Dark Matter on Small Scales

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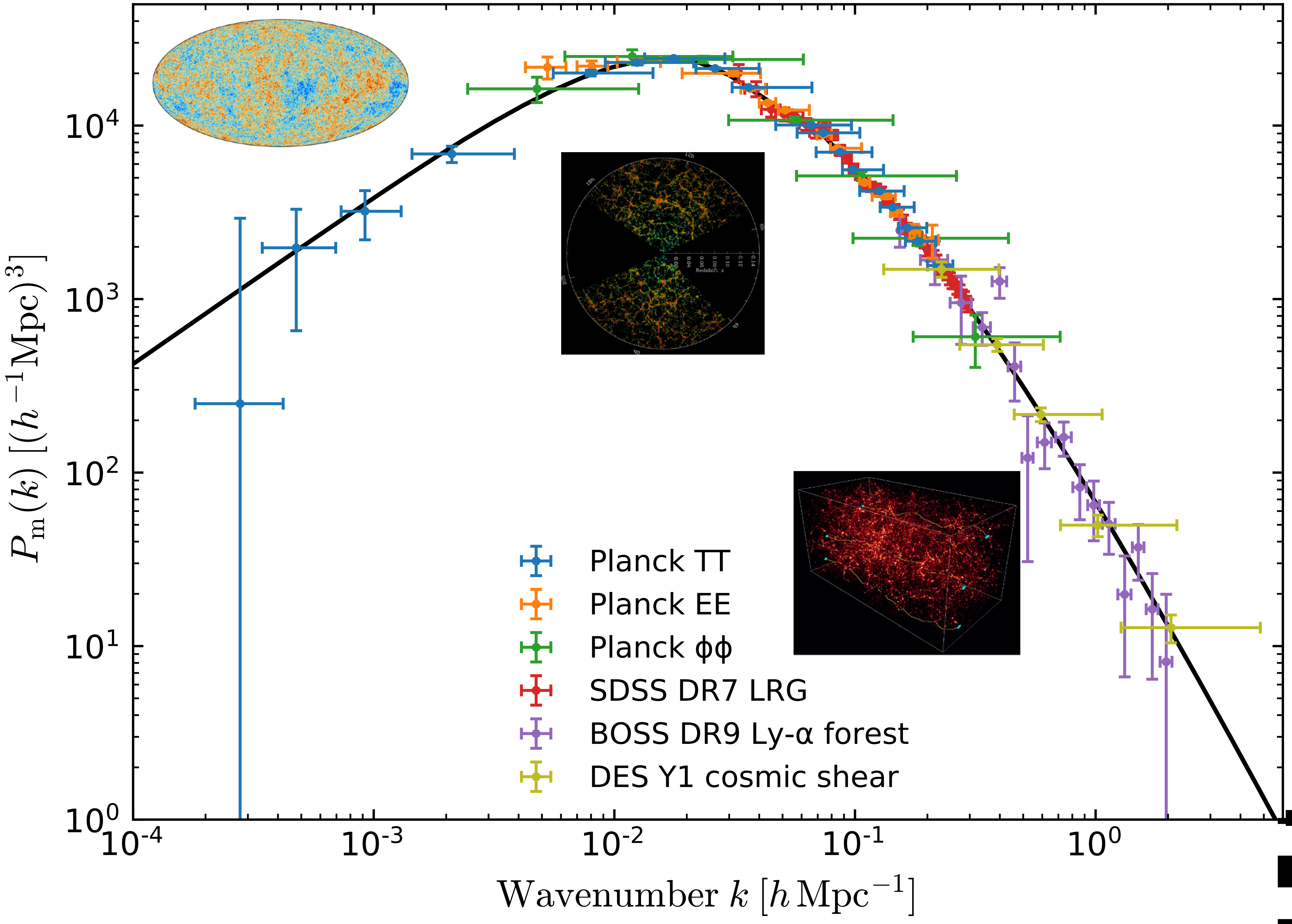
Cosmic Indicators of Dark Matter 2024

Oct. 17, 2024

Λ Cold Dark Matter model



ESA and the Planck Collaboration

Large scale (> 1Mpc)

⇒ Remarkable success!

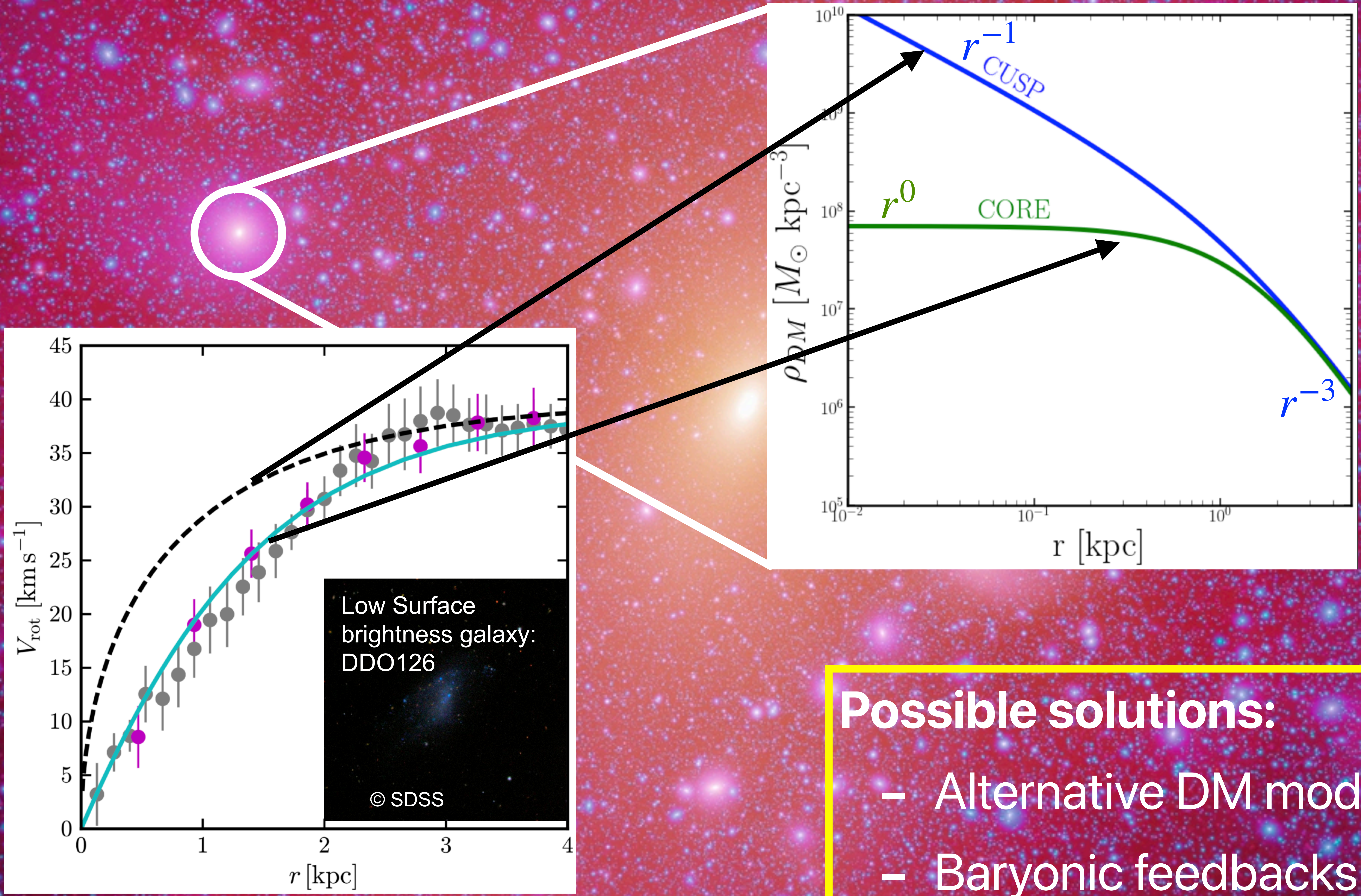
Small scale (<1 Mpc)

⇒ What's going on?

?

The core-cusp problem:
controversial issue on CDM theory

Credit: Aquarius project

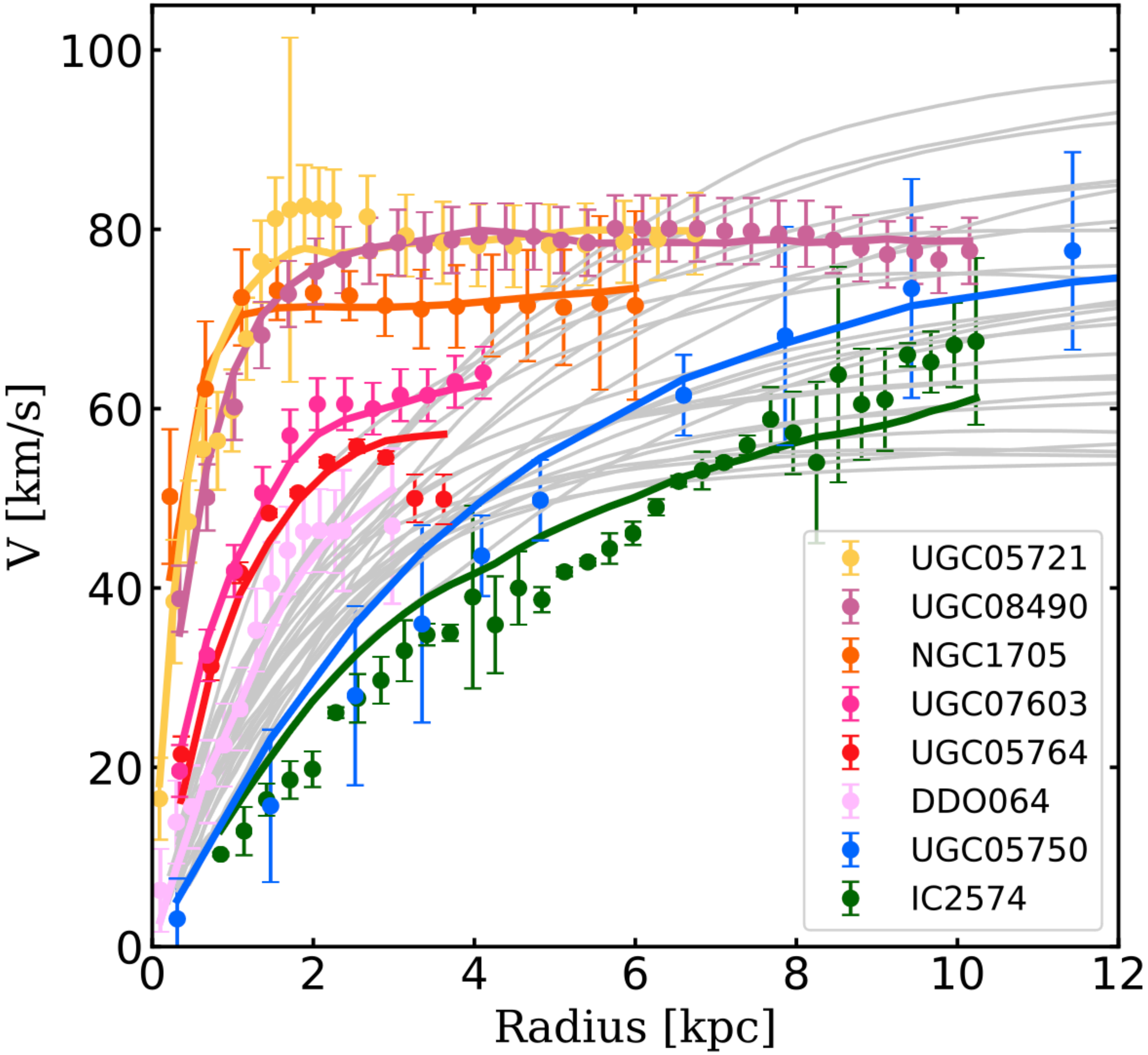


Possible solutions:

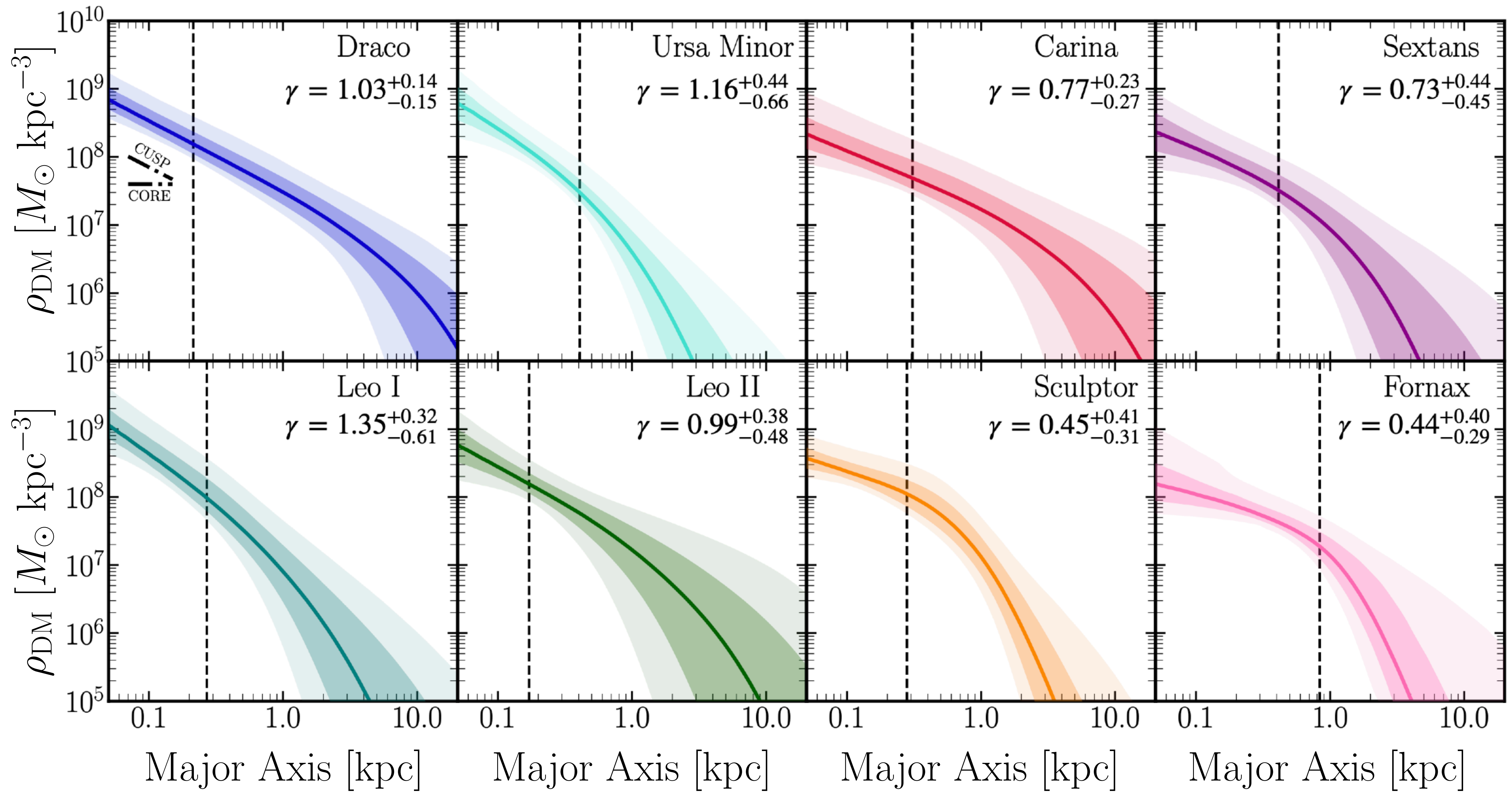
- Alternative DM models (e.g., SIDM, FDM)
- Baryonic feedbacks

~~Core-Cusp Problem~~ ⇒ Diversity Problem

Kaplinghat, Ren, Yu (2019)



- Rotation curves of low-mass galaxies have a *diversity*.
- DM density profiles in dwarf spheroidal galaxies also have a *diversity*.



KH, Chiba & Ishiyama (2020)

~~Core-Cusp Problem~~ ⇒ Diversity Problem

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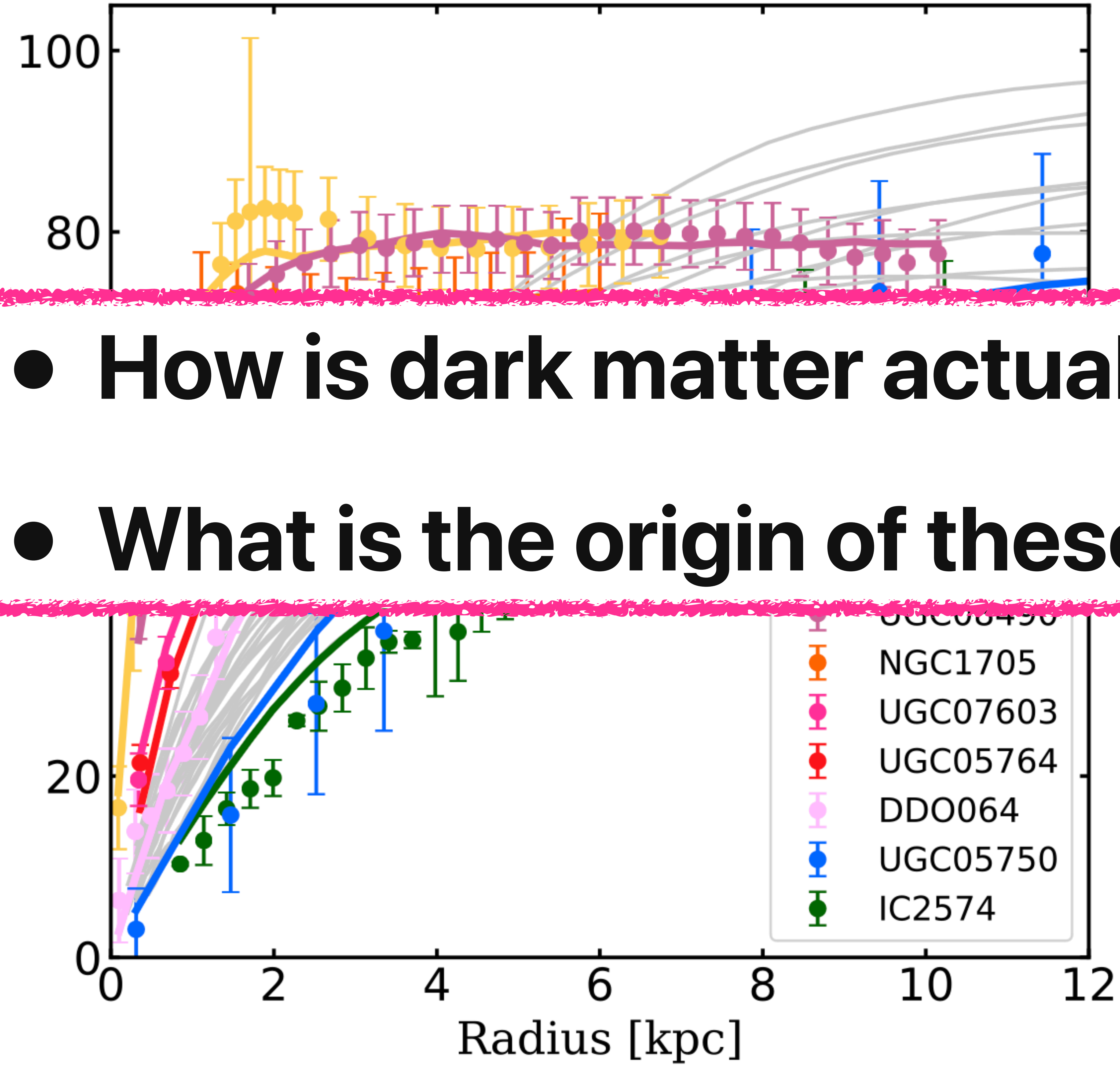

