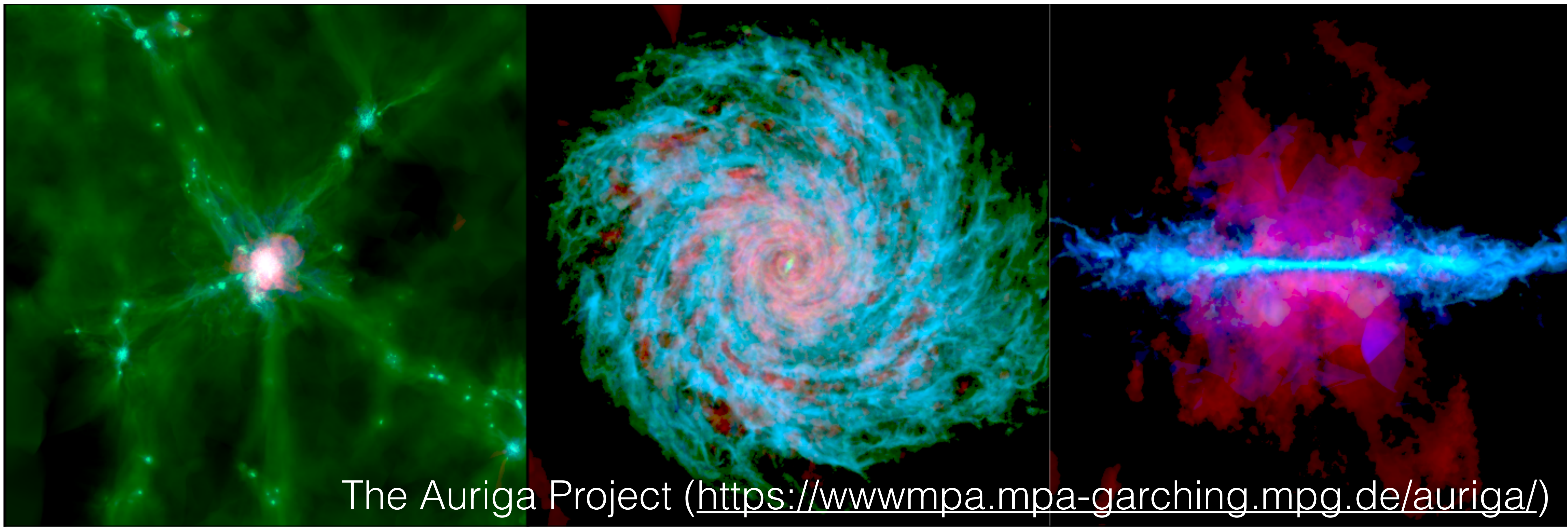
How dynamical substructure biases MW mass estimates from the local high velocity tail



Rob Grand (MPA)

in collaboration with

Volker **Springel** (MPA), Rüdiger **Pakmor** (MPA), Facundo **Gomez** (La Serena), Federico **Marinacci** (Bologna), Christine **Simpson** (Chicago), Adrian **Jenkins** (Durham), Carlos **Frenk** (Durham), Simon **White** (MPA), Alis Deason (Durham)

Current status of Milky Way mass estimates

Dynamical tracers:

- Modelling of stellar streams (e.g. Mahlan+18)
- Globular cluster kinematics (e.g. Watkins+18)
- Satellite kinematics (e.g. Callingham+ 19)
- Halo stars kinematics (e.g. Deason+19)

The Gaia mission has increased the sample size and precision of tracers substantially.

Total mass estimates seem to be converging to ~1x10^{12} Msun

$$M_{200,\mathrm{tot}} = 1.00^{+0.31}_{-0.24} \times 10^{12} M_{\odot}$$ (Deason+19)

$$M_{200,\mathrm{tot}} = 1.0 - 1.3 \times 10^{12} M_{\odot}$$ (Watkins+18,Posti+Helmi 19, Vasiliev19)

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1. **Recent application to Gaia DR2**
2. **Testing biases/precision with cosmo sims**

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Modelling the high velocity tail of halo stars (Deason+19)

Model:

- The high-velocity tail of local accreted stars and the escape velocity radial profile follow a power law

$$f(v|v_e, k) \propto (v - v_e)^k \qquad v_e = v_{e,0}(r/r_0)^{-\gamma/2}$$

3 parameters to constrain

$$v_e(r) \propto \sqrt{2\Phi(r)}$$

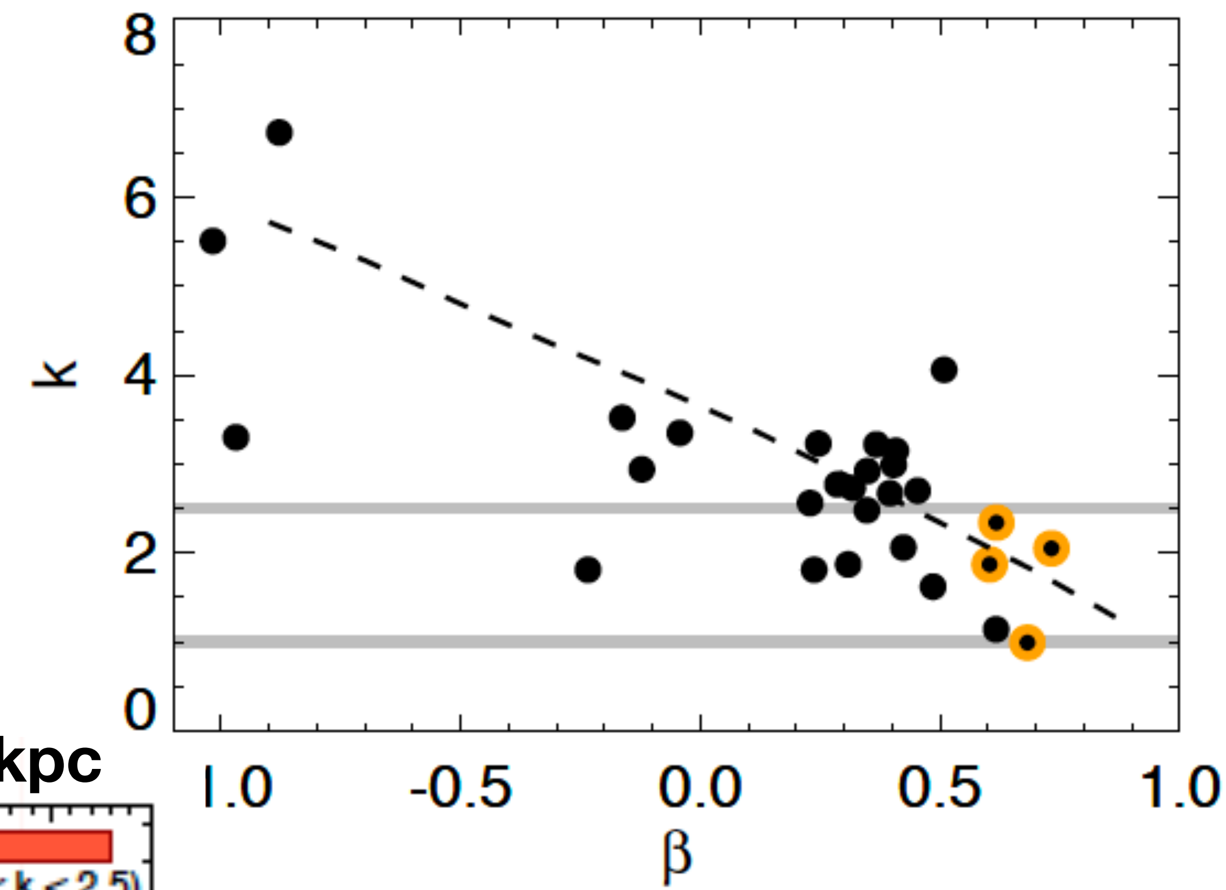
Assumptions:

- The distribution function of the system is smooth, i.e. is well-mixed in phase space (Leoneard+Tremaine 90)

