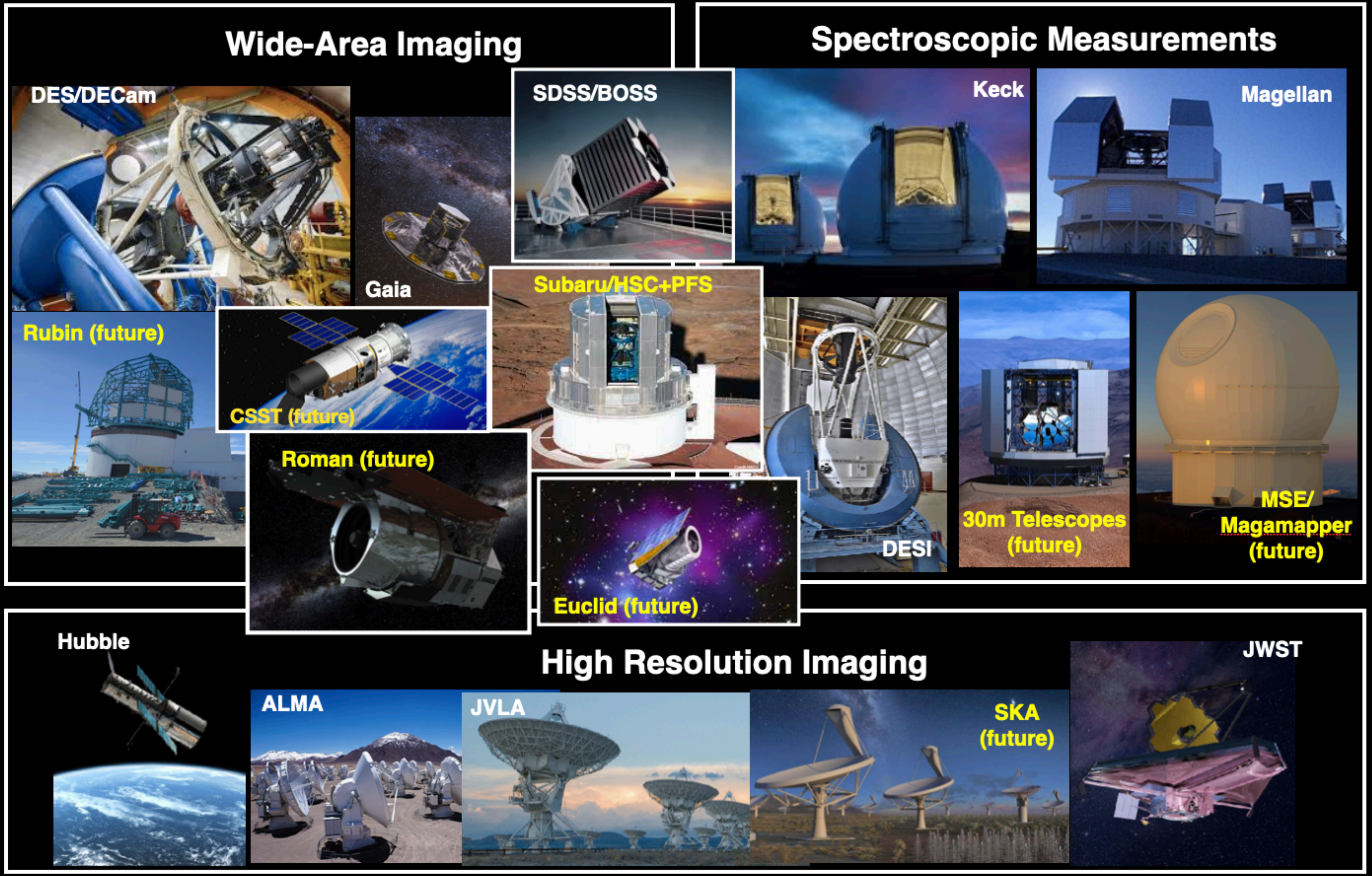
Observational Frontier for Dark Matter Physics

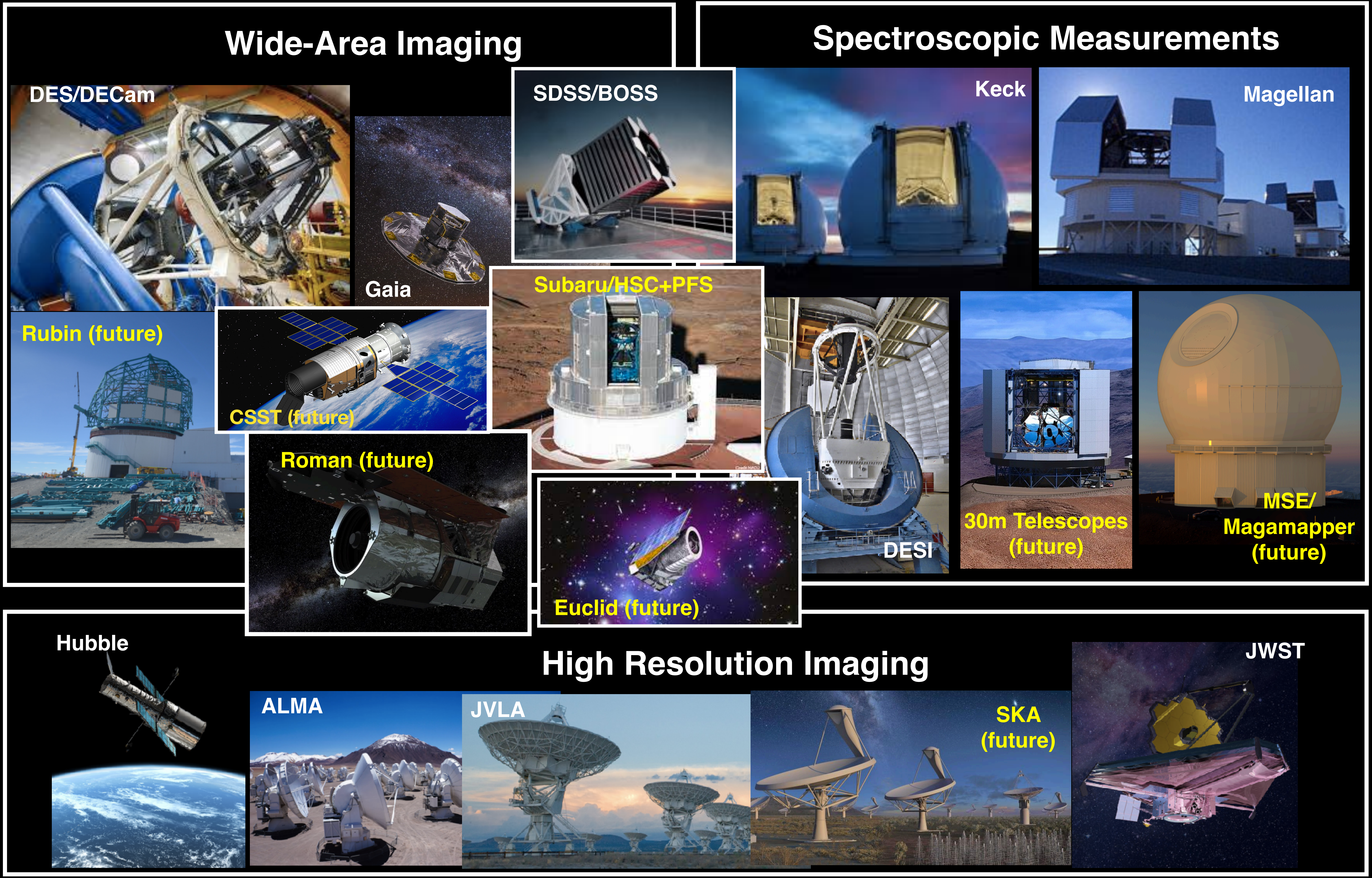
Ting S. Li

University of Toronto



Pollica Workshop on Self-Interacting Dark Matter: Models, Simulations and Signals

Pollica, June 26, 2023



Wide-Area Imaging
DES/DECam
Gaia
SDSS/BOSS
Subaru/HSC+PFS
Rubin (future)
CSST (future)
Roman (future)
Euclid (future)
Spectroscopic Measurements
Keck
Magellan
DESI
30m Telescopes (future)
MSE/ Magamapper (future)
High Resolution Imaging
Hubble
ALMA
JVLA
SKA (future)
JWST

There are a lot of observing results you might have missed due to pandemic, and here they are!
We need more work on simulations/modeling to catch up!

The next decade will be full of data for dark matter astrophysics!

There are a lot of observing results you might have missed due to pandemic, and here they are!

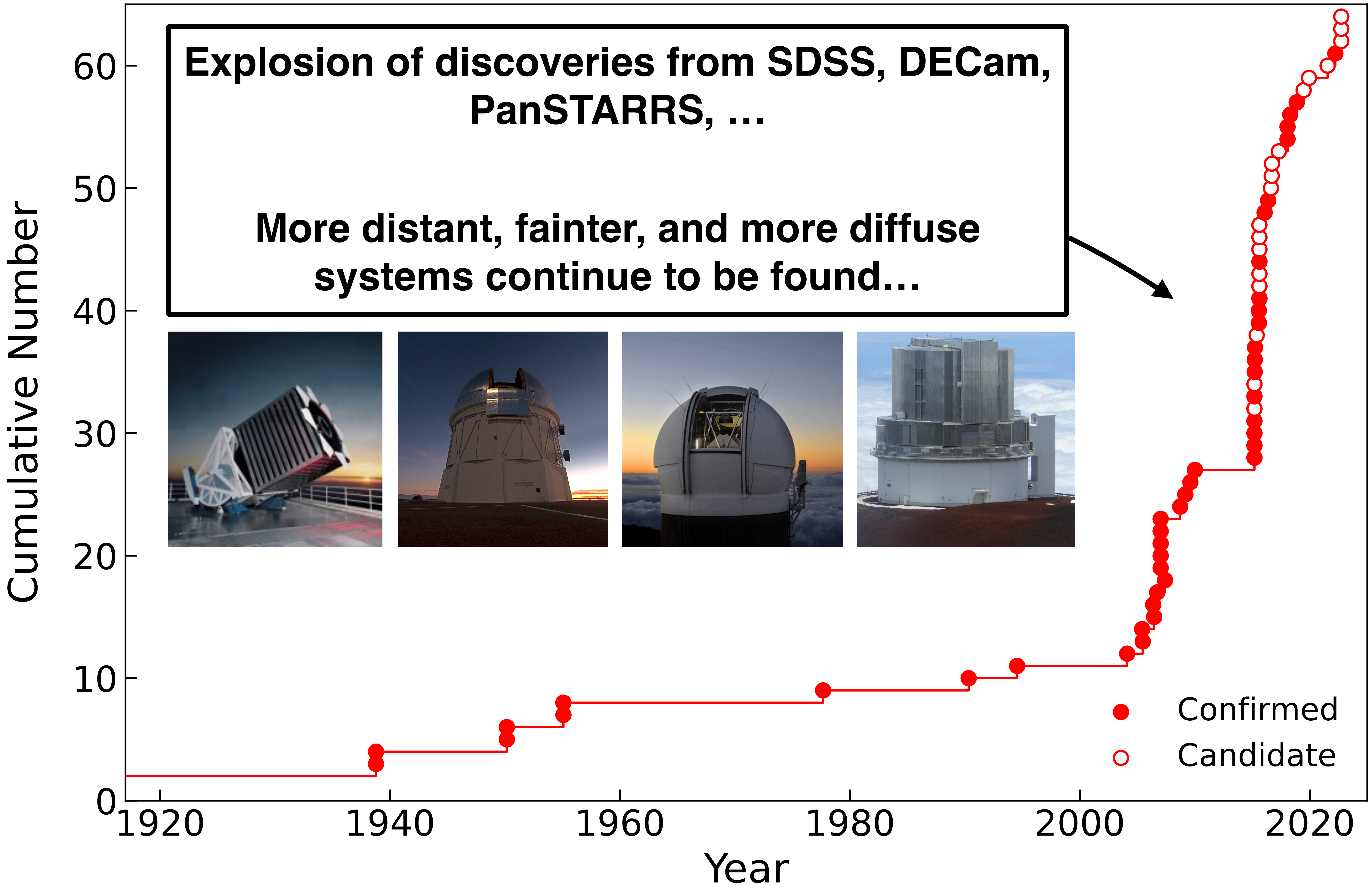
We need more work on simulations/modeling to catch up!

- Subhalo mass function below the galaxy formation
- Properties of disrupted satellite systems
- Impact of Large Magellance Cloud
- Smallest dwarf galaxies?

The next decade will be full of data for dark matter astrophysics!

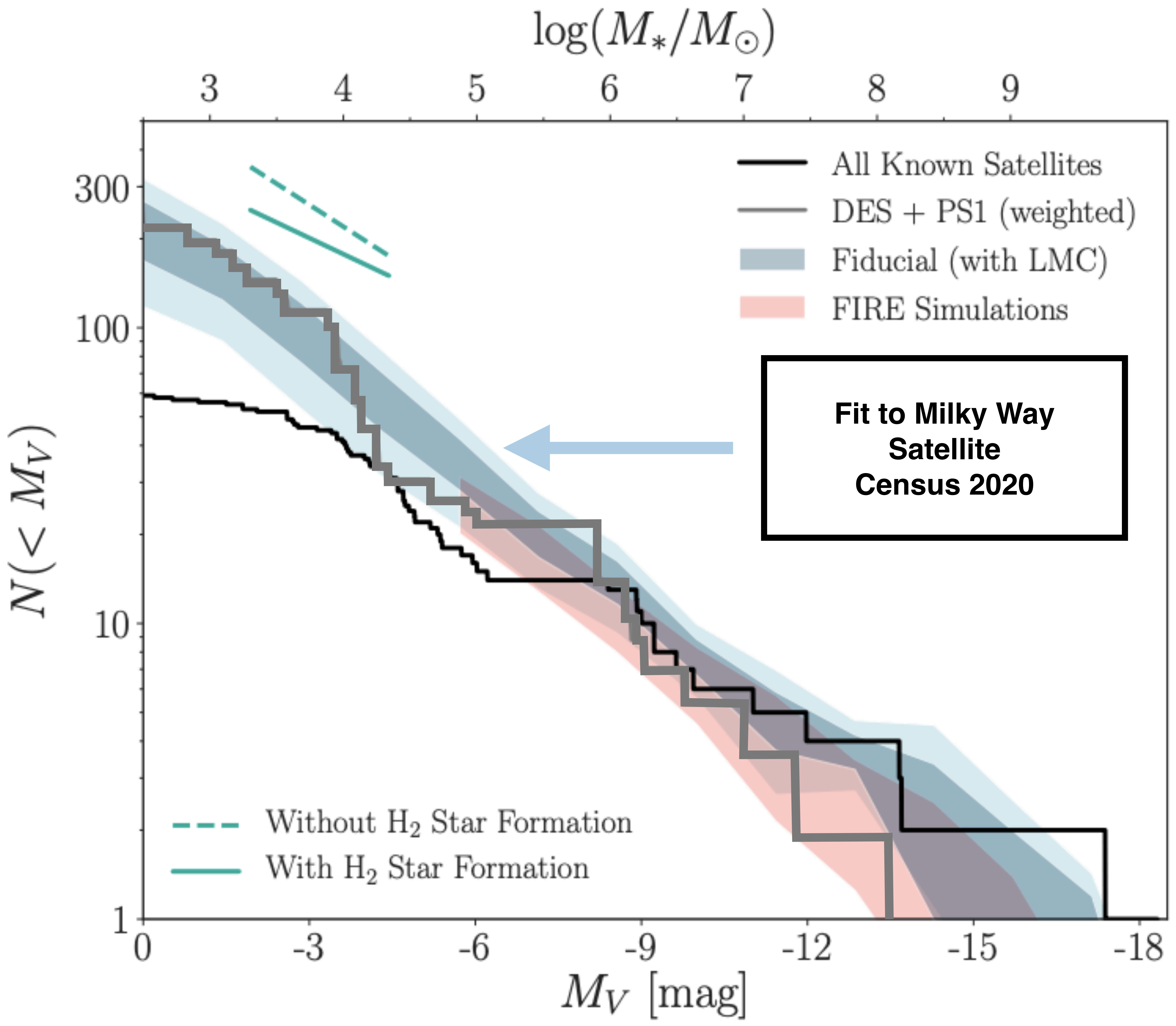
Subhalo mass function below the galaxy formation

Milky Way Satellite Galaxy Discovery Timeline



Milky Way Satellite Luminosity

Satellites Brighter than Mv



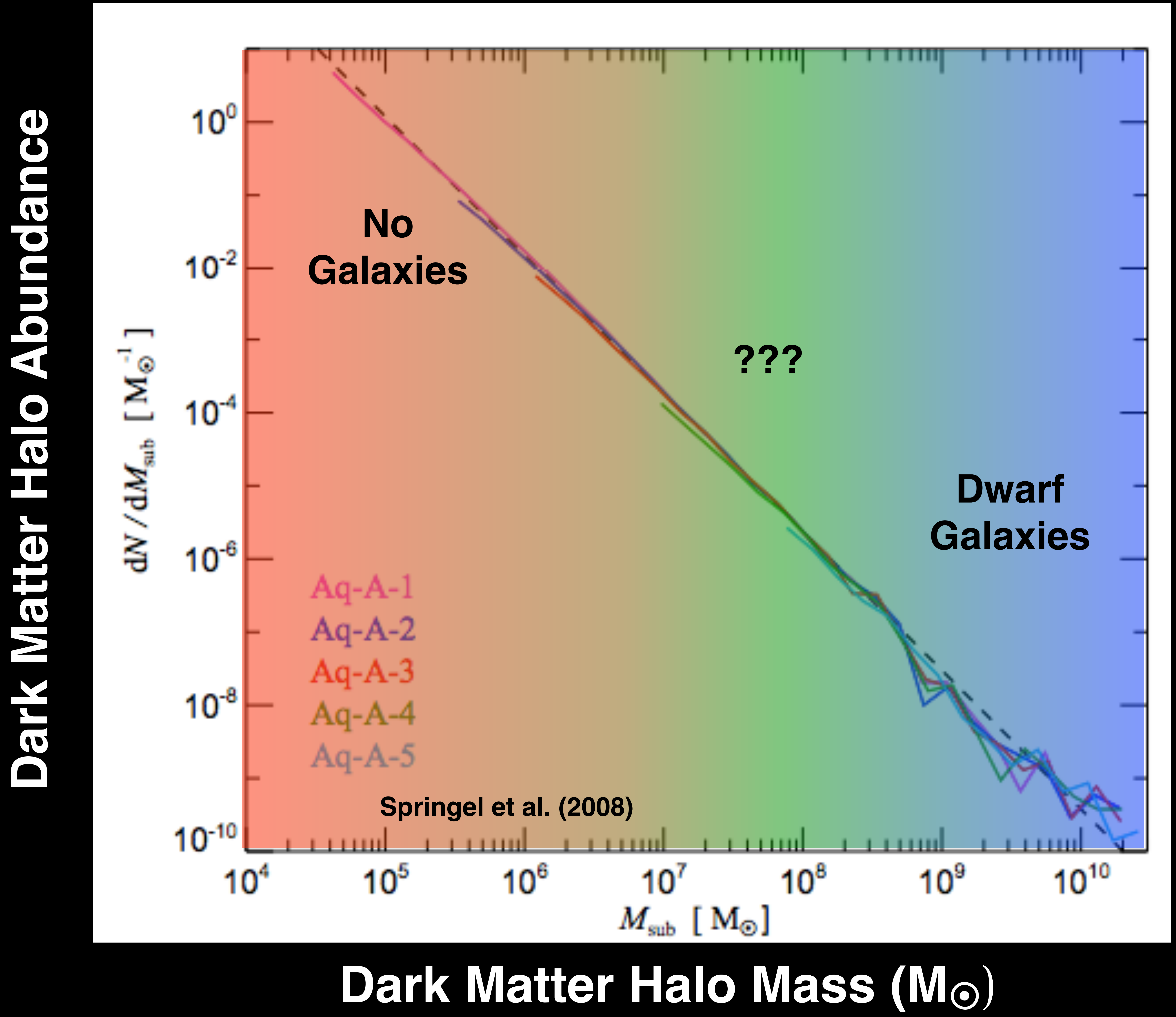
Satellite Luminosity

Observed satellites are consistent with CDM + galaxy formation.

See also: Jethwa et al. 2018, Newton et al. 2018, Kim et al. 2018, Applebaum et al. 2020

Nadler et al. ApJ 893, 48 (2020)

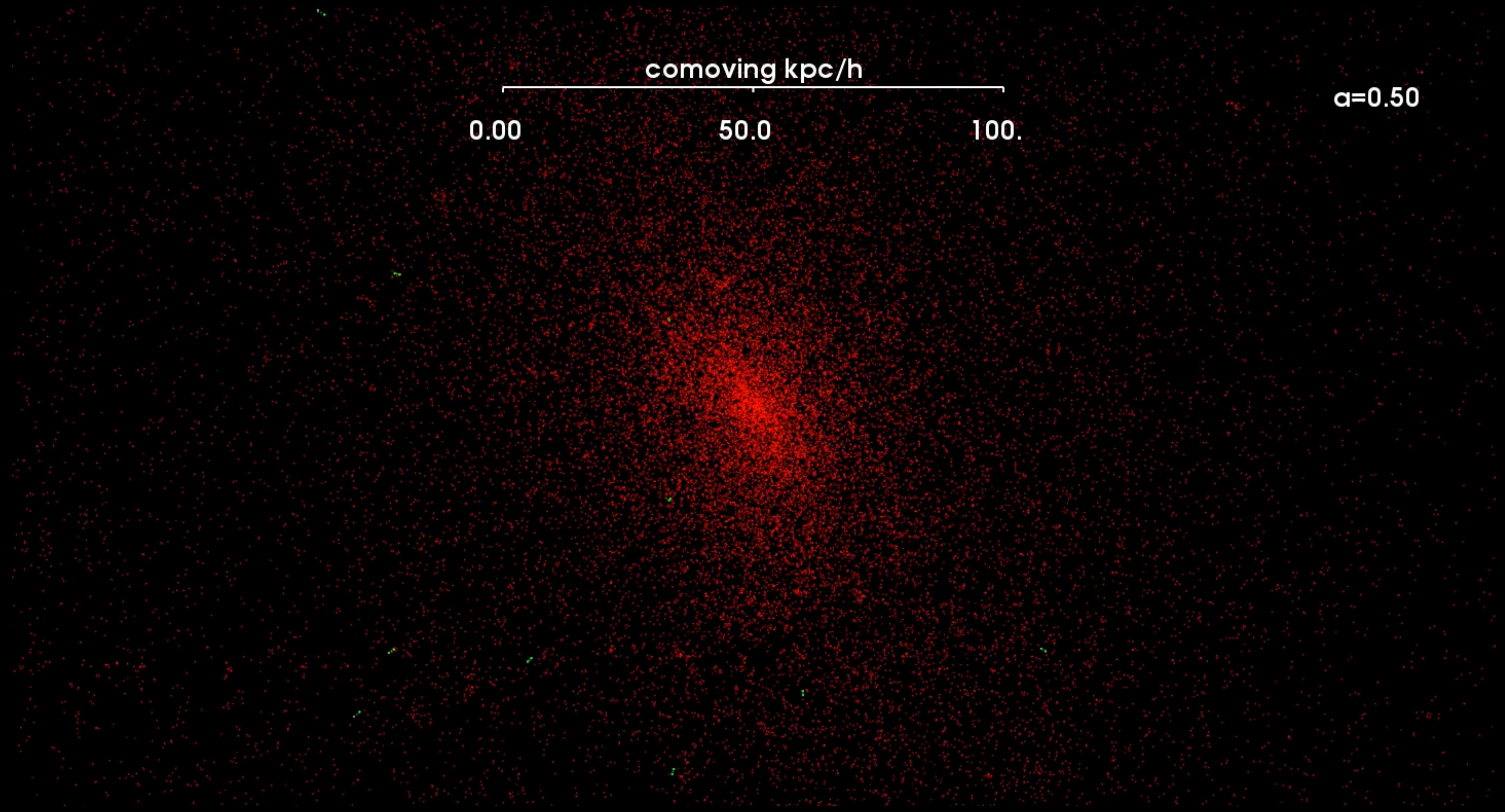
Pushing to Lower Mass



Standard CDM predicts the existence of **small subhalos**.

How do we detect **completely dark** subhalos?

Milky Way's Stellar Streams



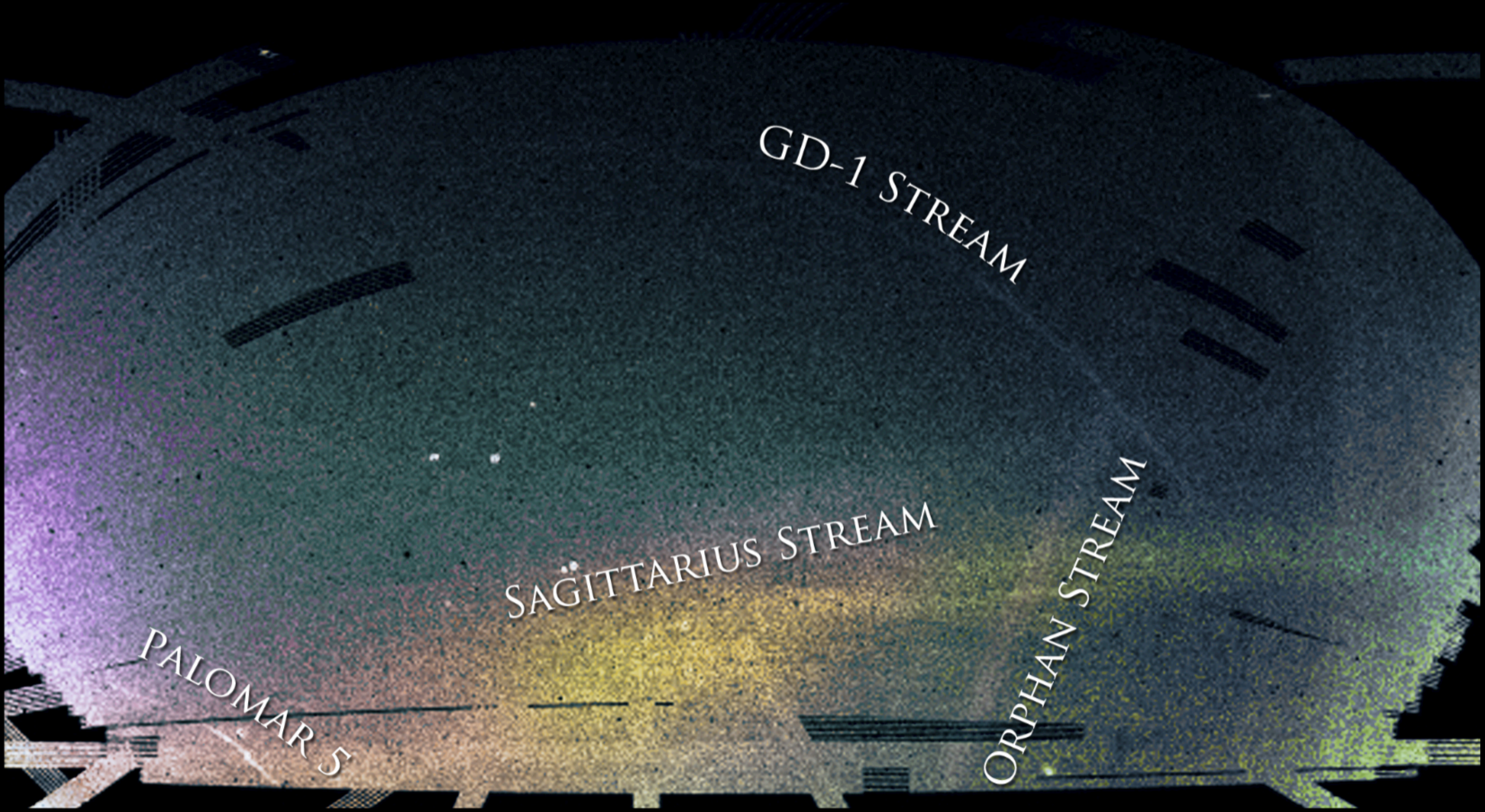
Milky Way like galaxies are assembled by accretion and disruption of many smaller systems

Stellar Streams:

- tidally disrupted
  - dwarf galaxies
  - globular clusters
- but not fully mixed

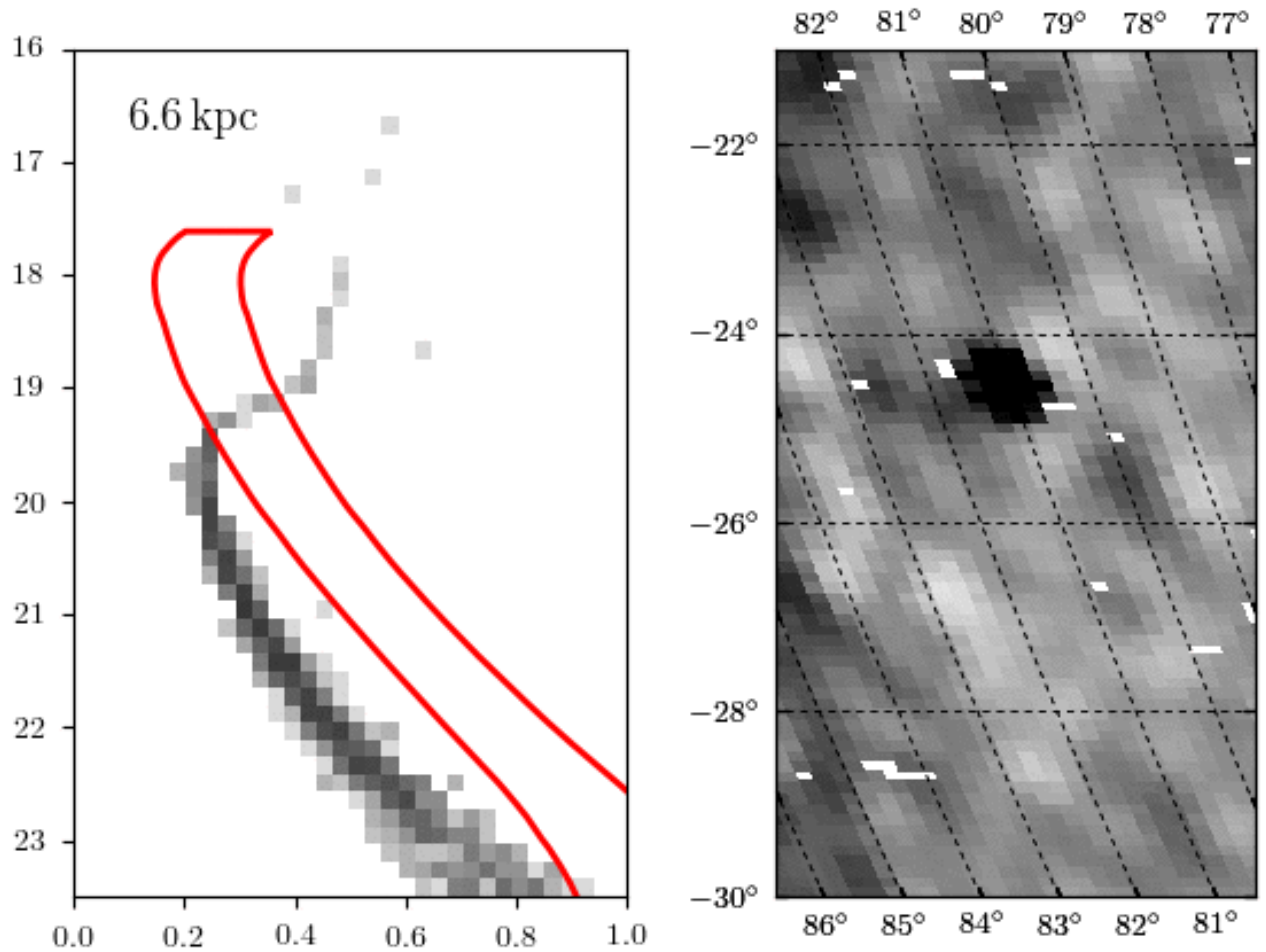
Credit: Denis Erkal

NORTHERN SKY



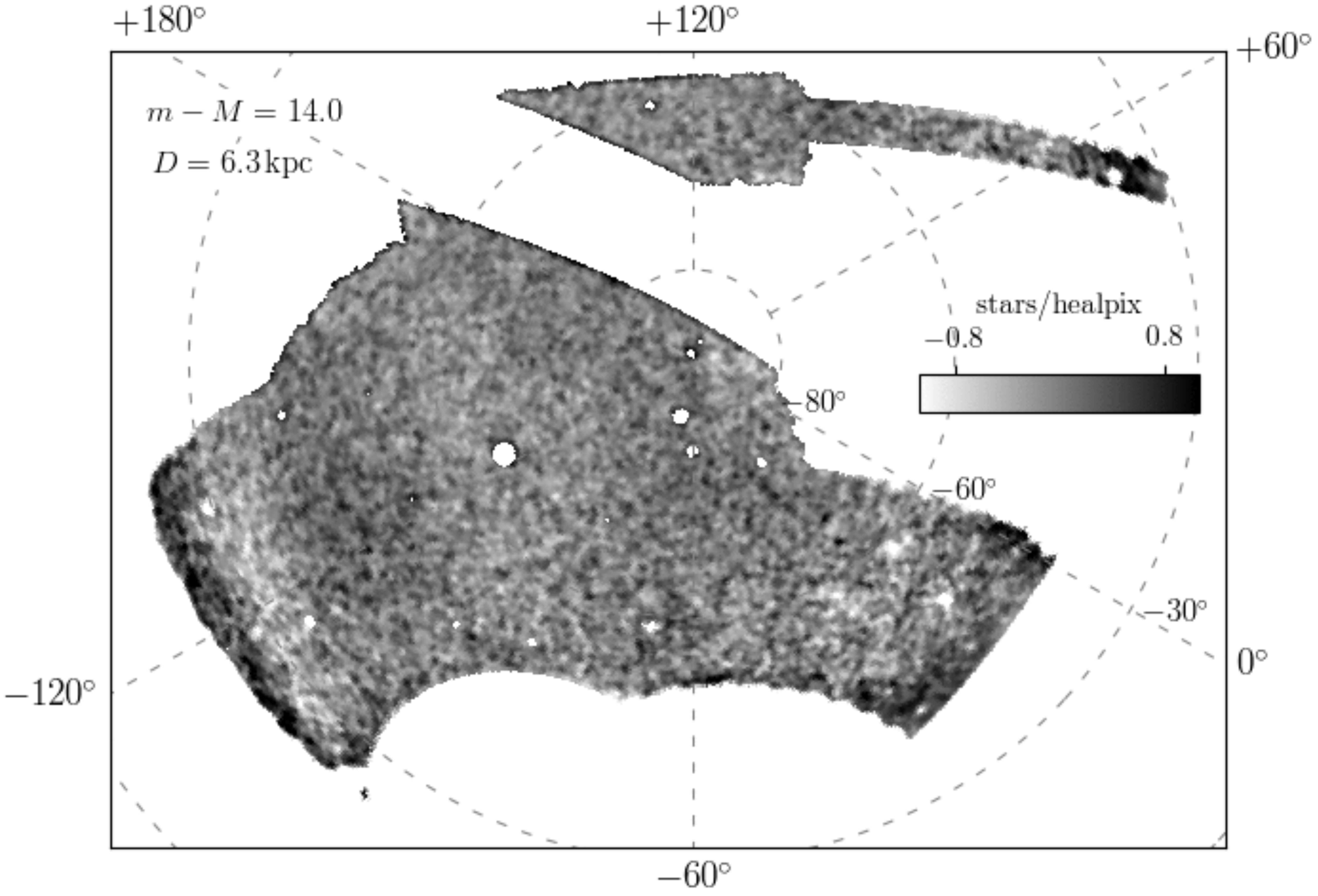
Sloan Digital Sky Survey SDSS DR8 / Bonaca, Giguere, Geha

Isochrones Scanning through in distance



Credit: Alex Drlica-Wagner

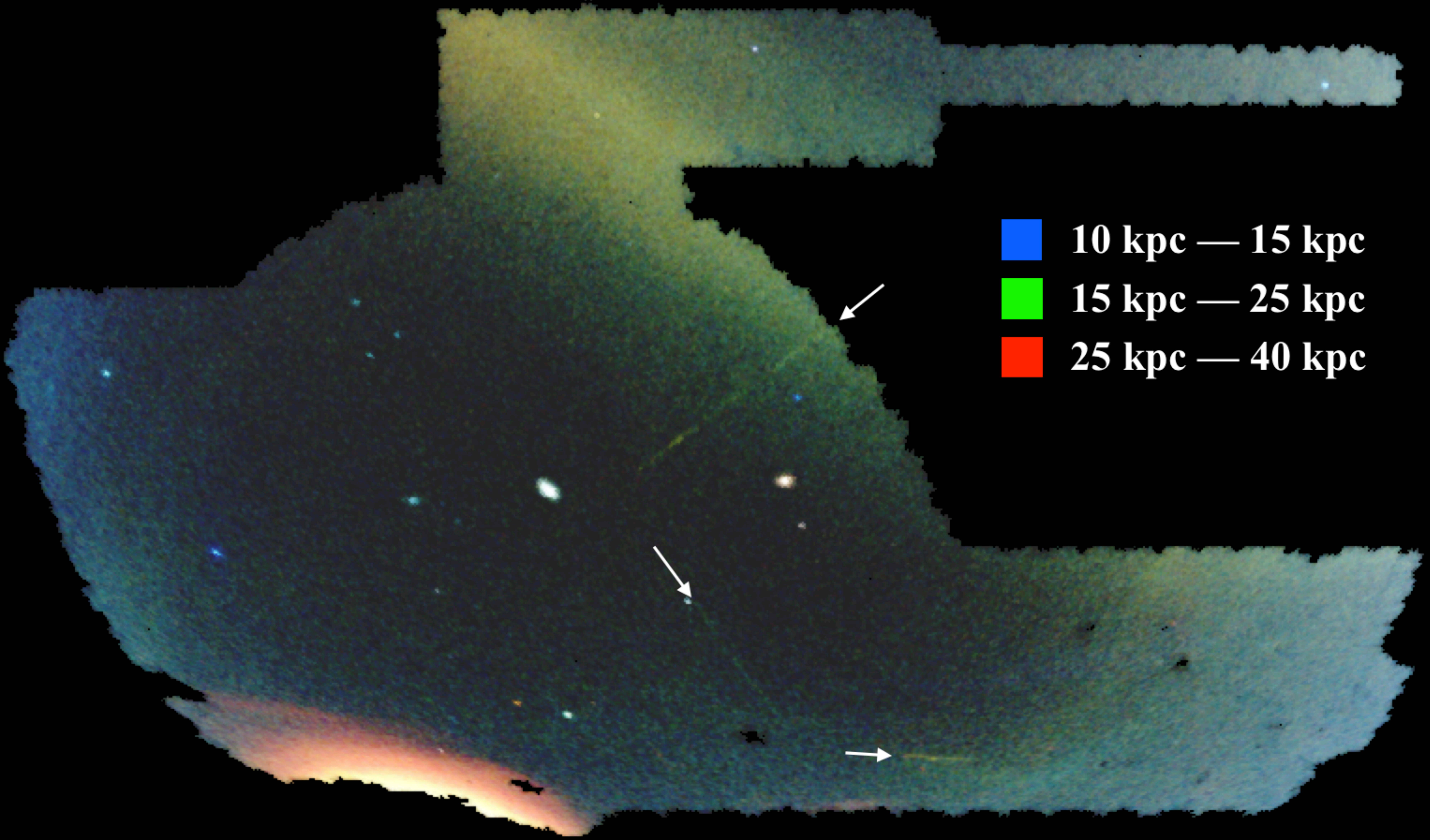
Streams in the Dark Energy Survey



Shipp et al. 2018
(DES Collaboration)

13 new streams from DES + 2 previous known

SOUTHERN SKY



Dark Energy Survey DES / Shipp, Drlica-Wagner et al. 2018

Southern Stellar Stream Spectroscopic Survey (S^5)

Key Members of S5 Team

https://s5collab.github.io/

Ting Li

Daniel Zucker

Geraint Lewis

Kyler Kuehn

Alex Ji

Sergey Koposov

Denis Erkal

Andrew Pace

Nora Shipp

Yao-Yuan Mao

Sophia Lilleengen

Lara Cullinane

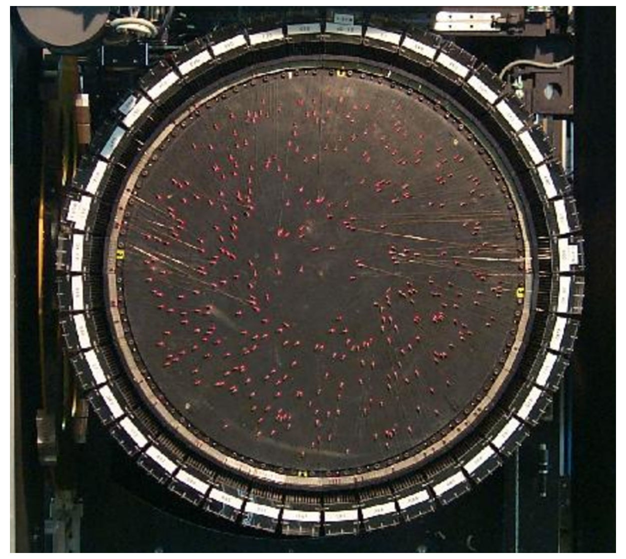
Sarah Martell

and Joss Bland-Hawthorn, Gary Da Costa, Dougal Mackey, Zhen Wan, Eduardo Balbinot, Keith Bechtol, Vasily Belokurov, Andrew Casey, Gayandhi De Silva, Alex Drlica-Wagner, Marla Geha, Terese Hansen, Jennifer Marshall, Jeremy Mould, Sanjib Sharma, Jeffery Simpson, Josh Simon, Douglas Tucker, Kathy Vivas, Risa Wechsler, Brian Yanny and many more …

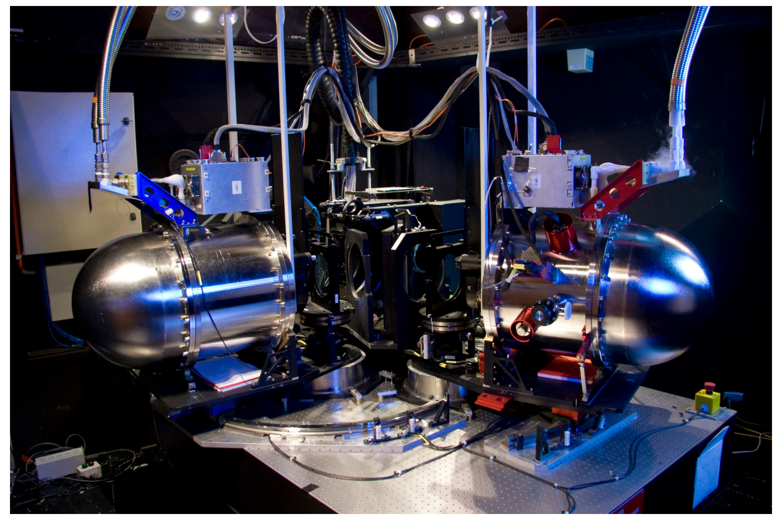
S⁵: DES+Gaia+AAT

Since Summer 2018

3.9-m Anglo-Australian Telescope (AAT)



2-degree-Field (2df) fibre positioned



AAOmega spectrograph

Efficient Target Selection w/

DES DR1 photometry | Gaia DR2 proper motions

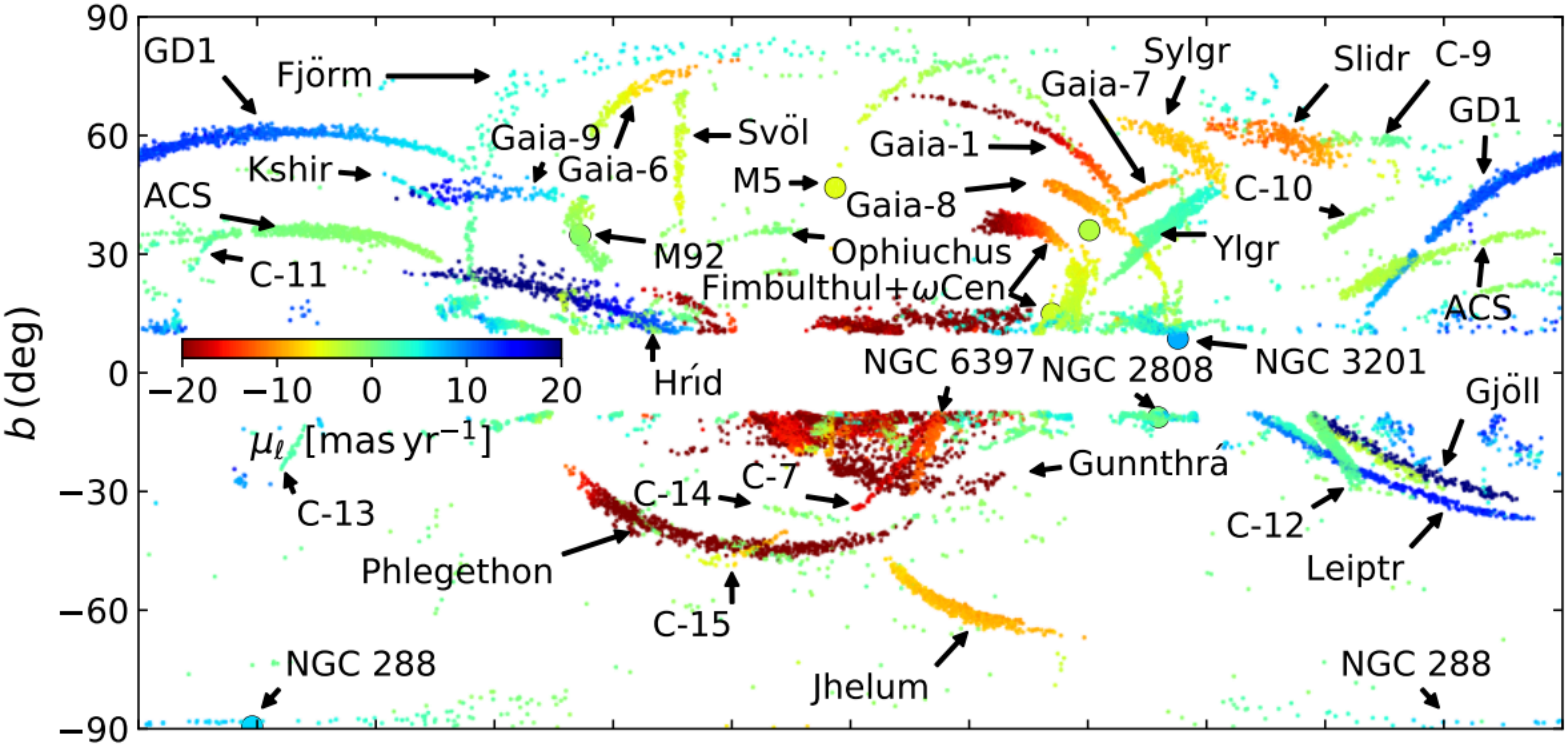
DARK ENERGY SURVEY

gaia

The Southern Stellar Stream Spectroscopic Survey (S5): Overview, Target Selection, Data Reduction, Validation, and Early Science

TSL et al. 2019, arXiv:1907.09481

Gaia EDR3 detections, [3, 12] kpc



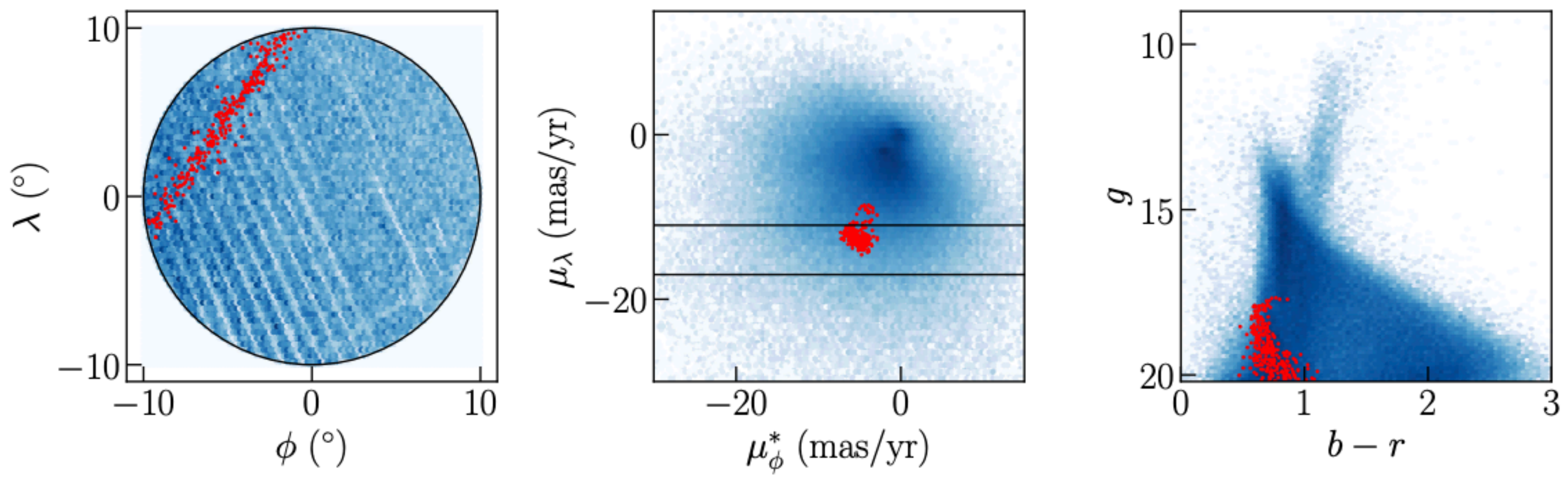
Gaia EDR3 / Ibata et al. 2021

Stream Search w/ Machine Learning

Via Machinae: Searching for Stellar Streams using Unsupervised Machine Learning

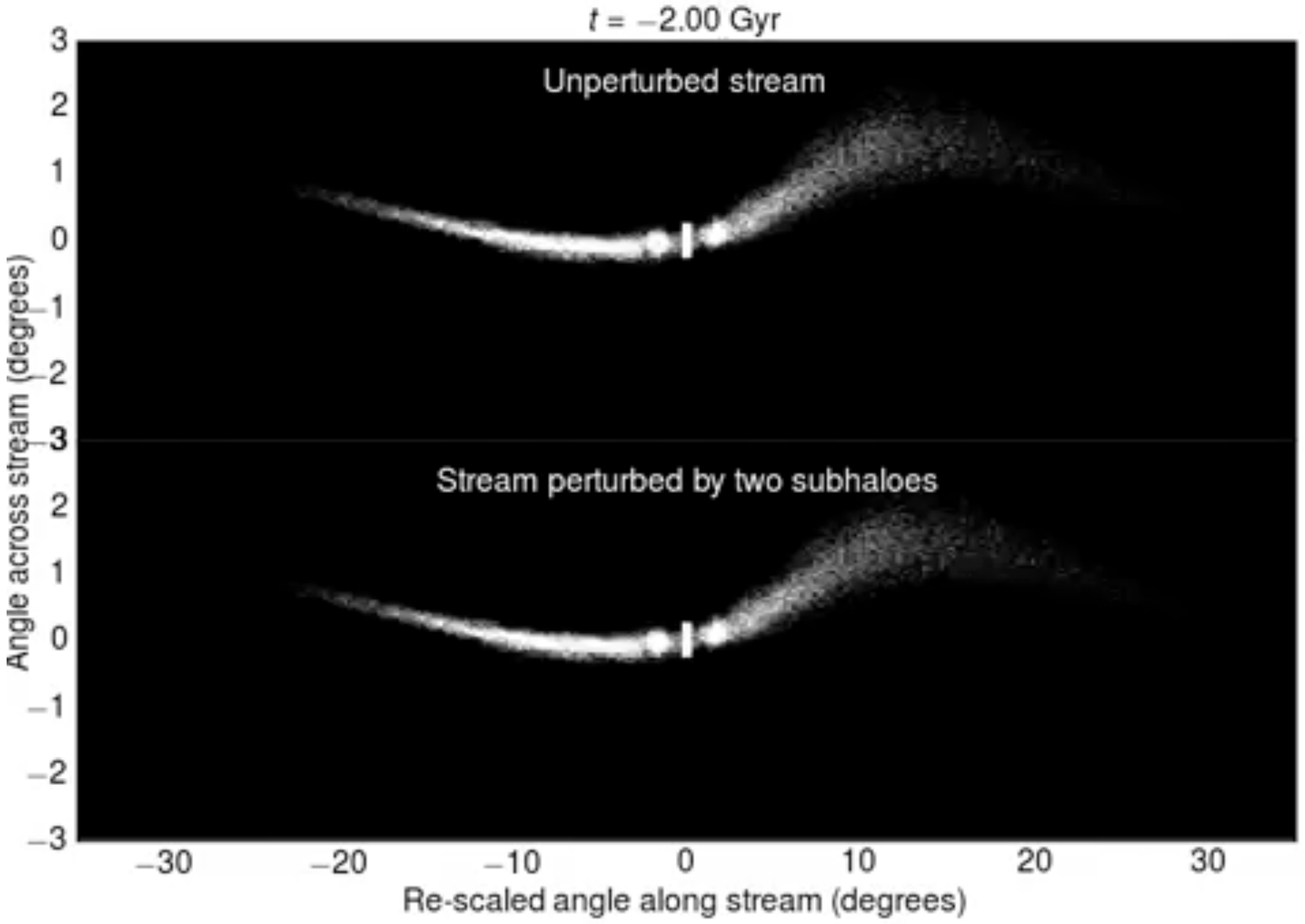
David Shih,[1★] Matthew R. Buckley,[1] Lina Necib,[2,3,4] and John Tamanas[5]
[1]NHETC, Dept. of Physics and Astronomy, Rutgers, Piscataway, NJ 08854, USA
[2]Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA
[3]Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
[4]Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
[5]Department of Physics, University of California Santa Cruz, 1156 High Street, Santa Cruz, California 95064, USA

based on the deep learning anomaly detector ANODE 90 new streams discovered?



Shih et al. 2021, 2023

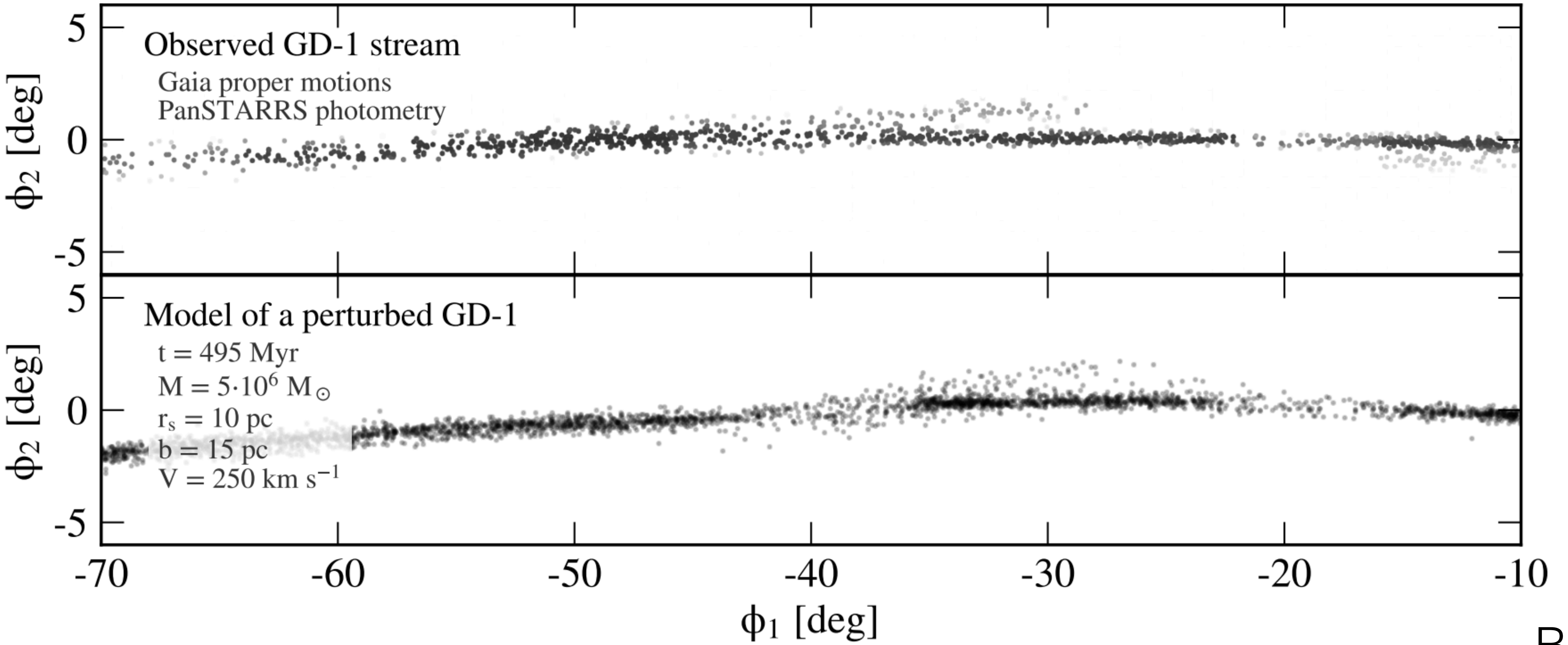
Subhalo Mass Function with Cold Streams



Cold streams may be perturbed by subhalo flyby

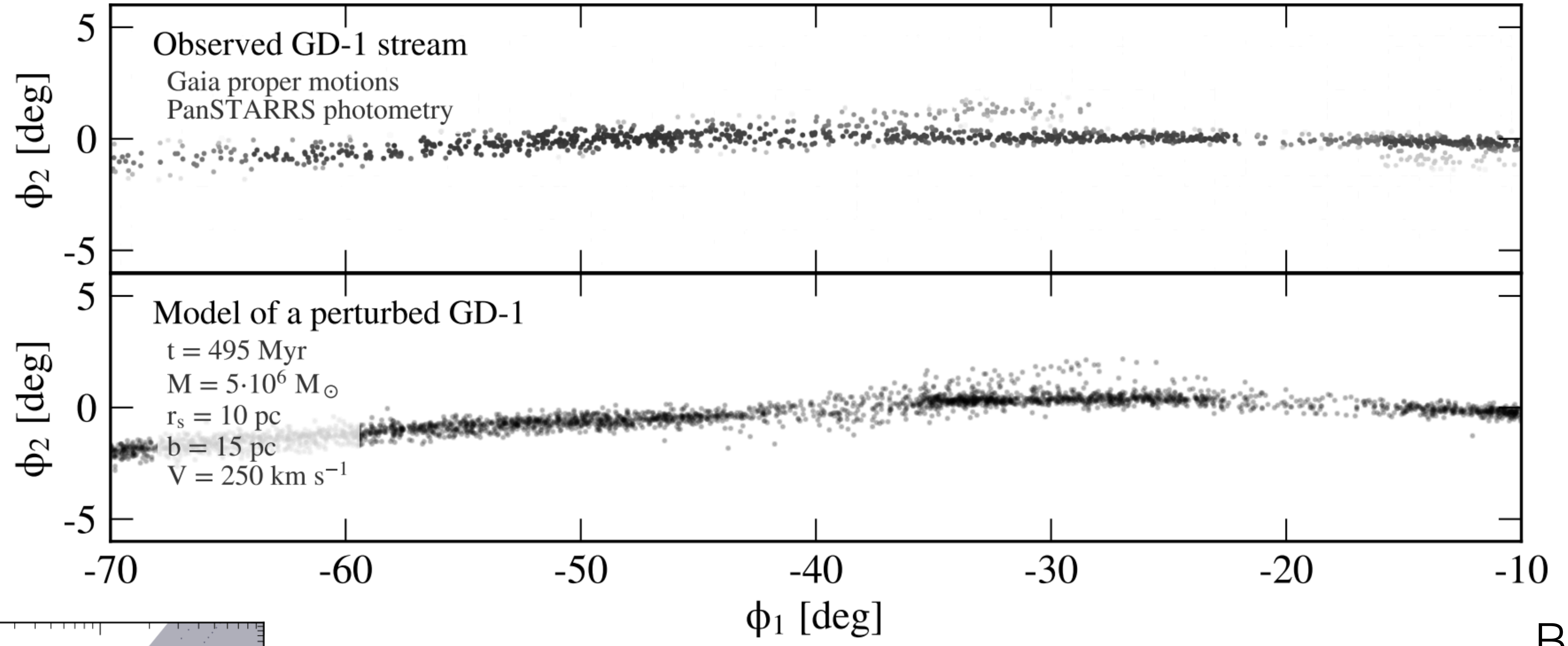
Credit: Denis Erkal

Science with Stellar Streams

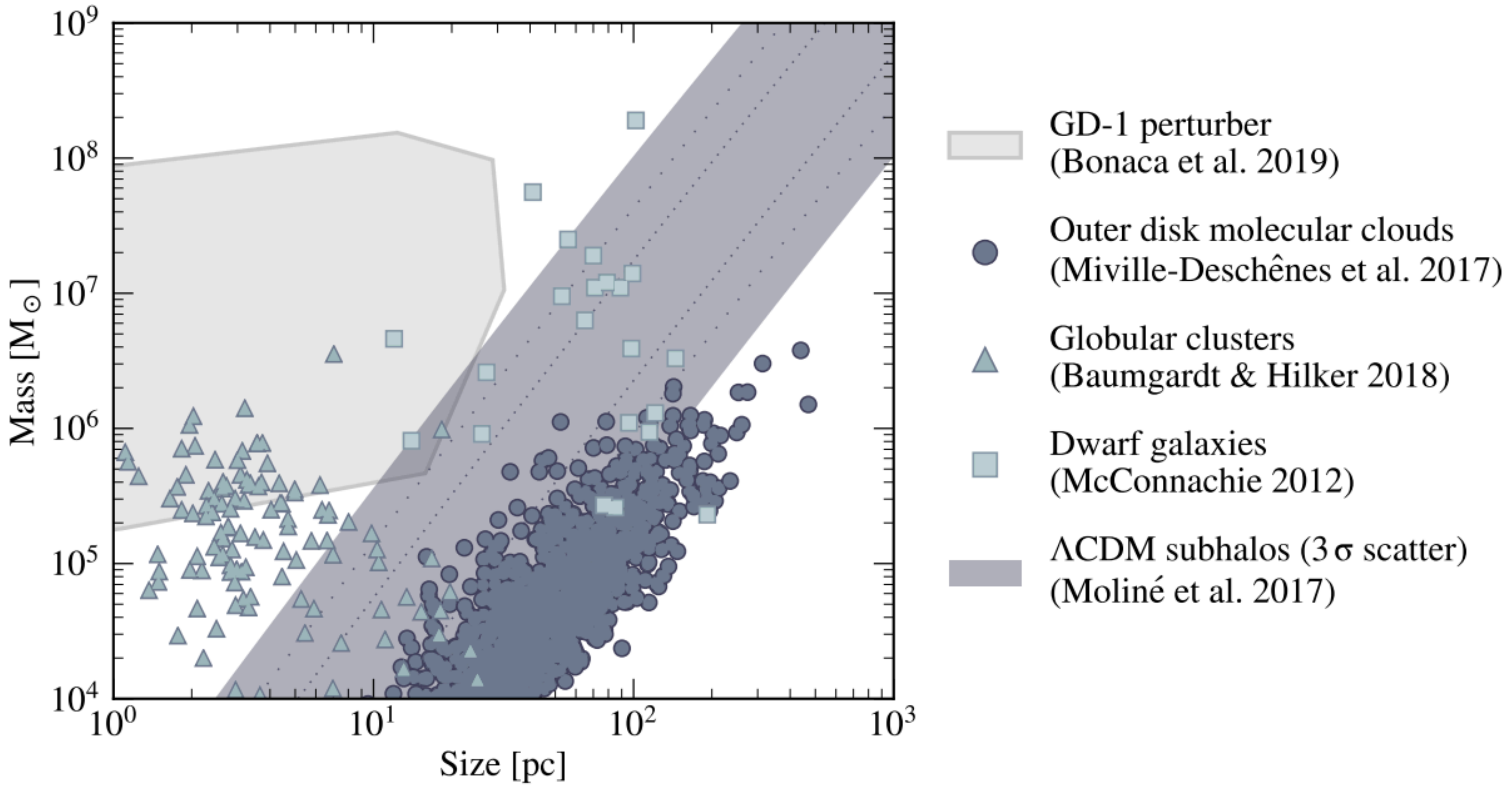


Bonaca et al. (2019)

Science with Stellar Streams

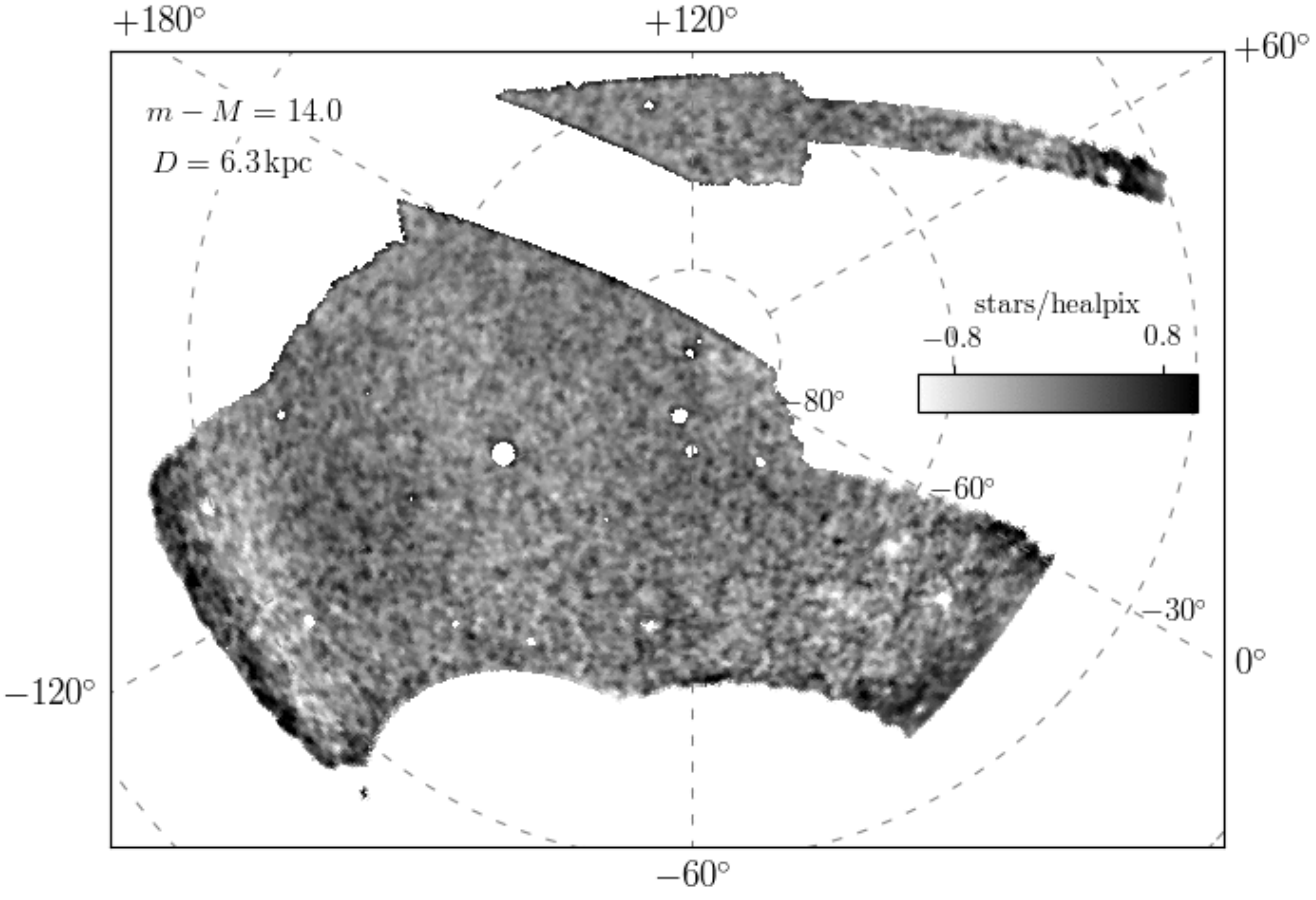


Bonaca et al. (2019)



- Spur come from a compact perturber?
- However, de Boer et al (2019) shows that the spur might caused by an interaction with Sagittarius dwarf galaxy.

