Resolving GC formation in cosmological simulations:

Status, challenges, and future directions

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Clusters20KITP@Zoom
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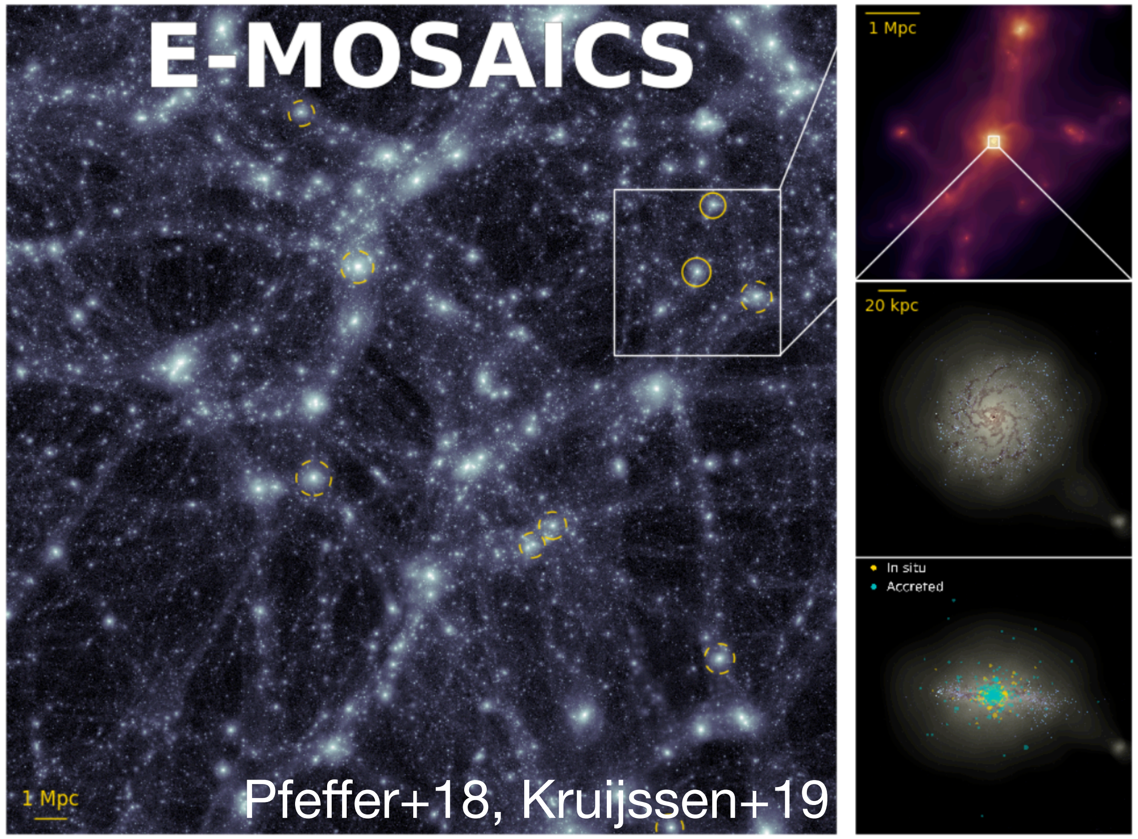
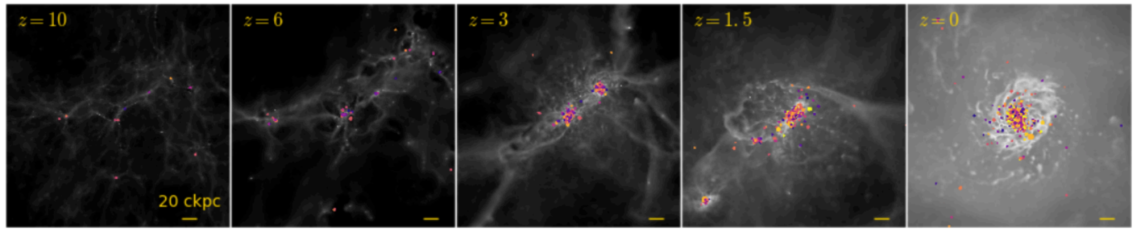
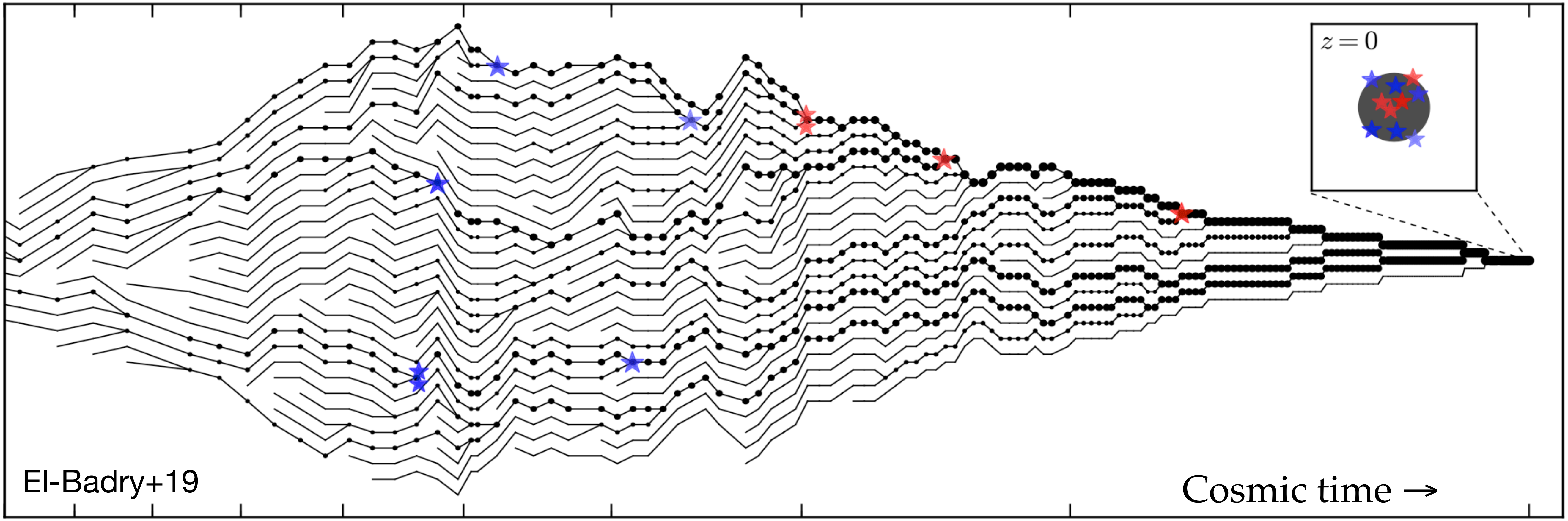
Key ingredients in modeling GCs in a cosmological context

- Formation (gas mass, merger, pressure, …)
- Mass loss from stellar evolution
- Mass loss due to internal dynamics
- Cluster disruption by tidal forces
- Dynamical friction
- …



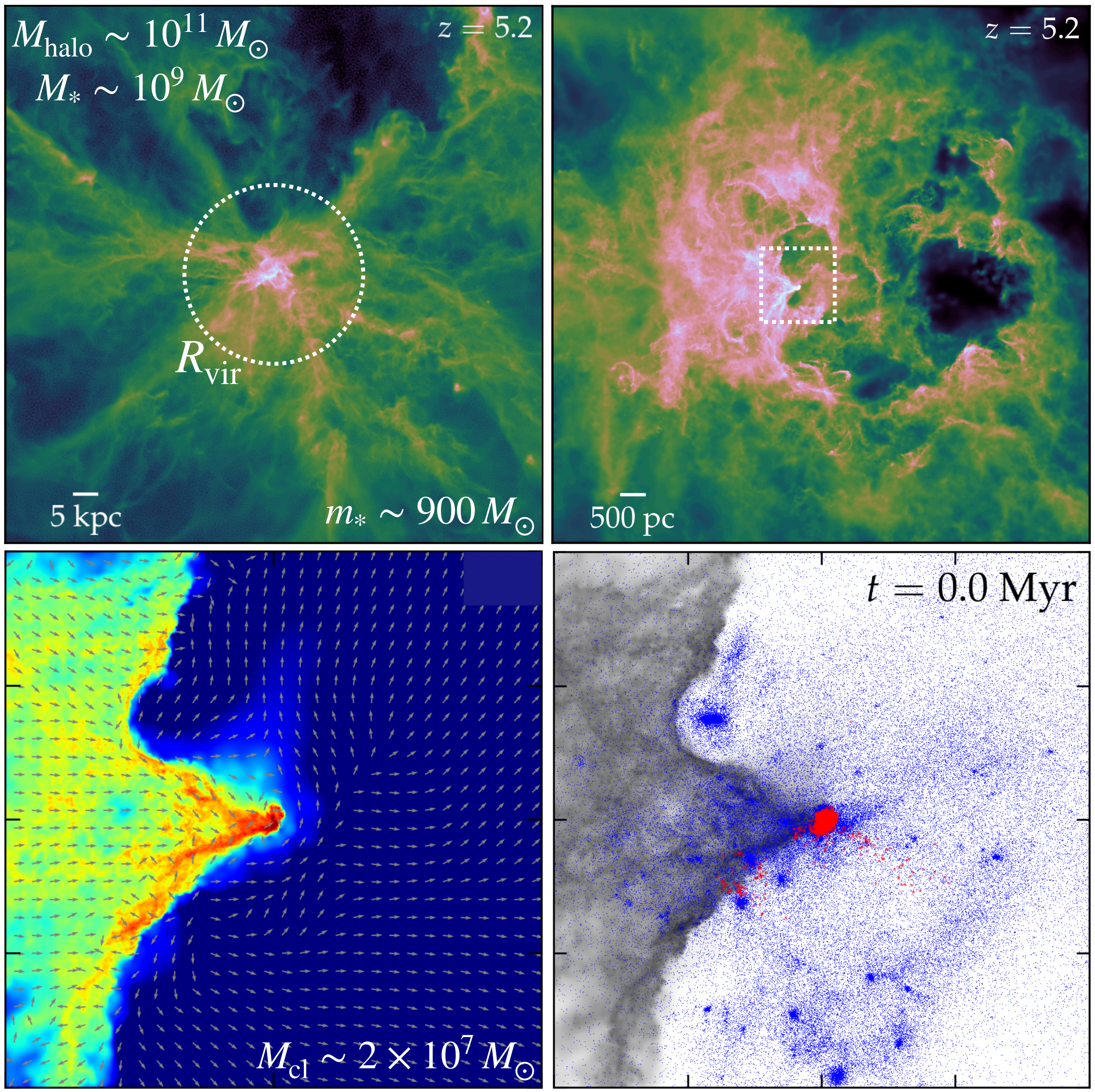


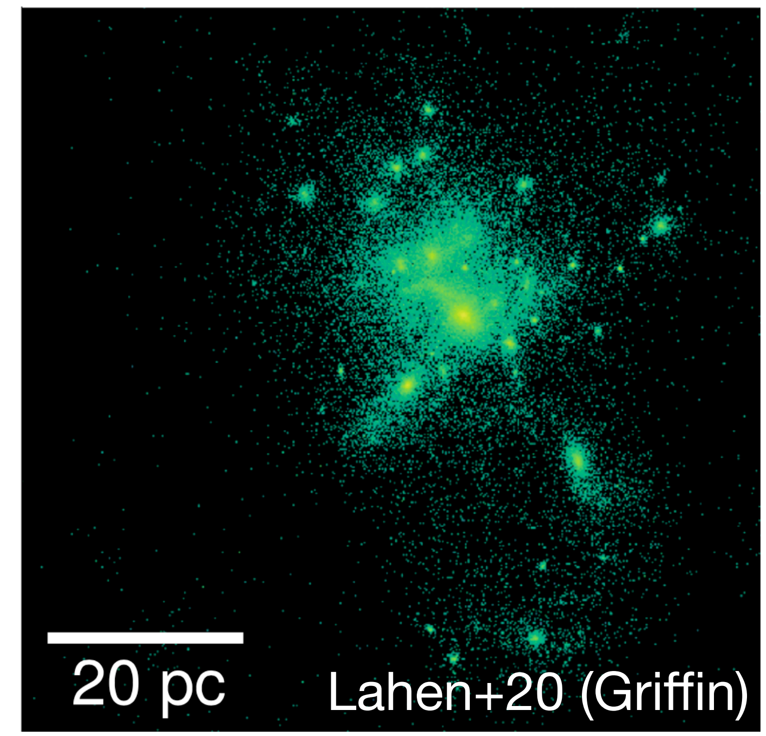
(see also Muratov & Gnedin 10; Li & Gnedin 14; Choksi+18)

