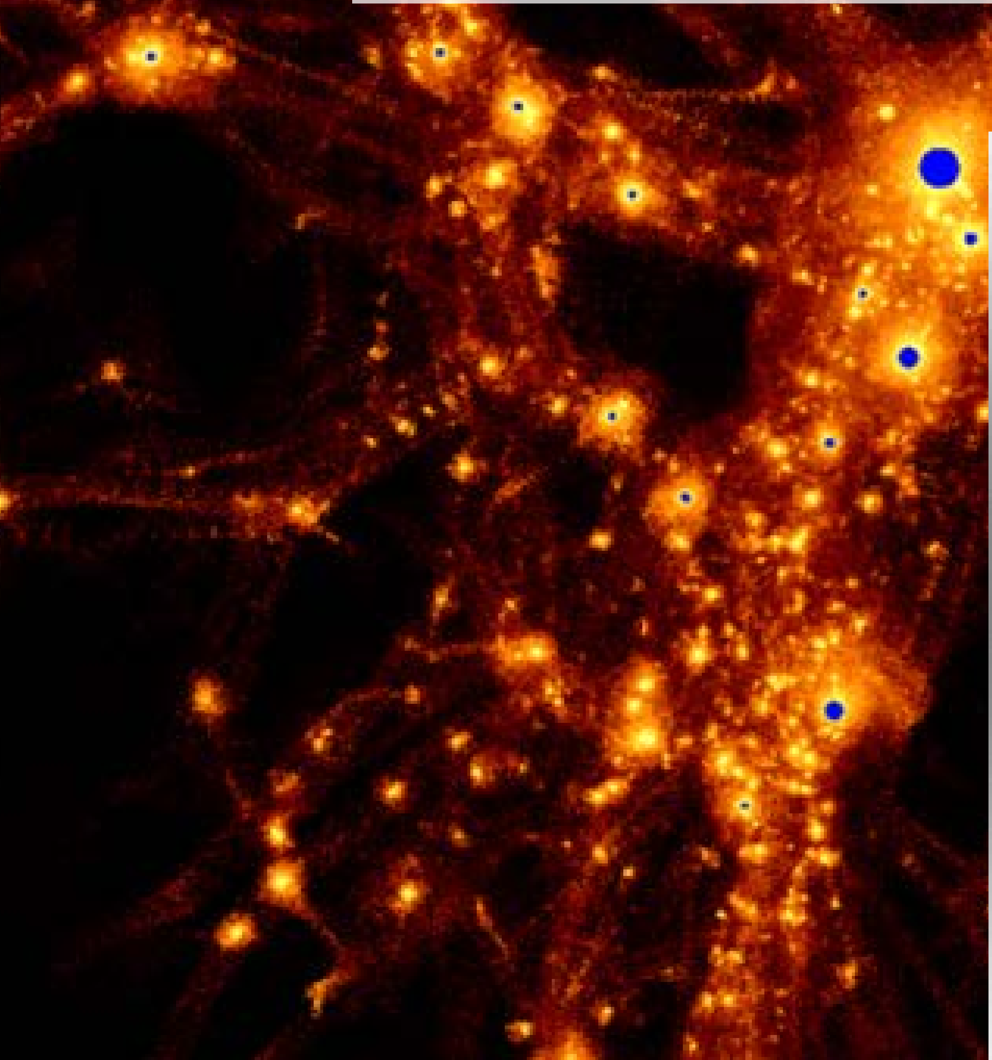
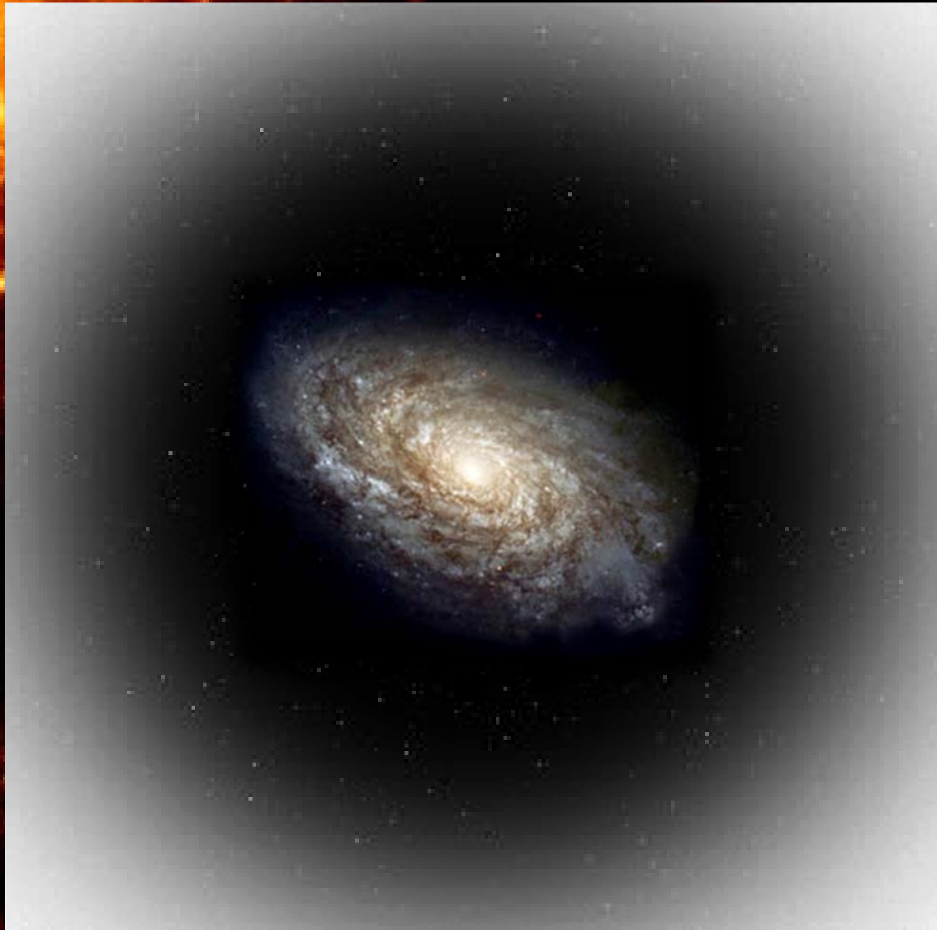
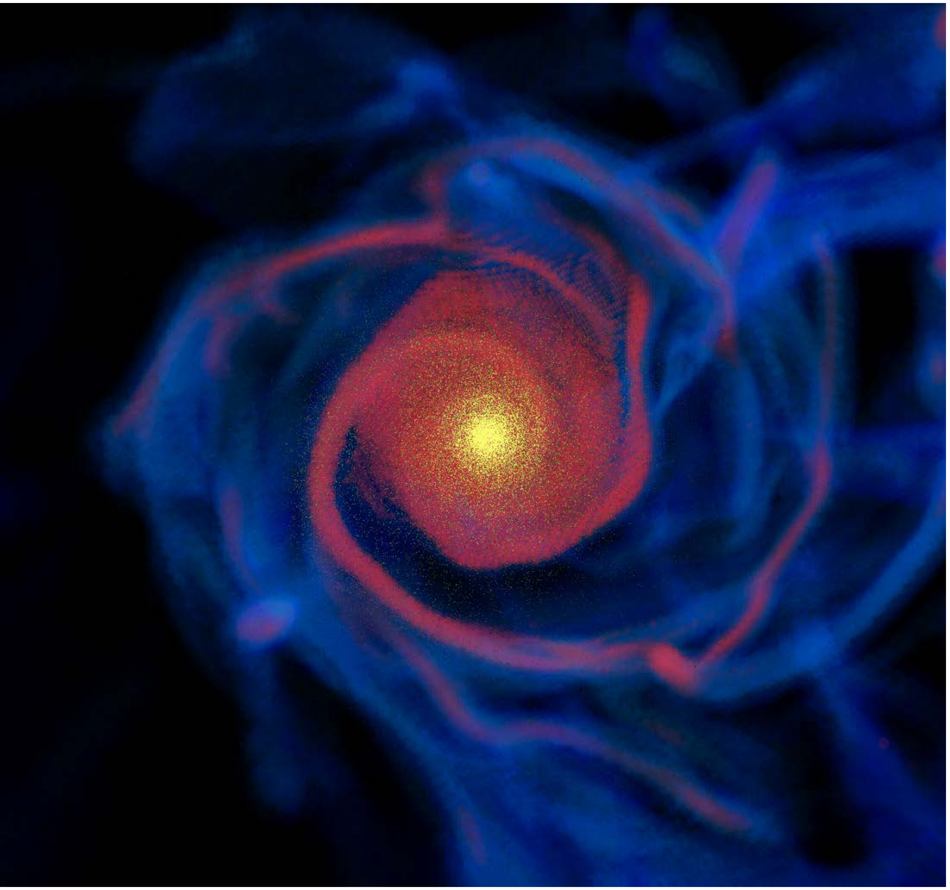
Recent Progress in Modeling of Galaxy Formation