Streams in the Dark Energy Survey



Shipp et al. 2018
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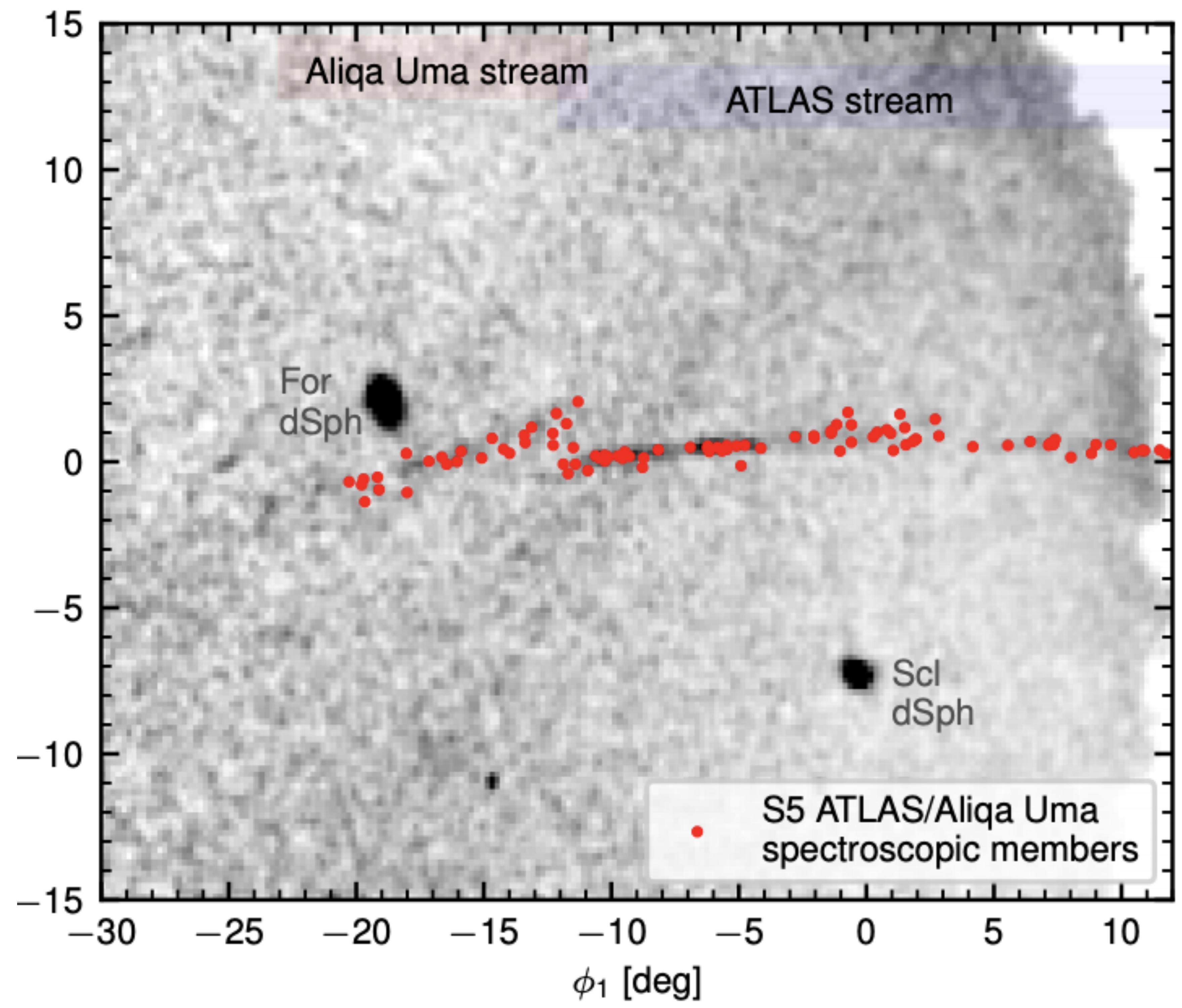
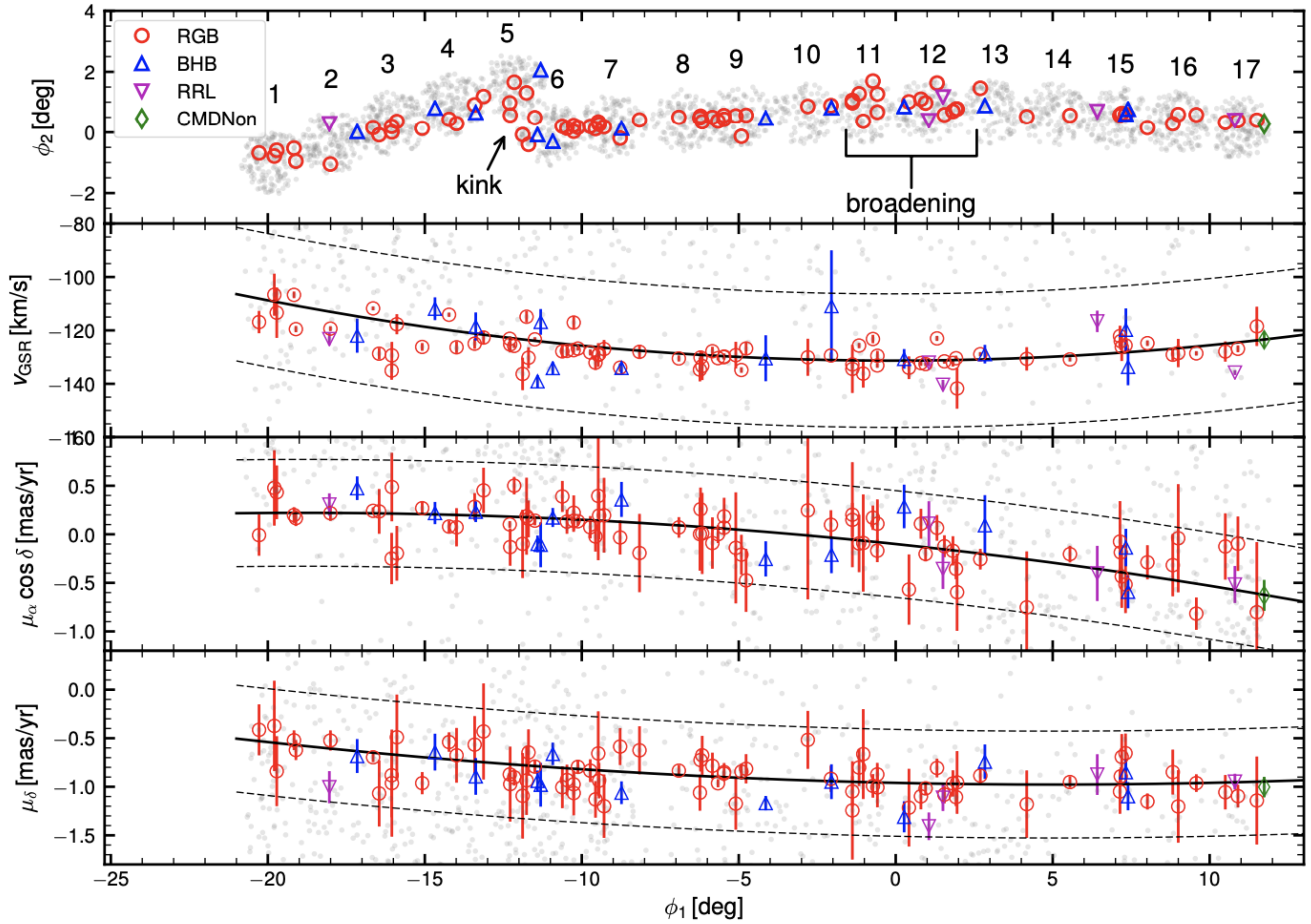
13 new streams from DES + 2 previous known

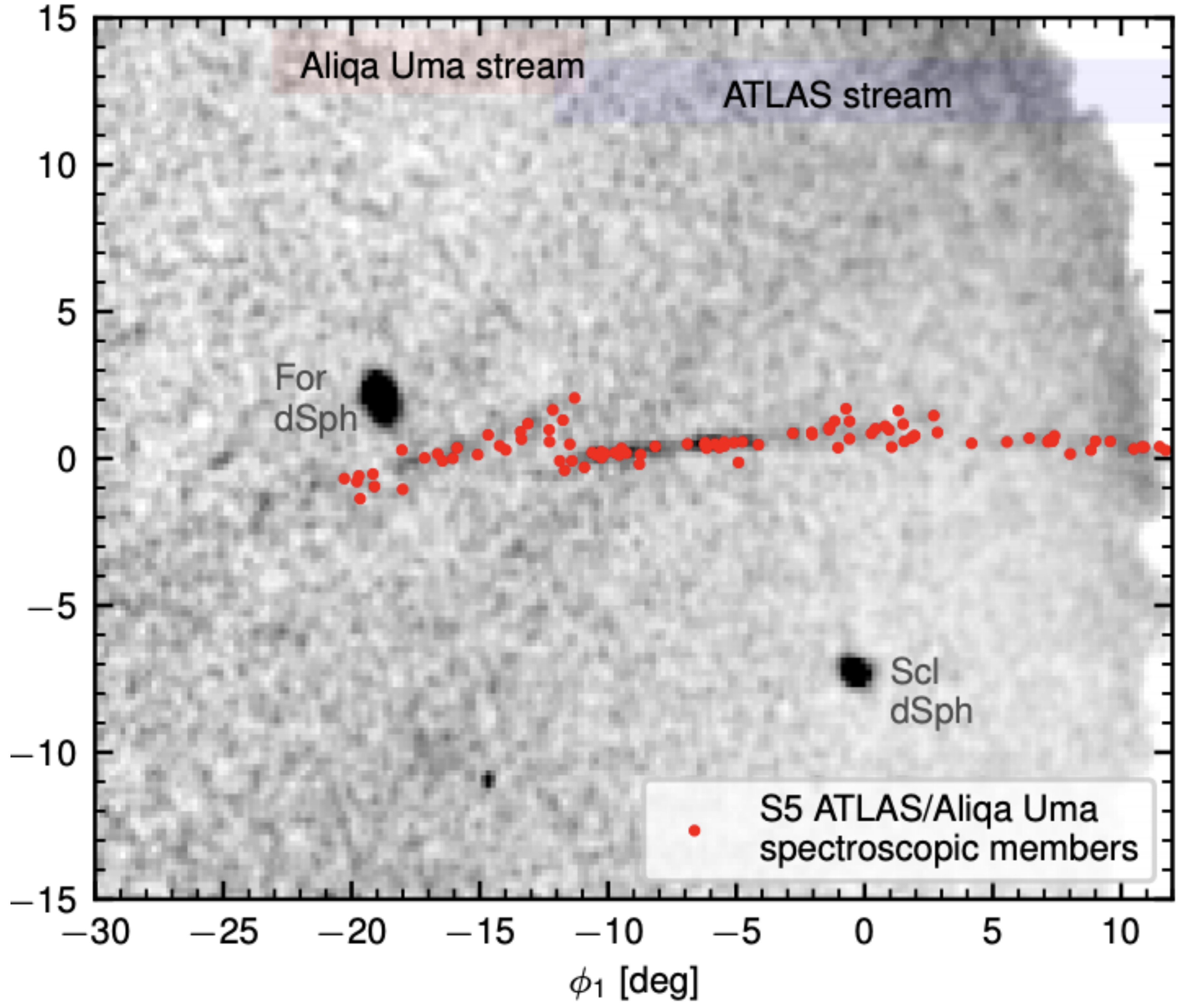
Broken stream perturbed by dark matter subhalo?

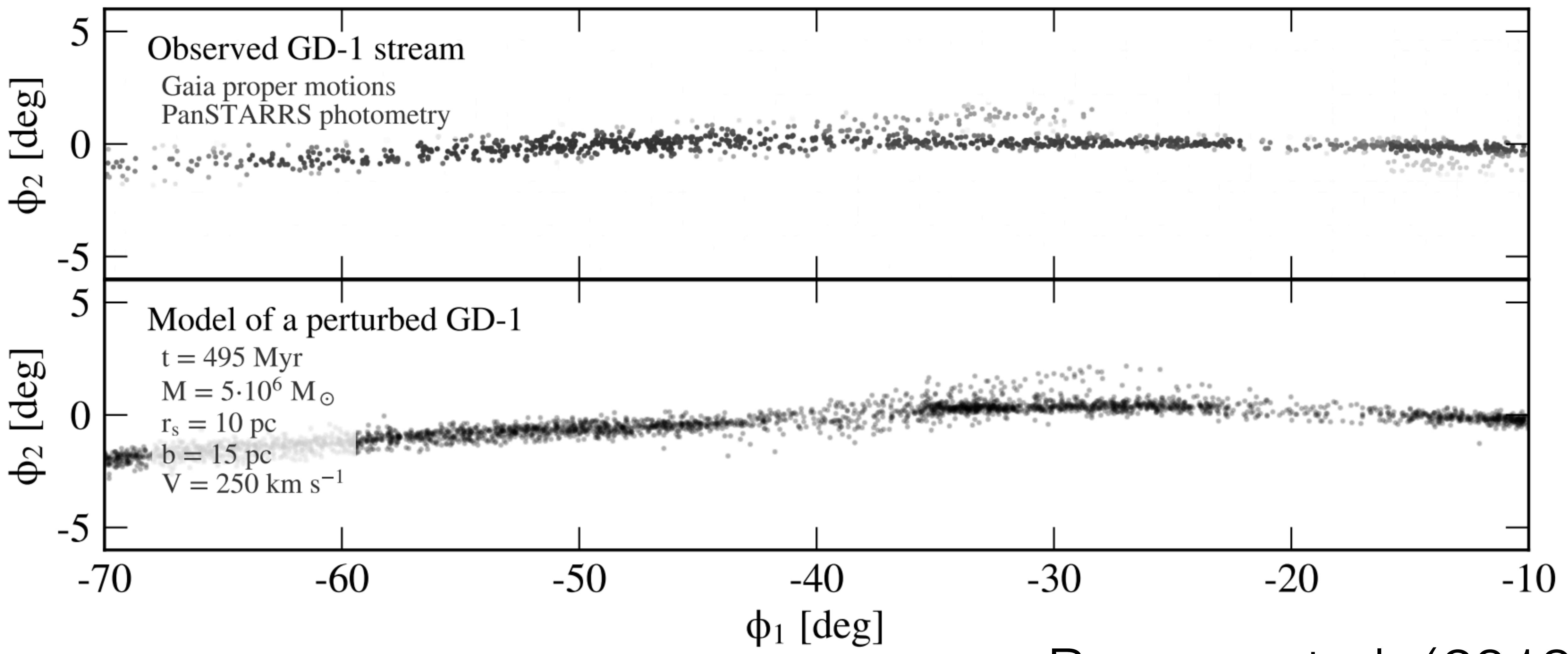




TSL et al (2021)
(S5 Collaboration)

Broken stream perturbed by dark matter subhalo?





Bonaca et al. (2019)

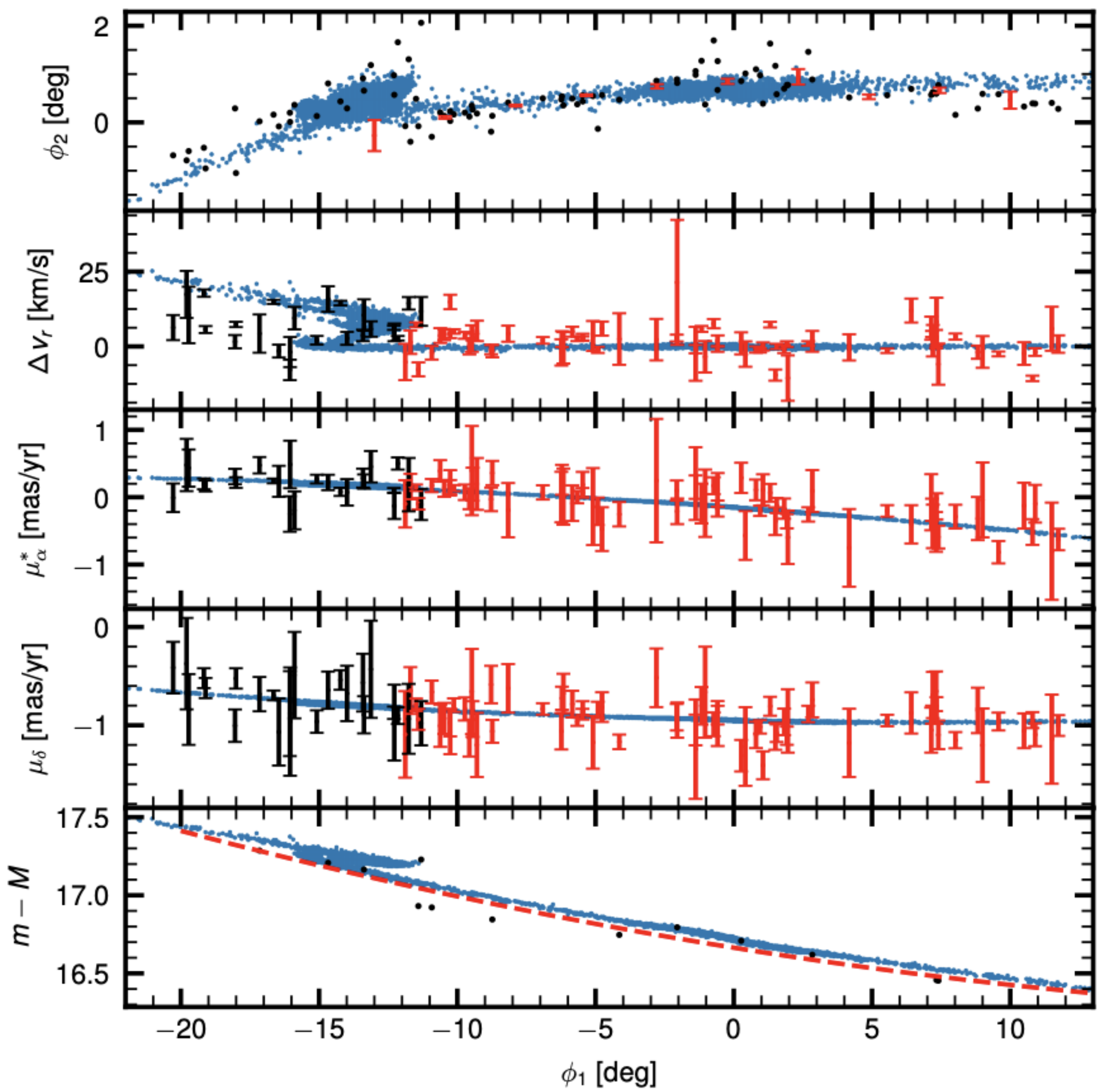
Another GD-1 like stream?

TSL et al (2021)
(S5 Collaboration)

Perturbation Might Be Caused by Sagittarius Dwarf Galaxy?

- ❌ Milky Way Bar
- ❌ Giant Molecular Clouds
- ❌ Spiral Arms
- ❌ Globular Clusters
- ❌ Progenitor
- ? Classical Satellite Galaxies
- ? Dark Matter Subhalo

2% of the realizations



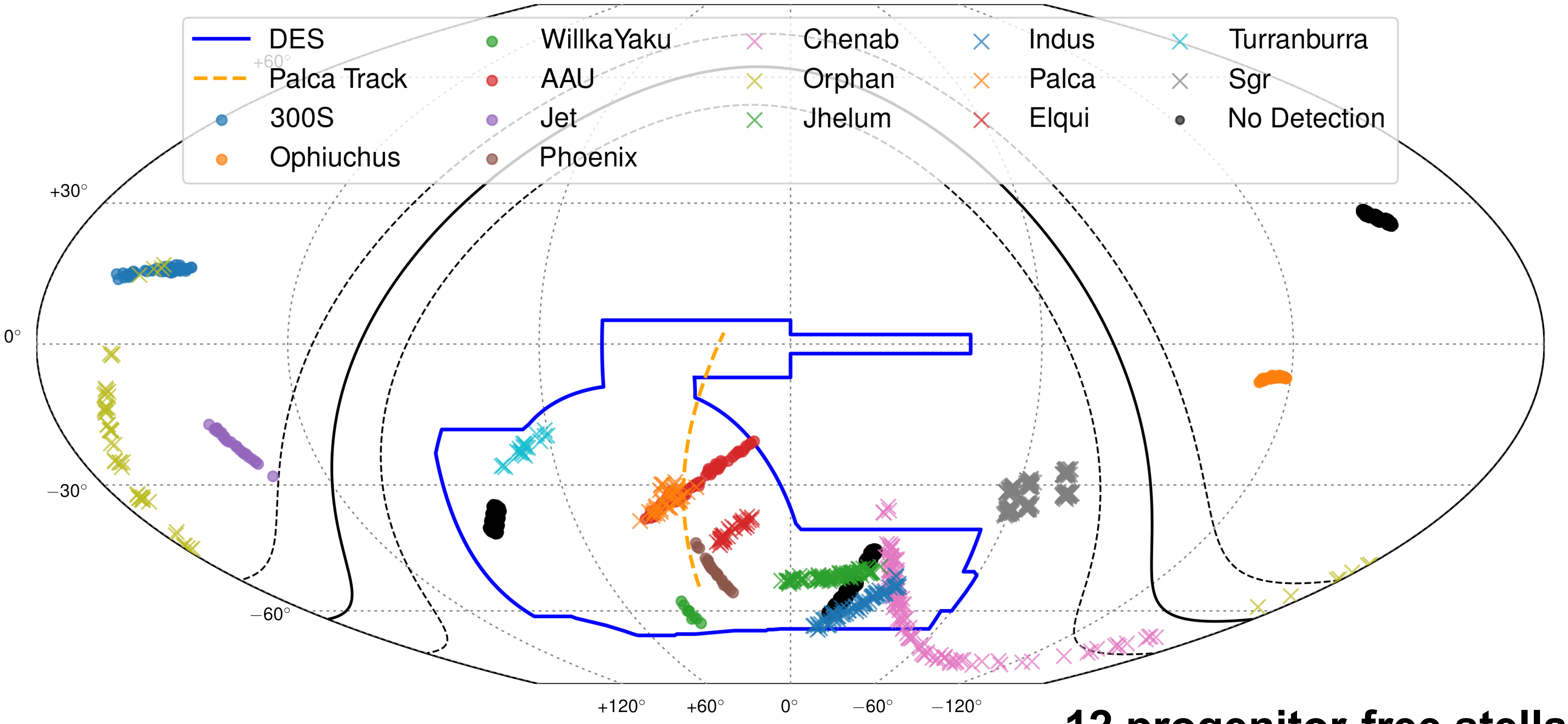
TSL et al. (2021)
(S[5] Collaboration)

Subhalo mass function below the galaxy formation

We are probing the sub halos below 10^8 solar mass region. But we need more modeling work to really “detect” these subhalos.

Properties of Disrupted Satellite Systems in the Milky Way

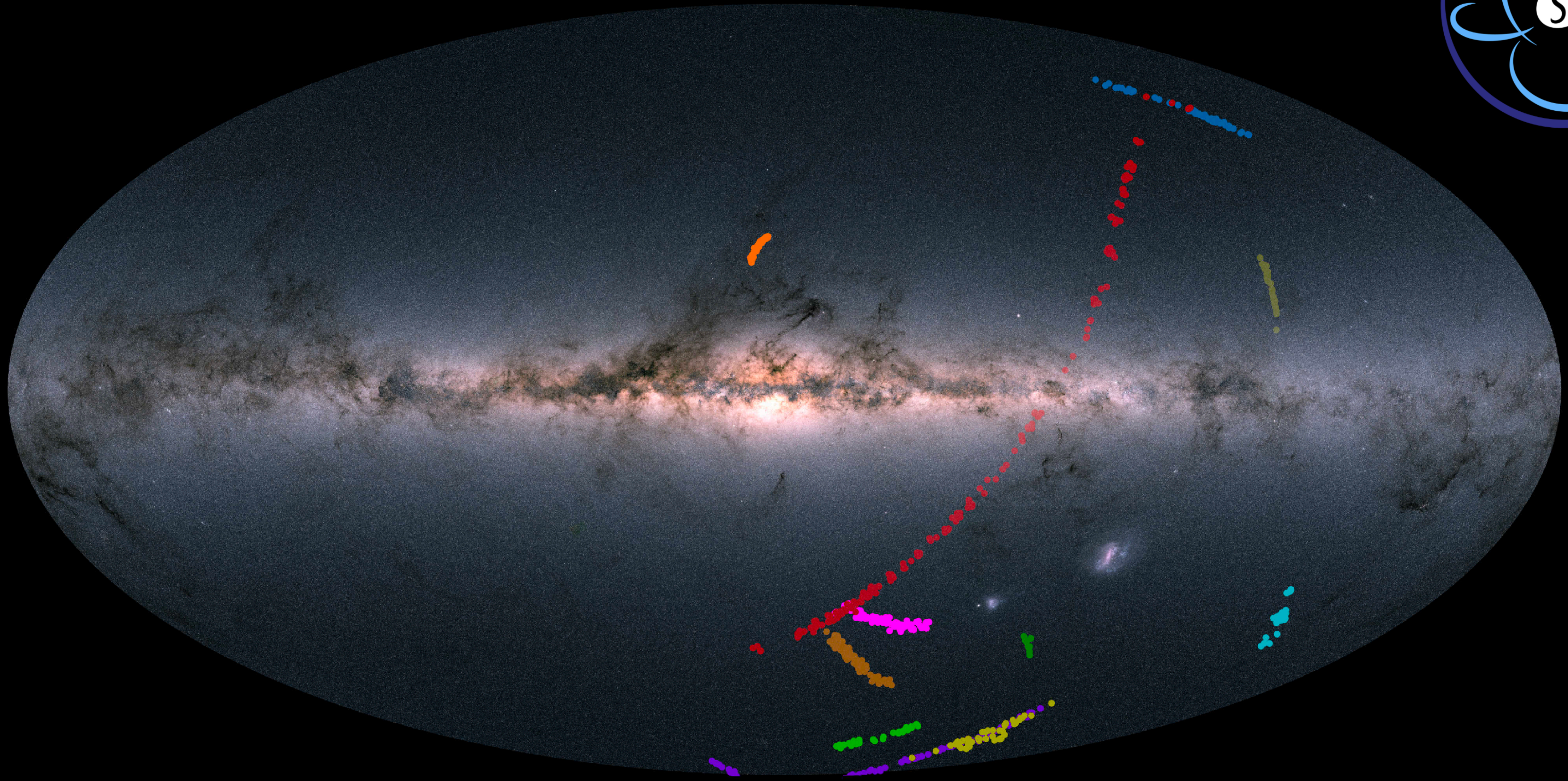
Orbital and Chemical Properties of Stellar Streams



S5: The Orbital and Chemical Properties of One Dozen Stellar Streams

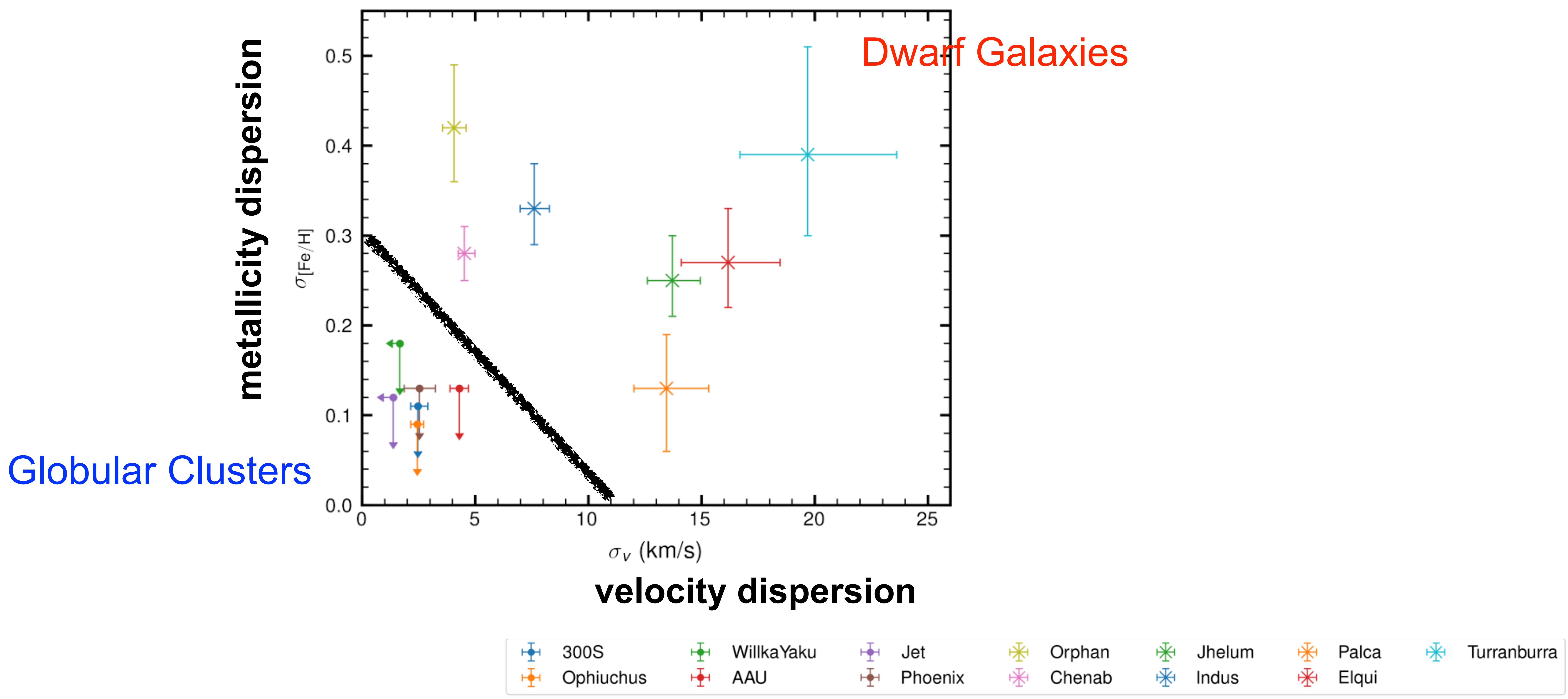
TSL et al (2022), arXiv: 2110.06950

12 progenitor-free stellar streams at ~10-50 kpc observed in 2018-2020



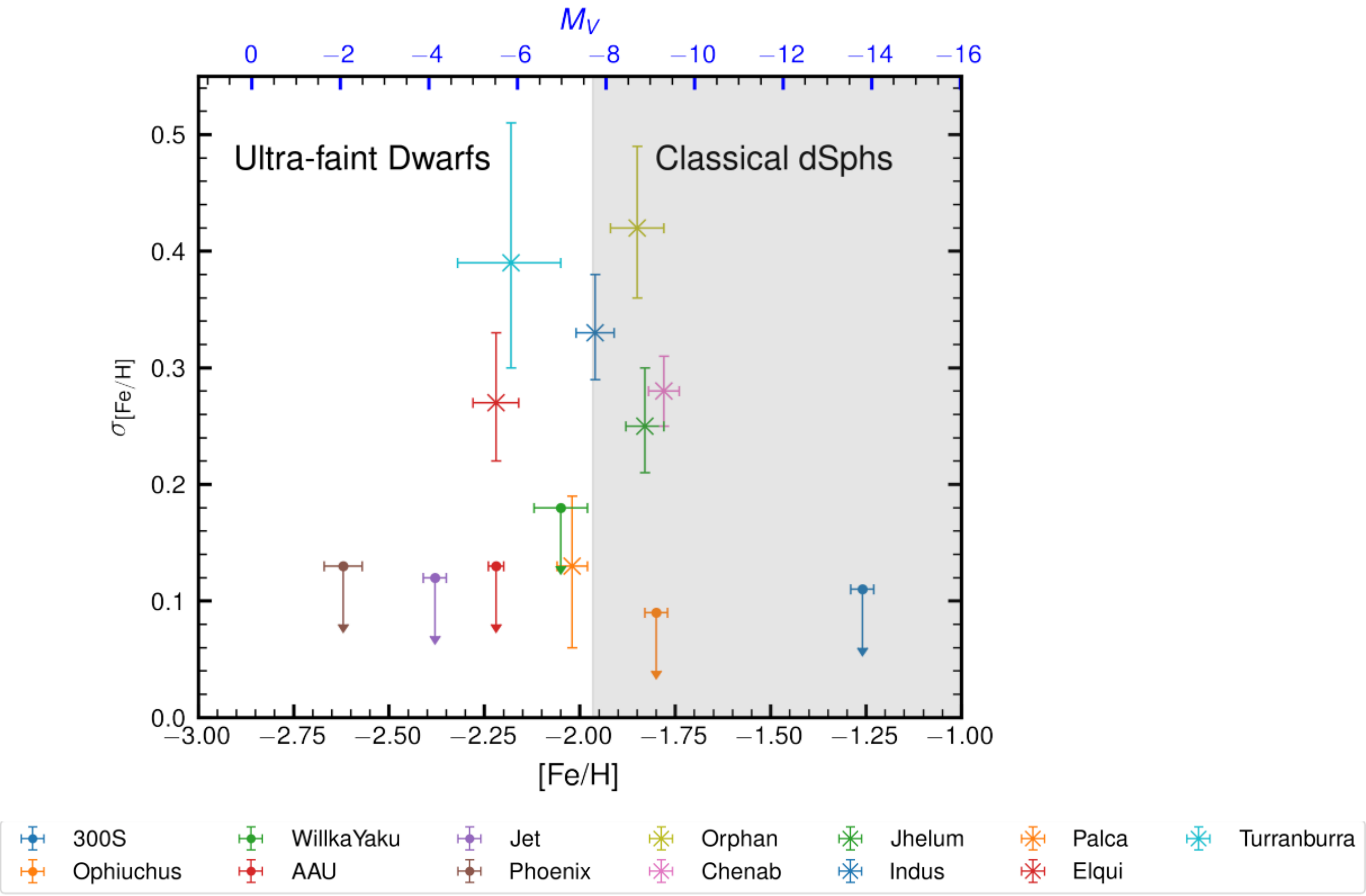
Credit: Gaia + S5

What are the Progenitors? Dwarf Galaxies or Globular Clusters?



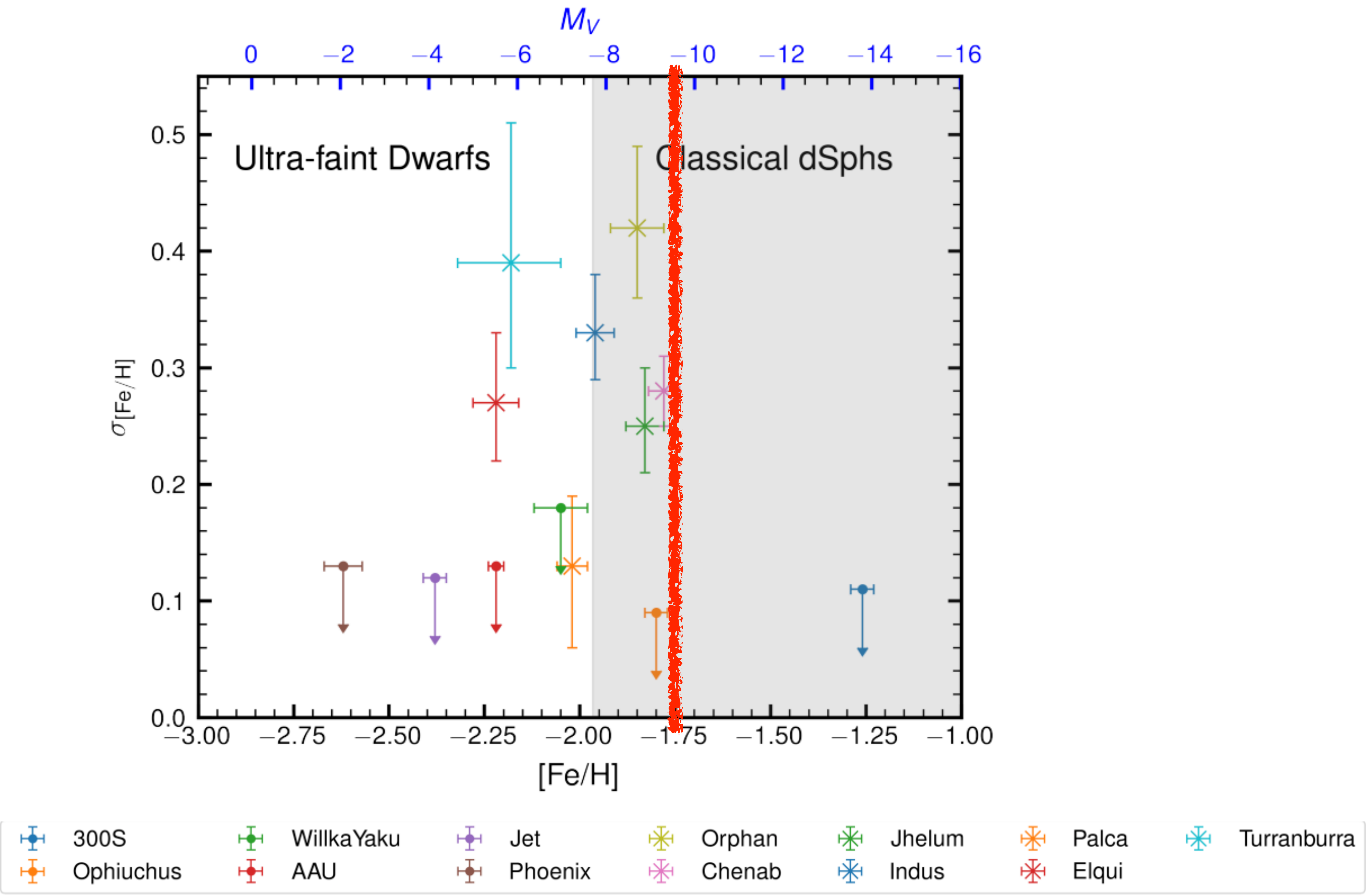
TSL et al (2021)
(S5 Collaboration)

Luminosity / Stellar Mass of the Stream Progenitors



TSL et al (2021)
(S^5 Collaboration)

Luminosity / Stellar Mass of the Stream Progenitors



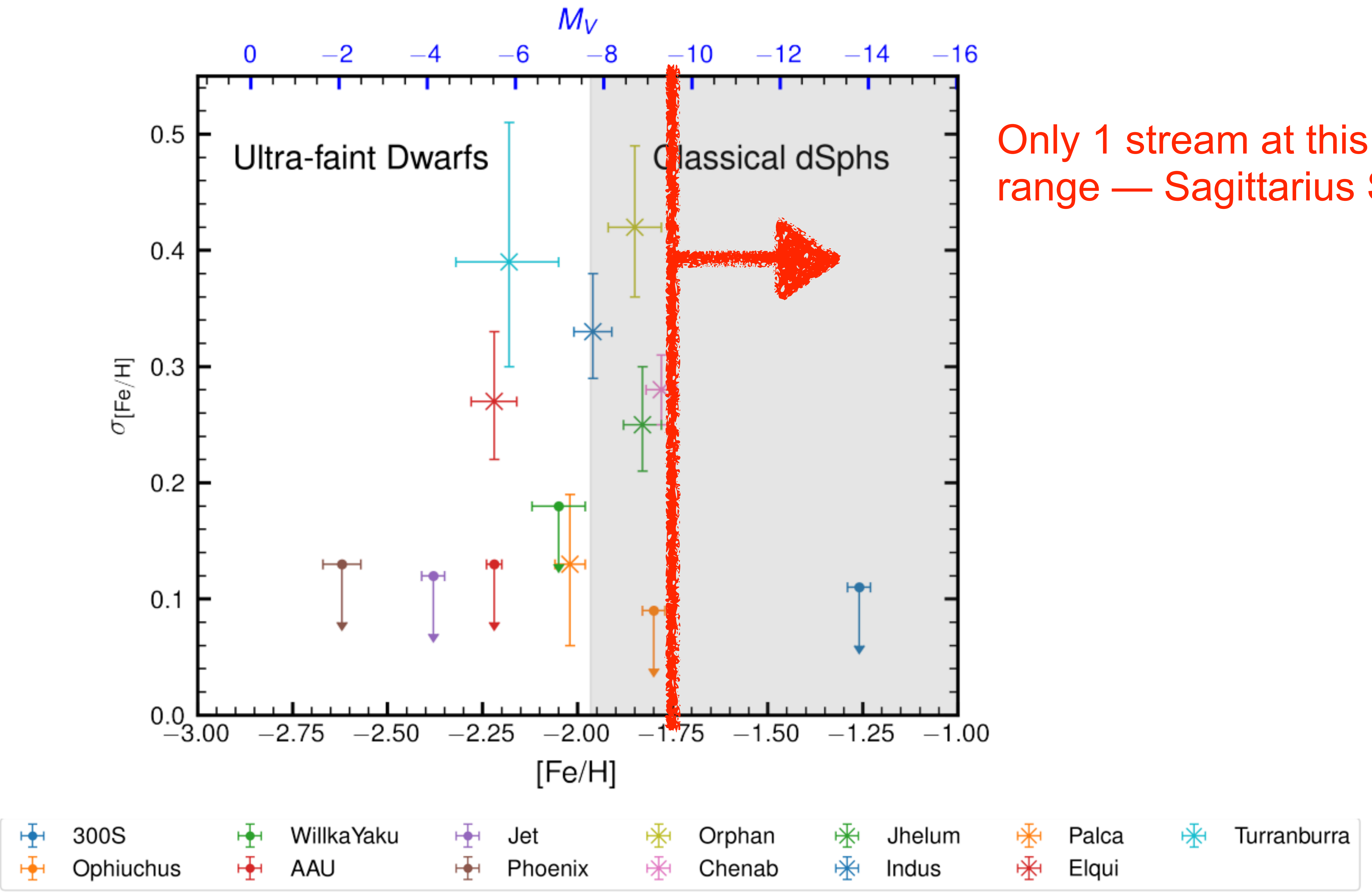
TSL et al (2021)
(S^5 Collaboration)

# of stream at > 5 x10^5 $M_\odot$
Predicted by FIRE-2 simulation

sim name	m_{200m}[M$_\odot$]	r_{200m}[kpc]	N
m12i	1.18×10^{12}	336	9
m12f	1.71×10^{12}	380	8
m12m	1.58×10^{12}	371	8
m12c	1.35×10^{12}	351	7
m12b	1.43×10^{12}	358	8
m12r	1.10×10^{12}	321	3
m12w	1.08×10^{12}	319	3
Romeo	1.32×10^{12}	341	13 [10]
Juliet	1.10×10^{12}	321	12 [6]
Romulus	2.08×10^{12}	406	9 [6]
Remus	1.22×10^{12}	339	8 [5]
Thelma	1.43×10^{12}	358	10 [9]
Louise	1.15×10^{12}	333	8 [8]

Panithanpaisal et al. 2021

“Too Big to Fail” in Stream?



Only 1 stream at this mass range — Sagittarius Stream

# of stream at > 5 x10^5 $M_\odot$
Predicted by FIRE-2 simulation

sim name	$m_{200m}[\mathrm{M}_\odot]$	r_{200m}[kpc]	N
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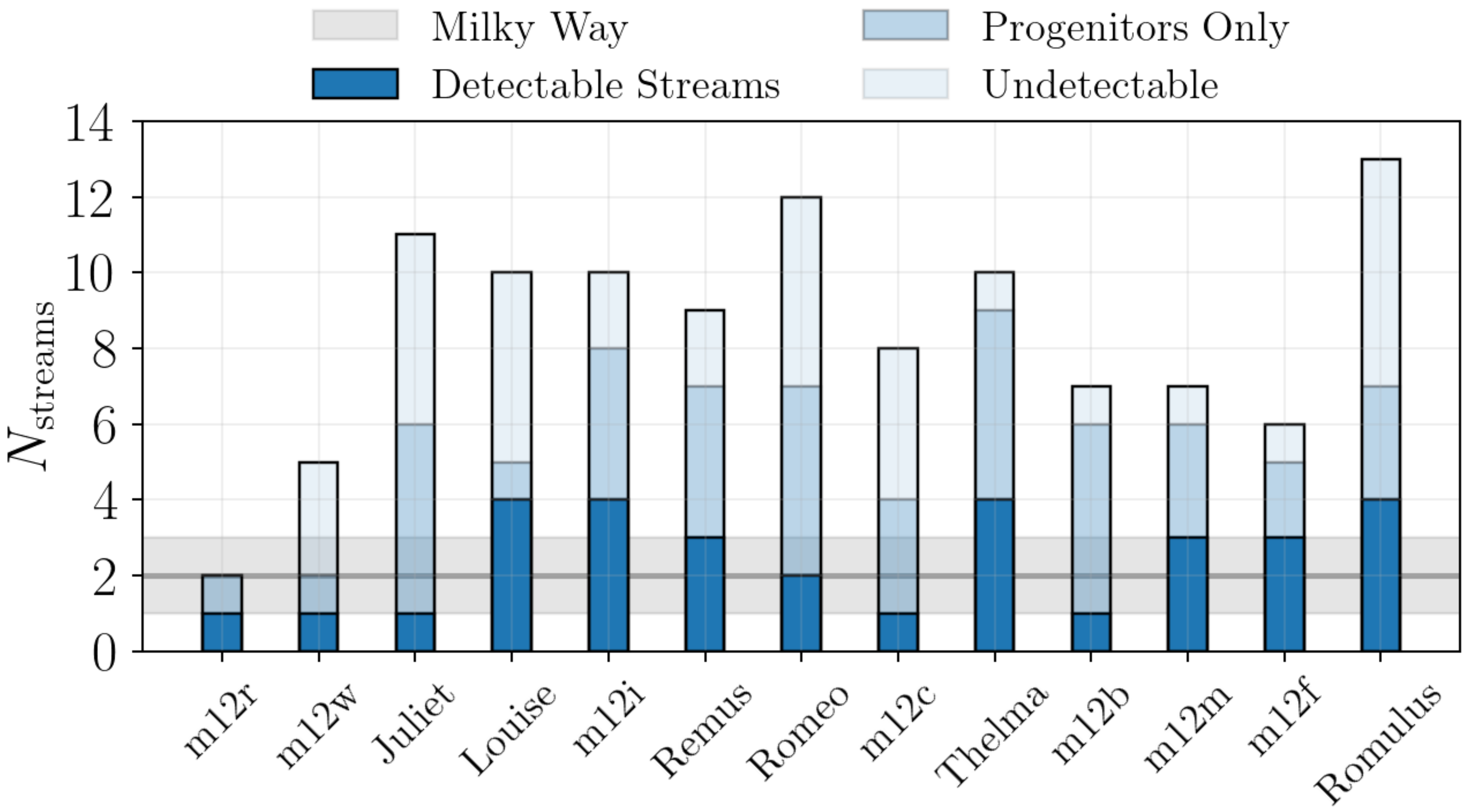
TSL et al (2021)
(S^5 Collaboration)

Panithanpaisal et al. (2021)

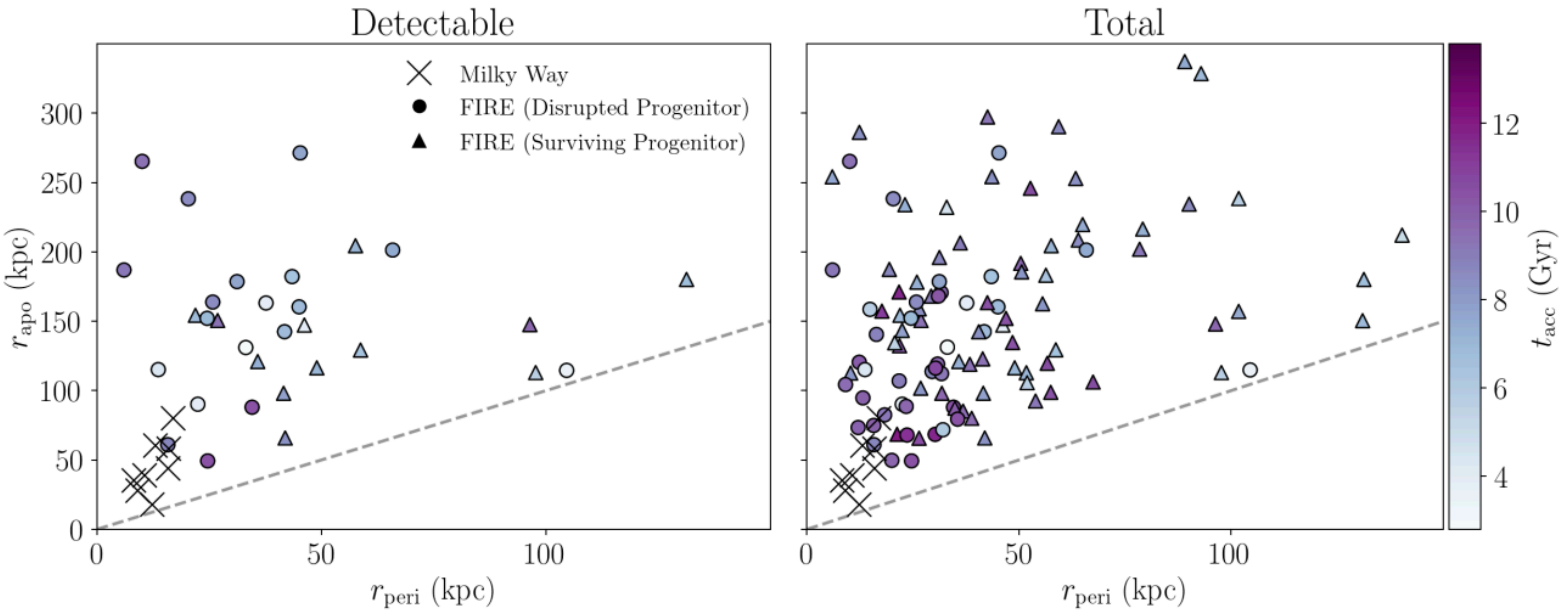
"Too Big to Fail" in Stream?

FIRE-2 matches with observations after detectability is taken into consideration.



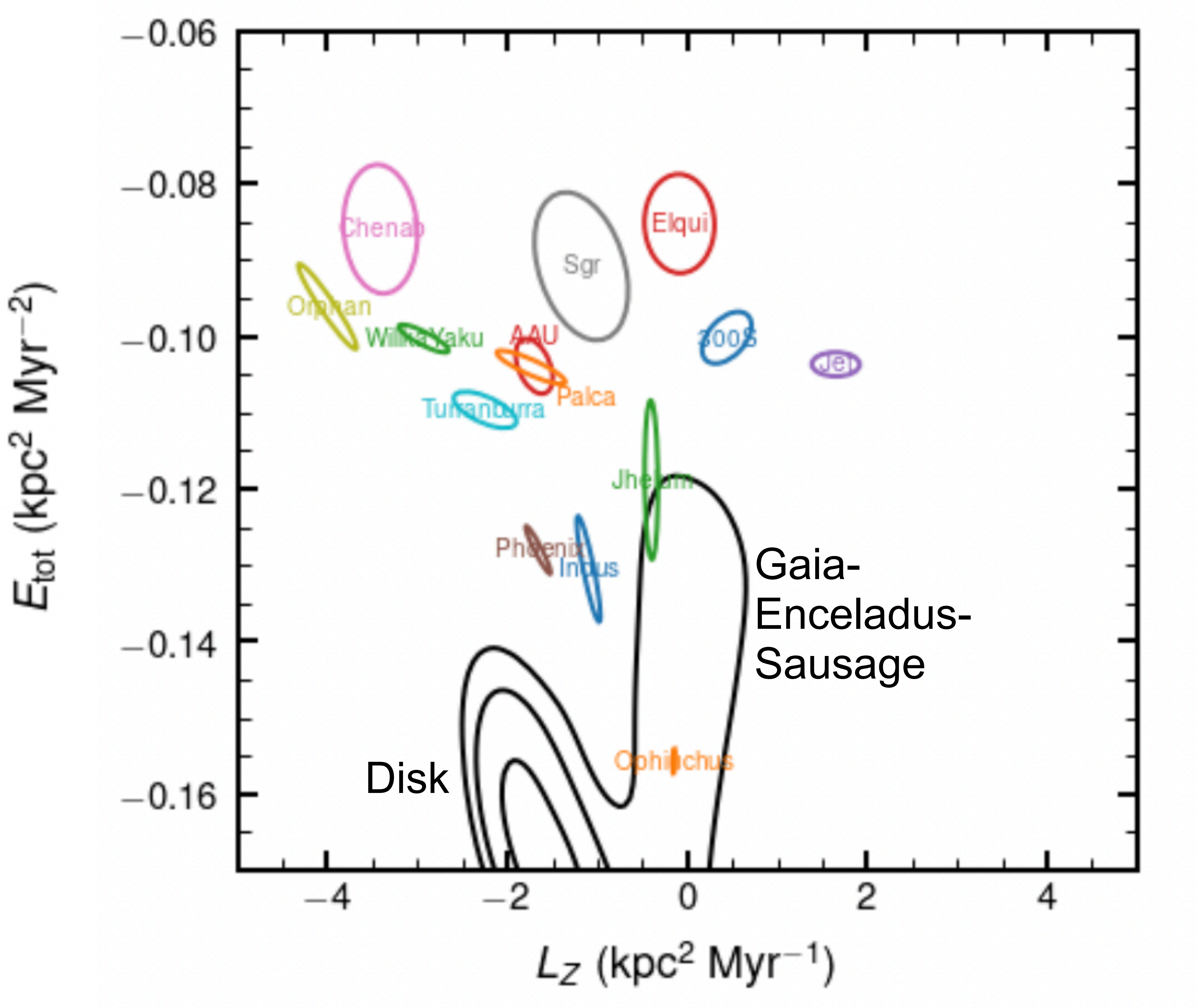
Shipp et al. w/ TSL (2022)
(S5 & FIRE Collaboration)

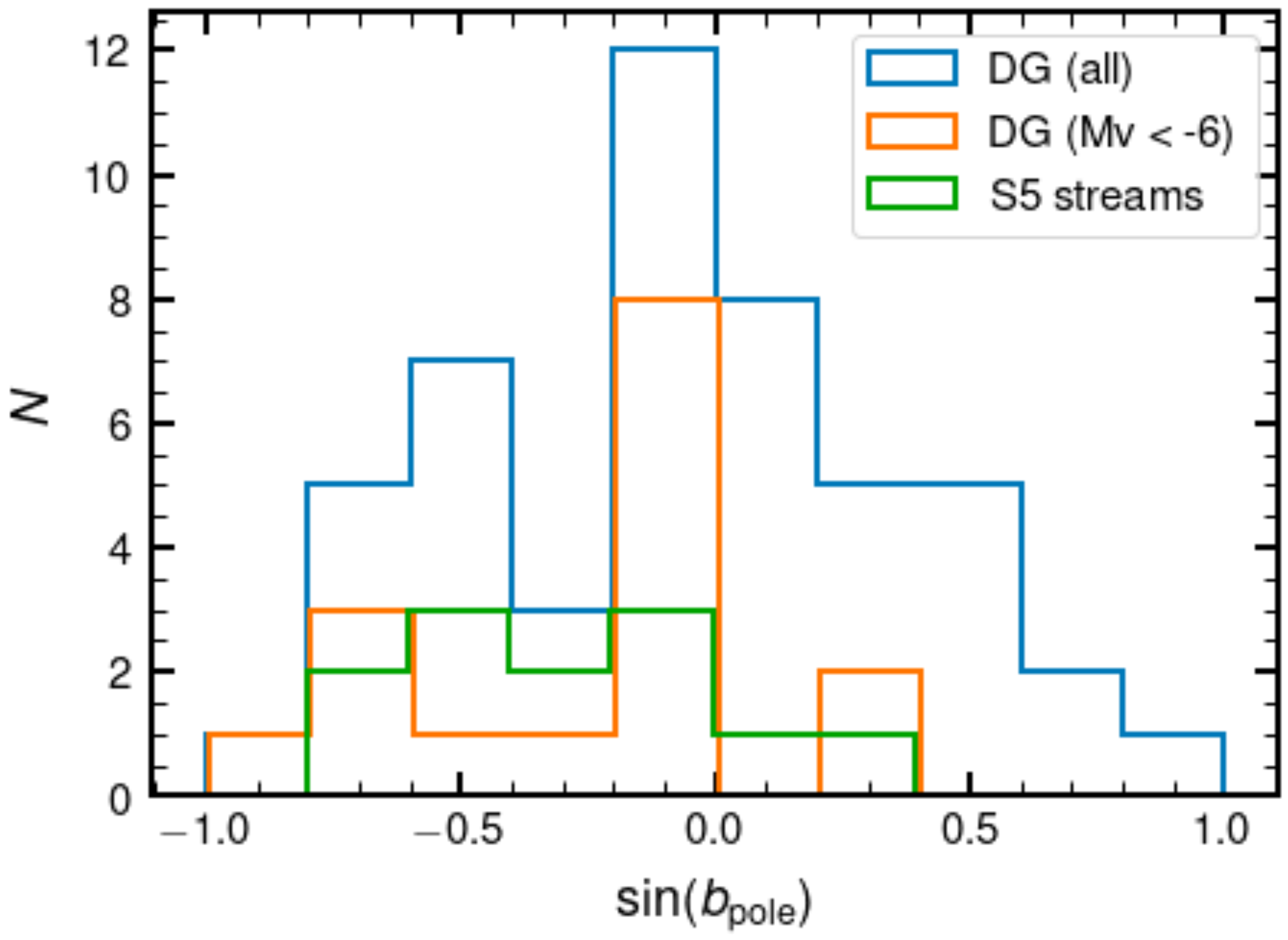
Is FIRE over disrupting satellites?



