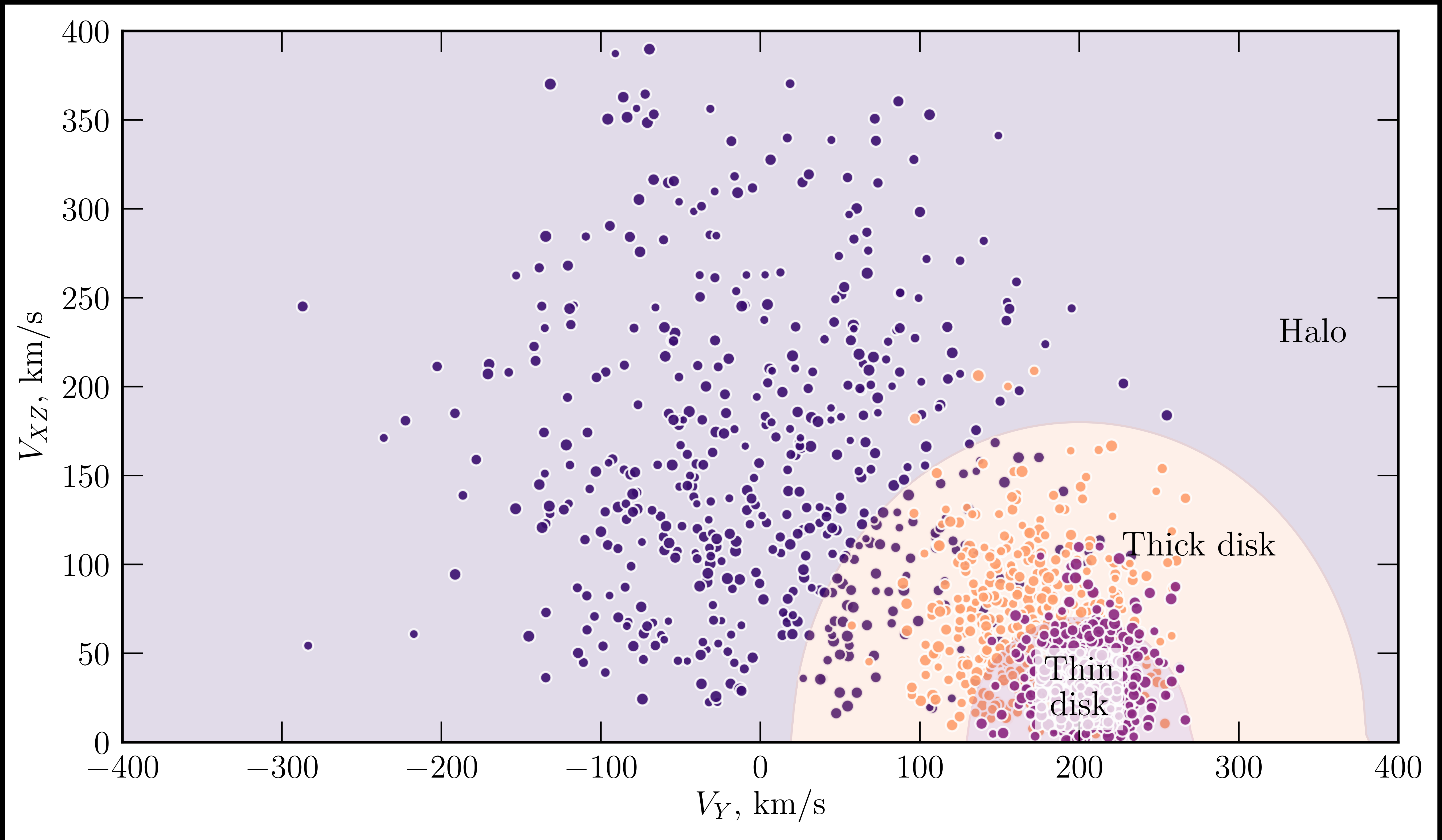
- “dark halo” - the dark matter in the Galaxy

- “stellar halo” - stars with an orbit distribution centered on the Galactic center, roughly isotropic and roughly non-rotating

- “accreted stellar halo” - stars that acquired this distribution because they formed in other galaxies that merged with the MW

- “stellar disk” - stars with a defined sense of rotation, mostly in a [relatively] thin plane

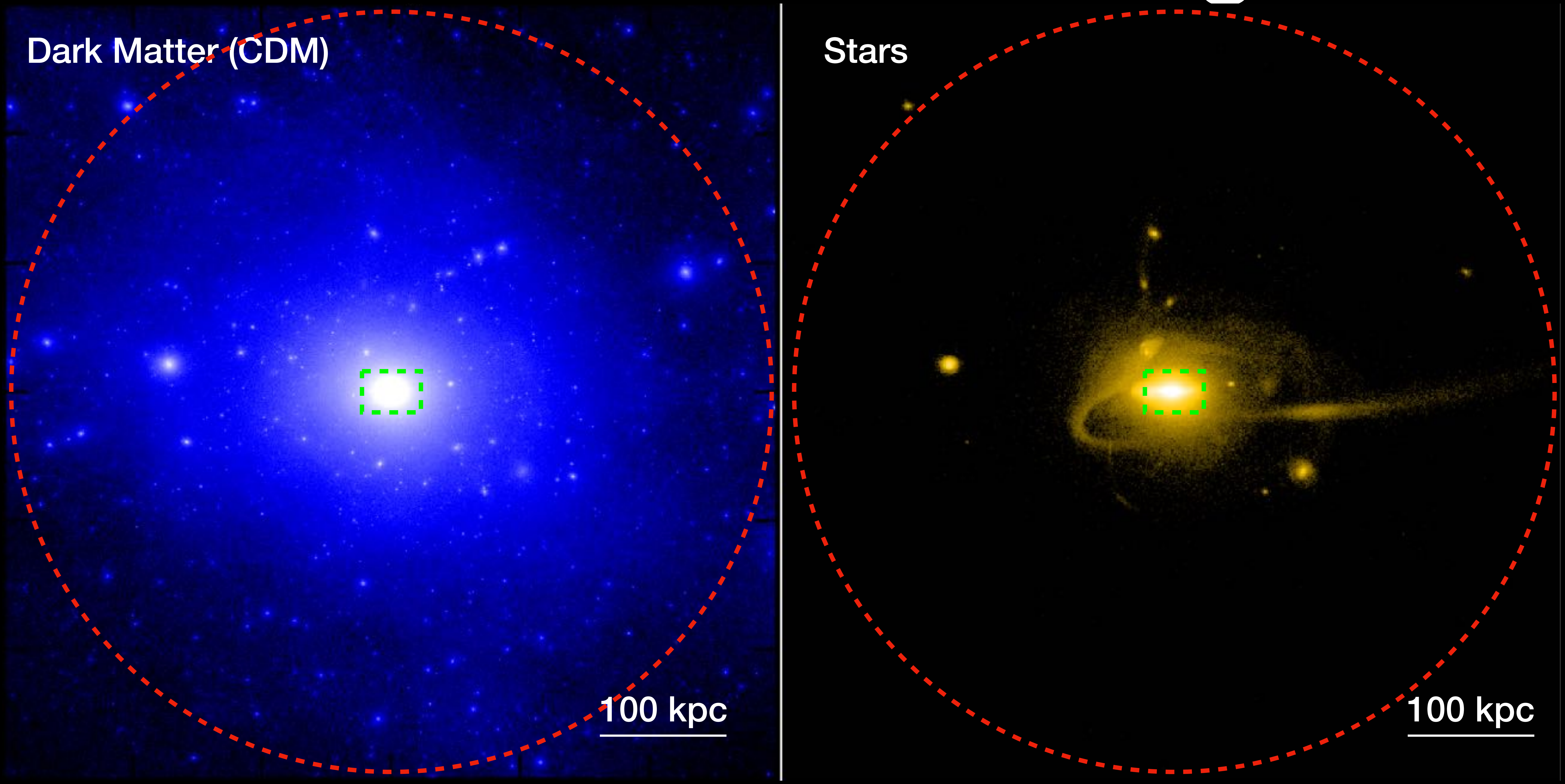
Galactocentric non-azimuthal velocity $\sqrt{v_R^2 + v_z^2}$



Galactocentric azimuthal velocity v_ϕ

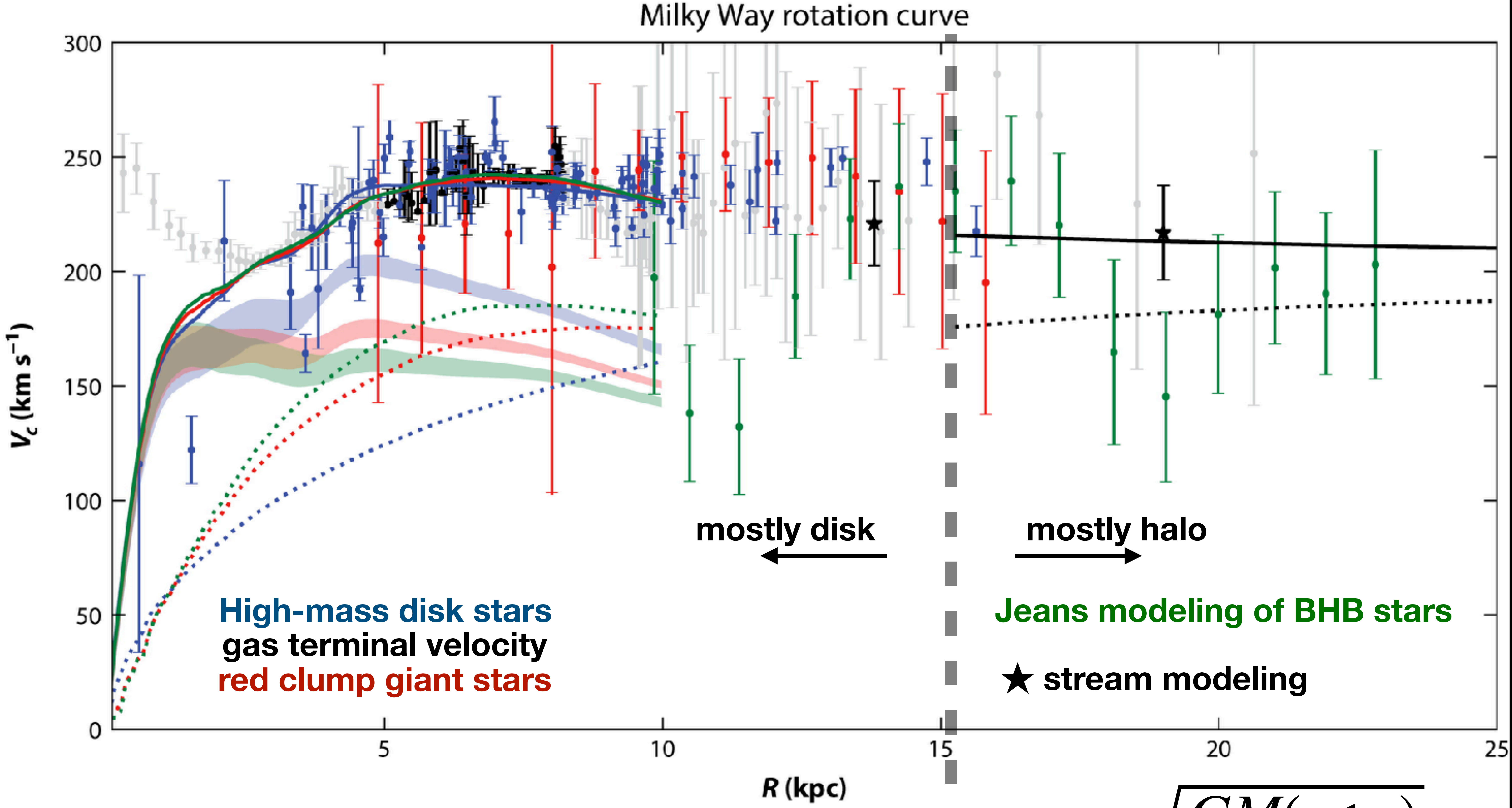
Figure courtesy A. Bonaca

The halo is dominated by dark matter rather than stars and gas



FIRE-2 simulation *m12i*, Wetzel et al 2016

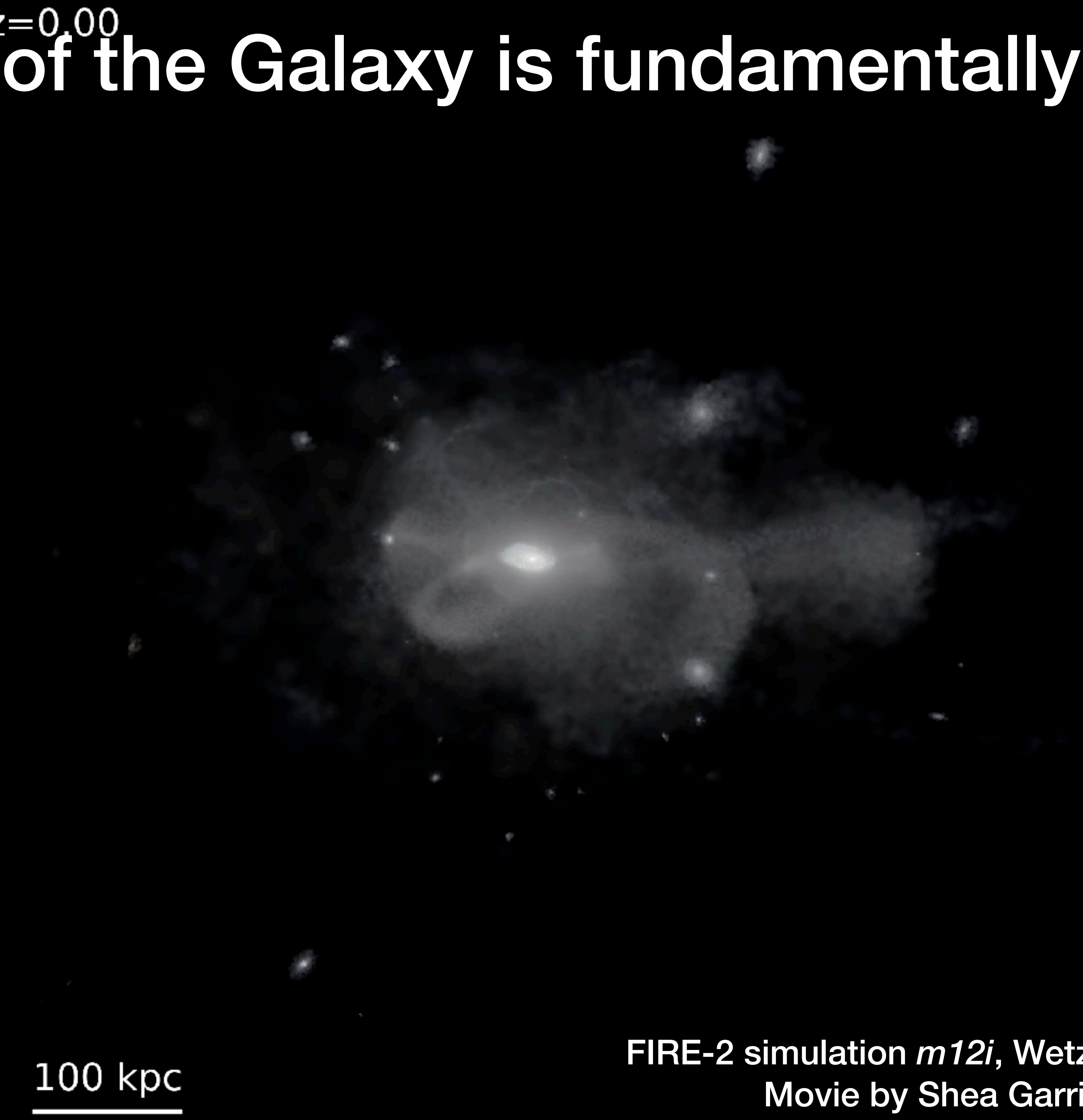
The halo's mass is dominated by dark matter



