Emergence of galactic structure

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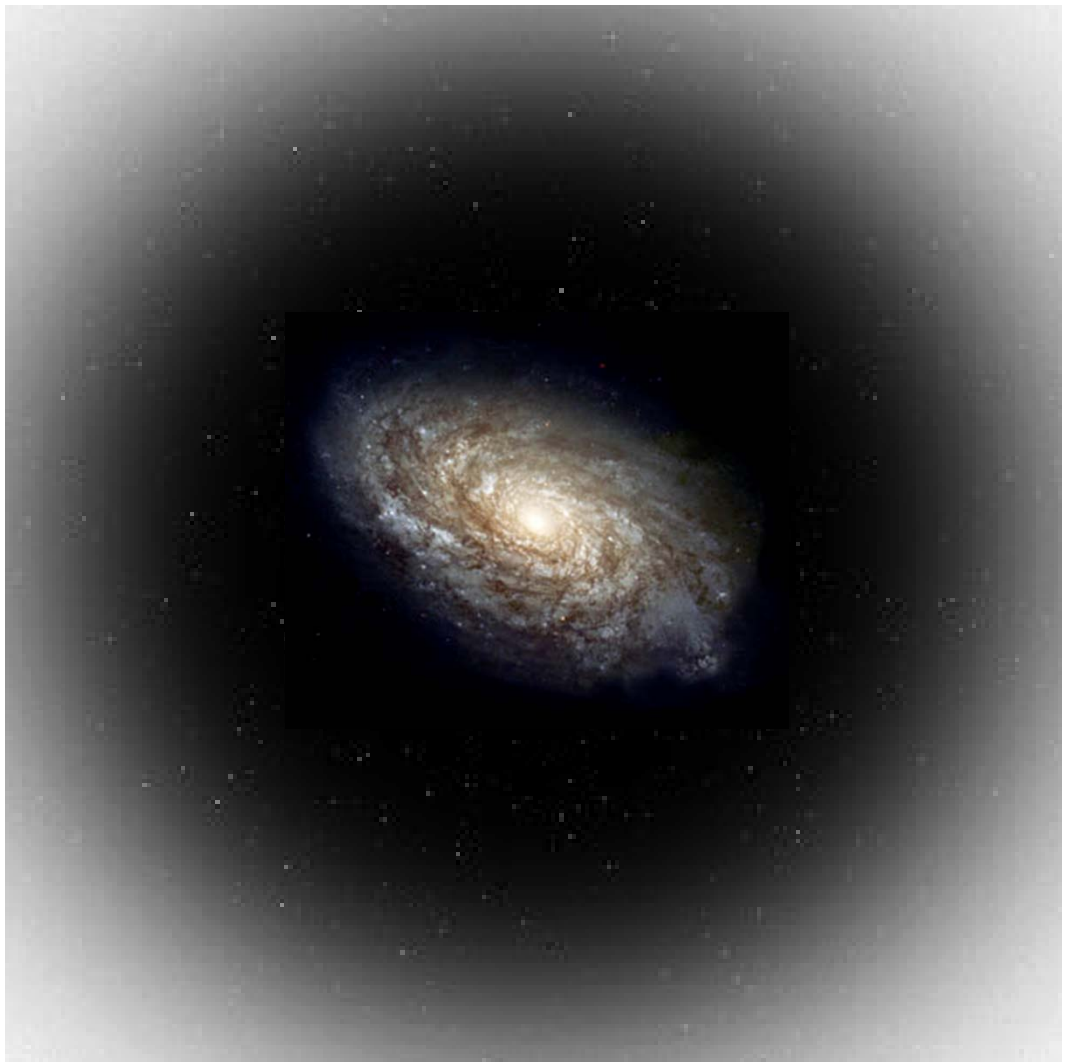
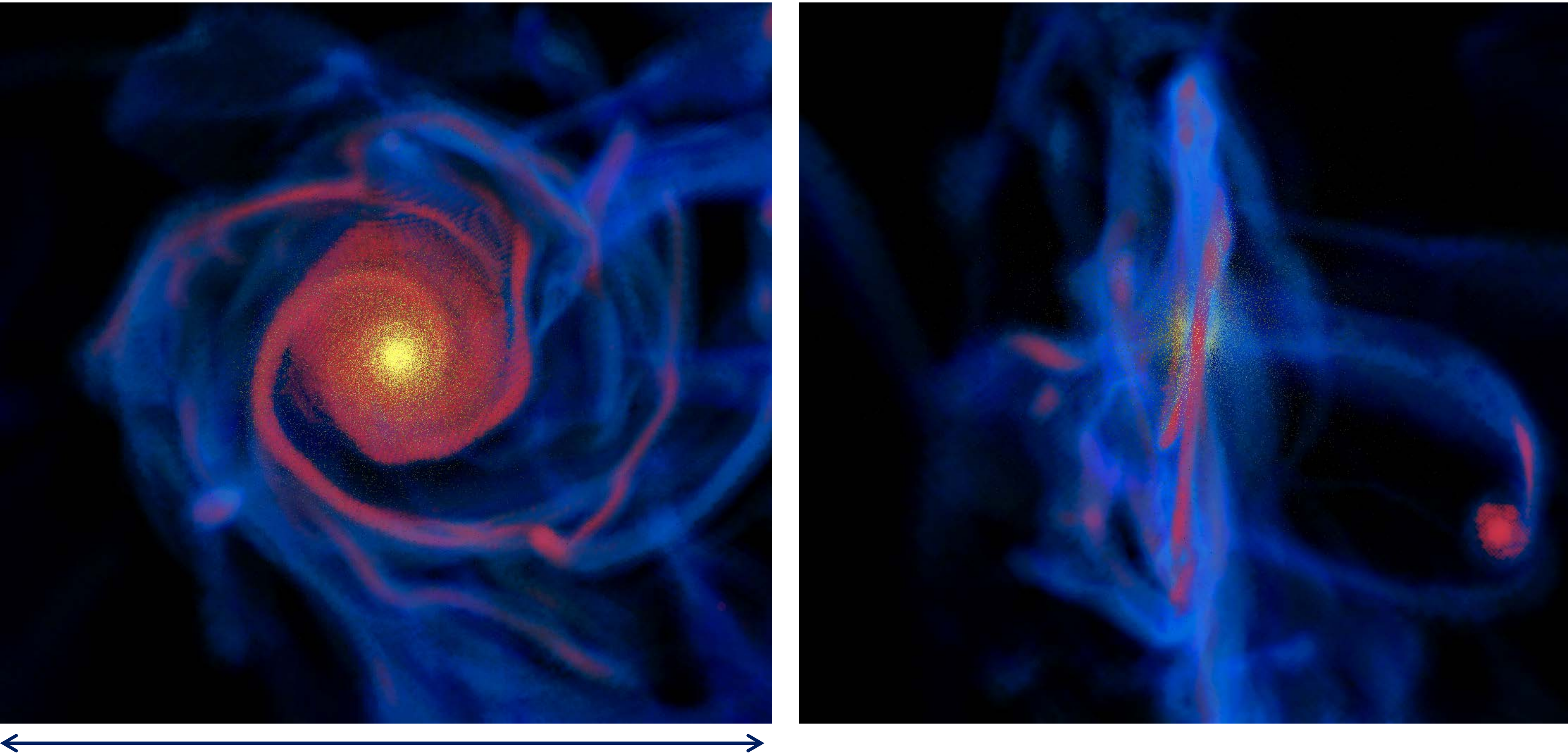


In current simulations, galaxies look like this:



Disk galaxy at z=3: stars, molecular gas, atomic gas

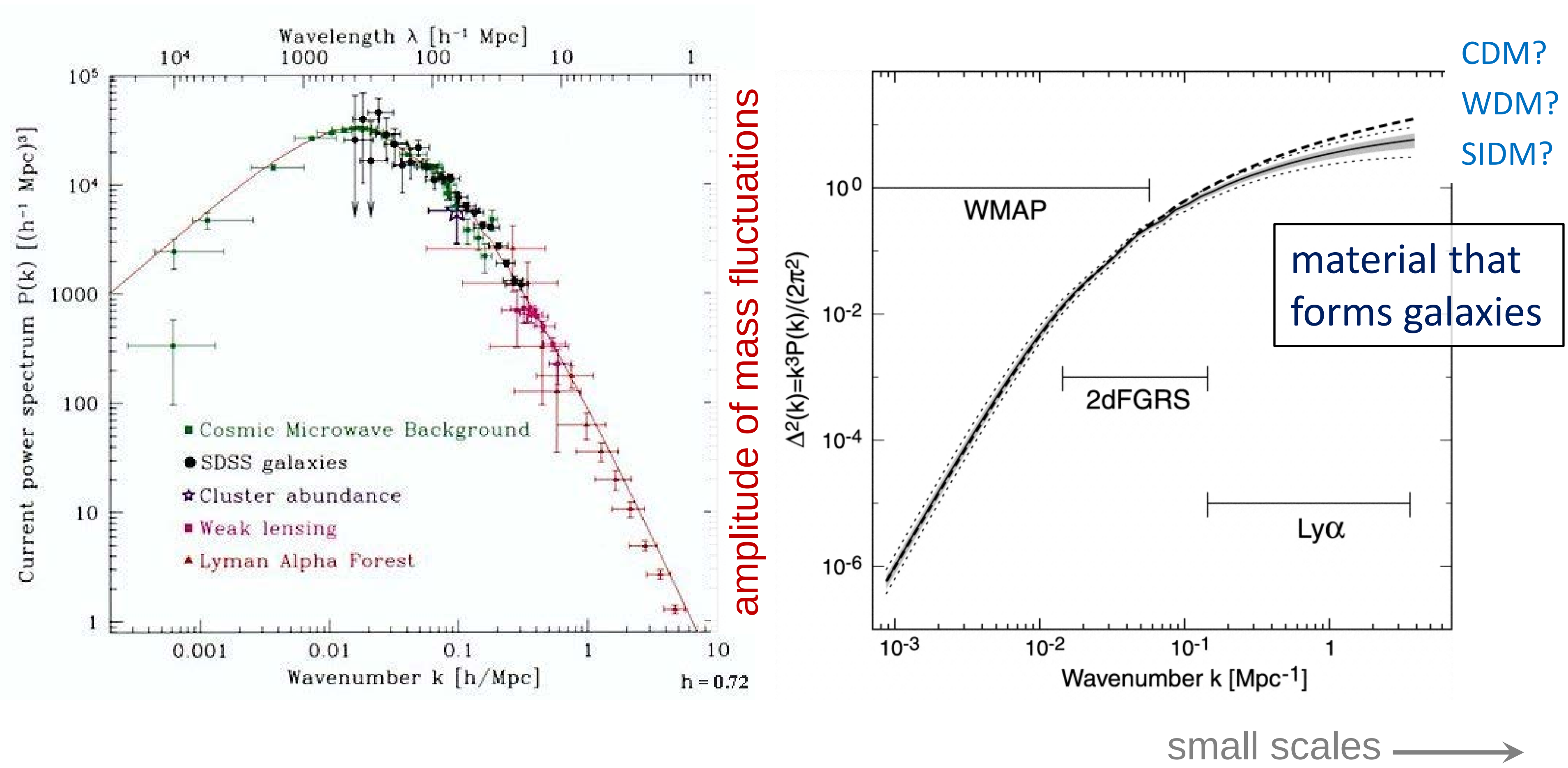
Zemp, OG, N. Gnedin, Kravtsov (2012)