Shipp et al. w/ TSL (2022)
(S5 & FIRE Collaboration)

Prograde vs. Retrograde

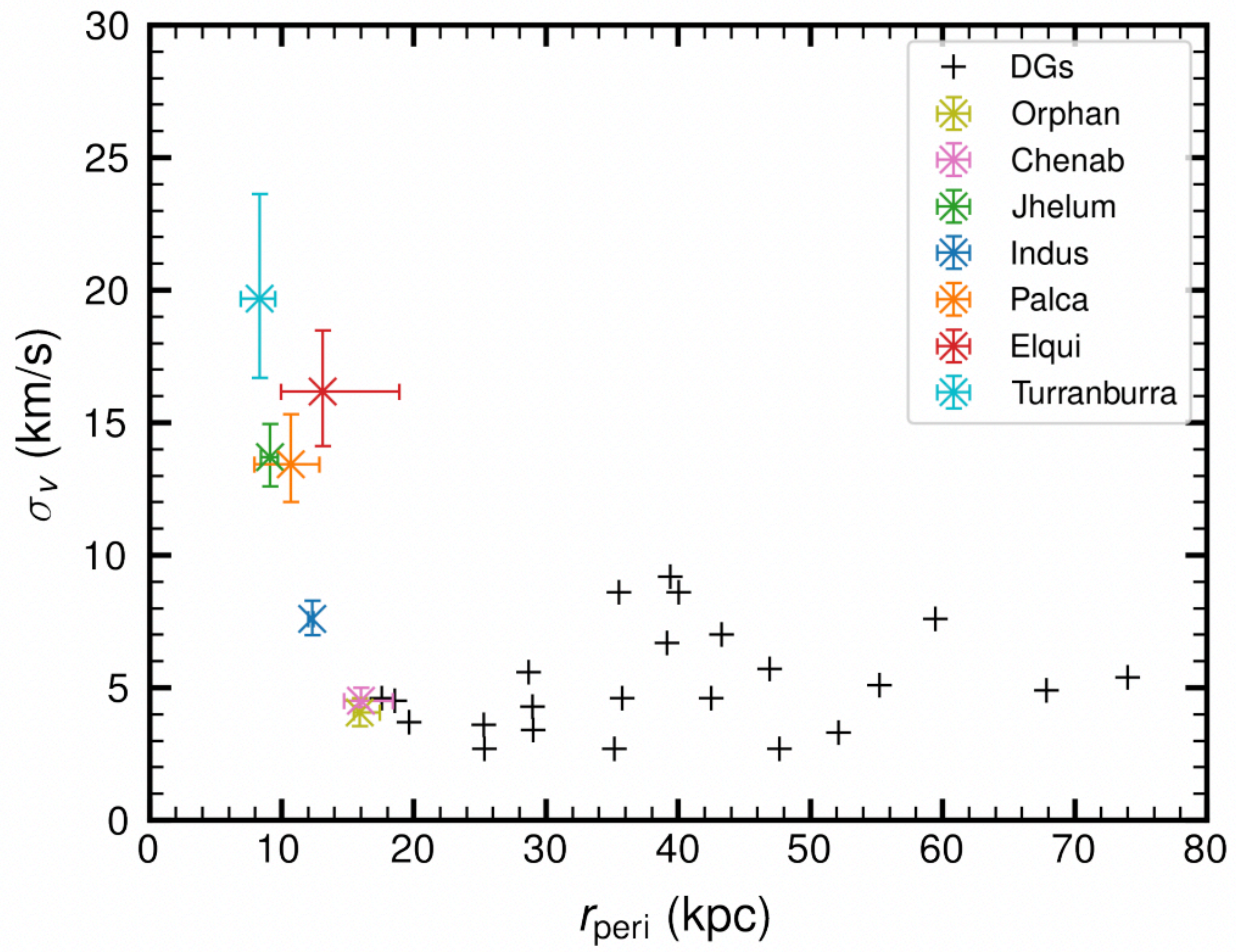




prograde retrograde

TSL et al (2021)
(S5 Collaboration)

Velocity dispersion vs pericenter



TSL et al (2021)
(S[5] Collaboration)

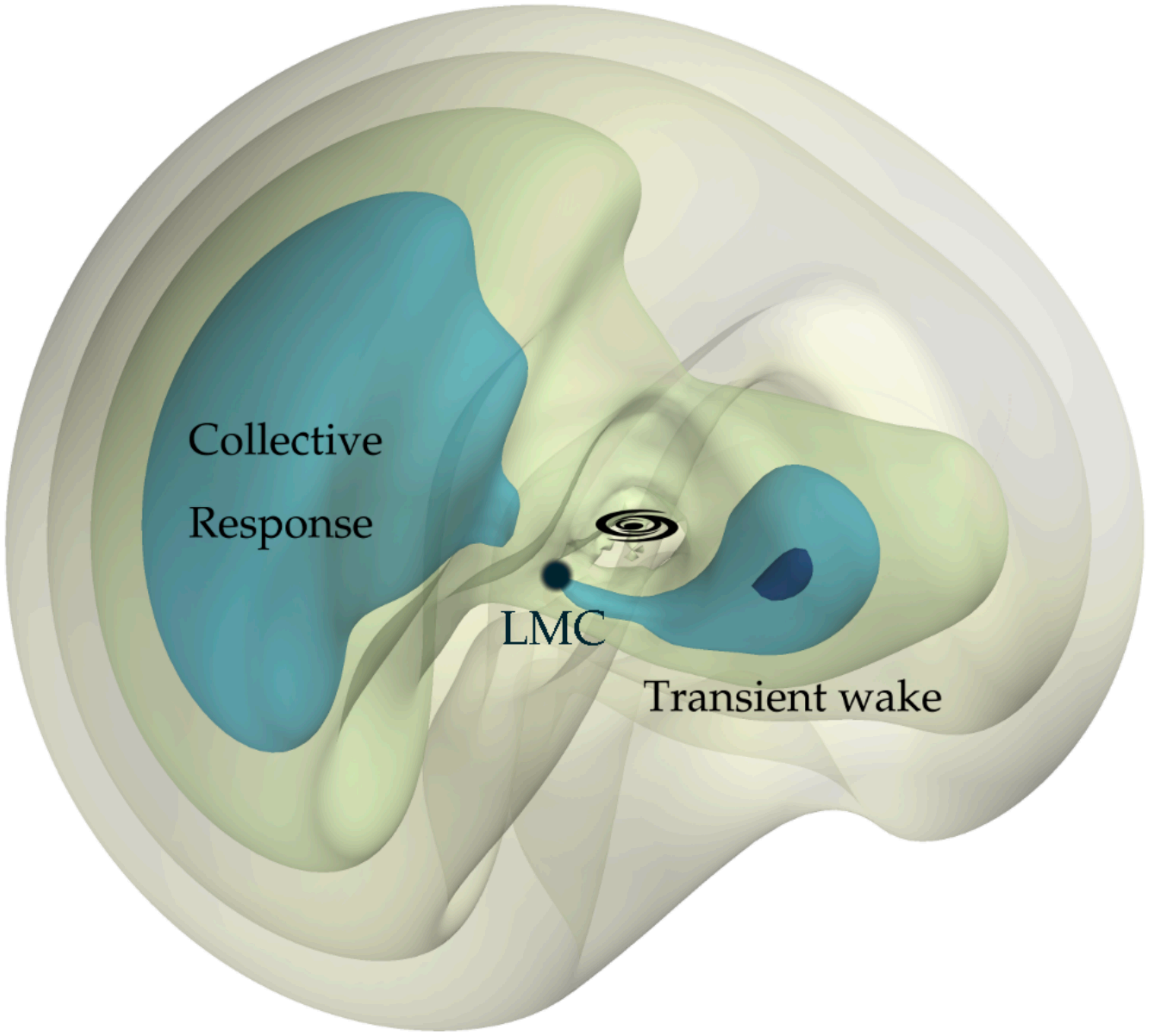
Properties of Disrupted Satellite Systems in the Milky Way

We have a lot of observational data on the properties of stellar streams, e.g. orbits, and awaiting for simulations for comparison

The Impact of Large Magellanic Cloud

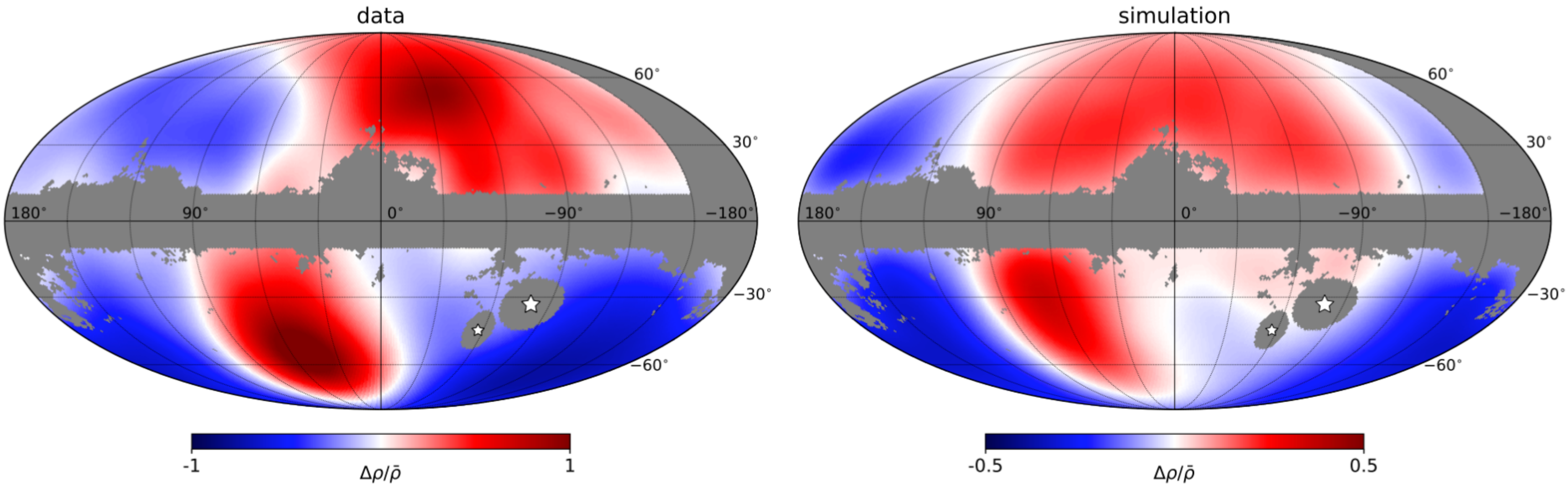

Large Magellanic Cloud
Small Magellanic Cloud

The impact of LMC — on Milky Way Halo



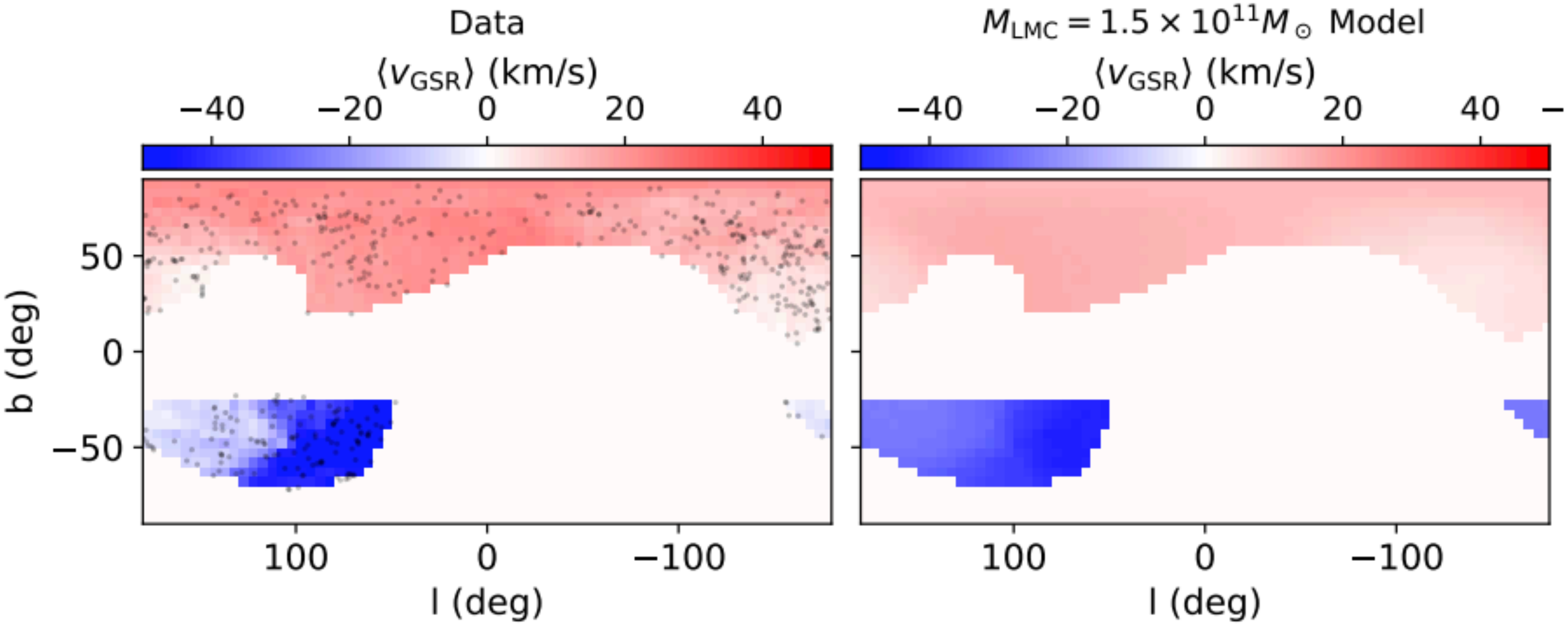
N. Garavito-Camargo et al., 2020

The impact of LMC — density perturbation



C. Conroy et al. 2021

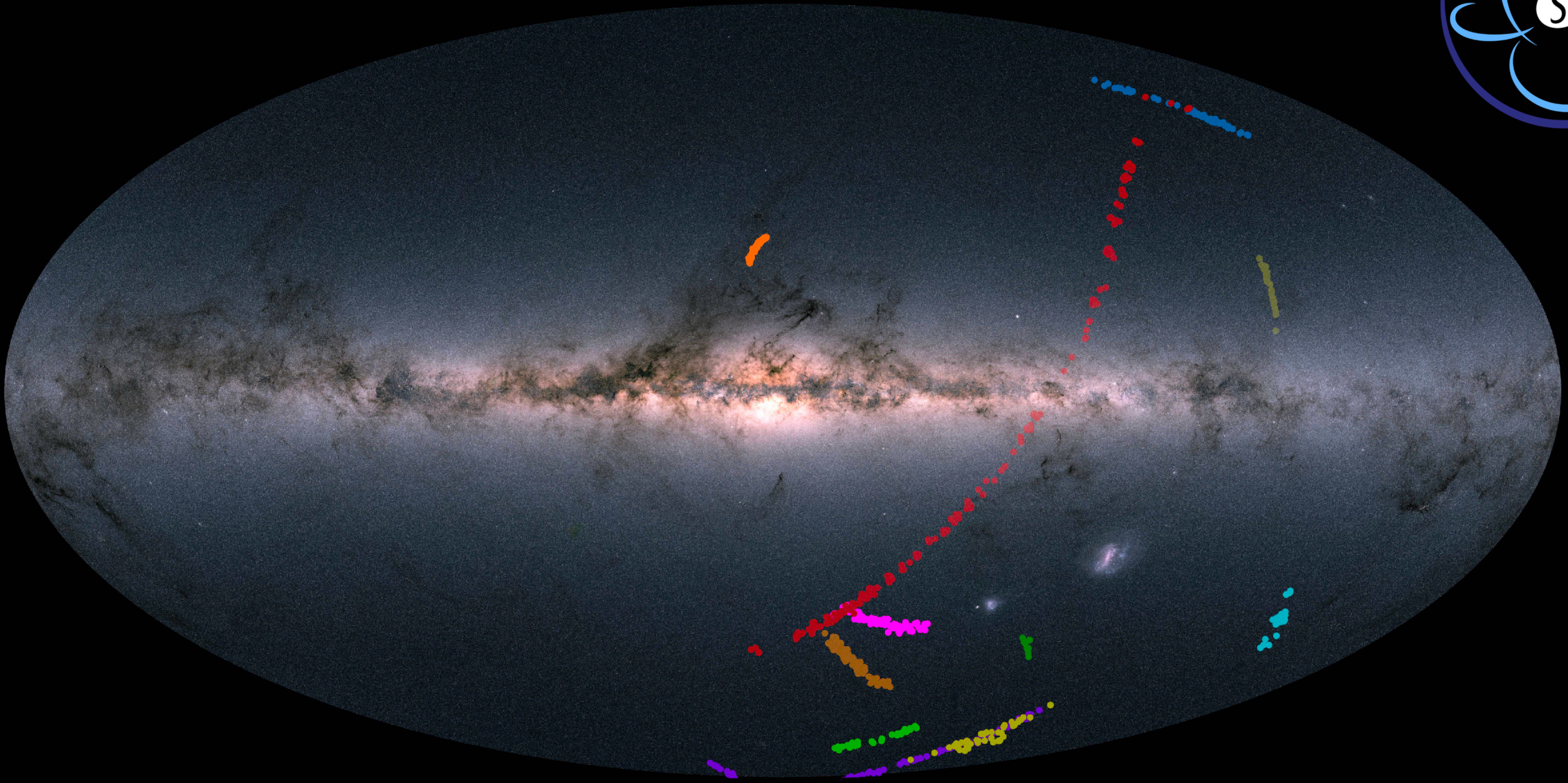
The impact of LMC — kinematic perturbation



D. Erkal et al. 2021

Milky Way is not in Dynamical Equilibrium!

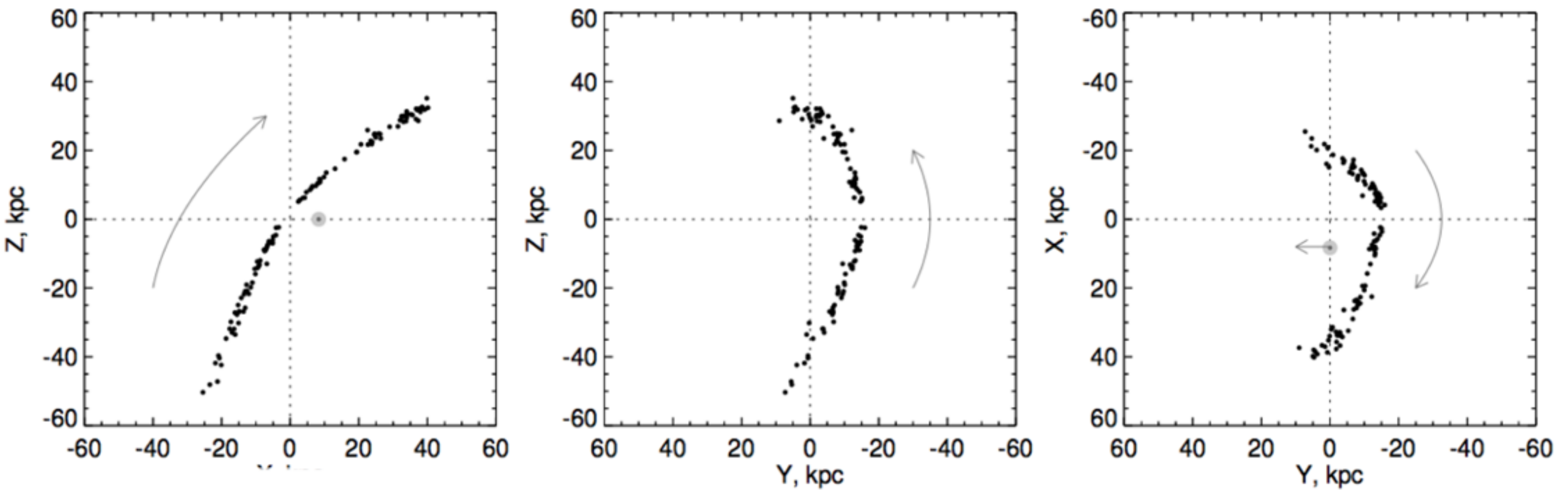
How about the impact on Milky Way's Companions?

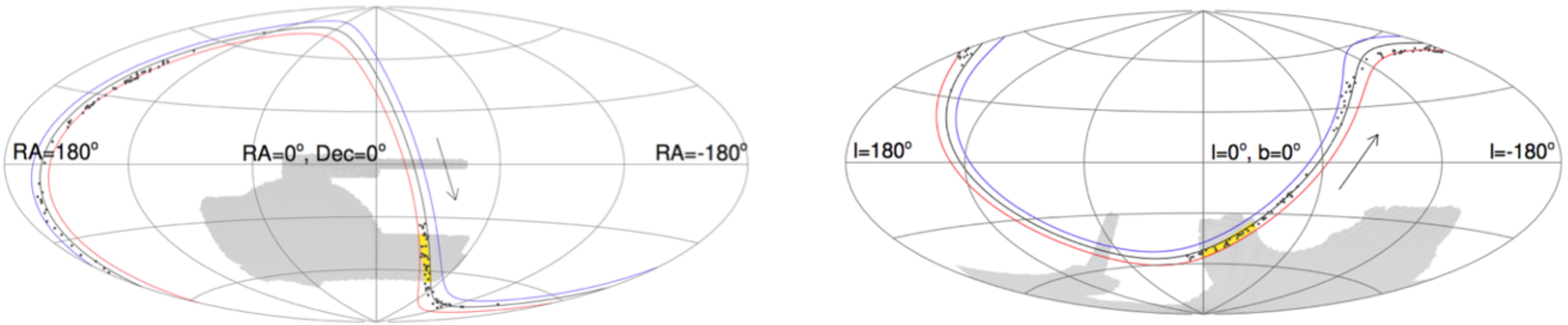


Credit: Gaia + S5

The impact of LMC — on Orphan-Chenab Stream

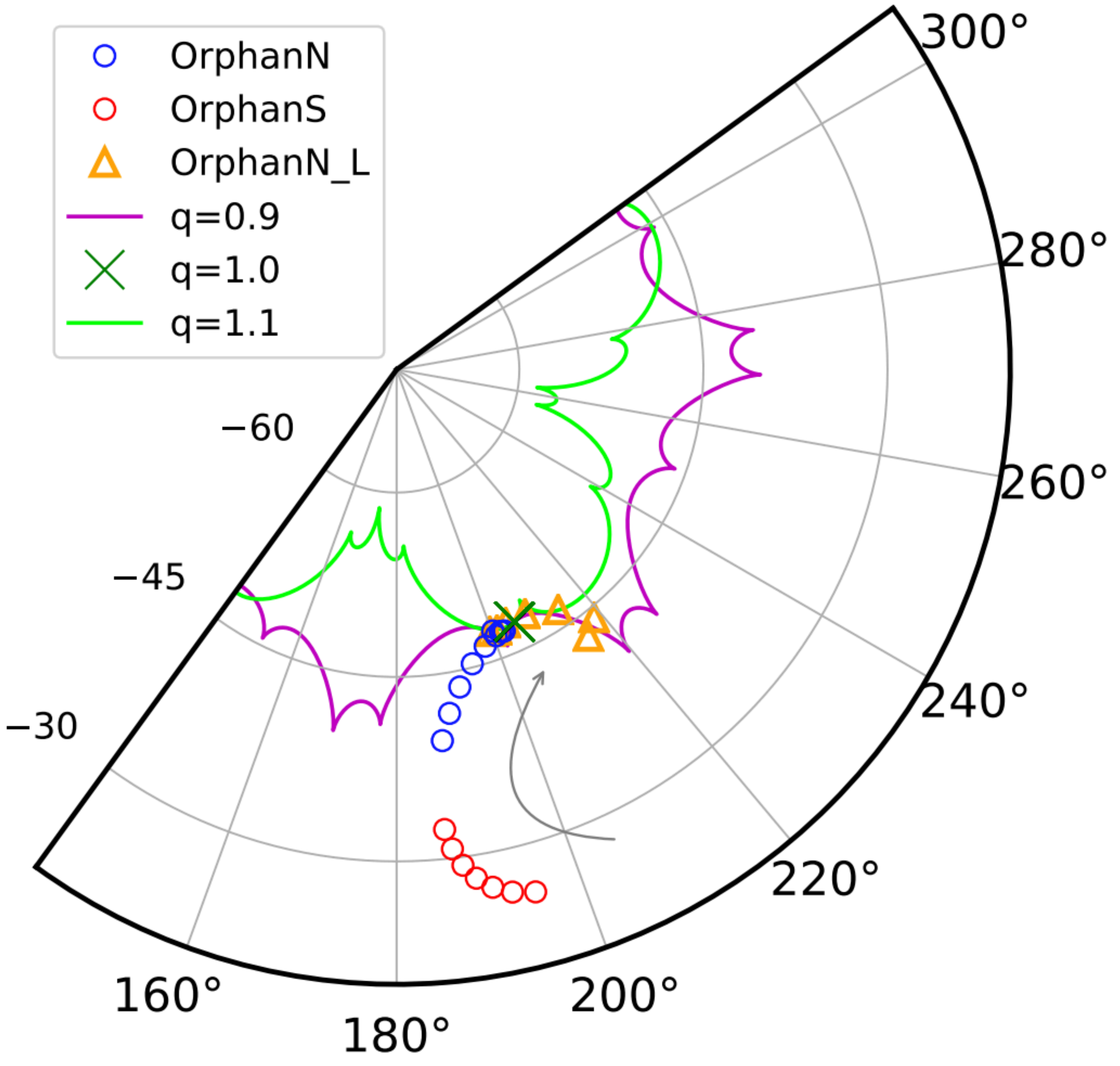
RR Lyrae stars in Gaia DR2





S. Koposov, V. Belokurov, TSL et al. 2019
(The OATs Collaboration)

The impact of LMC — on Orphan-Chenab Stream



S. Koposov, V. Belokurov, TSL et al. 2019
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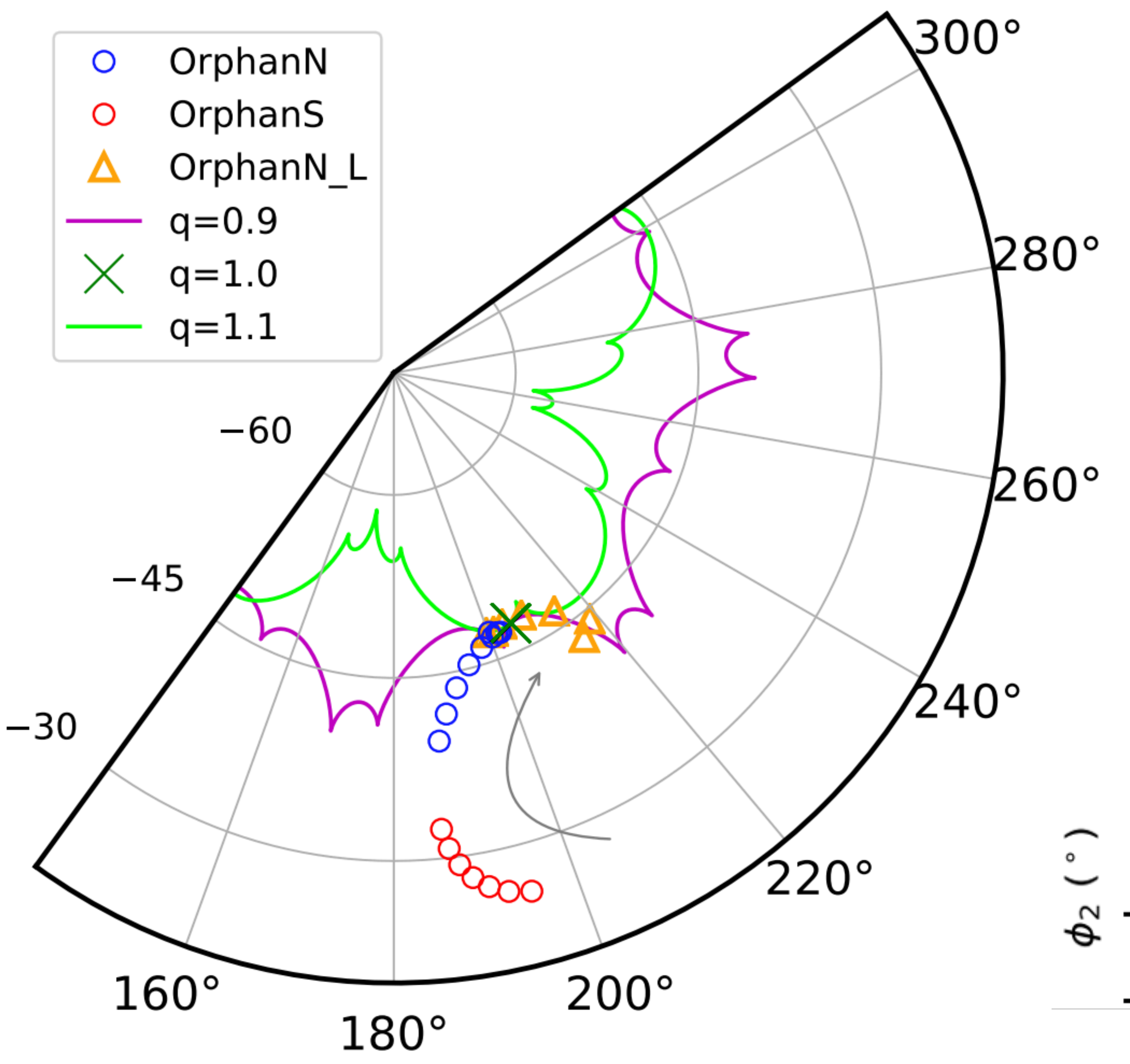

S. Koposov, V. Belokurov, TSL et al. 2019
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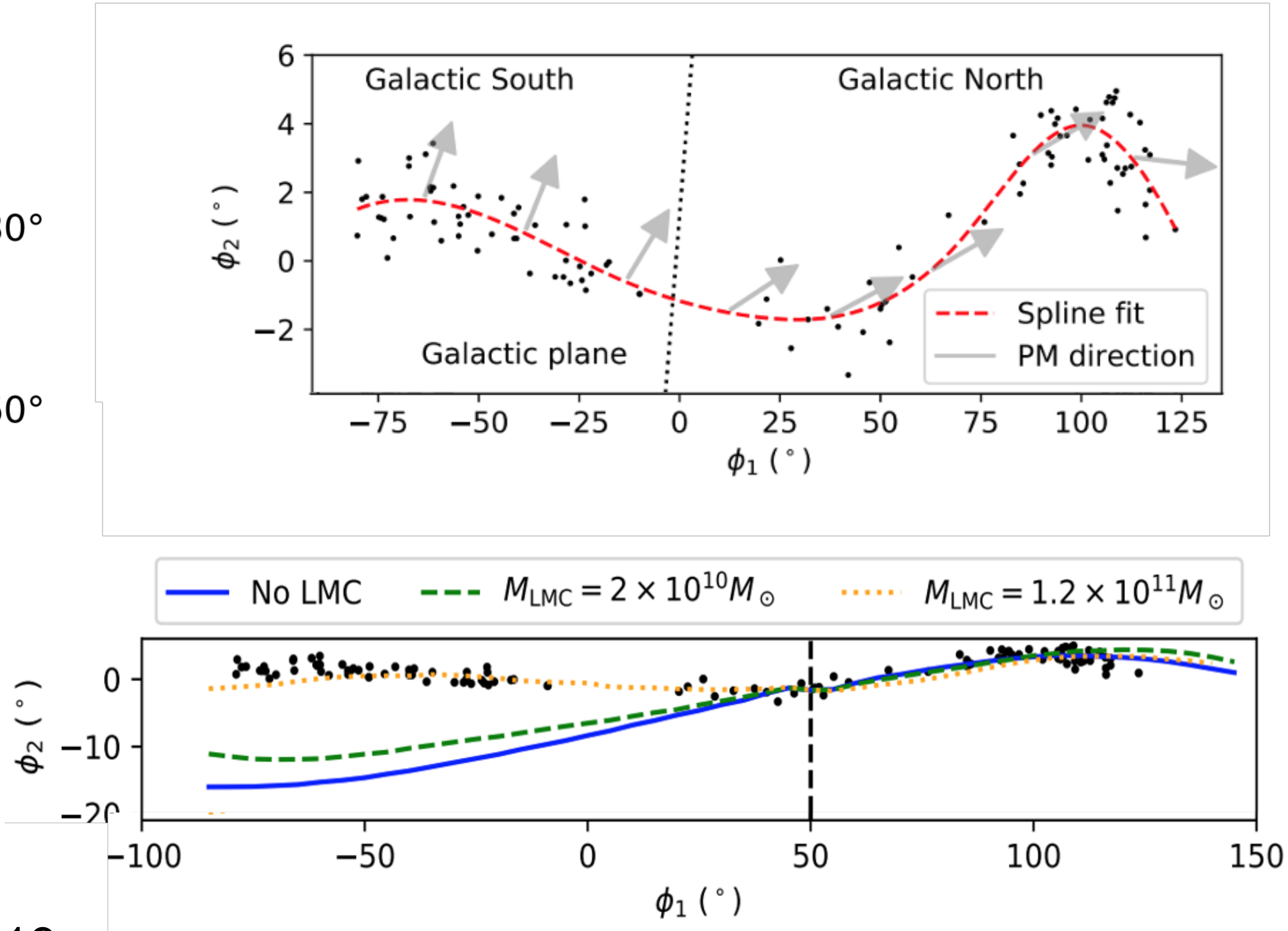
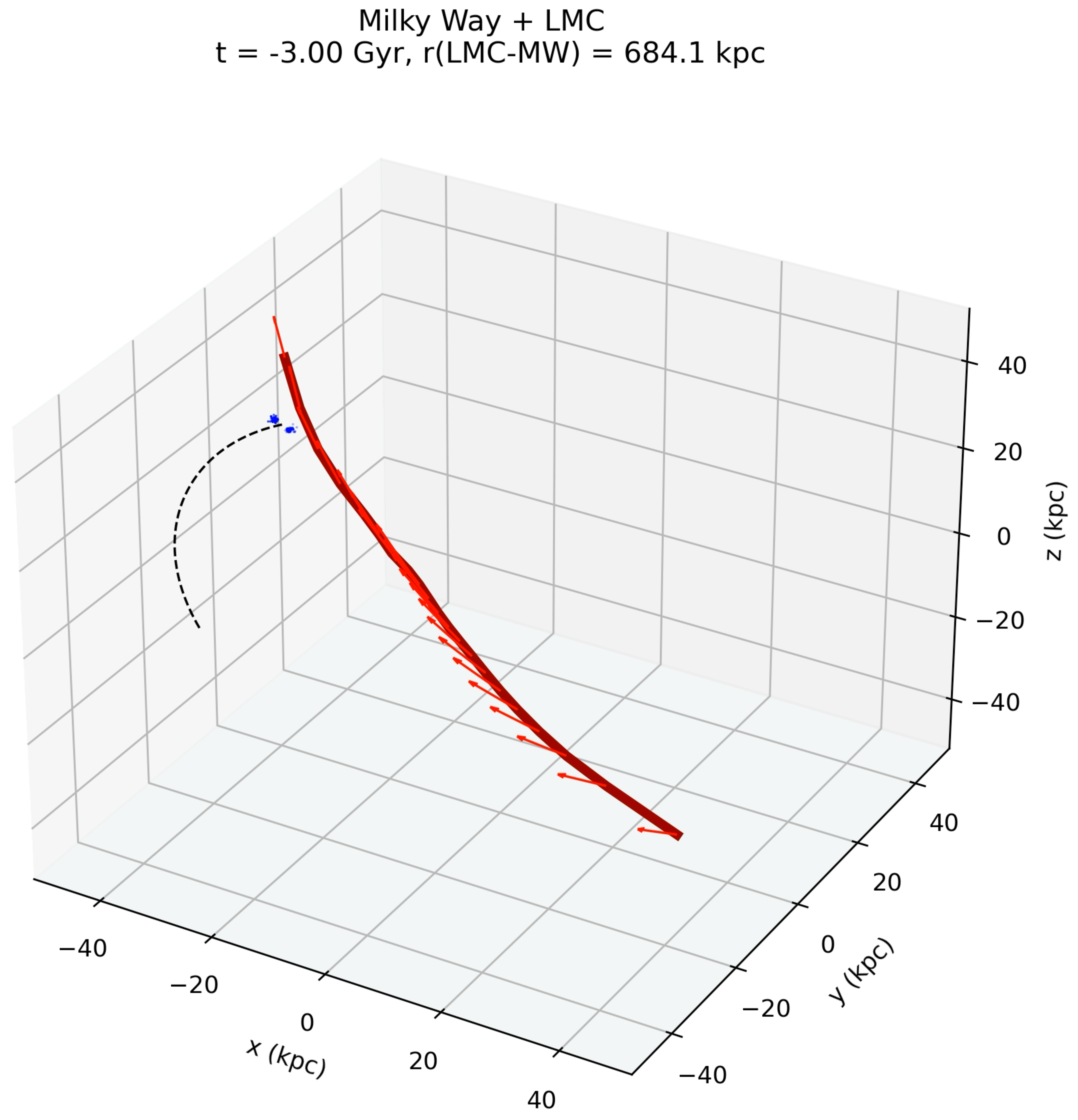
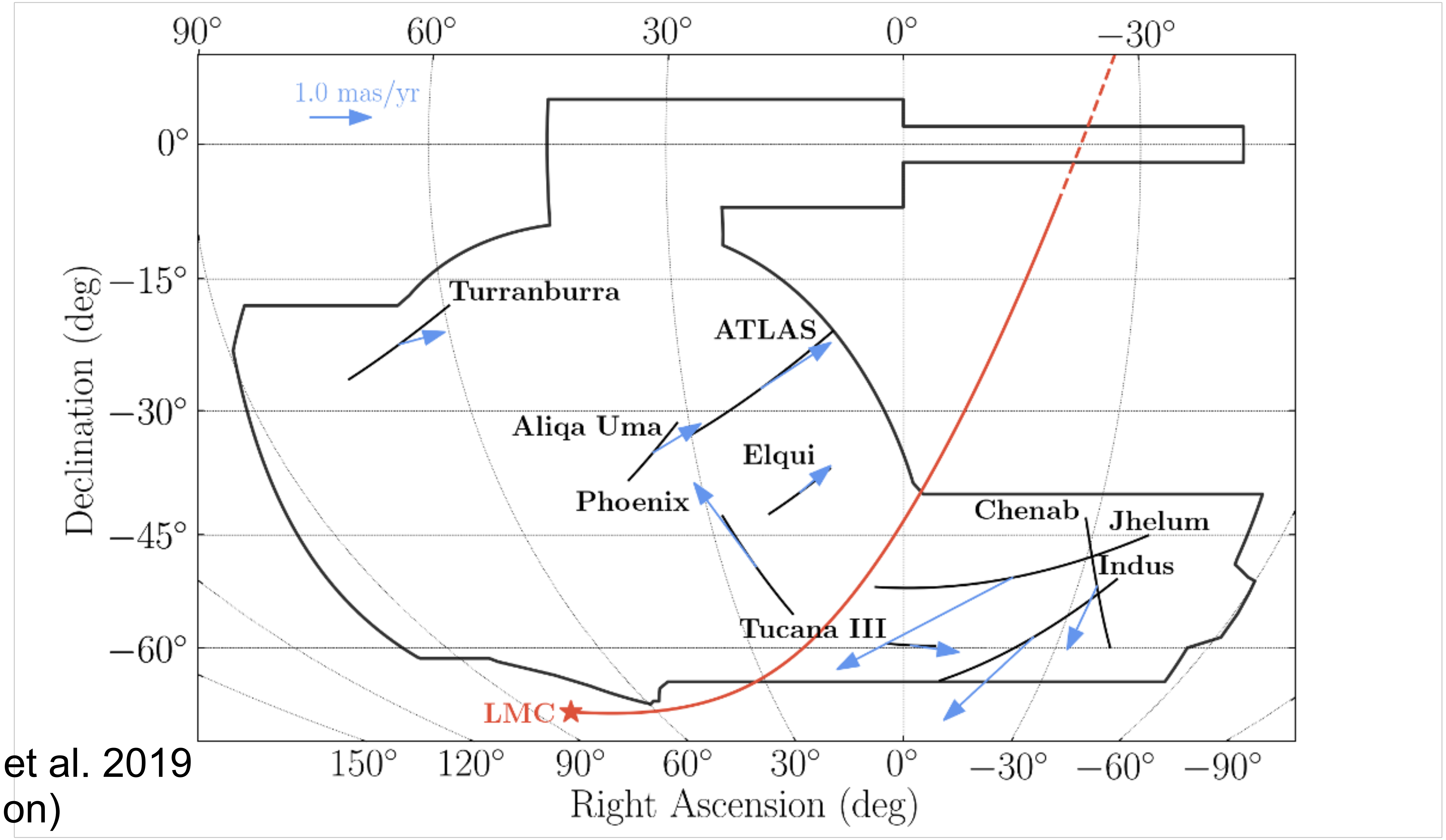


D. Erkal, …, TSL et al. 2019
(The OATs Collaboration)



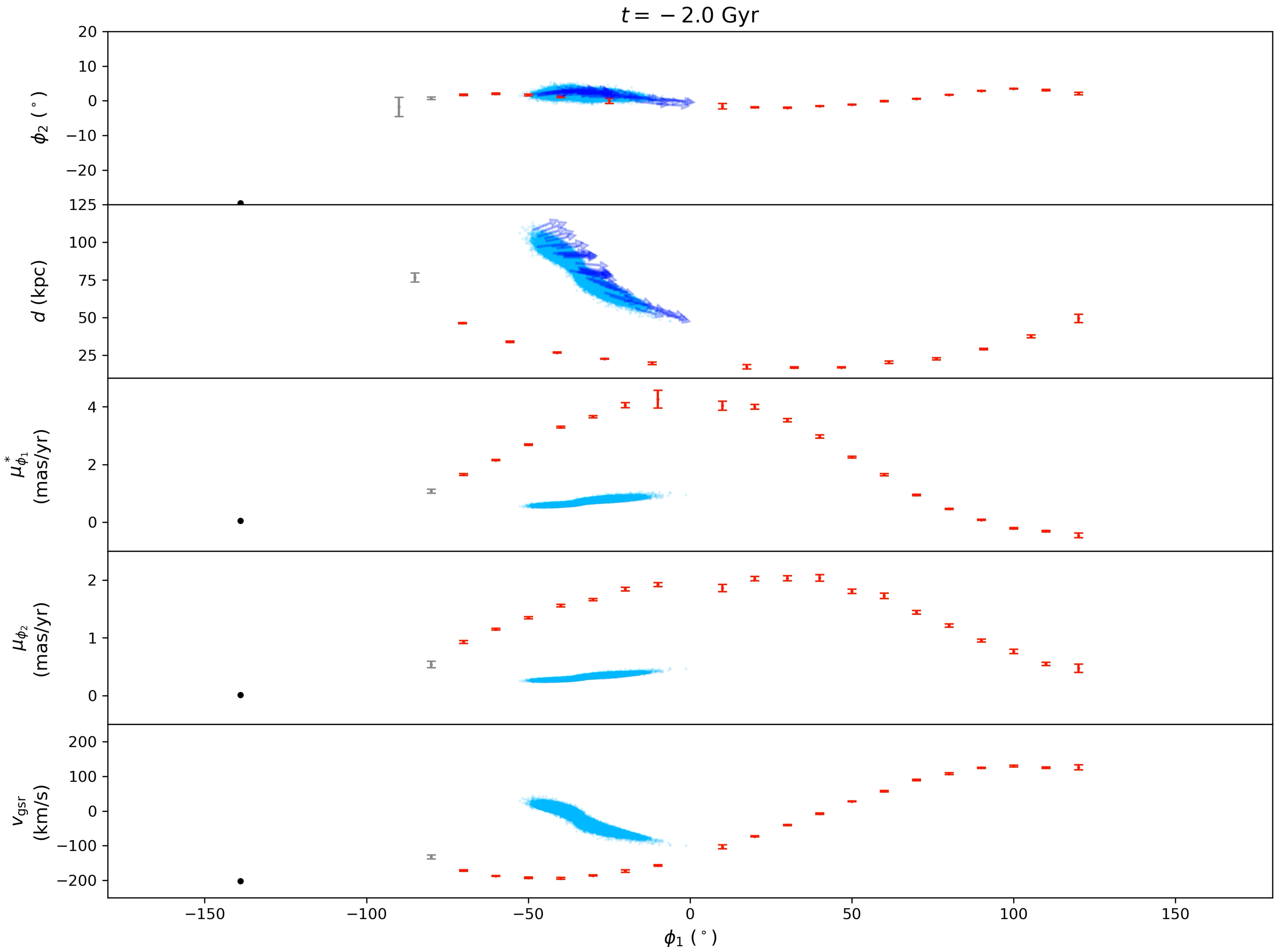
Credit: Denis Erkal

The impact of LMC — on Orphan-Chenab Stream



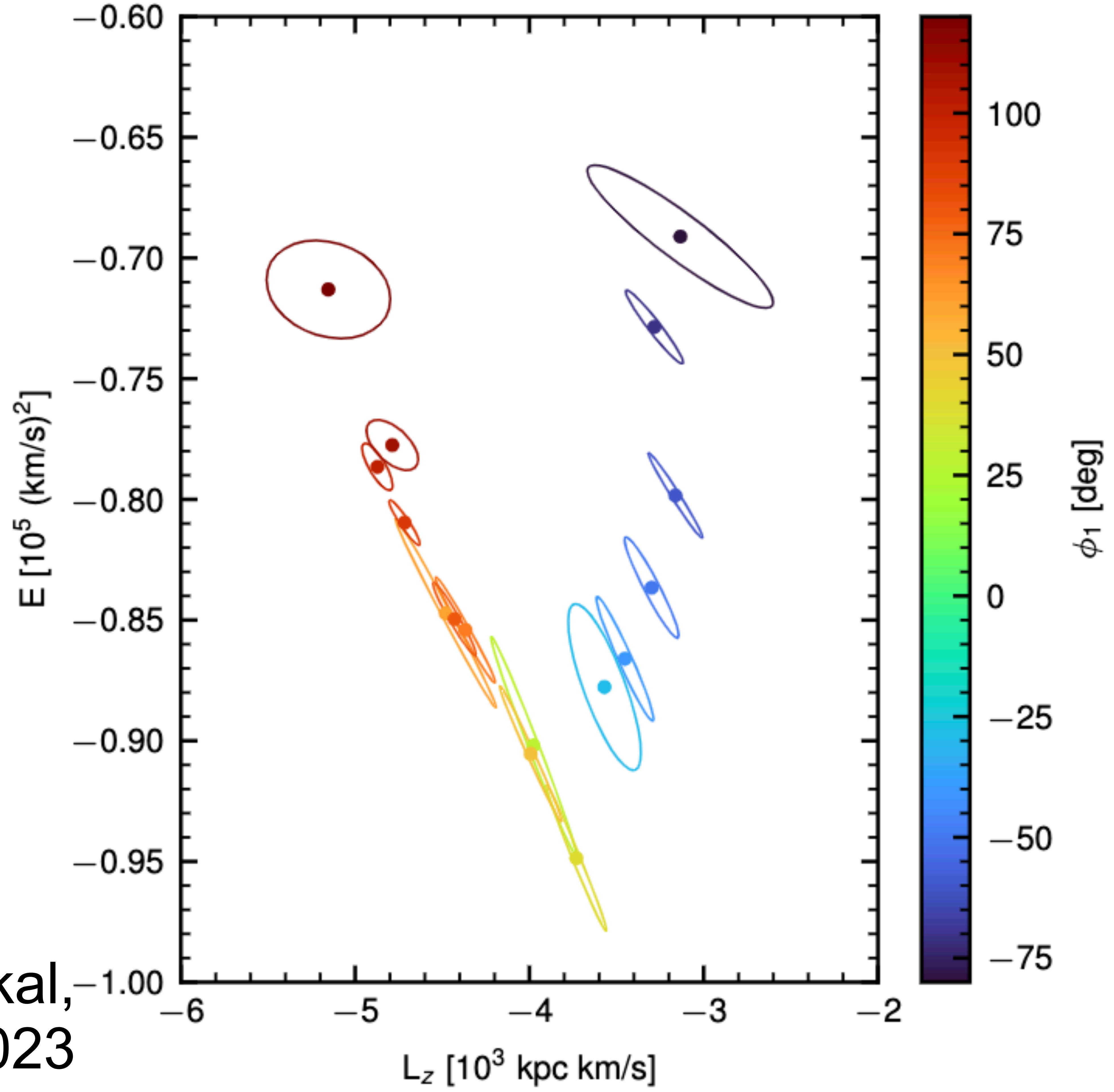
N. Shipp, TSL et al. 2019
(S5 Collaboration)

Orphan-Chenab Stream: fitting w/ full 6D
Constraining Milky Way and LMC Potential Simultaneously



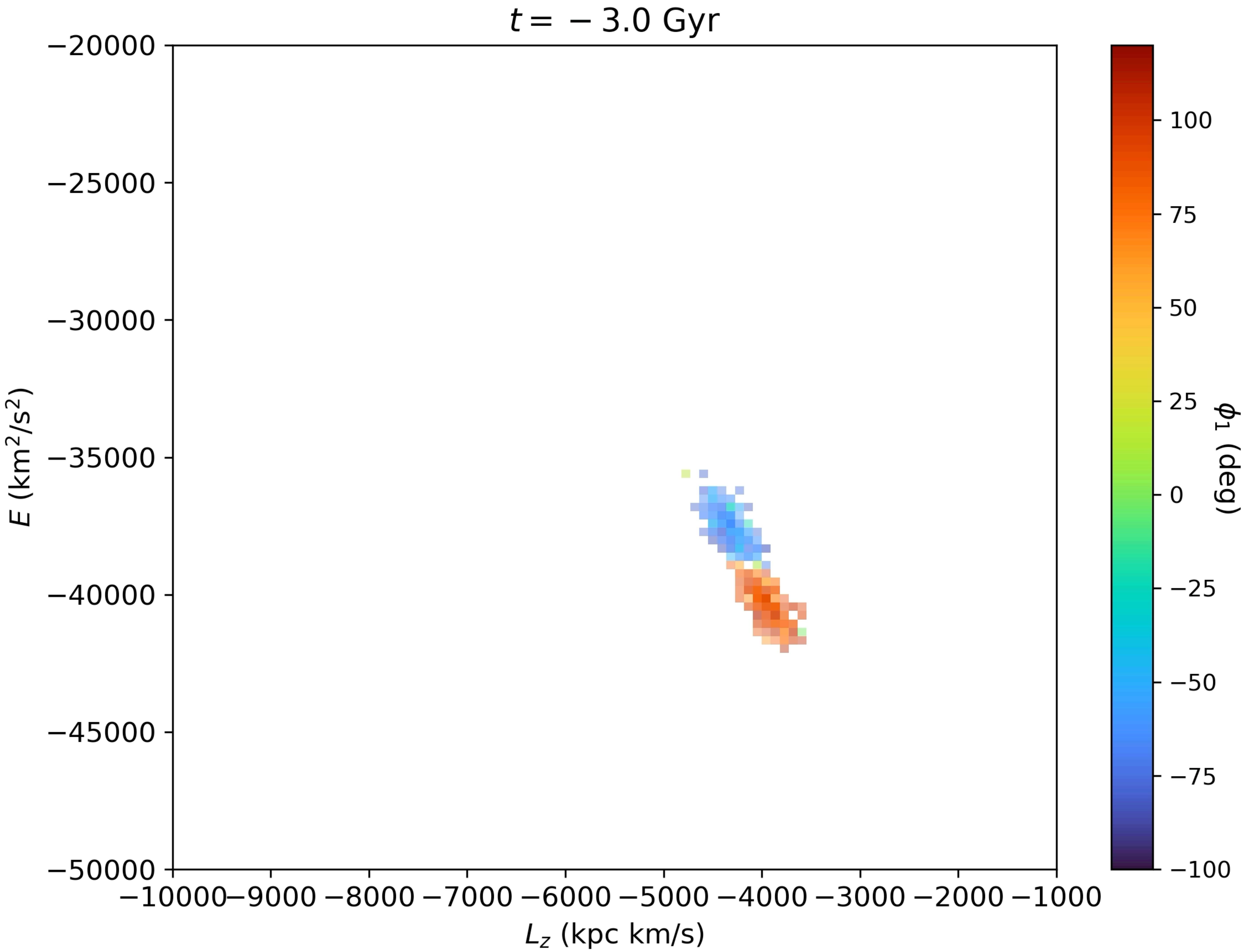
S. Koposov, D. Erkal, TSL et al. 2023 (S^5 Collaboration)

Perturbations in Energy Angular Momentum Space



S. Koposov, D. Erkal, TSL et al. 2023 (S^5 Collaboration)

Perturbations in Energy Angular Momentum Space



S. Koposov, D. Erkal, TSL et al. 2023 (S^5 Collaboration)

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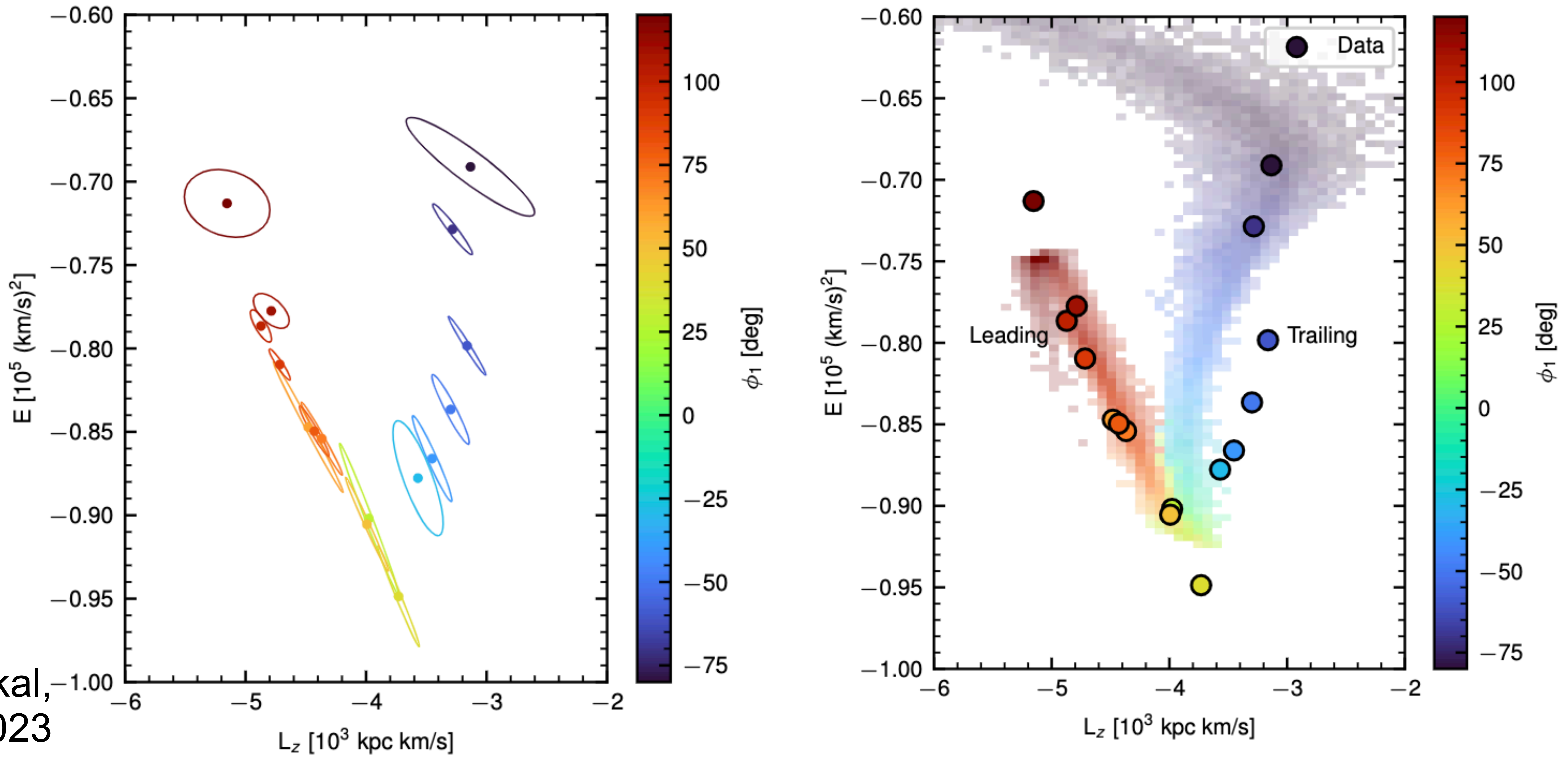
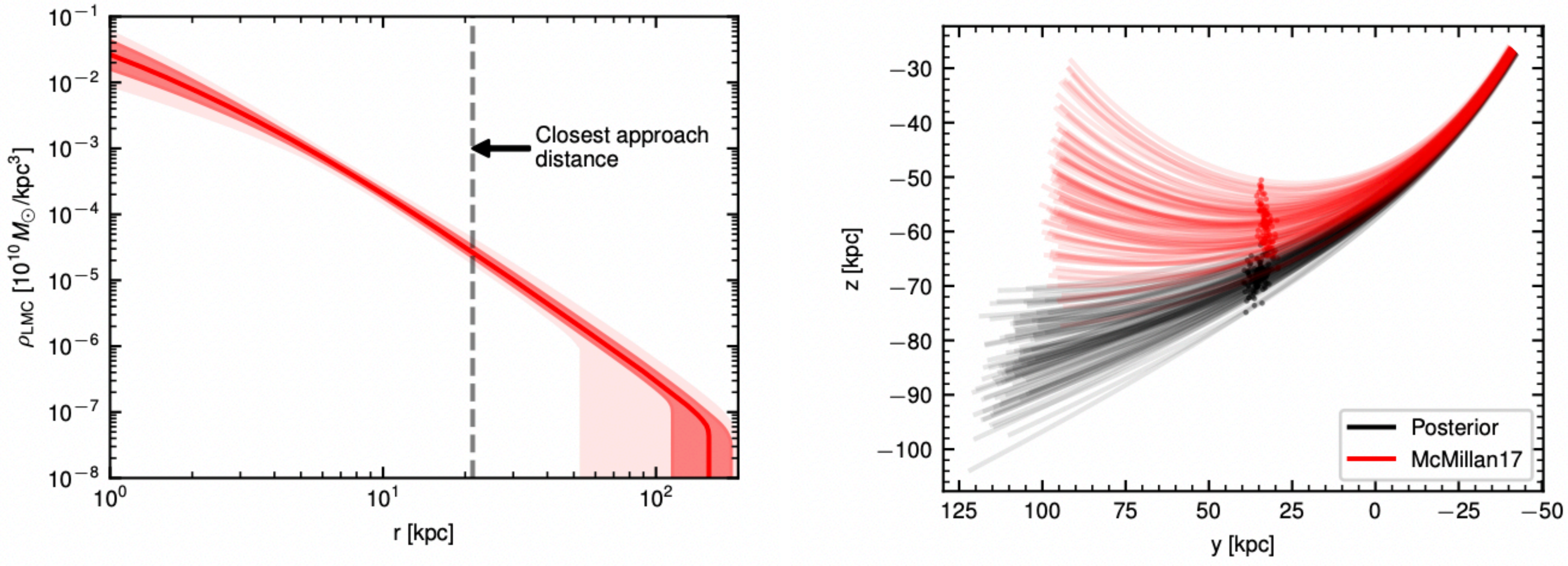


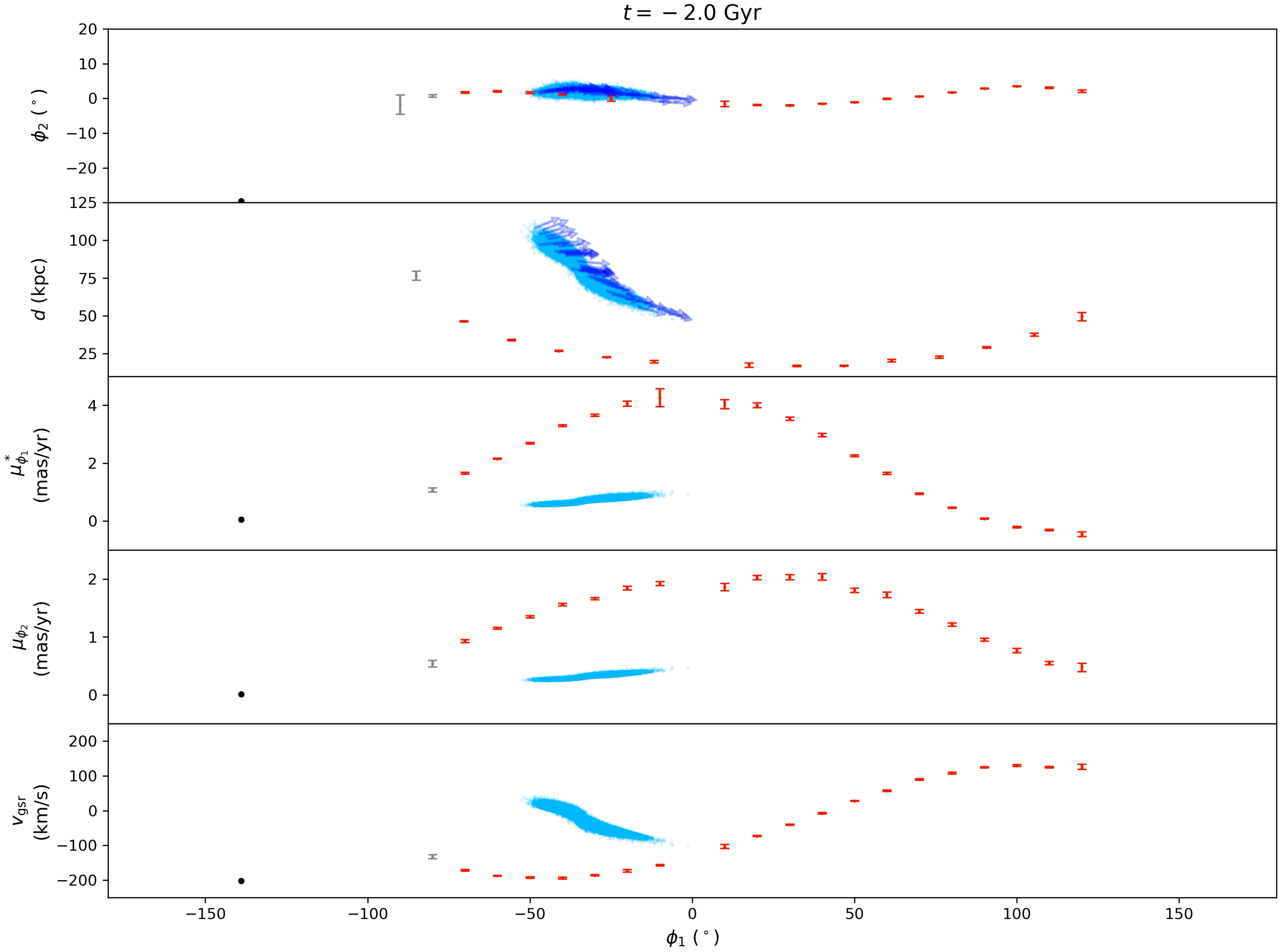
S. Koposov, D. Erkal, TSL et al. 2023 (S[5] Collaboration)

Constraints on LMC mass profile and orbits



S. Koposov, D. Erkal, TSL et al. 2023 (S^5 Collaboration)

Orphan-Chenab Stream: fitting w/ full 6D
Constraining Milky Way and LMC Potential Simultaneously



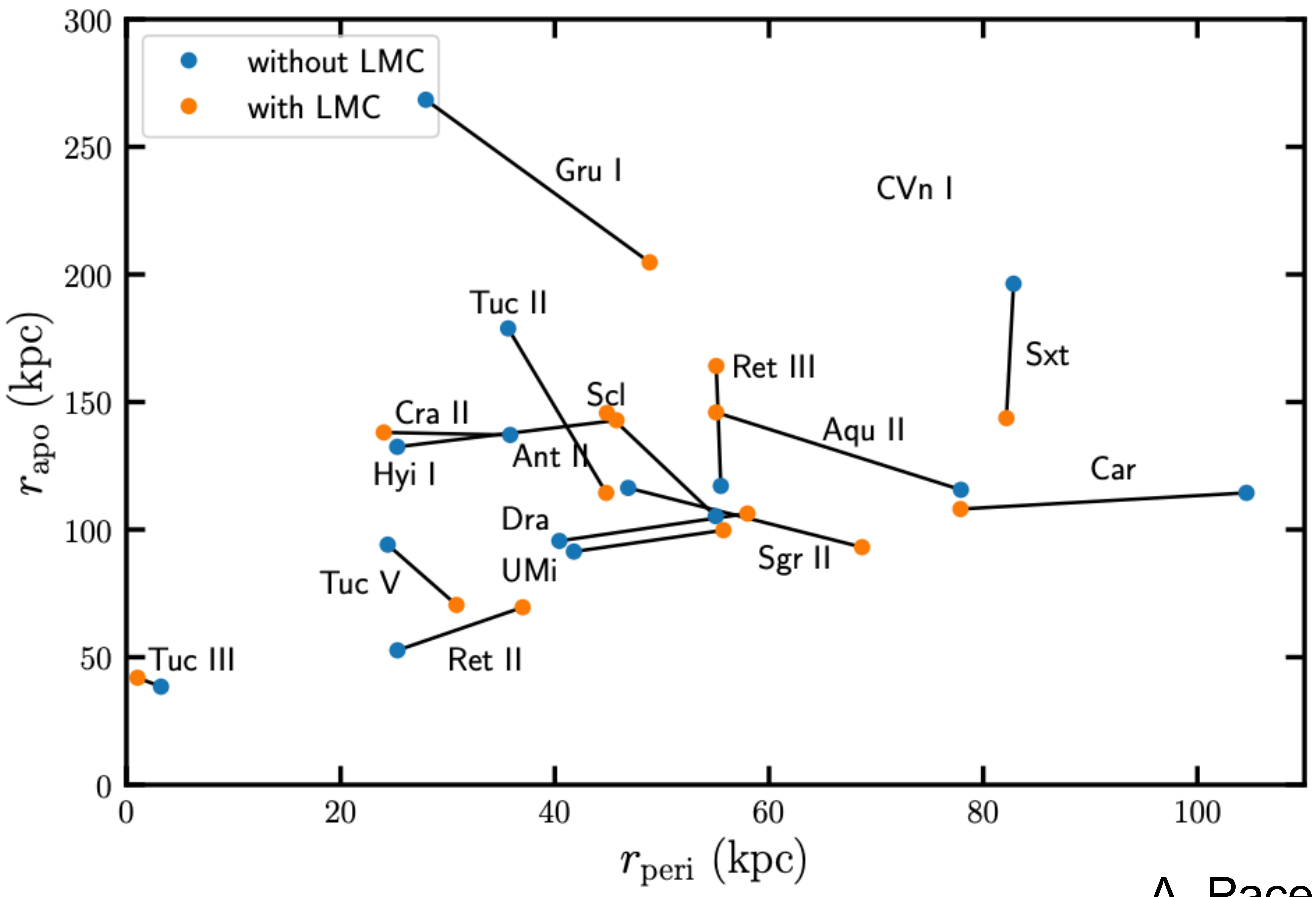
S. Koposov, D. Erkal, TSL et al. 2023 (S[5] Collaboration)

The Impact of Large Magellanic Cloud

Milky Way is not in dynamical equilibrium. One needs to be careful in computing the Milky Way mass w/ any halo tracers assuming dynamical equilibrium. We need more sims w/ LMC in!

How about the impact on Milky Way’s Satellites due to the LMC infall?

