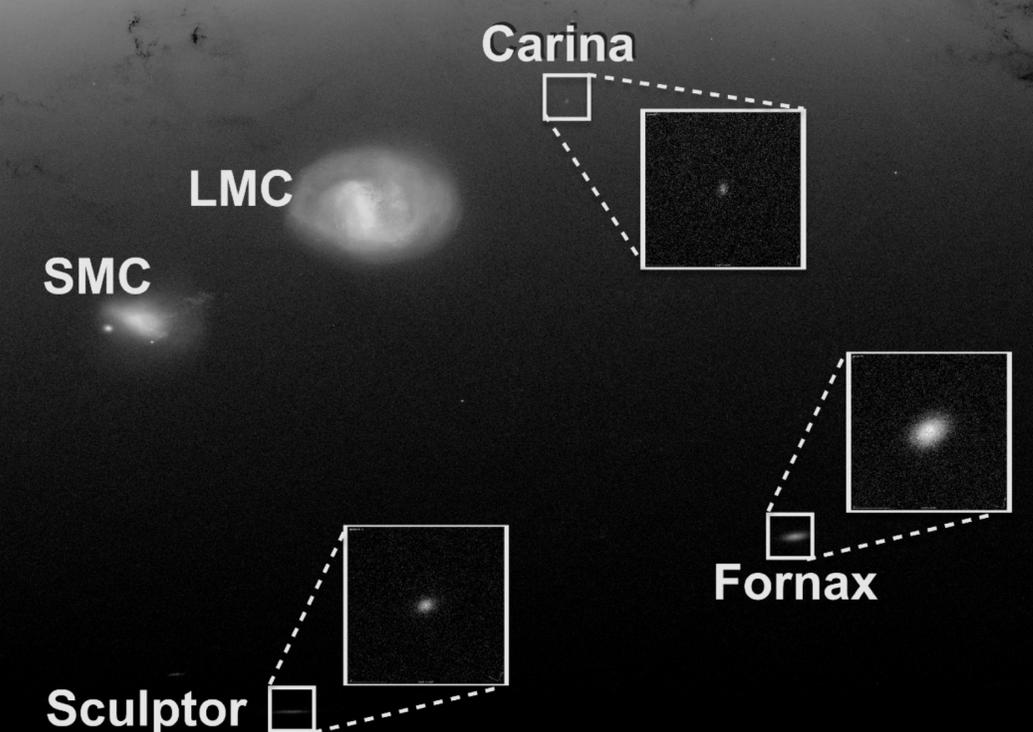
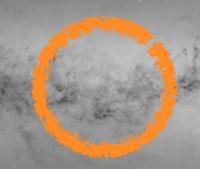
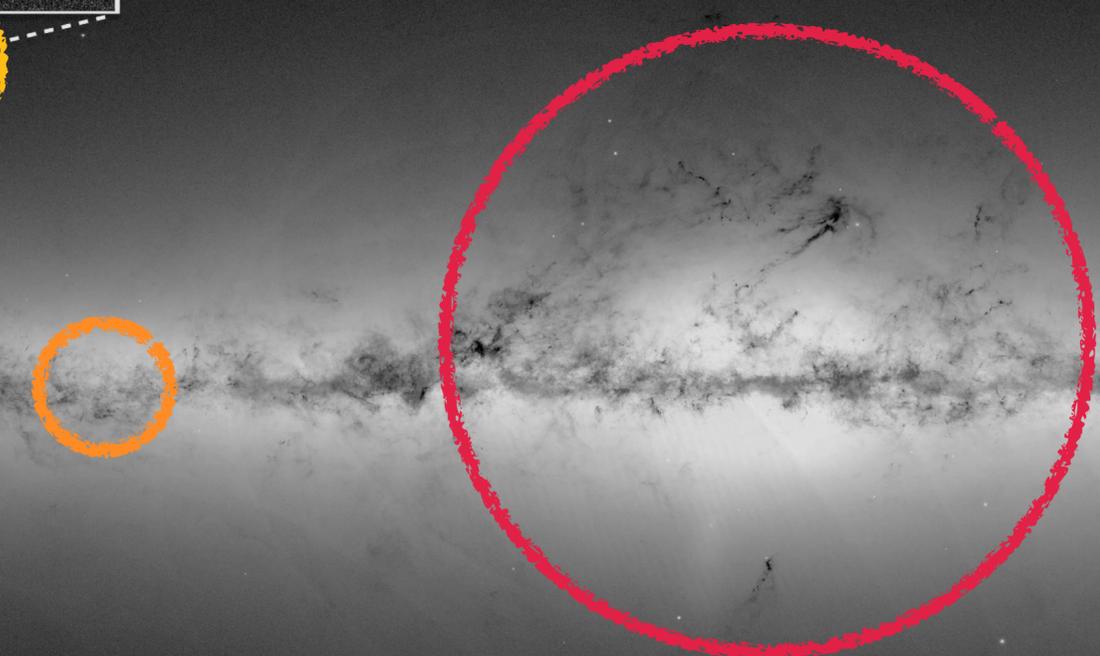
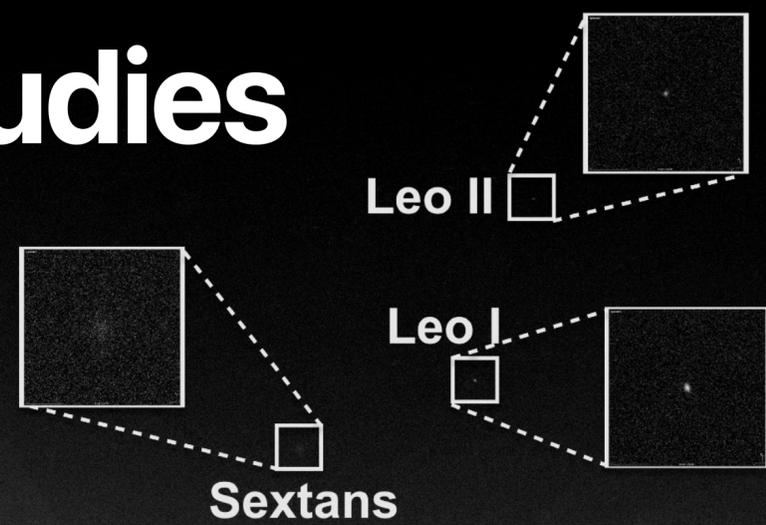
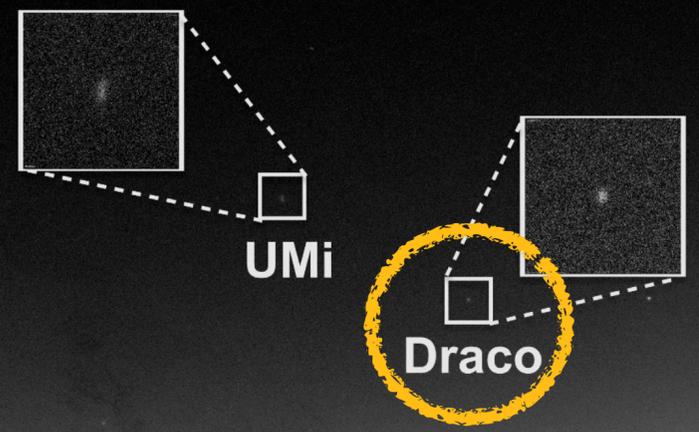


Dark Matter in the Milky Way: From the Galactic Center to the Solar Neighborhood

Kohei Hayashi (NIT, Sendai college)

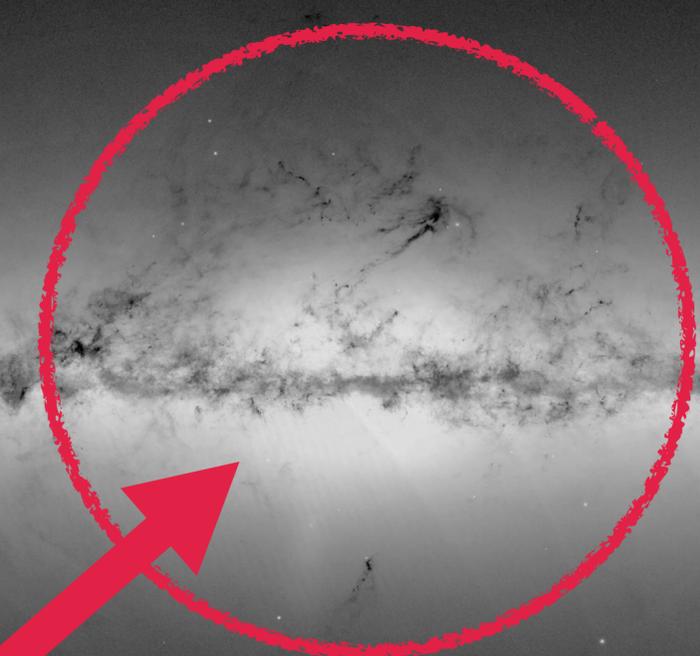
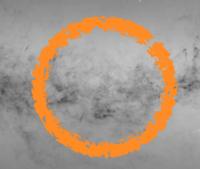
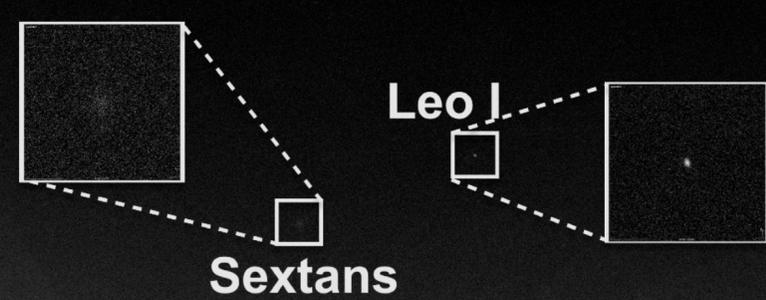
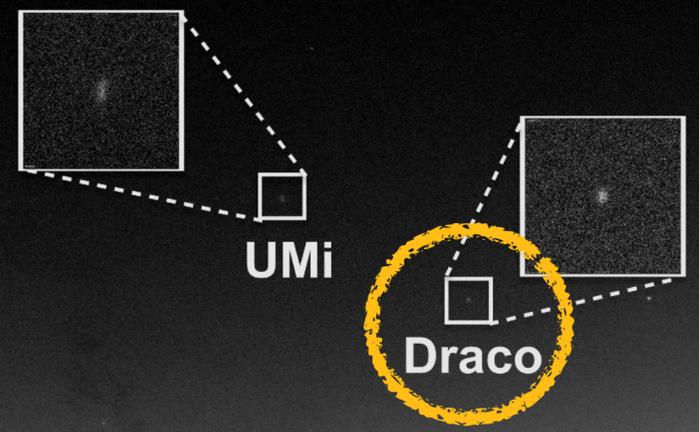
The Milky Way as a unique target of dark matter studies



Target:

- Galactic Center
- Solar Neighborhood
- Dwarf Spheroidals

The Milky Way as a unique target of dark matter studies



LMC

Carina

Sculptor

Target:

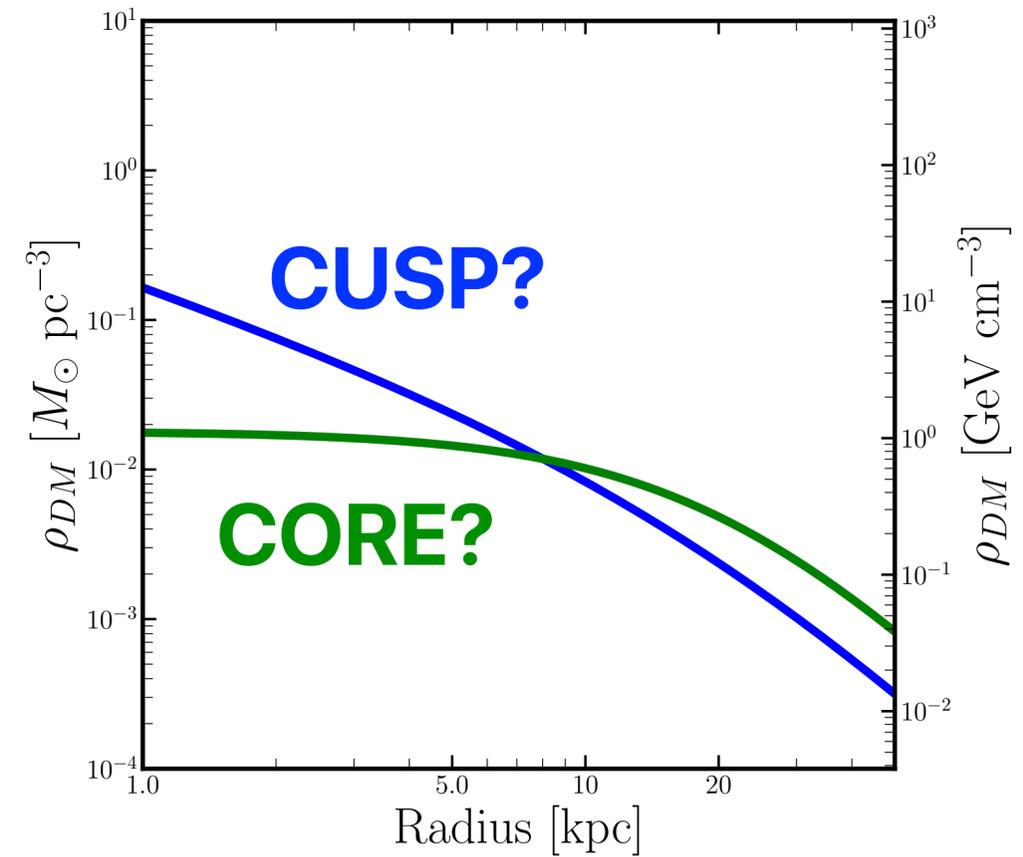
- Galactic Center
- Solar Neighborhood
- Dwarf Spheroidals

