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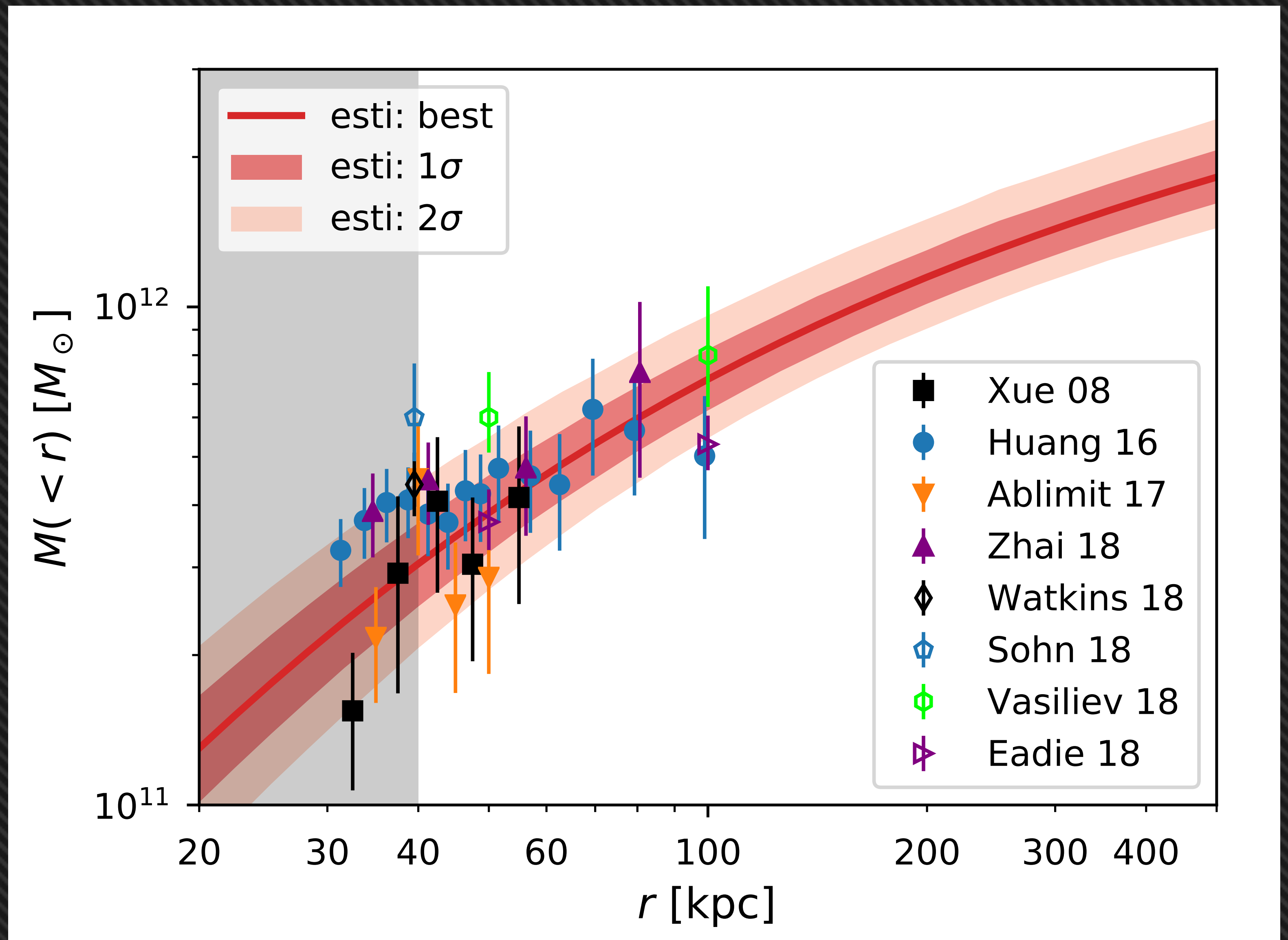
Constrain the Milky Way Mass Profile with Phase Space Distribution of Satellite Galaxies

$M\,(< r\,|\,M_{vir}, c)$



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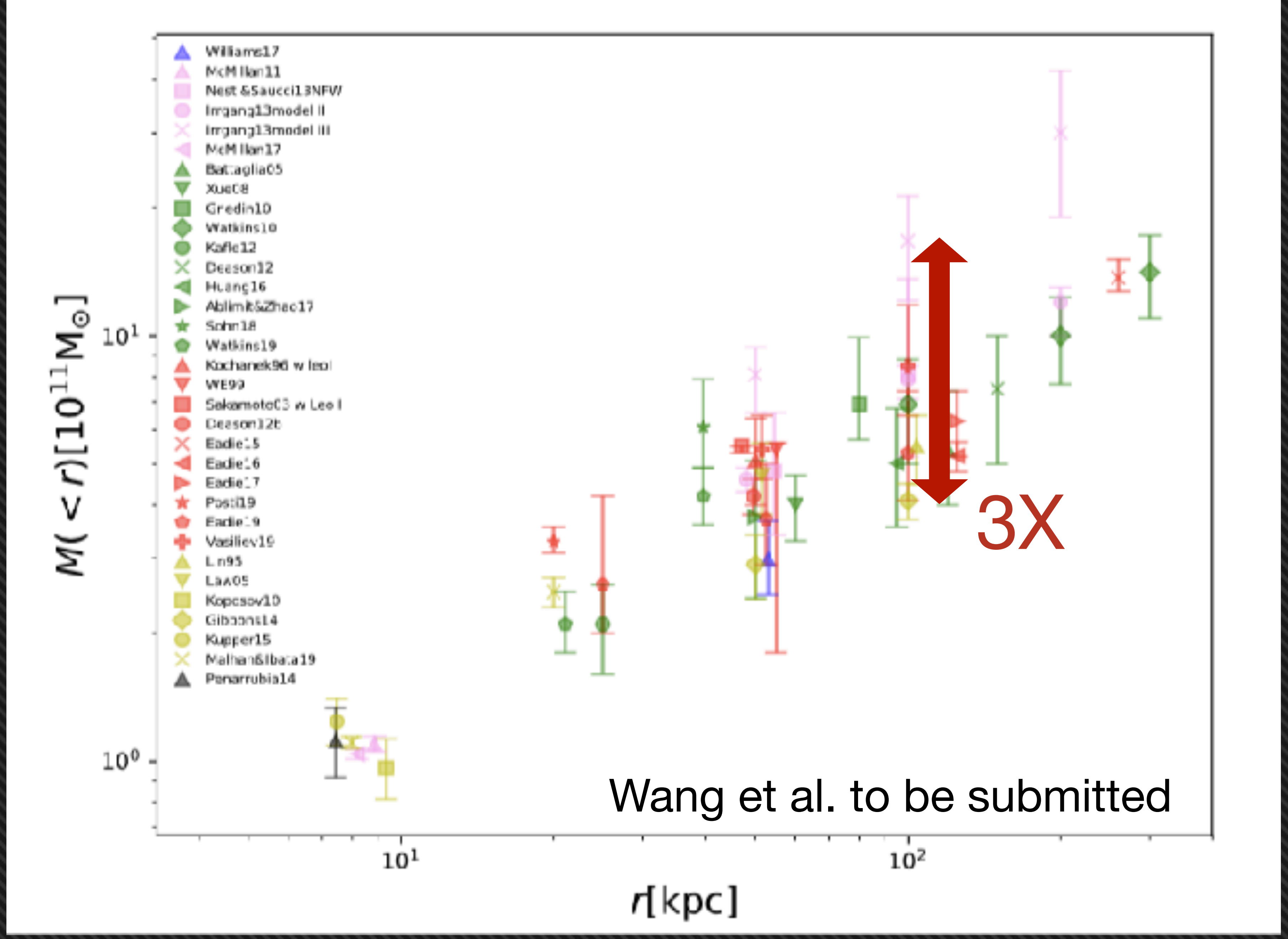
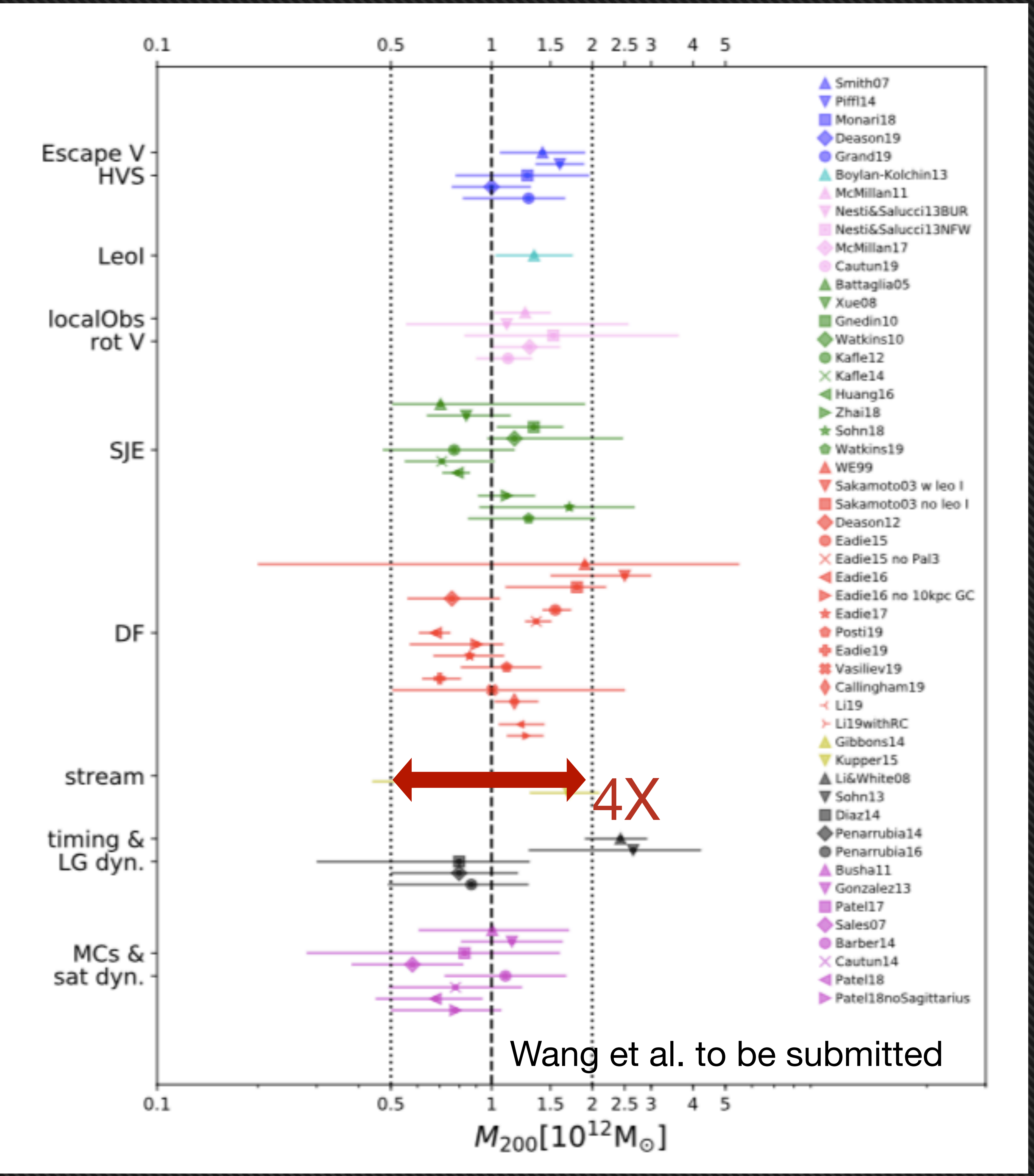
Nov 6 2019@SJTU

Why we care about Milky Way mass & profile

- Basic properties of our home galaxy
  - Galactic dynamics
  - Formation and assembly history of the MW
- Basis for validating theory predictions from local observation
  - Dark matter detection
  - Cosmology, e.g. expected baryon fraction, number of satellites
  - Gravity Theory

Milky Way (MW) Mass: still very uncertain!

