Cosmological Puzzles: Dwarf Galaxies and the Local Group

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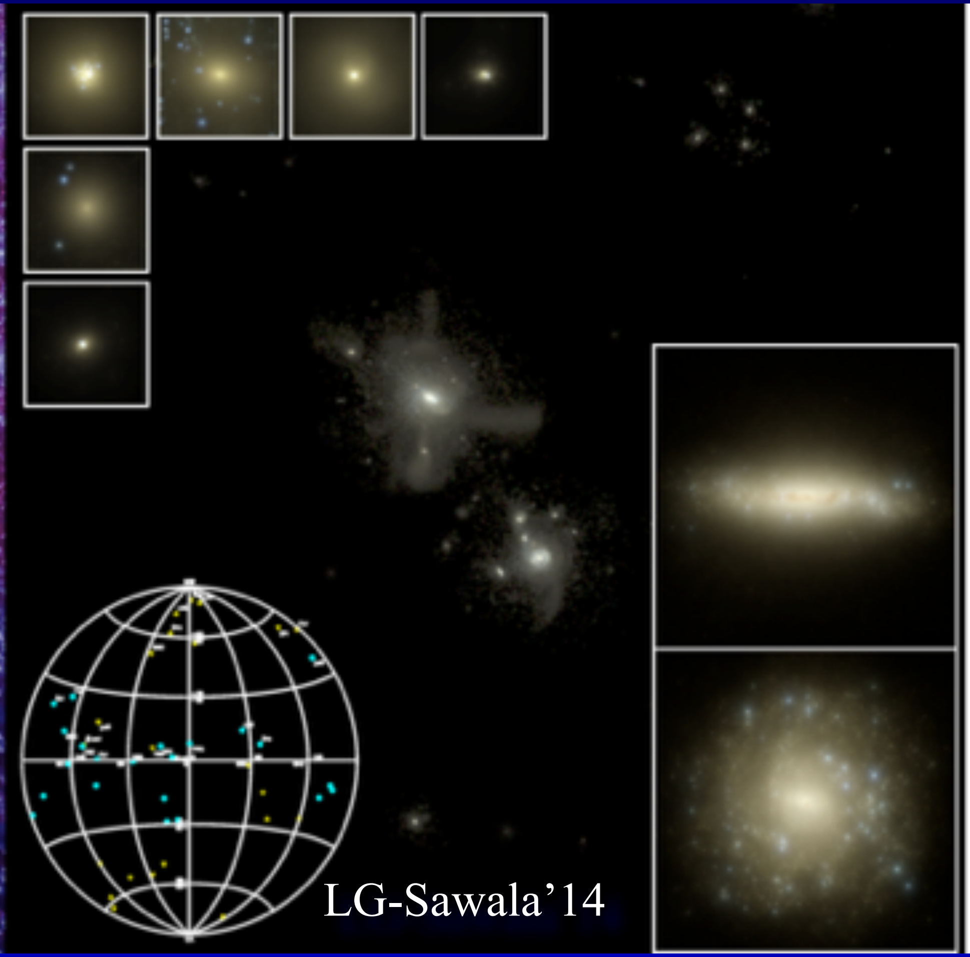
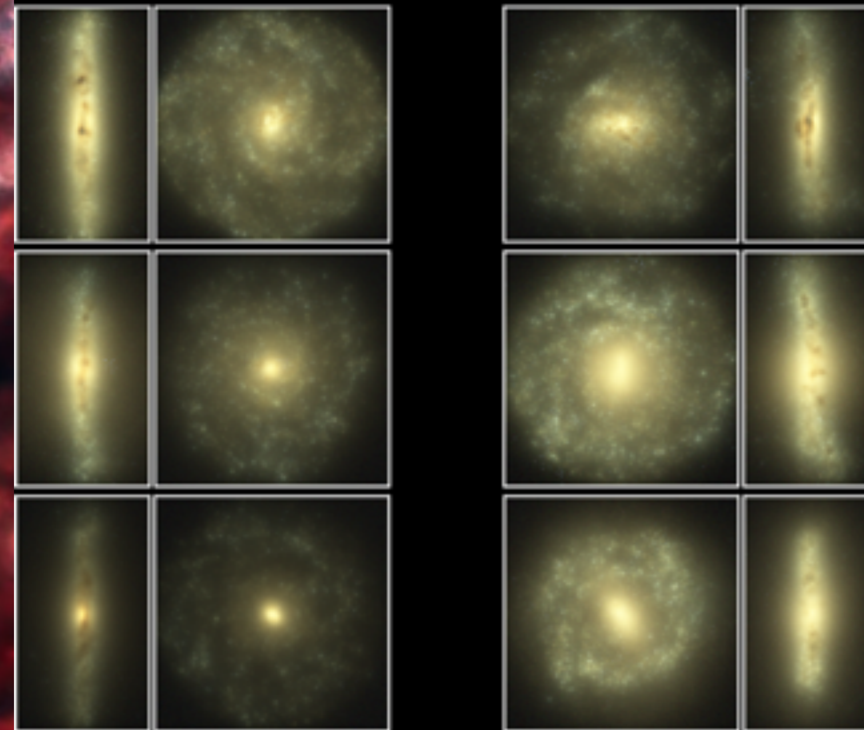
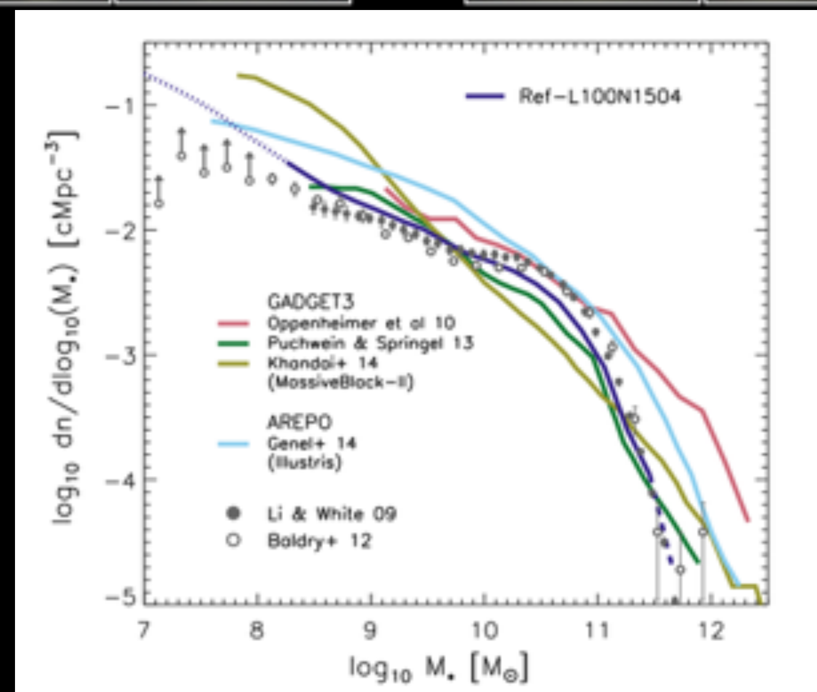
- Dark-matter-only simulations have highlighted a number of cosmological puzzles
- Local Group puzzles
  - ”Missing satellites” problem
  - “Satellite alignment” problem
  - “Too big to fail” problem
- Dwarf Galaxy puzzles
  - Rotation curves or “cusp vs core” problem

Think Locally: Local Group and Dwarfs



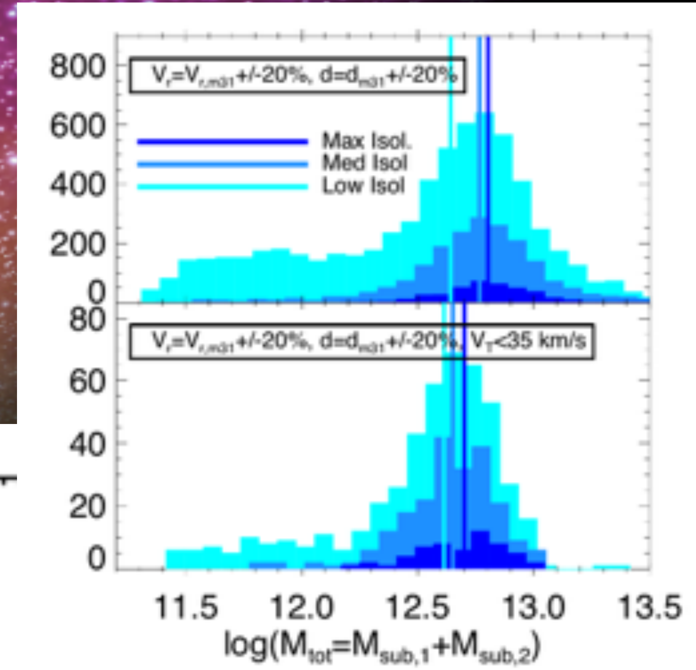
•Local Group simulations can help to exploit the abundance of data being gathered on very faint galaxies, and to address the potential biases that may arise from our particular environment

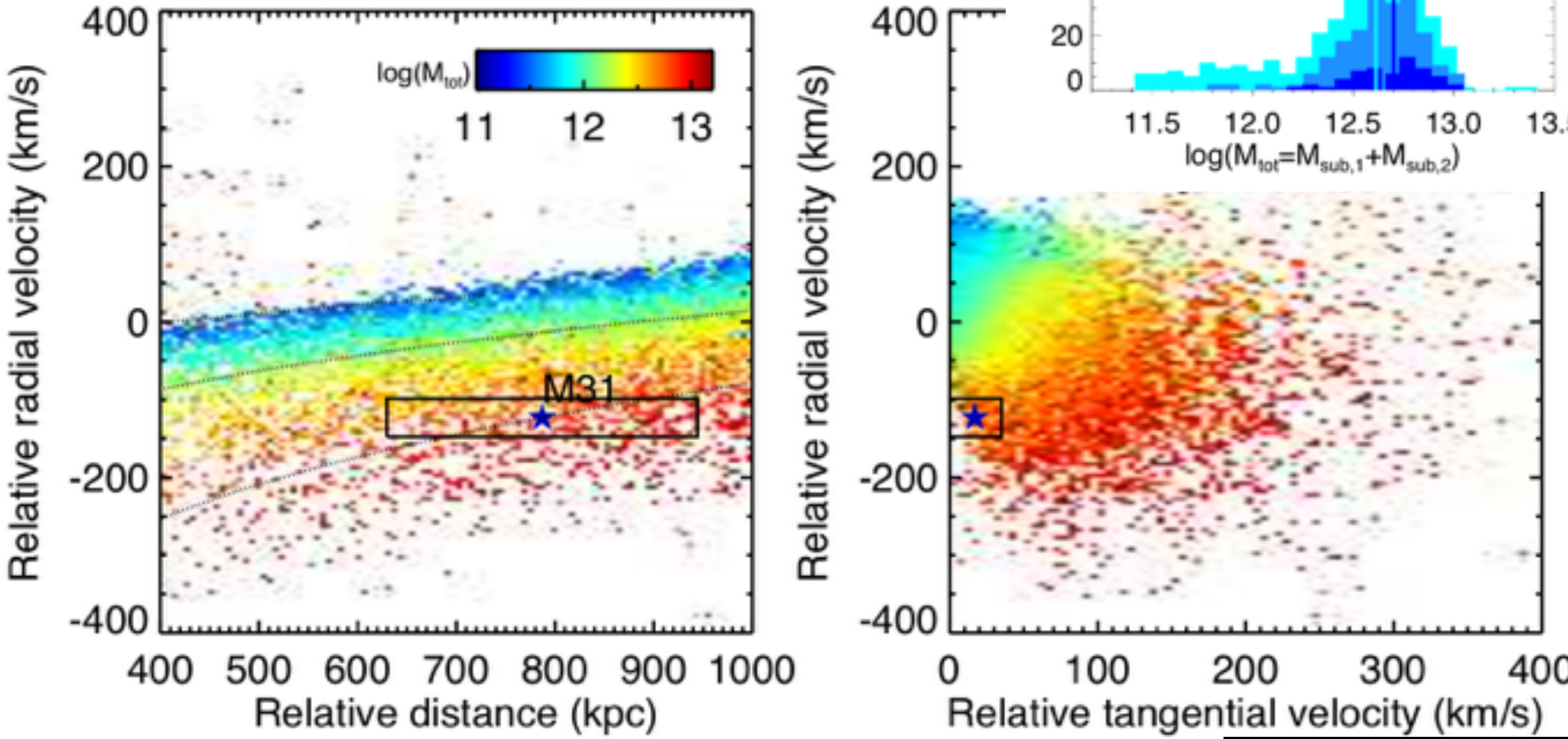




- Twelve LG candidates have been re-simulated using the *same* code used for the EAGLE project
- Any success on LG scales does not come at the expense of failures on large scales