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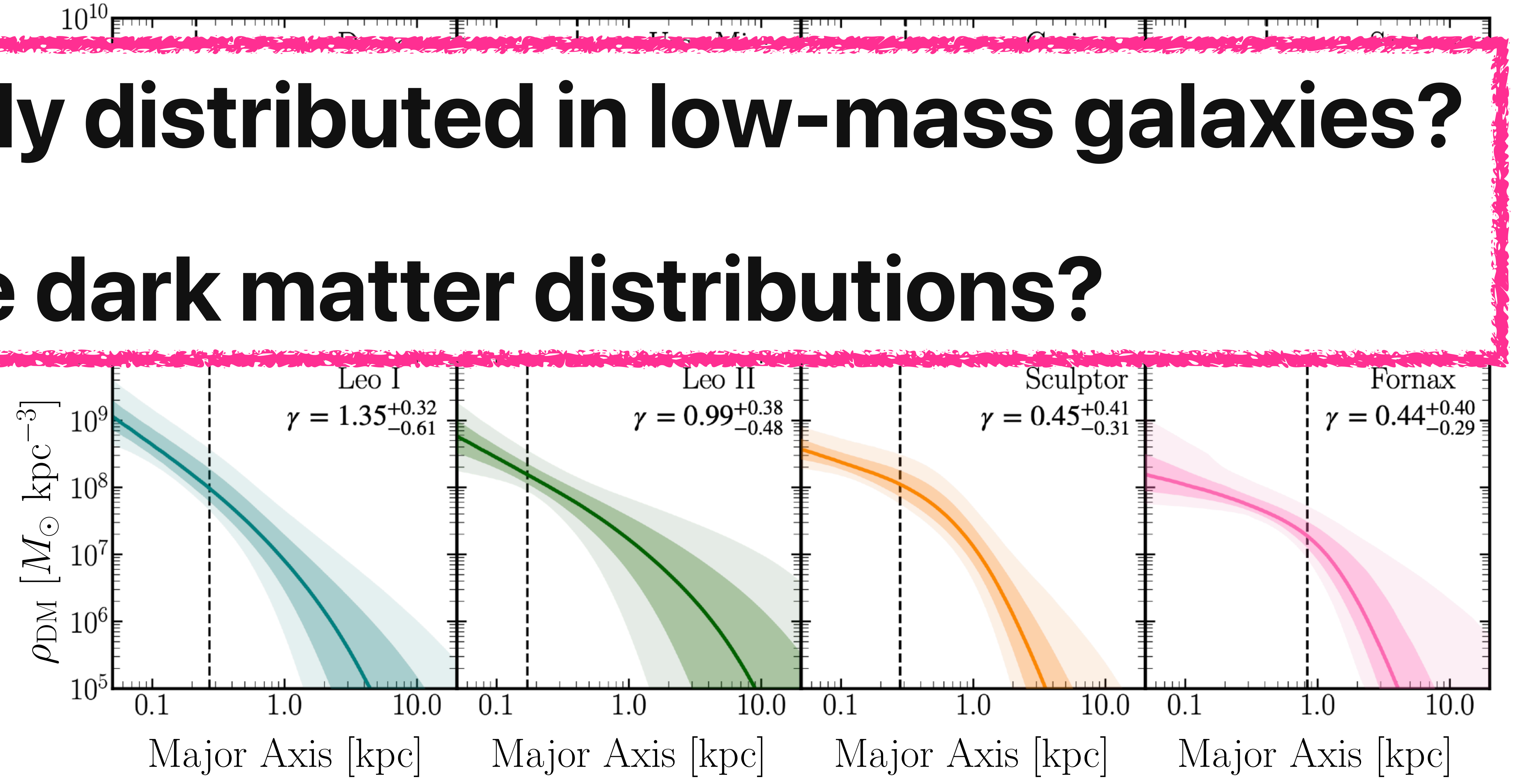


KH, Chiba & Ishiyama (2020)

- **How is dark matter actually distributed in low-mass galaxies?**
- **What is the origin of these dark matter distributions?**

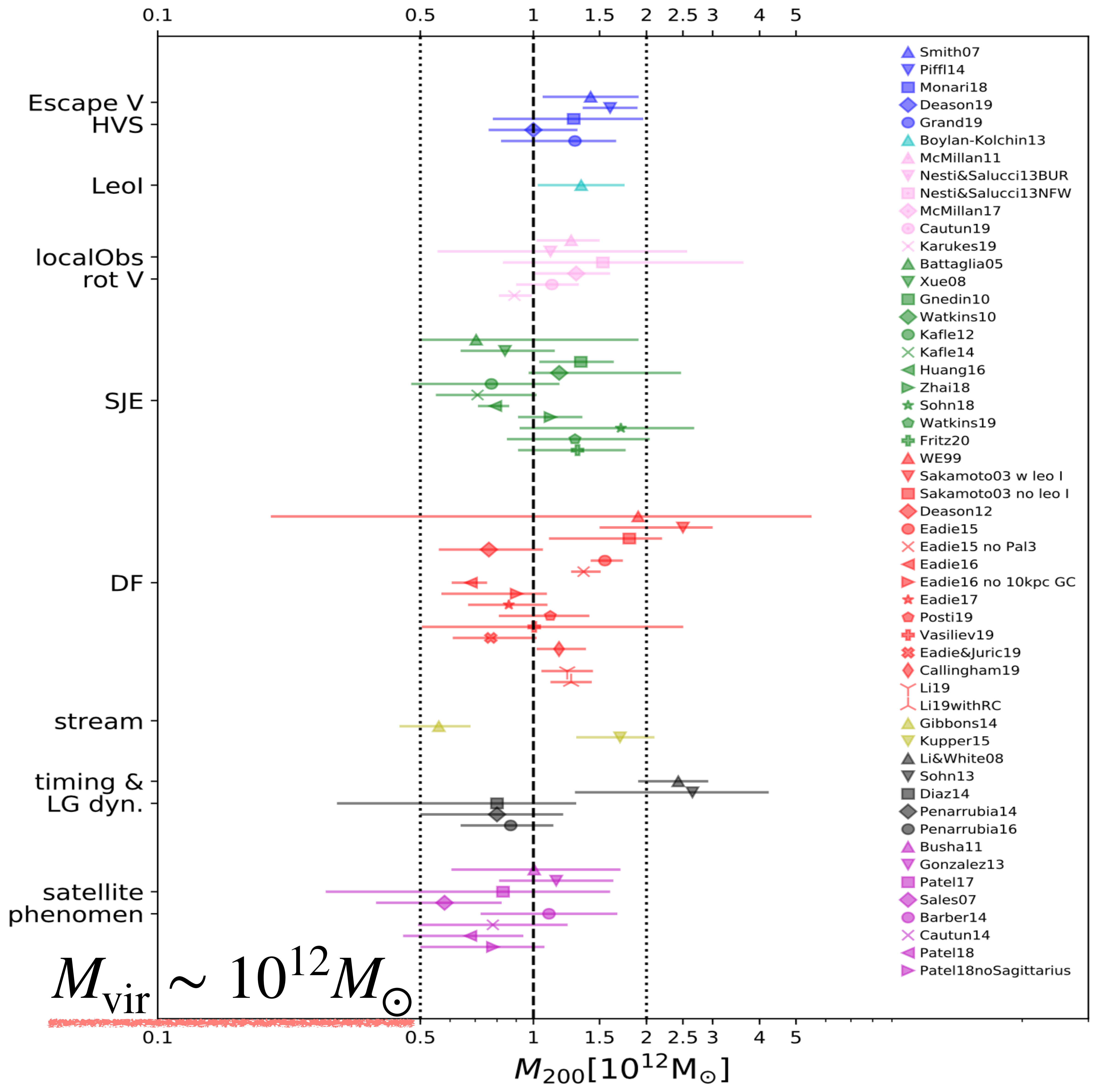
How to get limits on DM distribution?

Dark matter distribution in the Milky Way

How to get limits on DM distribution?

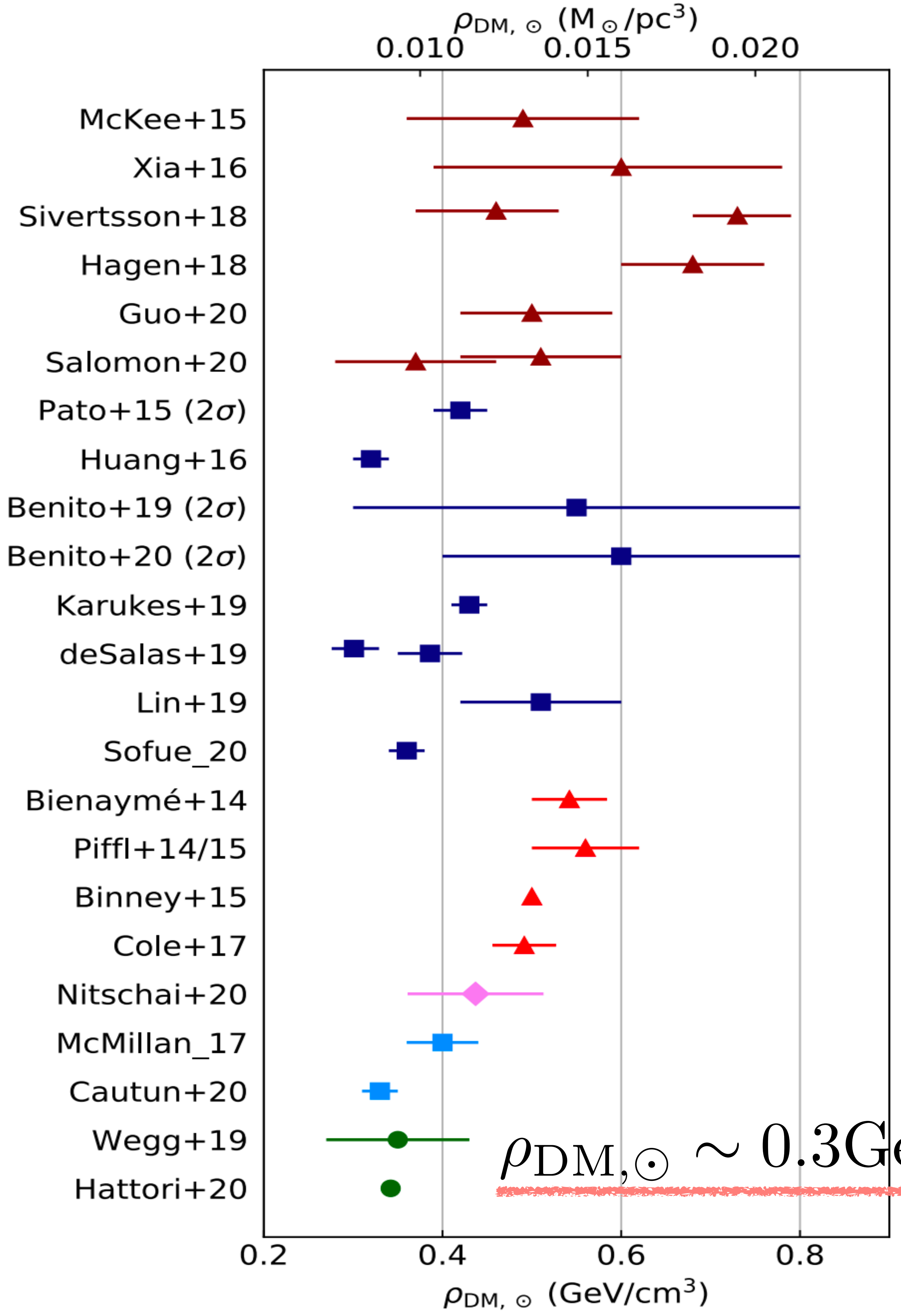
Dark matter virial mass & local density

Wang et al. (2020)



$M_{\rm vir} \sim 10^{12} M_\odot$

de Salas & Widmark (2020)



$\rho_{\rm DM,\odot} \sim 0.3 {\rm GeV/cm^3}$

Dark matter density profile

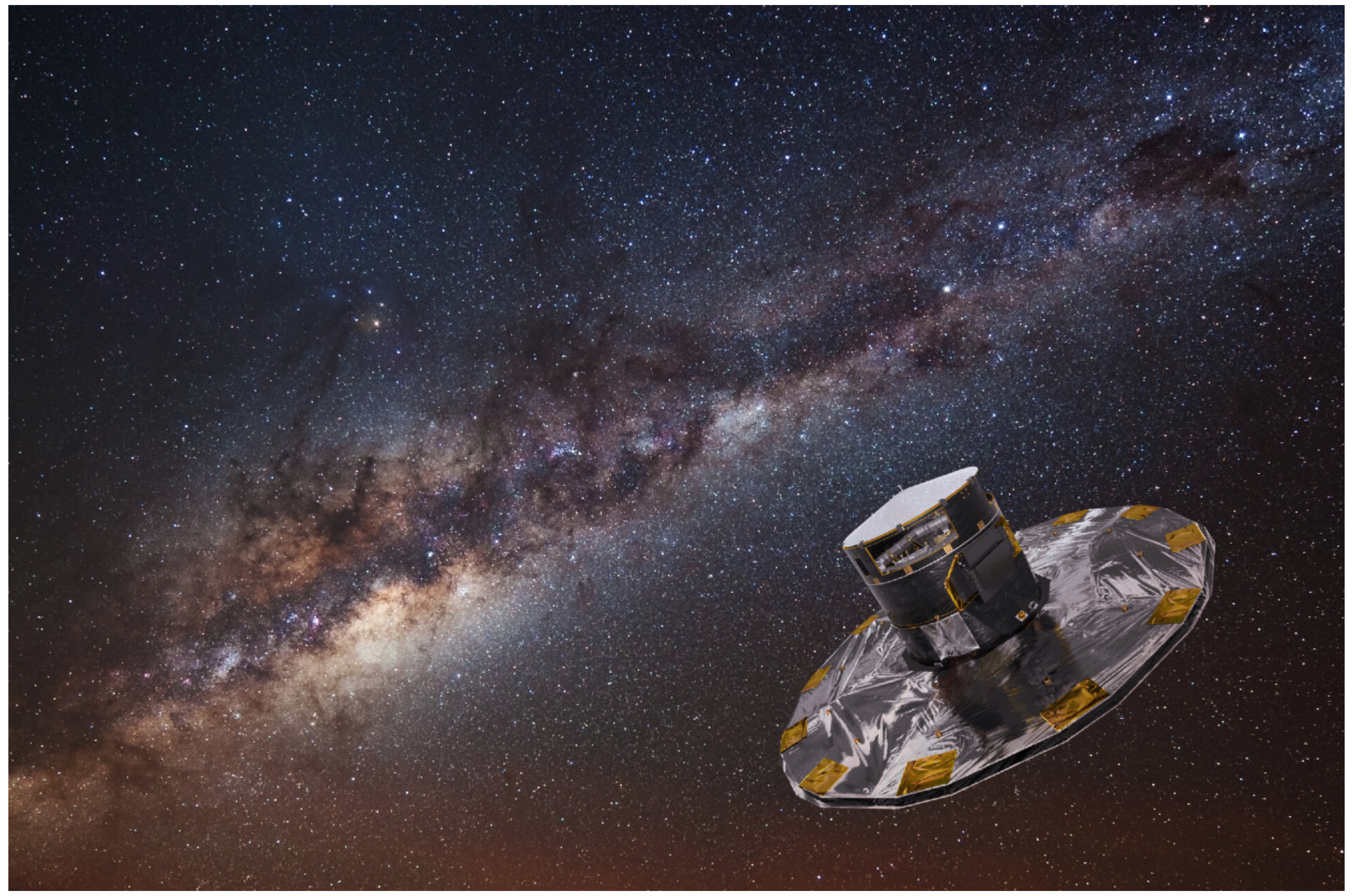
- Using old halo stars (outer regions)

- Data

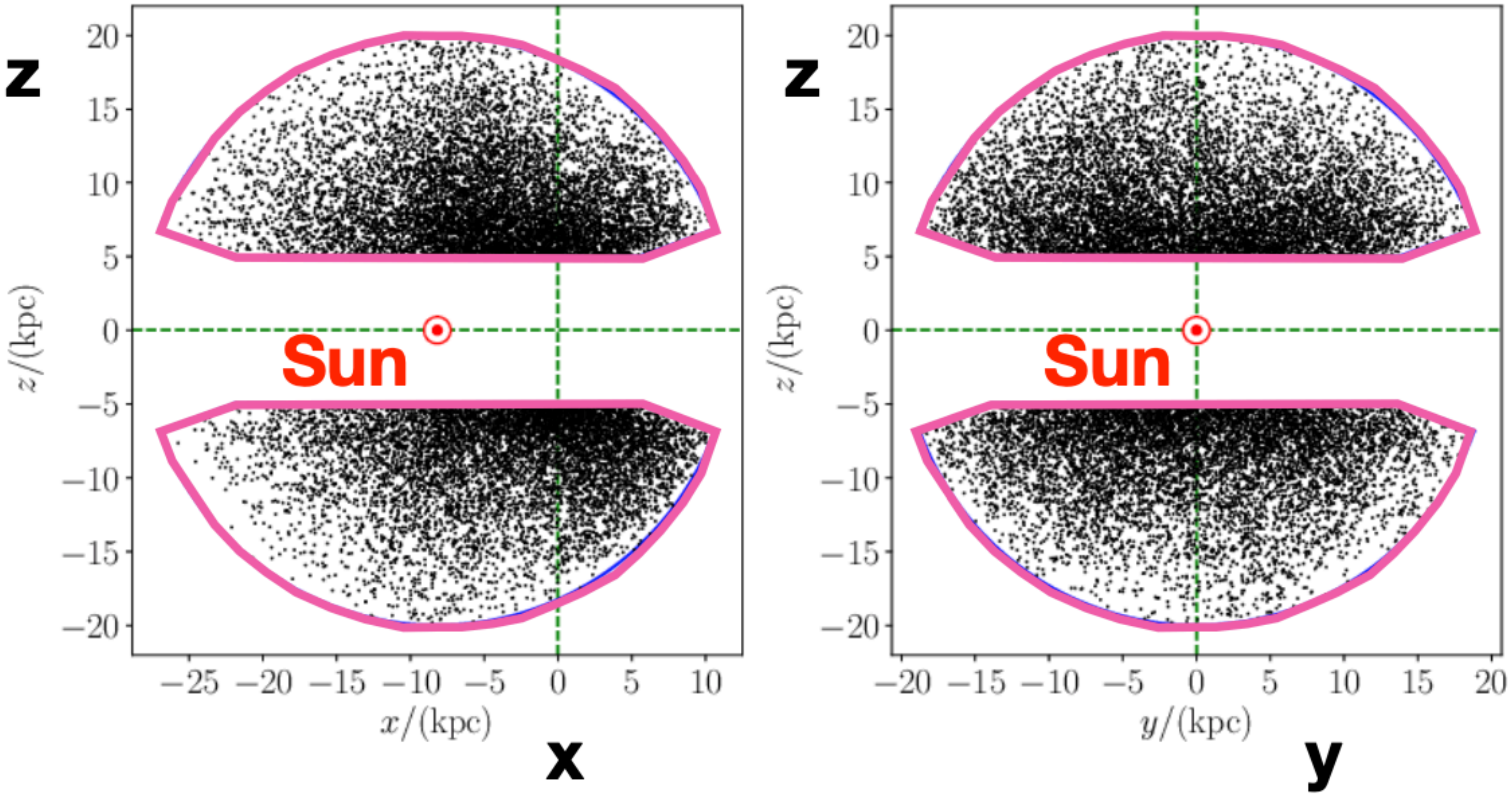
a) Proper motions of RR Lyrae stars by Gaia EDR3

