Credit: HSC collaboration / Kavli IPMU

Dark Matter distributions of the Milky Way and its satellites

The 2nd DMNet International Symposium
Direct and Indirect Detection of Dark Matter

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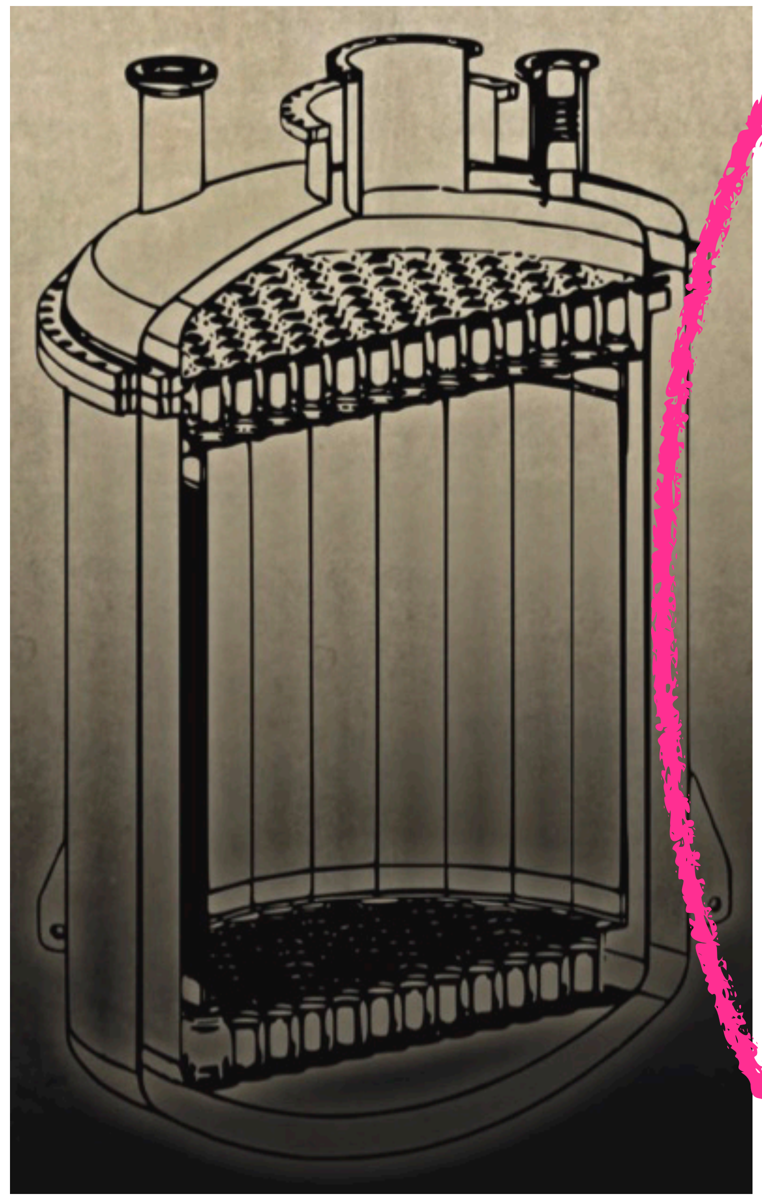
DMNet

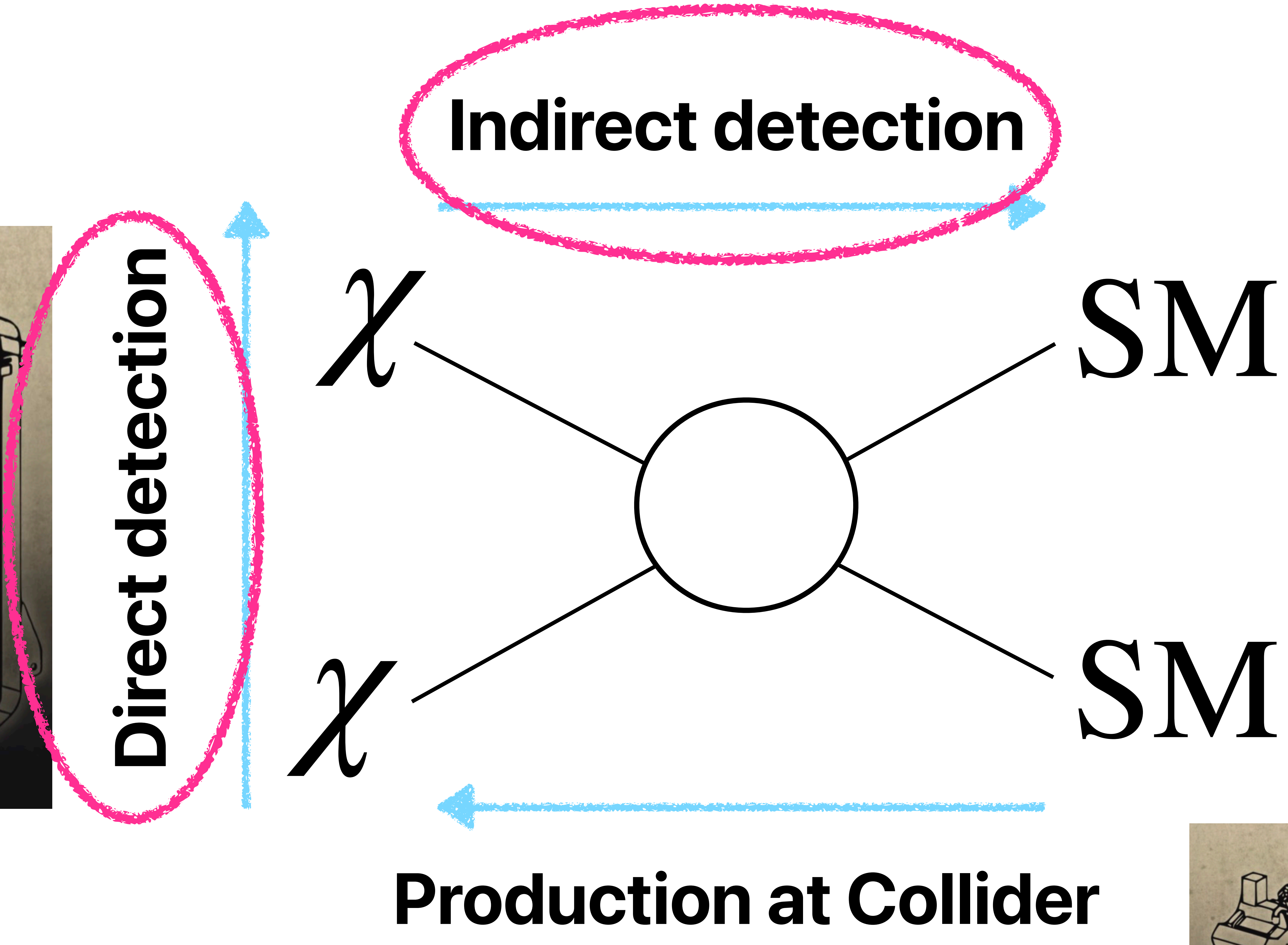
Sep. 13, 2022

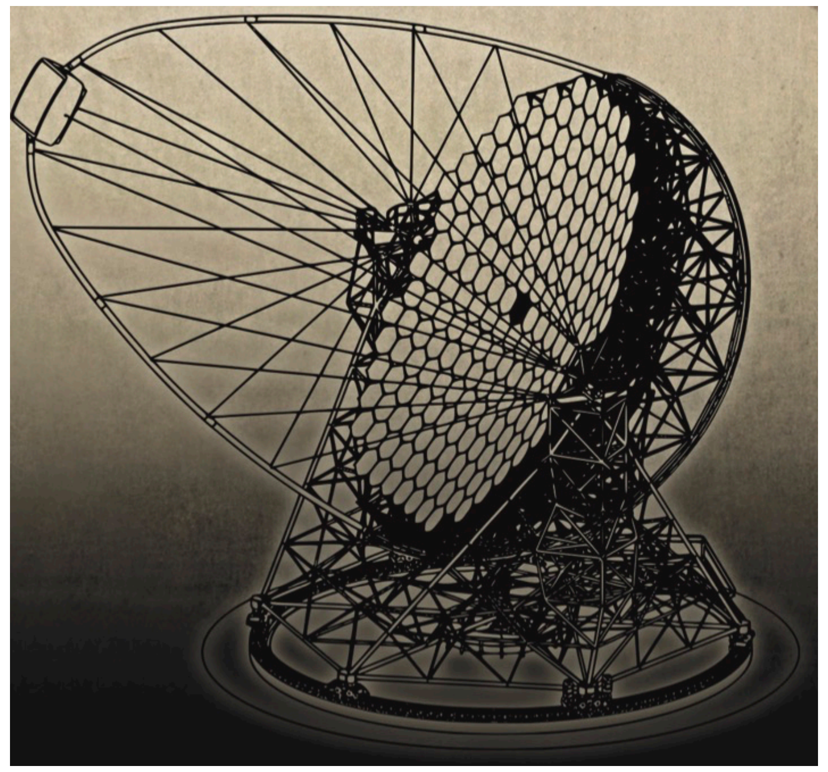
Outline

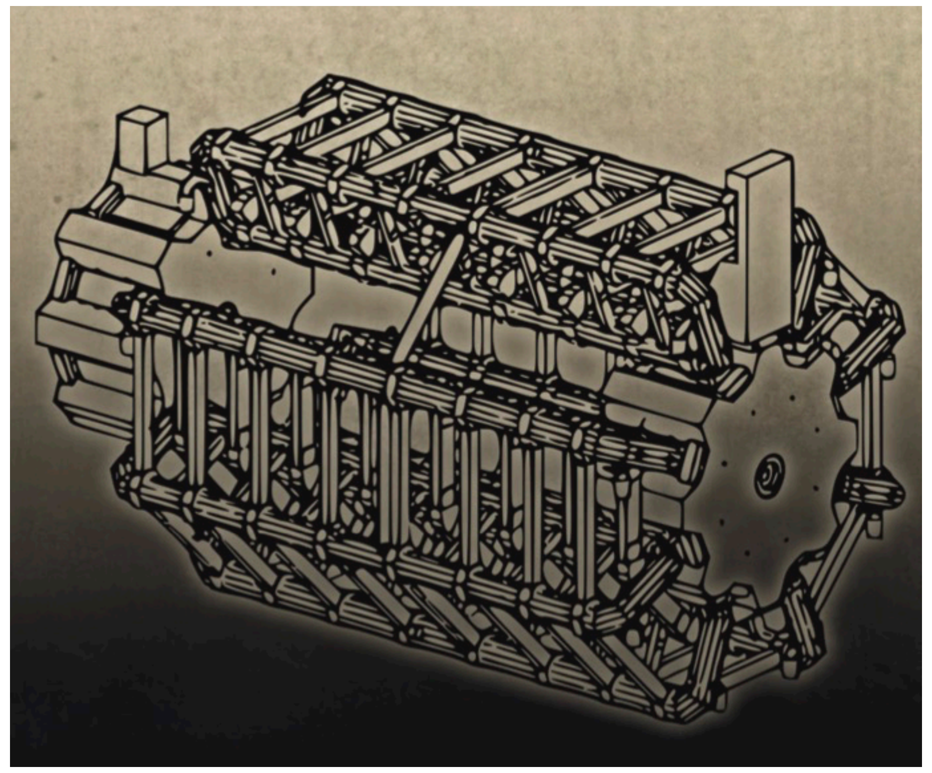
1. Introduction
2. Dark Matter density profiles in the MW
3. Dark Matter density profiles in the MW dSphs
4. Future prospects for Subaru-Prime Focus Spectrograph
5. Summary

Dark Matter: the biggest mystery of modern physics









The Milky Way as a unique target of dark matter detection

The Milky Way
as a unique target of dark matter detection

Dark matter distribution in the Milky Way

Dark matter halo mass

To obtain the mass…

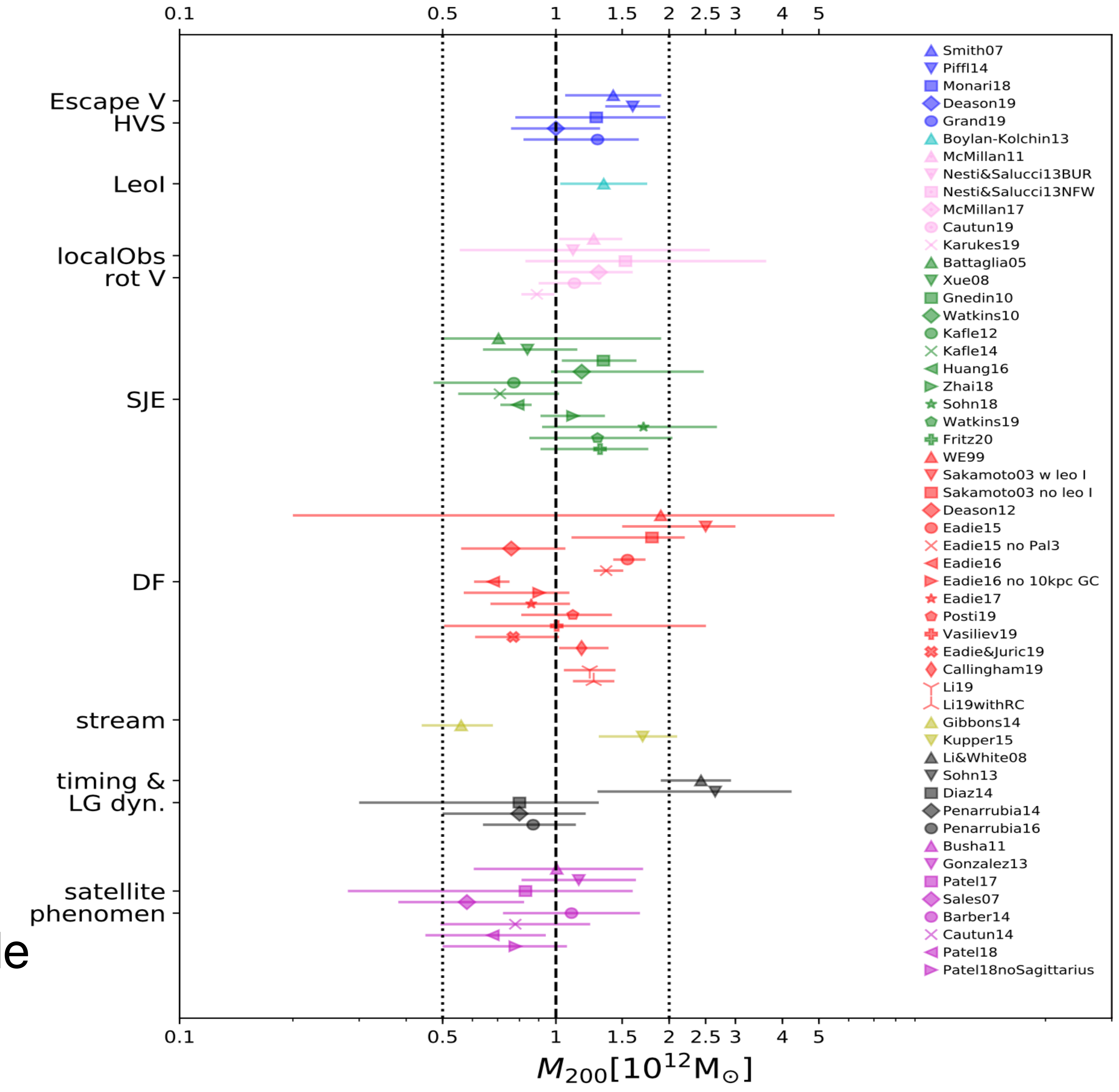
- Escape velocity
- Galactic rotation
- Sph. Jeans eq. for halo stars
- Distribution function
- Stellar streams
- The number of satellites…

$$M_{200} \sim 1.0 \times 10^{12} M_{\odot}$$

The mass enclosed within a radius R_{200}, inside which the density is 200 times the critical density of the universe.

Caution:
- Most studies assumed **spherical NFW** density profile
- A degeneracy between the mass and concentration

Wang et al. (2020, 1912.02599)



Dark matter density profile

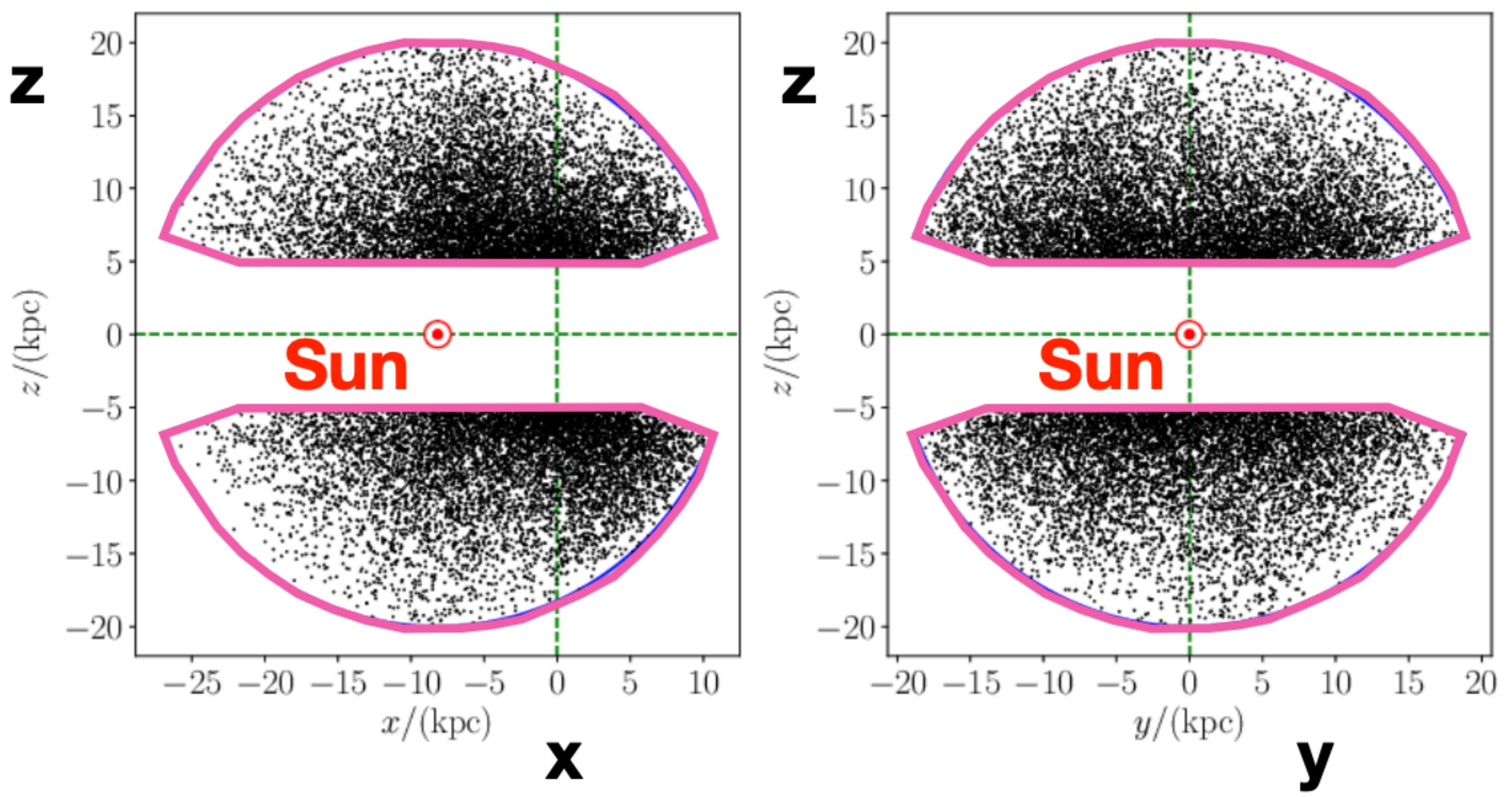
- Using old halo stars (outer regions)

- Data

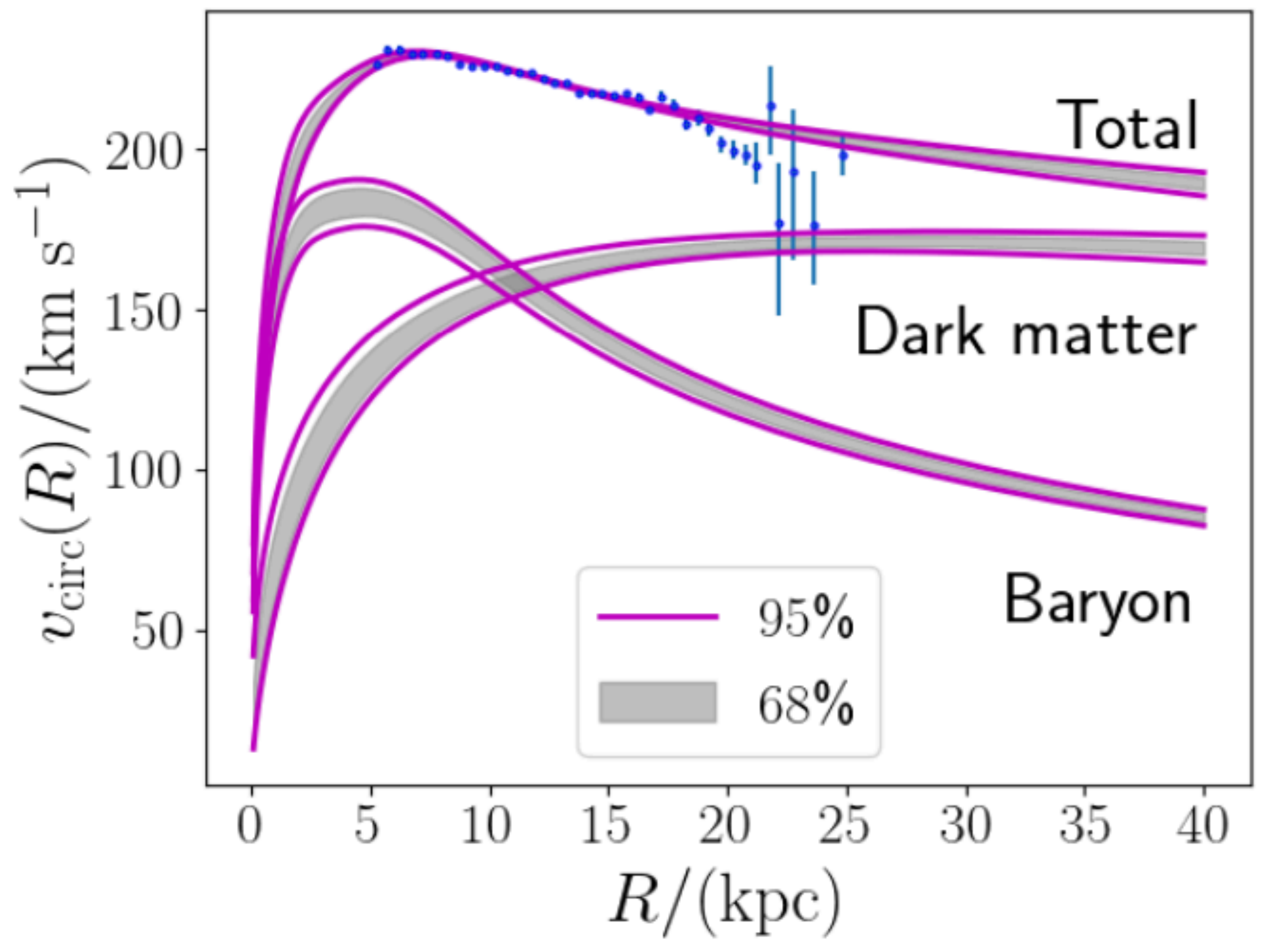
a) Proper motions of RR Lyrae stars by Gaia EDR3

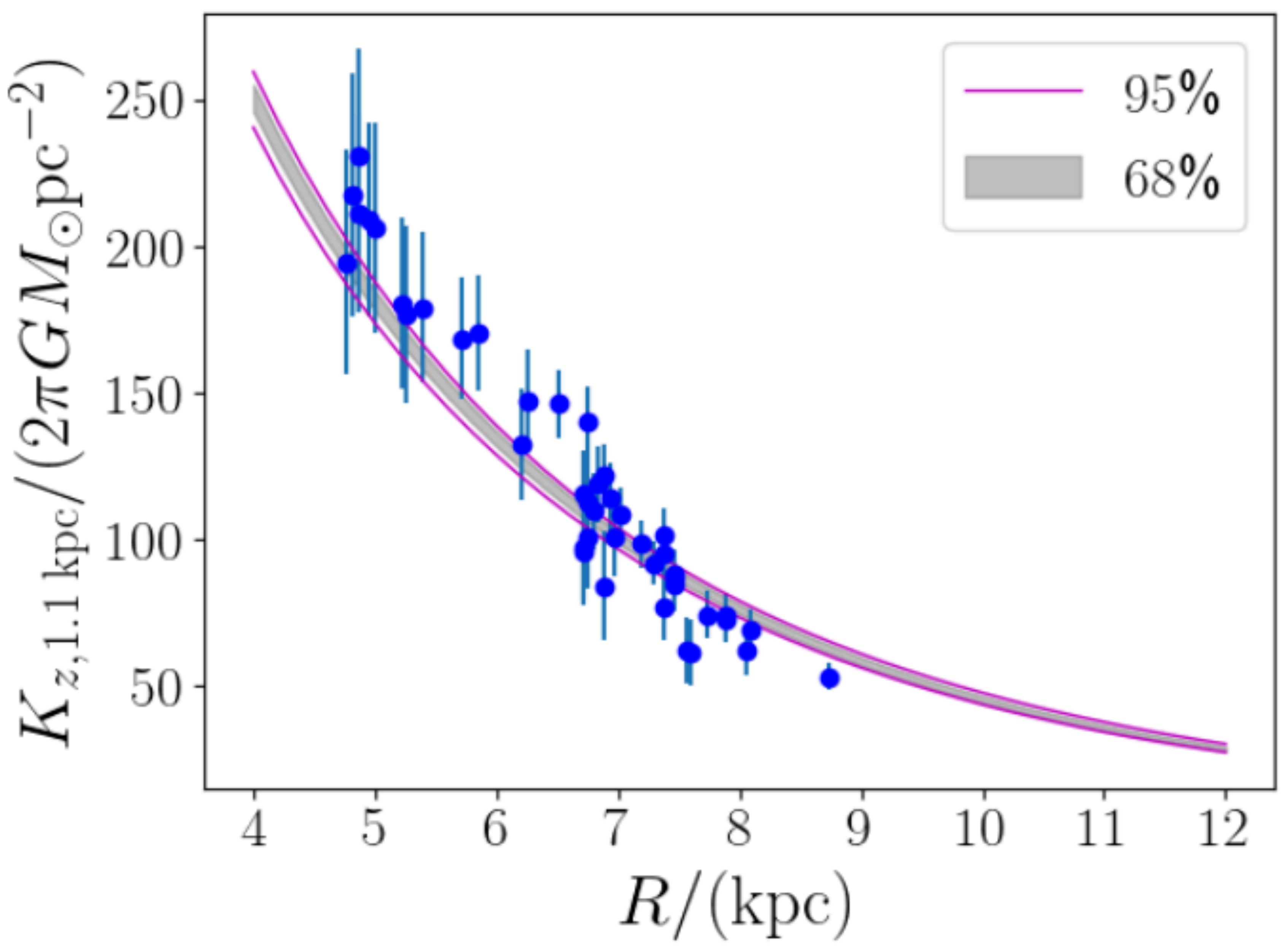
- Old halo stars
- Measure the distance by period-luminosity relation