DM density at
the Galactic Center

Dark matter distribution at the Galactic center

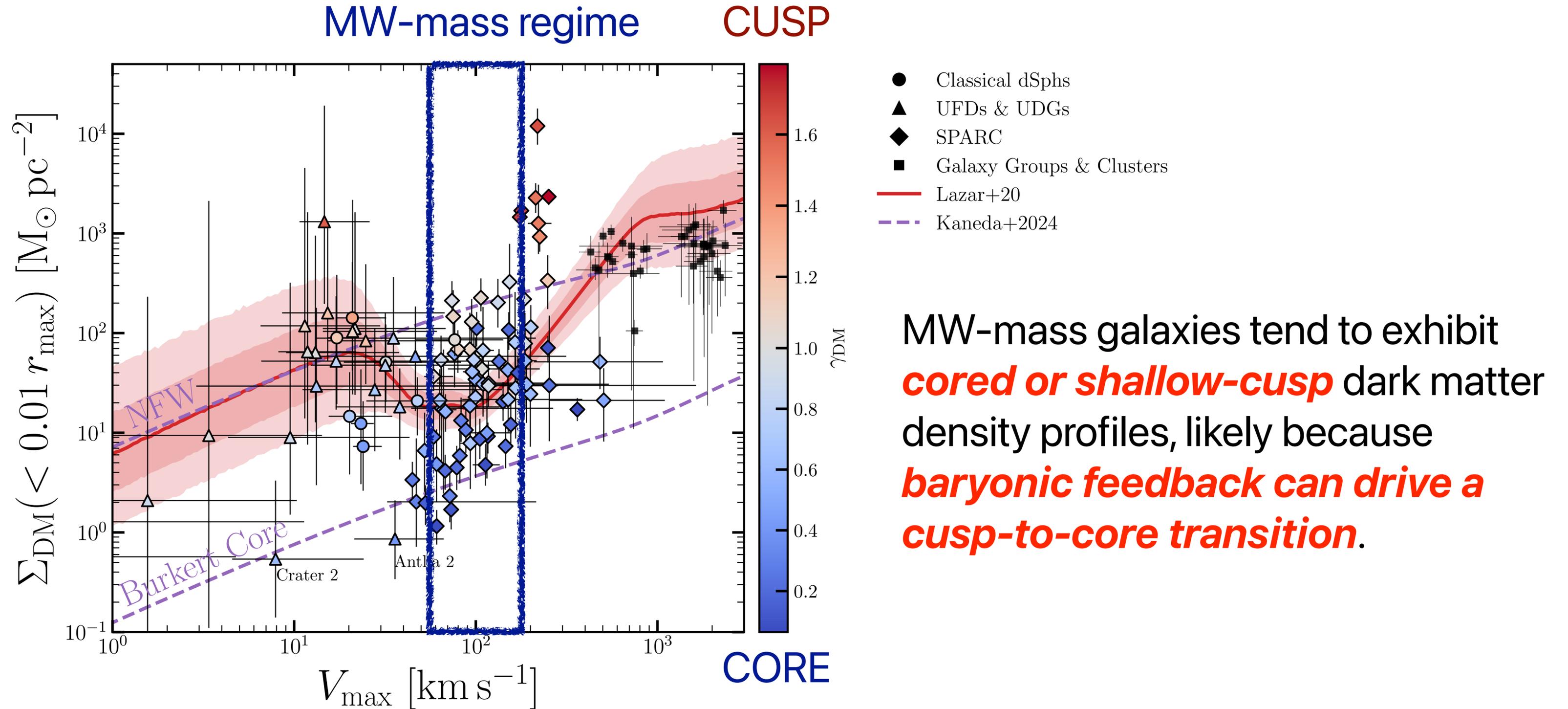
KEY QUESTION:

Does the Milky Way have a cusp or core?



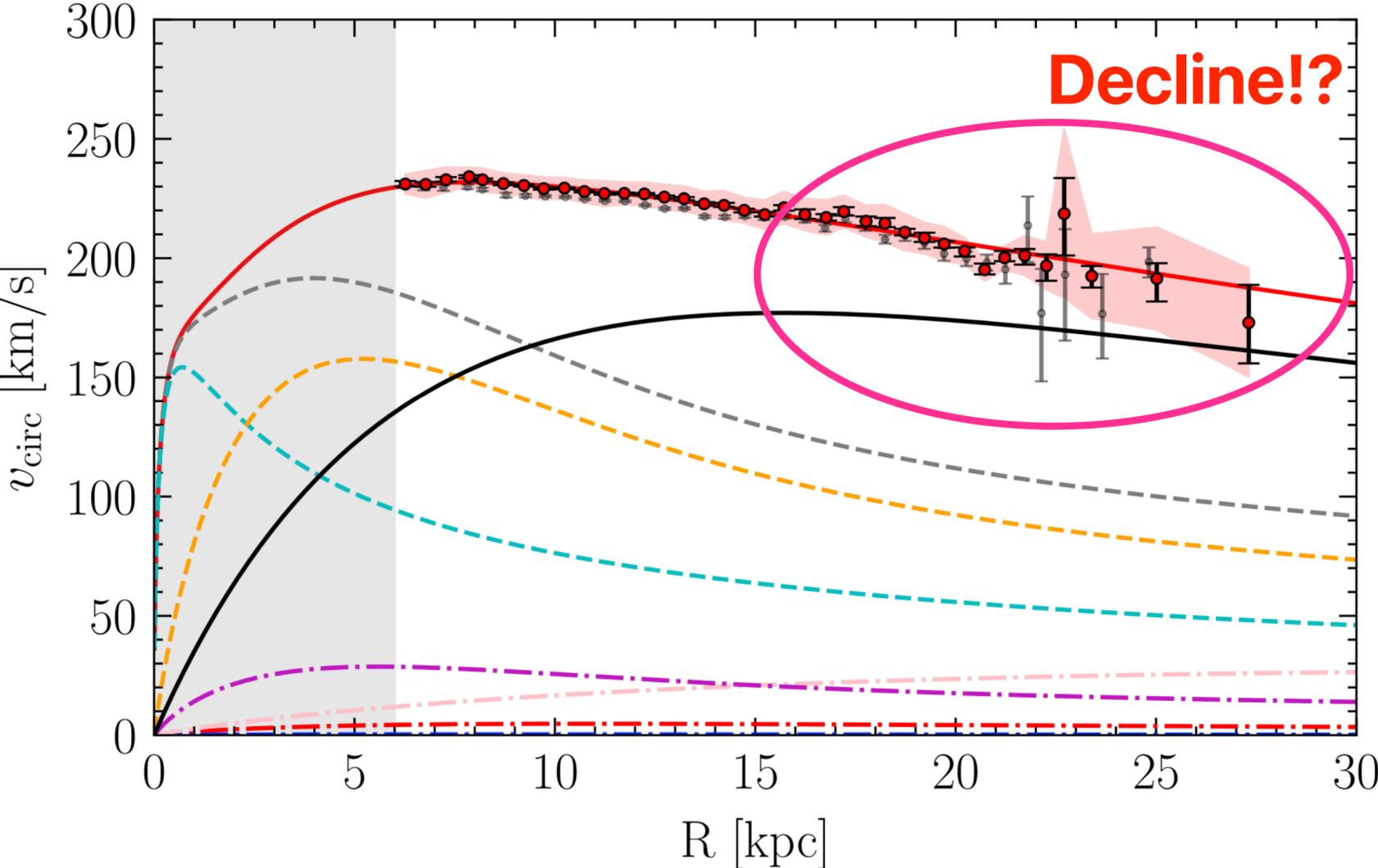
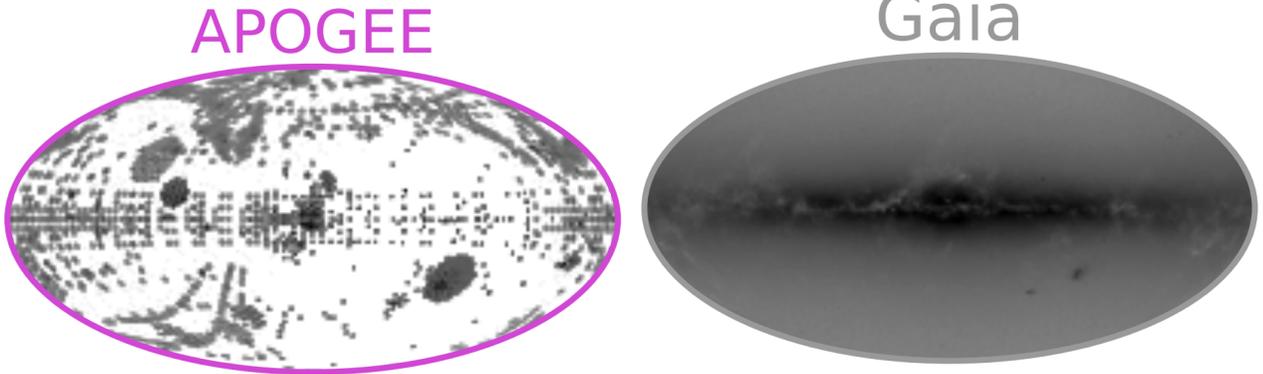
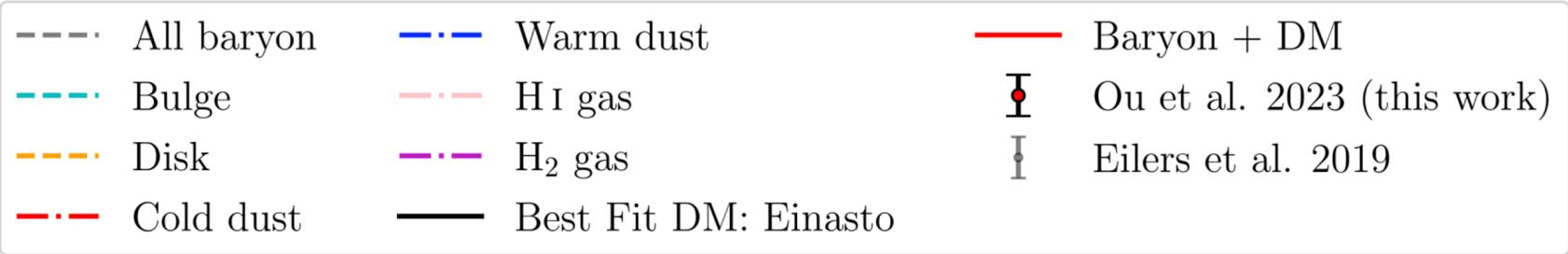
Hints from MW-like Galaxies on the MW's Inner DM Profile

Inner DM Densities of MW-Mass Galaxies from Rotation Curves (KH+2026 in press, 2507.22155)



Dark matter density from the rotation curve

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



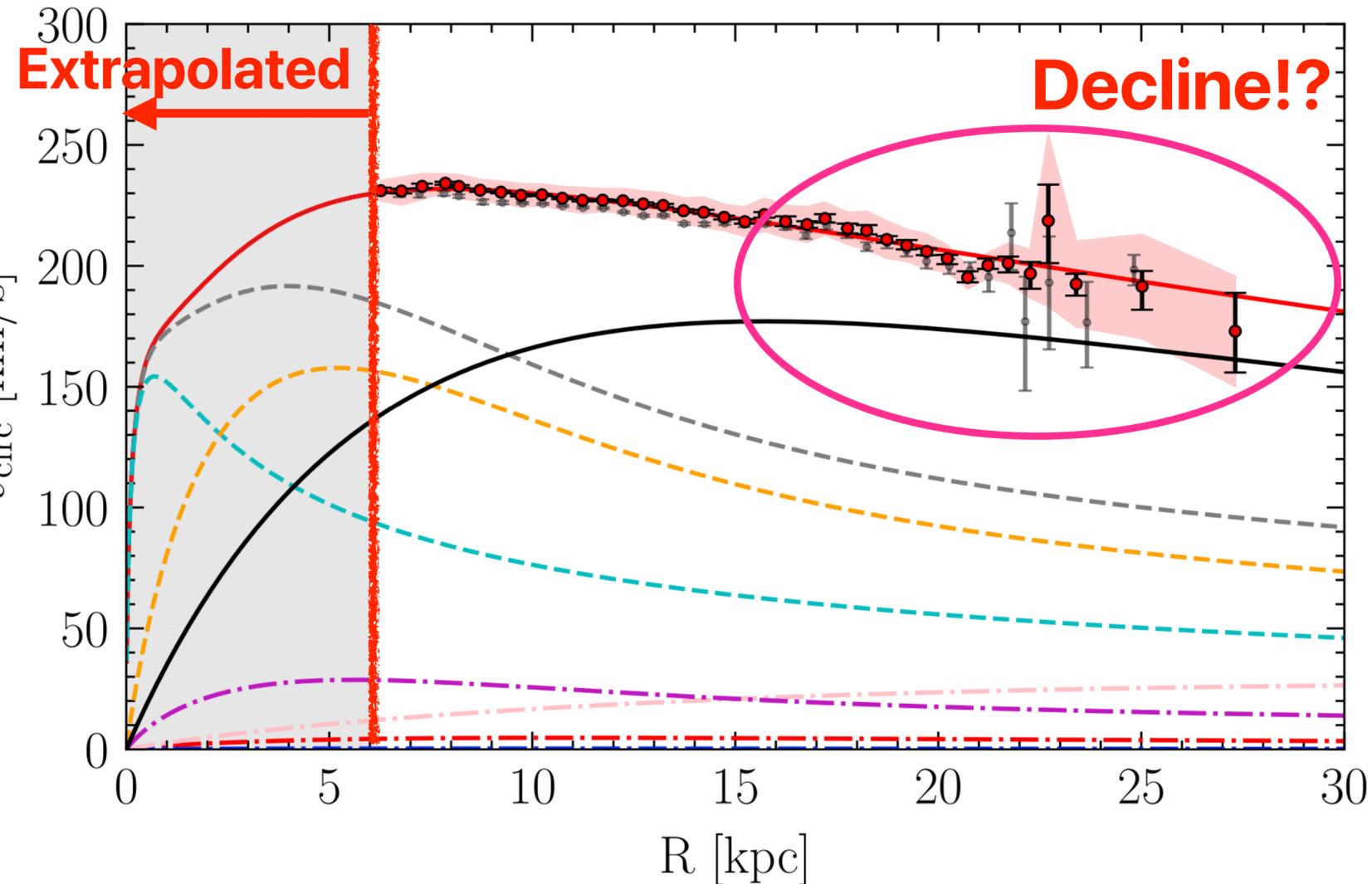
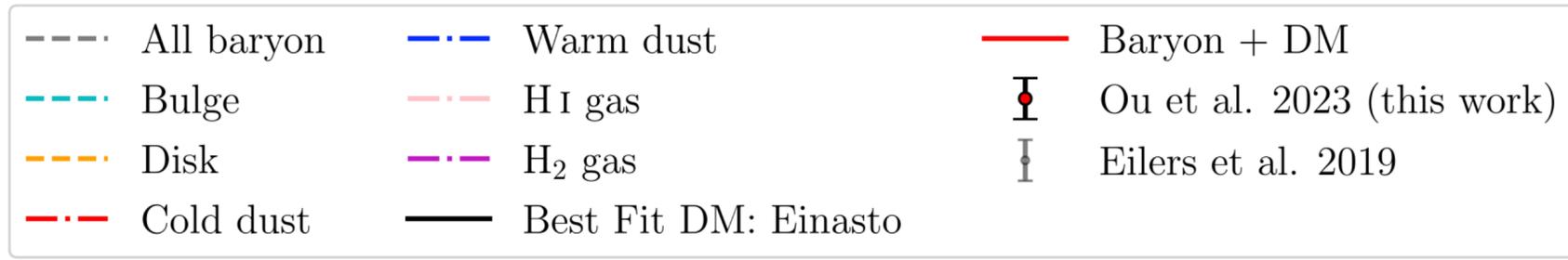
- ❖ **Cored Einasto profile**, can explain the decline beyond 10 kpc.
- ❖ This result is in tension with other dynamical studies, which favor cuspy inner profiles (e.g., Hattori+2021).
- ❖ The decline feature is still under debate.

