Comparison between the c–M relation and the Observations of Dark Matter Haloes

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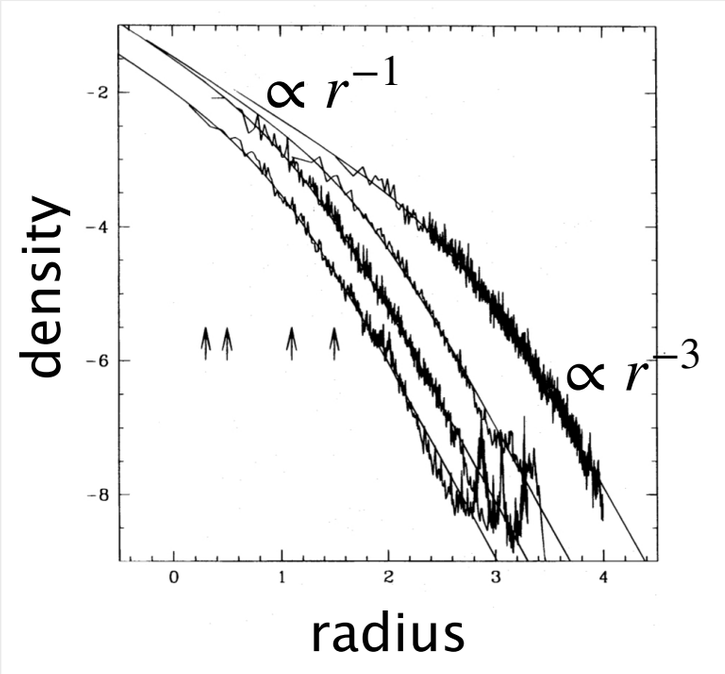
GALAXY-IGM WORKSHOP 2022

In Cosmological N-body Simulations



universal mass density distribution

ex) NFW profile Navarro, Frenk & White(1996)

$$\rho(r) = \frac{\rho_s r_s^3}{r(r+r_s)^2}$$

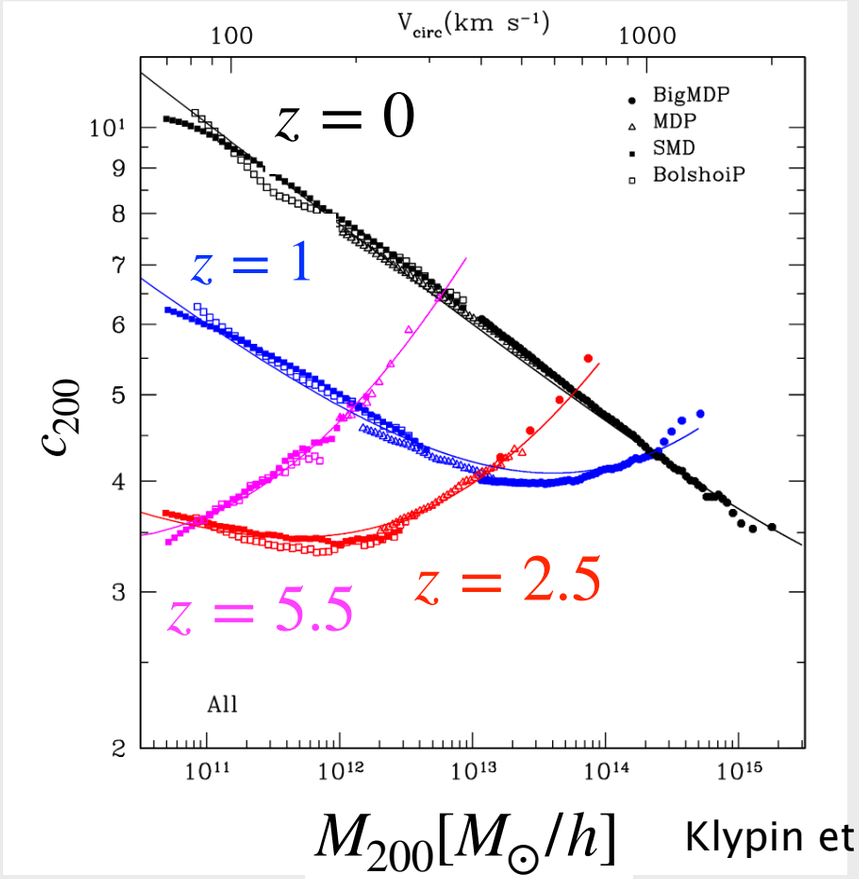
r_s: scale radius
ρ_s: scale density

concentration-mass relation (c-M relation)

$$c_{200} \equiv \frac{r_{200}}{r_s}$$: concentration

r_{200}: virial radius

$$M_{200} \equiv \frac{4}{3}\pi 200 \rho_{\mathrm{crit},0}(1+z)^3 r_{200}^3$$



Klypin et al. (2016)

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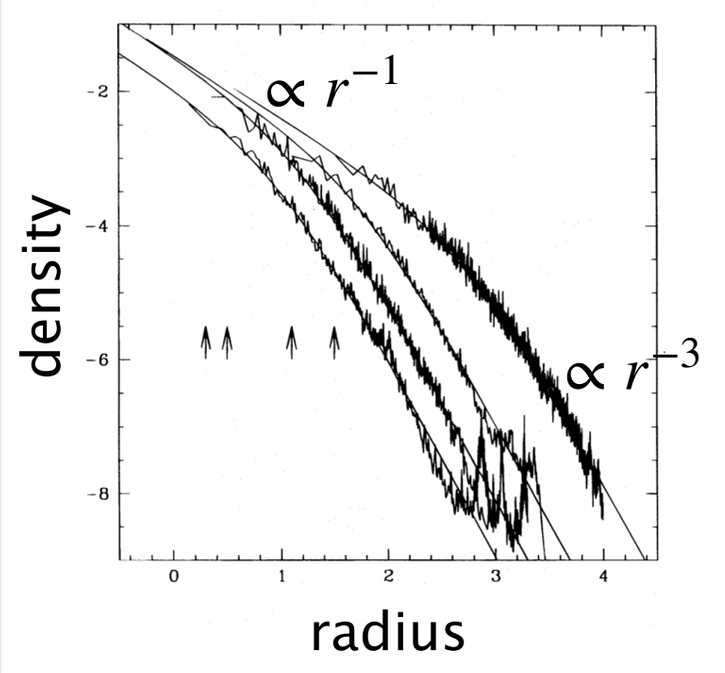