$$v_c(r) = \sqrt{\frac{GM(<r)}{r}}$$

Bland-Hawthorn J, Gerhard O. 2016.
Annu. Rev. Astron. Astrophys. 54:529–96

This region of the Galaxy is fundamentally cosmological



FIRE-2 simulation *m12i*, Wetzel et al 2016
Movie by Shea Garrison-Kimmel

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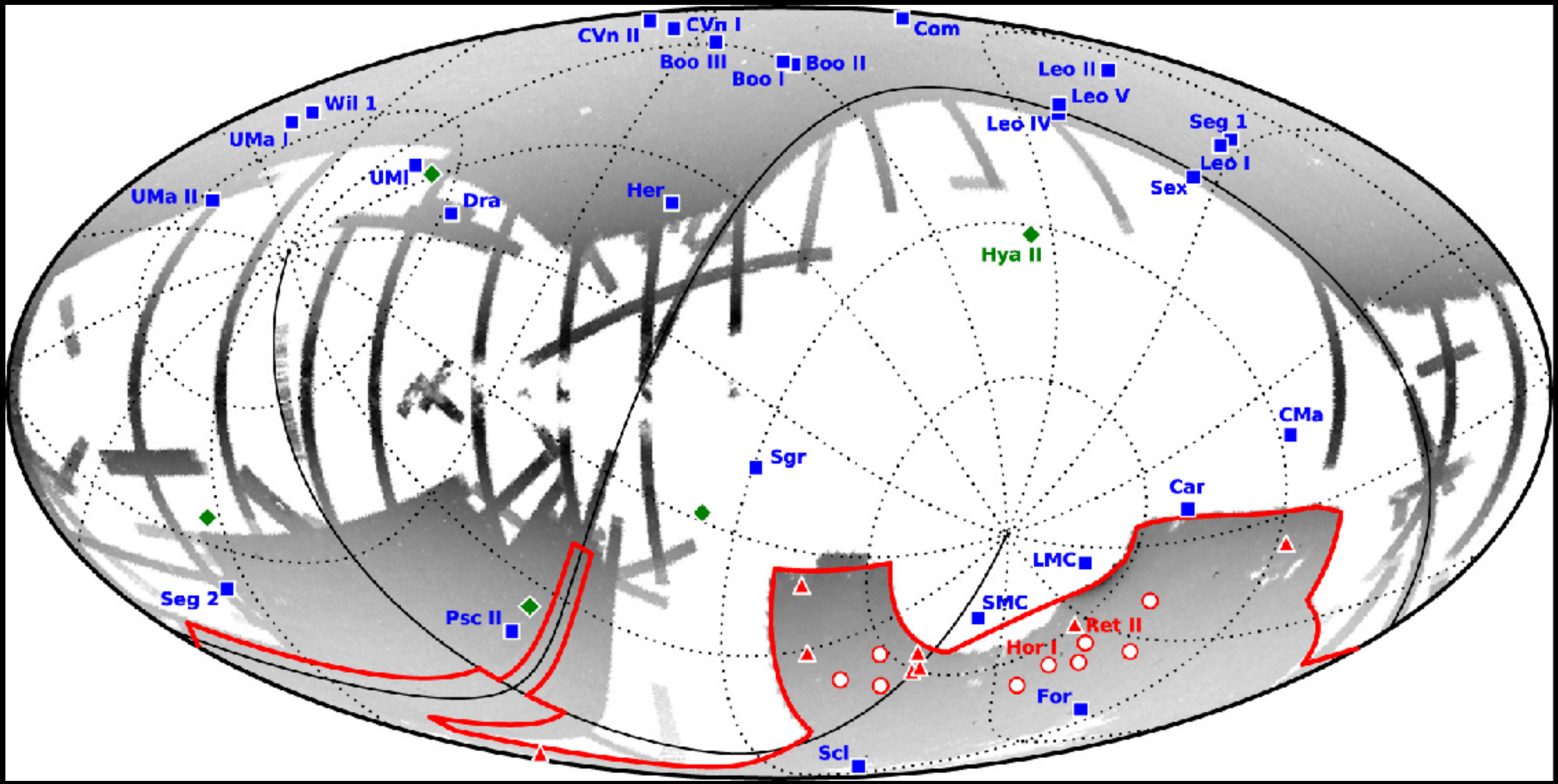
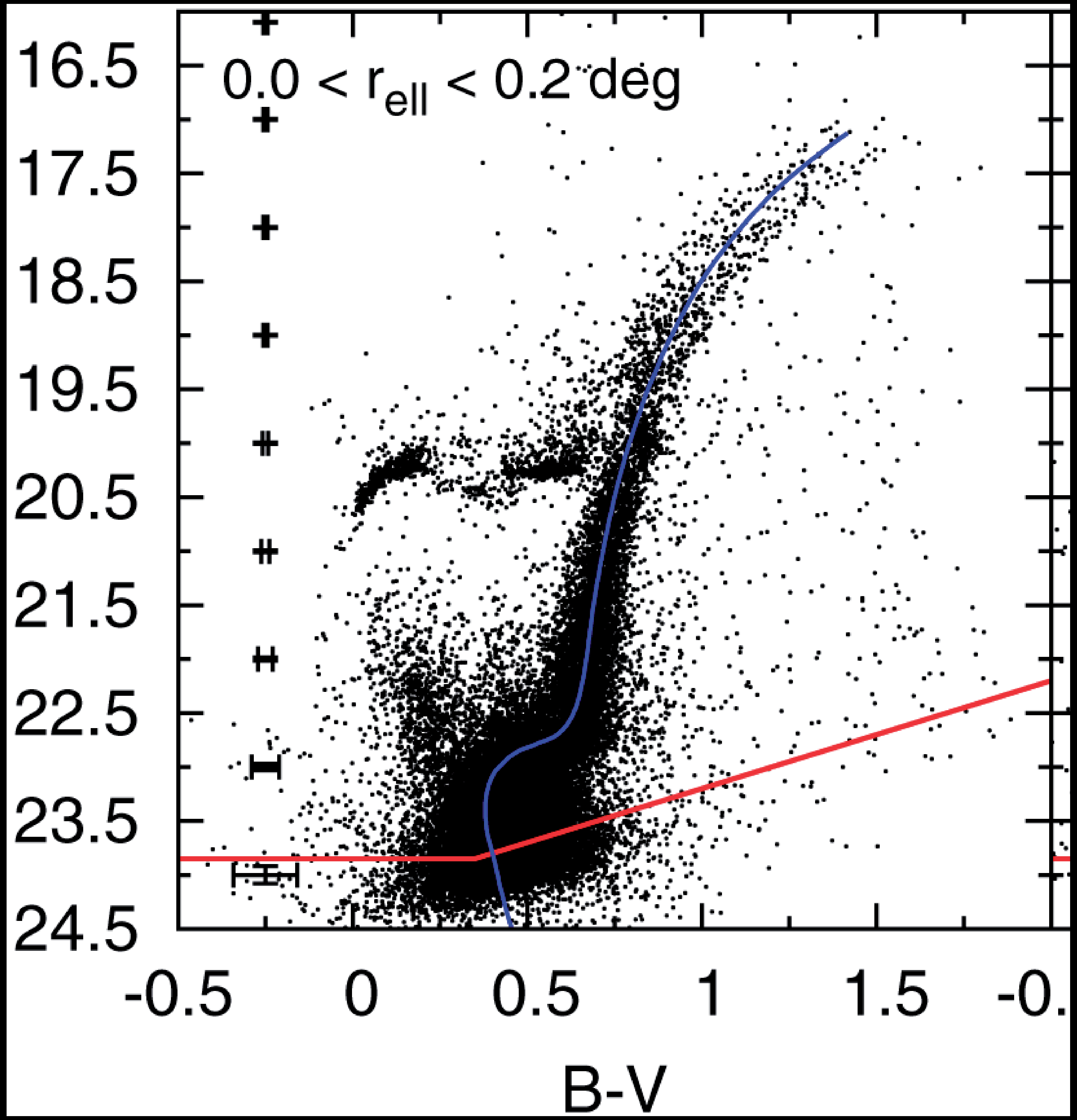


Galactic positions of known satellite galaxies + surveyed regions of sky (as of 2015). Drlica-Wagner et al. 2015 (DES collab)



Deep color-magnitude diagram of the Sculptor dwarf satellite galaxy de Boer et al. 2011

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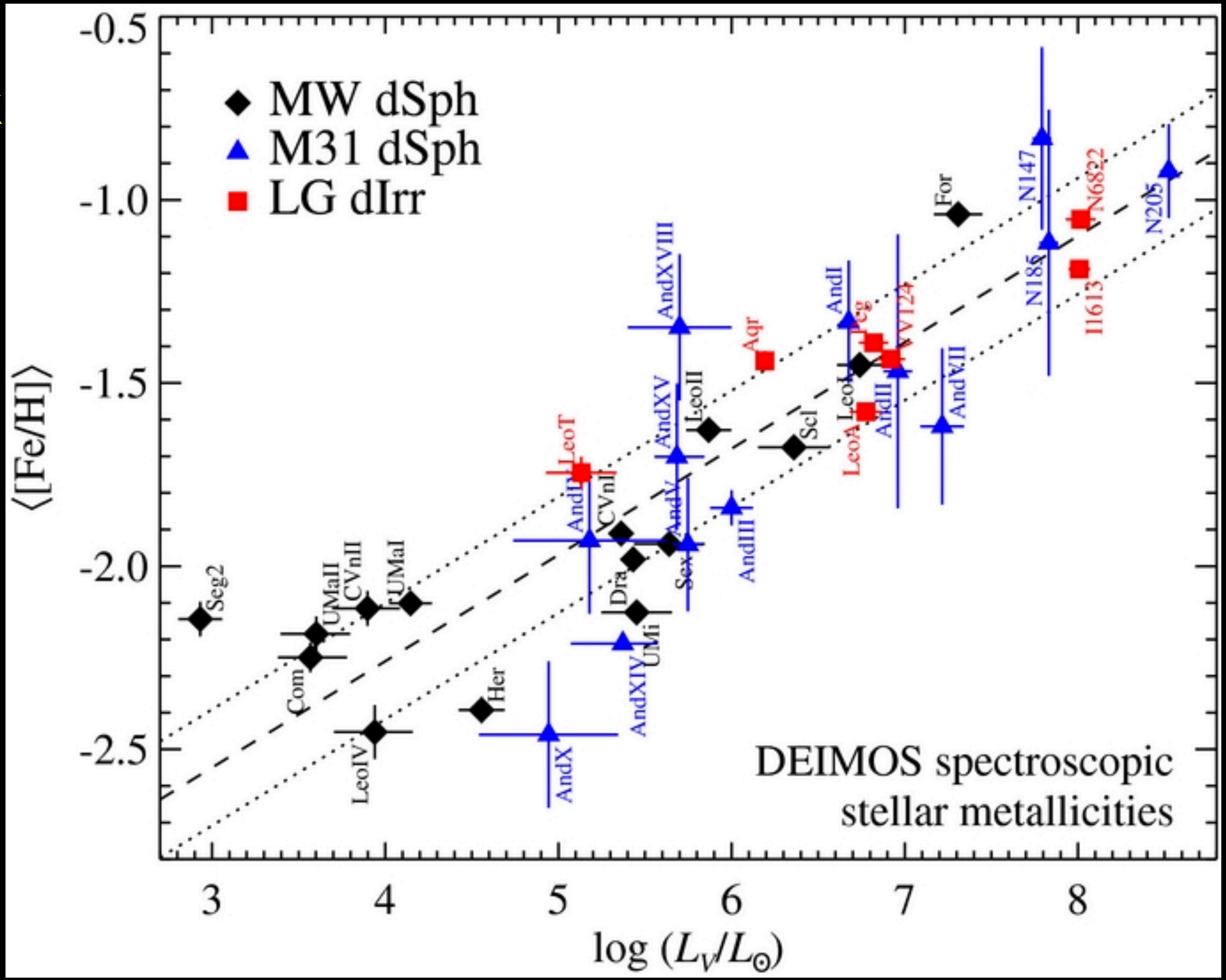
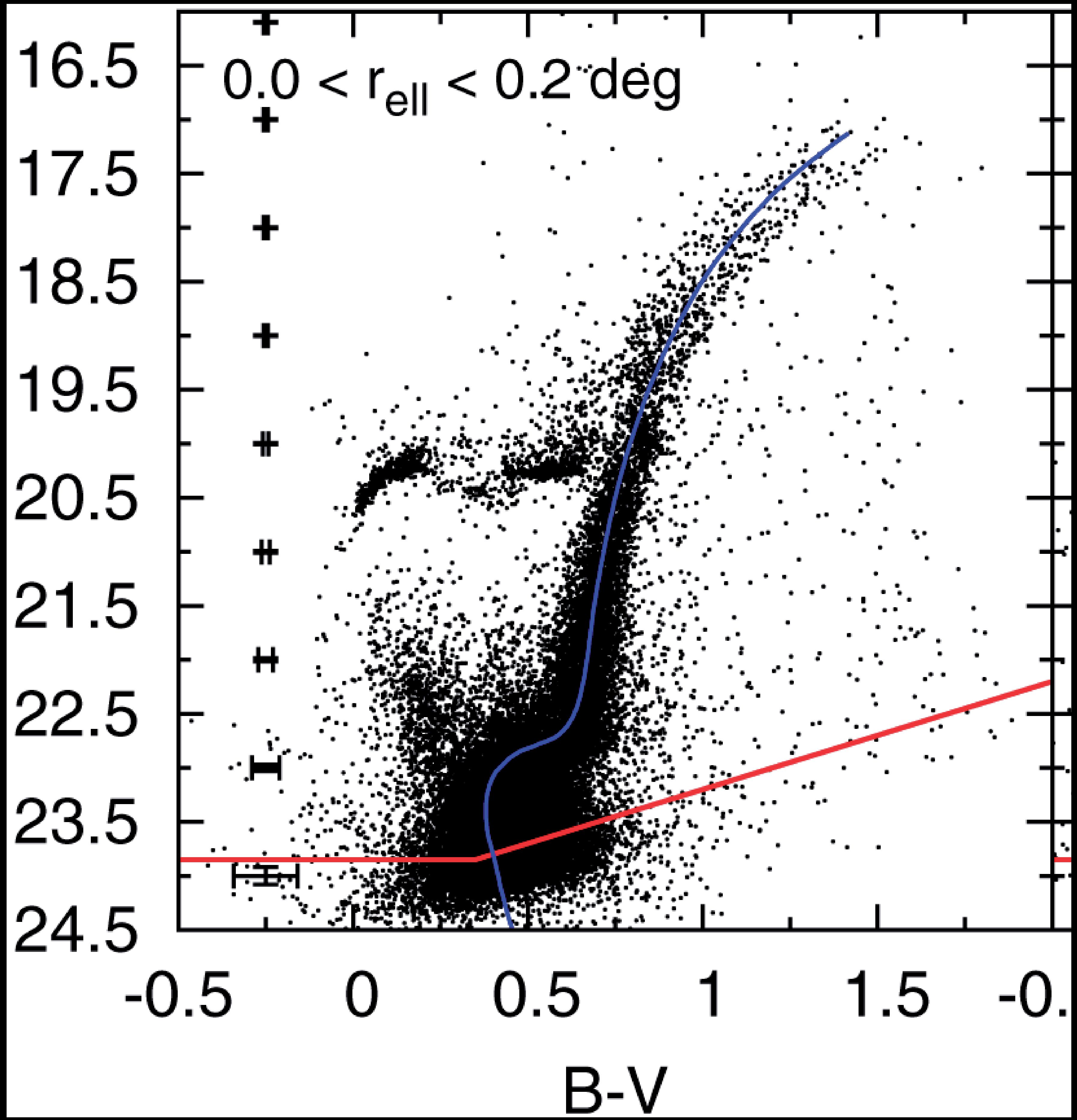


luminosity-metallicity reln for dwarf satellites
(Kirby et al. 2013)



