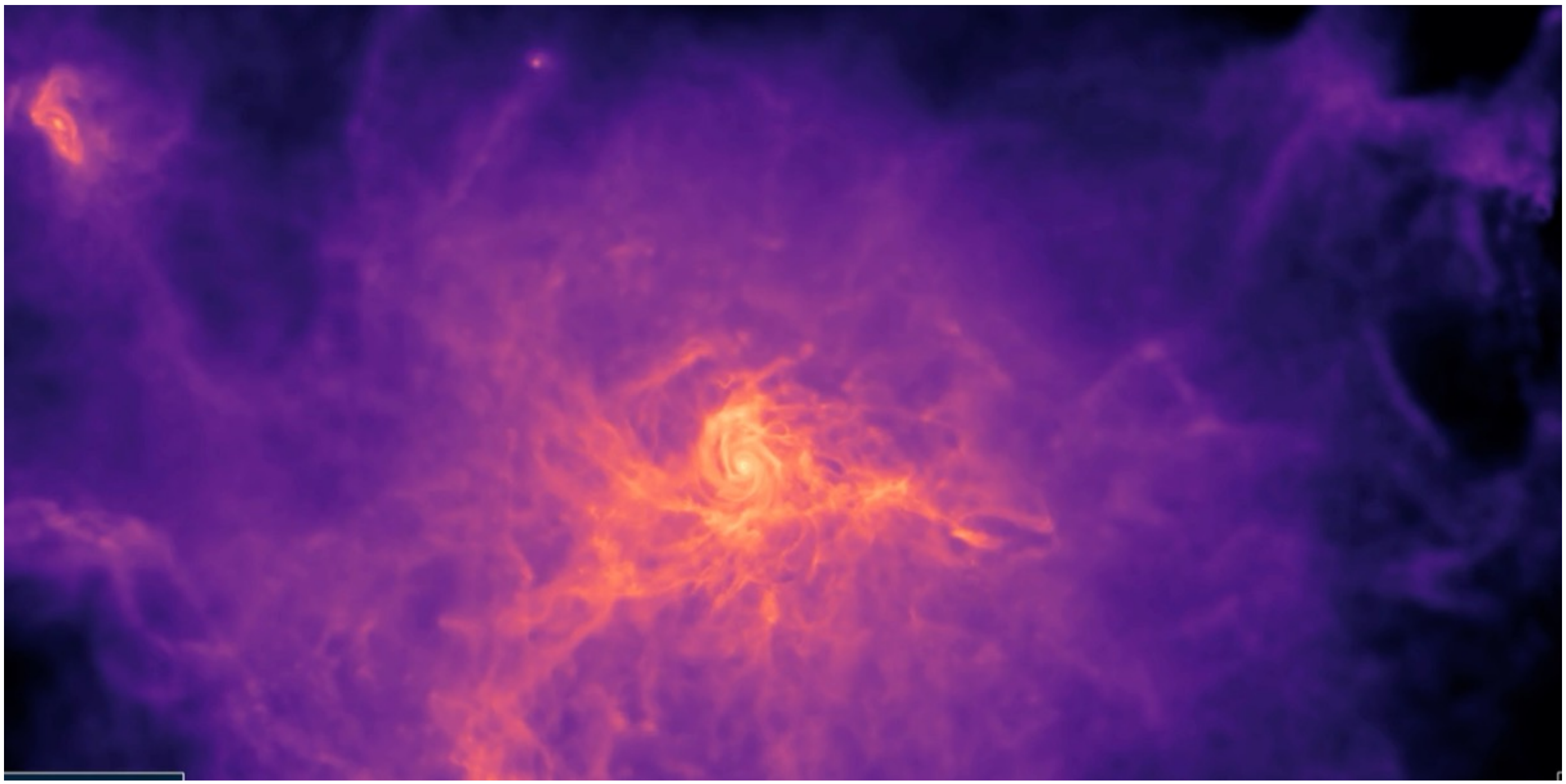
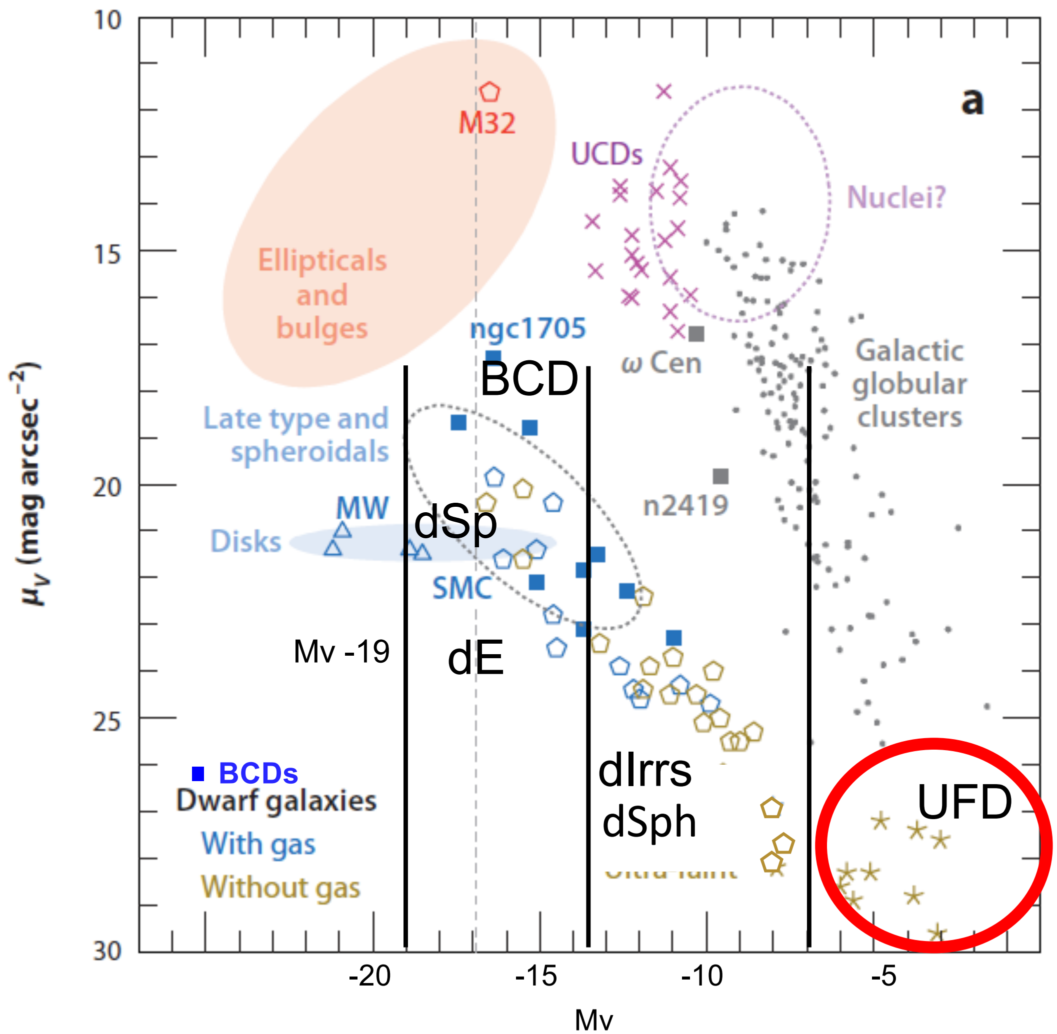
Structure Formation



