

Galaxy clusters as the knots of the cosmic web: what do simulations tell us about their emergence?

Stefano Borgani

Dept. of Physics - University of Trieste

INAF – Astronomical Observatory of Trieste

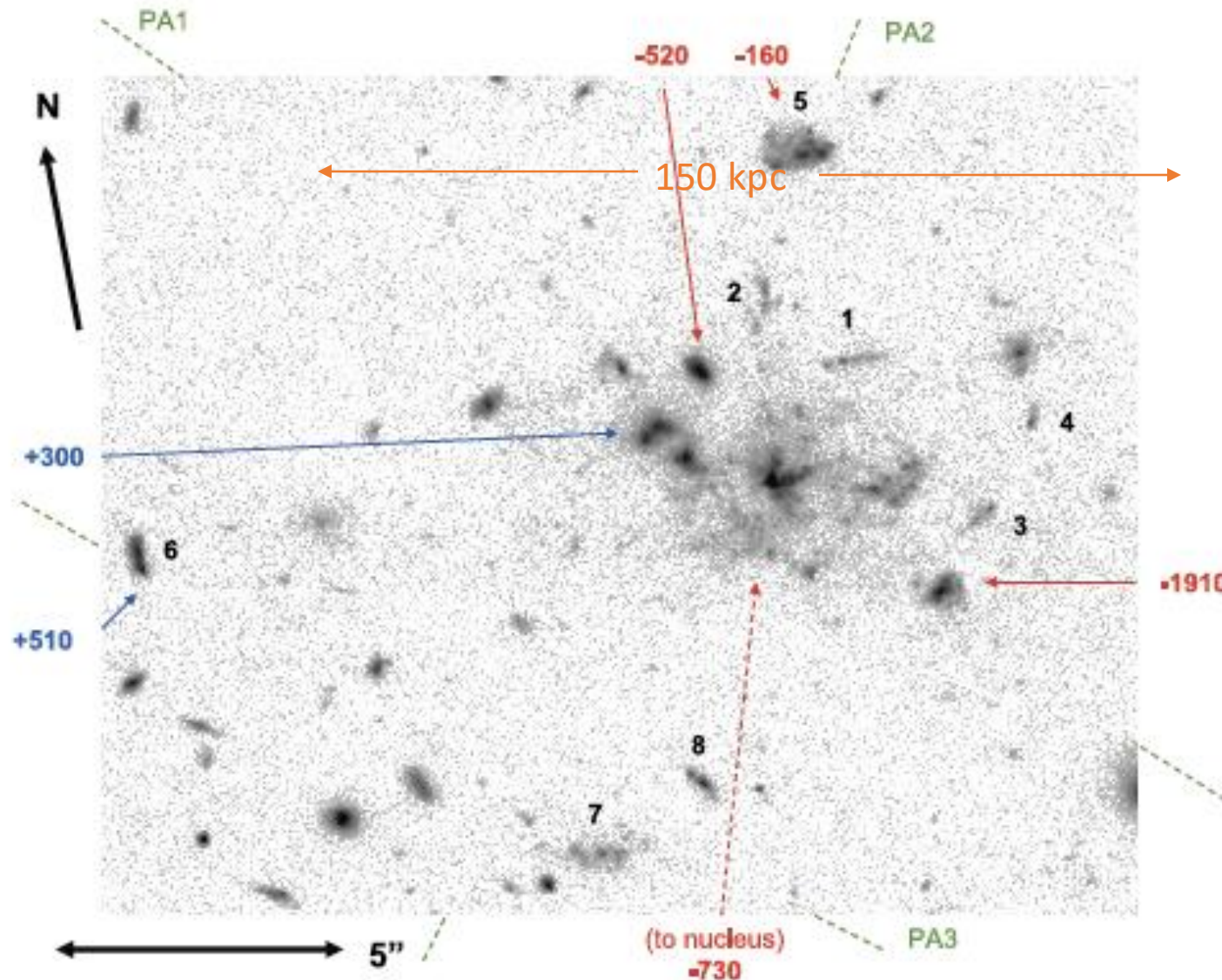
INFN – National Institute for Nuclear Physics – Trieste

ICSC - National Center for HPC, Big Data and Quantum Computing

- I. Simulating the infancy of galaxy clusters
 - I.a Properties of the proto-ICM and their low-z fossil record
 - I.b Star formation rates in protoclusters
- II. Connecting to the properties of the low-z BCGs and ICM
- III. AGN feedback and treatment of the BH orbits

PART 1:
Simulating the Infancy
of Galaxy Clusters

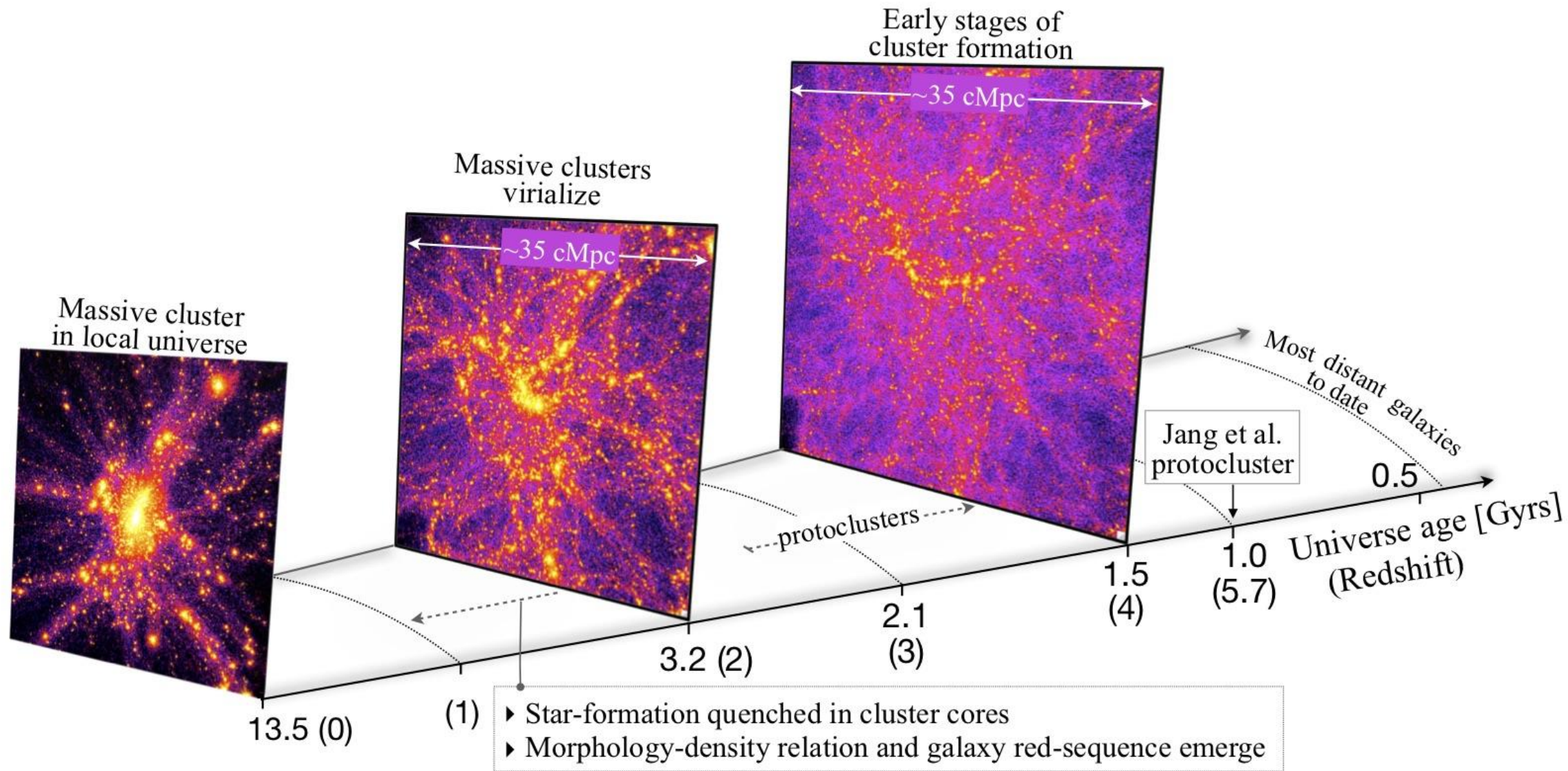
How does a galaxy cluster look like at $z > 2$?



HST-ACS image of MRC 1138-262

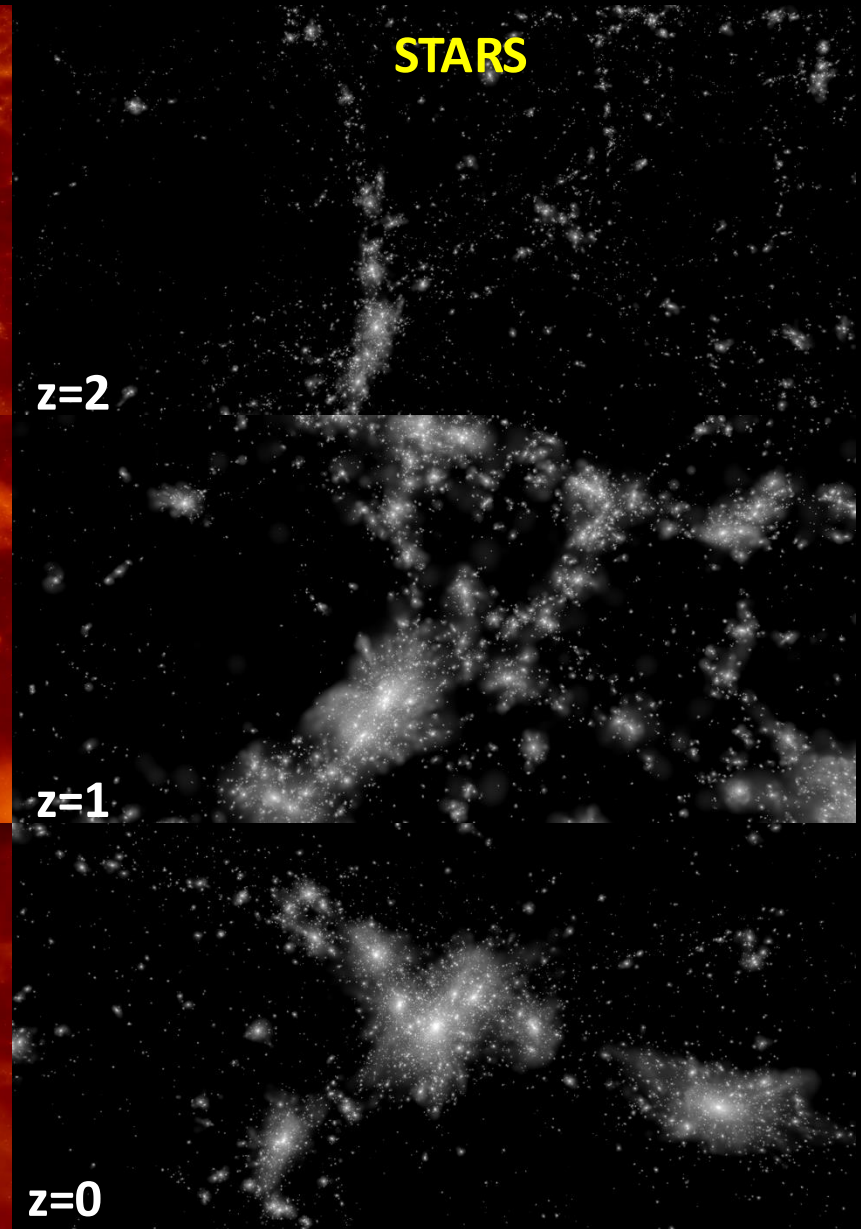
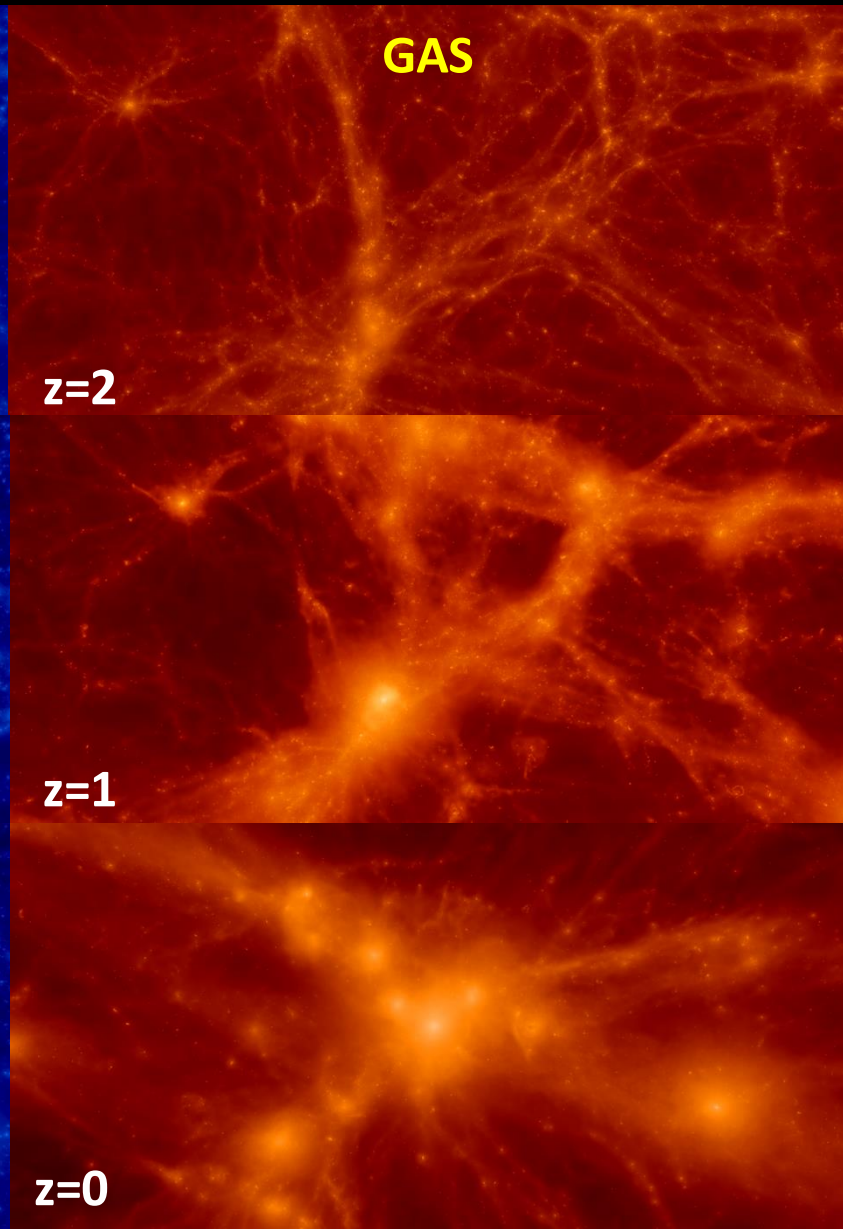
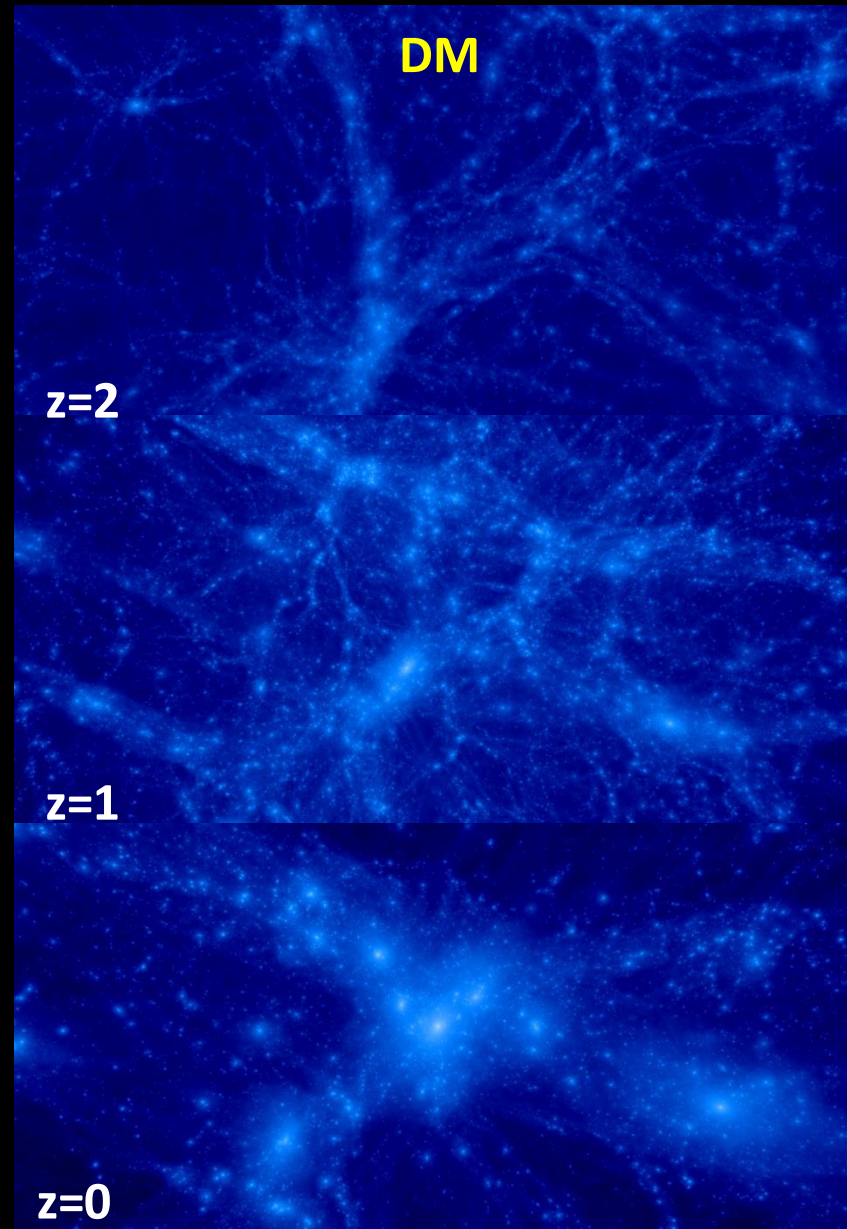
The “Spiderweb” galaxy (Miley+06)