- The velocities extend all the way up to the escape velocity

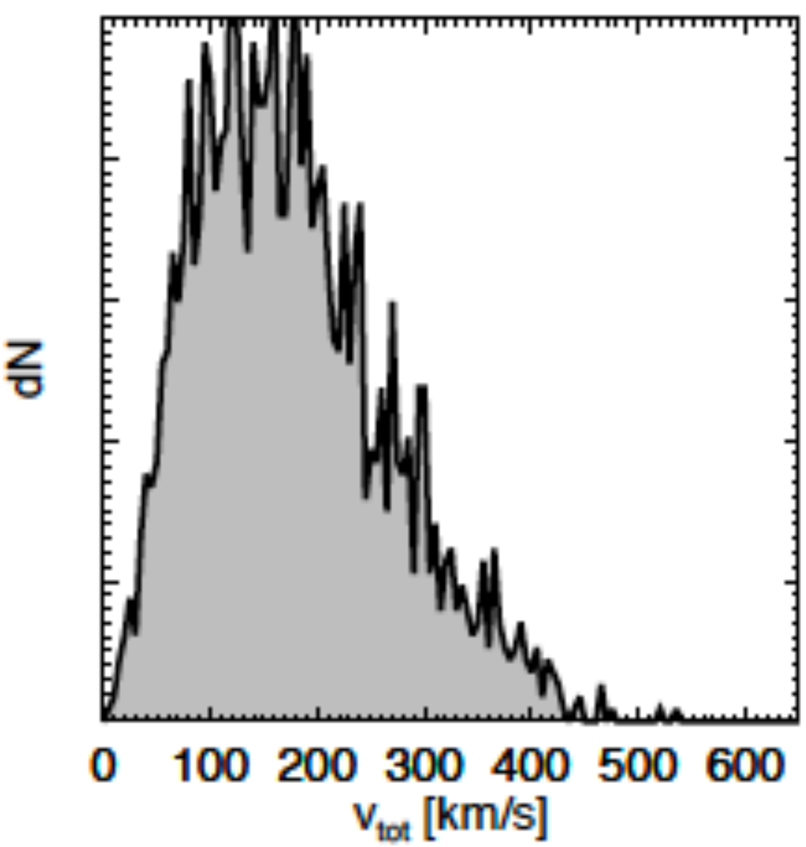
Modelling the high velocity tail of DR2 halo stars (Deason+19)

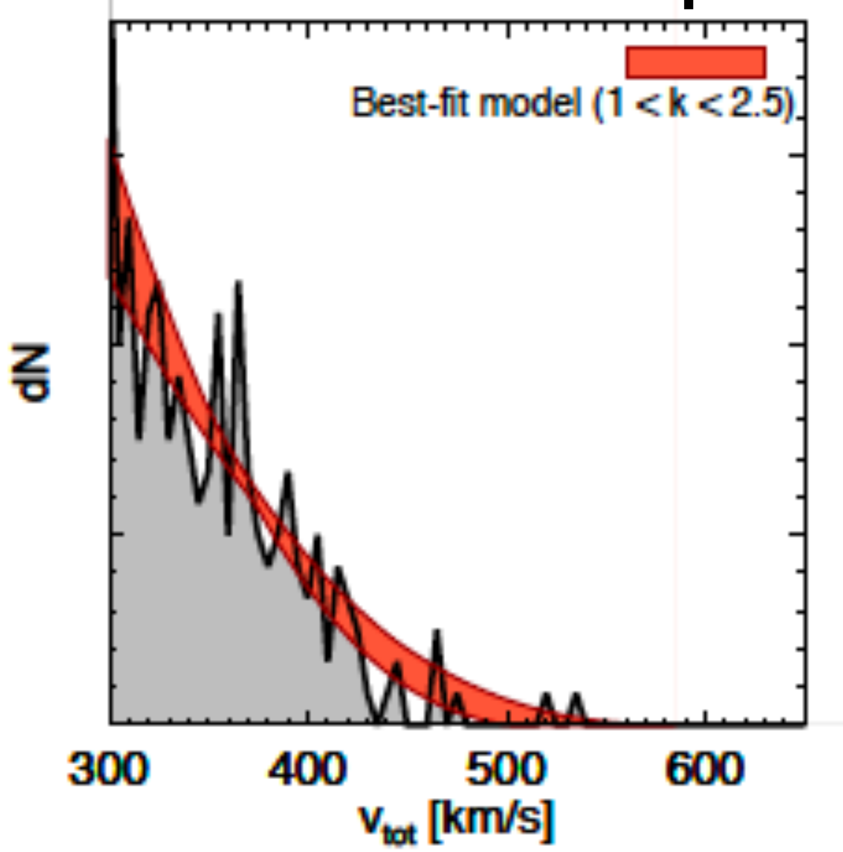
Model input: radii and total velocities (Gaia DR2) of (counter-rotating) stars with radial velocity information



Put prior on k, by calibrating to simulated stellar haloes with high velocity anisotropy
(Gaia Sausage/Enceladus, Belokurov+18, Helmi+19, Fattahi+19)

240 CR stars with heliocentric distance < 3kpc





Apply Bayesian likelihood technique to find best v_e, k marginalising over poorly constrained γ

$$v_{esc}(r_0) = 528^{+24}_{-25} \text{ km s}^{-1}$$

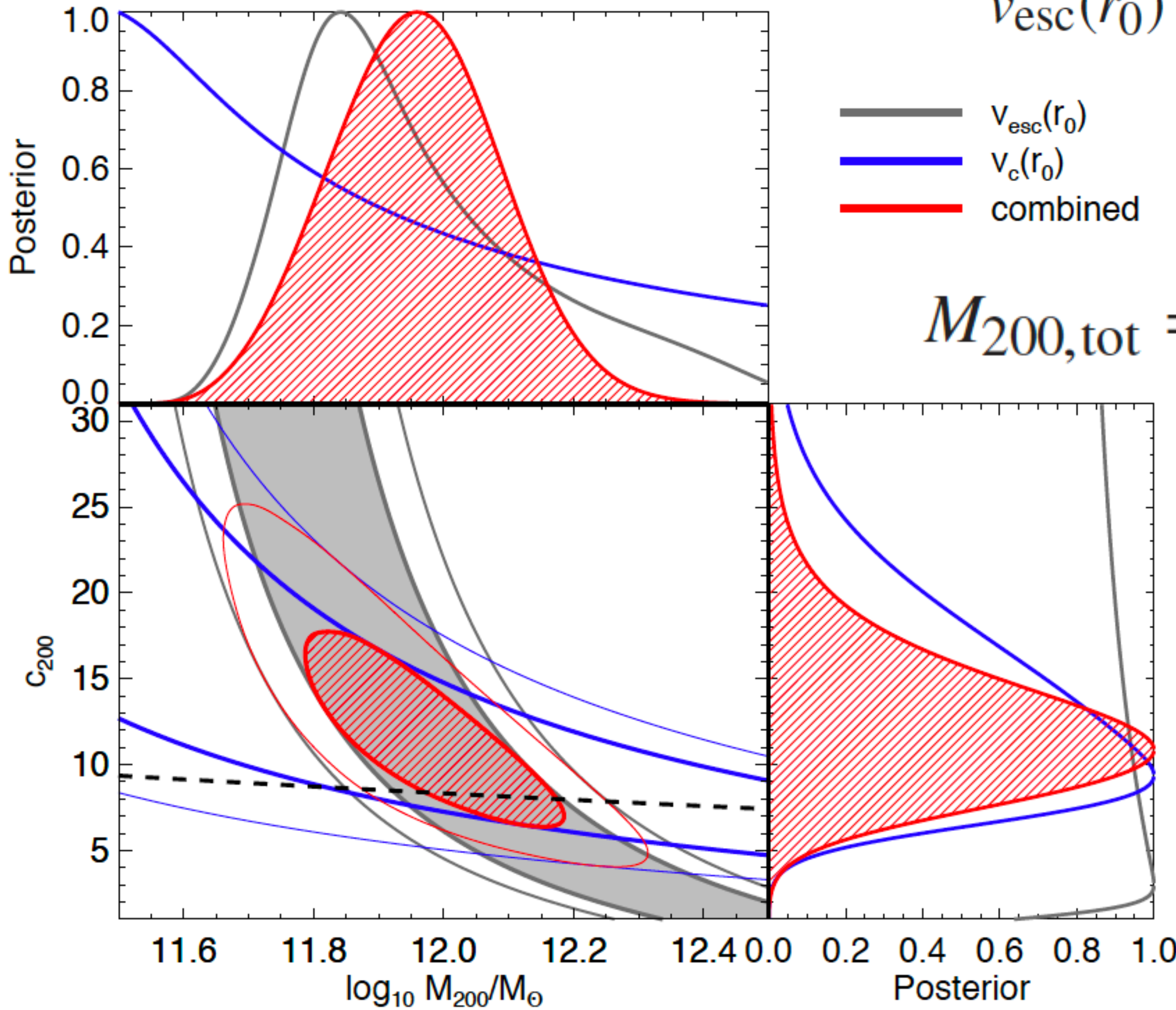
Modelling the high velocity tail of halo stars (Deason+19)