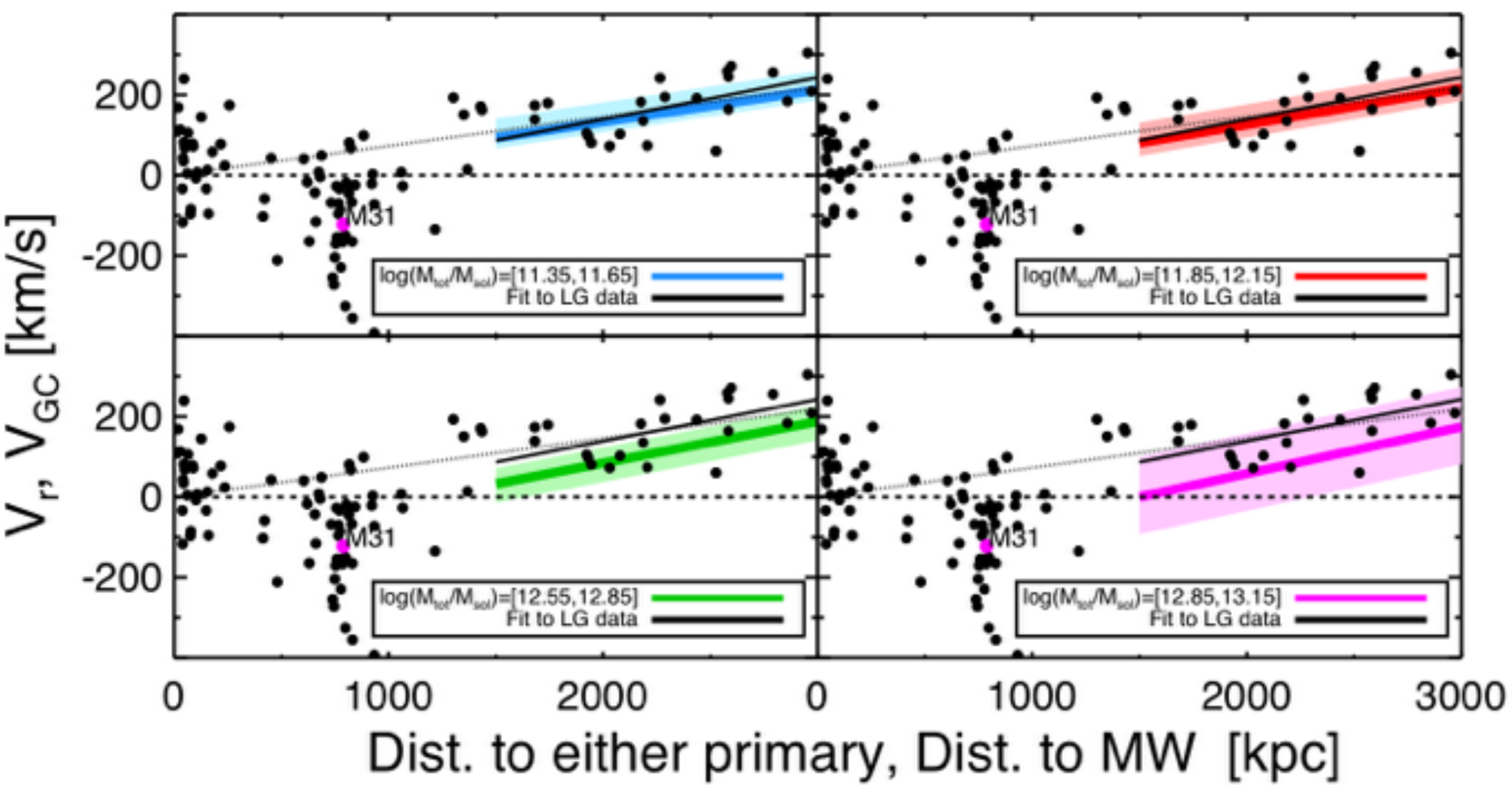
The Mass of the Local Group: Timing Argument





Fattahi+14

The Mass of the Local Group: Hubble Flow



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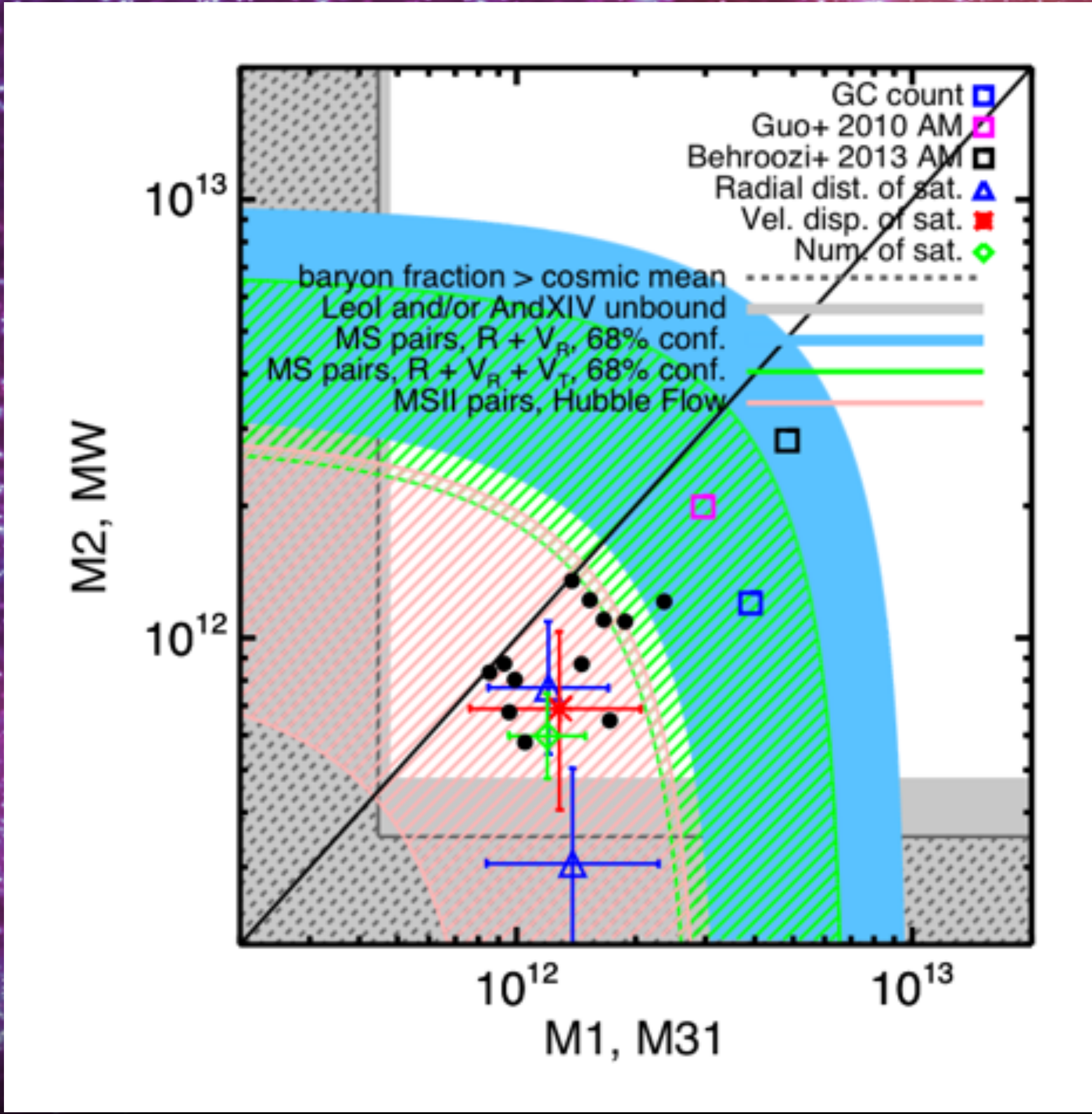
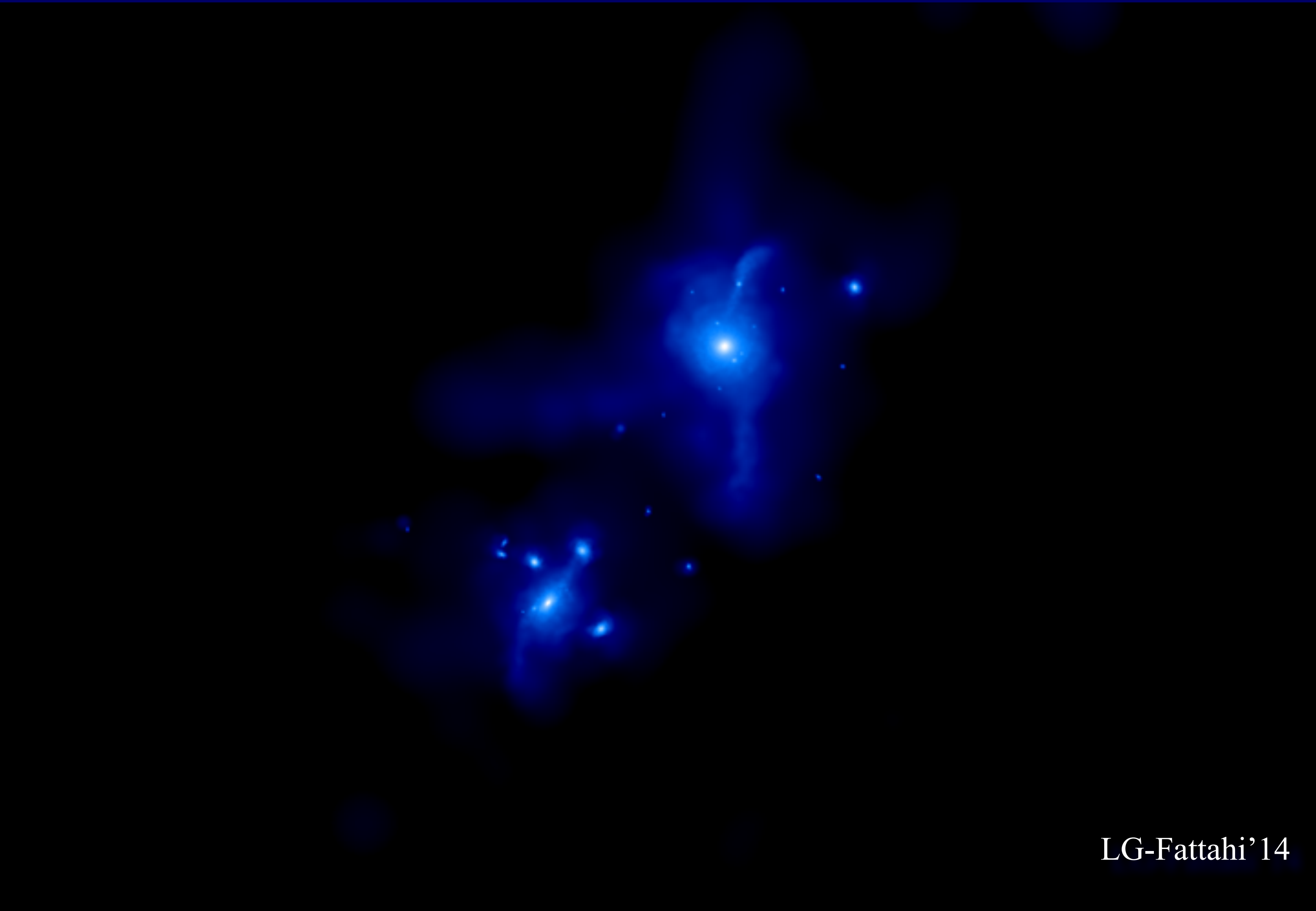
The Mass of the Local Group



