(Small-scale) Challenges to the ΛCDM Paradigm

SUT School in Astronomy and Cosmology

11 May 2024

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(Small-scale) Challenges to the ΛCDM Paradigm

Missing Satellite

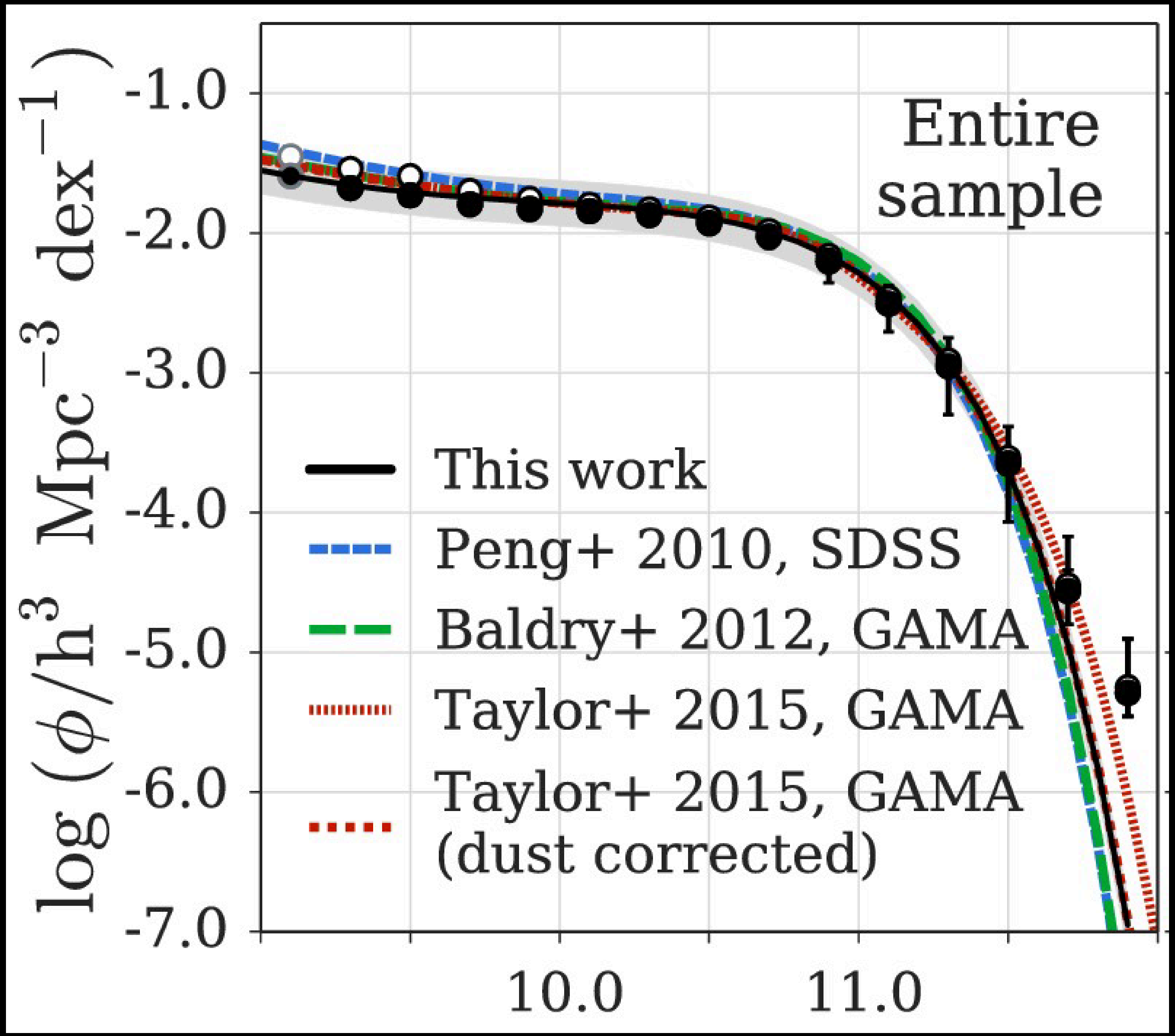
Cusp-Core Problem

Too bit too fail

Further read:Bullock and Boylan-Kolchin 2019

Scales in galaxy-cosmology studies

Scales in galaxy-cosmology studies: stellar mass



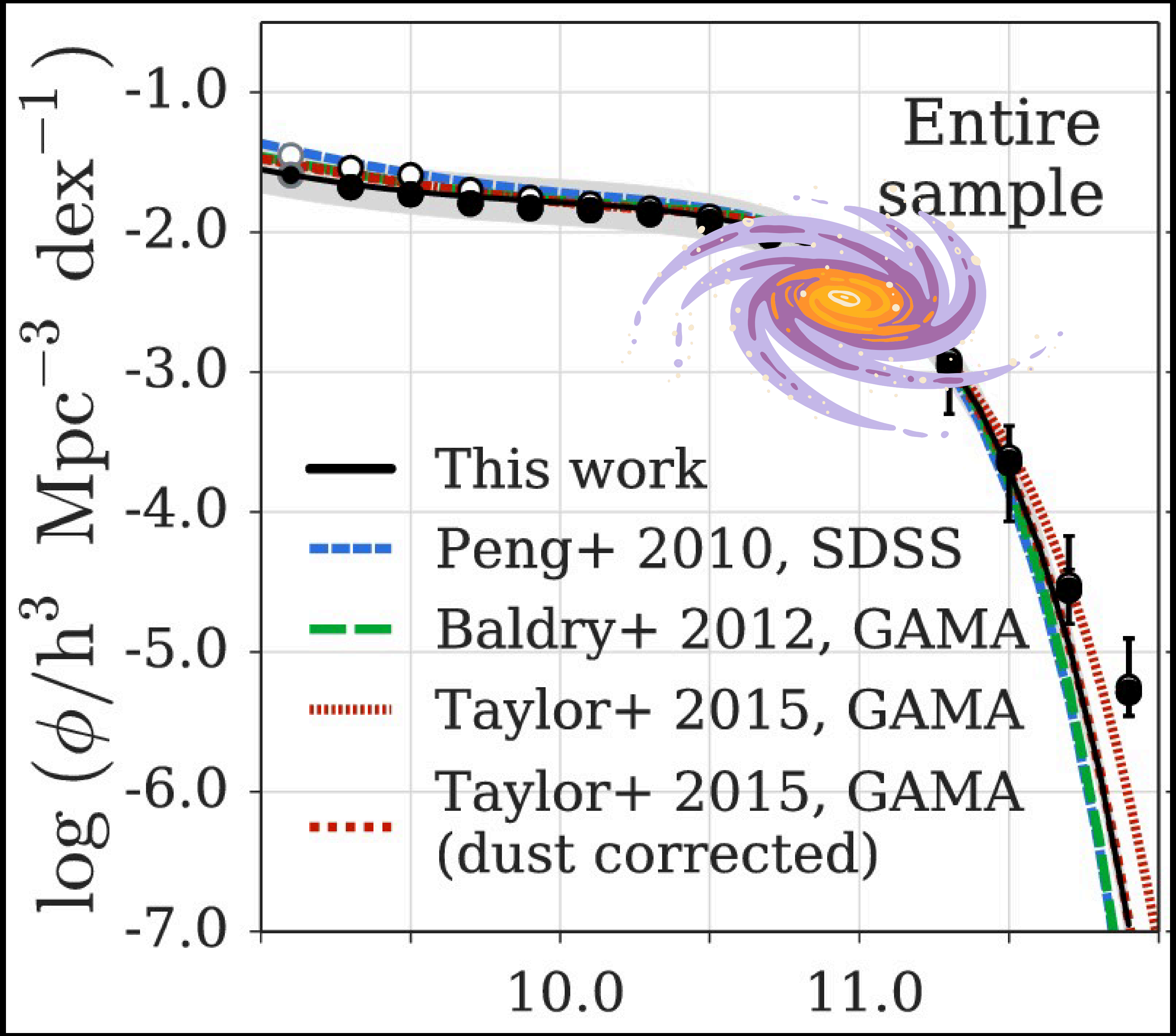
log (M*/Msun)

Typical galaxy stellar mass is
10^6-10^{12} Msun

Weigel+2016

Scales in galaxy-cosmology studies: stellar mass

Milkyway is a typical galaxy



log (M*/Msun)

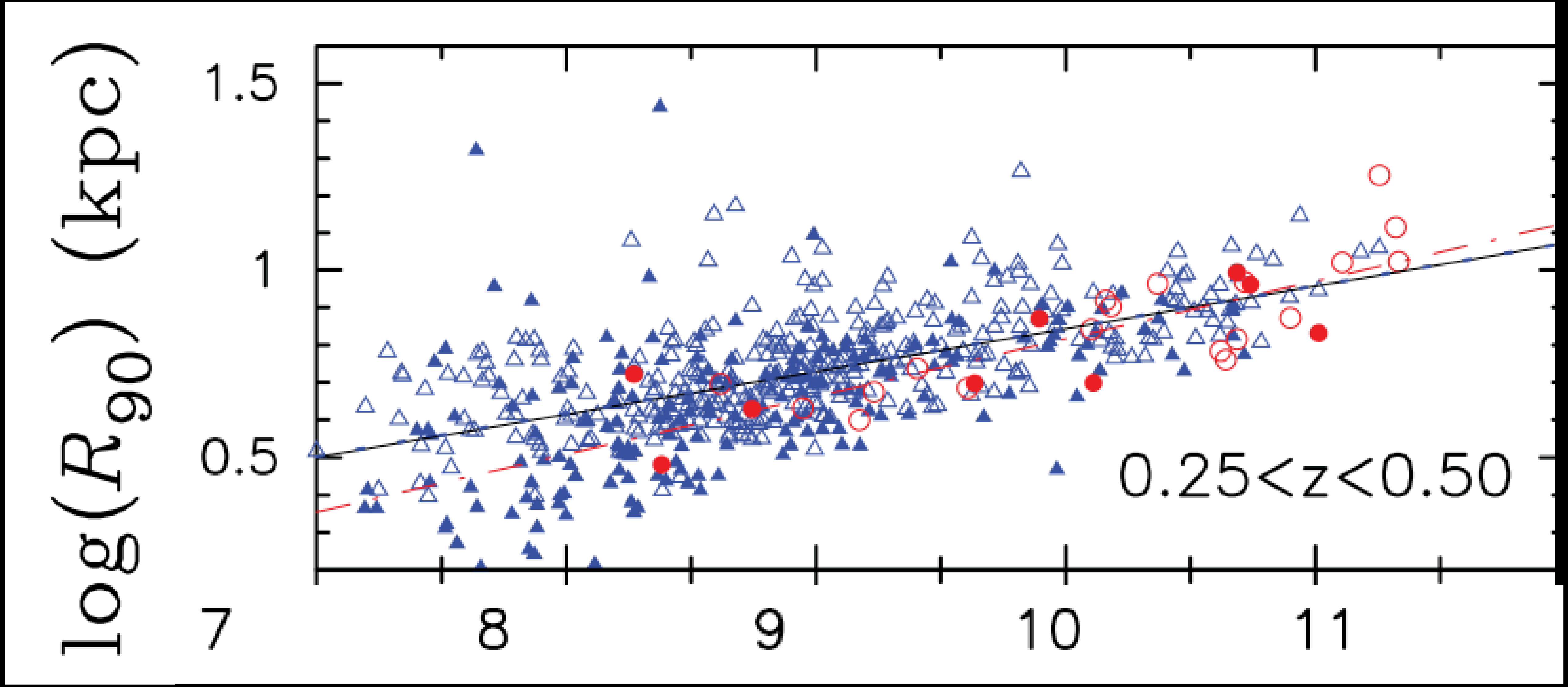
Weigel+2016

Typical galaxy stellar mass is

10^{6}-10^{12} Msun

Scales in galaxy-cosmology studies: galaxy sizes

Typical galaxy size is 1-10 kpc



log (M*/Msun)