Determining mass (M_{200}) and concentration (***NFW profile***) from constraints on:

- Escape velocity (outer mass distribution);
- Circular velocity (inner mass distribution)

Assume baryonic disc parameters

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



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

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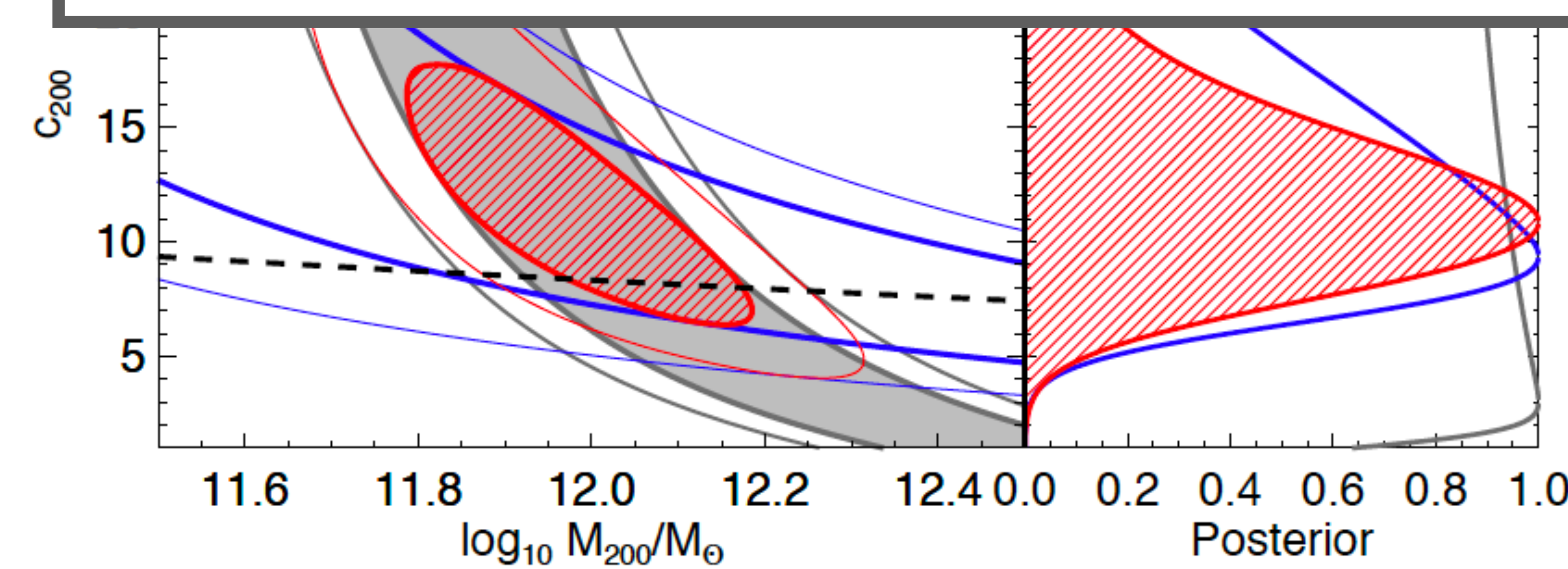
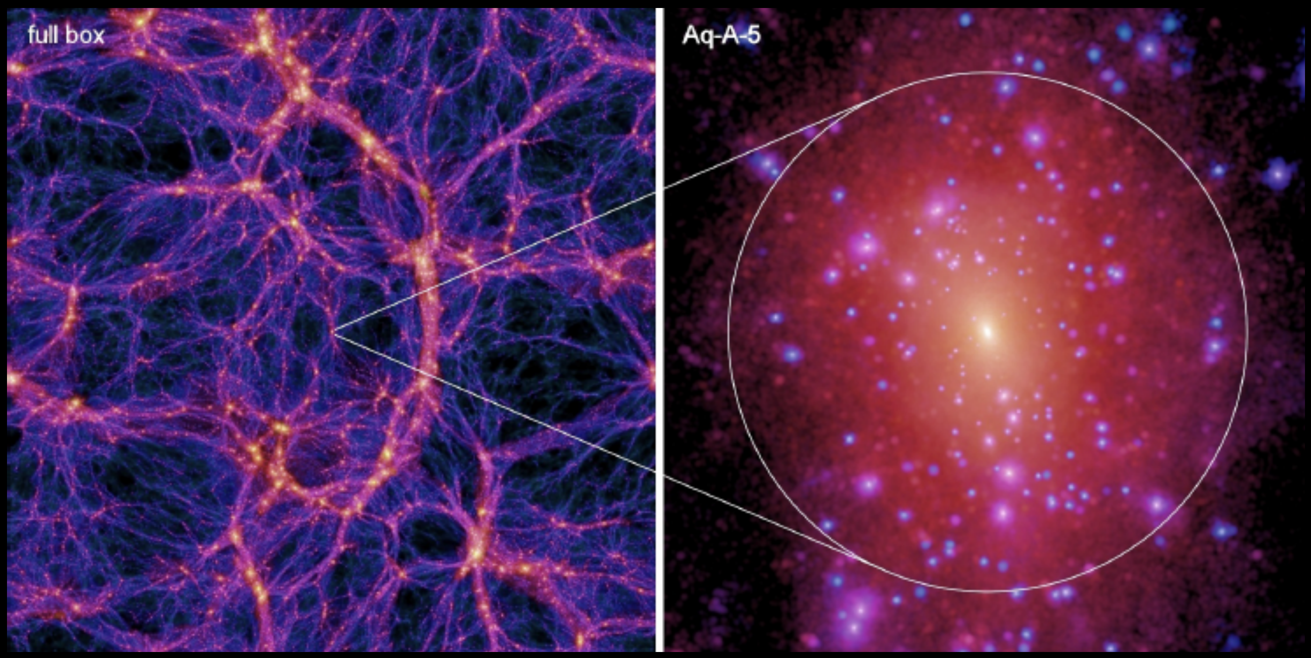
Testing the assumptions: Smooth, well phase-mixed velocity distribution?

- **How important is dynamical substructure for the estimate and scatter?** Dependence on merger history, location within disc?
- **Spherical NFW?**
- Implications for future larger volume samples?



