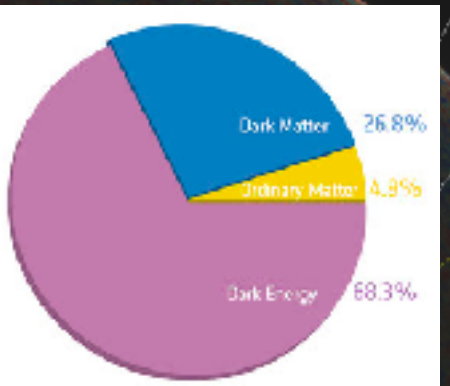
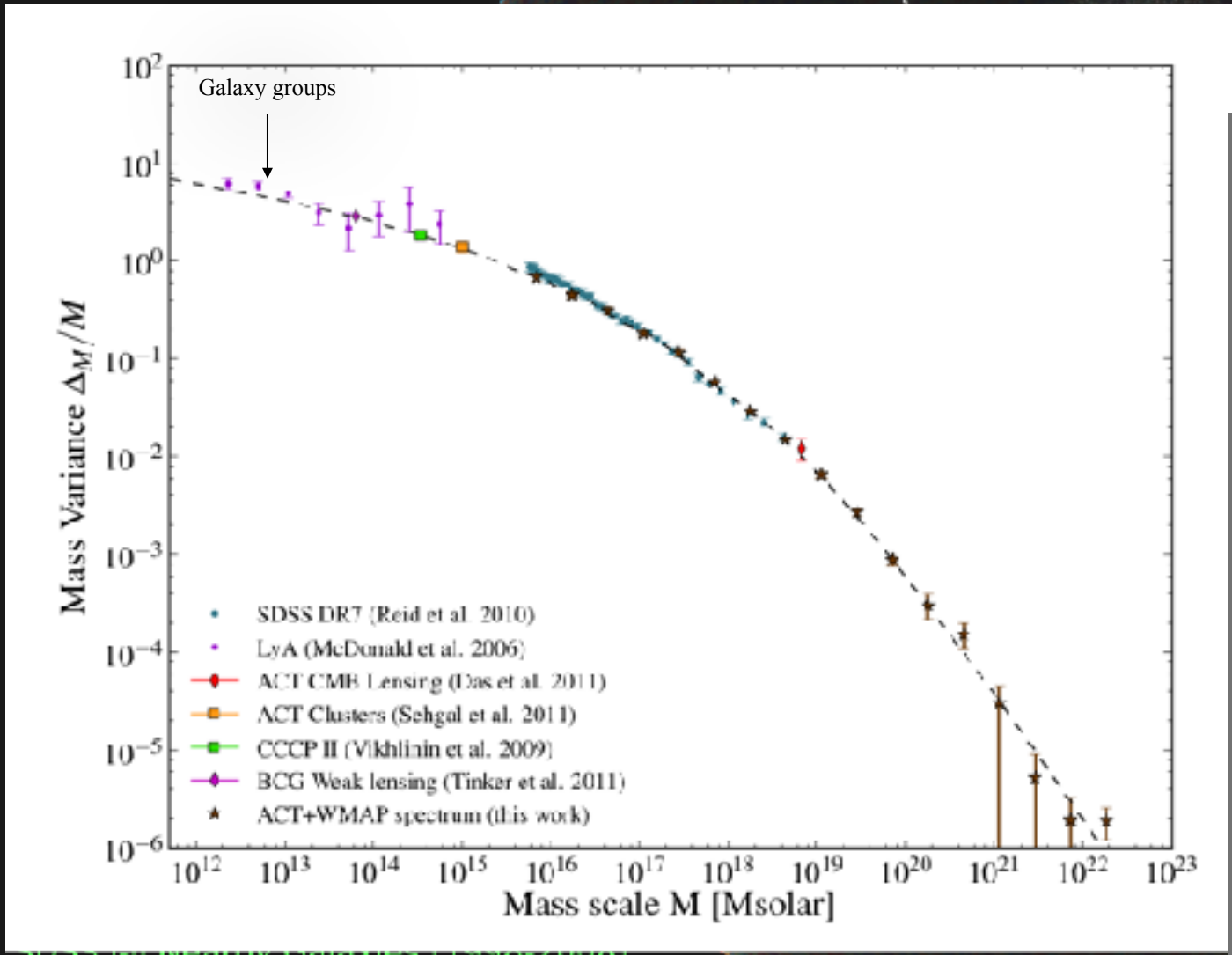
Non-linear structures in Lambda Cold Dark Matter

Julio F. Navarro

- Lecture 1: Basic Cosmological Facts
- Lecture 2: Non-Linear Structures in LCDM
- Lecture 3: Galaxy Structure in LCDM
- Lecture 4: Small Scale Constraints to LCDM

The LCDM paradigm: Structure in the Universe in the Linear Regime



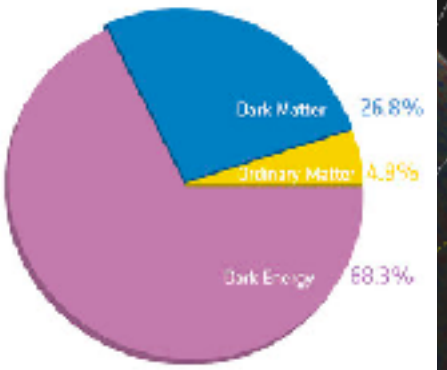


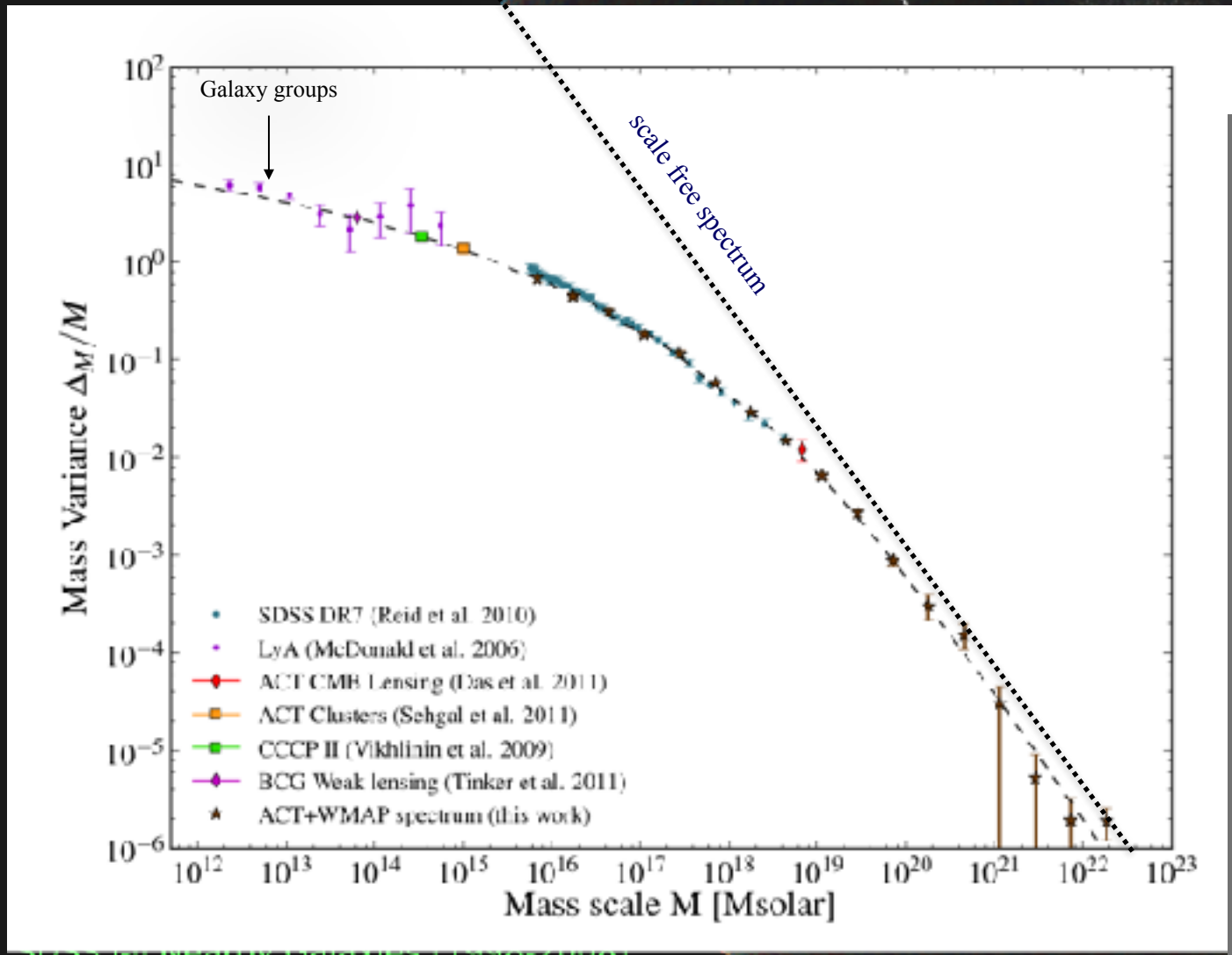
Hlozek et al 2012

The power spectrum of density fluctuations in the linear regime is very well matched by assuming that the initial density fluctuations are Gaussian and that the Universe is dominated by collisionless **Cold Dark Matter (CDM)**

This represents astonishing success!

The LCDM paradigm: Structure in the Universe in the Linear Regime





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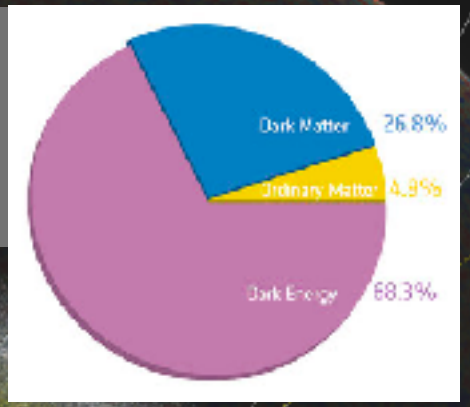
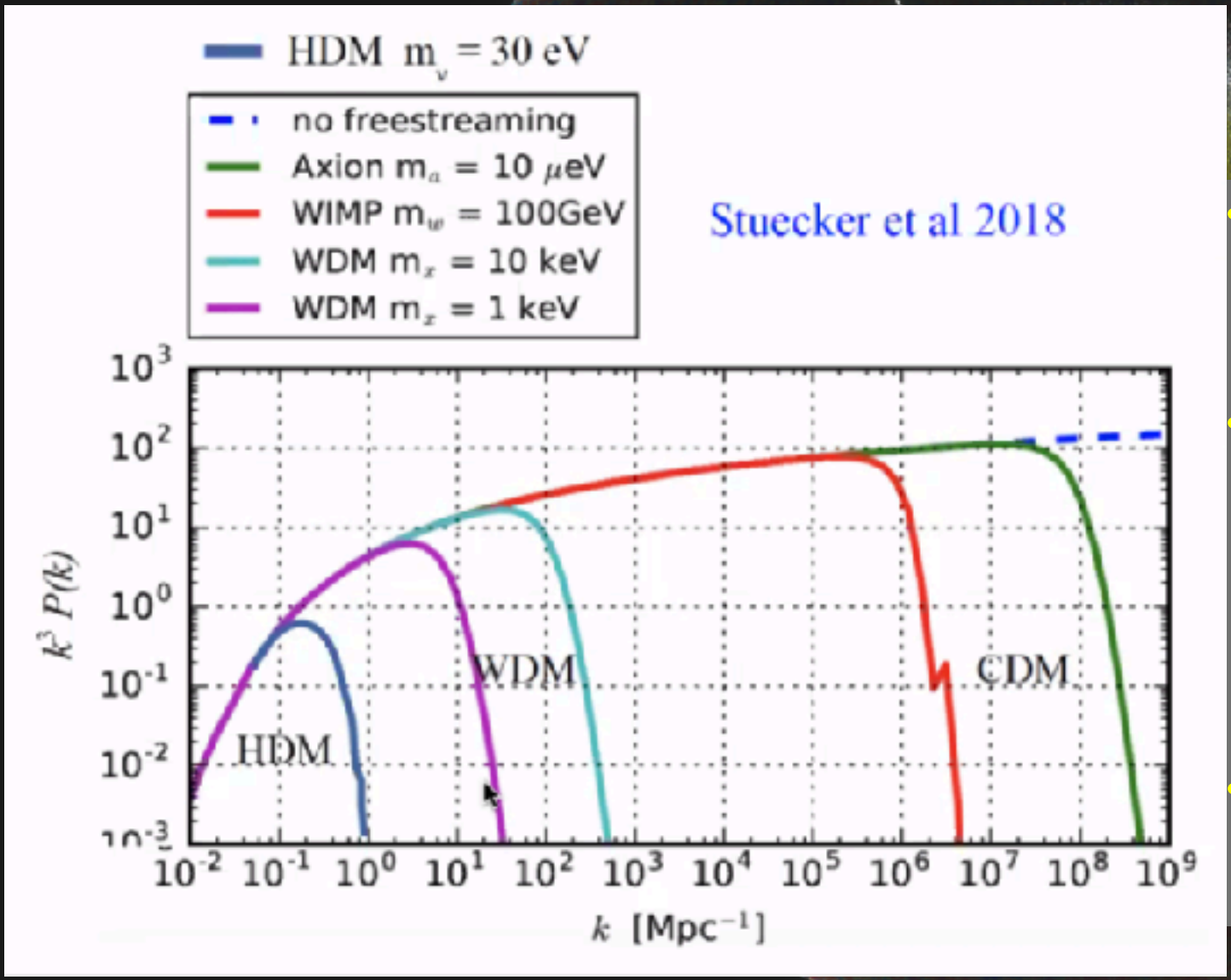
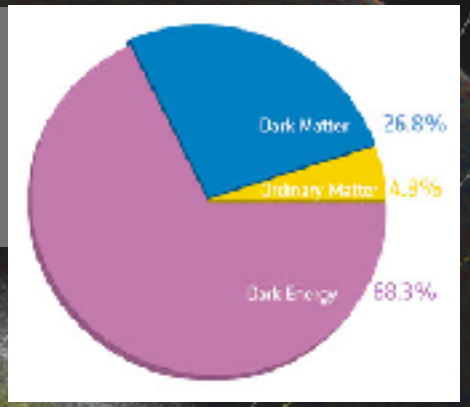
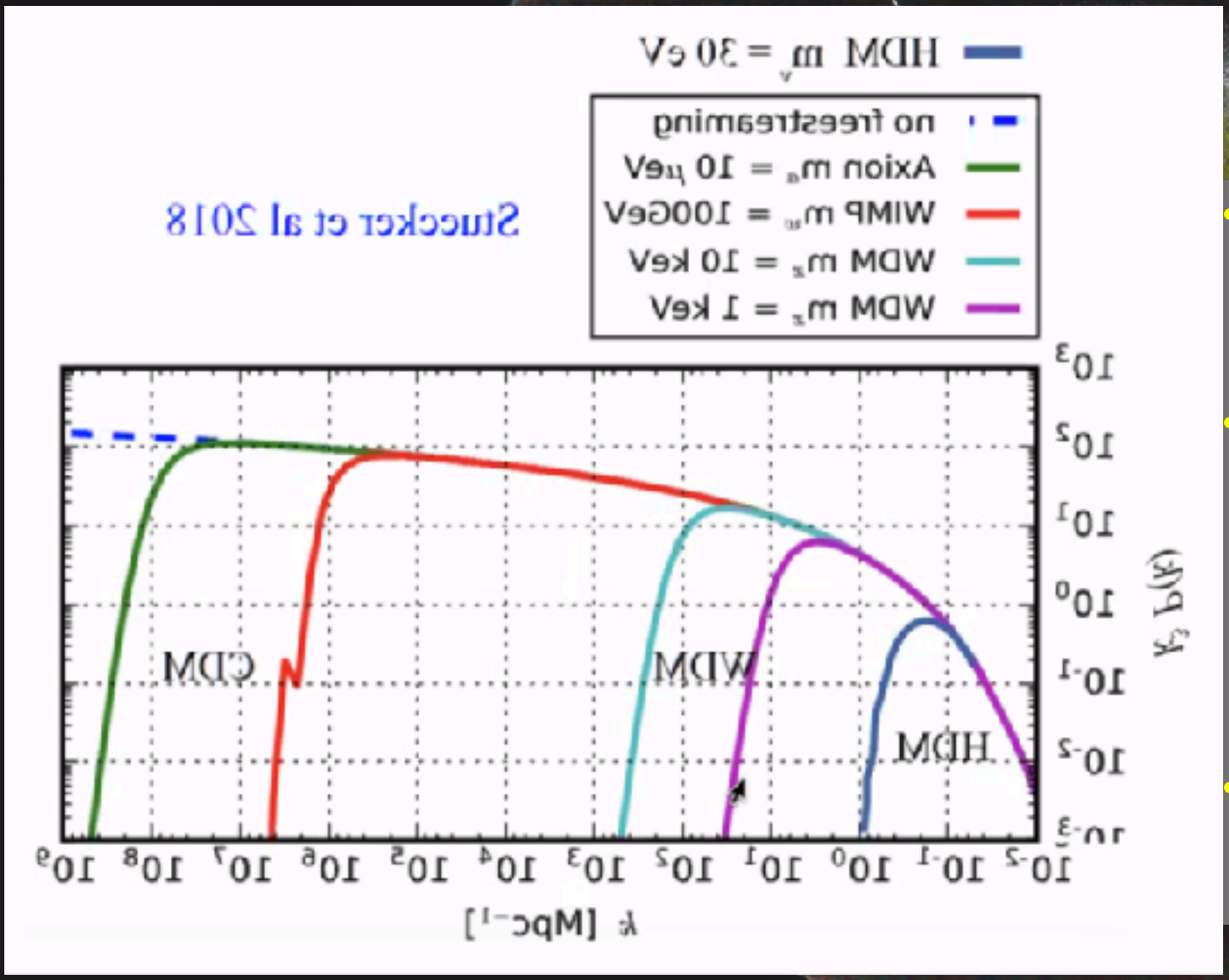




- What happens on smaller scales, like those of dwarf galaxies?
- Or on non-linear scales, such as individual galaxies, where we have plentiful kinematic tracers?
- Are observations still consistent with CDM?

The LCDM paradigm: Structure in the Universe in the Linear Regime





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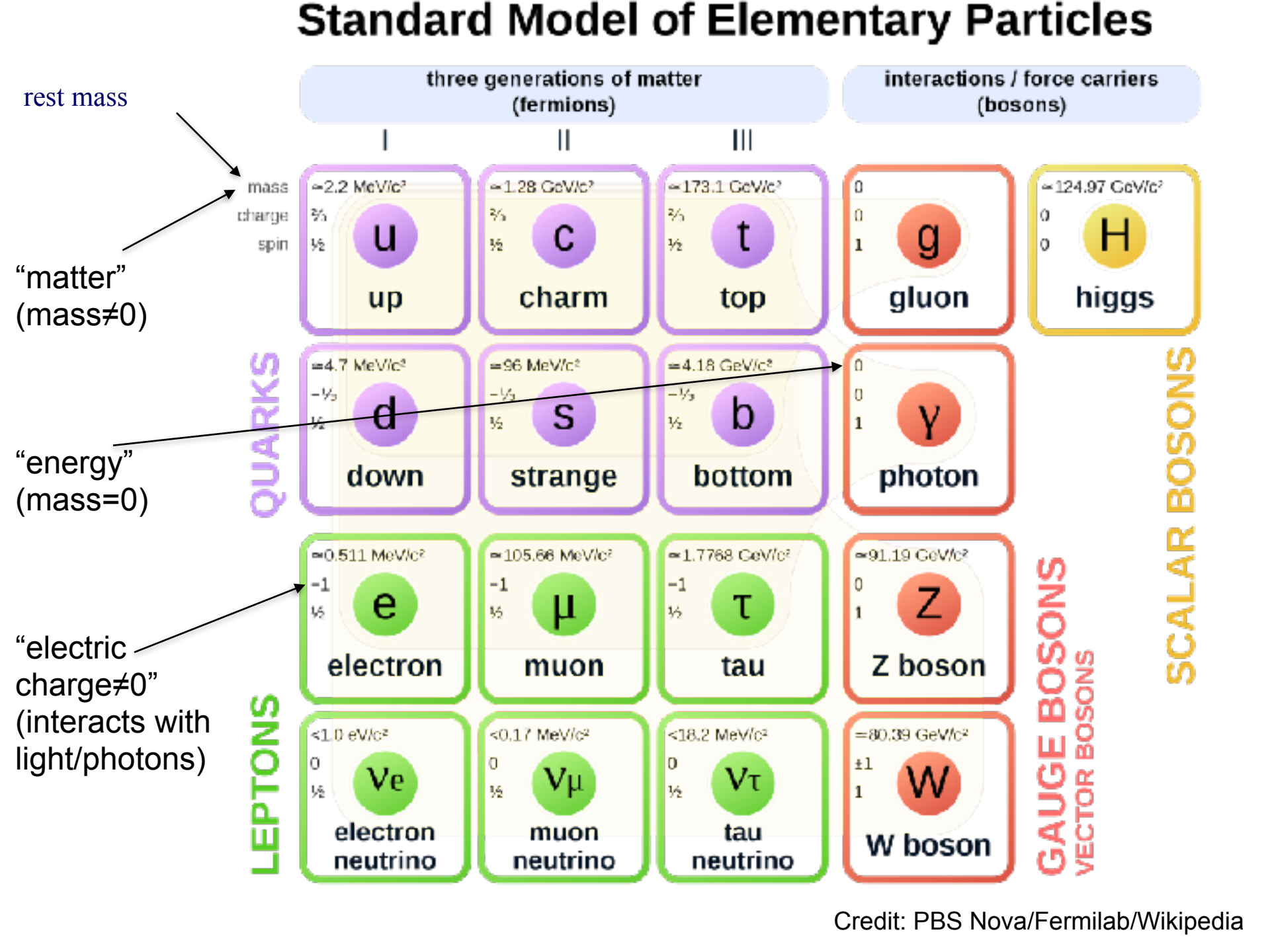
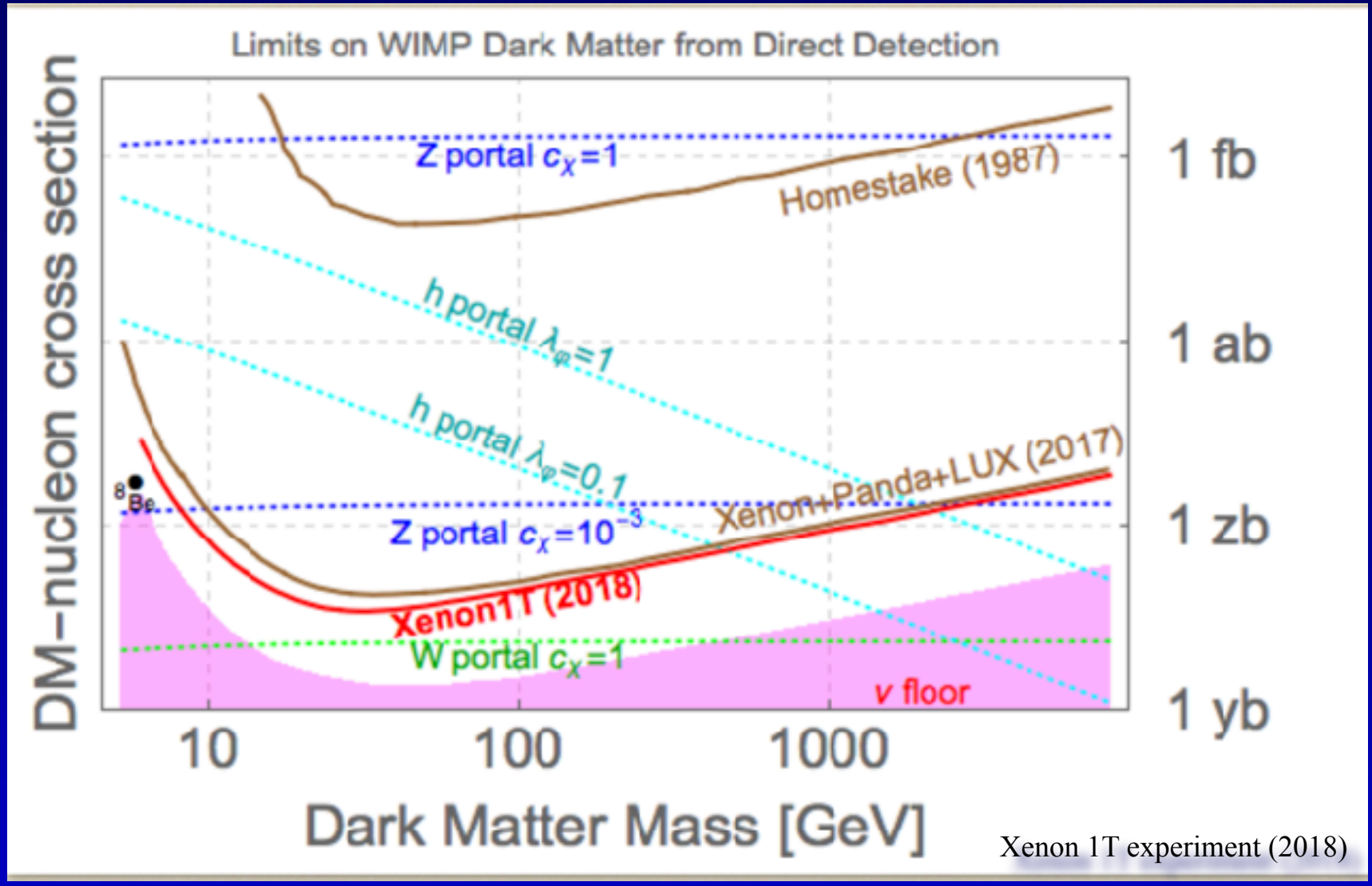


