Galactic Total Mass: The big unknown?

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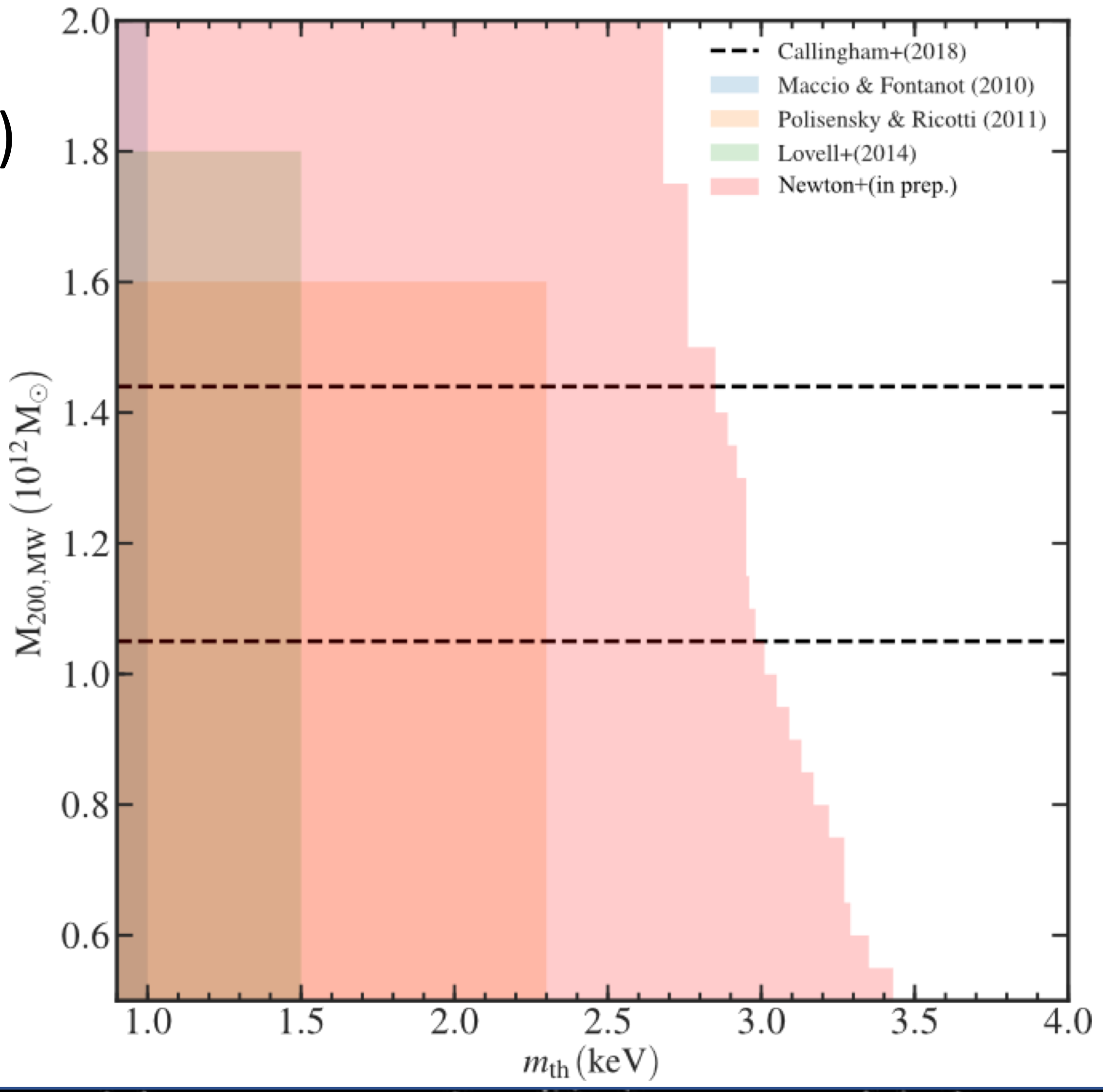
THE ROYAL SOCIETY

Why the Mass of the MW matters?

- Fundamental parameter.
- (Think of the poor simulators)
- Degree of freedom in most Galactic measurements.

- Nature of dark matter.
- Near-field cosmology.



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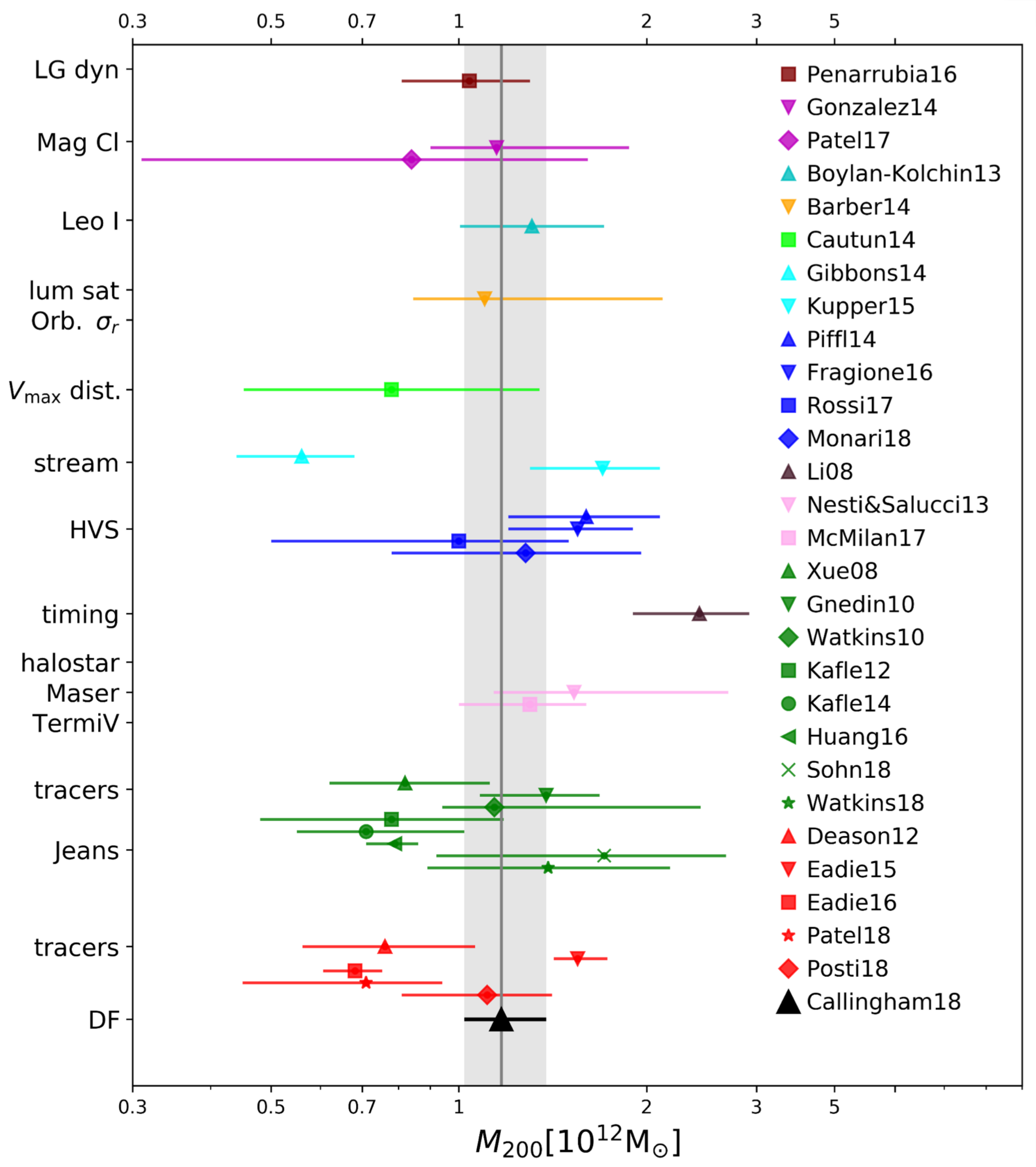
Previous Literature

- Many methods: timing argument, high velocity stars, baryon fraction…
- Infer DM halo properties through observable dynamical tracers.

$$M_{200}^{MW} \approx [0.5{,}2]\times\mathbf{10^{12}}\boldsymbol{M_\odot}$$

- Underestimated systematic errors, untested methods, noisy data, missing data…
- **But now we have *Gaia*!**



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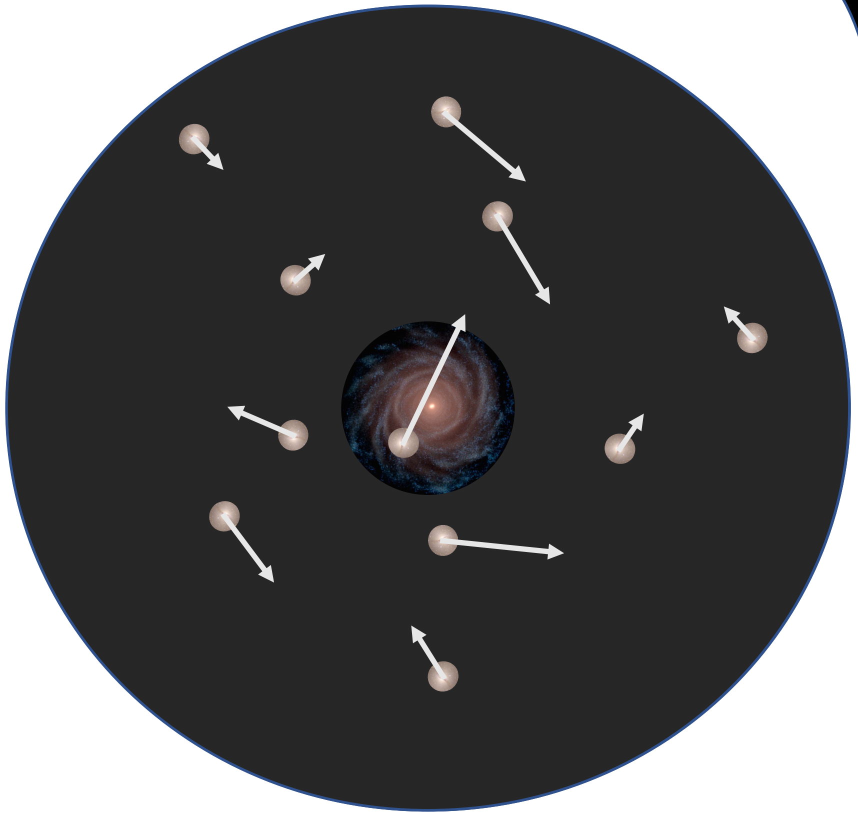
Satellite Dynamics

