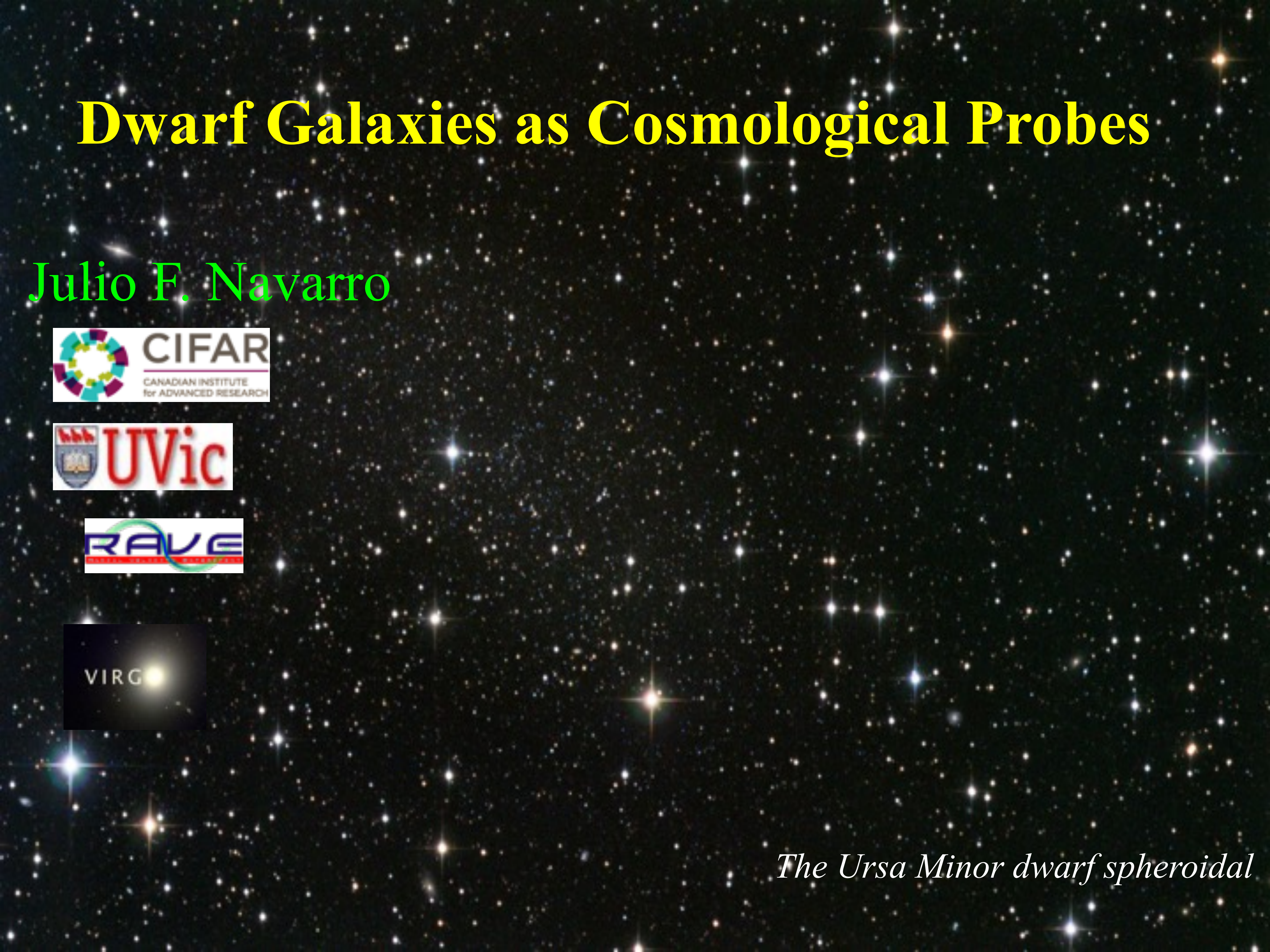
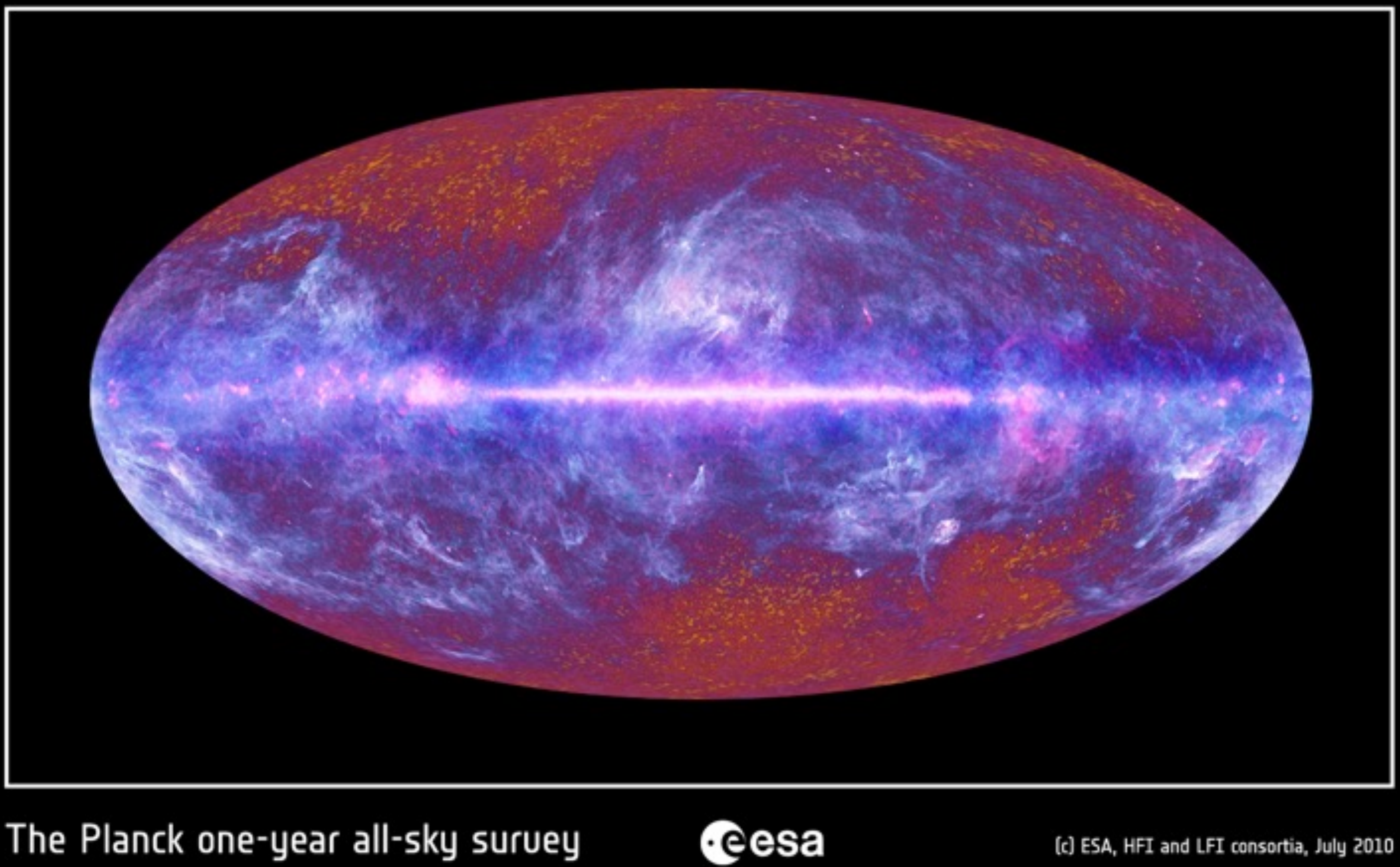
Dwarf Galaxies as Cosmological Probes

Julio F. Navarro

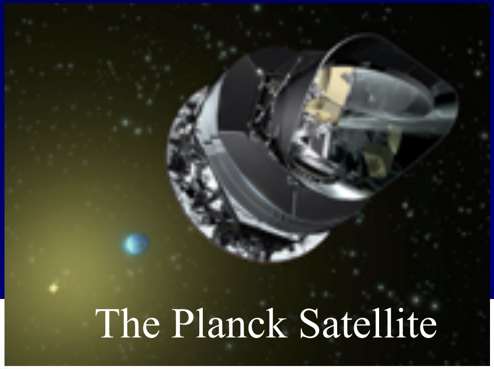


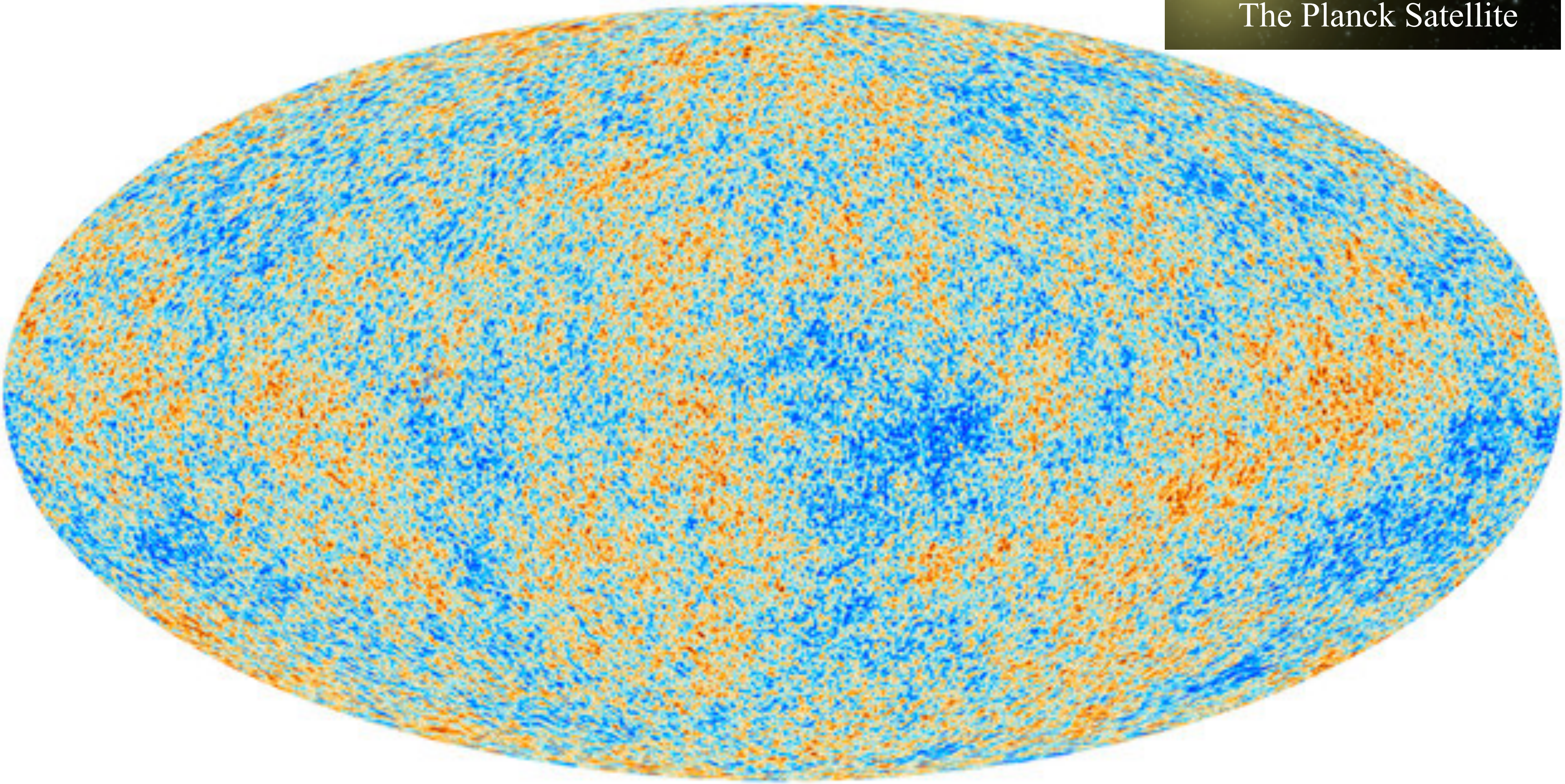
The Ursa Minor dwarf spheroidal

First Light

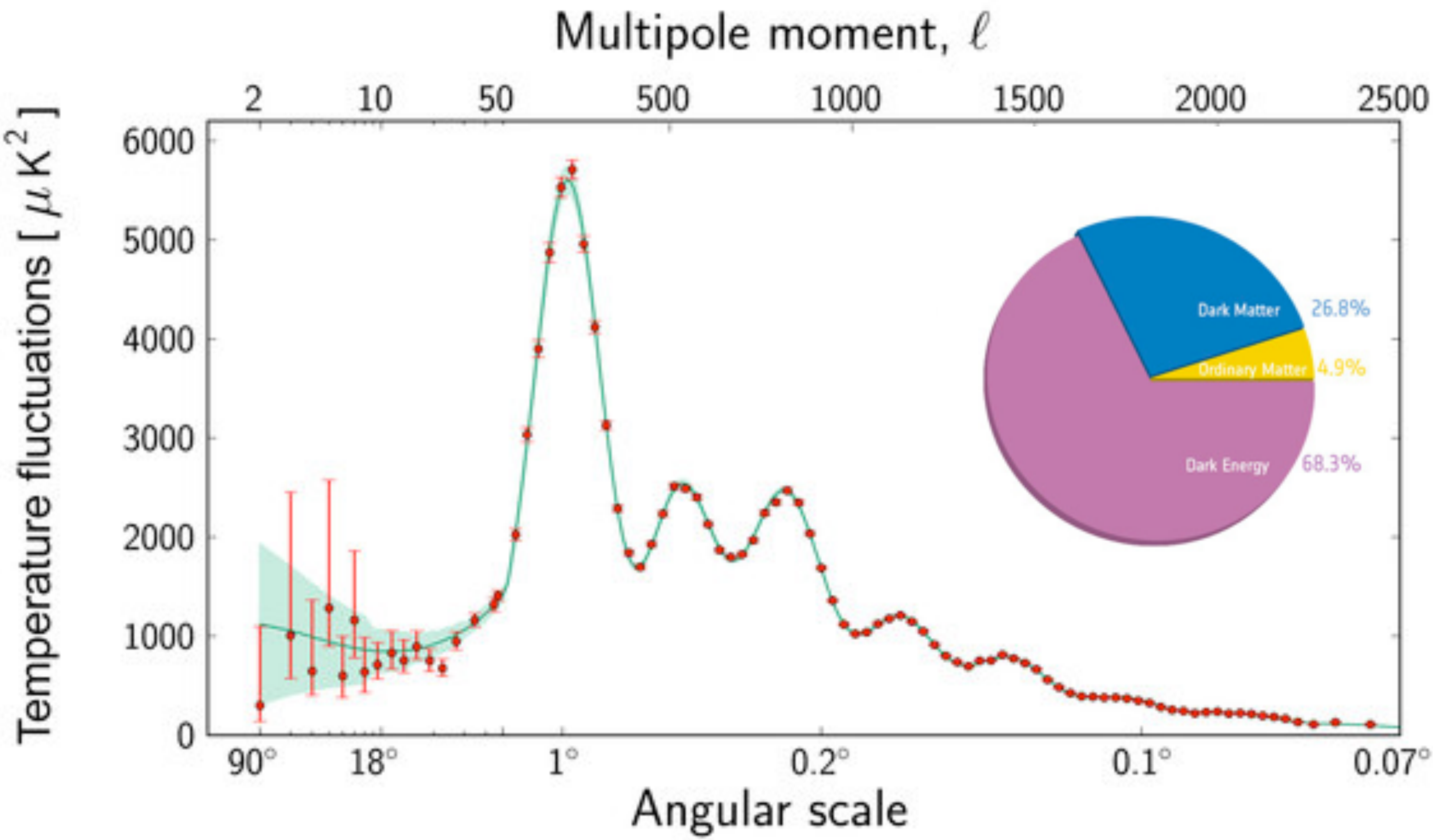

The Planck one-year all-sky survey
(c) ESA, HFI and LFI consortia, July 2010

First Light



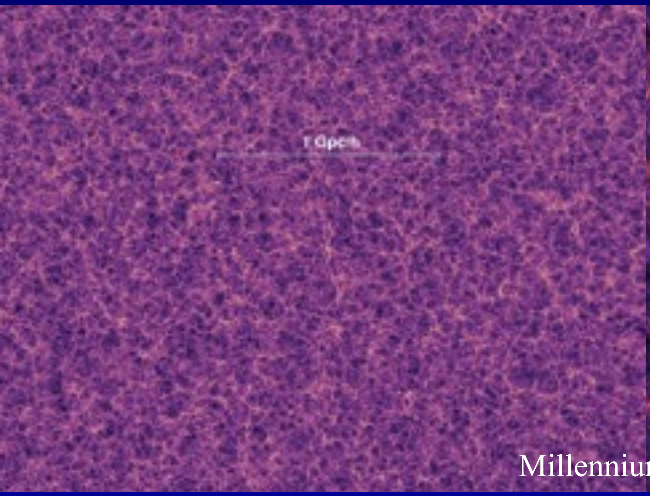
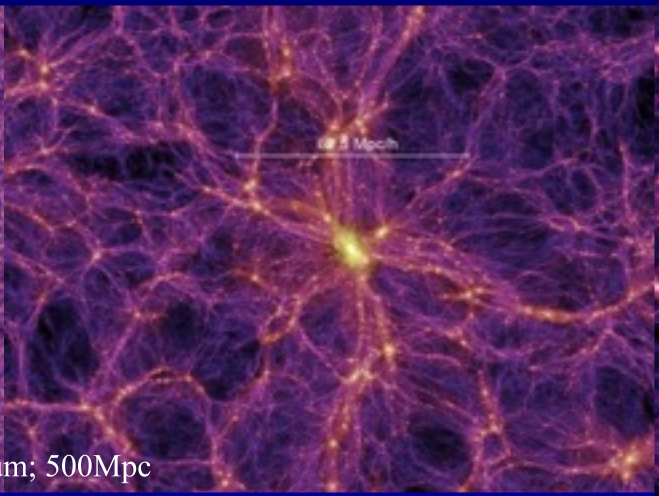