Credit: PBS Nova/Fermilab/Wikipedia

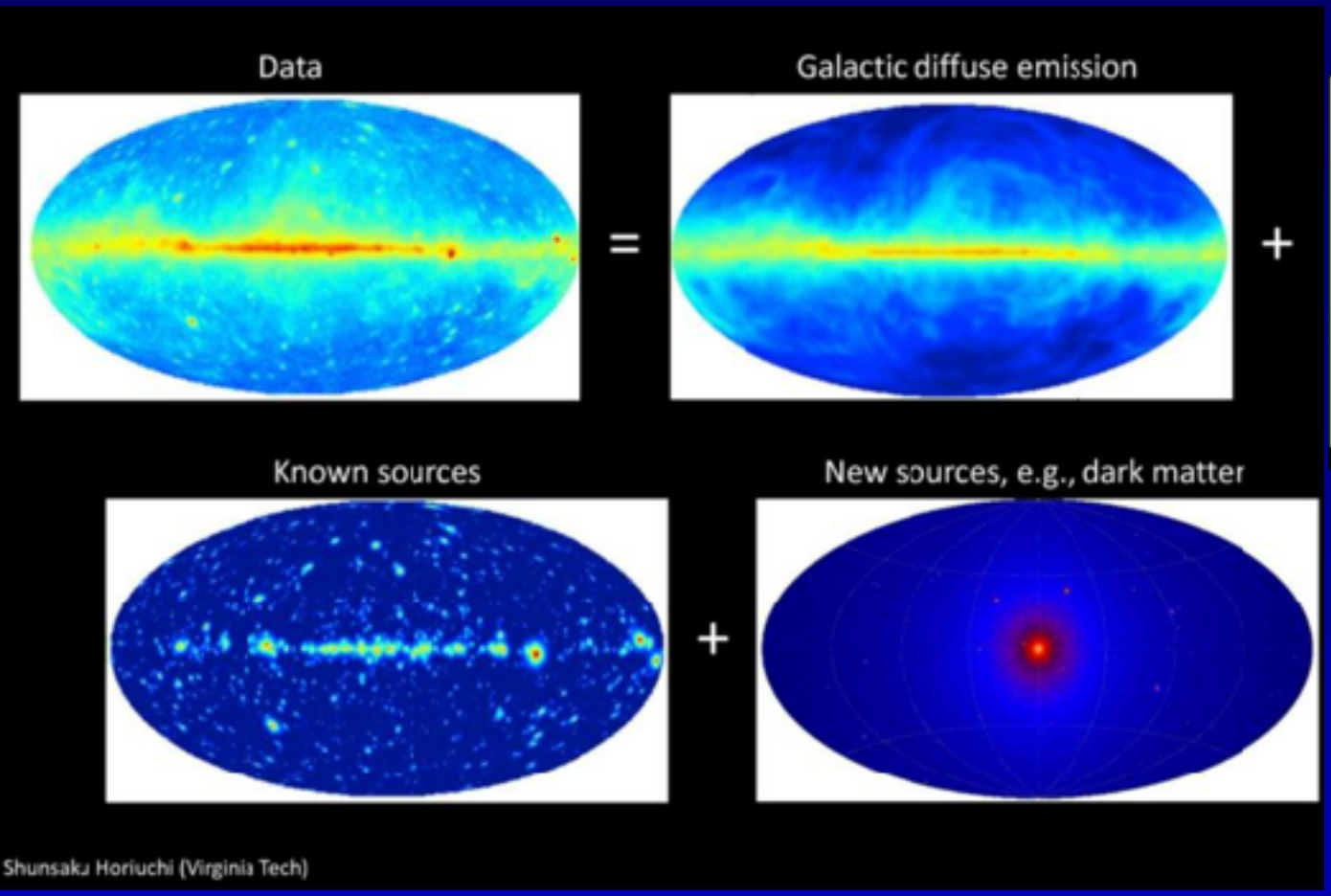
Dark Matter Crisis I: Detection Experiments

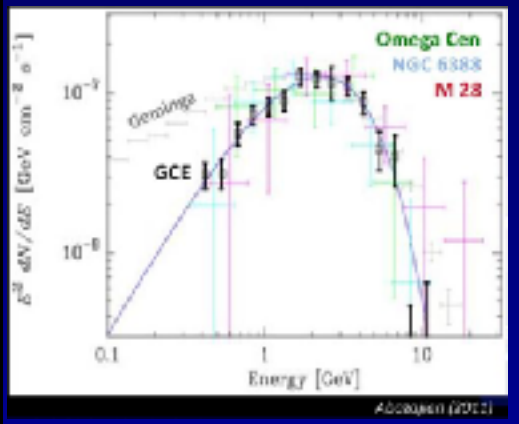


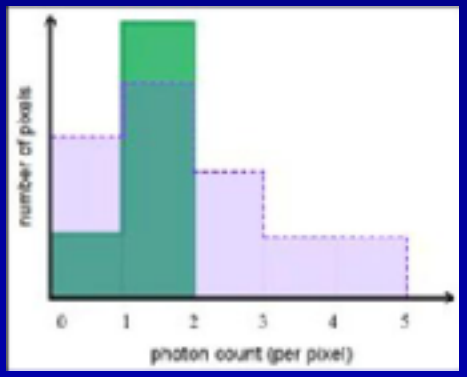
Xenon 1T experiment (2018)

The laboratory evidence for dark matter is still lacking: are WIMPS dead?

Dark Matter Crisis II: Indirect detection

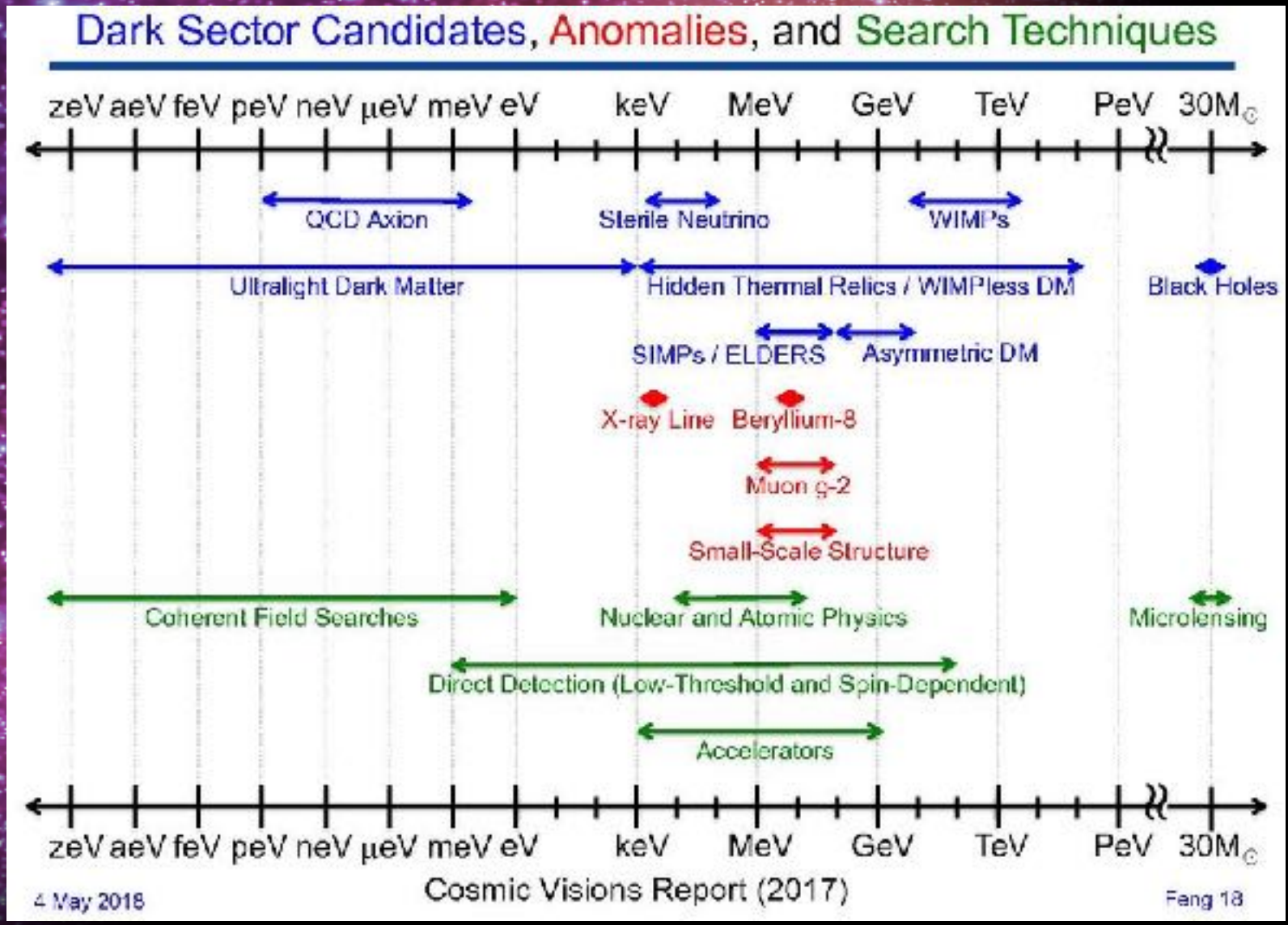


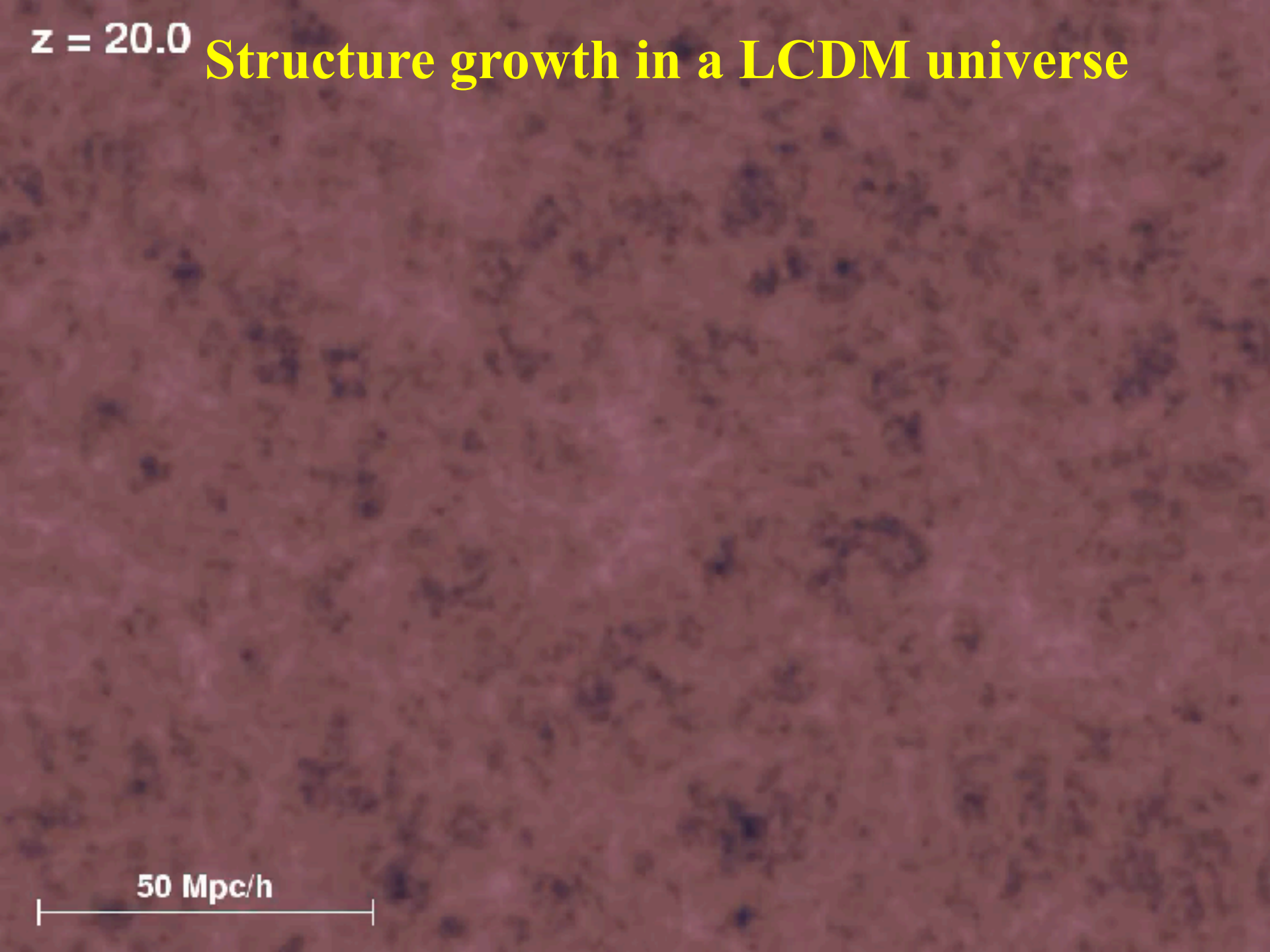


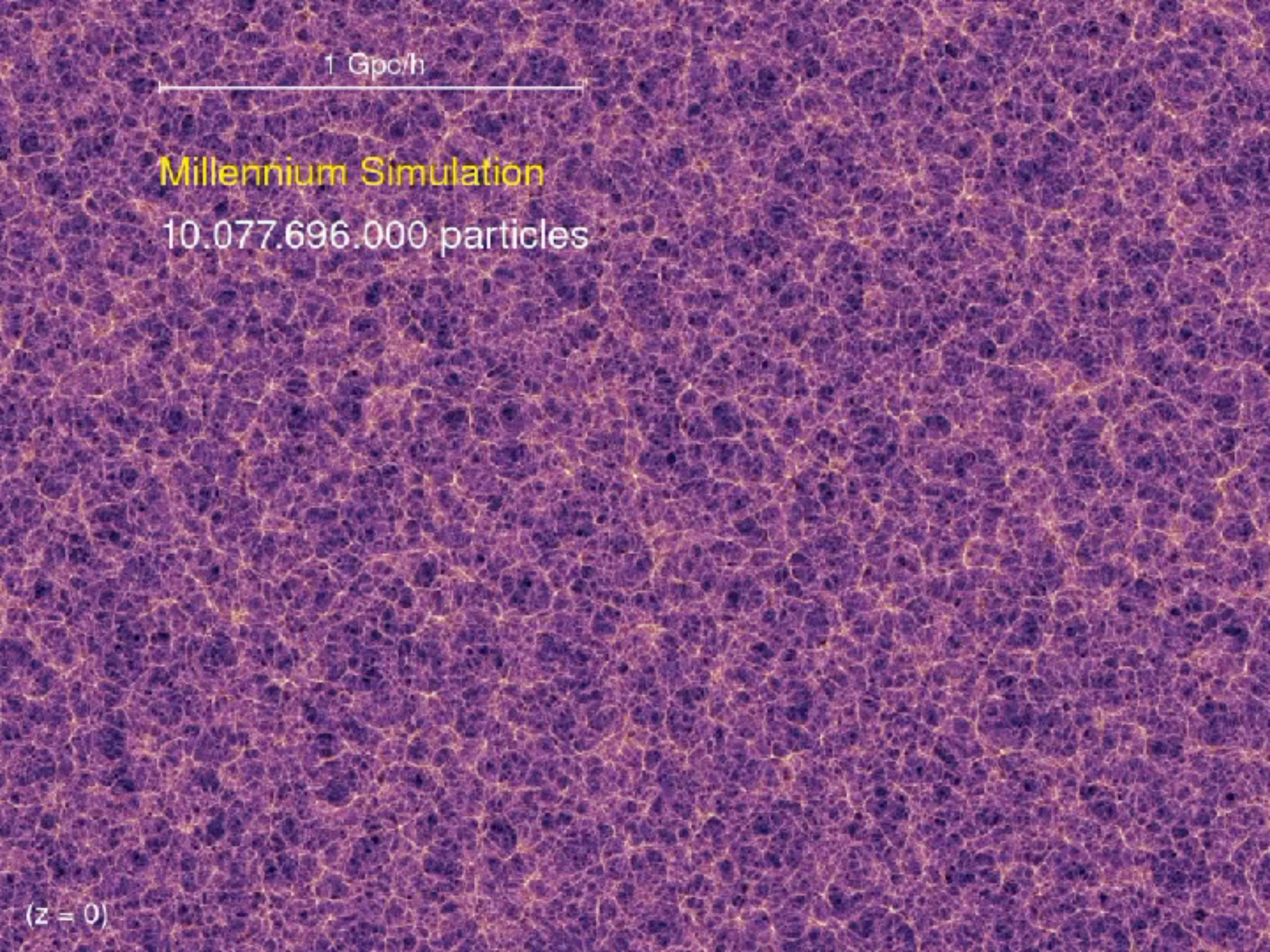


- Indirect evidence for dark matter (in the form of gamma-rays produced by its annihilation) is also controversial
- Astrophysics is in the (un)enviable position of being currently the only way we can probe dark matter properties
- Much of the progress is die to the completion of cosmological N-body simulations

The Future of DM Searches



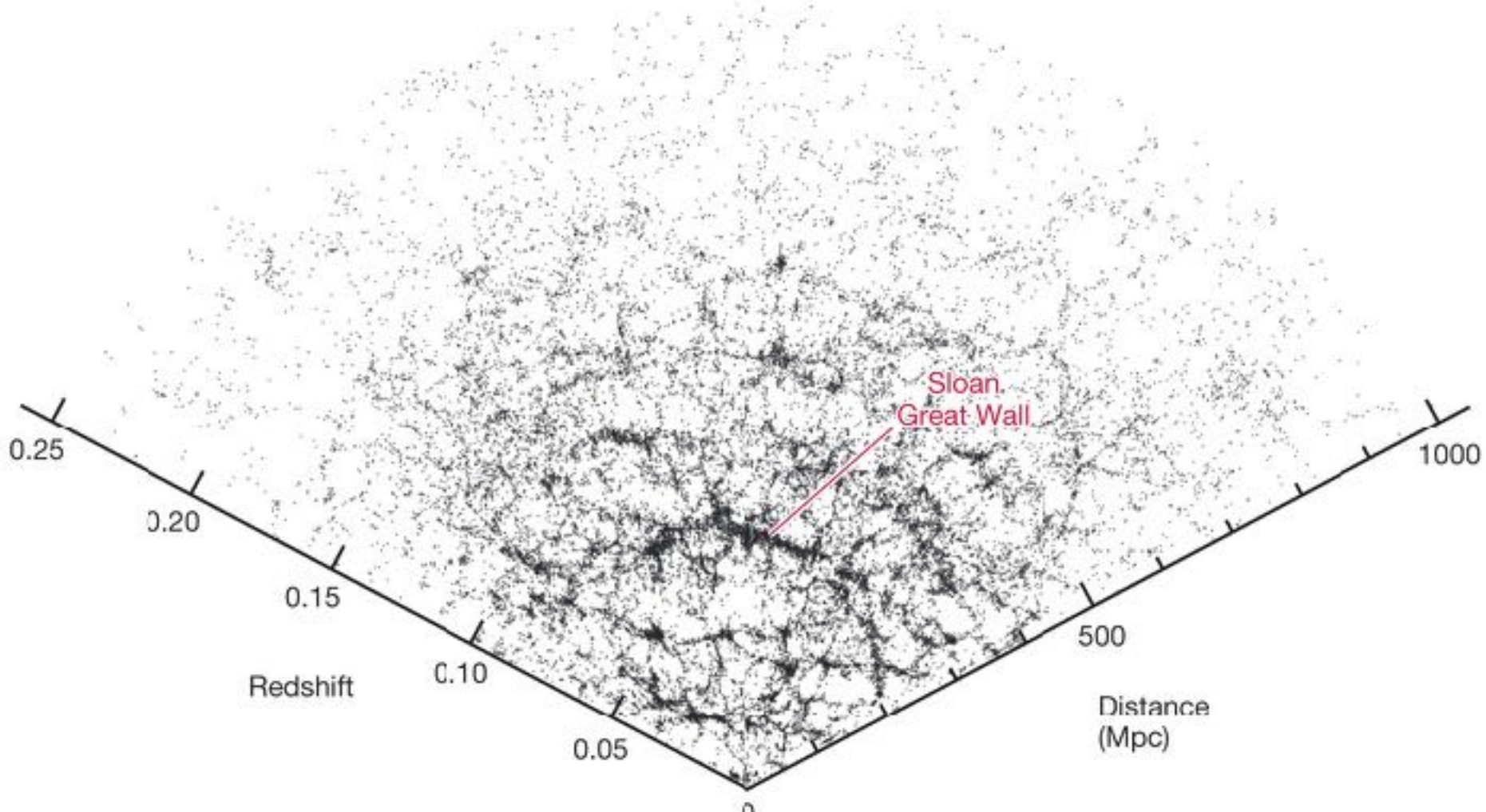

z = 20.0
Structure growth in a LCDM universe
50 Mpc/h


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

The Universe on Large Scales

On large scales (beyond a few tens of Mpc) the best estimate of "distance" to a galaxy is its redshift.