Ultra Faint Dwarfs

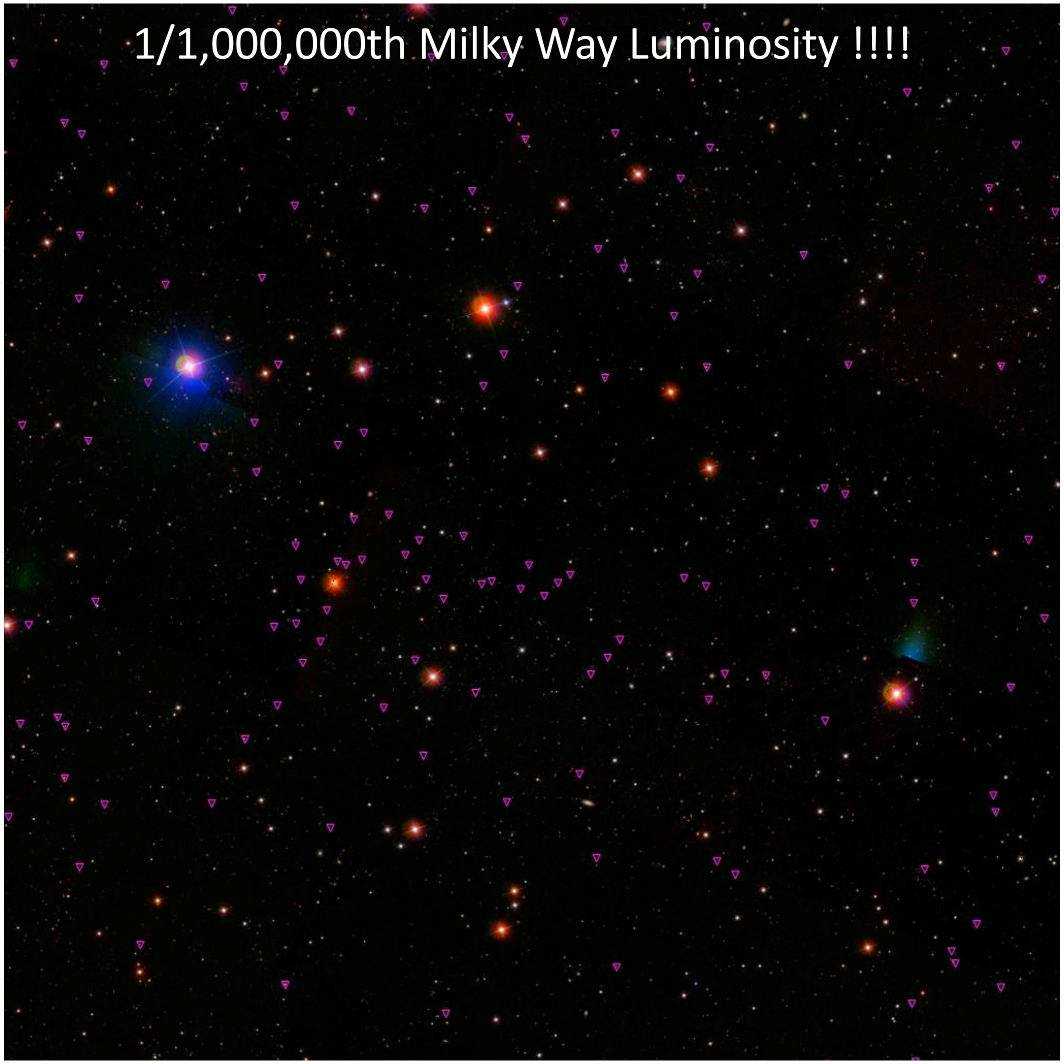
$M^* < 10^5 M_\odot$



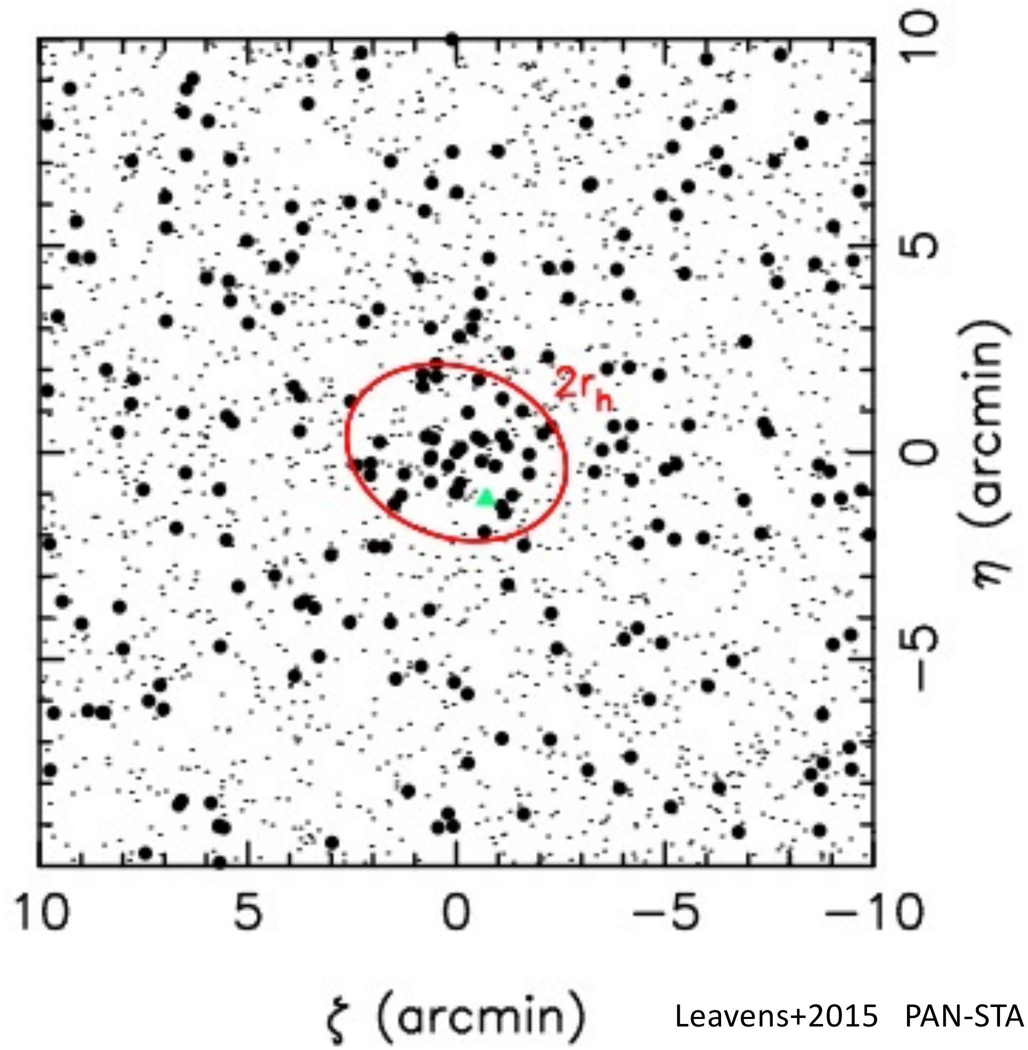
Tolstoy+ 2009

Ursa Major I:

Willman + 2005

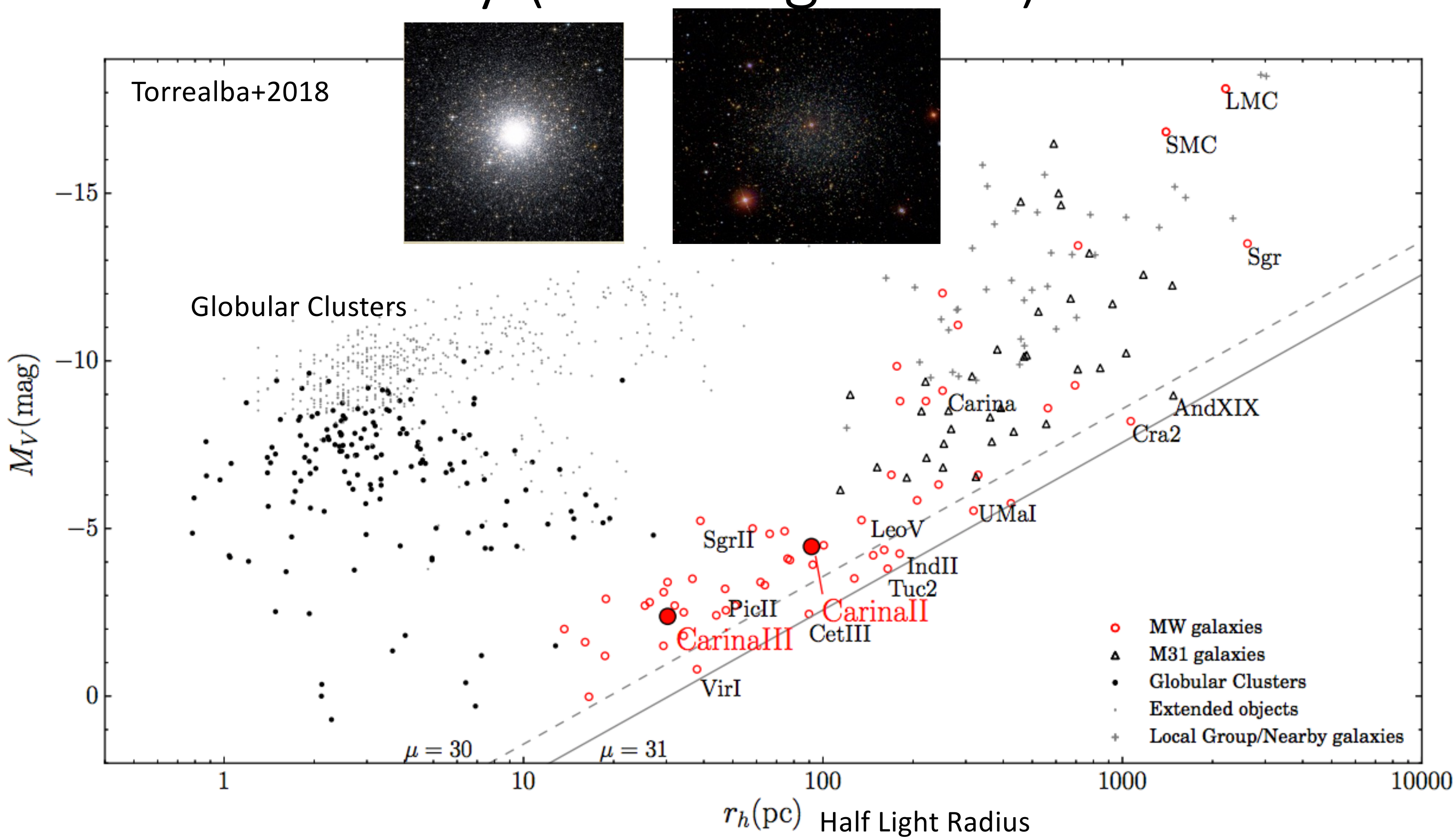


Diameter
~ 13000 Ly



Leavens+2015 PAN-STARRS discovery paper

Size vs Luminosity (abs. magnitude)



Recall: Definition of a "Galaxy"

- Willman & Strader 2012: "Galaxy" Defined

A galaxy is a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons (gas & stars) and Newton's laws of gravity.

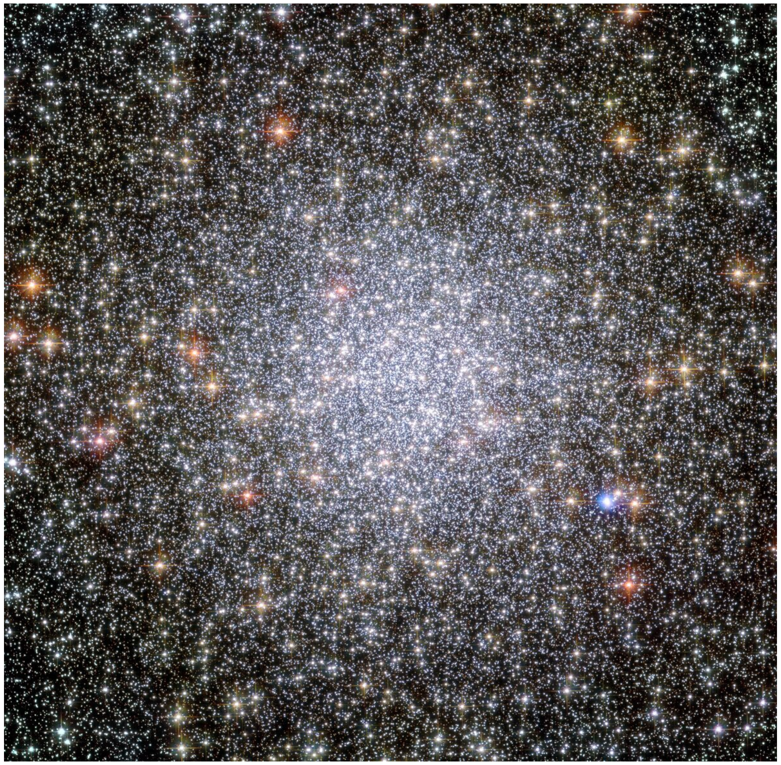
Part 1 of Lab 5: Dynamical Mass Estimator

Wolf et al. 2010

$$M(< r_{1/2}) = 3\, G^{-1}\, \sigma_{\rm los}^2\, r_{1/2}$$
$$= 4\, G^{-1}\, \sigma_{\rm los}^2\, R_e\ .$$

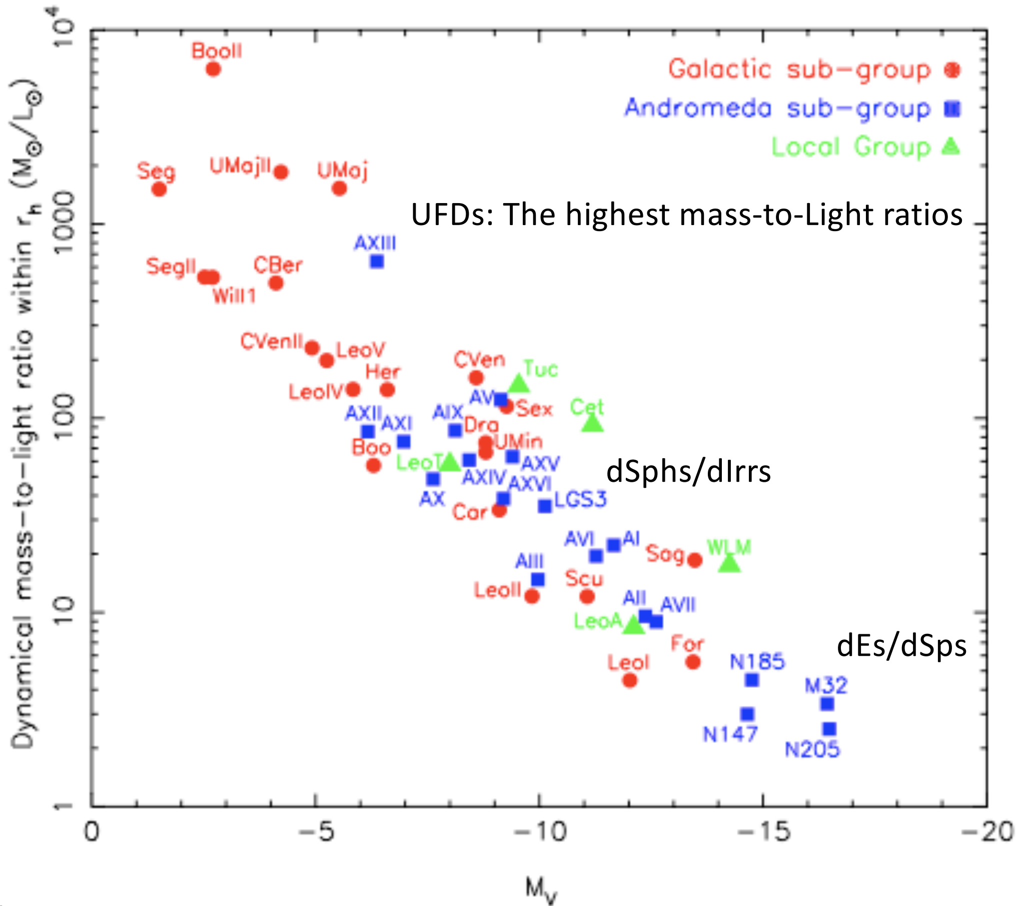
$$r_{1/2} \approx 4R_e/3,$$

Re = 2D radius that contains half the stellar mass (projection of $r_{1/2}$)



