The Local Group mass and its connection to cosmic puzzles

Till Sawala (University of Helsinki)

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HELSINGIN YLIOPISTO
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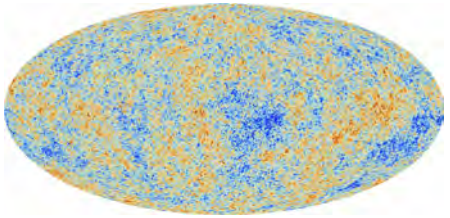
Cosmological Simulations



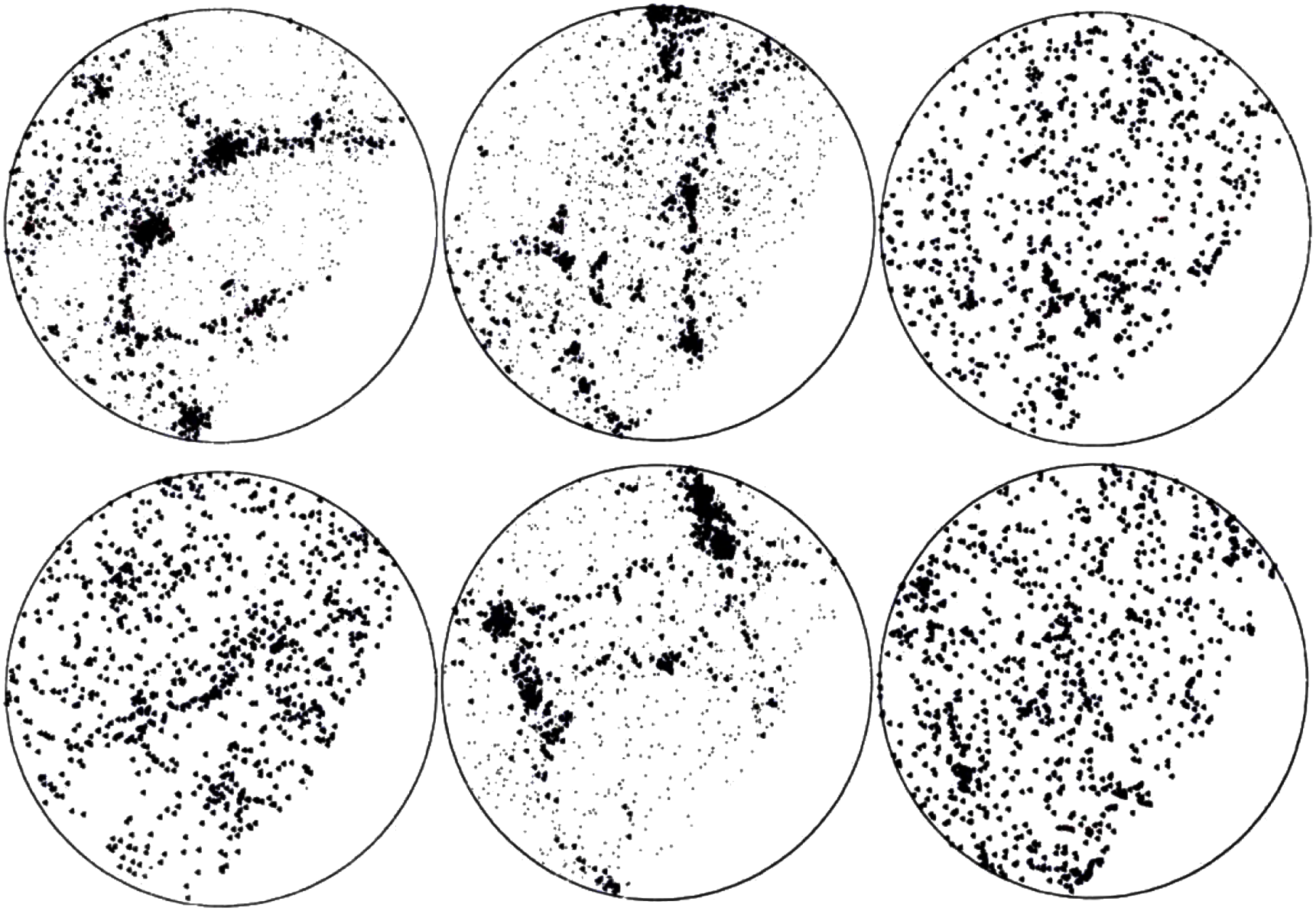
Planck (z~1100)

- Initial Conditions (for cosmological simulations, white noise field with primordial power spectrum, evolved through the linear phase to e.g. z=127)
- Realisation using either particles (discretising mass) or a mesh (discretising space) in a volume with periodic boundary conditions
- Newtonian calculations, global expansion of space in the form of a coordinate transformation, global radiation background
- Calculation of forces (gravity and hydrodynamics, cooling, magnetic fields) and resulting accelerations, velocities and displacements (or flows through cell boundaries) using approximative, fast methods. Discretisation of time (adaptively)
- Sub-Grid models for processes that are not resolved ab initio: star formation, stellar evolution, optically thick cooling, stellar winds, supernova feedback (and coupling to the ISM), formation of SM black holes, BH mergers, accretion and AGN feedback

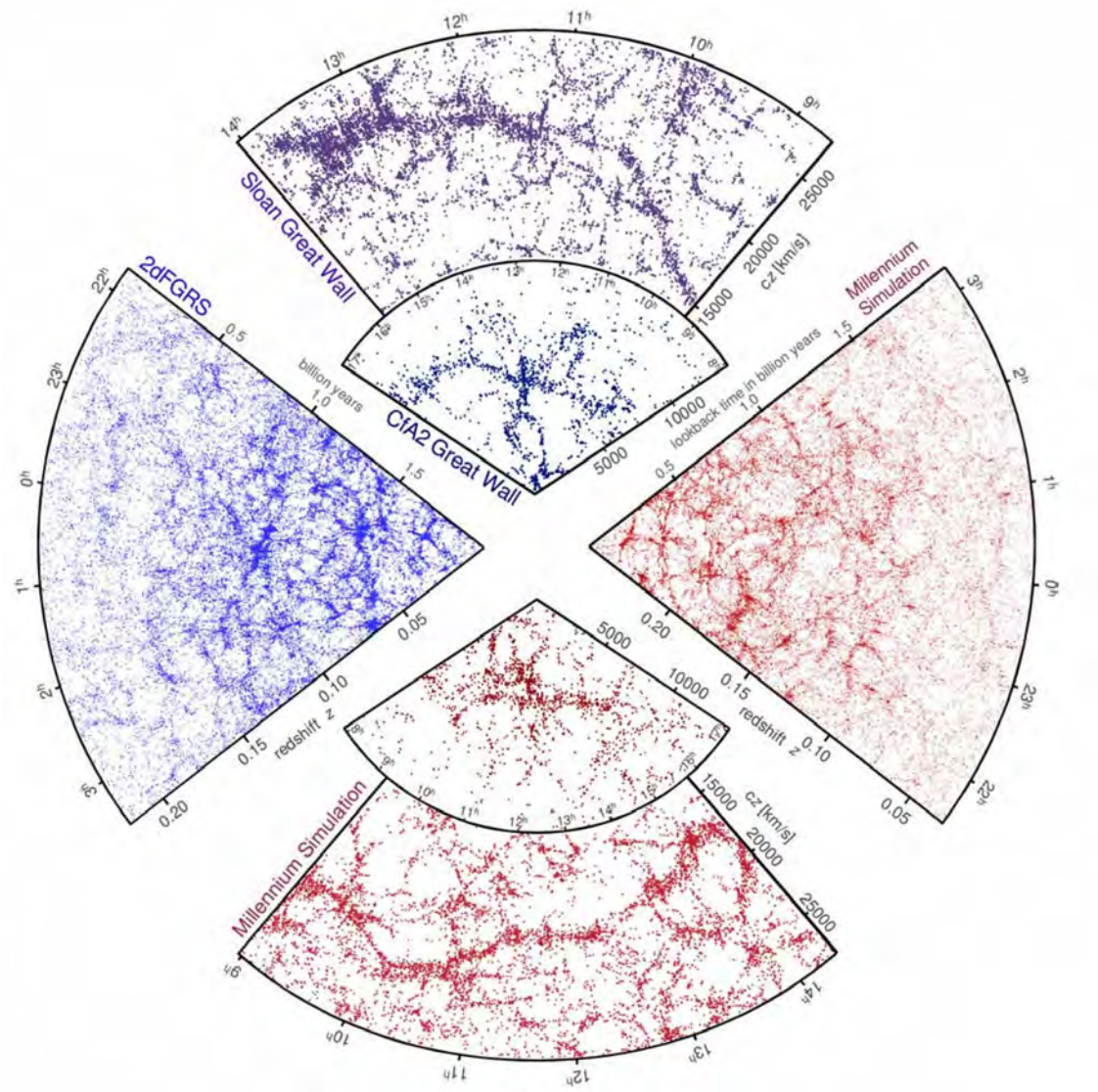


Illustris Collaboration (z=0)

(other flavours *are* available!)