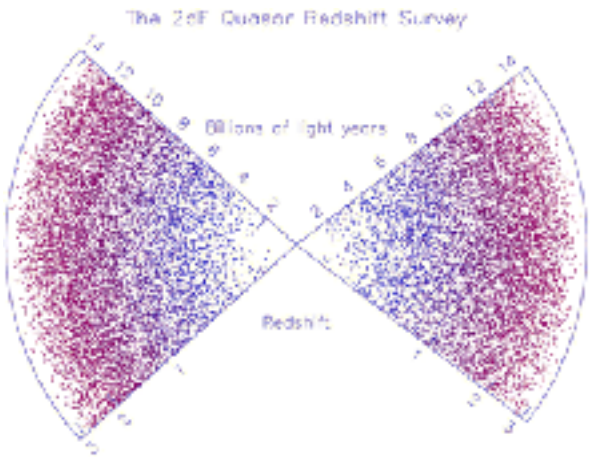
This galaxy map shows one of the largest structure known in the universe, the Sloan Great Wall.

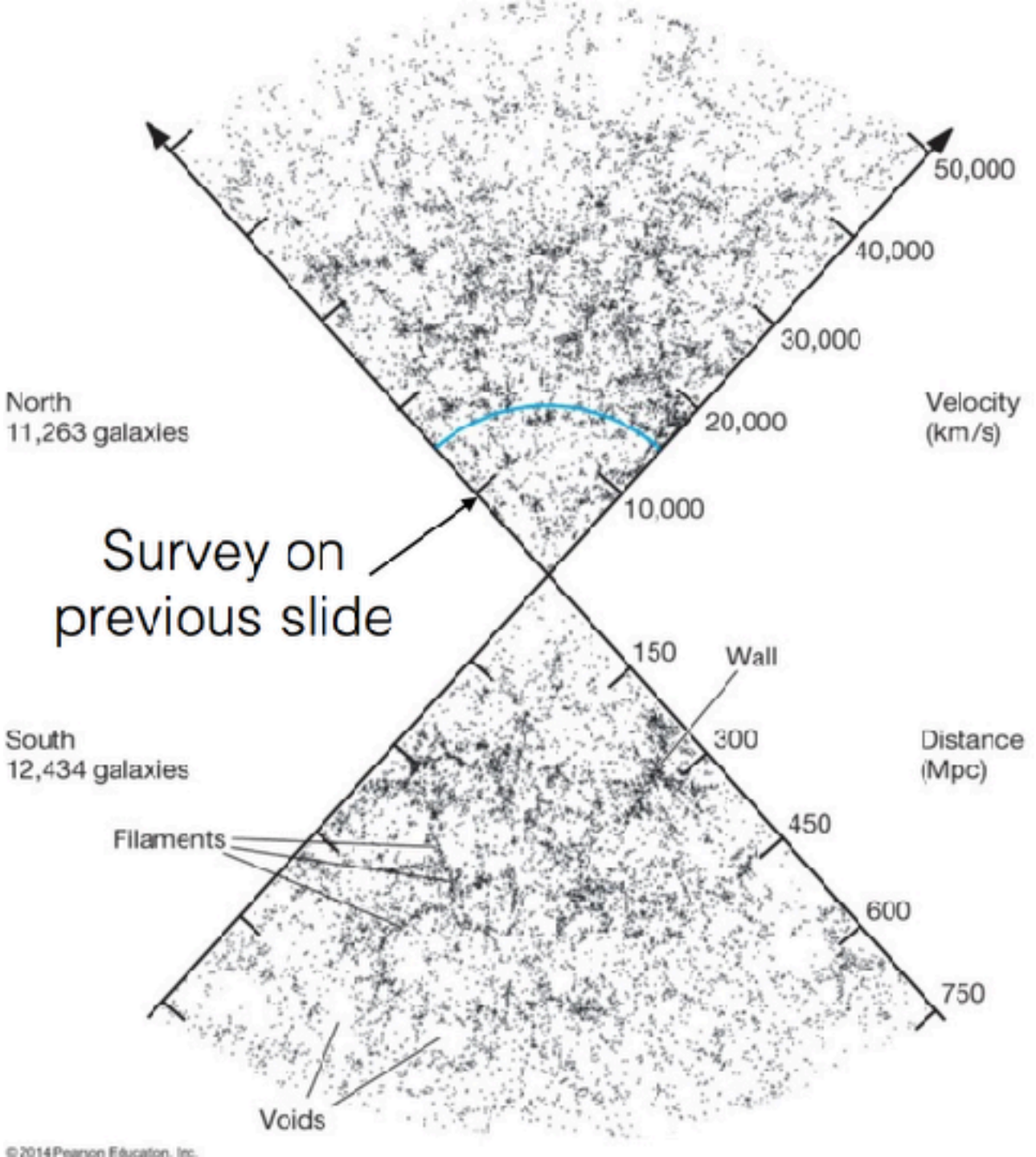


The Universe on Large Scales

On larger scales structures seem to "disappear".

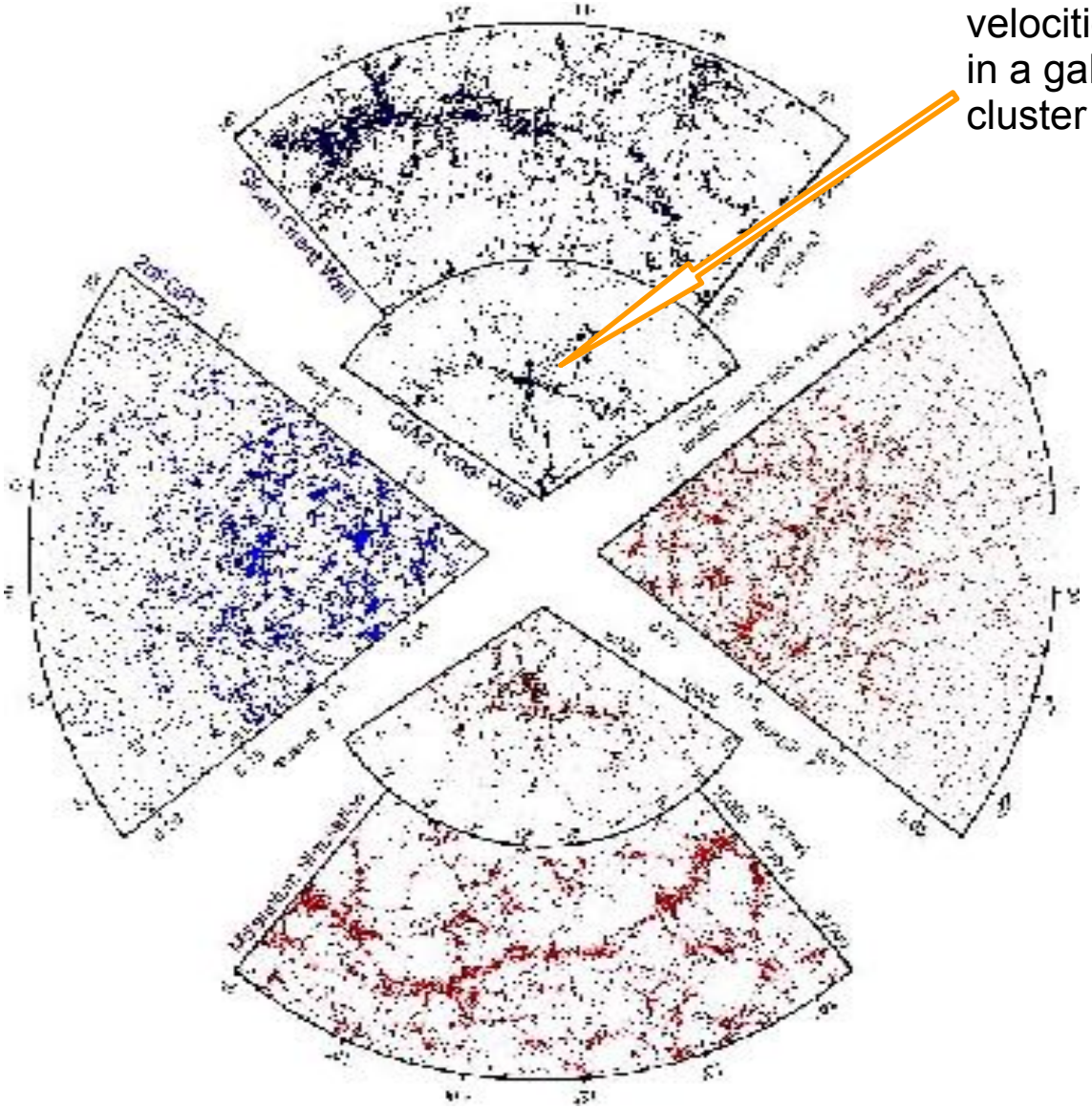
Beyond ~300 Mpc the Universe appears roughly uniform and isotropic



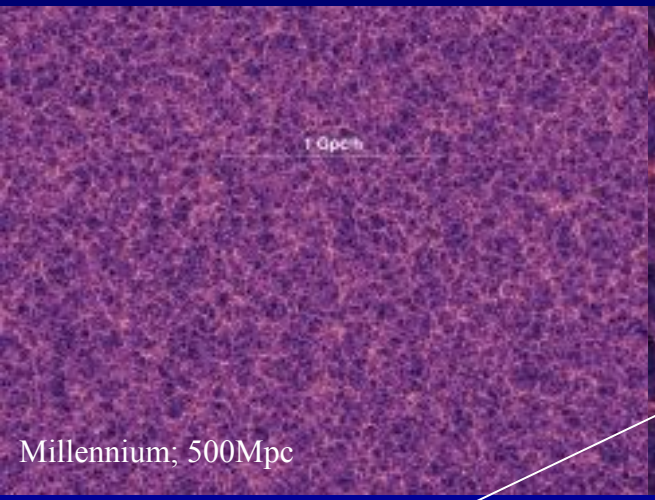


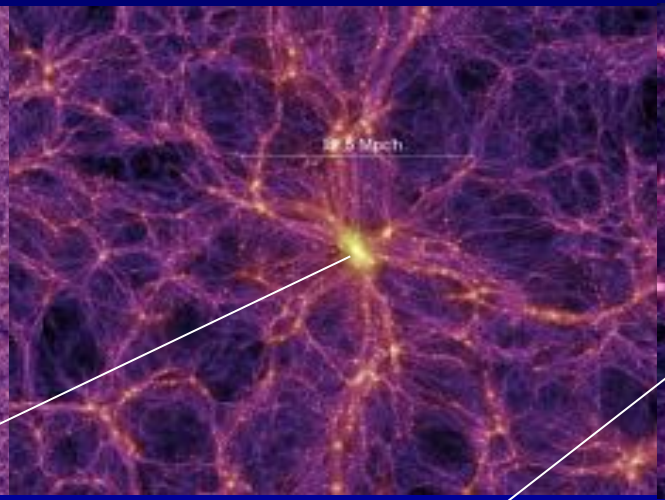
The Universe on Large Scales

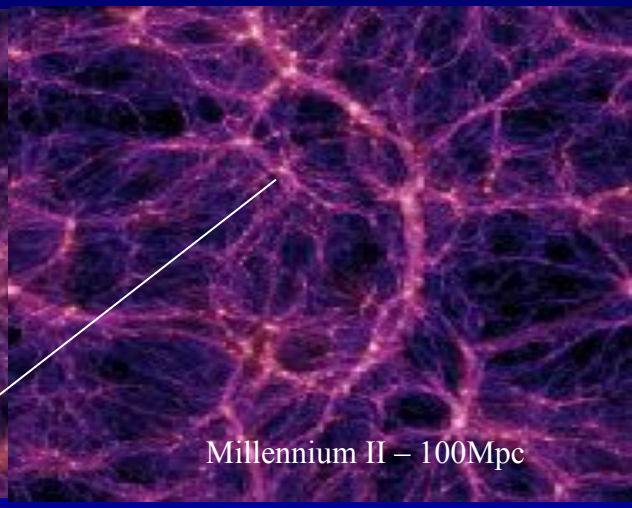
On smaller scales, “walls” and “fingers of God” (clusters) are clearly visible.



The Clustering of Dark Matter

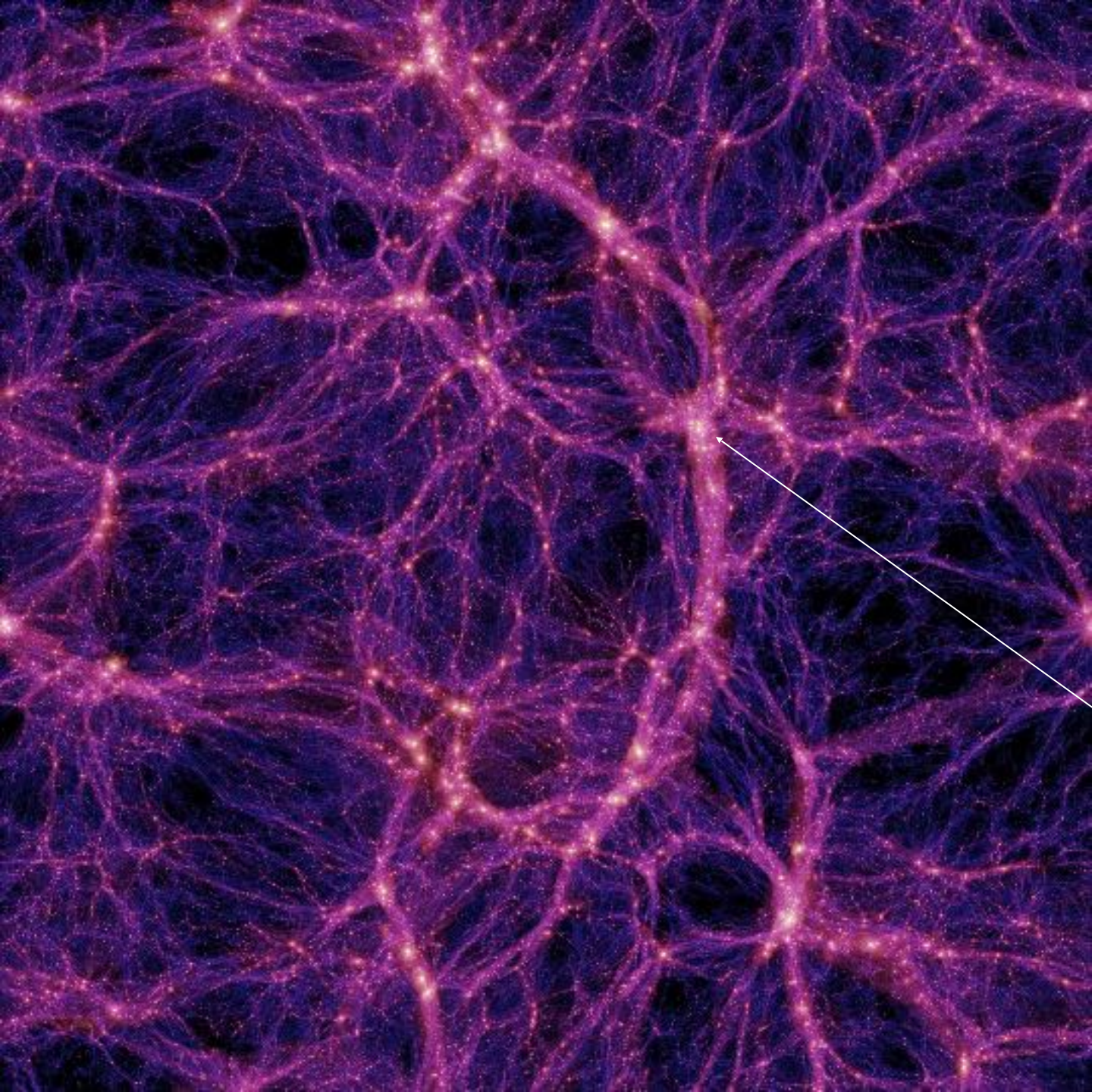






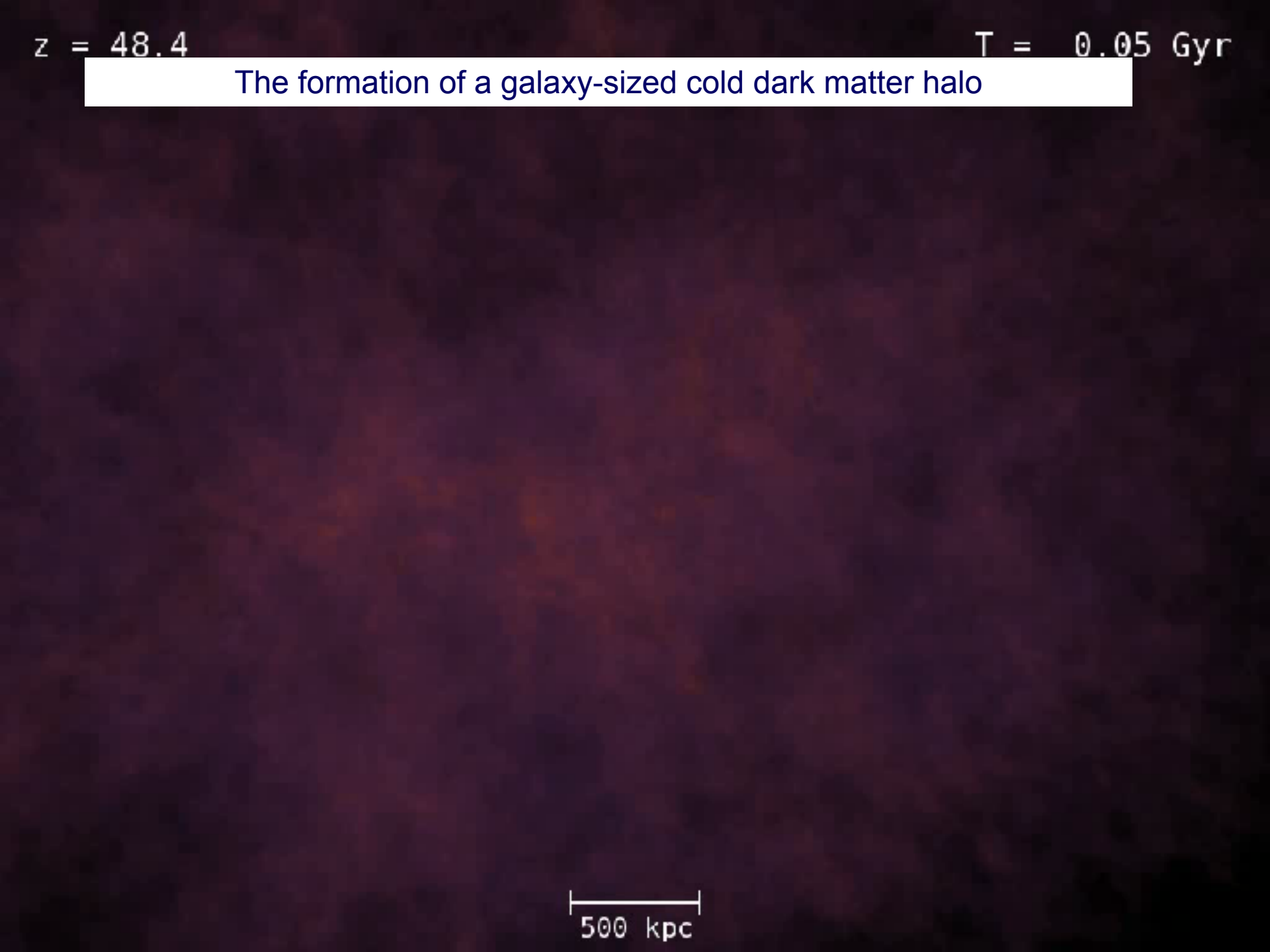
Simulations have enabled a full characterization of the clustering of cold dark matter on essentially all astrophysically-relevant scales.

Cold Dark Matter halos are self-similar

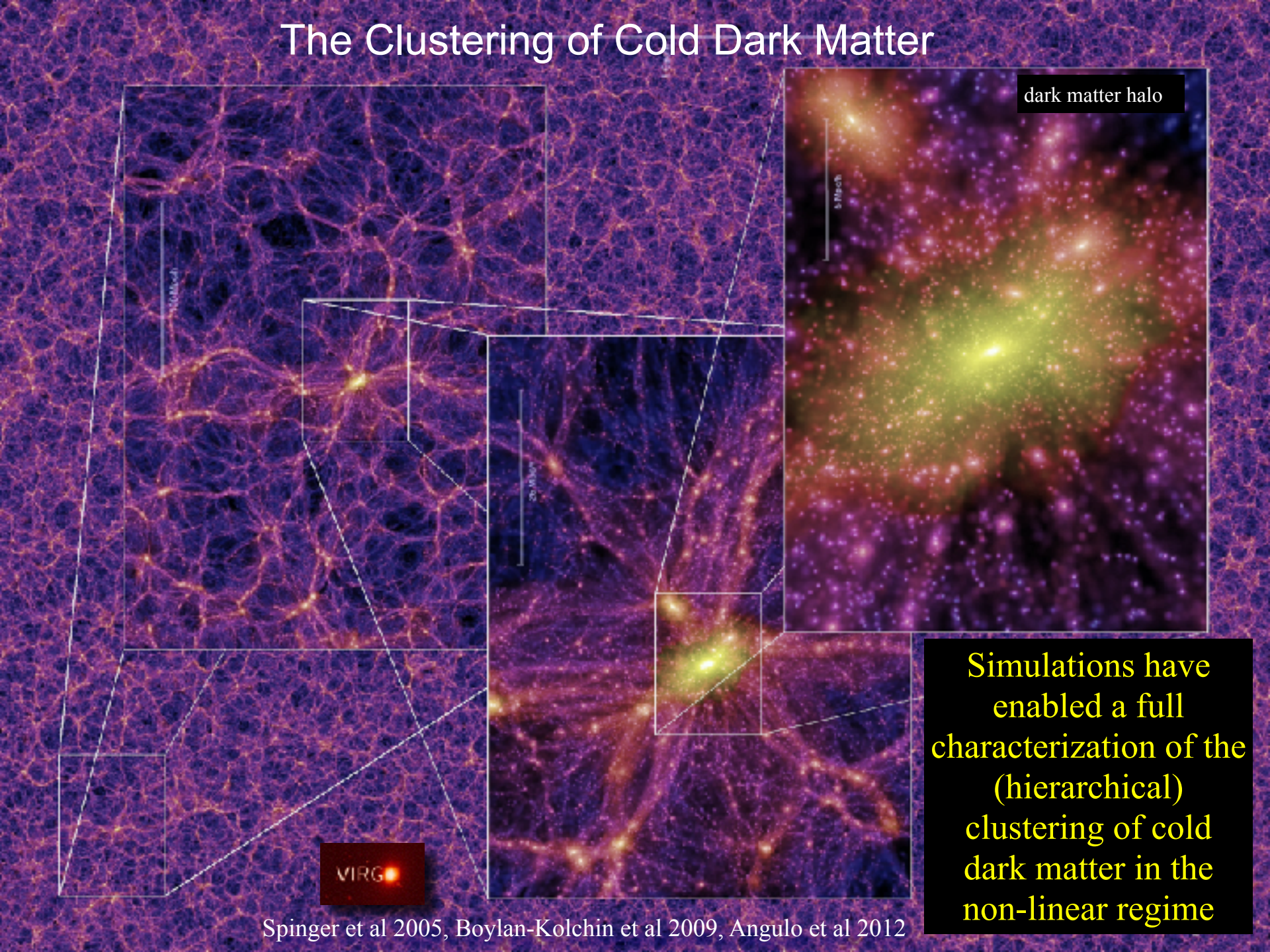


The Aquarius Project: Cold Dark Matter Halos under a Numerical Microscope

One of the Aquarius halos in the 100Mpc/h box parent simulation.