Real galaxies look like this:

(more structure, extended disks, young stars, gas emission, dust lanes)

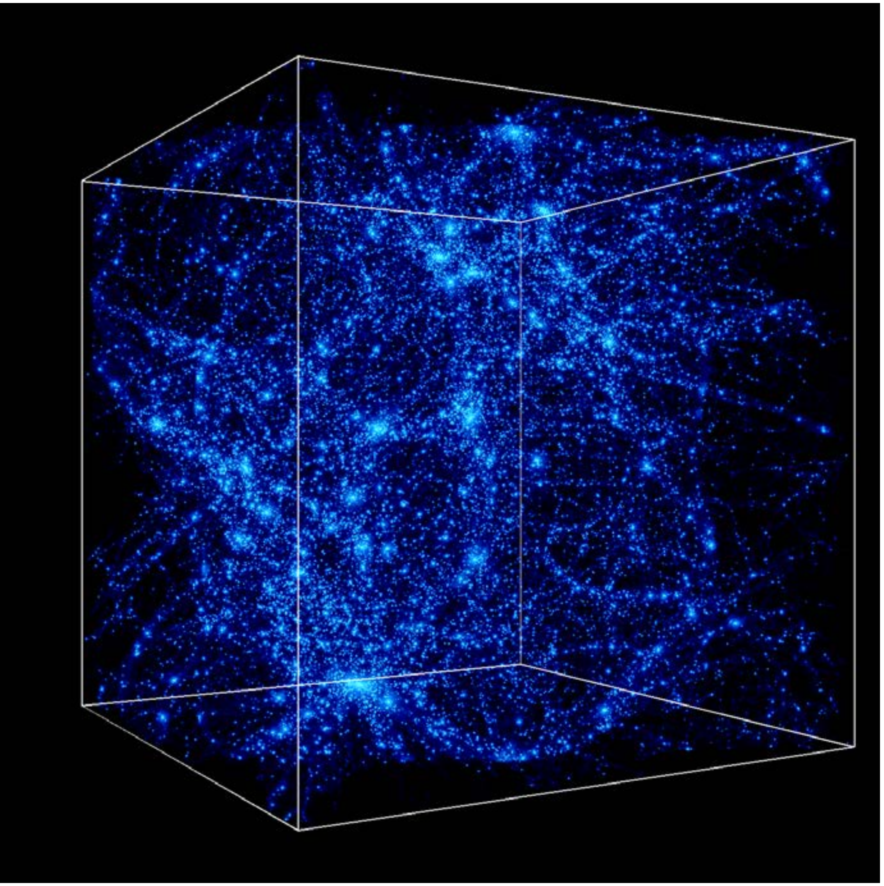
Which results are model-dependent and which are not?

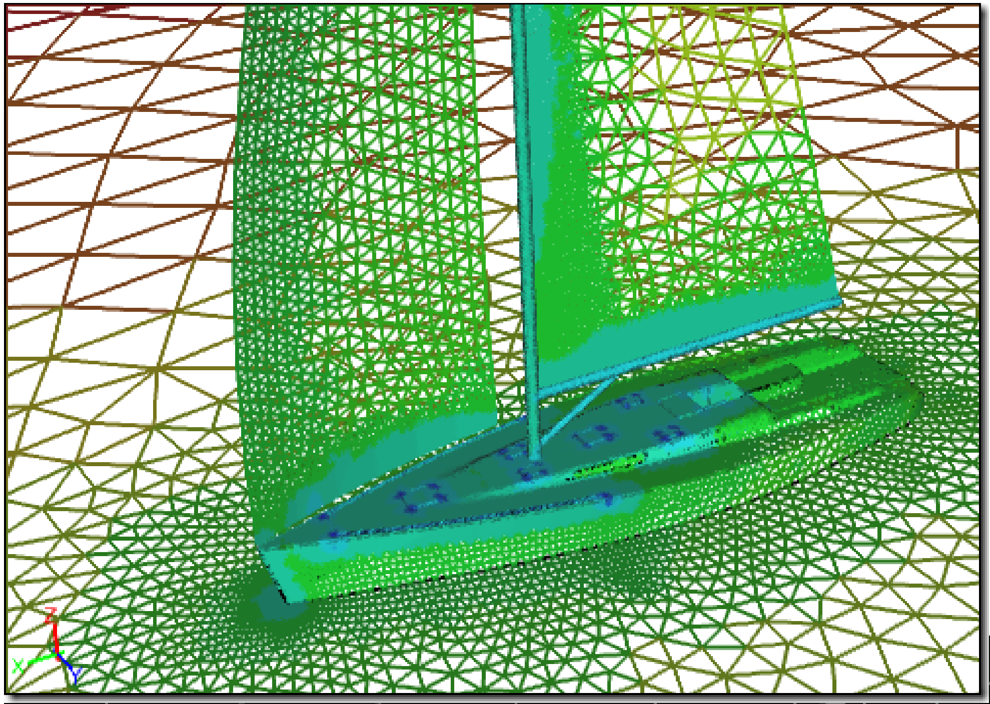
Stronger (measured) primordial fluctuations on small scales determine that low-mass *halos* form before high-mass *halos*

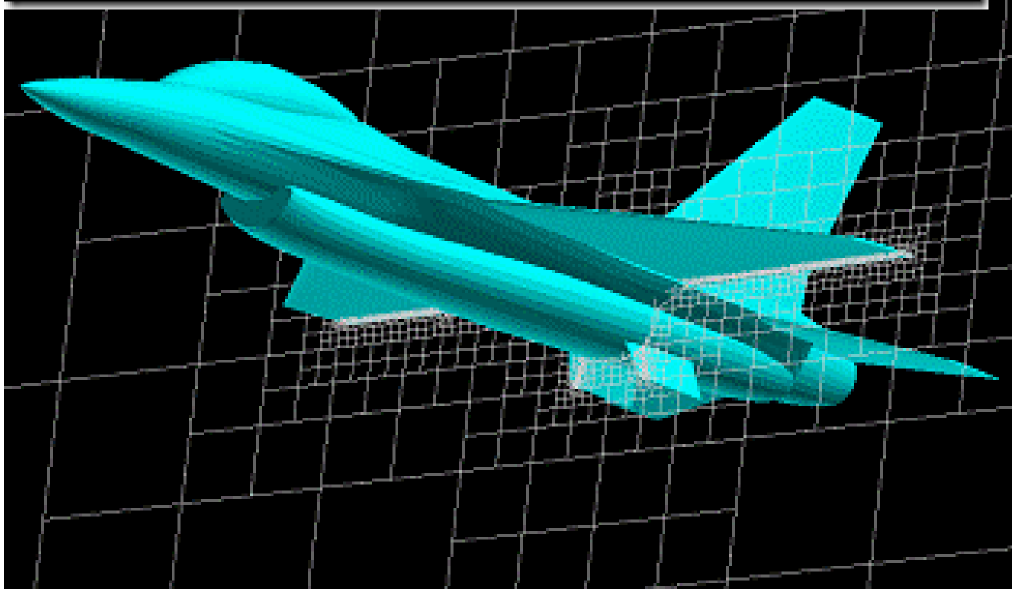


Once the spectrum of fluctuations is known, and phases are Gaussian, cosmic structure can be calculated without any free parameters (although DM self-interaction could make a small difference later at centers of dwarf galaxies)

