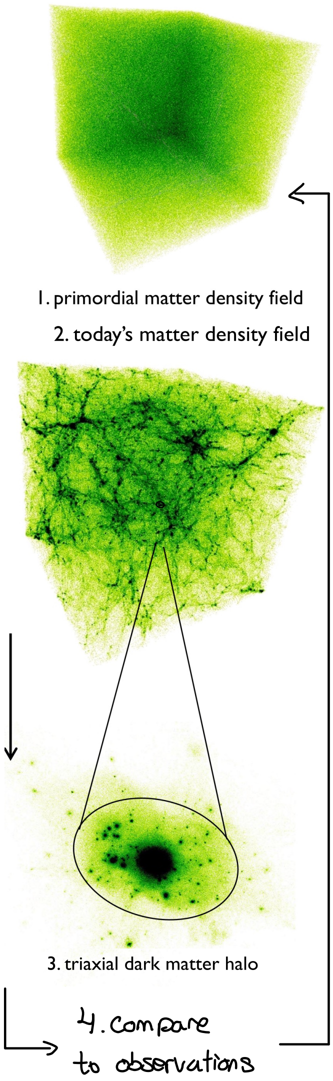
XIII. Open problems in Cosmology

13.1. CDM crisis (?)

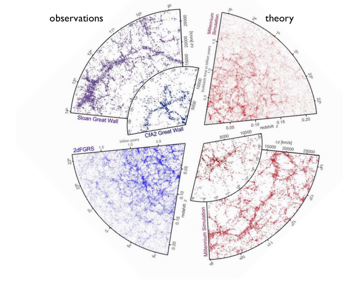
Observations Vs. Theory. Numerical simulations.

Until now, we have been developing a Cosmological model to explain our observations of the Universe. Now we have to wonder: Can we explain everything? Is there room for improvement? We had covered the theory, and all our observations come from counting photons. For example, astronomers are obtaining observational maps of the Large Scale structure of the Universe, while we have analytical tools to make predictions. These analytical models are limited, so we need numerical simulations.

Computational cosmology.



To simulate structure formation using numerical methods, we need to generate initial conditions to integrate the differential equations. These initial conditions are chosen to be an homogeneous and isotropic distribution with small perturbations, given by the mass "translation" of the CMB anisotropies ($\frac{\Delta T}{T} \to \frac{\Delta \rho}{\rho}$). Doing so, we generate a matter density field that corresponds to the power spectrum of the density perturbations. Thus, we have initial positions and velocities (x_i, v_i) coming from the Zel'dovich approximation. We can integrate the equations forward in time until we reach $z=0$. There, we can use "software telescopes" to find gravitationally bound objects in the simulation output. These objects can be (statistically) compared to observations. If we do not find a match, it is necessary to make adjustments, either on the assumptions of the model, on the model itself, on the initial conditions or on the numerical code. Once that our setup seems to work, we can keep on making comparisons between predictions of the cosmological model and observations.

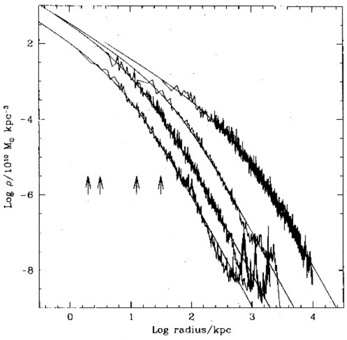


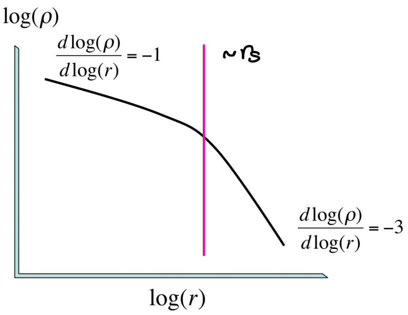
One of the possible test is comparing the large scale structure observations with simulated mocks of some of the existent surveys (2dF, Sloan, ...) It looks qualitatively fine, but it is necessary to check all the properties in a statistical sense. Some of the disagreements (+ problems) found are the cusp-core problem, the missing satellite problem, the lack of bulge-less galaxies in simulations, the existence of the Council of Giants, the speeding bullets, the existence of large clusters at high redshift (el Gordo) and the Hubble tension. Bullock & Boyland-Kolchin (2017) wrote a review article discussed these problems.