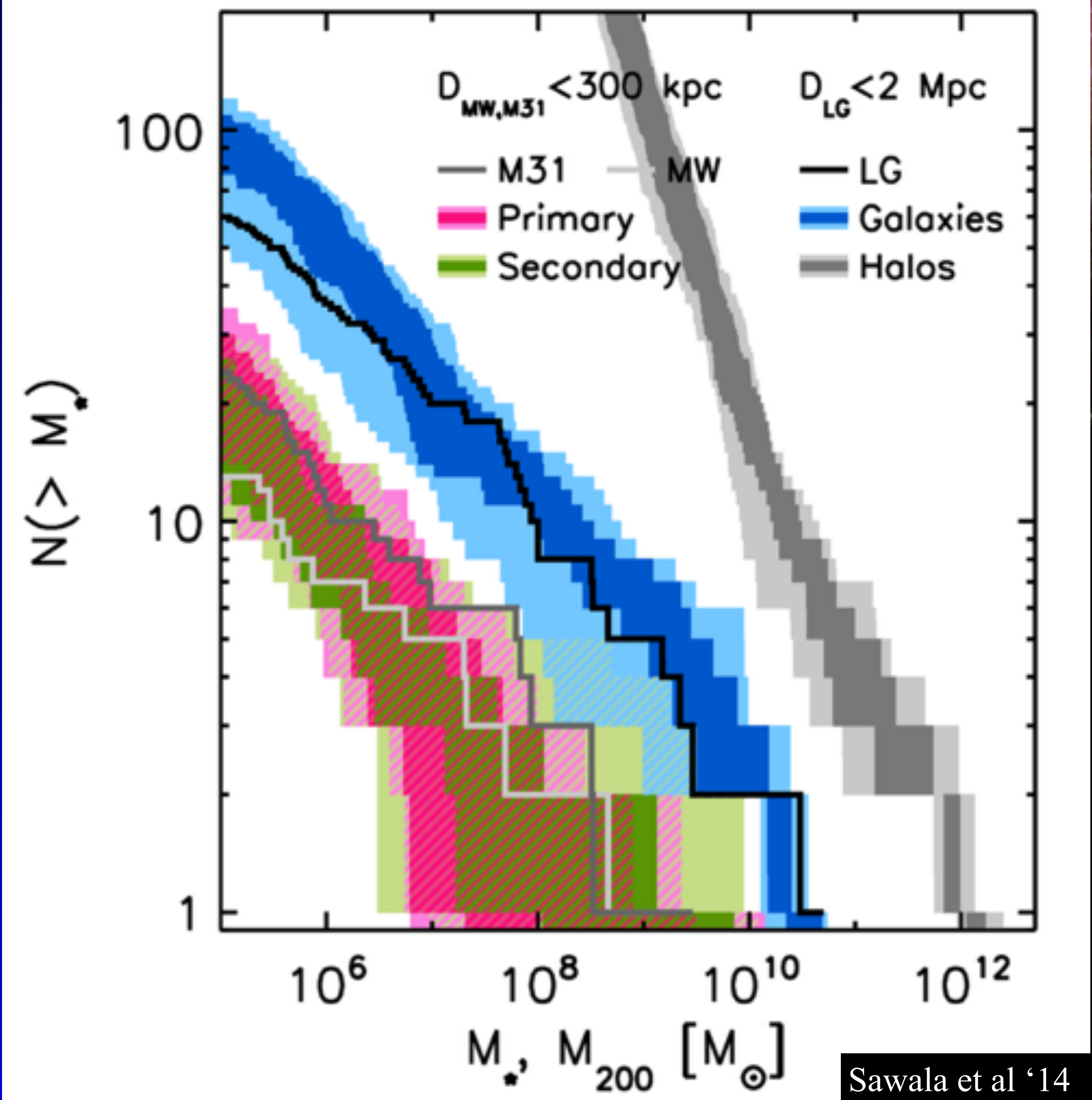
- Local Group masses inferred using different diagnostics yield somewhat conflicting results.
- Whatever mass is chosen for simulations, it will be a ~2-sigma outlier for some observed constraint.
- The LG project target LG systems with $M_{tot}=M_{MW}+M_{31}\sim 2\times10^{12}\ M_{sun}$

Fattahi+14

Dark Matter, Gas and Stars in the Local Group



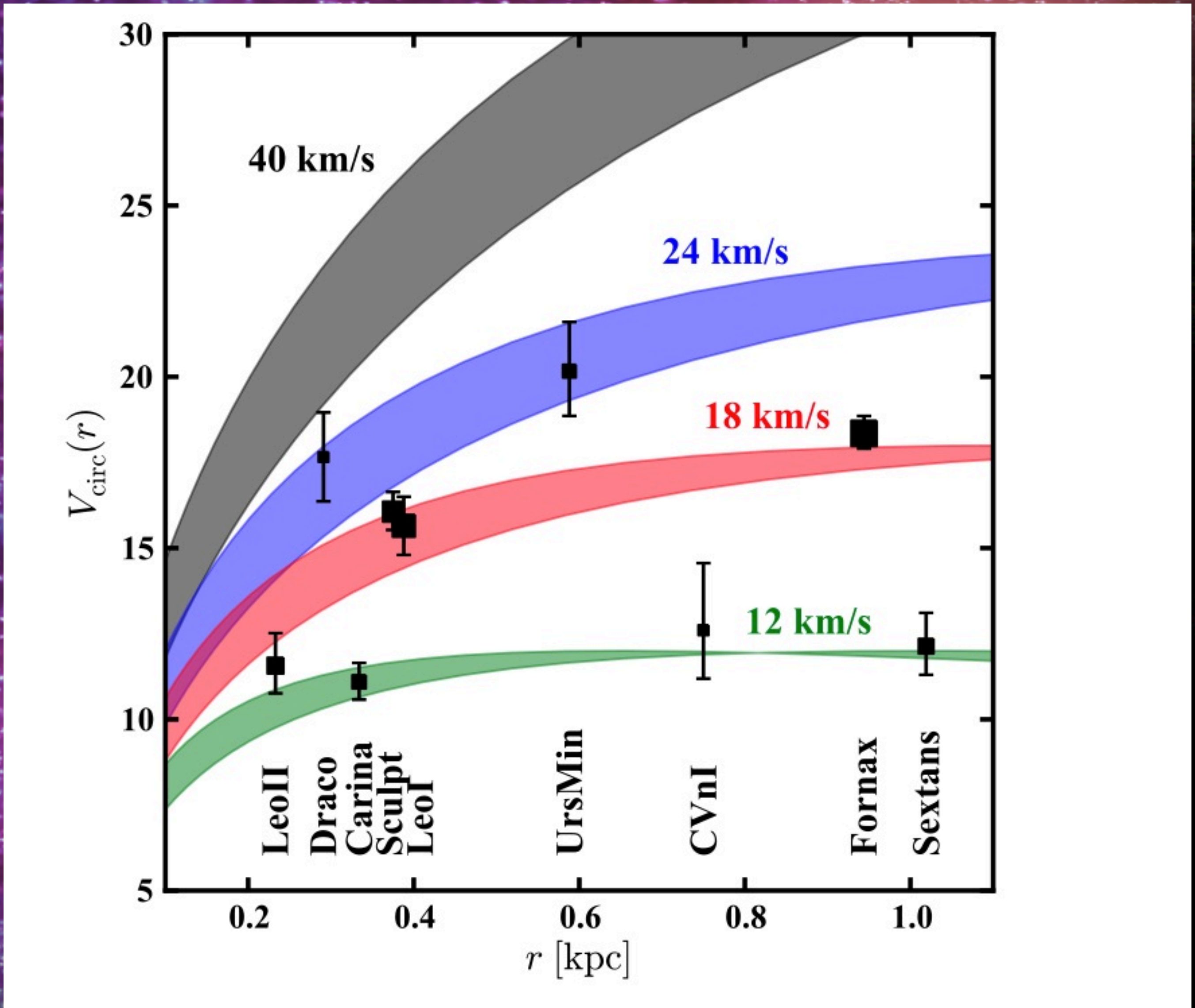
The “missing satellites” problem



Sawala et al ‘14

- Reionization and feedback prevent the formation of luminous galaxies in low-mass halos
- The Local Group re-simulations match quite well the observed number of satellites of each primary and the number of dwarfs within ~2 Mpc from the LG barycentre, down to stellar masses of order ~10^5 M_{sun}

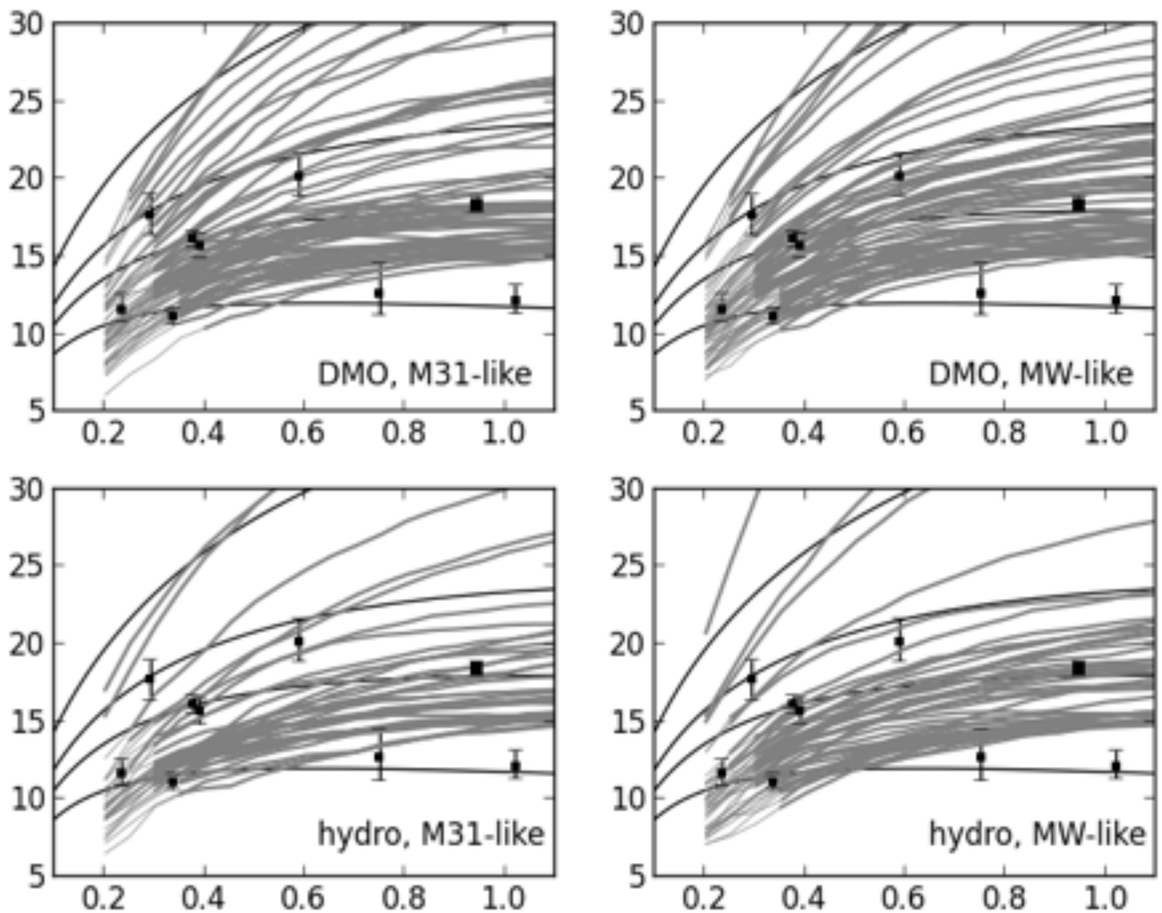
The "too big to fail" problem



- MW satellites appear to inhabit low-mass halos.
- Only three MW satellites (LMC, SMC, Sag) live in halos with V_{max}>25-30 km/s
- MW-sized halos in dark matter-only simulations typically have 7-8 sub-halos exceeding that mass

