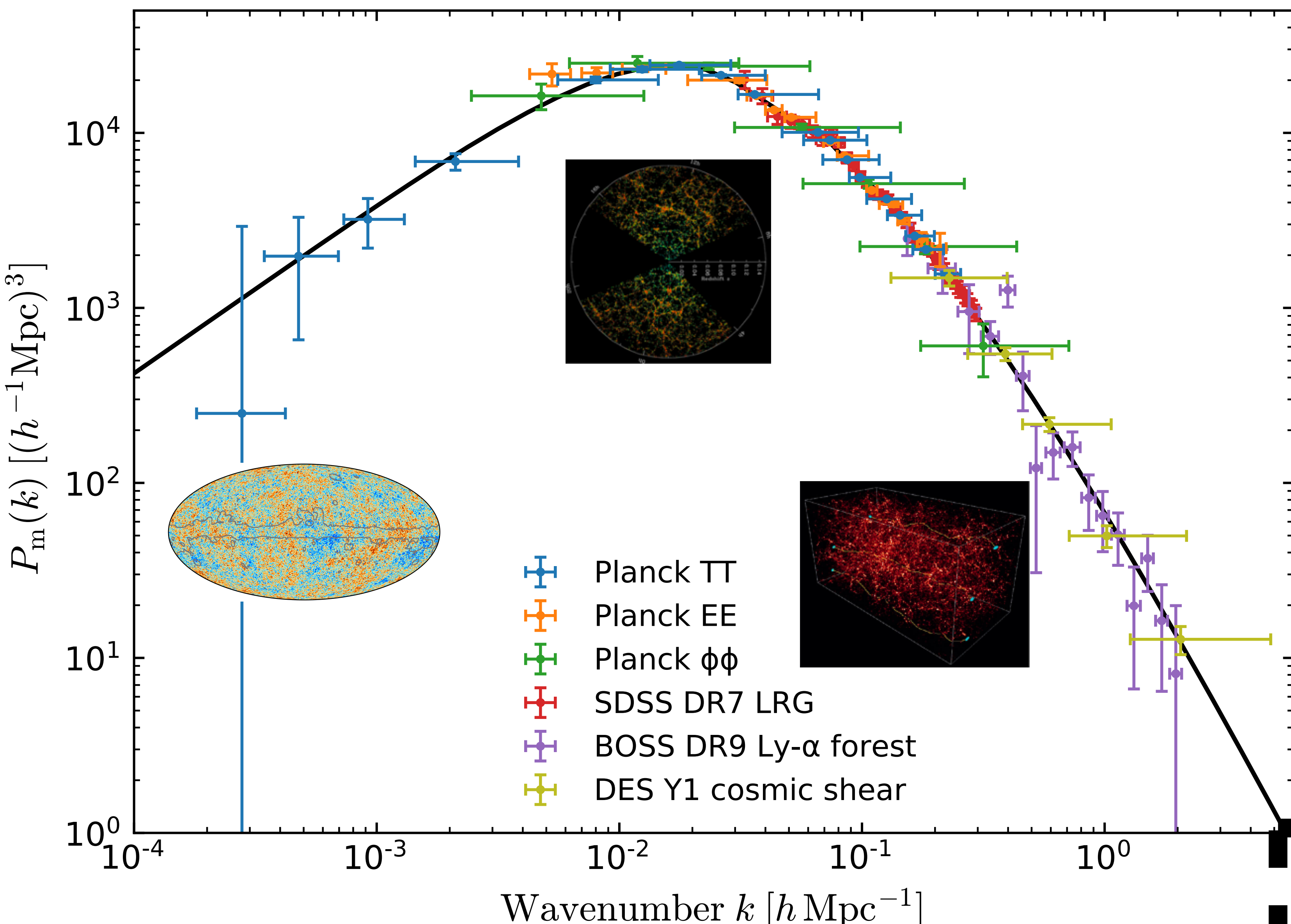
Galactic Archaeology: Unveiling the nature of dark matter

Kohei Hayashi (JSPS fellow)

Institute for Cosmic Ray Research, The University of Tokyo

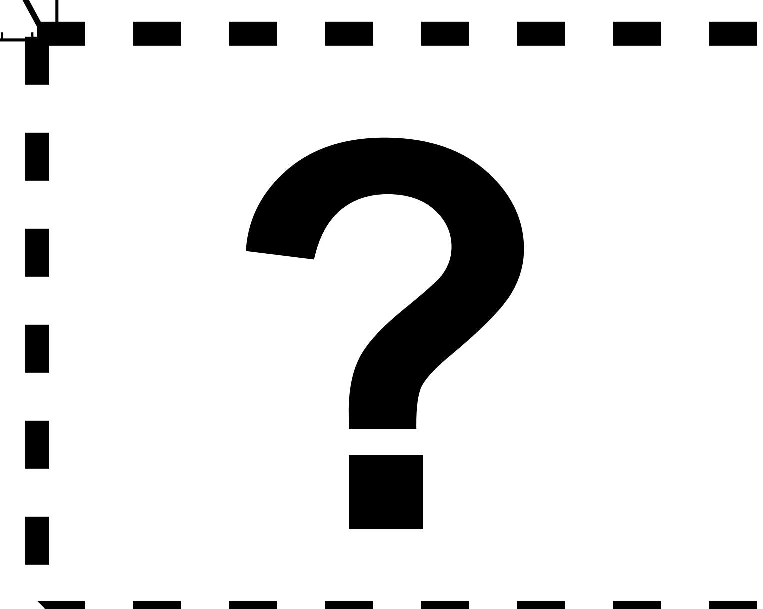
Λ-based cold dark matter universe

- **The matter power spectrum inferred from different cosmological probes**



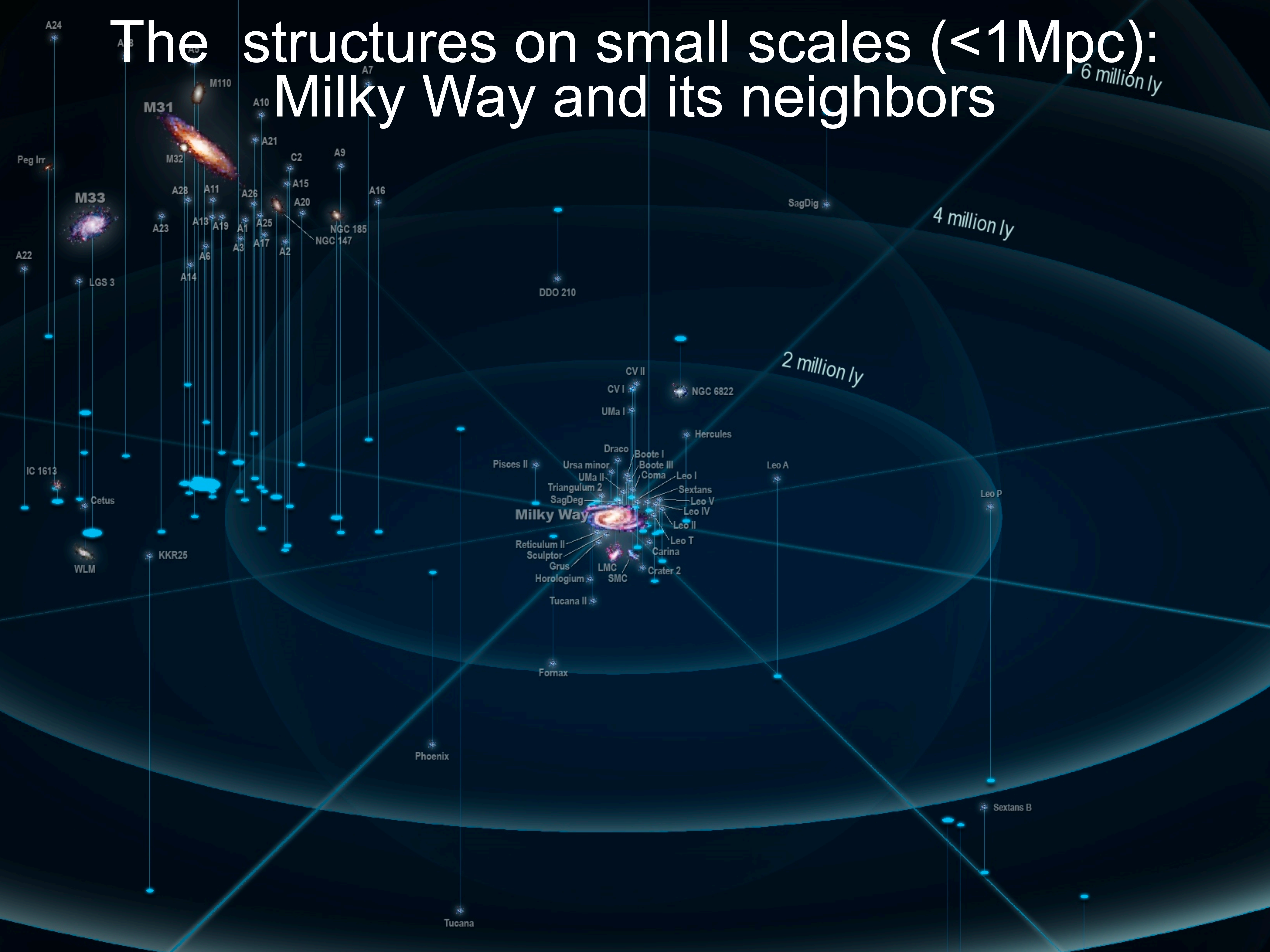
Large scale (> 1Mpc)
⇒ Remarkable success!

Small scale (<1 Mpc)
⇒ What’s going on?



ESA and the Planck Collaboration (2018)

The structures on small scales (<1Mpc): Milky Way and its neighbors



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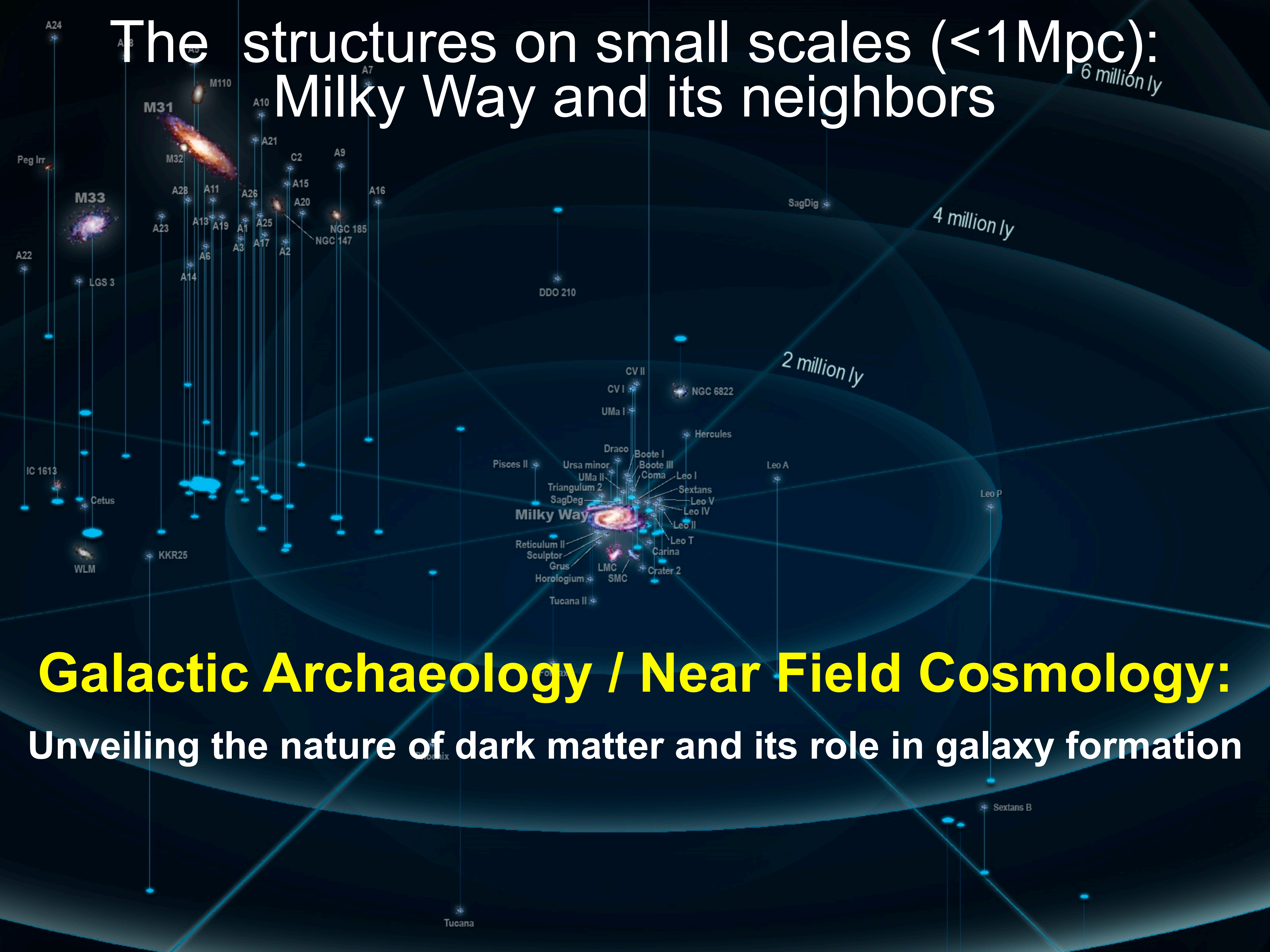

Galactic Archaeology / Near Field Cosmology:

