The astrophysical perspective

Outline:

1.- What is "dark matter" for the astronomers?

2.- Searches for the nature of DM in astronomy

- core-cusp "tension"

3.- Where are we going?

What is DM for the astronomers?

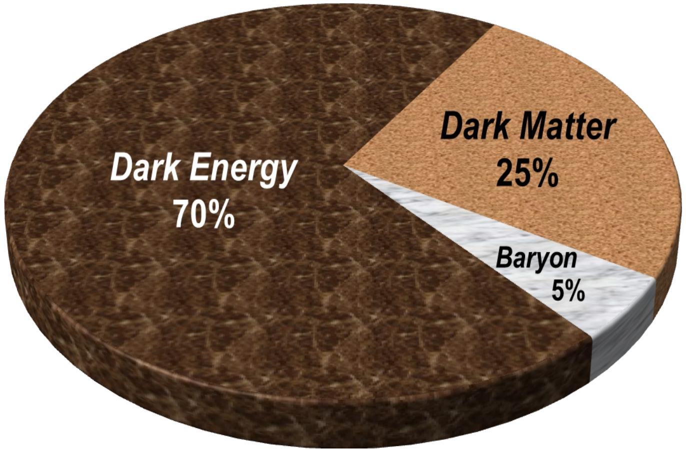
- It is an old issue (Zwicky 1933)

- The luminous matter gravity is insufficient to explain the motions observed in galaxies and larger objects.

- It originally was, and probably still is, an astronomical problem, in a sense that DM is needed to explain astronomical observations (cosmological observations included).

- 90 years after Zwicky, its nature remains unknown. Is it an elementary particle? Is it regular matter assembled in light-less clumps (e.g., black holes?)

- DM is now part of the ΛCDM cosmological model. It is **assumed to be cold**, meaning that the velocity of whatever DM is made of has velocities negligible compared with the speed of light.



1931

Fritz Zwicky

Technocracy Technical Alliance: Front row L-R: Oppenheimer, Harry Bateman, Richard Chace Tolman, William Vermillion Houston, Millikan, Einstein, Paul Sophus Epstein, Zwicky, Ernest Charles Watson ; 2nd Row far left: Charles Lauritsen; fourth from left 2nd row: Jesse DuMond, Physics Department faculty and graduate students; California Institute of Technology; Pasadena

Coma Cluster, by NASA / JPL-Caltech / L. Jenkins

Discovery paper … modern arguments and conclusions
(Zwicky 1933, Helvetica Physica Acta, Vol. 6, p. 110-127)

As we have seen in sect. 3, there exist in the Coma cluster apparent differences in velocity of at least 1500 to 2000 km/s. In relation with this enormous velocity dispersion one can mak the following considerations.

1. If one assumes that the Coma system has reached a mechanically stationary state, it follows from the Virial theorem

$$\bar{\varepsilon}_k = -\frac{1}{2}\bar{\varepsilon}_p \quad (4)$$

where $\bar{\varepsilon}_k$ and $\bar{\varepsilon}_p$ denote the mean kinetic and potential energies, e.g. per unit mass in the system. For the purpose of estimation, we assume that matter is distributed uniformly in th cluster. The cluster has a radius R of approximately one million light years (equal to 10^{24} cm) and contains 800 individual nebulae each of a mass of 10^9 solar masses. The total mass M o the system is therefore

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45} \text{ g}. \quad (5)$$

From this we have for the total potential energy Ω:

$$\Omega = -\frac{3}{5}\Gamma\frac{M^2}{R} \quad (6)$$

where Γ = gravitational constant

or

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12} \text{ cm}^2/\text{s}^2 \quad (7)$$

and furthermore

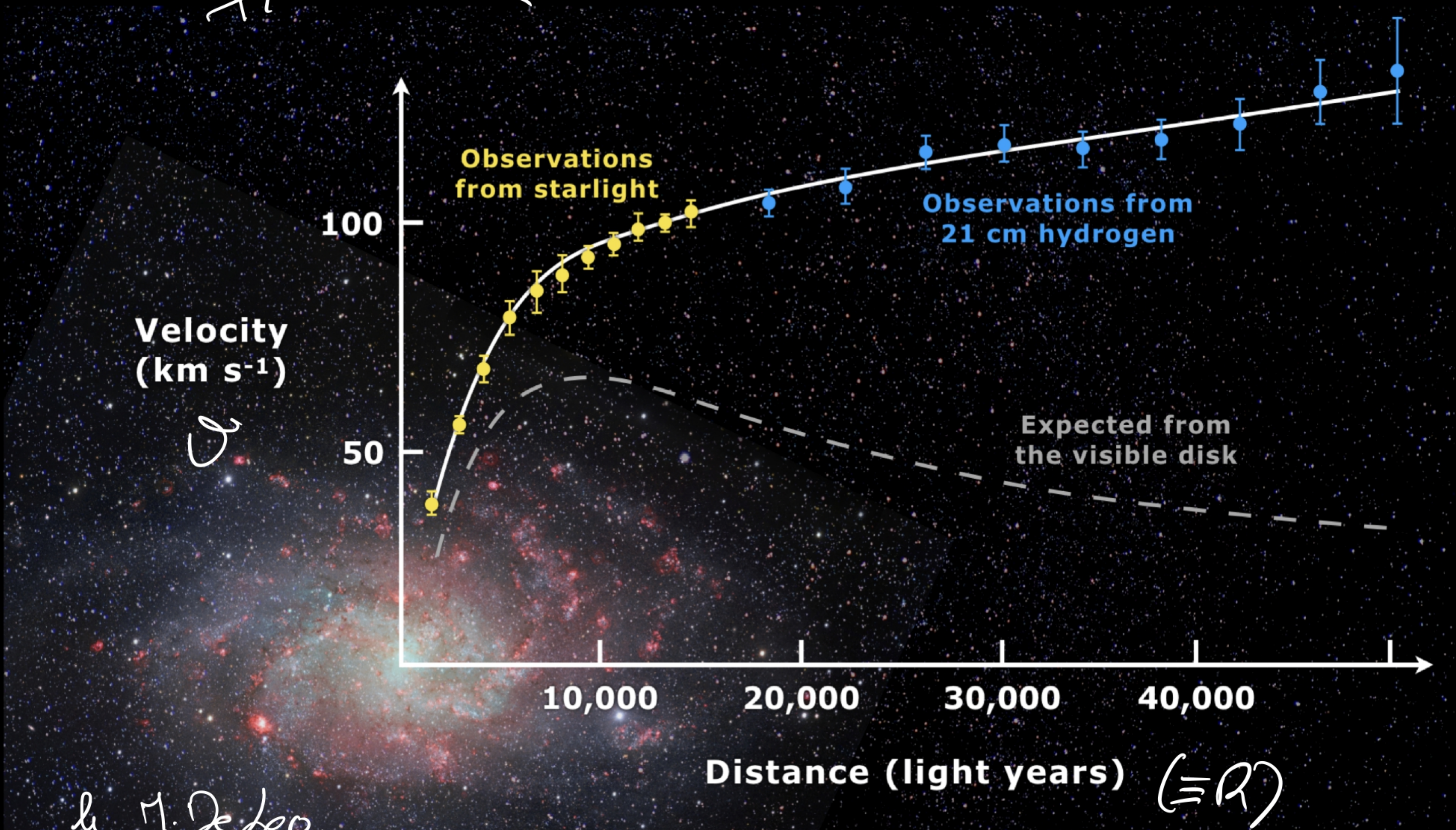
$$\begin{aligned} \bar{\varepsilon}_k = \overline{v^2}/2 = -\bar{\varepsilon}_p/2 = 32 \times 10^{12} \text{ cm}^2/\text{s}^2 \\ (\overline{v^2})^{1/2} = 80 \text{ km/s}. \end{aligned} \quad (8)$$

