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ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

From high-z protoclusters to local BCGs: Challenges for simulations

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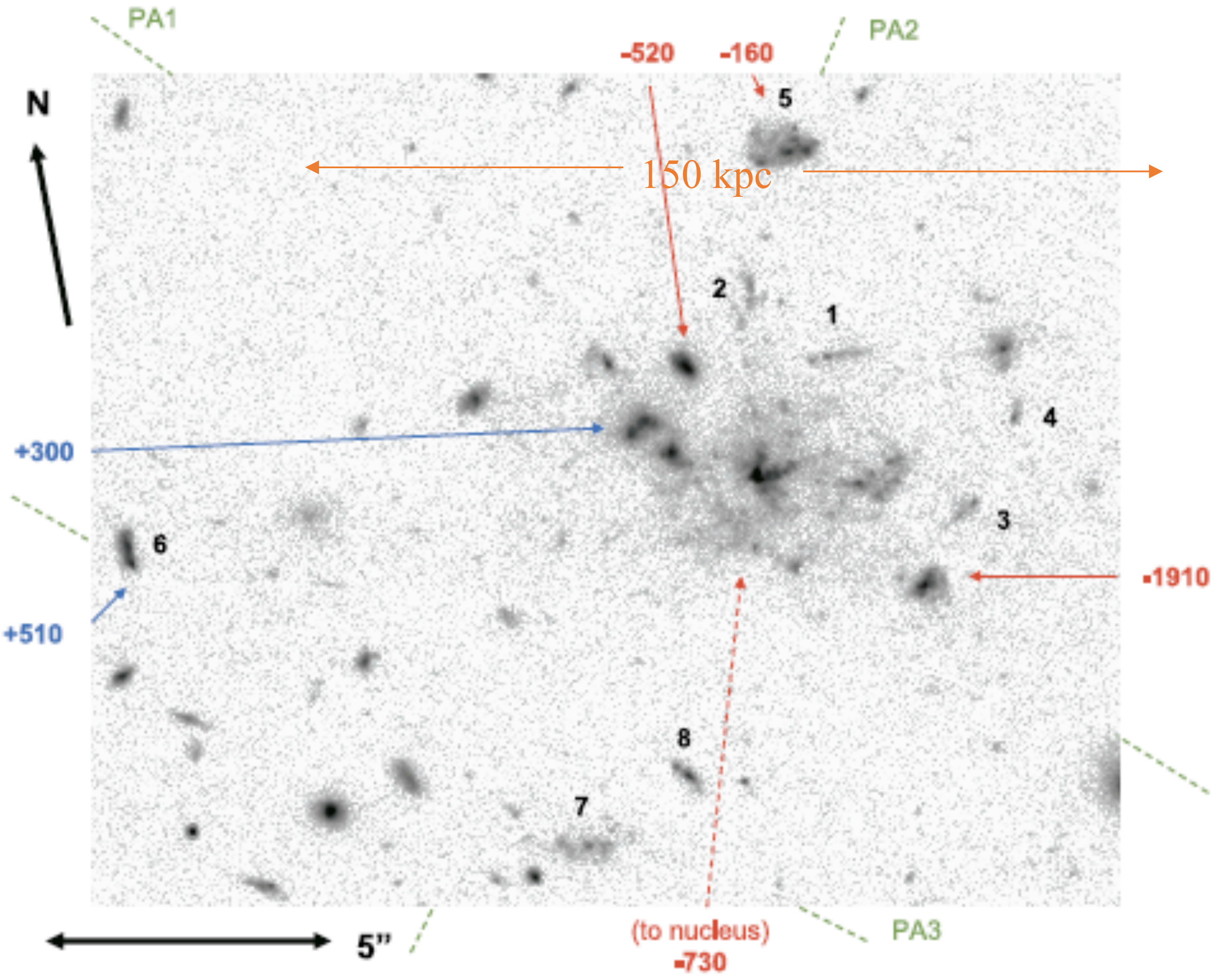
I. Simulating protoclusters: environment of the early BCG assembly
 - I.a Properties of the proto-ICM and their low-z fossil record
 - I.b Star formation rates in protoclusters

II. Connecting to the properties of the low-z BCGs
 - II.a Stellar masses and SFR of BCGs
 - II.b Metal share in ICM and stars

PART 1:
Simulating Protoclusters

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



HST-ACS image of MRC 1138-262

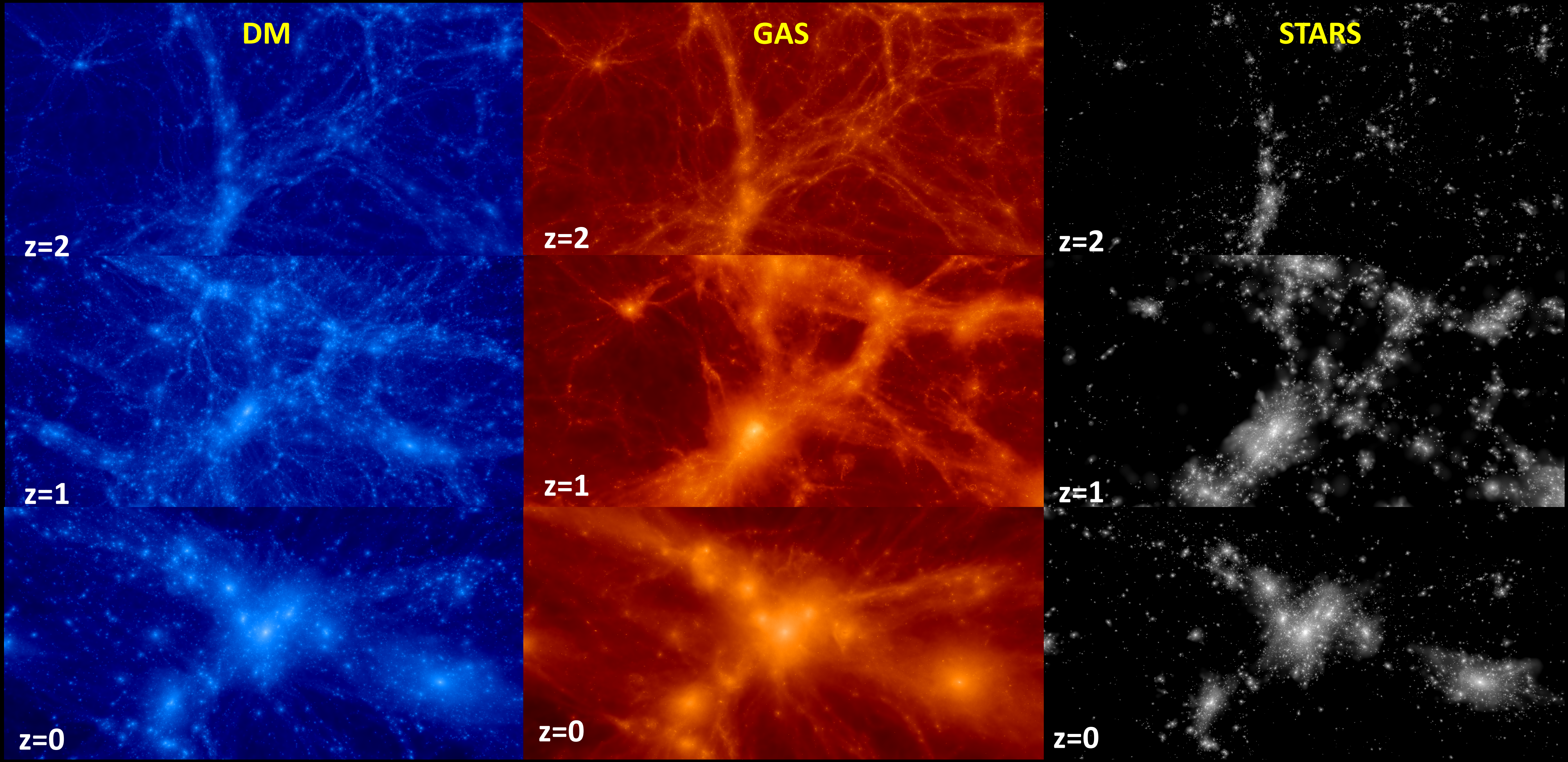
The “Spiderweb” galaxy (Miley+06)

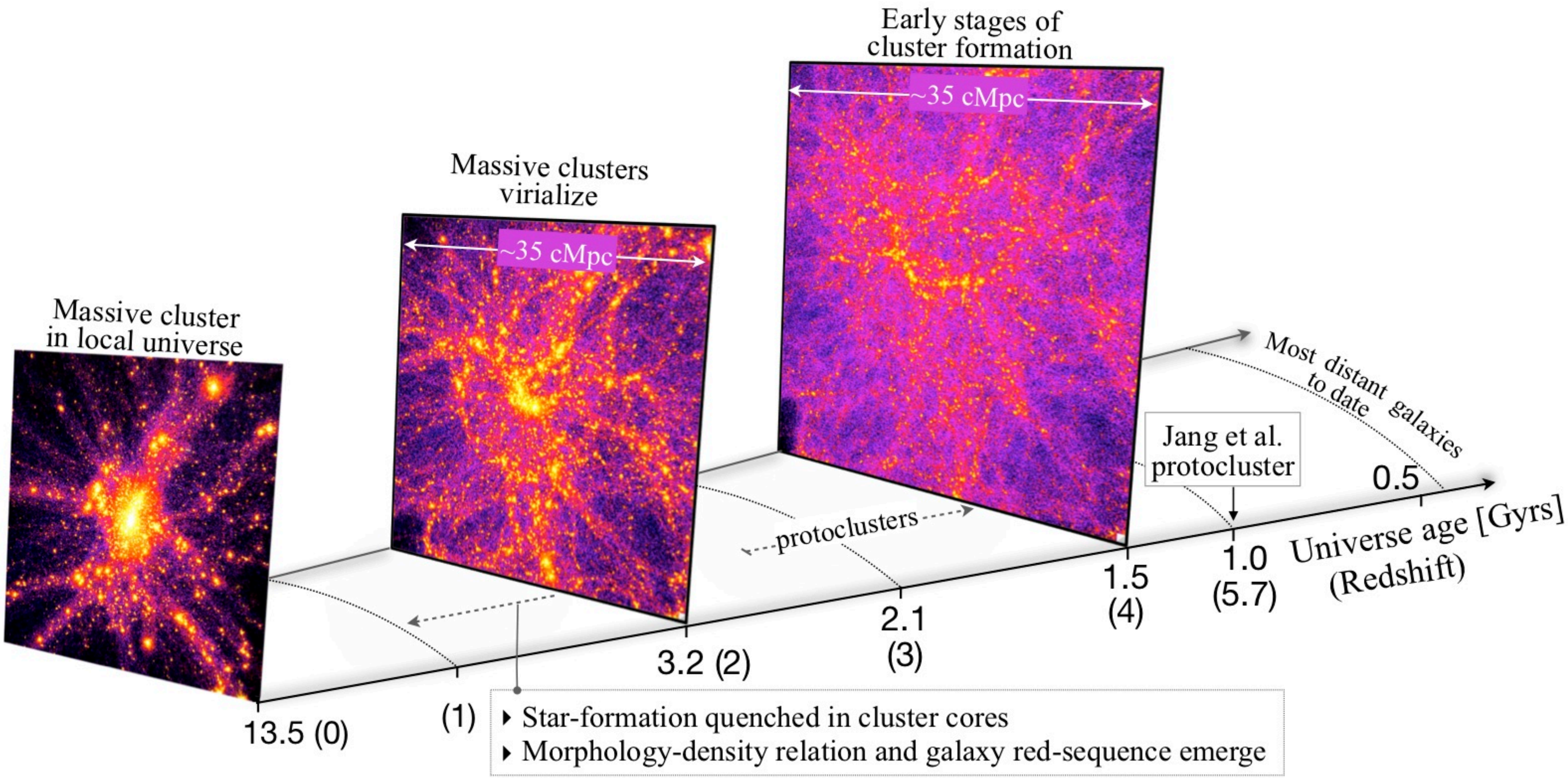
➔ Complex dynamics of galaxies merging into the FR-II radio galaxy

➔ “Flies” moving with v_{los} of up to $\sim 10^3$ km s^{-1}

➔ How typical is all this in the Λ CDM structure formation paradigm?

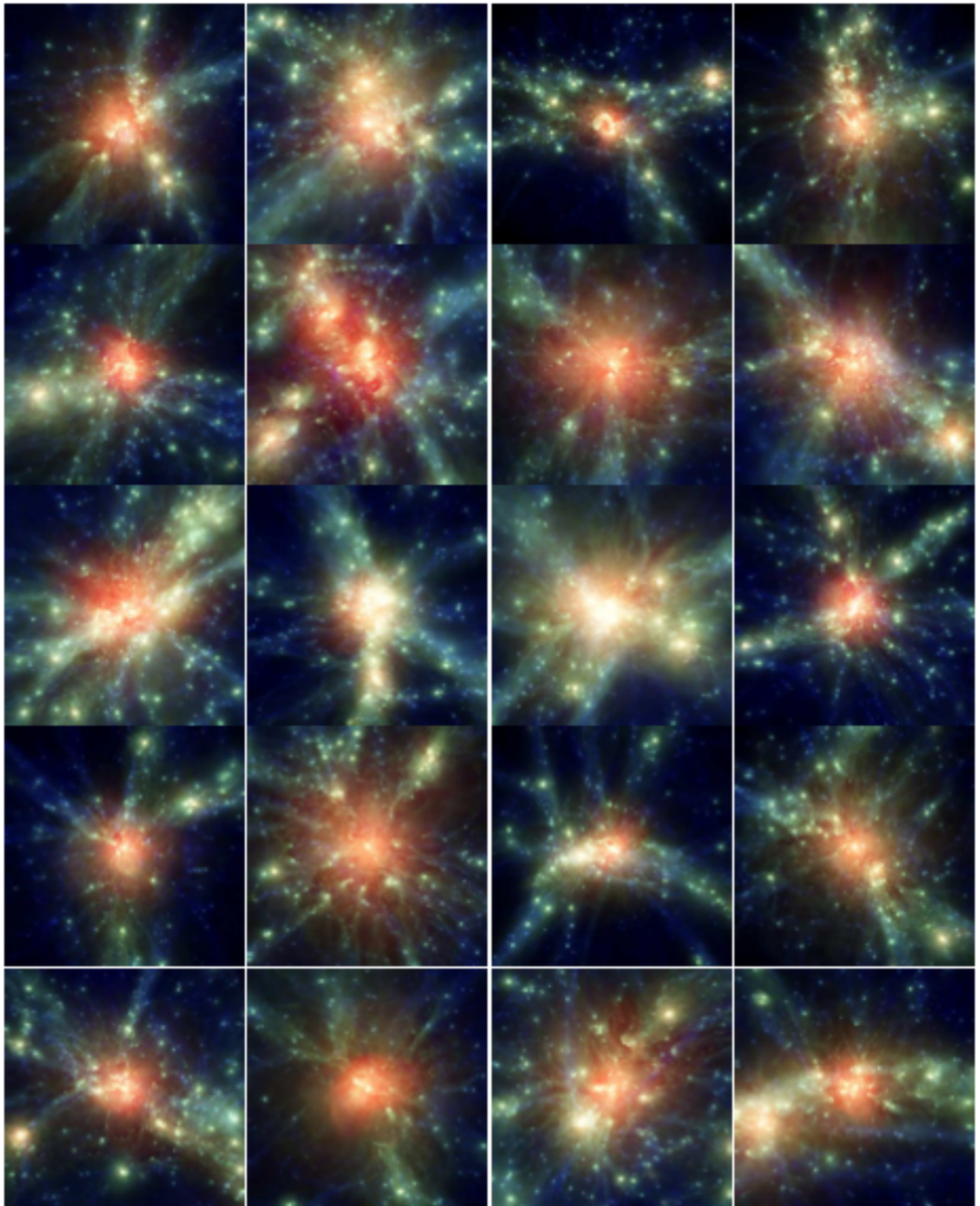
Dianoga Simulations





Courtesy of P. Rosati

The Dianoga Set with OpenGADGET3



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

$m_* = 2.6\ 10^6\ h^{-1}\ M_\odot$; $\varepsilon_* = 250$ 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

