The Milky Way dwarf galaxies view through Gaia

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Beyond the Milky Way

COST MW-Gaia WG1/WG4 Workshop

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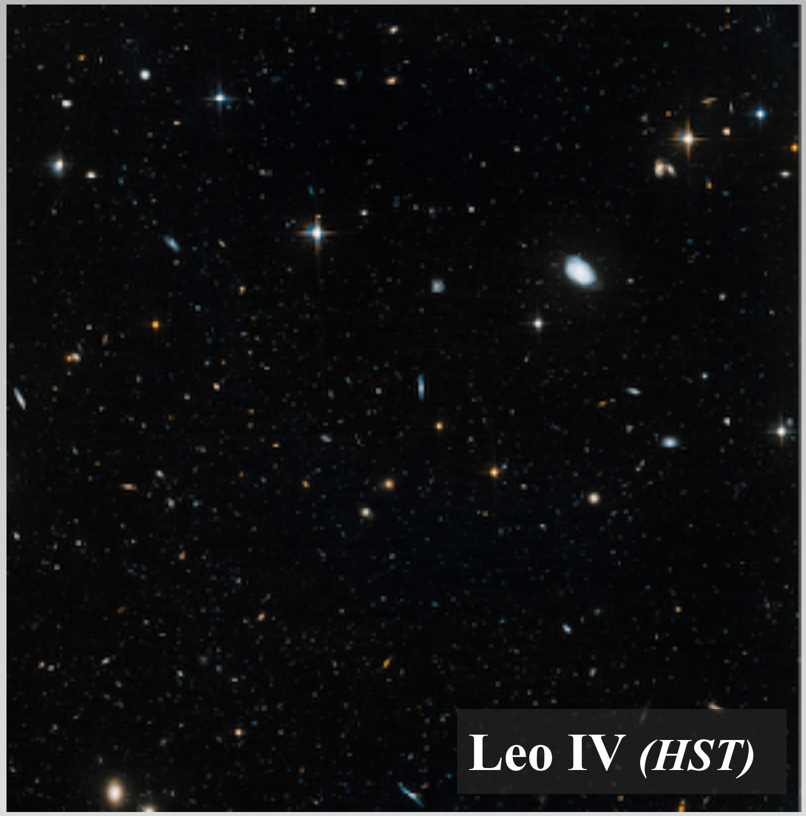
WHAT IS A DWARF GALAXY ?

Dwarf irregulars

"Classicals" dSph

Ultra-Faint Dwarfs (UDF)



- Composed of metal-poor, old stars
- Dark matter dominated (M/L > 10)
- Around the MW, SFH tends to be halted 8-10 Gyr ago *(e.g. Tolstoy et al. 2009; Brown et al. 2014; Gallart et al. 2015)*
- Building-blocks of the $L_\star$-galaxies (hierarchical formation scenario)

See also the recent reviews of Simon 2019 and Battaglia & Nipoti 2022

THE REVOLUTION OF GAIA

gaia

- Precise all-sky photometry
- **Proper motions**

Membership selection

Internal dynamics

Global motion

Find new galaxies

Orbits

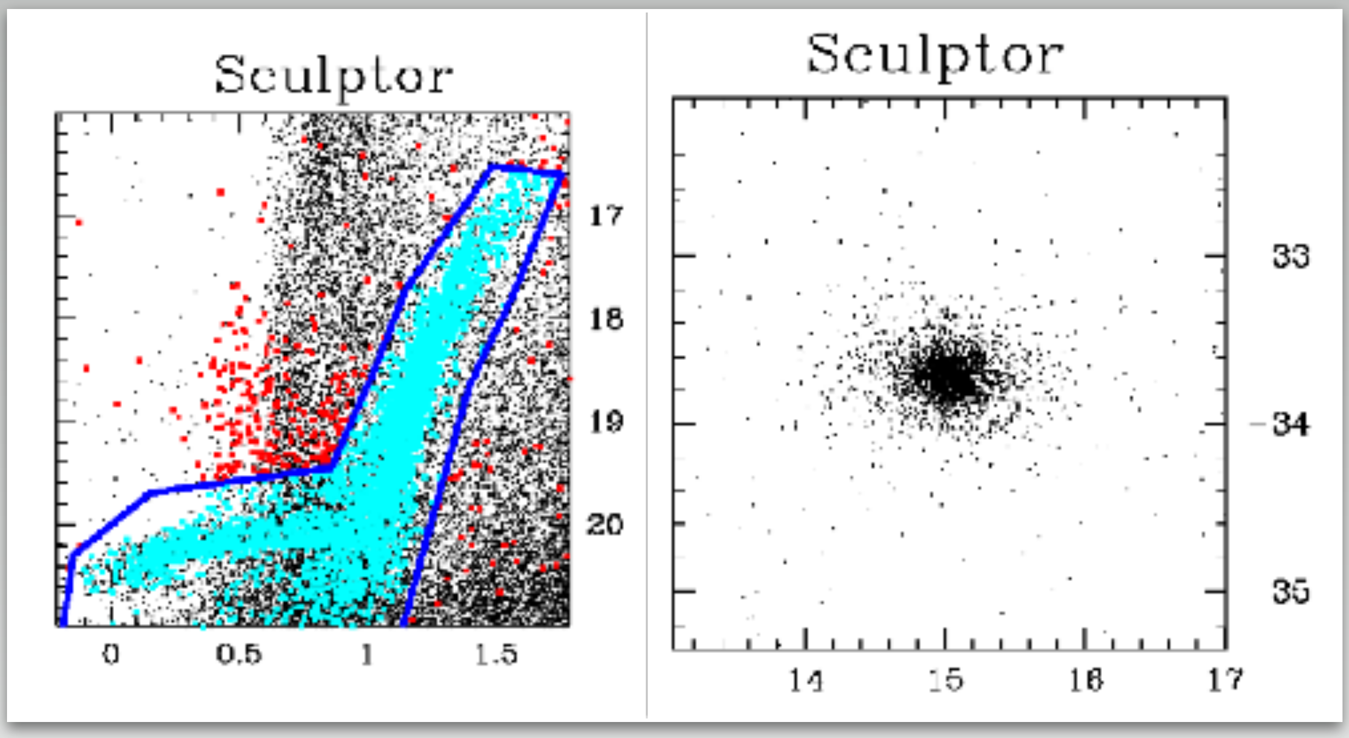
Mass of the MW

Group of infalling galaxies

Stability of the VPOS

MEMBERSHIP SELECTIONS

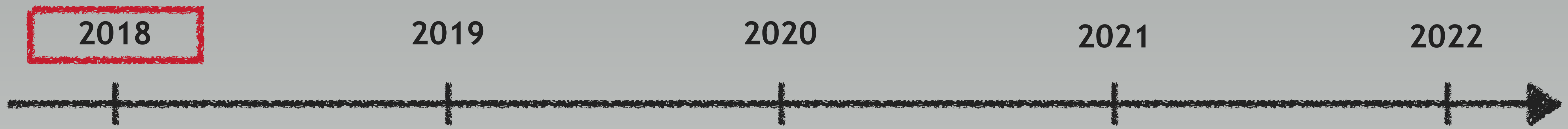
2018 2019 2020 2021 2022

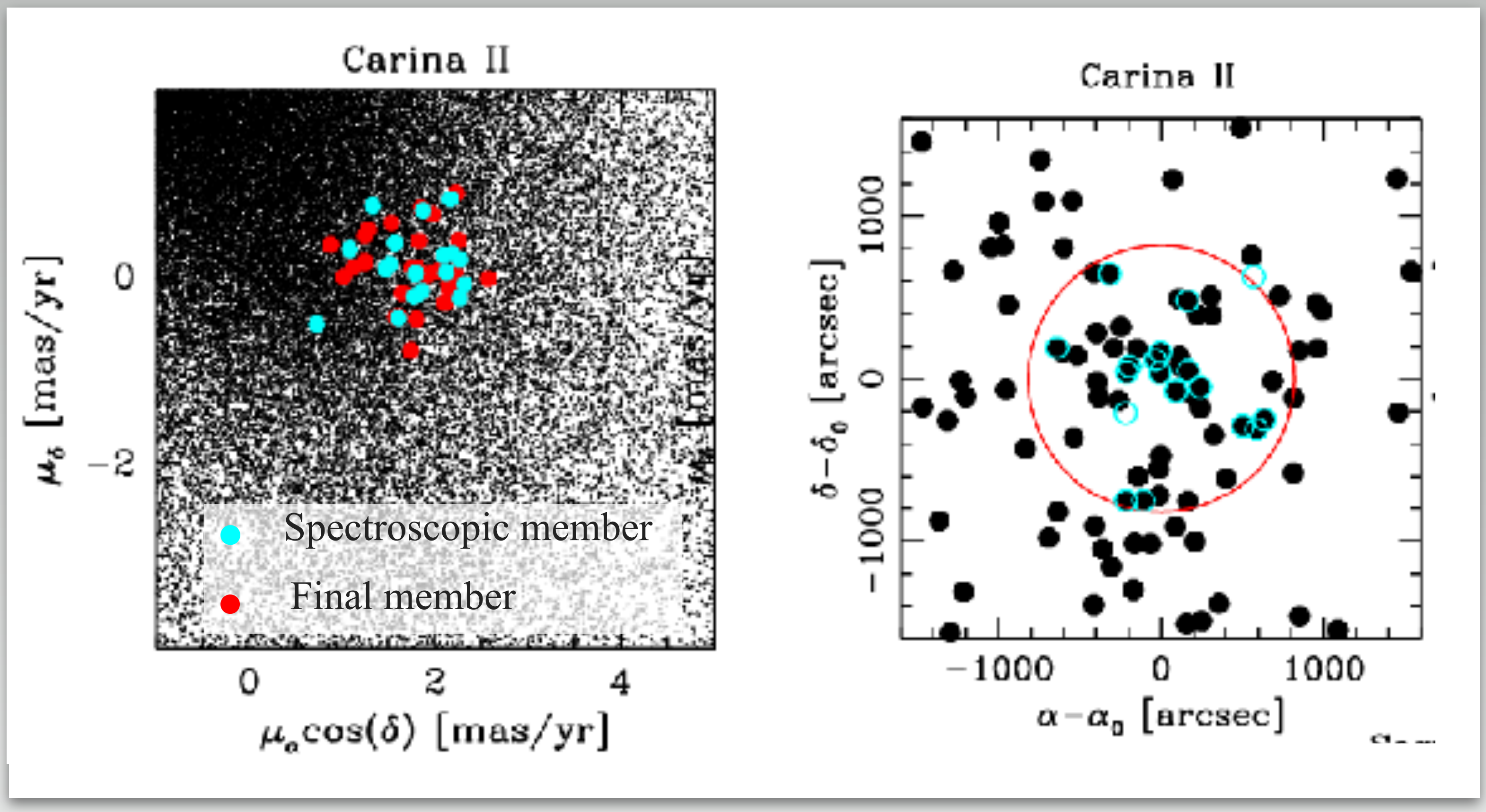


Gaia Collaboration et al. 2018

1. RGB+BHB
2. Parallax cut
3. σ-clipping

MEMBERSHIP SELECTIONS

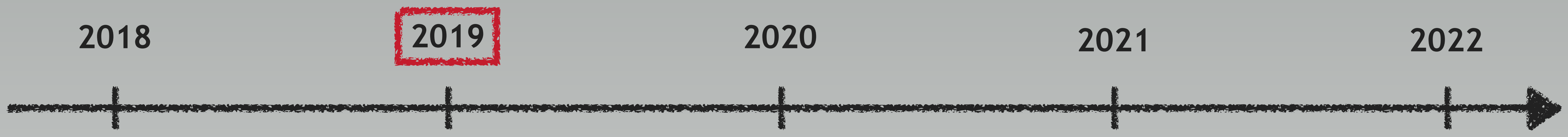


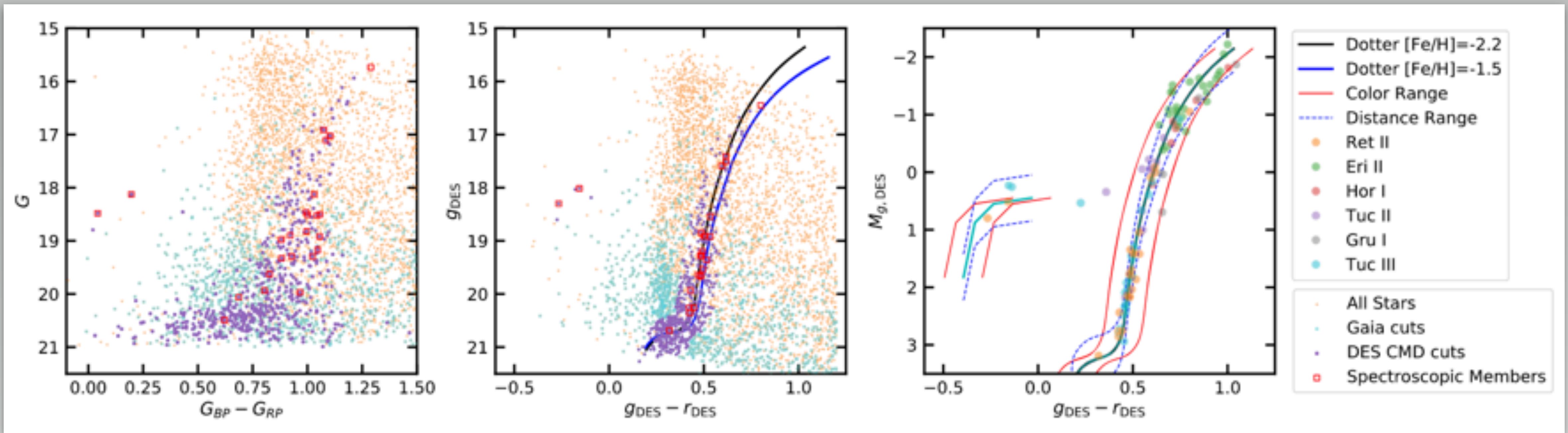


Kallivayalil et al. 2018; ***Massari & Helmi, 2018***

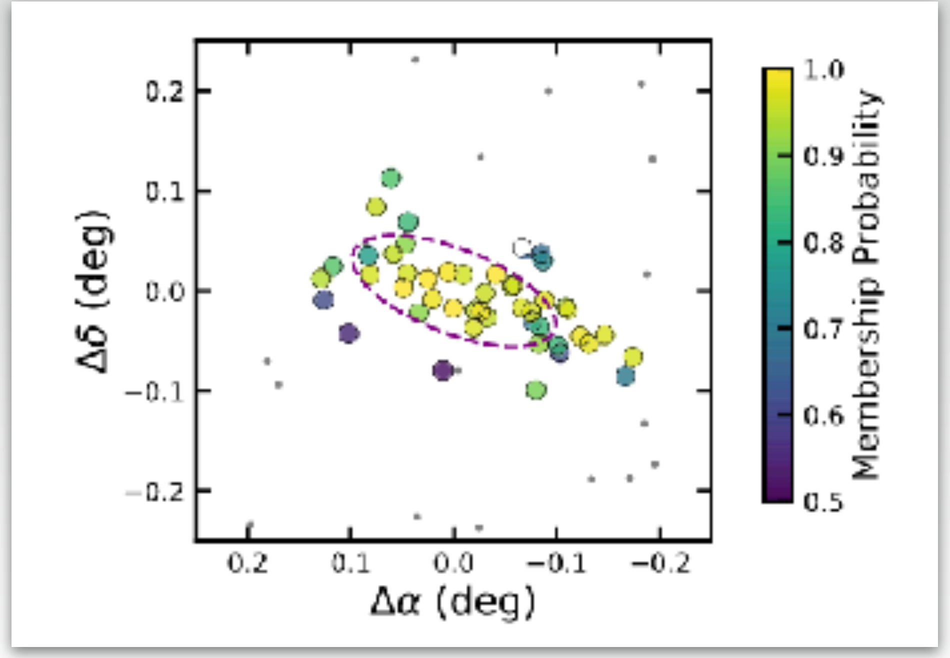
1. Get the mean PM from stars selected from spectroscopy or HB
2. Select stars from CMD
3. σ-clipping on PM

MEMBERSHIP SELECTIONS





Pace & Li, 2019, *Pace et al. 2022*



1. Pre-selection of candidate member stars from CMD
2. Bayesian selection from position & PMs

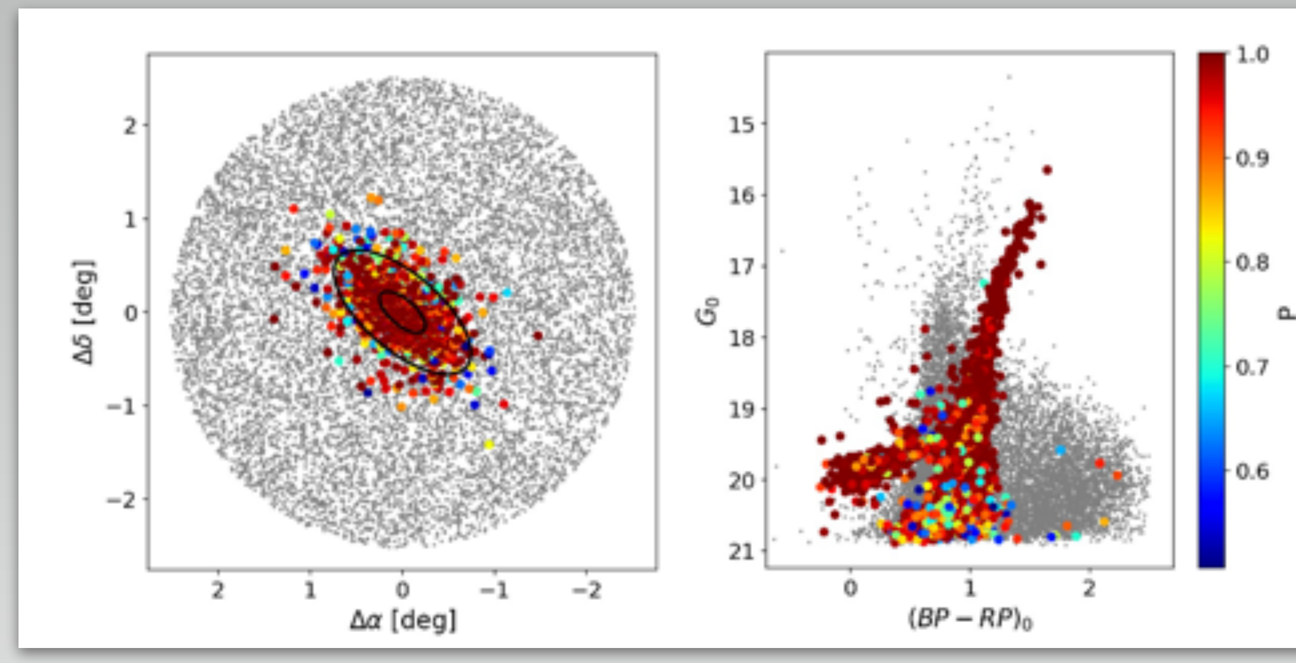
$$\mathcal{L} = (1 - f_{\rm MW})\mathcal{L}_{\rm satellite} + f_{\rm MW}\,\mathcal{L}_{\rm MW}$$

with $\mathcal{L}_{\rm satellite/MW} = \mathcal{L}_{\rm spatial}\mathcal{L}_{\rm PM}$