Scales in galaxy-cosmology studies

Typical distance between galaxies is

Scales in galaxy-cosmology studies

Typical distance between galaxies is

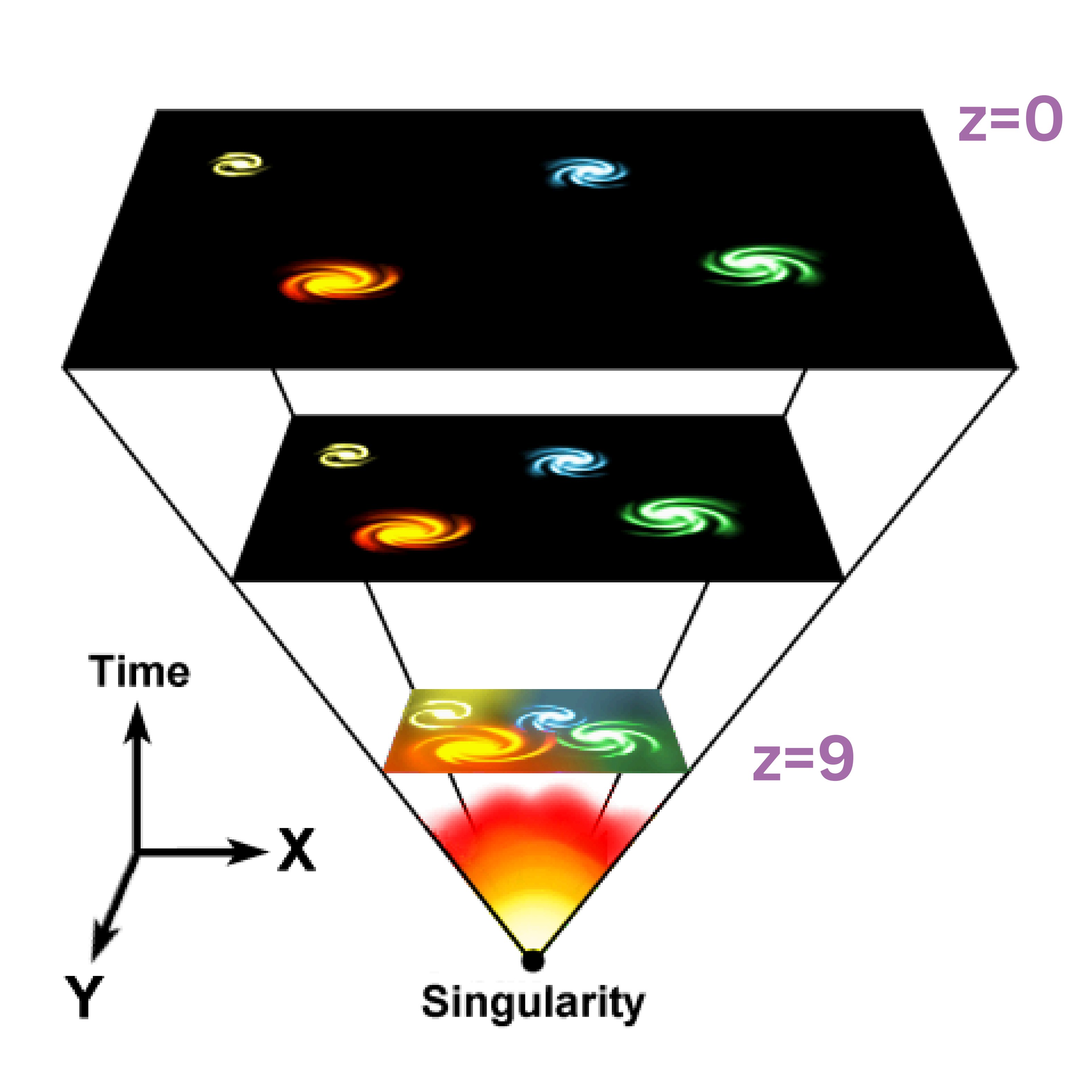
Scales in galaxy-cosmology studies: universe scale

What about size of the universe??

search: cosmology calculator

galaxy at redshift z = 11?

Scales in galaxy-cosmology studies: universe scale

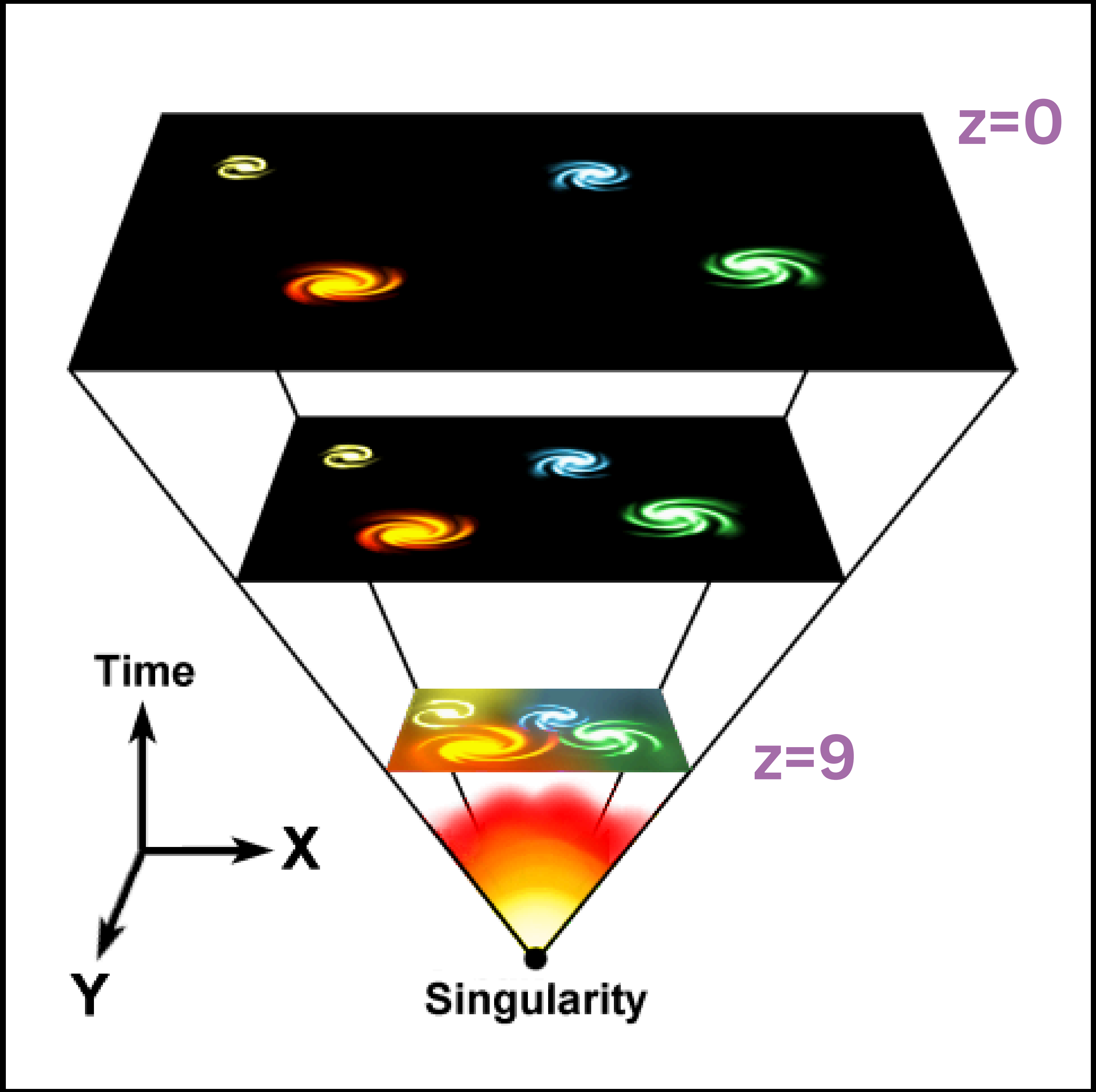


scale factor

$a(z) \equiv 1/(1+z)$

where $a(z=0) = 1$

Scales in galaxy-cosmology studies: universe scale



scale factor

$$a(z) \equiv 1/(1+z)$$

where $a(z=0) = 1$

Comoving distance
is ‘how far we are from that galaxy if the universe were to be frozen now (z=0)’

Scales in galaxy-cosmology studies

So, what is the observable universe (the horizon) size in comoving scale?

Scales in galaxy-cosmology studies

So, what is the observable universe (the horizon) size in comoving scale?

~15000 Mpc in radius

Scales in galaxy-cosmology studies

Conclusion:

galaxy stellar mass: 10^6-10^{12} Msun
galaxy size: 1-10 kpc
distance between galaxies: 1 Mpc
Universe size: 15000 Mpc

Observations

the Universe

Cosmological Simulations

universes that are statistically consistent with the Universe

Cosmological Simulations

ΛCDM (Lambda cold dark matter) model – standard model of Big Bang cosmology

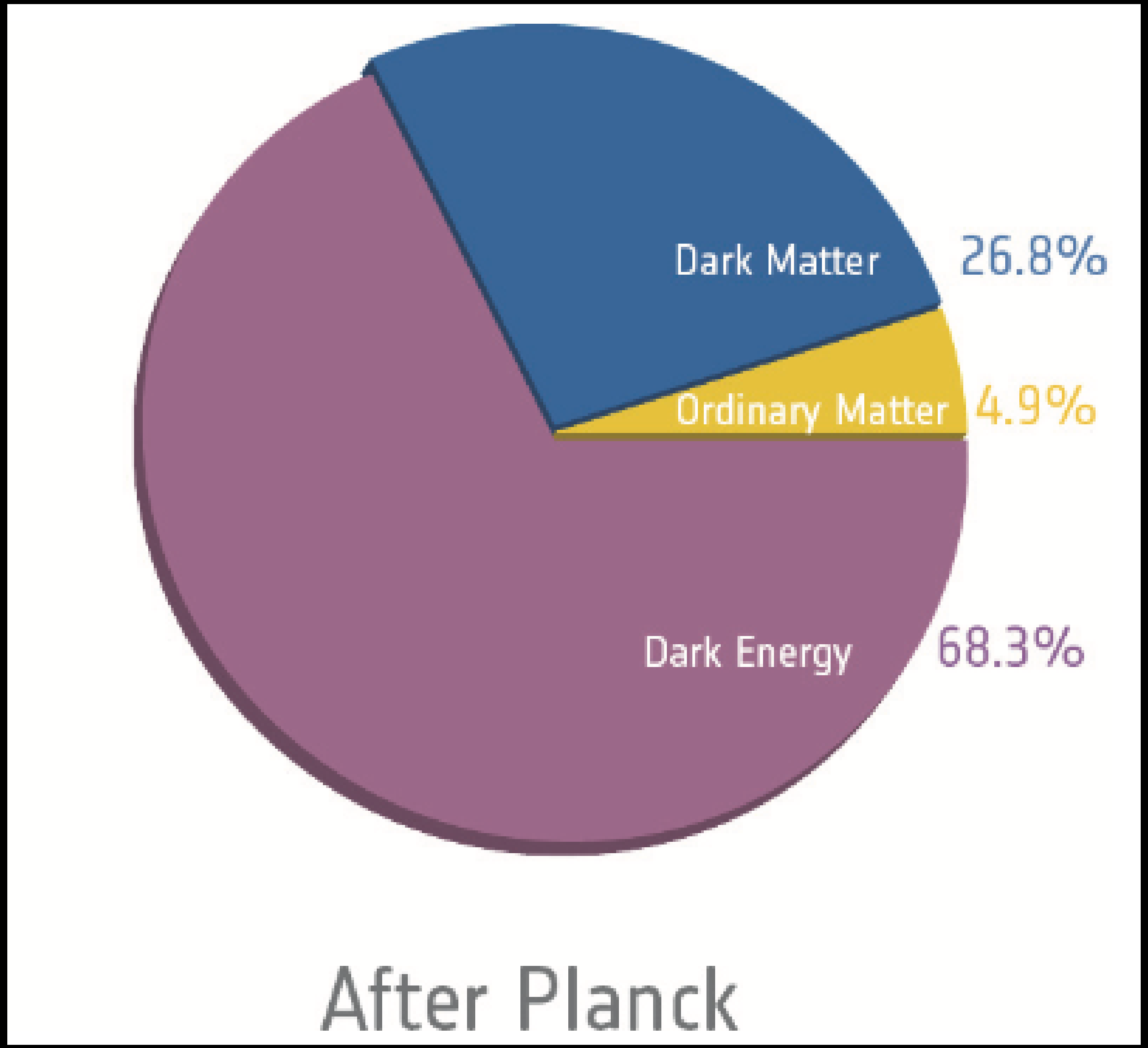


Image credit: ESA and the Planck Collaboration

A universe that is dominated by cold dark matter and dark energy

Space-time described by Friedmann equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{3} + \frac{\Lambda c^2}{3},$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3},$$

With some definitions, the first eq can be written in a more familiar form:

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}.$$

Cosmological N-Body simulations:

work well for large scales (>0.1-10 Mpc)

Ingredients

- Cold gravitating components
- Cosmological Constant

Initial Conditions

Gaussian initial field (primordial fluctuation right after Big Bang)

Physics

- GR at background level
- gravity

Slide taken from Cosmological Simulations (Lecture 1) by R. Angulo (Youtube)

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> tions are obtained in a quasi-Lagrangian fashion. For cosmological simulations, gravity is treated in a fully Newtonian framework using periodic boundary conditions. The solution of the general relativity equations (i.e. the Friedman–Lemaitre–Robertson–Walker equations with null curvature) determine the expansion (or contraction) of space as a function of cosmic time. Spatial quantities and coordinates are expressed in comoving units, where the mapping between the scale factor a and cosmic time depends on the adopted cosmological parameter values.