Dark matter density from the rotation curve

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

APOGEE

Gaia

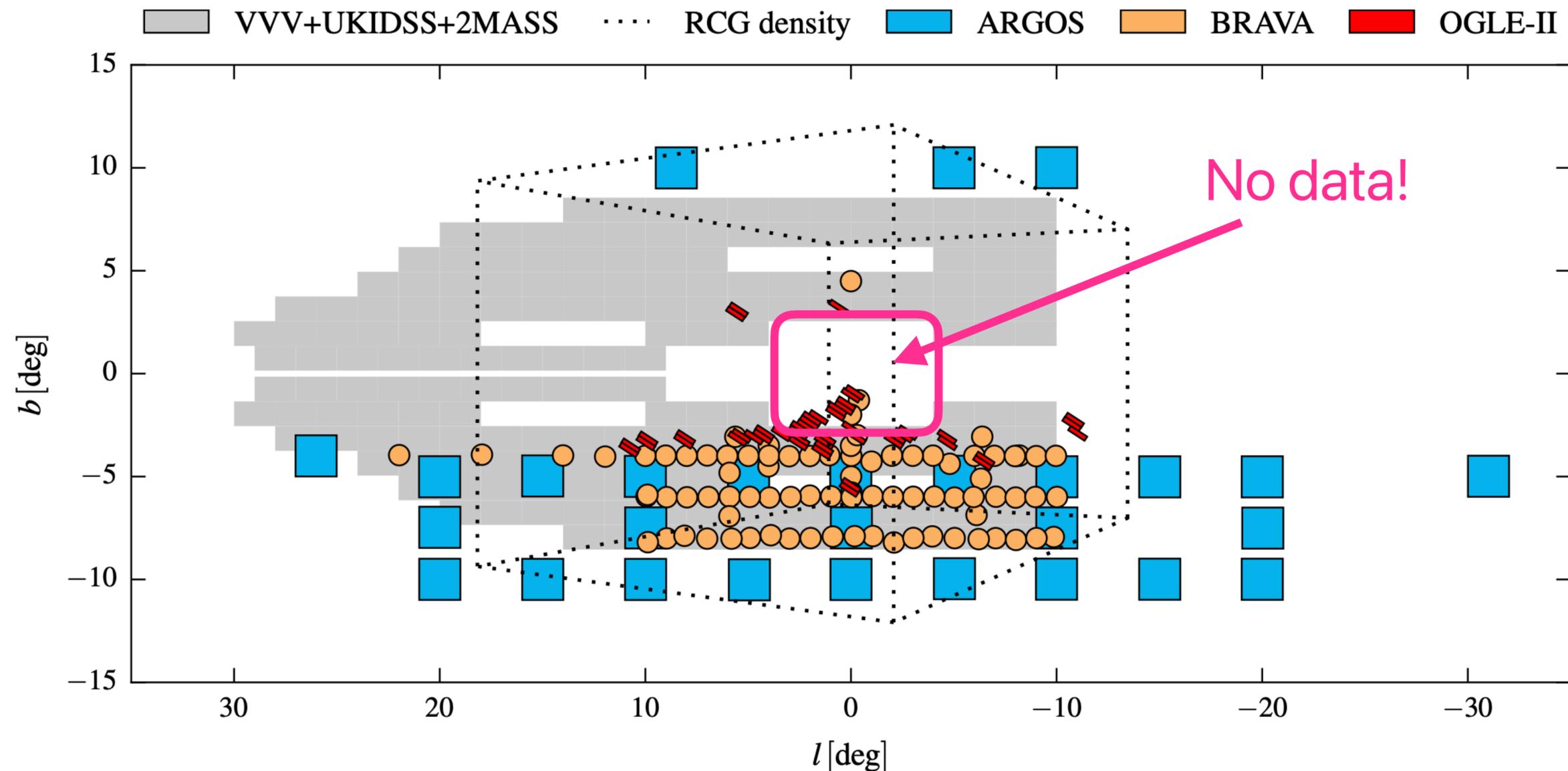


- Such dynamical analyses depend strongly on the type of data used (disk or halo stars? stars, gas, or ISM?) and on the dynamical models adopted.
- Gaia, the optical astrometry satellite, **cannot** obtain the astrometry data toward the Galactic center due to the dense interstellar dust.

Dark matter density from the inner kinematics

Portail et al. (2017)

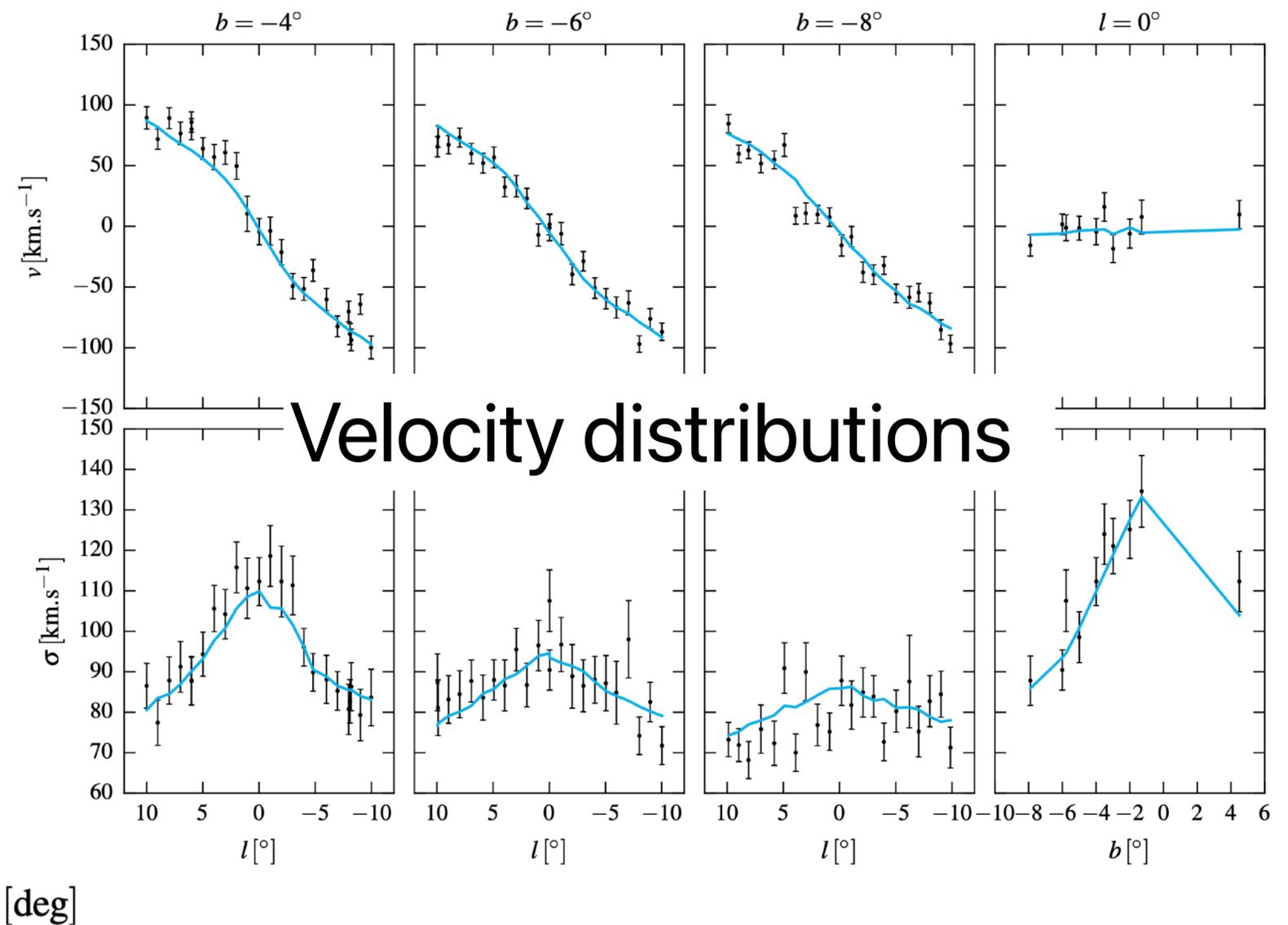
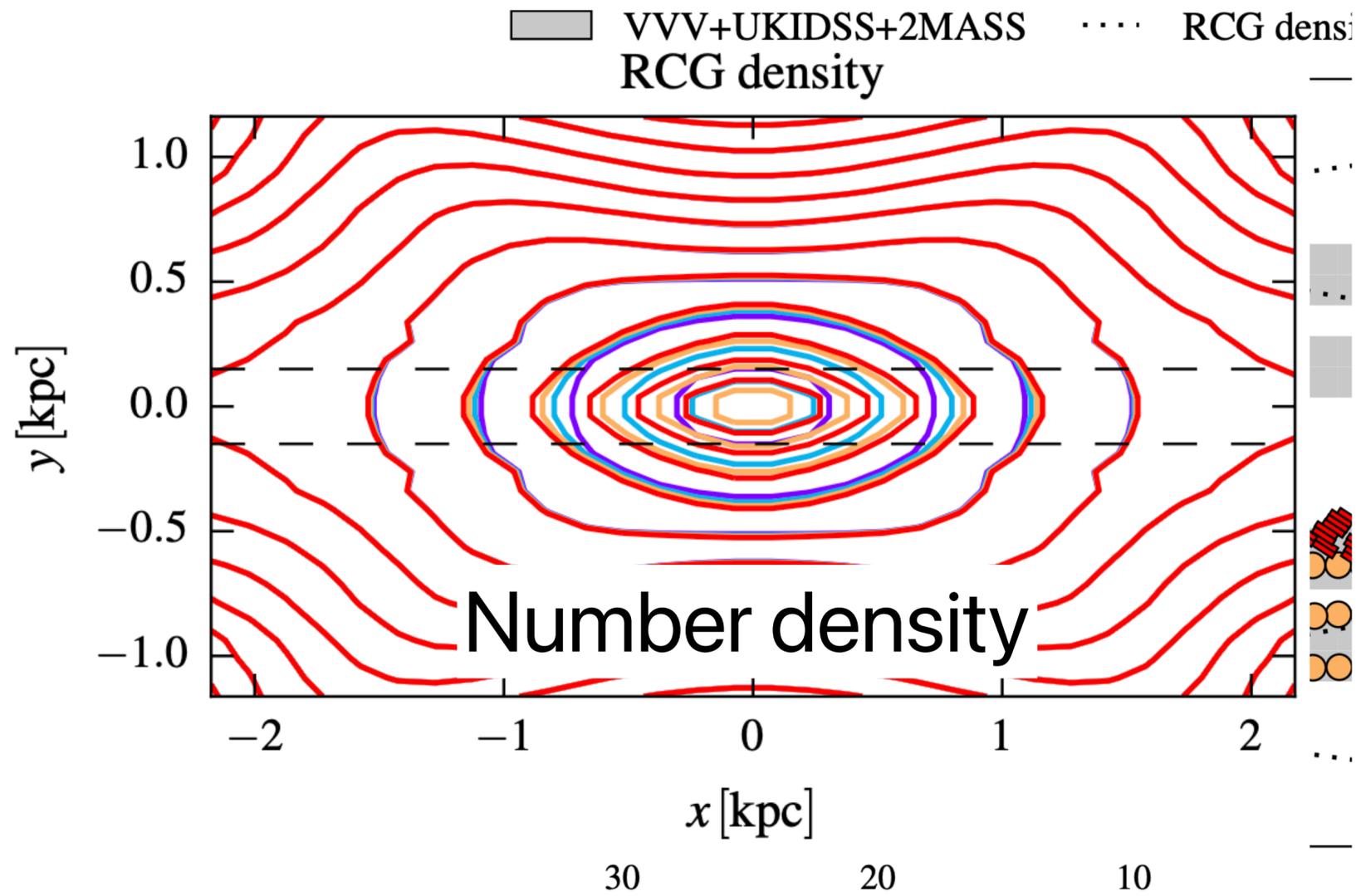
- Red clump giant star density (VVV, UKIDSS and 2MASS): ~10 million stars
- Stellar kinematics in the bulge (the BRAVA and OGLE surveys): ~10,000 and 500,000 stars
- Stellar kinematics in the bar (ARGOS survey): 30,000 stars



Dark matter density from the inner kinematics

Portail et al. (2017)

