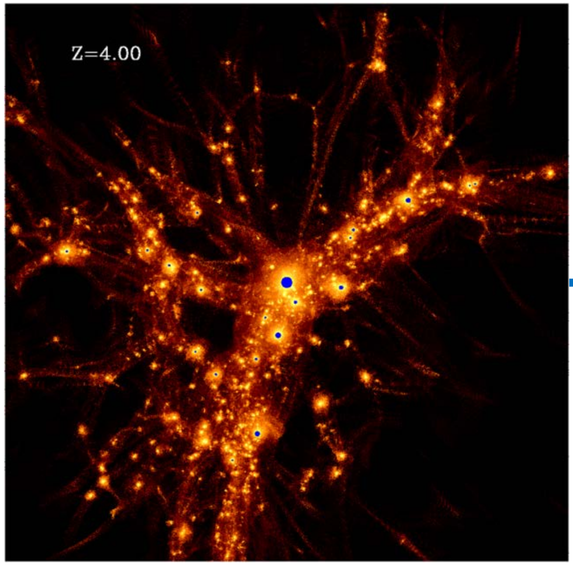
Towards Realistic Modeling of Massive Star Clusters

Oleg Gnedin

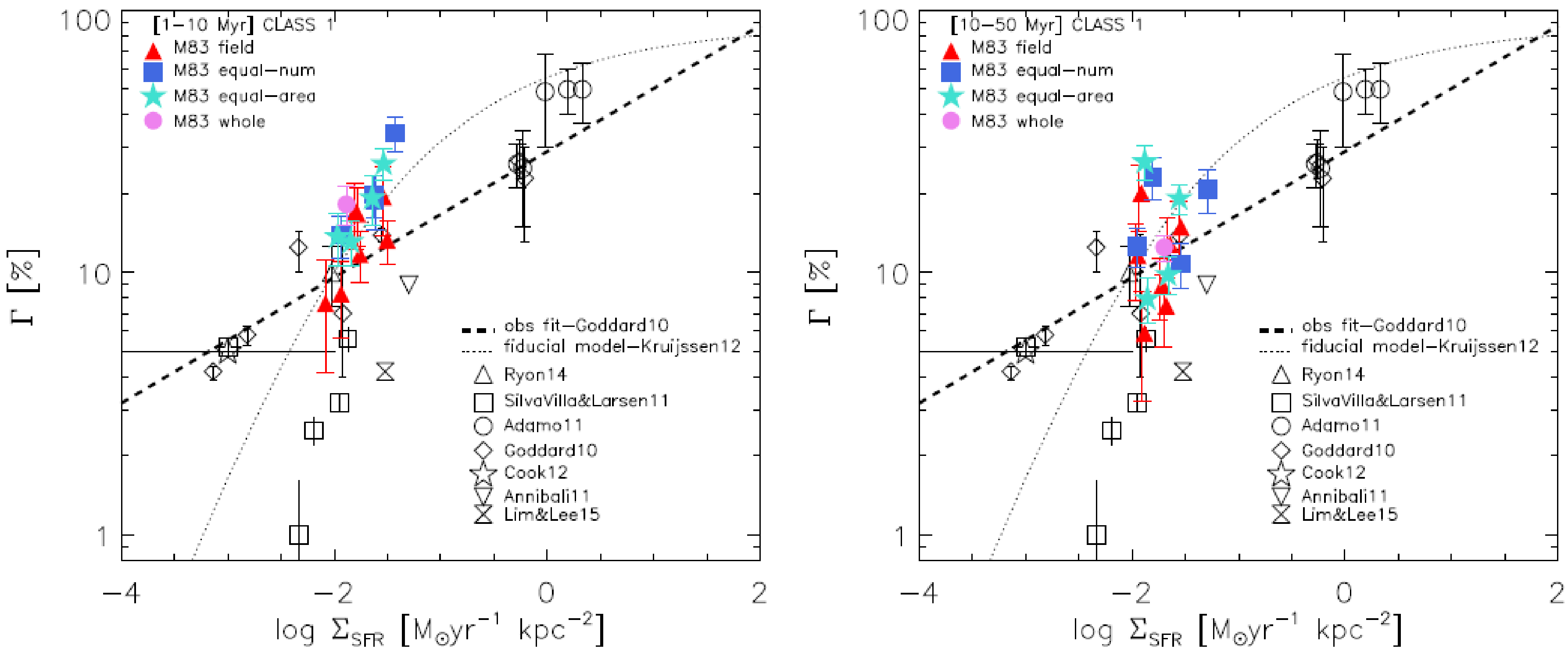
(University of Michigan)

graduate student

Hui Li



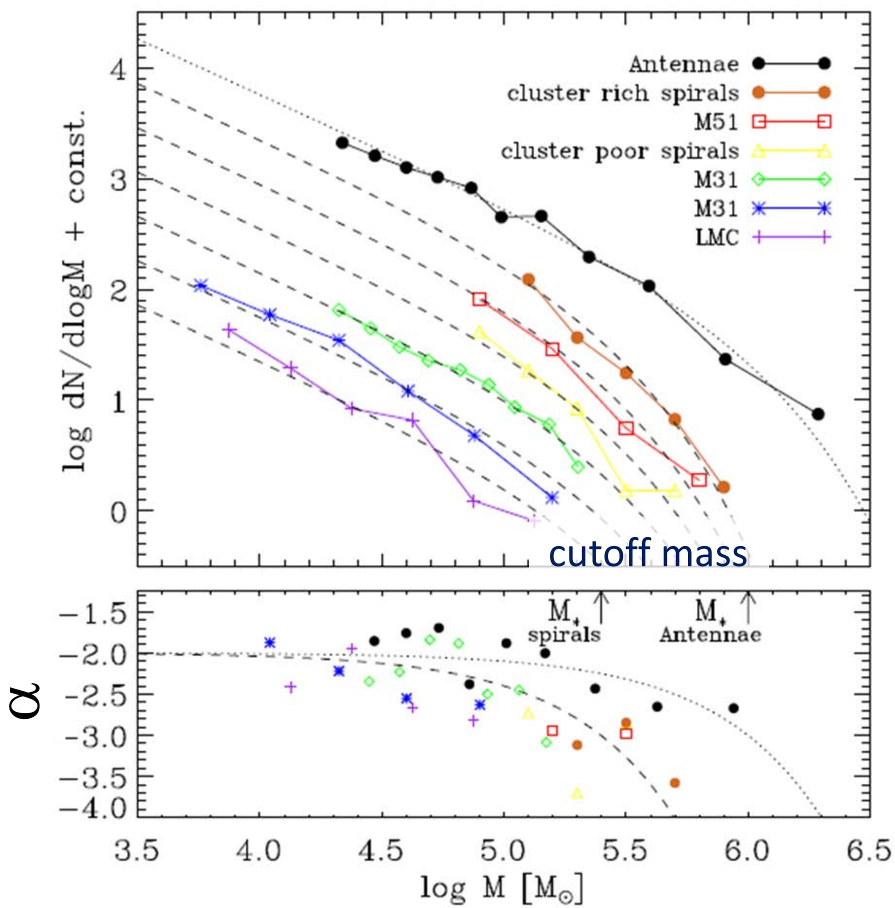
Star clusters are dominant components of active star formation: *they connect small-scale SF (local) and global processes in galaxies*

