Dark Matter in the Milky Way and its satellites

Kohei Hayashi (NIT, Sendai college)

KMI2025: The 6th KMI International Symposium

Mar. 5, 2025

The Milky Way as a unique target of dark matter studies

Target:

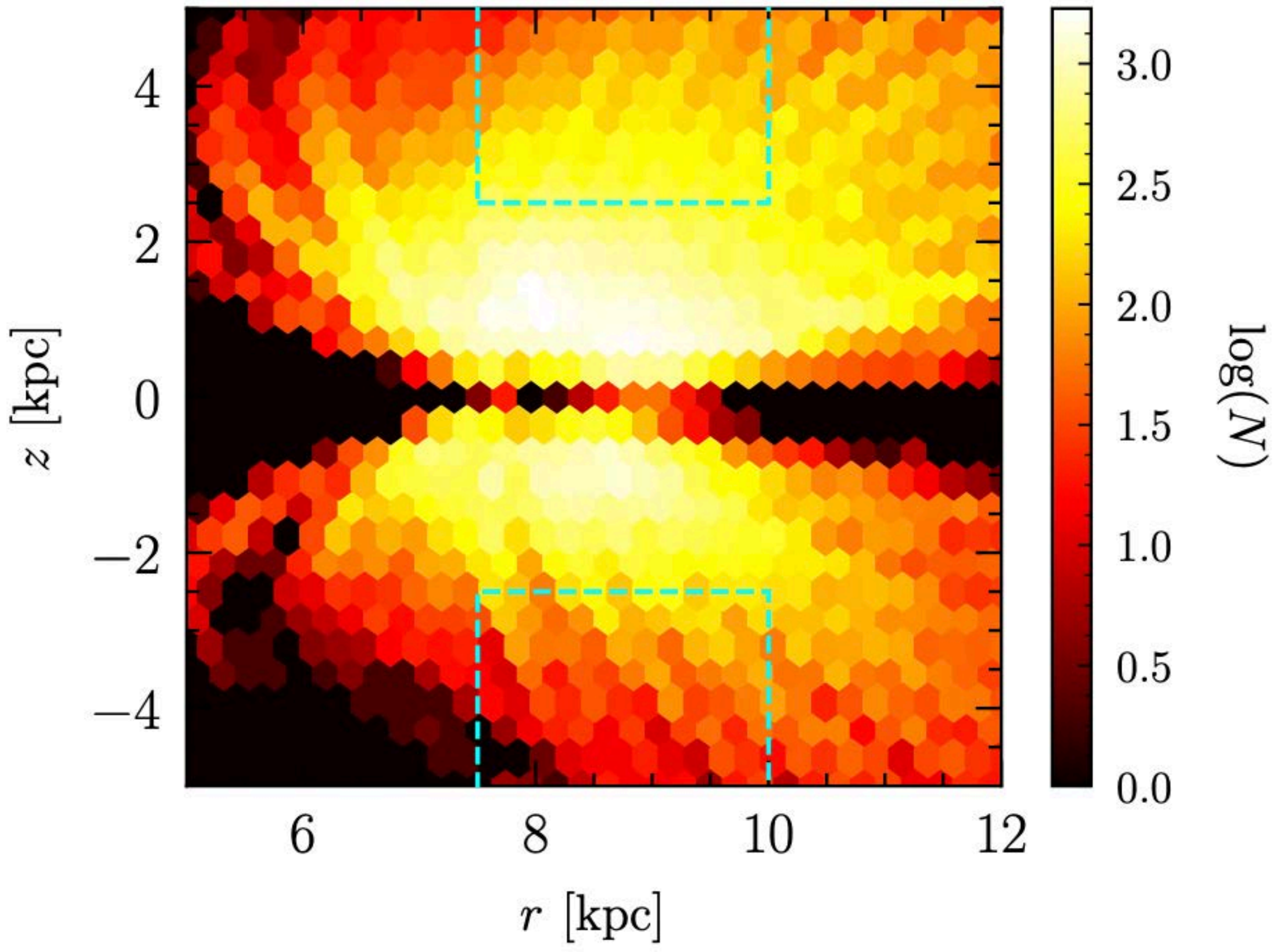
- Galactic center
- Solar neighborhood
- Dwarf spheroidal galaxies

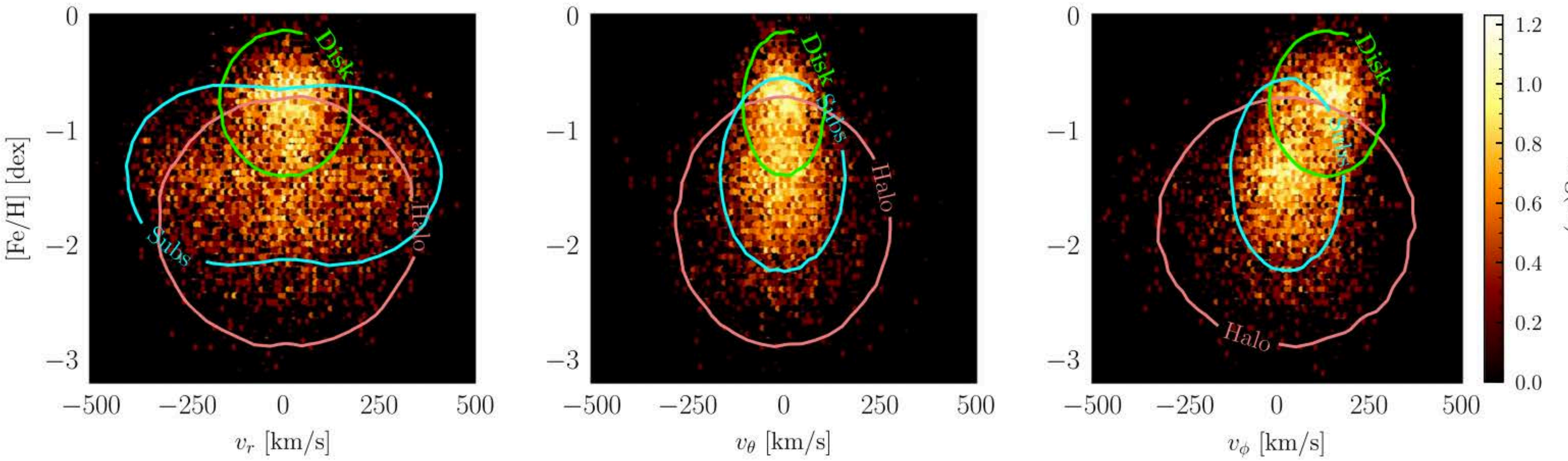
Dark matter velocity distribution

Necib et al. (2019)

- found a substructure in the solar neighborhood using GaiaDR2-SDSS data.
- It can be explained as the tidal debris of a disrupted massive satellites on a highly radial orbit.
- The simulations predict that DM traces the kinematics of the tidal debris.

Gaia-SDSS data

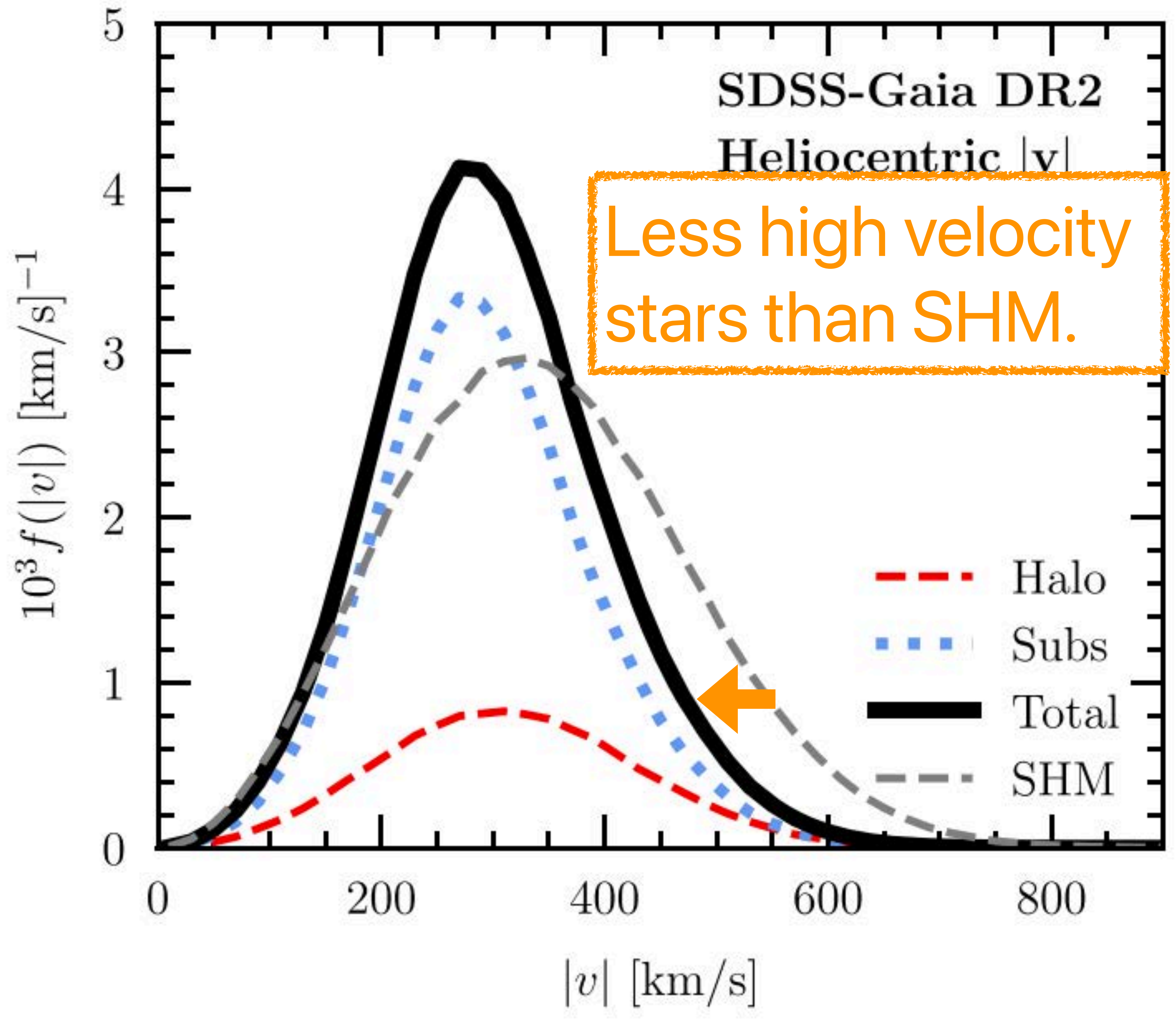


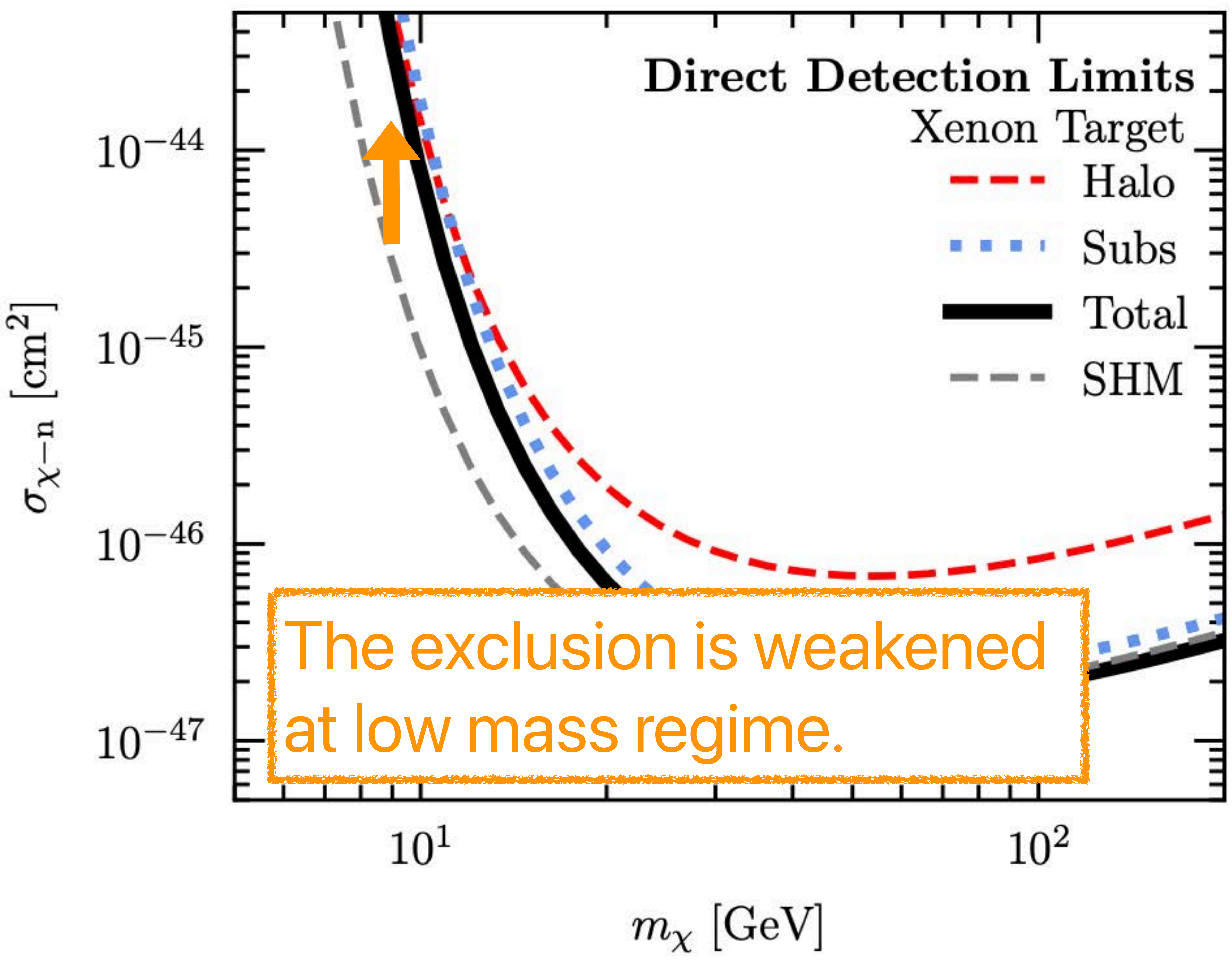


Dark matter velocity distribution

Necib et al. (2019)

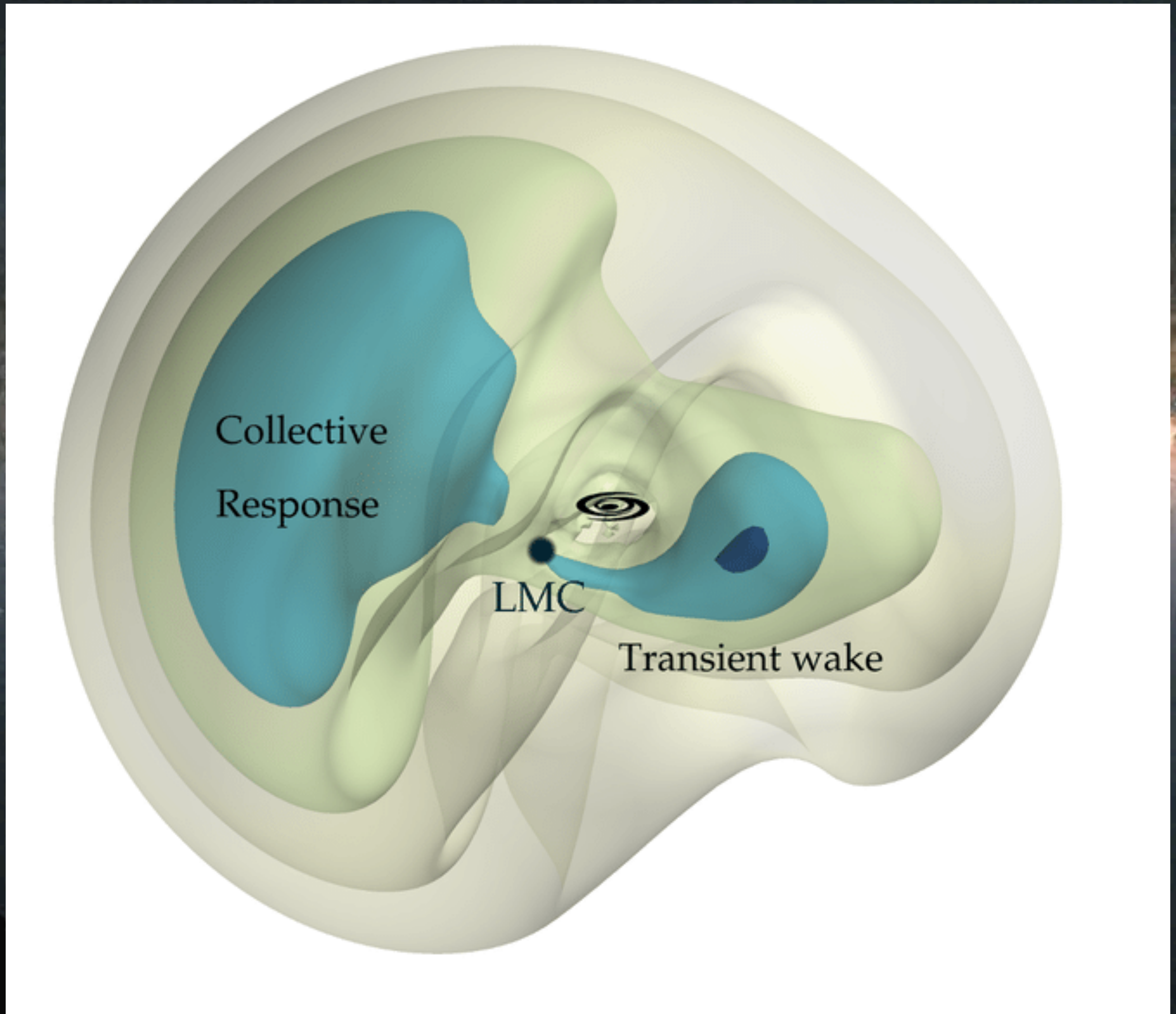
Assumed that the velocity distribution of DM is consistent with that of old stellar counterpart.