- Red clump giant star density (VVV, UKIDSS and 2MASS): ~10 million stars
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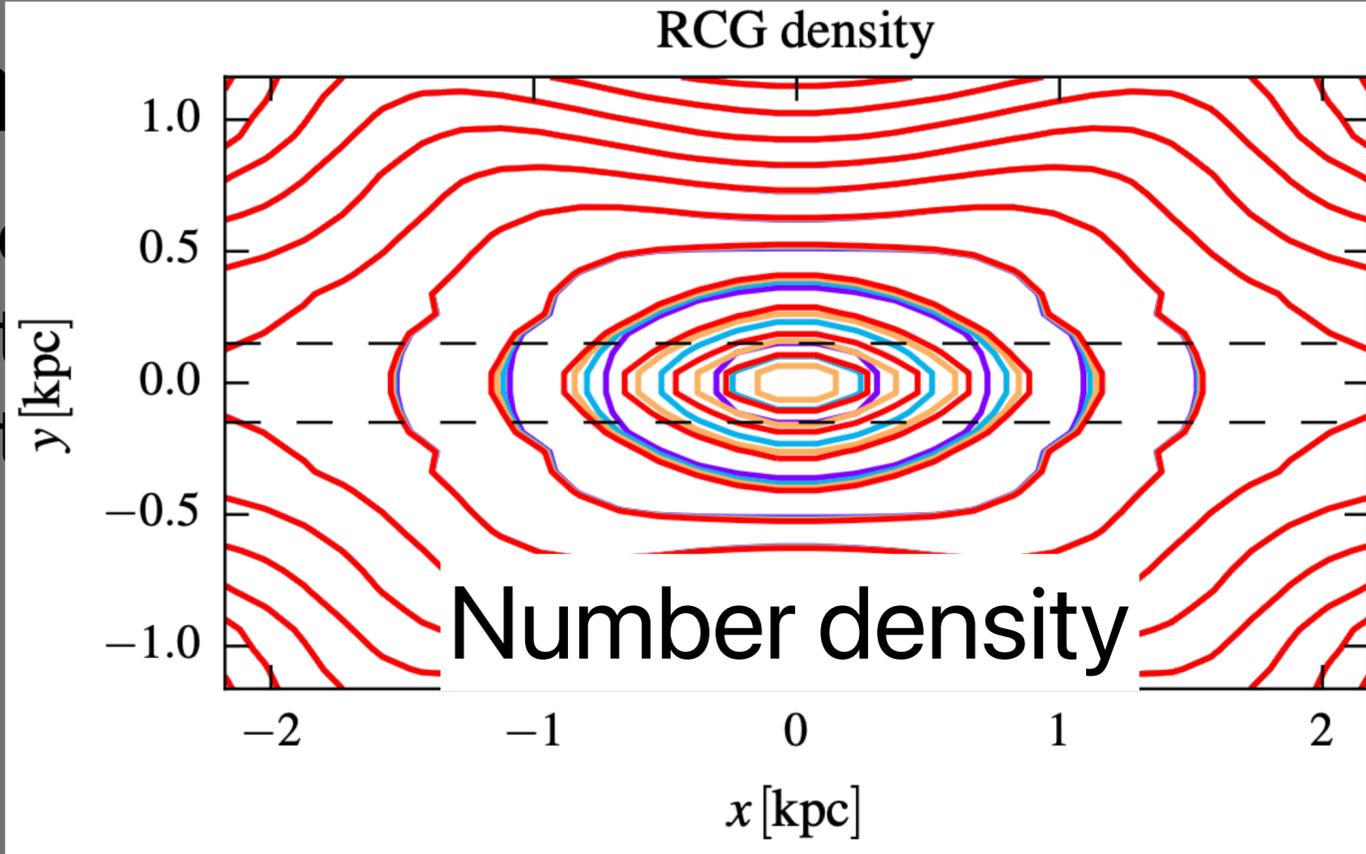


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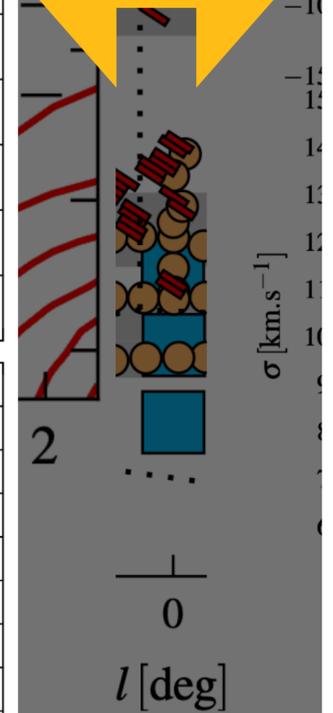
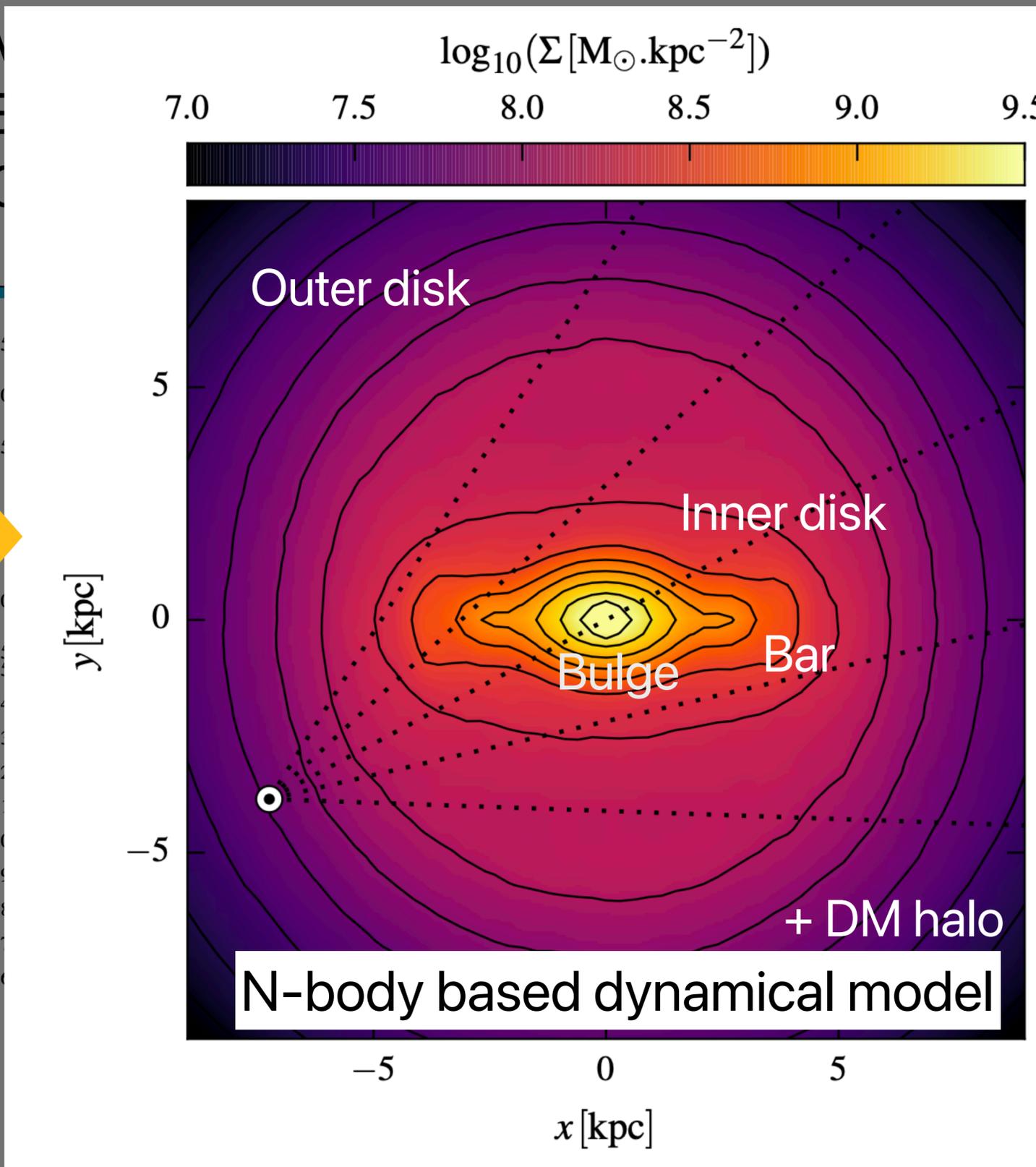
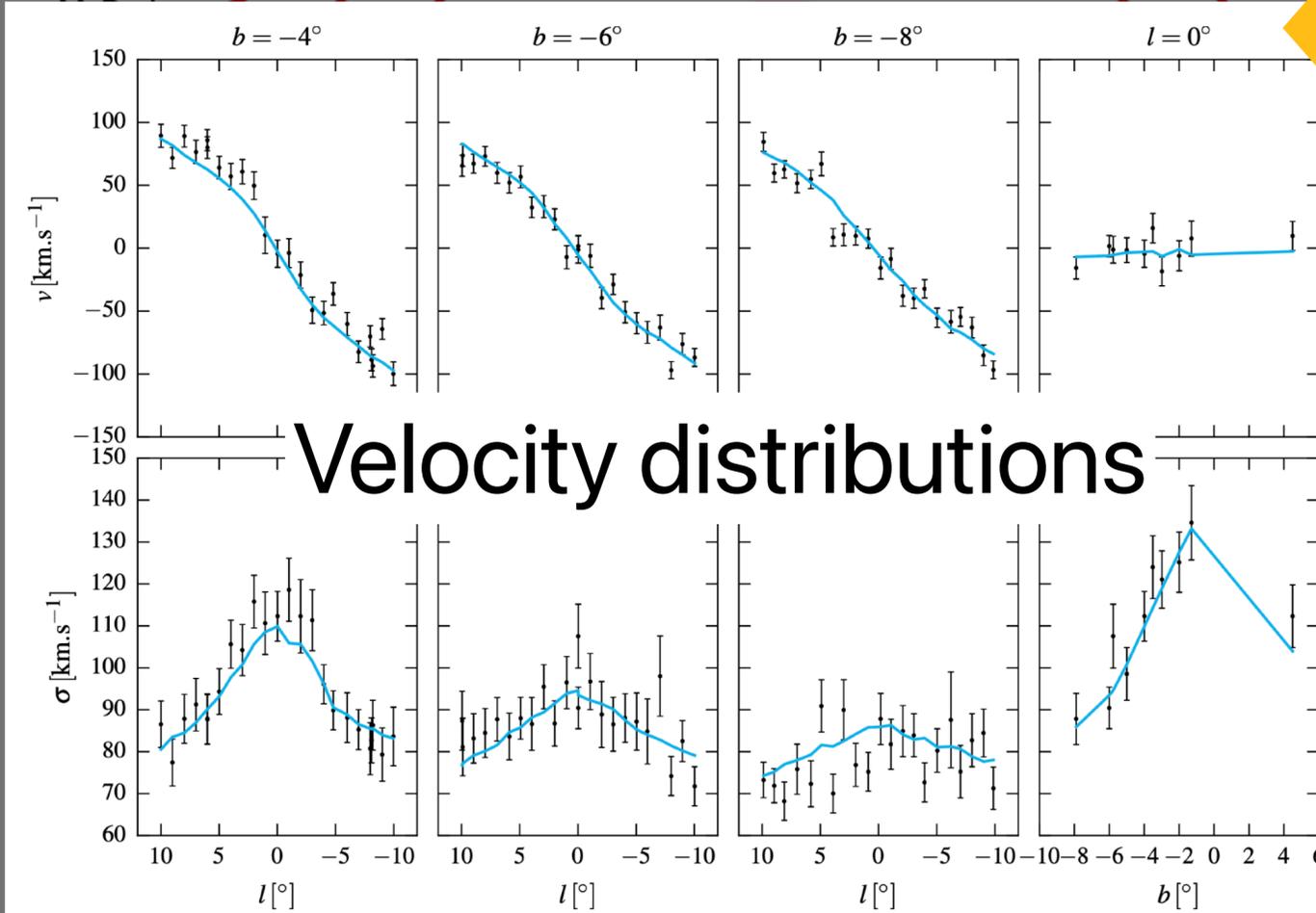
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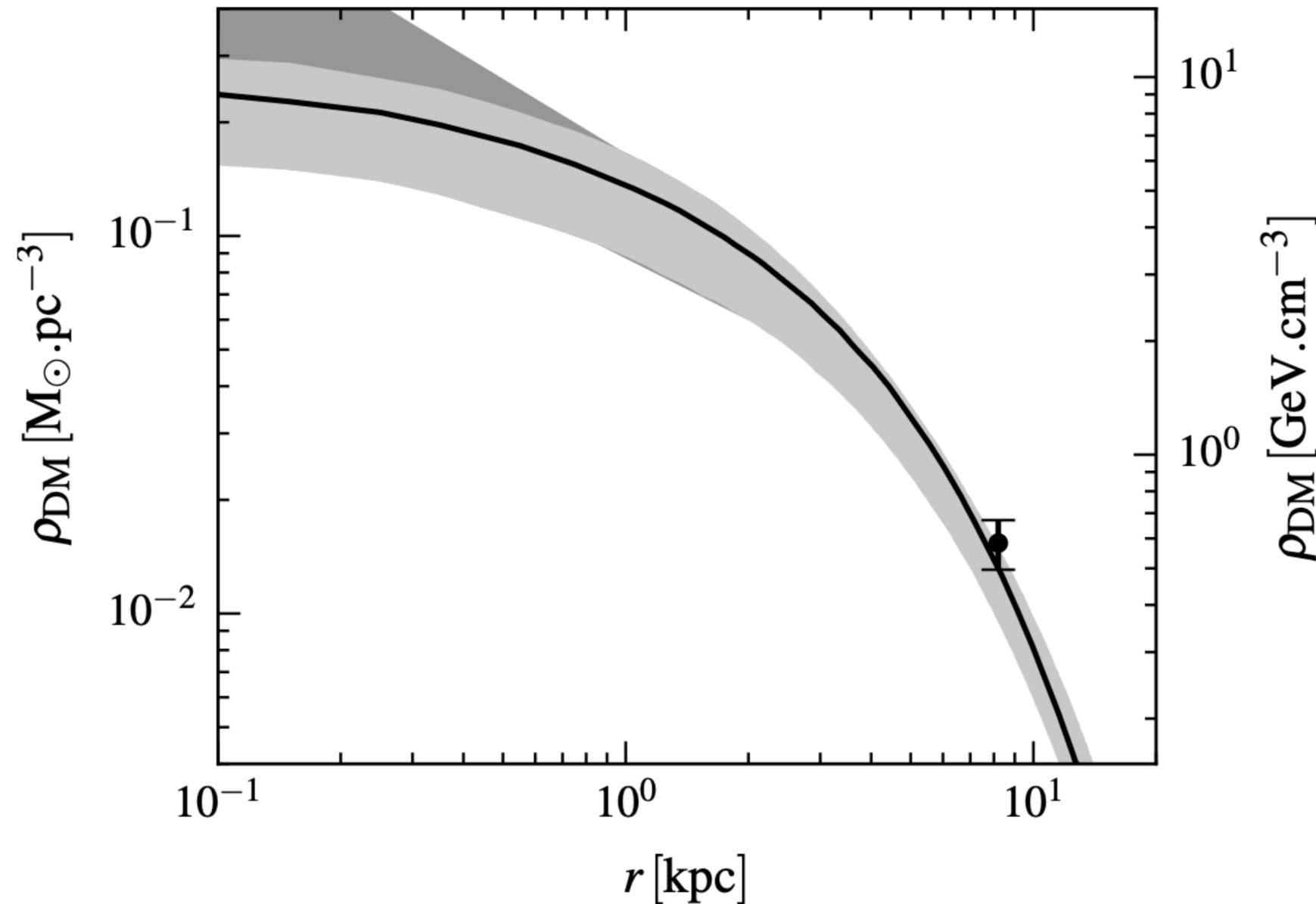
The inner kinematics

Portail et al. (2017)