Oleg Gnedin (University of Michigan)



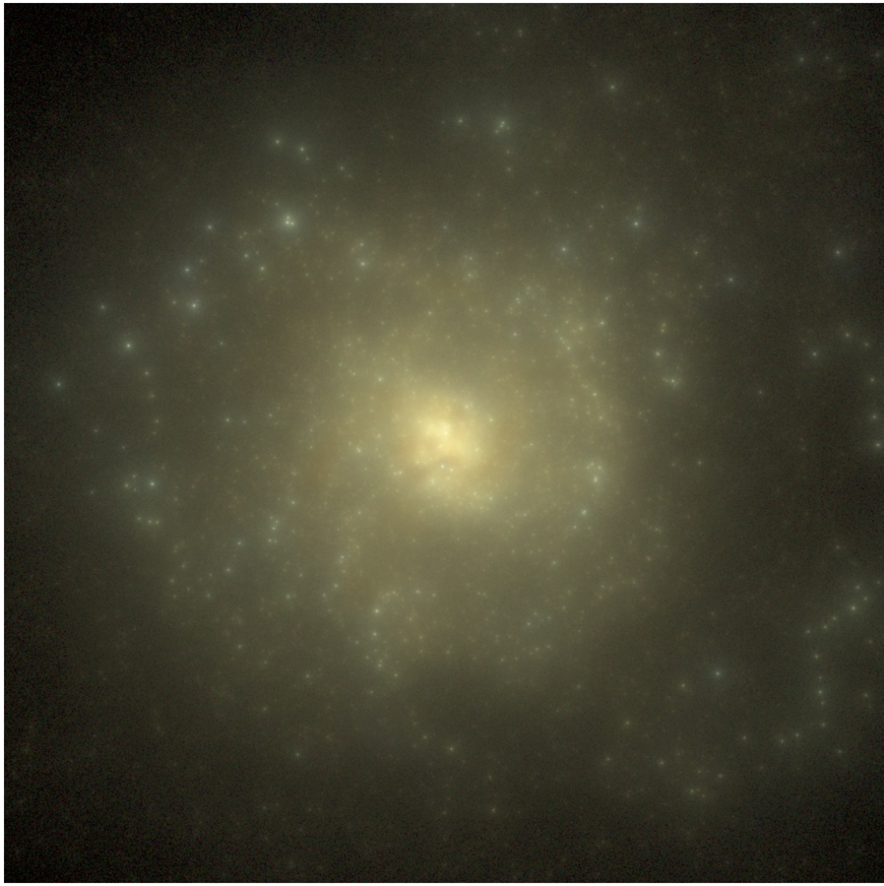


In current simulations, galaxies look like this:



10 kpc

Disk galaxy at z=3: stars, molecular gas, atomic gas (Zemp, OG et al. 2012)



Disk galaxy at z=0 (Eagle simulation, Schaye et al. 2015)

Real galaxies look like this:

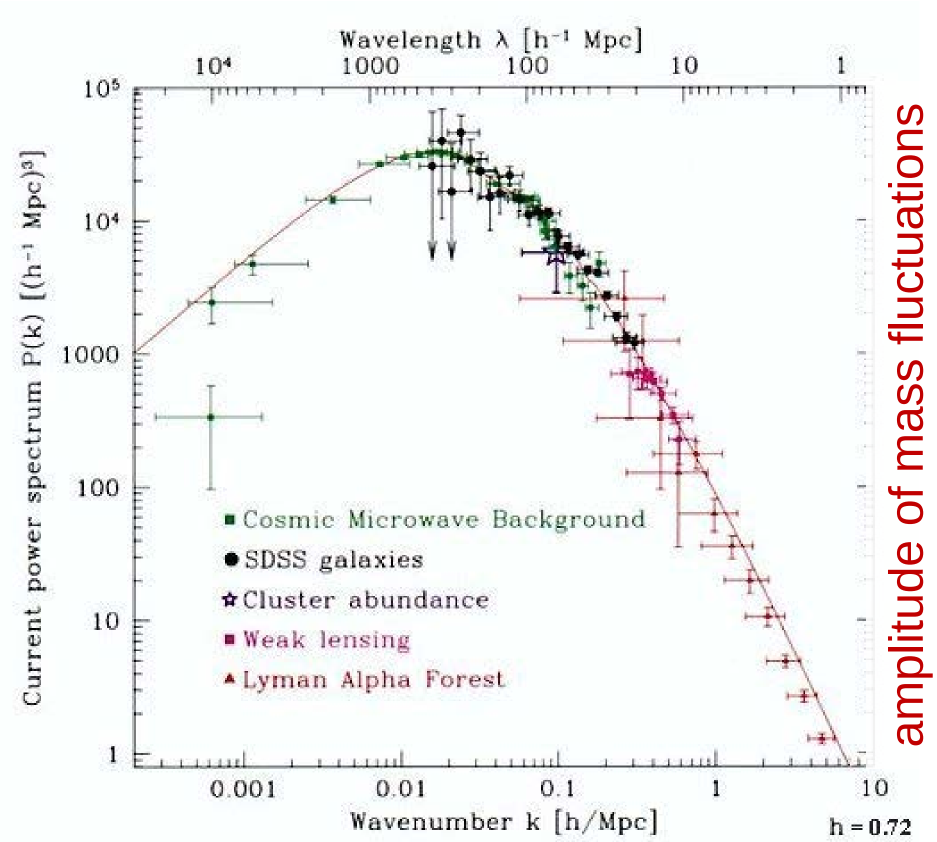
(more structure, extended disks, young stars, gas emission, dust lanes)

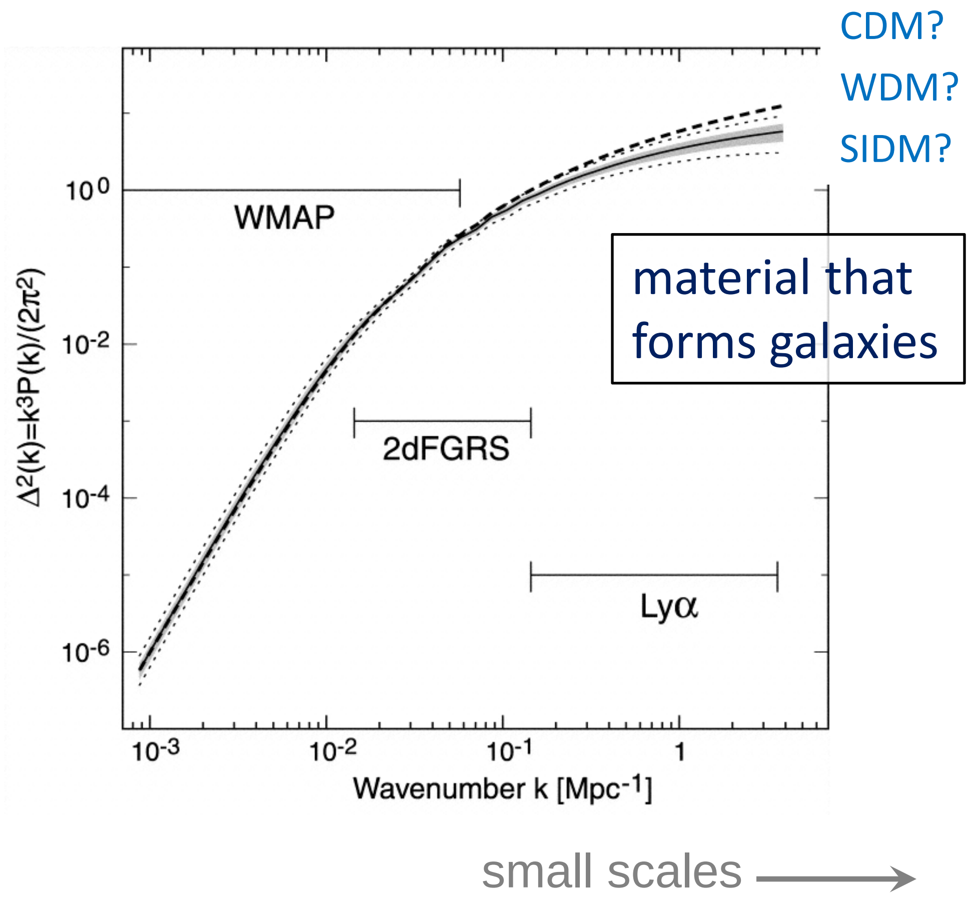
How much progress are we making and what are the difficult issues?

