Han+ 2025, accepted to A&A,
arXiv:2507.06301

NewCluster

: A high-resolution galaxy cluster simulation

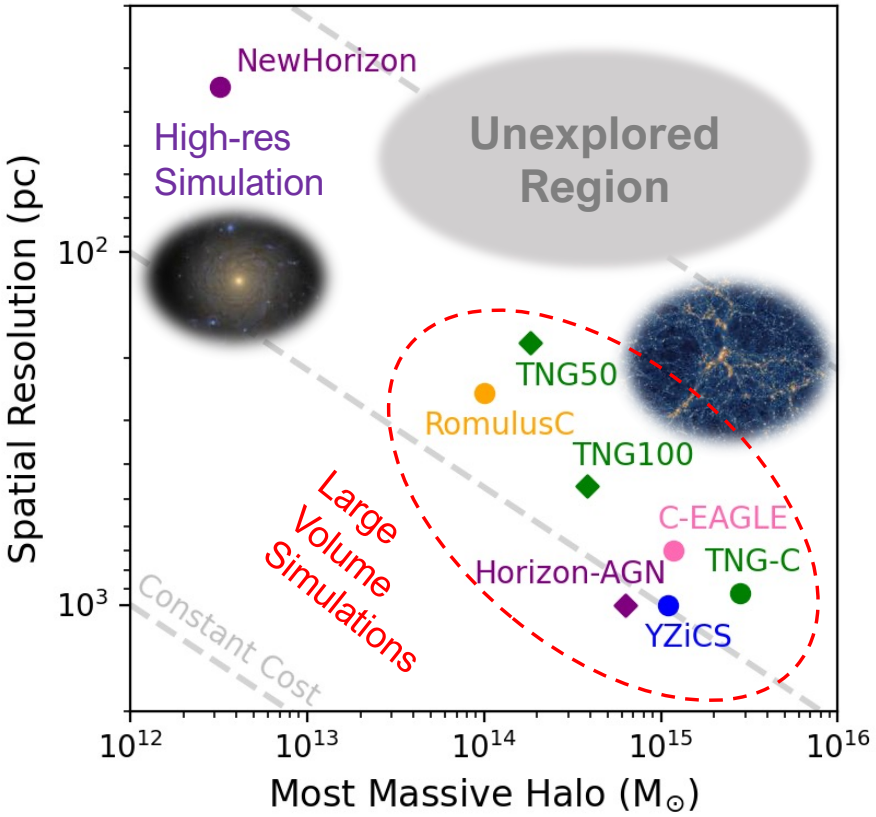
San Han[1]

Sukyoung Yi[2], Yohan Dubois[1]

Jinsu Rhee[1,3], Seyoung Jeon[2], J. K. Jang[2], Gyeong-hwan Byun[2], Corentin Cadiou[1], Taysun Kimm[2], Juhan Kim[4] and Christophe Pichon[1]

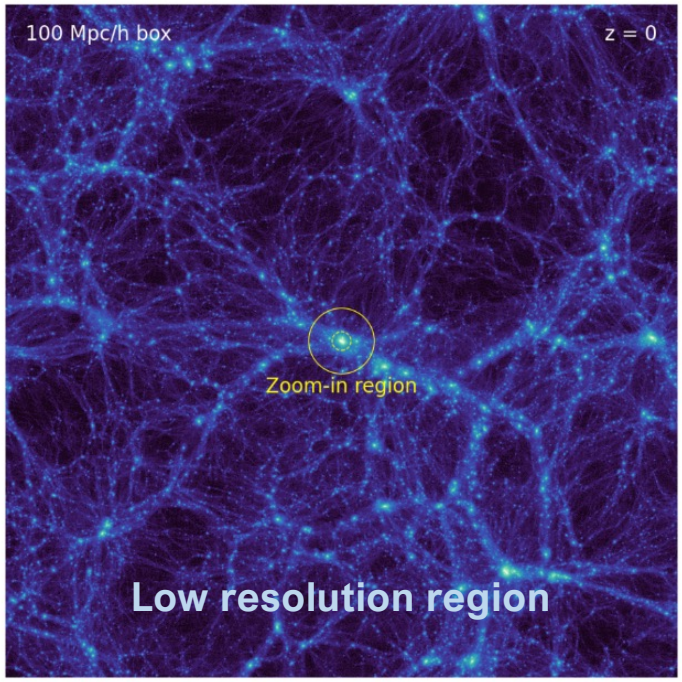
[1]Insitut d'Astrophsique de Paris, [2]Yonsei University, [3]Korea Astronomy and Space science Institute, [4]Korea Institute of Advanced Study

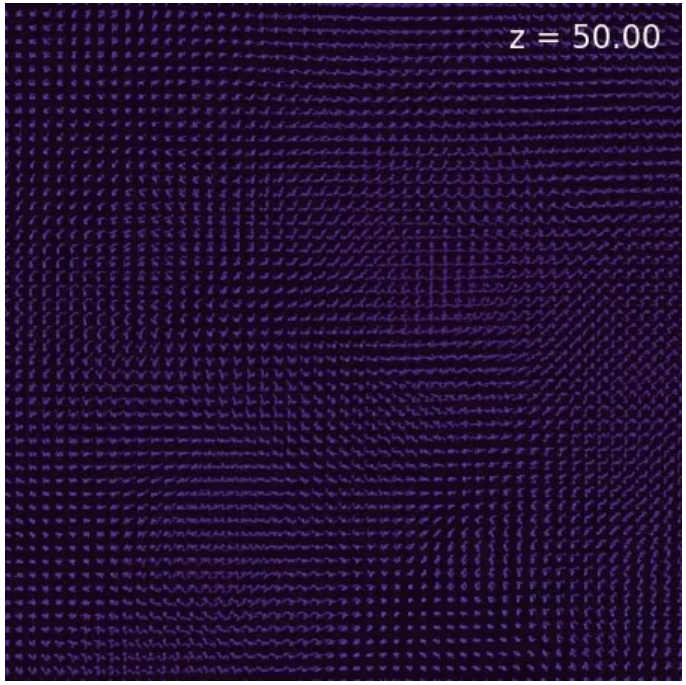
Galaxy Clusters: The last frontier of cosmological simulation



- **Massive and Hot** – CFL condition constrains the time resolution for the numerical reproduction
- **Interactive** – As galaxies are highly interactive to each other, simulation must cover **complete cluster**, requiring a large amount of data to be processed