Compare



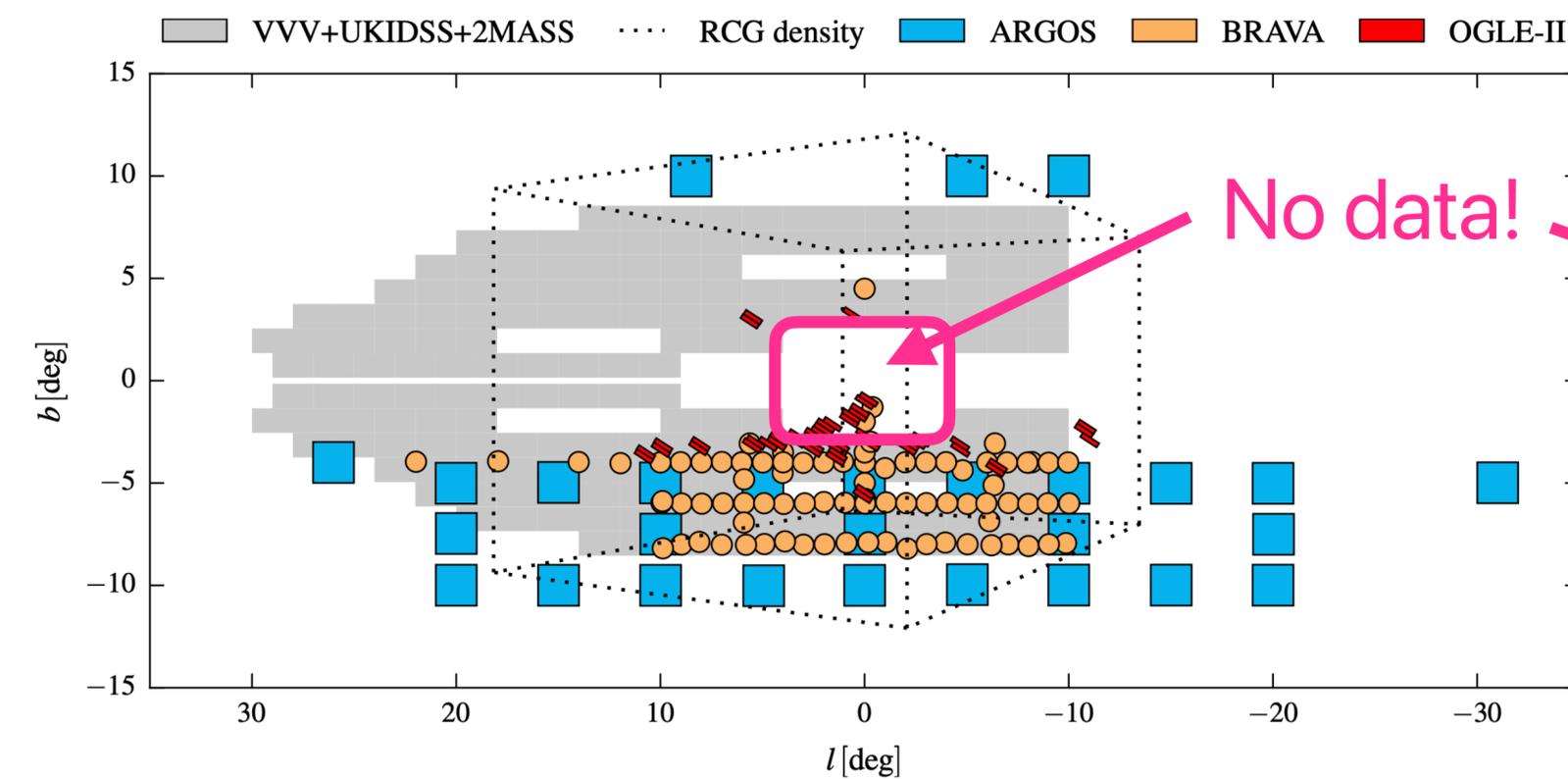


A cored or shallow-cusp dark matter profile may be favored, but significant uncertainties remain.

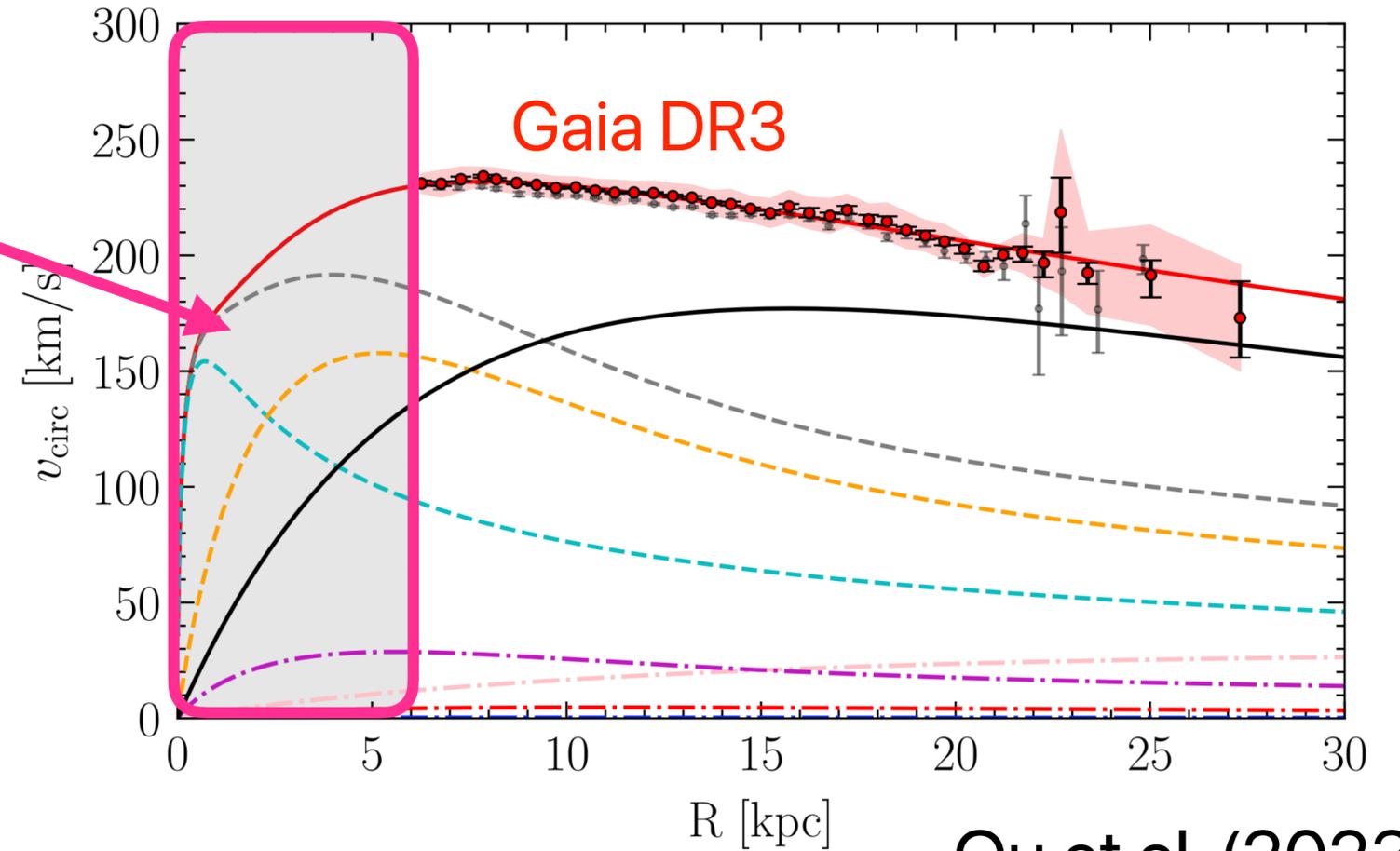
Main issues:

- The inner Milky Way is structurally complex, including the bulge, bar, and disks.
- Observational data in the central region of the Milky Way are still limited.

Current status and Future prospect of the inner stellar kinematics



Portail et al. (2017)



Ou et al. (2023)

- ▶ There is no kinematic data at the center of MW so far.
- ▶ Gaia, the optical astrometry satellite, **cannot** obtain the astrometry data toward the Galactic center due to the dense interstellar dust.

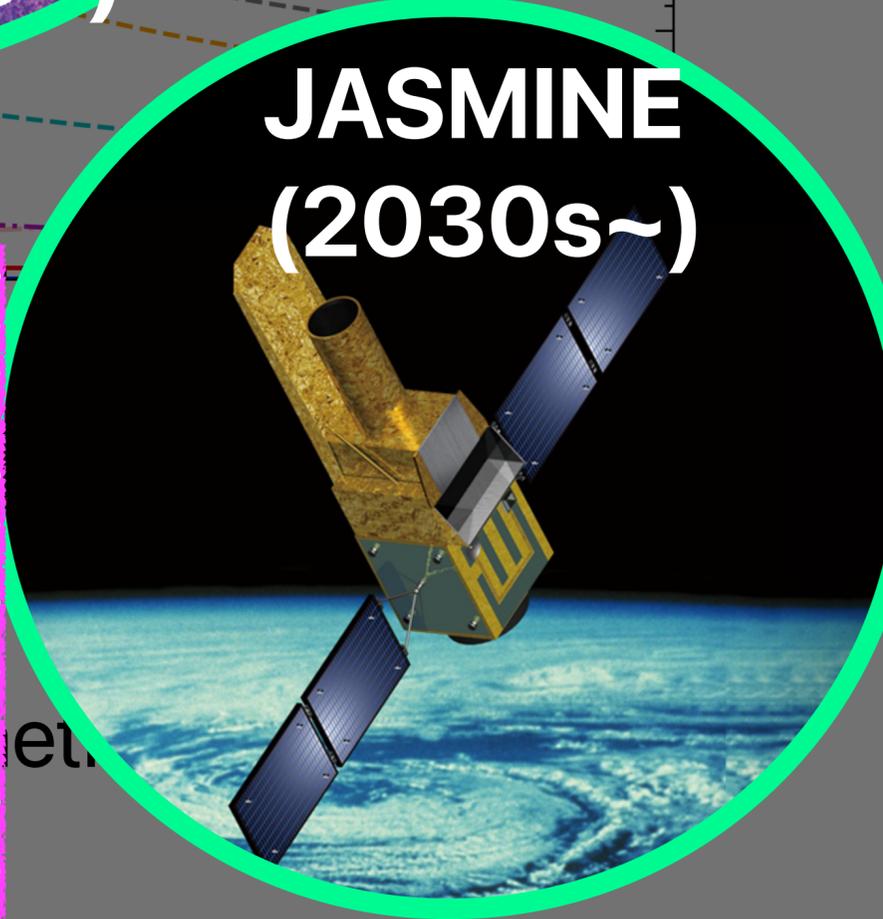
Current status and Future prospect of the inner stellar kinematics



Subaru/PFS (2025~)



Roman (2026~)



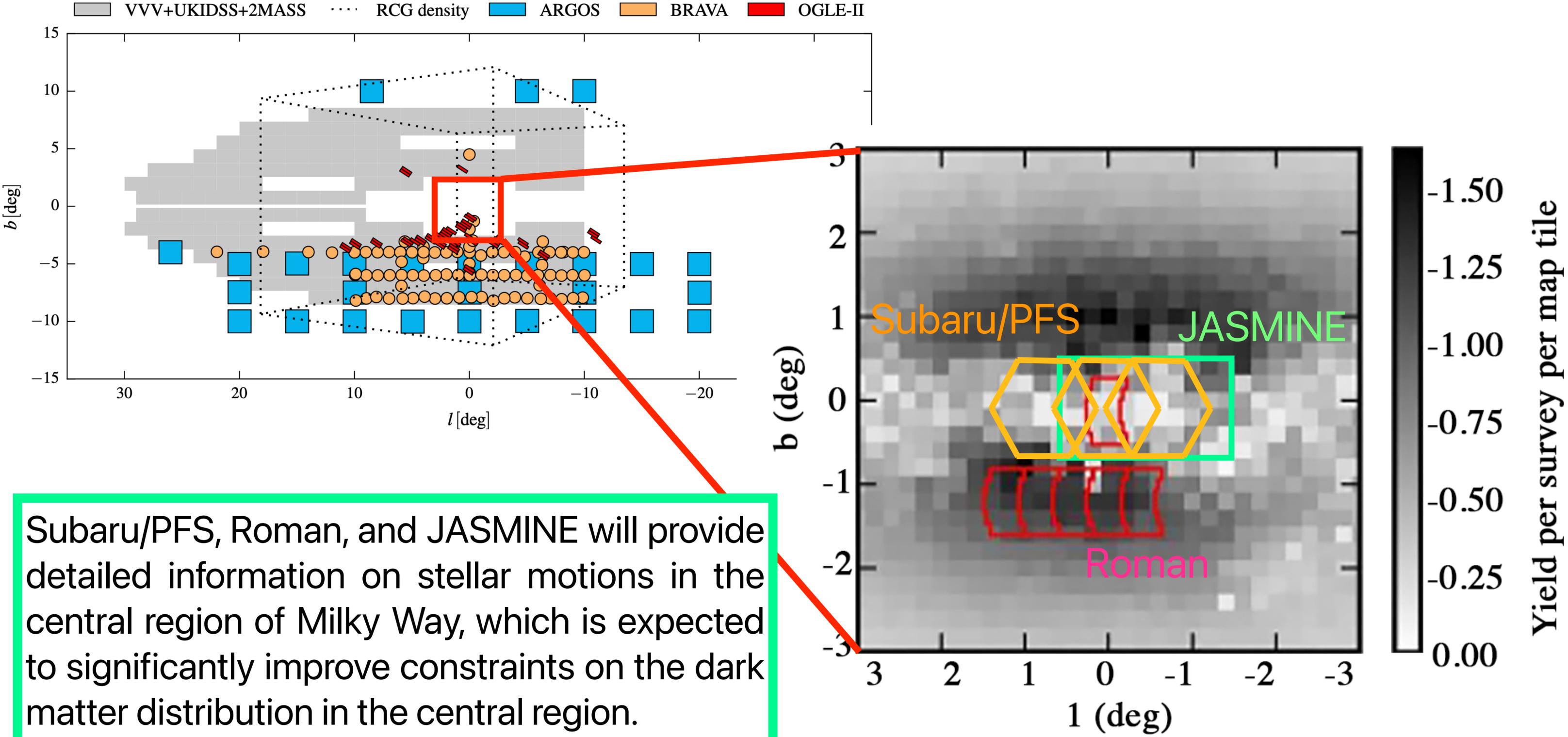
JASMINE (2030s~)

Subaru/Prime Focus Spectrograph
will measure radial velocities of stars over a wide field of view.

Nancy Grace Roman Space telescope
will provide proper motions of stars through precise astrometry.

JASMINE
will measure parallaxes and proper motions of stars in the central Milky Way.