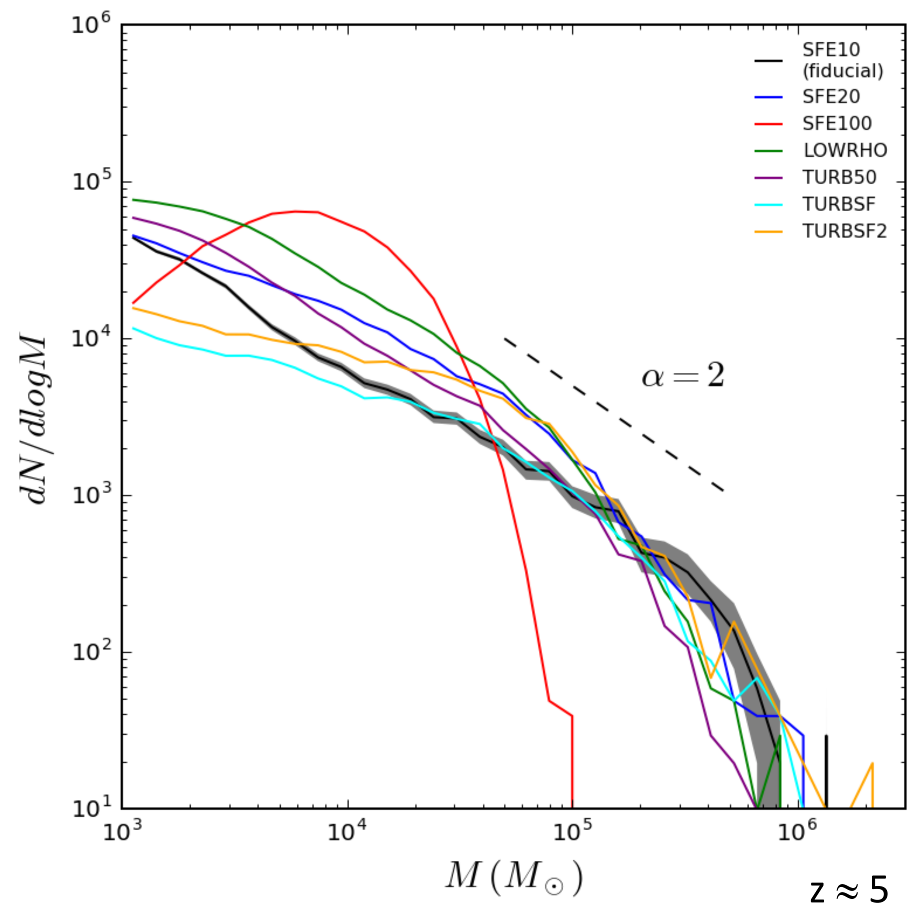


Adamo et al. 2015

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

Initial Mass Function of young clusters is almost invariant





z ≈ 5

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

slope $\alpha \approx 2$

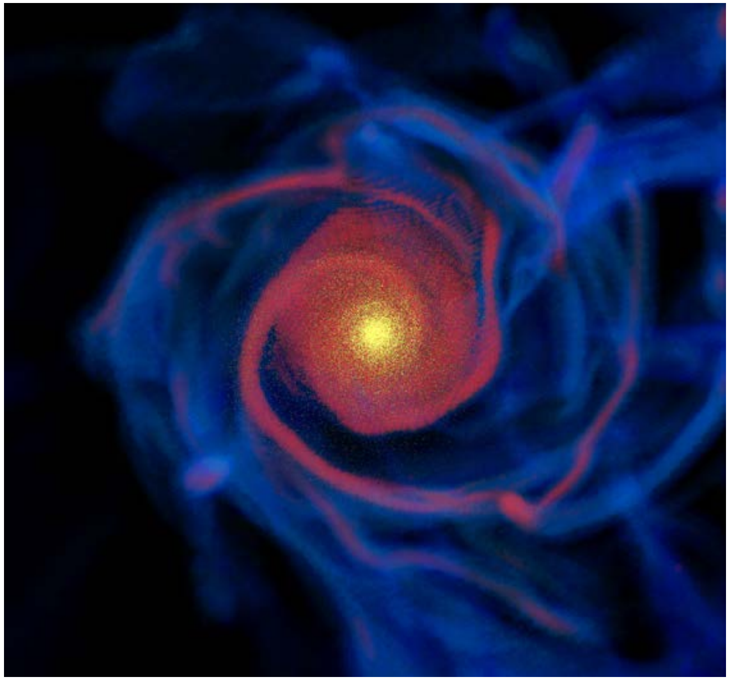
it's a number, not a free cluster

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)

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

- 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)
- Novel treatment of subgrid-scale turbulence (Semenov et al. 2016)



z=3:
stars
H_2 gas
HI gas

Zemp et al. (2012)