Setting up the Zoom-in Simulation



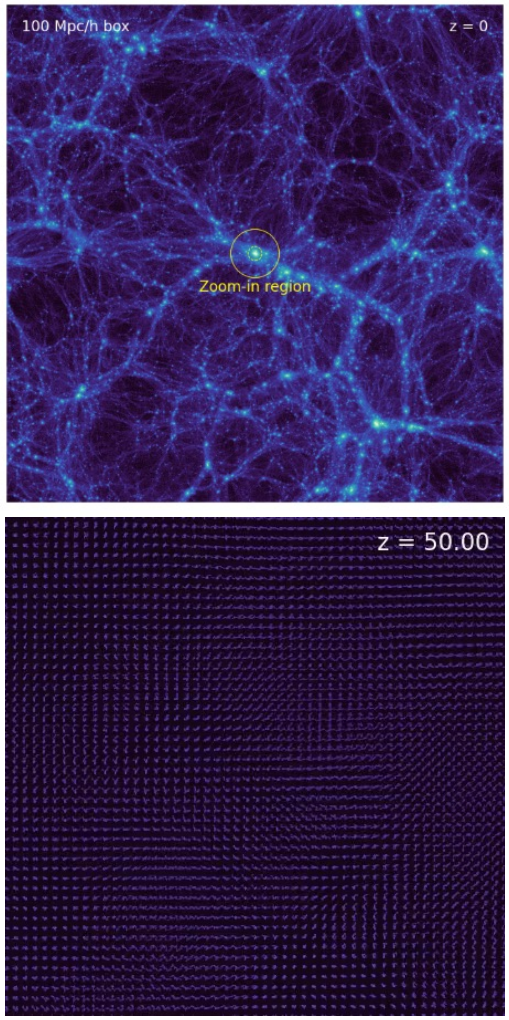


Founding simulation - Zoom-in target selected from pre-run DM-only volume simulation with $(100\text{Mpc/h})^3$

Zoom-in region selected centering target cluster with $M_{vir} \sim 4.7\times10^{14}M_{\odot}$ and up to $3.5R_{vir}$, containing the total mass of $\sim8.6\times10^{14}M_{\odot}$.

Target cluster experiences **Major Merger** at z ~ 0.7-0.4

General descriptions for the simulation



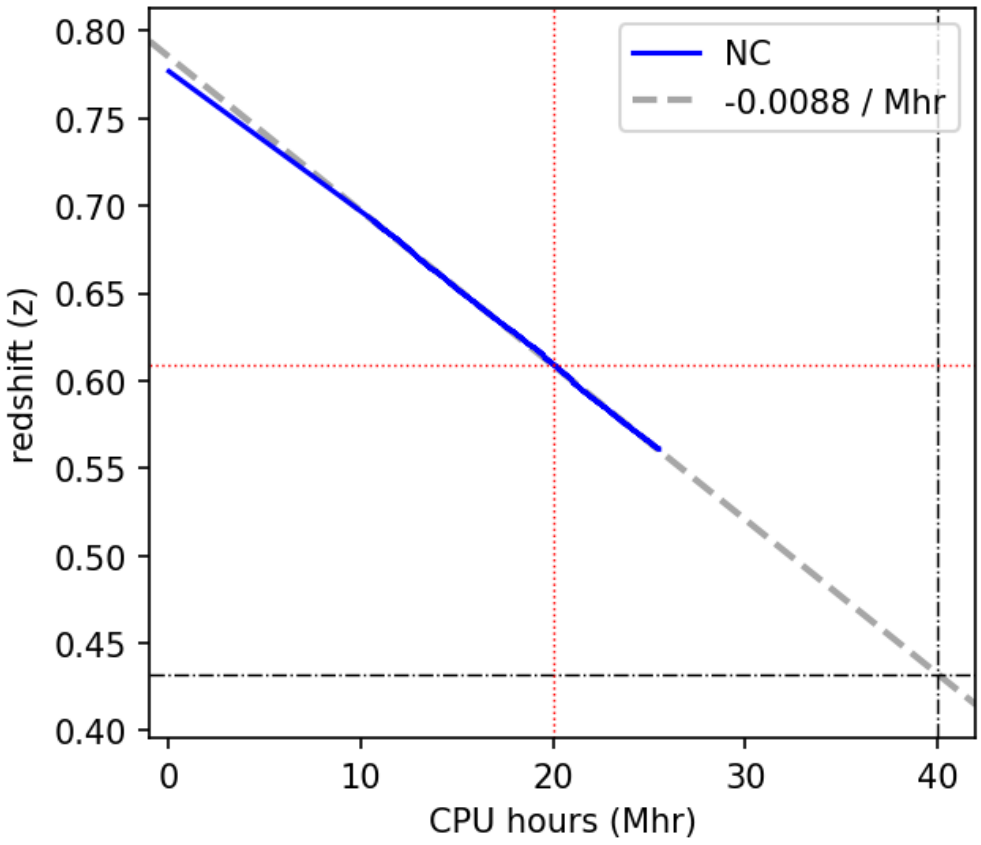
Specs and Dimensions

- **Code: RAMSES-yOMP** (an OpenMP version of RAMSES)
- **Mass: 8.6 × 10^{14} $M_\odot$** (zoom-in region), **4.7 × 10^{14} $M_\odot$** (M_{vir} of the final cluster)
- **Volume:** ~23,300 Mpc^3 (zoom-in region)
- **Resolution: ~70pc (Hydro, Gravity), ~2 × 10^4 $M_\odot$ (Star), ~1.3 × 10^6 $M_\odot$ (DM)**
- **Cosmology:** WMAP (h=0.704, Ω_Λ=0.728, Ω_m=0.272)

Baryonic Physics

- **Stellar feedback** - Mechanical feedback from Core-collapse SN (Kimm & Cen 14, Kimm+ 17), delay time fixed to 5 Myr
  - **Type Ia SN** - Mechanical feedback same as SNc, delay time distribution derived from Maoz+ 12
  - **Stellar winds** from Starburst99 with Geneva model (Schaller+ 92)
- **Black Holes** - Thermal / Kinetic AGN feedback (Dubois+ 12)
  - Dynamical friction from gas (Ostriker 99, Dubois+ 13), DM and stars (Pfisher+ 19)
  - Spin evolution (McKinney+ 12, Dubois+ 21)
  - **New formation criteria** for seeds (high stellar density)
- Cooling & heating – Gas cooling (Sutherland & Dopita 93), UV background (Haardt & Madau 96)
- **Dust evolution** (similar to Dubois+ 24) - Carbon & Silicate with 2 sizes, 0.005 and 0.1μm
- **Chemical enrichment -** 9 Chemical species (**H, C, N, O, Si, S, Mg, Fe, D**) – **Thanks to improvements on the memory management of OpenMP!**

Inherited Features **New Features**



Running the simulation

Selected Supercomputing Times

- KISTI Supercomputing Center (Nurion)
  - KSC-2022-CRE-0088 (20M hours)
  - KSC-2022-CRE-0344 (20M hours)
  - KSC-2023-CRE-0343 (20M hours)
  - KSC-2024-CHA-0009 (70M hours)
- IBS Supercomputer (Olaf) (10M hours)
- TGCC Irene-Rome
  - A0150414625 (40M hours)
  - **A0180416216 (40M hours, ongoing)**