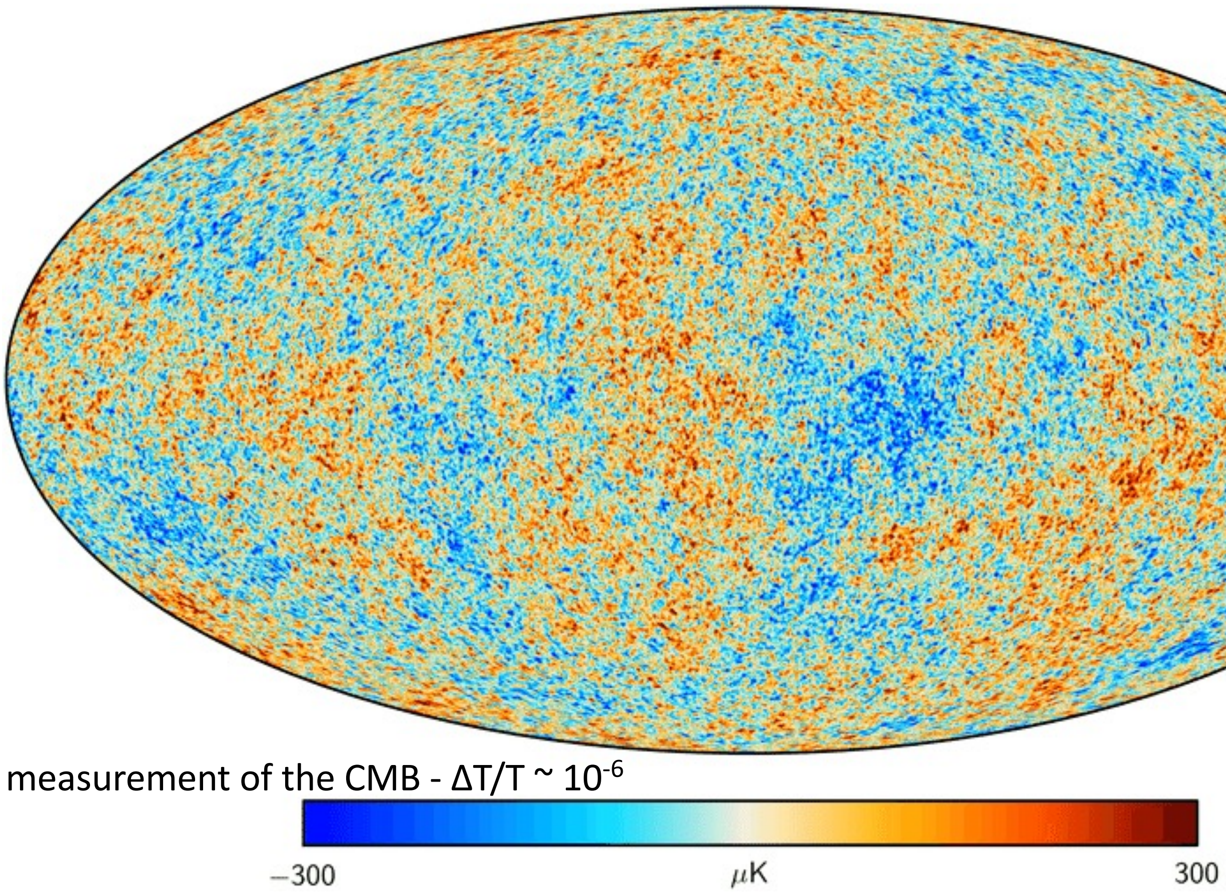

$M_{Dynamical}$ /L Ratios

Segue (Seg) only has a stellar mass of 340 Msun!

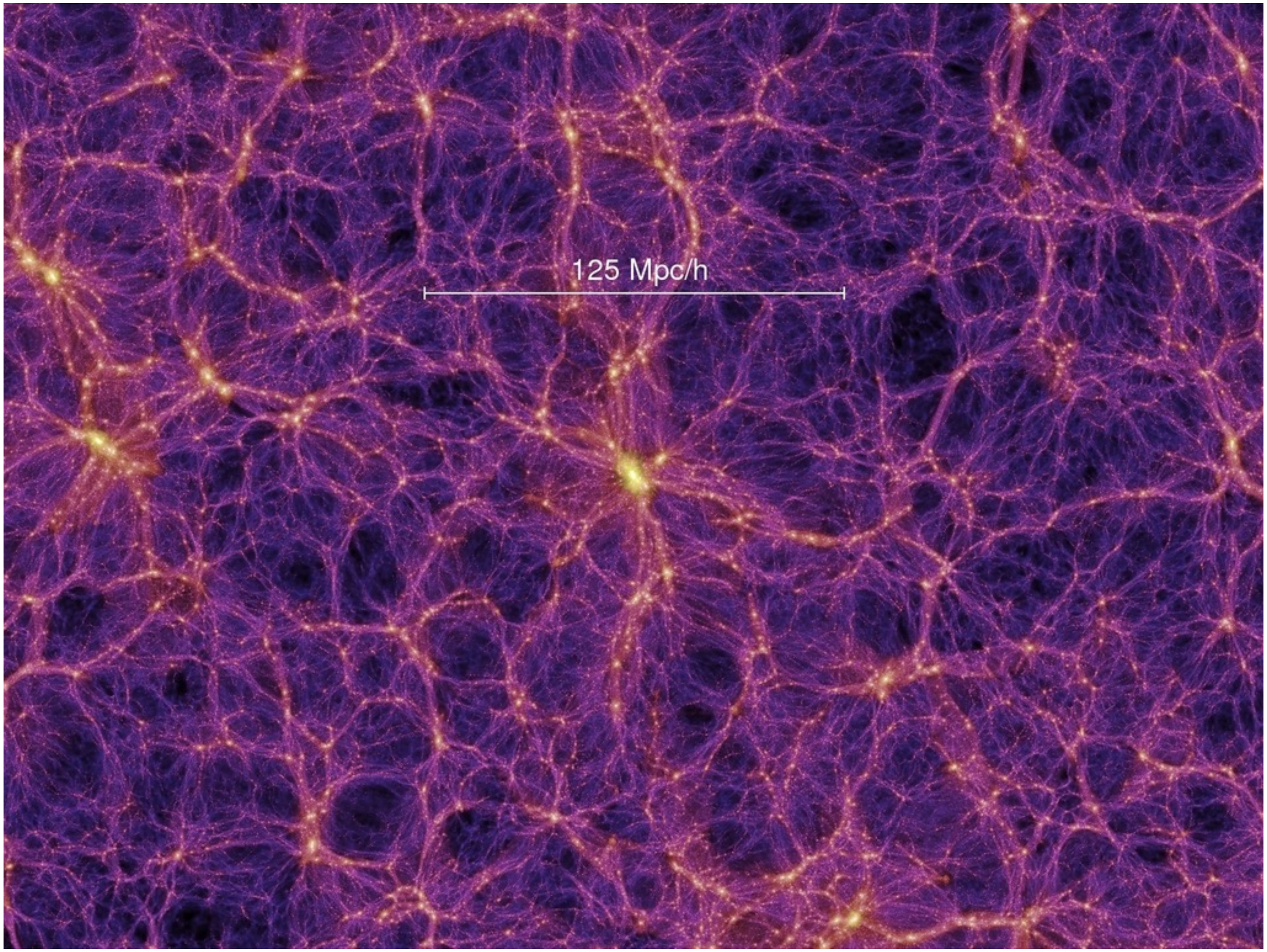


McConnachie 2012

Start with fluctuations in density after the Big Bang…



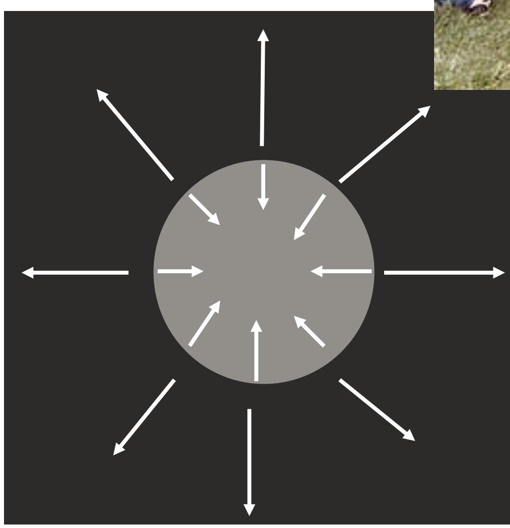
Planck measurement of the CMB - $\Delta T/T \sim 10^{-6}$


125 Mpc/h

Formation of Structure: Λ Cold Dark Matter Theory

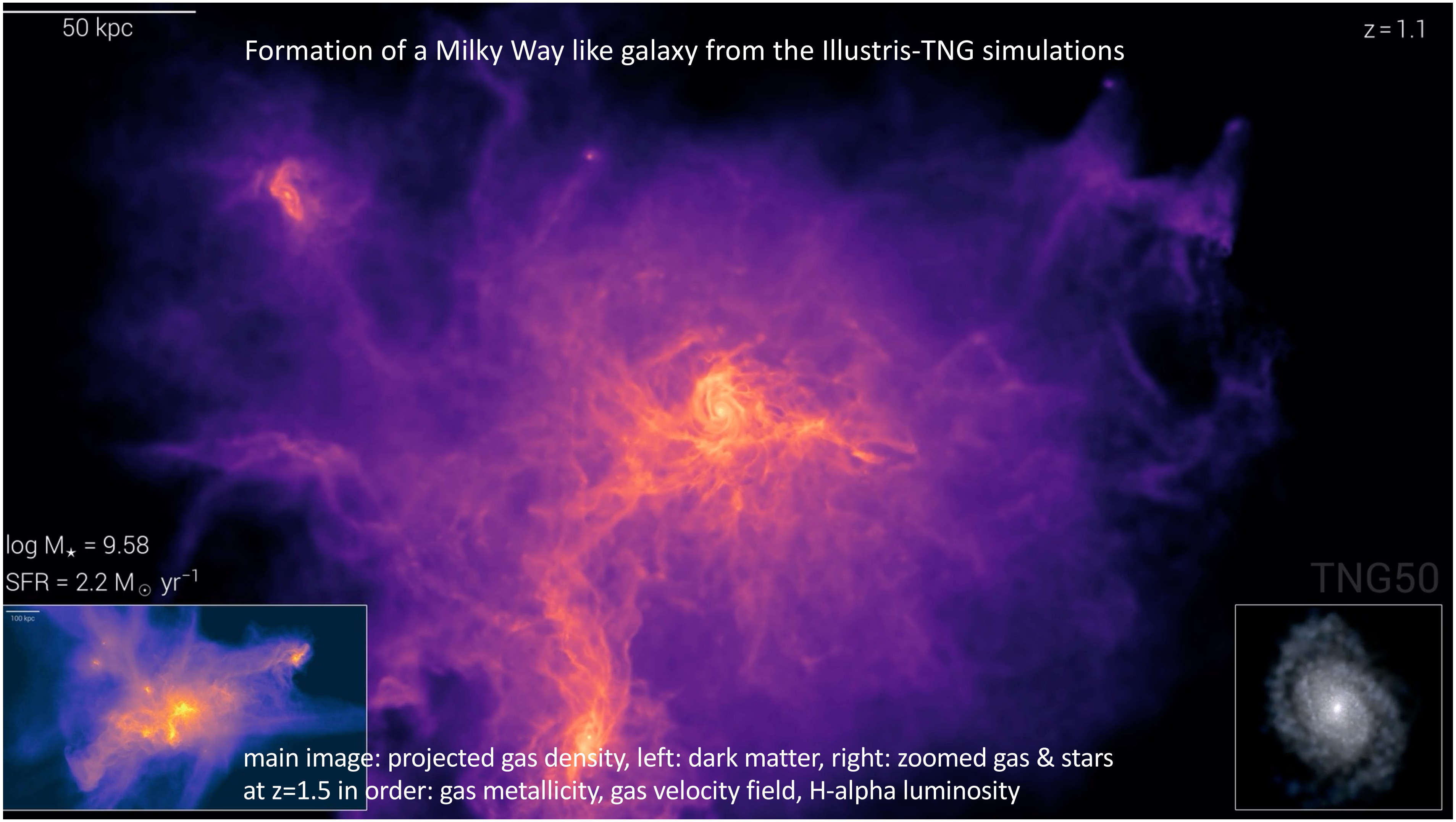
Cosmological expansion

Gravity/dark matter



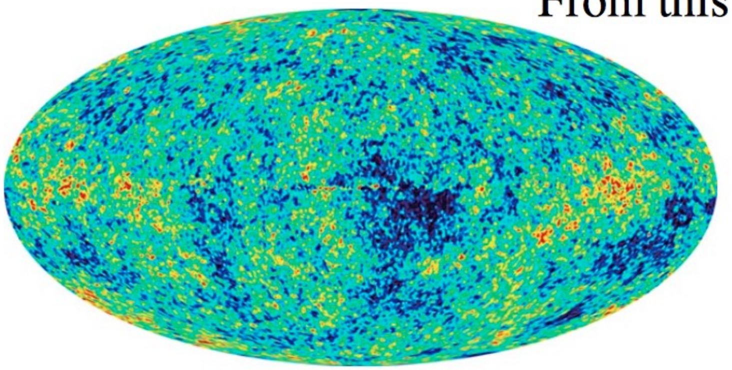
Overdensities (local regions of higher dark matter density than average) grow into gravitationally bound structures once they overcome expansion.

Space between bound overdensities expands.

