Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

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

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

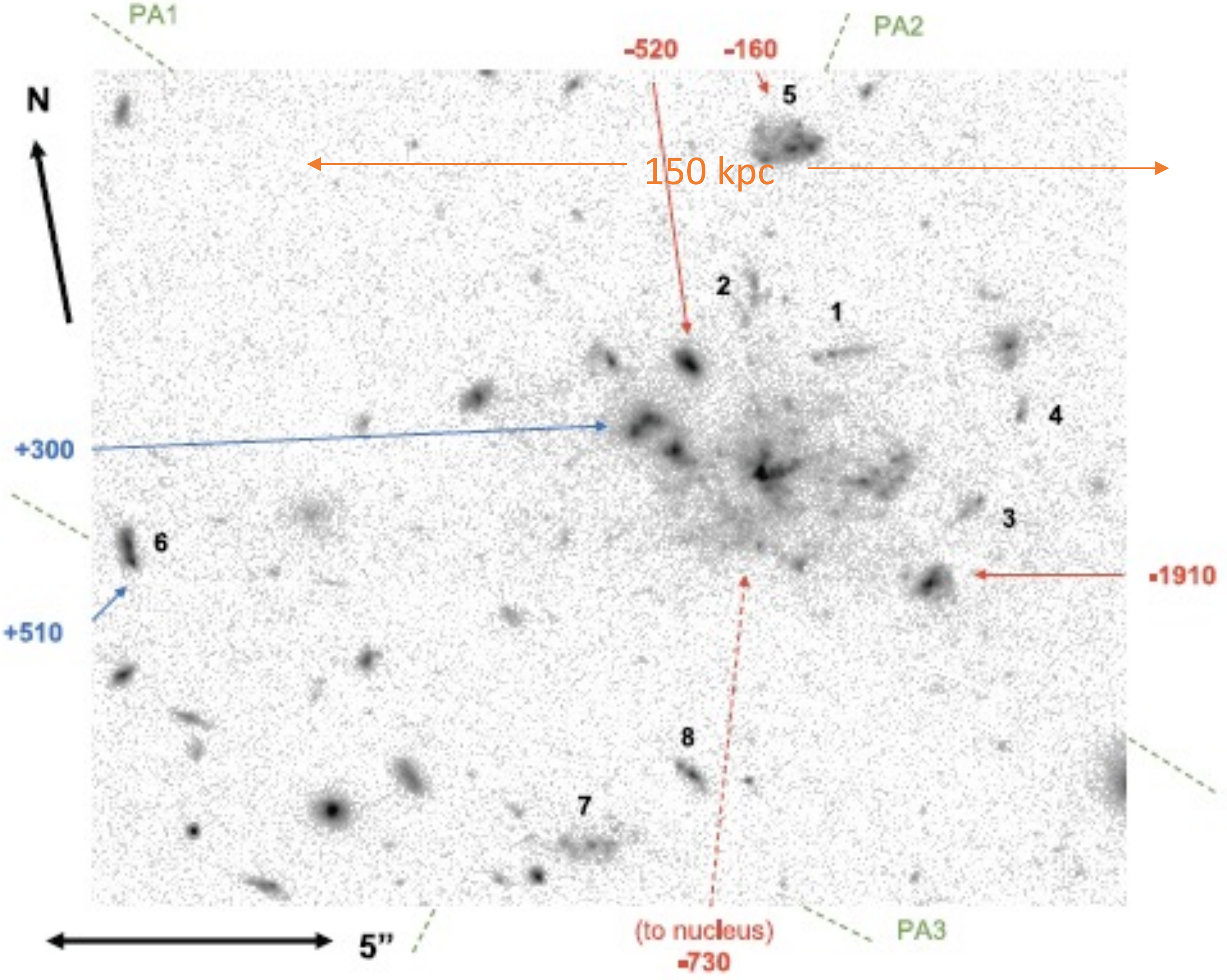
I. Simulating protoclusters: environment of the early BCG assembly
- I.a Properties of the proto-ICM and their low-z fossil record
- I.b Star formation rates in protoclusters

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

Talk @ "HydroSim-24", Ljubljana – 29 July / 1 August, 2024

PART 1:
Simulating Protoclusters

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



HST-ACS image of MRC 1138-262

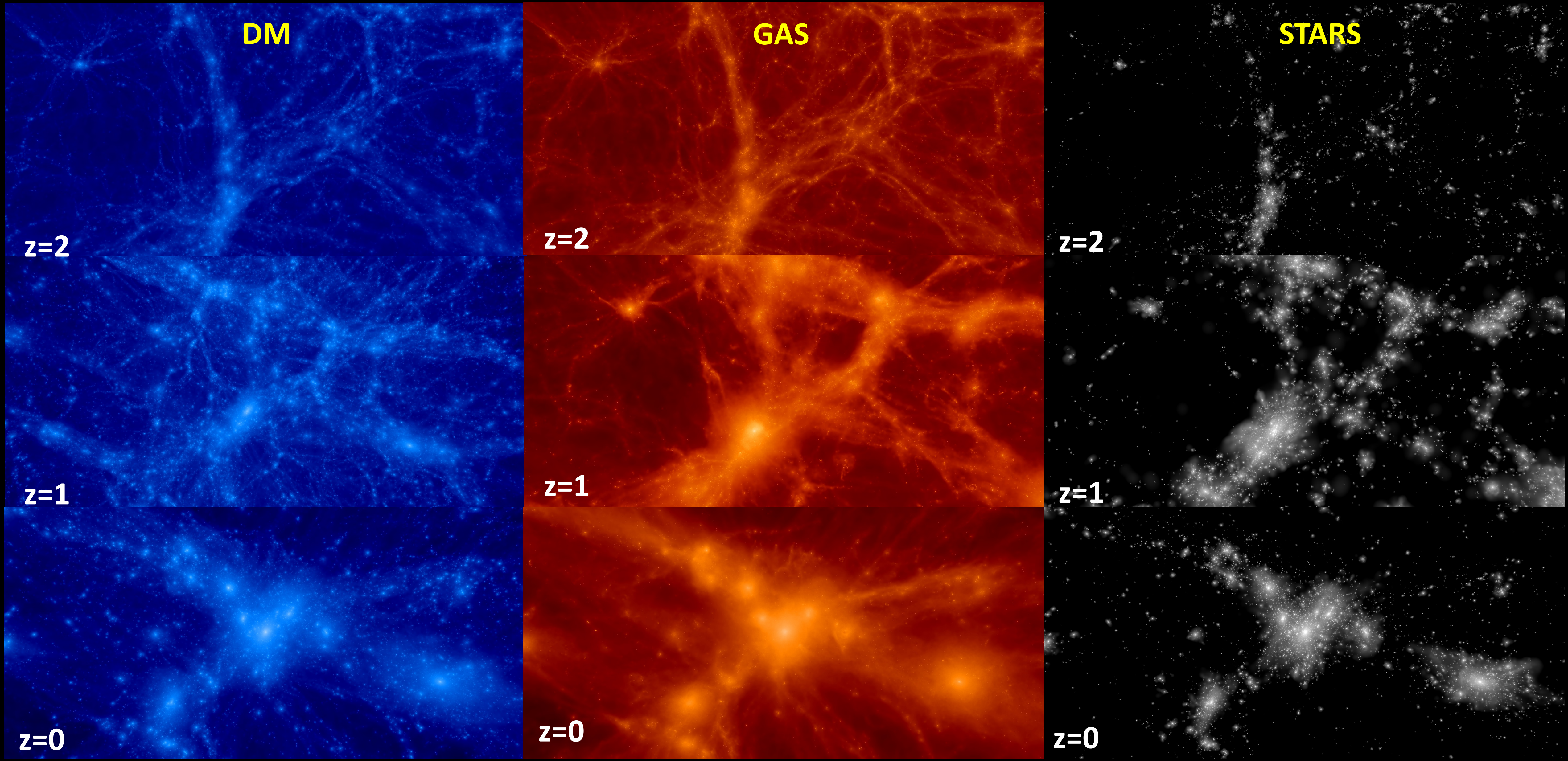
The "Spiderweb" galaxy (Miley+06)

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

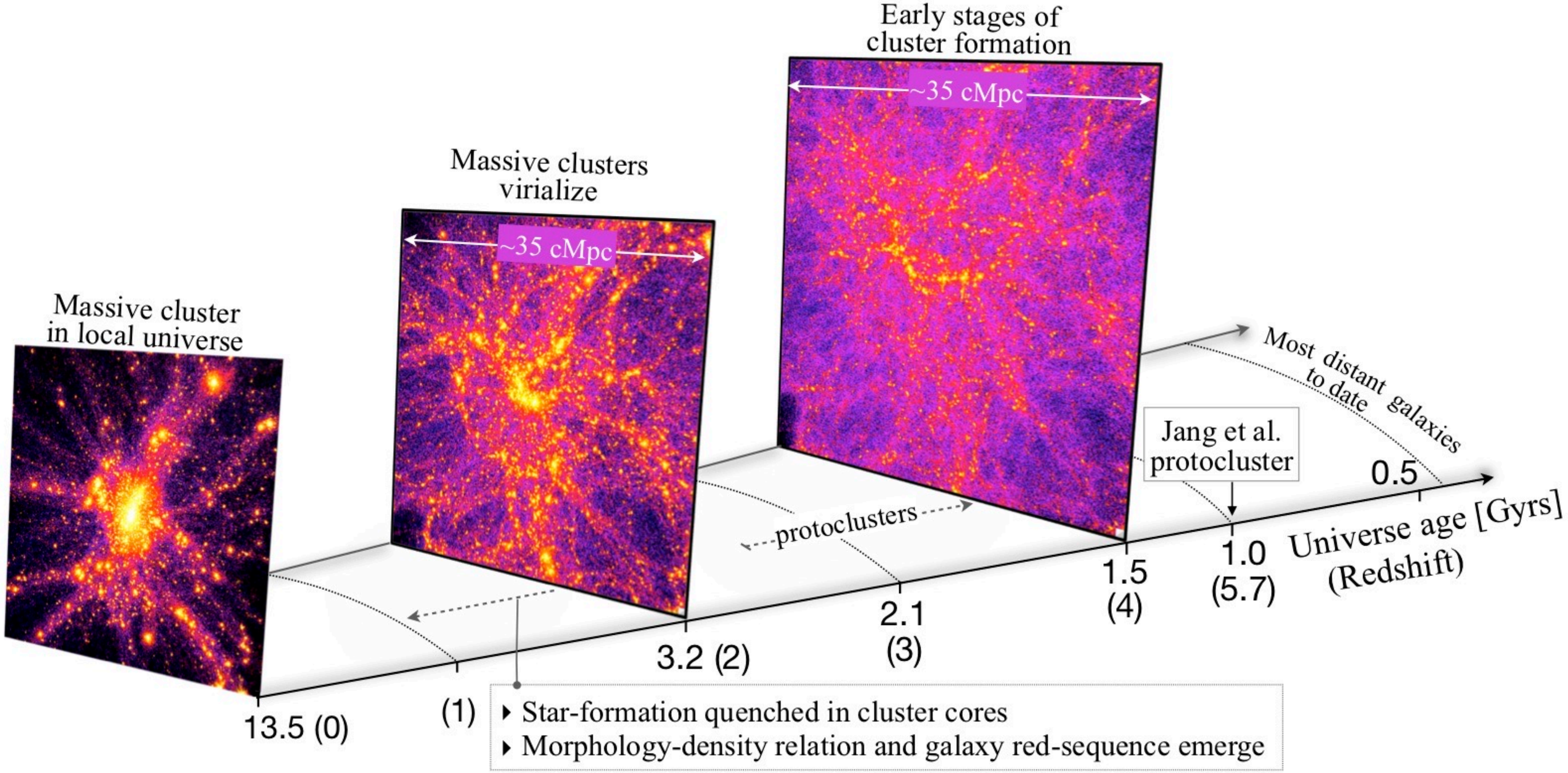
➔ "Flies" moving with v_{los} of up to $\sim 10^3$ km s^{-1}