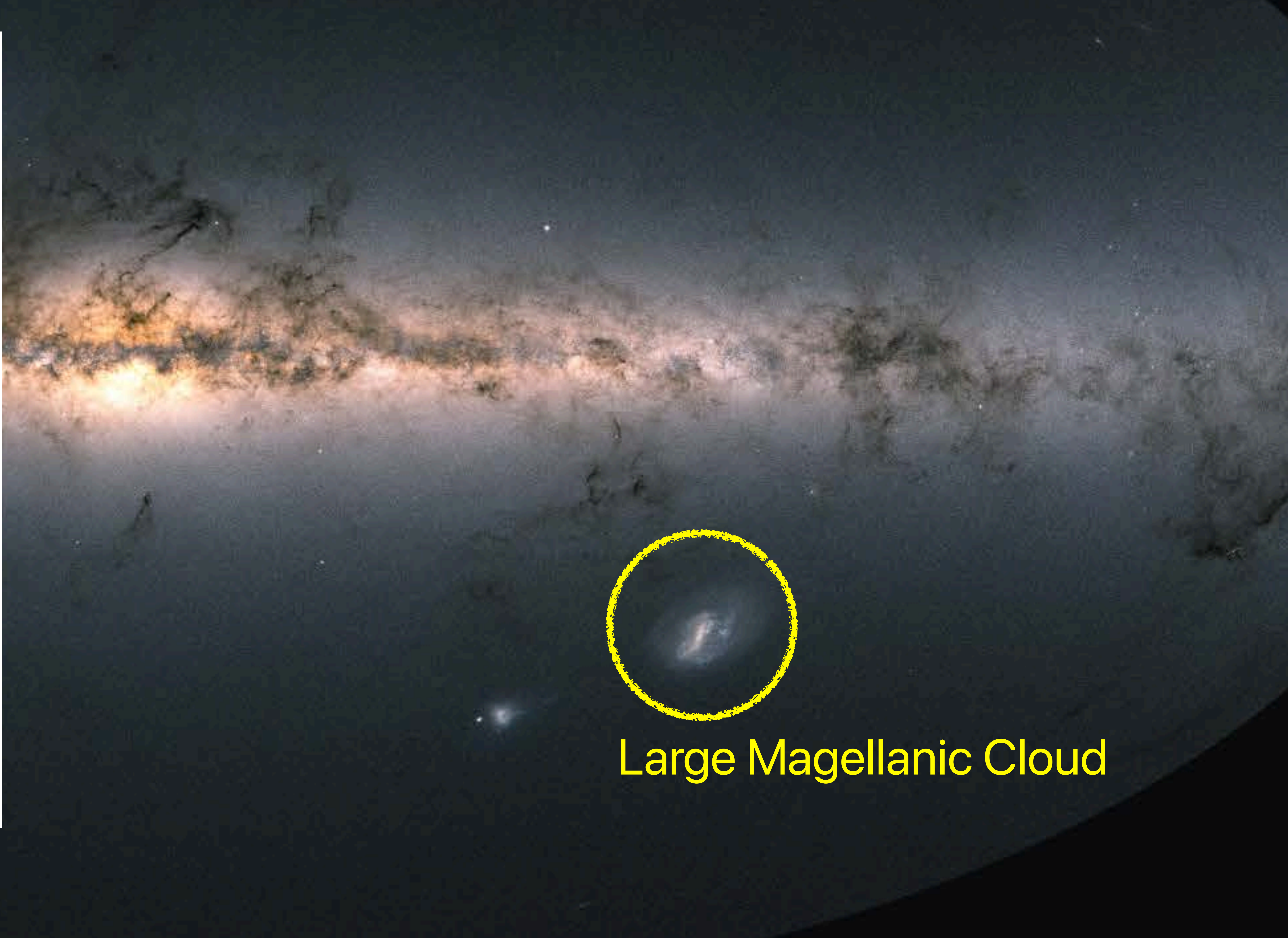


Dark matter velocity distribution

Large Magellanic Cloud could perturb DM and stellar halo, and **DM velocity distributions**.



Garavito-Camergo et al. (2021)



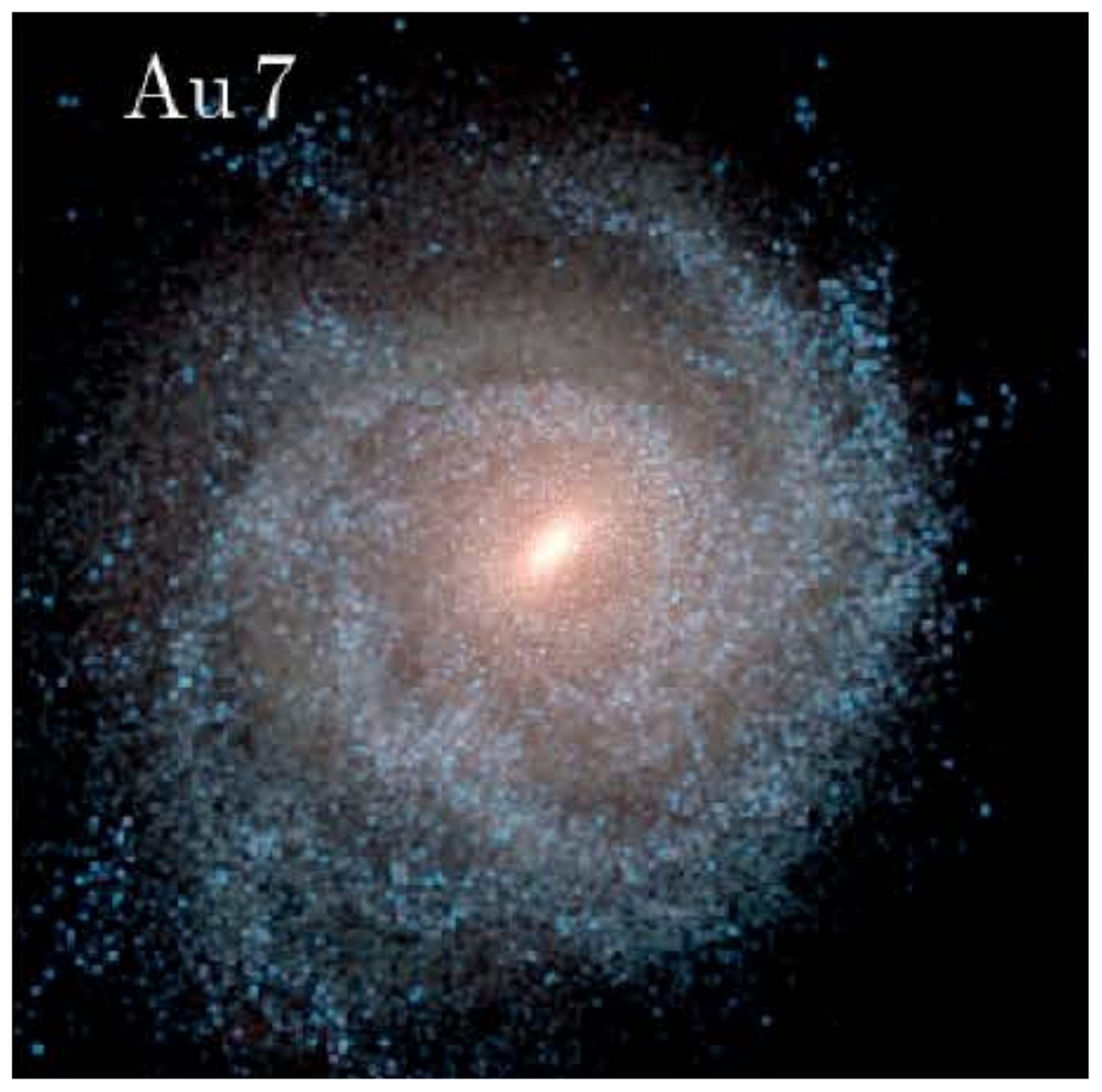
Gaia's EDR3 sky map. Credit: ESA/Gaia/DPAC

Dark matter velocity distribution

Large Magellanic Cloud could perturb DM and stellar halo, and **DM velocity distributions**.

Smith-Orlik et al. (2023)

- Use *Auriga cosmological simulations* and identify 15 MW-LMC analogues.
- Study the impact of the LMC on the local DM distribution at different times (snapshots) in its orbits.



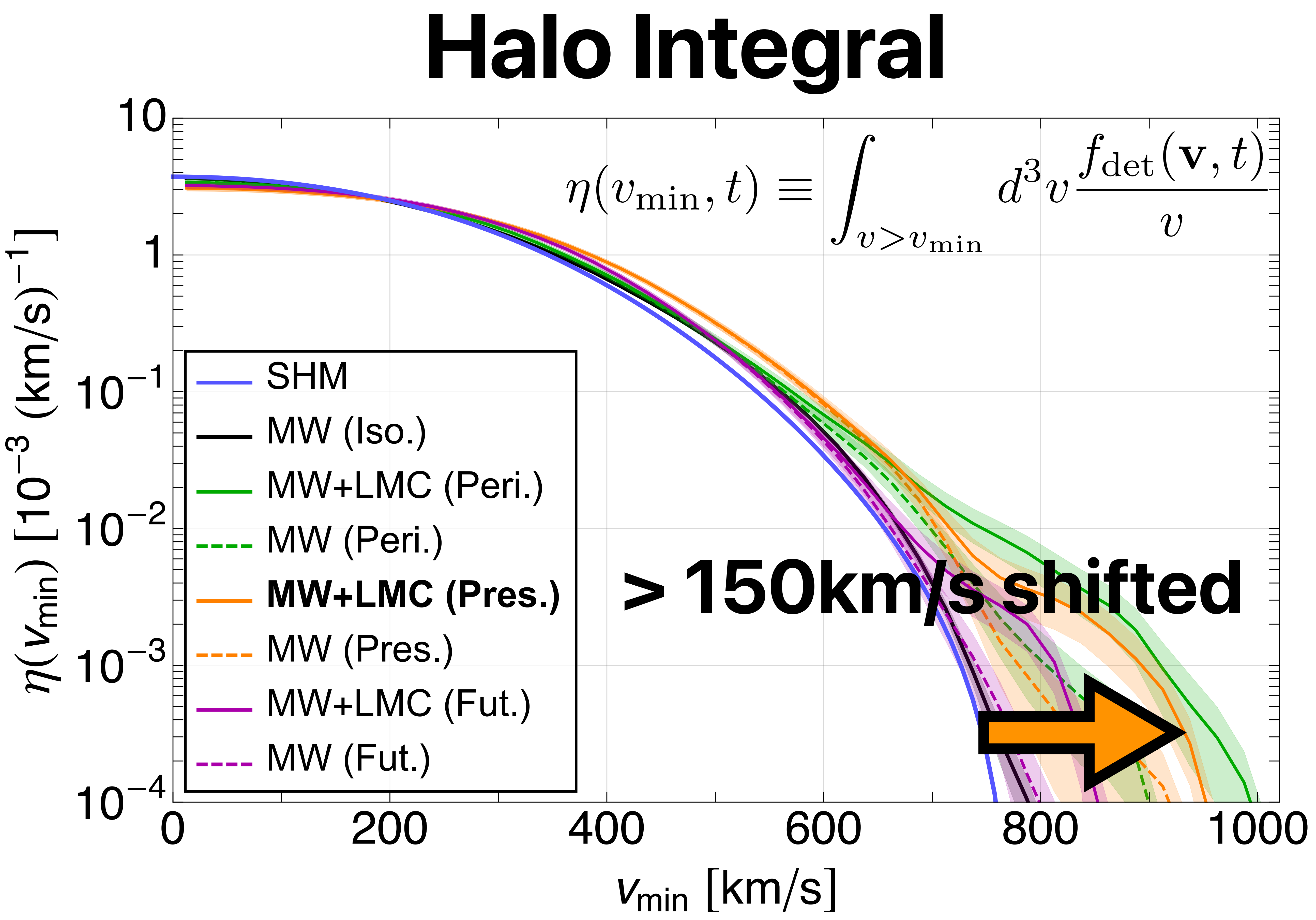
Snapshot	Description	$t - t_{\text{Pres.}}$ [Gyr]	r_{LMC} [kpc]
Iso.	Isolated MW analogue	−2.83	384
Peri.	LMC's first pericenter approach	−0.133	32.9
Pres.	Present day MW-LMC analogue	0	50.6
Fut.	Future MW-LMC analogue	0.175	80.3

Large Magellanic Could

Gaia's EDR3 sky map. Credit: ESA/Gaia/DPAC

Dark matter velocity distribution

Smith-Orlik et al. (2023)



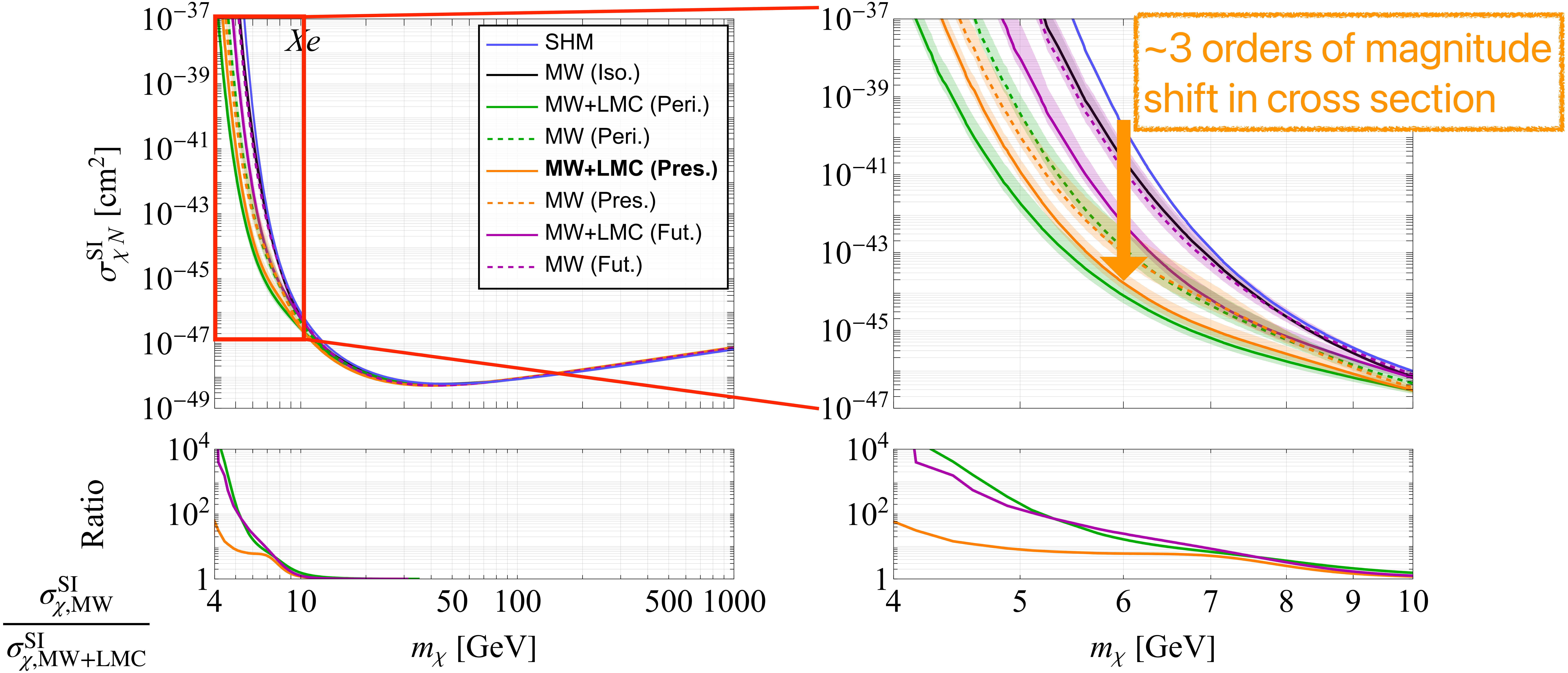
- Although the DM number fraction originating from LMC is small, the LMC significantly impacts the high velocity tail of the DM velocity distribution.
- The high velocity tail of MW+LMC are shifted over 150km/s from that of SHM.
- High velocity LMC DM particles + MW's response to the LMC affect the high velocity tail of the halo integrals.