Illustris magnetohydrodynamical cosmological simulations, Pillepich+2017

Slide taken from Cosmological Simulations (Lecture 1) by R. Angulo (Youtube)

Cosmological hydrodynamical simulations:

most powerful tool to study stellar halos (galaxies, galaxy clusters,etc)

Ingredients

- Cold gravitating components
- Cosmological Constant
- baryons

Initial Conditions

Gaussian initial field (primordial fluctuation right after Big Bang)

Physics

- GR at background level
- gravity
- hydrodynamics, star formation and evolutions, feedback (winds/SN/AGNs), blackholes

Cosmological hydrodynamical simulations:
Powerful. Yet, challenges remain

computationally expensive (20-100X more than DM only)

Unresolved physics remain -> assumptions on star formation, feedback etc

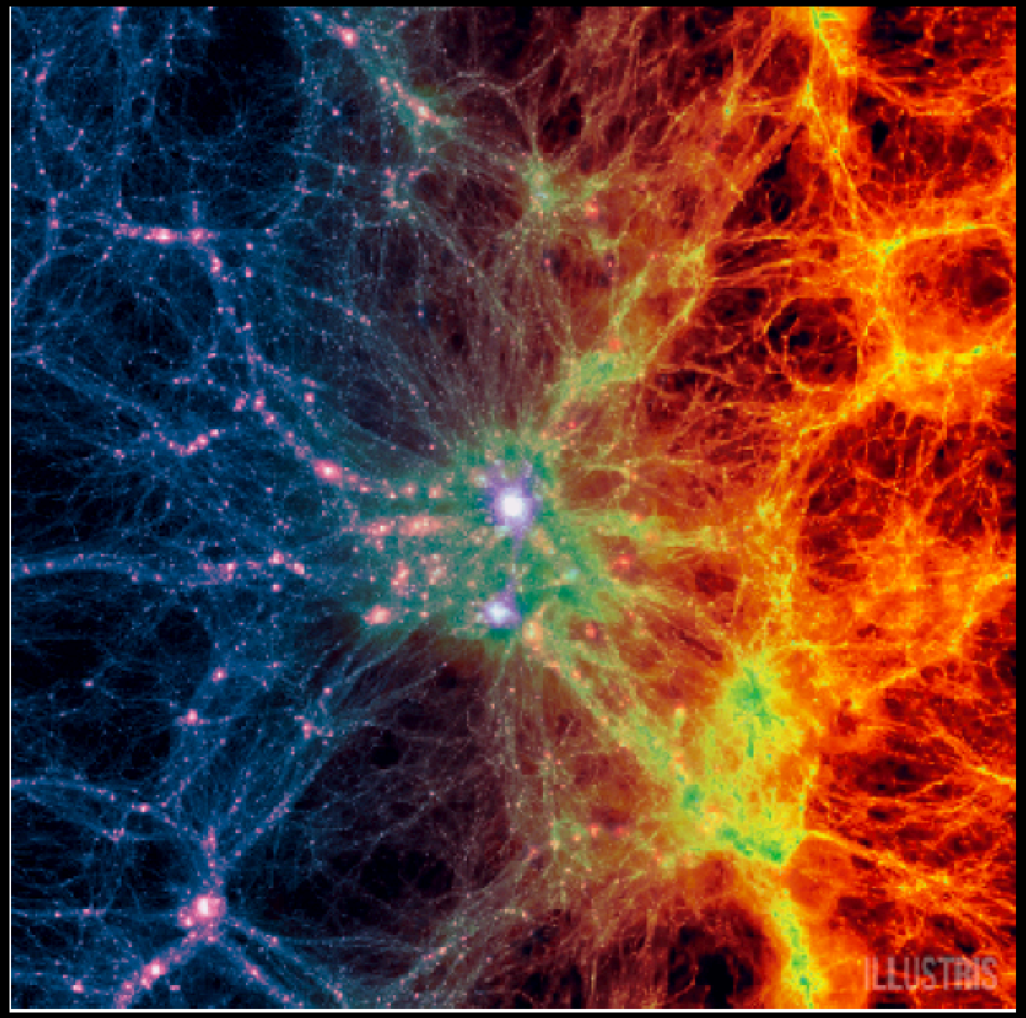
Slide adapted from https://www2.mpia-hd.mpg.de/homes/stellarhalos2018-loc/sh2018/slides/02.07.Wetzel.pdf

Cosmological hydrodynamical simulations:

There are two main kinds

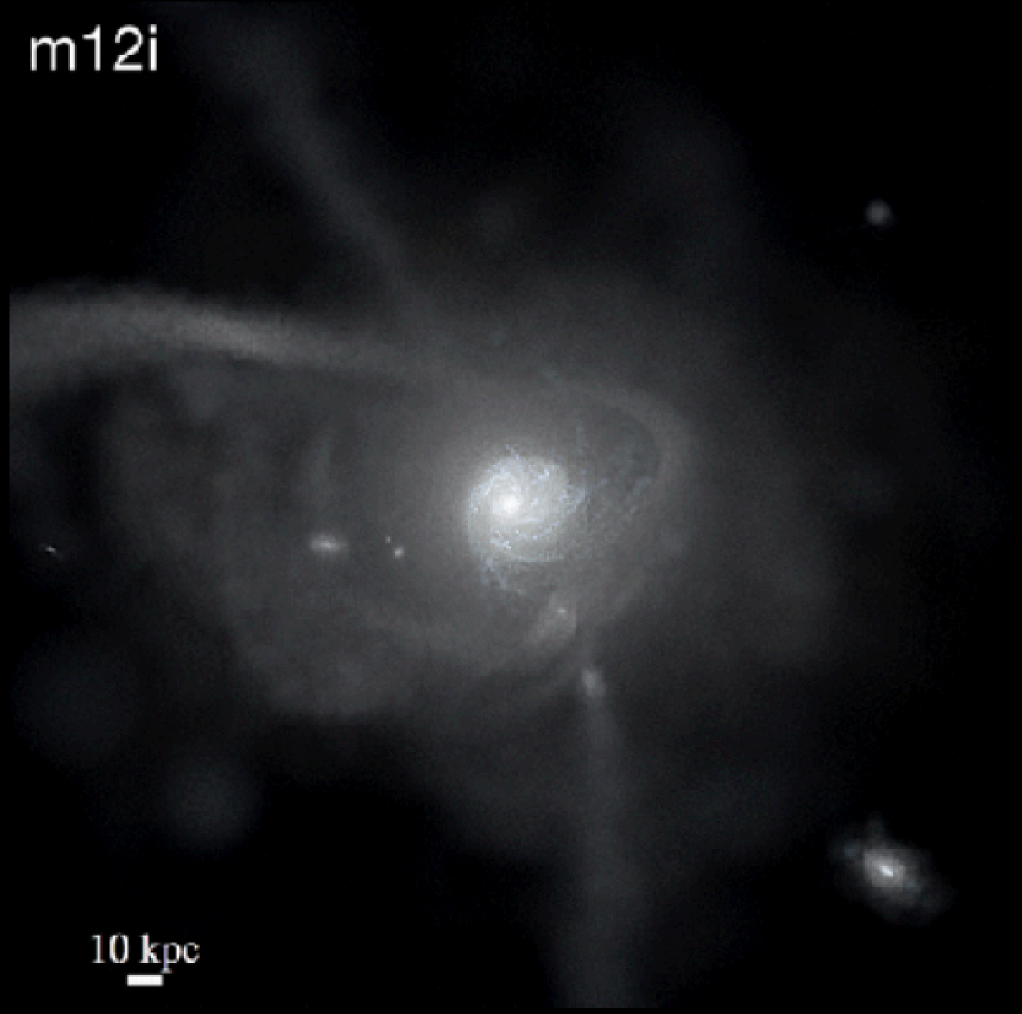
Big Box simulations

Illustris, EAGLE, Horizon-AGN,...



Zoom-in simulations

FIRE, APOSTLE, NIHAO,...



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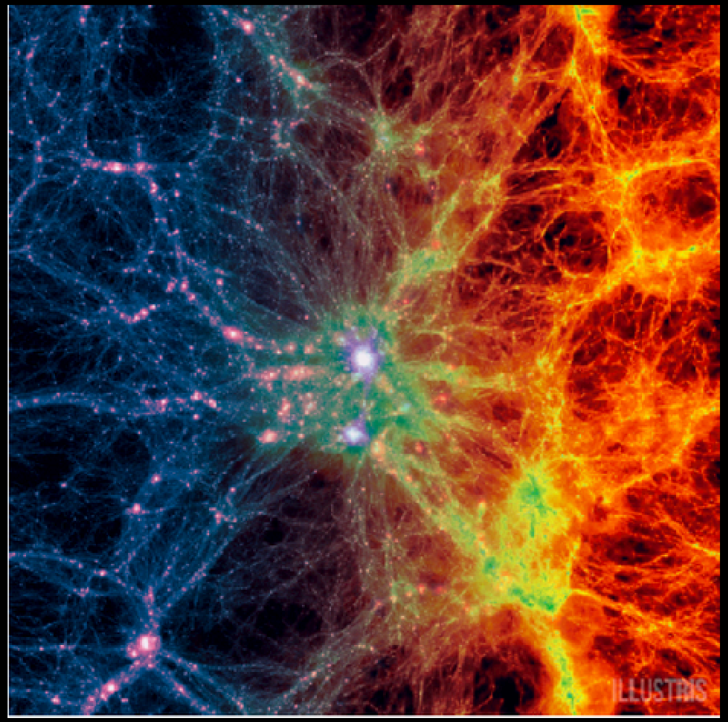
Cosmological hydrodynamical simulations:
There are two main kinds

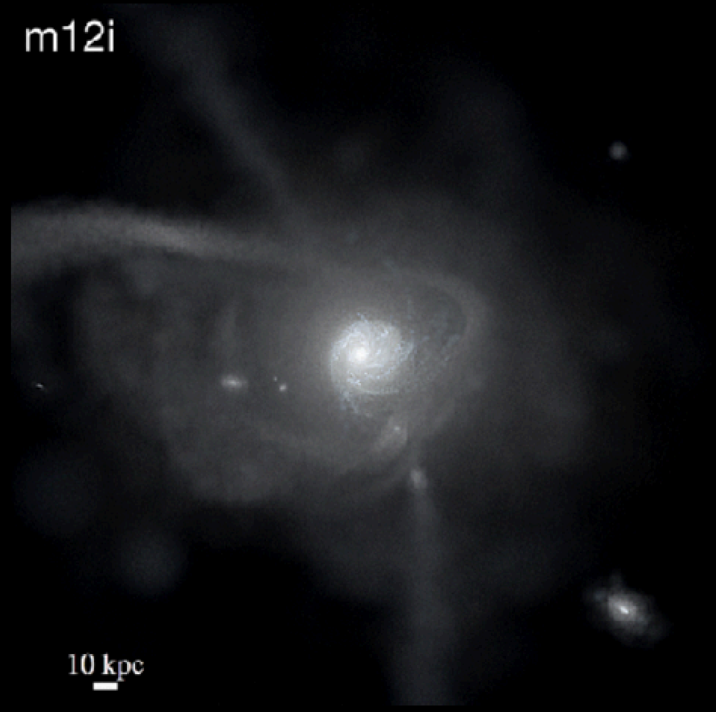
Big Box simulations
Illustris, EAGLE, Horizon-AGN,...