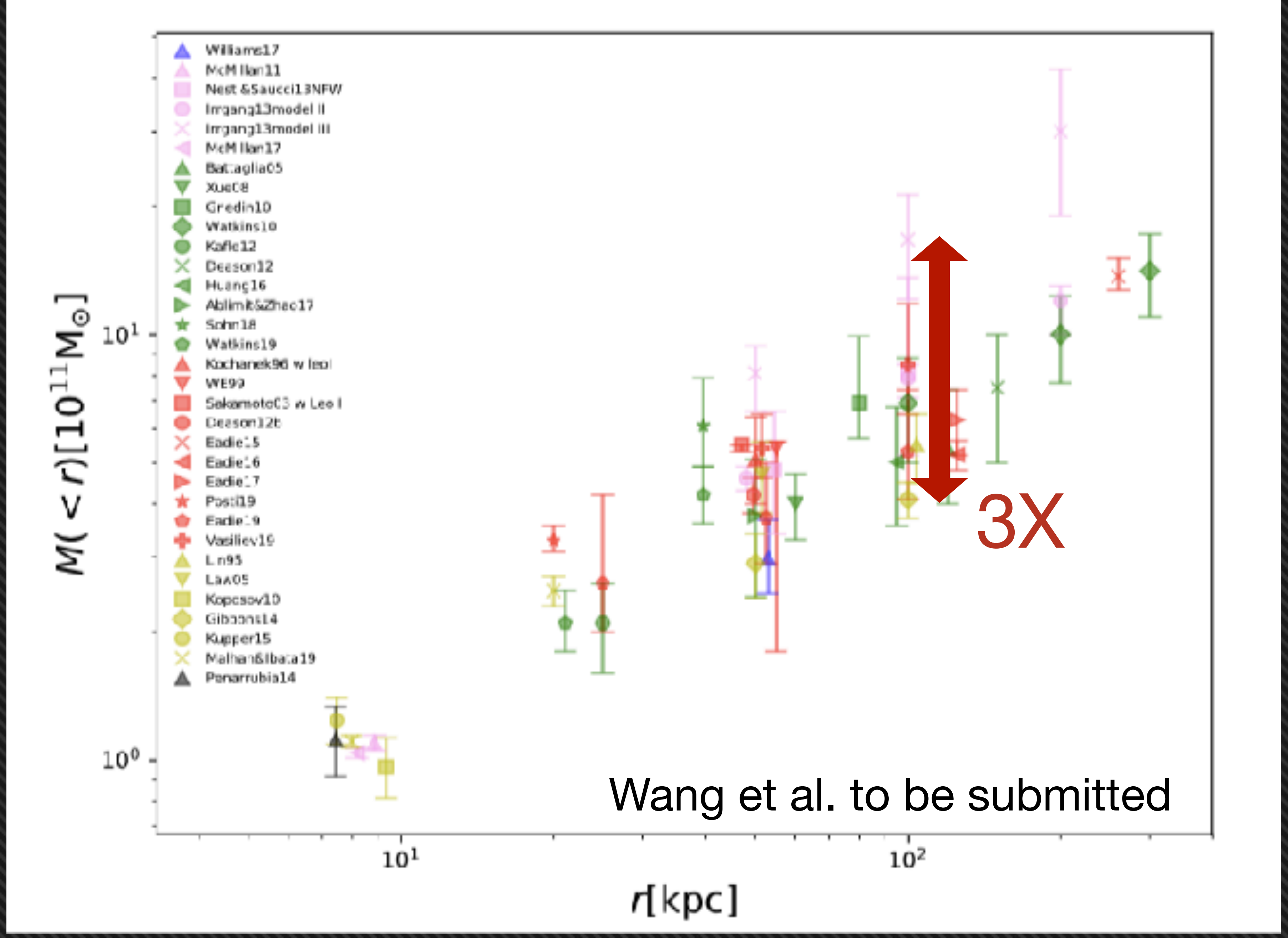


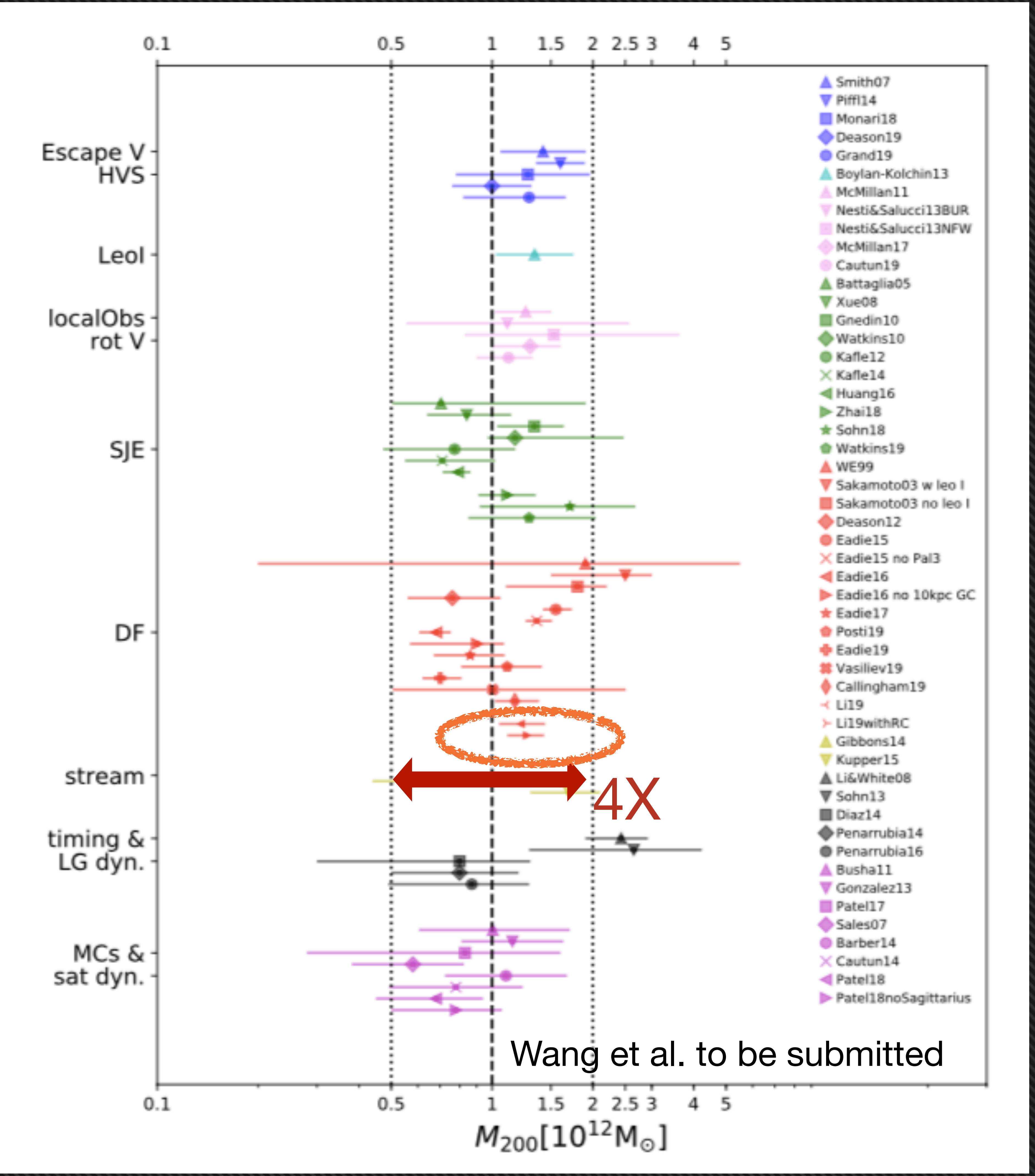


Challenges in data & model

- Virial radius is far beyond tracers like stars
- Poor observations in outer halo
- Model uncertainty: $\beta(r)$, $n(r)$ or form of DF
- Observation error and incompleteness

Milky Way (MW) Mass: still very uncertain!





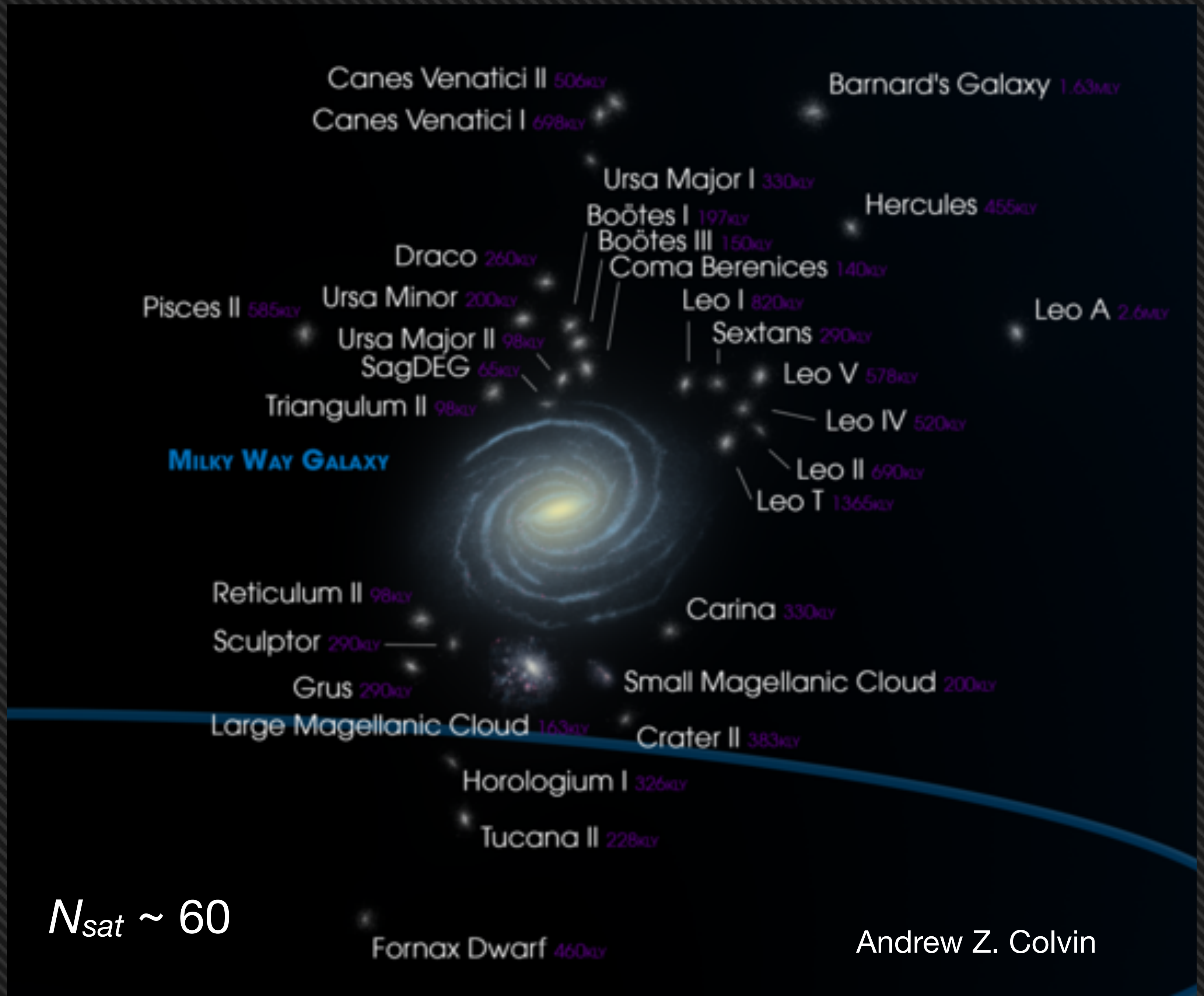
Challenges in data & model

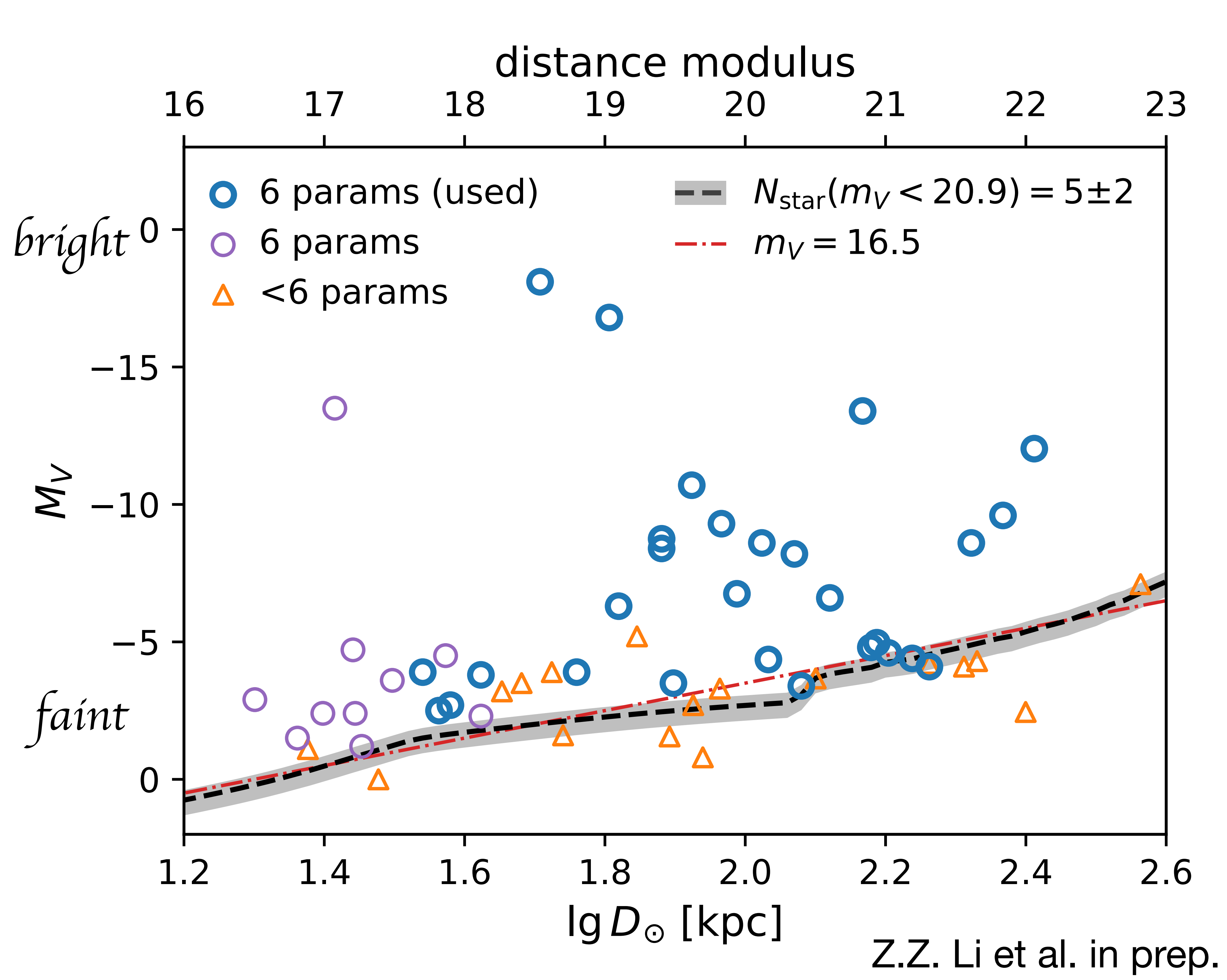
- Virial radius is far beyond tracers like stars
  - **Use satellite galaxies instead**
- Poor observations in outer halo
  - **Gaia**
- Model uncertainty: $\beta(r)$, $n(r)$ or form of DF
  - **Dynamical model based on simulation**
- Observation error and incompleteness
  - **Bayesian statistics**

Satellite galaxies: best tracers for MW outer halo

Virtues:

- Extended distribution
  the **only** tracers beyond 100 kpc or farther
- Proper motion (pm) available: Gaia
- Well understood population
  knowledge from theory and simulations
  well phase-mixed (Han+ 2019)
  ⇨ **physical model based on simulation and equilibrium assumption**





Data:

- 28 satellites with Gaia DR2 pm
  40 kpc < r < 280 kpc
- homogeneous selection function:
  distant and faint galaxies are missed
  $N_{star}(M_V < 20.9)$ ~ 5

How kinematics reveal mass

Popular methods: Jeans Equation, Distribution Function

Poor observation ⇨ heavier **model dependence** for outer halo

Extract info from **simulations** to mitigate model dependence

- ✦ statistics: instantaneous kinematics (*Busha+ 2011, Boylan-Kolchin+ 2013, Patel+2017, ...*), orbit circularity (*Barber+ 2013*), angular momentum (*Patel+2018*)
- ✦ **orbital distribution**: $p(E, L\,|\,M)$ (***Li+ 2017***, *Callingham+ 2018*)
  more efficient use of both data and simulation
  E is not observable ⇒ calibration required
- ✦ **phase space distribution function**

$$p(\boldsymbol{r}, \boldsymbol{v}) = \frac{p(E, L)}{8\pi^2 L T_r(E, L)} \equiv f(E, L)$$

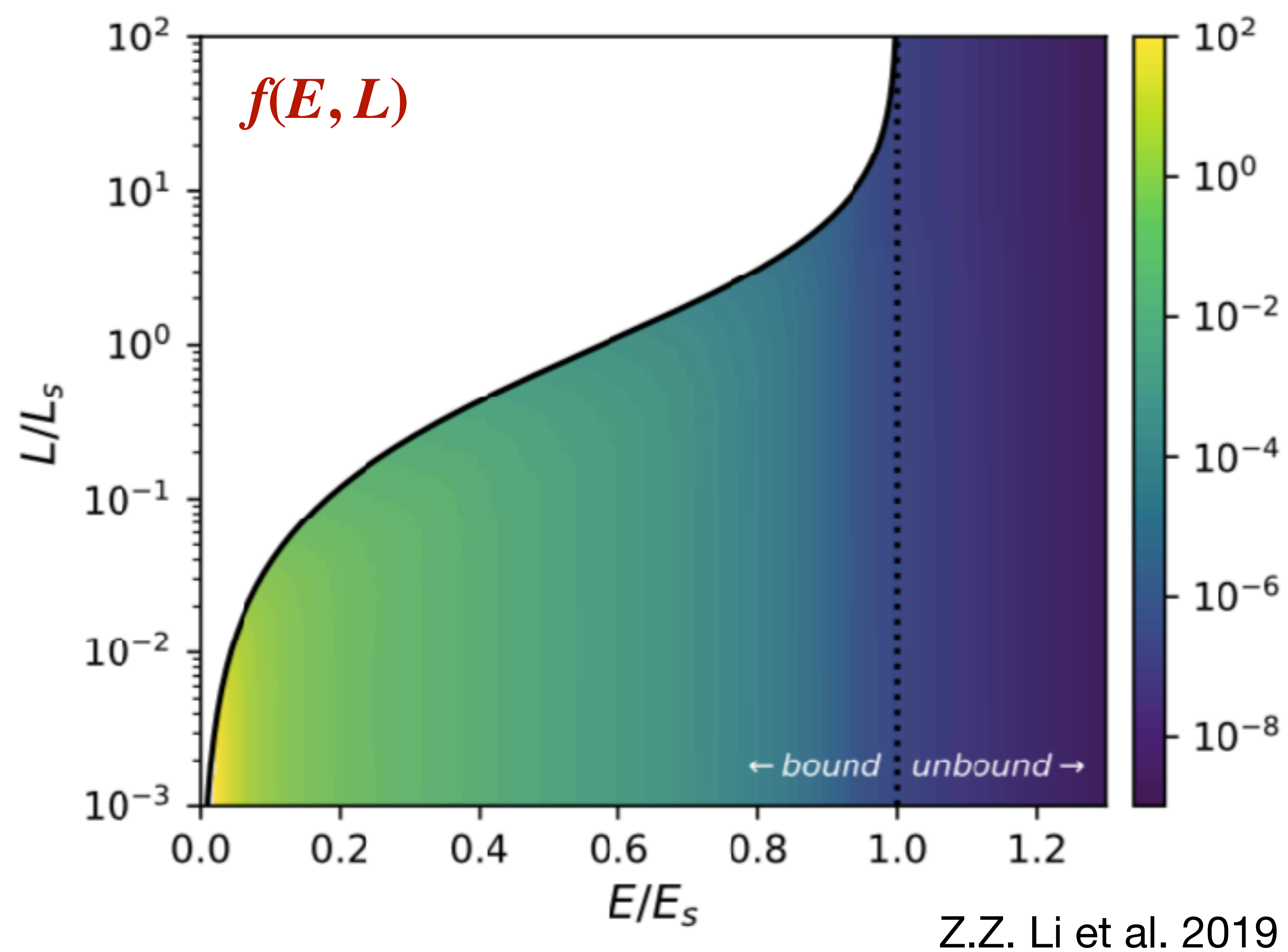
similarity in halo structures ⇒ stacking & scaling

$$p(\boldsymbol{r}, \boldsymbol{v}\,|\,M, c) = \frac{1}{r_s^3 v_s^3} \tilde{f}\left(\frac{E}{v_s^2}, \frac{L}{r_s v_s}\right)$$