Unveiling the nature of dark matter and its role in galaxy formation

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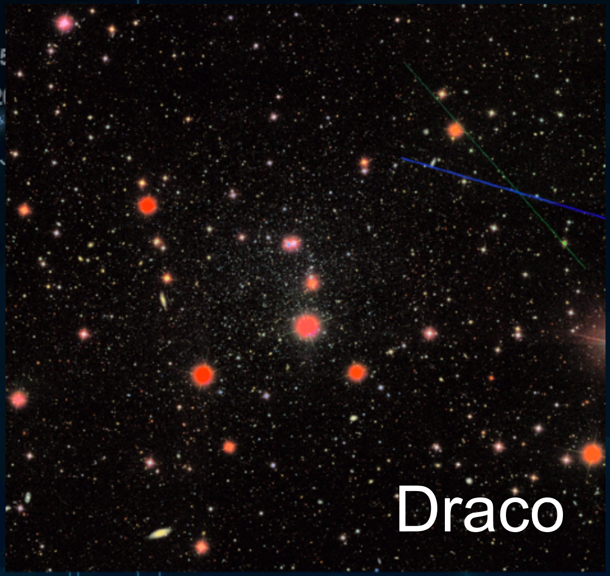
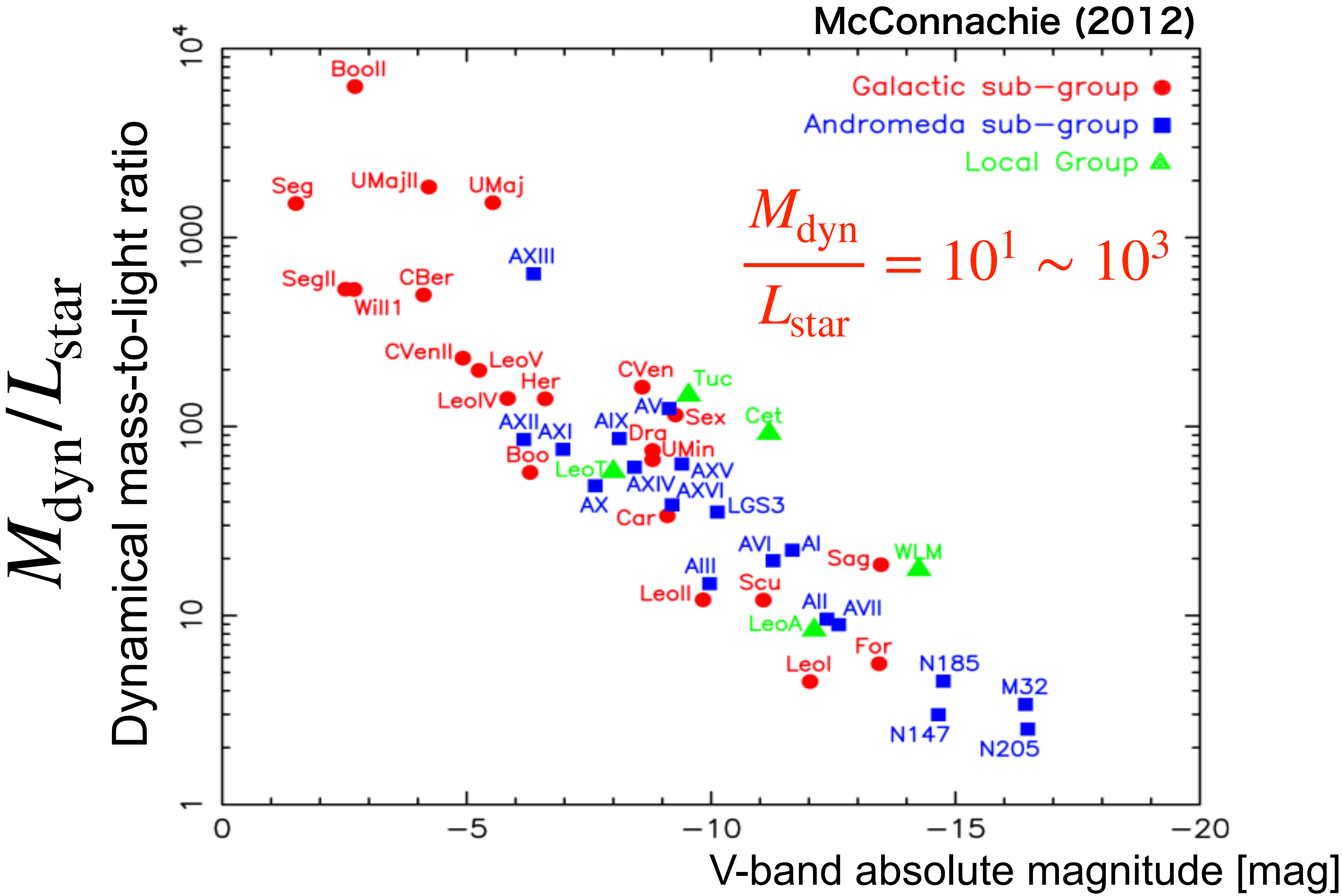


Galactic Archaeology / Near Field Cosmology:

Unveiling the nature of dark matter and its role in galaxy formation

dSphs: dark matter dominated system



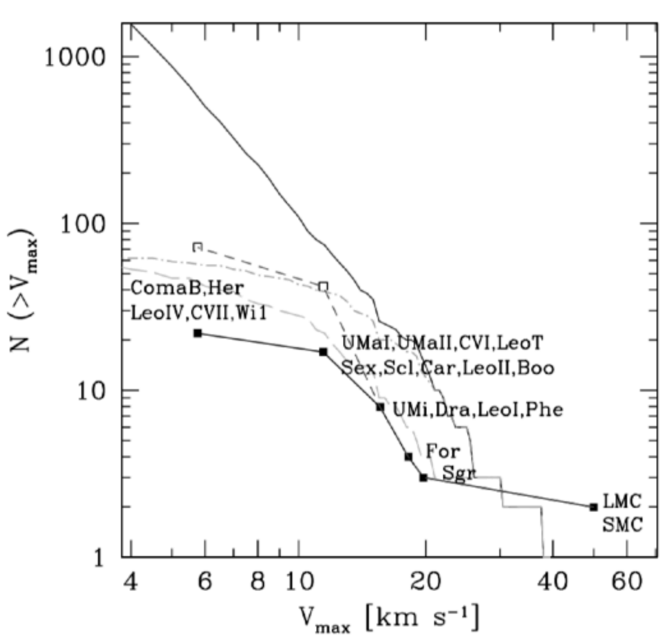
DSphs are ideal sites for studying the nature of DM!

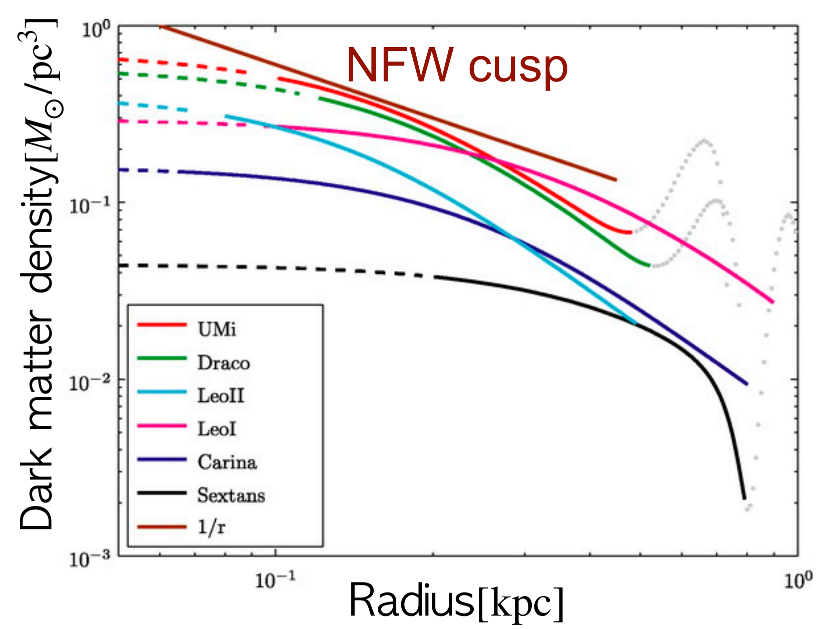
Small scale challenges to ΛCDM paradigm

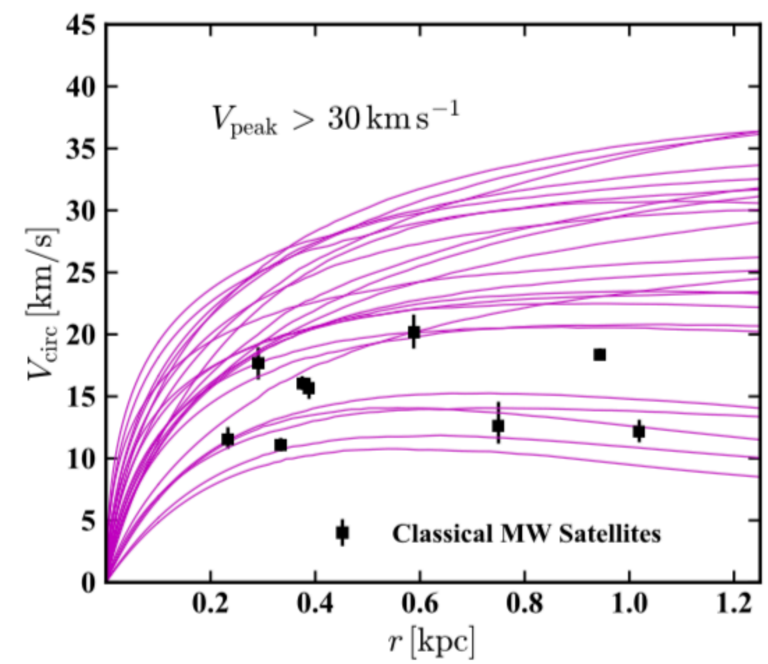
ICRR Institute for Cosmic Ray Research University of Tokyo

- ✦ **Missing satellite problem (Moore+ 1999, Klypin+ 1999)**
  - Overabundance of CDM subhalos
- ✦ **Core-cusp problem (Moore 1994, Gilmore+ 2007)**
  - Cuspy central density in CDM halos vs. cores in observed galaxies
- ✦ **Too-big-to-fail problem (Boylan-Kolchin+ 2014)**
  - Most massive subhalos are more concentrated than observed satellites

+ the other problems (satellite planes, shapes of dark halo…)







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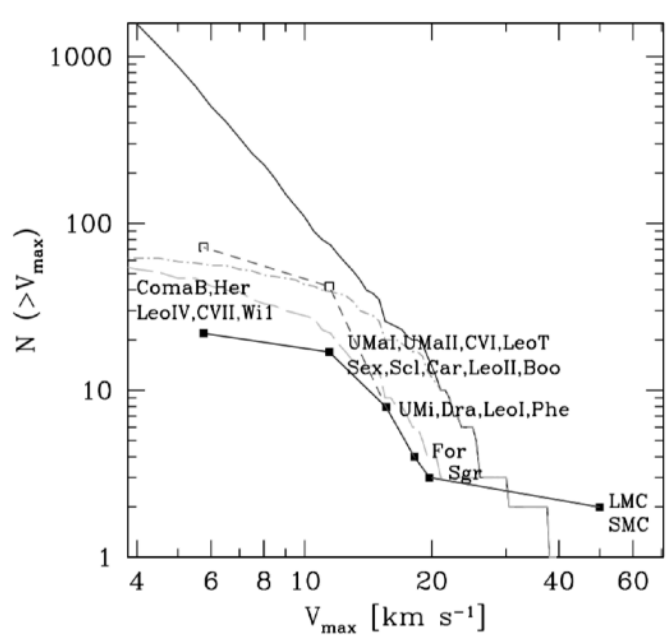
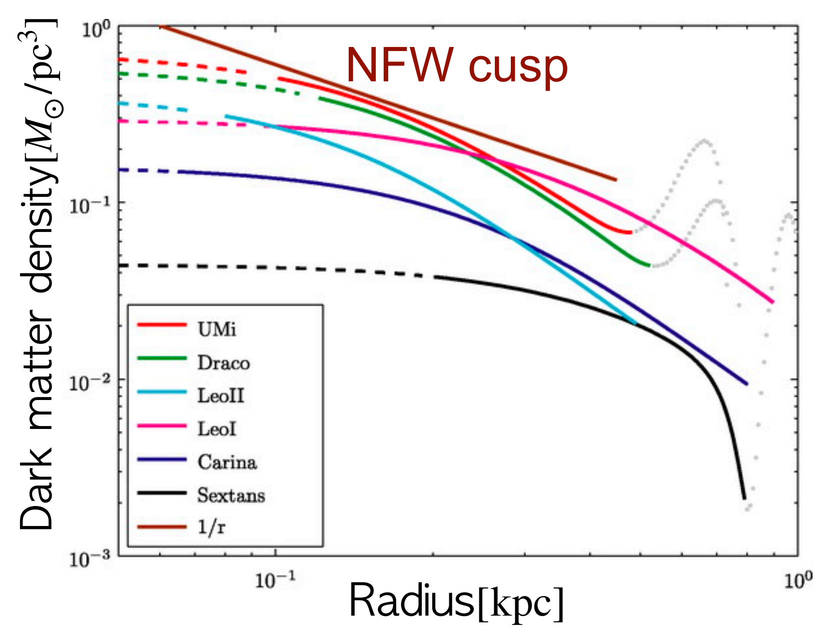
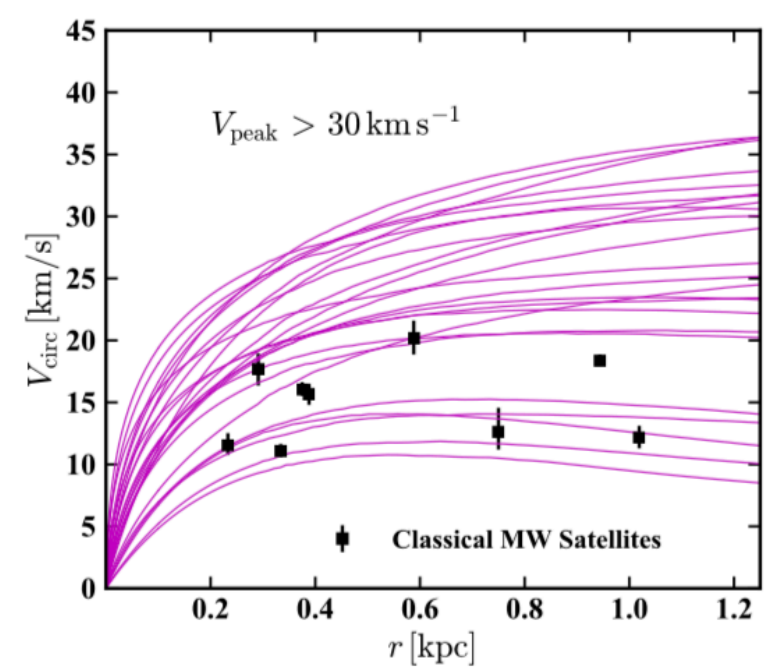




