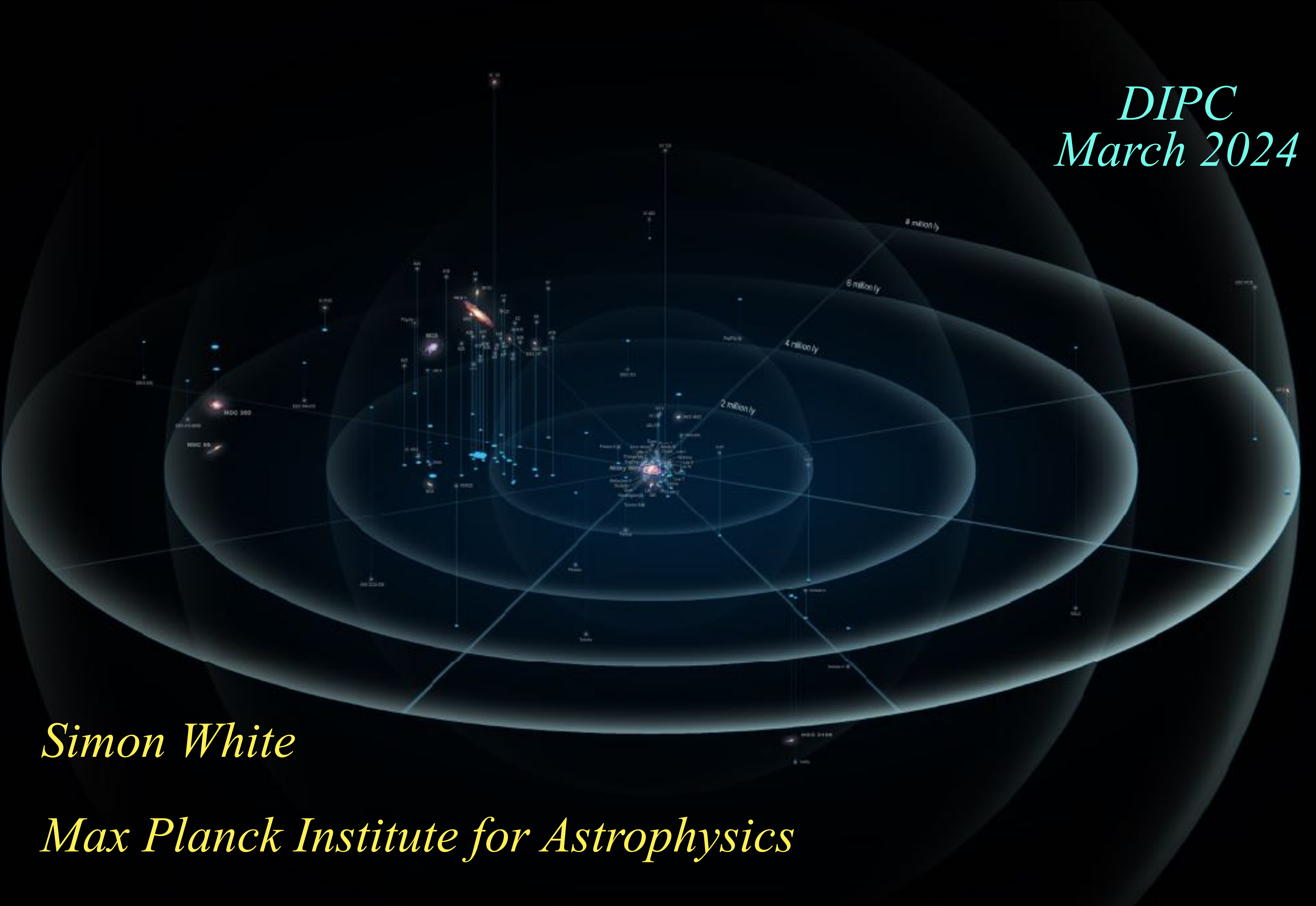
The mass distribution in and around the Local Group

DIPC
March 2024



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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 130 NOVEMBER 1959 NUMBER 3

INTERGALACTIC MATTER AND THE GALAXY

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Received May 18, 1959

ABSTRACT

It is shown that the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter. A detailed discussion shows that this matter consists mainly of ionized hydrogen and that stars can contribute only a small fraction to its total mass. The most likely values for the intergalactic temperature and density are found to be 5×10^5 degrees and 1×10^{-4} proton/cm^3, respectively. It is thought that this gas confines the halo. The distortion of the disk of the Galaxy, revealed by 21-cm observations, is analyzed. This effect cannot be regarded as a relic from a primeval distortion, which occurred at the time of formation of the Galaxy; a more promising explanation for it can be given in terms of the flow pattern of the intergalactic gas past the Galaxy and of the resulting pressure distribution on the halo.

double galaxy. We shall adopt the following data: The masses of M31 and of the Galaxy with their companions are about 4×10^{11} and 1×10^{11} solar masses; their distance apart is 600 kpc (cf. Schmidt 1956, 1957).

The radial velocity of M31 with respect to the local standard of rest near the sun is -296 km/sec, according to the accurate 21-cm data (van de Hulst *et al.* 1957). With a circular velocity of 216 km/sec near the sun (Schmidt 1958), we find that the centers of M31 and of our Galaxy approach each other with a speed of 125 km/sec. An estimated uncertainty of ± 25 km/sec in the circular velocity near the sun makes this figure uncertain by ± 20 km/sec. The fact that the motion is one of approach is significant. For if the Local Group is a physical unit, the Galaxy and M31 are not likely to have been formed very far from each other, certainly not at a much greater distance than their present separation. This indicates that they must have performed the larger part of at least one orbit around their center of gravity during a time of about 10^{10} years. Consequently, their orbital period must be less than 15 billion years. From this we obtain the total mass of the system as follows. According to Kepler's third law, we have

$$P^2 = \frac{4\pi^2}{GM^*} a^3 \leq 2 \times 10^{35} \text{ sec}^2, \tag{1}$$

where M^* represents the effective mass at the center of gravity. To obtain a minimum estimate for M^*, we assume that the system has no angular momentum. Then conservation of energy gives, for our Galaxy,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k, \tag{2}$$

where D denotes the present distance of the Galaxy to the center of gravity (480 kpc) and E_t is its present kinetic energy per unit mass. From these equations we obtain

$$\boxed{M^* \geq 1.8 \times 10^{12} m_\odot ,} \tag{3}$$

which is six times larger than the reduced mass of M31 and the Galaxy.

The Timing Argument modernised

- Using modern values for the MW-M31 separation and relative motion

$\longrightarrow$ $M_{M31+MW} = 4.27 \pm 0.53 \times 10^{12} \, M_{\odot}$ (van der Marel et al 2012)

- …but what is this the mass of? …and where is the mass?

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- If we *assume* ΛCDM, then we can use simulations to *calibrate* the Timing Argument against, for example, the sum of the two halo virial masses,

$\longrightarrow$ $0.35 < \Sigma M_{200c} / M_{TA} < 1.9$, [5%, 95%] range. (Li+White 2008)

- Thus $\Sigma M_{200c} < 1.5$ or $> 8.2 \times 10^{12} M_\odot$ is excluded at 95% confidence.

The total mass of the Milky Way

- Leo I has $D = 261 \pm 13$ kpc, $V_{rad} = 168 \pm 3$ km s^{-1}, $V_{tan} = 101 \pm 34$ km s^{-1}

$\longrightarrow$ $M_{MW}(260\ \text{kpc}) > 1.2 \times 10^{12}\ M_{\odot}$ for it to be bound

$\longrightarrow$ $M_{MW,TA} = 1.6 \times 10^{12}\ M_{\odot}$ from the Timing Argument

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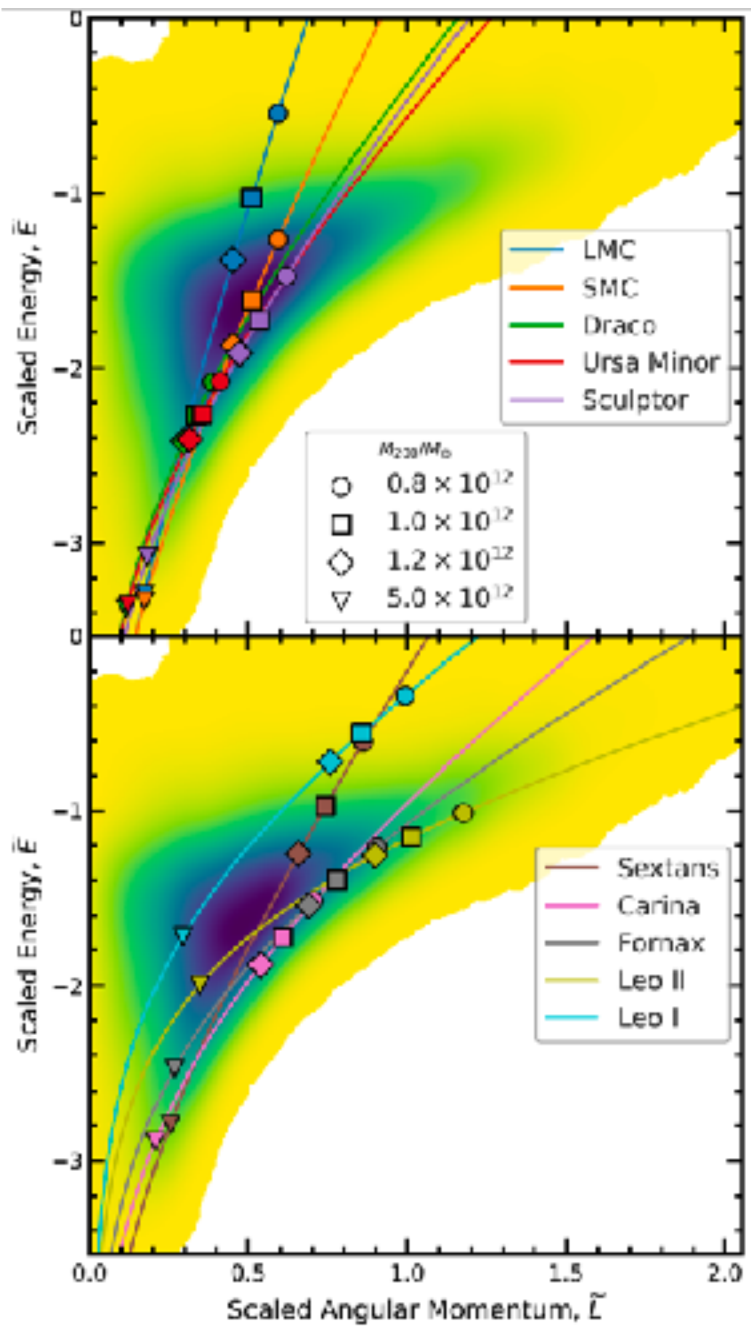