The impact of LMC — on satellite orbits



Andrew Pace (CMU)

A. Pace, D. Erkal, TSL, 2022

Credit: Vasiy Belokurov

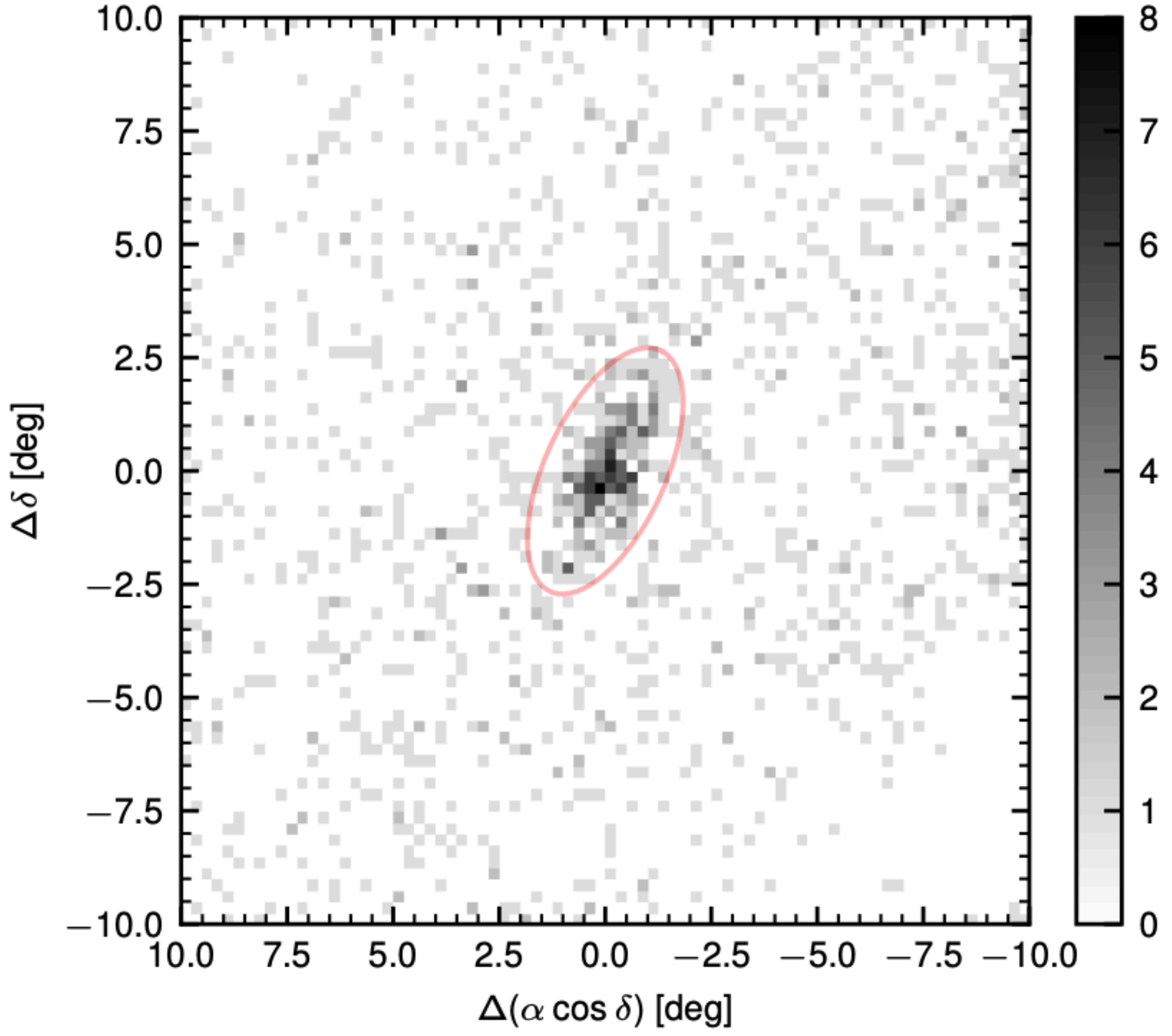
Antlia 2 is under tidal stripping

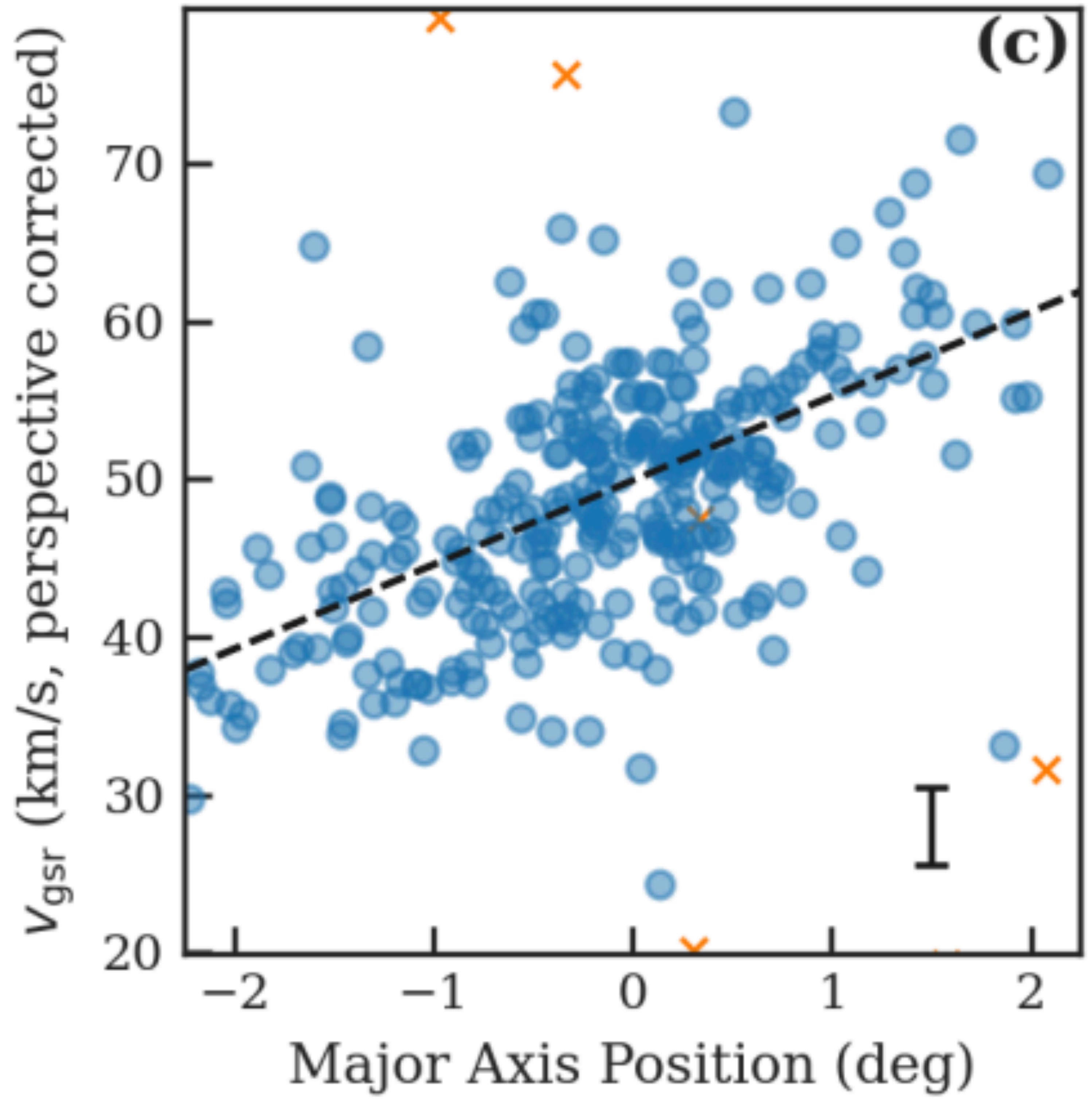
Distance: 130 kpc

Size: ah ~ 4 kpc

Pericenter: 40 kpc

Apocenter: 140 kpc





A. Ji, S. Koposov, TSL et al. 2021
(S[5] Collaboration)

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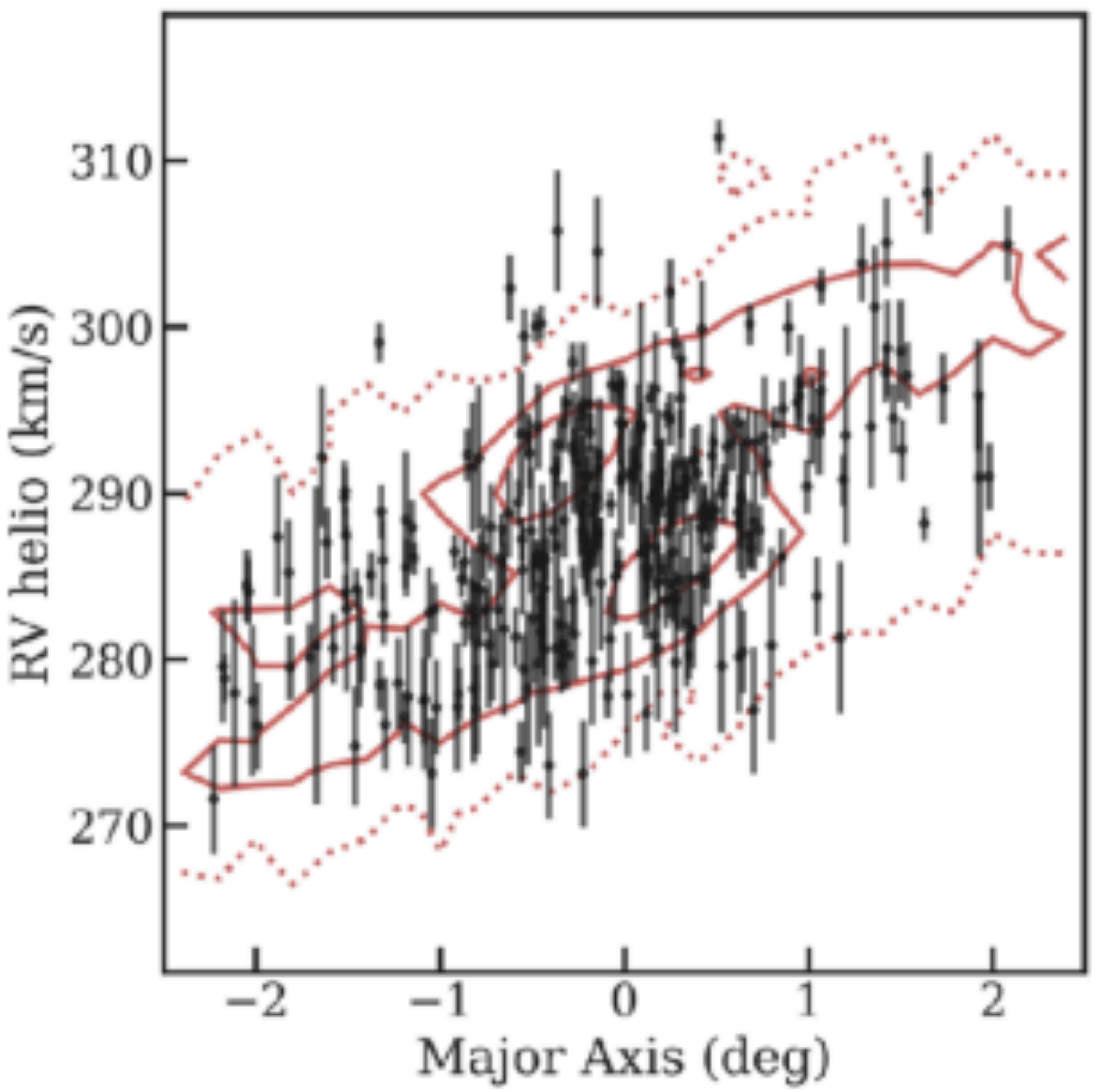
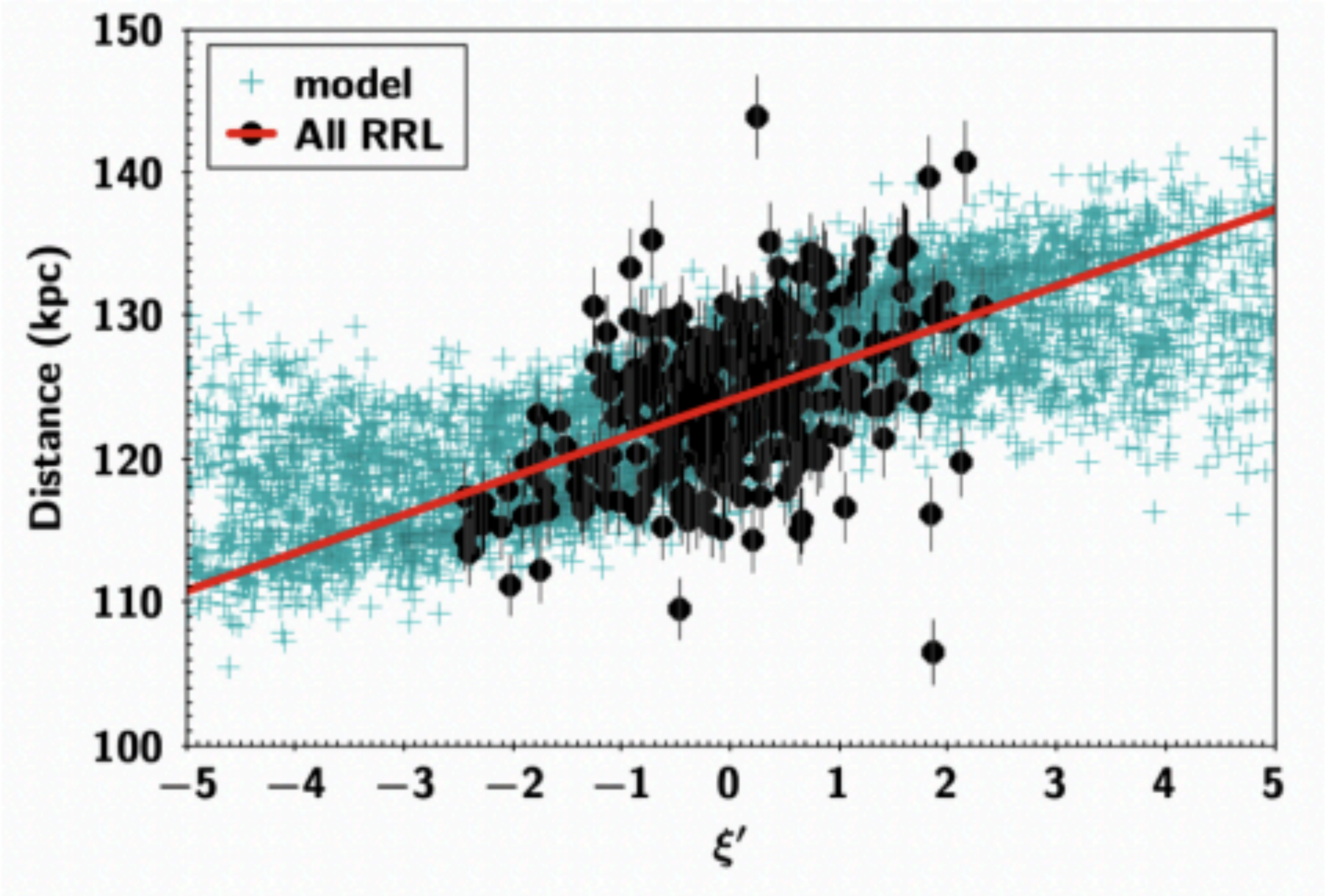
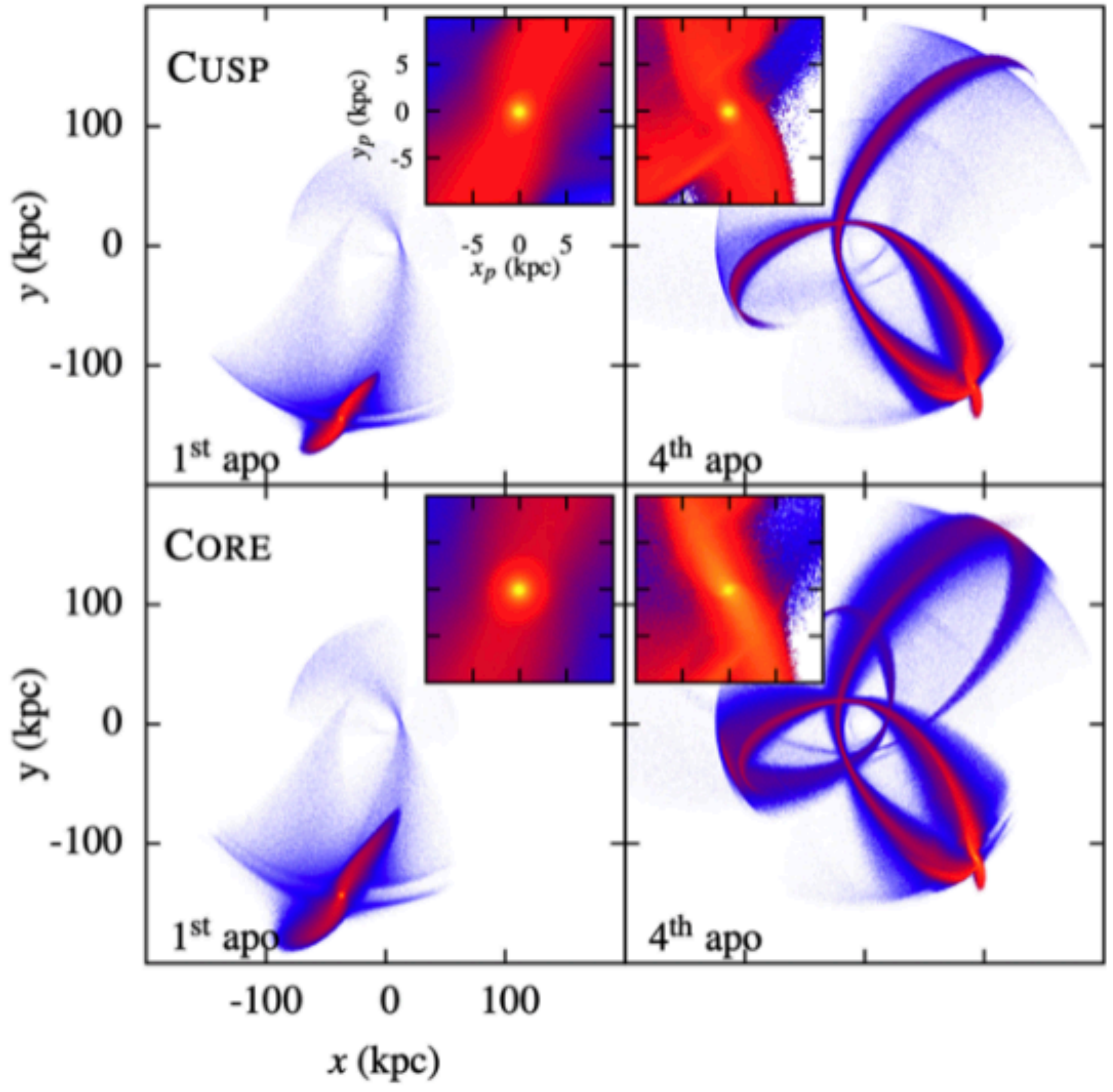


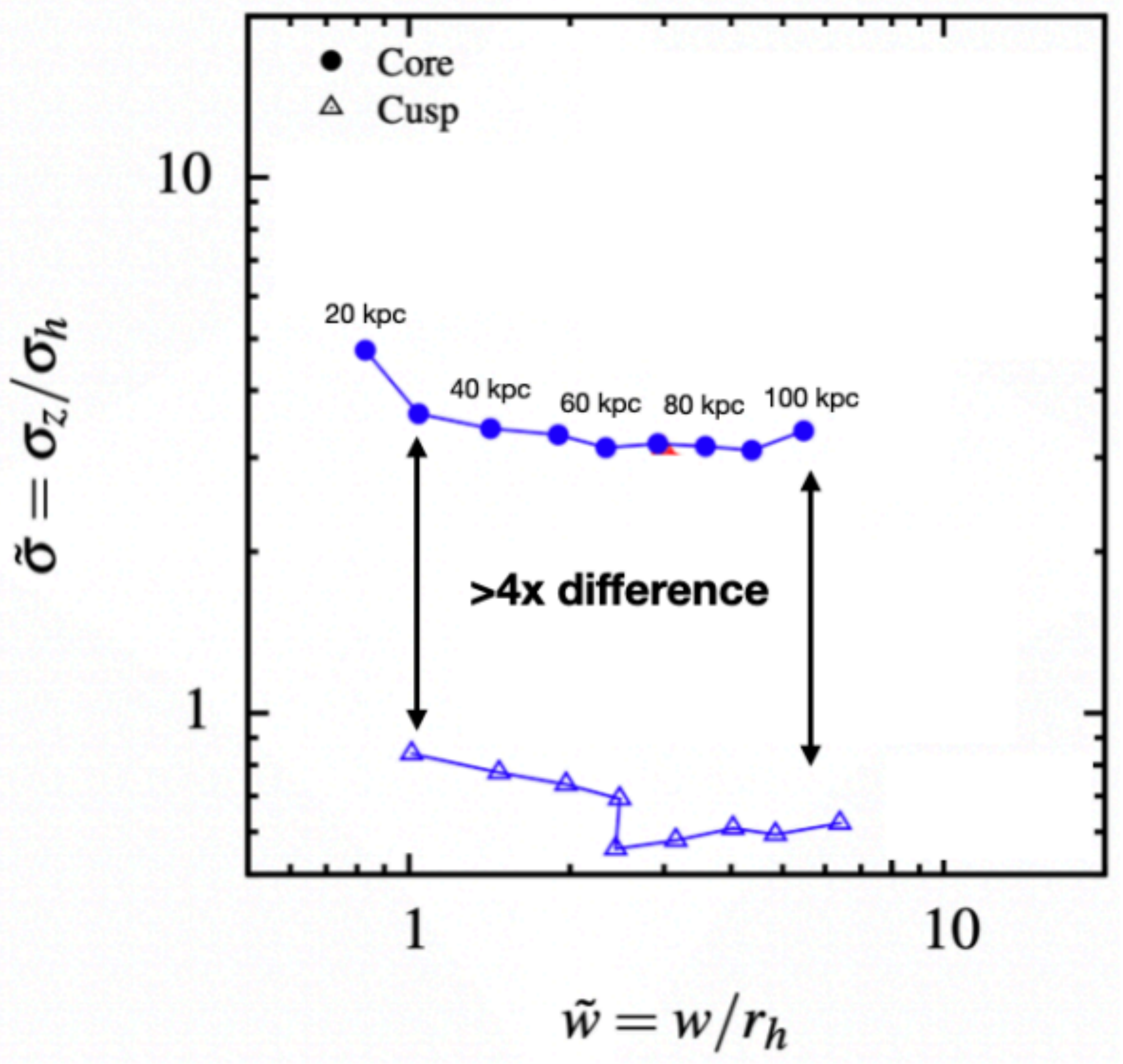


A. Ji, S. Koposov, TSL et al. 2021
(S^5 Collaboration)

Vivas, A. K. et al. w/ TSL (2022)

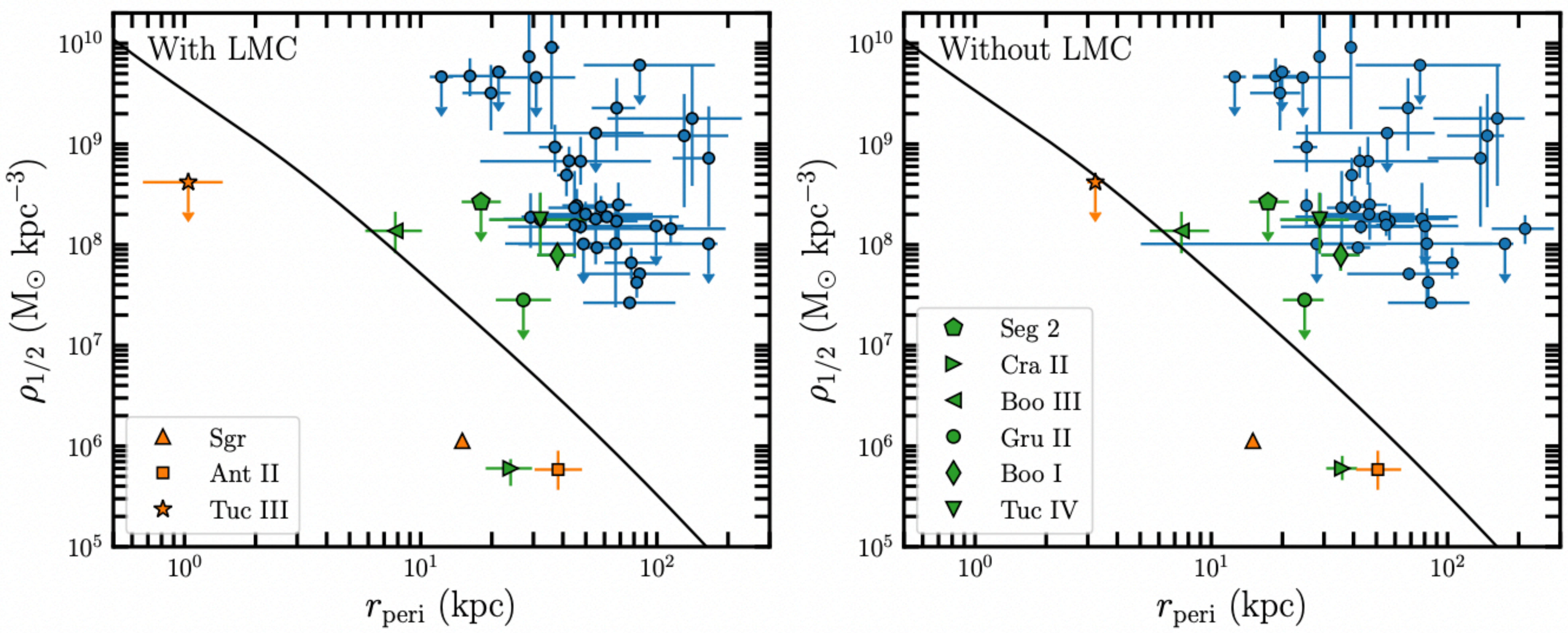
Cusp/Core w/ disrupting galaxies?





Errani, R. et al. (2015)

MW satellite galaxies under tidal stripping



A. Pace, D. Erkal, TSL, 2022

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The impact of LMC — on Antlia 2

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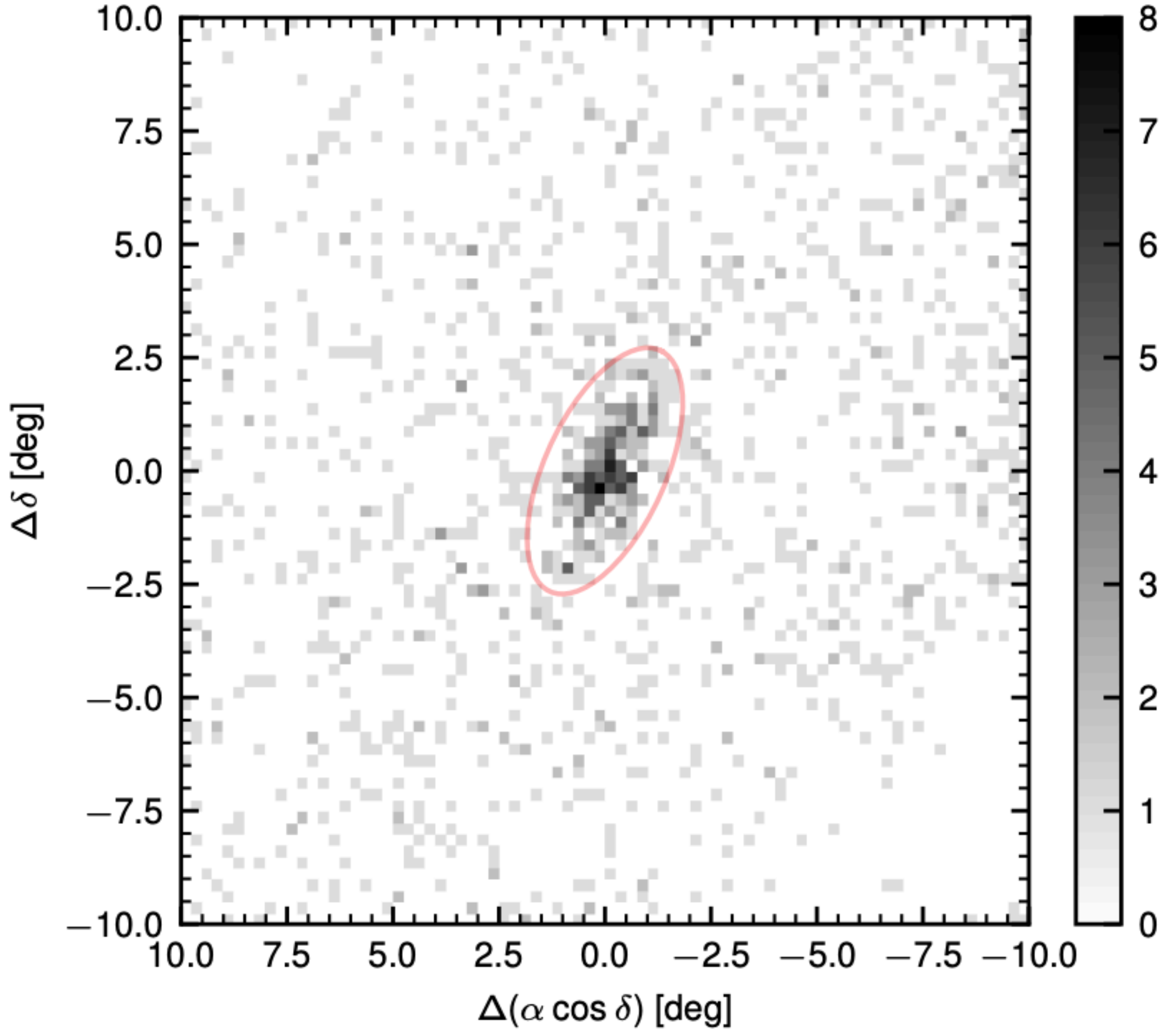

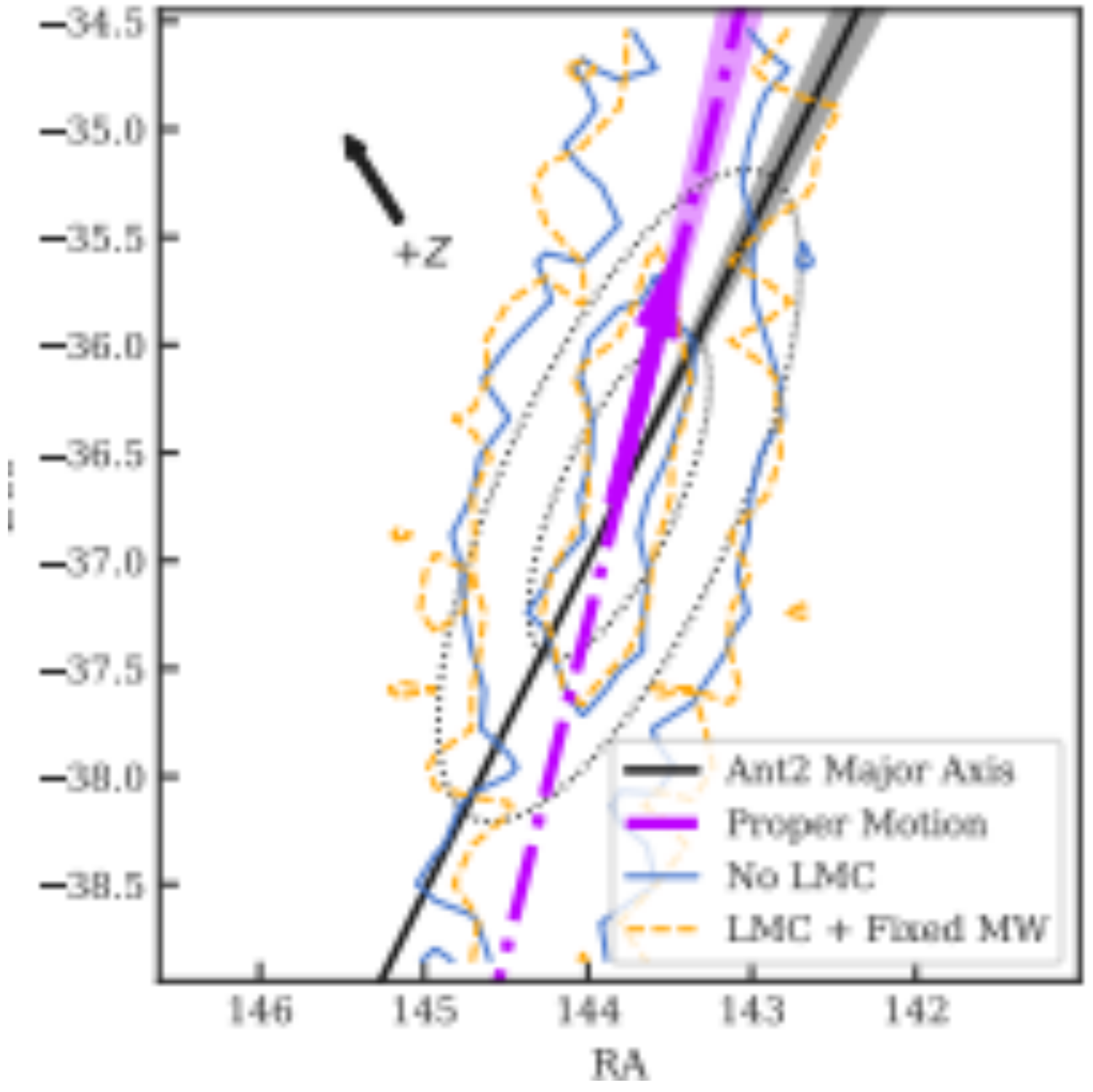

A. Ji, S. Koposov, TSL et al. 2021
(S5 Collaboration)

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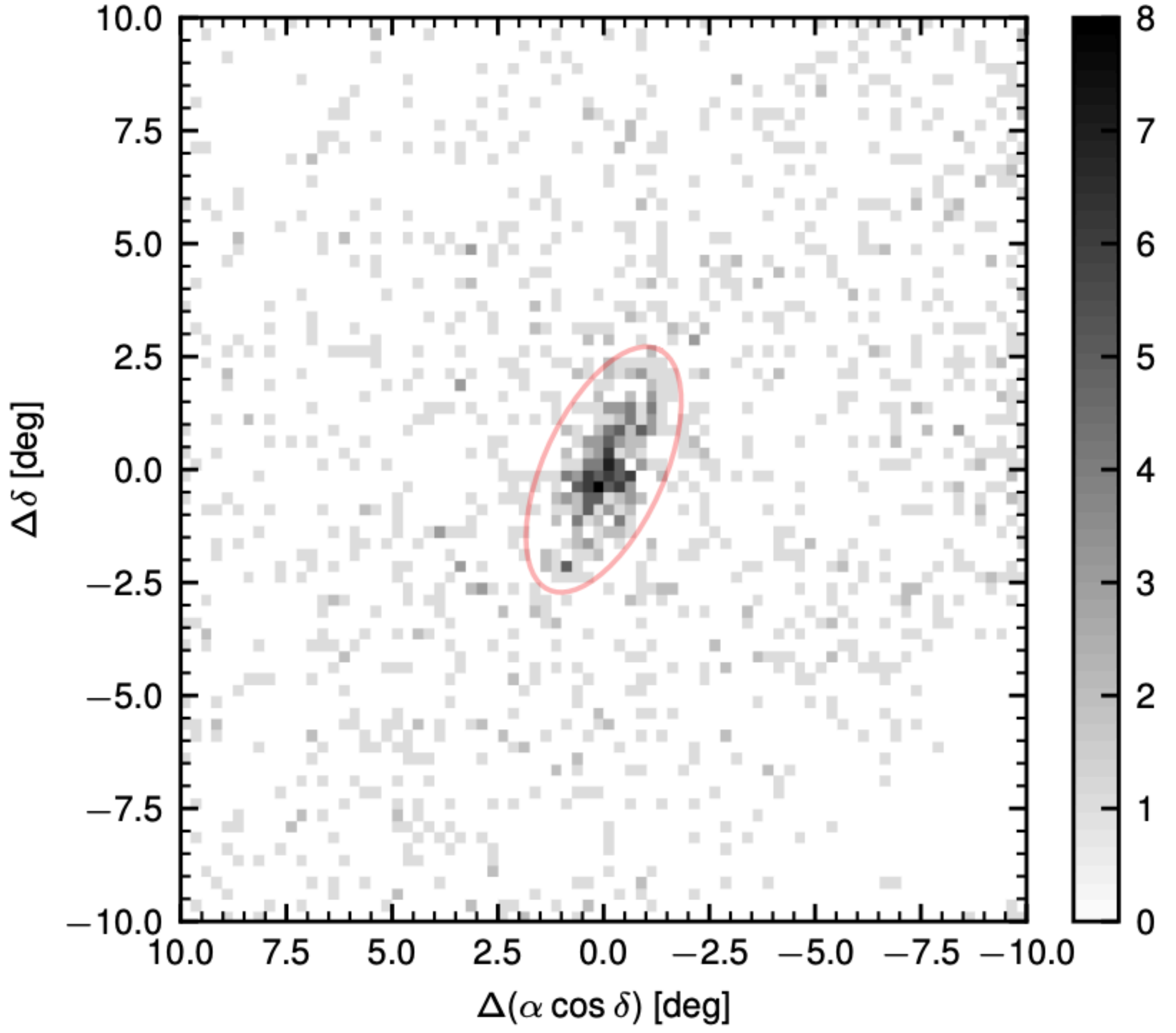
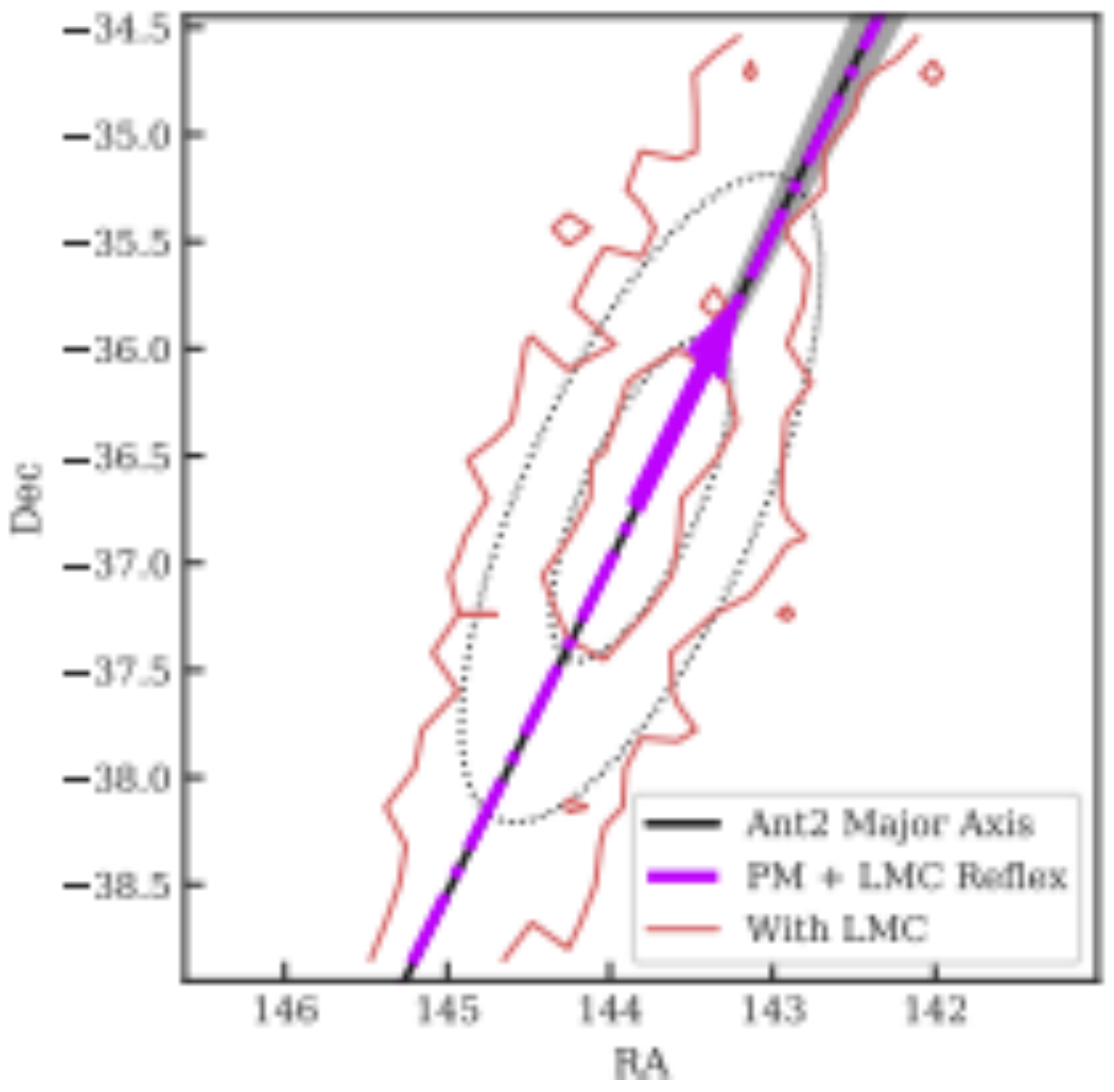


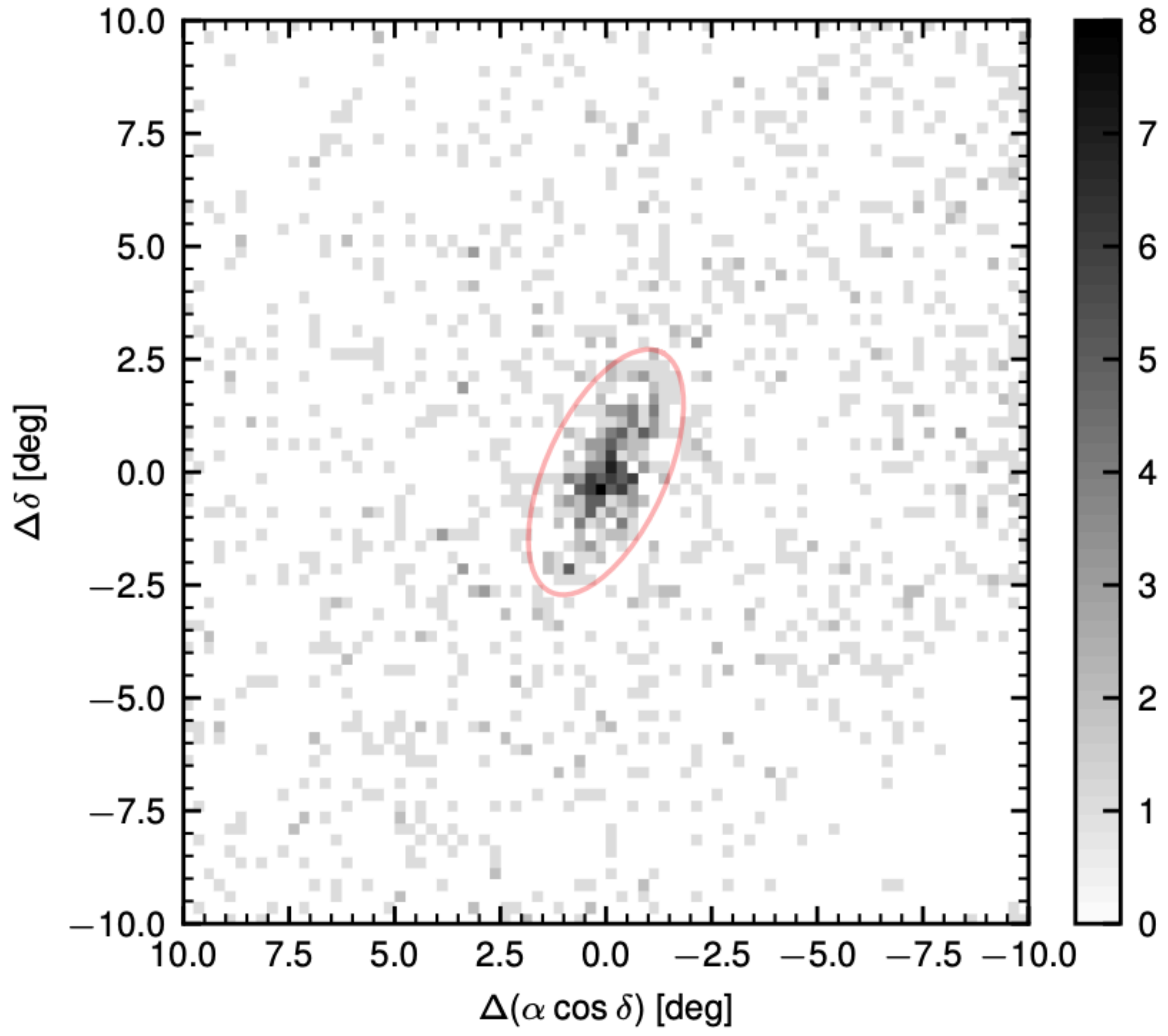


A. Ji, S. Koposov, TSL et al. 2021
(S^5 Collaboration)

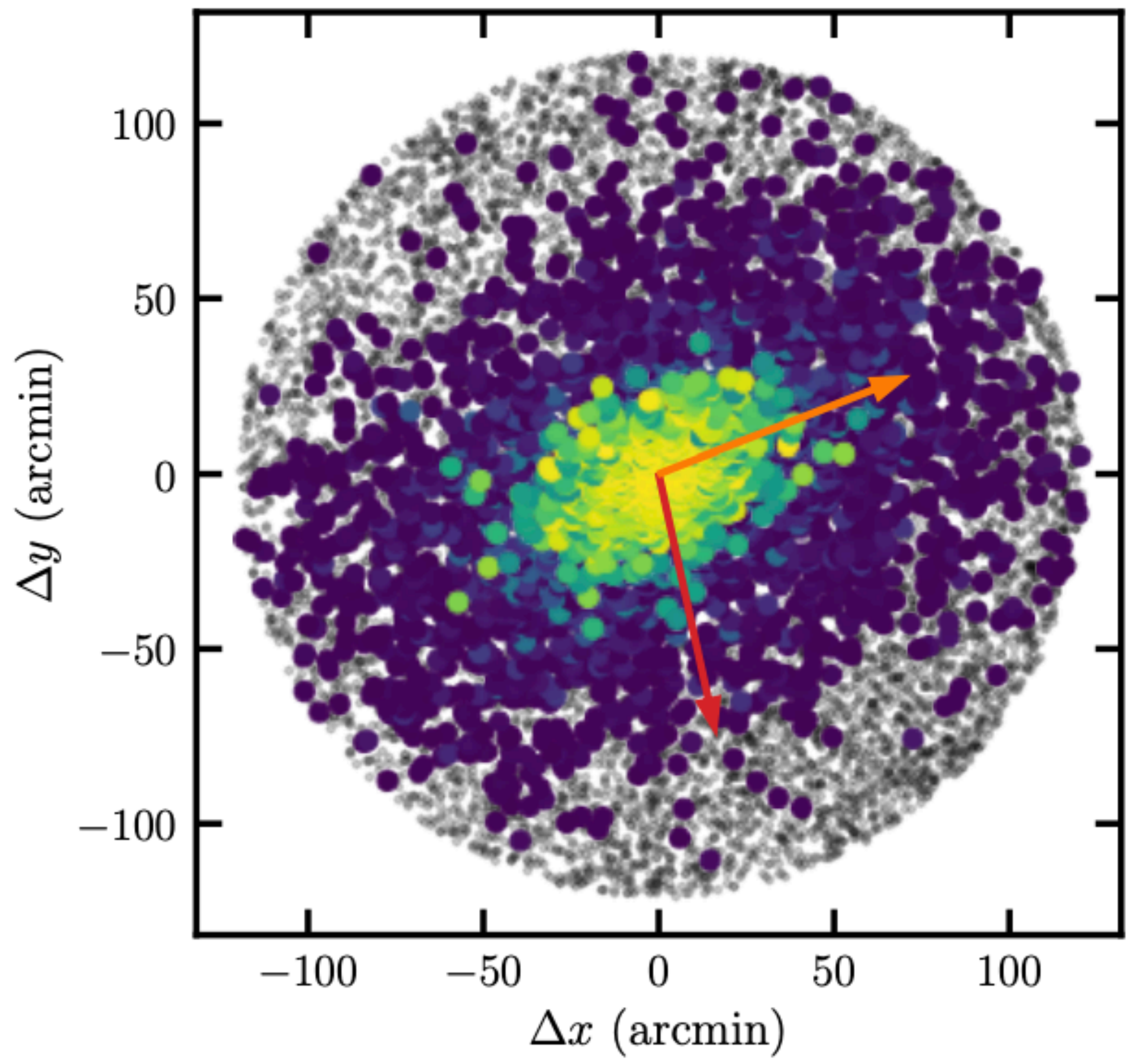
Dwarf Galaxy Triaxility:
Dark Matter or Tides?

Some Milky Way's Dwarf Galaxies are Elliptical

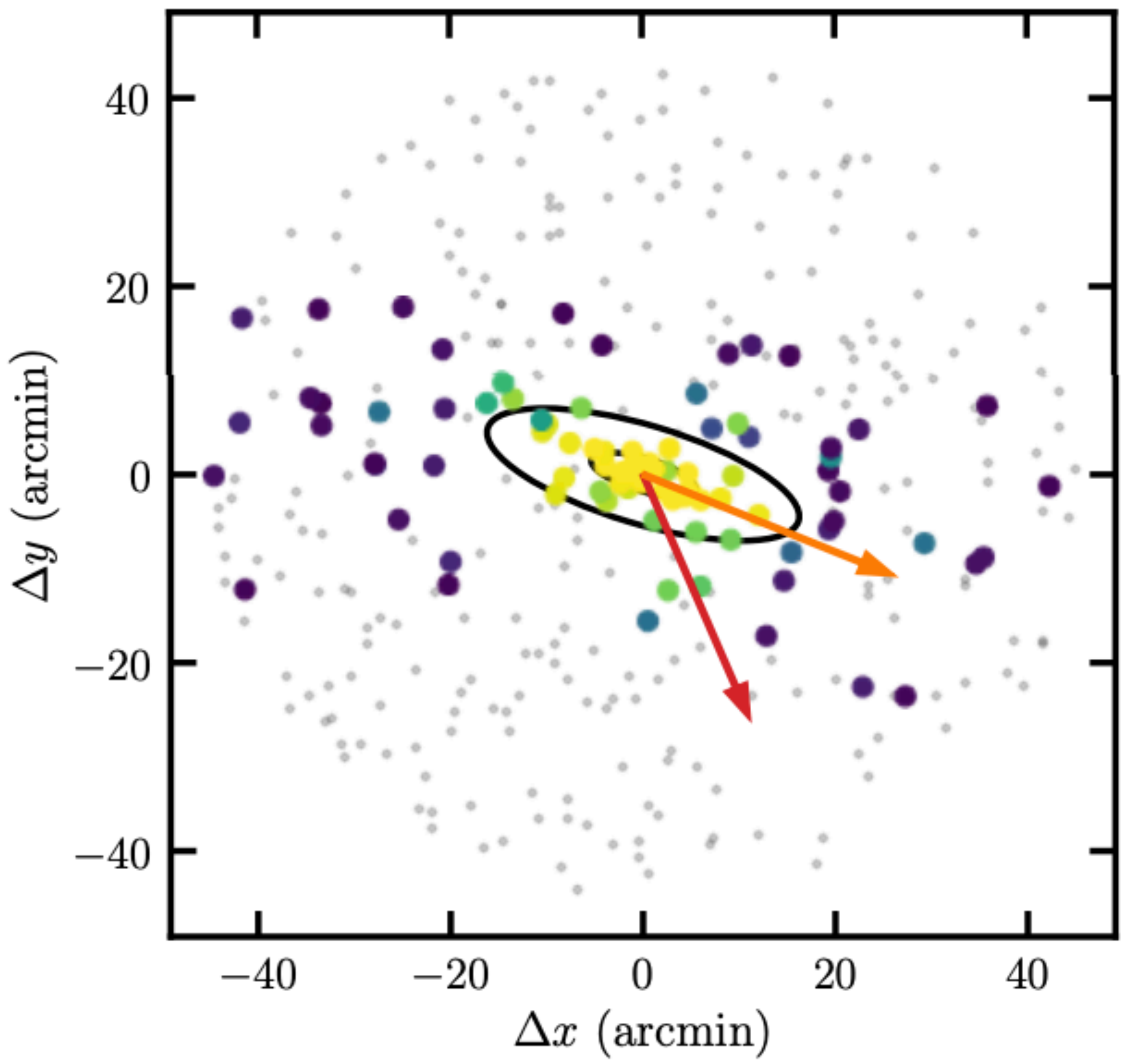
Antlia II



Carina



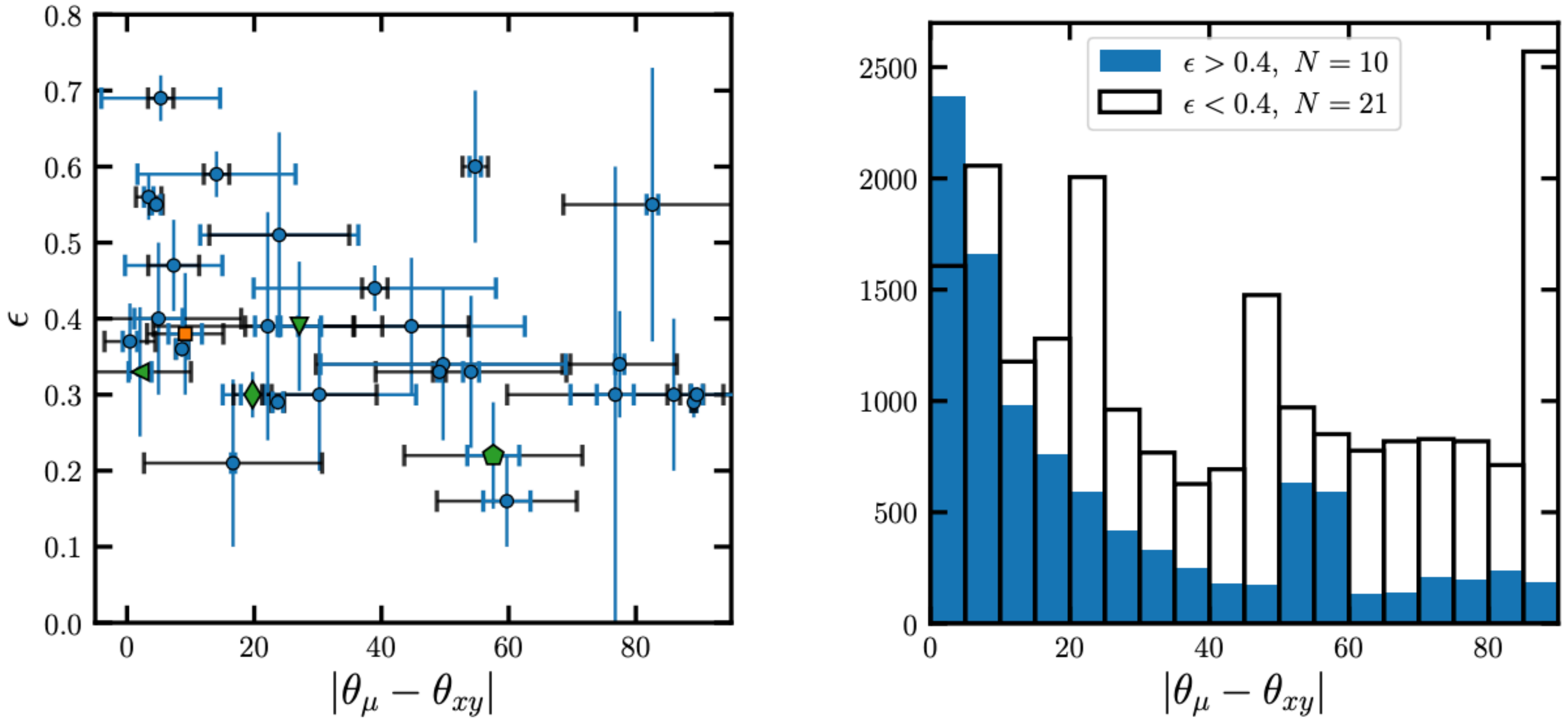
Hercules



A. Ji, S. Koposov, TSL et al. 2021
(S^5 Collaboration)

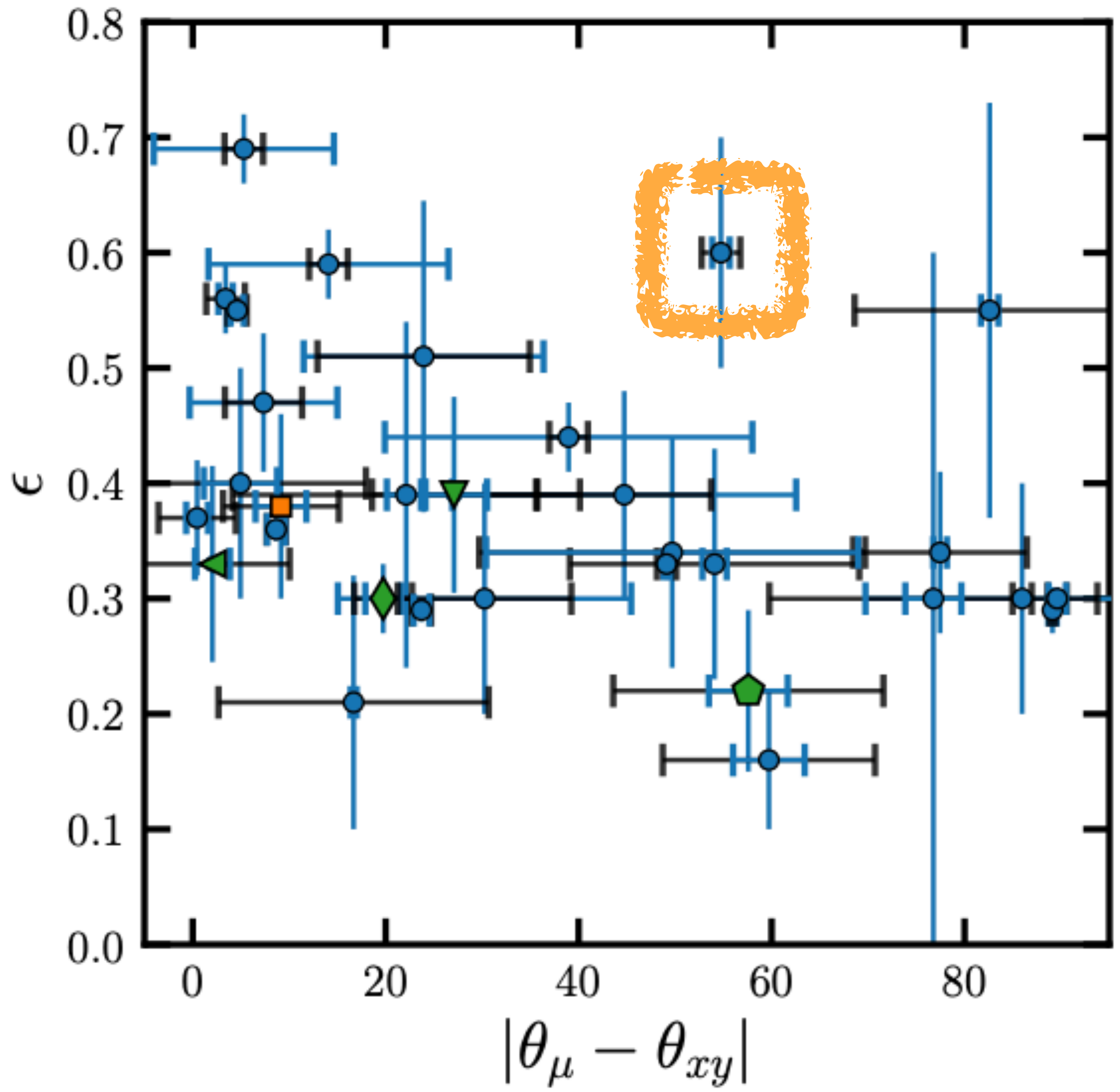
A. Pace, D. Erkal, TSL, 2022

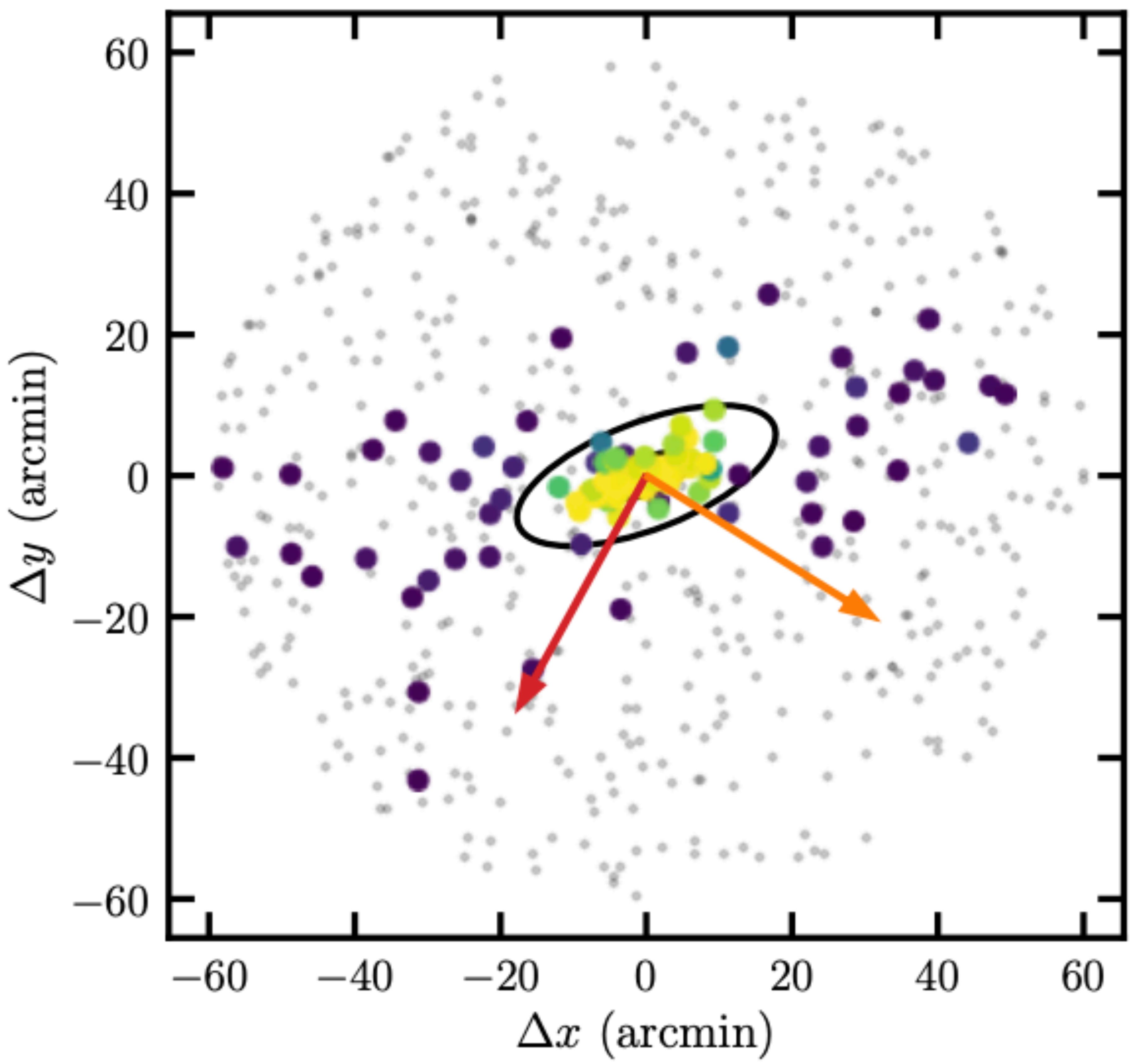
Are the ellipticity all aligned with the motion?



A. Pace, D. Erkal, TSL, 2022

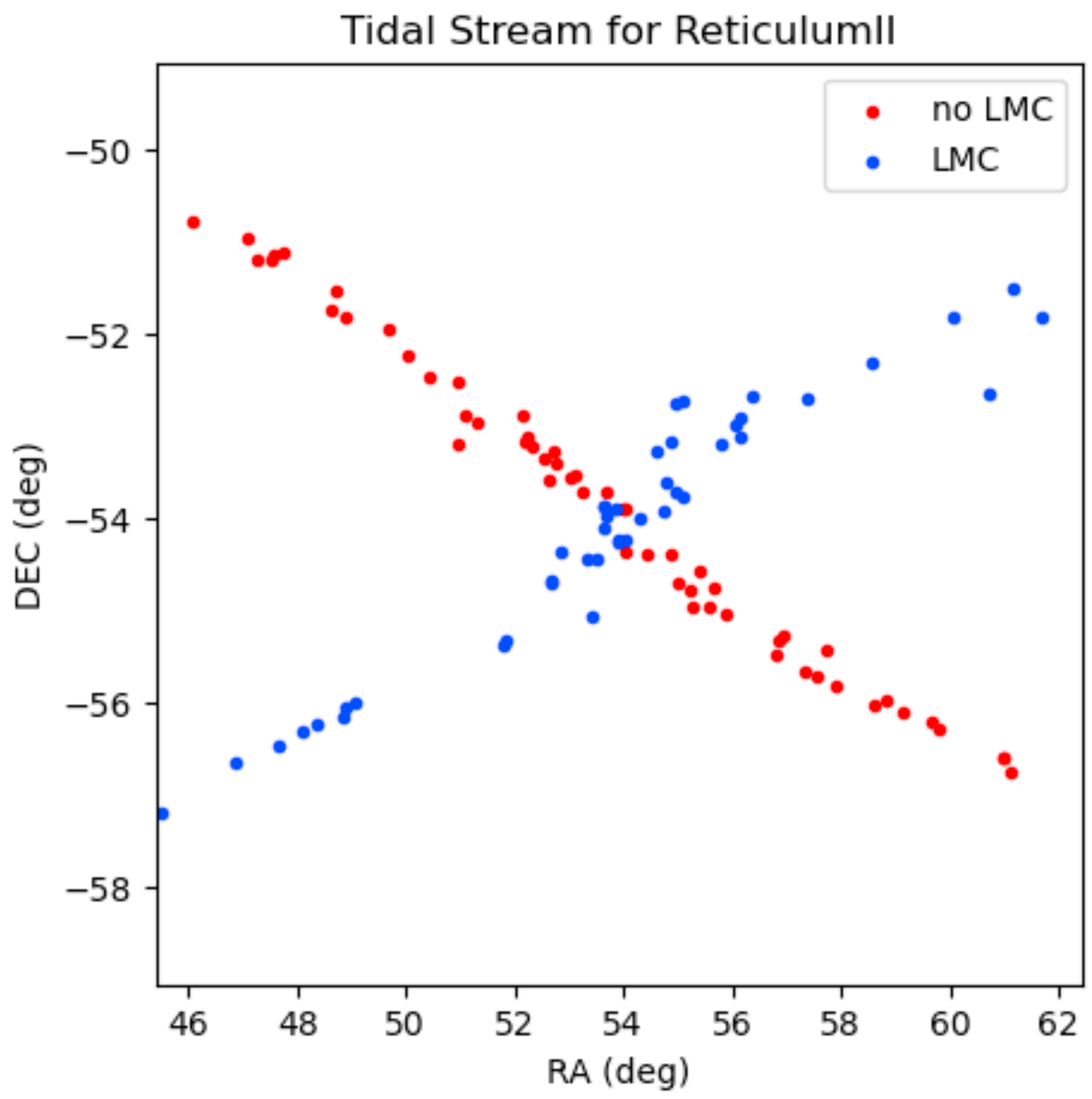
Reticulum II is not

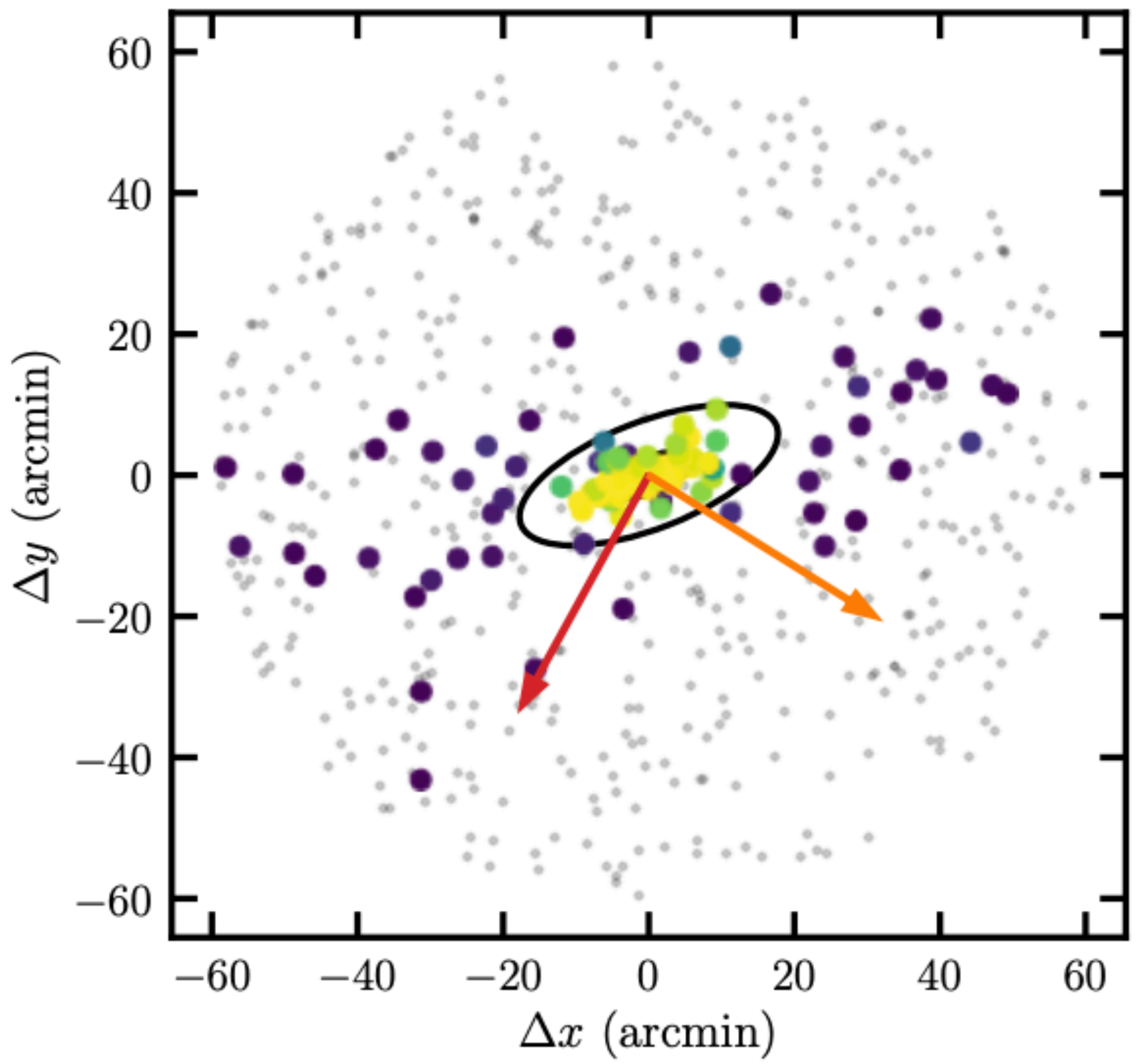




A. Pace, D. Erkal, TSL, 2022

Reticulum II is not? — can be explained by LMC!