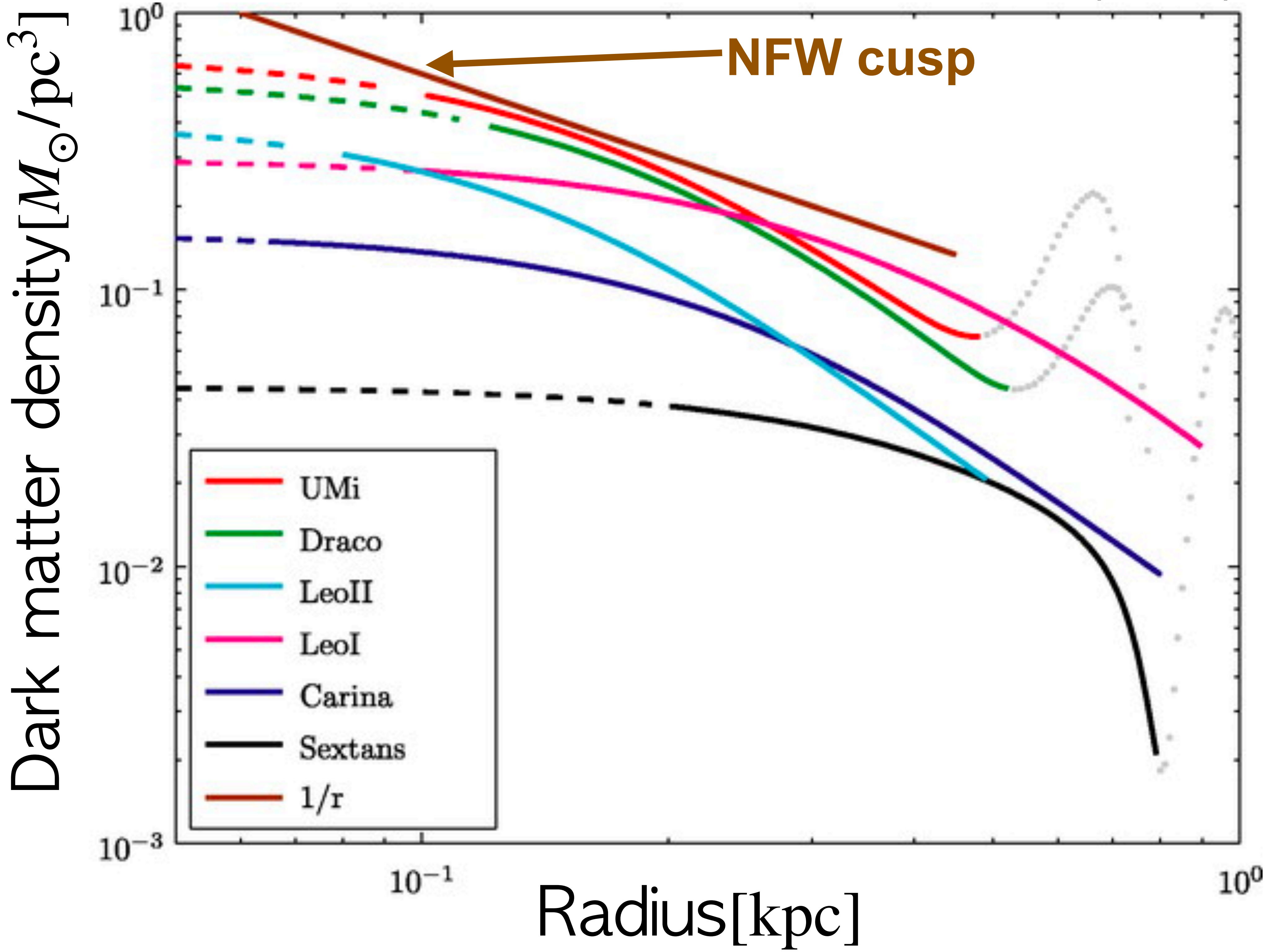


The core-cusp problem

in dwarf spheroidal galaxies

The core-cusp problem: controversial issue on CDM theory

Gilmore+ (2007)

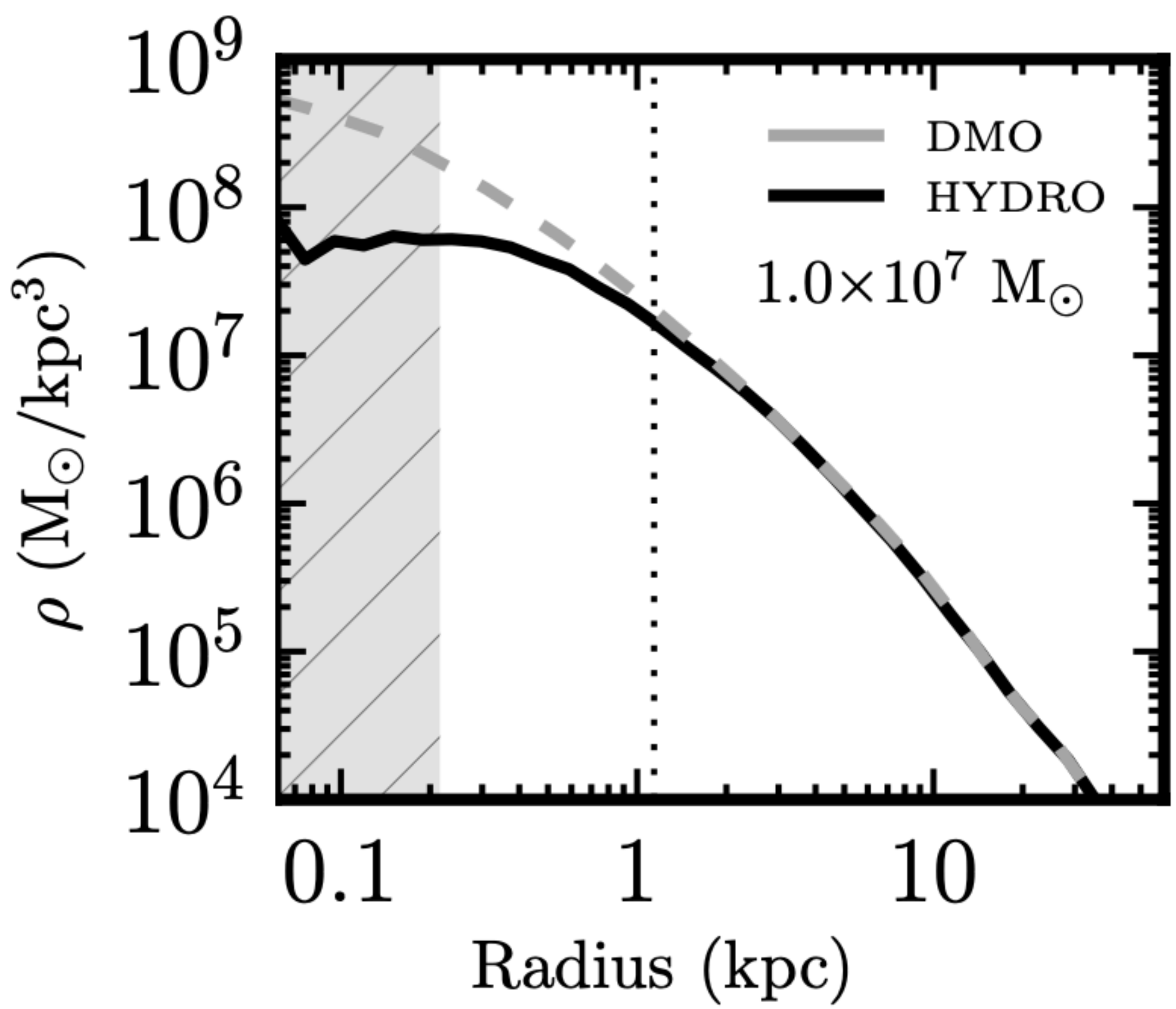


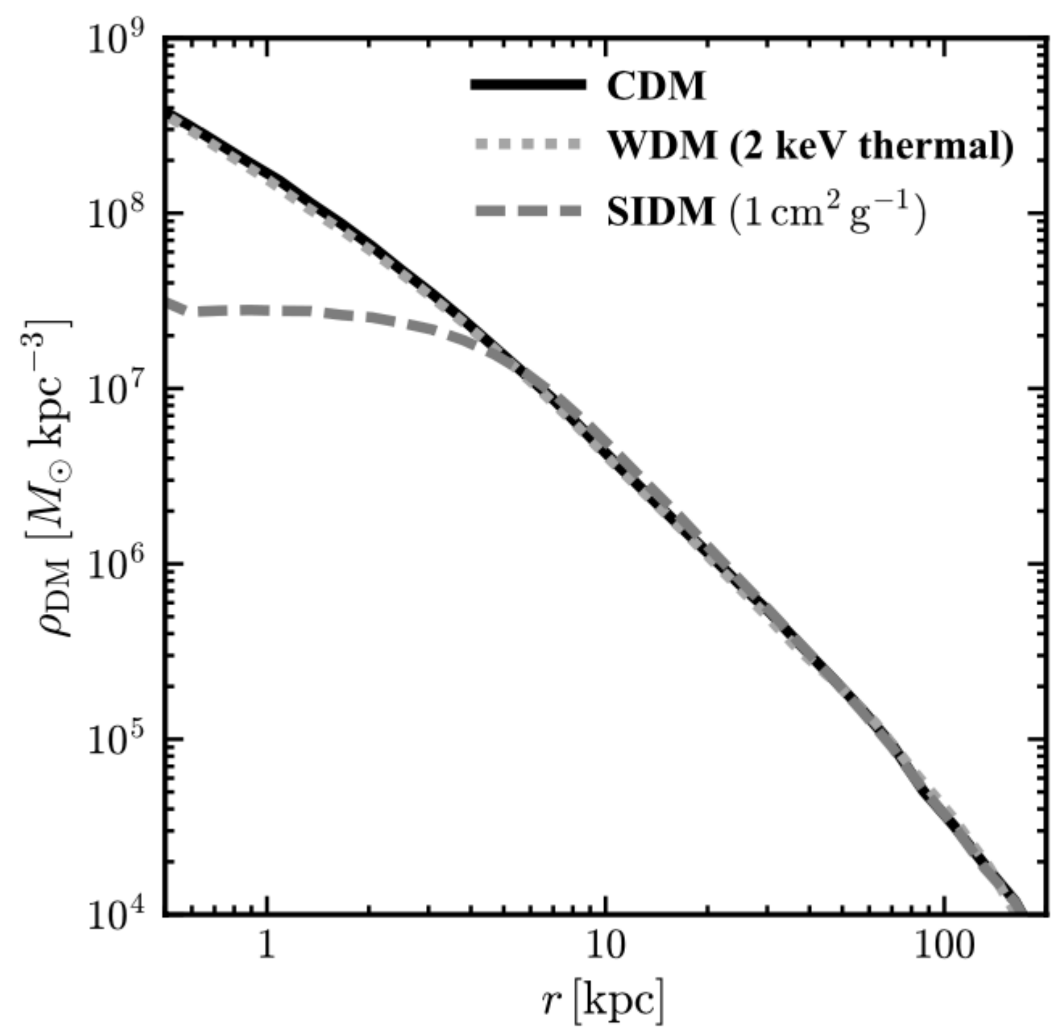
Moore 1994, de Blok 2000, Gilmore et al. 2007, Oh et al. 2015, Read et al. 2017

The core-cusp problem: controversial issue on CDM theory

Possible solutions:

- **Baryonic feedbacks**
  Stellar feedback such as SNe can transform central cusp into cored dark matter profiles.
- **Alternative DM models**
  The other dark matter models motivated by particle physics (SIDM, ultralight DM…) can create a cored density profiles without relying on any baryon effects.





Bullock & Boylan-Kolchin (2018)

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CORE OR CUSP?

CORE

A METHOD FOR MEASURING (SLOPES OF) THE MASS PROFILES OF DWARF SPHEROIDAL GALAXIES

MATTHEW G. WALKER[1,2,3] & JORGE PEÑARRUBIA[2]

Dark matter cores and cusps: the case of multiple stellar populations in dwarf spheroidals

N. C. Amorisco⋆ and N. W. Evans⋆

THE KINEMATIC STATUS AND MASS CONTENT OF THE SCULPTOR DWARF SPHEROIDAL GALAXY[1]

G. BATTAGLIA,[2,3] A. HELMI,[3] E. TOLSTOY,[3] M. IRWIN,[4] V. HILL,[5] AND P. JABLONKA[6]

THE DARK MATTER DENSITY PROFILE OF THE FORNAX DWARF

JOHN R. JARDEL AND KARL GEBHARDT

The core size of the Fornax dwarf spheroidal

N. C. Amorisco,[1,2] A. Agnello[1] and N. W. Evans[1]⋆

CUSP

Kinematics of Milky Way satellites in a Lambda cold dark matter universe

Louis E. Strigari,[1]⋆ Carlos S. Frenk[2] and Simon D. M. White[3]

MEASURING DARK MATTER PROFILES NON-PARAMETRICALLY IN DWARF SPHEROIDALS: AN APPLICATION TO DRACO

JOHN R. JARDEL[1], KARL GEBHARDT[1], MAXIMILIAN FABRICIUS[2], NIV DRORY[3], AND MICHAEL J. WILLIAMS[2]

On the Dark Matter profile in Sculptor: Breaking the β degeneracy with Virial Shape Parameters

Thomas Richardson[⋆1], Malcolm Fairbairn[†1]

Dynamical models for the Sculptor dwarf spheroidal in a ΛCDM universe

Louis E. Strigari[1], Carlos S. Frenk[2] and Simon D. M. White[3]

The case for a cold dark matter cusp in Draco

J. I. Read[1⋆], M. G. Walker[2], P. Steger[3]

UNCLEAR

Model comparison of the dark matter profiles of Fornax, Sculptor, Carina and Sextans

Maarten A. Breddels and Amina Helmi

Orbit-based dynamical models of the Sculptor dSph galaxy

Maarten A. Breddels,[1]⋆ A. Helmi,[1] R. C. E. van den Bosch,[2] G. van de Ven[2] and G. Battaglia[3]