- Compare observed satellite dynamics to sample from EAGLE simulations.
- *HST+Gaia* observations of classical Satellites with 6D Phase Space.
- **Callingham**, Cautun, Deason + (2019)
- Observe (r, v, v_t)



$$(r, v, v_t) \longrightarrow (E, L)$$

NFW+ (M_{200}, C)

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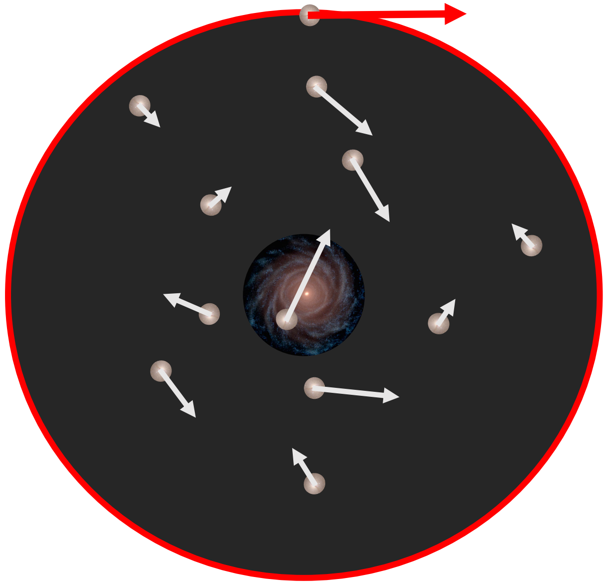
Mass Scaling

- Galaxies are approximately self similar, scaling with mass (e.g. Li+ 2017).
- Dynamics of the Satellites scales with mass.

$$(r, v, v_t) \propto (M_{200})^{1/3}$$

$$(E, L) \propto (M_{200})^{2/3}$$



$$E_0 = \frac{GM_{200}}{R_{200}}$$

$$L_0 = \sqrt{GM_{200}R_{200}}$$

Characteristic circular values

$$(\tilde{E}, \tilde{L}) = \left(\frac{E}{E_0}, \frac{L}{L_0}\right)$$

Independent of M_{200}

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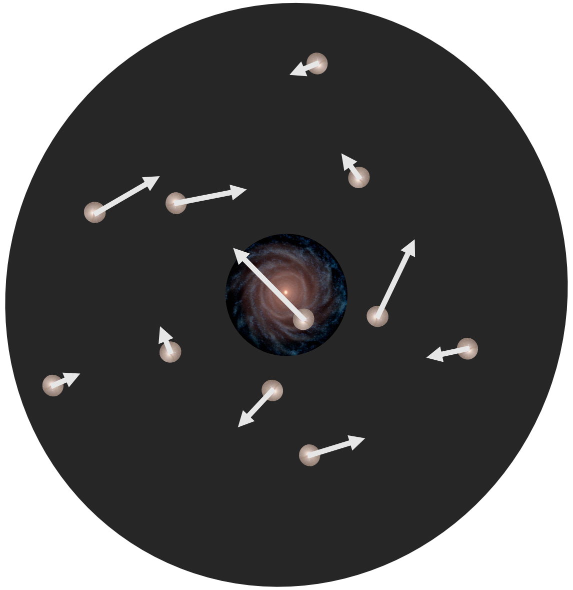
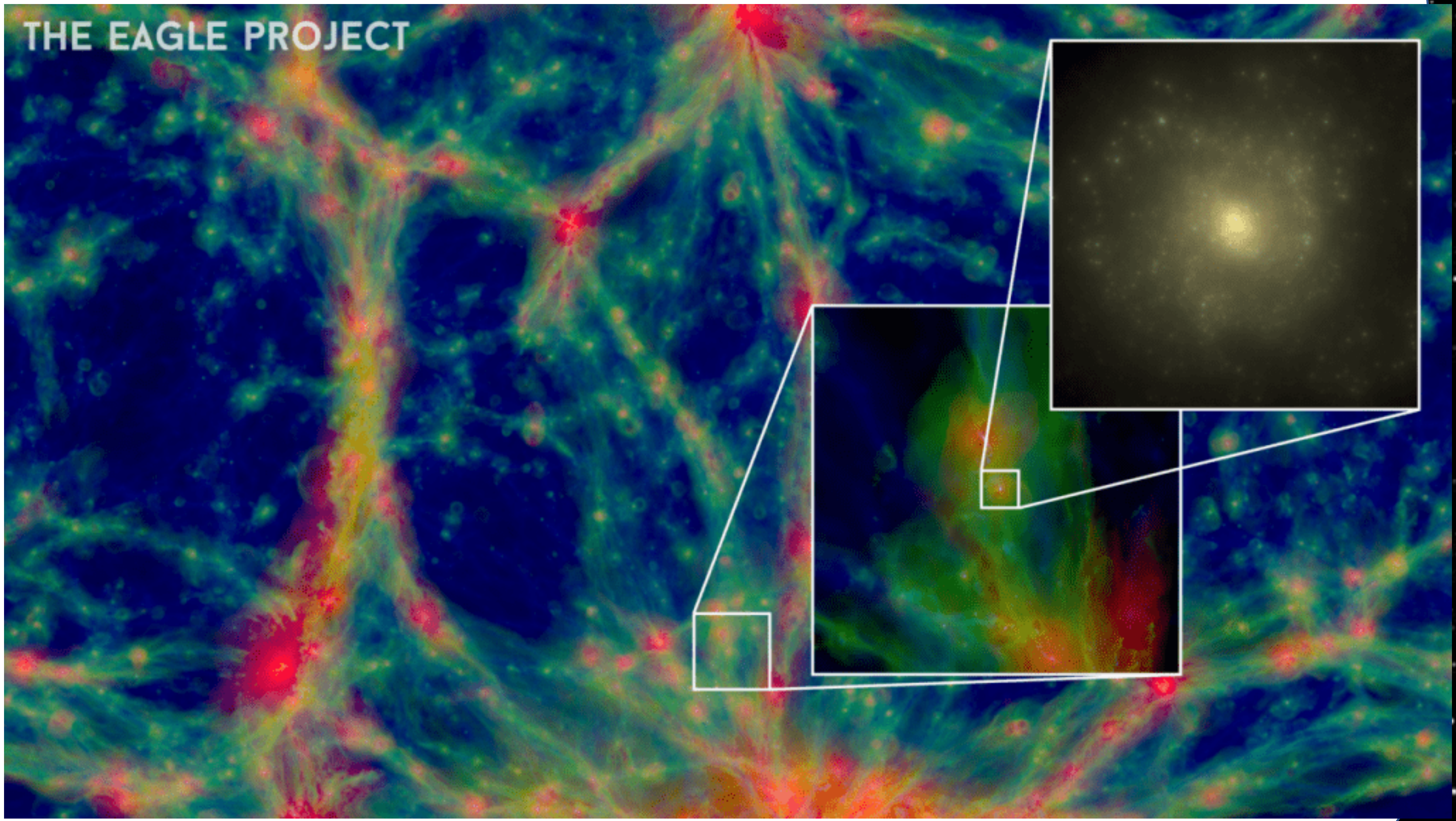
Callingham, Cautun, Deason+ (2019)

EAGLE simulations

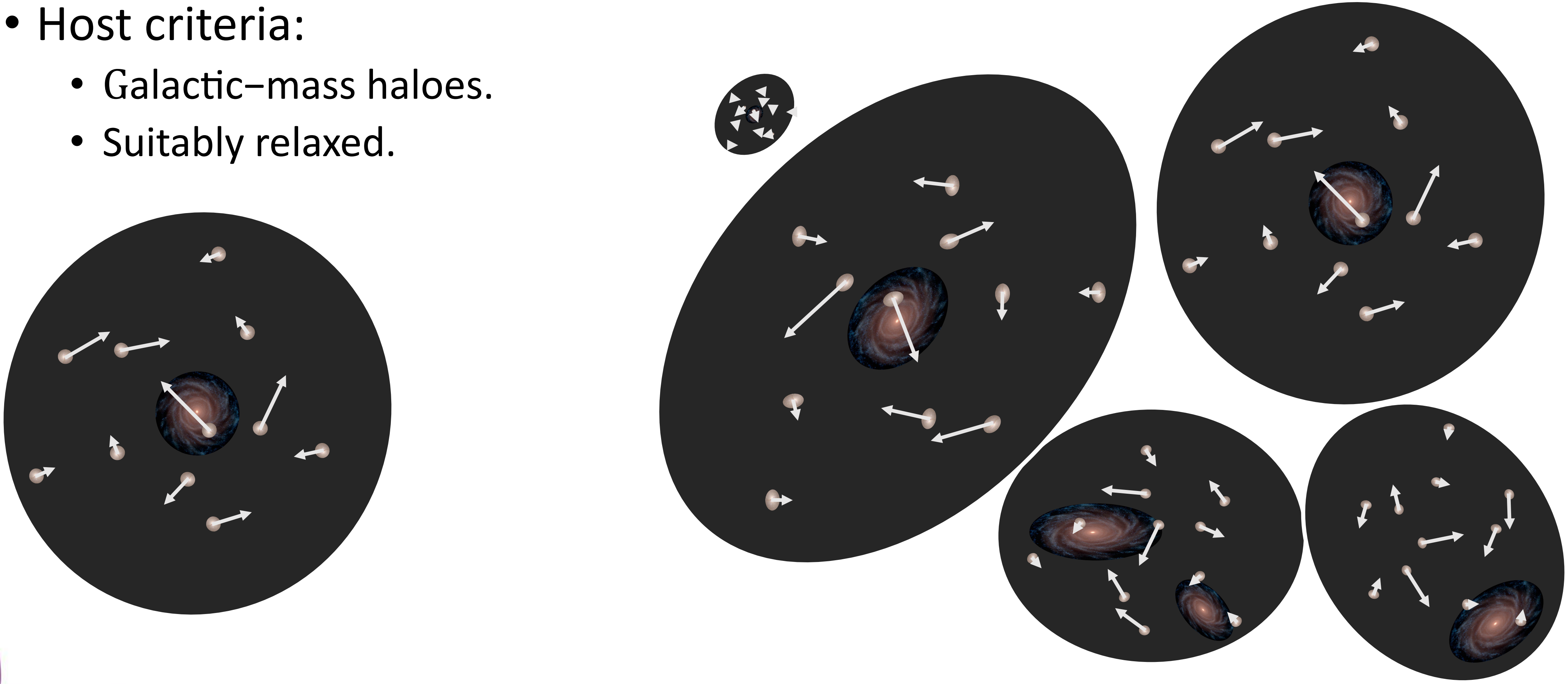




Callingham, Cautun, Deason+ (2019)

EAGLE Sample

- Host criteria:
  - Galactic–mass haloes.
  - Suitably relaxed.