MEMBERSHIP SELECTIONS

2018 — 2019 — **[2020 — 2021 — 2022]**

Ursa Minor

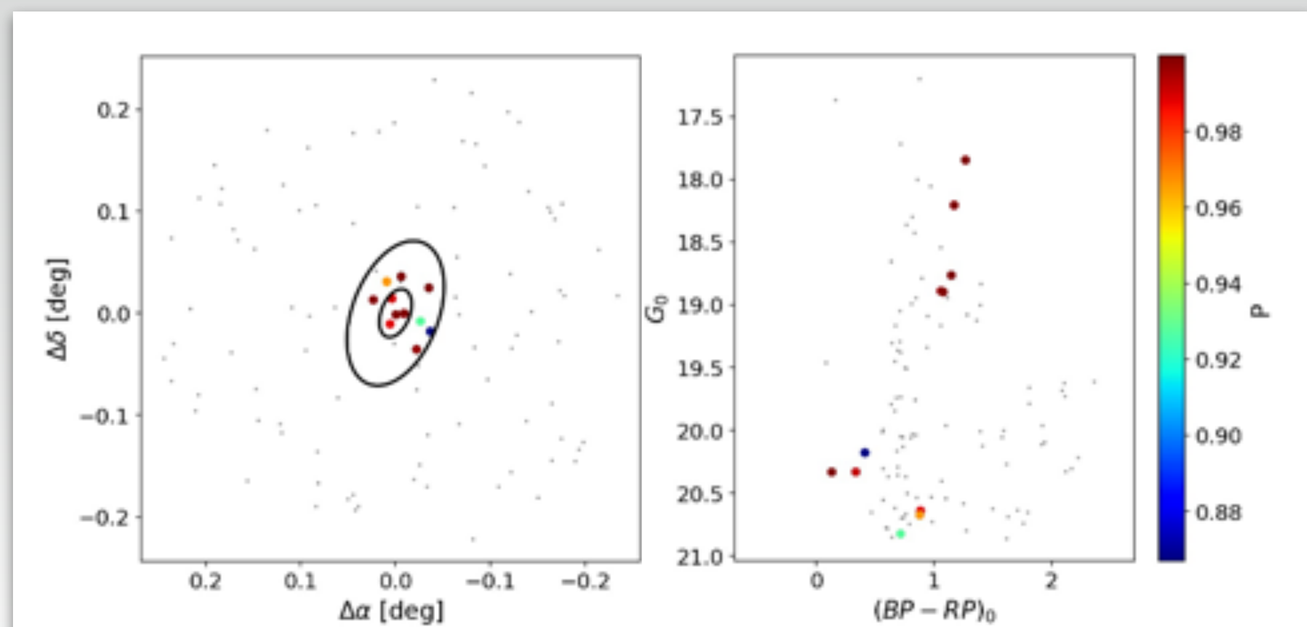


1. Bayesian selection from position, CMD, PMs (& V_{los})

$$\mathcal{L} = (1 - f_{MW})\mathcal{L}_{satellite} + f_{MW}\,\mathcal{L}_{MW}$$

with $\mathcal{L}_{sat} = \mathcal{L}_s \mathcal{L}_{CM} \mathcal{L}_{PM}$

Phoenix II



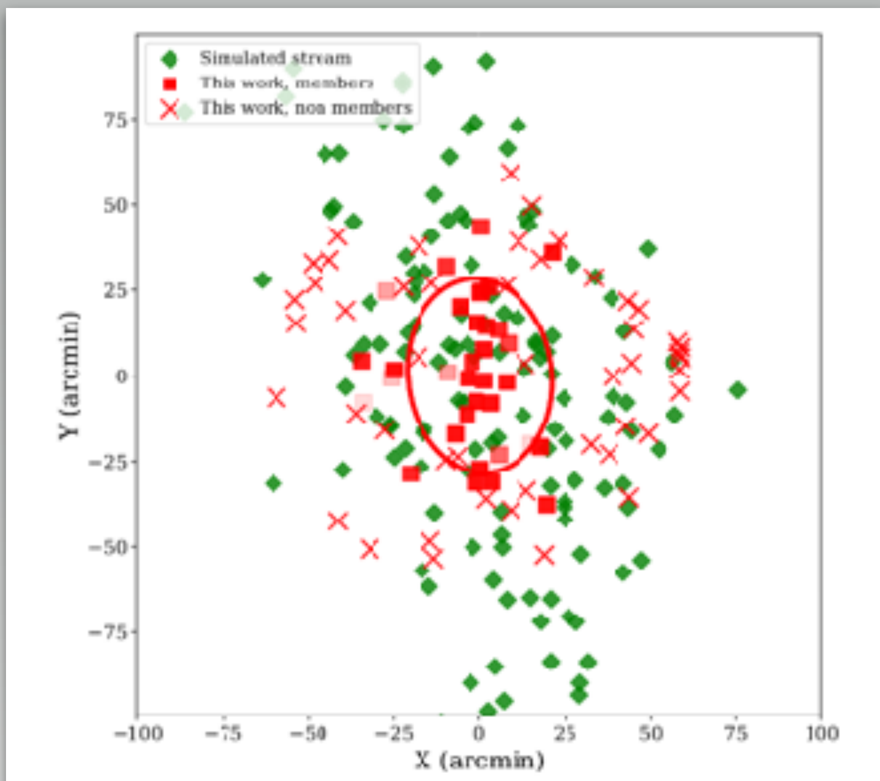
Catalogue of individual members available on VizieR

https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/657/A54

McConnachie & Venn, 2020 a, b, McConnachie et al. 2021 ***Battaglia & al. 2022***

MEMBERSHIP SELECTIONS

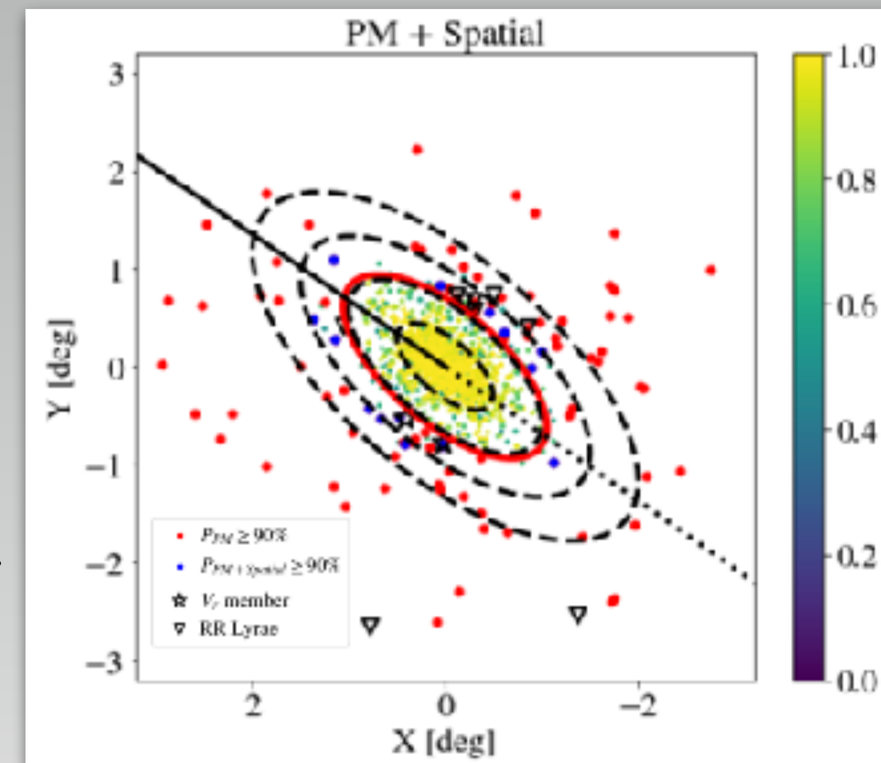
Detection of extra-tidal candidates



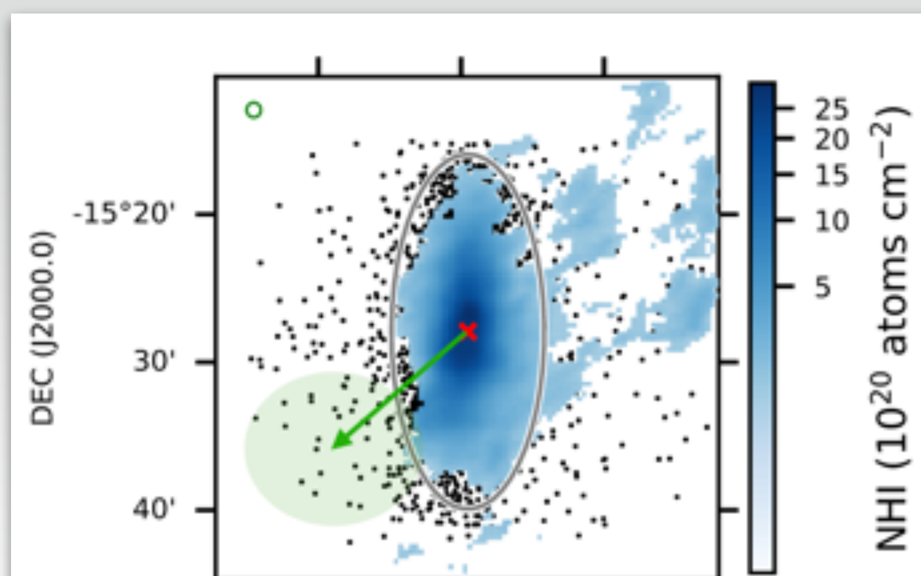
Longeard et al., 2022

- **Ca H&K+ Gaia :** possible tidal disruption of Boötes I

- **Gaia:** extended stellar halos or tidal debris around 6 classical dSph



Qi et al. 2022



Yang et al, 2022

- **Subaru+ MeerKat+ Gaia:** Evidence of ram-pressure in WLM

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gaia

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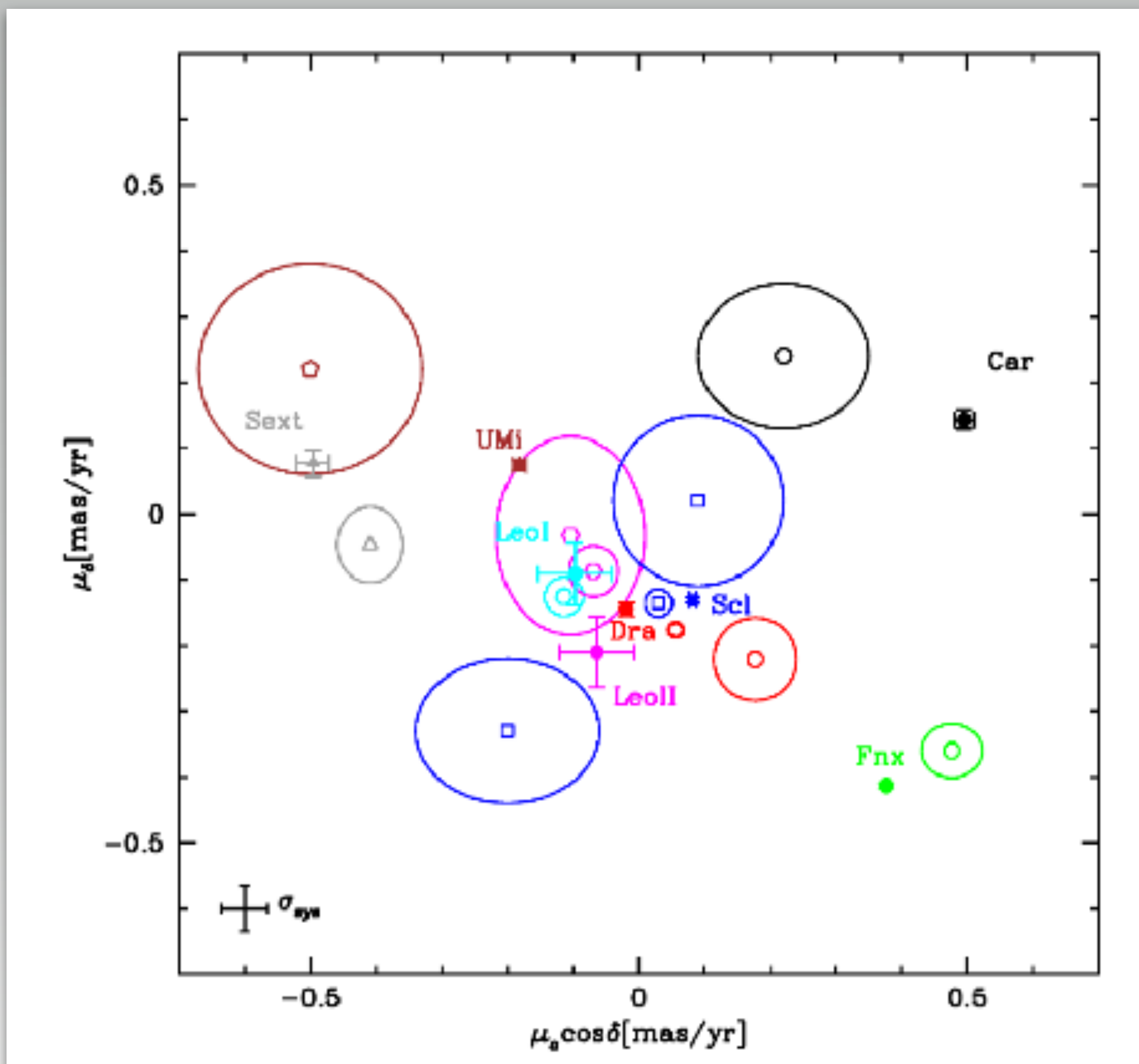
GLOBAL MOTIONS (SYSTEMICS)

2018 | 2019 | 2020 | 2021 | 2022



Gaia Collaboration et al. 2018

➡ Better accuracy of the PMs with Gaia

➡ Consistent at 2-σ with previous measurements

… But only for 10 galaxies

GLOBAL MOTIONS (SYSTEMICS)

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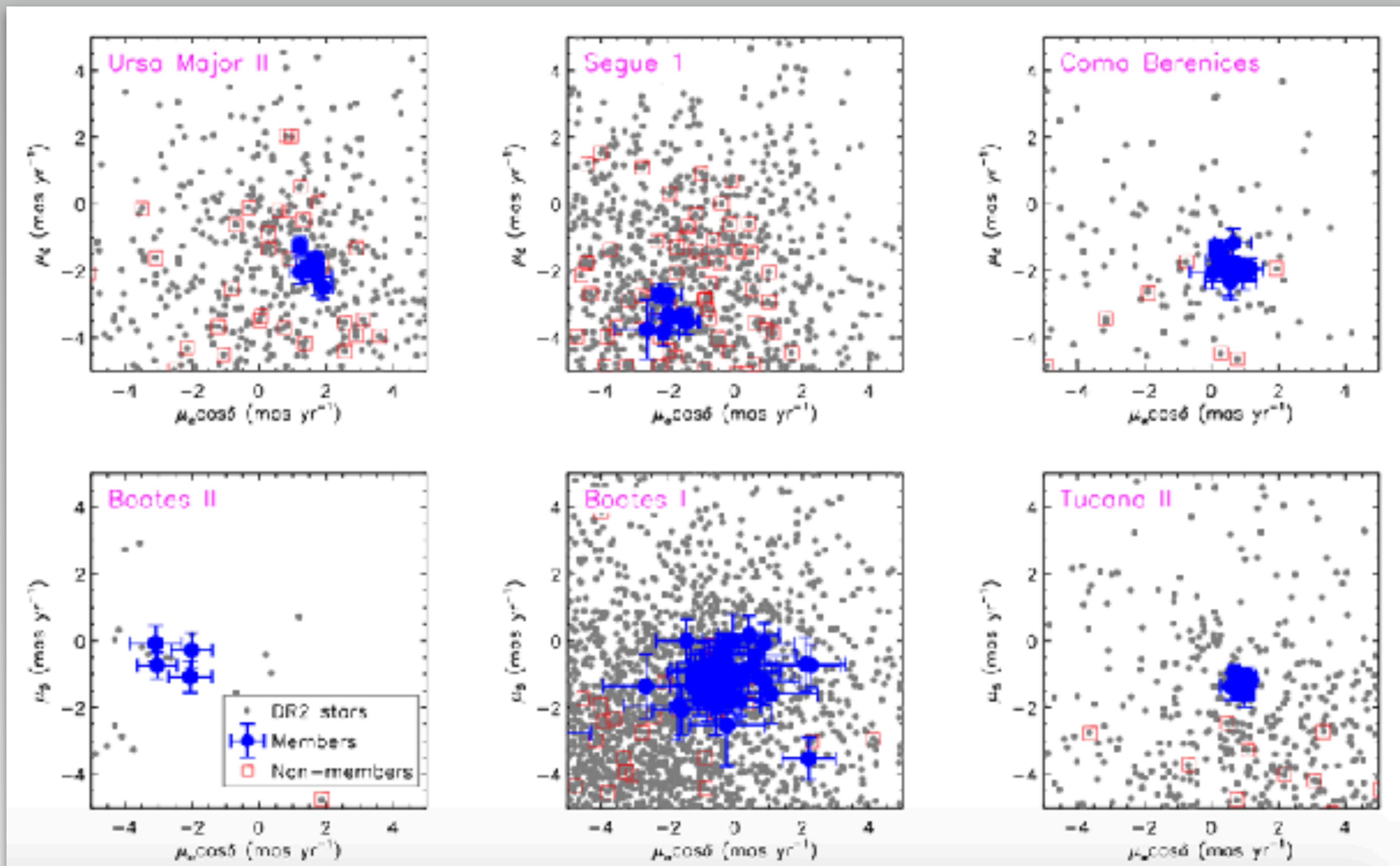


Simon 2018*; Fritz et al. 2018, Li et al. 2021*

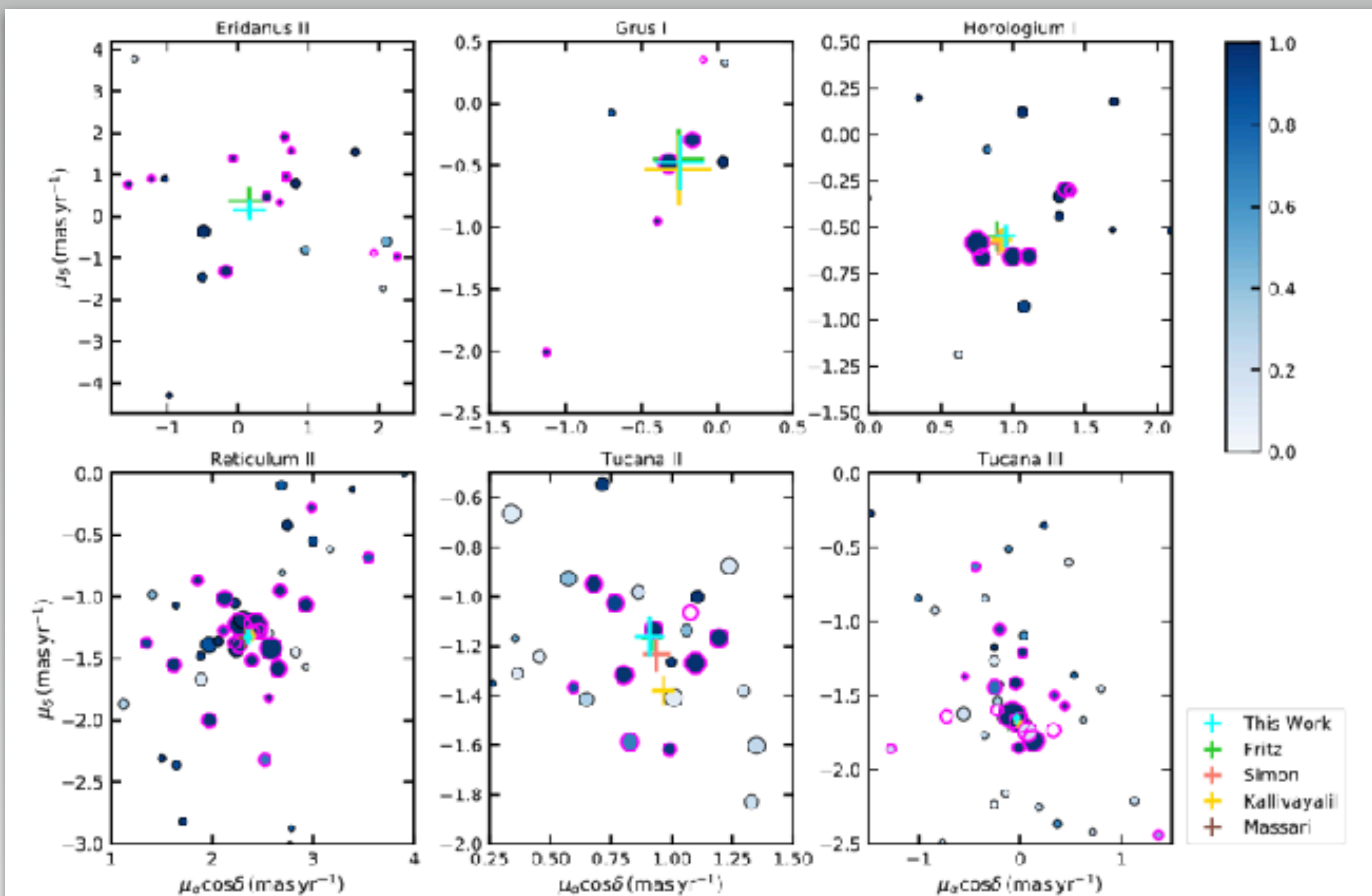
- Use of spectroscopically confirmed members