Direct detection limits

Smith-Orlik et al. (2023)

Xenon based detector

$\rho_\chi = 0.3\ [\mathrm{GeV/cm^3}]$ fixed



Dark matter local density

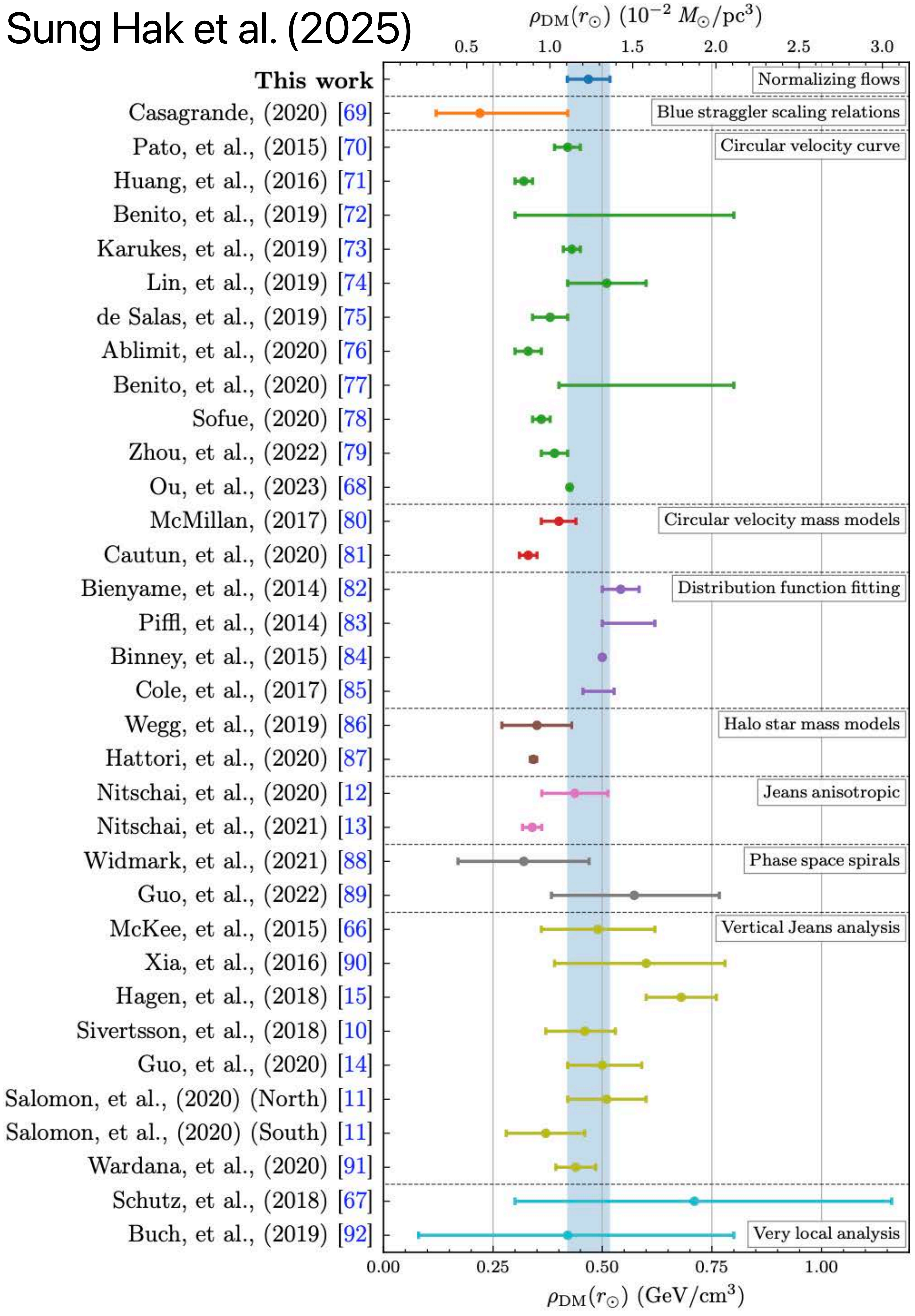
To obtain the density…

- Vertical stellar motions of solar neighborhood
- Rotation curve
- Escape velocity
- Motions of the MW halo stars
- …

Current estimation:

$$\bar{\rho}_{\mathrm{DM},\odot} = 0.47 \pm 0.05\,\mathrm{GeV}/\mathrm{cm}^3$$

Sung Hak et al. (2025)



See also Hunt and Vasiliev (2025) for a review

Dark matter local density and density profile

Commonly-used dynamical modeling: **Jeans equations (equilibrium & axisymmetry)**

Total gravitational potential

$$\frac{\partial \Phi}{\partial R} = \frac{\overline{v_\phi^2}}{R} - \frac{\overline{v_R^2}}{R} - \frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_R^2})}{\partial R} - \frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_R v_z})}{\partial z} \quad \Rightarrow \quad v_{\rm circ}(R) \equiv \sqrt{R\frac{\partial \Phi}{\partial R}}\bigg|_{z=0}$$

Circular vel.

$$\frac{\partial \Phi}{\partial z} = -\frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_z^2})}{\partial z} - \frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_R v_z})}{\partial R} - \frac{\overline{v_R v_z}}{R} \quad \Rightarrow \quad K_z \equiv \frac{\partial \Phi}{\partial z}$$

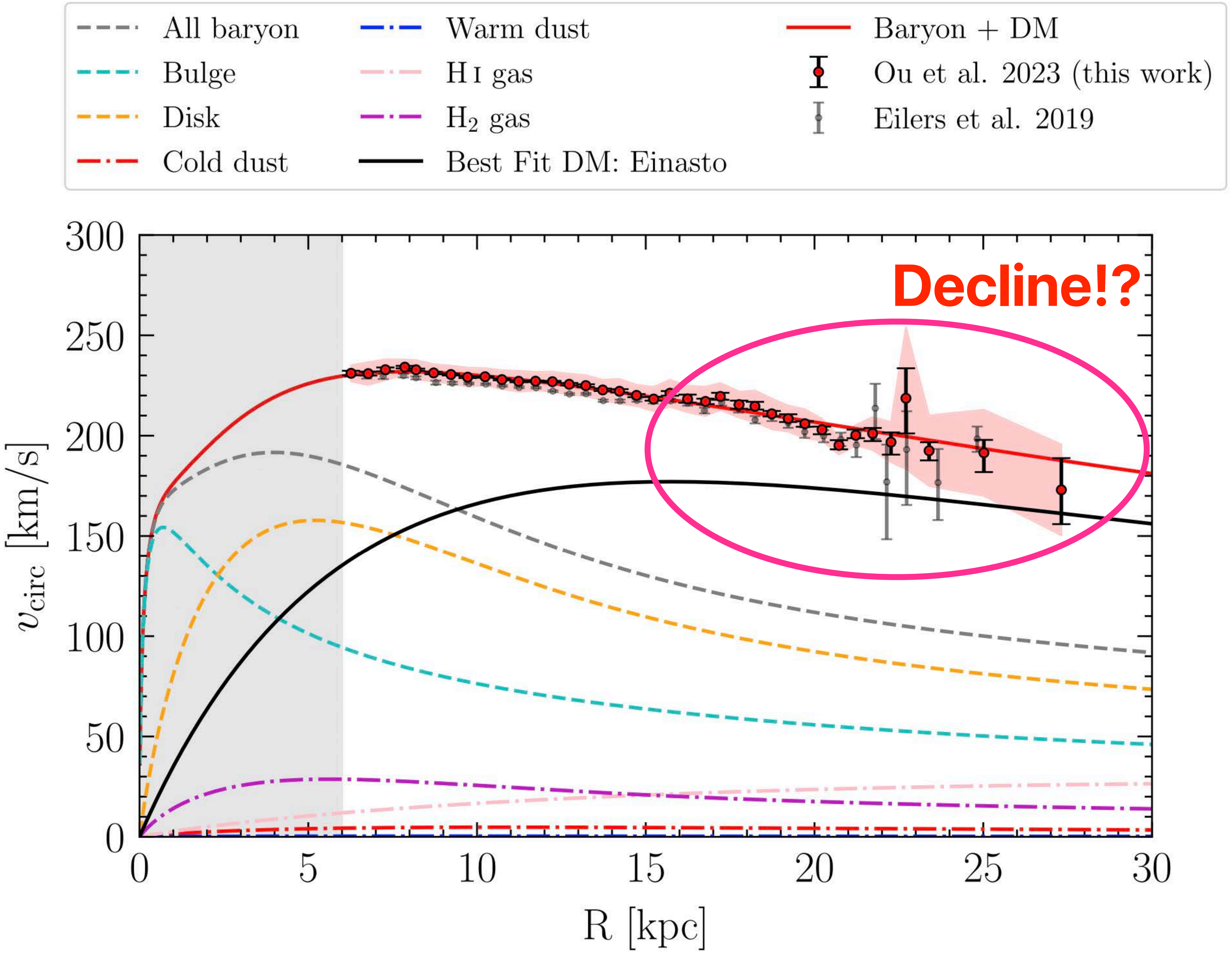
Vertical force

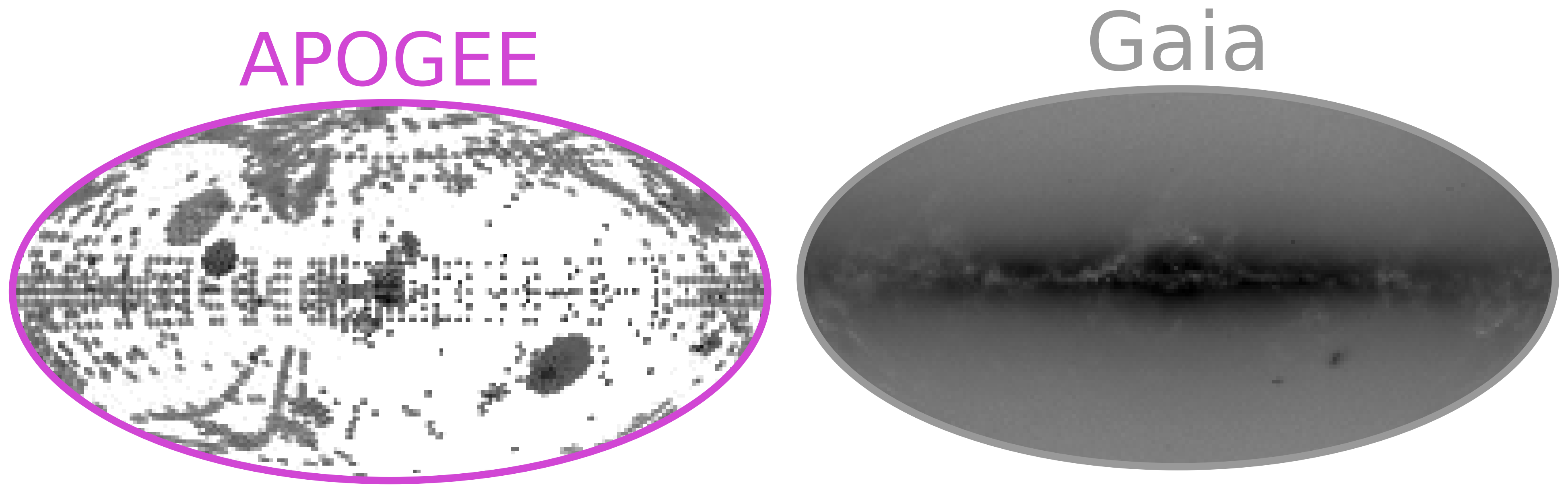
Challenges…

- Inhomogeneous and incomplete data sample
- **Dynamical disequilibrium**
- Lack of data towards the Galactic Center
- Triaxiality
- Modeling for baryonic components (thin/thick discs, bulge, bar, star/gas, and so on…)

Dark matter density from the rotation curve

- Using 120,309 disk stars (Gaia DR3 + APOGEE DR17)





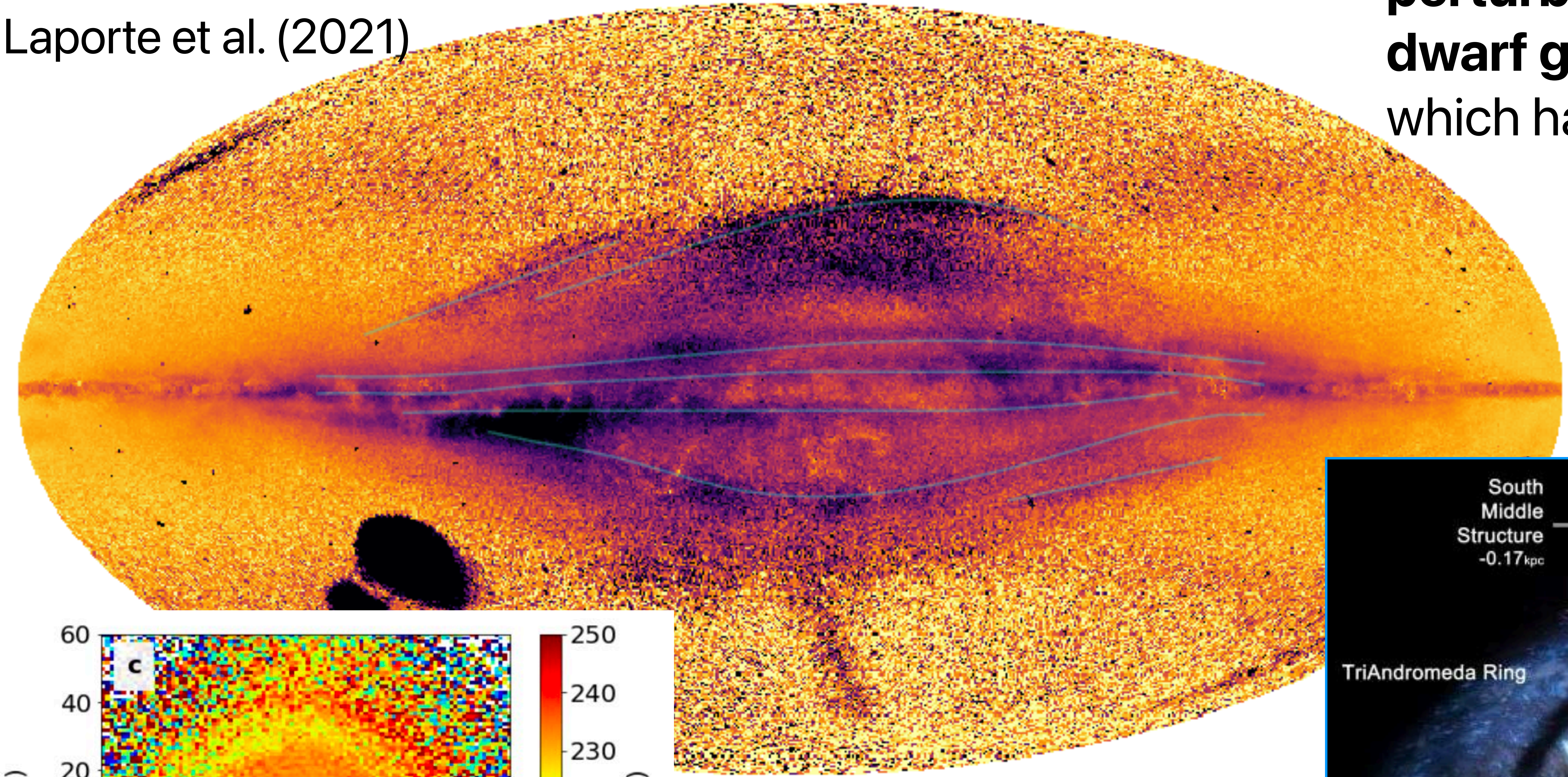
- ✤ Exponential drop-off such as the ***cored Einasto profile***, can explain the decline beyond 10 kpc.
- ✤ Estimated virial mass of the MW is $\sim 1.8 \times 10^{11}\, M_{\odot}$, which is **much lower than the previous estimates**.
- ✤ What is the origin of this **declining feature**?