The cusp-core problem

We can obtain the volume density profile of dark matter haloes using radial shells. Navarro, Frenk and White found that the same profile was obtained no matter what the cosmological assumptions were (i.e. universal DM halo density profile).

(Navarro, Frenk & White 1996)





$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

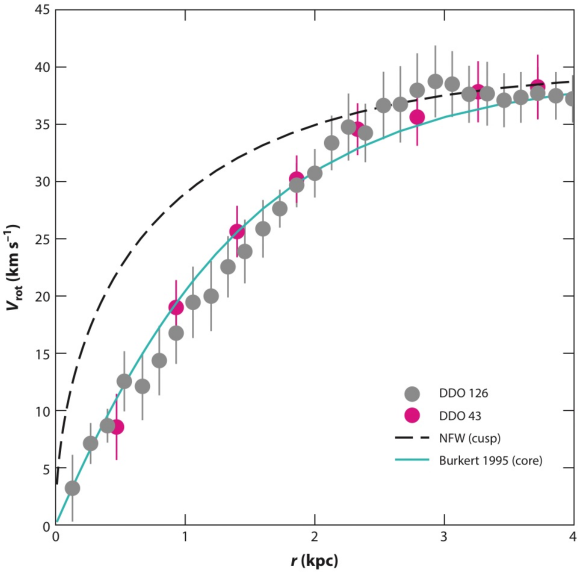
→ normalization

→ parameter to set the radius where the slope changes $-1 \rightarrow -3$

Numerous groups did the same analysis with their own simulations, finding similar values $\alpha \sim 1$ ($\rho^{DM}_{central}(r) \propto r^{\alpha}$ $\alpha < 0$) →

Navarro, Frenk & White (1996, 1997):	α = -1
Moore (1999):	α = -1.5
Ghigna (2000):	α = -1.5
Fukushige & Makino (2001):	α = -1.5
Dahle, Hannestad, Sommer-Larsen (2003):	α = -(0.9-1.6)
Power et al. (2003):	α = -1.2
Ricotti (2003):	α = -(1-1.4)
Fukushige, Kawai & Makino (2004):	α < -1.5
Tasitsiomi et al. (2004):	α = -1.2
Hayashi et al. (2004):	α ≈ -1.0
Diemand, Moore & Stadel (2004):	α = -1.16
Navarro et al. (2004):	α = α(r)
Caimmi, Marmo & Valentinuzzi (2005):	α = -1
Reed et al. (2005):	α = -1.4
Diemand et al. (2005):	α = -1.2
…	

$$V_{rot}(r) = \sqrt{\frac{G\,M(<r)}{R}}$$

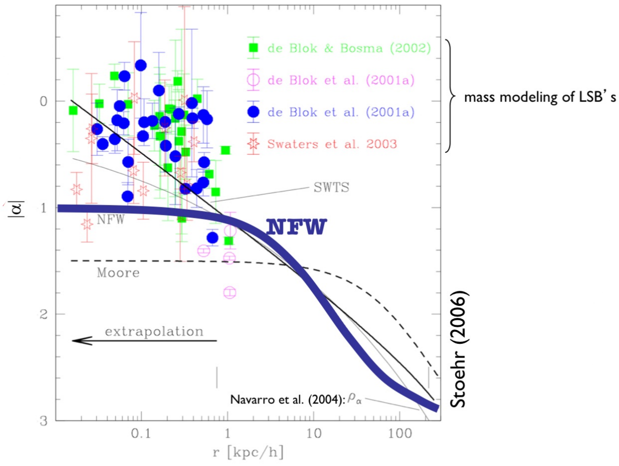


(Bullock & Boylan-Kolchin 2017)

However, if we compare this to observations (deriving the mass density profile from the rotation curve), we find that the model predicts a higher mass than what we get from the rotation curve. However, we cannot "remove" dark matter since we need it to flatten the rotation curve for large radii.