COMPLEXITY ON DWARF GALAXIES SCALE: A BIMODAL DISTRIBUTION FUNCTION IN SCULPTOR

MAARTEN A. BREDDELS AND AMINA HELMI

A UNIVERSAL MASS PROFILE FOR DWARF SPHEROIDAL GALAXIES?*

MATTHEW G. WALKER[1], MARIO MATEO[2], EDWARD W. OLSZEWSKI[3], JORGE PEÑARRUBIA[1], N. WYN EVANS[1], AND GERARD GILMORE[1]

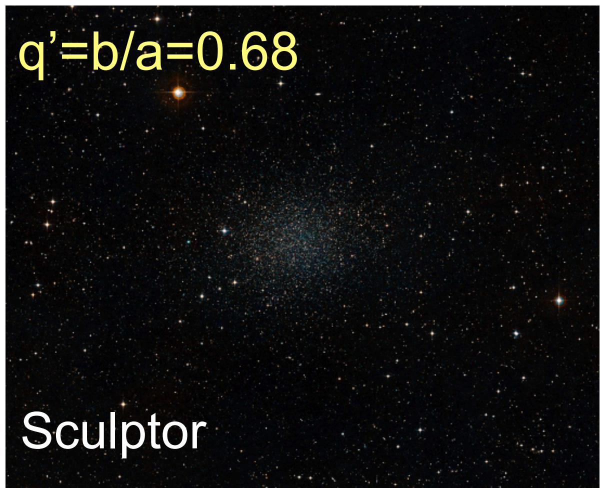
Cores in Classical Dwarf Spheroidal Galaxies? A Dispersion-Kurtosis Jeans Analysis Without Restricted Anisotropy

Thomas Richardson[⋆1], Malcolm Fairbairn[†1]

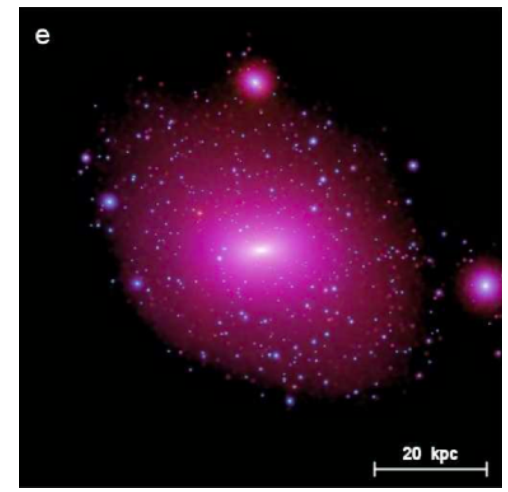
Non-spherical models

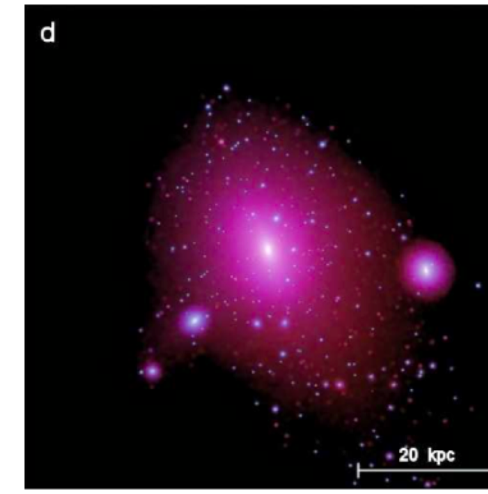
Major systematic uncertainty: spherical symmetry

1. Observed dSphs are **NOT** spherical shape



2. DM models predict **NON-spherical** DM halo

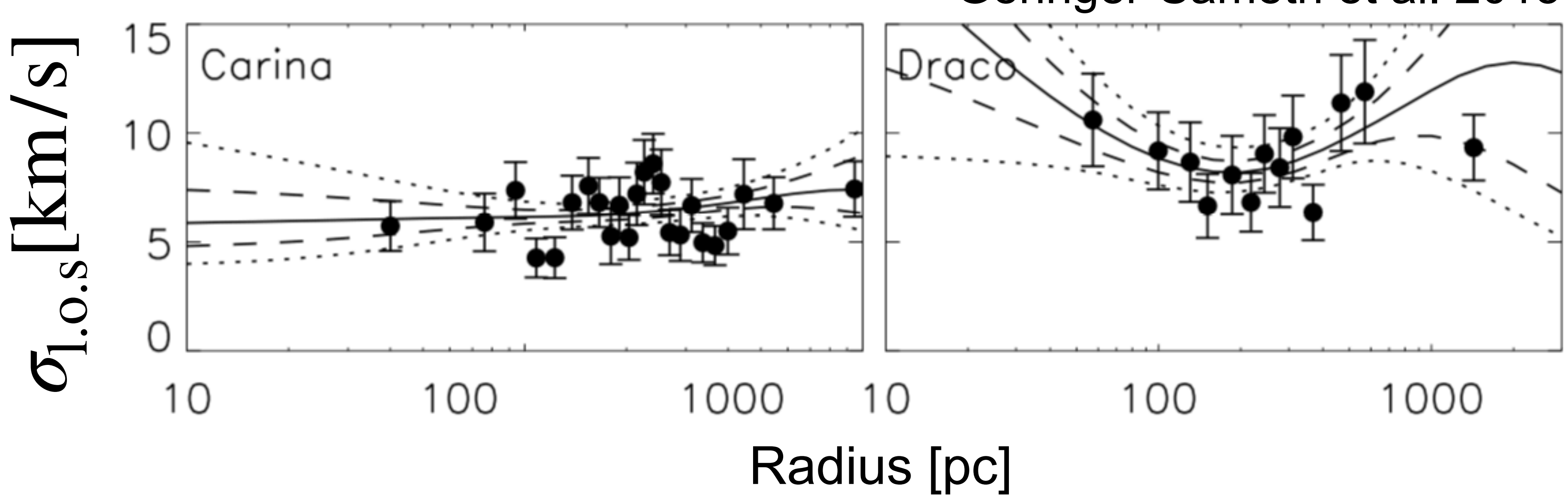




credit: Aquarius project

3. 1D spatial information

Geringer-Sameth et al. 2015



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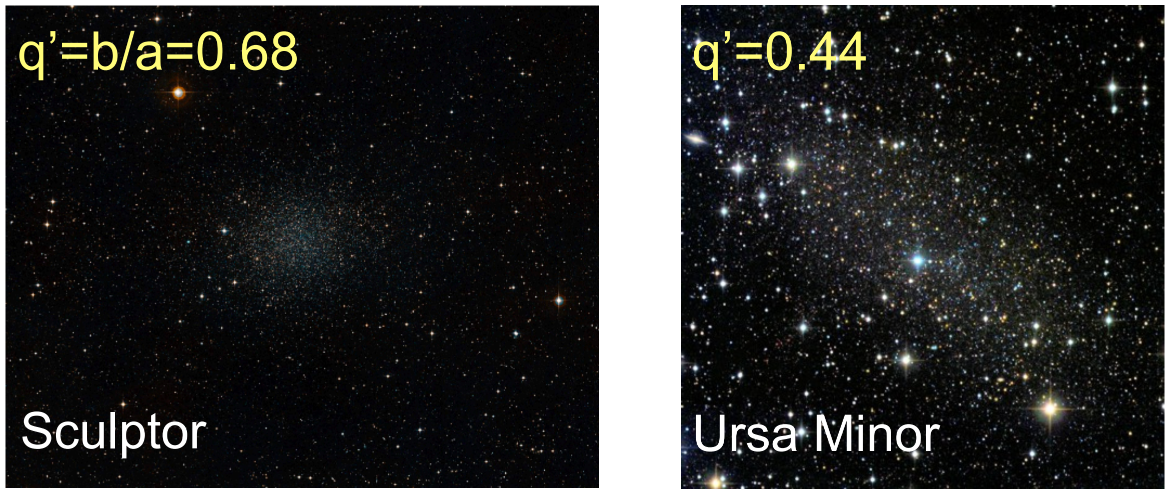

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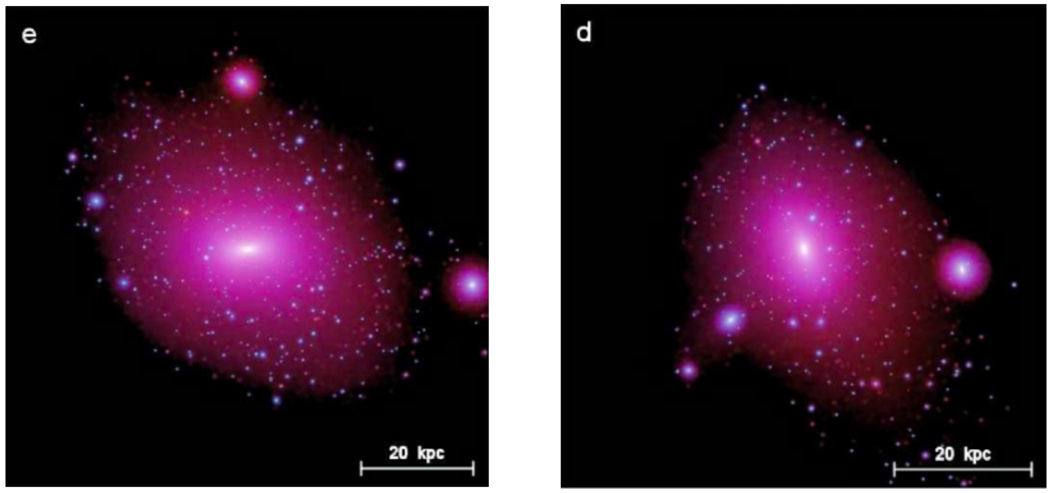

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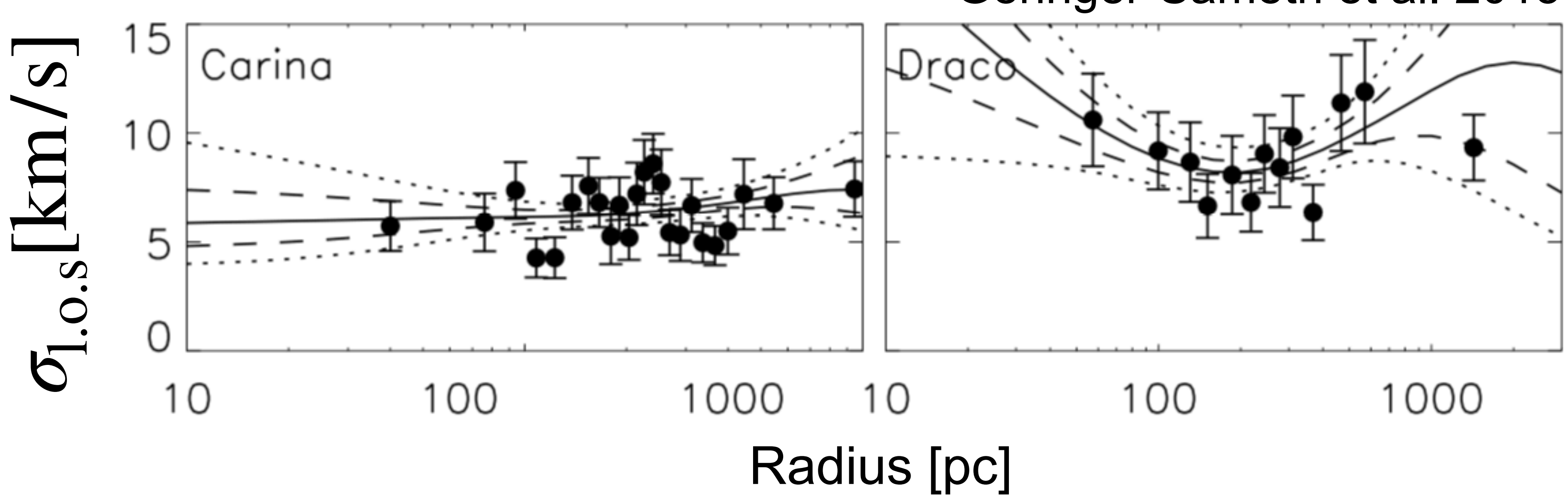
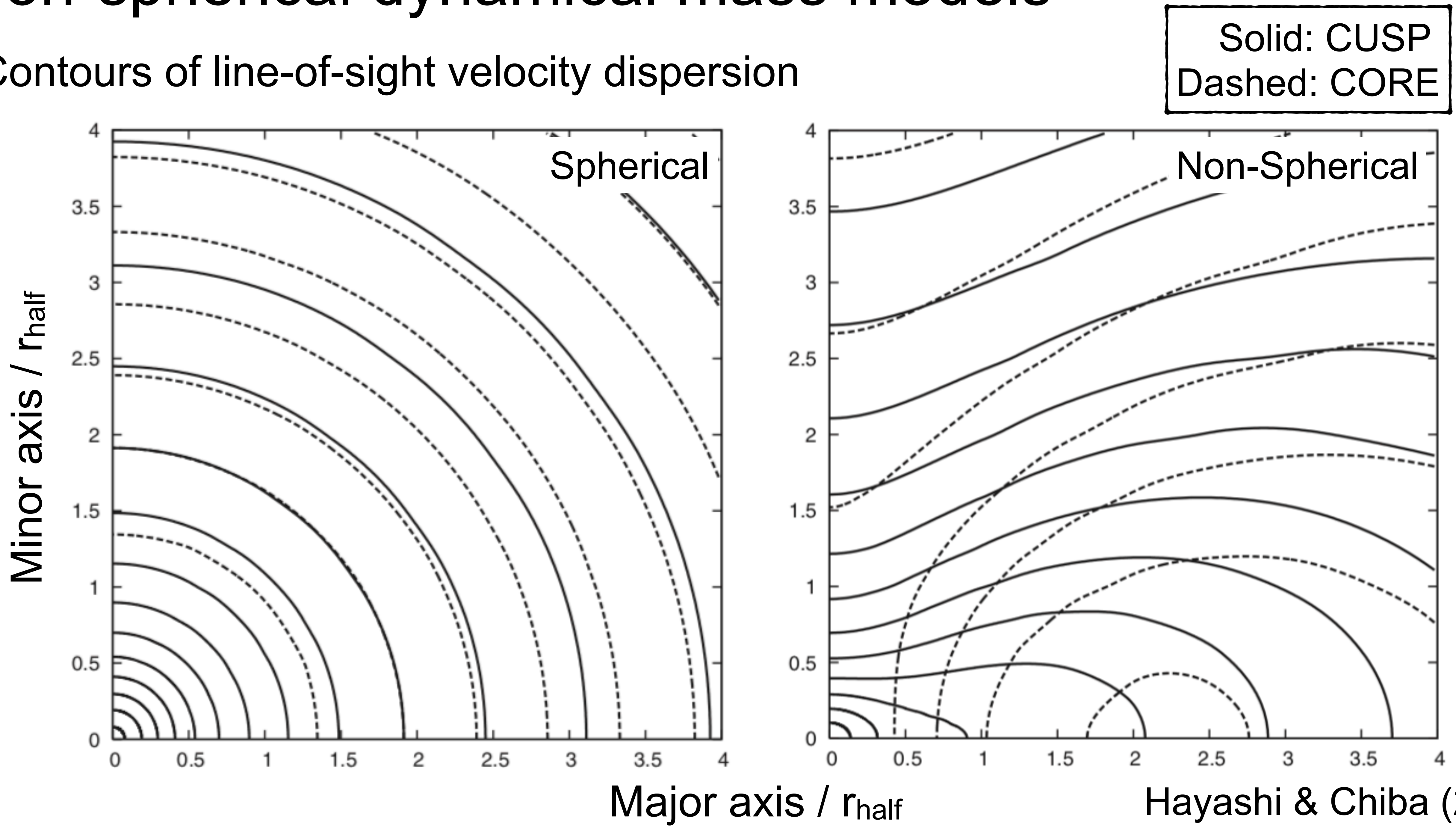