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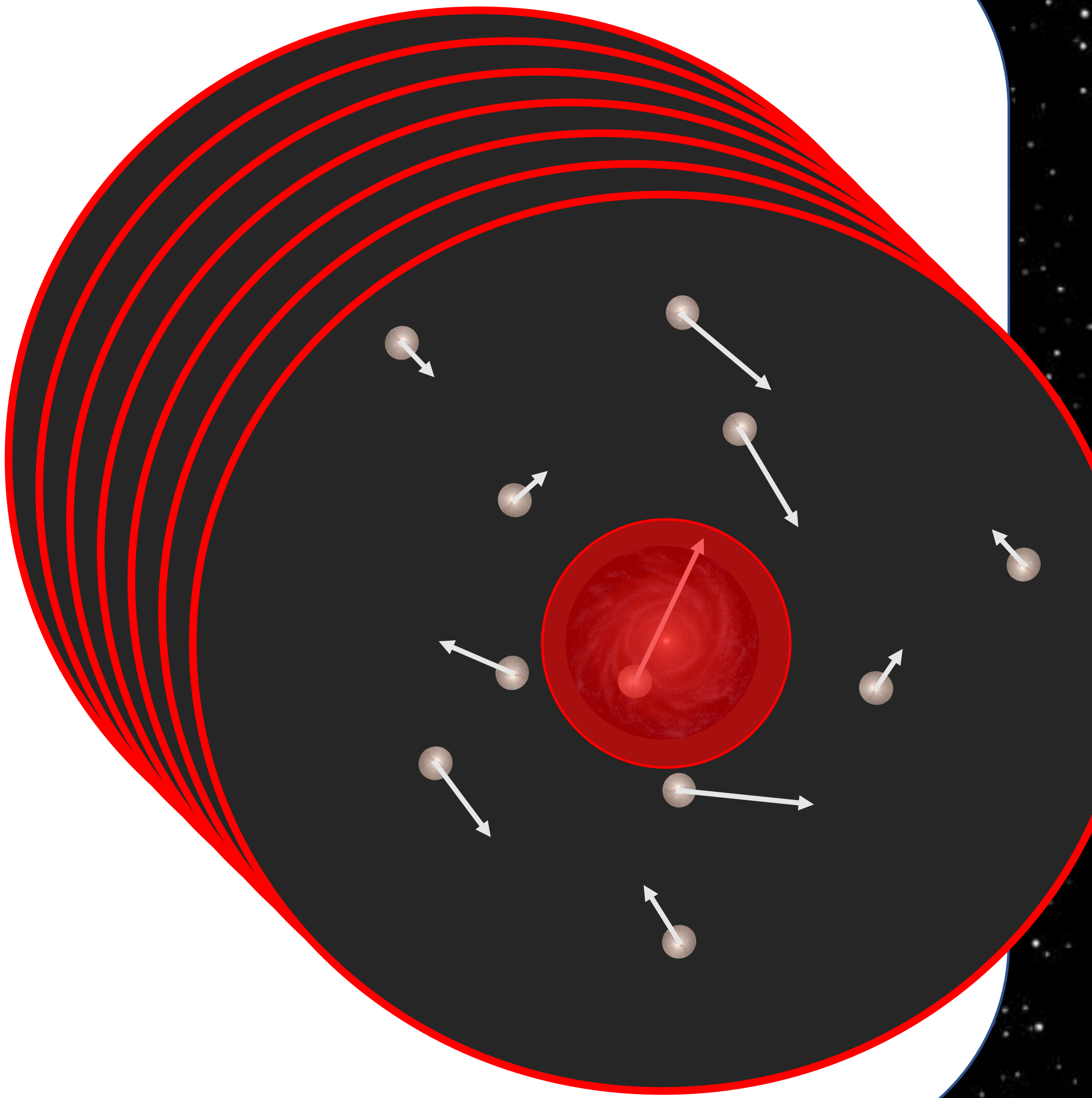
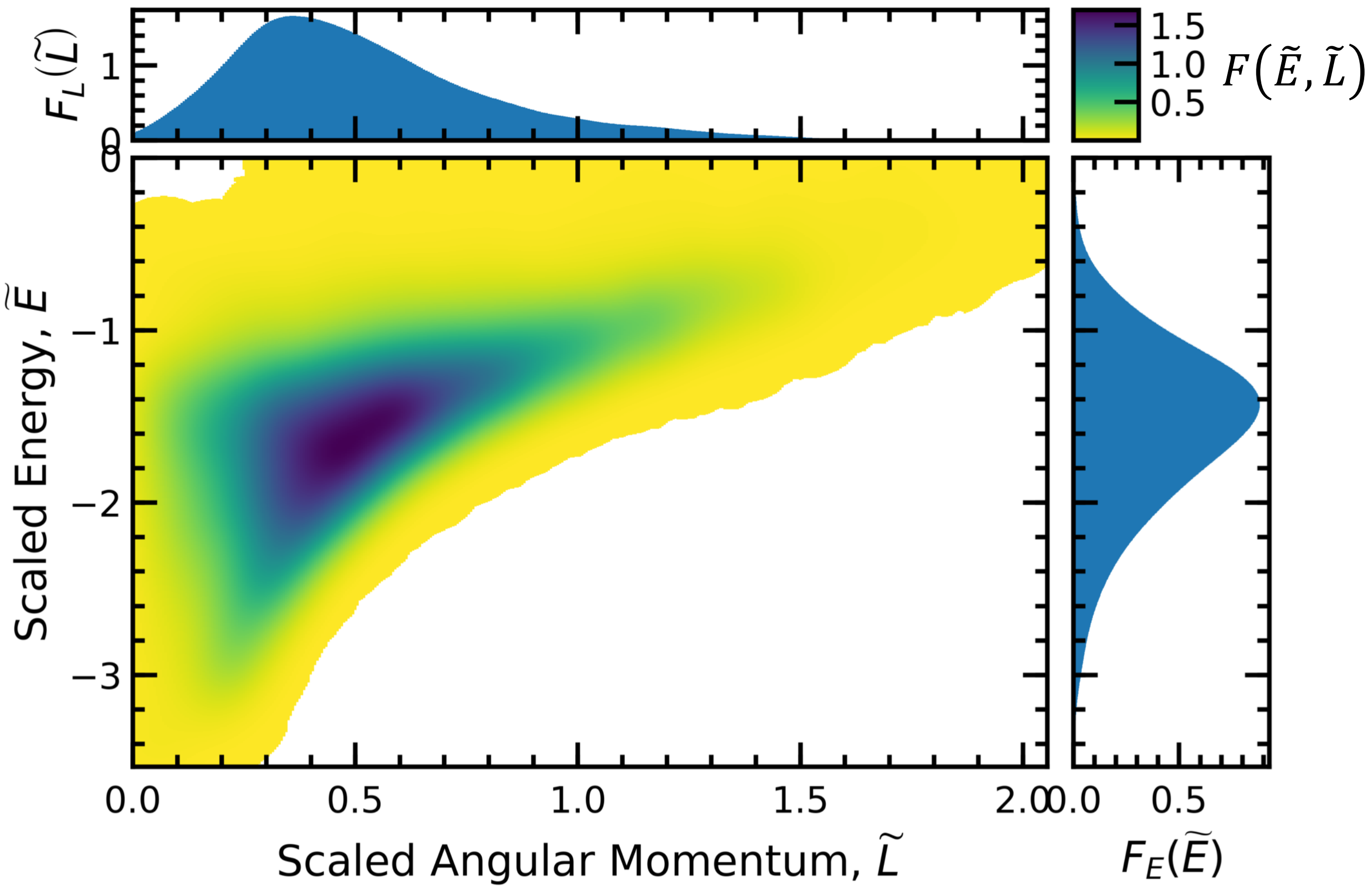
EAGLE Sample

- Host criteria:
  - Galactic−mass haloes
  - Suitably relaxed
- Satellite criteria:
  - Bright satellites.
  - Scaled radial cuts.
- Calculate scaled values $(\tilde{E}, \tilde{L})$
- Construct distribution $\mathrm{F}(\tilde{E}, \tilde{L})$ stacking.