In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derive on the basis of observations of luminous matter [This would be in approximate accordance with the opinion of Einstein and de Sitter as discussed in Sect. 4.]. If this should be verified, i would lead to the surprising result that dark matter exists in much greater density than luminous matter.

These considerations indicate that the large velocity dispersion in the Coma system (and other dense clusters of nebulae) holds an unsolved problem.

M 33 rotation curve:

$$\frac{v^2}{R} = G\frac{M}{R^2} \Longrightarrow v \propto R^{-1/2}$$



What is DM for the astronomers?

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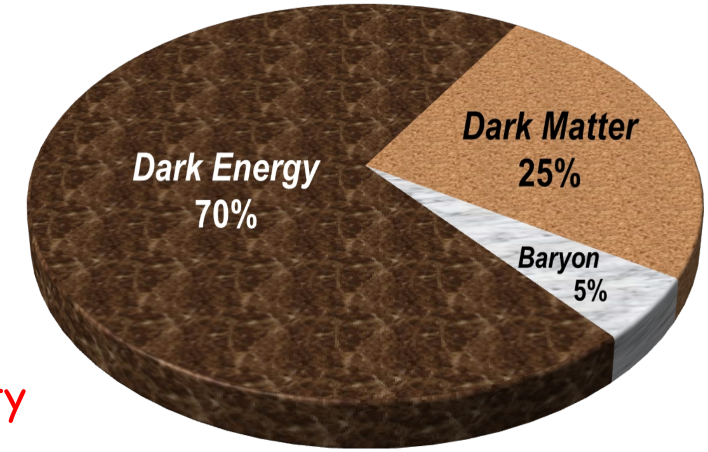
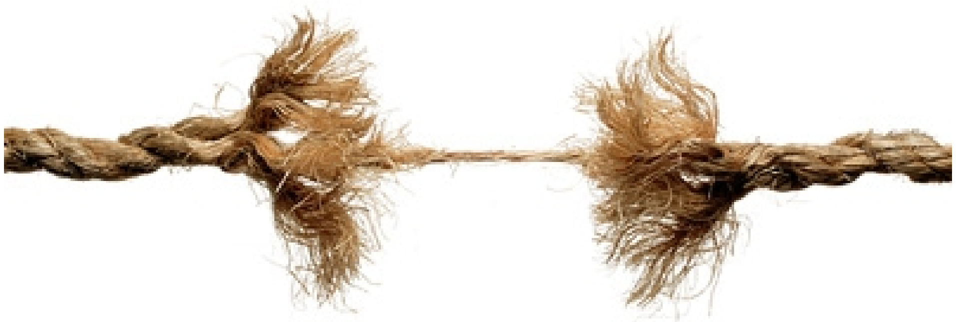
- DM 85% of the gravity



Searches for the nature of DM within astronomy

- ΛCDM is a fantastic model of Universe according to its extreme observational success, but cannot be the final model. It is not self-contained (e.g., Peebles 2021) E.g., the coincidence problem. (Need to resort to the anthropic principle and multiverses, etc.)

- According to Peebles (and many others), the way to advance is looking for 'tensions' in the ΛCDM model that may be related to the nature of DM.

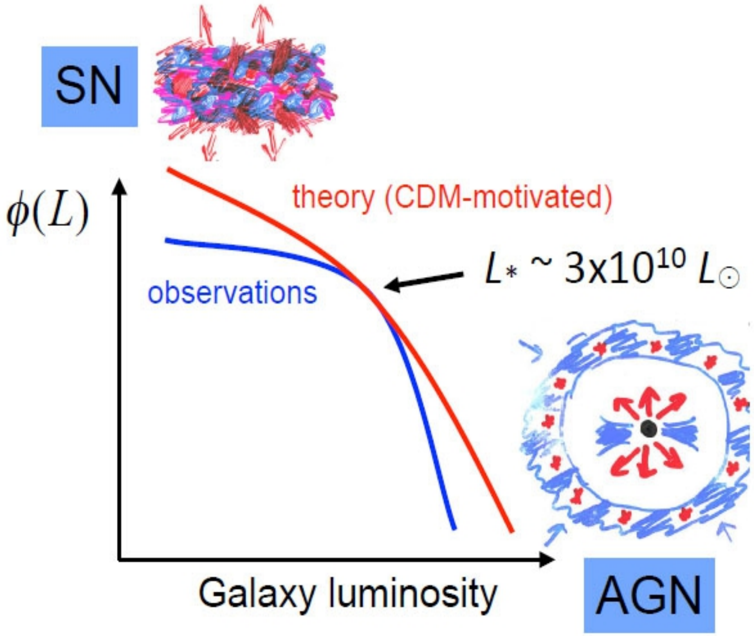


- Current tensions: H_0 (4-sigma), S_8 (2-sigma; matter clumpiness parameter) (e.g., Lahav & Silk 21) … and the so-called small-scale problems (SSP) of the ΛCDM (?-sigma), which I will focus on