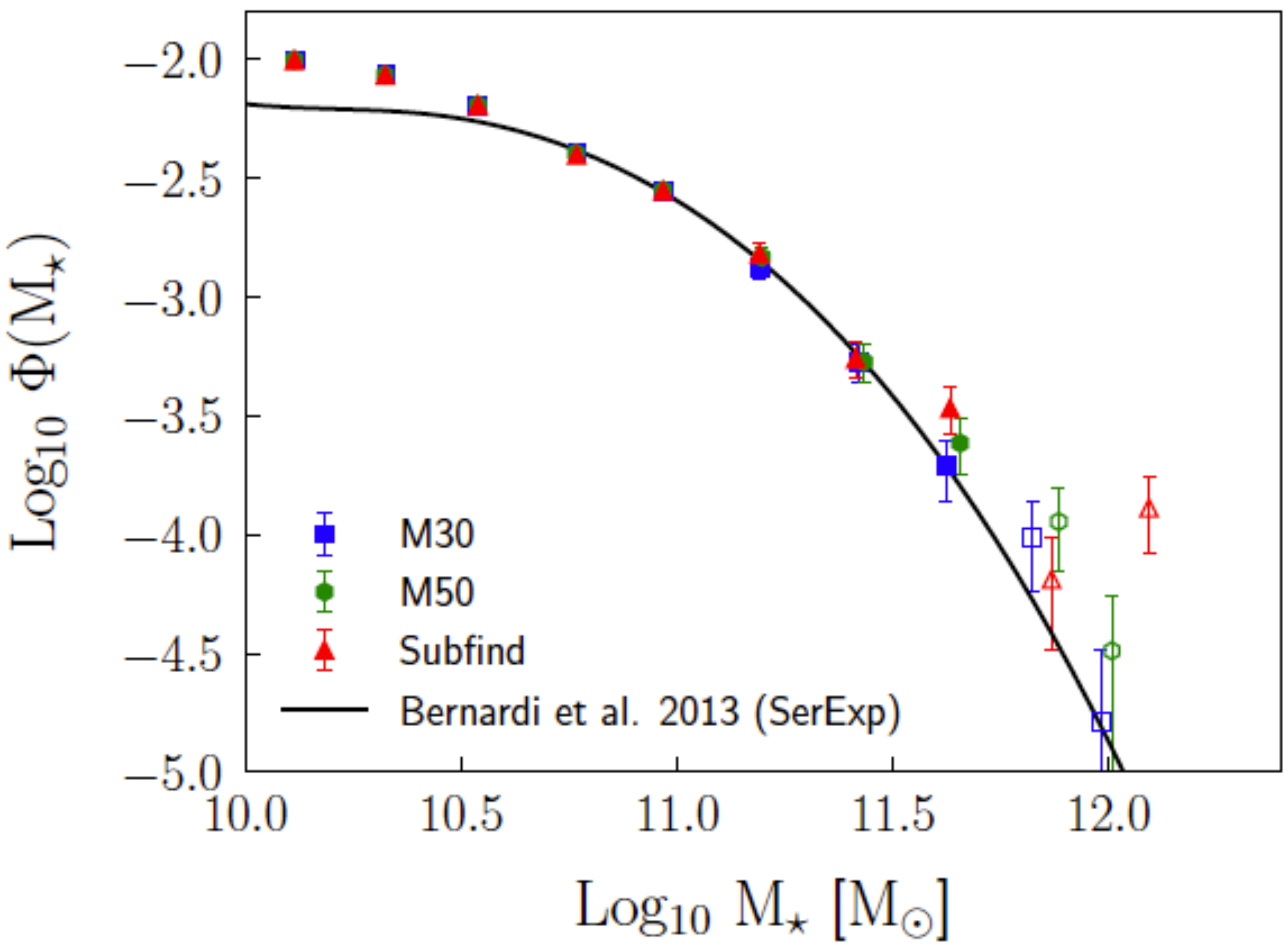
➔ **Hydro-2**: MFM (Groth+23):

➔ Astrophysics:

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

Tuning a model of AGN feedback

(Bassini et al. 2021)

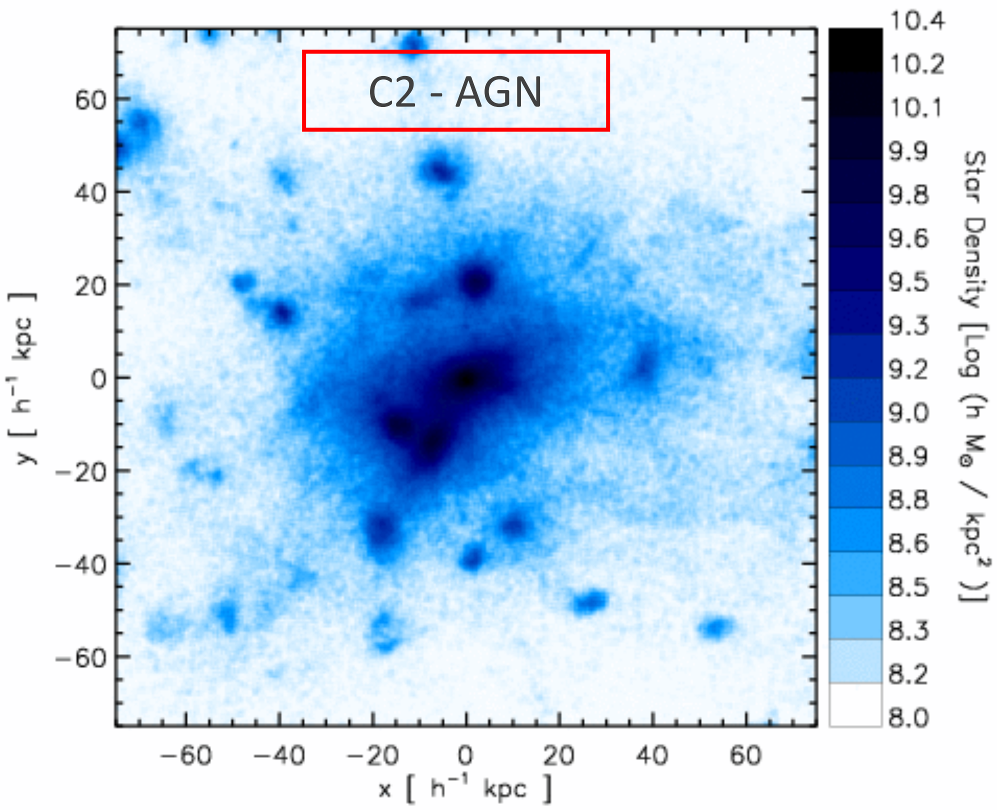


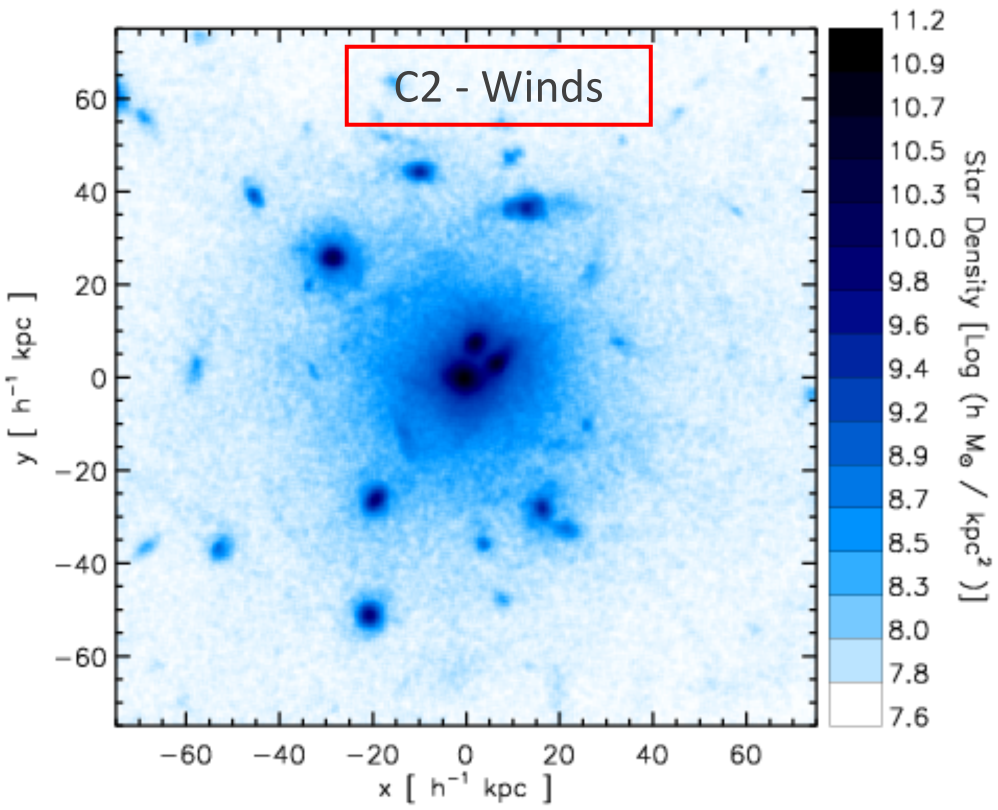
➔ Adjust the parameters of feedback to reproduce the observed scaling between SMBH masses and host stellar masses

➔ Predict the correct SMF of cluster galaxies

Simulating the formation of a proto-cluster at z~2

Saro, SB et al. 2009

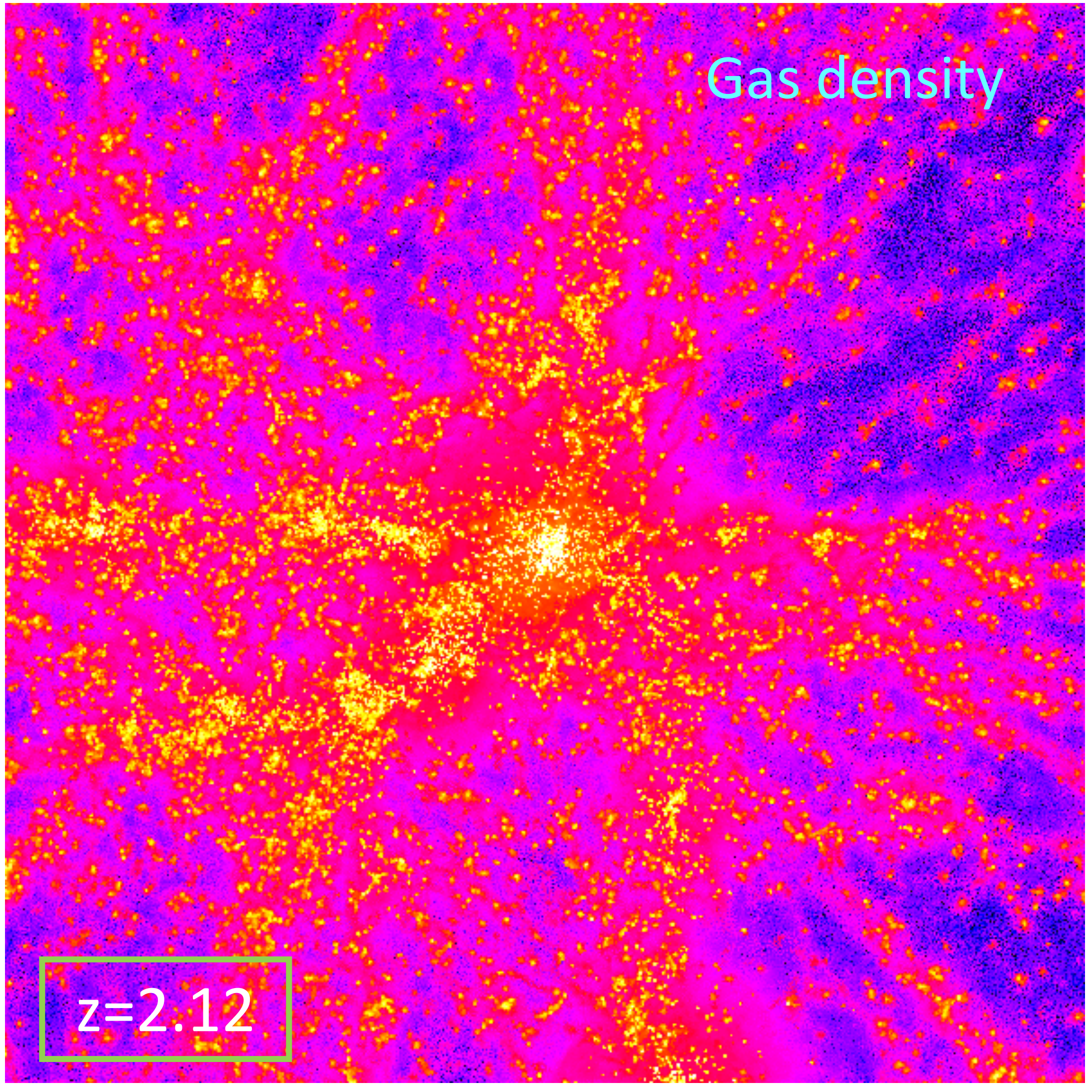




- SN-driven winds: SFR ~ 1750 $M_{\odot}\ yr^{-1}$
- + AGN feedback: SFR ~ 1300 $M_{\odot}\ yr^{-1}$
- Significant amount of diffuse ICL already in place at z=2.16

Simulating the formation of a proto-cluster at z~2

Saro, SB 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:

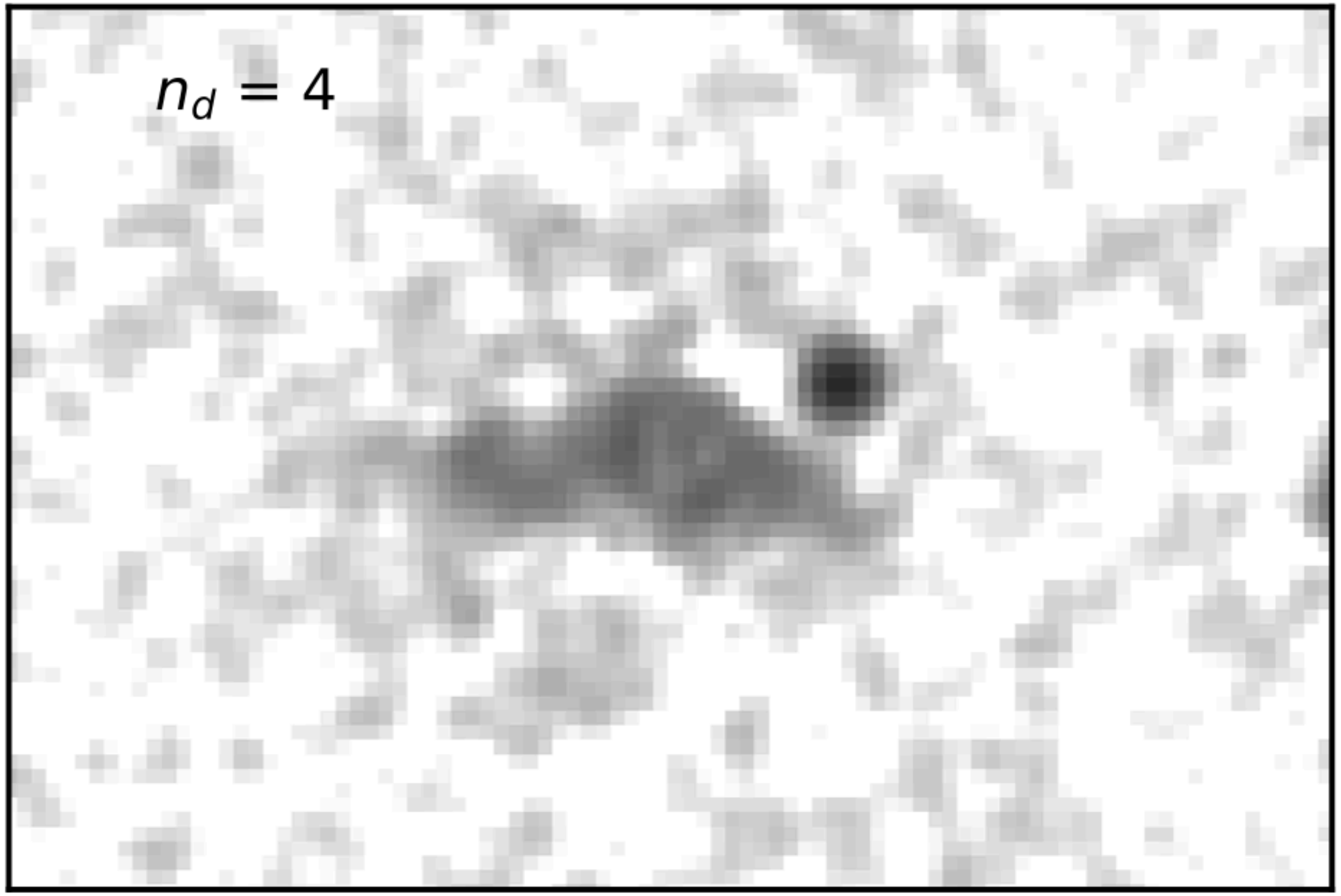
$$L_{0.5\text{-}2}= 1.4 \times 10^{44}\ \mathrm{erg\ s^{-1}}$$

$$T_X=3.8\ \mathrm{keV}$$

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

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)*



Predicted

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

T_X=3.8 keV

Z_{Fe}= 0.57 $Z_\odot$

Observed

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

T_X=$2.0^{+0.7}_{-0.4}$ keV

Z_{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)*

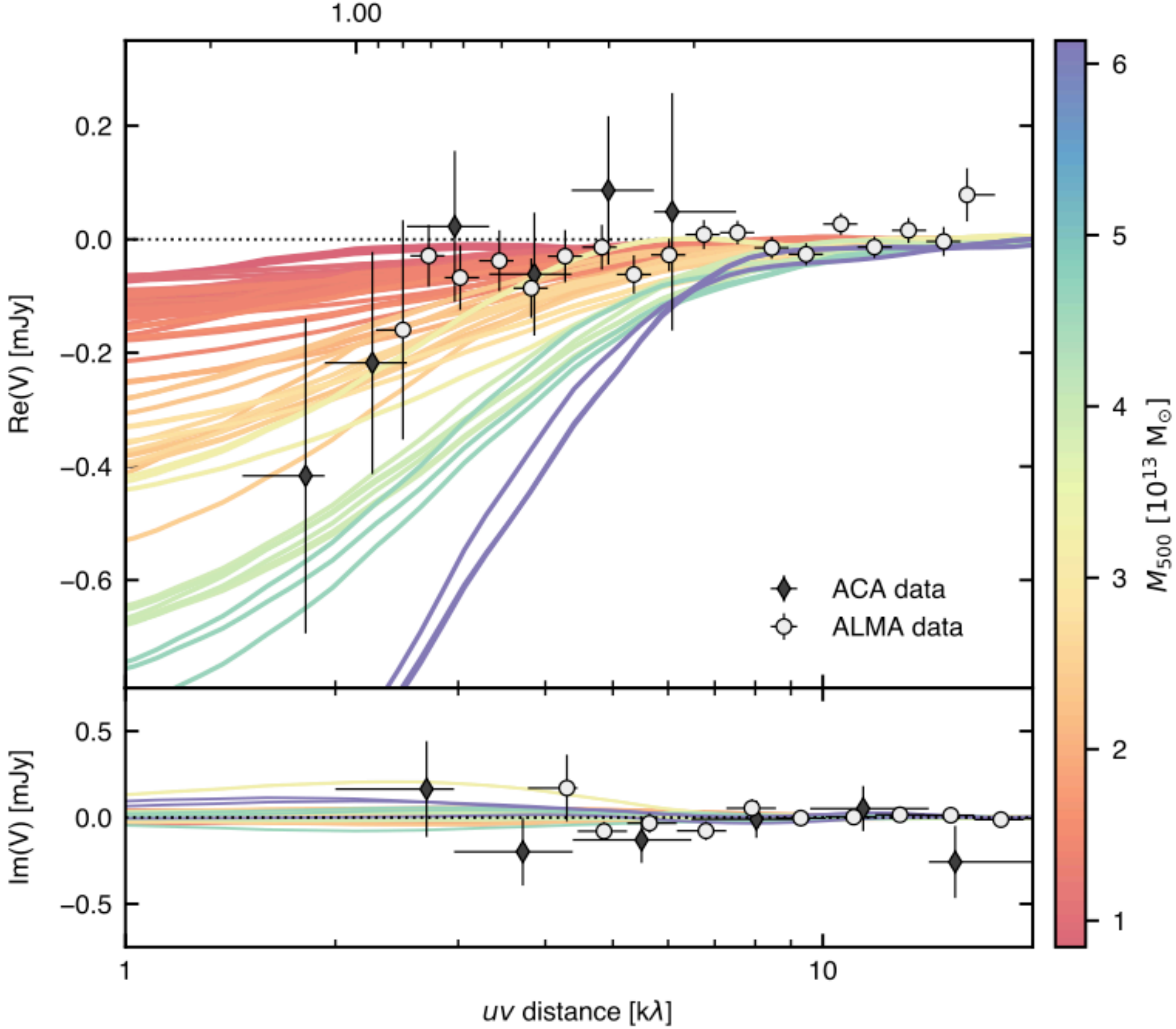
➜ ALMA+ACA observations secured the detection of the SZ signal from the proto-ICM (significance at $\simeq 6\sigma$)

➜ Robust evidence for a pressurized athmosphere 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 ~ $3 \times 10^{13}\ M_\odot$

Di Mascolo+2023



Effect of feedback on high-z SF & enrichment

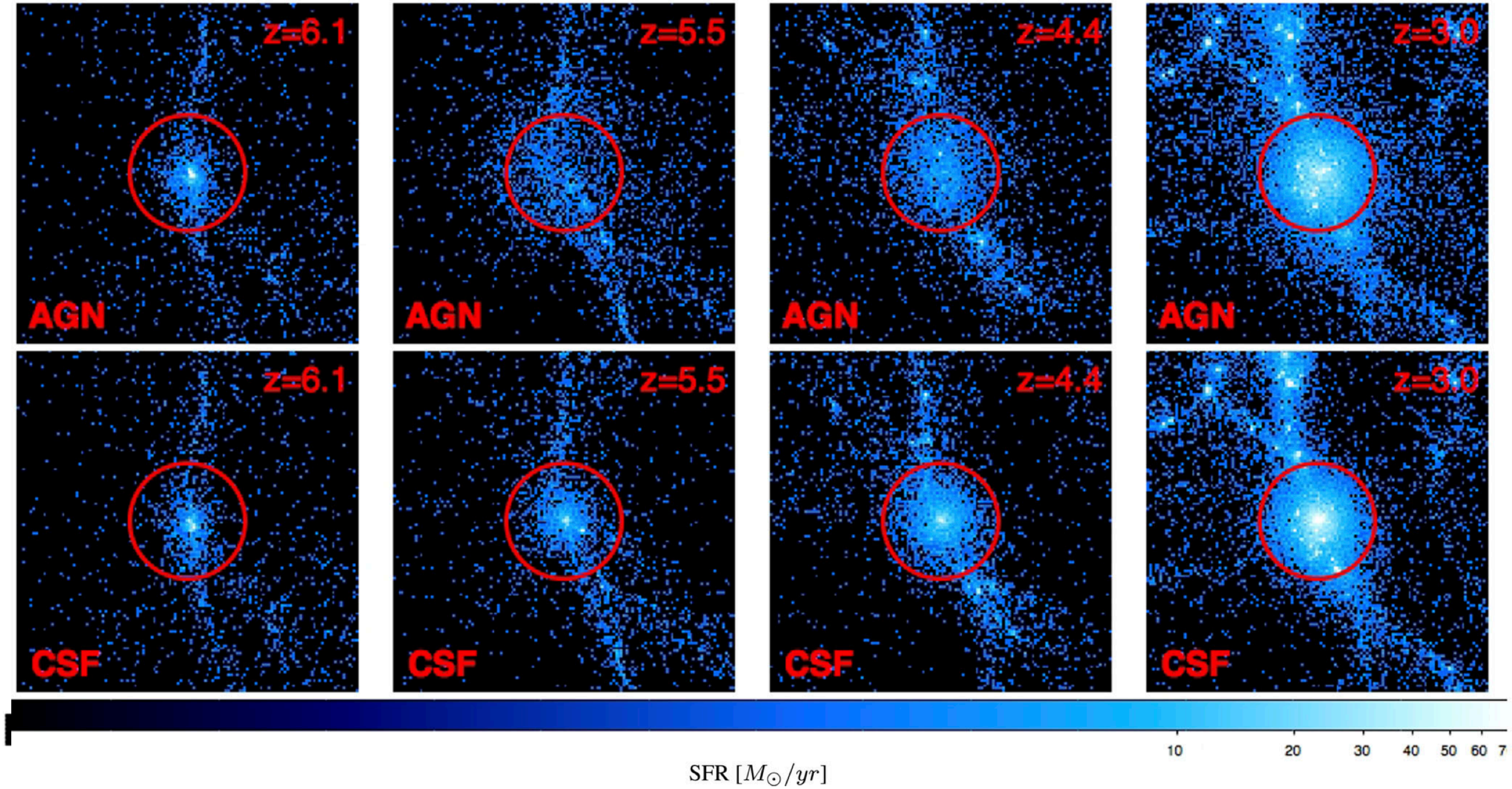
Biffi et al. 2017

AGN feedback causes:

➜ More widespread IGM enrichment at high redshift

➜ Suppression of star formation

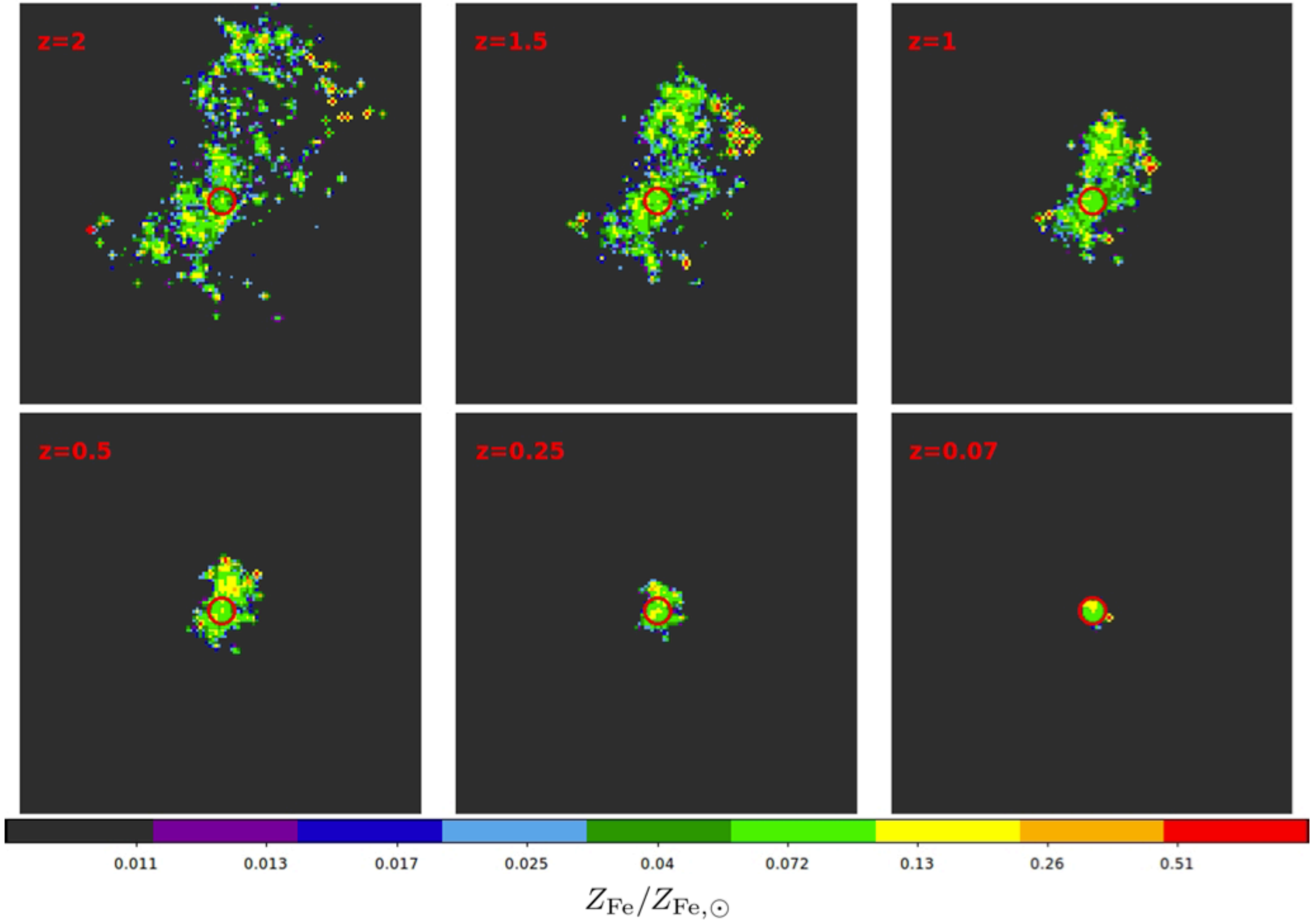
➜ Many fewer metals locked back in later star formation