~16,000 RR Lyrae stars



b) Rotation curve + vertical force





Hattori et al. (2021, 2012.03908)

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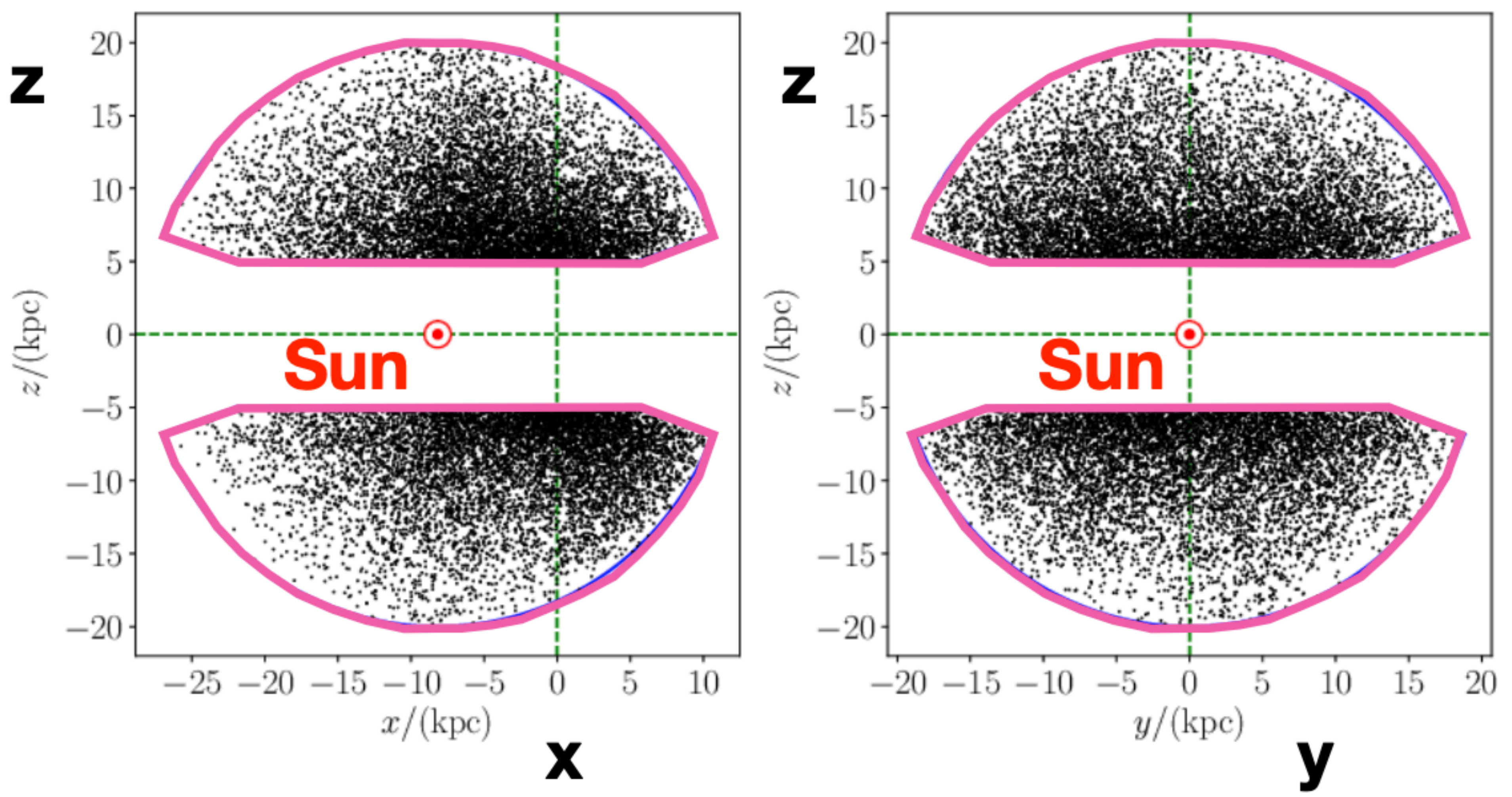

- Model

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

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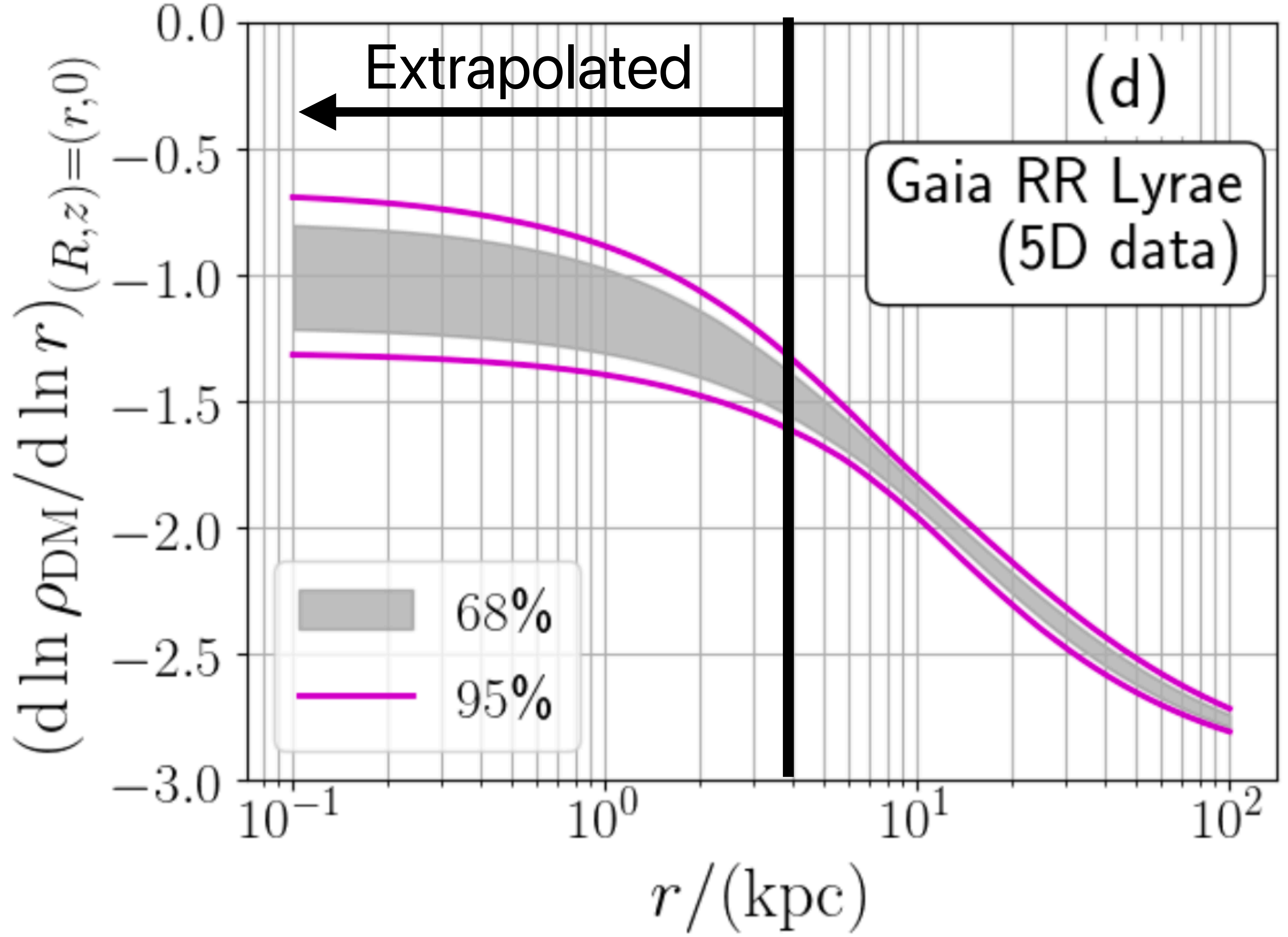
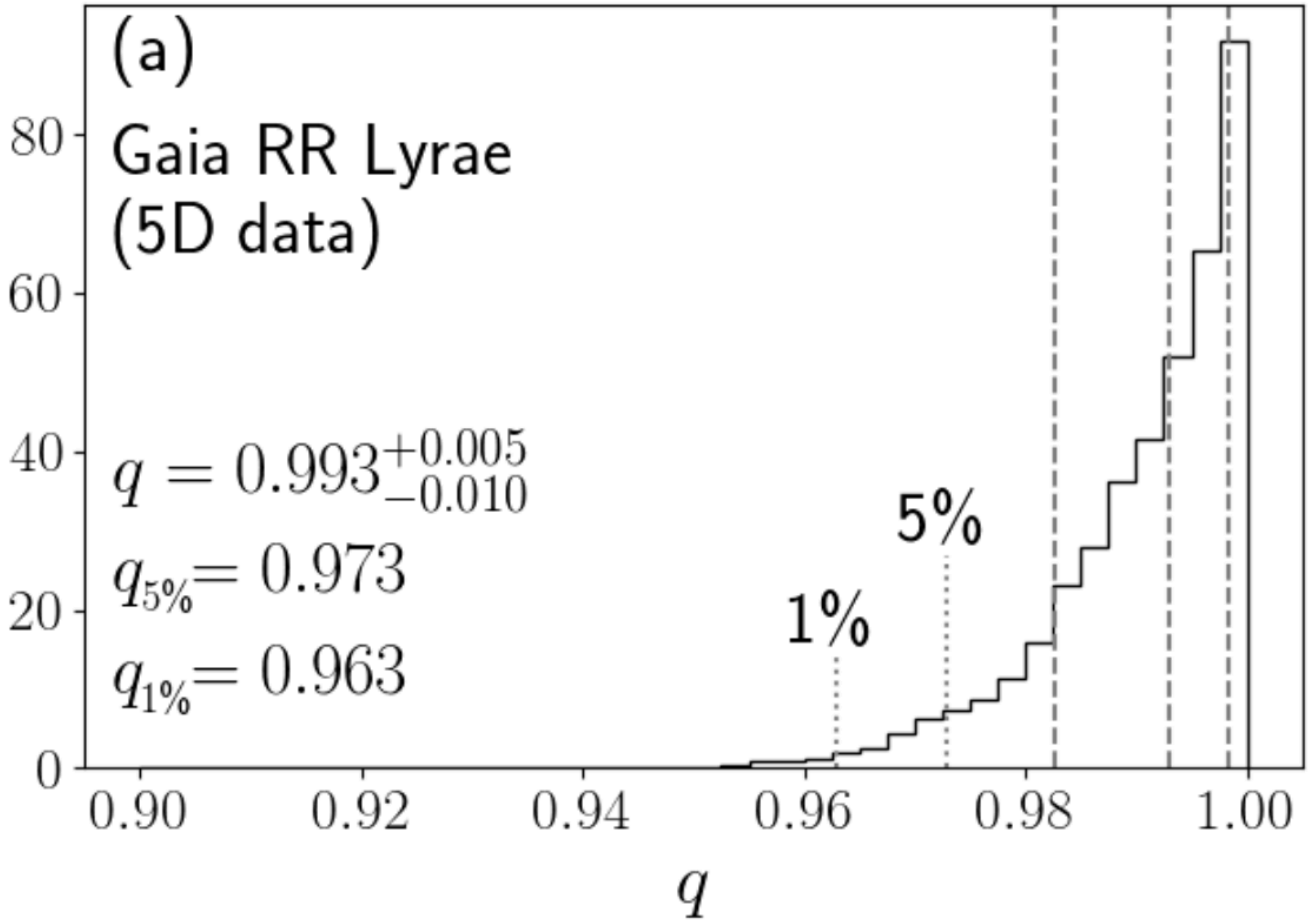




$$\rho_{\rm DM,\odot} = 0.342 \pm 0.007\ \mathrm{GeV/cm^3}$$

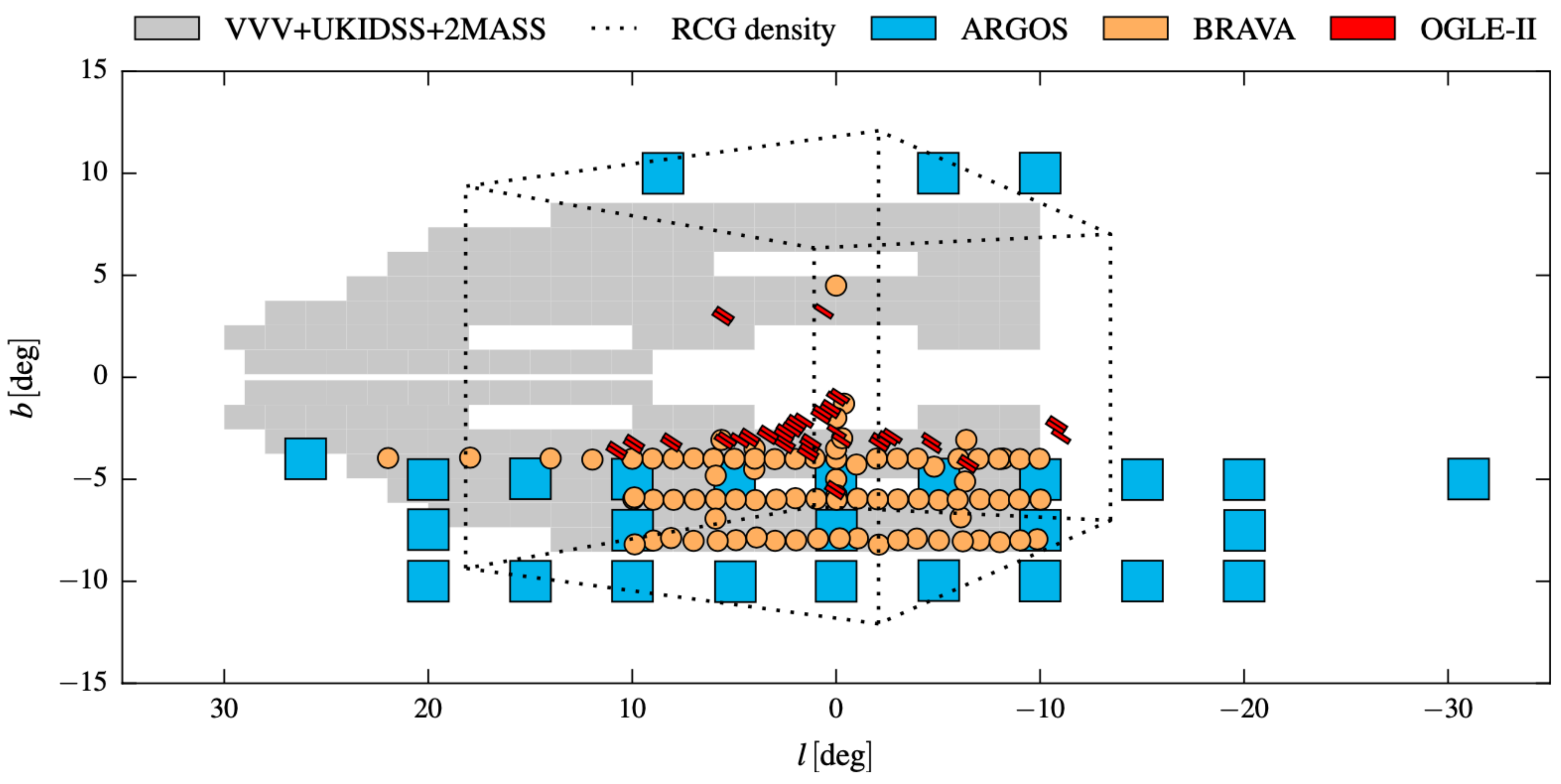
- Favors an NFW cuspy DM profile
- Disfavor oblate shape
- The local DM density can be narrow dawn

Hattori et al. (2021, 2012.03908)

Dark matter density profile

- Using inner parts of the MW

Sky coverage of the data sets



- Stellar kinematics around the Galactic center region taken from several infrared surveys
- Very complicated system
  bar + bulge + stellar disk + gas disk + Einasto DM halo
- Adopting N-body based (Made-to-Measure (M2M)*) models to the observed stellar density and kinematics in the bulge region.

*This N-body model is then slowly adapted by modifying the weights of the N-body particles such as to make the model reproduce a given set of constraints.

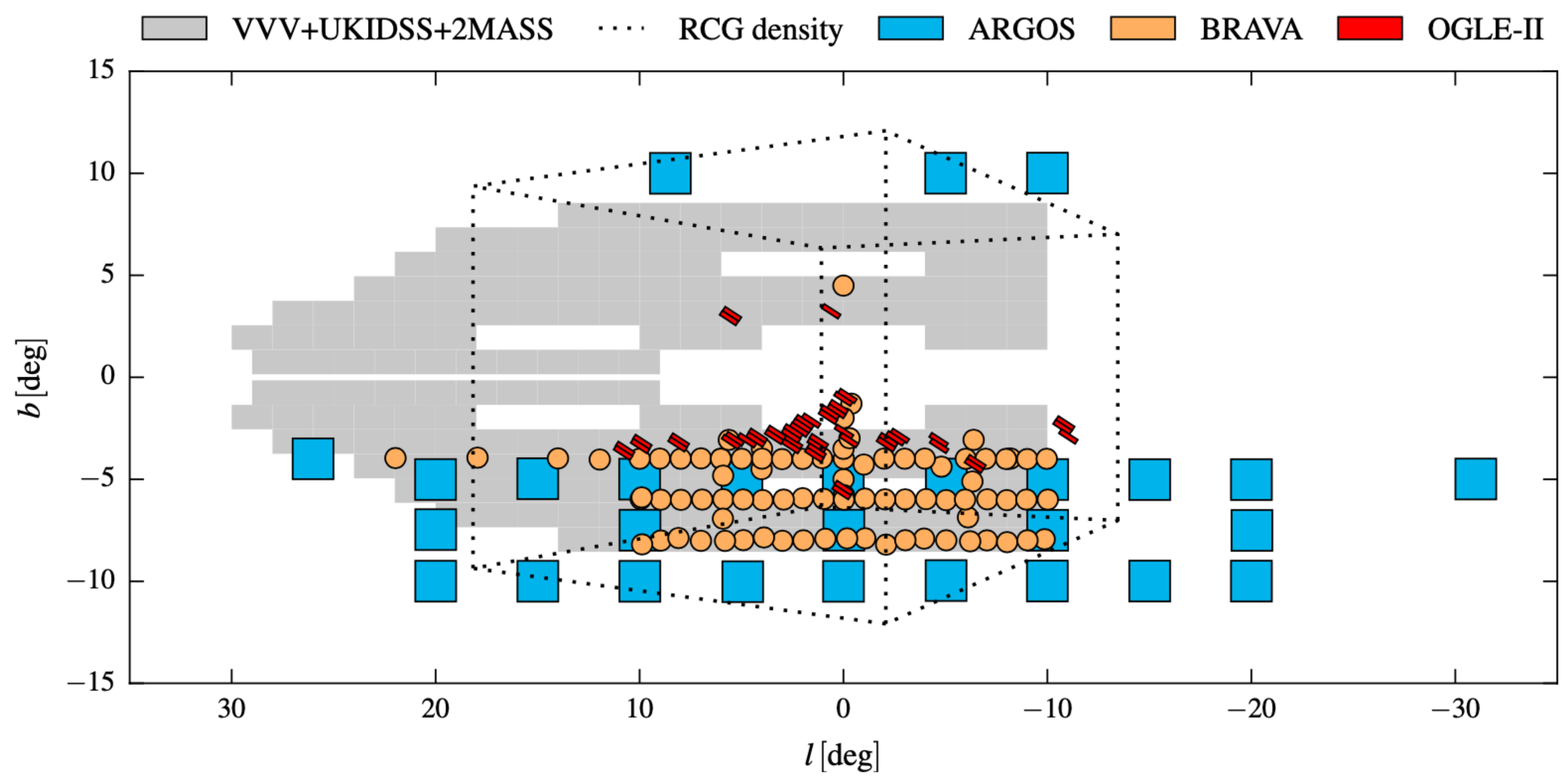
Portail et al. (2016, 1608.07954)

Dark matter density profile

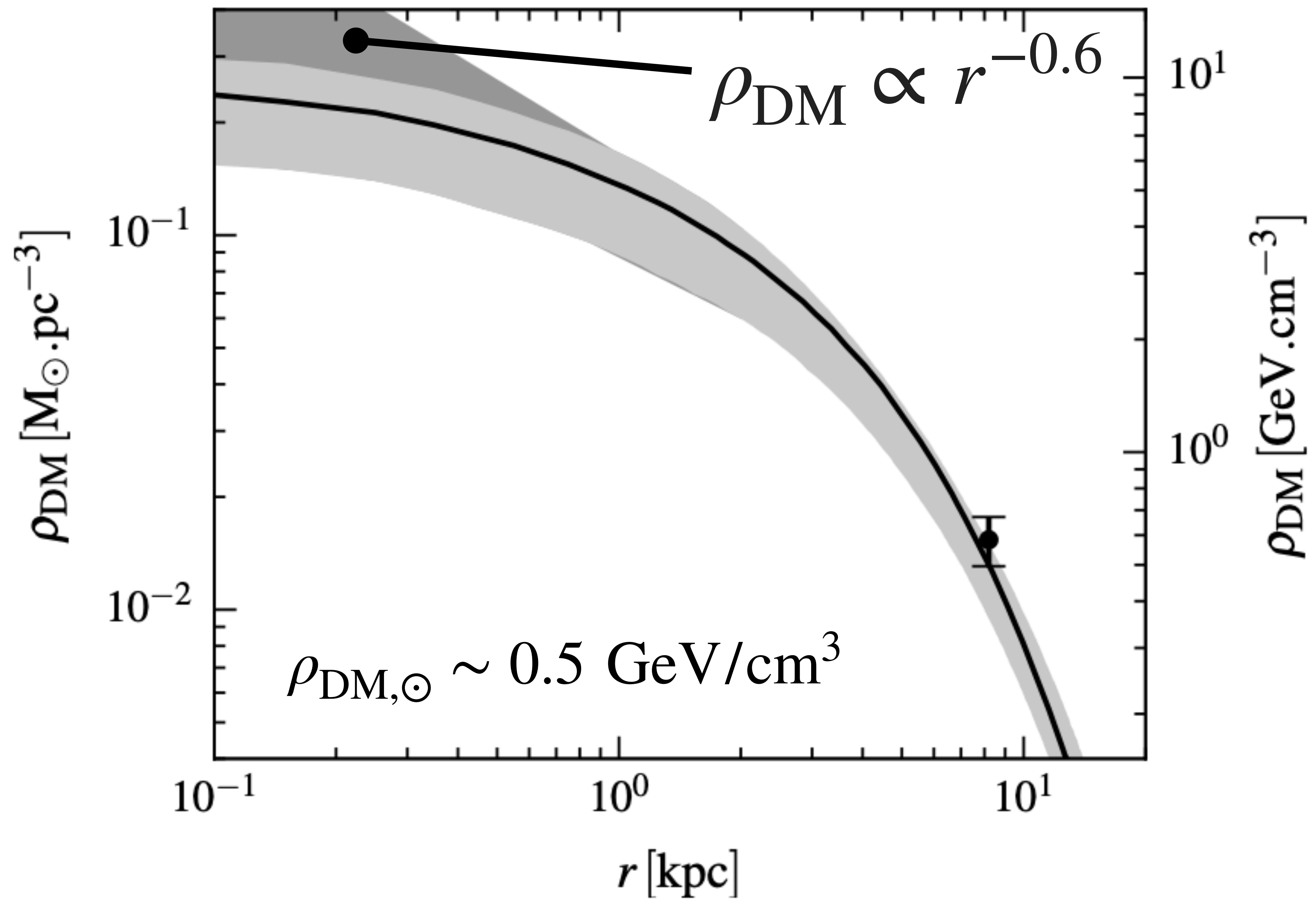
- Using inner parts of the MW

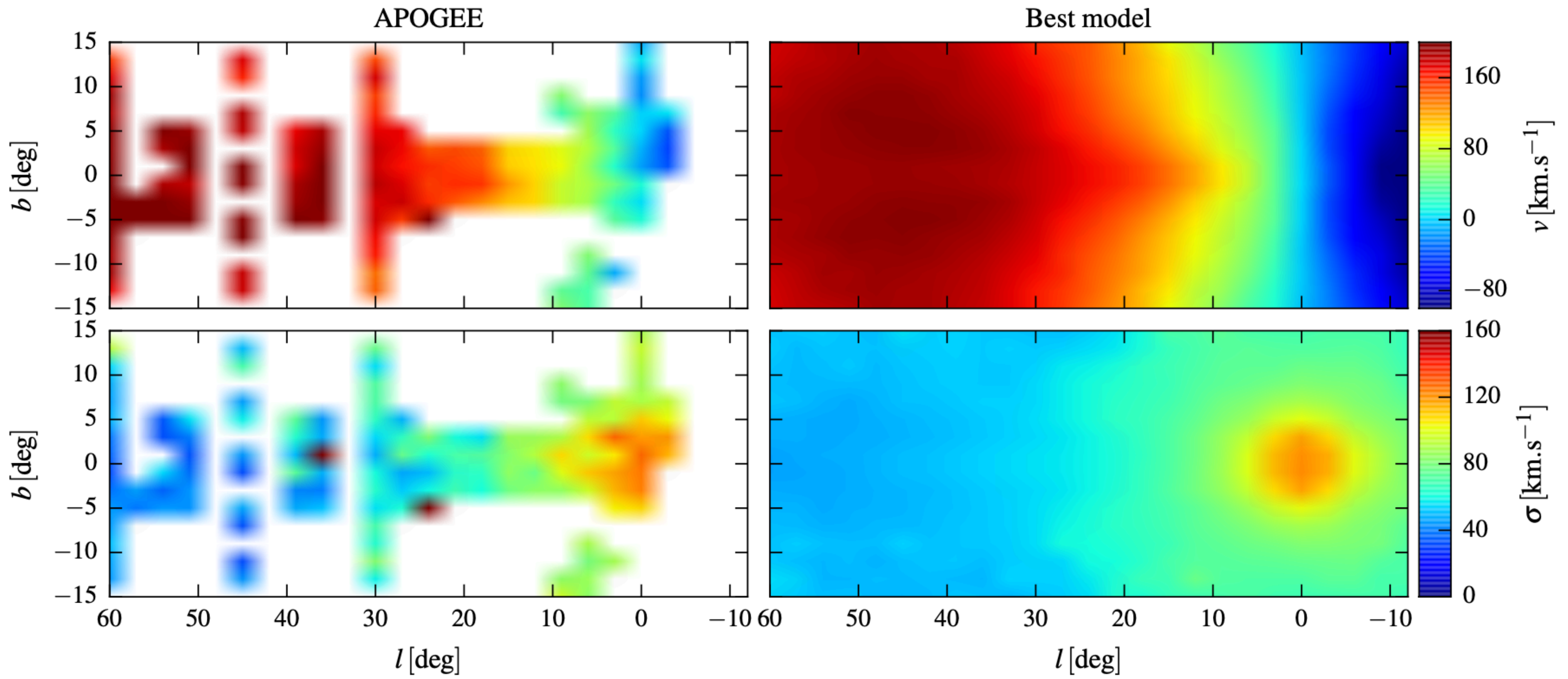
- Very complicated system
  bar + bulge + stellar disk + gas disk + Einasto DM halo
- Adopting N-body based (Made-to-Measure (M2M)*) models to the observed stellar density and kinematics in the bulge region.
- From the analysis, DM density favors shallower cusped or cored density inner slope.