Solutions

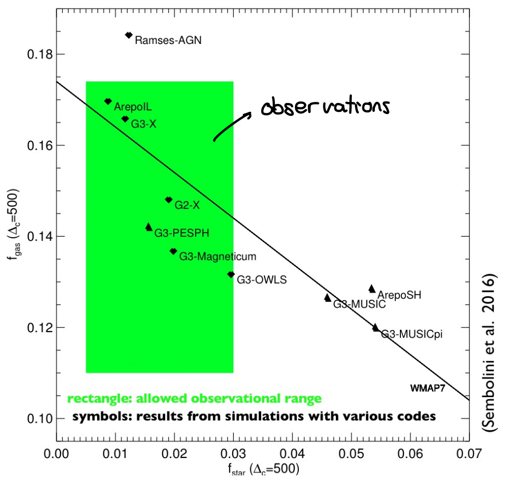
This could be solved either by re-interpreting the results or adjusting the CDM model.



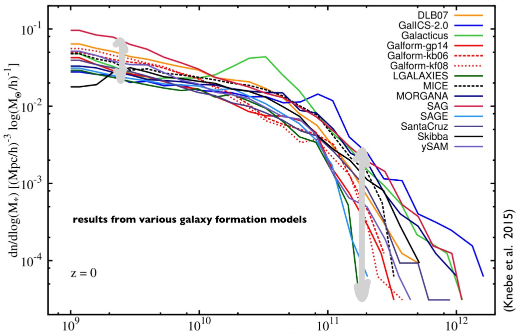
1. "Stationary"
   - Triaxial halo
   - Non-circular motions (bulge, bar, disc, ...)
2. Dynamical
   - adiabatic contraction
   - bar - DM interactions
   - baryonic feedback → importan, since baryon effects are not taken into account in DM only simulations

We cannot directly implement baryons it is necessary to make some assumptions.

The effect of different assumptions (implemented for different codes with the same initial conditions and cosmological models) can be compared to observations using the fraction of gas and stellar mass within $\Delta_c = 500$



We can also look at the stellar mass function.
As before, we have the same initial conditions and cosmological model.
Different baryon models produce a scatter of almost two orders of magnitude in the high mass end.



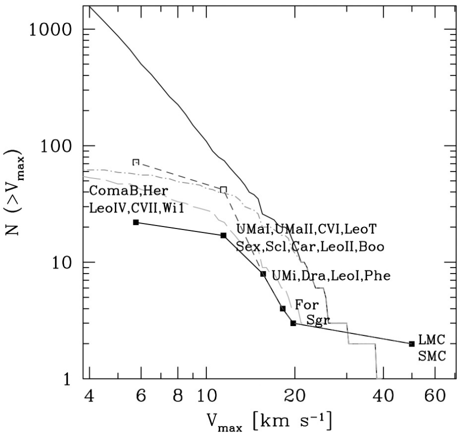
⟶ Need to solve this before addressing cusp-core problem

Satellite galaxies

Missing satellite galaxies

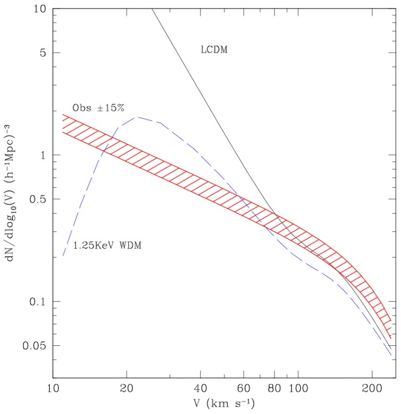
If we count the satellites orbiting the Milky Way and Andromeda and compare it to the number of haloes found in MW-like simulations, we find that the number of haloes is much larger than expected from observations.