Low resolution but large --> good for large scale structures, statistic samples



Zoom-in simulations
FIRE, APOSTLE, NIHAO,...

High resolution but small samples --> better tools to study small scales such as giant molecular clouds, star clusters, satellite galaxies



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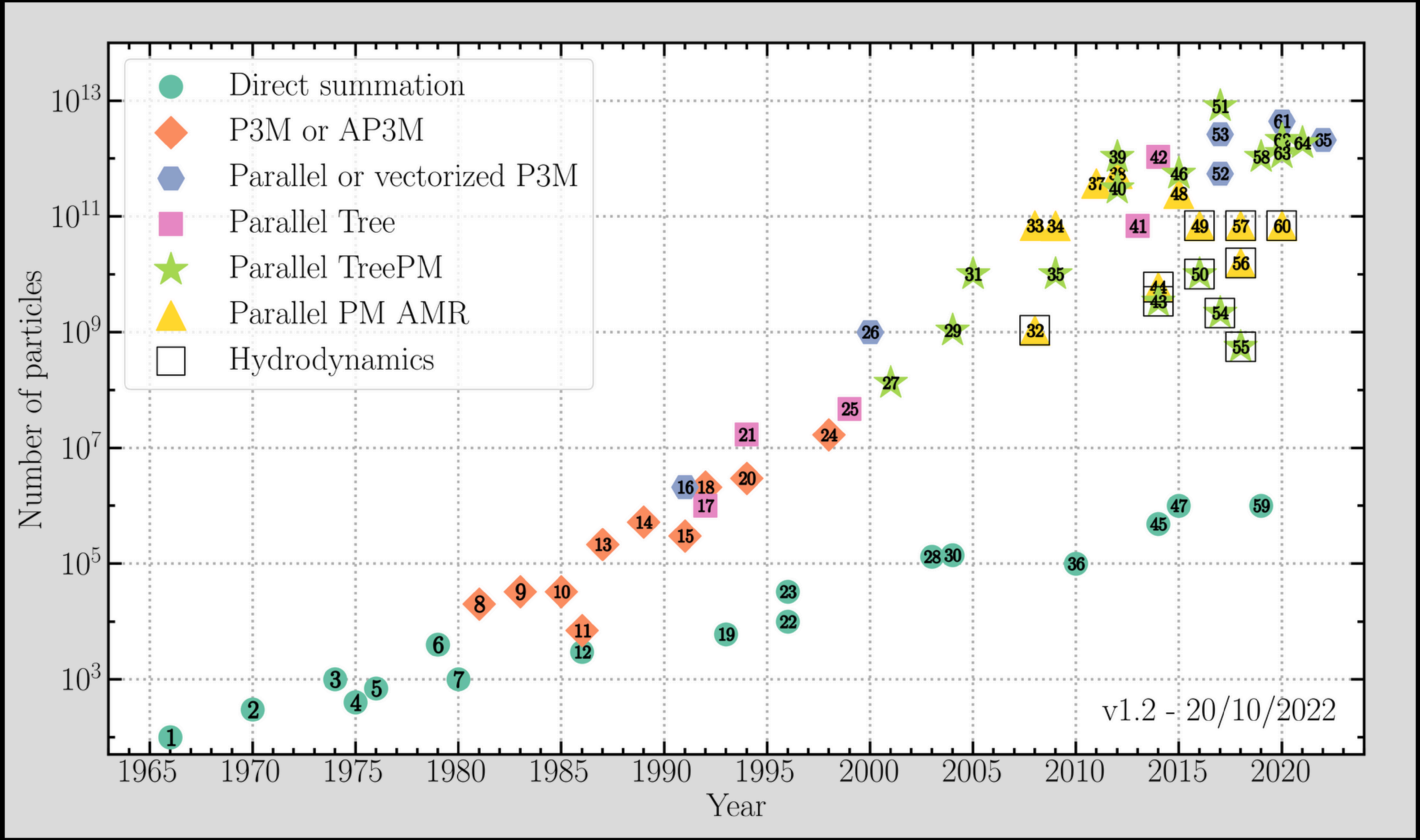
Number of particles in N-body simulations has been increasing exponentially



31 - Millenium
43 - Eagle
55 - FIRE-2
56 - Illustris-TNG
62 - Uchuu

credit: Florent Leclercq's Blog and Github

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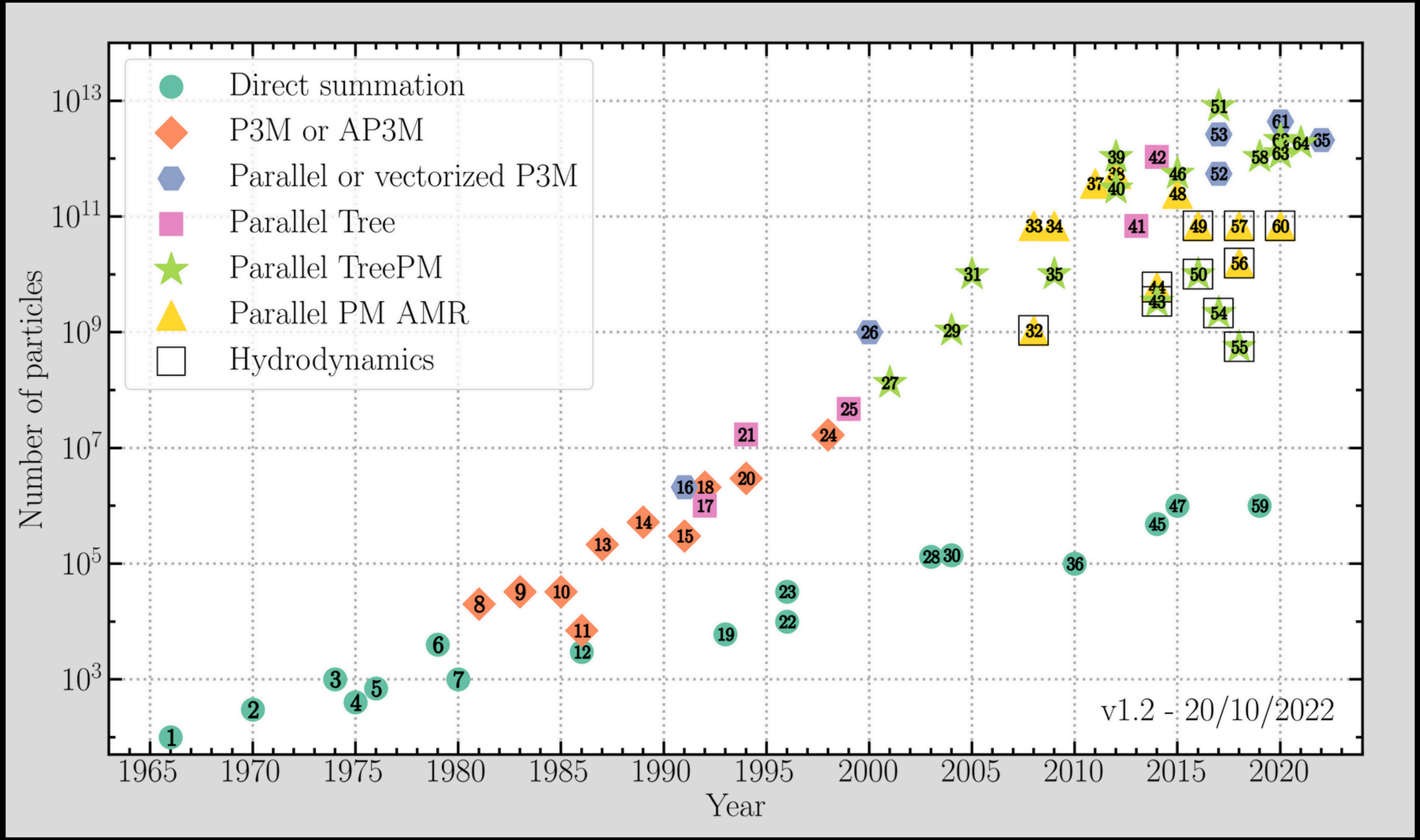

31 - Millenium : 500 cMpc

43 - Eagle : 25-100 cMpc

55 - FIRE-2 : ~25 cMpc

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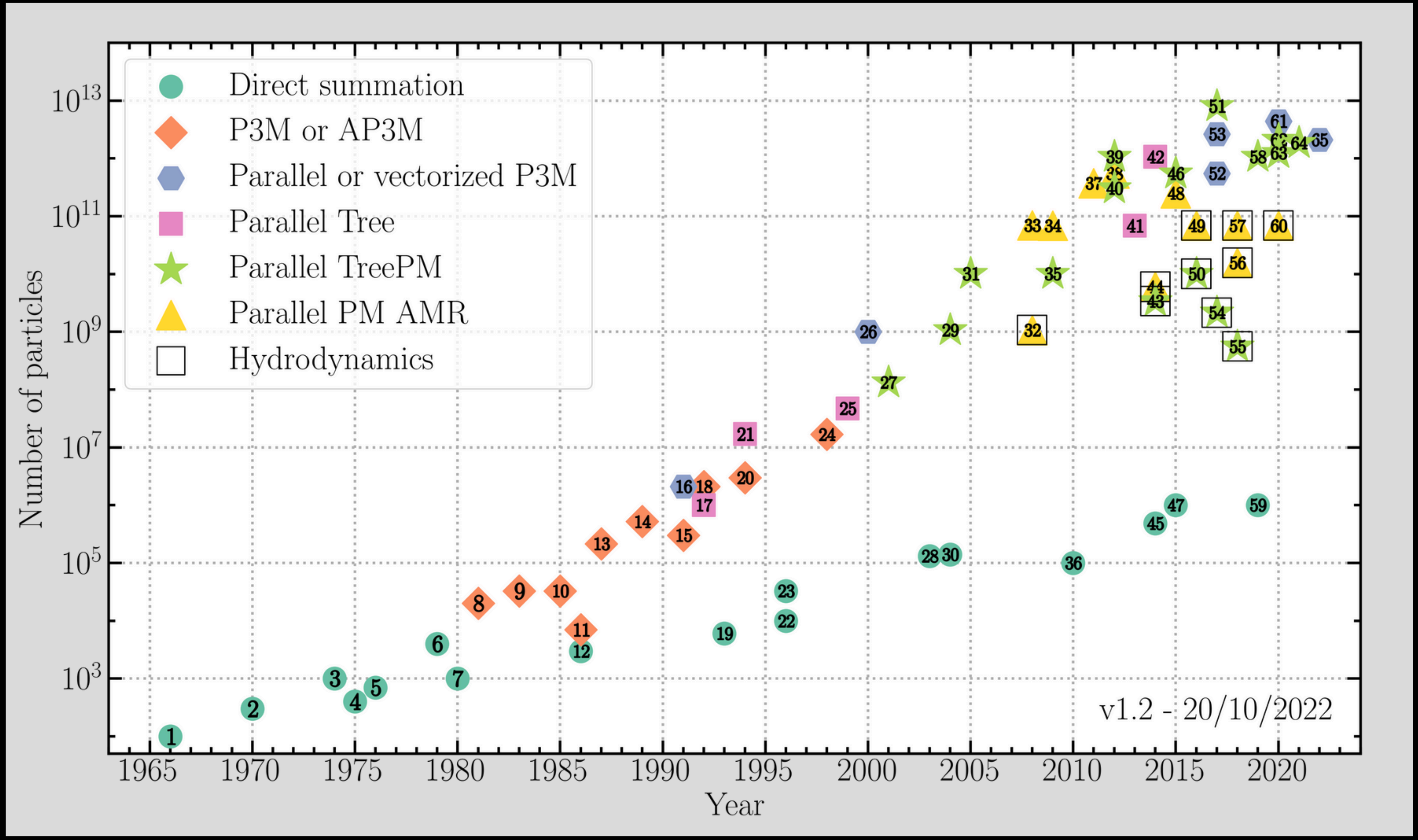

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Scales:

galaxy stellar mass: 10^6-10^{12} Msun
galaxy size: 1-10 kpc
distance between galaxies: 1 Mpc
Universe size: 15000 Mpc