Distribution Function



- 1,200 Systems
- 14,000 Satellites

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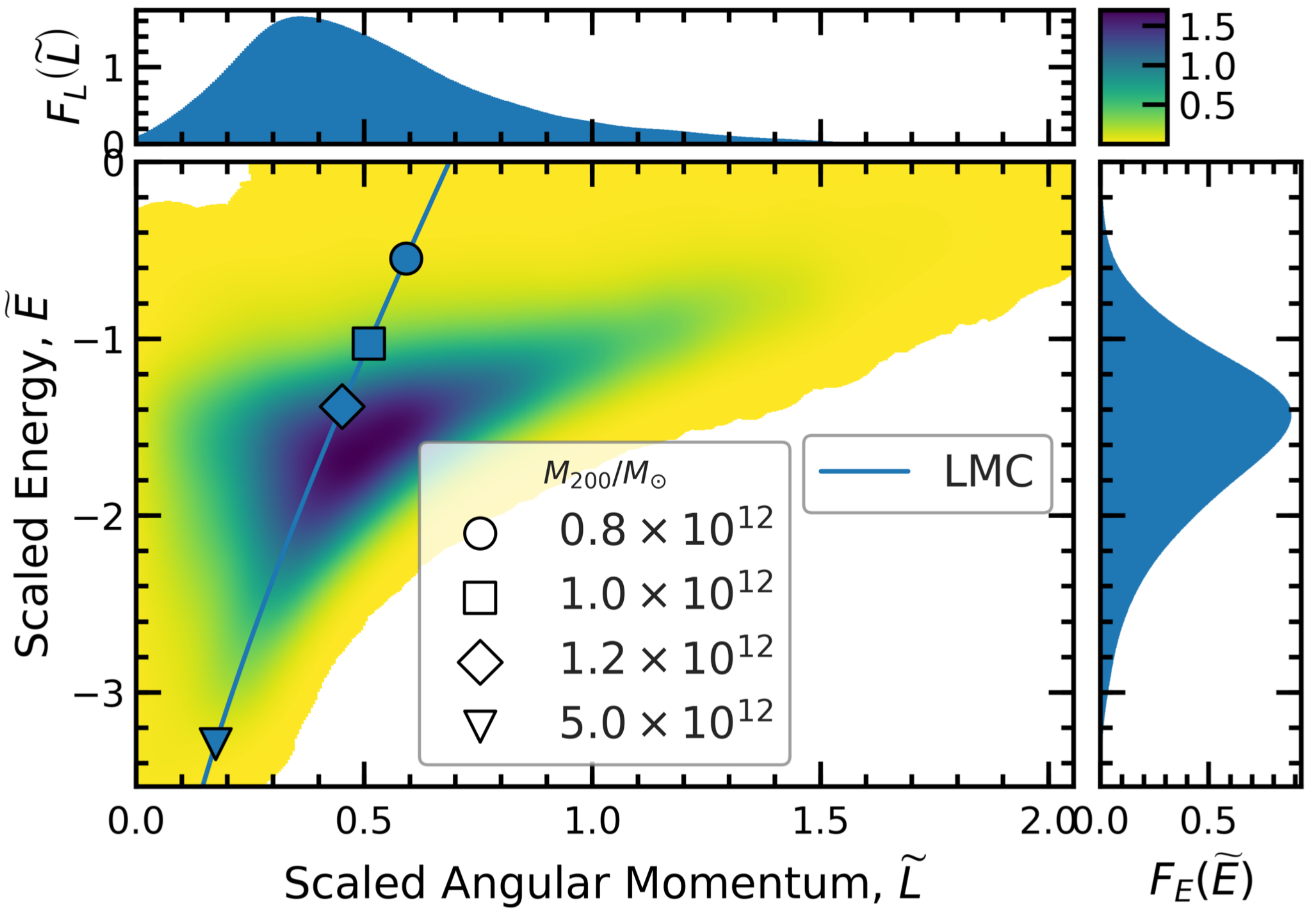
Inferring the Mass



$$(r, v, v_t) \xrightarrow{M_{200}} (\tilde{E}, \tilde{L})|_{M_{200}}$$

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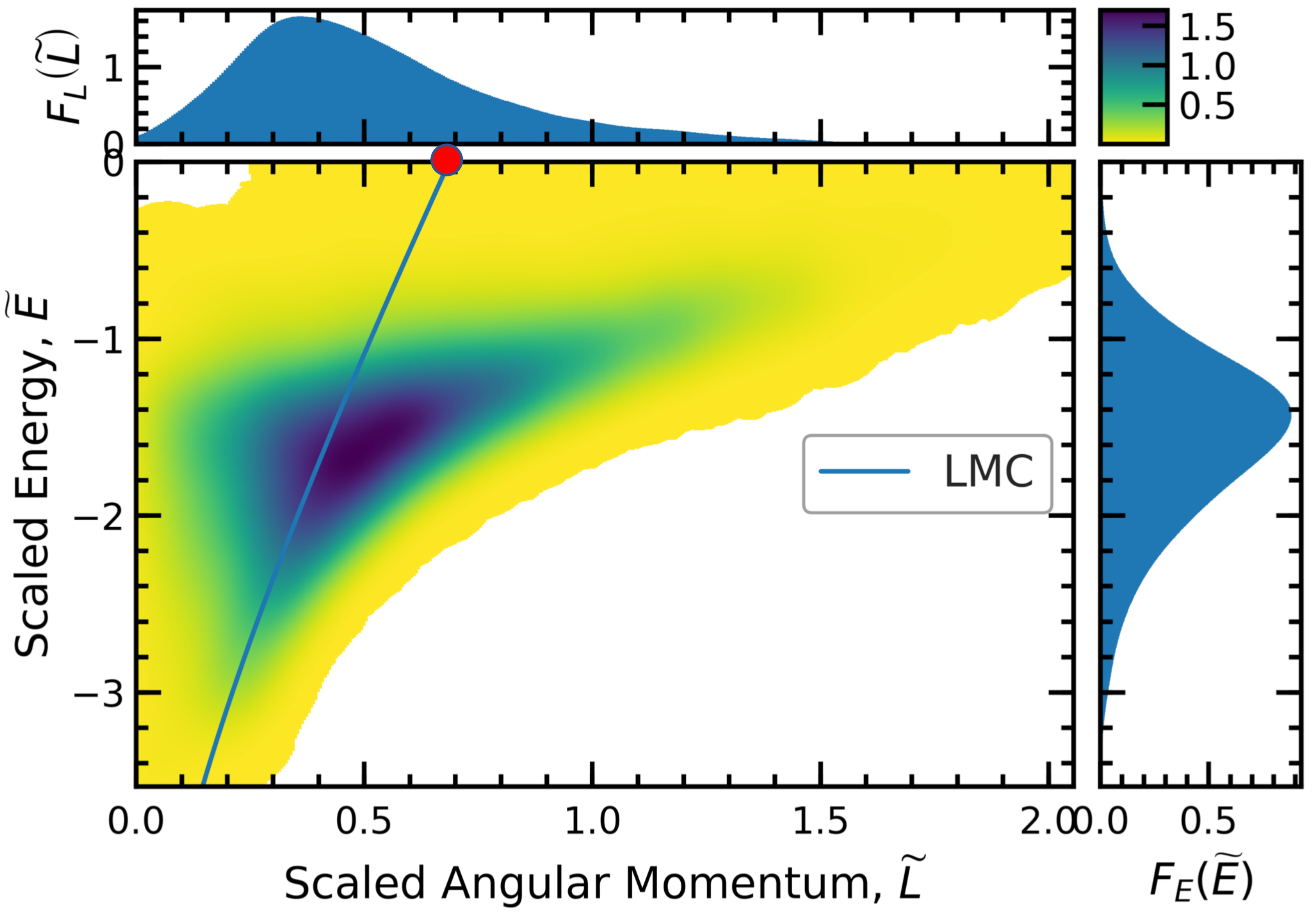
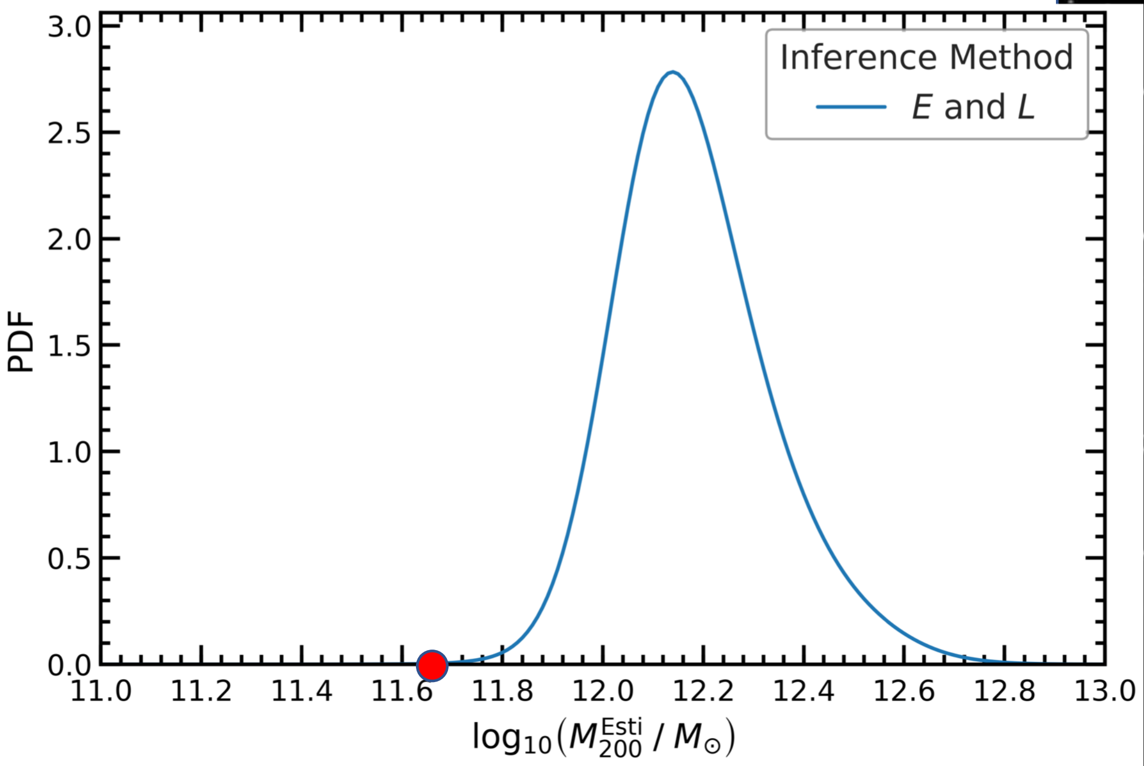
Callingham, Cautun, Deason+ (2019)