The Cosmological Paradigm

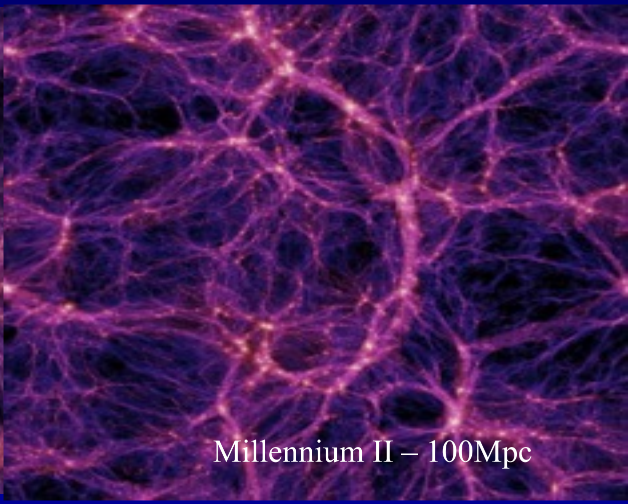


The Clustering of Dark Matter

The Millennium Simulation Series

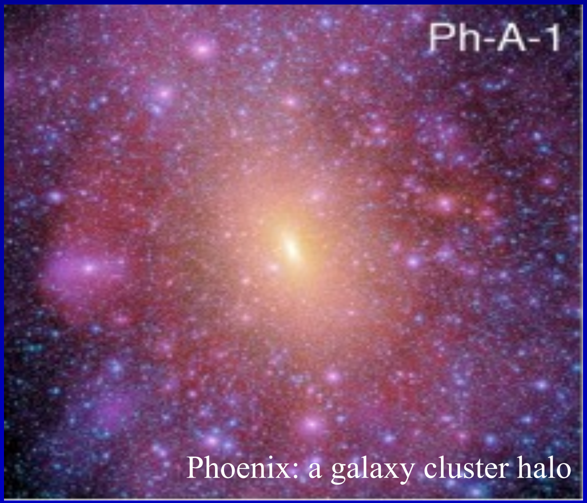



Millennium; 500Mpc



Millennium II – 100Mpc

Aquarius: a galaxy halo

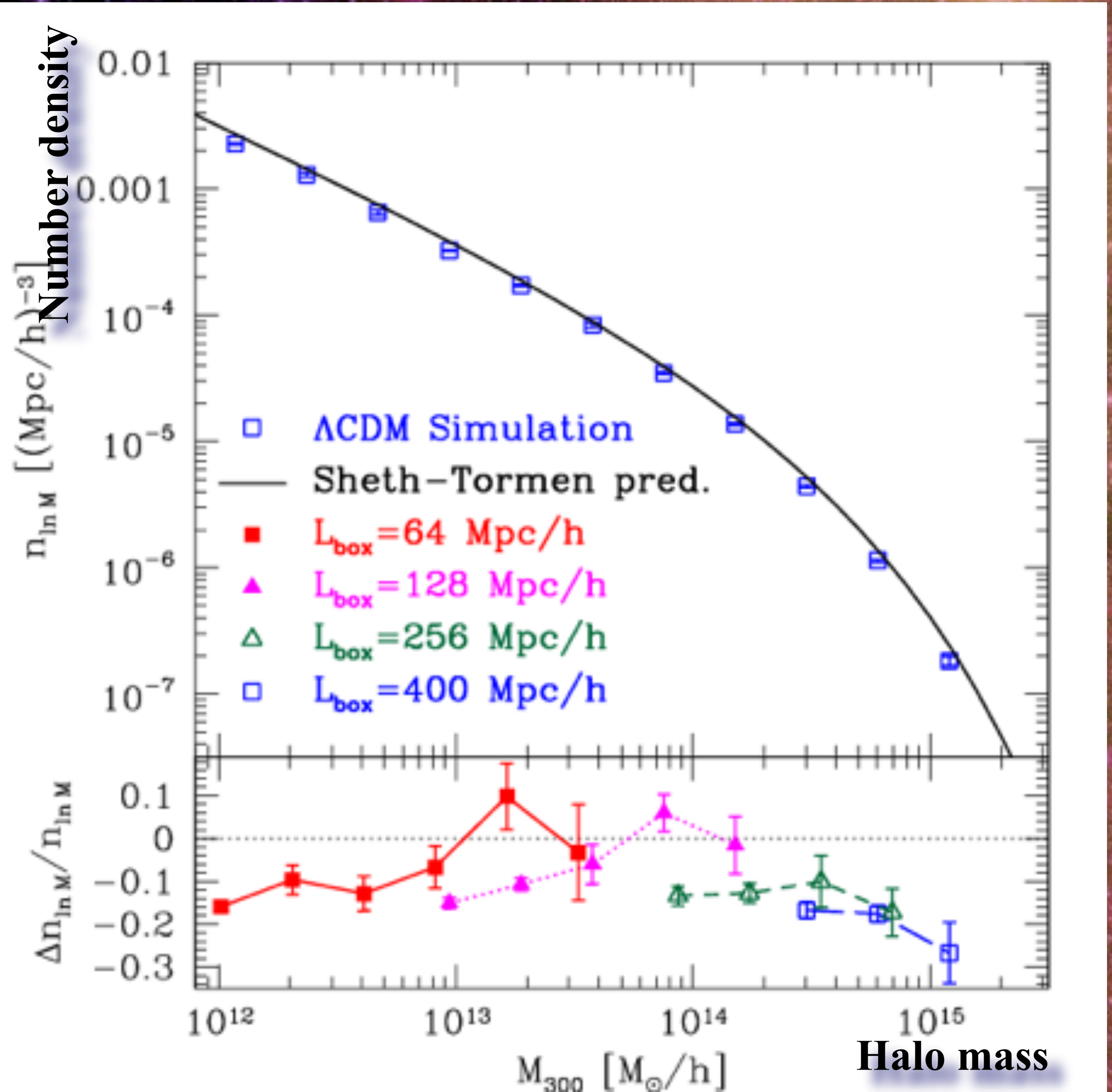


Phoenix: a galaxy cluster halo

Simulations have enabled a full characterization of the clustering of cold dark matter on large and small scales.

VIRGO

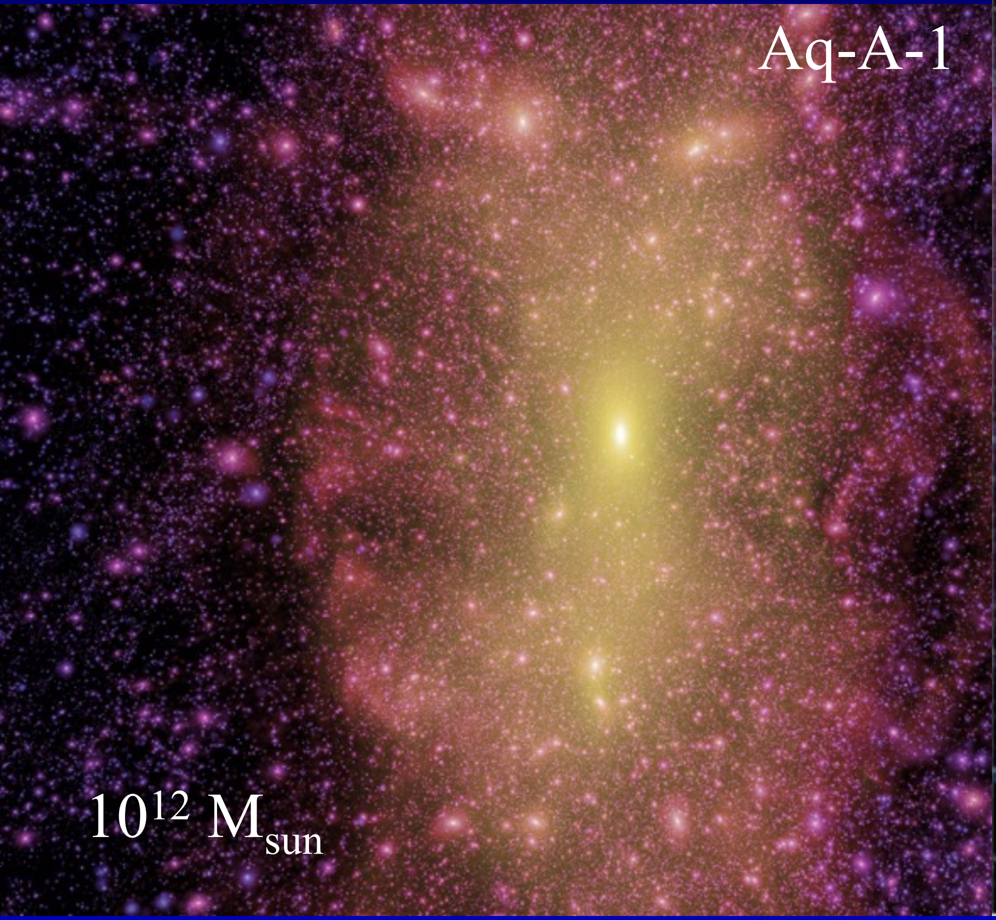
CDM halo mass function

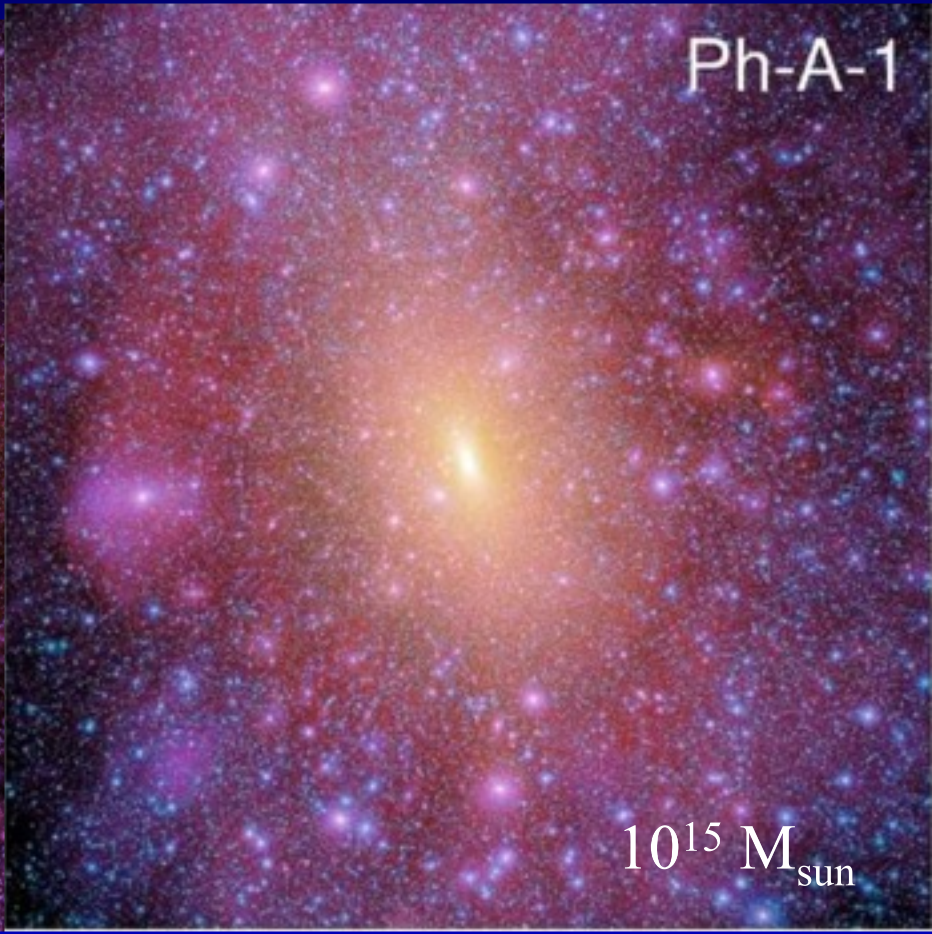


- CDM halo mass function is now very well understood in all mass scales relevant to galaxy formation.

Schmidt et al 2009

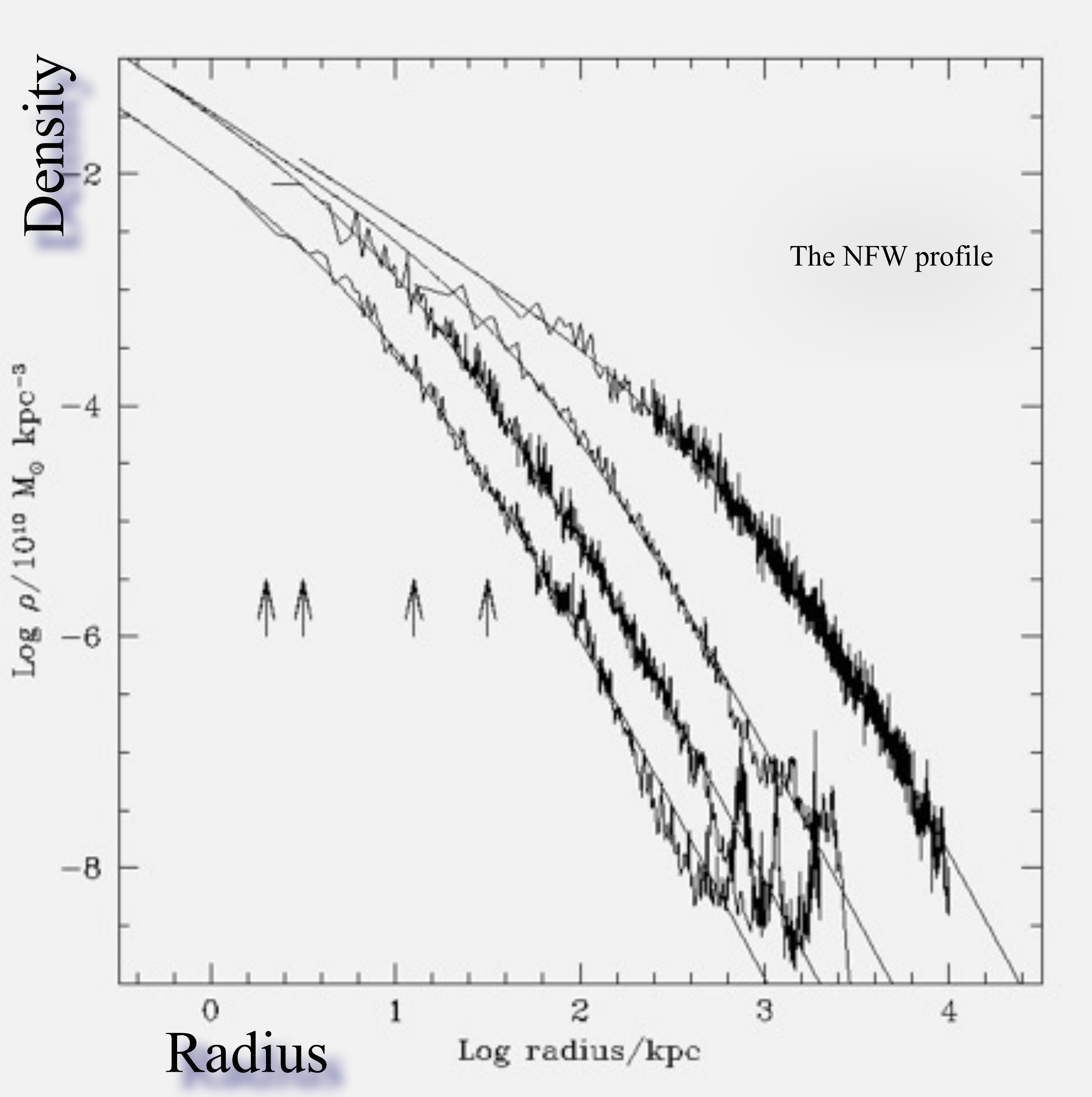
The self-similar nature of LCDM halos





The structure and substructure of CDM halos are approximately self-similar

The Mass Profile of Cold Dark Matter halos



- The shape of the mass profiles of dark mater halos is roughly independent of halo mass and cosmological parameters