Sky coverage of the data sets



Best-fit DM density profile





The mean velocity and velocity dispersion maps from the best fit model.

Portail et al. (2016, 1608.07954)

Dark matter density profile

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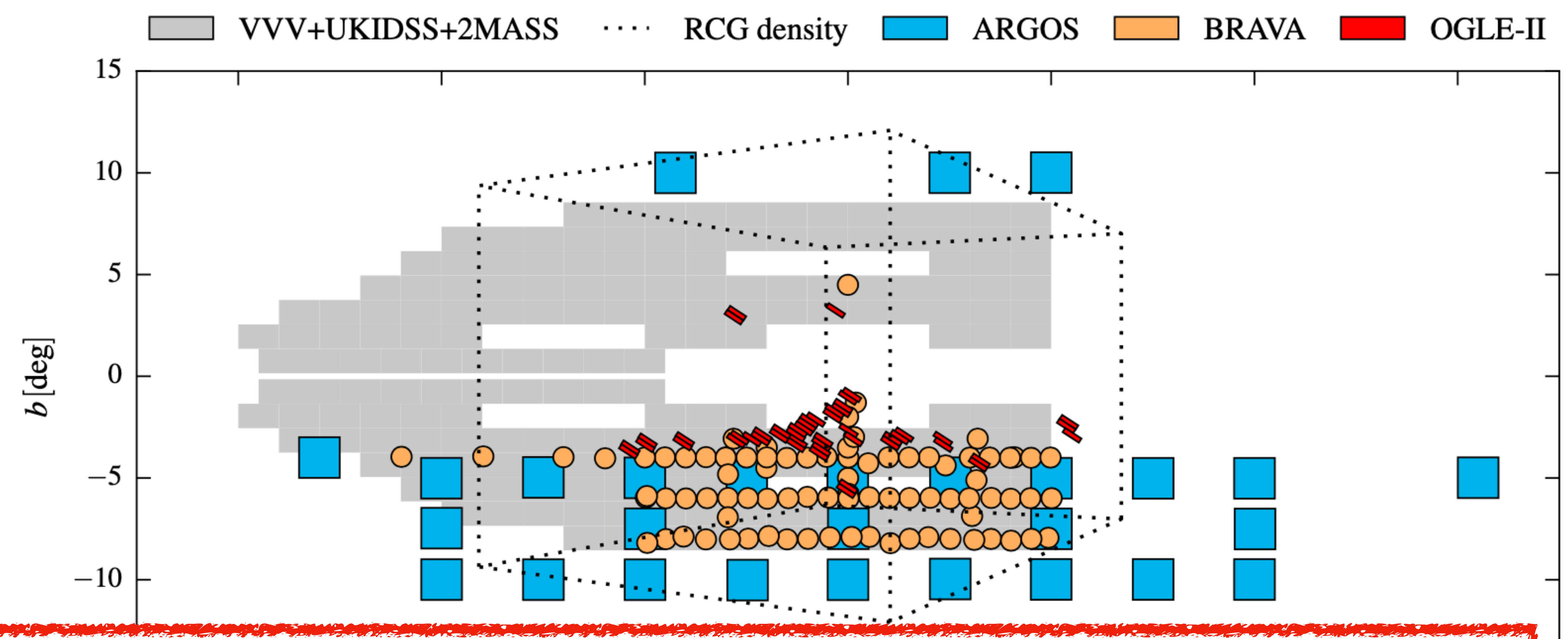
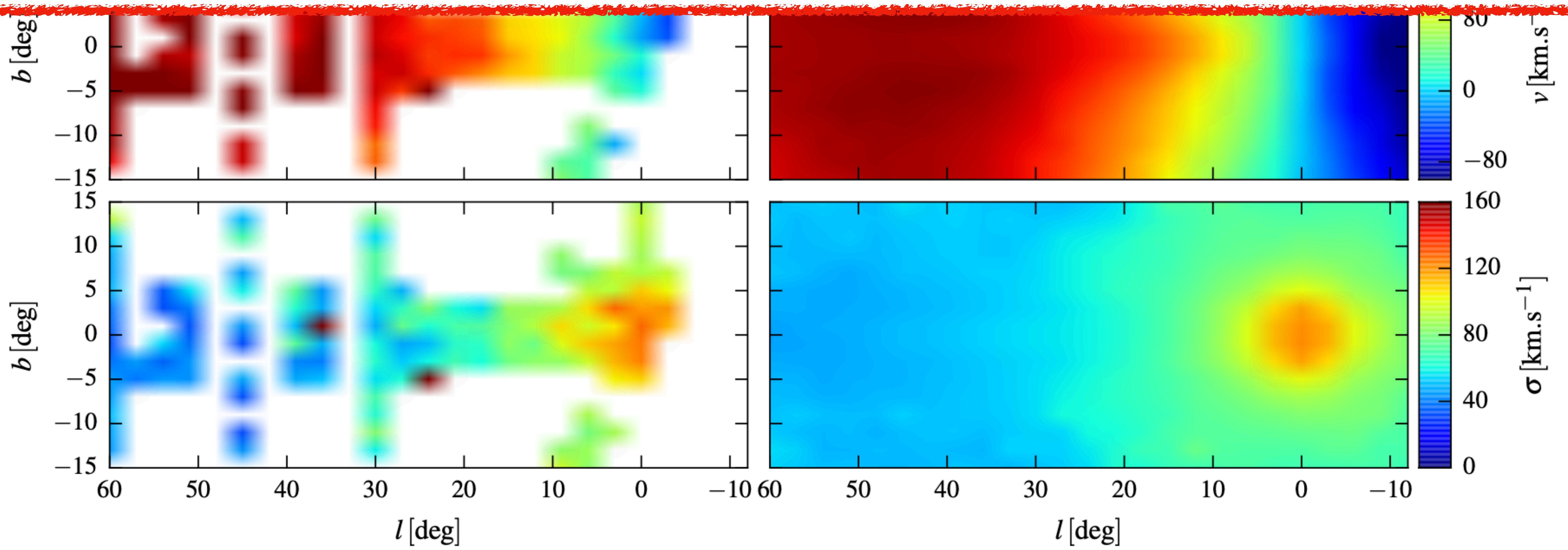


DM density inner slope of the MW is still unknown, although there are many efforts to estimate it...



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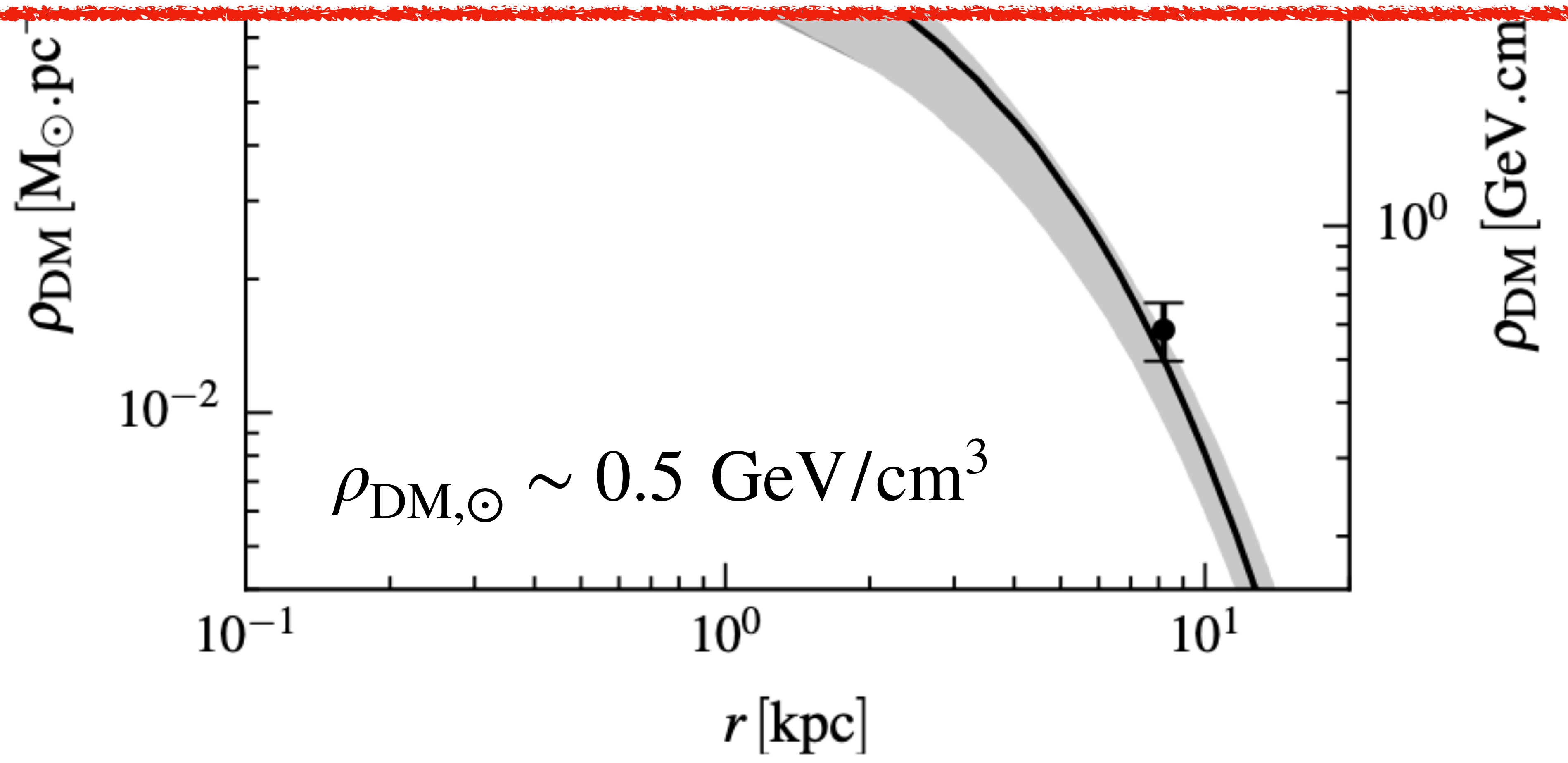


Portail et al. (2016, 1608.07954)

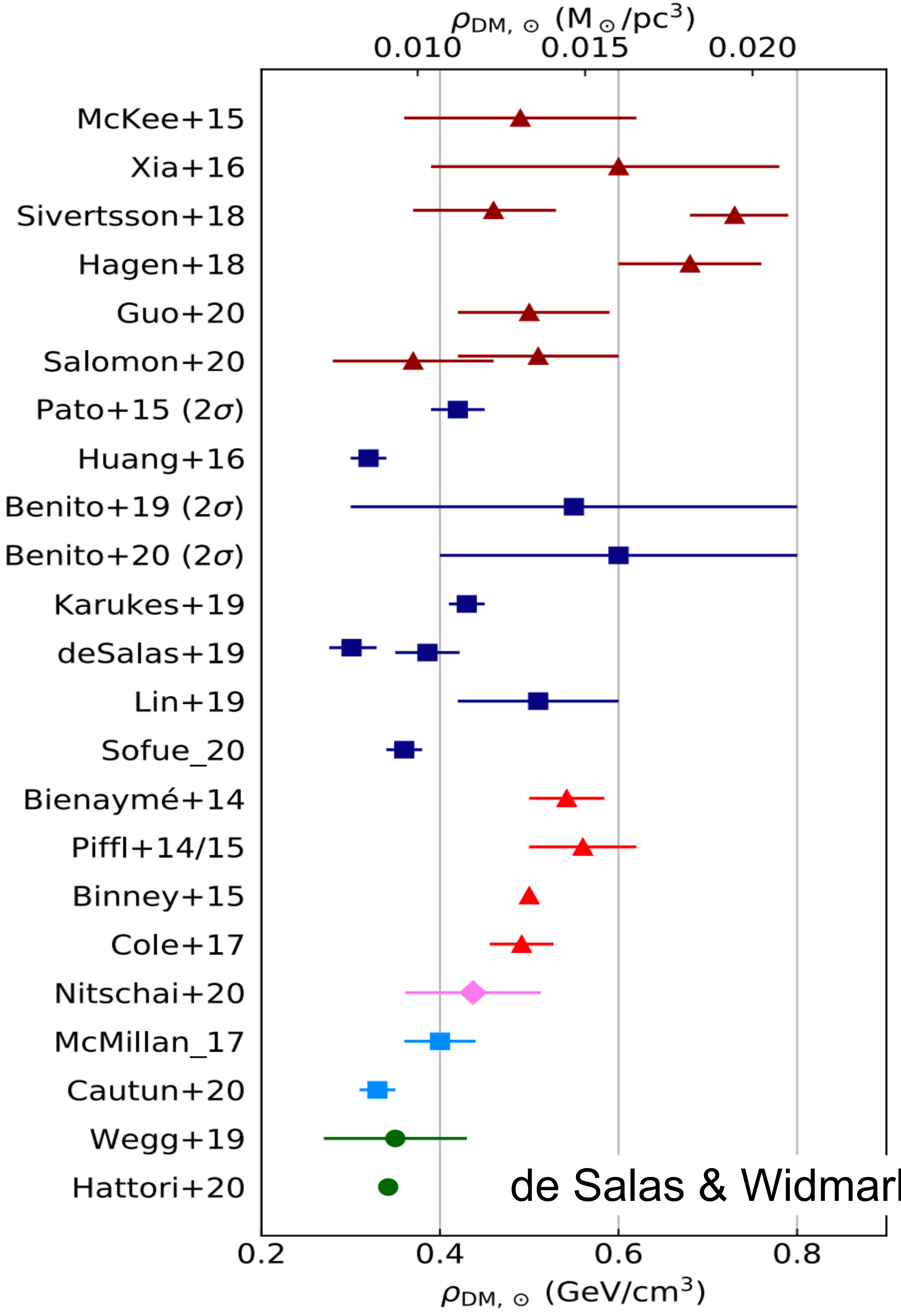
Dark matter local density

To obtain the density...

- Rotation curve
- Vertical stellar motions of solar neighborhood
- Global mass distribution of the MW

Current estimation:

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



de Salas & Widmark 2020

Dark matter local density

To obtain the density…

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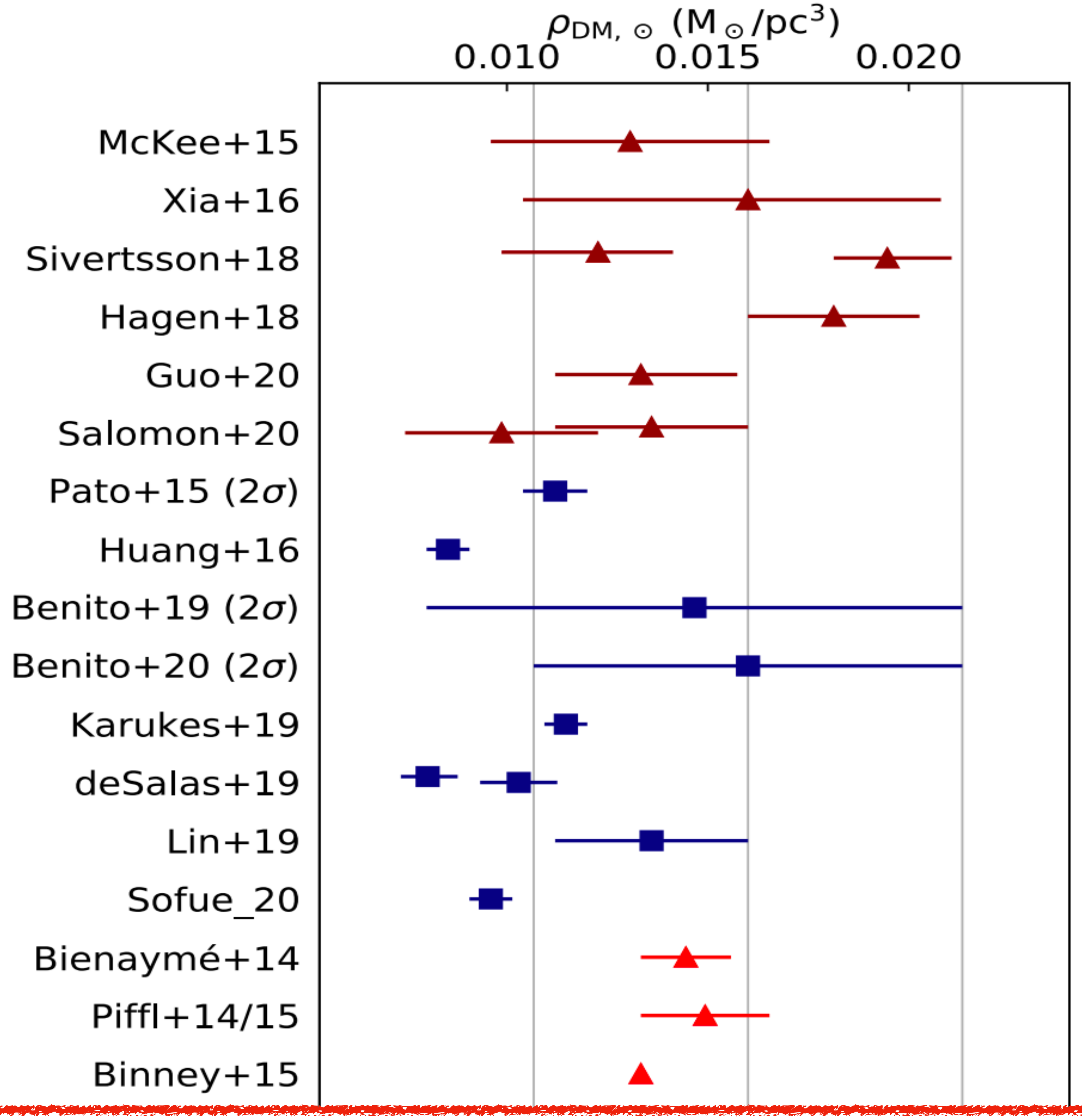


Current estimation:

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

Most studies assumed the Galactic disk is a dynamical equilibrium, but…

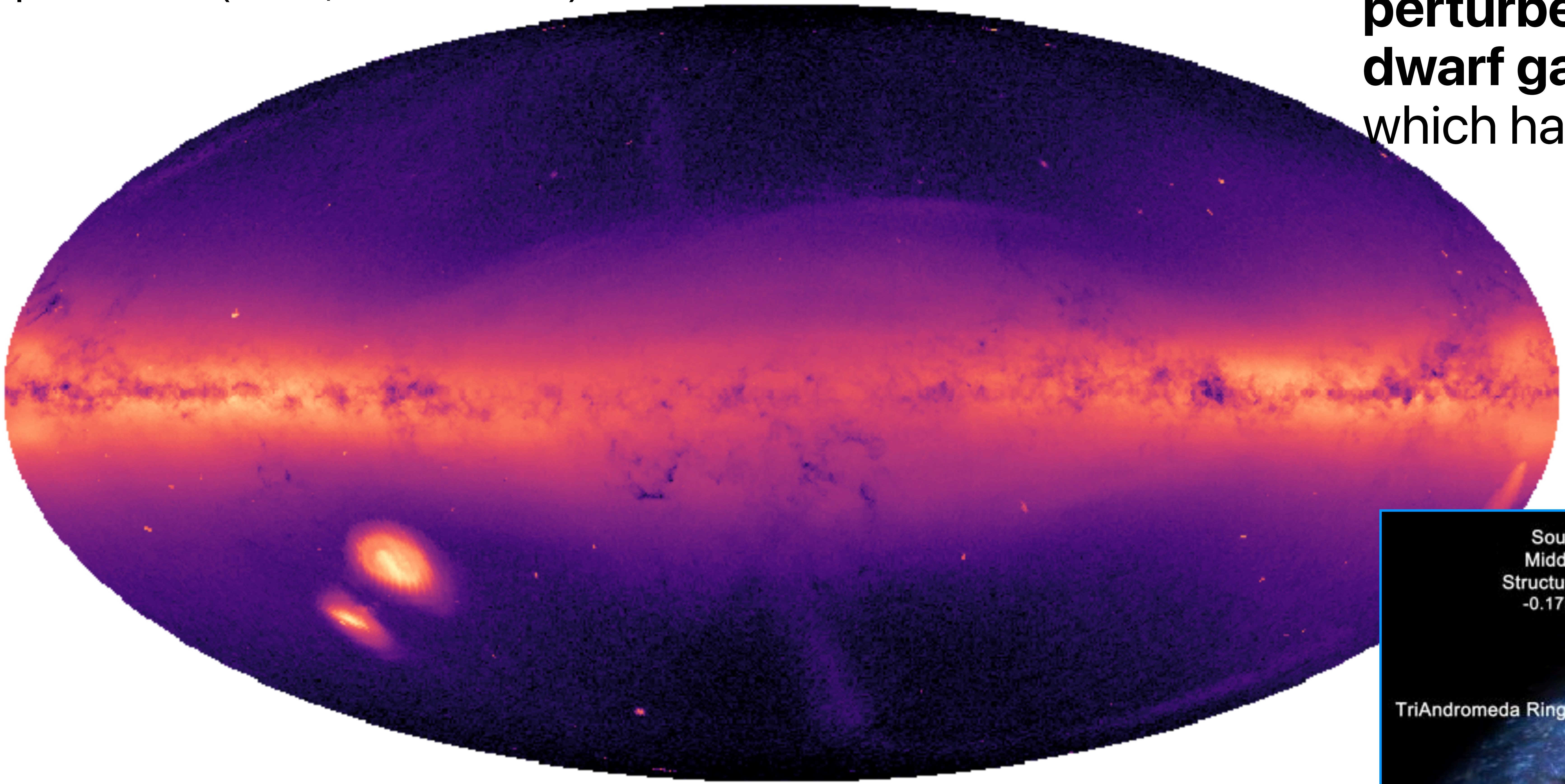
0

$\rho_{DM,\odot}$ (GeV/cm^3)