Deep color-magnitude diagram of the
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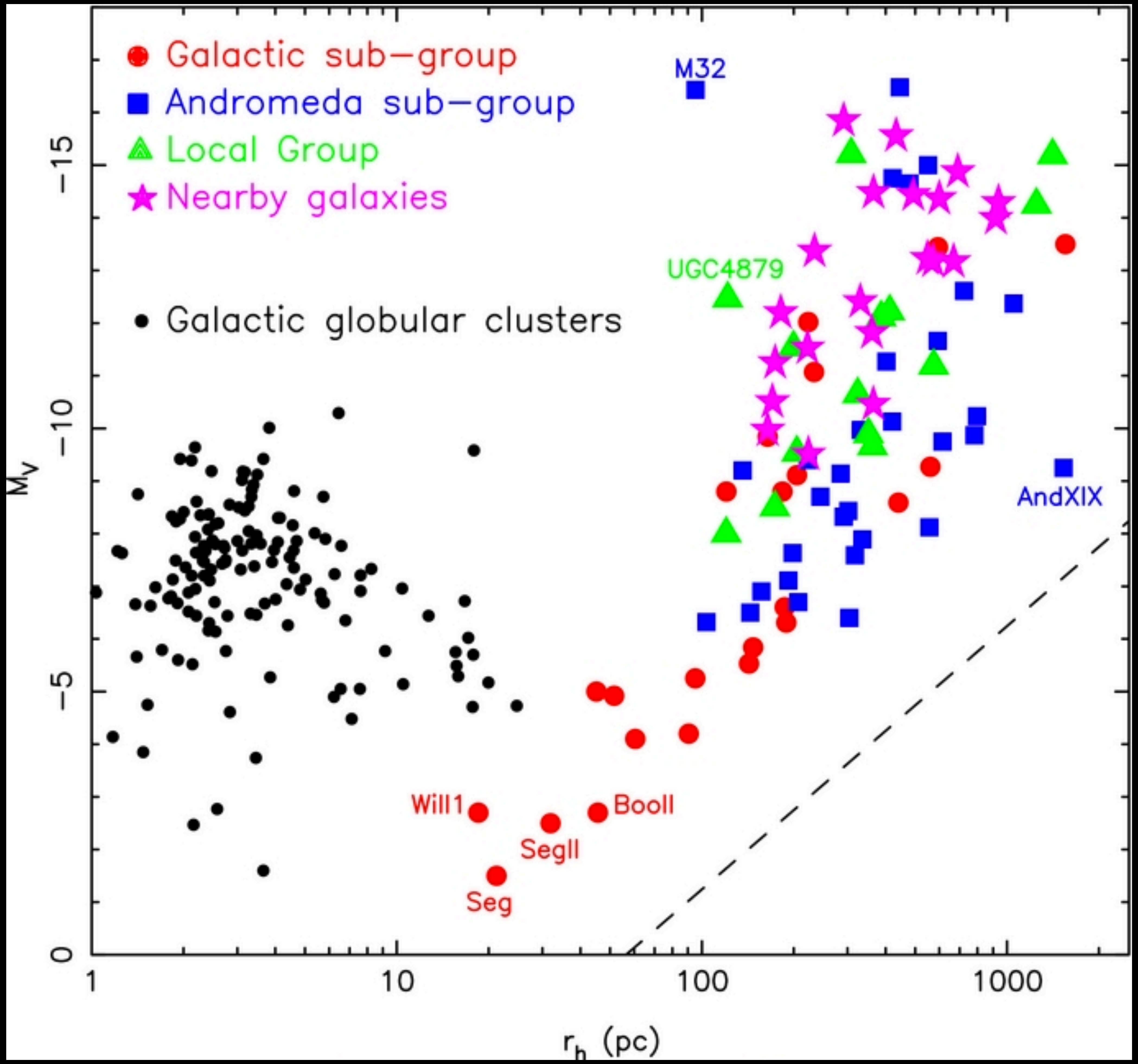

Absolute magnitude (total brightness)

Half-light radius (apparent size)

McConnachie 2012

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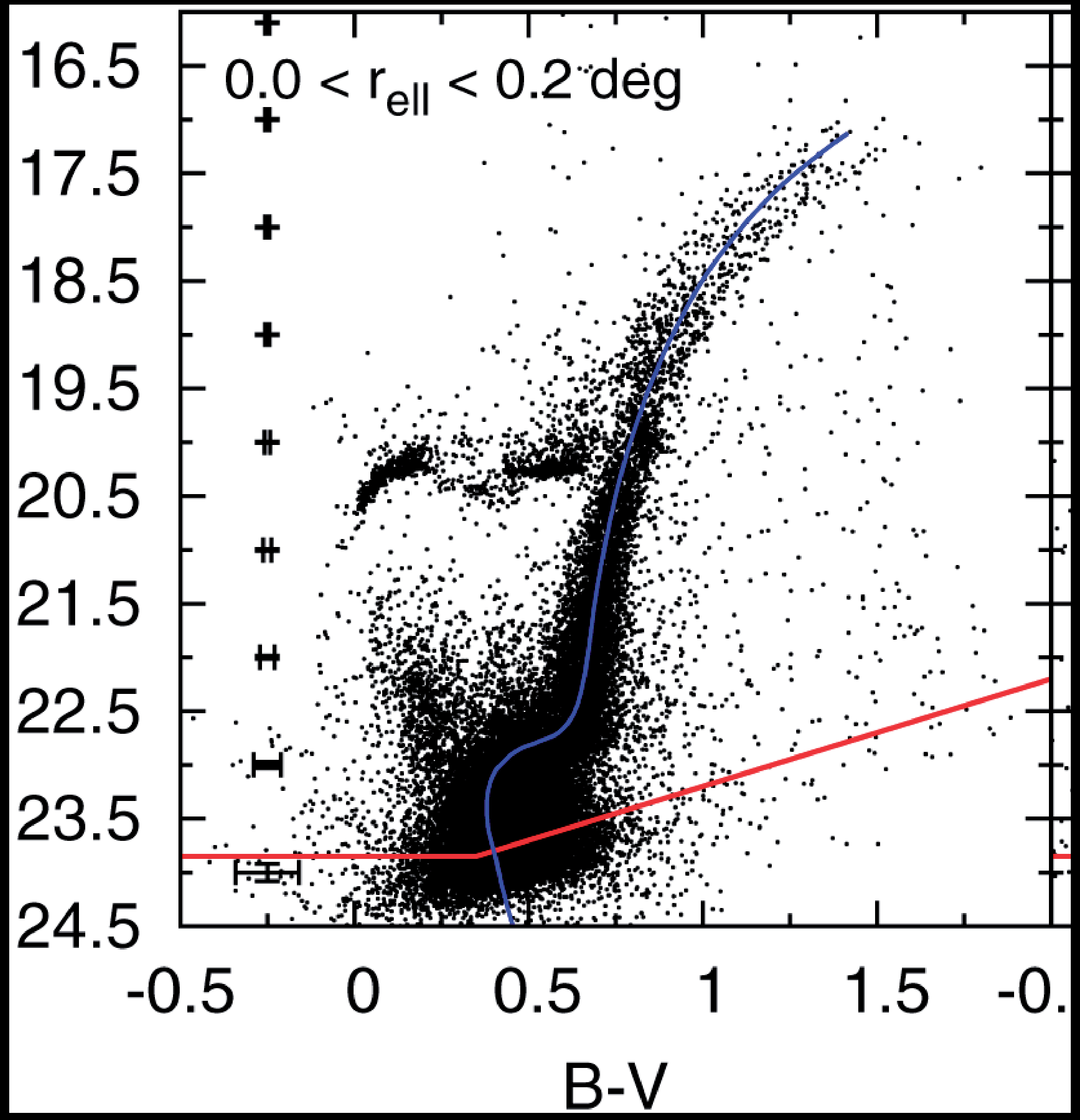
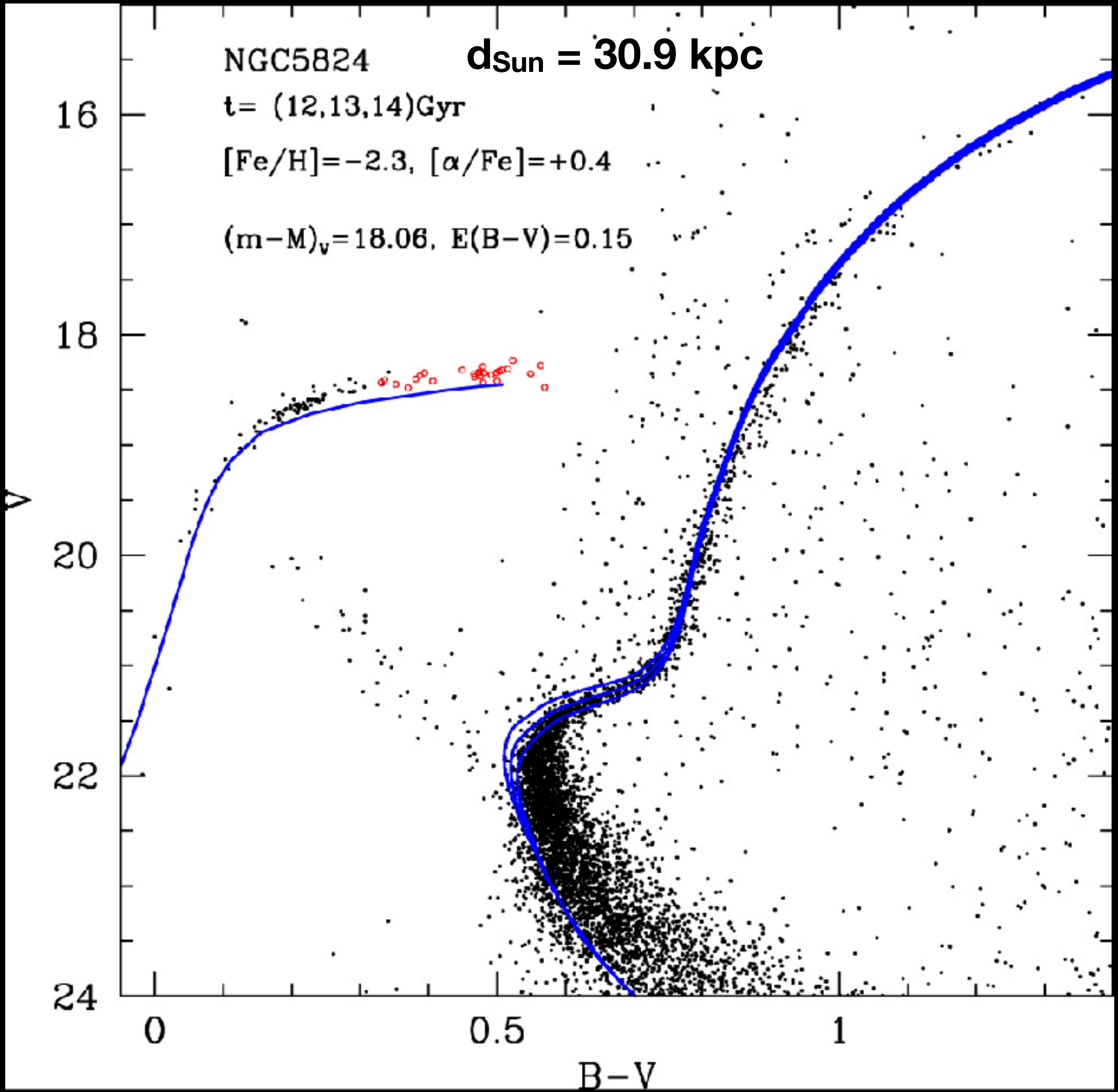


CMD of Sculptor
de Boer et al. 2011



A.R. Walker et al. 2017

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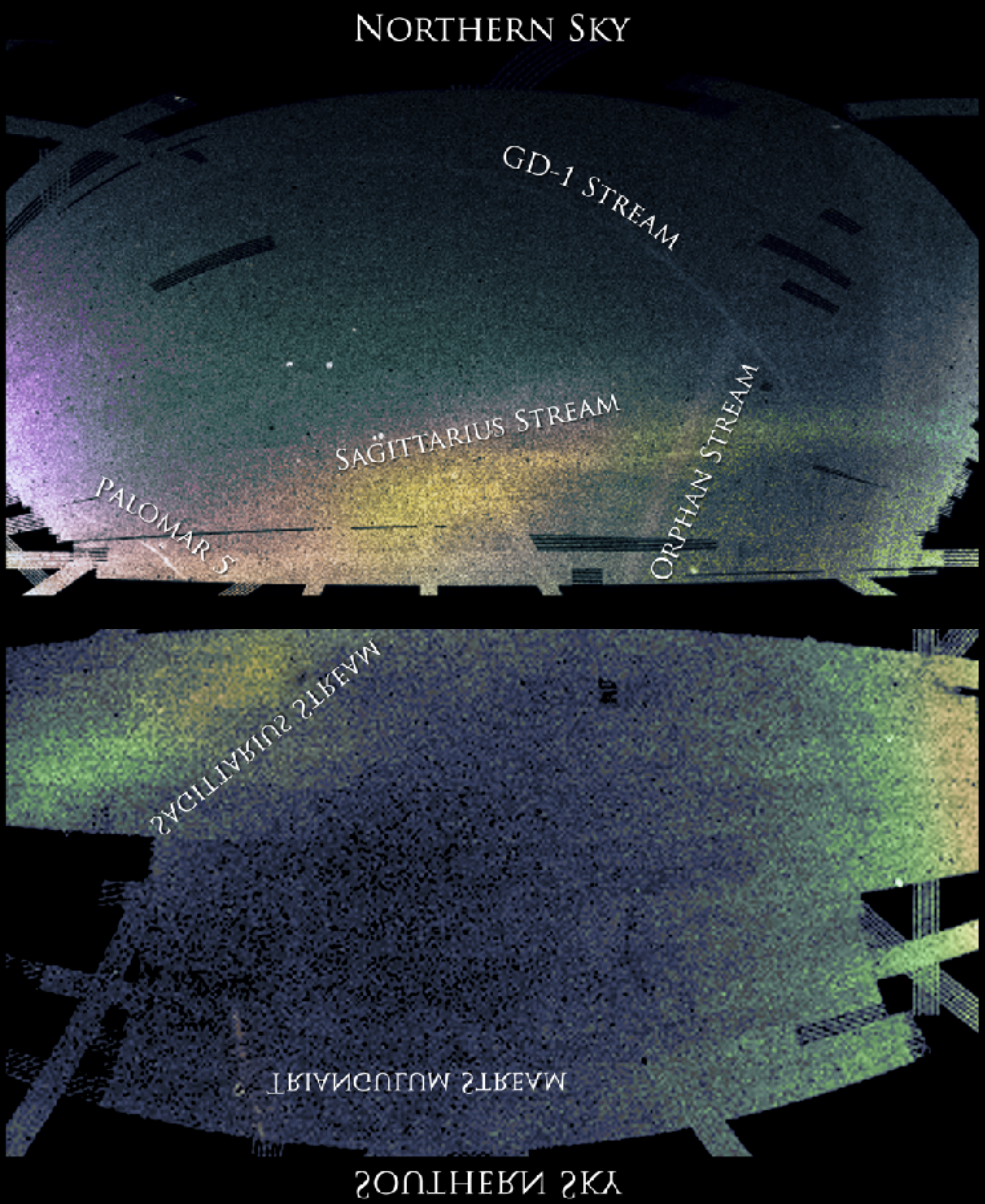
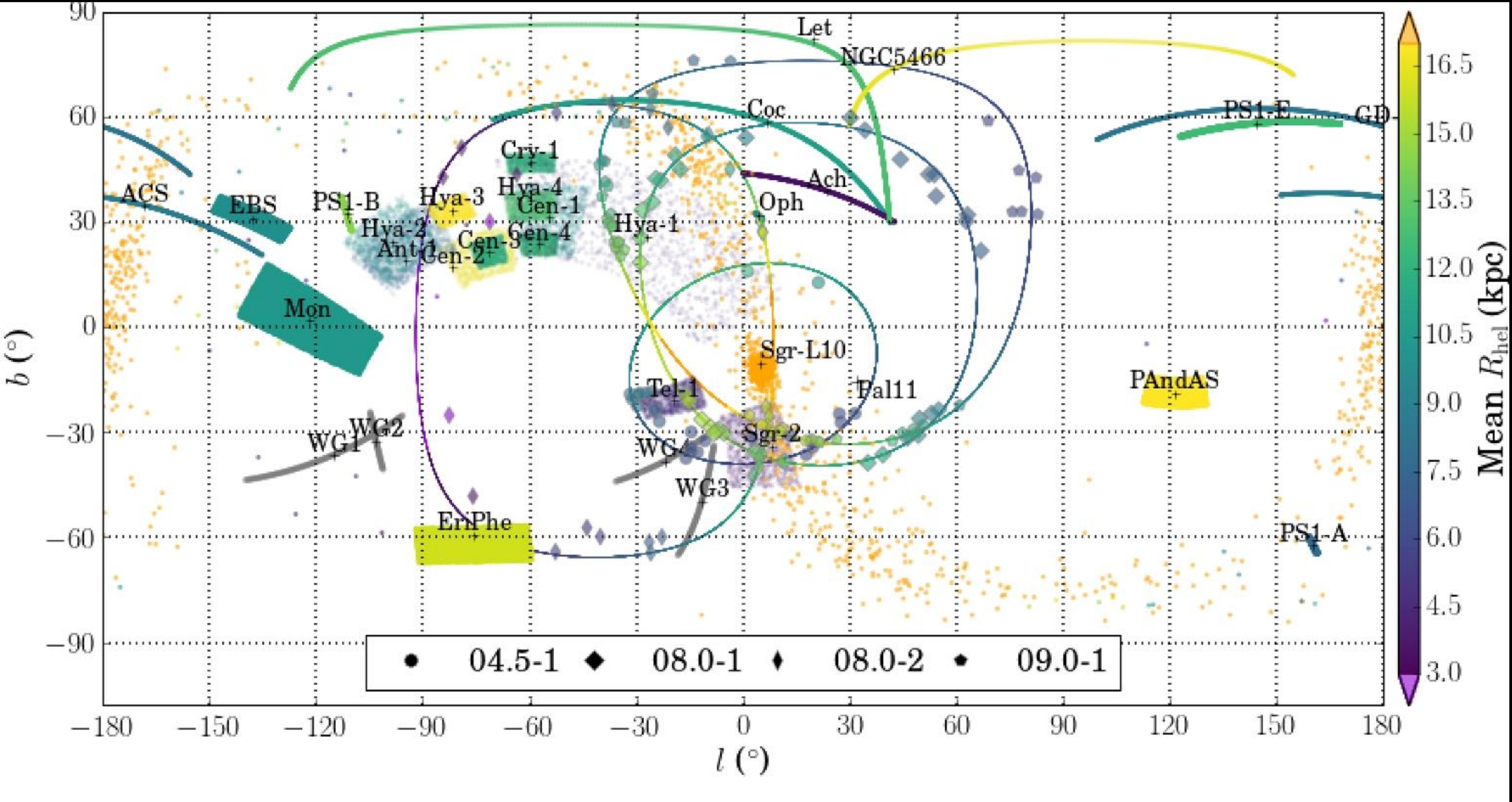