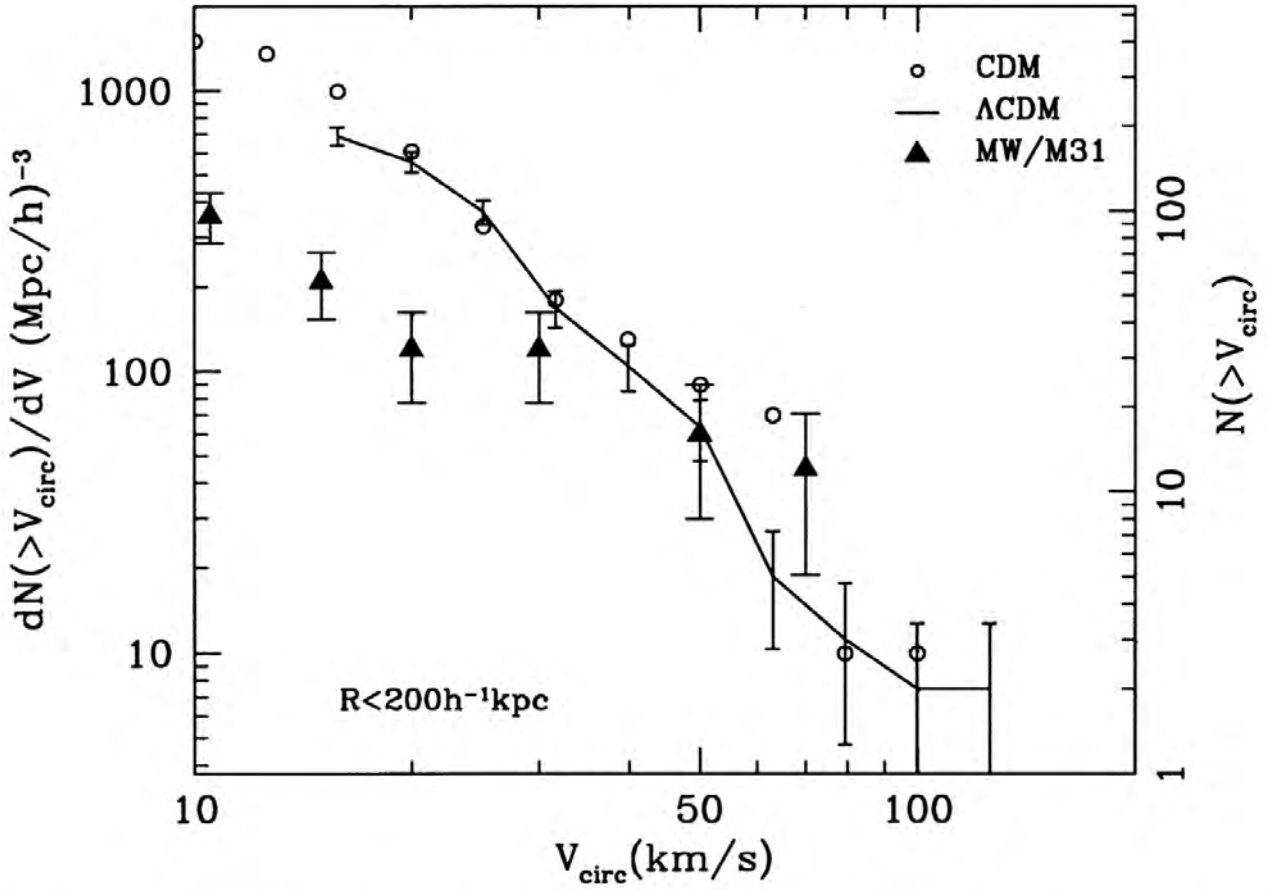
White, Davis, Frenk (1983)



Springel et al. (2005)

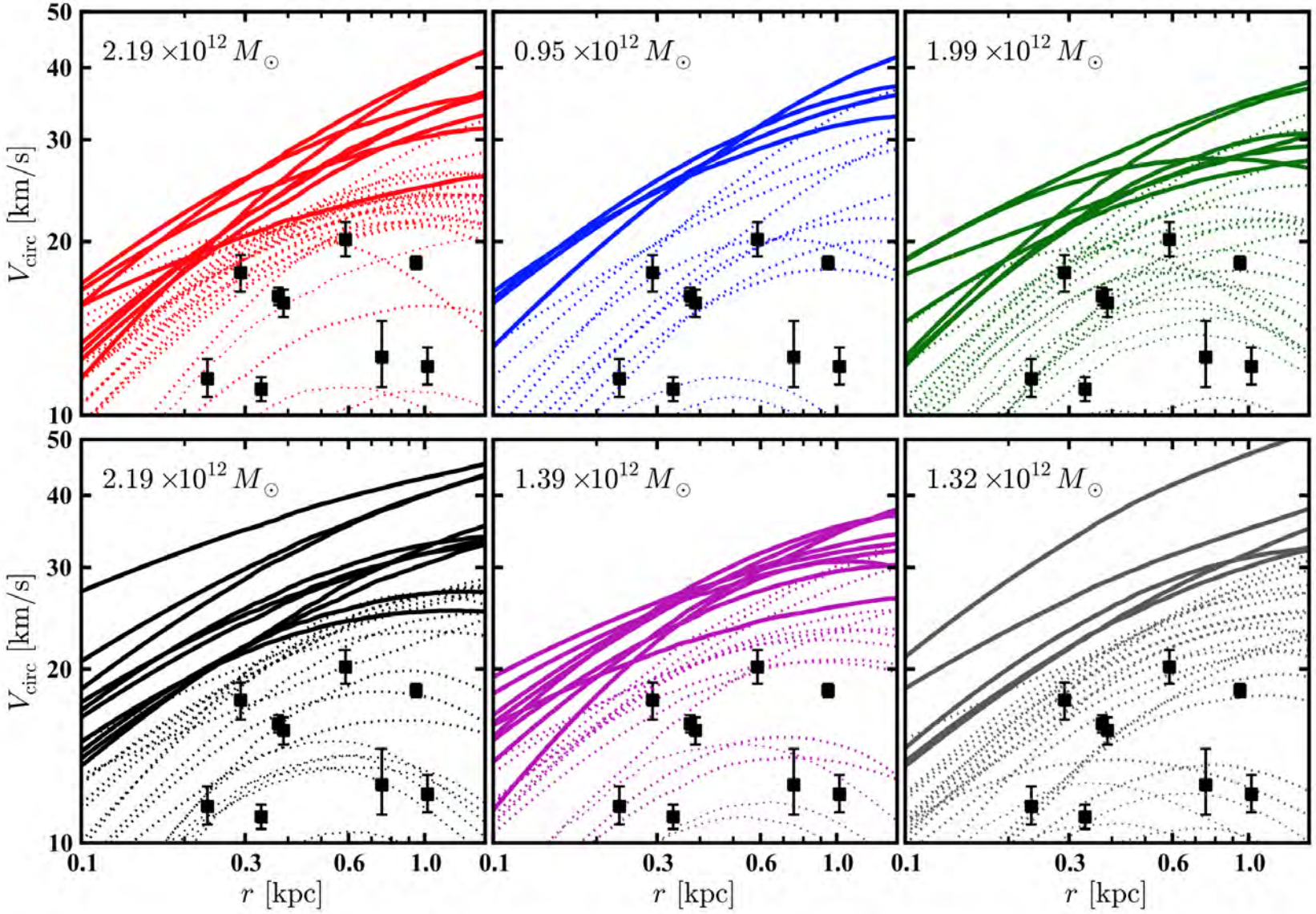
On **large scales**, the Lambda-Cold Dark Matter (ΛCDM) model accuarately predicts the formation of structures.

Small scales: Missing Satellites?



Klypin et al. (1999)

Small scales: still *too big to fail*?



Boylan-Kolchin et al. (2010)

- In the large scale limit, gravity is the only relevant force, to which baryons and dark matter respond identically.
- On large enough scales, observations agree with dark matter only (DMO) calculations. Problems arise on small (sub Mpc) scales.
- Are the problems afflicting ΛCDM in the Local Universe due to the neglect of baryonic effects?
- Answer requires hydrodynamic simulations (or for some aspects, at least semi-analytic models)