Modeling the emergence of cosmic structure (galaxies and cosmic web) is essentially an *initial value problem* with *periodic boundary conditions*:

- We know (*statistically*) the initial conditions from anisotropies of Cosmic Microwave Background radiation
- Distribution of matter is uniform on large scales > 10^8 pc, therefore each smaller piece (*we will take a cube*) repeats on all sides
- What makes it hard is the size of objects of interest is MUCH smaller: Sun < 10^{-7} pc, nearest star is at 1 pc, star clusters ~10 pc, Milky Way galaxy ~10^4 pc

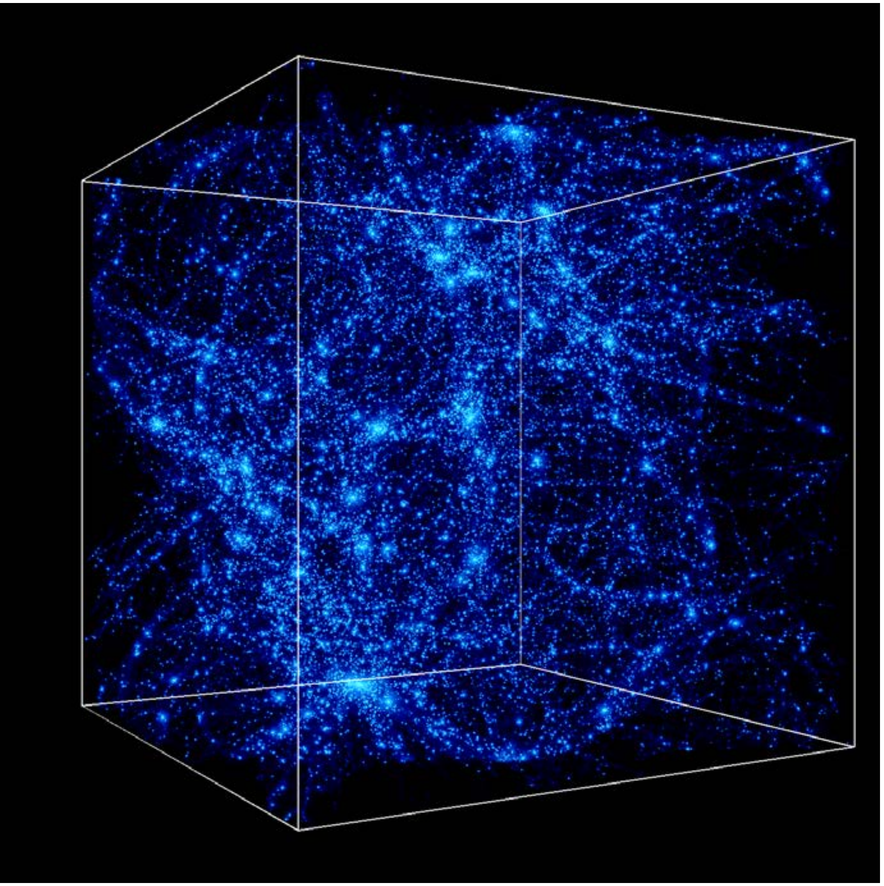
Stronger (measured) primordial fluctuations on small scales determine that low-mass *halos* form before high-mass *halos*

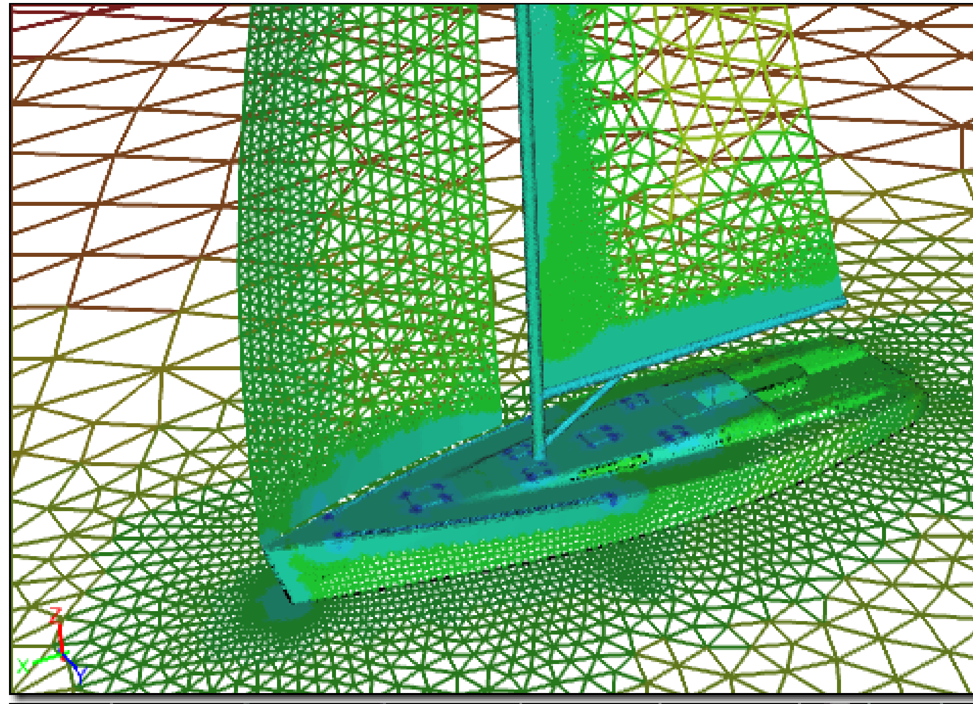


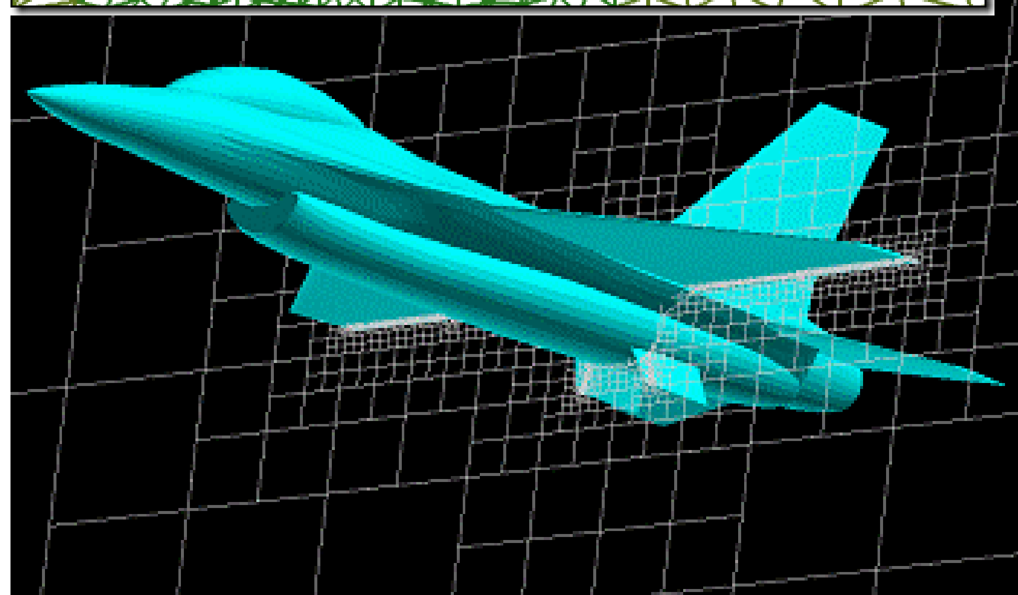


Once the spectrum of fluctuations is known, and phases are Gaussian, cosmic structure can be calculated without any free parameters (although DM self-interaction could make a small difference later at centers of dwarf galaxies)