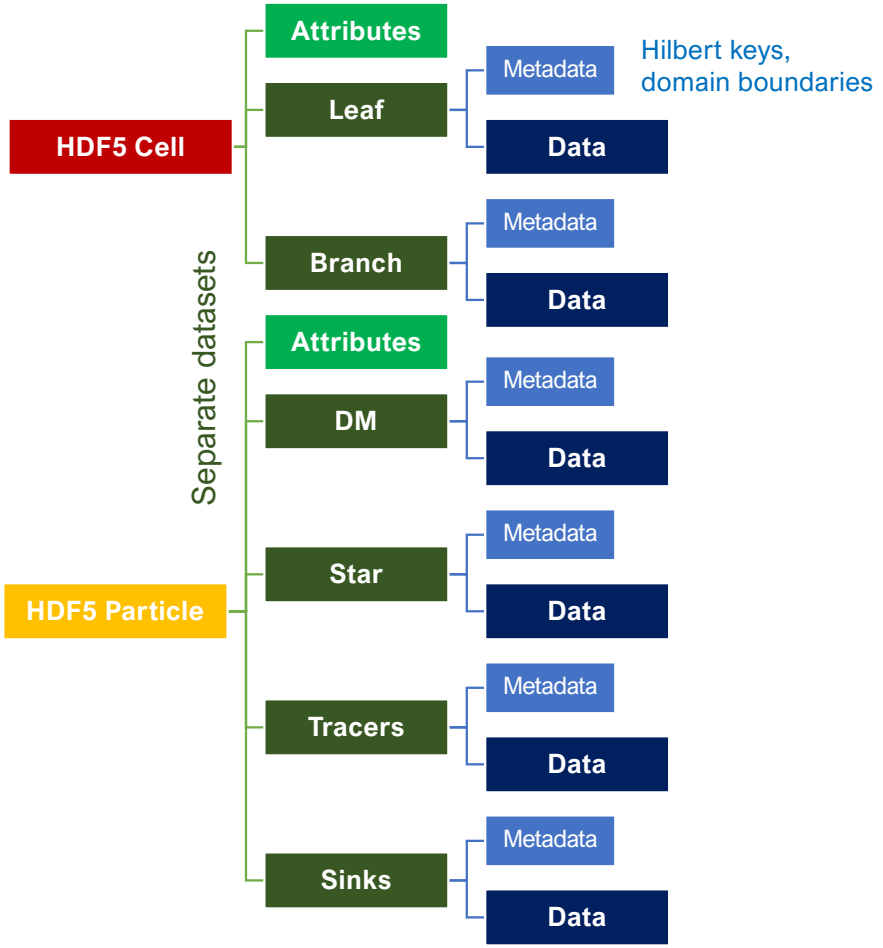
Total 220M hours (140M on Korea, 80M on France)

Timeline

- Run started on 2022/05
- Reached z=2 on 2023/03
- Reached z=1.5 on 2023/08
- Reached z=1 on 2024/07
- Reached z=0.8 on 2025/01
- Reached z=0.6 on 2025/09 @ Irene-Rome
  - Now reached z=0.56 on 2025/11, expected to reach z=0.4 on 2026/04

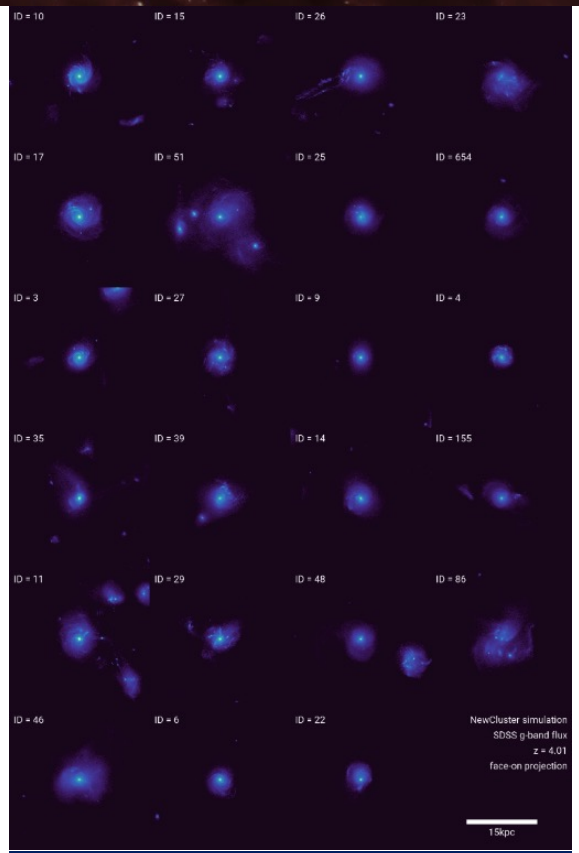
Conversion from RAMSES to HDF5 format

- **RAMSES raw format** : ~650GB / snapshot
- **HDF5 format** : ~170GB / snapshot (~25%)
  - Consists of two (part_*.h5, cell_*.h5) files
  - Double precision fields except for positions are converted to single precision
  - Reduced unnecessary / duplicate data (e.g., metallicities for DM particles, communication grids at the domain interface)
  - LZF compression for further reduction, Fletcher32 checksum for stability (performance-free)
  - New Hilbert indexing consists of 8000 domains (previously 960)

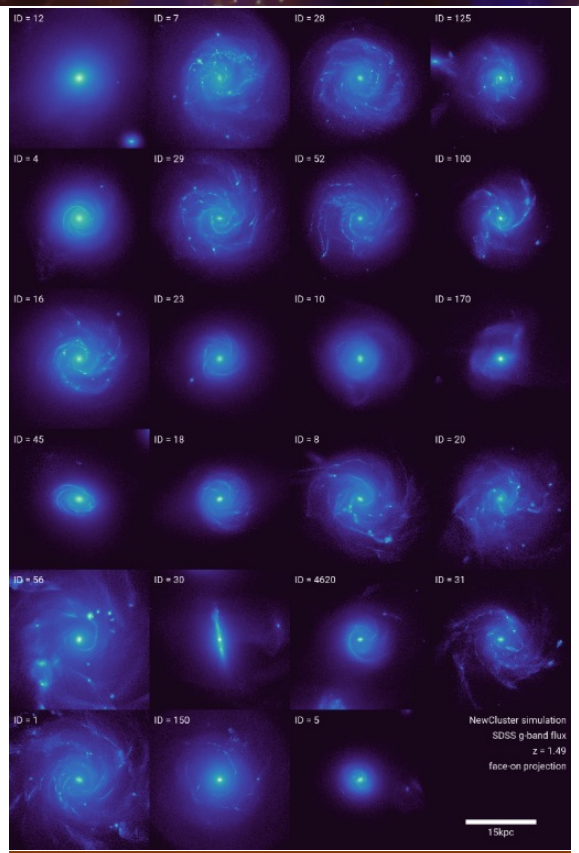



5 cMpc
The simulation has reached z=0.6 on 2025/09
NewCluster: from z = 50 to 0.8
Red: gas density, Blue: gas temperature, White: stars