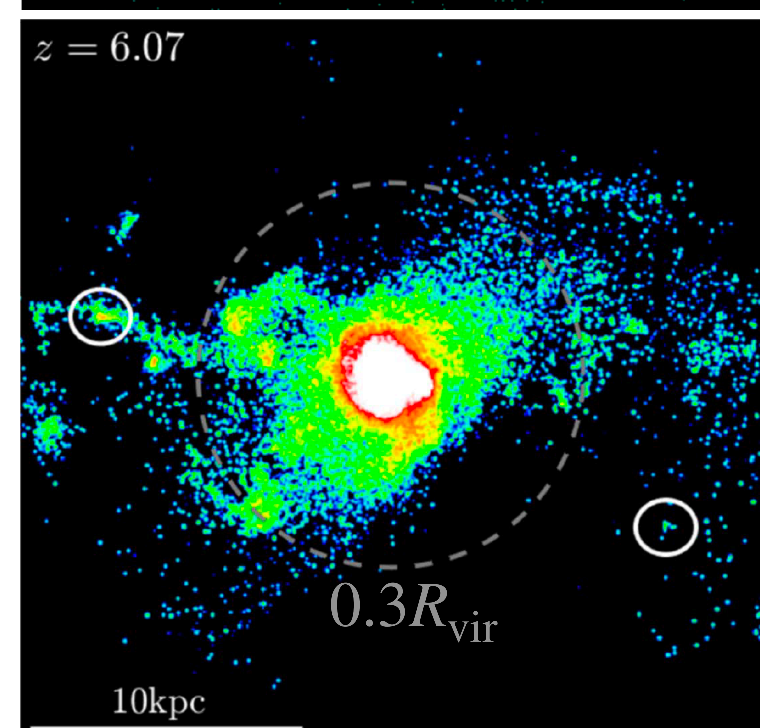


Resolving GC formation in (cosmological) simulations

- Compact, self-gravitating stellar structures with ~30–10^5 particles in simulations with resolved multi-phase ISM







Ma+20 (HiZ-FIRE; also Kim, Ma+18)

Mandelker+18 (VELA)

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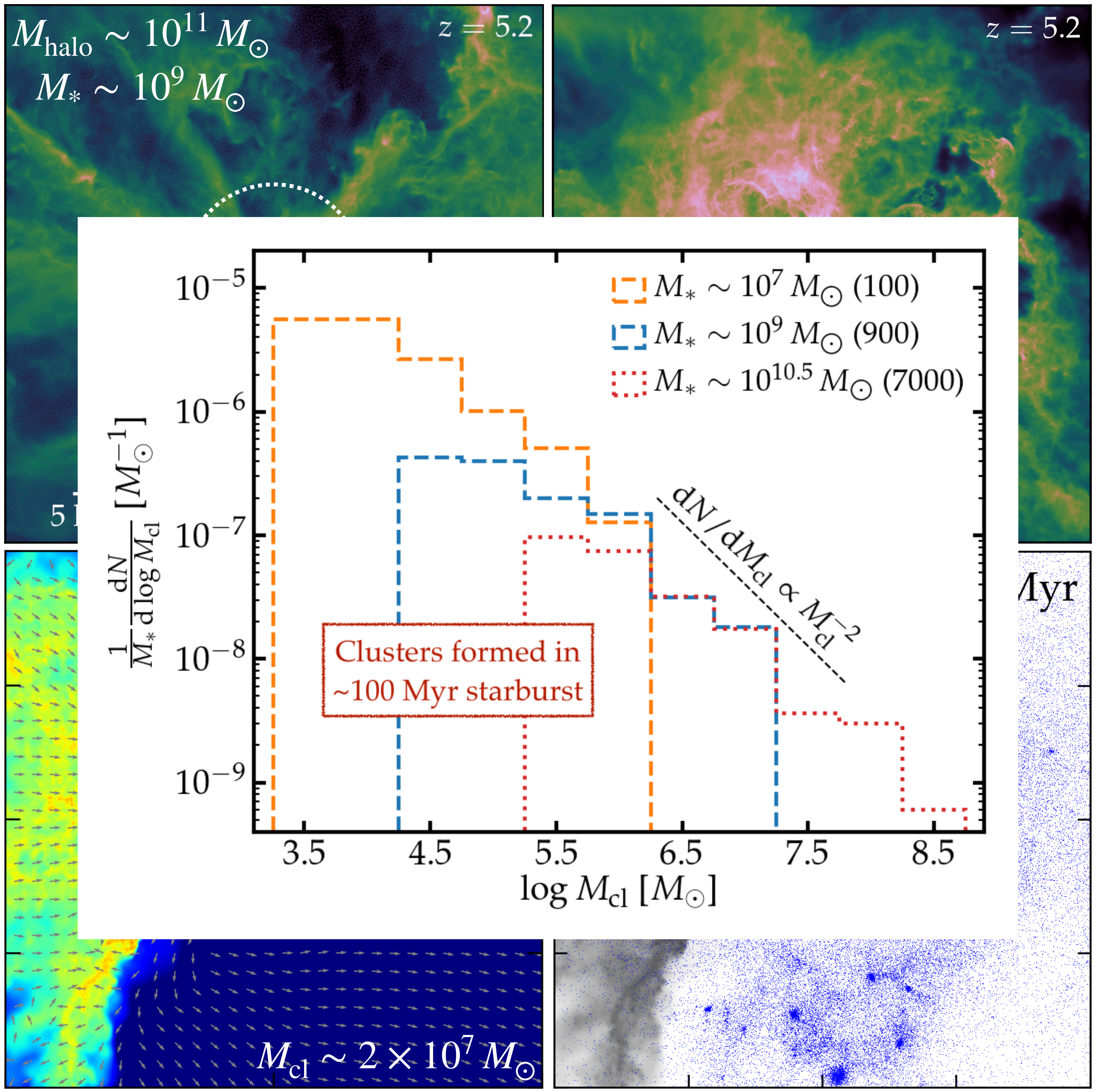

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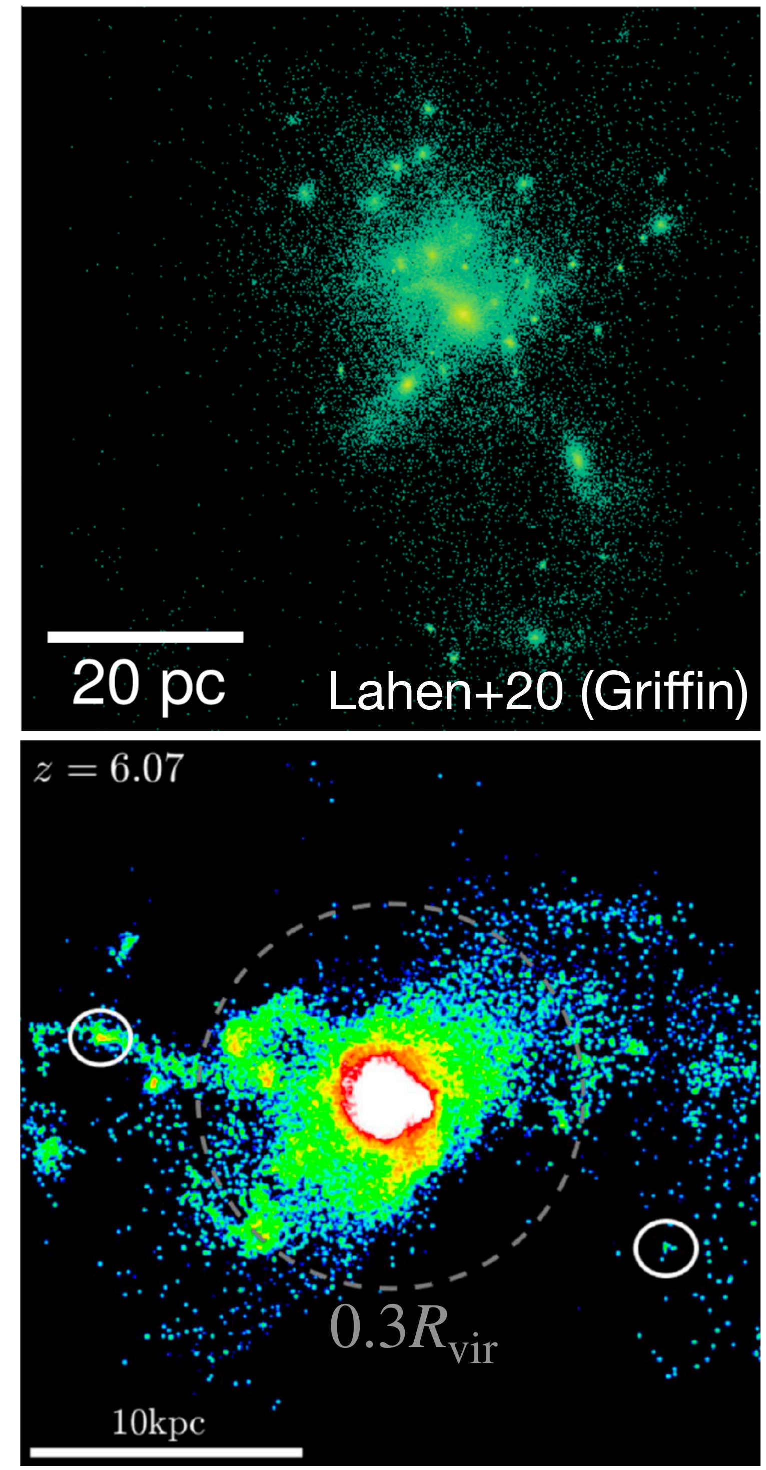
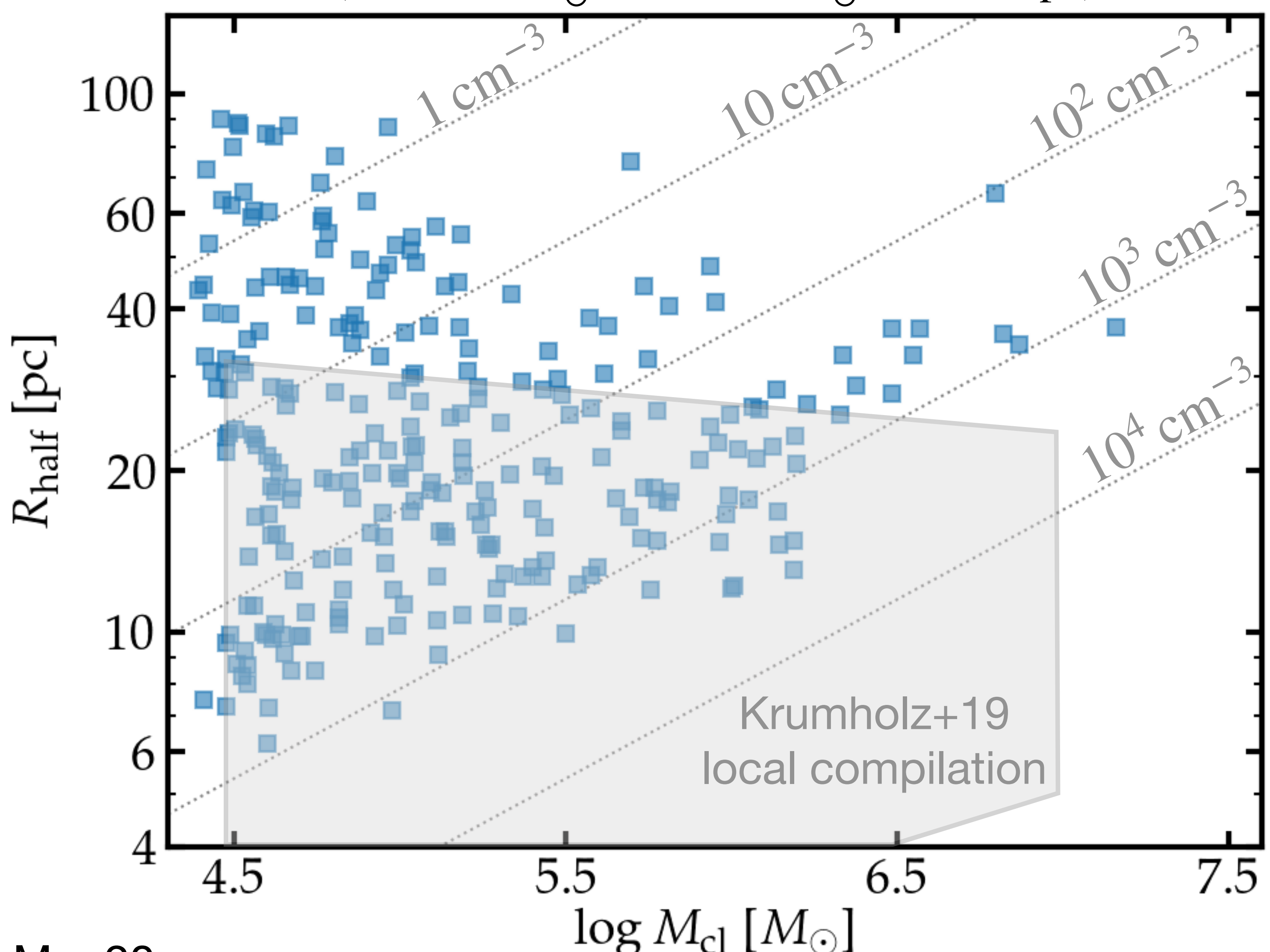