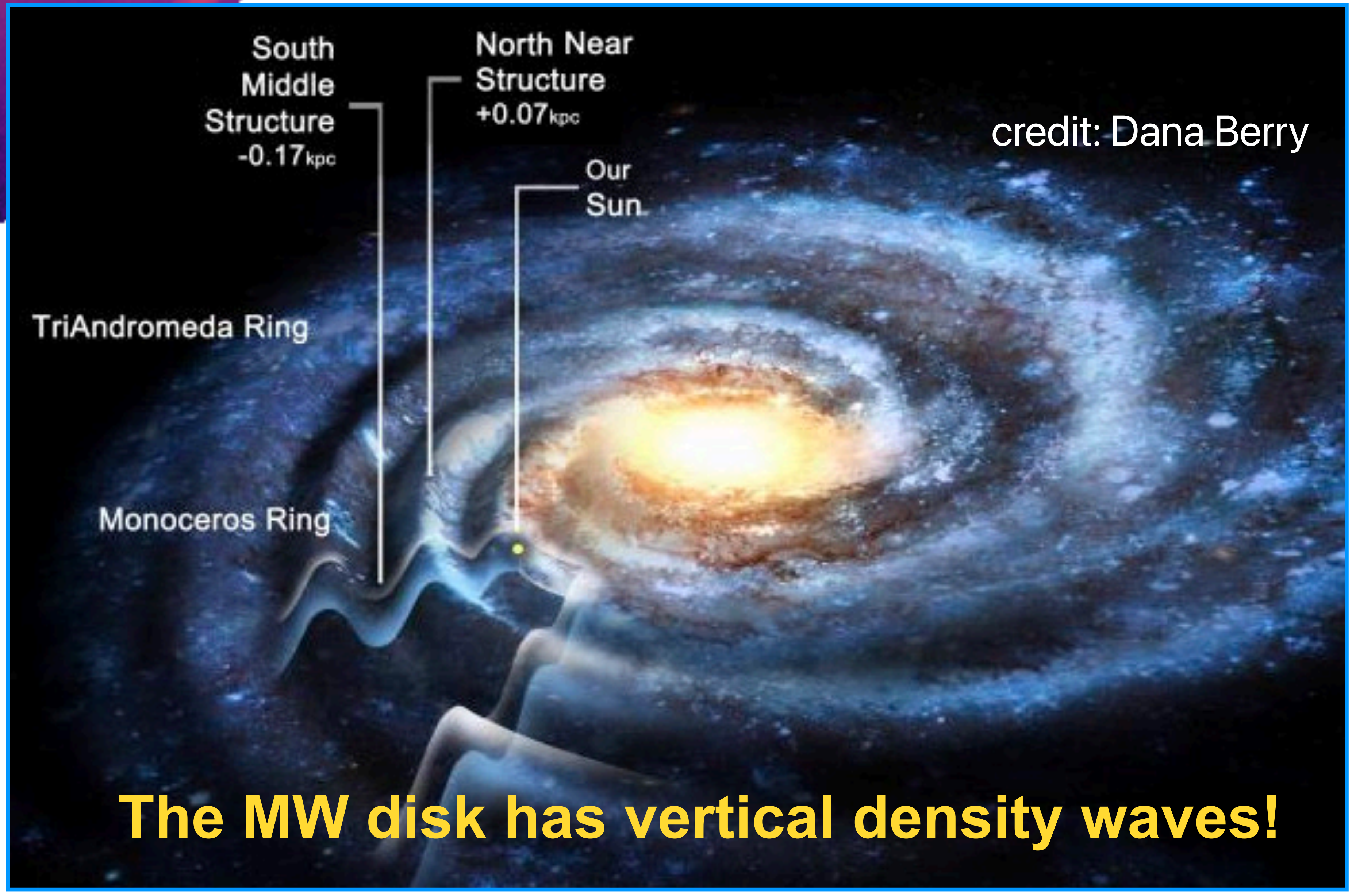
Galacto-seismology

Laporte et al. (2021, 2103.12737)

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



Unveiling substructures at the edge of the Milky Way

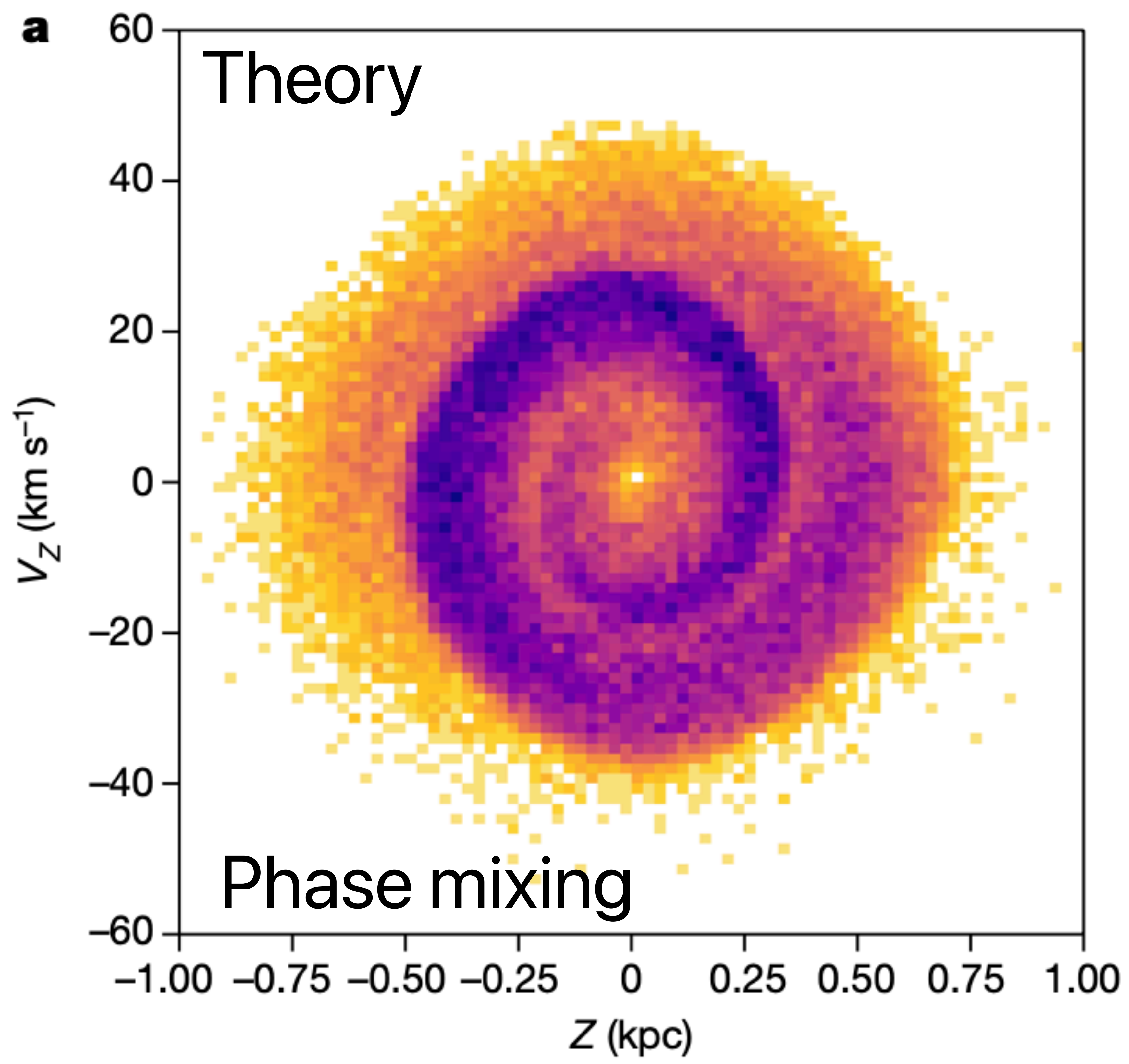


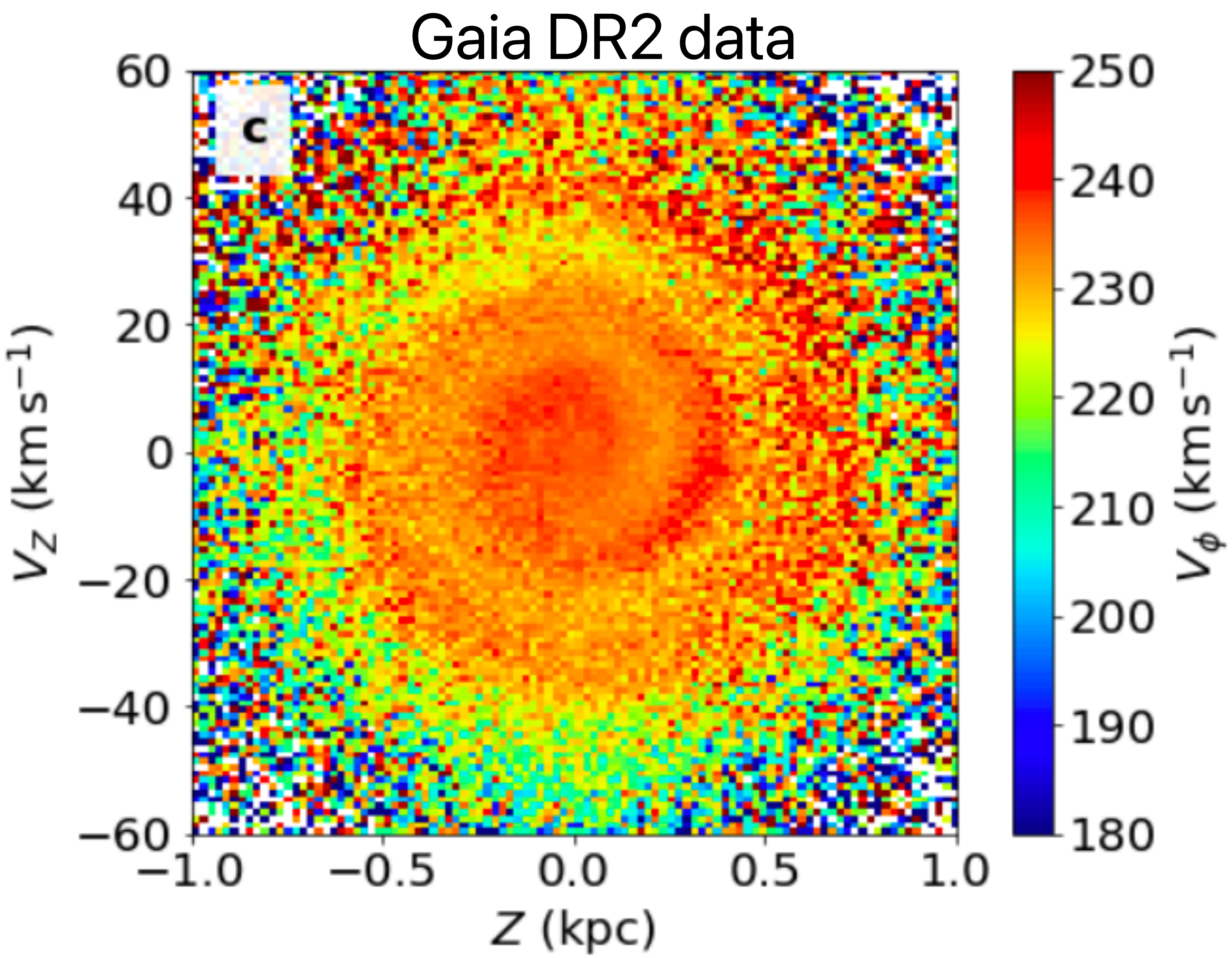
see also Crane+'03, Martin+'07, Slater+'14, Li+'17

Dynamically young and perturbed MW disk

Antoja et al. (2018, Nature)

- Phase-mixing on $V_z - z$ plane was discovered.
- The phase-mixing is a smoking gun that the MW disk was perturbed 3-9 Gyr ago. That is, **the MW disk deviates from dynamical equilibrium**.
- **Sagittarius dSph was approaching the MW disk around 6-7 Gyrs ago** (see also Laporte+ 2019).



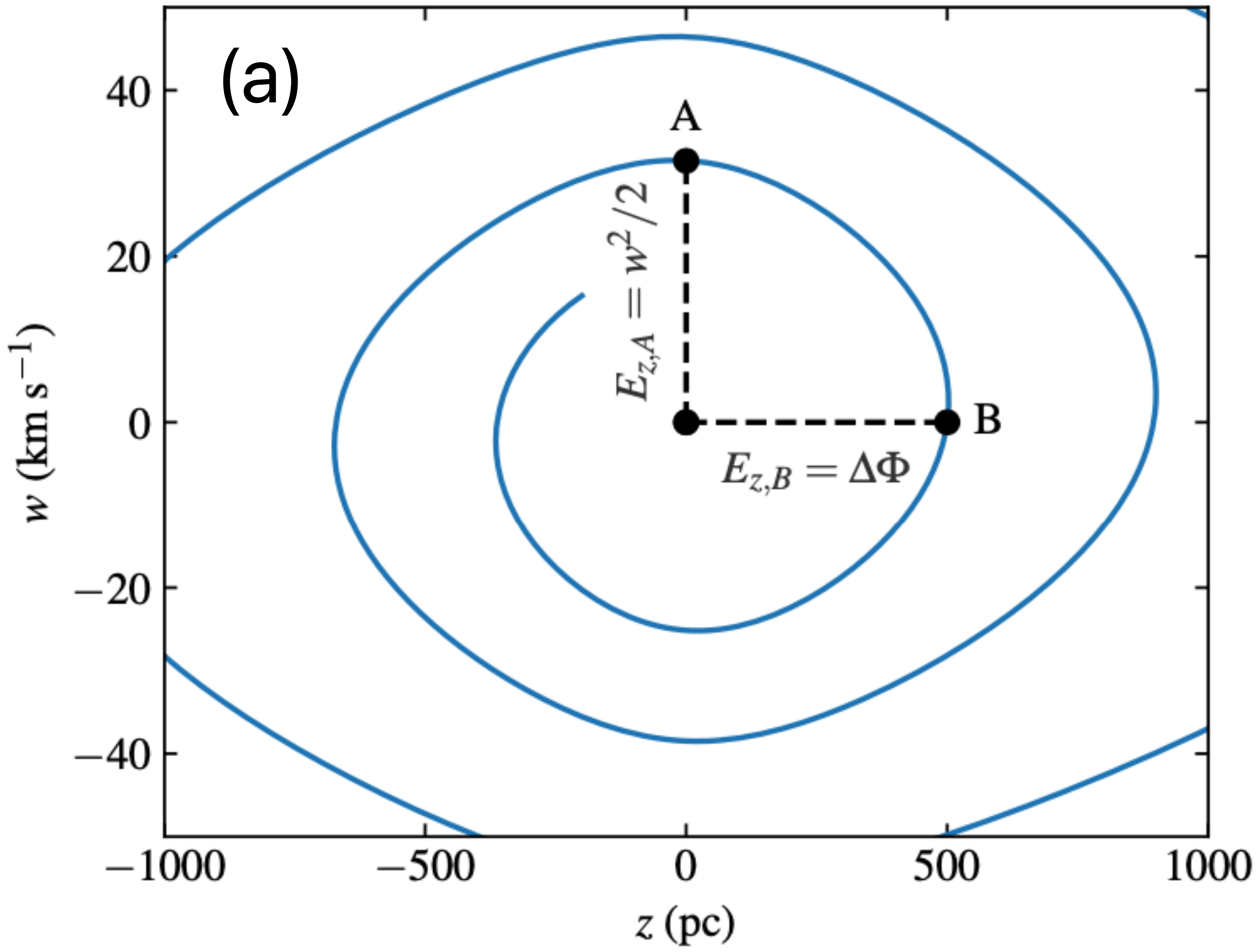


DM local density constrained by perturbed MW disk

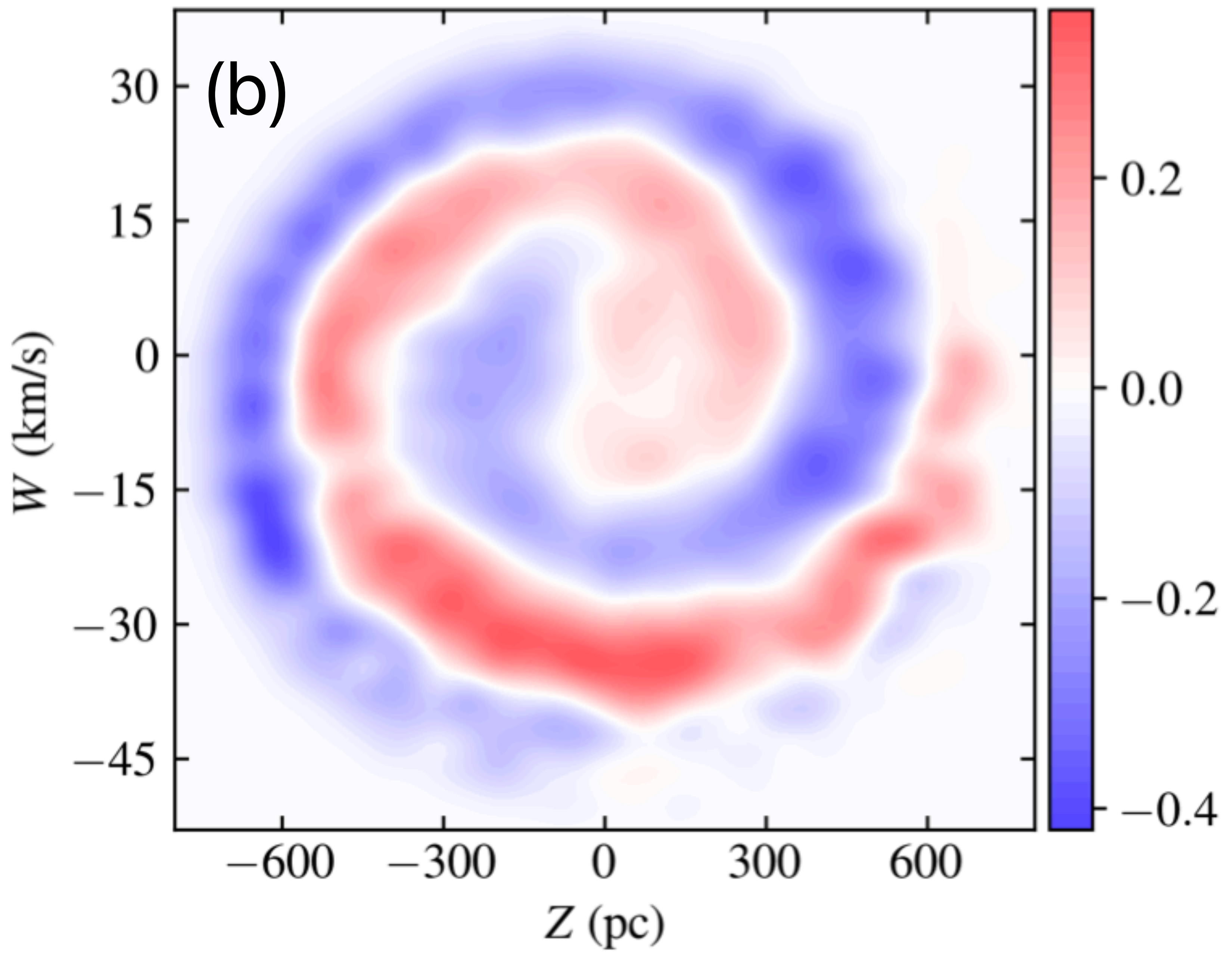
Widmark et al. (2021a,b)

- Winding of the phase space spiral on $W\ (V_z) - z$ plane depends on gravitational potentials (panel a).
- Assuming density profiles of the MW components, they searched the best-fit densities, which can reproduce phase space spiral.
- Even considering non-equilibrium MW disk, the estimated DM local density is $\rho_{\mathrm{DM},\odot} = 0.32 \pm 0.15\ \mathrm{GeV/cm^3}$, which is similar to the results from previous ones.
- However, DM density profile is assumed as independent of the z-direction.

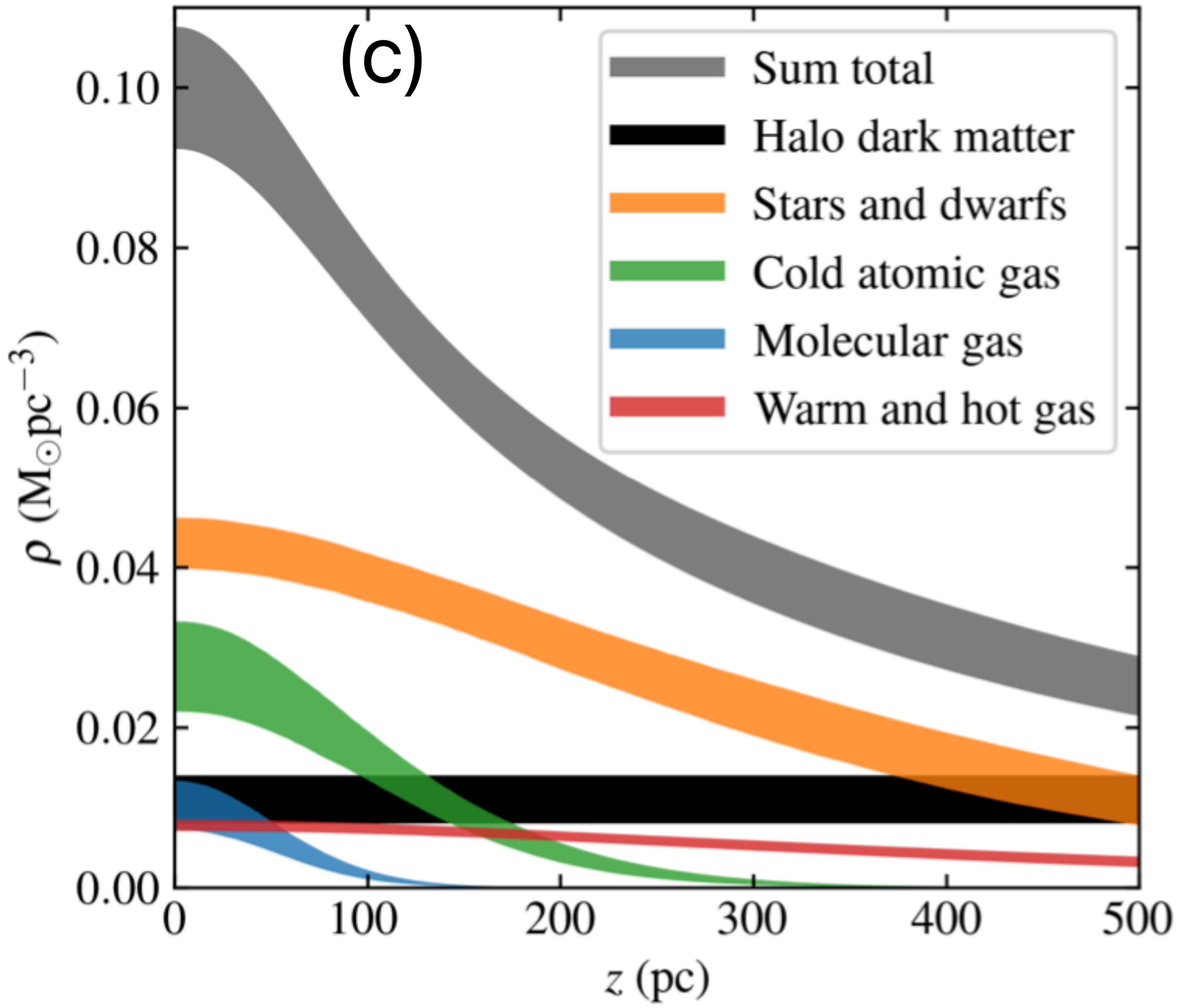
Model prediction



Data by Gaia EDR3



Best-fit density model



The current status of dark matter density in the MW

- **The shape of DM density profile is still on-going debate.**

  ✓ The DM density inner slope still depends largely on data properties, modelings.

- **Dark matter local density is** $\rho_{\mathrm{DM},\odot} \sim 0.3\ \mathrm{GeV/cm^3}$ **estimated by the recent works**

  ✓ Even considering dynamical equilibrium/non-equilibrium, the estimates of DM local density are similar values.