Boylan-Kolchin et al '11

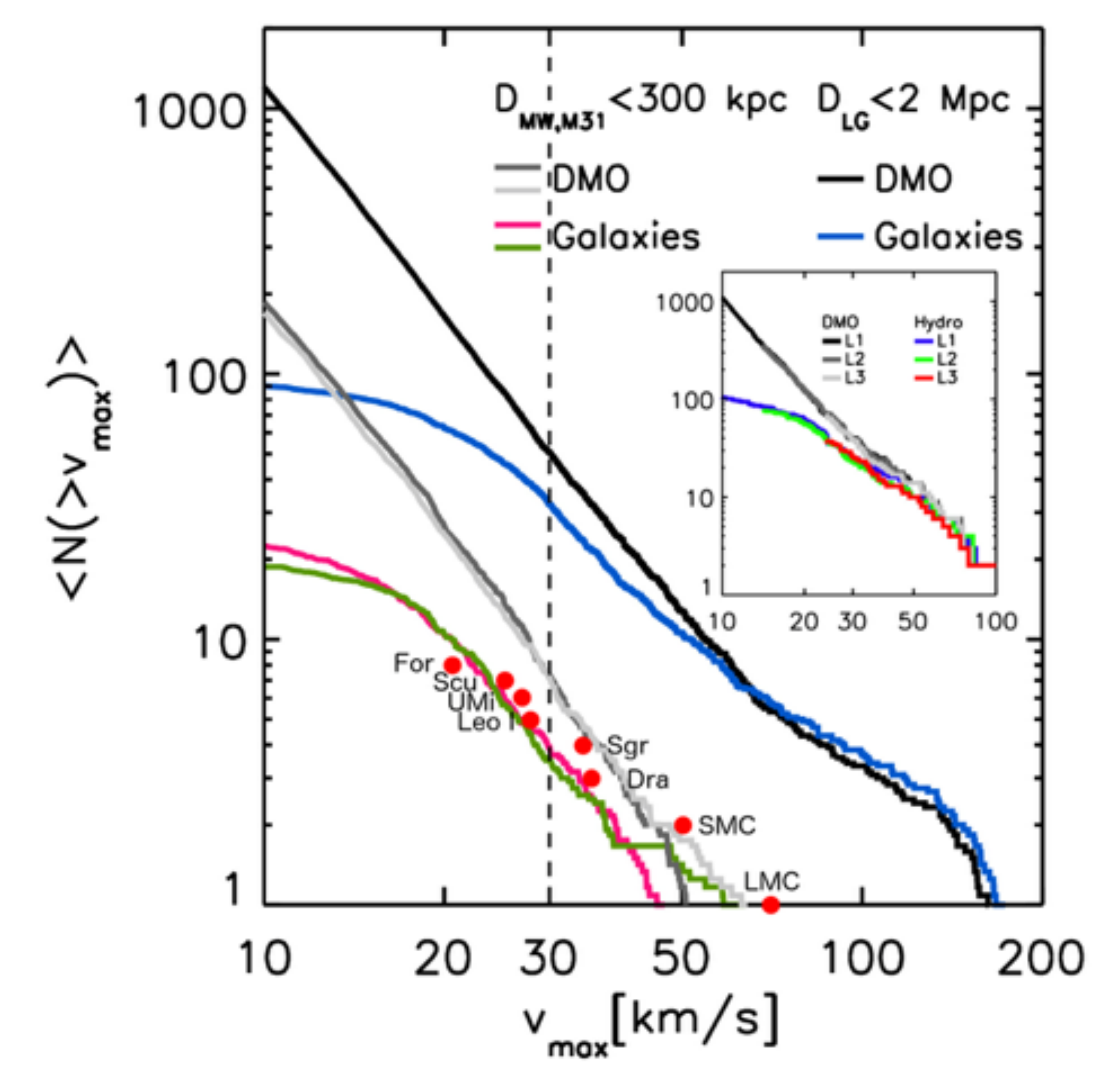
The "too big to fail" problem



- The number of sub-halos is greatly reduced at given V_{max} in simulations that include baryons
- This has been ascribed to tidal stripping and the formation of "cores"
- Our simulations show similar reduction in numbers, although cores do not form

Sawala et al 2014

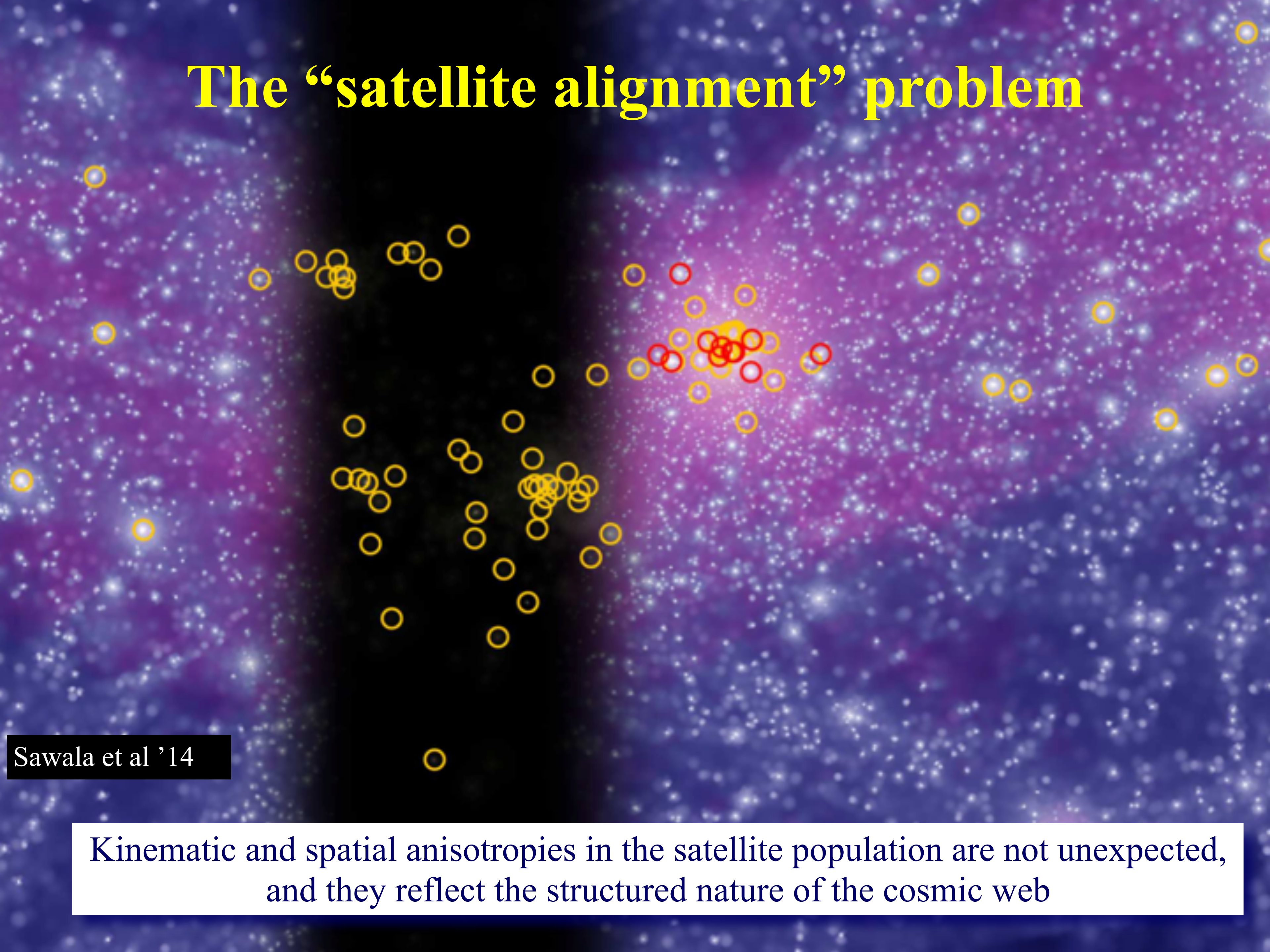
The "too big to fail" problem



- Low-mass subhalos experience a reduction in V_{max} of order 15-20% because of the loss of the baryonic mass.
- This reduces by a factor of ~2 the number of sub halos with V_{max} > 30 km/s, resolving the "too big to fail" problem

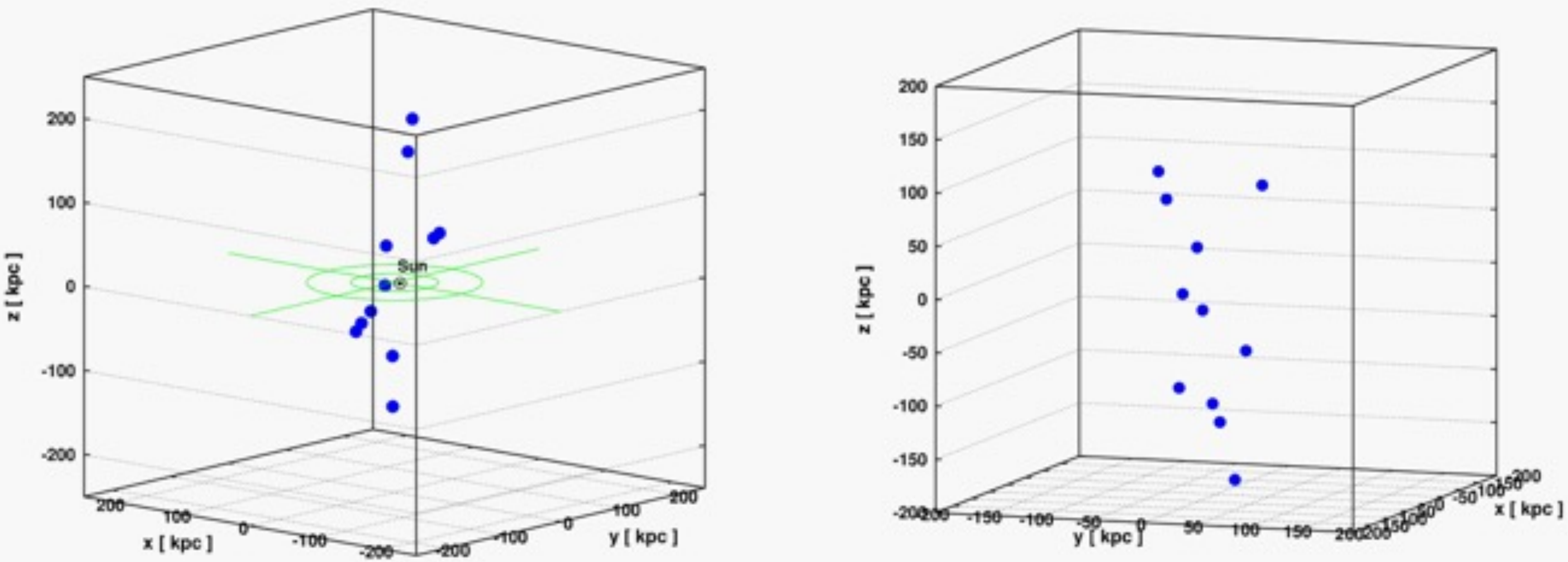
Sawala et al '14

The “satellite alignment” problem



Kinematic and spatial anisotropies in the satellite population are not unexpected, and they reflect the structured nature of the cosmic web