The Auriga simulations: cosmological "zoom" simulations for the formation of Milky Way mass galaxies (Grand et al. 2017)



Dark matter only 100 Mpc box

➜ Isolated, Milky Way mass

Re-simulated with gas (AREPO) and galaxy formation model:

Reionisation:
- *spatially uniform UV background (Faucher-Giguere 2009)*
- *completes at z=6*

Star formation and ISM:
- *cold clouds in a warm ambient medium (Springel & Hernquist 2003)*
- *density threshold crit (>0.13/cc)*

Cooling:
- *primordial*
- *metal line*

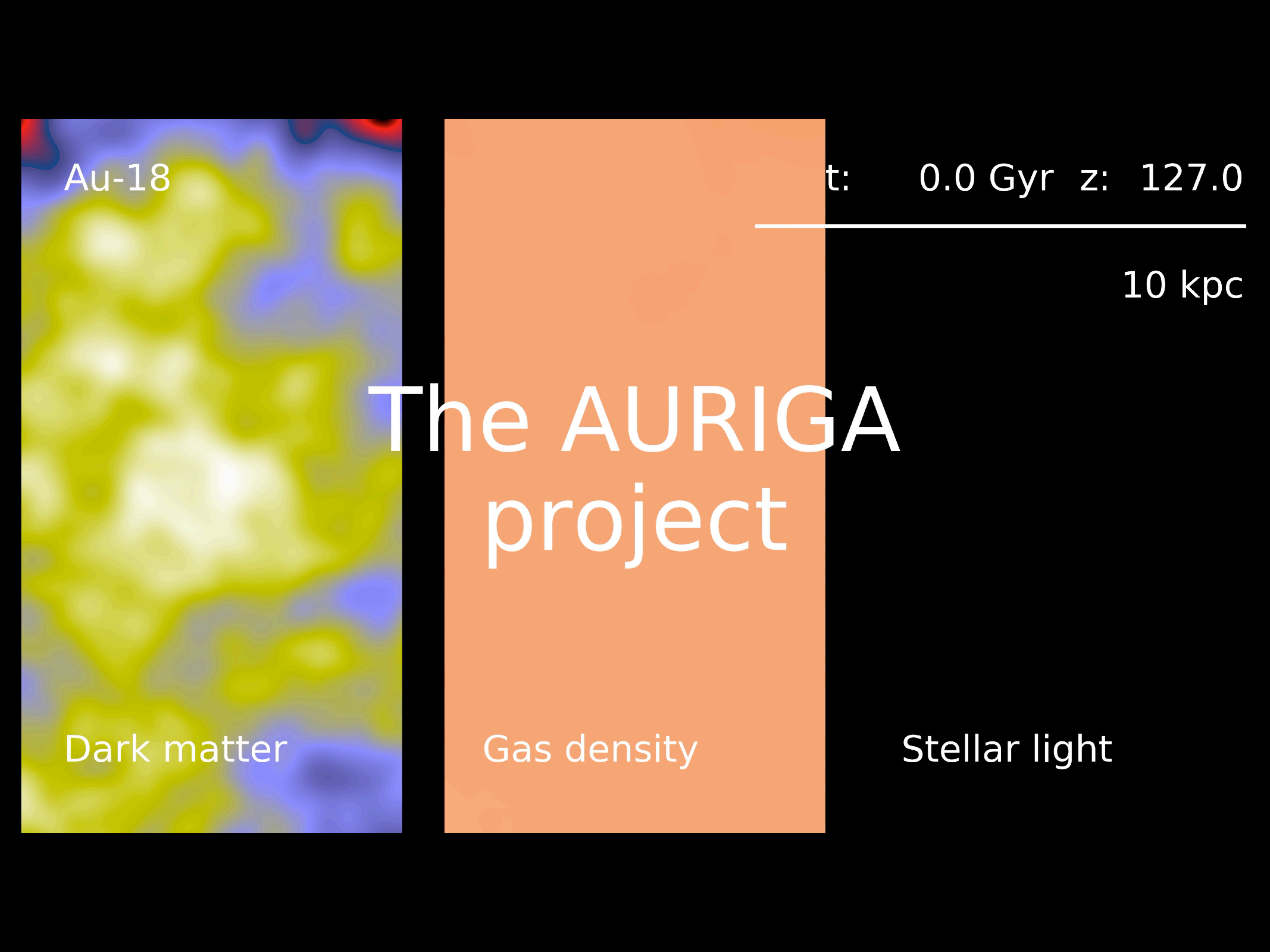
Black holes:
- *seeded at ~10^5 Msun*
- *growth (Bondi accretion)*

Energetic feedback:
- *SNII winds (non-local, thermal+kinetic)*
- *AGN (Radio+quasar)*

Mass & Metal enrichment:
- *SN Ia & AGB (local,isotropic)*

Magnetic fields seeded at 10^{-10}cG at z=128


Au-18
t: 0.0 Gyr z: 127.0
10 kpc
The AURIGA project
Dark matter
Gas density
Stellar light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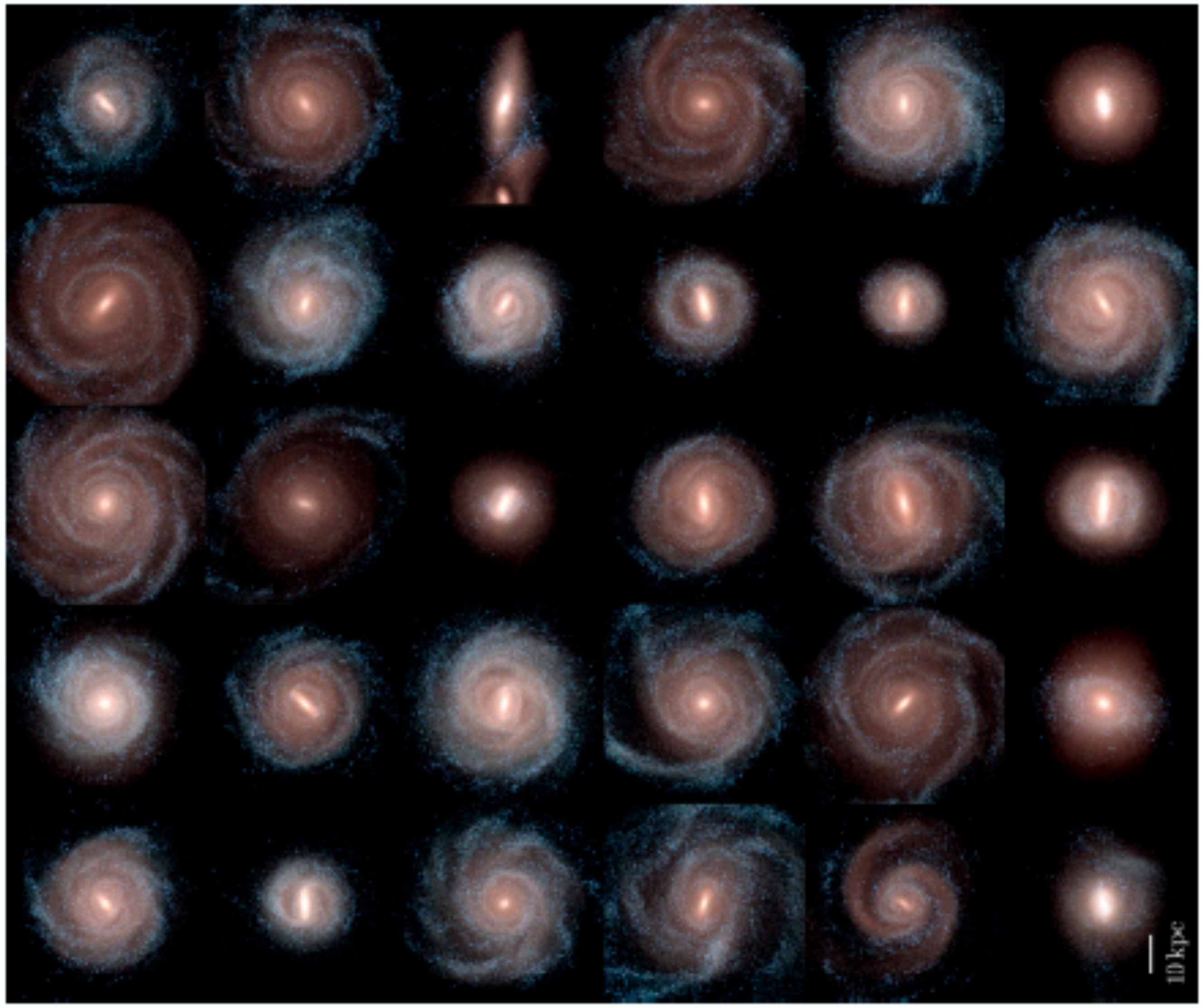
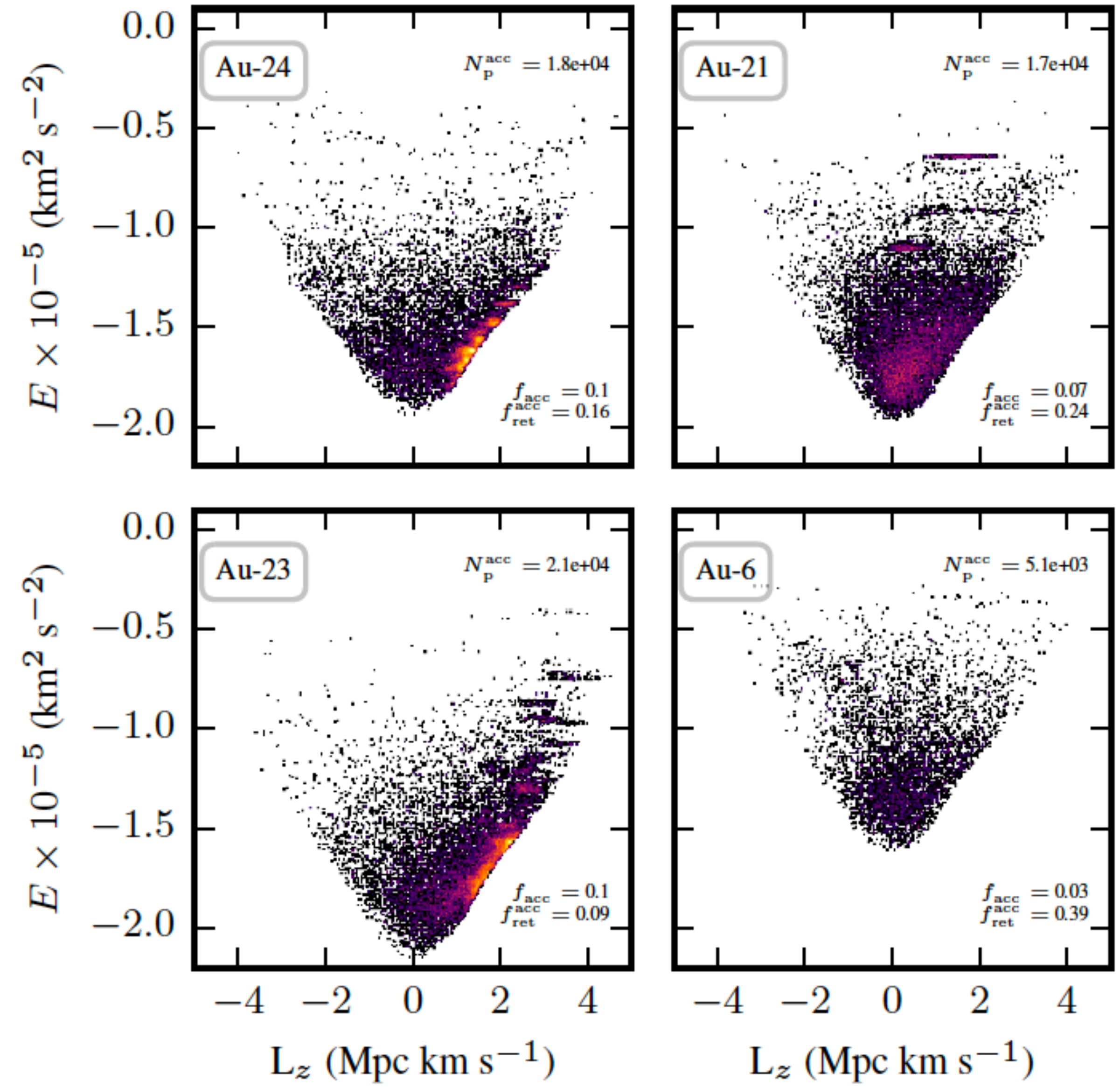
A large suite of **star-forming, disc dominated** MW-mass systems