Dark matter distribution in the dwarf spheroidals

The uncertainties on DM distributions (i.e. J-factors) in the dSphs

$$\Phi(E, \Delta\Phi) = \left[\frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \sum_f b_f \frac{dN_\gamma}{dE}\right] \times \int_{\Delta\Omega} \int_{\rm l.o.s} d\ell \, d\Omega \rho_{\rm DM}^2(\ell, \Omega)$$

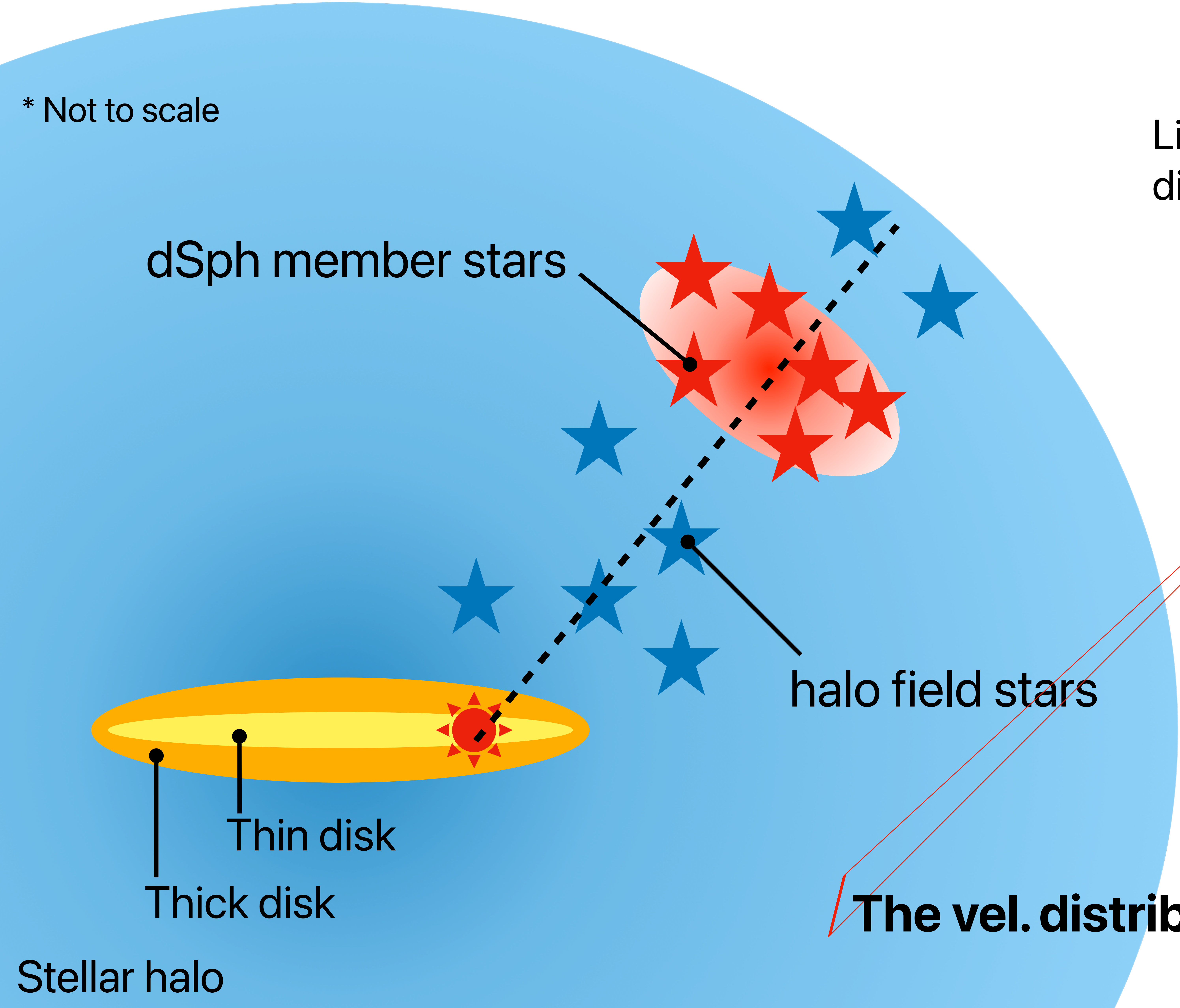
J-factor

The dSphs are simpler systems than the MW, but observable information are projected ones only.
Various sources of uncertainties in the DM distribution estimates from stellar kinematics.

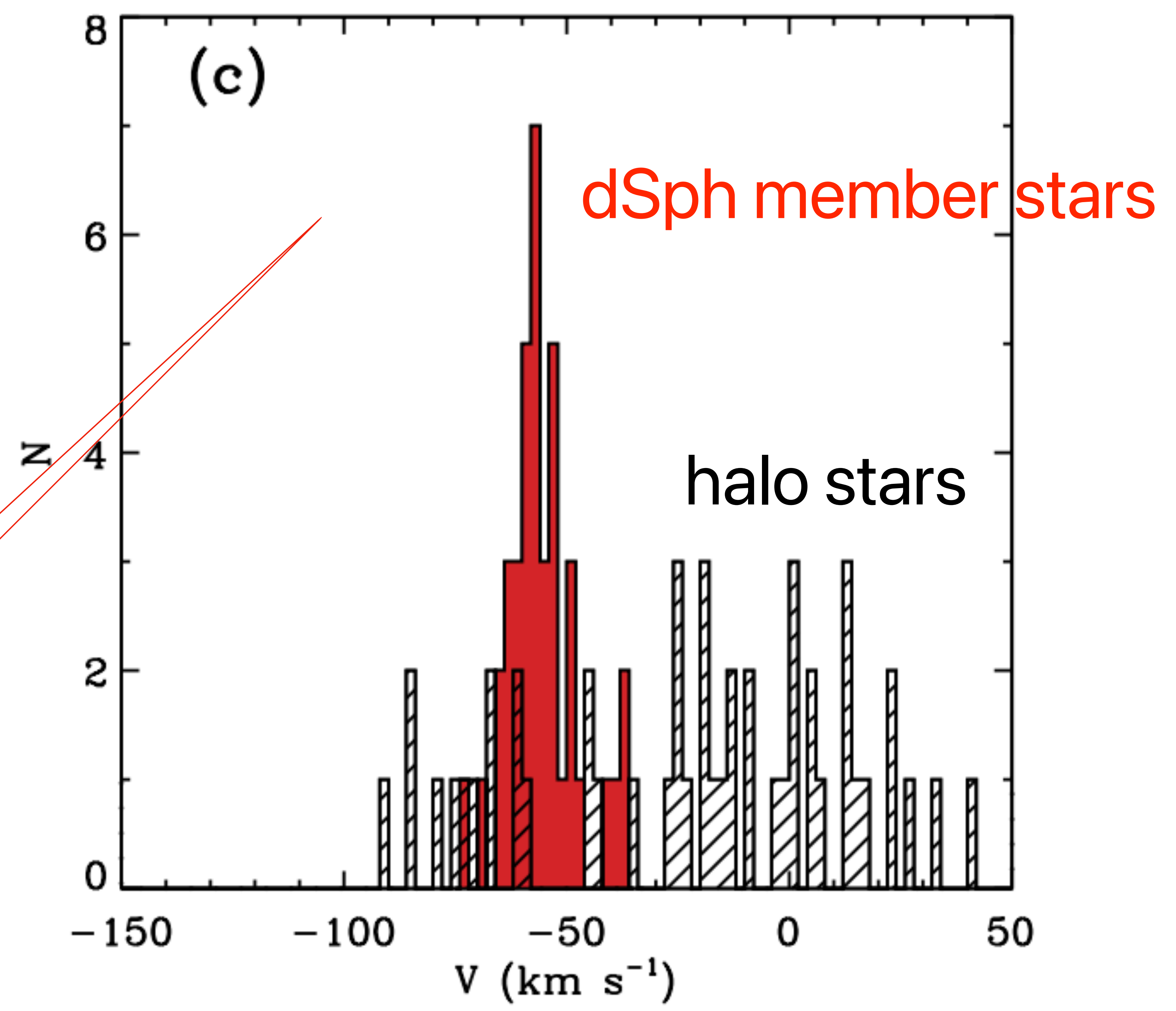
Major uncertainties:

1. **Contaminations for stellar kinematics (non-member stars/binary stars)**
   Bonnivard et al. (2015), Ichikawa et al. (2017, 2018), Horigome et al. (2021)
2. **Priors of dark matter halo parameters**
   Ando et al. (2020), Horigome et al. (2022)
3. **Non-sphericity of DM halo**
   Hayashi et al. (2016, 2020), Klop et al. (2016)
4. **Degeneracy between DM inner density and stellar velocity anisotropy**
   Read et al. (2018), Genina et al. (2020), Massari et al. (2020)
5. **Low statistics**

Contaminations for stellar kinematics



Line-of-sight velocity distribution of stars in the direction of UMaI (Simon & Geha 2007)



The vel. distributions overlap ⇒ Contamination

Contaminations for stellar kinematics

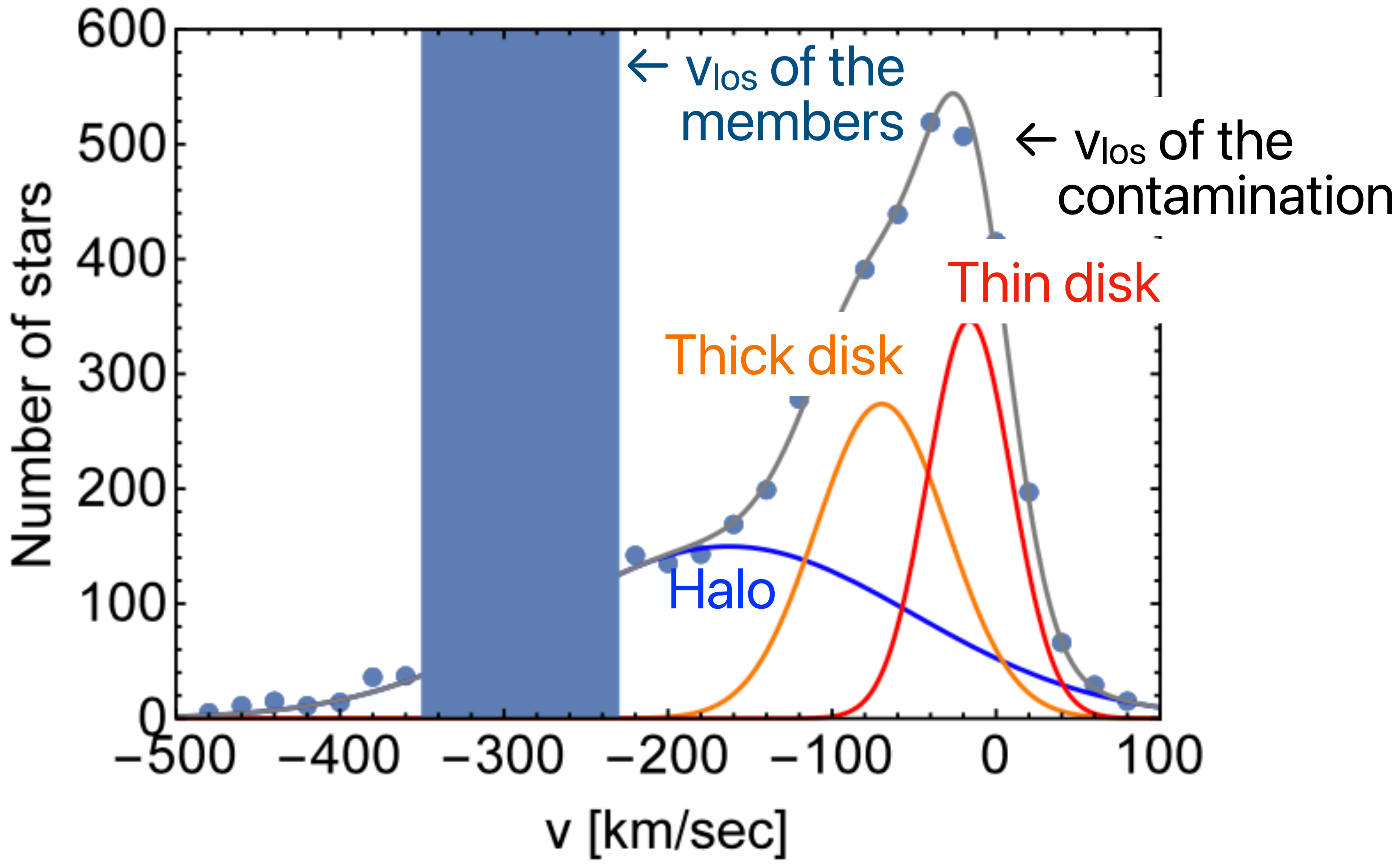
Ichikawa (incl. KH) et al. (2017, 2018)

- The likelihood function is constructed taken the contamination into account
- The contamination is modeled based on prior knowledge about the distribution of the major stellar components in the MW

$$-2\ln L_m = -2\sum_i \ln(s f_{\rm Mem}(v_i, R_i) + (1-s) f_{\rm FG}(v_i, R_i))$$

$$f_{\rm Mem}(v, R) = 2\pi R \Sigma_*(R) C_{\rm Mem} \mathcal{G}\left[v; v_{\rm Mem}, \sigma_{l.o.s.}(R)\right]$$

$$f_{\rm FG}(v, R) = 2\pi R C_{\rm FG} \prod_{j=1}^{3} \mathcal{G}\left[v; v_{\rm FGj}, \sigma_{\rm FGj}\right]$$



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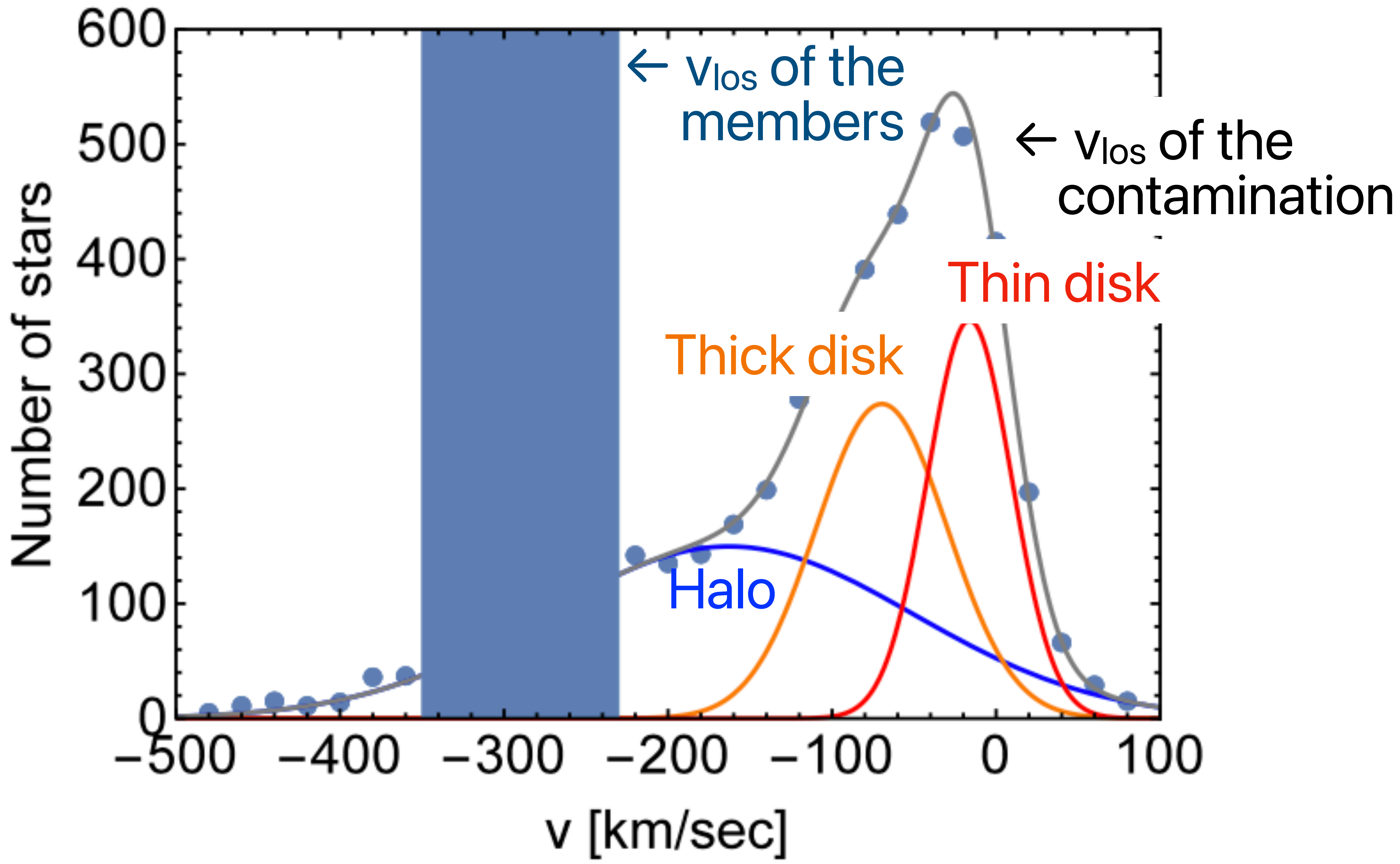