complete description to satellite kinematics

precise & unbiased

rigorous treatment to observation error and incompleteness

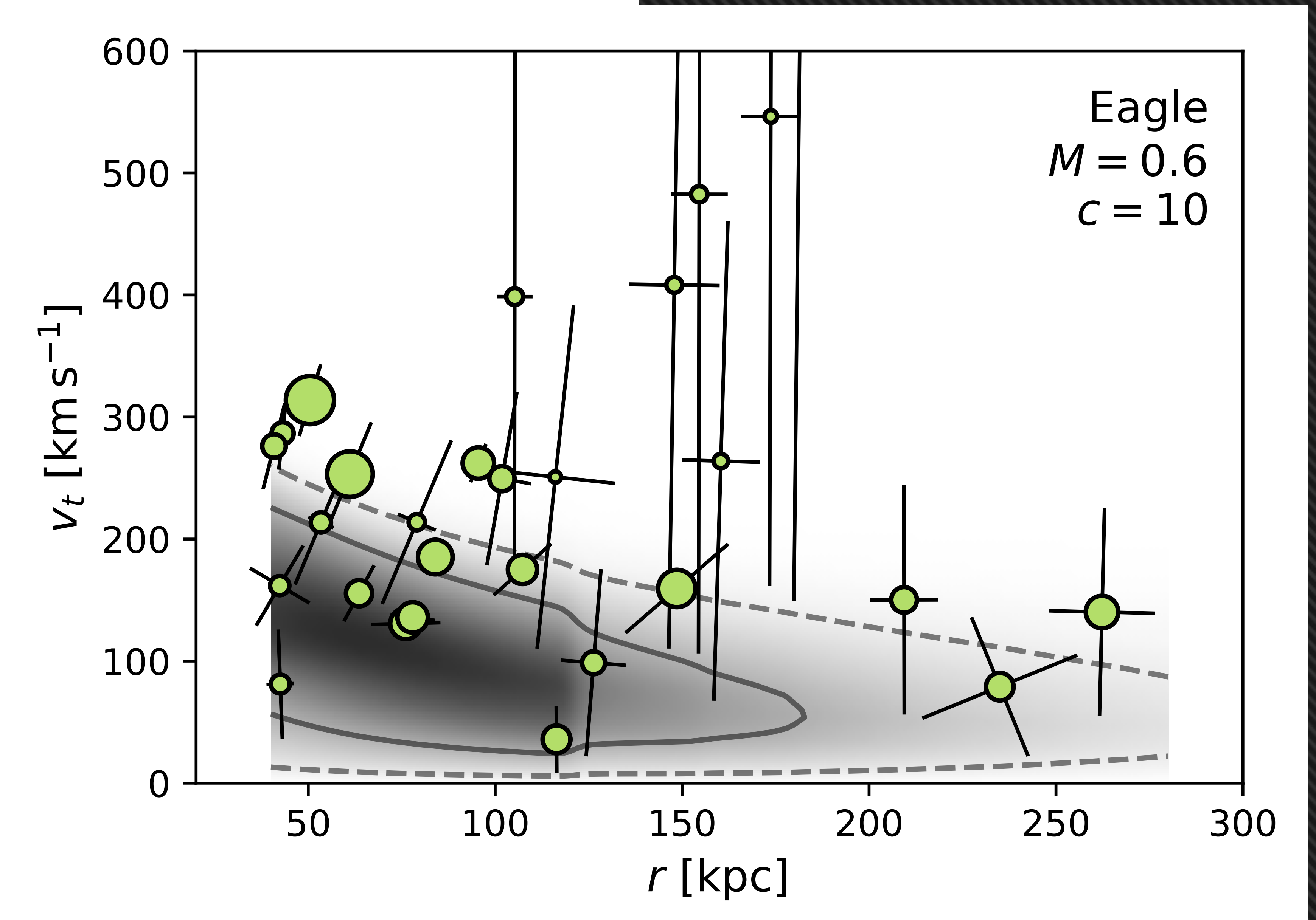


Z.Z. Li et al. 2019

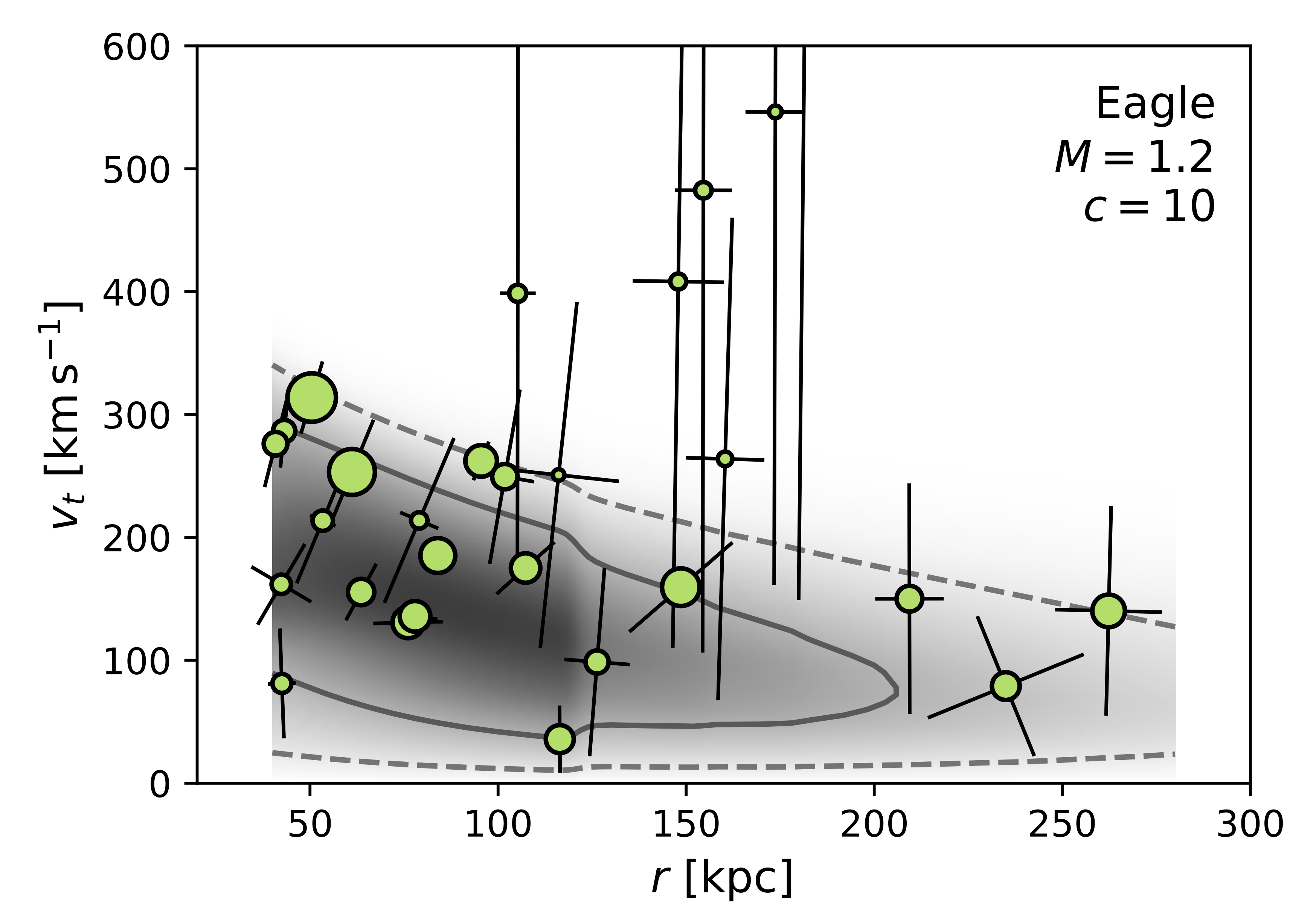
Infer Mass & concentration

Observation (r, v) **vs Model** $p_{\mathrm{obs}}(r, v \,|\, M, c)$

M = 0.6×10¹²M☉



M = 1.2×10¹²M☉



Likelihood:

$$p(M, c \,|\, \{\boldsymbol{w}\}) \propto \left[\prod_{i=1}^{n_{\mathrm{sat}}} p_{\mathrm{obs}}(\boldsymbol{w}_i \,|\, M, c)\right] p(c \,|\, M) p(M)$$

Observational effects included

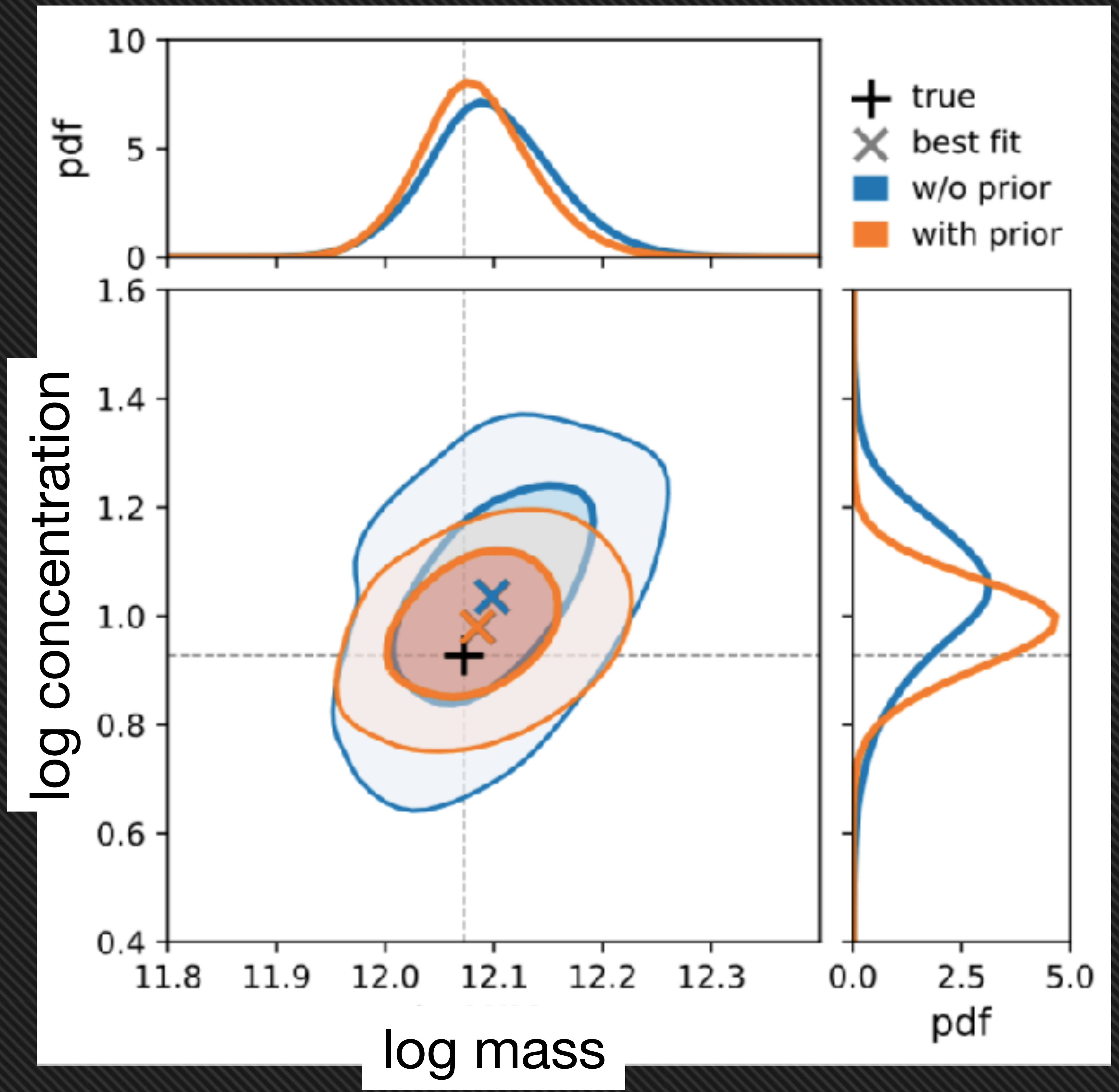
Prior information: e.g. *M*-*c* relation, or other indep. measurements