- ➔ Complex dynamics of galaxies merging into the FR-II radio galaxy
- ➔ “Flies” moving with v_{los} of up to $\sim 10^3 \text{ km s}^{-1}$
- ➔ How typical is all this in the Λ CDM structure formation paradigm?

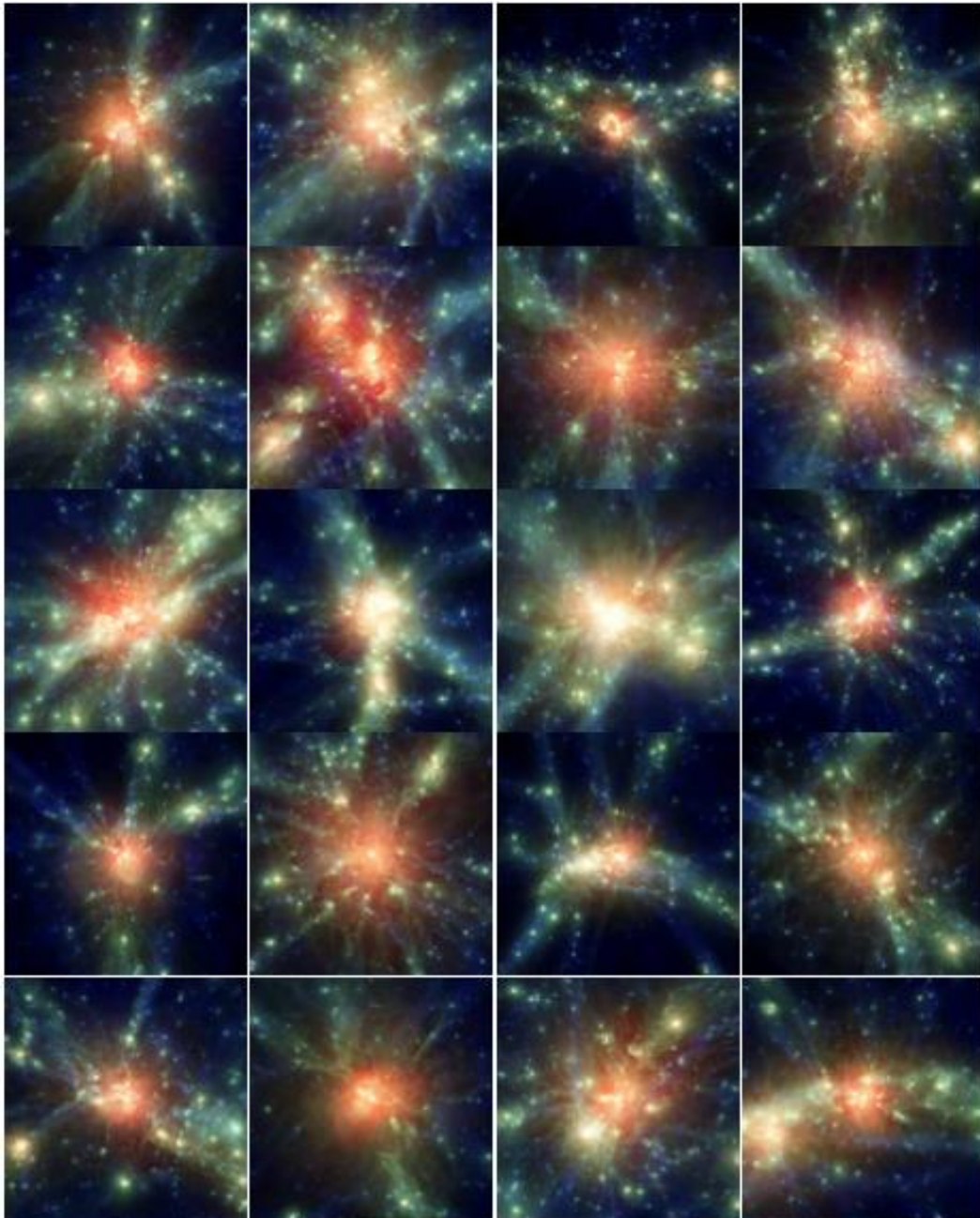
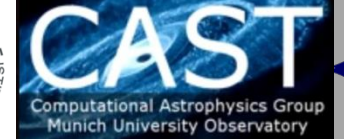


Courtesy of P. Rosati

Dianoga Simulations



The Dianoga Set with OpenGADGET3



→ 29 cluster Lagrangian regions resimulated at high resolution (Bonafede+12; Rasia+15; SB+24)

$$m_* = 2.6 \cdot 10^6 h^{-1} M_\odot ; \epsilon_* = 250 \text{ cpc}$$

OpenGADGET3 code: TreePM + SPH/MFM;

→ Hybrid MPI/OpenMP/OpenACC parallelism

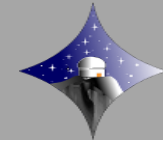
→ **Hydro-1**: SPH (Beck+16)

- Higher-order kernels, “Wake-up” for time-step of gas particles, Time-dependent artificial viscosity, Artificial conduction

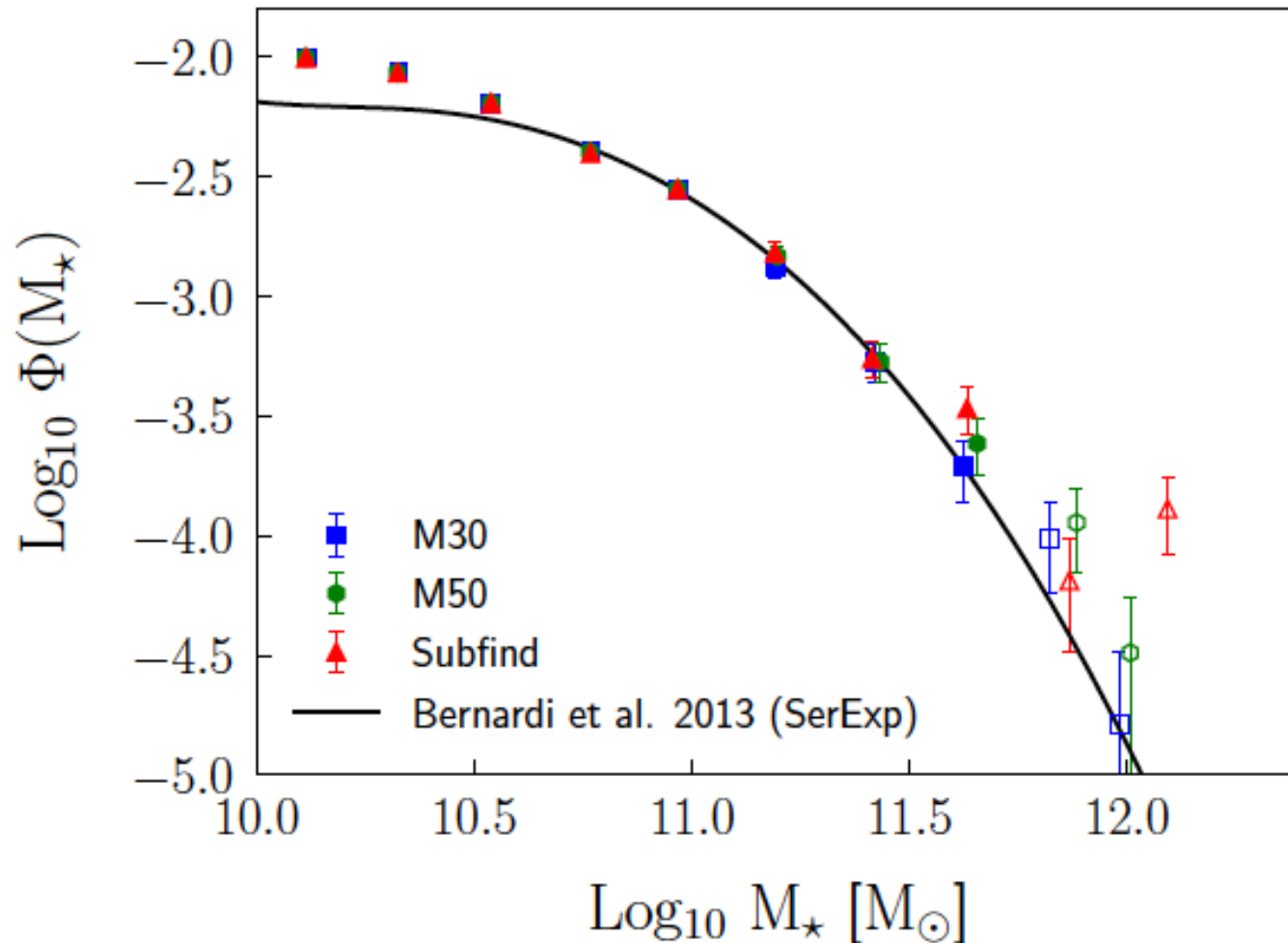
→ **Hydro-2**: MFM (Groth+23):

→ Astrophysics:

- Cooling + SF + SN feedback (Springel & Hernquist 03; Valentini+18), Chemical enrichment (Tornatore+07), AGN feedback (Fabjan+14; Steinborn+15)



(Bassini et al. 2021)

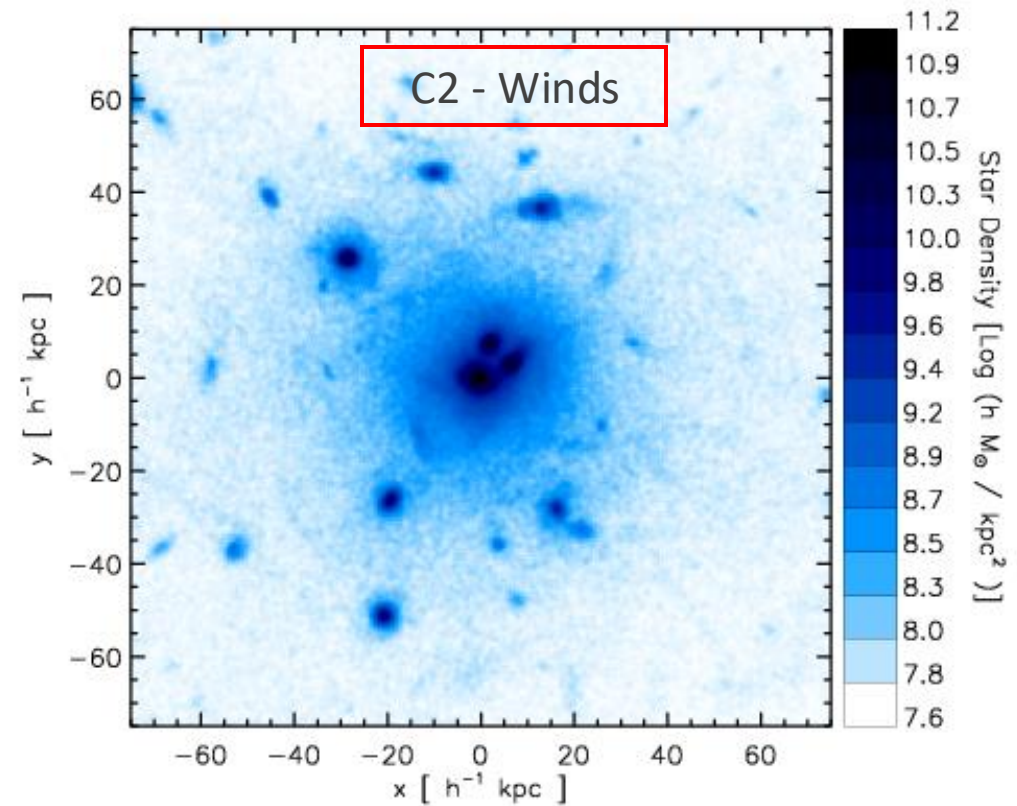
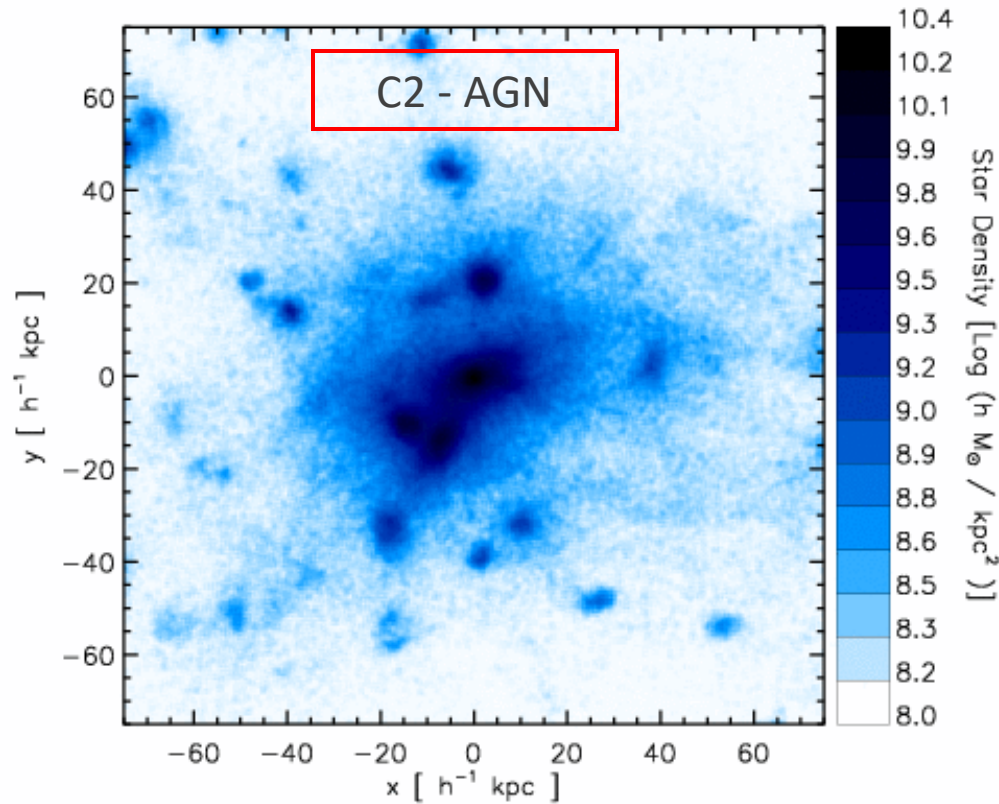