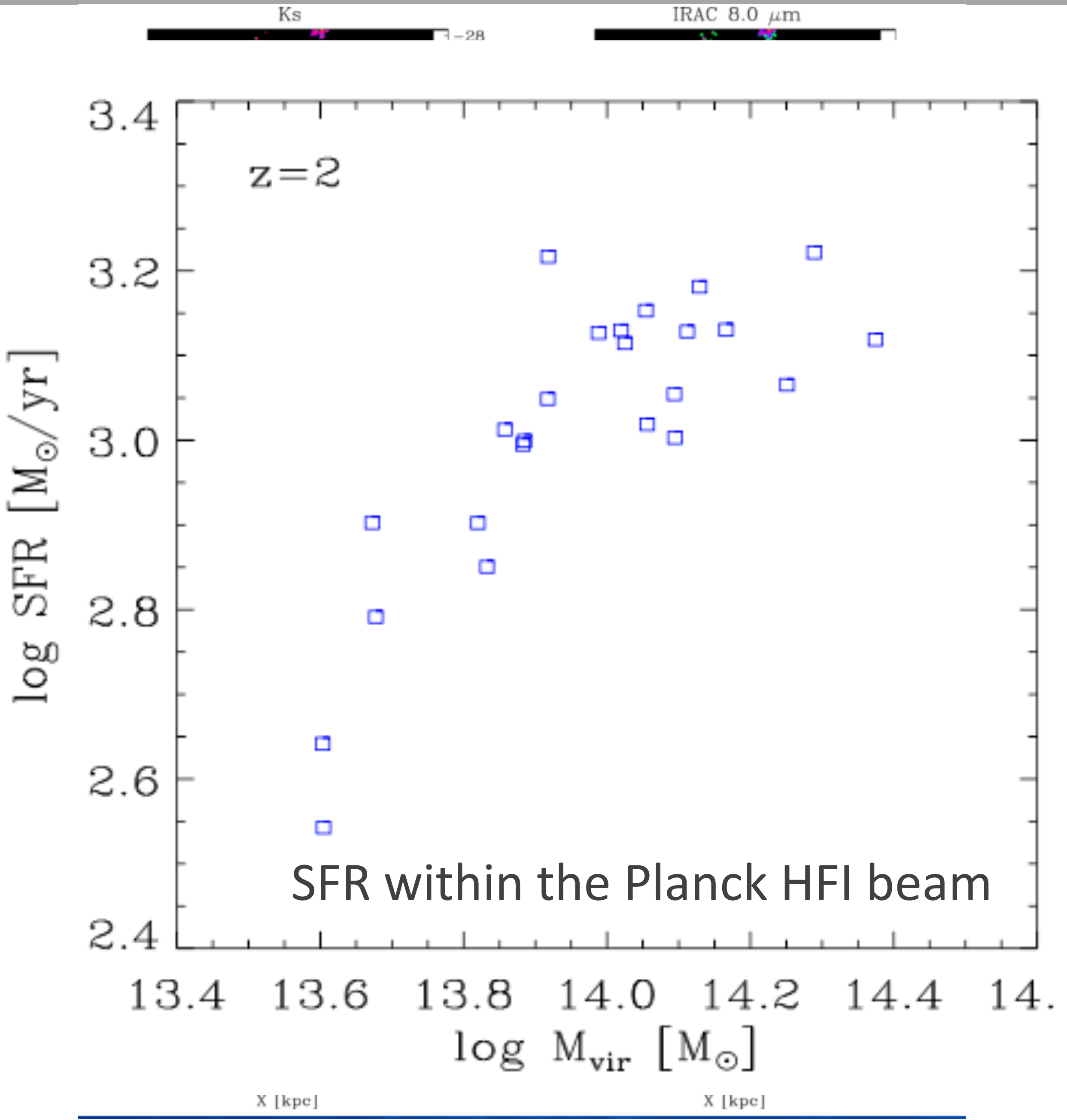
Low-z ICM metallicity as a fossil record of feedback history

***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 $(0.8 < R/R_{vir} < 1.2)$
- ➜ Originated from diffuse and pre-enriched IGM/CGM
- ➜ Results from the action of AGN feedback



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:

➔ *$Flux_{HFI}$~ 1200 mJy (@857 GHz)*

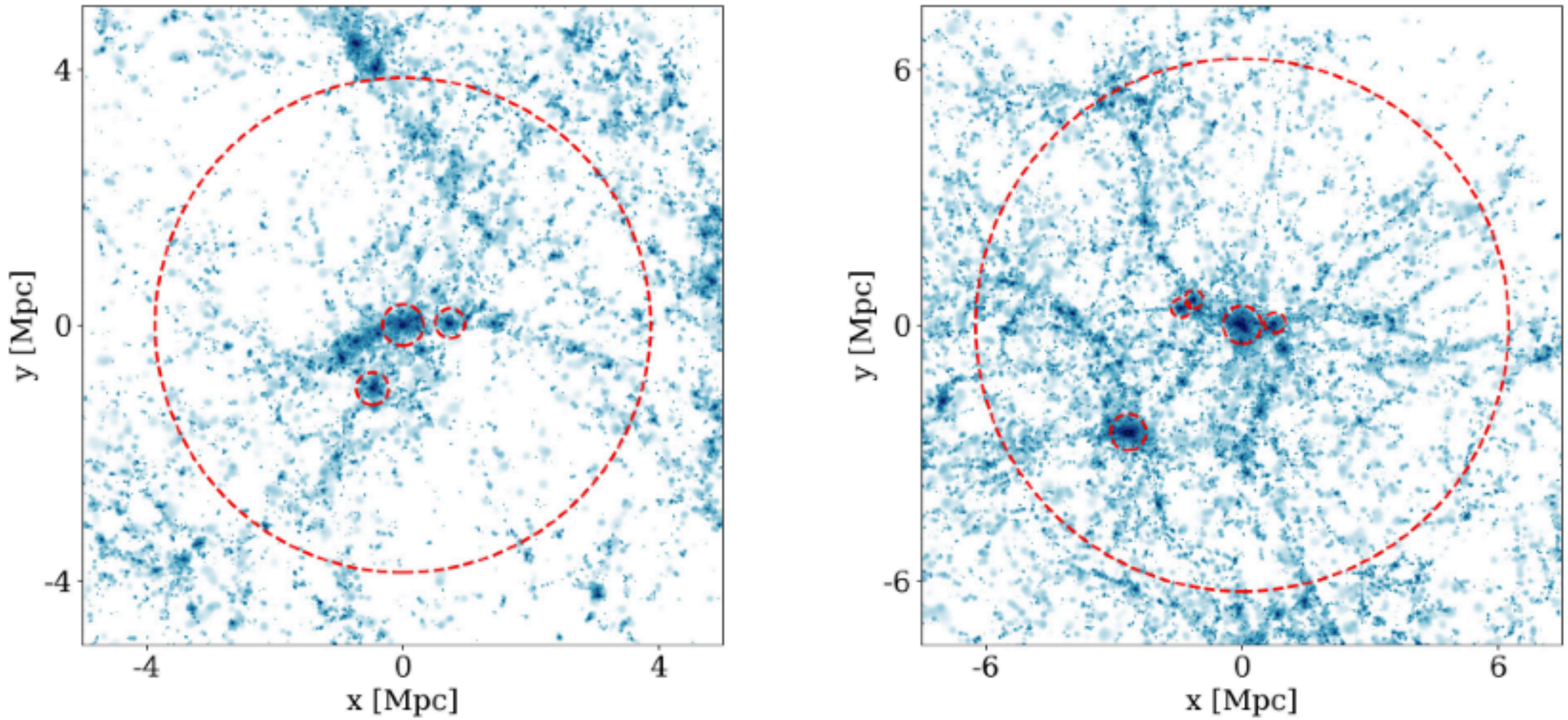
➔ Far larger than obtainable from simulations

- Clemens+2014: SFR within Planck beam for two *z~2* clusters: [***2.9 – 7] x 10^3 $M_\odot$/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. 2024, in prep.)*



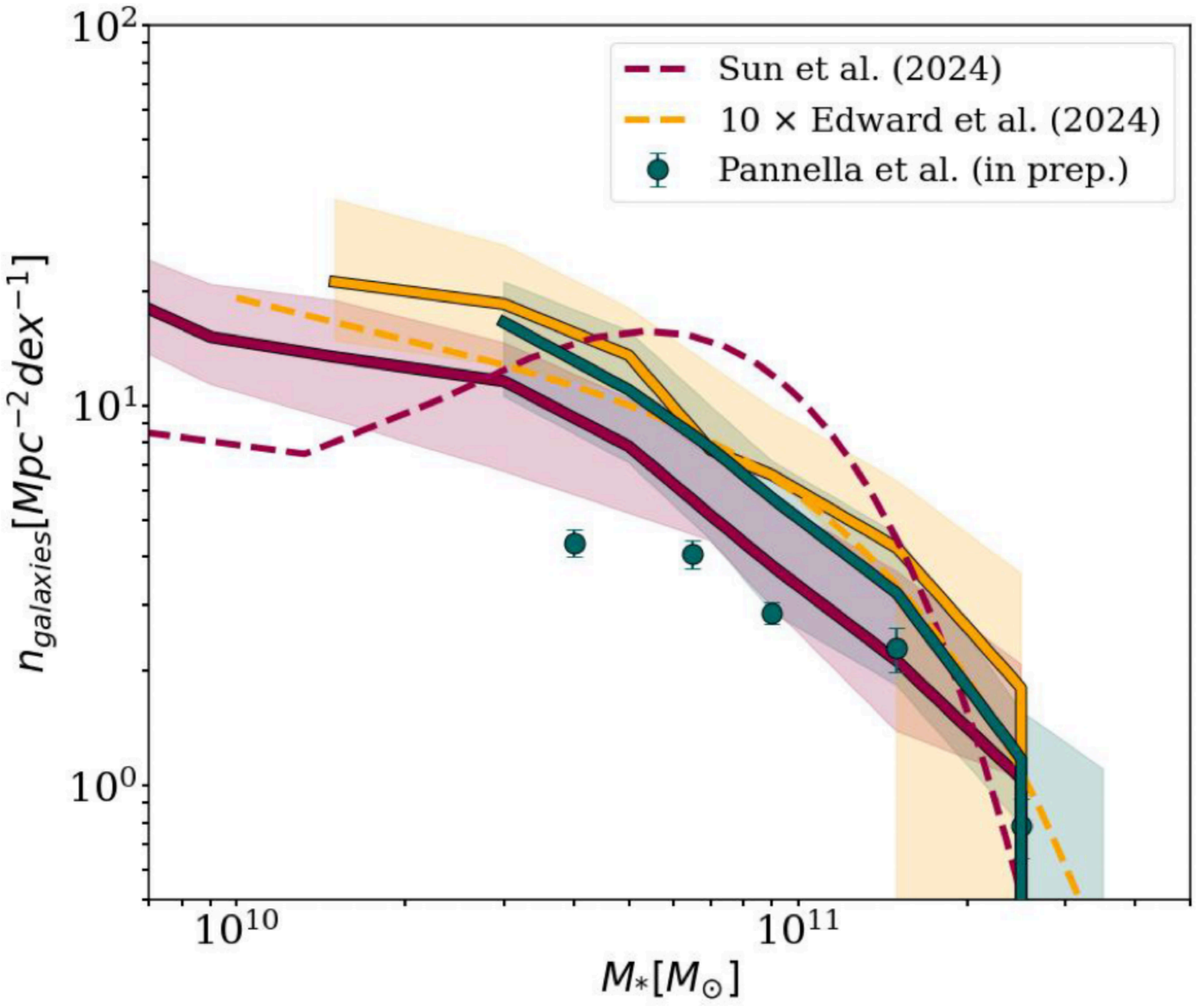
z=2.2

➜ 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. 2024, in prep.)



Relationship between mass and velocity dispersion

➜ In line with extrapolation from calibration from simulations at z=0

➜ Good agreement with results from Shimakawa+2014

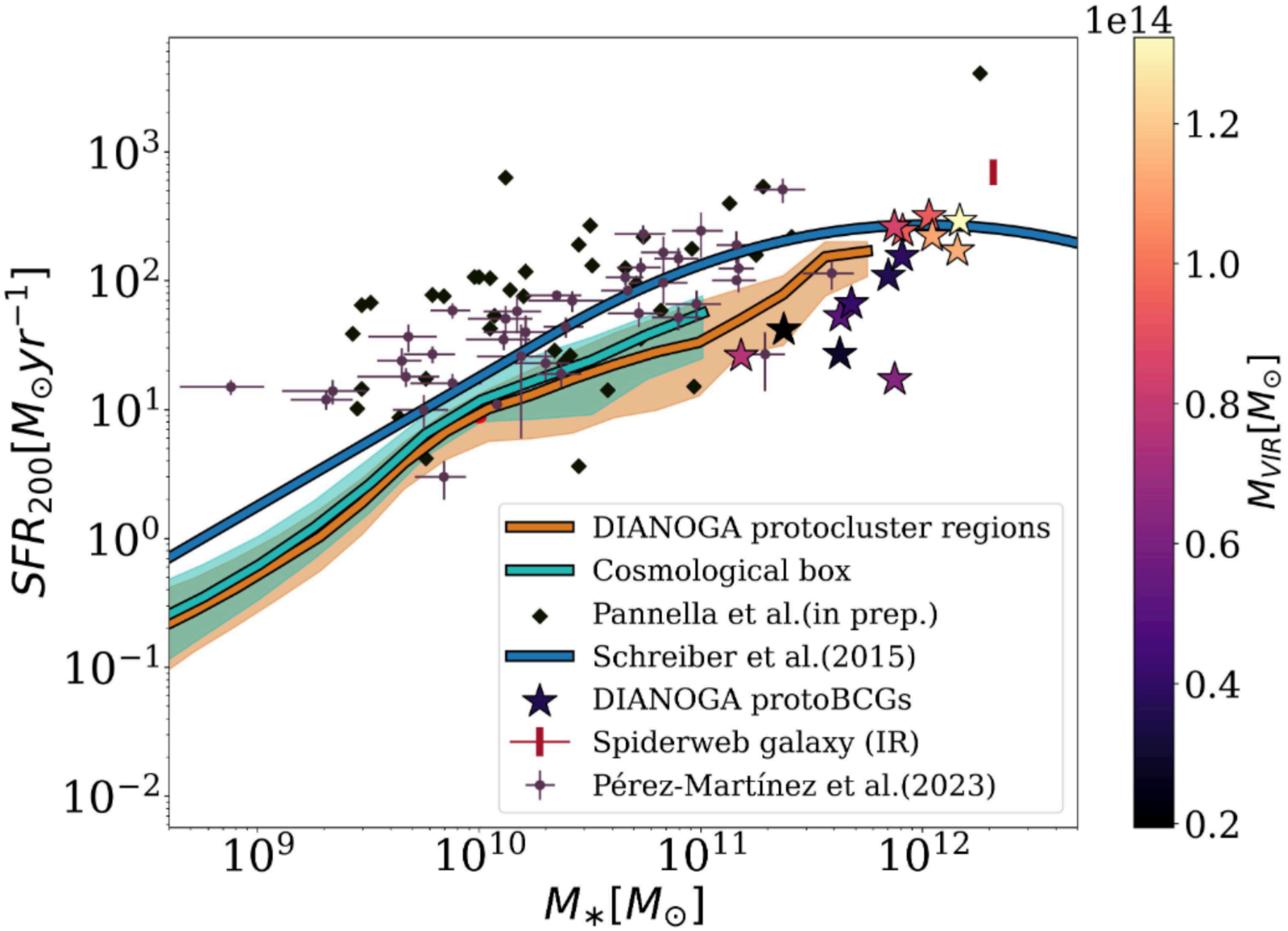
Comparison between observed and simulated SMF:

➜ Generally consistent, especially in the high-mass end

➜Exception of Edwards+24, which well agrees in shape but with too high normalization

Star formation in proto-cluster regions

(Bassini et al. 2021; Esposito et al. 2024, in prep.)