Non-spherical mass model

Non-spherical dynamical mass models

Contours of line-of-sight velocity dispersion



Hayashi & Chiba (2012)

Non-sphericity ➡ distinguish **Cusp or Core**

Non-spherical dynamical mass models

Non-spherical dark matter density profile

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

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

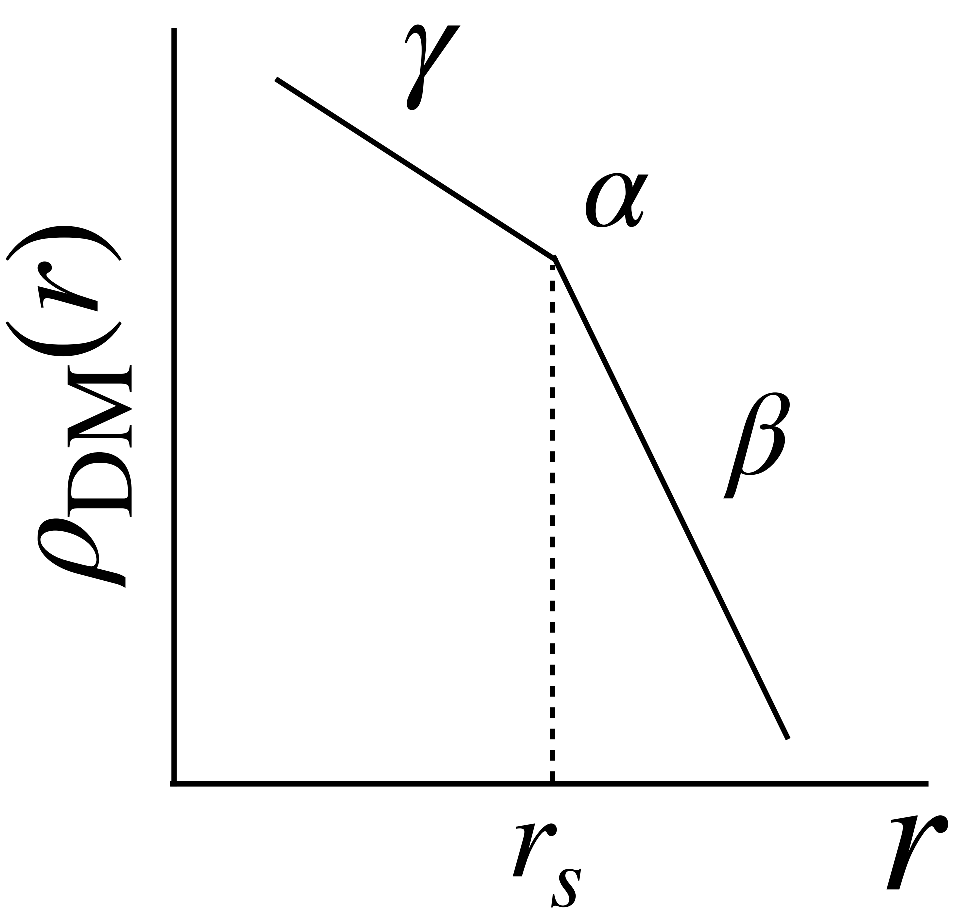
DM halo axial ratio

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



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stellar axial ratio

Axisymmetric Jeans equations

$$(\overline{v_z^2}, \overline{v_\phi^2})$$

$\overline{v_R^2}$ is unknown parameter as

$$\beta_z = 1 - \overline{v_z^2}/\overline{v_R^2}$$

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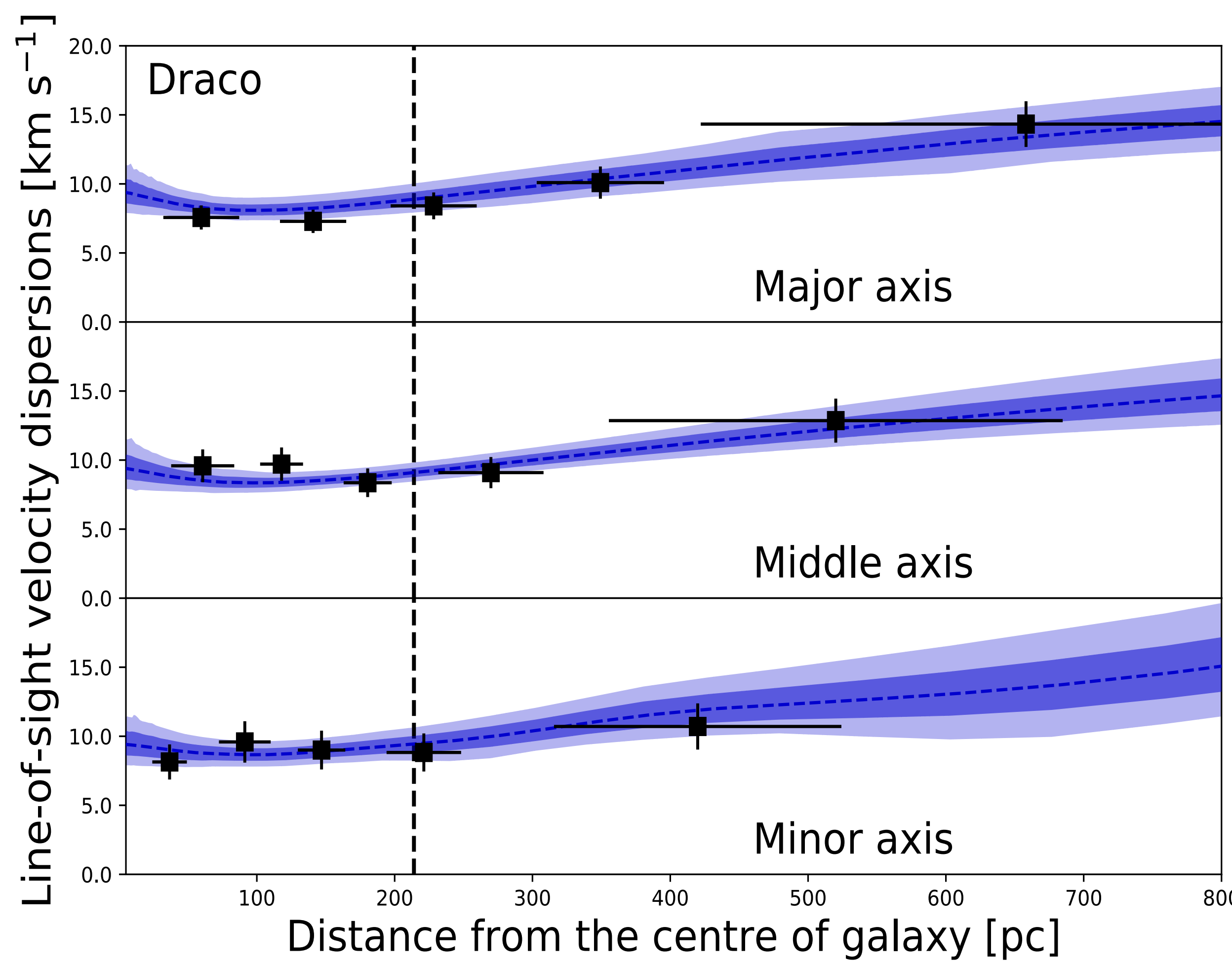
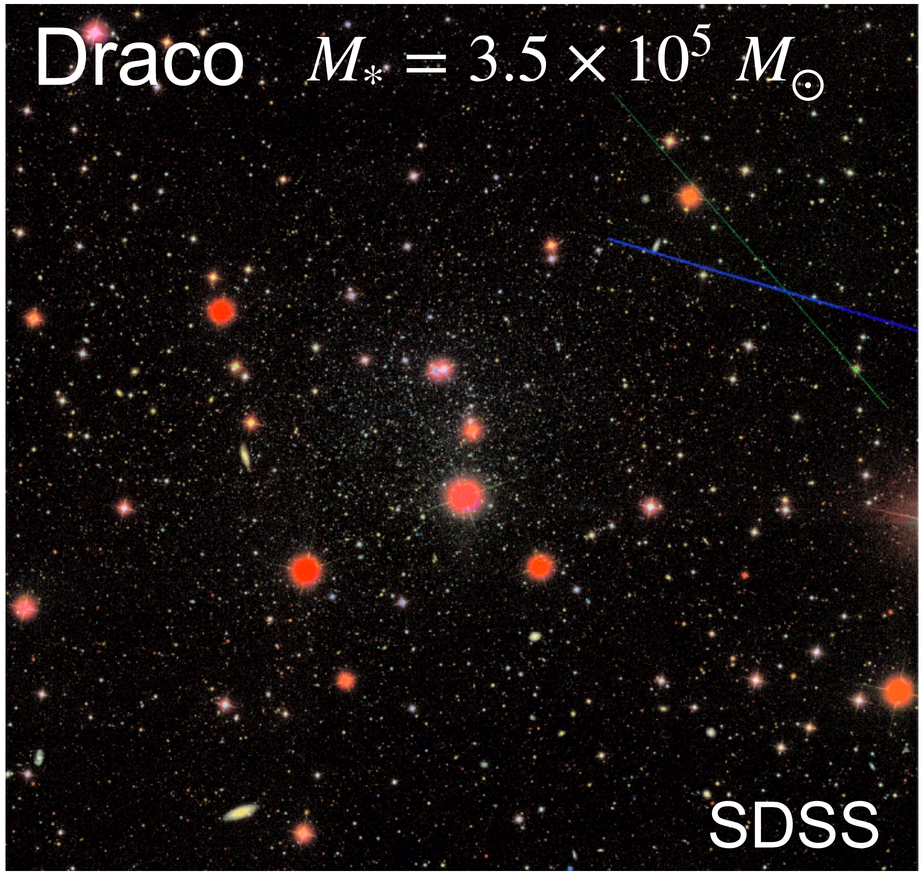
$$\sigma_{\mathrm{l.o.s}}^{(\mathrm{Theory})} \overset{\textbf{FIT}}{\longleftrightarrow} \sigma_{\mathrm{l.o.s}}^{(\mathrm{obsrved})}$$