stellar streams are found all over the Galaxy

4-10 kpc Galactocentric

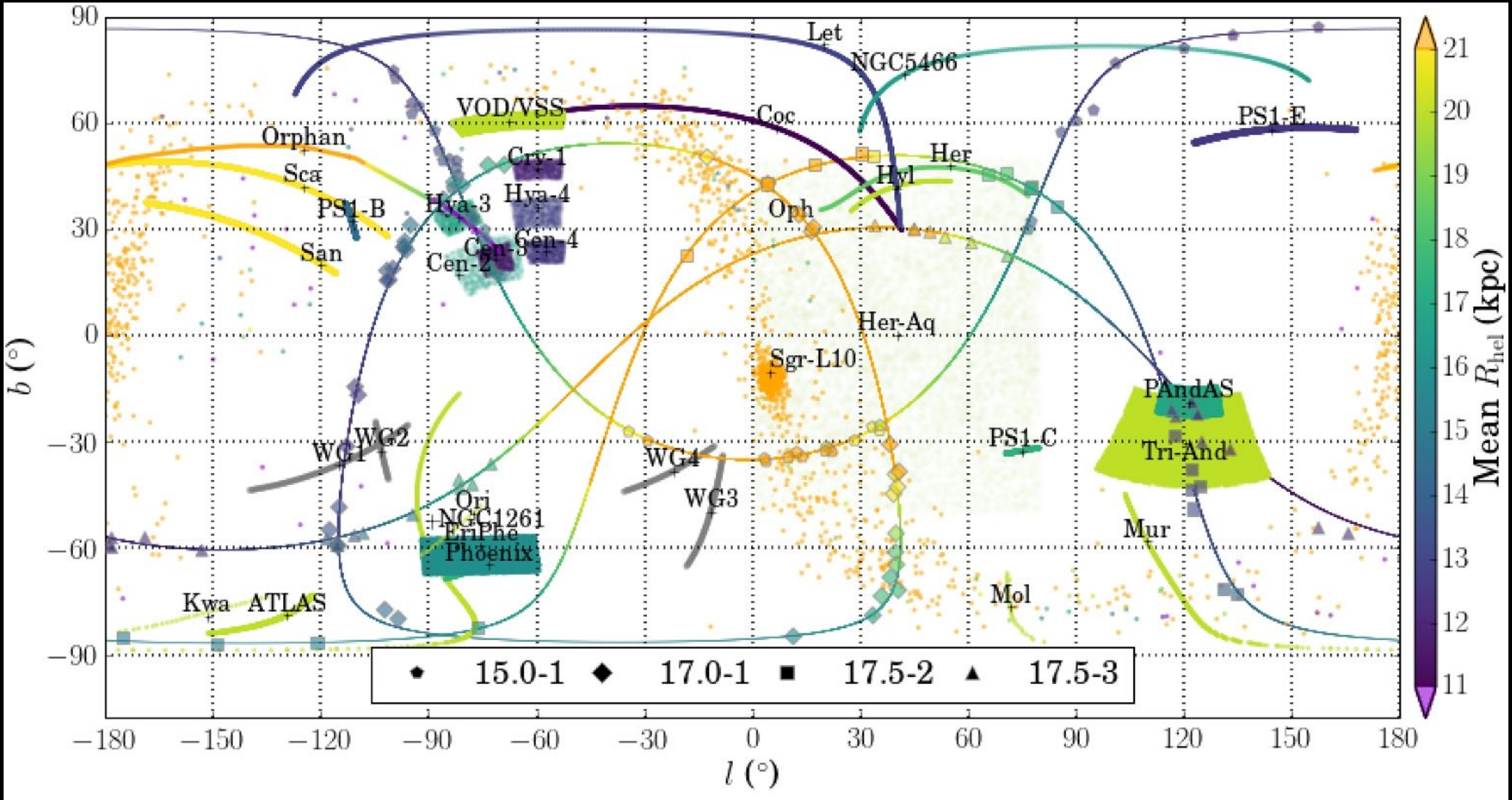


https://github.com/cmateu/galstreams

Mateu, Read, & Kawata 2018

stellar streams are found all over the Galaxy

15-21 kpc Galactocentric

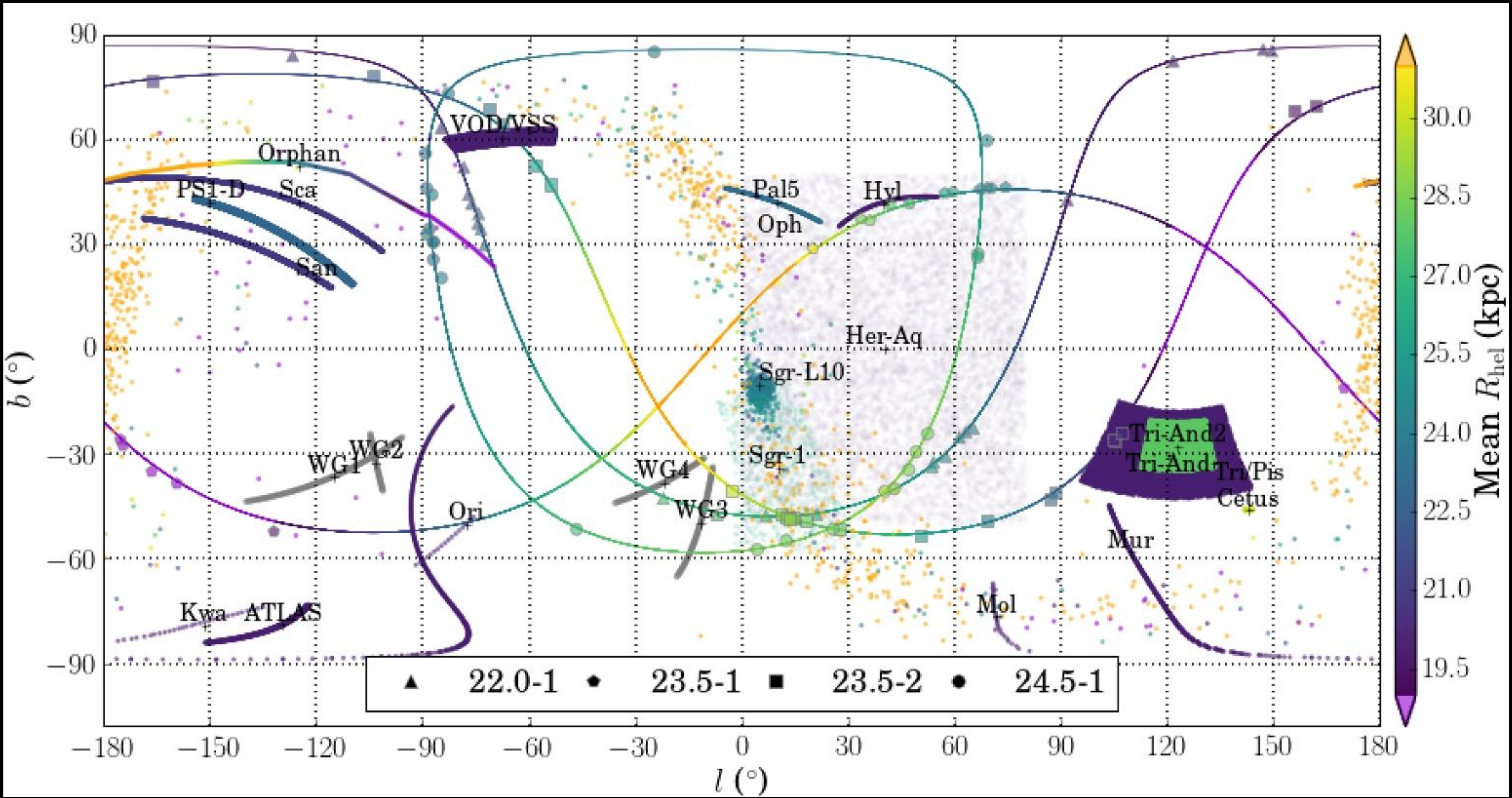


https://github.com/cmateu/galstreams

Mateu, Read, & Kawata 2018

stellar streams are found all over the Galaxy

21-26 kpc Galactocentric



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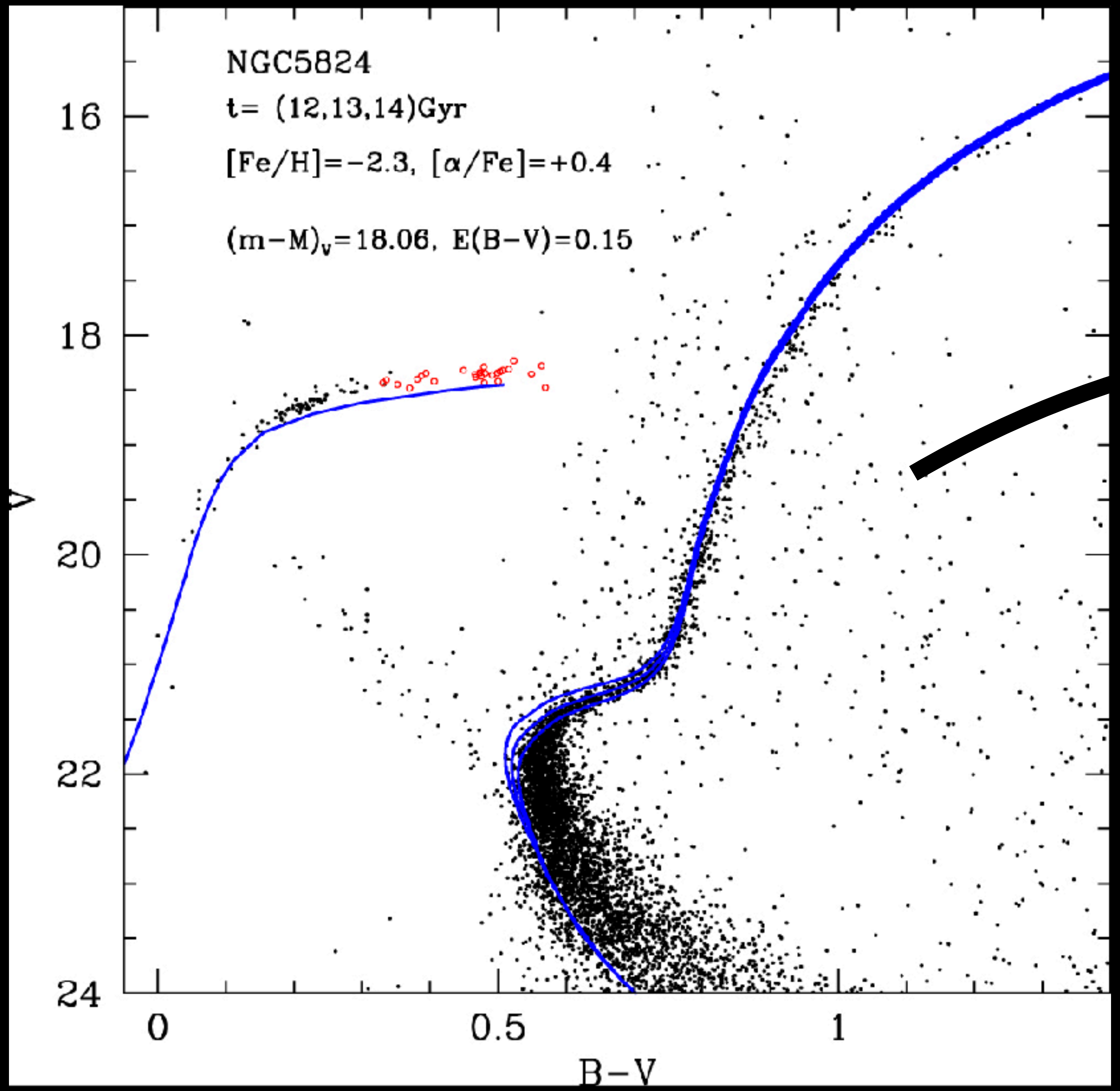
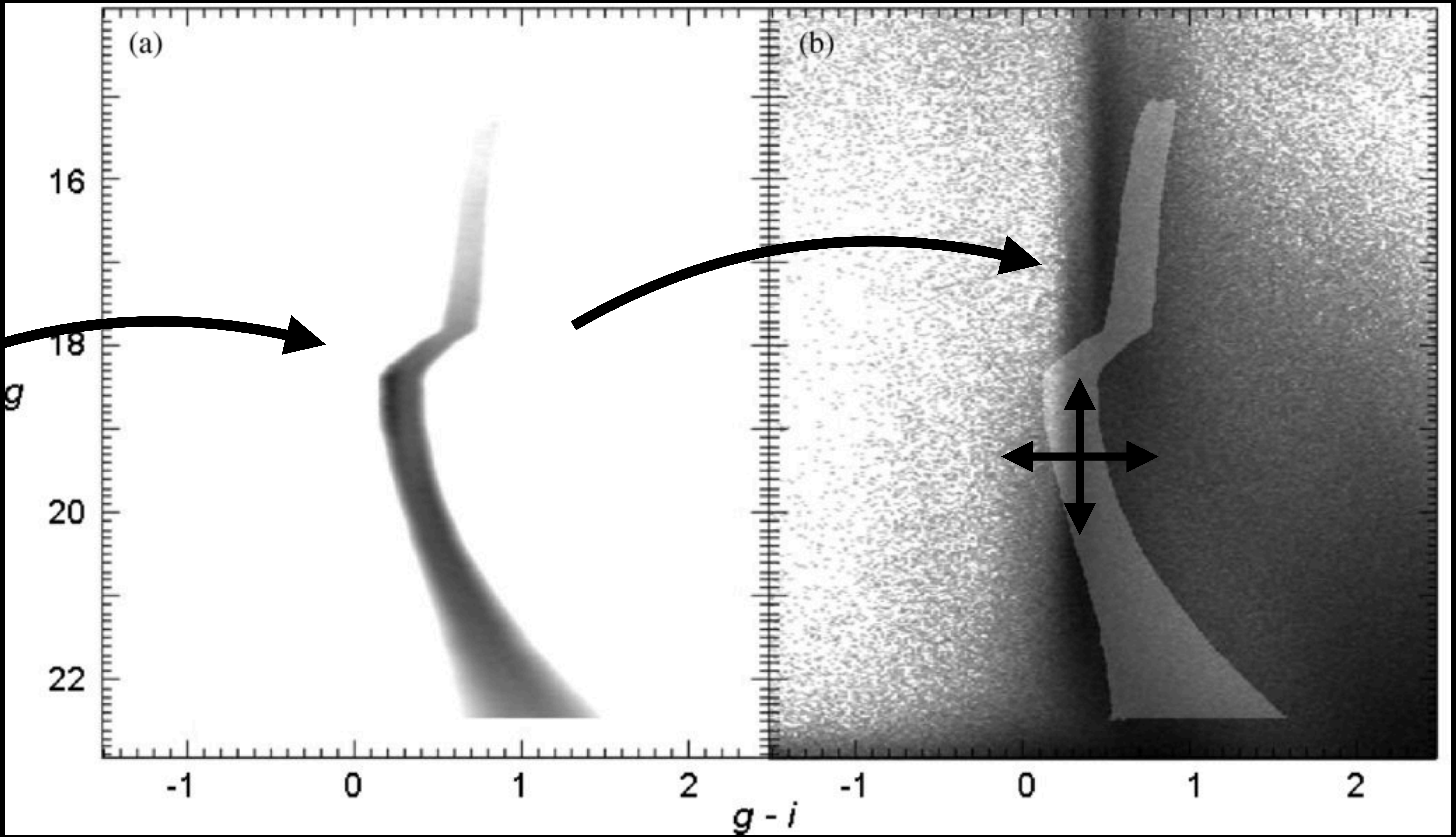
Mateu, Read, & Kawata 2018

most streams used to be found via “matched filtering” operating on photometric surveys like SDSS…