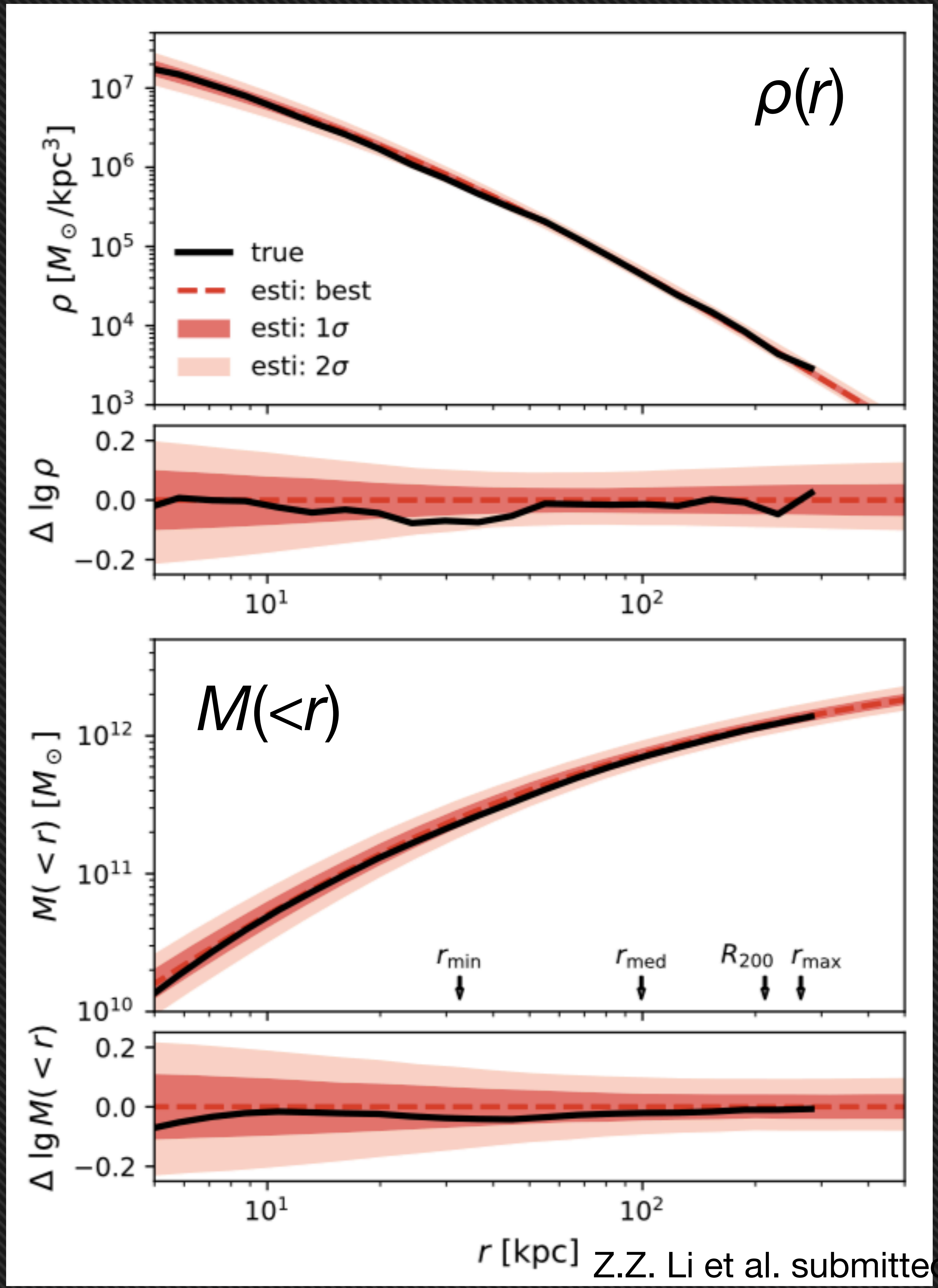
Test with mock sample from simulation

Example using 40 tracers

~15% precision level for halo mass

well recover the mass profile





Z.Z. Li et al. submitted

Method comparison: better than Jeans method

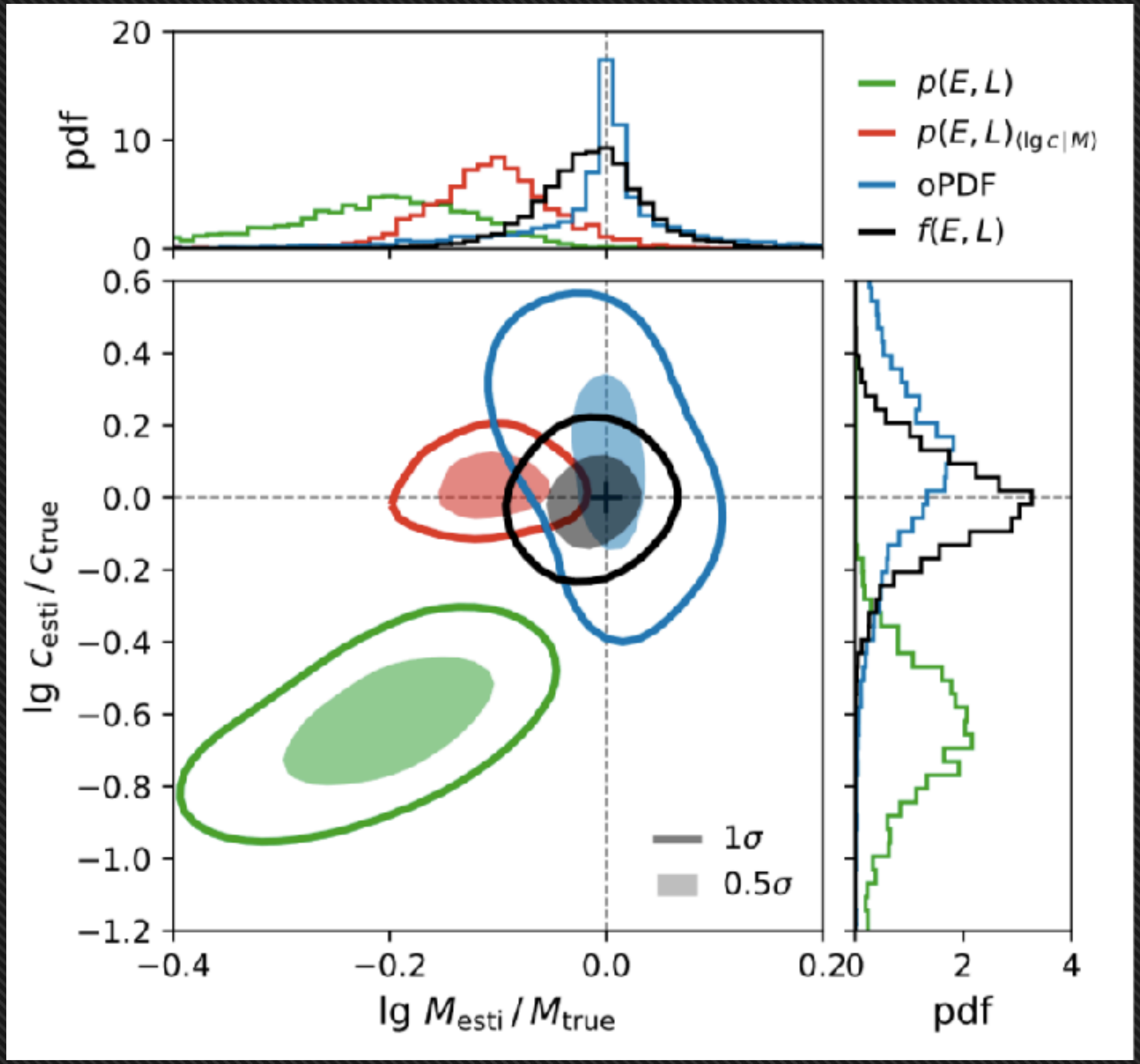
- *p*(*E*, *L* | *M*, *c*): orbital distribution
  - *p*(*E*, *L* | *M*): **Li+ 2017**; Callingham+ 2018; *M*-*c* relation assumed
- oPDF (Han+ 2015): based on steady-state assumption
  representative to **Jeans equation** and **Schwarzschild modeling**
- *f*(*E*, *L* | *M*, *c*): phase space distribution (this work)

phase space distribution — radial distribution along one orbit — orbits distribution

$$p(\boldsymbol{r},\boldsymbol{v}) = \frac{|v_r|}{8\pi^2 L}\, p(r\,|\,E,L) \times p(E,L)$$

steady state (oPDF) ⇨

$$p(\boldsymbol{r},\boldsymbol{v}) = \frac{p(E,L)}{8\pi^2 L T_r(E,L)} \equiv f(E,L)$$

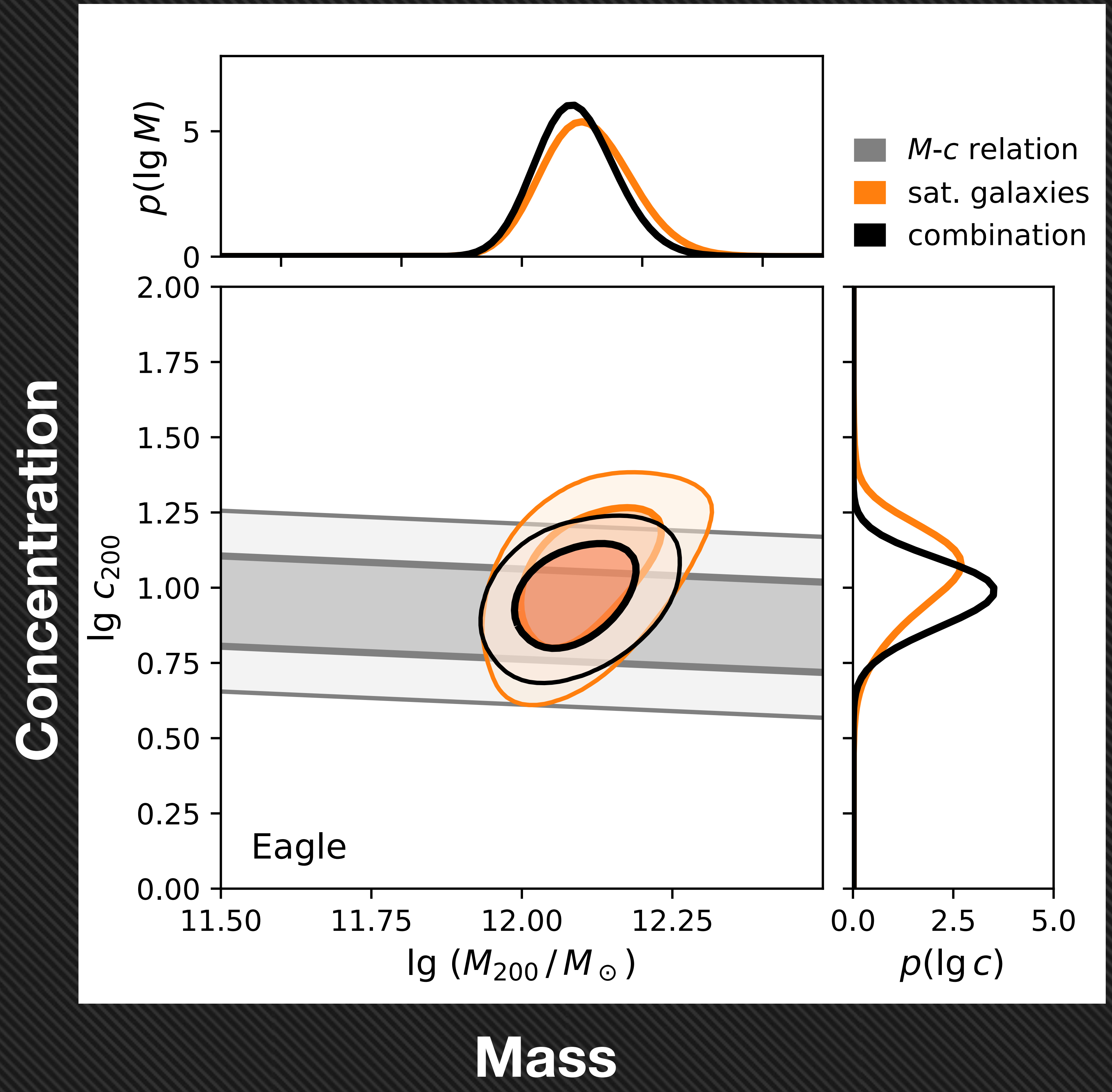


Z.Z. Li et al. 2019

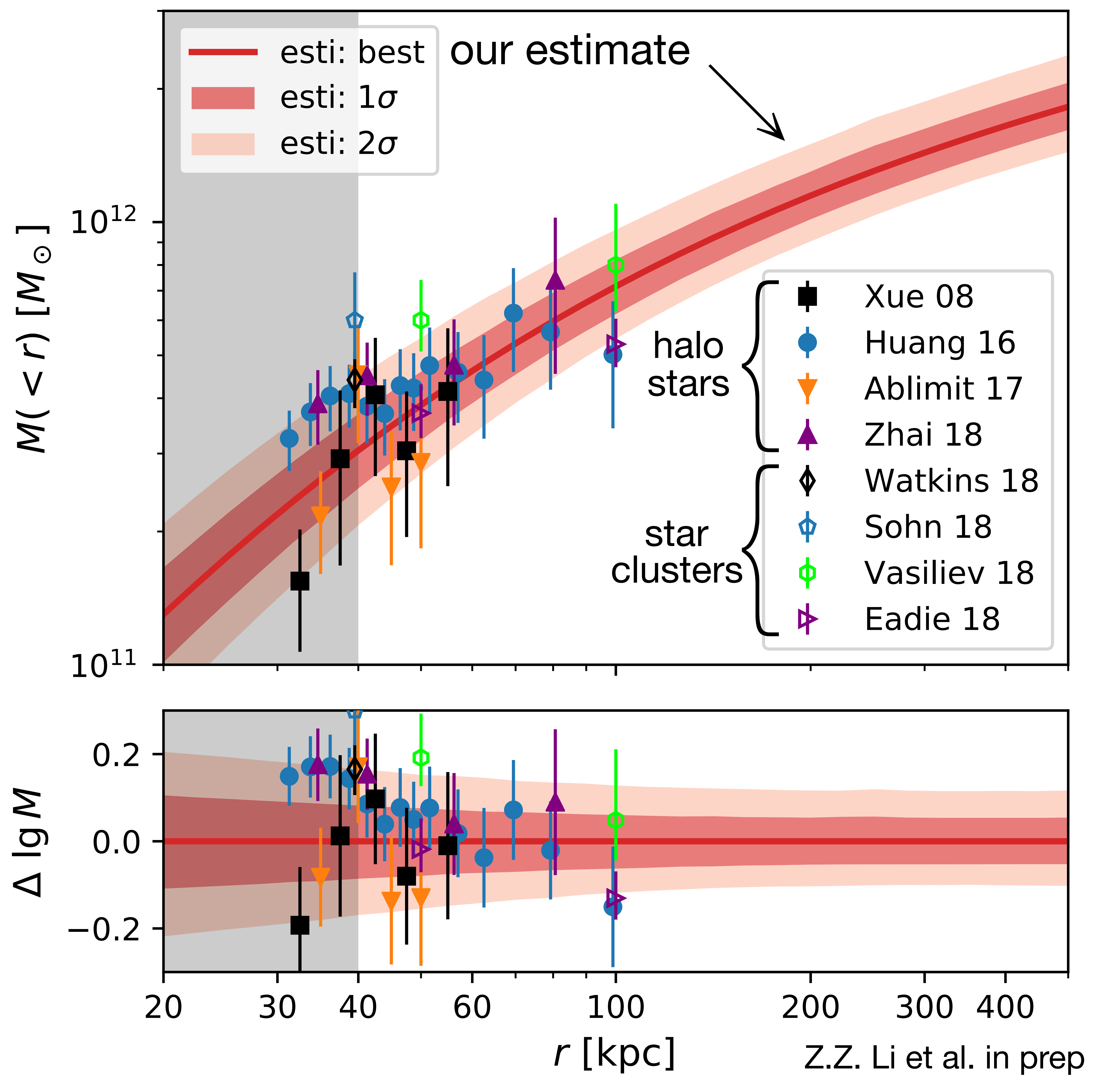
Current best estimation to MW halo mass

DF model based on **Eagle** simulation
28 MW satellites with **Gaia** measurement
⇨ Constrain total halo mass within **20%**

$$M = 1.23^{+0.21}_{-0.18} \times 10^{12} M_\odot$$
$$c = 9.4^{+2.8}_{-2.1}$$



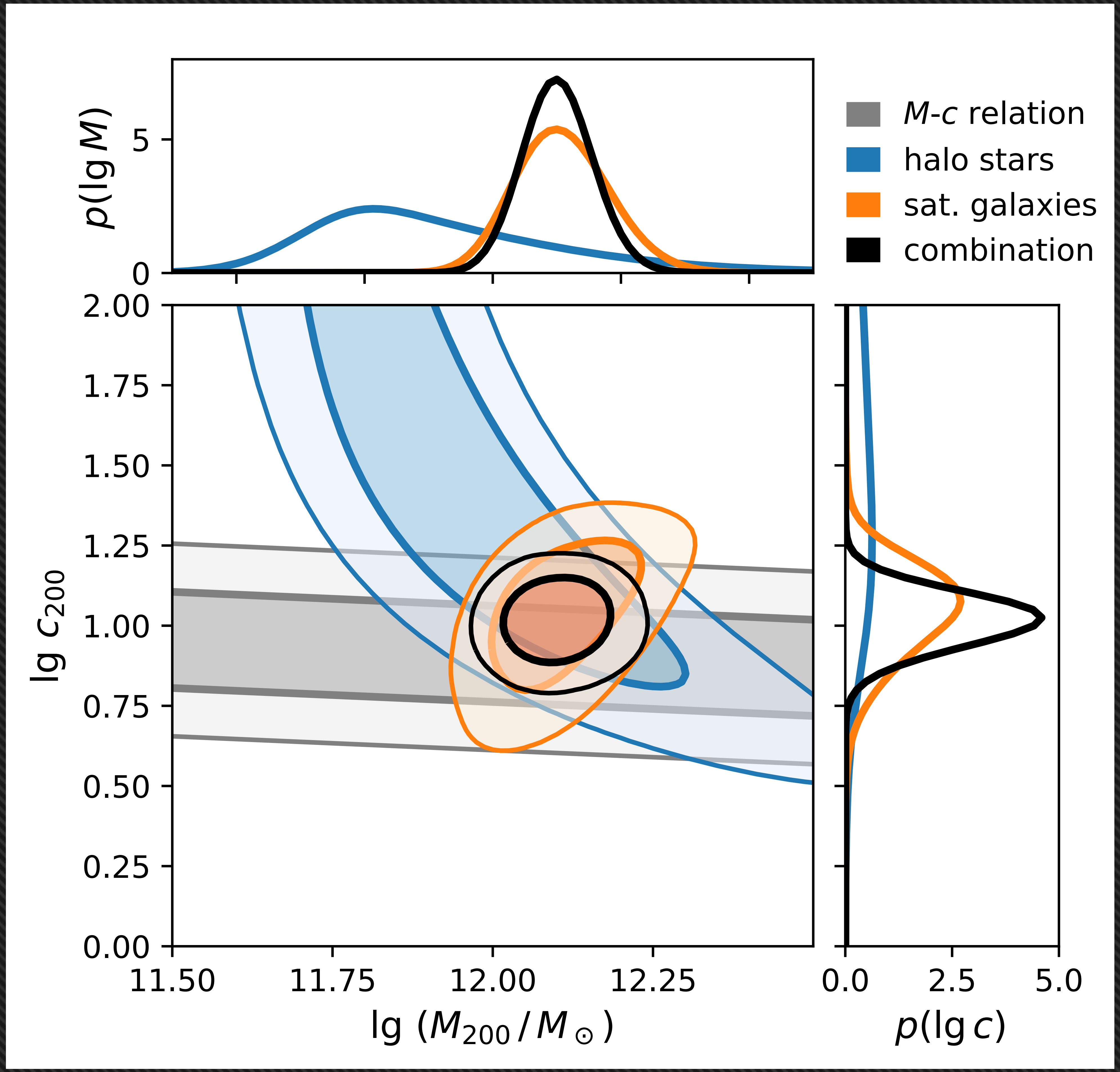
Inferred MW mass profile



Z.Z. Li et al. in prep

Even better: using multiple tracer populations

Satellite Galaxies
⇨ Total halo mass
Satellites + Stars
⇨ Shape of potential



	Satellites		Satellites + Halo Stars	
	flat prior	M-c relat.	flat prior	M-c relat.
M[a]	$1.29^{+0.24}_{-0.20}$	$\mathbf{1.23^{+0.21}_{-0.18}}$	$1.27^{+0.17}_{-0.15}$	$1.26^{+0.17}_{-0.15}$
c	$11.0^{+4.8}_{-3.3}$	$\mathbf{9.4^{+2.8}_{-2.1}}$	$11.7^{+3.2}_{-2.5}$	$10.4^{+2.3}_{-1.9}$