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

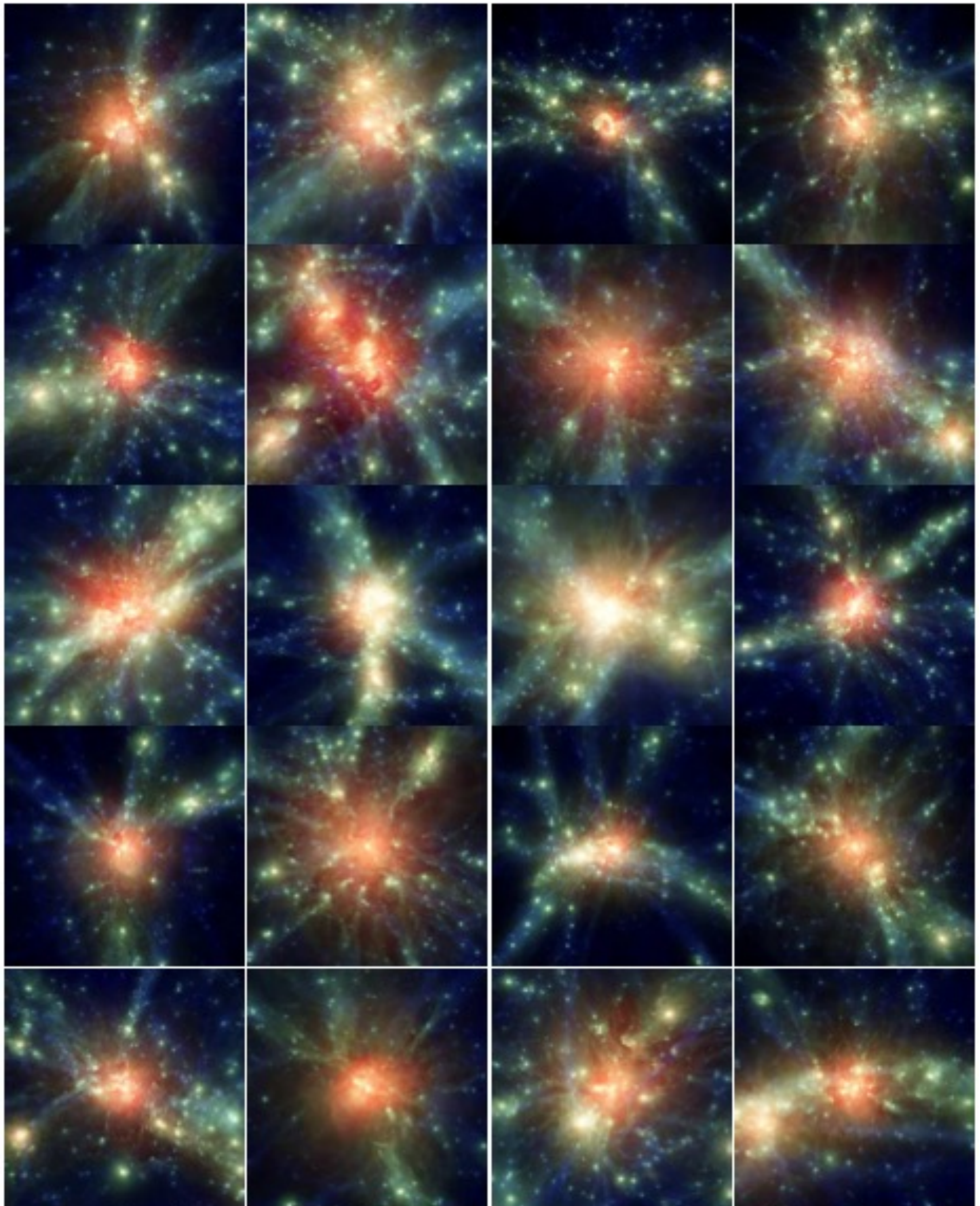
Dianoga Simulations



Courtesy of P. Rosati



The Dianoga Set with OpenGADGET3



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

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

OpenGADGET3 code: TreePM + SPH/MFM;