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$$\rho(r) = \frac{\rho_s r_s^3}{r(r+r_s)^2}$$

r_s: scale radius
ρ_s: scale density

integrate

$$M(r) = 4\pi\rho_s r_s^3 f\left(\frac{r}{r_s}\right)$$

where $f(x) = \ln(1+x) - \frac{x}{1+x}$

within r_{200}

$$M_{200} = 4\pi\rho_s r_s^3 f\left(\frac{r_{200}}{r_s}\right)$$

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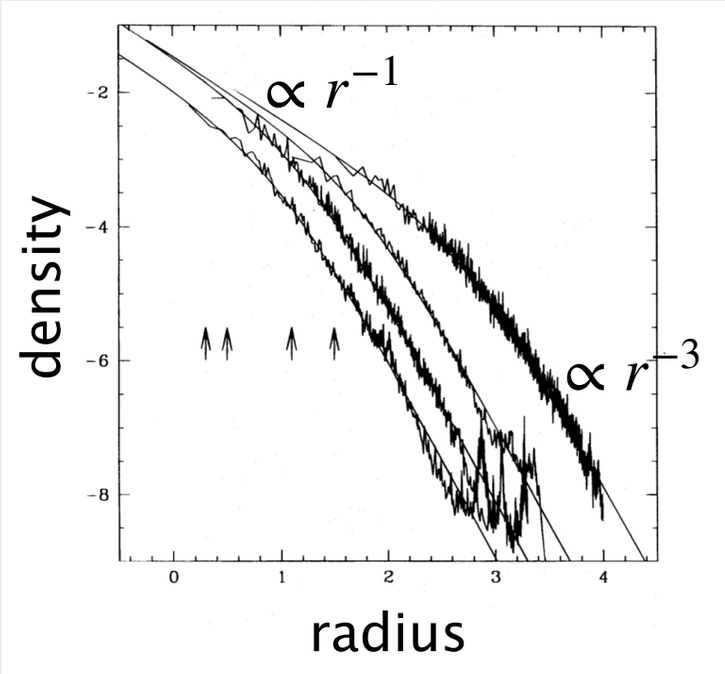

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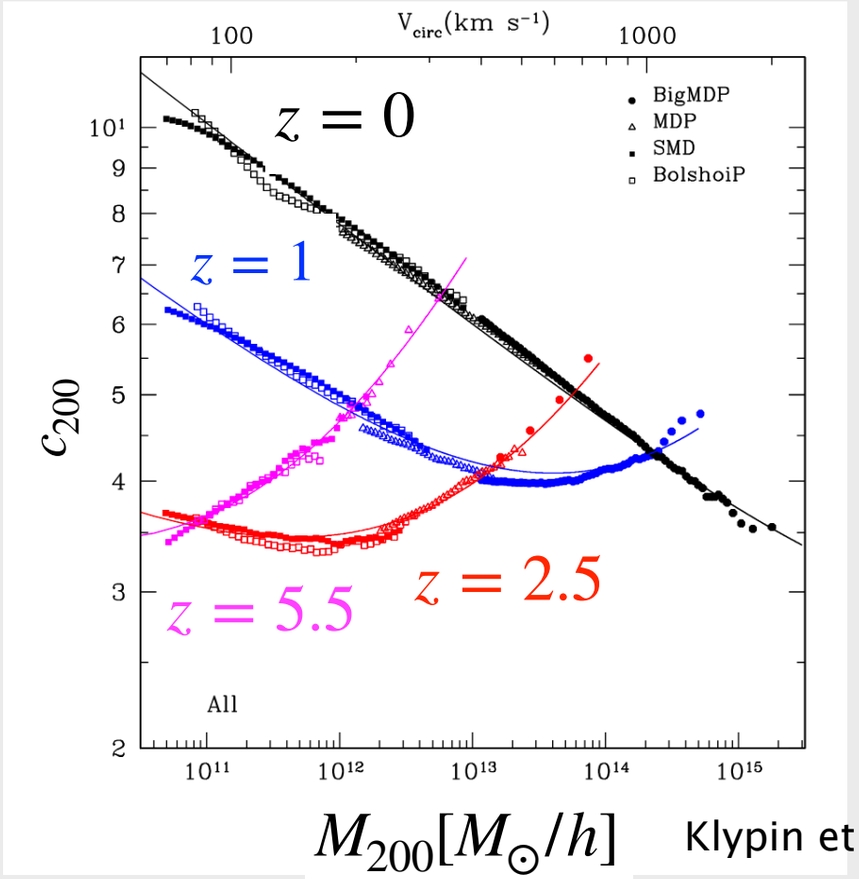