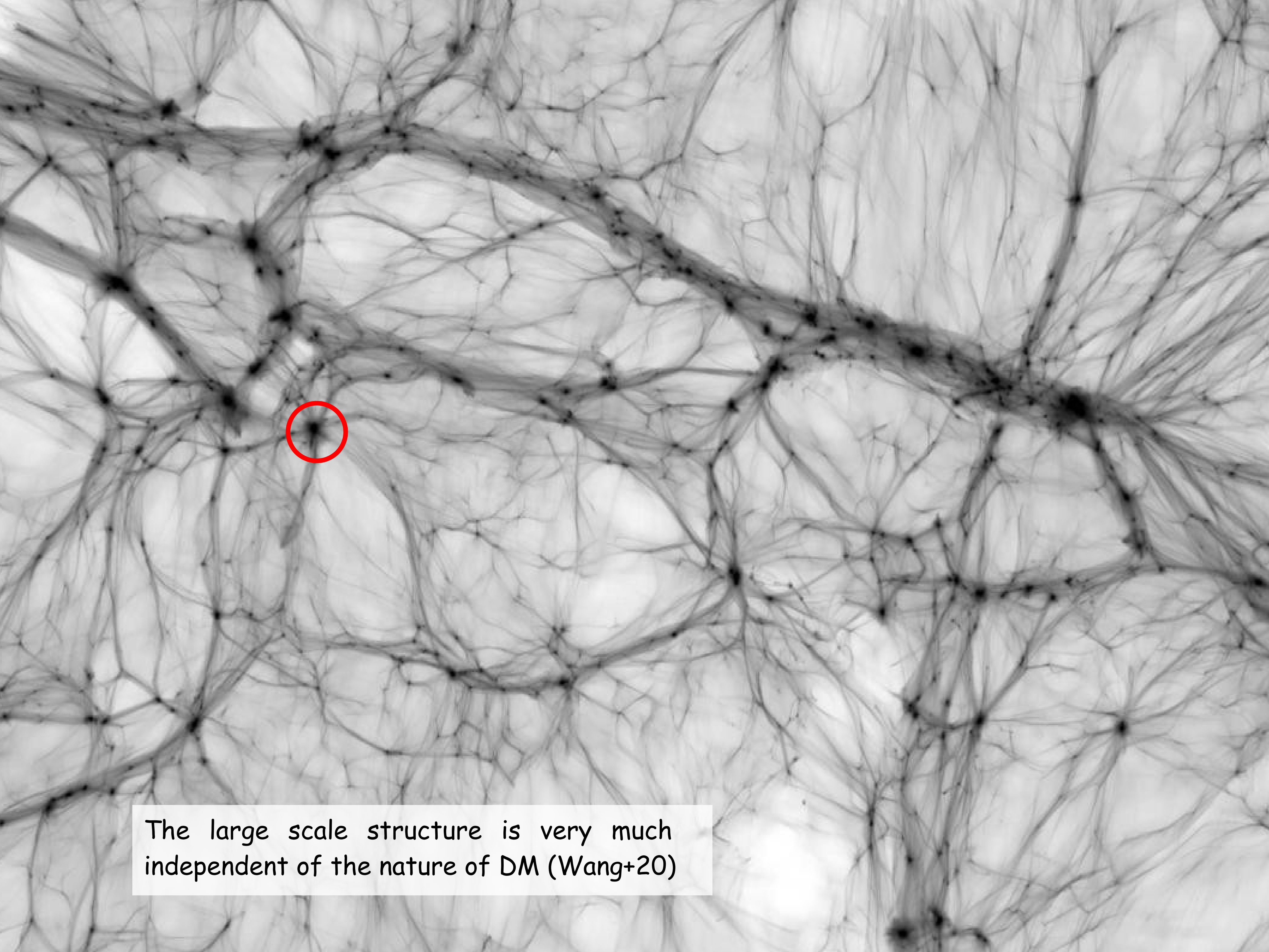
- SSP: there seem to be physical mechanisms erasing scales of 1kpc and smaller. Rich smaller-scale structure are expected from Cold DM alone, but can be created by other types of DM, … as well as by baryon driven processes.

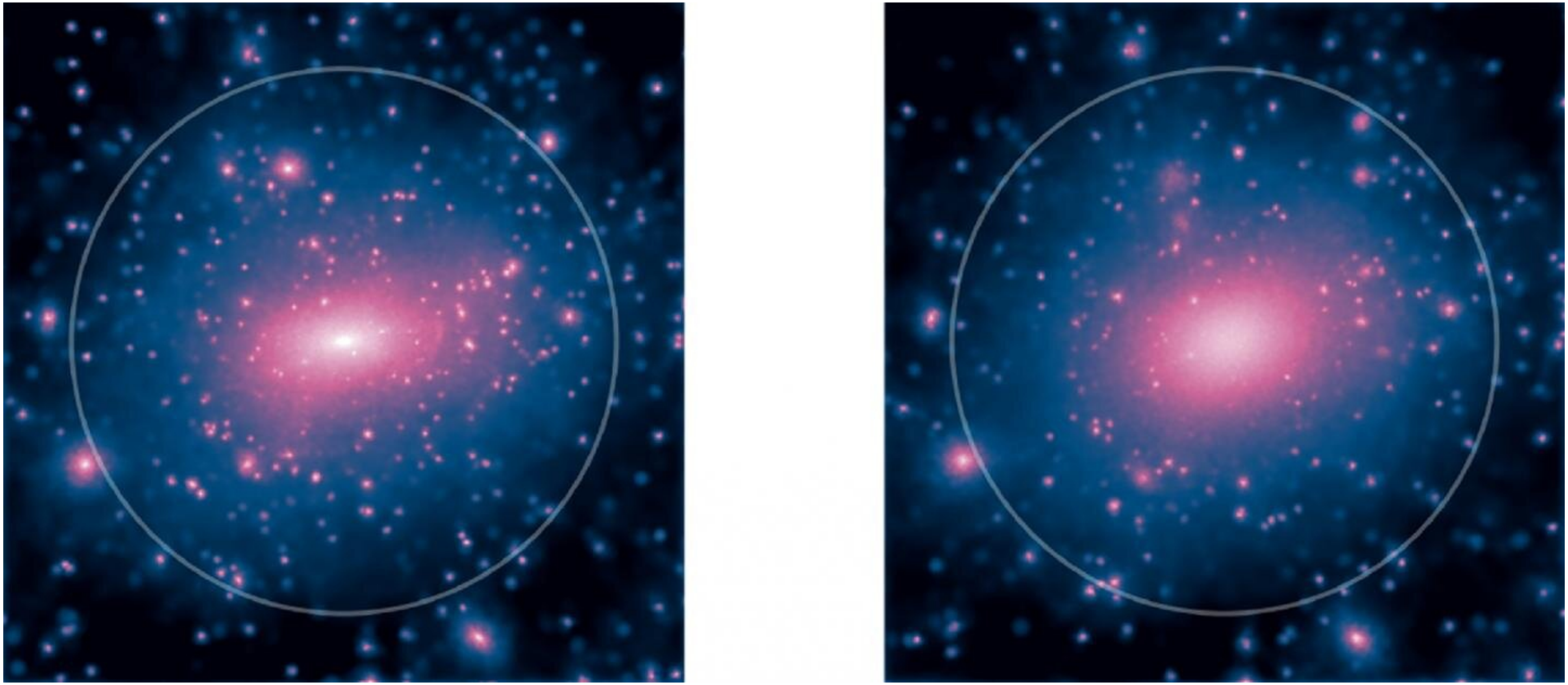
- Start with the power spectrum of density fluctuations set by the CMB, and carry out numerical simulations of galaxy formation. Do they agree with observed galaxies?

- Numerical simulations fundamental since the galaxies are highly non-linear evolution of the original small density perturbations. Including baryon physics is also fundamental since the affect the way galaxies evolve (and look).