A. Pace, D. Erkal, TSL, 2022

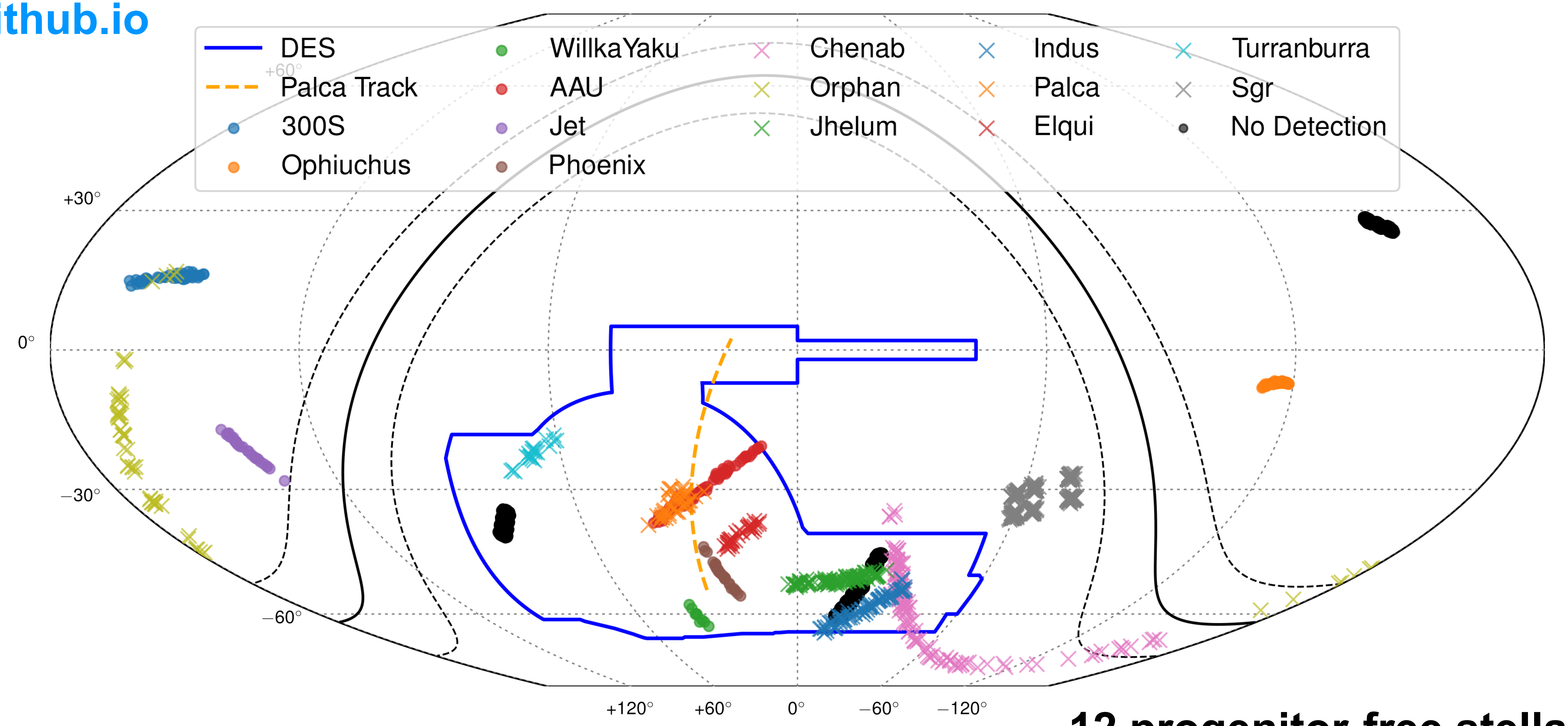
Dwarf Galaxy Triaxility:
Dark Matter or Tides?

- Are dwarf galaxies elliptical because of tides?
- Were they born in spherical and then get elliptical?
- Were they born in elliptical and aligned due to torque?

Smallest Galaxies or the most metal-poor globular clusters

What about disrupted globular clusters?

s5collab.github.io



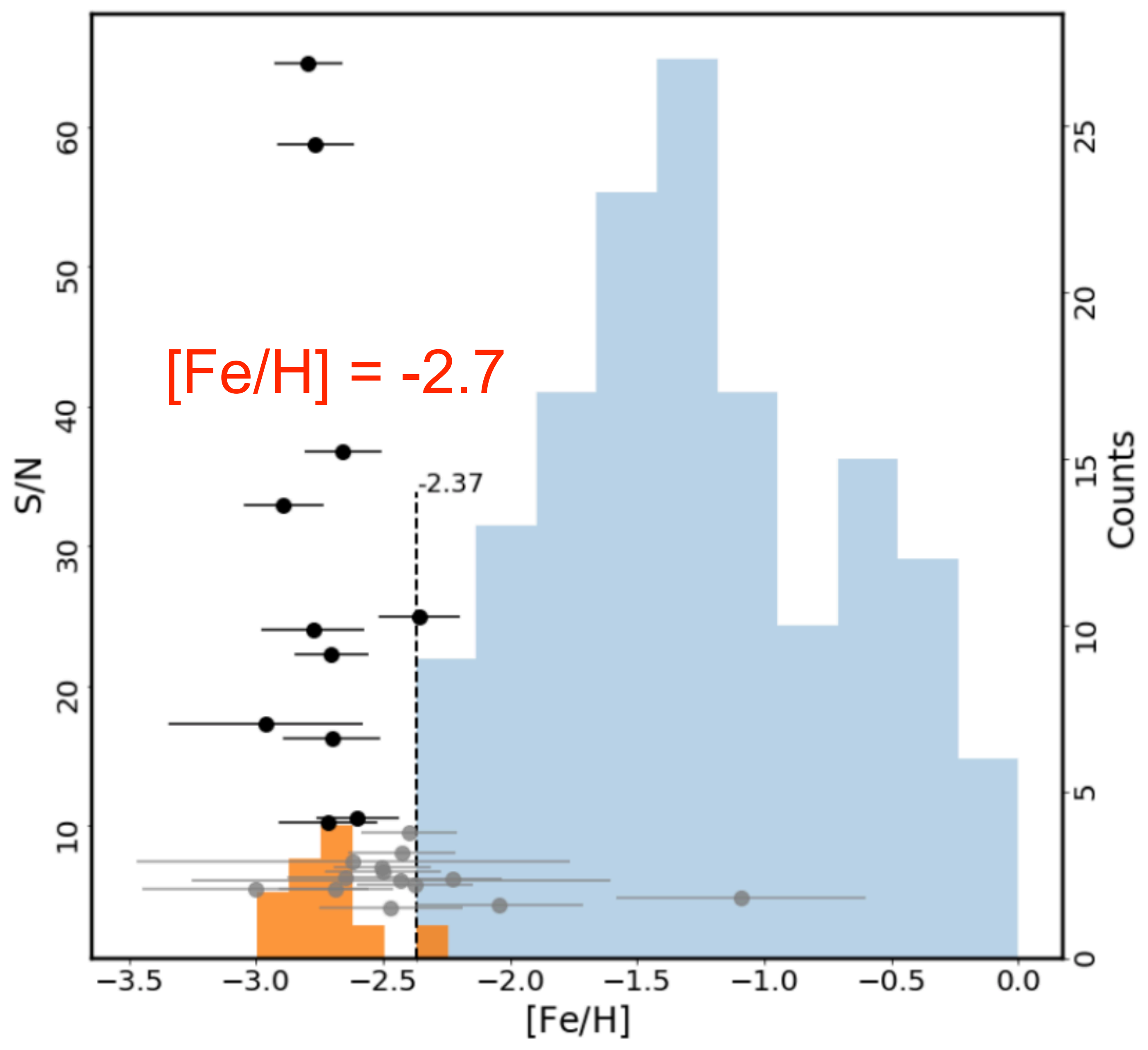
S5: The Orbital and Chemical Properties of One Dozen Stellar Streams
TSL et al (2022), arXiv: 2110.06950

12 progenitor-free stellar streams at ~10-50 kpc observed in 2018-2020

stellar stream remnant of globular clusters (?) below the metallicity floor

s5collab.github.io

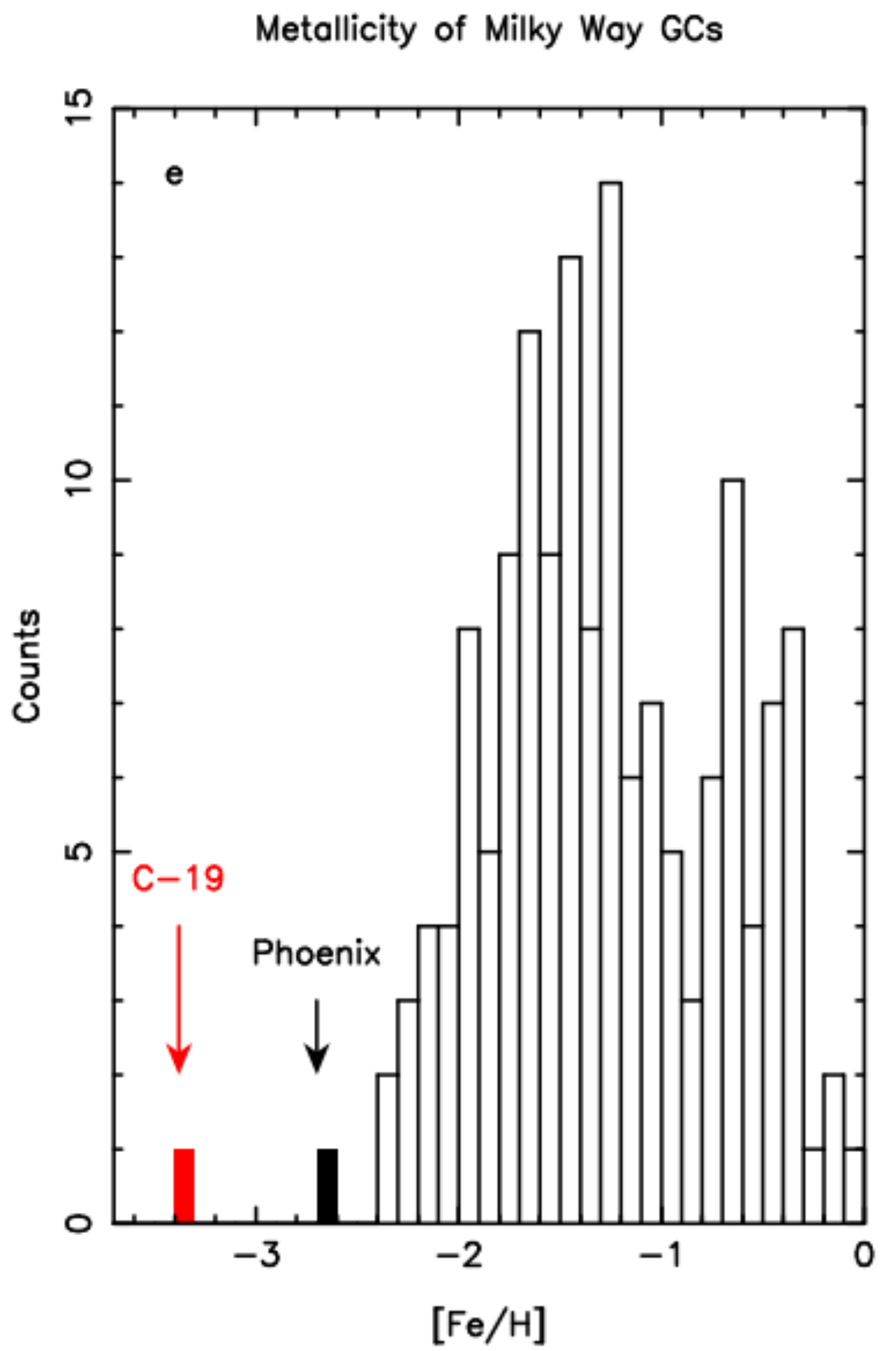
Phoenix Stream:



Cyan: globular cluster in Milky Way
Orange: stars in Phoenix Stream

Wan, Lewis, TSL et al. 2020 Nature

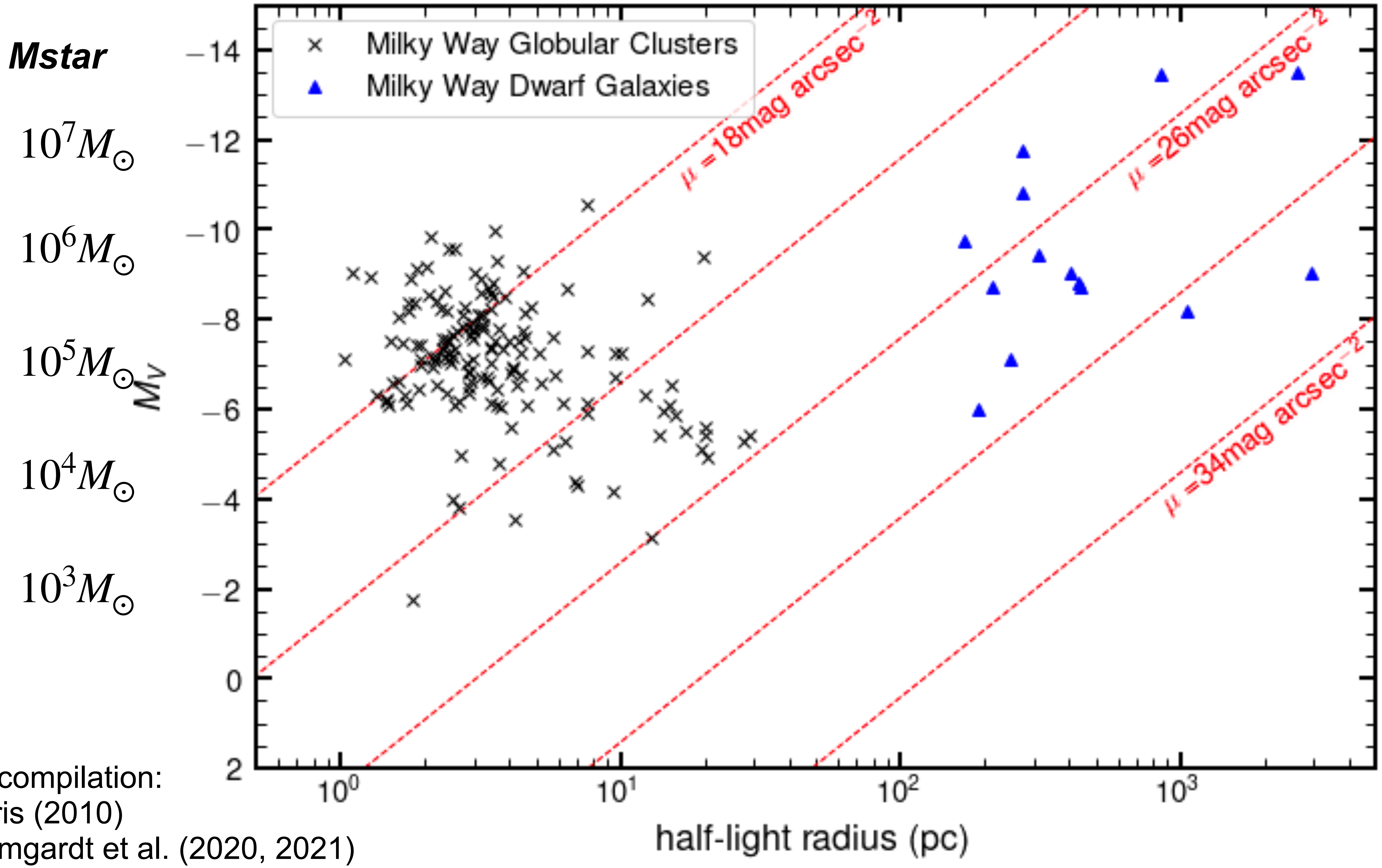
C-19 Stream:



Martin et al. 2022 Nature

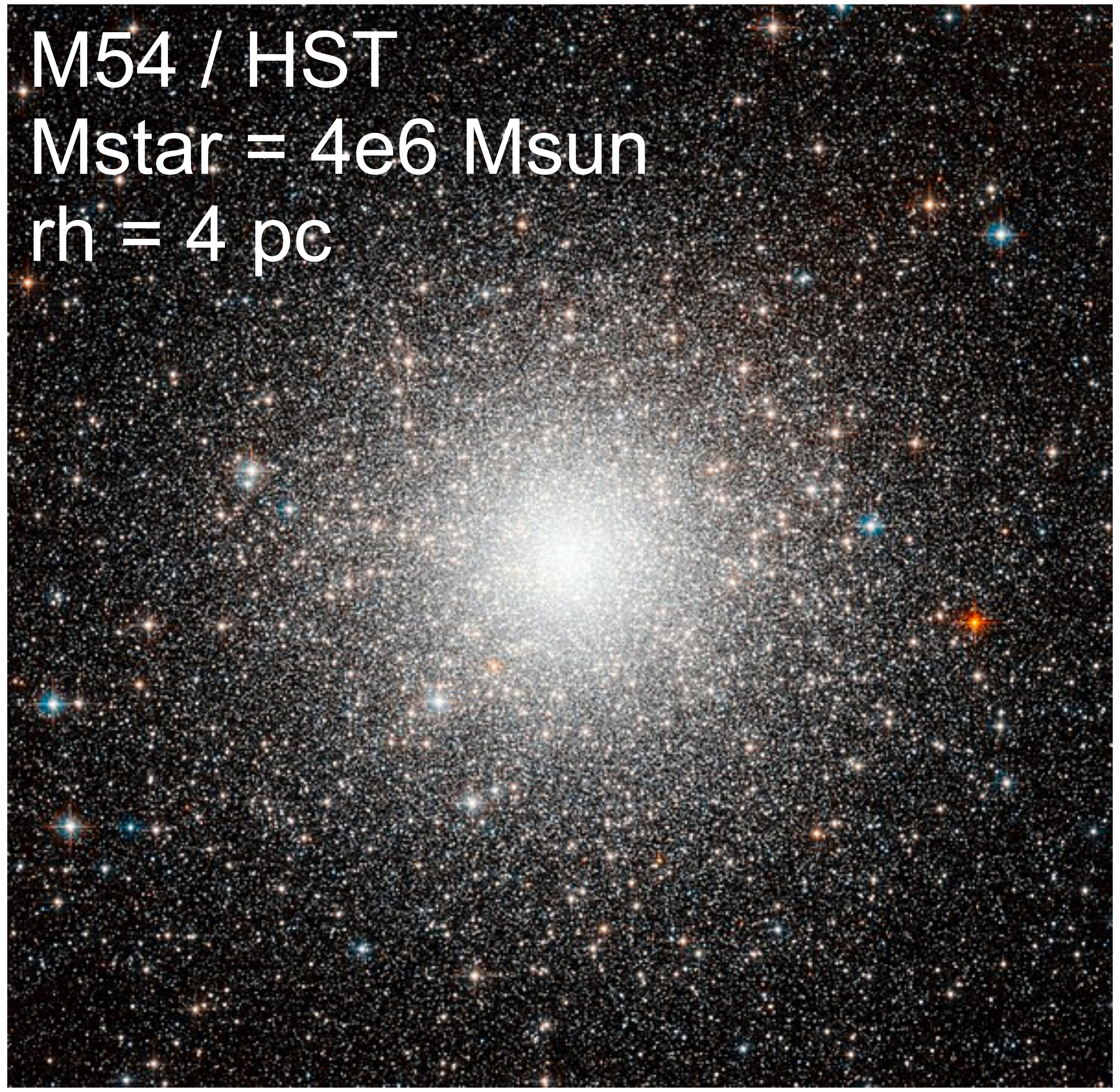
What about the intact globular clusters?

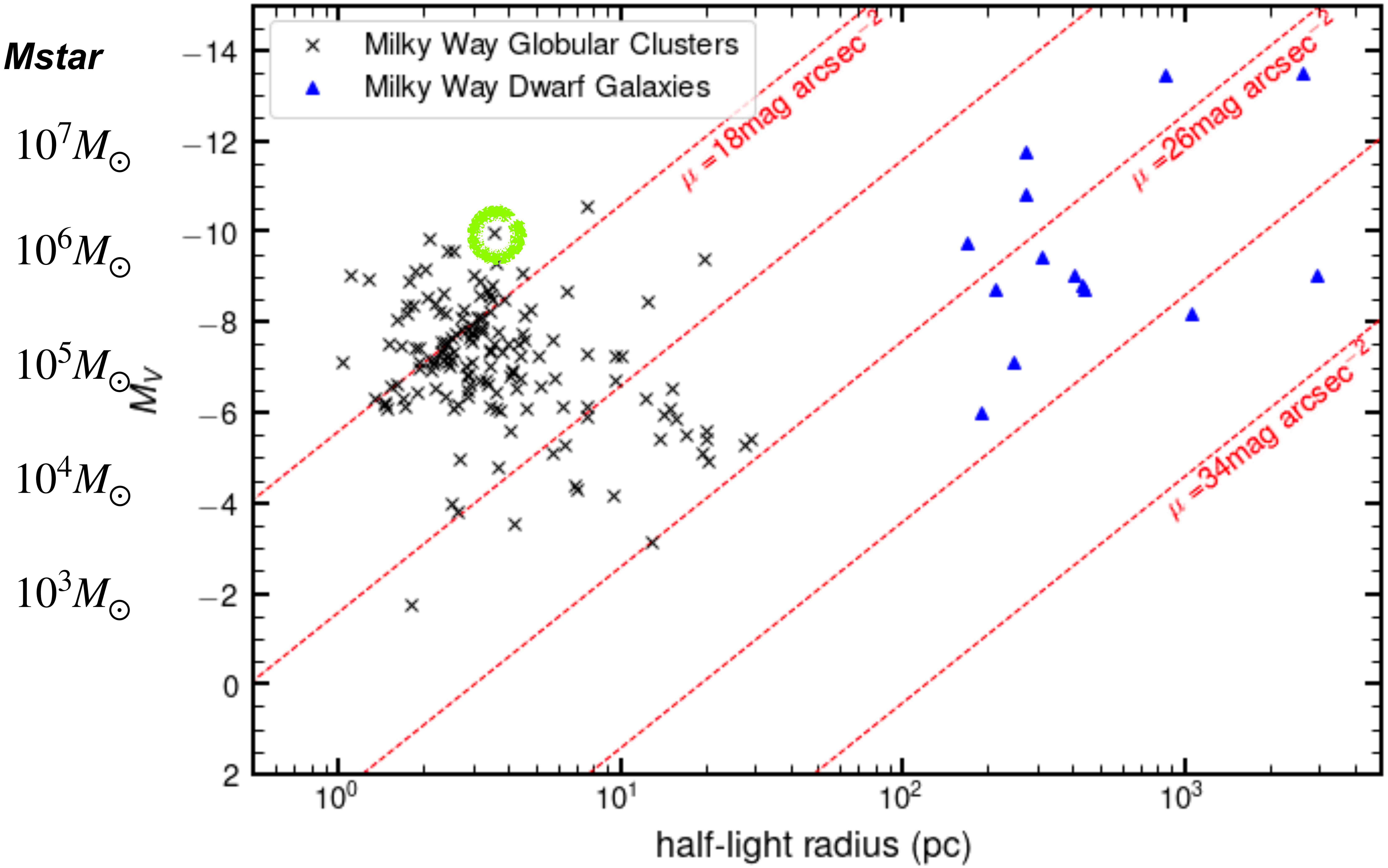
Luminosity vs Size for Galactic Satellites



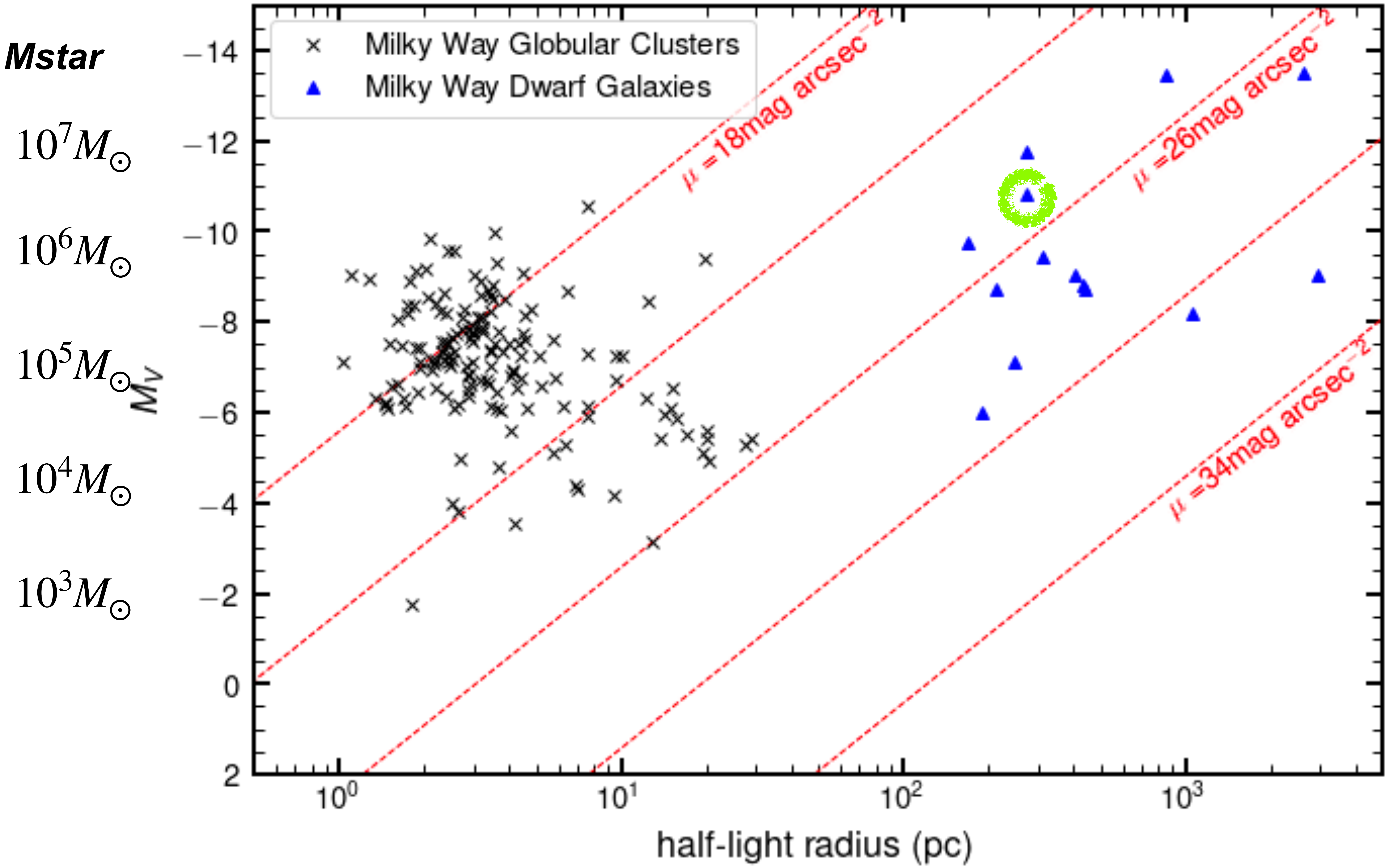
GC compilation:
Harris (2010)
Baumgardt et al. (2020, 2021)

Luminosity vs Size for Galactic Satellites





Luminosity vs Size for Galactic Satellites



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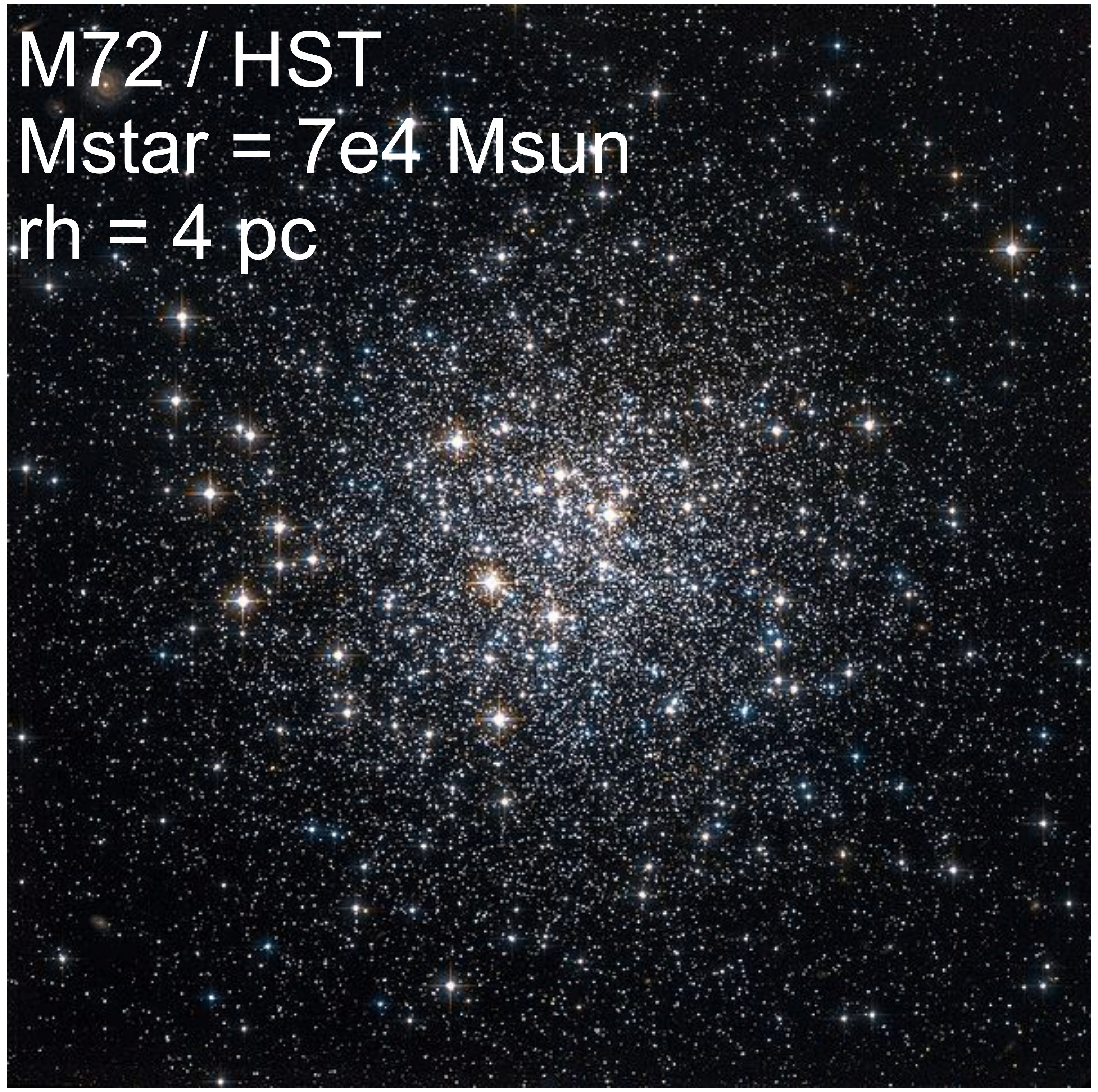

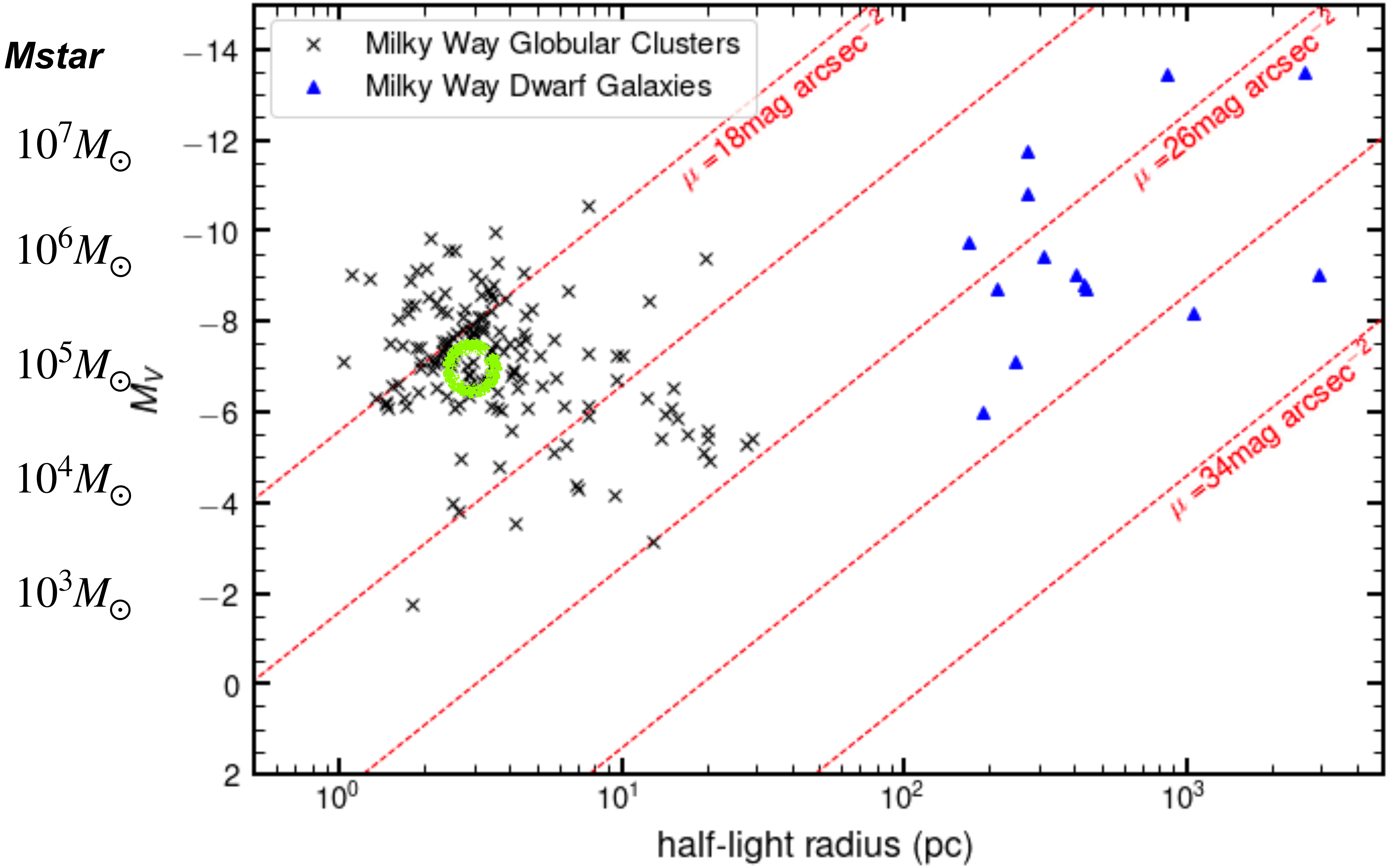

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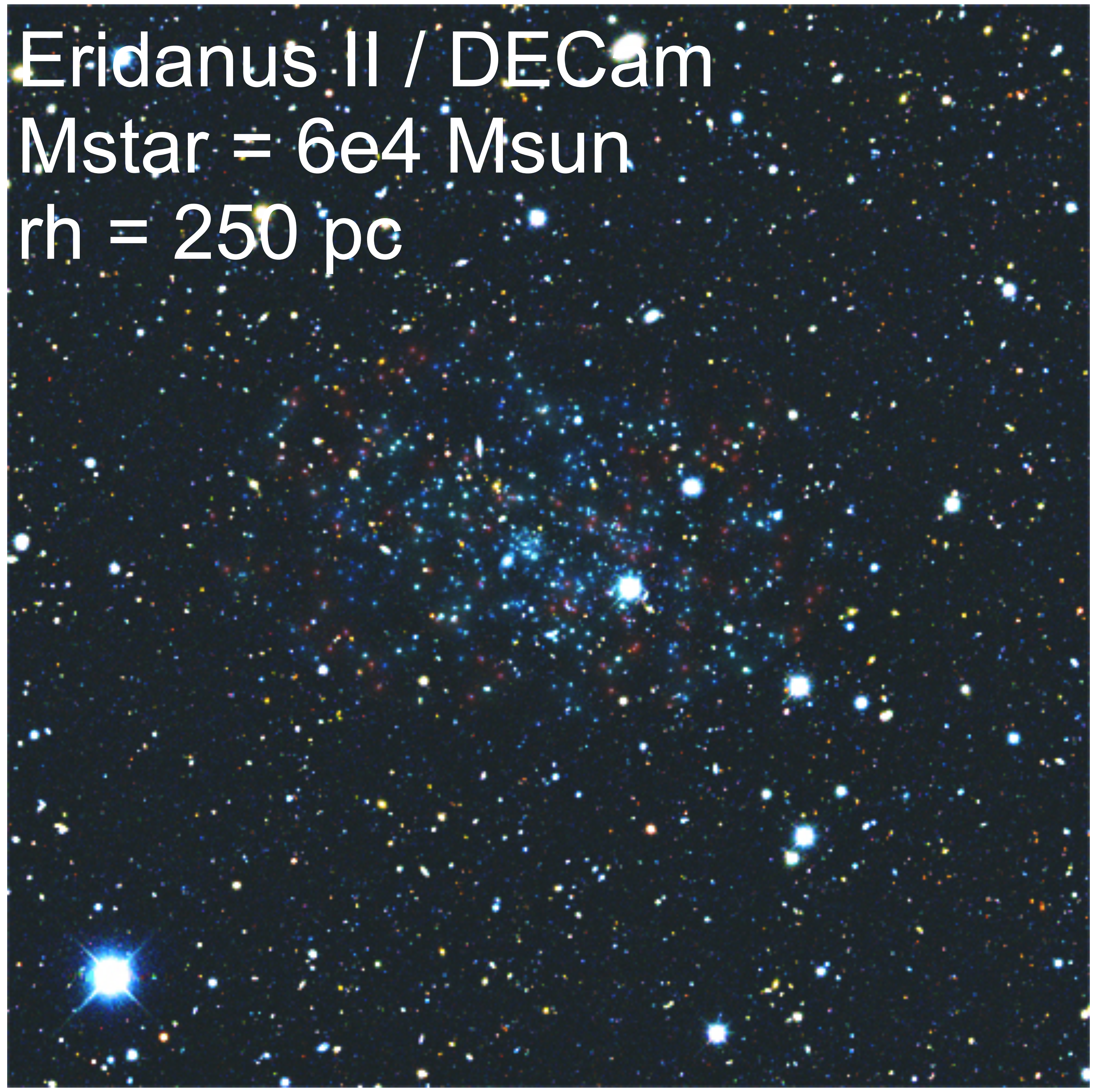


Mstar

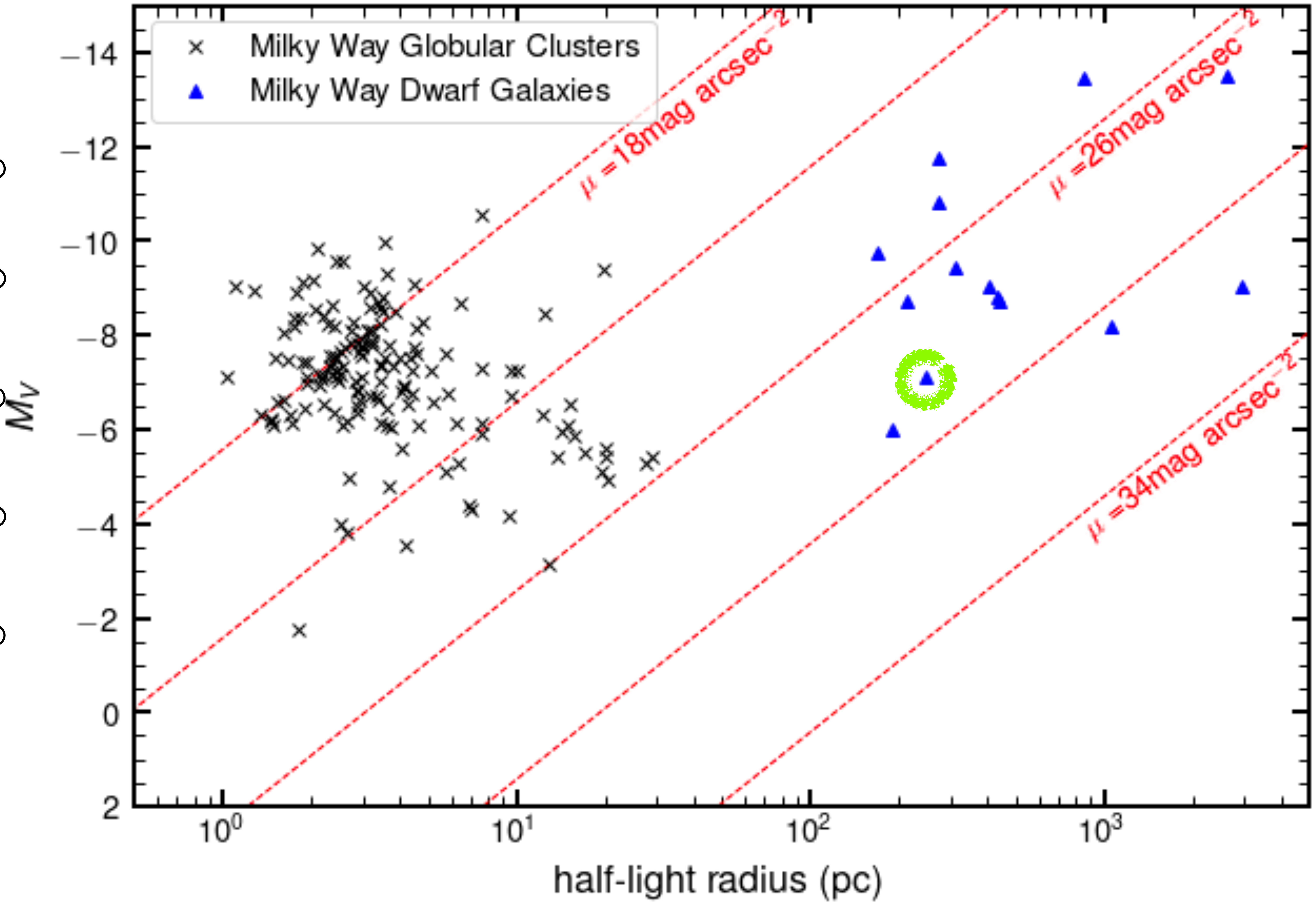
$10^7 M_\odot$

$10^6 M_\odot$

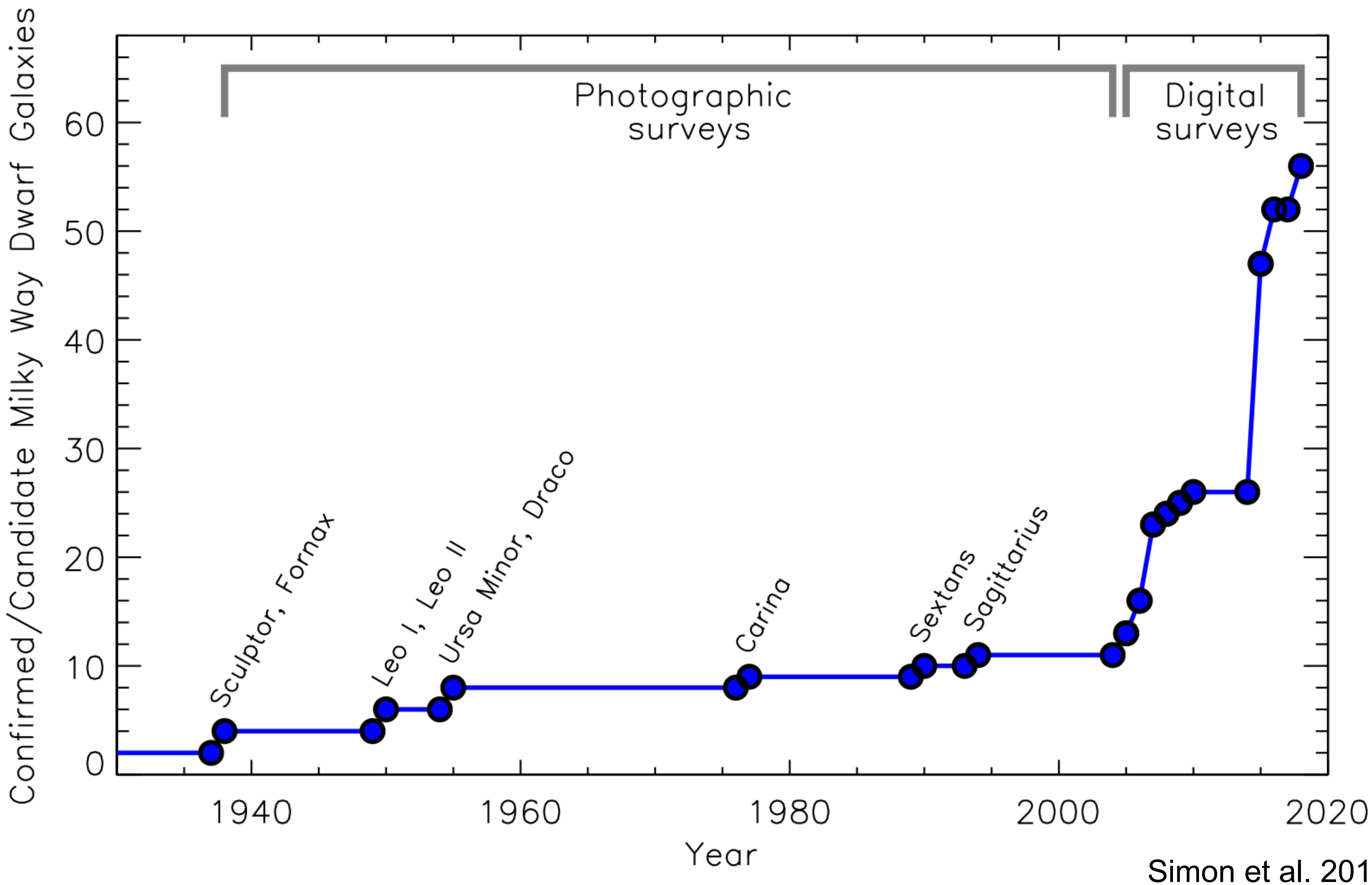
$10^5 M_\odot$

$10^4 M_\odot$

$10^3 M_\odot$

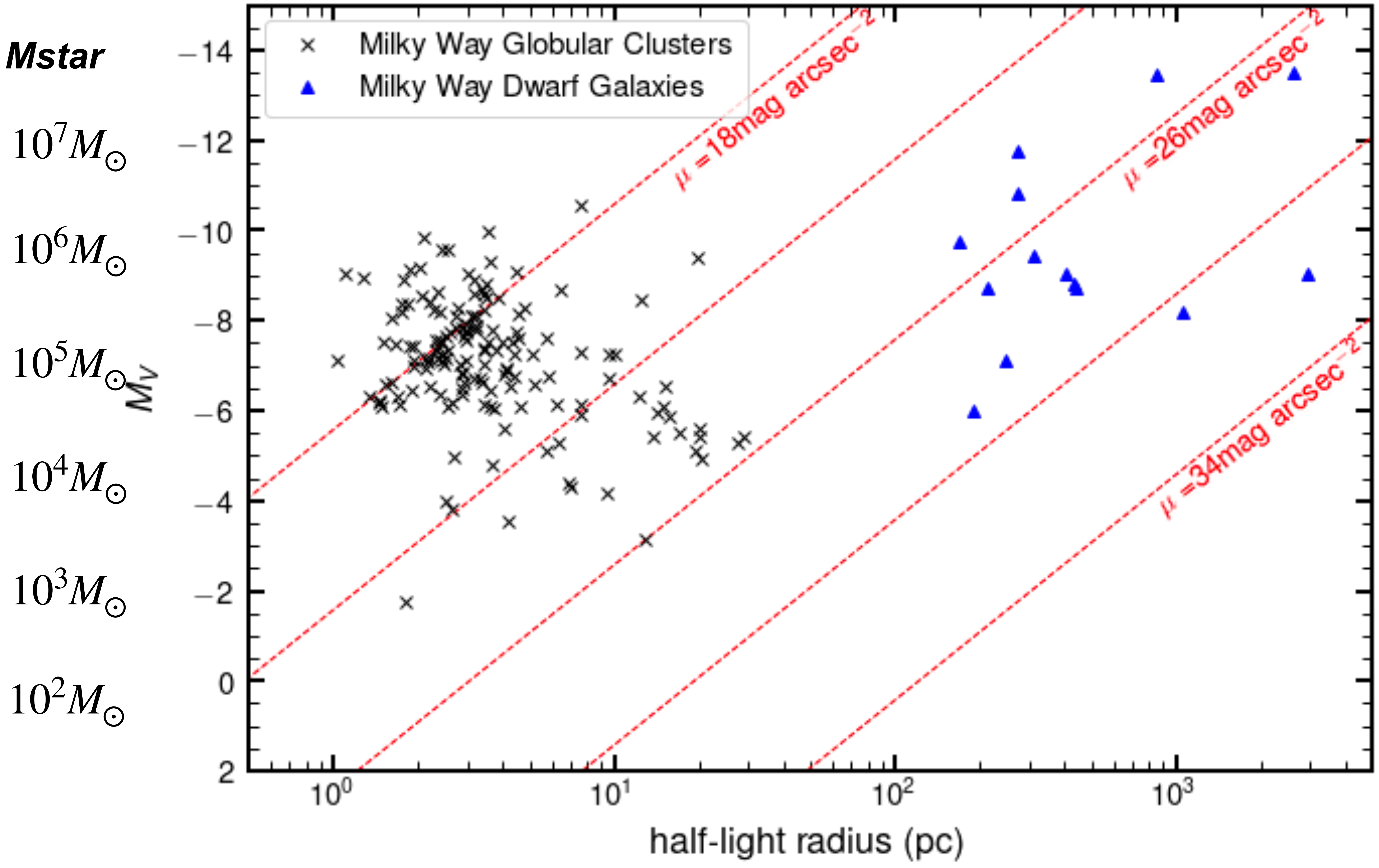


Dwarf Galaxy Discovery Timeline



Simon et al. 2019, ARAA

Luminosity vs Size for Galactic Dwarf Galaxies pre-SDSS



Luminosity vs Size for Galactic Dwarf Galaxies post-SDSS

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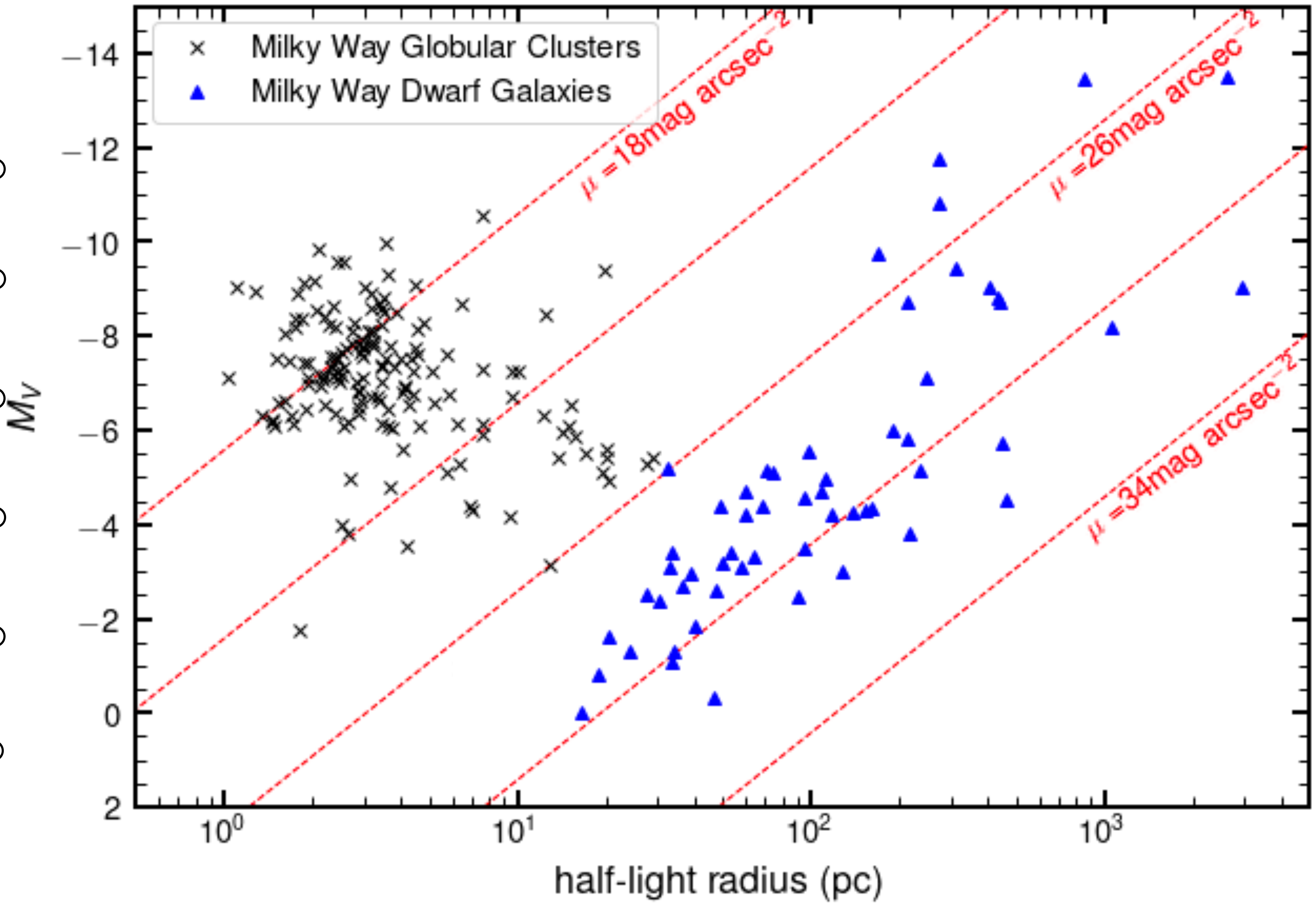
$10^2 M_\odot$



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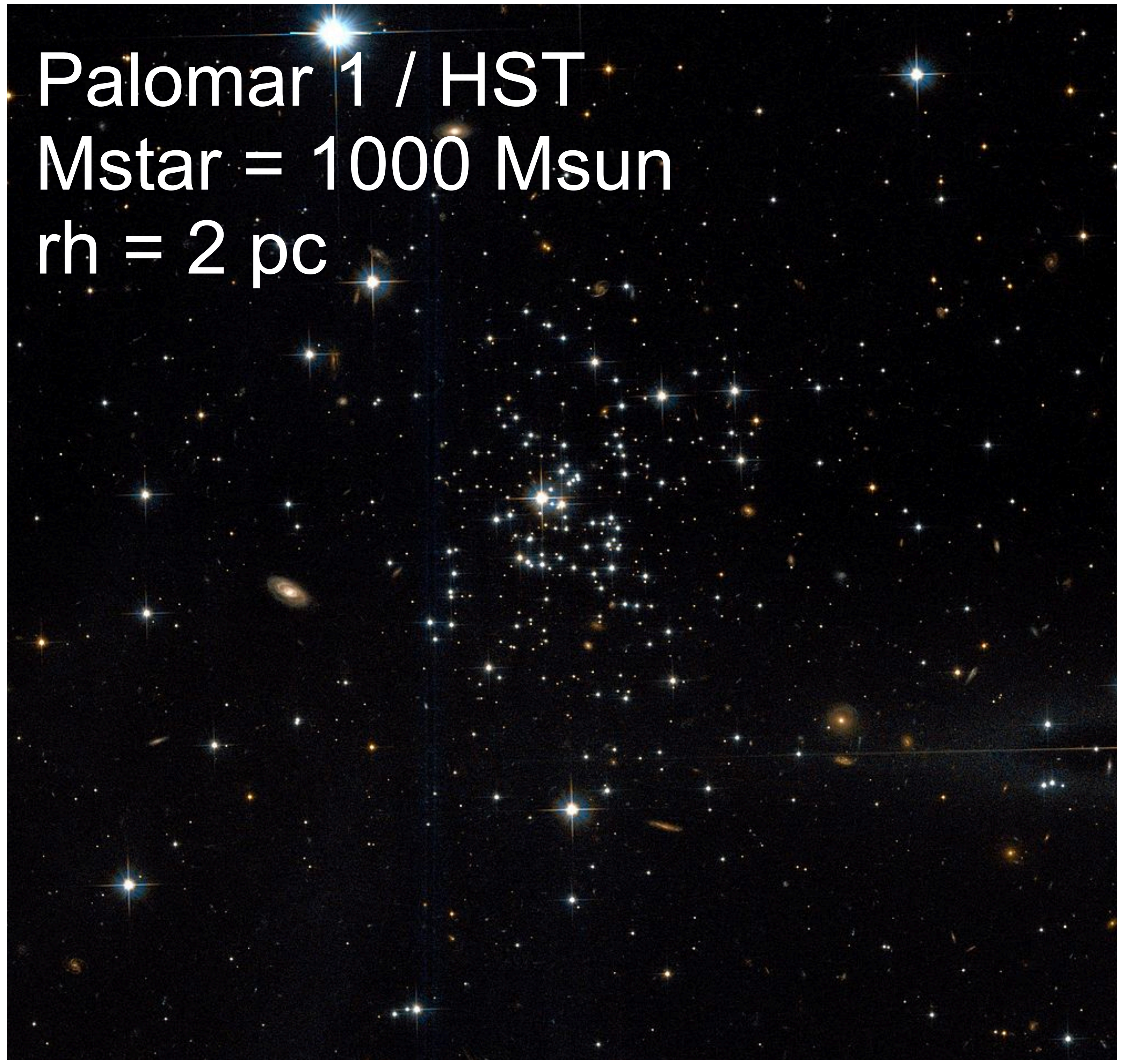

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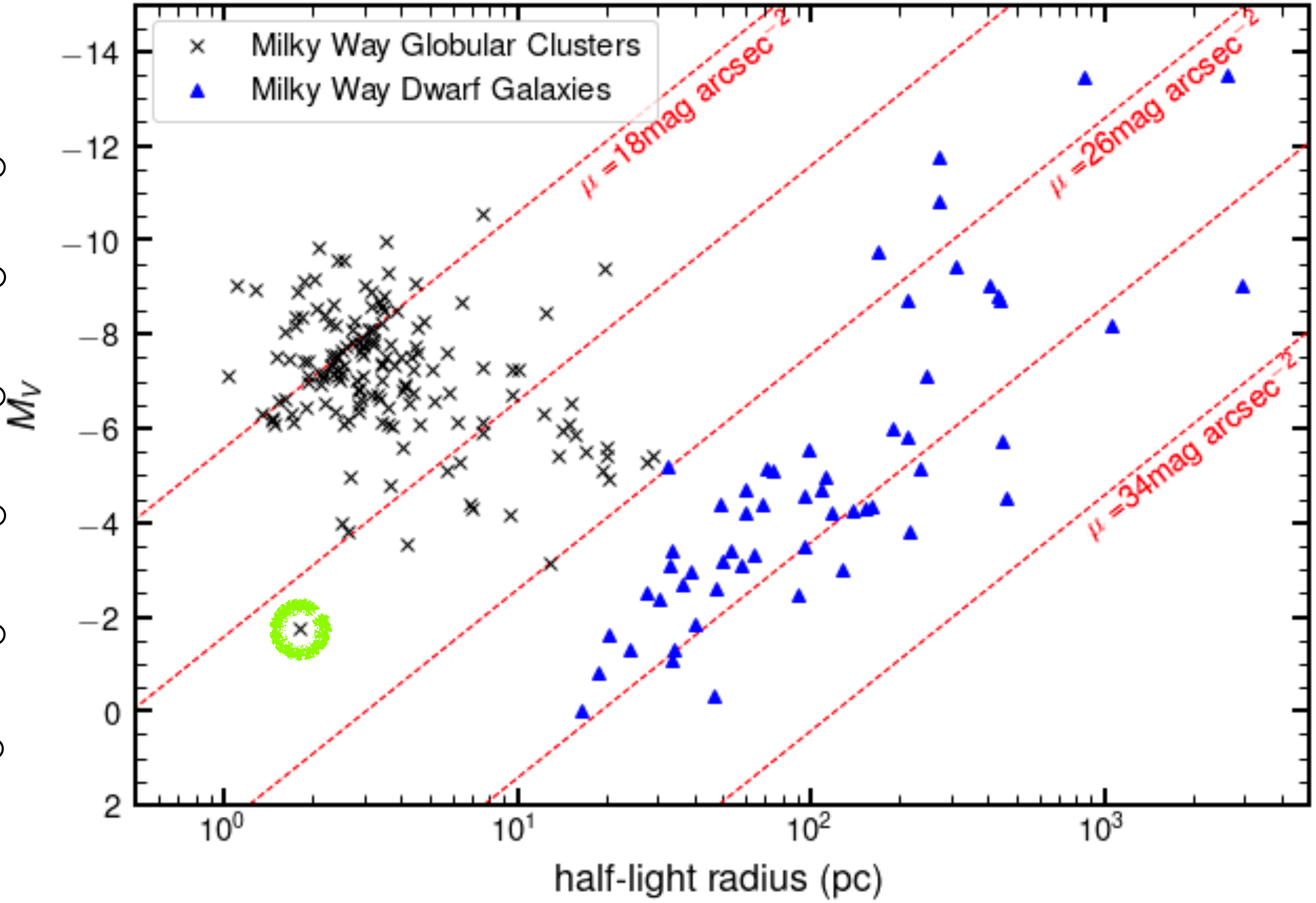

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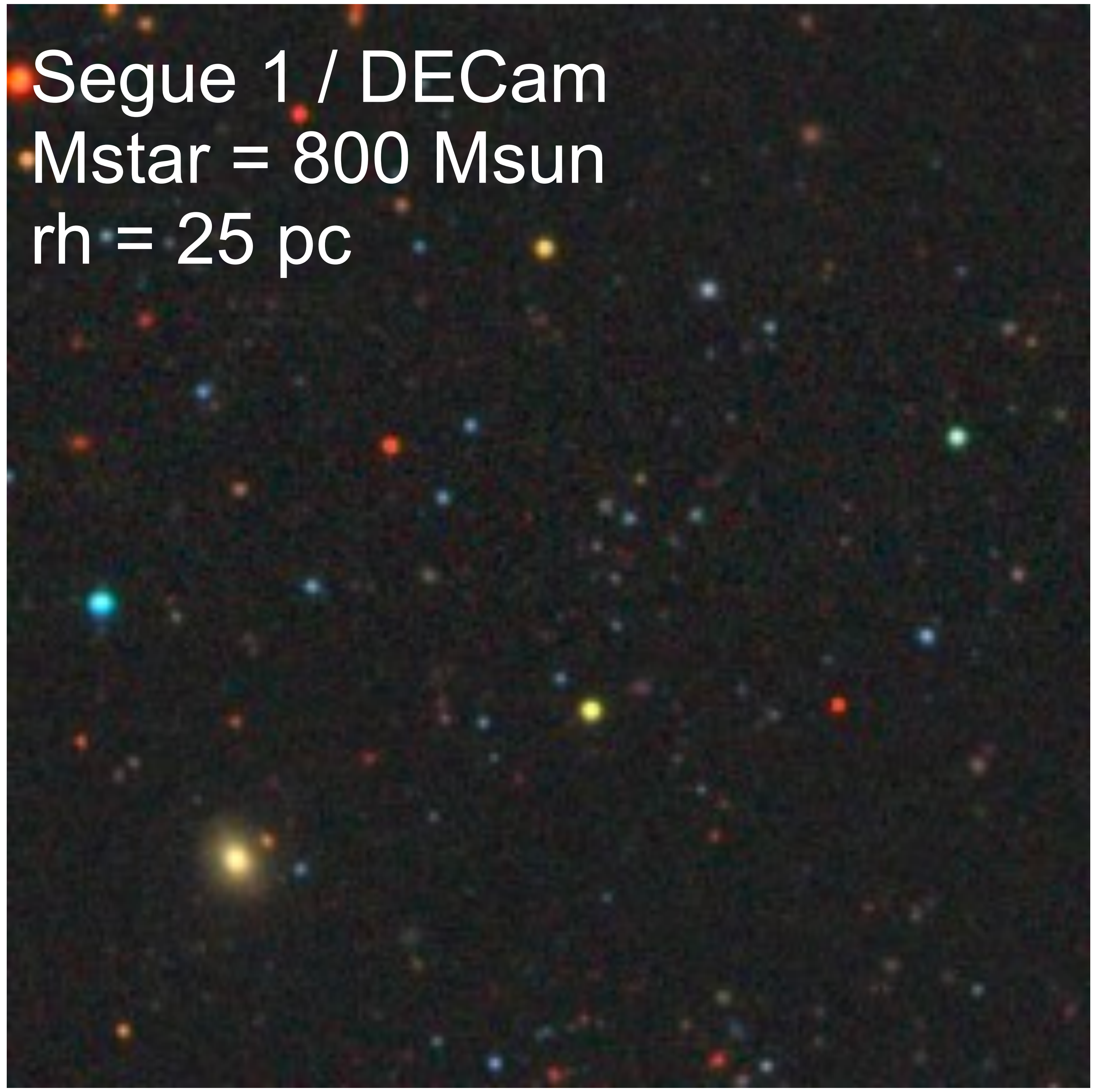