A.R. Walker et al. 2017

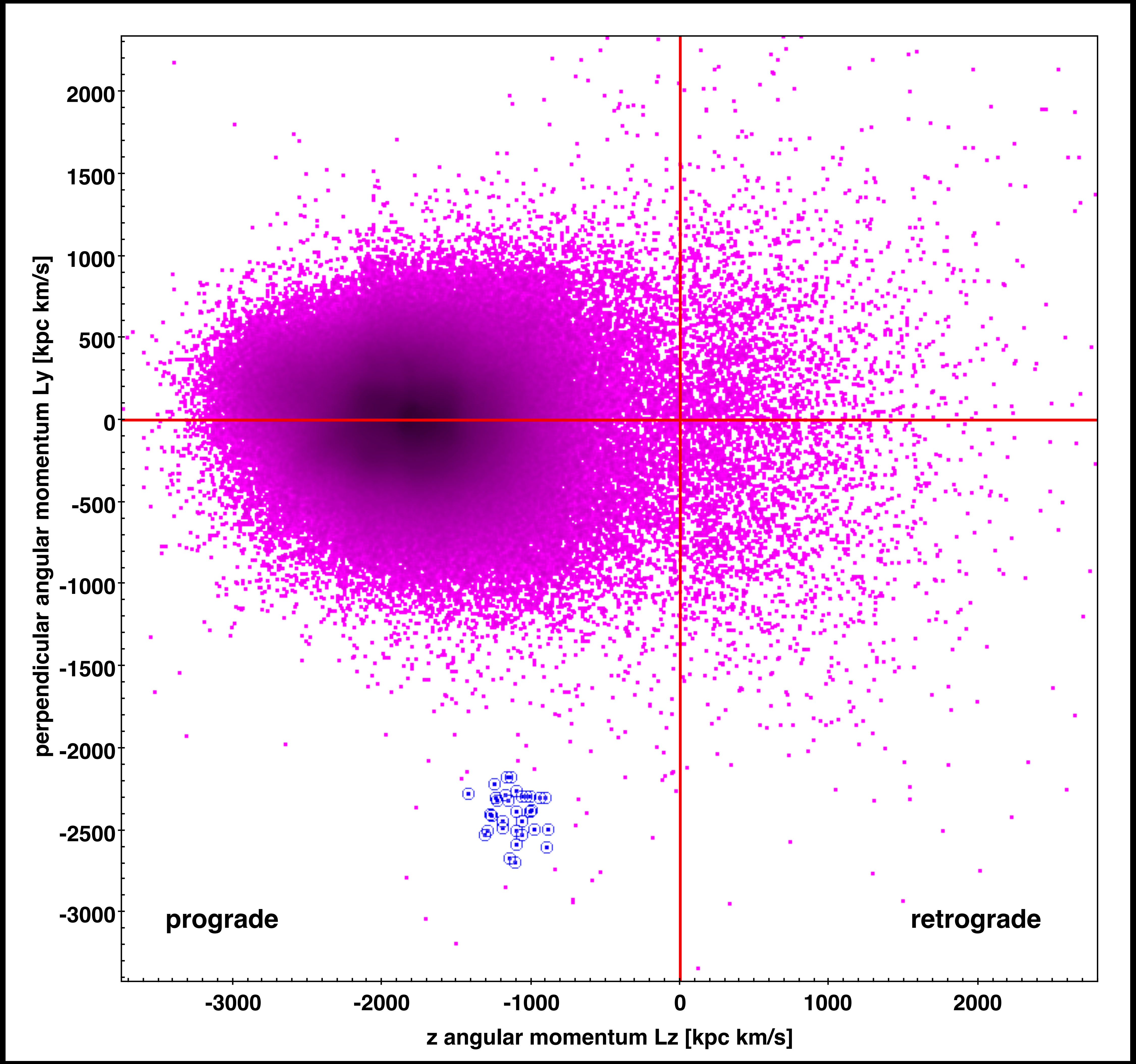


Grillmair 2009

…but now Gaia allows searches in position + proper motion (e.g. Malhan & Ibata 2018)

around the Sun, Gaia & predecessors showed streams passing through the solar neighborhood in phase space

Angular momentum distribution, looking toward Galactic anticenter



Gaia Collaboration, Helmi et al. 2018

Gaia view of solar neighborhood

Gaia data | **Simulation of a 1:5 merger**

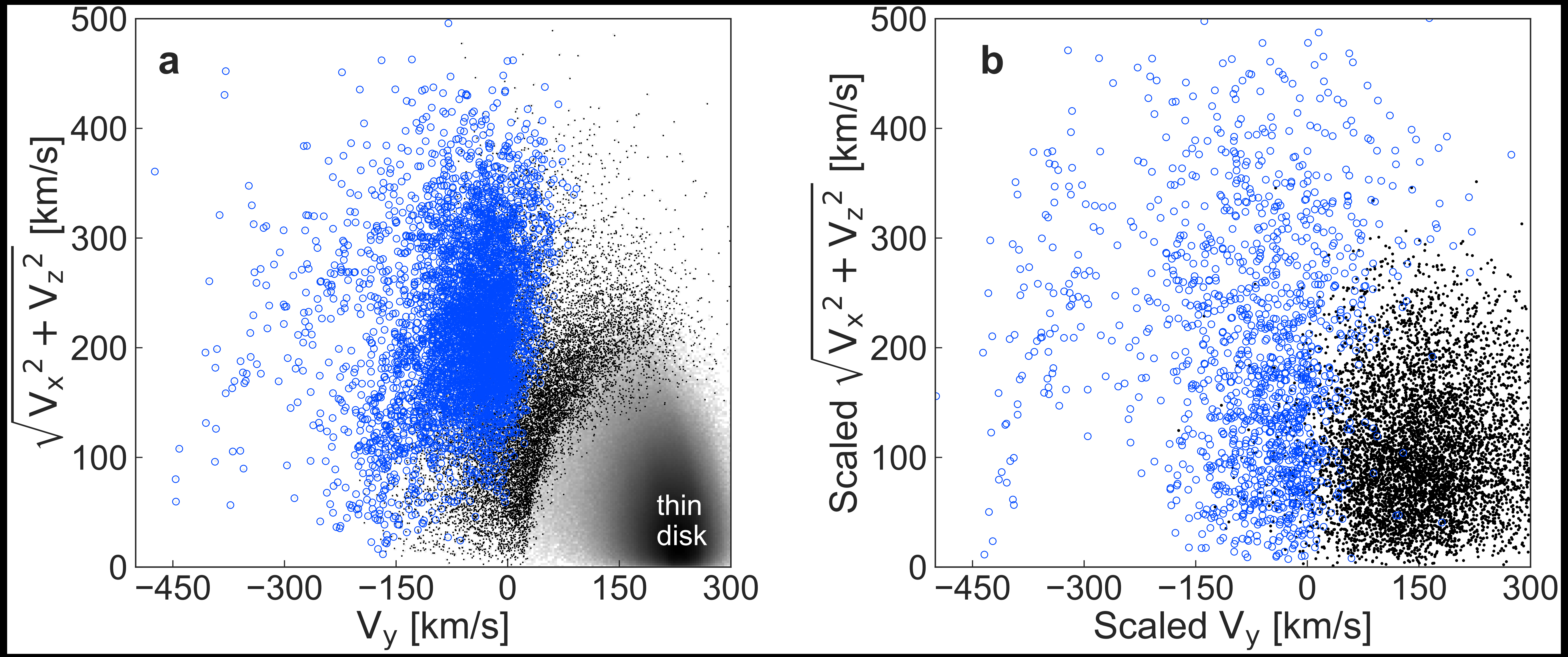
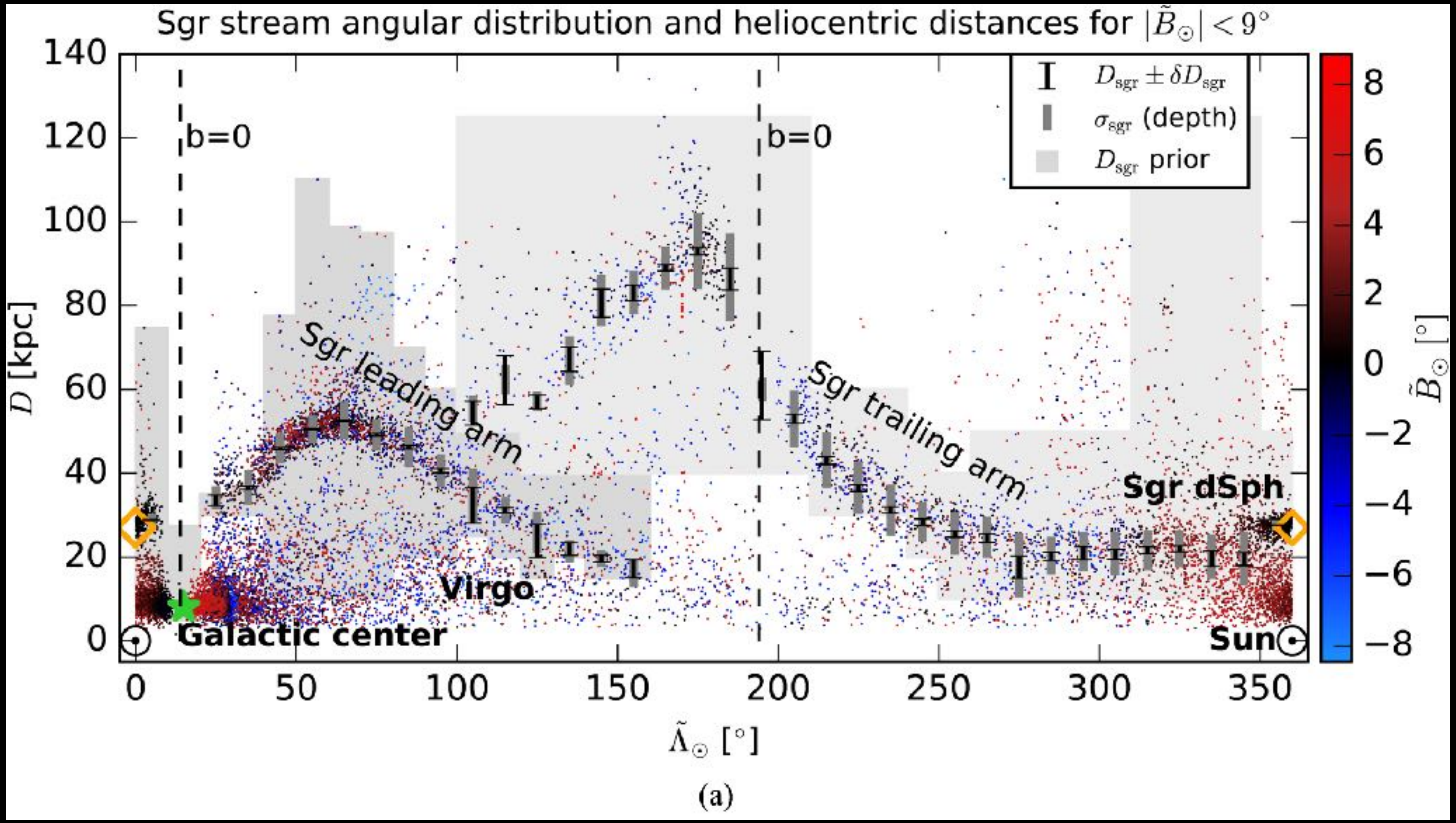


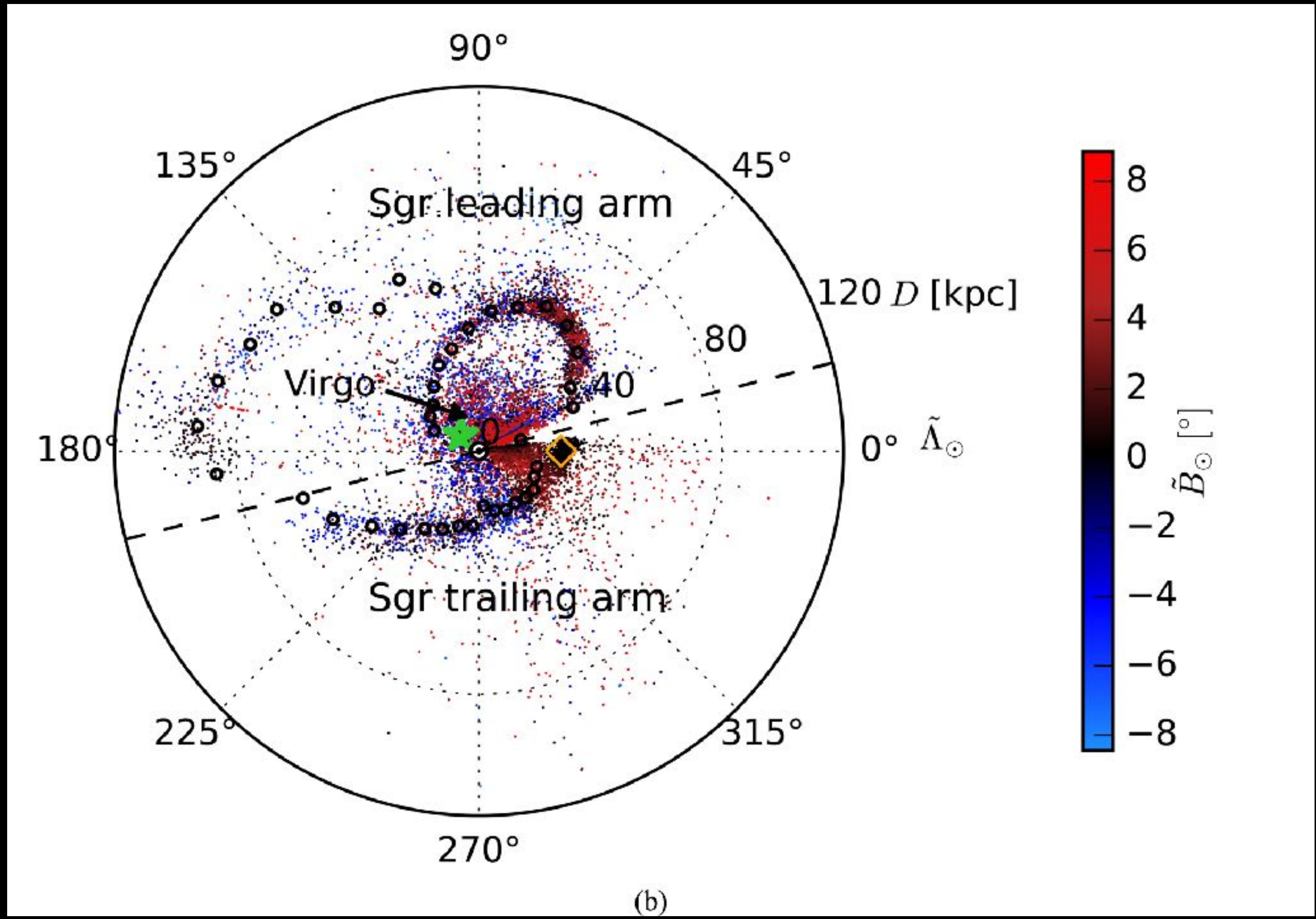
Figure from Helmi et al. 2018
see also Belokurov et al 2018