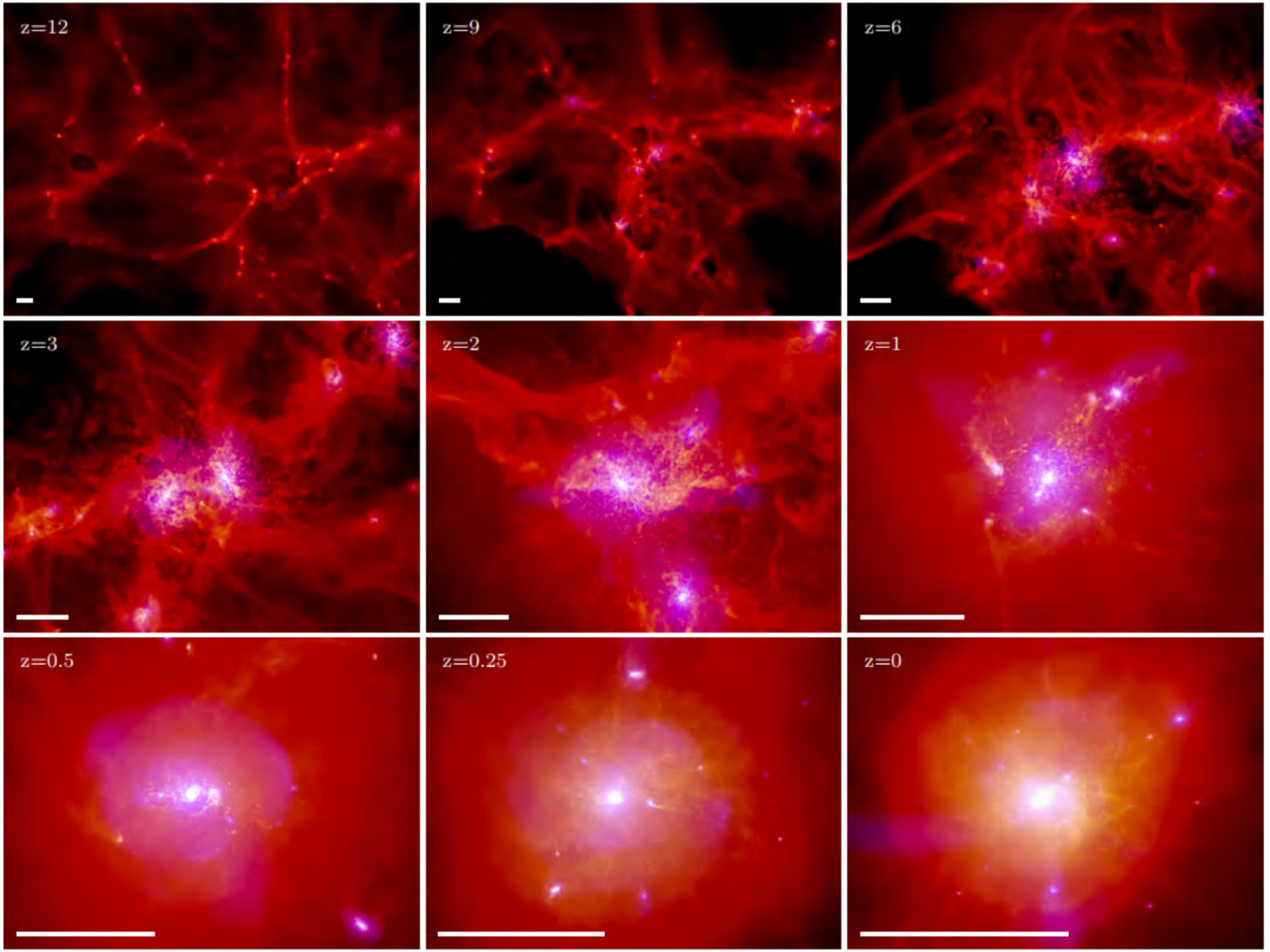
Galaxies-Intergalactic Medium Interaction Calculation
Evolution and Assembly of GaLaxies and their Environments
A Project Of Simulating The Local Environment

also: Aquila, CLUES, Illustris, Fire, Latte, Mufasa, Magneticum, MassiveBlack, and *many* others

A Project **O**f **S**imulating **T**he **L**ocal **E**nvironment

- 12 Local Group analogues selected to match the LG's kinematic properties from a 100^3 Mpc^3 DMO simulation with ΛCDM cosmology and WMAP-7 parameters
- Re-simulated as DMO and hydrodynamic simulations using the EAGLE code and galaxy formation model, particle mass up to 5 x 10^3 $M_\odot$, softening up to 94 pc
- Collisionless ΛCDM, ν-coupled ΛCDM, and ΛWDM simulations with identical phases.
- Subhalo Merger-Trees that trace the evolution of objects across time, and particle IDs encoding the Lagrangian position that allow matching of individual objects across simulations.

Baryons: solutions to the LG's cosmic puzzles.



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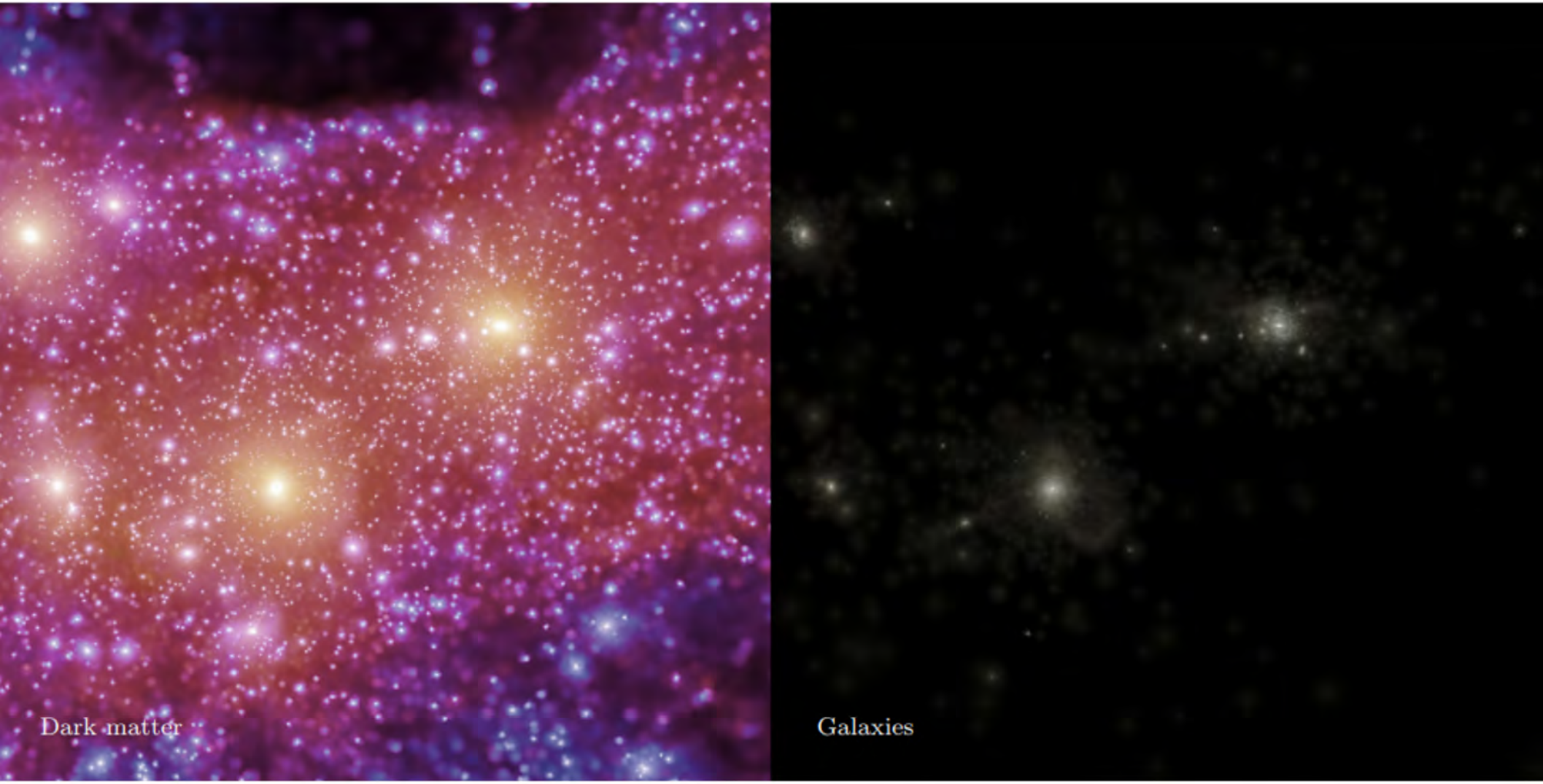

T.S.+ (2016)

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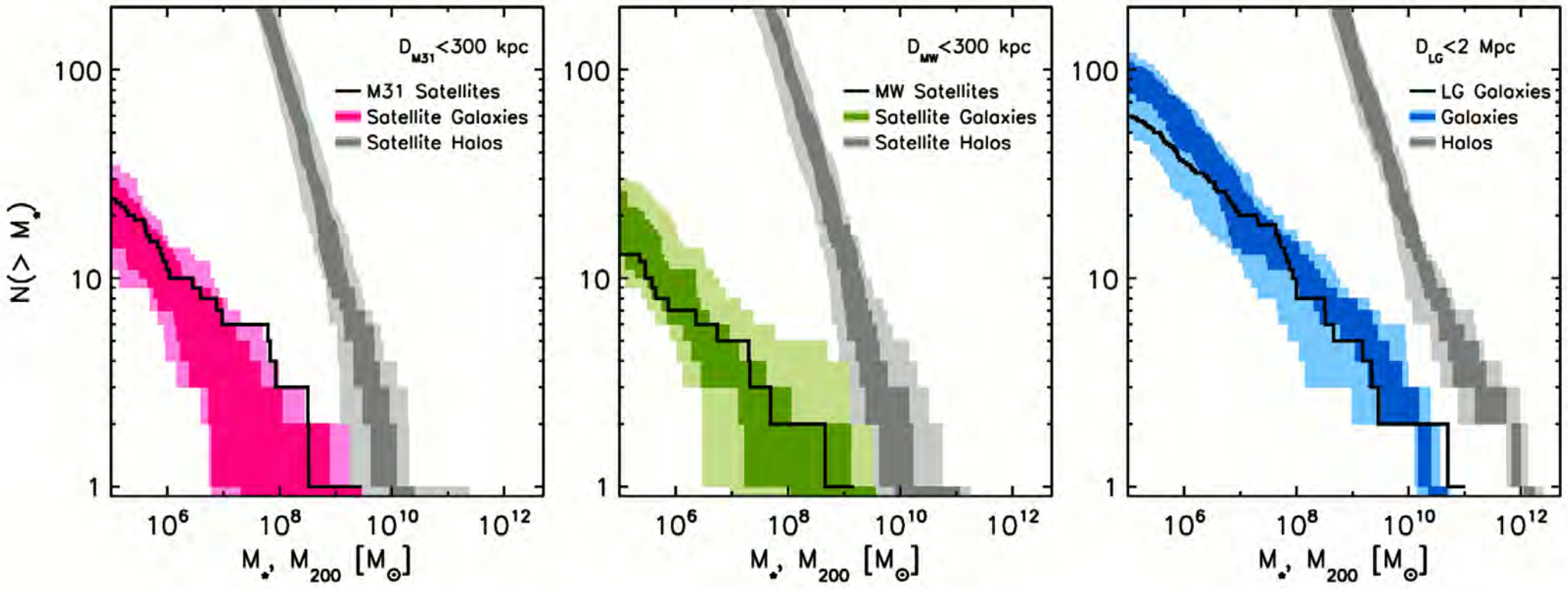