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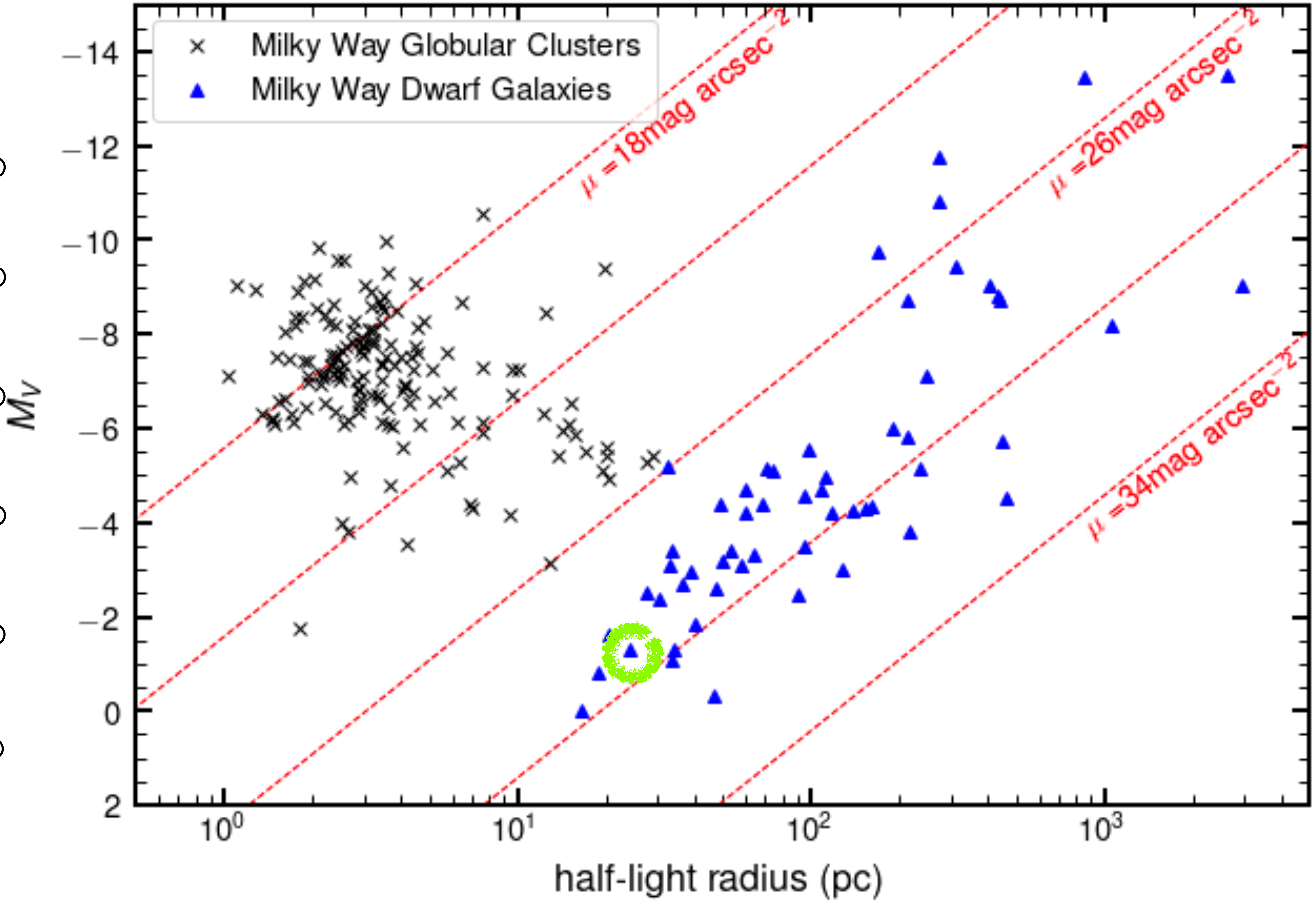

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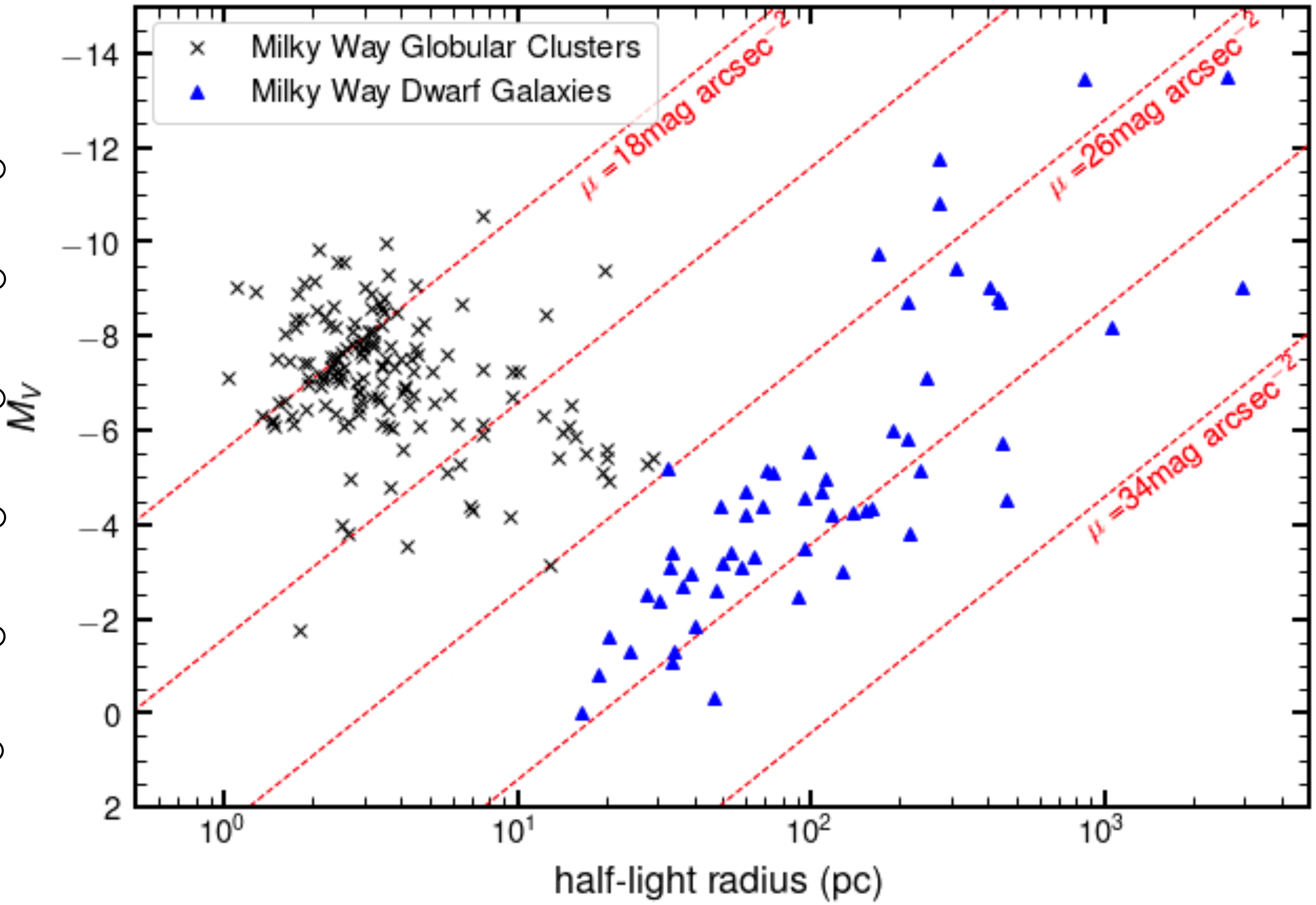
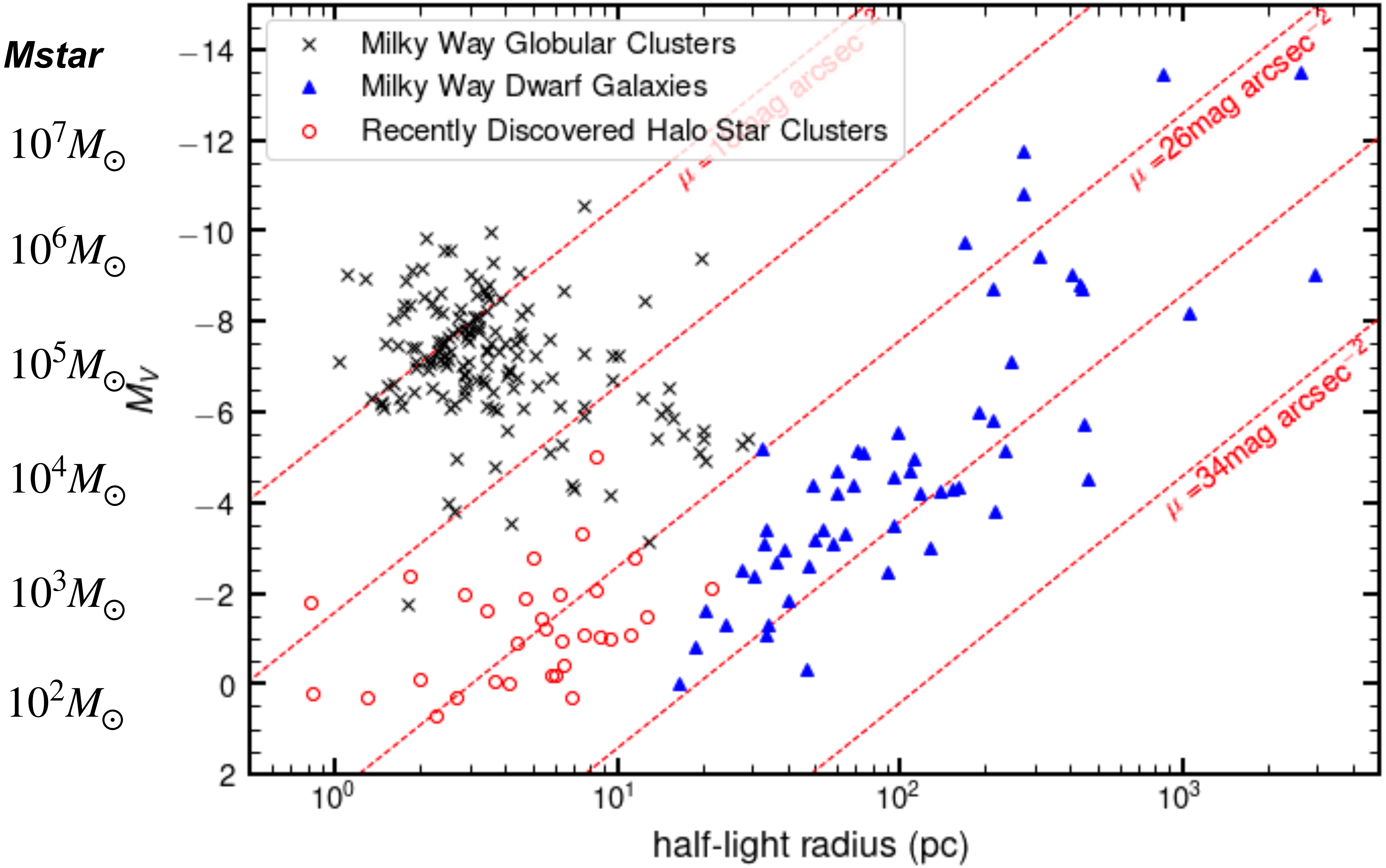


Ultra faint star clusters (? maybe)

30+ faint clusters discovered in the past 15 years!

Andrew Pace (CMU)



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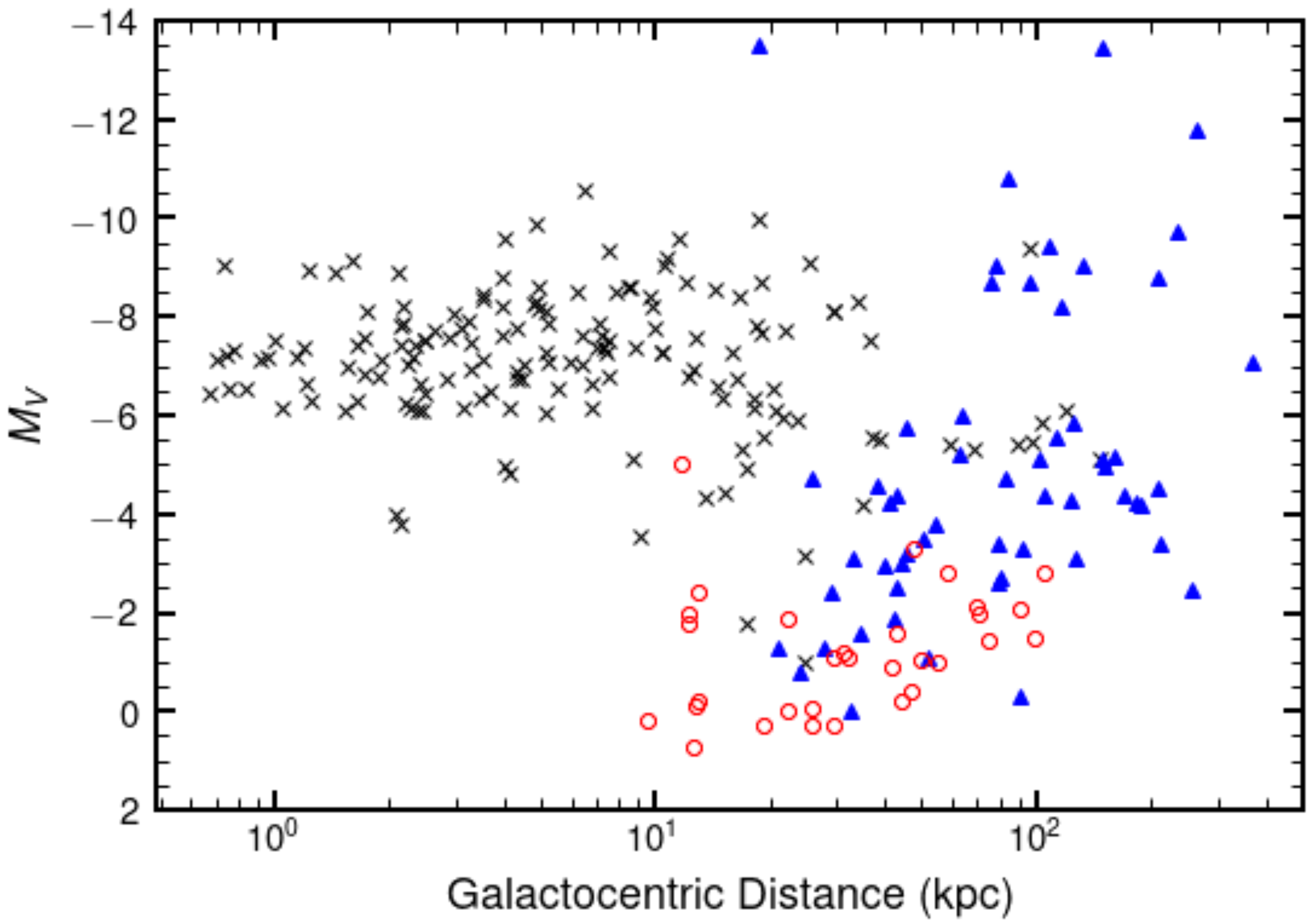

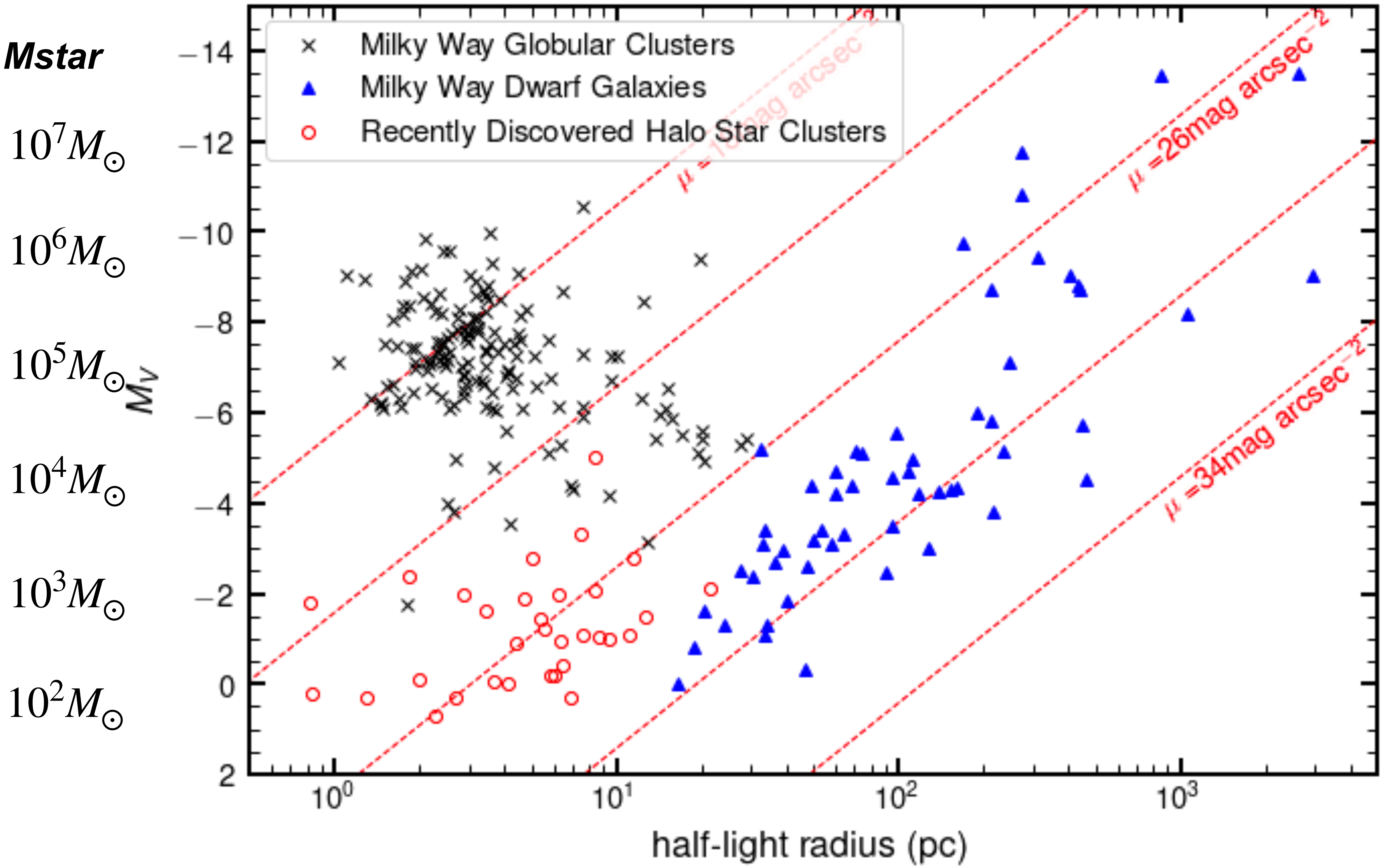

What is the Boundary?
Dwarf Galaxy vs. Star Clusters

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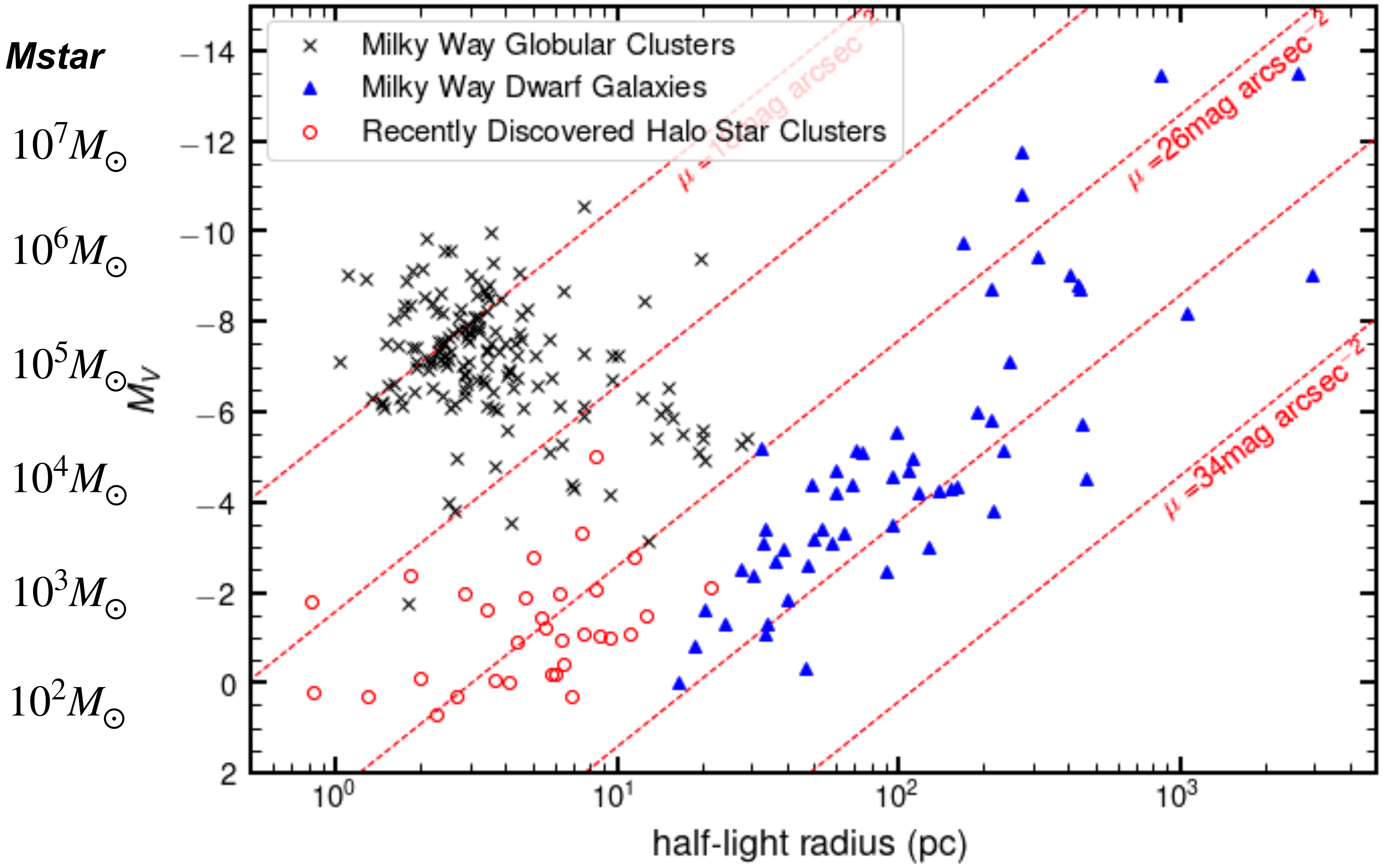

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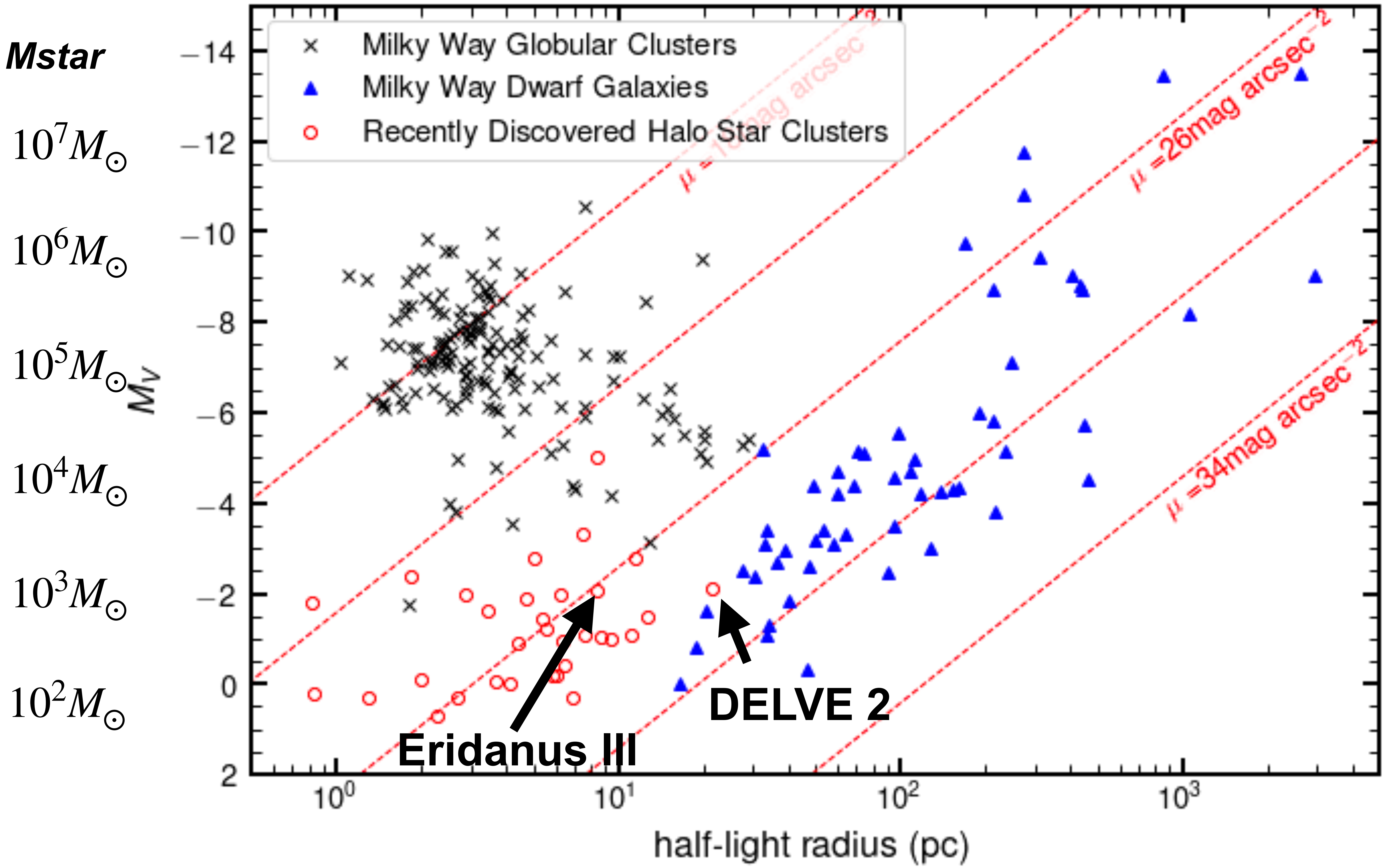
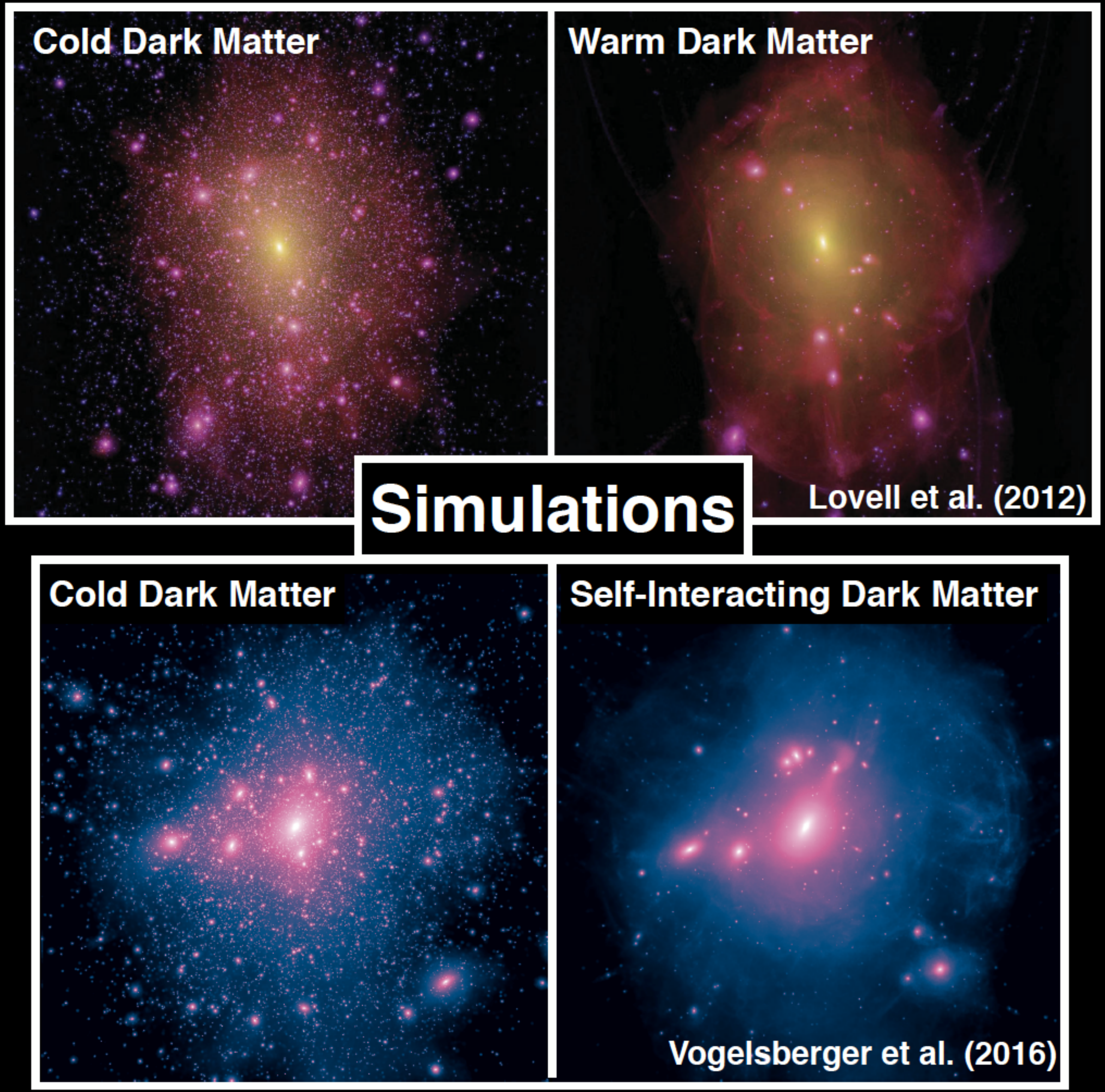
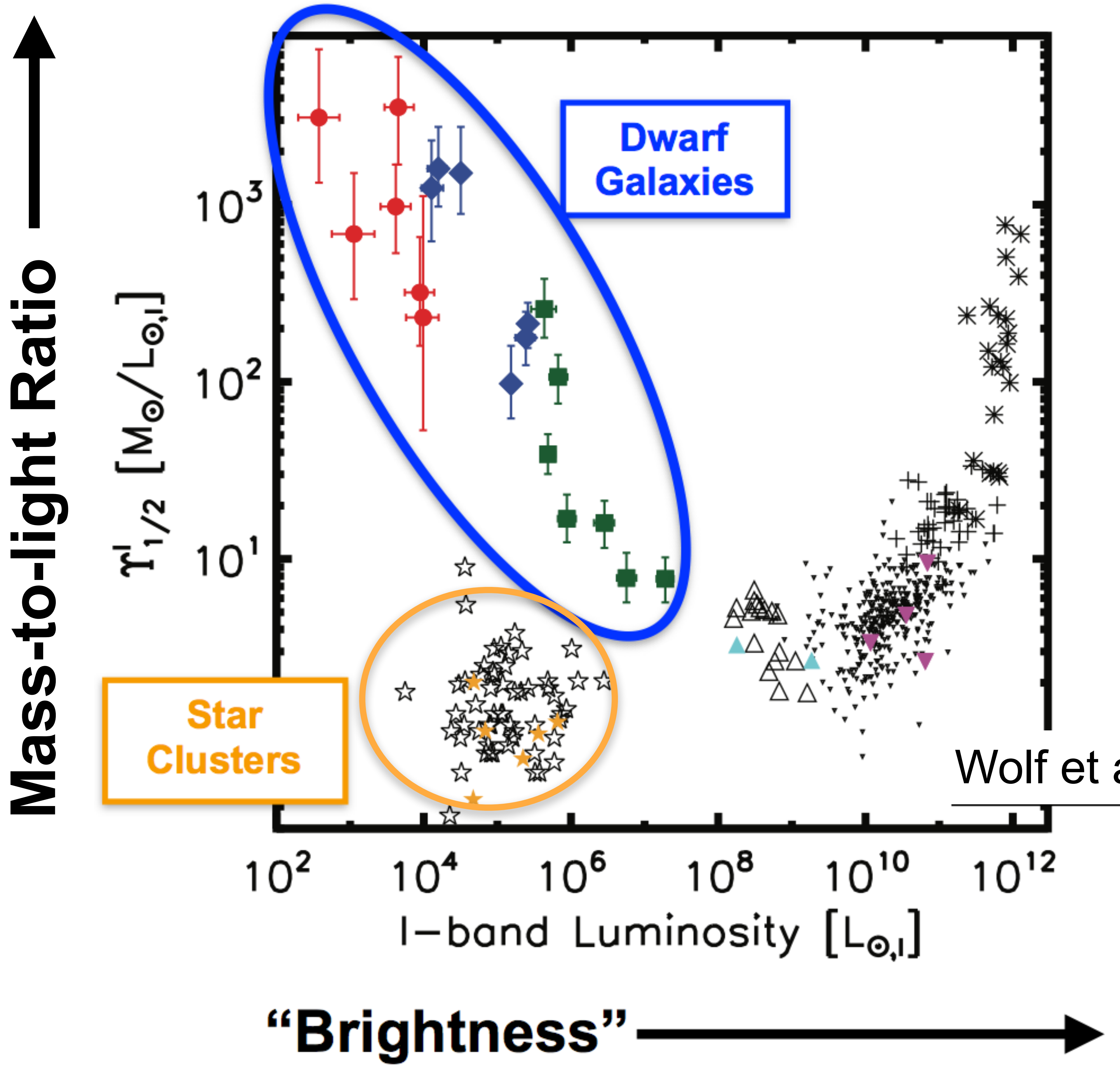


Smallest Structures Probe Fundamental Characteristics of Dark Matter

subhalo
mass
function

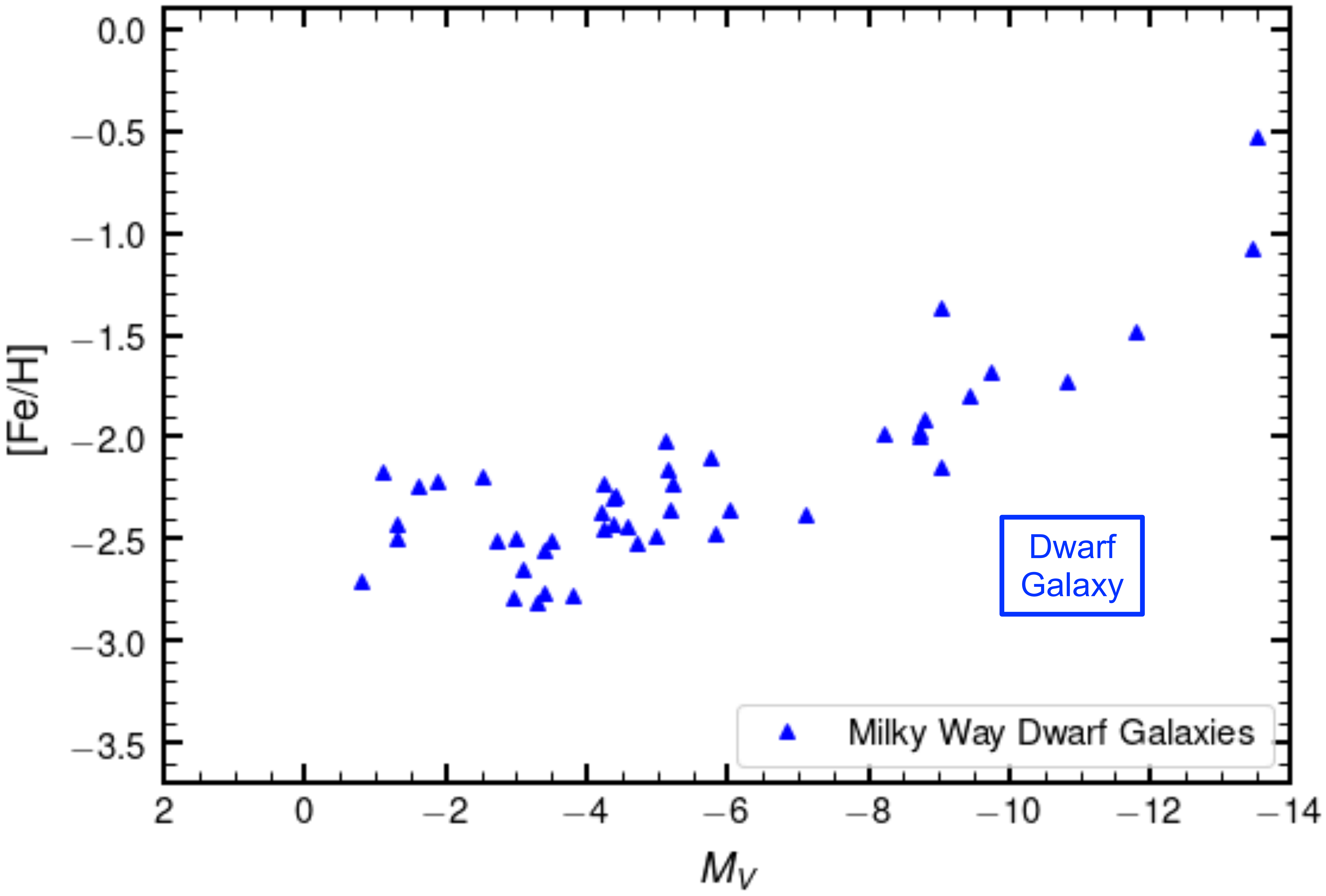


Dwarf Galaxies vs Star Clusters via (dynamical) mass-to-light ratio



Wolf et al. 2010

Dwarf Galaxies vs Star Clusters via (stellar) mass-metallicity relation



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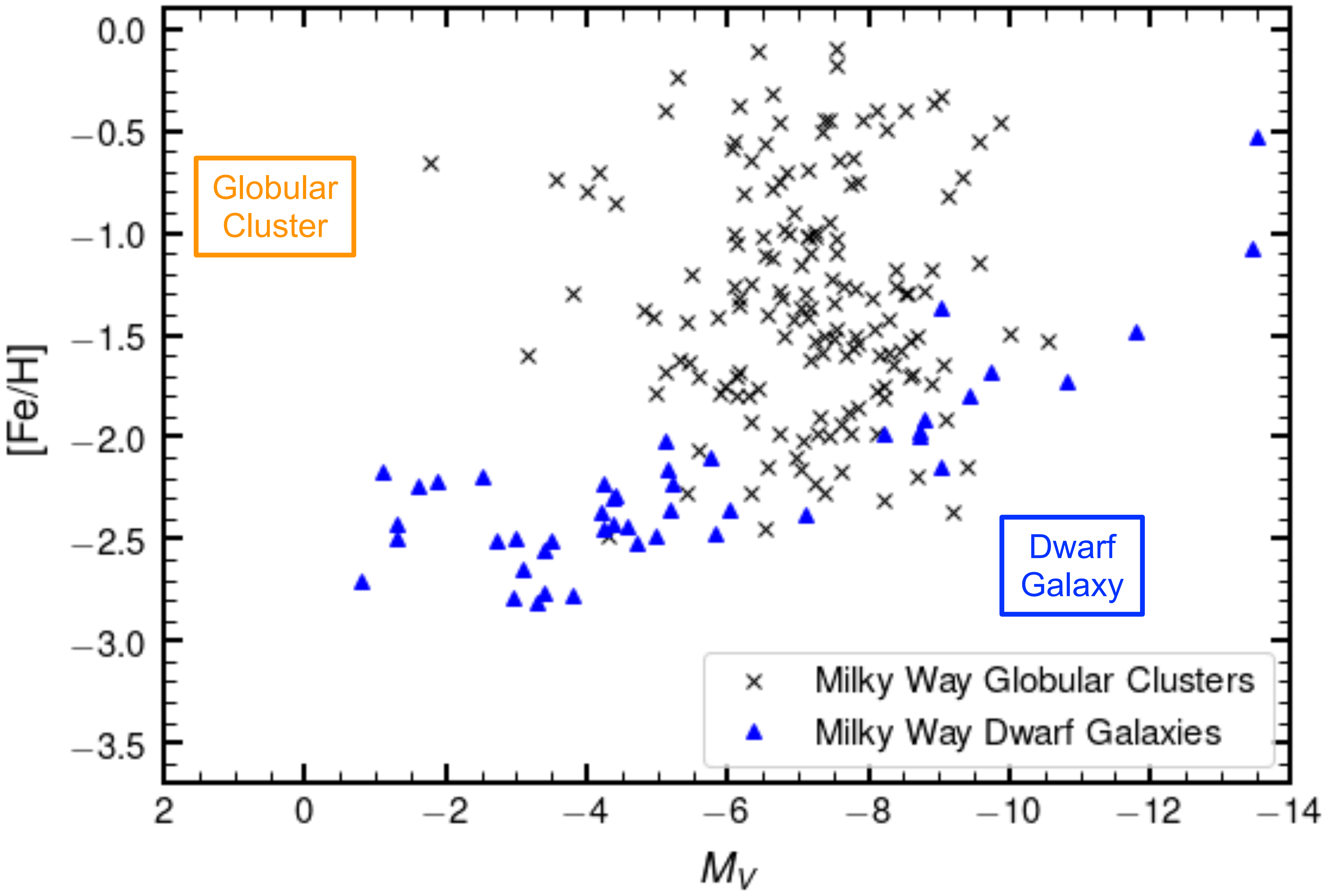
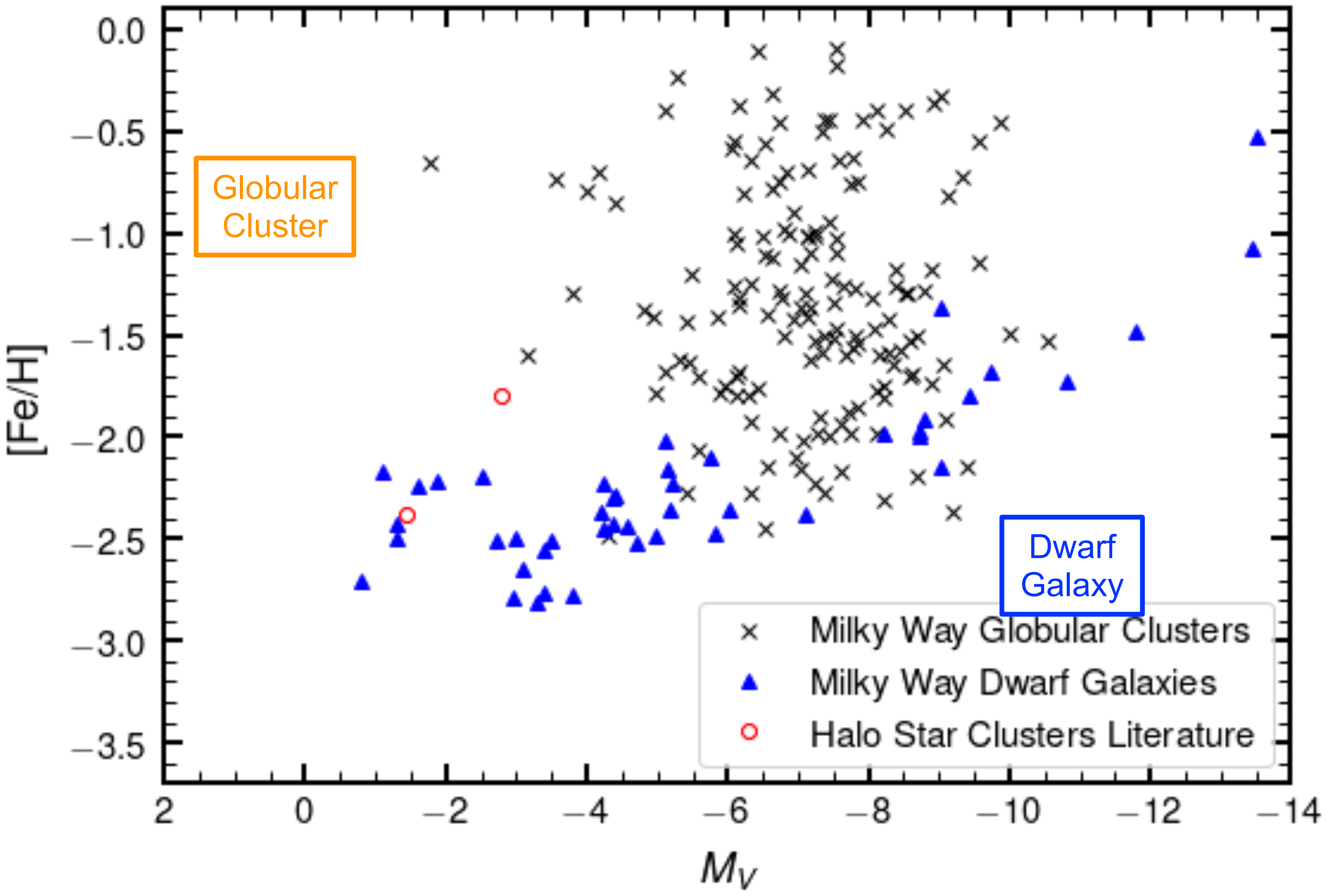


Dwarf Galaxies vs Star Clusters
via (stellar) mass-metallicity relation



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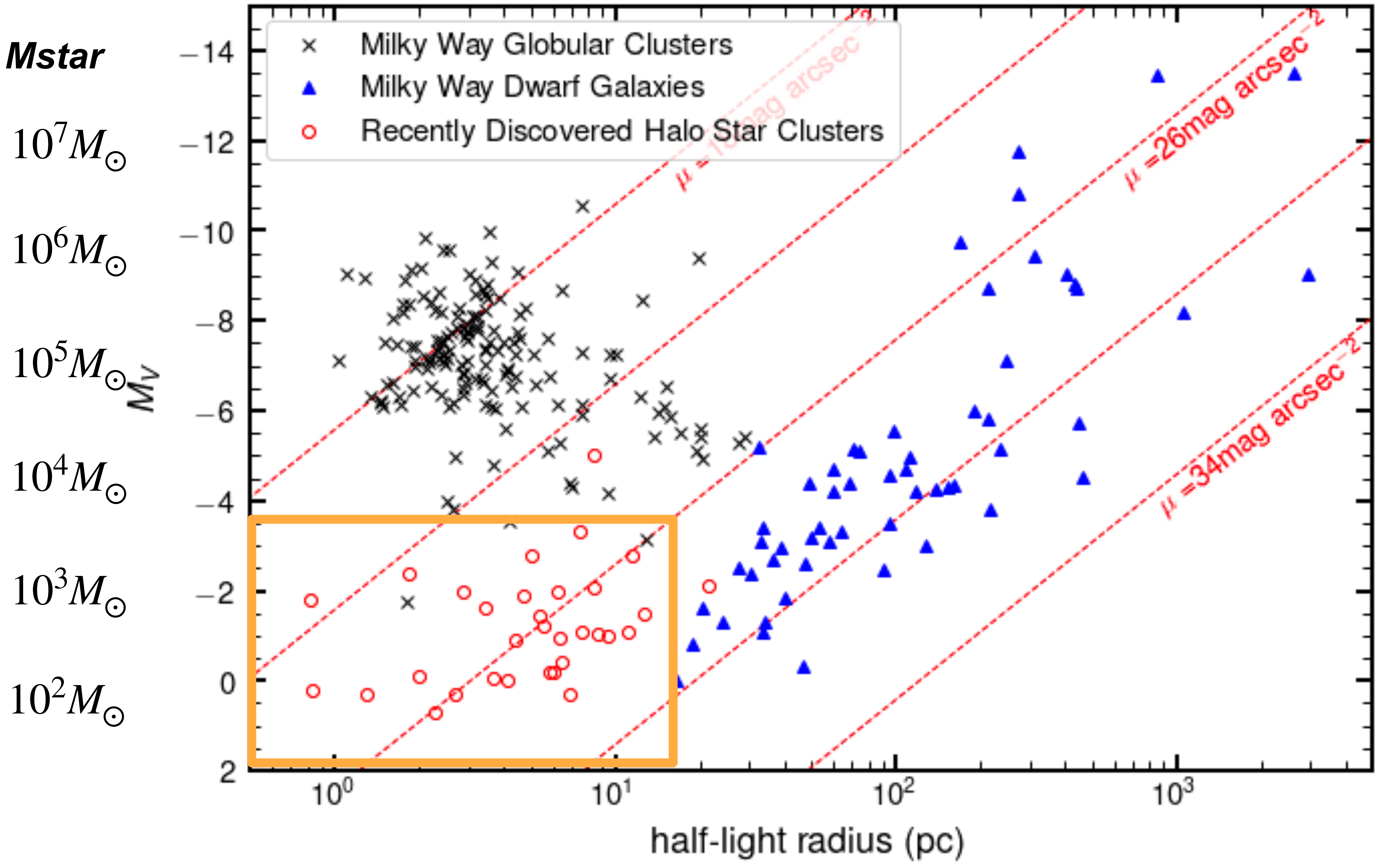

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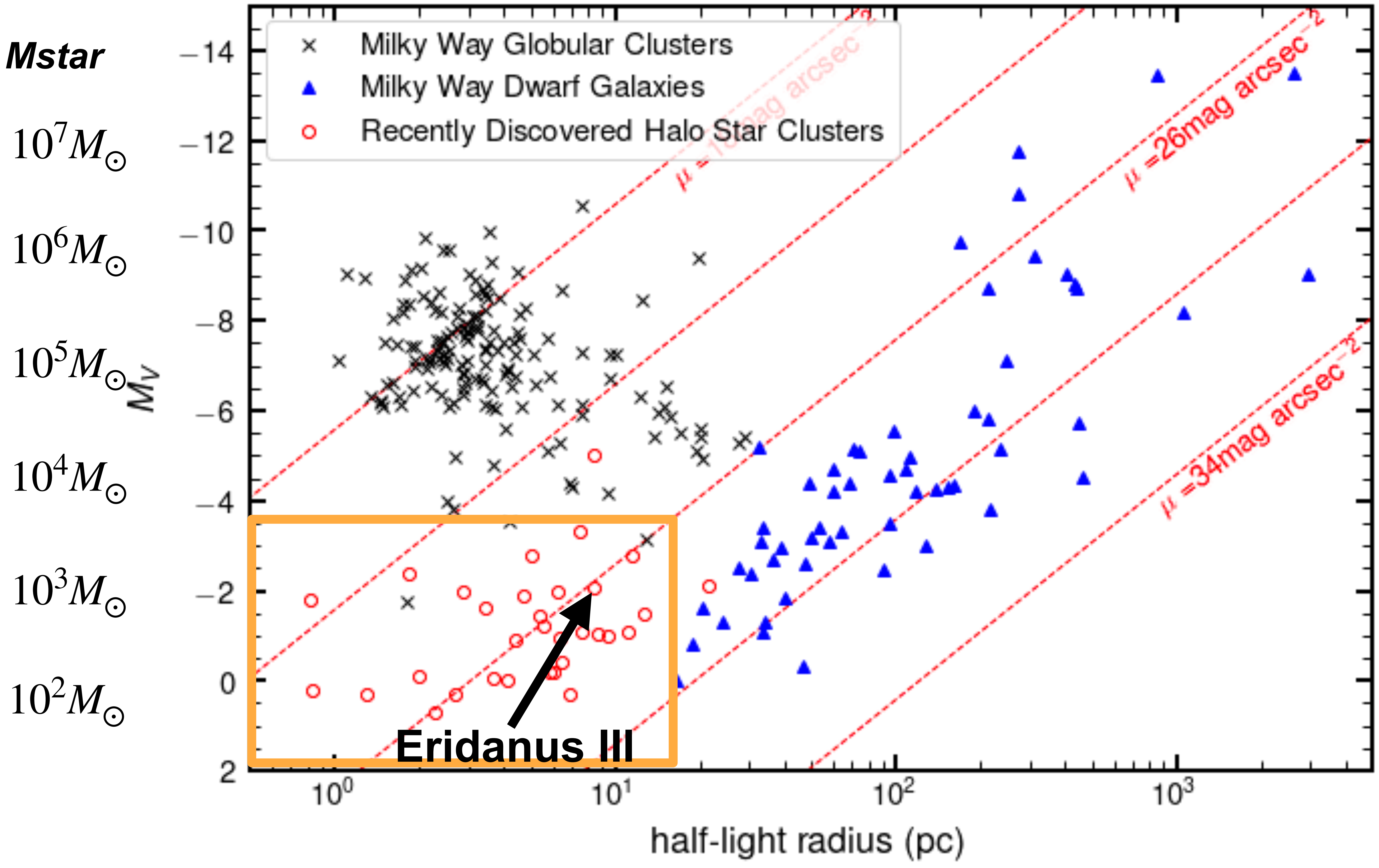


Eridanus III
Dwarf Galaxy or Star Clusters?

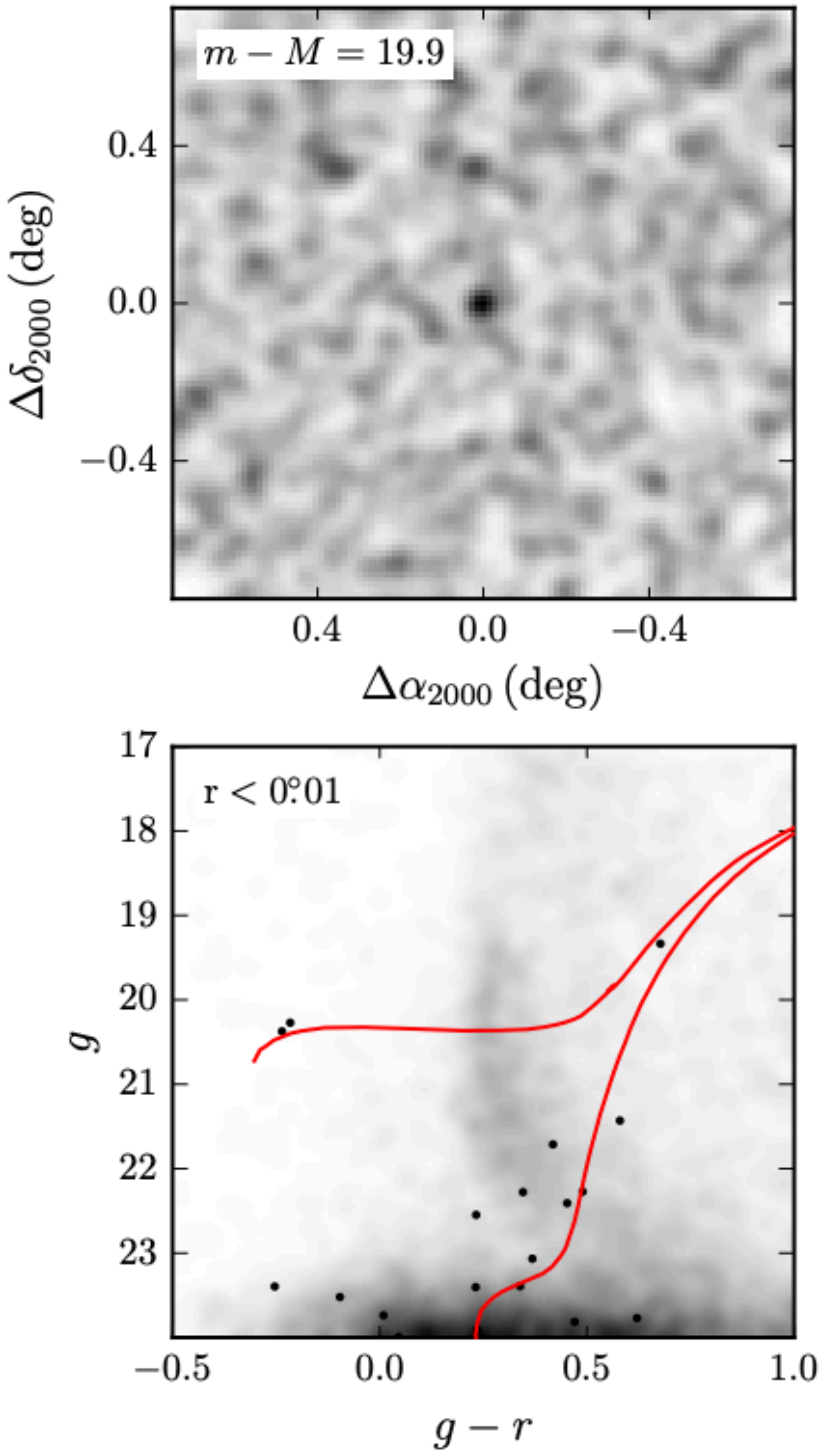
Eridanus III

Mstar ~ $10^3 M_\odot$

rh = 8 pc

d = 91 kpc

First discovered in the Dark Energy Survey



Bechtol et al. 2016

Eridanus III
Dwarf Galaxy or Star Clusters?

Eridanus III

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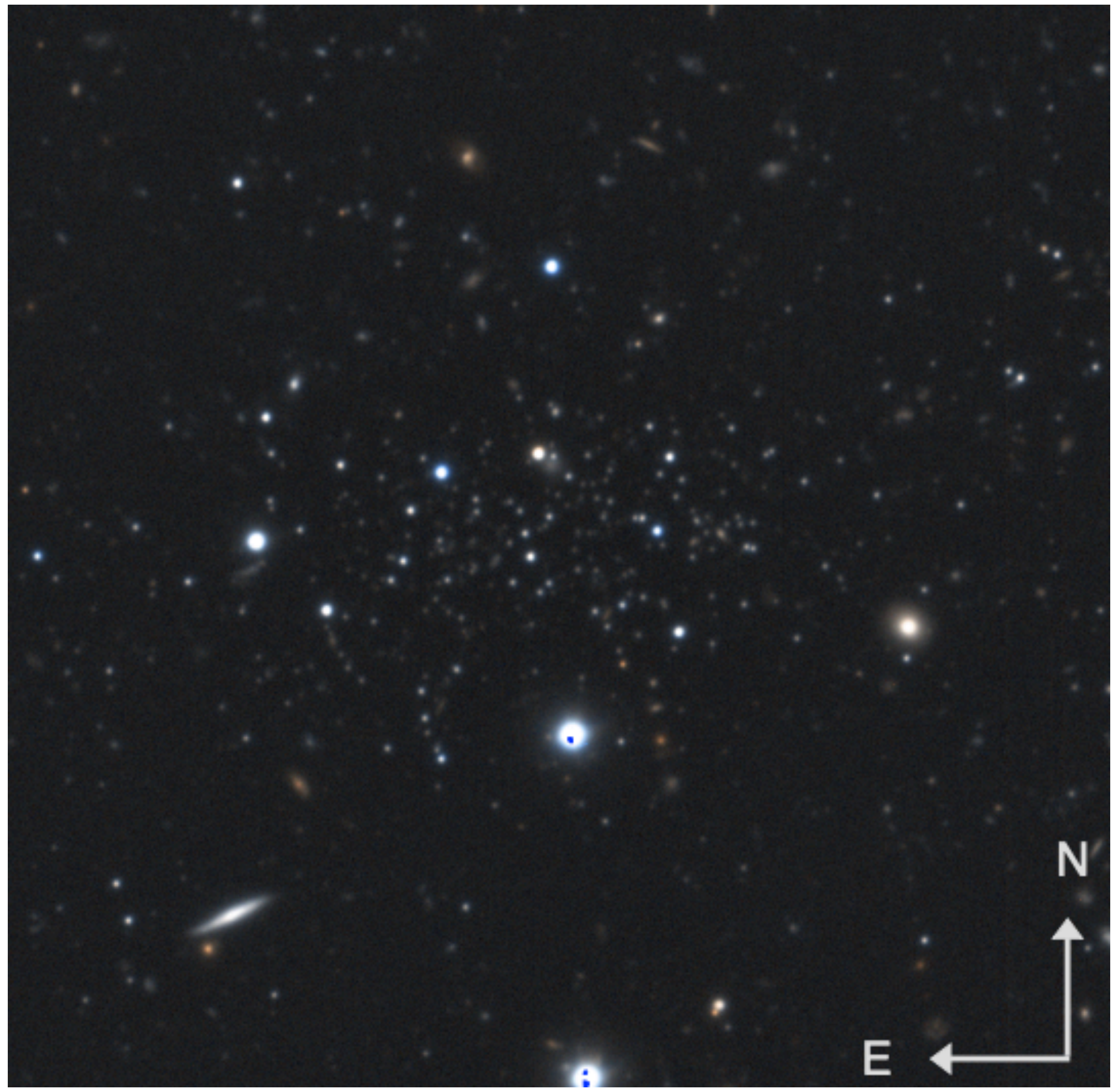
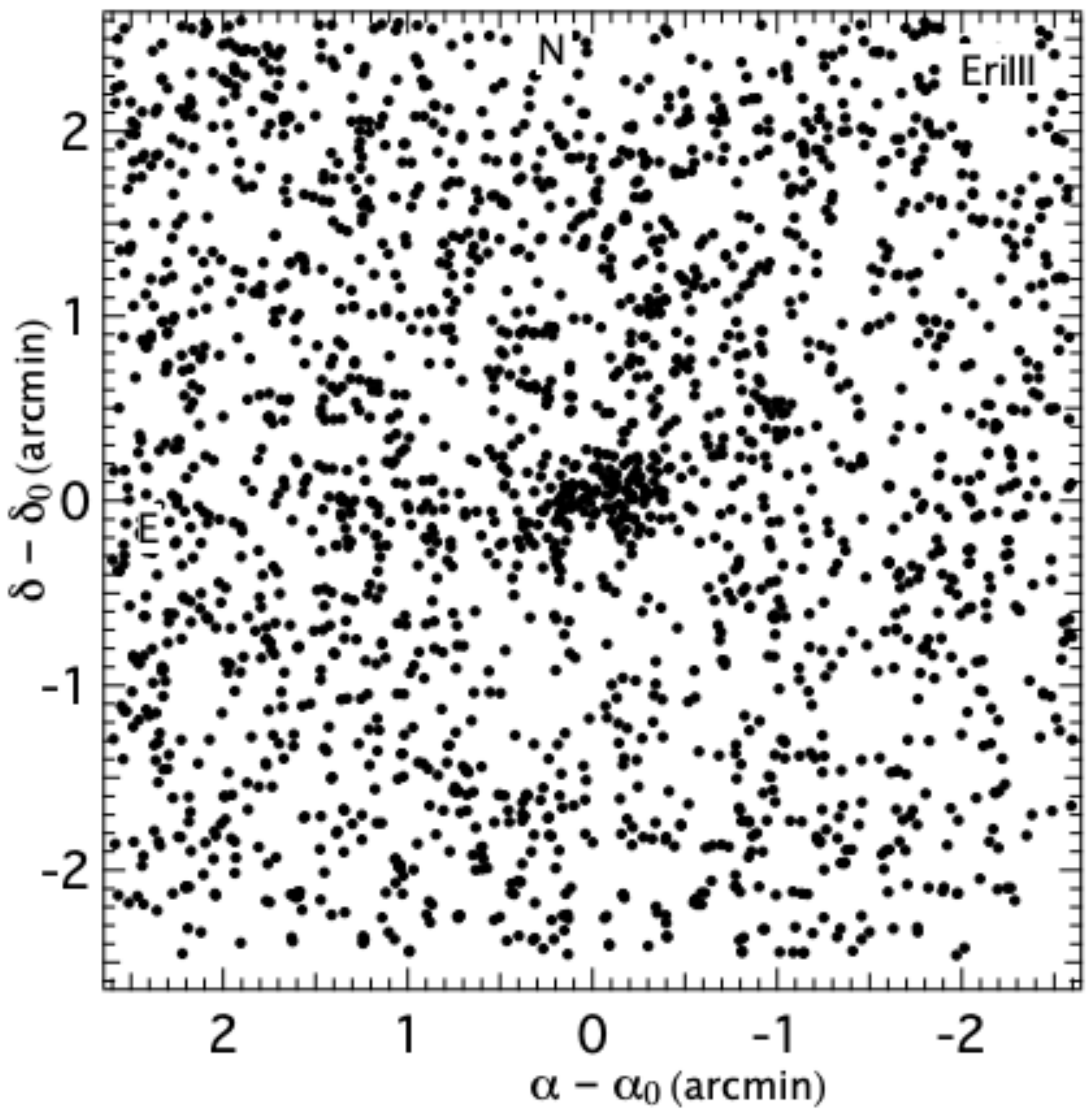
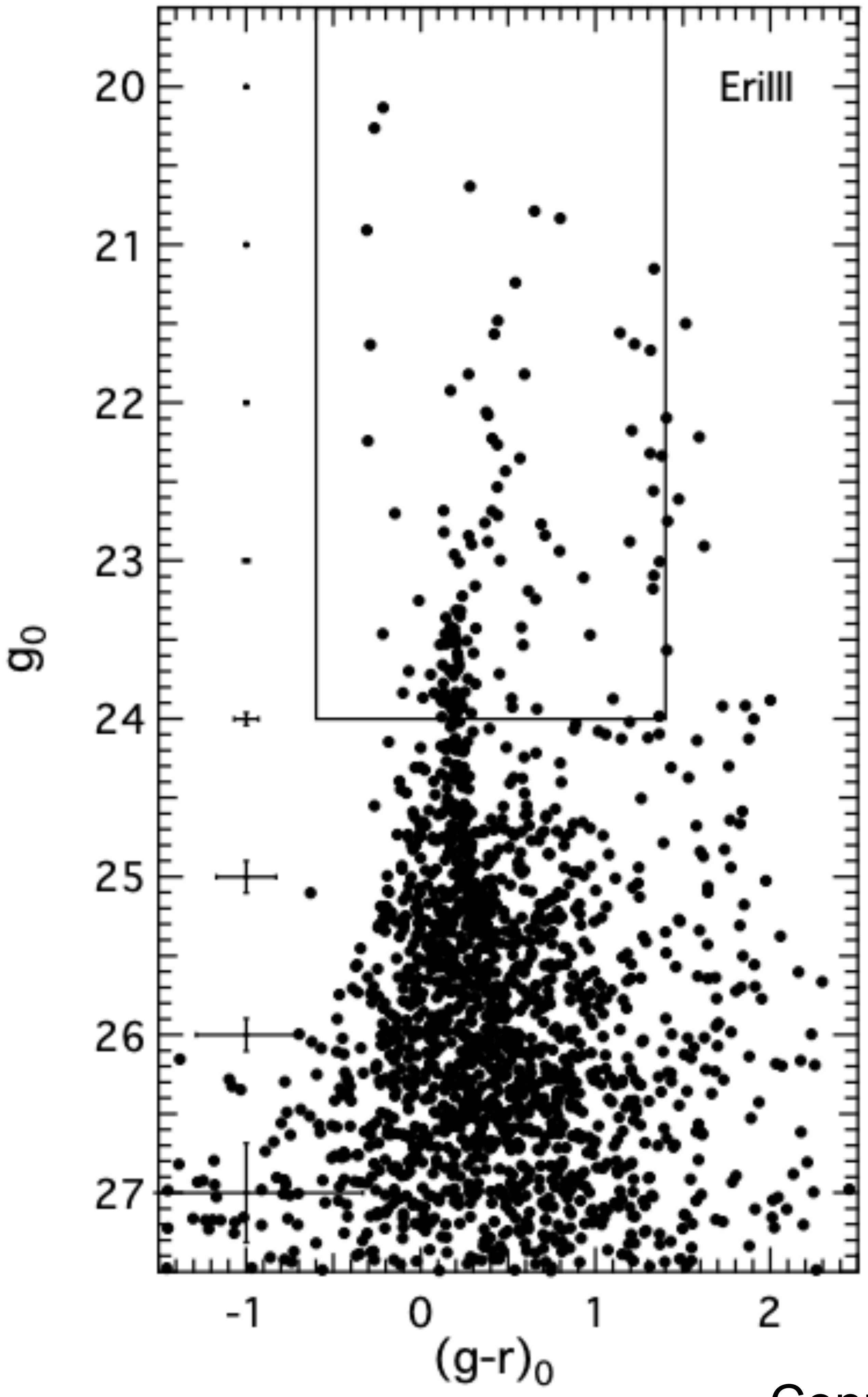
Deep imaging w/ Gemini/GMOS







Conn et al. 2018

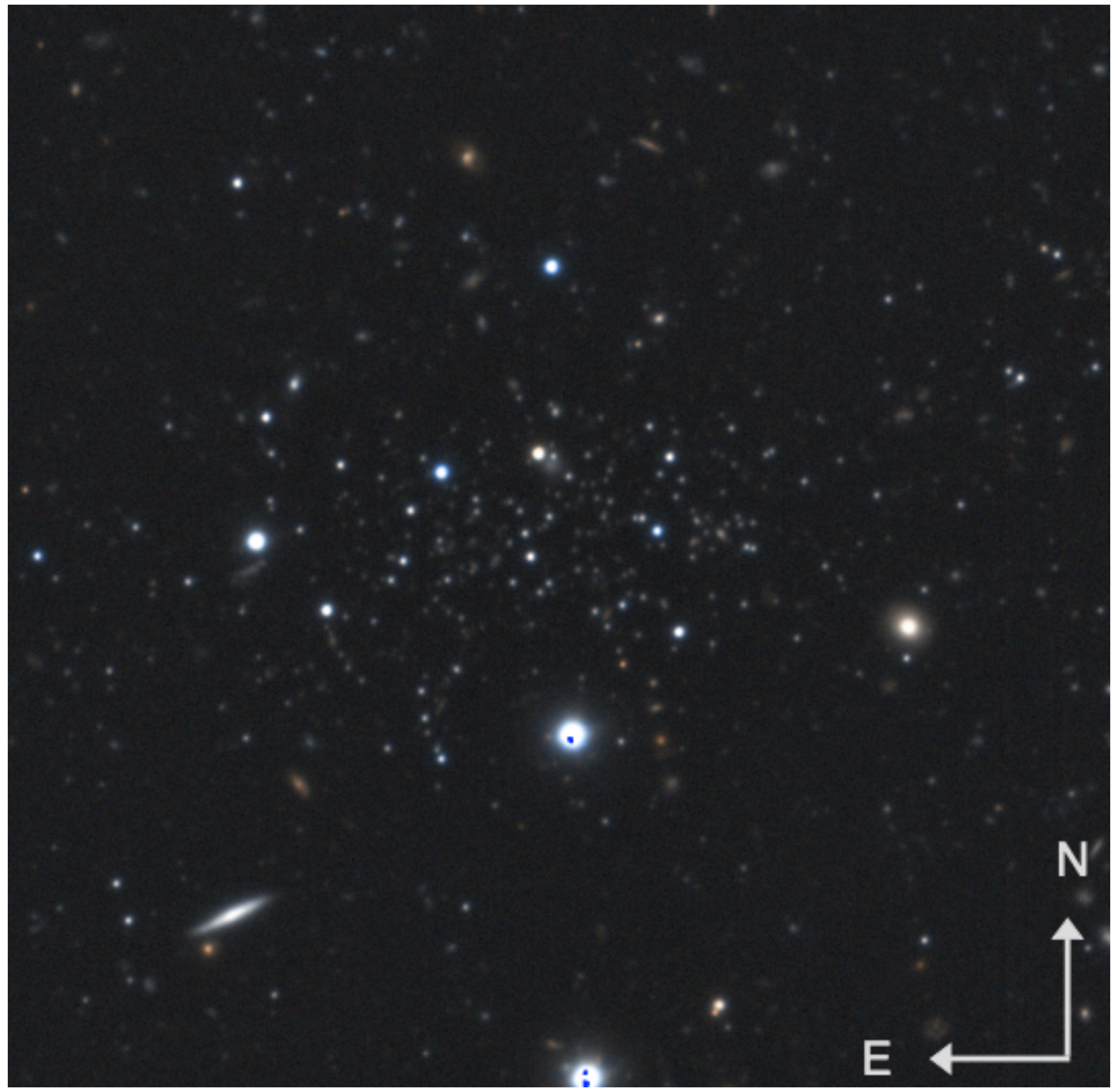
Eridanus III
Dwarf Galaxy or Star Clusters?