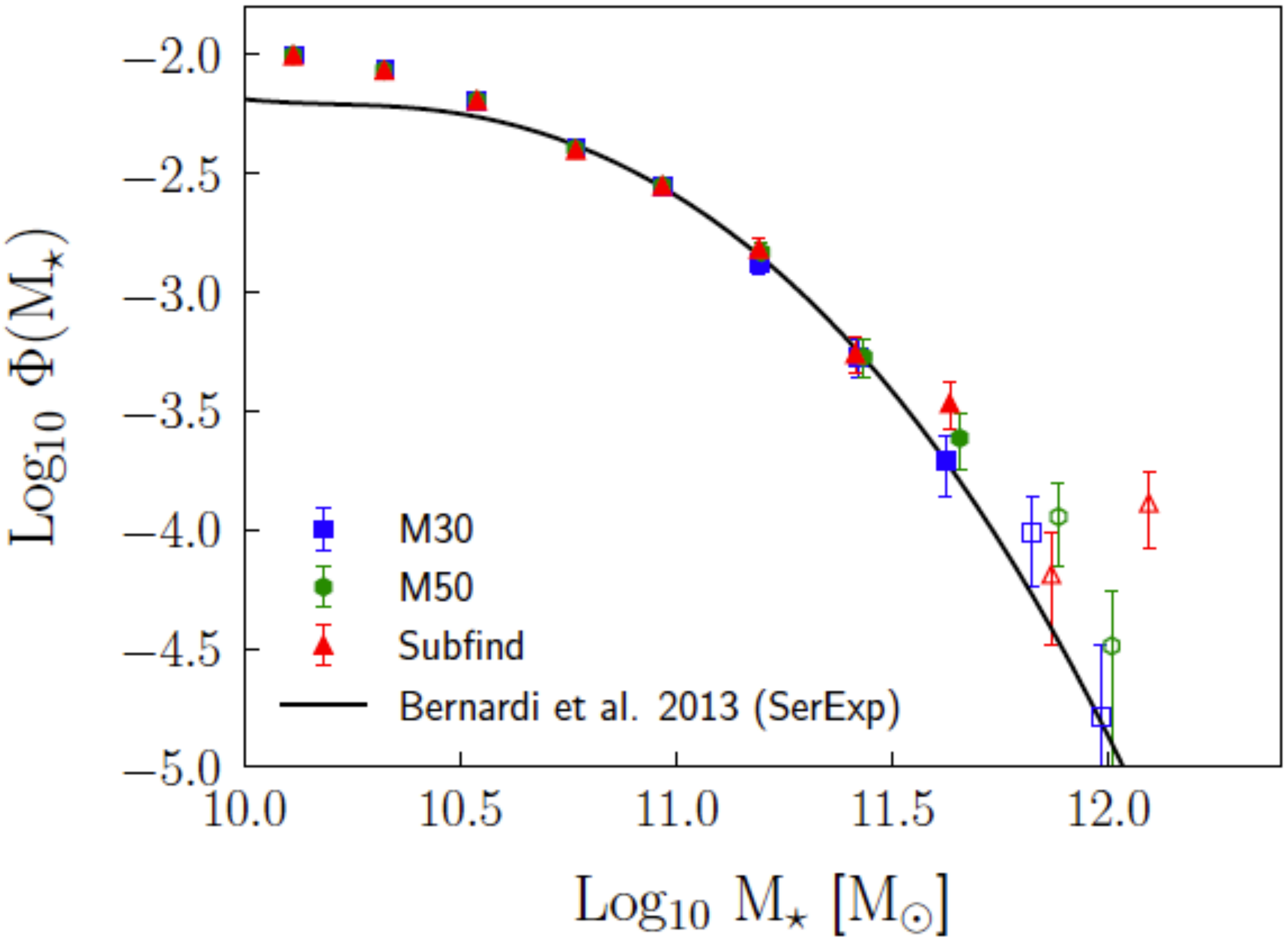
- Hybrid MPI/OpenMP/OpenACC parallelism

- **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

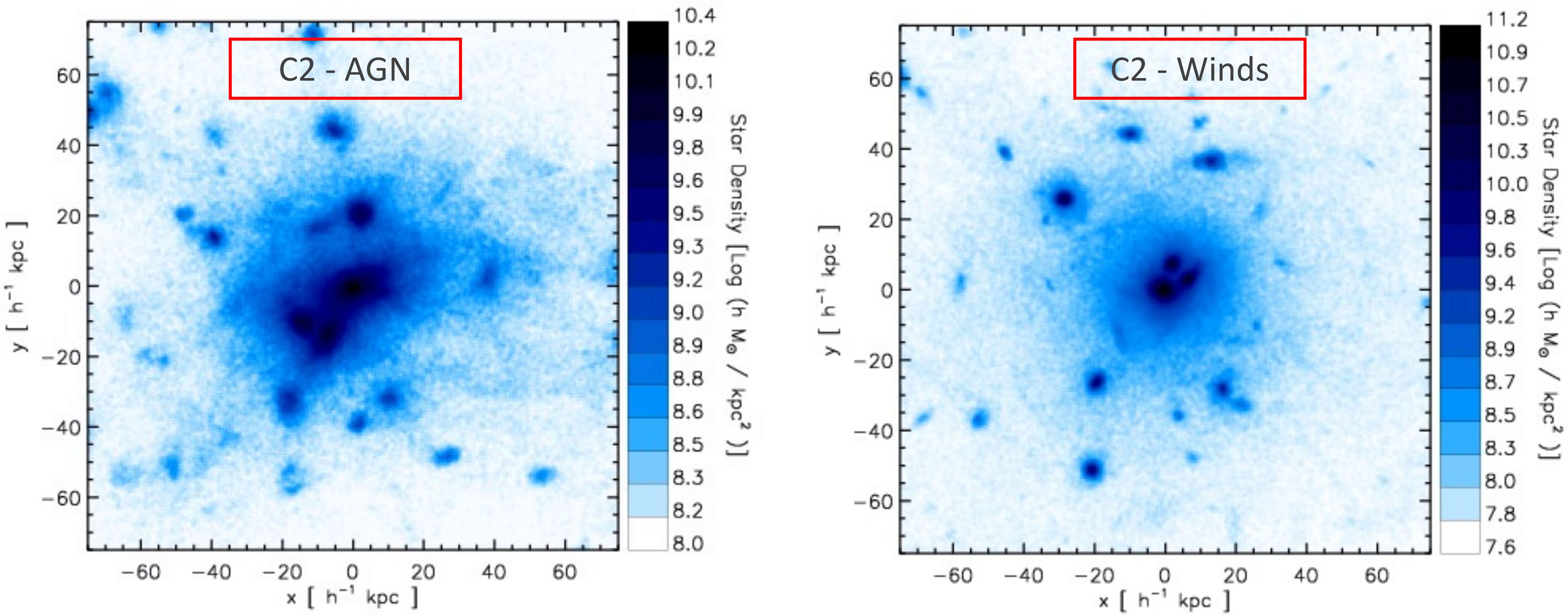
(Bassini et al. 2021)



- ➔ 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

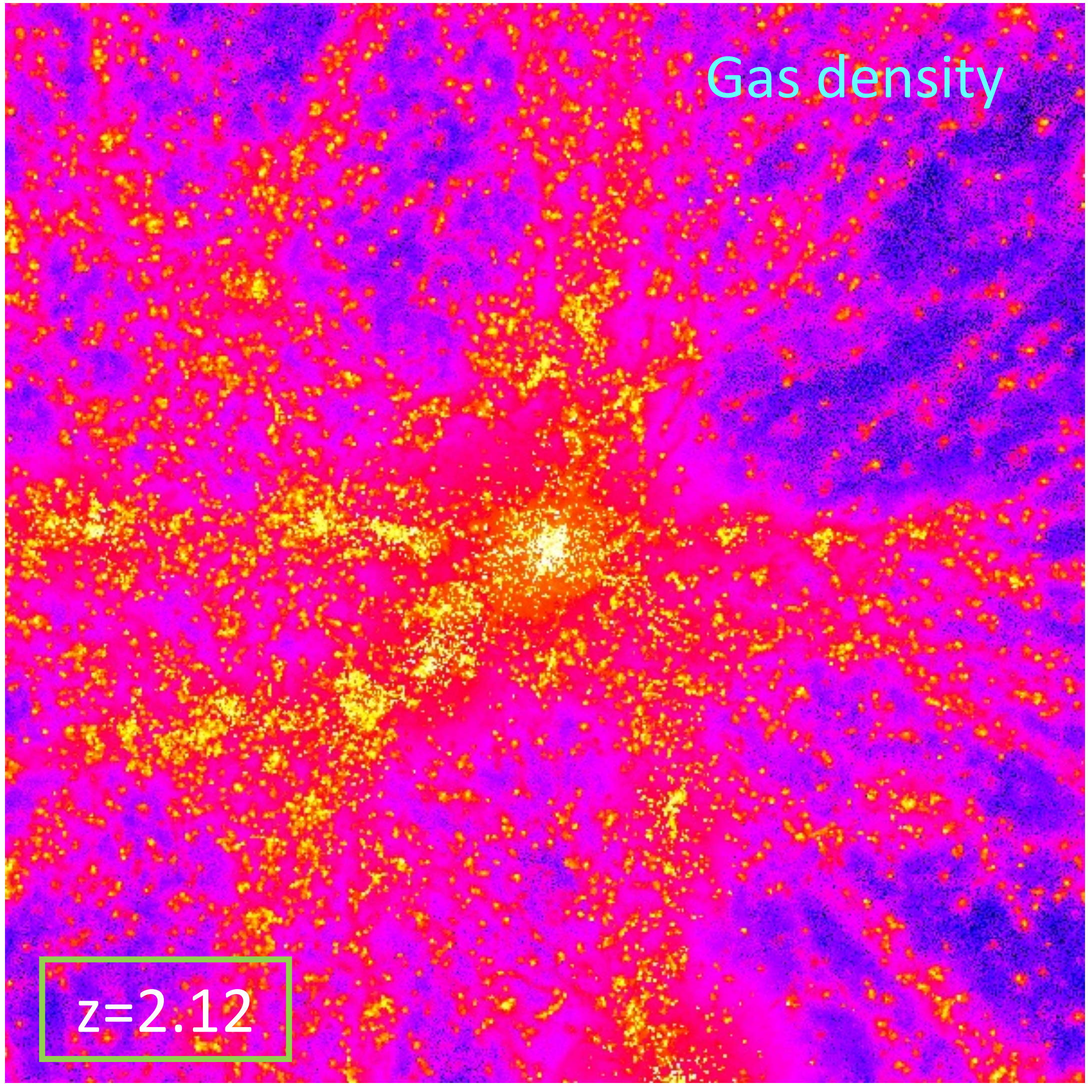
Saro, SB et al. 2009



- ➔ 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 (see talk by Nina Hatch; poster by Paola Dimauro)

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:

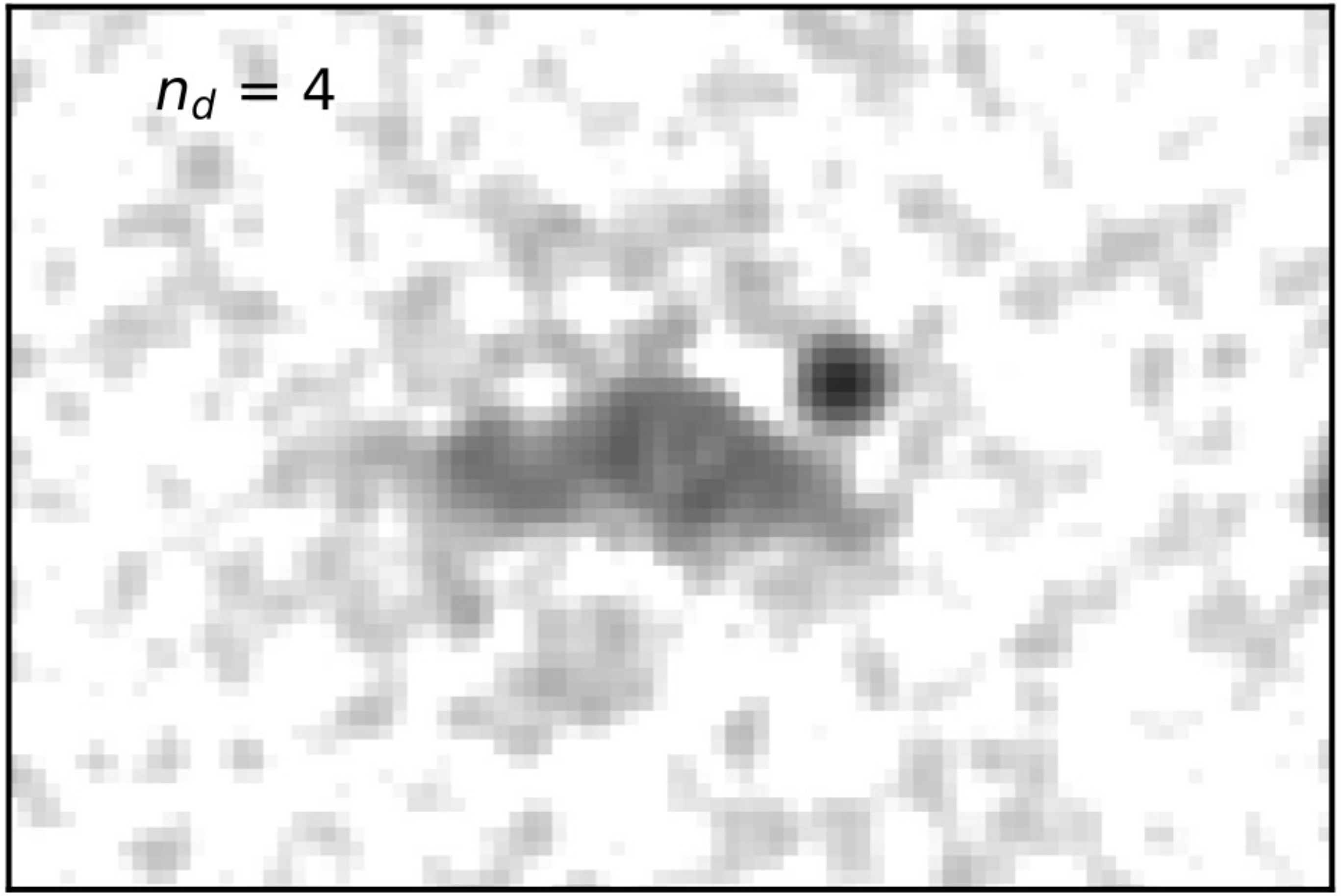
$L_{0.5\text{-}2}= 1.4 \times 10^{44}$ erg s^{-1}