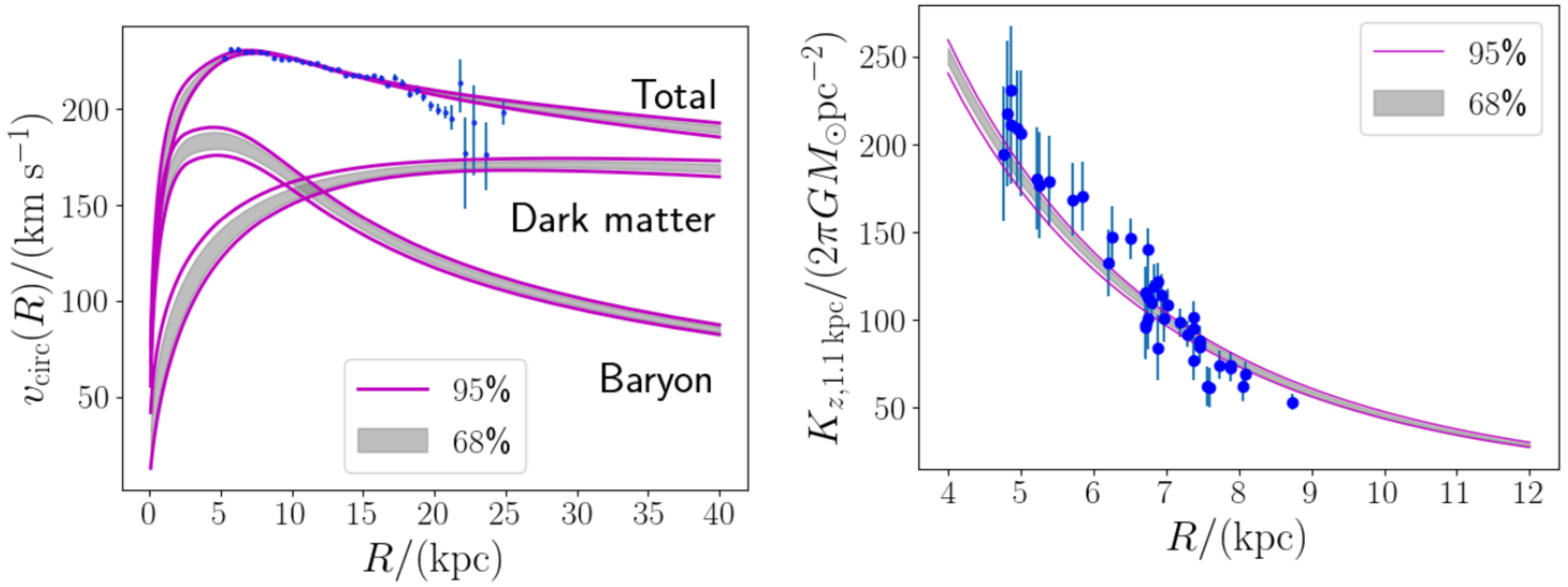
- Old halo stars
- Measure the distance by period-luminosity relation

b) Rotation curve + vertical force



~16,000 RR Lyrae stars





↑ Rotation curve & vertical force

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

Hattori et al. (2021, 2012.03908)

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

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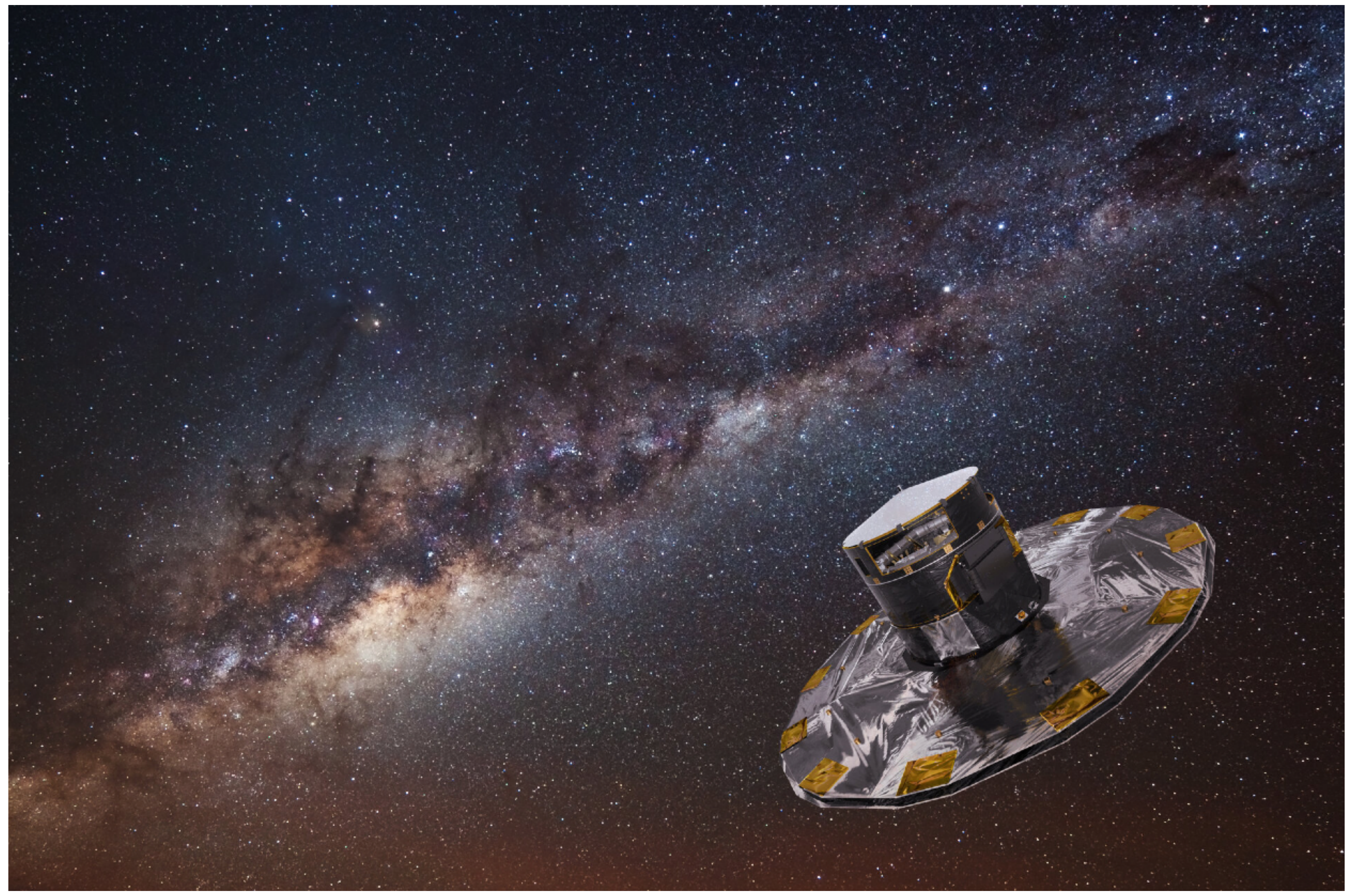


- Model

  1. Parameterized distribution function for halo stars:

J : Action variables

$$f_{\rm main}(J_r, J_\phi, J_z) = \frac{C_A}{(2\pi J_0)^3}\left(\frac{h(\boldsymbol{J})}{J_0}\right)^{-\Gamma}\left[1+\left(\frac{g(\boldsymbol{J})}{J_0}\right)\right]^{(\Gamma-B)}\left[1+\kappa\tanh\left(\frac{J_\phi}{J_{\phi,0}}\right)\right]$$

Possibility that a RRL star exists at the position $(\mathbf{x}_i, \mathbf{v}_i)$ in the 5D phase space

$$\Pr(\mathbf{x}_i, \mathbf{v}_i) = f(\mathbf{x}_i, \mathbf{v}_i) = f(\mathbf{J}[\mathbf{x}_i, \mathbf{v}_i])$$

+ observed errors + selection function

2. Gravitational potential:

- Baryonic components（spherical bulge, flattened stellar/gas disks）
- Spheroidal dark matter halo

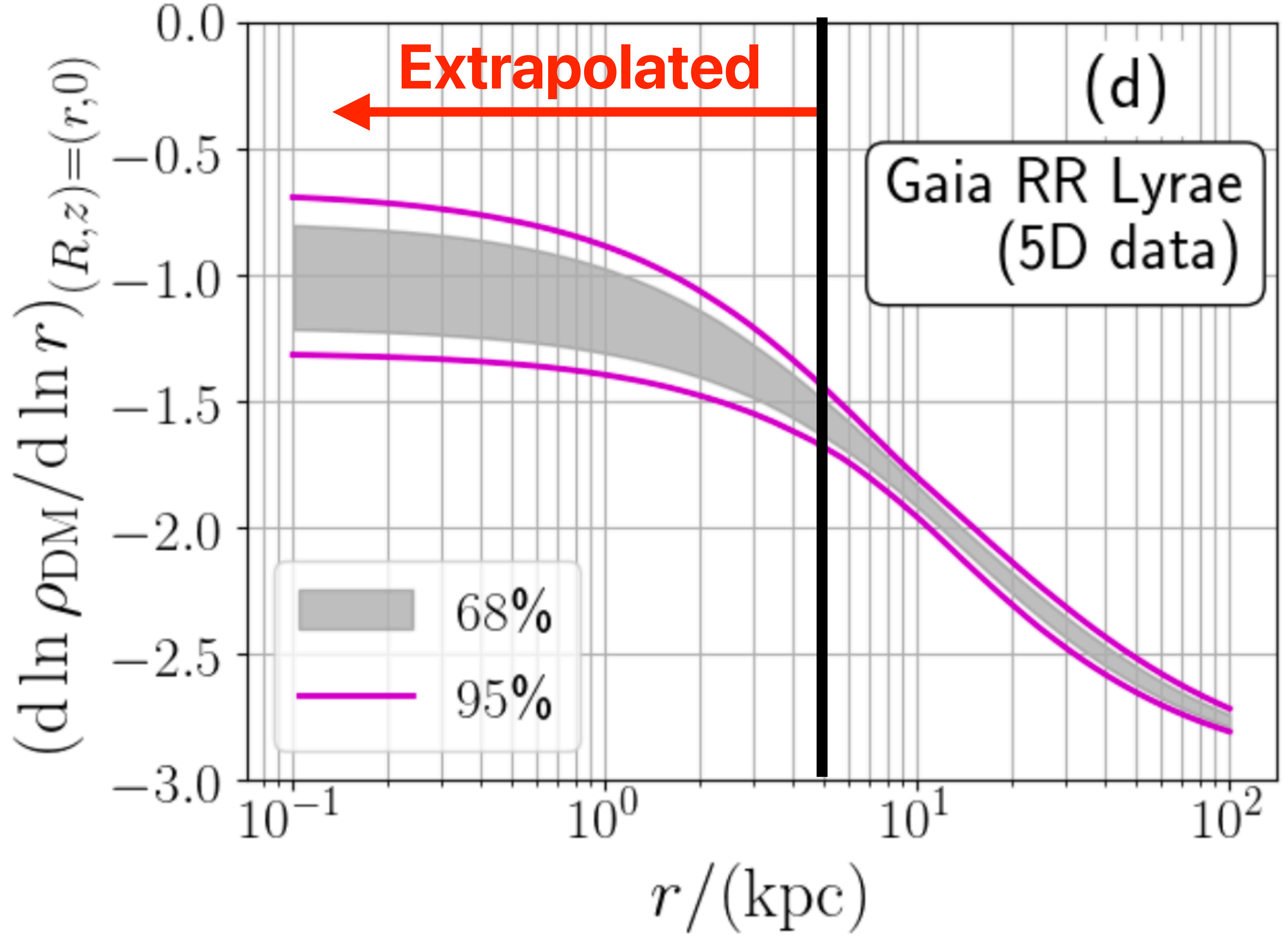
$$\rho_{\rm DM}(R, z) = \rho_0 \frac{a^3}{m^\gamma (a+m)^{3-\gamma}},$$

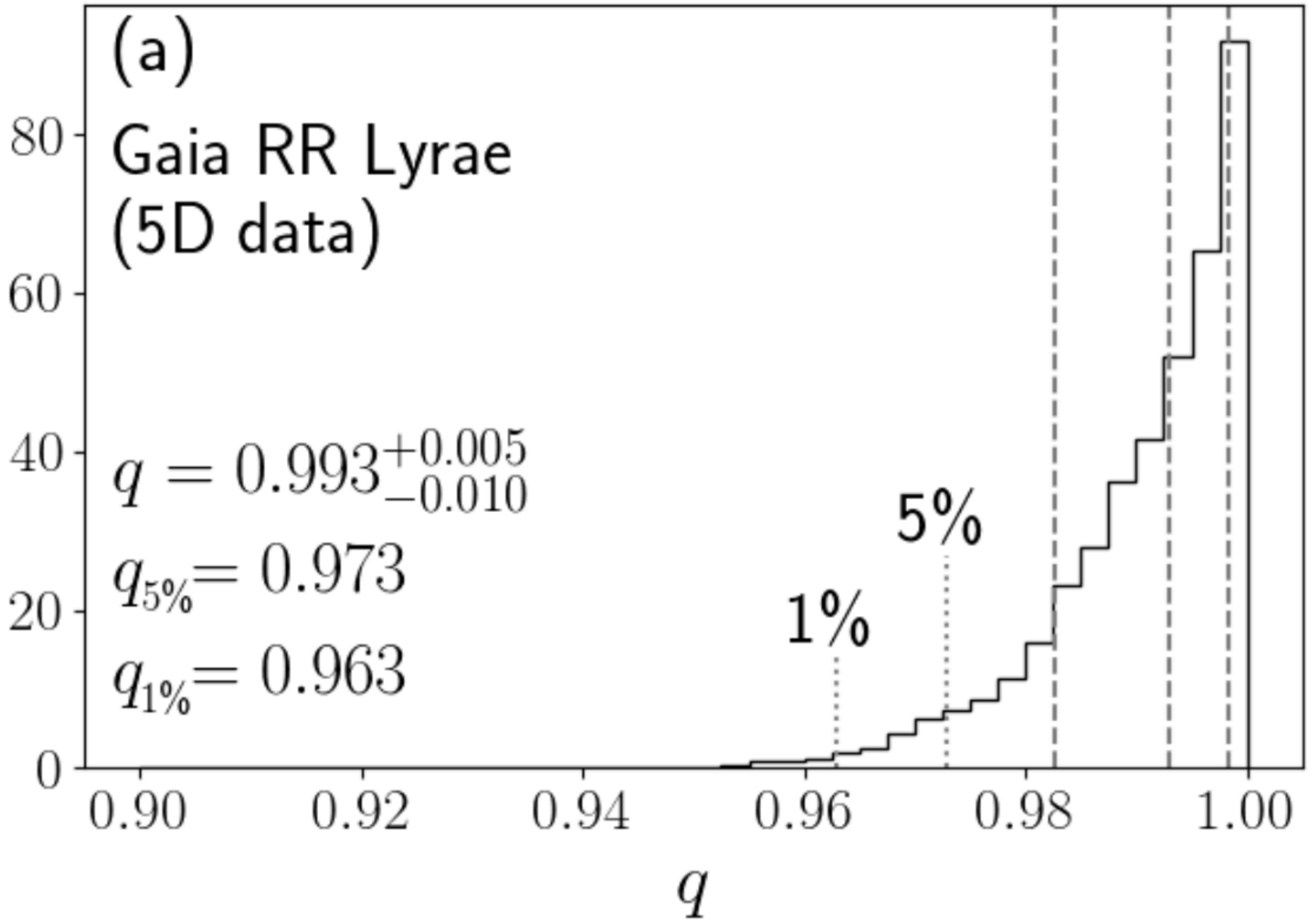
$$m^2 = R^2 + (z/q)^2 \qquad q \leqq 1$$

Hattori et al. (2021, 2012.03908)

Dark matter density profile

- Using old halo stars (outer regions)





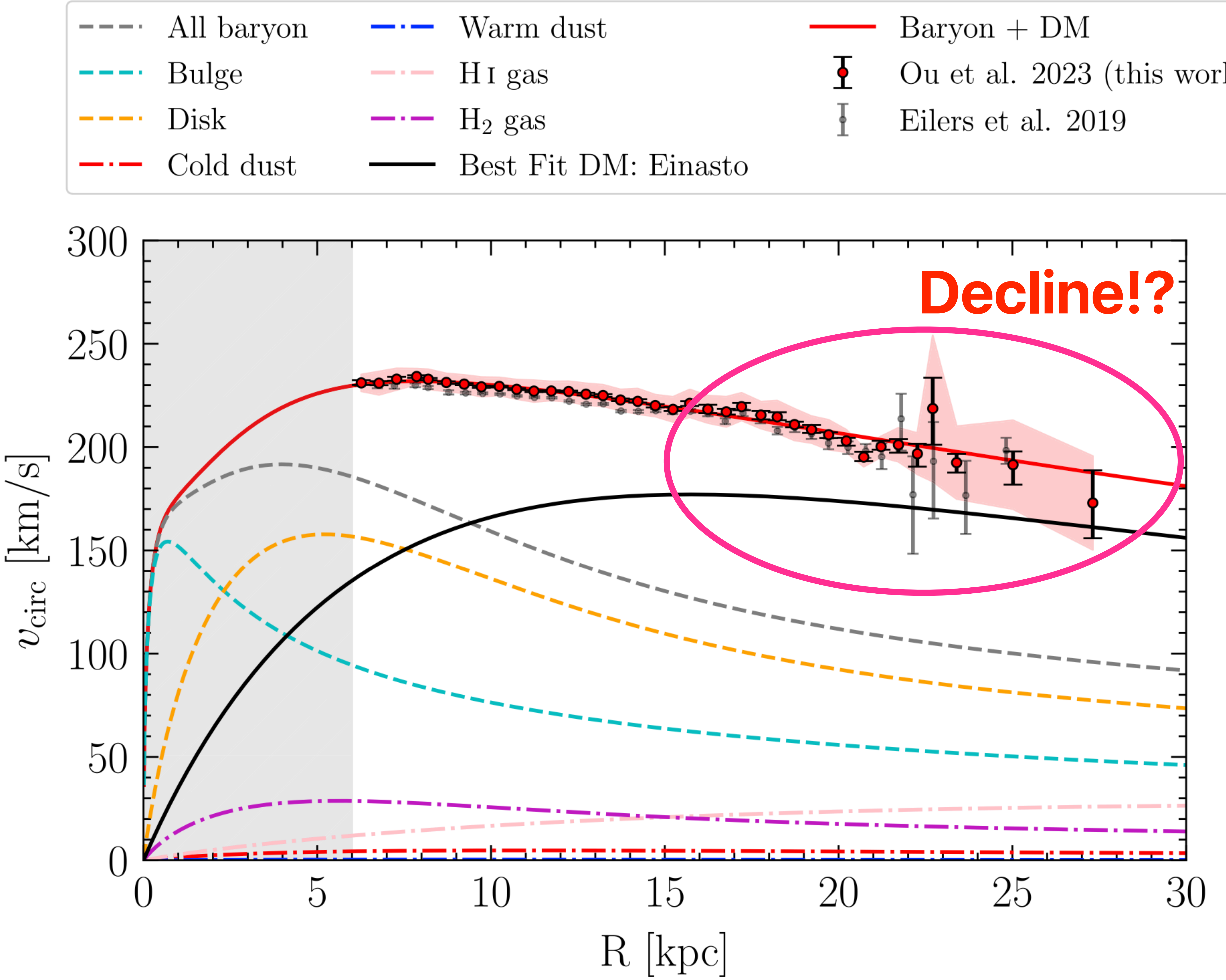
$$\rho_{\mathrm{DM},\odot} = 0.342 \pm 0.007\ \mathrm{GeV/cm^3}$$