z = 48.4
T = 0.05 Gyr
The formation of a galaxy-sized cold dark matter halo
500 kpc

The Clustering of Cold Dark Matter



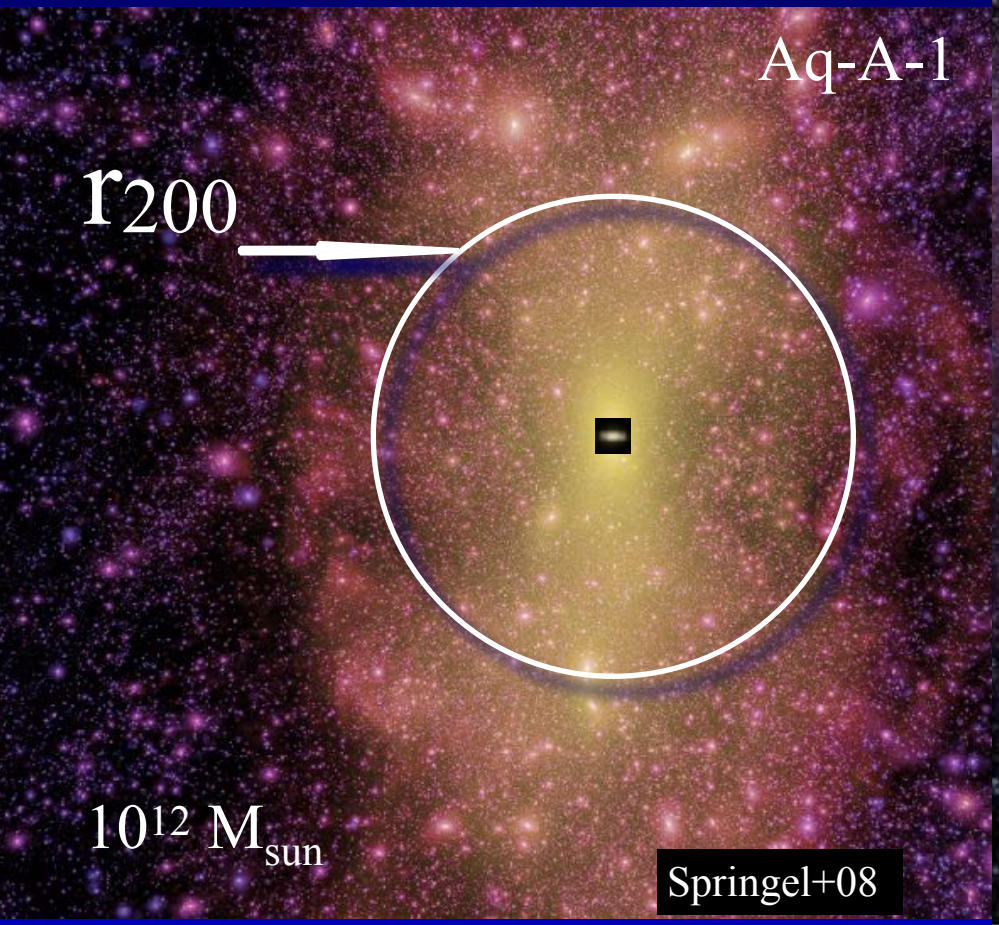
Simulations have enabled a full characterization of the (hierarchical) clustering of cold dark matter in the non-linear regime

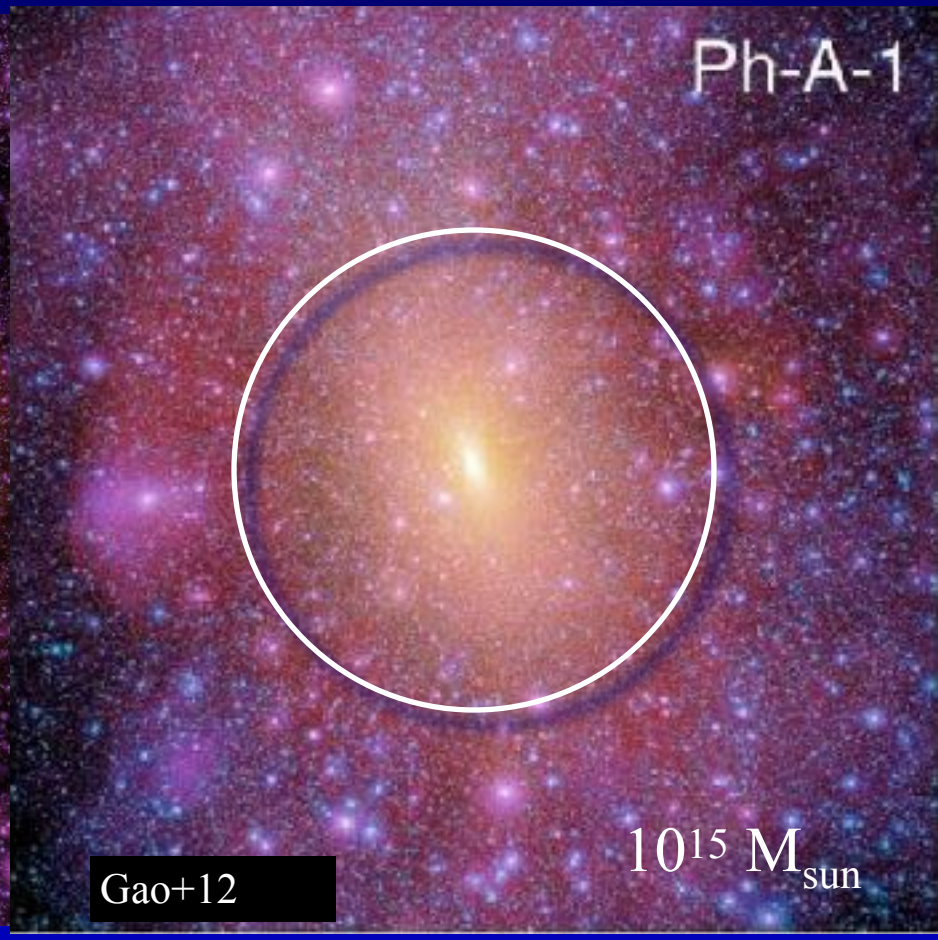
Spinger et al 2005, Boylan-Kolchin et al 2009, Angulo et al 2012

Cold Dark Matter halos

- Halos are the basic non-linear structures in LCDM
- Their abundance and clustering as a function of mass is well understood
- Their internal structure and substructure is approximately self-similar and well-characterized empirically

The self-similar nature of LCDM halos



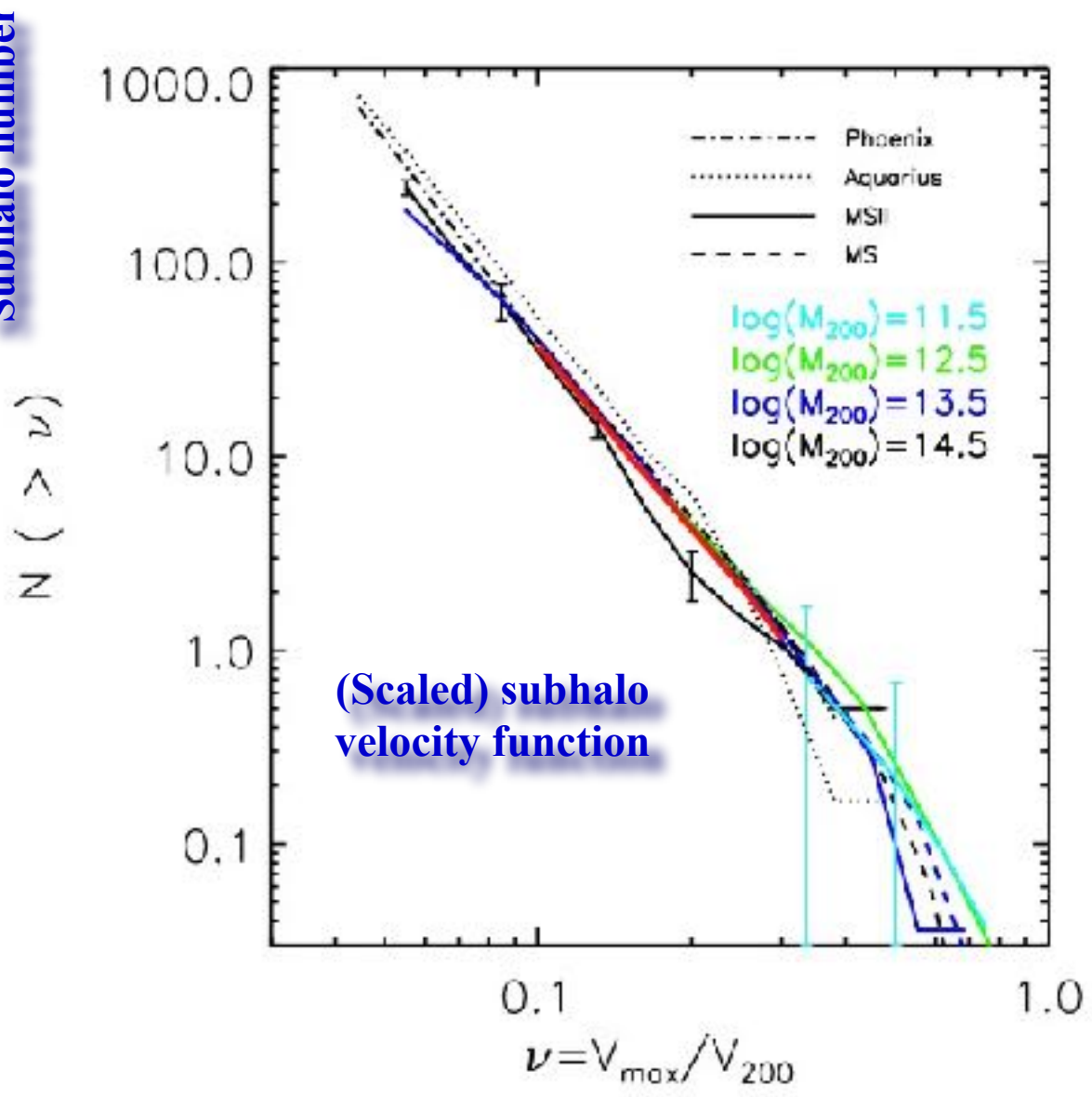


DM halos: self-similar structures linked by the age of the Universe

M_{200}/r_{200}^3=constant

$M_{200} \propto V_{200}^3$

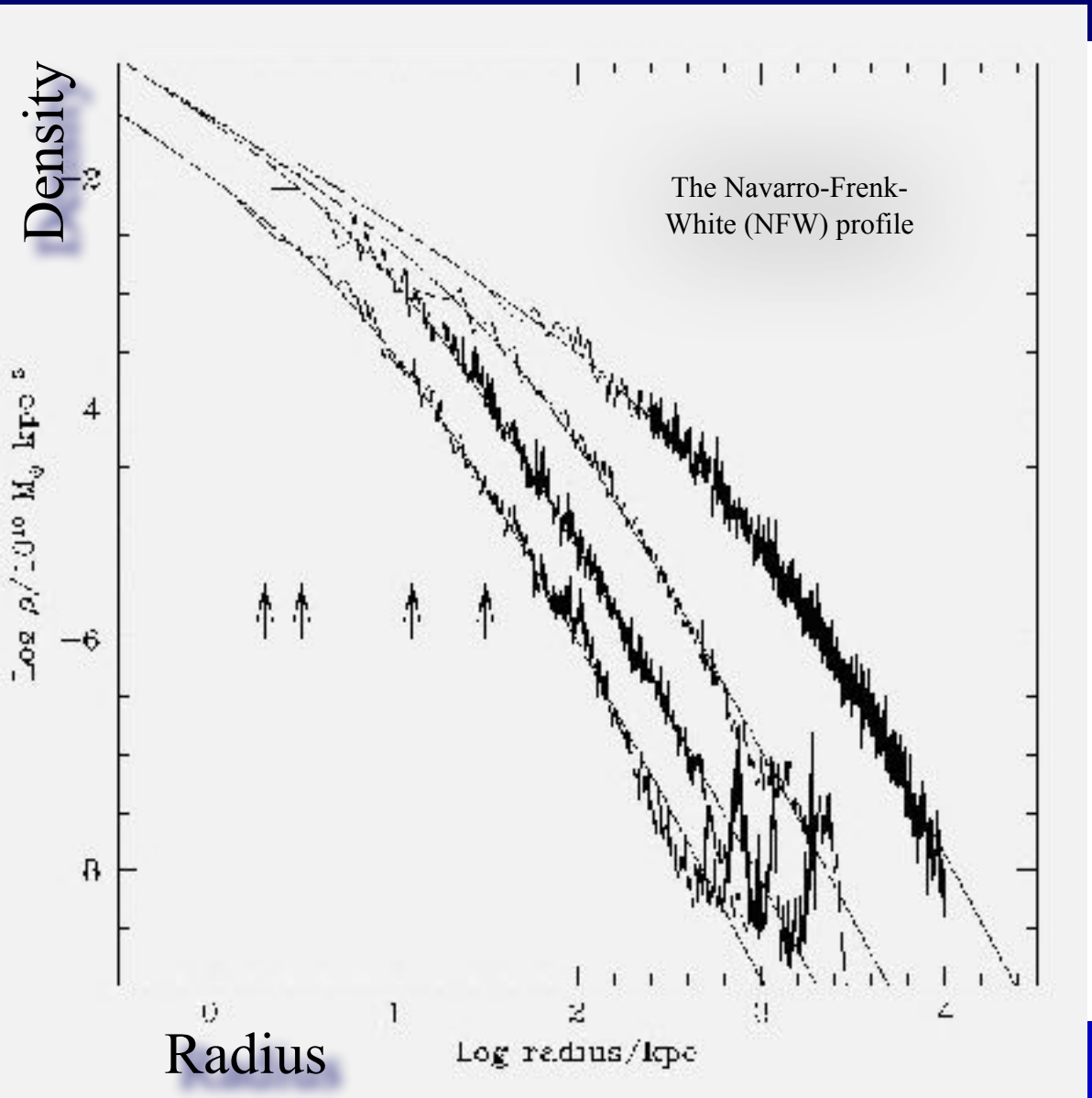
The invariance of the subhalo mass function



- The (scaled) subhalo mass function is independent of host halo mass
- More massive halos have more subhalos!
- Typically, halos have only one subhalo more massive than ~3% of the host halo virial mass

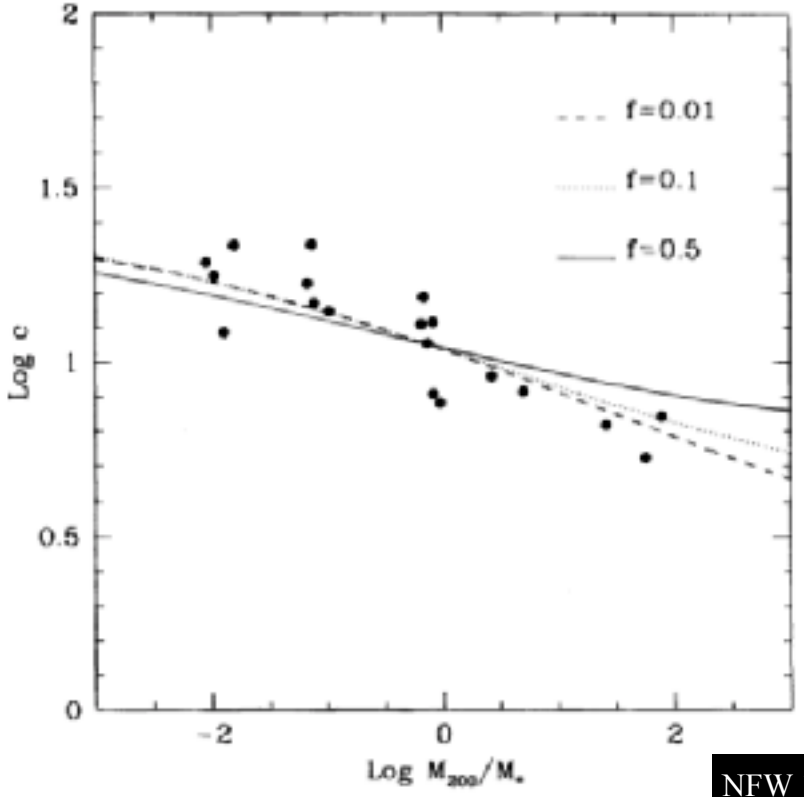
Wang et al 2012

The Mass Profile of Cold Dark Matter halos

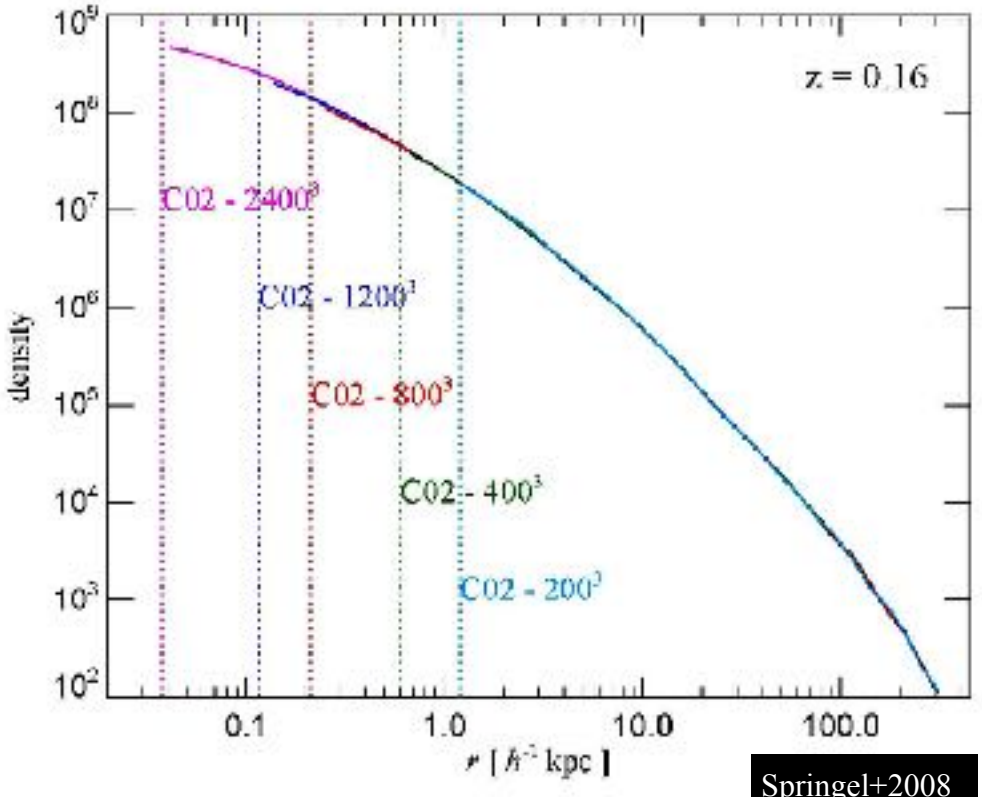


- The shape of the mass profiles of dark matter halos is roughly independent of halo mass and cosmological parameters
- Density profiles are "**cuspy**" and clearly differ from power laws
- May be fitted by scaling a simple formula $\rho/\rho_{crit}=\delta_c/[(r/r_s)(1+r/r_s)^2]$
- Curves do not cross

The mass-concentration relation



NFW 1996



Springel+2008

- Halos are usually parameterized by the virial mass, M_{200}, and a "concentration" $c=r_{200}/r_s$
- What determines the mass-concentration relation?
- What determines the particular "shape" of the NFW profile?

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 58:39–66, 1985 May
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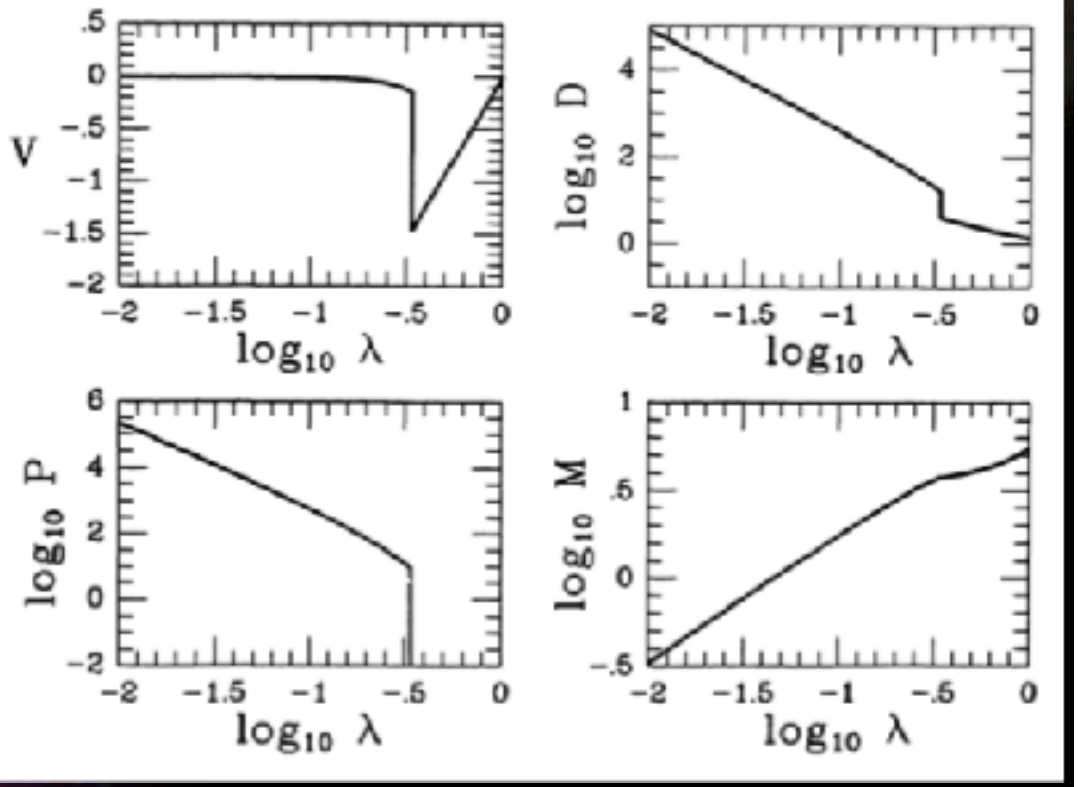
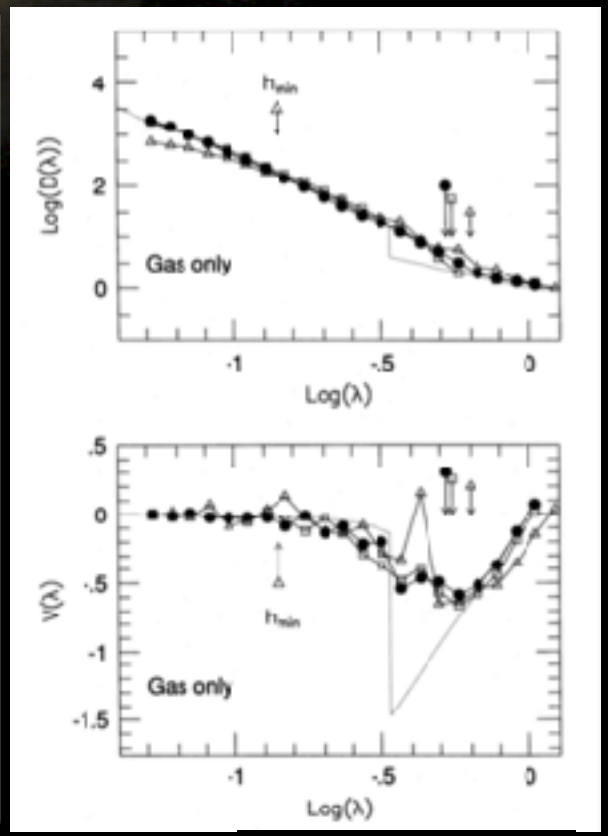
Self-similar gravitational clustering