$T_X=3.8$ 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

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

T_X=3.8 keV

Z_{Fe}= 0.57 $Z_\odot$

Observed

$L_{0.5-2}$= (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)*

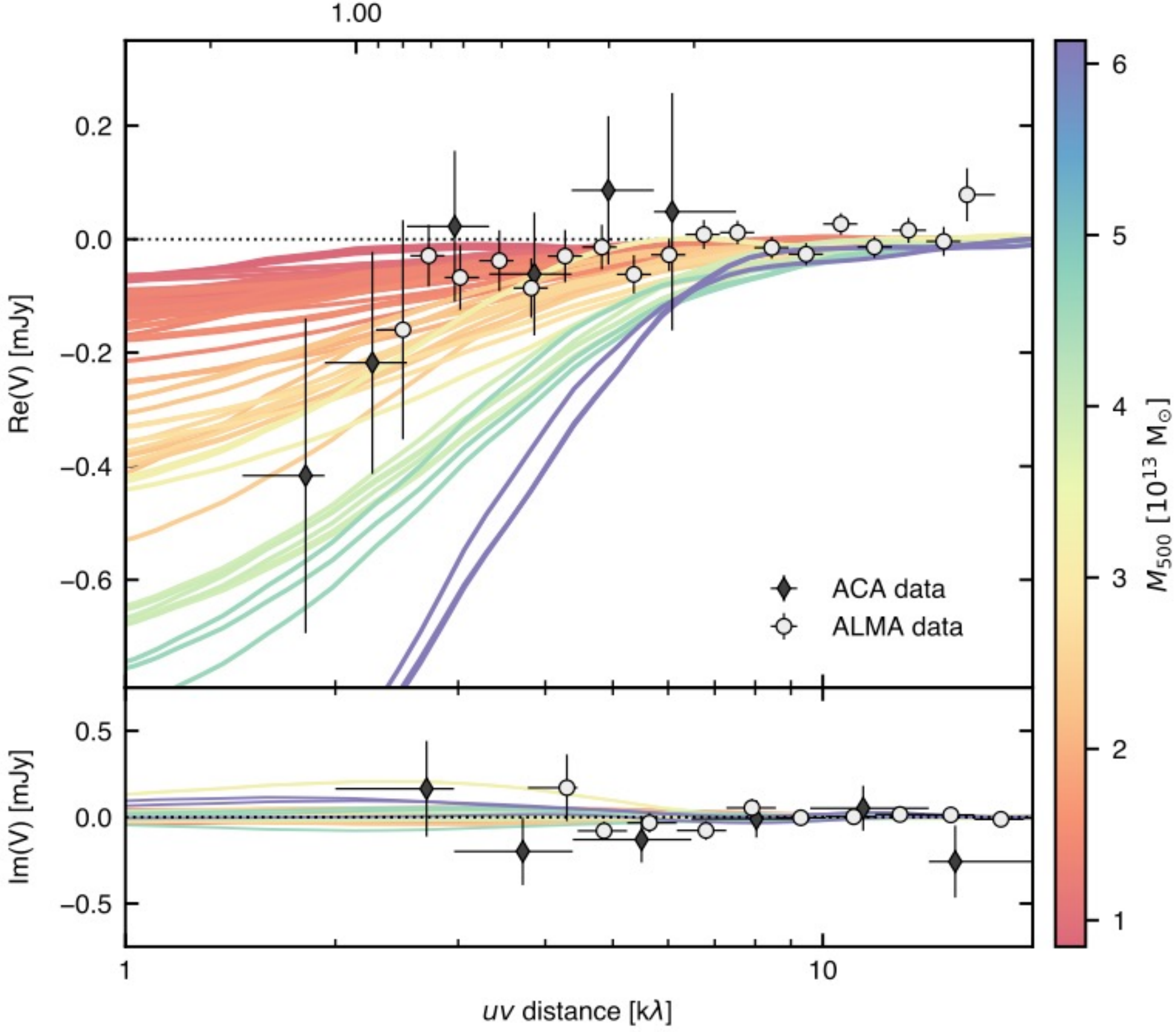
→ ALMA+ACA observations secured the detection of the SZ signal from the proto-ICM (significance at $\simeq 6\sigma$)

→ 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

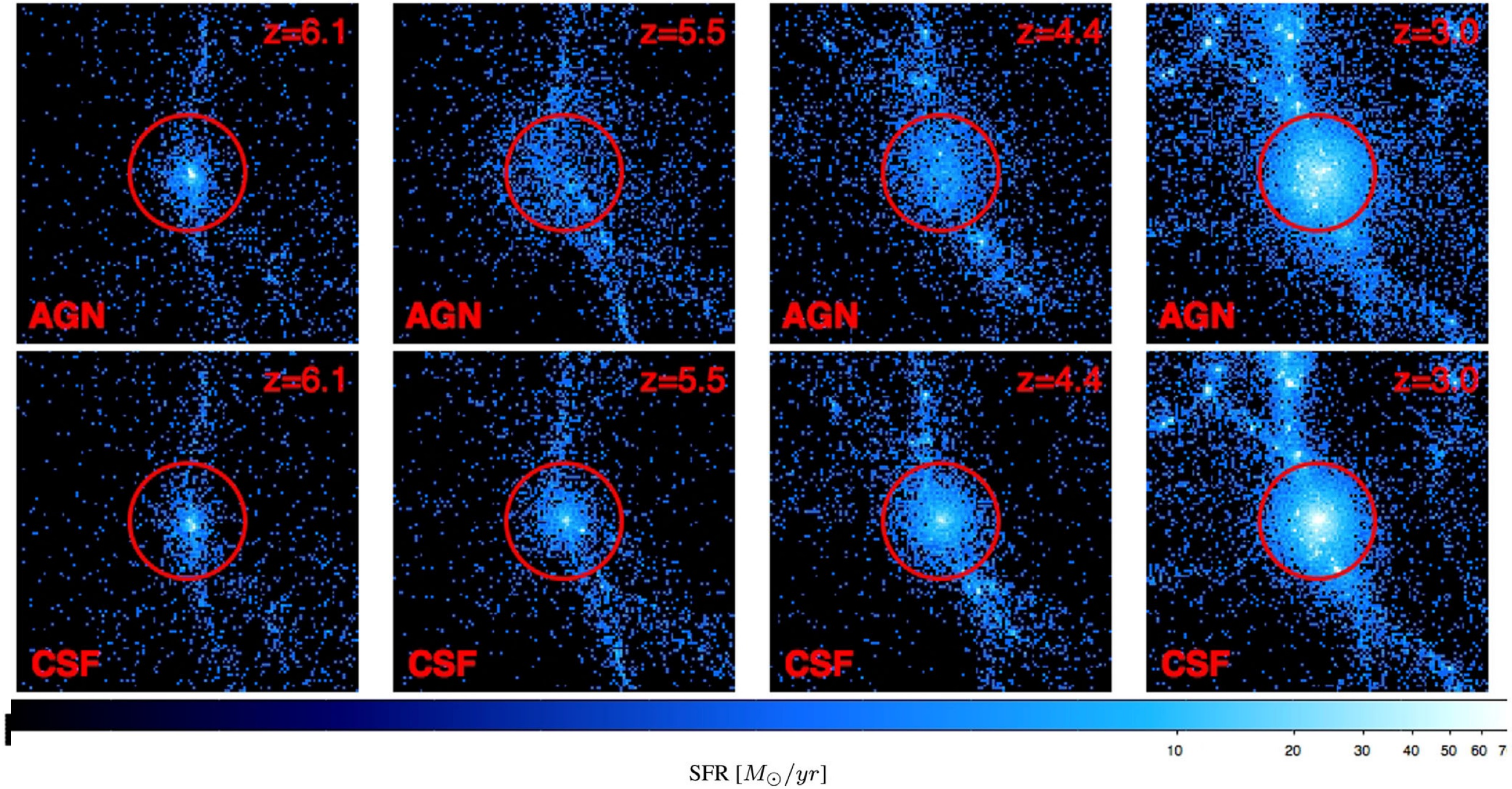
Biffi et al. 2017

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

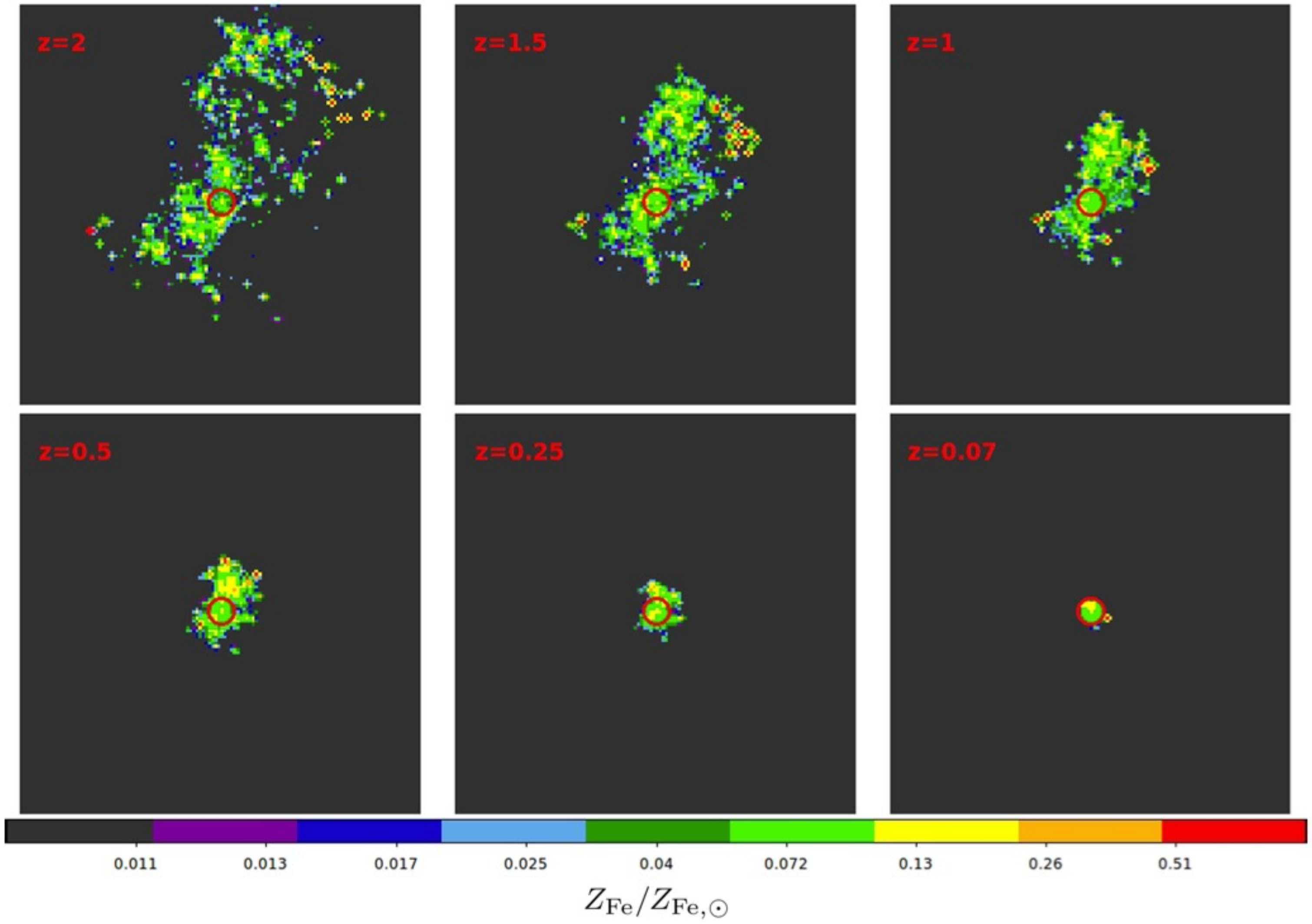
Biffi et al. 2018 (see also Fabjan+2014, McCarthy+2015)