➔ Adjust the parameters of feedback to reproduce the observed scaling between SMBH masses and host stellar masses

➔ Predict the correct SMF of cluster galaxies

Simulating the formation of a proto-cluster at $z \sim 2$

Saro et al. 2009



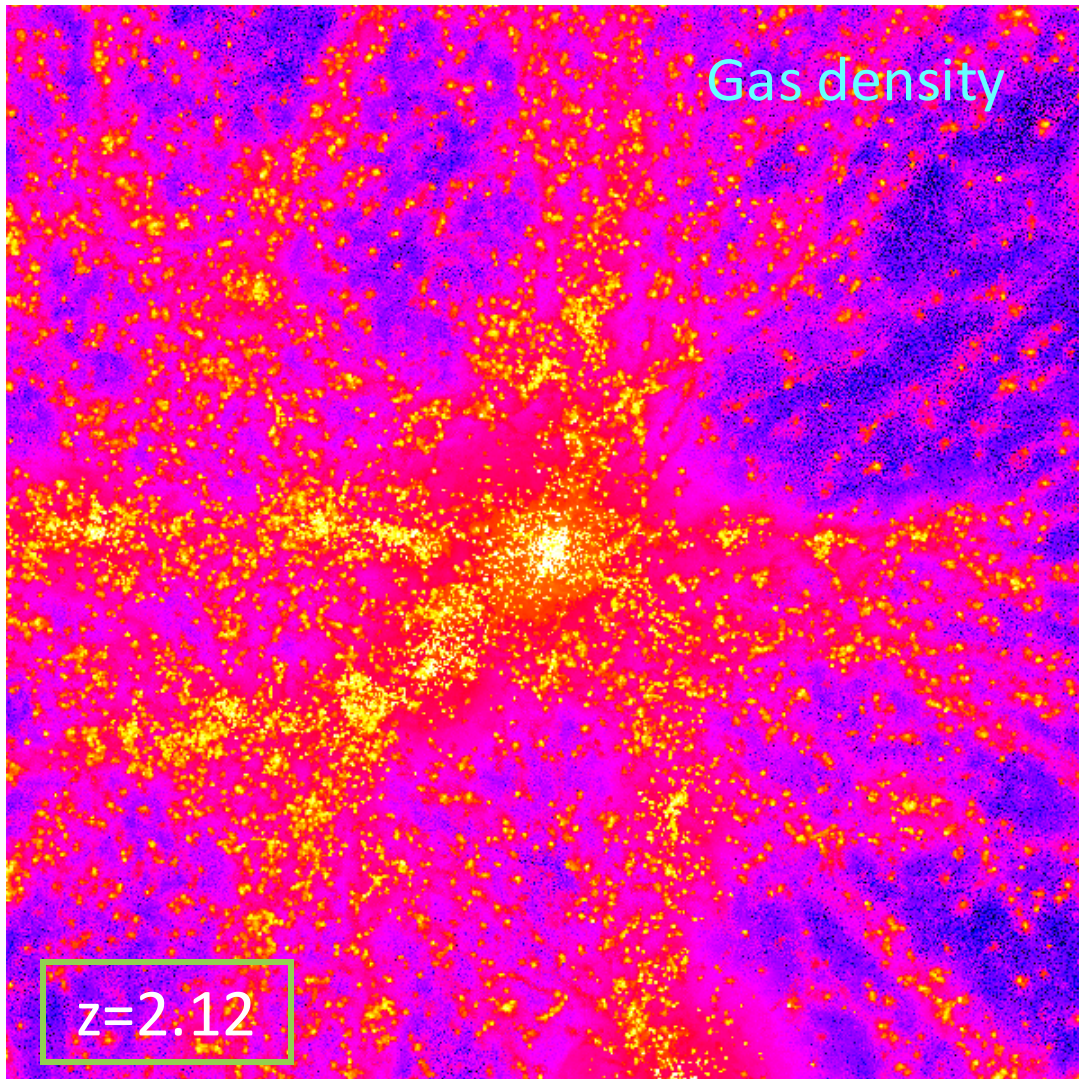
➔ SN-driven winds: $\text{SFR} \sim 1750 M_{\odot} \text{ yr}^{-1}$

➔ + AGN feedback: $\text{SFR} \sim 1300 M_{\odot} \text{ yr}^{-1}$

➔ Significant amount of diffuse ICL already in place at $z=2.16$

Simulating the formation of a proto-cluster at $z \sim 2$

Saro et al. 2009



→ Progenitor of a today massive galaxy cluster:

$$M_{200}(z=0) = 1.5 \times 10^{15} h^{-1} M_{\odot}$$

At $z=2.1$: hosting a hot, X-ray bright and metal-enriched proto-ICM:

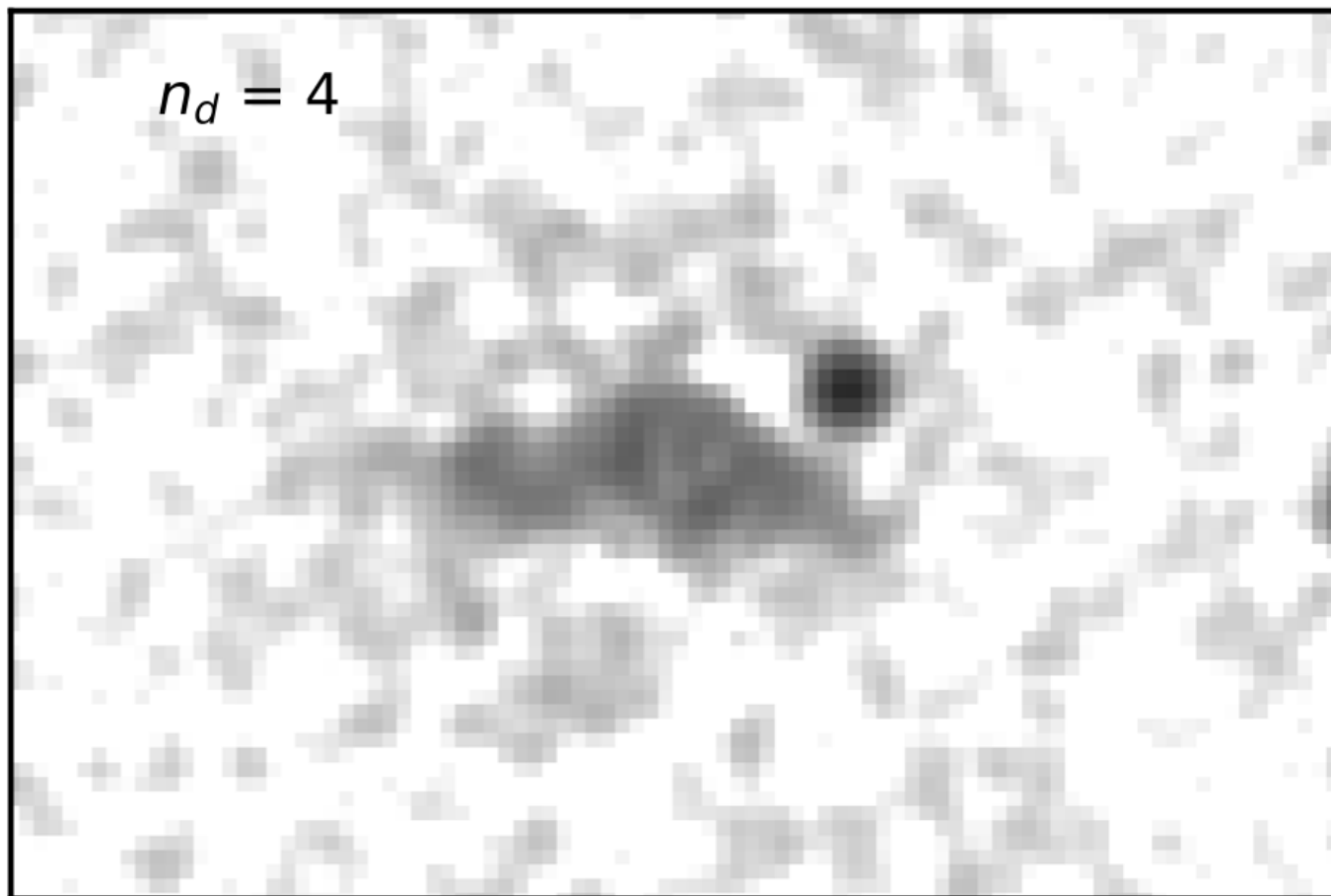
$$L_{0.5-2} = 1.4 \times 10^{44} \text{ erg s}^{-1}$$

$$T_x = 3.8 \text{ keV}$$

$$Z_{\text{Fe}} = 0.57 Z_{\odot}$$

A deep (700 ks) Chandra exposure on the “Spiderweb”

→ Large Chandra program (700 ks) to characterize the proto-ICM and the AGN population in the “Spiderweb” protocluster (*PI: P. Tozzi – Tozzi+2022 ; Lepore+2023*)
(see Paolo’s Talk)



Predicted

$$L_{0.5-2} = 1.4 \cdot 10^{44} \text{ erg s}^{-1}$$

$$T_x = 3.8 \text{ keV}$$

$$Z_{\text{Fe}} = 0.57 Z_{\odot}$$

Observed

$$L_{0.5-2} = (2.0 \pm 0.5) \cdot 10^{44} \text{ erg s}^{-1}$$

$$T_x = 2.0^{+0.7}_{-0.4} \text{ keV}$$

$$Z_{\text{Fe}} < 1.6 Z_{\odot}$$

A high-sensitivity ALMA observation of the “Spiderweb”

→ ALMA Cycle-6 proposal to detect the SZ signal around the Spiderweb galaxy (*PI A. Saro*)

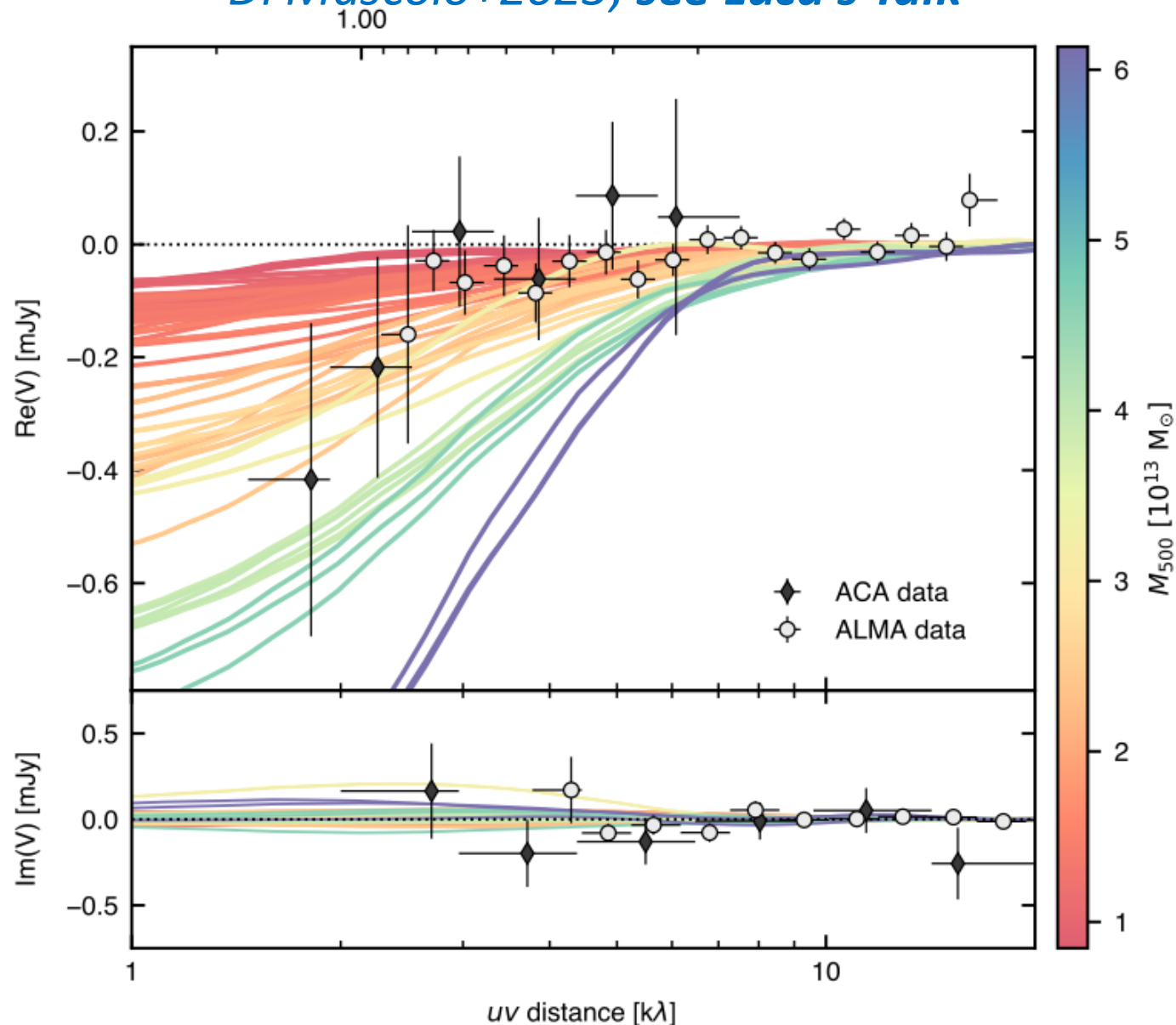
→ ALMA+ACA observations secured the detection of the SZ signal from the proto-ICM (significance at $\approx 6\sigma$)

→ Robust evidence for a pressurized atmosphere around the Spiderweb galaxy at $z=2.16$

→ Comparison with simulations: generation of realistic mock ALMA observations

→ Consistent with being associated to a virialized halo of mass $\sim 3 \times 10^{13} M_{\odot}$