The inner kinematics from Roman & JASMINE & Subaru/PFS



Subaru/PFS, Roman, and JASMINE will provide detailed information on stellar motions in the central region of Milky Way, which is expected to significantly improve constraints on the dark matter distribution in the central region.

Dark matter distribution at the Galactic center

KEY QUESTION:

Does the Milky Way have a cusp or core?

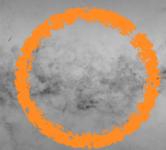
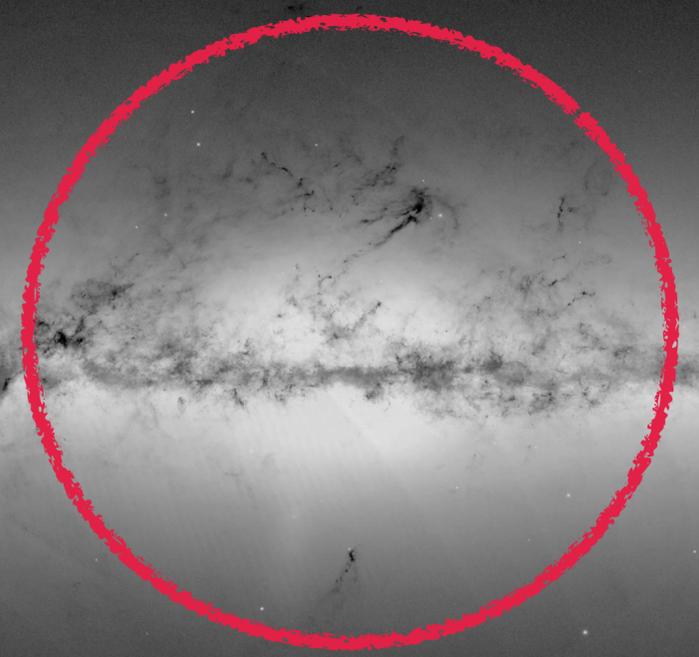
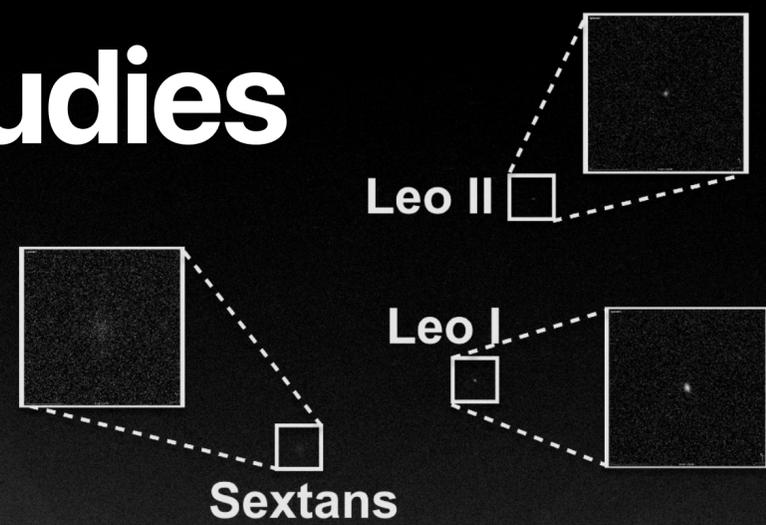
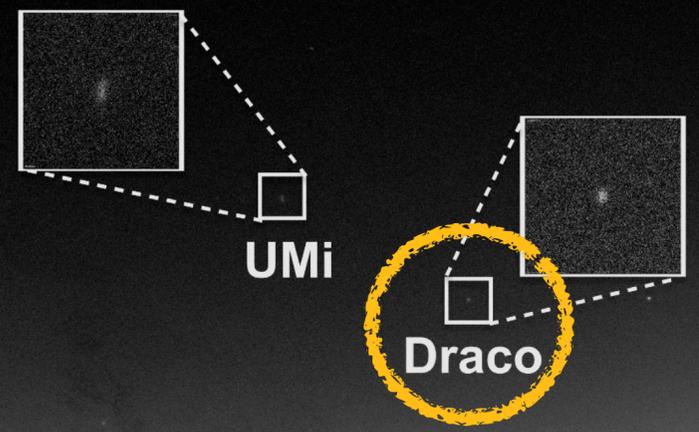


There is no conclusive observational evidence, because of lack of data and *complicated baryonic structures*.



Subaru/PFS & Roman & JASMINE will enable us to hunt large number of kinematic data!

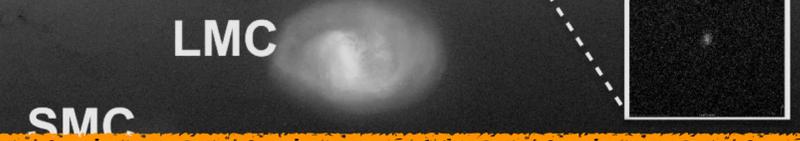
The Milky Way as a unique target of dark matter studies



Target:

- Galactic center
- Solar neighborhood
- Dwarf spheroidal galaxies

**DM density and velocity
in the Solar neighborhood**



Dark matter velocity distribution

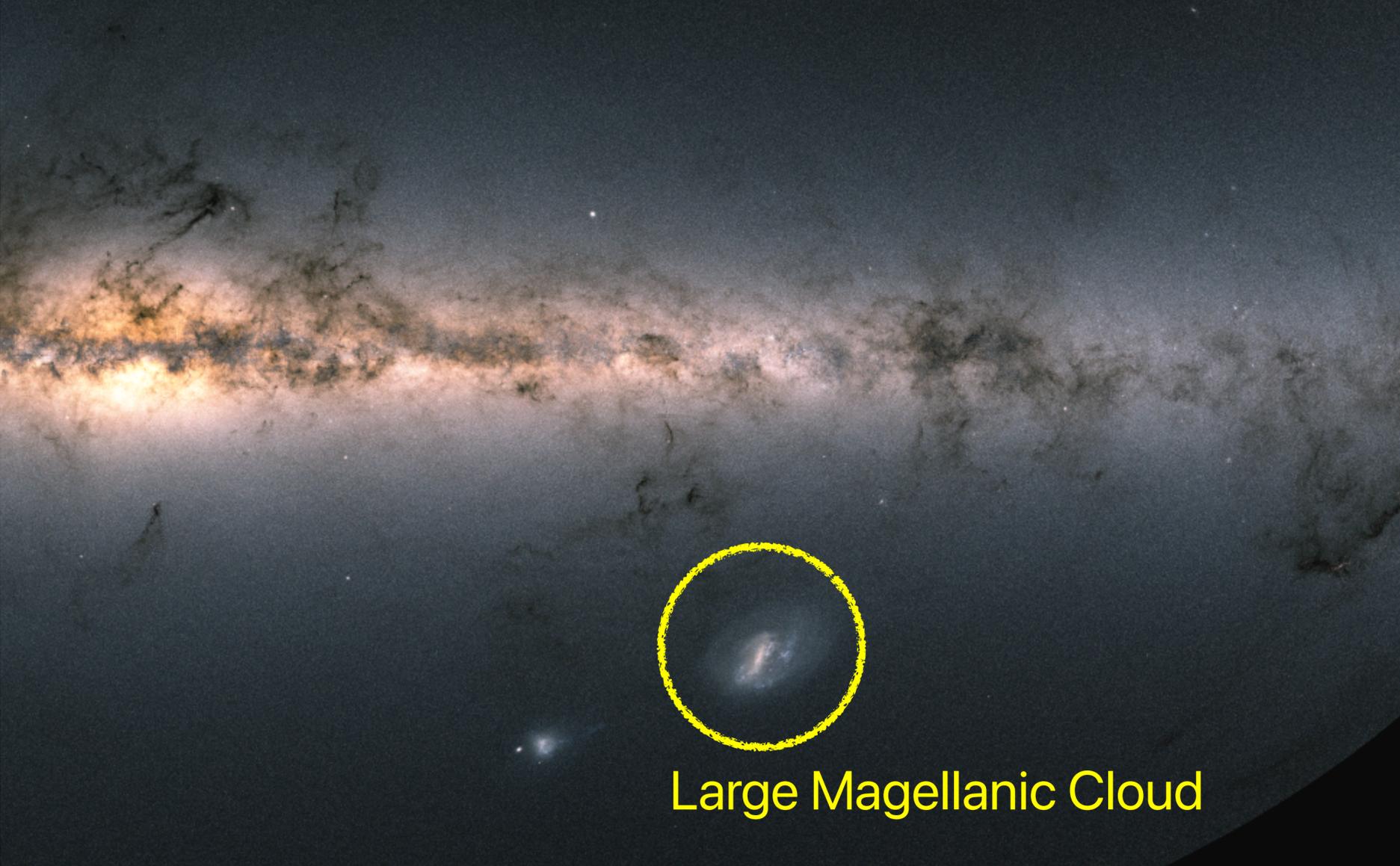
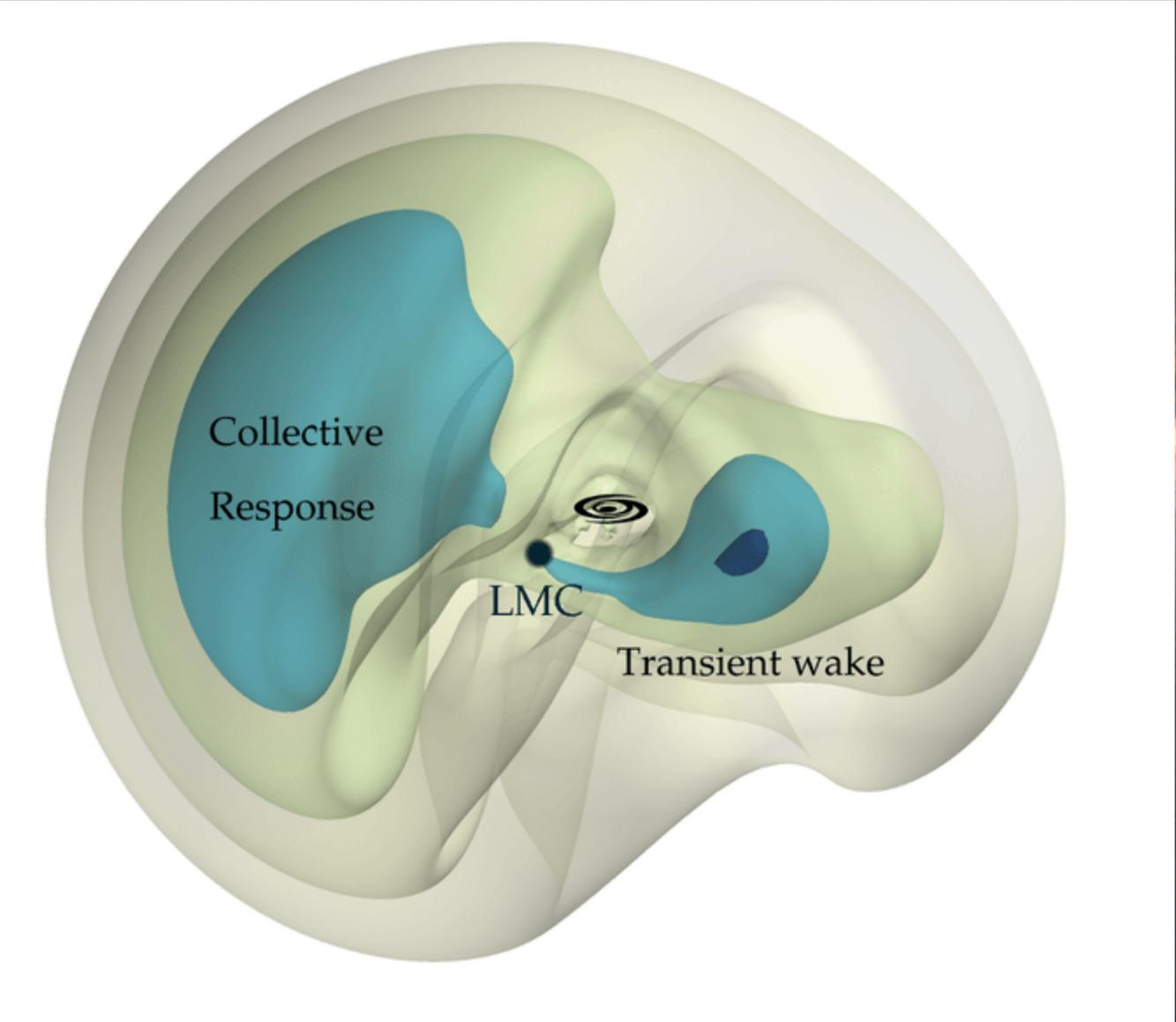
As a starting point, it remains challenging to constrain the DM velocity distribution observationally.

KEY QUESTION:

Is the Standard Halo Model assumption justified?

Is the Standard Halo Model assumption justified?

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



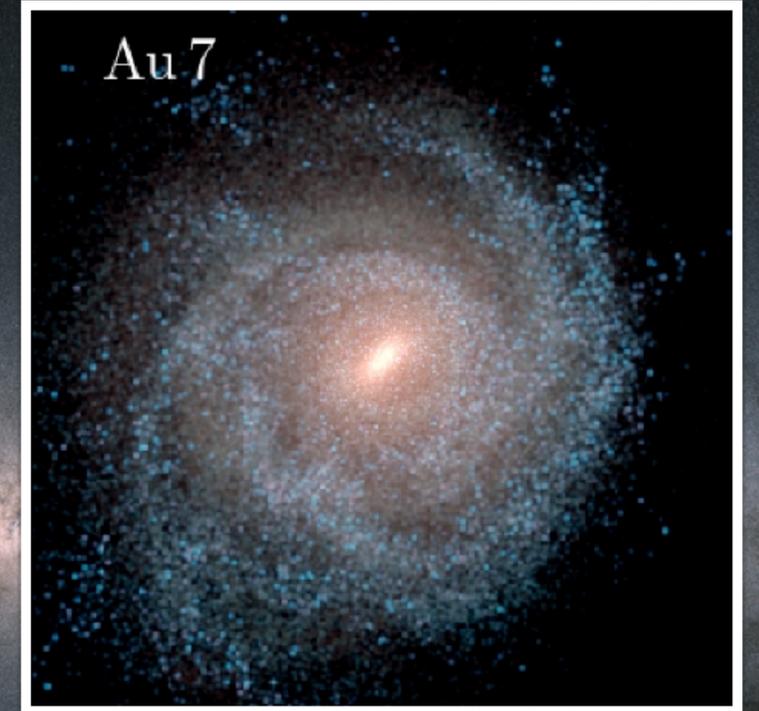
Garavito-Camargo et al. (2021)

Is the Standard Halo Model assumption justified?