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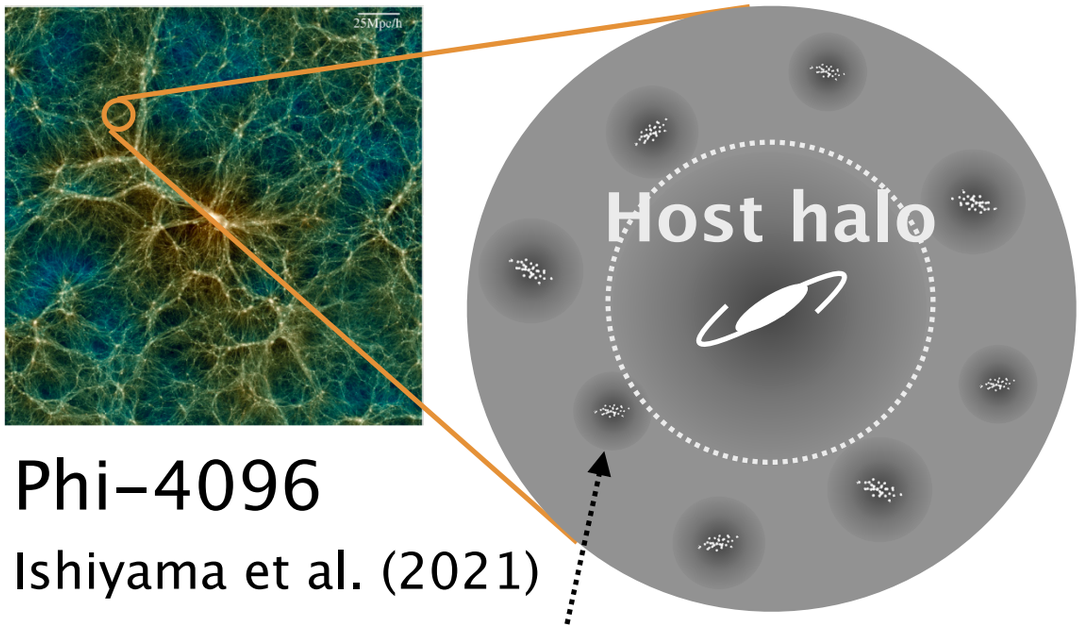
Purpose of This Study I

to investigate the c–M relation of the **low mass** haloes **statistically** using the results of the **ultra-high resolution** simulation

Data and Methods



Phi-4096

Ishiyama et al. (2021)

Sub-galactic haloes
= Subhaloes

Properties of Phi-4096 ▼

Name	N	L (h^{-1}Mpc)	ε (h^{-1}kpc)	m_p ($h^{-1}M_\odot$)
Phi4096	4096^3	16.0	0.06	5.13×10^3

N : number of particle
L : box length
ϵ : softening length
m_p : particle mass resolution

✦at $z = 0$

✦host haloes

Milky Way sized ($3.40 \times 10^{11}\, M_\odot h^{-1} < M_{\rm vir} < 2.04 \times 10^{12}\, M_\odot h^{-1}$)