Di Mascolo+2023; see Luca's Talk



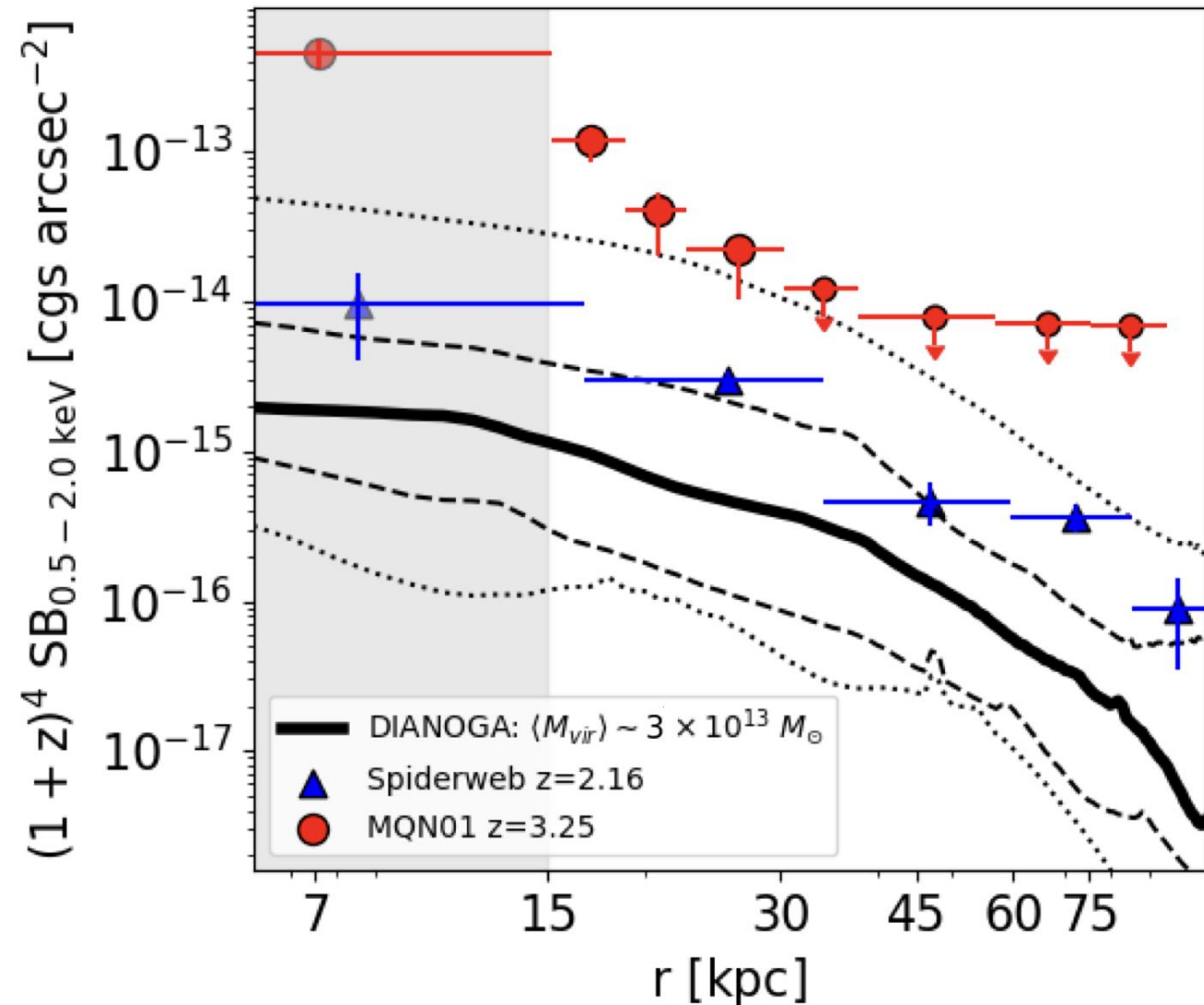
Evidence of proto-ICM at $z > 3$?

Travascio+2025; see Sebastiano's Talk

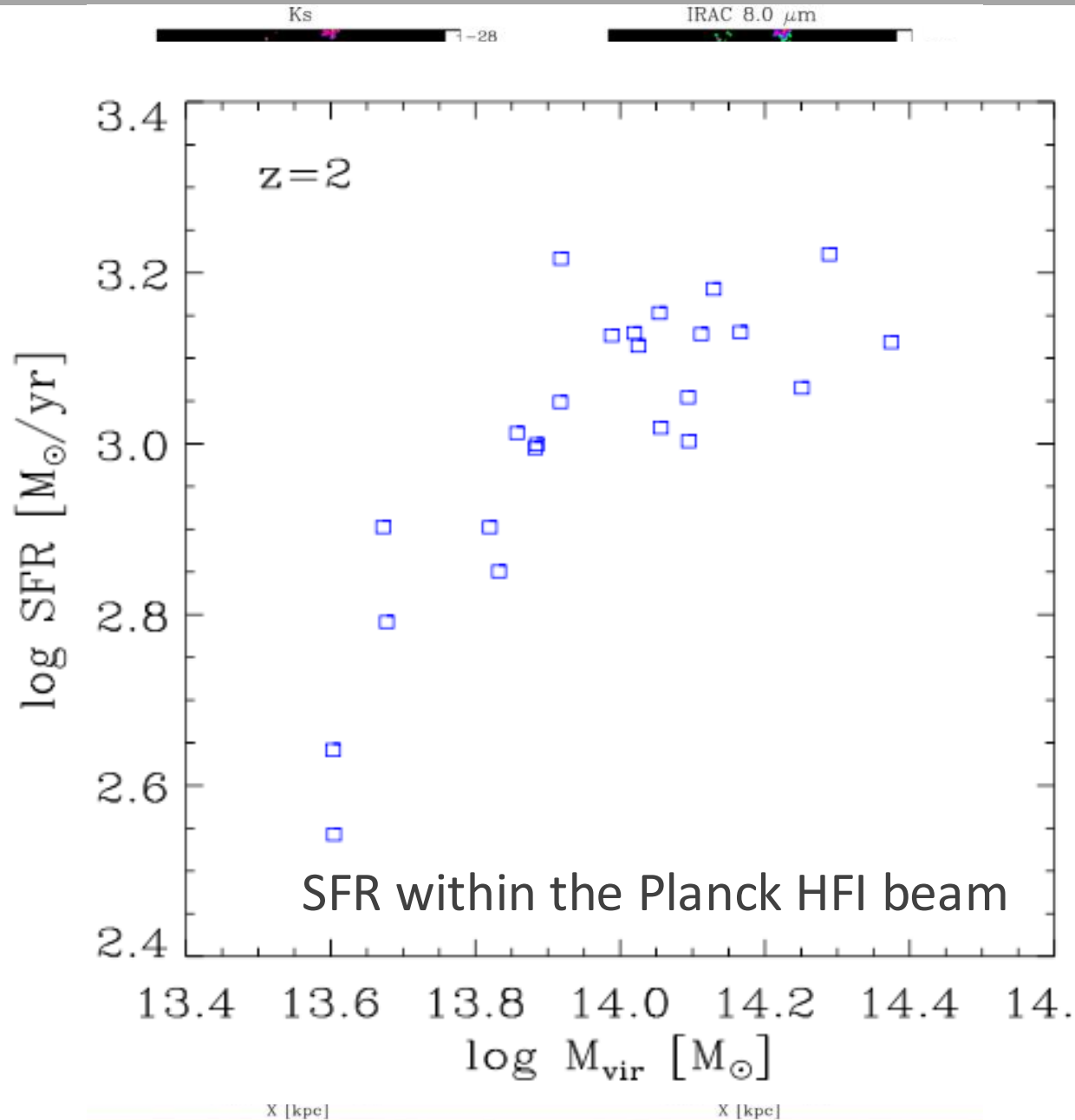
- Deep Chandra observation (PI S. Cantalupo) of the MQN01 Cosmic Structure
- Very bright Ly α nebula and strong galaxy overdensity
- $\sim 8\sigma$ evidence (66 photons) in the [0.5-2] keV band of an extended emission out to ~ 30 kpc from MQN01 at $z=3.25$
 $T = 1.8 \pm 0.4$ keV ; $L_x \simeq 2 \times 10^{45}$ erg s $^{-1}$

Comparison with Dianoga simulated SB profiles:

- OKish at $r > 20$ kpc
- Simulated structures are less luminous and with shallower profiles at smaller radii
- Evidence of the earliest assembly of ICM?
- Evidence of a "classical" cool core at high z ?



Star formation in “Planck blobs” with Herschel



Granato+2015

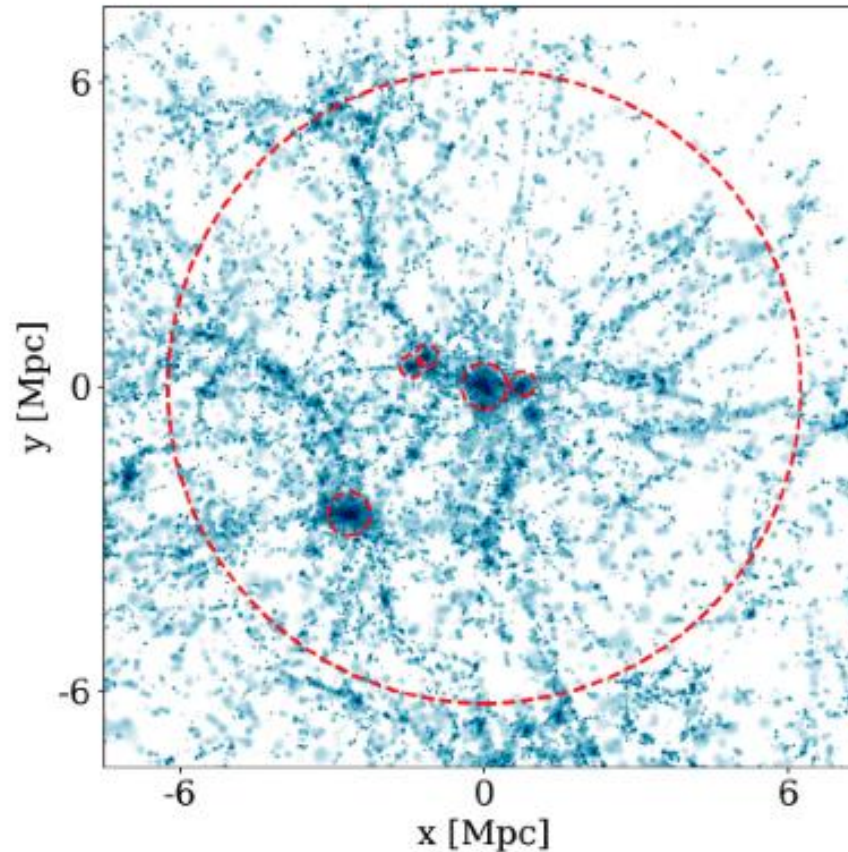
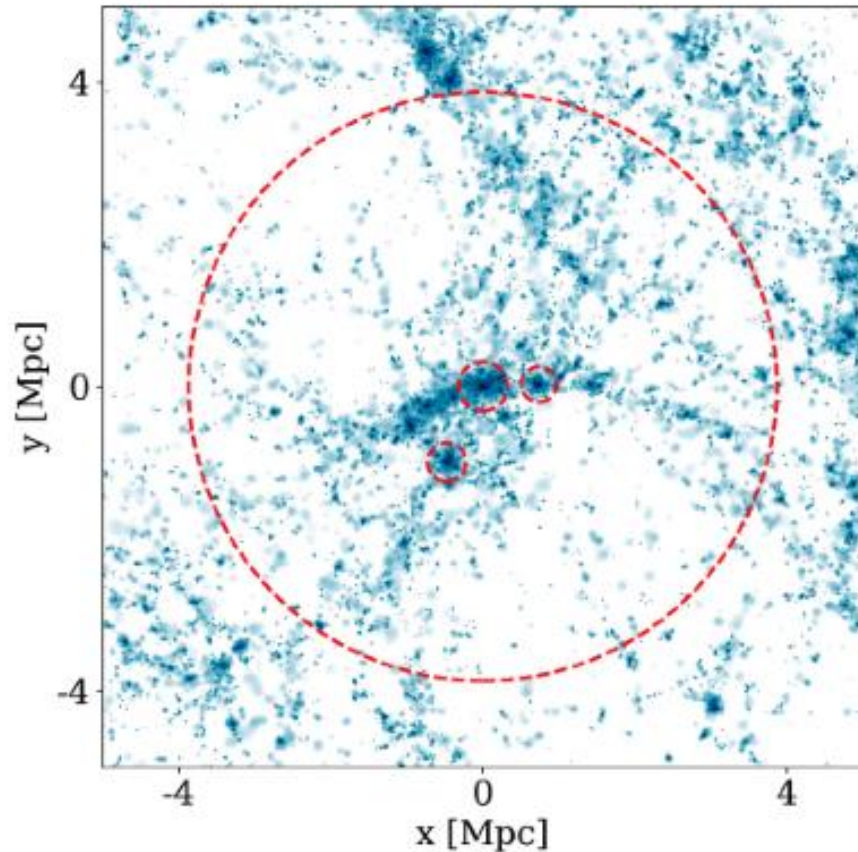
- Analyze progenitors of 24 clusters with $M(z=0) > 10^{15} M_{\odot}$
- Use GRASIL-3D to account for dust reprocessing
- Mock IR and sub-mm images at $z=2$

For the two observed clusters:

- ➔ $Flux_{\text{HFI}} \sim 1200 \text{ mJy} (@857 \text{ GHz})$
 - ➔ Far larger than obtainable from simulations
 - Clemens+2014: SFR within Planck beam for two $z \sim 2$ clusters: $[2.9 - 7] \times 10^3 M_{\odot}/\text{yr}$
- Q:** how to get such a high SFR at $z=2$, still smaller BCGs by $z=0$?

On the properties of simulated proto-clusters

→ *Stellar mass density maps (Esposito et al. 2025)*



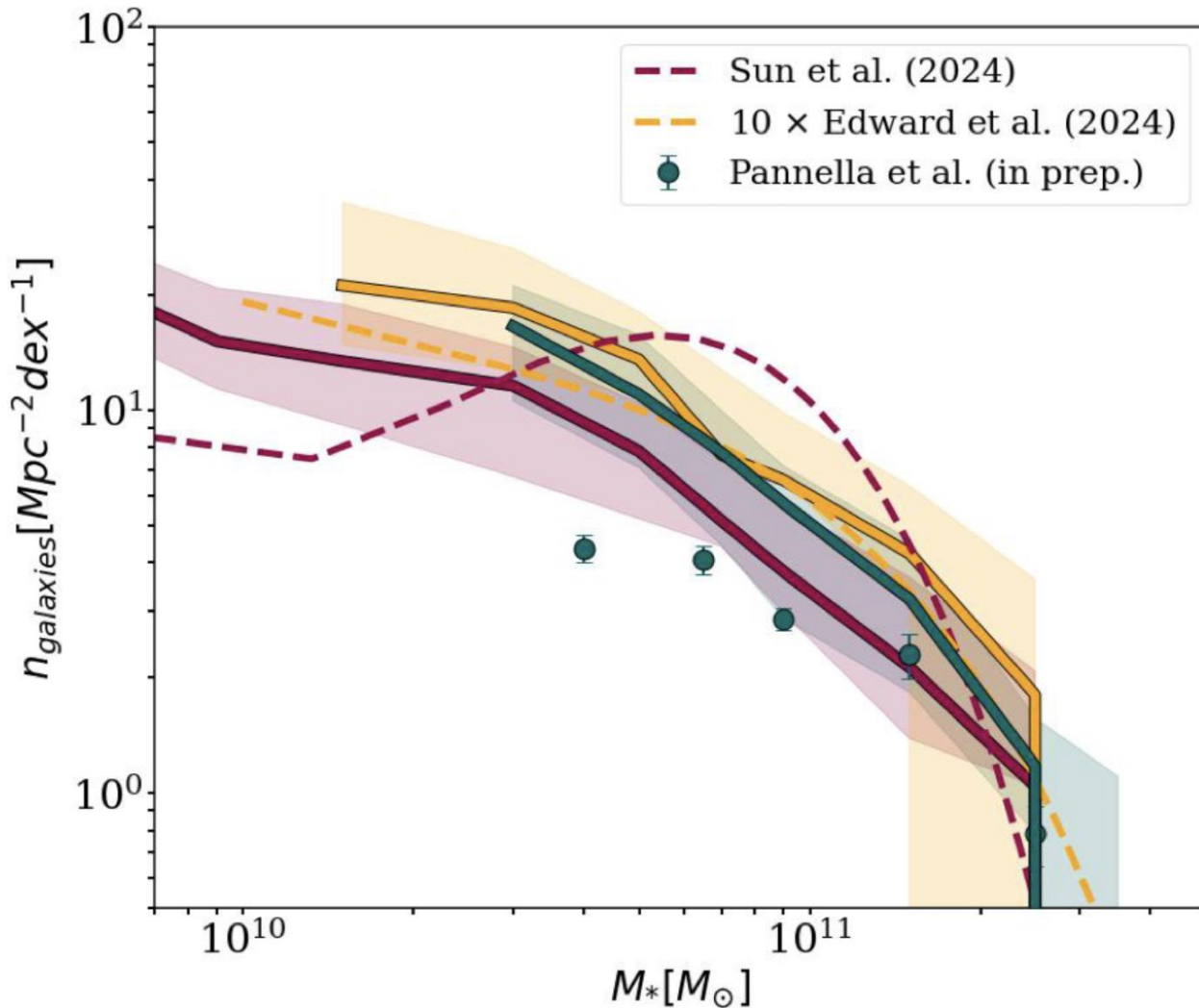
$z=2.2$

- Larger circles: radius of the circles centered on the main cluster progenitor and containing 80% of the DM particles identified within R_{200} at $z=0$
- Smaller circles: R_{200} at $z=2.2$