(Silk & Mamon 2012)

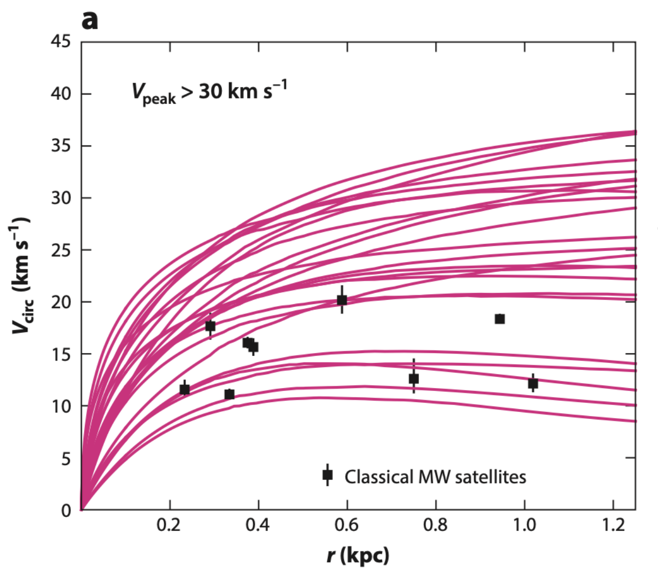

The large scale structure is very much independent of the nature of DM (Wang+20)



DM only simulation cold (left) and self-interacting (right) starting off
from identical initial conditions (Brinckmann+2018)

The small-scale structure (say kpc scales) very much depends on the nature of DM

SSP: Too Big to Fail

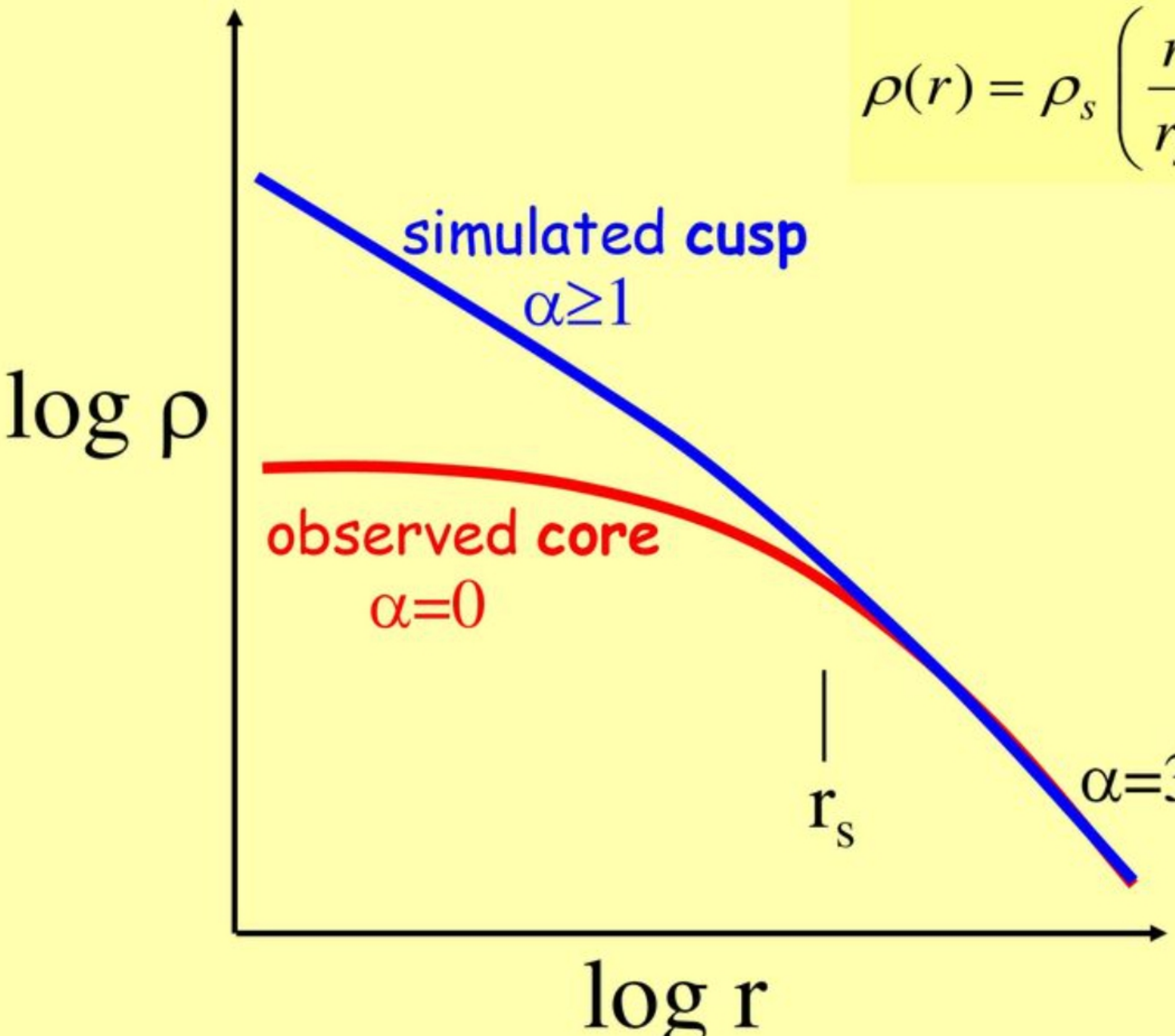


Cold DM simulations predict a number of massive (centrally concentrated) satellites around the MW which are not observed (Boylan-Kolchin et al. 2011).

(Bullock & Boylan-Kolchin, 2017)

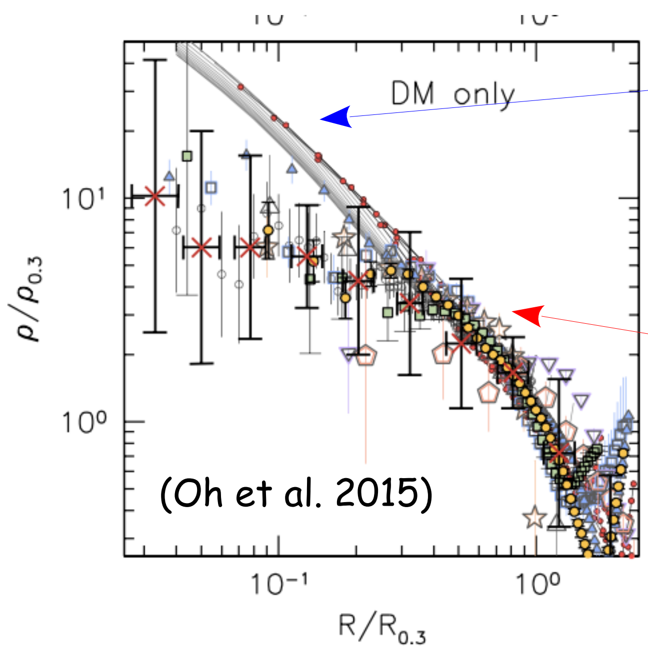
The core-cusp "problem" of CDM

$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\alpha_0} \left(1 + \frac{r}{r_s}\right)^{-3+\alpha_0}$$