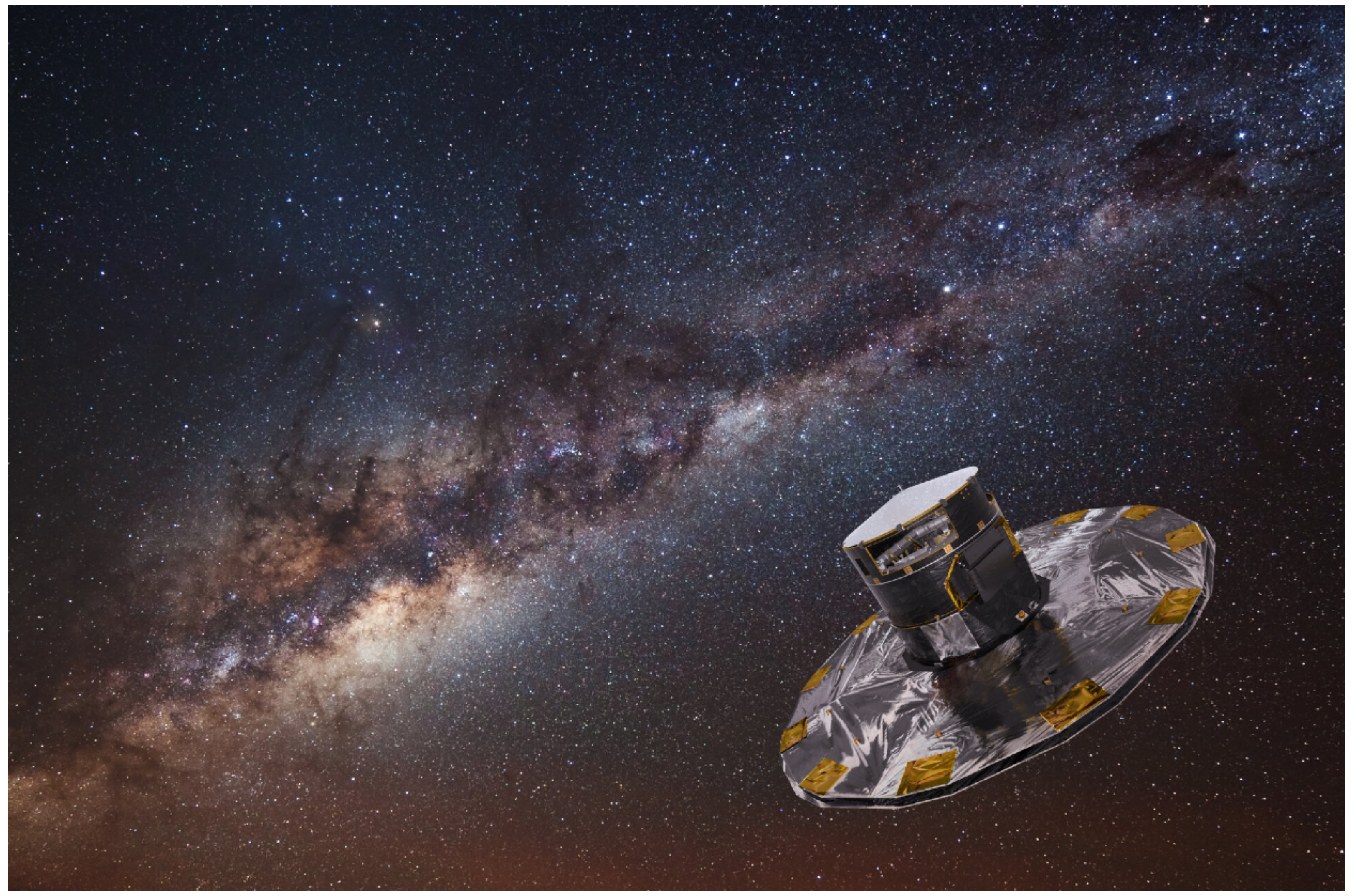
$$M_{\mathrm{vir}} = 0.73^{+0.046}_{-0.052} \times 10^{12} M_\odot$$

- Favors an NFW cuspy DM profile
- Disfavor oblate shape
- The local DM density can be narrow down

Dark matter density profile

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

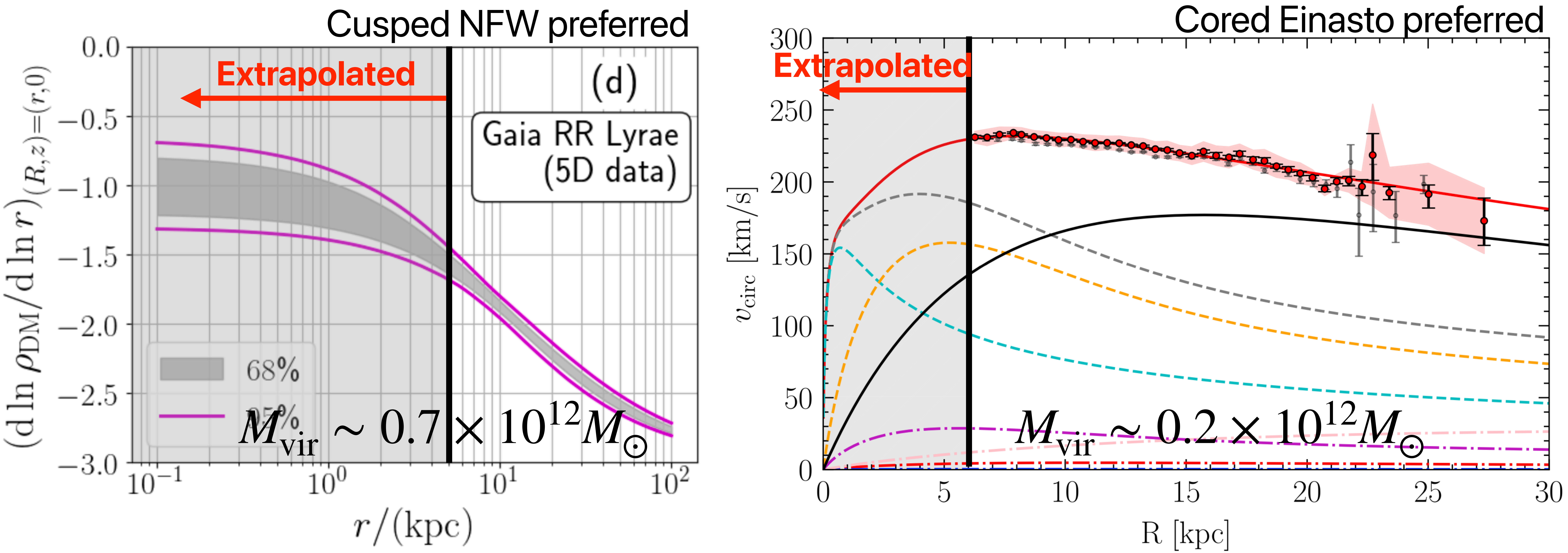




- Exponential drop-off such as the ***cored Einasto profile***, can explain the decline outside of 10 kpc.
- Estimated virial mass of the MW is $\sim 1.8 \times 10^{11} M_{\odot}$, which is overall lower than the previous estimates.
- The local DM density is 0.447 ± 0.004 [GeV/cm^3].

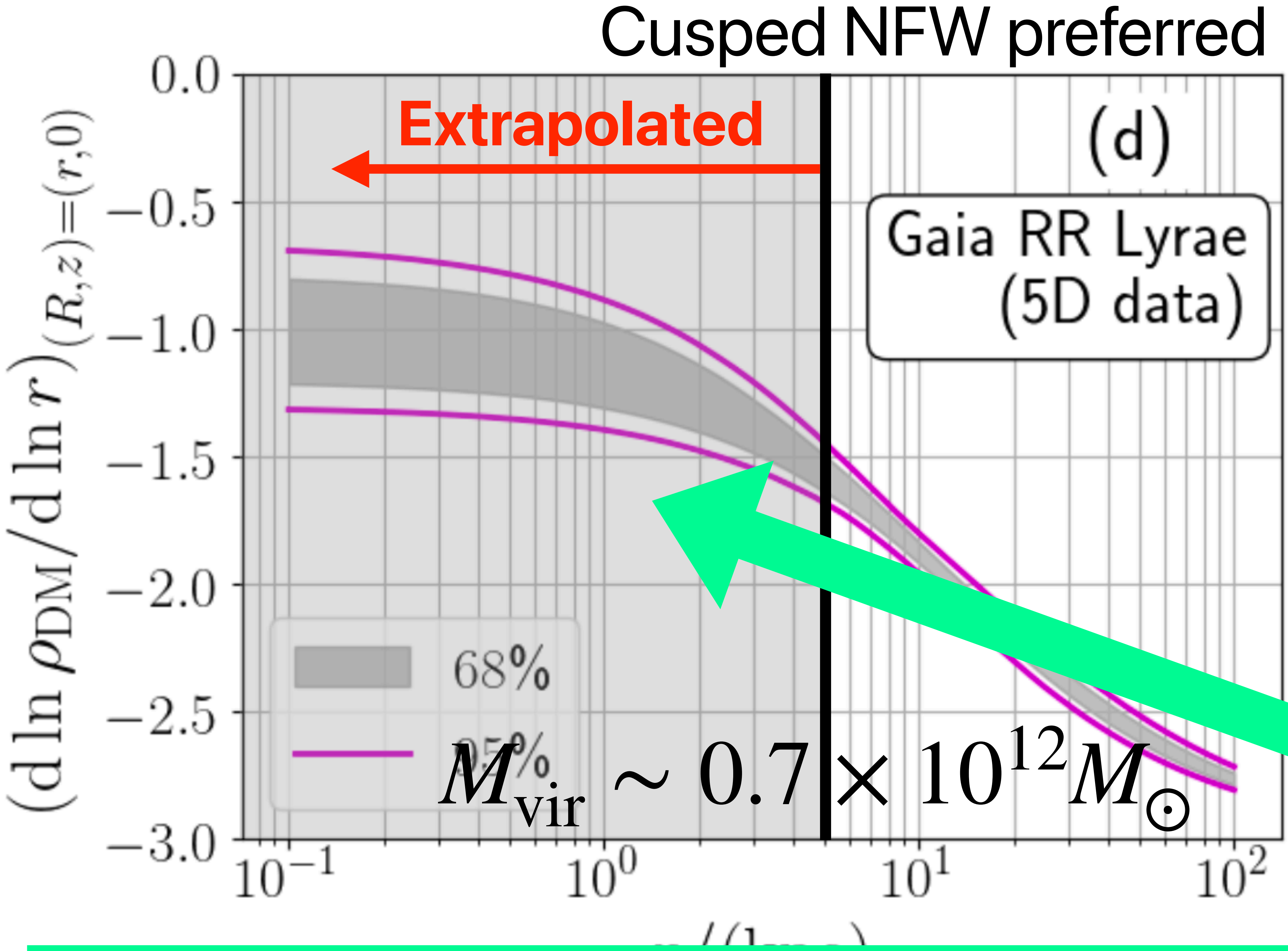
Ou et al. (2023, 2303.12838)

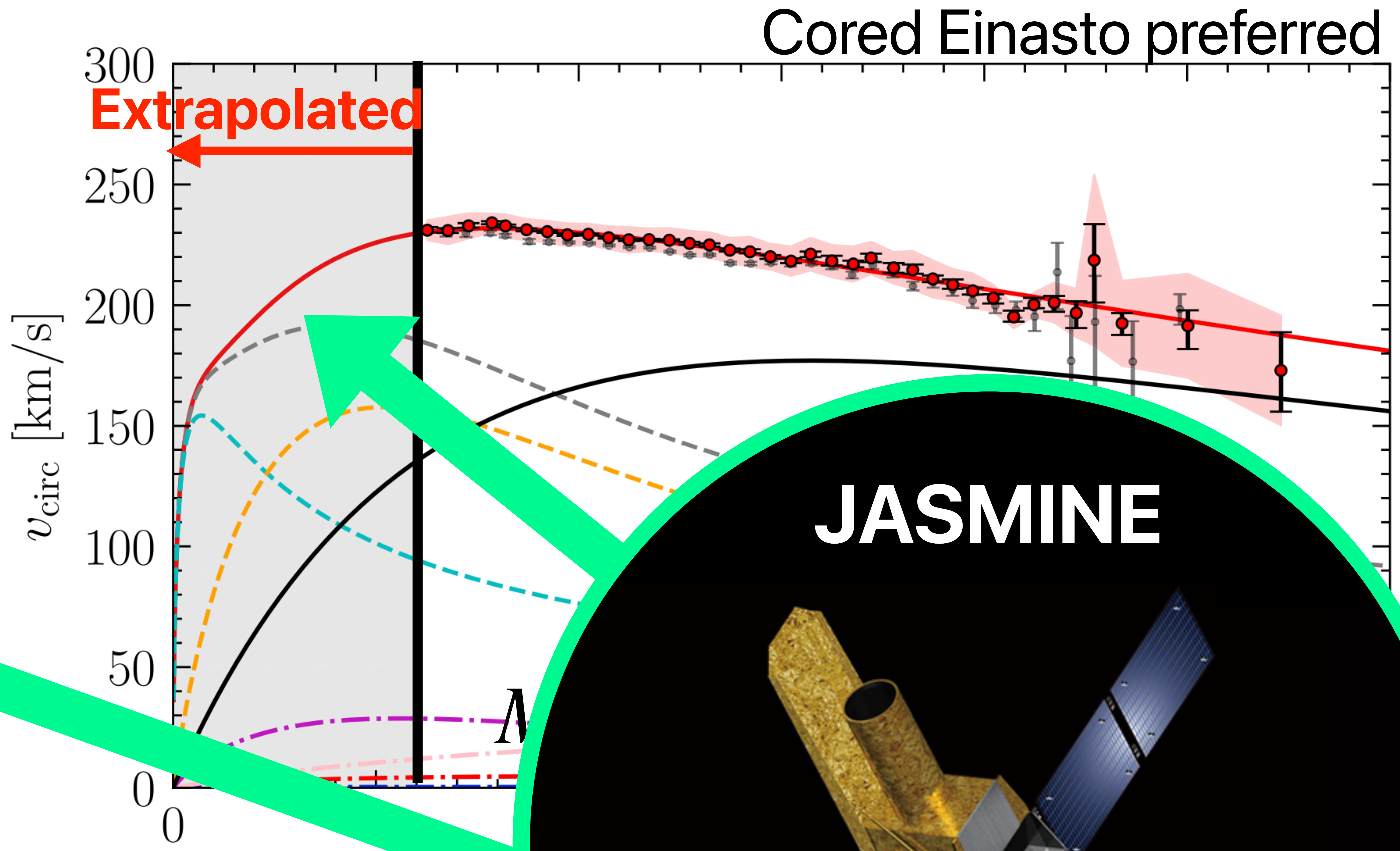
Core or cusp?

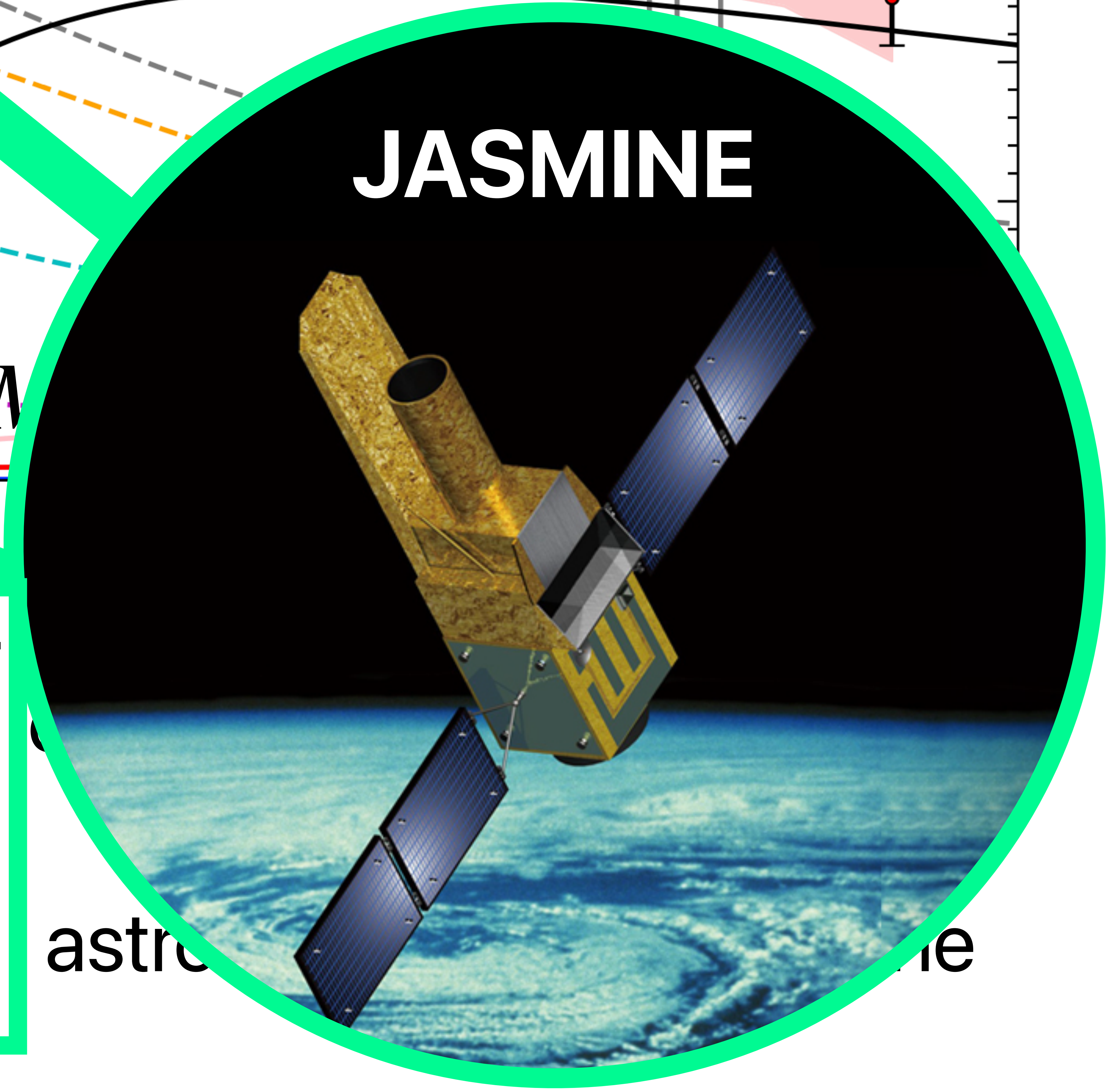


- The DM density inner slope and the virial mass still depends largely on data properties and modelings.
- Gaia, the optical astrometry satellite, ***cannot*** obtain the astrometry data toward the Galactic center due to the dense interstellar dust.

Core or cusp?





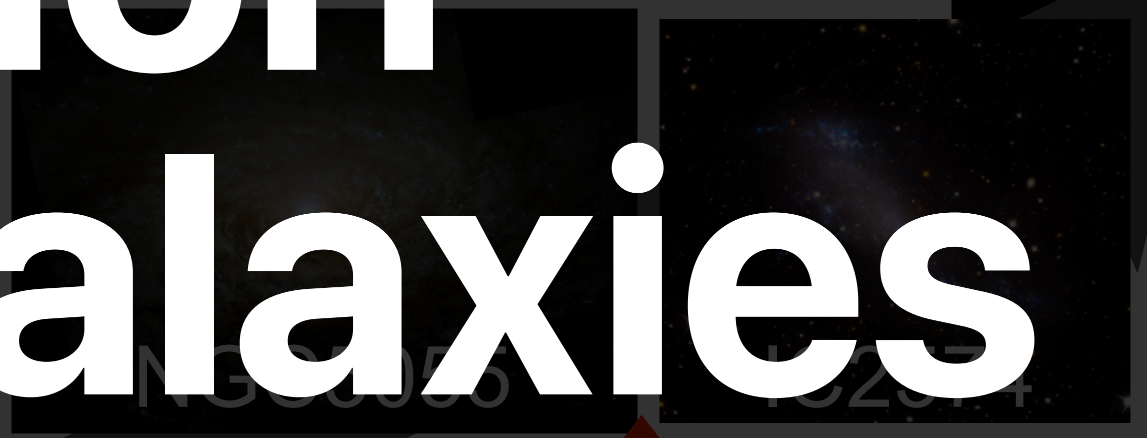


JASMINE will provide detailed information on stellar motion in the interior of the Milky Way, and is expected to greatly improve the determination of the dark matter distribution in the central region.

Dark matter distribution in the dwarf spheroidal galaxies

How to get limits on DM distribution?