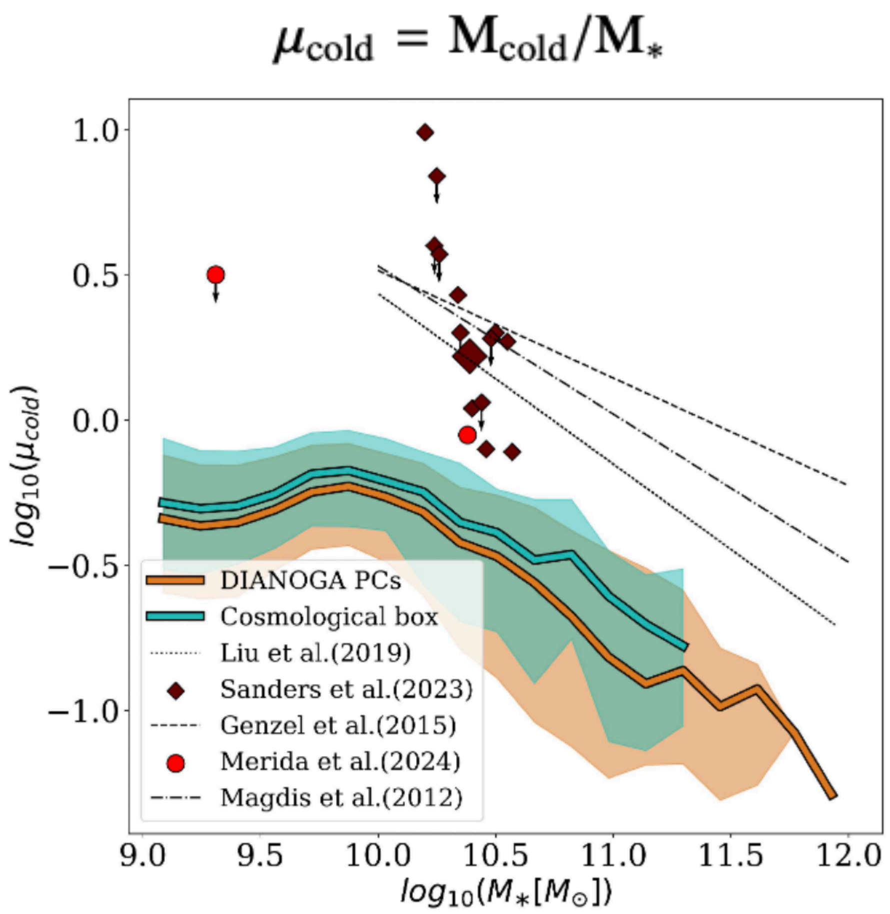
➜ Model-prediction of the main sequence at z~2 below the observed one, both in the field and in protocluster

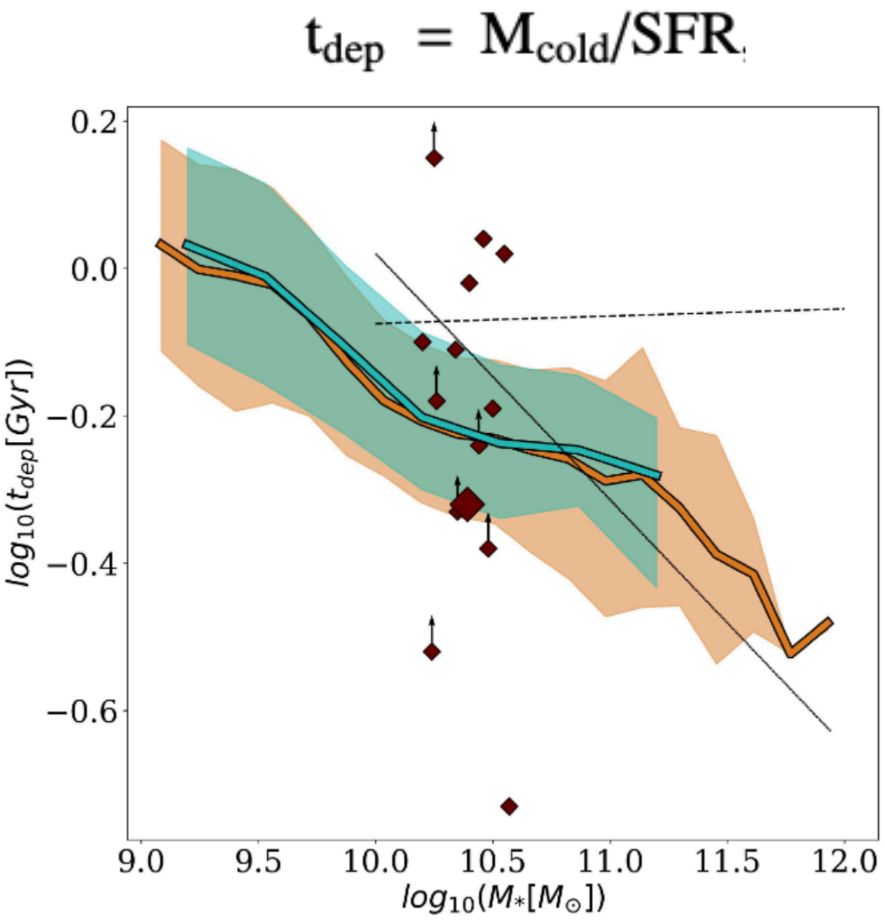
➜ Result almost independent of the adopted model of SF

➜ 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



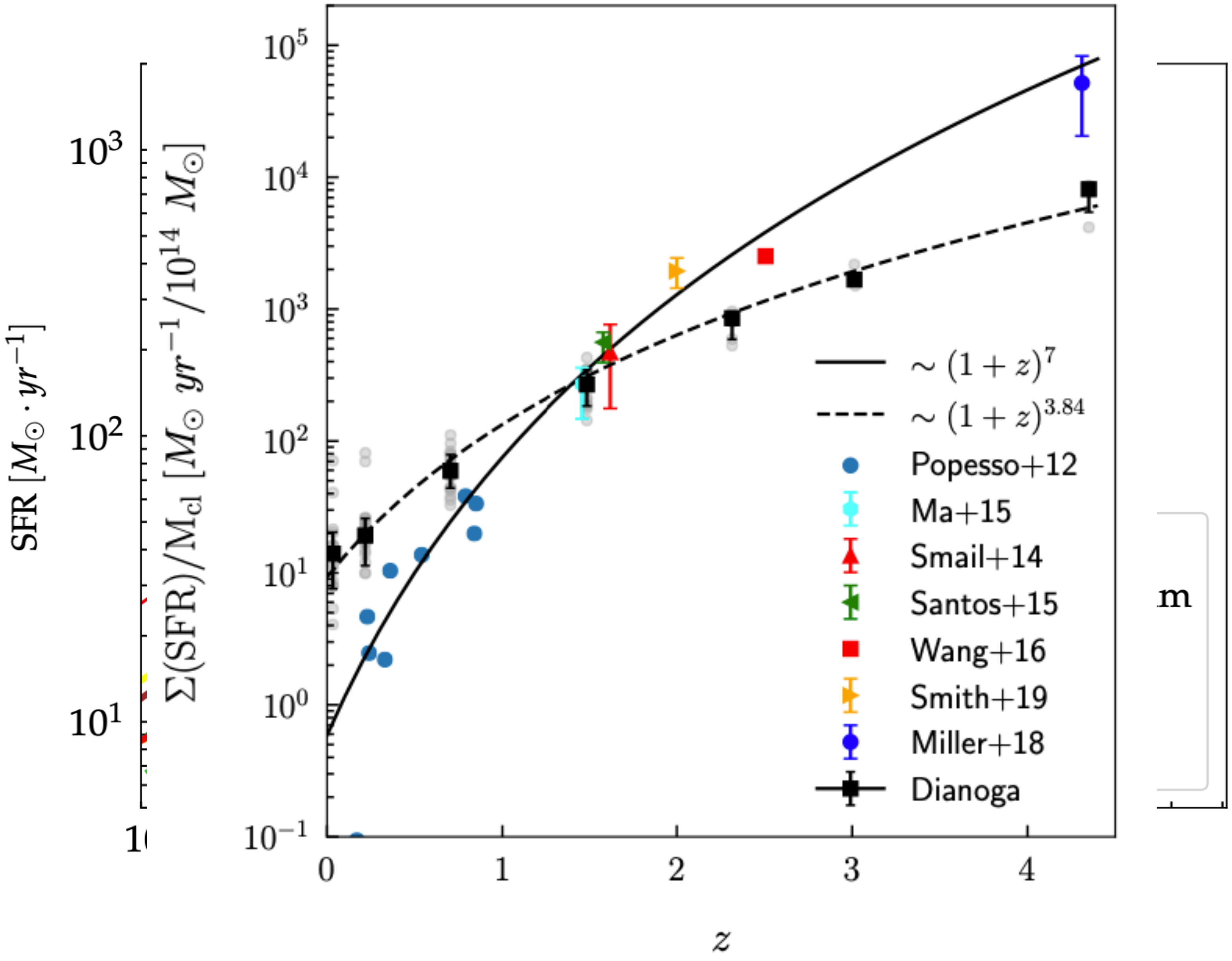


(Esposito et al. 2024)

➜ 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….)

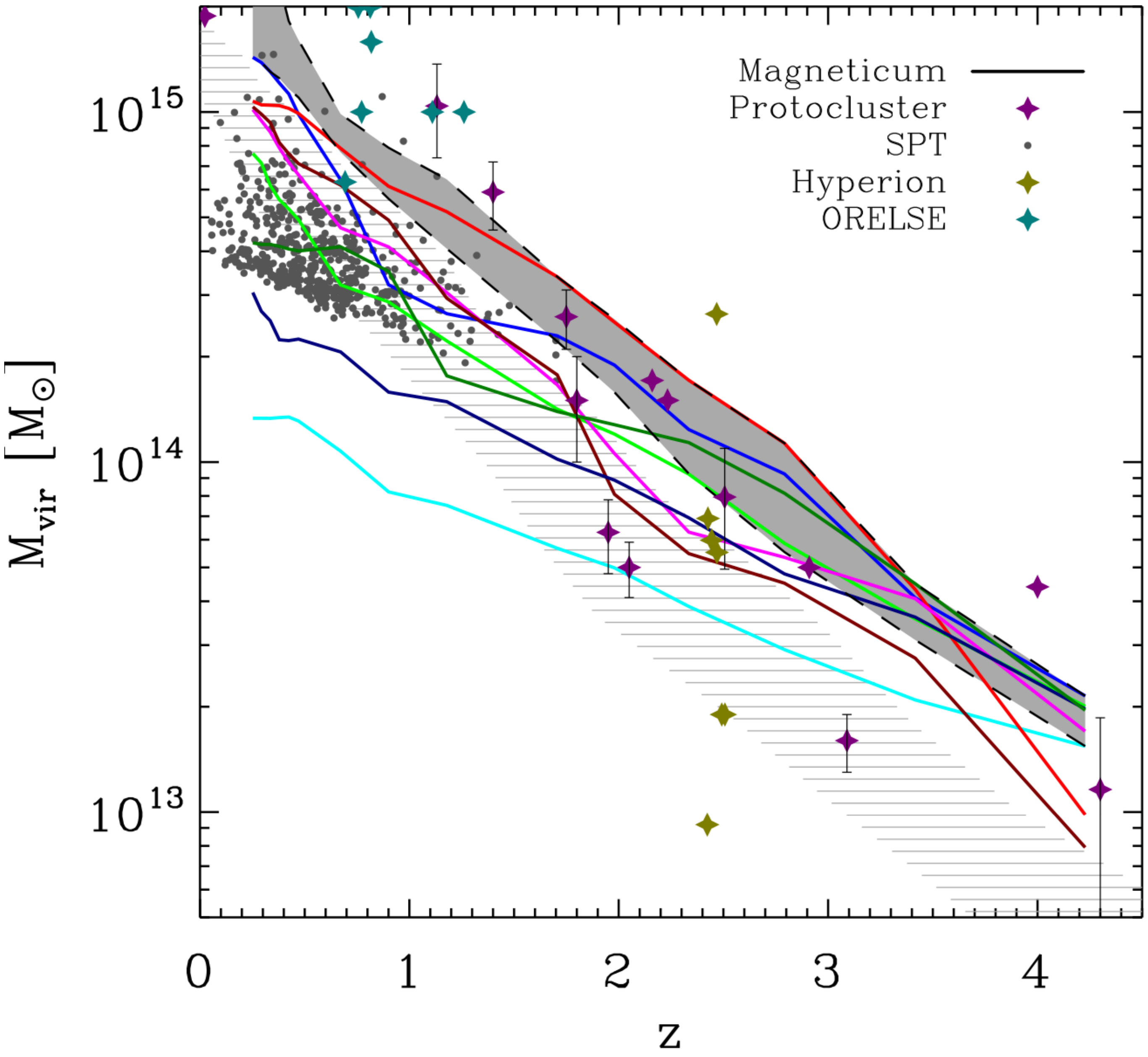
Star formation in proto-cluster regions



(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

What are the descendants of high-z overdensities ?



Remus+2023

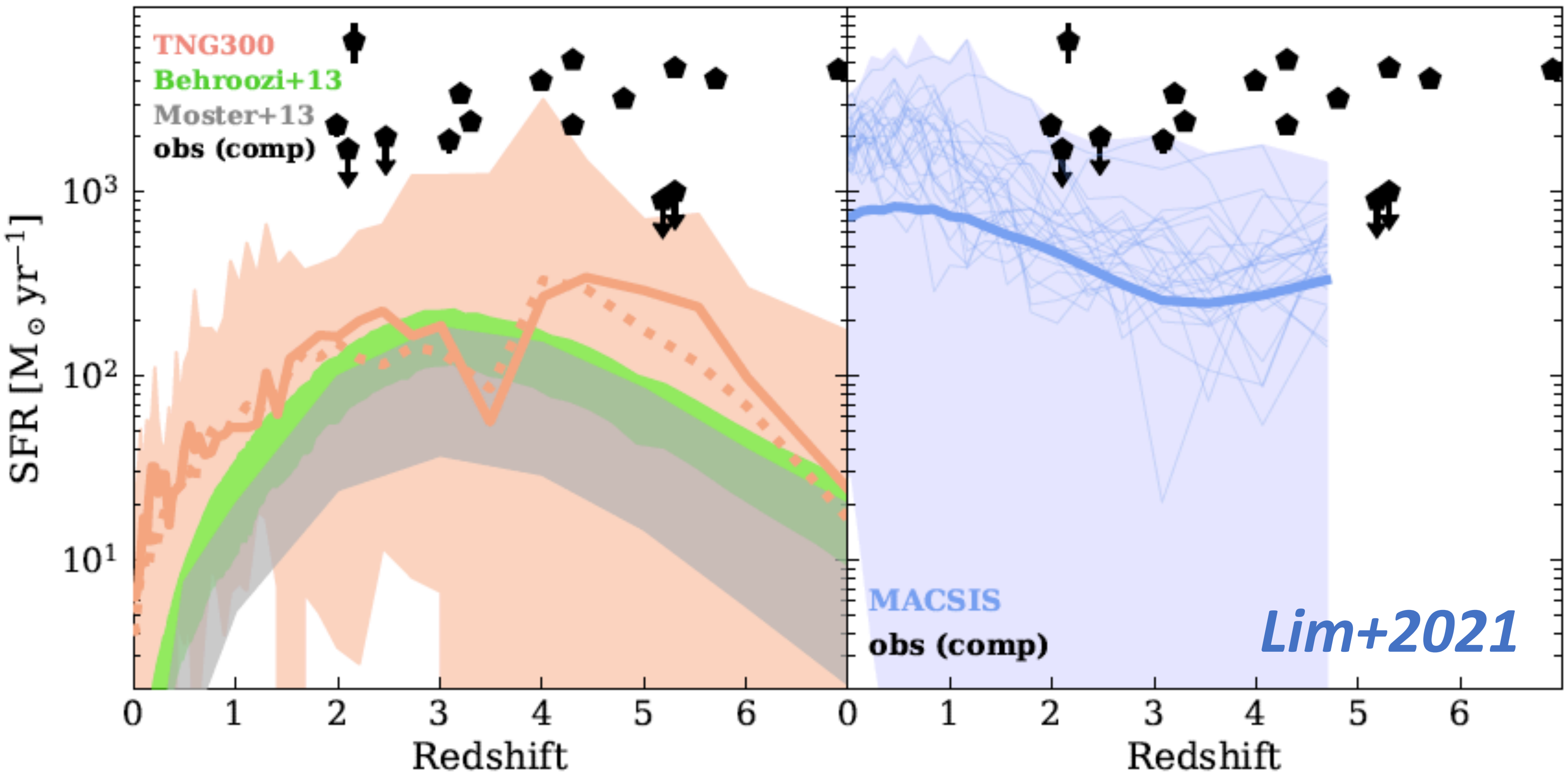
Use <u>Magneticum</u> cosmological boxes to:

- Identify galaxy overdensities at *z=4*
- Verify the descendants to assess whether they end-up in genuine clusters by *z=0*

➔ None of the most massive halos identified at *z=4.2* ends up amongst the 15 most massive halos at z=0.2

➔ Need for a homogeneous definition of proto-clusters to compare observations and simulations

Star formation in proto-cluster regions

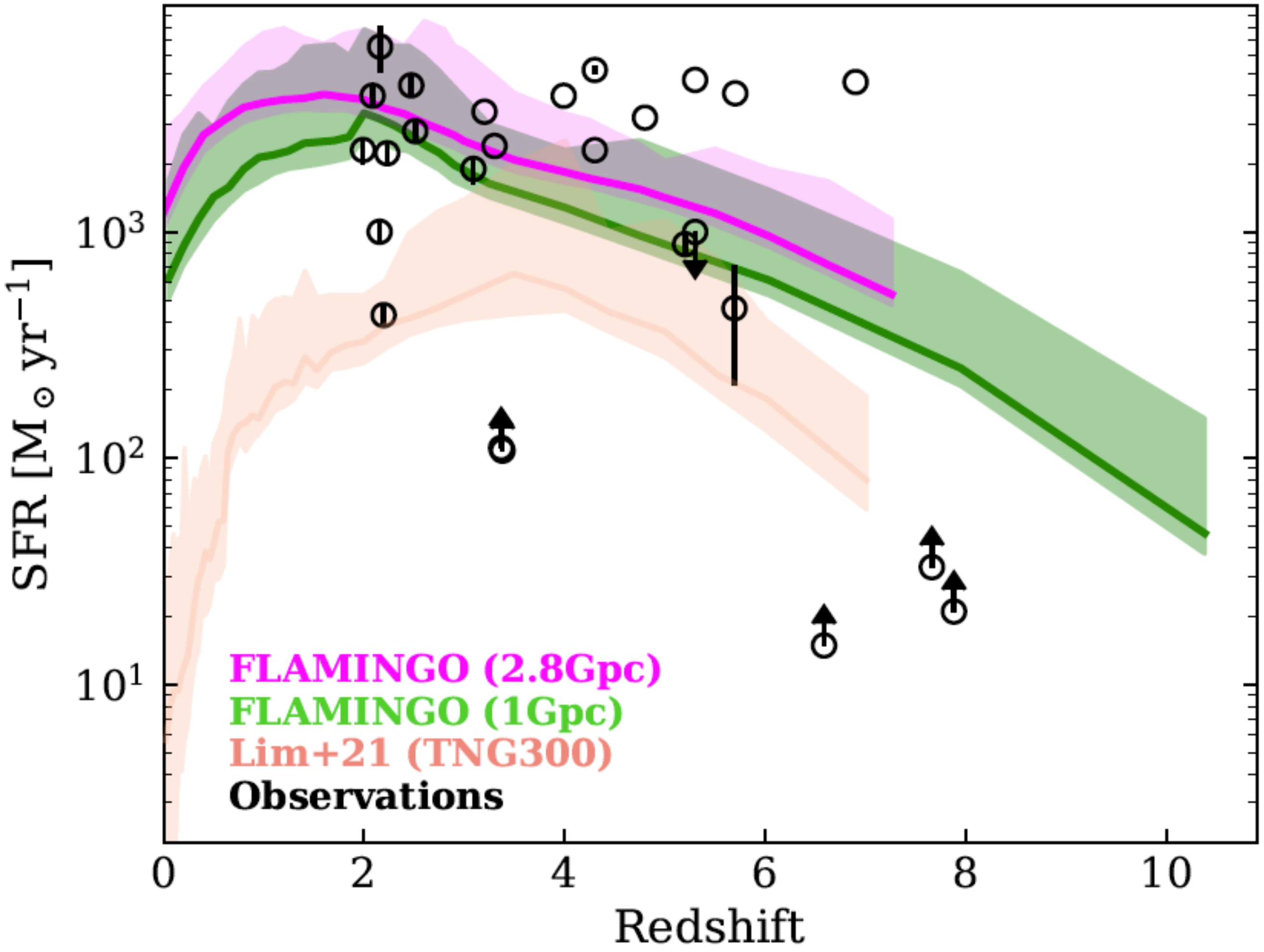


Comparison of <u>TNG300 & MACSIS</u> predictions on SFR in proto-clusters to observational data

➜ 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

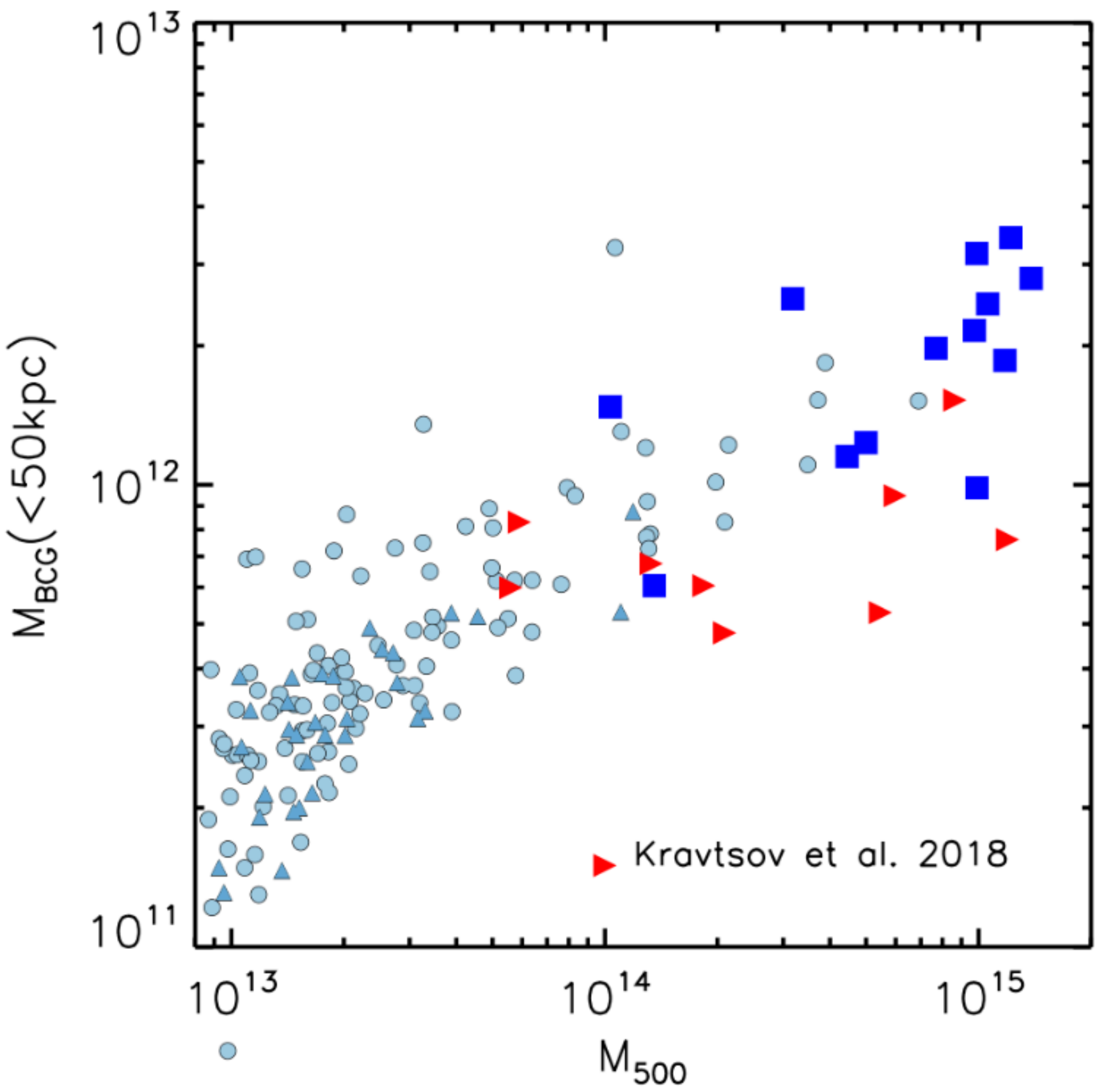
- ➜ Use FLAMINGO simulations (Schaye et al. 2023) to trace SFR in protoclusters
- ➜ Compare the total SFR within FoF halos to observational data
- ➜ Results in better agreement with observational data

But:

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

PART 2:
Simulating BCGs

BCG and stellar masses



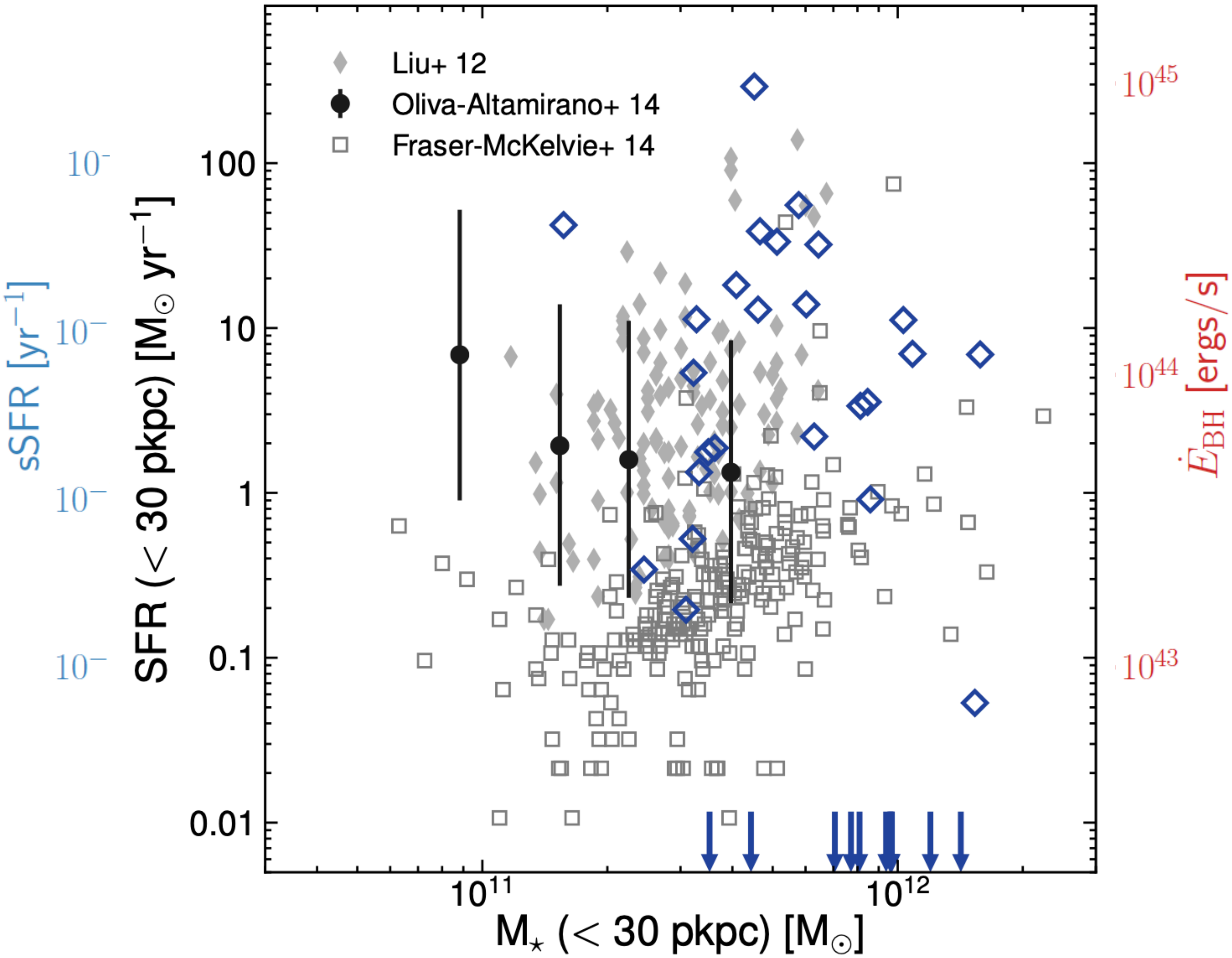
➔M_{*BCG}-M_{500} close to observations at low resolution (Ragone-Figueroa+2018)

➔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)

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

Star formation rates in BCGs



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

➔ RomulusC (Tremmel+2019):