SELF-SIMILAR SECONDARY INFALL AND ACCRETION IN AN EINSTEIN–DE SITTER UNIVERSE

EDMUND BERTSCHINGER
Princeton University Observatory; and Department of Astronomy, University of Virginia
...ted 1984 November 15

Gas accretion onto a point mass perturber; Ω=1

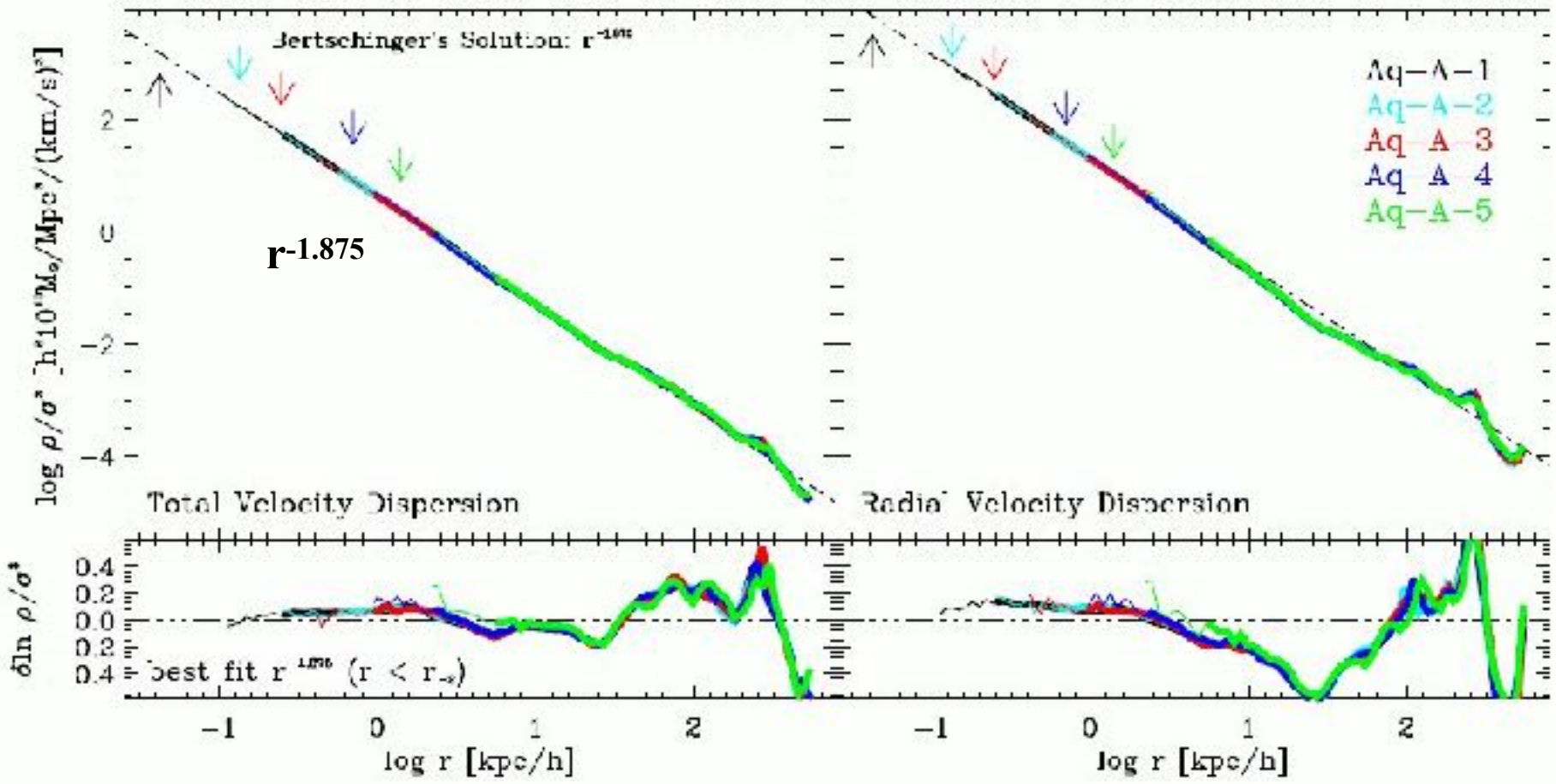




ρ/σ^3 (or PV^{γ}) is a power law of radius

Navarro & White 1993

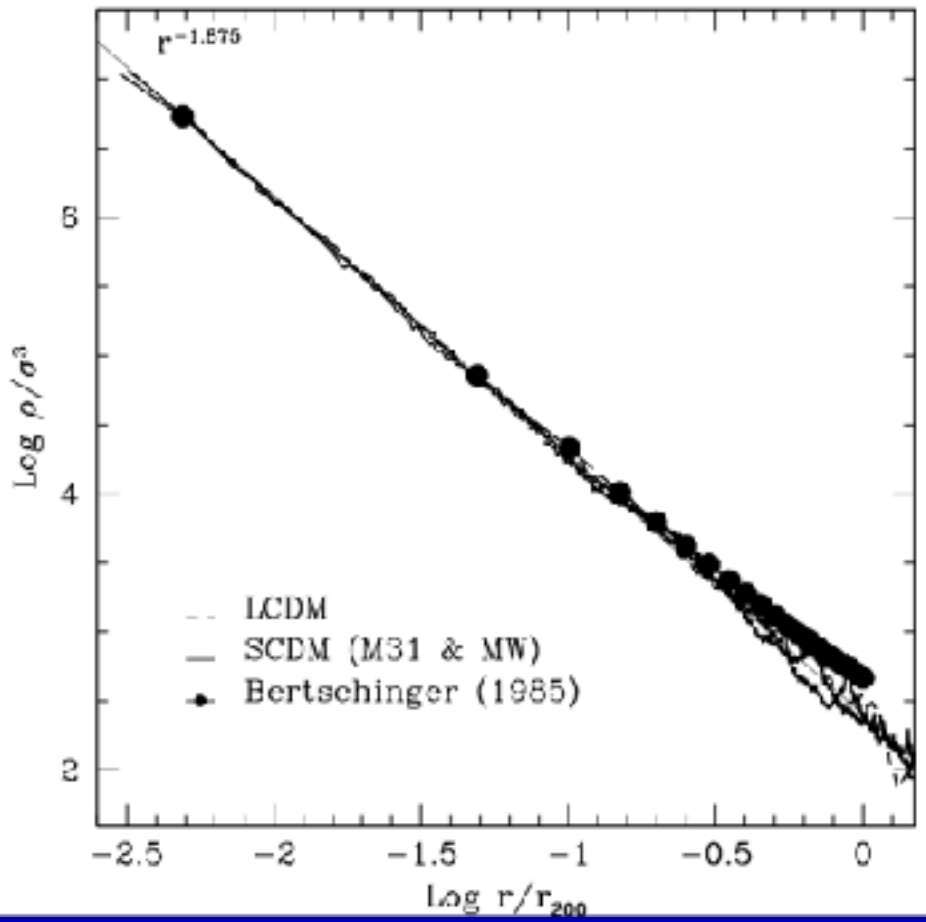
The "Phase-Space Density" Profile

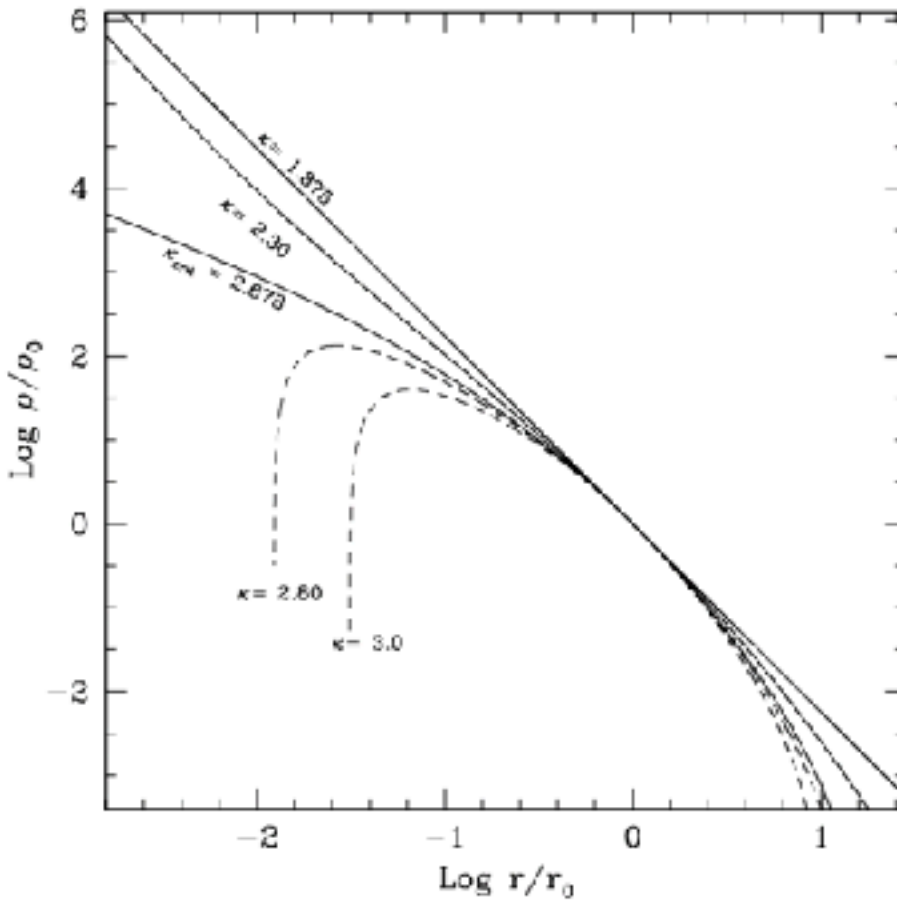


- Remarkably, the "phase-space density", ρ/σ^3, scales like a power law of radius
- This is the same dependence as in Bertschinger's secondary infall similarity solution
- Radial shells of dark matter settle at radii proportional to their turnaround radius

Taylor & Navarro 2001

The "Phase-Space Density" Profile





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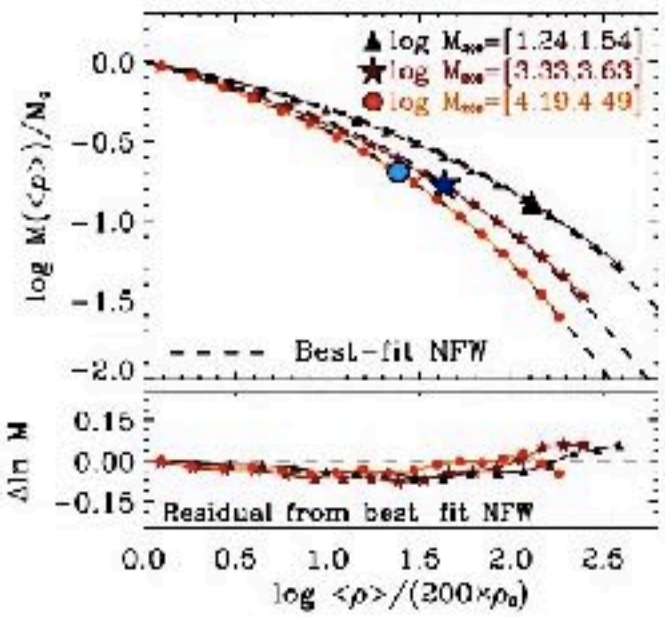
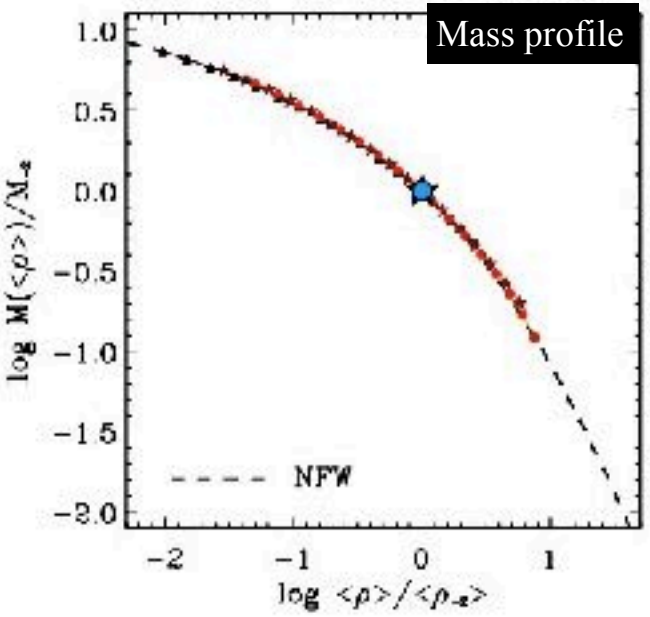
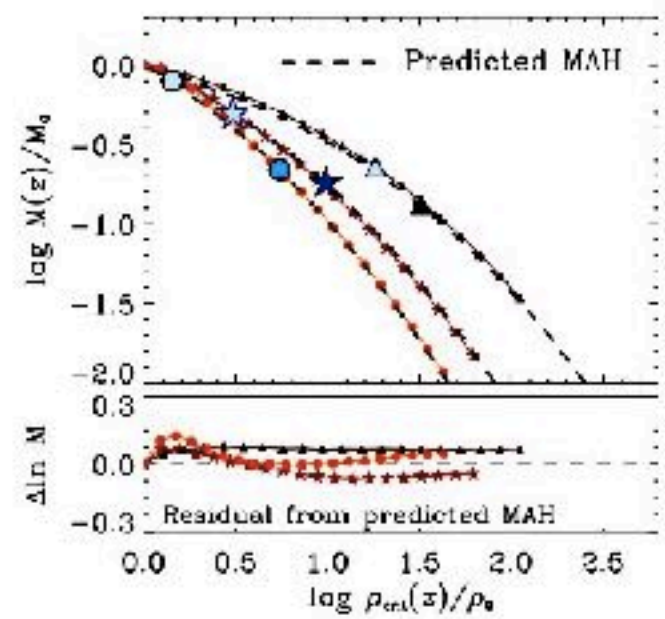
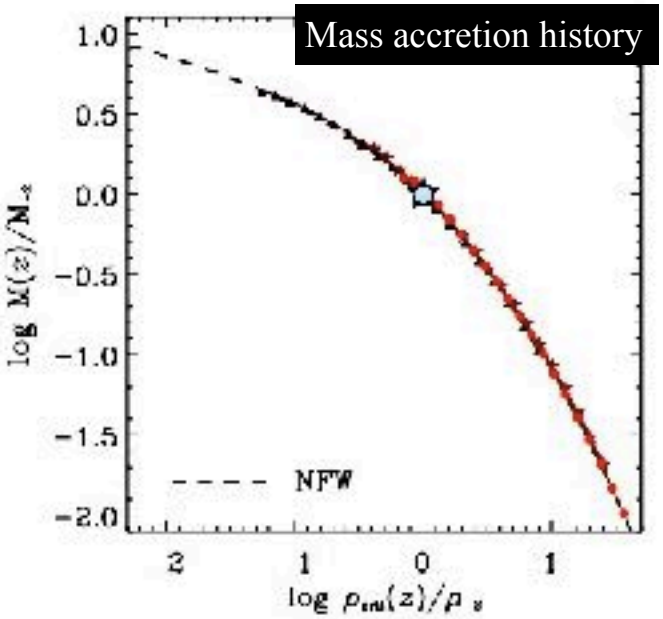
Origin of the NFW concentration and shape





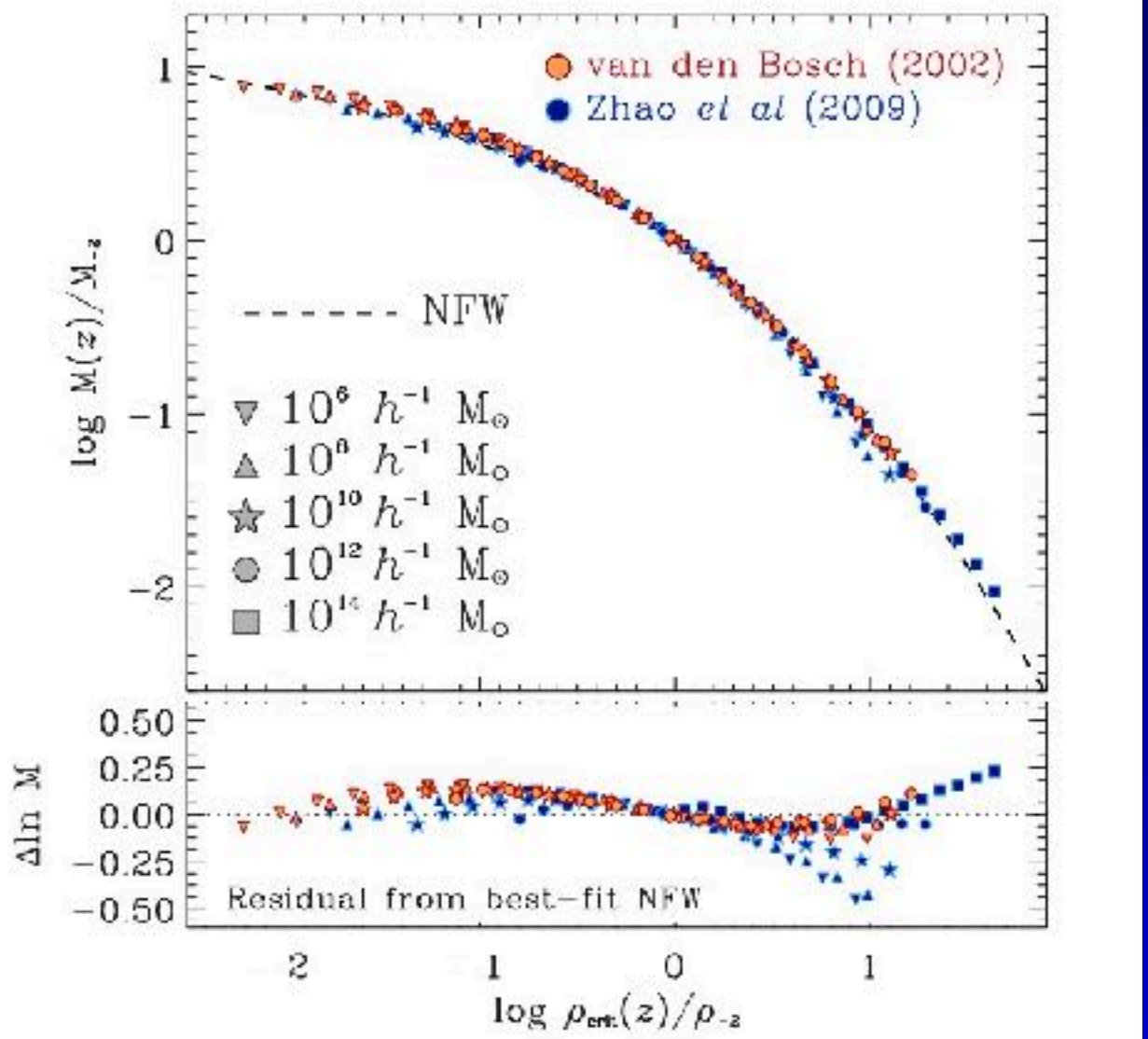




- The shape of the mass profile resembles that of the accretion history.
- Both are well approximated by the NFW shape
- Similarity of mass profiles is due to similarity of mass accretion histories (van den Bosch 2002)

Ludlow+NFW+2014

Accretion history shapes are independent of mass

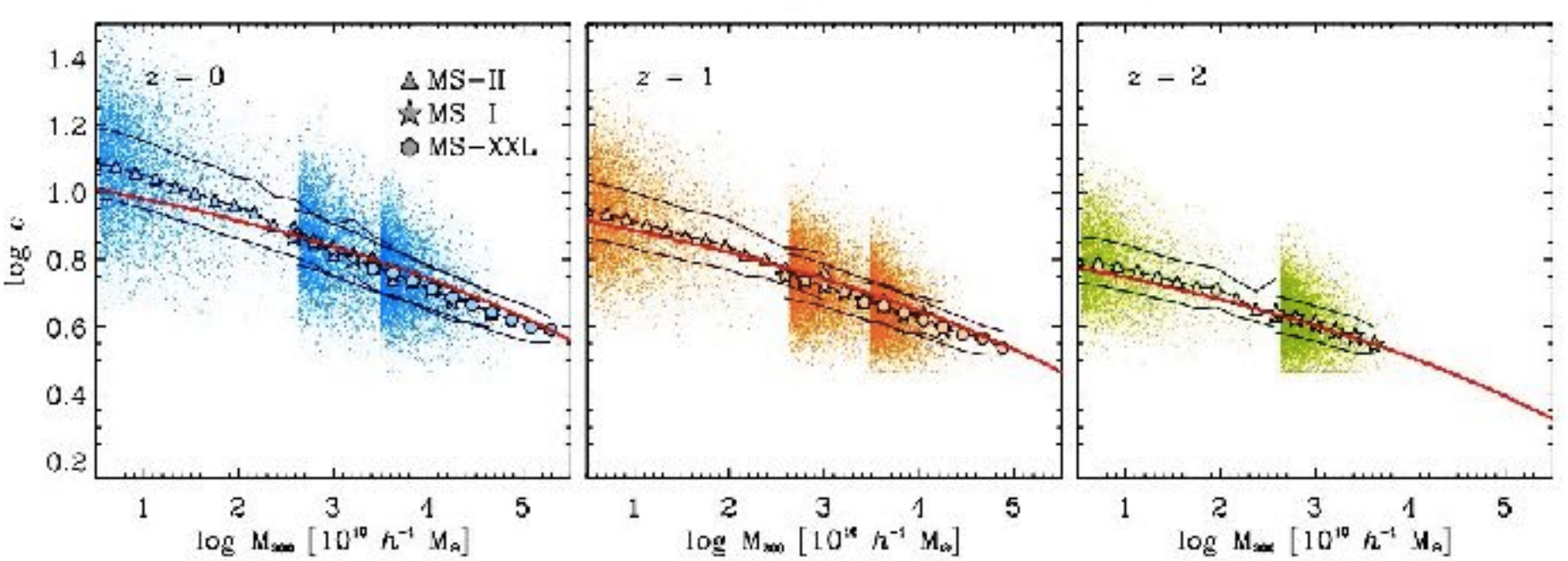


Origin of the Concentration and Shape Parameters

- Halo mass profiles are nearly self-similar because mass accretion histories are nearly self-similar.