Taken from G. Bryant (2018)

SSP: The core-cusp problem

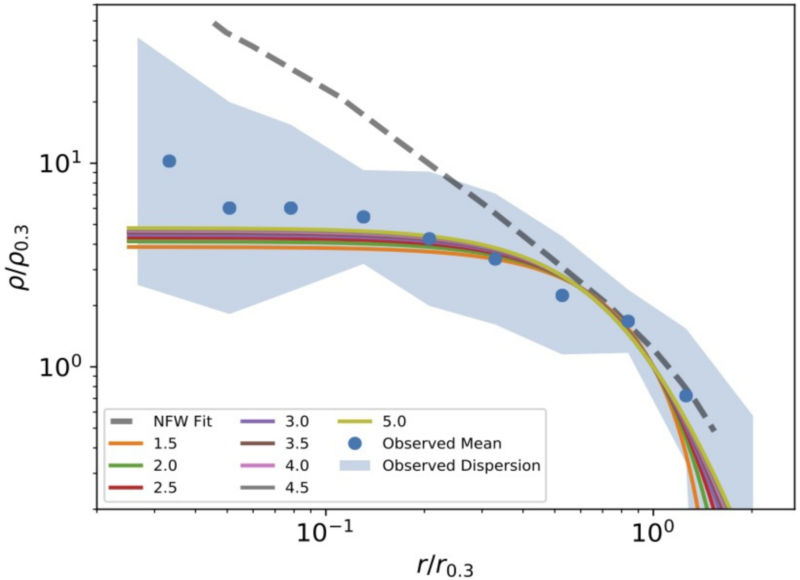


NFW profile (Navarro-Frenk-White), expected for cold DM simulations. It has a cusp. Thought to set by the initial conditions, i. e., the primordial power spectrum of density fluctuations (e.g., Brown+20).

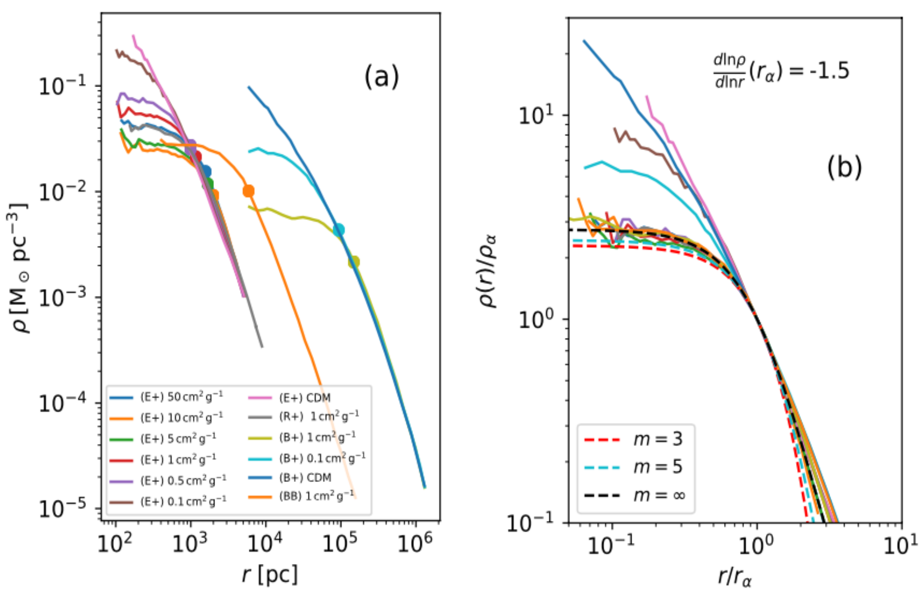
However, cores are observed

Cores can be caused by (1) baryon feedback on DM, or (2) the DM not being cold … i.e., **by the nature of DM**.

Various types of "natures" can cause the cores (warm DM, self-interacting DM, Fuzzy DM, sterile neutrinos, solar mass black holes, ...)

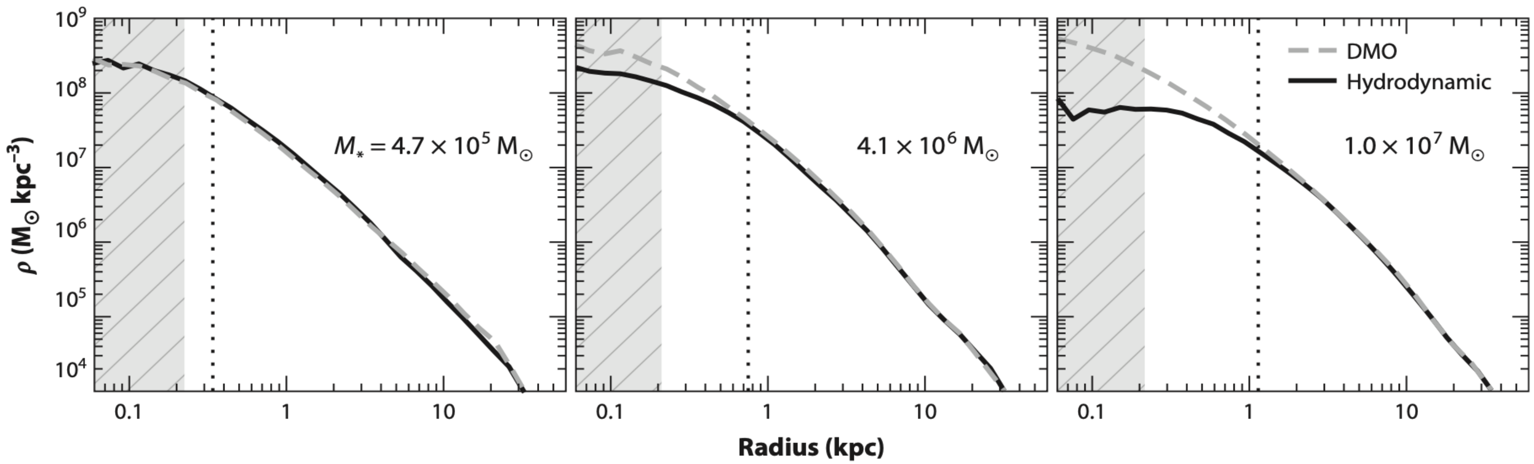


Cores (as observed) are expected in self-gravitating n-body systems in thermodynamical equilibrium (e.g., SA+20), but cold DM does not reach equilibrium within the age of the atmosphere.