Inferring the Mass





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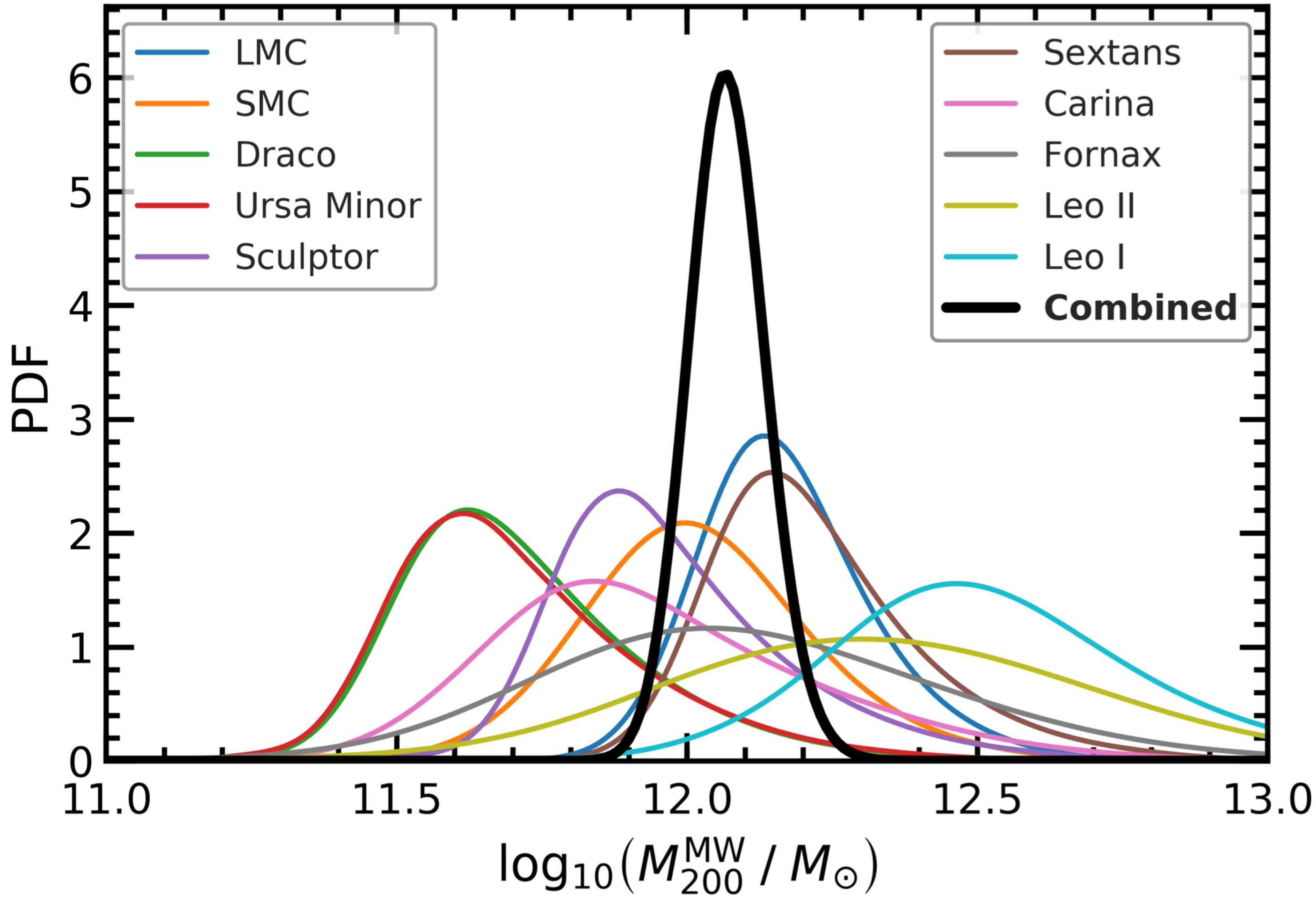
Callingham, Cautun, Deason+ (2019)

Inferring the Mass



- Combine satellite PDFs to give total PDF of the system.
- The peak gives $M_{200}^{\rm MW}$, errors from 0.16 and 0.84 percentiles.
- **Method tested on EAGLE and Auriga**. Checked for biases, calibrated error distributions.

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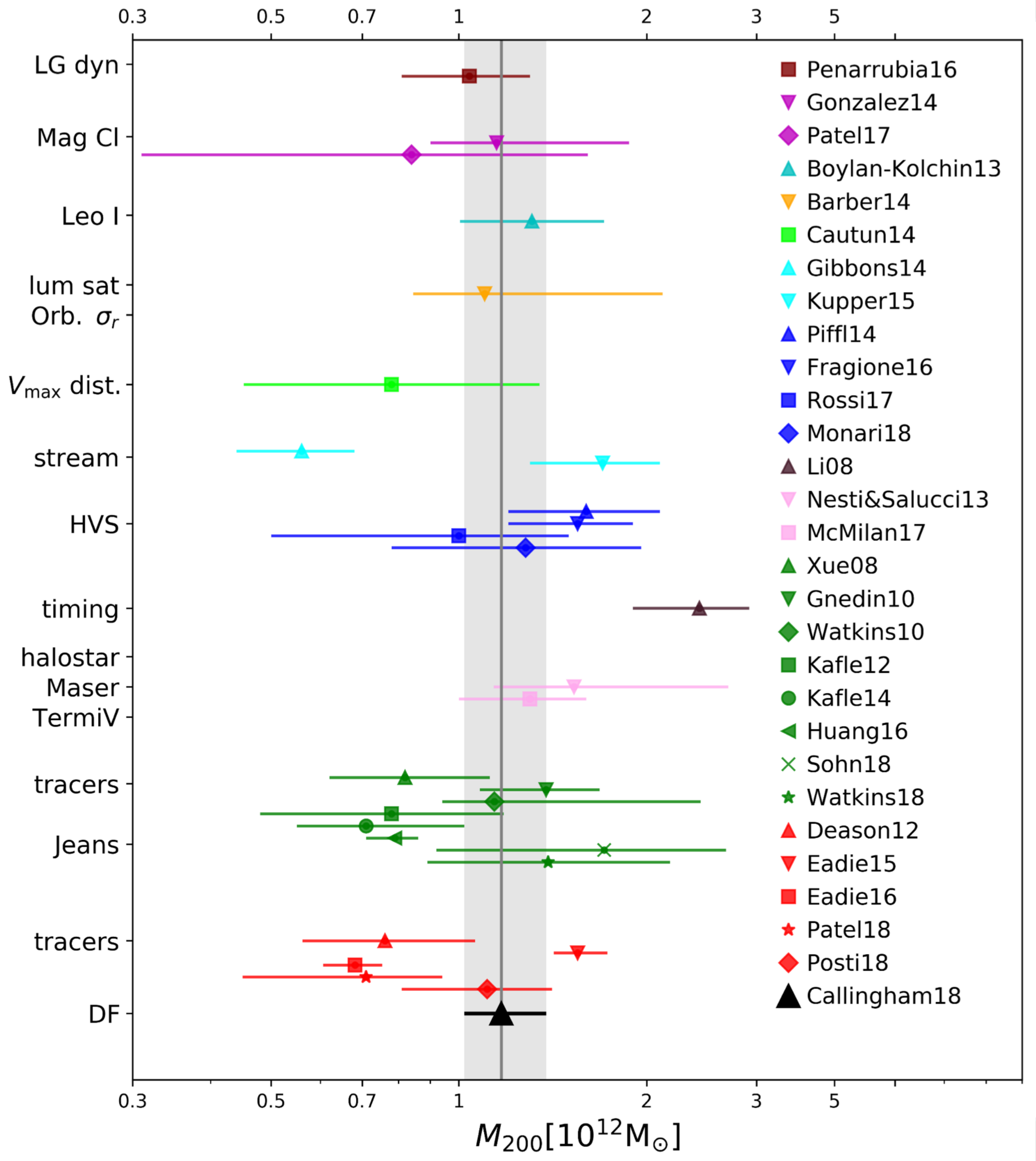
Conclusions from Callingham et al.

- Use satellite dynamics from GDR2 + cosmological simulations to get halo mass.
- Calibrated and well tested method.

$$M_{200}^{\mathbf{MW}} = 1.17^{+0.21}_{-0.15} \times 10^{12} M_{\odot}$$

Callingham+19, MNRAS.484.5453C



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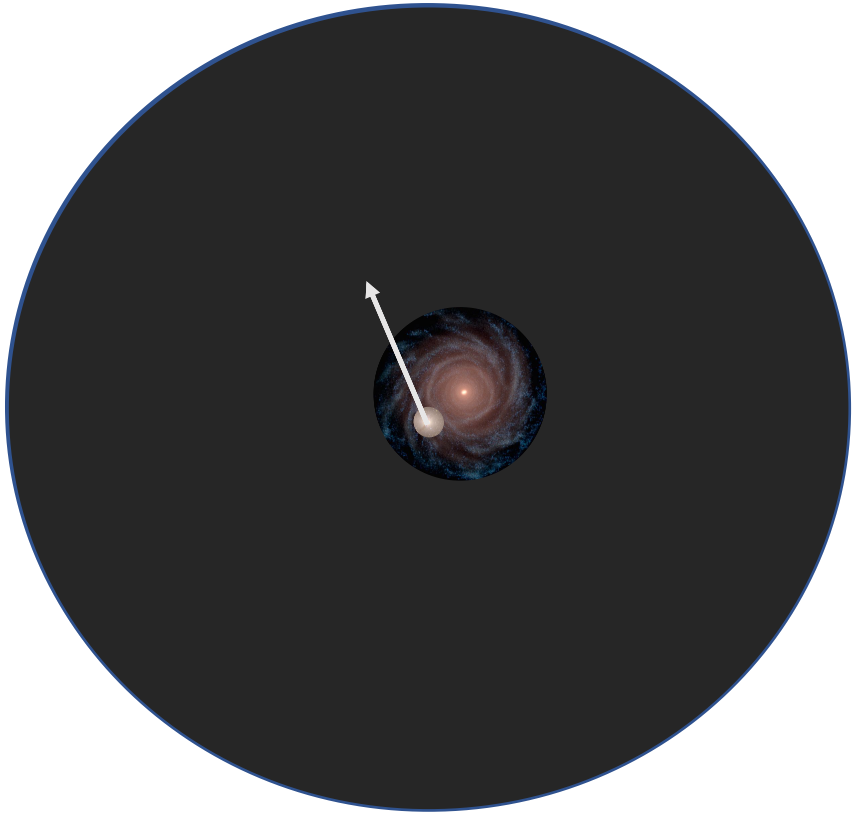
Galactic Escape Velocity

- The fastest stars in the solar neighborhood can (potentially!) probe out to the virial radius of the Galaxy.
- Local Escape velocity can tell you **total** halo mass.
- Leonard & Tremaine Approximation (as v approaches v_e) :



$$f(v|v_e, k) \propto (v - v_e)^k$$

Shape of high velocity tail (unknown)

