The dark matter content of Milky Way dwarf spheroidal galaxies: Draco, Sextans and Ursa Minor

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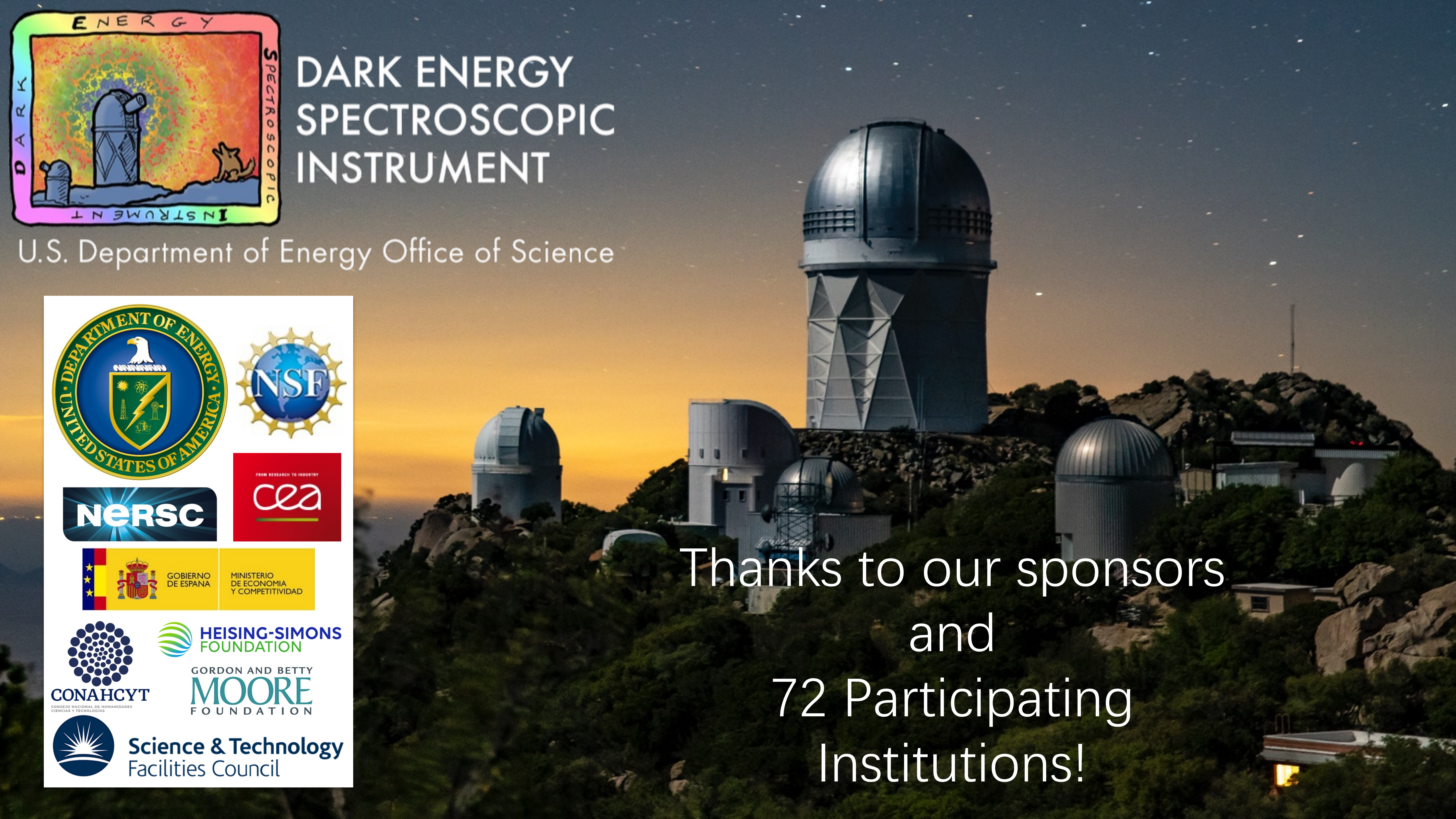
In collaboration with: **Wenting Wang**, Ling Zhu, Ting Li,
Sergey Koposov, Jiaxin Han, Songting Li, Rui Shi …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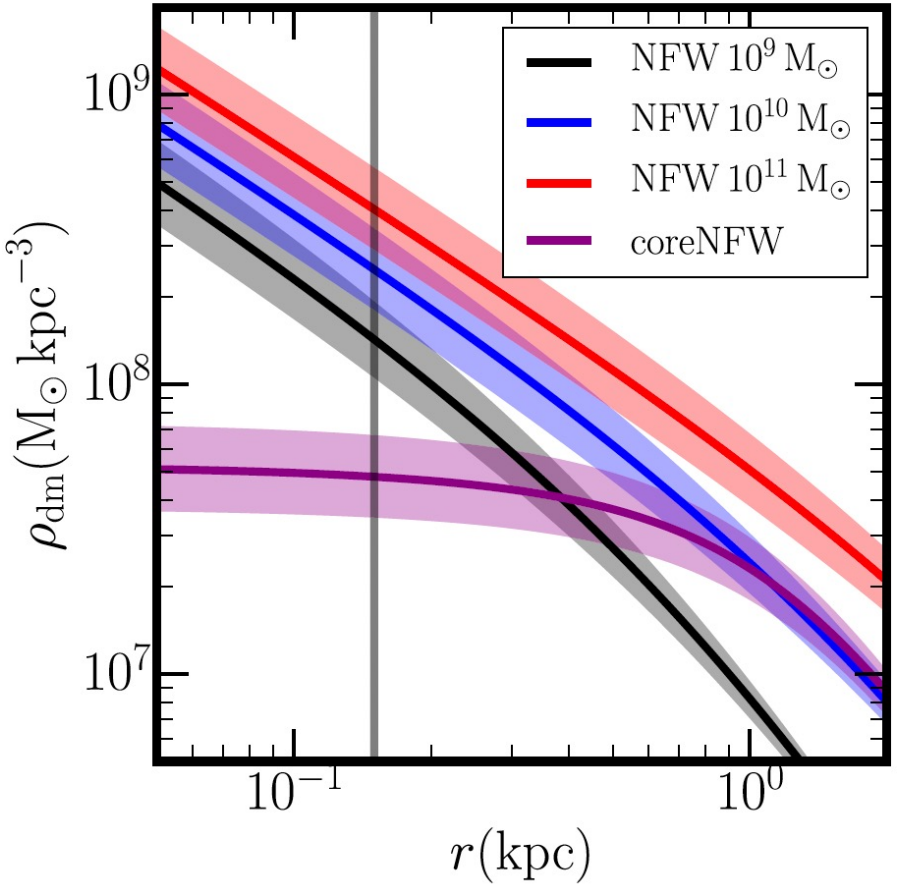
1. Introduction

The core-cusp problem



Read et al. 2019

- Cold dark matter (CDM) simulations predict dark matter halos with inner slopes close to -1 (**cusp**)
- Observations of dwarf galaxies sometimes indicate inner density slopes close to 0 (**core**)
- Possible solutions:
  - alternative dark matter models (e.g. SIDM, FDM)
  - baryonic physics (e.g. stellar feedback)

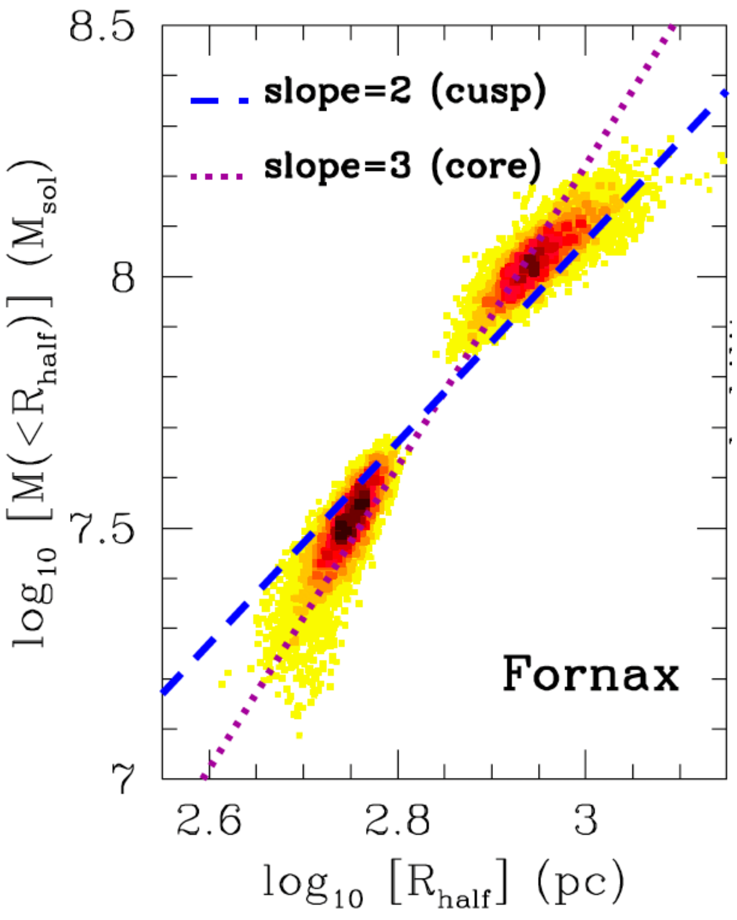
1. Introduction

The systematics behind dynamical modeling

- The deviation from steady states can resulting in under/over-estimated inner density profile (e.g. Genina et al. 2018; Wang et al. 2022)

- $\mathrm{M}(<\mathrm{R_{half}})$ is not sensitive to mild deviations from steady states

- Joint modeling of multiple populations provides multiple measured $\mathrm{M}(<\mathrm{R_{half}})$, hence may bring better constraints



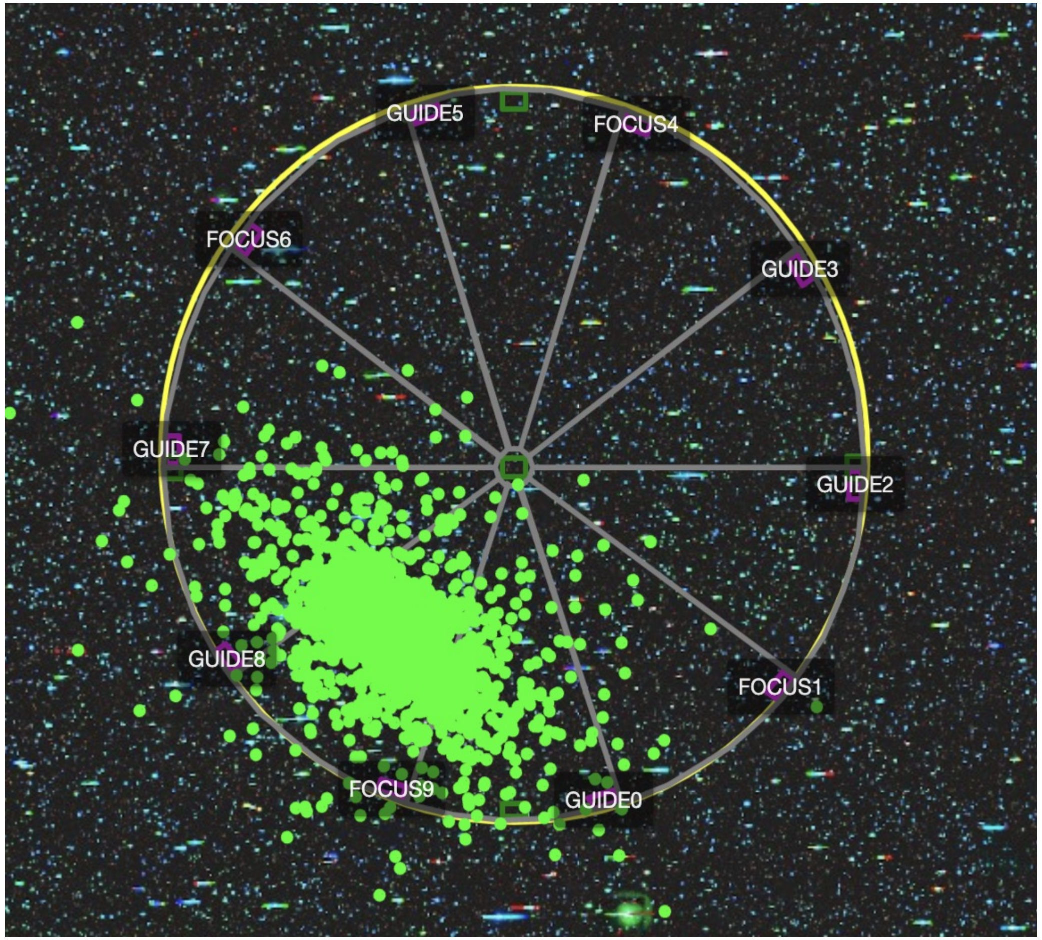
Walker & Penarrubia 2011

2. Data

We combine data from:

- DESI Milky Way Survey (MWS)
- Walker et al. 2023

Object	$N_{\rm tot}$	$N_{\rm DESI}$	$N_{\rm W23}$
Draco	407	96	374
Sextans	440	240	368
Ursa Minor	1046	1003	416