Grand+17



Simpson+ in prep



$5 \times 10^{11} < M_{vir}/M_{sun} < 2 \times 10^{12}$

40 simulations with:

- ~10^4 Msun per baryonic element

8 simulations with:

- ~10^3 Msun per baryonic element

A range of substructure resolved in local volumes
—> *ideal for testing assumptions*

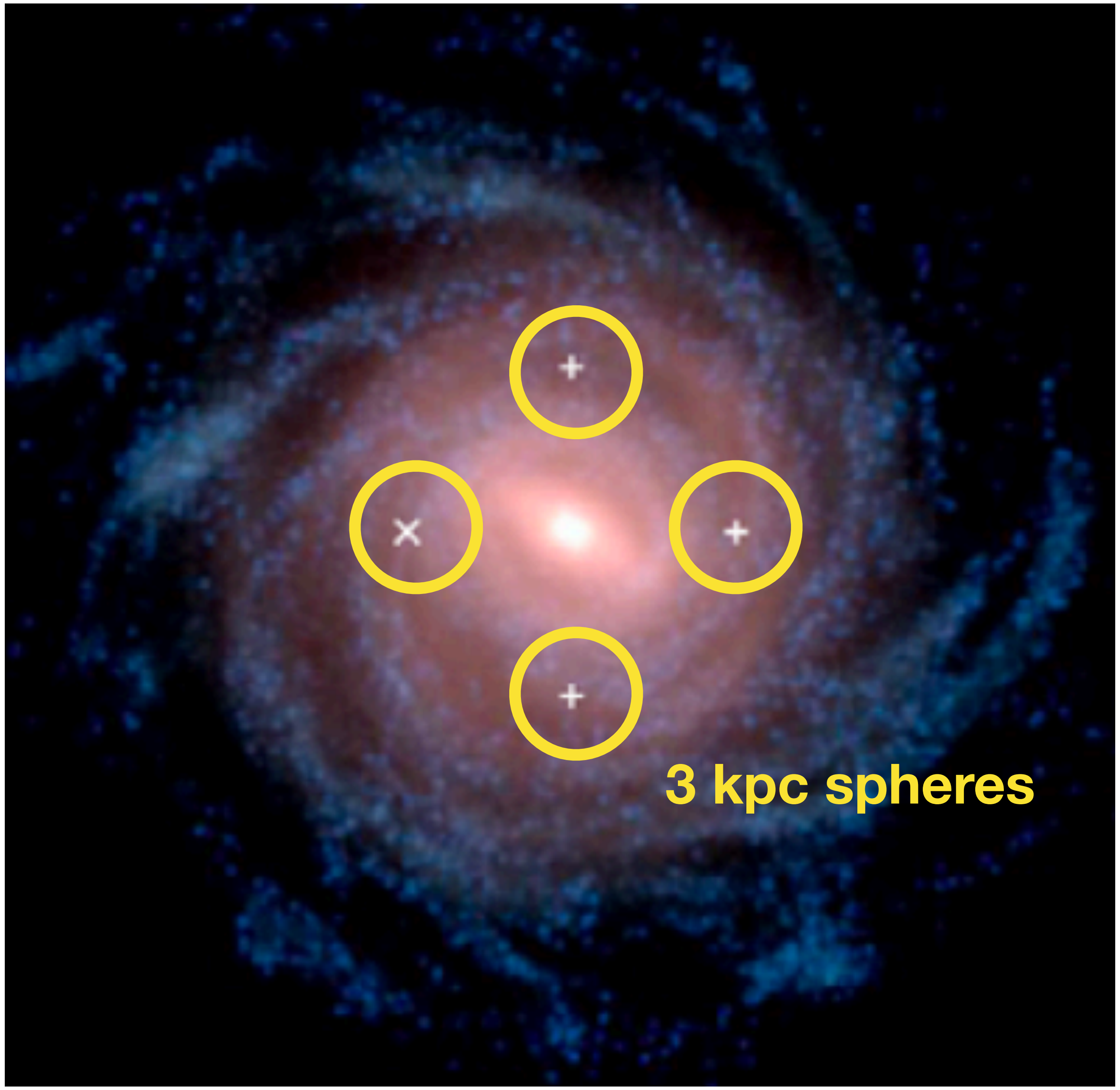
The impact of substructure with Auriga (Grand+ subm.)