Mandelker+18 (VELA)

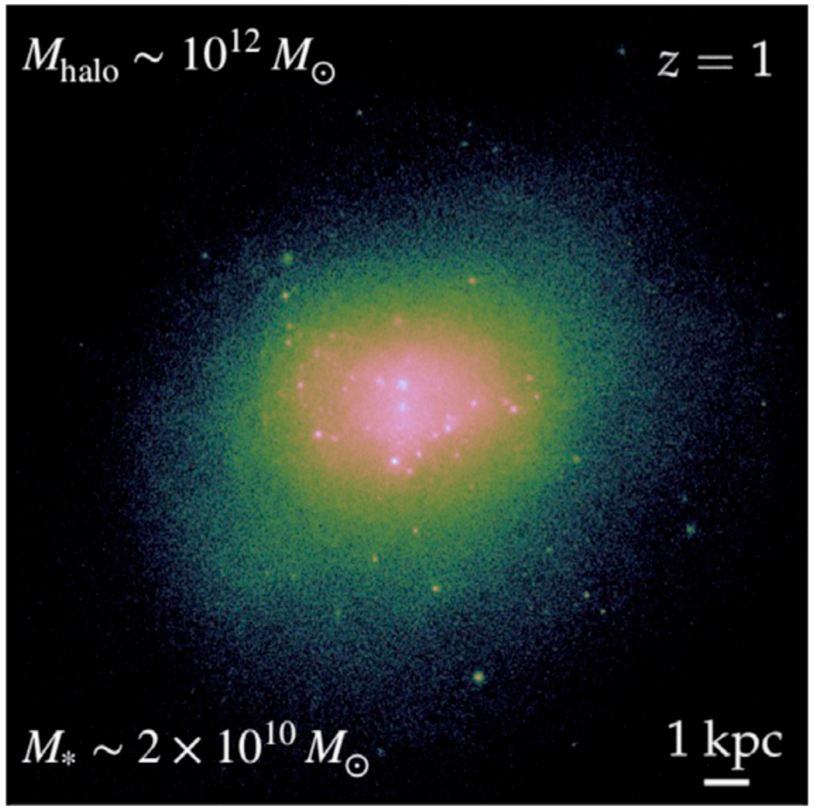
Resolved GCs in cosmological simulations: challenges

- Large force softening lengths — cluster size too large
- Small number of particles — internal dynamics wrong, numerical disruption
- Long-term dynamical evolution cannot be properly tracked

Clusters formed in a ~100 Myr starburst
($M_* \sim 10^9\,M_\odot$, $m_* \sim 900\,M_\odot$, $\epsilon_* \sim 1.4$ pc)



Ma+20



$m_* \sim 7000\,M_\odot$, $\epsilon_* \sim 2$ pc

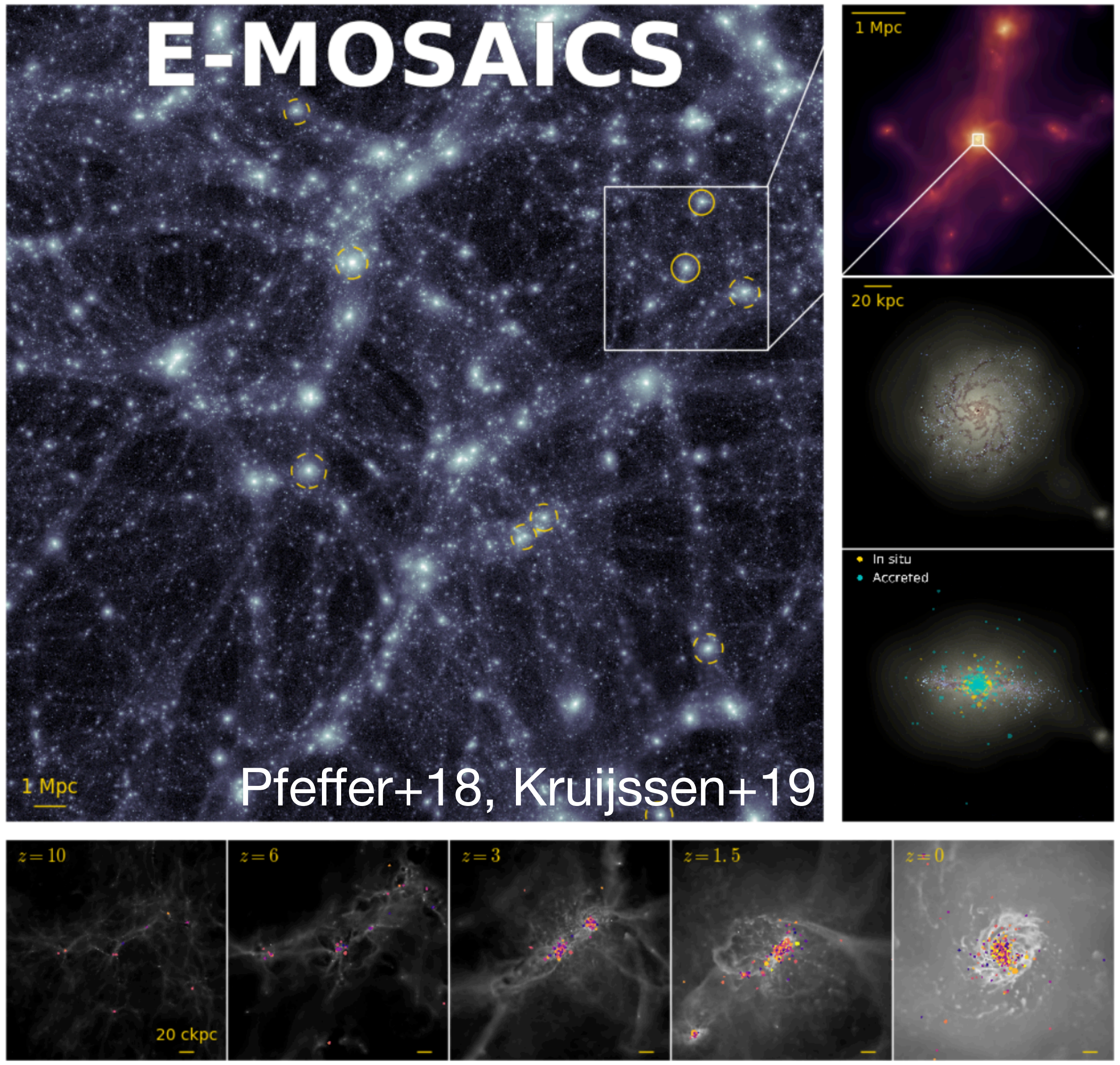
Wetzel+16 (Latte/FIRE)

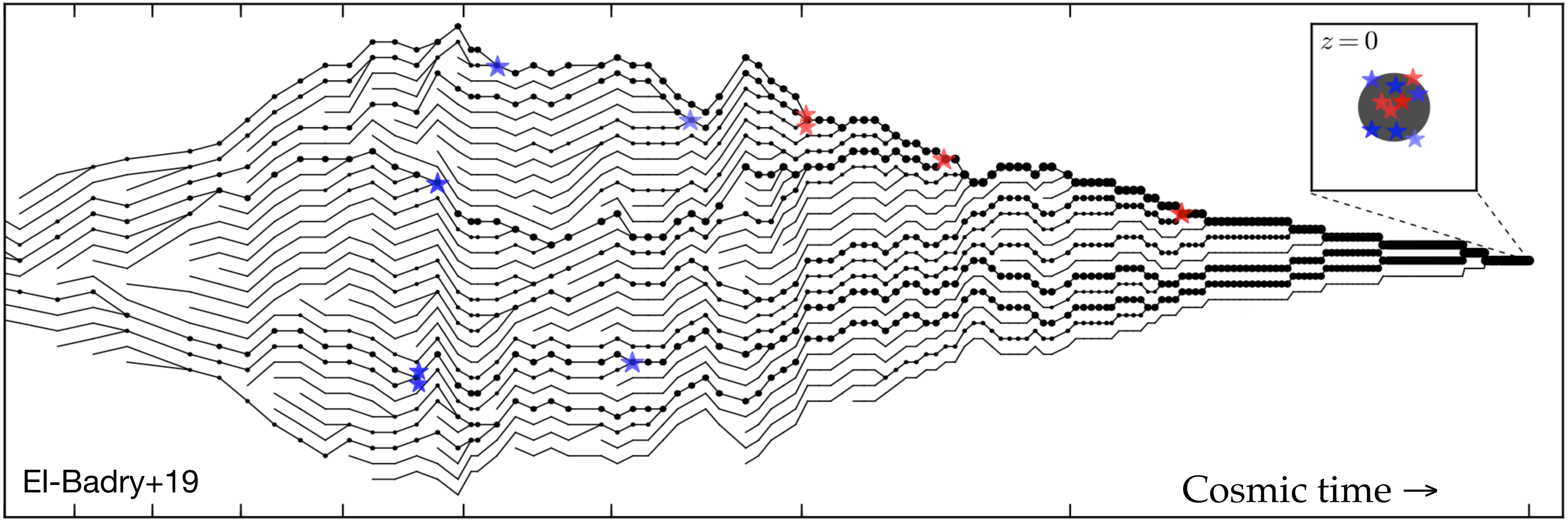
Key ingredients in modeling GCs in a cosmological context

- Formation (gas mass, merger, pressure, …)
- Mass loss from stellar evolution
- Mass loss due to internal dynamics
- Cluster disruption by tidal forces
- Dynamical friction
- …

Not possible any time soon, possibly need a hybrid approach

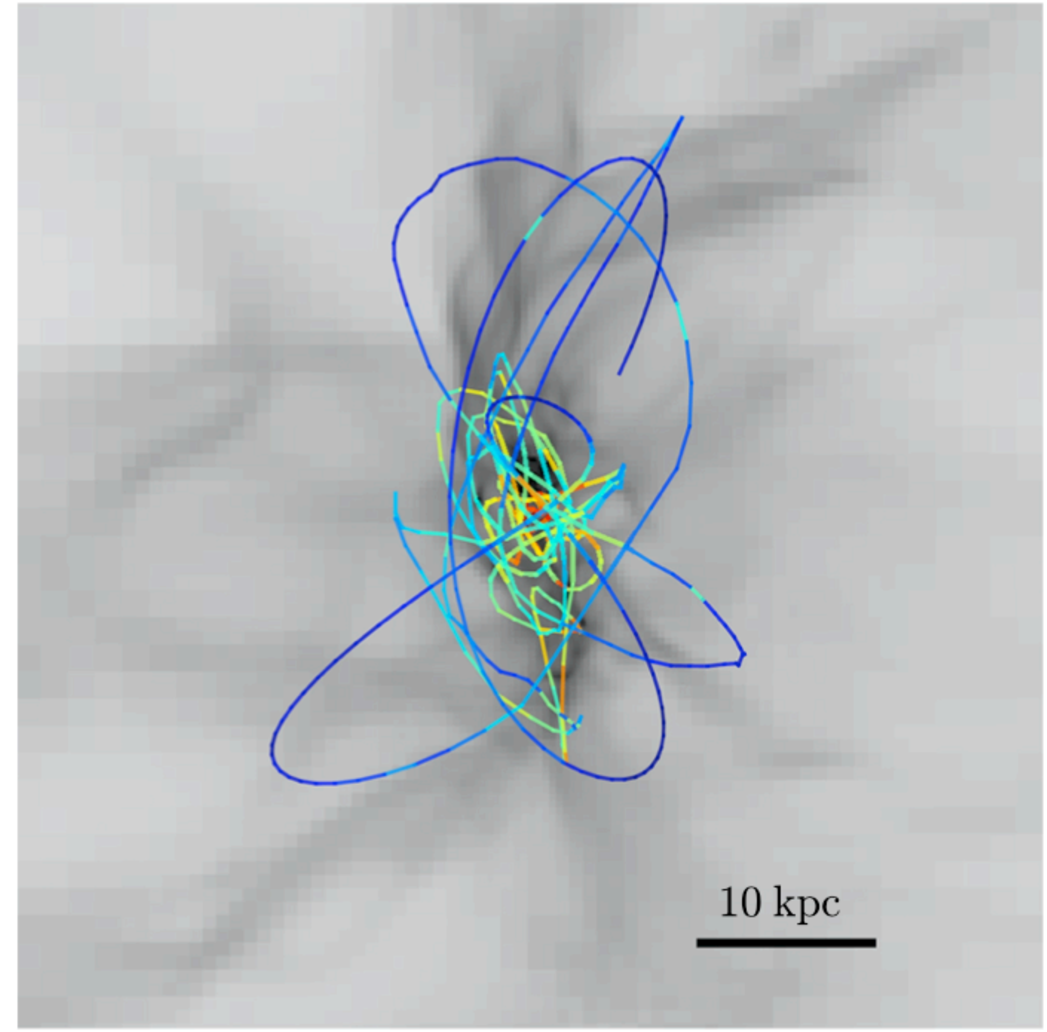
(see also Muratov & Gnedin 10; Li & Gnedin 14; Choksi+18)