How do we study the formation of galaxies? With numerical simulations



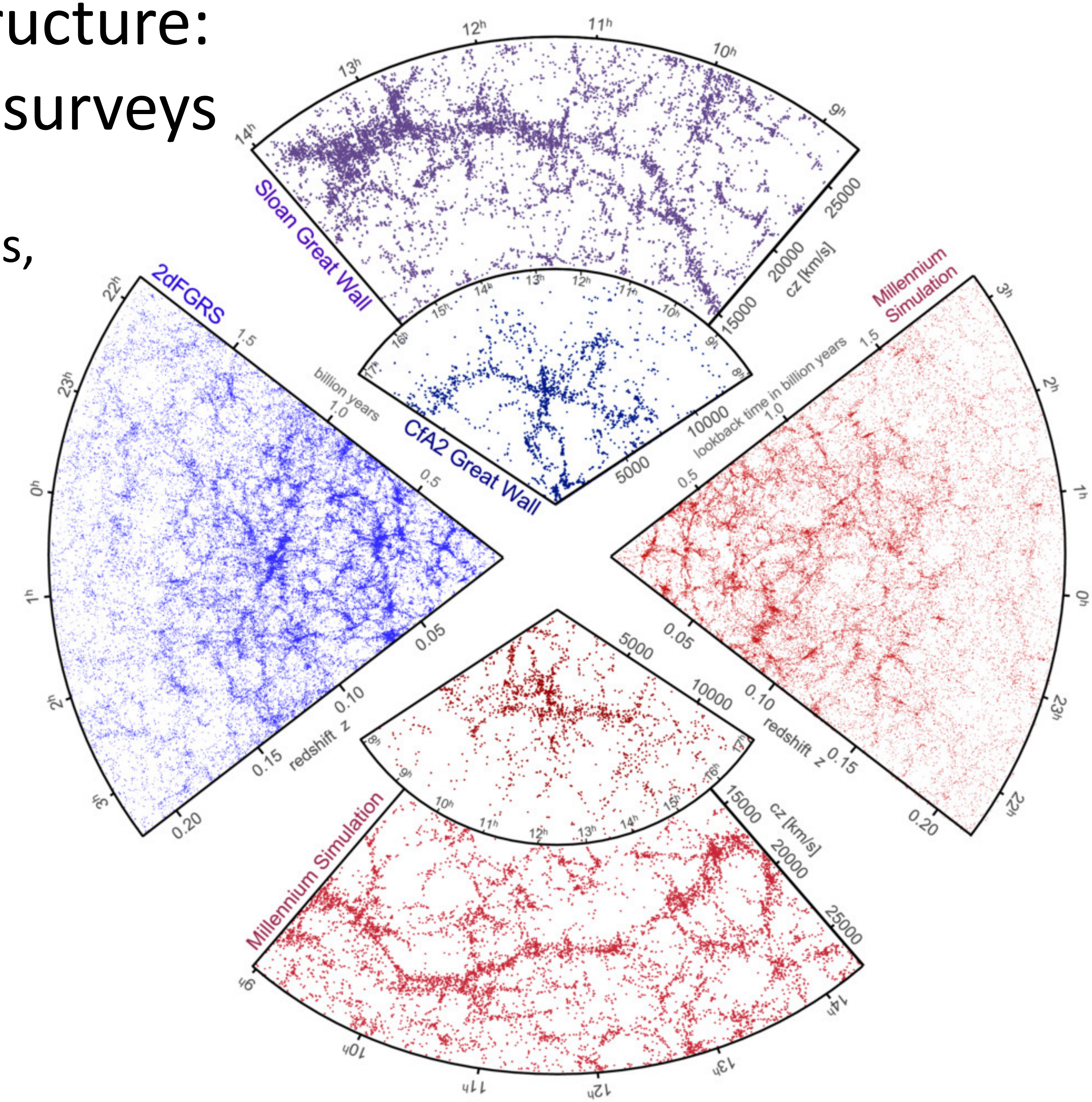




Numerical techniques are borrowed from aerospace engineering and well tested

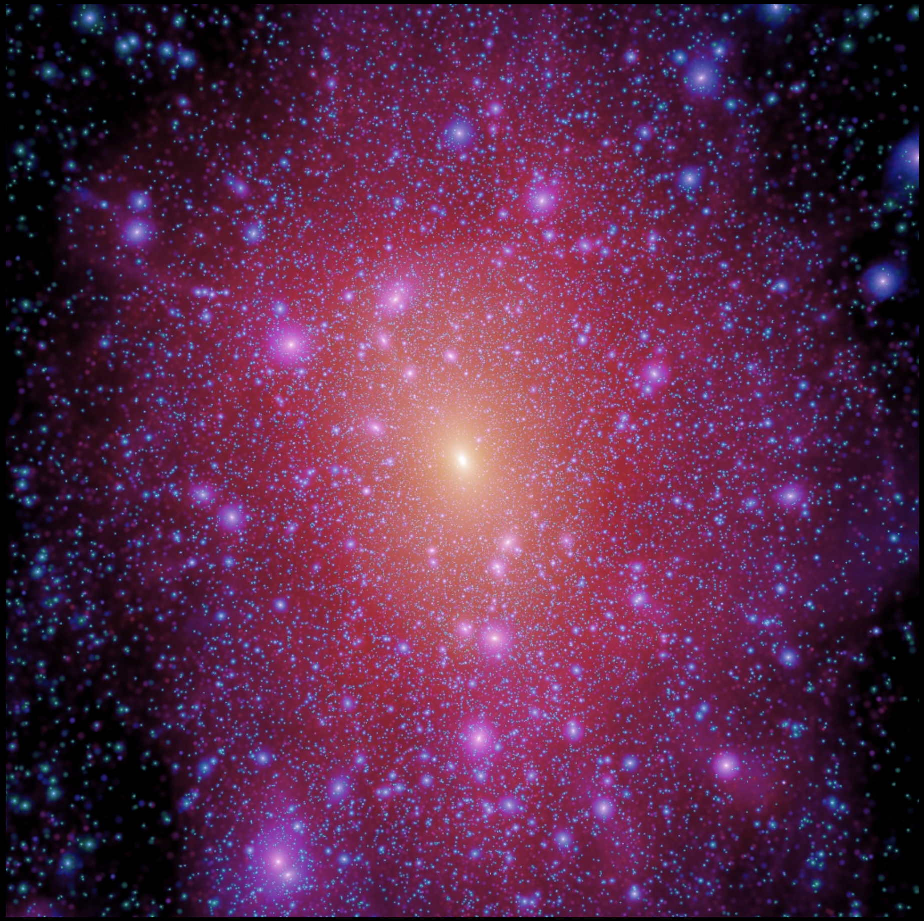
Large-scale structure: distant galaxy surveys

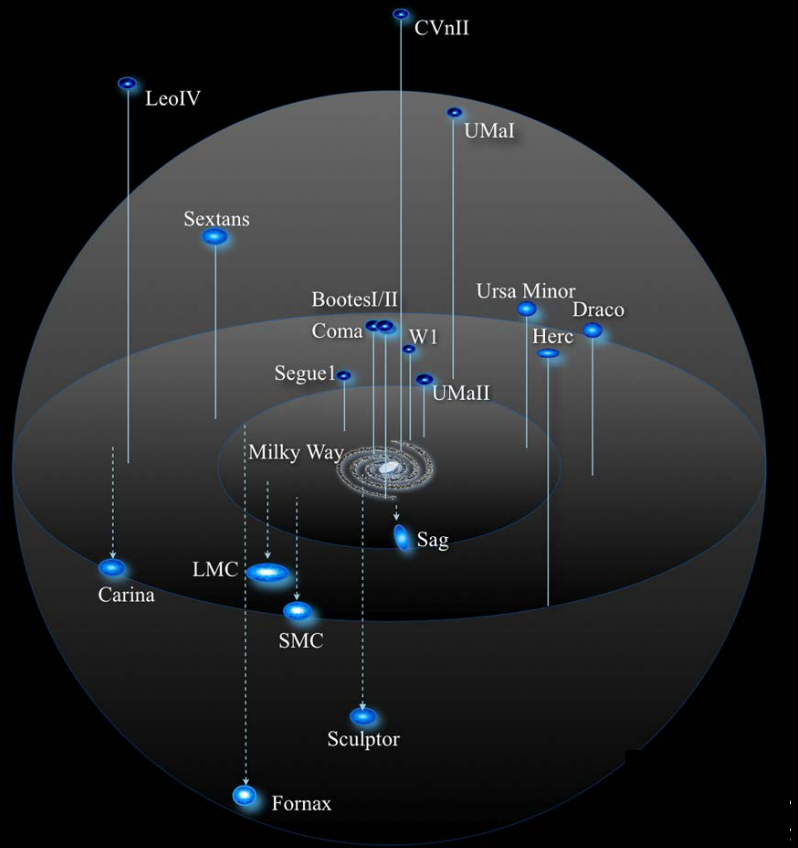
Blue is observations,
Red is simulations:
very similar