- *Assuming* ΛCDM, we can use simulations to *calibrate* the relation between satellite orbits and M_{200c}

- Post-Gaia, full orbital information is available for all ten classical dwarf satellites of the Milky Way

→ M_{200c} = 1.2 ± 0.2 x 10^{12} $M_{\odot}$ (Callingham et al 2019)

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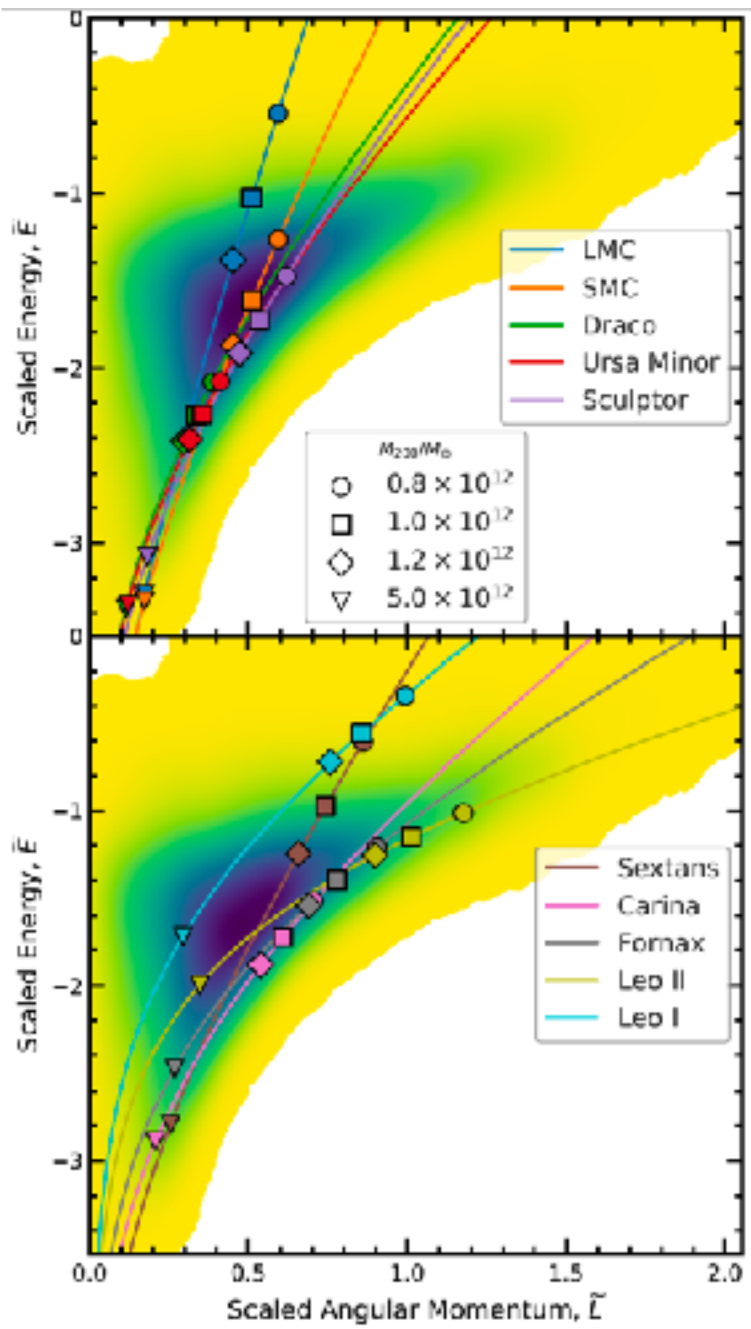

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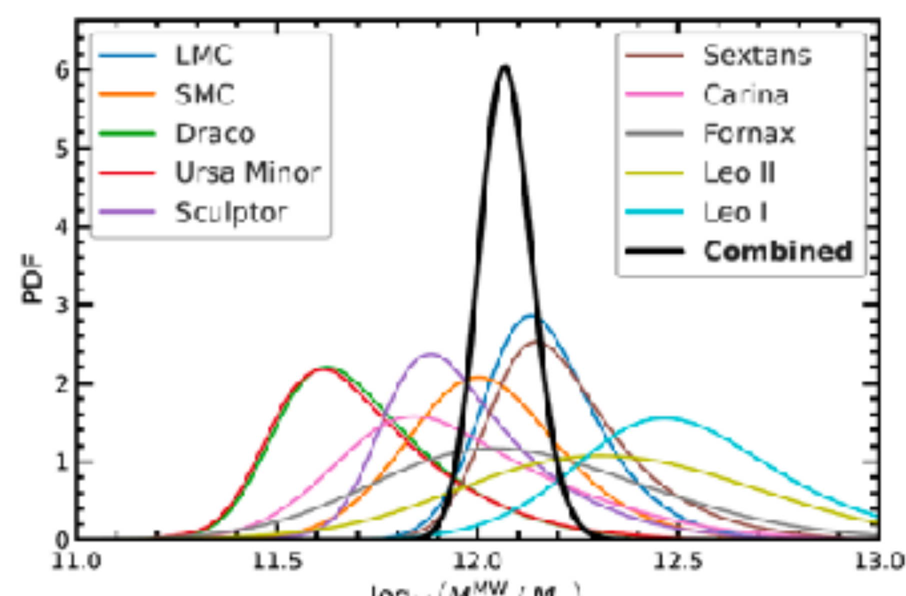
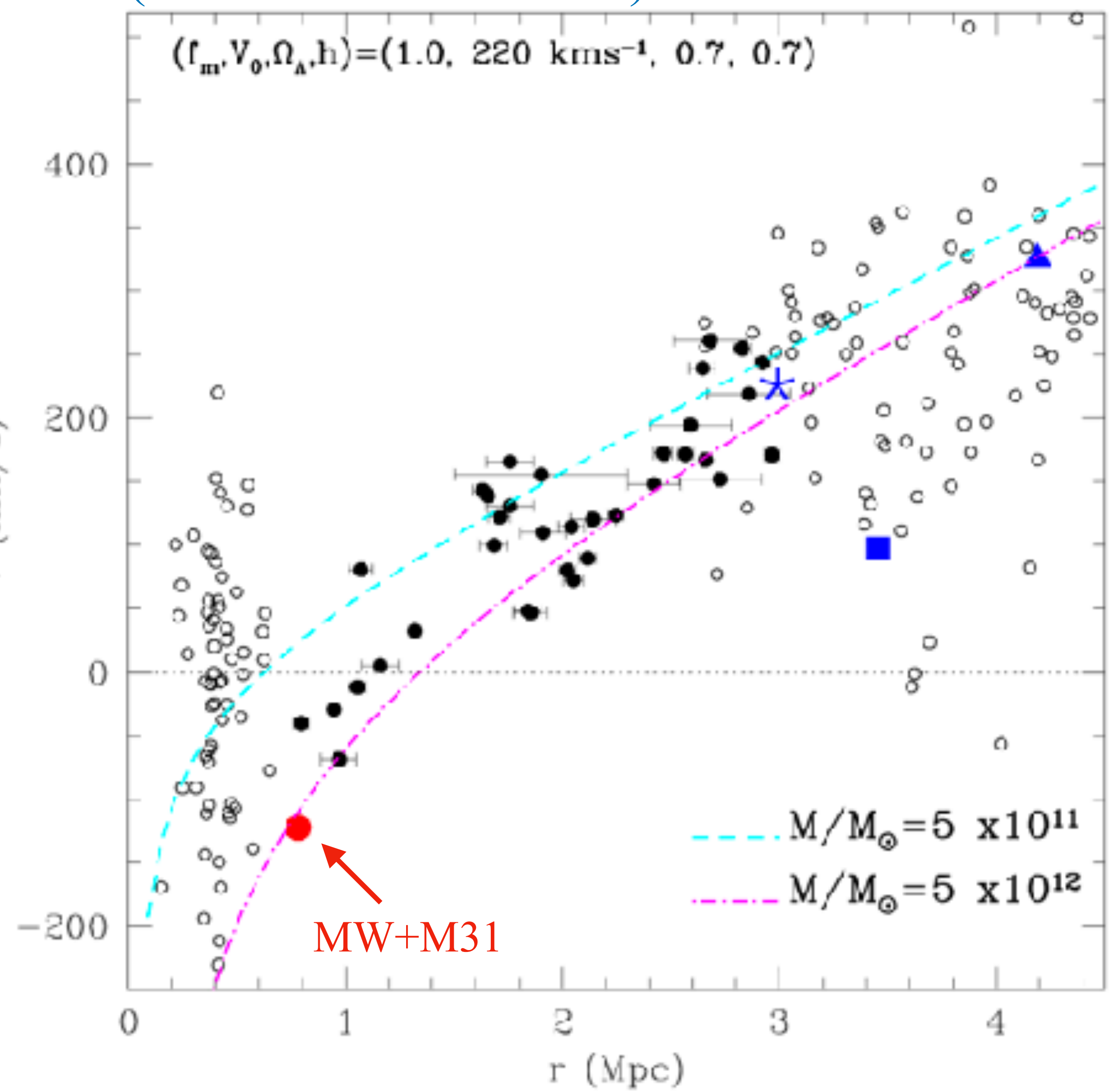
- For this mass, Leo I is unlikely but not impossible



The quiet local Hubble flow

(Penarrubia et al 2014)



- The relatively quiet Hubble flow around the Local Group puts limits on the mass in the region
- The magenta curve assumes the *only* mass in this region is that implied by the TA
- Best fit of this model to the solid points

$\rightarrow$ $M_{MW+M31} = 2.3 \pm 0.7 \times 10^{12}\ M_\odot$
with $M_{MW} \sim 0.5\ M_{M31}$