➡ 39 galaxies up to 420 kpc

… but need spectroscopic observations & does not use the full information available

GLOBAL MOTIONS (SYSTEMICS)

2018 — **2019** — 2020 — 2021 — 2022



__Pace & Li, 2019__, Pace et al. 2022

- Use pre-selected stars based on CMD
- Bayesian approach
- No need of spectroscopic data

➡ 13 galaxies in DES

$$\mathcal{L} = (1 - f_{\rm MW})\,\mathcal{L}_{\rm satellite} + f_{\rm MW}\,\mathcal{L}_{\rm MW}$$

with $\mathcal{L}_{\rm satellite/MW} = \mathcal{L}_{\rm spatial}\,\mathcal{L}_{\rm PM}$

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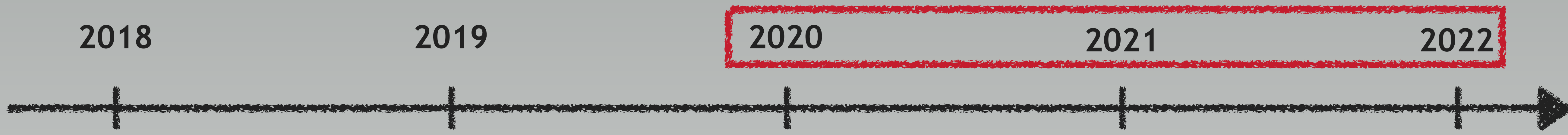

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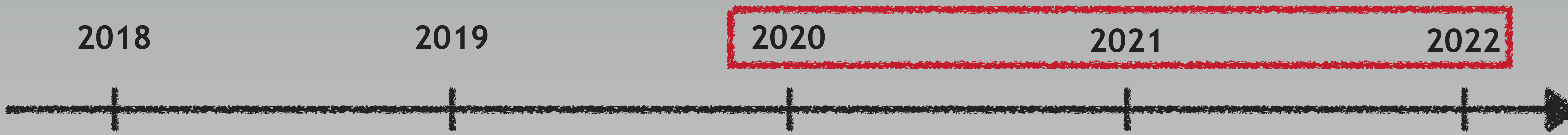

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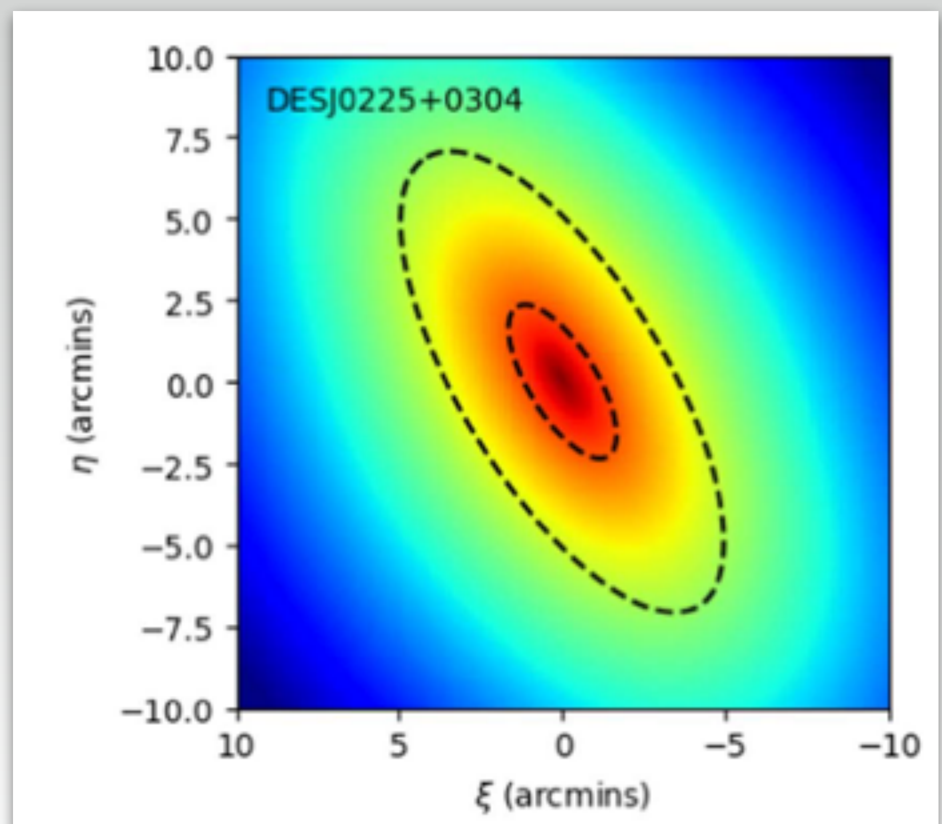
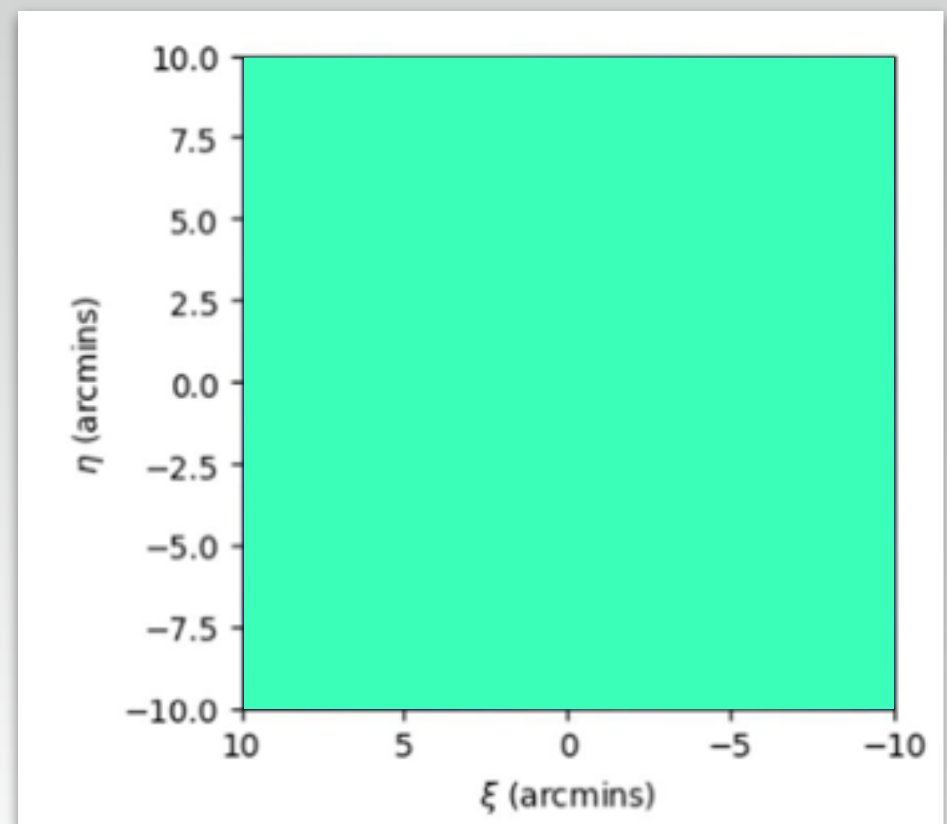
Satellite



Contaminant



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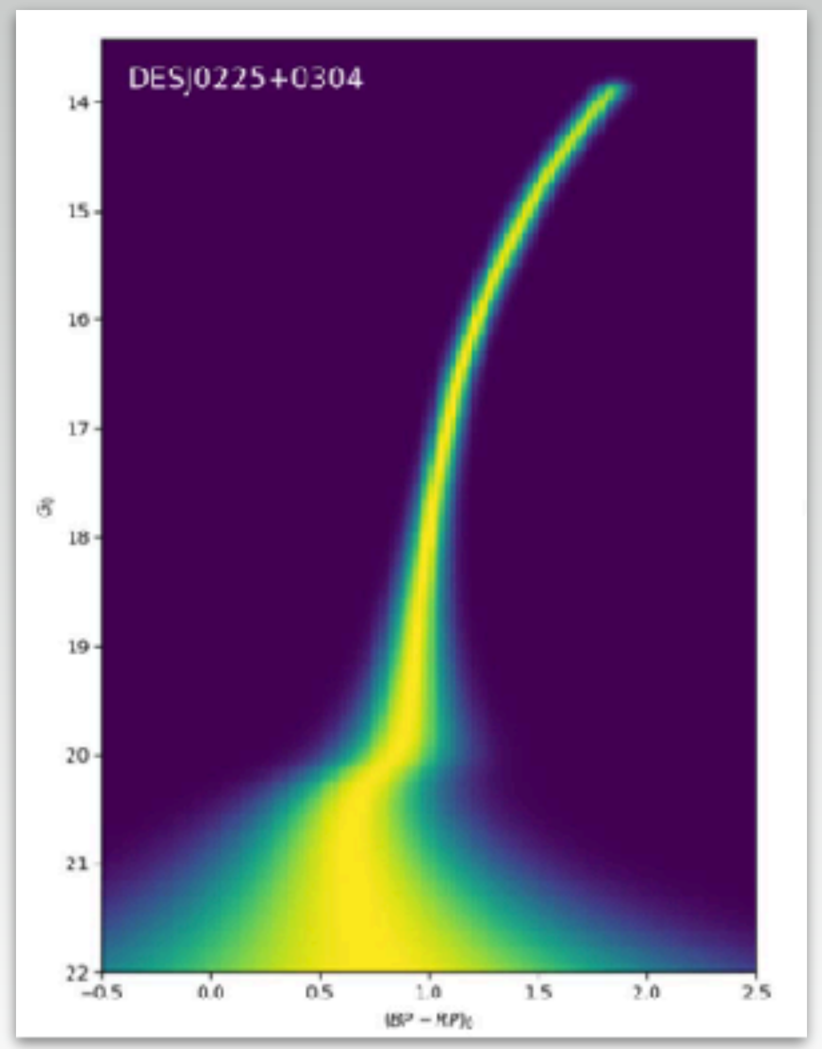

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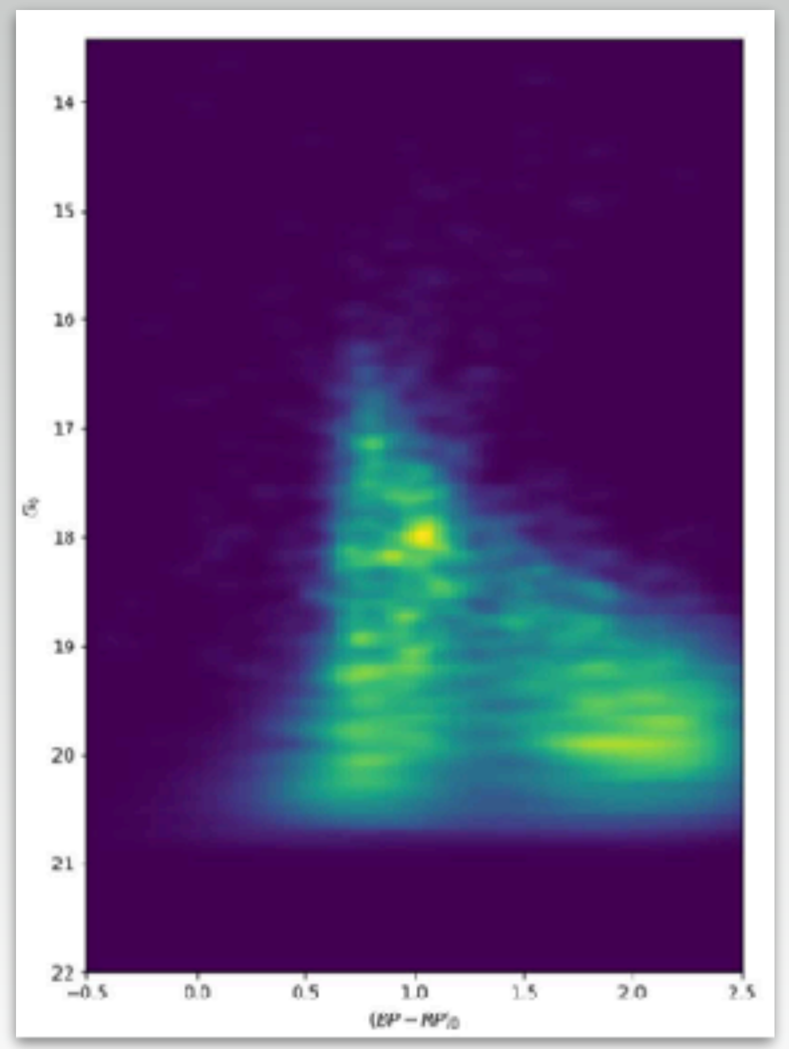

Constructed from stars at the edges of the galaxy (>5 R_h)

GLOBAL MOTIONS (SYSTEMICS)

2018 — 2019 — 2020 — 2021 — 2022

McConnachie & Venn, 2020 a, b, McConnachie et al. 2021, Battaglia & al. 2022

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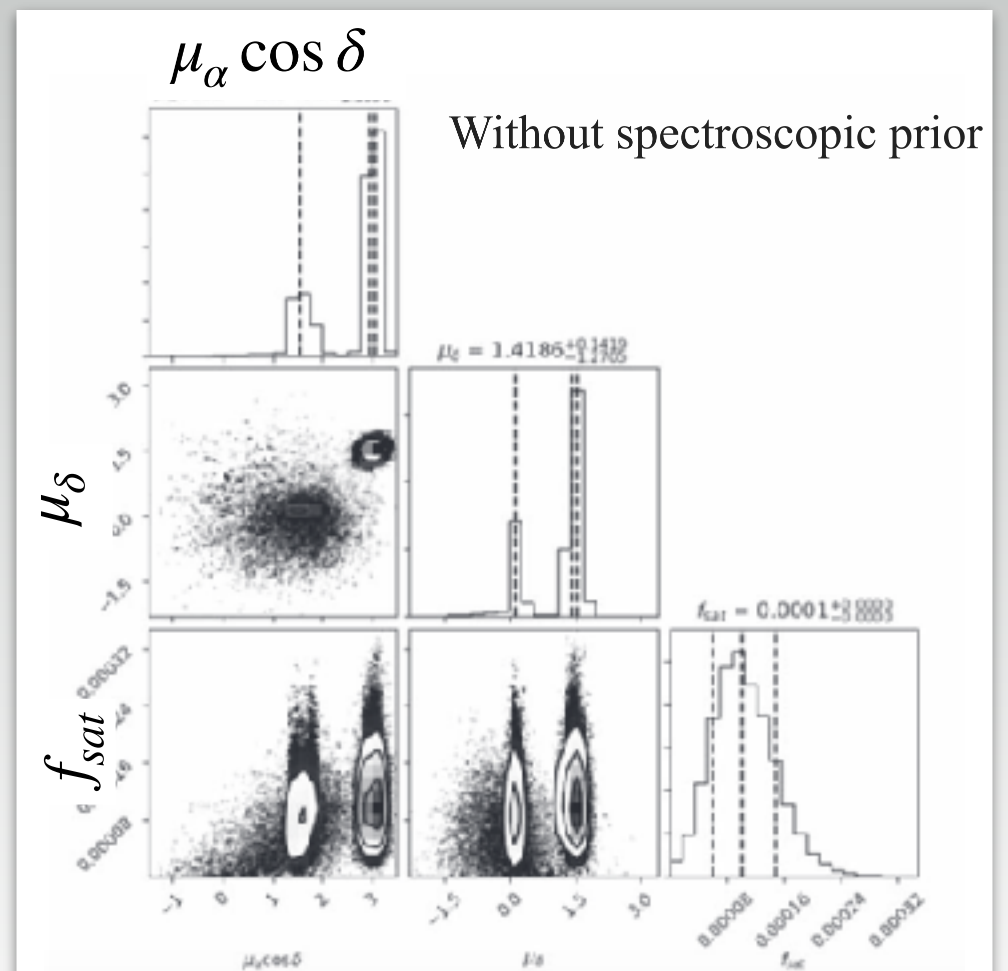