- Density profiles are "**cuspy**" and clearly differ from power laws

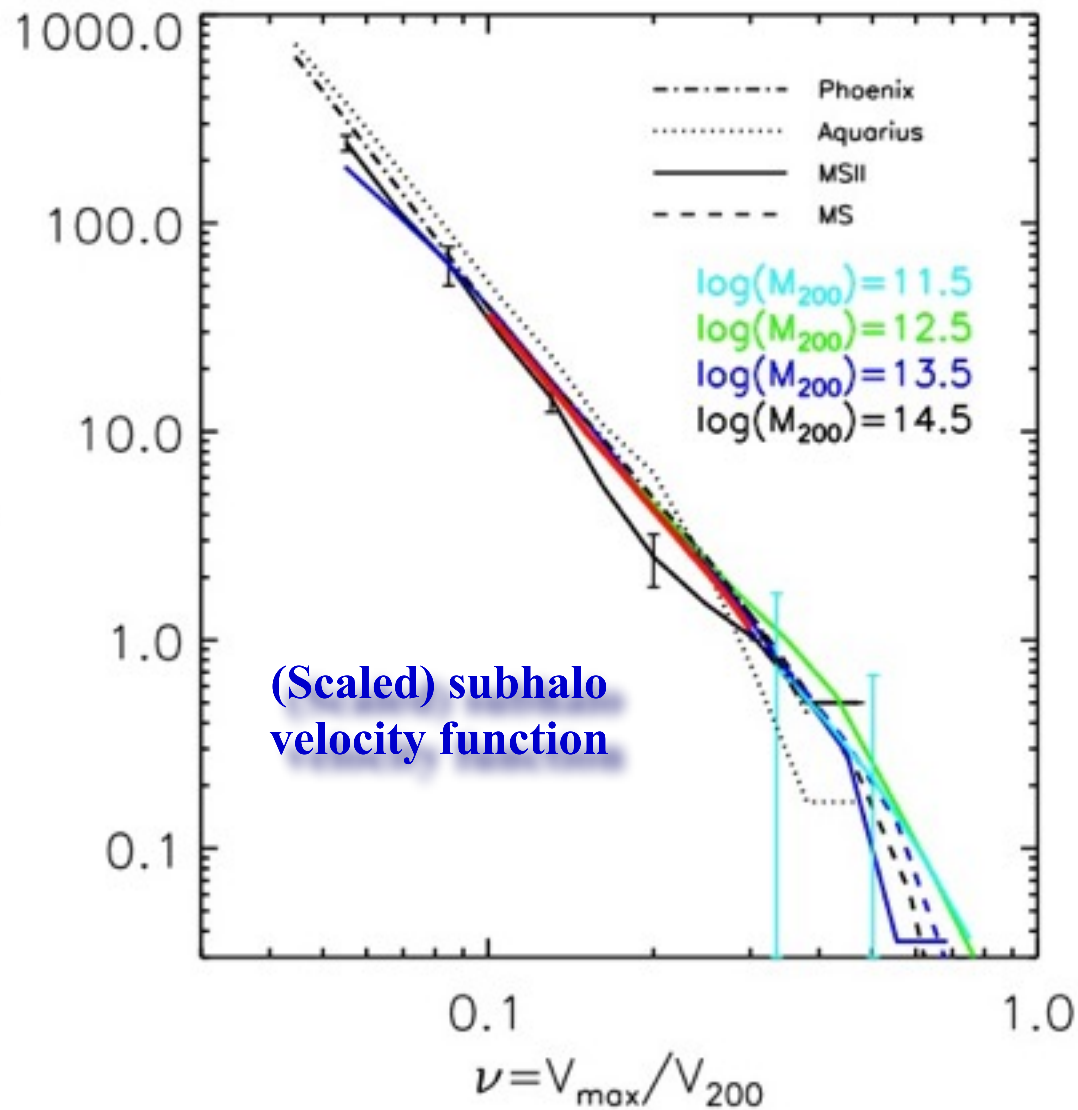
- May be fitted by scaling a simple formula $\rho/\rho_{crit}=\delta_c/[(r/r_s)(1+r/r_s)^2]$

- Curves do not cross

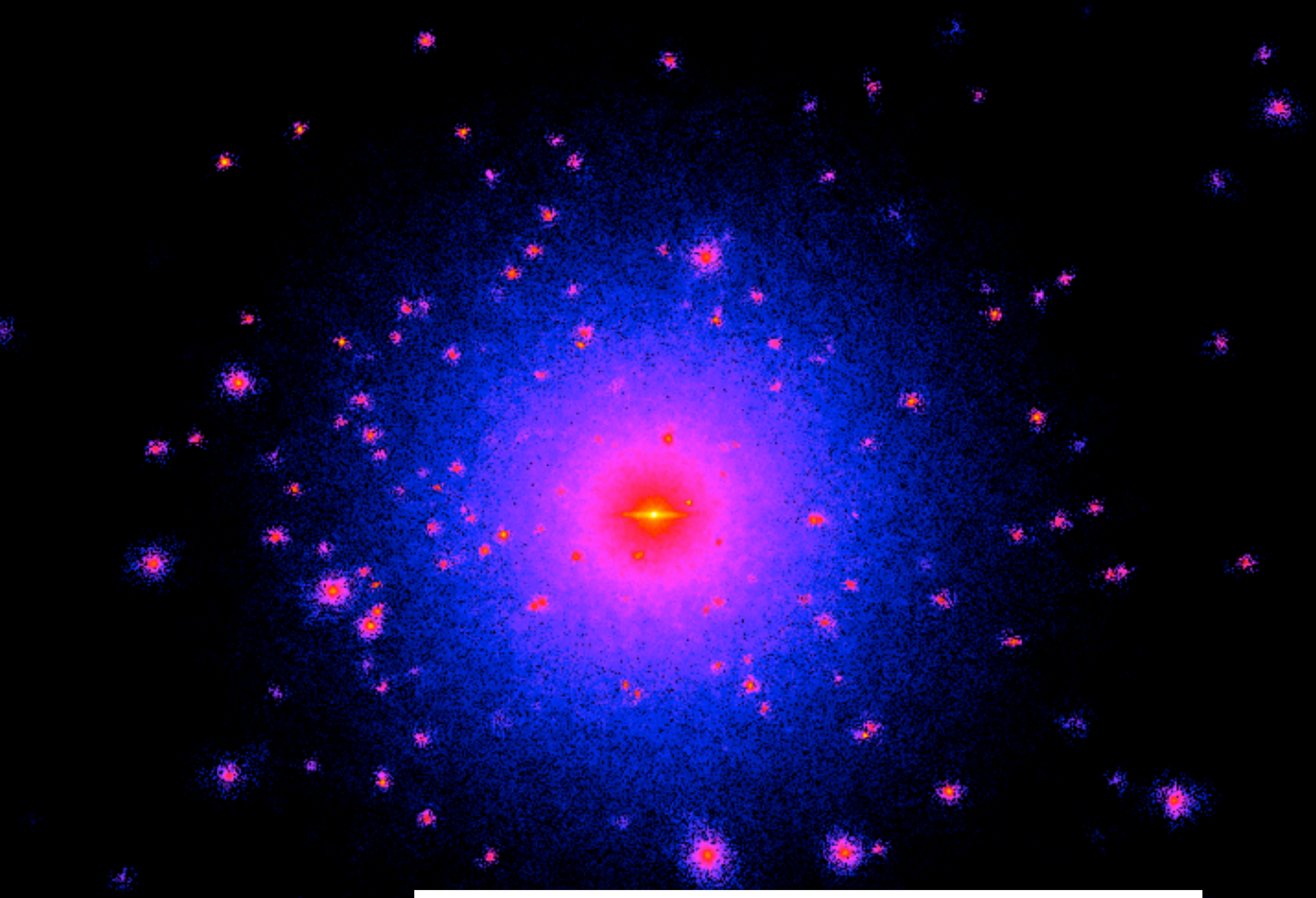
- DM is "colder" near the center.

The invariance of the subhalo mass function

Subhalo number



- The (scaled) subhalo mass function is independent of host halo mass
- Large sets of halos can be assembled from different simulations to explore the statistics of rare massive subhalos.
- Typically, halos have only one subhalo more massive than ~3% of the host halo virial mass

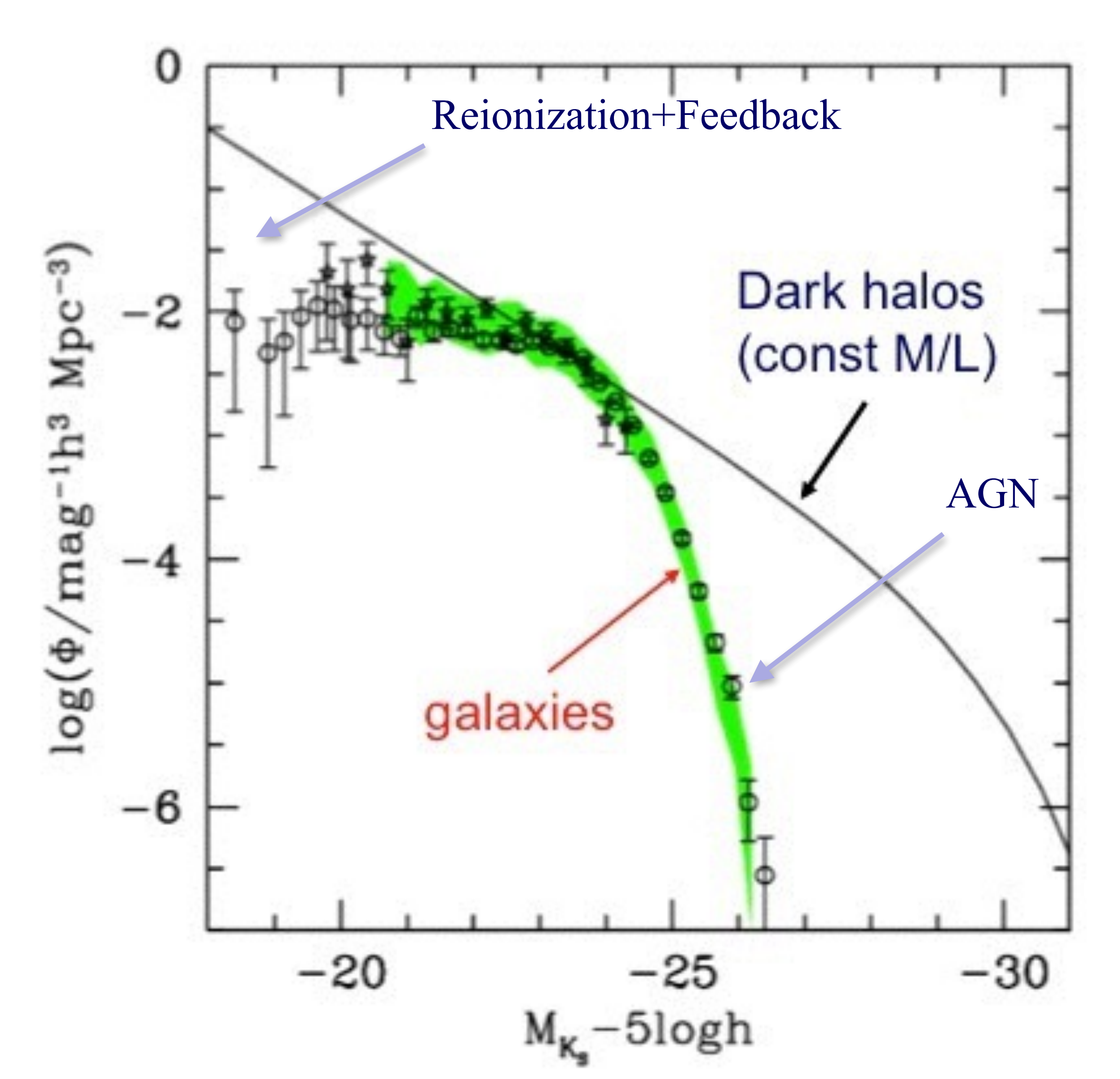


One galaxy ==> one halo

A Milky Way-sized galaxy and its surrounding dark matter halo

Font+2001

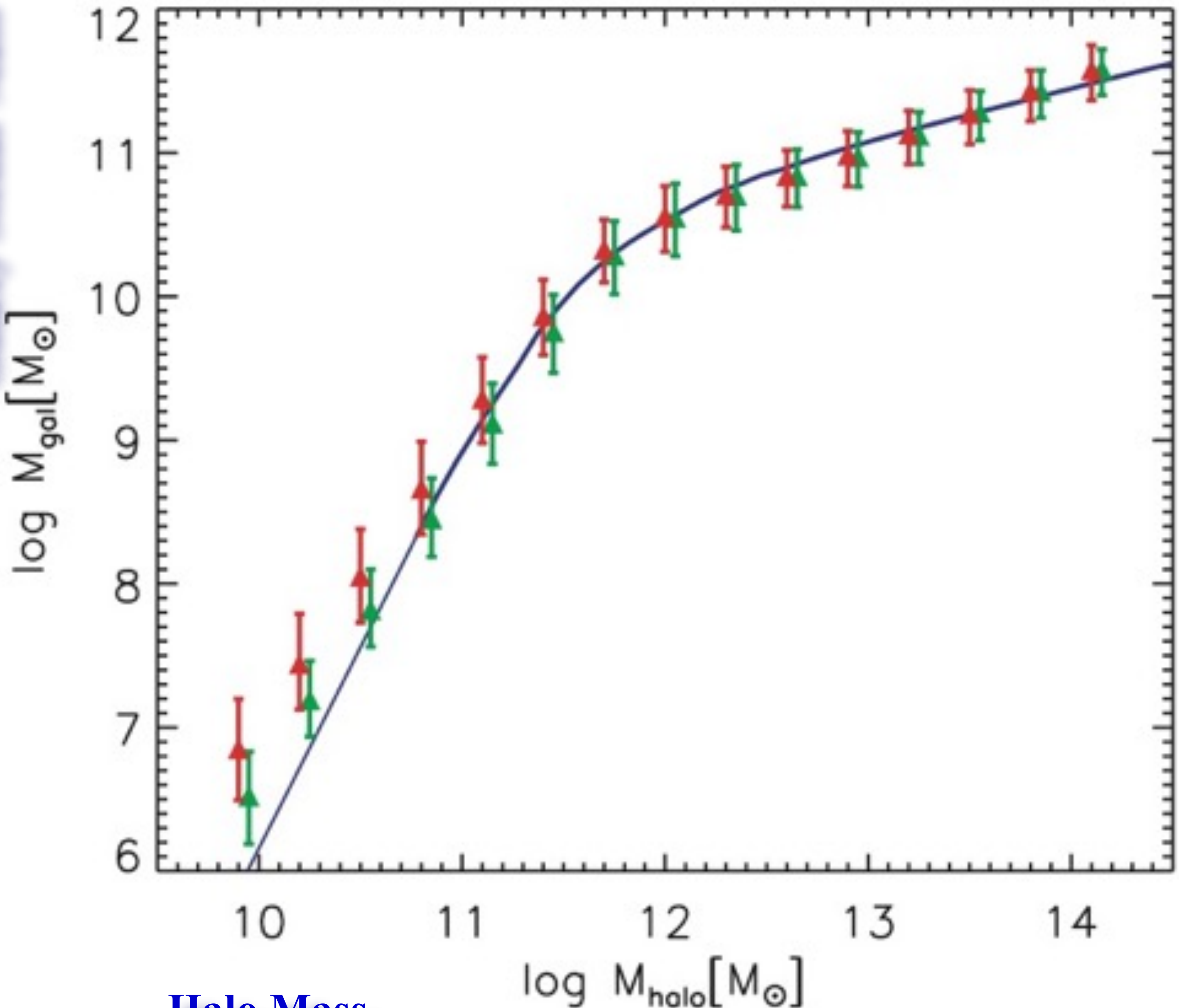
CDM halo mass function vs galaxy luminosity function



- CDM halo mass function *much steeper* than the galaxy luminosity function at the faint end
- This is a robust prediction of the CDM scenario
- Reconciling the two requires a highly non-linear dependence between galaxy and halo mass, presumably caused by reionization, as well as feedback from evolving stars and supermassive black holes

Abundance Matching:
Galaxy Stellar Mass vs Halo Mass

Galaxy Stellar Mass

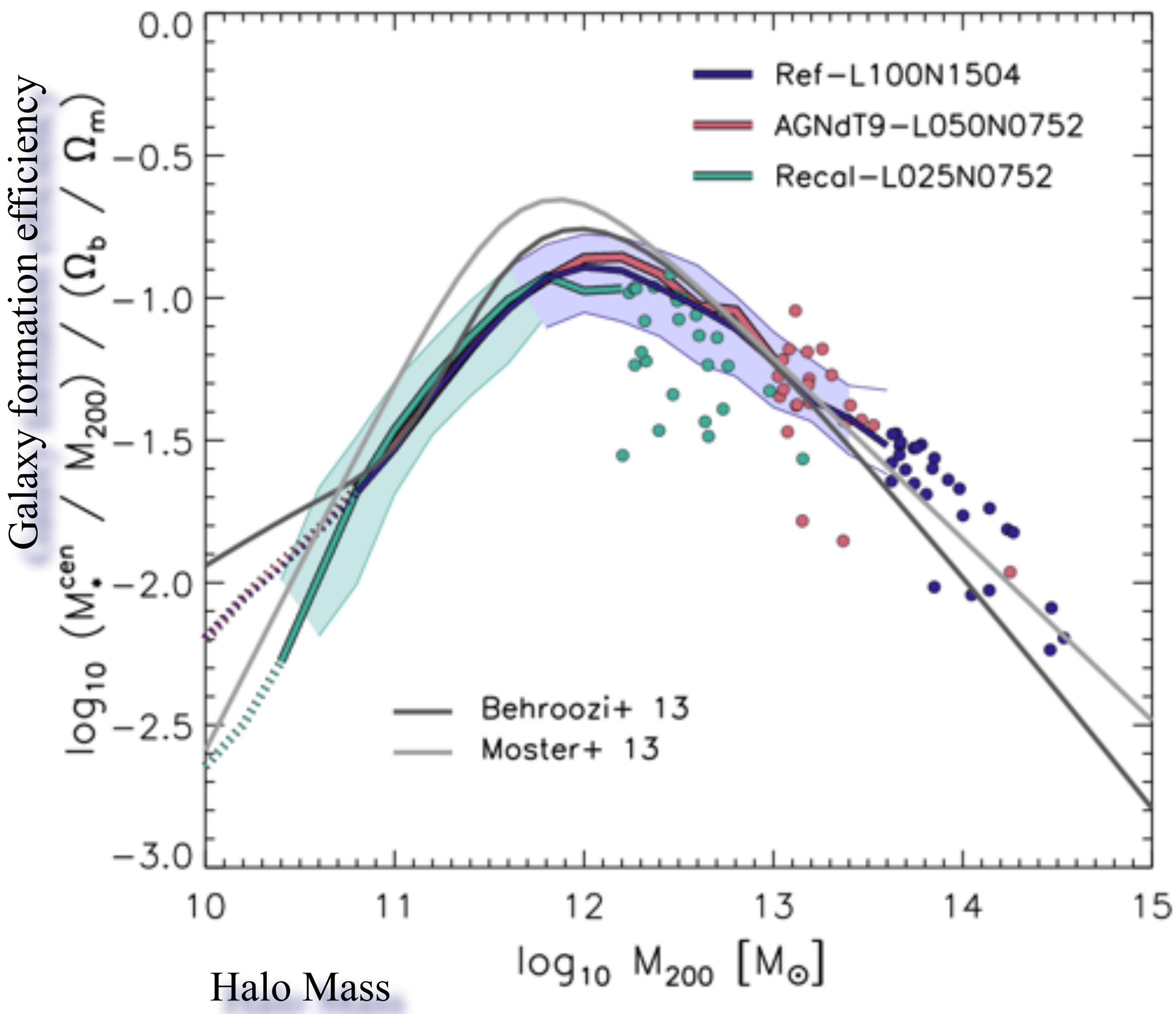


Halo Mass

- Steep dependence at low halo mass--a fundamental result of galaxy formation models.
- Most dwarfs form in halos of similar mass and hence similar properties —-what is the origin of their diversity then?
- Essentially no luminous galaxies should form in halos with mass below a "threshold" of 10^{10} M_{sun}