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



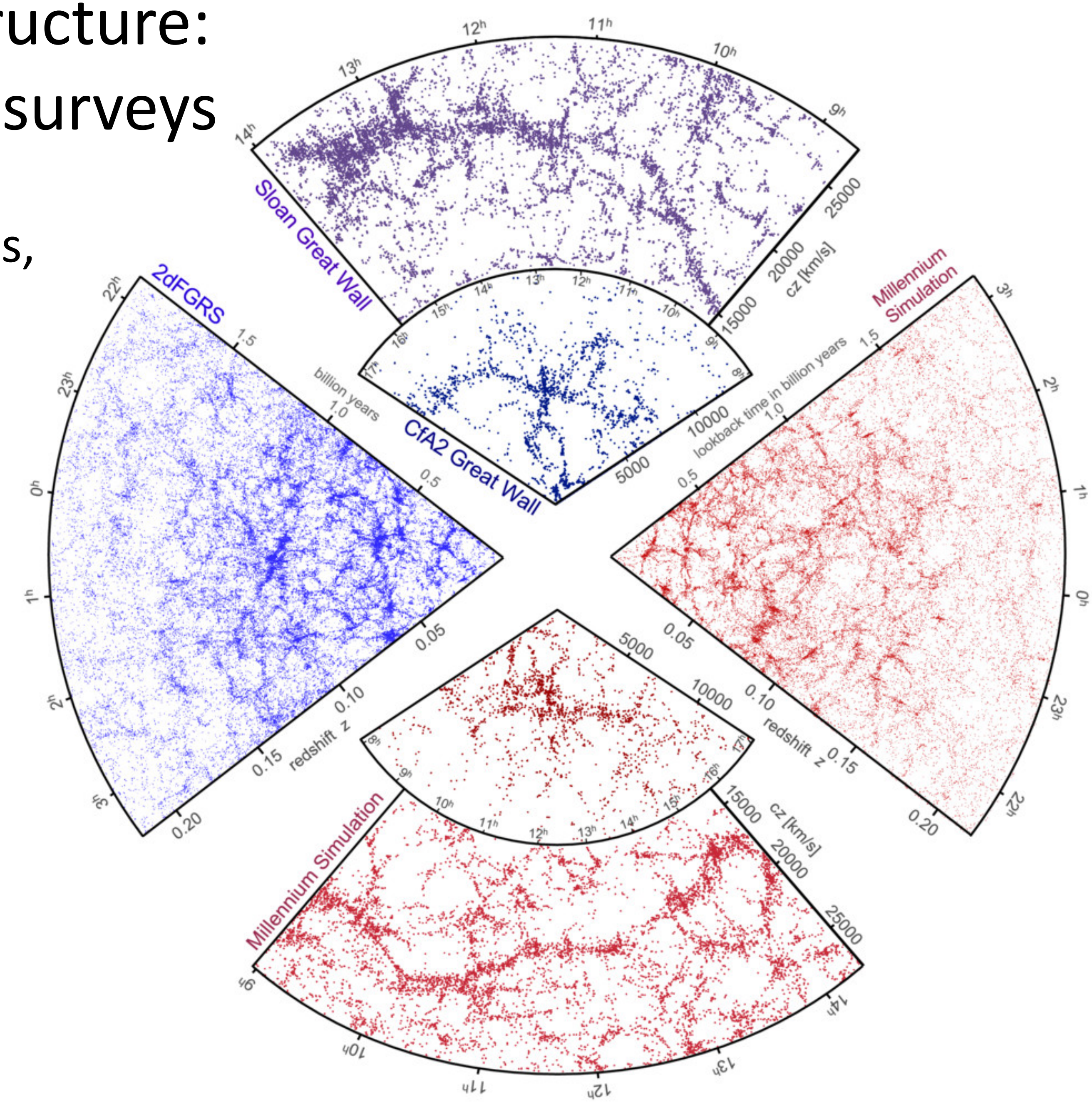




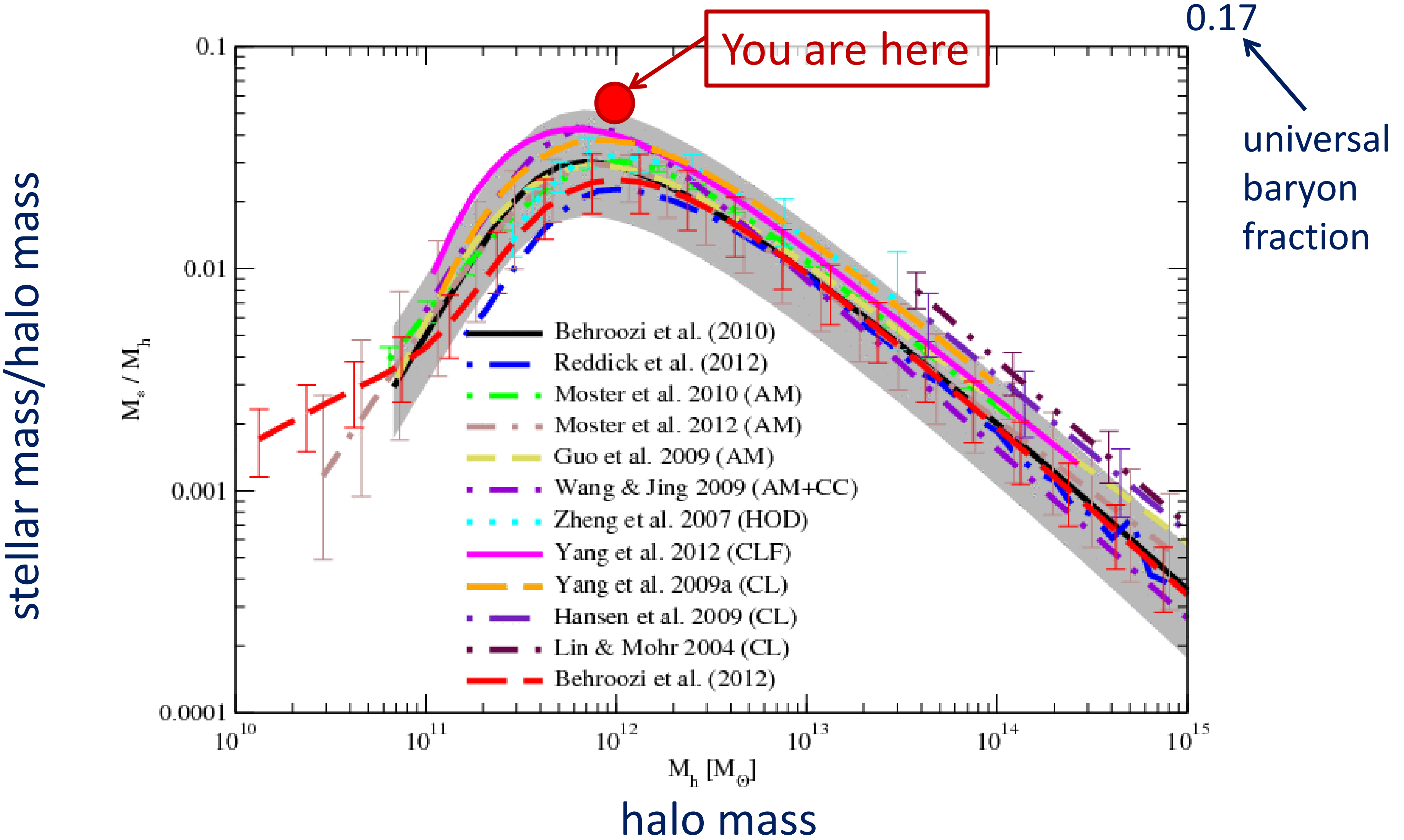
Numerical techniques are borrowed from aerospace engineering and well tested

Large-scale structure: distant galaxy surveys

Blue is observations,
Red is simulations:
very similar



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 the skeleton of large-scale structure and galaxy potential wells
- *radiative cooling:* shocks and UV radiation heat the baryons, but dissipative particle collisions allow cosmic gas to radiate away its thermal energy and sink to the center of the potential well, where it can reach high enough density to form stars

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, momentum, and metals released during thermonuclear burning back to the interstellar medium, and thus regulate formation of future stars

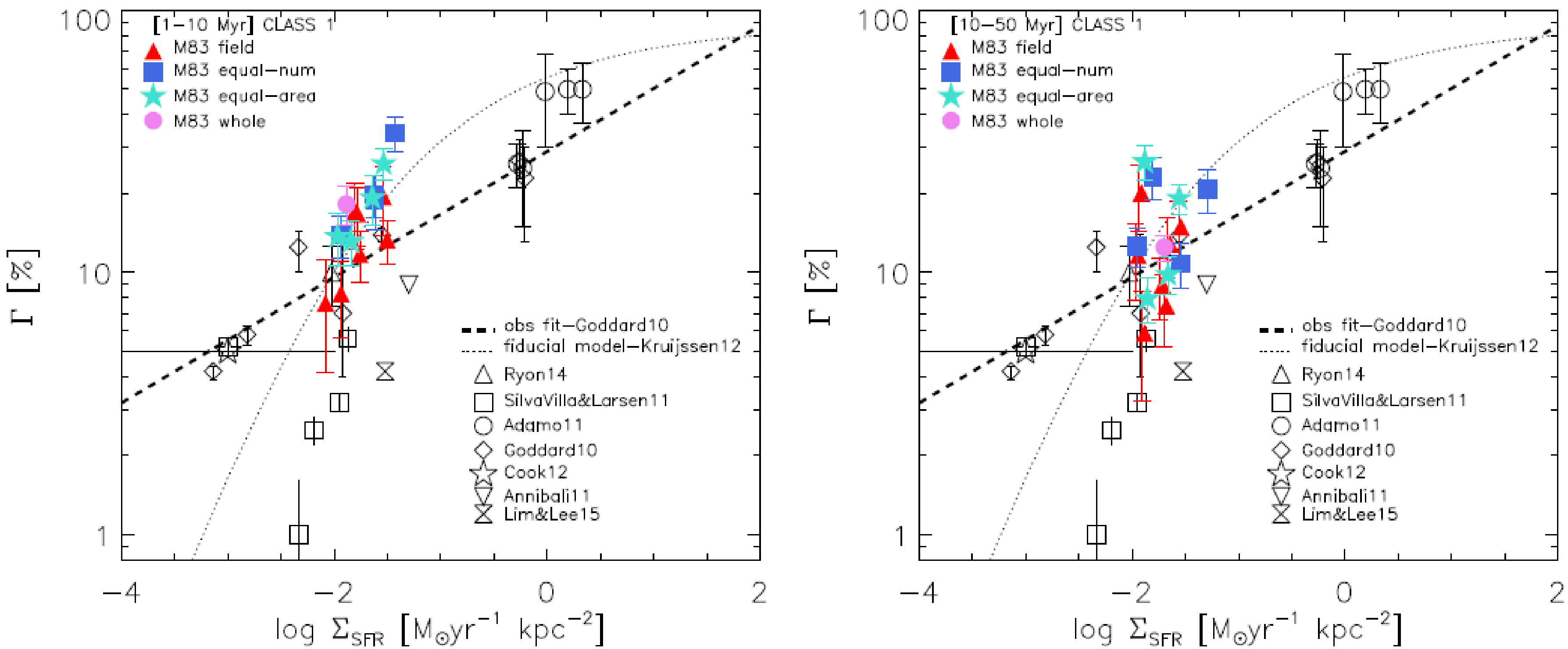
Detailed structure of galaxies, their star formation histories, number of satellites, etc. are necessarily model-dependent.