→ Prediction on metallicity of ICM outskirts with AGN feedback in line with Suzaku observations (Urban+2017)

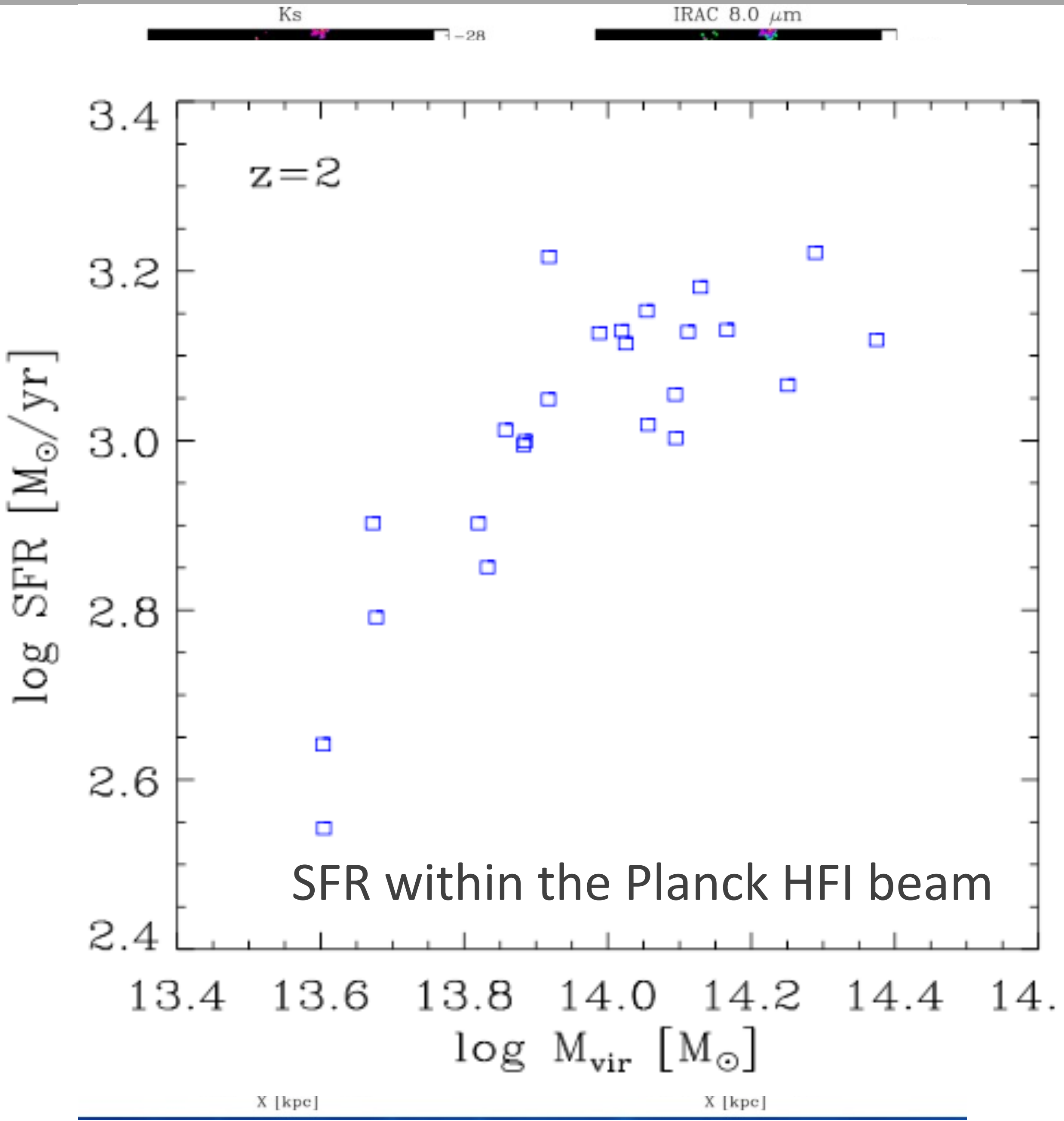
→ Track to z=2 the ICM residing in cluster outskirts $(0.8 < R/R_{vir} < 1.2)$

→ 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)*

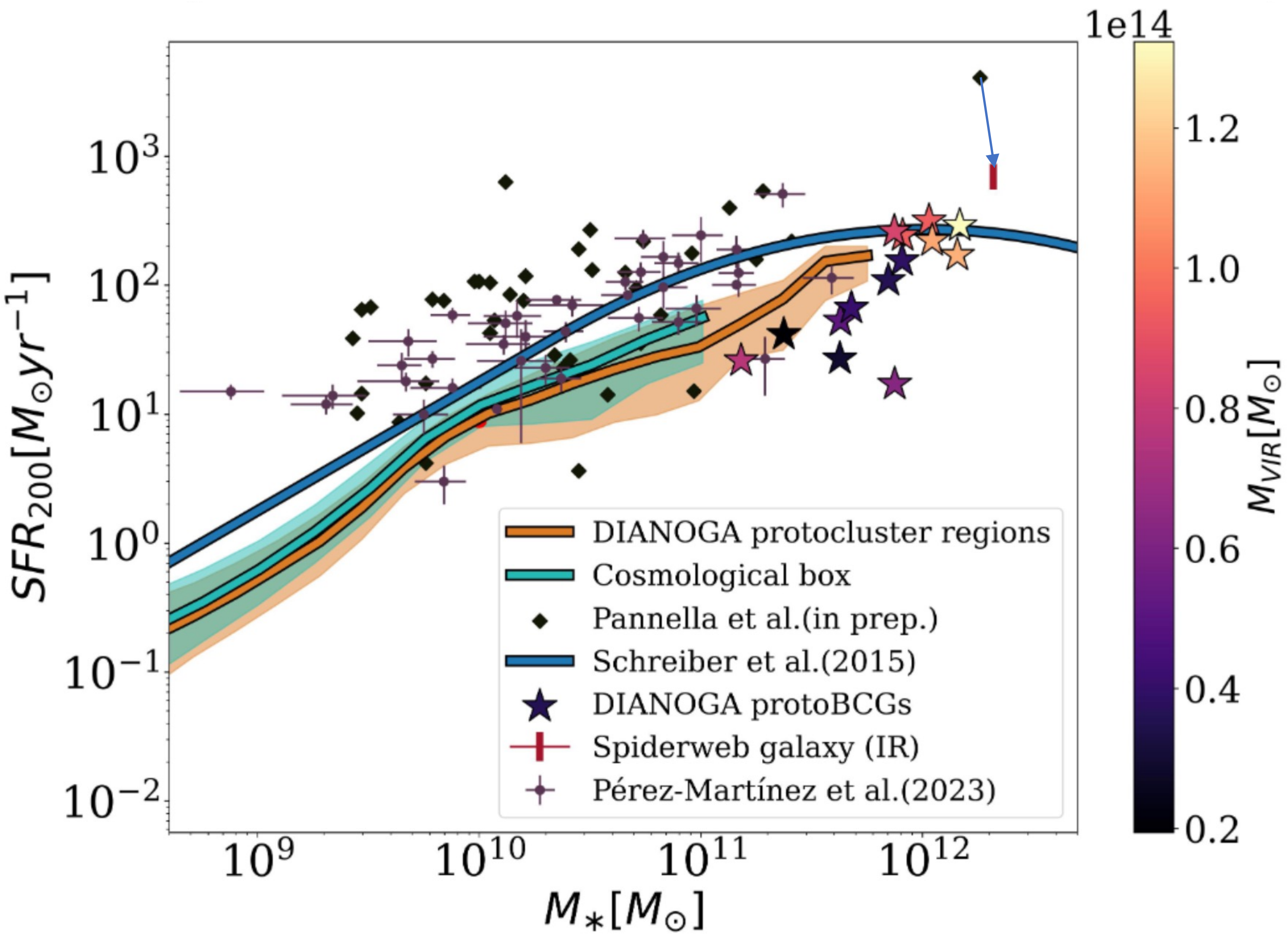
➔ Far larger than obtainable from simulations

- 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?