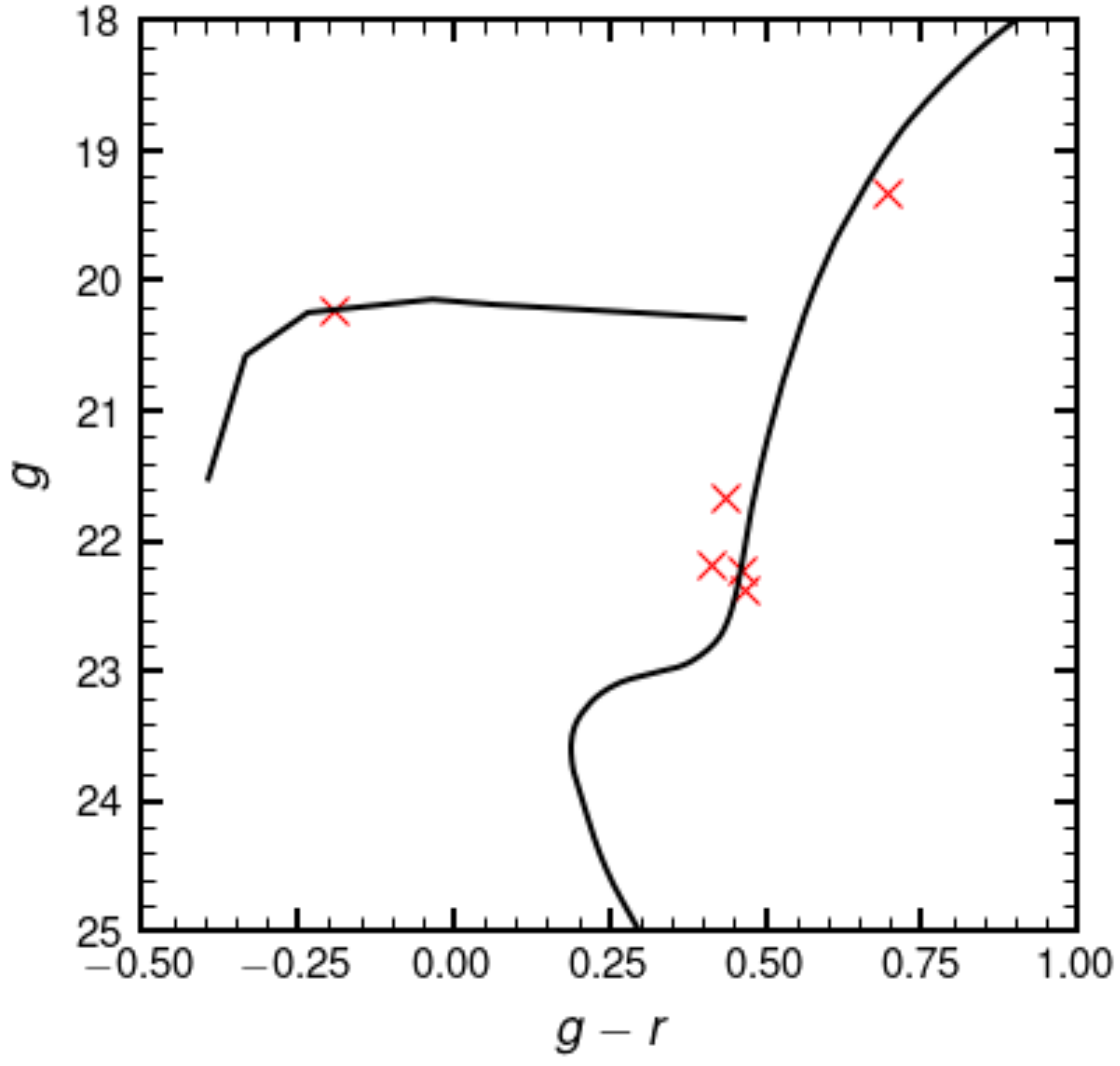
Eridanus III

Mstar ~ $10^3 M_{\odot}$

rh = 8 pc

d = 91 kpc





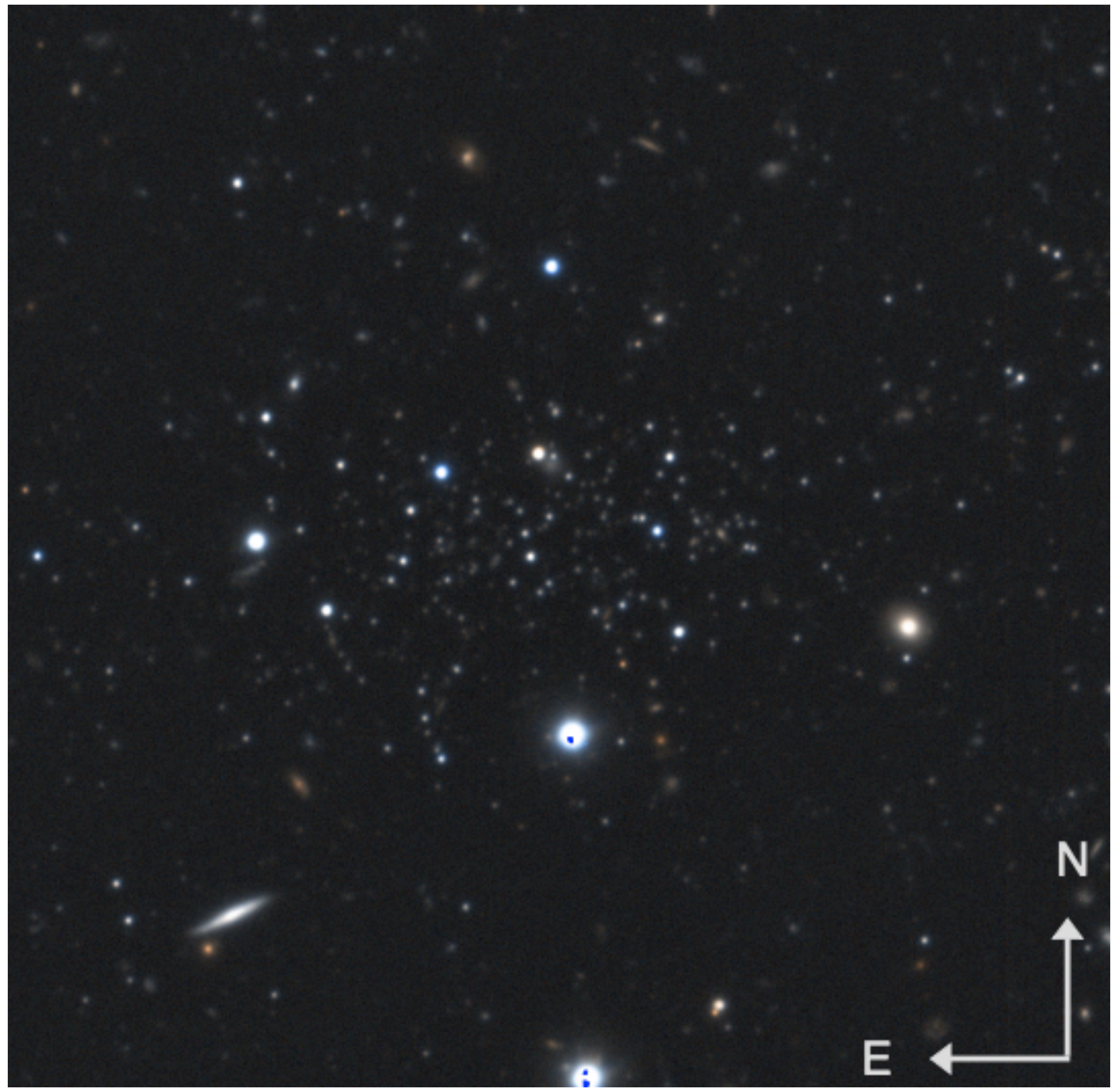
Eridanus III
Dwarf Galaxy or Star Clusters?

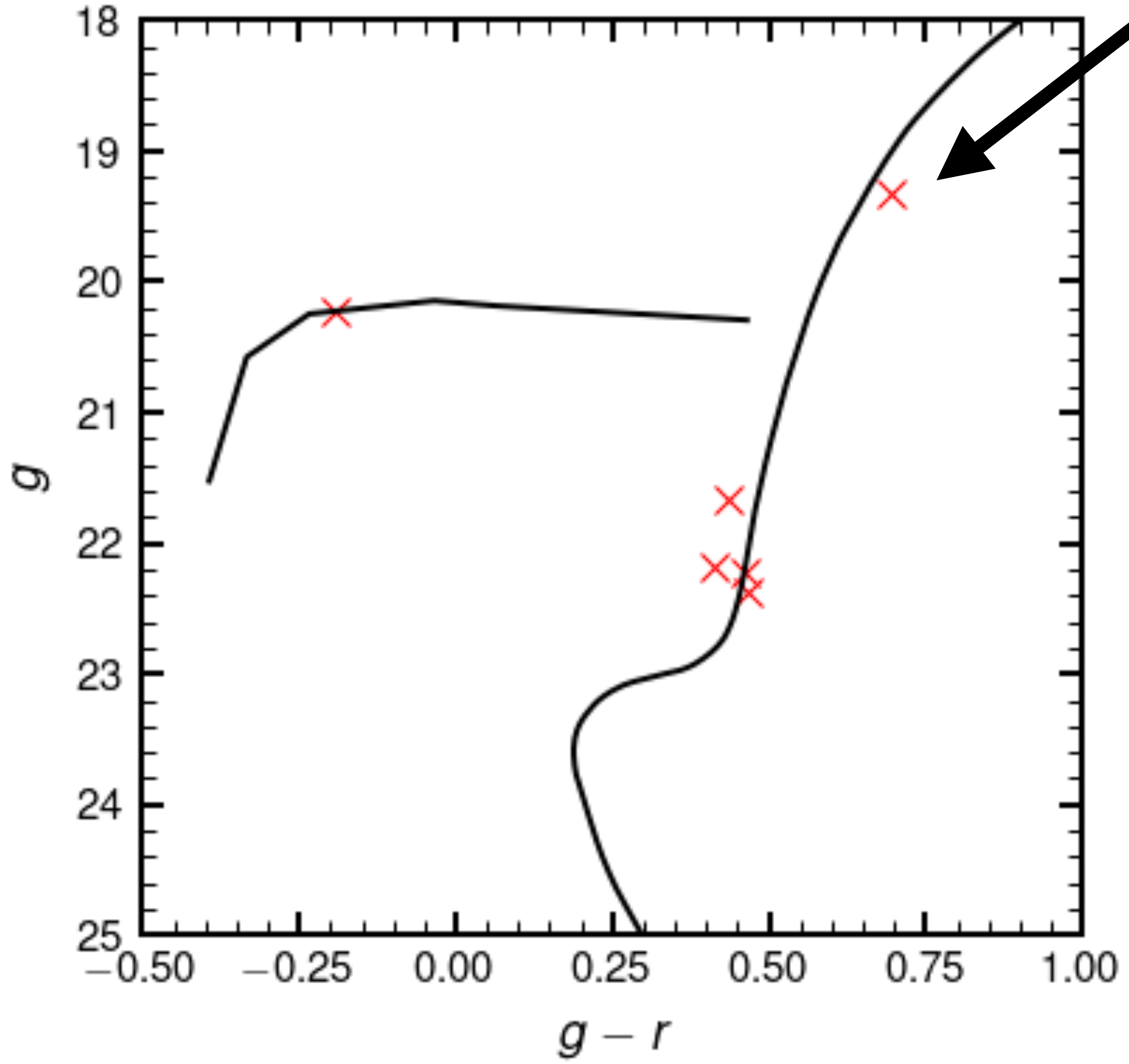
Eridanus III

Mstar ~ $10^3 M_\odot$

rh = 8 pc

d = 91 kpc





The brightest member has [Fe/H] = -3.3 !

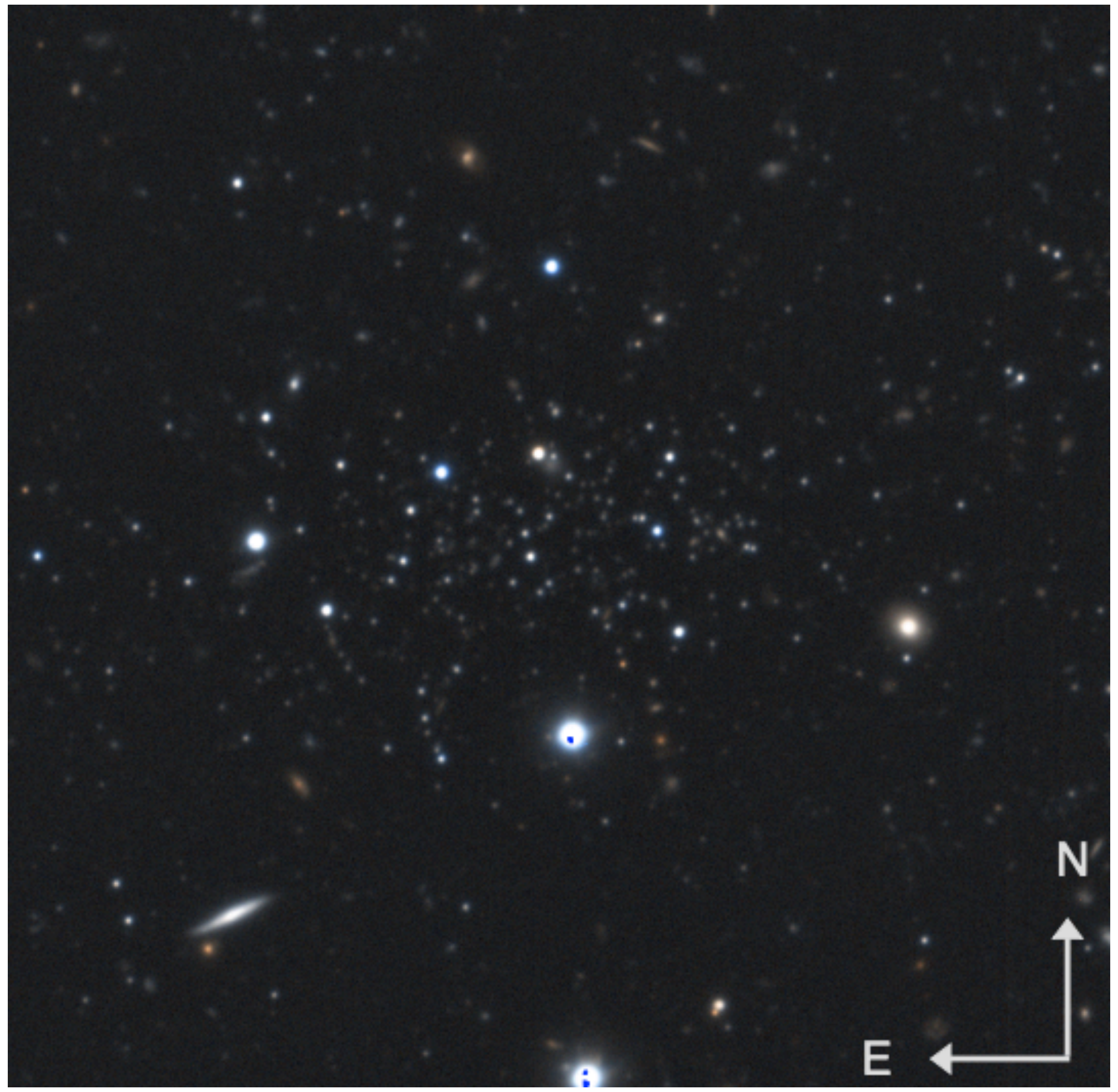
Eridanus III
Dwarf Galaxy or Star Clusters?

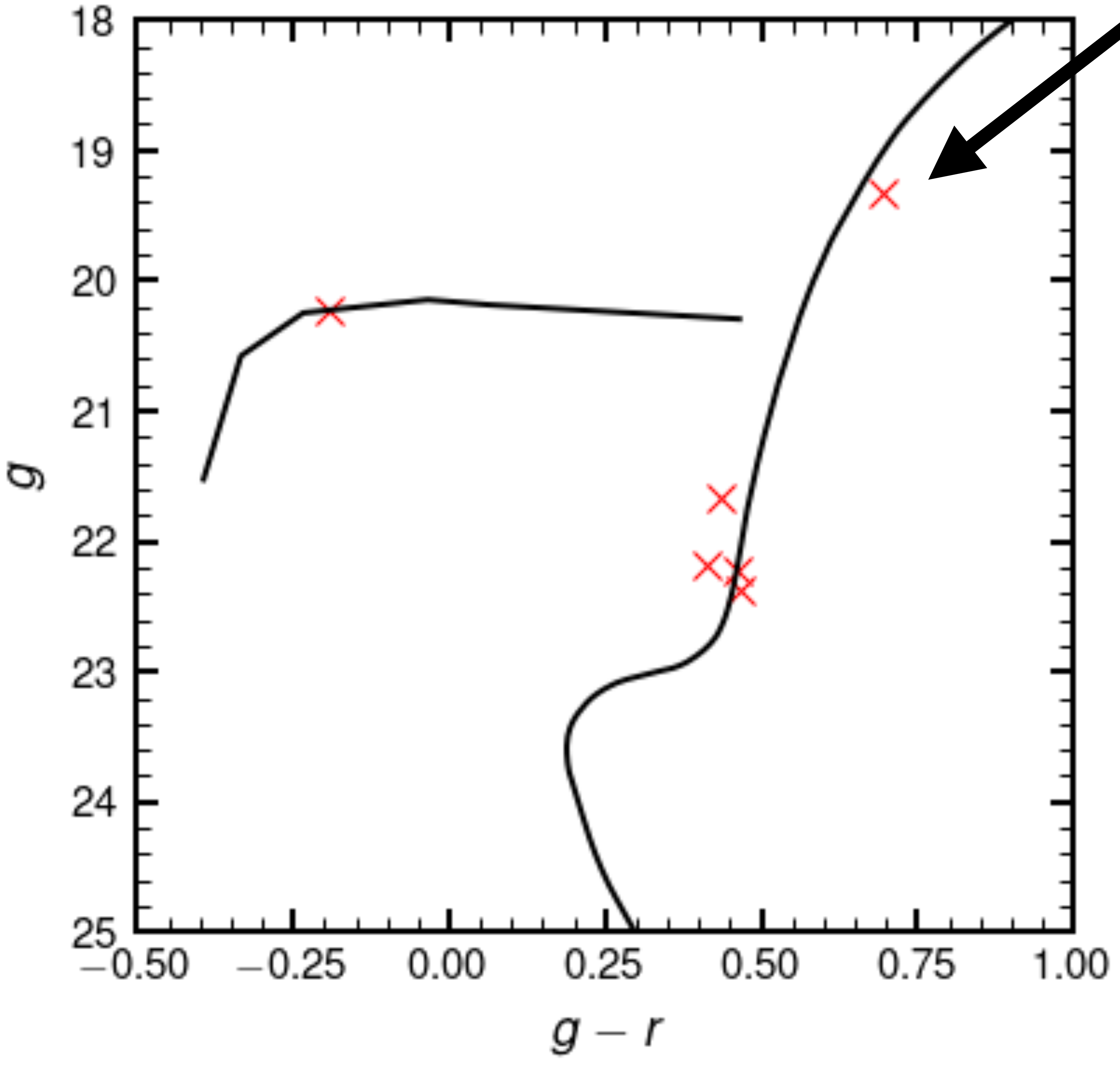
Eridanus III

***Mstar* ~** $10^3 M_\odot$

rh = 8 pc

d = 91 kpc

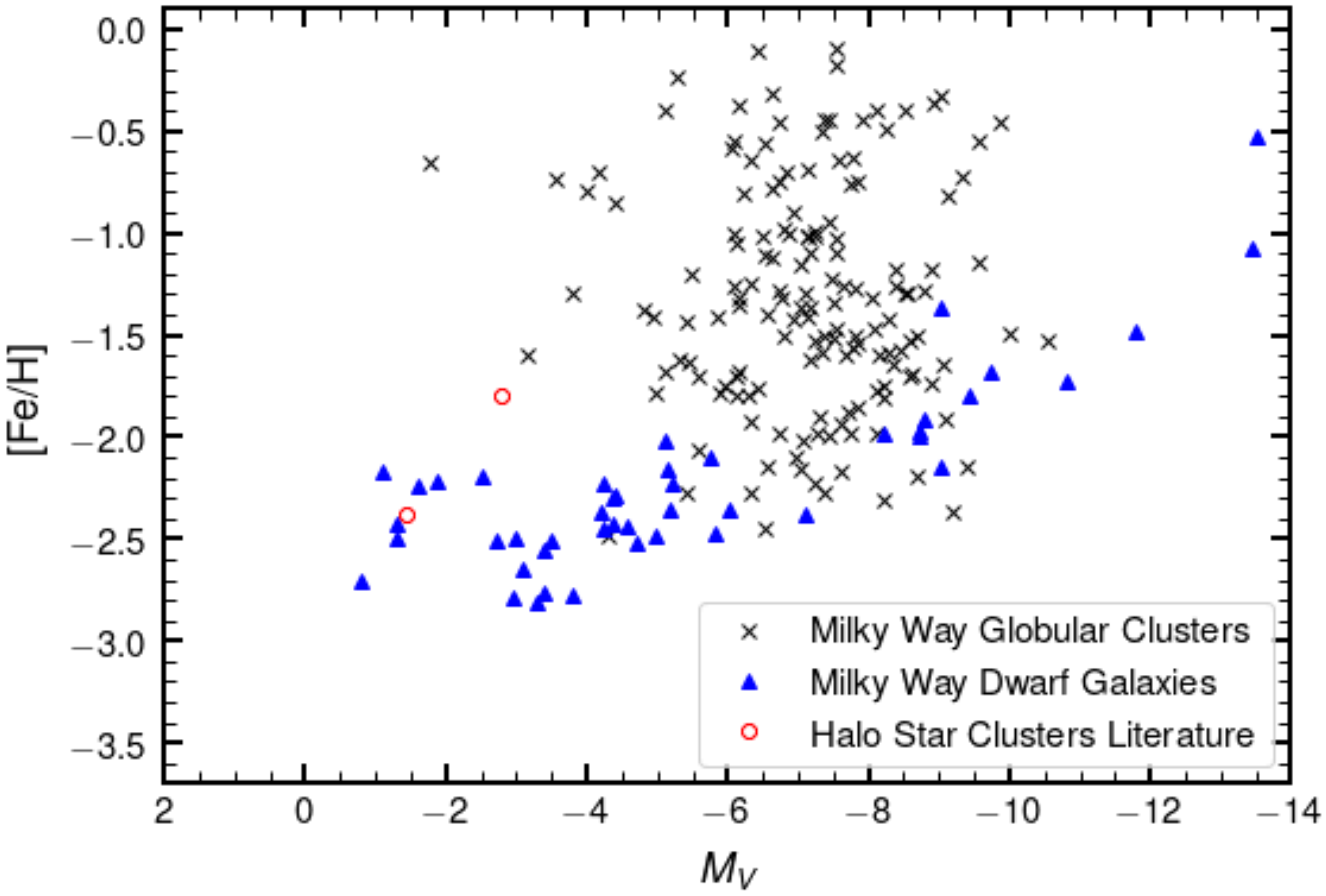




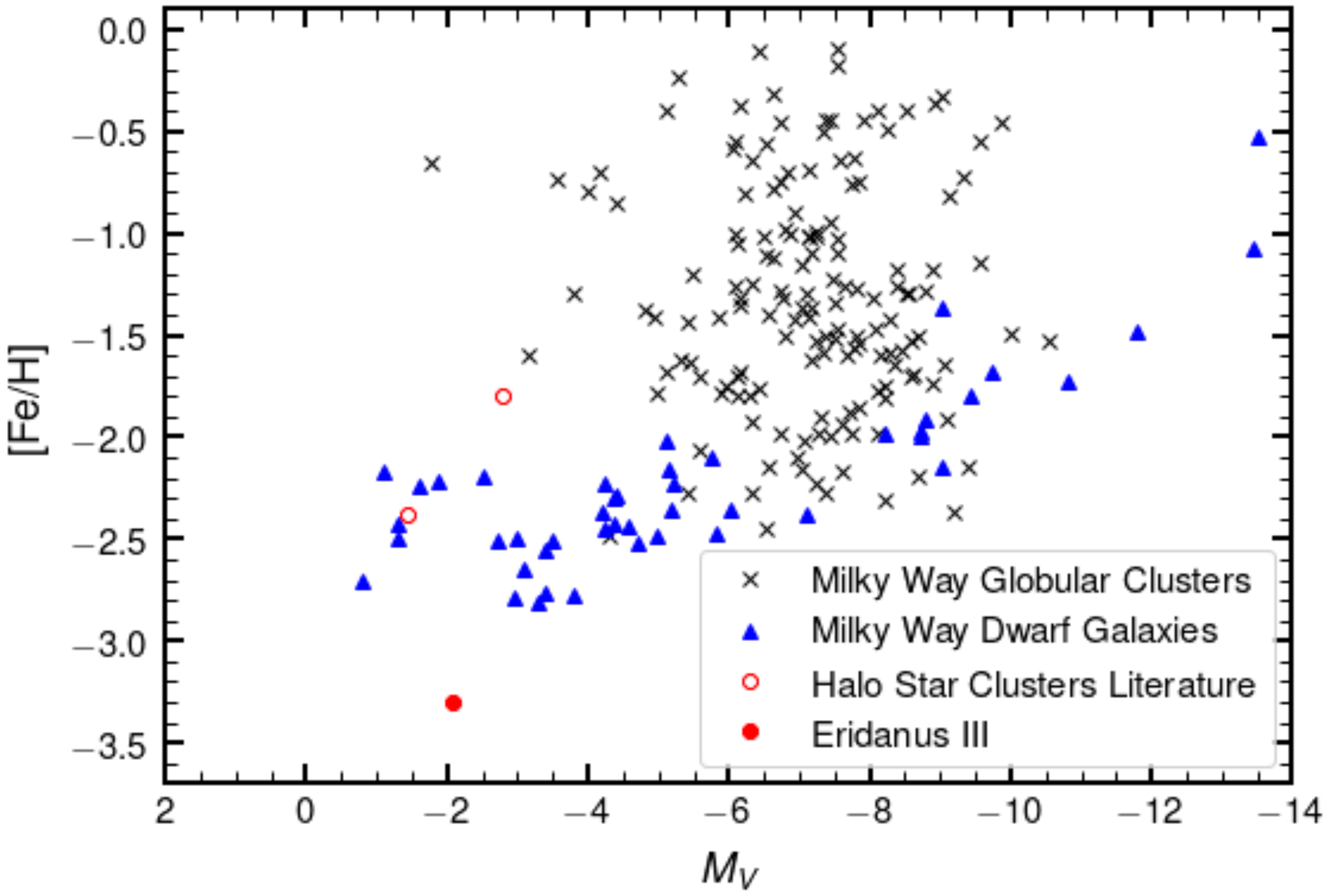
The brightest member has [Fe/H] = -3.3 !

Is Eridanus III the most metal-poor star cluster or most compact dwarf galaxy?

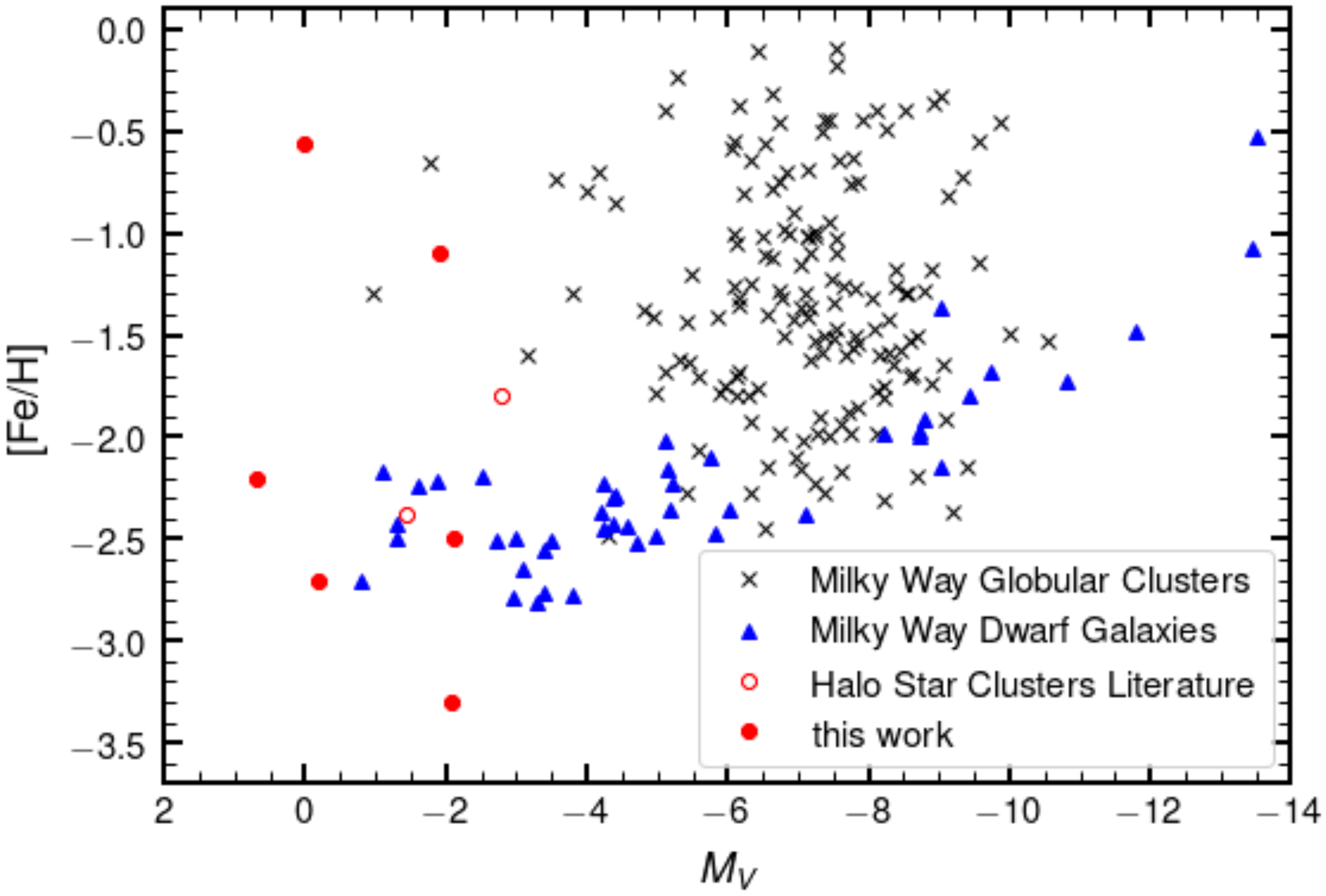
Dwarf Galaxies vs Star Clusters via (stellar) mass-metallicity relation



Dwarf Galaxies vs Star Clusters via (stellar) mass-metallicity relation



Dwarf Galaxies vs Star Clusters
via (stellar) mass-metallicity relation

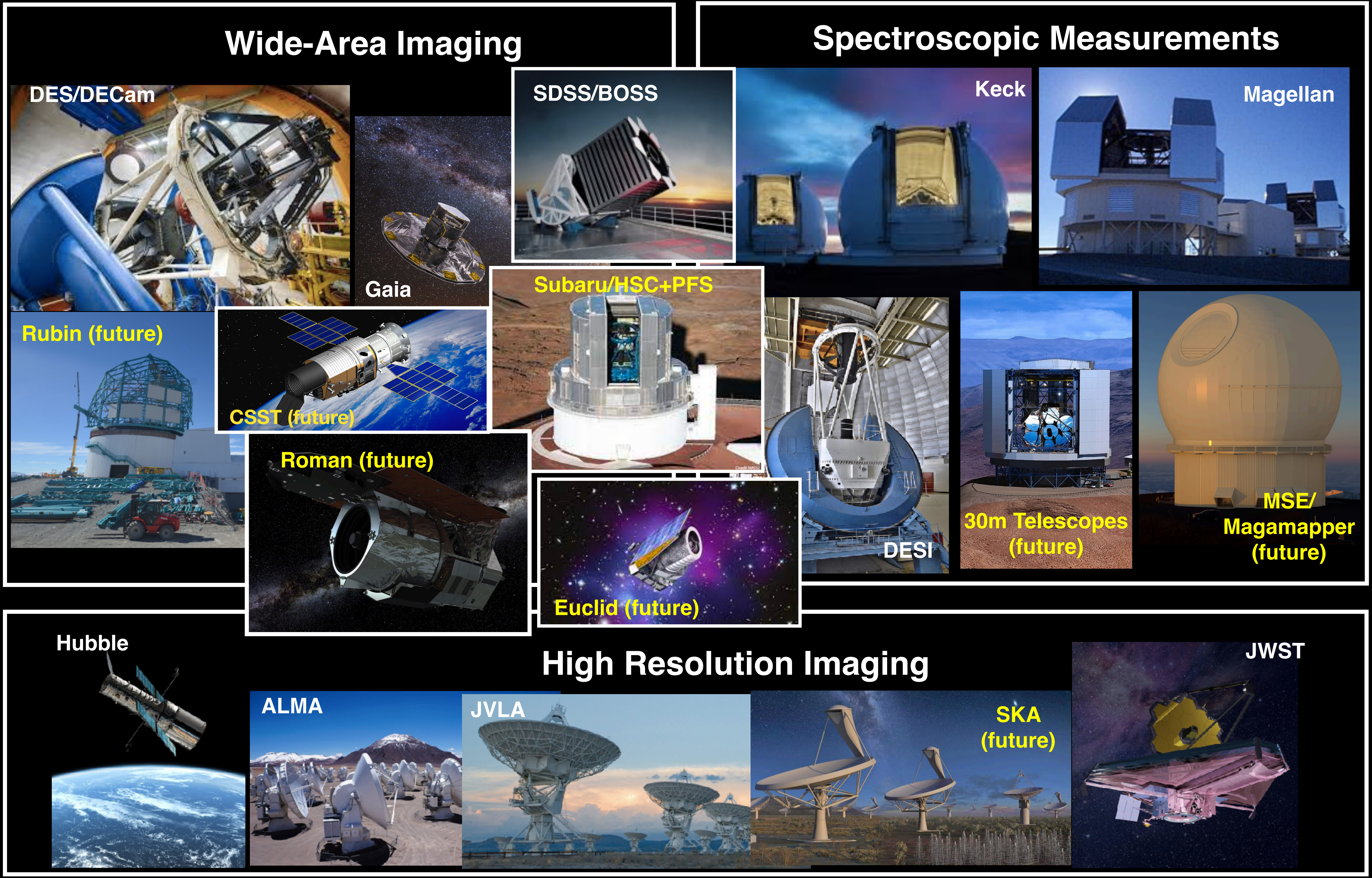


Smallest Galaxies or the most metal-poor globular clusters

We are finding tons of faintest systems (and compact) in the deep photometric data, and MORE are coming for the next decade? What are these?

There are a lot of observing results you might have missed due to pandemic, and here they are!
We need more work on simulations/modeling to catch up!

The next decade will be full of data for dark matter astrophysics!



Wide-Area Imaging
DES/DECam
Gaia
SDSS/BOSS
Subaru/HSC+PFS
Rubin (future)
CSST (future)
Roman (future)
Euclid (future)
Spectroscopic Measurements
Keck
Magellan
DESI
30m Telescopes (future)
MSE/ Magamapper (future)
High Resolution Imaging
Hubble
ALMA
JVLA
SKA (future)
JWST

DESI — Dark Energy Spectroscopic Instrument

MWS — Milky Way Survey

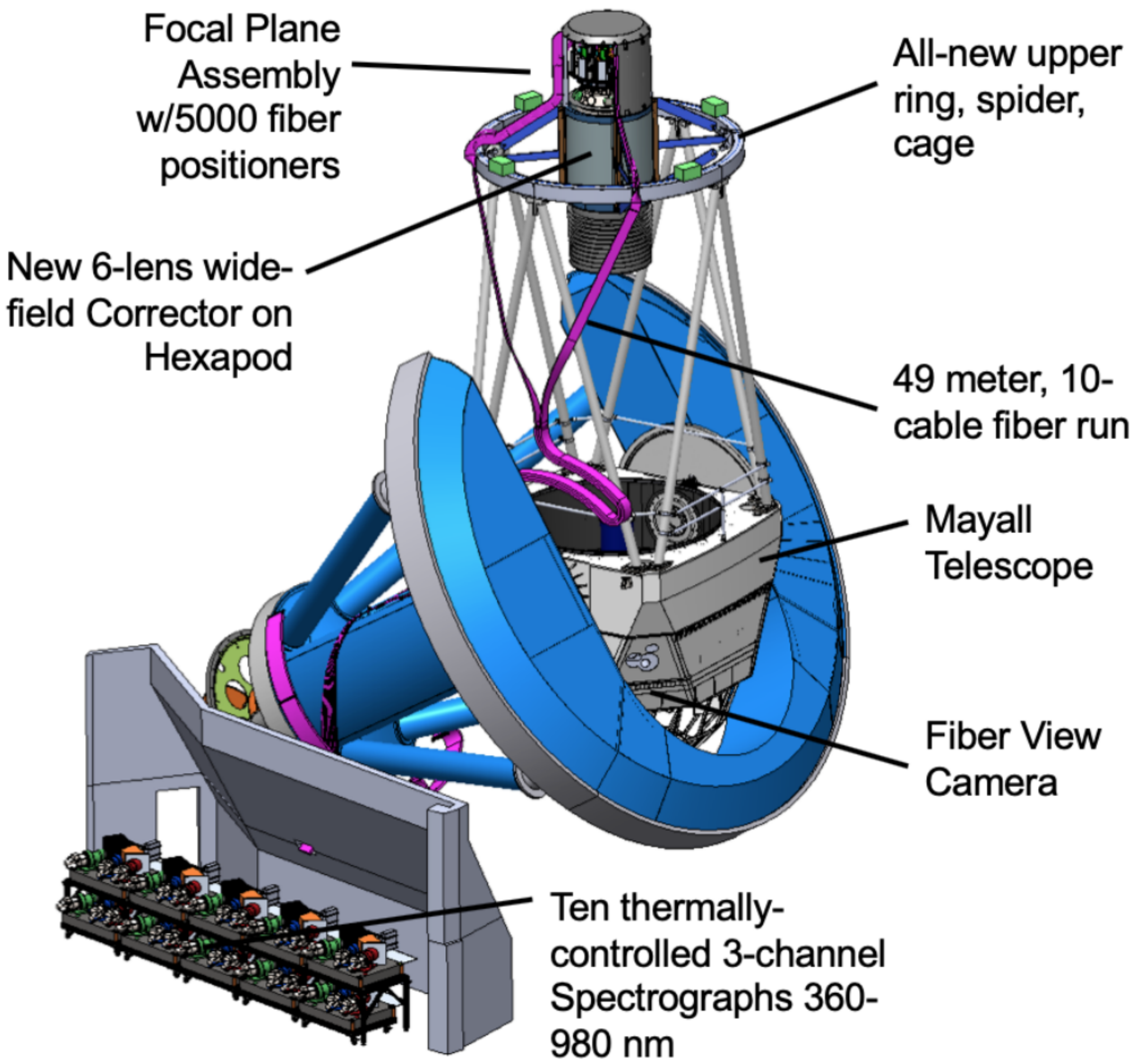
Co-chairs: Chris Manser (Imperial College London)
Ting Li (U of Toronto)

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

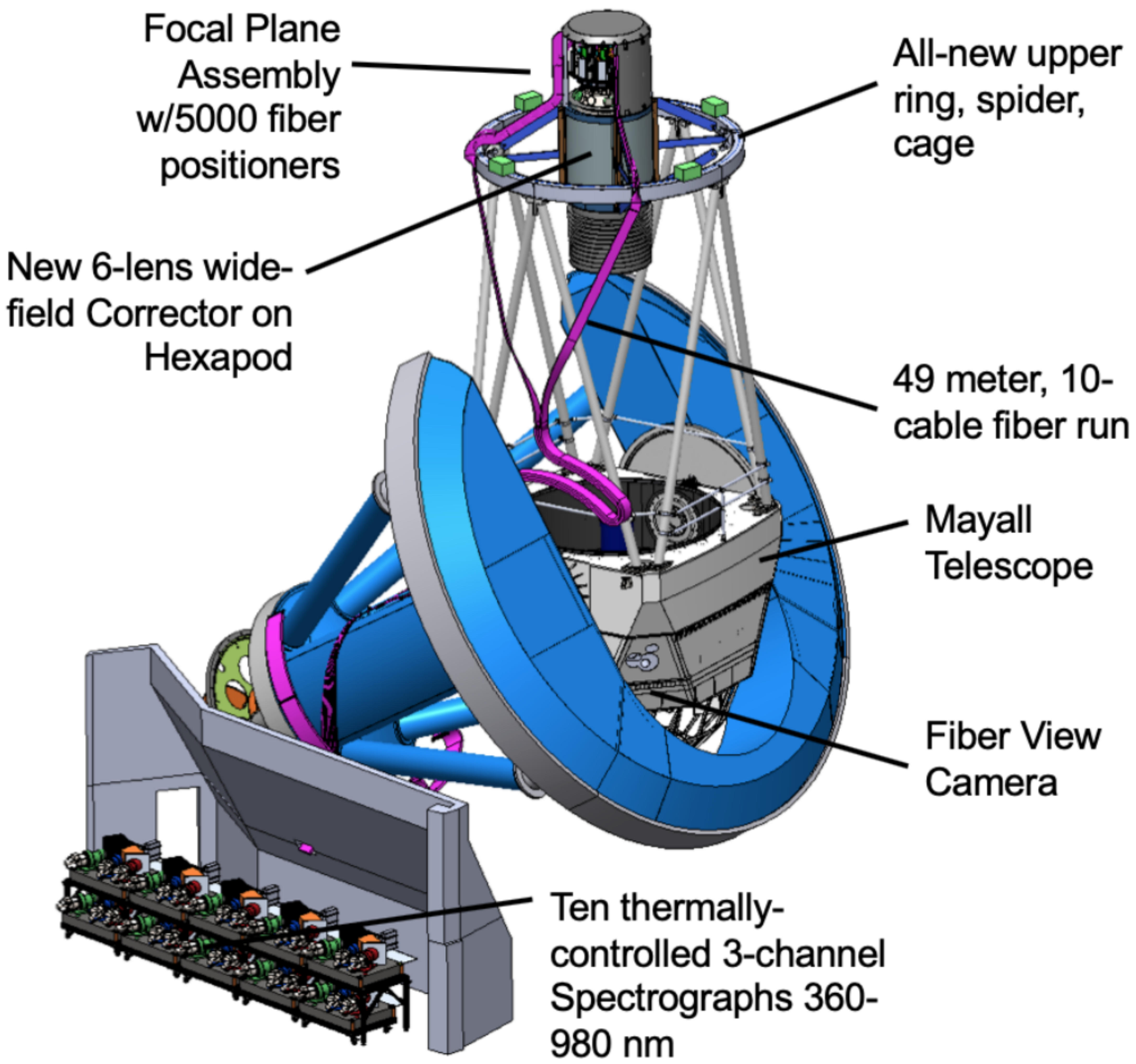
DESI, the instrument in a nutshell



- 4-m Mayall Telescope at KPNO
- 6-Len Wide-field Corrector
- 5000 Robotic Fibers
- 10 3-Channel Spectrograph

Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument
DESI Collaboration et al. 2022, arXiv:2205.10939

DESI, the instrument in a nutshell



- 4-m Mayall Telescope at KPNO
- 6-Len Wide-field Corrector
- 5000 Robotic Fibers
- 10 3-Channel Spectrograph

- Dec 2020 - May 2021: Commissioning and Science Verification
  - Early Data Release in June 2023
- May 2021: Main Survey (5 yr)
  - Year 1: May 2021 - June 2022

Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument
DESI Collaboration et al. 2022, arXiv:2205.10939

DESI, the instrument in a nutshell

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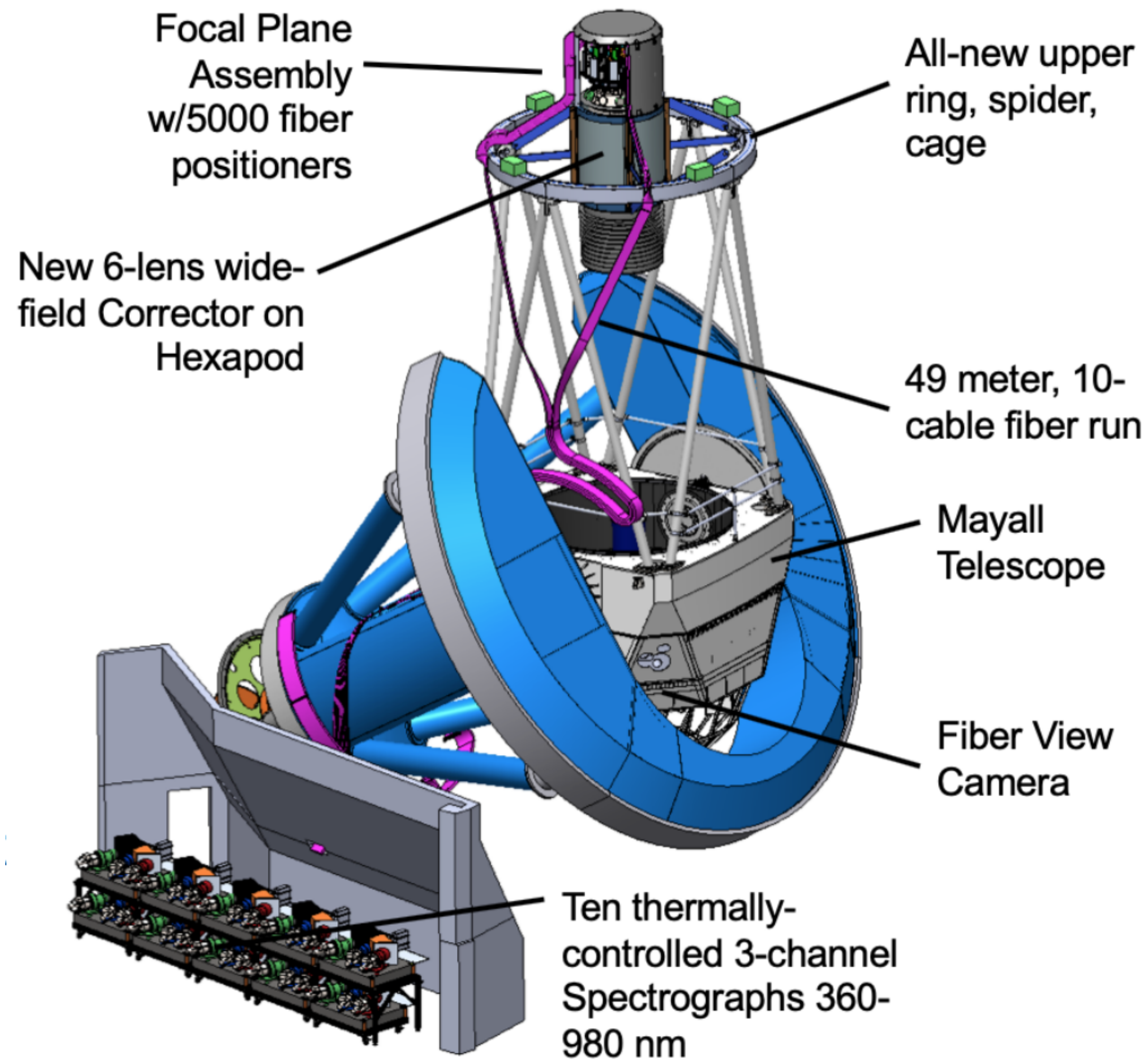
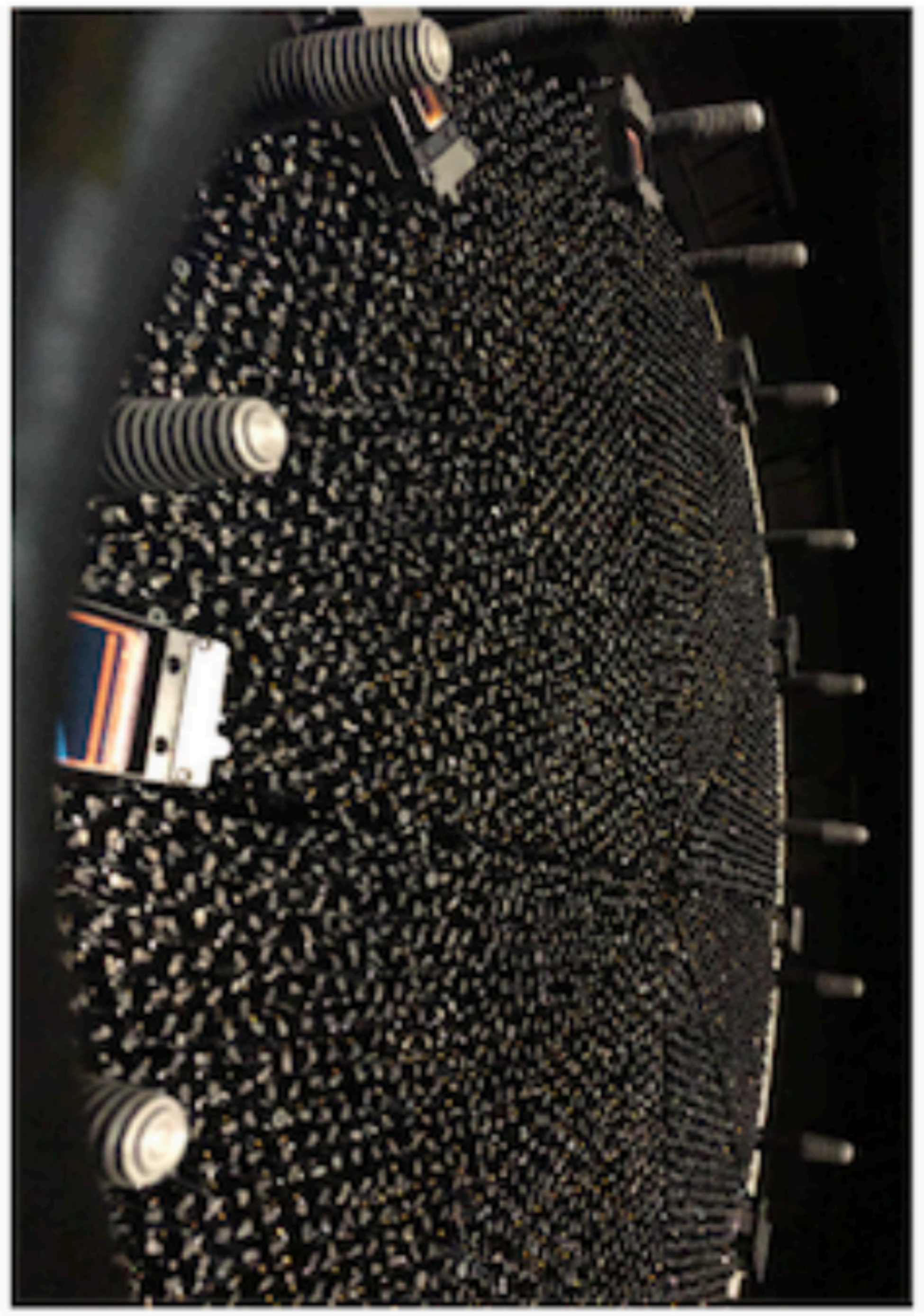
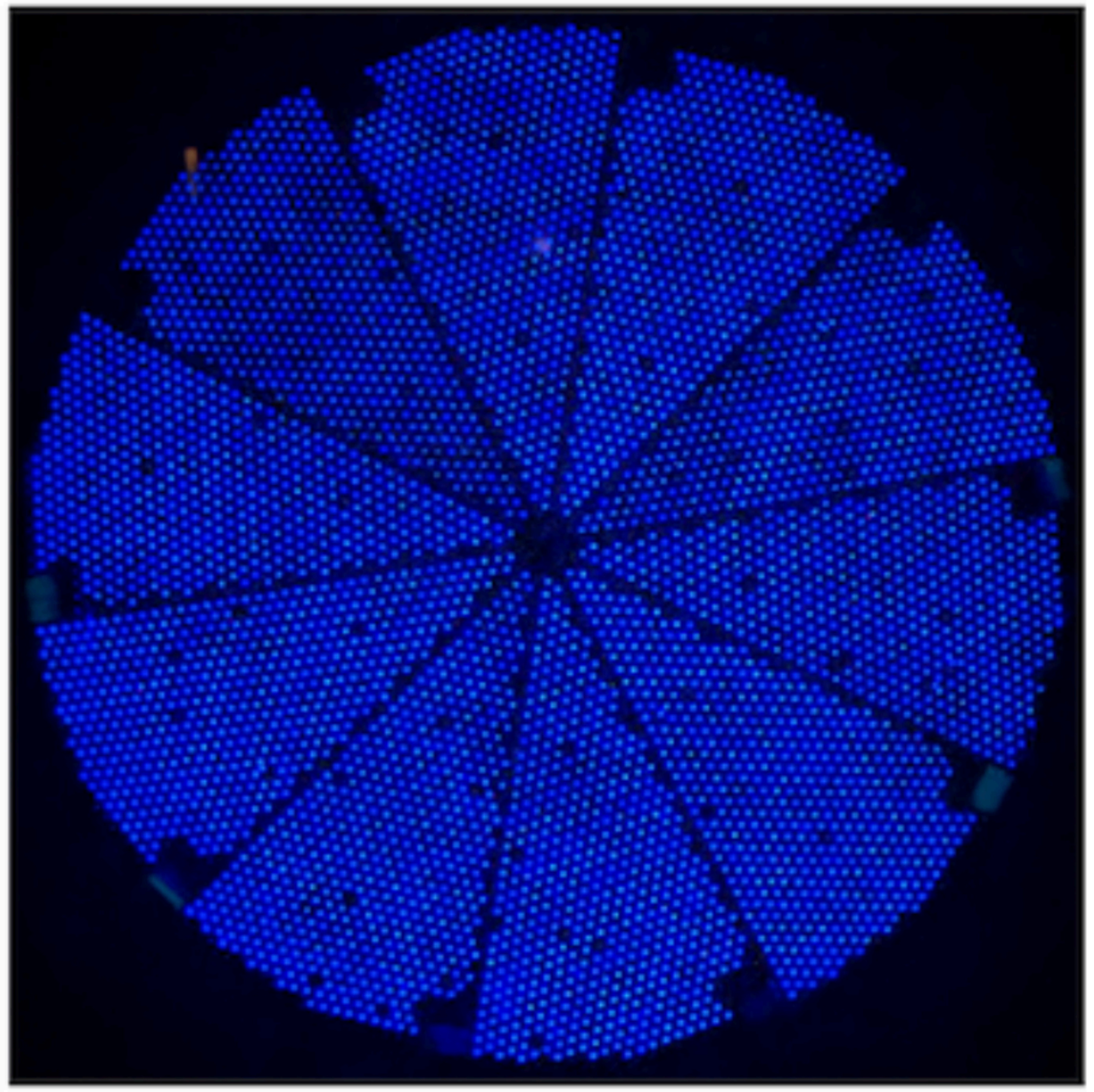
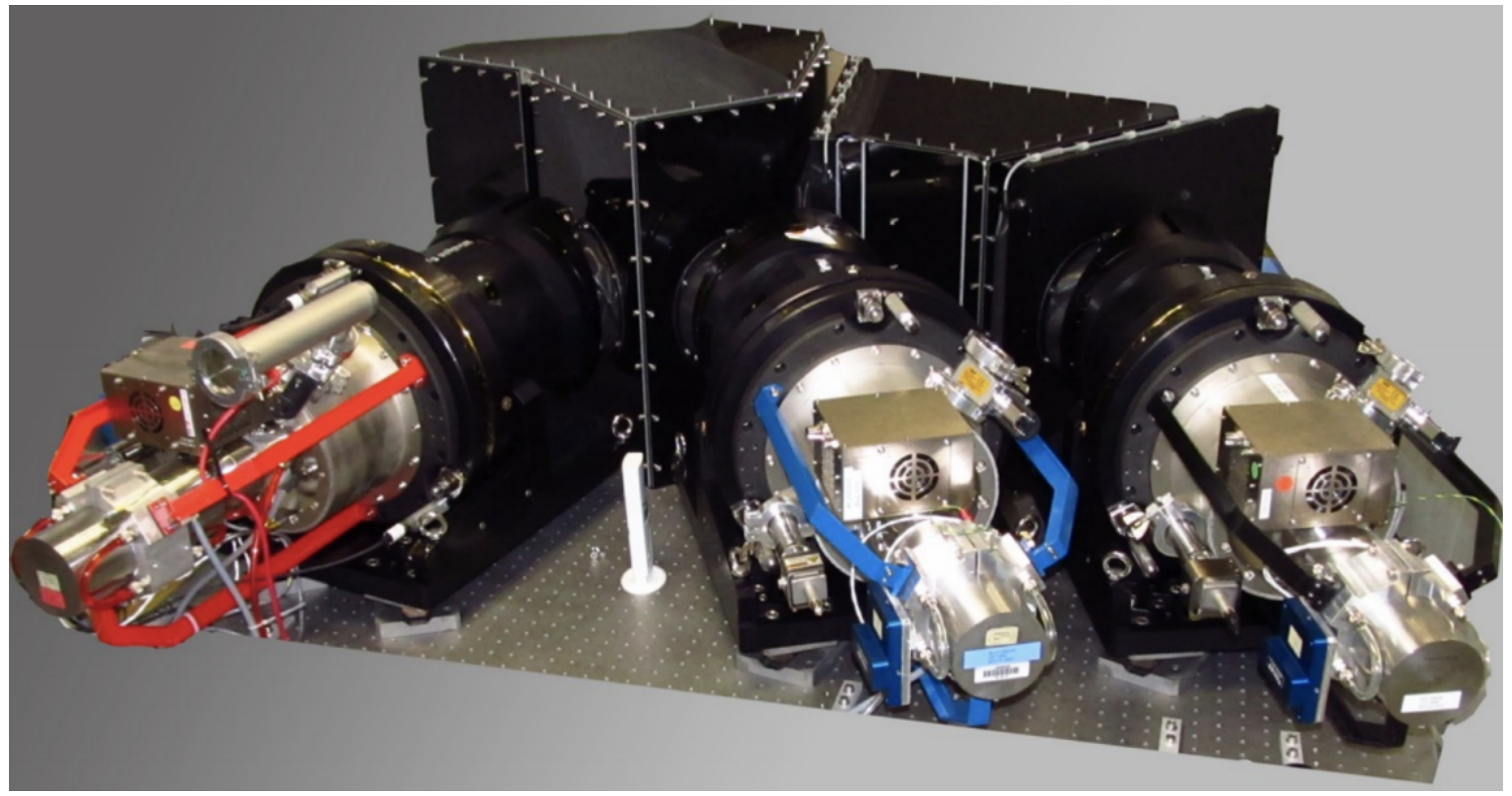