It is work in progress for the next 10 years.

Many degeneracies: these are global galactic properties that can be produced by a variety of different small-scale models.

Clustering of star formation:

Star clusters connect small-scale star formation (local) and global processes in galaxies

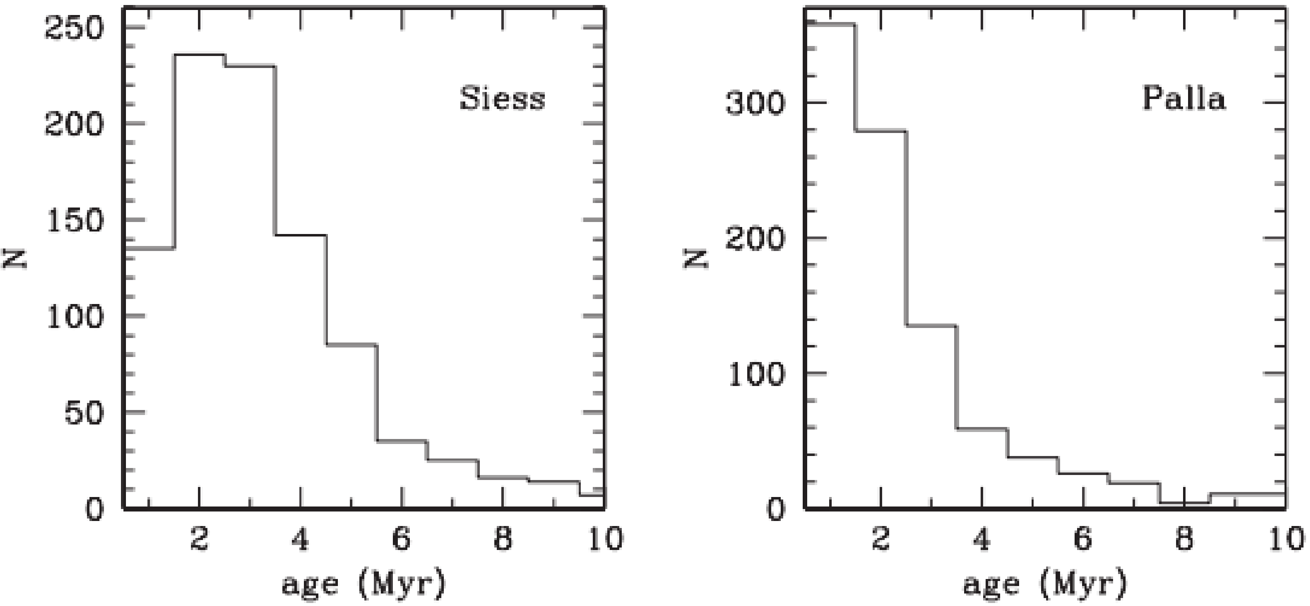


Adamo et al. 2015

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

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

Ages of stars in Orion Nebulae Cluster

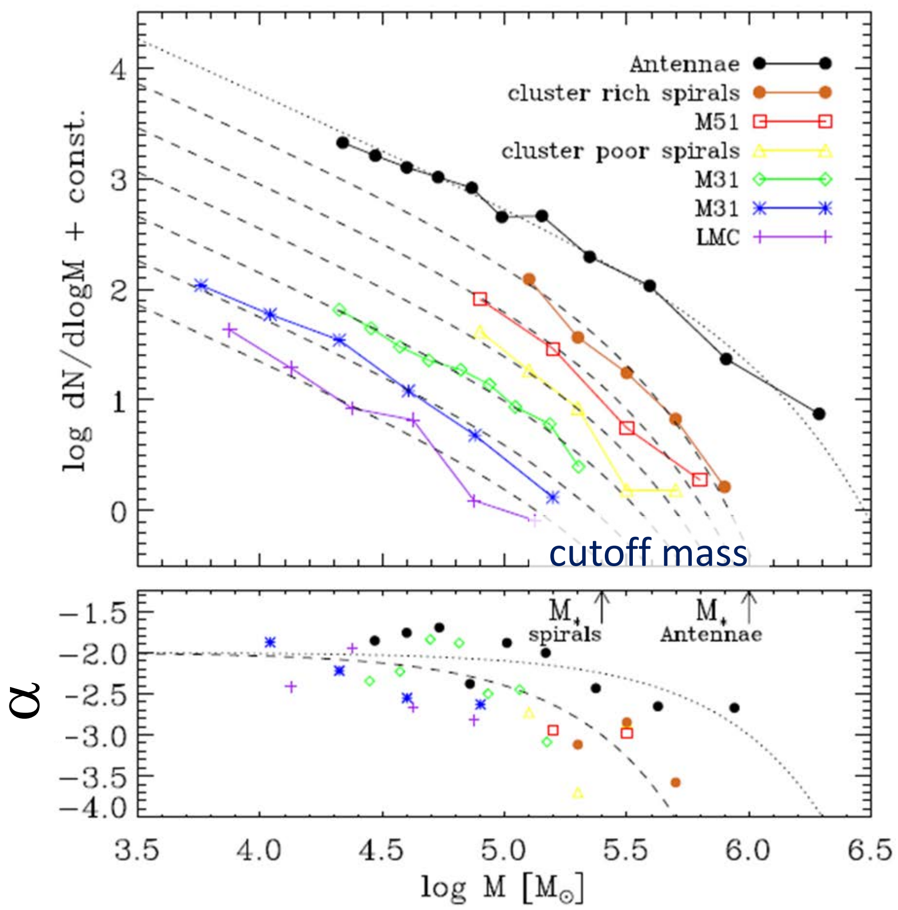


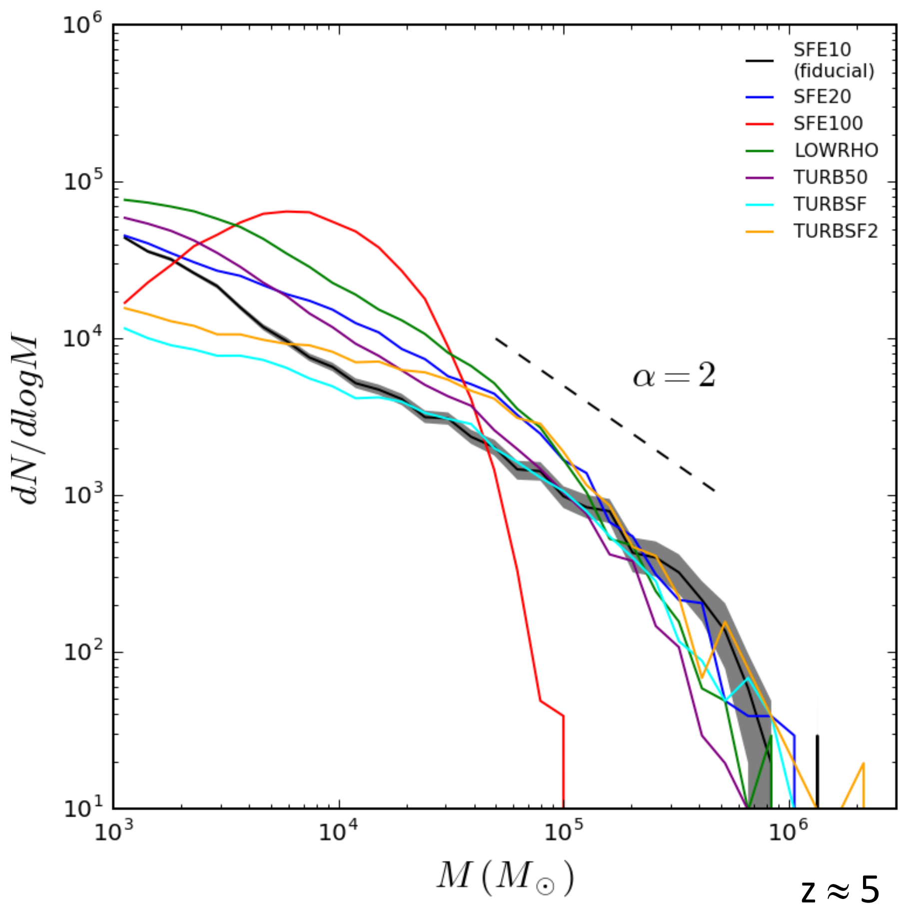
Hartmann et. al. 2012

NGC 602
young star cluster in SMC