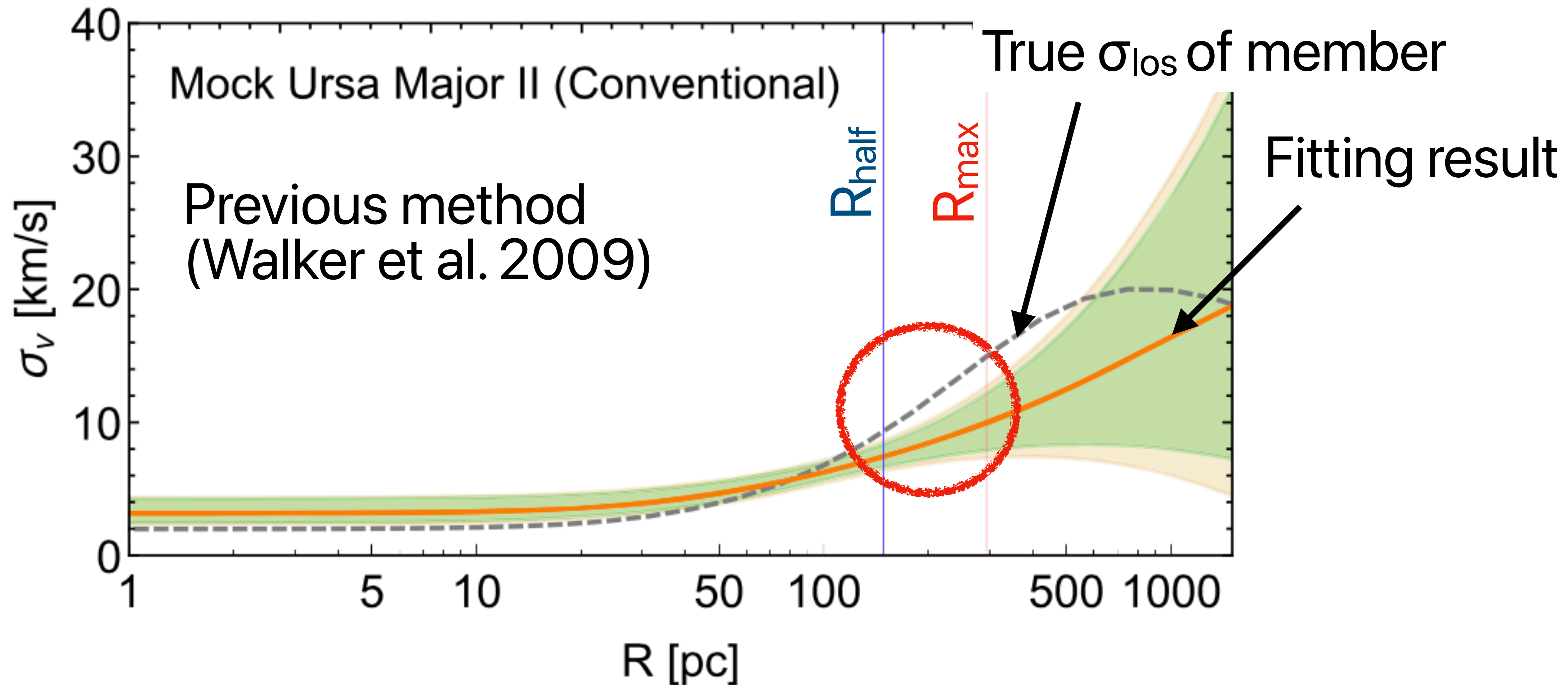

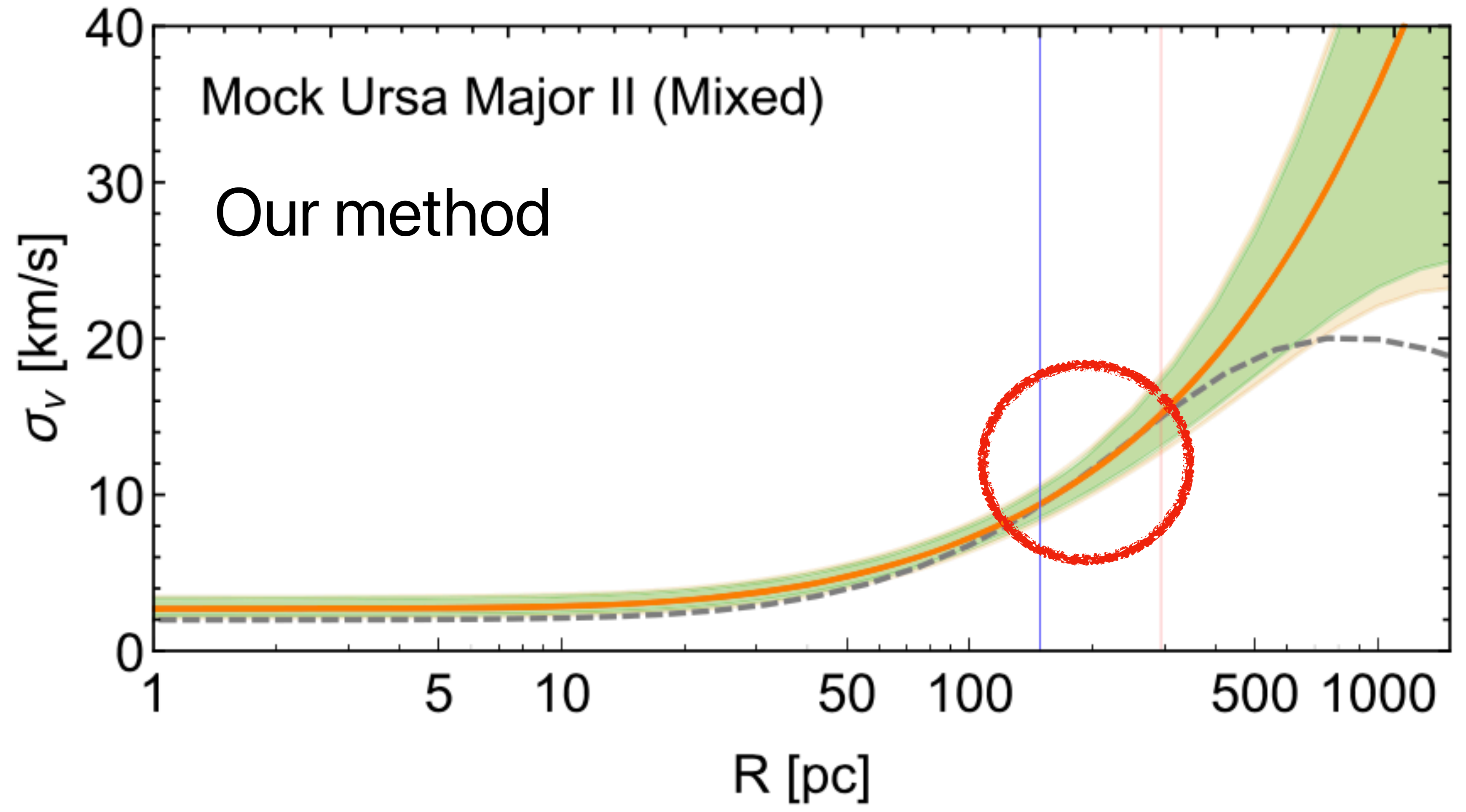

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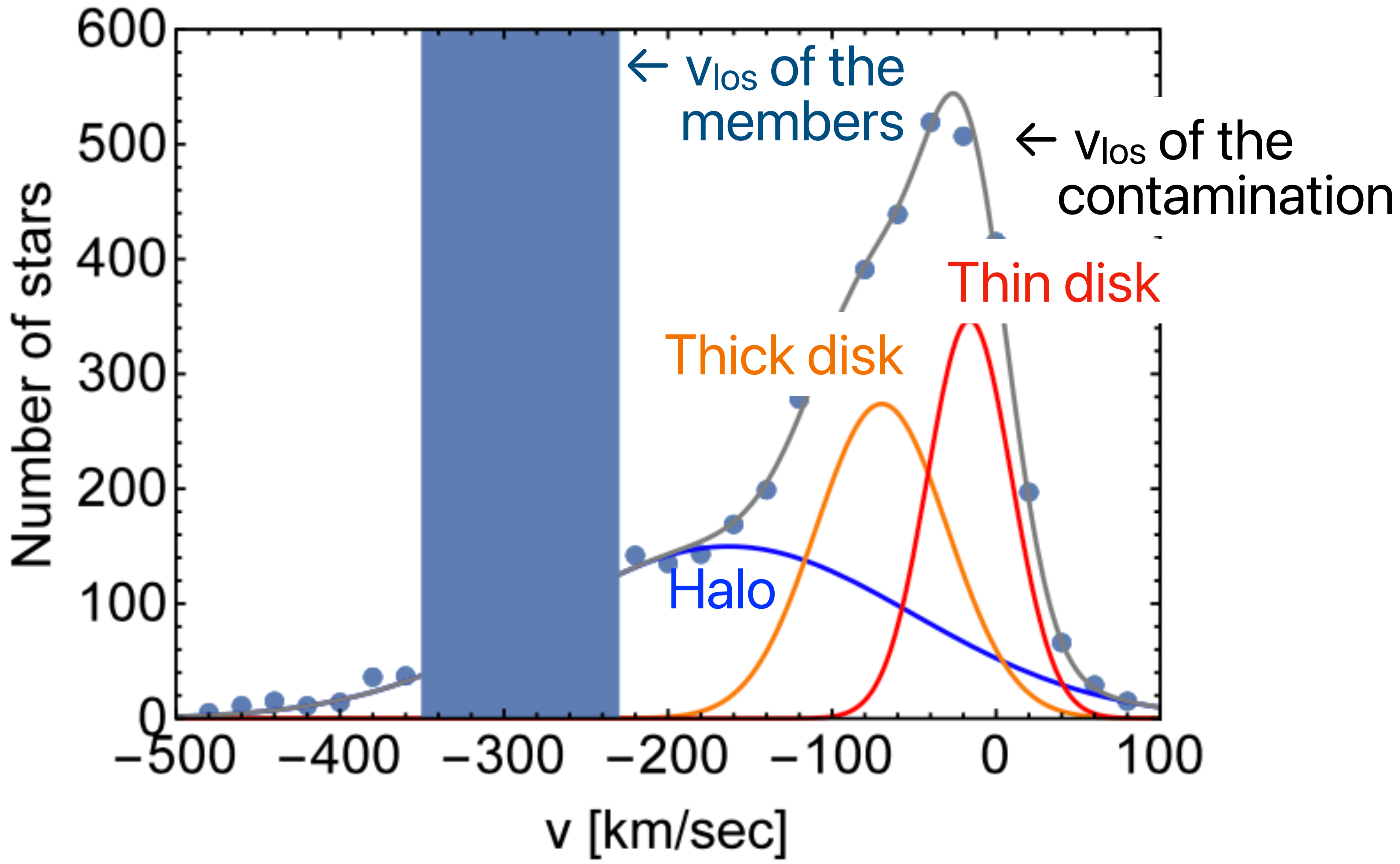
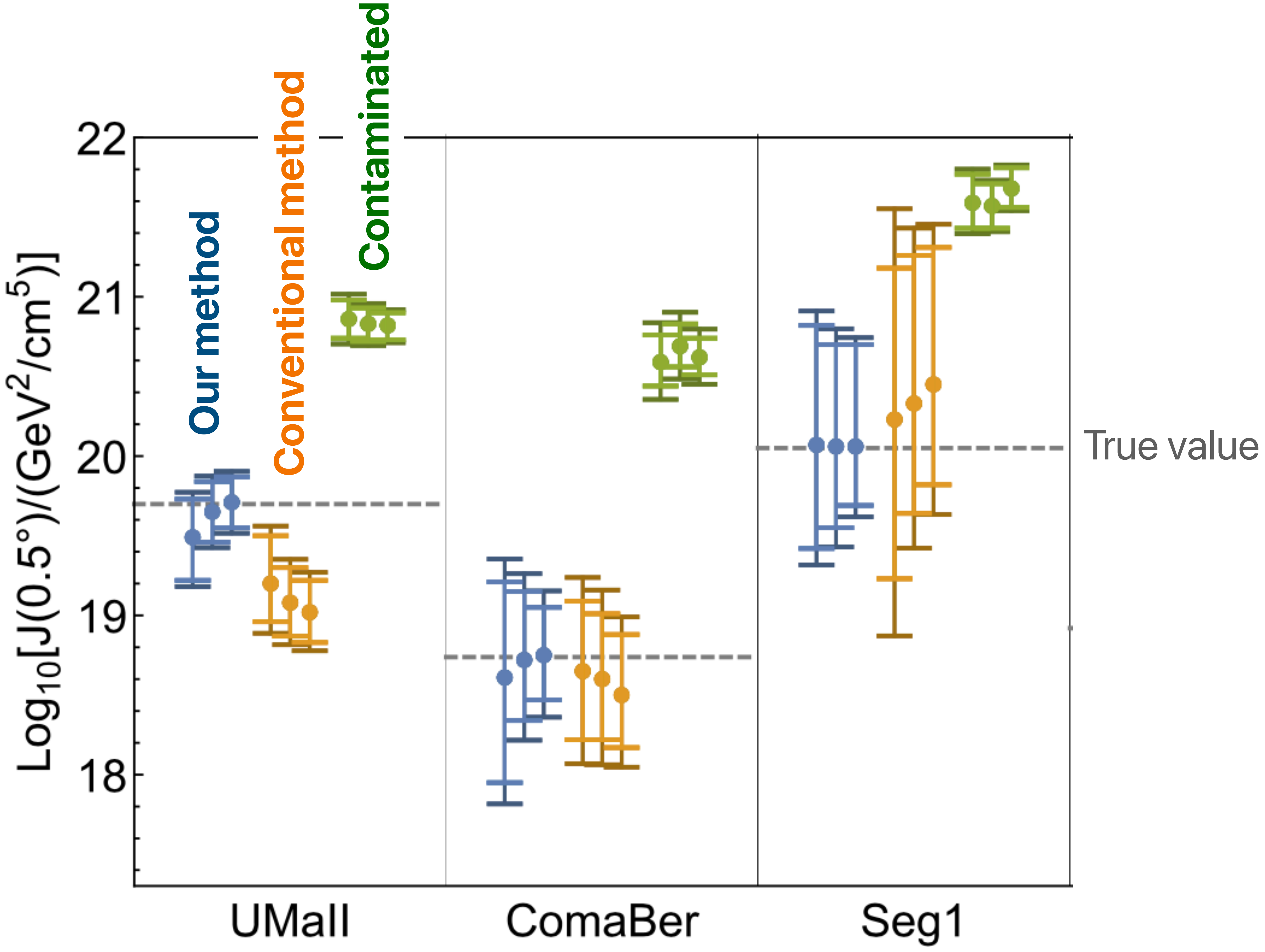
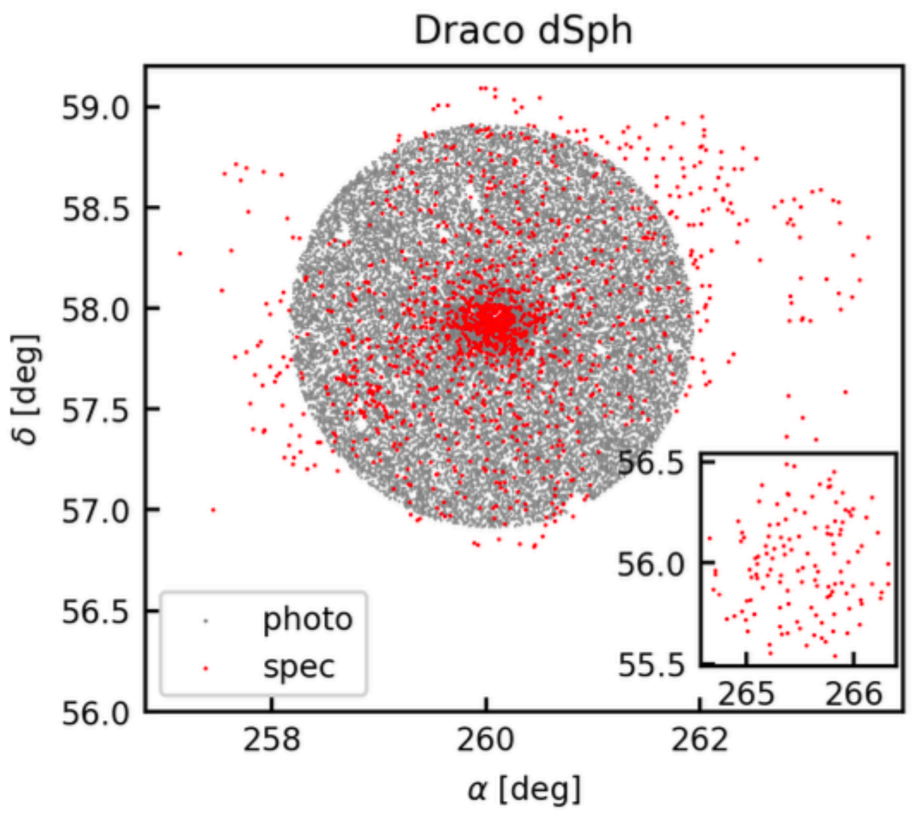


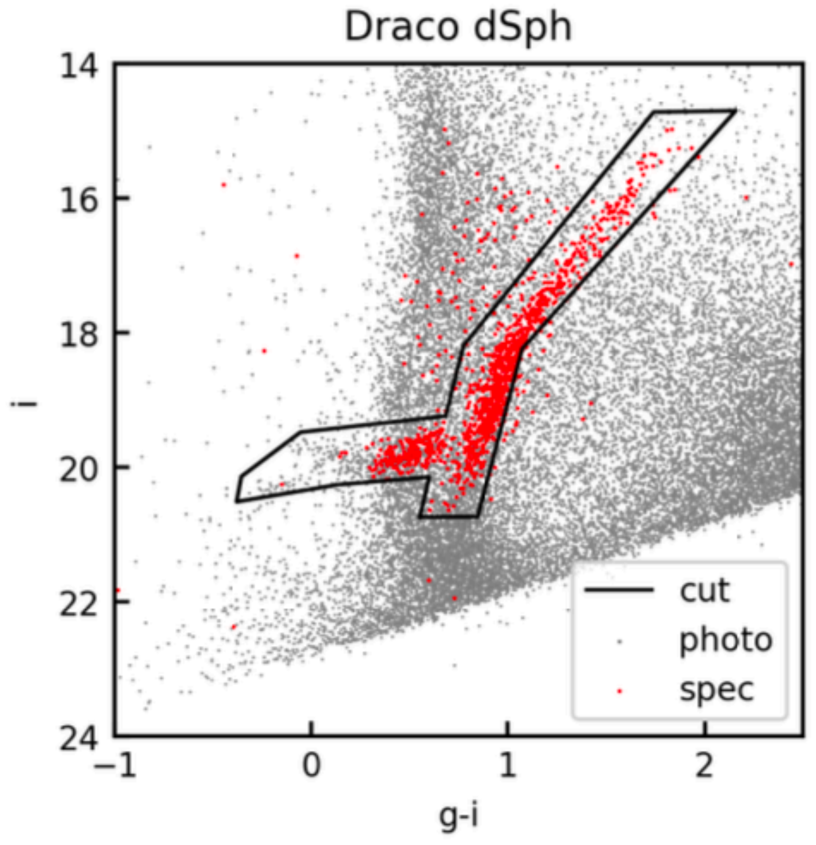


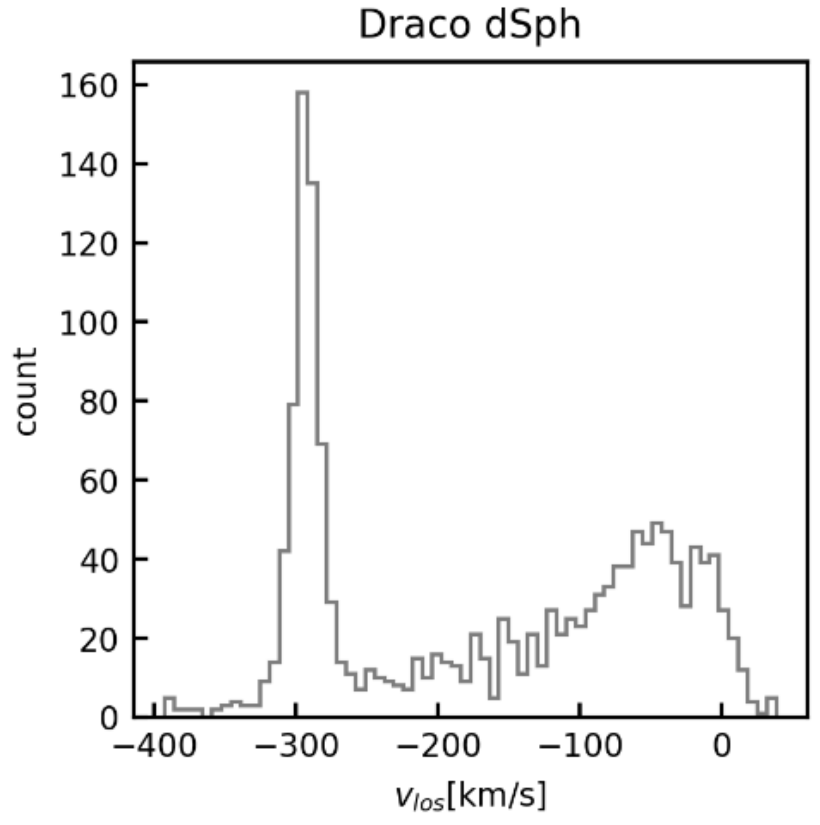
Application to the real data

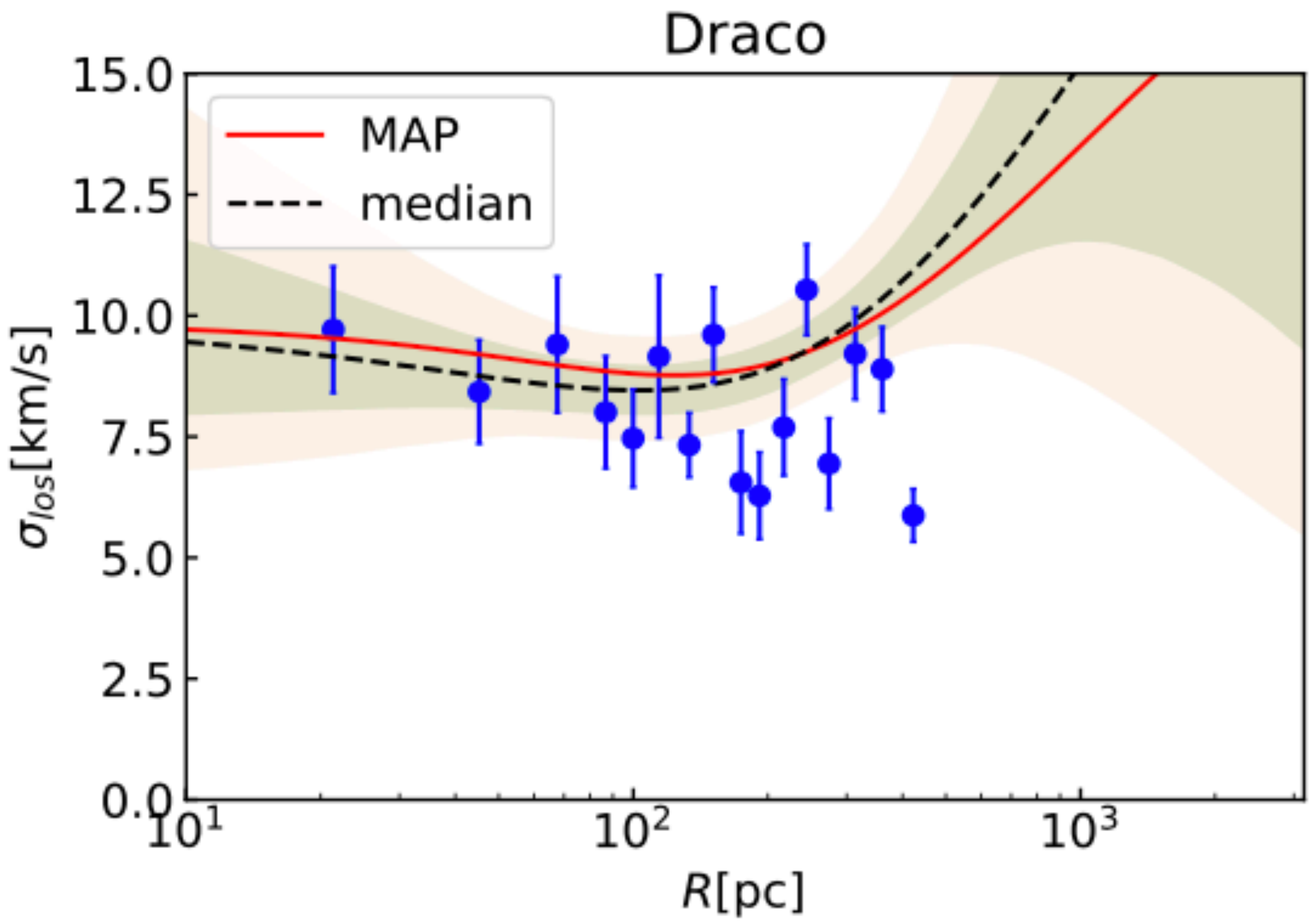
Horigome (incl. KH) et al. (2021)

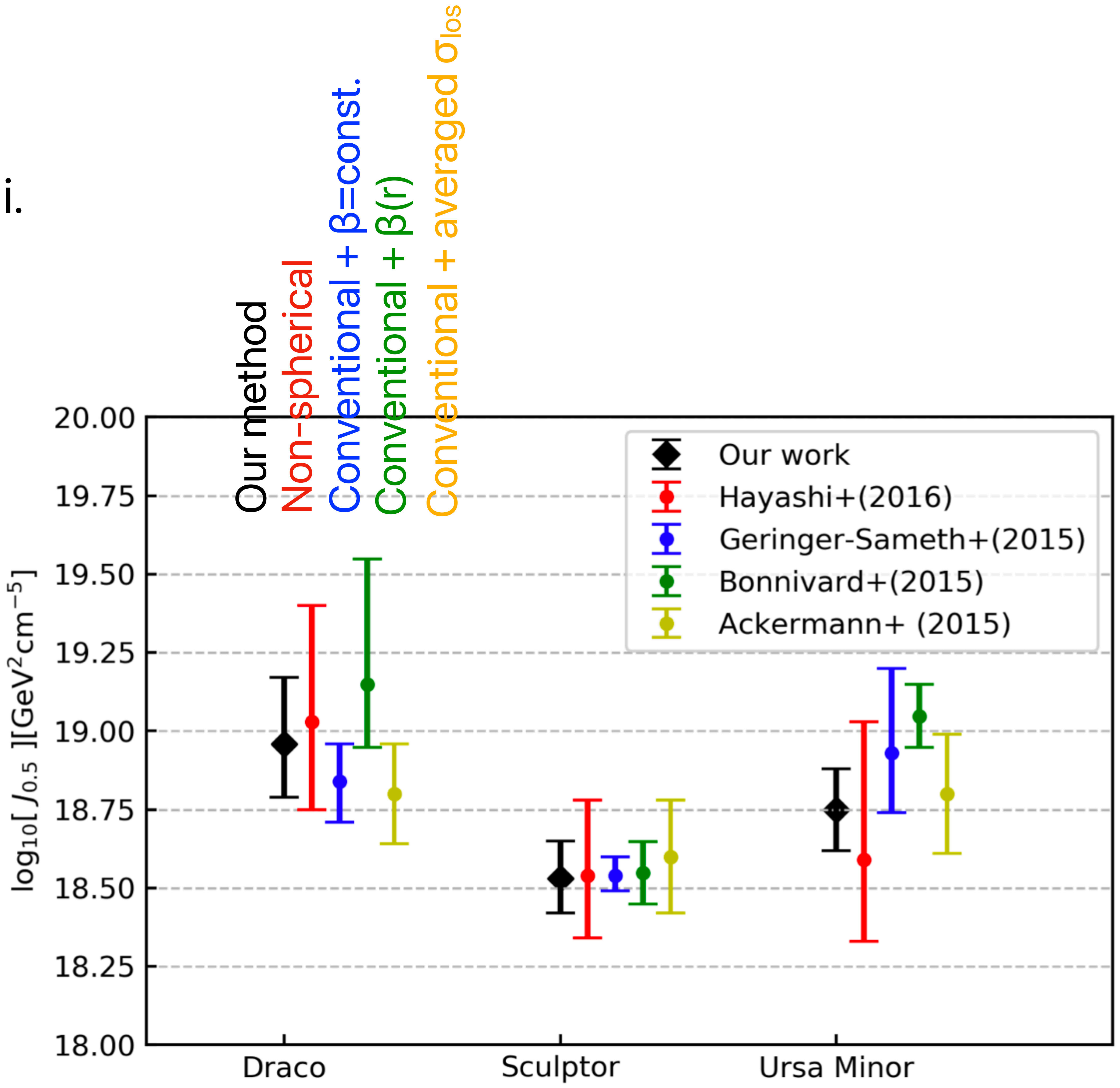
- Improve likelihood function to take the sampling bias into account
- Apply the likelihood function to the real data of Draco, Sculptor, and UMi.









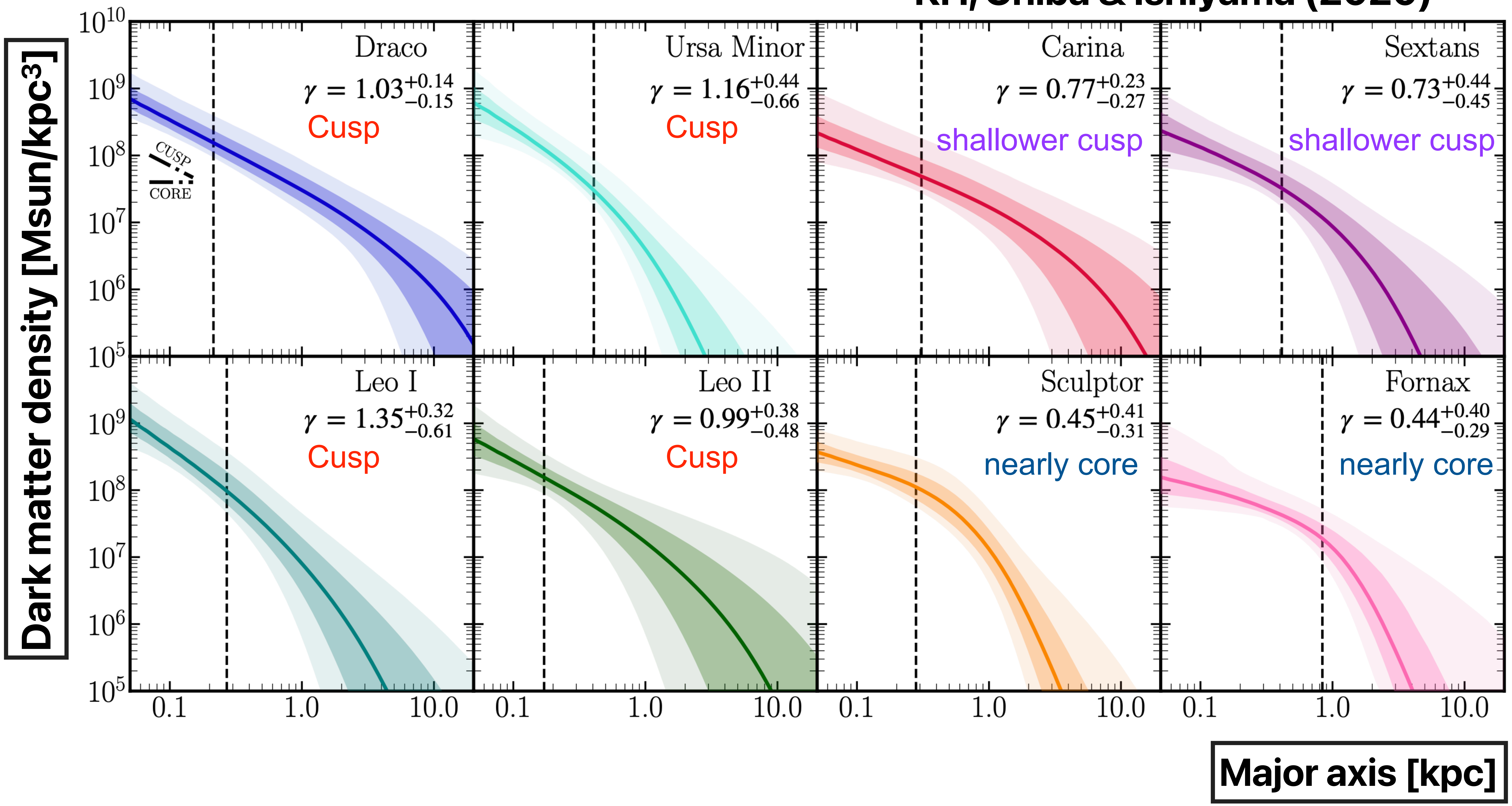


Non-spherical DM halo

Hayashi et al. (2020, 2022)

- Based on axisymmetric Jeans eqs., we found **the diversity of the DM density profiles in the dSphs**

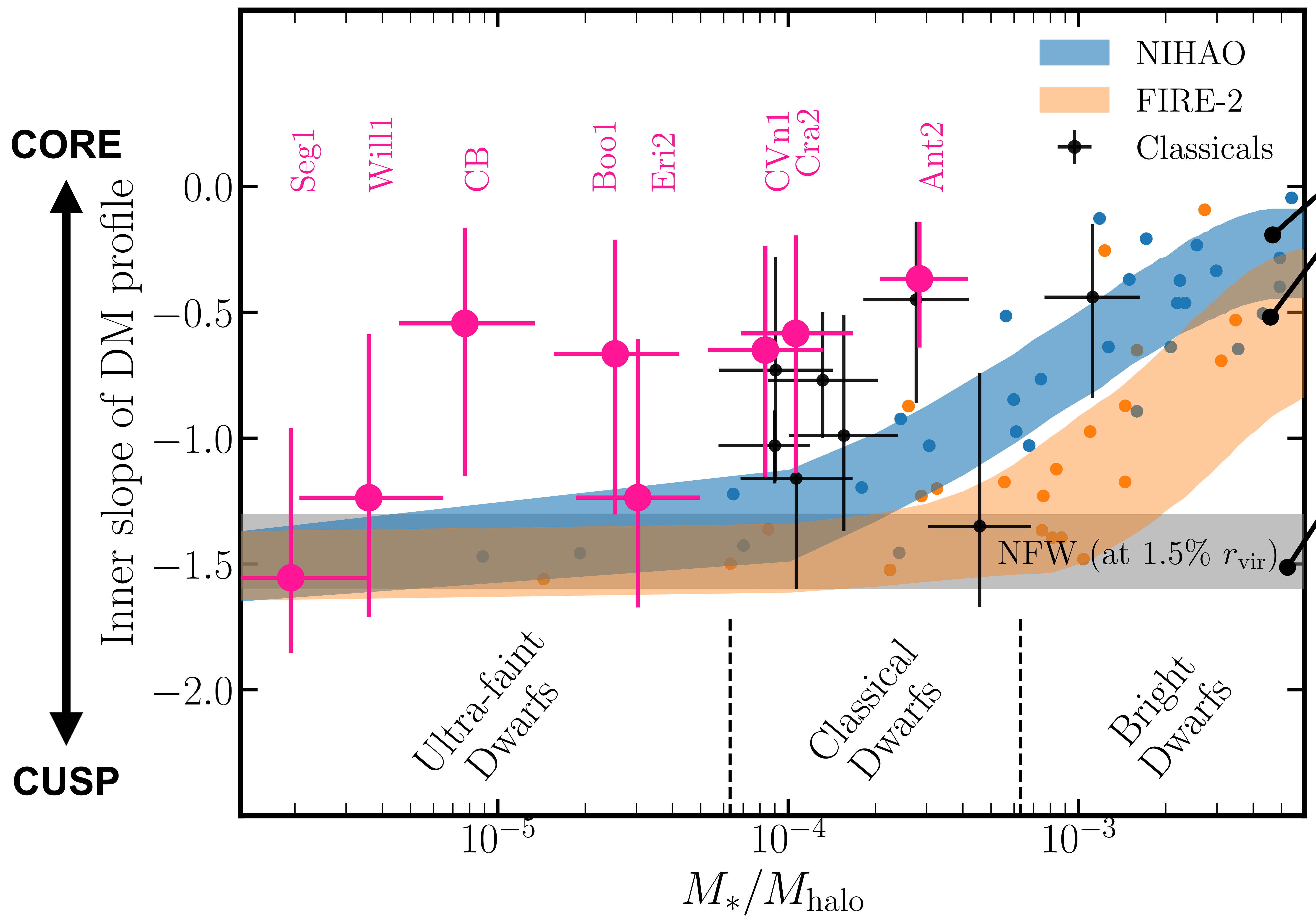
KH, Chiba & Ishiyama (2020)



Non-spherical DM halo

Hayashi et al. (2020, 2022)

- Based on axisymmetric Jeans eqs., we found **the diversity of the DM density profiles in the dSphs**
- The diversity can exist in ultra-faint dSphs regime, even though there is large uncertainties on their inner slopes, γ.