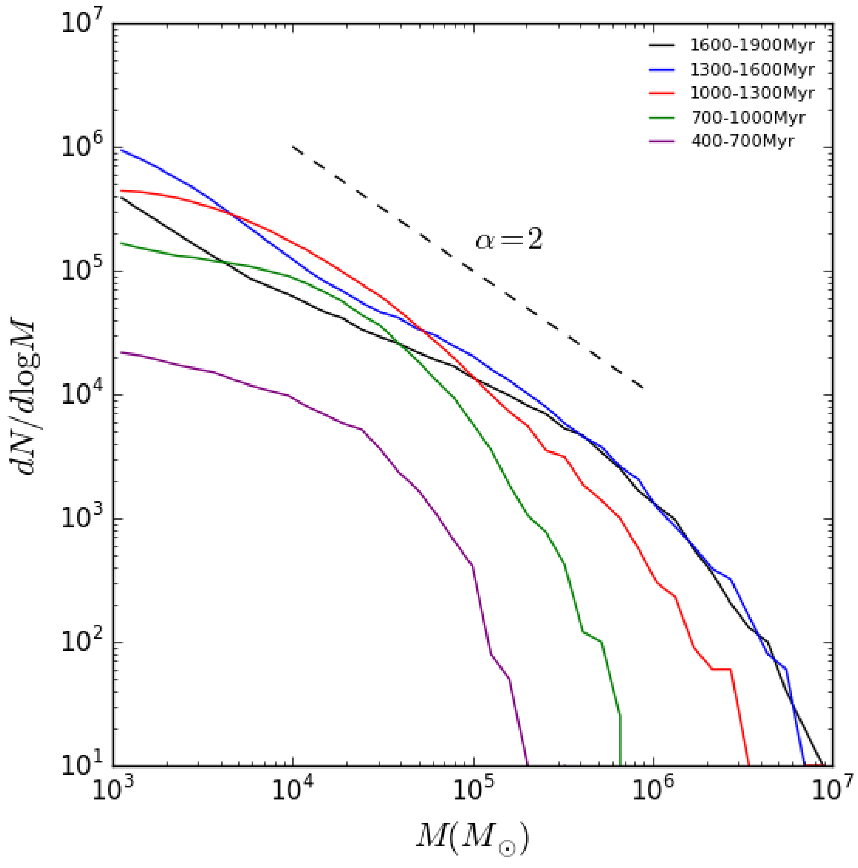
$$\frac{\partial n_j}{\partial t} + 3Hn_j + \frac{1}{a}\mathrm{div}_x(n_j\vec{v}) = \dot{\mathcal{I}}_j + \dot{\mathcal{M}}_j + \dot{\mathcal{D}}_j,$$