T.S.+ (2016)

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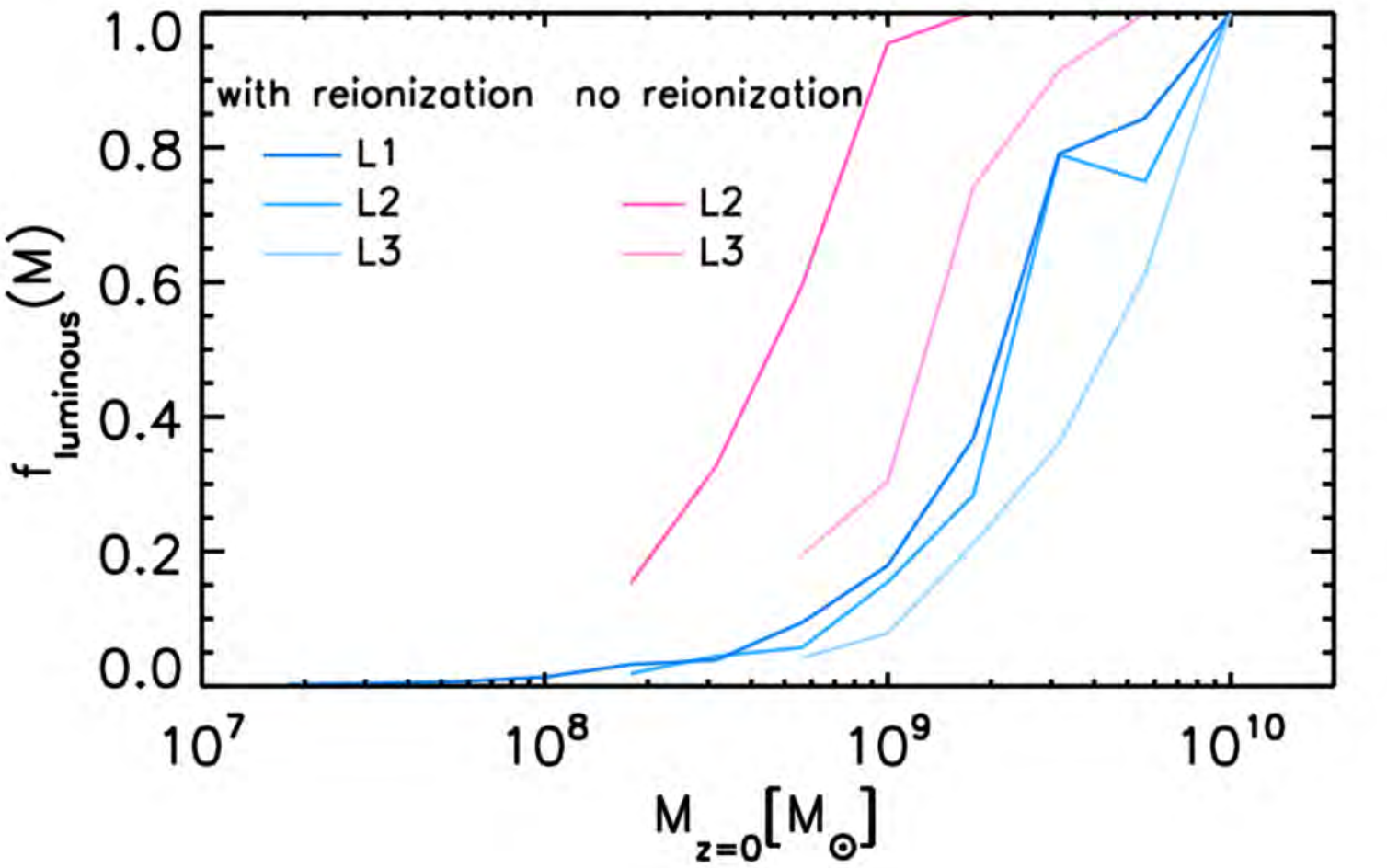

T.S.+ (2016b)

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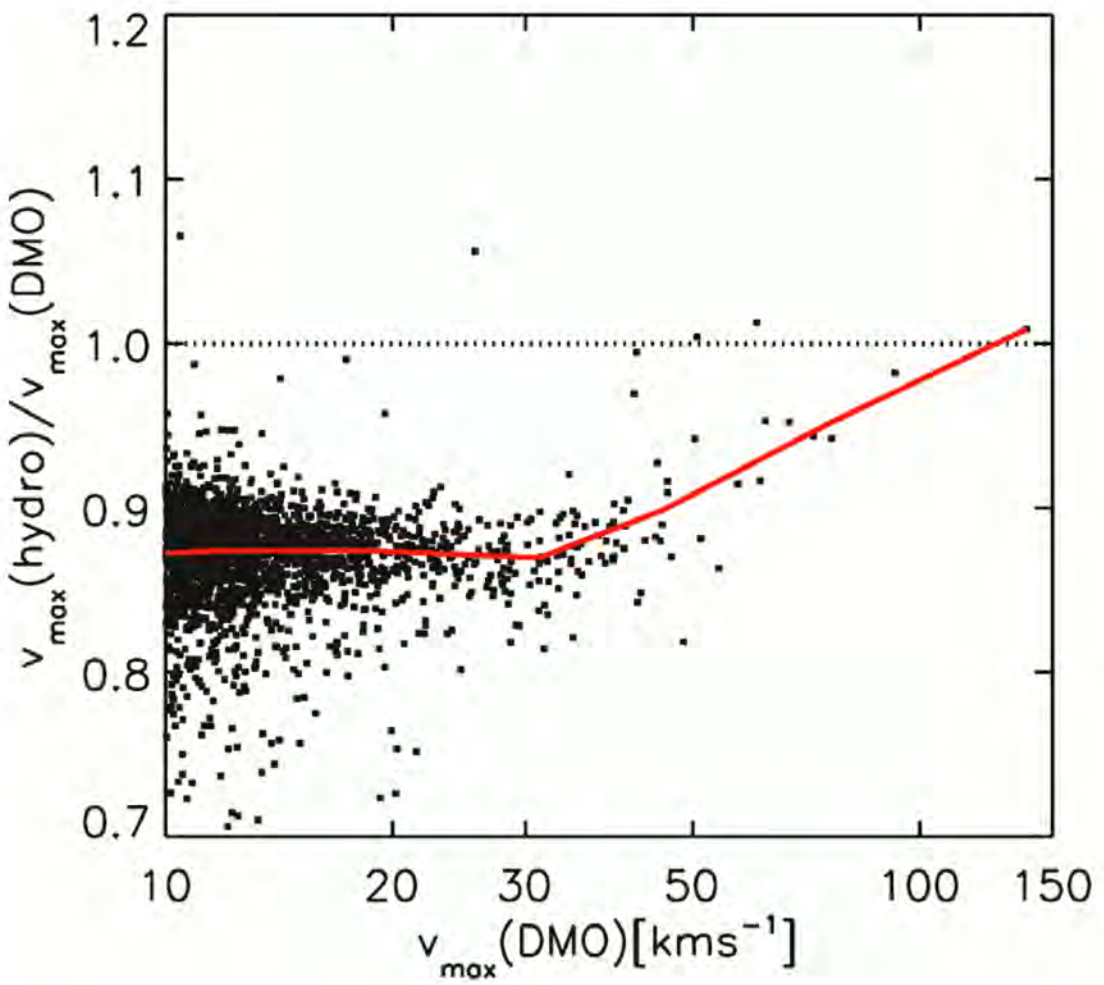
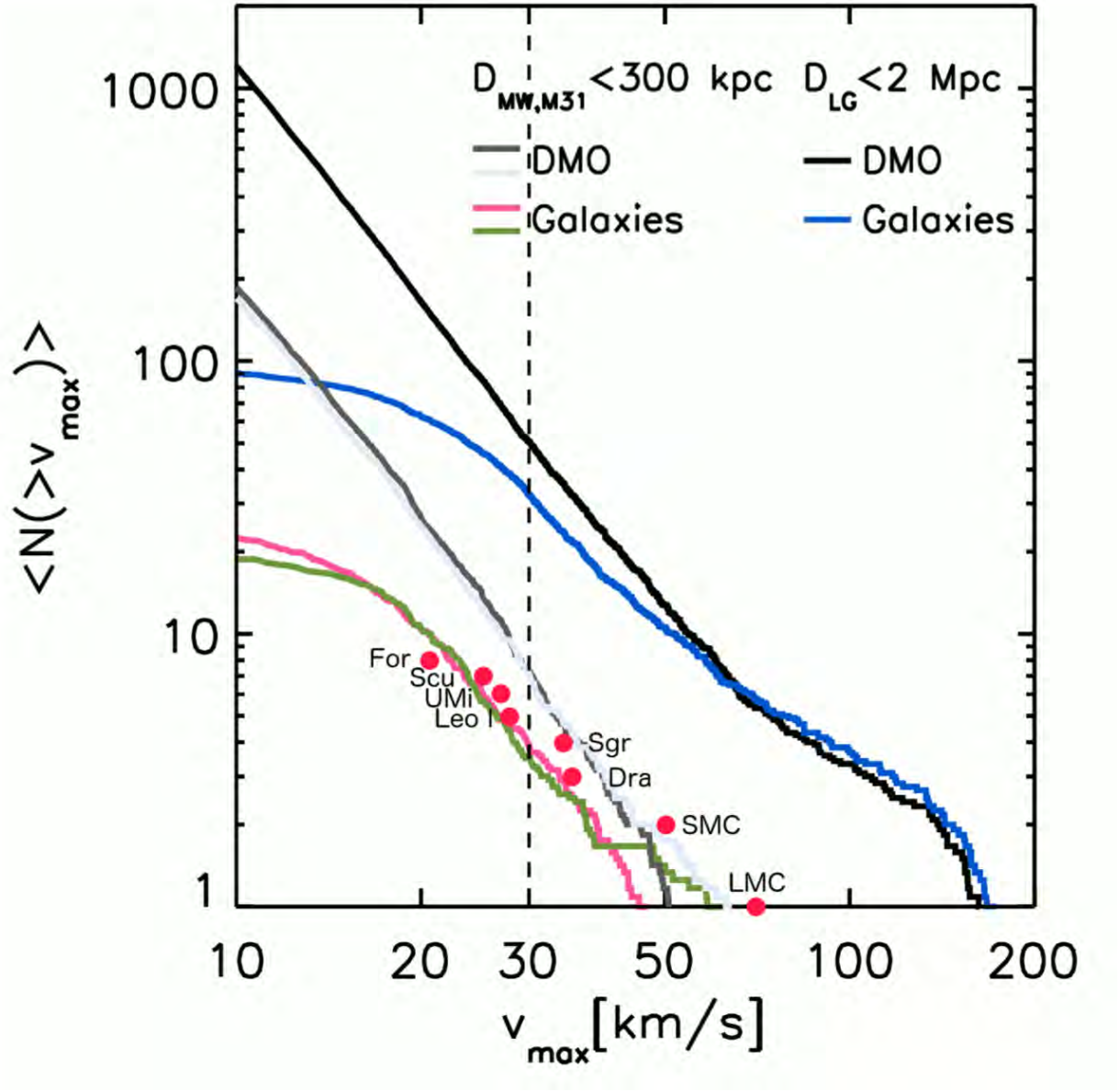