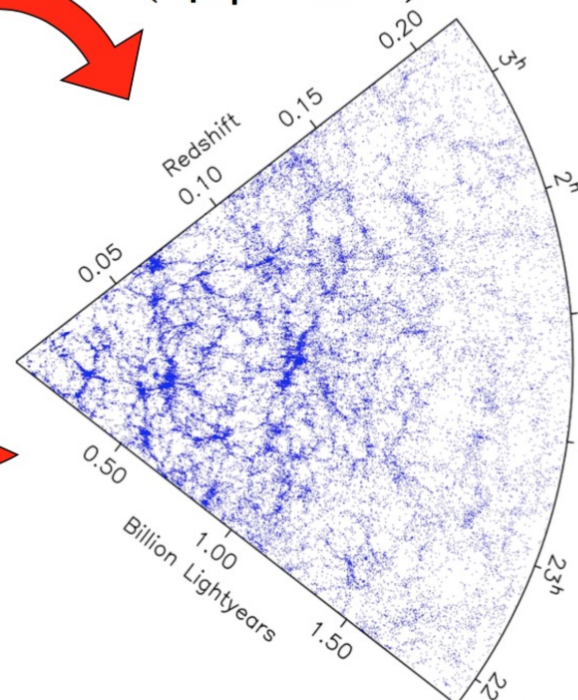

50 kpc
z = 1.1
Formation of a Milky Way like galaxy from the Illustris-TNG simulations
log M⋆ = 9.58
SFR = 2.2 M☉ yr⁻¹
100 kpc
TNG50
main image: projected gas density, left: dark matter, right: zoomed gas & stars
at z=1.5 in order: gas metallicity, gas velocity field, H-alpha luminosity

Structure Formation and Evolution

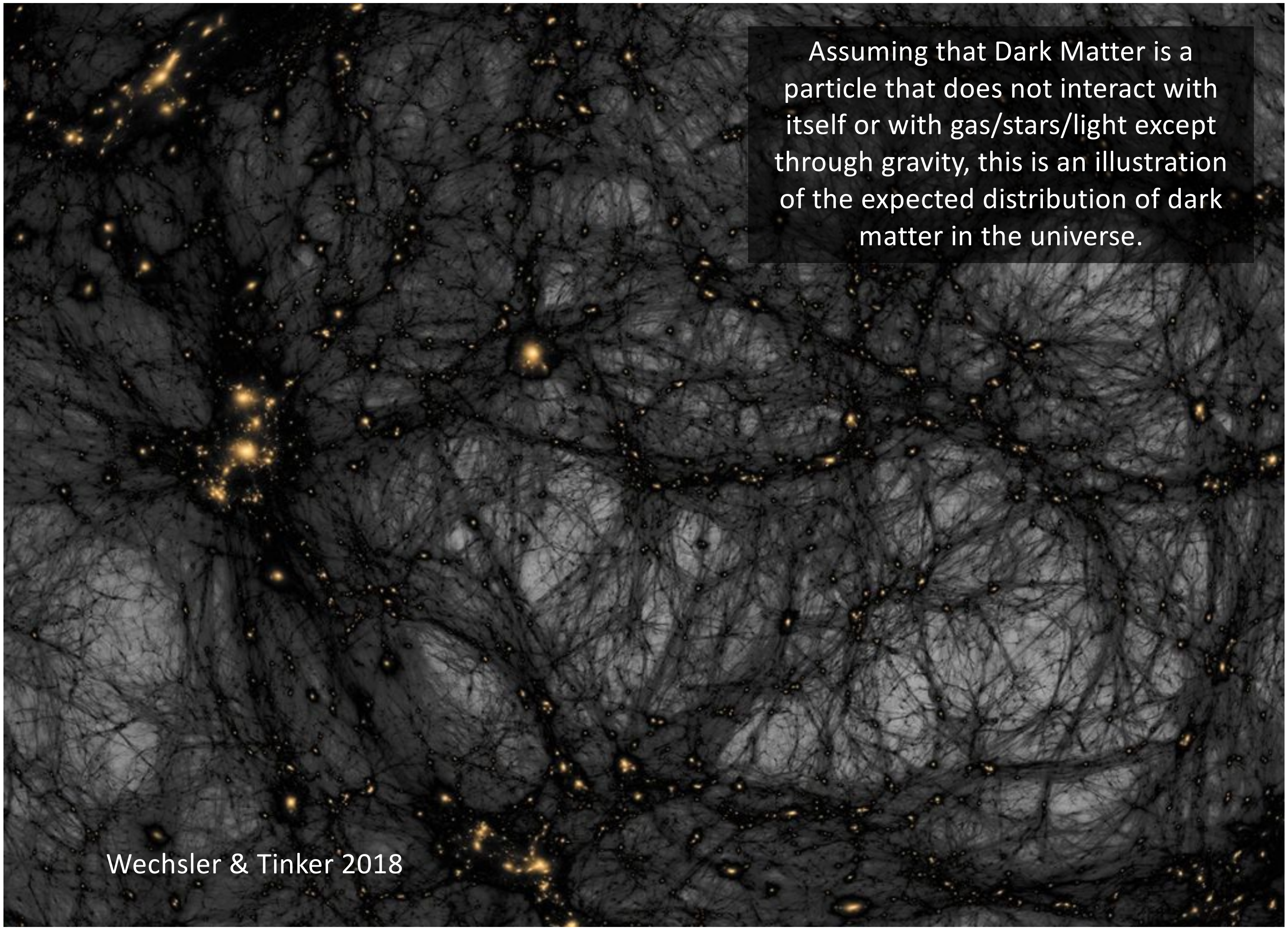
From this ($\Delta\rho/\rho \sim 10^{-6}$)

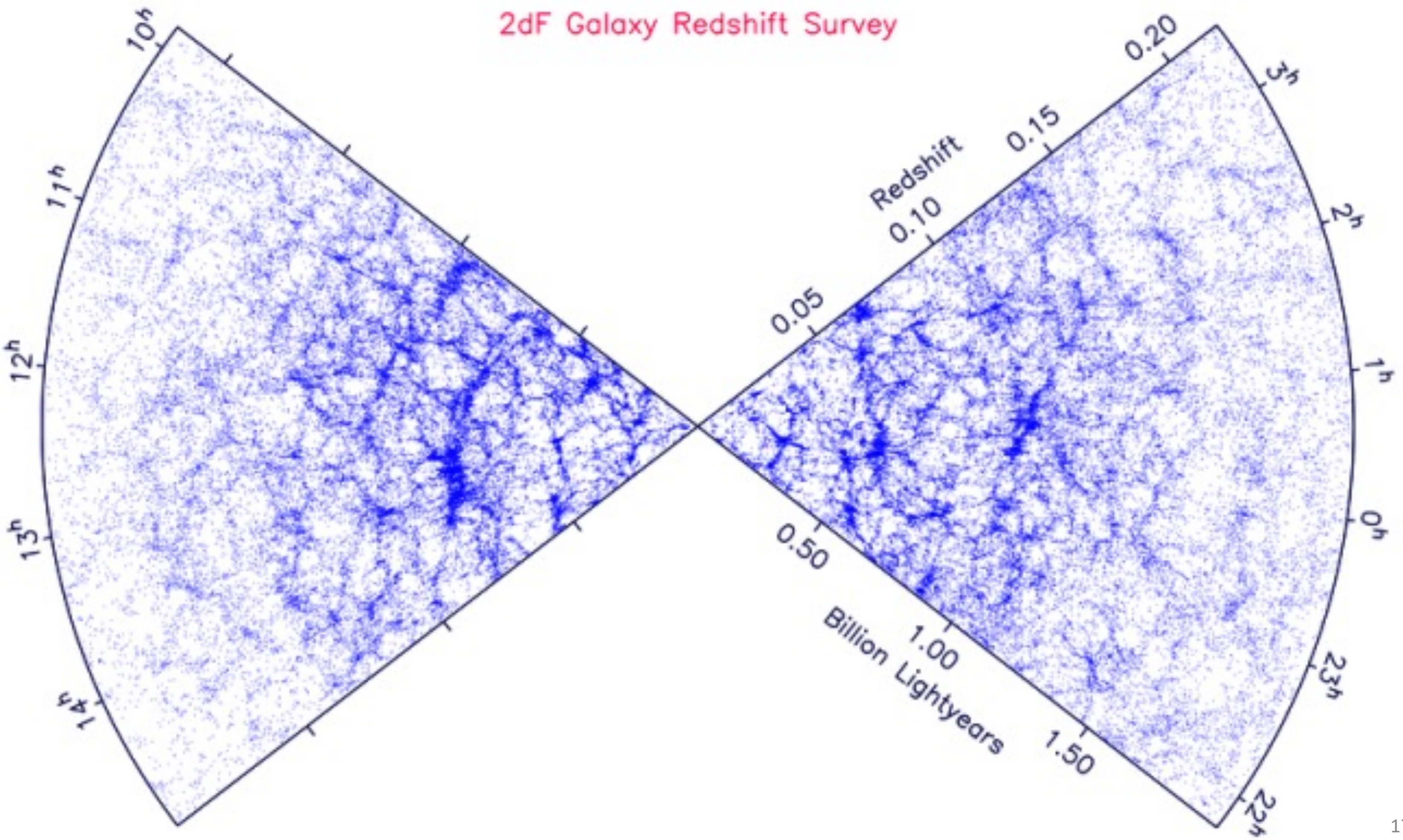


to this
($\Delta\rho/\rho \sim 10^{+2}$)



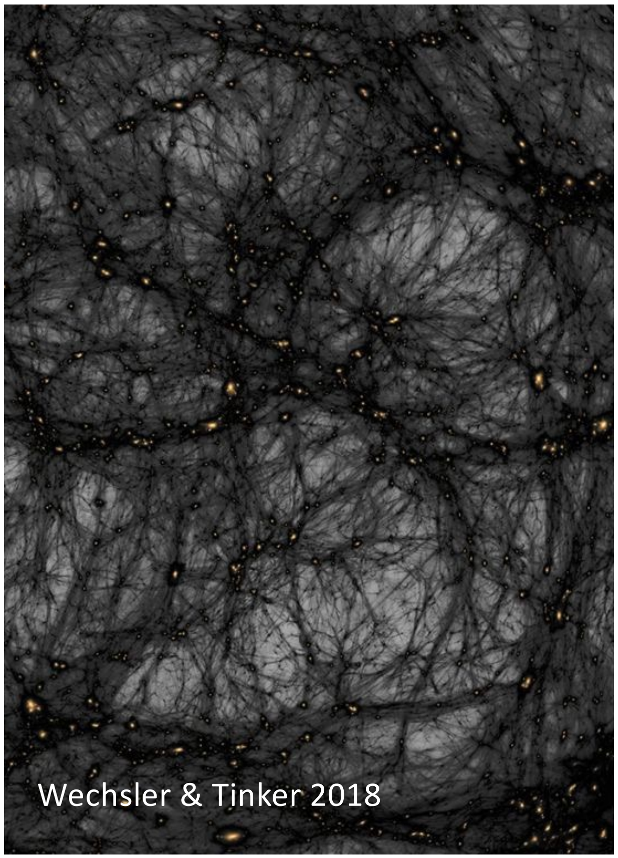
to this
($\Delta\rho/\rho \sim 10^{+6}$)

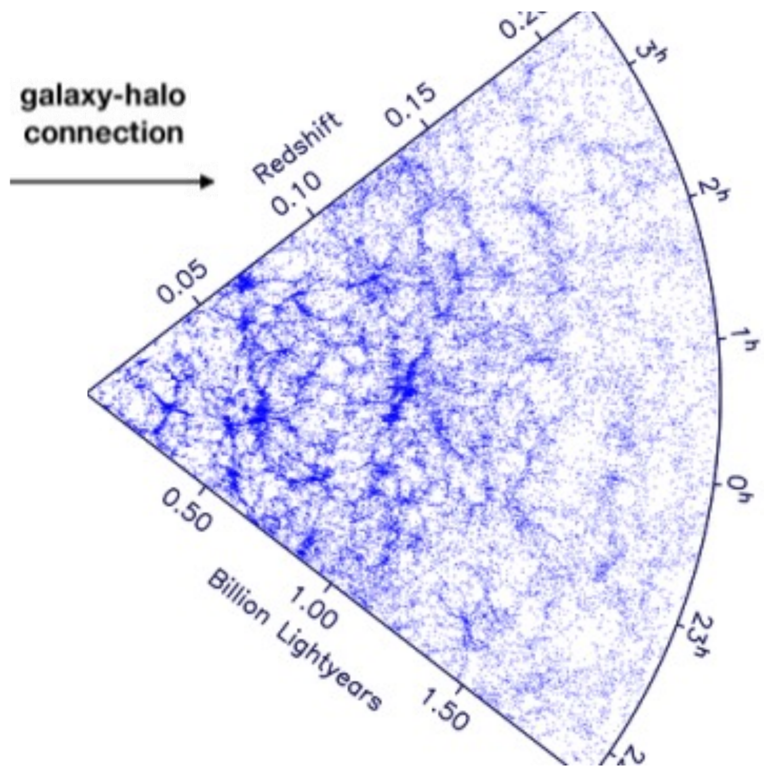

Assuming that Dark Matter is a particle that does not interact with itself or with gas/stars/light except through gravity, this is an illustration of the expected distribution of dark matter in the universe.
Wechsler & Tinker 2018