The “satellite alignment” problem

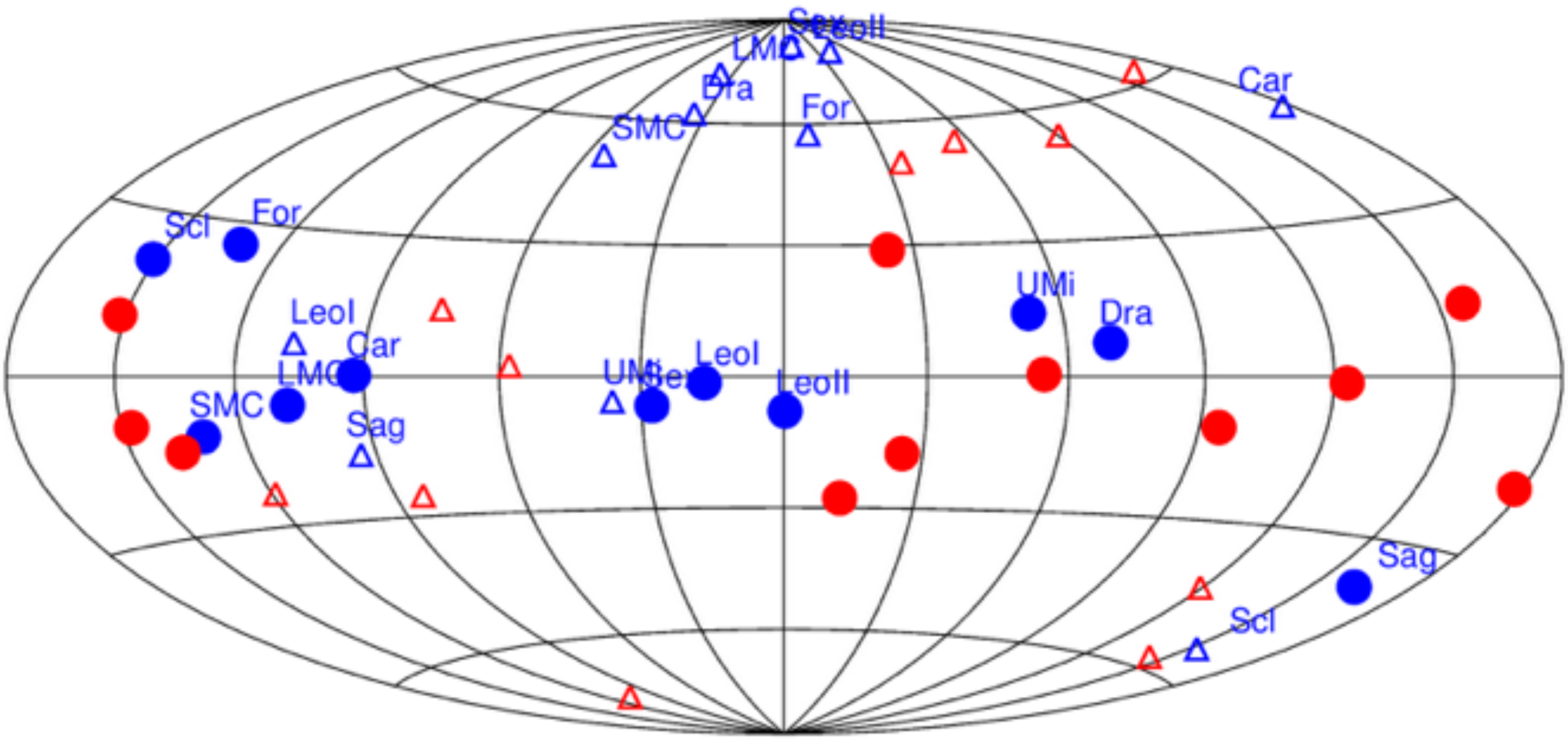


Milky Way LG-5

- Kinematic and spatial anisotropies in the satellite population are not unexpected, and they reflect the structured nature of the cosmic web
- The satellite population of one of our resimulated LG candidates is as “flat” as that of the Milky Way

Sawala et al ’14

The “satellite alignment” problem



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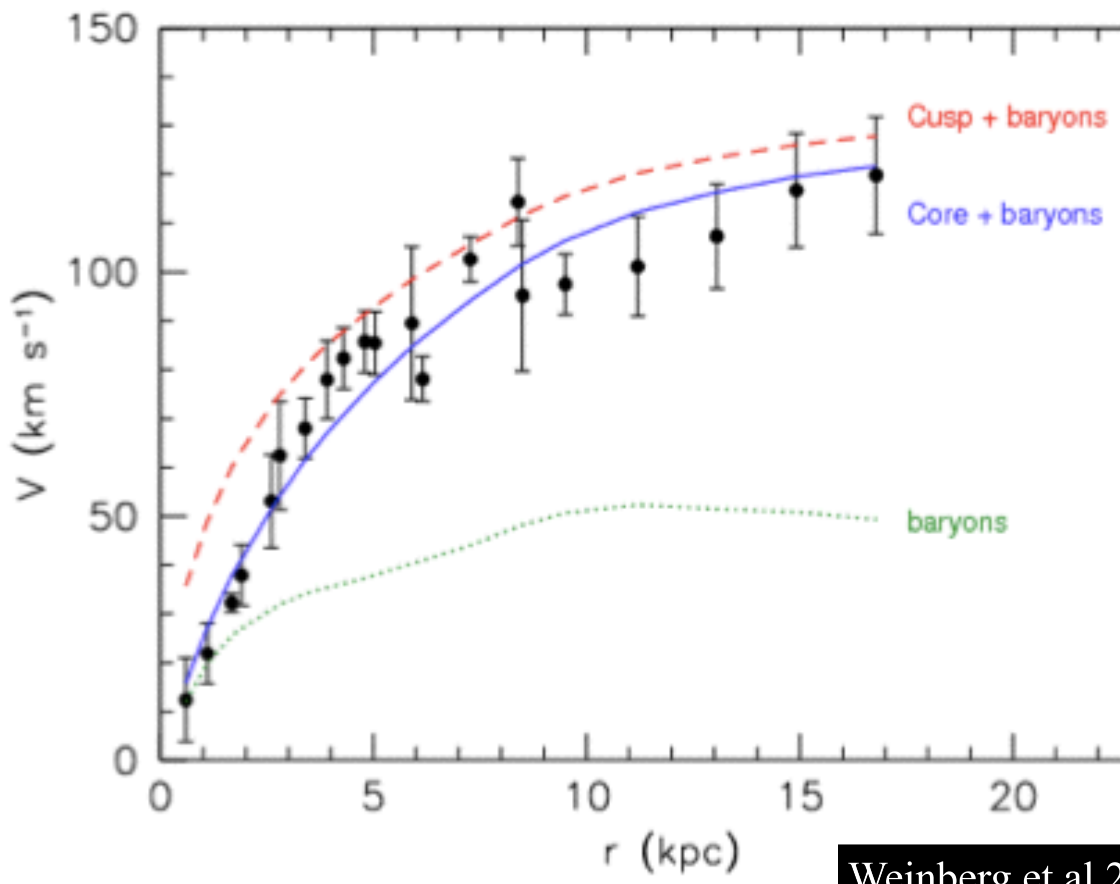
Sawala et al ’14

The rotation curve ("cusp vs core") problem



Weinberg et al 2013

A constant density "core" at odds with the predicted cuspy profiles has been predicated on the basis of rotation curves of disk galaxies.

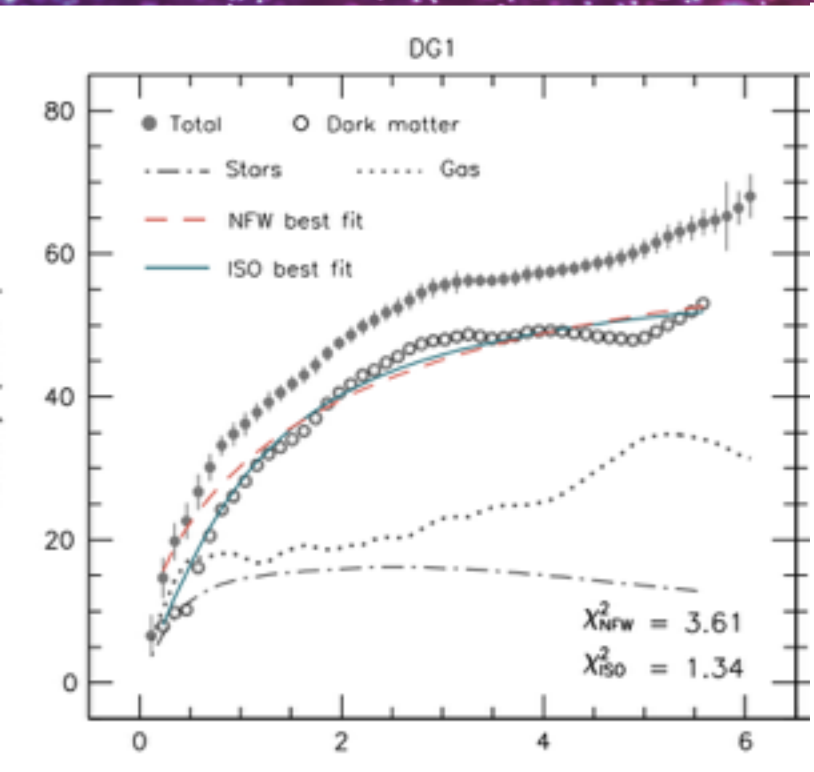
This is a 20+ yr-old problem (Flores & Primack1994; Moore 1994)

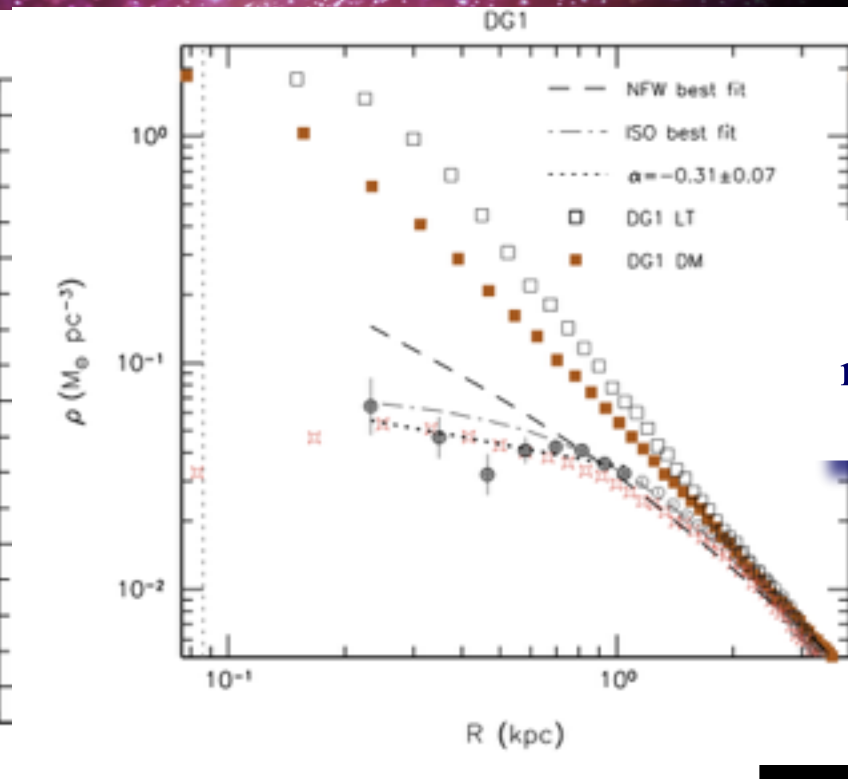
What has changed since?