On the properties of simulated proto-clusters



(Esposito et al. 2025)



Relationship between mass and velocity dispersion

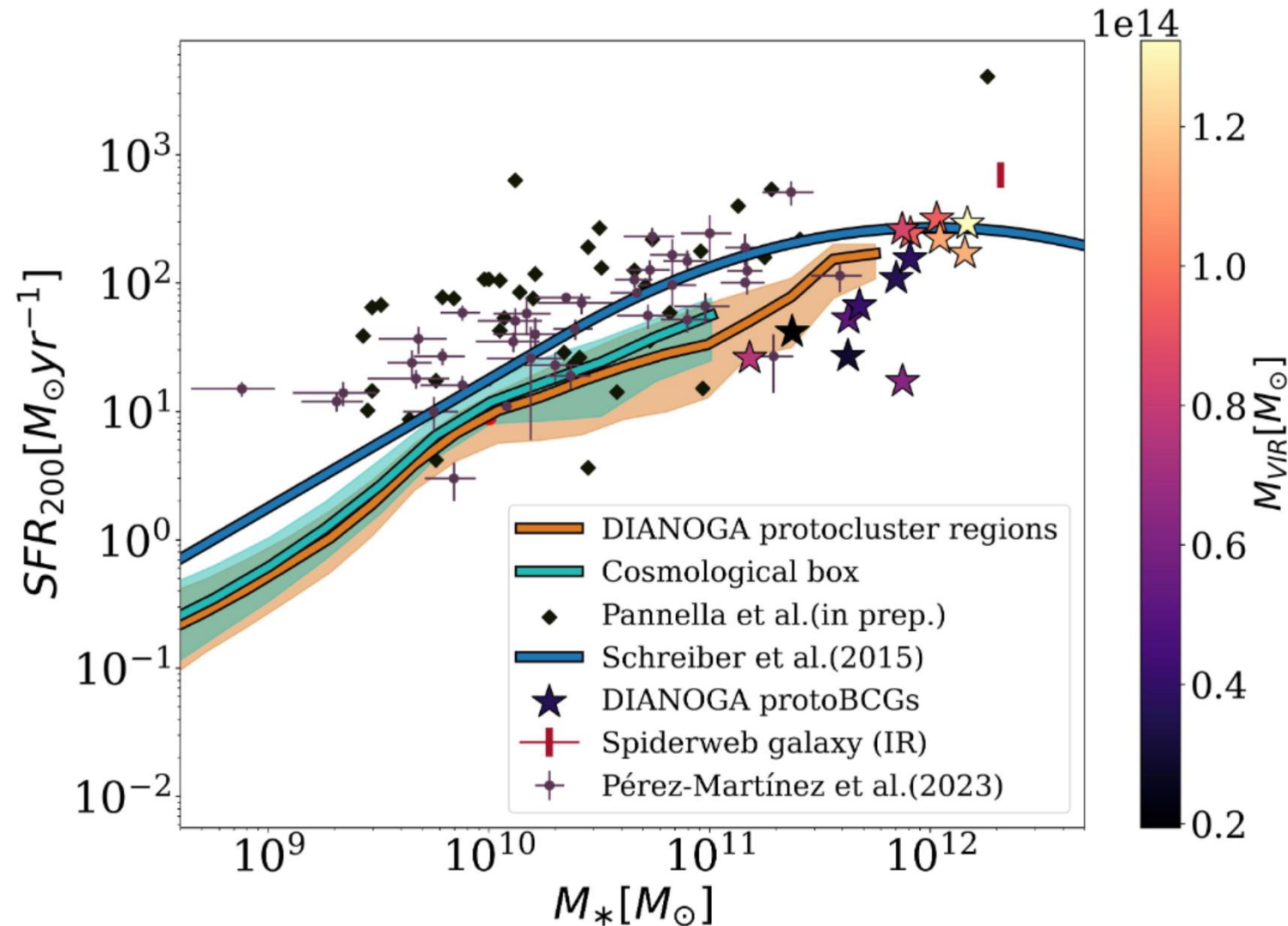
- In line with extrapolation from calibration from simulations at $z=0$
- Good agreement with results from [Shimakawa+2014](#)

Comparison between observed and simulated SMF:

- Generally consistent, especially in the high-mass end
- Exception of [Edwards+24](#), which agrees well in shape but with too high normalization

Star formation in proto-cluster regions

(*Bassini et al. 2021; Esposito et al. 2025*)



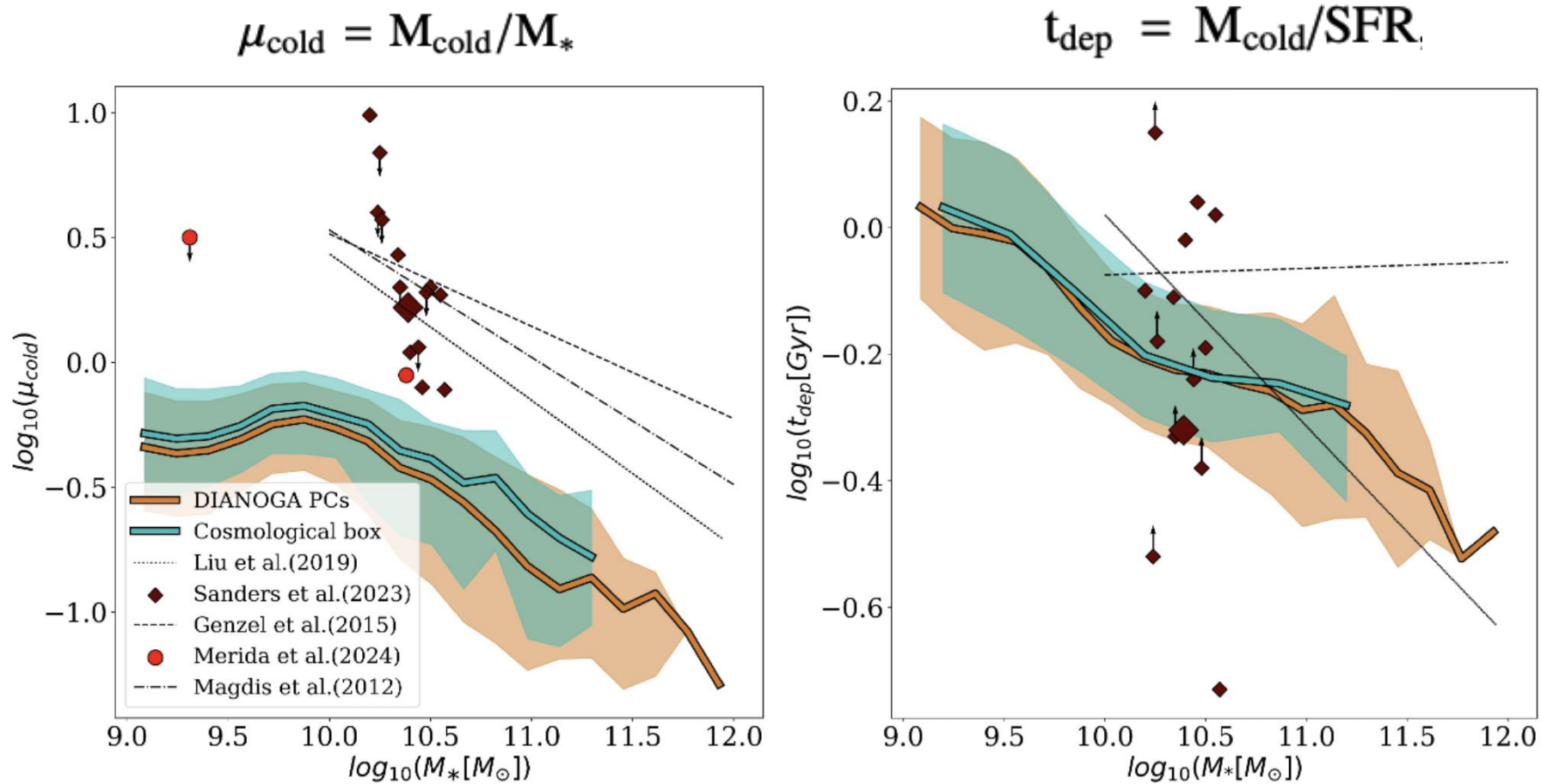
→ Model-prediction of the main sequence at $z \sim 2$ below the observed one, both in the field and in protocluster

→ Result almost independent of the adopted model of SF

→ SFR of the Spiderweb much reduced when including FIR data (*Seymour+2012; Drouart+2014*), besides UV dust-corrected fluxes (*Pannella+2024, in prep*)

→ "Only" a factor 2-3 above simulation predictions

Star formation in proto-cluster regions

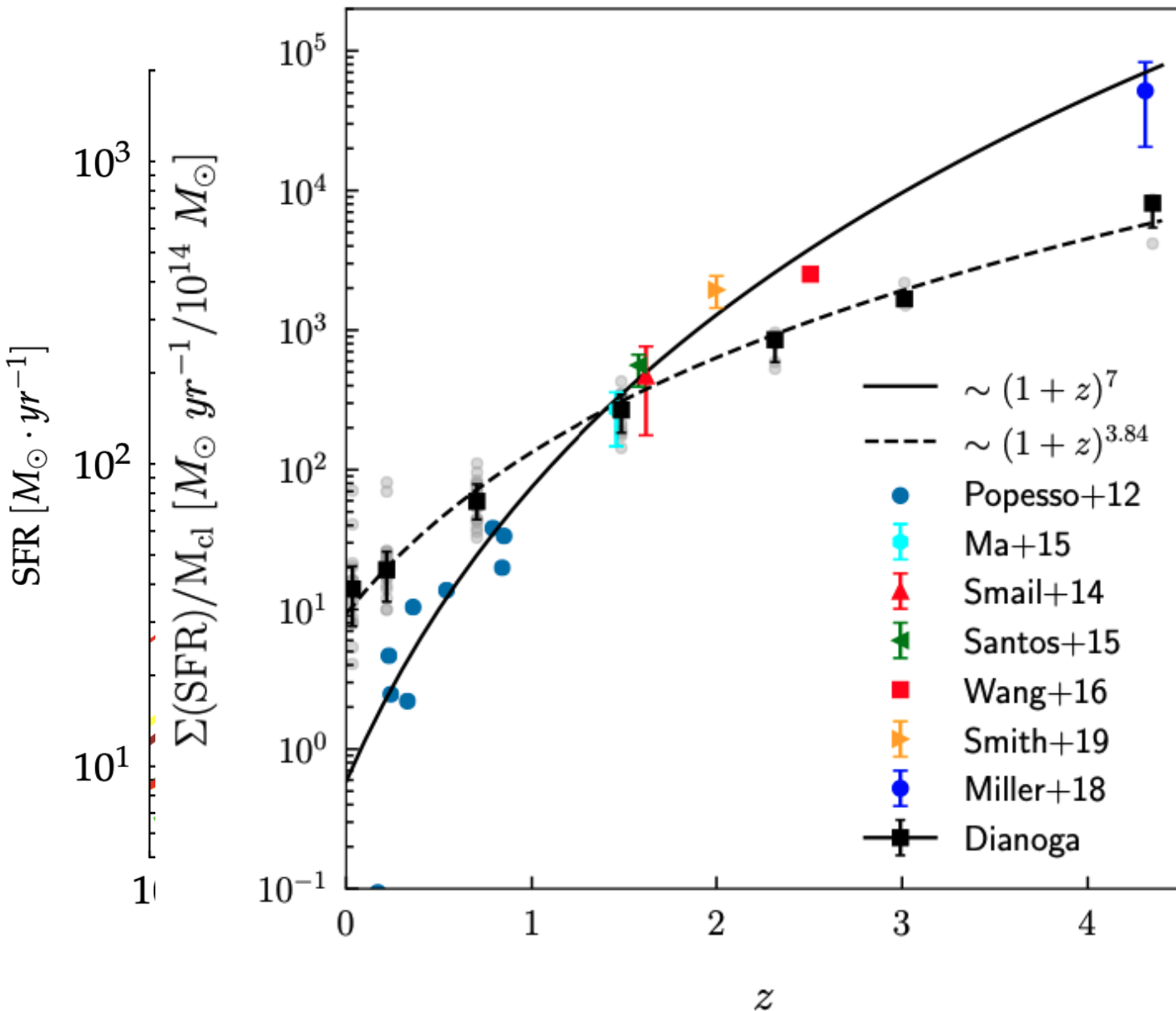


(Esposito et al. 2025)

→ Comparison with ALMA-based observational results for Main-Sequence galaxies at $z=2.2$

- Correct depletion time predicted by simulations → Consistent star formation efficiency
- Too small fraction of cold gas from simulations →
 - (a) Exceedingly efficient feedback;
 - (b) Too much early gas consumption (but SMF is still OK....)