2dF Galaxy Redshift Survey
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h

Simulated “web” matches the observed distribution of galaxies

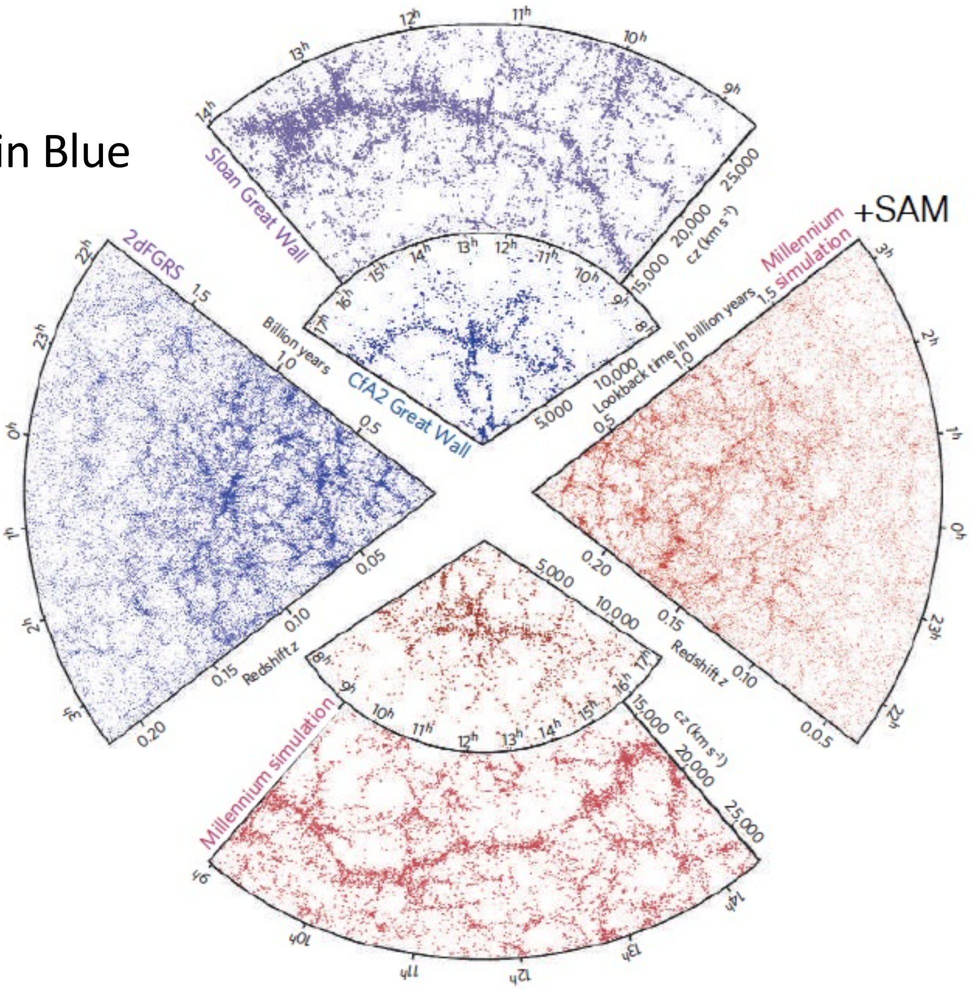




2dF Galaxy Redshift Survey

Observations in Blue

The successful reproduction of the large scale structure of the universe (Filaments and Voids) is one of the greatest successes of LCDM theory.



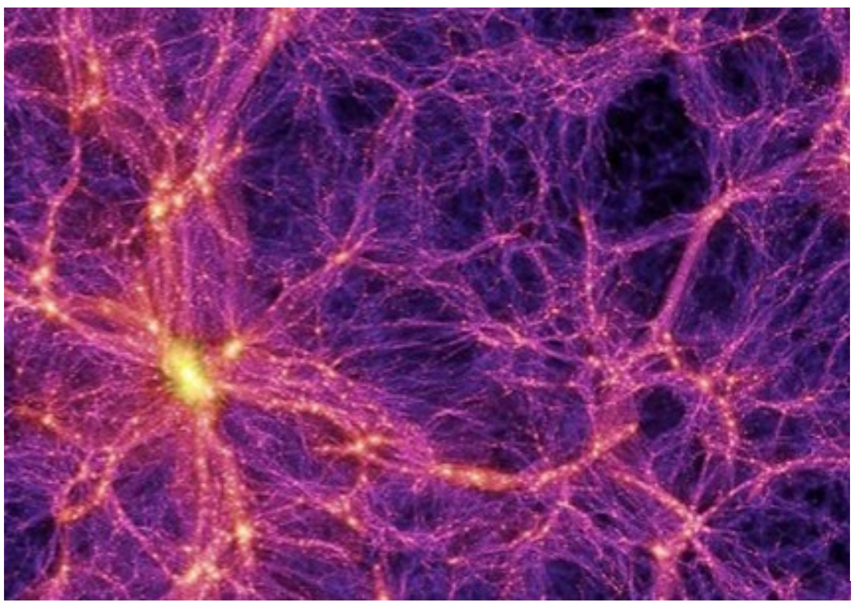
Theory in Red

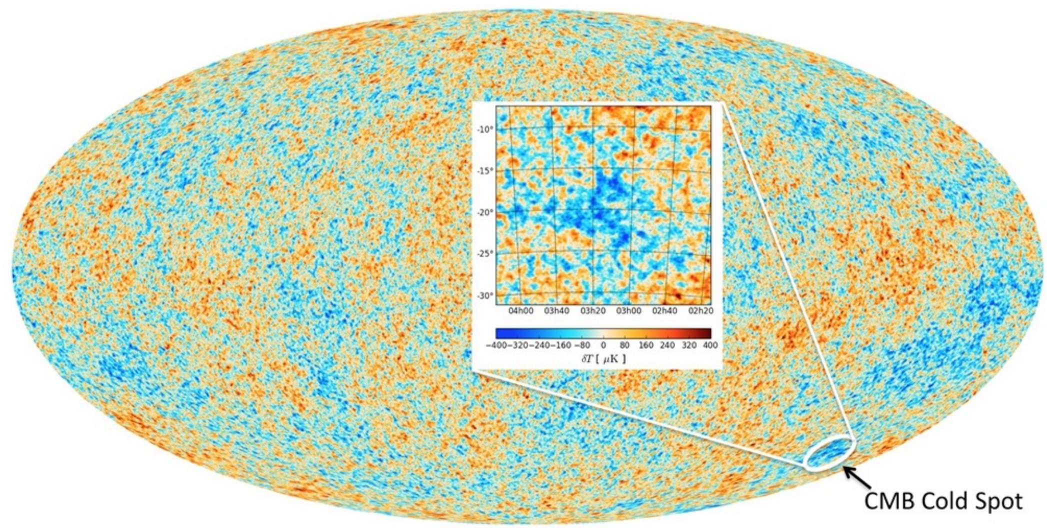
Springel, Frenk, White 06

Cosmic Voids:

- Large spaces (10-100 Mpc) between filaments that contain very few galaxies.
- Average density of dark matter in a void is ~ 1/10th the mean density of the universe