1) Data are substantially better
2) Cosmology and its parameters are now fixed
3) Simulations produce realistic galaxies, allowing for meaningful predictions?

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."—Max Planck

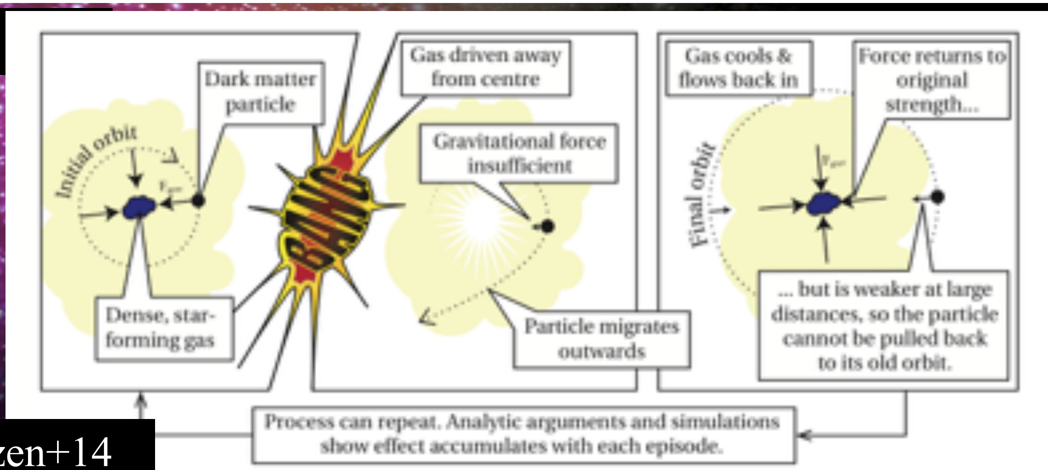
The rotation curve problem





Some simulations now produce "cores"

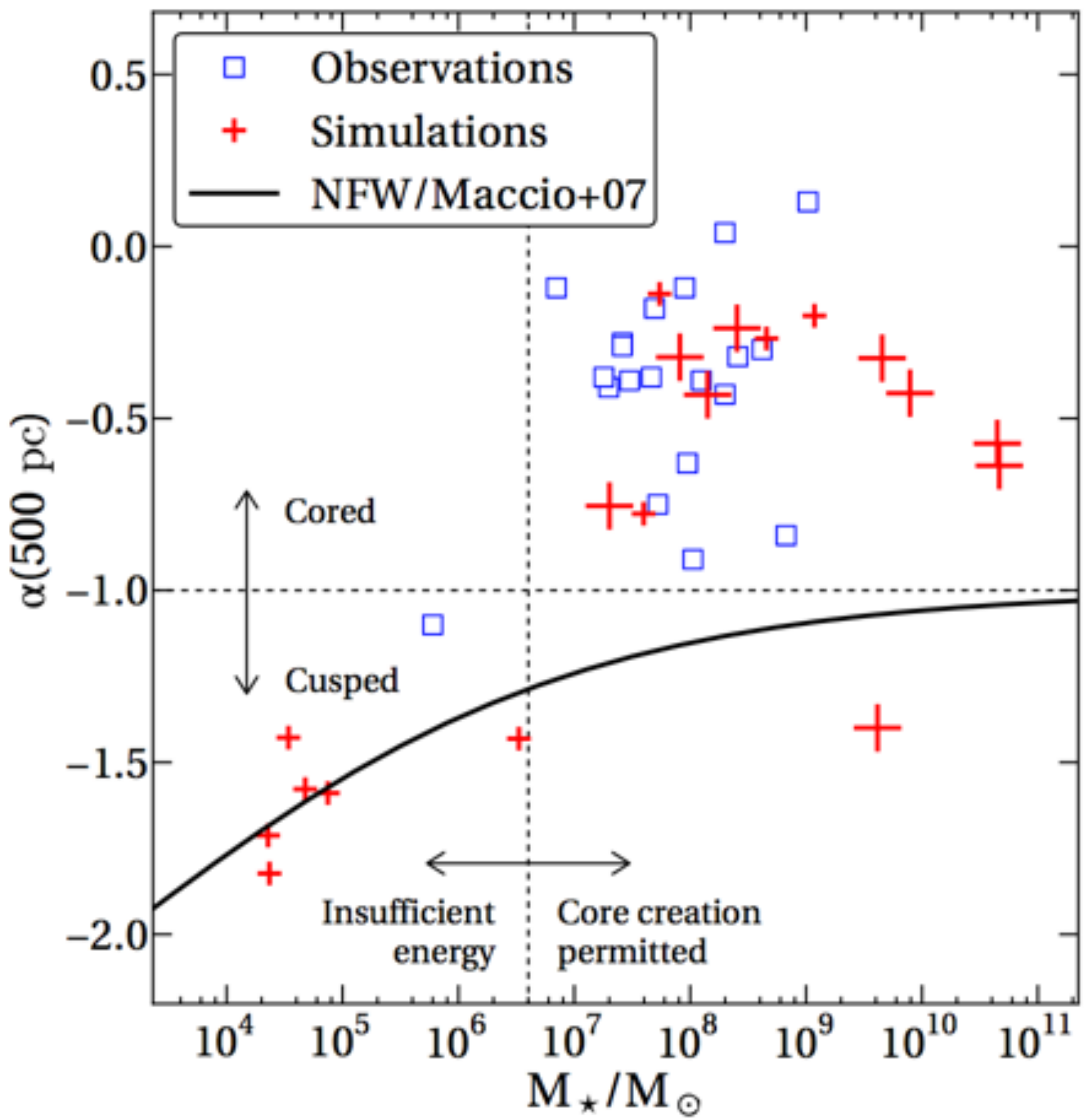
Oh+11



Pontzen+14

- Under *some conditions*, the central density profile of DM halos can be changed by baryonic effects.
- The effect, however, is small, and mainly noticeable at the center

The rotation curve problem

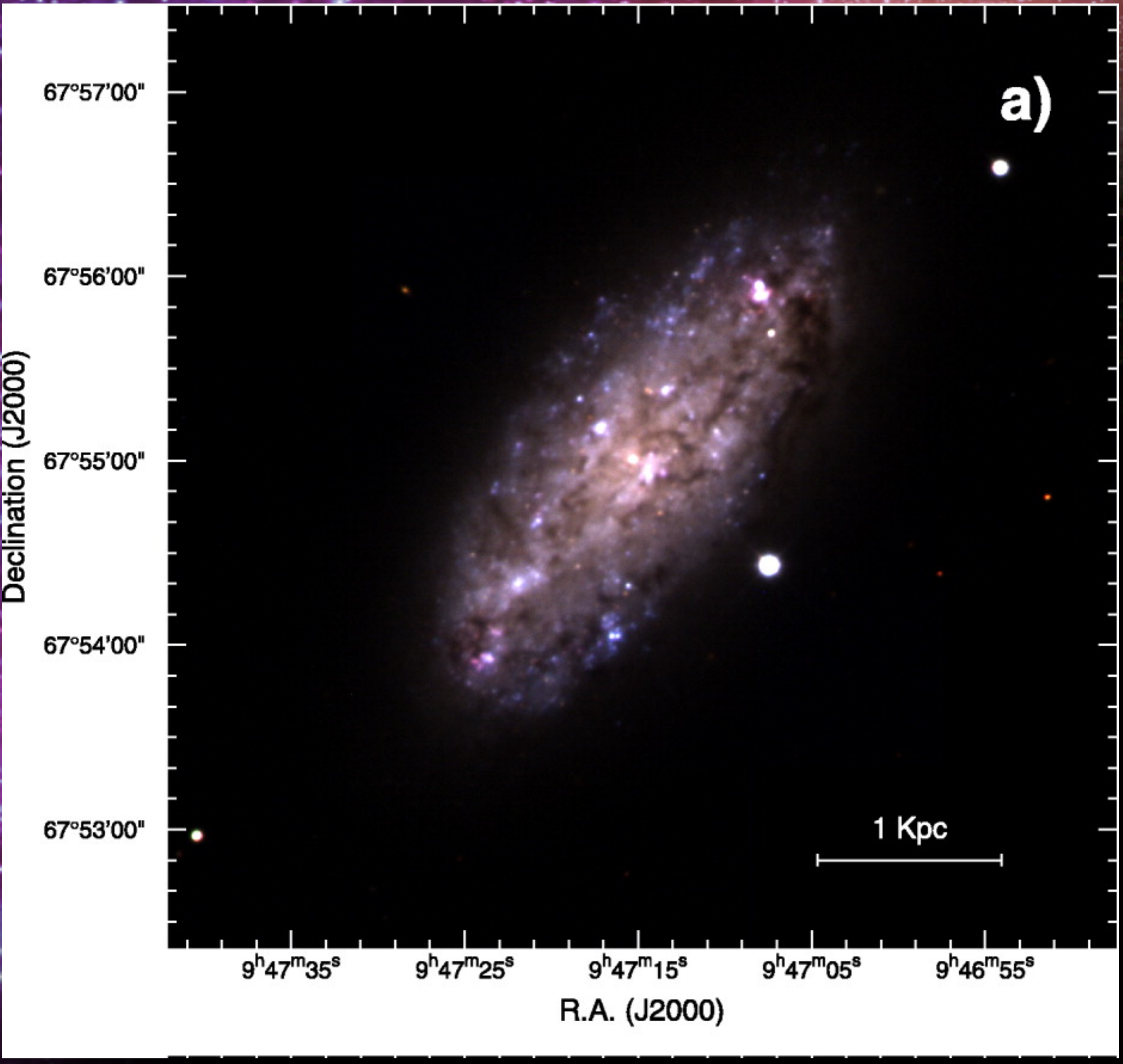


- The comparison between data and simulations have focussed on the inferred slope of the dark matter density profile in the inner (~500pc!!) regions