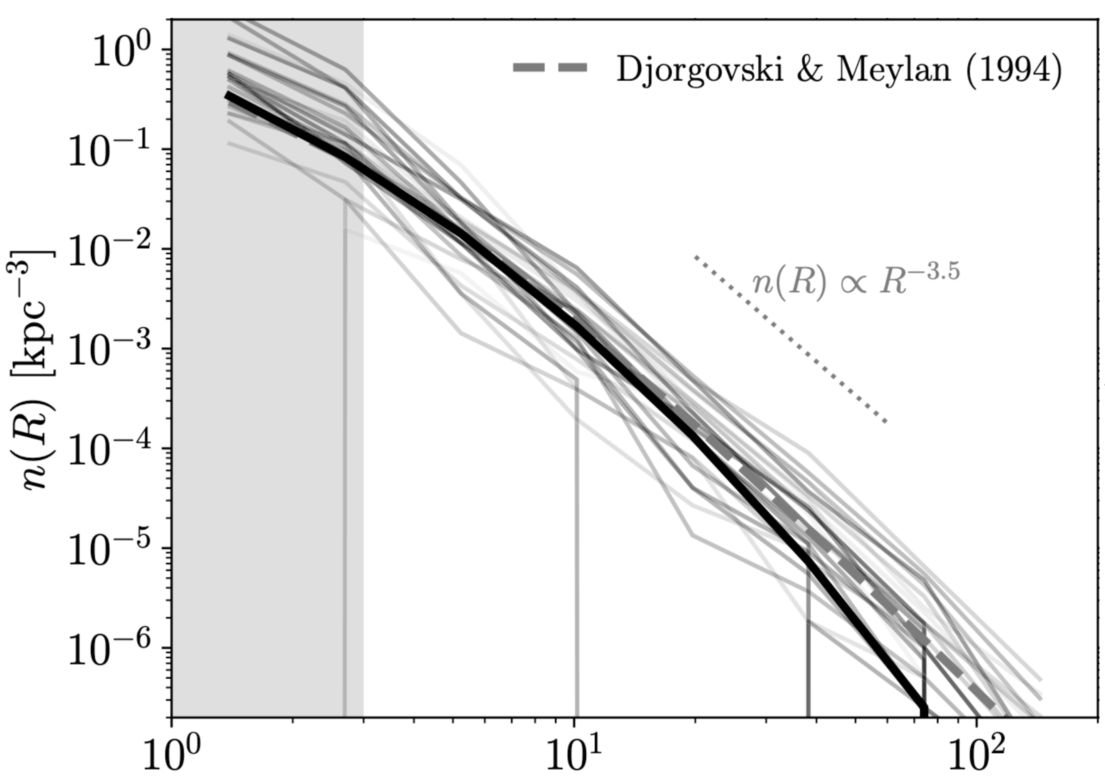


A different approach of modeling GCs in cosmological simulations

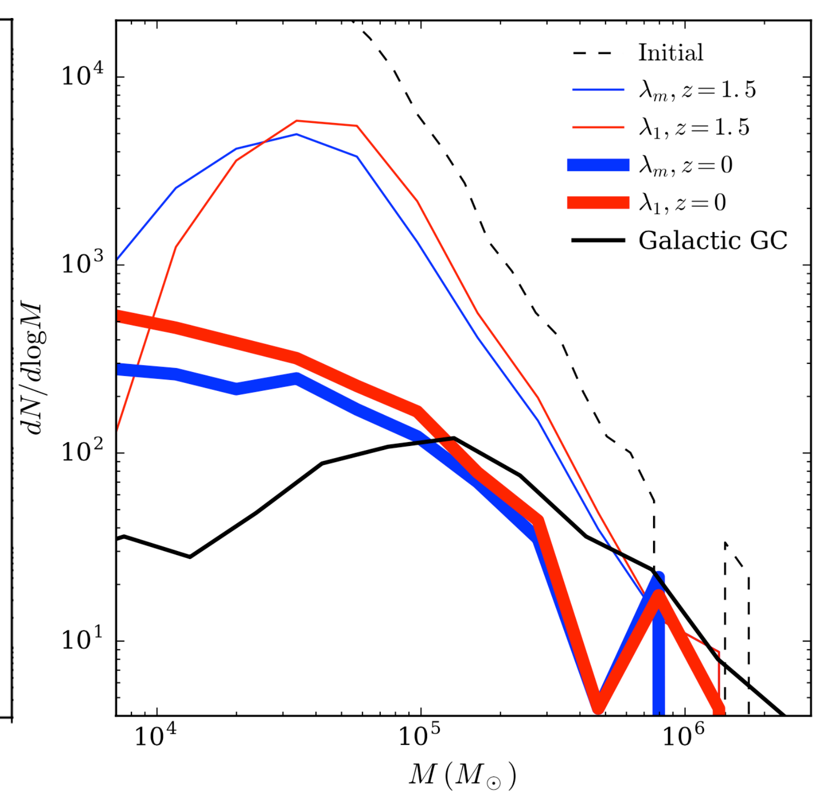
- “Continuous cluster formation” treatment on a Milky Way-like galaxy (H. Li+17,18,19)
- Each particle is a cluster formed out of a GMC
- Cluster particles grow until stopped by feedback
- Able to follow dynamical evolution to low-z