30 haloes; 4 solar positions (R=8 kpc, equidistant azimuth) per halo

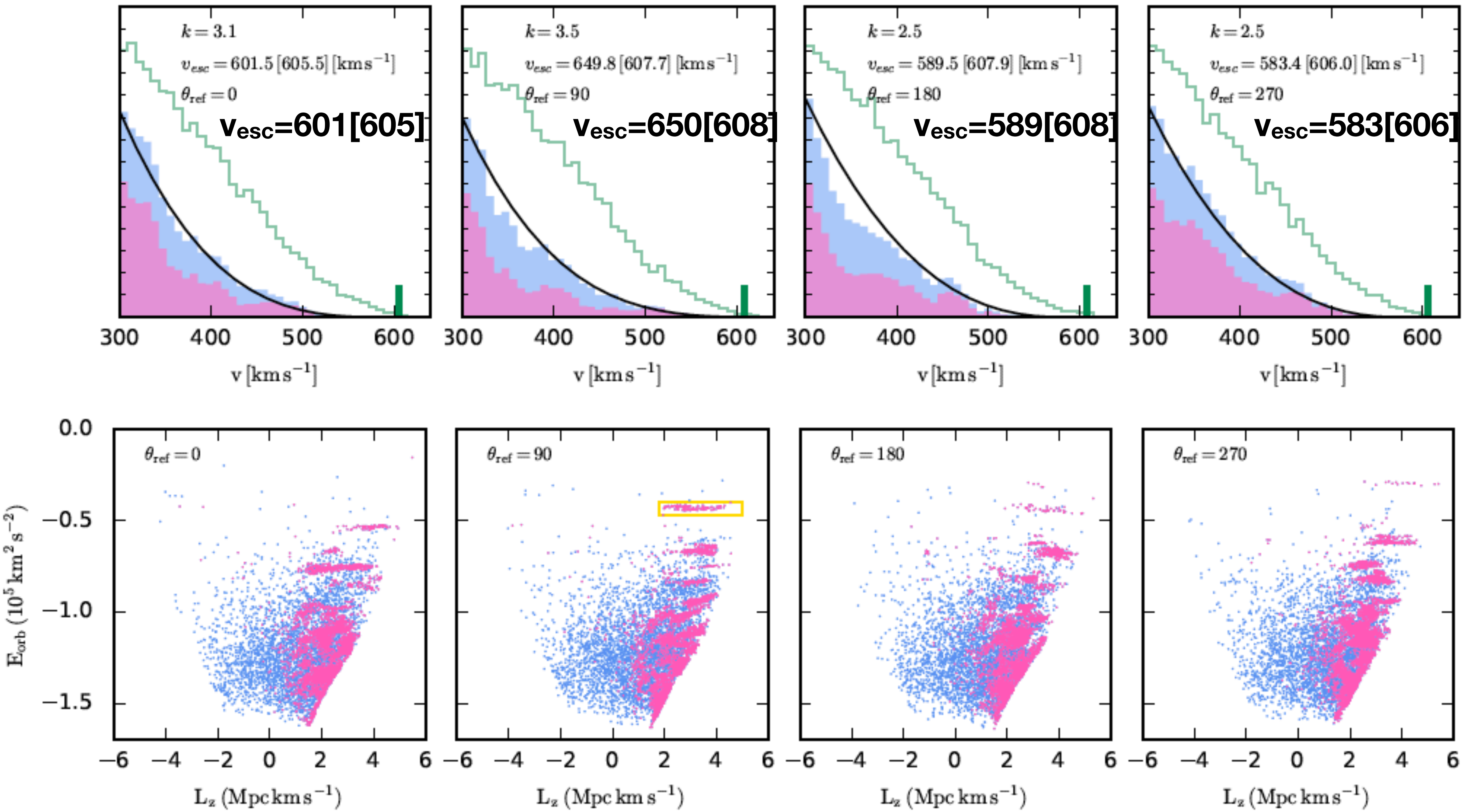
Mimicking the selection from Deason+19:

- Select accreted star particles in each local volume
- Take subsamples of 240 stars until star particles used up (i.e. 4 subsamples in a volume containing 1000 star particles)

—> 892 local accreted star samples



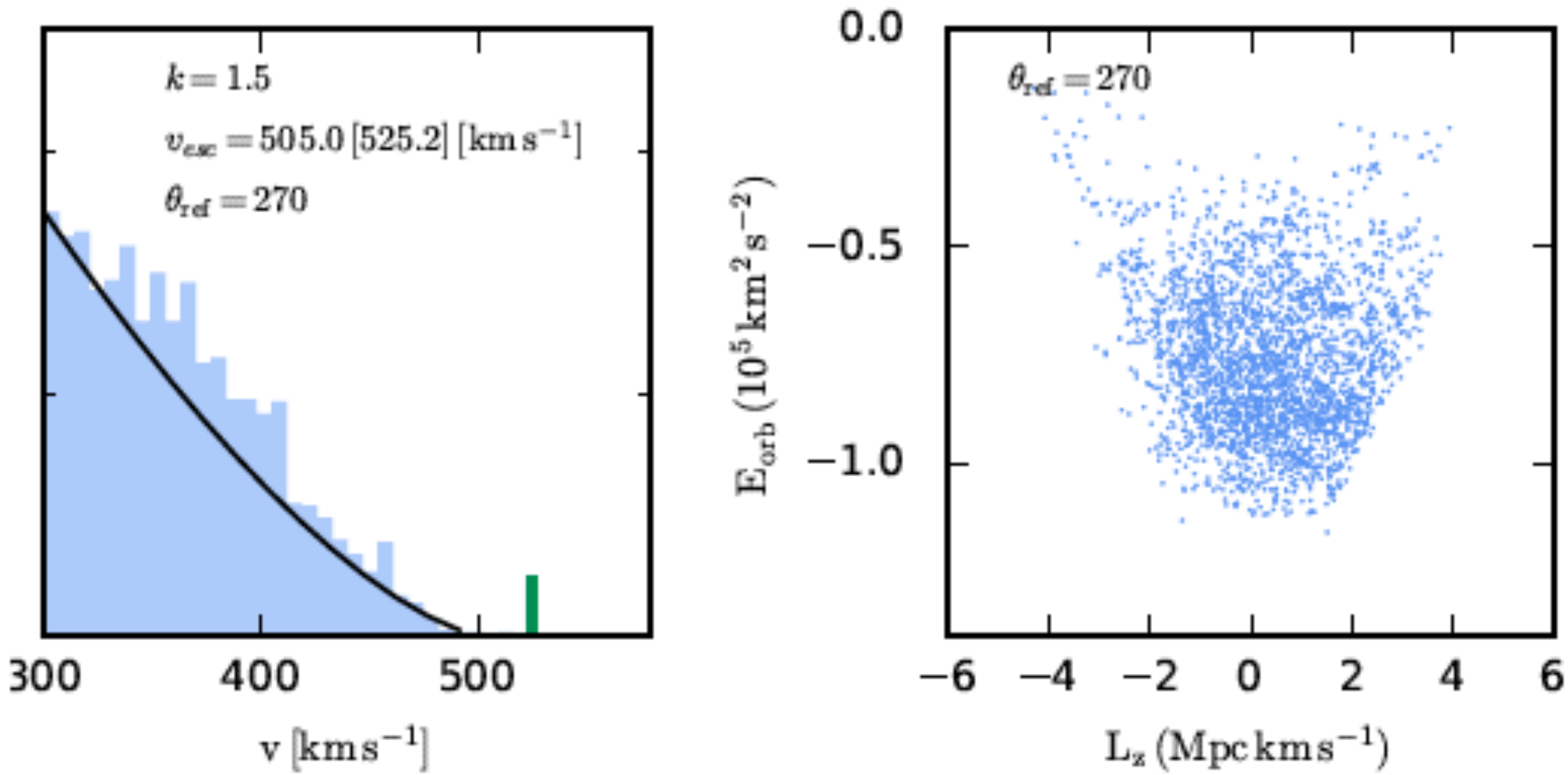
Highly substructured phase space leads to under-/over-estimates



Velocity distribution sporadically populated with bumps (differently at each solar pos)