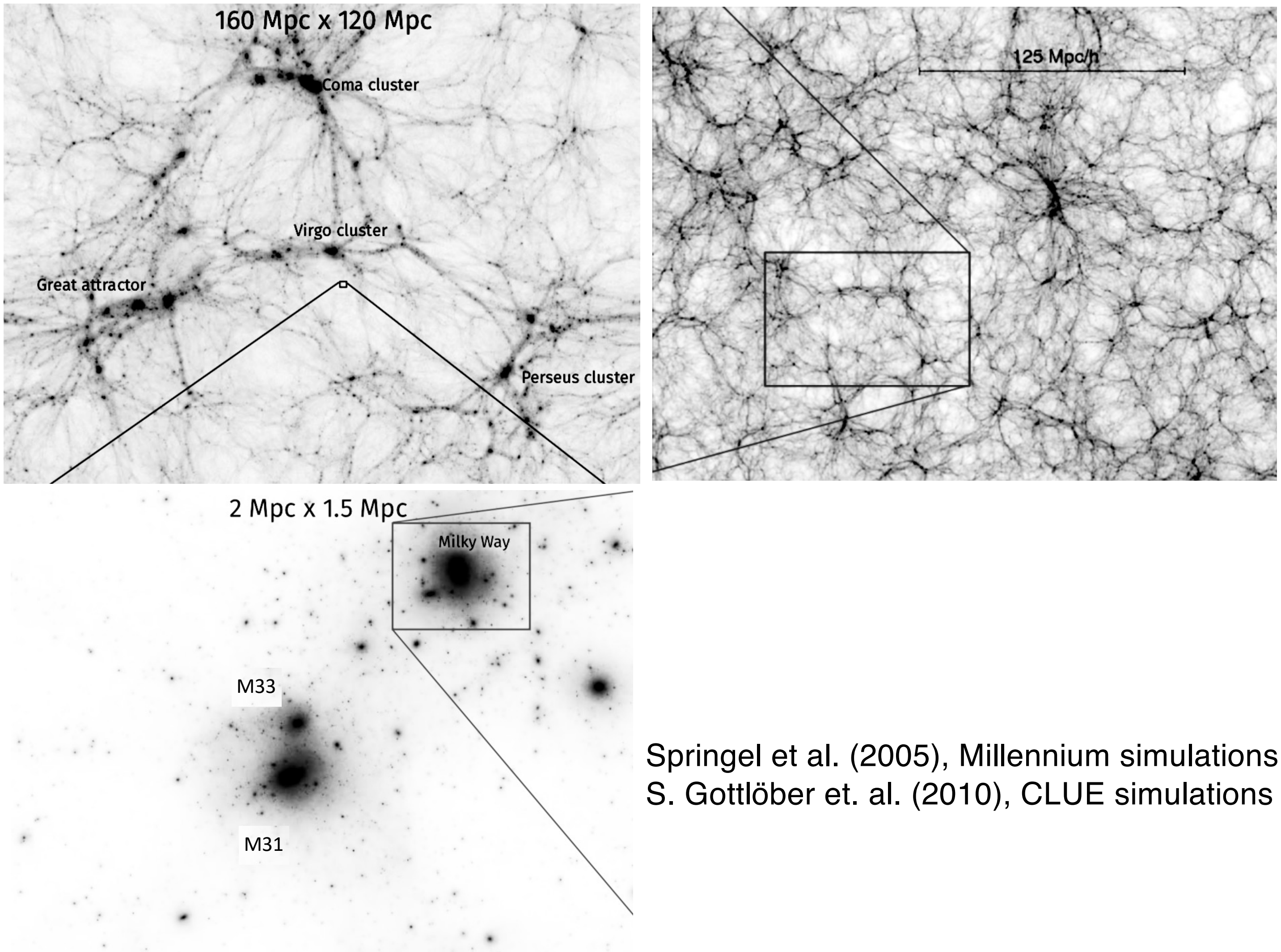
x



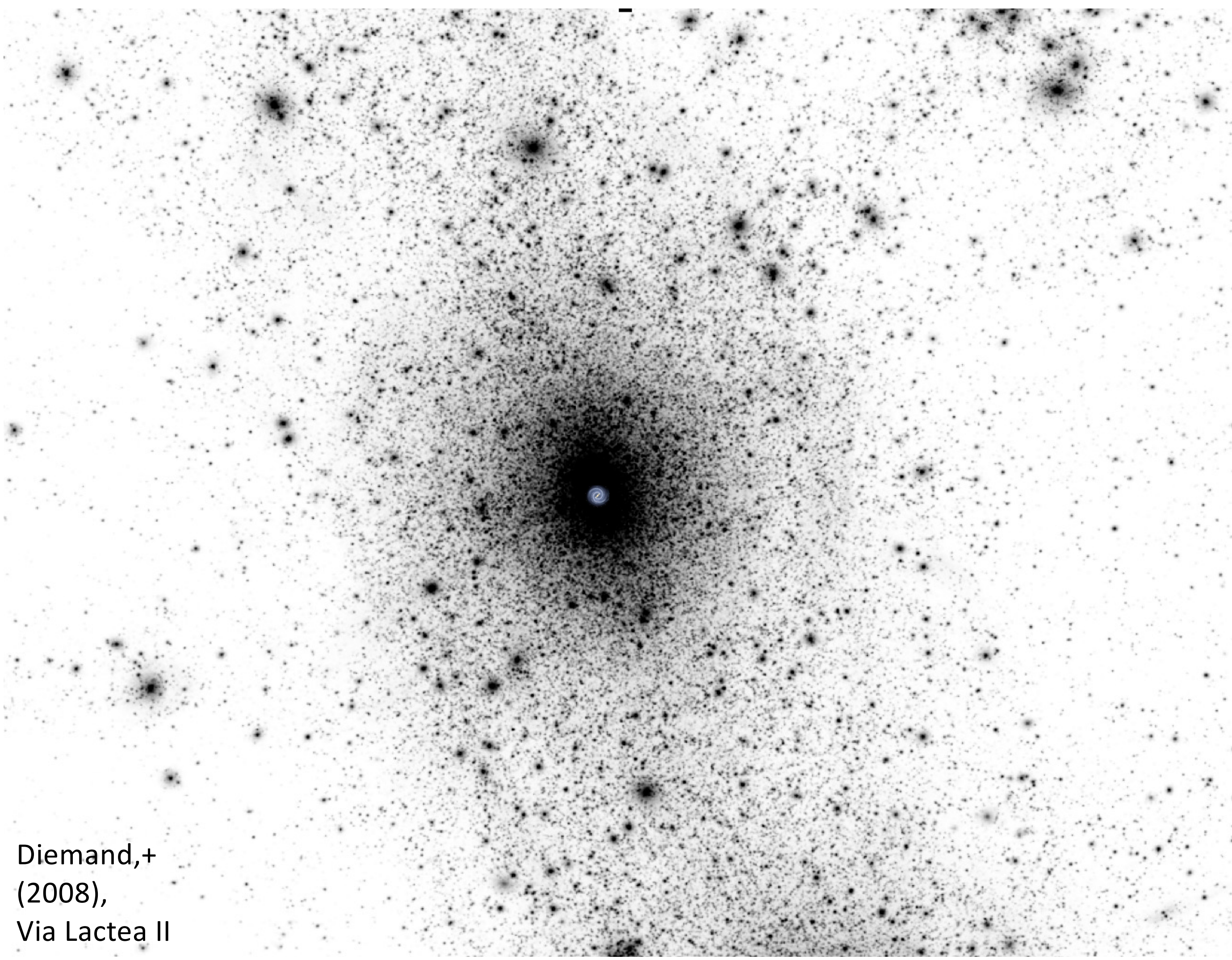


The Cold Spot is an area of the cosmic microwave background with a lower temperature than its surroundings. On this map created by the Planck satellite, warmer CMB temperatures appear redder and cooler temperatures appear bluer.

ESA and Durham University



Springel et al. (2005), Millennium simulations
S. Gottlöber et. al. (2010), CLUE simulations


Diemand,+
(2008),
Via Lactea II

Dark Matter Halo

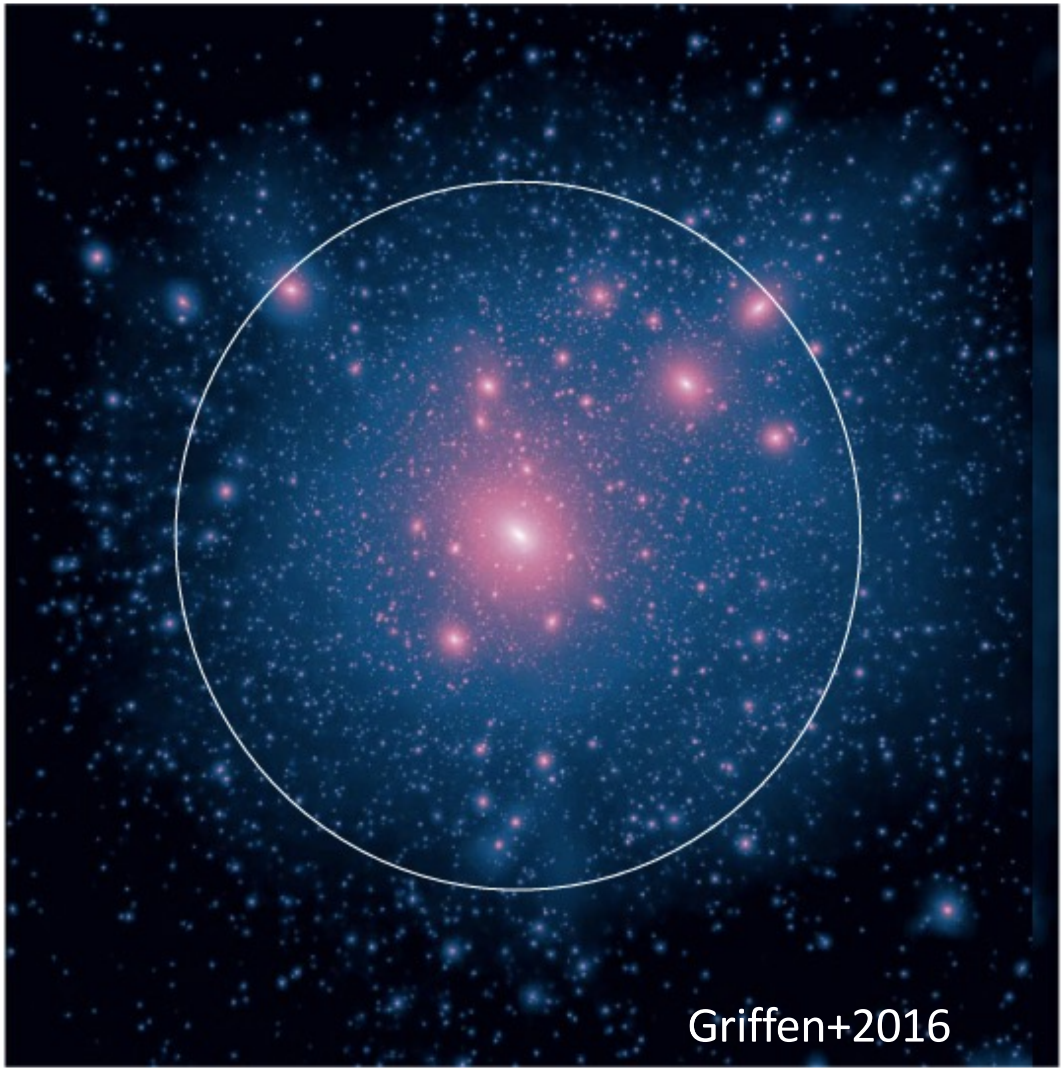
What is the size of the halo?

Rvir = Virial Radius: where the dark matter density is 360x the average dm density of the universe. (assuming Planck cosmology)

R200 = where the dark matter density is 200x the critical density needed to close the universe.

Rvir > R200

For MW: Rvir is ~ 17 x size of disk = ~260 kpc (if halo = 1e12 Msun)



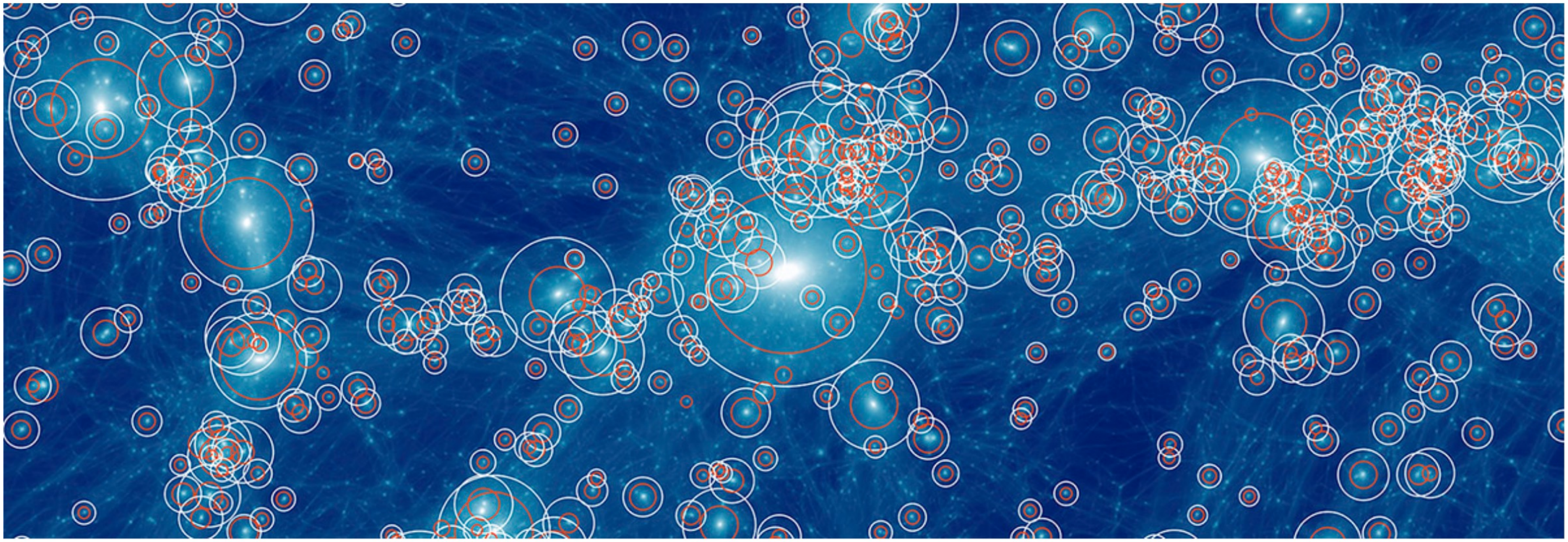
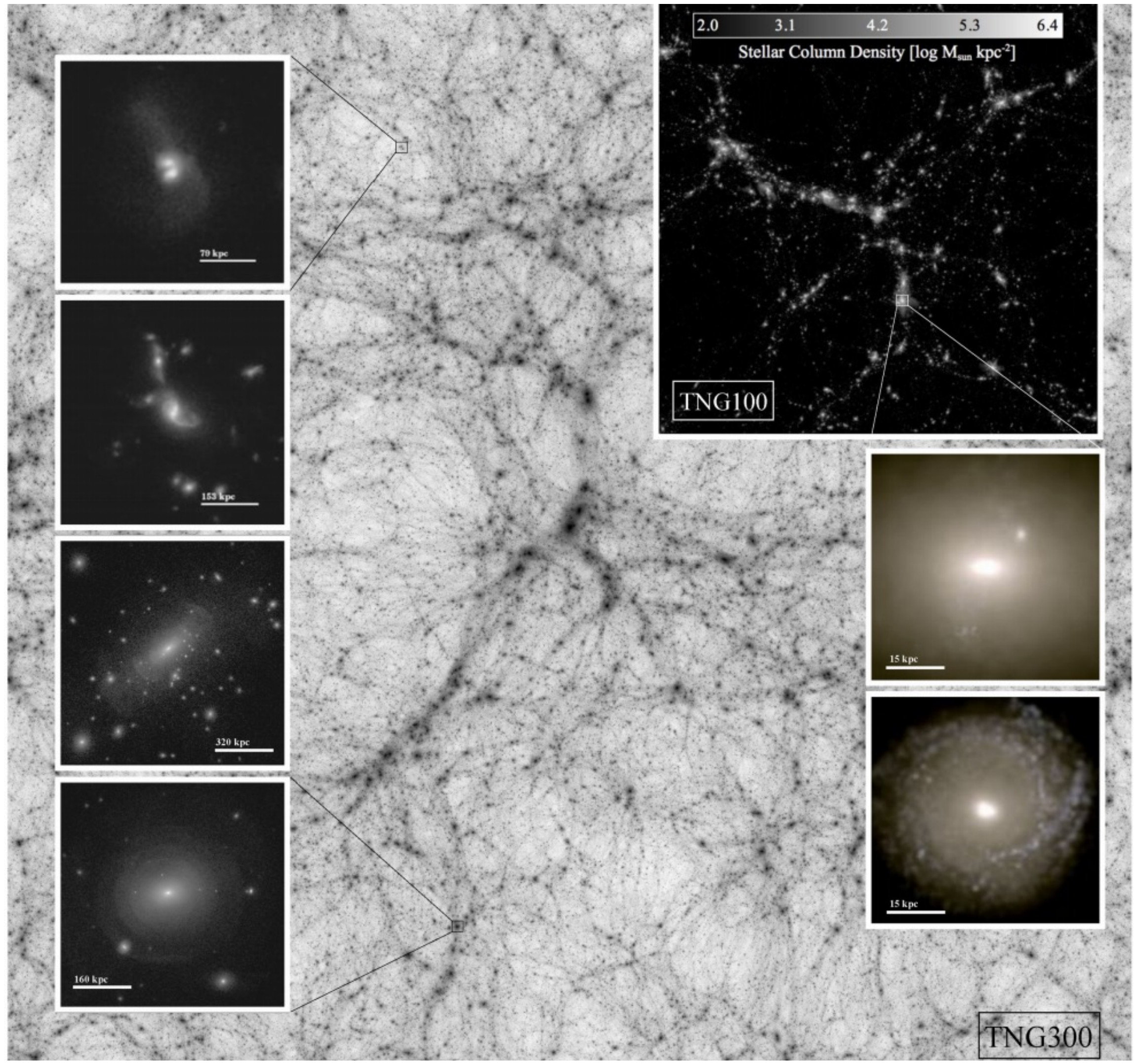