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

Initial Mass Function of young clusters is almost invariant





z ≈ 5

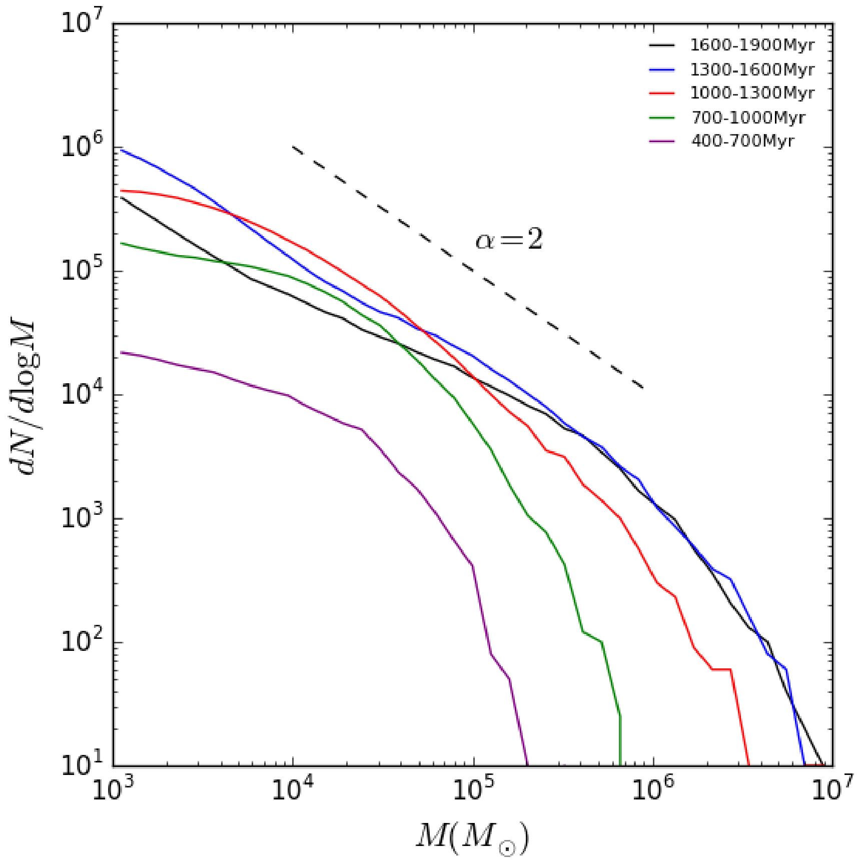
$$\frac{dN}{dM} \propto M^{-\alpha} \exp(-M/M_{\rm cut})$$

slope $\alpha \approx 2$

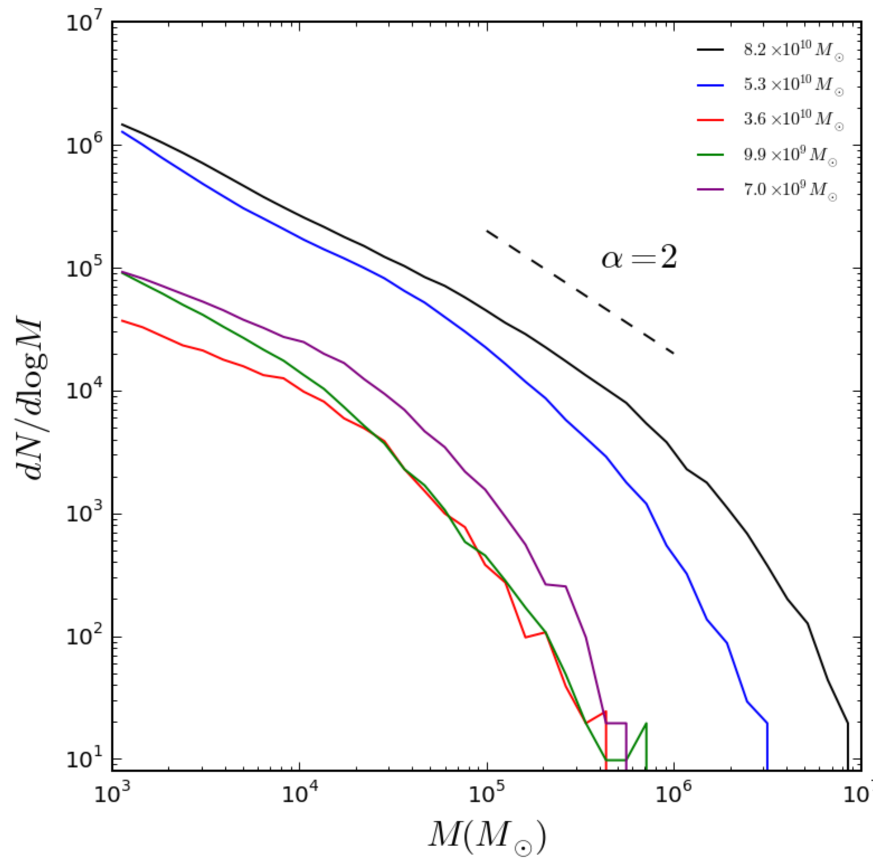
Cosmological simulation of a Milky Way sized-galaxy (Li & OG 2016):

- MF is a power law as observed for young star clusters
- Unless star formation is too disruptive (i.e., 100% SFE)

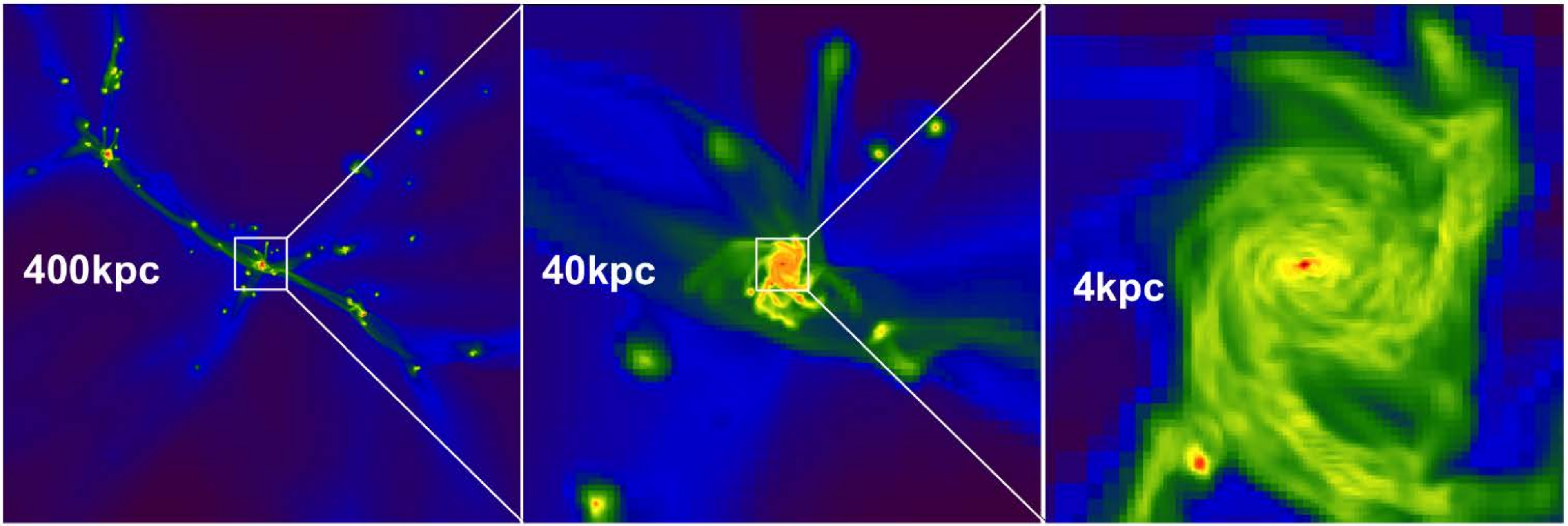
In the simulations, cluster mass function remains a stable power-law for some models and varies for others – good for constraining models