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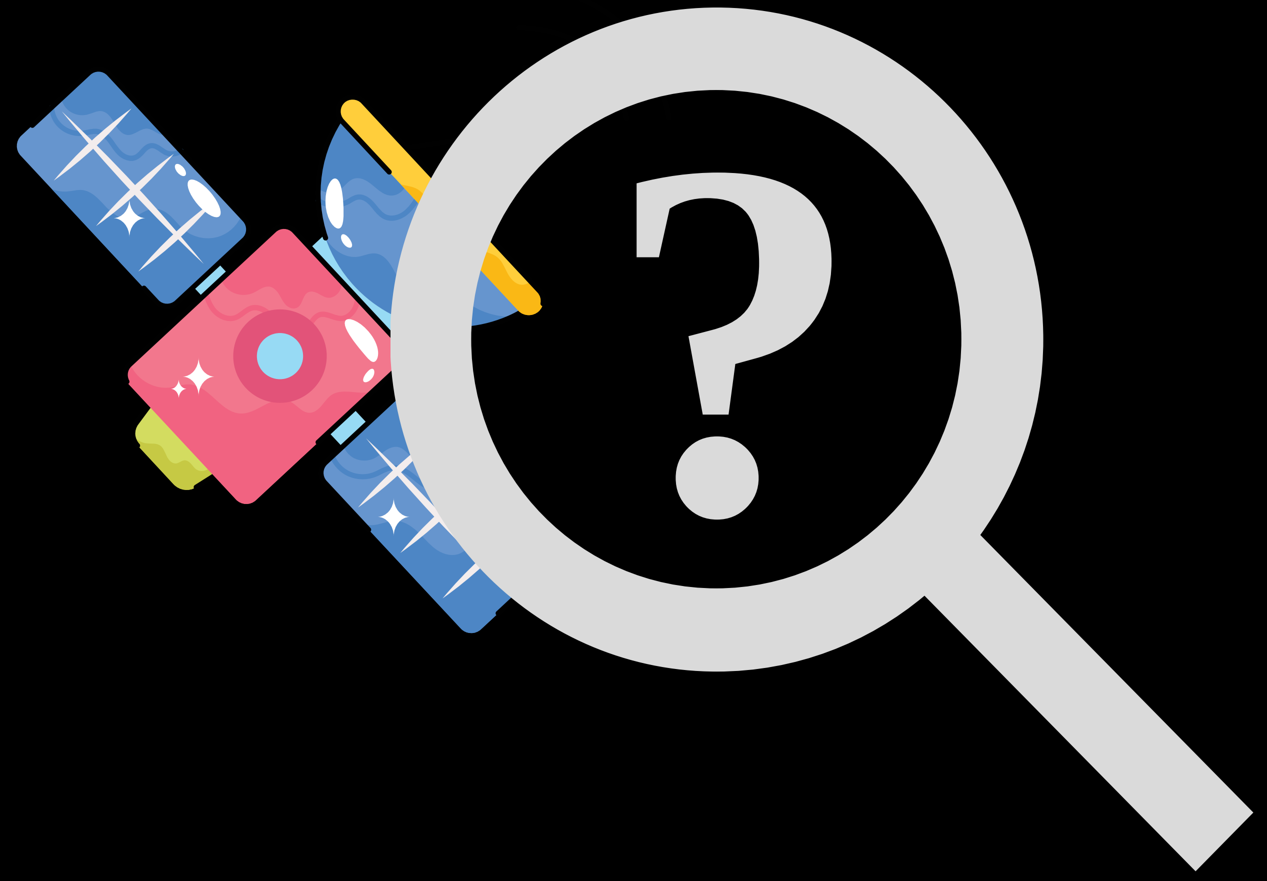


Missing satellites problem

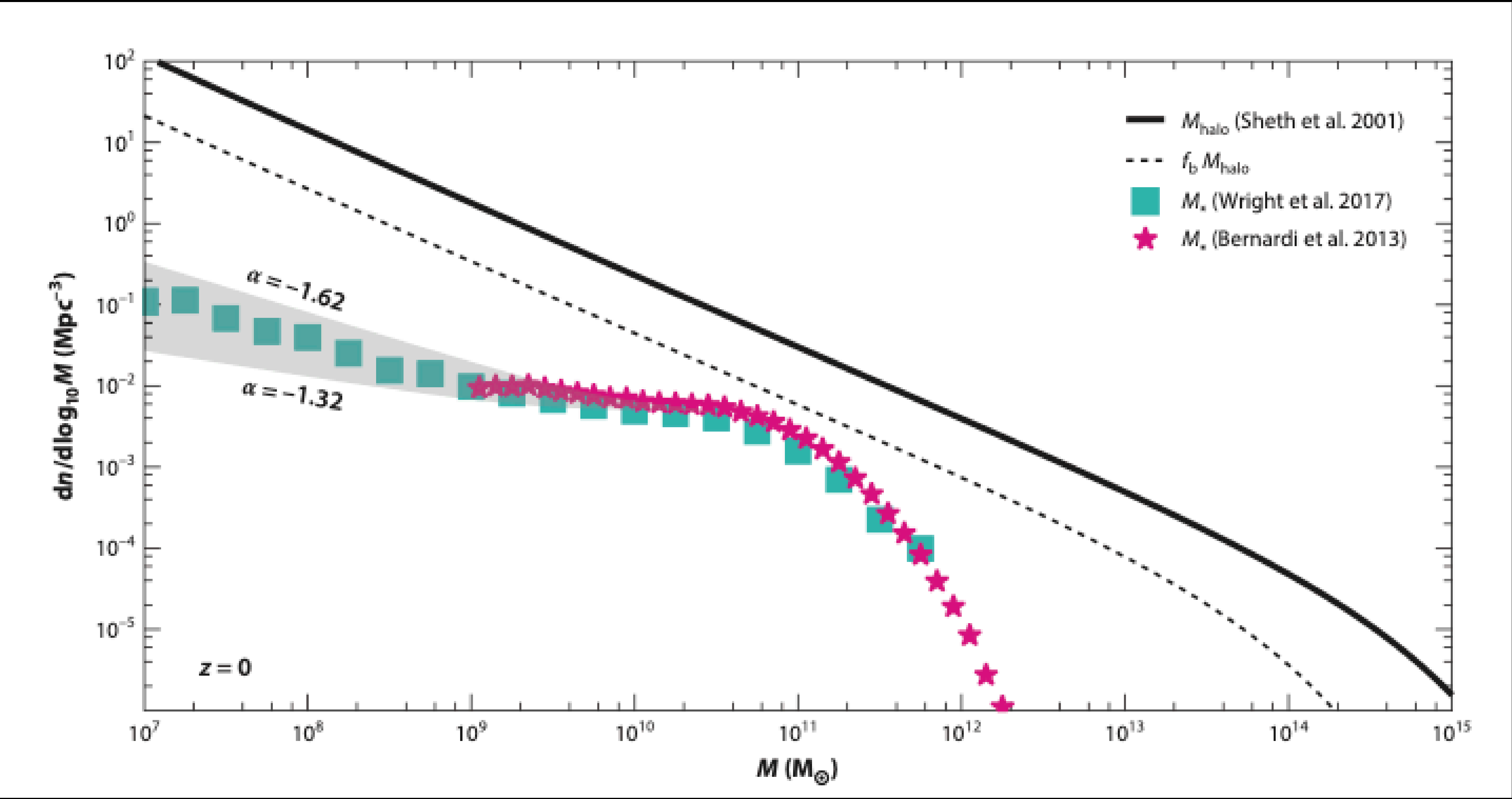
The problem is noticed even at the early dark matter only simulations

Method to relate dark matter halos in the simulations to observed light from stars and gas (baryons) in galaxies

Abundance matching

Abundance matching

Main assumption: Galaxies and dark matter halos are related in a one-to-one way; the most massive galaxies live in the most massive dark matter halos



Bullock and Boylan-Kolchin 2019

In principle, $M_{halo} > 10^7\ M_\odot$ should be large enough to support molecular cooling

Abundance matching

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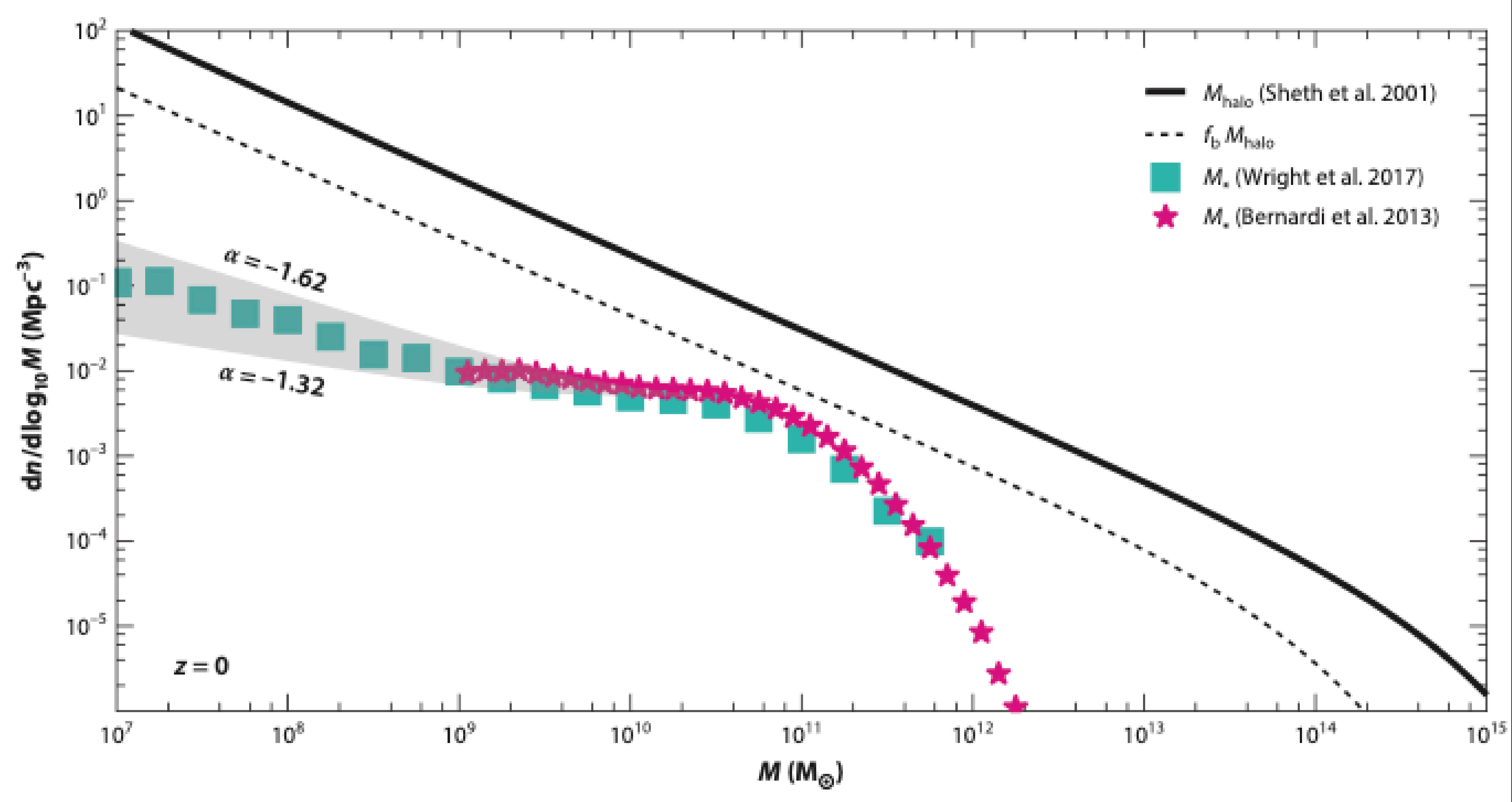
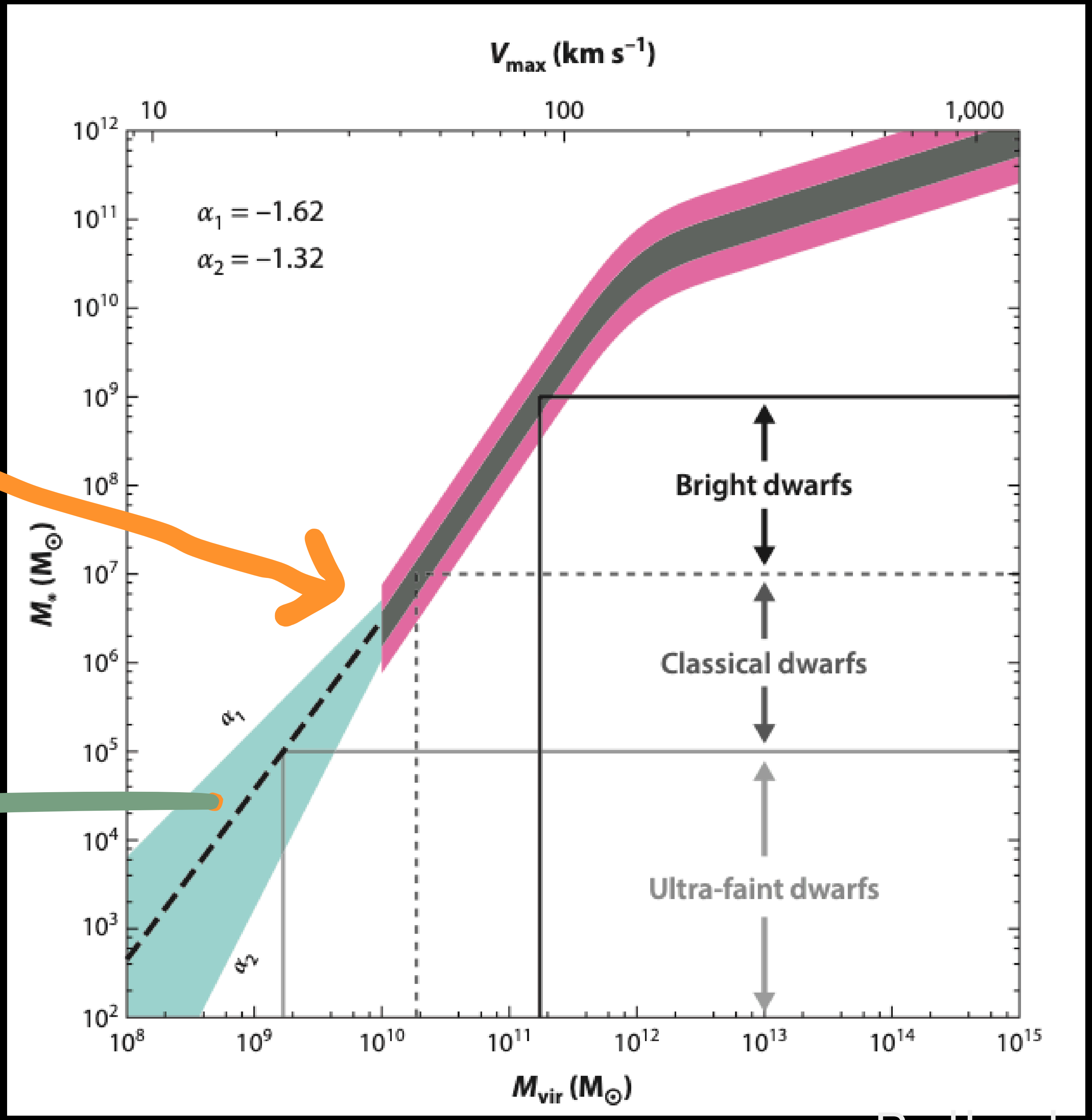