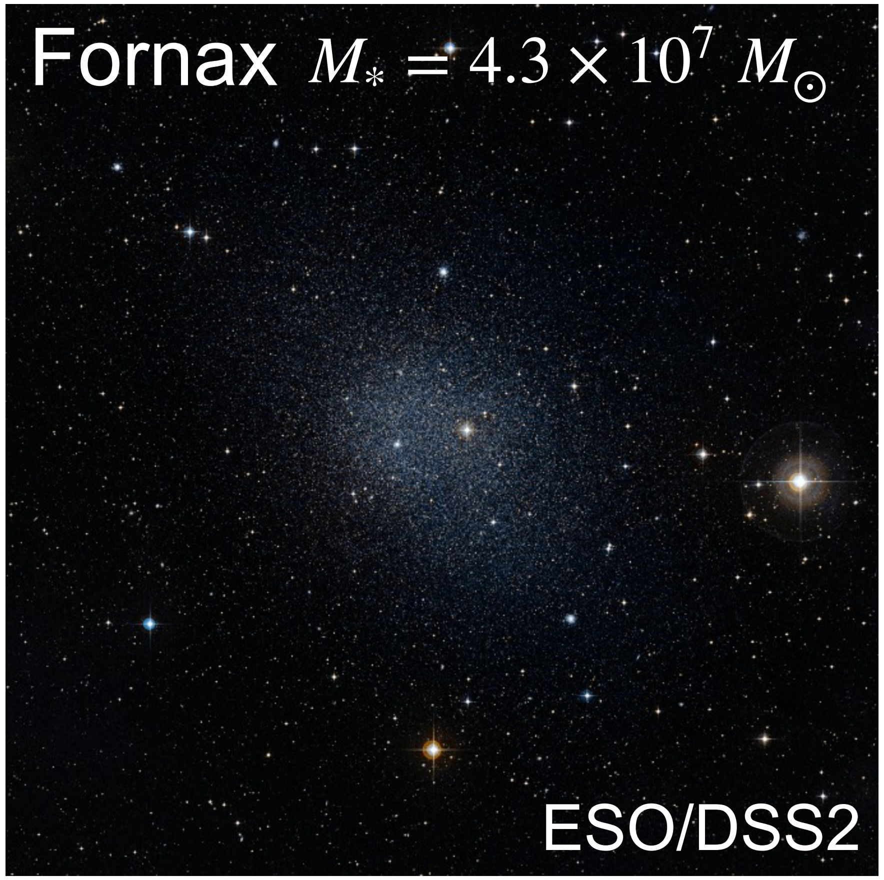


Hayashi & Chiba 2012, 2015b, Hayashi et al. 2016, 2018

Dark Matter profiles in the MW dSphs

Dark Matter Density Profiles of the biggest and smallest dSphs





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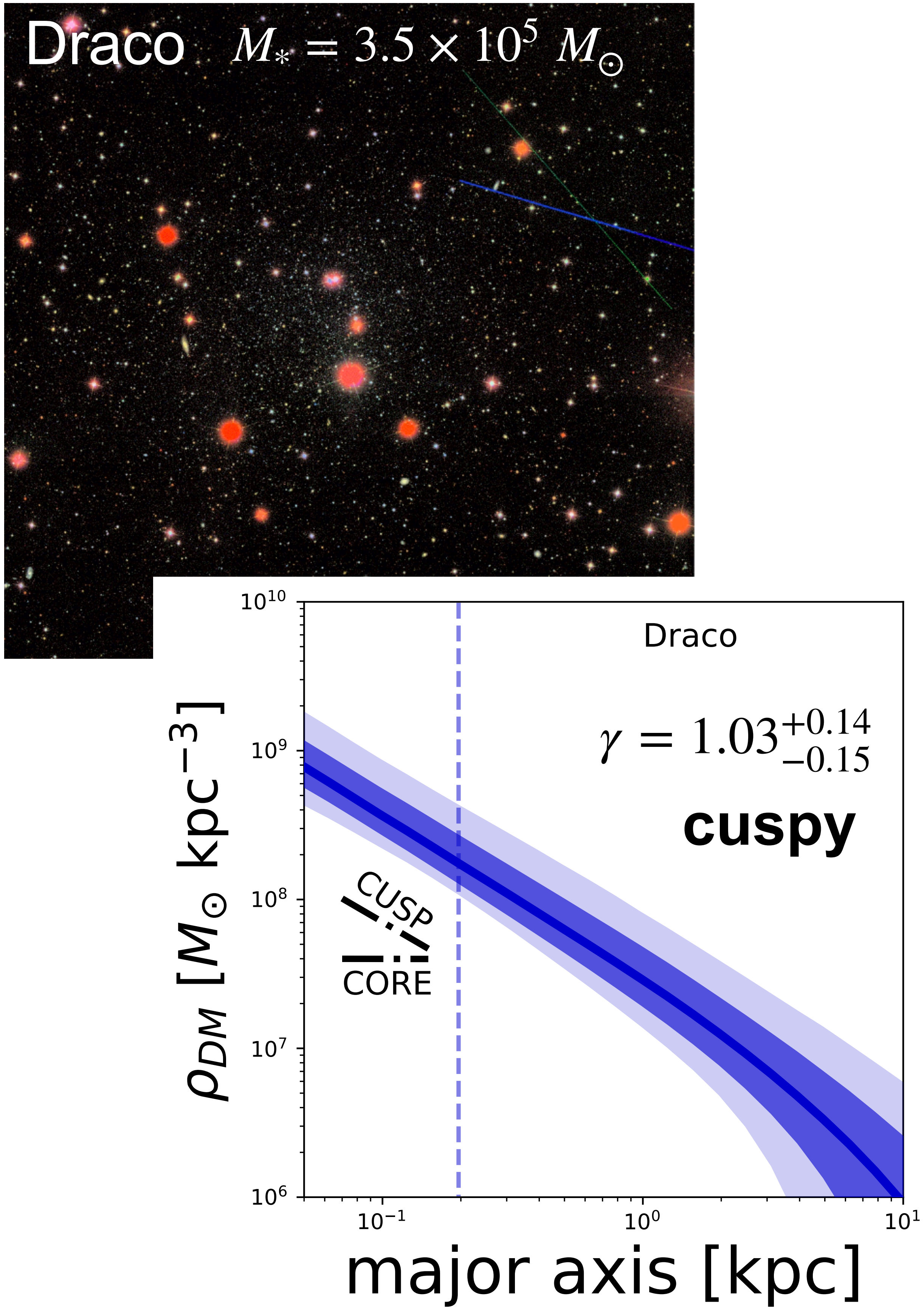
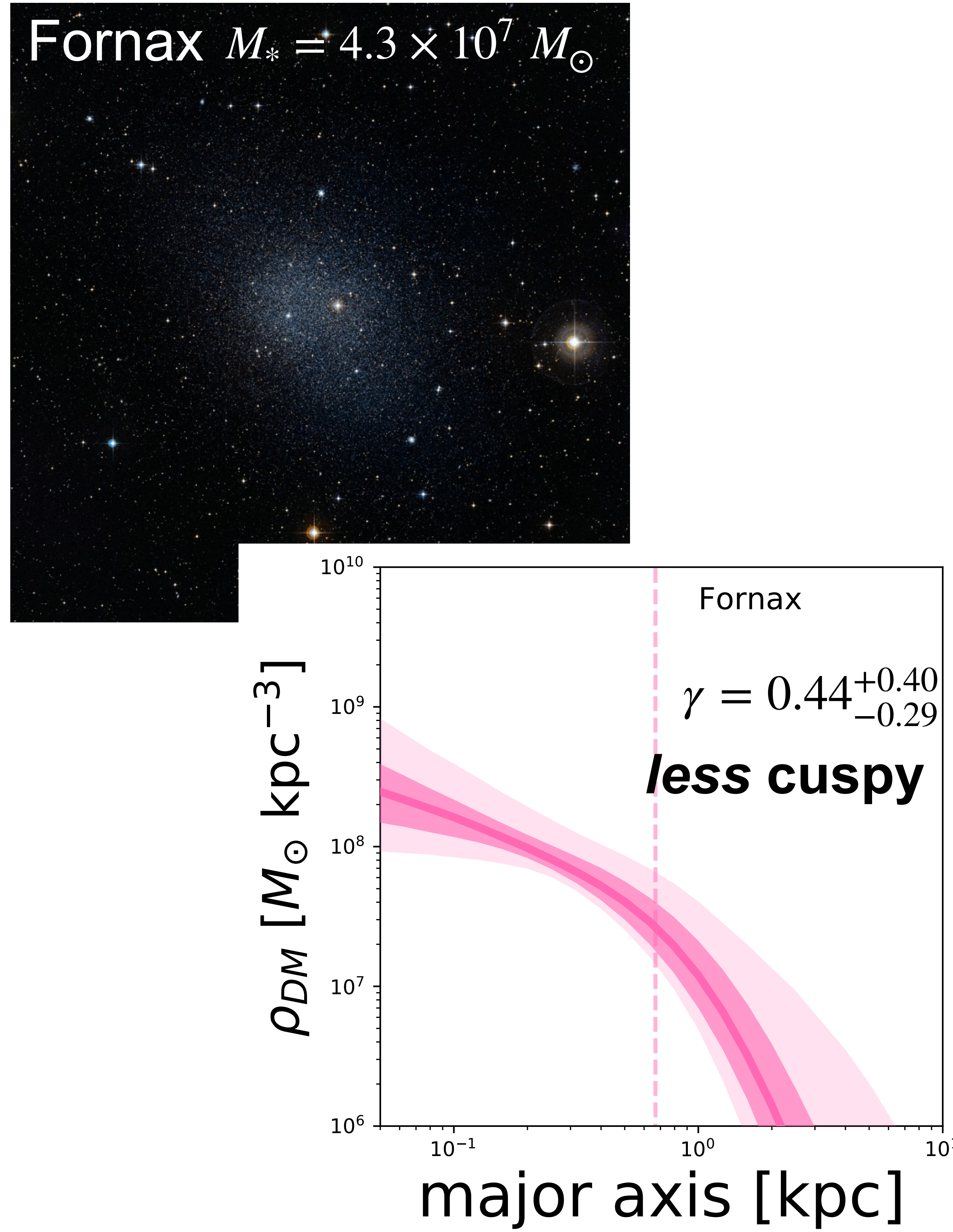
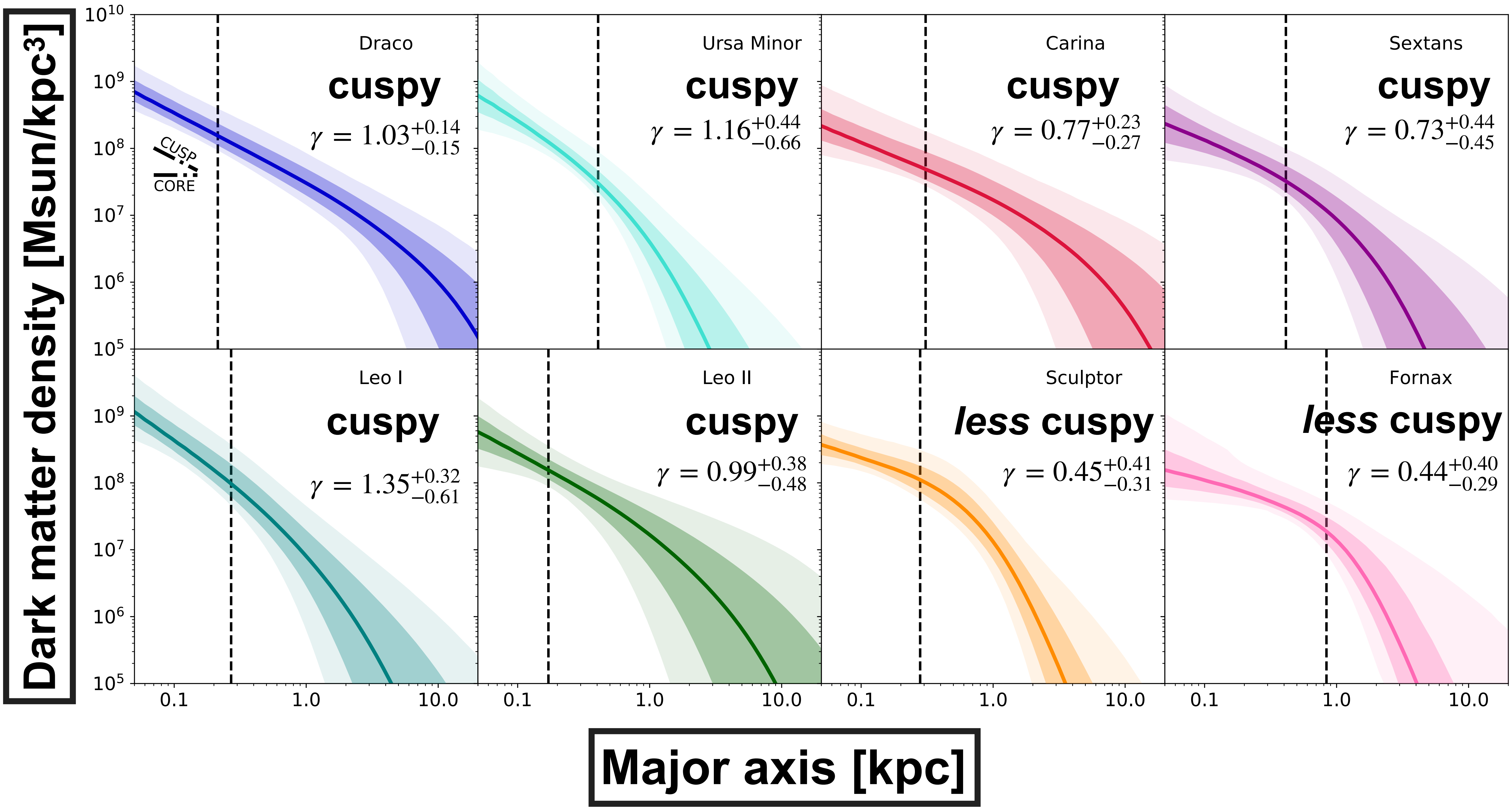




Hayashi+ (2020, in prep.)

Diversity of DM density profiles of dSphs



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What’s the origin of the diversity?