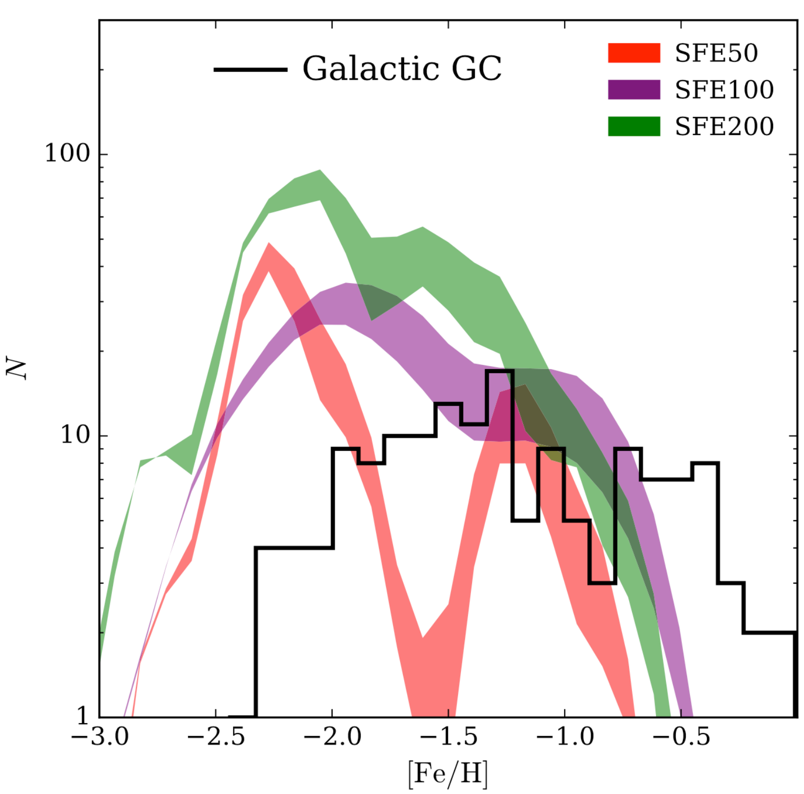


Li+19



Kruijssen+19



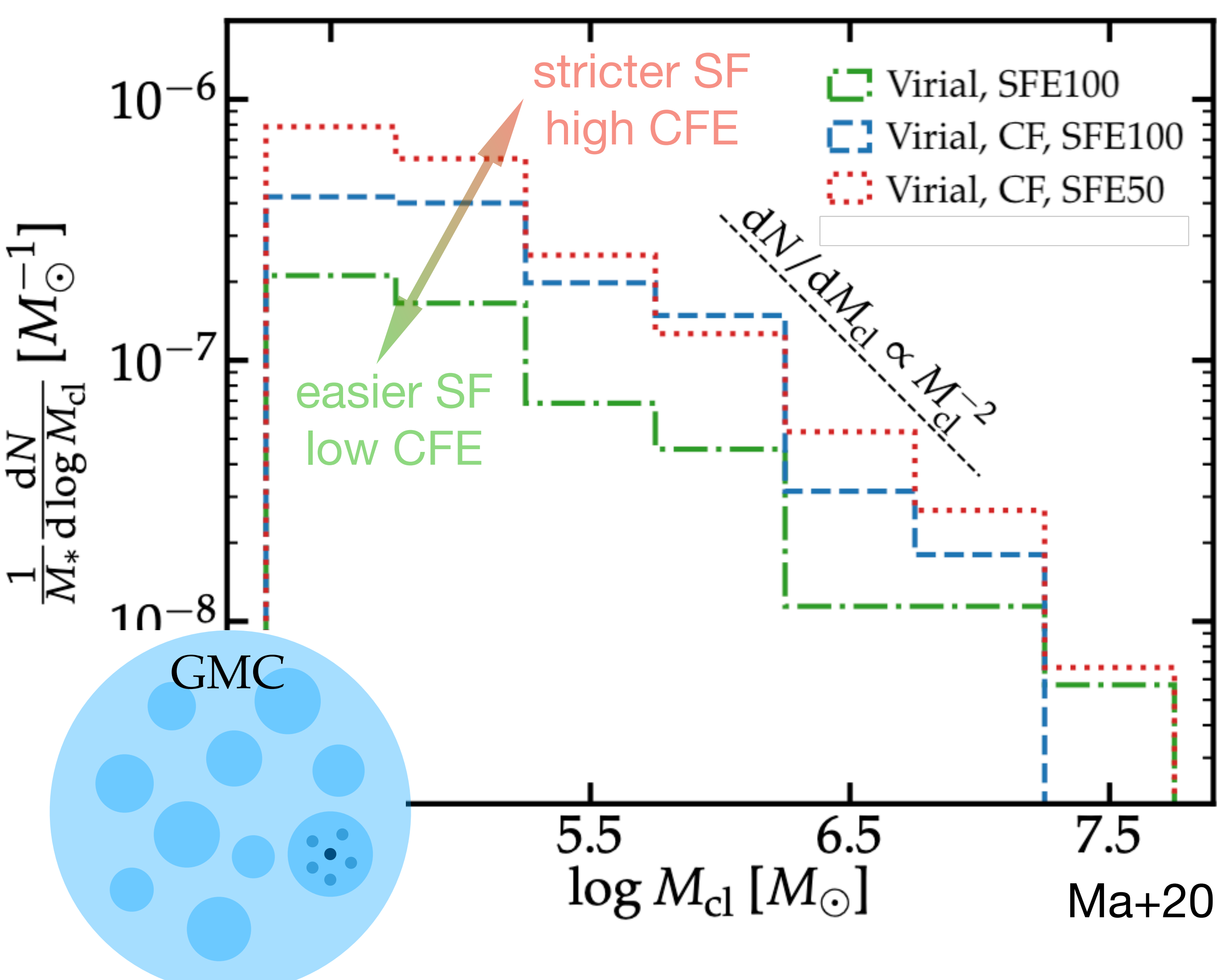


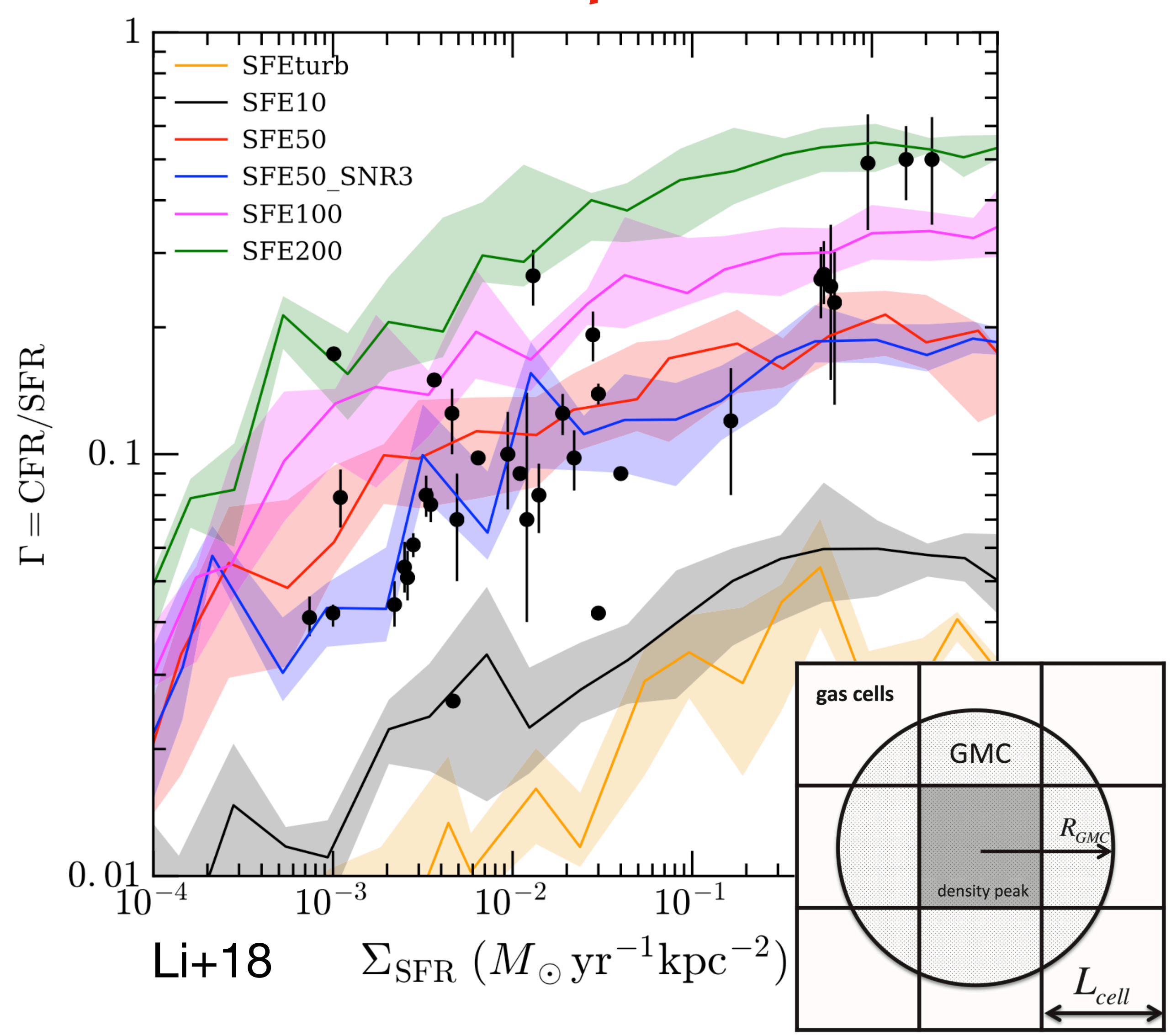
Uncertainties: dependence on “sub-grid” models

- The FIRE model — stricter (easier) SF criteria ☞ high (low) CFEs

  Low local SFE ☞ cloud further collapses, more bound ☞ high CFE
- Li+18 model — low SFE ☞ cloud collapses, more gas expelled ☞ low CFE
- Different definition of SFE, feedback implementation, Lagrangian vs. AMR, …

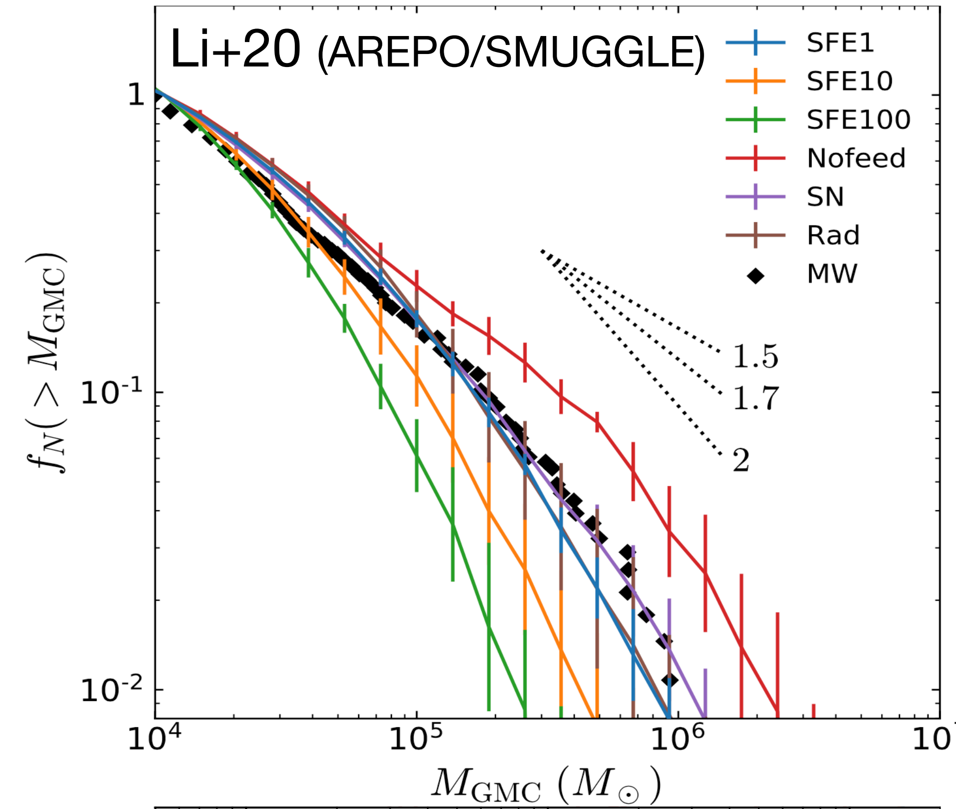
How to compare models and understand the discrepancies?

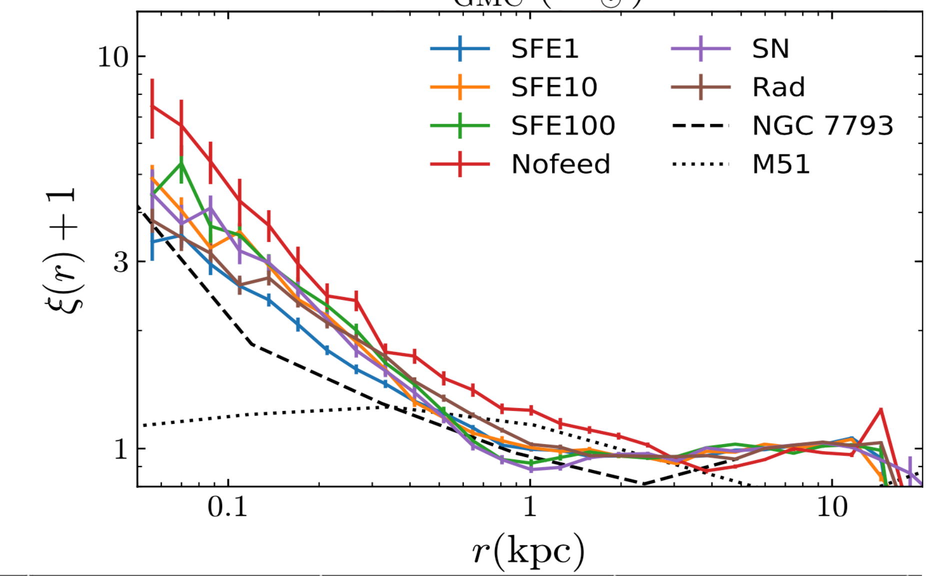




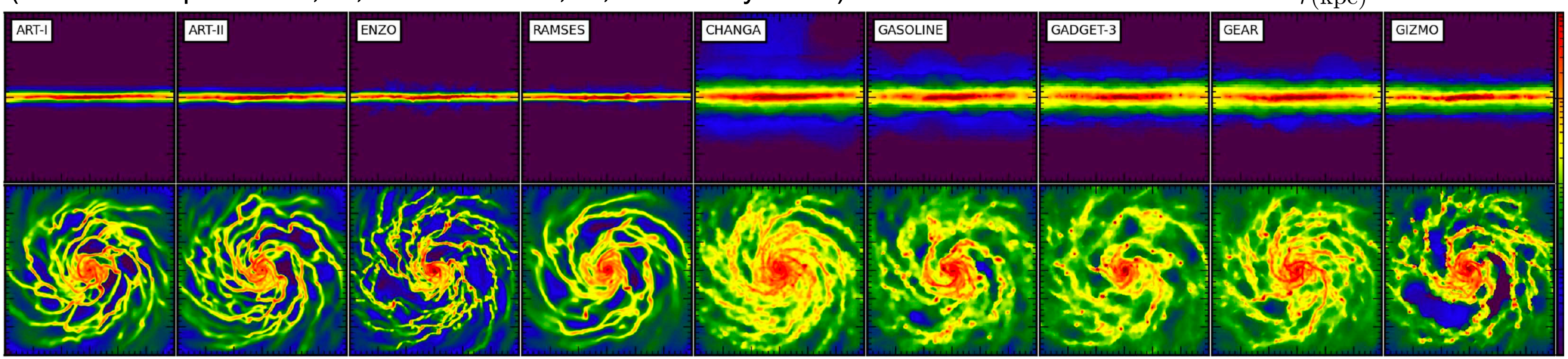
More on sub-grid models: isolated disks

- The SFR, K–S law almost independent of sub-grid models: self-regulated SF in quasi-equilibrium disk (Silk 91; Krumholz & McKee 05; Thompson+05; Faucher-Giguere+13; Krumholz+09,18; …)
- Slope of GMC MF and 2-point correlation function may test the sub-grid models (H. Li+20)
  - Numerous, high-quality data available
  - Hard observations, higher-order quantities
  - Dependence on scale lengths, B/T, gas fraction, …





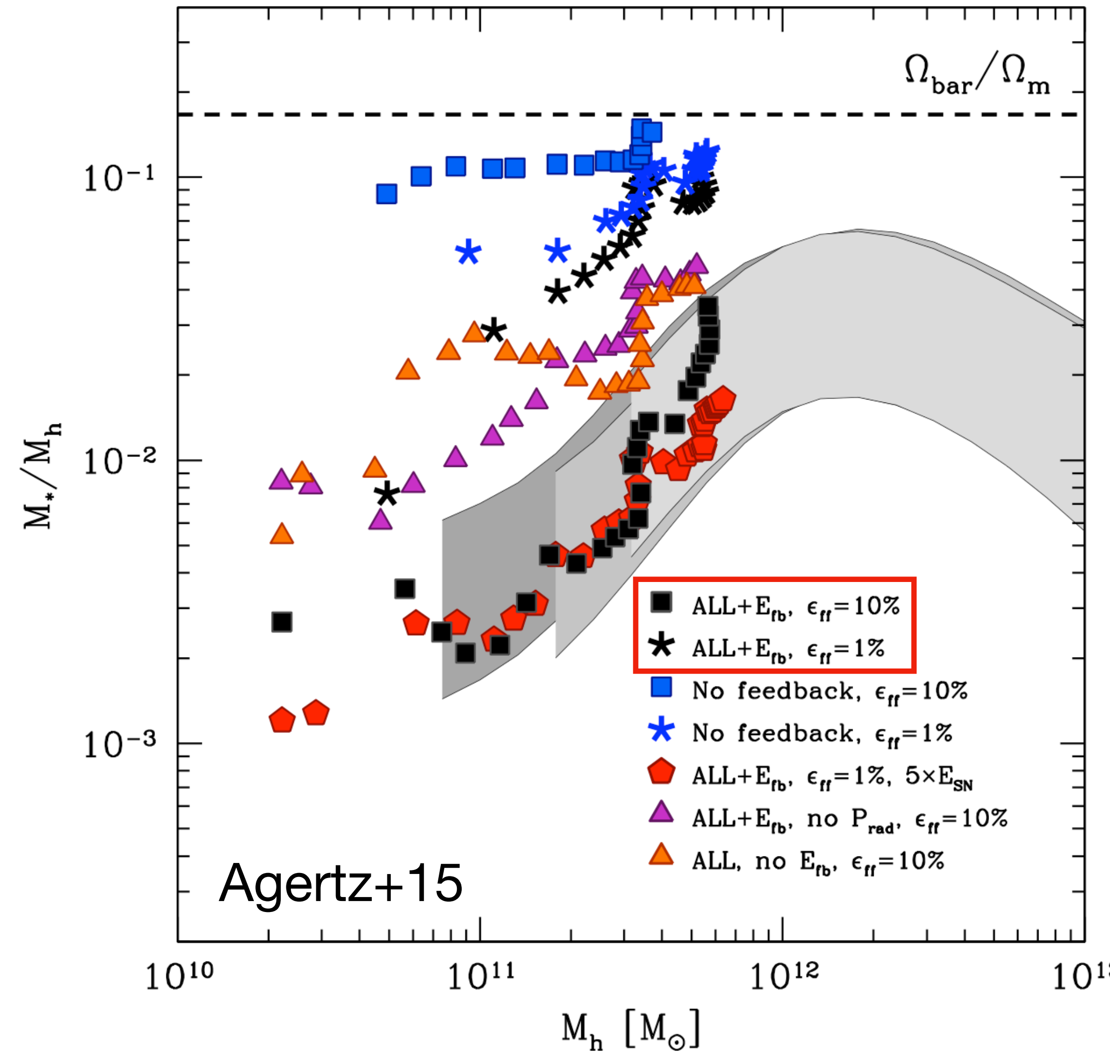
(see also Hopkins+11,12; Semenov+17,18; and many more)