Ionization by cosmic and local interstellar UV flux

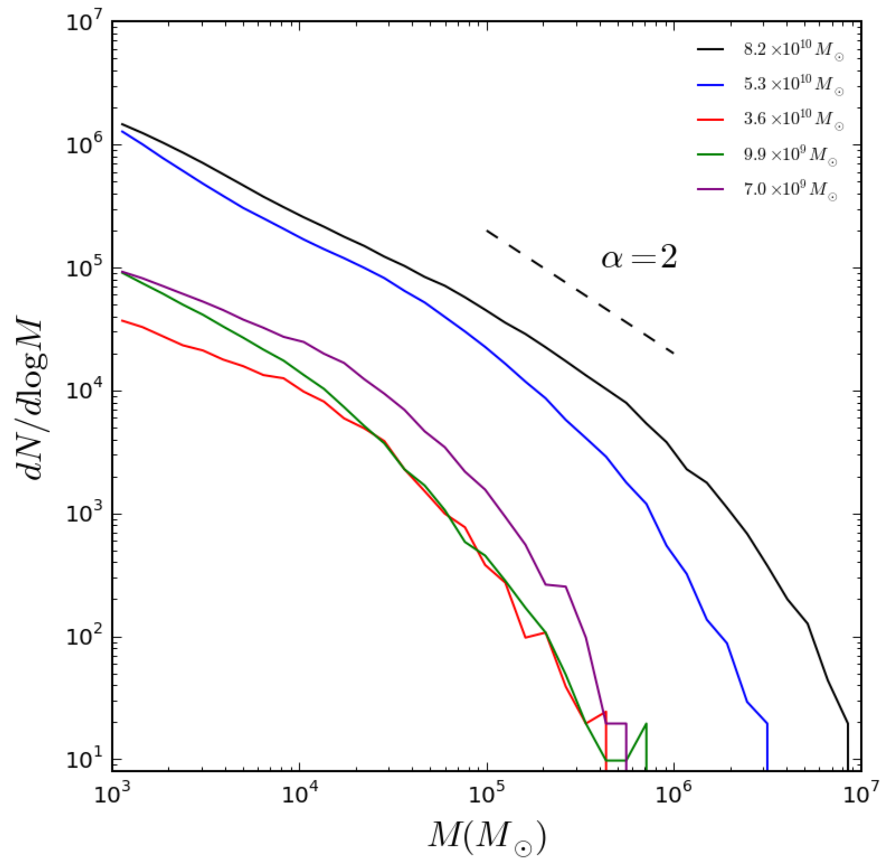
atomic and molecular chemistry

dust chemistry

In the simulations, cluster mass function remains a stable power-law

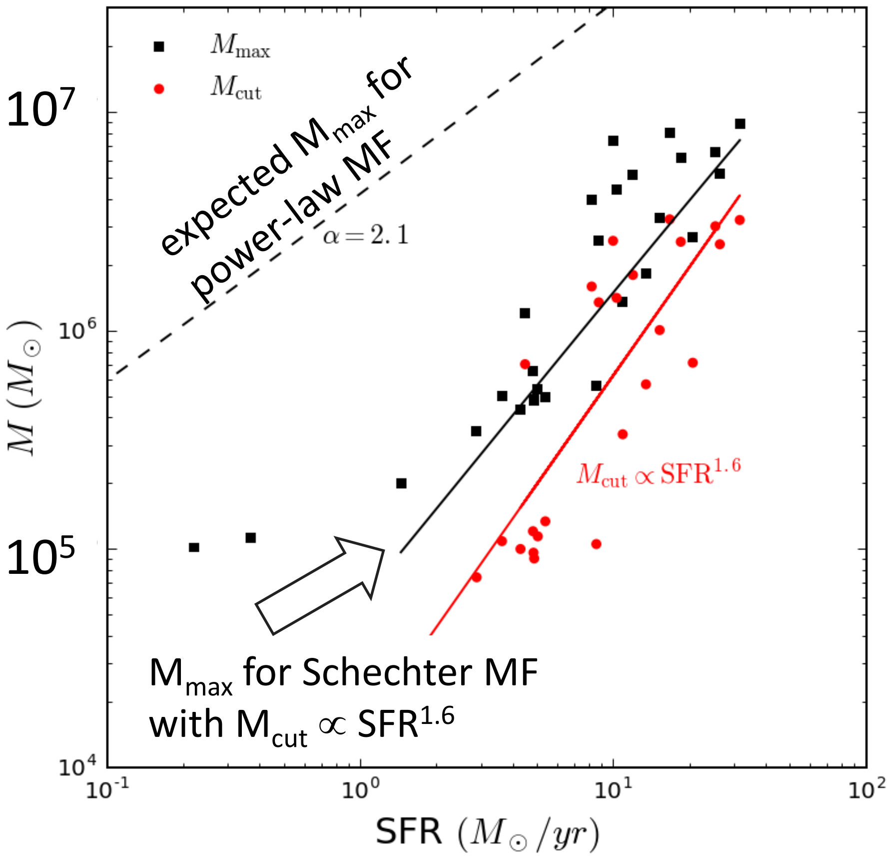


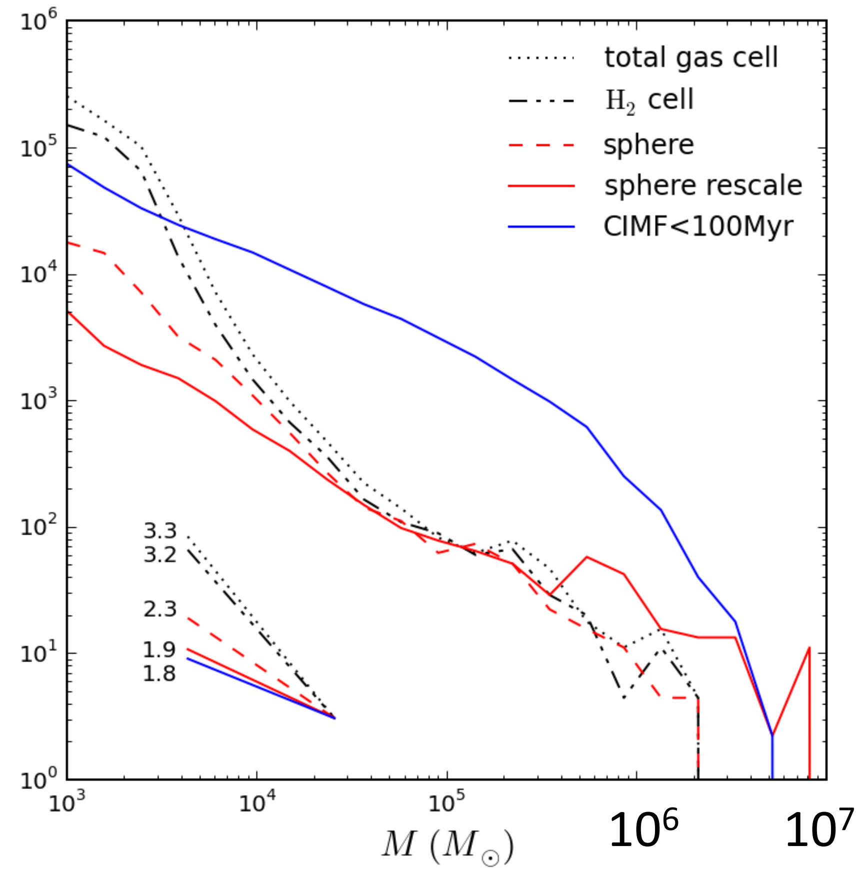
Different epochs within the same central galaxy