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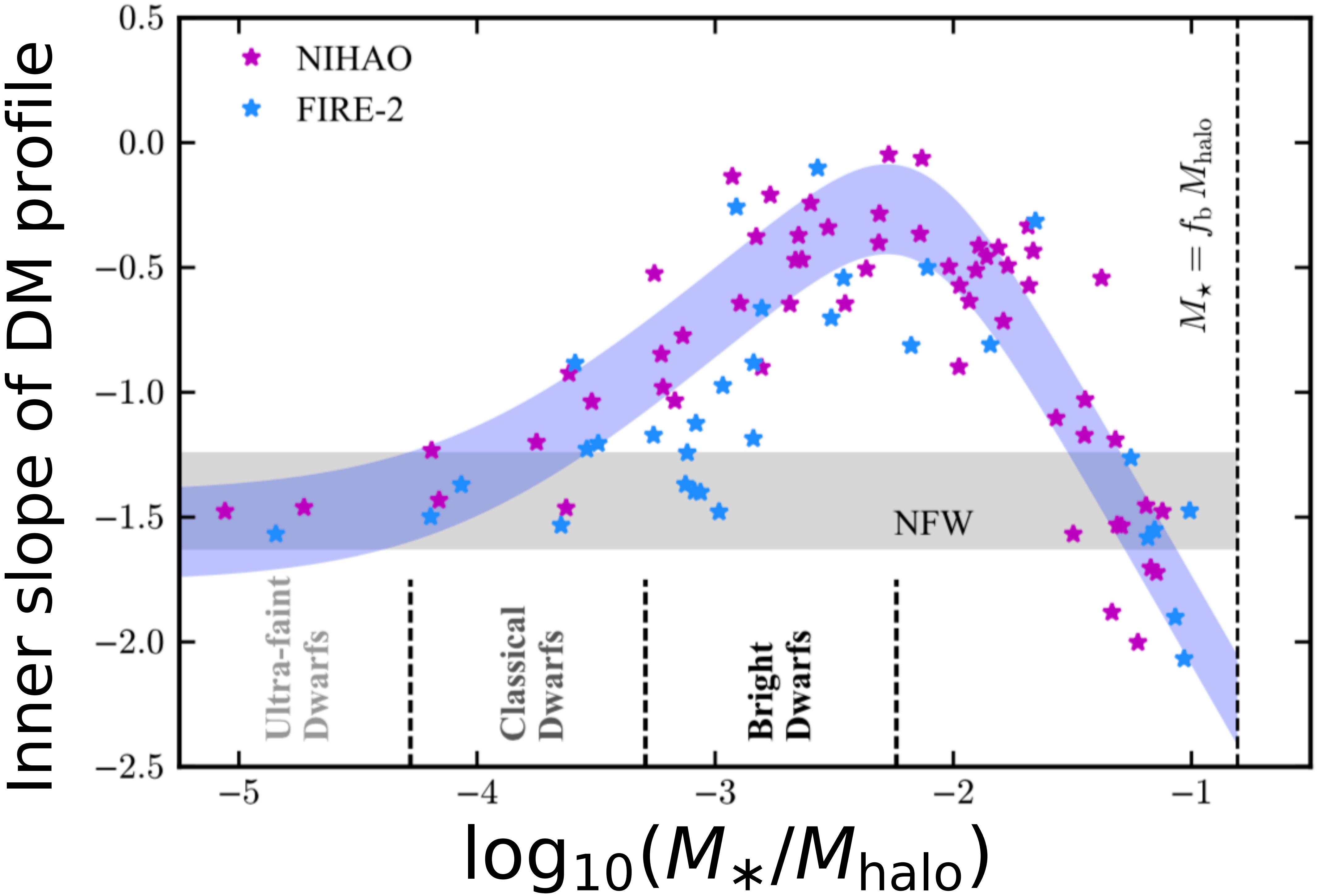
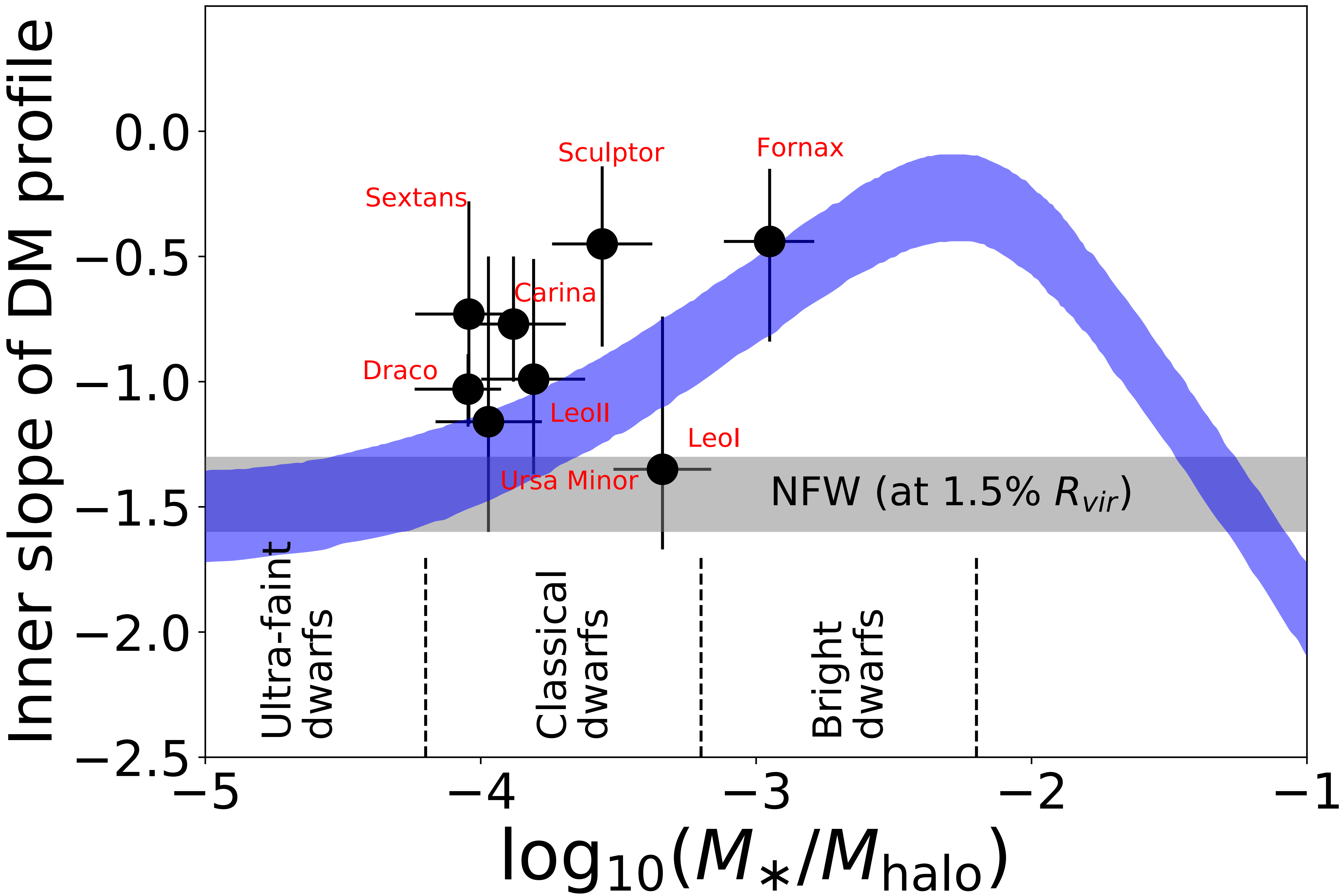


<u>Inner DM density depends on stellar-to-halo mass ratio</u>

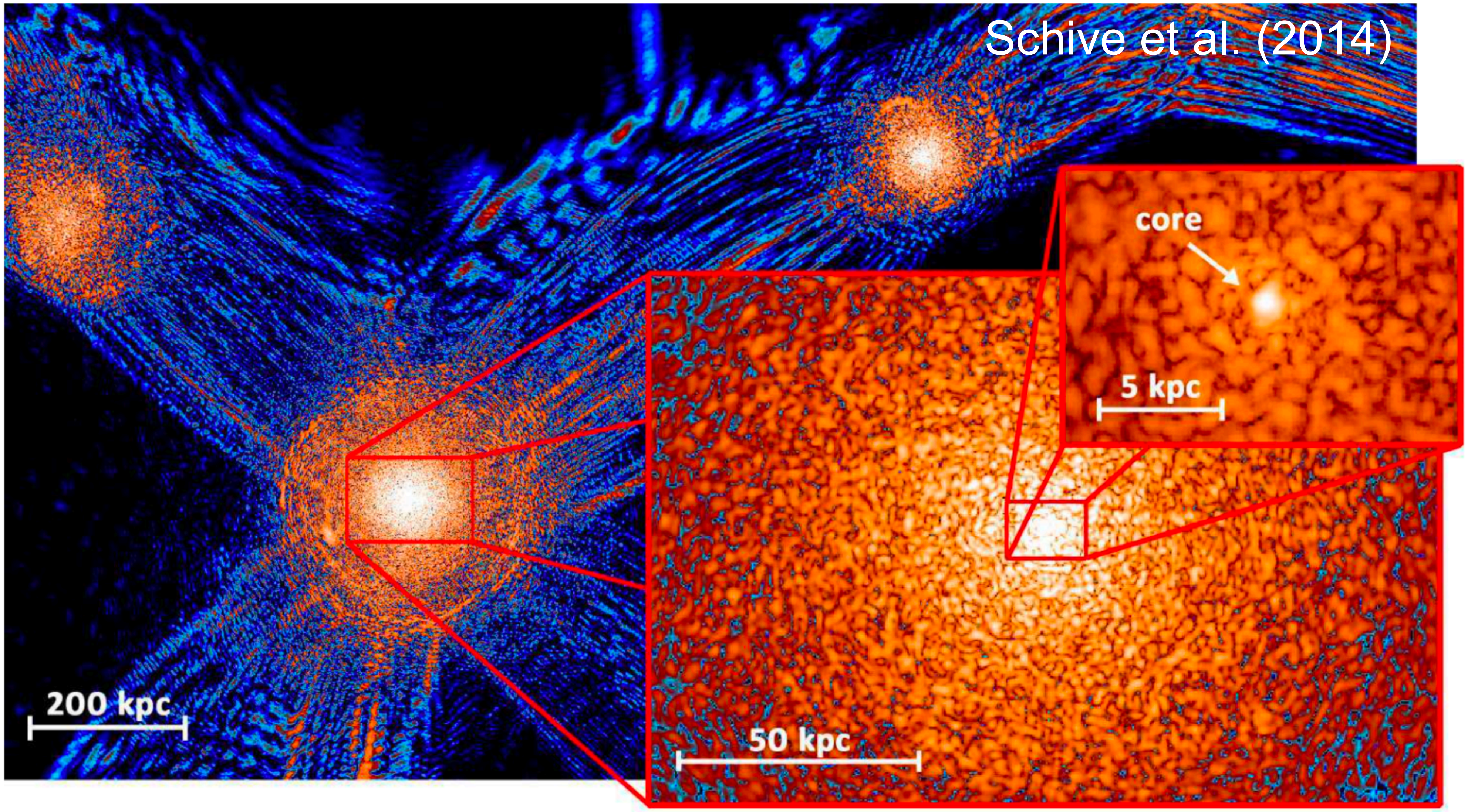
Bullock & Boylan-Kolchin (2017)

What's the Origin of the diversity?



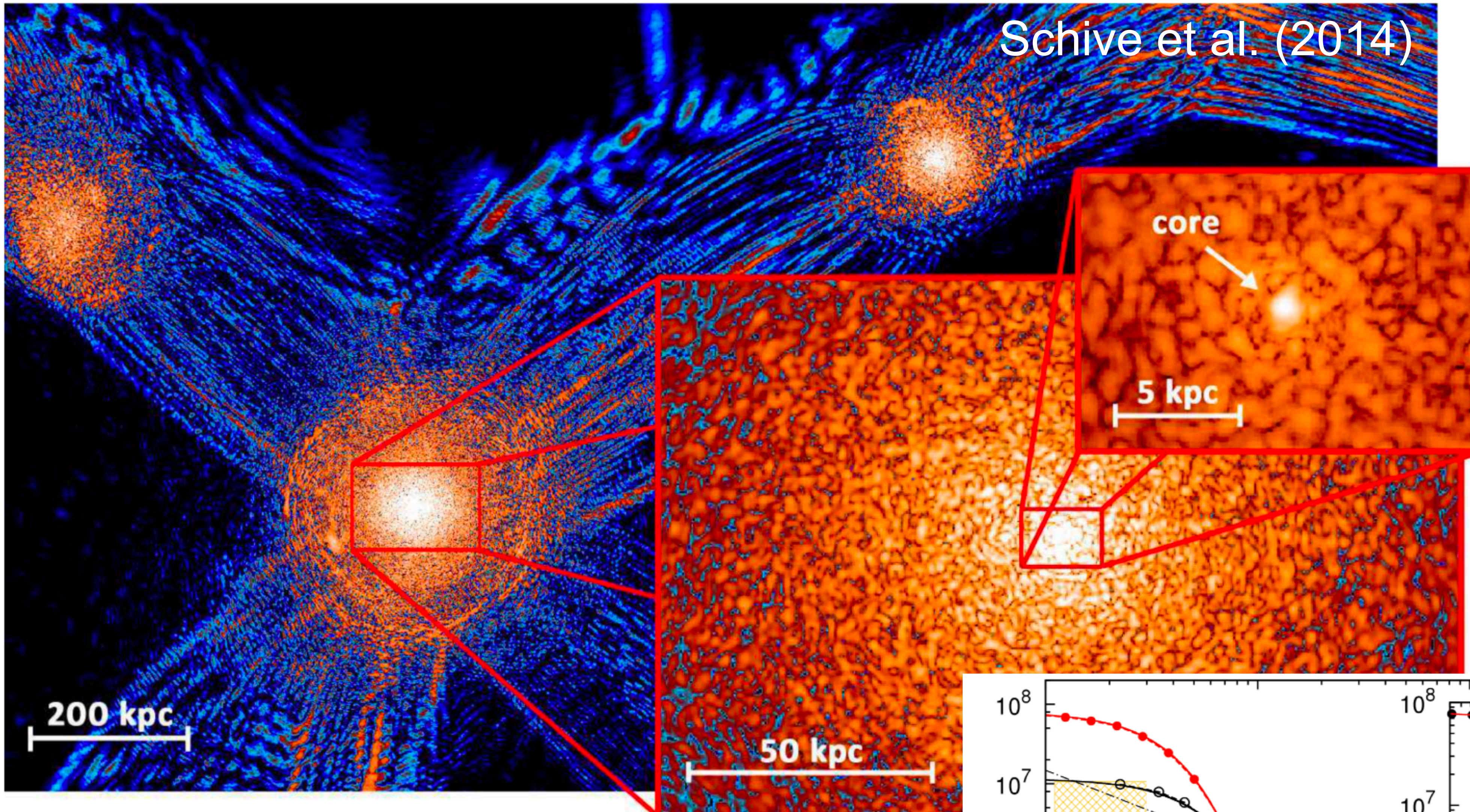
Hayashi+ (2020, in prep.)