Comparing this quantitatively, one finds a discrepancy in the low mass range between observations and simulations.



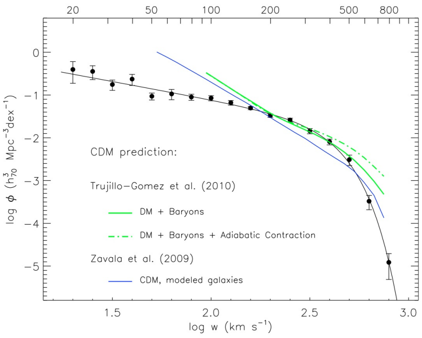
Madau et al. (2008)

Local Volume



Klypin et al. (2015)

In general
↓

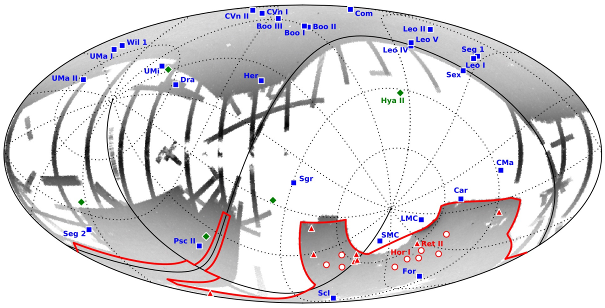


Papastergis et al. (2011)

This is problematic in general, not only for the local universe.

Some of the possible solutions are:

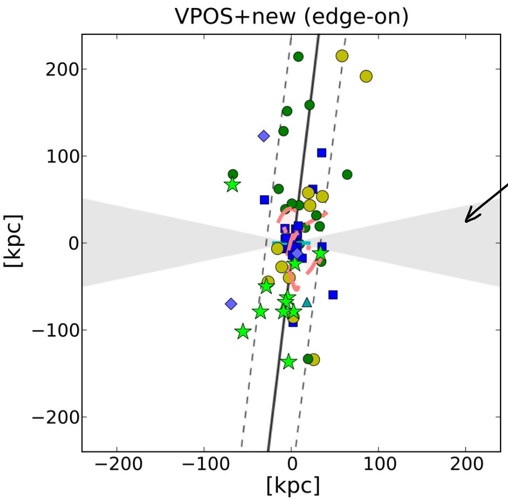
- This is an observational problem: they had not been discovered yet.
  DES collaboration doubled the number of satellites, but it was still not enough



🟥 new from DES 🟩 new from others

🟦 previously Known

- There are some physics missing (modelling problem).
  One of the proposed solutions was the effect of reionization, which suppresses galaxy formation in small haloes (the gas is too hot to collapse or has even been blown away). However, even if we cannot observe these satellite haloes directly, we can detect them through the effect of gravitational lensing. (This gives rise to the opposite problem: with lensing, we observe more dark satellites than predicted).
  ⟶ baryonic feedback.
- Tinkering with fundamental physics (gravity, WDM - which will be addressed later, CDE, VDE, ...)



Galactic plane

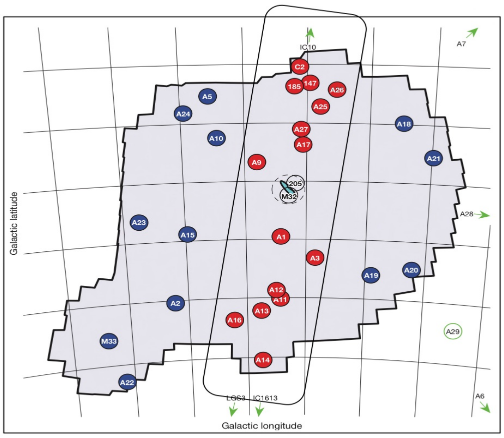
Pawlowski et al. (2015)

Planar distribution of satellite galaxies

Observations suggest that the satellites of the MW lie on a plane. The same is found for the Andromeda galaxy.