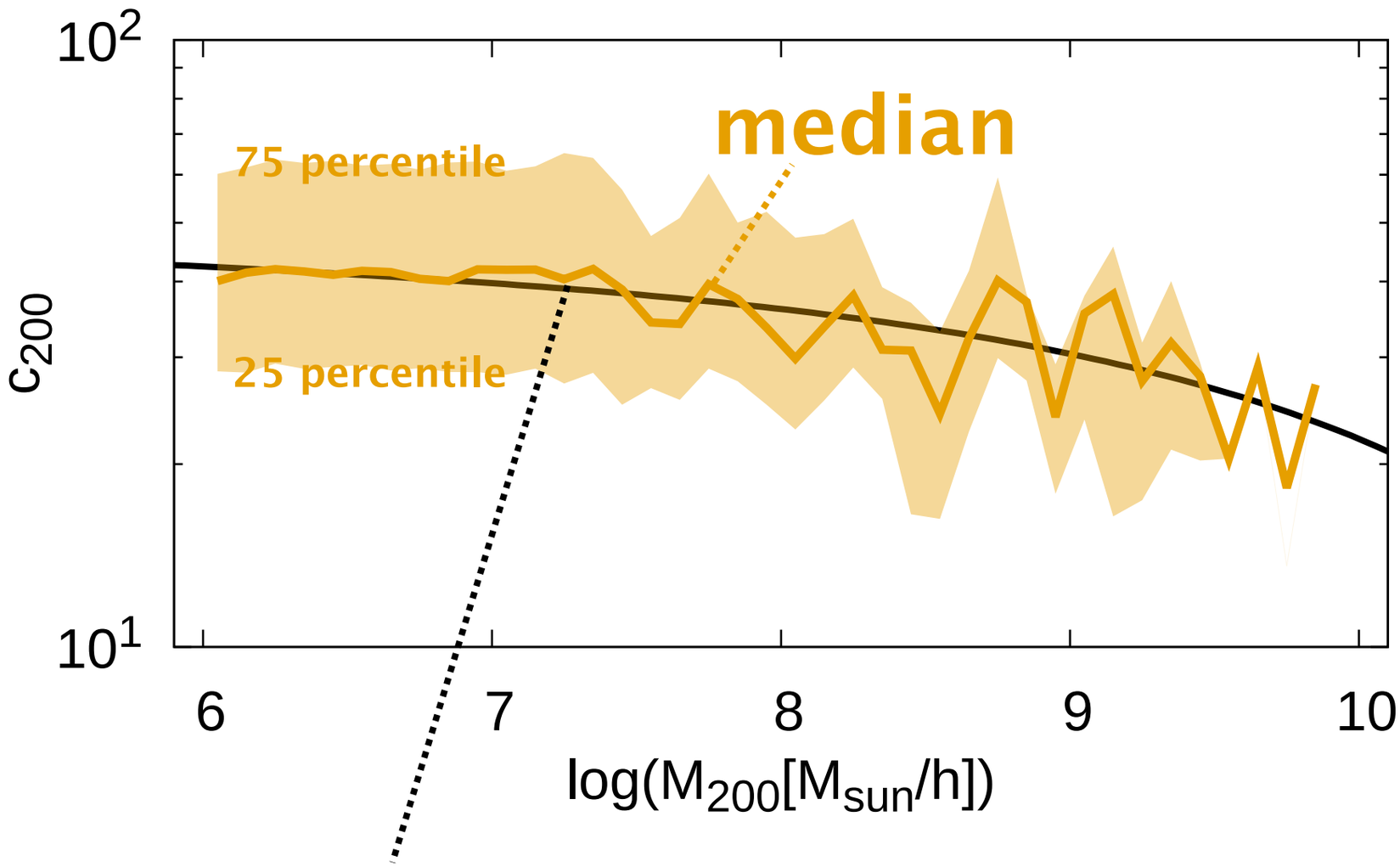
-> 27models

✦subhaloes

$< 2 \times r_{\rm vir}$

-> 3×10^5 models for over $10^6 M_\odot h^{-1}$

The *c-M* Relation



$c_{200} \equiv \frac{r_{200}}{r_s}$: concentration

r_{200}: virial radii
r_s: scale density of NFW profile

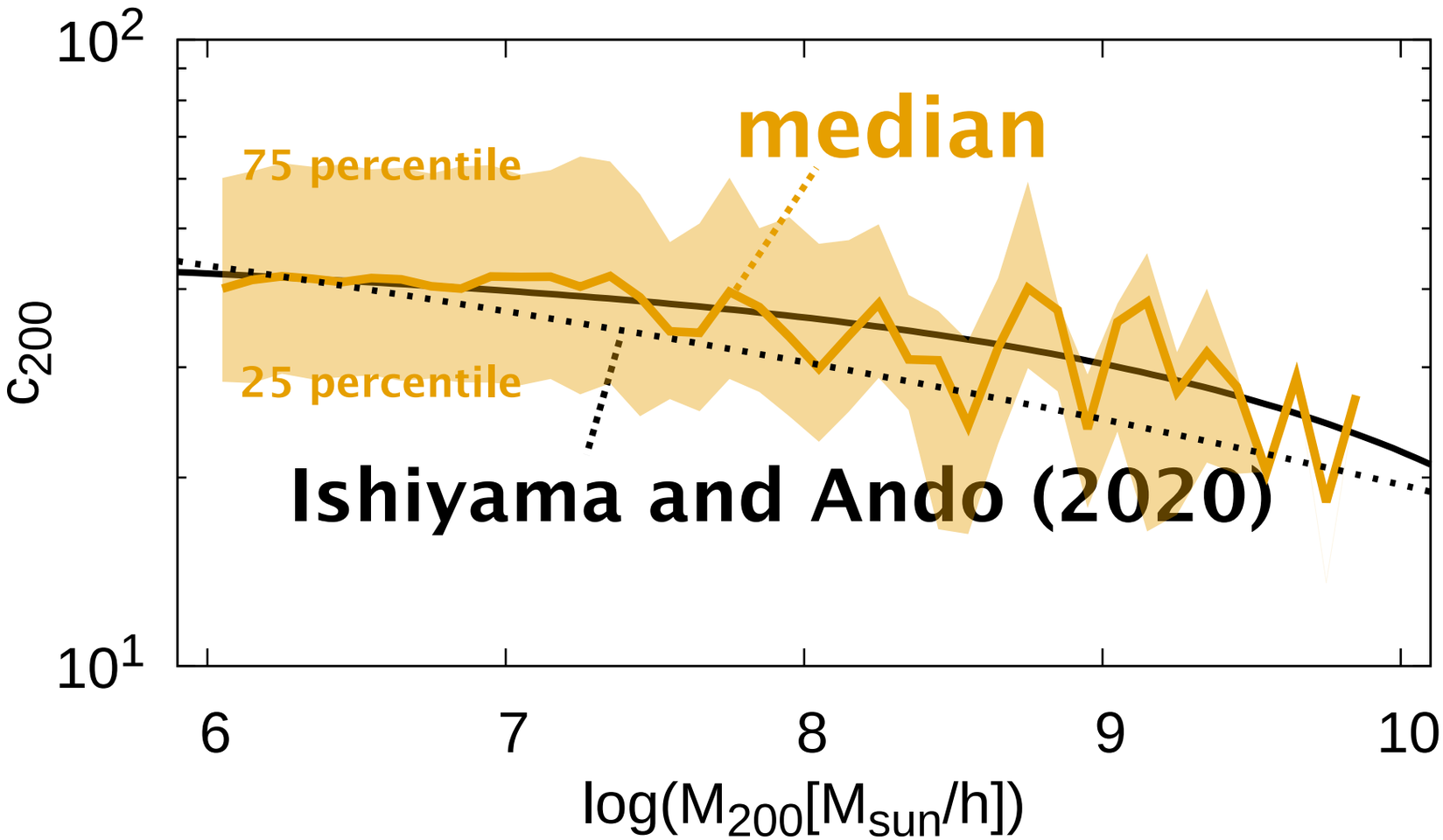
M_{200}: virial mass

fitting function

$$c_{200} = \sum_{i=0}^{3} c_i \times \left[\log\left(\frac{M_{200}}{M_\odot h^{-1}}\right)\right]^i$$

$$c_i = [80.533, -15.3184, 2.31062, -0.136397]$$

The *c-M* Relation



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r_{200}: virial radii
r_s: scale density of NFW profile

M_{200}: virial mass

our fitting function

$$c_{200} = \sum_{i=0}^{3} c_i \times \left[\log\left(\frac{M_{200}}{M_\odot h^{-1}}\right)\right]^i$$