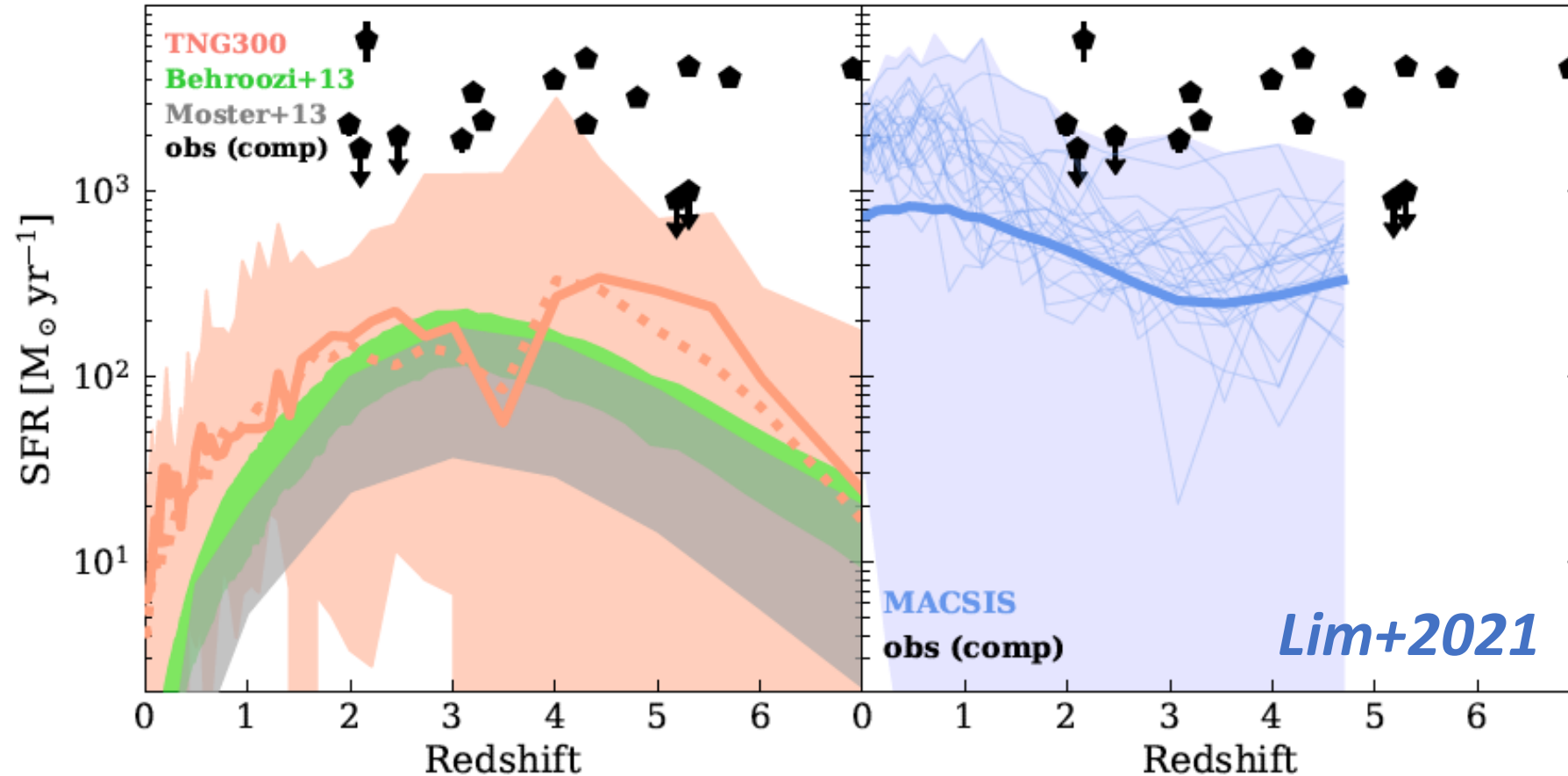
Star formation in proto-cluster regions



(Bassini et al. 2021)

- Apparently a common feature of several semi-analytical and full hydro simulations
- Observational trend for stronger SFR in (proto-)clusters at larger redshift qualitatively reproduced by simulations
- Trend in simulations weaker than observed
- Excess SF at low- z and deficit at high z

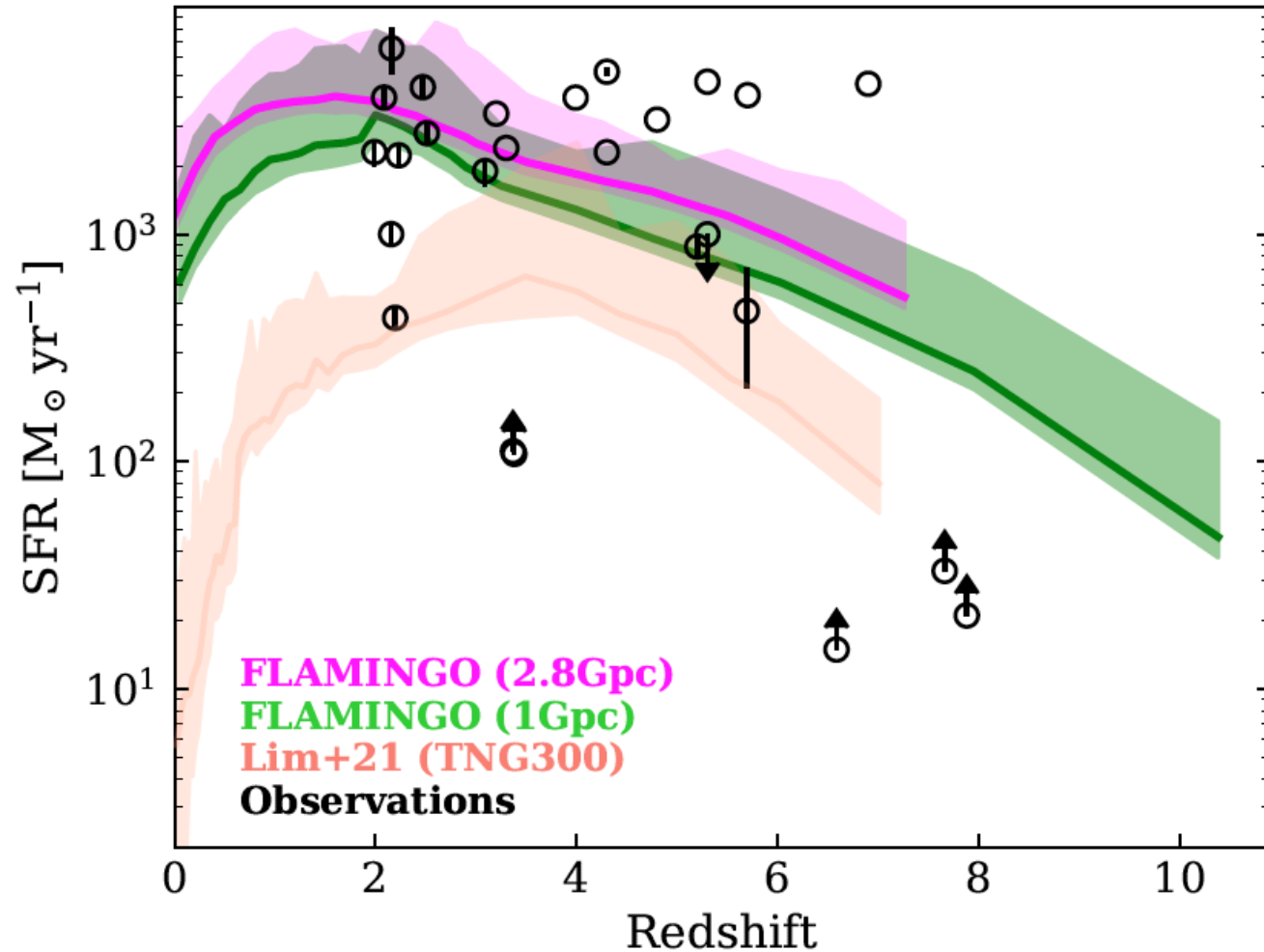
Star formation in proto-cluster regions



Comparison of TNG300 & MACSIS predictions on SFR in proto-clusters to observational data

- Model predictions ~ 1 order of magnitude below observed SFR
- Similar results for the “empirical model” by Moster+13 and Behroozi+13

Star formation in proto-cluster regions



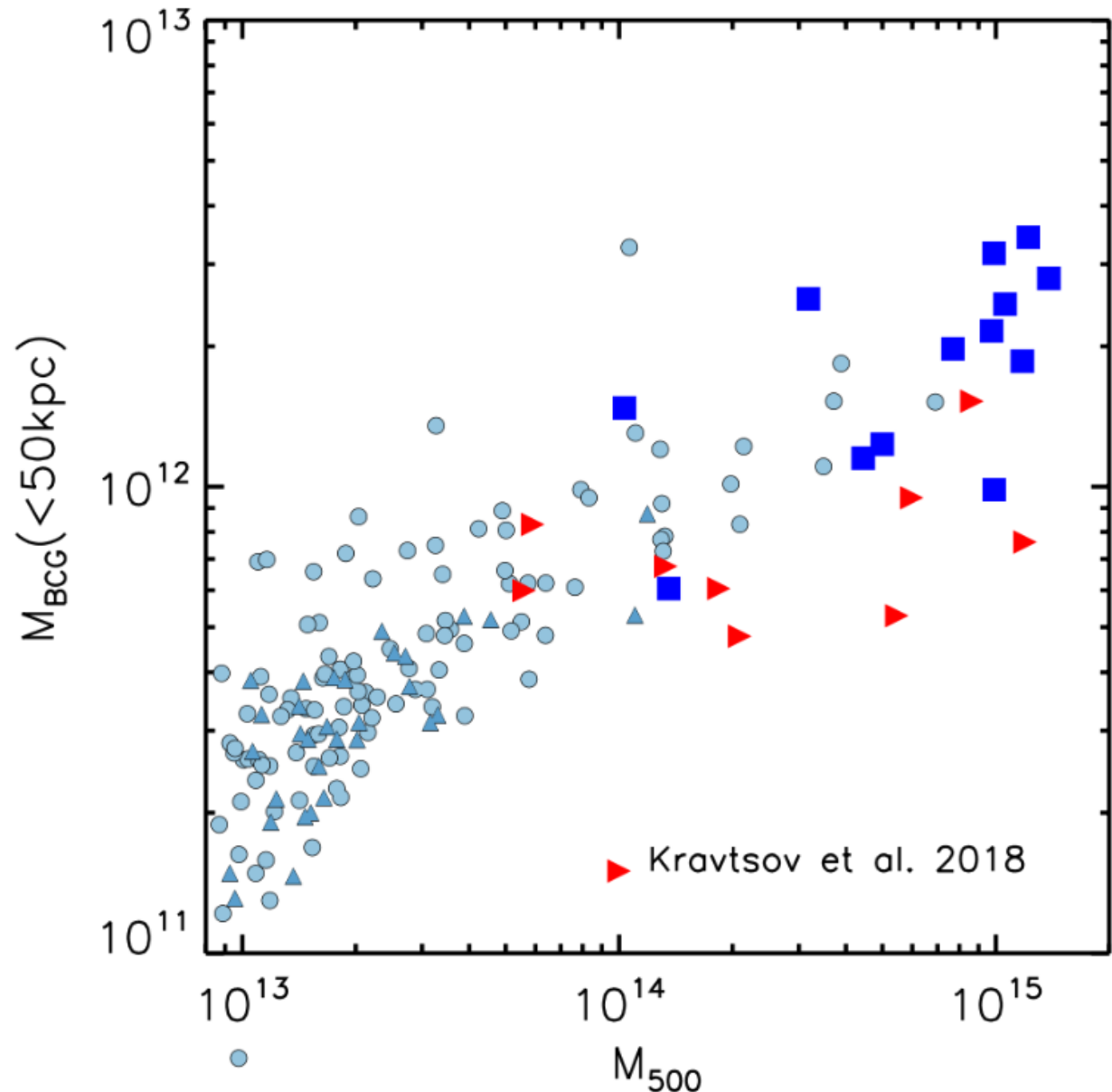
Lim+2024

- Use FLAMINGO simulations (Schaye et al. 2023) to trace SFR in protoclusters
- Compare the **total SFR within FoF halos** to observational data
- Results in better agreement with observational data

But:

- Still low SFR at $z > 4$?
- 2dex higher SFR than TNG at $z = 0$
- What about SFR in nearby BCGs?

PART 2:
Connecting to the Properties
of the low- z BCGs and ICM



⑨ $M_{* \text{BCG}} - M_{500}$ close to observations at low resolution (Ragone-Figueroa+2018)

⑨ At higher resolution different simulations all consistently predict too massive BCGs, especially in massive clusters:

Bassini+2021 – Dianoga (Gadget-3)

Bahè+2017 – Hydrangea/C-EAGLE (Gadget-3)

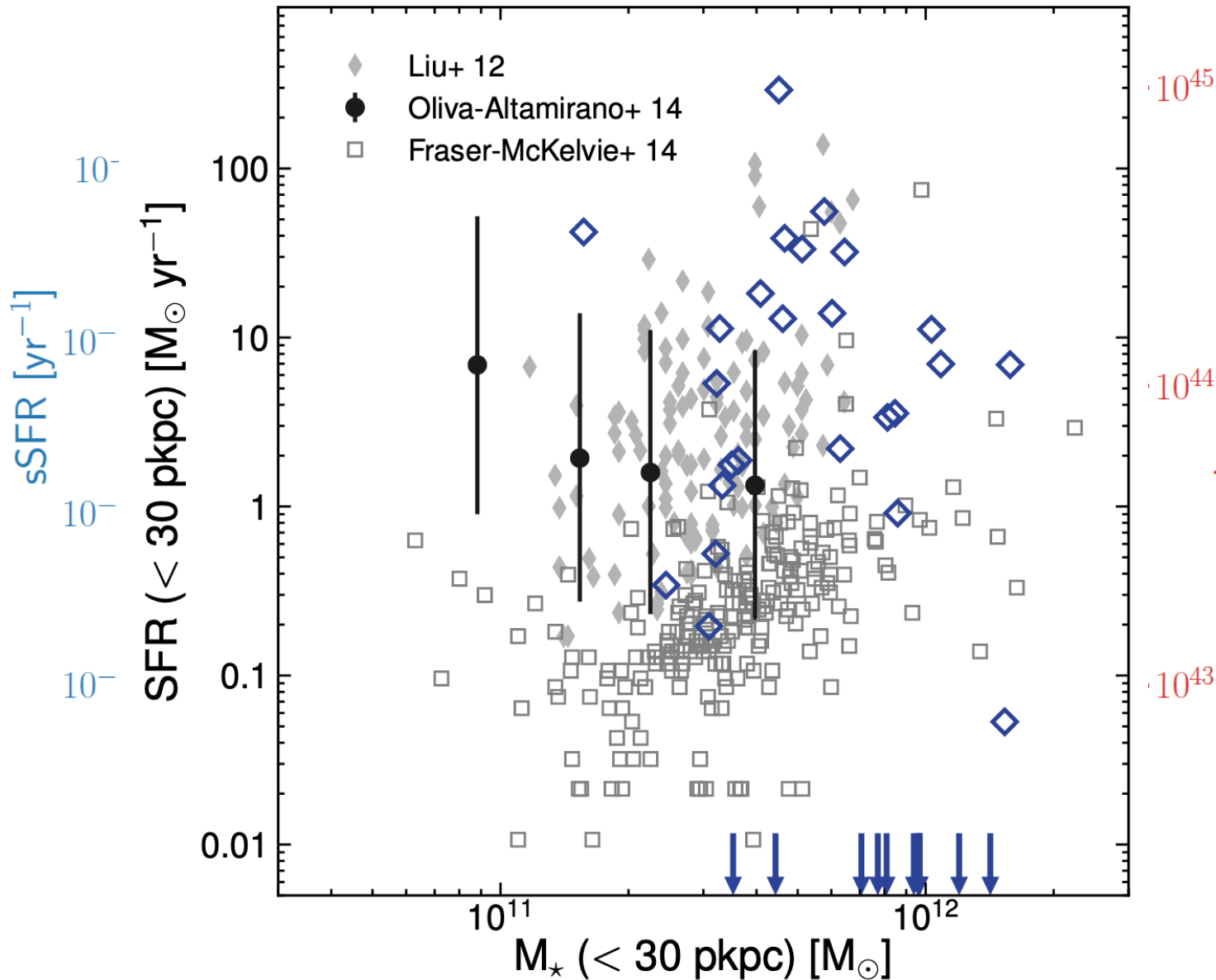
Tremmel+2019 – RomulusC (ChaNGa)

Nelson+2024 – TNG-Cluster (AREPO)

Henden+2020 – FABLE (AREPO)

⑨ Same result for Dianoga when further increasing mass resolution (by a factor 2.5; SB+2024)

Star formation rates in BCGs



⑨ Dianoga (Bassini+2021): SFR (and sSFR) in BCGs too large by ~ 1 dex

⑨ RomulusC (Tremmel+2019):

- simulation of a relatively poor cluster with $M_{200} \sim 10^{14} h^{-1} M_{\square}$
- some sSFR excess below $z \sim 1.5$ ($t_{\text{Age}} \sim 4$ Gyr), despite quenching

⑨ FABLE (Henden+2020):