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

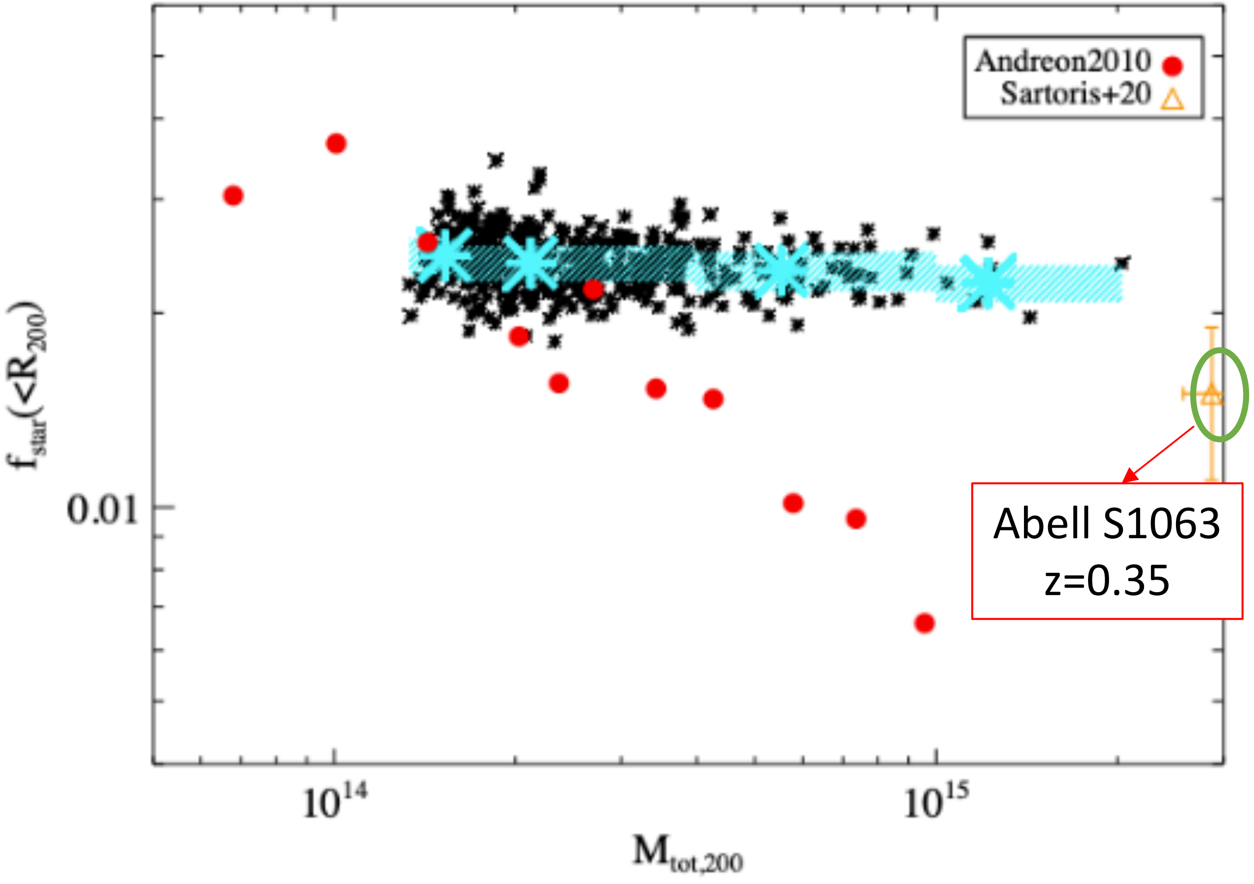
➔ FABLE (Henden+2020):

- Still tendency for too large SFR at z~0.2

Metal share in galaxy clusters

$$\mathfrak{I}_{500} \equiv \frac{M_{\mathrm{Fe},500}}{Z_\odot M_{\mathrm{star},500}}$$

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+2024: comparison with 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 $M_{Fe,gas} - M_{gas,500}$ relation

→ Due to excess of star formation in simulations? Quite possible, but then correct ICM Fe content just a coincidence... (see also Molendi+2024)

→ 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!!

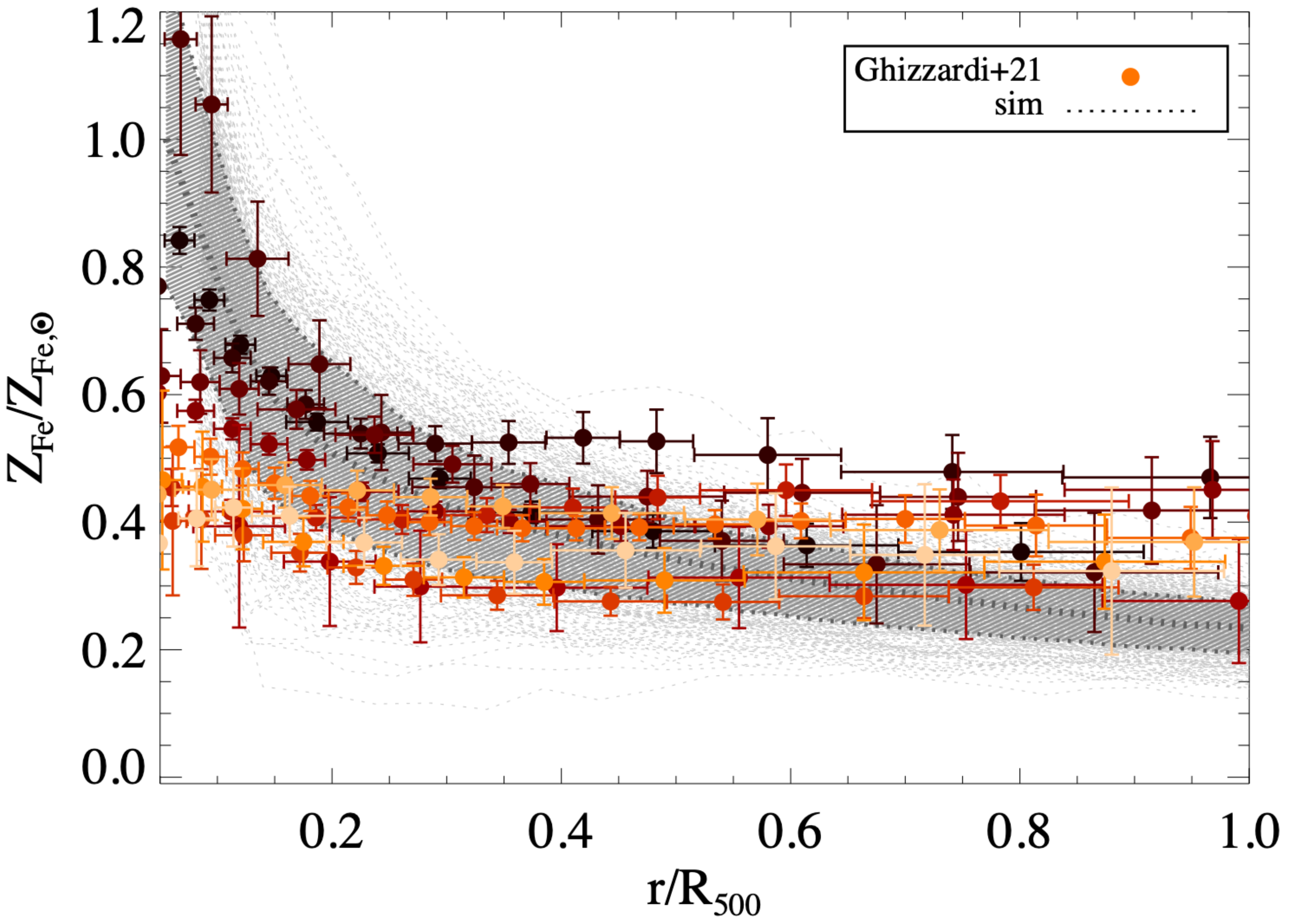
Low-z ICM metallicity as a fossil record of feedback history

Biffi et al. 2024 – Comparison with X-COP clusters

➜ Simulated profiles slightly steeper than observed

➜ Overall good agreement within the observational scatter

➜ In line with the agreement between simulations and observations in the relation between *total Fe mass* and *total gas mass*



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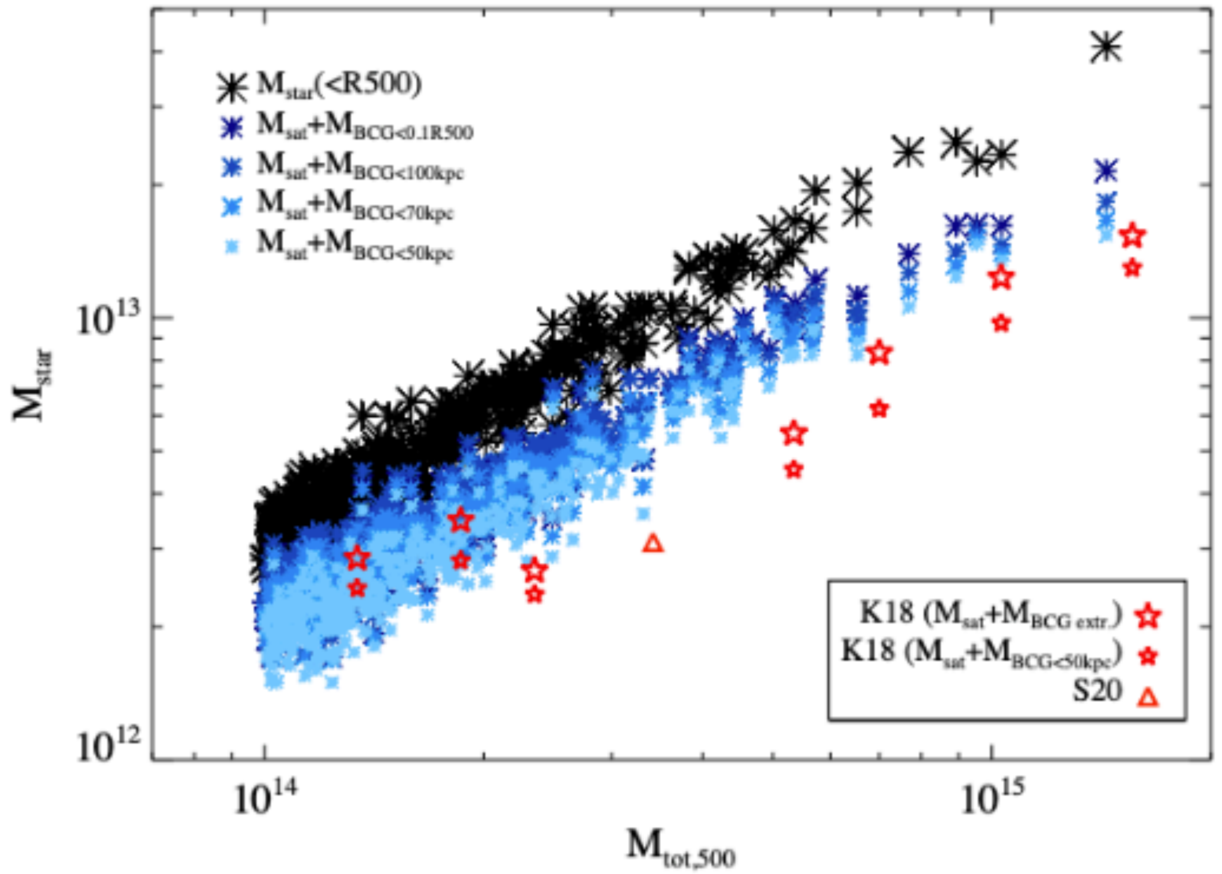

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➔ Large fraction of overall Fe budget in the diffuse gas

Biffi+2024 in prep: comparison with Dianoga and Magneticum simulations

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➔ Apparently, not an issue with the ICM Fe content: good agreement with observed $M_{\mathrm{Fe,gas}} - M_{\mathrm{gas,500}}$ relation

➔ Due to excess of star formation in simulations?

- Quite possible, but then correct ICM Fe content just a coincidence...
- But 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!!

Tracking BH orbits in cosmological simulations

Damiano+2024; arXiv:2403.12600 – Damiano+2025 in prep.

Problem: How to correctly integrate orbits 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

$$\boldsymbol{F}_{\mathrm{DF}} = -4\pi\rho\left(\frac{\mathrm{GM_{BH}}}{v_{\mathrm{BH}}}\right)^2 \mathrm{F}(x)\ln(\Lambda)\widehat{v}_{\mathrm{BH}} \qquad \mathrm{F}(x) = \mathrm{erf}(x) - \frac{2x}{\sqrt{\pi}}e^{-x^2} \;;\; x = \frac{v_{\mathrm{BH}}}{\sigma_v}$$

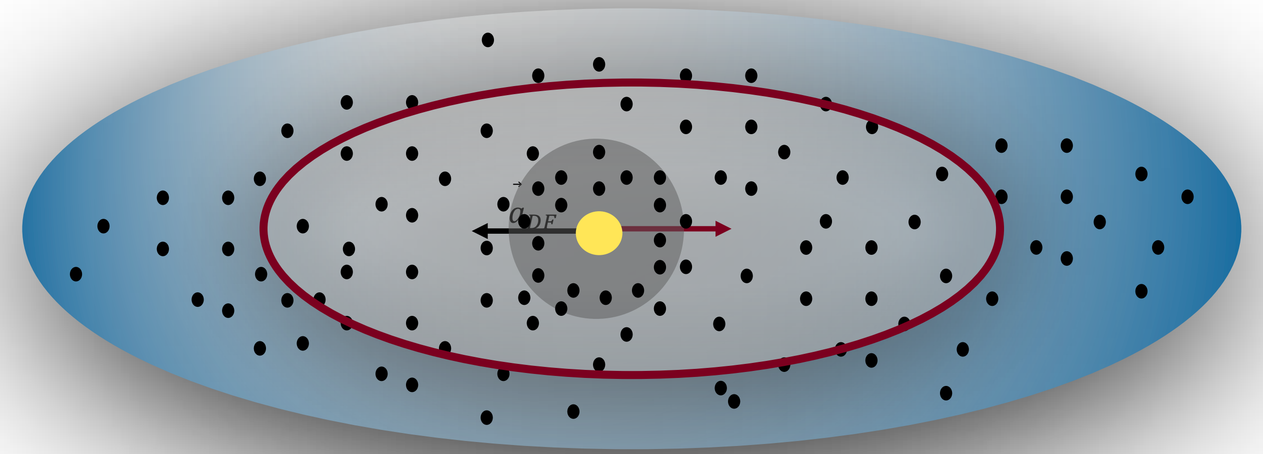
Hirschmann et al. (2014):

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

Tremmel et al. (2015):

1. $b_{max} = softening$

Correcting for the unresolved dynamical friction



[Damiano+2024; arXiv:2403.12600](https://arxiv.org/abs/2403.12600)

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

$$\left.\frac{d\boldsymbol{v}_{\mathrm{M}}}{dt}\right|_{\boldsymbol{v}} = 2\pi \ln\left[1 + \Lambda(m, \boldsymbol{v})^2\right] G^2 m(\mathrm{M}+m) f(\boldsymbol{v}) d^3\boldsymbol{v} \frac{(\boldsymbol{v}-\boldsymbol{v}_{\mathrm{M}})}{|\boldsymbol{v}-\boldsymbol{v}_{\mathrm{M}}|^3} \qquad \Lambda(m, \boldsymbol{v}) = \frac{b_{\max}(\boldsymbol{v}-\boldsymbol{v}_{\mathrm{M}})^2}{G(\mathrm{M}+m)}$$

→ Particles within the softening tracing the velocity distribution according to

$$f(\boldsymbol{v}) = \frac{3}{4\pi {\epsilon_{\mathrm{BH}}}^3} \sum_{i=1}^{N(<\epsilon_{\mathrm{BH}})} \delta(\boldsymbol{v} - \boldsymbol{v}_{m,i})$$