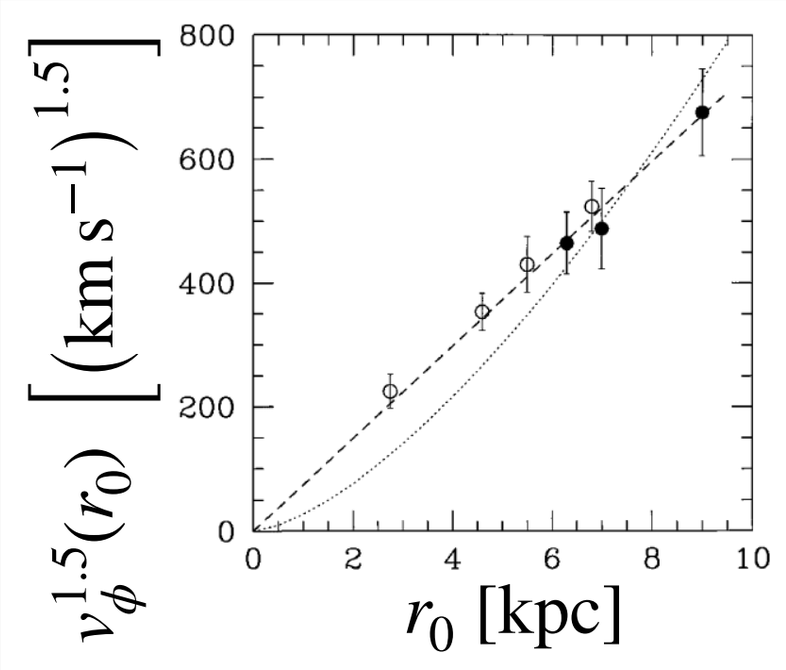
$$c_i = [80.533, -15.3184, 2.31062, -0.136397]$$

Scaling Relations of Observations

What are "scaling relations"?

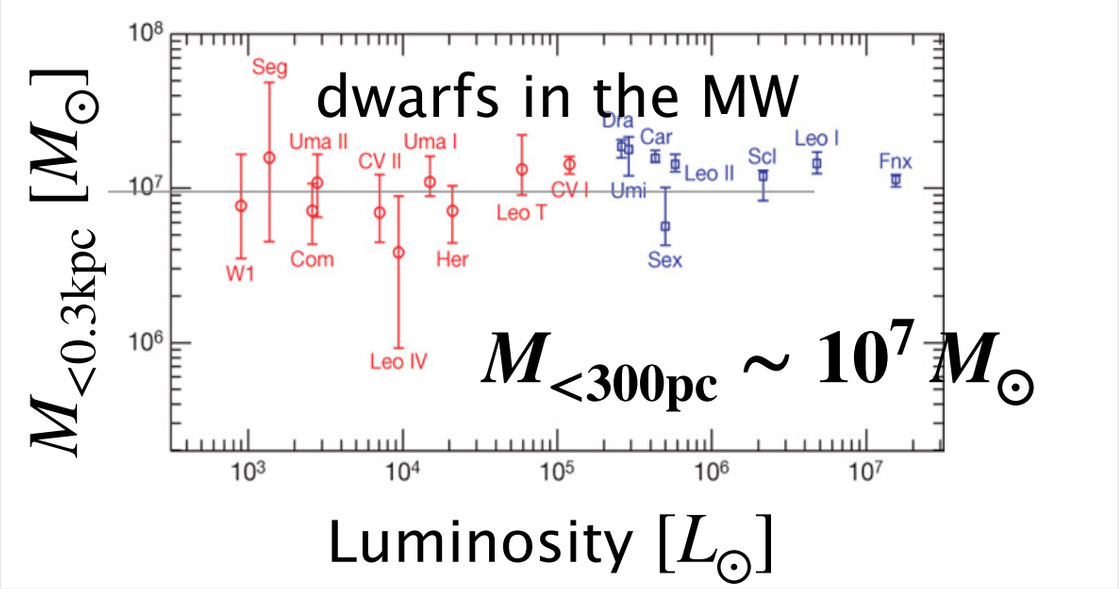
universal correlation of properties in DM haloes