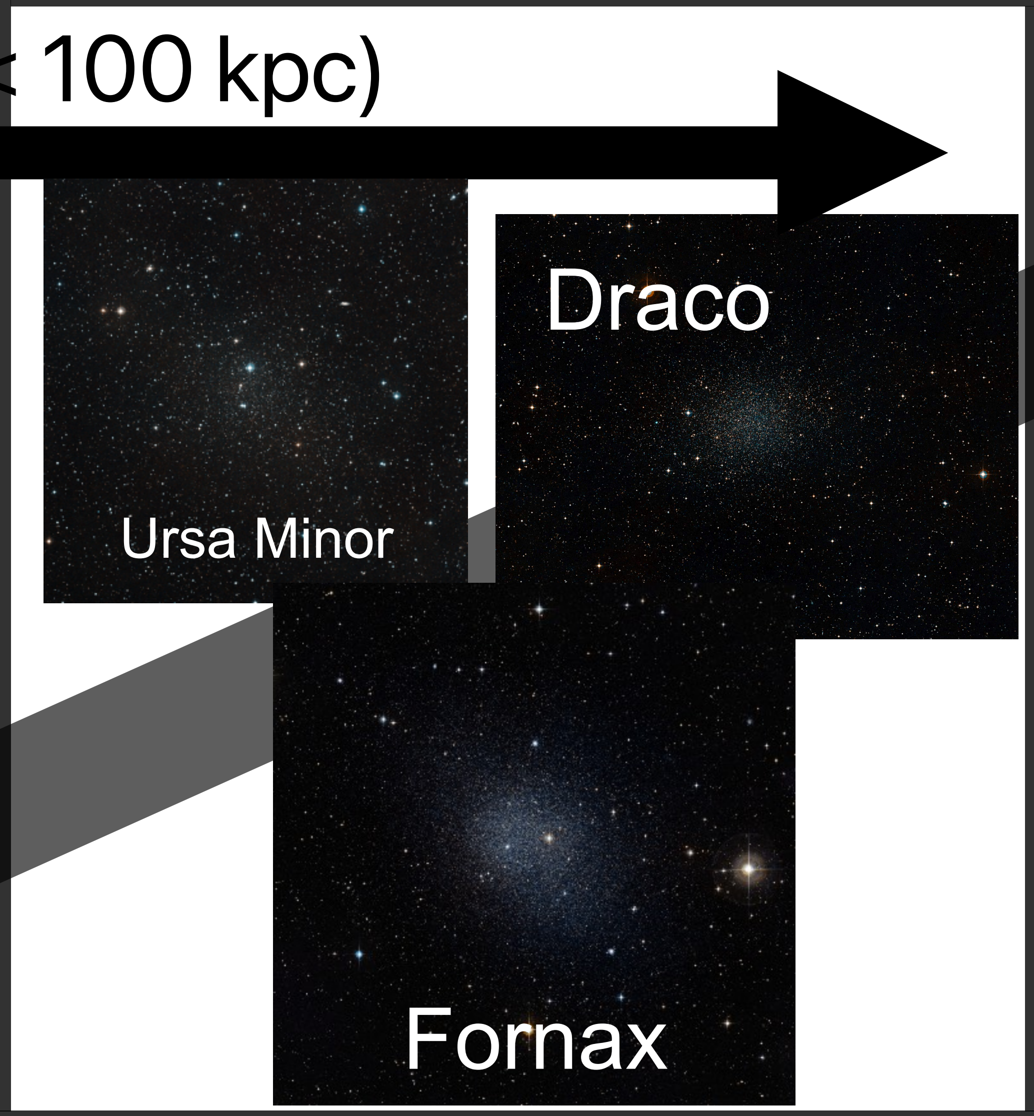
Local Volume: low surface brightness gals (< 10 Mpc)



HI/Hα gas rotation vel.
Spectroscopy/Radio

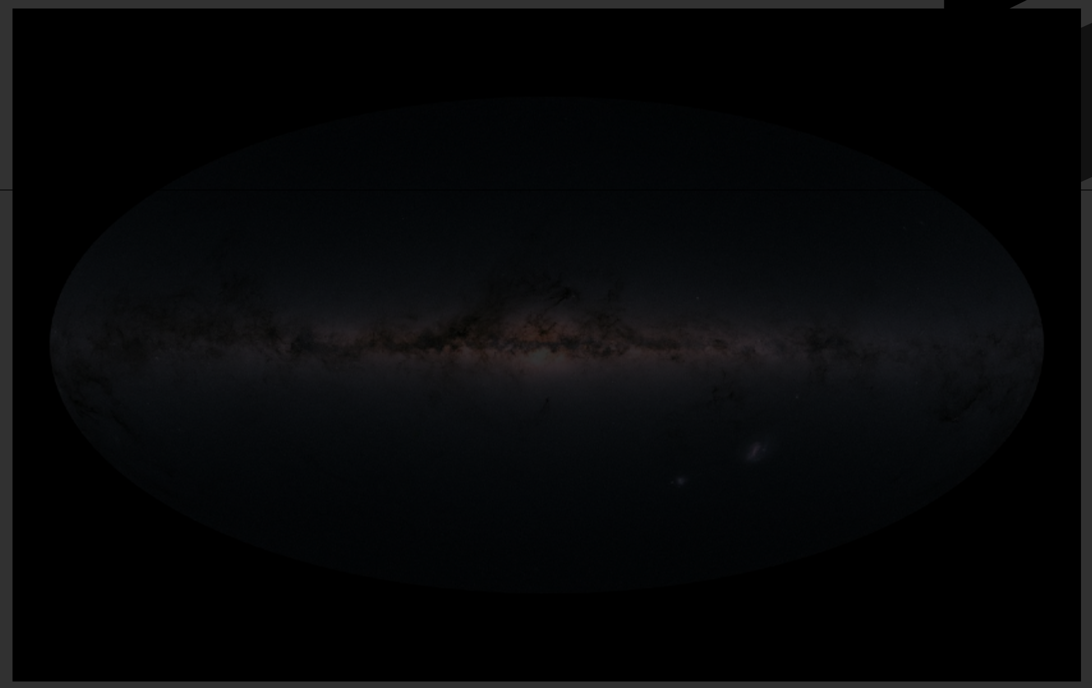
+ HI/Hα gas rotation vel.
Photometry/Radio

MW dwarf spheroidal galaxies (D < 100 kpc)



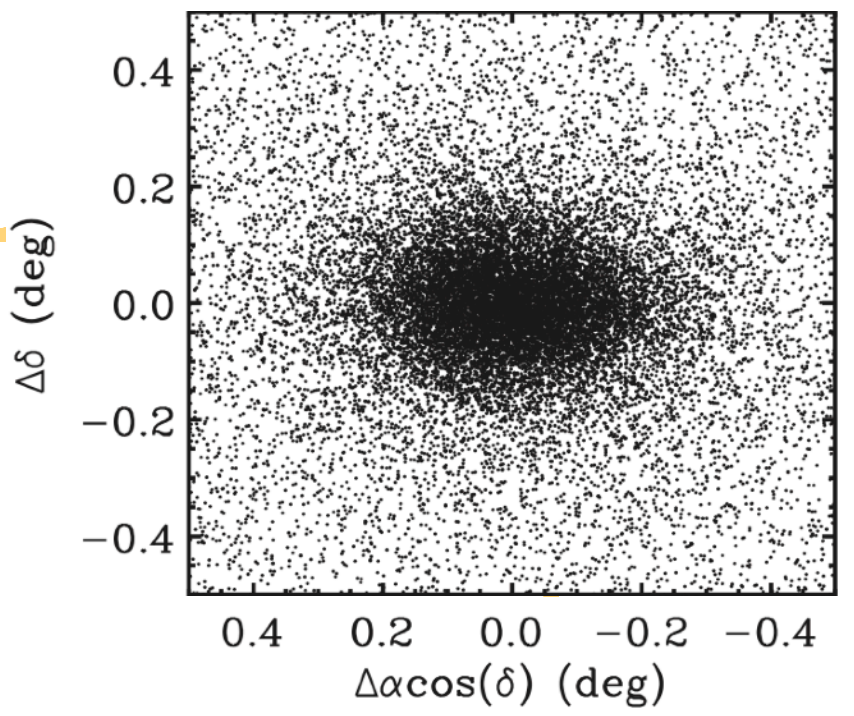
Projected position + line-of-sight vel.
Photometry Spectroscopy

Our Galaxy (D < 20 kpc)



5D (position+proper motion) + radial vel.
Gaia Spectroscopy

Non-spherical dynamical mass models



Non-spherical dark matter density profile

$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$r^2 = R^2 + \frac{z^2}{Q^2}$$

DM halo axial ratio

Non-spherical stellar profile

$$\rho_*(r_*) = \frac{3L}{4\pi r_p^3}\left[1+\frac{r_*^2}{r_p^2}\right]^{-5/2}$$

$$r_*^2 = R^2 + \frac{z^2}{q^2}$$

stellar axial ratio

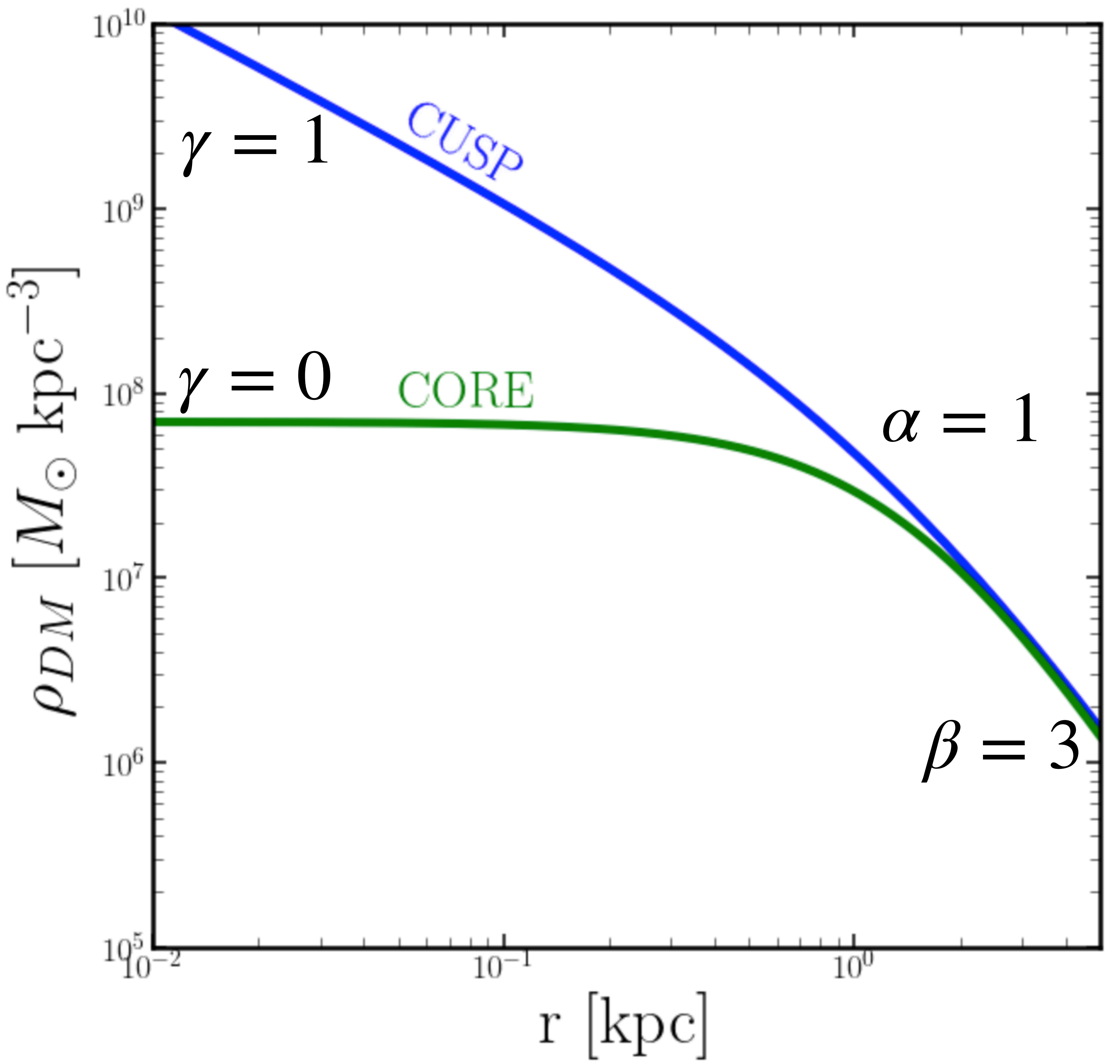
Axisymmetric Jeans equations

$$\overline{u_z^2} = \frac{1}{\nu(R,z)}\int_z^\infty \nu\frac{\partial\Phi}{\partial z}dz,$$

$$\overline{u_\phi^2} = \frac{1}{1-\beta_z}\left[\overline{u_z^2} + \frac{R}{\nu}\frac{\partial(\nu\overline{u_z^2})}{\partial R}\right] + R\frac{\partial\Phi}{\partial R}$$

$\beta_z = 1 - \overline{u_z^2}/\overline{u_R^2}$: velocity anisotropy (unknown)

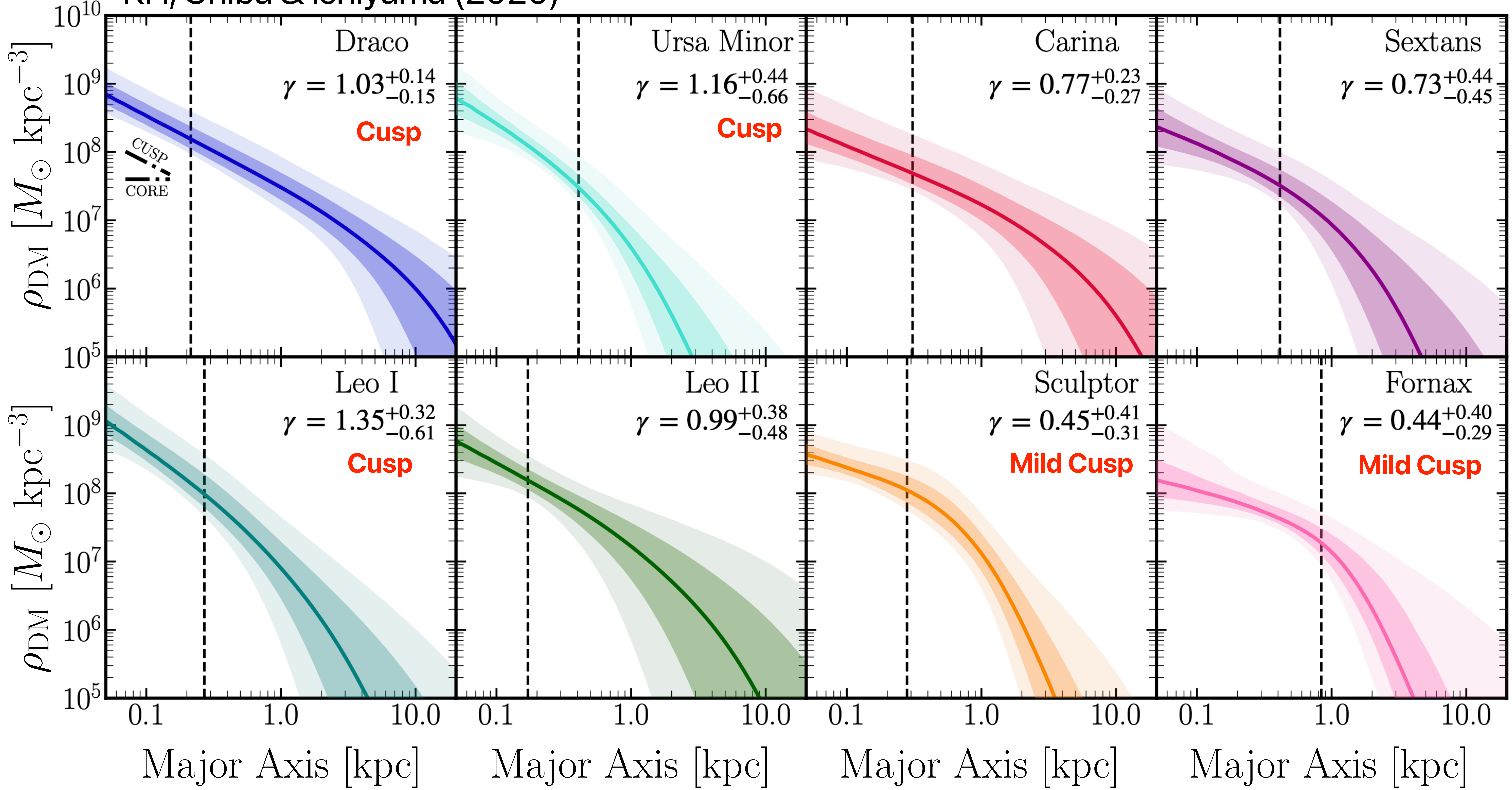
$\sigma_{\rm l.o.s}^{\rm (Theory)}$ **FIT** $\sigma_{\rm l.o.s}^{\rm (observed)}$



Dark matter density profiles: Classicals

KH, Chiba & Ishiyama (2020)

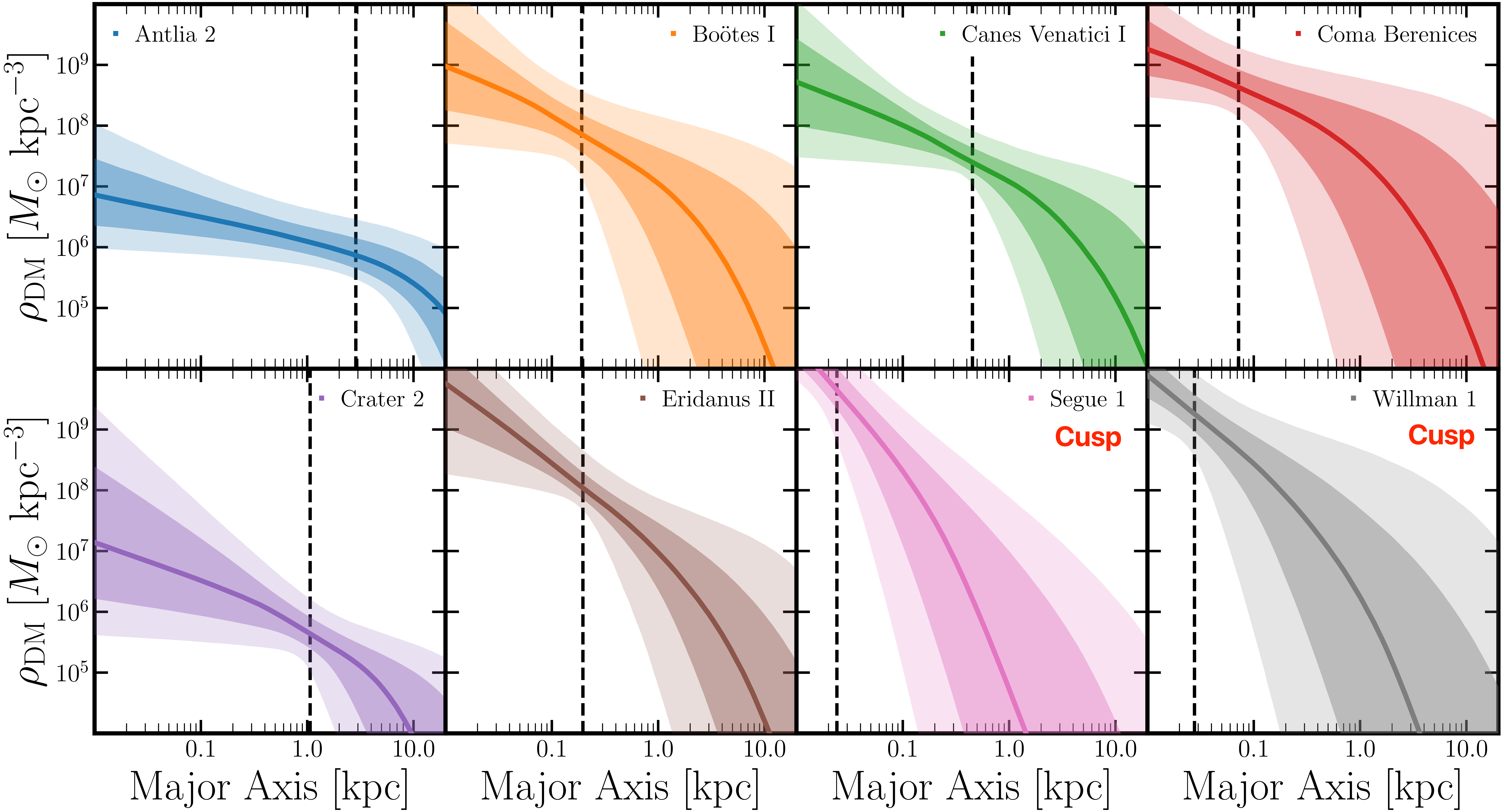
$(0.0 \leq \gamma \leq 2.0)$



Dark matter density profiles: UFDs & UDGs

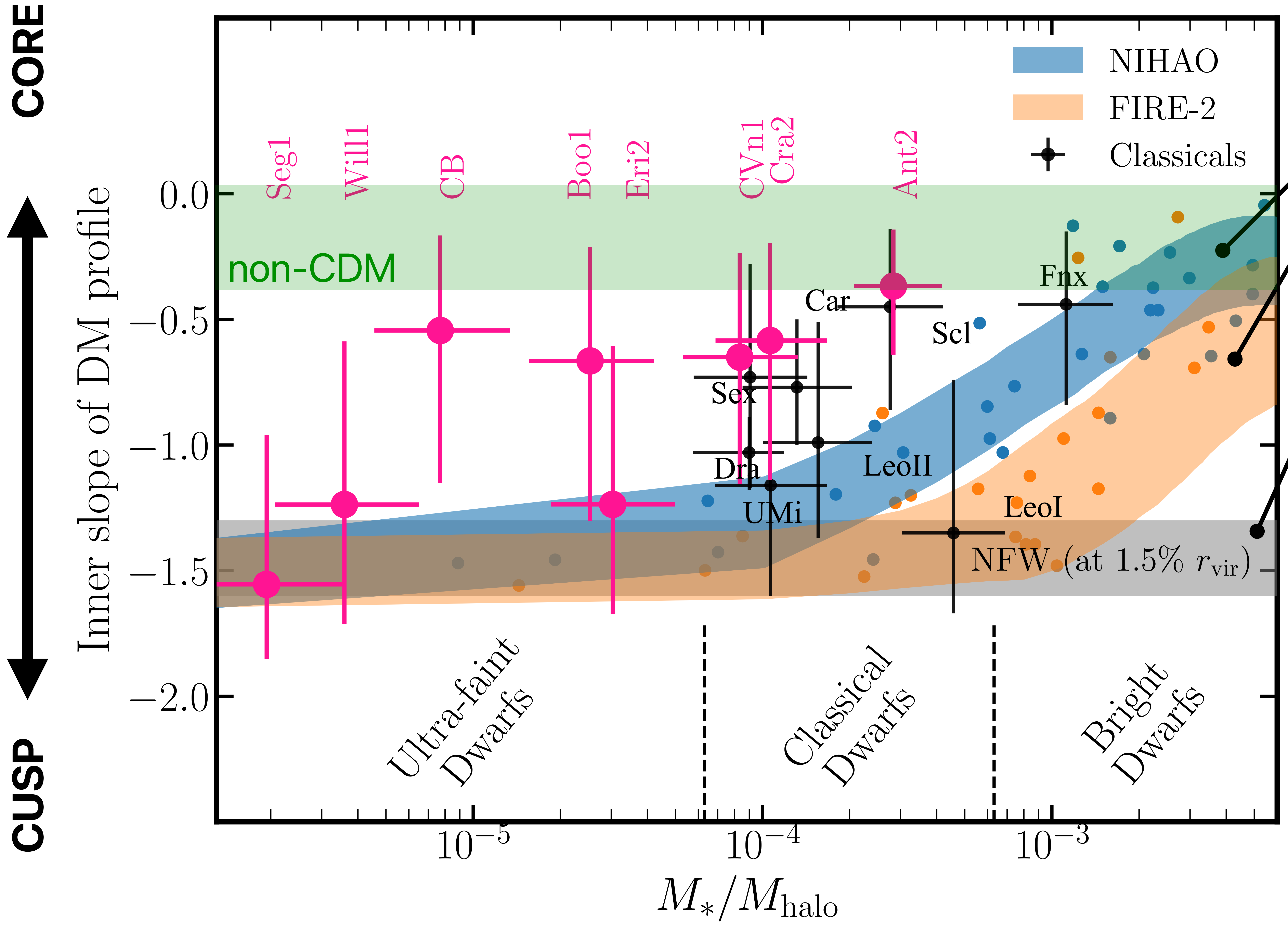
KH, Hirai, Chiba & Ishiyama (2023)

$(0.0 \leq \gamma \leq 2.0)$



Diversity of the DM distributions?