Missing Satellite Galaxies

Klypin et al. 1999, Moore et al. 1999



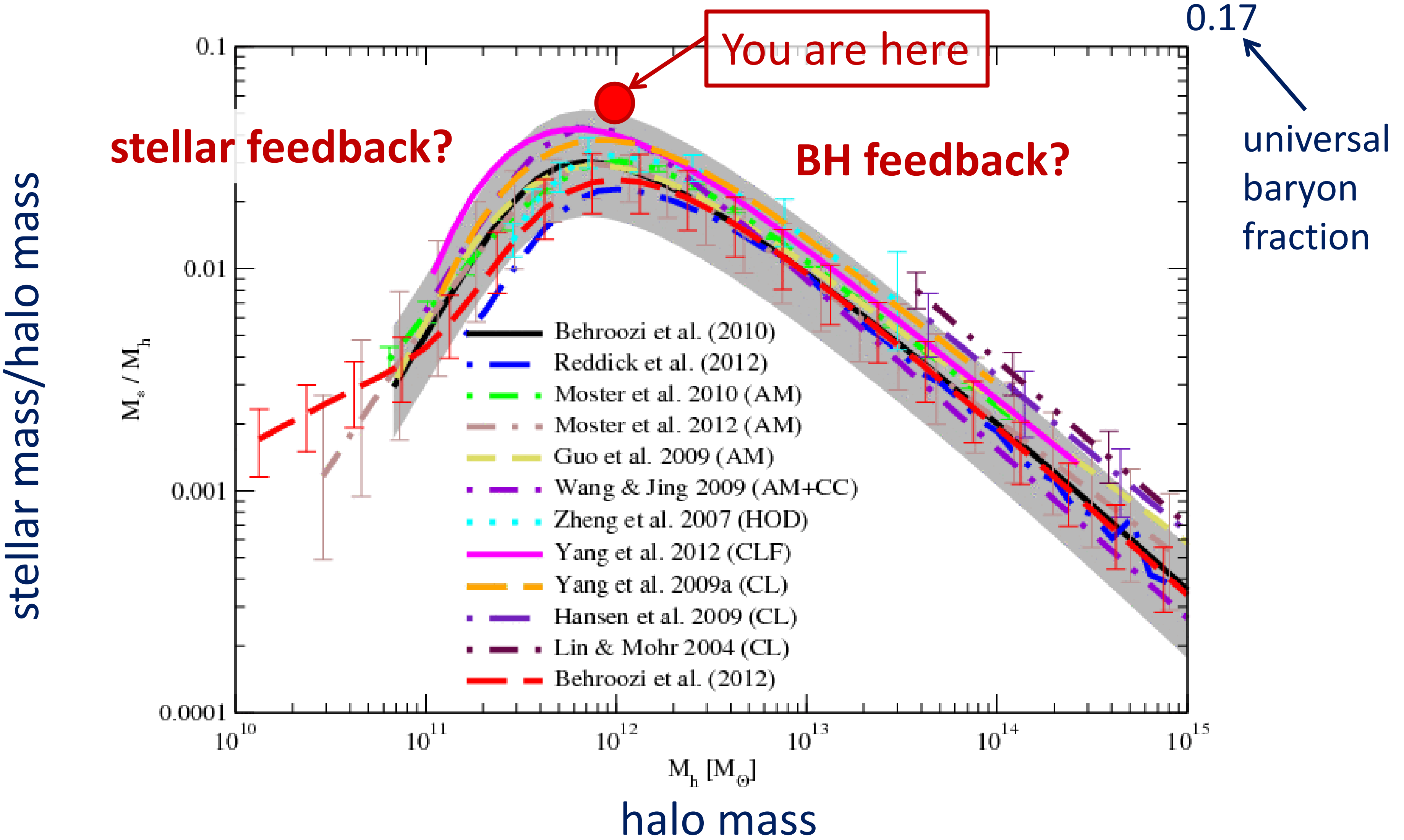


$>10^5$ identified subhalos

25 satellite galaxies $(L_V > 10^5 L_\odot)$

Aquarius simulation

Matching numbers of halos and galaxies indicates that star formation is inefficient, especially at low and high masses



Behroozi et al. 2012

Gravity is the easy part. Ingredients of galaxy simulations:

Green is good (understood)

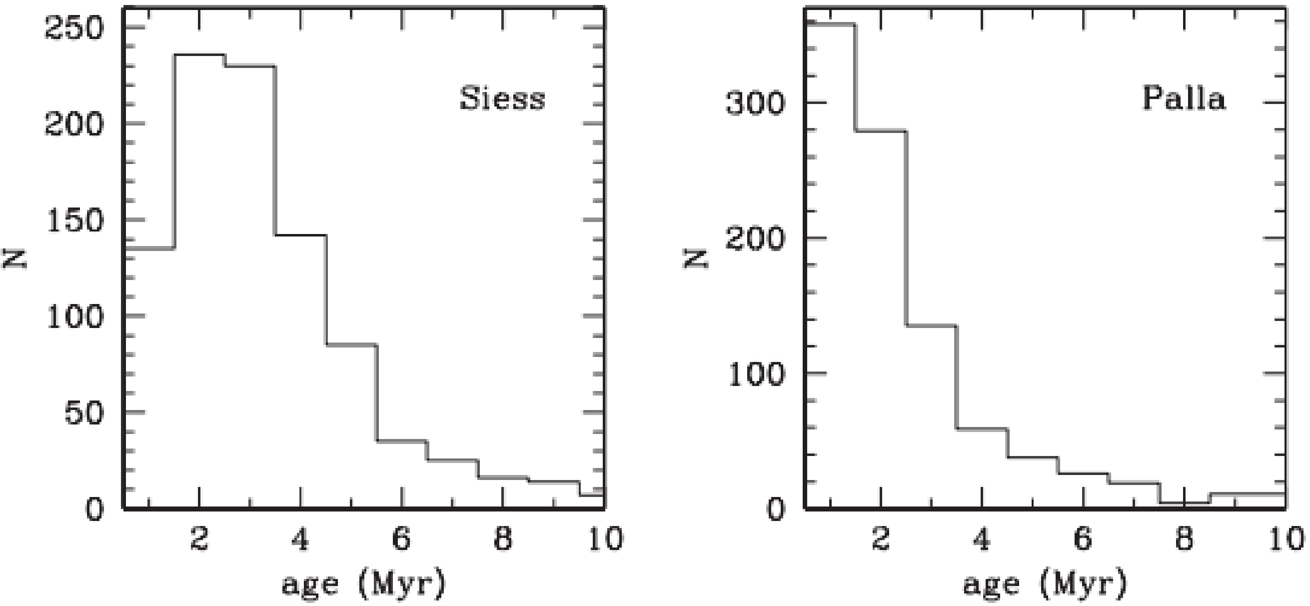
- *CDM model:* provides well-motivated initial conditions
- *dark matter:* dominates gravitationally on scales > kpc, shapes skeleton of the large-scale structure and galaxy potential wells, in which baryonic drama of galaxy formation plays out
- *radiative cooling:* shocks and UV radiation heat the baryons, but dissipative particle collisions allow baryonic matter to radiate away its thermal energy and sink to the center of the potential well, where it can reach high enough density required for star formation

Red is bad (not understood)

- *star formation:* although we do not yet have a complete understanding of star formation, empirically we know that stars form in densest, molecular regions of the interstellar medium
- *stellar feedback:* newly born stars inject energy and metals released during thermonuclear burning back to the interstellar medium and thus regulate formation of future stars

Young star clusters: test bed of star formation and feedback physics

Ages of stars in Orion Nebulae Cluster



Hartmann et. al. 2012

NGC 602
young star cluster in SMC

Lifetime of molecular clouds is set by the formation within them of massive stars and star clusters

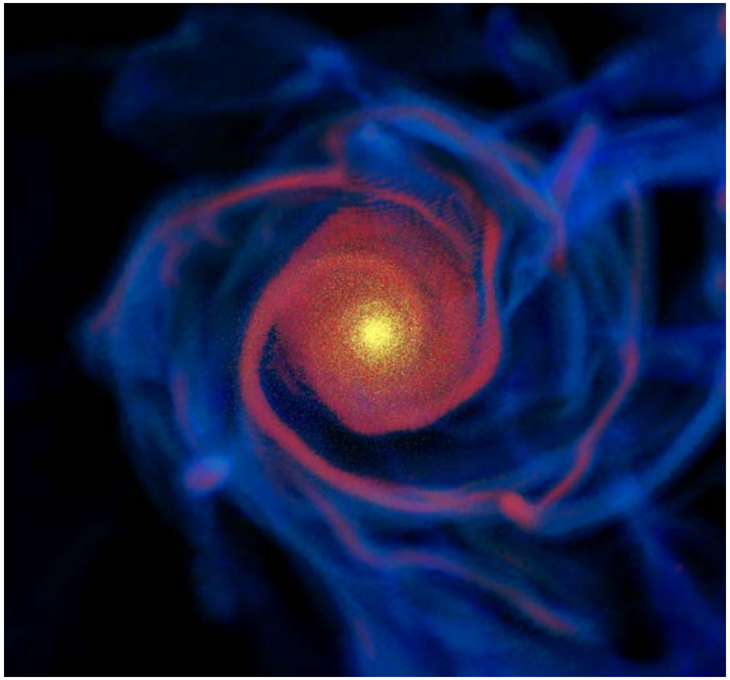
Detailed structure of galaxies, their star formation histories, number of satellites, etc. are necessarily model-dependent.

It is work in progress for the next 10-20 years.