- This is very hard to do, in simulations *and* in observations

Pontzen+14

Observed inner slopes: the cautionary tale of NGC2976



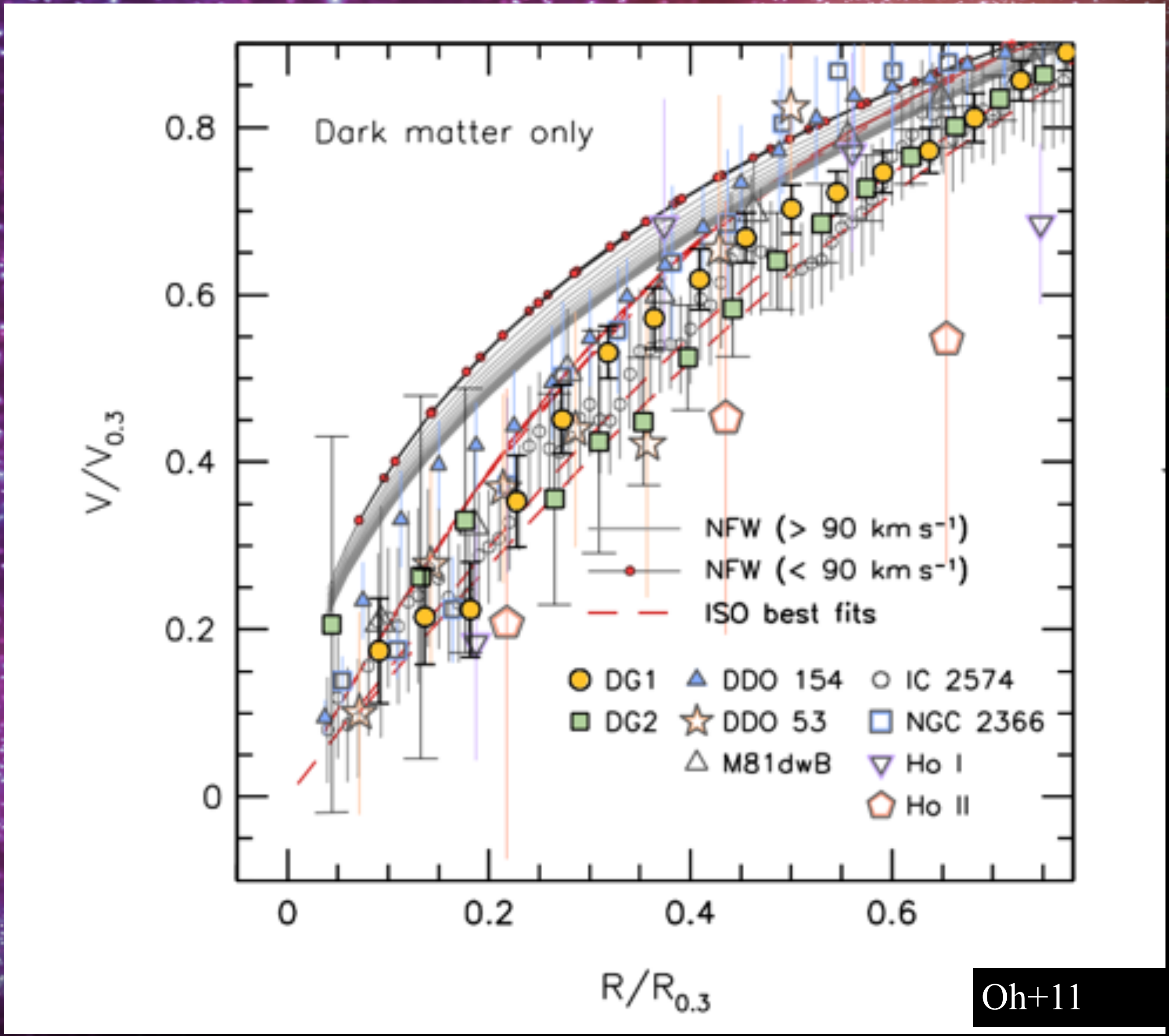
- "…independent of any assumptions about the stellar disk or the functional form of the density profile, NGC 2976 does not contain a cuspy dark matter halo" (Simon+2004)

- "The…fit suggests a DM cusp…and excludes a DM core…" (Adams+2013)

- "NGC 2976…looks cored when the gas velocity field is fit with a radial component and cuspy when fit with the gas velocity field plus a bar component… (Adams+2014)

- **The total mass profile, however, is changes little in these analyses.**

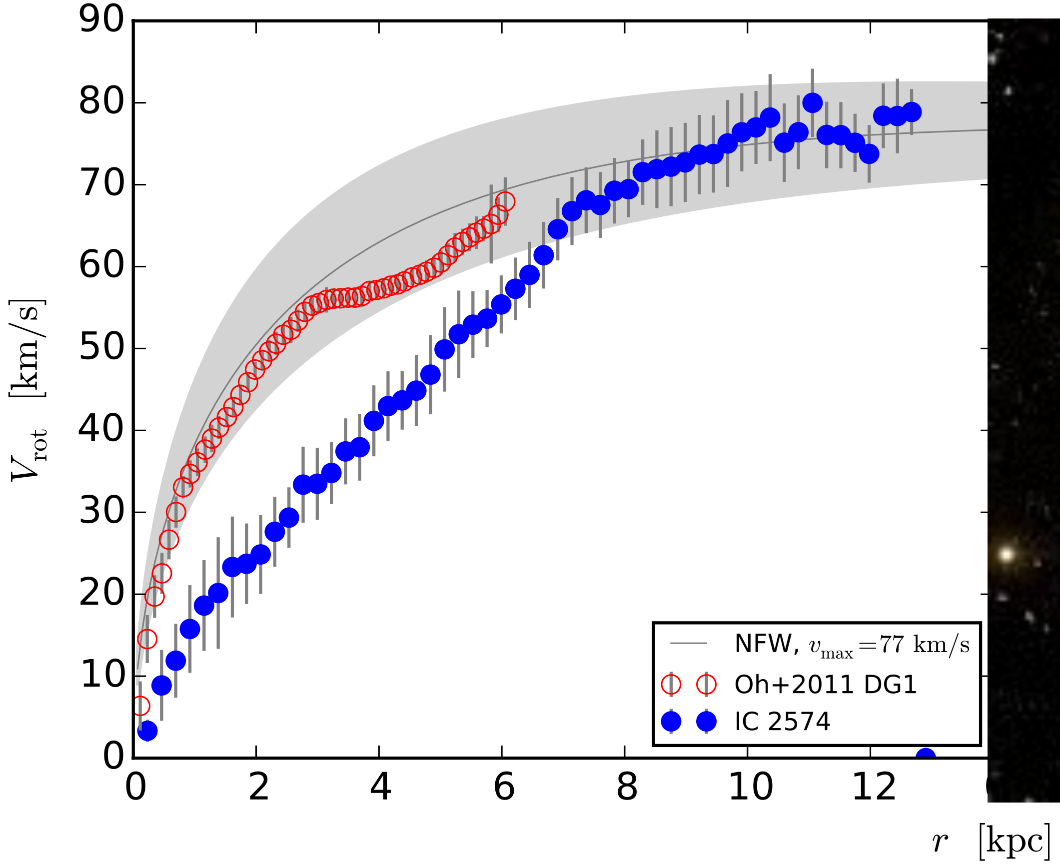
Simulated inner slopes: the cautionary tale of IC2574



Oh+11

- "This confirms that the baryonic feedback processes included in the simulations are efficiently able to …. induce DM halos with a central mass distribution similar to that observed in nearby dwarf galaxies." (Oh +2011)
- This is based on "rescaled" rotation curves, as in this figure.

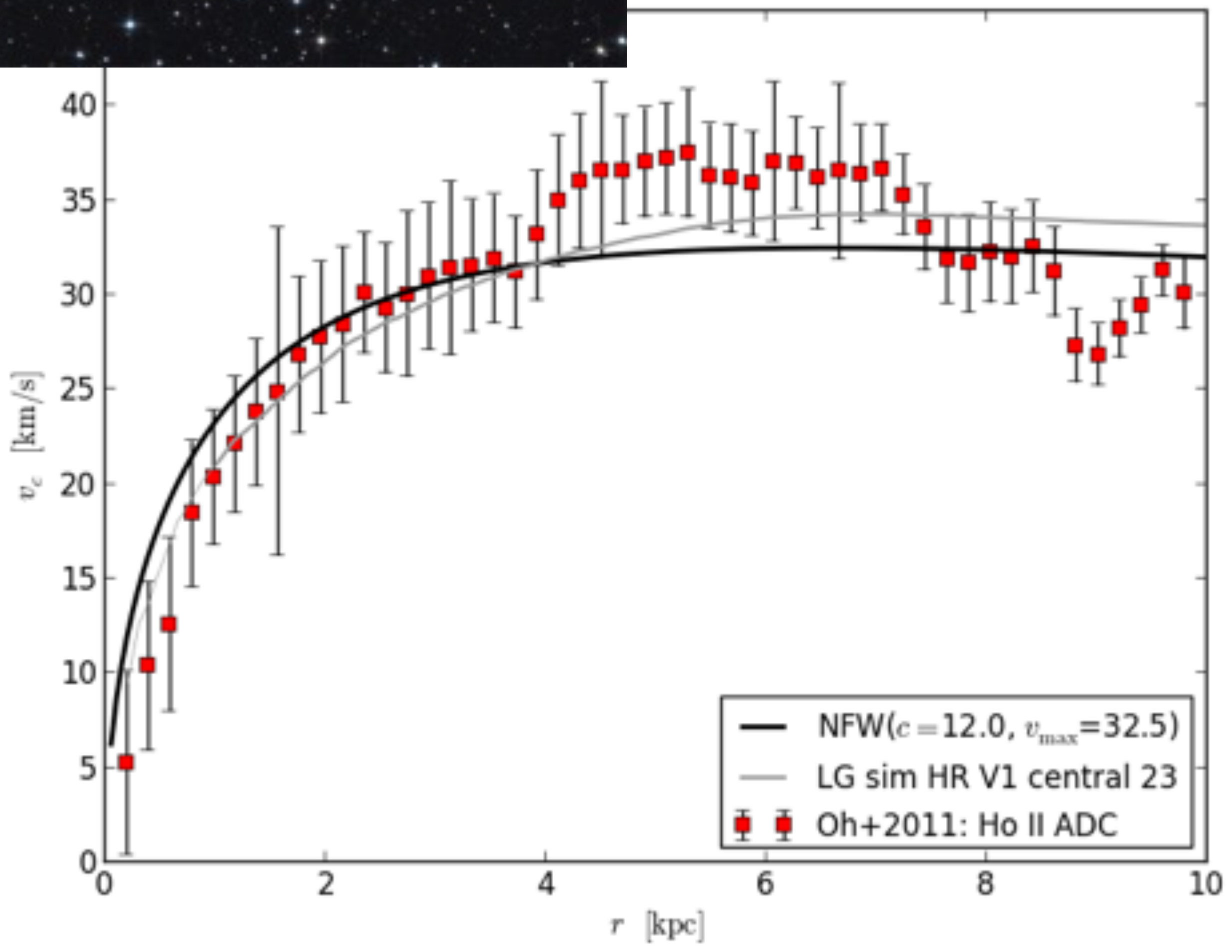
Simulated inner slopes: the cautionary tale of IC2574



- Although the observed and simulated “inner DM slopes” may be similar, this does not necessarily reconcile LCDM with the rotation curve data, since *no rescaling is possible once the LCDM cosmological parameters are fixed*.