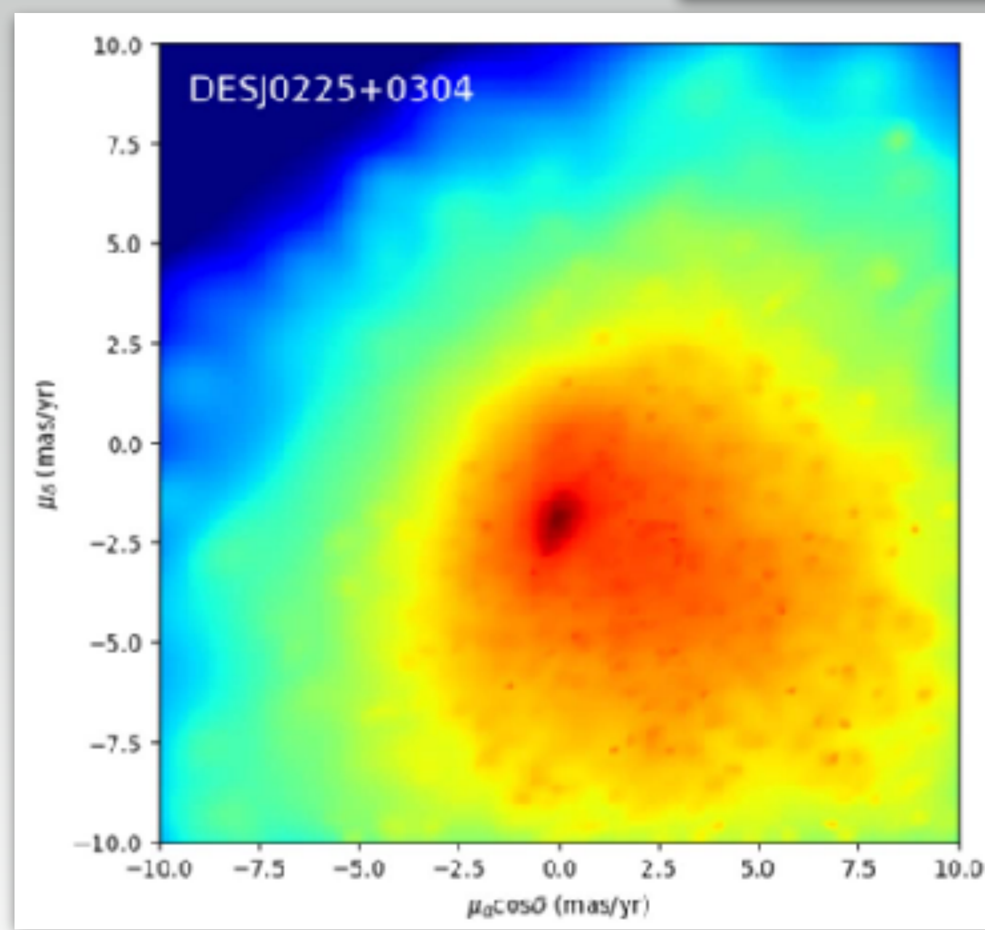

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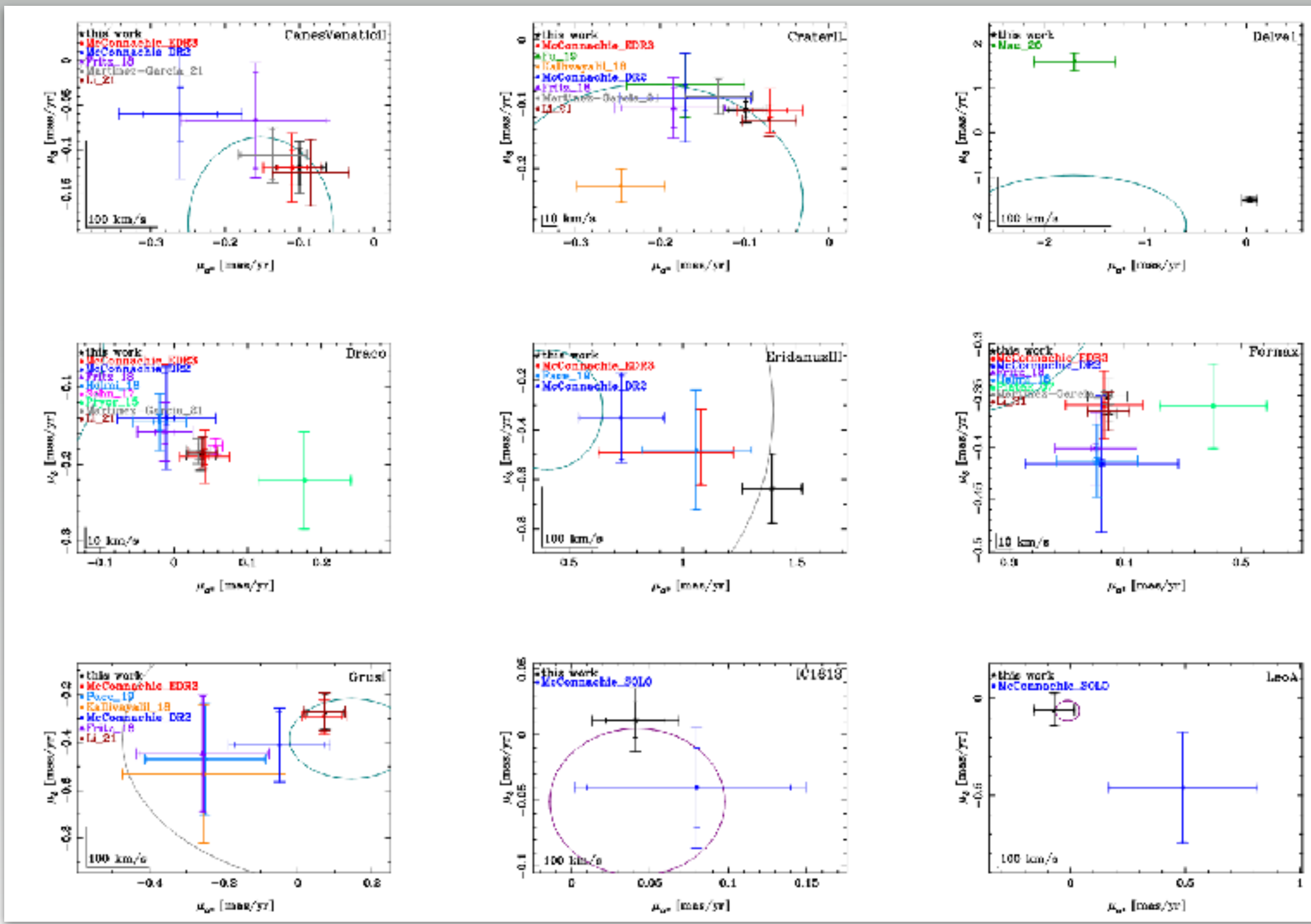


- Use maximum of the information available

➡ eDR3 more precise than DR2

➡ Global convergence

➡ Differences due to the approach and the treatment of the systematics

McConnachie & Venn, 2020 a, b; McConnachie et al. 2021; ***Battaglia & al. 2022****; Pace et al. 2022*

ORBITS OF DWARF GALAXIES

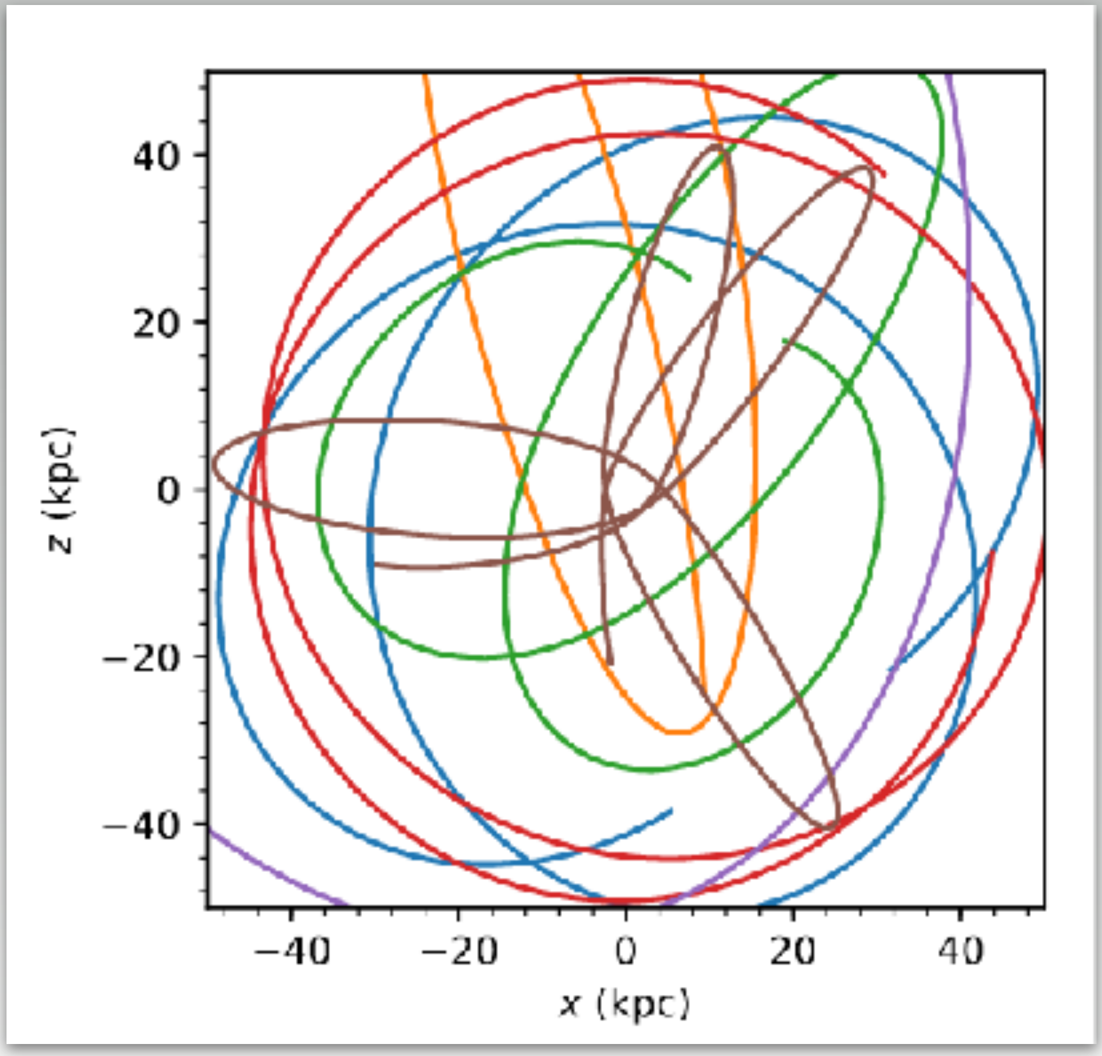
Systemic PMs

L.O.S velocities

Global motion

Potential of the MW (LG)

Orbits



Simon et al. 2018

ORBITS OF DWARF GALAXIES

- 2 categories of potential used to compute the orbits:
  - *isolated* MW from 0.3-2.5×10^{12} M$_\odot$

    e.g. Gaia Collaboration et al. 2018, Fritz et al., 2018; Simon, 2018; Li, Hammer et al., 2021; ***Battaglia et al. 2022***

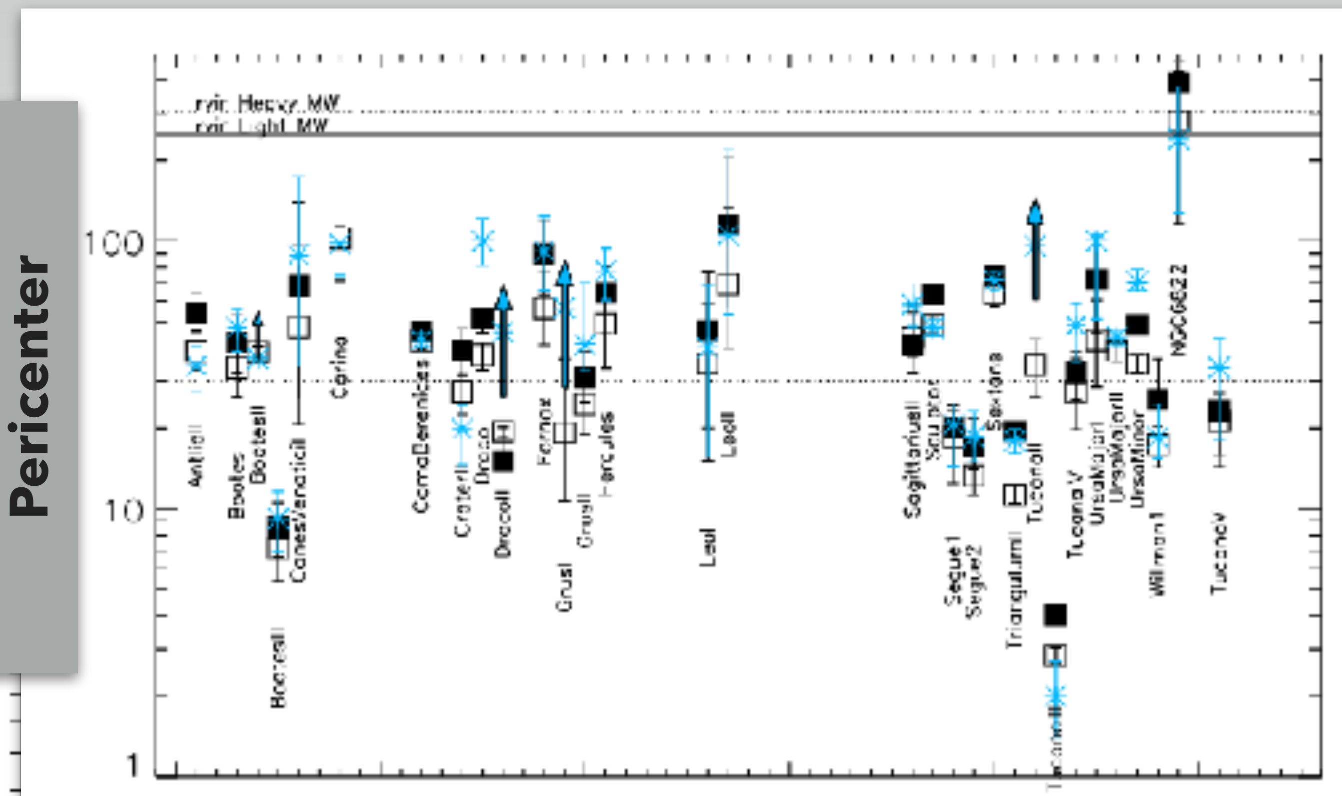
  - MW *perturbed* by massive LMC 1-2.5×10^{11} M$_\odot$

    e.g. (Kallivayalil et al. 2018), Patel et al. 2020; ***Battaglia et al. 2022****, Correa-Magnus & Vasiliev 2022, Pace et al. 2022*

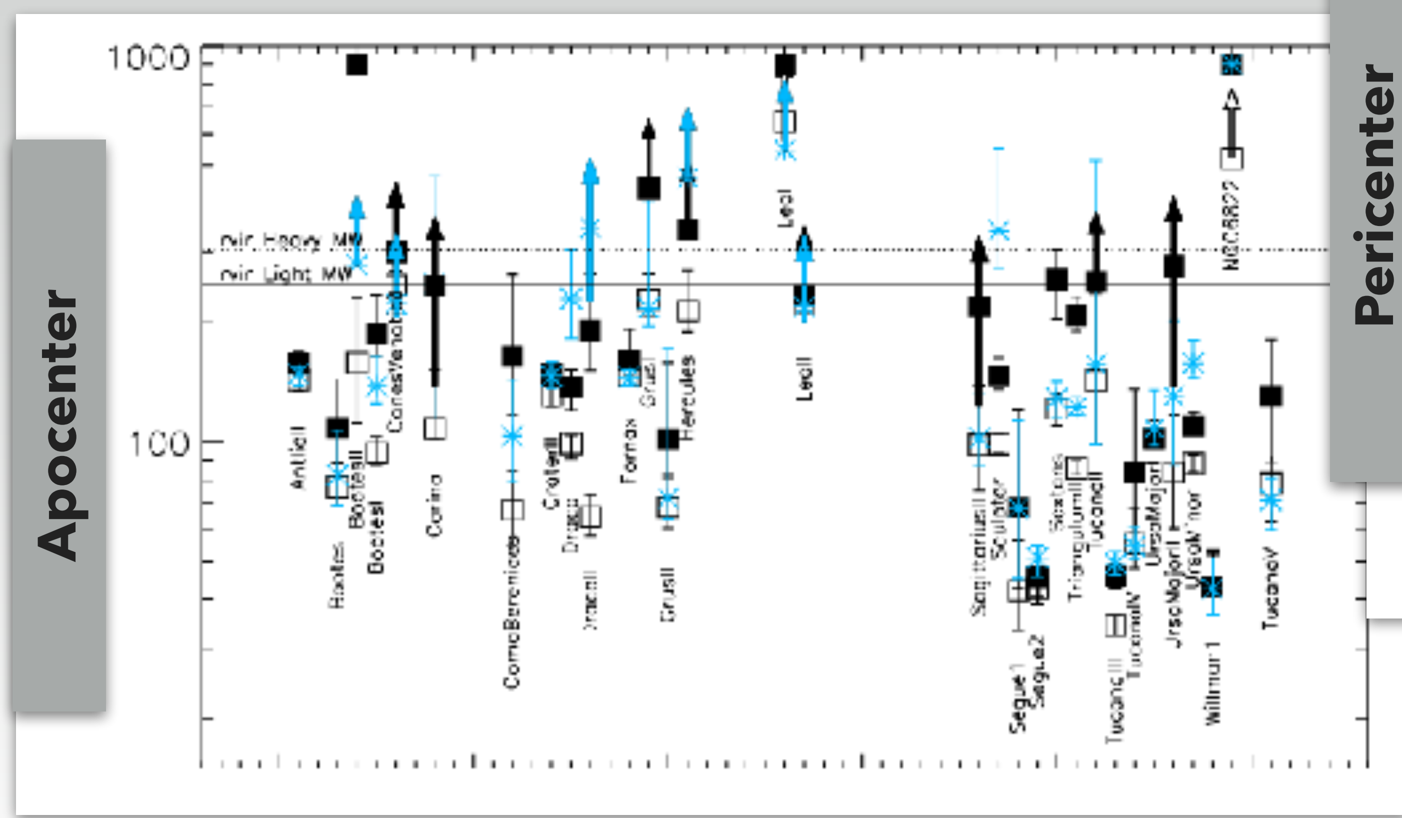
Legend

- ■ Light MW (0.88 ×10^{12} M$_\odot$)
- □ Massive MW (1.6 ×10^{12} M$_\odot$)
- x Perturbed MW

Pericenter



Apocenter



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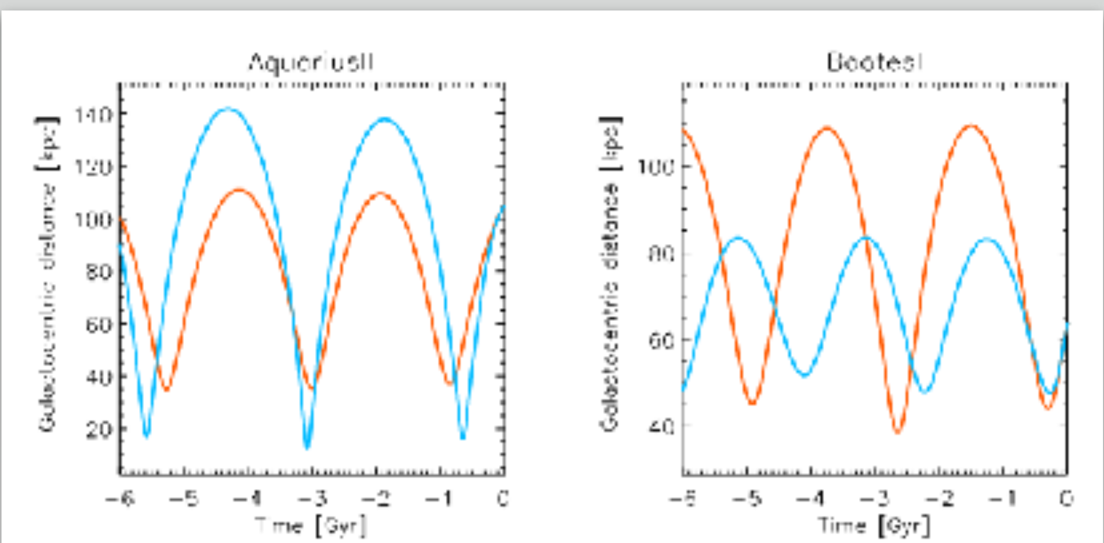
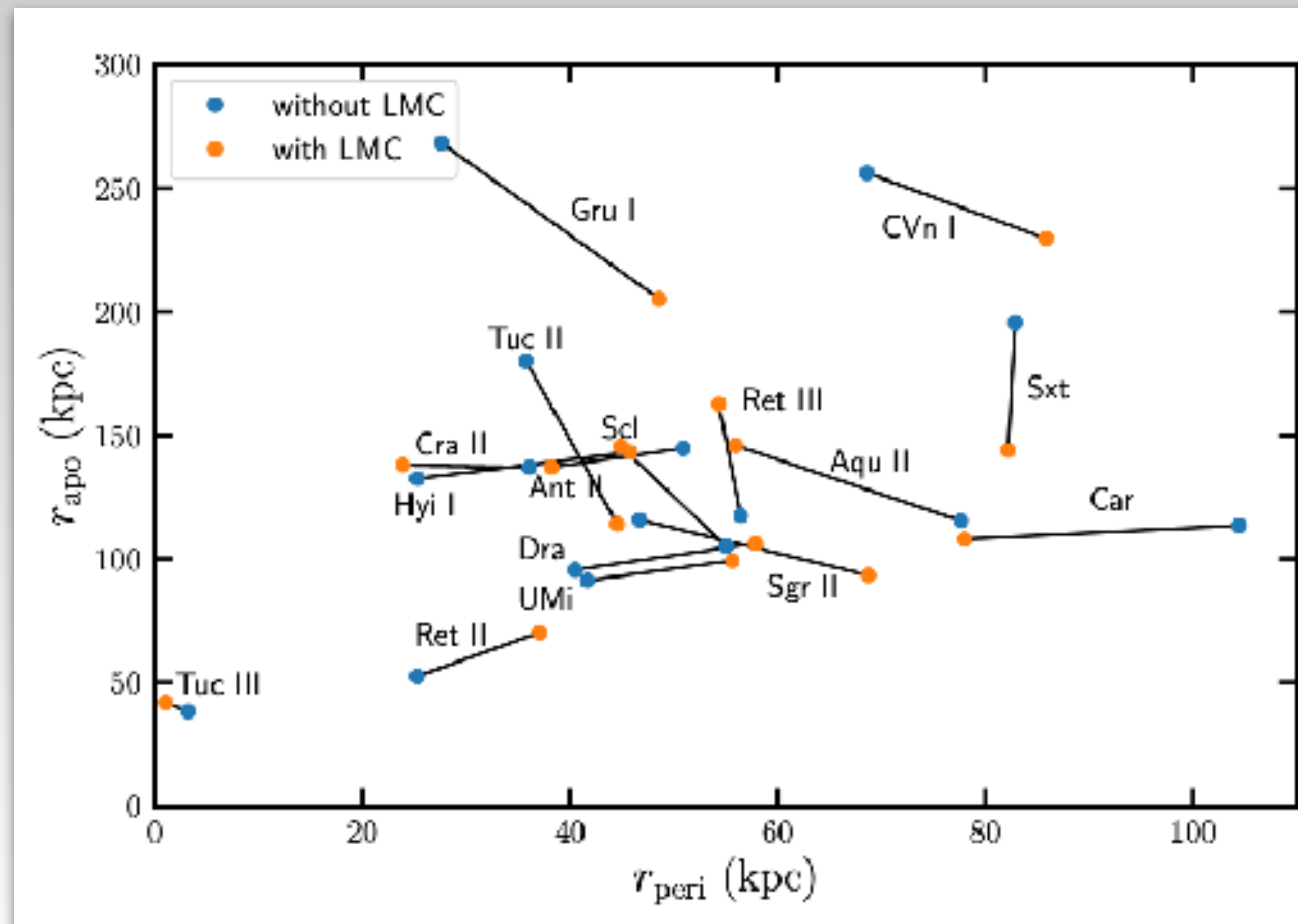
See also: Armstrong et al. 2021 for orbits in evolving MW
McConnachie et al. 2021 for the LG