Guo et al 2011

Galaxy formation efficiency



- Fewer than ~10% of the baryons of each halo make it into galaxies--- halo assembly and galaxy assembly may differ substantially

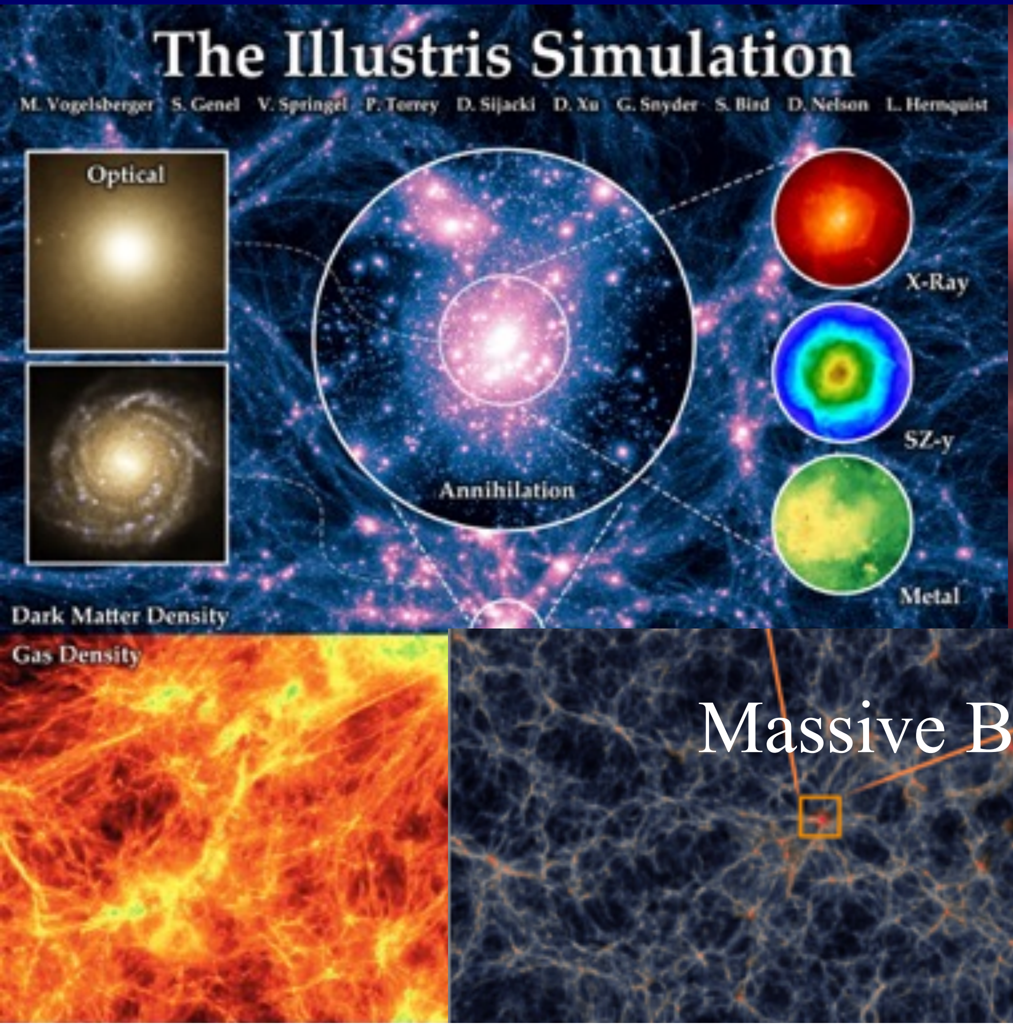
- Halo mass accretion rates ≠ SFR.

- Halo merger rates may be only indirectly related to galaxy merger rates and hence to galaxy morphology

- Angular momentum of baryons may have little relation with the angular momentum of halos.

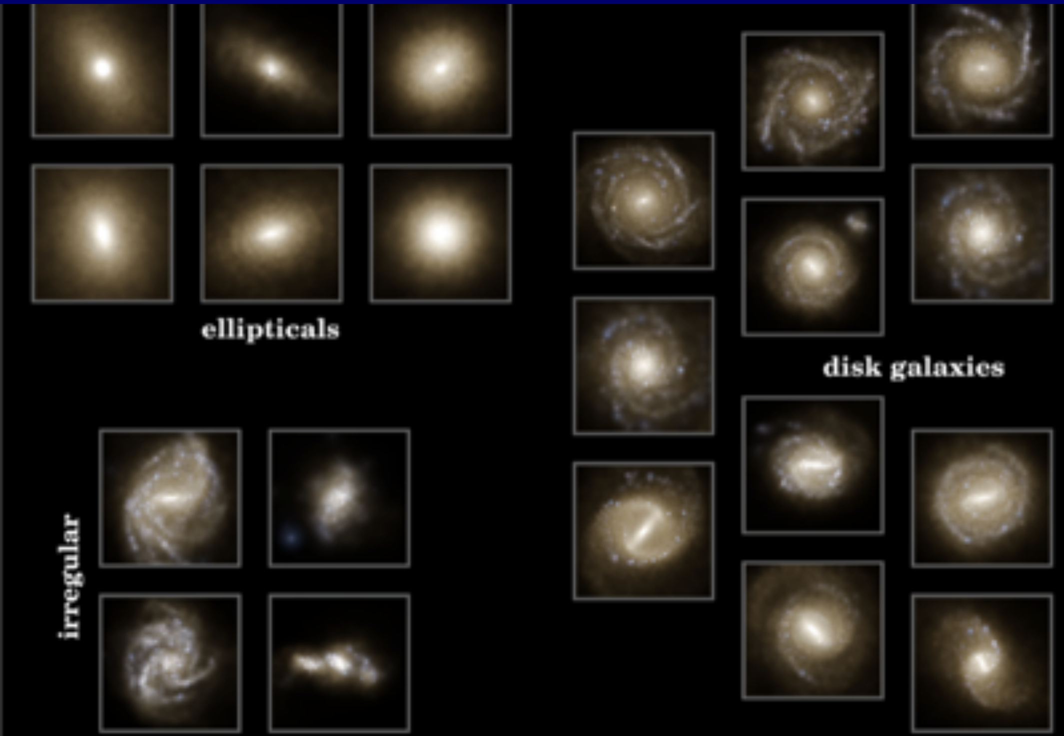
Schaye et al 2014

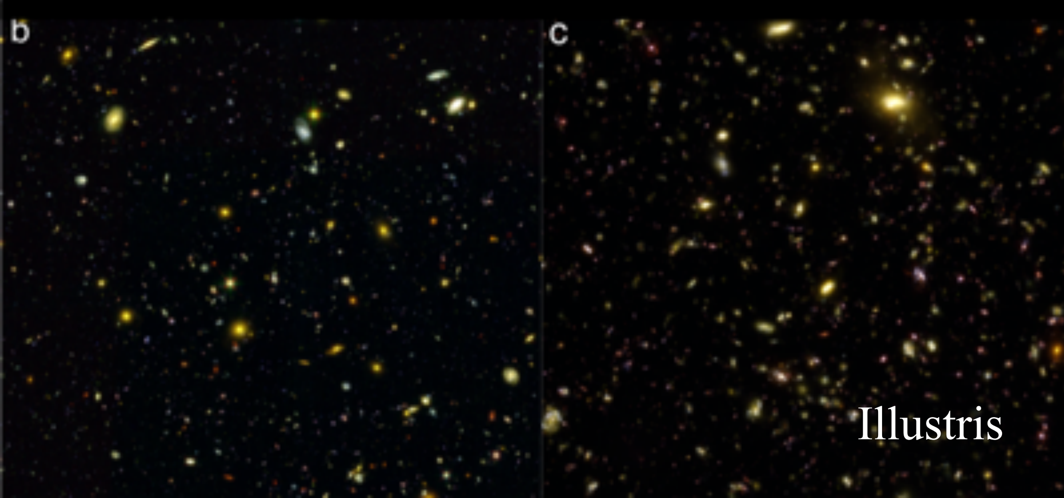
Galaxy Population Simulations

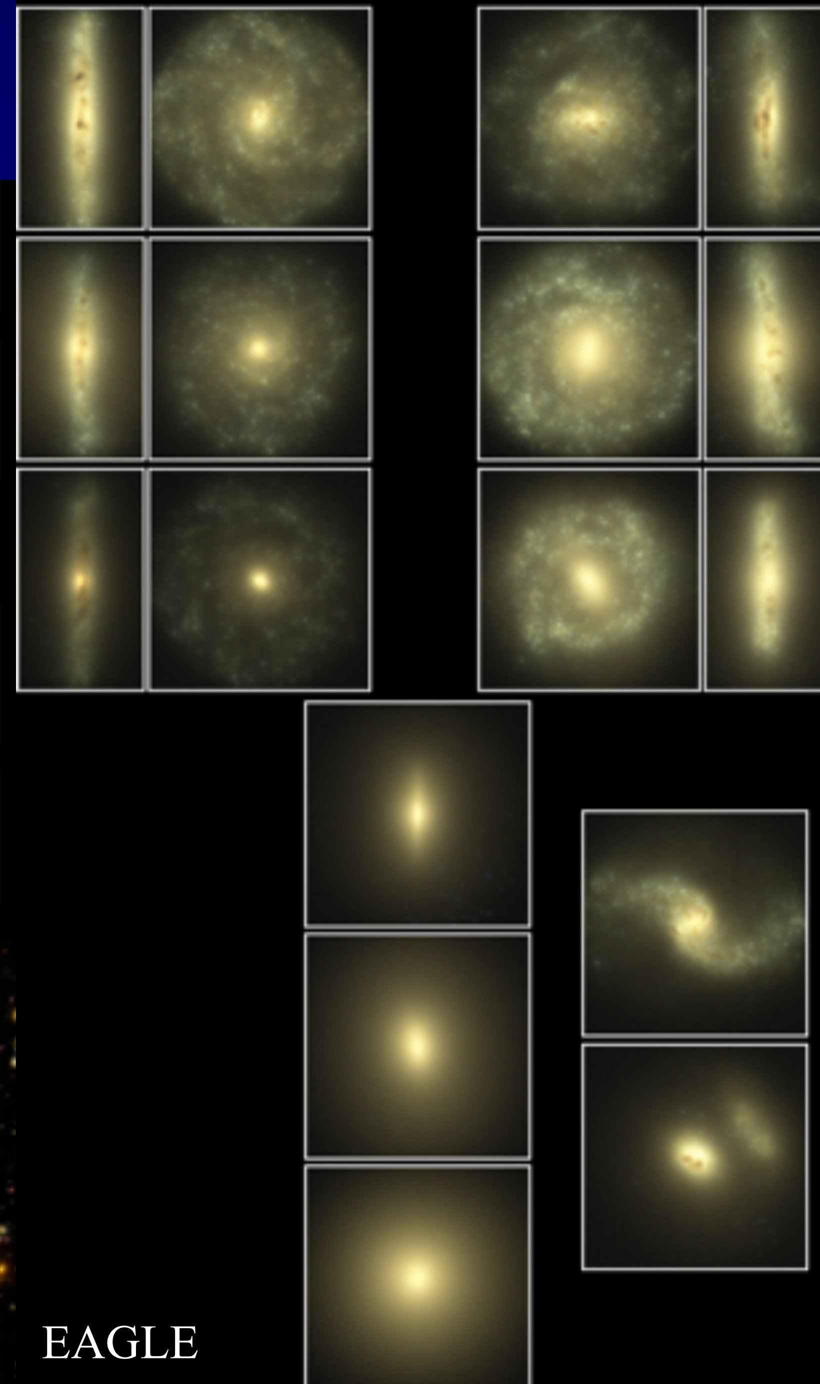


- Three large simulation suites of cosmologically representative volumes (~100 Mpc box) have recently been completed
- Resolution (per galaxy) is worse than individual galaxy simulations, but agreement with observation is quite good

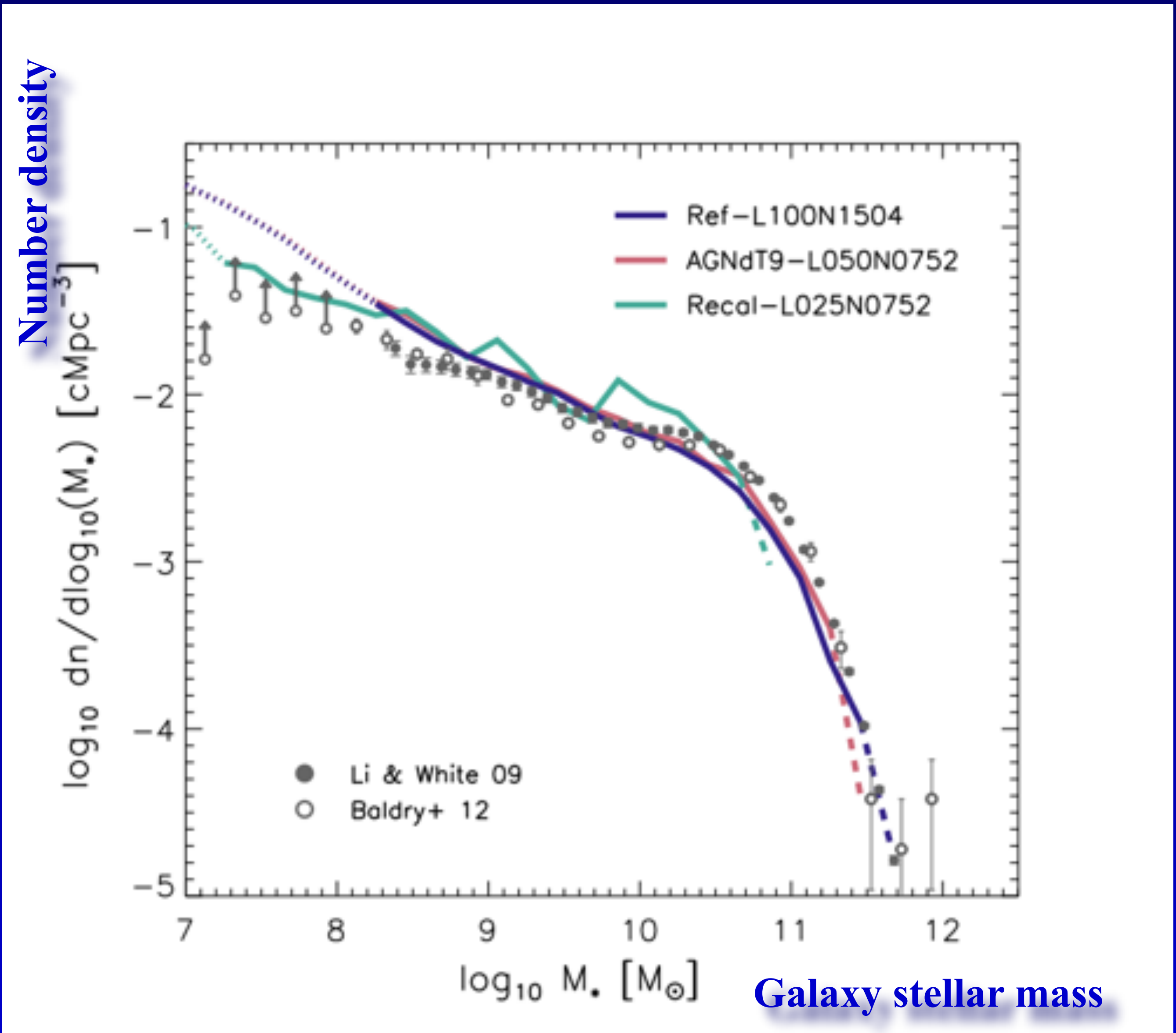
Galaxy gallery







EAGLE Galaxy Stellar Mass Function



- Recent simulations have been able to include reionization and feedback effects to reproduce the galaxy stellar mass function down to galaxies of $M_* \sim 10^8$ solar masses in stars

- They also match reasonably well other properties of the observed galaxy population

- Does this success extend to the faintest dwarfs?