Bullock and Boylan-Kolchin 2019

The results of the abundane matching is the relationship between virial mass (~halo mass) and stellar mass

limit of observation

Does the unobserved population really follow this trend? Are there that many of them?



Bullock and Boylan-Kolchin 2019

It is unlikely that there are thousands of undiscovered dwarf galaxies

Simulation

Observation

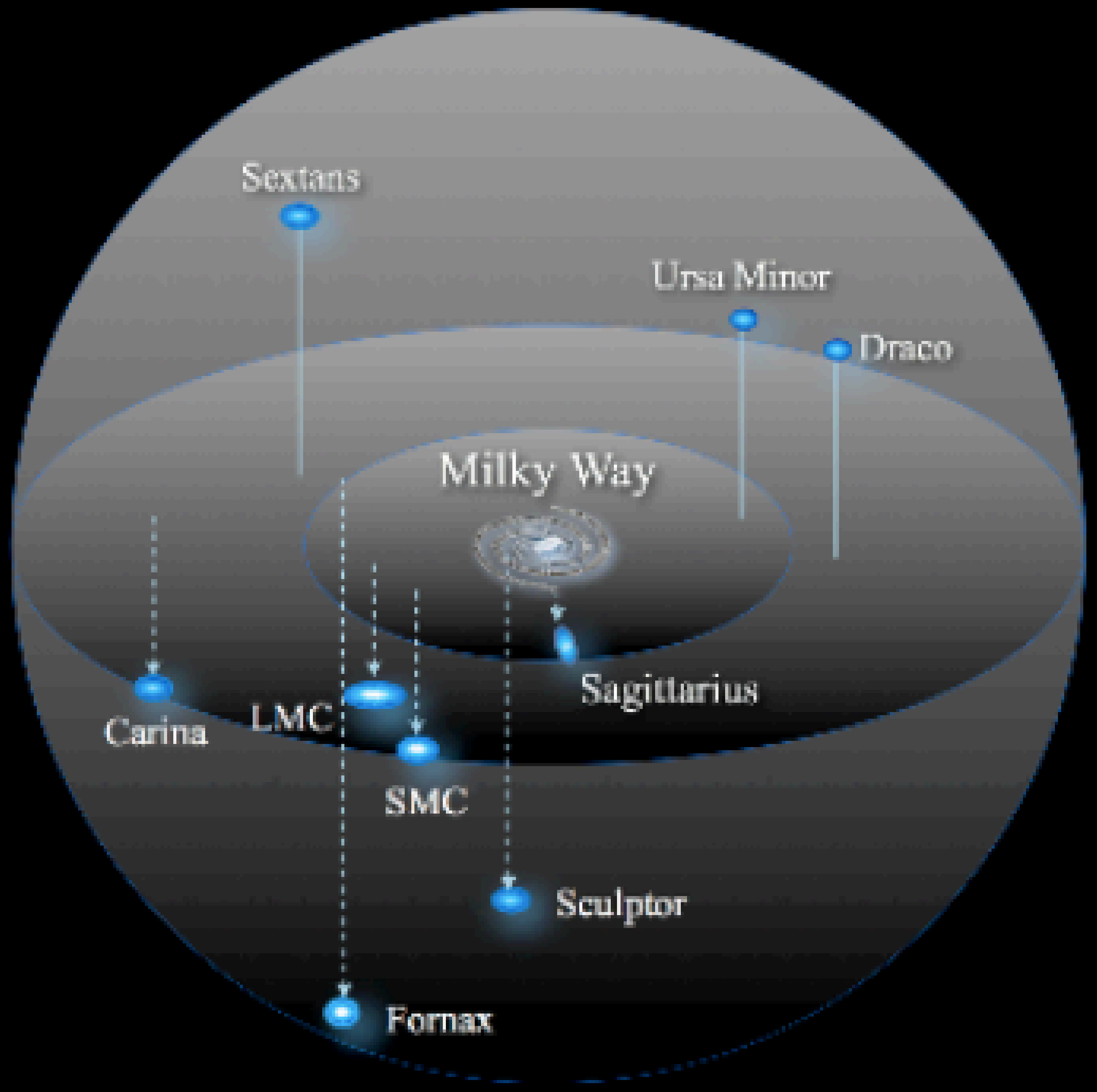
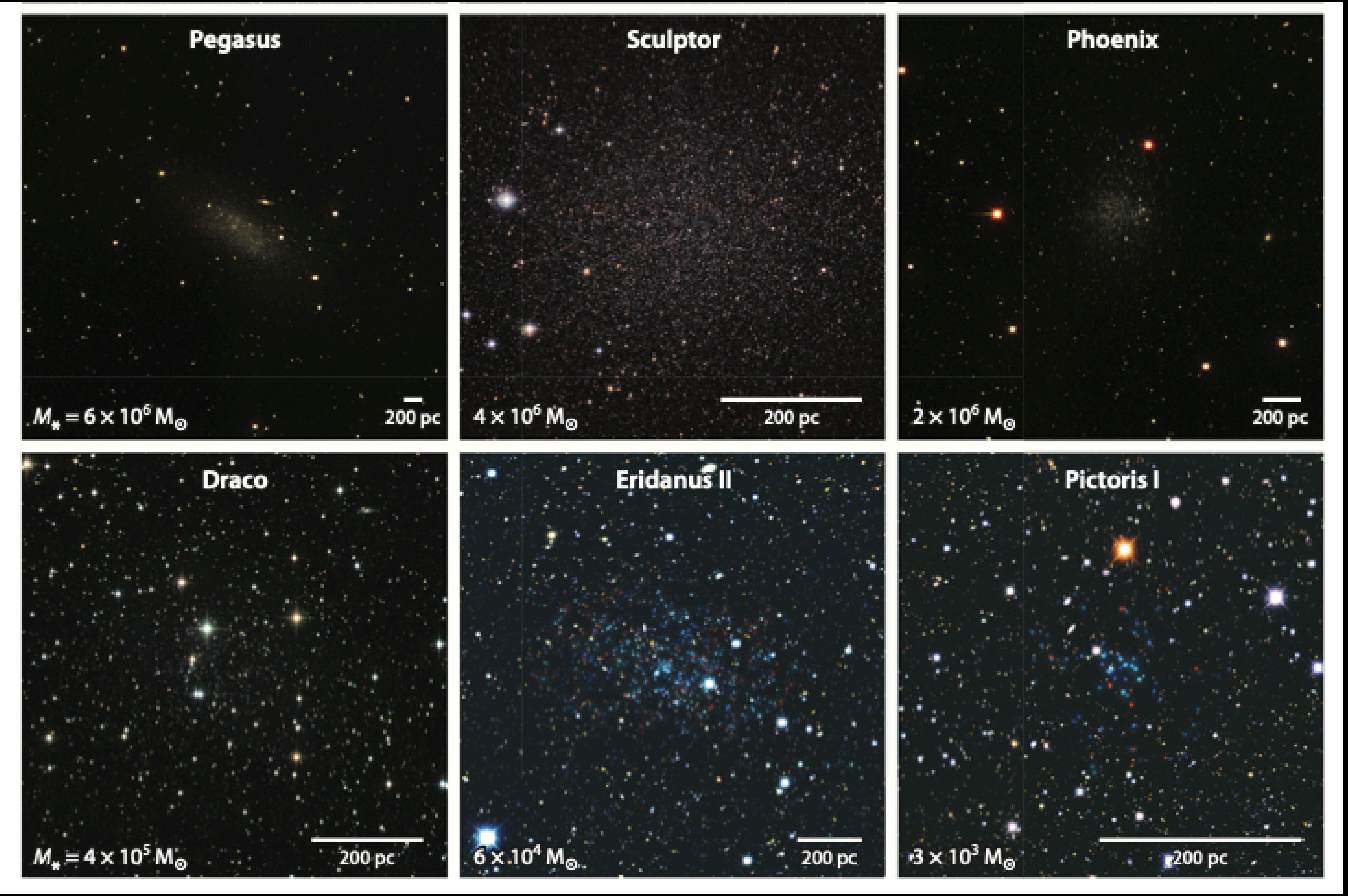


Image credit: https://astrobites.org/2017/11/22/no-missing-satellites/

Not suggesting any solutions, but to point out how difficult to detect dwarf galaxies



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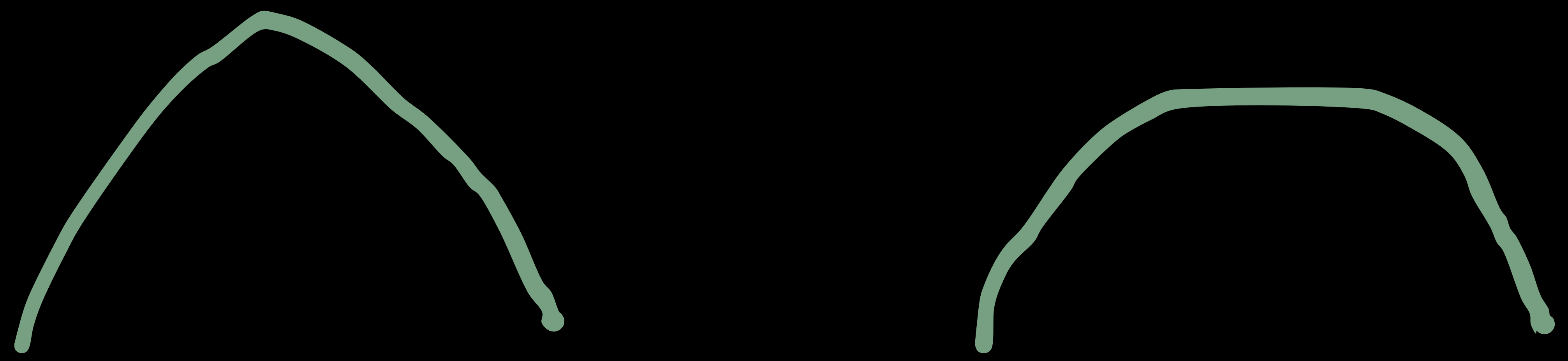