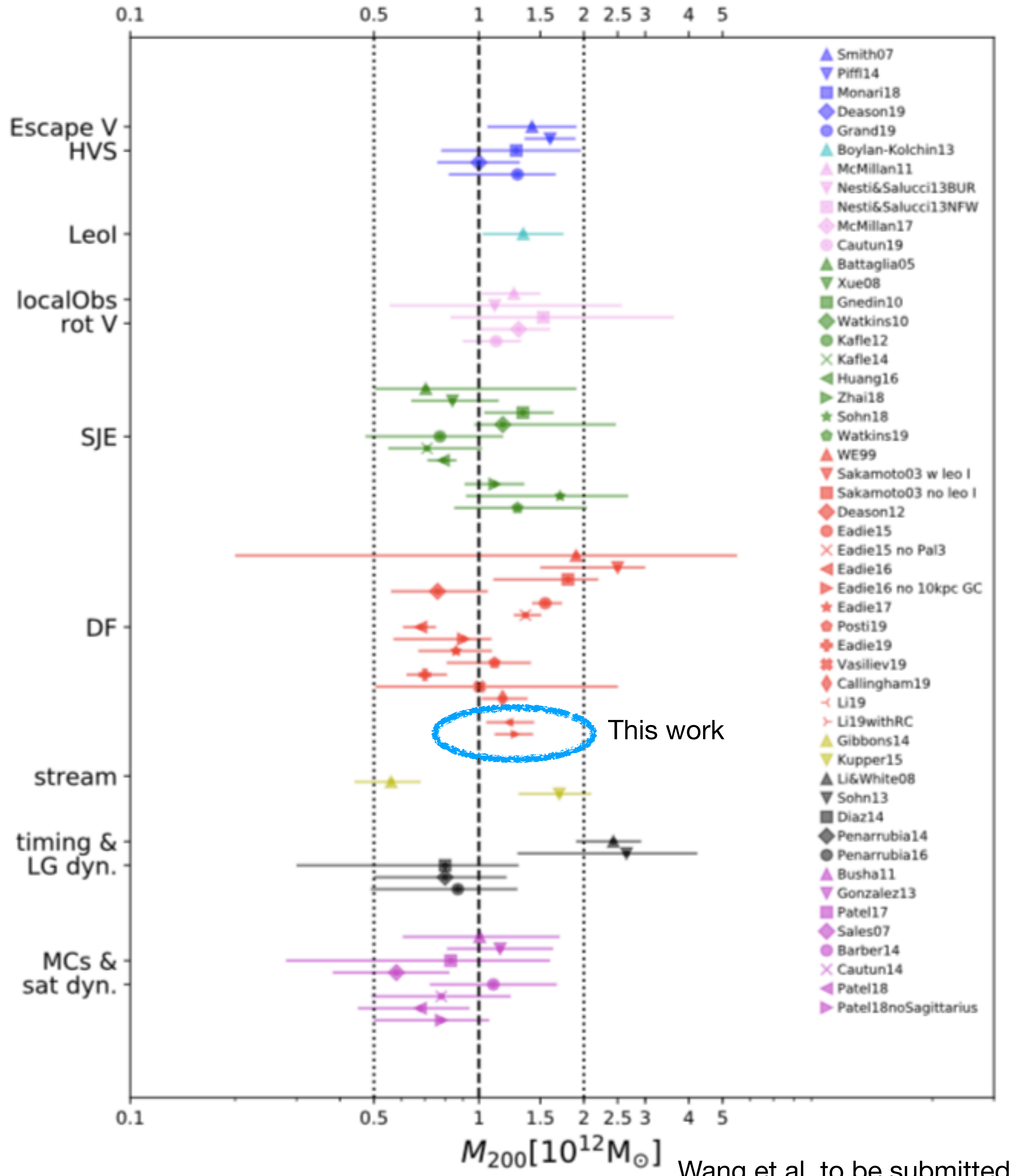
[a] The unit of M is $10^{12} M_\odot$.

M-c relation: Dutton & Macciò 2014

Halo stars: 40 to 80 kpc
Rotation curve measured by Huang+ 2016

Satellites: 40 to 300 kpc

Z.Z. Li et al. in prep

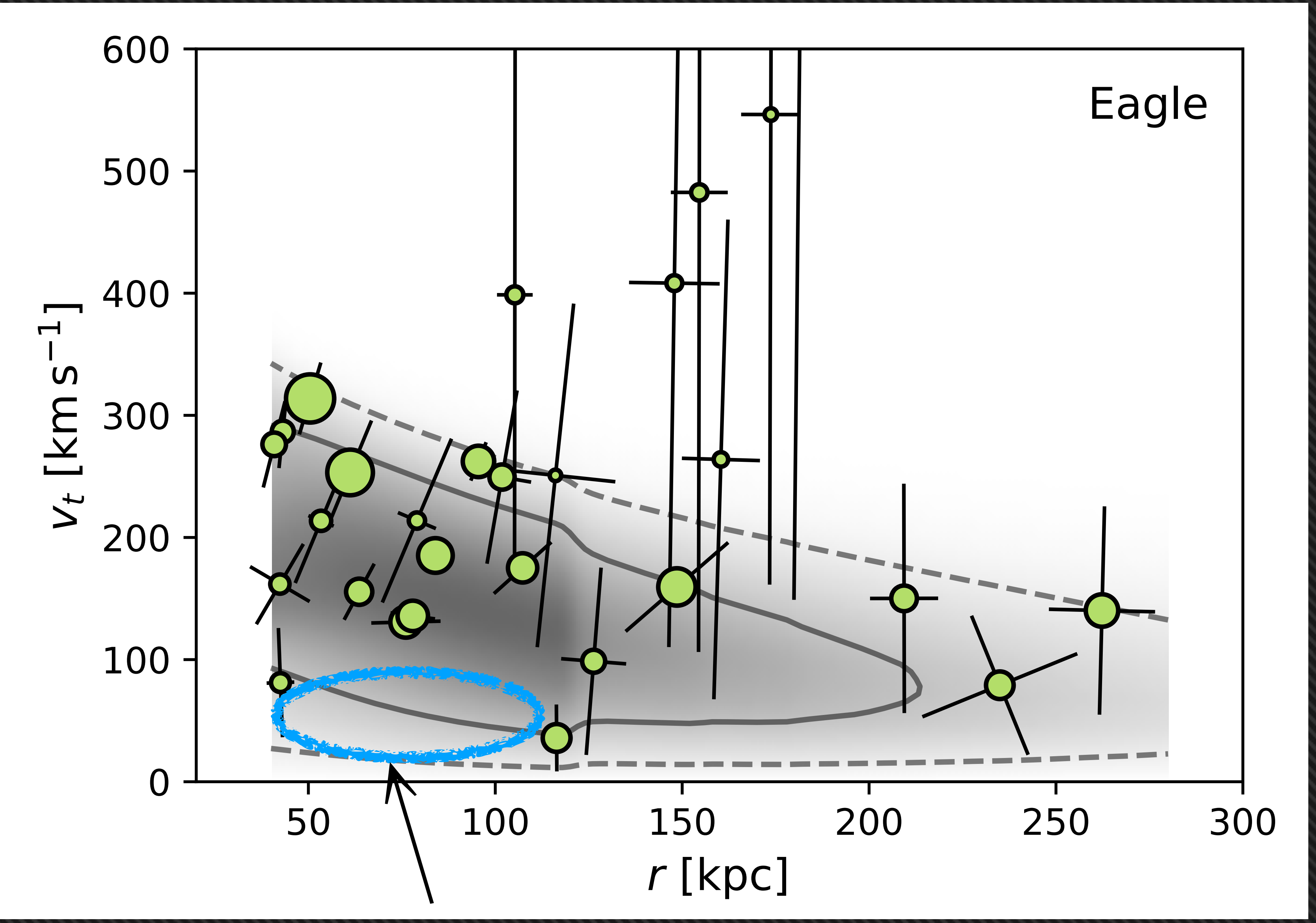


Wang et al. to be submitted

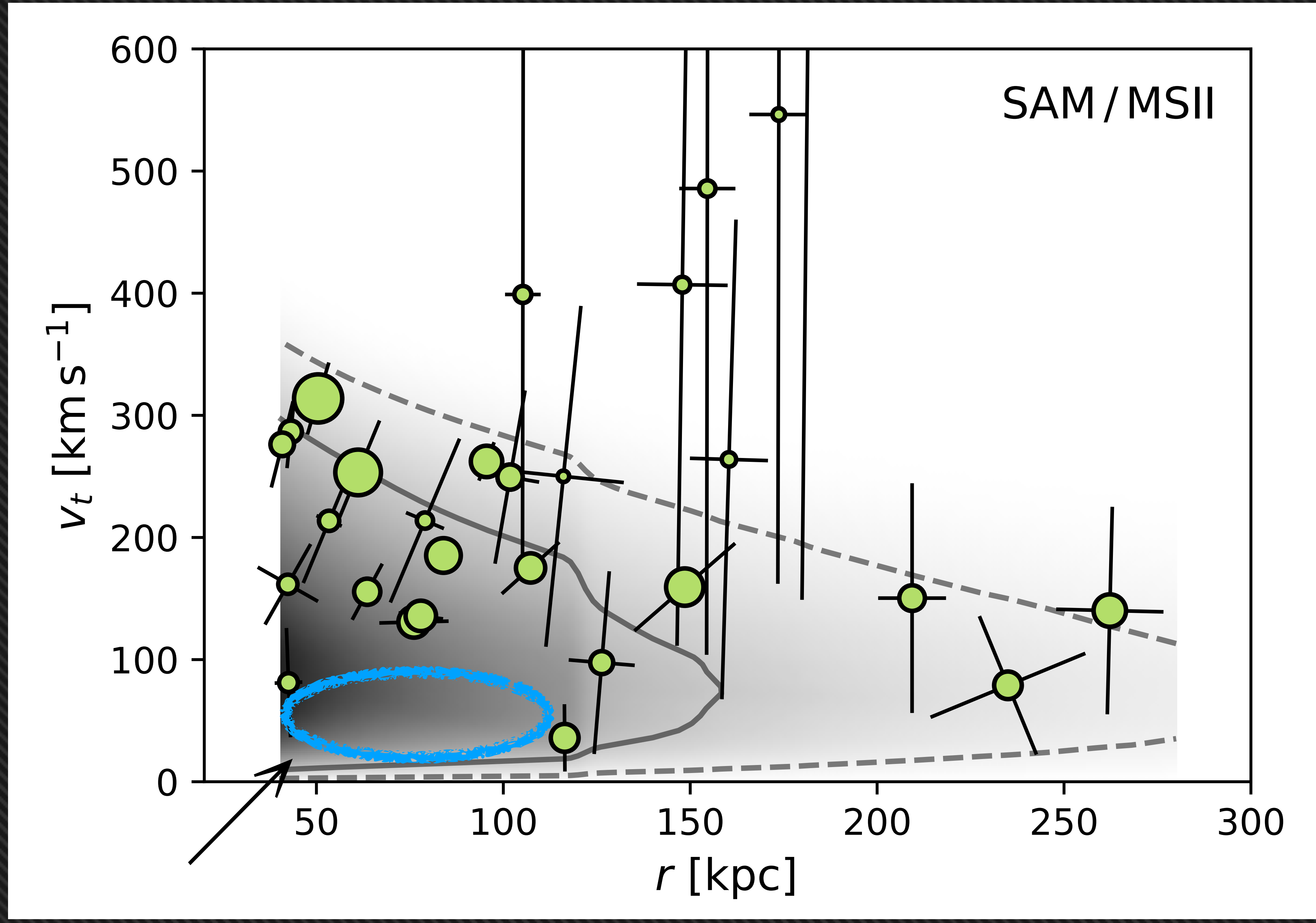
Hydro simulation matches MW satellites better

The Bayesian Evidence of Eagle is 25 times higher than SAM

Hydro simulation



Semi-analytical model on dark simulation



Orbits of small pericenter distance

Enhanced satellite disruption due to stellar disc in hydro and real world

Circles: observed satellites

Shade: expected distribution predicted by DF based on simu.

Z.Z. Li et al. in prep

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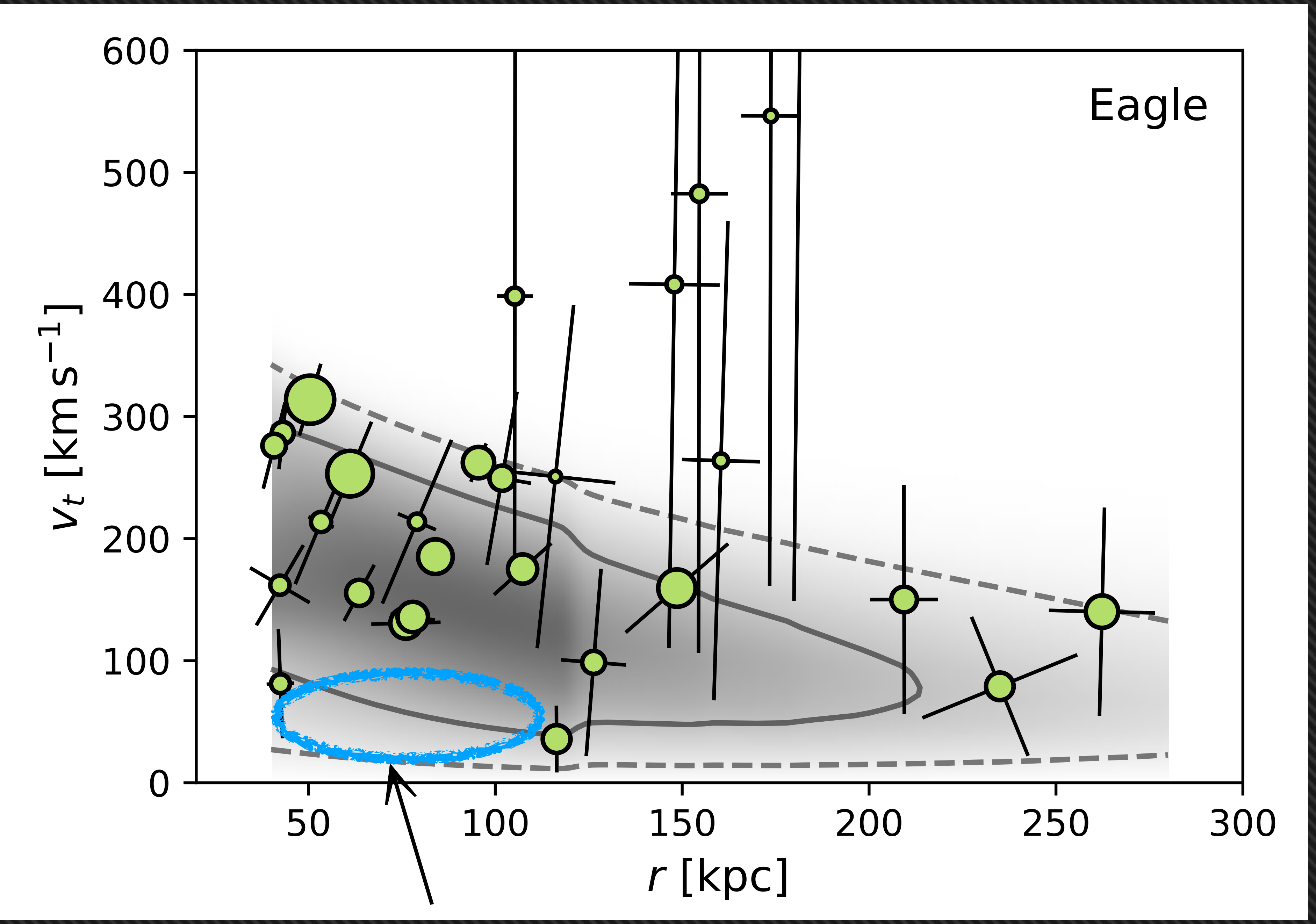