Prediction from LCDM based N-body+hydro sims.

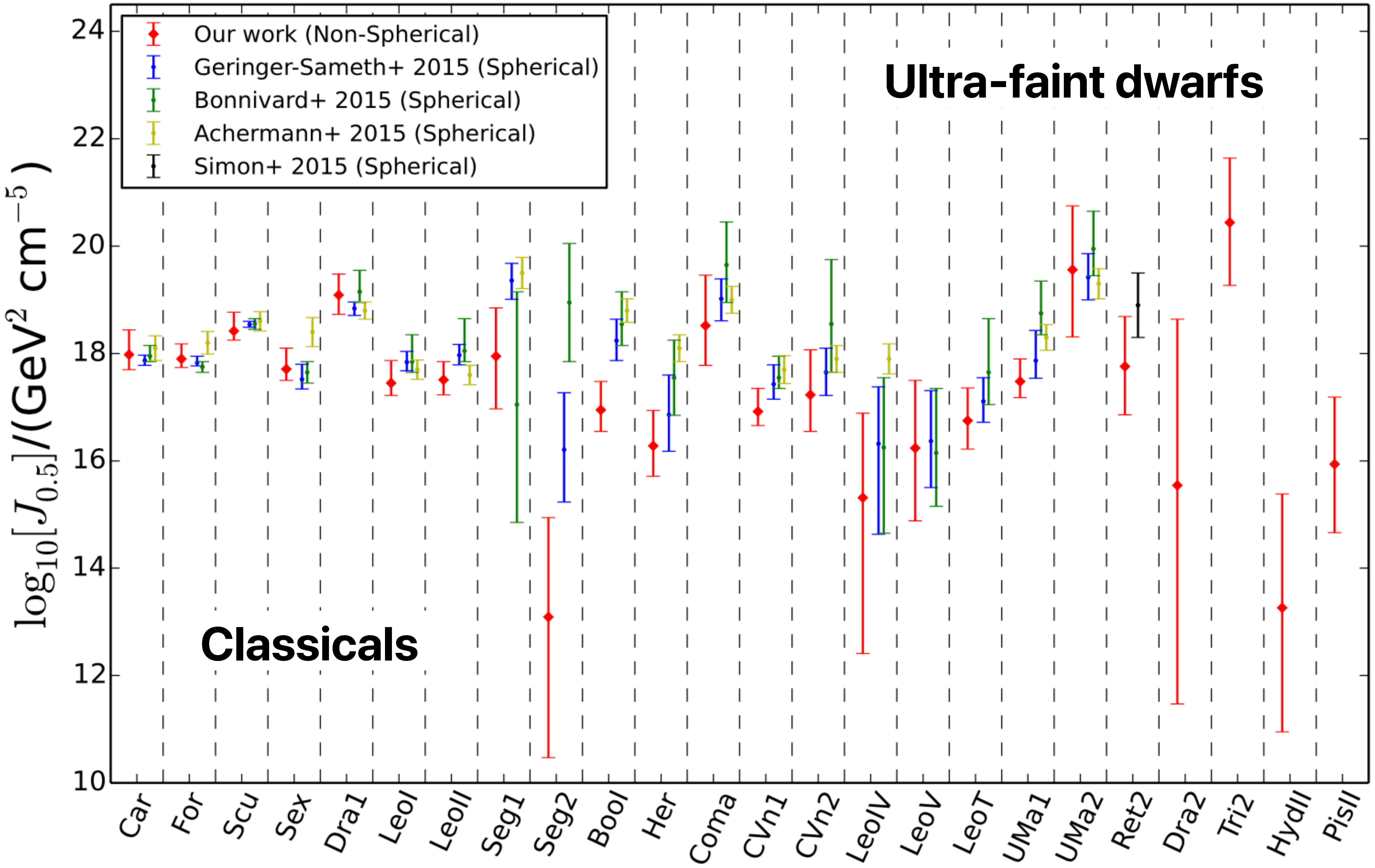
Prediction from LCDM based pure N-body sims.

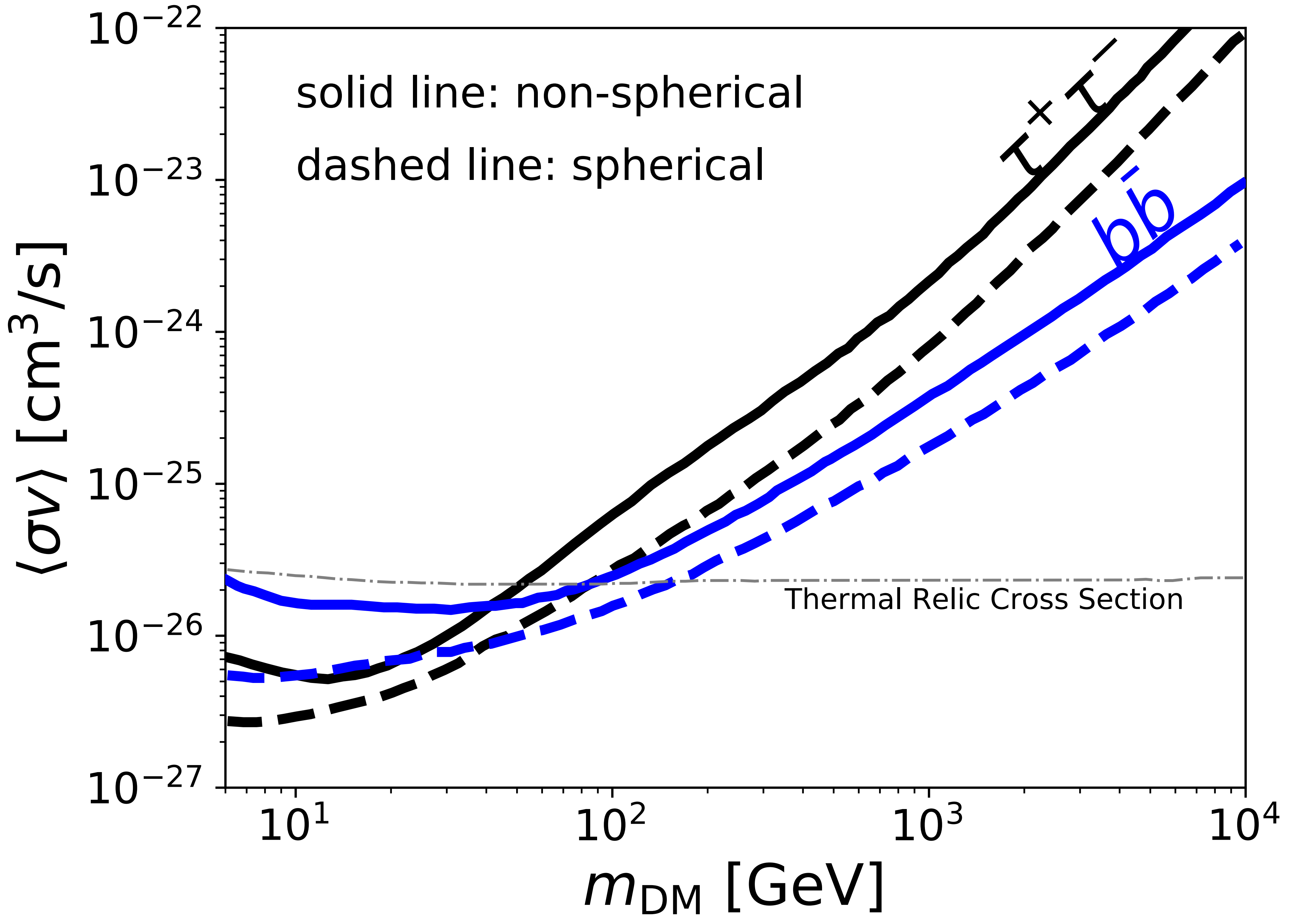
The systematic trend could be roughly in agreement with the predictions with considering baryon feedbacks.

Non-spherical DM halo

Hayashi et al. (2016), Klop et al. (2016)

- Based on axisymmetric Jeans eqs., J-factors is estimated taken non-spherical stellar and dark components into account.
- Up to a few orders of magnitude difference in the J-factor estimates, in comparison with spherical models.
- The non-sphericity of luminous and dark components influences the estimate of J-factors





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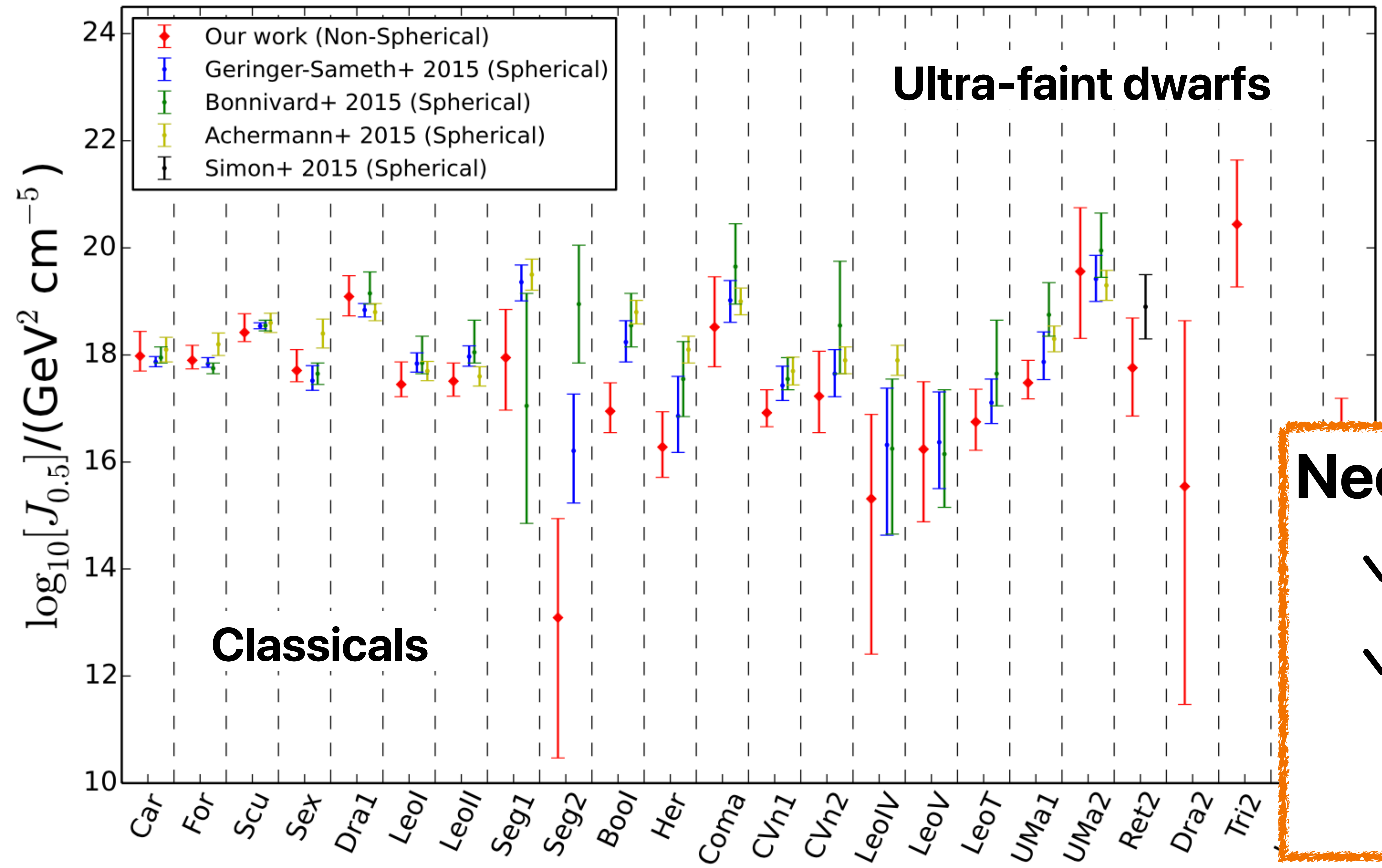
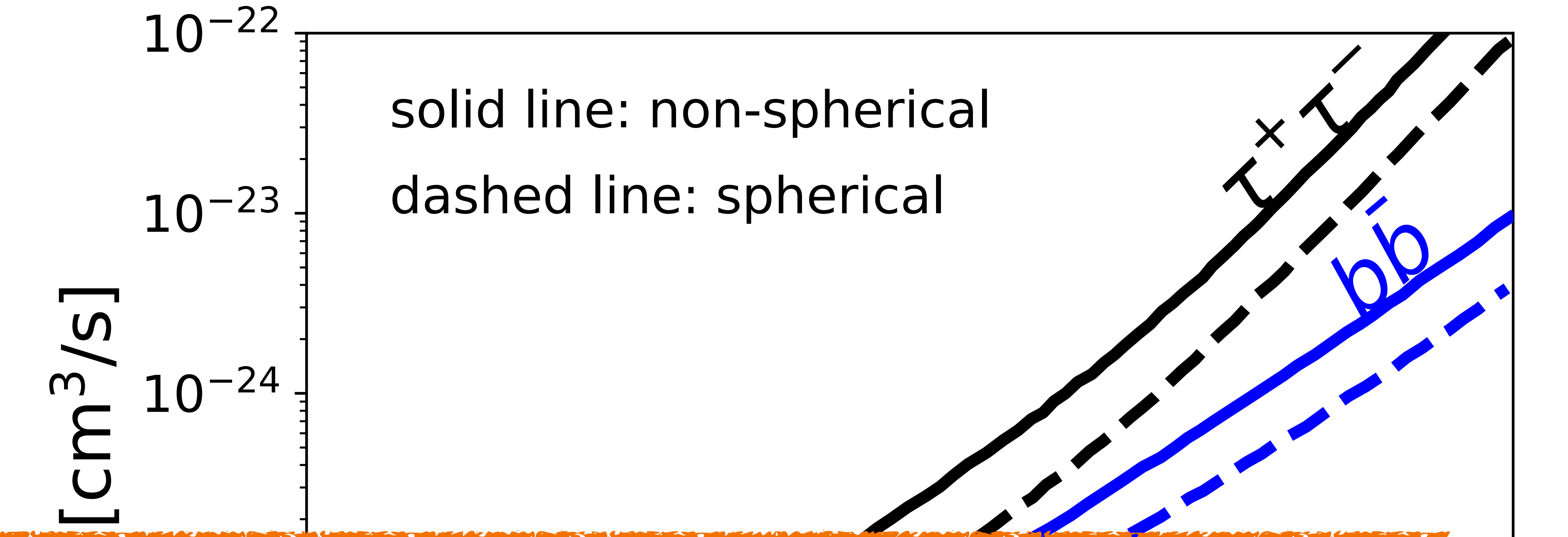
- Up to a few orders of magnitude difference in the J-factor estimates, in comparison with spherical models.
- The non-sphericity of luminous and dark components influences the estimate of J-factors





Need to update:

✓Contamination effects

✓Break $\rho_{\mathrm{DM}} - \beta_{\mathrm{ani}}$ degeneracy

- Higher-order velocity moments
- Transverse motions of stars

The current status of dark matter density in the dSphs

- There are many uncertainties in estimation of DM density profiles of the dSphs
- Updates on dynamical modelings taking these uncertainties into account should be needed
- To set robust constraints on the DM profiles, a large number of kinematic sample with high precision are required.

Future perspective

Stellar kinematic measurements for MW and the dSphs in the future

We will be able to hunt a large amount of stellar velocities and proper motions at the Galactic center, the Galactic disk, and the Galactic dSphs by upcoming large surveys.

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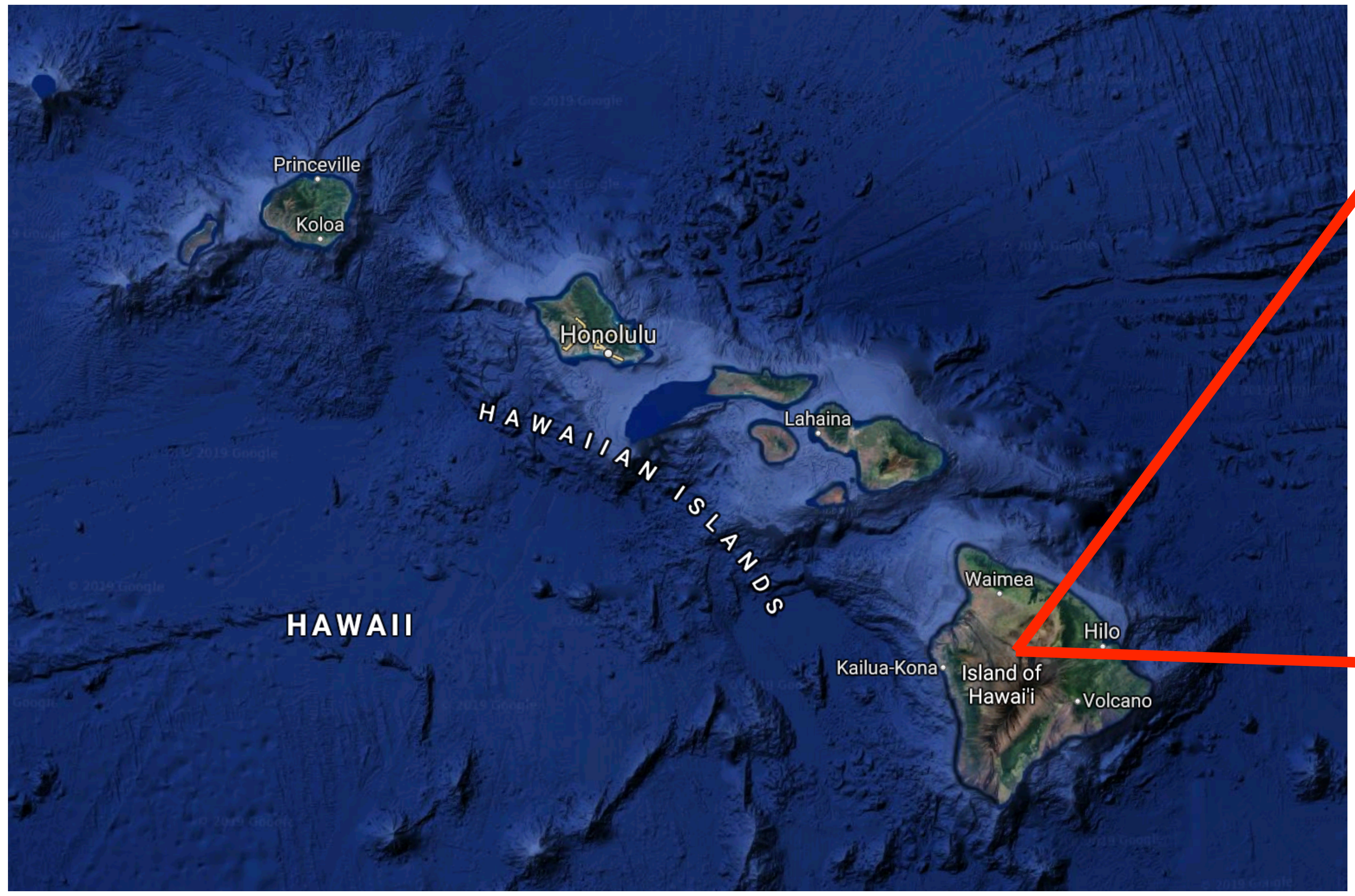
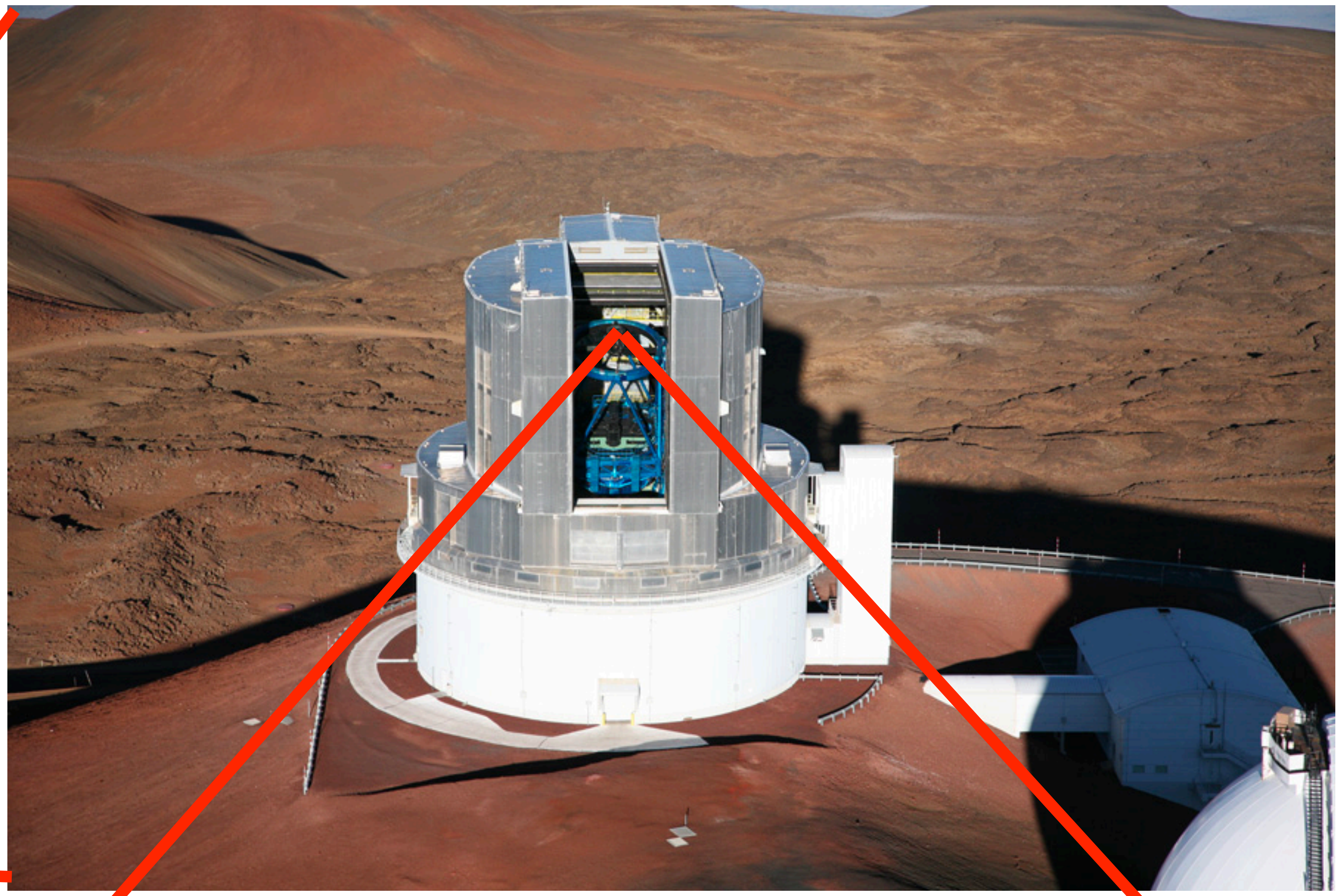
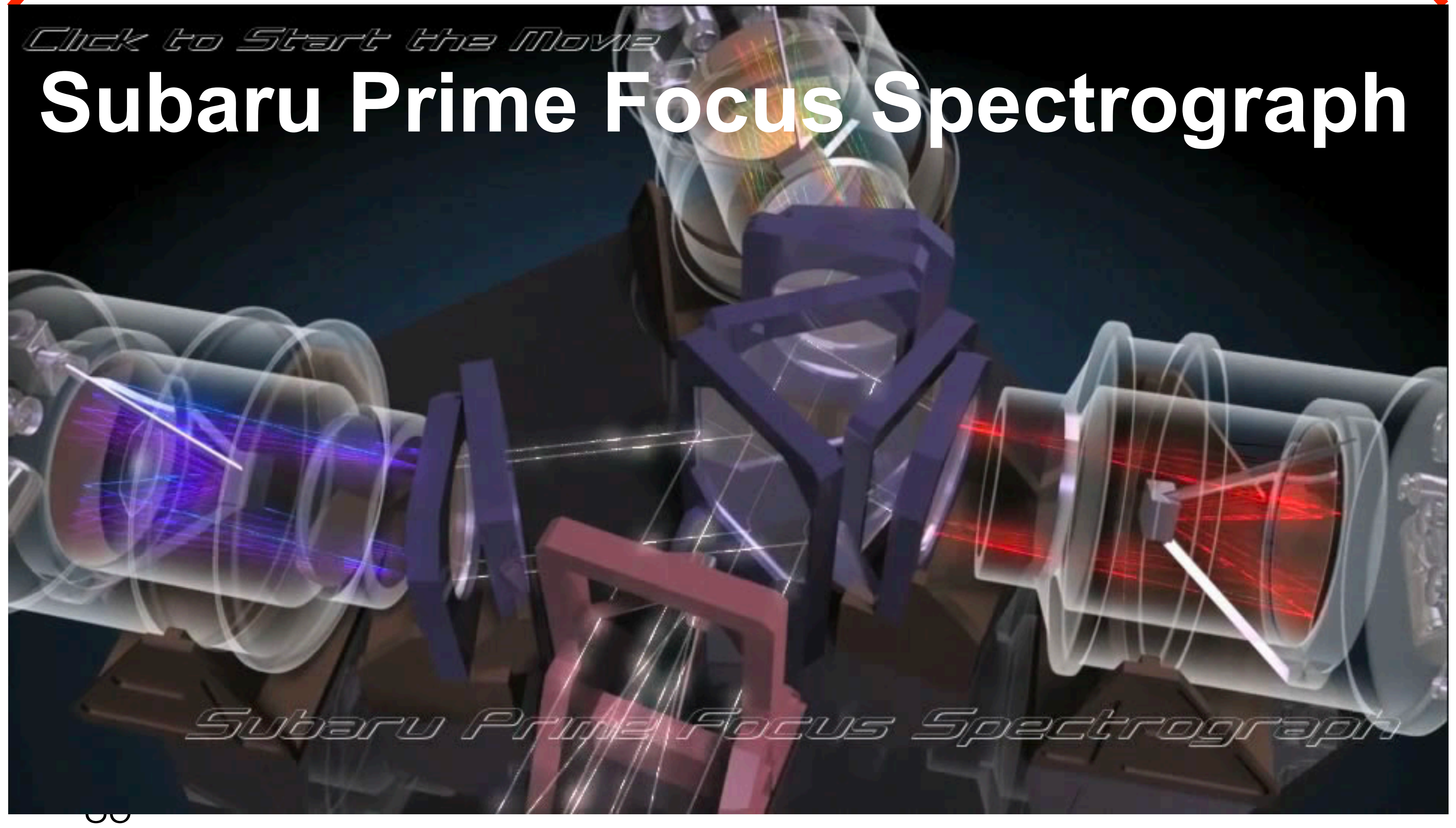
Subaru Prime Focus Spectrograph