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

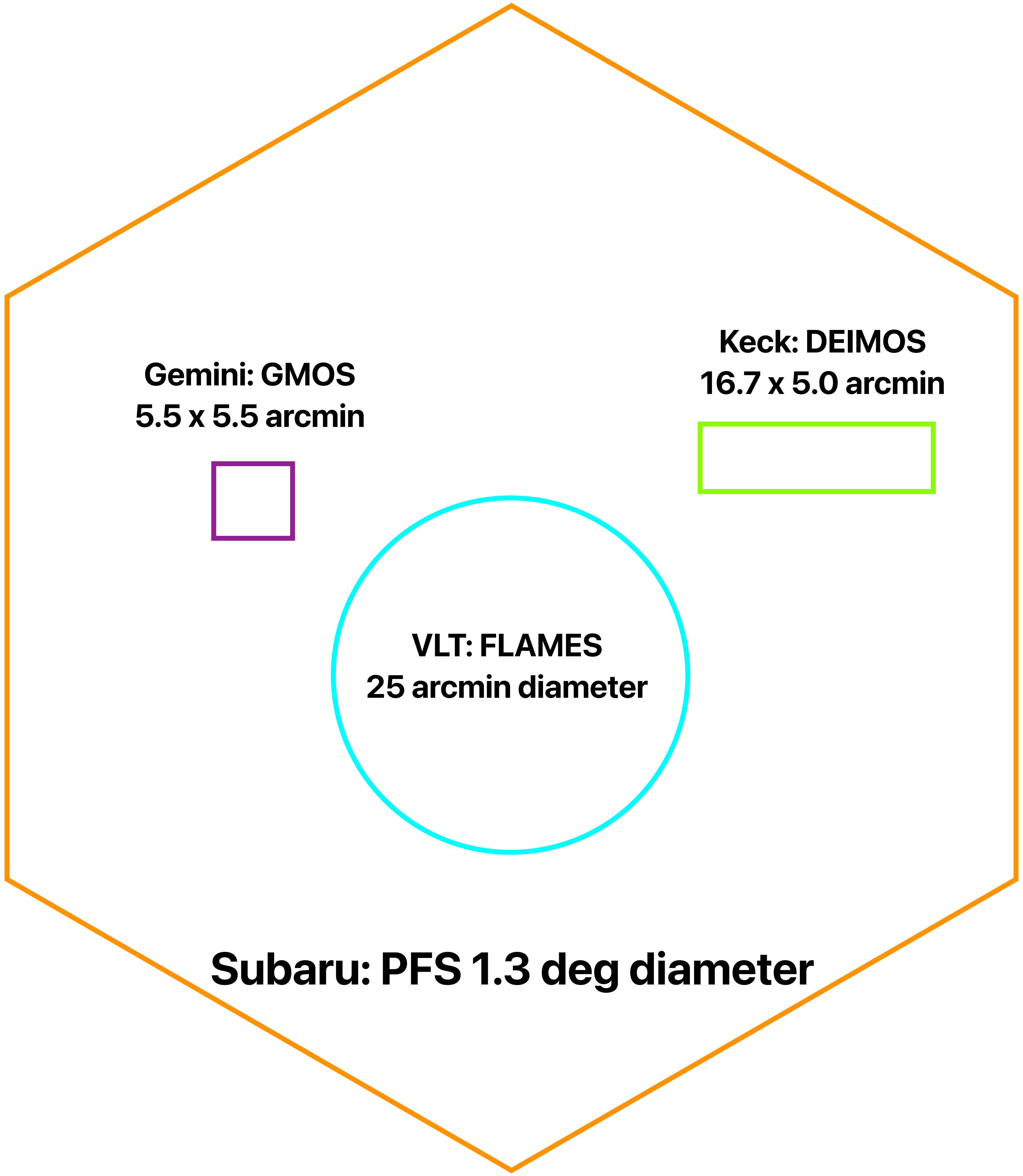


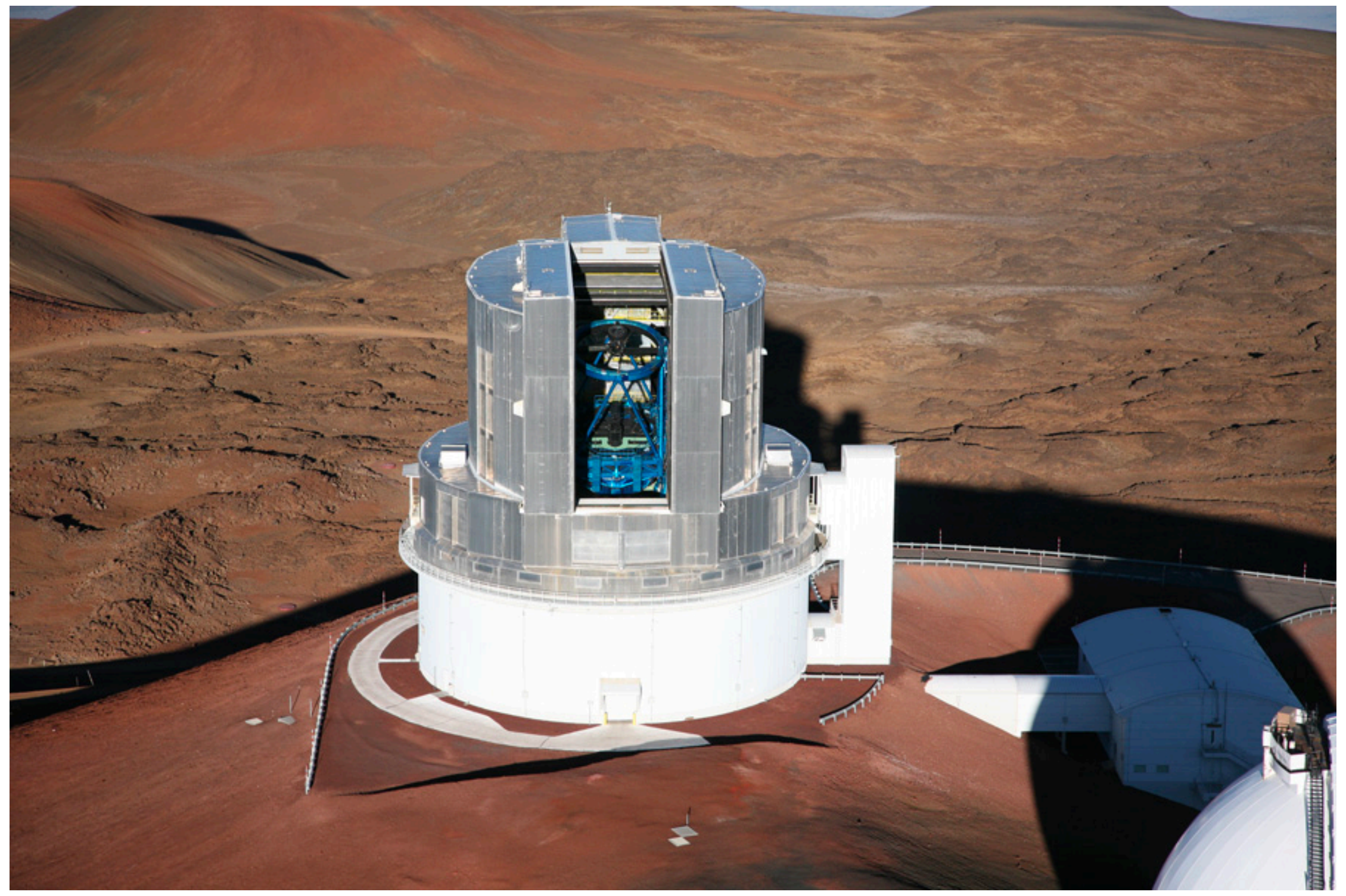
Prediction from LCDM based N-body+hydro sims.

Prediction from LCDM based pure N-body sims.

- Several dSphs (Dra, UMi, Seg1, Will1) favor cusped DM central profiles
- **The diversity of the DM density profiles in the dSphs.**
- There are still **large uncertainties on their inner slopes**.

Uniqueness of Subaru-PFS





Subaru Telescope

+

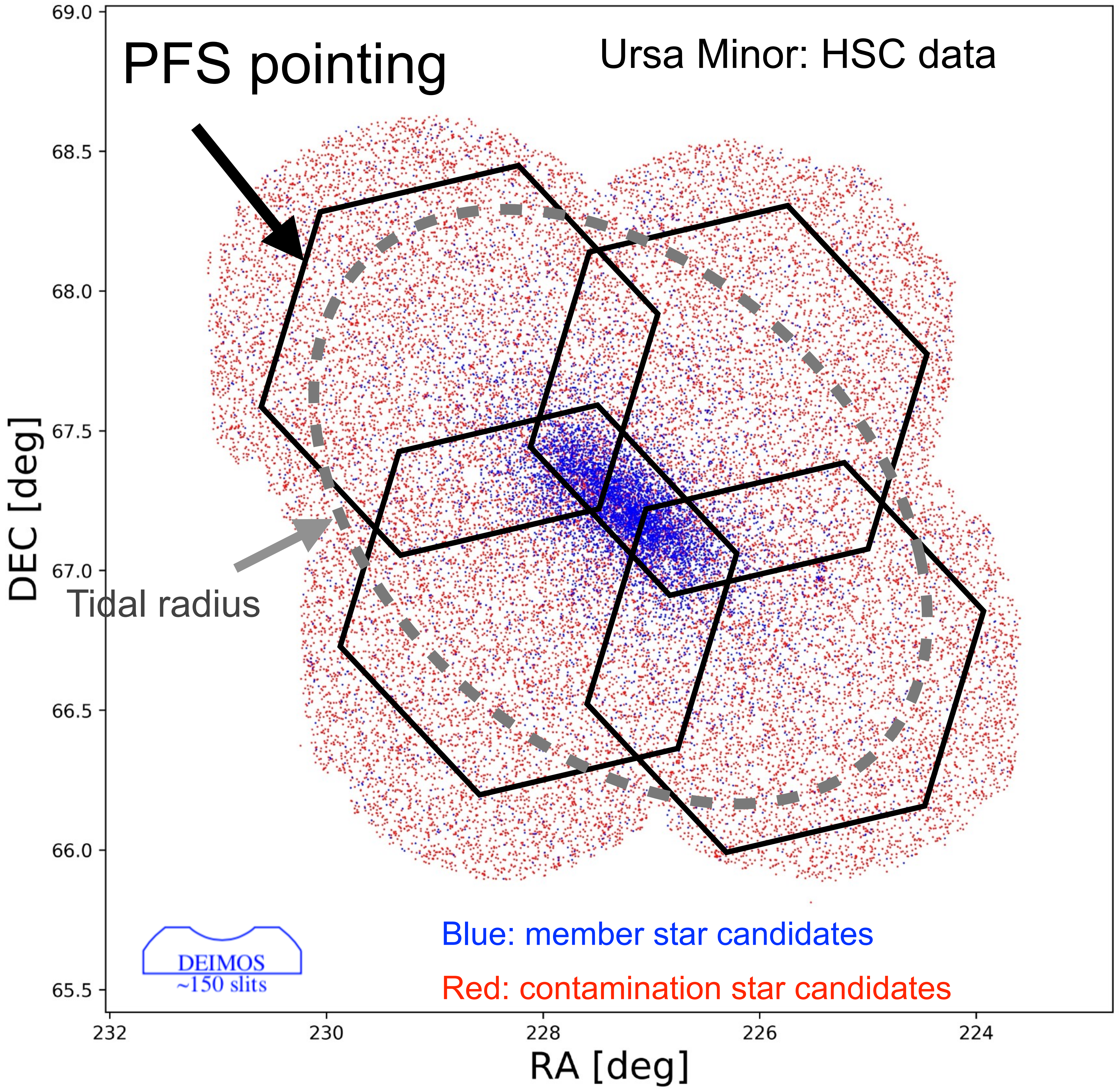
Wide Field of View

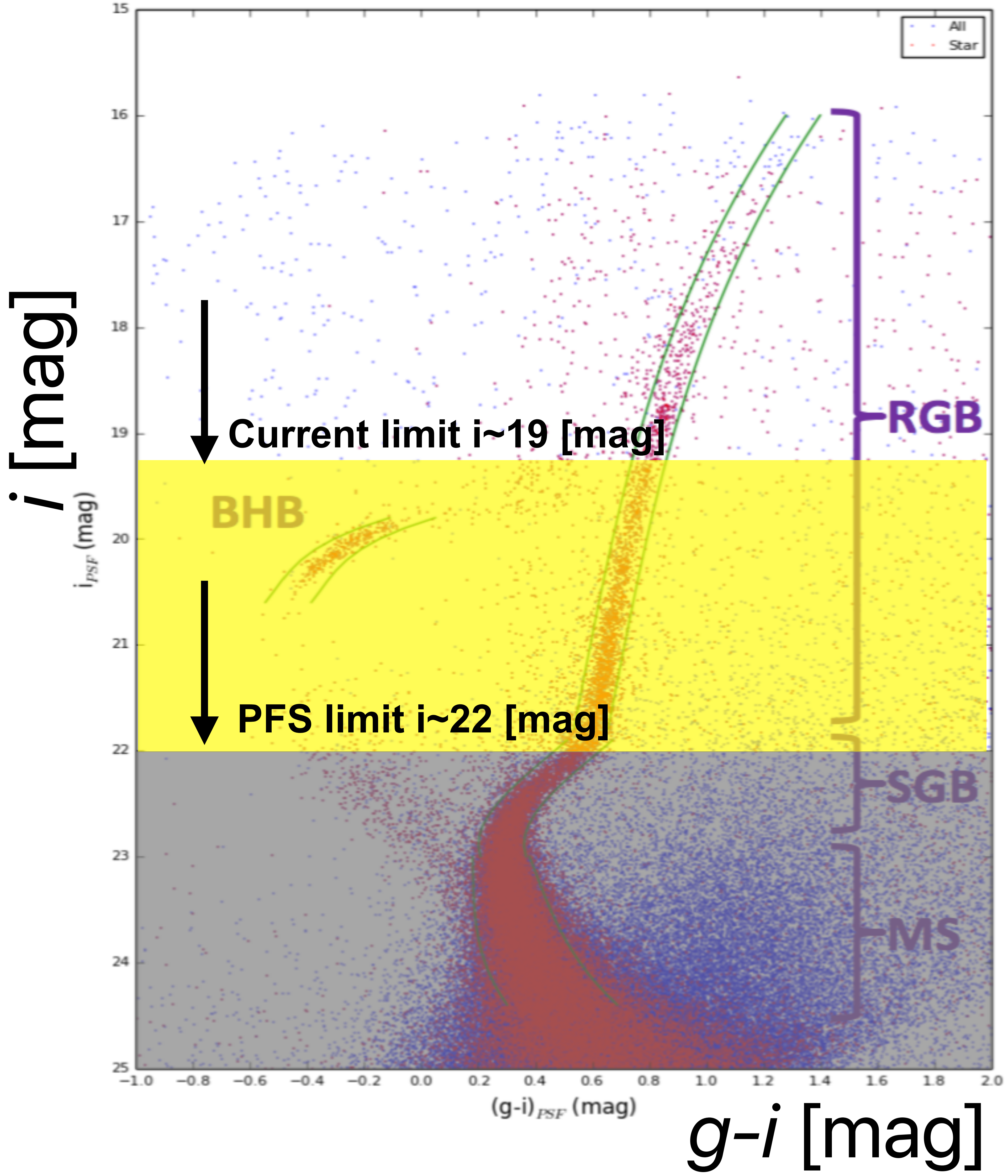
||

Wide and Deep

spec. survey

Uniqueness of Subaru-PFS





Current → PFS

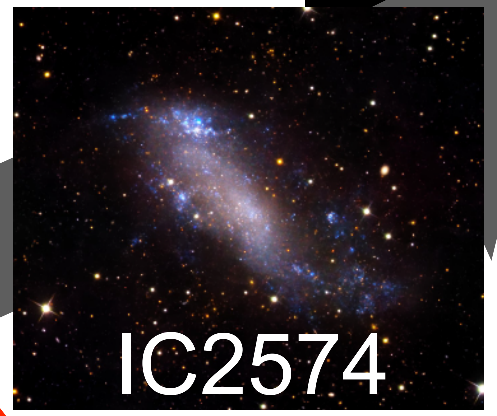
$N_{spec.} \sim 300$ ⇨ $N_{spec.} \sim 5000$

<u>Wide & deep PFS survey:</u>

Huge number of stellar kinematics out to the outskirts of the Galactic dSphs.

How to get limits on DM distribution?