Star formation in proto-cluster regions

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



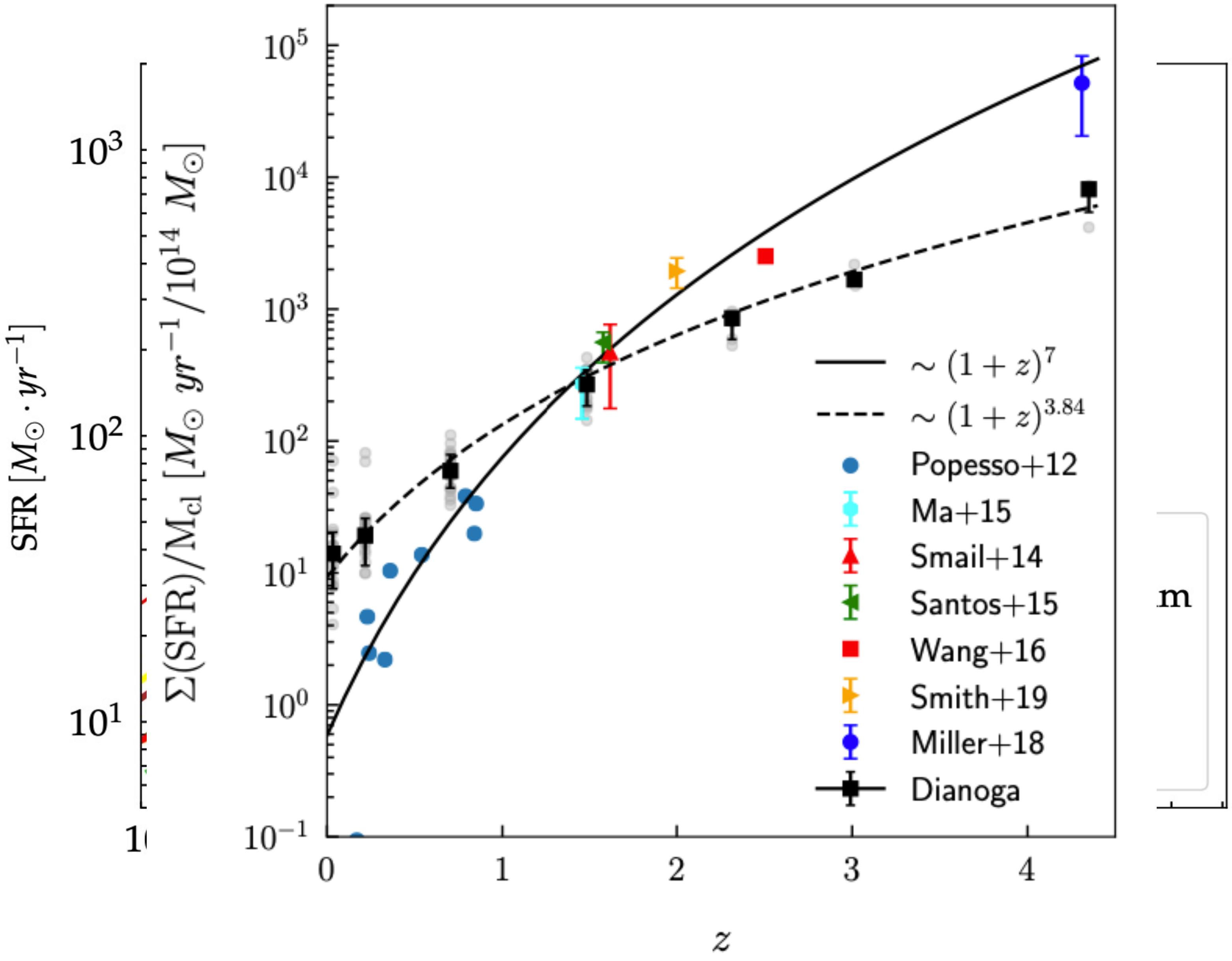
→ Model-prediction of the main sequence at z~2 below the observed one, both in the field and in protocluster

→ Result almost independent of the adopted model of SF

→ SFR of the Spiderweb much reduced when including IR data, besides UV dust-corrected fluxes *(Pannella et al. 2024, in prep)*

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

Star formation in proto-cluster regions



(Bassini et al. 2021)

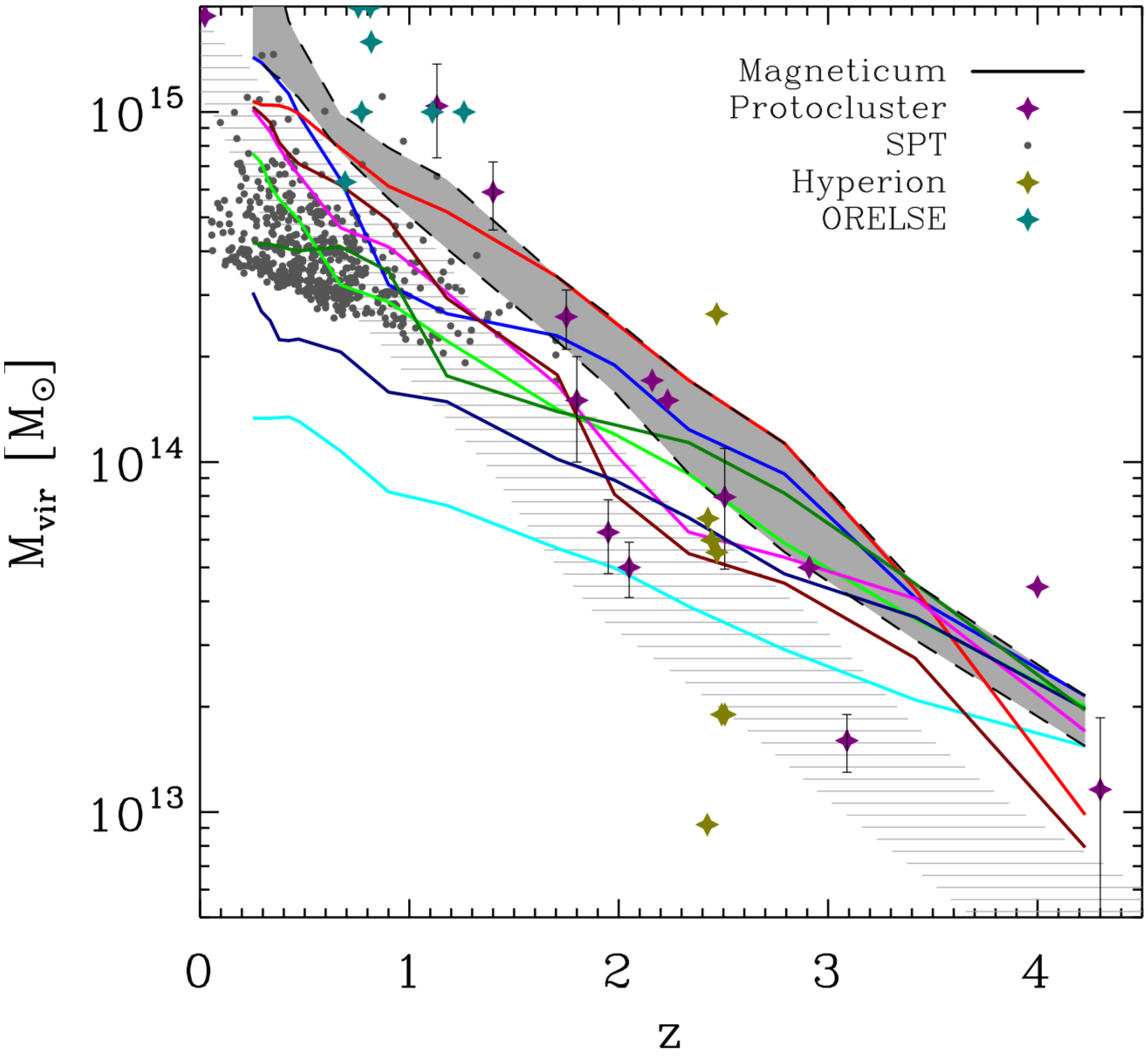
→ Apparently a common feature of several semi-analytical and full hydro simulations

→ 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

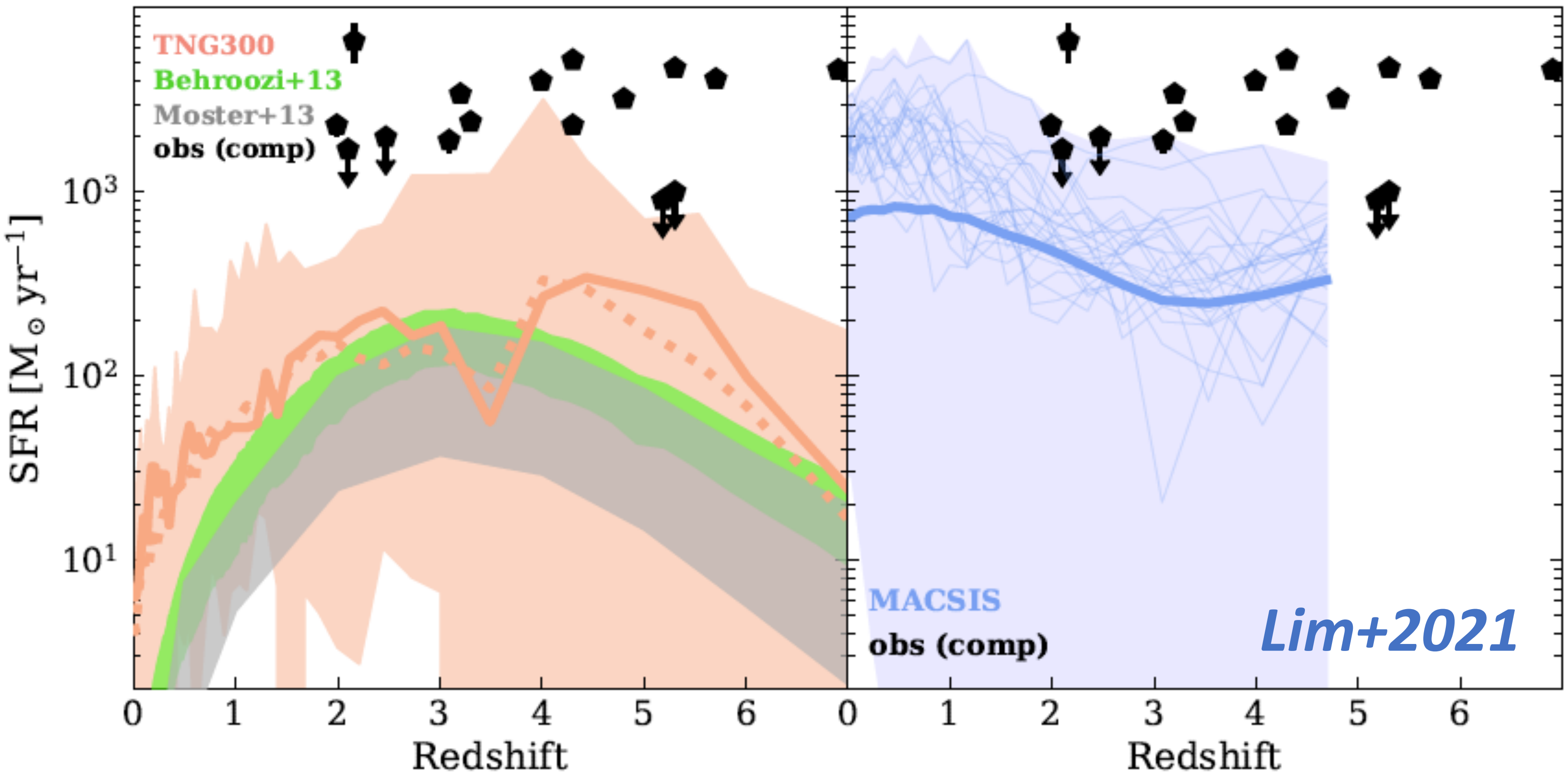
Use Magneticum cosmological boxes to:

- 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

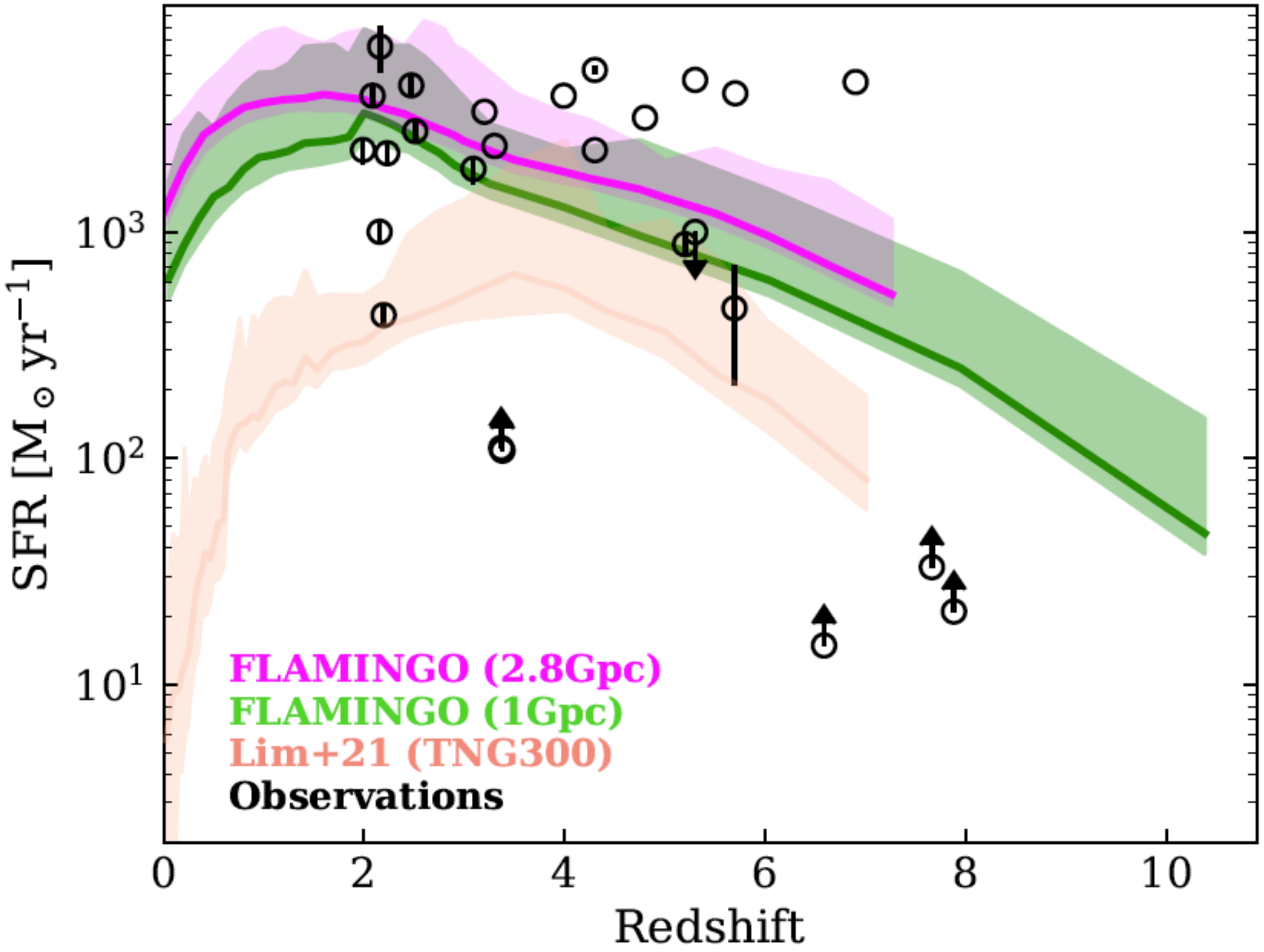


Comparison of <u>TNG300 & MACSIS</u> predictions on SFR in proto-clusters to observational data

→ 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

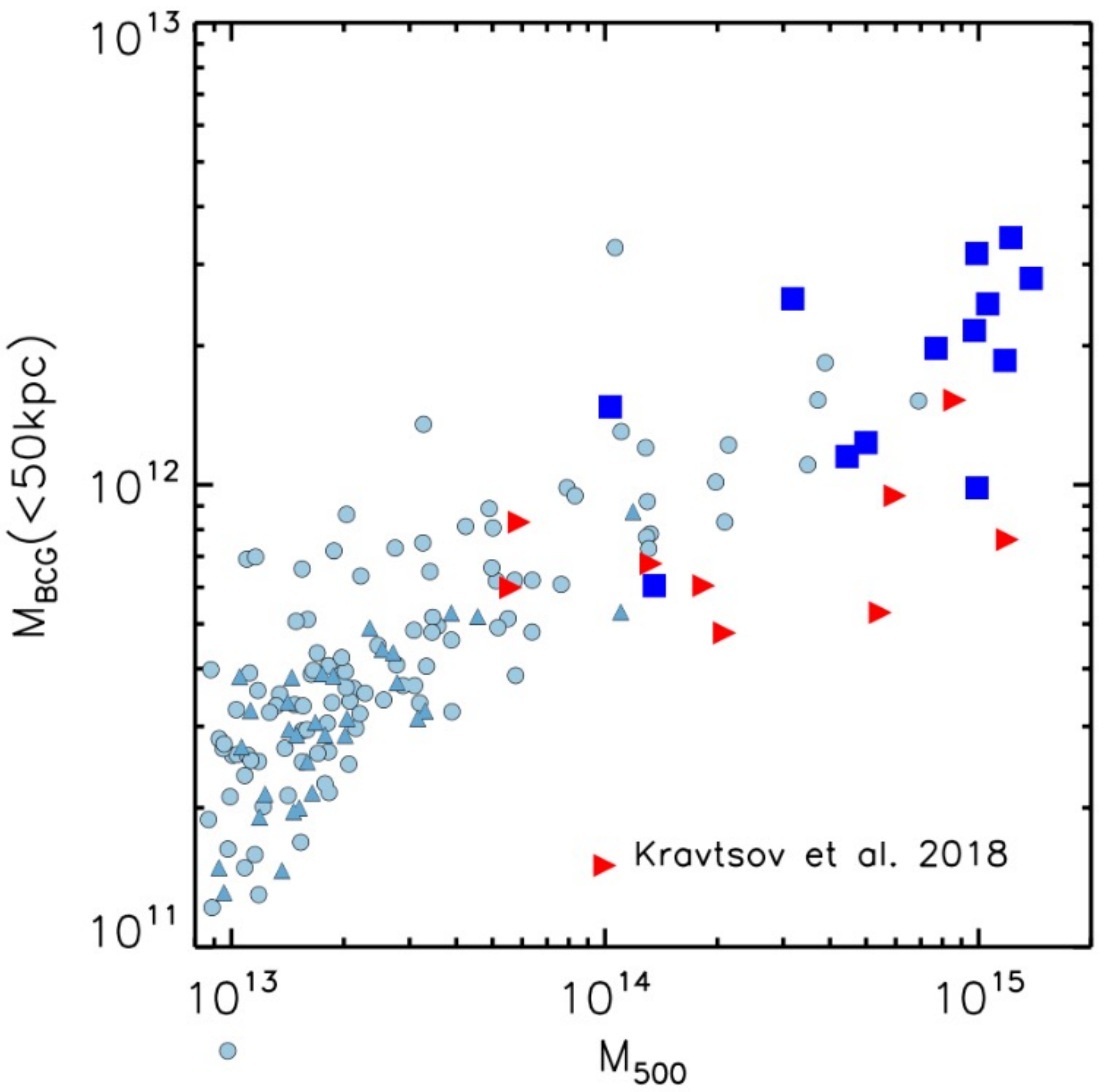
But:

- 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)