Ludlow+NFW+2014

Origin of the Concentration and Shape Parameters

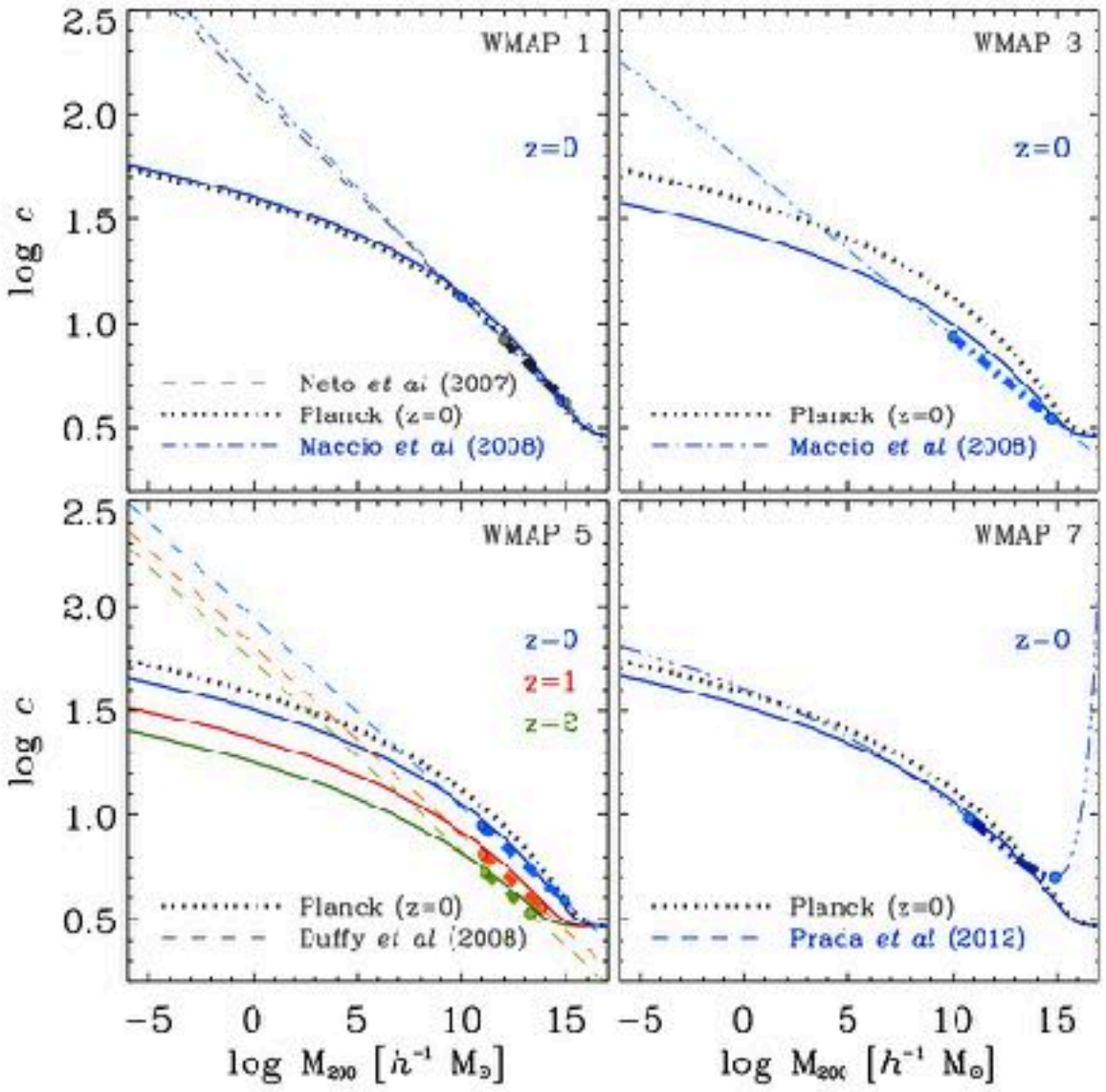


Concentrations PREDICTED from the mass accretion histories of individual halos

- Mass accretion histories may be used to predict successfully the dependence of the concentration on mass and redshift.

Ludlow+NFW+2014

Mass-concentration relation

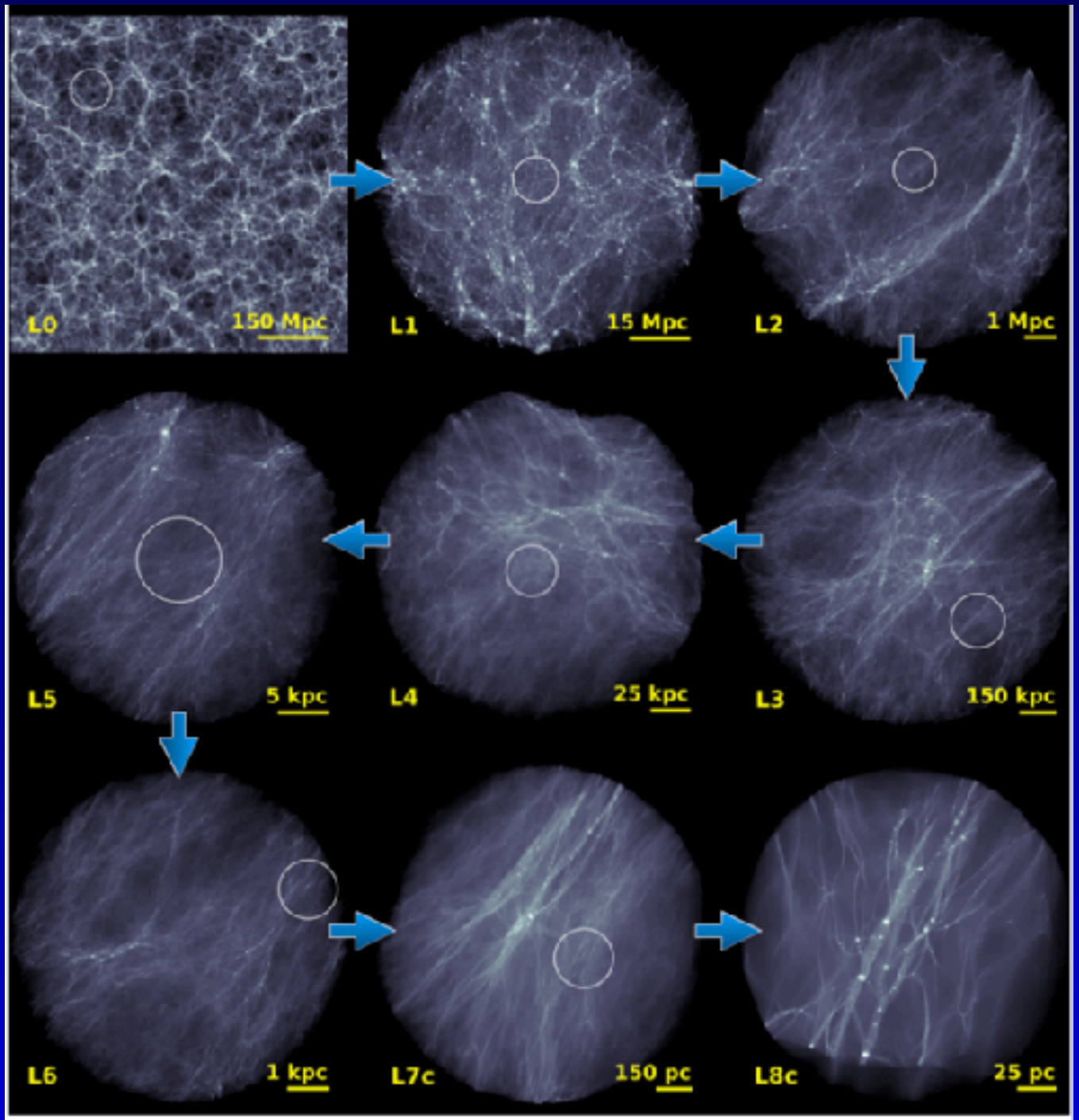


Origin of the Concentration and Shape Parameters

- Concentrations approach a constant value at high masses and are much low halo mass than expected from extrapolations of power-law fits to simulations of limited mass resolution range

- Can have a large effect (~10+) on substructure self-annihilation "boost" factors

Ludlow+NFW+2014



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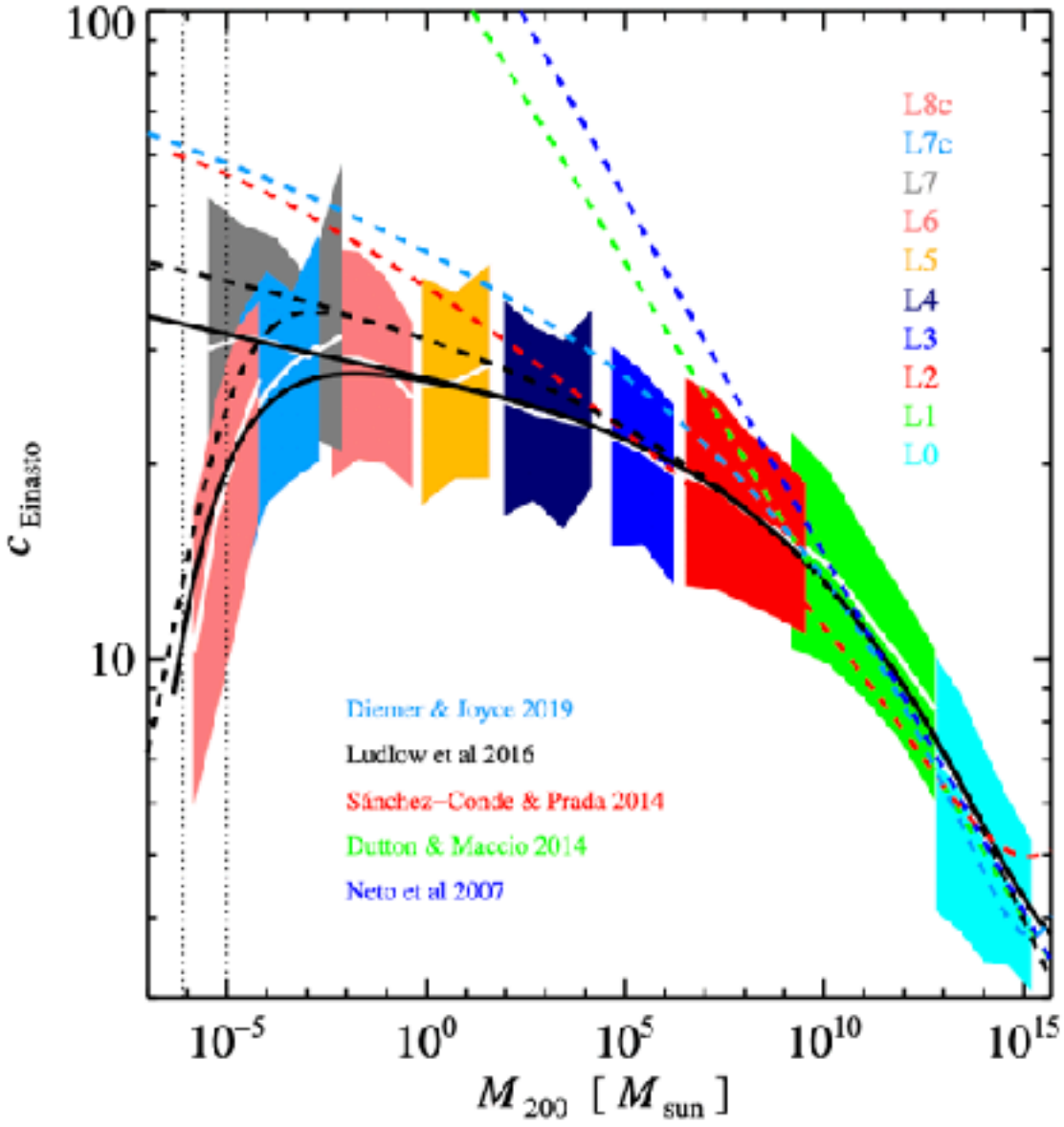
Wang+2020

Mass-concentration relation



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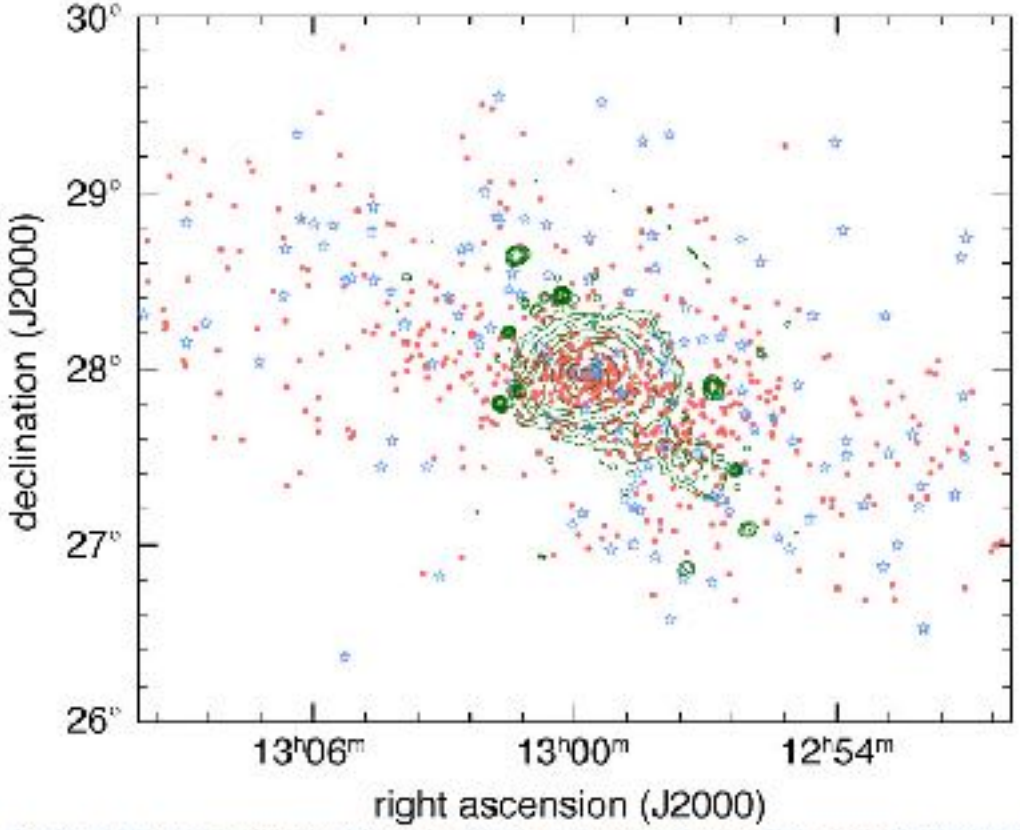
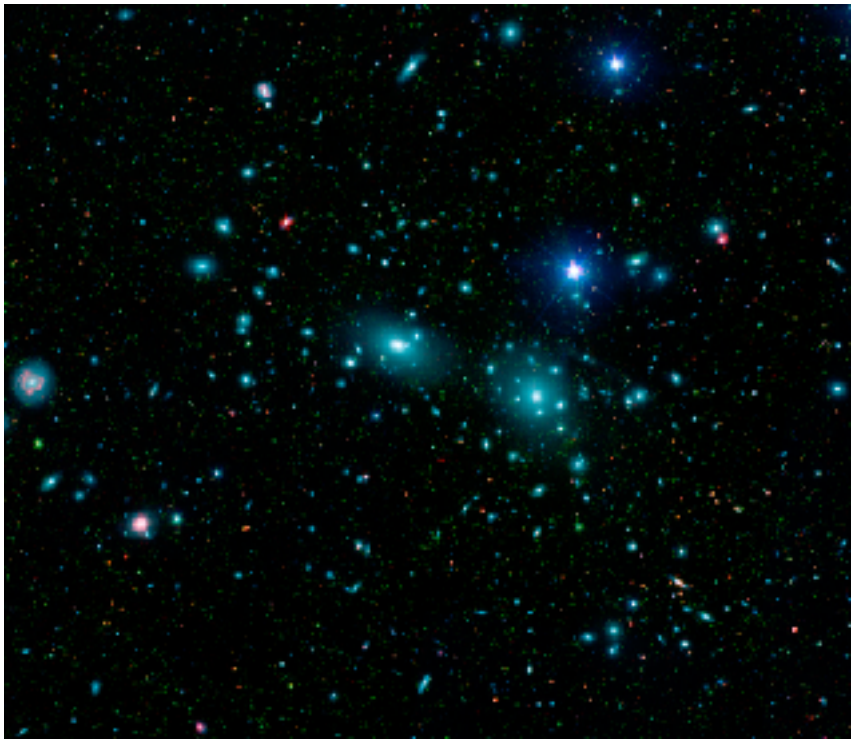
Wang+2020

Rich Galaxy Clusters

- The Coma cluster is one of the most massive nearby clusters
  - Large fraction of E and S0 galaxies, especially near the center
  - Ellipticals are the orange dots
  - Spirals are the open starred symbols
  - X-ray contours are shown in green

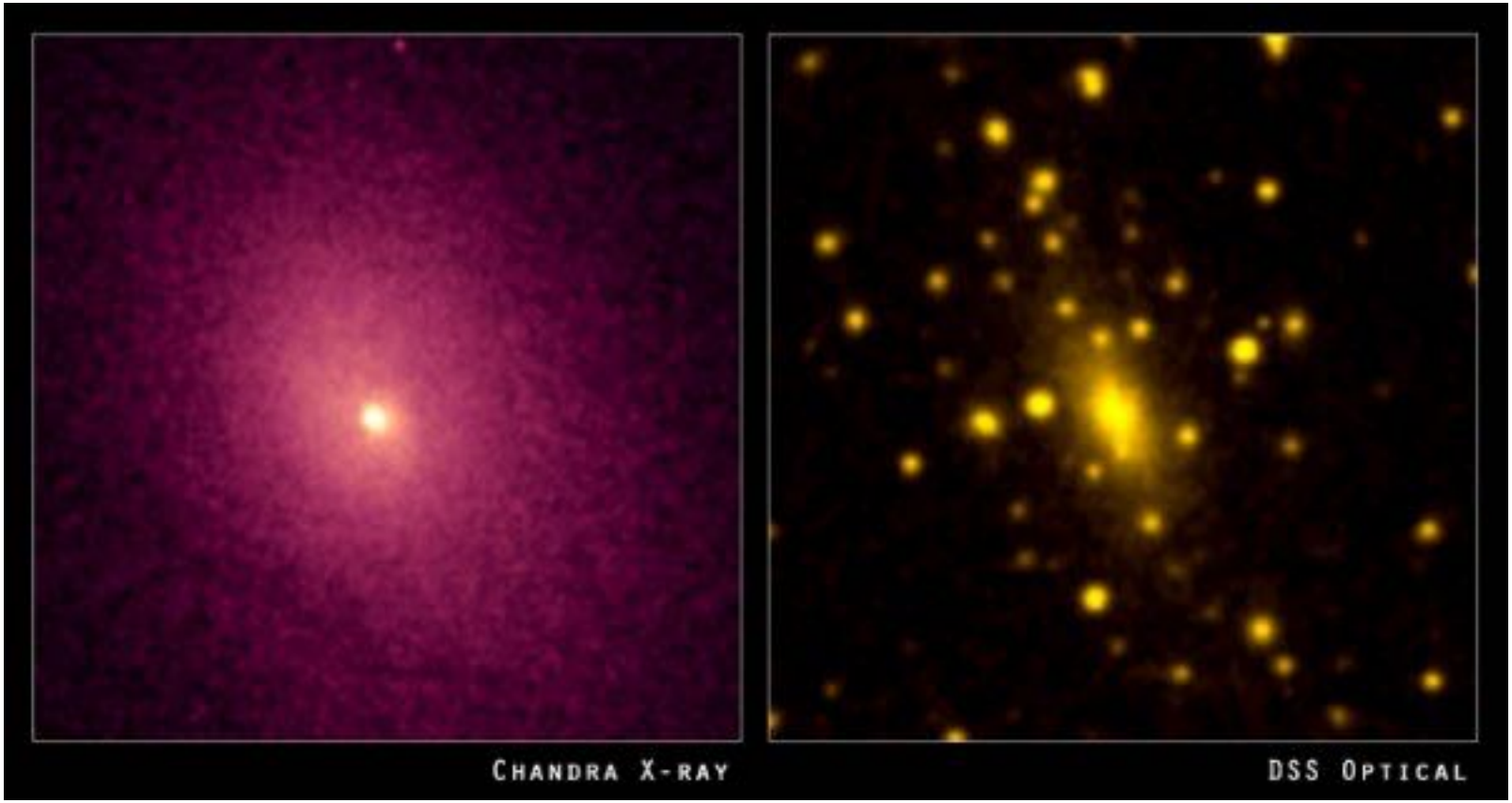




Credit: Spritzer Space Telescope

X-ray Clusters

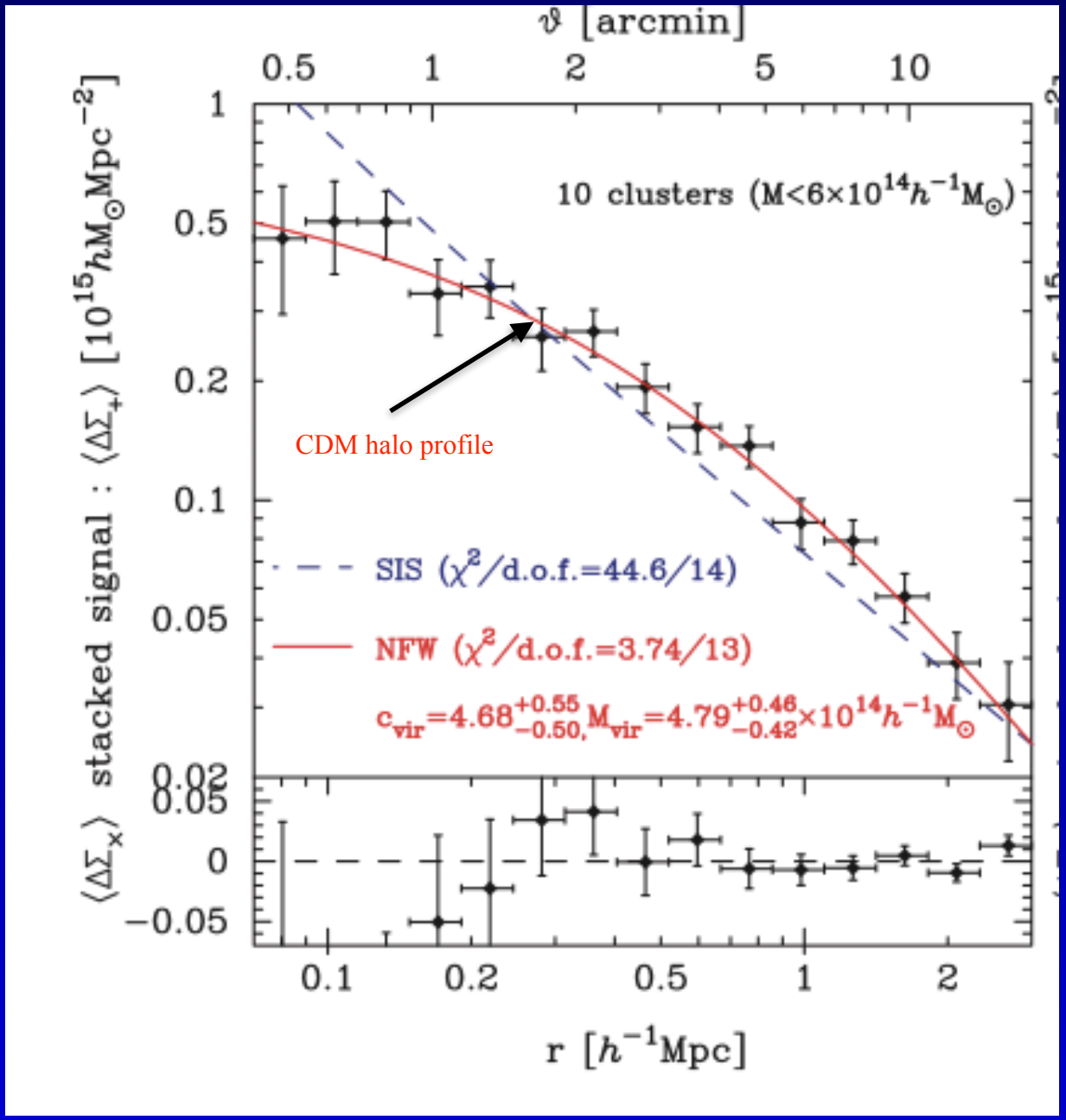
- Most of the baryons in a galaxy clusters are not in galaxies, but in the X-ray emitting intracluster medium (ICM)
- The ICM fills the cluster and has a mass that can exceed the total combined mass of all cluster galaxies by a factor of 10 or more.
- One can use the virial theorem or the hydrostatic equilibrium equation to estimate the total mass and mass profile of a cluster
  - Very convincing evidence for the presence of dark matter.