Streams are detected to large distances in the halo



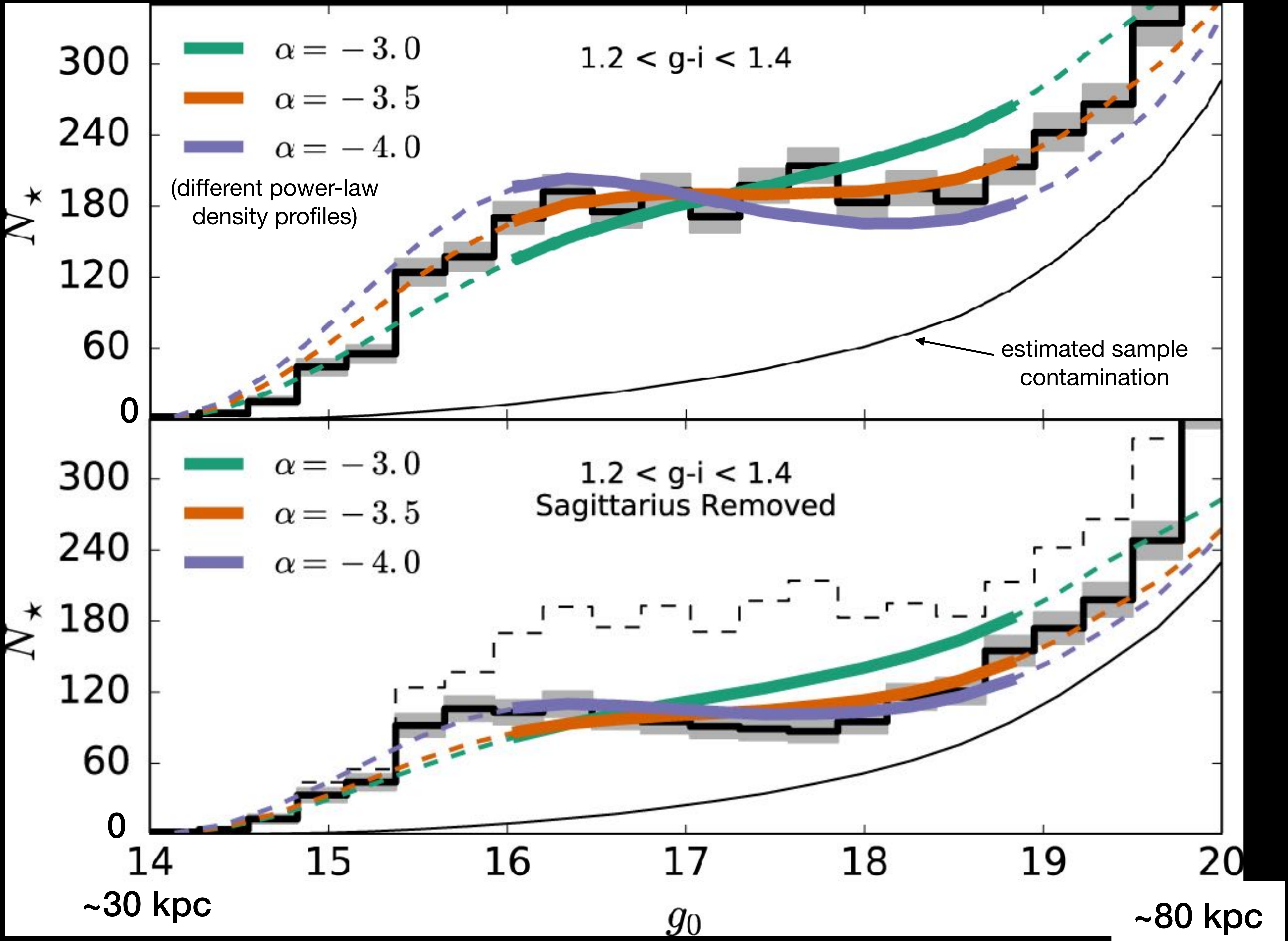
(a)

Hernitschek et al. 2017



(b)

Not all stars are readily assigned to a particular stream



Slater et al. 2016

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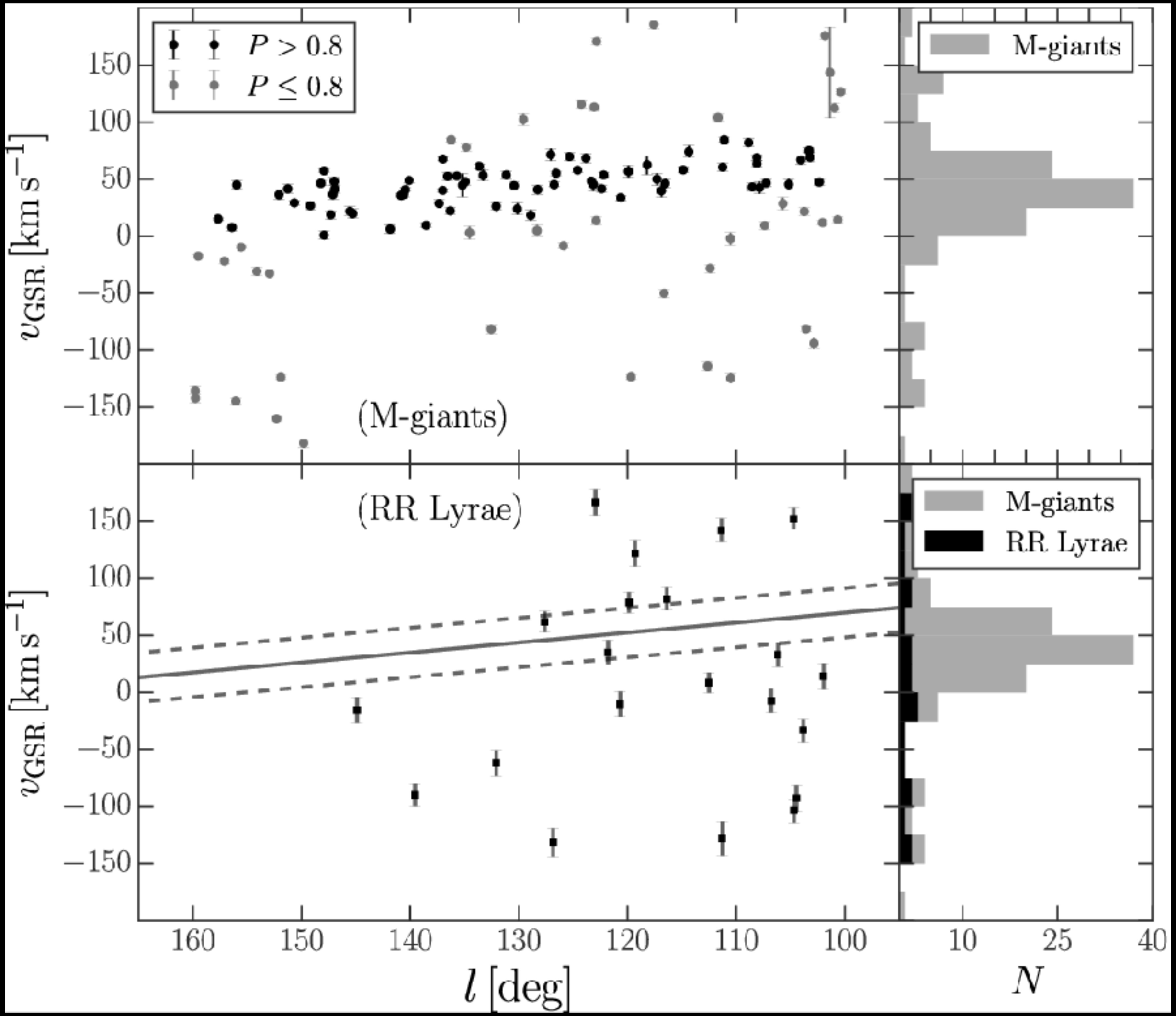

projected phase-space distribution for different types of stars in the “Triangulum-Andromeda” structure Price-Whelan et al. 2015

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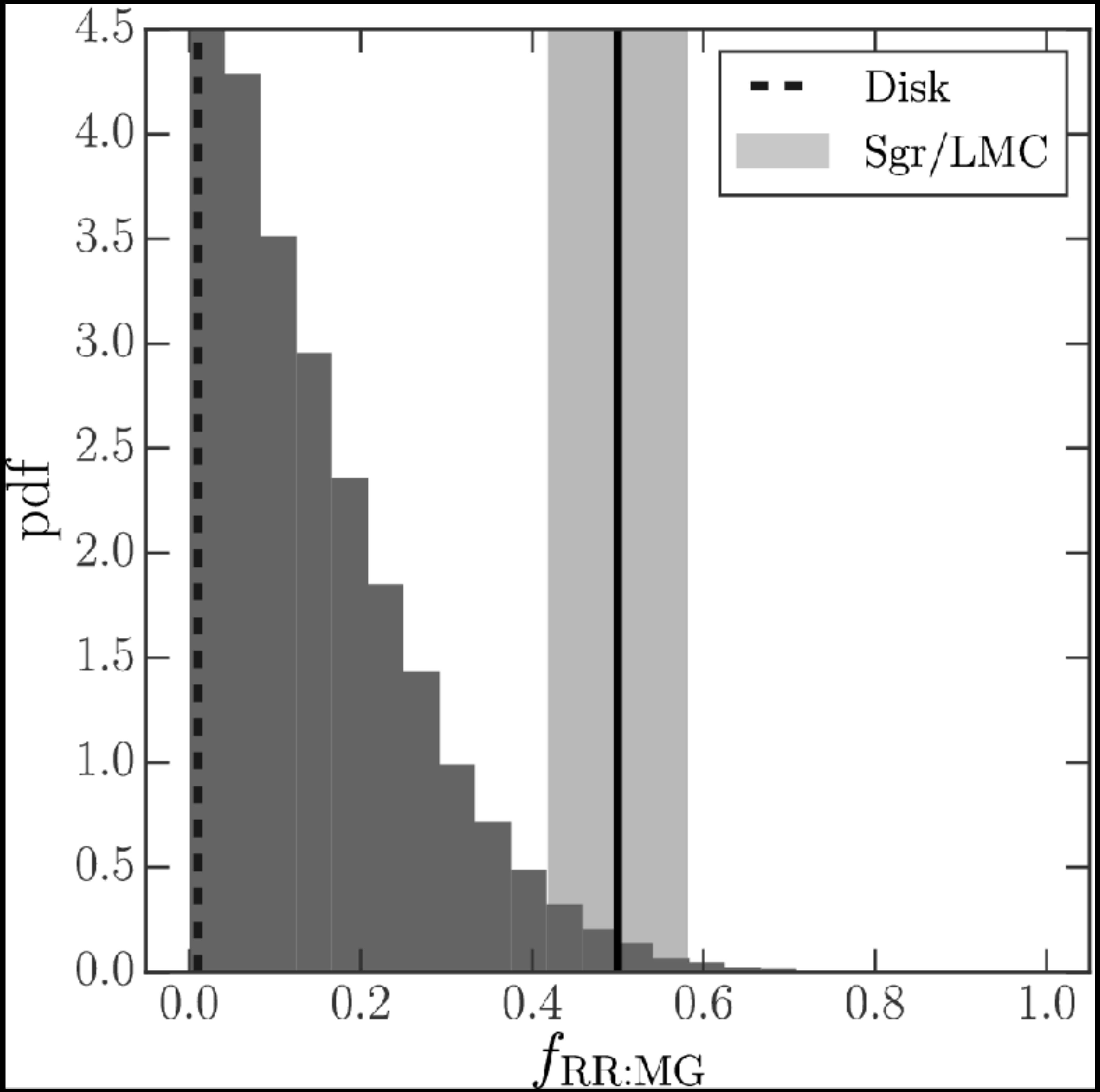

ratio of RR Lyr to M giant stars in the TriAnd structure compared to the disk, Sagittarius dwarf galaxy and LMC Price-Whelan et al. 2015

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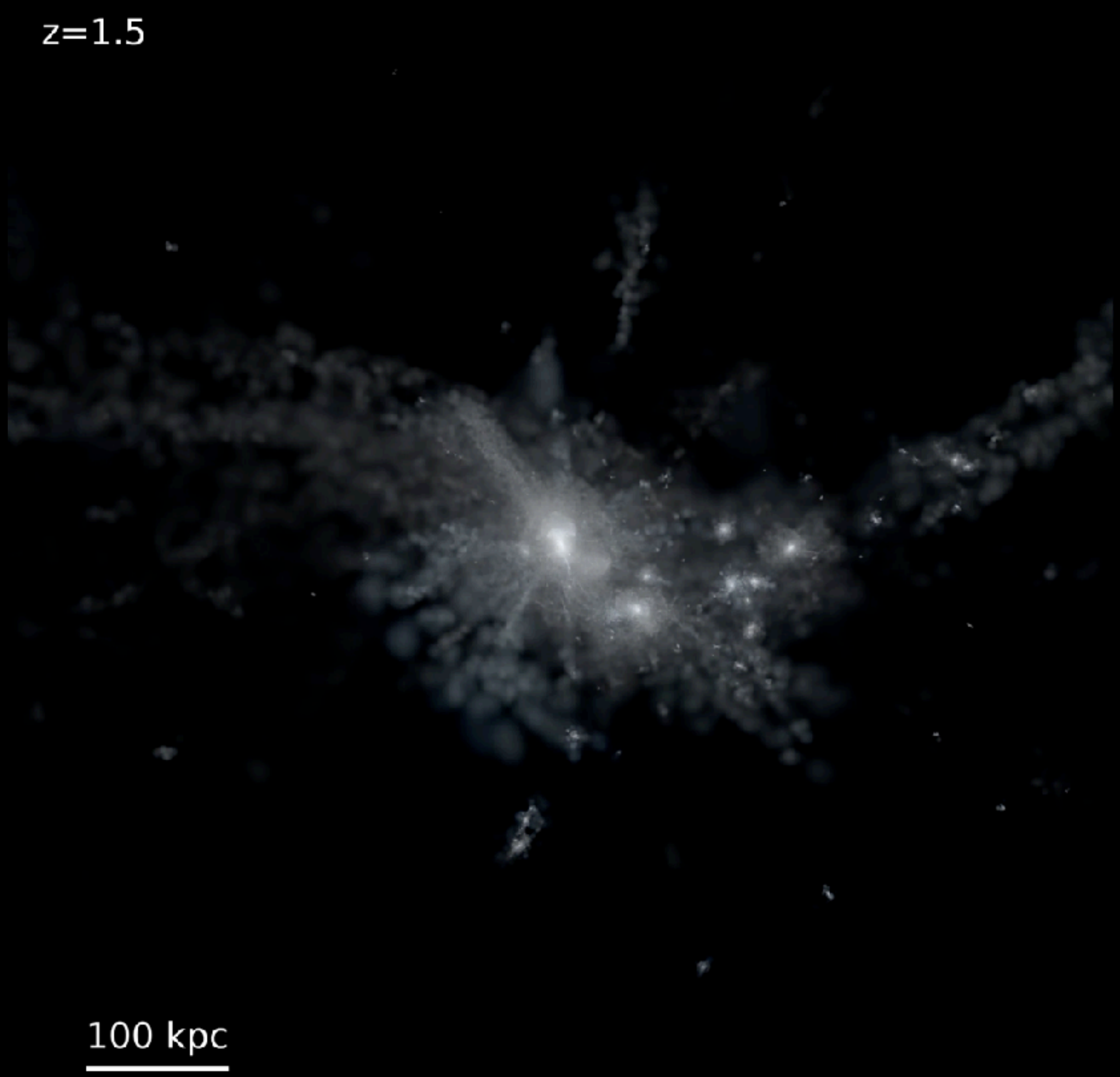