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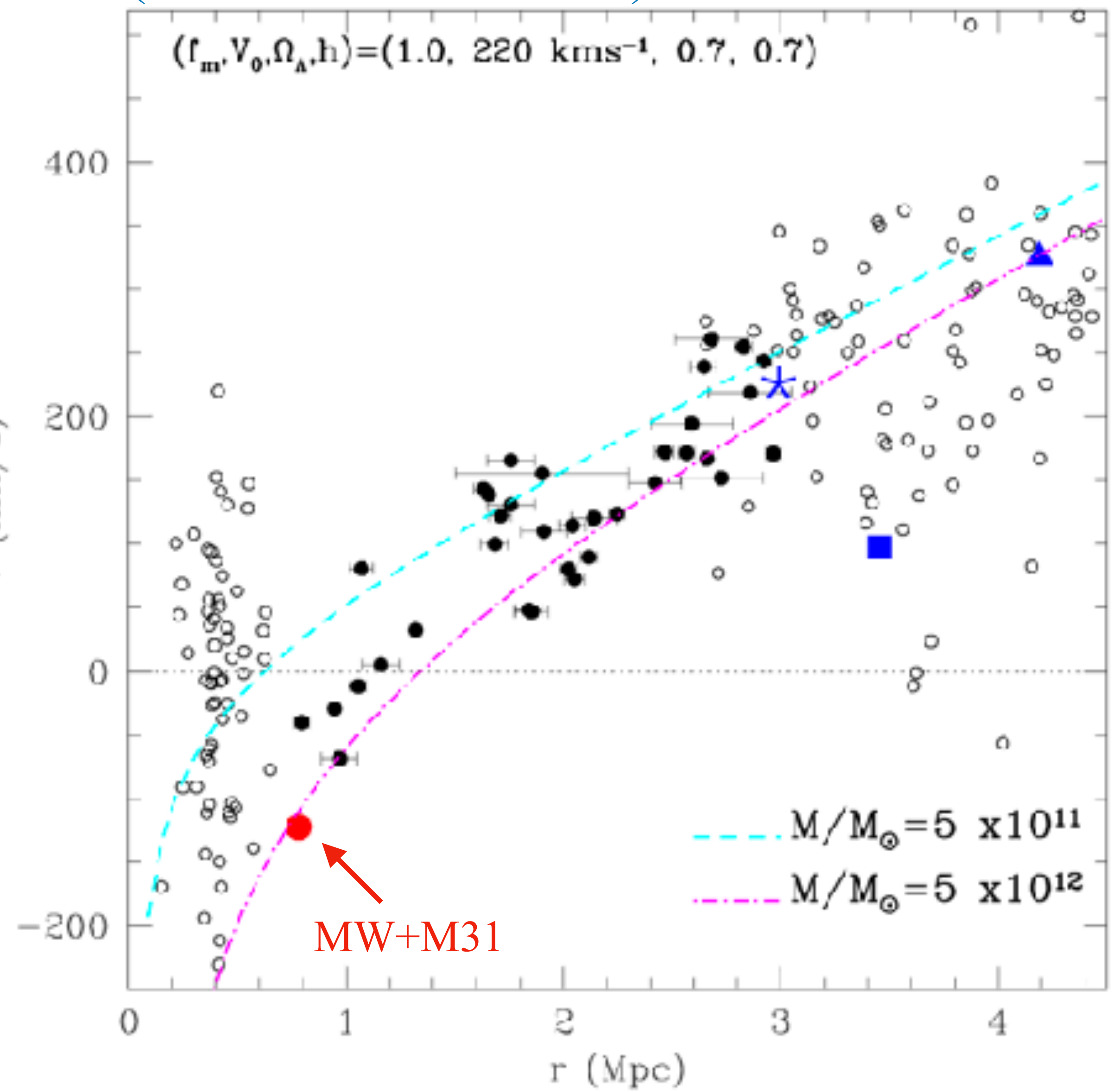

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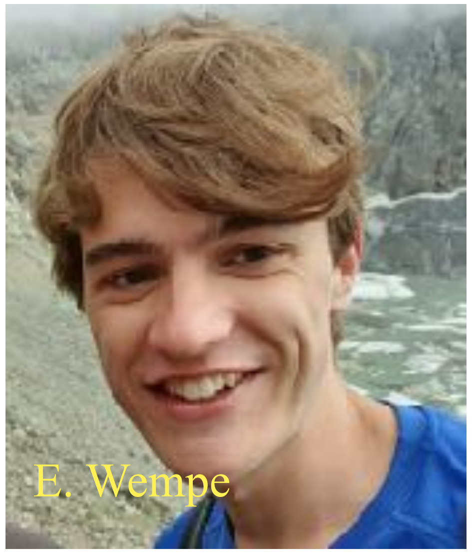
$\longrightarrow$ $M_{MW+M31} = 2.3 \pm 0.7 \times 10^{12}\, M_\odot$ with $M_{MW} \sim 0.5\, M_{M31}$

- This is a factor of two smaller than the TA value of M_{MW+M31}
- There must be mass within 3 Mpc in addition to $M_{MW} + M_{M31}$
- Are all these measurements mutually consistent with ΛCDM?

A Bayesian approach to the local mass distribution



Ewoud Wempe, G. Lavaux, J. Jasche, A. Helmi + SW

The Prior: A *Planck* ΛCDM cosmology

The Data: (i) Tracer kinematics in the MW halo, summarised as a filtered mass and its uncertainty

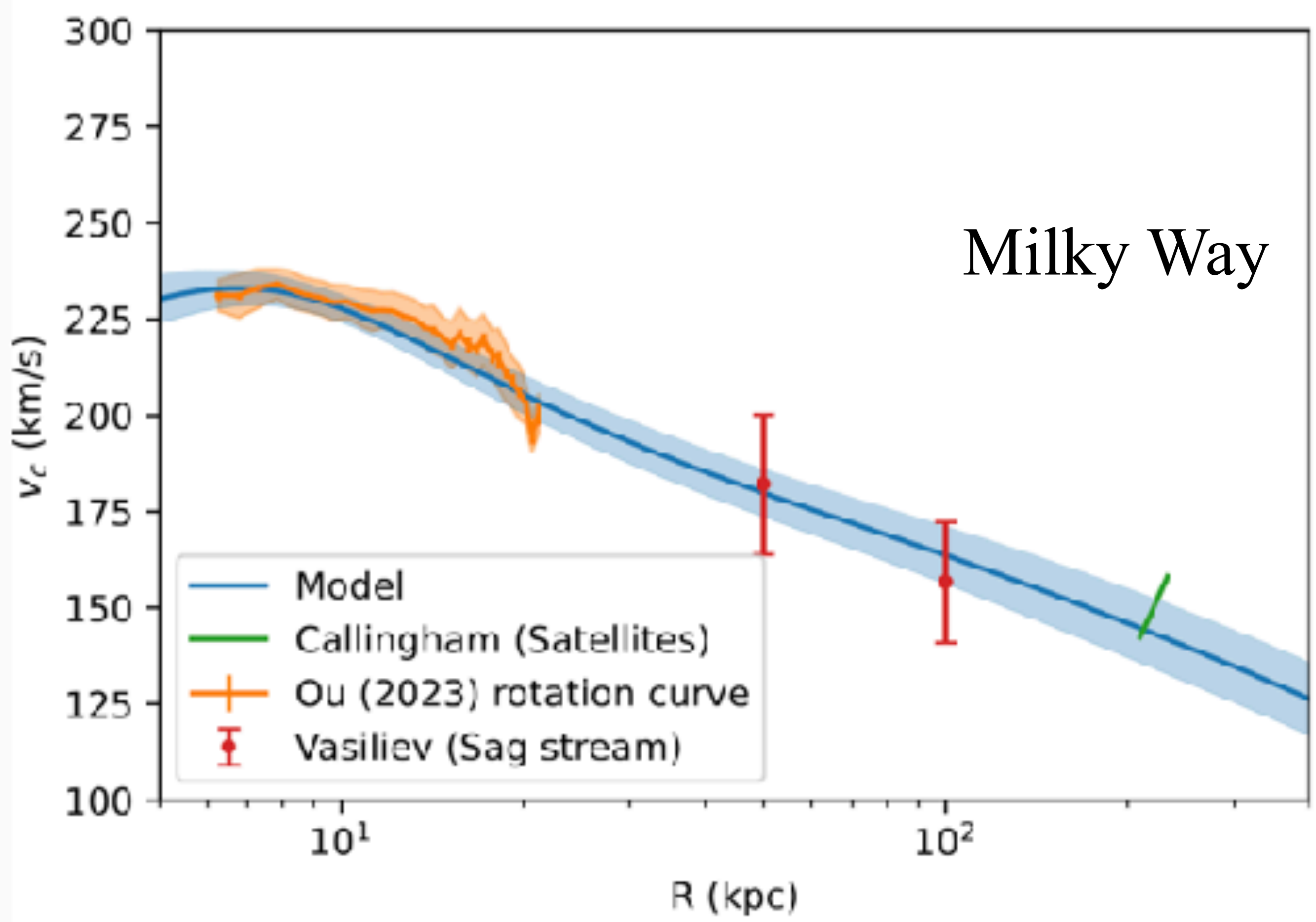
(ii) Tracer kinematics in M31's halo, again summarised as filtered mass and its uncertainty