Cosmological hydrodynamic simulations with run-time treatment of H_2 chemistry, stellar feedback, and radiative transfer

- Adaptive Mesh Refinement ART code
- star formation in molecular gas, supernovae feedback and metal enrichment, stellar mass loss
- radiative cooling and heating: Compton, UV background, with density and metallicity dependent rates
- 3D radiative transfer
- H2 formation on dust grains/destruction by UV, with self-shielding and shielding by dust

  (N. Gnedin & Kravtsov 2011)



z=3:
stars
H_2 gas
HI gas

Zemp et al. (2012)

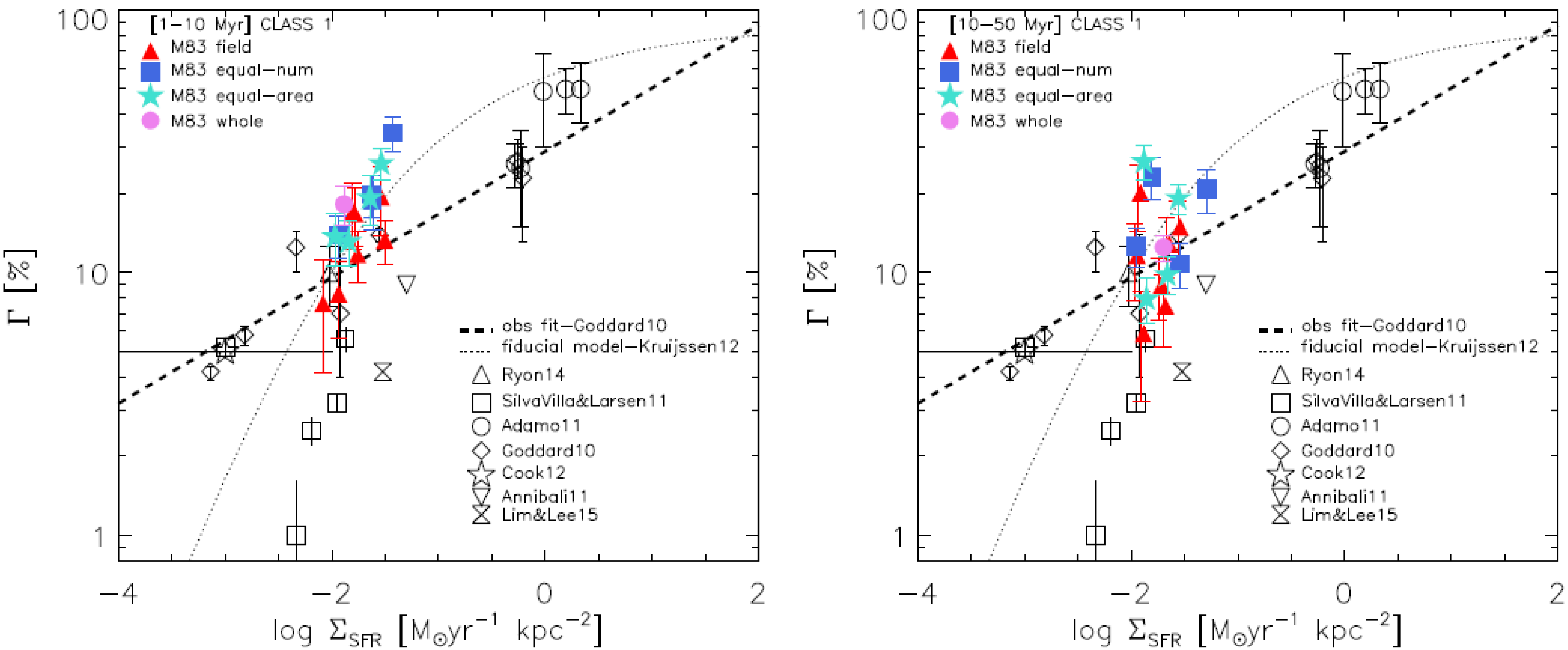
$$\frac{\partial n_j}{\partial t} + 3Hn_j + \frac{1}{a}\mathrm{div}_x(n_j\vec{v}) = \dot{\mathcal{I}}_j + \dot{\mathcal{M}}_j + \dot{\mathcal{D}}_j,$$

Ionization by cosmic and local interstellar UV flux

atomic and molecular chemistry

dust chemistry

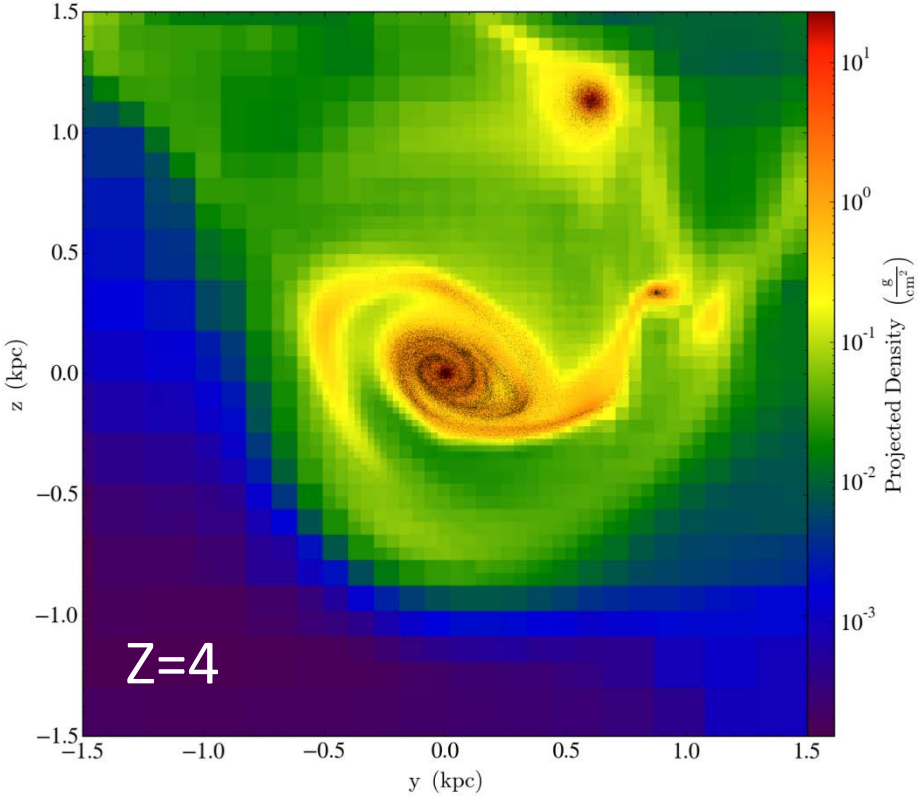
Young star clusters are dominant components of very active star formation

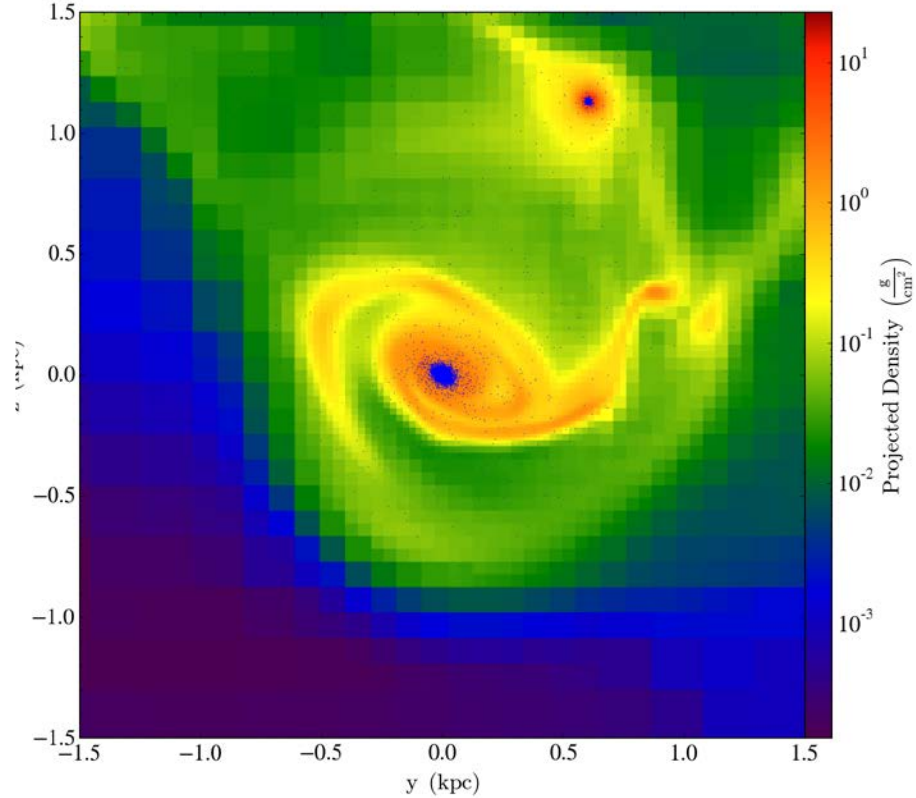


Adamo et al. 2015

Fraction of all young stars contained in massive star clusters increases with the intensity of star formation, up to 50-60%