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

Origin of the shape of cluster mass function

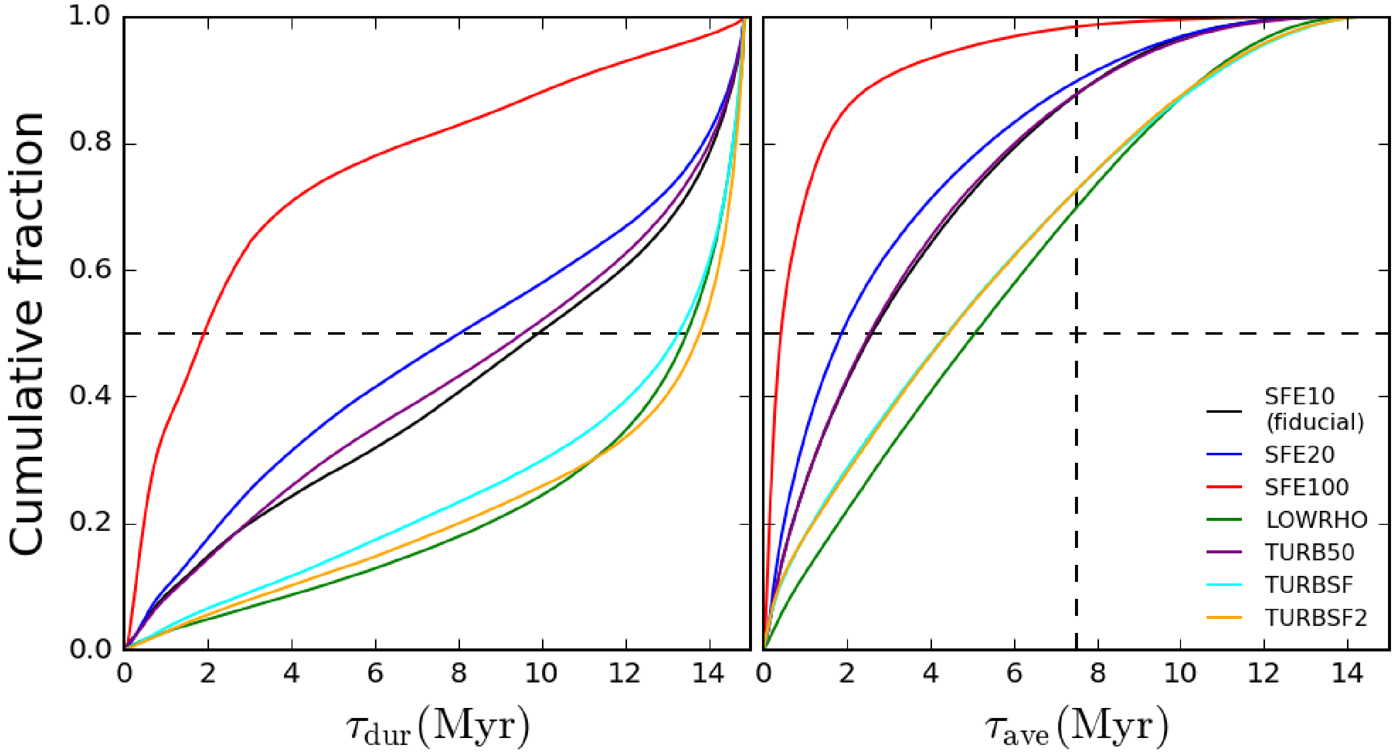




Maximum cluster mass is consistent with that expected for a Schechter function with truncation mass scaling as $SFR^{1.6}$

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

Feedback of own stars terminates star formation within a *few Myr* and sets the final cluster mass



$\rho > 10^3\ \mathrm{cm}^{-3}$

ε_{ff} = 10-100%

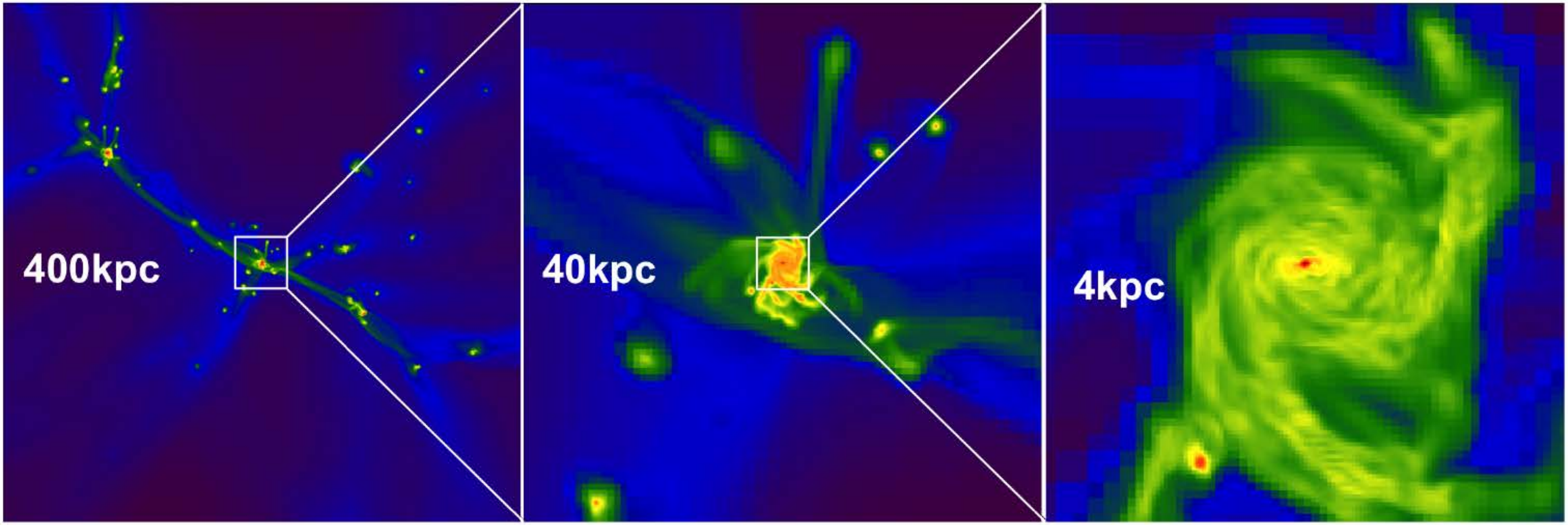
also:

$\rho\ \ > 10\ \mathrm{cm}^{-3}$

ε_{ff} from SGS turbulence model (Semenov et al. 2016)

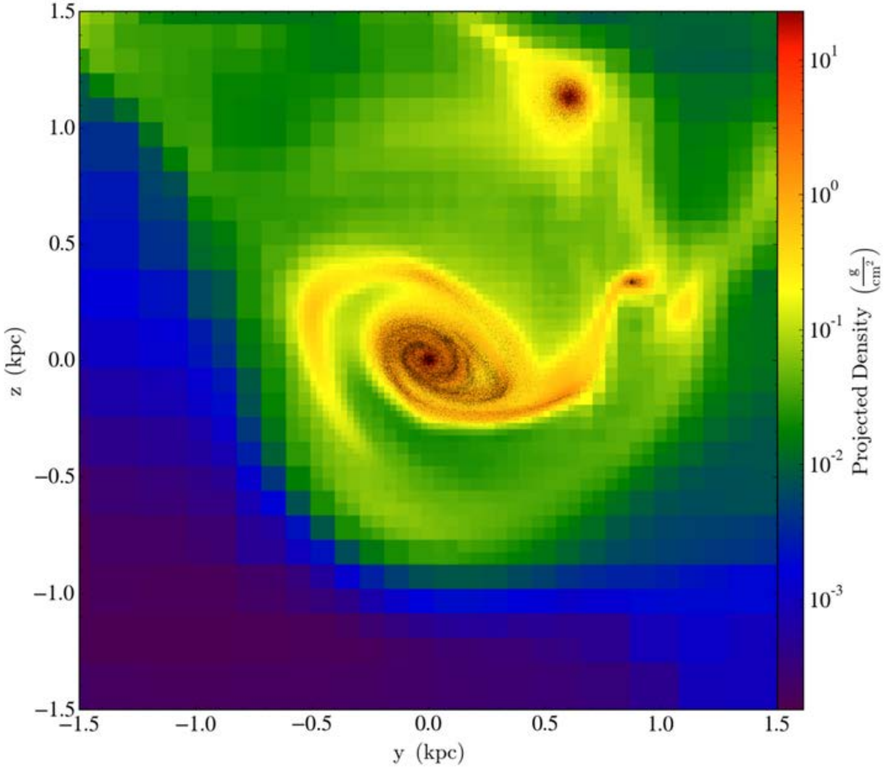
- spatial resolution 5 pc at z=5
- typical timestep 10^3 yr – *resolved cluster growth*
- clusters grow from gas mass inside fixed-sized sphere of 10 pc (*typical GMC core/clump*)