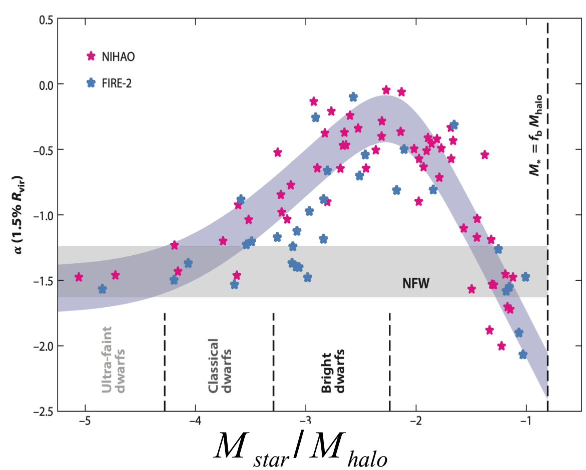
For example, self-interacting DM of BH-BH collisions do produce the cores (SA+Trujillo 21).

Can we distinguish between between baryon driven feedback and DM not being cold?



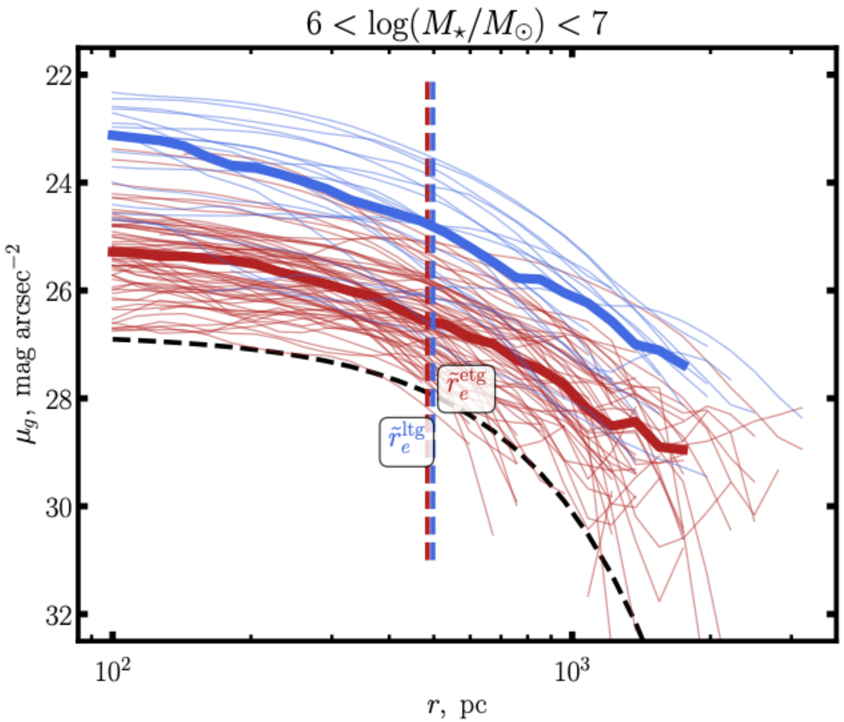
(Bullock and BK+17; Di Cintio+14)

$$\alpha = \frac{d \ln \rho}{d \ln R}$$



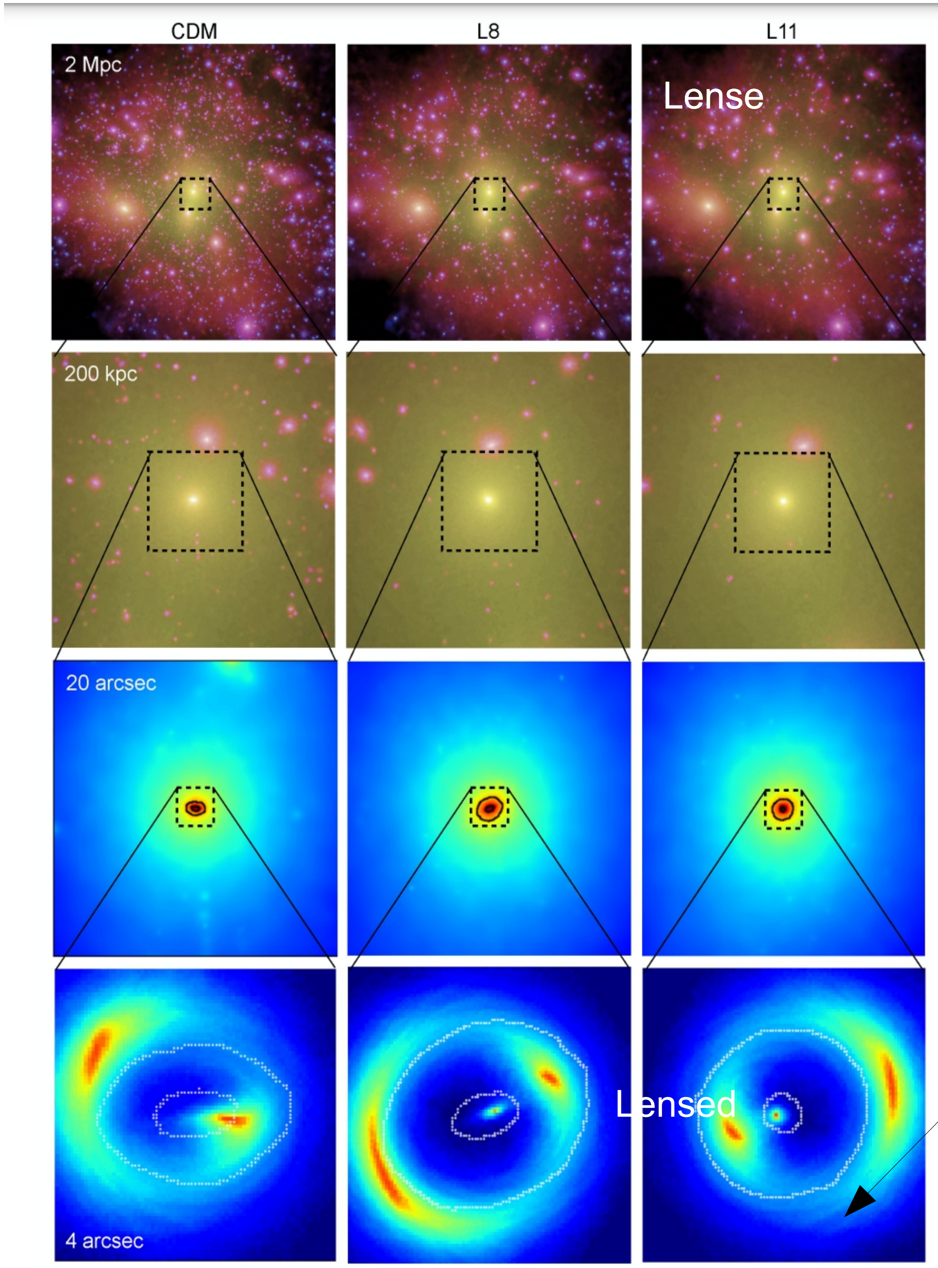
Baryon feedback no longer works for $M_* < 10^6$ $M_{\odot}$ (e.g., Di cintio+14). This is a solid limit since all the energy of the observed stars is not sufficient to modify the NFW gravitational well (e.g., Peñarrubia+12).