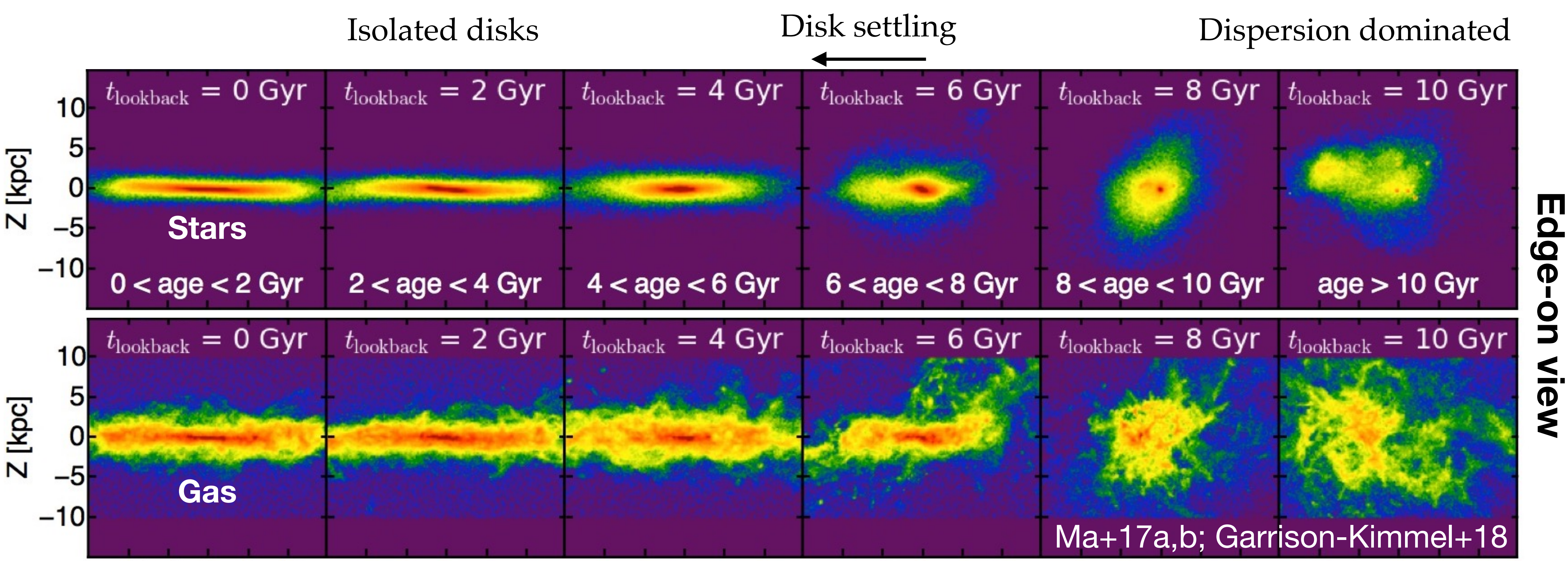


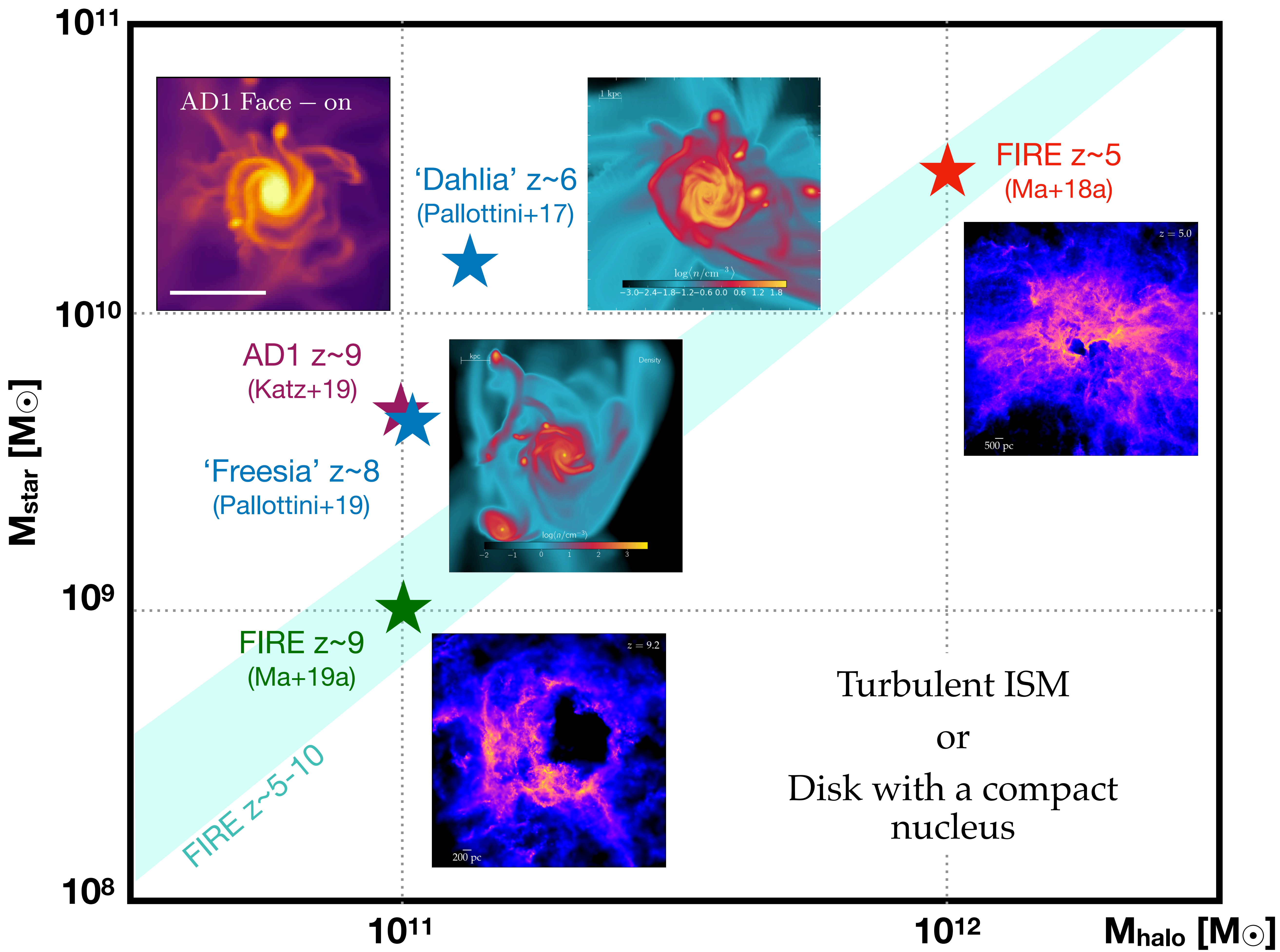
Kim+16 (the AGORA project)

More on sub-grid models: dispersion-dominated regime

- All galaxies have undergone this phase (dwarfs, progenitors at high redshift) — gas-rich, turbulent ISM, bursty SF, peak of GC formation
- 0th-order predictions (e.g. stellar mass) are sensitive to sub-grid models



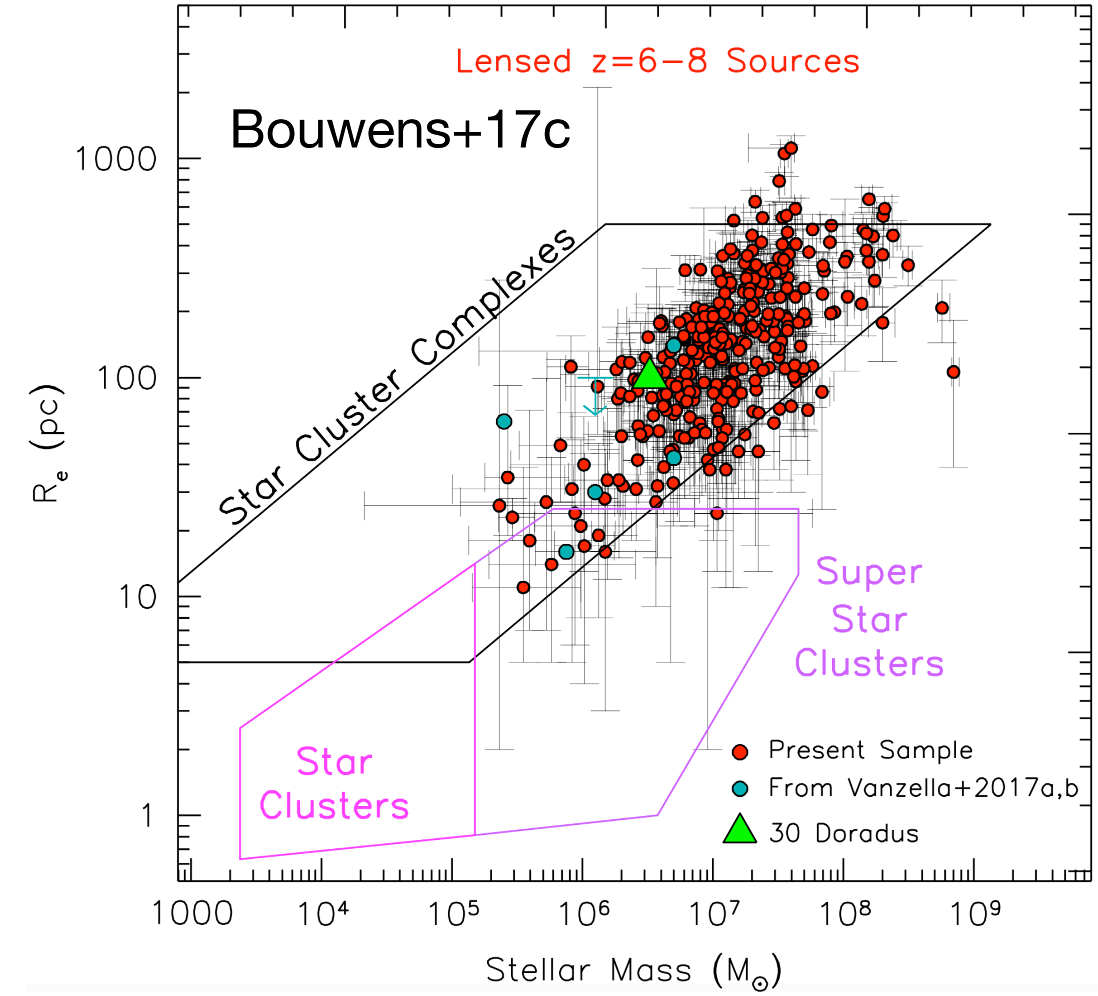


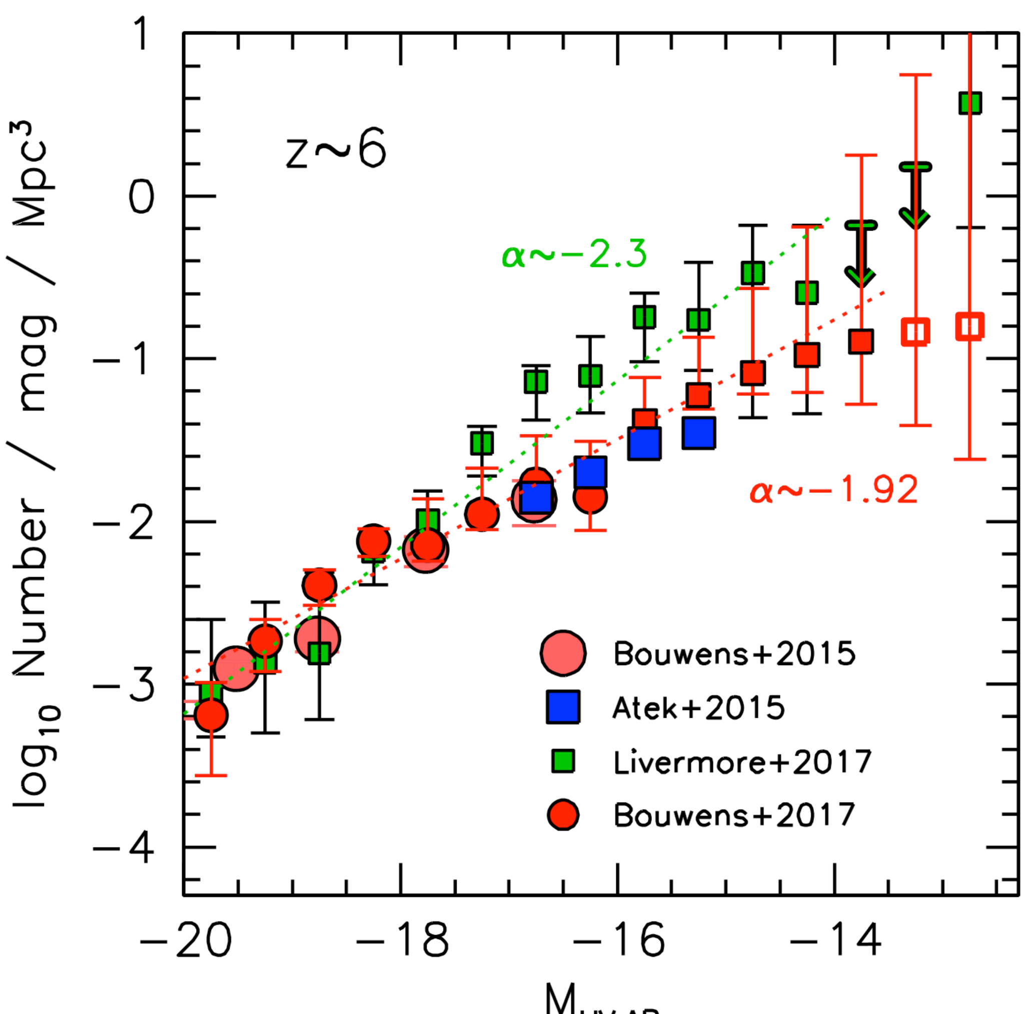


10^{11}
10^{10}
10^{9}
10^{8}
M_{star} [$M_\odot$]
10^{11}
10^{12}
M_{halo} [$M_\odot$]
AD1 Face − on
'Dahlia' z~6
(Pallottini+17)
1 kpc
$\log\langle n/\mathrm{cm}^{-3}\rangle$
−3.0 −2.4 −1.8 −1.2 −0.6 0.0 0.6 1.2 1.8
FIRE z~5
(Ma+18a)
z = 5.0
500 pc
AD1 z~9
(Katz+19)
'Freesia' z~8
(Pallottini+19)
kpc
Density
$\log(n/\mathrm{cm}^{-3})$
−2 −1 0 1 2 3
FIRE z~9
(Ma+19a)
z = 9.2
200 pc
FIRE z~5-10
Turbulent ISM
or
Disk with a compact
nucleus