Spatial Distribution of Star Clusters

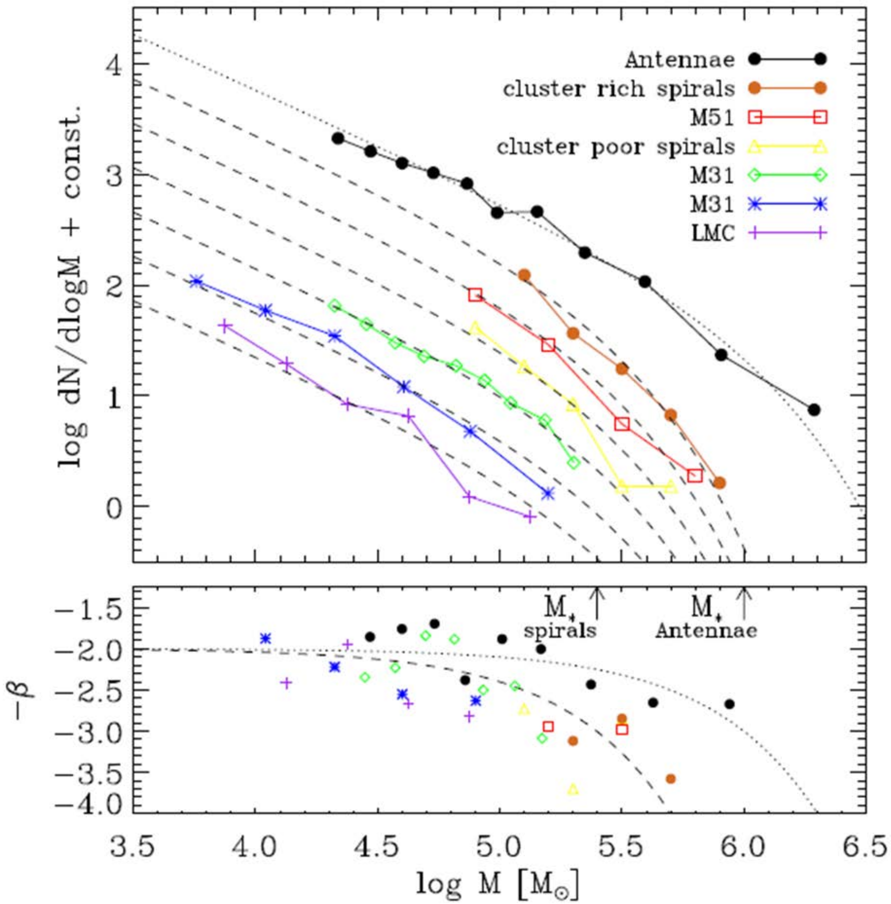


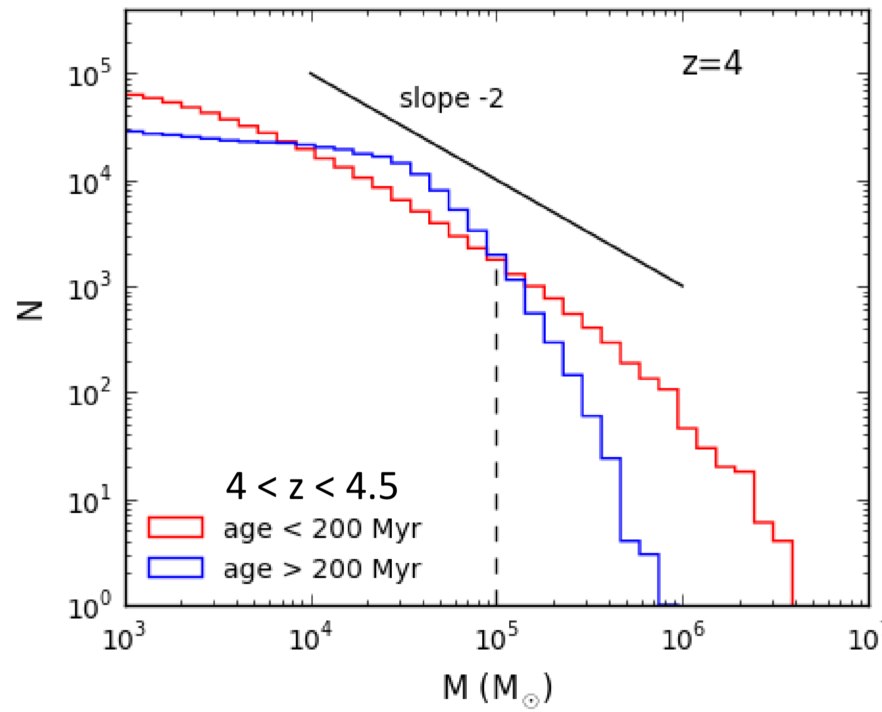


Young star clusters
age < 15 Myr

Massive clusters
mass > 10^5 M_{sun}

Initial Mass Function of Young Clusters

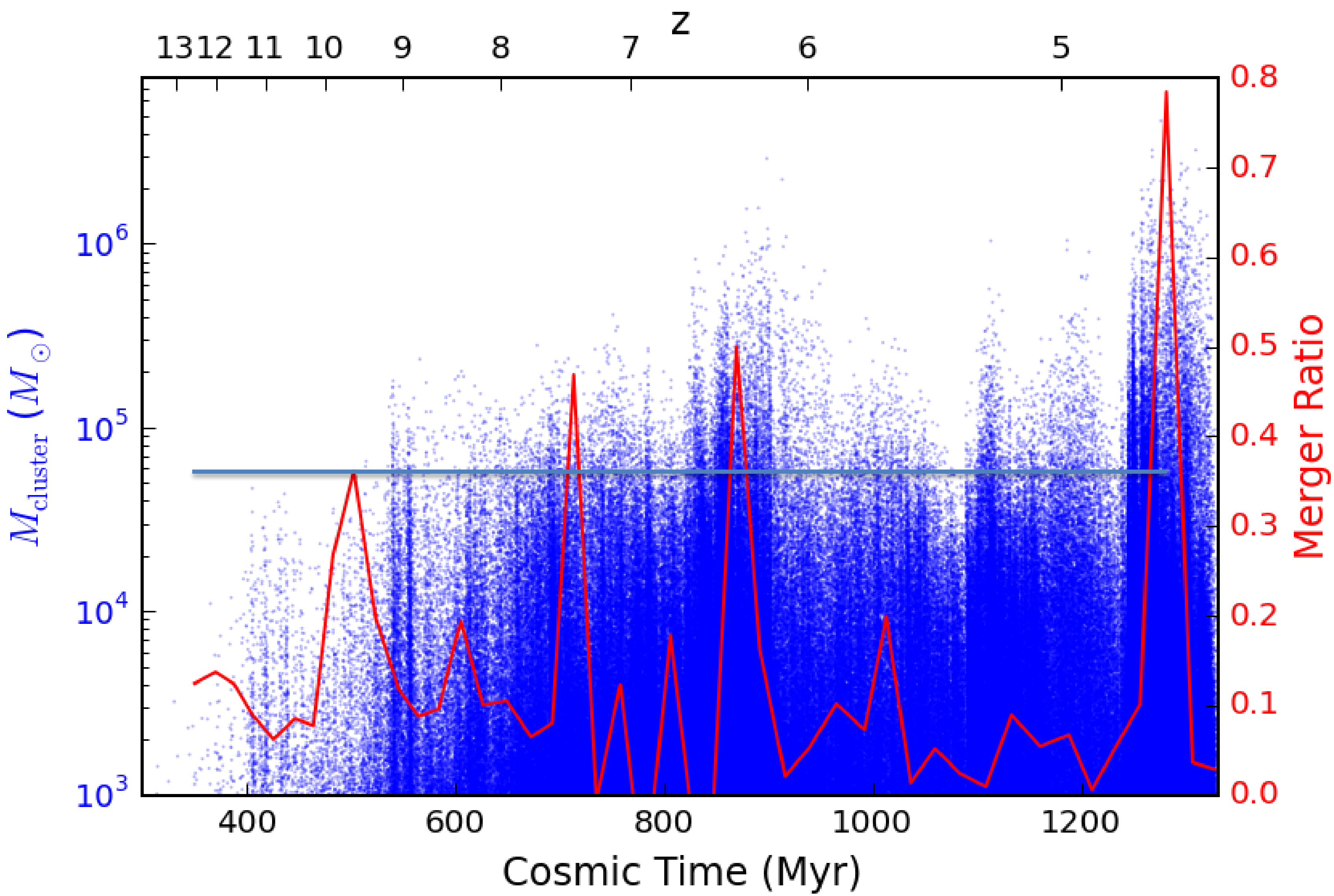




Cosmological simulation of a Milky Way sized-galaxy (Li & OG 2015):

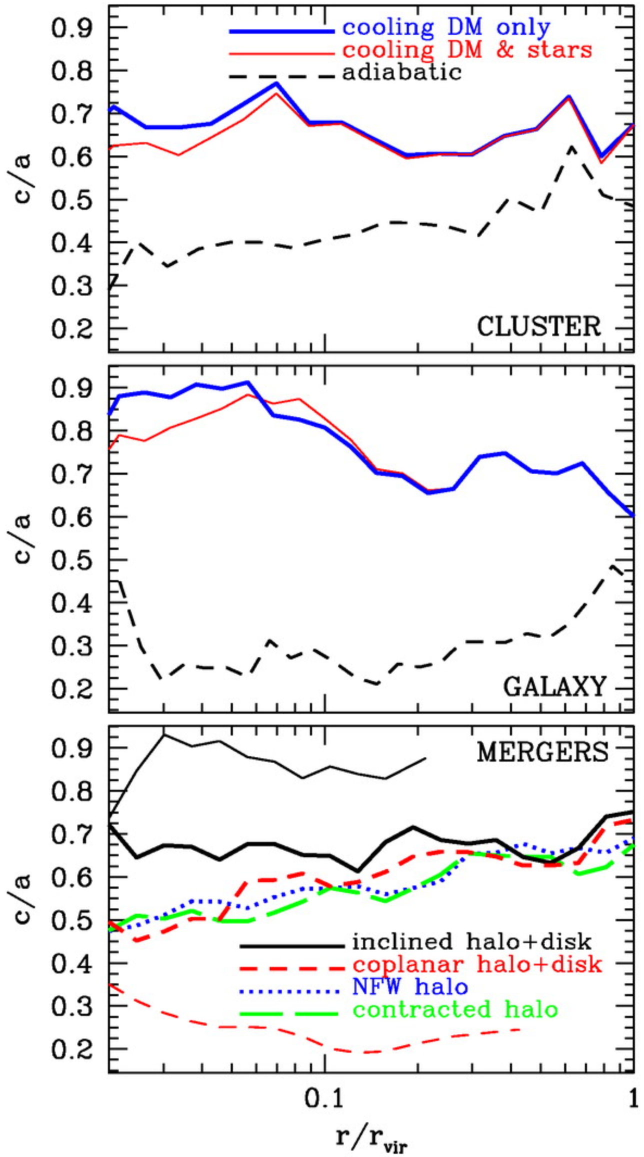
- After a gas-rich merger event, MF of new clusters is a power law as observed for young star clusters
- Fewer massive clusters between mergers