✦ **Burkert**

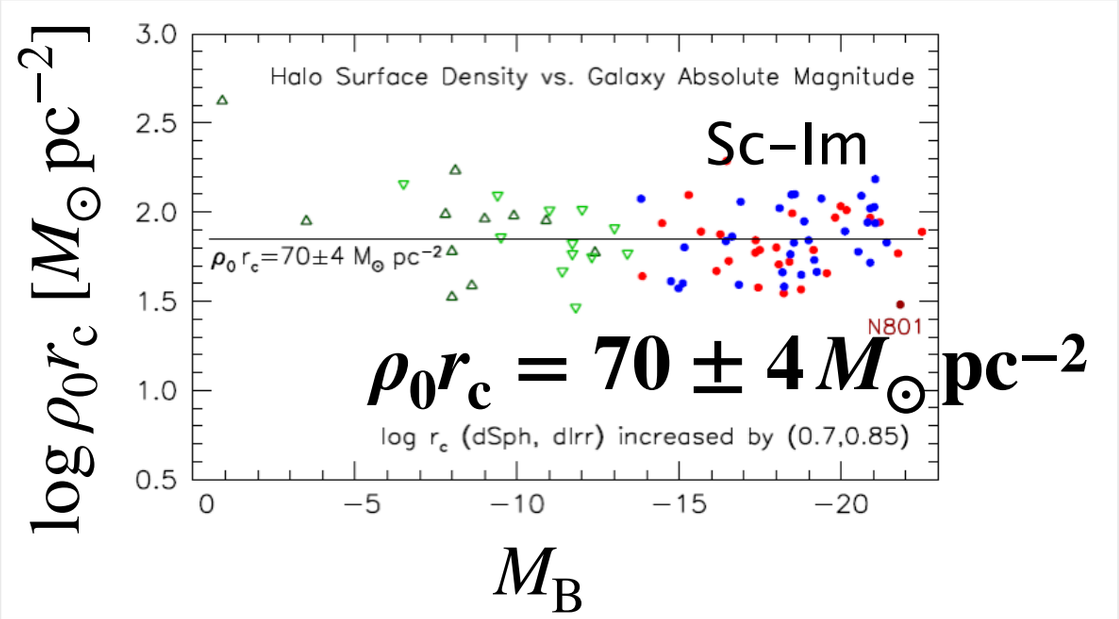


$$v_0 = 17.7 \left(r_0\ \mathrm{kpc}^{-1}\right)^{2/3}\ \mathrm{km\,s^{-1}}$$

✦ **Strigari et al. (2008)**



✦ **Kormendy & Freeman**

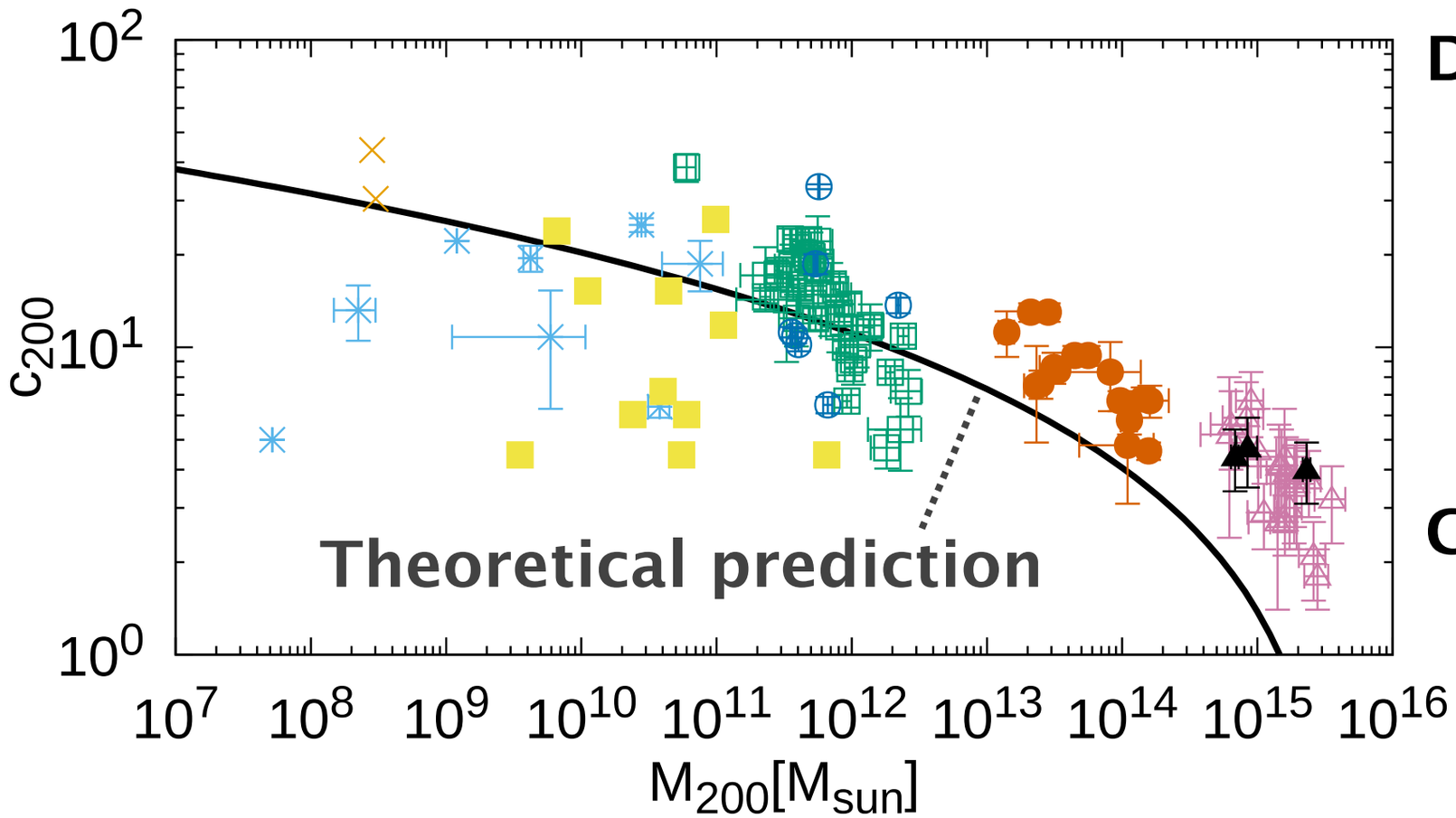


Purpose of This Study II

to explore the **origin** of the properties of the observed haloes

compare "**theoretical prediction**" and "**observations**"

The *c-M* Relation with Observations



selection criteria

1. error < main value
2. $r_s < 2.0 \times$ (last mesured radius)

Dwarf Galaxies/Galaxies

<Spectroscopic>

- de Bolk et al. (2008)
- Spano et al. (2008)
- Oh et al. (2015)
- Sofue (2016)
- Hayashi et al. (2020)*