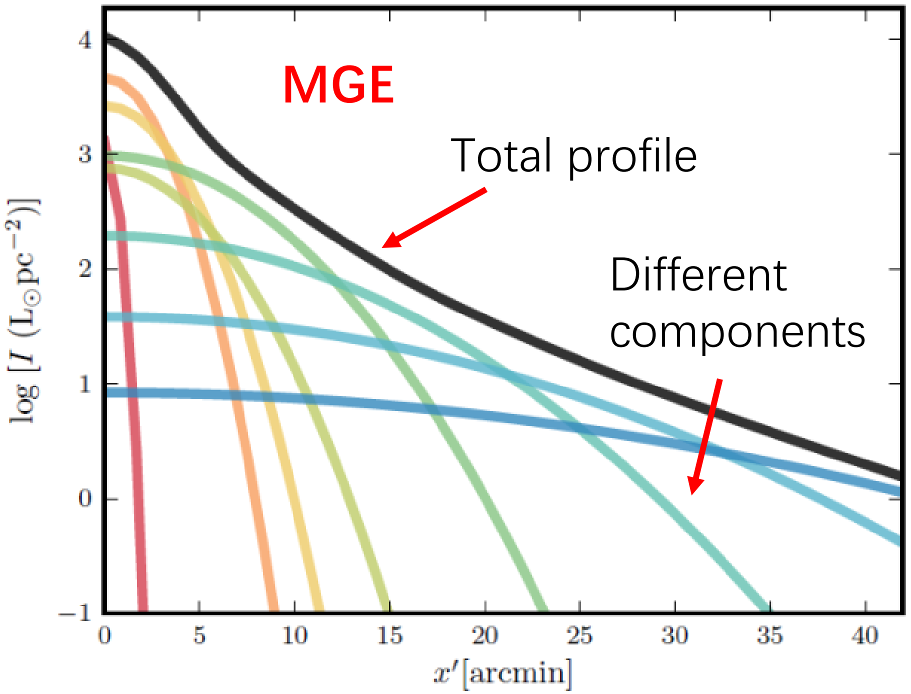


3. Method

Single-population model

Jeans Anisotropic Multi-Gaussian Expansion (jam) modeling (e.g. Watkins et al. 2013; Zhu et al. 2016)

- Axis-symmetric Jeans Equations
- Multi-Gaussian Expansion (MGE): each Gaussian component has analytical solutions
- Solutions to velocity moments are first obtained in the intrinsic frames: can fit any functional form of the potential model
- Then they are transformed to the observed frame (through the inclination angle) to be compared with observations



3. Method

Chemodynamical model

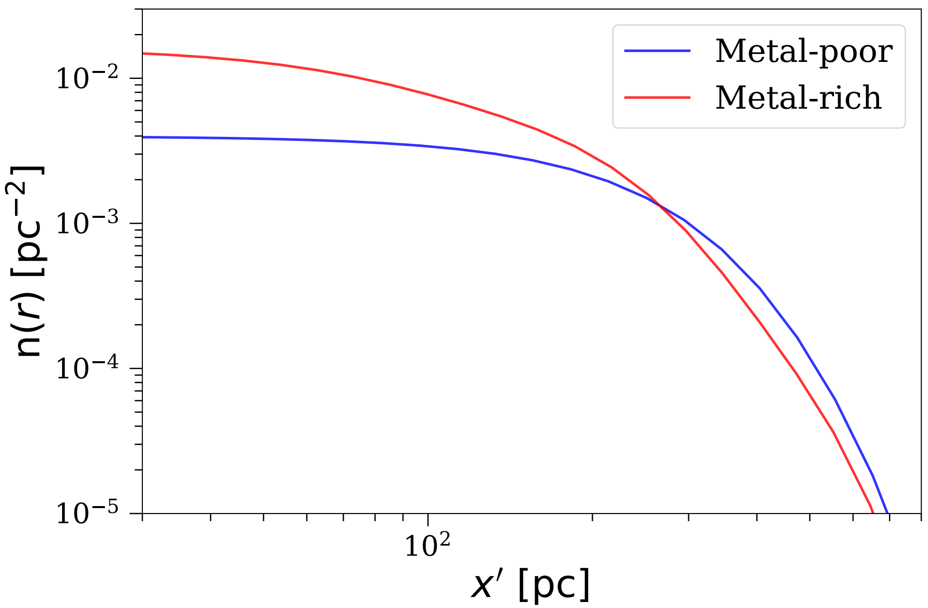
Extension of the single-population model to multi-population cases (Zhu et al. 2016)

- **Multiple populations** impose stronger constraints on inner slopes of dark matter halos
- Two populations: a metal-rich and a metal-poor population
- Joint modeling of spatial + metallicity + kinematical properties
- Based on the posterior distribution, each star has a probability to be classified as the metal-rich or metal-poor population…

4. Results

Properties of two populations: Draco

surface number density profile

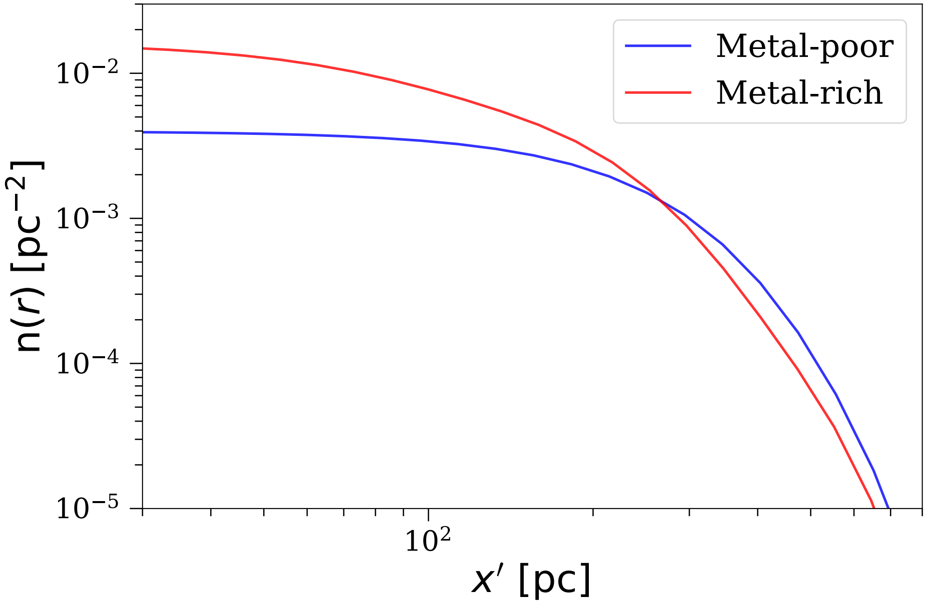


- **Metal-poor populations (blue)**:
  more spatially extended
- **Metal-rich populations (red)**:
  more centrally concentrated

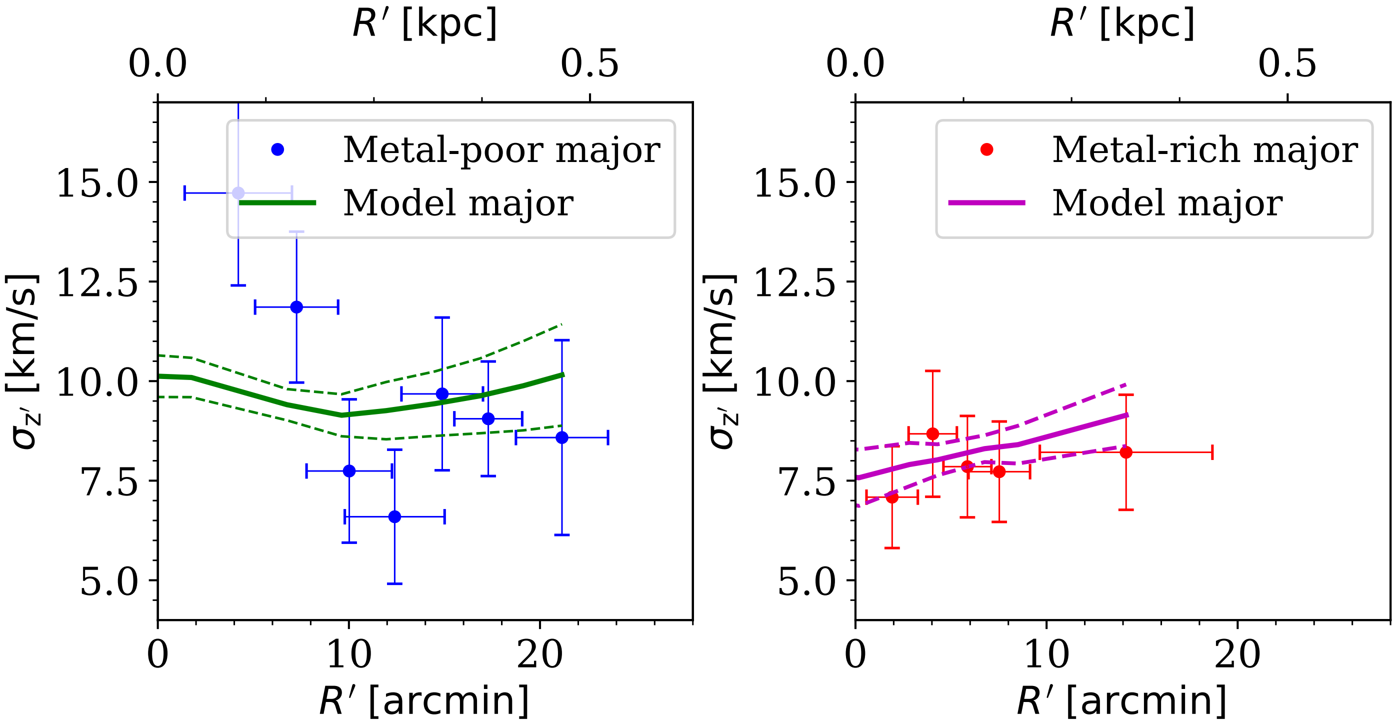
4. Results

Properties of two populations: Draco

surface number density profile



line-of-sight velocity dispersion profile



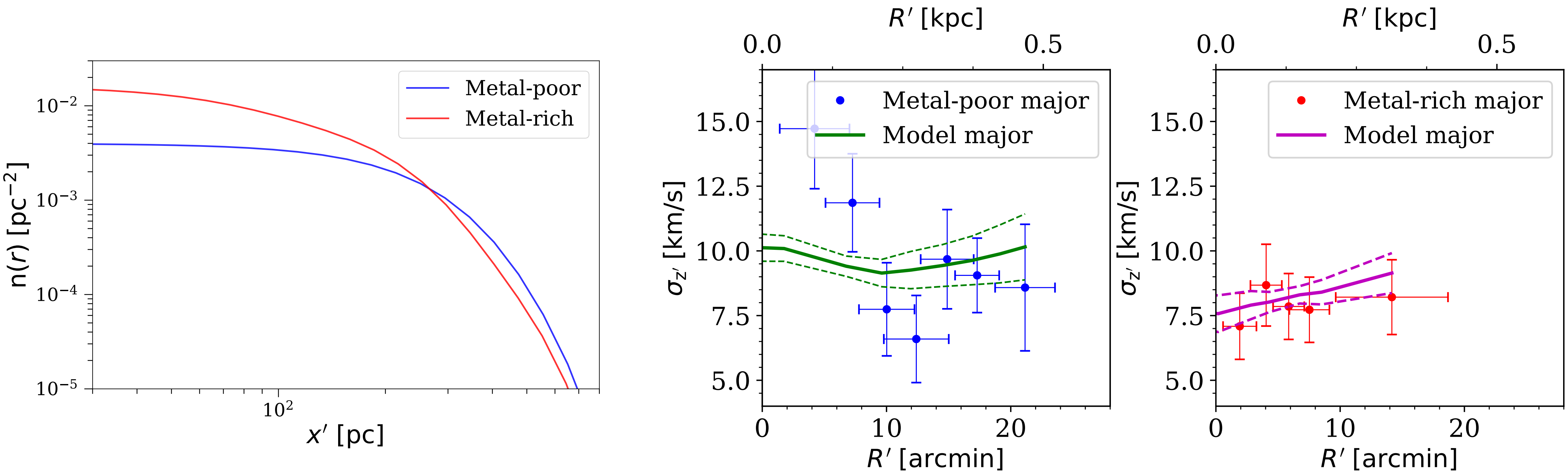
- **Metal-poor populations (blue)**:
  more spatially extended kinematically hotter with negative gradients in velocity dispersion
- **Metal-rich populations (red)**:
  more centrally concentrated kinematically colder with flattened velocity dispersion profiles

4. Results

Properties of two populations: Draco

surface number density profile

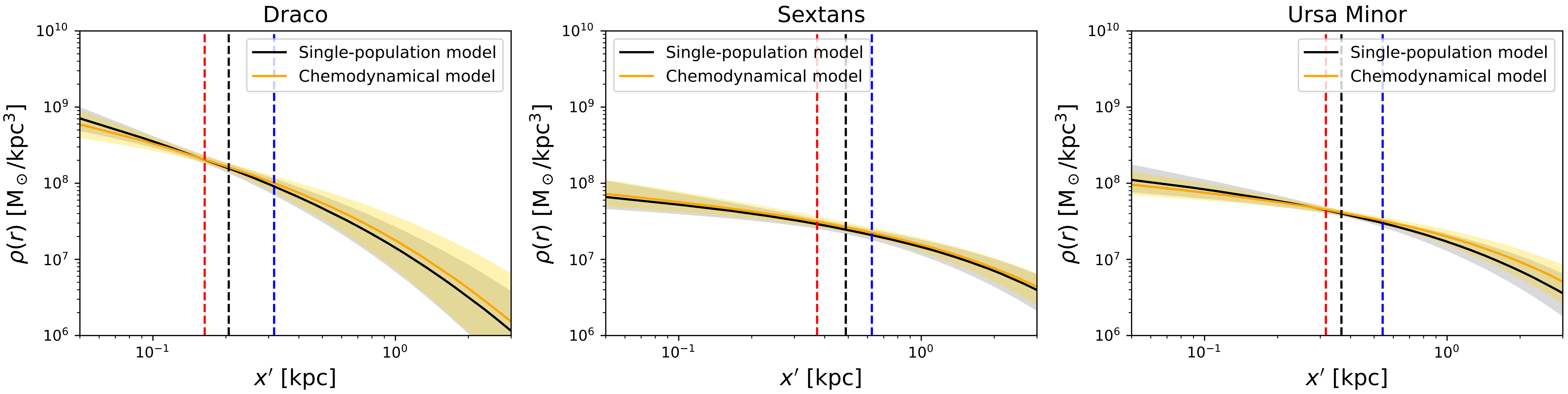
line-of-sight velocity dispersion profile



The nearly factor of 2 difference may reflect the deviation from the steady-state!