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.



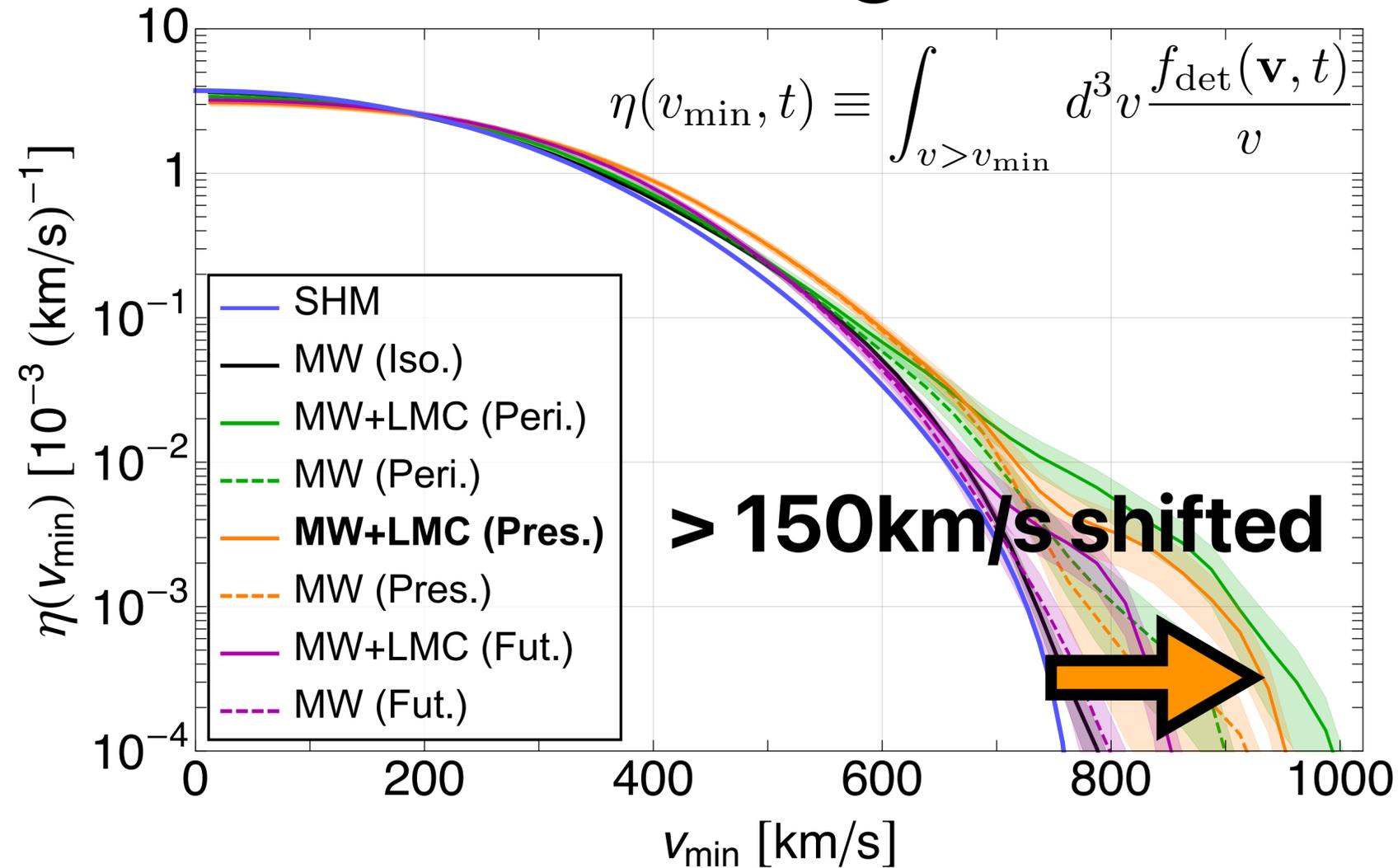
Large Magellanic Cloud

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

Dark matter velocity distribution

Smith-Orlik et al. (2023)

Halo Integral



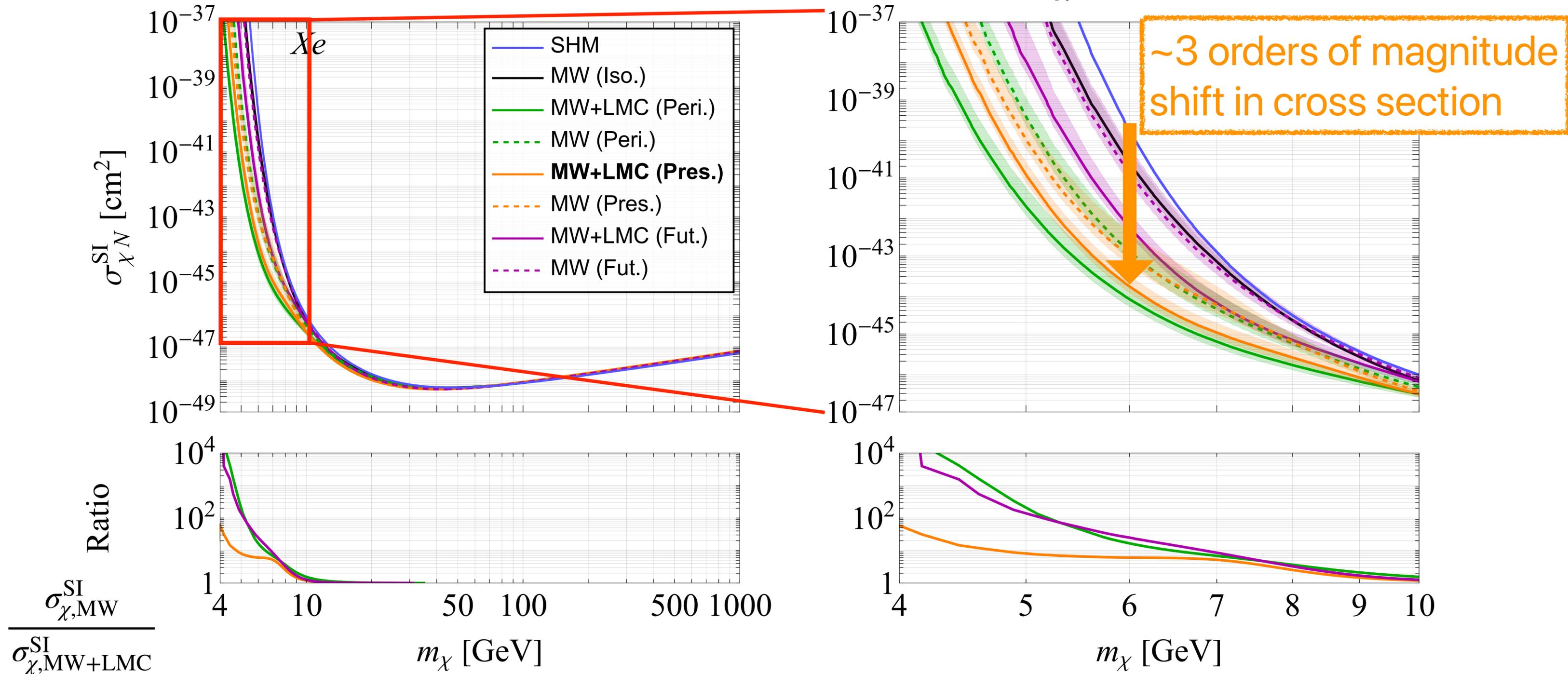
- Although the DM number fraction originating from LMC is small, the LMC significantly impacts the high velocity tail of the DM velocity distribution.
- The high velocity tail of MW+LMC are shifted over 150km/s from that of SHM.
- High velocity LMC DM particles + MW's response to the LMC affect the high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

Direct detection limits

Smith-Orlik et al. (2023)

Xenon based detector

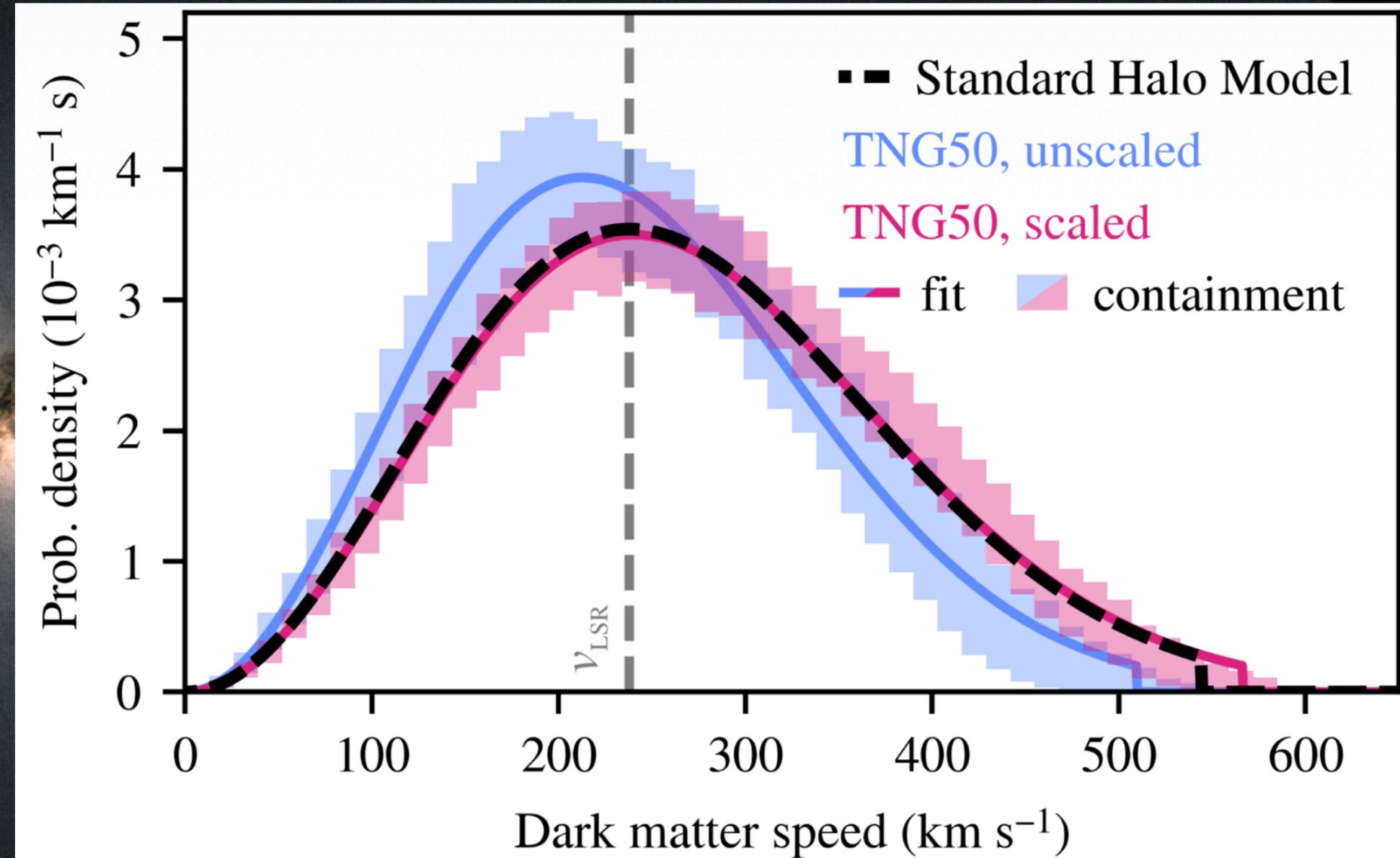
$\rho_\chi = 0.3 \text{ [GeV/cm}^3\text{]} \text{ fixed}$



Is the Standard Halo Model assumption justified?

Folsom et al. (2025), PRL, 135, 211004

- MW-like galaxies in *Illustris-TNG50* simulations
- They selected 100 host galaxies based on
 1. Stellar mass consistent with the MW
 2. Incl. of M31 analogs
 3. Incl. of LG-like system analogs
- Scaled at V_{LSR}

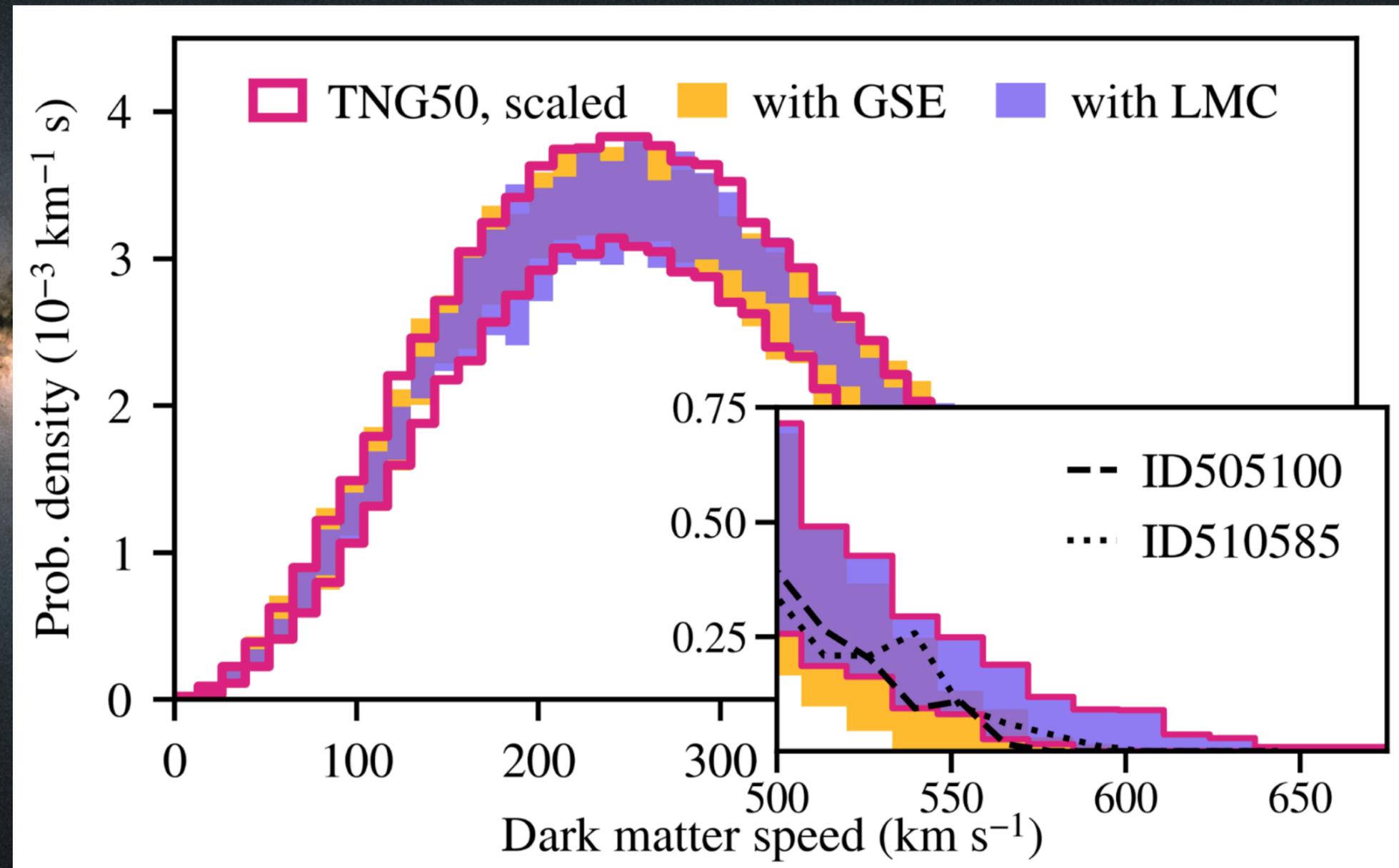


Overall, the simulated distributions are **statistically** consistent with the SHM.