$$\tau_{\rm ave} = \frac{\int_{t_{\rm creation}}^{t_{\rm end}} (t' - t_{\rm creation})\,\dot{m}_c(t')\,dt'}{\int_{t_{\rm creation}}^{t_{\rm end}} \dot{m}_c(t')\,dt'}$$



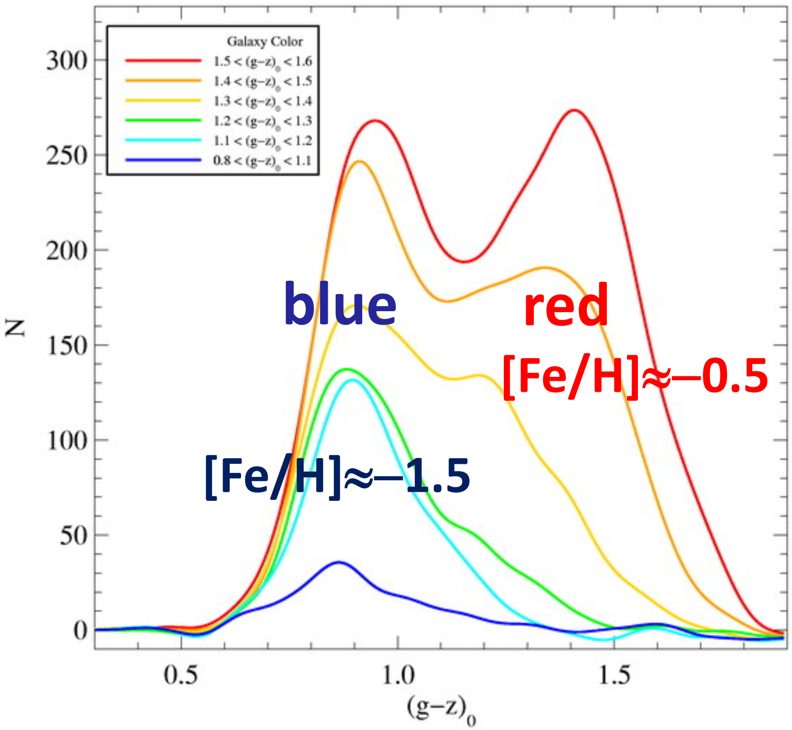
z ≈ 3.3

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

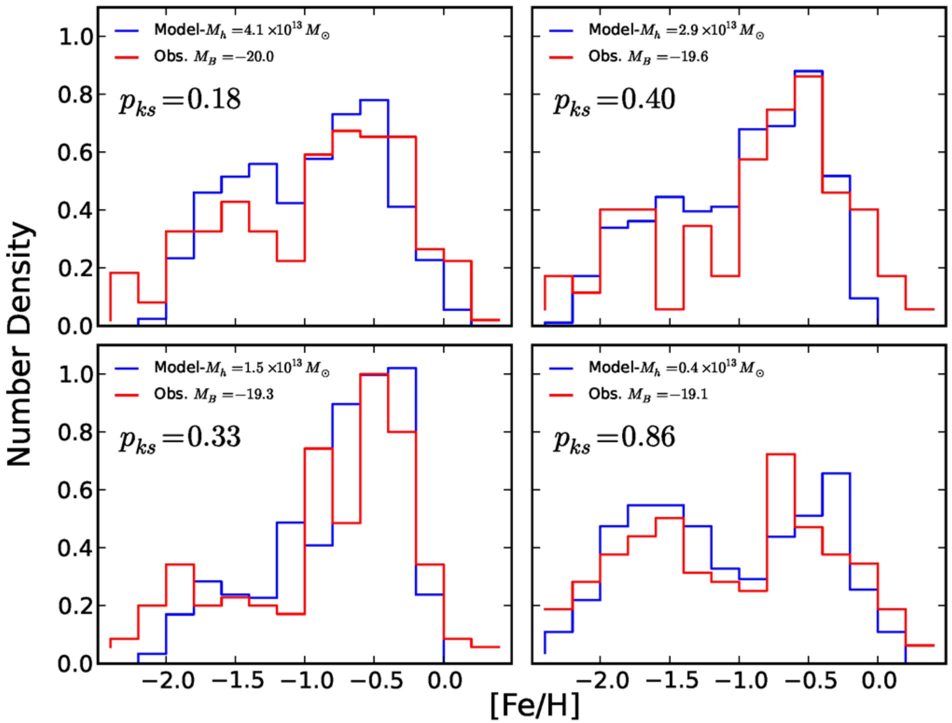


z ≈ 4

Analytical models based on simulations match GC mass and metallicity distributions in MW and in ellipticals in Virgo cluster