Total velocity

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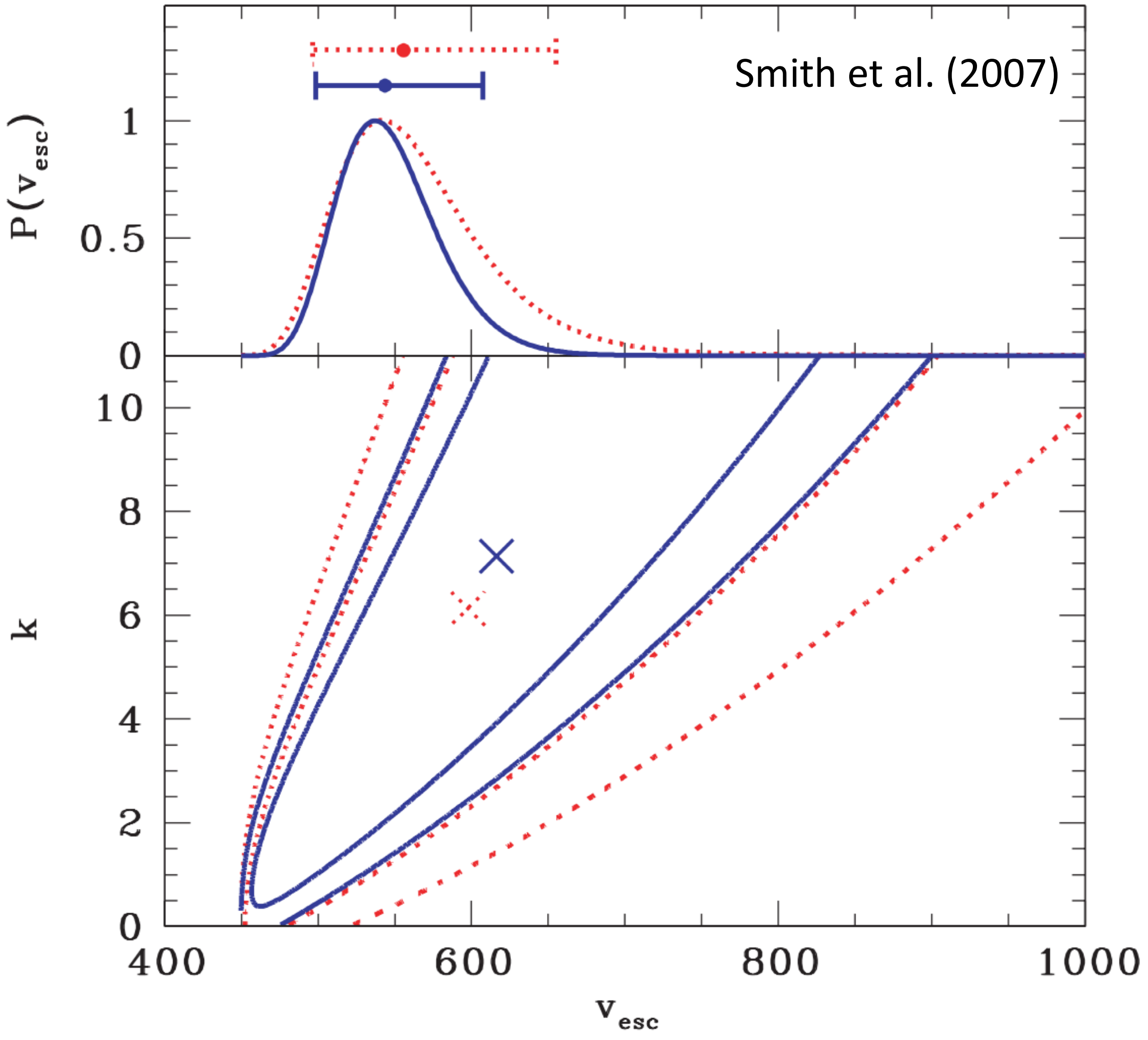
Shape of total velocity distribution

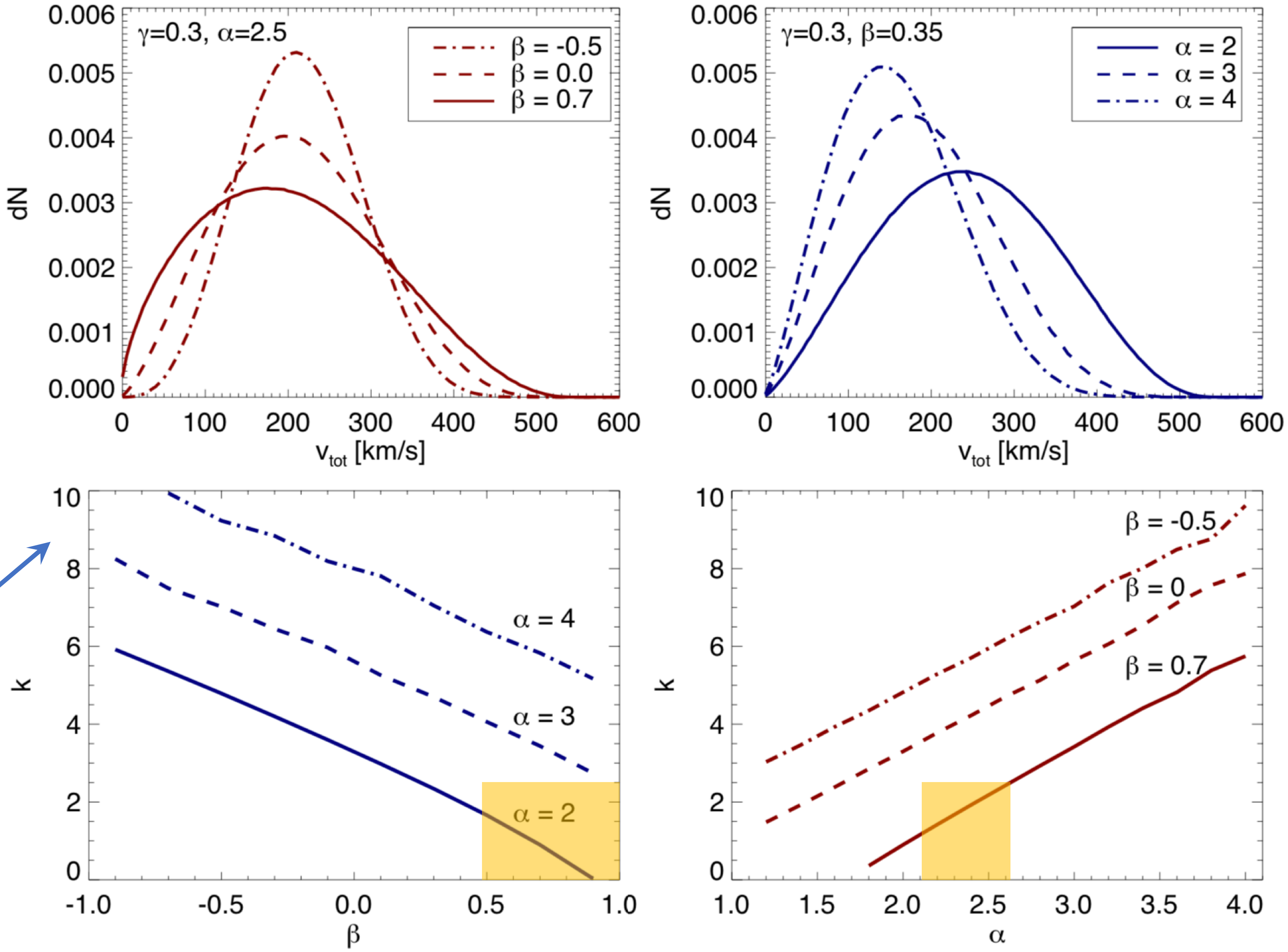
- Shape (k) is strongly degenerate with escape velocity!
- Previous work constrains k from cosmological simulations (Smith et al. 2007; Piffl et al. 2014).
- But **wide range of k values** (varies from halo-to-halo).



Shape of total velocity distribution

- Shape of high velocity tail depends on velocity anisotropy and density profile (and hence assembly history!).
- **We know these properties for the Milky Way stellar halo!**

"Toy", power-law distribution functions.
(α= density profile slope, β=velocity anisotropy, ɣ= potential slope).