Gas-rich mergers trigger massive cluster formation

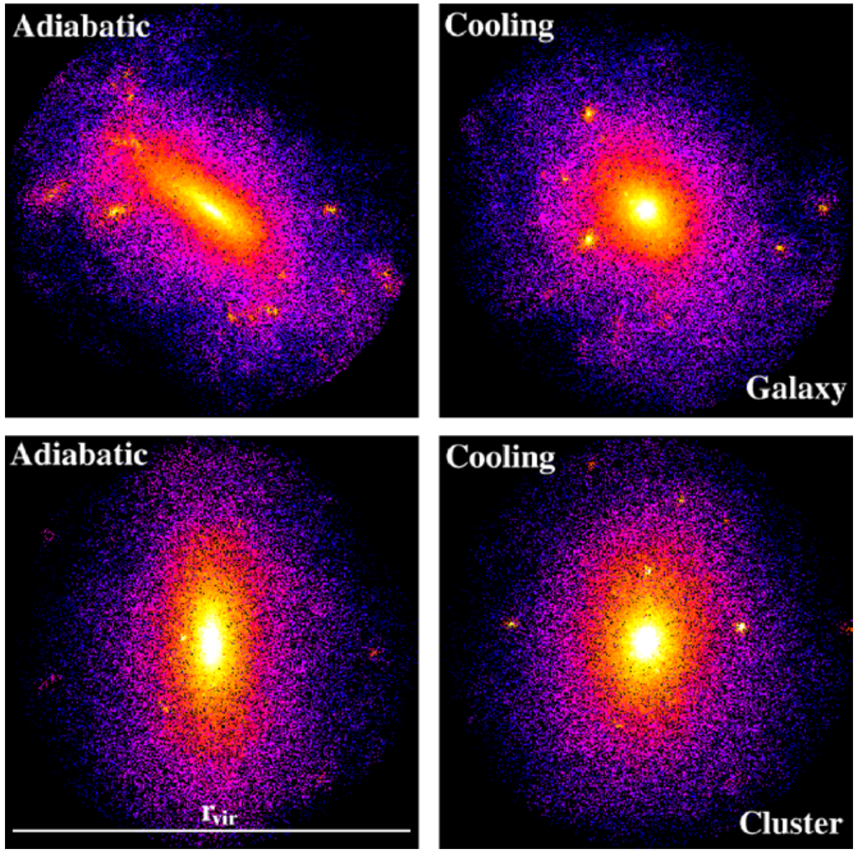


Muratov & Gnedin 2010, Li & Gnedin 2014

Cooling of cosmic gas changes the structure of dark matter halos: halo shape turns from triaxial to round

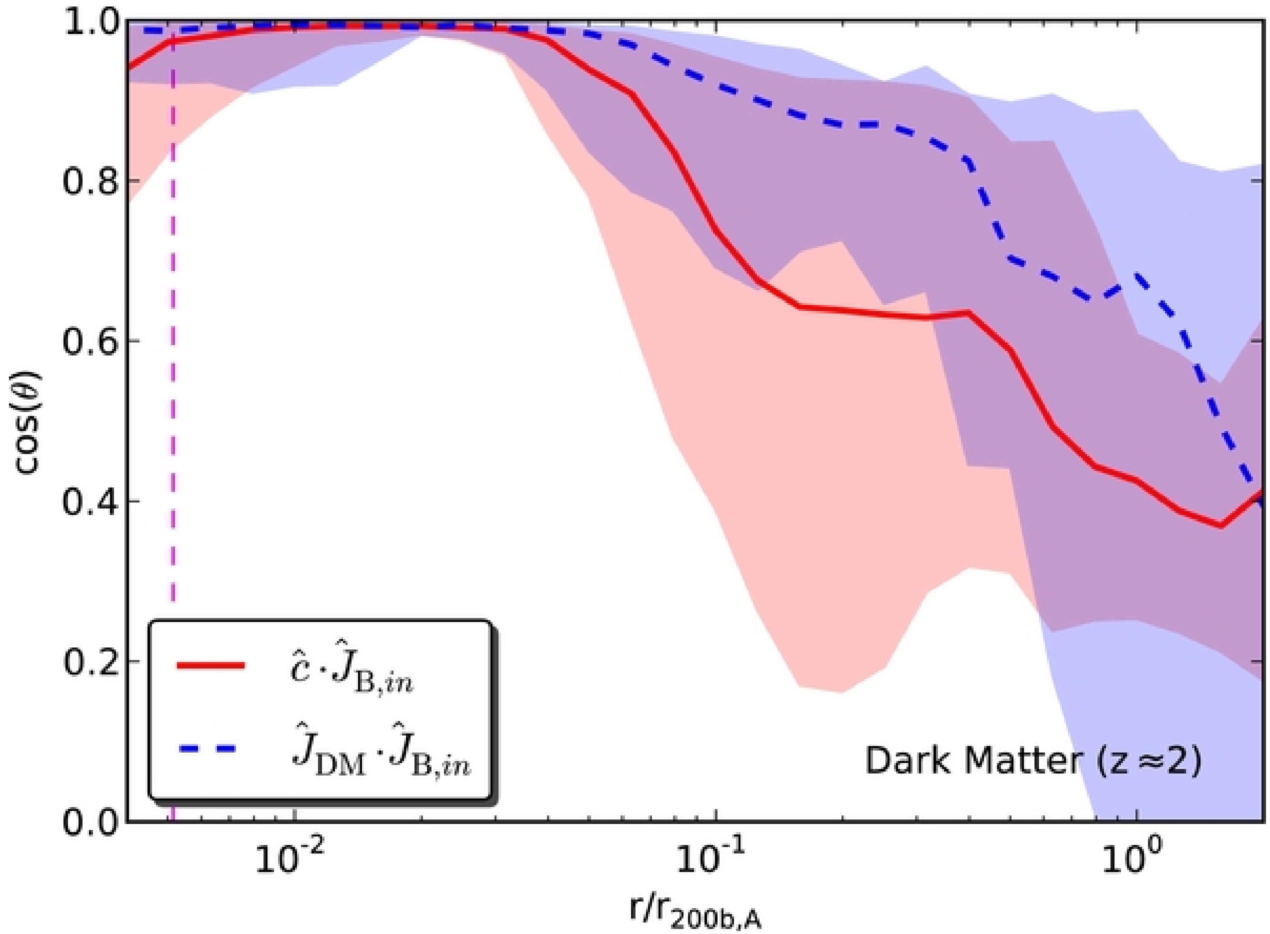


In the inner regions where baryons dominate mass, halo becomes rounder
(Kazantzidis et al. 2004, and many others since)



Inner part of DM halo is aligned with the baryon disk, outer part retains memory of dissipationless formation (halo twists with radius)

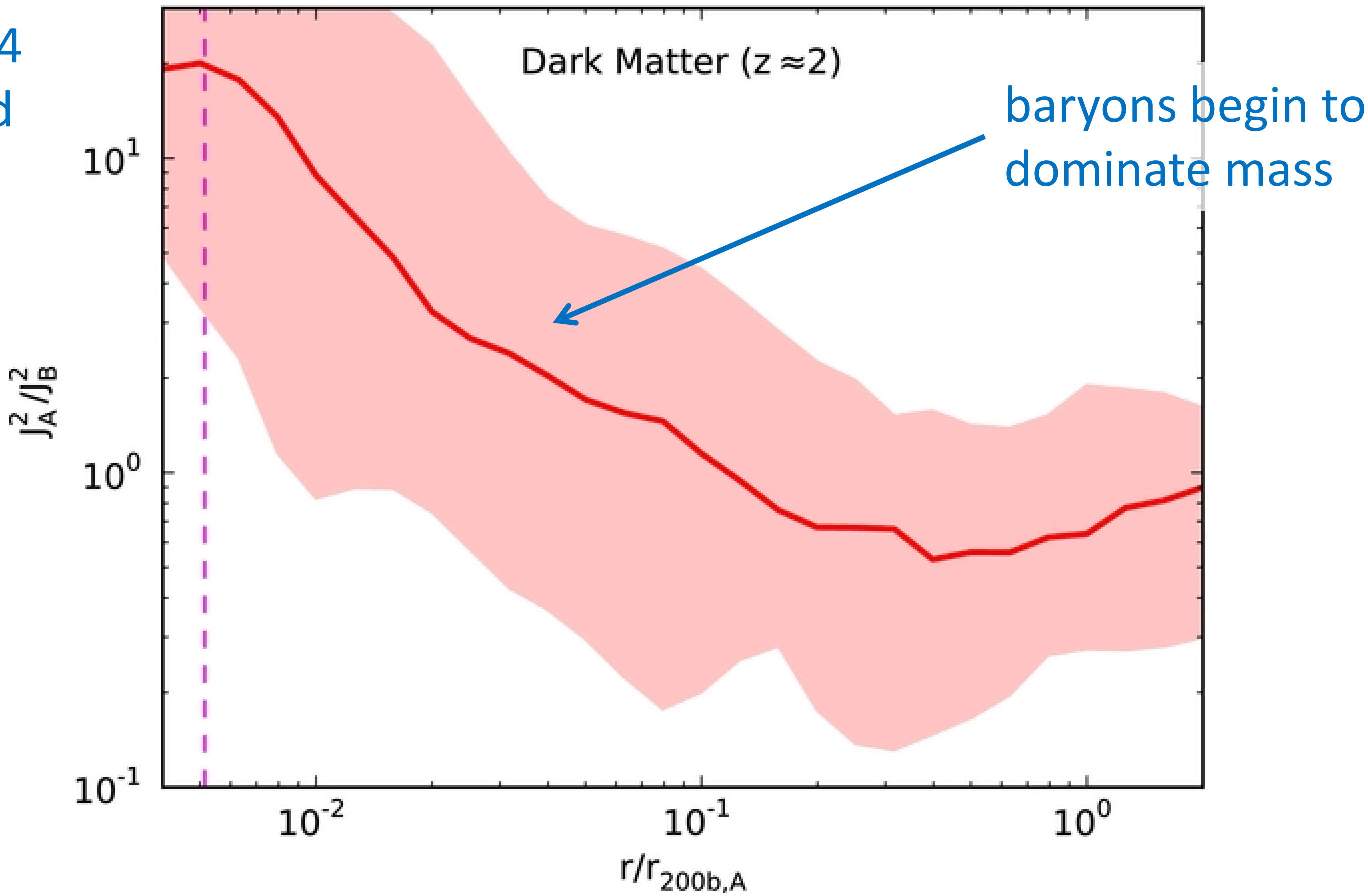
Angle between ang. mom. of baryons in inner 2 kpc and ang. mom. of DM or minor axis of halo