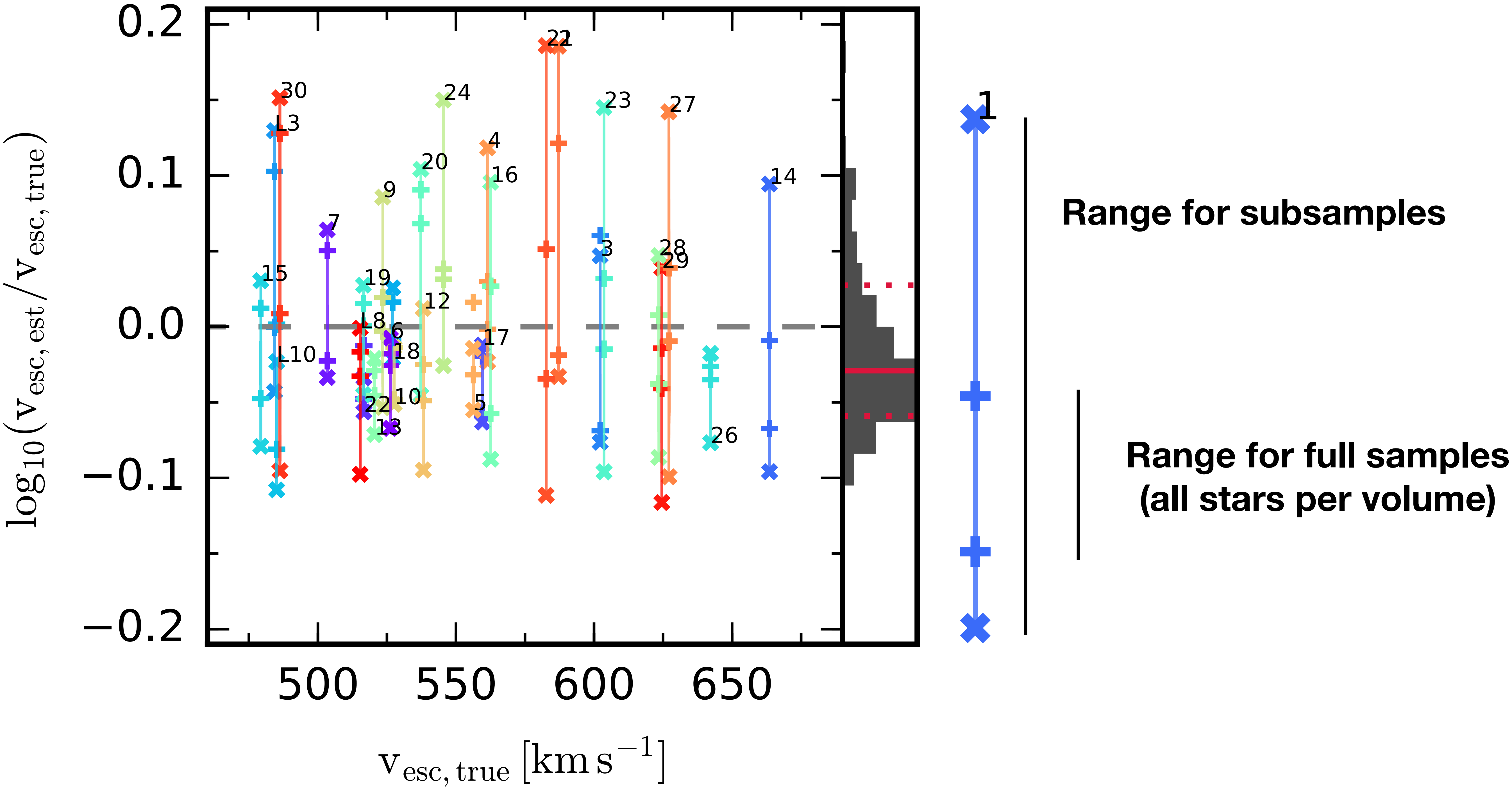
—> range of position-dependent escape velocities

Example of Smooth phase space —> more accurate Escape velocities between positions



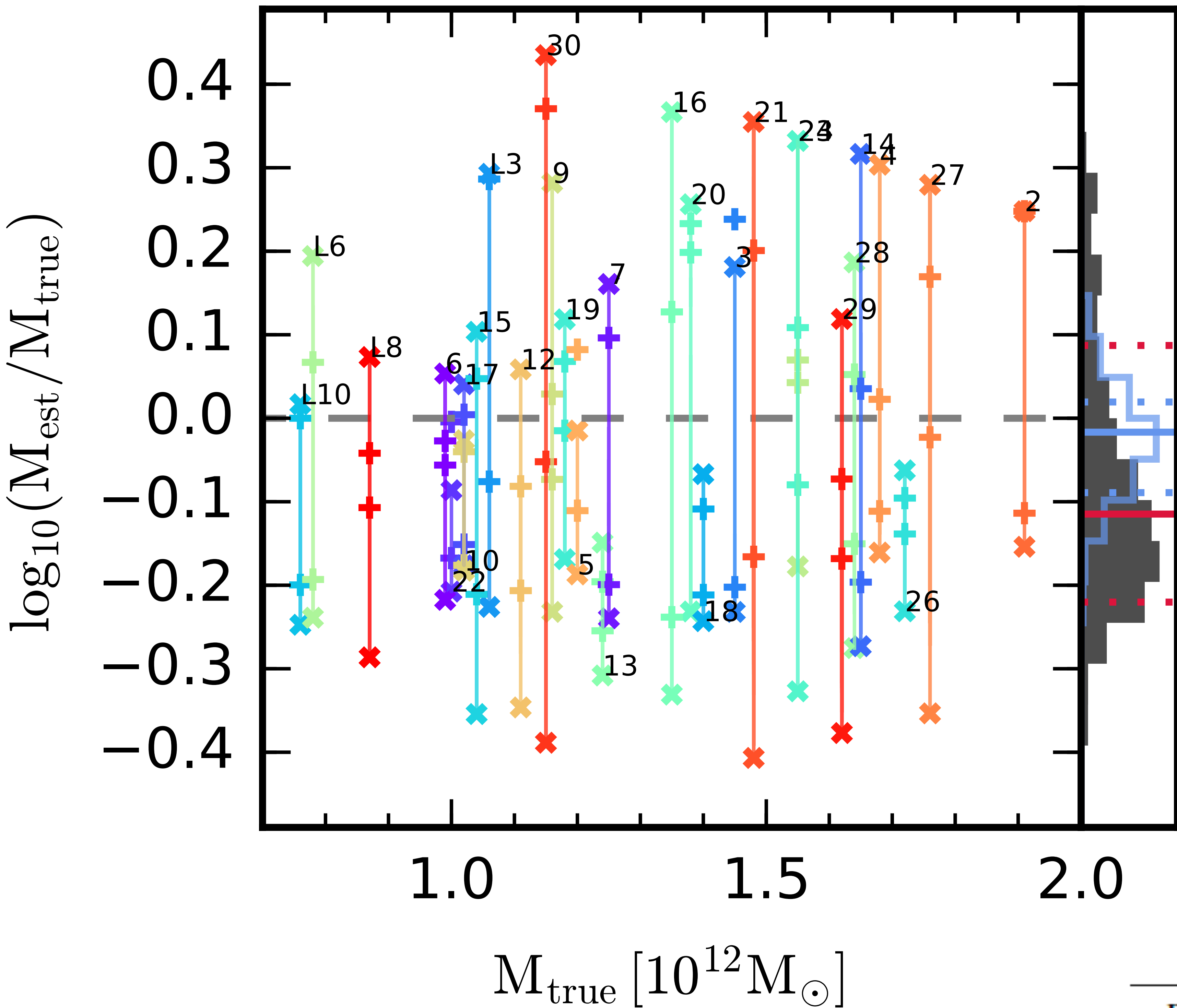
…but sometimes high-velocity tail truncates below true escape speed

Distribution of escape speed estimates across simulation suite



- Generally, subsamples lead to larger scatter (0.1 dex) than full samples
- Mild bias toward underestimates (~10%)

Much larger scatter (~x2) and bias (~20%) for total masses



Scatter:

75% comes from noise and variation of dynamical substructure

25% is spherical NFW dark halo assumption

Bias:

High velocity tail does not reach true escape speed in most haloes

Merger history dependence:

Haloes with largest variations often have late-time mergers

Run	$\log_{10}(M_{*,pk}/M_\odot)$	n_{peri}	$t_{merge}\,[Gyr]$
Au 21	9.52	2	0.34
Au 23	9.73	2	2.67
Au 24	9.59	3	2.67