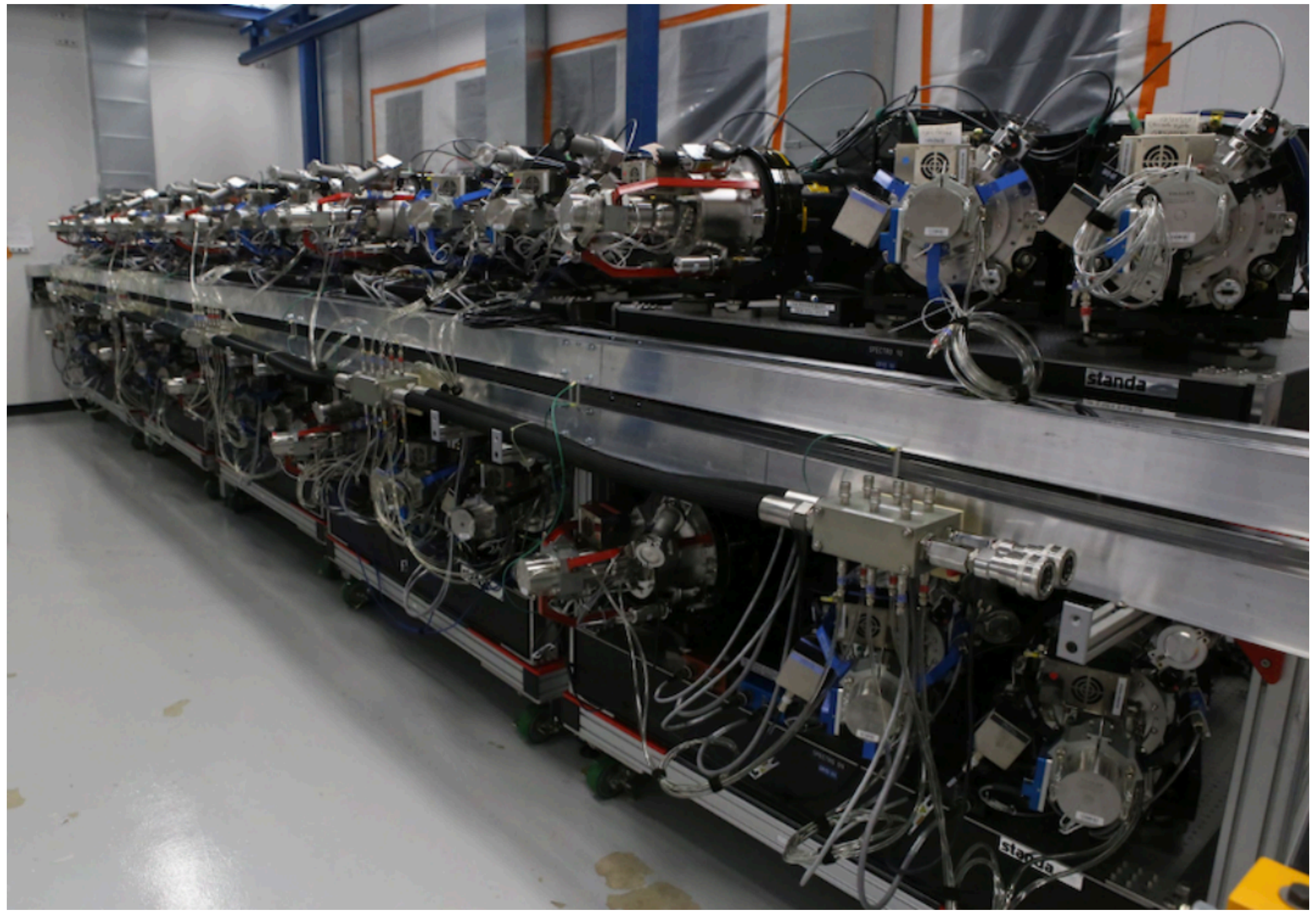




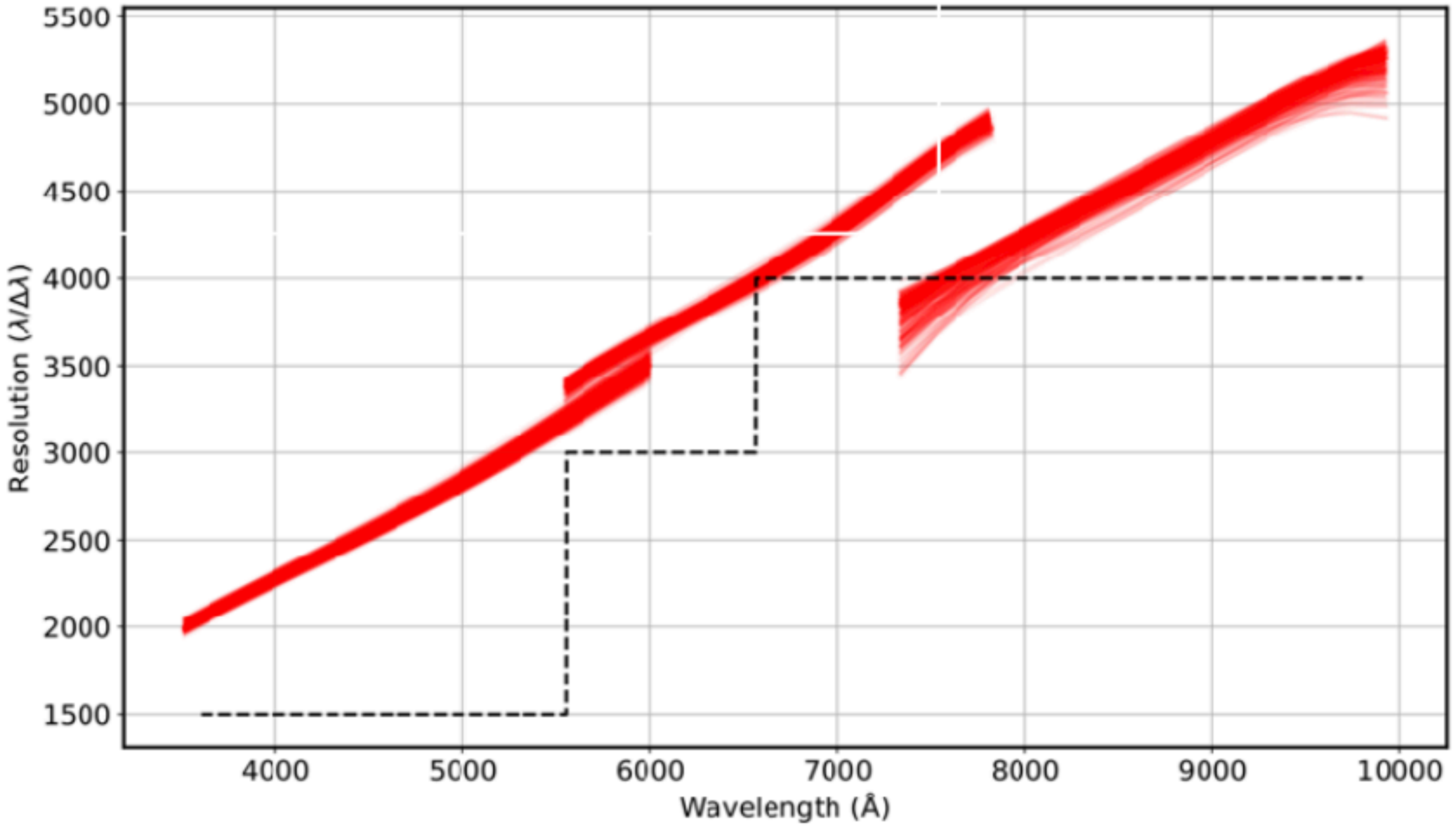
Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument
DESI Collaboration et al. 2022, arXiv:2205.10939

10 3-channel Spectrographs





Spectral Resolution: R~2500-5000



Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument
DESI Collaboration et al. 2022, arXiv:2205.10939

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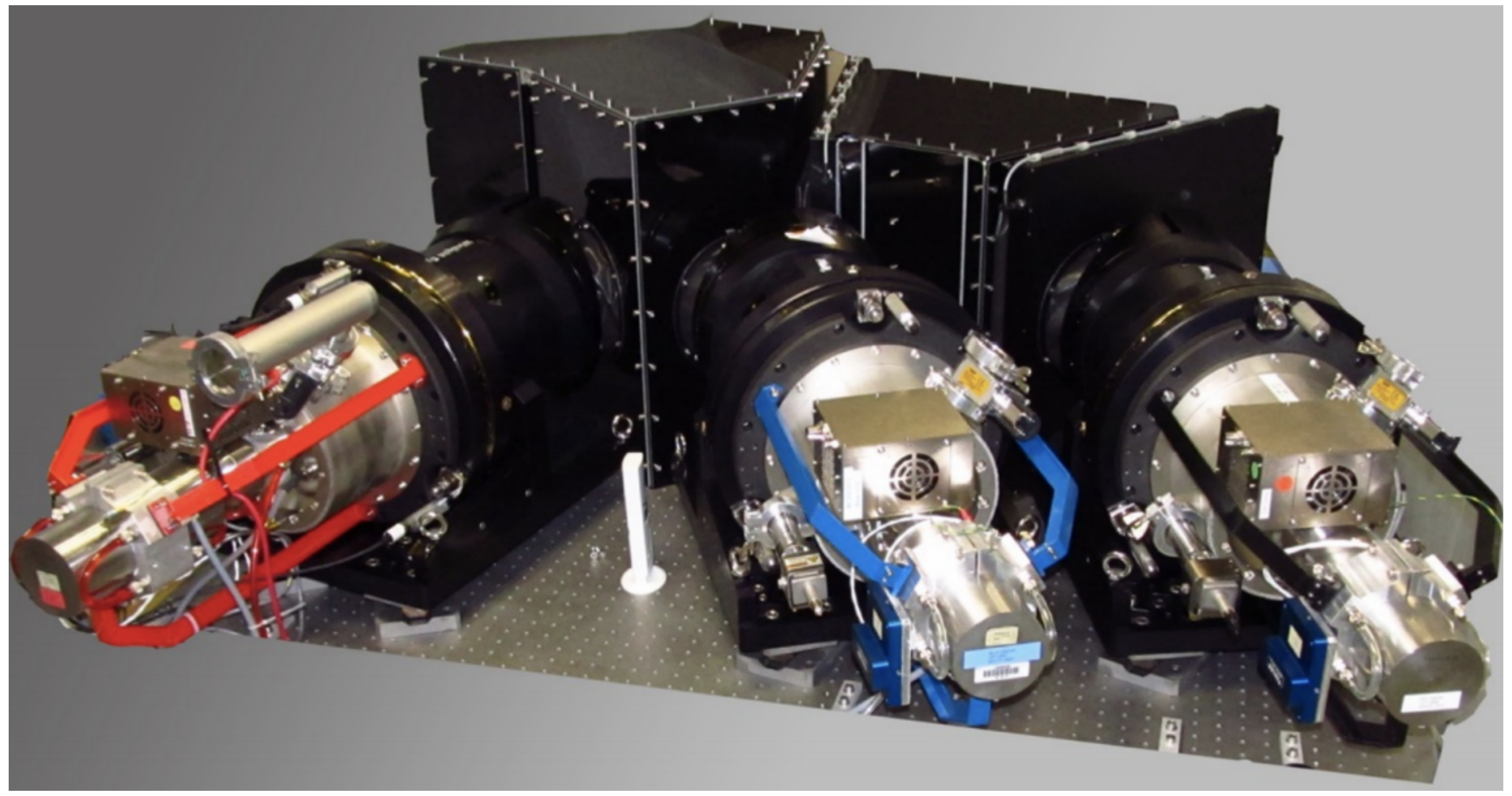
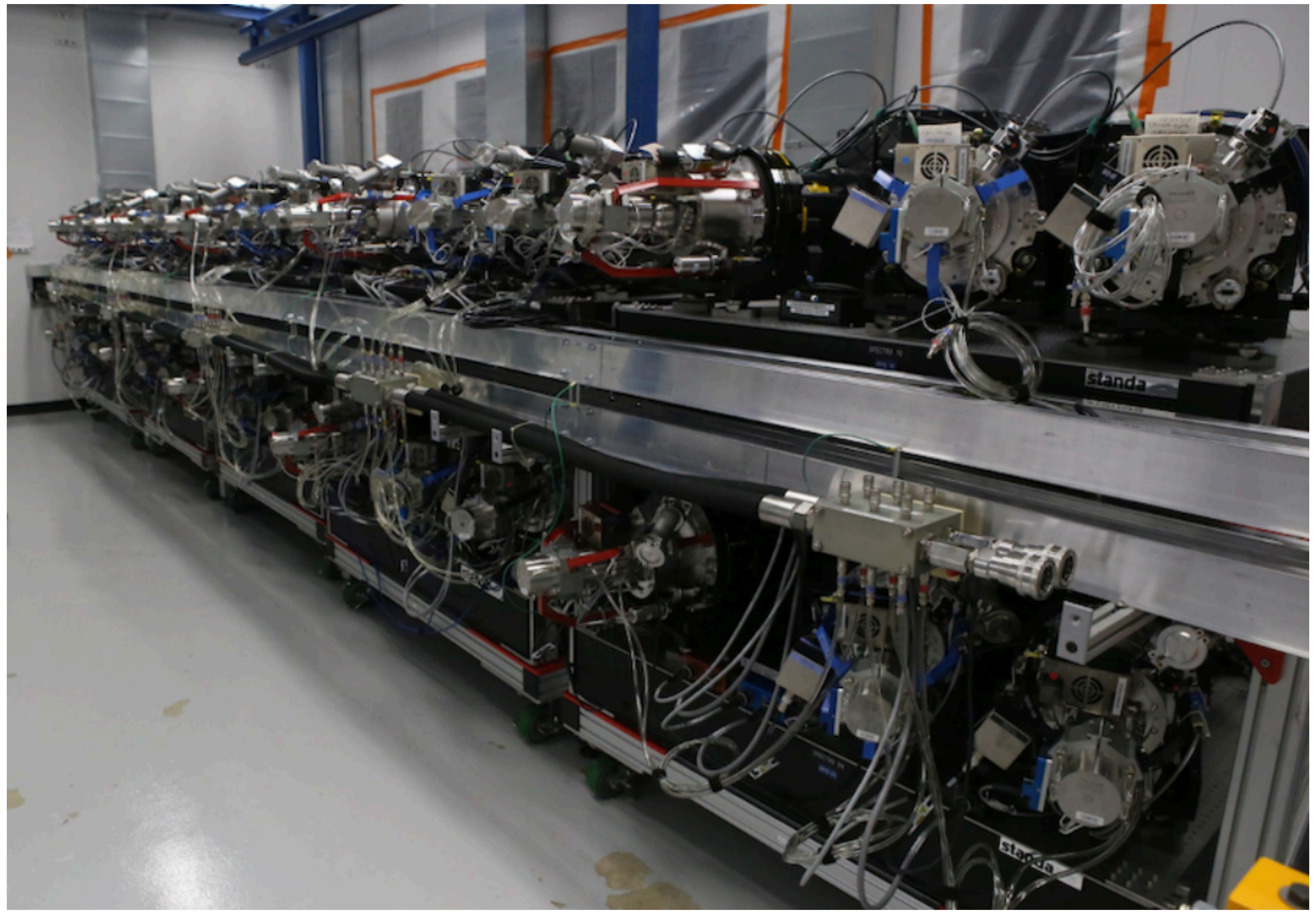
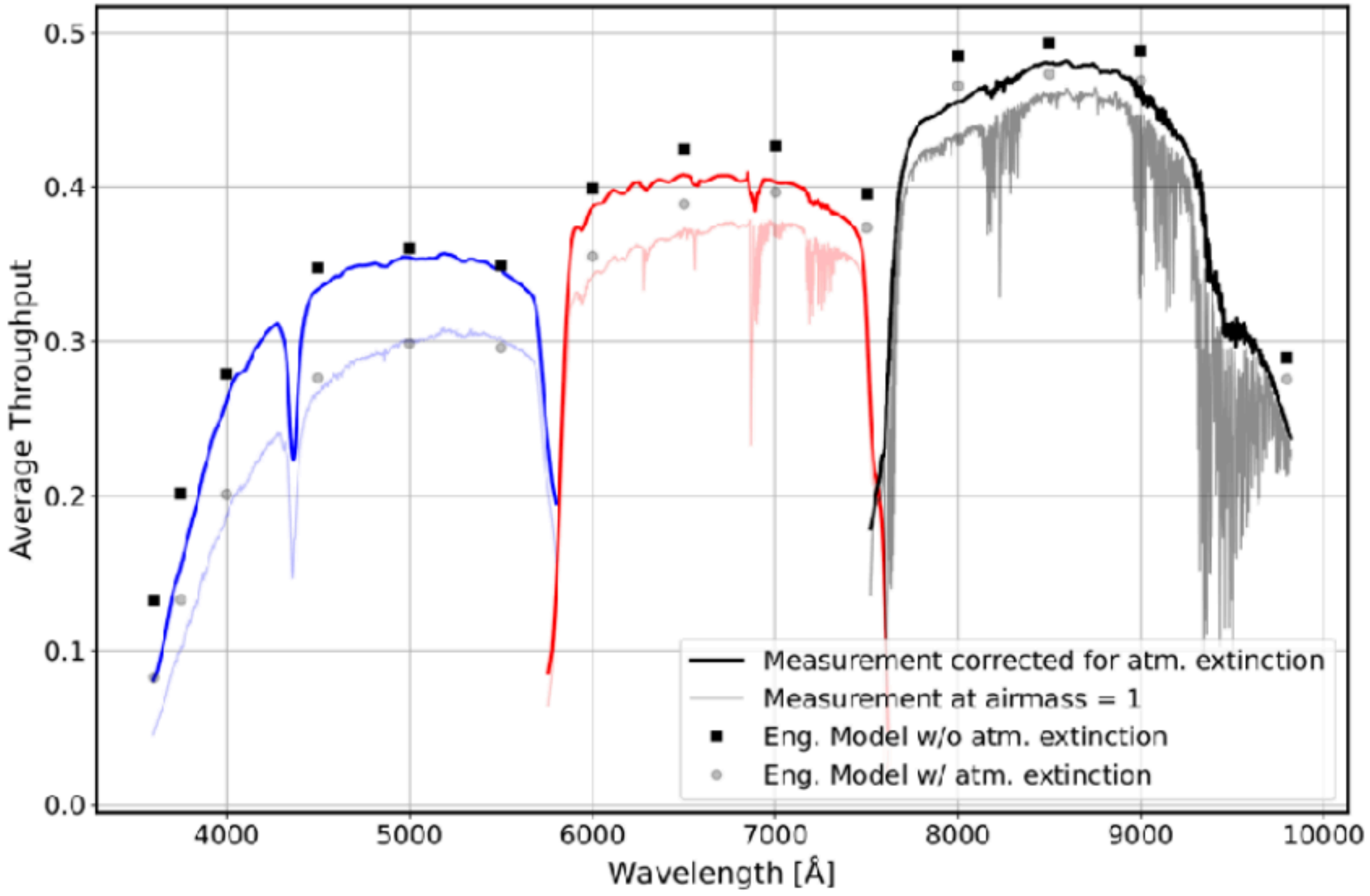
10 3-channel Spectrographs





Throughput: 30-50%



Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument
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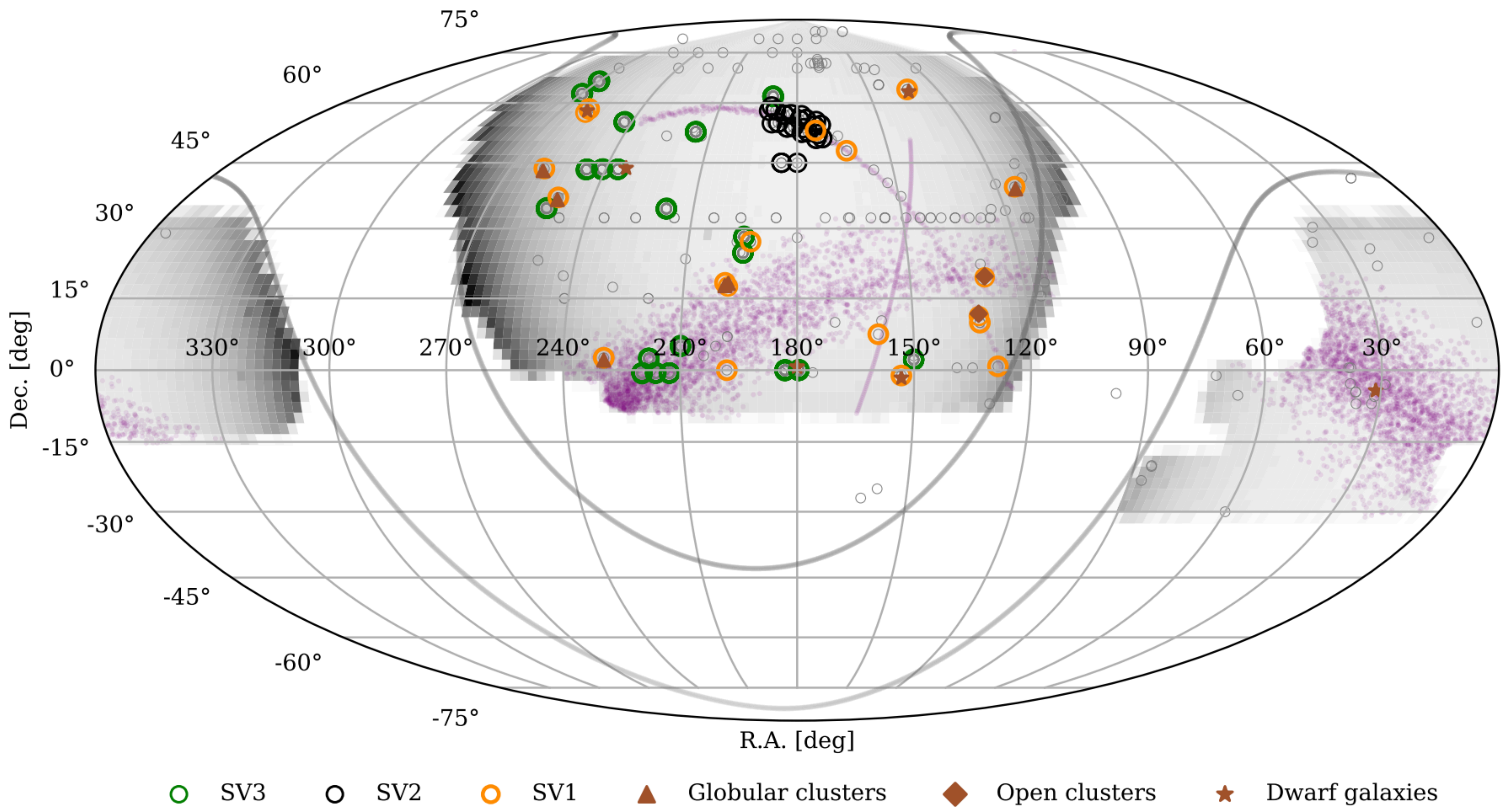
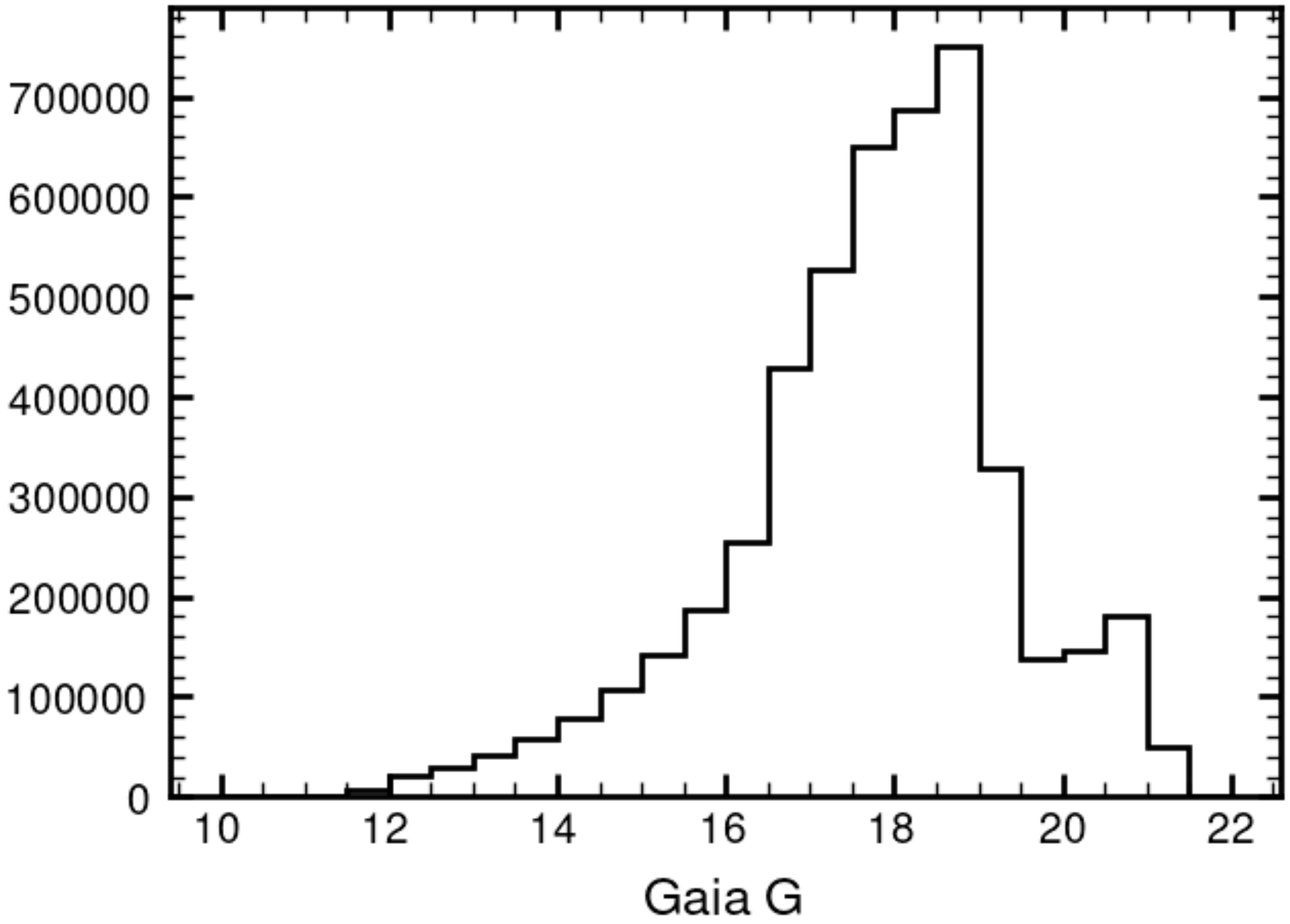
Milky Way Survey in a nutshell

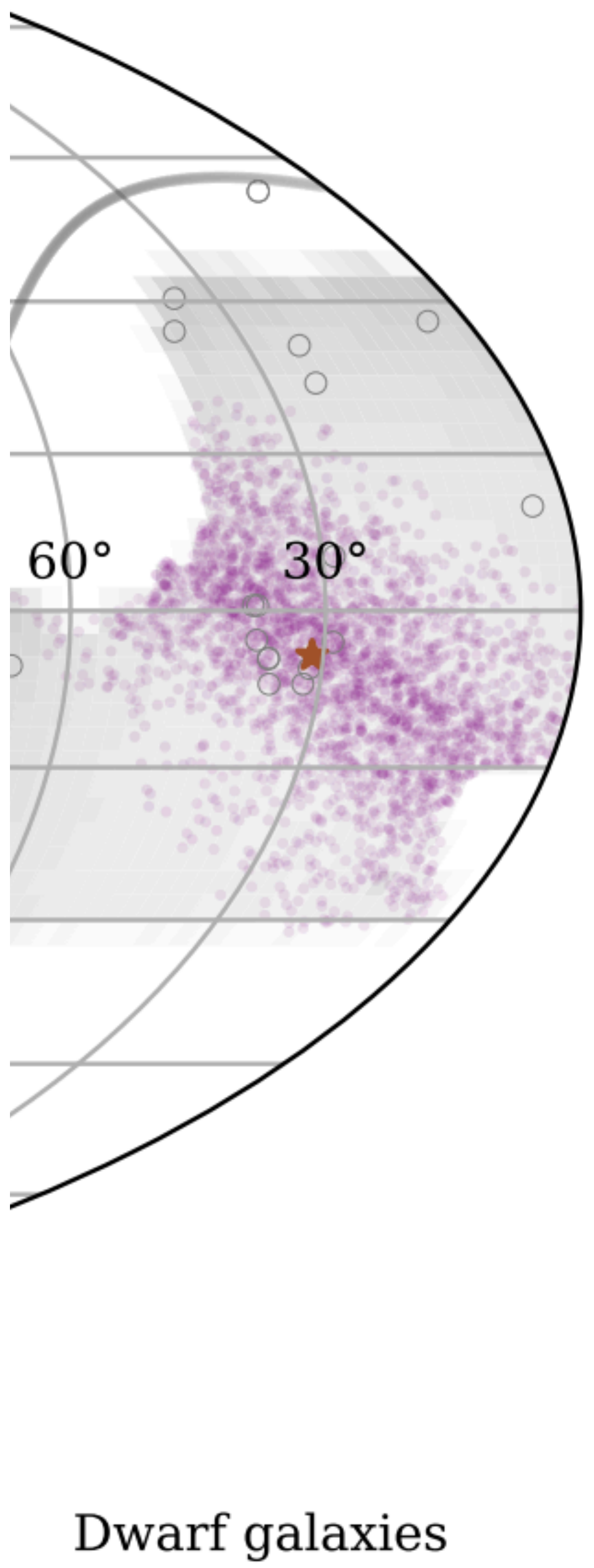


- DESI Bright Time Survey
- ~120s effective exposure time
- Goal: stars at |b|>20
  - 7M Main 16<r<19
  - 0.6M Faint
  - 6M Backup

Overview of the DESI Milky Way Survey
Cooper et al. 2023 arXiv:2208.08514
(DESI Collaboration et al)

Milky Way Survey in a nutshell





- DESI Bright Time Survey
- ~120s effective exposure time
- Goal: stars at |b|>20
  - 7M Main 16<r<19
  - 0.6M Faint
  - 6M Backup

- SV+Year1: >4M star w/ RV<10 km/s

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DESI Stellar Spectra

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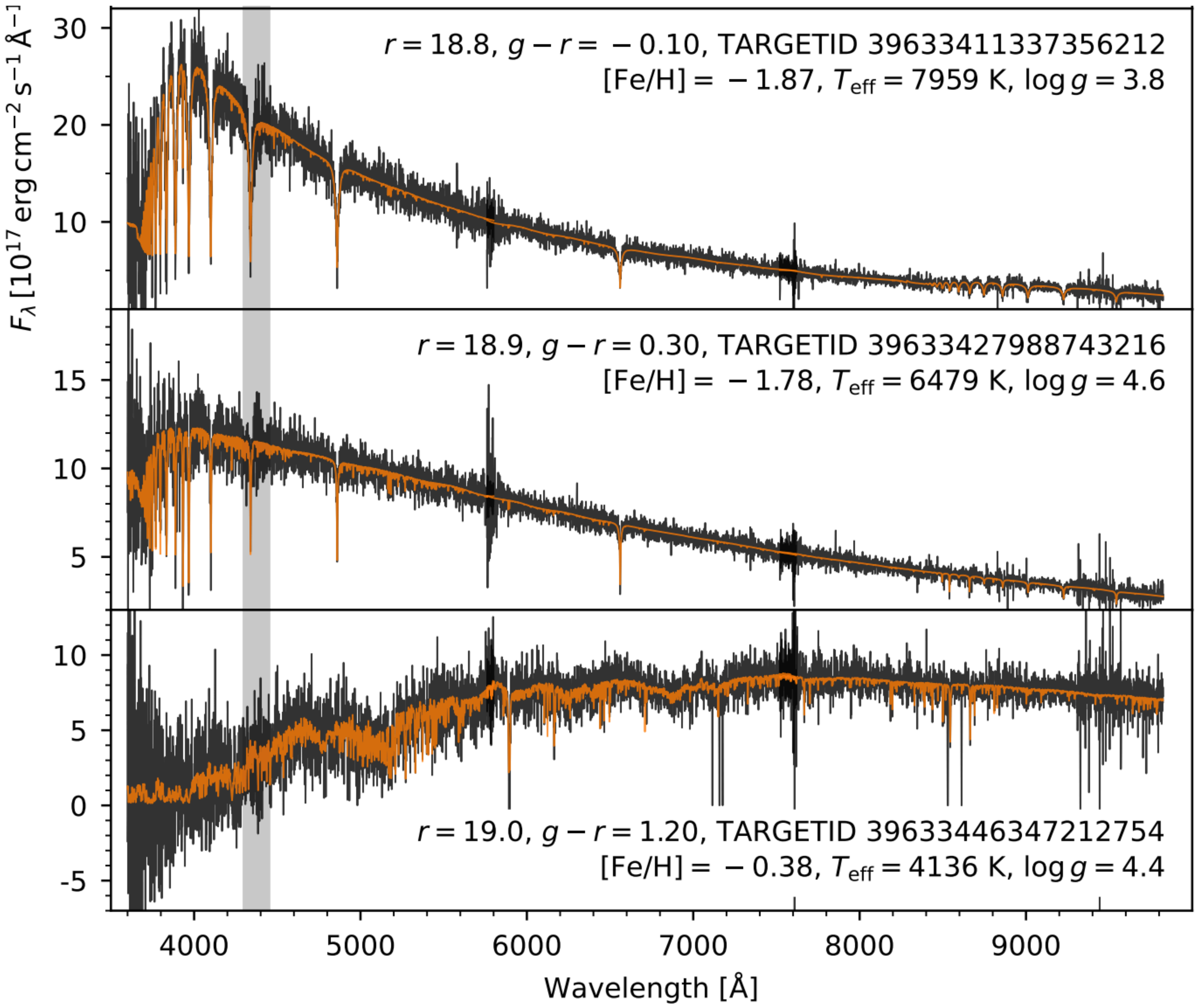

Stellar template fits to spectra w/

- RVSpecfit (S. Koposov)
- FERRE (C. Allende-Prieto)
- Radial velocity, log g,Teff, [Fe/H]

Under development:

- Distance
- Chemical Abundance

Data and best-fit Phoenix template

Overview of the DESI Milky Way Survey
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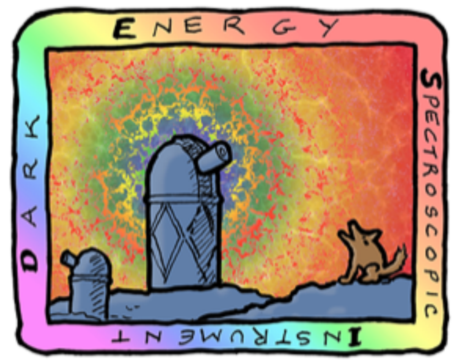
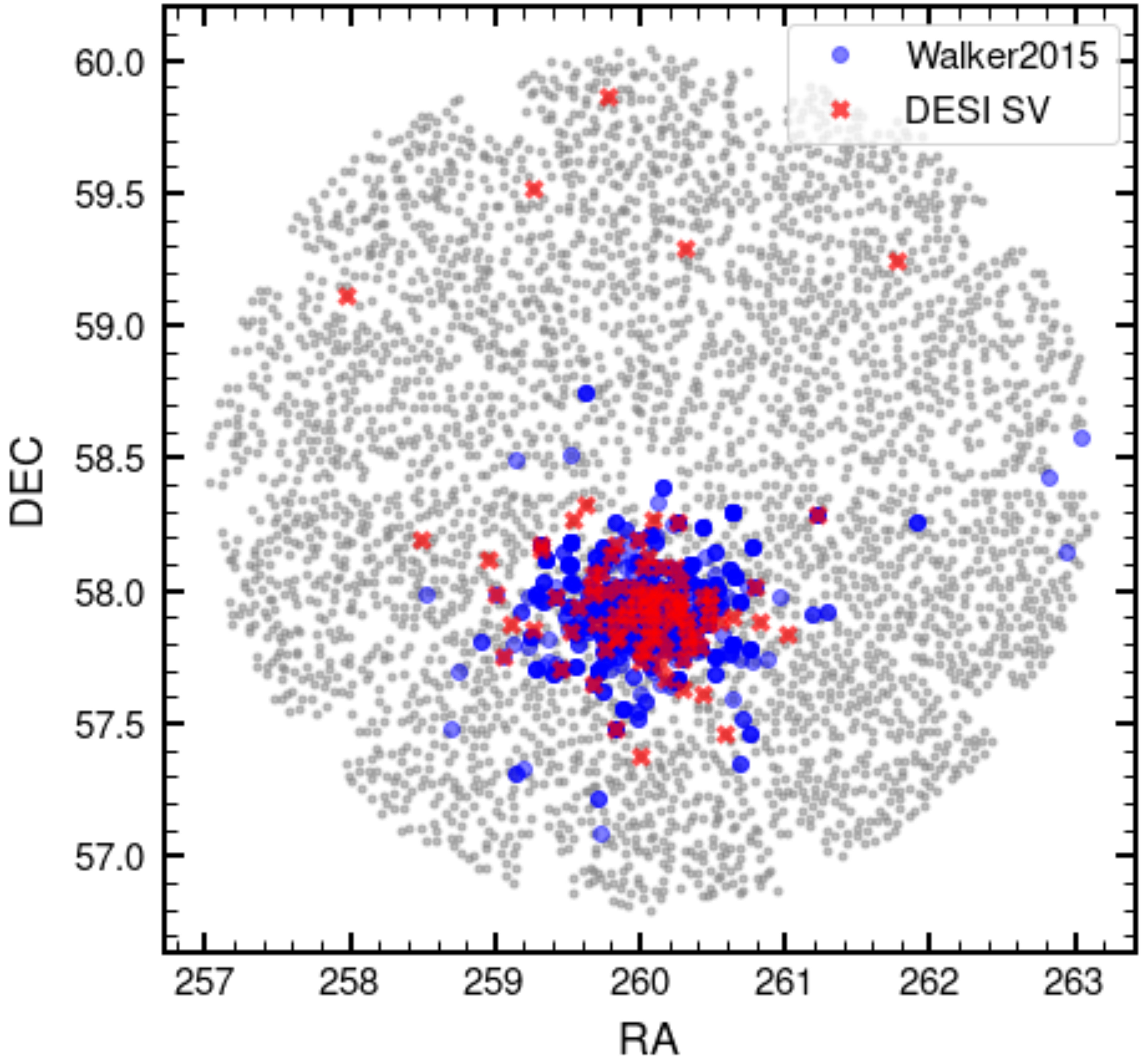
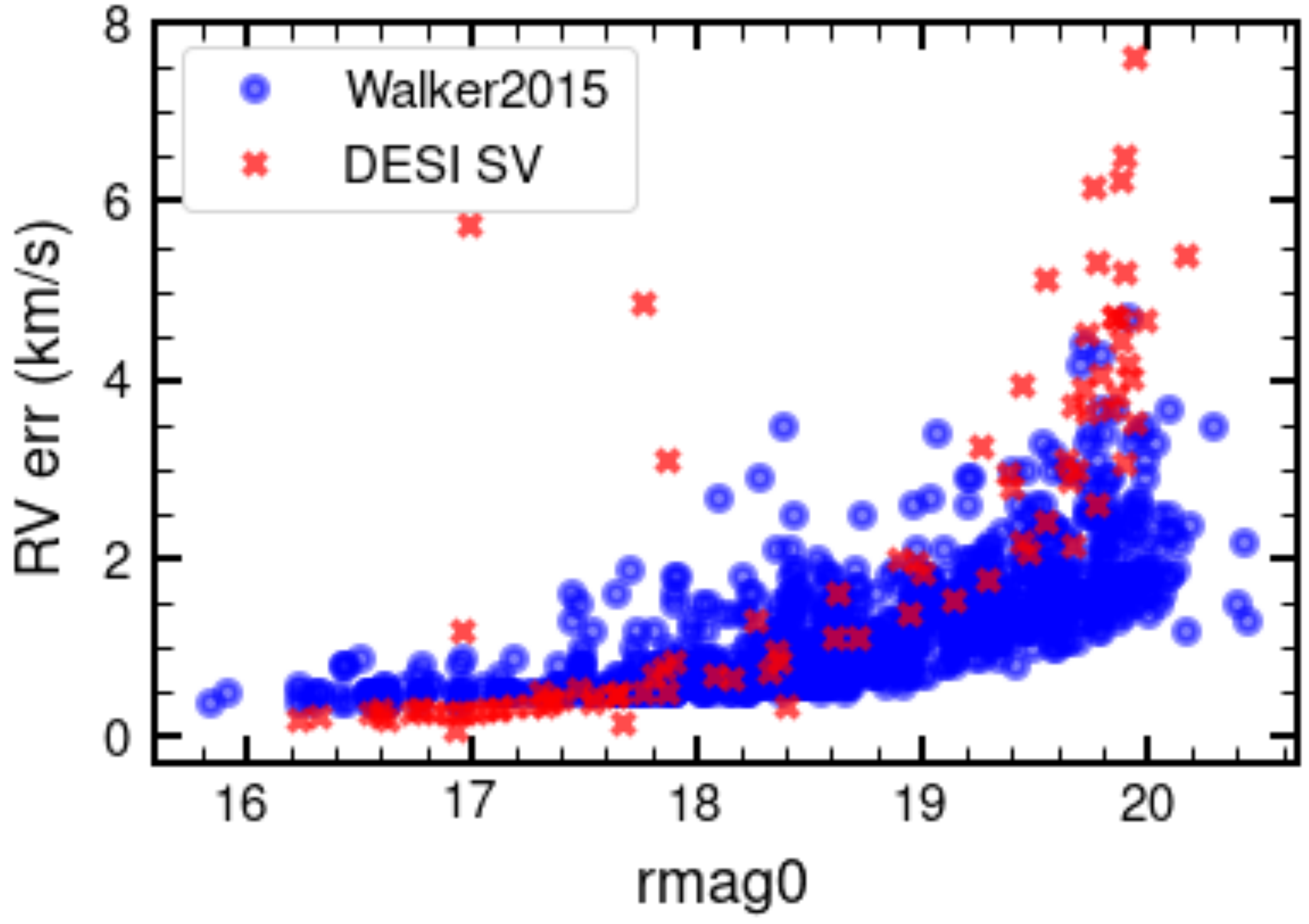


DESI Observation on Draco (45 min Dark Time in SV)



- Walker et al. 2015: ~500 members
- ~200 members in one DESI pointing

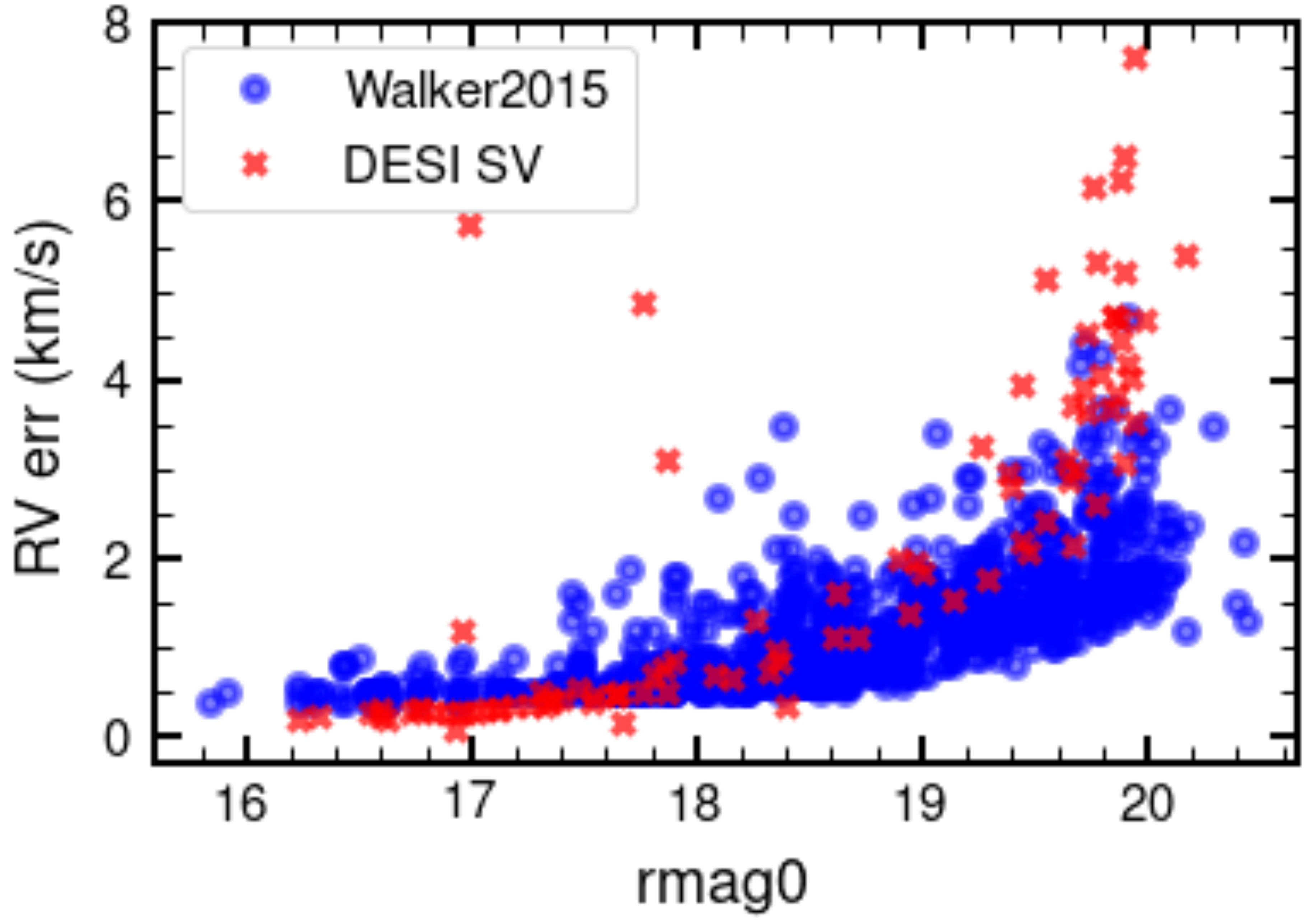


...rvation on Draco ...ark Time in SV)

Table 1. Log of Hectochelle Observations of Draco fields

Field	α_{2000} [a] [hh:mm:ss]	δ_{2000} [a] [°:′:″]	UT Date [dd/mm/yyyy]	HJD[b] [days]	N_{exp} [c]	Exp. Time[d] [seconds]
Dra-01	17:20:24.65	+57:53:06.9	19/04/2006	2453844.87	4	7200
Dra-02	17:23:50.00	+57:52:12.0	25/04/2006	2453850.78	5	4846
Dra-03	17:20:24.64	+57:53:06.9	23/02/2007	2454154.98	3	5400
Dra-04	17:17:37.81	+57:46:30.2	27/02/2007	2454158.96	3	5400
			11/03/2007	2454170.89	4	7200
Dra-05	17:20:38.90	+57:28:04.3	03/03/2007	2454162.94	3	5400
			09/03/2007	2454168.90	3	5400
Dra-06	17:19:23.67	+58:28:22.4	06/03/2007	2454165.90	3	5400
Dra-07	17:14:24.40	+57:28:47.6	22/04/2007	2454212.89	3	5400
Dra-08	17:26:35.35	+58:15:25.6	23/04/2007	2454213.83	3	5400
Dra-09	17:30:06.97	+57:38:24.2	24/02/2008	2454520.94	5	6000
Dra-10	17:20:25.01	+57:53:11.7	27/02/2008	2454523.99	3	3600
Dra-11	17:11:57.01	+58:18:03.1	27/02/2008	2454523.93	3	4500
Dra-12	17:10:09.01	+57:29:41.0	20/03/2009	2454910.85	2	4096
			21/03/2009	2454911.86	3	7200
Dra-13	17:20:06.72	+57:55:32.6	21/03/2009	2454911.96	2	4800
			24/03/2009	2454914.92	4	7200
Dra-14	17:41:60.00	+56:00:00.0	23/03/2009	2454913.87	4	9600
Dra-15	17:20:15.99	+57:55:30.0	15/05/2010	2455331.74	4	6000
Dra-16	17:20:15.99	+57:55:30.0	15/05/2010	2455331.84	3	4500
Dra-17	17:15:23.52	+57:55:42.0	16/05/2010	2455332.73	2	3600
			16/05/2010	2455332.78	3	4500
Dra-18	17:20:23.58	+58:24:30.0	16/05/2010	2455332.85	3	4500
Dra-19	17:20:11.57	+57:24:54.0	16/05/2010	2455332.91	3	4500
Dra-20	17:20:15.99	+57:55:30.0	29/01/2011	2455590.99	3	3600
			25/05/2011	2455706.92	4	4500
Dra-21	17:20:15.99	+57:55:30.0	25/05/2011	2455706.77	3	5400
Dra-22	17:20:15.99	+57:55:30.0	25/05/2011	2455706.84	3	5400
Dra-23	17:22:55.93	+58:02:34.0	26/05/2011	2455707.75	3	5400
Dra-24	17:17:39.05	+57:53:14.0	26/05/2011	2455707.83	3	5400
Dra-25	17:20:46.45	+57:17:29.3	26/05/2011	2455707.91	4	4800
Dra-26	17:20:00.58	+58:37:30.6	27/05/2011	2455708.86	3	5400
Dra-27	17:20:15.99	+57:55:30.0	27/05/2011	2455708.93	3	3600
			31/05/2011	2455712.87	3	3600
Dra-28	17:20:19.72	+57:52:21.9	27/05/2011	2455708.76	4	9600
			28/05/2011	2455709.89	3	6000
Dra-29	17:19:02.64	+57:22:36.0	29/05/2011	2455710.84	3	5400
Dra-30	17:22:06.84	+58:27:53.3	29/05/2011	2455710.91	3	4500
Dra-31	17:20:17.49	+57:54:42.0	29/05/2011	2455710.76	3	5400
Dra-32	17:26:54.32	+58:29:28.6	30/05/2011	2455711.90	3	5400
			31/05/2011	2455712.93	3	3600
Dra-33	17:14:13.51	+57:40:52.9	31/05/2011	2455712.78	4	7200

- Walker et al. 2015: ~500 members
- ~200 members in one DESI pointing
- 45 min DESI vs 60+ hr on MMT



Milky Way Survey Main Science Goal

Probing the Dark Matter and Accretion History of the Milky Way

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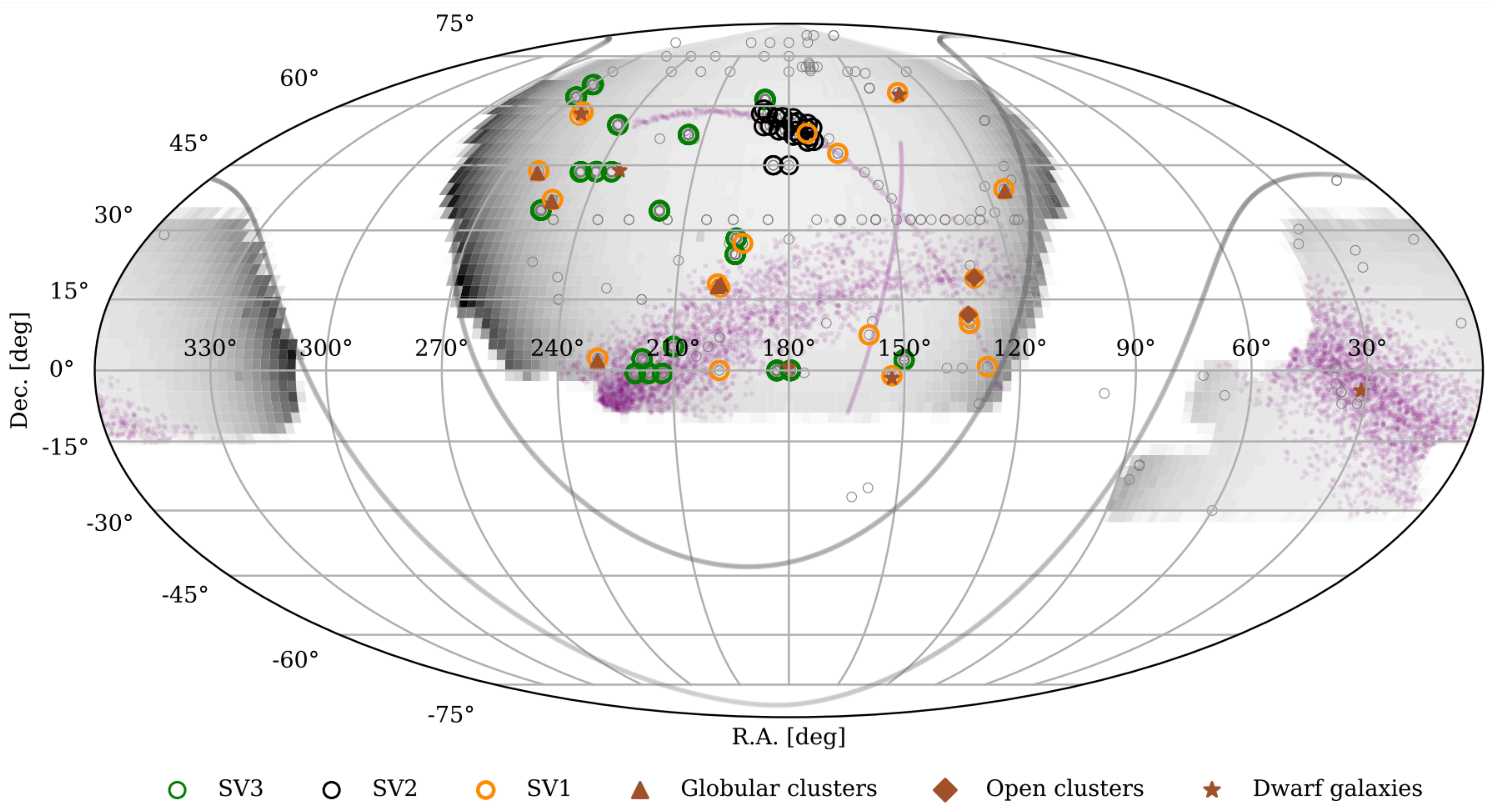
- **The Shape and Mass of the Dark Matter Halo**
- Small-scale Substructure in the Dark Matter Halo
- The Assembly History of the Milky Way Halo
- The Formation History of the Milky Way Thick Disk
- Primordial/Metal-Poor Stars in the Milky Way



Overview of the DESI Milky Way Survey
Cooper et al. 2023 arXiv:2208.08514
(DESI Collaboration)

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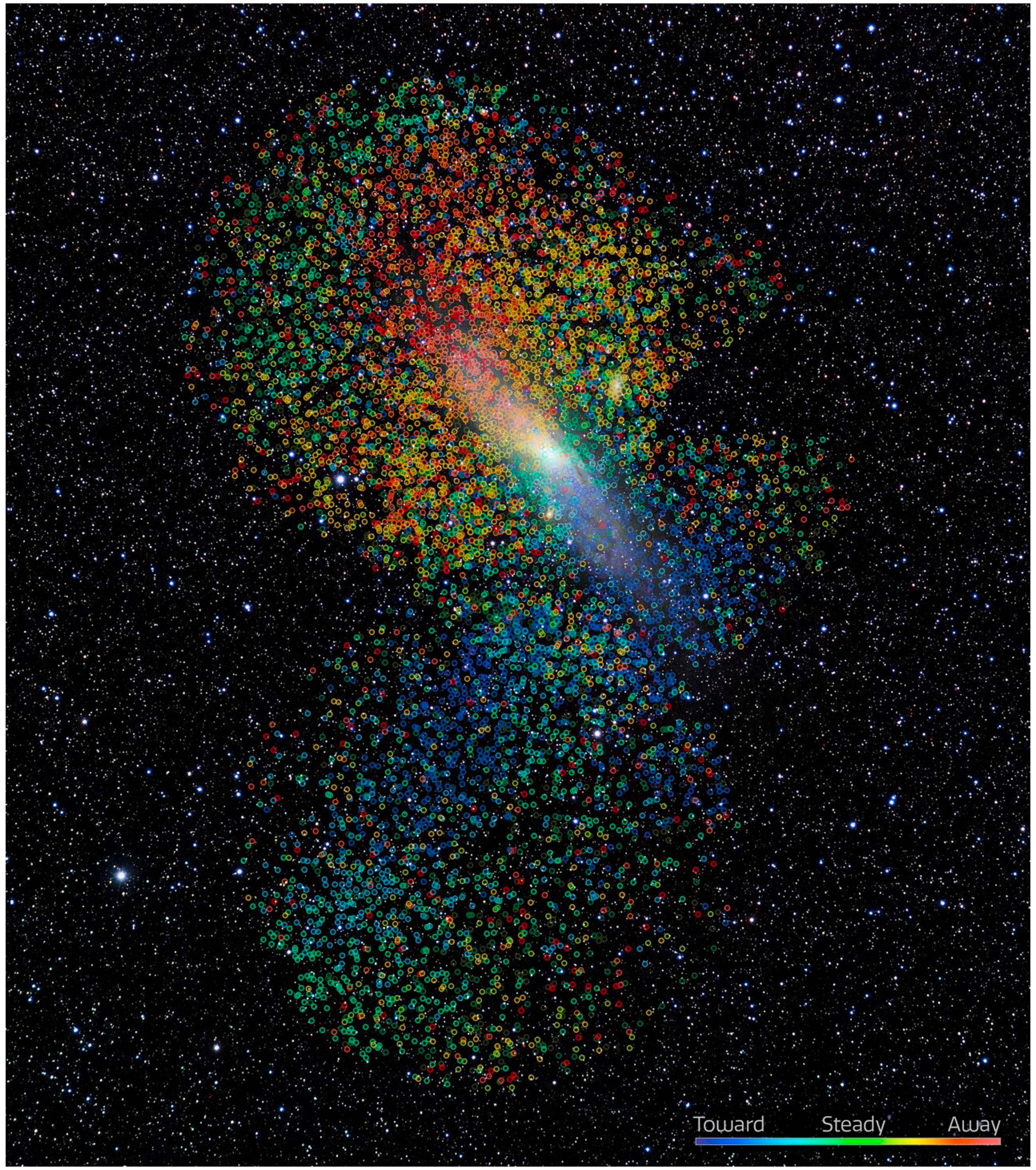
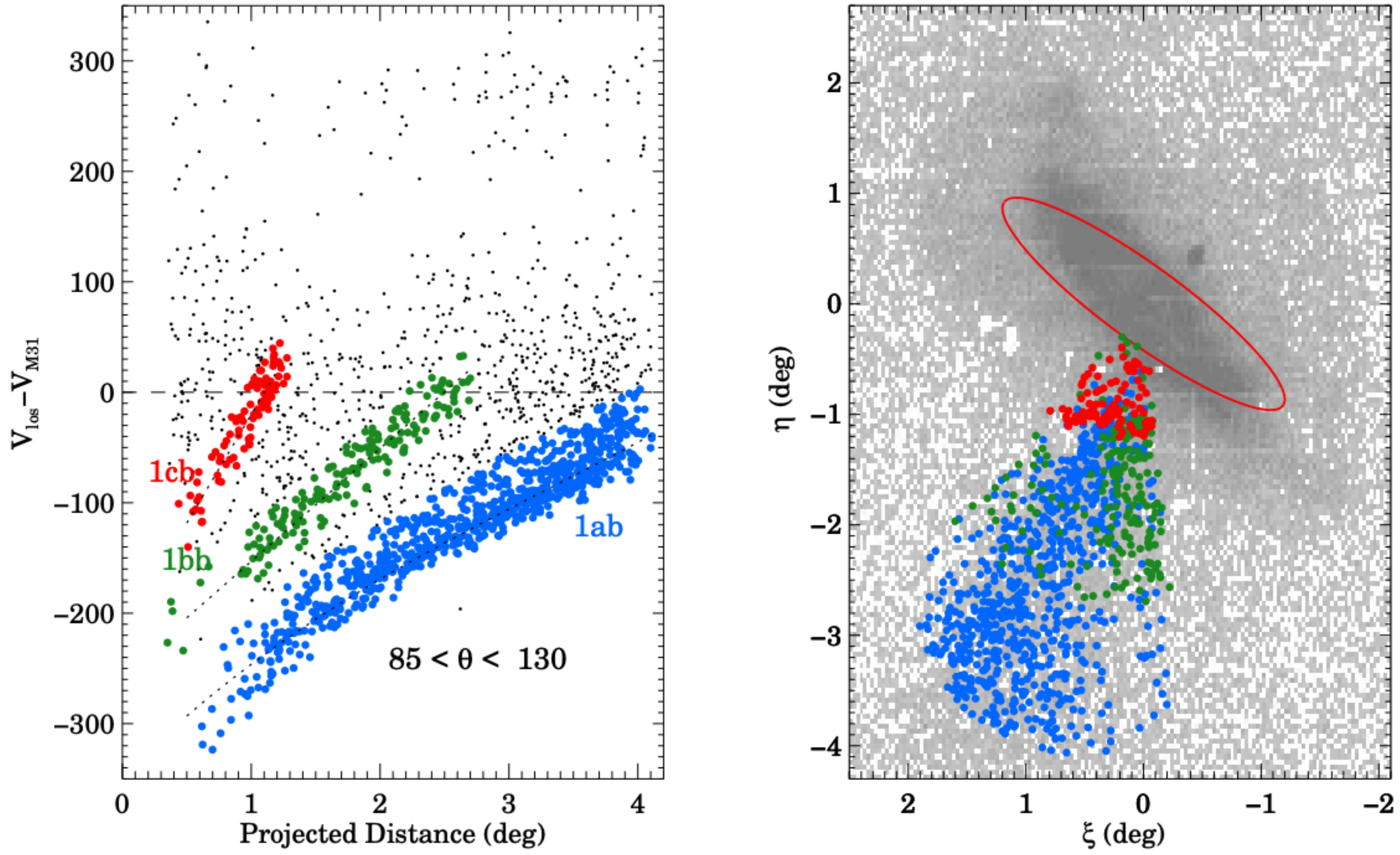
U.S. Department of Energy Office of Science

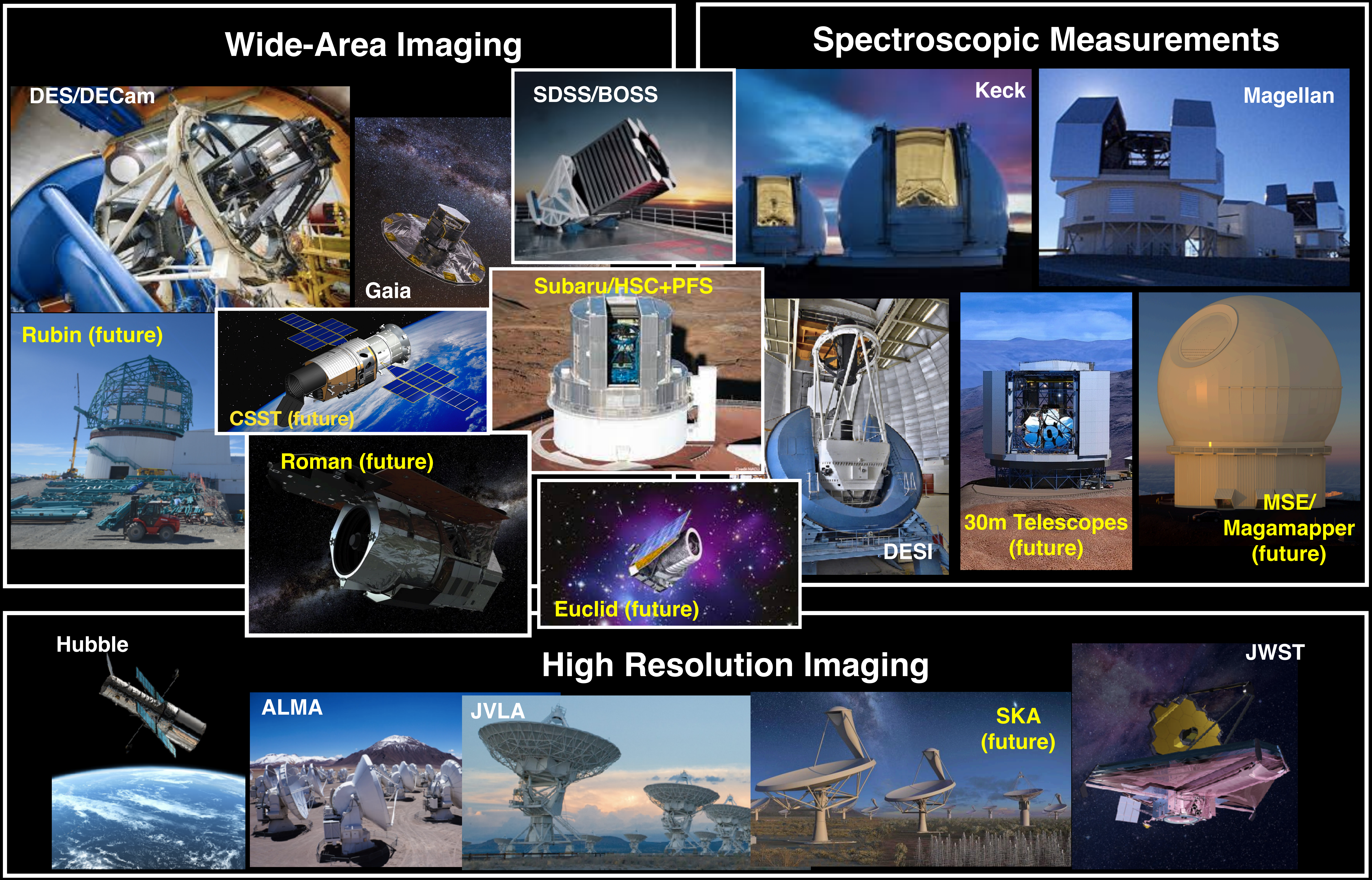
ESI's view on Andromeda and the Giant Stellar Stream



Credit: KPNO/NOIRLab/AURA/NSF/E. Slawik/D. de Martin/M. Zamani



Dey, Nijita, Koposov et al. 2023 arXiv:2208.11683 (DESI Collaboration)



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