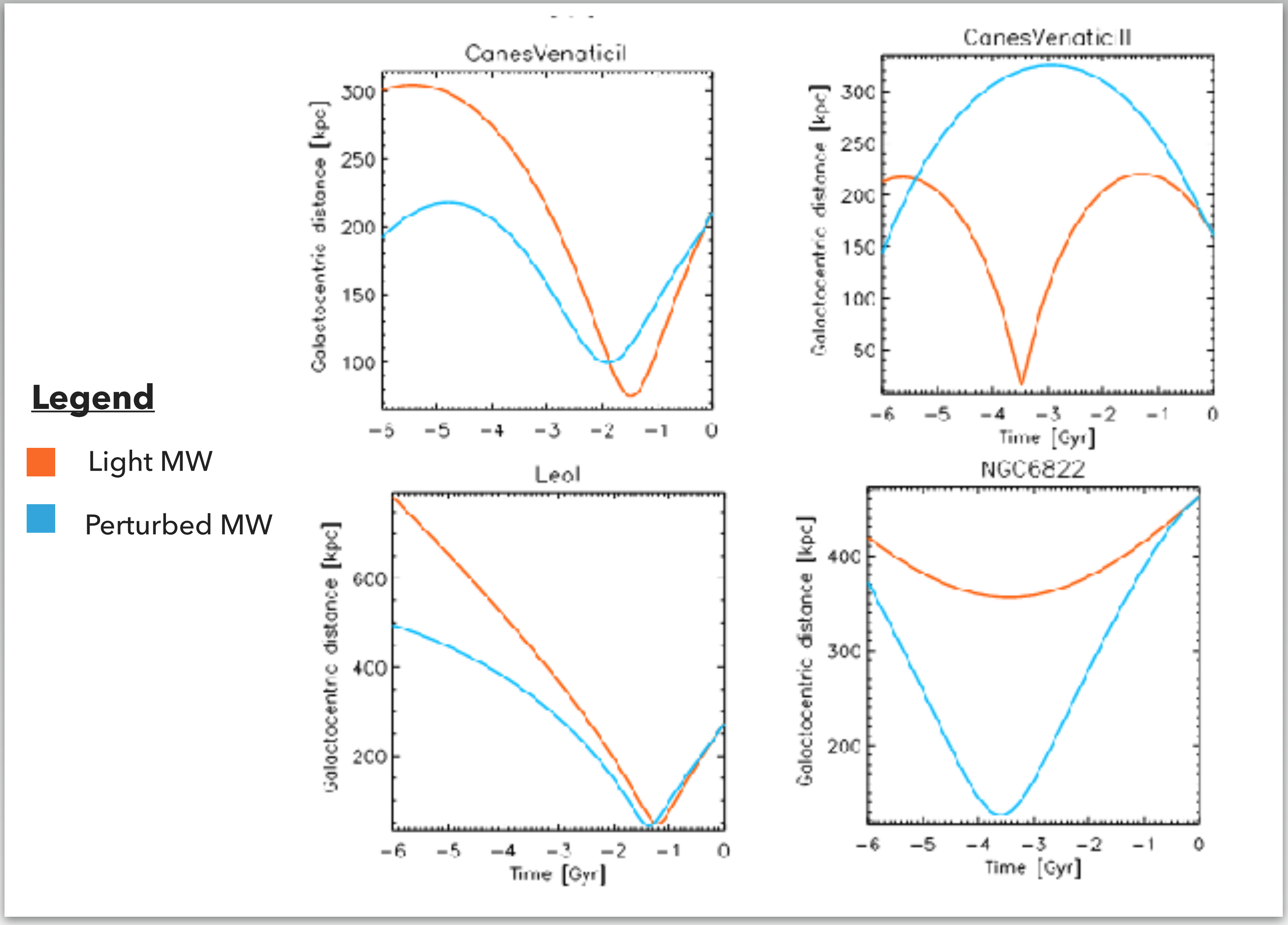
THE BOUNDS, THE STRIPPED AND THE BACKSPLASHED

Unbounds dwarfs

- Eridanus II
- (NGC 6822)
- (Leo T)
- (Phoenix)
- Pisces II

Backsplashed dwarfs

- Leo I
- (Canes Venaci I & II)
- (Draco II)
- (NGC 6822)
- (Leo T)
- (Phoenix)

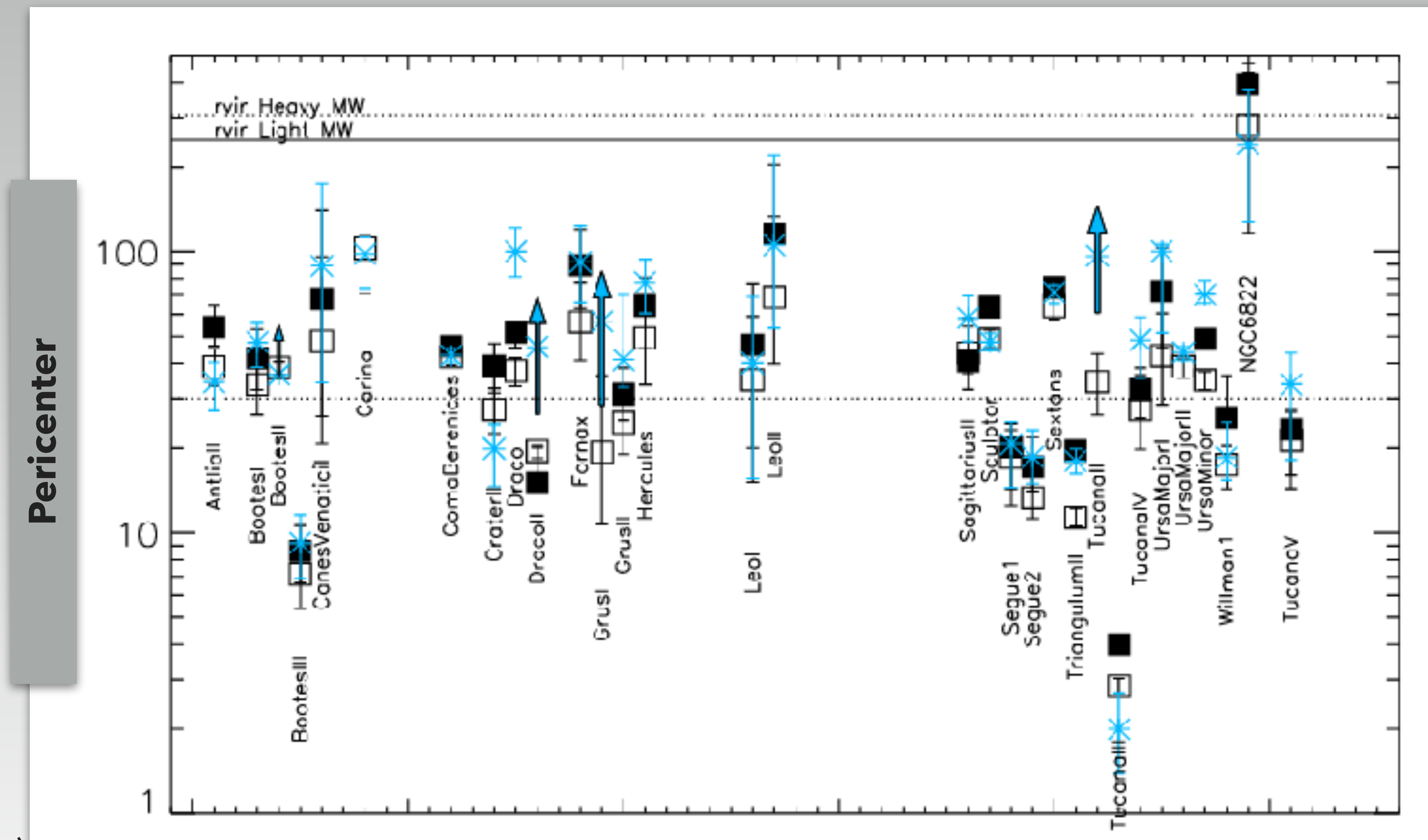


*McConnachie et al. 2021; **Battaglia et al., 2022**; Pace et al. 2022*

THE BOUNDS, THE STRIPPED AND THE BACKSPLASHED

Stripped dwarfs

- **Boötes III**
- **Tucana III**
- **Sgr**
- *(Crater II)*
- (Antlia II)
- (Segue I)
- (*Segue 2*)
- (Triangulum II)
- (Canes Venaci I)
- (Hercules)
- (Willman 1)
- *(Grus II)*
- *(Böotes I)*
- *(Tucana IV)*
- (Tucana V)
- (Draco II)



Legend

■ Light MW (0.88 ×10¹² M☉)

□ Massive MW (1.6 ×10¹² M☉)

X Perturbed MW

Fritz et al. 2018; Simon et al 2018; ***Battaglia et al., 2022****; Pace et al. 2022*

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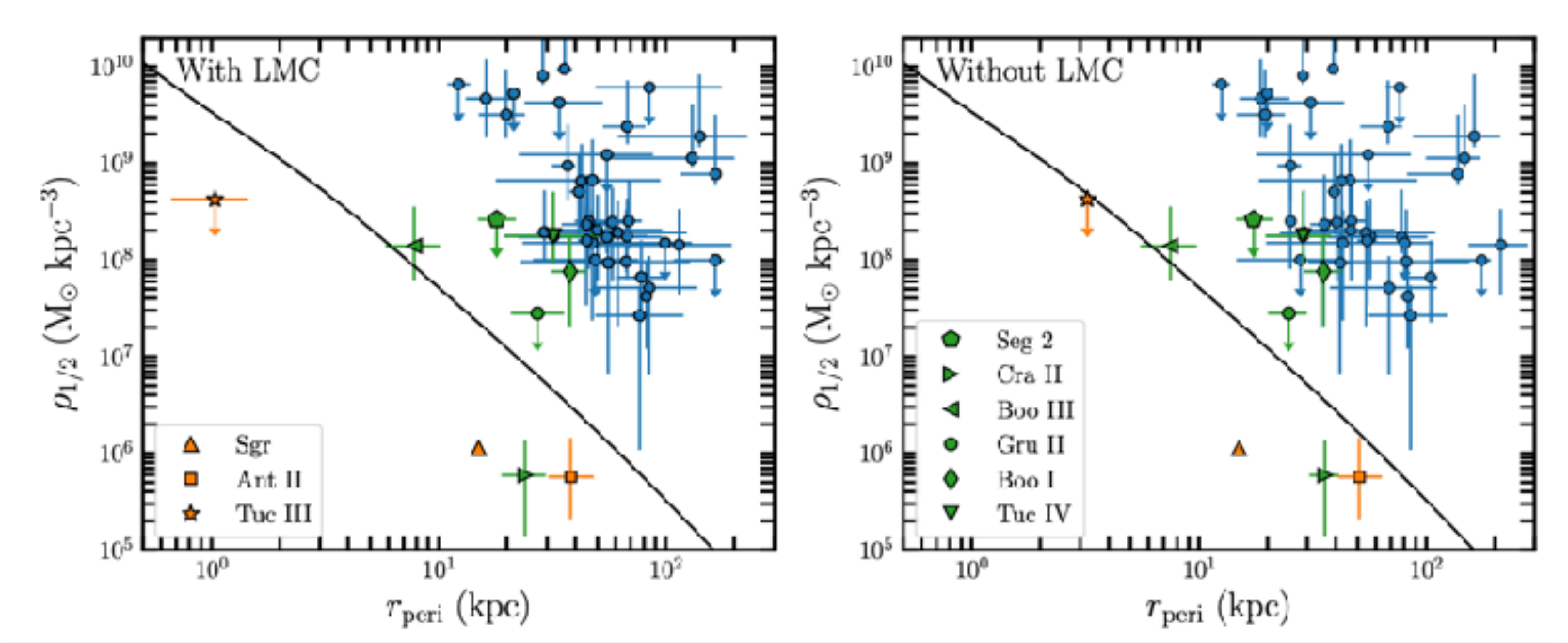

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ORBITS OF DWARF GALAXIES

- Isolated MW: dwarfs preferentially located near their pericenter

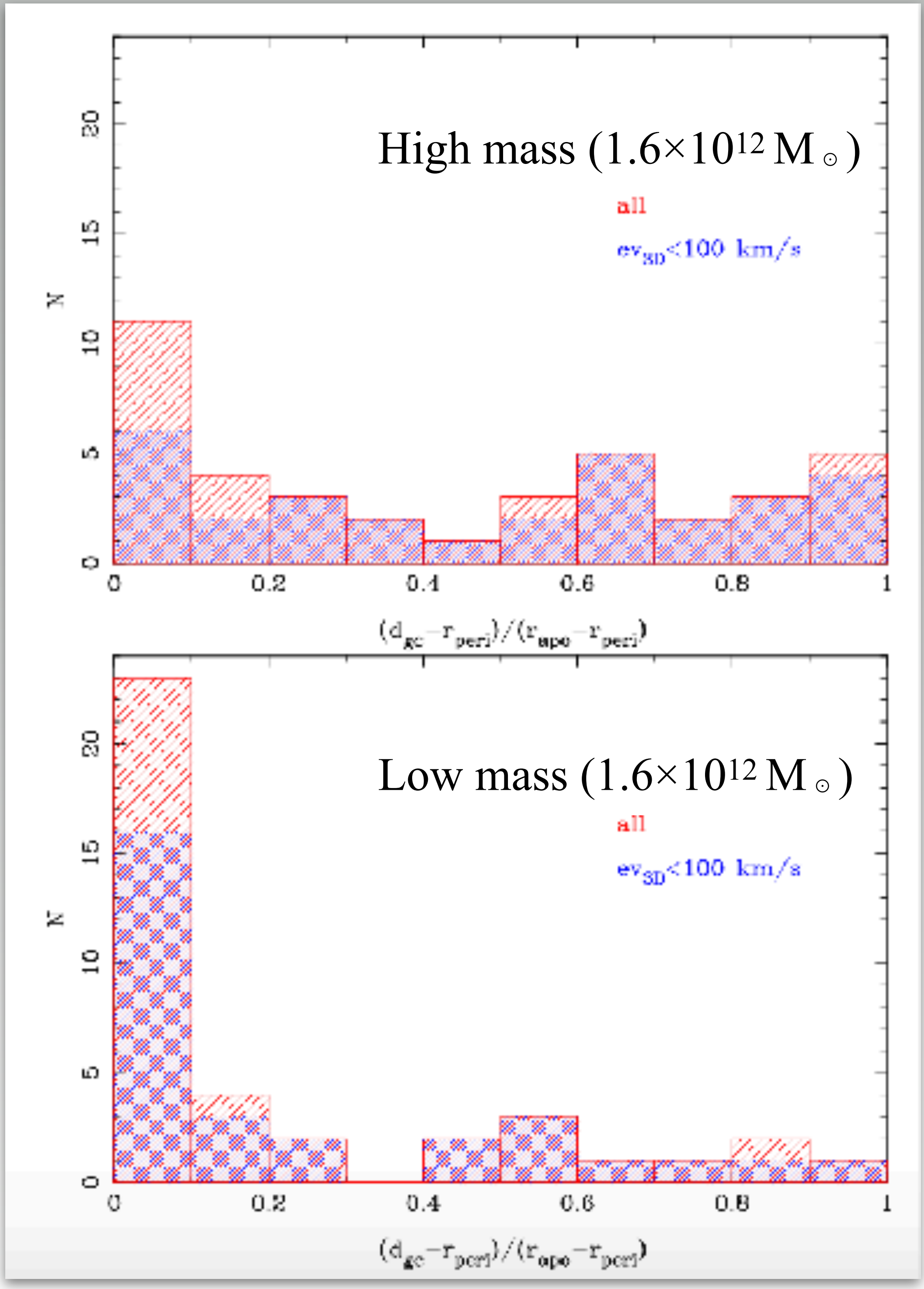
Fritz et al., 2018; Simon, 2018; Li, Hammer et al., 2021

Pb: 3rd Kepler law ⟶ mostly near their apocenter

(Probability~ 2×10^{-7} for MW $\leq 10^{12}\,M_\odot$) *Hammer et al. 2020*

➡ Bias of detection (missing UFD) *Fritz et al., 2018*

➡ Strong tidal shocks *Hammer et al. 2020*



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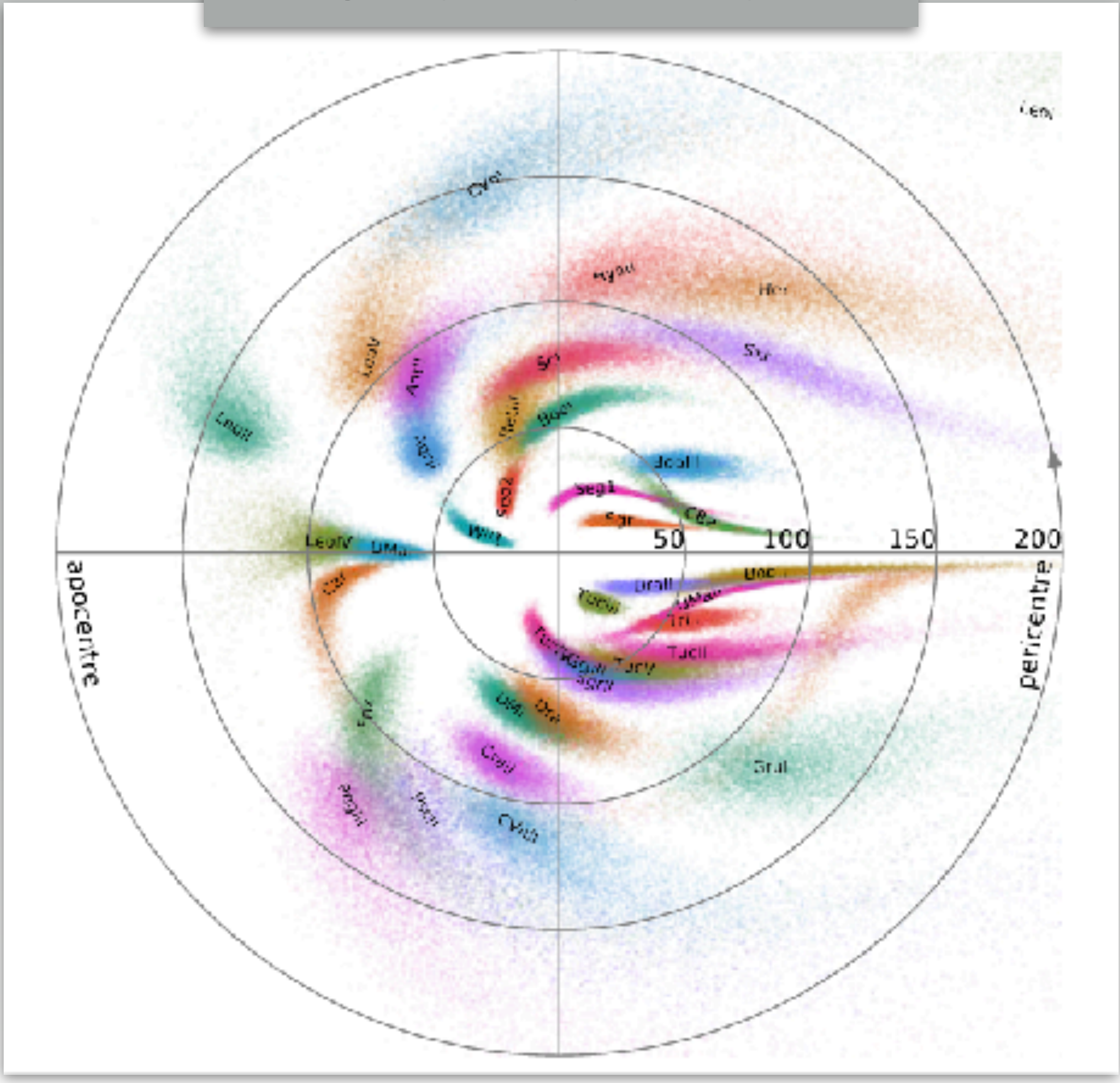
➡ “Inference” problem: using posterior-weighted uncertainties rather than raw measurements