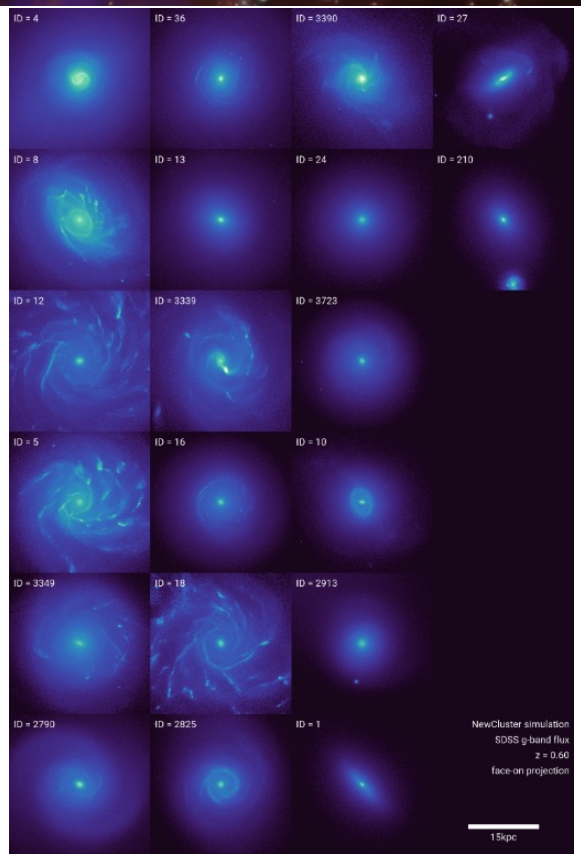
Evolution of NC galaxies



z = 4.0



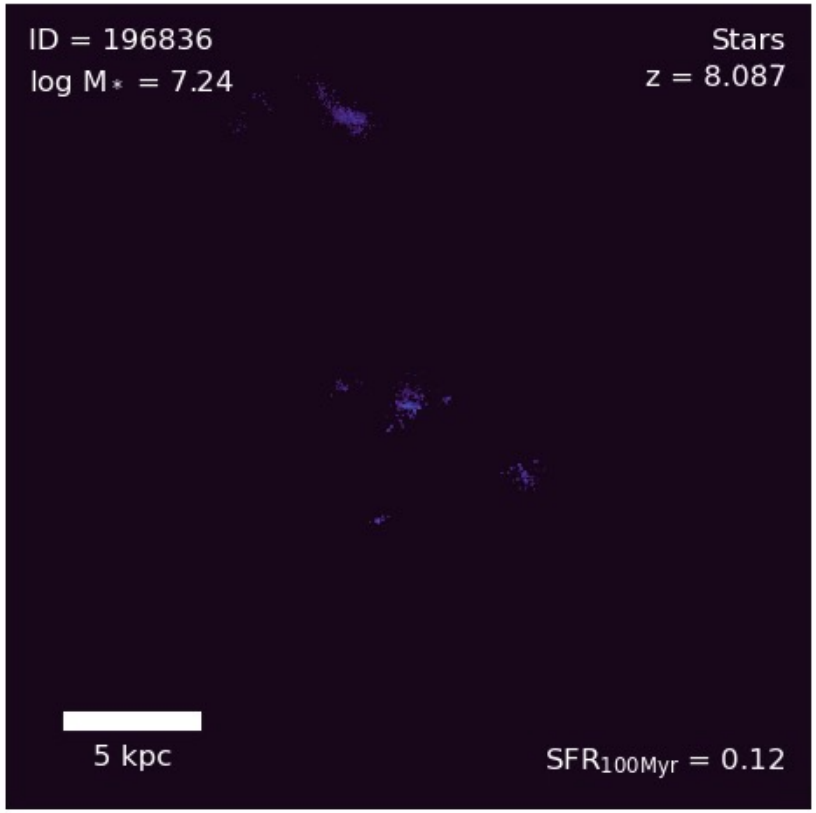
z = 1.5

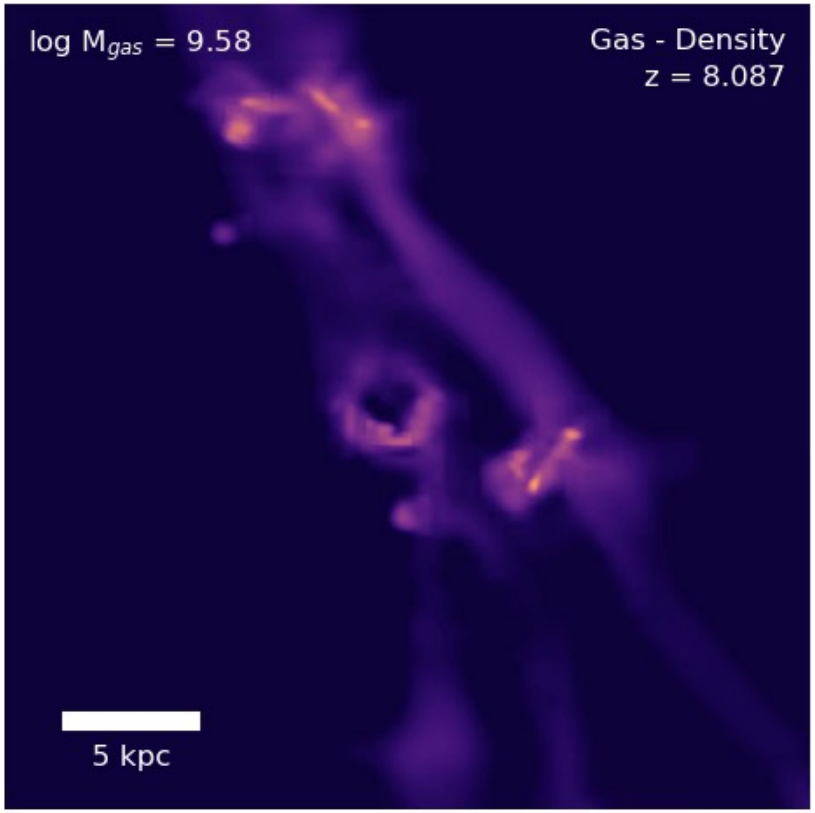


z = 0.6

Increasing population of early type galaxies over time

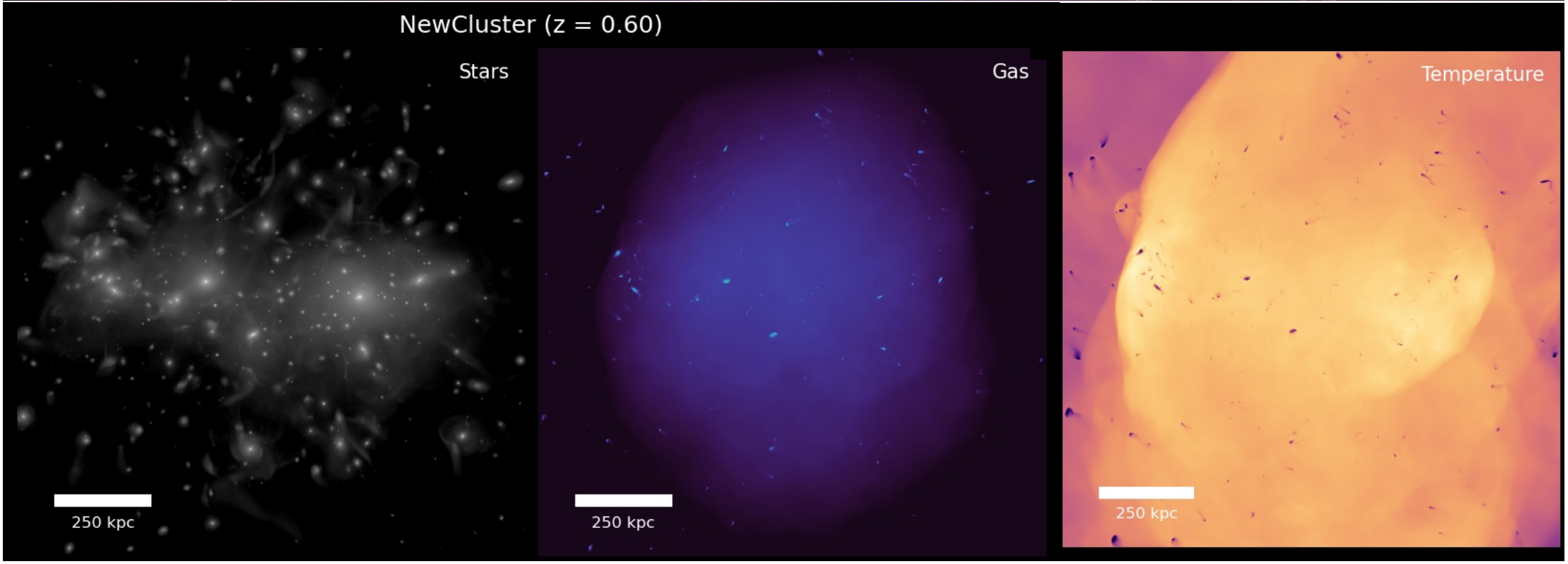
Tracing a galaxy evolution



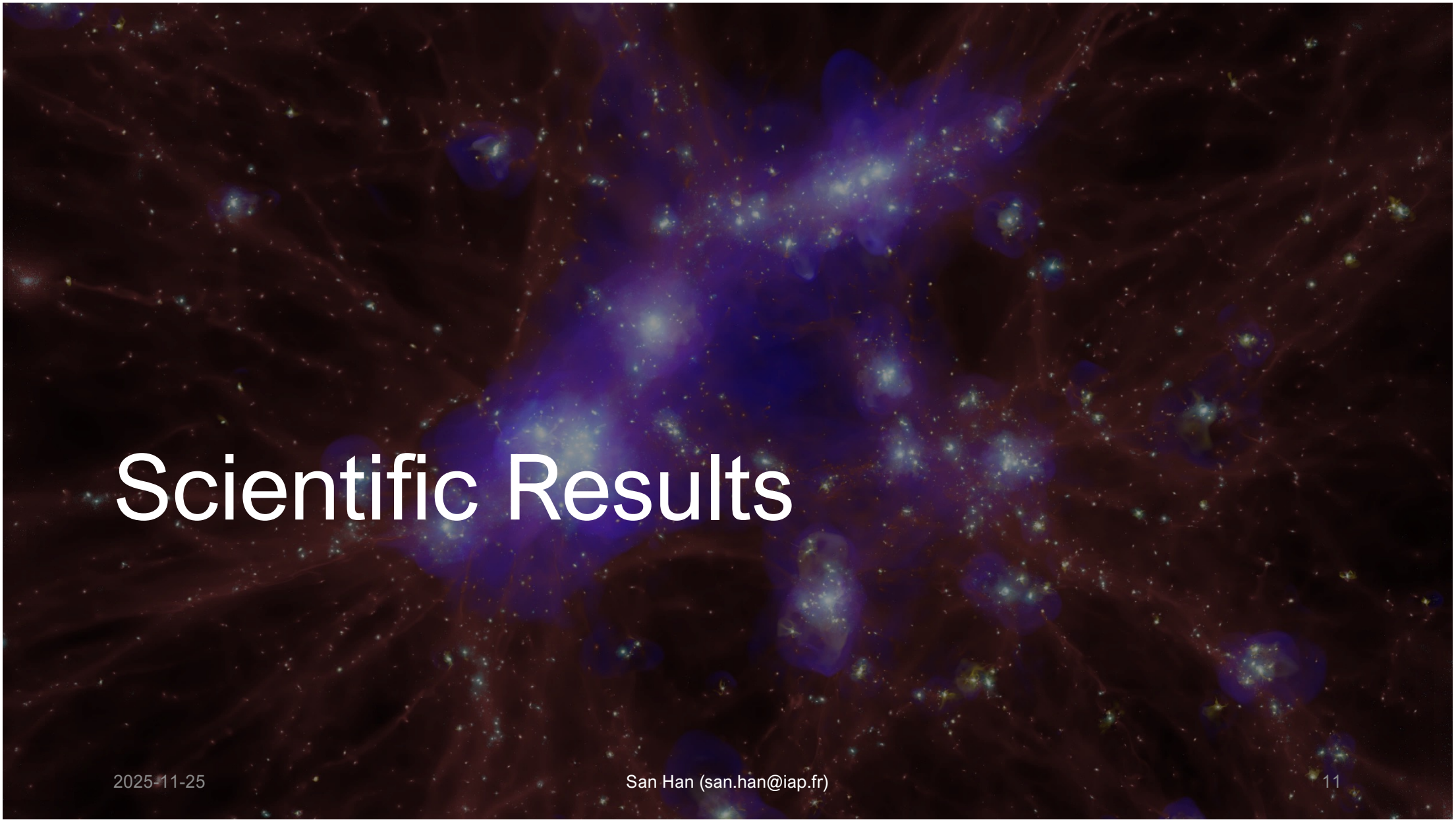


Time resolution ~ 15Myr

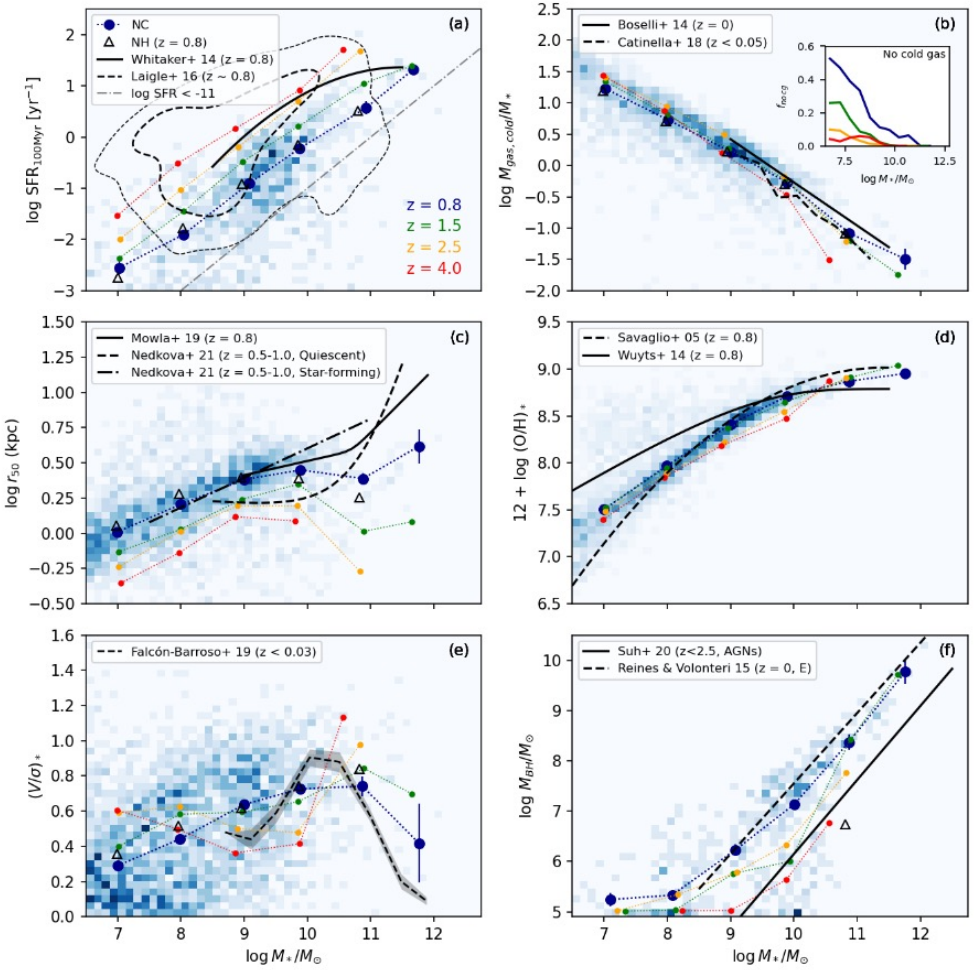