Galaxy Groups/Clusters

<X-ray>

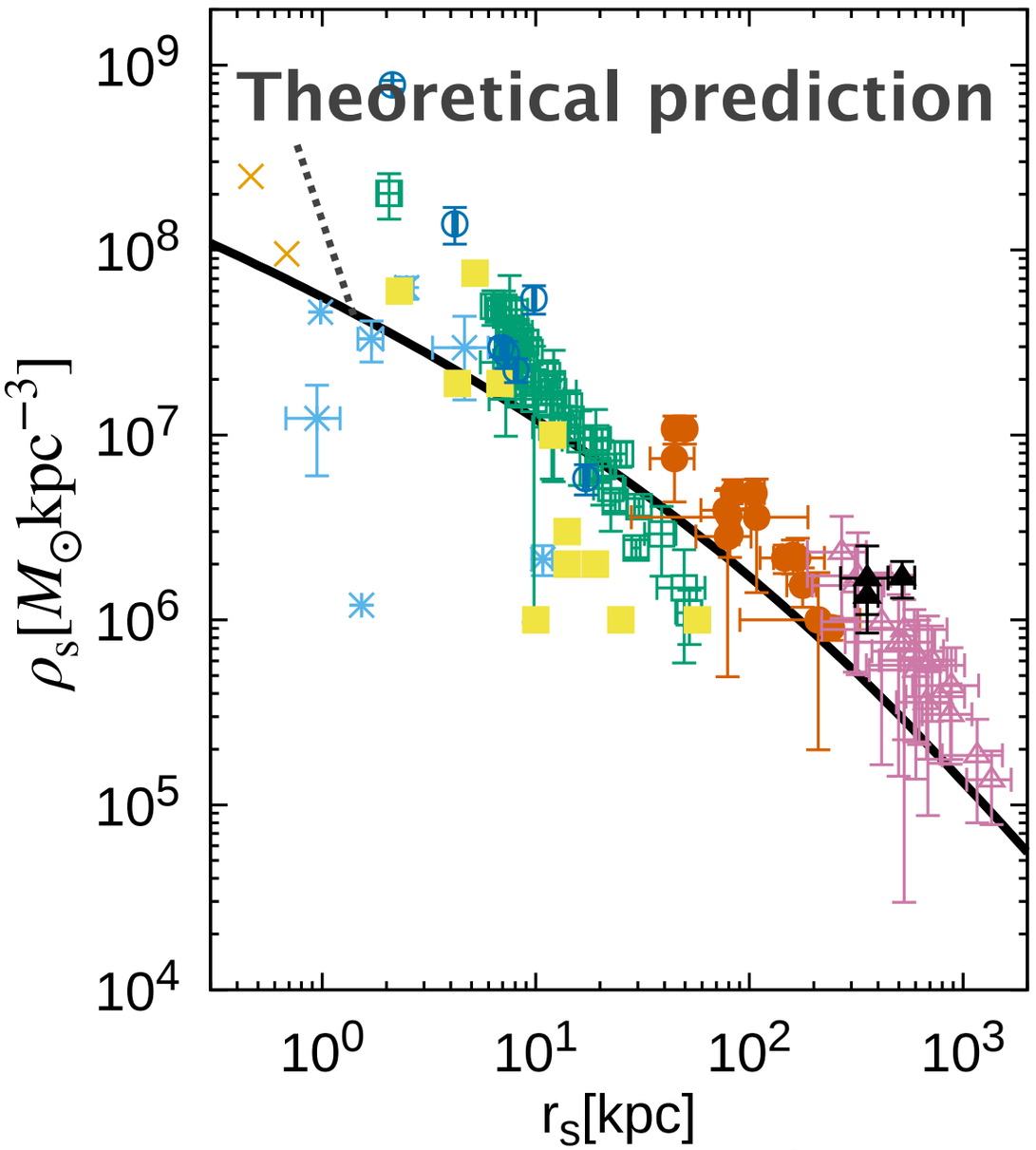
- Gastaldello et al. (2007)

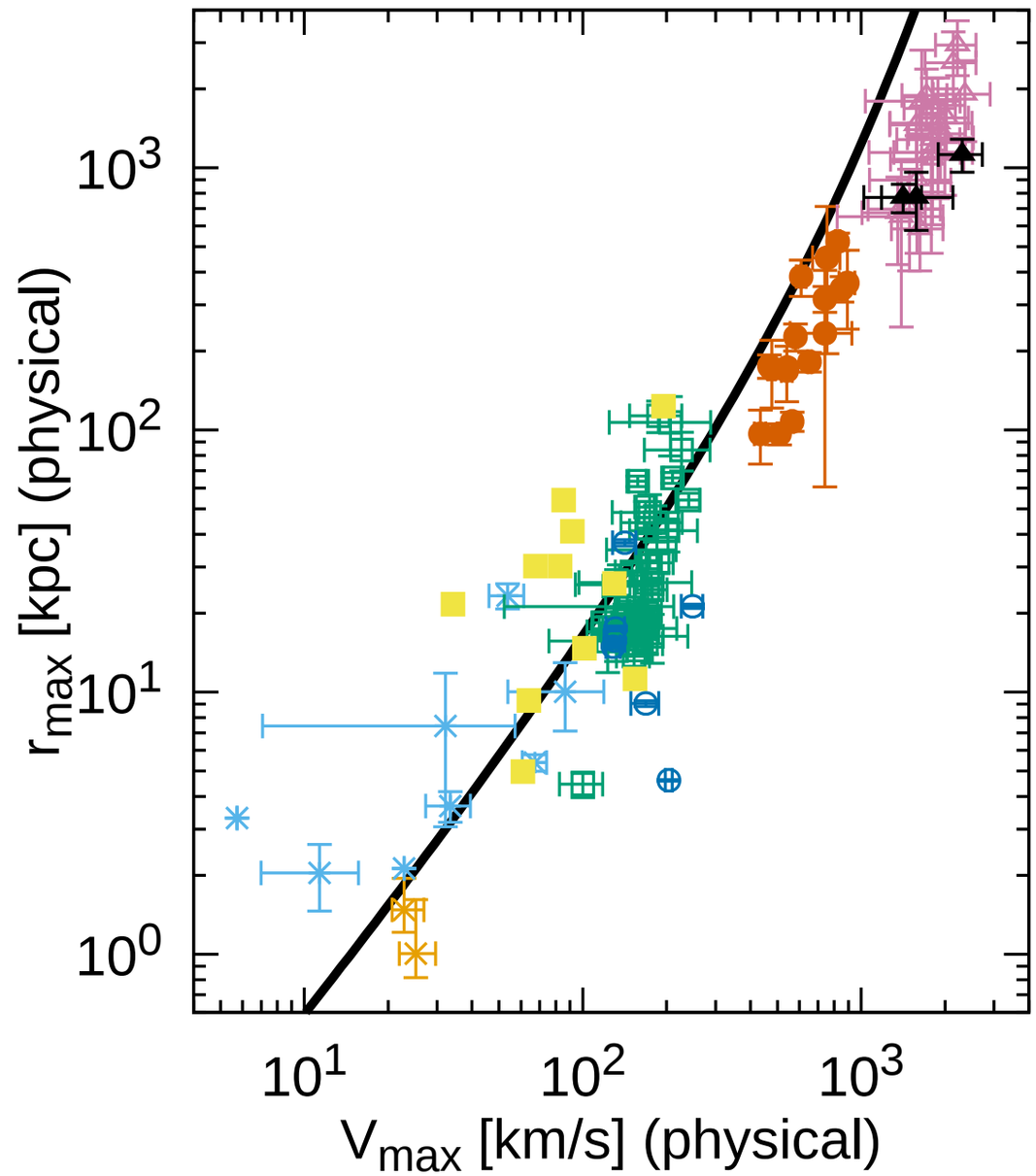
<Gravitational Lensing>

- Merten et al. (2015)
- Umetsu et al. (2016)