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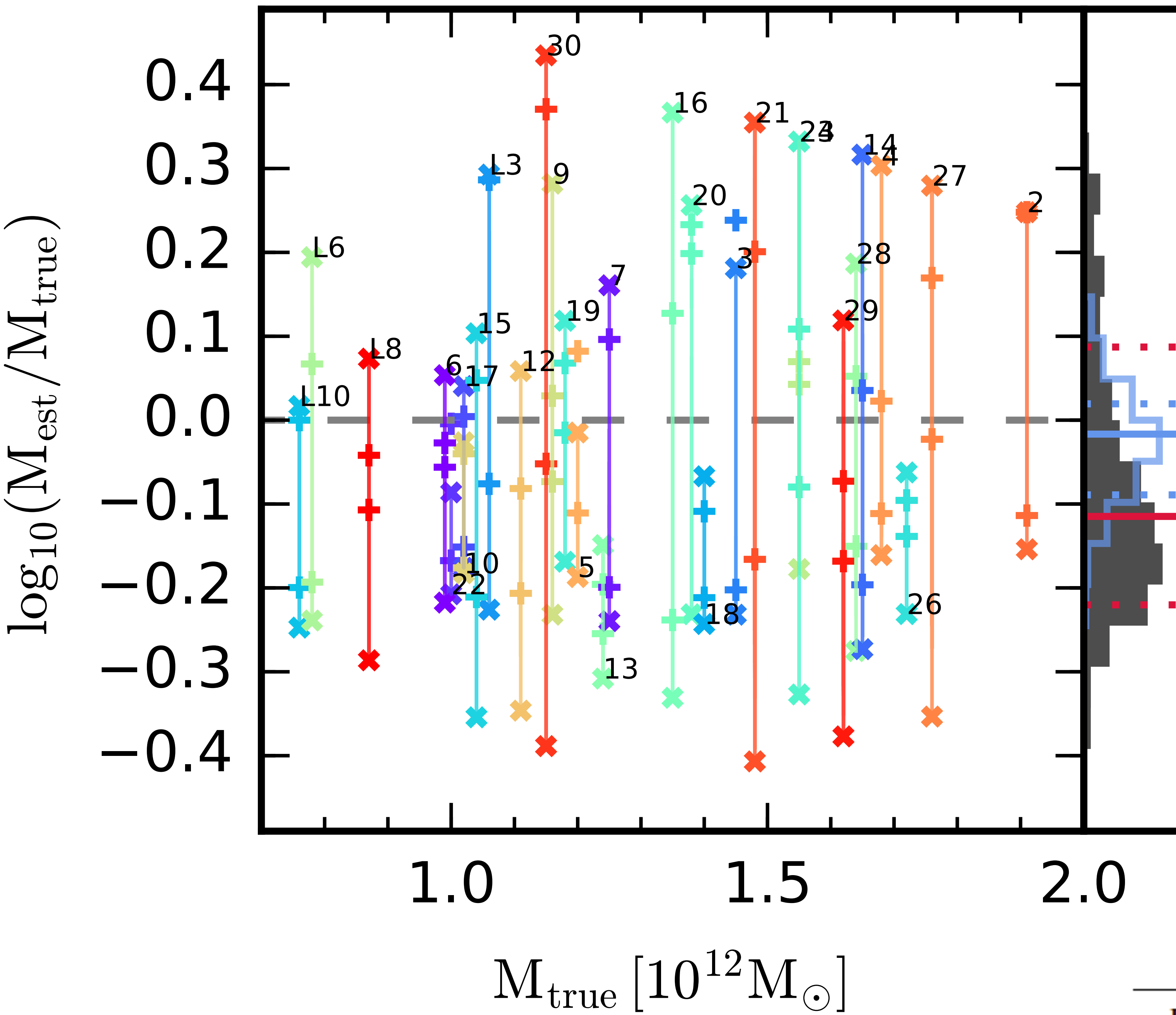

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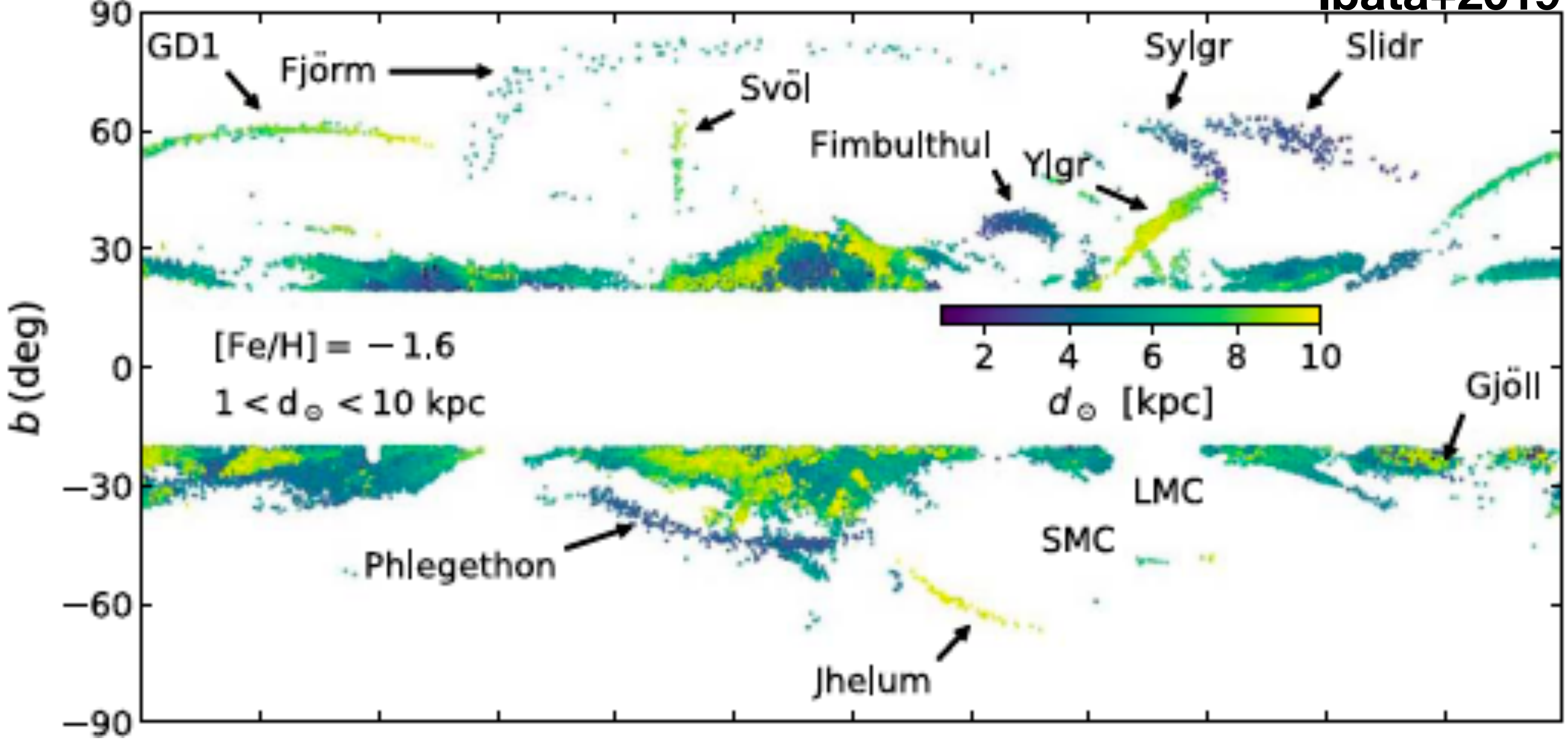
We can revise the mass estimate from Deason+19 to: $1.29^{+0.37}_{-0.47} \times 10^{12}\ M_\odot$

Outlook:

- We know there is substructure in the local vicinity (Helmi+17,Koppelman+18,Ibata+19)
- Larger volume data will likely capture more substructure

Ibata+2019



We need a better understanding of the substructure in the local vicinity in addition to more data to progress with this method