Peng et al. 2006 – HST Virgo Cluster Survey



Muratov & OG 2010
Li & OG 2014

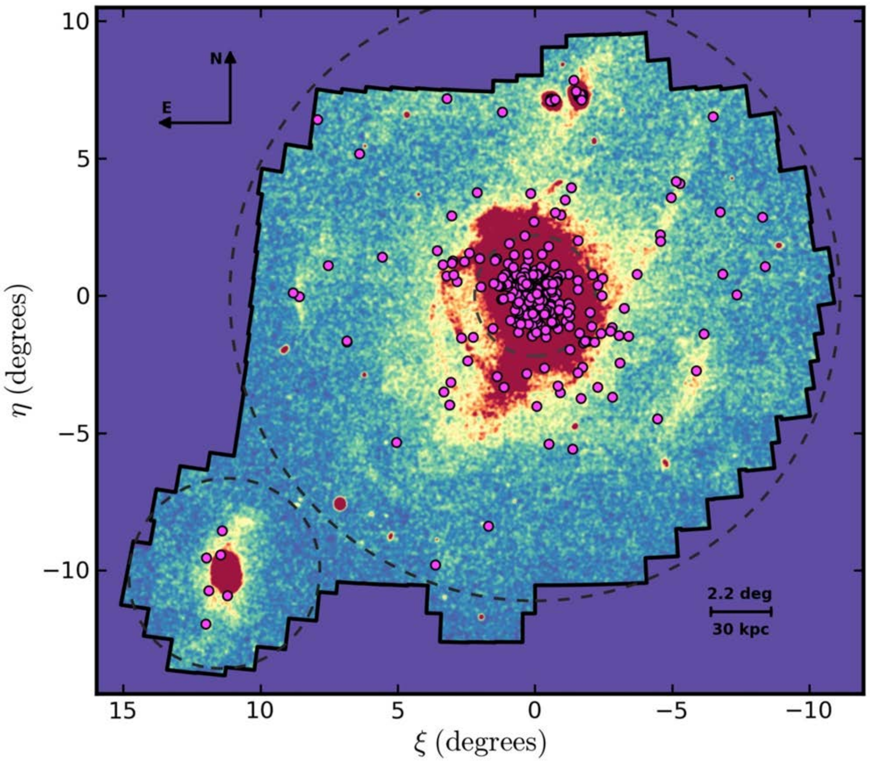
Color/metallicity distribution of GCs in most galaxies is multimodal

Each metallicity group tells us about different episodes of cluster formation

GC formation is triggered by gas-rich mergers,
metallicity assigned from observed M-Z relation for host galaxies*

Formation of massive star clusters *may* be triggered/enhanced by major mergers of gas-rich galaxies

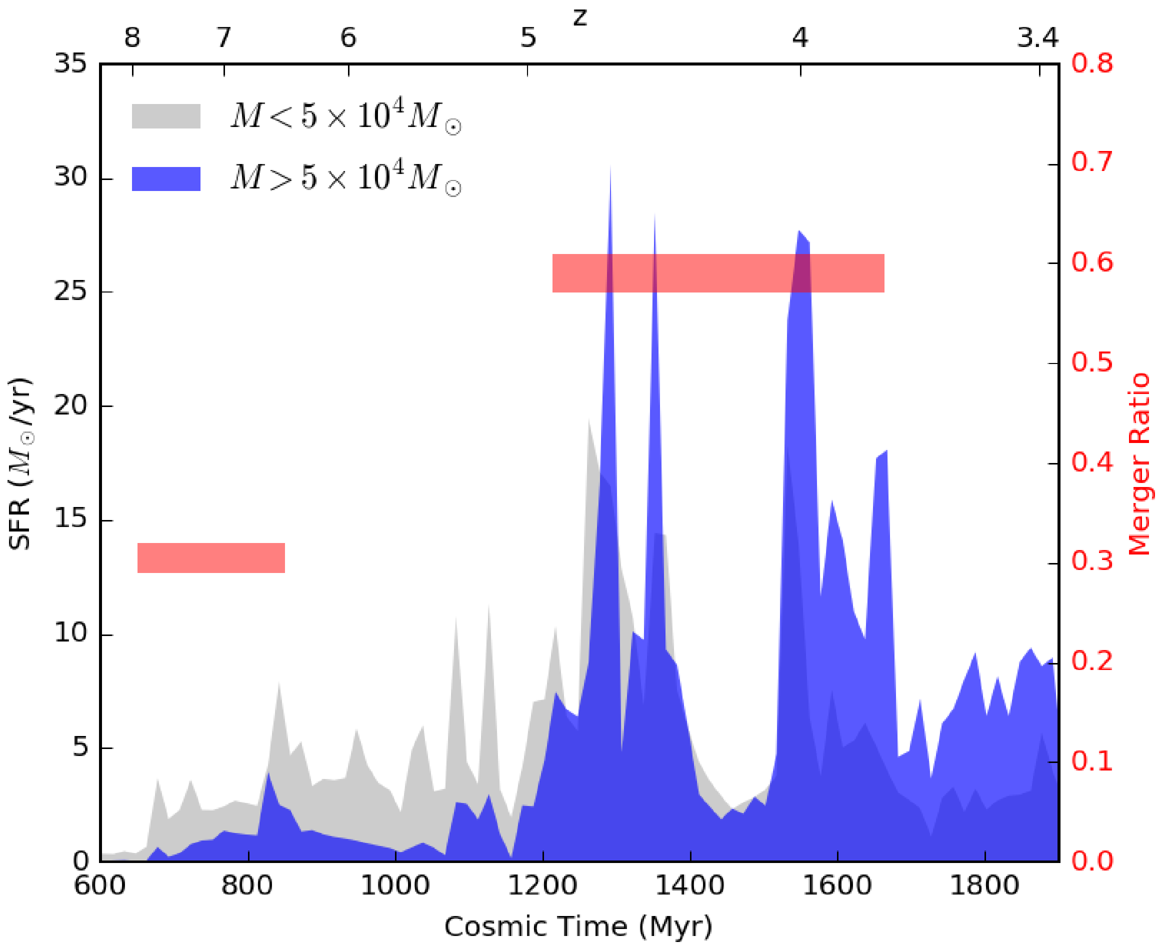
- Star clusters form in giant molecular clouds (GMC)
- Higher density of globular clusters requires higher external pressure on GMC
- Interstellar medium is over-pressured during galaxy mergers
- Extreme masses of proto-globular GMC require very gas-rich galaxies



In addition, accreted satellites bring their populations of GCs

outer GCs in M31 are associated with tidal streams (D. Mackey)