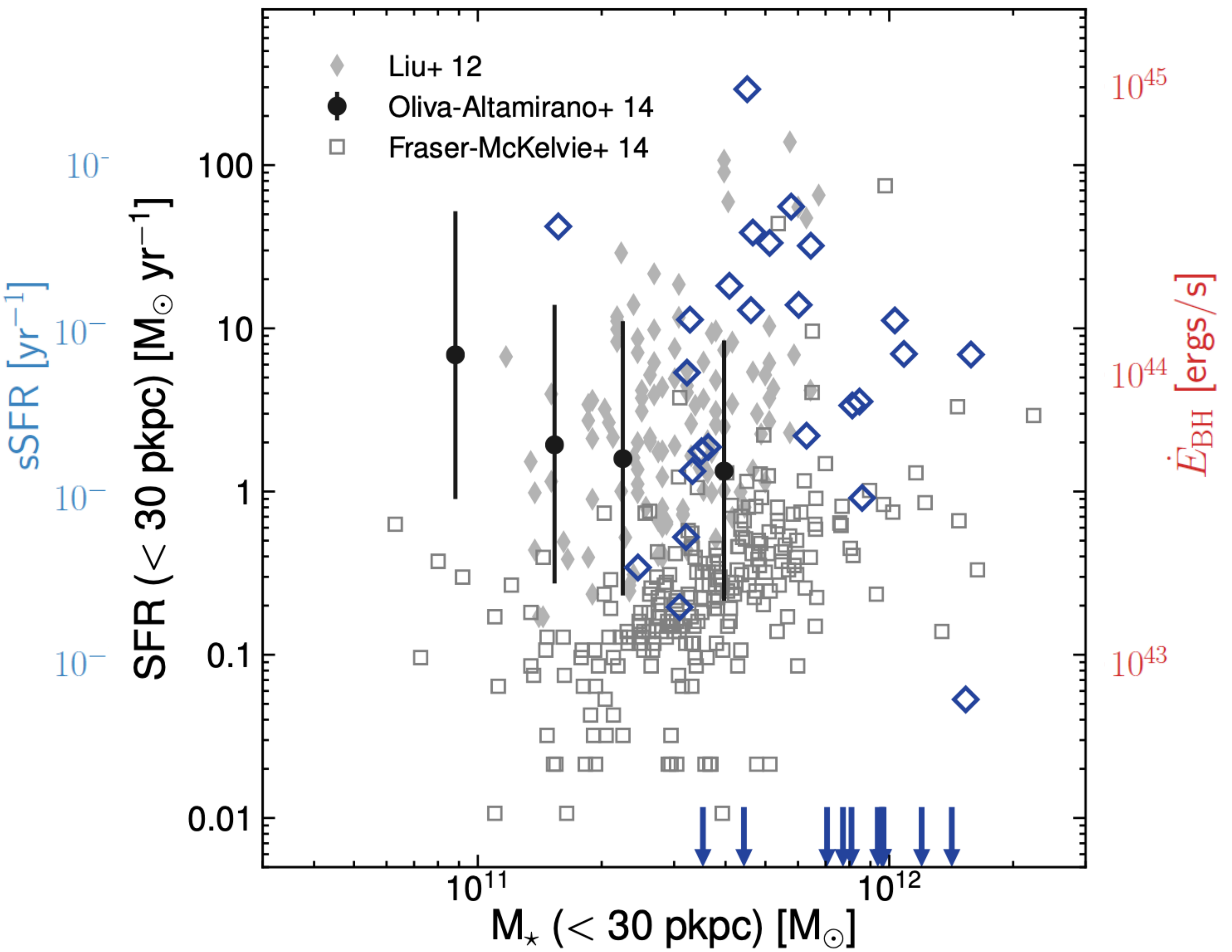
Tremmel+2019 – RomulusC (ChaNGa)

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

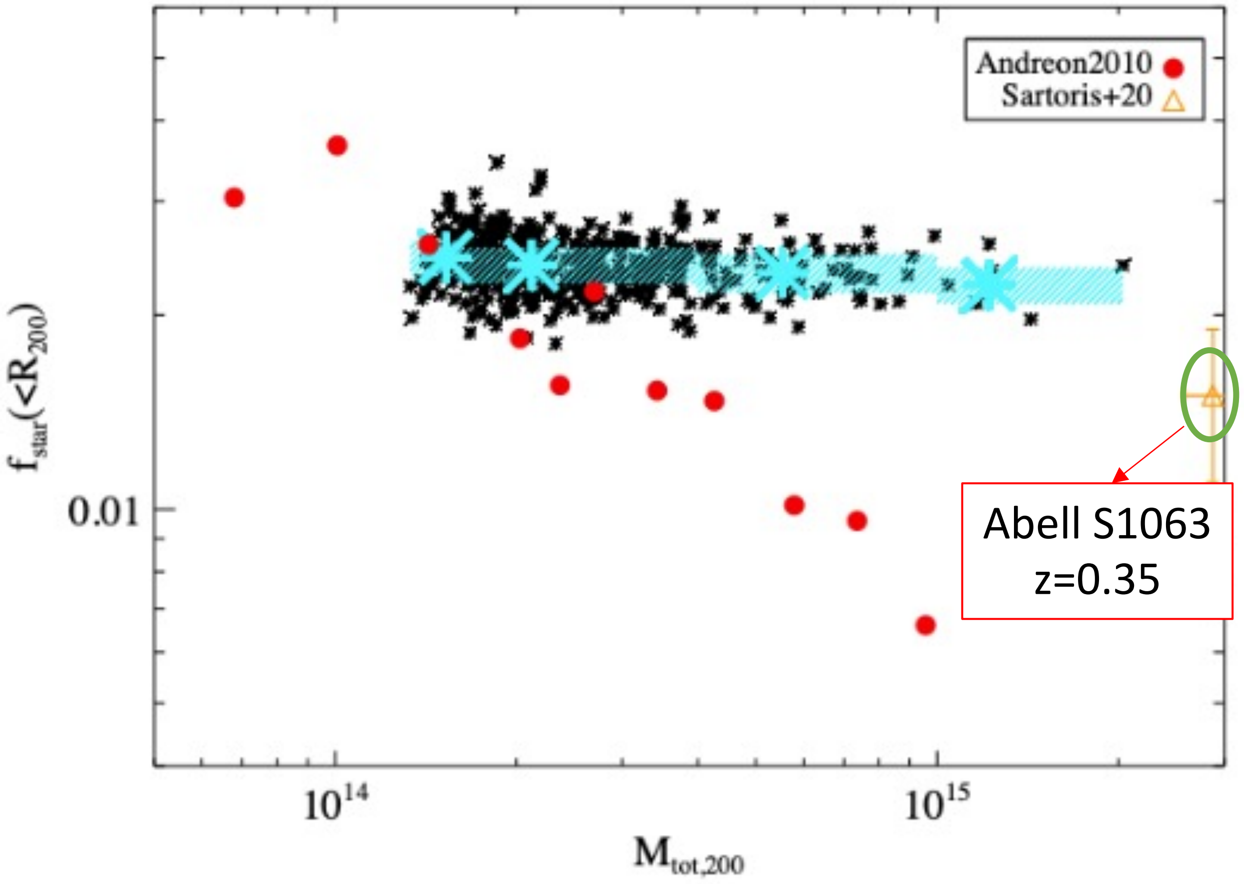
➔ FABLE (Henden+2020):

- 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 in prep: 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 $M_{\mathrm{Fe,gas}} - M_{\mathrm{gas},500}$ relation

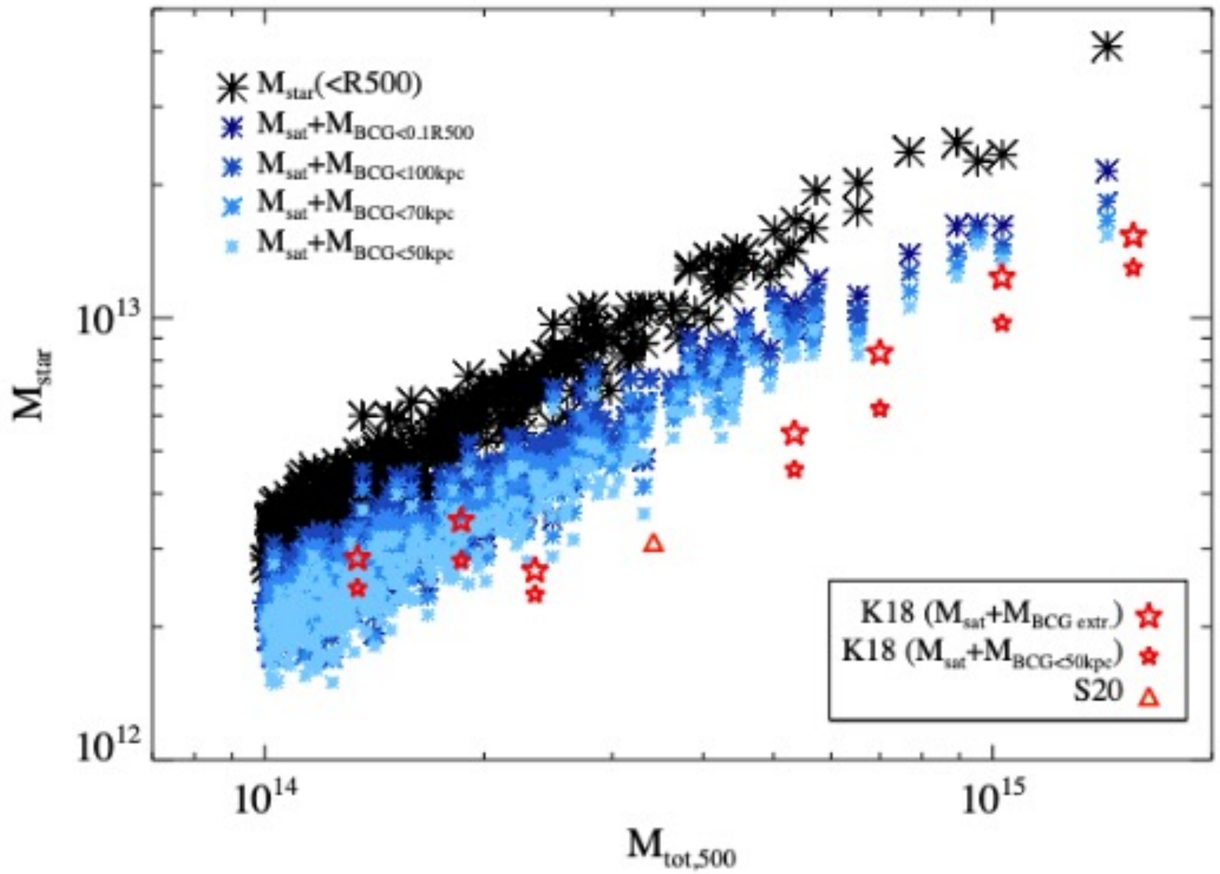
➔ Due to excess of star formation in simulations? Quite possible, but then correct ICM Fe content just a coincidence... (see also Molendi+2024)

➔ 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!!

Metal share in galaxy clusters

$$\Im_{500} \equiv \frac{M_{Fe,500}}{Z_{\odot} M_{star,500}}$$

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 in prep: 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 $M_{Fe,gas} - M_{gas,500}$ relation

➔ Due to excess of star formation in simulations?

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

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 *(waiting for MUPPI….)*
- Need to quench SF in BCGs and reduce their stellar masses at low redshift *(new tests done @ 25x)*
- Too much mass in metals predicted by simulations to be locked in stars – but ICM metallicity OK…

→ Simulations need to produce bursty SF at $z = 2 - 4$, then a highly efficient feedback mechanism:

- to rapidly quench SF;
- 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?