Schaye et al 2014

The Cosmological Puzzles of Dwarf Galaxies

- Observations of dwarfs have revealed a number of challenges when compared to dark matter-only LCDM simulations
- Dwarf Galaxy puzzles
  - Rotation curves or “cusp vs core” problem
- Local Group puzzles
  - ”Missing satellites” problem
  - “Too big to fail” problem
  - “Satellite alignment” problem

A related challenge: the diversity of dwarf galaxies

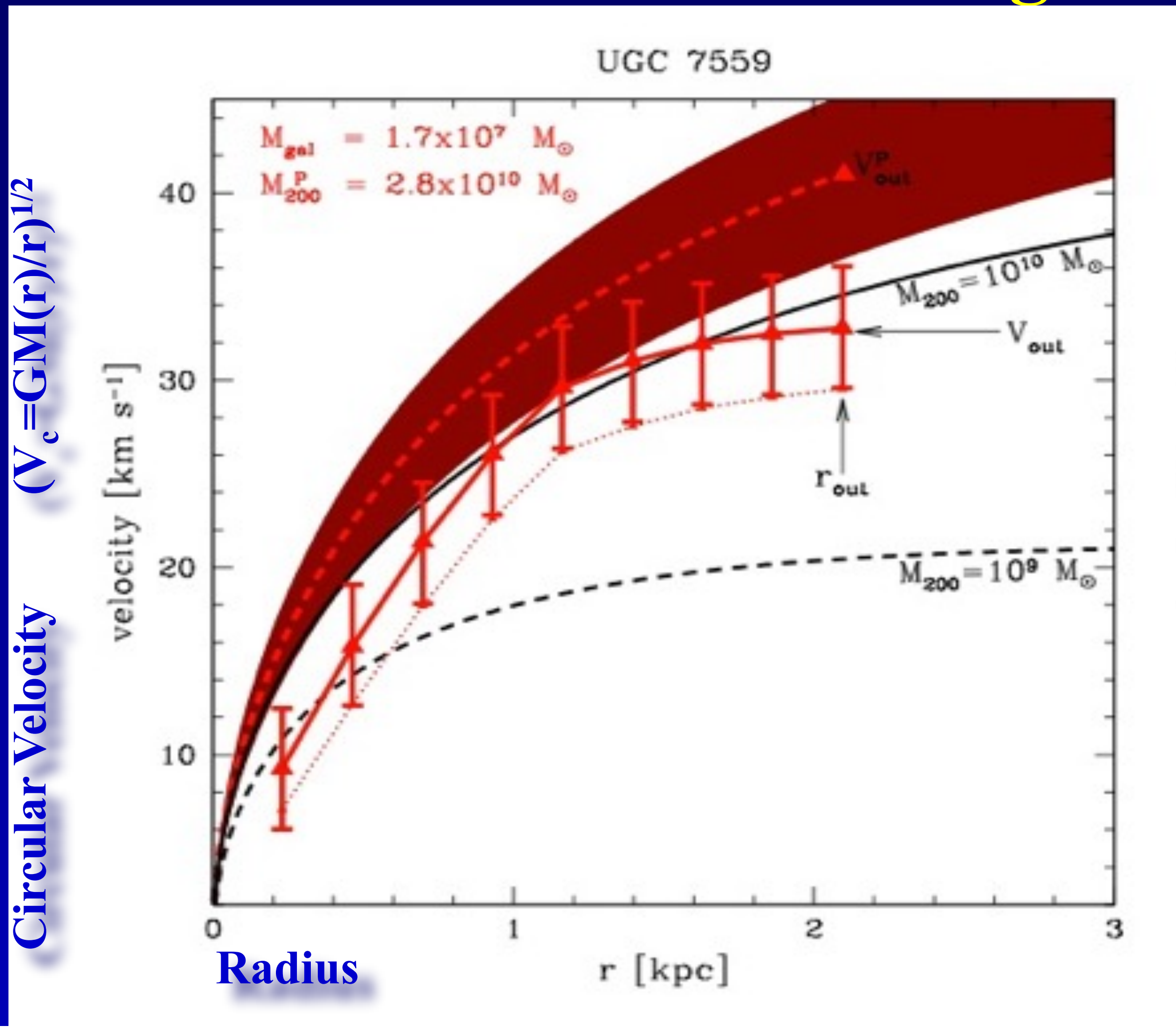
- The steep M_{gal}-M_{halo} relation implies that most dwarfs should populate halos of similar mass and hence should have similar mass profiles

- There is an effective "threshold" in halo mass for galaxy formation: luminous galaxies should shun very low-mass halos

- Most low-mass halos are dark, mainly due to the effects of reionization
  - feedback cannot be important in very faint galaxies
  - what is the signature of reionization on dwarfs?

- Why are then dwarf galaxies so diverse?

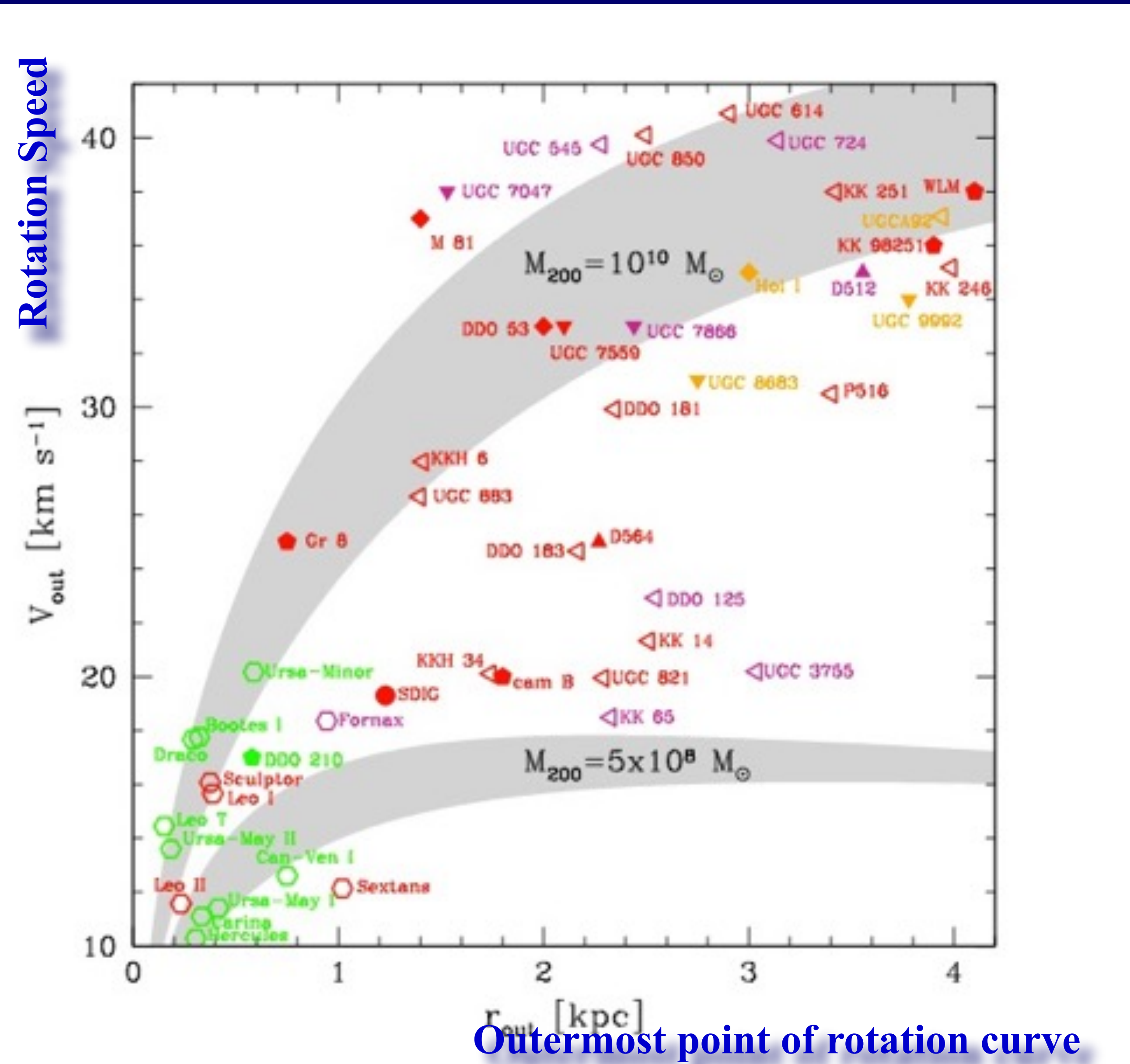
The halo mass of isolated dwarf galaxies



- NFW-like halos of different mass have circular velocity curves that do not cross
- If the mass inside any radius sufficiently far from the center can be measured, then the total halo mass may be estimated

Ferrero et al 2012

The halo mass of isolated dwarf galaxies

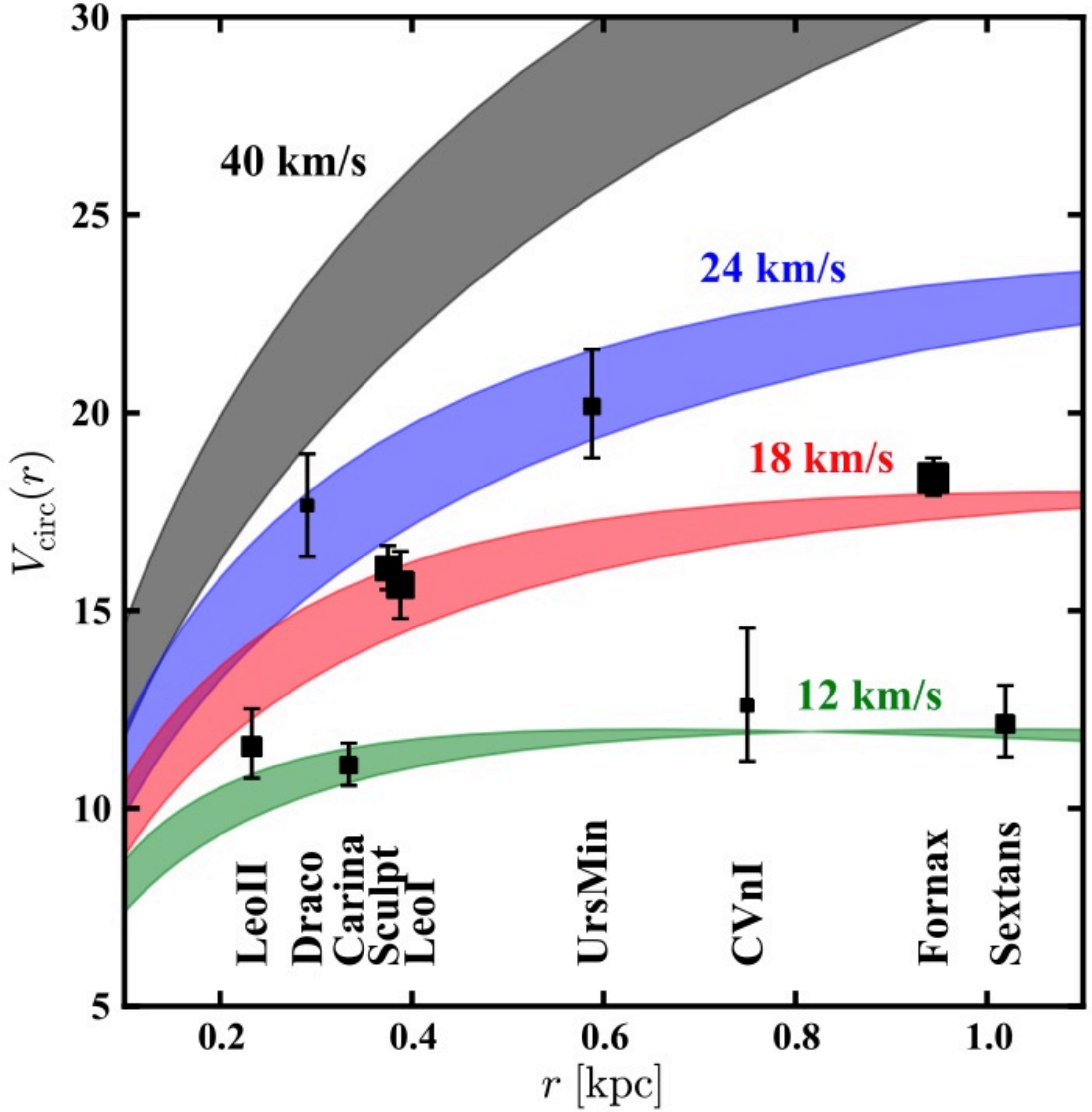


Outermost point of rotation curve

- Rotation curves typically extend far enough to allow meaningful estimates of the total mass of the halos
- Many galaxies seem to inhabit very low mass halos, well below 10^{10} M_{sun}

Ferrero et al 2012

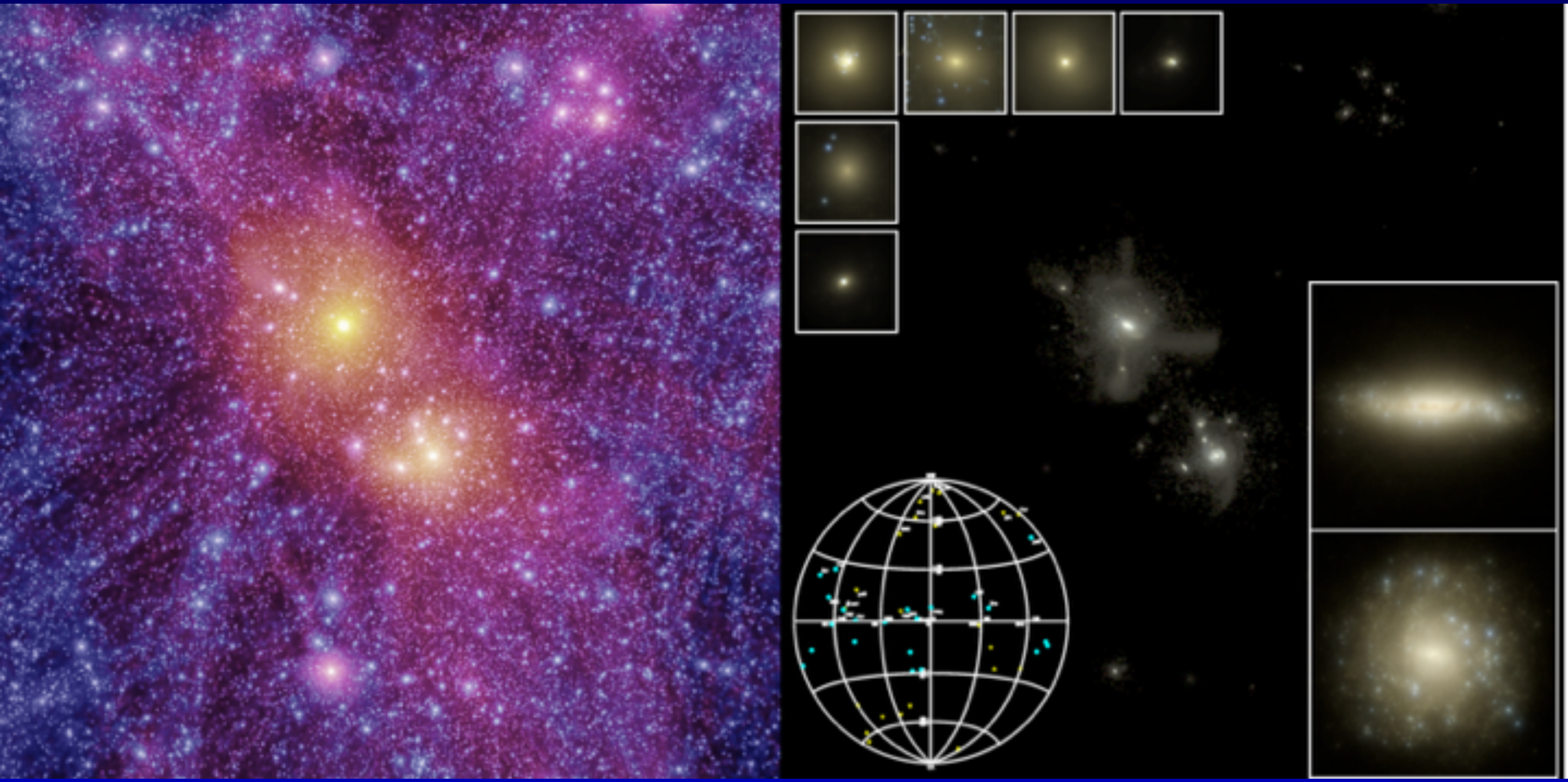
The halo mass of satellite galaxies: the"too big to fail" problem



- Too big to fail?
- Only 3 Milky Way satellites appear to inhabit halos more massive than V_{max}~30 km/s
- On average, 10 subhalos more massive than this are present in Aquarius halos