Cusp - Core problem

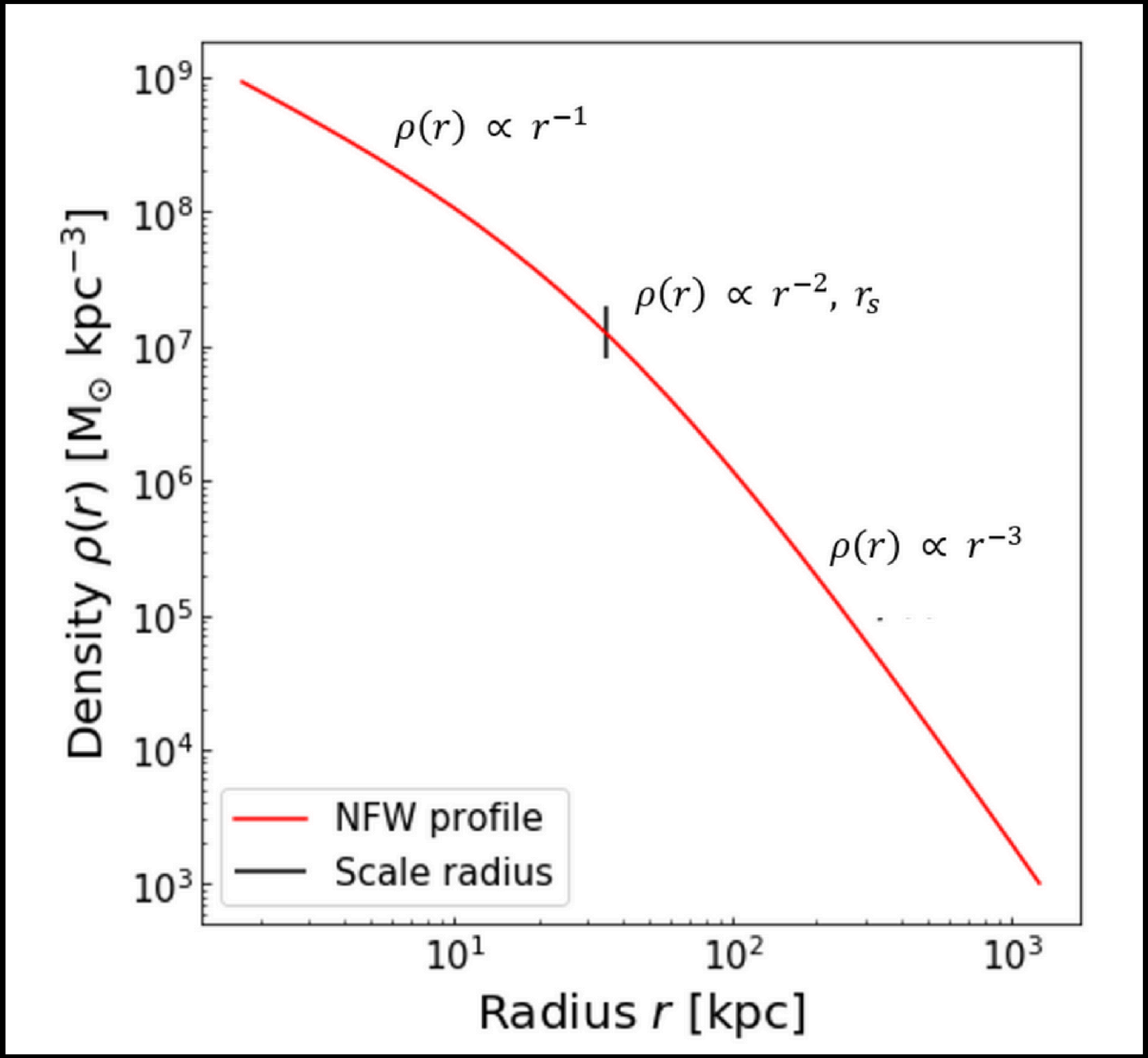
Cold dark matter halos in simulations show the profile that is cuspy in the middle

NFW profile

$$\rho(r) = \frac{4\rho_{-2}}{(r/r_{-2})(1 + r/r_{-2})^2}$$

What happen at large r? What about small r?

Cold dark matter halos in simulations show the profile that is cuspy in the middle



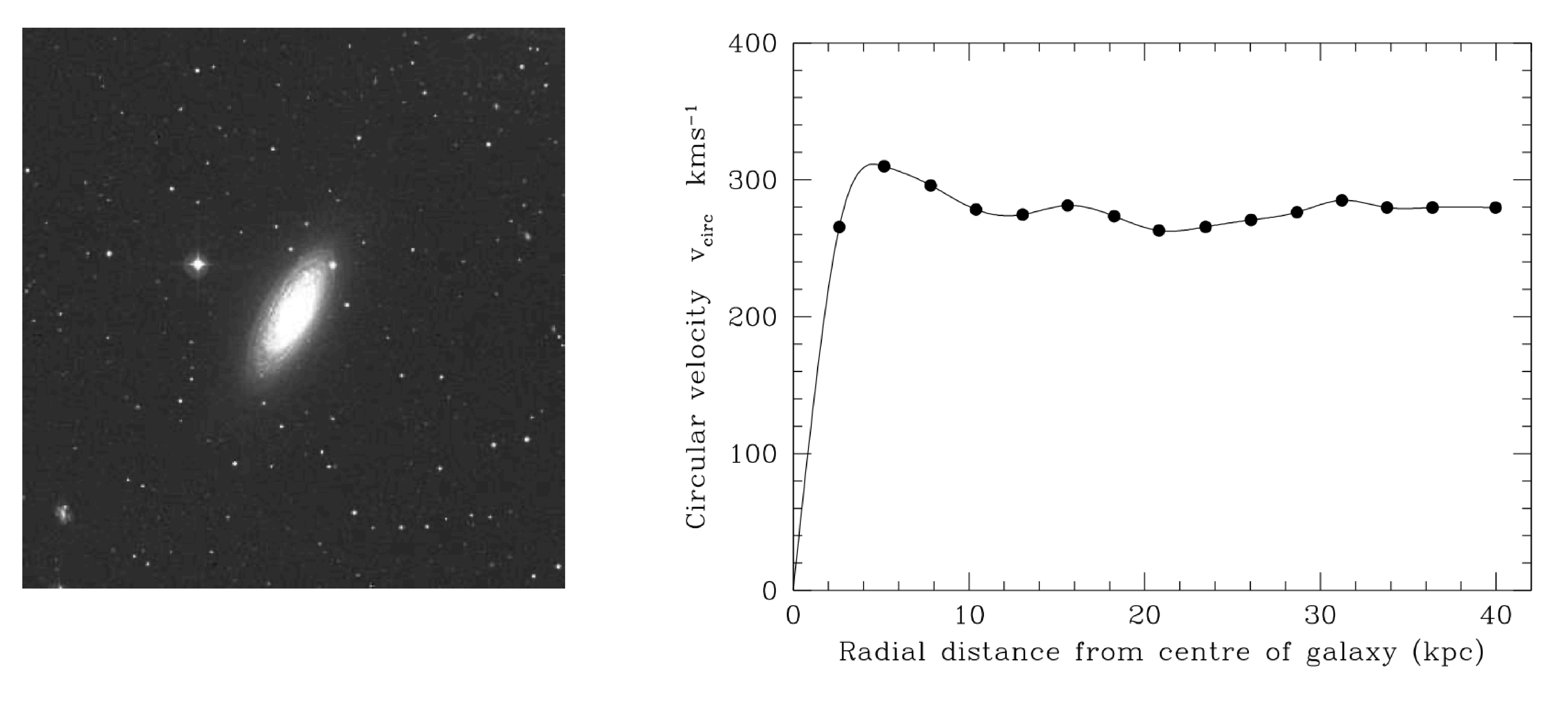
NFW profile

$$\rho(r) = \frac{4\rho_{-2}}{(r/r_{-2})(1 + r/r_{-2})^2}$$

Observationally, another way to relate dark matter to observable is via rotation curve (in addition to abundance matching)

$$\frac{v_{circ}^2}{R} = \frac{GM(R)}{R^2}$$

First rotation curves were measured in 1970s. Soon we found that disc galaxies have flat rotation curves.



What does flat rotation curve mean? Is it consistent with NFW profile?