Cluster merger at z=0.6



- Dual merger shocks in a Bullet cluster–analogous ICM distribution
- The final coalescence is expected to take place at z~0.4

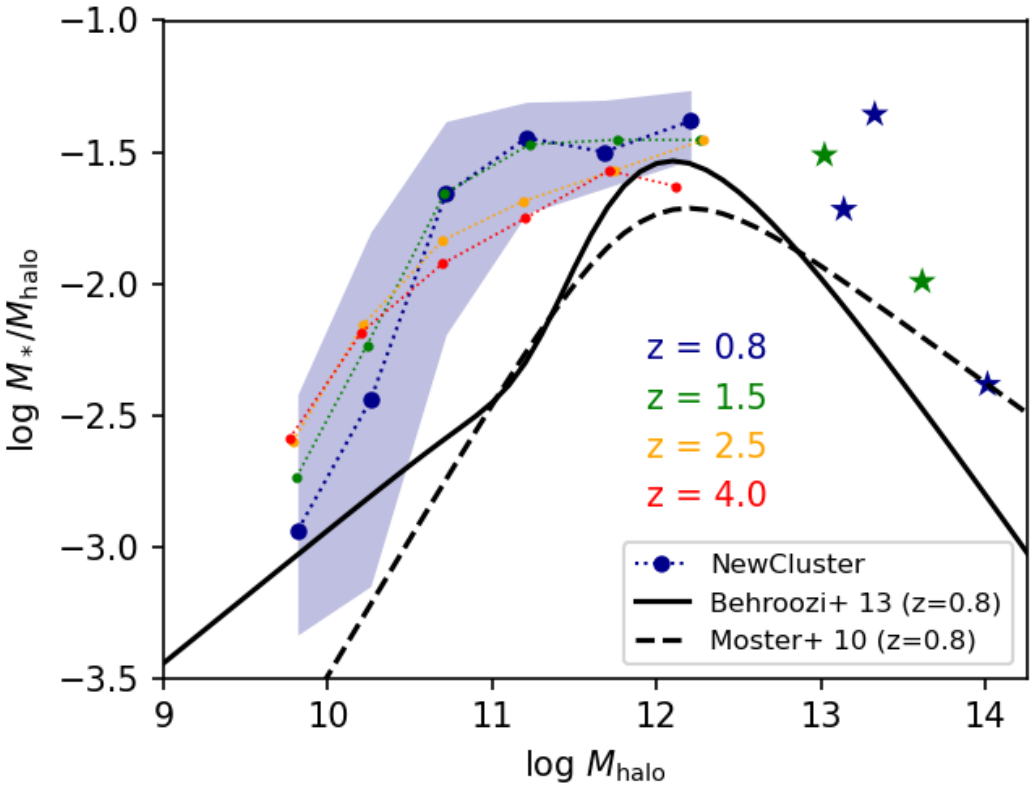

Scientific Results

Scaling relations (z = 0.8)



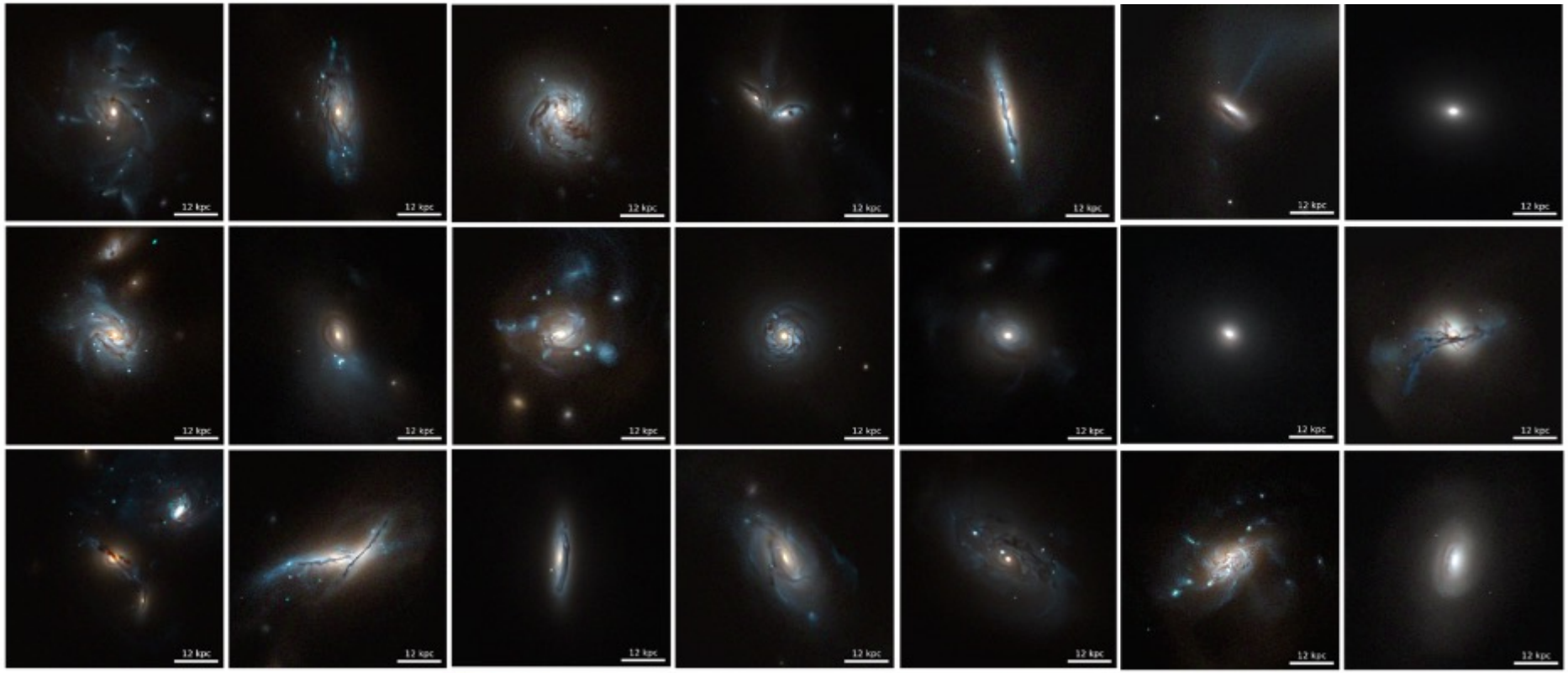
- **SFR** – Decreasing over time for all mass ranges, below the main sequence except for the high-mass end
- **Cold gas fraction** – No strong evolution, reproduces the observation at z = 0
- **Effective radius** – Strong overall increase with time, especially for high-mass galaxies
- **Metallicity** – No strong evolution
- **V/σ** - Strong evolution over time, Disk galaxies turns into slow rotator
- **BH mass** – moderate evolution over time, possibly due to the morphological transition
- Overall trend is similar to NH, except for the BH masses