Boylan-Kolchin et al '11

Think Locally: The Local Group Simulation Project



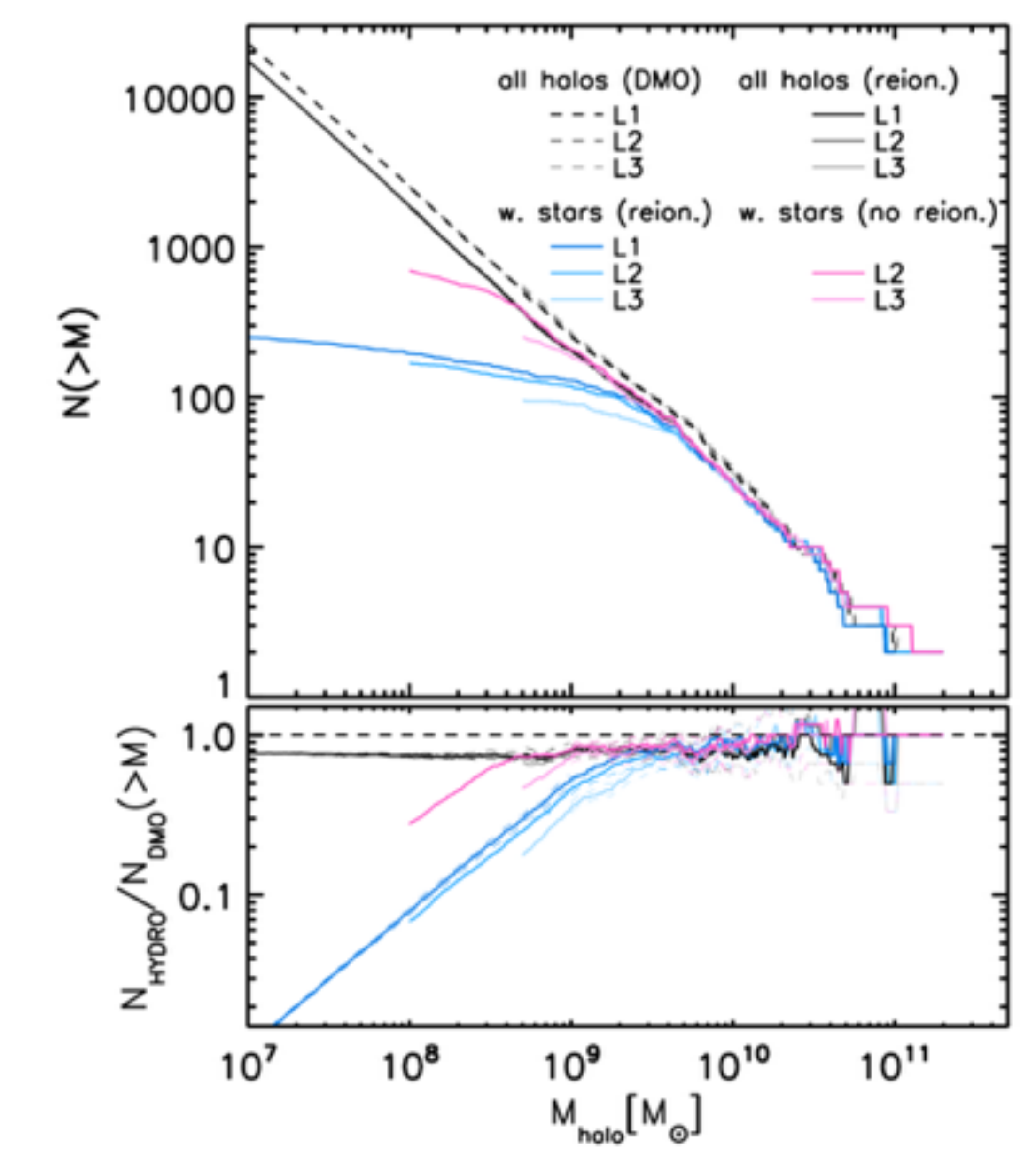
LG-Sawala'14

- 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

Dark Matter, Gas and Stars in the Local Group

LG-Fattahi'14

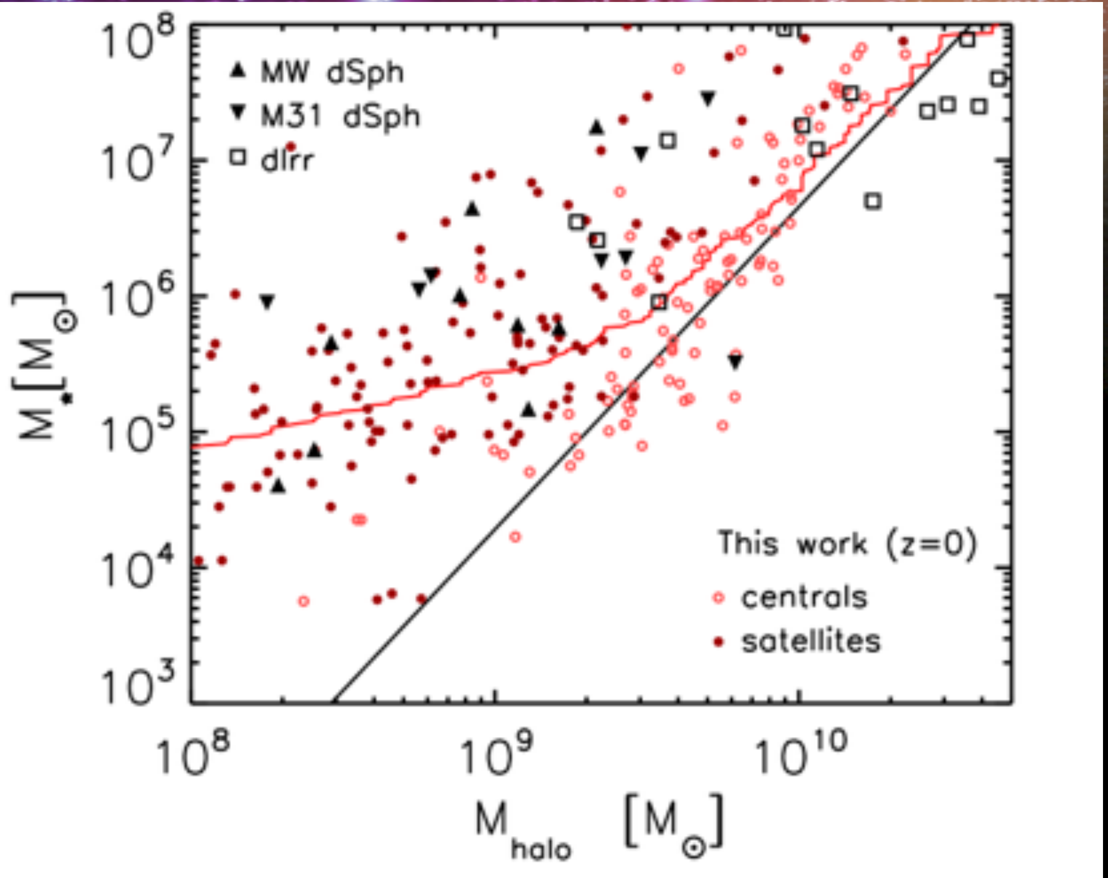
Bailed by Baryons



- Abundance-matching estimates of dwarf galaxy halo masses are heavily biased because they assume that every halo hosts a galaxy
- Only half of all 10^9 M_{sun} halos host luminous galaxies
- Halo masses can actually be quite low when this effect is taken into account

Sawala+2014

Bailed by Baryons:



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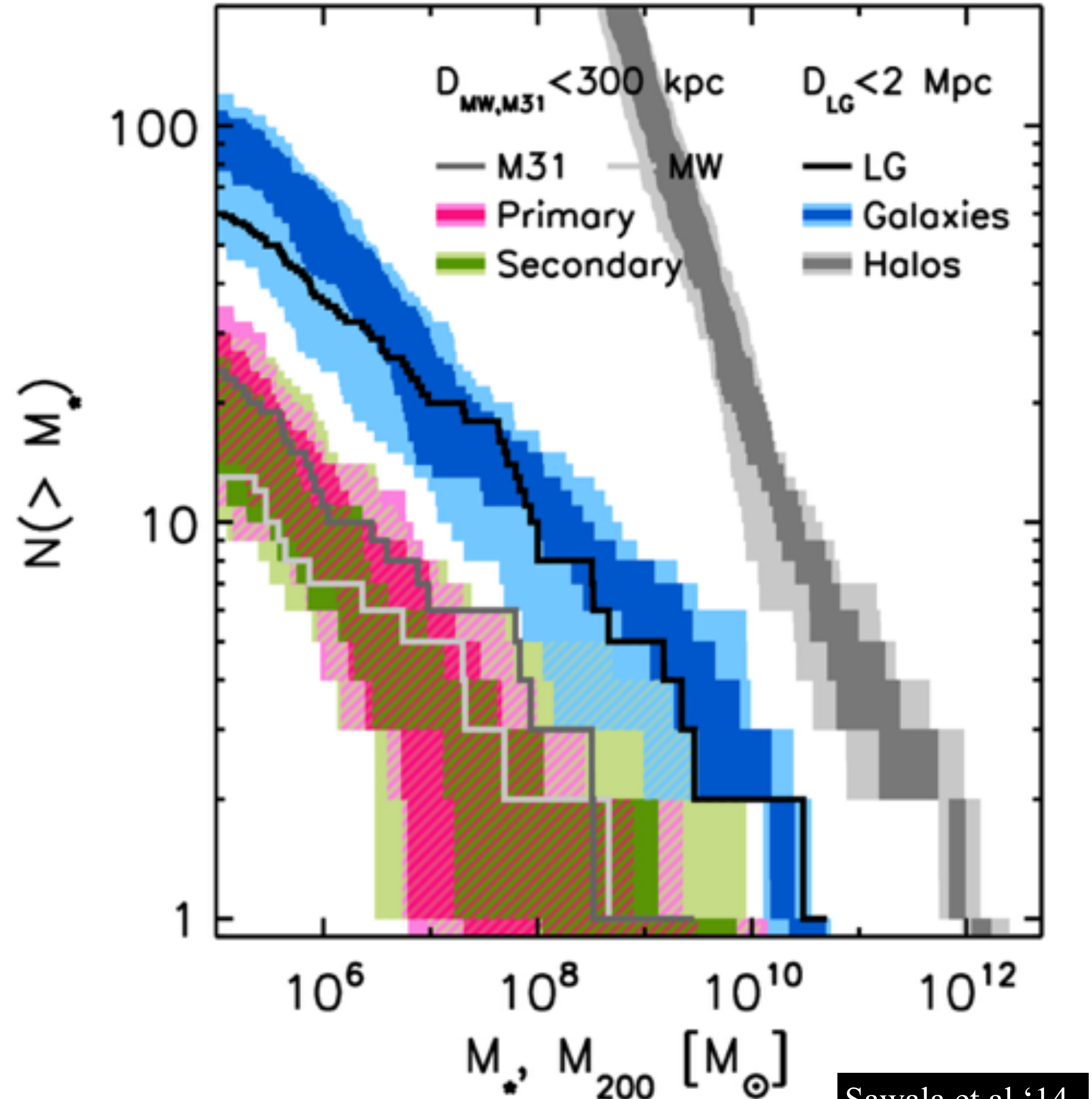
Sawala+2014

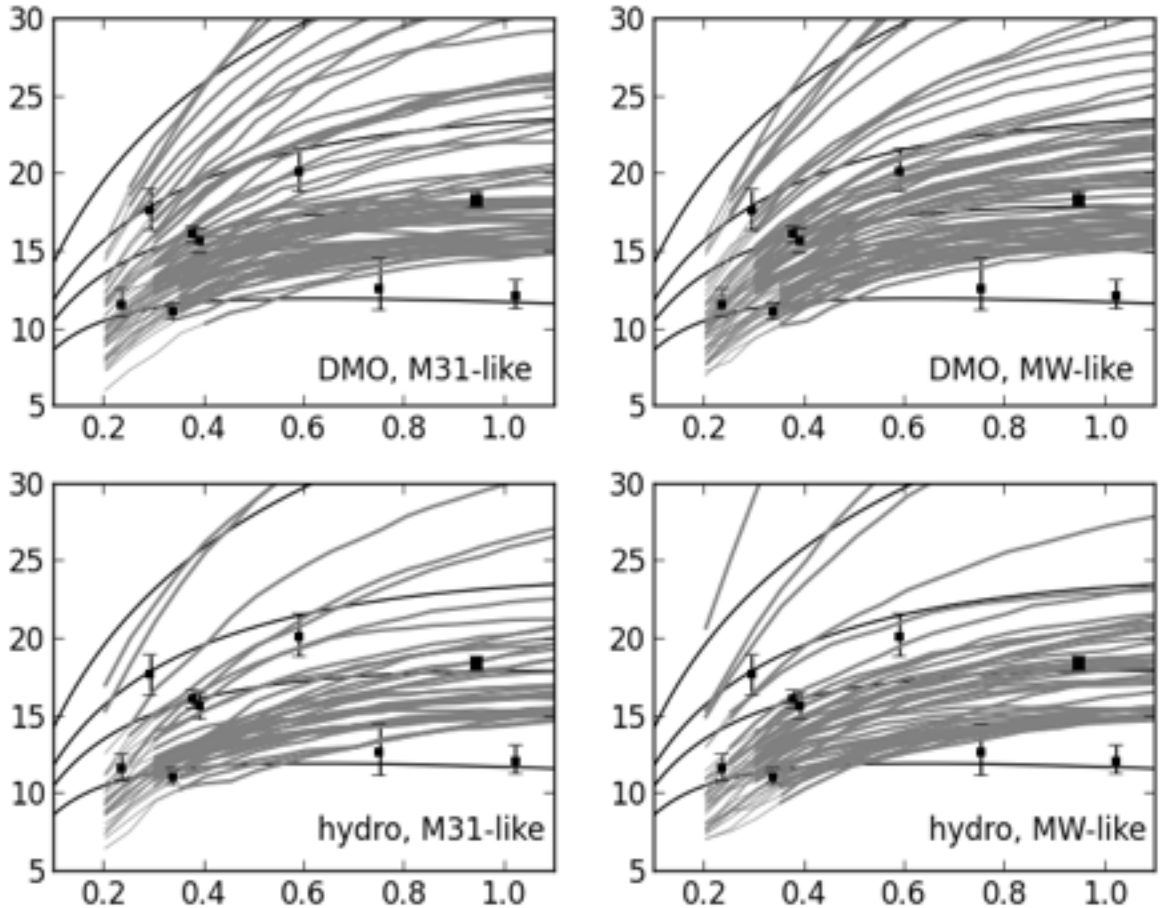


Sawala et al '14

The "missing satellites" problem

- 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}

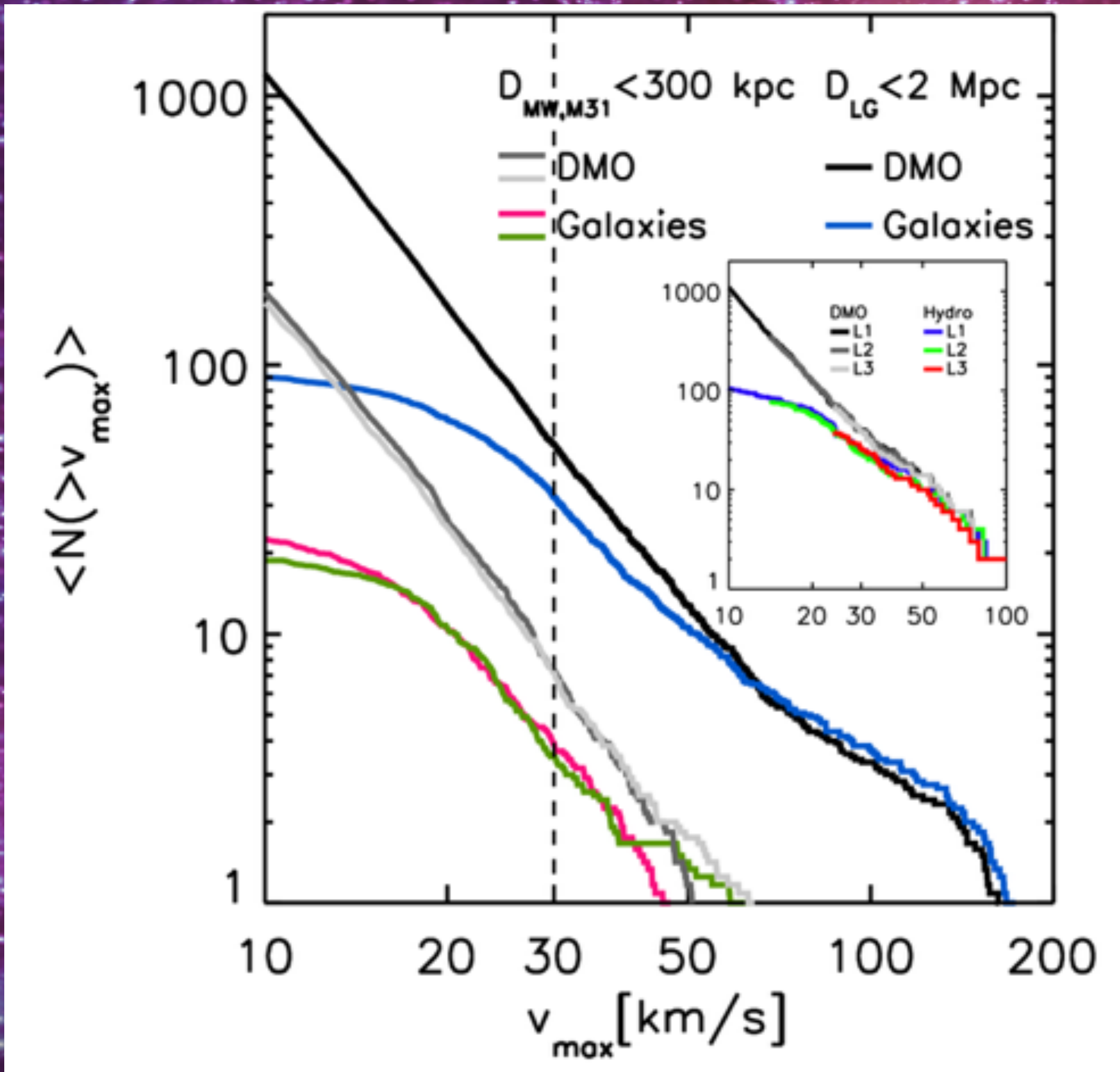
The “too big to fail” problem



- The number of sub halos is greatly reduced, at given V_{max}, in hydrodynamical simulations compared with dark-matter-only runs