- Still tendency for too large SFR at $z \sim 0.2$

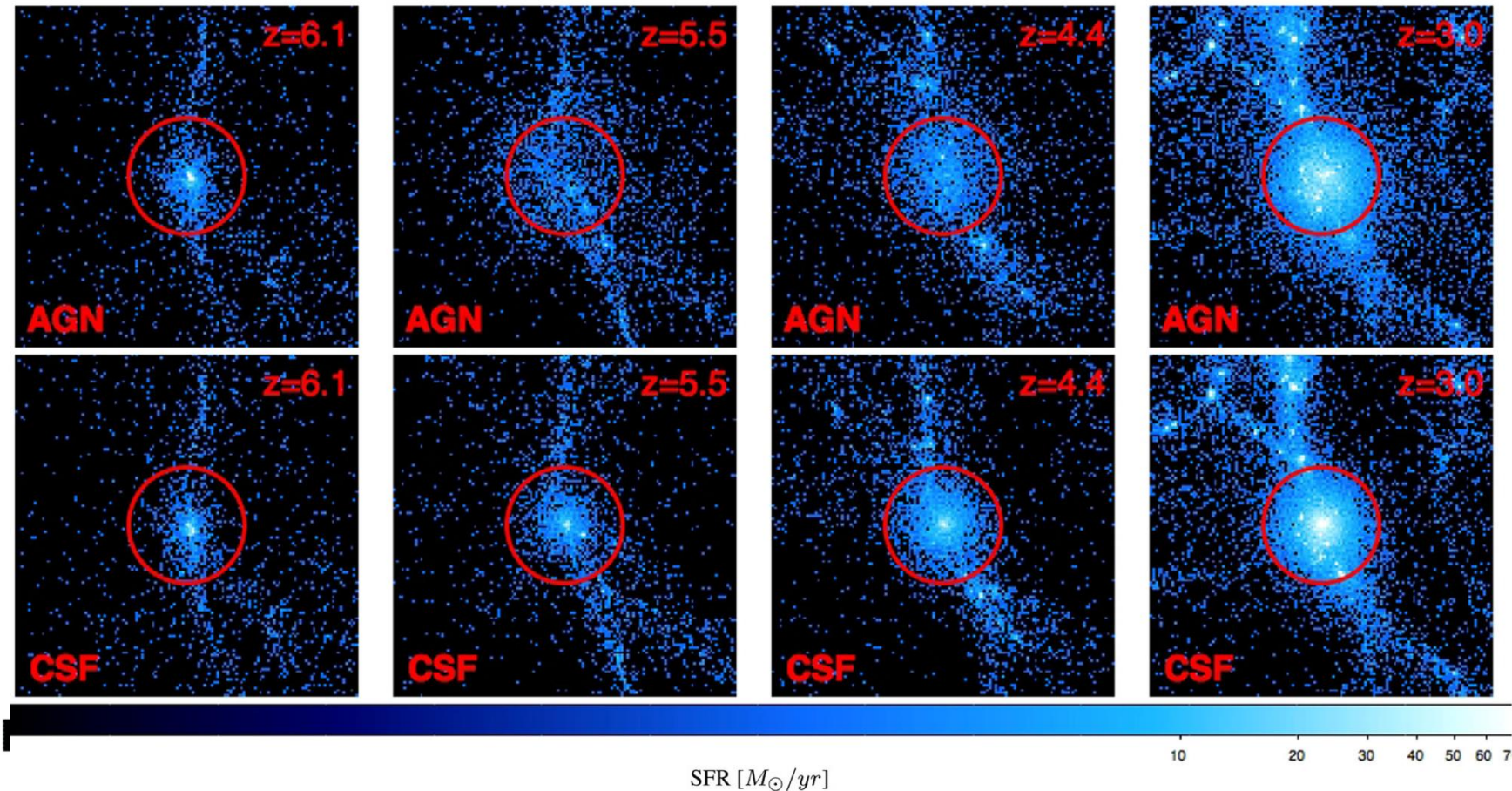
Biffi et al. 2017

AGN feedback causes:

→ More widespread IGM enrichment at high redshift

→ Suppression of star formation

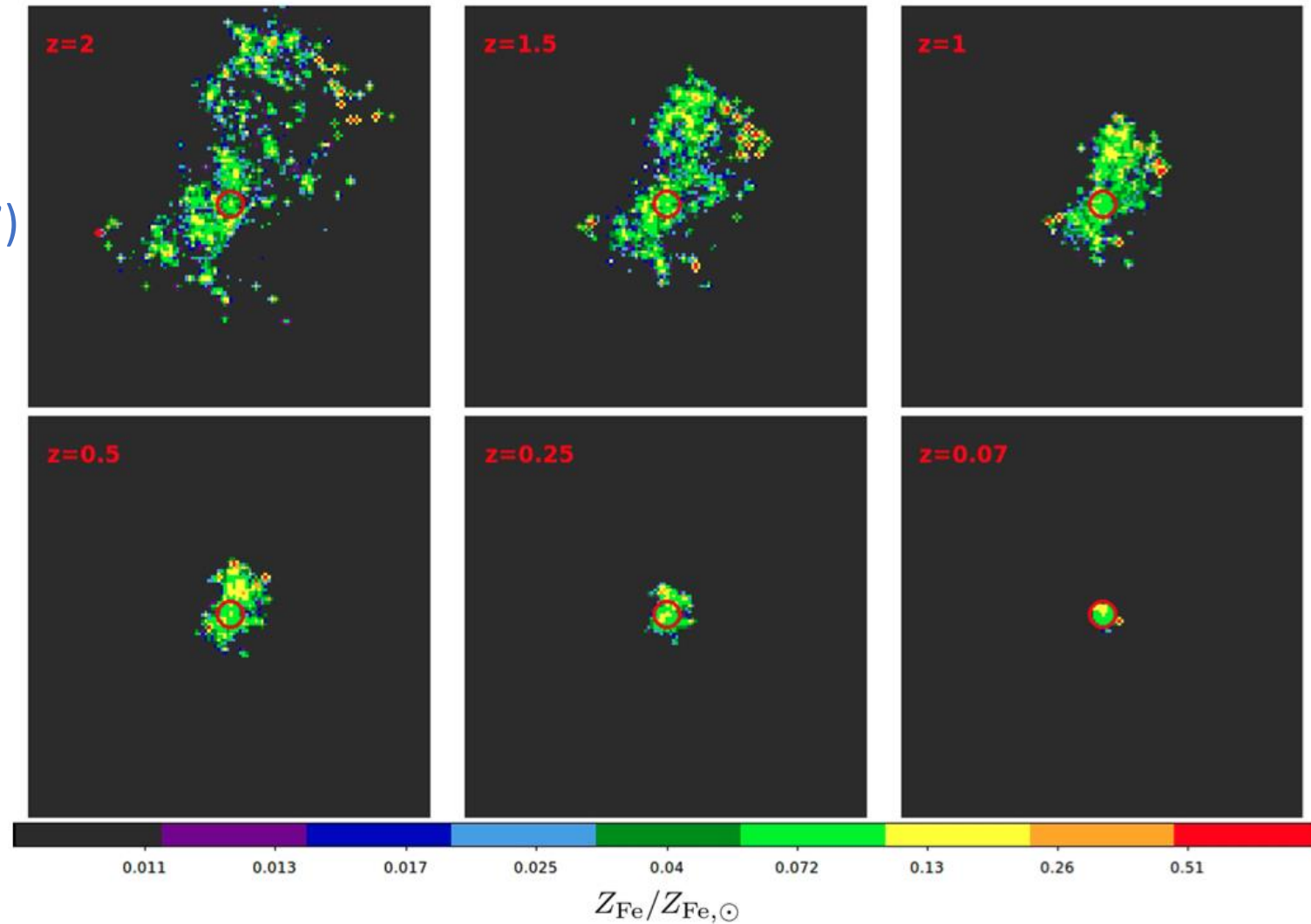
→ Many fewer metals locked back in later star formation



Low-z ICM metallicity as a fossil record of feedback history

Biffi et al. 2018 (see also *Fabjan+2010*, *McCarthy+2015*)

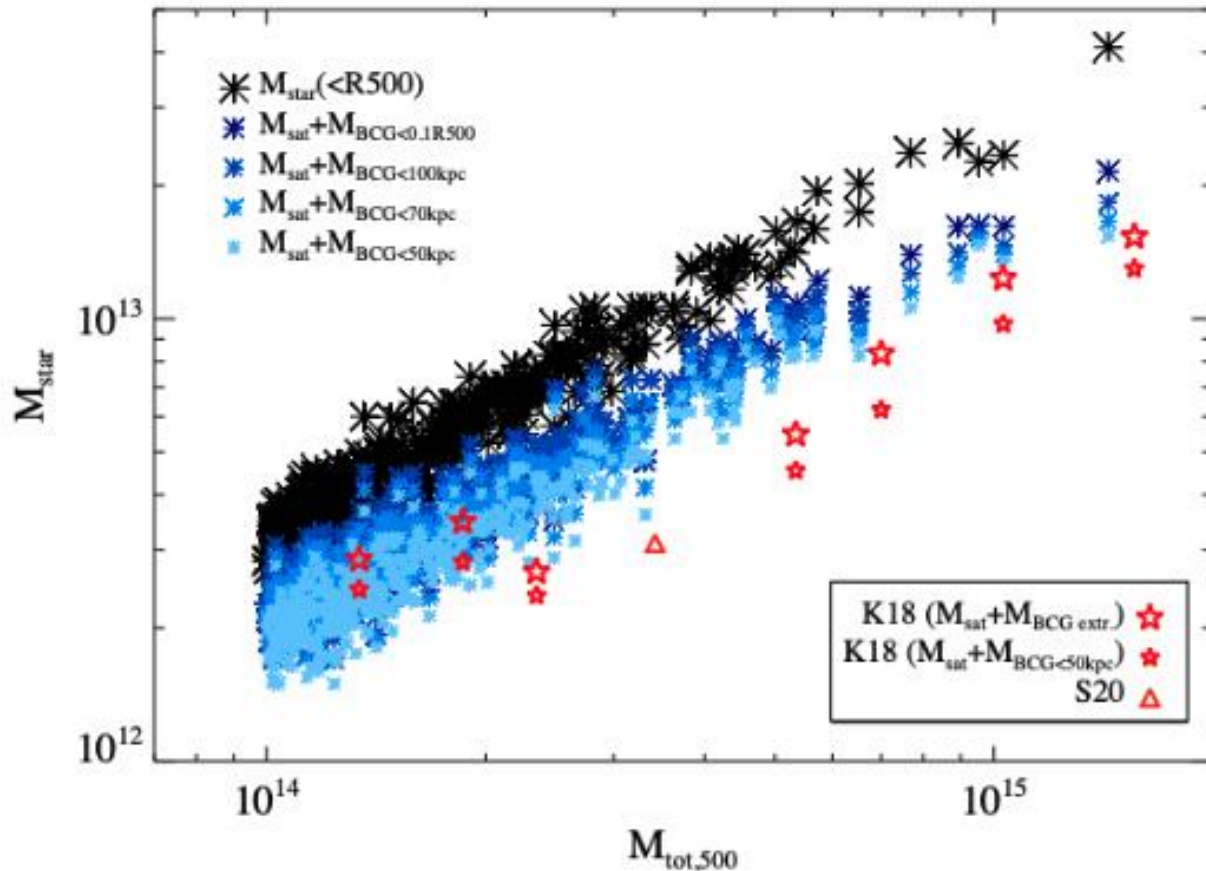
- Prediction on metallicity of ICM outskirts with AGN feedback in line with Suzaku observations ([Urban+2017](#))
- Track to $z=2$ the ICM residing in cluster outskirts ($0.8 < R/R_{\text{vir}} < 1.2$)
- Originated from diffuse and pre-enriched IGM/CGM
- Results from the action of AGN feedback



Metal share in galaxy clusters

$$\mathfrak{J}_{500} \equiv \frac{M_{\text{Fe},500}}{Z_{\odot} M_{\text{star},500}}$$

Ratio between Fe diffused in the ICM and locked into stars (assumed to have solar metallicity)



Ghizzardi+2021: ICM metallicity from X-COP clusters (XMM-Newton) for which stellar metallicities are also available

- Fe-share for few clusters
- Large fraction of overall Fe budget in the diffuse gas

Biffi+2025: comparison with **Dianoga** and **Magneticum** simulations

- Much lower Fe share: larger amount of Fe locked in stars
- Apparently, not an issue with the ICM Fe content: good agreement with observed $M_{\text{Fe,gas}} - M_{\text{gas},500}$ relation
- Due to excess of star formation in simulations?
- Quite possible, but then correct ICM Fe content just a coincidence...
- and no problem at the scale of poor clusters....
- Which definition of stellar mass? Within which radius? Including ICL? Down to which surface brightness?

→ Important implications on feedback mechanism responsible for both circulation of metal-enriched gas and quenching of star formation in (proto-)cluster BCGs/massive cluster galaxies!!

PART 3:
AGN Feedback and
Treatment of the BH Orbits

Tracking BH orbits in cosmological simulations



Damiano+2024, 2025

Problem: How to correctly integrate orbits of BH particles in a regime where dynamical friction can be mis-represented by the N-body solver, due to the limited mass and force resolution?

Chandrasekhar (1943)

- Homogenous and isotropic distribution of particles with Maxwellian velocity distribution function
- Mass of the “sea” particles much smaller than the mass of the BH particle

$$F_{\text{DF}} = -4\pi\rho \left(\frac{GM_{\text{BH}}}{v_{\text{BH}}} \right)^2 F(x) \ln(\Lambda) \widehat{v}_{\text{BH}} \quad \Lambda = \frac{b_{\text{max}}}{b_{\text{min}}} \quad F(x) = \text{erf}(x) - \frac{2x}{\sqrt{\pi}} e^{-x^2} \quad ; \quad x = \frac{v_{\text{BH}}}{\sigma_v}$$

Hirschmann et al. (2014):

1. $b_{\text{max}} = R_{\text{HMS}}$
2. Maxwellian distribution of surrounding particles velocities
3. Negligible mass of surrounding particles

Tremmel et al. (2015):

1. $b_{\text{max}} = \textit{softening}$

Correcting for the unresolved dynamical friction



Damiano+2024, 2025

→ Correct for the unresolved DF by accounting for the individual contributions of neighboring particles (i.e. within softening) to the force acting on the BH.