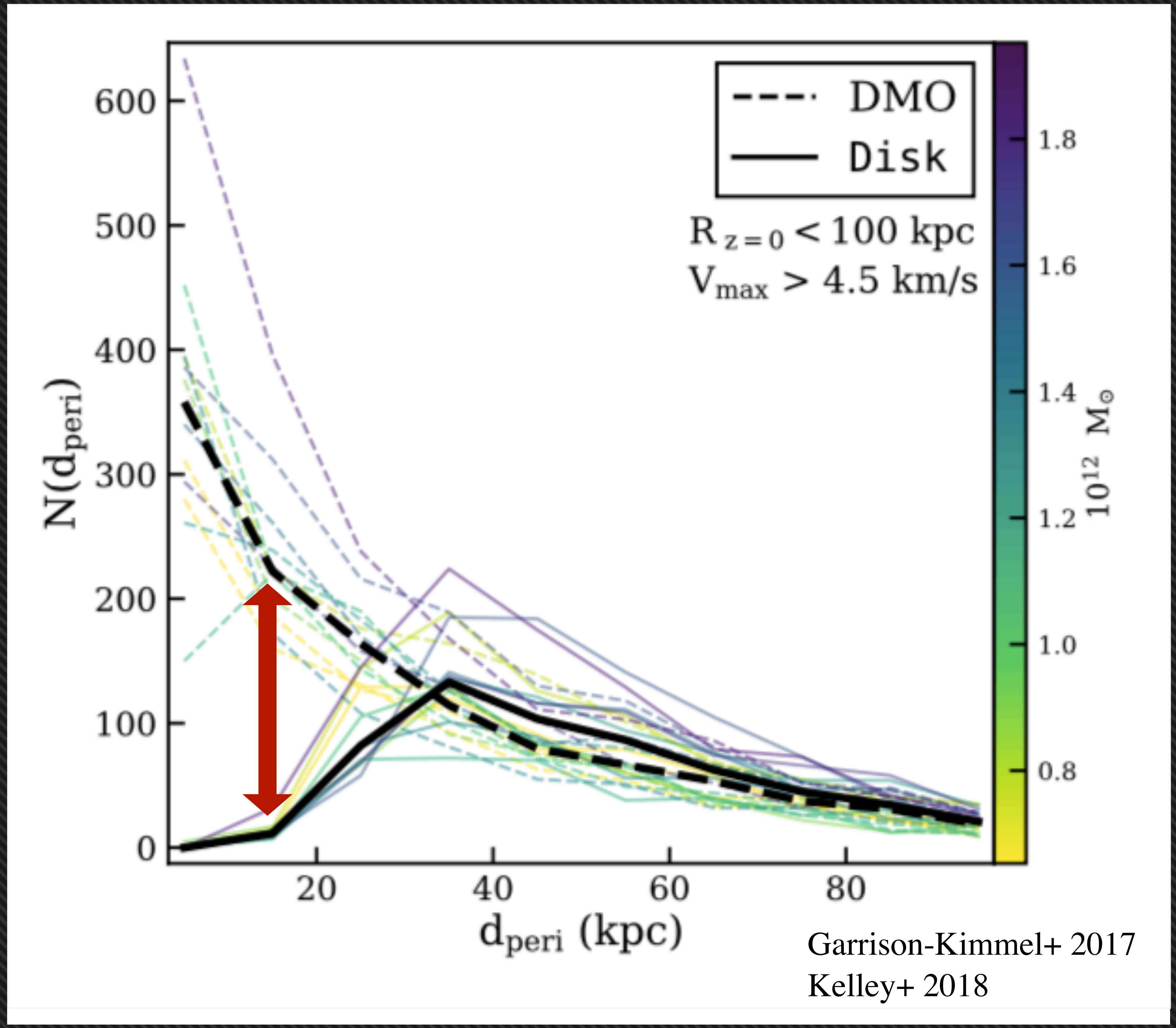

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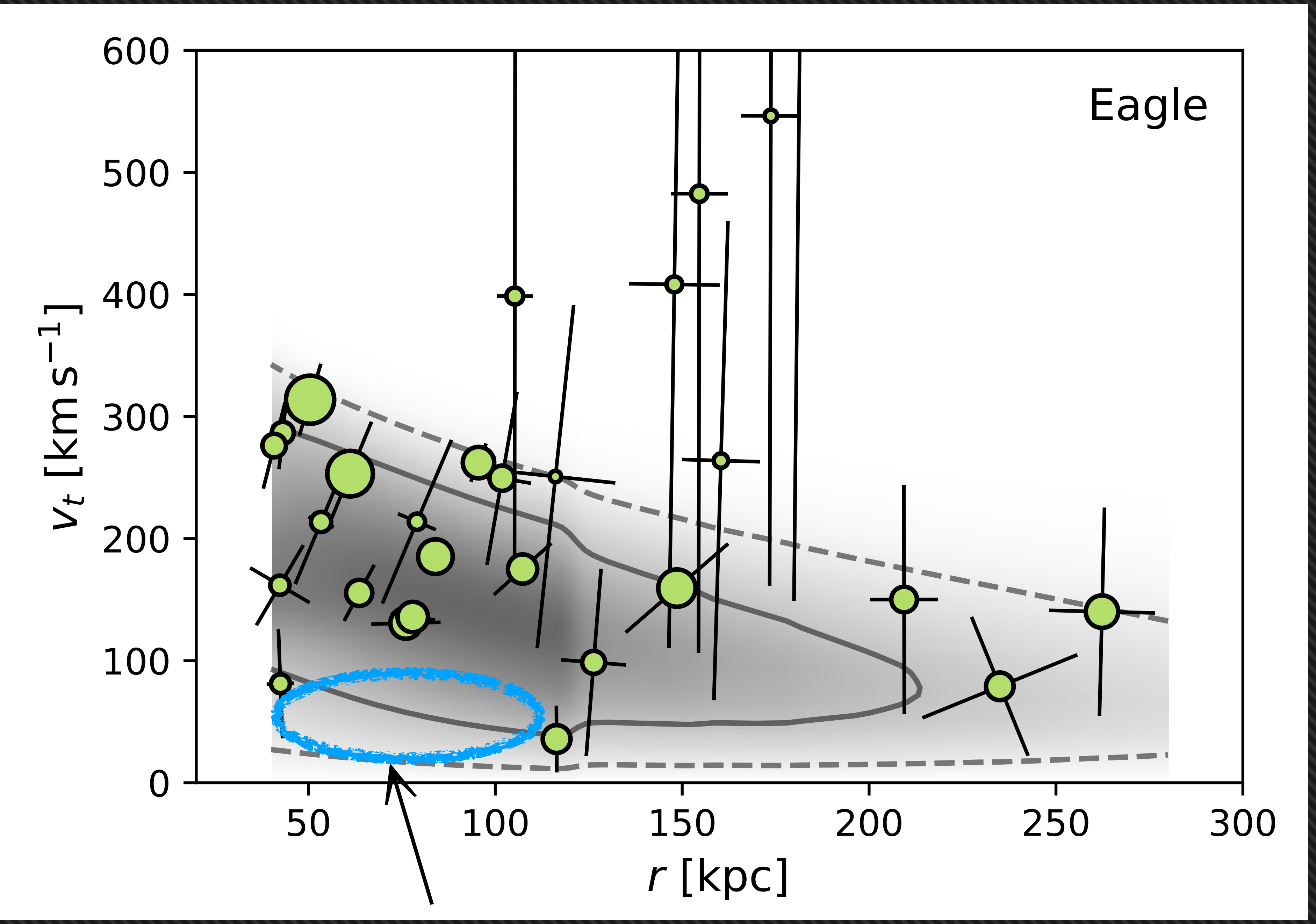
Z.Z. Li et al. in prep

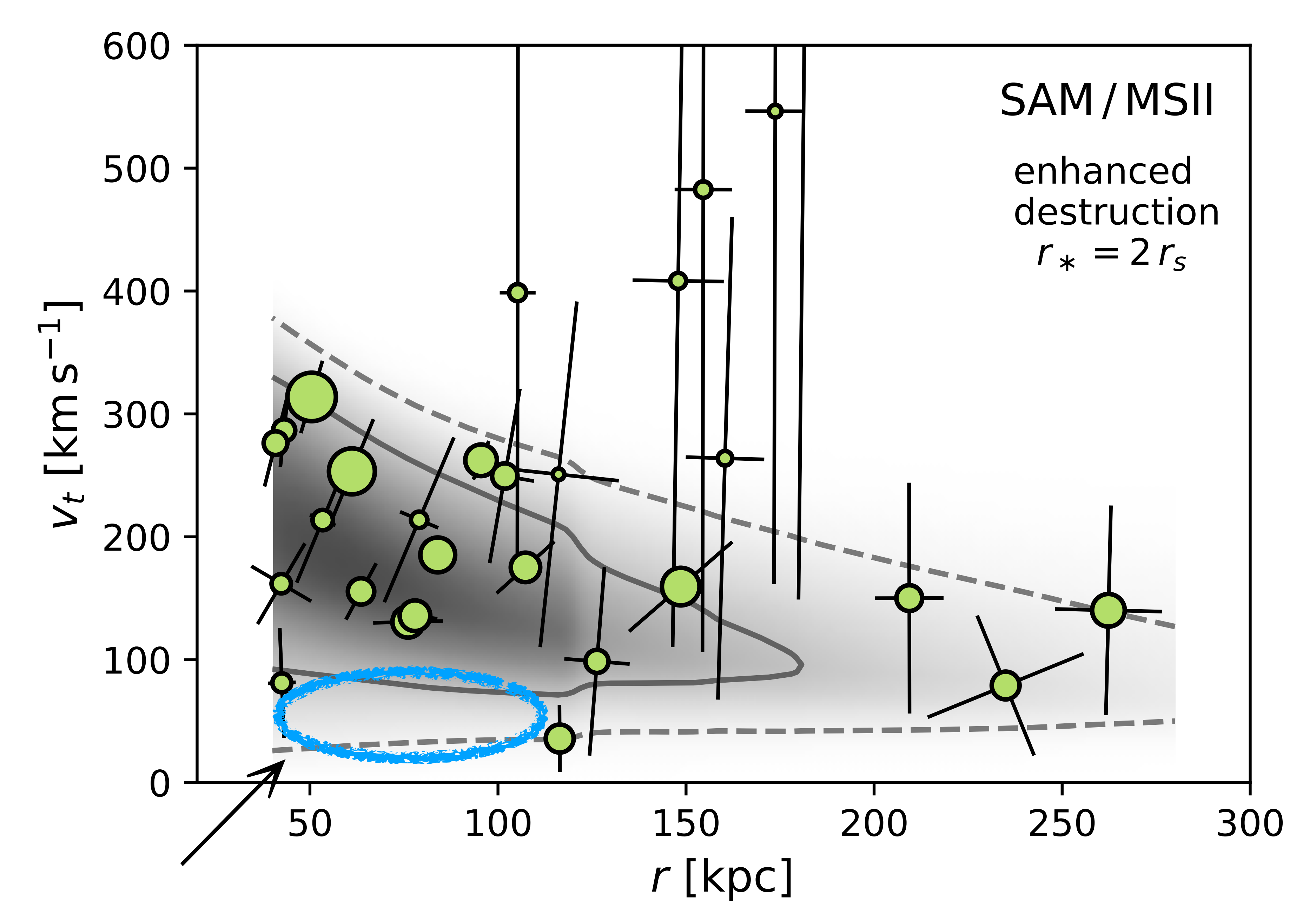
Hydro simulation matches MW satellites better

Mimic the extra disruption by manually remove a fraction of orbits with small d_{peri} in SAM

Hydro simulation



Semi-analytical model on dark simulation with enhanced disruption



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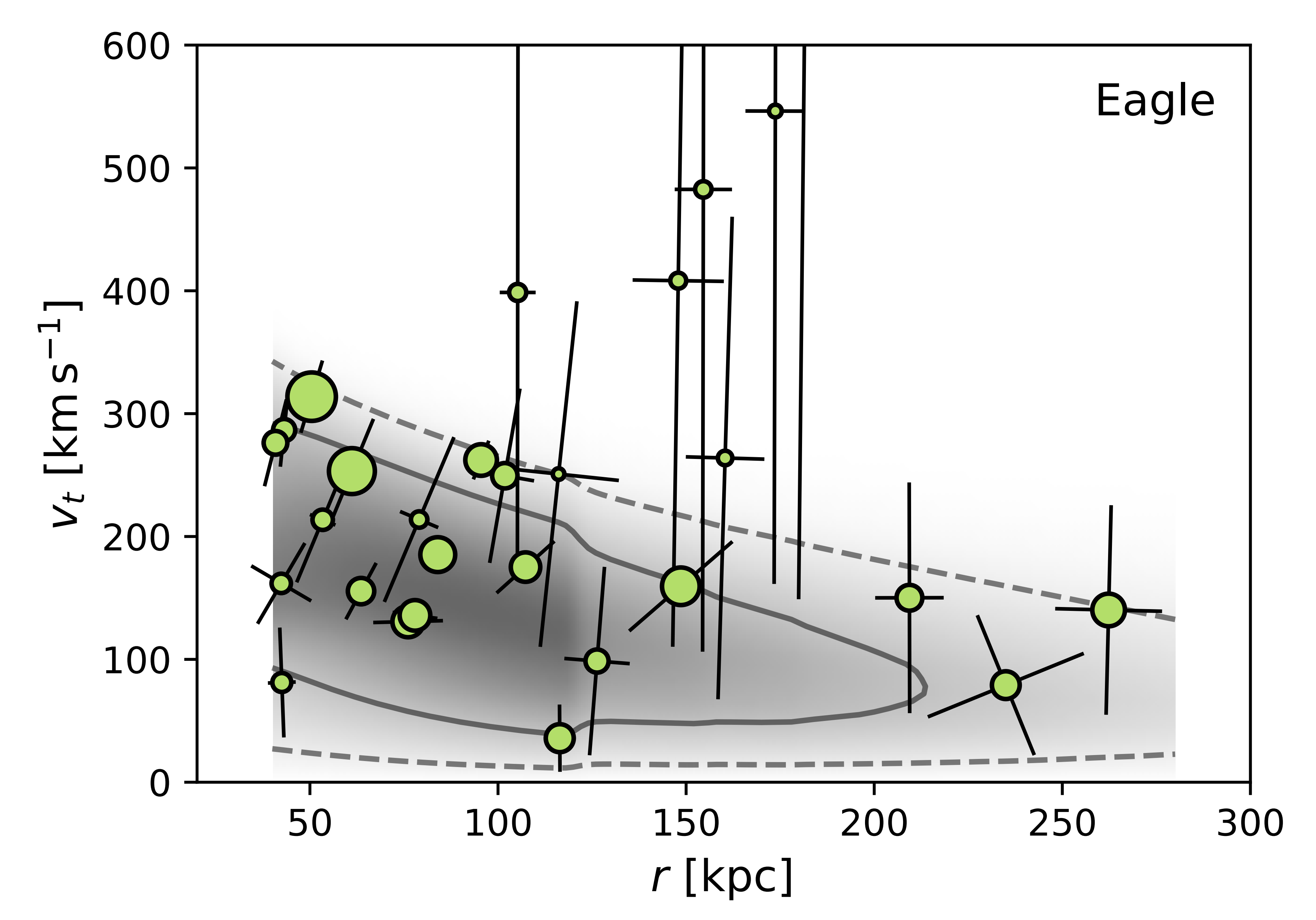
Z.Z. Li et al. in prep