This could be explained by:

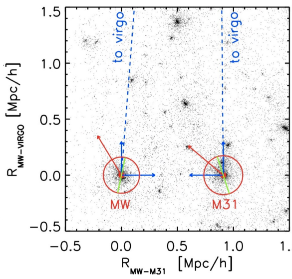
1. Environmental effects: the Local Group is a very special place.



Ibata et al. (2013, PAndAS survey)

- Binary system
- Situated in a fillament towards the Virgo cluster

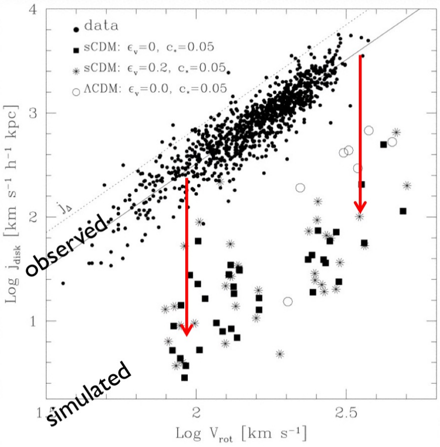
Simulations of MW and M31 in our real environment show that both fly towards Virgo through filaments. Satellite planes are aligned with those fillaments.



(Libeskind et al. 2011)

2. Dynamical effects: eg. radial alignment of orbits. Satellites can start with a randomly oriented orbit, but end up in the plane.
3. It is due to the definition of the planes: this causes a bias. This is difficult to test with simulations because it is necessary to use the same definitions.

Bulge-less disc galaxies



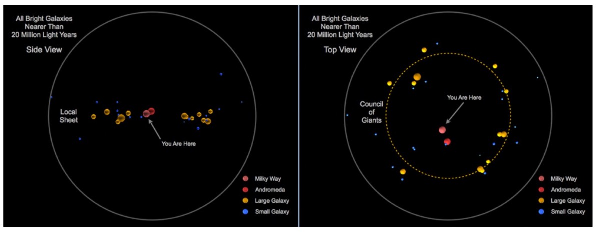
Steinmetz & Navarro (2000)

The formation of disc galaxies is linked to the conservation of angular momentum. Observations show that there are some galaxies without a bulge, i.e. they are 100% rotation supported. This is not found in numerical simulations: there is always a component supported by pressure (velocity dispersion). This happens because angular momentum is not fully conserved in simulations.

Some possible solutions are baryonic effects (model problem) or the improvement of the numerical model: new codes that conserve angular momentum have been developed. They include the baryonic effect, and can form bulge-less galaxies.

The Council of Giants

If we plot the position of the MW and the massive bright galaxies (~4 Mpc), it seems that the MW is at the centre of a 2D ring, surrounded by the other galaxies.



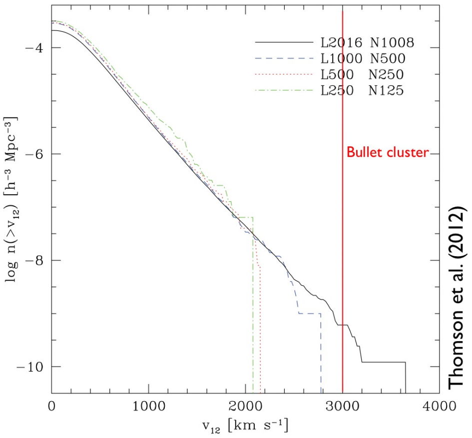
(c) Marshall McCall

Until now, we have not found an explanation, and this is currently being investigated using Constrained Local Universe Simulations (CLUES).
If we plot our bright neighbours up to 12 Mpc, we find another "council".