4. Results

Dark matter density profile

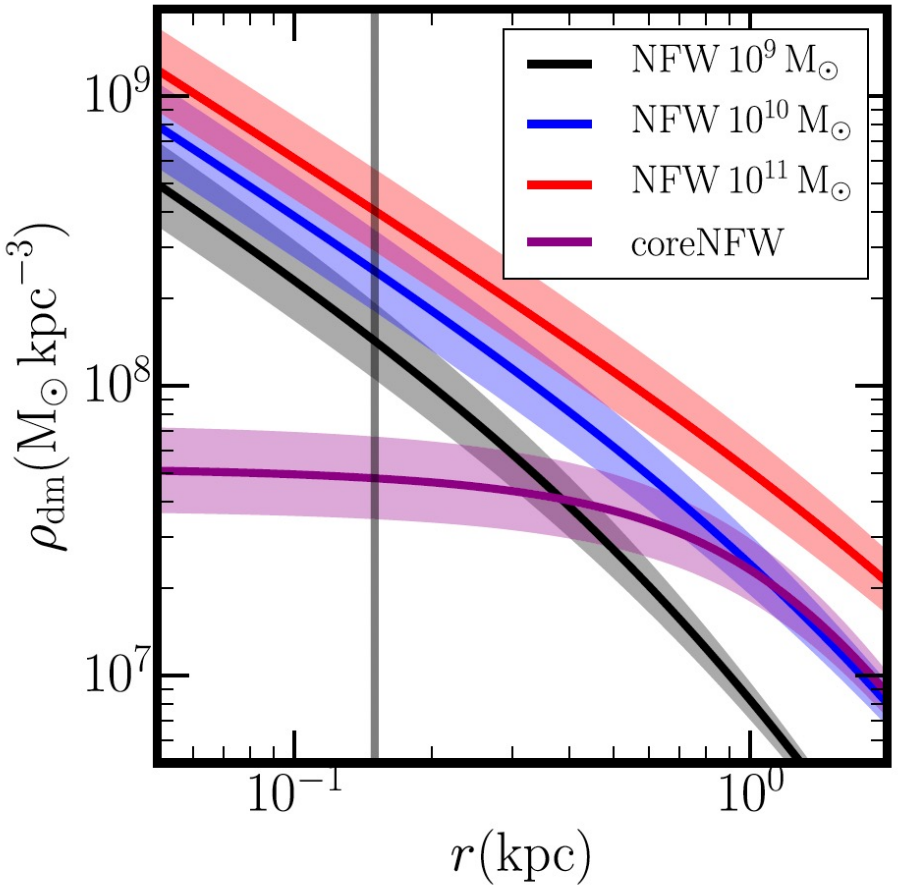


(Black, red, blue dashed vertical lines: R_{half} of the total, metal-rich, and metal-poor populations)

- Results of the single-population and two-population chemodynamical models are fully consistent
- Dark matter density profiles are best constrained around the half-number radii of tracer populations

4. Results

Comparison with previous works

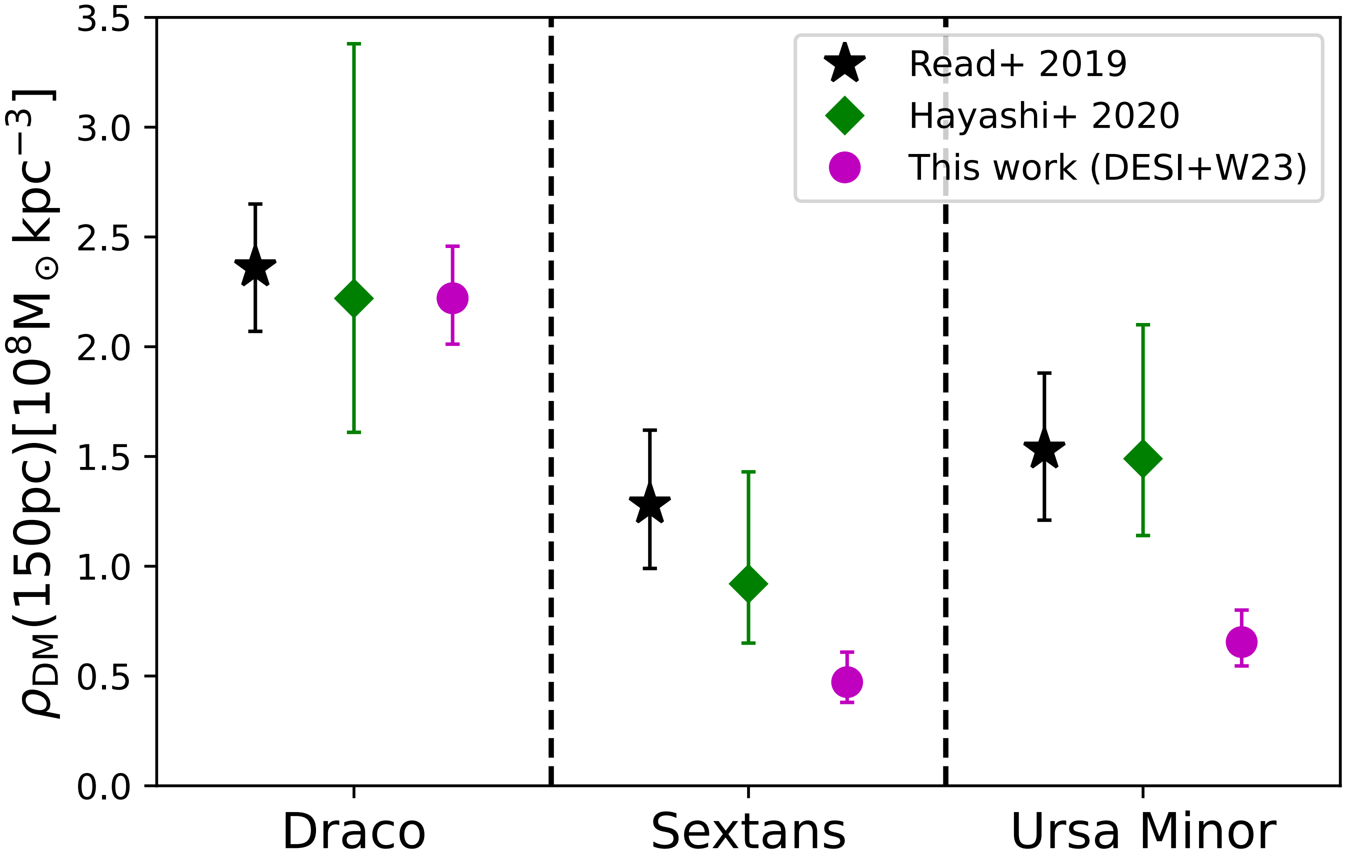


Read et al. 2019

- Read et al. 2019 use $\rho_{DM}(150\text{pc})$ as a proxy of the inner density slope γ
- A single measurement of $\rho_{DM}(150\text{pc})$ is sufficient to differentiate the models, independently of the halo mass

4. Results

Comparison with previous works



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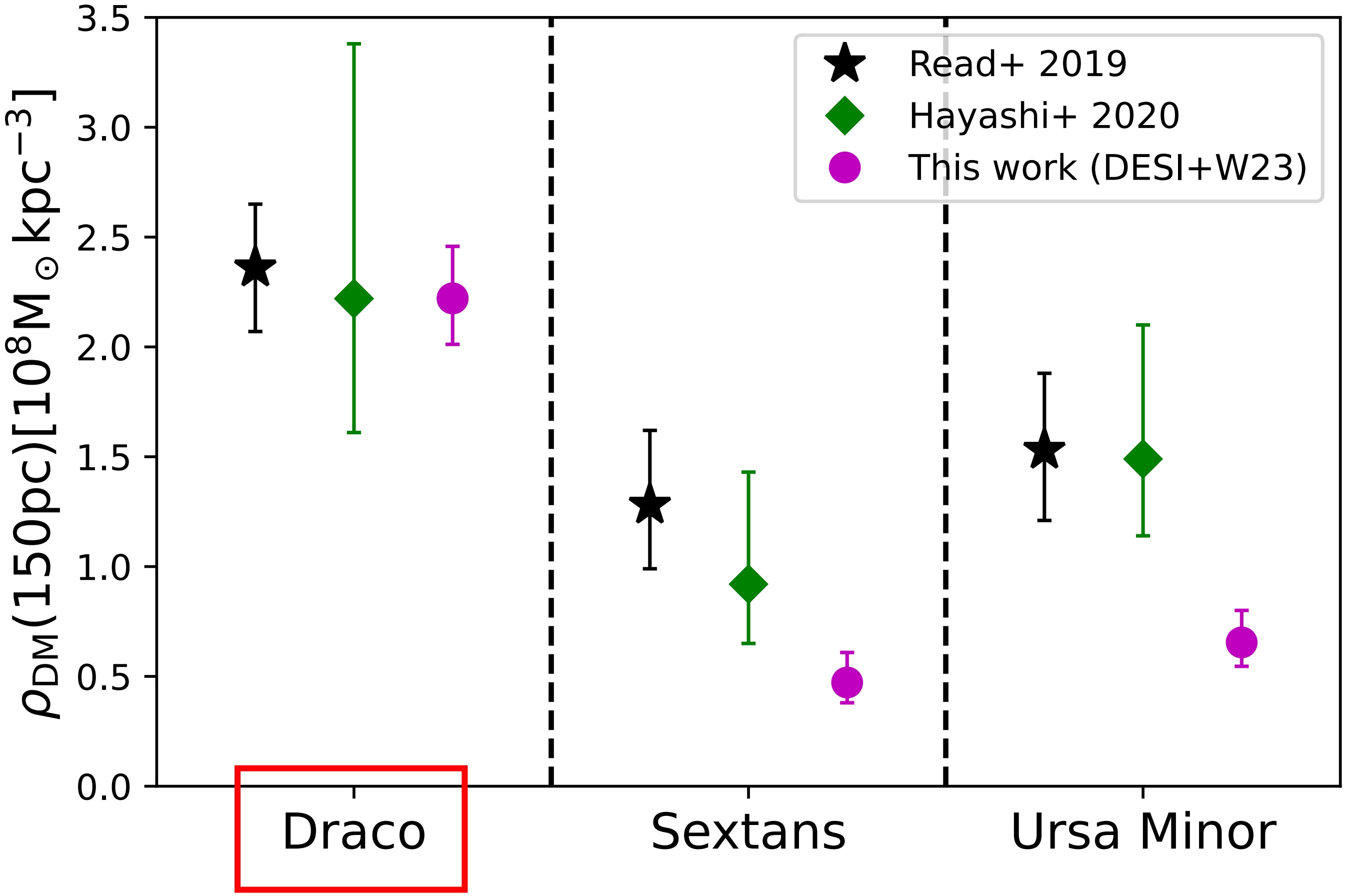

Draco:

- **Our result agrees well with Read2019 and Hayashi2020**

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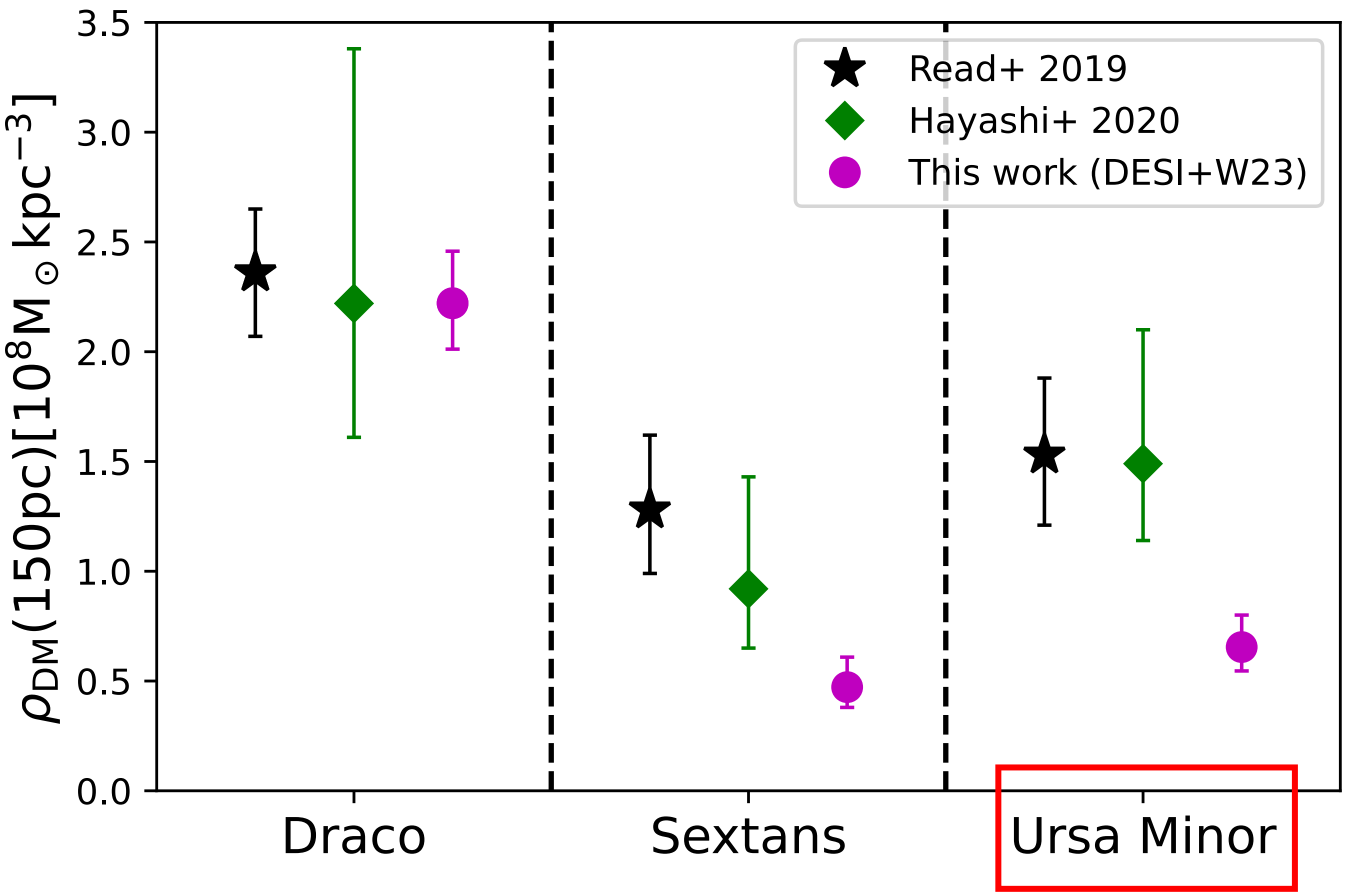
4. Results

Comparison with previous works

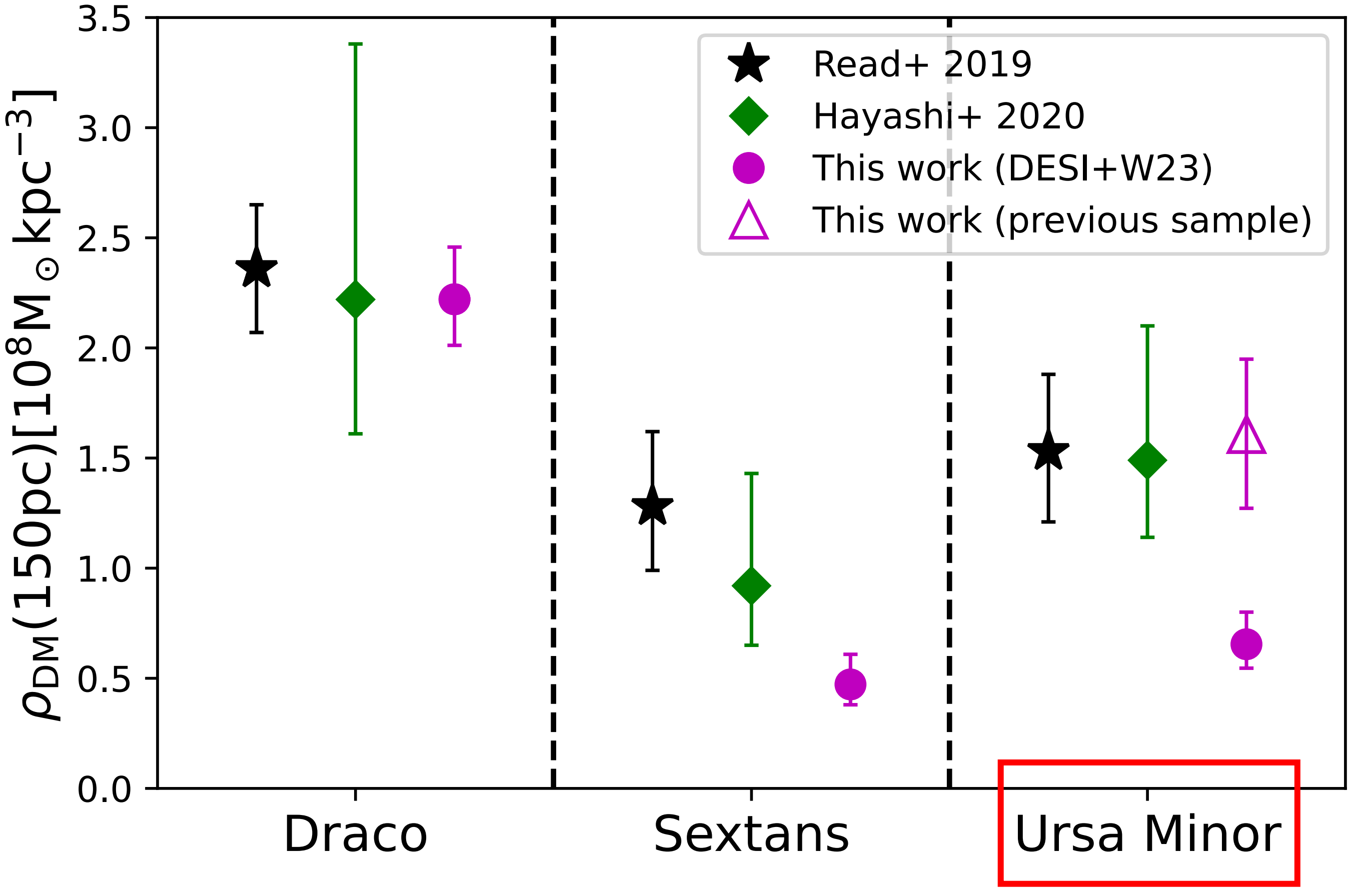


Ursa Minor:

- **Discrepancy is caused by the difference in the sample of member stars used**
- **We can reproduce previous results if using their sample of member stars**

4. Results

Comparison with previous works



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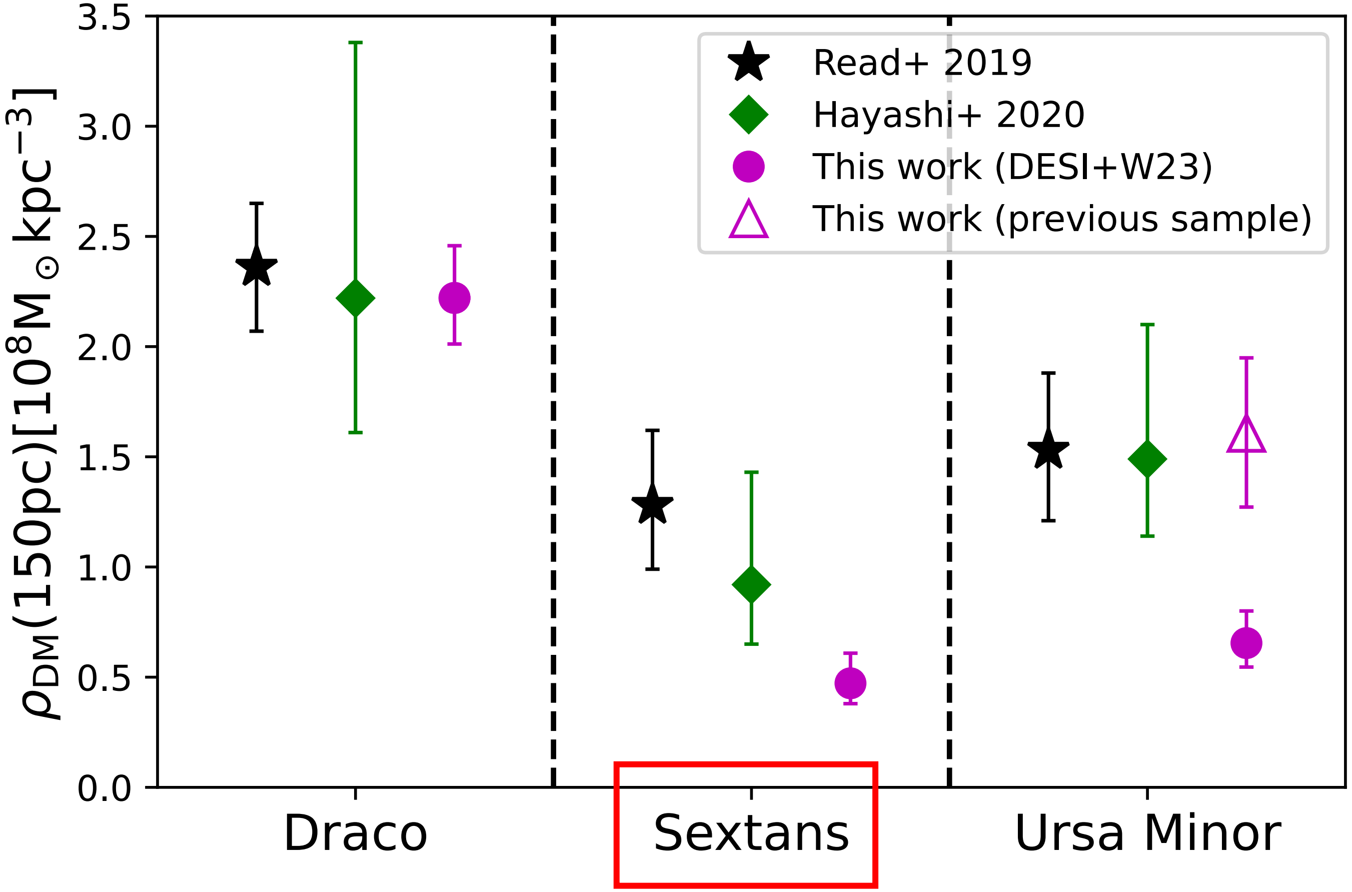


Sextans:

- **Discrepancy is caused by difference in the sample of member stars used**
- **And by different model assumptions:**

  This work and Hayashi2020:

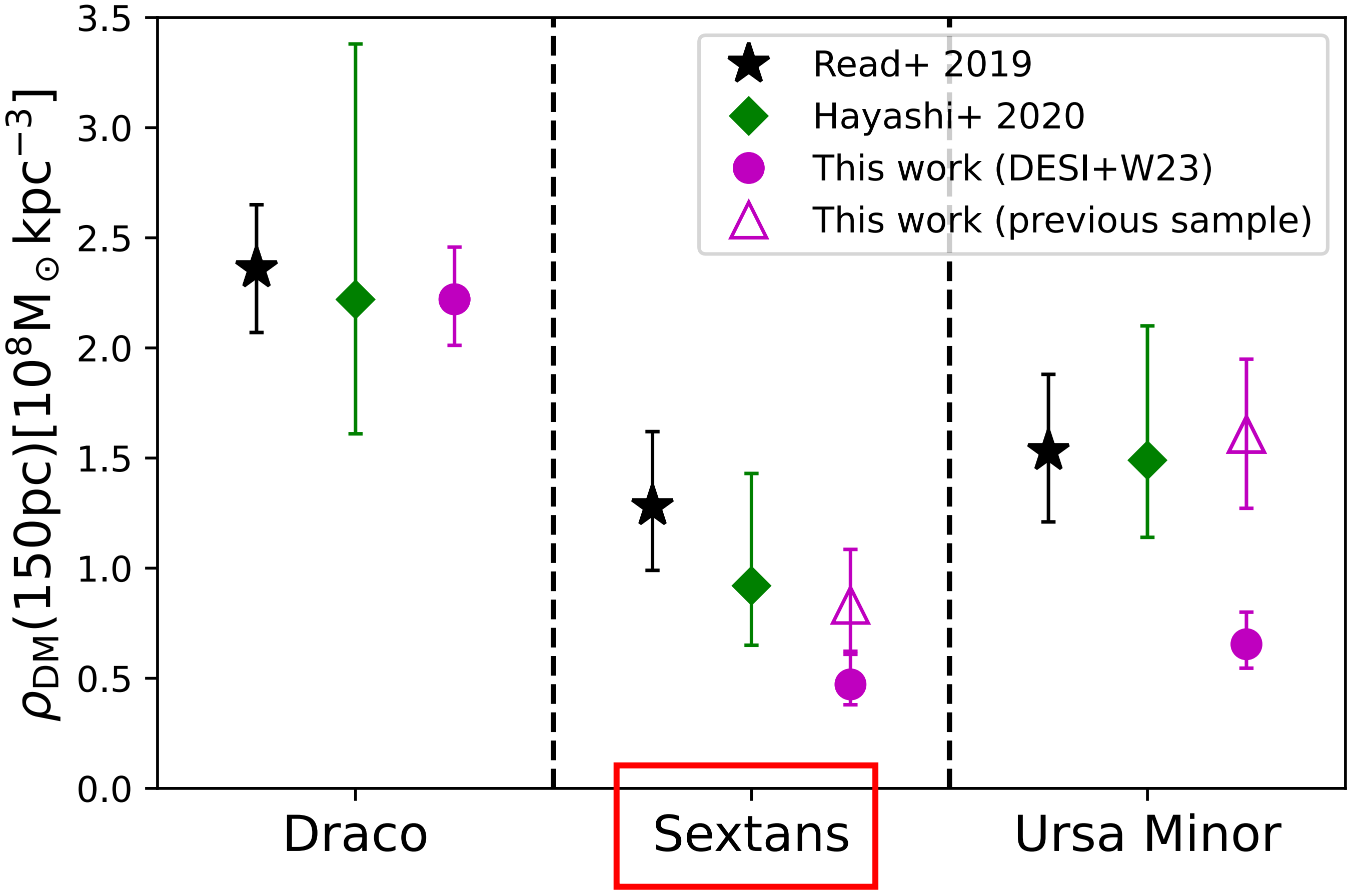
  <u>axis-symmetric</u> Jeans analysis

  Read2019:

  <u>spherical</u> Jeans analysis

4. Results

Comparison with previous works



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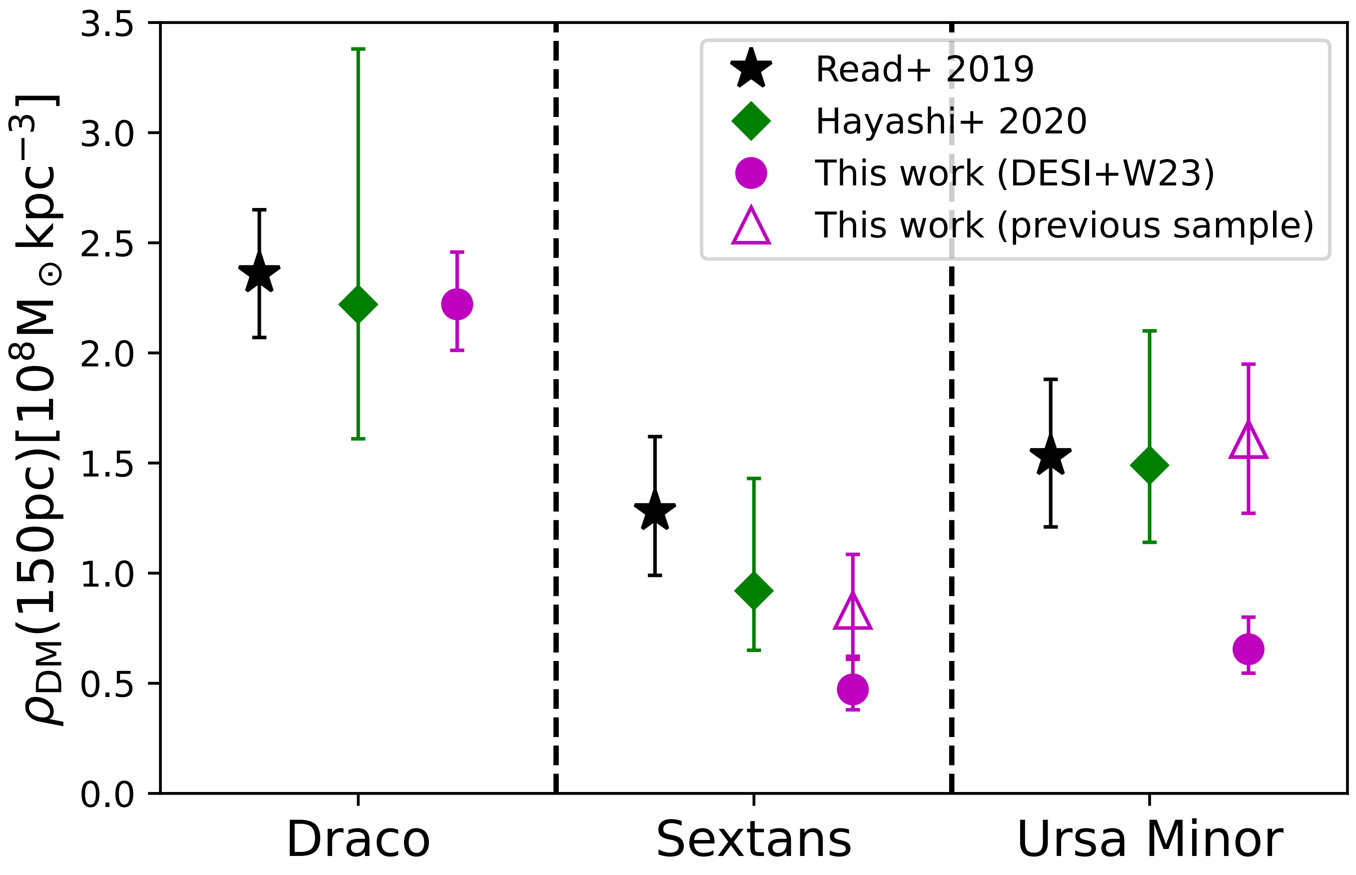
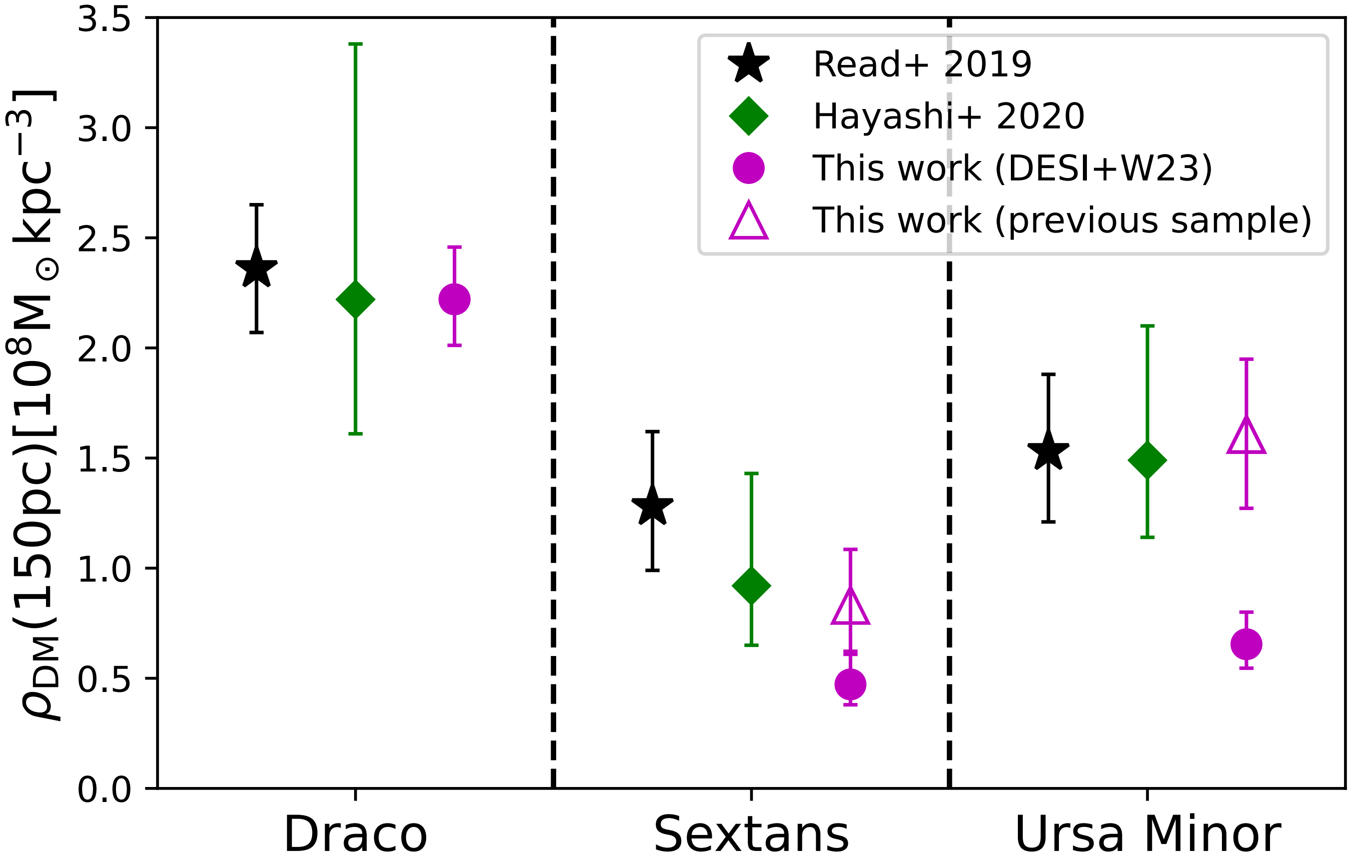
Comparison with previous works



- **The intrinsic velocity dispersion profiles vary for different member star samples**
  - The previous samples have higher intrinsic velocity dispersions in the central region

4. Results

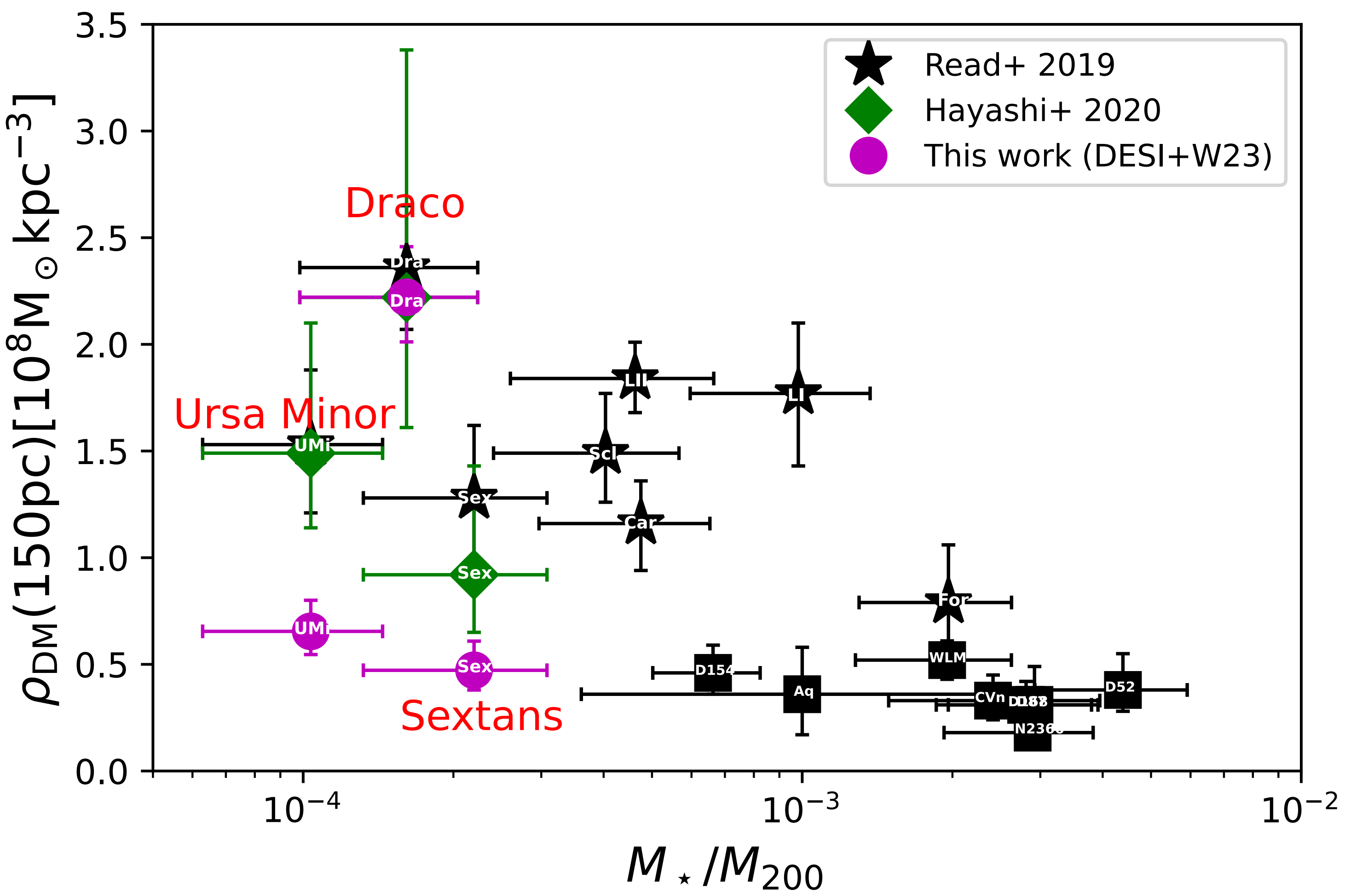
Comparison with previous works



- **The intrinsic velocity dispersion profiles vary for different member star samples**
- **The different intrinsic velocity dispersions are due to the difference in the selection functions**