Stellar to Halo Mass Relation (Centrals)



- Intermediate-mass halos show overproduction of stars compared to the empirical stellar to halo mass ratio.
- The ratio decreases halos with group sizes or above (log M_* > 13)

Galaxy Morphologies (Mock images)

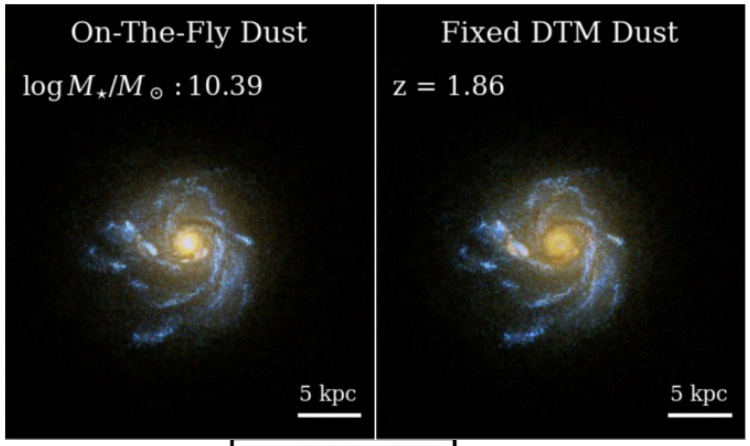


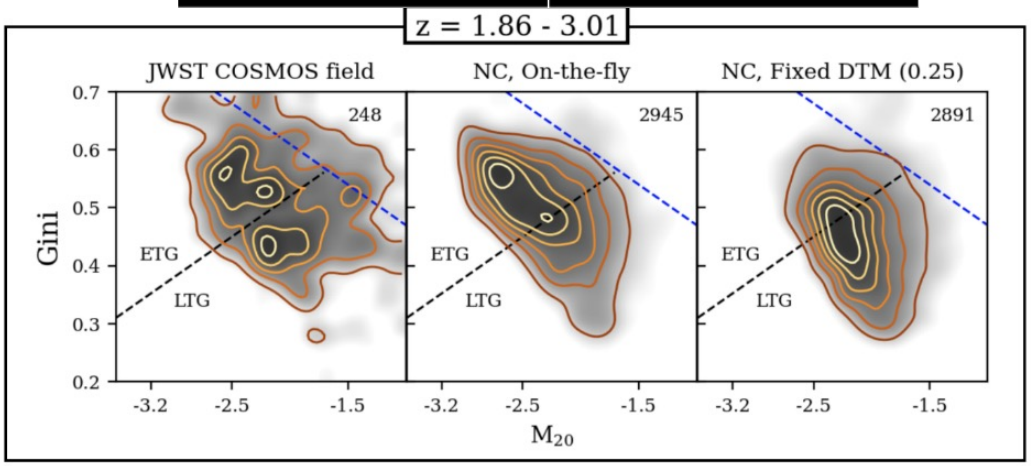
Han+ 2025

- **On-the-fly implementation of dust** allows realistic mock imaging of simulated galaxies.
- **Mock images** reveal galaxies with various morphologies and kinematics, such as **spirals**, **ellipticals**, **lenticular**, **irregular galaxies**

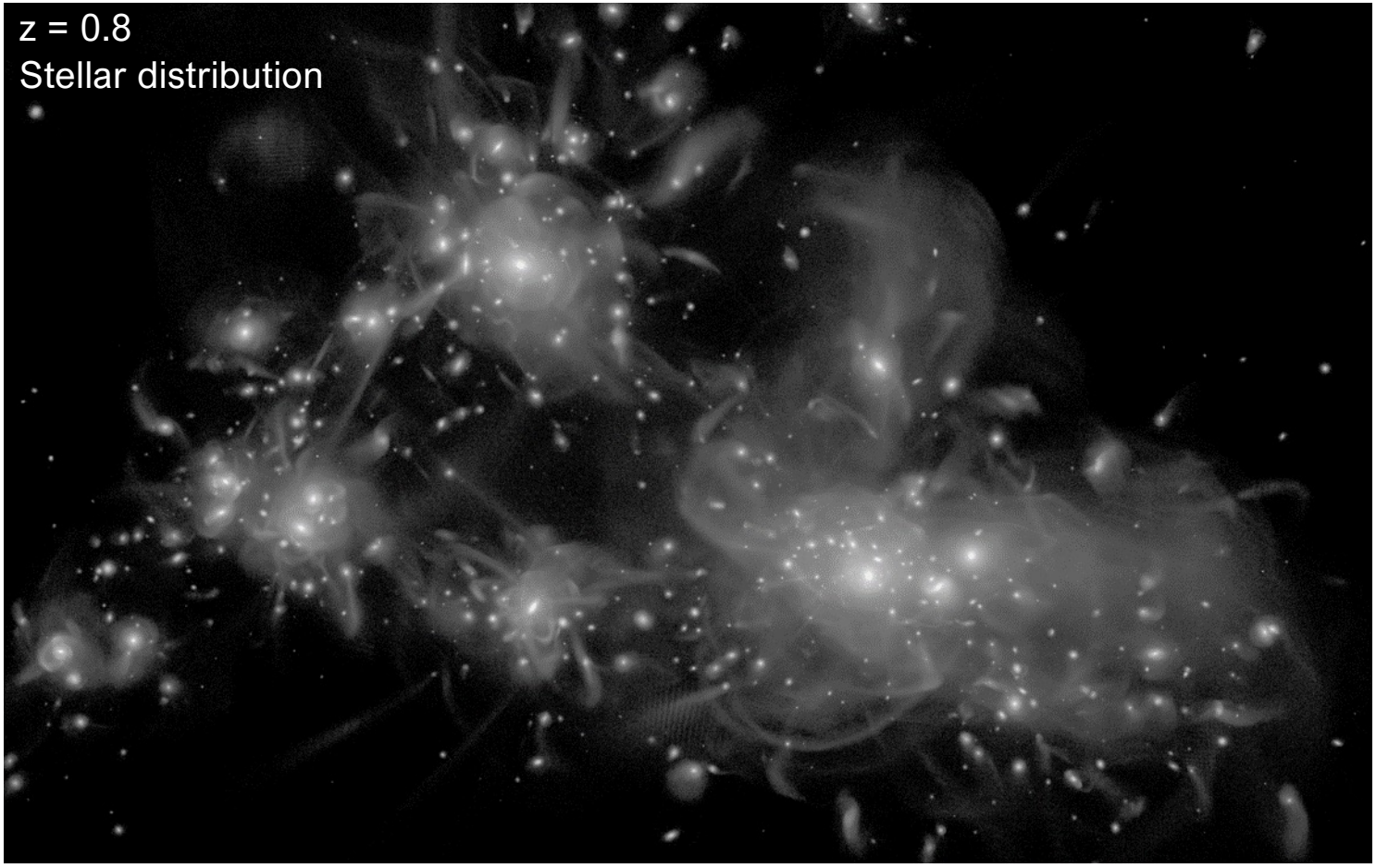
Effect of on-the-fly dust models (Byun+ 2025, published in ApJ)