Local Volume: low surface brightness gals (< 10 Mpc)



HI/Hα gas rotation vel.
Spectroscopy/Radio

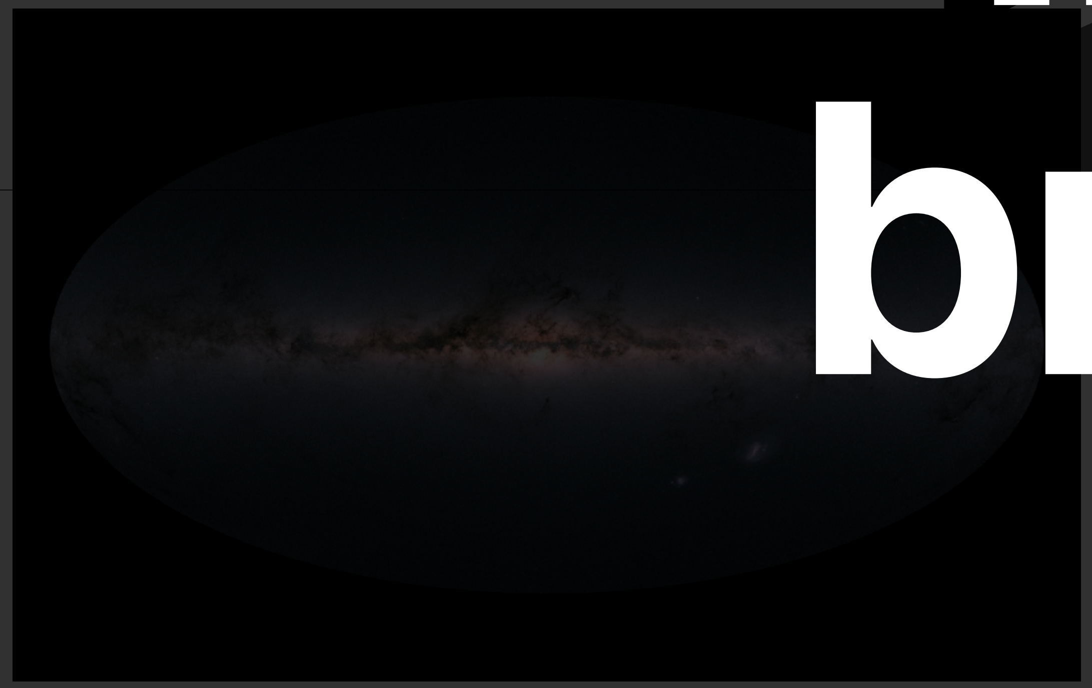
Local Group: dwarf Irregular, M31 (< 1 Mpc)

+ HI/Hα gas rotation vel.

MW dwarf spheroidal galaxies (*D* < 100 kpc)

Projected position + line-of-sight vel.
Photometry Spectroscopy

Our Galaxy (*D* < 20 kpc)

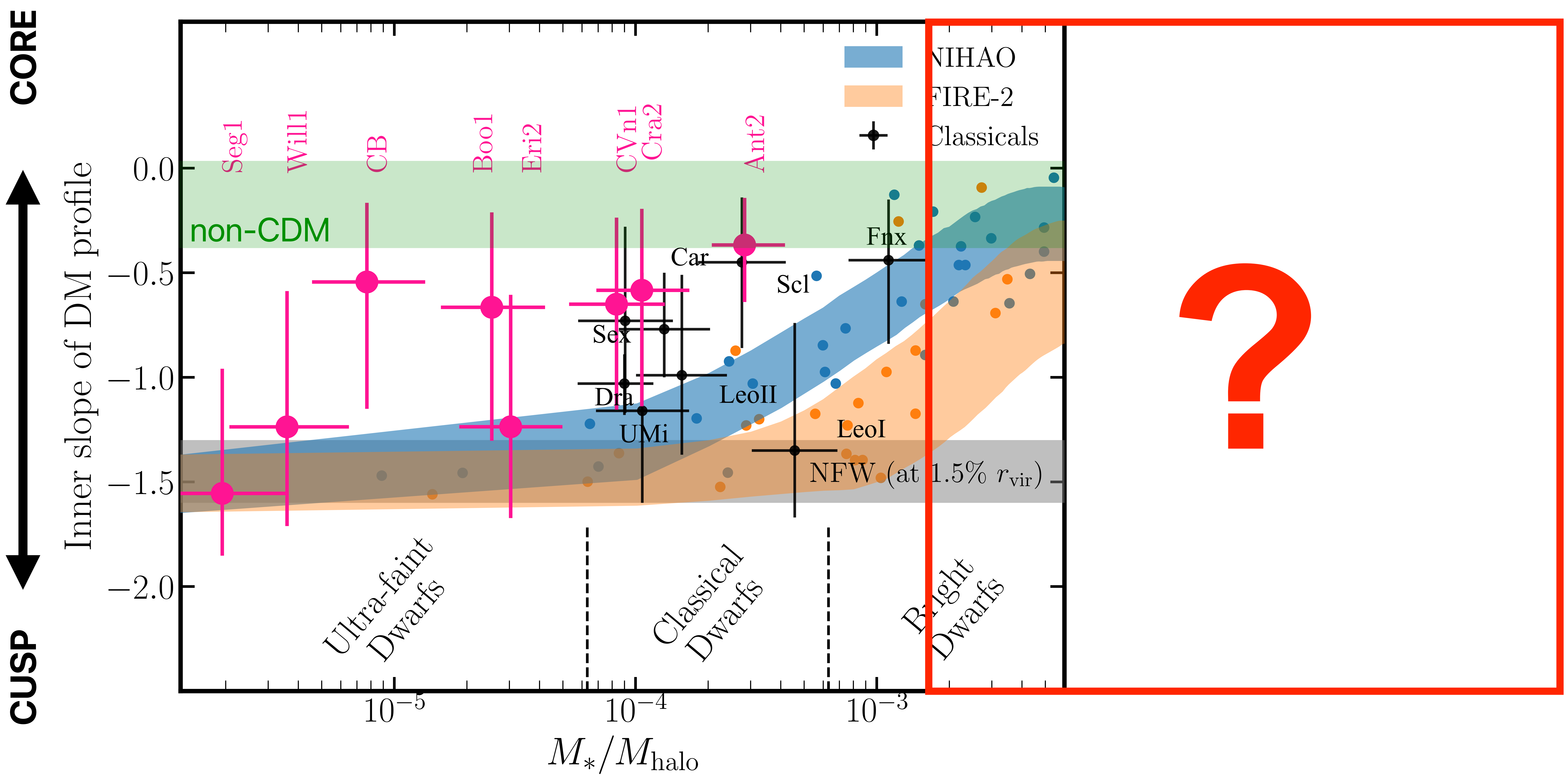


5D (position+proper motion) + radial vel.
Gaia Spectroscopy

Dark matter distribution in the low surface brightness galaxies

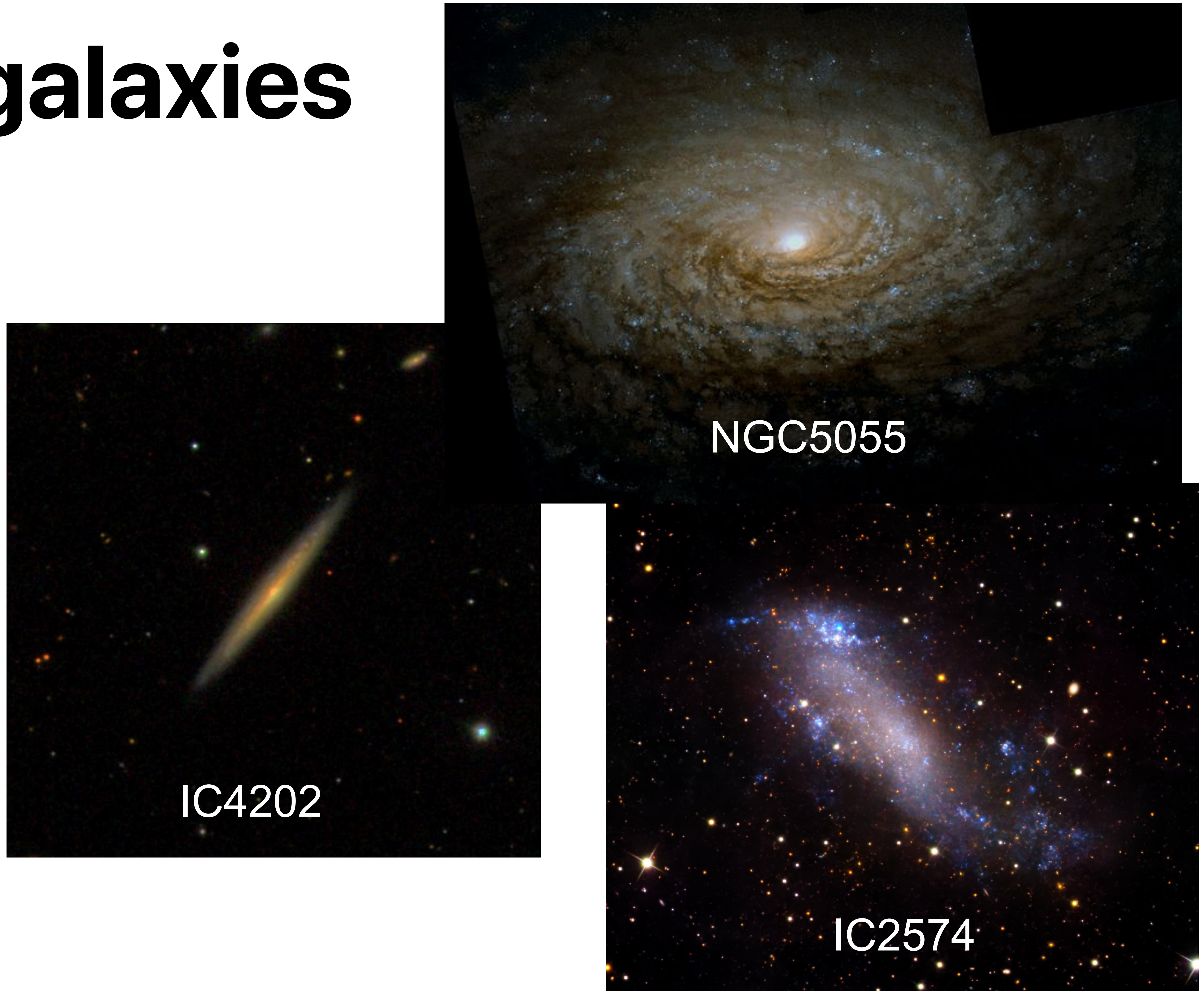
Diversity of the DM distributions?

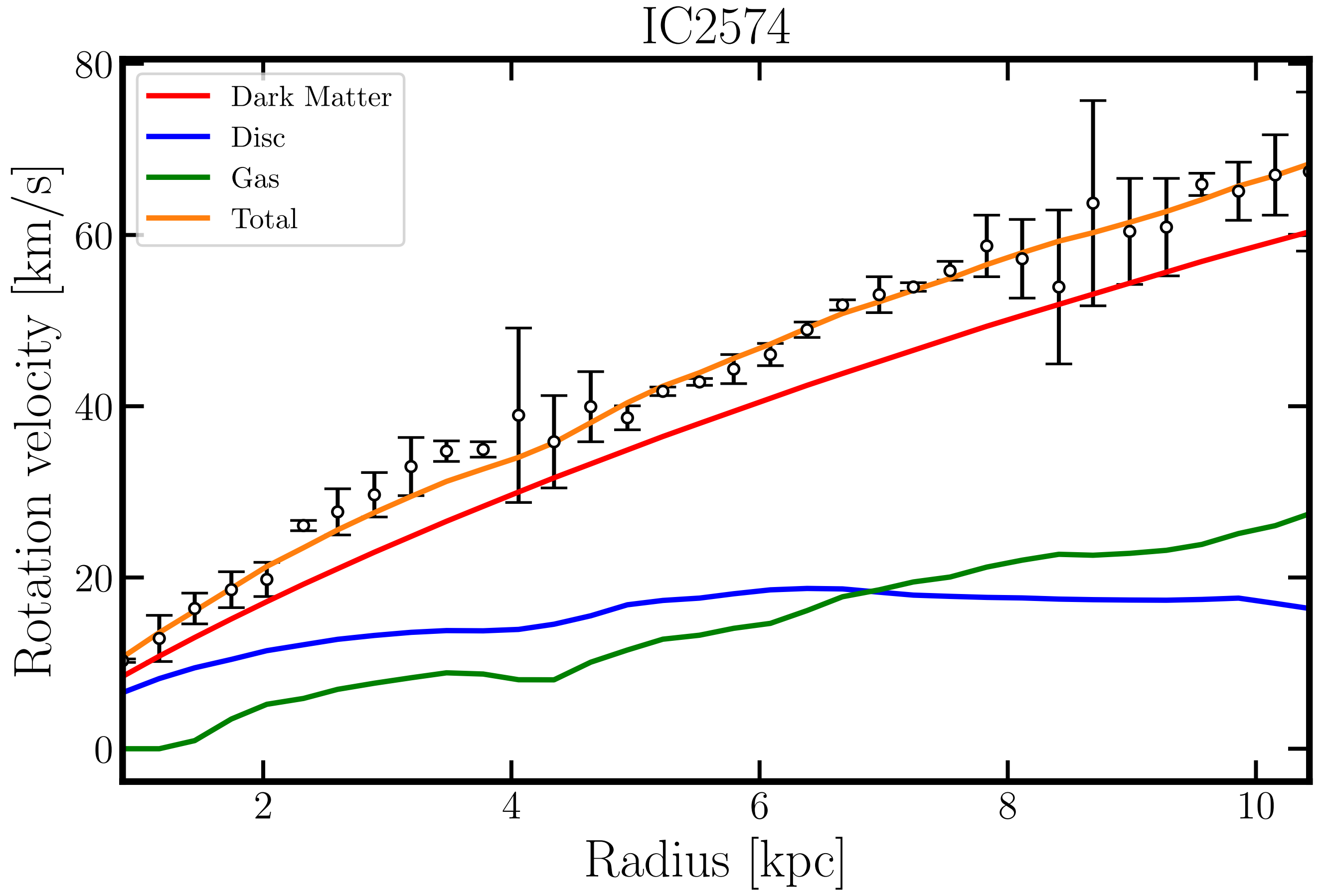
KH, Chiba & Ishiyama (2020)
KH, Hirai, Chiba & Ishiyama (2023)

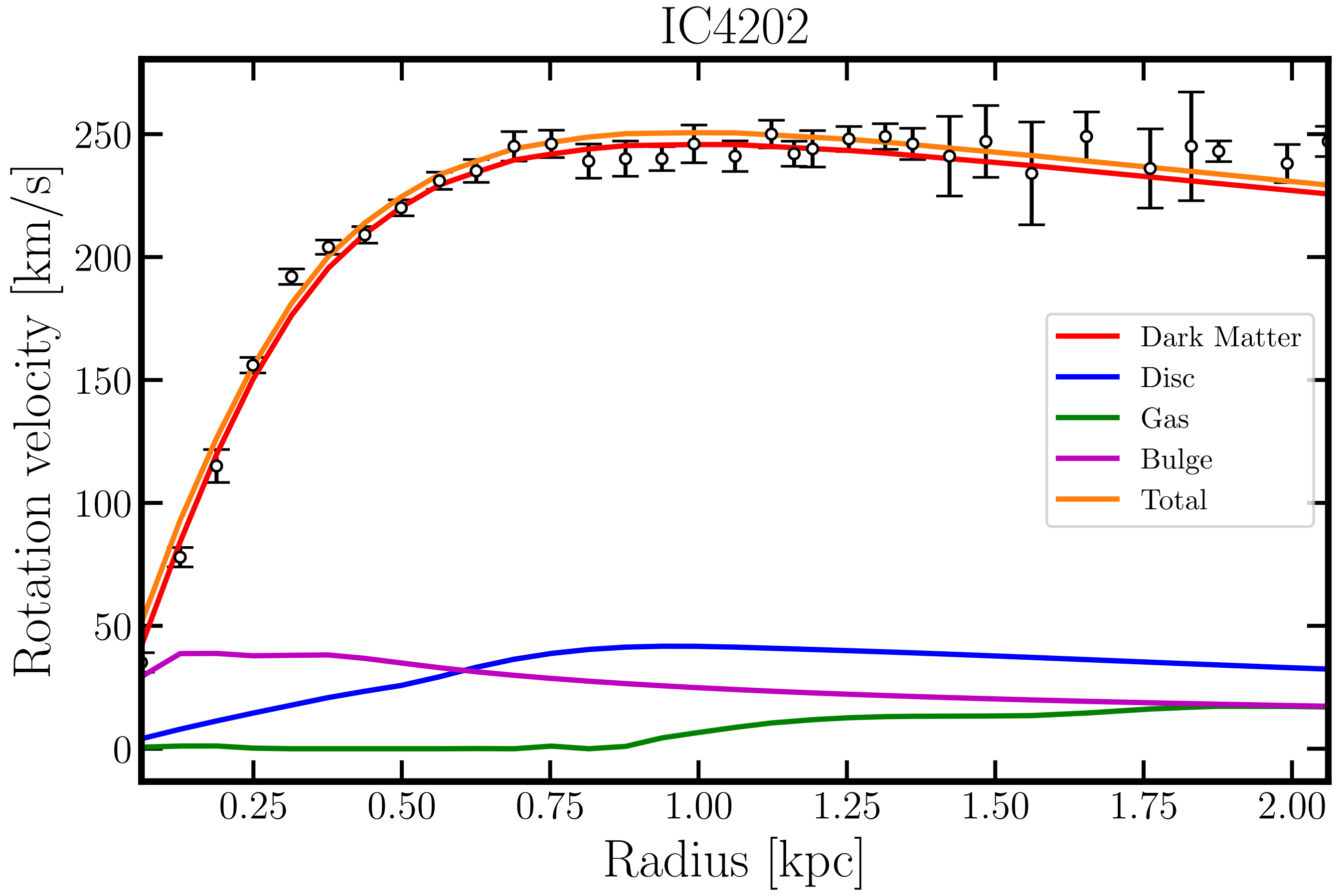


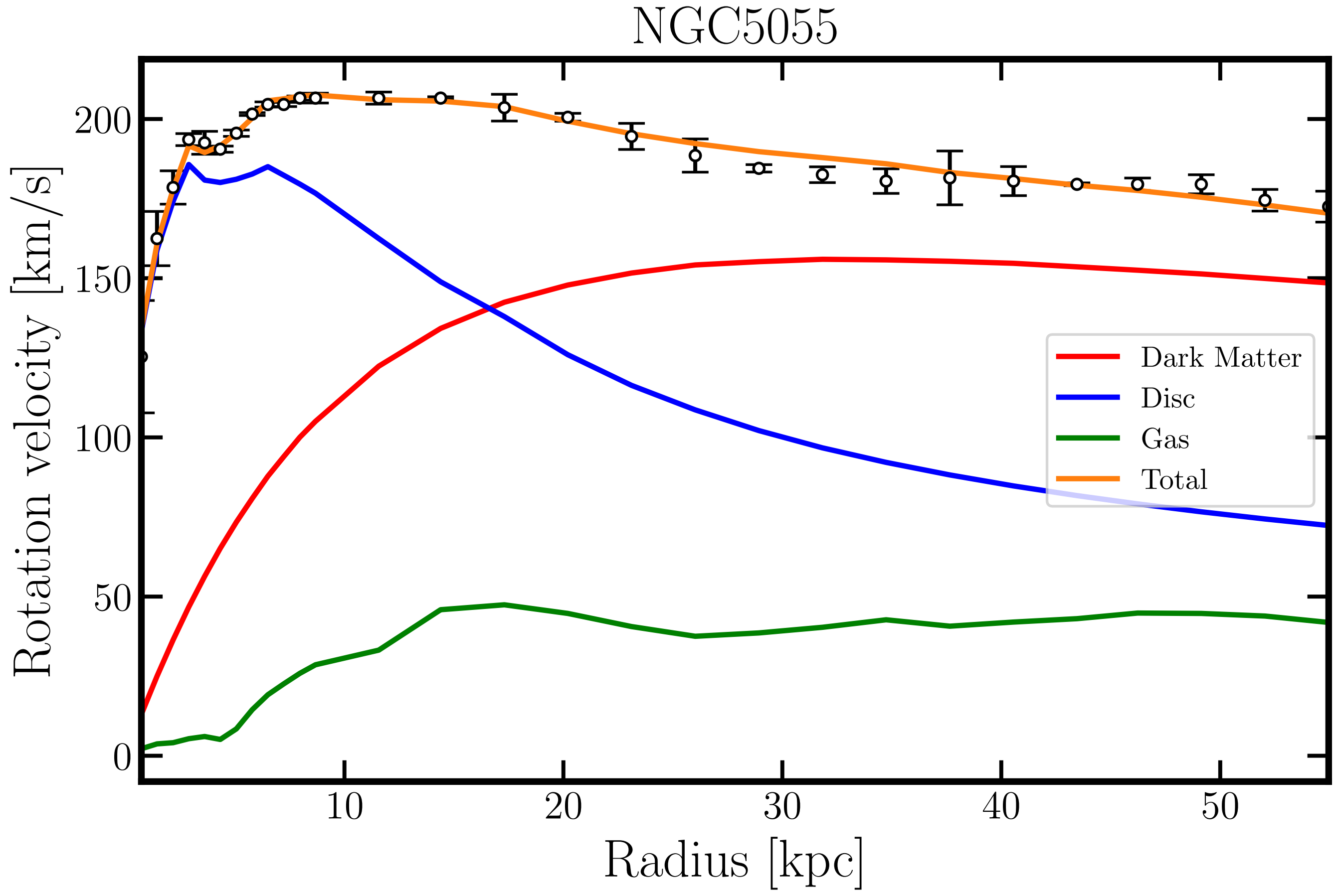
Low surface brightness (LSB) galaxies

- Most LSBs are bright dwarf galaxies, and most of their baryonic matter is in the form of neutral gaseous hydrogen, rather than stars.
- They appear to have over 95% of their mass as dark matter.
- Rotation curves can be measured by HI or Hα observations.
- There are a variety of rotation curves.