Image: Benedikt Diemer

Splash back radius (white), where particles reach the apocenter of their first orbit, is larger than Rvir (orange)

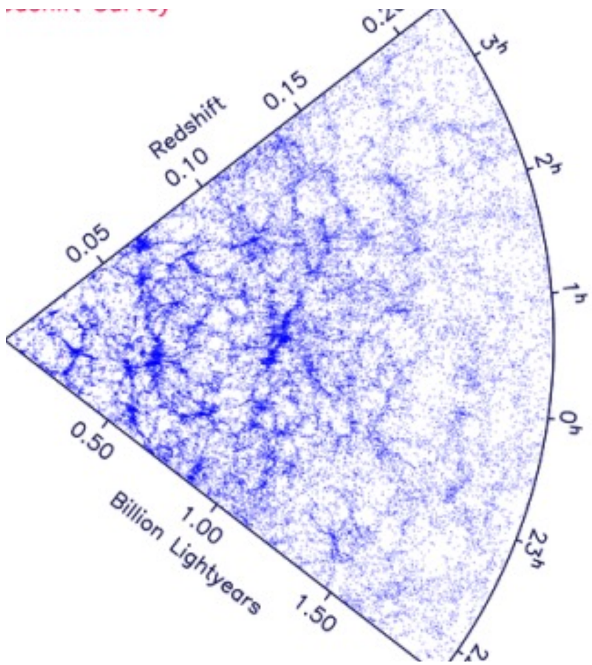
See also More, Diemer & Kravtsov 2015

How do we put the right stellar mass galaxy into the the halo with the right dark matter mass ?



Pillepich+
MNRAS 475, 2018

Galaxy Luminosity Function



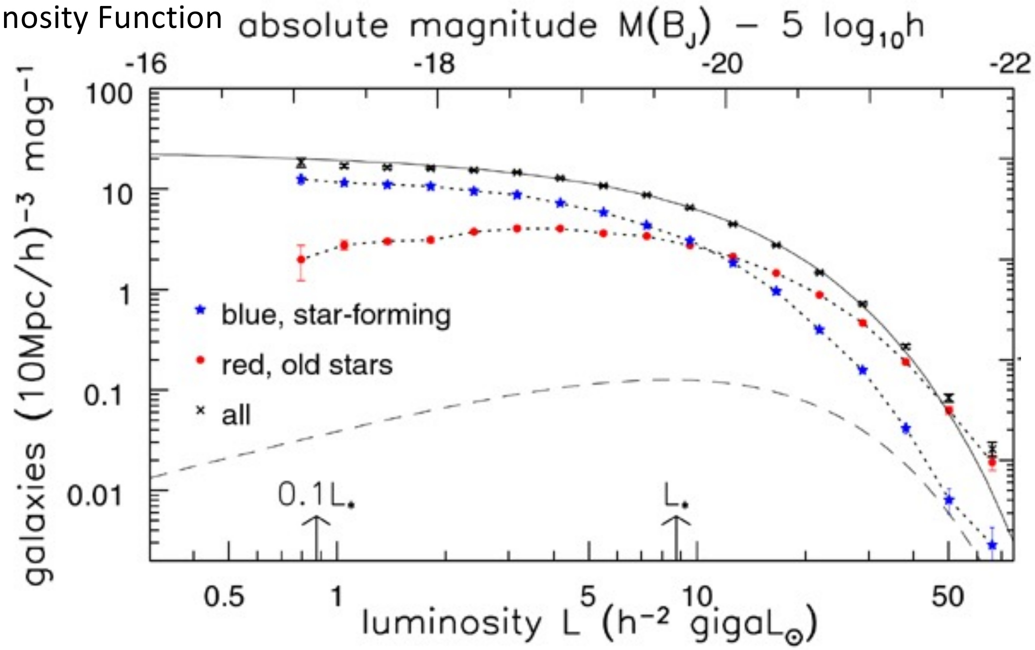


Fig 1.16 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

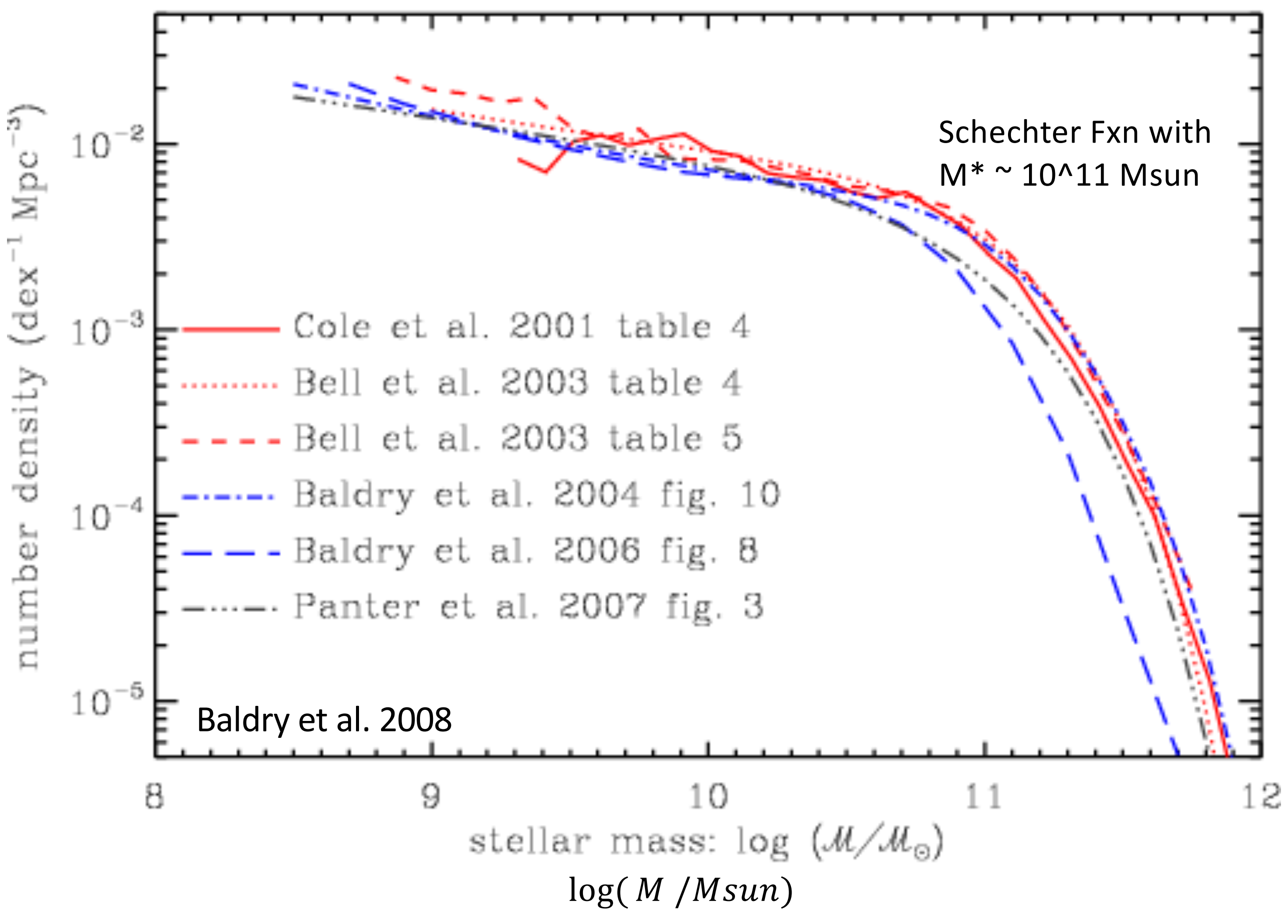
Fig. 1.16. Number of galaxies per 10 Mpc cube between absolute magnitude $M(B_J)$ and $M(B_J) + 1$ (crosses). Dotted lines show numbers of blue (stars) and red (filled dots) galaxies making up this total; vertical bars indicate errors. The solid line shows the luminosity function of Equation 1.24; the dashed line gives $\Phi(M) \times L/L_\star$, the light from galaxies in each interval of absolute magnitude. The blue bandpass B_J is matched to the photographic plates used to select the galaxies – 2dF survey, D. Croton.

Sparke & Gallagher Ch 1

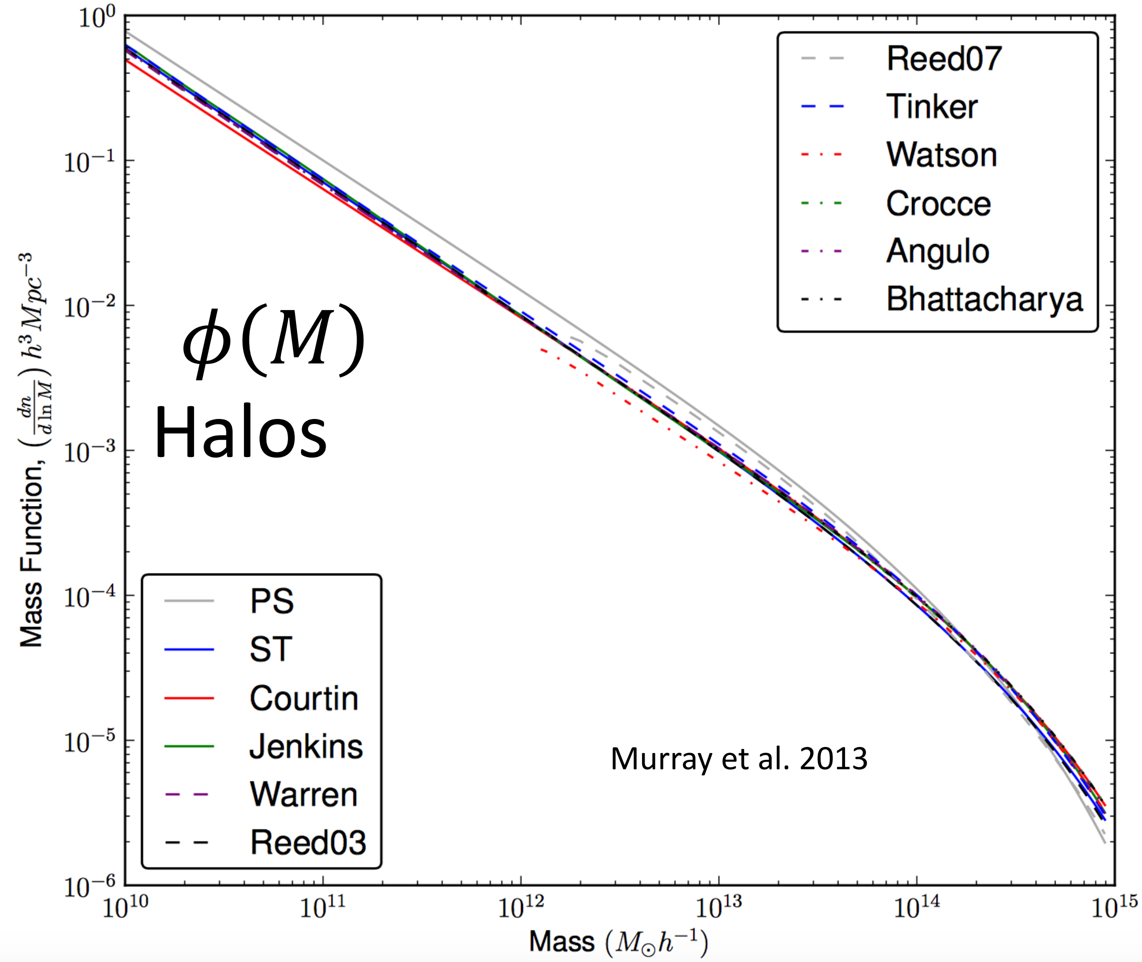
If we can determine each galaxy's mass-to-light ratio (M/L) we can construct a **galaxy stellar mass function**

$\phi(M)$

Galaxy



From dark matter-only simulations, we can find the mass function of dark matter halos.