4. Results

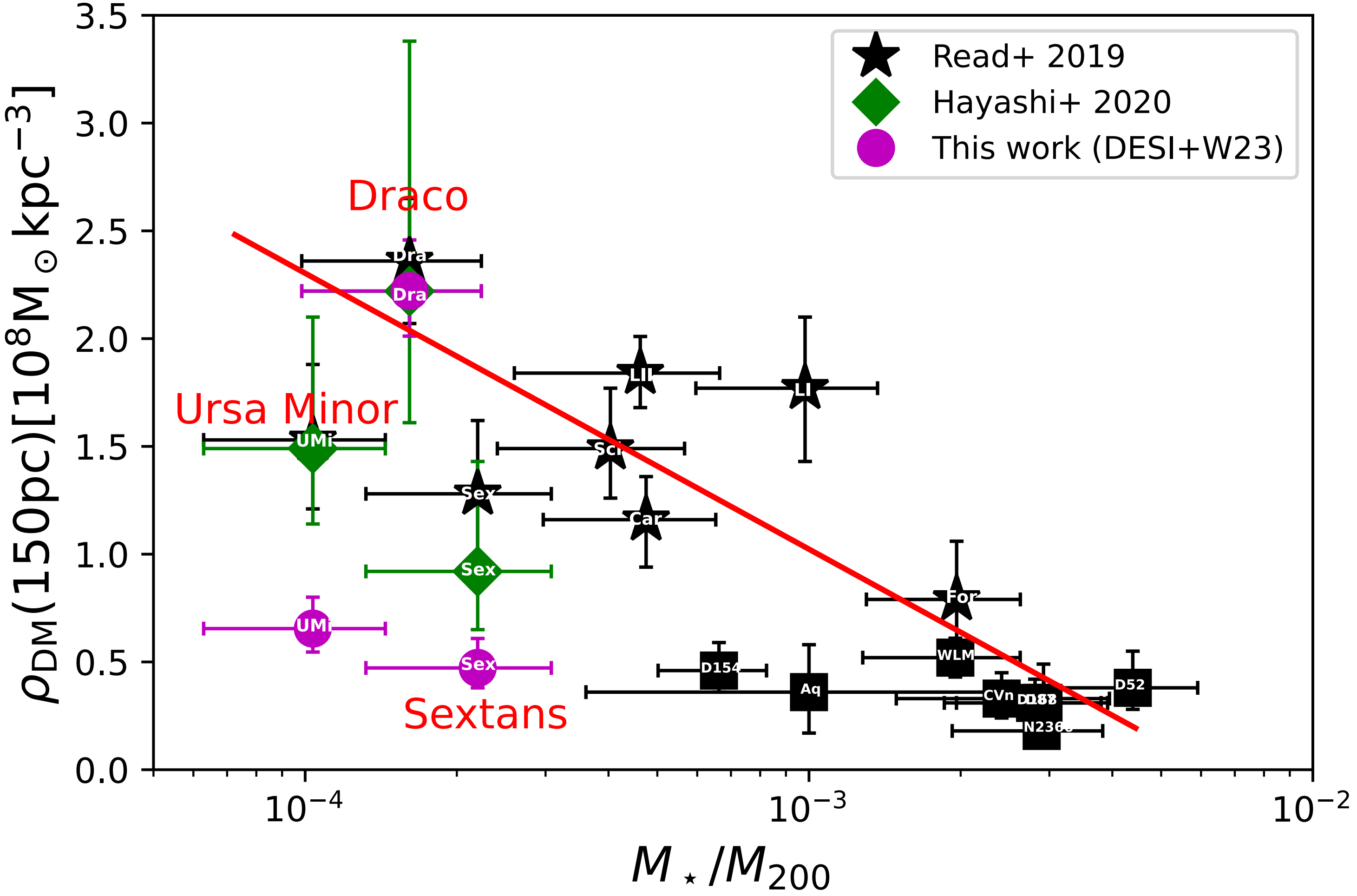
Revisit the core-cusp problem



- Read2019 finds a **negative** correlation between $\rho_{DM}(150\text{pc})$ and M_*/M_{200}

4. Results

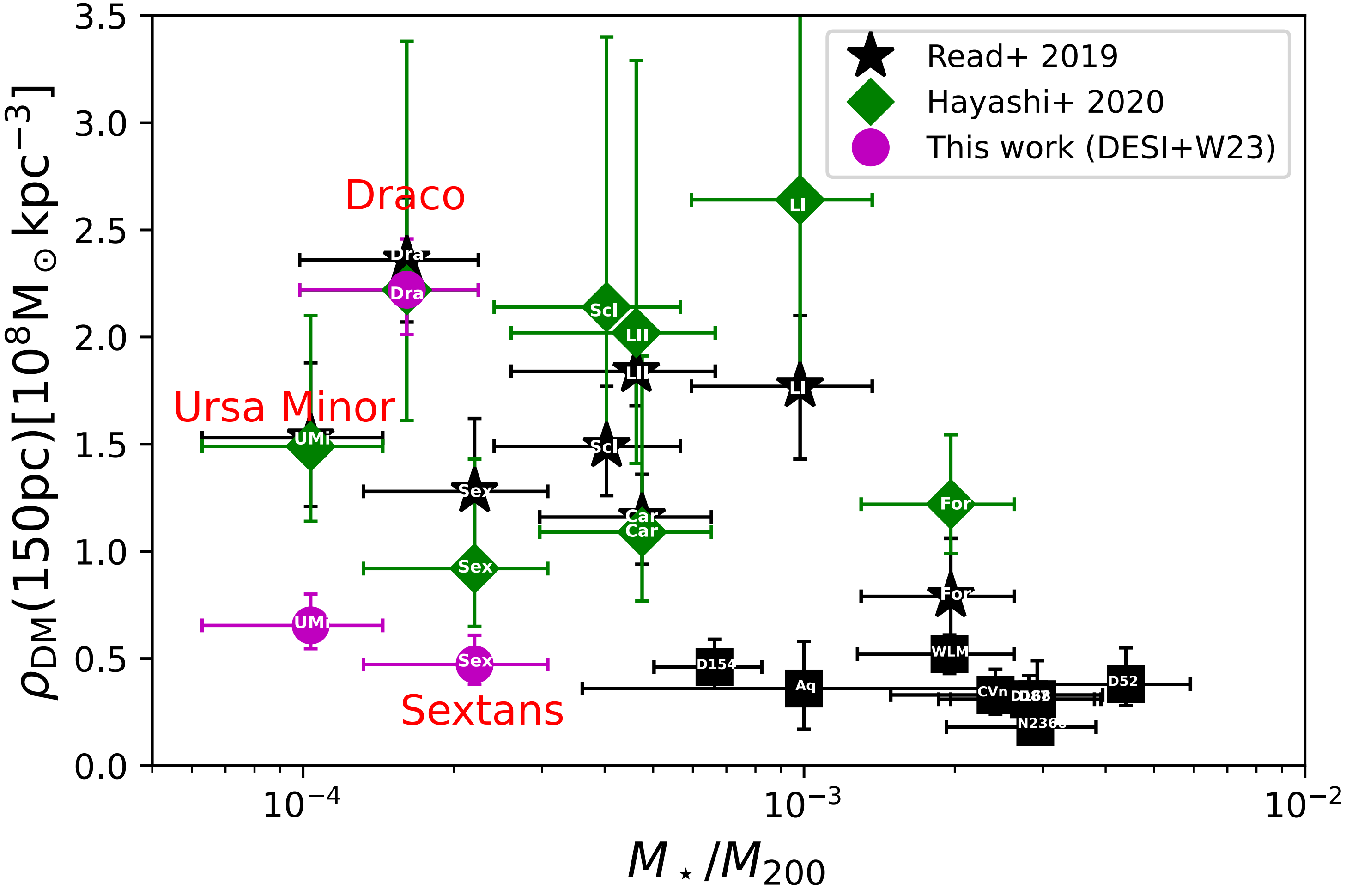
Revisit the core-cusp problem



- Read2019 finds a **negative** correlation between $\rho_{DM}(150\mathrm{pc})$ and M_*/M_{200}
  -- supporting stellar feedback as the main mechanism of explaining the core-cusp problem

4. Results

Revisit the core-cusp problem

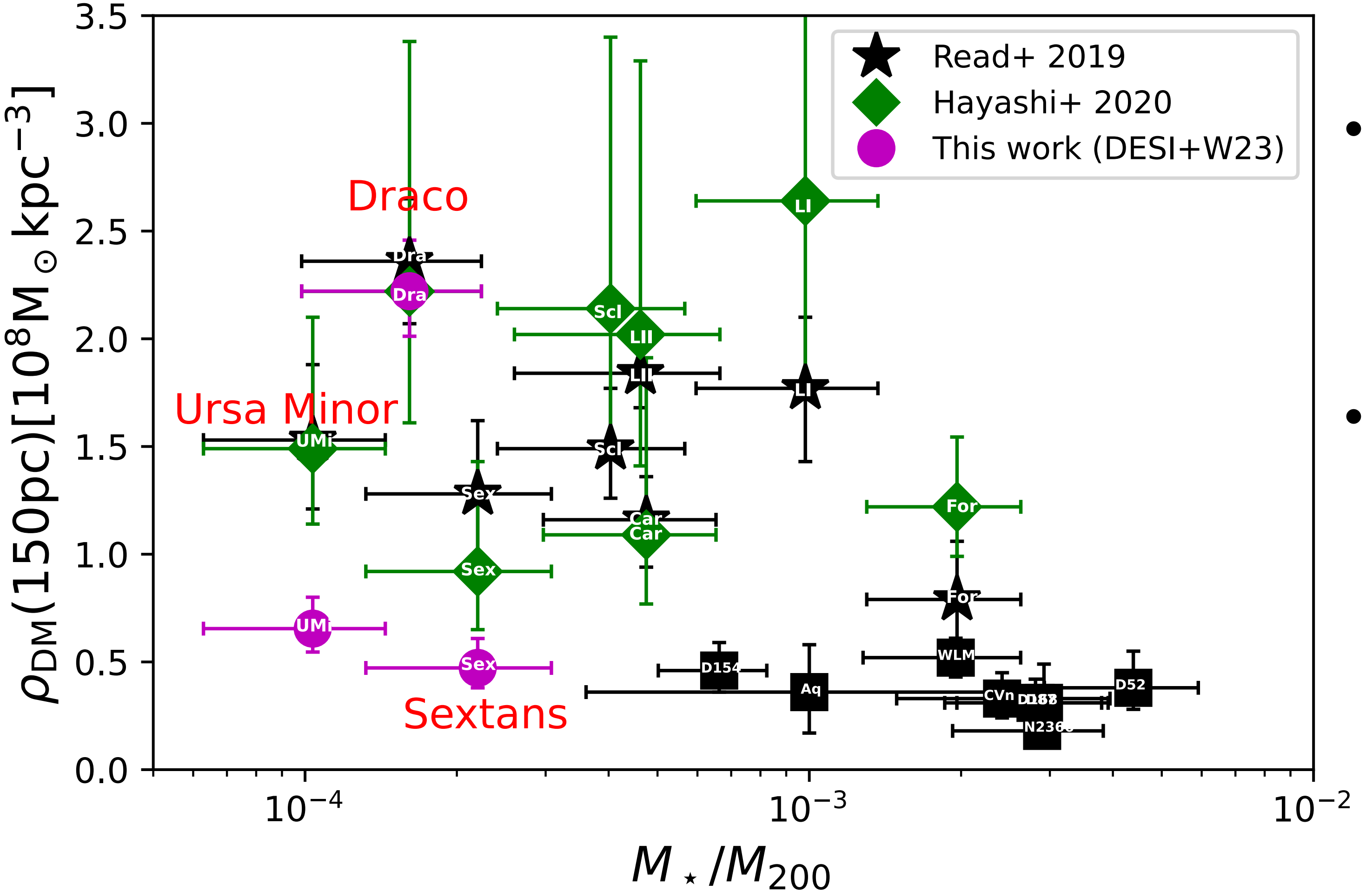


- Read2019 finds a **negative** correlation between $\rho_{DM}(150\text{pc})$ and M_*/M_{200}

- However, similar trend is **not** clearly seen in Hayashi2020 (Green diamonds)

4. Results

Revisit the core-cusp problem



- A **diversity** of $\rho_{DM}(150\text{pc})$, or the inner density slope γ
- The currently best constraints are still sensitive to the **model assumptions** and to the **sample selection effects**