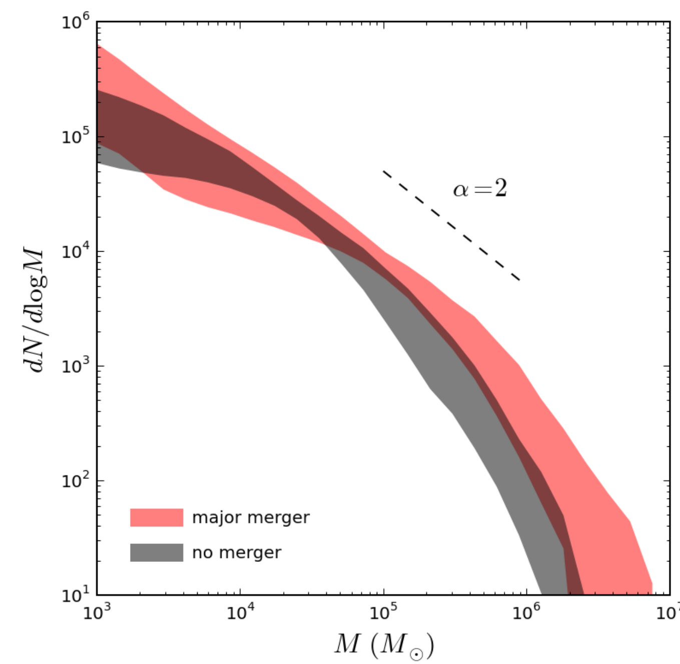
Gas-rich mergers of massive galaxies trigger cluster formation



Li & OG 2016

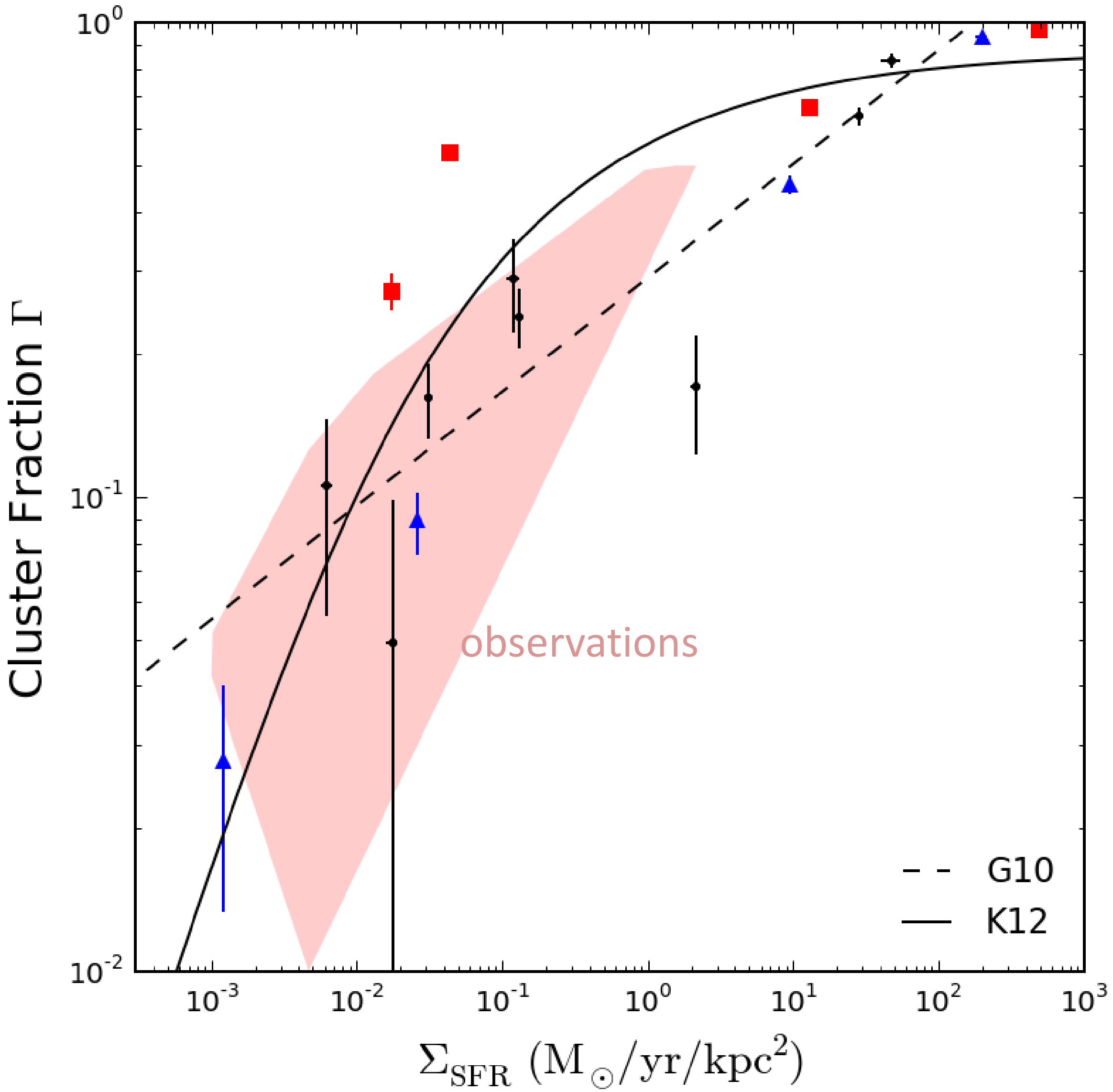
no merger

major merger



Cluster MF is more strongly truncated between mergers

Cluster formation efficiency



fraction of total mass of young stars contained in star clusters more massive than $10^4\ M_\odot$

--- central galaxy
--- first satellite
--- other satellites

z = 3.3

Summary

- Mass function of young star clusters is a truncated power law, both in observations and galaxy formation simulations

- Truncation mass and maximum cluster mass scale with SFR

- Mergers of gas-rich galaxies may trigger/enhance formation rate of massive star clusters ($M > 10^5\ M_\odot$)

- Globular clusters could be used to trace major episodes of mass assembly of their host galaxies