Correa-Magnus & Vasiliev 2022

Current distribution



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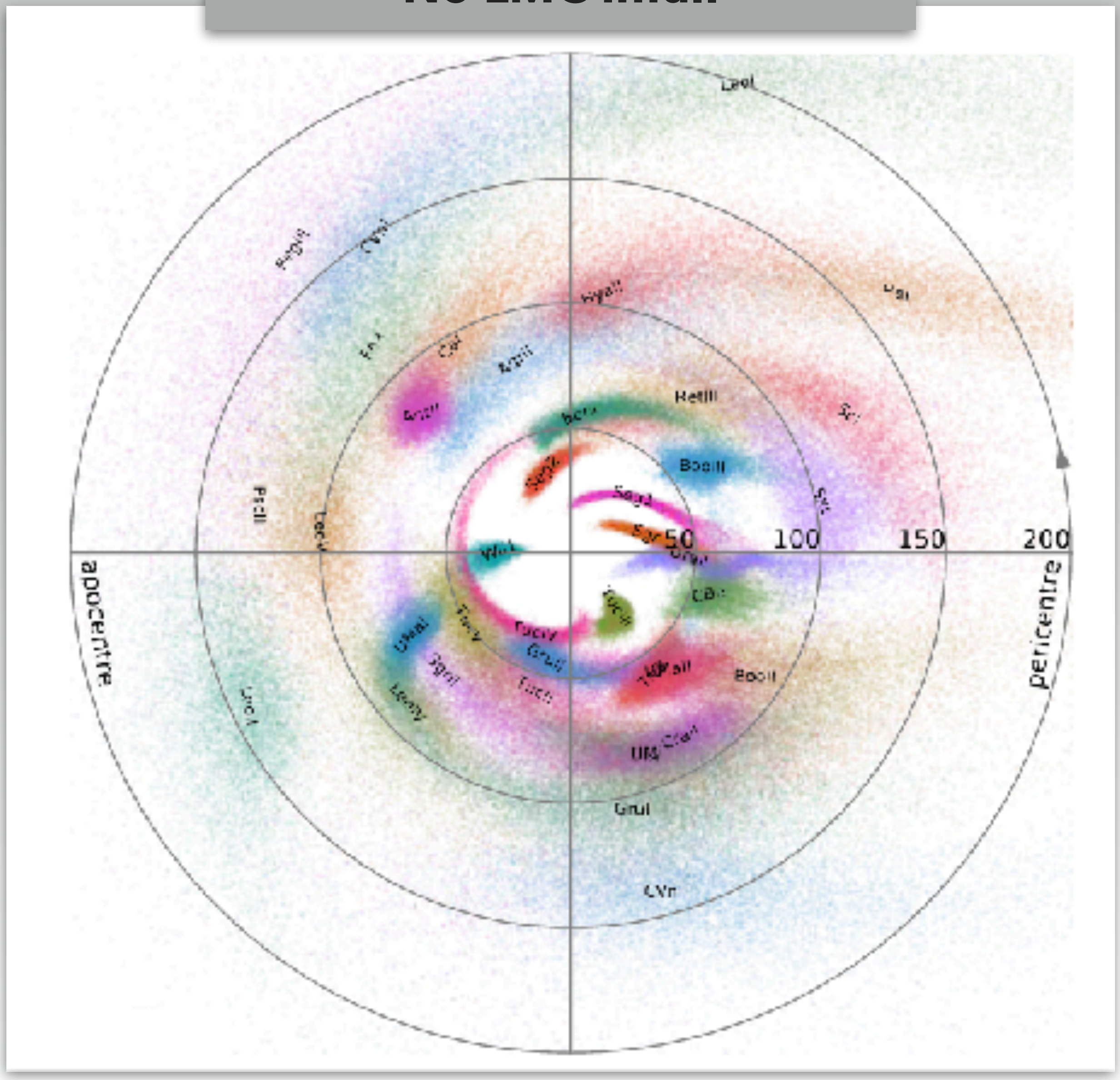
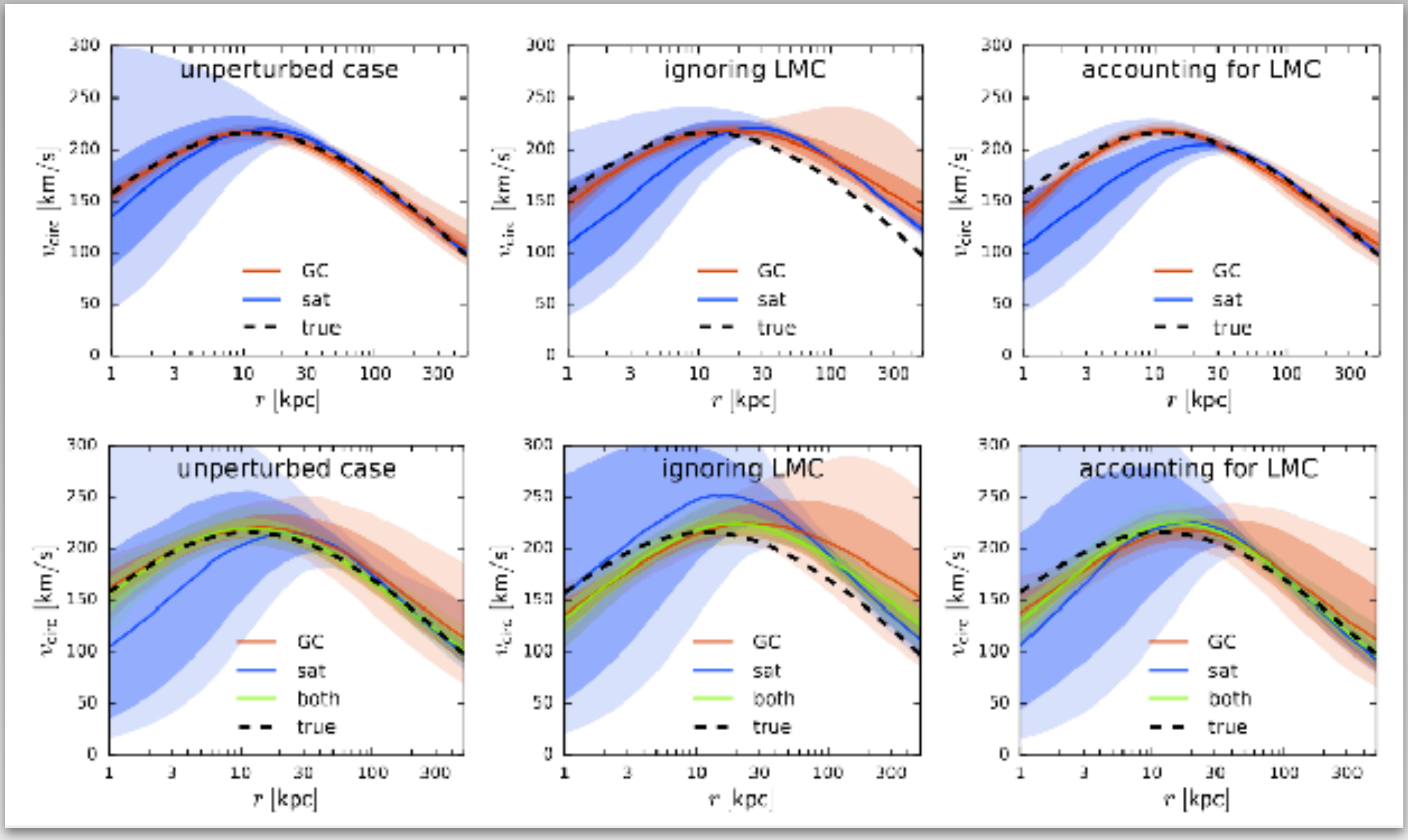
No LMC infall



DWARFS AS GALACTIC SCALE

- Use both dwarfs galaxies and GCs
- Include the perturbation of the LMC
- Treatment of outliers



- Choice parameters for potential of the MW and LMC and for the DF of the tracers
- Backward orbit rewinding integration for t_{reward}
- Compute likelihood of the model with respect to the observation (incl. uncertainties)

Correa-Magnus & Vasiliev 2022

(See also Fritz et al. 2020; Slizewski et al. 2022 for other methods)

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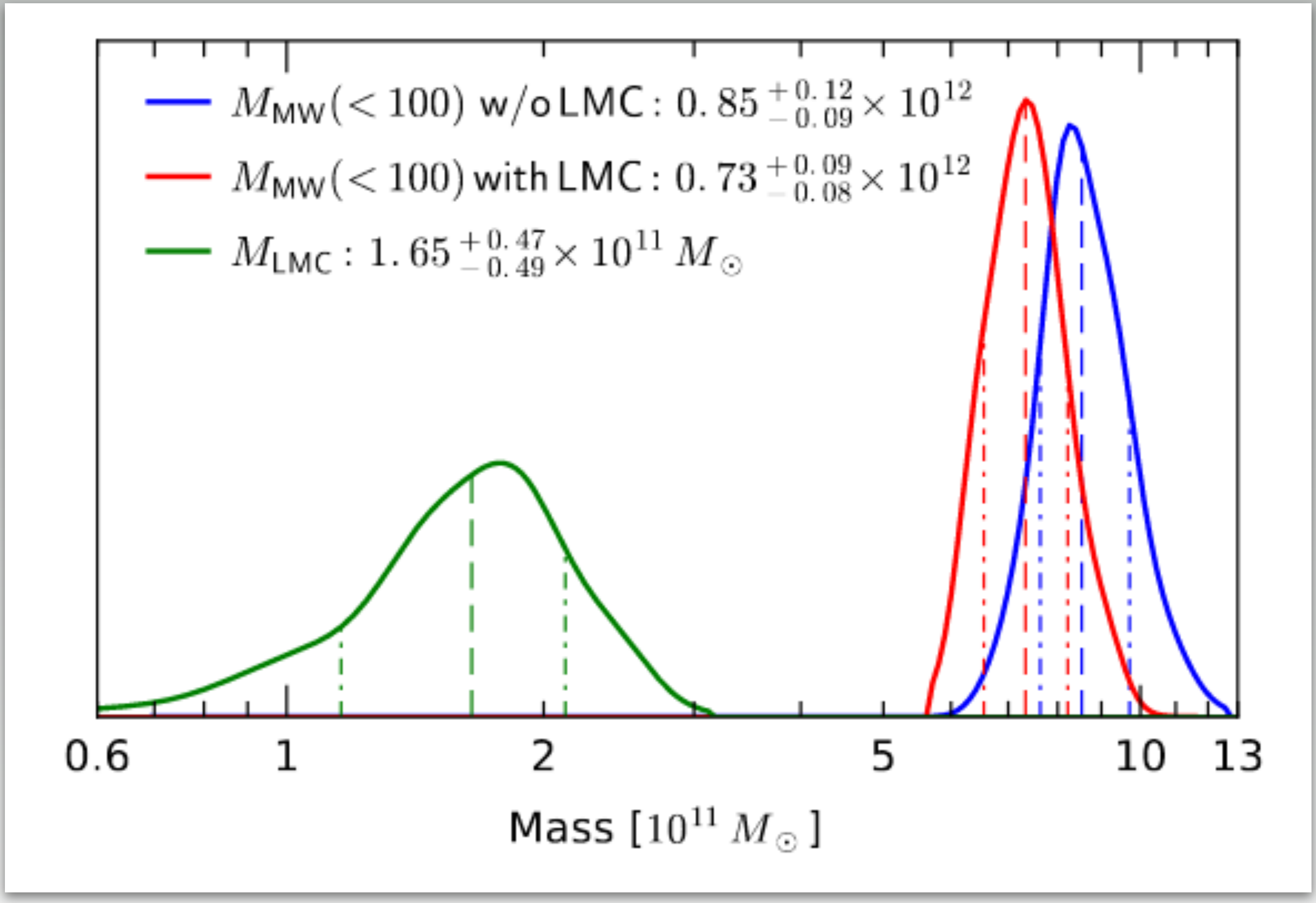

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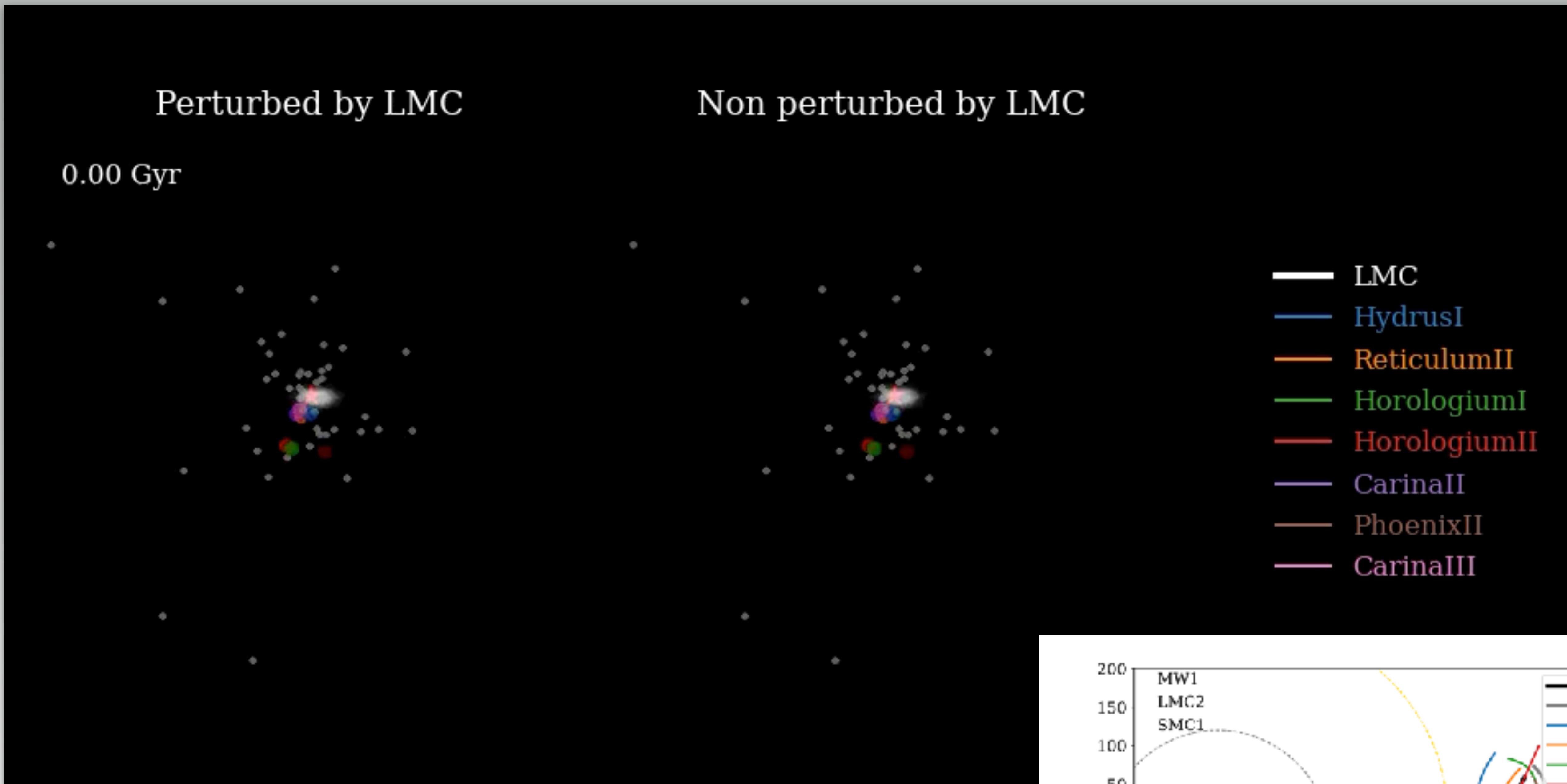
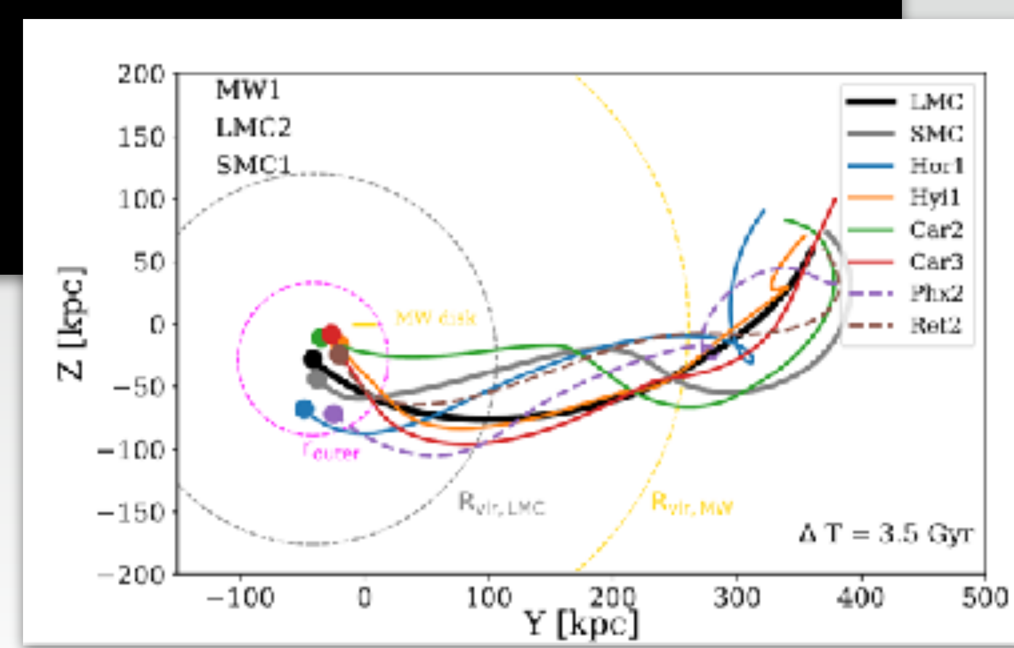
GROUPS OF INFALLING GALAXIES





*Kallivayalil et al. 2018; Erkal & Belokurov et al. 2019; Fritz et al. 2019; **Patel et al. 2020;** Pardy et al. 2020; **Battaglia et al. 2022;** Correa-Magnus & Vasiliev 2022, Pace et al. 2022*