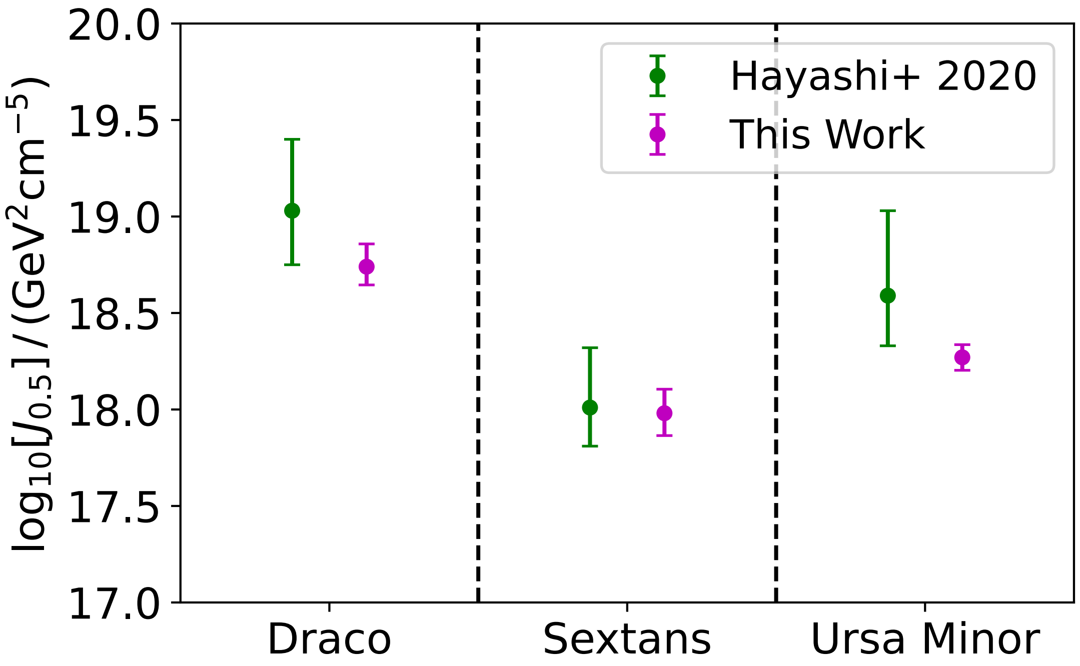
4. Results

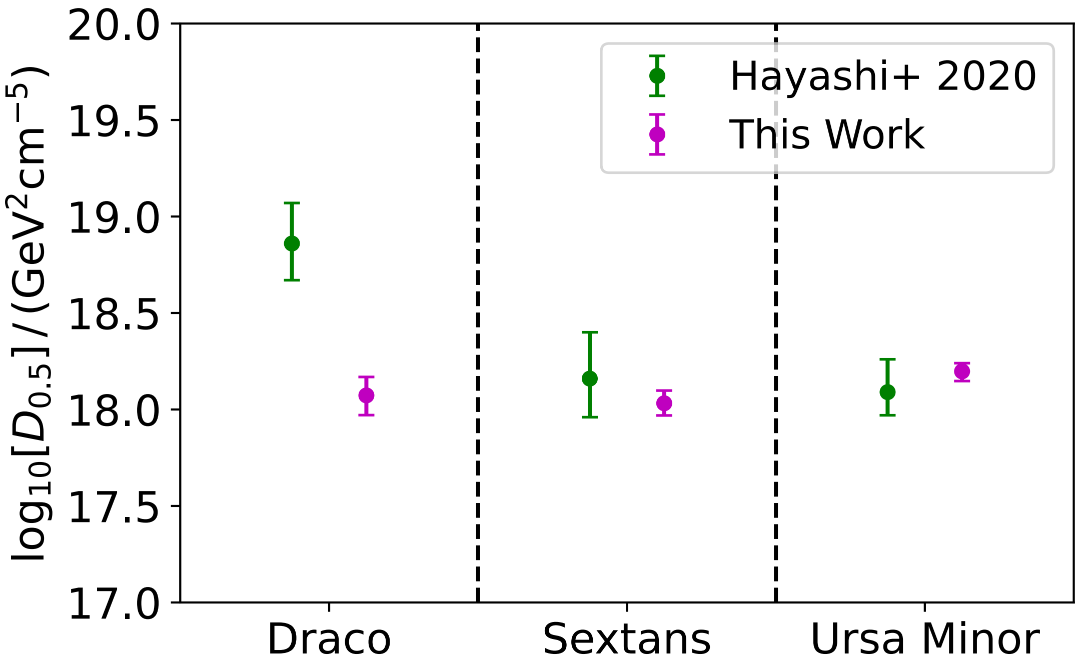
J factor (DM annihilation)

$$J = \iint \rho^2_{\rm DM}(l,\Omega)\,{\rm d}l{\rm d}\Omega$$

D factor (DM decay)

$$D = \iint \rho_{\rm DM}(l,\Omega)\,{\rm d}l{\rm d}\Omega$$



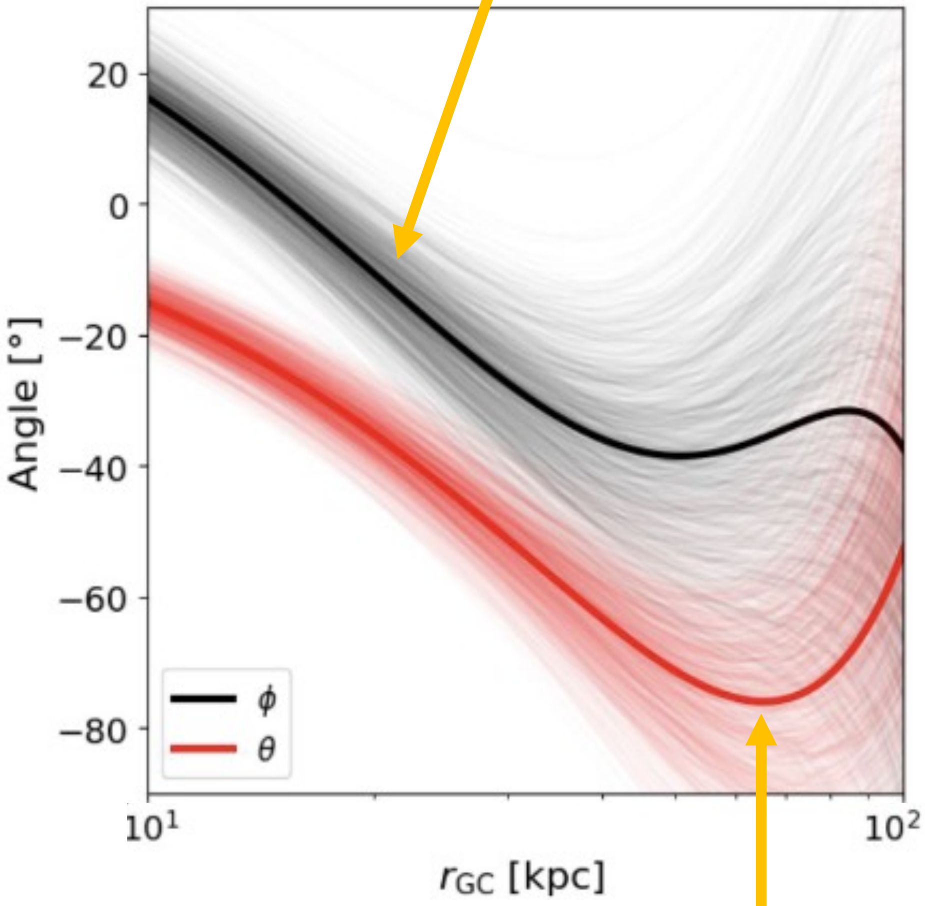


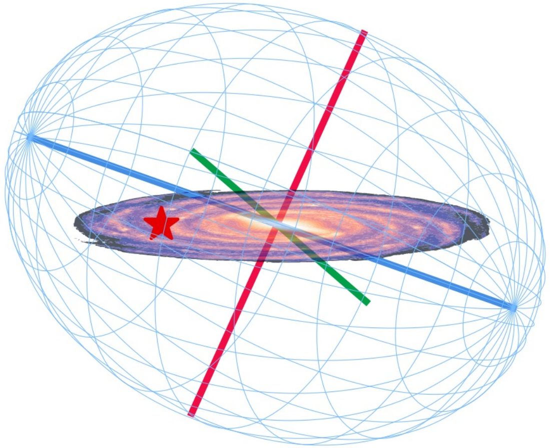
- The differences are due to different dark matter density profiles and different truncation radii

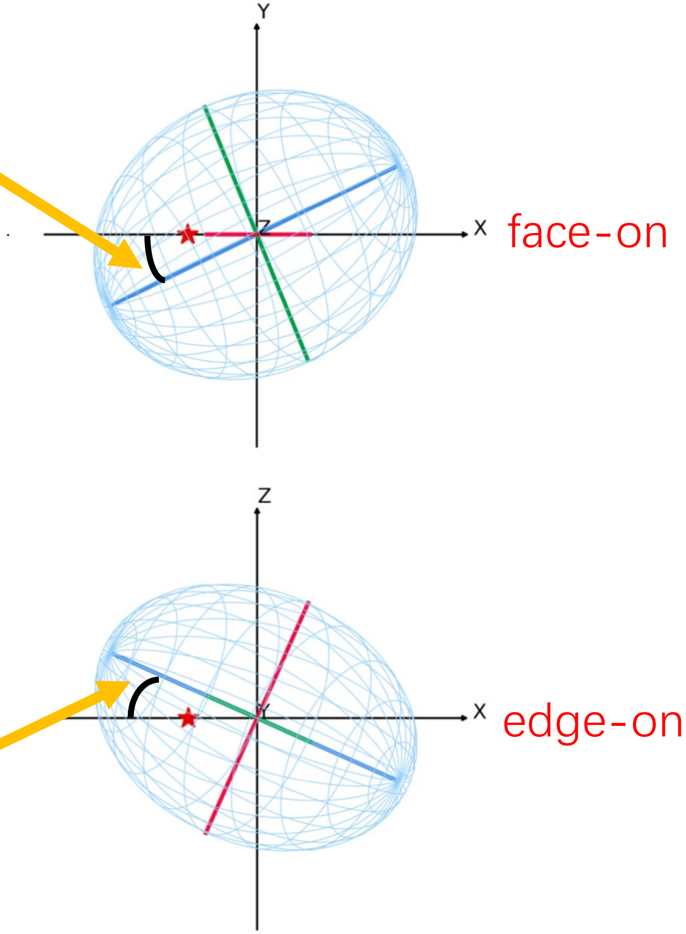
MW Stellar halo is twisted

李嵩霆
Li et al. in prep

Yaw angle: angle between projection of the major axis of stellar halo within the disc plane and the GC-sun line