Different epochs within the same central galaxy



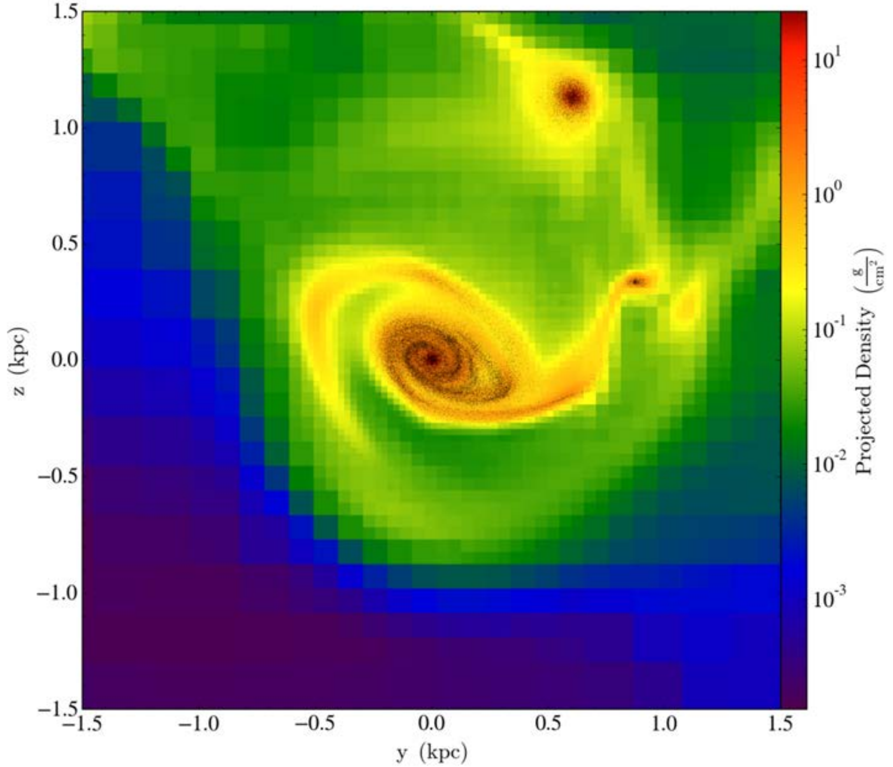
Different galaxies at the same epoch ($z \approx 3.3$)



z ≈ 3.3

Massive clusters form within galaxy disks, but the disks are perturbed by frequent mergers and accretion of satellites

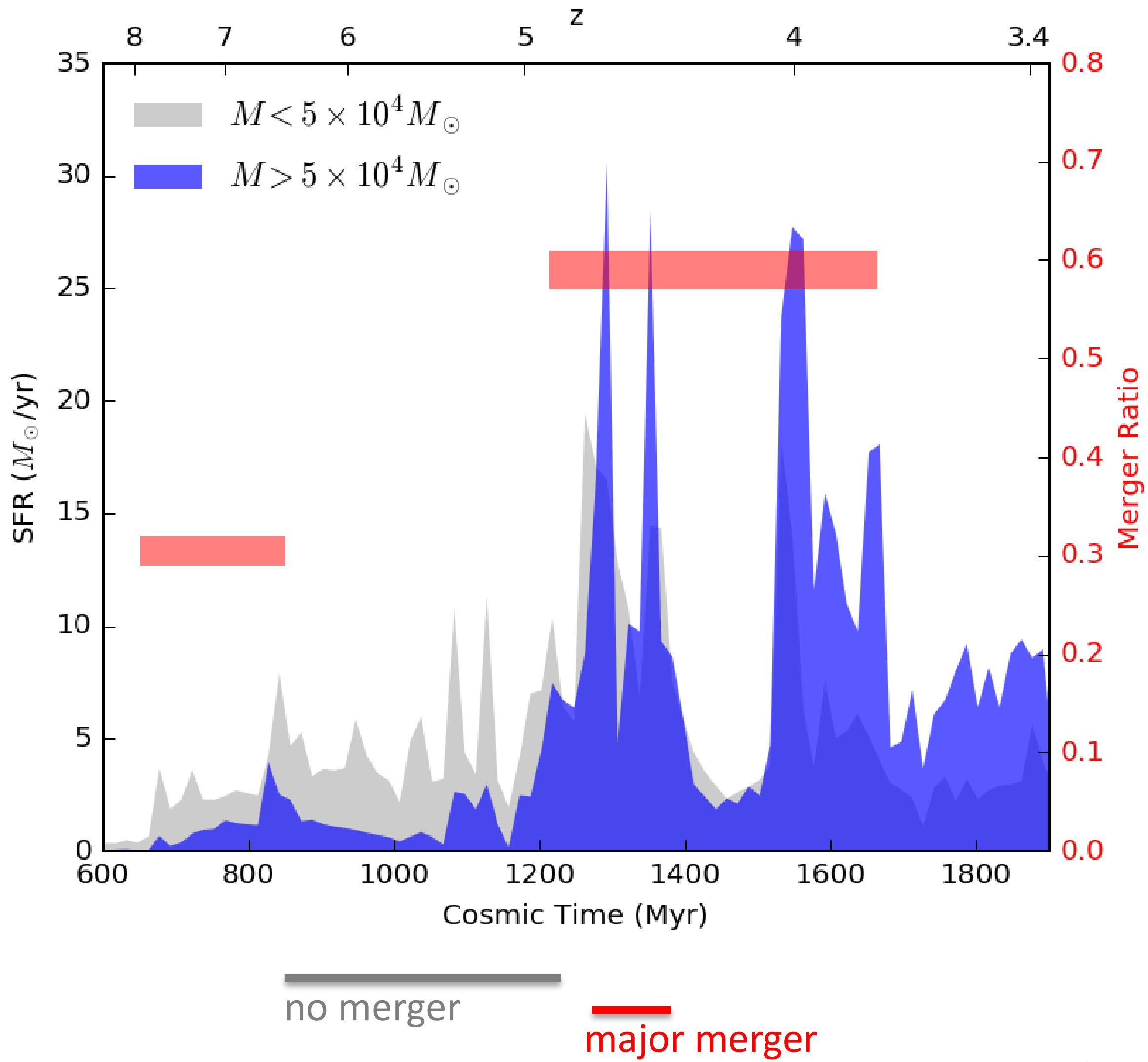
z ≈ 4



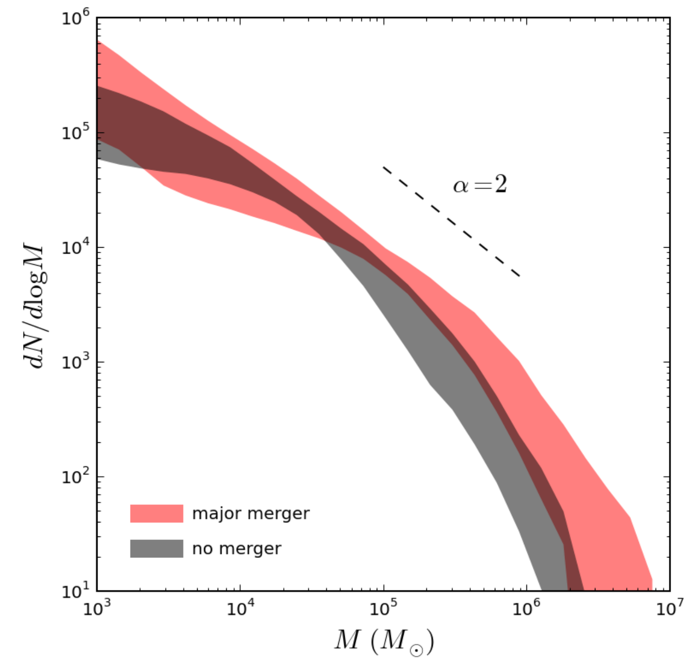
Formation of massive star clusters *may* require major mergers of gas-rich galaxies

- Star clusters form in giant molecular clouds (GMC)
- Higher density of globular clusters requires higher external pressure on GMC
- Interstellar medium is over-pressured during galaxy mergers
- Extreme masses of proto-globular GMC require very gas-rich galaxies