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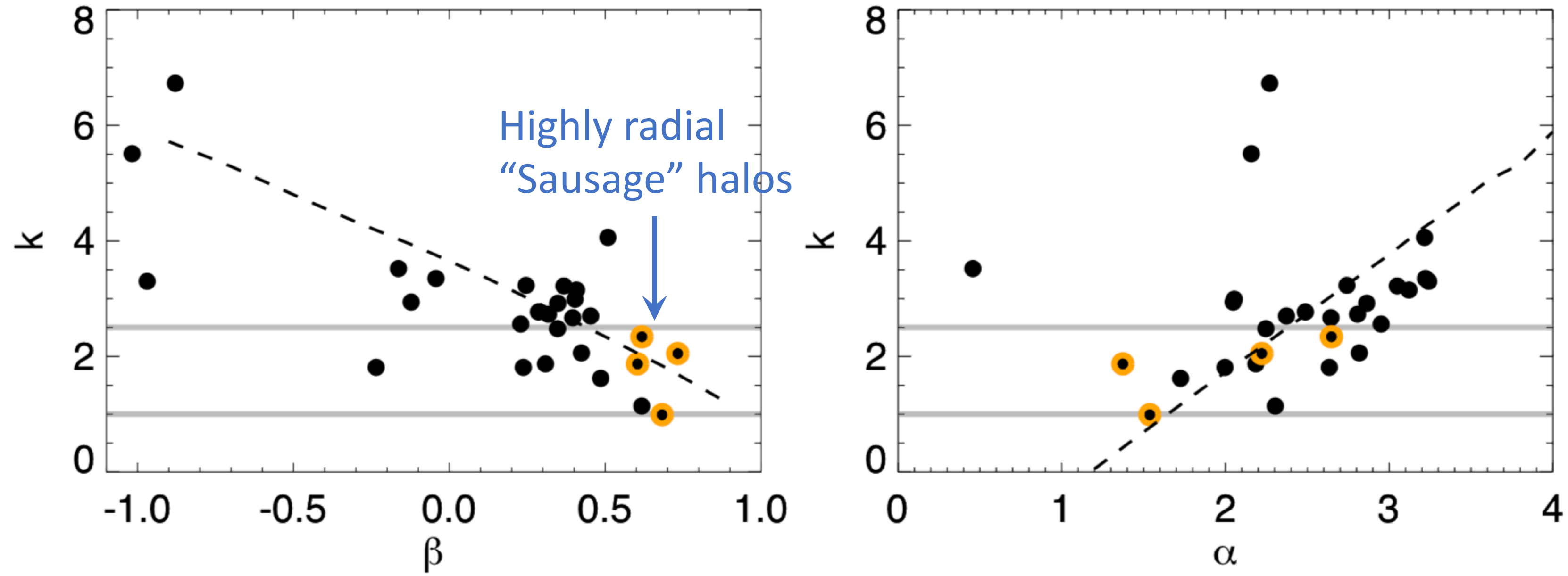
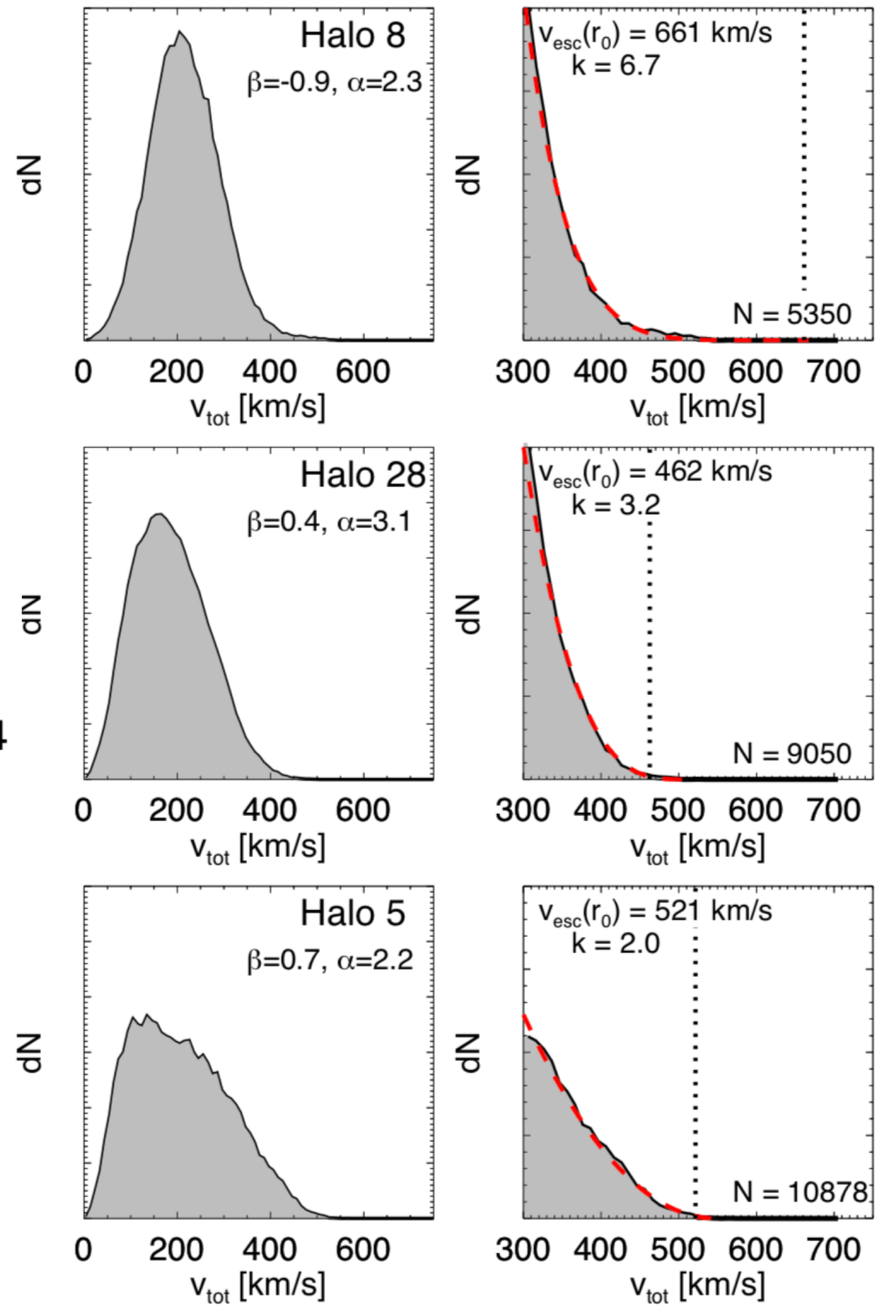
Test with Auriga simulation





Auriga haloes show same relation has toy models: **Adopt prior on k (1.0-2.5) based on Auriga haloes.**

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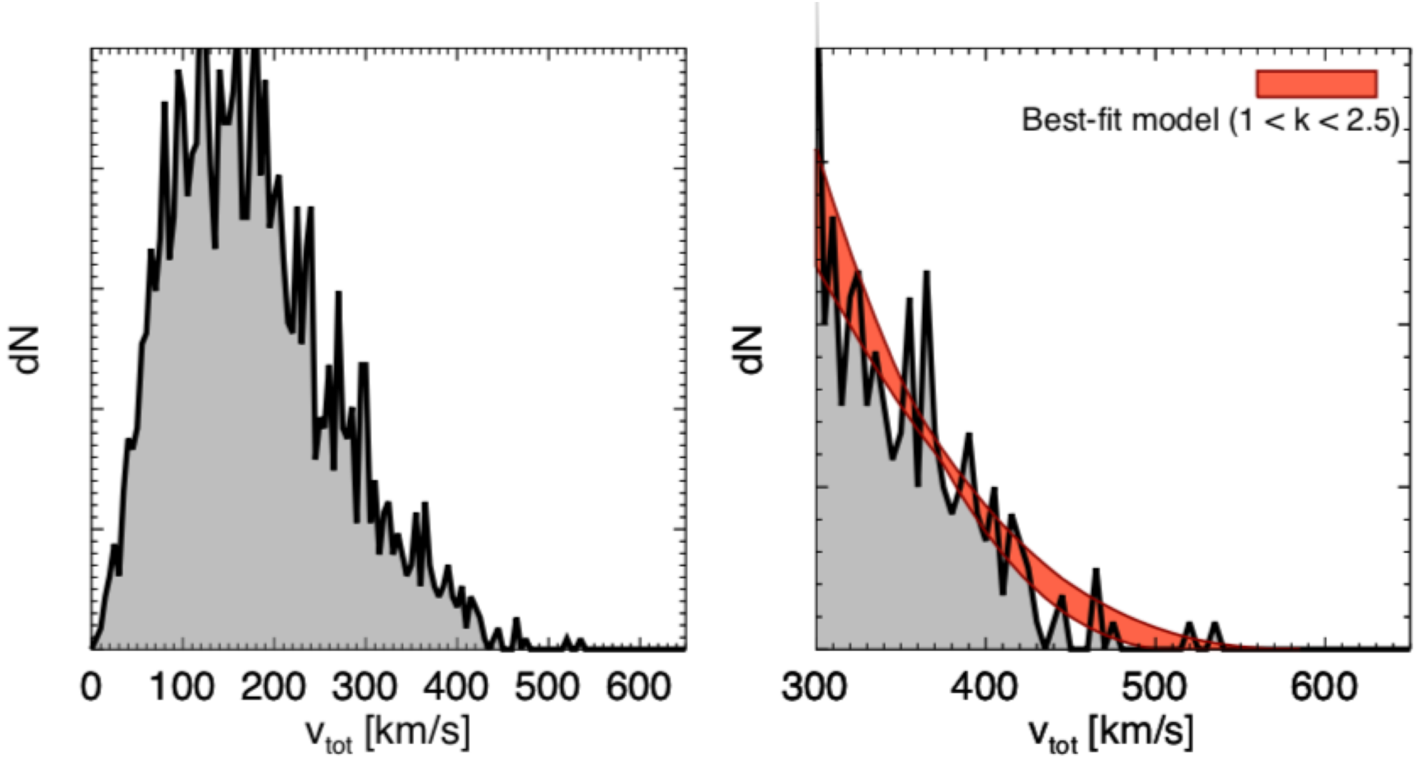
Apply to GDR2

- Use GDR2 stars with 6D phase space.
- Limit to D < 3 kpc (parallax informative).
- Model tail with v > 300 km/s using MLE.
- Bootstrap observational errors.



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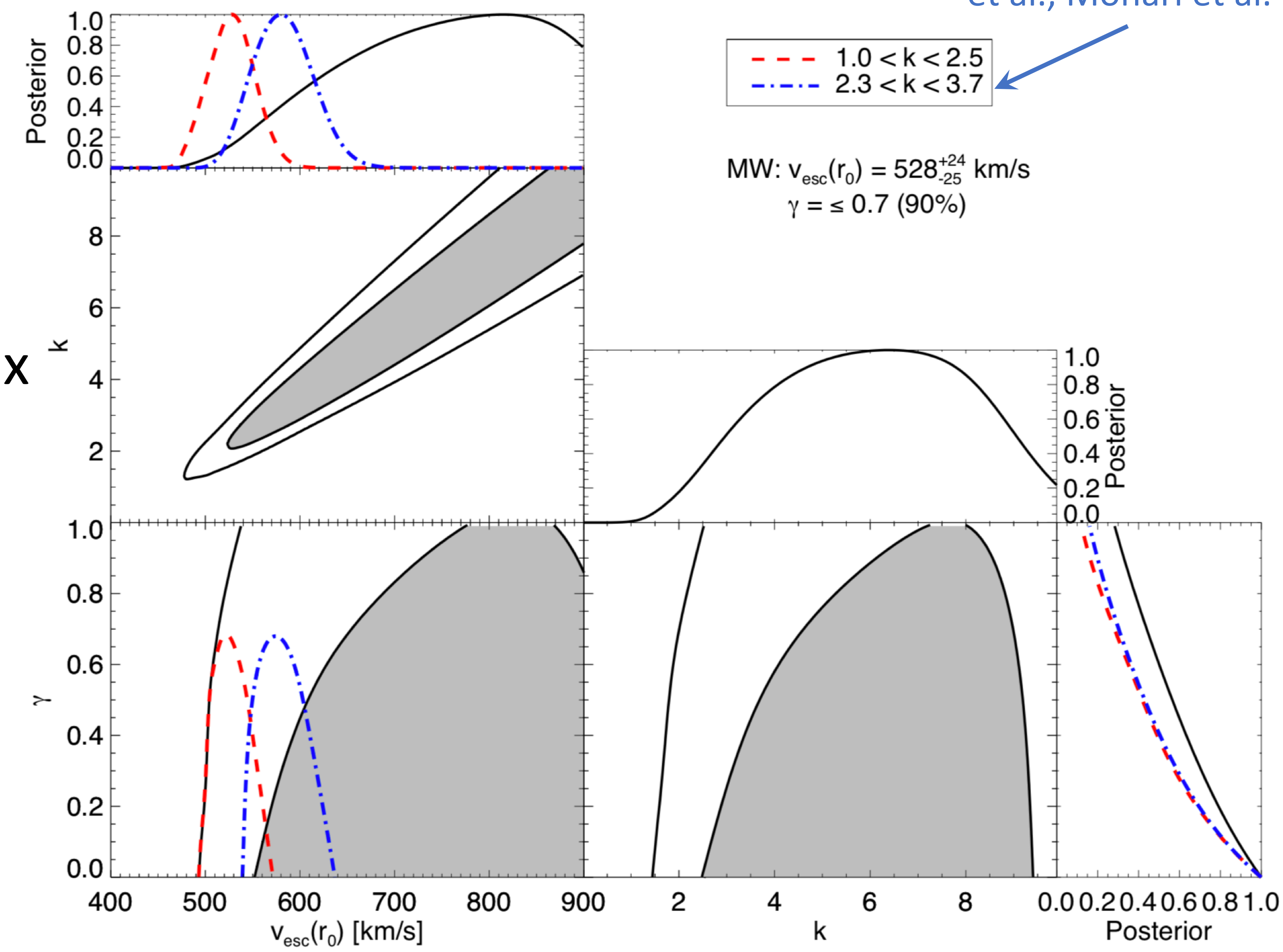