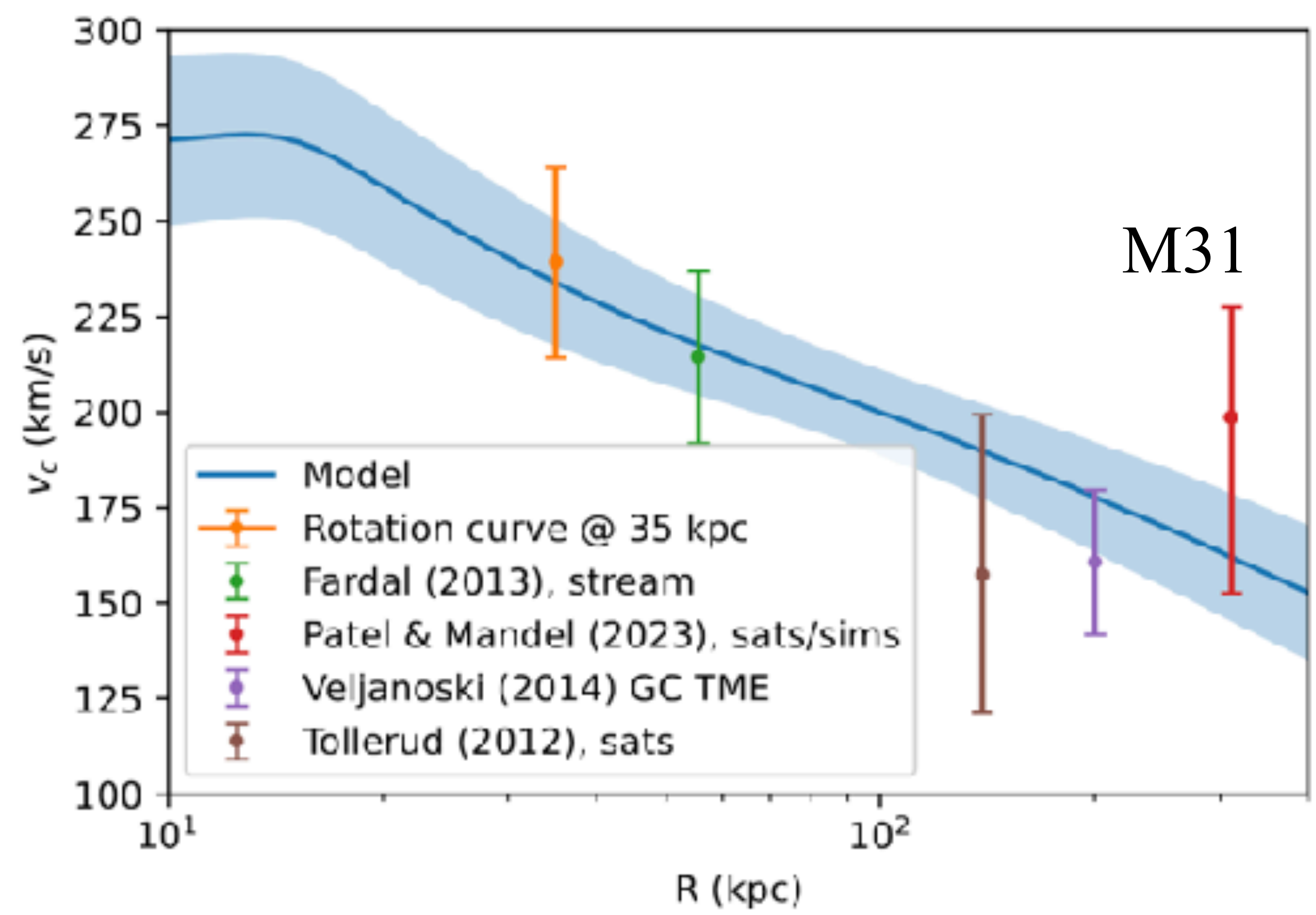
(iii) Positions and relative velocity of the MW and M31

(iv) Positions and peculiar velocities of dwarfs at $1 < d/\text{Mpc} < 4.5$

The Posterior: A statistically representative sampling of mass distributions and assembly histories for the Local Group and its surroundings given the observed dynamical constraints

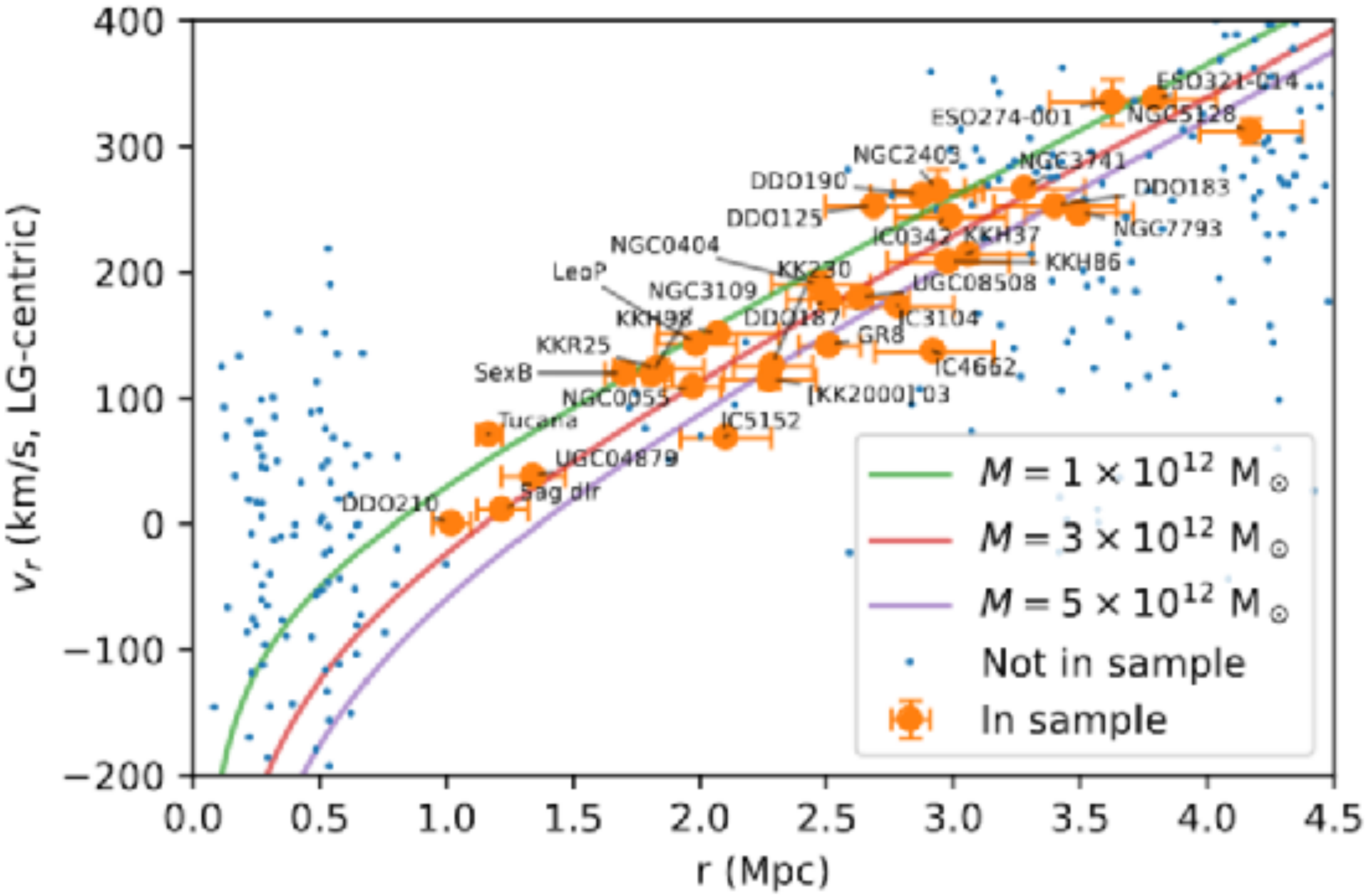
The required constraints on the two halos



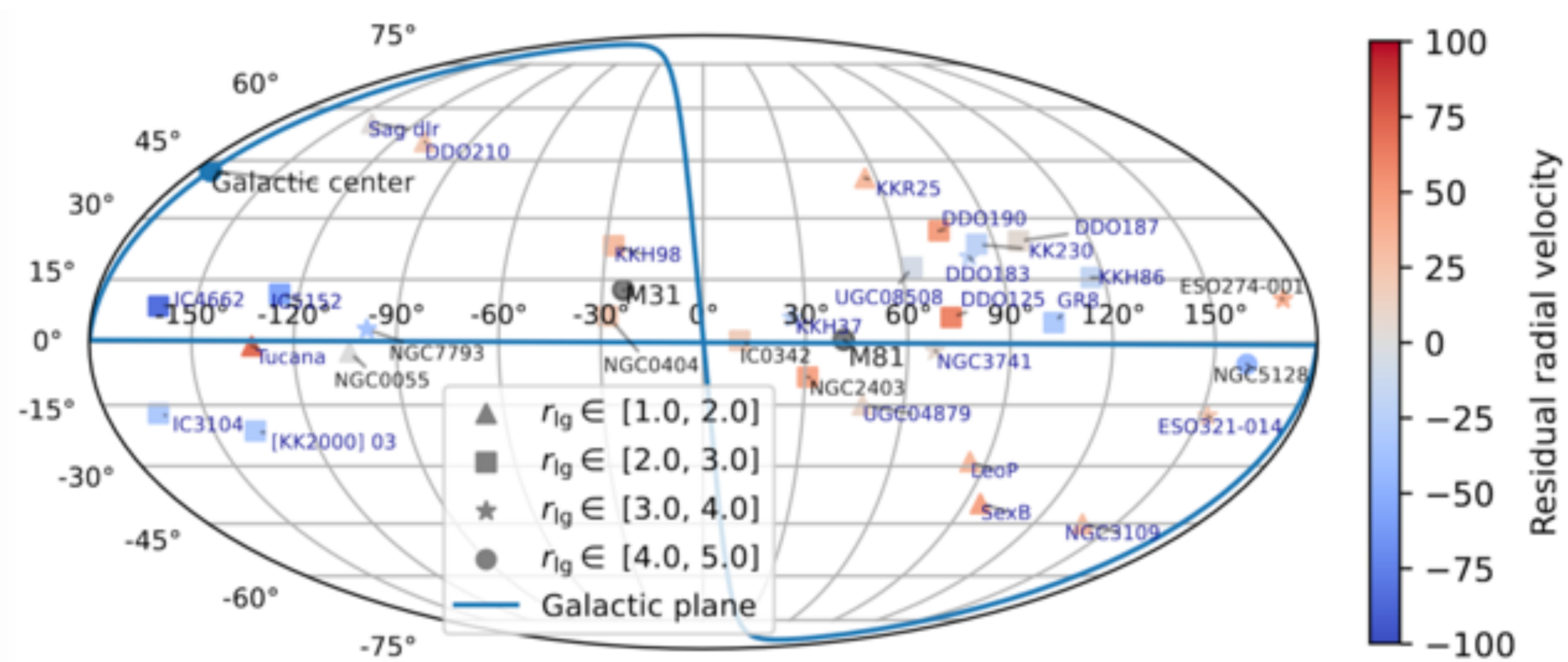


- The measurements at larger radii all assume an NFW-like potential
- Different measurements have different systematic uncertainties
- We constrain the mass filtered with a 3D gaussian, $\sigma = 100$ kpc
- The (filtered) barycentres must match the observed positions within 30 kpc
- The (filtered) relative velocity must match the observation within its errors