The observation of rotation curves of low mass (isolated) galaxies is extremely challenging, but will be done. Moreover, light distribution is well within reach, e.g., (Carlsten+21).

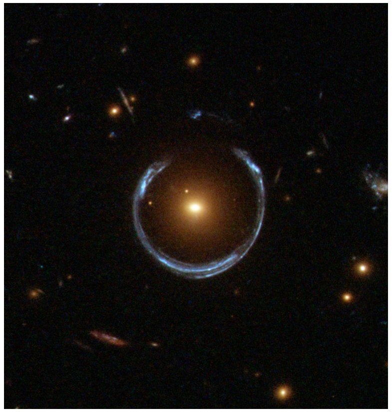


We may be able to say something on the non-cold nature of the DM soon.

SSP: clumpiness



To be detected using strong gravitational lensing



(Despali+20 model for sterile neutrinos)

Where are we going?

Message to carry over to the next views

- ΛCDM is great but, fortunately, it starts to have "tensions"

- Exploit these tensions of the ΛCDM model depending on the nature of DM

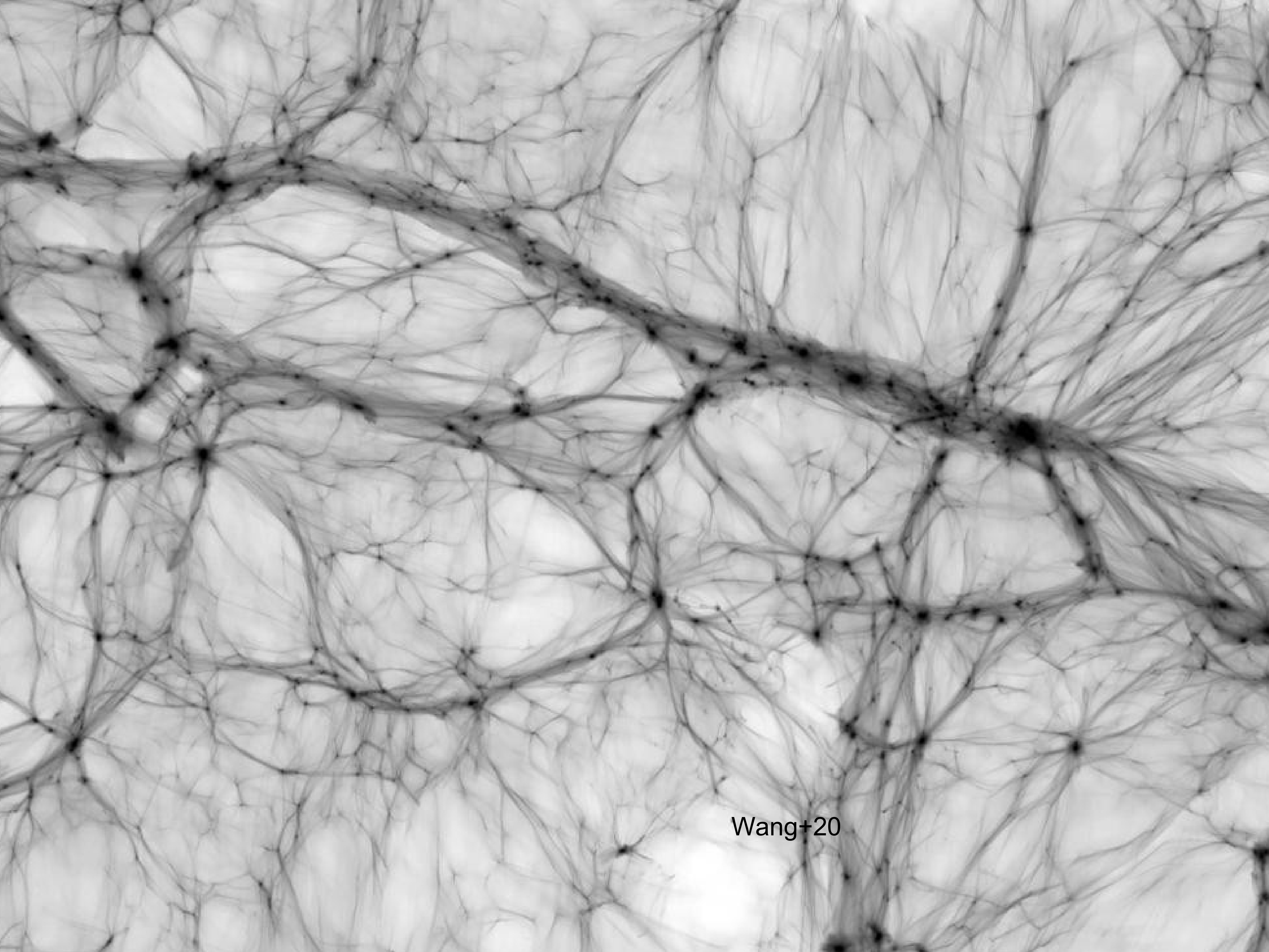
- In particular the so-called small scale problems … cusp-core inc.

- Improve the predictions. Numerical modeling is needed to include baryon physics, to model alternative DM particles, to model lensing effects ... (this is an issue that I have not commented on.)

- Fine tuned observations are needed (e.g., lensing distortion)

- Example: observe mass profiles of extremely low mass galaxies (< 10^6 $M_\odot$ with exquisite detail)

- We may be close to be able to say that the DM is not cold ...


Wang+20

References:

The literature on the subject is endless. These “references” contain a few recent reviews to start pulling the thread if needed, historical references, as well as a few other papers cited along the slides.

- Boylan-Kolchin, 2011, MNRAS, 415, L40. *Too big to fail? The puzzling darkness of massive Milky Way subhaloes.* Where the too big to fail problem was posed.

- Brinckmann et al. 2018, MNRAS, 474, 746. *The structure and assembly history of cluster-sized haloes in self-interacting dark matter*

- Brown et al. 2020, MNRAS, 495, 4994. *Connecting the structure of dark matter haloes to the primordial power spectrum.* The NFW profile shape is set by the primordial power spectrum of density fluctuations ultimately set by Big Bang.

- Bullock & Boylan-Kolchin, 2017, ARA&A, 55, 343. *Small-scale challenges of the ΛCDM paradigm*
Good overview of the astrophysical perspective

- Carlsten et al. 2021, ApJ, submitted (2021arXiv210503435C) *ELVES I: Structures of Dwarf Satellites of MW-like Galaxies; Morphology, Scaling Relations, and Intrinsic Shapes.* 10^6 $M_{\odot}$ stellar mass galaxies always showing cores.