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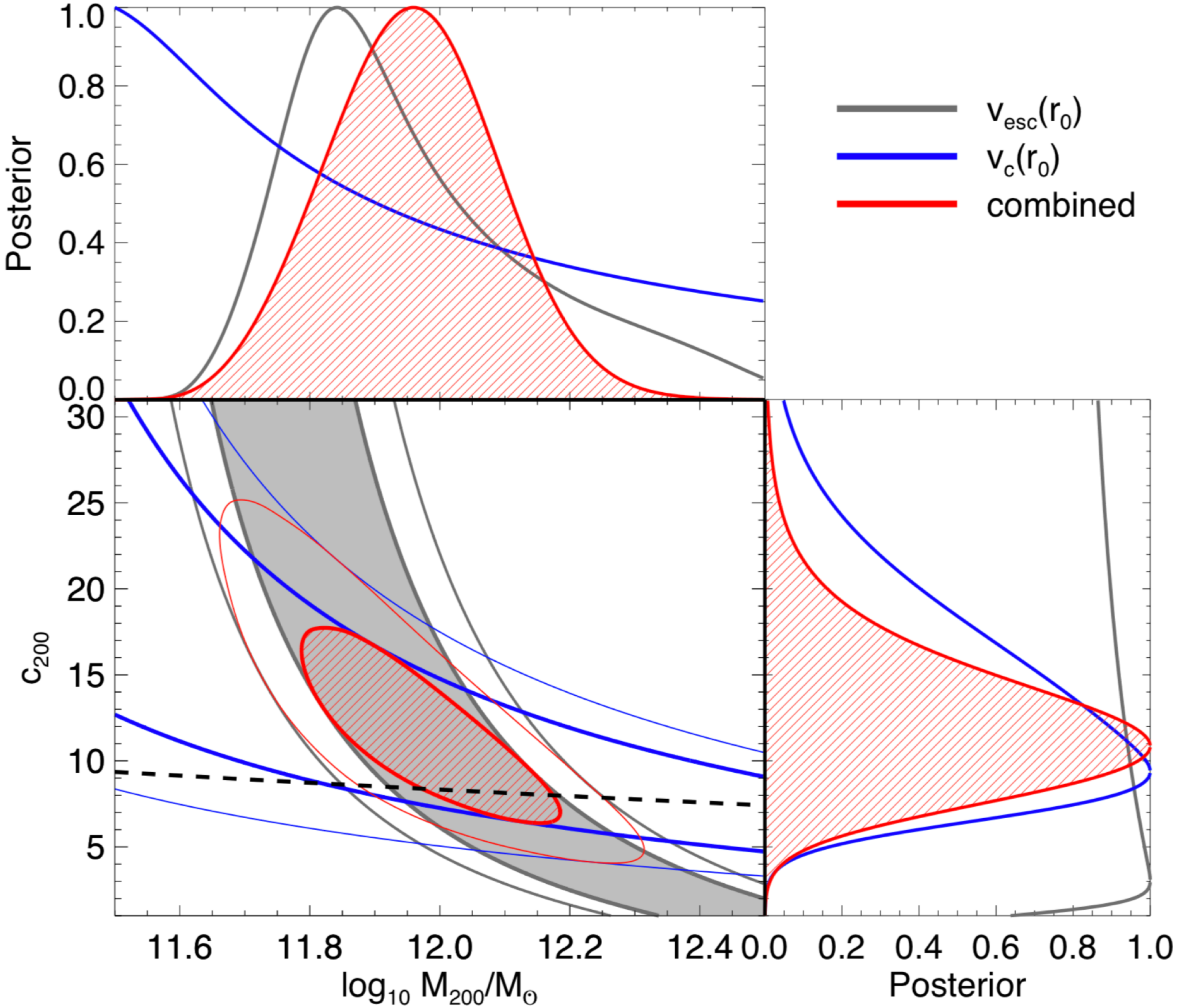
Mass Estimate

- Escape velocity = escape to $2r_{200}$.

$$v_{esc}(r_0) = \sqrt{2\left(\Phi(r_0) - \Phi(2r_{200})\right)}.$$

- Combine escape velocity with circular velocity (Eilers et al. 2019).
- Assume NFW potential.

$$M_{200}^{MW} = 1.00^{+0.31}_{-0.24} \times 10^{12} M_{\odot}$$



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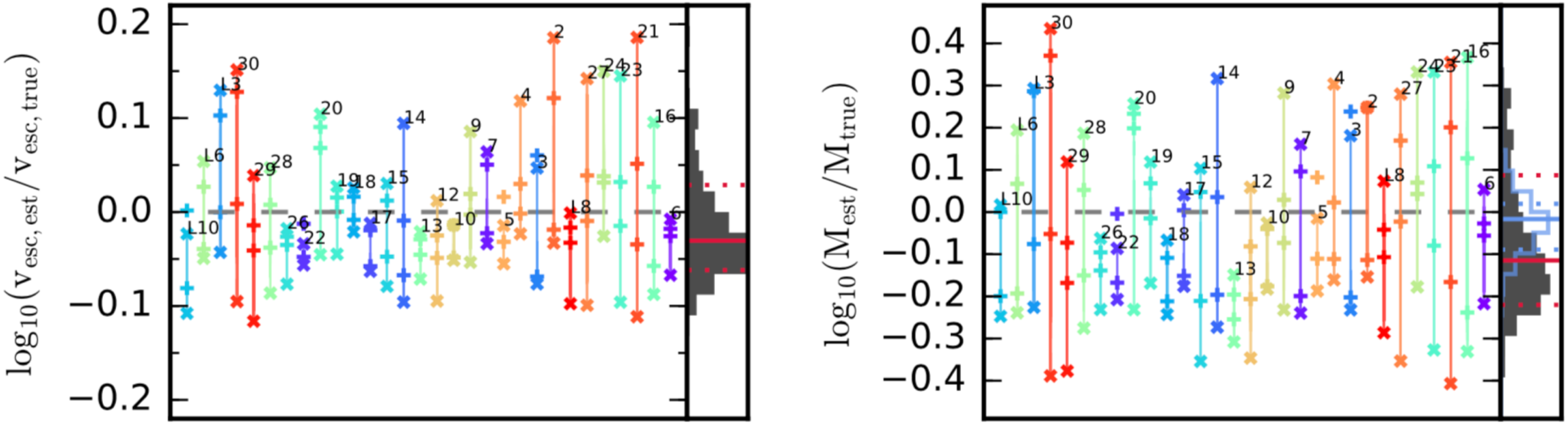
Grand, Deason+(2019)

Systematics?



- Use Auriga simulations to test Galactic escape velocity modelling.
- Escape velocity underestimated by 7%, total mass underestimated by 20%. Scatter larger than observational estimate.
- Underestimate mainly because orbits of early merger ($z > 1$) progenitors typically do not reach out as far as today's $2R_{200}$ after disruption.

$$M_{200}^{MW} = 1.29^{+0.37}_{-0.47} \times 10^{12} M_{\odot}$$

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Post-DR2 total MW Mass estimates

$M_{200}^{\mathrm{MW}} \neq M_{\mathrm{vir}}^{\mathrm{MW}}$

- *Globular clusters:* Watkins et al. (2019), Posti & Helmi (2019), Vasiliev (2019): $M_{200}^{\mathrm{MW}} = 1.0 - 1.3 \times 10^{12} M_{\odot}$

Simulations used to estimate systematics

- *Satellite dynamics:* Callingham et al. (2019): $M_{200}^{\mathrm{MW}} = 1.2 \times 10^{12} M_{\odot}$
- *Escape velocity:* Deason et al. (2019), Grand et al. (2019): $M_{200}^{\mathrm{MW}} = 1.0 - 1.3 \times 10^{12} M_{\odot}$
- *Circular velocity:* Eilers et al. (2019): $M_{200}^{\mathrm{MW}} = 0.7 \times 10^{12} M_{\odot}$
- *Streams*: GD1 (Malhan & Ibata 2019) $\mathrm{M}_{200}^{\mathrm{MW}} \sim 1.7 \times 10^{12} \mathrm{M}_{\odot}$, Orphan (inc. LMC, Erkal et al. 2019) $\mathrm{M}_{200}^{\mathrm{MW}} = 0.9 \times 10^{12} \mathrm{M}_{\odot}$

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Where are we now?

- Current best estimate: $\boldsymbol{M_{200}^{\mathrm{MW}} = 1.0 - 1.3 \times 10^{12} M_{\odot}}$
- This is a significant improvement!
- Can we do better than 20% error? Do we want/need to?

- Independent tracers out to virial radius (halo stars?).
- **Include affect of LMC!**
Non-trivial, but important.

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