T.S.+ (2016), also see T.S.+ (2012), Schaller+ (2015)

Baryons: solutions to the LG's cosmic puzzles.



T.S.+ (2016)

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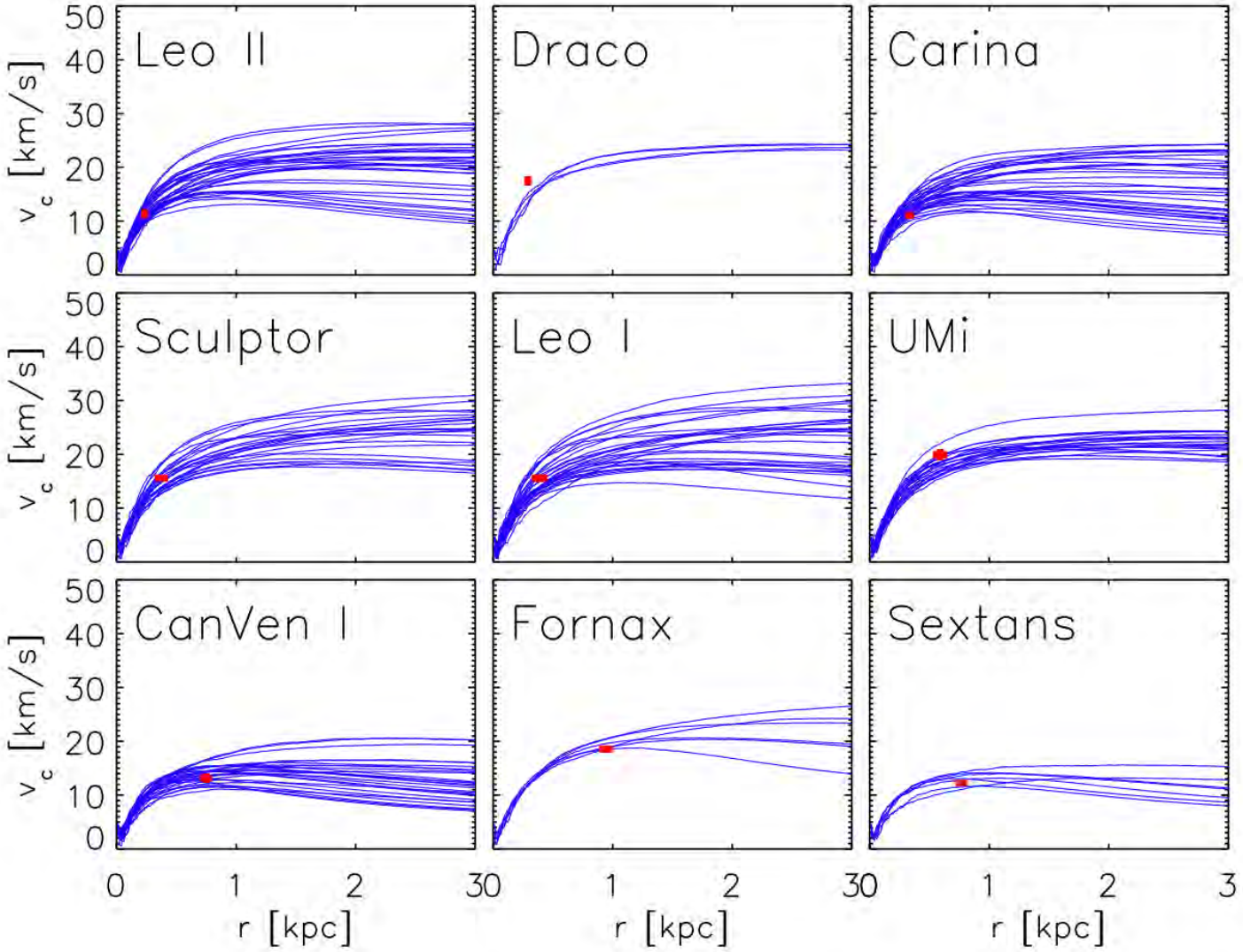
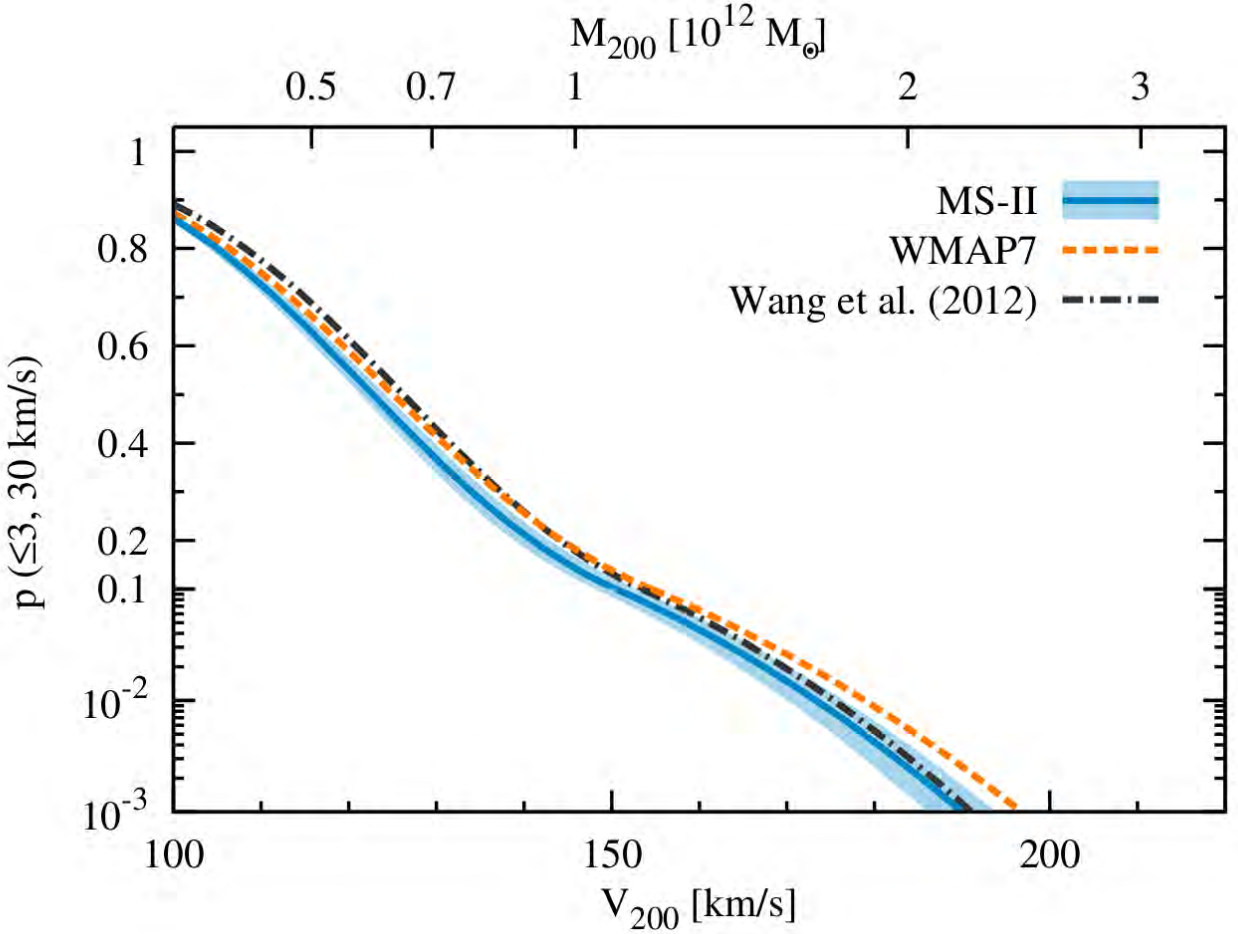