*assuming axisymmetric mass distribution

The *c-M* Relation with Observations





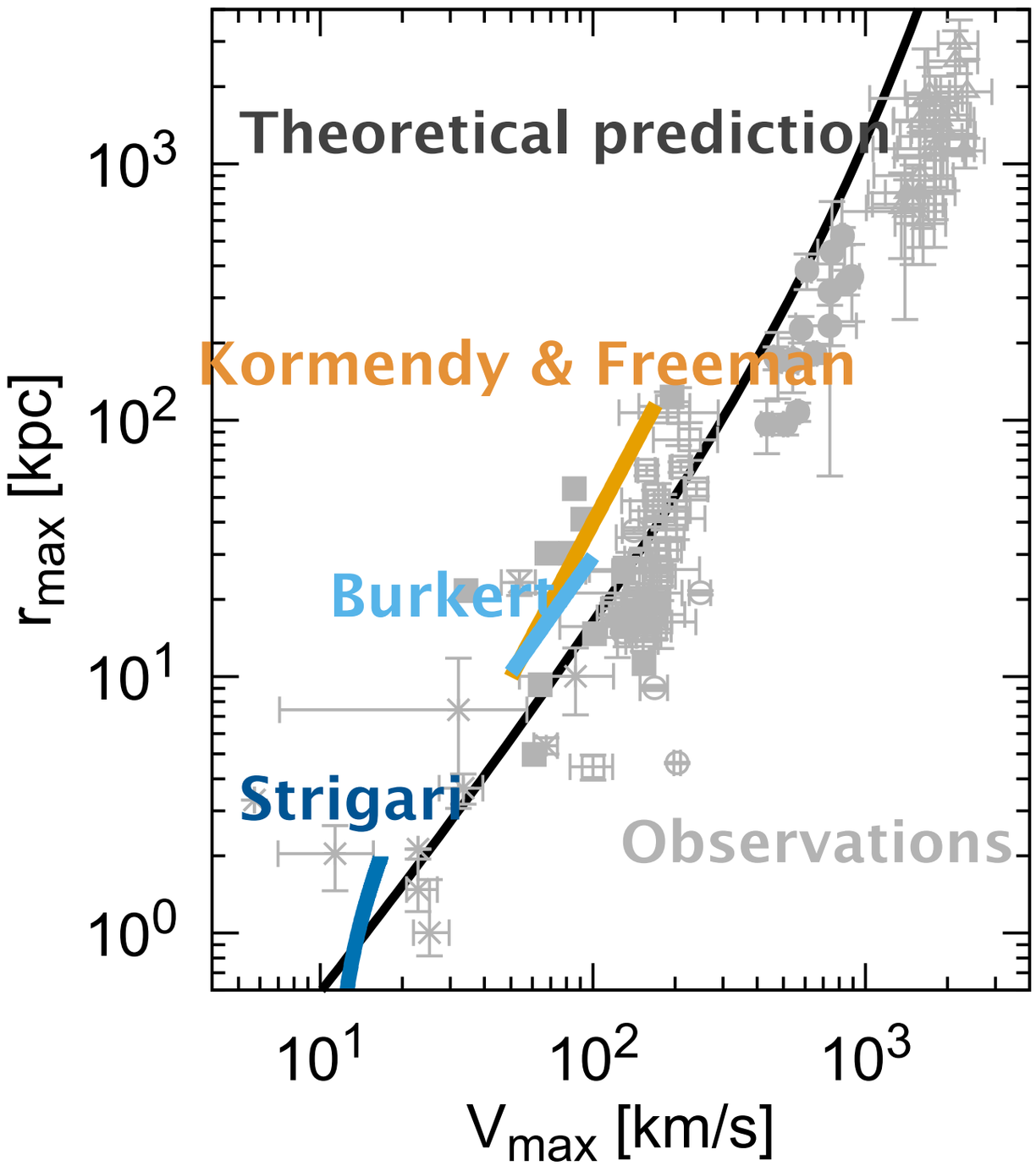
NFW profile: $\rho(r) = \dfrac{\rho_s r_s^3}{r(r+r_s)^2}$

r_s: scale radus, ρ_s: scale density

$r_{\max}$: radius where the rotation curve has a maximum circular velocity

$V_{\max}$: maximum circular velocity

Comparison with the Scalings



- Burkert relation:
  $v_0 = 17.7 \ \left(r_0 \ \mathrm{kpc}^{-1}\right)^{2/3} \ \mathrm{km\,s}^{-1}$
- Strigari relation:
  $M_{<300\mathrm{pc}} \sim 10^7 \, M_\odot$
- Kormendy & Freeman relation:
  $\rho_0 r_c = 70 \pm 4 \, M_\odot \, \mathrm{pc}^{-2}$

r_{max} : radius where the rotation curve has a maximum circular velocity

V_{max} : maximum circular velocity

Summary & Discussion

- ✓ our c–M relation (25–75 percentile) 🤝 Ishiyama–Ando function
- ✓ theoretical c–M relation well reproduces the observations from dwarf galaxies to clusters of galaxies
- ✓ observation with higher resolution for dwarfs is expected to constrain the c–M relation models
- ✓ scaling relations anchor c–M relation
- ✓ the gap between the scaling relations and the c–M relation

  –> investigate the origin of this in relation to the core–cusp problem