The required constraints on the local Hubble flow

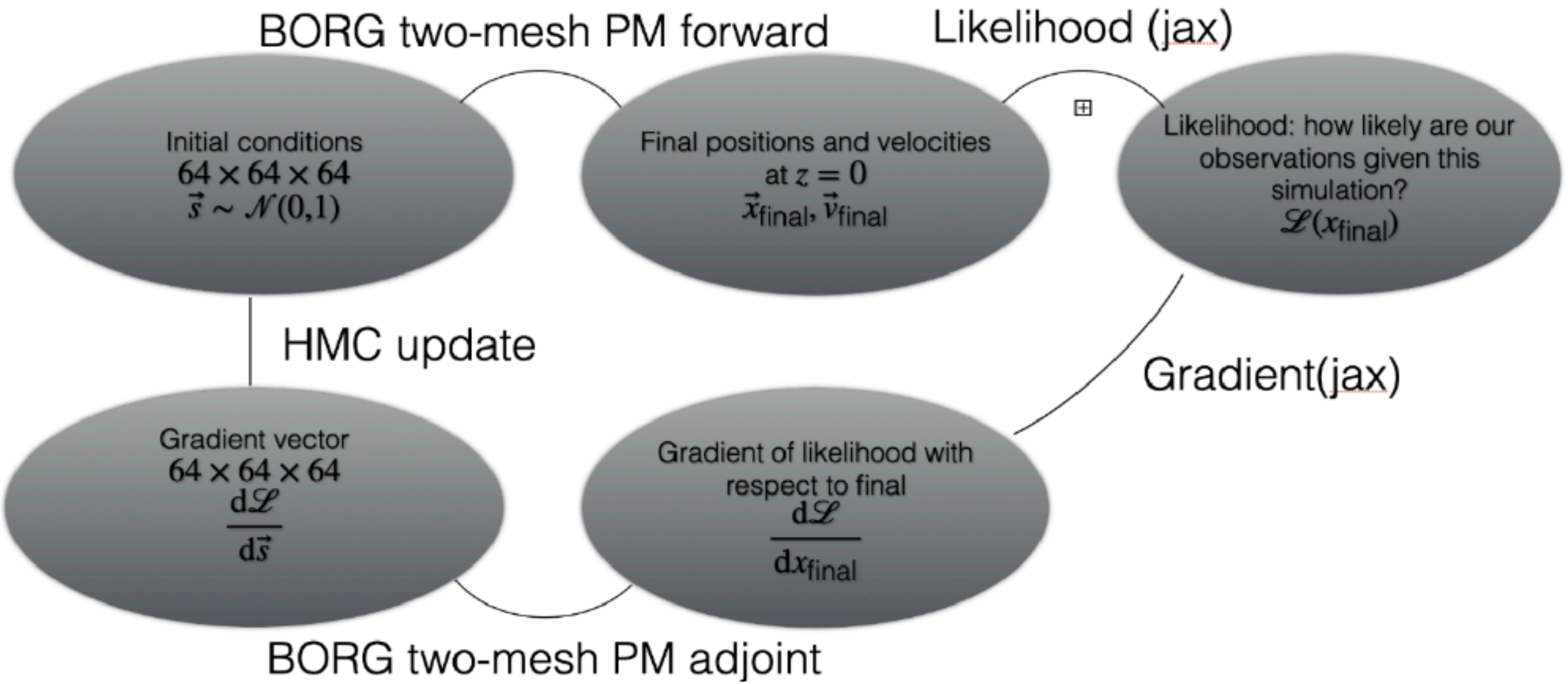


- 31 isolated galaxies with distances $1.0 < r_{LG}/\text{Mpc} < 4.5$
- Exclude satellite galaxies and M81
- Match smoothed peculiar velocity of each to that observed



- Most of these are near the Supergalactic Plane

Hamiltonian Monte Carlo Markov Chains



$$\log P(\boldsymbol{s}) = \log \pi(\boldsymbol{s}) + \log \mathcal{L}(F(\boldsymbol{s}))$$

$$H(\boldsymbol{s}, \boldsymbol{p}) = -\log P(\boldsymbol{s}) + \frac{1}{2}\boldsymbol{p}^T \boldsymbol{M}^{-1} \boldsymbol{p}$$

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}\tau} = -\frac{\partial H}{\partial \boldsymbol{s}} = \boldsymbol{\nabla} \log P(\boldsymbol{s})$$

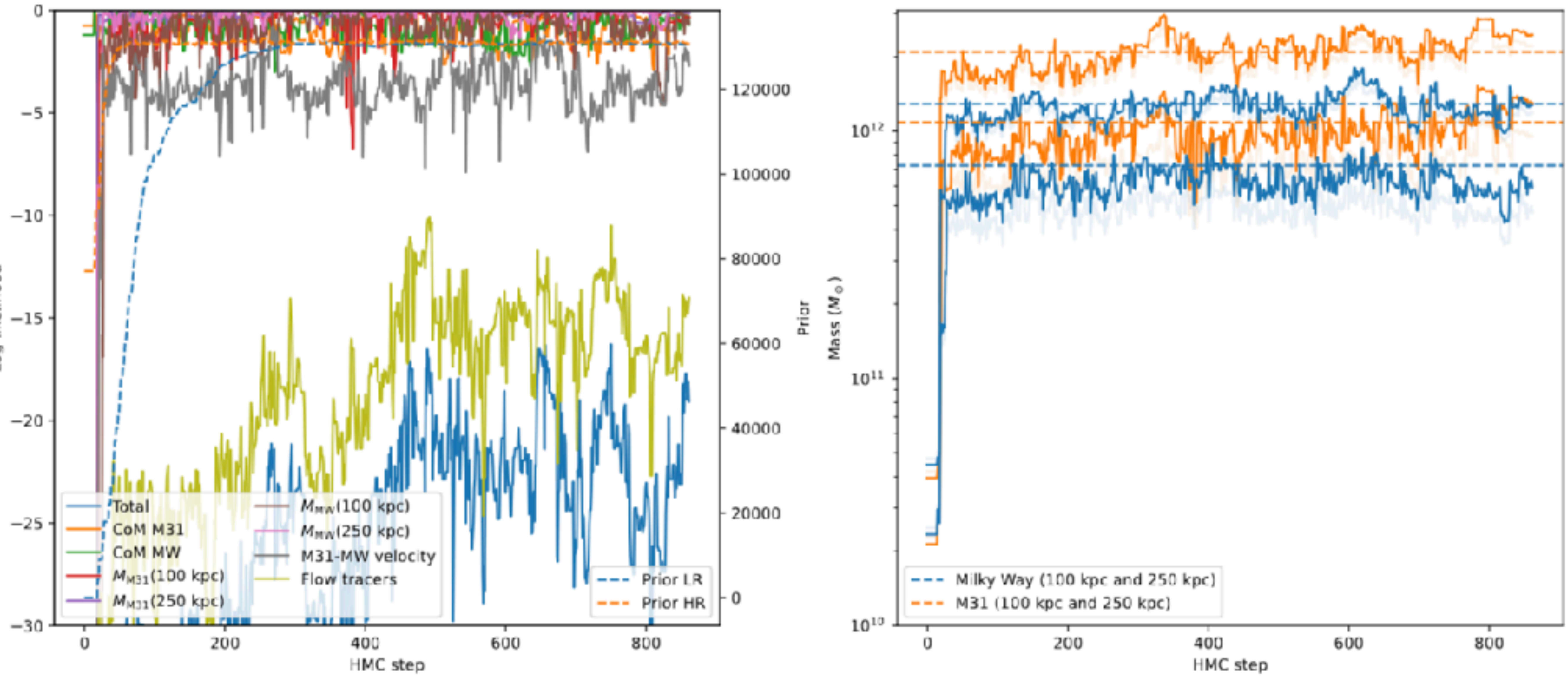
$$\frac{\mathrm{d}\mathbf{s}}{\mathrm{d}\tau} = \frac{\partial H}{\partial \boldsymbol{p}} = \boldsymbol{M}^{-1}\boldsymbol{p}$$

The following results are all preliminary!