T.S.+ (2016)

The LG mass: the next “Factor of Two” issue



Probability that a halo has at most 3 subhalos with vmax > 30 km/s

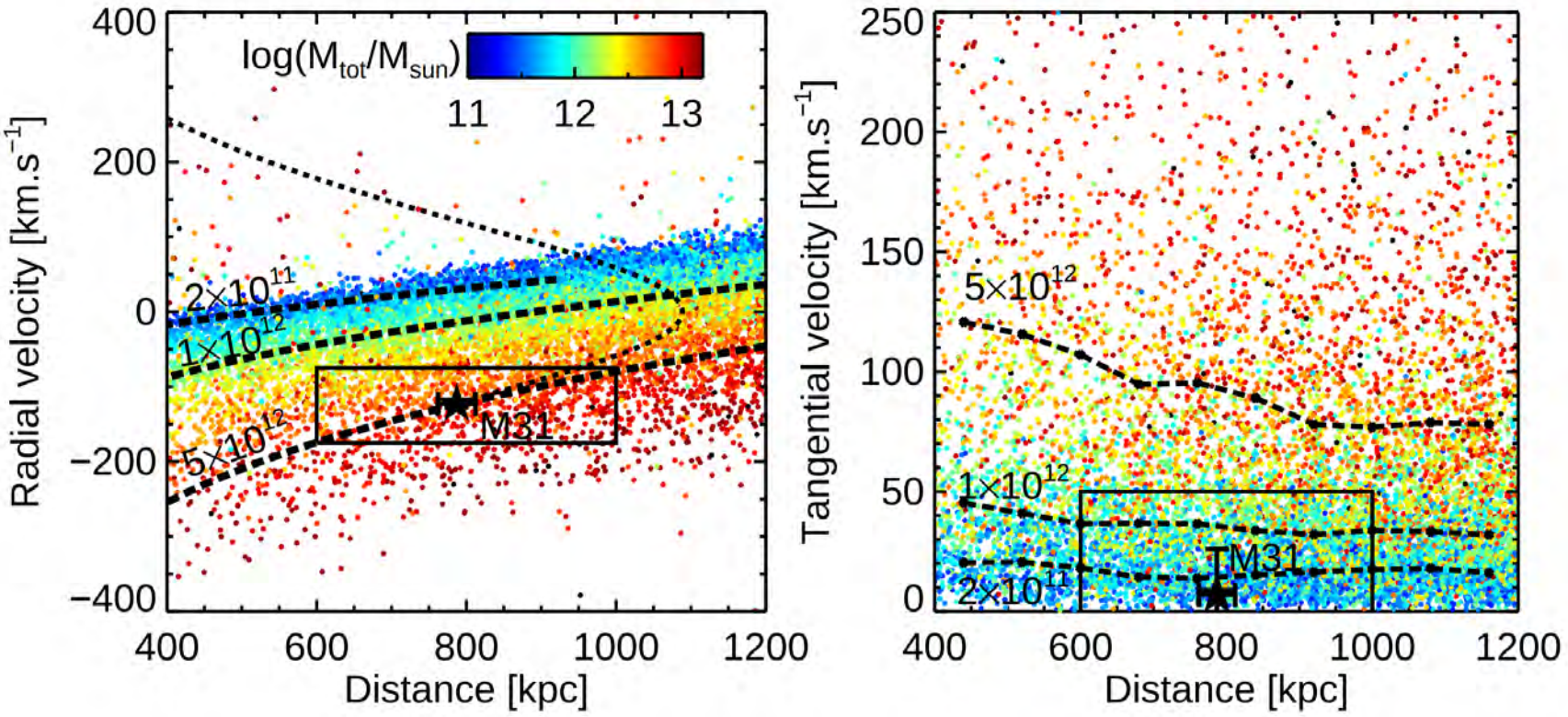
If the Milky way halo is 10^{12} $M_\odot$ it is fairly typical (1 in 5).
If the Milky way halo is 10^{12} $M_\odot$ it is very unusual (1 in 500).

Cautun+ (2016)

The LG mass: the next “Factor of Two” issue

- From the *timing argument*, assuming an initial separation of zero, followed by expansion and turn-around, the Local Group mass can be derived from the radial velocity and separation.
- We can also look for Local Group analogues in large cosmological simulations.

Dotted: Timing argument track

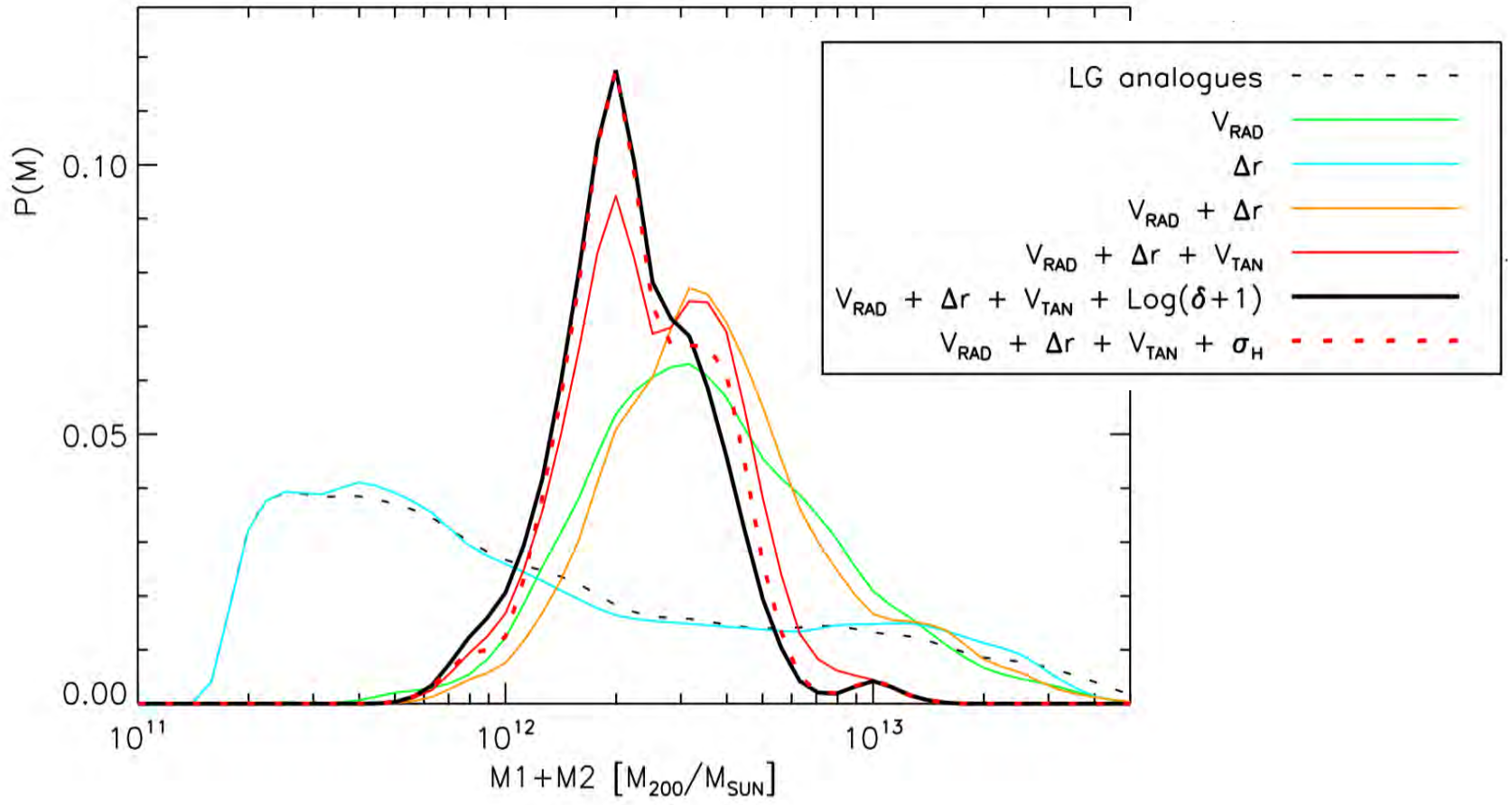


At fixed separation, greater radial velocity correlates with mass.

At fixed separation, greater tangential velocity correlates with mass.