Speeding bullets

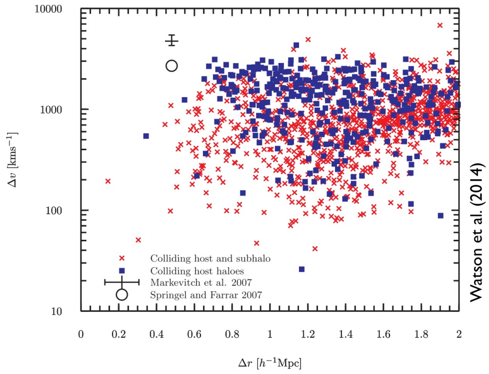
Analysing the DM and gas distributions of two collissioning galaxy clusters (specifically, the shape of the shock front), it was found that its velocity was $v \sim 3000\,km/s$ (really high). These are very rare objects, yet we observe quite a few:

- Bullet Cluster (1E 0657-56)
- "line of sight bullet" (Abel 576)
- "Cosmic Train Wreck" (Abel 520)
- MACS J0025.4-1222



Thomson et al. (2012)

From simulations: not all get to the speed of these encounters. The difference between them is the size of the box (simulated volume).

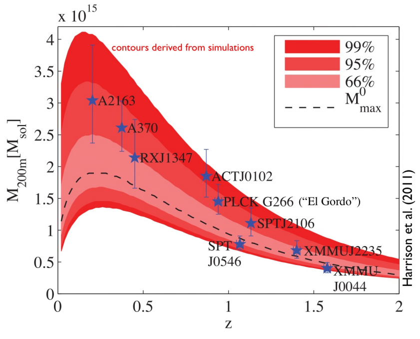


Watson et al. (2014)

Taking the Jubilee simulation (6 Gpc), we do find a lot of collisions with that velocity, but with higher impact parameter (not head-on).

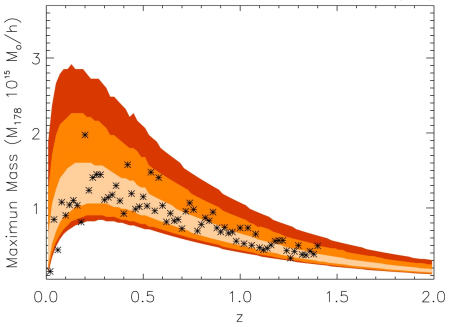
El Gordo

In our hierarchical formation scenario, we have small objects at high z that merge and form larger objects. Since the largest objects should be formed the latest, we should not find these large objects at high z.
However, we DO observe them (15σ density peak, very low probability). Again, increasing the simulated volume gives better results (statistical problem, not that the clusters at a given redshift are too massive for ΛCDM).

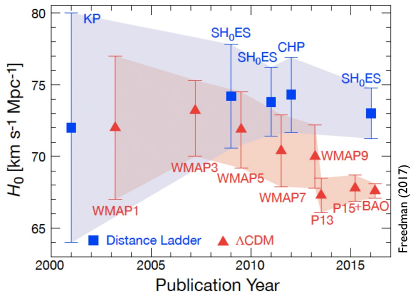


Harrison et al. (2011)

Watson et al. (2015)



Hubble tension



Derivations of the Hubble parameter coming from CMB observations, in comparison to local estimations, are outside from eachother errorbars. These discrepancy has not been solved yet.

Recap: problems and probable solutions

Proper modelling of baryonic physics could solve:

- The cusp-core problem
- Missing satellites
- Bulge-less disc galaxies

Taking into account environmental effects could solve:

- Satellites planar distribution
- Concil of Giants

Larger volume simulations could mitigate:

- Speeding bullets
- El Gordo
- Hubble tension

But these problems may also hint as something more fundamental, like the nature of dark matter and dark energy.

13.2. Solutions beyond concordance model

Alternative cosmologies

- Warm dark matter
- MOdified Newtonian Dynamics
- Lemaitre-Tolman-Bondi void models
- Quintessence models
- Modified gravity $f(R)$ models

...

We will get a bit more into the nature of DM.

[But for this you'll need to get back to the slides because I ran out of time.
Un besito y que os vaya todo bien ♥]