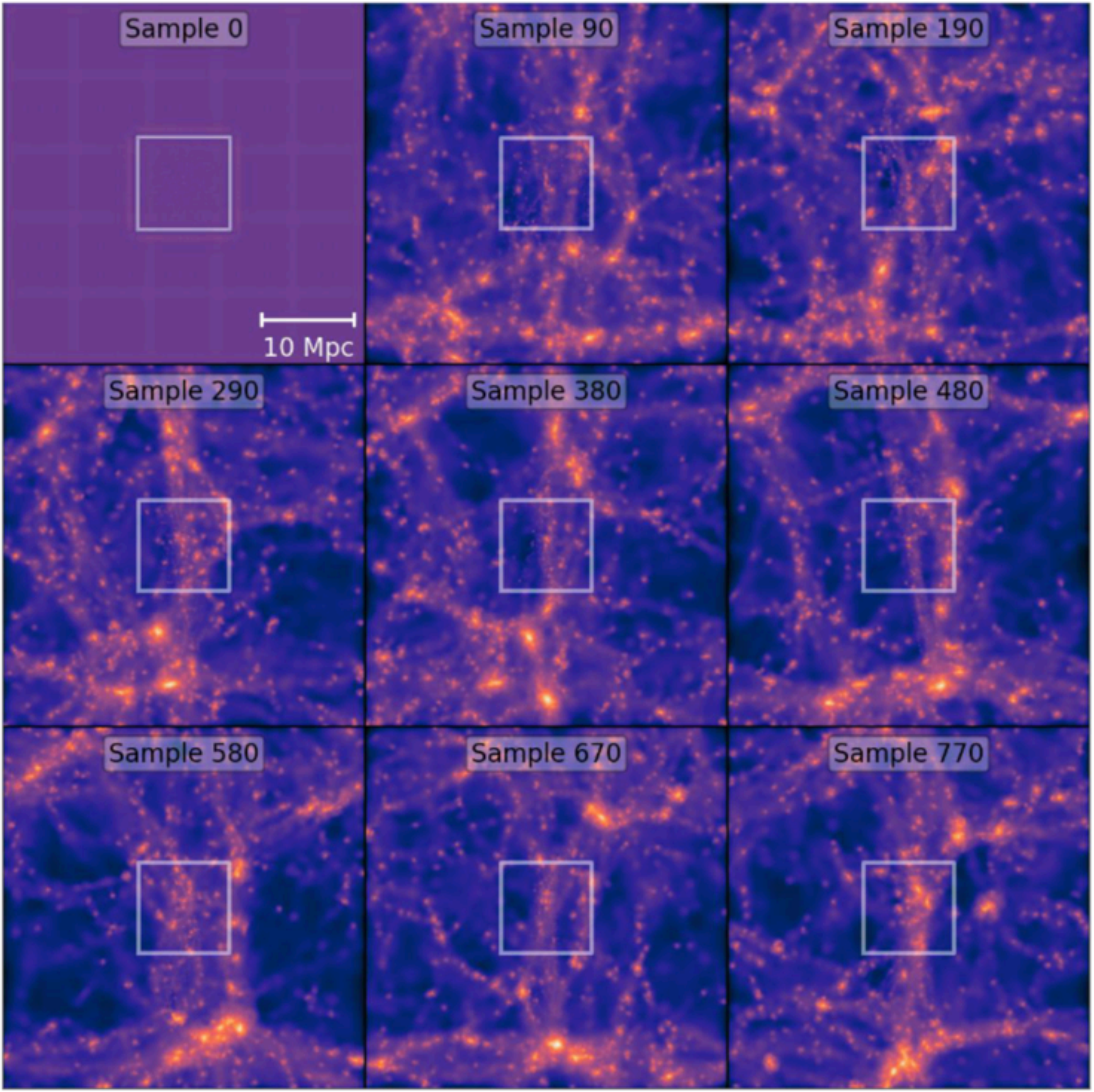
Convergence of the chains

Log Likelihoods

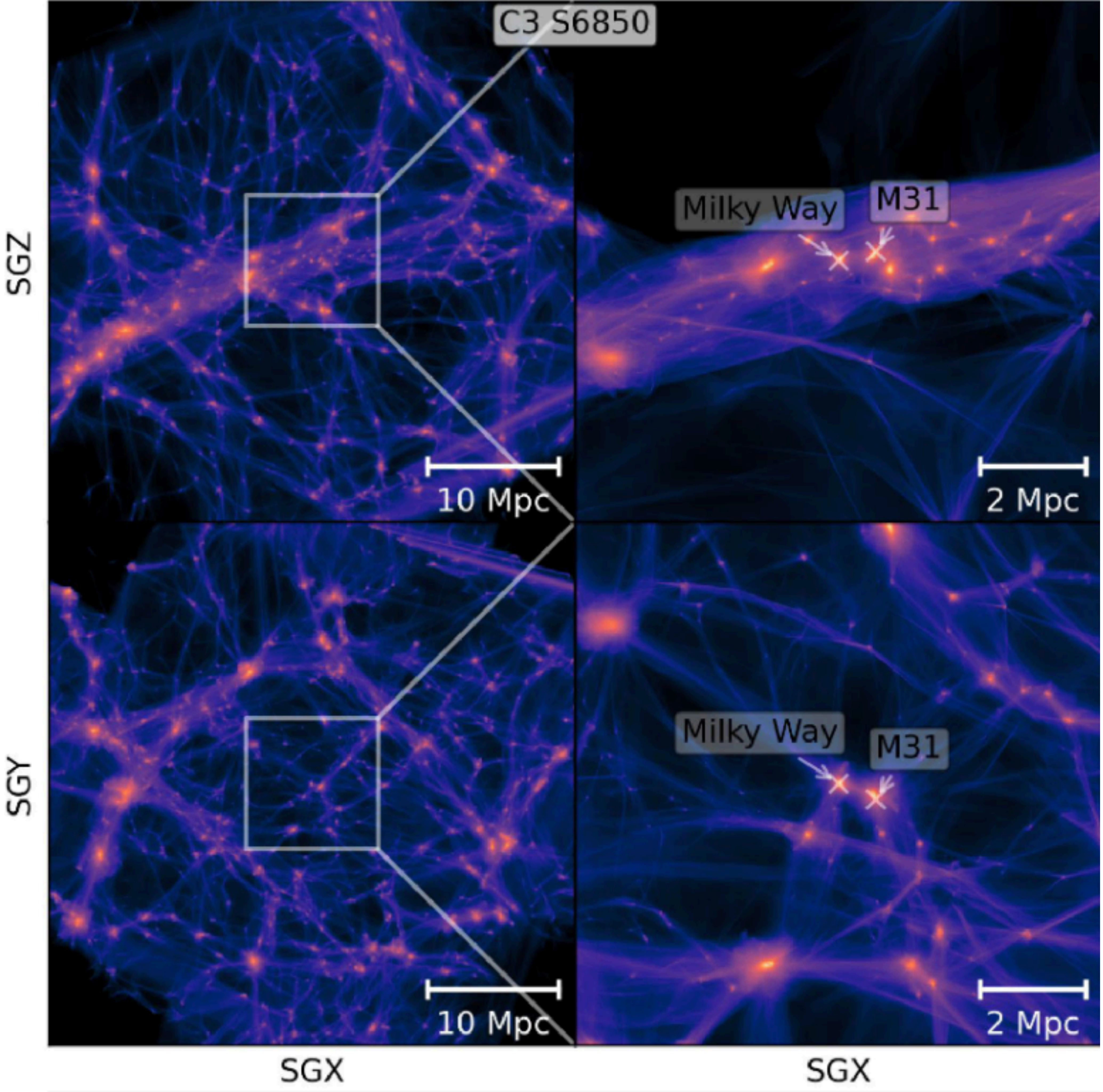
Filtered halo masses



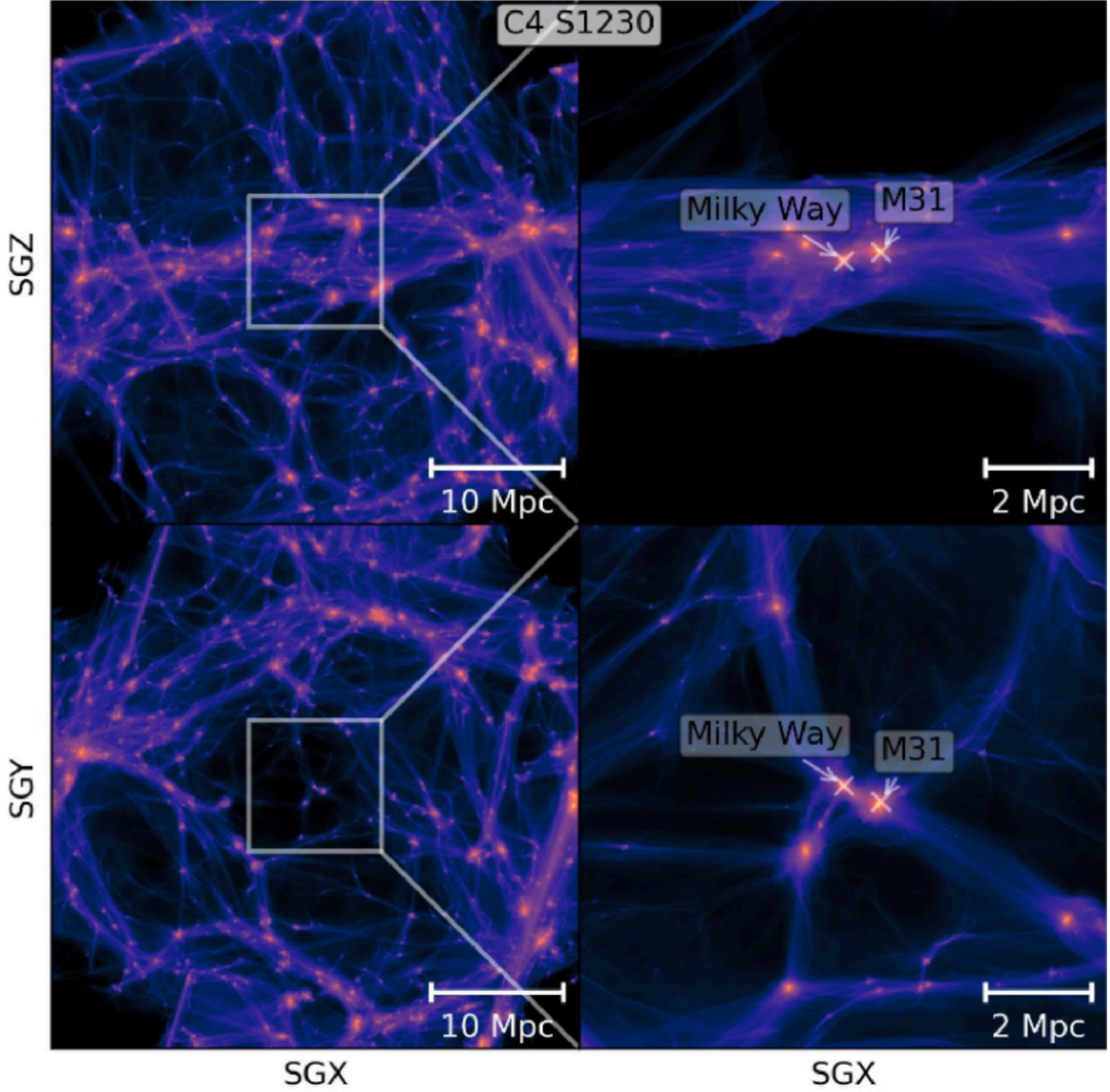
- The scheme is able to match all constraints simultaneously
- The flow tracer velocities currently take longest to "burn in"