Bonus: reducing uncertainty in satellite orbits

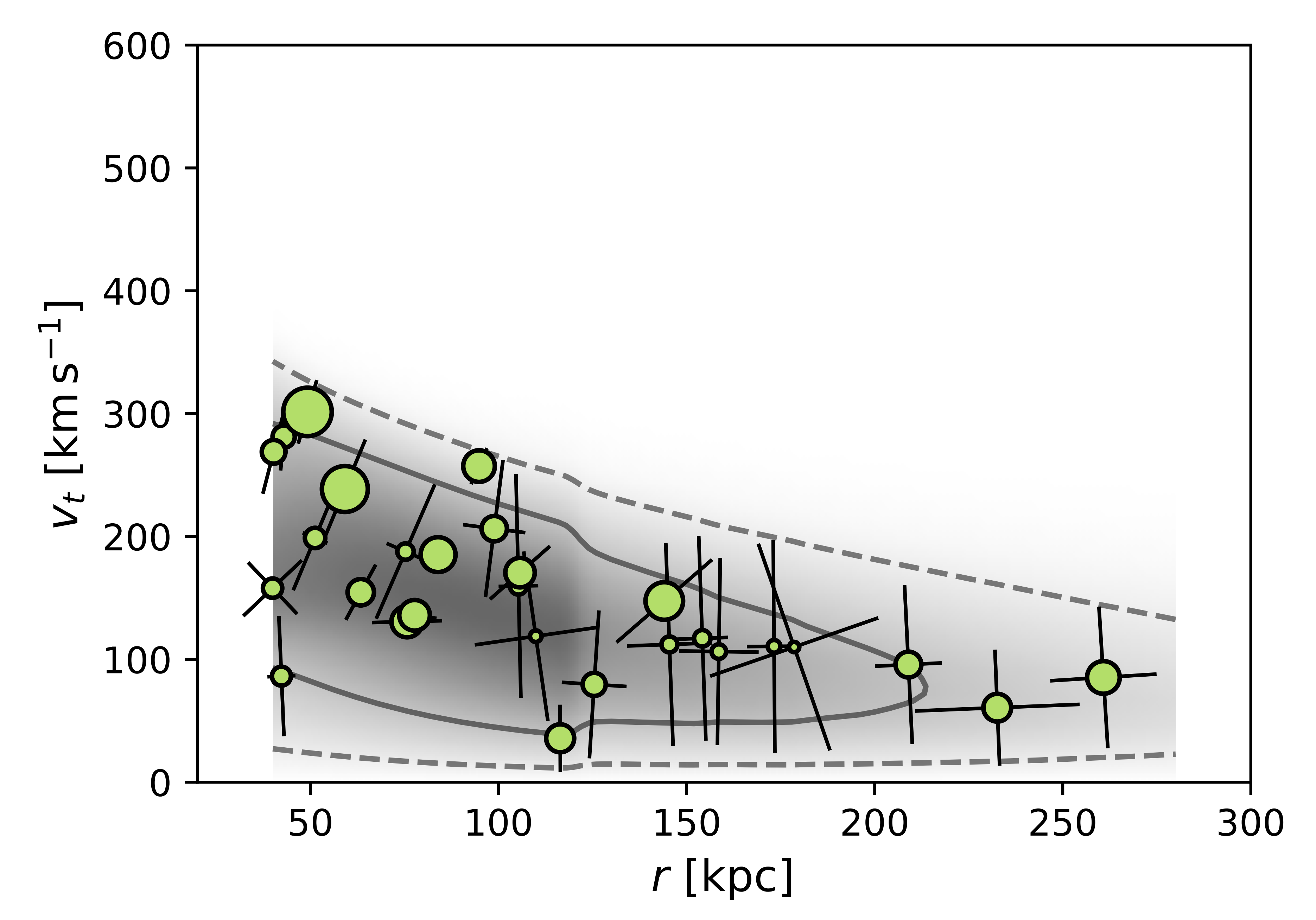
Satellite orbits reveal their infall history and the assembly of MW
The usage is blocked by large uncertainty in proper motion
Using DF model as prior can **reduce the uncertainty** in satellite orbits

Raw measurements



⇨

Posterior kinematics



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Summary and Outlook

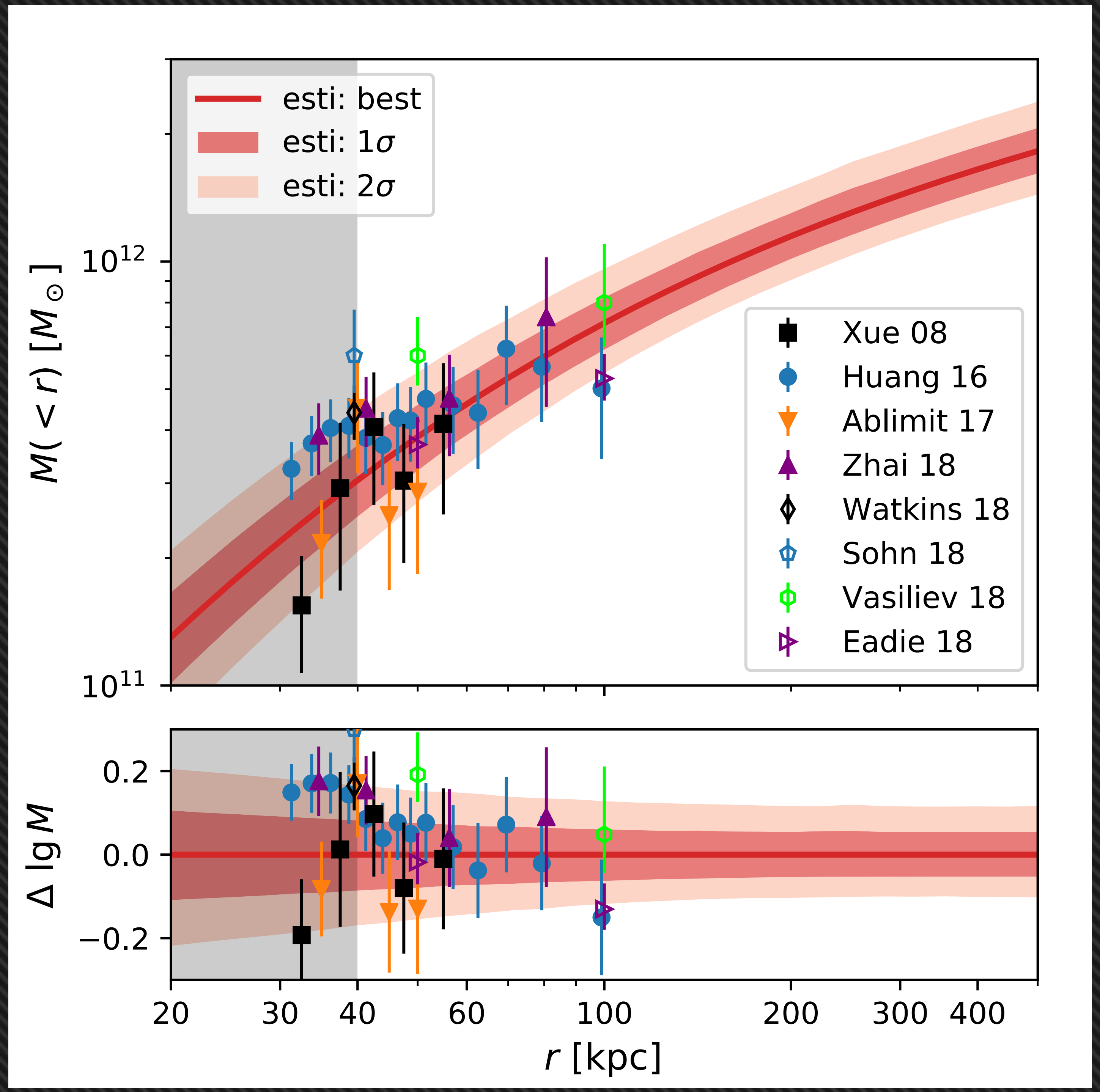
- Current **BEST** estimation to MW halo mass
  - ✓ best **tracer** for outer halo: satellite galaxies
  - ✓ best **data** available: 28 satellites with *Gaia* DR2 proper motion
  - ✓ realistic **model**: physical DF from simulation → wide usage
  - ✓ rigorous **statistics**: Bayes for selection function, observational error

    Li et al. 2017 ApJ, 850, 116
    Li et al. 2019 arxiv:1910.11257
    Li et al. 2019 in prep, coming soon!

$$M = 1.23^{+0.21}_{-0.18} \times 10^{12} M_\odot$$

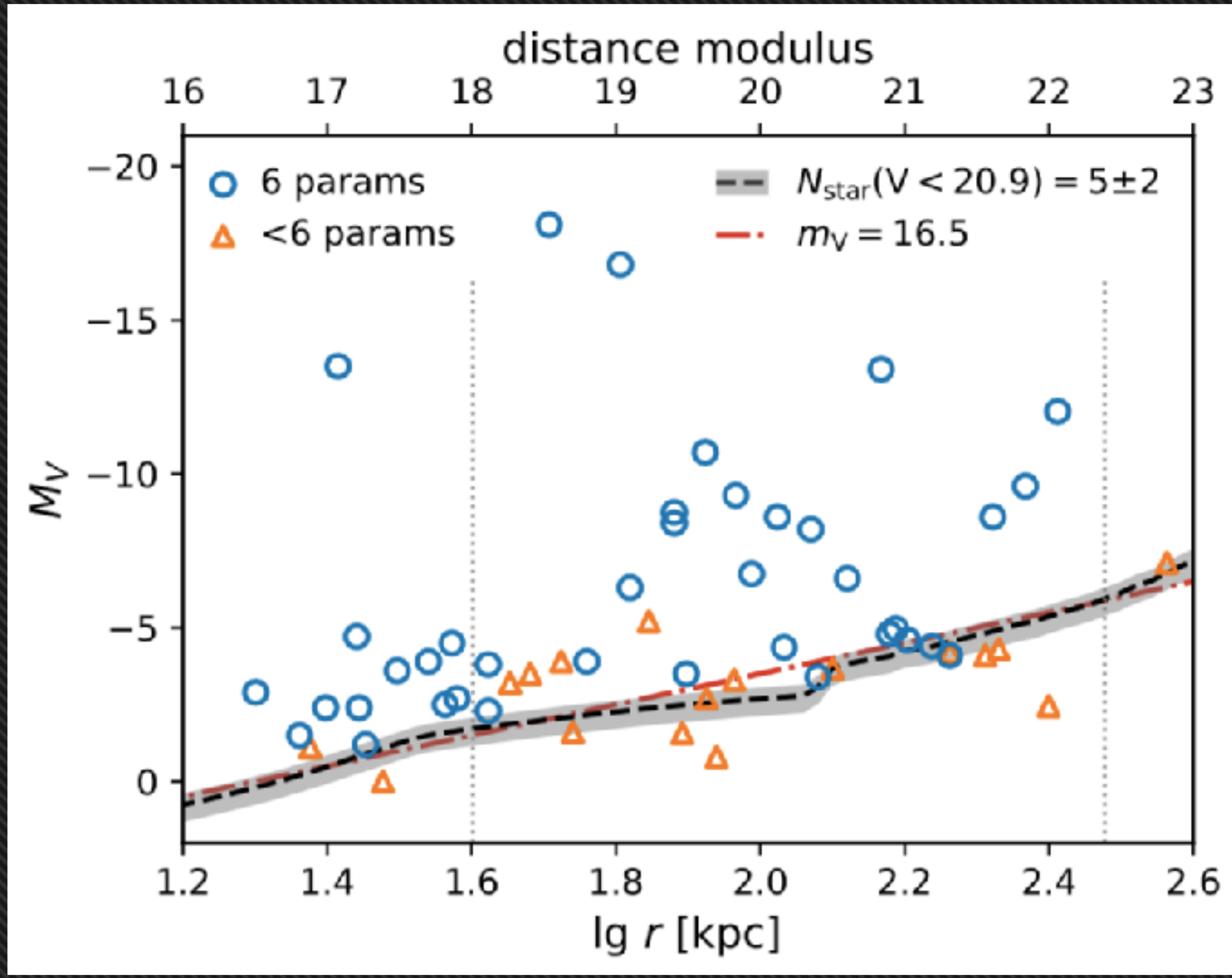
$$c = 9.4^{+2.8}_{-2.1}$$

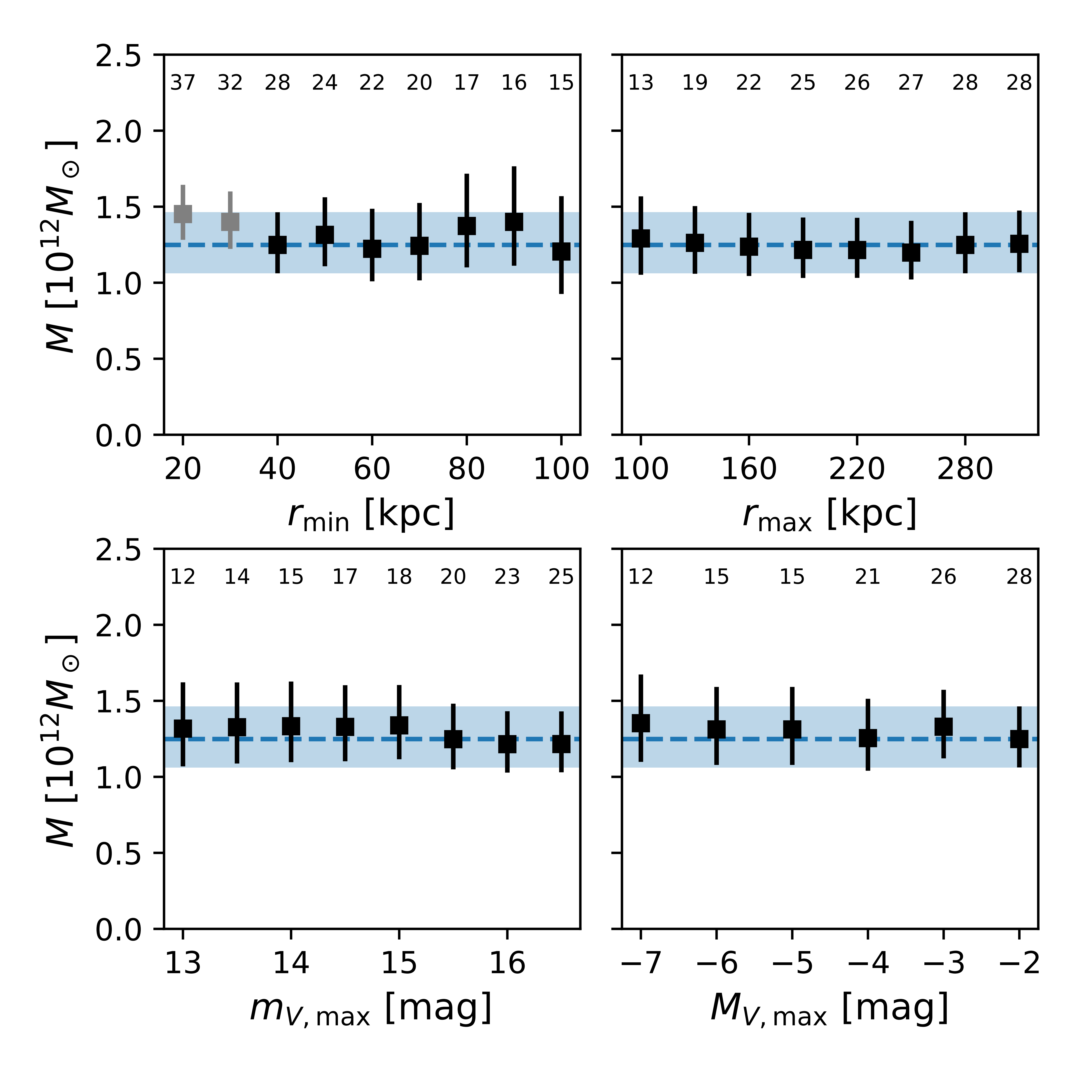
- Hydro simulations indeed match satellite dynamics better
- Future improvements in MW mass
  - more satellites
  - combination with other tracers (e.g. halo stars, star clusters)
  - peculiarities of MW and its history
- The DF construction method can apply to other tracers or galaxy groups & clusters