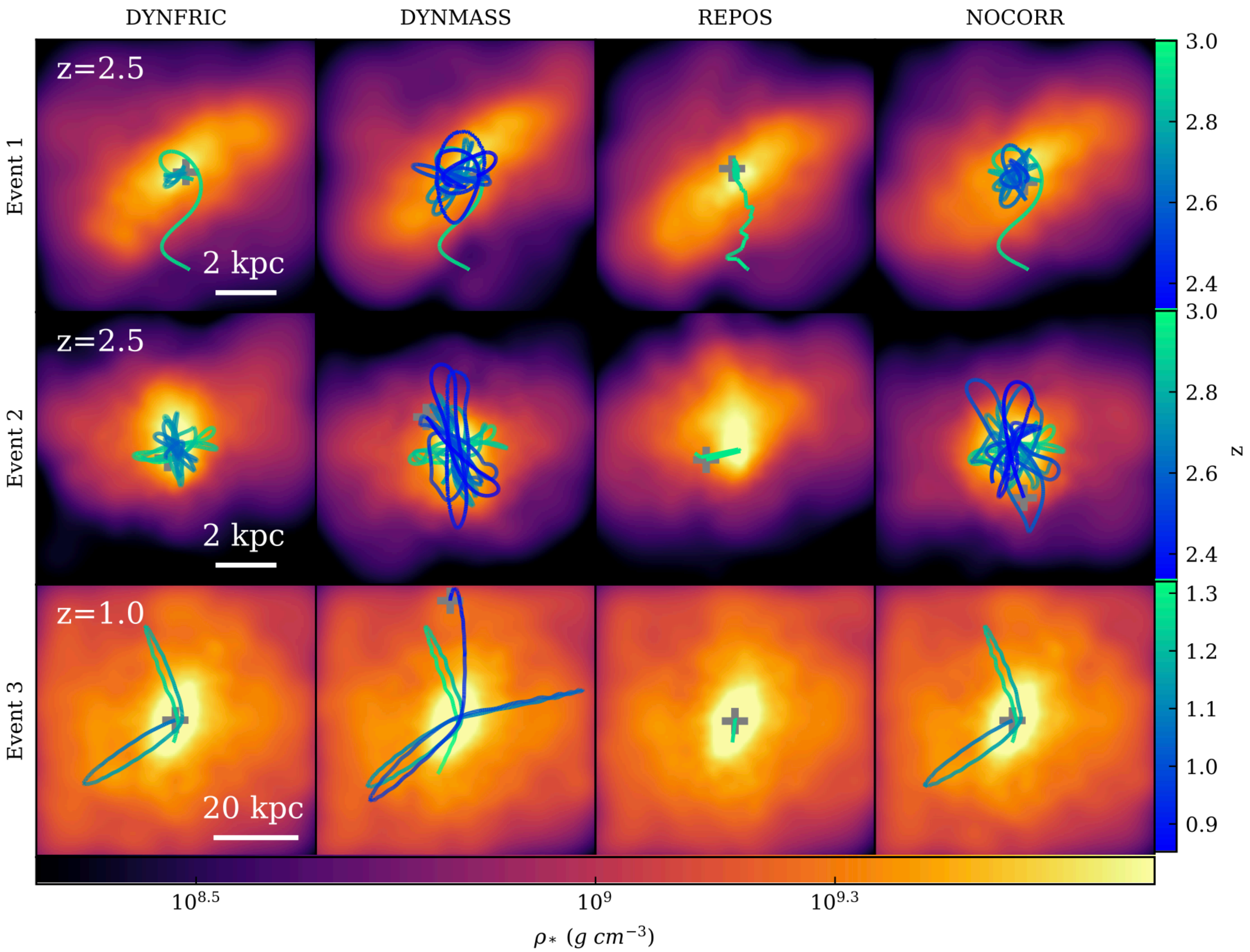
→ $$\boxed{\frac{d\boldsymbol{v}_{\mathrm{M}}}{dt} = \frac{3G^2}{2{\epsilon_{\mathrm{BH}}}^3} \sum_{i=1}^{N(<\epsilon_{\mathrm{BH}})} \ln\left[1 + \Lambda(m_i)^2\right] m_i(\mathrm{M}+m_i) \frac{(\boldsymbol{v}_{m,i}-\boldsymbol{v}_{\mathrm{M}})}{|\boldsymbol{v}_{m,i}-\boldsymbol{v}_{\mathrm{M}}|^3}}$$

Improving the description of BH dynamics

<u>Alternative ad-hoc prescription:</u>

<u>Large dynamical mass:</u> enhance by hand the BH dynamical mass at seeding to amplify the resolved DF
➔ *Significant change in the local potential*

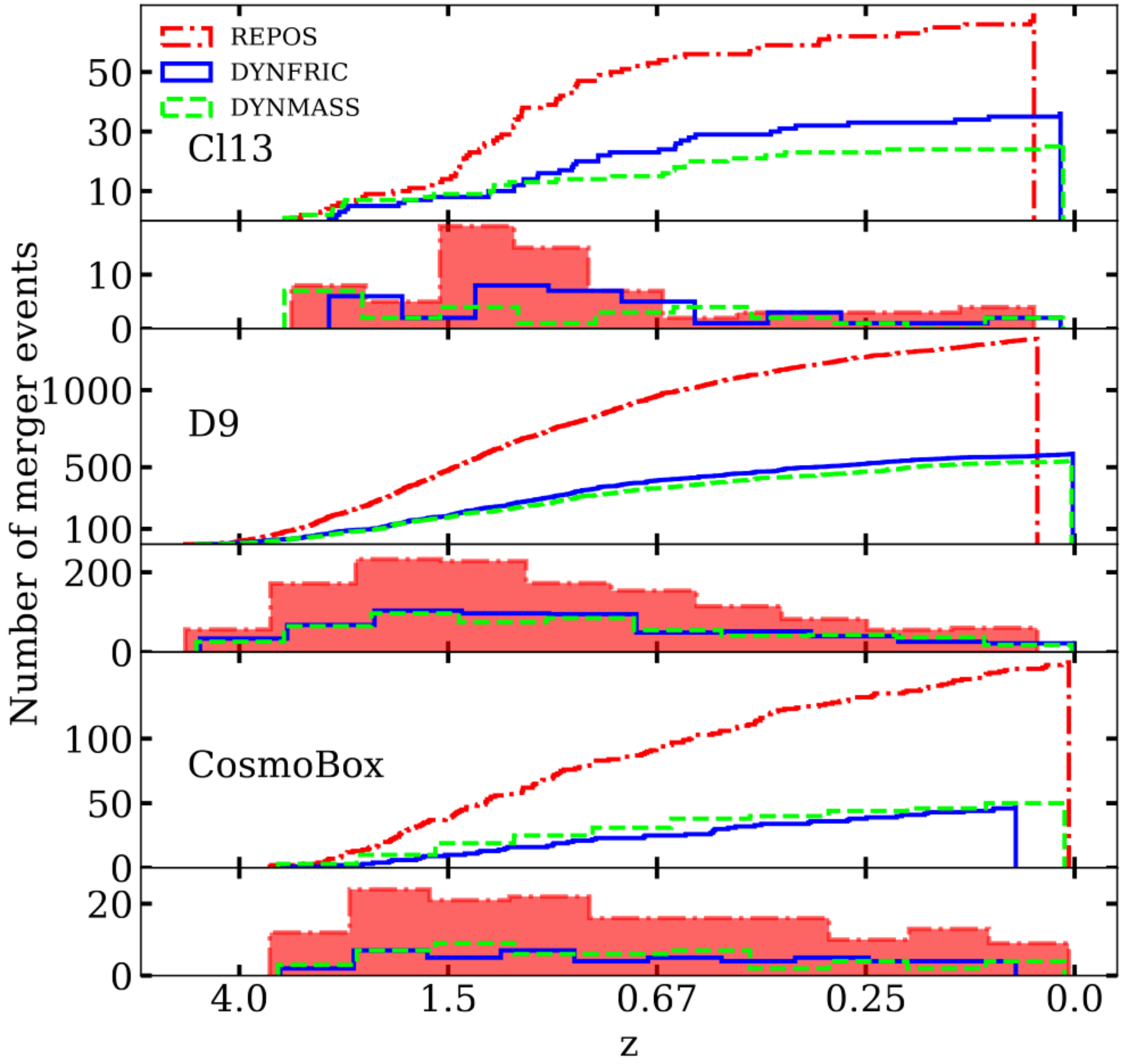
<u>Continuous repositioning:</u> at every time-step pin the BH on the local minumum of the potential
➔ *Merging time-scales completely wrong*



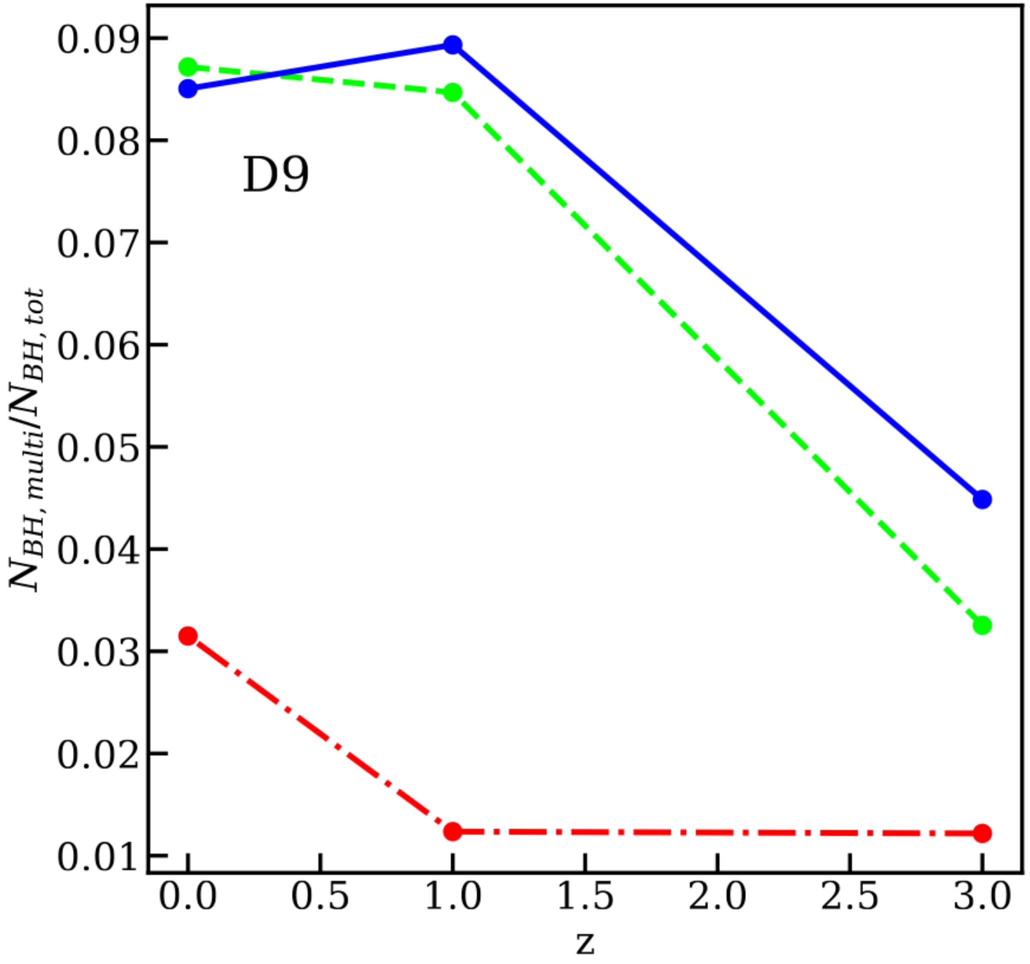
Improving the description of BH dynamics

Damiano+2024; arXiv:2403.12600

Effect on the number of BH-BH mergers

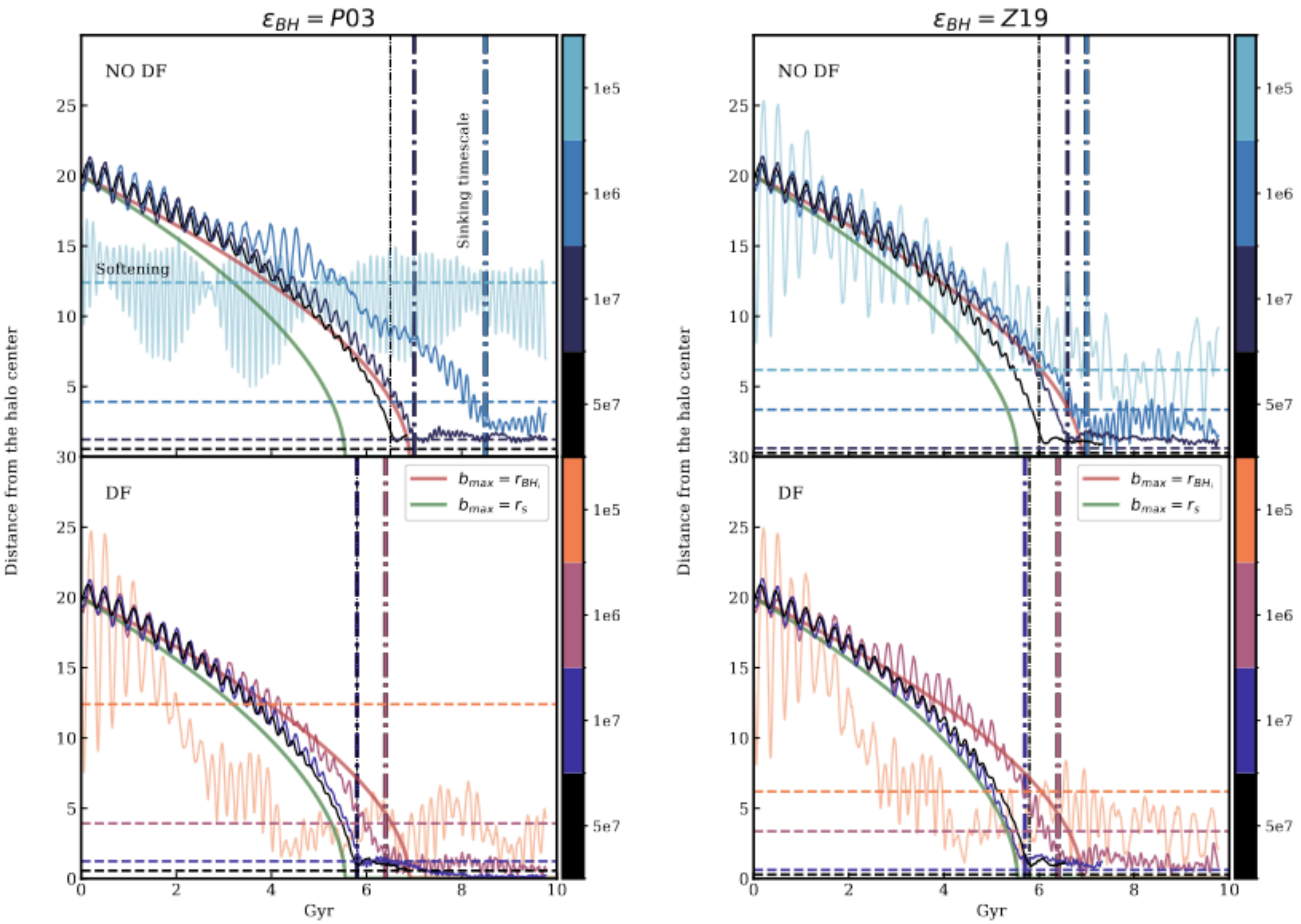


Effect on the fraction of halos hosting more than one BH



Improving the description of BH dynamics

Damiano+2025; in prep.



➔ Controlled simulations in an Isolated NTW halo at varying resolution and softenings

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

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

➔ Increasing resolution makes simulations 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 assemblying proto-BCGs, along with formation of an ICL component
- ➜ Connection between high-z proto-cluster phase and low-z fossile 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
- Too much mass in metals predicted by simulations to be locked in stars – but ICM metallicity OK…

Directions to improve simulations:

Deeply revise the SF model to produce bursty SF at $z = 2 - 4$;
Revise the AGN feedback model (a) to rapidly quench SF; (b) to circulate metals in the CGM/ICM before they are locked back in stars.

Q1: How robust is *observed stellar mass* within low-z massive clusters?

Q2: How much ICL can we reasonably think we're missing in observations?