Sawala et al 2014

The “too big to fail” problem

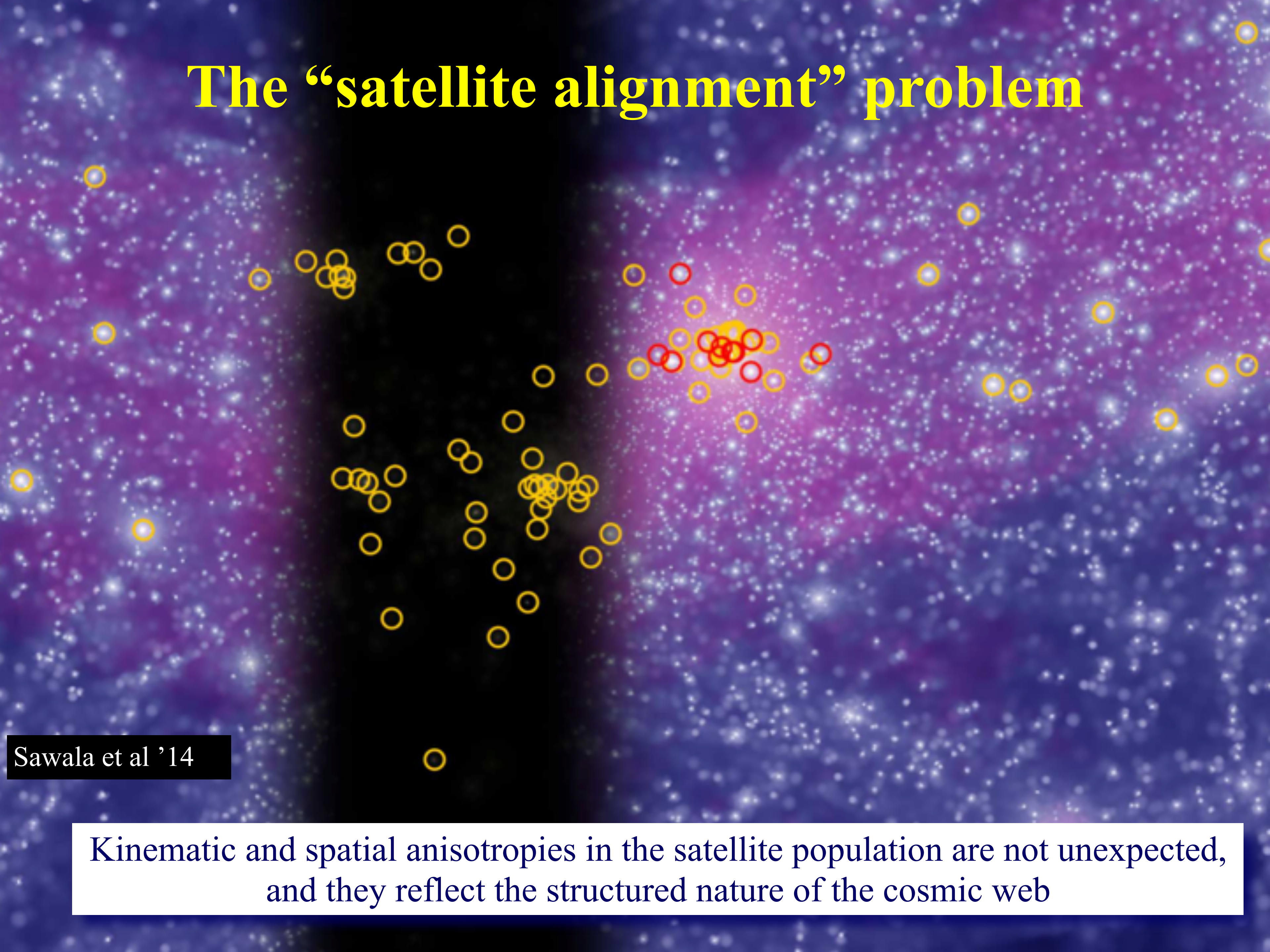


- Low-mass subhalos experience a reduction in V_{max} of order 15-20% because of the loss of the baryonic mass.

- 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

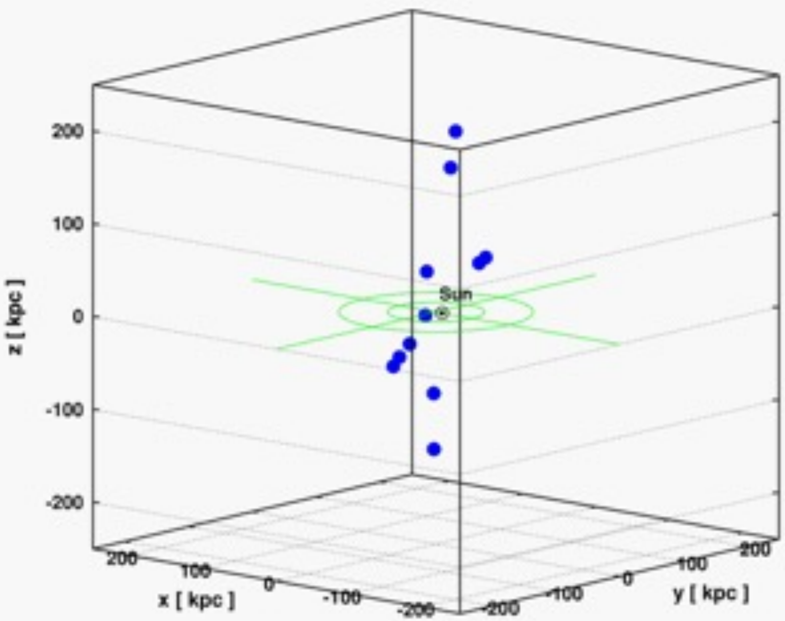
Sawala et al ’14

The “satellite alignment” problem

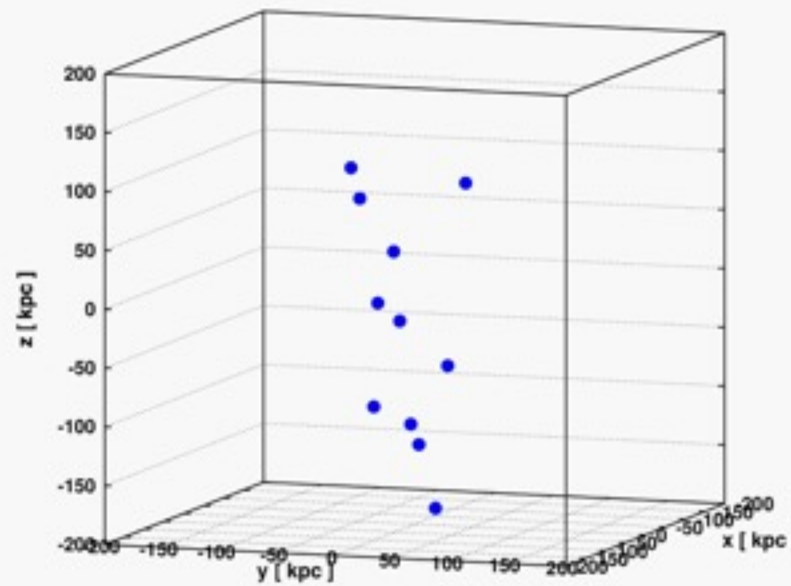


Kinematic and spatial anisotropies in the satellite population are not unexpected, and they reflect the structured nature of the cosmic web

The “satellite alignment” problem



Milky Way

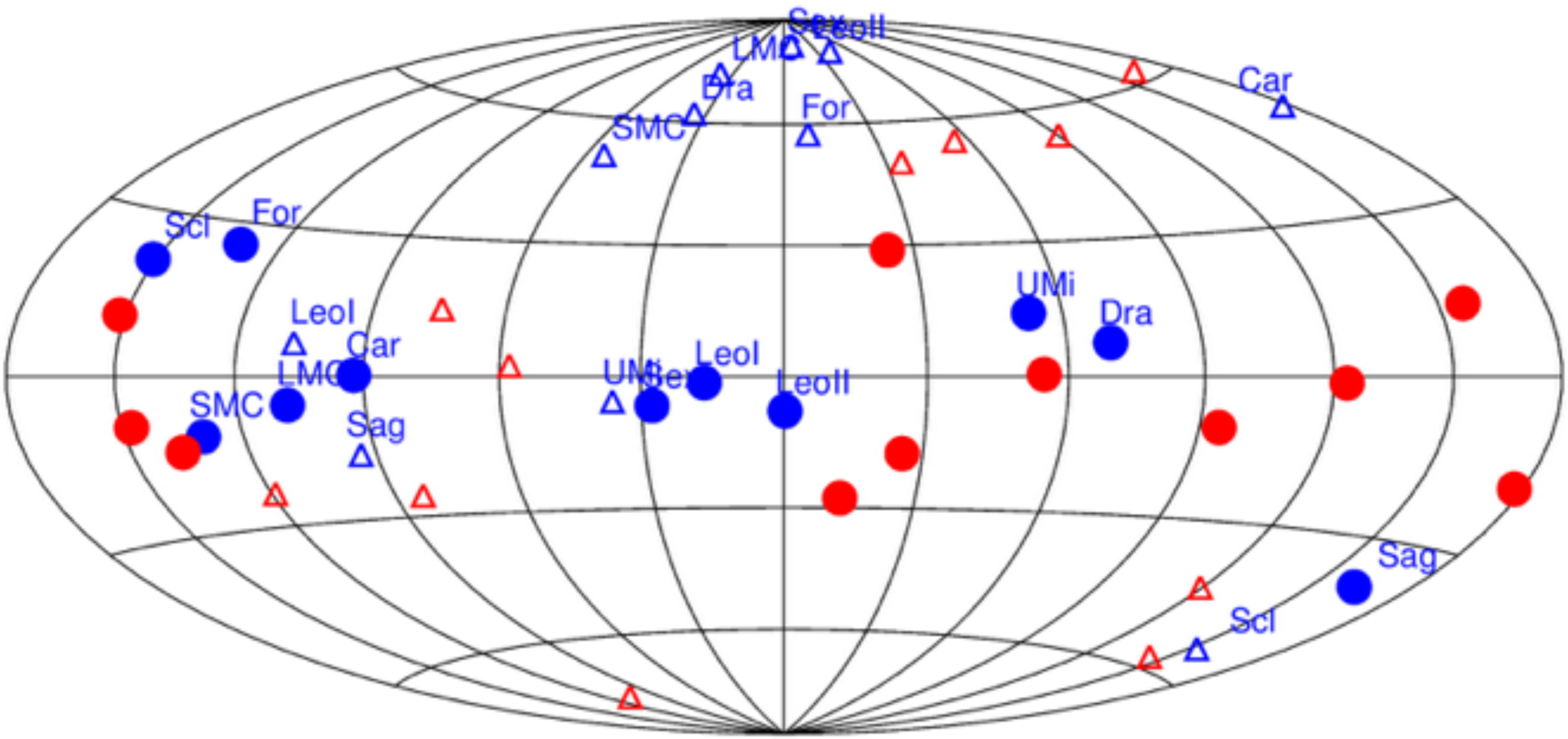


LG-5

- 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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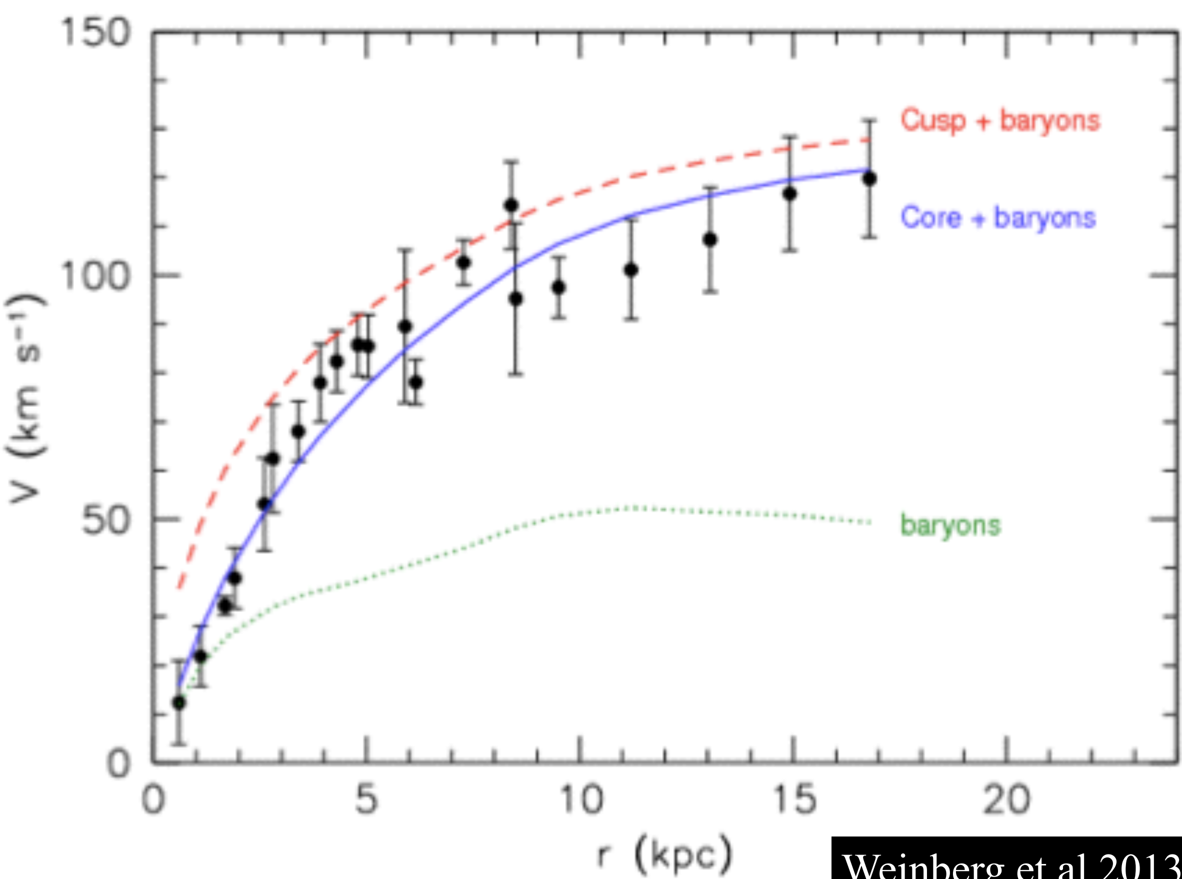
Sawala et al ’14