Oman+14

The rotation curve problem

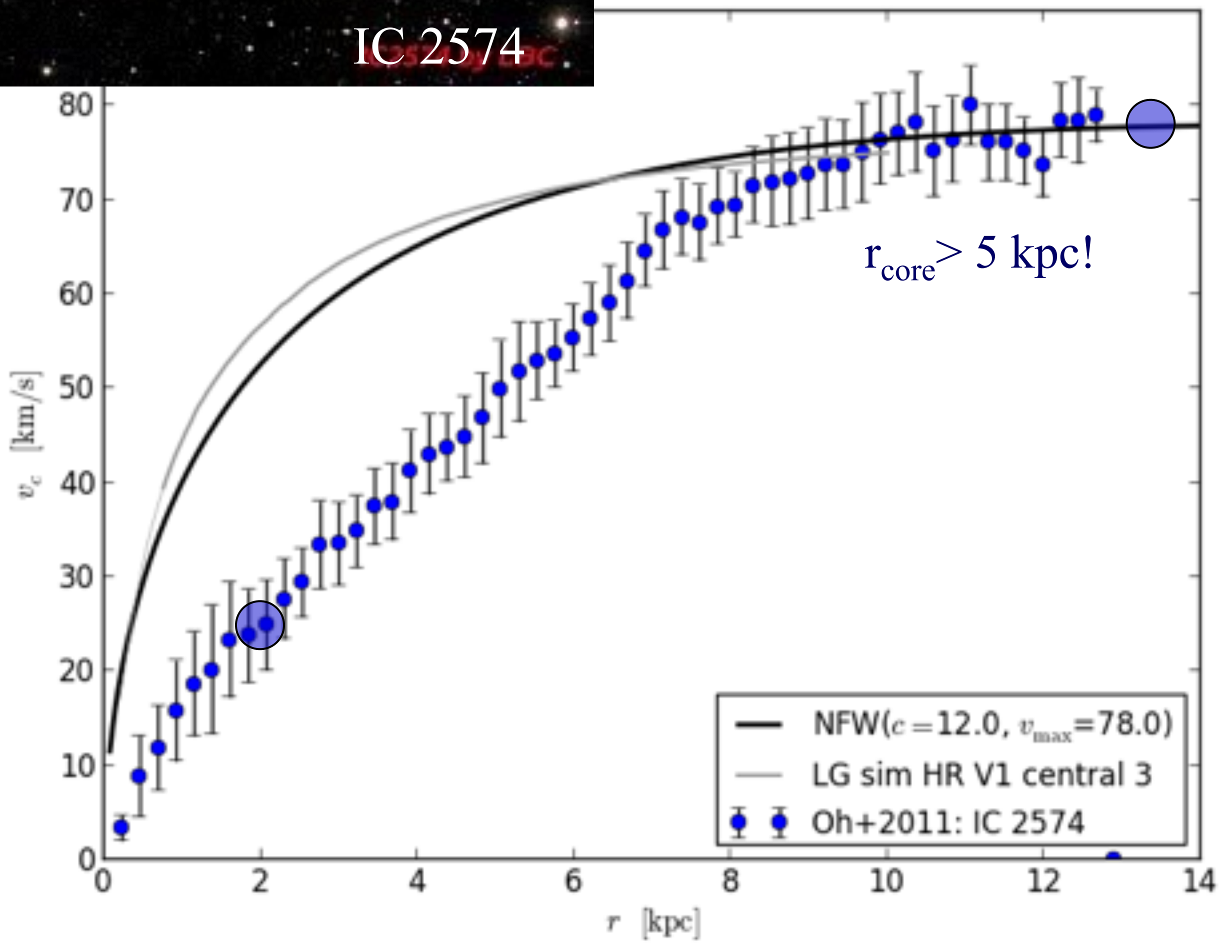


- A more direct approach is to compare the circular velocity curves inferred from observations *directly* with simulations

- Some galaxies are well fit by simulated data (like Hol II)

Oman+14

The rotation curve problem

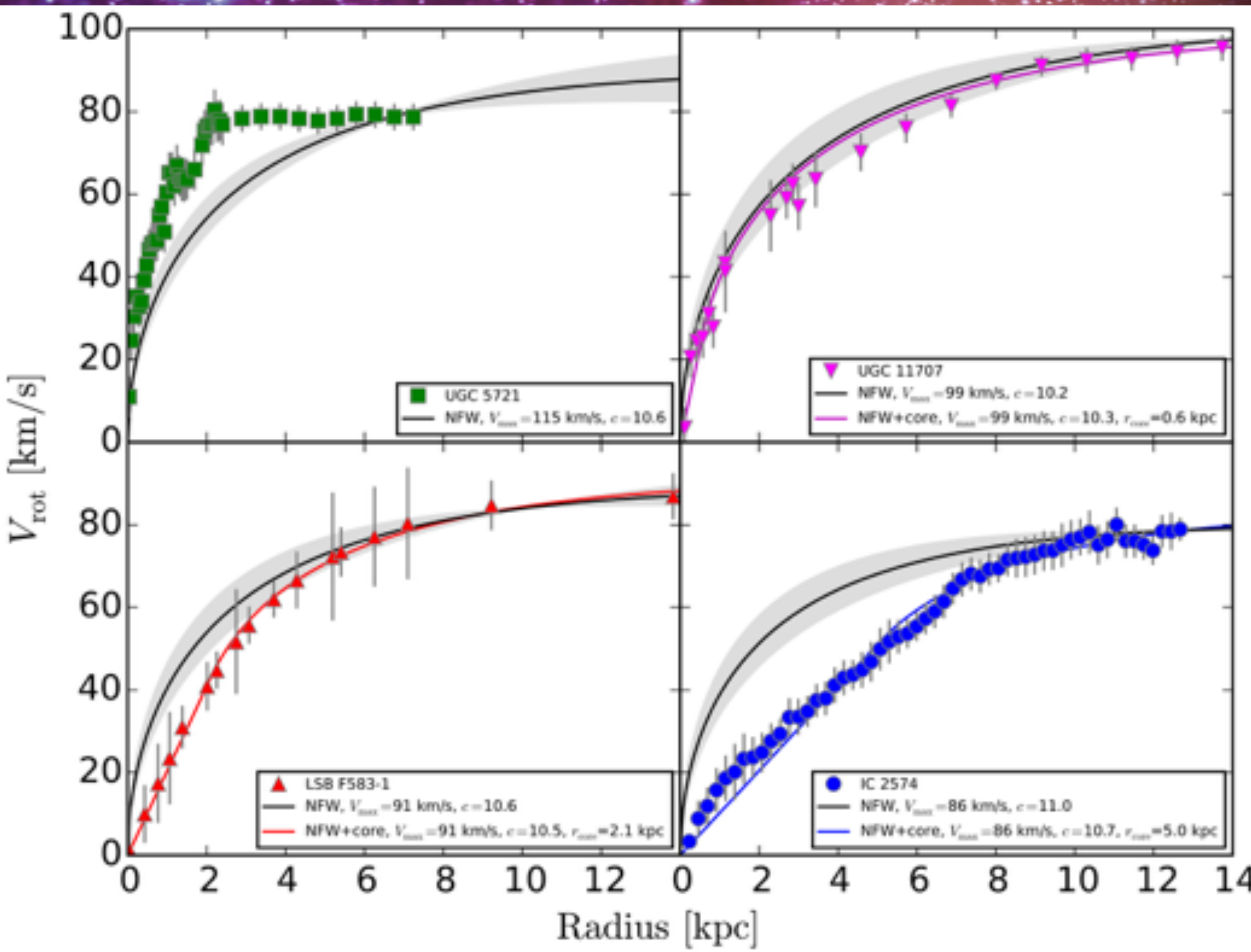


- Some galaxies are not well fit in LCDM

- The cusp vs core problem is best expressed as a *deficit of matter in the inner regions* of *some* galaxies, compared with the LCDM predictions

Oman+14

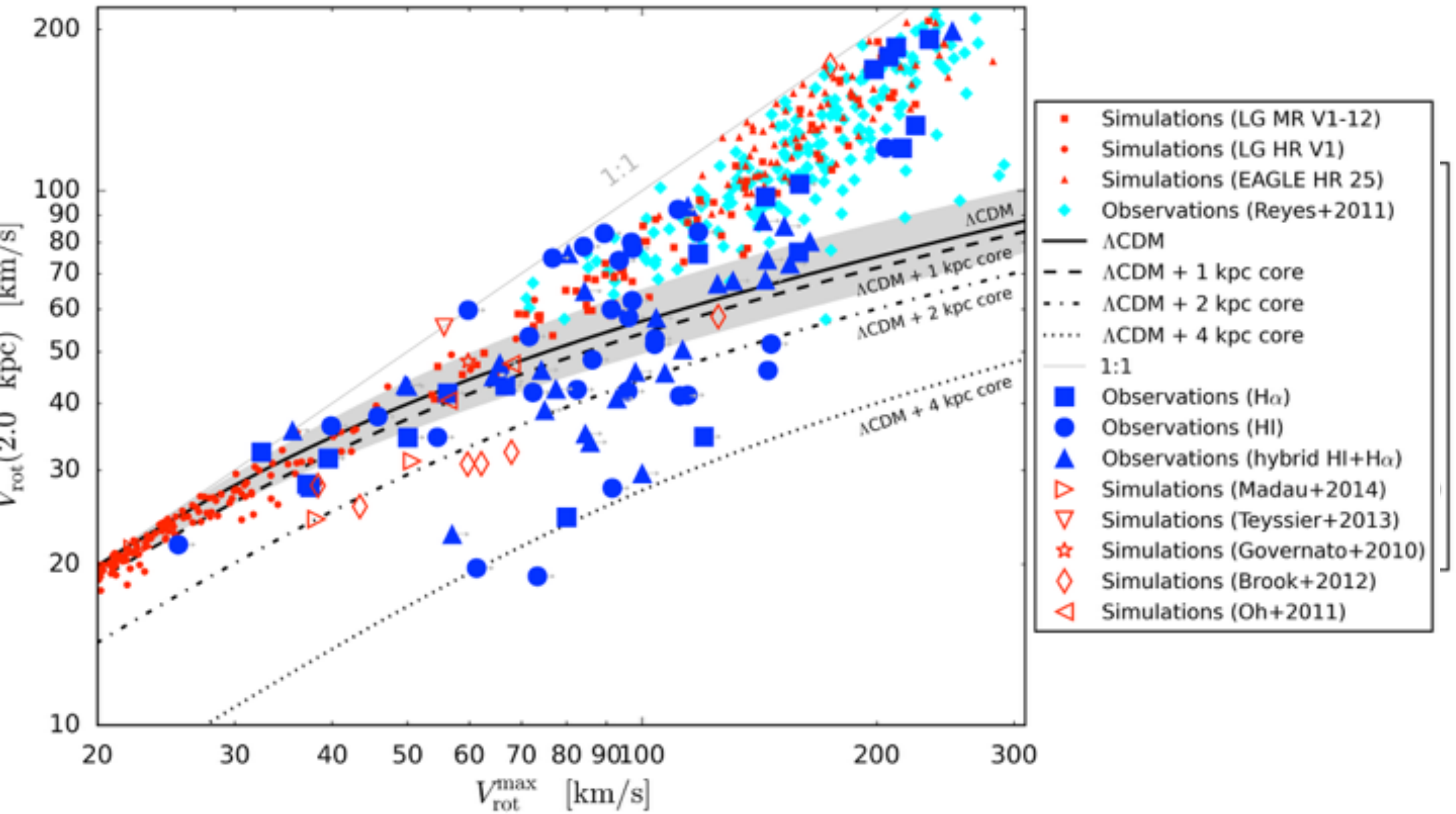
The rotation curve problem



- The rotation curve problem is also one of **diversity**.
- CDM predicts a **single** profile for a given velocity scale, *unlike* observed rotation curves
- Note that **this precludes a particle physics solution** to the problem (e.g, "self-interacting" or "warm" dark matter).

Oman+14

The rotation curve problem



- Dwarf galaxies have a wide diversity of rotation curves
- Some galaxies are consistent with CDM, others are not
- "Cores" seem present in galaxies up to ~150 km/s
- Inferred core radii are larger than simulations seem able to account for

Oman'14

SUMMARY

Julio F. Navarro

- Numerical simulations that include the effects of baryons seem to **resolve three cosmological puzzles** brought about by observations of satellites in the Local Group.
  - The “missing satellites” problem
  - The “satellite alignment” problem
  - The “too big to fail alignment” problem
- Rotation curves of dwarf galaxies, taken at face value, present a problem for LCDM
  - The problem is one of **diversity** at given velocity/mass scale: some galaxies seem to show a deficit of inner mass, others do not
  - One+ of these statements must be true:
    - Dark matter is more complex than so far considered
    - Current simulations do not capture the essential physics of dwarf galaxy formation
    - The mass profiles inferred from kinematic data of dwarfs are incorrect