$$\frac{v_{circ}^2}{R} = \frac{GM(R)}{R^2}$$

NFW profile

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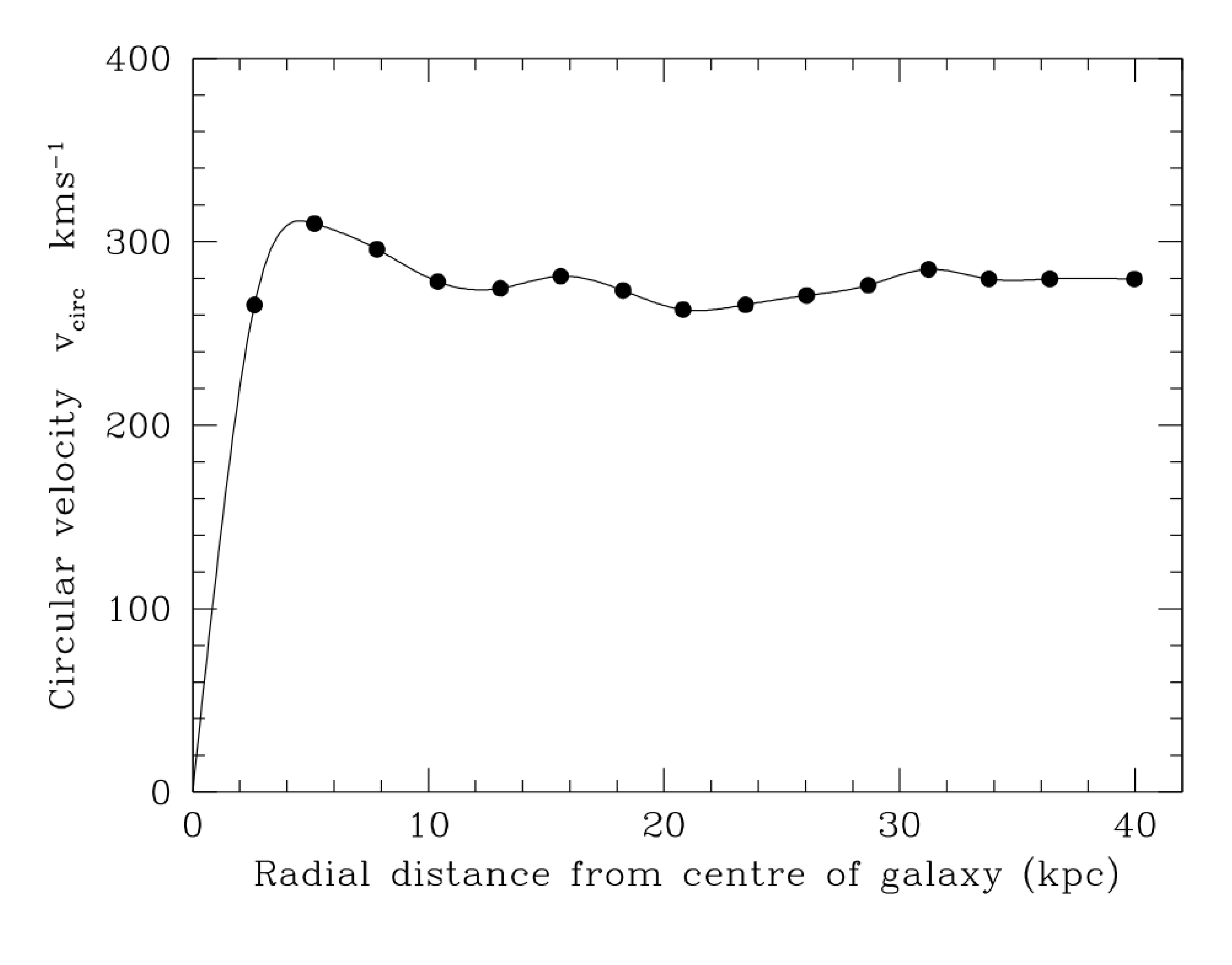
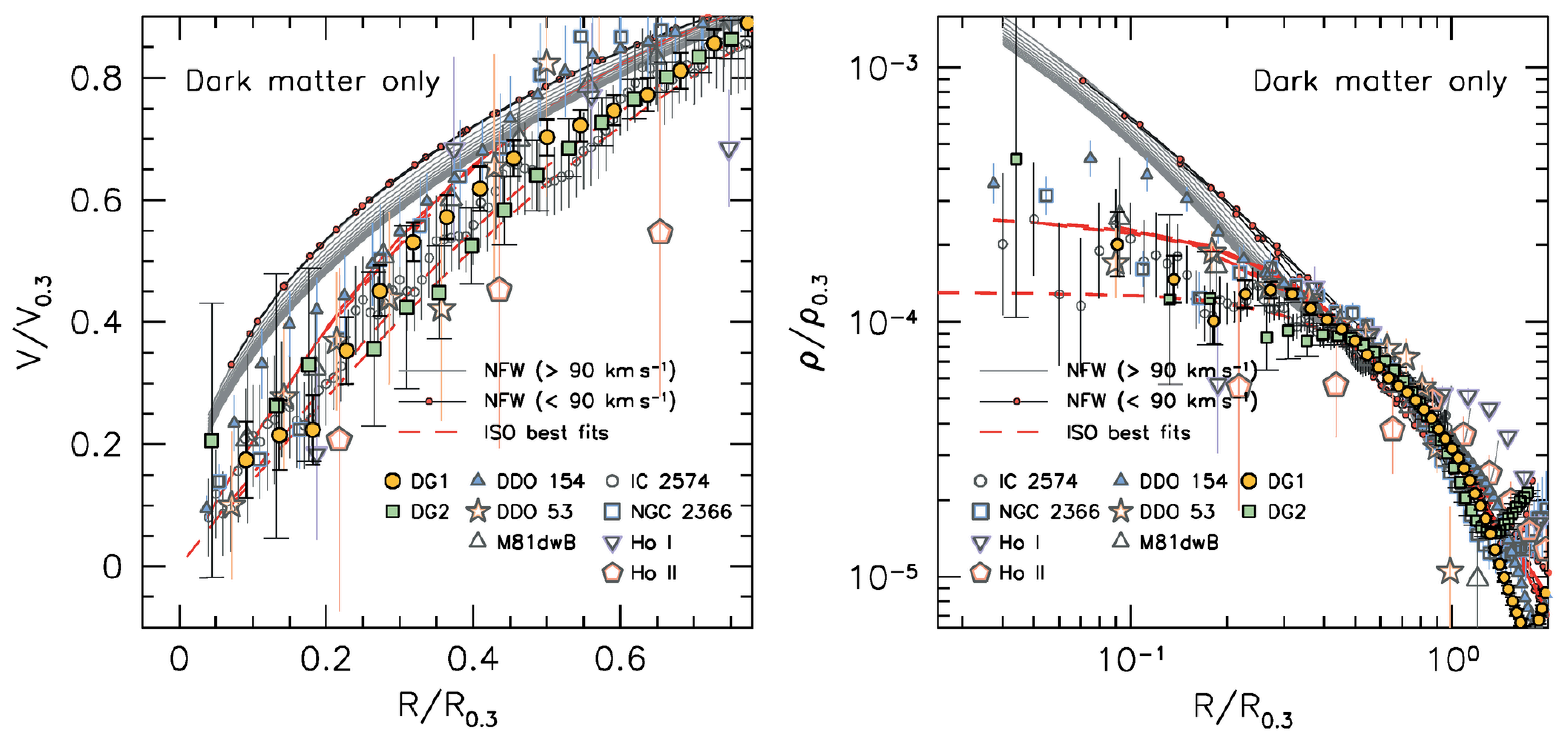


When we measure the rotation curves in the inner core of dwarf galaxies we found that they all have flat density profile at the core



Too big too fail problem

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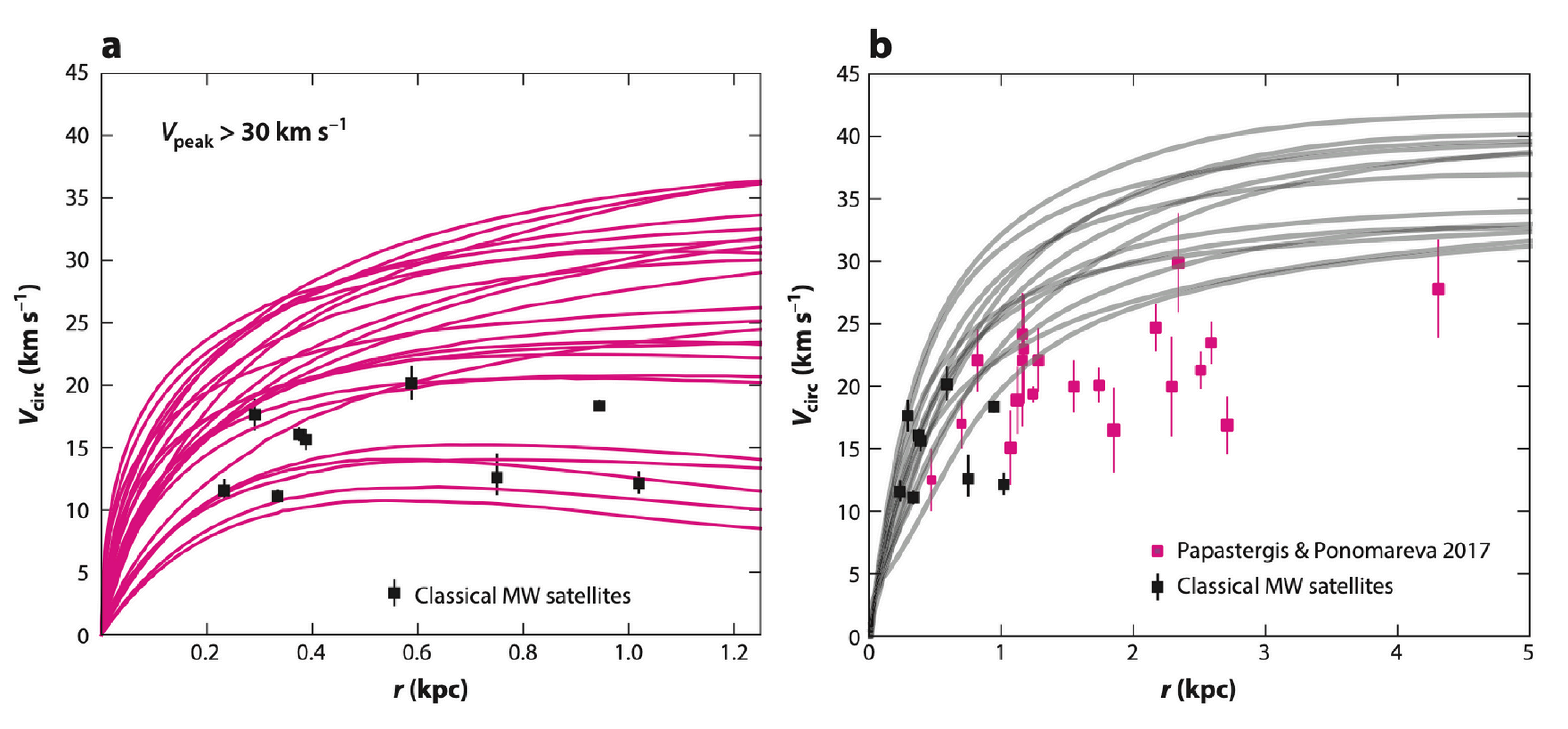


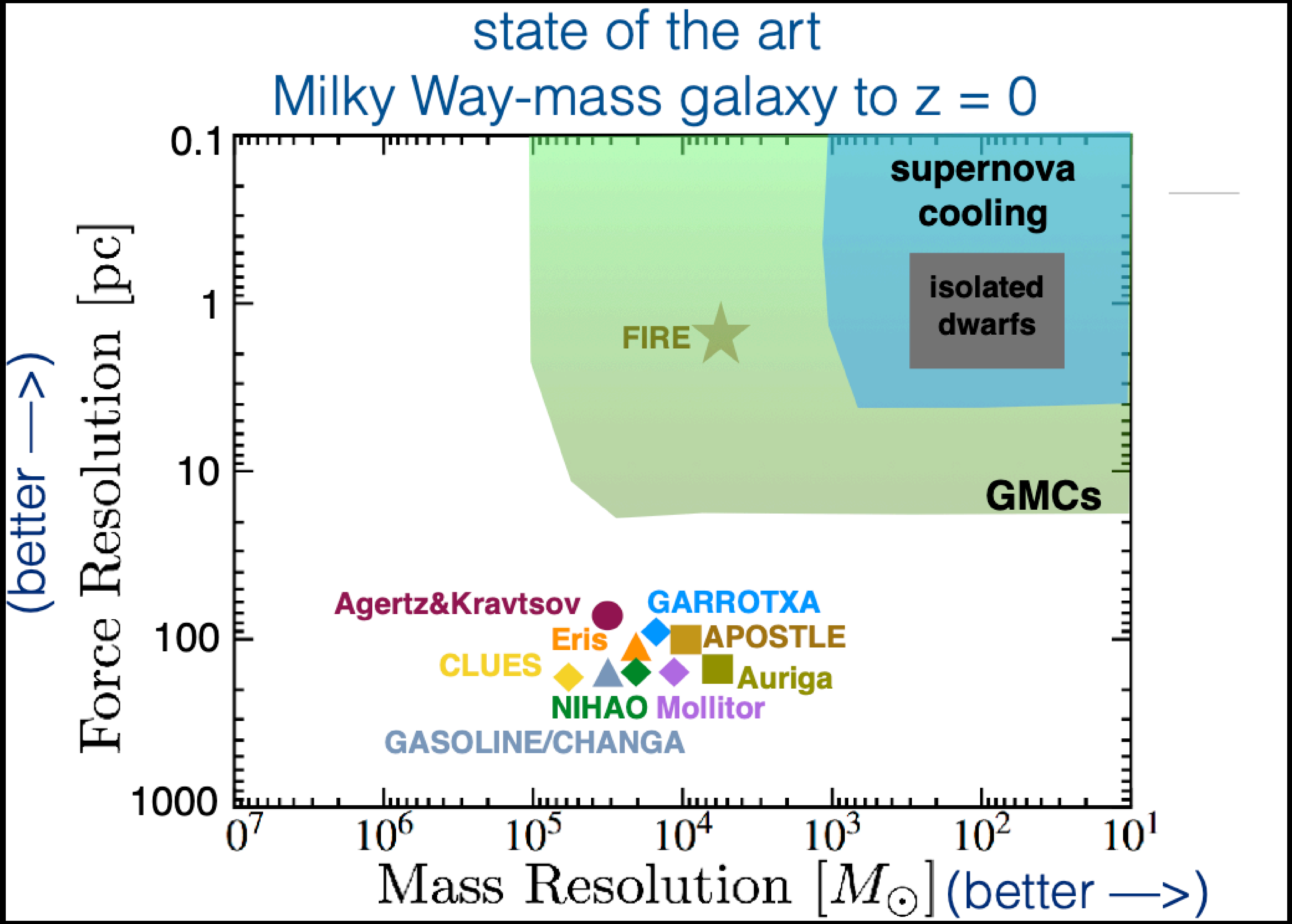
Bullock and Boylan-Kolchin 2019

Your turn to look for solutions

Lambda-CDM

Simulations

Observation



Conclusion:

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Wetzel+2016 RECONCILING DWARF GALAXIES WITH ΛCDM COSMOLOGY: SIMULATING A REALISTIC POPULATION OF SATELLITES AROUND A MILKY WAY–MASS GALAXY

Kim+2016 There is No Missing Satellites Problem

Slide adapted from https://www2.mpia-hd.mpg.de/homes/stellarhalos2018-loc/sh2018/slides/02.07.Wetzel.pdf