Large-scale field along a chain



Independent converged examples



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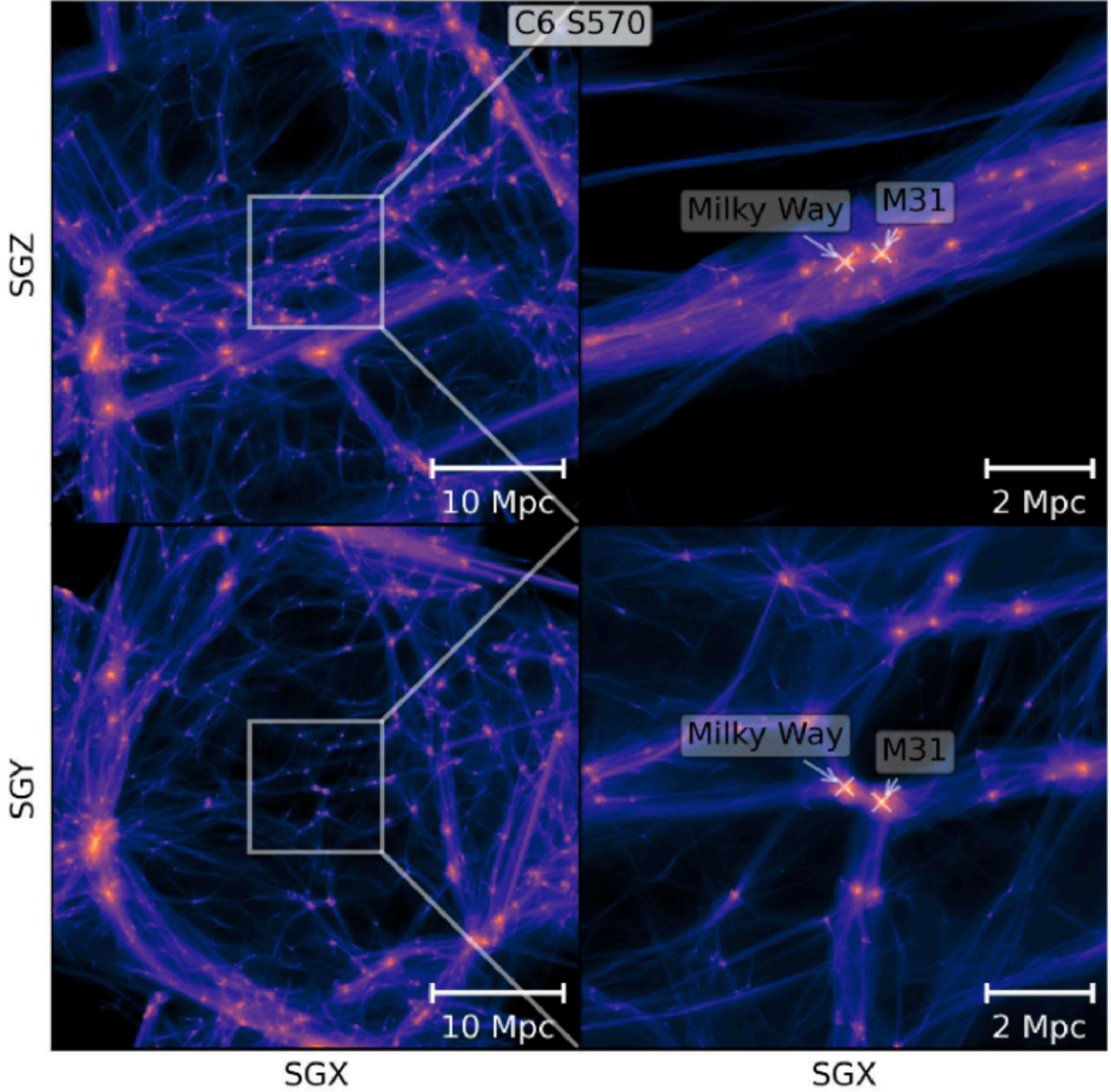

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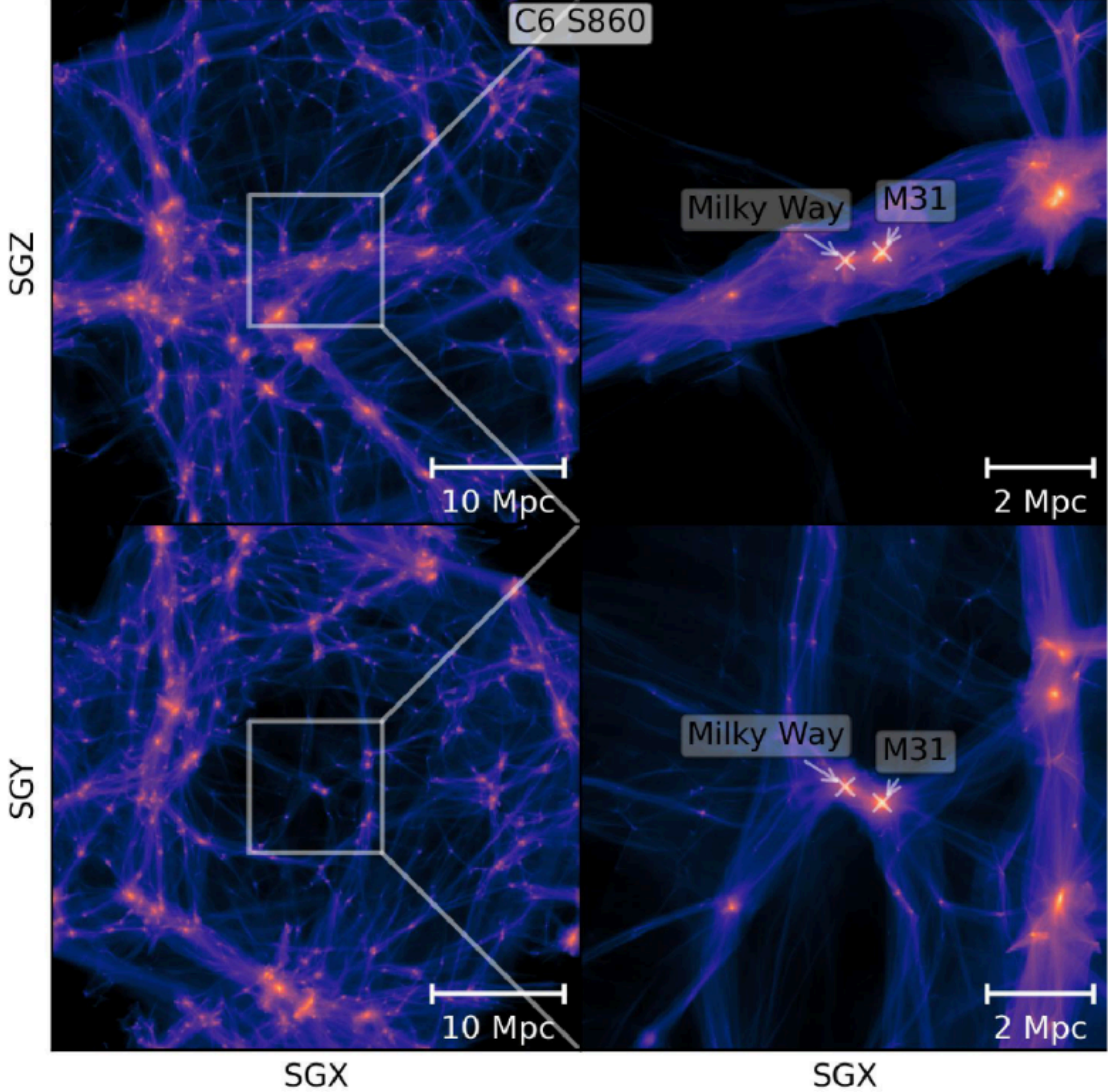
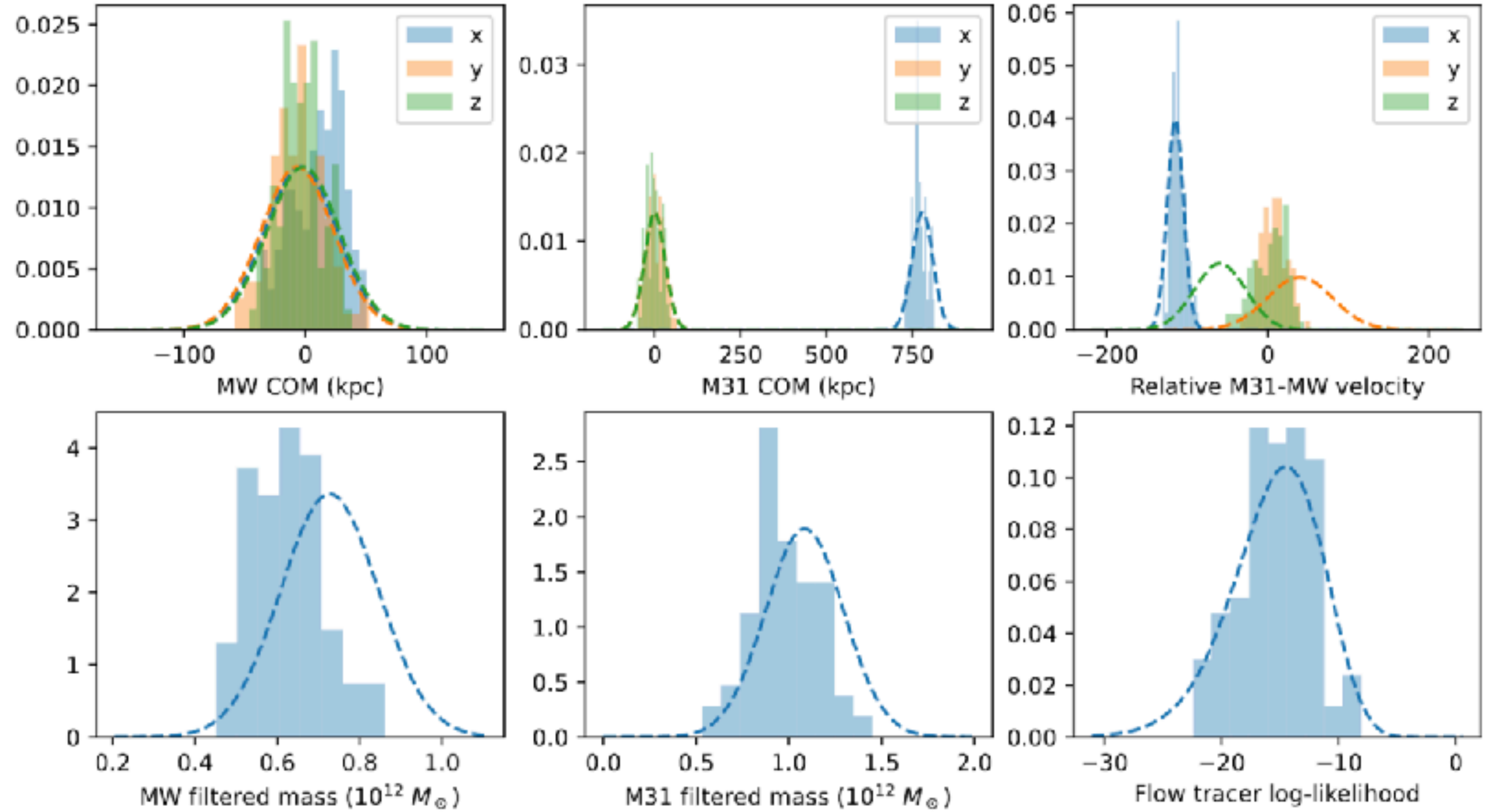