Resolved GCs in cosmological simulations: applications

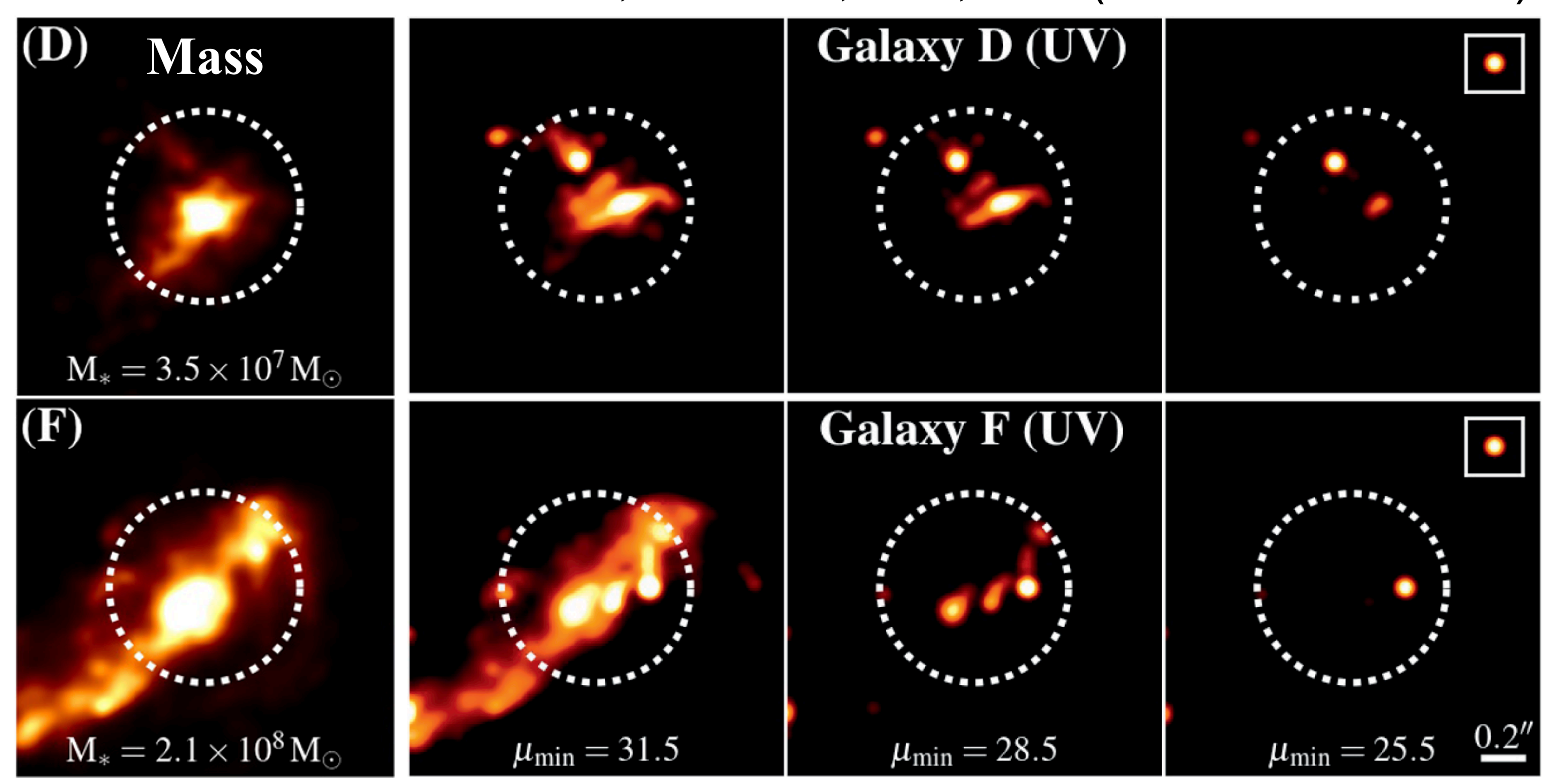
- Proto-GC candidates discovered up to z~6 (Vanzella+17a,b,19; Zick+20)
- High-z sources in the lensing fields are small: galaxies or star clusters?
- Large uncertainties to the faint-end UVLFs





Bouwens+17b

Ma+18b, MNRAS, 477, 219 (arXiv:1710.00008)

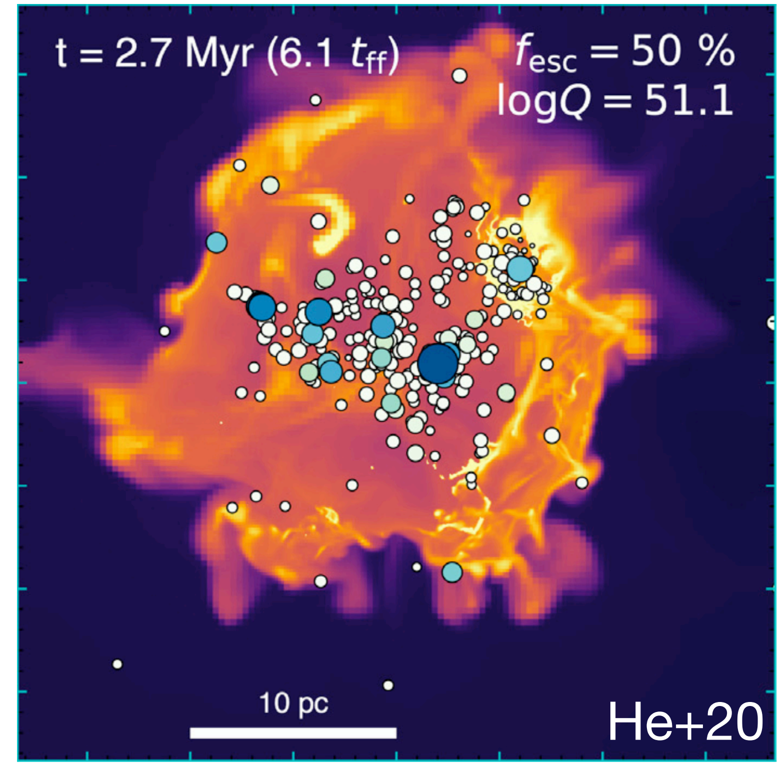


→ Decreasing sensitivity

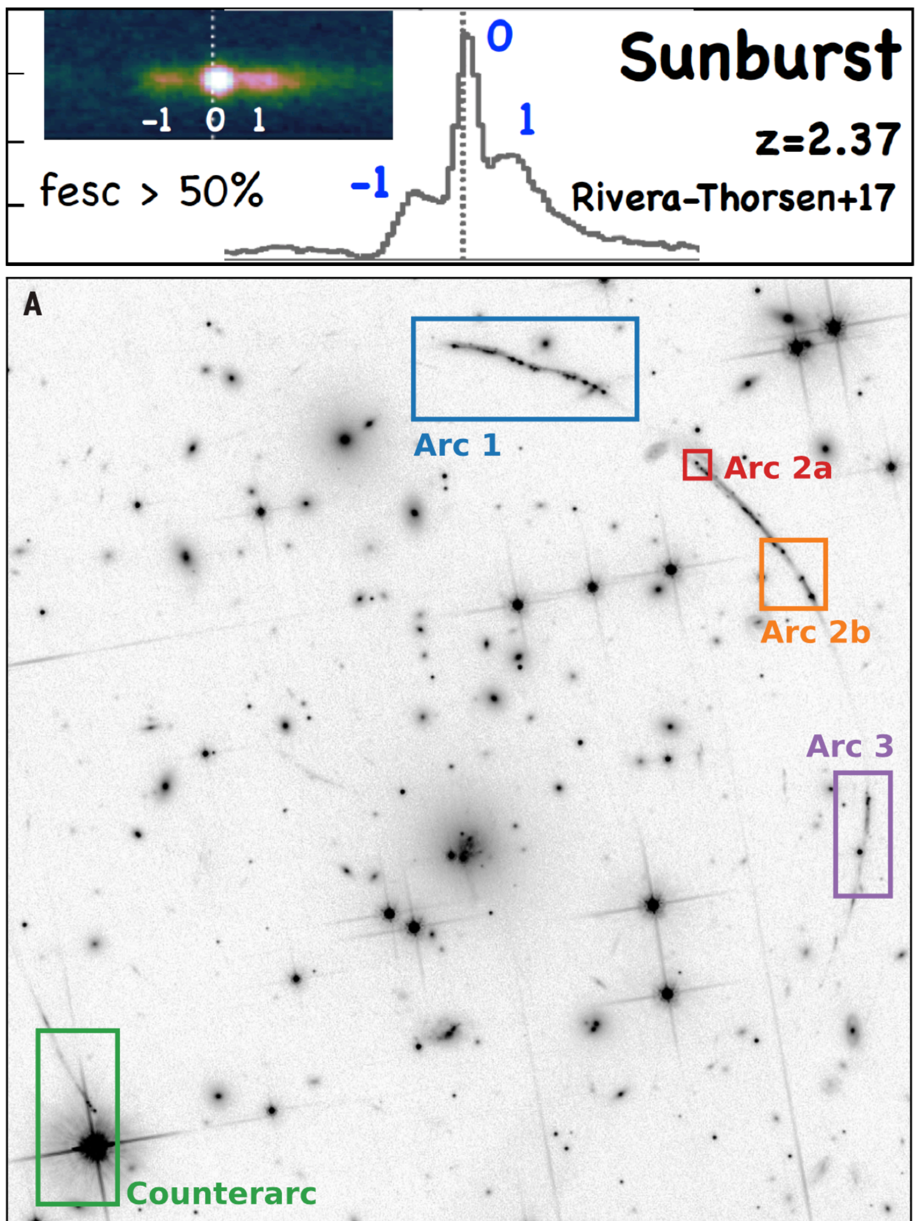
(see also Pfeffer+19; Meng & Gnedin 20)