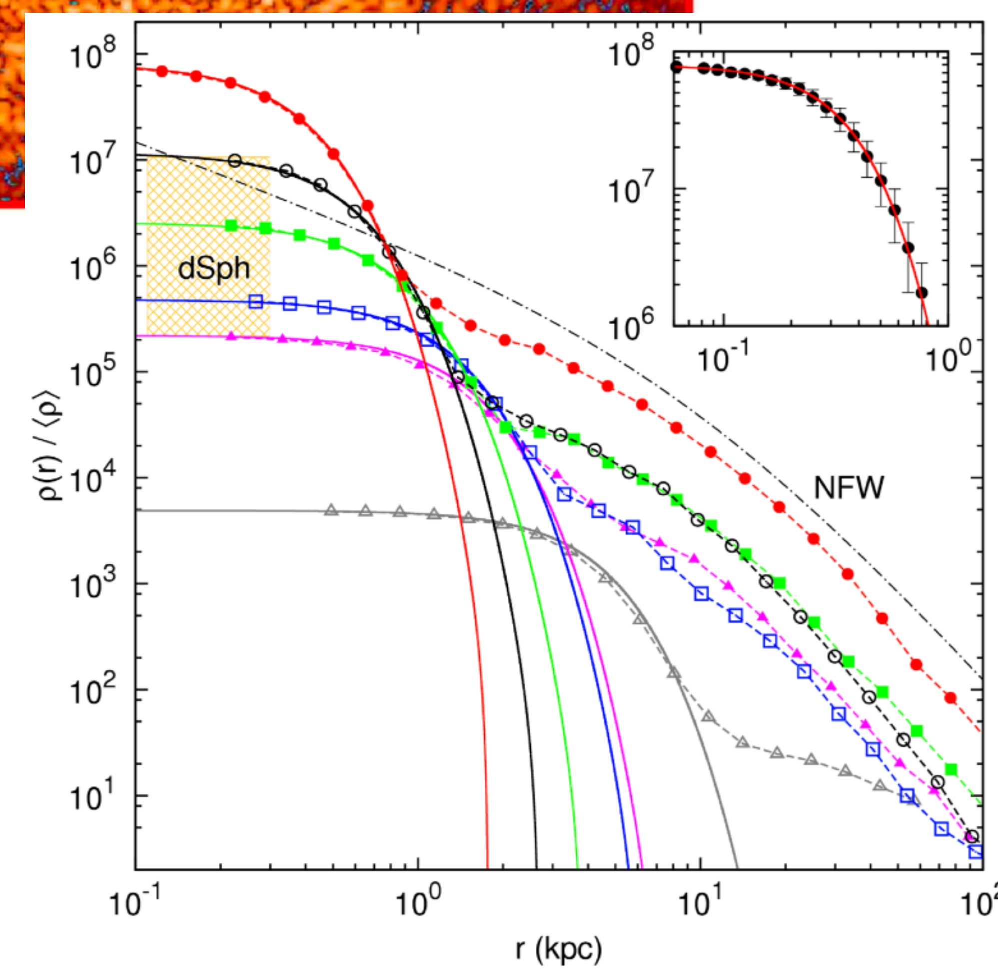
Ultralight dark matter



- The lightest particle among dark matter candidates ($m_\psi \sim 10^{-22}$ eV)

Ultralight dark matter





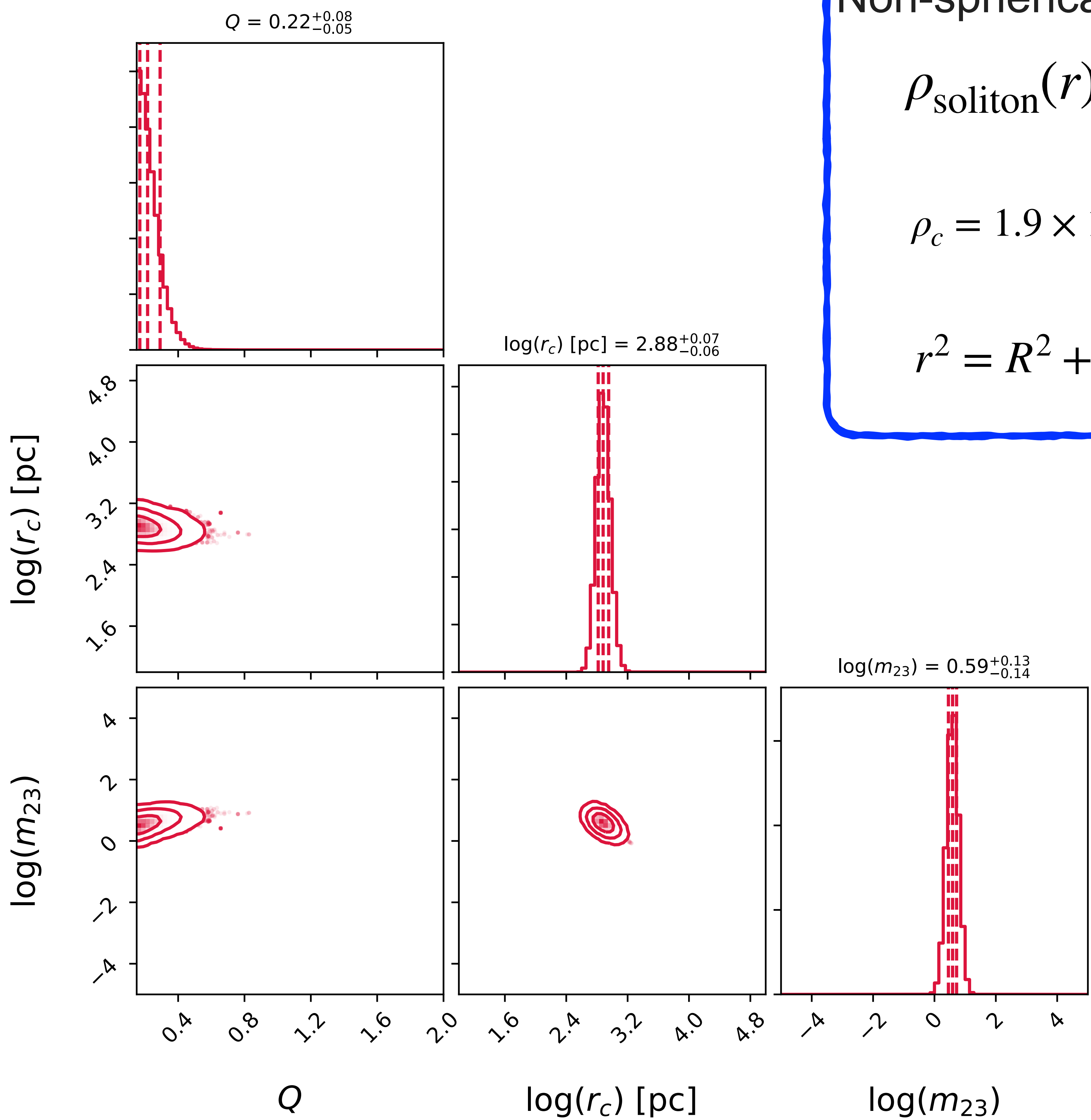
- The lightest particle among dark matter candidates (m_ψ~10^{-22} eV)
- Create **a central soliton core** + outer NFW DM profile

$$\rho_{\rm soliton}(r) = \frac{\rho_{\rm c}}{[1+0.091(r/r_c)^2]^8}$$

$$\rho_c = 1.9\times10^{12}\left(\frac{m_\psi}{10^{-23}\ \rm eV}\right)^{-2}\left(\frac{r_c}{\rm pc}\right)^{-4}\ [M_\odot\ {\rm pc}^{-3}]$$

Constraints on ultralight dark matter halo

Case for Draco



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Hayashi & Obata (2019)
1902.03054

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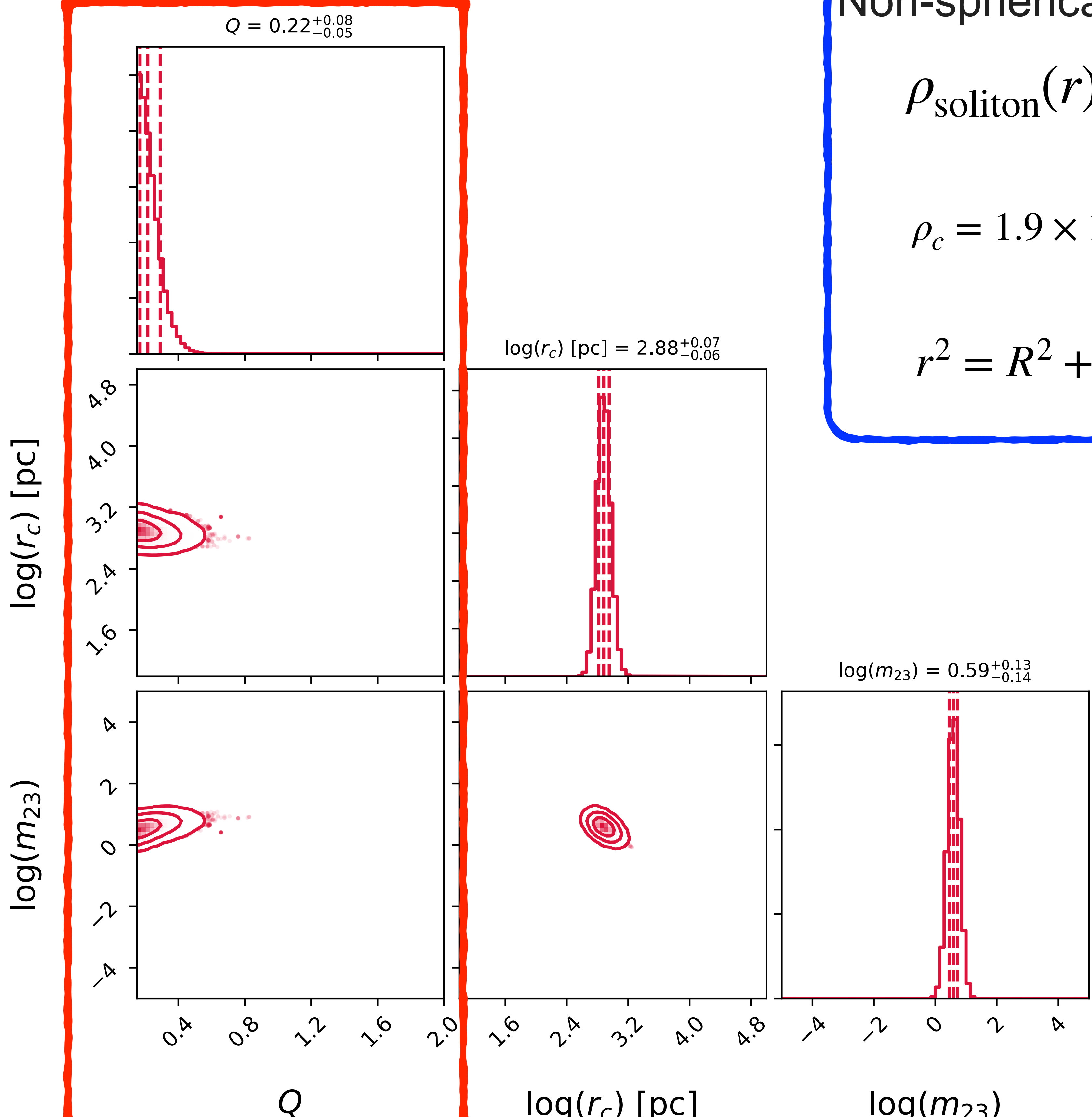

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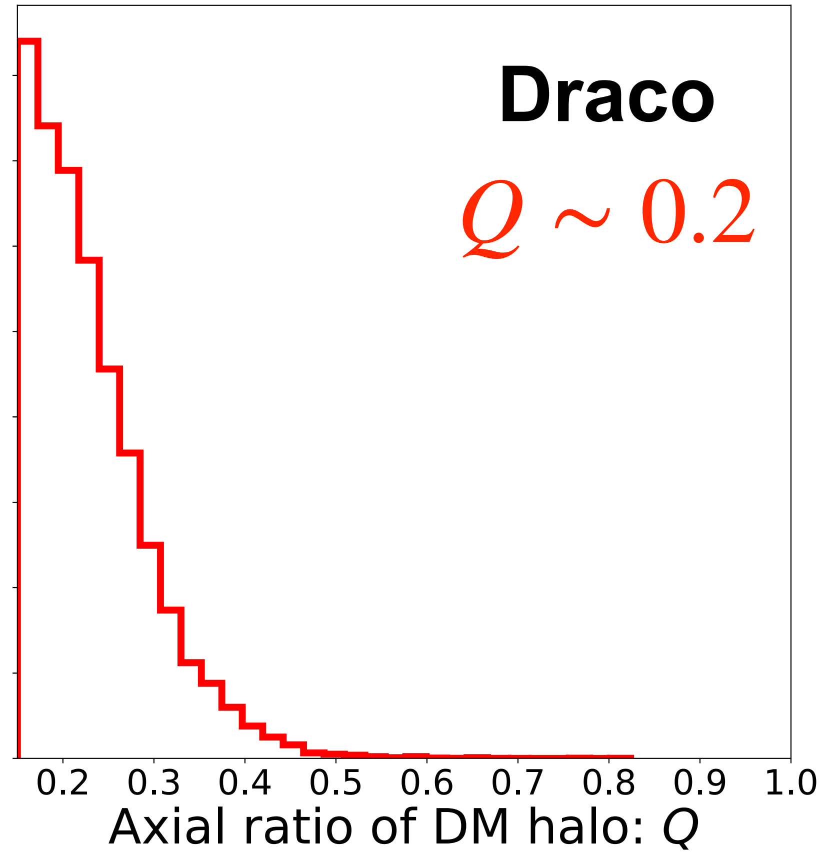

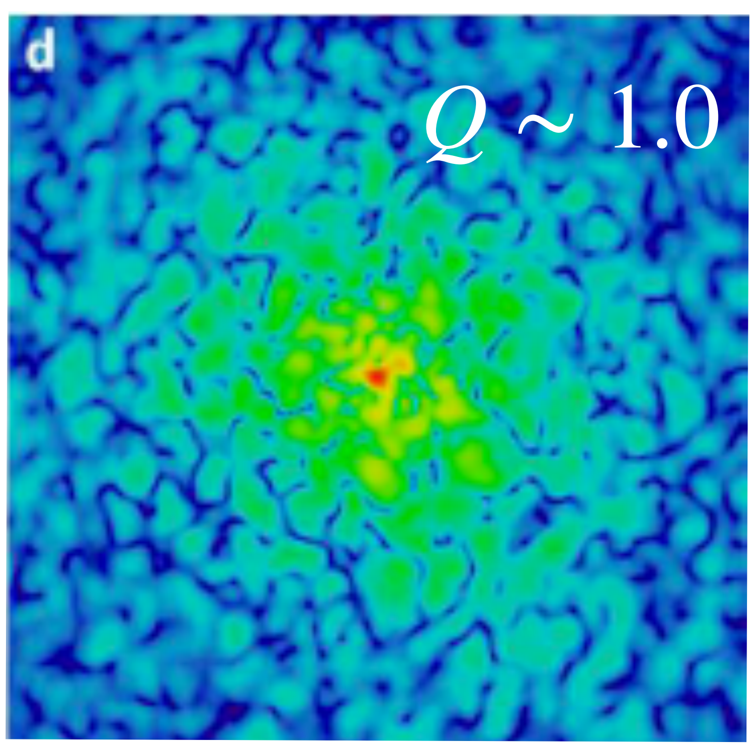

Schive et al. (2014)

- Draco has strongly elongated DM halo, **Q~0.2**, which means disky shape of DM halo(!!)
- Ultralight DM theory predicts much more rounder DM halo.
- To reproduce Draco's stellar velocity, an ***unphysical*** ultralight DM halo should be required.

Hayashi & Obata (2019)
1902.03054

Summary

- Revisit core/cusp problem using non-spherical mass modeling.
- The classical dSphs have ***cusped*** (or less-cusped) dark matter density profiles.
- The ***diversity*** of dark matter density profiles of the MW dSphs.
- Considering non-sphericity of dark matter halo, ultralight dark matter model is ***inconsistent*** with the observational facts of dSphs.

Kohei Hayashi