The rotation curve problem

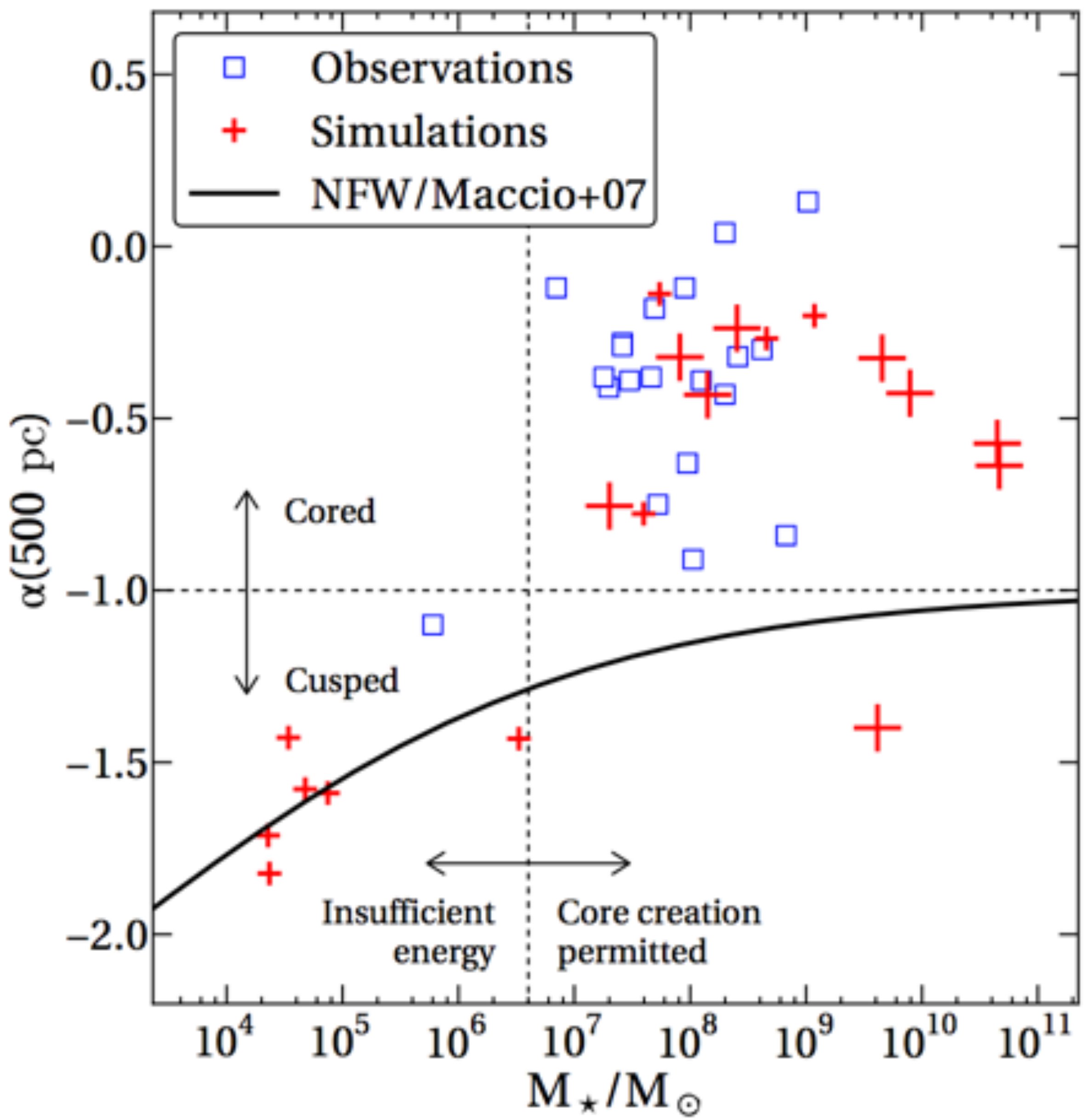


Weinberg et al 2013

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

"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

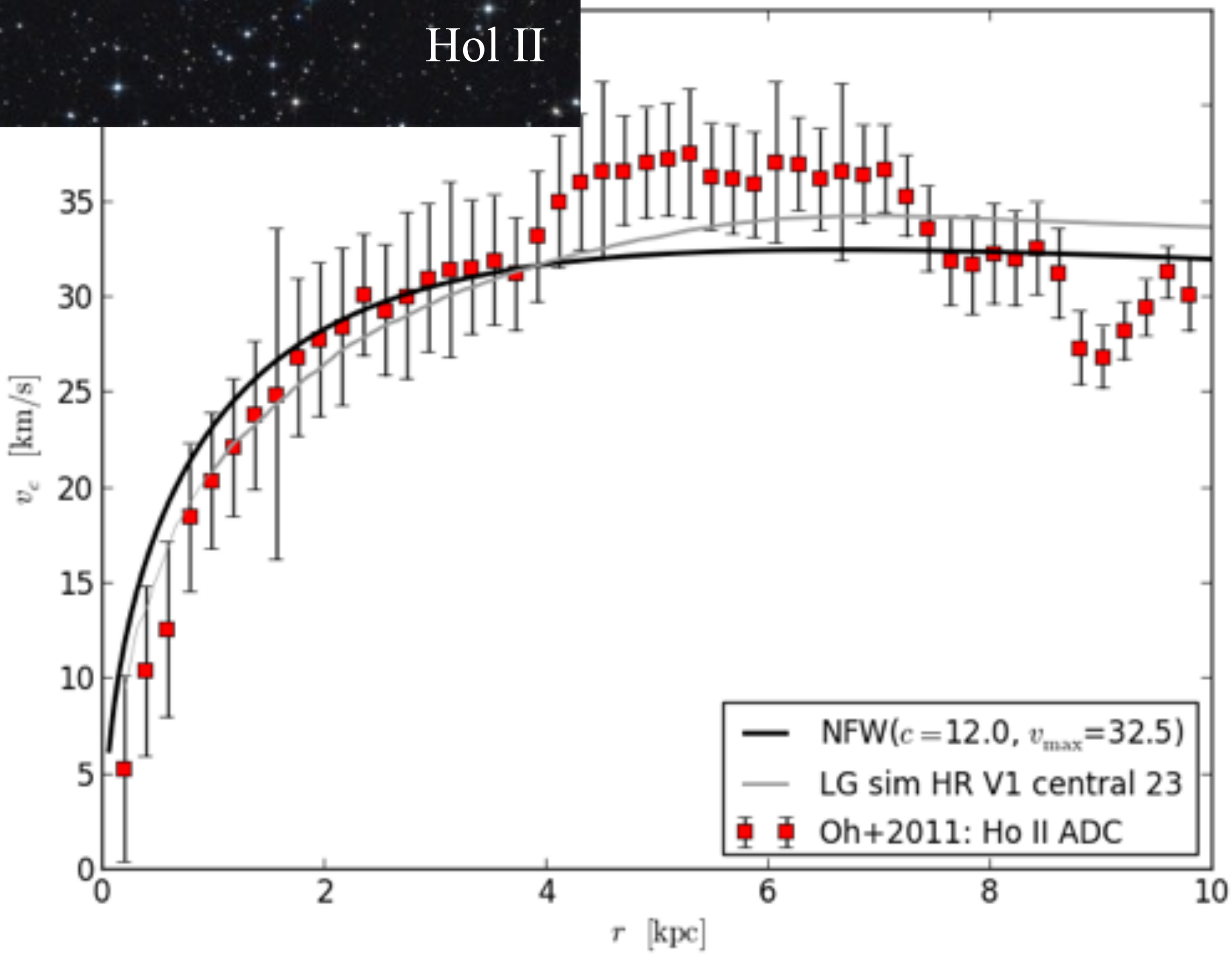
The rotation curve problem



- The comparison between data and simulations have focussed on the very inner regions (500 pc!) of a galaxy, where observations are very difficult and simulations most uncertain

Pontzen'14

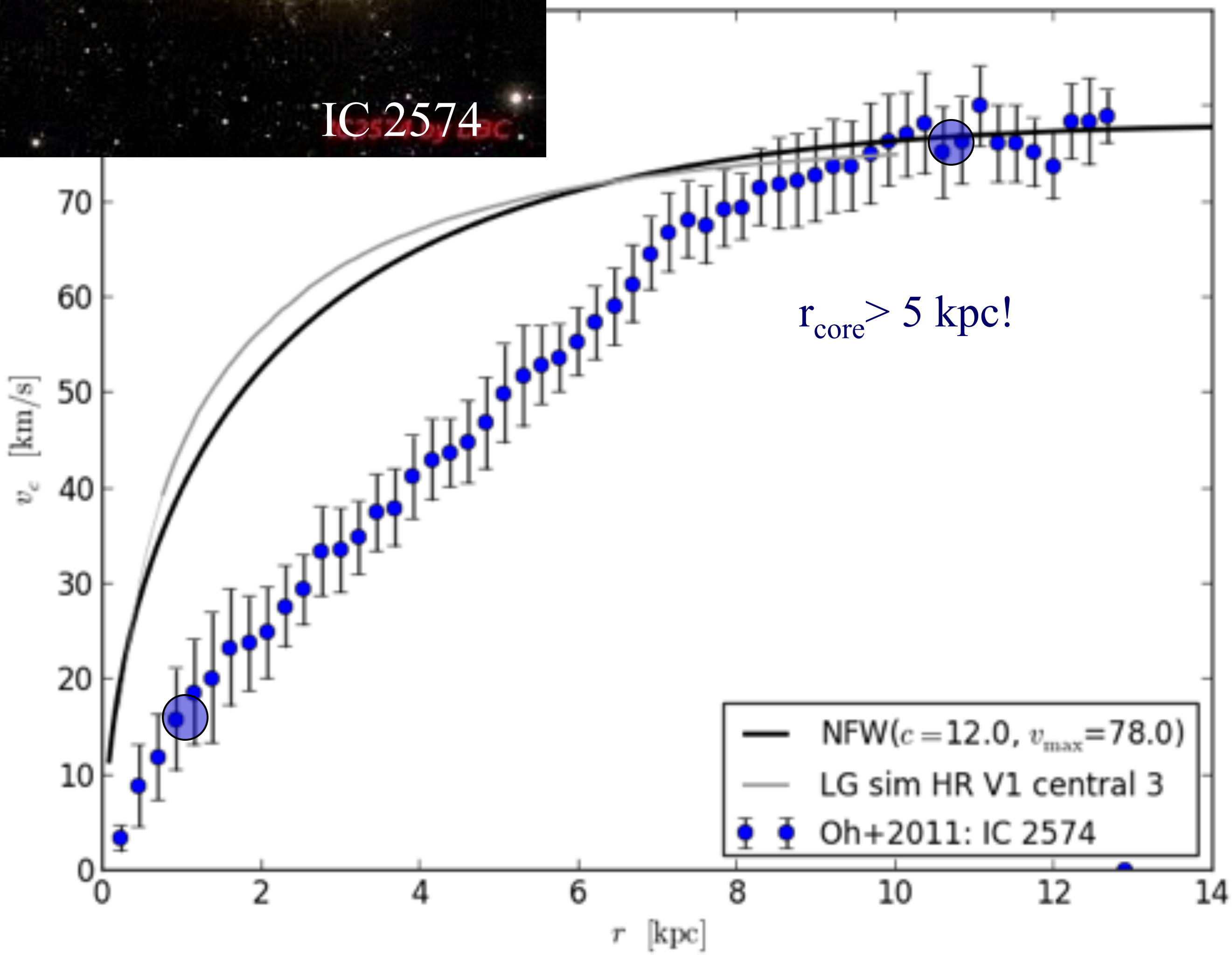
The rotation curve problem



- Some galaxies have rotation curves that agree with simulation predictions
- Others do not.

Oman'14

The rotation curve problem



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Oman'14

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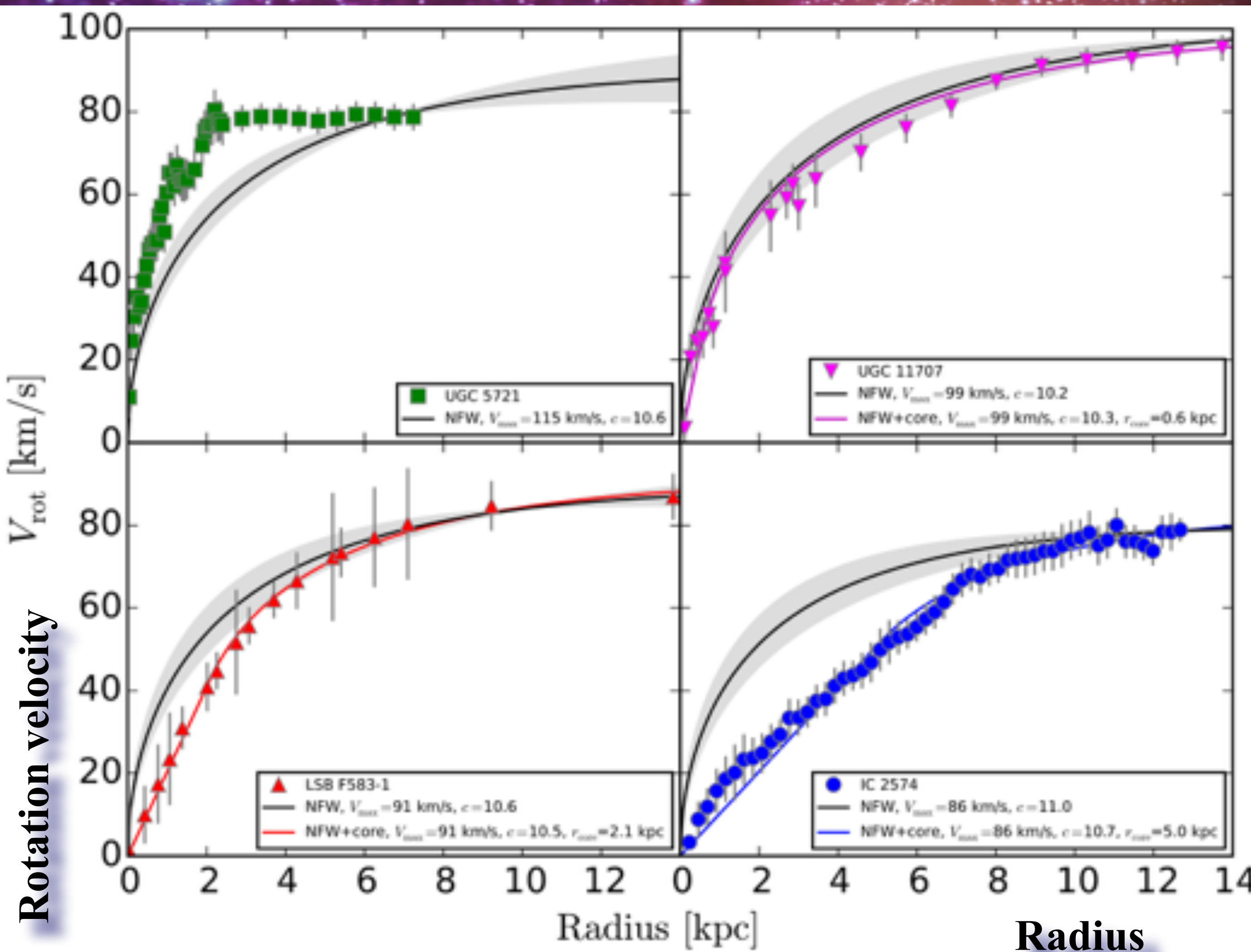
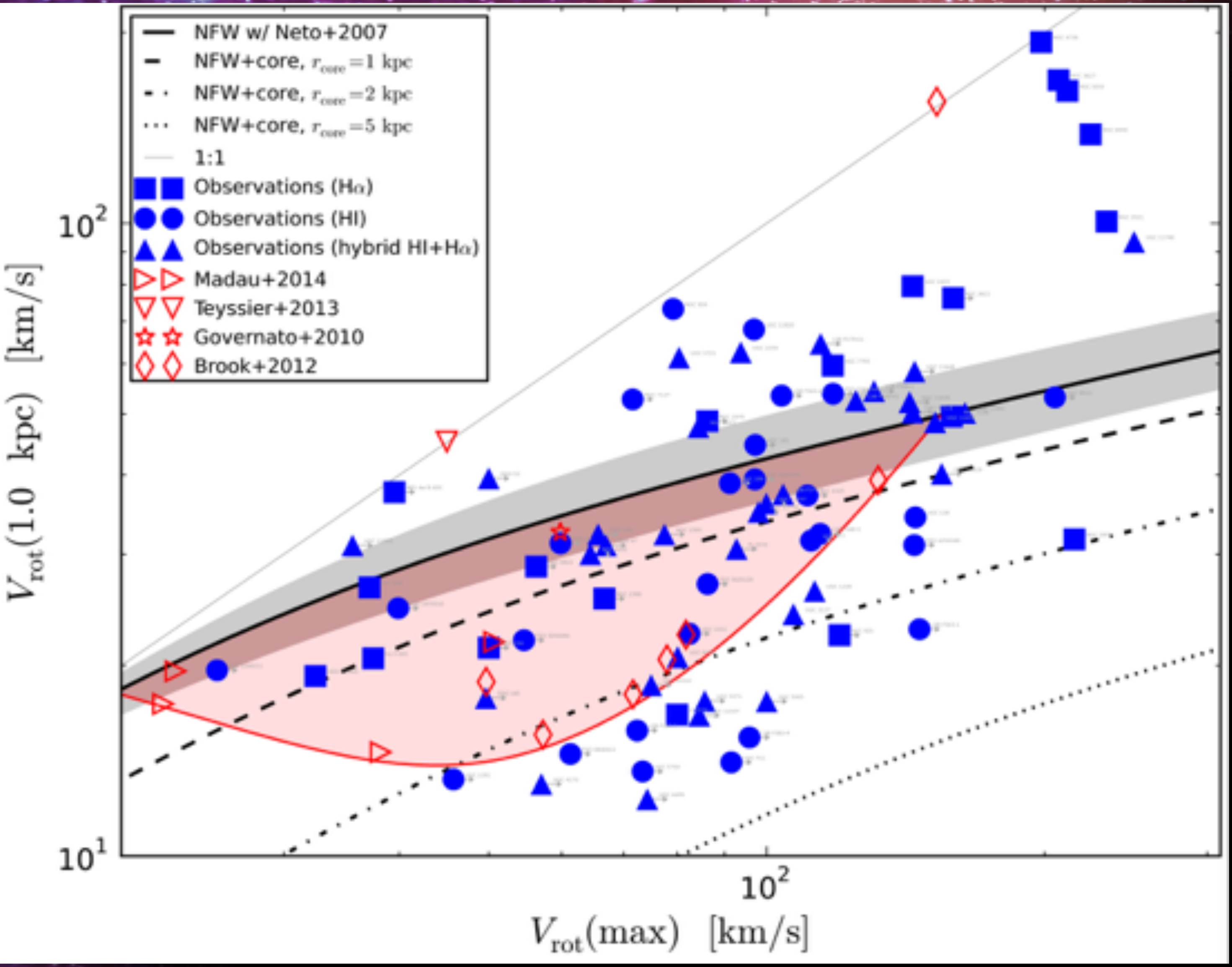


- The rotation curve problem is one of **diversity**.
- CDM predicts a **single** profile for a given velocity scale, *unlike* observed rotation curves
- Note that **this precludes a particle physics solution** to the problem (e.g, "self-interacting" or "warm" dark matter).

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 ~200 km/s
- Core radii are larger than simulations can produce

Oman'14