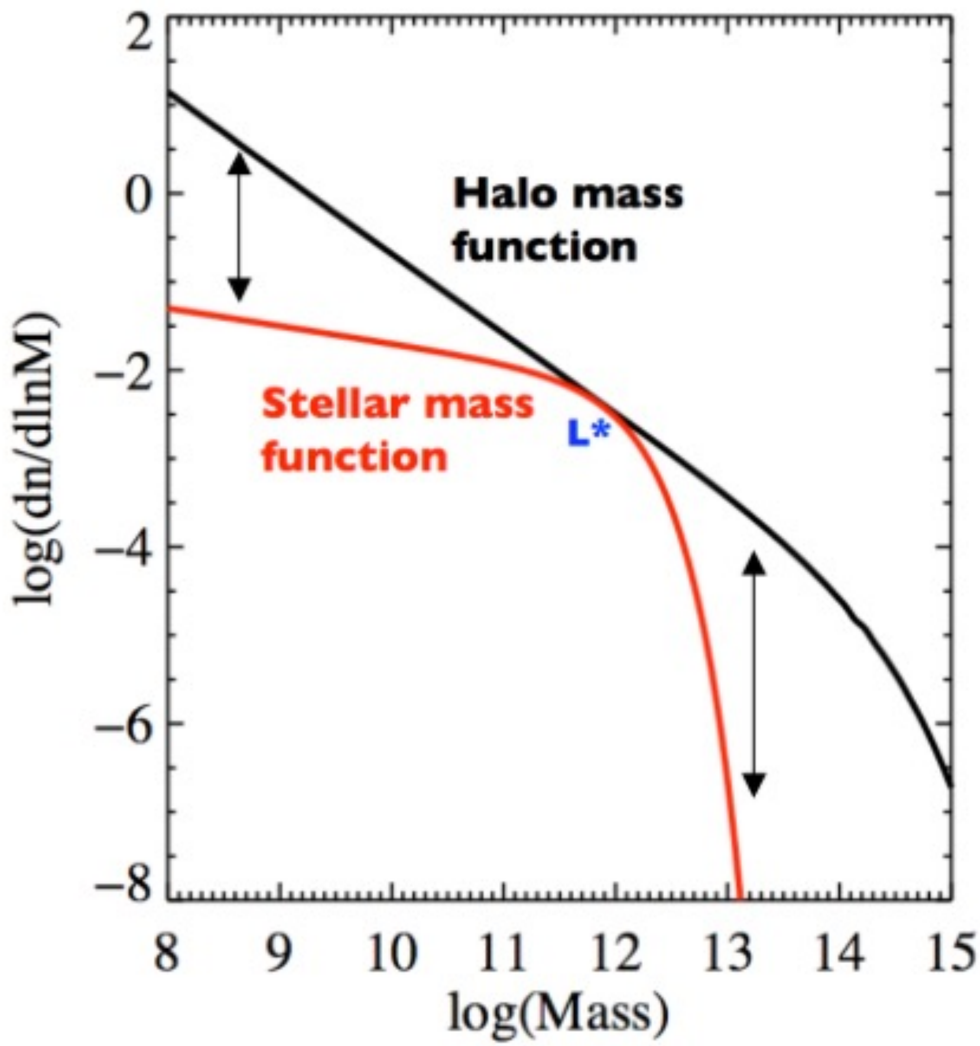


Need a relationship to connect

the number of halos per dark matter halo mass bin

to

the number of galaxies per galaxy stellar mass bin

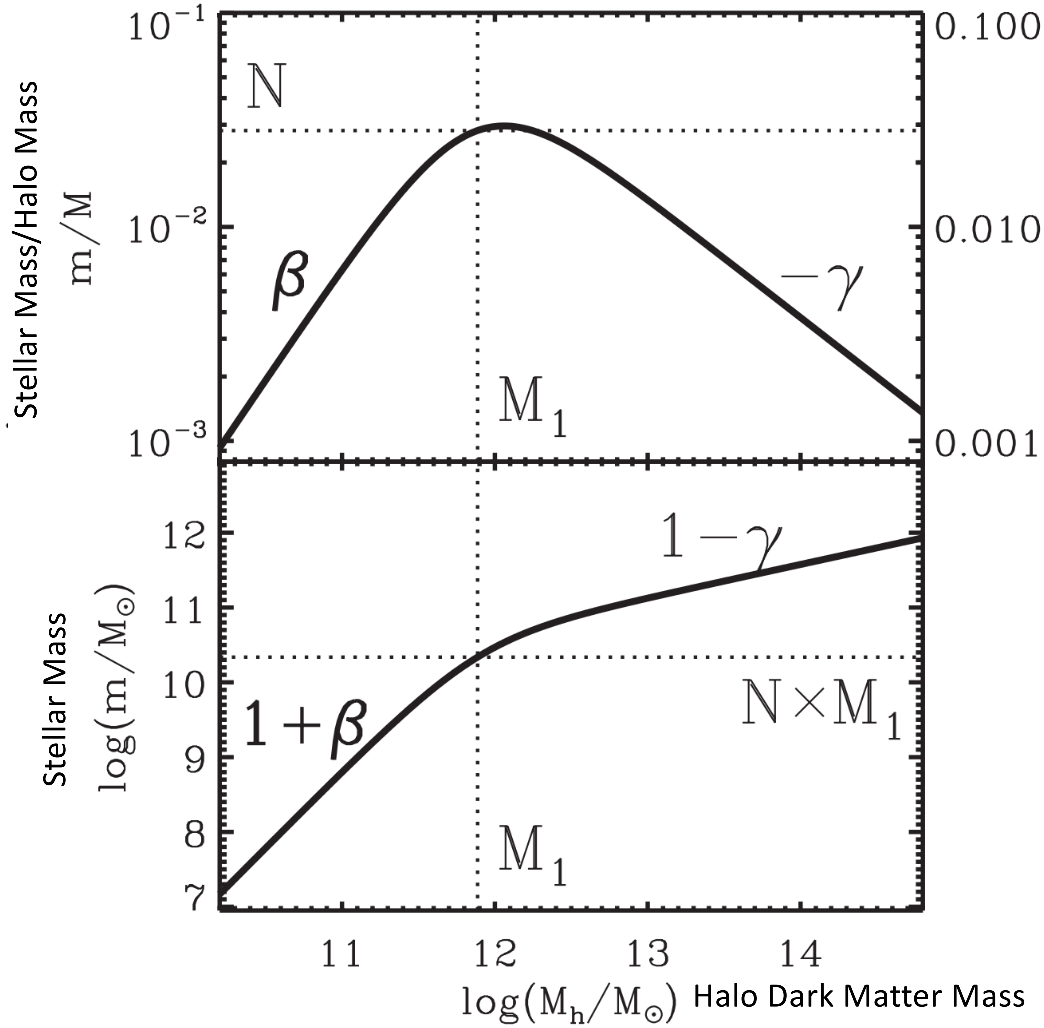


Halo Mass to Stellar Mass Relation

$$\frac{m}{M} = 2N\left[\left(\frac{M}{M_1}\right)^{-\beta} + \left(\frac{M}{M_1}\right)^{\gamma}\right]^{-1}$$

Moster + 2013 MNRAS 428, 3121

See also Behroozi+2013



Moster+2013 eqns 11-14, Table 1 : Lab 5 part B

$$\log M_1(z) = M_{10} + M_{11}(1-a) = M_{10} + M_{11}\frac{z}{z+1}$$

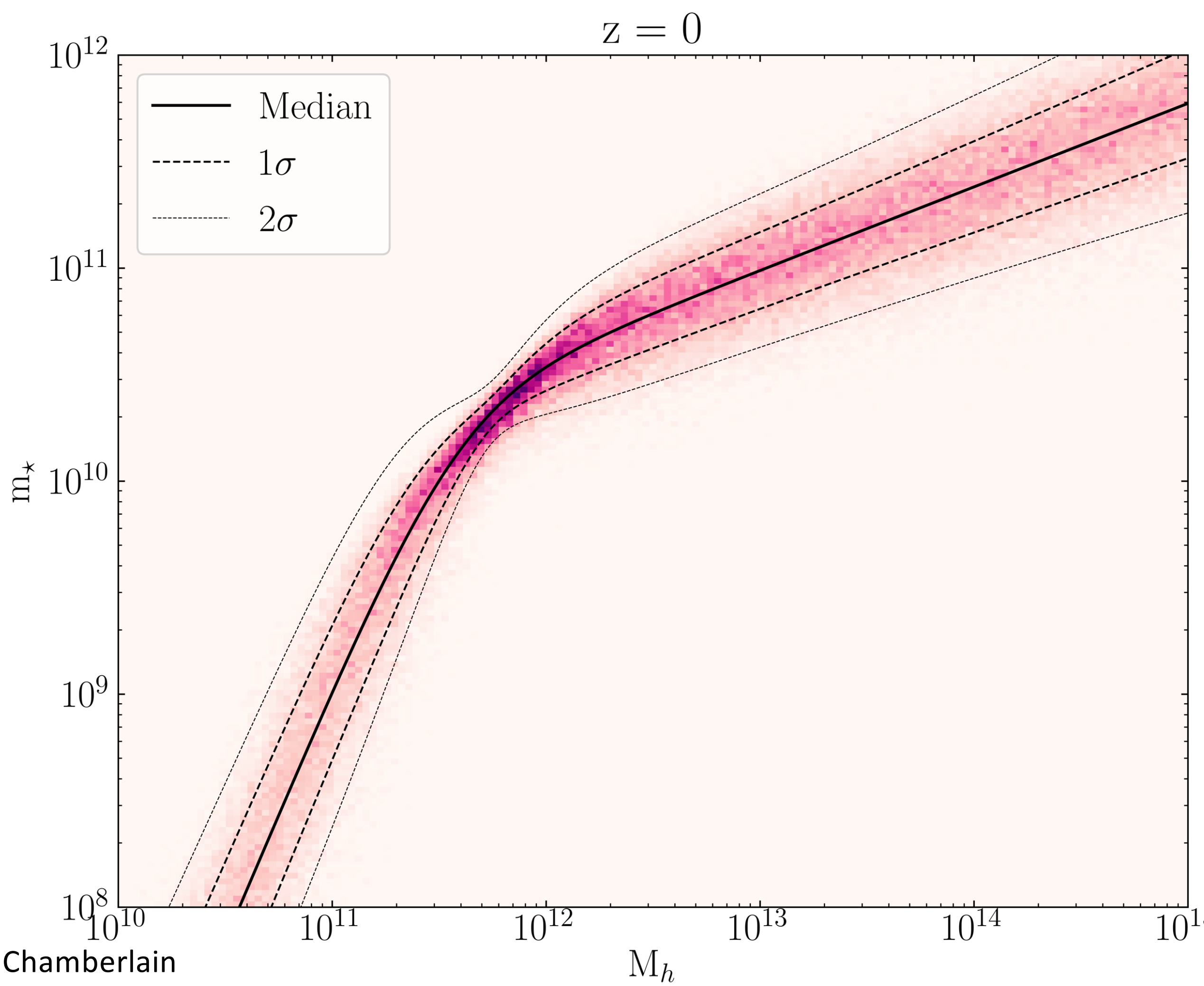
$$N(z) = N_{10} + N_{11}(1-a) = N_{10} + N_{11}\frac{z}{z+1}, \quad \gamma(z) = \gamma_{10} + \gamma_{11}(1-a) = \gamma_{10} + \gamma_{11}\frac{z}{z+1}.$$

$$\beta(z) = \beta_{10} + \beta_{11}(1-a) = \beta_{10} + \beta_{11}\frac{z}{z+1},$$

Table 1. Fitting results for the redshift-dependent SHM relationship.

	M_{10}	M_{11}	N_{10}	N_{11}	β_{10}	β_{11}	γ_{10}	γ_{11}
Best fit	11.590	1.195	0.0351	−0.0247	1.376	−0.826	0.608	0.329
Range ±	0.236	0.353	0.0058	0.0069	0.153	0.225	0.059	0.173

Notes. All masses are in units of $M_{\odot}$.



Courtesy: Dr Katie Chamberlain