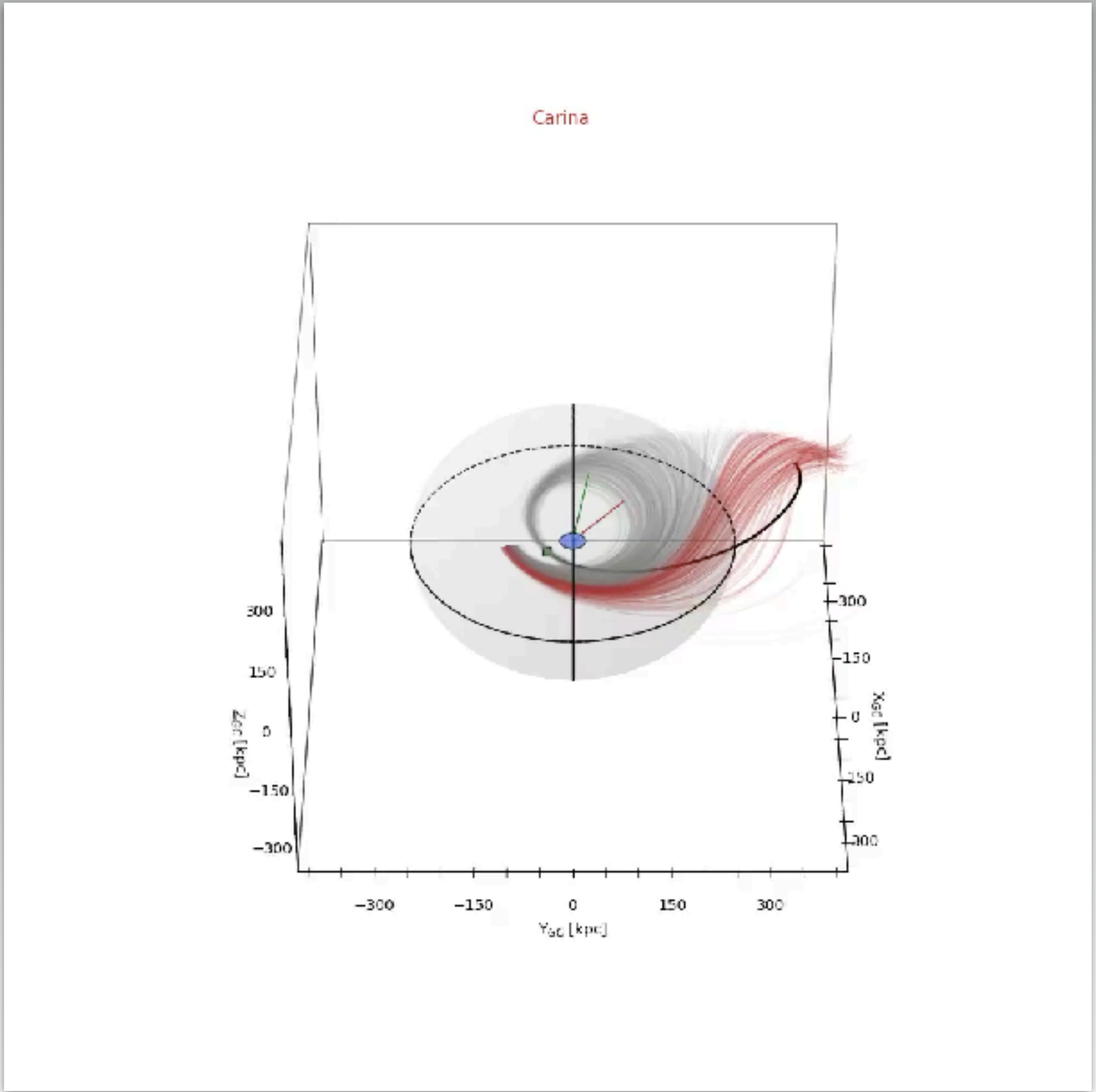
GROUPS OF INFALLING GALAXIES

+SMC

Galaxy	t_{ca} [Gyr]	R_{ca} [kpc]	V_{ca} [km.s^{-1}]	$\mathcal{F}_{link}$	T_{esc} [Gyr]
Highly parented to the LMC					
Carina II	-0.97	$12.18^{+14.02}_{-3.33}$	$174.12^{+15.77}_{-35.65}$	1.00	-0.58
Carina III	-0.18	$13.74^{+2.60}_{-1.54}$	$164.54^{+11.59}_{-12.12}$	0.99	-0.07
Horologium I	-0.12	$36.35^{+7.94}_{-7.20}$	$113.90^{+33.44}_{-34.31}$	0.84	-0.46
Hydrus I	-0.30	$13.09^{+7.14}_{-3.11}$	$146.25^{+14.48}_{-18.54}$	1.00	-0.14
Phoenix II	-0.43	$25.99^{+24.83}_{-14.49}$	$123.57^{+45.76}_{-47.04}$	0.90	-0.31
Reticulum II	-0.19	$14.69^{+1.21}_{-0.85}$	$155.57^{+7.01}_{-9.30}$	1.00	-0.08
Potentially parented to the LMC					
Horologium II	-0.04	$38.81^{+7.11}_{-6.89}$	$170.06^{+71.39}_{-65.89}$	0.56	-0.43
Tucana IV	-0.15	$6.57^{+5.64}_{-2.21}$	$220.88^{+19.99}_{-45.68}$	0.94	-0.06
Carina	0.00	$62.27^{+5.67}_{-5.81}$	$148.31^{+10.24}_{-8.86}$	0.25	-2.77
Recently captured (<1 Gyr) by the LMC					
Grus II	-0.34	$25.62^{+4.23}_{-3.33}$	$186.06^{+22.15}_{-30.59}$	0.57	-0.29

Kallivayalil et al. 2018; Erkal & Belokurov et al. 2019; Fritz et al. 2019; Patel et al. 2020; Pardy et al. 2020; ***Battaglia et al. 2022;*** *Correa-Magnus & Vasiliev 2022, Pace et al. 2022*

GROUPS OF INFALLING GALAXIES



Kallivayalil et al. 2018; Fritz et al. 2019; Patel et al. 2020; ***Battaglia et al. 2022****, Correa-Magnus & Vasiliev 2022, Pace et al. 2022*

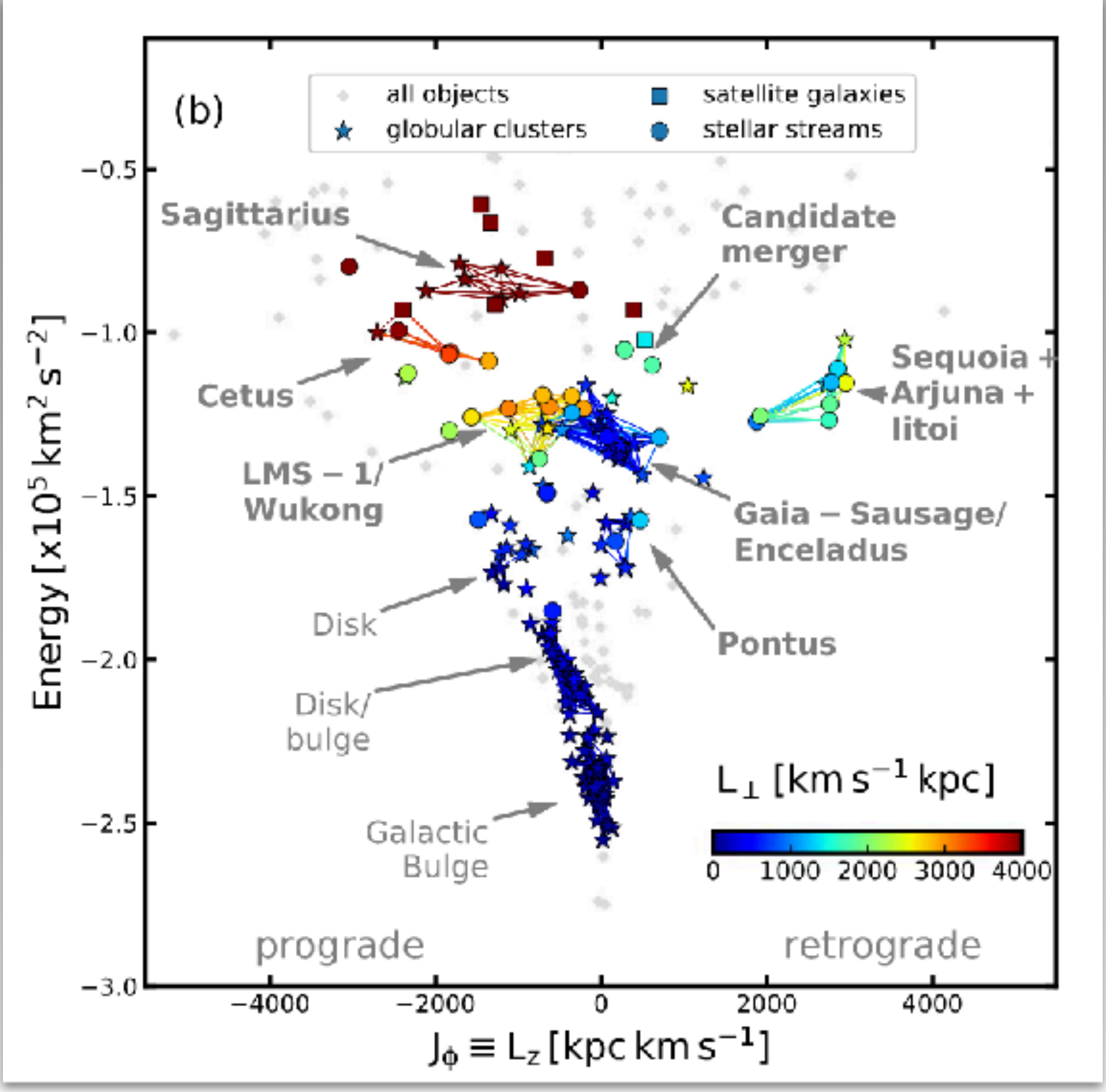
GROUPS OF INFALLING GALAXIES

- Grouped together streams, globular clusters and dwarfs based on Integral of motion space

➡ Galaxies tend to not be linked to other objects

➡ Polar orbits are stable

➡ No GCs linked to the LMC/SMC



Malhan et al. 2022

STABILITY OF THE VPOS

- High number of dwarfs located in a plane perpendicular to the disc plane *(39/46)* *Santos-Santos et al. 2020*

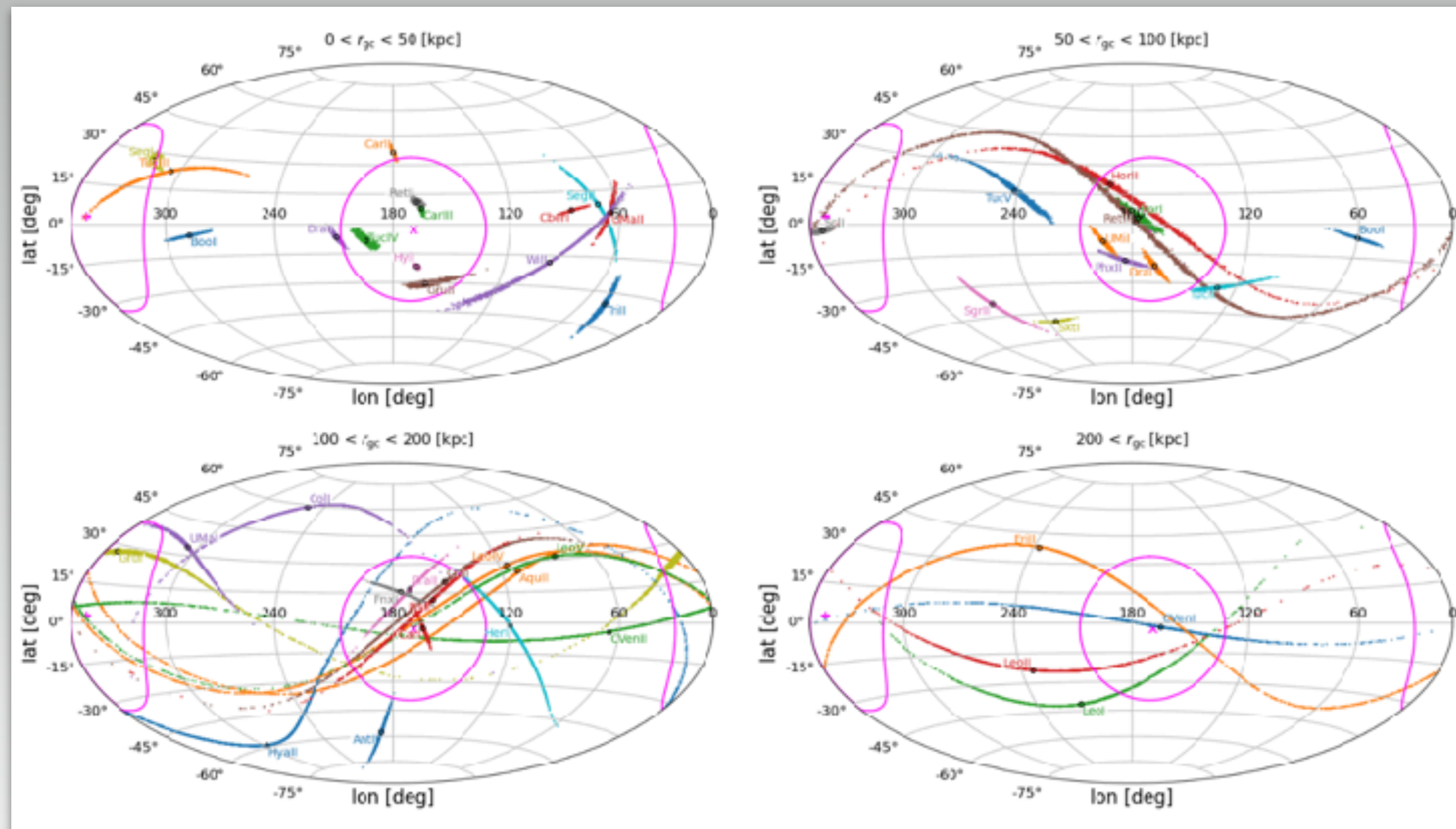
- Half of MW satellite in coronation

Santos-Santos et al. 2020; Li et al. 2021; Correa-Magnus & Vasiliev 2022

- Stable plane

- *c/a*~0.2

➡ Proposed that VPOS is a consequence of the LMC infall
Garavito-Camargo et al. 2021



Pawlowski et al. 2013; Fritz et al. 2018; Pawloswki & Kroupa 2019; Santos-Santos et al. 2020; ***Li et al. 2021****; Correa-Magnus & Vasiliev 2022*

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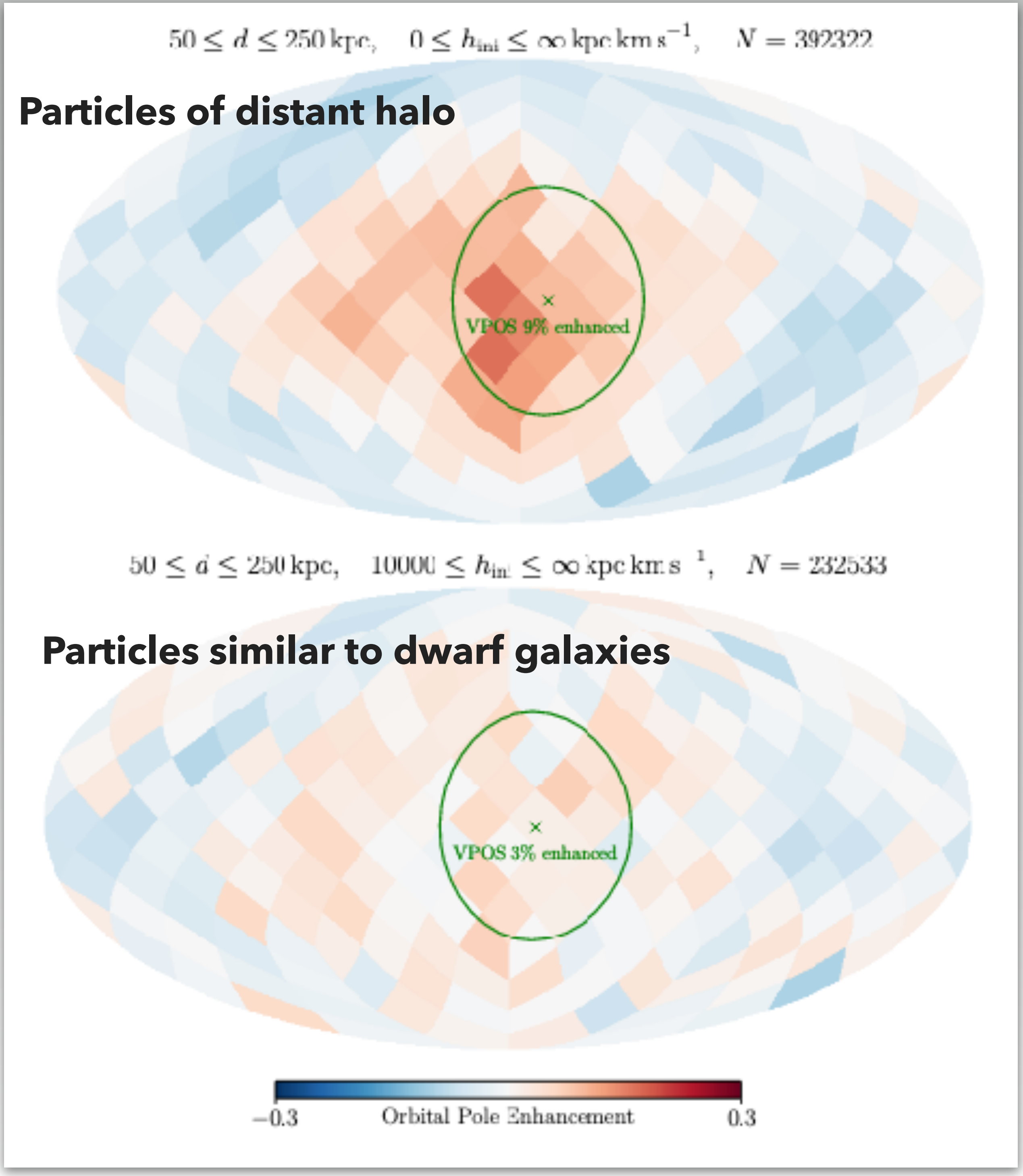
Garavito-Camargo et al. 2021

➡ Not enough to explain the VPOS (3% of enhancement)