Gravitational Lensing

- Clusters are so massive that they act as “gravitational telescopes”
- The light from background galaxies can be bent by the cluster, creating multiple images and distorting their shapes into *arcs*
  - Multiple images+distortion: “strong” gravitational lensing
  - Only distortion: “weak” gravitational lensing.

The dark matter profile of massive galaxy clusters



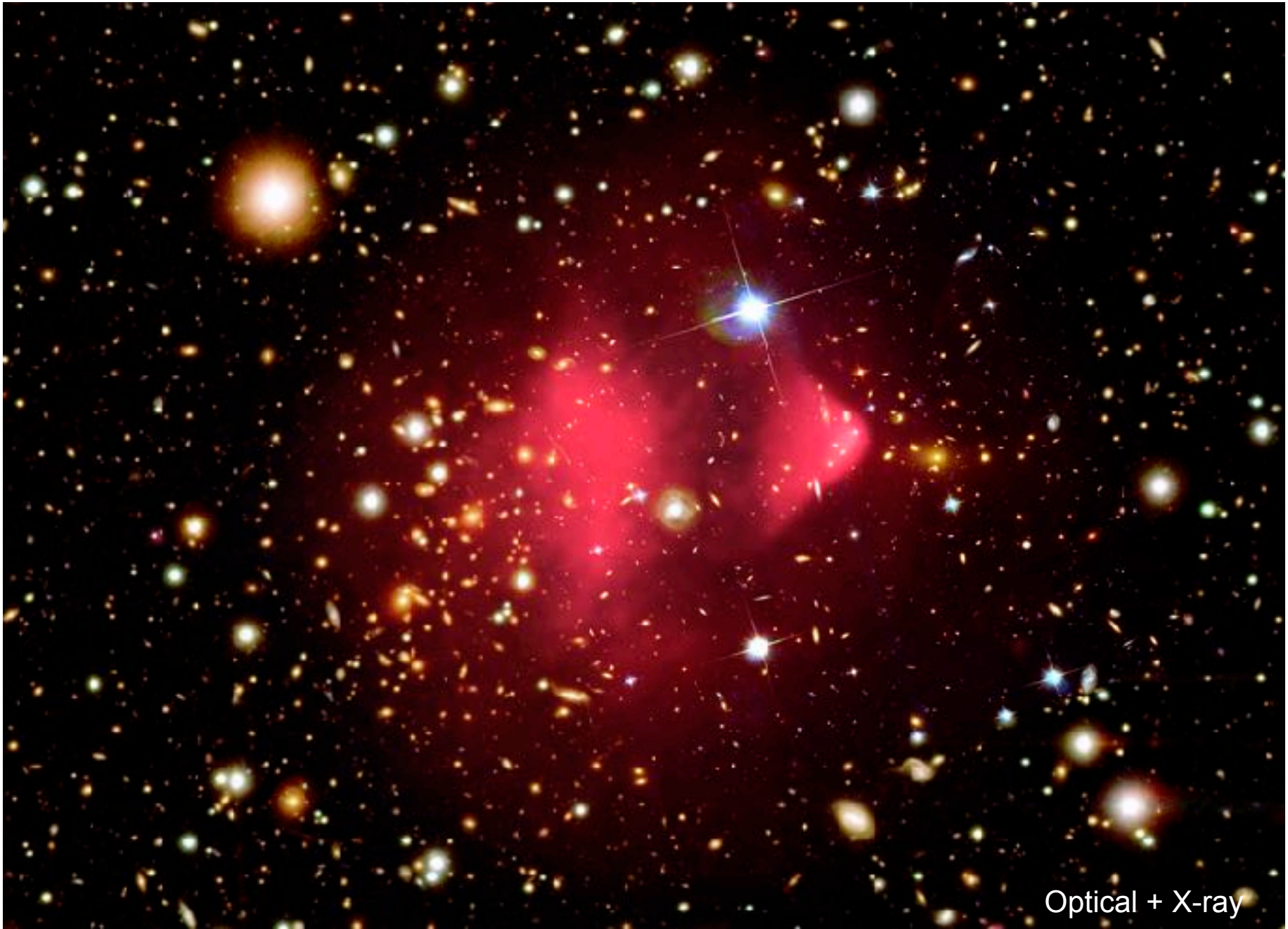
- There is good agreement between the mass profiles of a galaxy clusters (measured via gravitational lensing or X-ray emission profiles) and those of CDM halos

Okabe+2010, Umetsu+2011

The “Bullet Cluster”

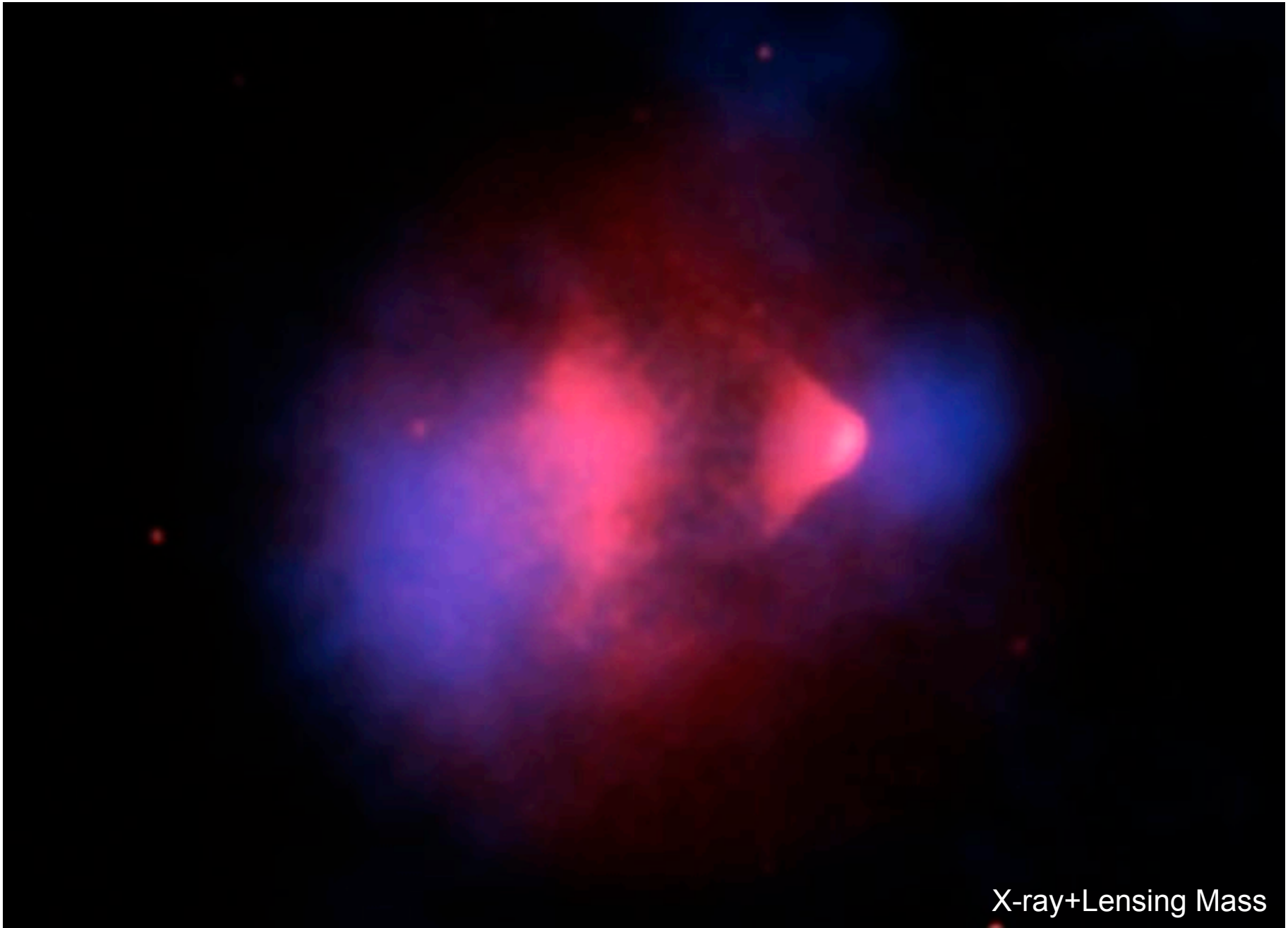
- A cluster undergoing a collision with another one provides spectacular evidence for dark matter

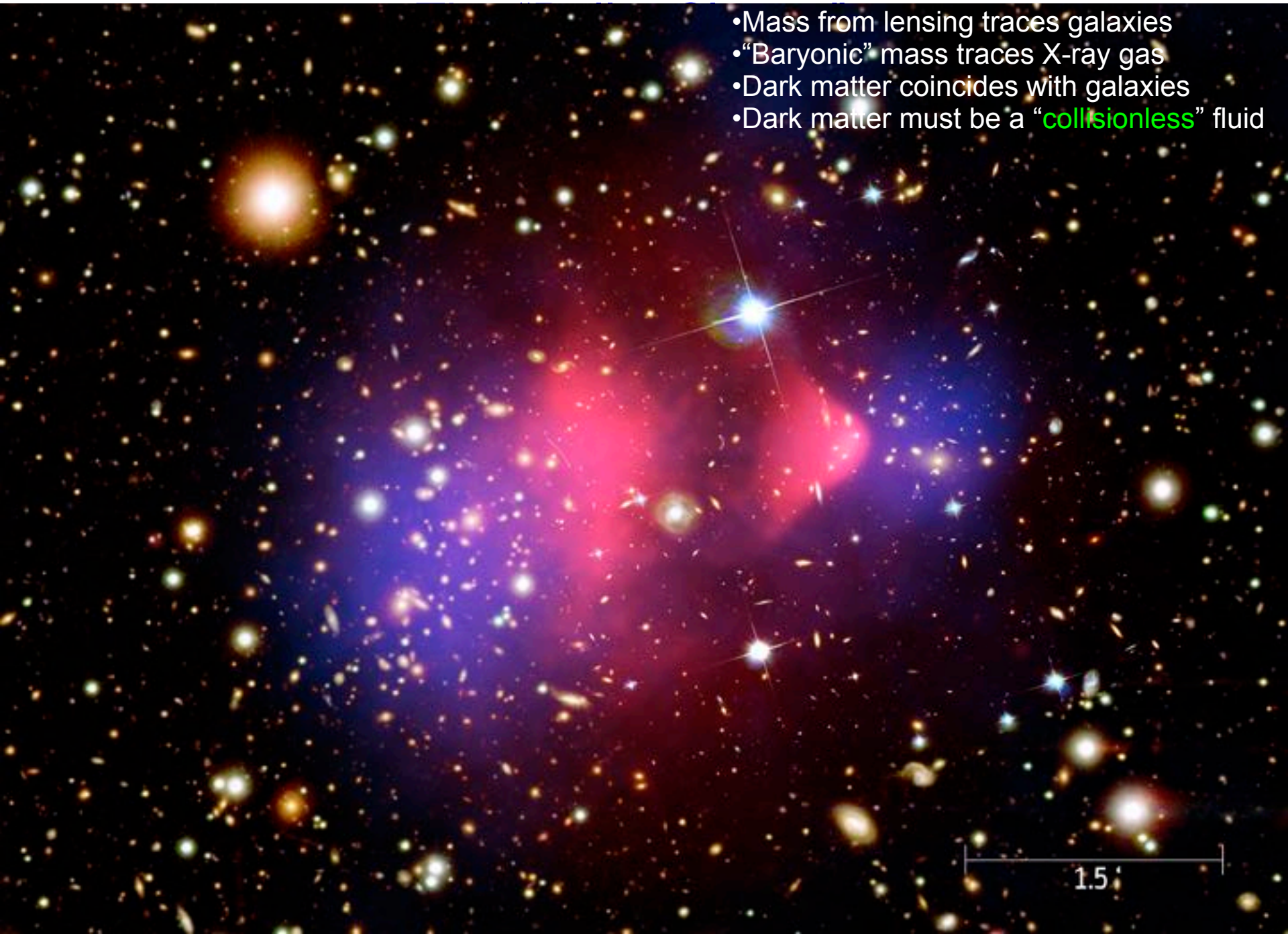
The “Bullet Cluster”



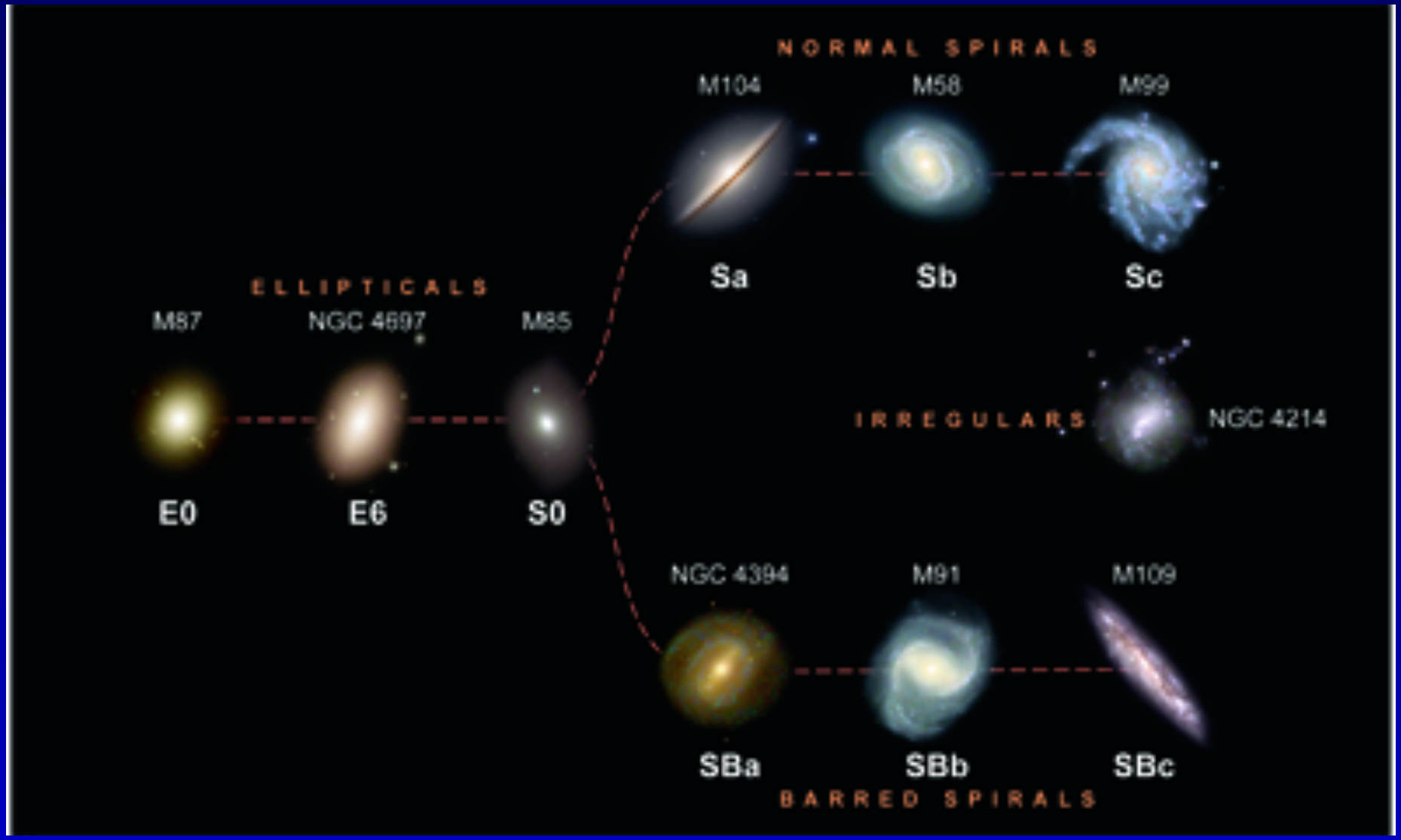
The “Bullet Cluster”

The “Bullet Cluster”

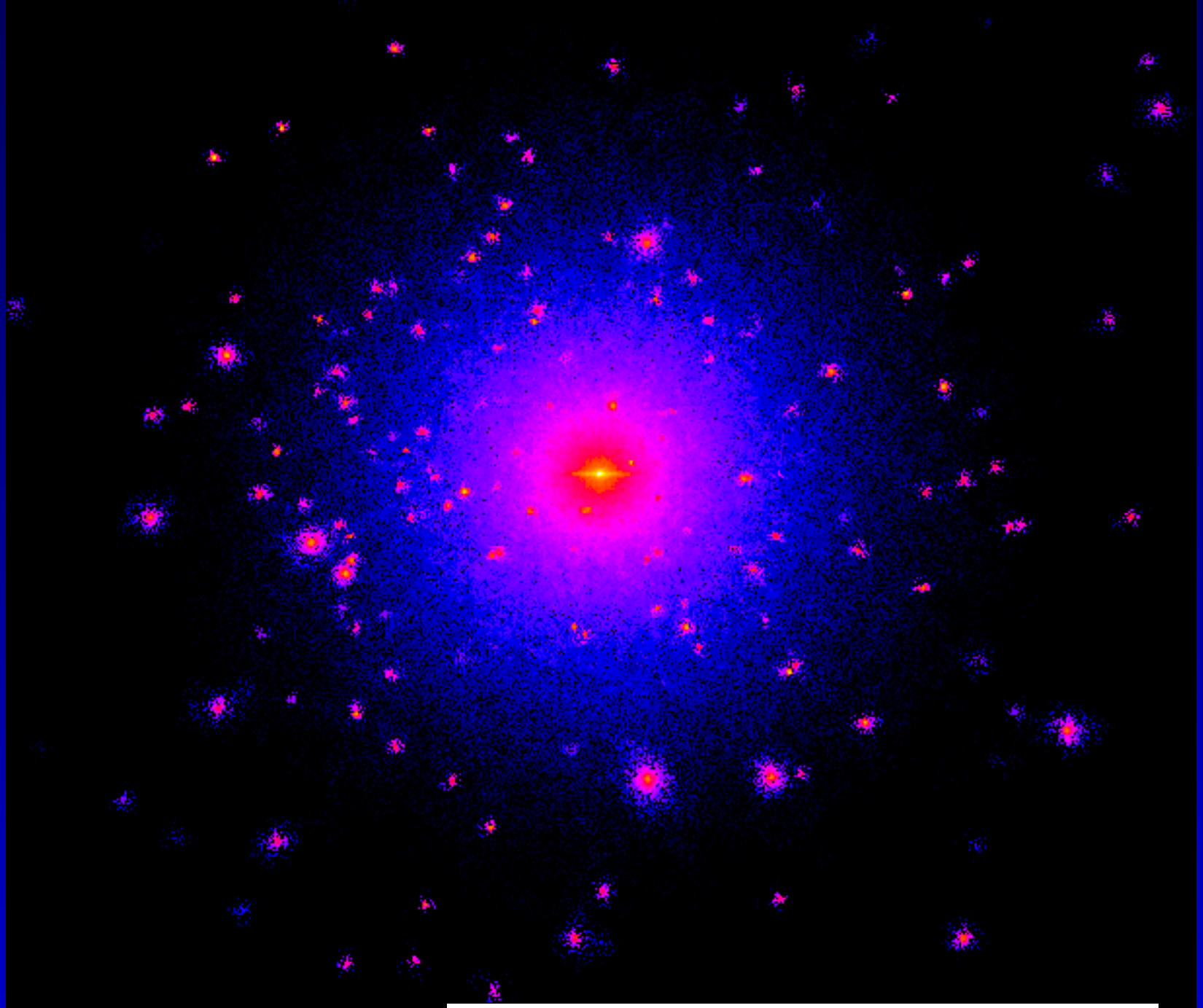



•Mass from lensing traces galaxies
•“Baryonic” mass traces X-ray gas
•Dark matter coincides with galaxies
•Dark matter must be a “collisionless” fluid
1.5'

Galaxies and LCDM



- Gas cools and condenses at the centres of dark matter halos, where stars may form
- Simulations require a hydrodynamical treatment of baryons in a cosmological setting