Gas-rich mergers of massive galaxies trigger cluster formation

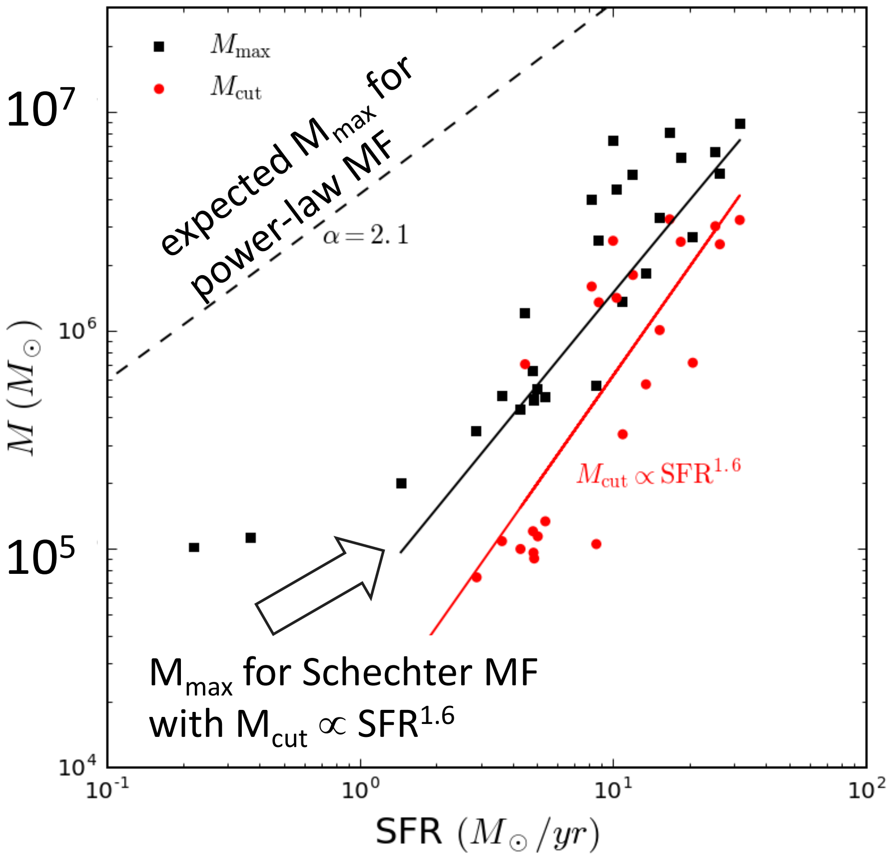


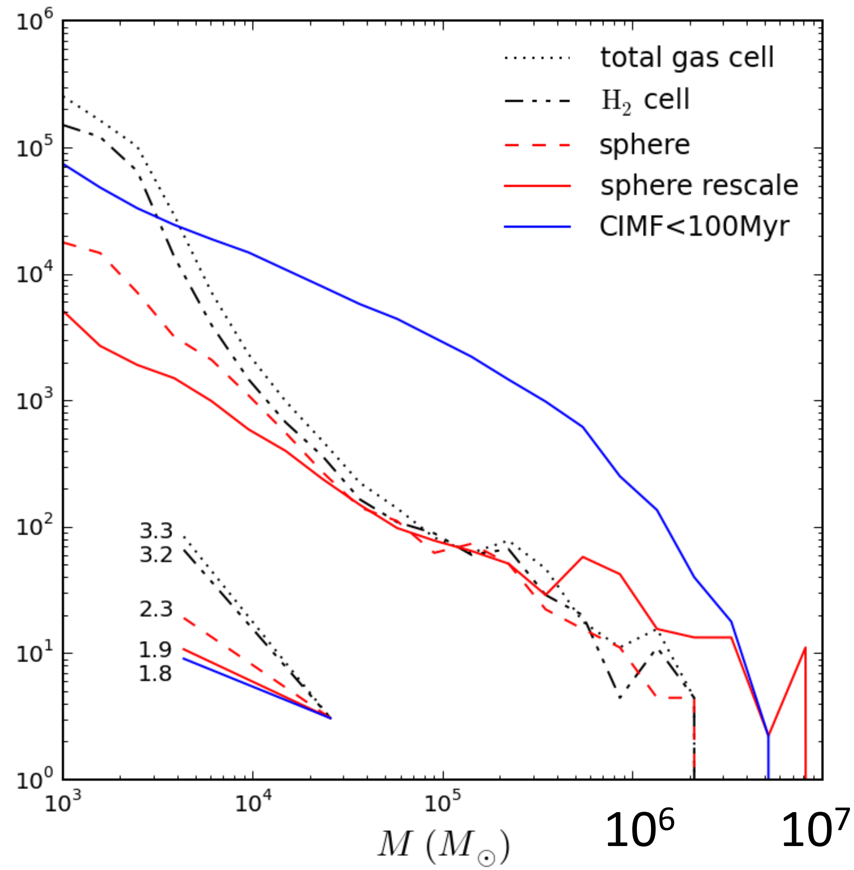
Li & OG 2016



Cluster MF is more strongly truncated between mergers

Origin of the shape of cluster mass function

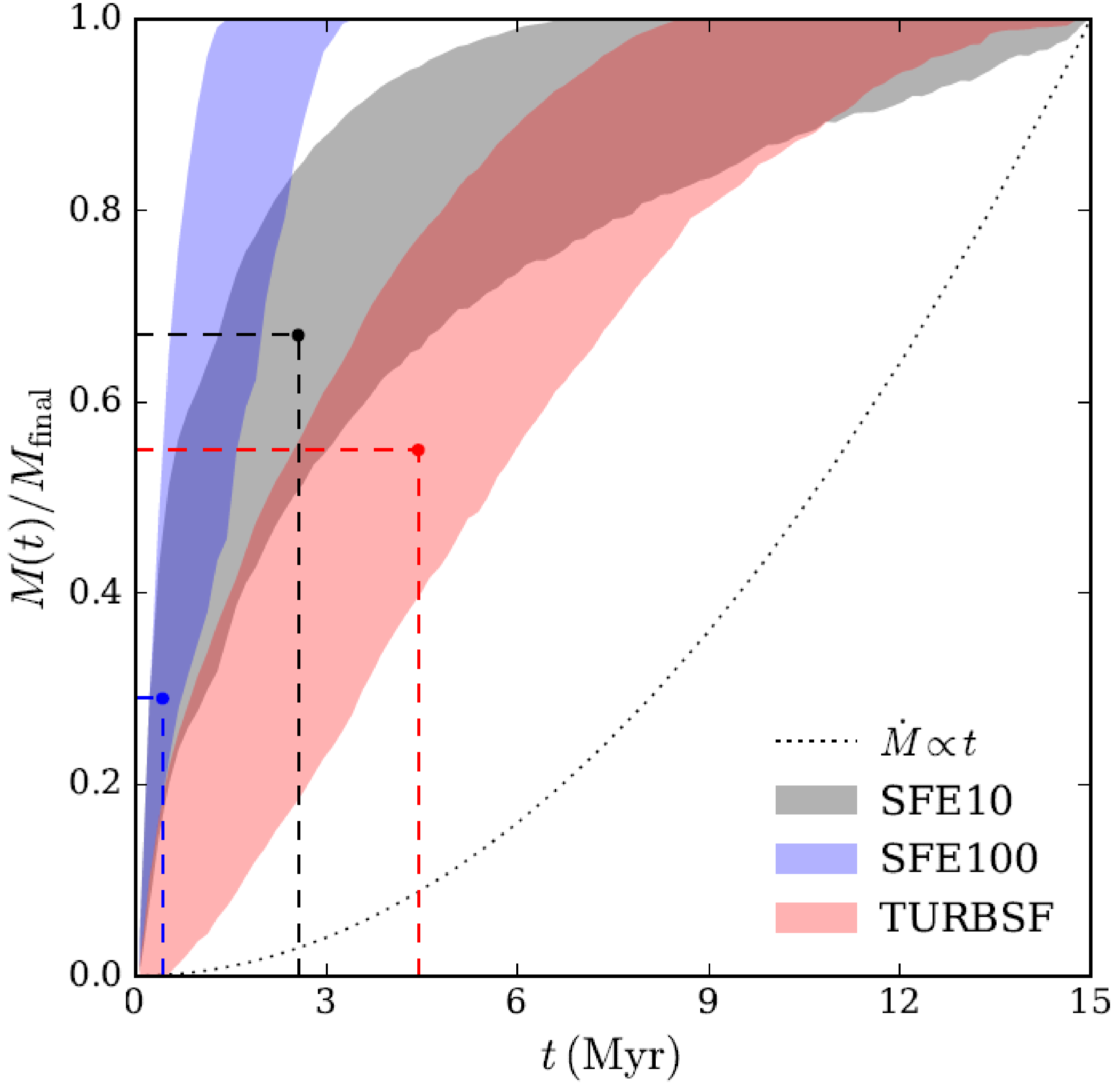




Maximum cluster mass is consistent with that expected for a Schechter function with truncation mass scaling as $SFR^{1.6}$

Power-law MF emerges from the gradual suppression of SFR of a cluster by feedback of its own young stars

How efficiently stars form locally, and how much feedback they create, determines the duration of star formation in molecular clouds (*observed as age spread of stars in clusters*)



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 (based on the cluster mass function and stellar age spread)
- Constraining the baryon processes will lead to much more accurate and reliable predictions for the distribution of dark matter around the Sun and elsewhere in the Galaxy