The transition from stars formed in situ to accreted likely varies widely

Sanderson et al. 2018

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Sanderson et al. 2018

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Making predictions for a 6+D galaxy

- **Simple mock accreted halos**
  (e.g. Sanderson, Helmi, & Hogg 2015)
  - spherical analytic halo
  - building blocks matched to satellite mass function
  - single tracers ad hoc
    (e.g. K giants, RR Lyrae)

- **Galaxia, GUMS**
  (Sharma et al. 2011; Gaia DPAC)
  - semi-analytic accreted halo
    (Bullock & Johnston 2005)
  - empirical disk, bulge
    (Robin et al 2001)
  - complete stellar populations
  - 6D+Fe,“alpha”+age

- **Aquarius**
  (Cooper et al. 2010, Lowing et al 2012)
  - Resampled cosmological sim
  - DM-only + tagging
    (no disk)
  - 6D positions, velocities

- **Ananke, Aurigaia**
  (Sanderson et al 2018, Grand et al. 2018)
  - Cosmological sim with hydro —> realistic central MW
  - 6D + 10 abundances + ages + …
  - Complete stellar populations

Making predictions for a 6+D galaxy

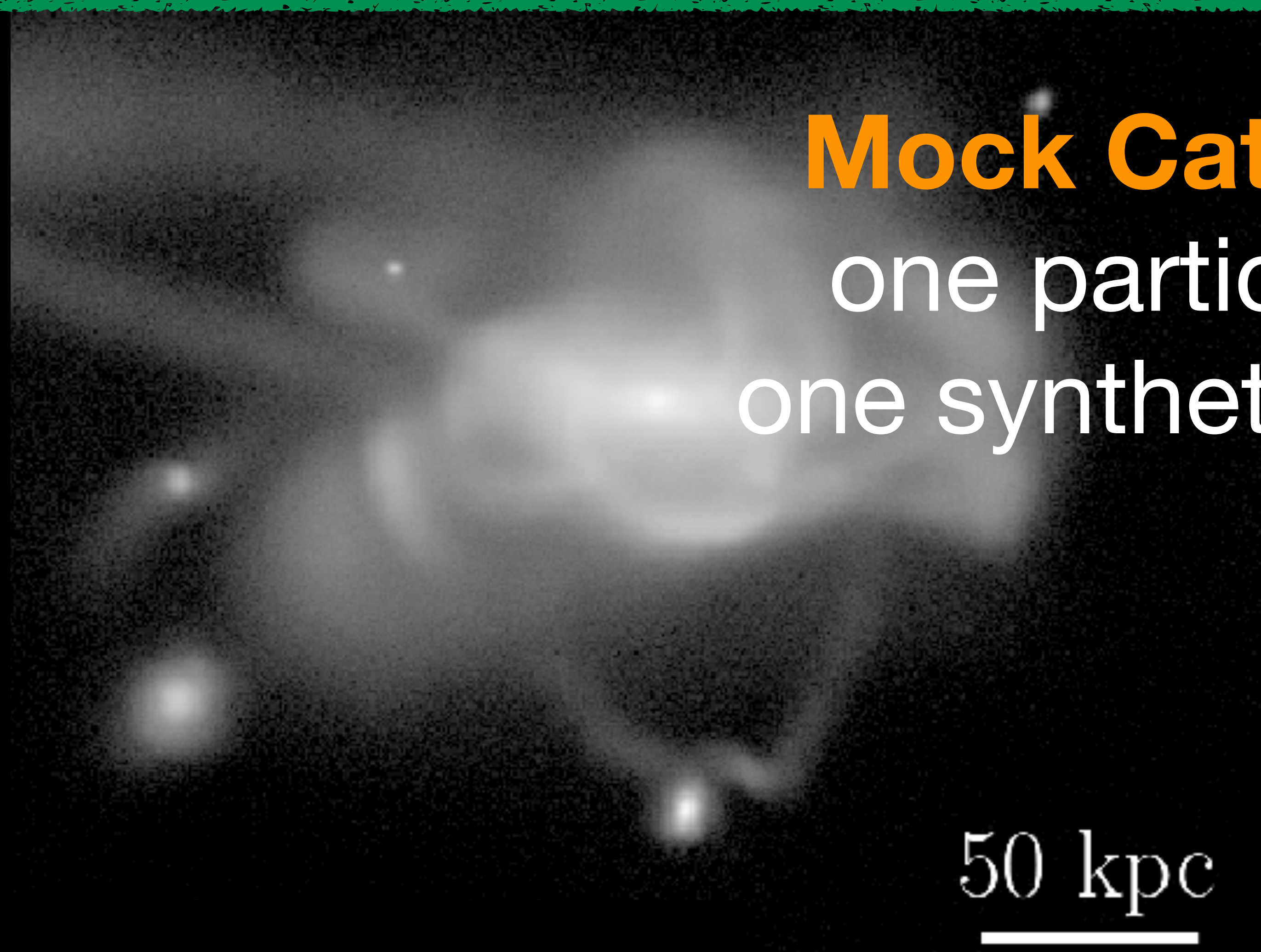
Galaxy Simulation
(cosmology, DM model, gravity, gas physics, star formation, stellar feedback, …)

One particle = many “stars”
…with same age, abundances

Stellar Populations

(stellar structure, stellar evolution, convection models, isochrone mapping, IMF, …)

Phase-space density estimation
(kernel dimension, smoothing scales, ages, accretion history, …)

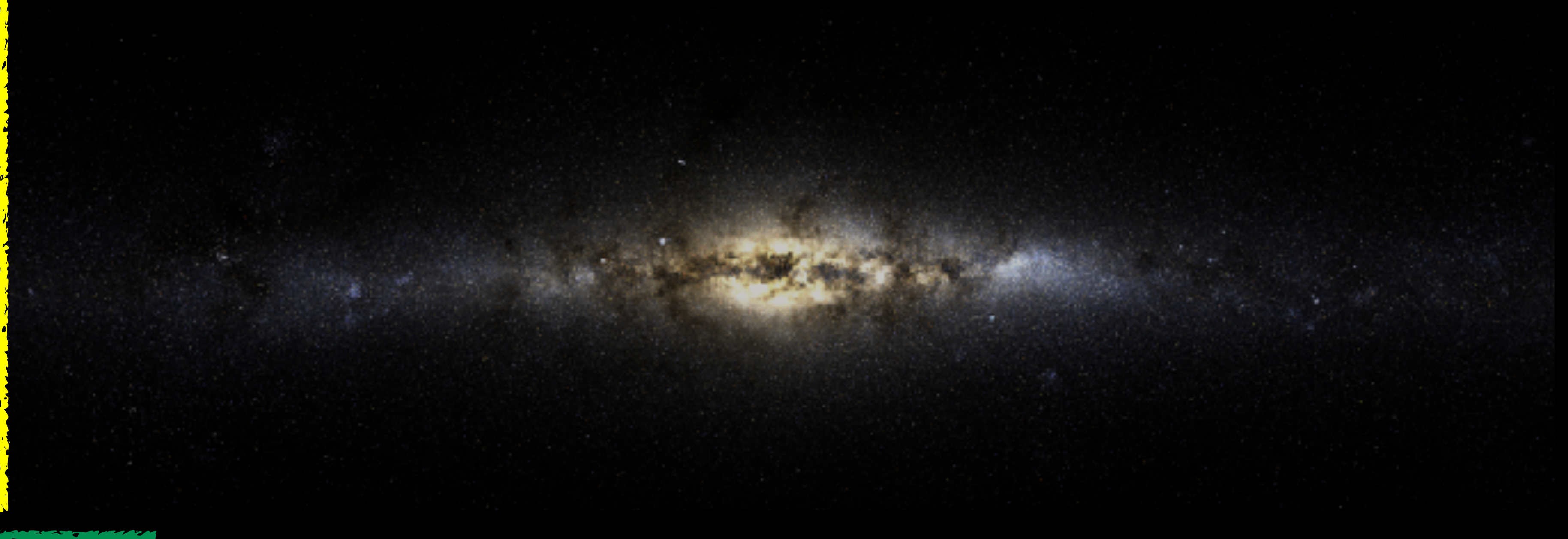


Mock Catalog
one particle = one synthetic star

Survey description

(Magnitude/color limits, extinction/reddening, selection function, error model, instrument model, …)

Synthetic Survey
one particle = one “observed” star



Ananke

Sanderson et al. 2018,

arXiv:1806.10564

- Cosmological sim with hydro —> realistic central MW
- 6D + 10 abundances + ages + …
- Complete stellar populations
- 3 simulations x 3 observation volumes = 9 surveys

Andrew Wetzel

Sarah Loebman

Sanjib Sharma

Available for Gaia DR2 on:

ananke.hub.yt

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What have we learned from Gaia so far?

- The disk-halo interface is really complicated! Mergers could move stars from the disk onto more halo-like orbits (see lectures by Hunt, Antoja). Hints before Gaia, now very obvious.
- It's still not clear whether the inner halo is an old spheroidal component ("in situ halo"), entirely the product of a few relatively massive mergers like Gaia-Enceladus, or both.

- There seems to be plenty of halo substructure passing by the Sun (papers by Helmi+, Belokurov+, Myeong & Evans, Meingast+, Necib+) ….
- …but is there some unifying event underneath? more than one? How can we compare with predictions?
- Gaia proper motions really clean up selections for known streams (e.g. Price-Whelan & Bonaca 2018)
- There is more stuff out there to find!

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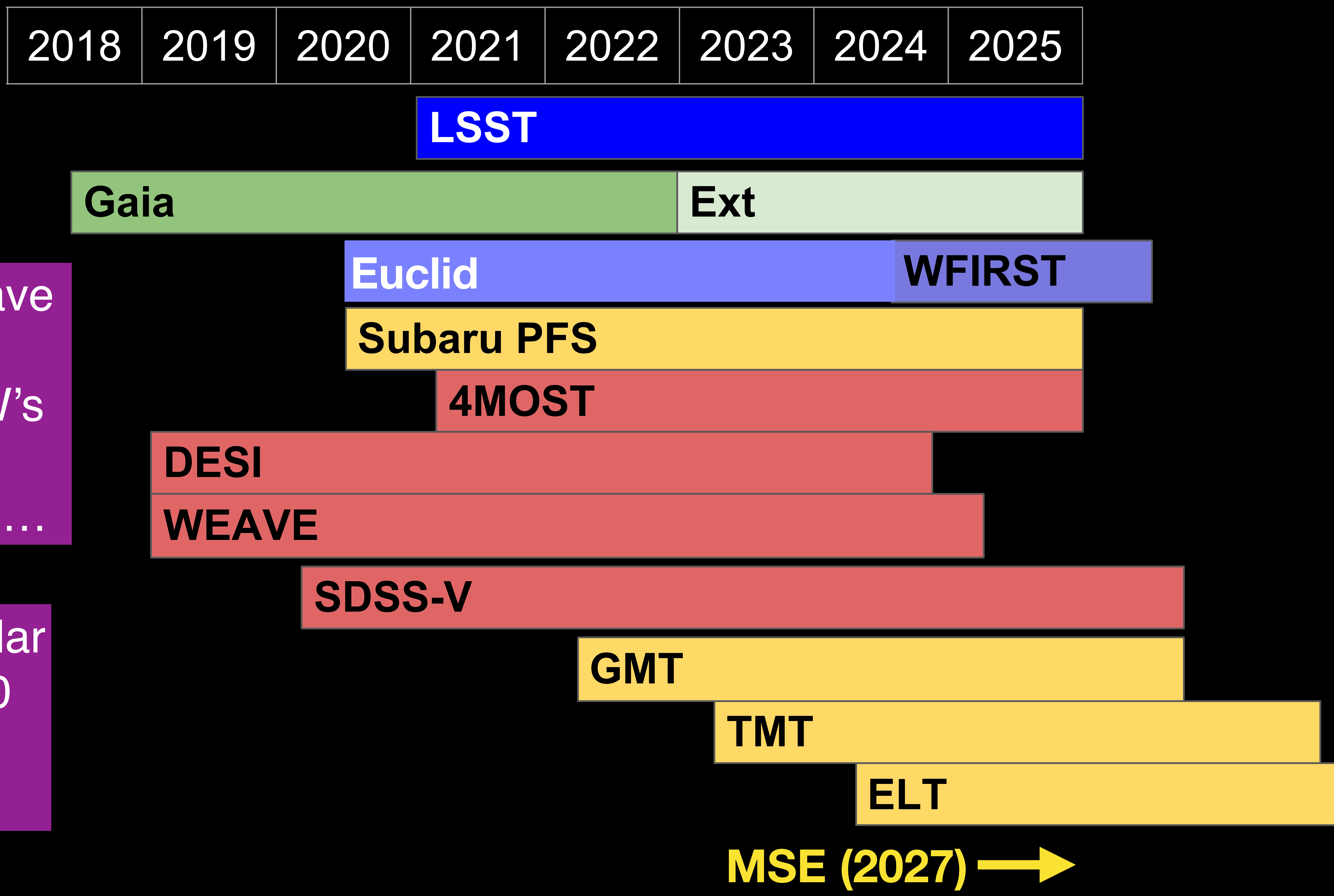
Gaia is only the beginning

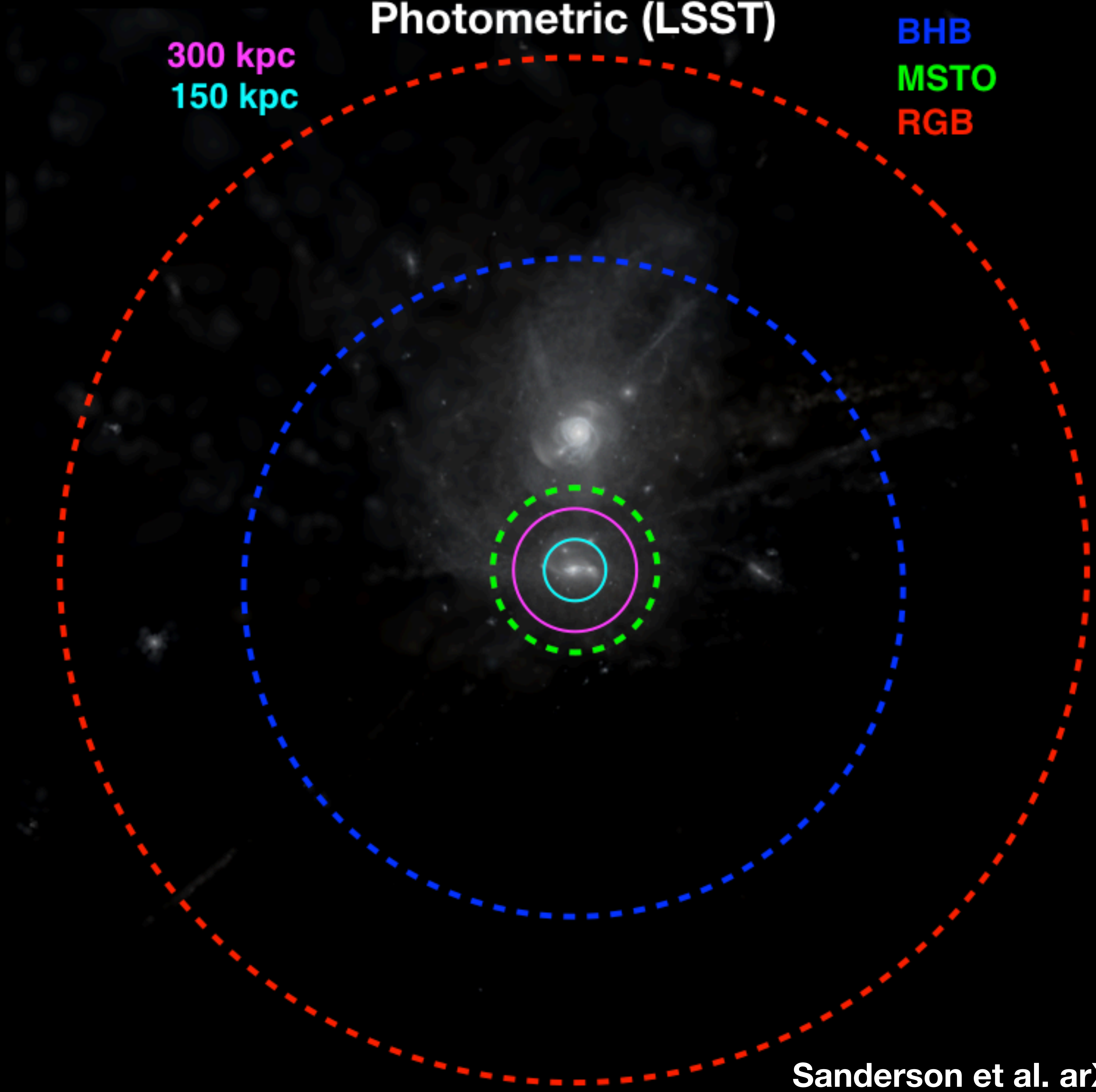
By 2028, we will have 6+D information for stars to the MW's virial radius and beyond (~300 kpc)…