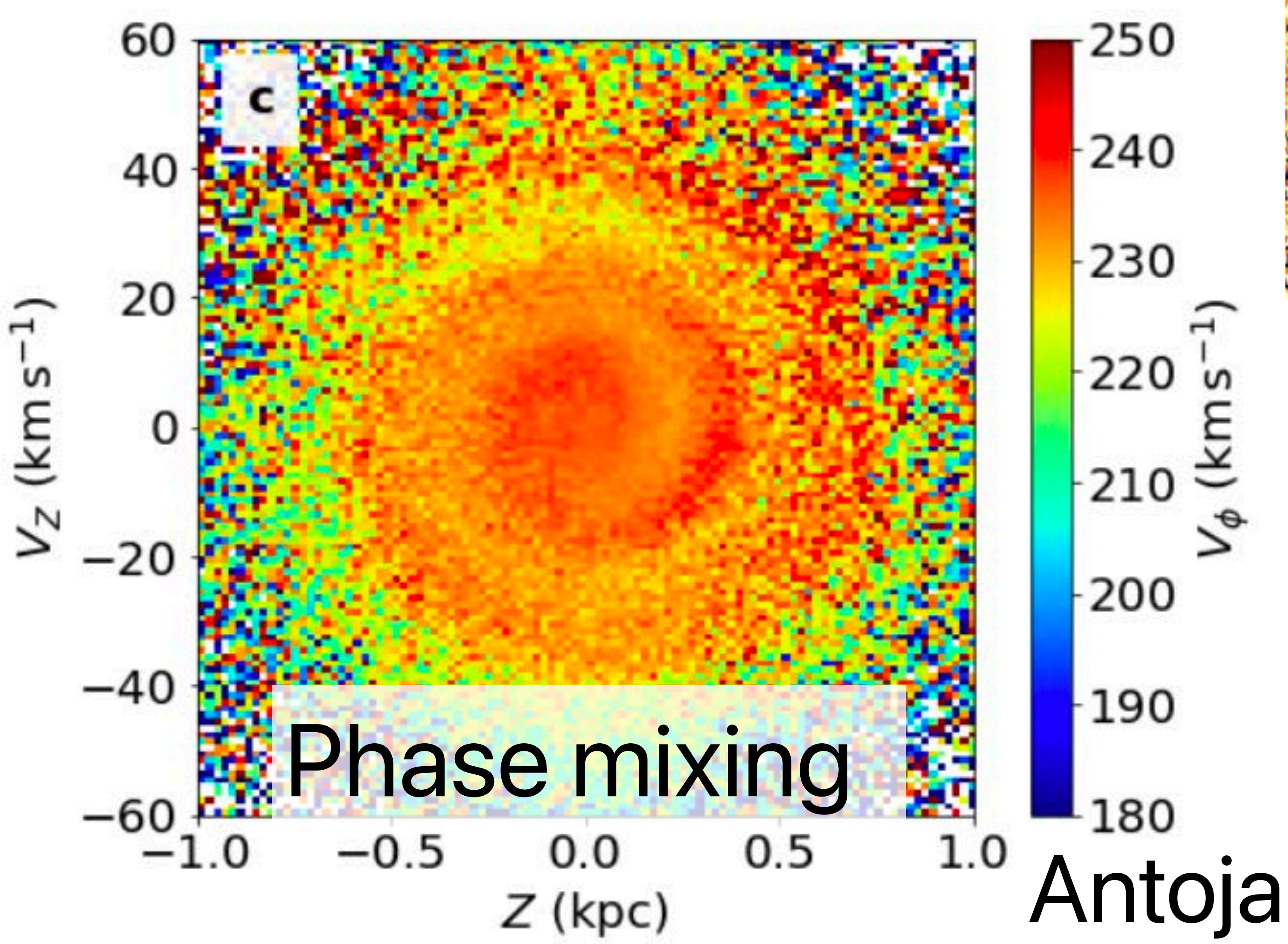
Ou et al. (2023, see also Zhou+23, Jiao+23)

Evidences of disequilibrium

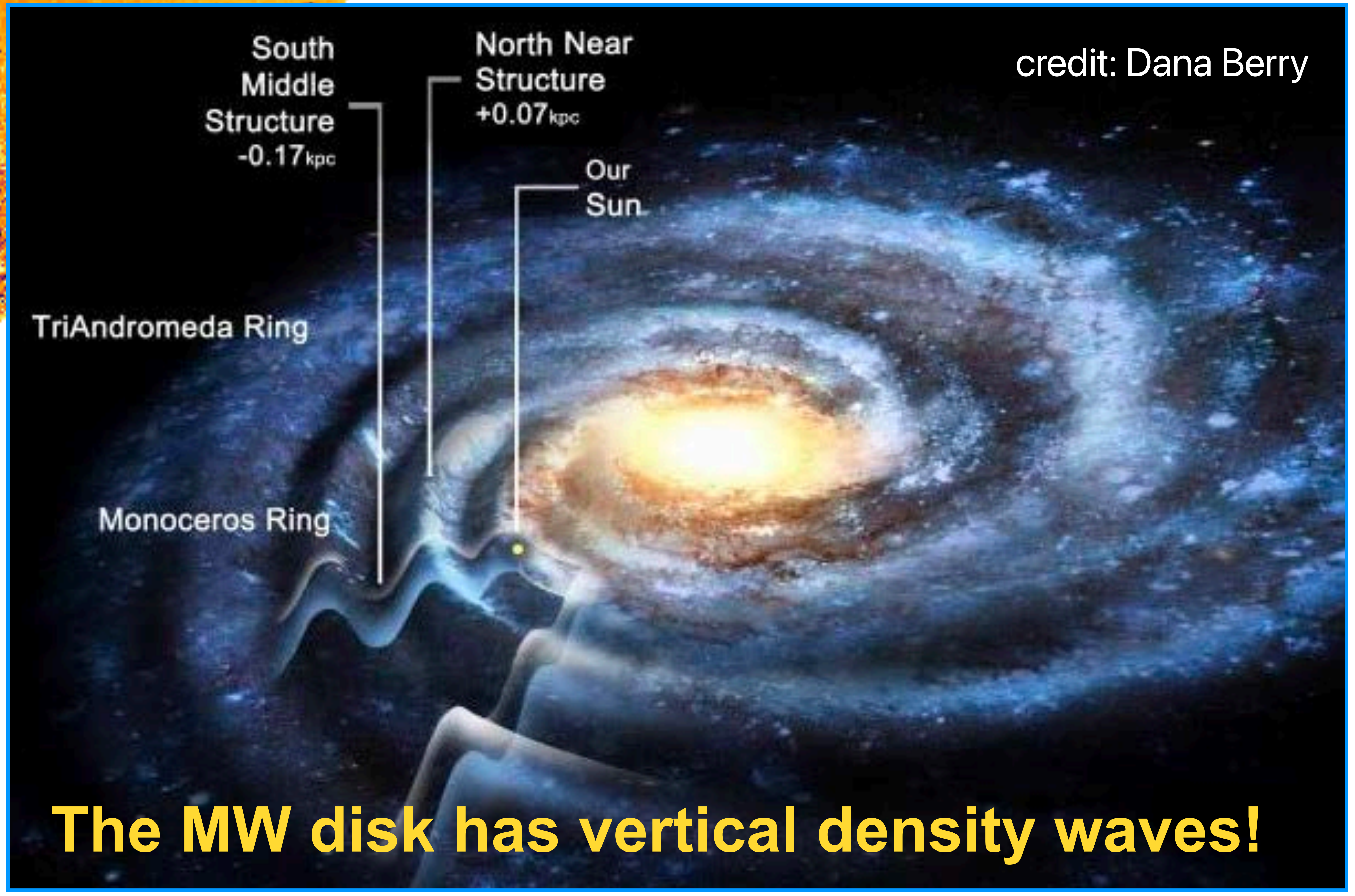
The Milky Way is thought to be **perturbed by the Sagittarius dwarf galaxy and Gaia-Enceladus** which has now dispersed its debris.

Laporte et al. (2021)





Antoja et al. (2018, Nature)



see also Crane+'03, Martin+'07, Slater+'14, Li+'17

Dark matter local density and density profile

Commonly-used dynamical modeling: **Jeans equations (equilibrium & axisymmetry)**

Total gravitational potential

$$\frac{\partial \Phi}{\partial R} = \frac{\overline{v_\phi^2}}{R} - \frac{\overline{v_R^2}}{R} - \frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_R^2})}{\partial R} - \frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_R v_z})}{\partial z} \quad \Rightarrow \quad v_{\rm circ}(R) \equiv \sqrt{R\frac{\partial \Phi}{\partial R}}\bigg|_{z=0}$$

Circular vel.

$$\frac{\partial \Phi}{\partial z} = -\frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_z^2})}{\partial z} - \frac{1}{\rho_*}\frac{\partial(\rho_* \overline{v_R v_z})}{\partial R} - \frac{\overline{v_R v_z}}{R} \quad \Rightarrow \quad K_z \equiv \frac{\partial \Phi}{\partial z}$$

Vertical force

Challenges...

- Inhomogeneous and incomplete data sample
- Dynamical disequilibrium
- **Lack of data towards the Galactic Center**
- Triaxiality
- Modeling for baryonic components (thin/thick discs, bulge, bar, star/gas, and so on...)

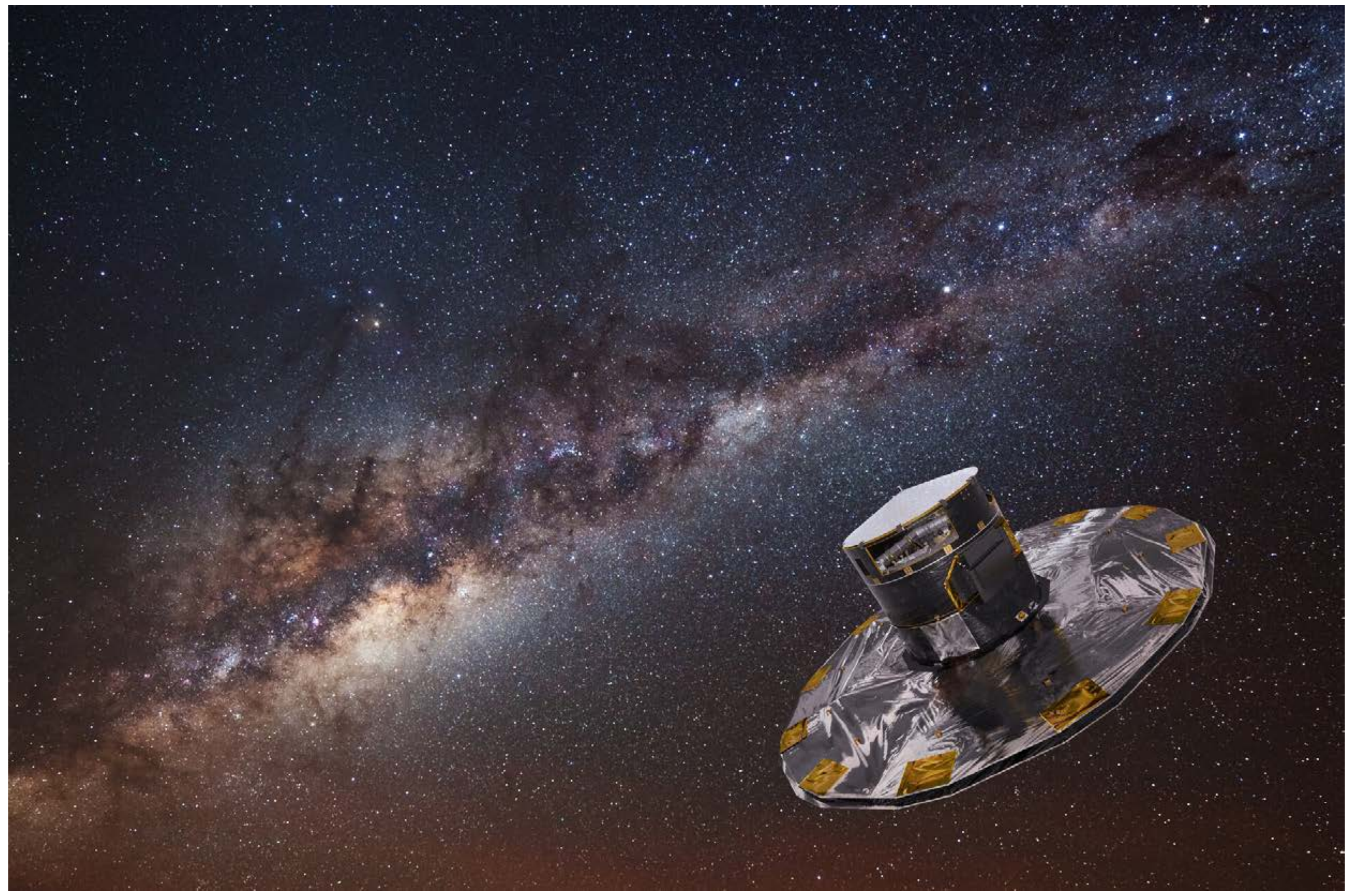
Dark matter density profile

- Using old halo stars (outer regions)

- Data

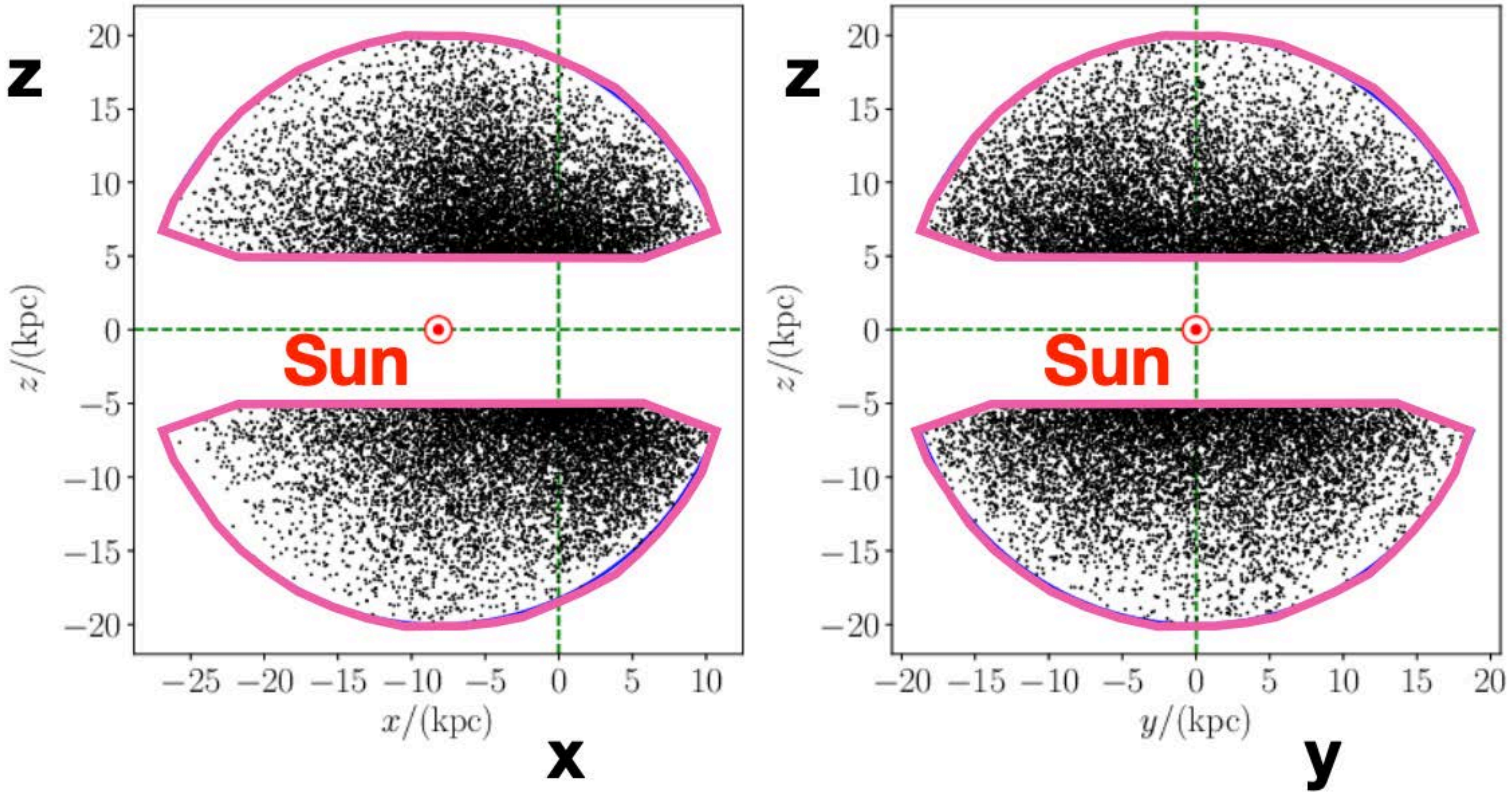
a) Proper motions of RR Lyrae stars by Gaia EDR3