Fattahi+ (2016)

The LG mass: the next “Factor of Two” issue

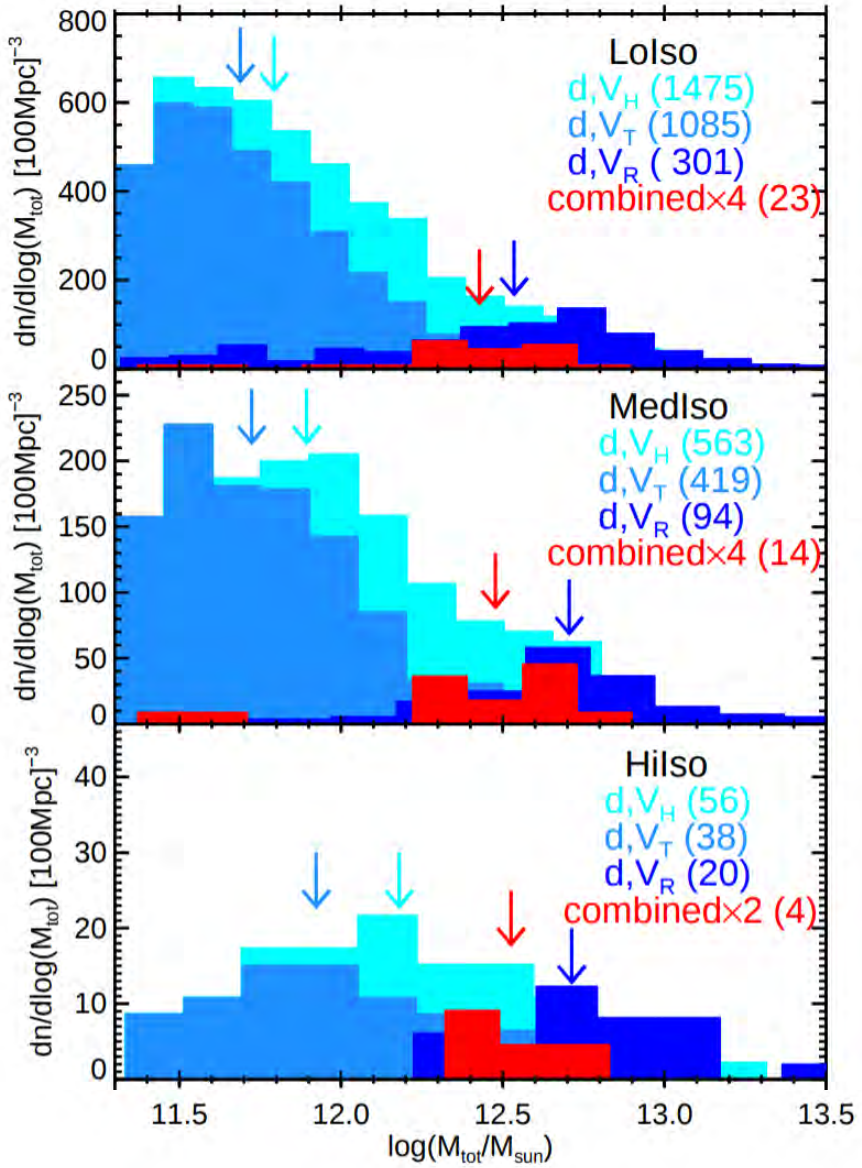


At fixed separation and radial velocity, lower tangential velocity means lower mass.

The measured LG tangential velocity (here: 17 km/s +/- 17 km/s, following Sohn+ (2012)) reduces the LG mass (MW+M31), from 4.8 x 10^{12} $M_{\odot}$ to 2.5 x 10^{12} $M_{\odot}$.

Gonzalez+ (2015)

Not so fast...



V_H: Hubble Flow Constraints
V_T: Tangential Velocity Constraints
V_R: Radial Velocity Constraints

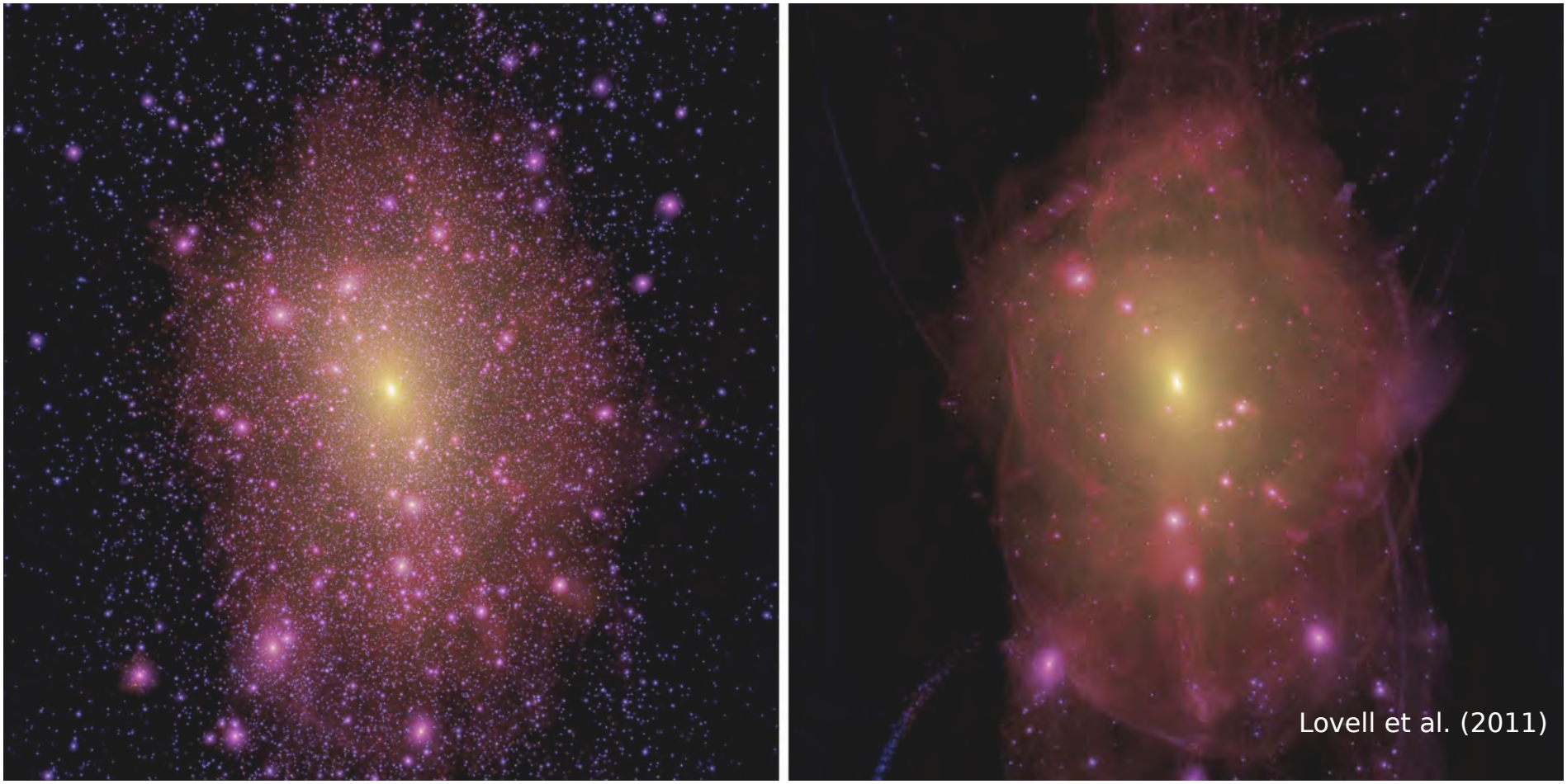
The overlap region is small (1/50)!

The low V_T/V_R ratio is very rare!

Note, however, that the low value of V_T *is* consistent with the Hubble flow constraints.

Fattahi+ (2016)

Warm vs Cold Dark Matter

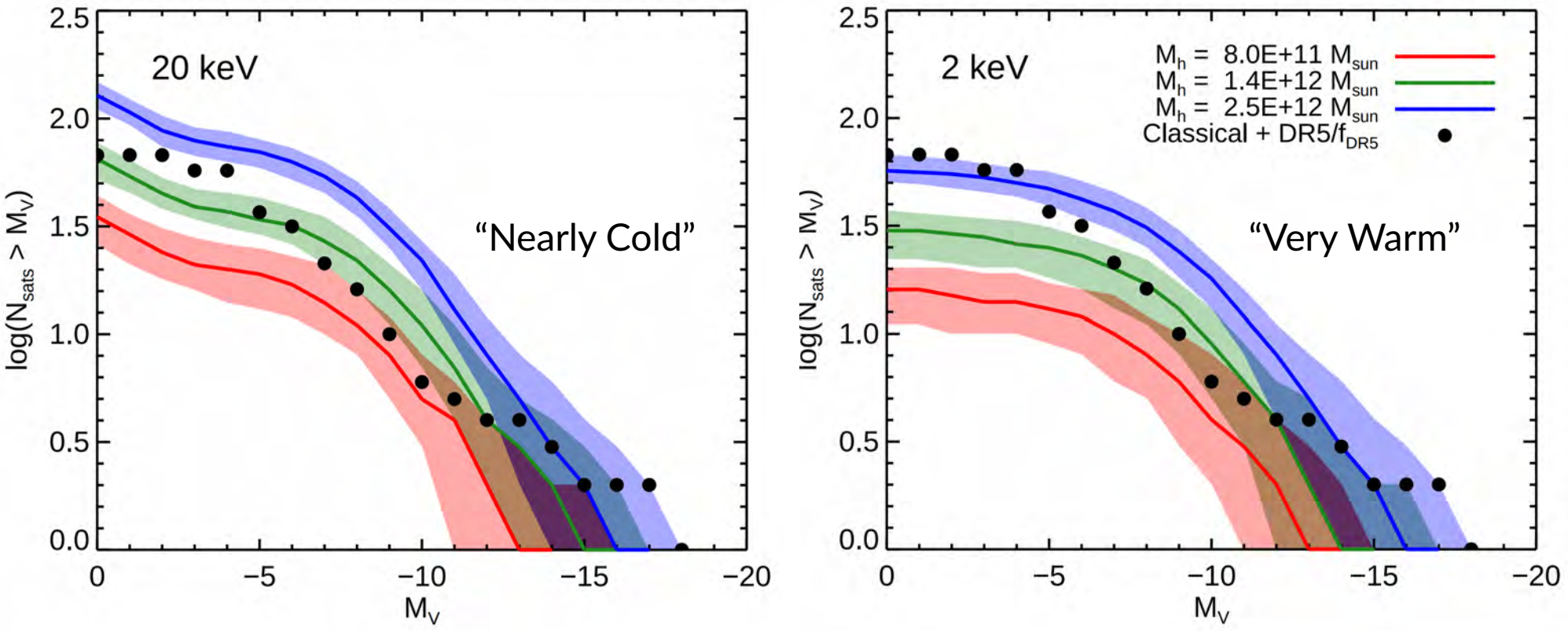


CDM

WDM (1.4 keV)