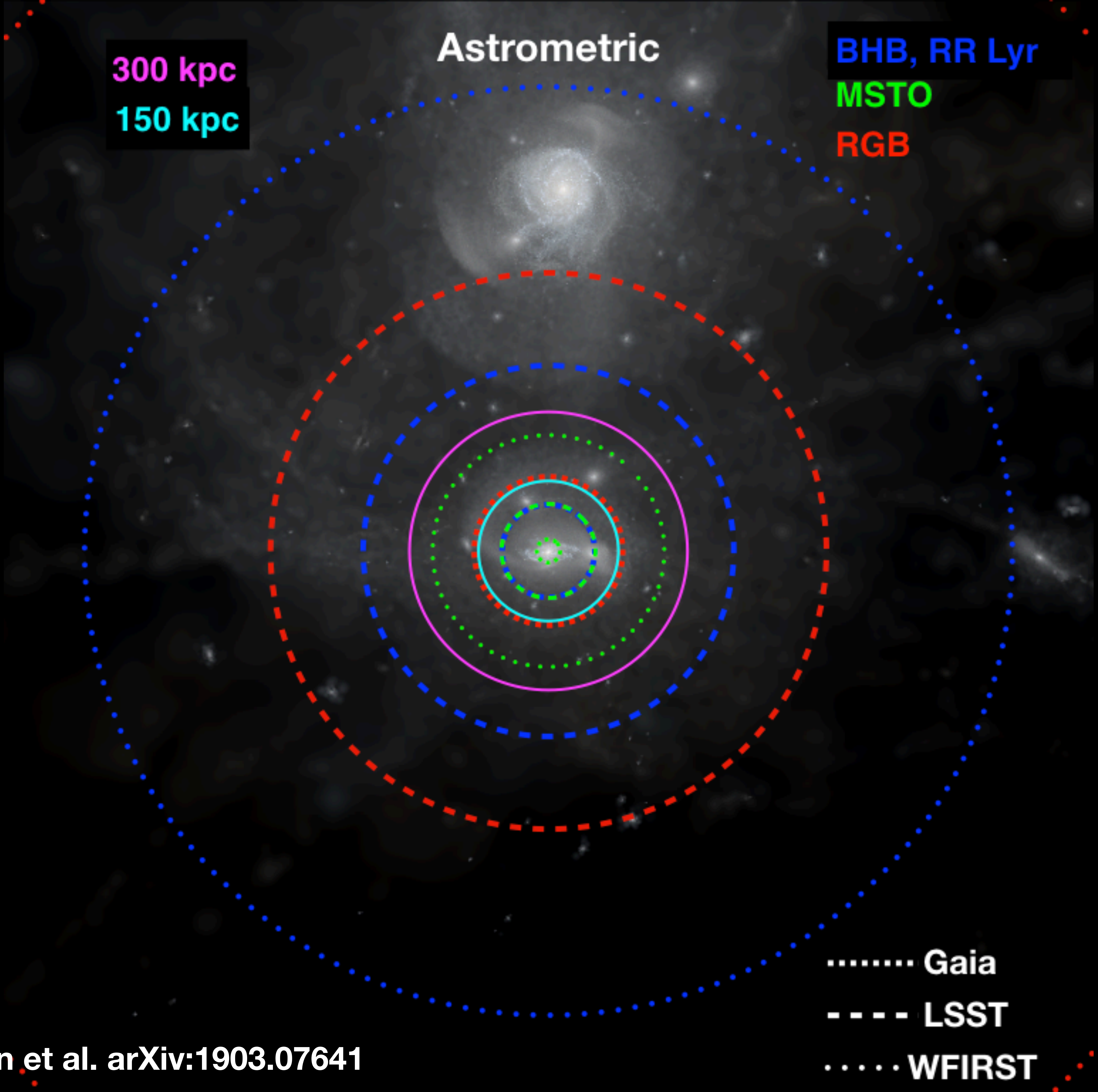
..and resolved stellar maps of the ~100 nearest MW-like galaxies

Astrometric + spectroscopic
Photometric + astrometric
Spectroscopic: <4-m class
Spectroscopic: >4-m class

Photometric (LSST)



Sanderson et al. arXiv:1903.07641



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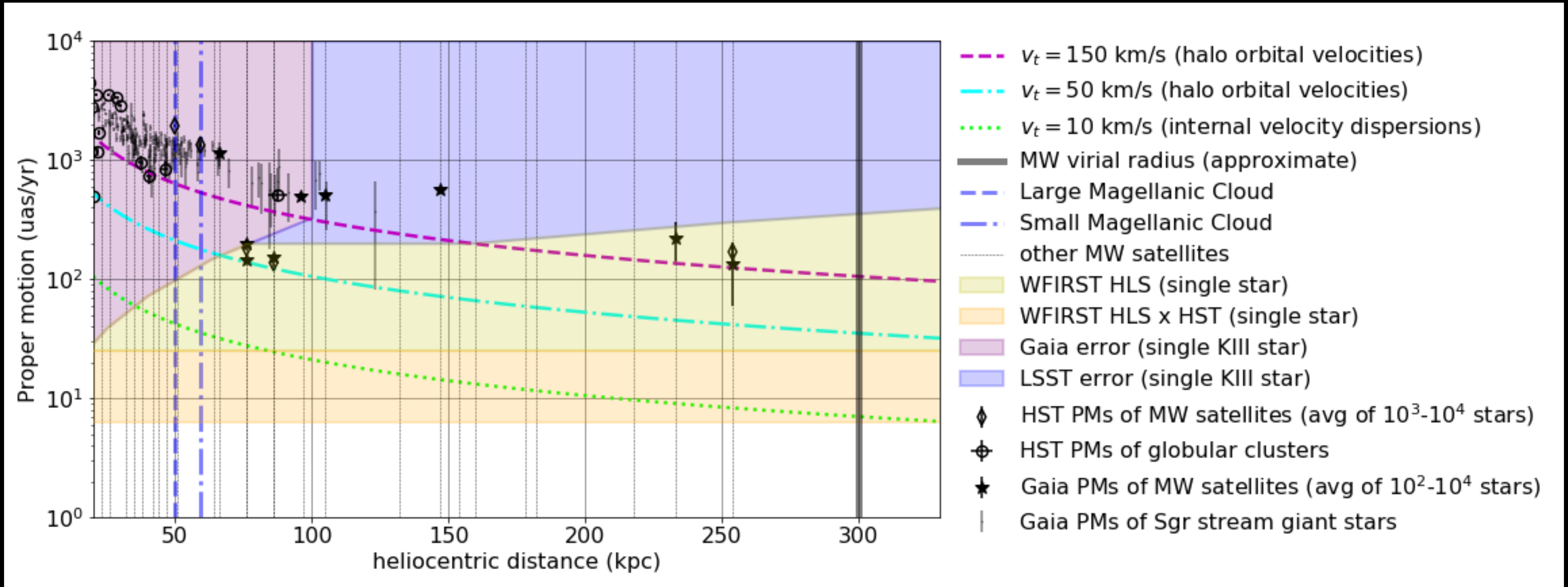
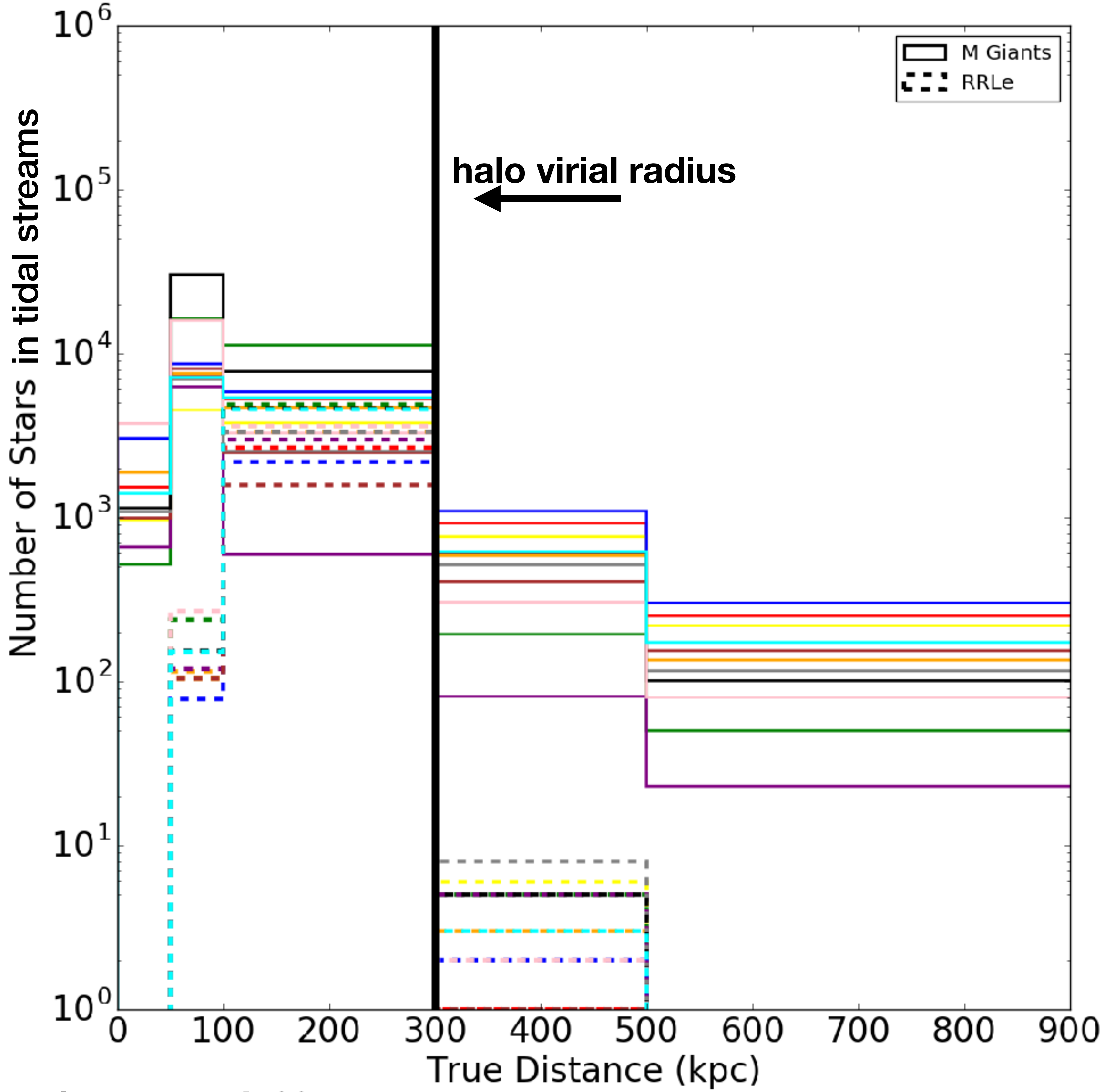


Sanderson et al. arXiv:1903.07641

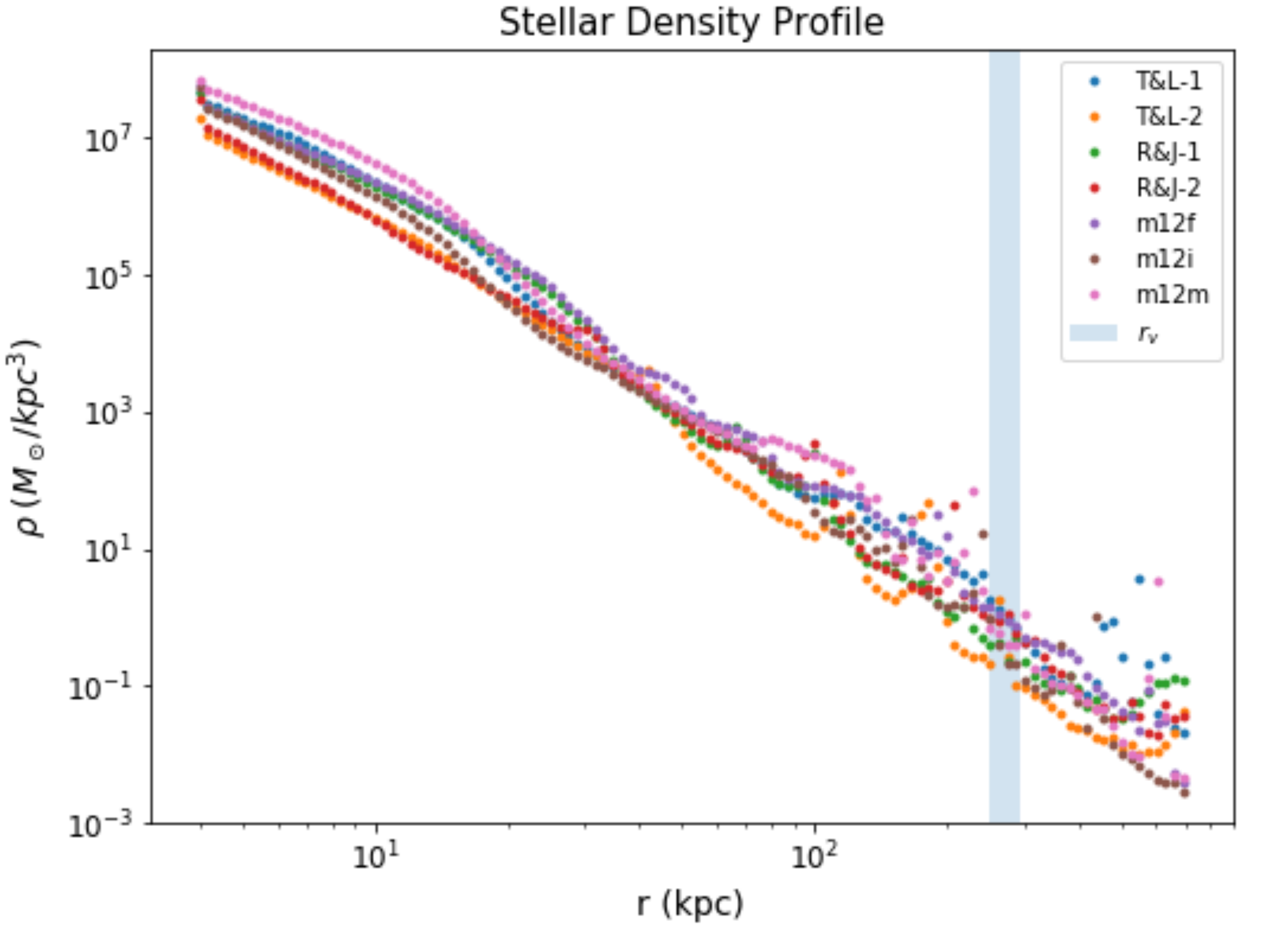
Spectroscopic
300 kpc
150 kpc
BHB, RR Lyr
MSTO
RGB
1600 kpc
4m
10m
30m
Sanderson et al. arXiv:1903.07641

Projections using simulated accreted stellar halos from Bullock & Johnston 2005



Sanderson et al. 2017

Stellar mass density in FIRE-2 simulated halos



Soos, Sanderson et al. in prep

There is lots out there still to find!