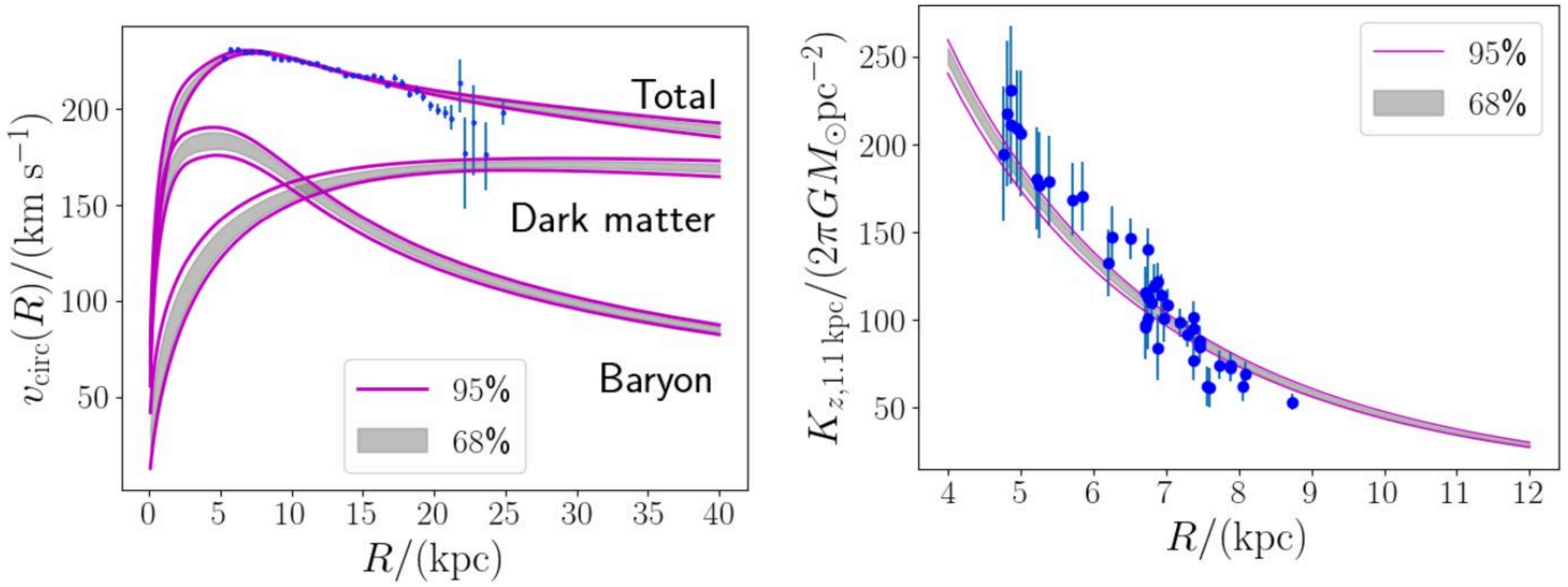
- Old halo stars
- Measure the distance by period-luminosity relation



b) Rotation curve + vertical force

~16,000 RR Lyrae stars



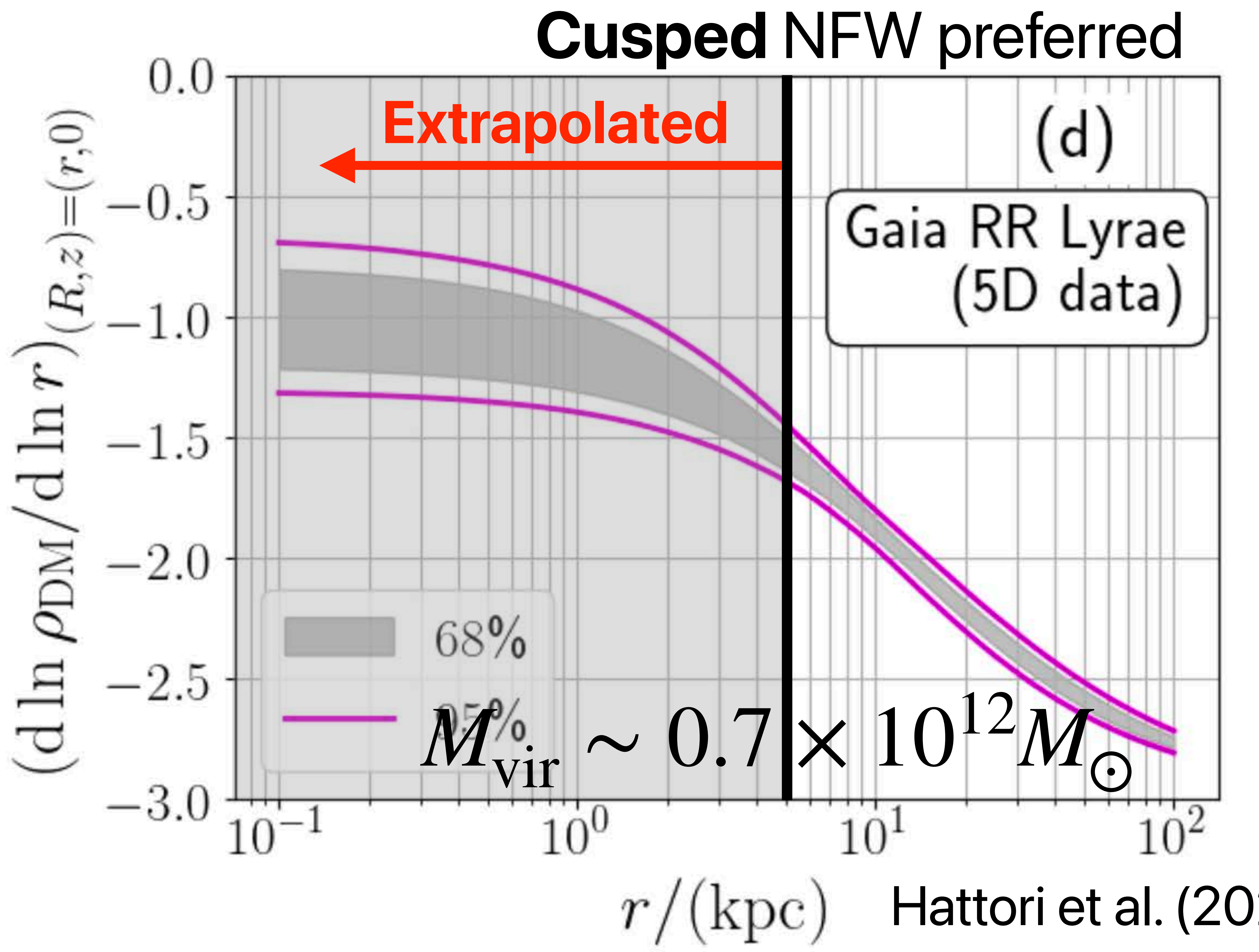


↑ Rotation curve & vertical force from parameterized distribution function

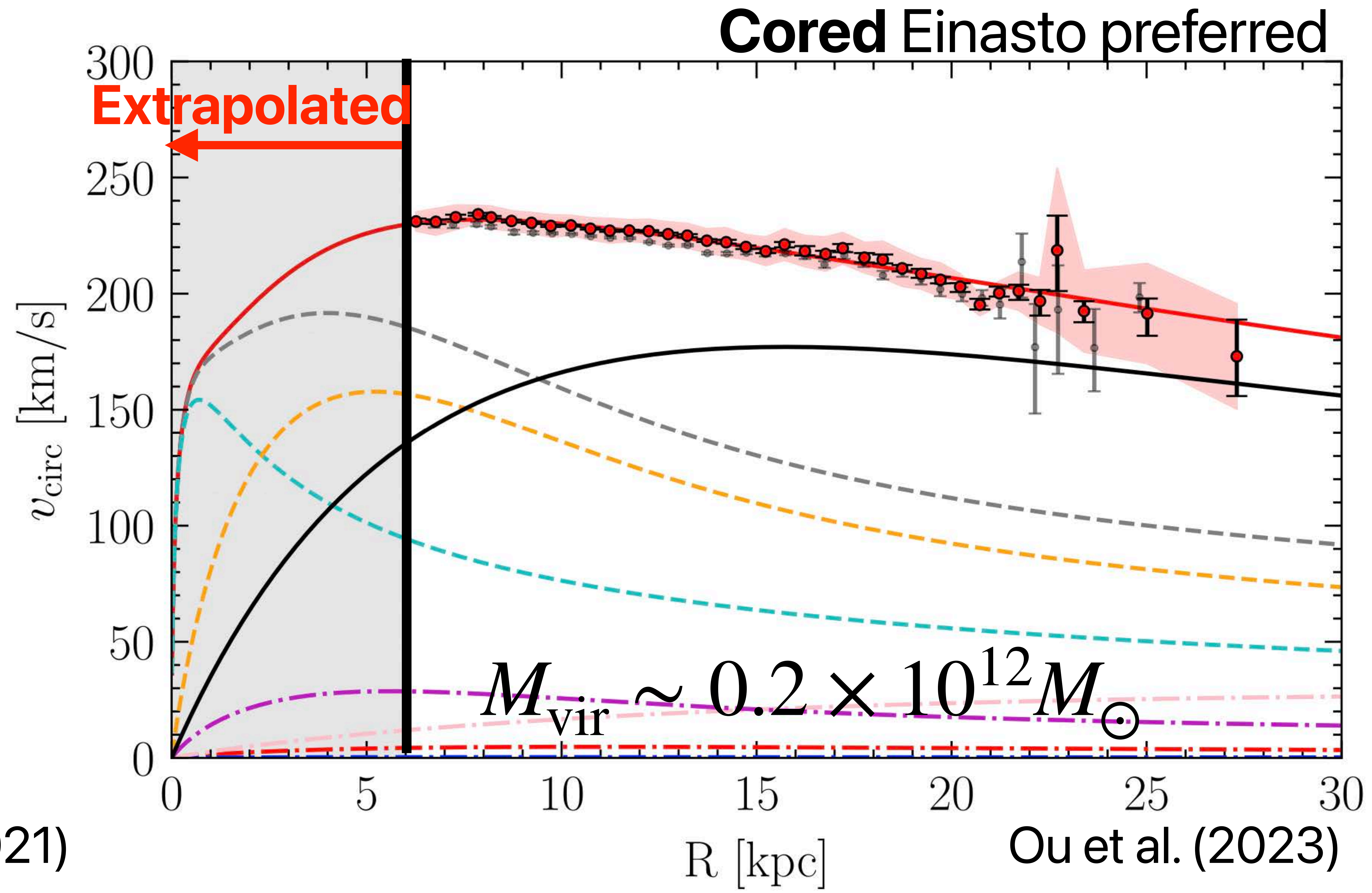
← 3D positions of ~16,000 RR Lyrae stars

Hattori et al. (2021, 2012.03908)

Core or cusp?



Hattori et al. (2021)

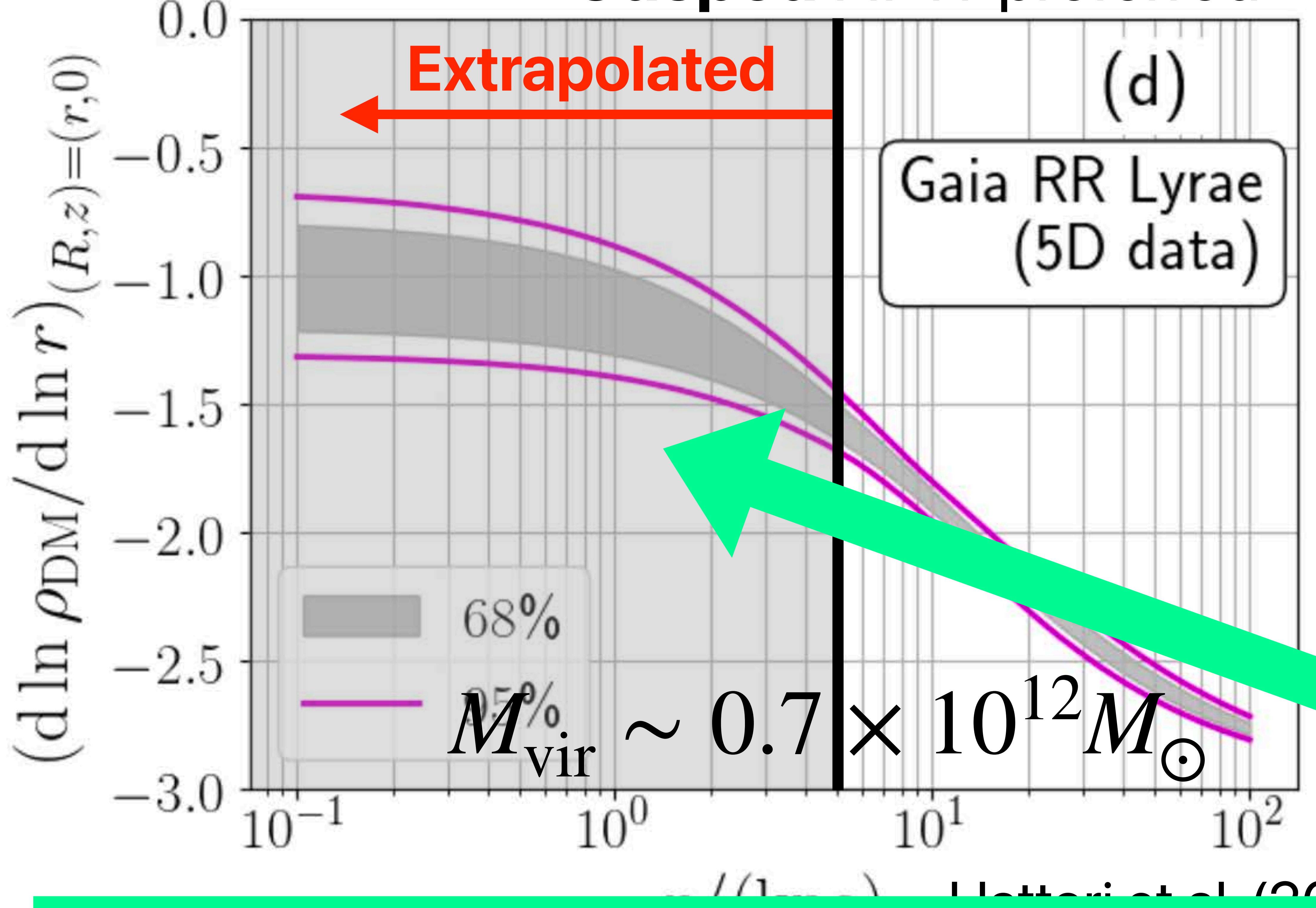


Ou et al. (2023)

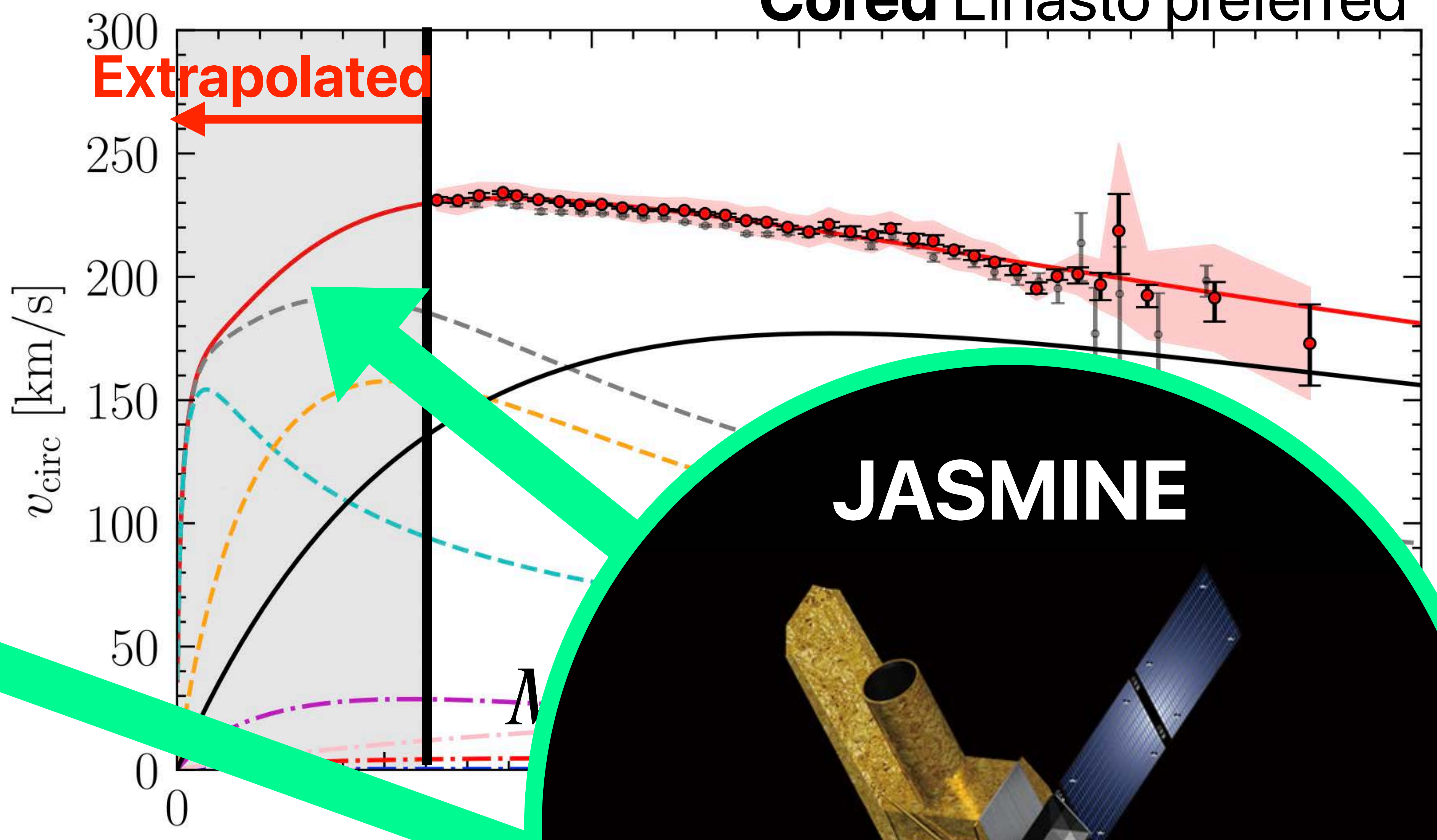
- The DM density inner slope and the virial mass still depends largely on data properties and dynamical modeling.
- Gaia, the optical astrometry satellite, ***cannot*** obtain the astrometry data toward the Galactic center due to the dense interstellar dust.