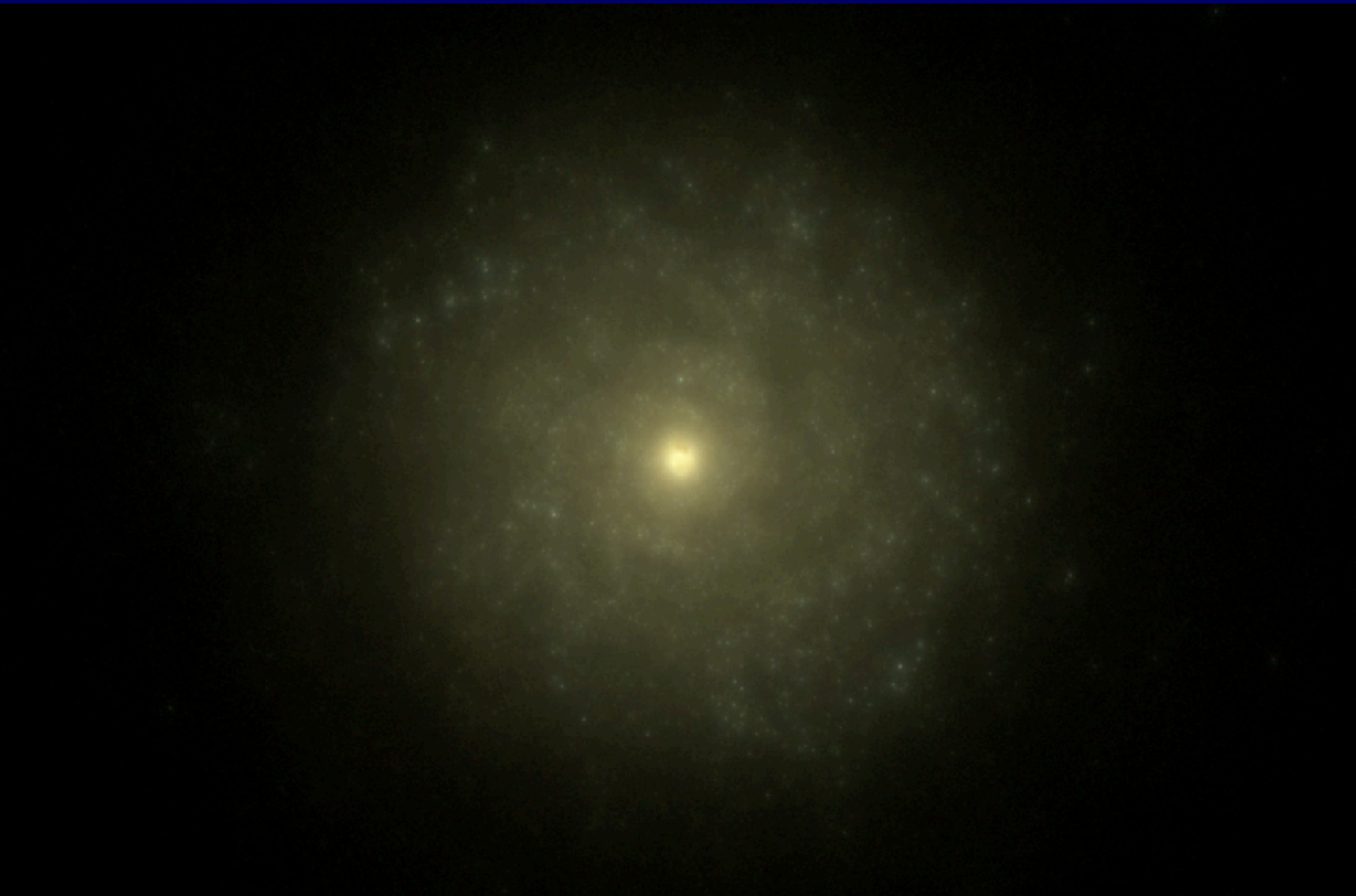
Font and Navarro 2001

A galaxy and its surrounding dark matter halo

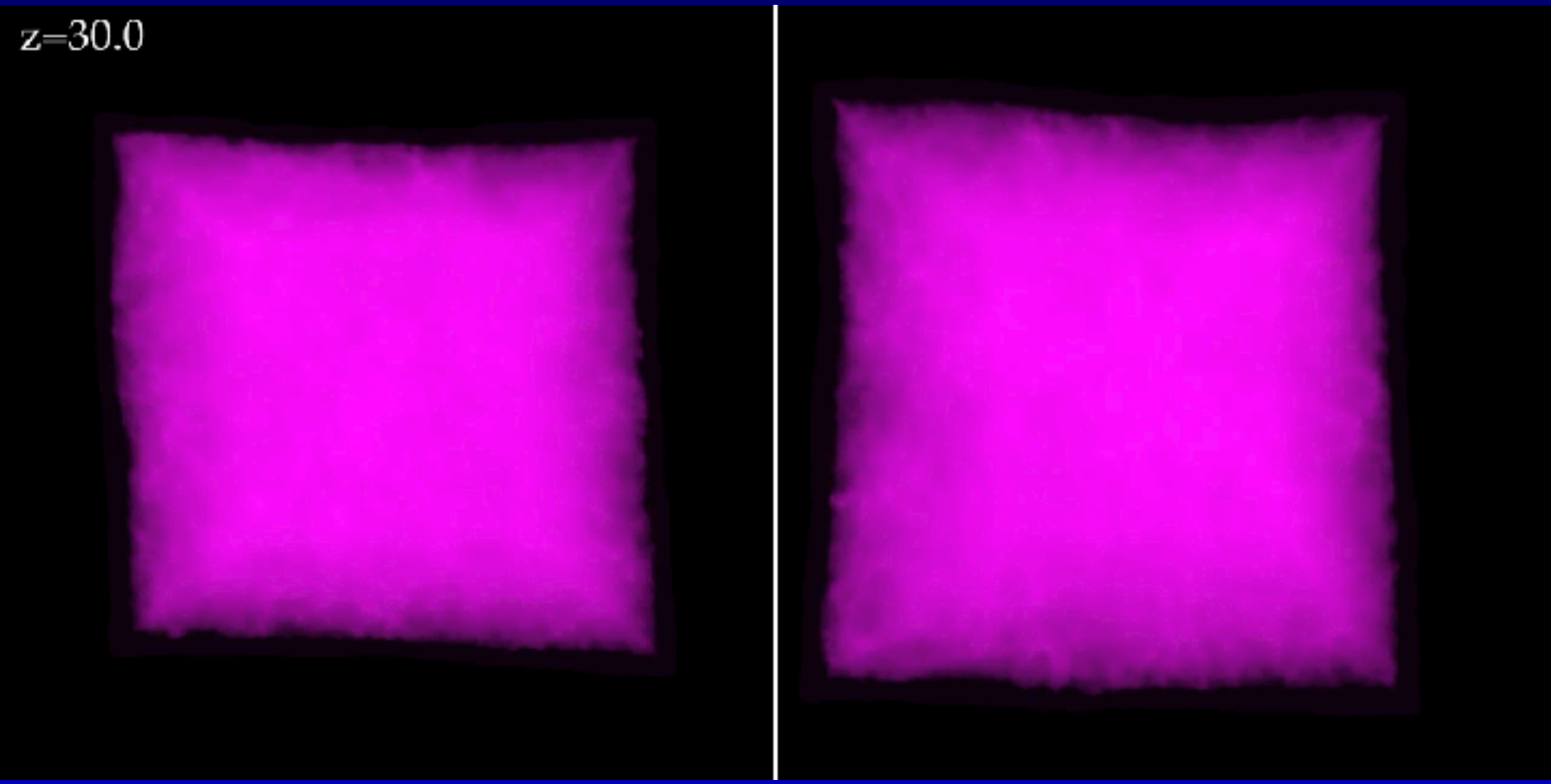
EAGLE: Evolution and Assembly of GaLaxies and their Environments

The evolution of intergalactic gas. Colour encodes temperature

A simulated disk galaxy in EAGLE

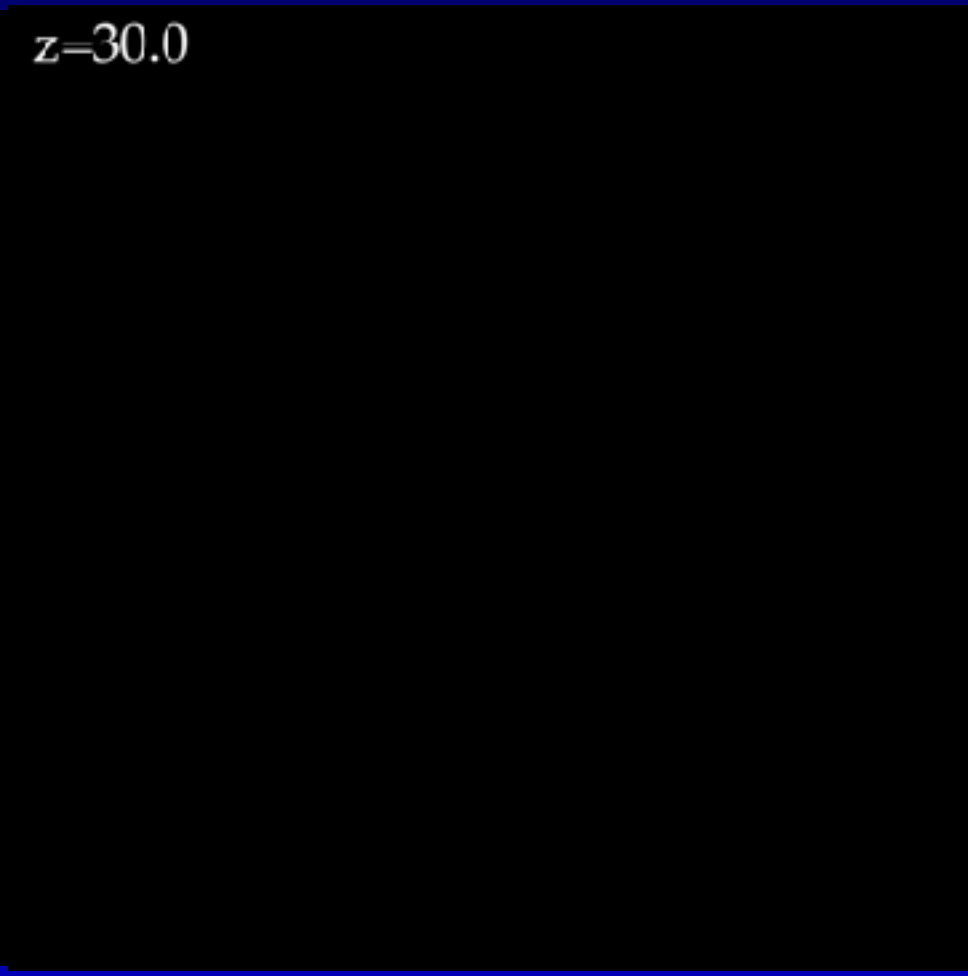


A simulated disk galaxy in its large scale structure



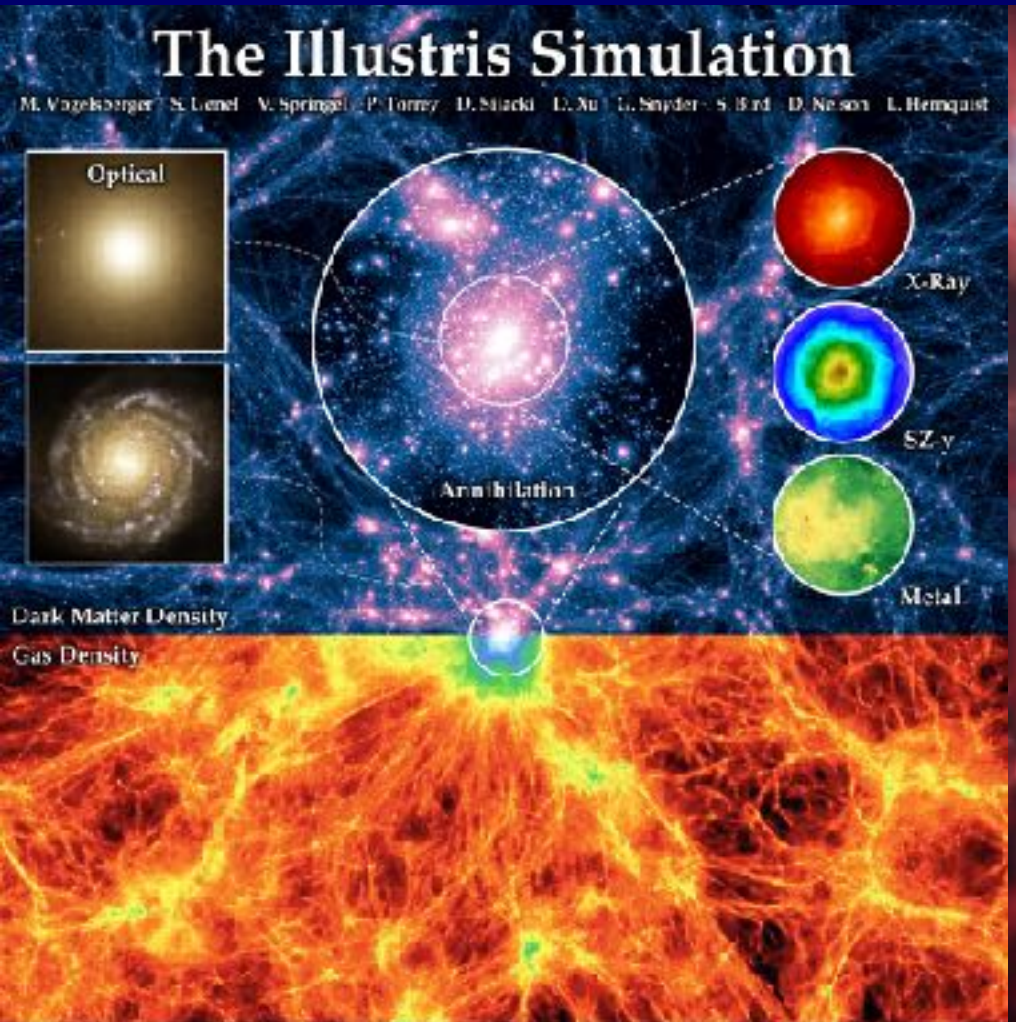
Credit: FIRE simulation project

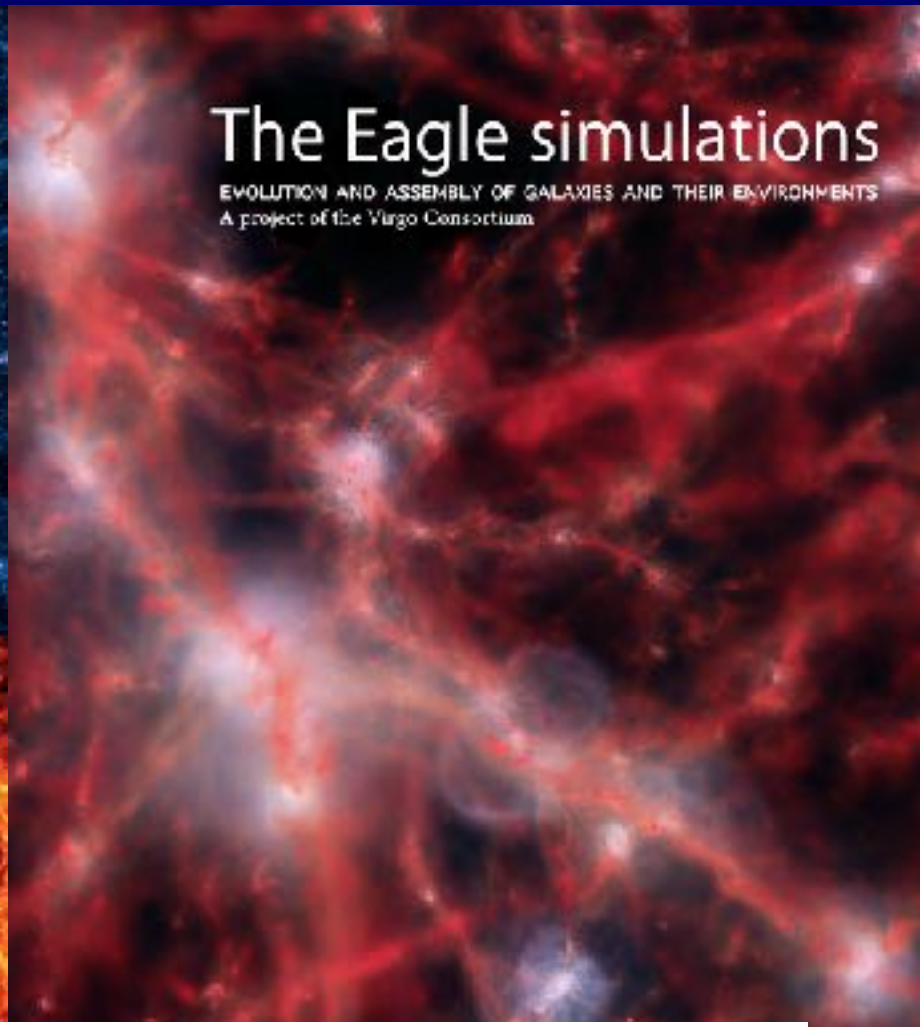
A simulated disk galaxy in FIRE



Credit: FIRE simulation project

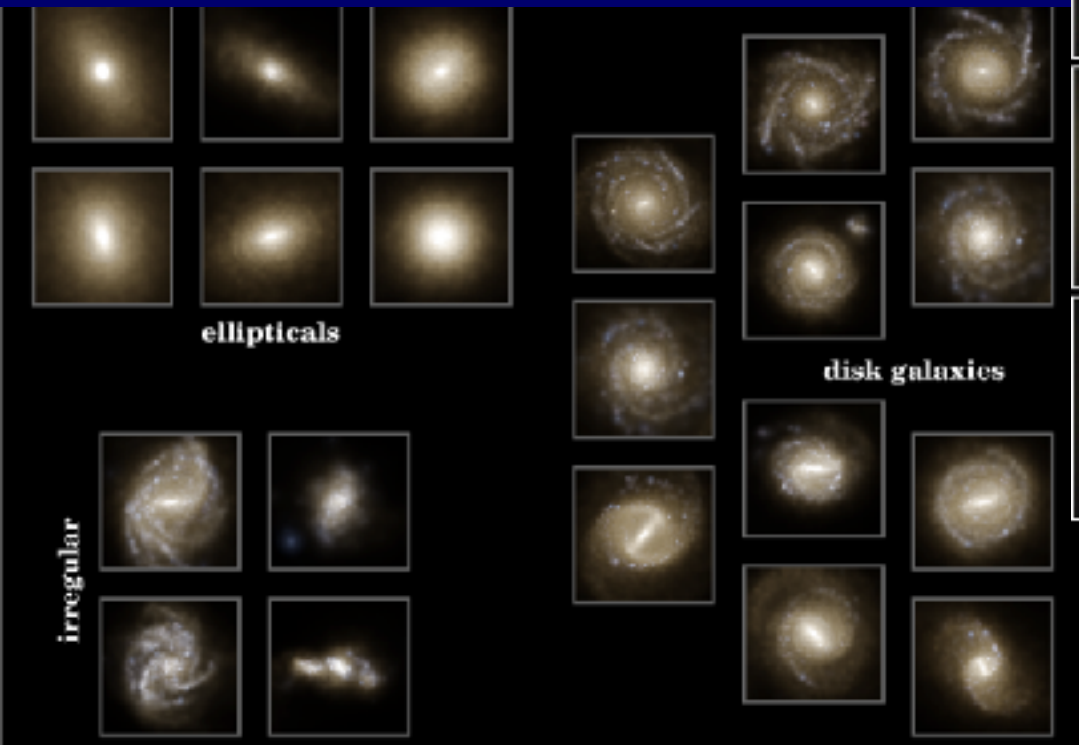
Galaxy Population Simulations

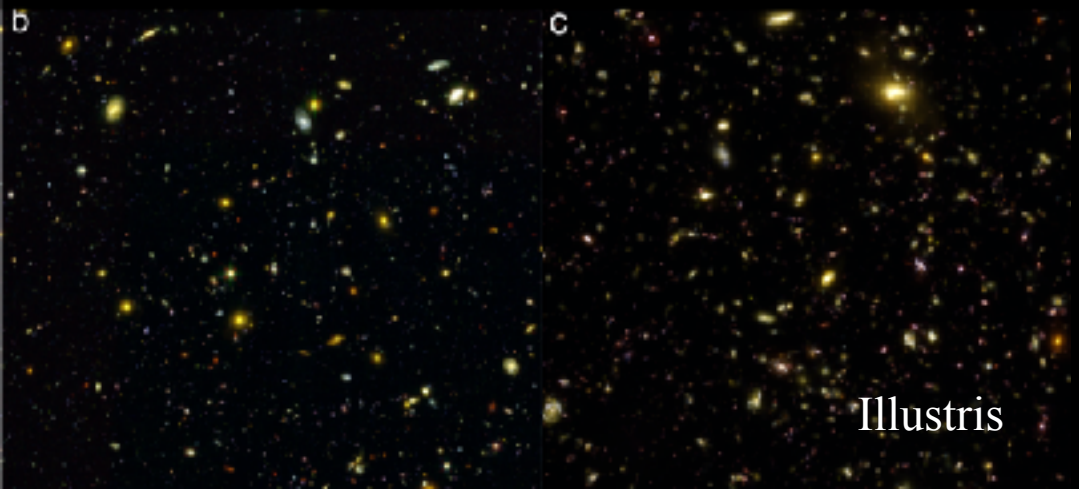




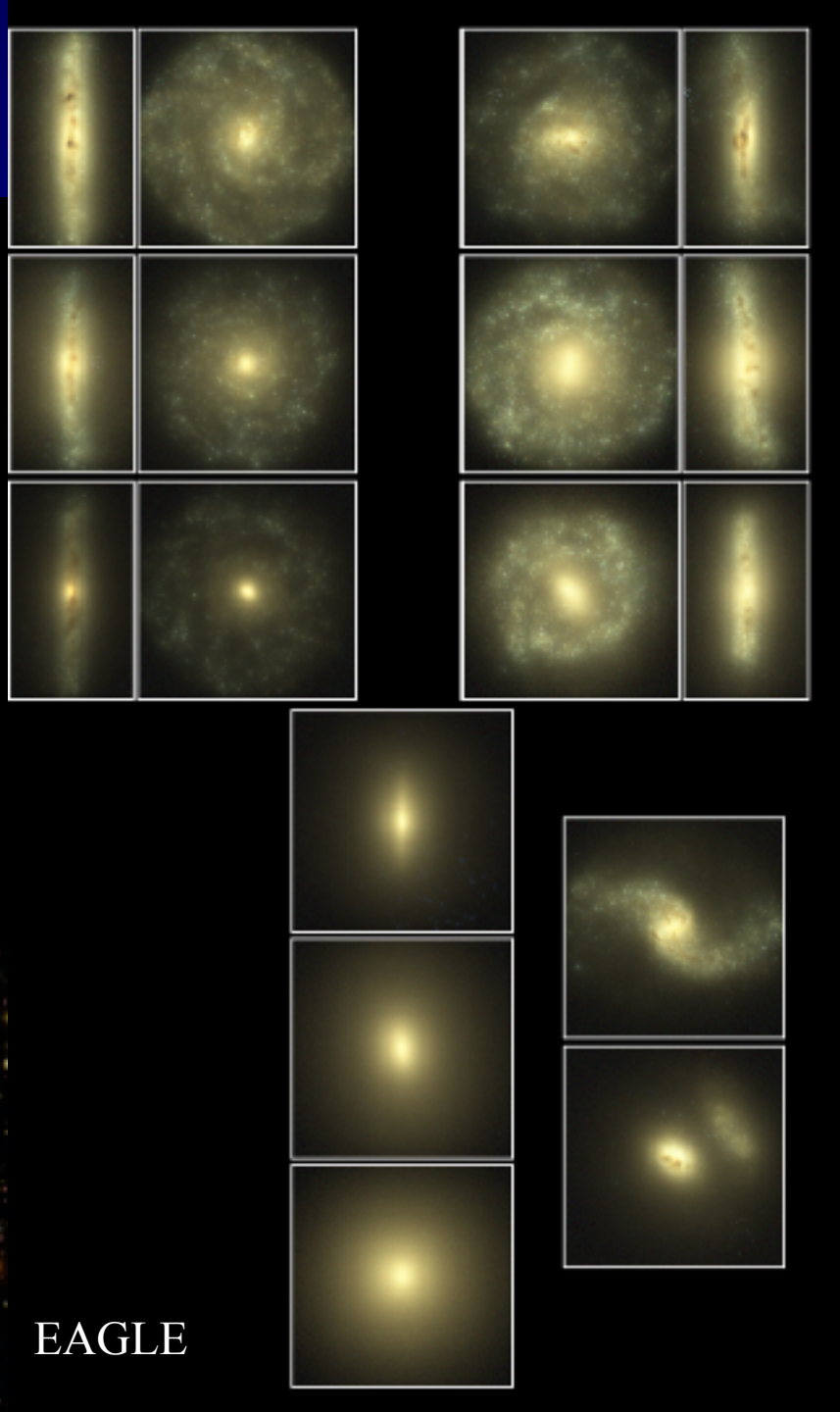
- Three large simulation suites of cosmologically representative volumes (~100 Mpc box) have recently been completed
- Resolution (per galaxy) is worse than individual galaxy simulations, but agreement with observation is quite good

Galaxy gallery





Illustris



EAGLE

End of Lecture 2