(We are also working on making the “dark” stuff detectable – ask me if you are interested)

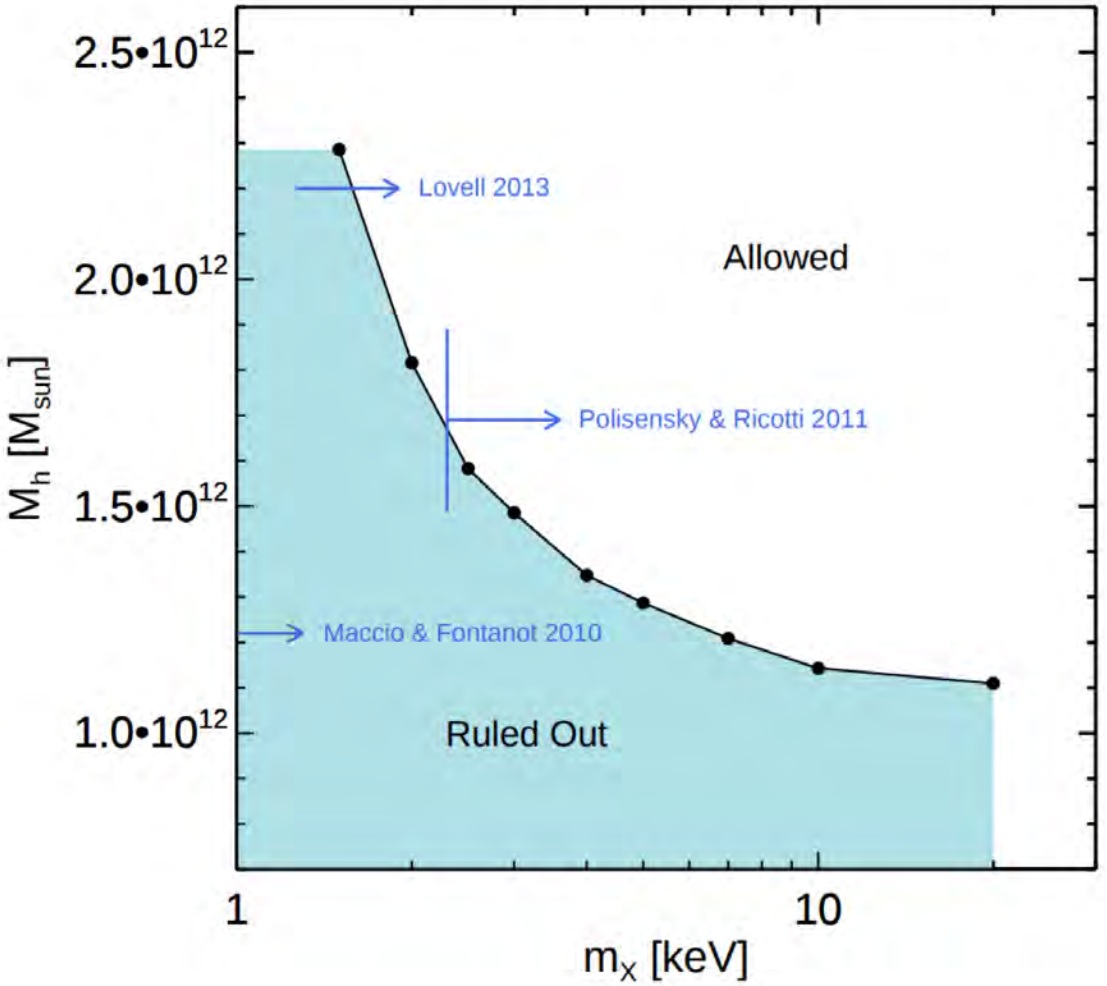
Warm vs Cold Dark Matter



A *high* Milky Way mass would disfavour ΛCDM. A *low* Milky Way mass may also disfavour (or rule out) some warm dark matter models - the flipside of the "substructure crisis".

Kennedy+ (2017)

Warm vs Cold Dark Matter



Kennedy+ (2017)

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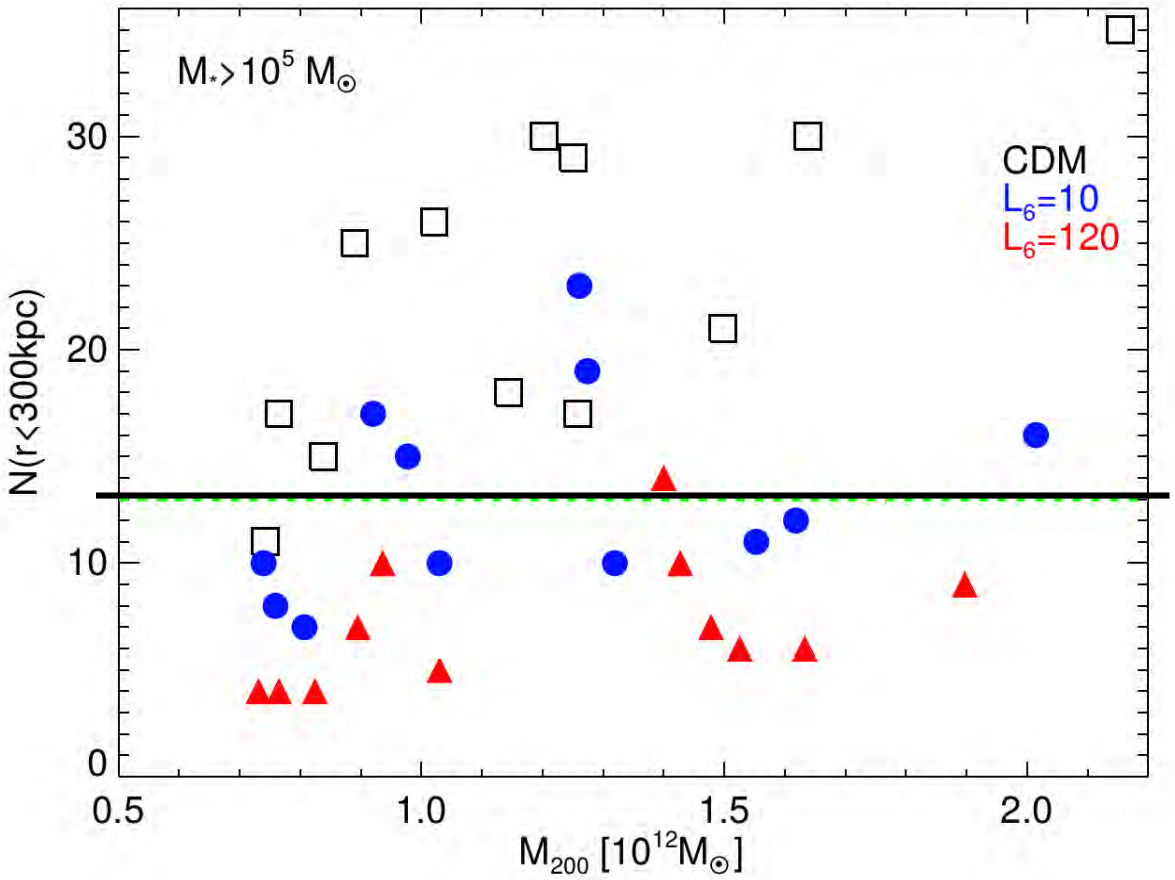

Warm dark matter models with 7 keV sterile neutrinos

MW observations

Lovell+ (2017)

Summary

- On large scales (>Mpc), current viable DM models are nearly indistinguishable.
- The inclusion of baryons in simulations resolves some of the ΛCDM problems on dwarf galaxy scales, provided that the LG mass is small enough.
- The mass of the LG, and of the MW thus become an important discriminant: high masses disfavour ΛCDM, low masses disfavour alternatives with less small scale power.

- Determining the MW-M31 velocity vector is crucial:

  A low tangential velocity (V_T ~ 20 km/s, V_R / V_T > 5) is very rare. It would imply a low LG mass, and be consistent with the local Hubble flow constraints.

  A high tangential velocity (V_T ~ 100 km/s, V_R / V_T ~ 1) is far more typical, but would imply a high LG mass, reinvigorating the ΛCDM problems.

- It is time to resolve “the other factor of two” issue!