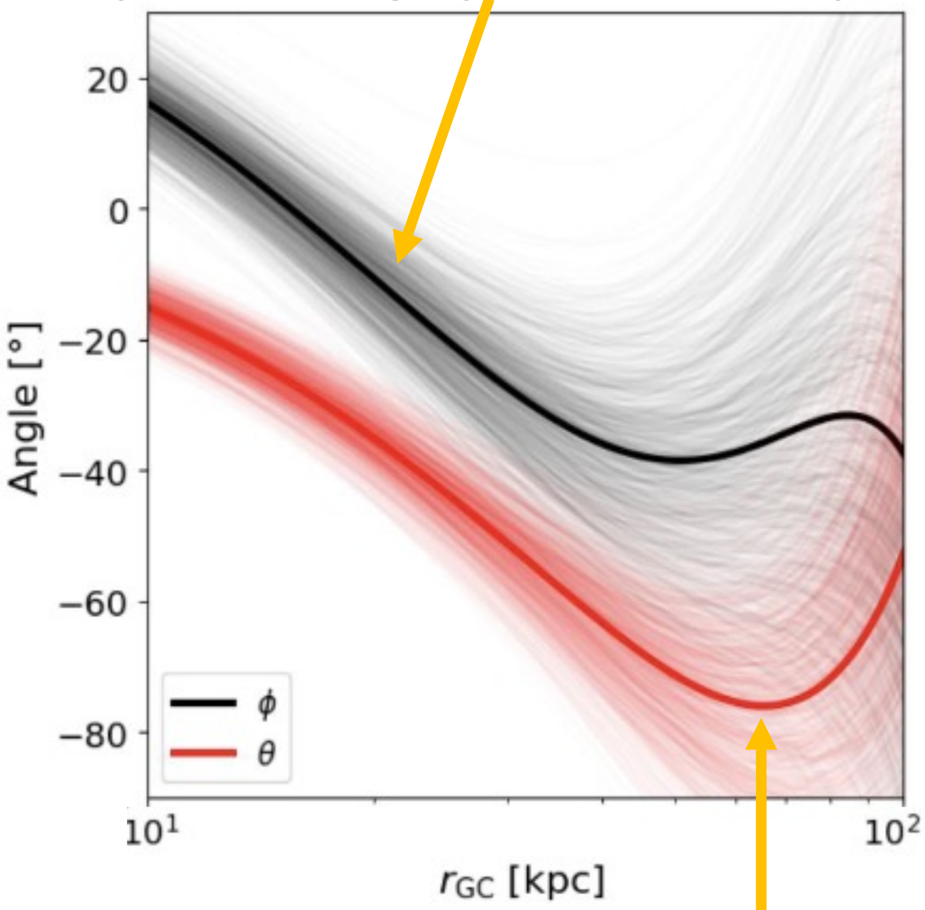
Han et al. 2022

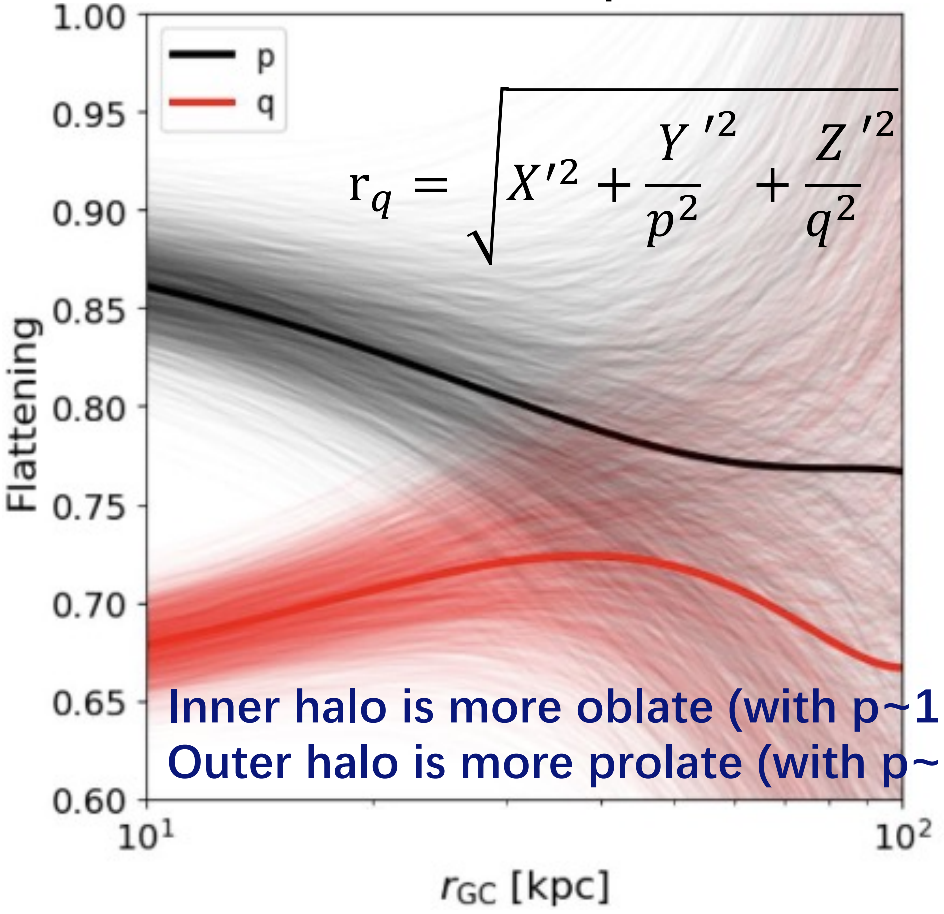
Pitch angle: angle between MW disk and major axis of stellar halo

The more inner stellar halo is aligned with the disk, whereas the outer halo becomes perpendicular to the disk

MW Stellar halo is twisted

Yaw angle: angle between projection of the major axis of stellar halo within the disc plane and the GC-sun line





Inner halo is more oblate (with p~1 and q~0.7)
Outer halo is more prolate (with p~q~0.75)

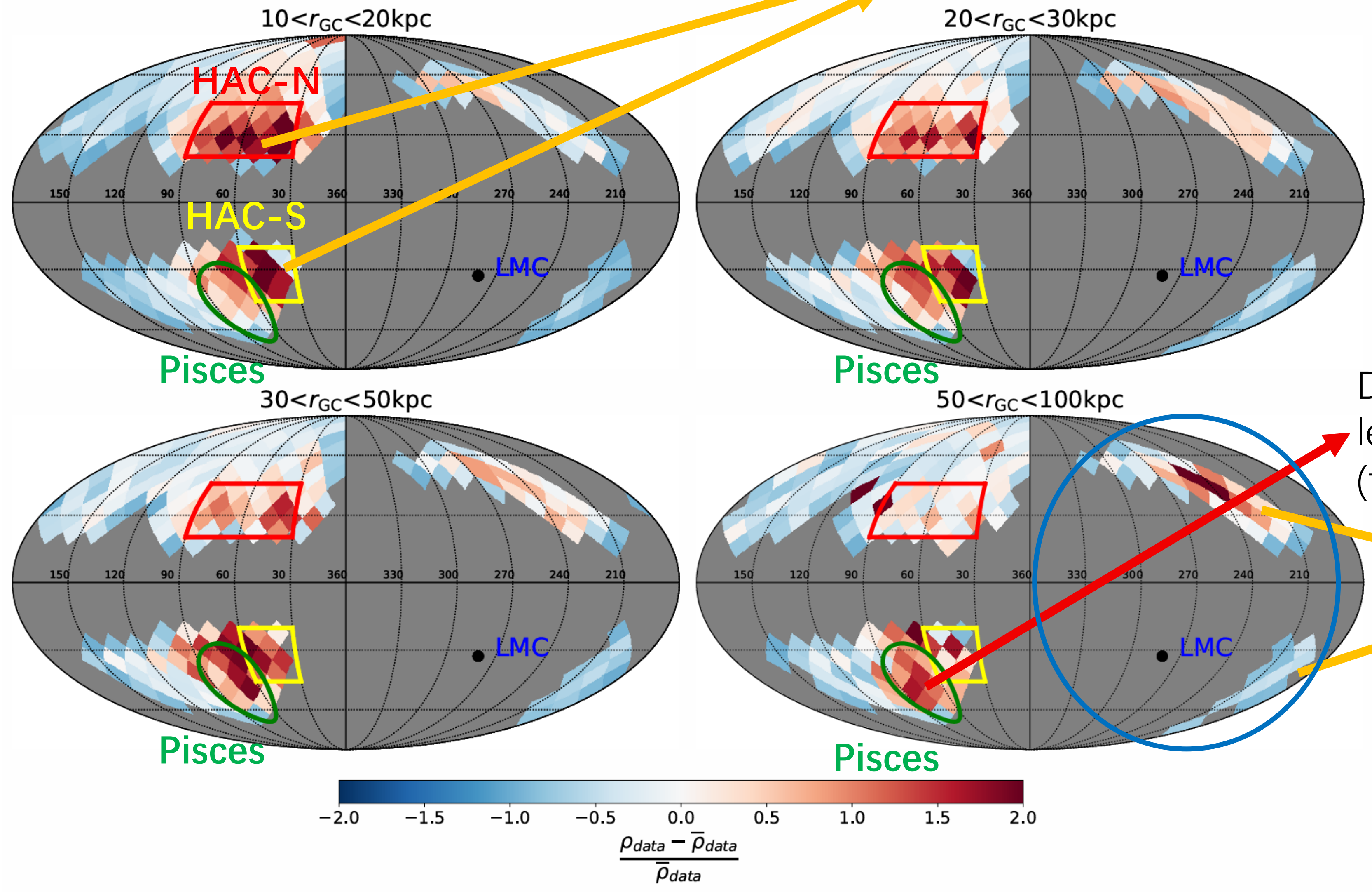
Pitch angle: angle between MW disk and major axis of stellar halo

The more inner stellar halo is aligned with the disk, whereas the outer halo becomes perpendicular to the disk

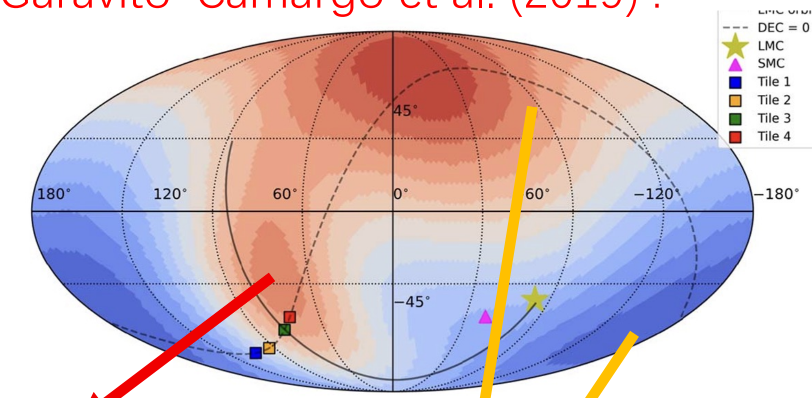
Anisotropy of stellar halo induced by GSE/LMC

A few well-known over-dense regions:

Associated with GSE



N-body simulation prediction
Garavito-Camargo et al. (2019) :

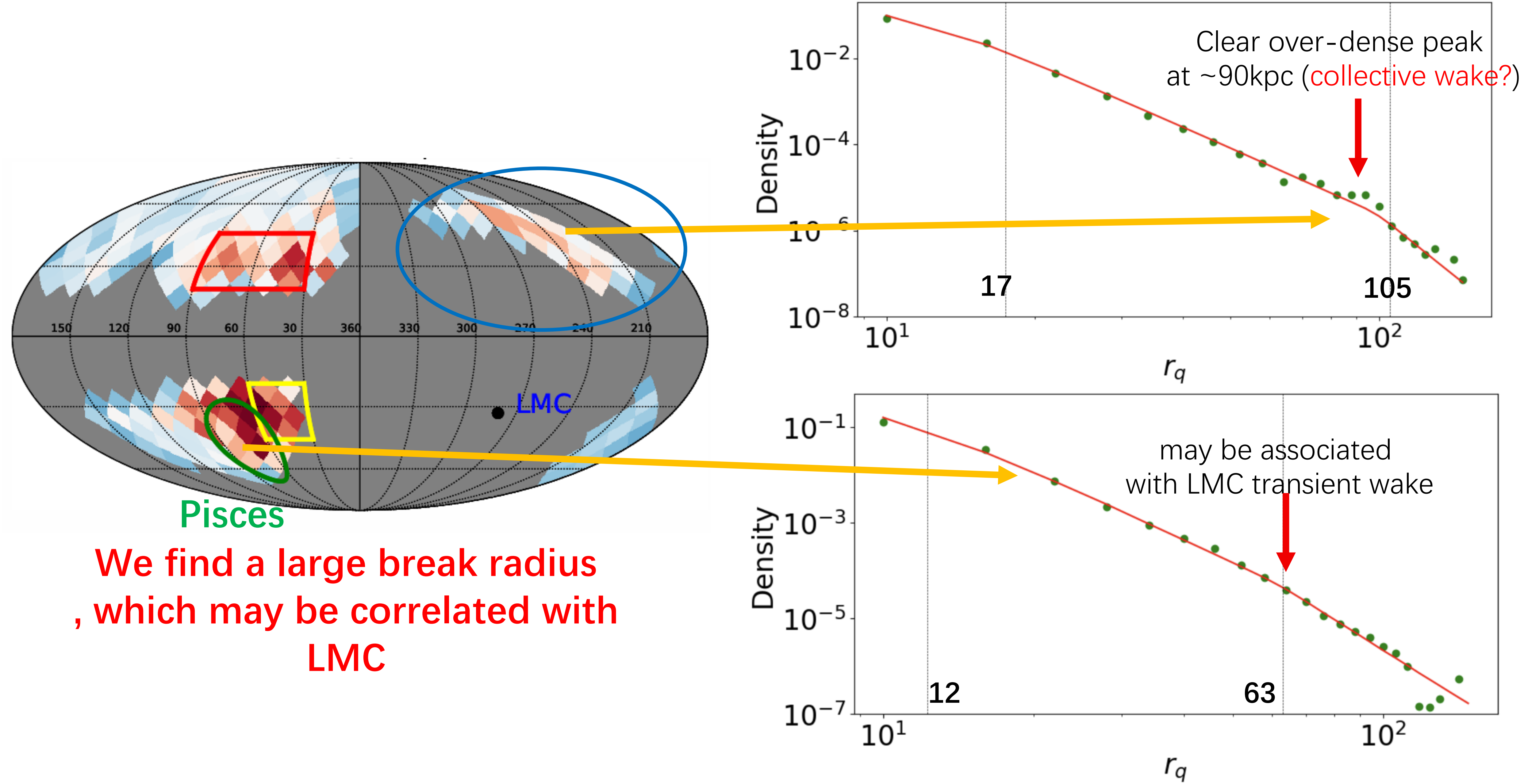


Dynamic fraction led to over-density (transient wake)

Corresponds to LMC collective wake.

The density contrast at different distances Is highly anisotropic.

Anisotropy of stellar halo induced by LMC



We find a large break radius , which may be correlated with LMC

Summary

➢ Milky Way dwarf spheroidal galaxies

- We combine data from DESI MWS and previous observations for three dwarf spheroidal galaxies: Draco, Sextans and Ursa Minor

- We apply the axisymmetric Jeans Anisotropic Multi-Gaussian Expansion (JAM) modeling approach:
    - single-population Jeans model
    - multiple population chemodynamical model

- We find a diversity of $\rho_{DM}(150\text{pc})$, or the inner density slope γ

- Our results indicate that currently best constraints are still sensitive to the model assumptions and to sample selection effects

➢ Milky Way stellar halo

- We find the inner stellar halo is oblate and aligned with the Galactic disc, whereas the outer stellar halo becomes prolate and perpendicular to the disc
- We find evidences for the anisotropy of the stellar halo induced by GSE/LMC

Thanks!