Deriving non-spherical DM profiles in the LSBs

Non-spherical dark matter density profile

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$r^2 = R^2 + \frac{z^2}{Q^2}$$

DM halo axial ratio

- Circular velocity from DM density profile

$$V_{\mathrm{circ}}^2(R) = R|-\nabla\Phi|$$

$$g_R(R, z=0) = -\frac{\partial\Phi}{\partial R} = -2\pi G Q a_0^3 R \int_0^\infty d\tau \frac{\rho_{\mathrm{DM}}(R, z=0)}{(\tau + a_0^2)^2\sqrt{\tau + Q^2 a_0^2}}$$

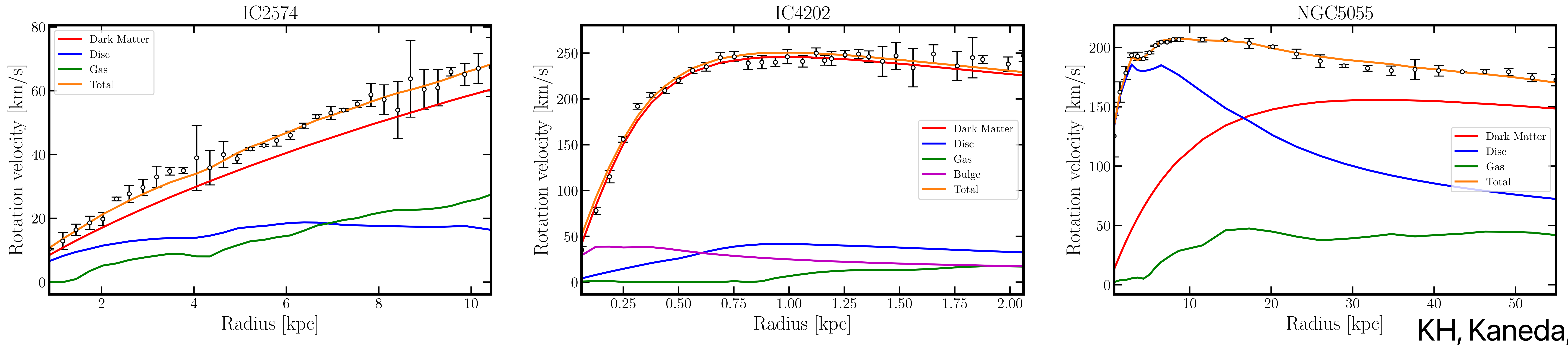
- Total circular velocity

$$V_{\mathrm{tot}}^2 = V_{\mathrm{DM}}^2 + \Upsilon_{\mathrm{disk}} V_{\mathrm{disk}}^2 + \Upsilon_{\mathrm{bulge}} V_{\mathrm{bulge}}^2 + V_{\mathrm{gas}}^2$$

From SPARC (Spitzer Photometry & Accurate Rotation Curves) obs.

- Free parameters

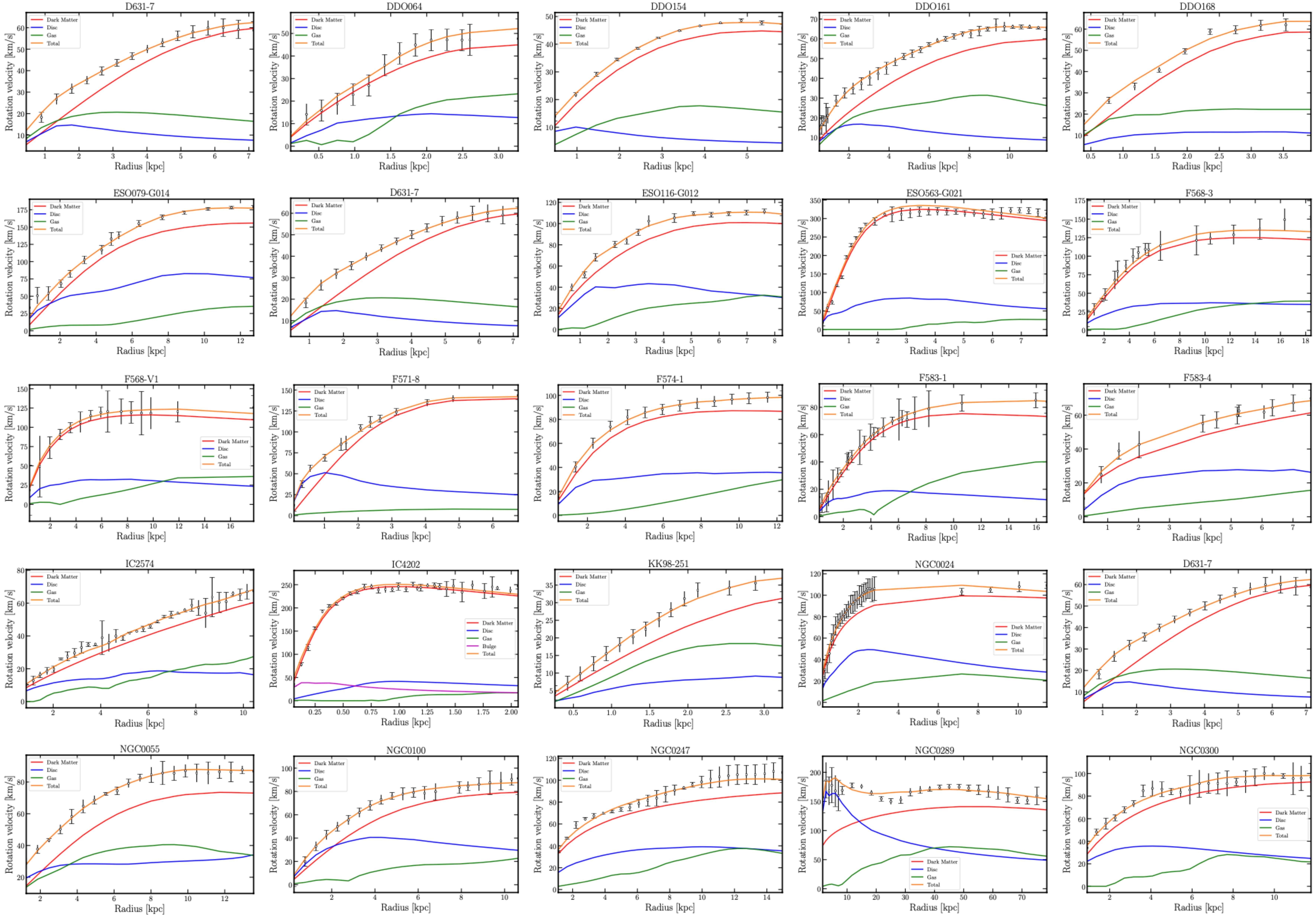
$$\Theta = (\alpha, \beta, \gamma, \rho_s, r_s, \Upsilon_{\{\mathrm{disk,bulge}\}}, D, i)$$



KH, Kaneda, Mori (in prep.)

Best-fit rotation curves of 115 LSB galaxies

KH, Kaneda, Mori (in prep.)



Orage: total

Red: DM

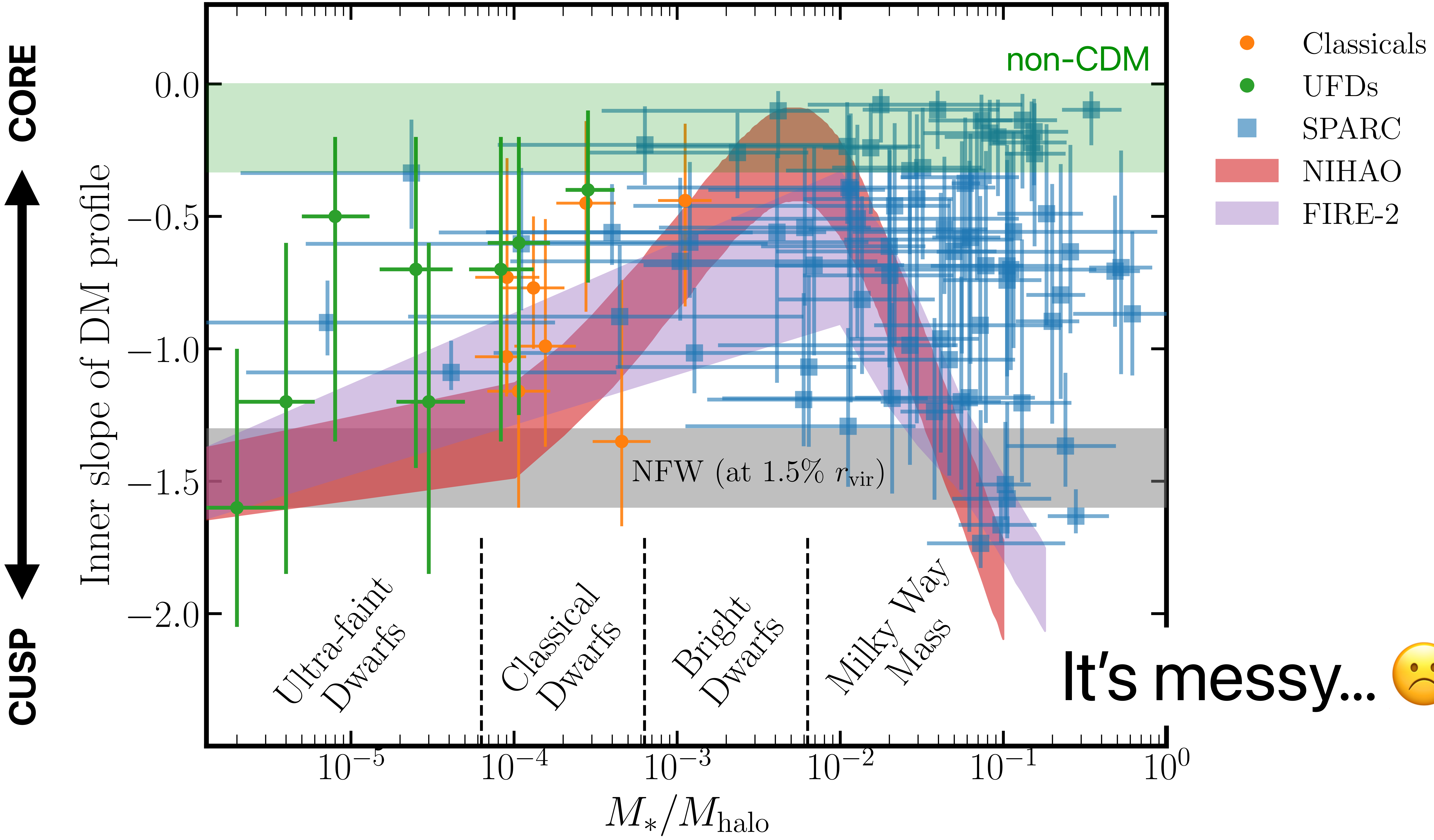
Blue: Disk

Green: Gas

And more…

Diversity of the DM distributions?

KH, Kaneda, Mori (in prep.)



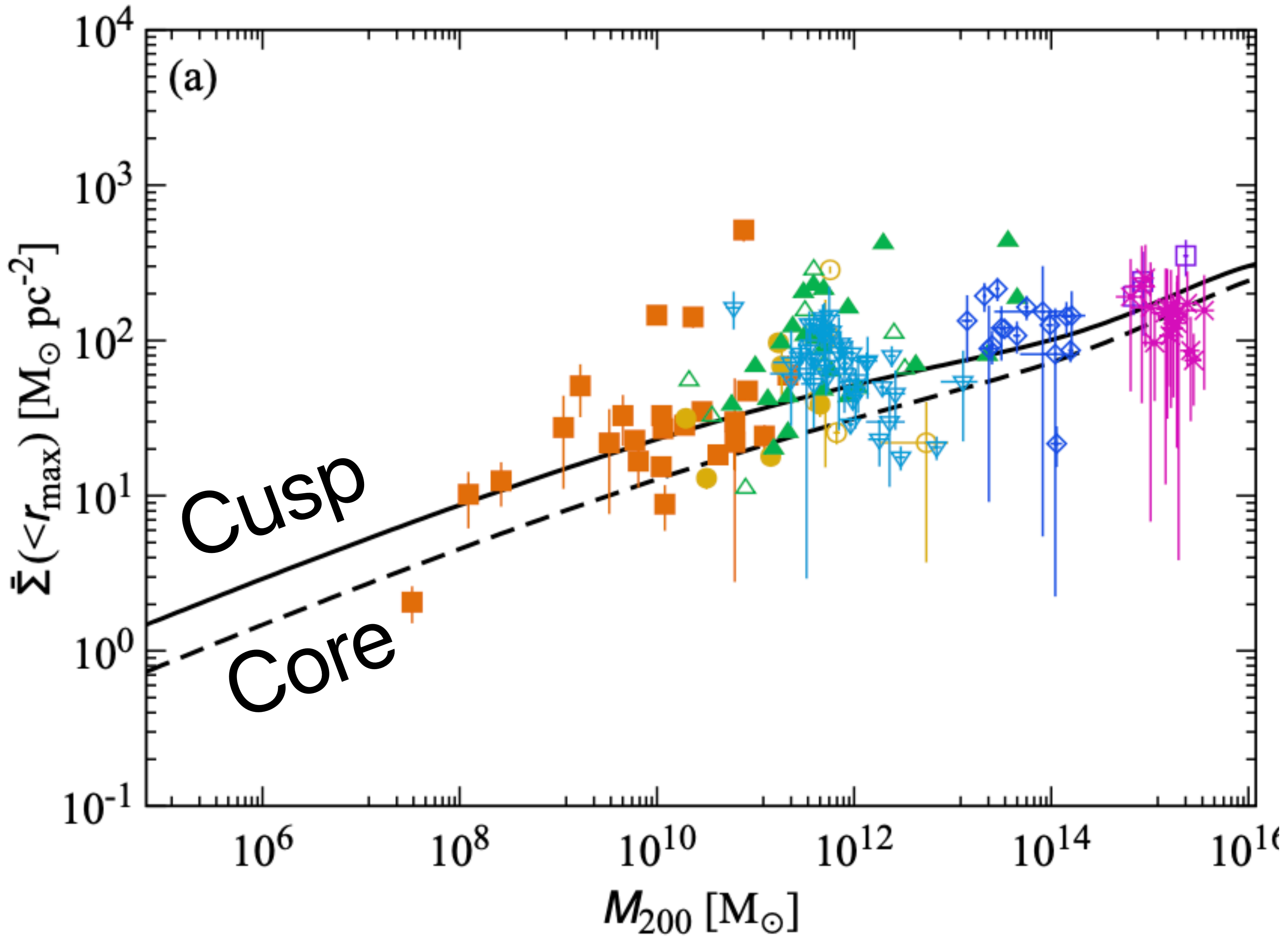
It's messy... ☹️

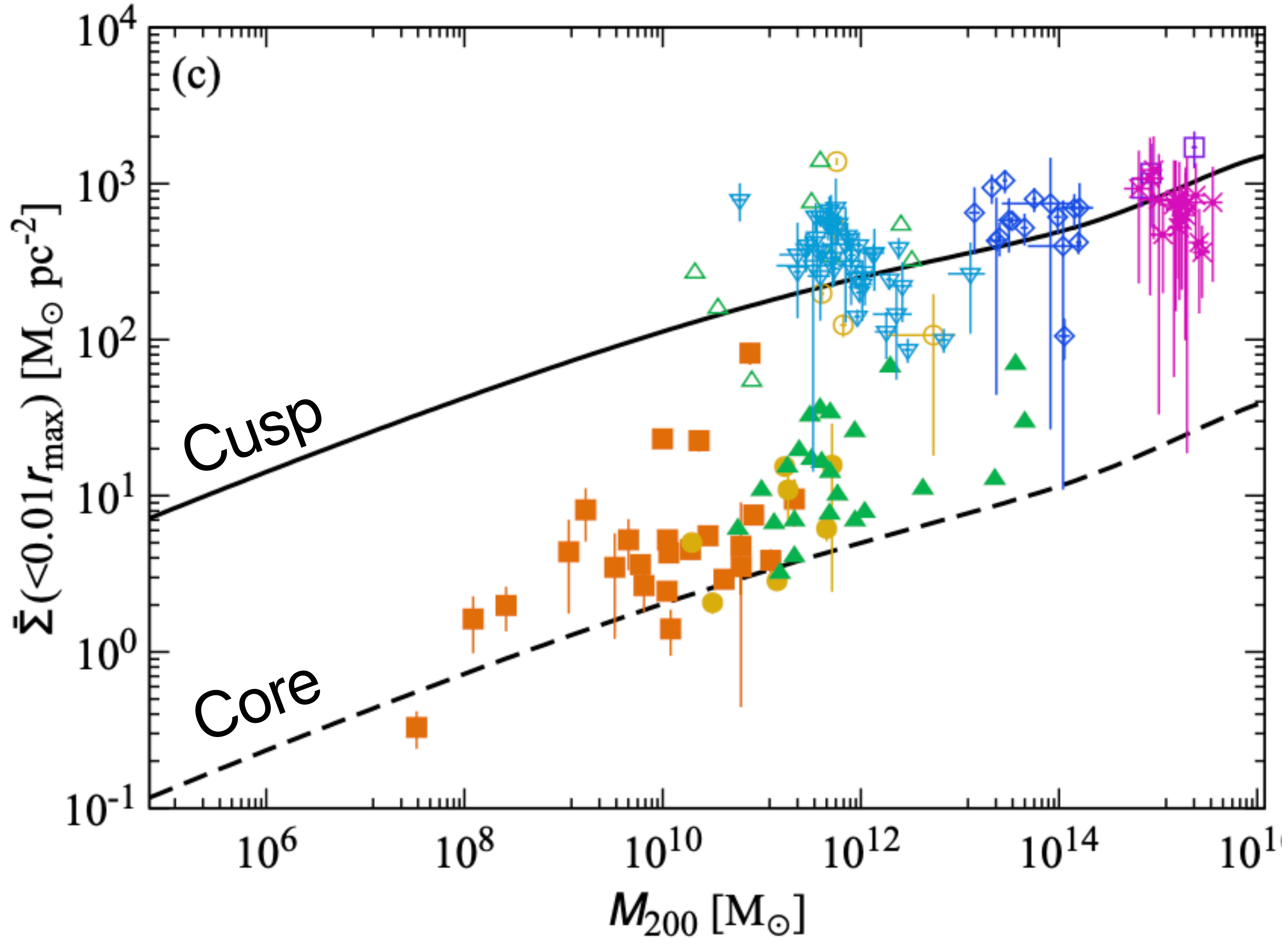
New indicator to distinguish between core and cusp

Kaneda, Mori, Otaki (2024)

- Dark matter surface density at $0.01 r_{V_{\max}}$

$$\Sigma(< 0.01 r_{V\max}) = \frac{M_{\rm DM}(< 0.01 r_{V\max})}{\pi (0.01 r_{V\max})^2}$$





When $r_{V_{\max}}$ is adopted, it is hard to distinguish between core and cusp.

See also KH & Chiba (2015a), KH et al. (2017)

Take Home Message

- Galaxies on the small scales are ideal target for studying the basic properties of dark matter.
- The central dark matter density in the Milky Way is still completely unknown. The kinematic information toward the center region should be needed.
- We found **the diversity of dark matter density profiles** in the dSphs, even though there are still large uncertainties. For DM studies in the dSphs, deep and wide spec. survey by **Subaru-PFS** should be essential.
- We try to detect the cusp-to-core transition phase by using low surface brightness galaxies.