More recent simulation with non-equilibrium H_2 chemistry, metal-line cooling, 3D radiative transfer (Zemp et al. 2012)

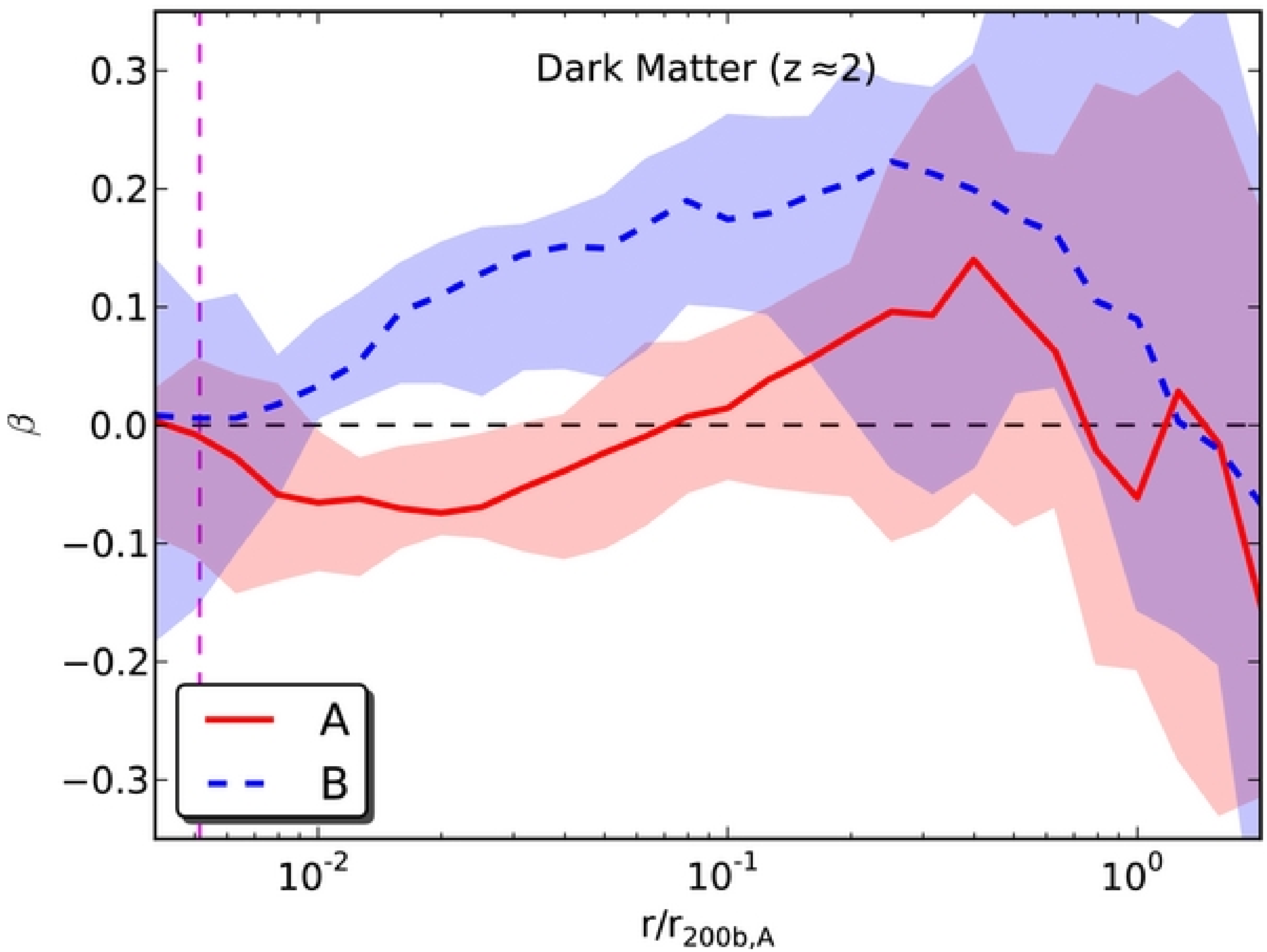
In addition to change in spatial distribution, inner dark matter gains angular momentum from the baryons

factor of 3-4 gain around the disk



Ratio of angular momentum of DM in simulation with gas cooling, star formation and feeeback to dissipationless run

Velocity distribution is close to isotropic, instead of radially-biased as in N-body sims.



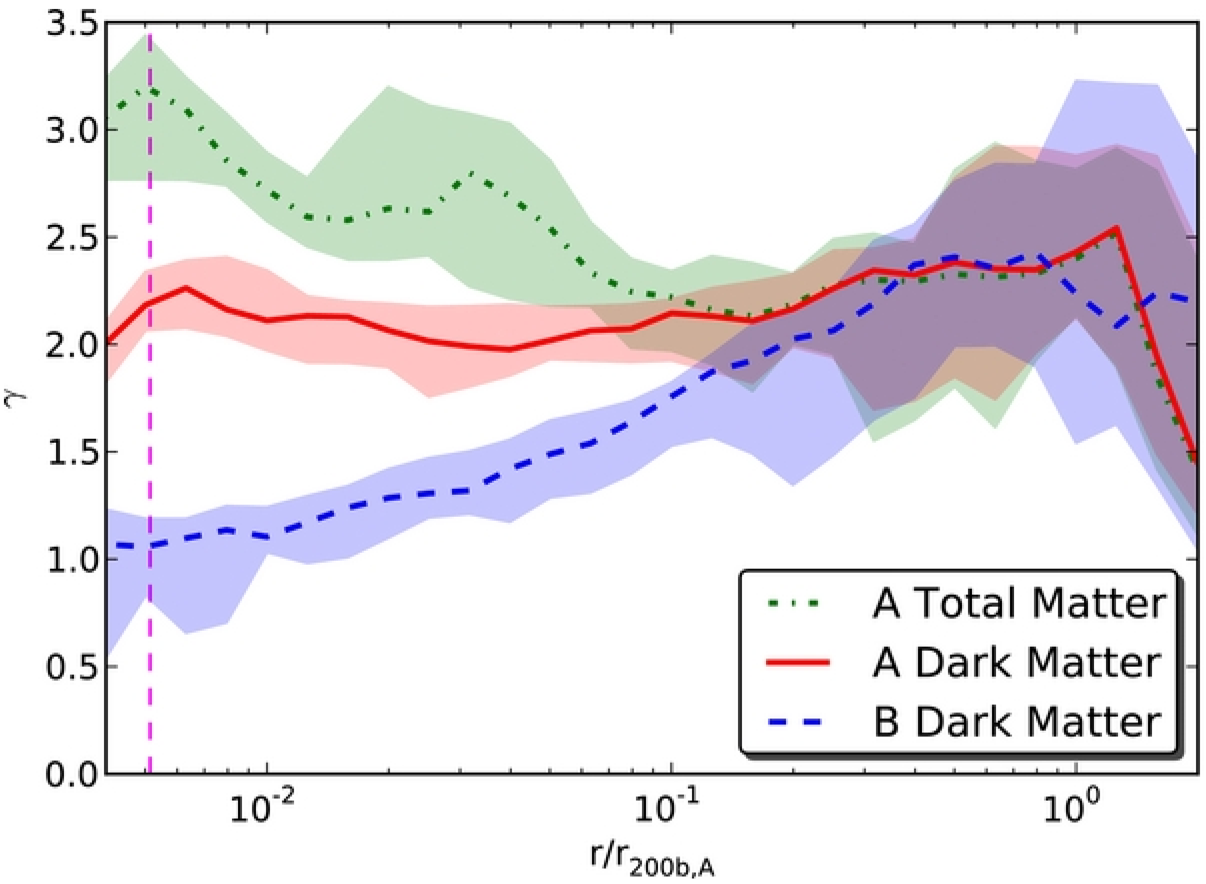
B: without gas cooling or star formation

A: with cooling, star formation, radiative transfer, SN feeeback

Zemp et al. (2012) with high SF threshold but weak feedback:

significant steeping of inner dark matter profile,
to approximately isothermal $\gamma \approx 2$

logarithmic density slope



Summary

- Power spectrum of primordial fluctuations is measured well enough to calculate the emergence of cosmic structure
  remaining uncertainty affects only dwarf galaxies
- Predicting structure of galaxies (stars and gas) is necessarily model-dependent
  formation of stars and their feedback are very uncertain
- Star clusters are dominant components of active star formation
  provide important tests for modeling baryon physics
- Baryons make halo shape more round
  at stellar half-light radius, but not at virial radius
- Dark matter halo rotates slowly
  gains angular momentum from collapsing baryons