Resolved GCs in cosmological simulations: applications

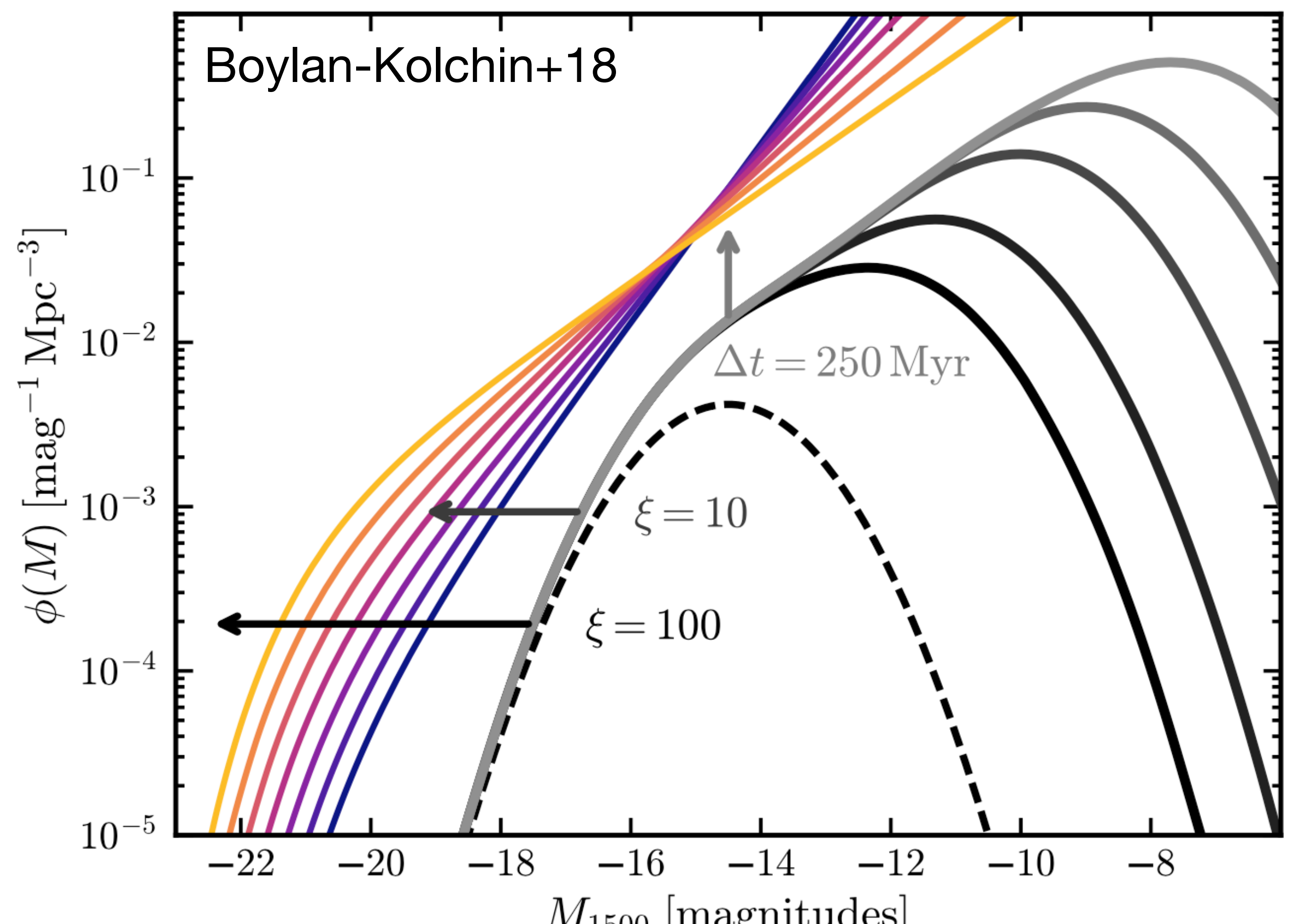
- Did proto-GCs dominate cosmic reionization?
  - What fraction of SF took place in proto-GC?
  - Did they have much higher f_{esc} than other stars? (need ISM/CGM environment)



(see also Ricotti 02; Griffen+13; Katz & Ricotti 13,14)

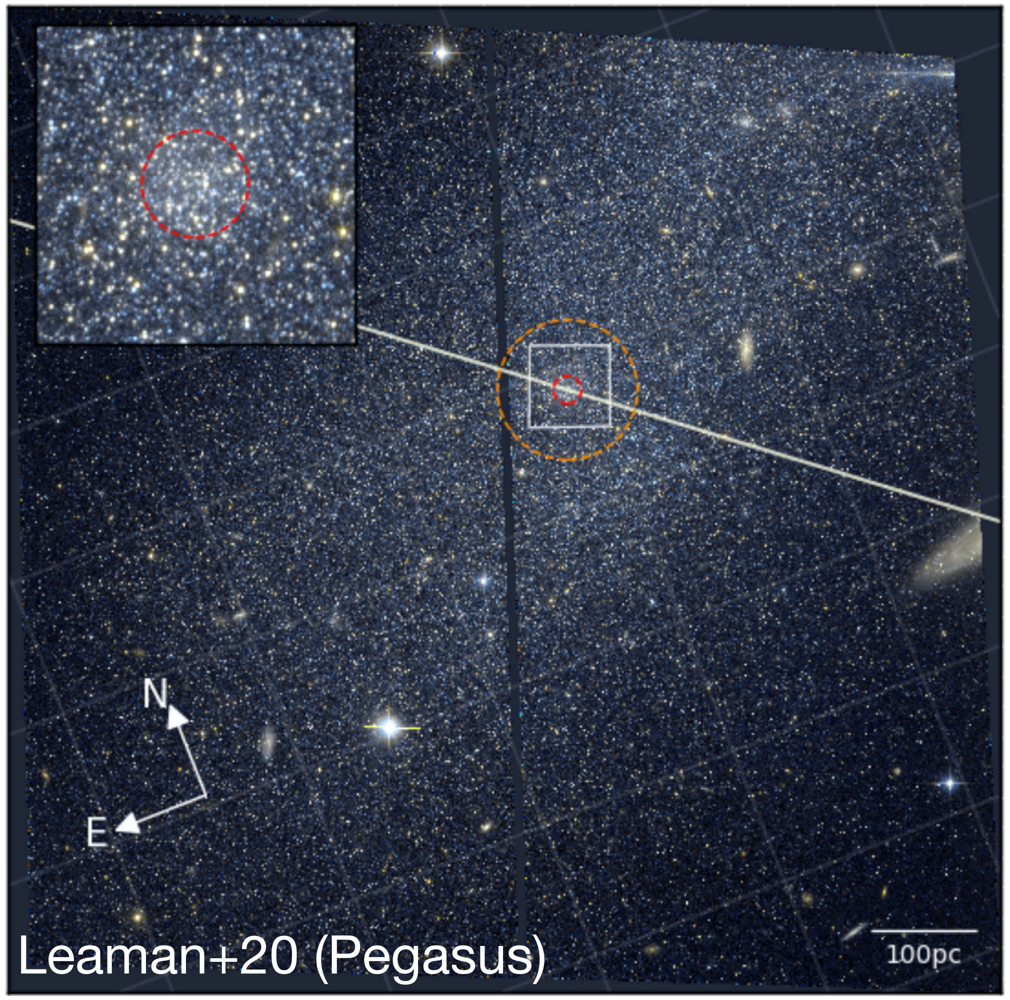


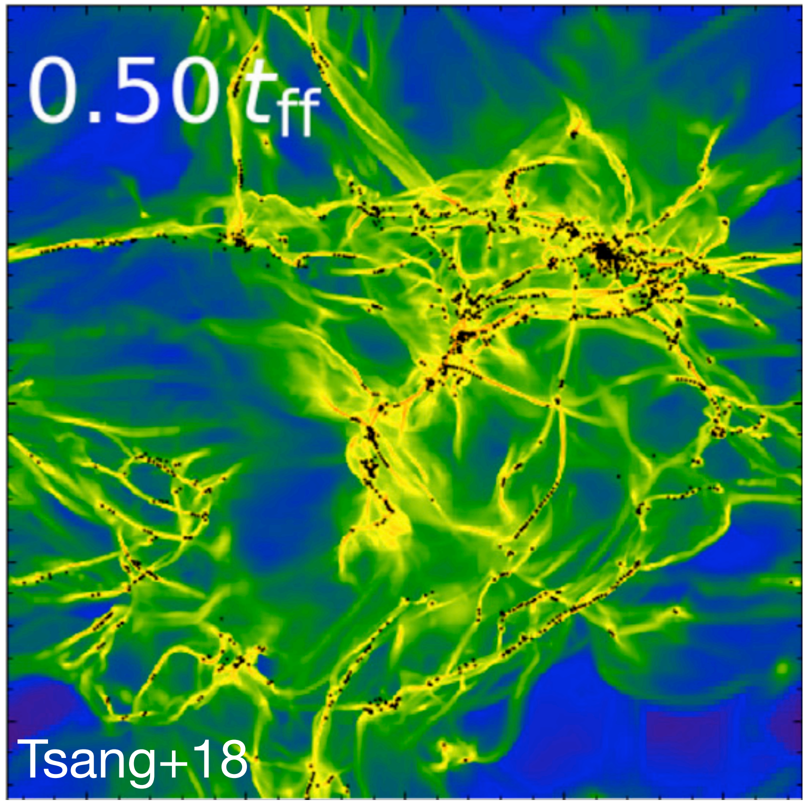
Rivera-Thorsen+17,19; Vanzella+20

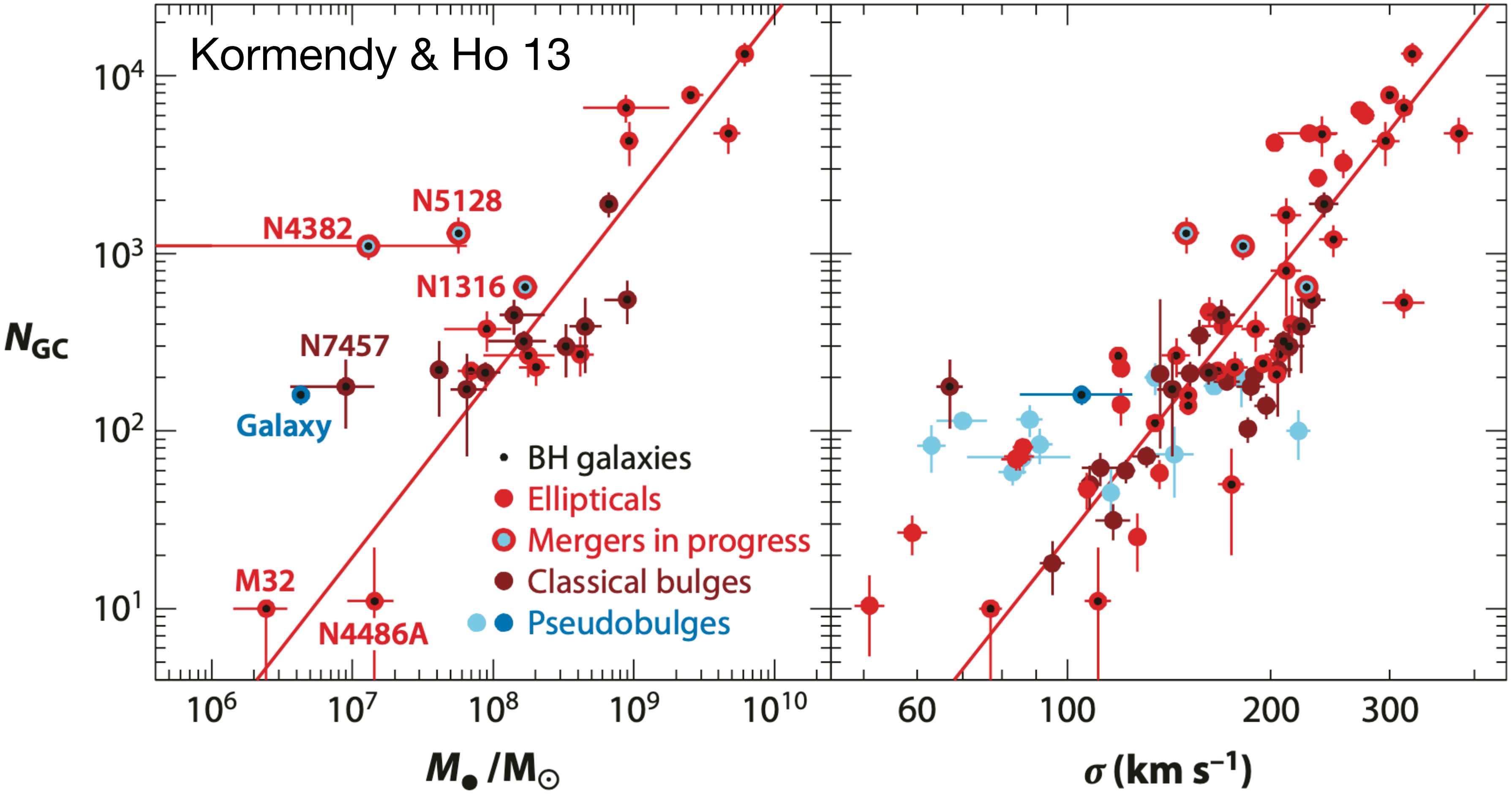


Resolved GCs in cosmological simulations: applications

- Initial conditions of GC formation (last week): Mach number, virial parameter, etc.
- Occupation of GCs in dwarf galaxies
- GC–halo (SMBH) connection
- ***Other ideas?***







Discussion

Resolved GCs in cosmological simulations:

- Small, self-gravitating structures with ~30–10^5 star particles in simulations with multi-phase ISM: cannot reliably track dynamical evolution over ~13.7 Gyr
- A hybrid approach is likely practical for future efforts to z=0

CFEs sensitive to “sub-grid” models:

- How to compare and reconcile the differences between simulations?

  [should consider it in a broader galaxy formation context: sub-grid models make higher-order (0^{th}-order) differences in isolated disks (dispersion-dominated regime)]

What we can do with these simulations?

- Provide insights for “initial conditions” of GC formation at high-z
- Understand observational signatures of YMCs, biases on the faint-end UVLFs at z~6, and contribution of GCs to cosmic reionization
- The occupation of GCs in dwarf galaxies
- GC–halo (SMBH) connection
- Reconstruct star formation history from GC populations
- Other ideas?