Pawlowski et al., 2021*;*
Correa-Magnus & Vasiliev 2022



THE REVOLUTION OF GAIA

gaia

- Precise all-sky photometry
- **Proper motions**

Membership selection

Internal dynamics | Global motion | Find new galaxies

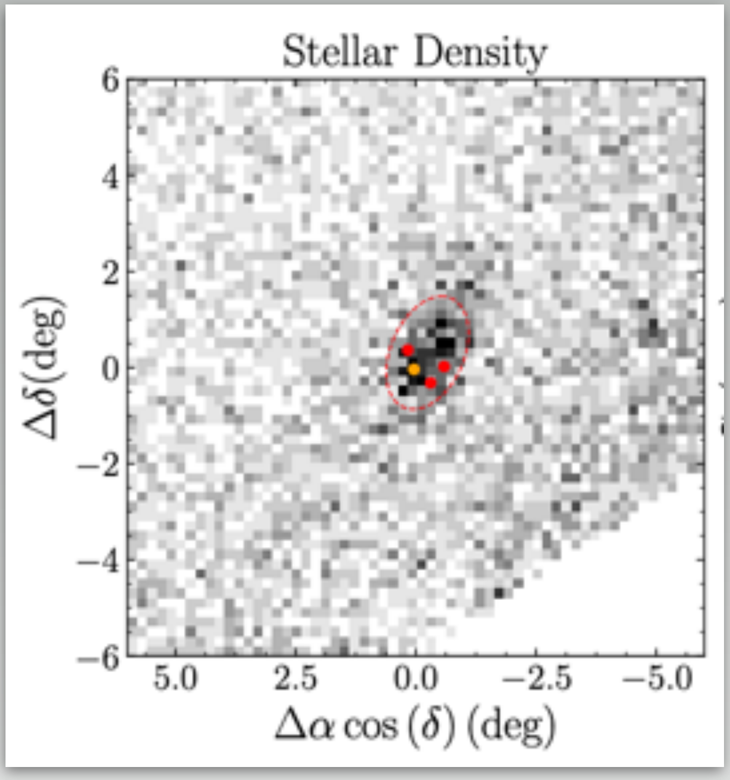
Orbits

Mass of the MW | Group of infalling galaxies | Stability of the VPOS

FINDING NEW GALAXIES

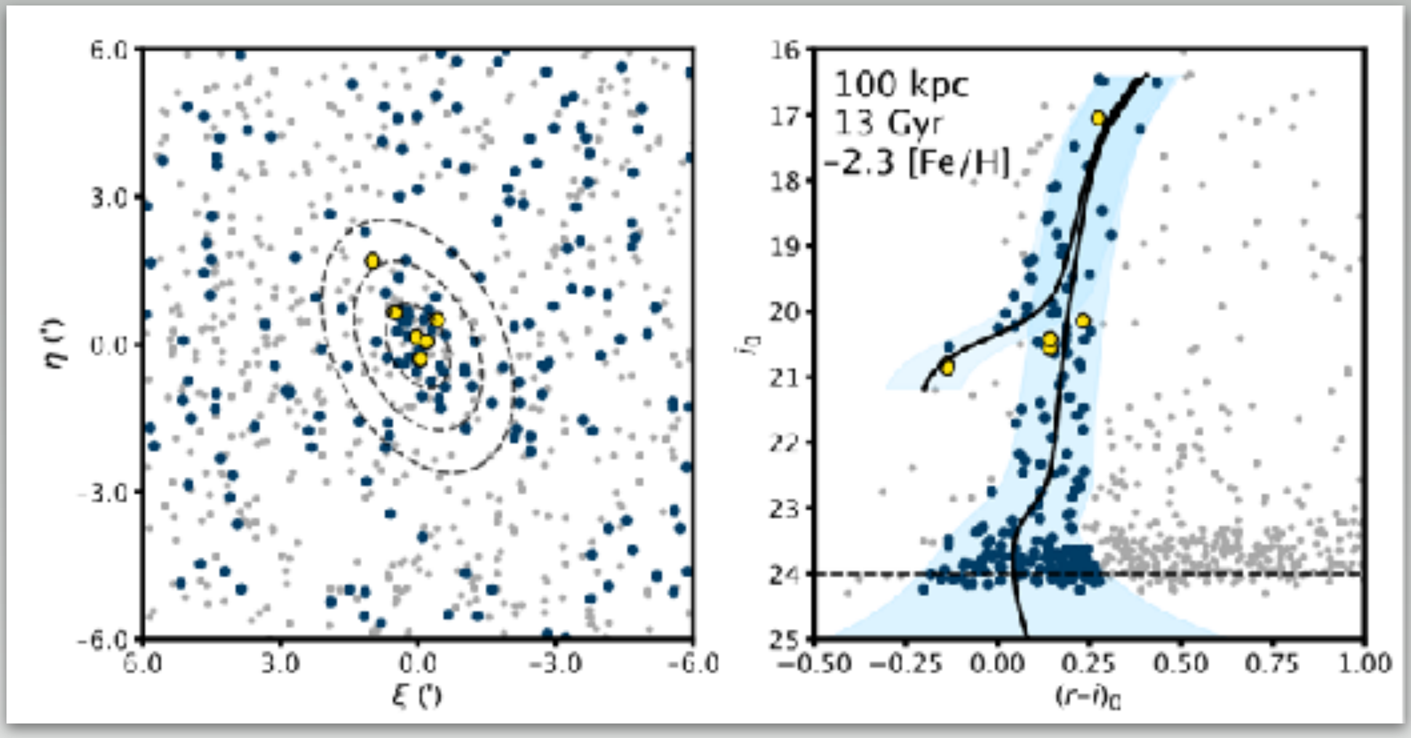
- Gaia helped to discover new galaxies and new disrupted galaxies

Antlia II



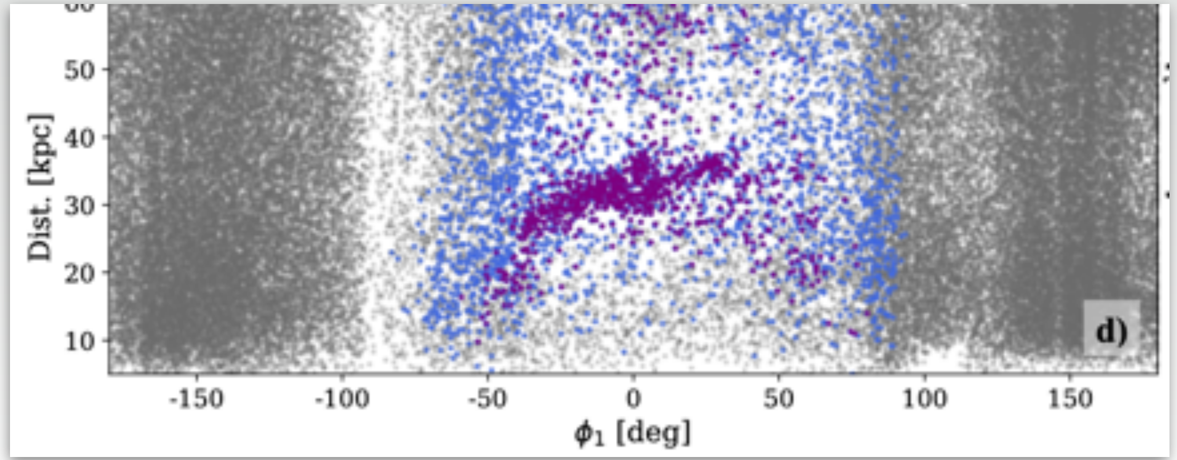
Torealba et al. 2019

Böotes V

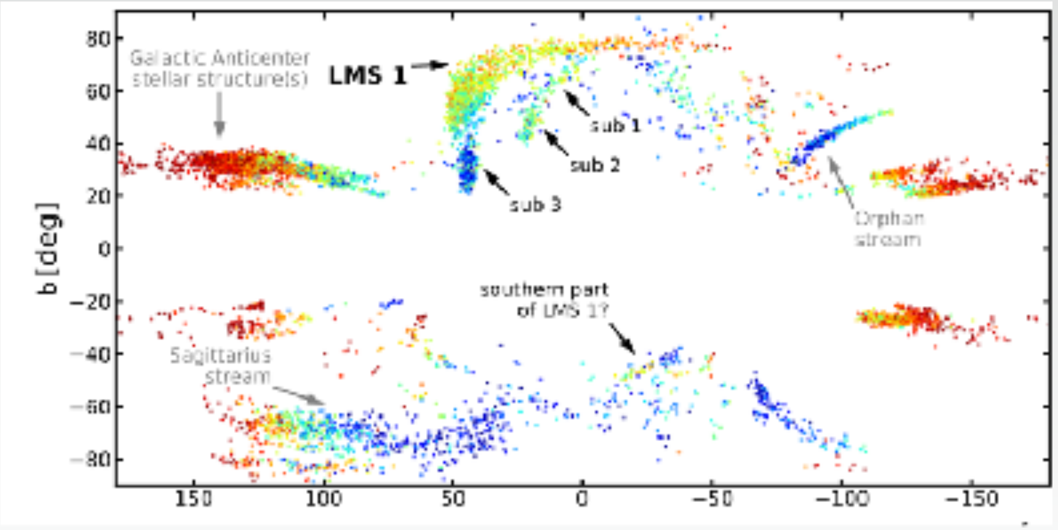


Smith et al. 2022; *Cerny et al. 2022*

Cetus-Palca stream



Thomas & Battaglia 2022;
Zhen et al. 2022



Malhan et al 2021

THE REVOLUTION OF GAIA

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GAIA: INTERNAL DYNAMICS

- Core of Sgr as residual internal rotation of 4.13 km.s^{-1}

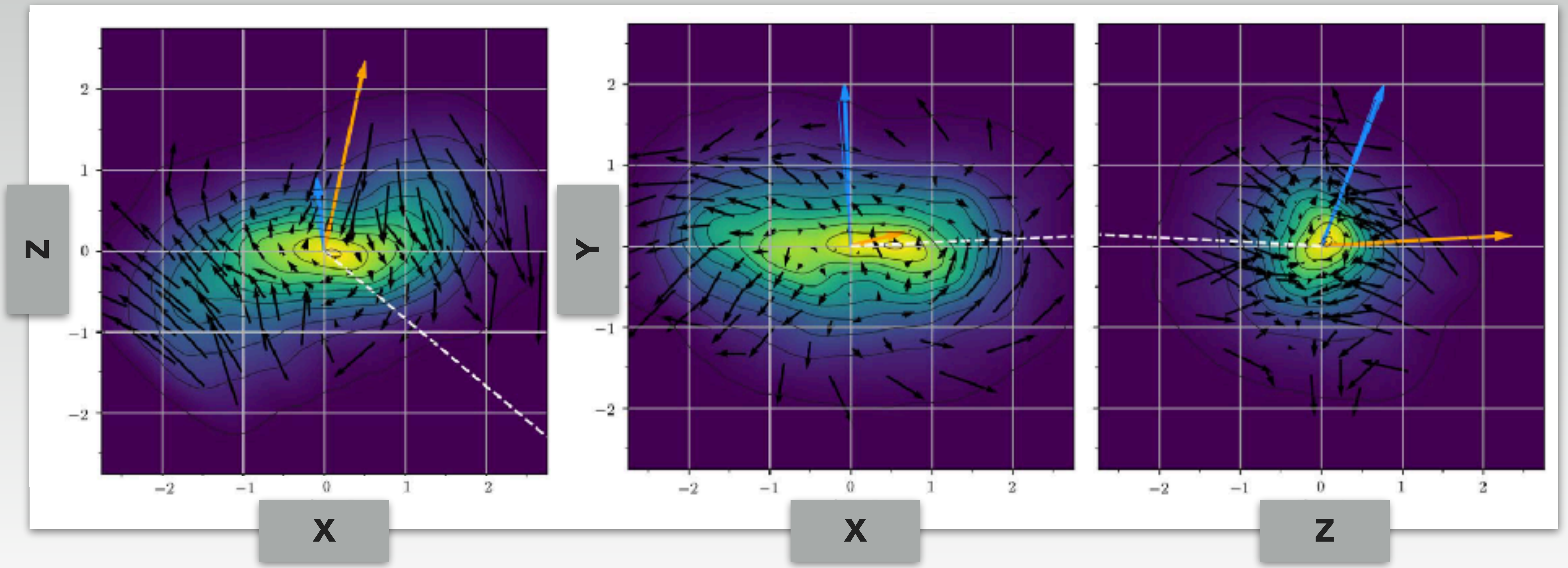
del Pino et al. 2021

- Sgr process a bar

➡ Indication of transition from disky dwarf to dSph *Łokas et al. 2014; Gajda et al. 2017*

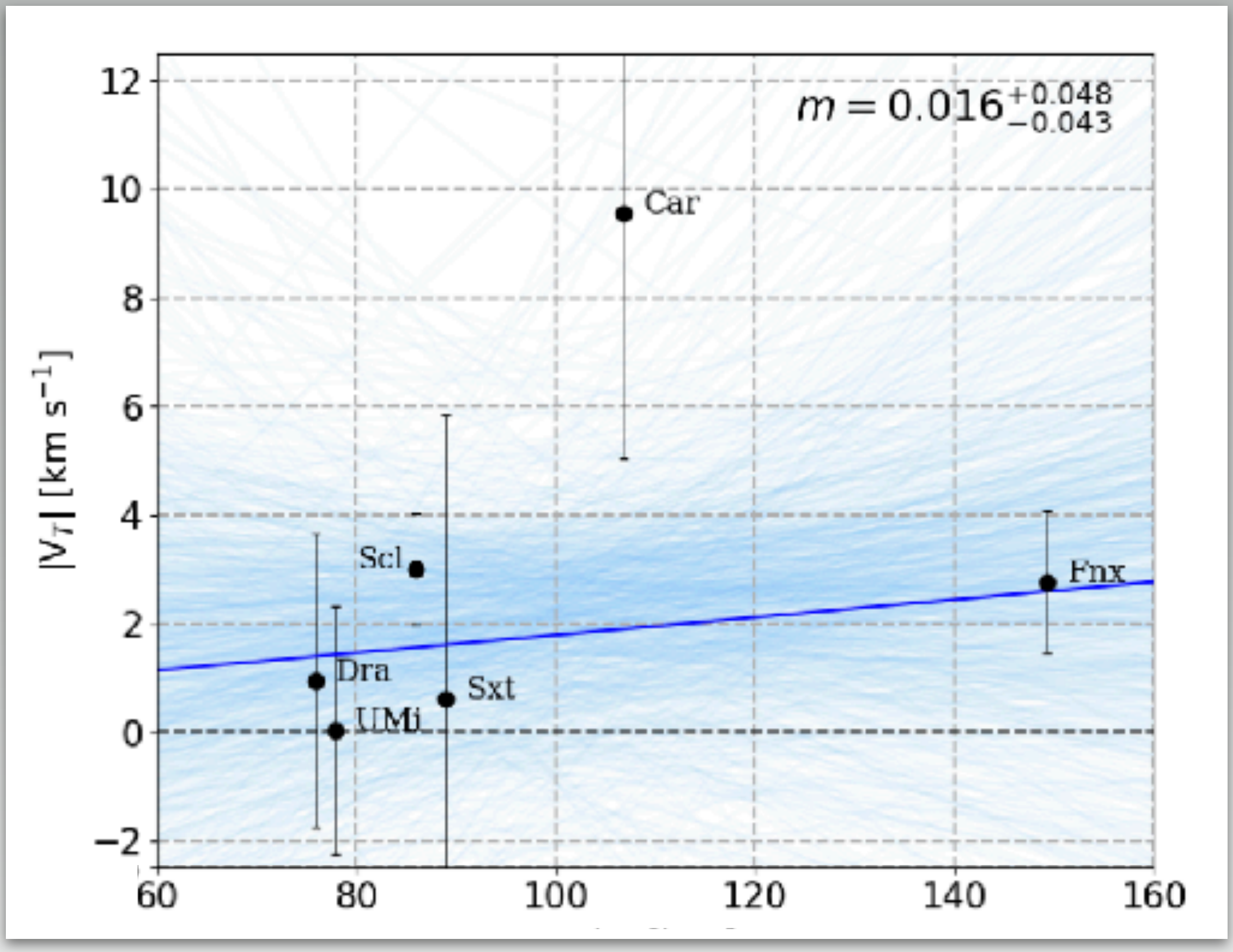
➡ In agreement with faint branch of the Sgr stream

Peñarrubia et al. 2010; Oria et al. 2022



del Pino et al. 2021

GAIA: INTERNAL DYNAMICS

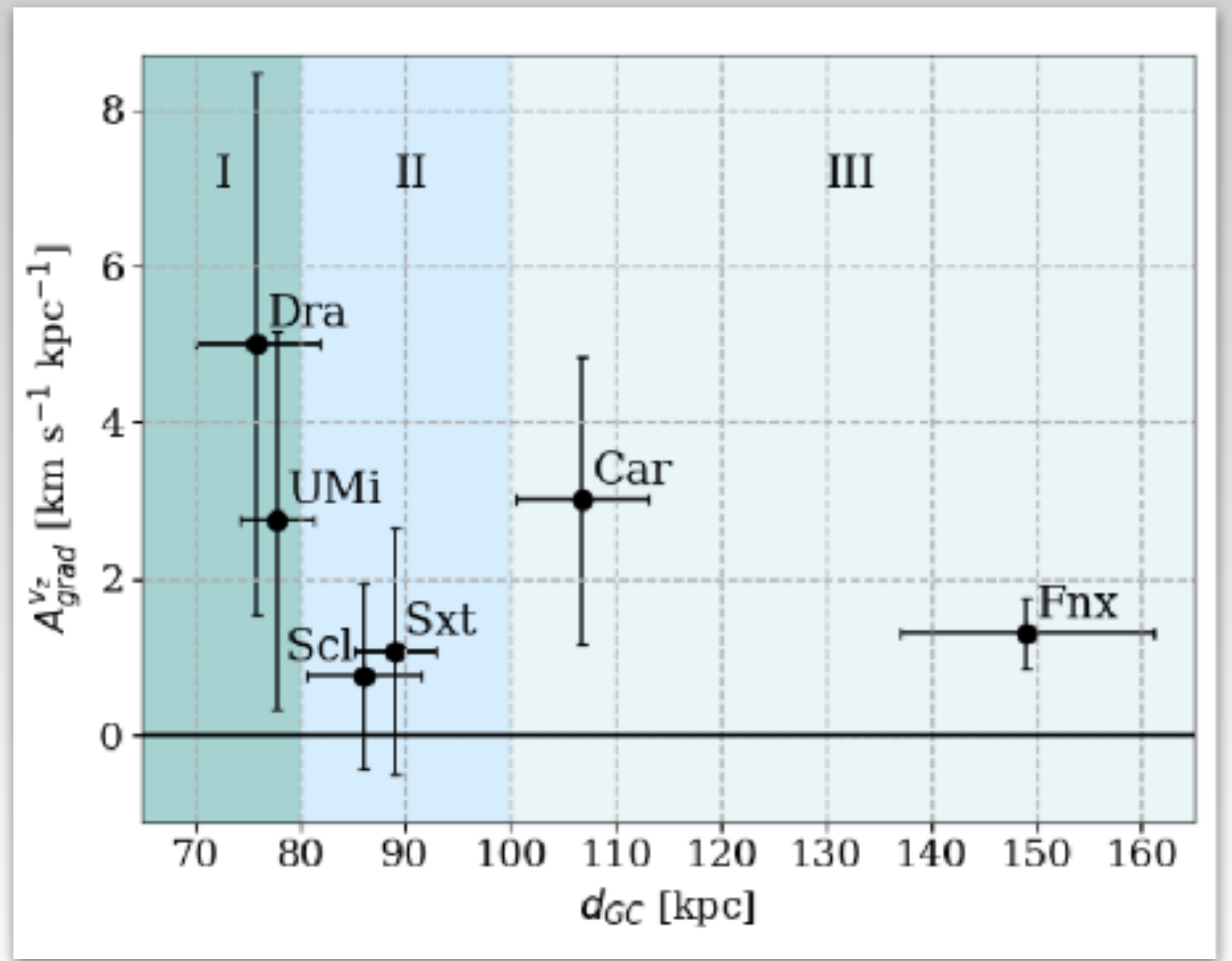


Martínez-García et al. 2021, 2022

- Significant rotation in Carina, Fornax and Sculptor
- All except Carina are pressure supported ($|V_T|/\sigma_V < 1$)
- Slow rotator tend to have: - Larger ellipticity
  - Small distances

- Stronger velocity gradient for galaxy at small distances

  ➡ Indication of weak tidal stirring effects



CONCLUSION

gaia **was <u>crucial</u> for:**

- Select stars members of dwarfs
- Find new galaxies
- Mesure the systemic motion
- Mesure the internal dynamics

Helped to answer many scientific questions

… and raised many more

- Origin of the VPOS
- Common origin of galaxies
- Evolution of the dwarf galaxies
- Mesure the mass of the MW and LMC

- Gaia DR4 will give better PMs and better constraint orbital parameters, internal dynamics, …
- Meanwhile HST+Gaia calibrated PM

  del Pino et al. 2022
- New multiplex spectroscopic (WEAVE, 4MOST, SDSS-V, MOONS, …) will complement Gaia

Complements to Battaglia & al 2022

http://research.iac.es/proyecto/GaiaDR3LocalGroup