- Del Popolo & Le Delliou, 2917, Galax., 5, 17. Small Scale Problems of the ΛCDM Model: A Short Review.
Up to date review of the SSP.

- Despali, 2020, MNRAS, 491, 1295. *The lensing properties of subhaloes in massive elliptical galaxies in sterile neutrino cosmologies.* Examples of how clumpiness can be diagnosed using strong lenses.

- Di Cintio+2014, MNRAS, 437, 415. *The dependence of dark matter profiles on the stellar-to-halo mass ratio: a prediction for cusps versus cores.* (E.g.) Cores should disappear for $M_{*} < 10^6$ $M_{\odot}$

- Lahav & Silk, 2021, Nat. Astron., 5, 855. *Knowing when to stop.* On ‘where are we going?’

- Metcalf & Amara, 2012, MNRAS, 419, 3414. *Small-scale structures of dark matter and flux anomalies in quasar gravitational lenses.* The flux ratio between images to disagree with any lens model with a smooth distribution of matter.

- Navarro et al., 1997, ApJ,.490, .49. *A Universal Density Profile from Hierarchical Clustering.* This is the paper introducing the so-called NFW profile characteristics of DM only halos. It has 7655 citations (as for Sep. 2021).

- Oh et al., 2015, AJ, 49,180, *High-resolution Mass Models of Dwarf Galaxies from LITTLE THINGS.* Up to date observations of cores in dwarfs

- Peebles 2021, arxiv.org/2106.02672. *Improving Physical Cosmology: An Empiricist's Assessment.* Up to date review. A bit erratic, but plenty of insight

- Peñarrubia et al. , 2012,ApJL, 759, L42. *The Coupling between the Core/Cusp and Missing Satellite Problems.* The energy released by low mass galaxies is insufficient to transform cusps into cores.

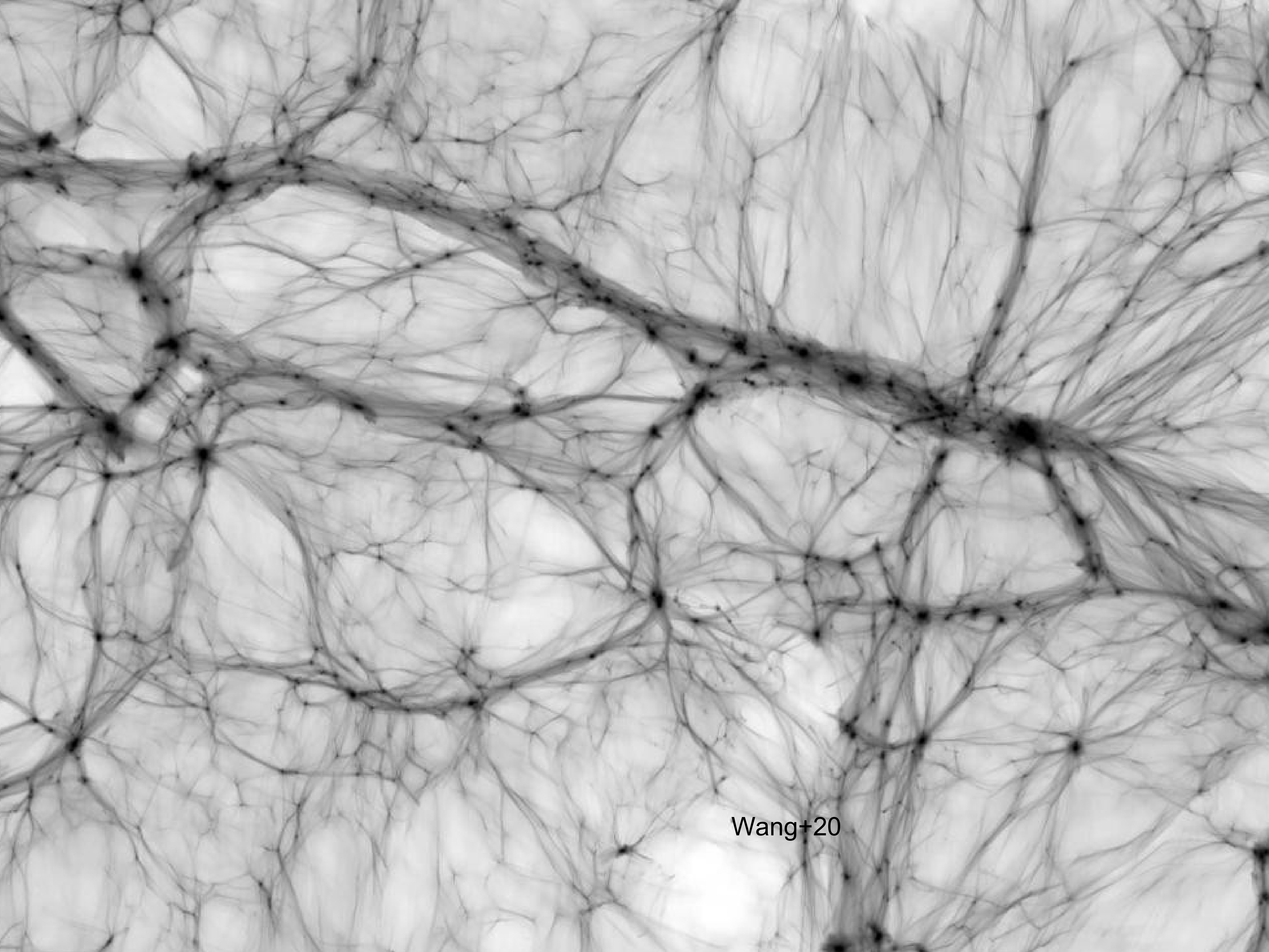
- Sanchez Almeida & Trujillo. 2021, MNRAS, 502, 2832. *Numerical simulations of dark matter haloes produce polytropic central cores when reaching thermodynamic equilibrium.* DM numerical simulations with enough collisions automatically produce the observed cores in DM profiles.

- Sanchez Almeida ,Trujillo, and Plastino, A&A, &42, L14. *The principle of maximum entropy explains the cores observed in the mass distribution of dwarf galaxies.* The title says it all.

- Silk & Mamon, 2012, RAA, 12, 917. *The current starus of galaxy formation.* Nice a bit out-of-date review on galaxy formation, with the iconic carton of luminosity functions predicted (DM) and observed.

- Wang et al. 2020, Nat., 585, 39. *Universal structure of dark matter haloes over a mass range of 20 orders of magnitude.* Impressive, state of the art N-body simulations.

- Zwicky, 1933, Helvetica Physica Acta, Vol. 6, p. 110-127. *Die Rotverschiebung von extragalaktischen Nebeln.* This is the original paper where need of DM (and the name DM) are introduced. An english translation can be found in http://ned.ipac.caltech.edu/level5/March17/Zwicky/frames.html


Wang+20