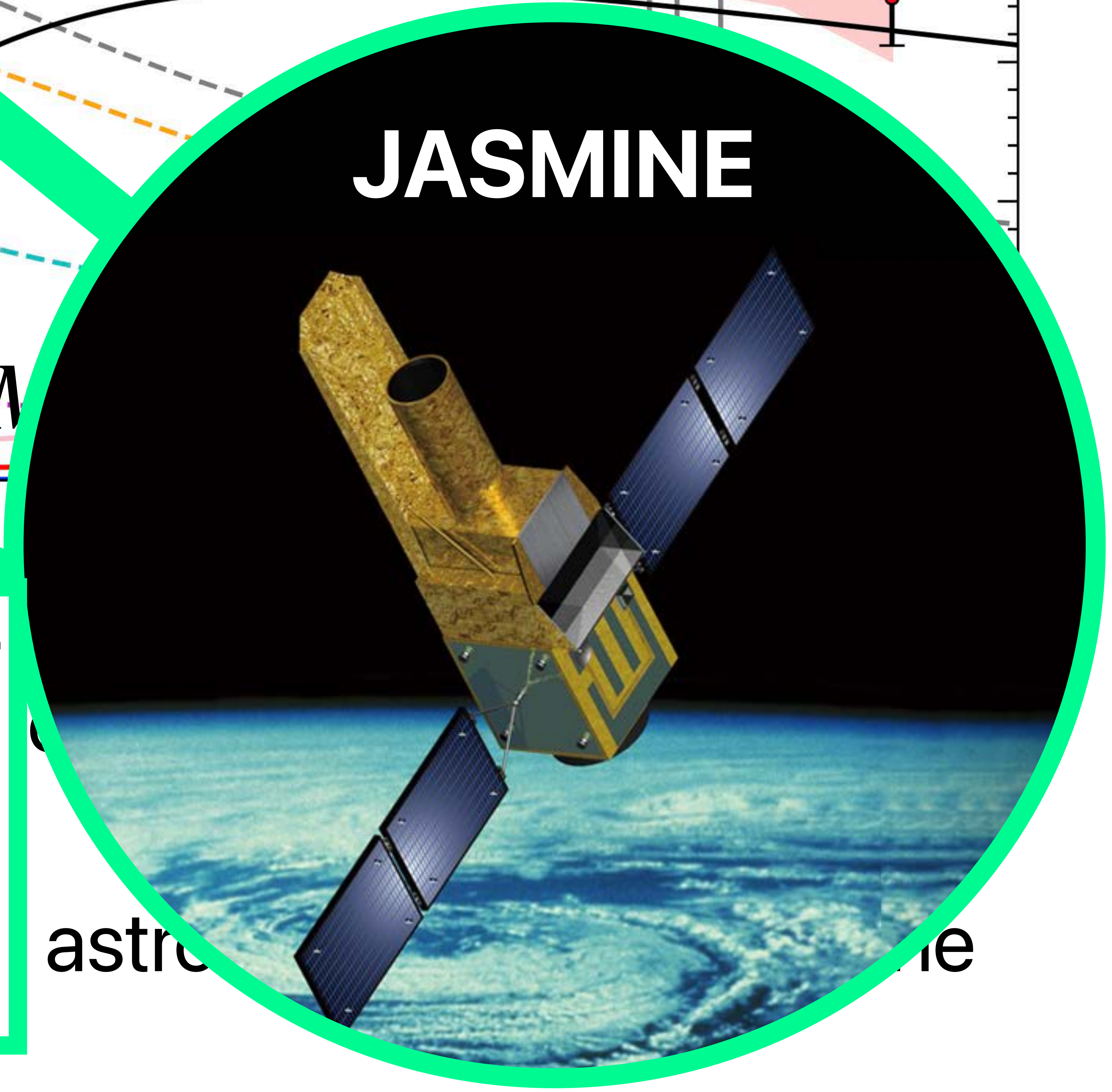
Core or cusp?

Cusped NFW preferred



Cored Einasto preferred





JASMINE provides detailed information on stellar motions in the interior of the Milky Way, and is expected to greatly improve the determination of the dark matter distribution in the central region.

The Milky Way
as a unique target of dark matter studies

Dark Matter distribution
in the dwarf spheroidals

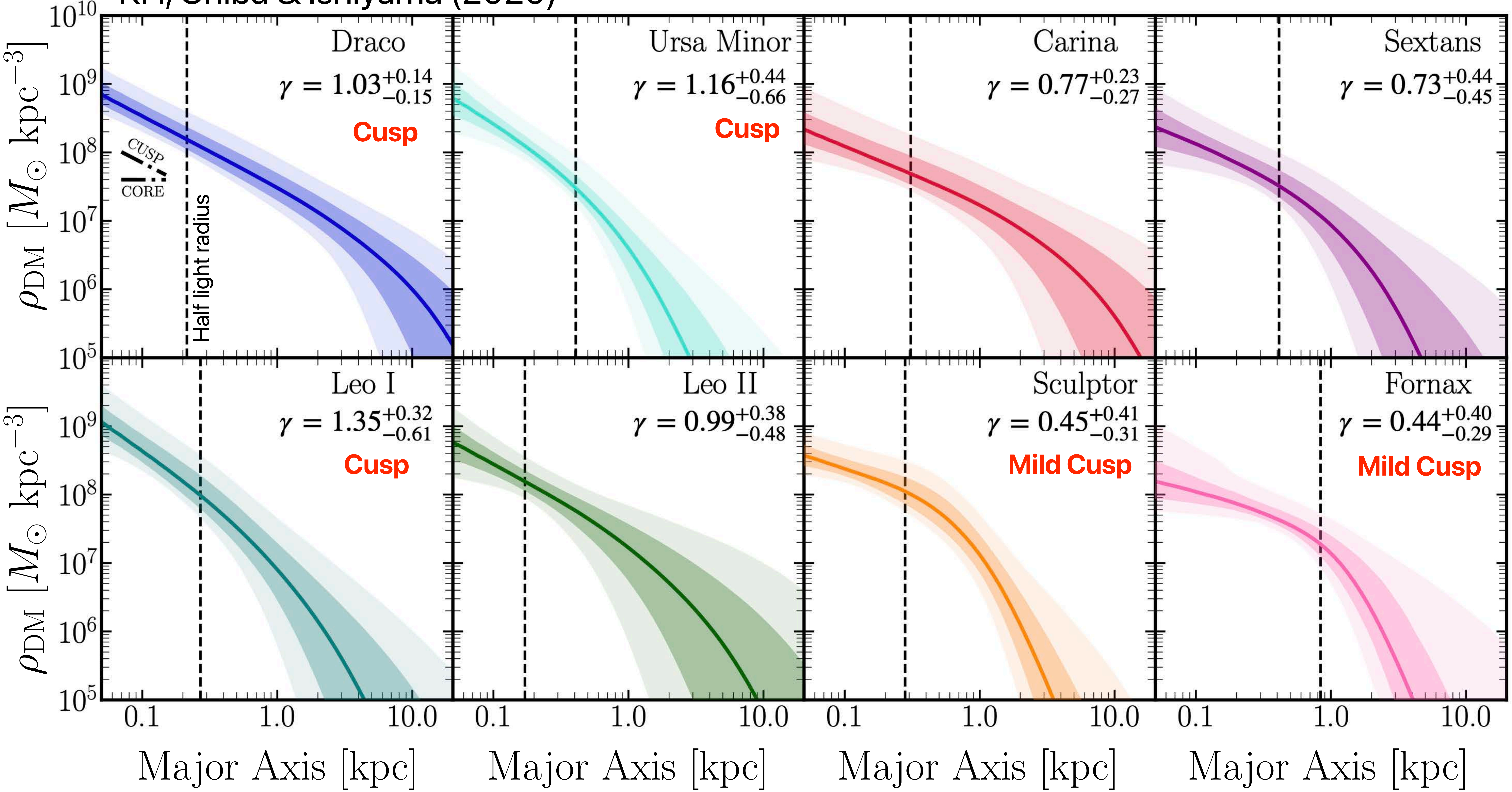
Target:

- Galactic center
- Solar neighborhood
- Dwarf spheroidal galaxies

Dark matter density profiles: Classicals

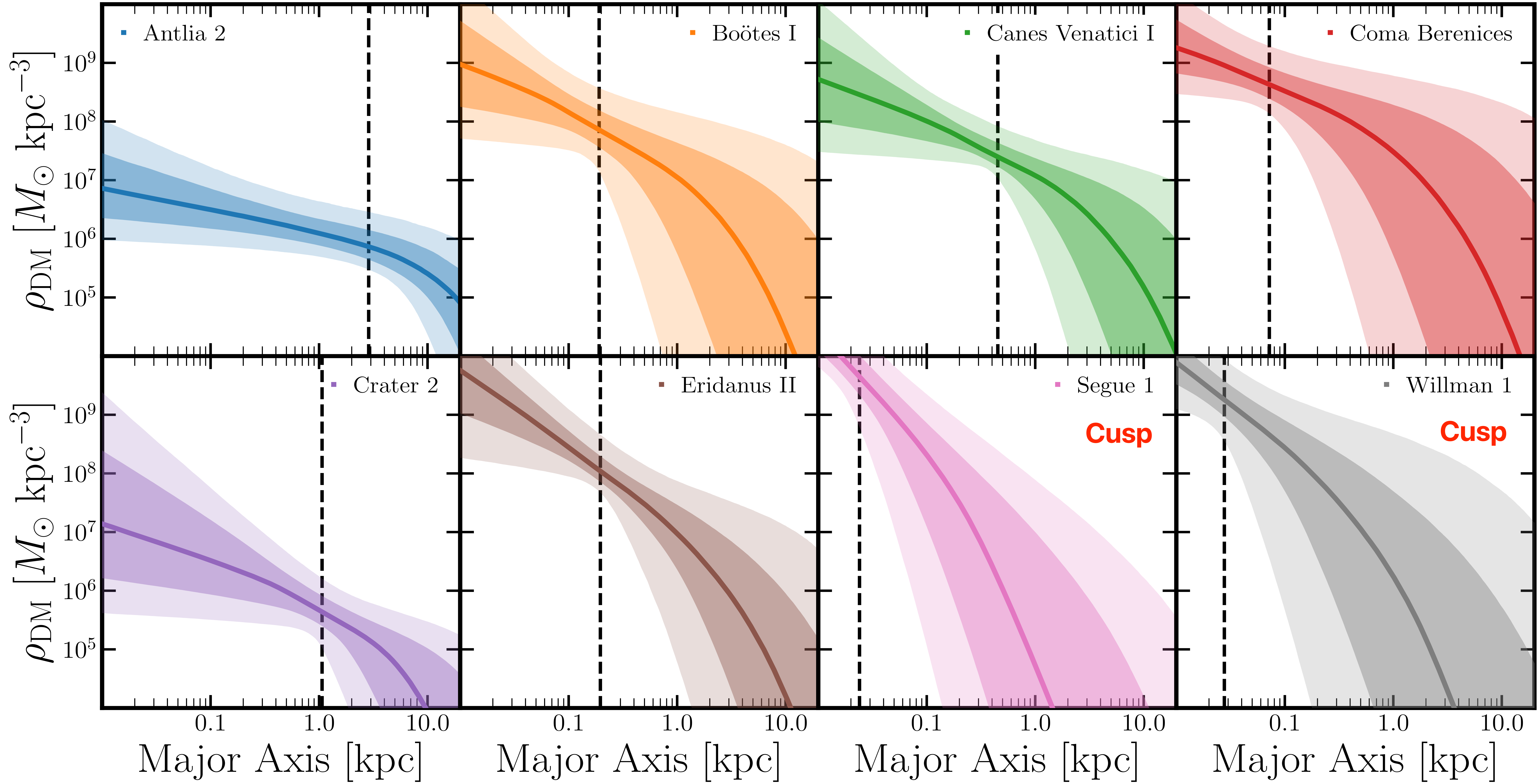
$\gamma = 1$: NFW cusp
$\gamma = 0$: Core

KH, Chiba & Ishiyama (2020)



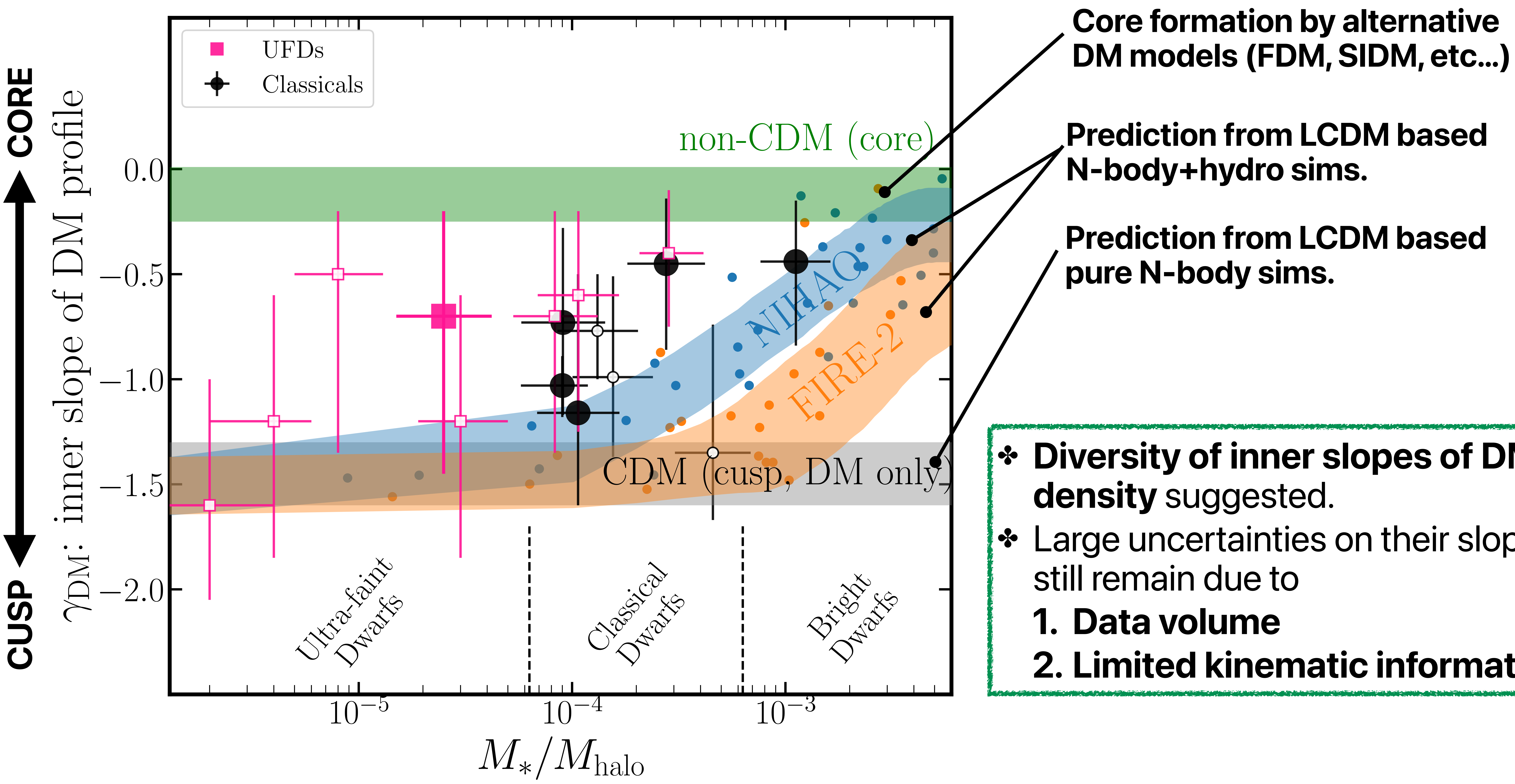
Dark matter density profiles: UFDs & UDGs

KH, Hirai, Chiba & Ishiyama (2023)



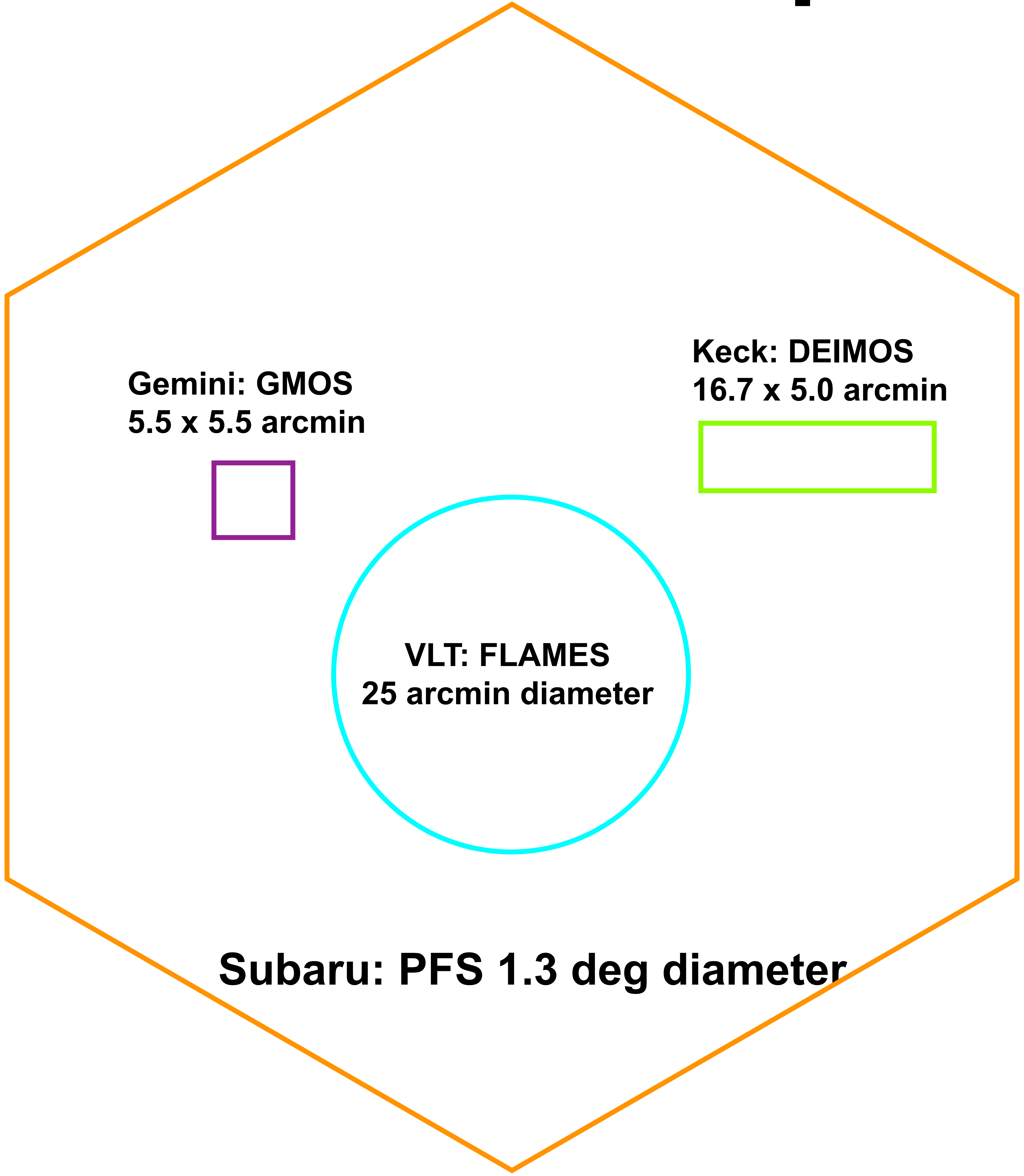
Diversity of the DM distributions?