Is the Standard Halo Model assumption justified?

Folsom et al. (2025), PRL, 135, 211004

- They selected 32 host halos that have had a GSE-like merger and another group of 11 halos with LMC-like satellites.
- **These merger histories do not appear to strongly affect the high velocity tails of the velocity distribution.**



Dark matter velocity distribution

As a starting point, it remains challenging to constrain the DM velocity distribution observationally.

KEY QUESTION:

Is the Standard Halo Model assumption justified?



Statistically yes,

but the answer depends largely on simulations :- (

	Resolution	Sample Volume
Auriga		
Illustris TNG50		

Trade-off

Dark matter local density

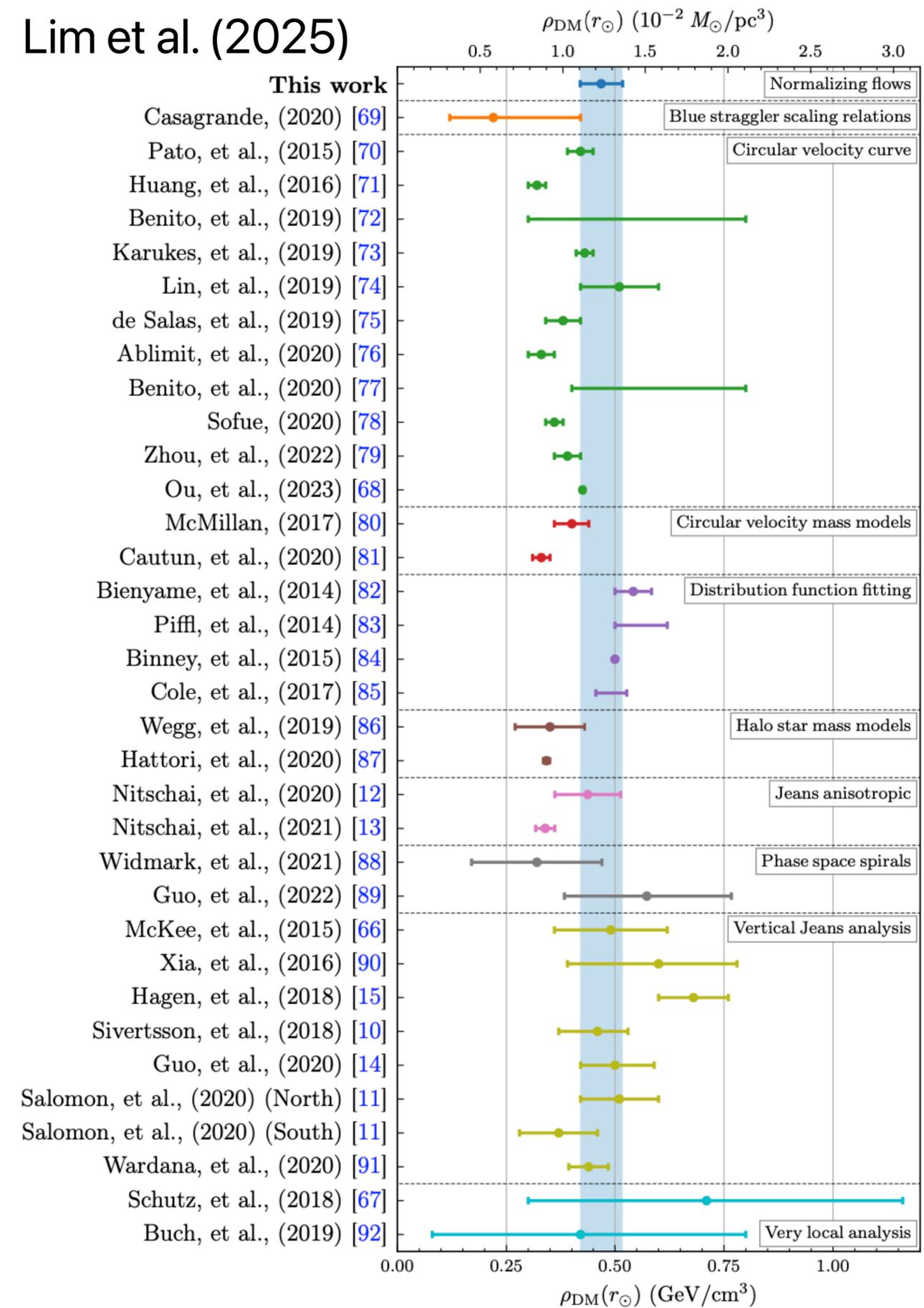
To obtain the density...

- Vertical stellar motions of solar neighborhood
- Rotation curve
- Escape velocity
- Motions of the MW halo stars
- **Machine Learning technique**

Current estimation:

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

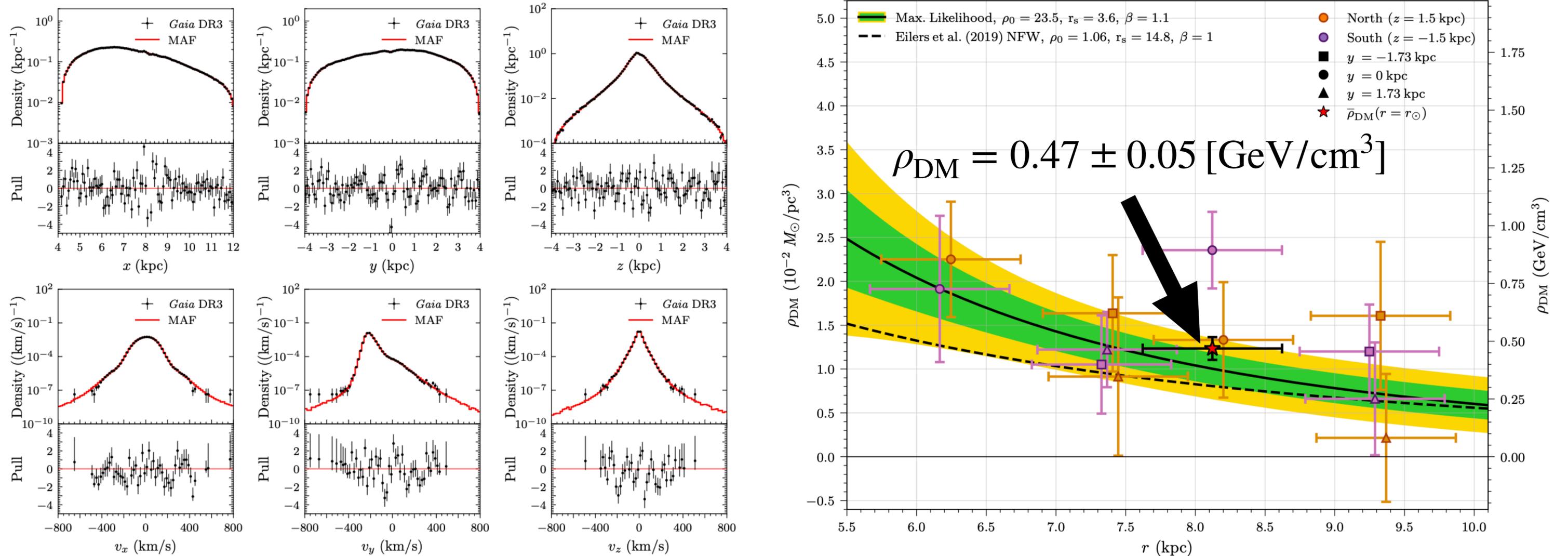
Lim et al. (2025)



See also Hunt and Vasiliev (2025) for a review

Dark matter local density

Phase-space density estimation with normalizing flows (Lim+2025)



- Uses 6 million nearby stars from *Gaia* DR3
- Reconstructs the stellar phase space distribution via unsupervised ML (normalizing flow)
- Enforces dynamical consistency by solving the *equilibrium* collisionless Boltzmann equation
- Enables an estimate of the local dark matter density

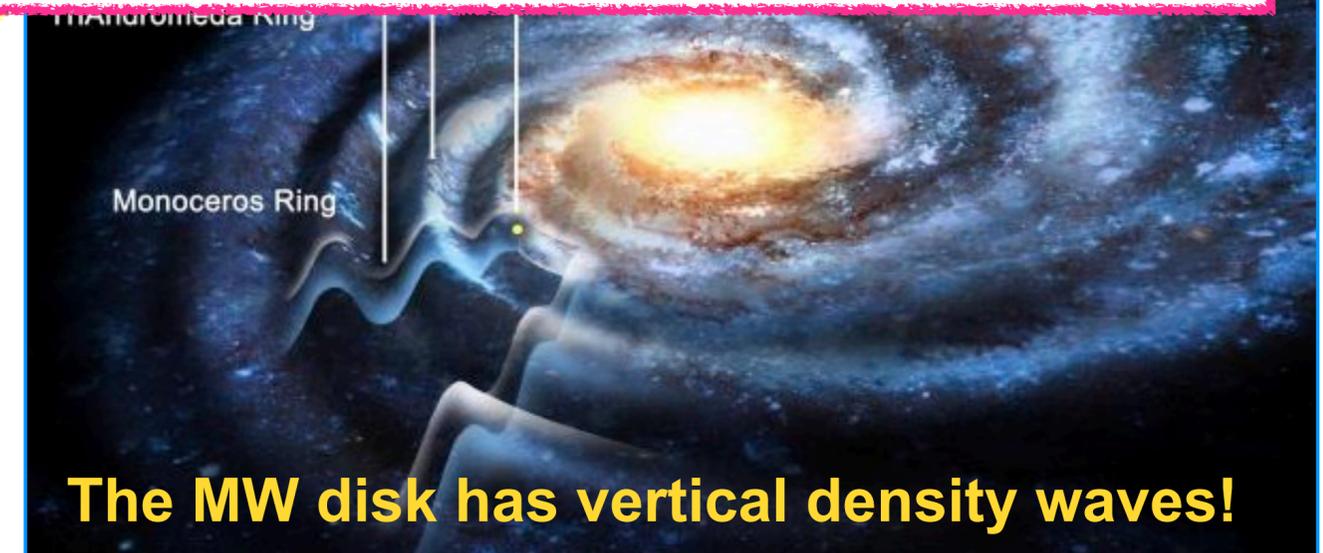
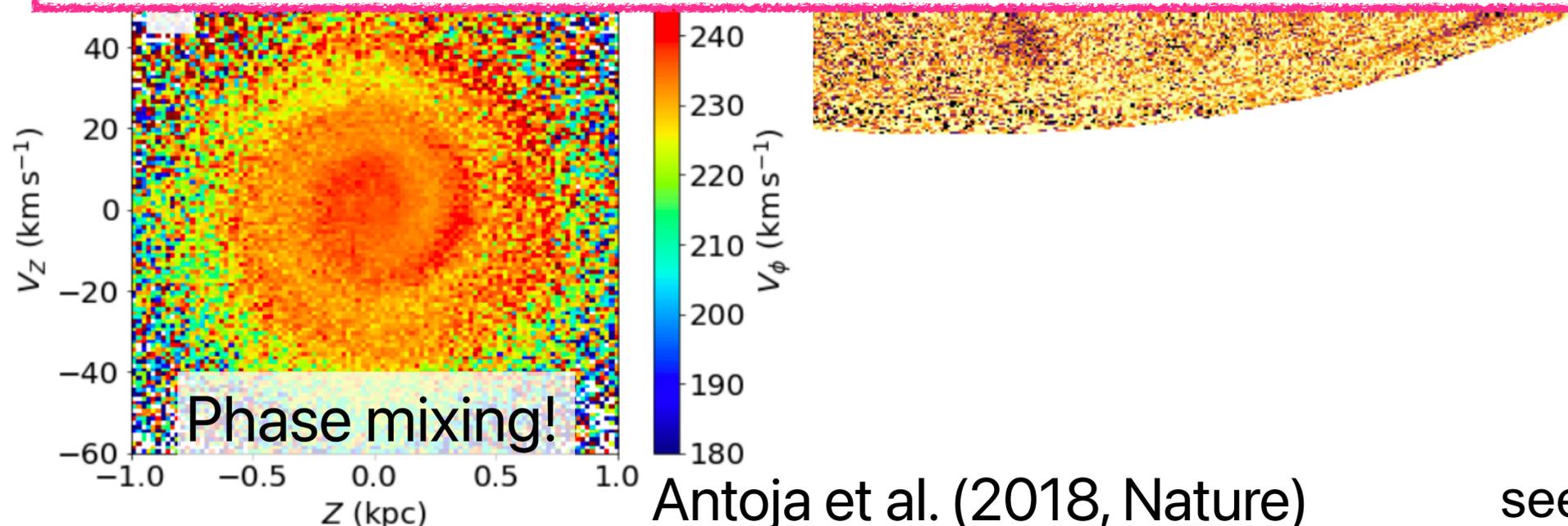
Evidences of disequilibrium

Laporte et al. (2021)

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

The dynamics must be modeled by solving the collisionless Boltzmann equation with assuming ***non-equilibrium***.

✧ R. Chiba et al. (2025, arXiv:2506.16512) take this effect into account for the Milky Way disk.



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

Take Home Message

Milky Way is the promising target for direct and indirect dark matter searches.

1. The inner MW DM distribution remains uncertain. The kinematic information toward the center region should be needed.
2. The Standard Halo Model is widely assumed, but high-resolution simulations are needed to test velocity-tail behavior.
3. Gaia + ML can reconstruct MW dynamics, though disk disequilibrium is a key systematic in local DM density estimates.