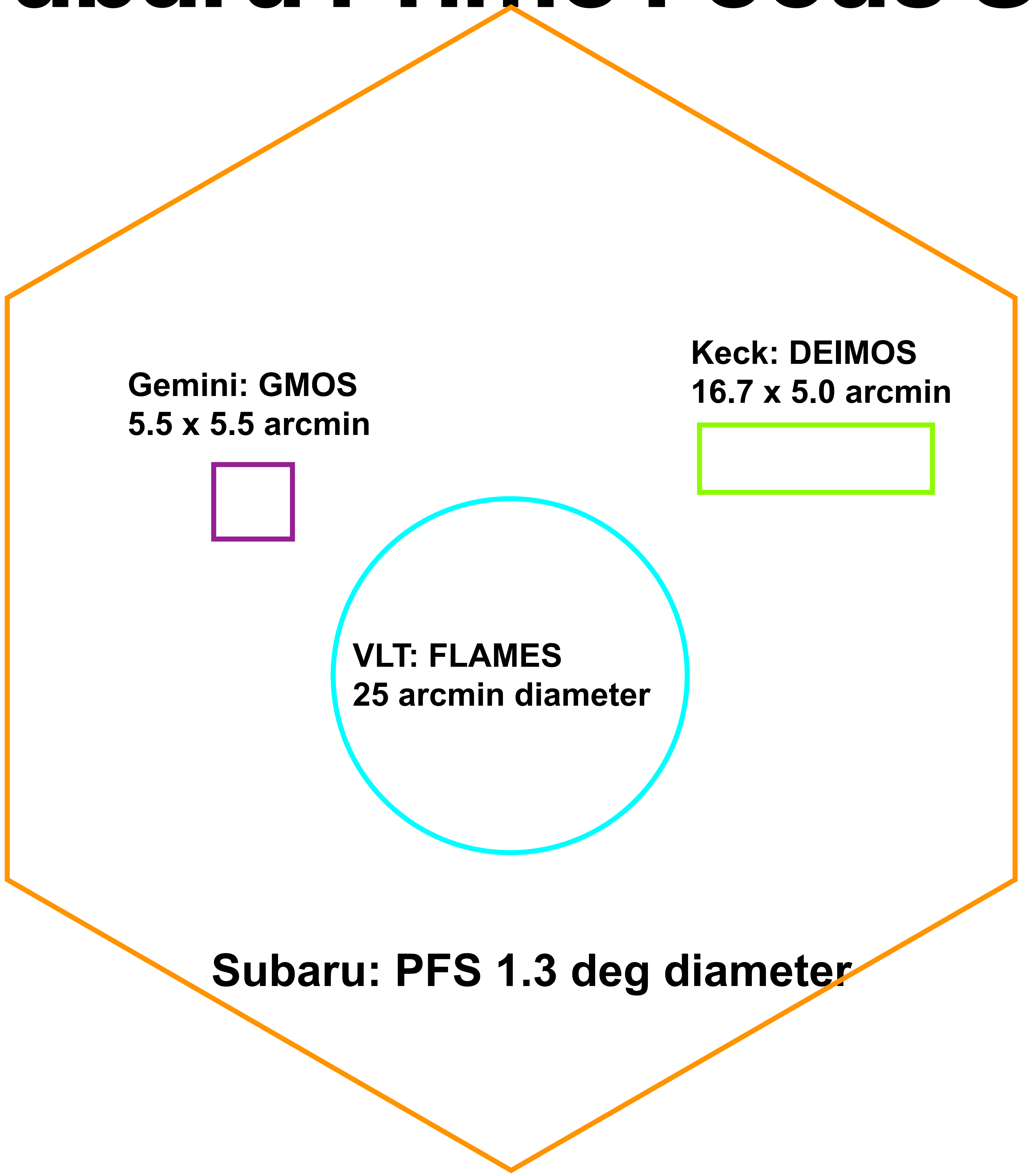


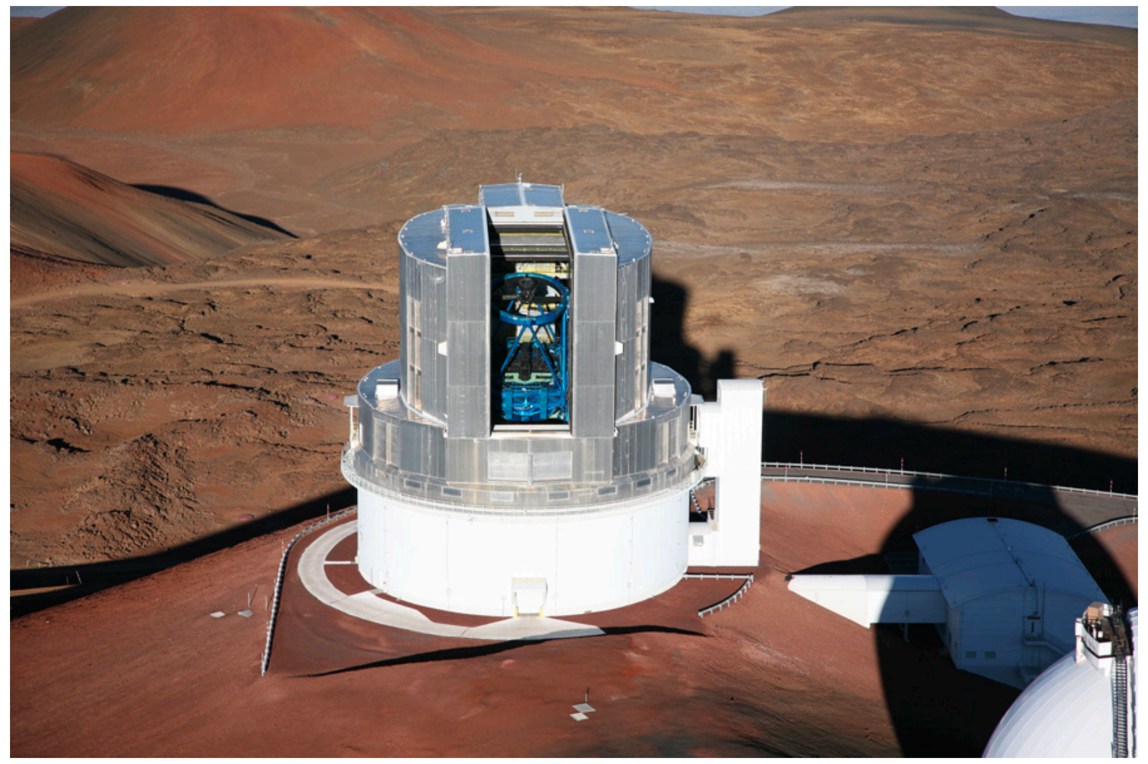




- **Subaru Prime Focus Spectrograph (PFS)** will be attached on Subaru 8m class telescope at the summit of Mauna Kea of Hawaii big island.
- PFS is progressed by large international collaborations.
- PFS science operation will start from 2024.

Subaru Prime Focus Spectrograph





Subaru Telescope

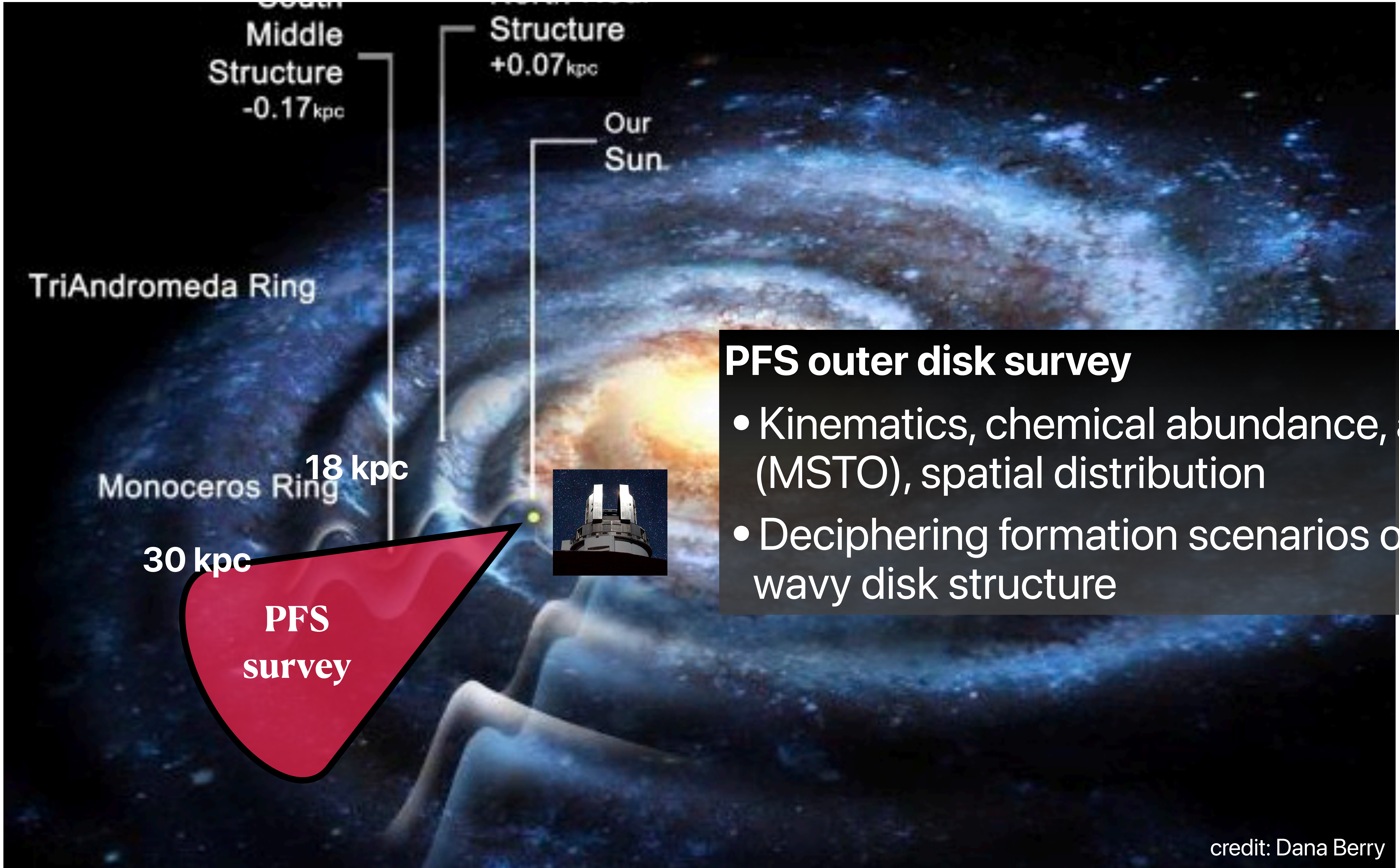
+

Wide Field of View

||

Wide and Deep
spec. survey

Large Spectroscopic Survey for MW outer disk

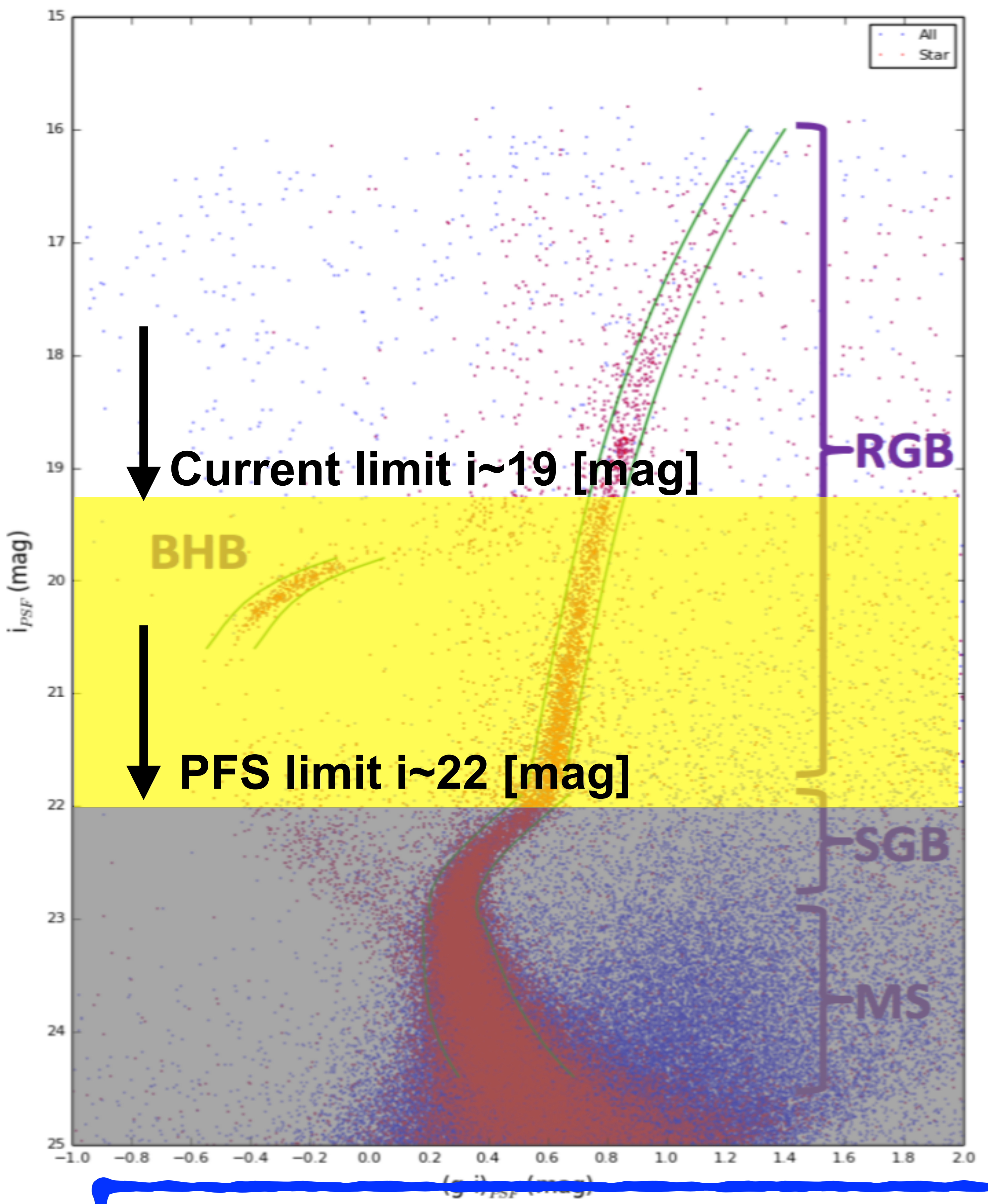


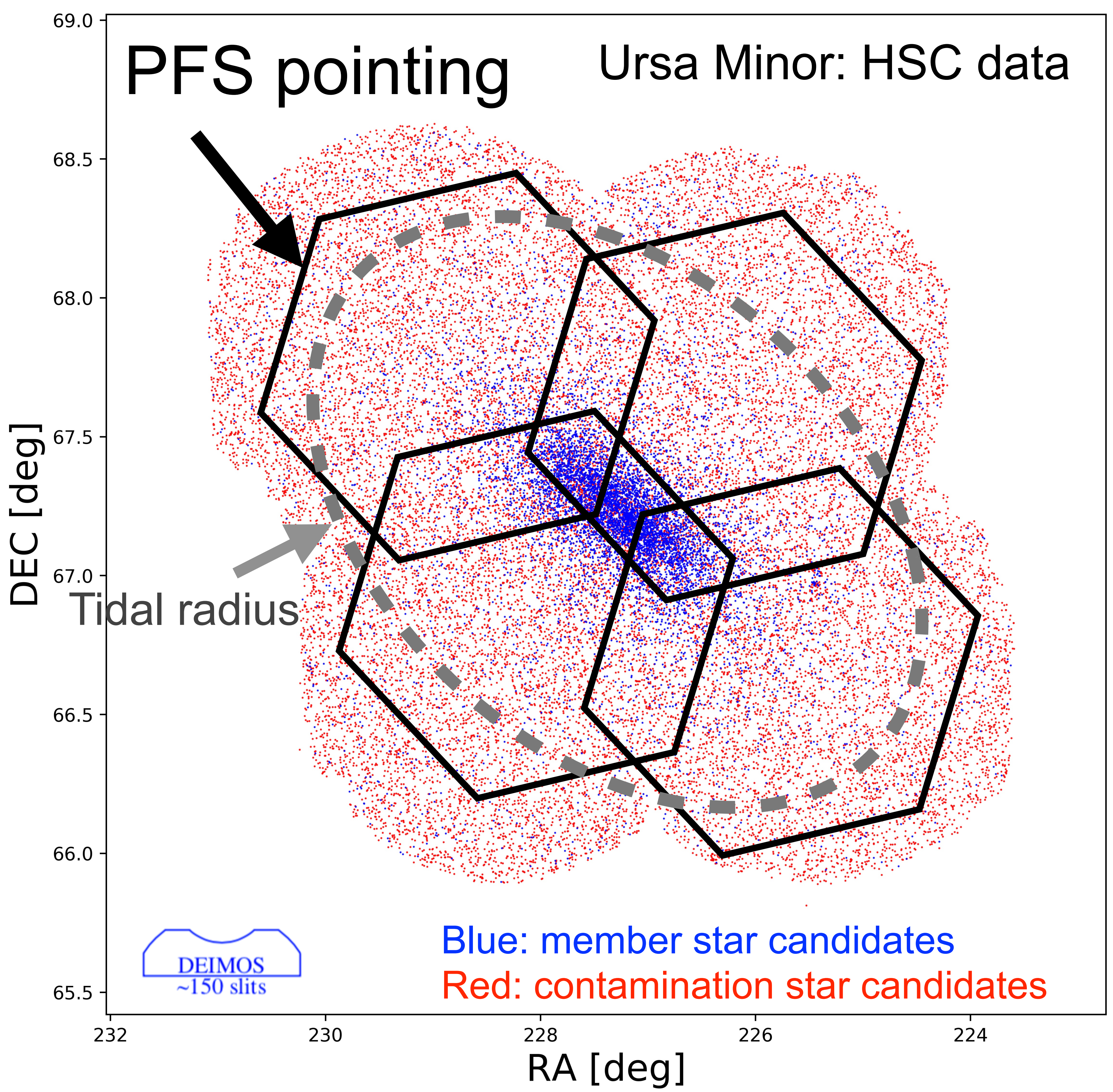
PFS outer disk survey

- Kinematics, chemical abundance, age (MSTO), spatial distribution
- Deciphering formation scenarios of wavy disk structure

Wide & deep PFS survey of dSphs

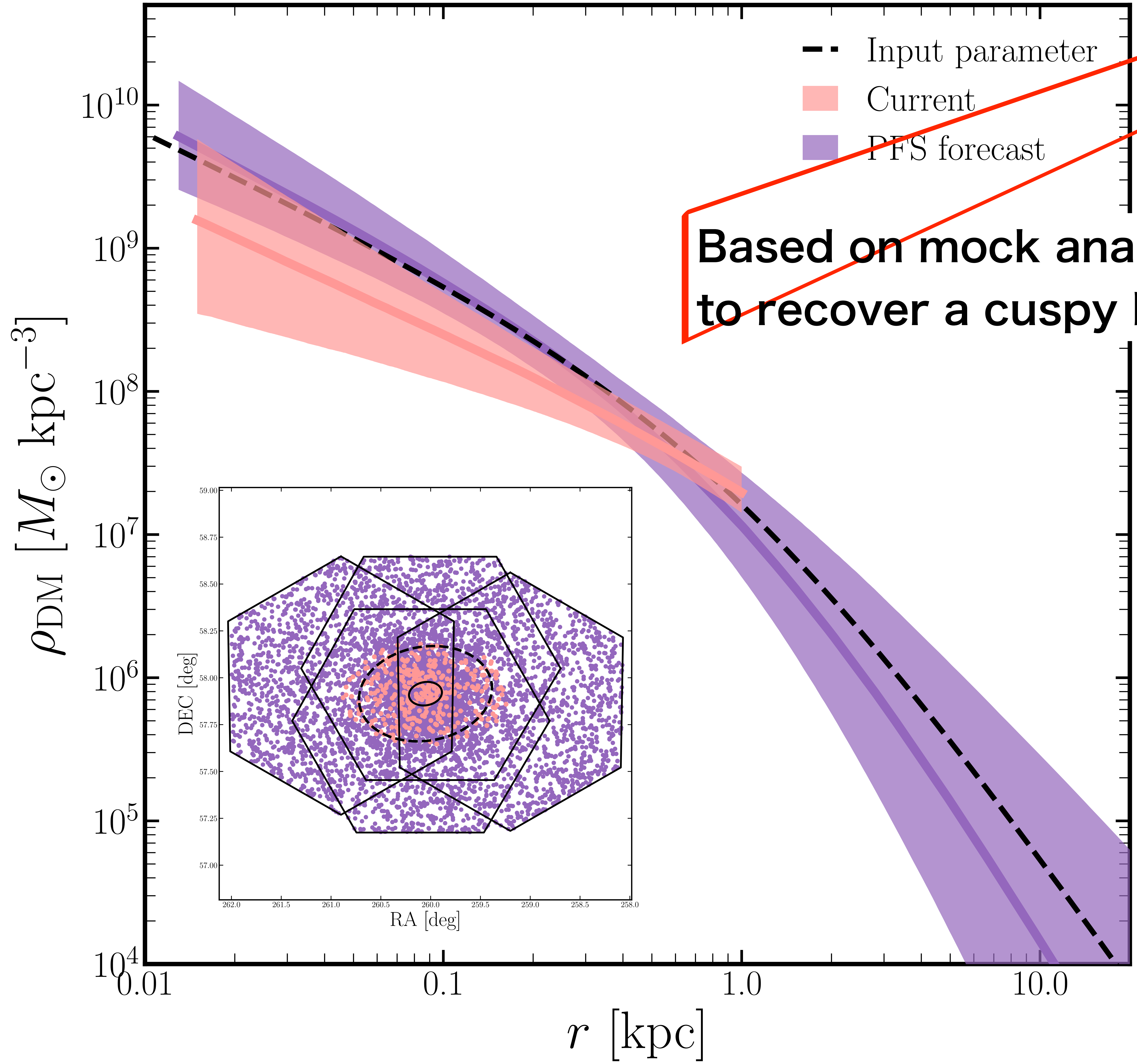
Plot by KH, Komiyama, and PFS-GA team





- ~5000 observable member stars in UMi dSph!
  ⇔ (current data is only ~300)
- Huge number of stellar kinematics out to the outskirts

PFS forecast



Based on mock analysis, PFS data will enable to recover a cuspy DM density profile.

- Contamination…
- Binary stars…
- Model dependence…
  - Jeans analysis?
  - DFs?
  - Orbit-based simulations?
- Survey strategy….

Summary

- The Milky Way and its satellites are promising targets of direct/indirect experiments searching for dark matter.
- DM density profile in the MW is still ongoing debate.
- There are many uncertainties in the estimate of DM density profile in the dSphs. We should address them seriously.
- **Future will be bright.** Upcoming surveys will enable us to obtain a large number of stellar kinematic sample.
- For DM studies, deep and wide spec. survey by **Subaru-PFS** should be essential.

KASHIWA DARK MATTER SYMPOSIUM 2022

November 29 - December 2, 2022

hybrid #dm2022kashiwa

ICRR
Institute for Cosmic Ray Research
University of Tokyo

- Abstract submission deadline: **October 14, 2022, 23:59 UTC**
- Registration deadline: **November 4, 2022, 23:59 UTC**

Rationale

We are happy to announce the fourth Kashiwa Dark Matter symposium at the Institute for Cosmic Ray Research of the University of Tokyo. For the first time since 2019, the symposium will take place again in-person at the University of Tokyo Kashiwa Library Media Hall* The symposium will be held fully hybrid, allowing a worldwide inclusive and eco-friendly participation in an ongoing pandemic.