Supplements

Varying satellite sample selection





The mass estimation is robust against various sample selection criteria

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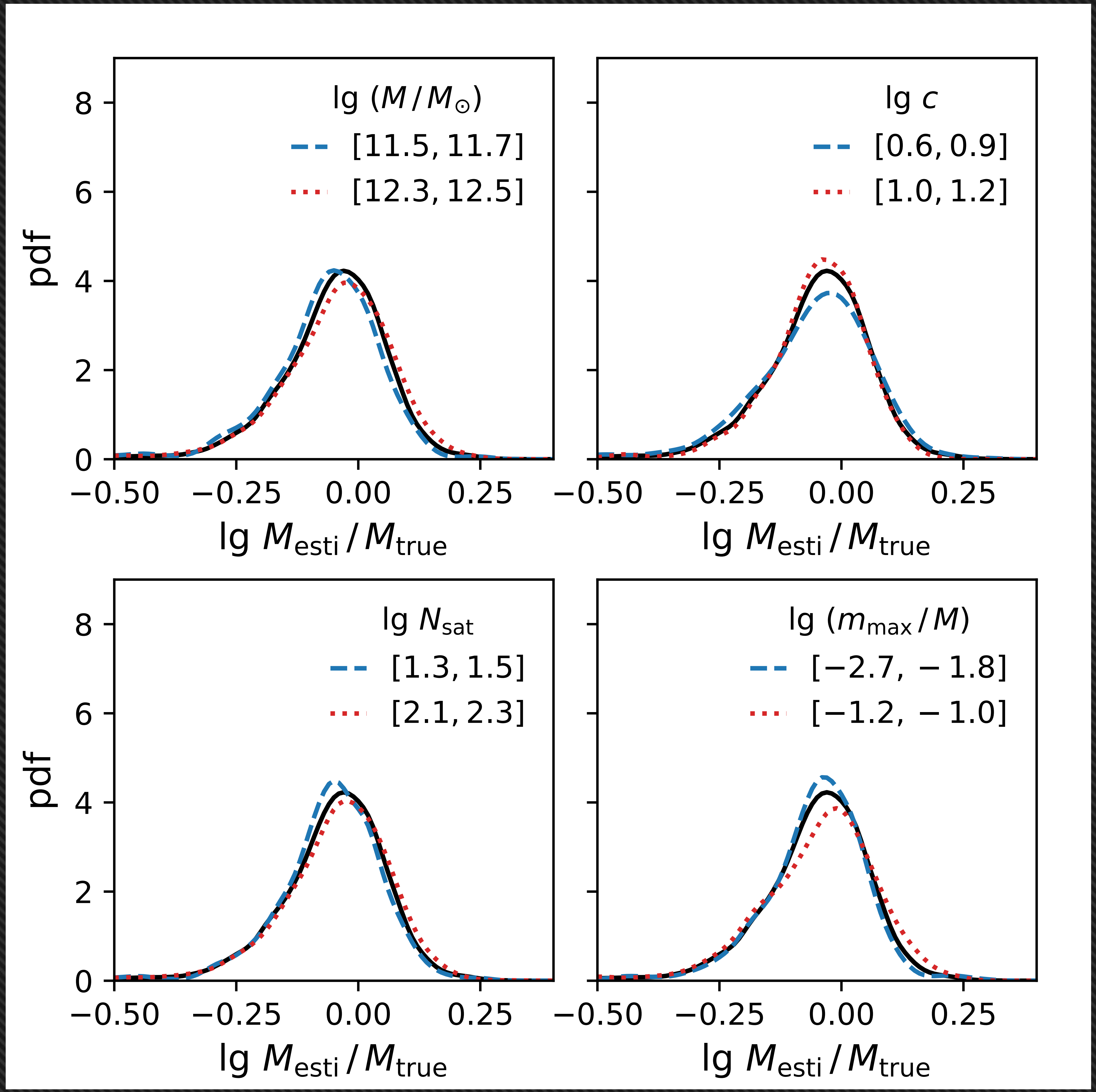
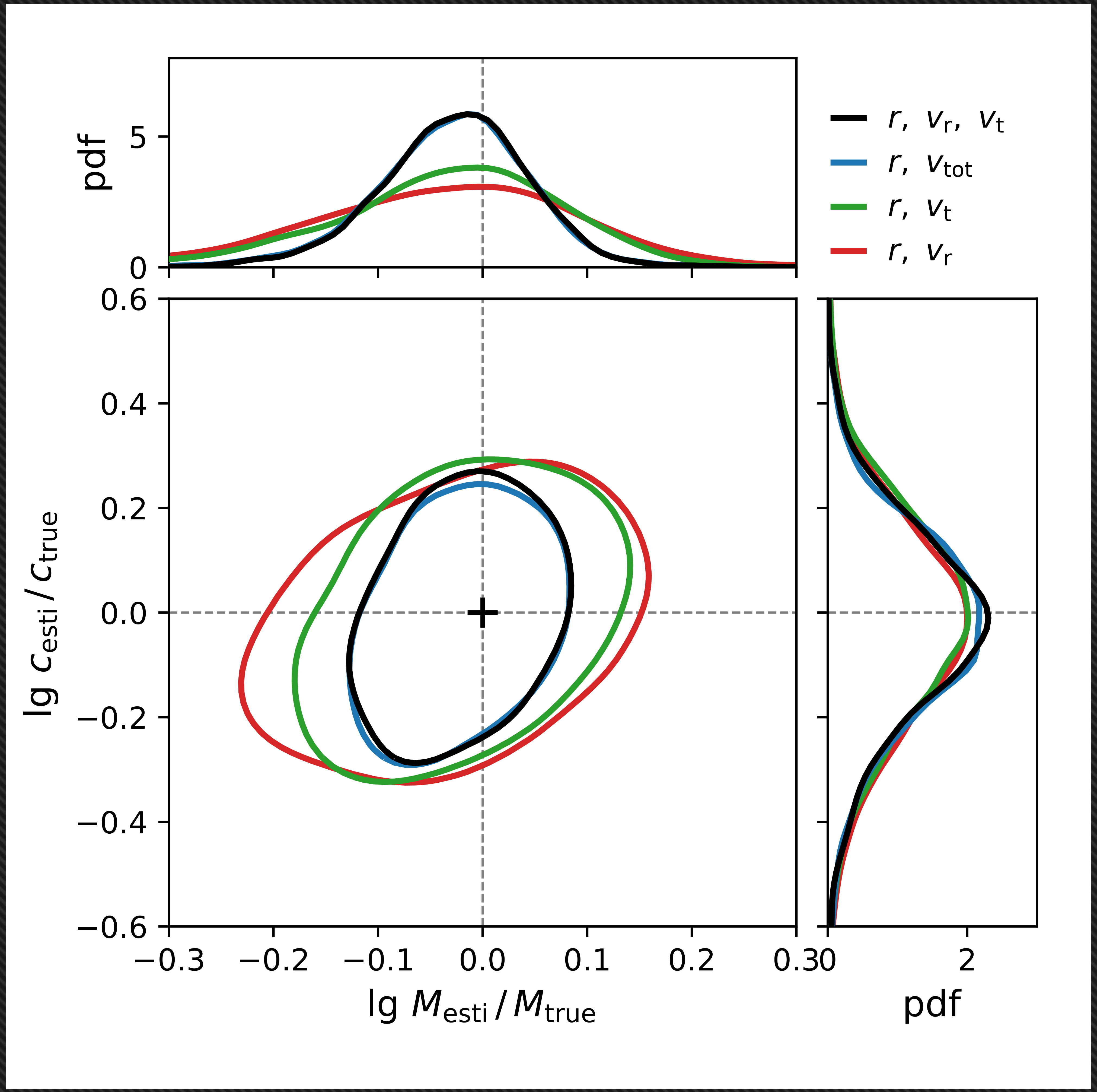
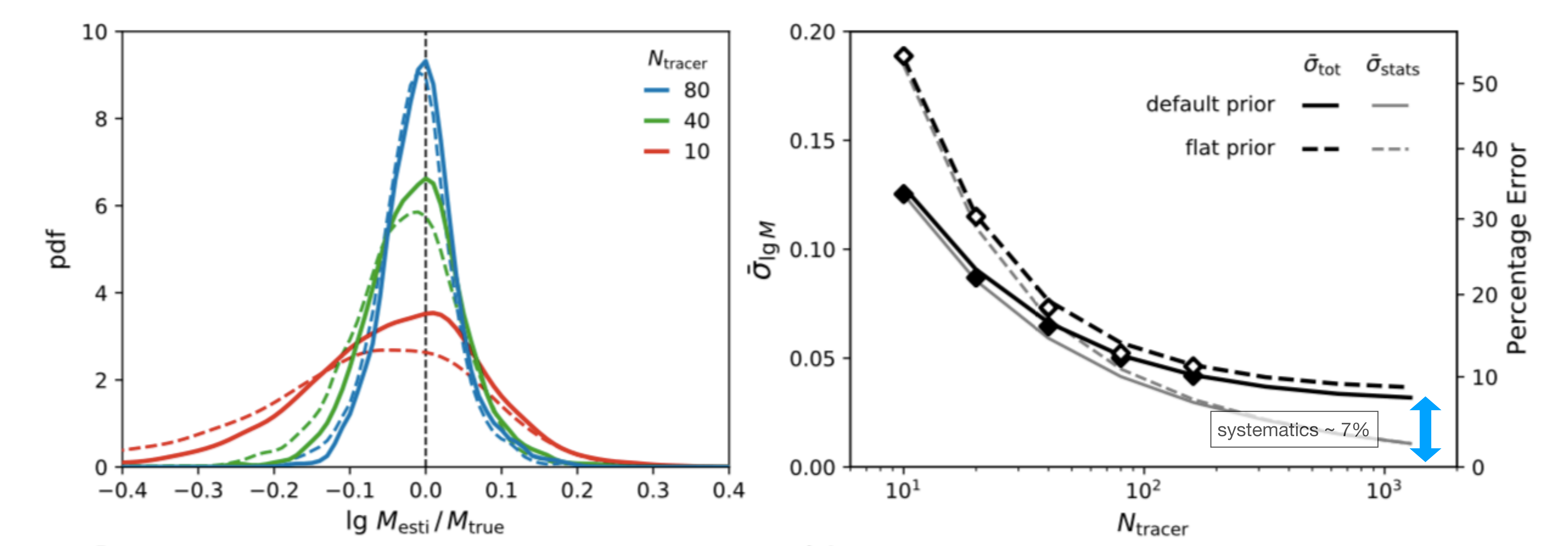

pdf
lg $(M/M_\odot)$
[11.5, 11.7]
[12.3, 12.5]
lg c
[0.6, 0.9]
[1.0, 1.2]
lg N_{sat}
[1.3, 1.5]
[2.1, 2.3]
lg (m_{max}/M)
[−2.7, −1.8]
[−1.2, −1.0]
lg M_{esti}/M_{true}


pdf
$r,\ v_r,\ v_t$
$r,\ v_{tot}$
$r,\ v_t$
$r,\ v_r$
lg c_{esti}/c_{true}
lg M_{esti}/M_{true}

General performance with mock sample

Varying the number of tracers

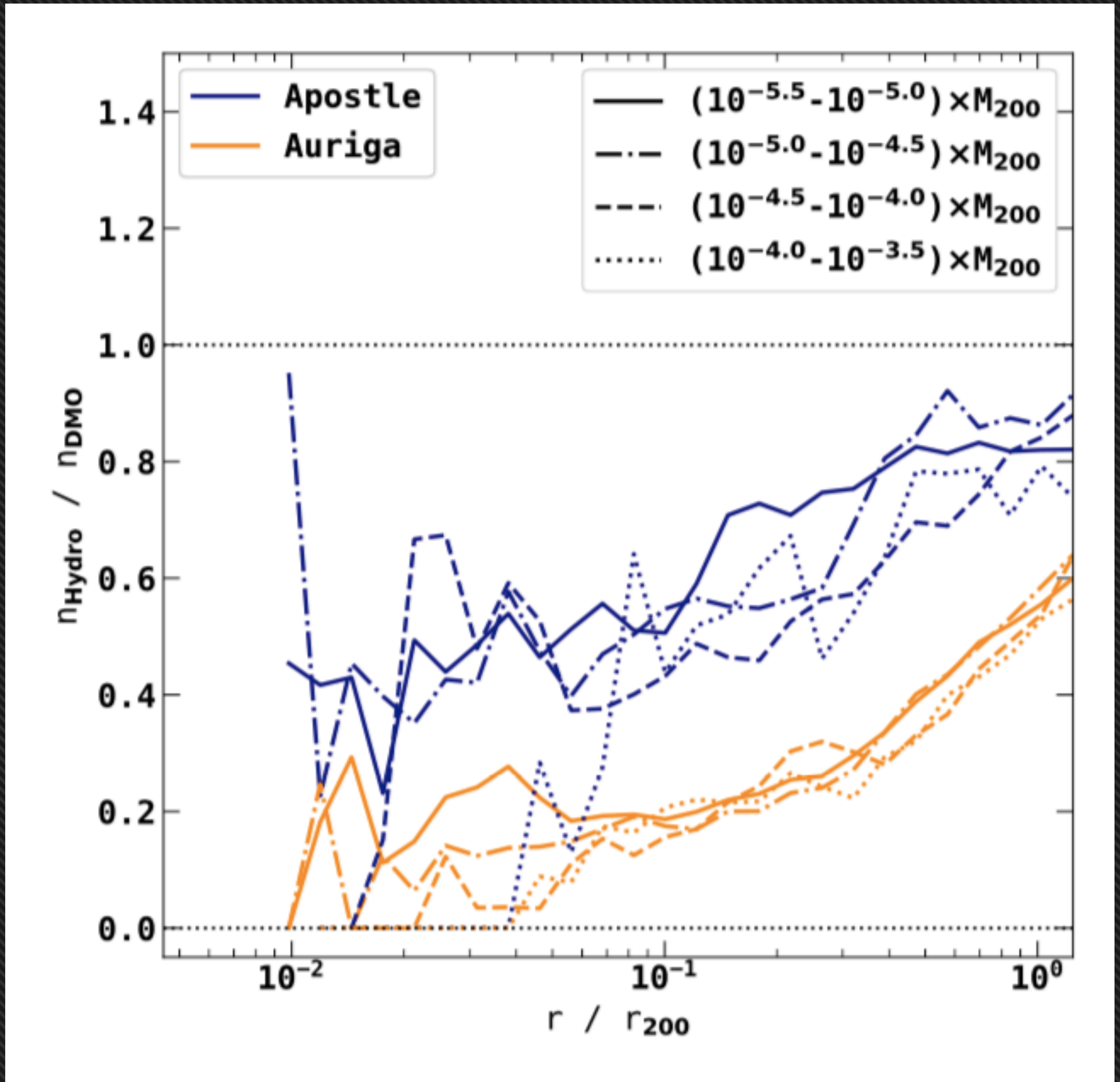
Mass



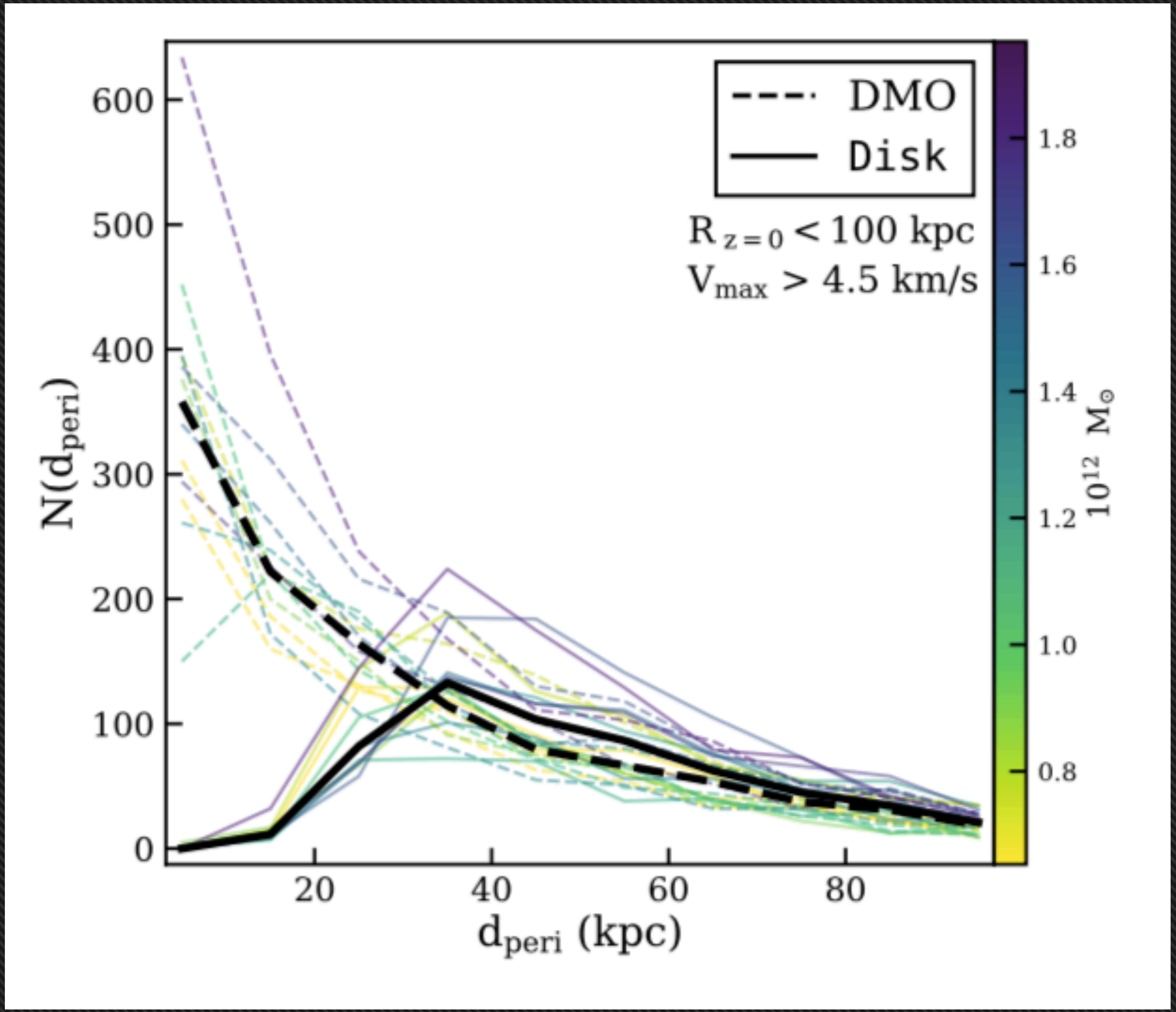
- Unbiased
- Low systematics (<10%)
  negligible comparing to current
  statistical uncertainty level

Z.Z. Li et al. 2019

Enhanced satellite disruption due to stellar disc in hydro simulations



Richings 2018



Garrison-Kimmel 2017, Kelley 2018