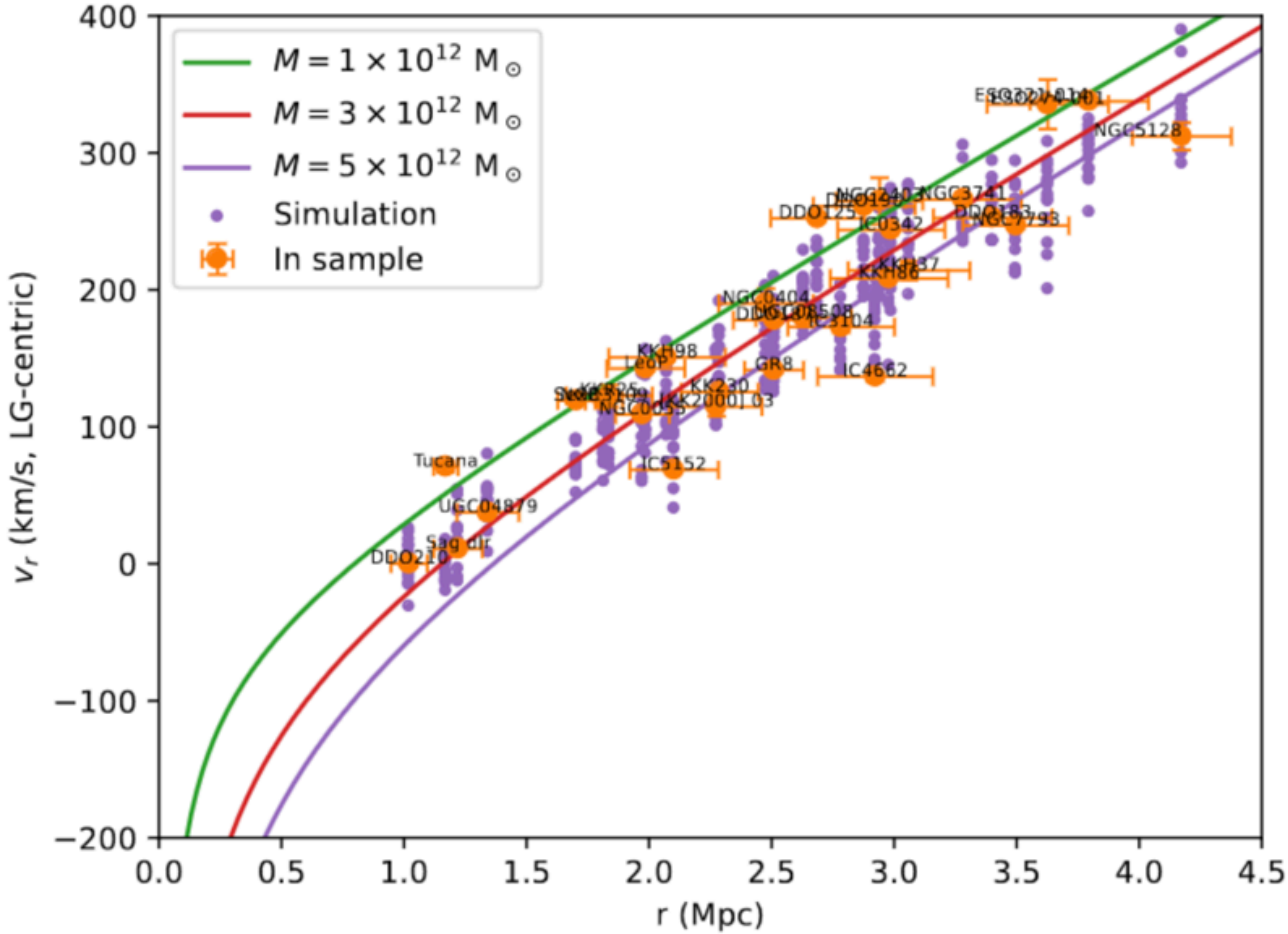
Independent converged examples

Posterior distributions of constrained quantities



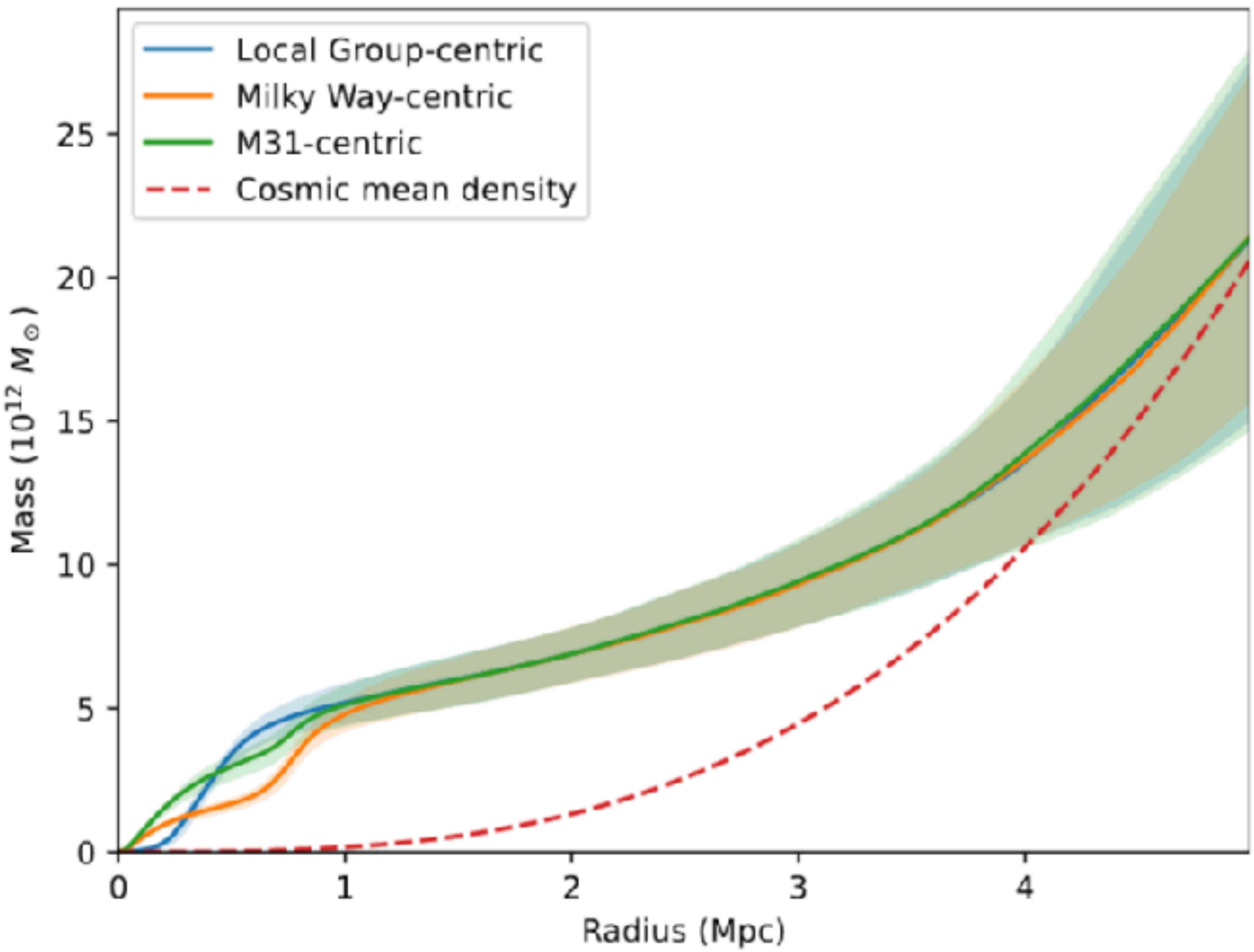
- The distributions of all quantities are consistent with the adopted constraints
- Halo masses are biased low: $M_{MW} \sim 0.5\ M_{M31}$, $\Sigma\ M_{200c} = 2.83 \pm 0.40 \times 10^{12}\ M_\odot$
- The tangential velocity of M31 is biased low, consistent with zero
- The Hubble flow tracers are always fit acceptably

Posterior distributions of constrained quantities



- Flow tracer velocities are reproduced without obvious systematics

Enclosed mass as a function of distance



- The enclosed mass within 1 Mpc is about twice $\Sigma\ M_{200c}$
- The enclosed density within 5 Mpc ≈ the cosmic mean
- The scatter around the mean curve is relatively small

Conclusions

- Hamiltonian MCMC can produce a representative sample of ΛCDM models matching all kinematic constraints in and around the Local Group

- Simultaneously matching internal halo kinematics, the Timing Argument data and the quiet nearby Hubble flow gives tighter constraints than matching the different types of data independently

- Consistent models give low masses for the halos of the two main galaxies, $M_{MW} \sim 0.5\ M_{M31}$, and an enclosed mass which increases rapidly as distance from the barycentre increases

- Resimulation gives detailed and representative (assuming ΛCDM) ensembles of "Local Groups" all satisfying the observed constraints

- These can be used to explore many problems, e.g.

  — The range of possible assembly histories for the MW and M31
  — The probability of coherent "planes of satellites", or of bright satellites like the LMC or M33
  — Predicted gas densities, velocities and shocks in and around the LG