Binney & Tremaine say:

$$\mathbf{a}_{\text{DF}}(\mathbf{r}) = -8\pi^2 \log(1 + \Lambda^2) G^2 m_p (m_{\text{BH}} + m_p) \frac{\int_0^{v_{\text{BH}}} v^2 f(v) dv}{v_{\text{BH}}^2} \hat{\mathbf{v}}_{\text{BH}}$$

$$\Lambda(m, \mathbf{v}) = \frac{b_{\text{max}}(\mathbf{v} - \mathbf{v}_M)^2}{G(M + m)} \quad b_{\text{max}} = \epsilon_{\text{BH}}$$

→ Assuming that the phase-space density below within ϵ_{BH} is approximated as a sum of the discrete contributions from neighbour particles

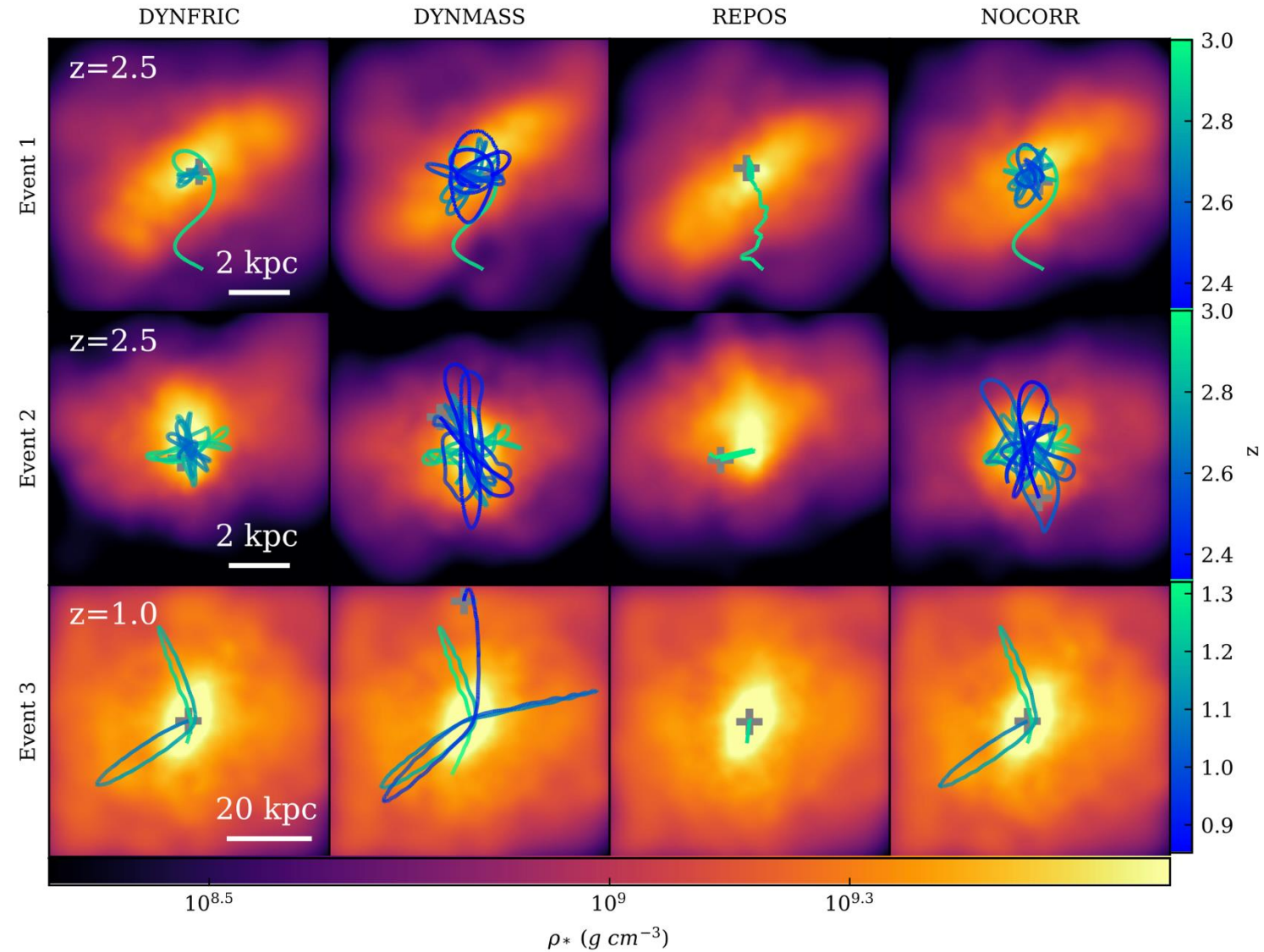
$$\rightarrow \mathbf{a}_{\text{DF}} = \sum_j^{N(<b_{\text{max},c})} -2\pi G m_j (M_{\text{BH}} + m_j) W(\mathbf{r}_j, \epsilon) \times \ln(1 + \Lambda(m_j)^2) \frac{v_{m_j} - v_{\text{BH}}}{|v_{m_j} - v_{\text{BH}}|^3}$$

Improving the description of BH dynamics

Alternative ad-hoc prescription:

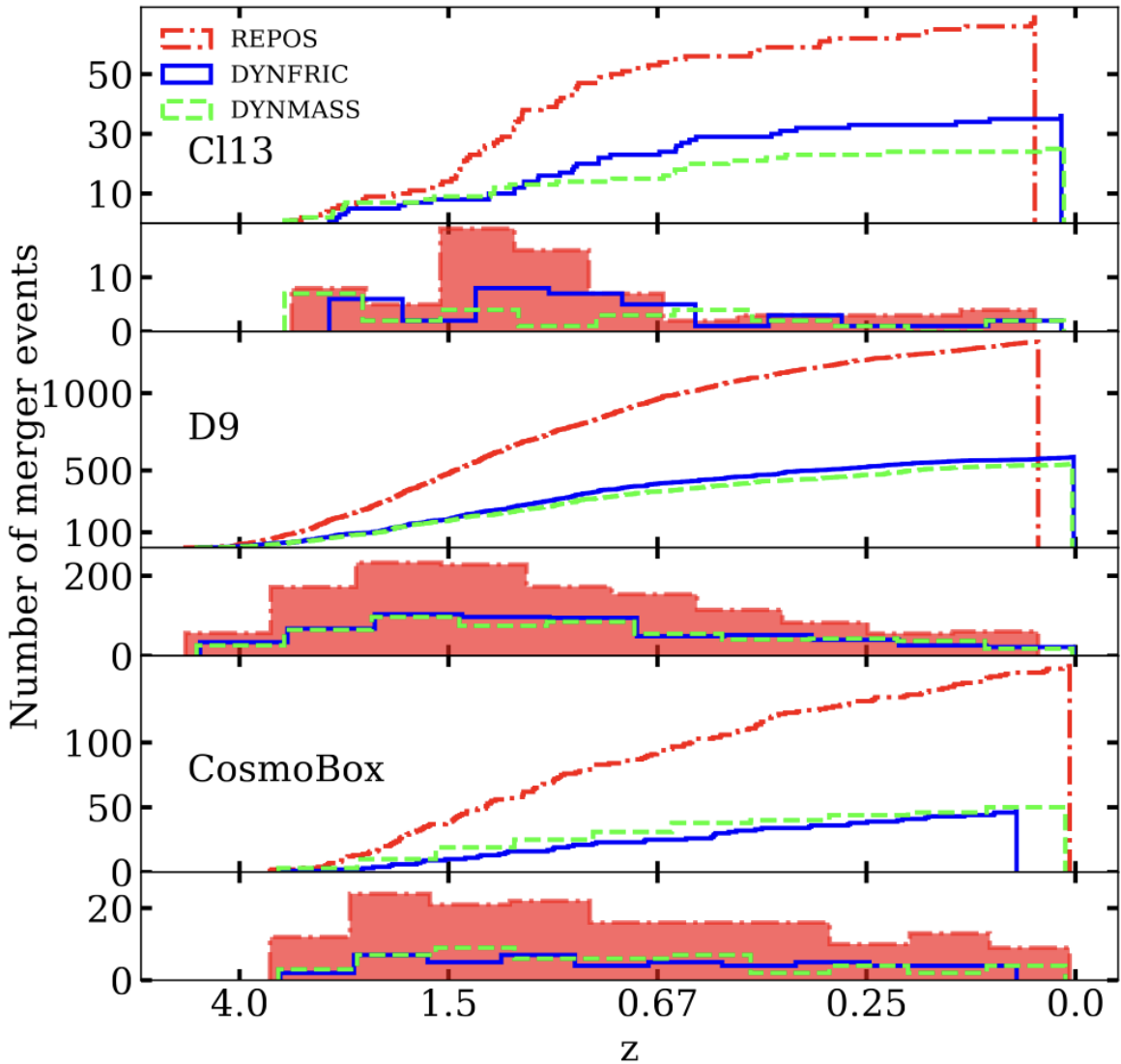
Large dynamical mass: enhance by hand the BH dynamical mass at seeding to amplify the resolved DF
→ *Significant change in the local potential*

Continuous repositioning: at every time-step pin the BH on the local minimum of the potential
→ *Merging time-scales completely wrong*



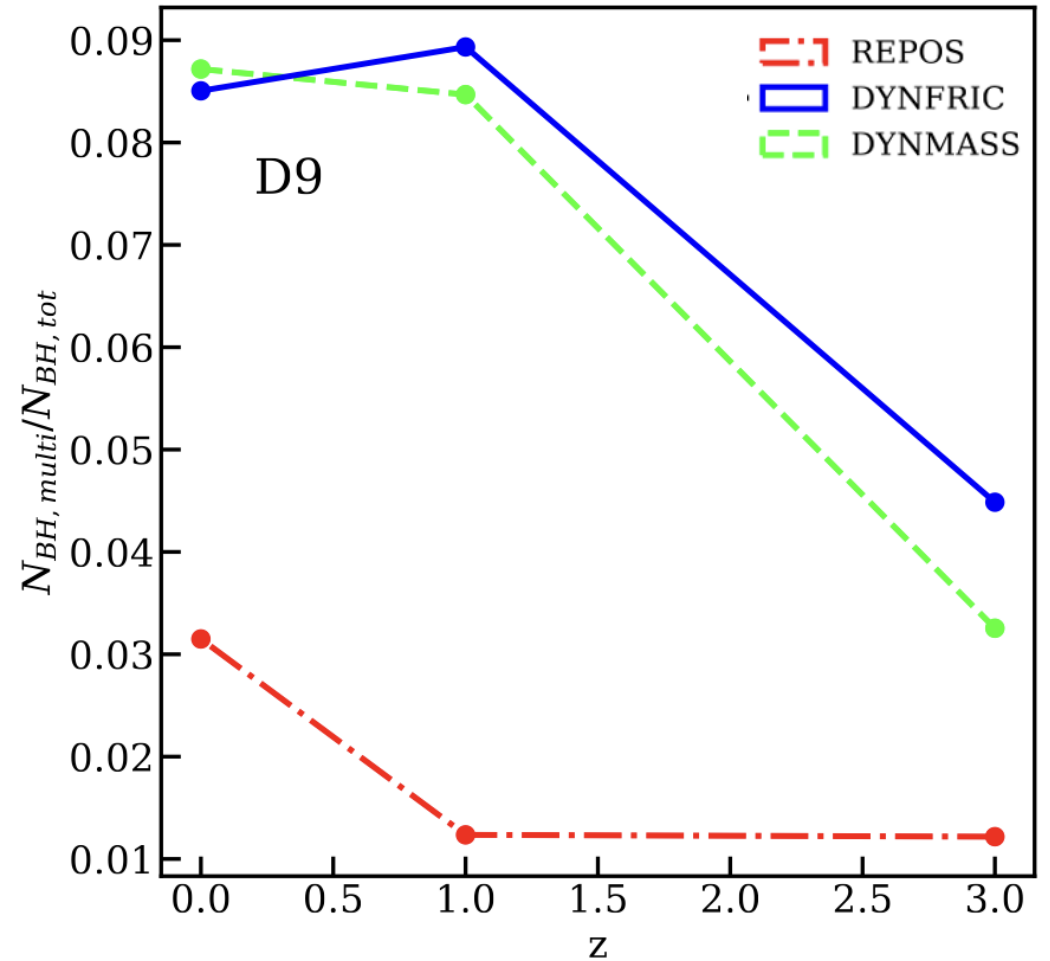
Improving the description of BH dynamics

Effect on the number of BH-BH mergers



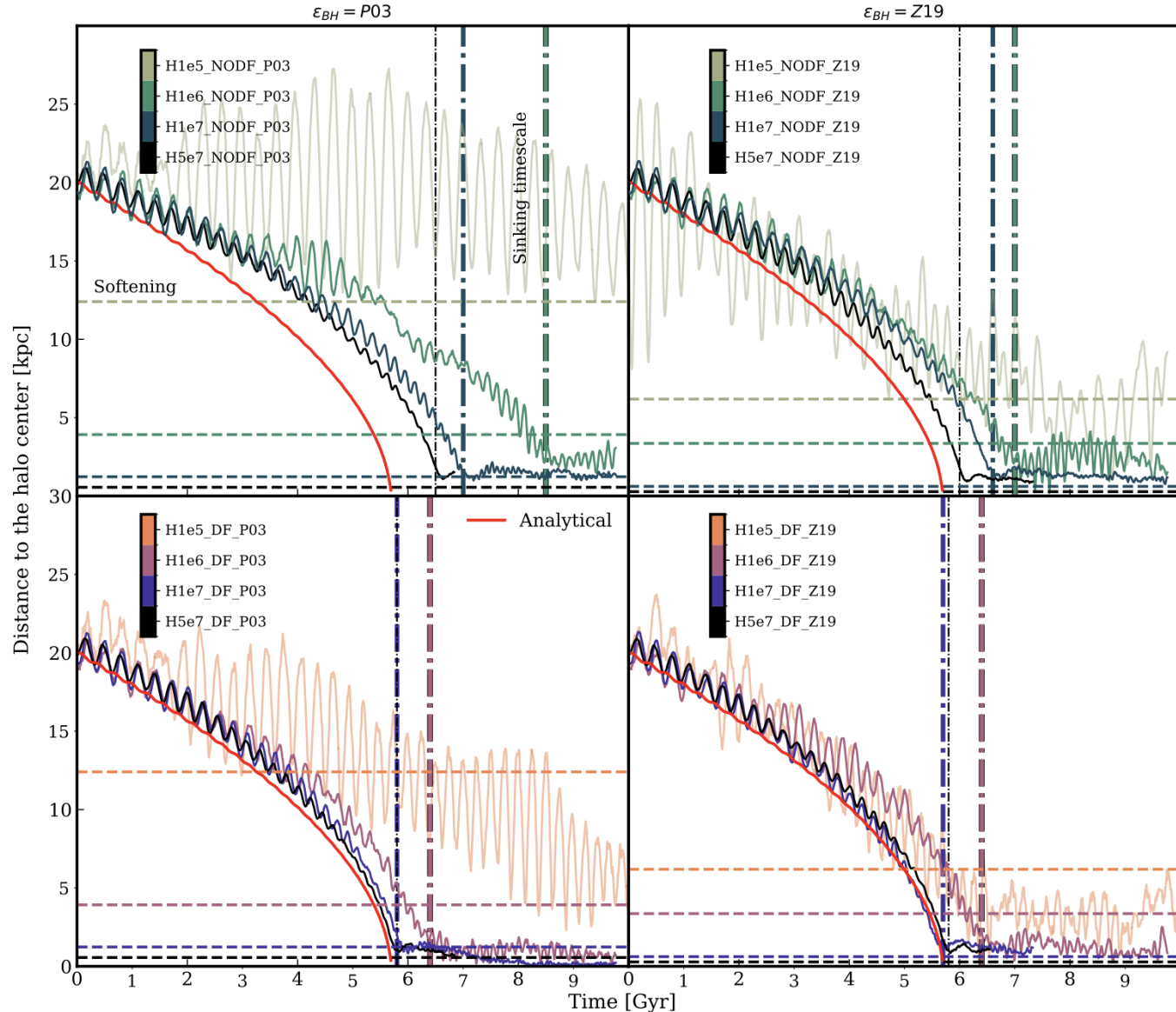
Damiano+2024

Effect on the fraction of halos hosting more than one BH



Improving the description of BH dynamics

Damiano+2025



→ Controlled simulations in an isolated NTW halo at varying resolution and softenings

$$h_P = \frac{4R_{vir}}{\sqrt{N_{vir}}} \quad \text{Power+2003}$$

$$h_Z = \frac{2R_{vir}}{\sqrt{N_{vir}}} \quad \text{Zhang+2019}$$

→ Increasing resolution makes simulation predictions on sinking time-scales approaching analytical predictions

→ Faster convergence (and shorter time-scales) predicted when DF correction is introduced

Conclusions



- General properties of proto-clusters correctly predicted by simulations since a long time:
 - Presence of hot (X-ray) and pressurized (SZ) proto-ICM in one proto-cluster (Spiderweb)
 - Intense star formation in assembling proto-BCGs, along with formation of an ICL component
 - Connection between high- z proto-cluster phase and low- z fossil records (*i.e. slope of ICM metallicity profiles*)

BUT:

- High level of SFR in proto-clusters is not trivial to produce in simulations
- Need to quench SF in BCGs and reduce their stellar masses at low redshift
- Iron share in low- z clusters: a problem with the *circulation of metals* in simulations, *excess of formed stars* or something to do with the *census of stellar mass in observations*?

Directions to improve simulations:

- Deeply revise the SF model to produce bursty SF at $z = 2 - 4$;
- Revise the AGN feedback model to rapidly quench SF;
- Relevance of description of unresolved DF → *Implications for SMBH-SMBH merger rates*