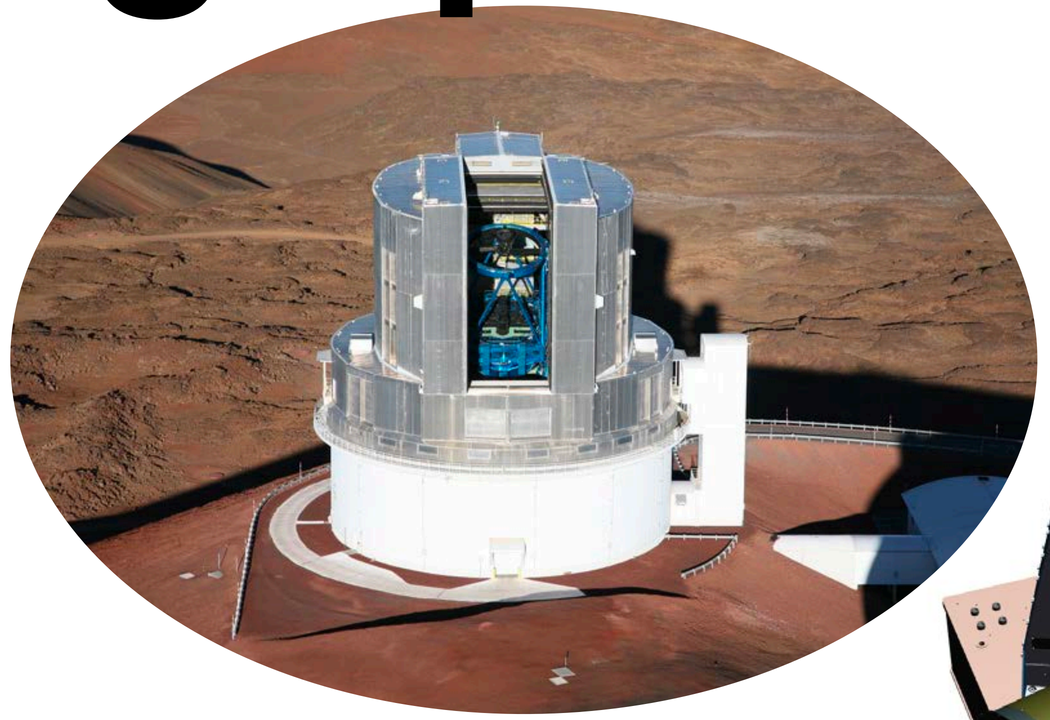
KH, Chiba & Ishiyama (2020)
KH, Hirai, Chiba & Ishiyama (2023)

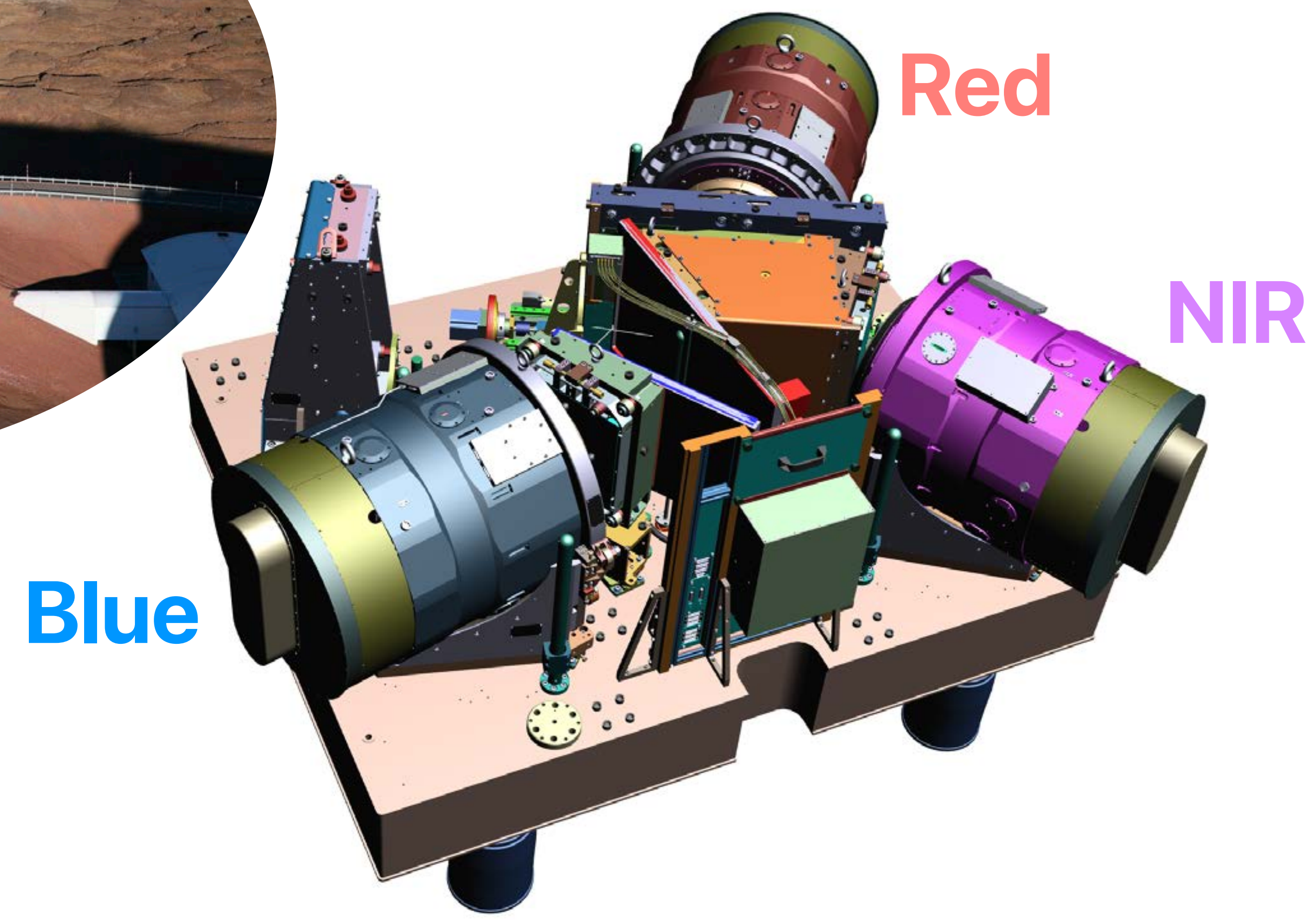


- ✤ **Diversity of inner slopes of DM density** suggested.
- ✤ Large uncertainties on their slopes still remain due to
  1. **Data volume**
  2. **Limited kinematic information**

Subaru-Prime Focus Spectrograph







Subaru Telescope

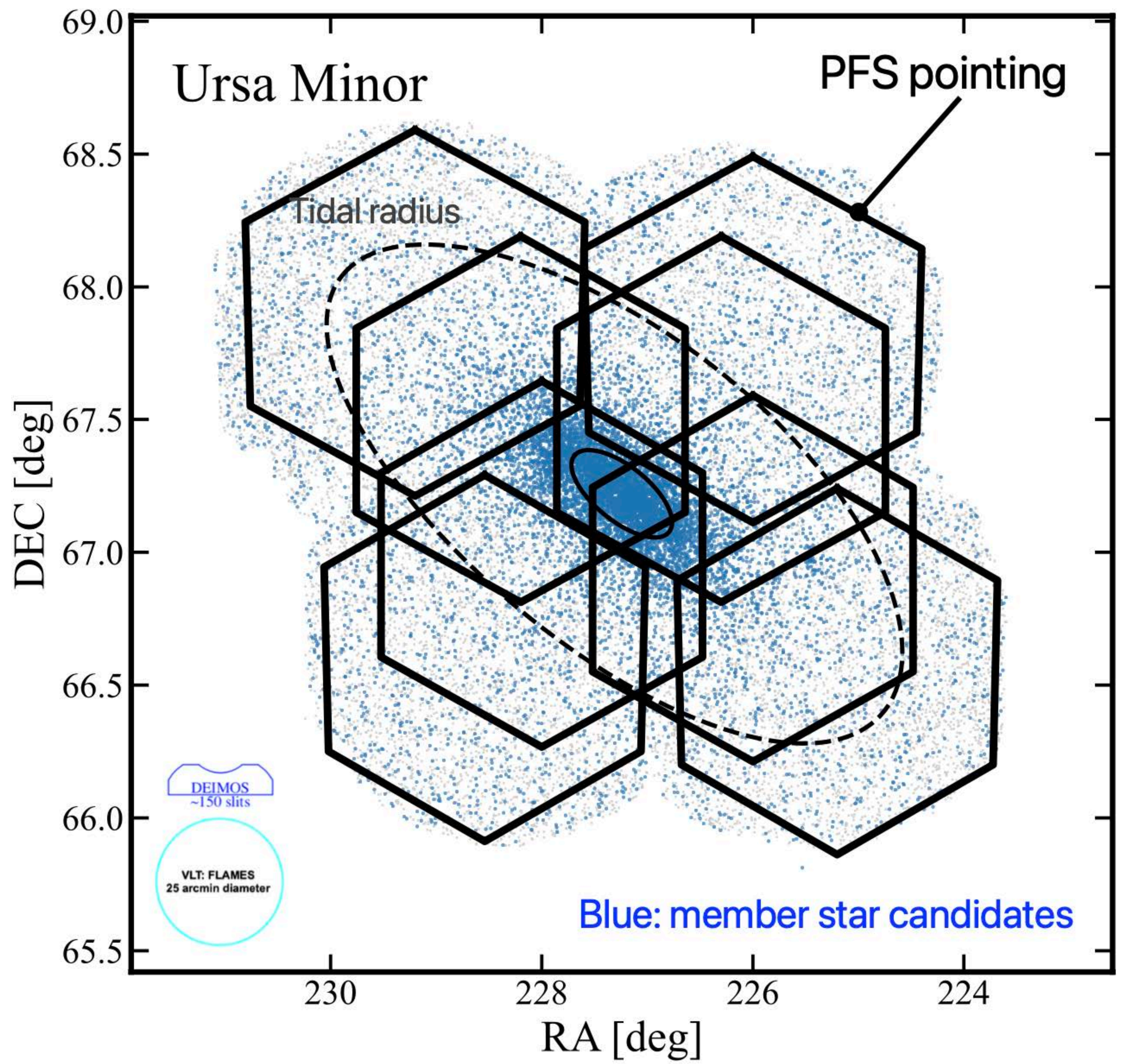
+

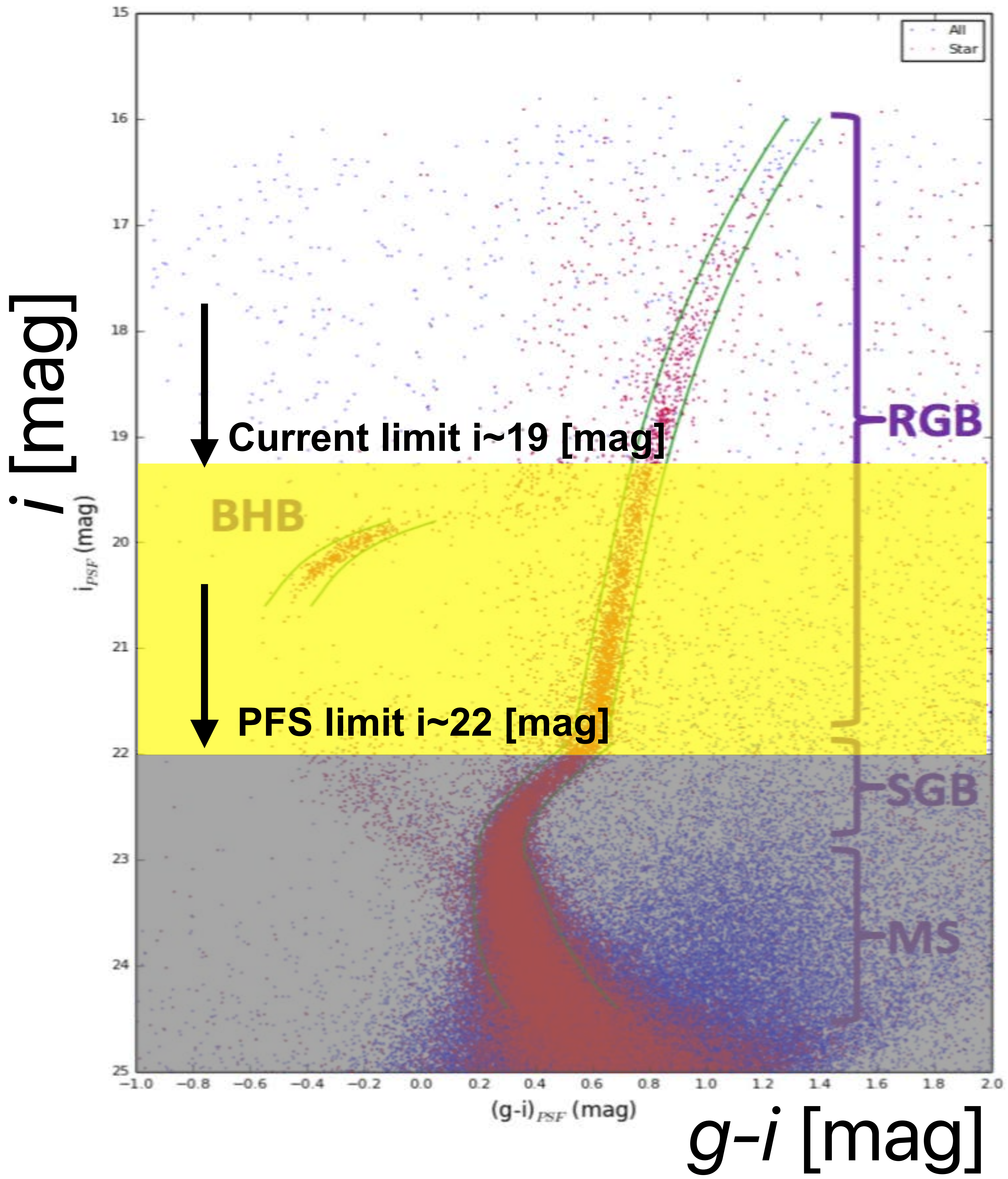
Wide Field of View

||

Wide and Deep spec. survey

Uniqueness of Subaru-PFS





Current $N_{\rm spec.} \sim 300$ ⇨ PFS $N_{\rm spec.} \sim 5000$

Wide & deep PFS survey:

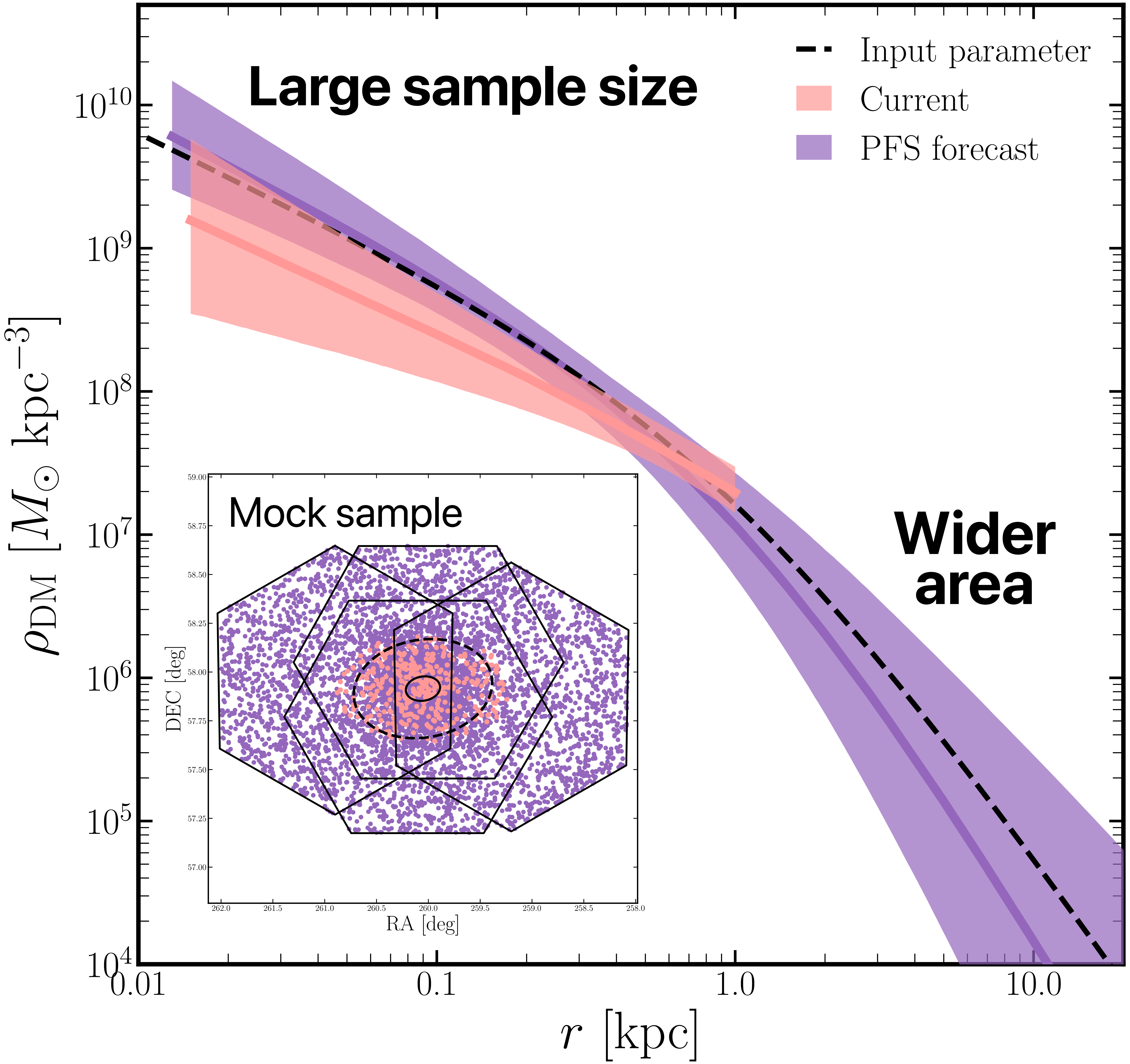
Huge number of line-of-sight velocities of each star out to the outskirts of the Galactic dSphs.

PFS forecast

KH and PFS-GA WG

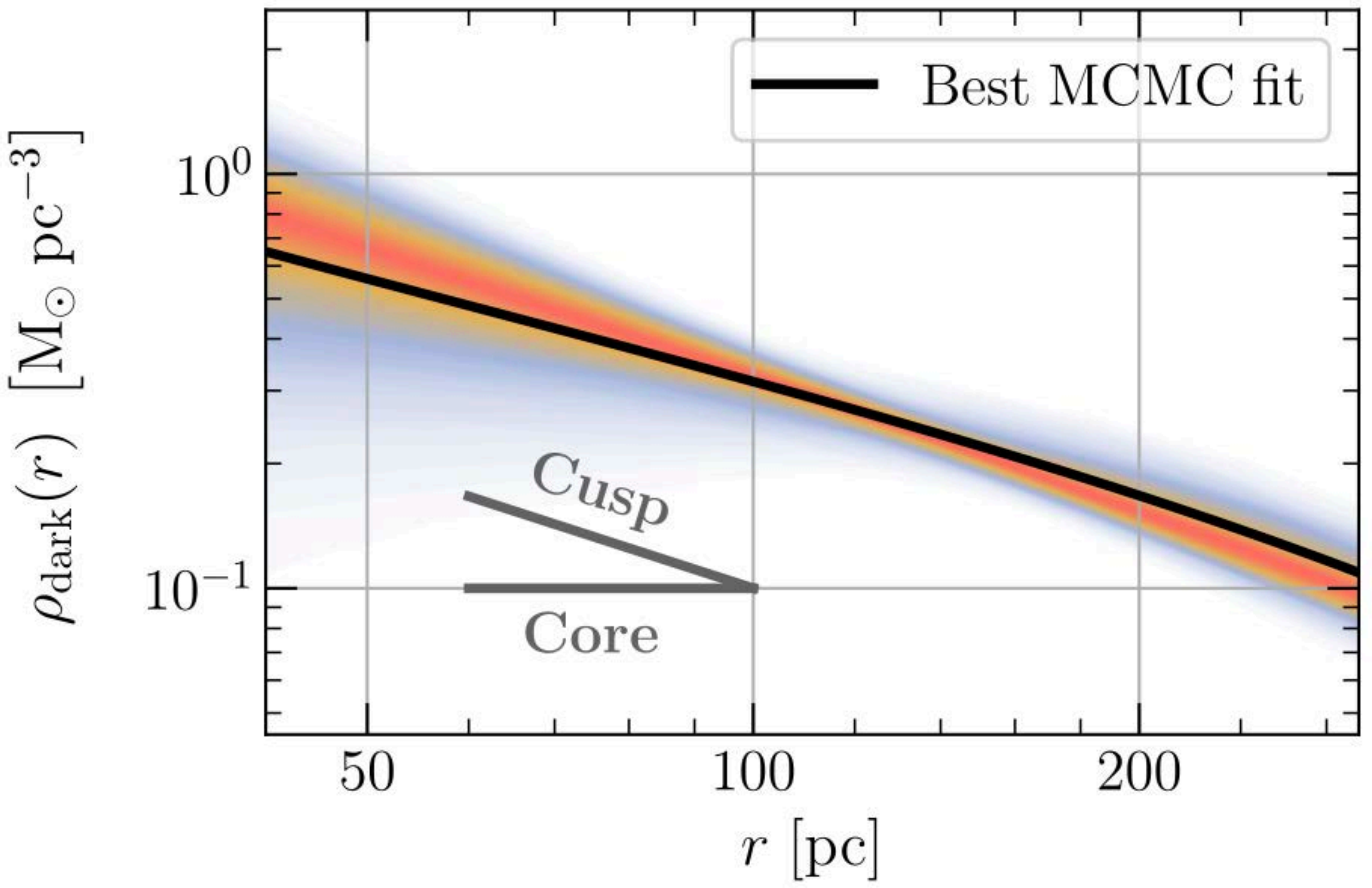
- Estimated mock DM density profiles from *non-spherical Jeans analysis* with current small data (pink) and PFS forecast large data volumes (purple).

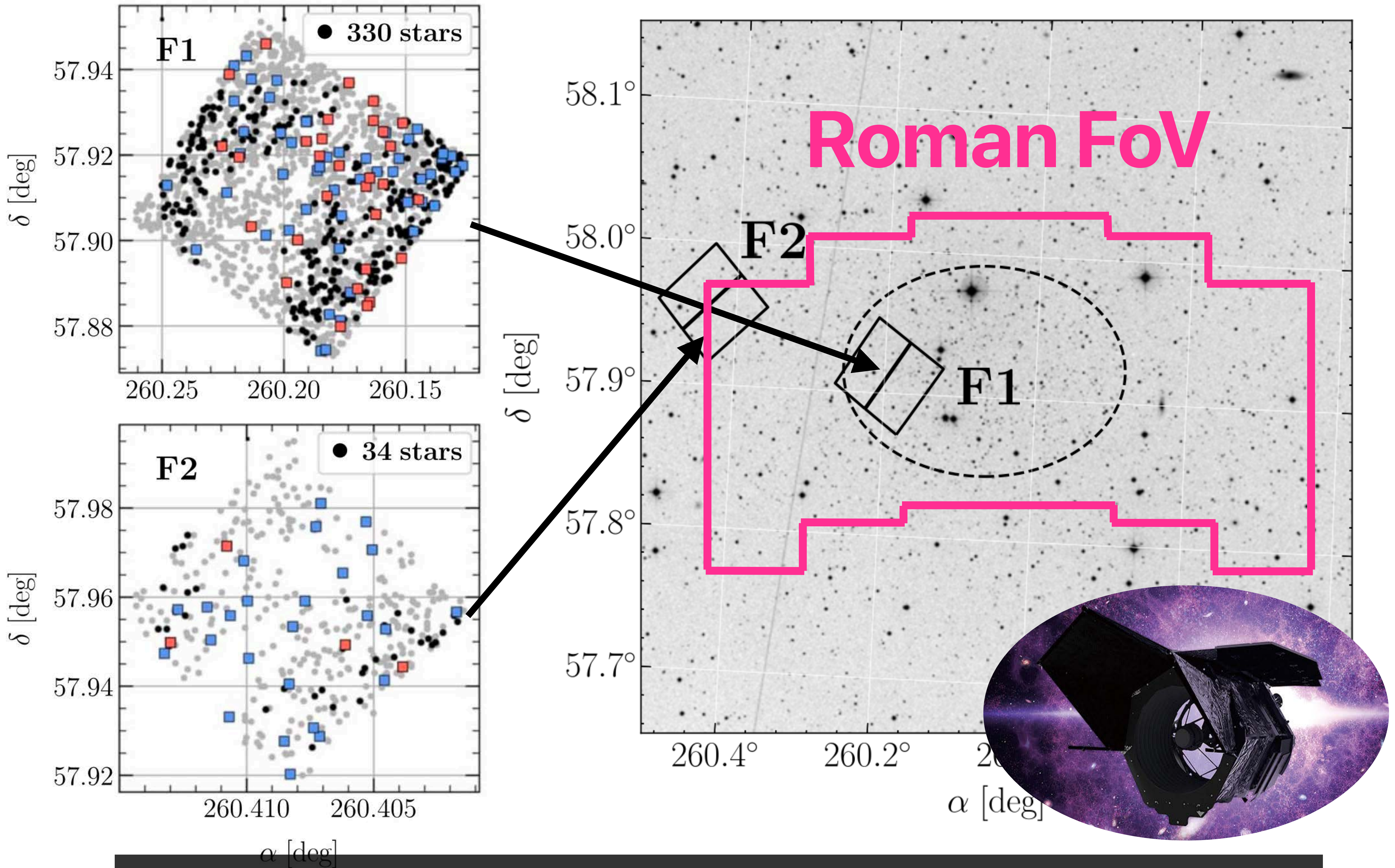
- The **large data volume over wide area by PFS** can recover the input dark matter density profile from the center to outer parts.



Proper motions of the Draco dSph by HST

- Vitral et al. (2024) analyzed four epochs of HST imaging over **18 yrs** for Draco dSph.
- They measured PMs for **364 stars** and combined them with existing line-of-sight velocities to obtain, for the first time, resolved ***3D velocity dispersion profiles***.
- They presented that Draco has a *cuspy* DM profile consistent with the other studies (e.g., KH+2020).

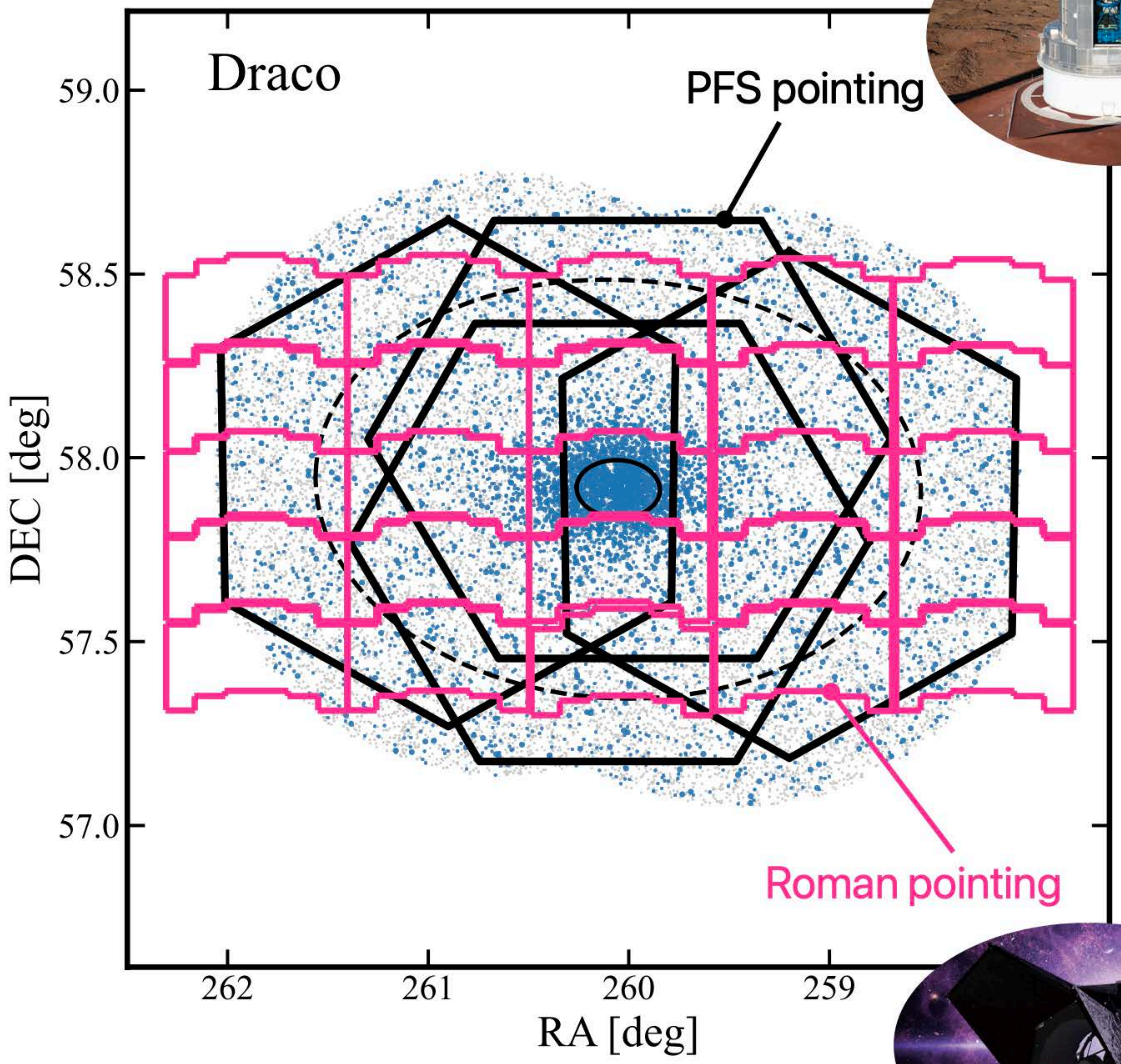


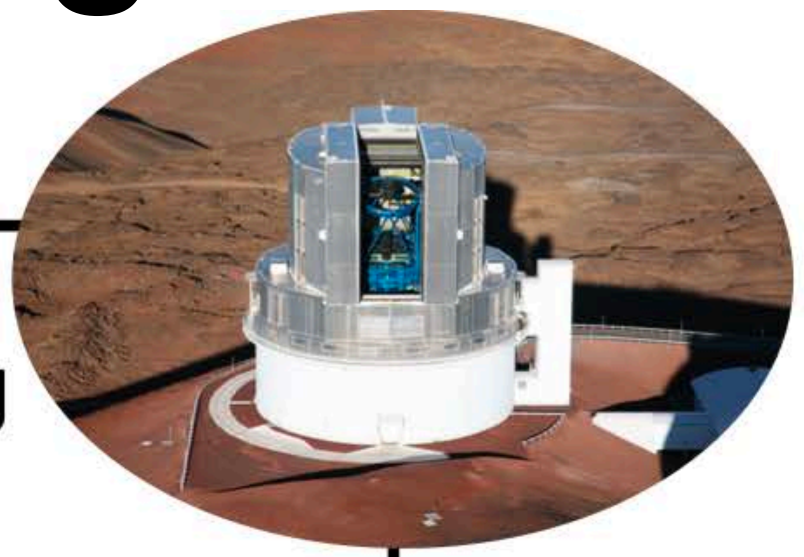


- The number of data is still not statistically sufficient to constrain DM density profile.
- HST pointings are really patchy.
- Roman can cover the central region of Draco dSph!

Synergistic observation between Roman and Subaru-PFS

- Because of its large FoV and high precision photometry of the star, Roman will enable us to measure proper motions of individual stars of the MW dSphs.
- The combination between Roman and Subaru-PFS will get a large number of 3D stellar motions of individual stars in the MW dSphs.
- ***This synergy will provide a new stringent constraint on the DM distributions of the dSphs.***





Take Home Message

- Milky Way and its satellites are promising targets for dark matter direct and indirect searches.
- DM velocity distribution (especially at the high velocity tail) can be affected significantly by LMC's orbital motion.
- **The MW disk can deviate from the dynamical equilibrium**, which is one of the major systematic uncertainties in the estimate of the DM density in the solar neighborhood.
- The central dark matter density in the Milky Way is still completely unknown. The kinematic information toward the center region should be needed.
- **The synergy with Roman and Subaru-PFS** will provide the large number of 3D stellar motions of individual stars in the dSph and it will allow us to place strong constraints on dark matter density profiles.