- Compared to previous model, **the on-the-fly dust model** produces mock images of galaxies with centrally enhanced brightness, driven by the presence of a ‘dust-to-metal cavity’ created by the intense central starburst.
- This result in higher fraction of morphological early-type galaxies in high-z universe.

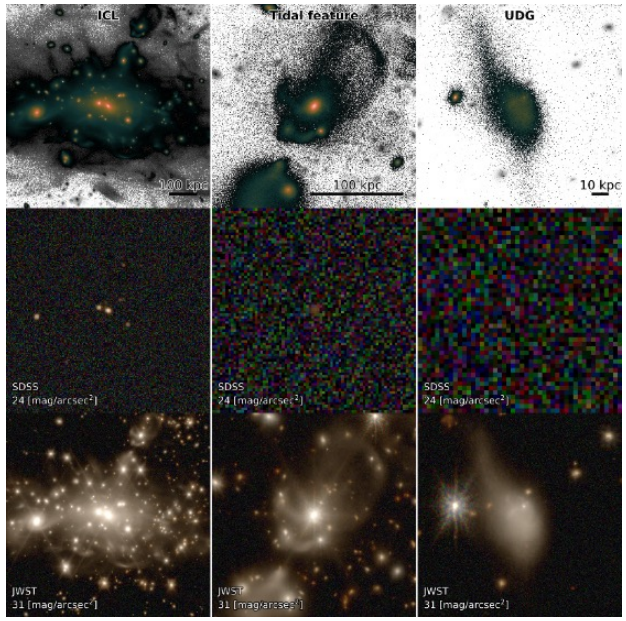




Low-surface Brightness Structures

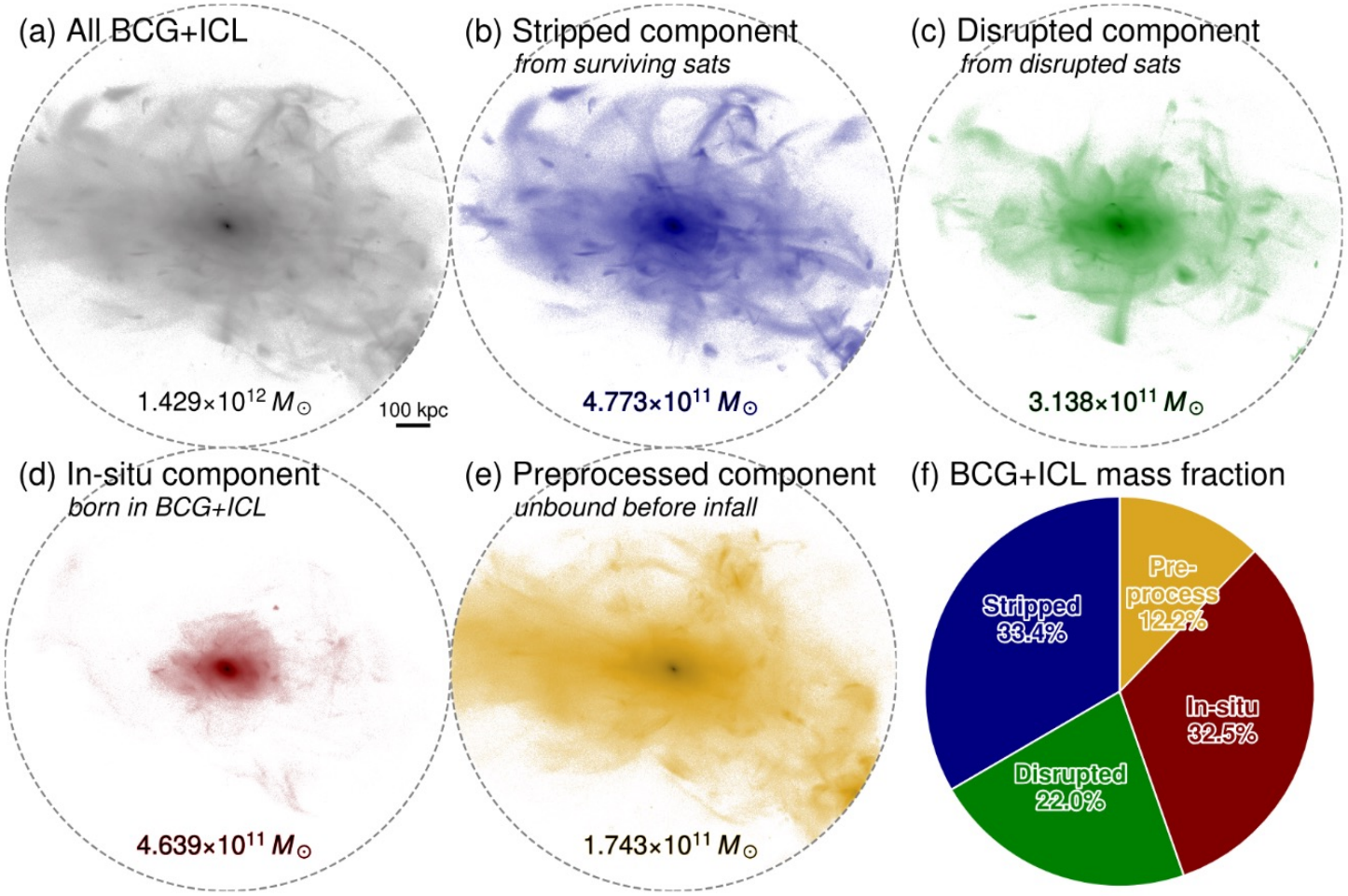


Han+ 2025



Simulation reveals LSB structures such as **intracluster light, shell galaxies, tidal streams, ultra-diffuse galaxies** in the advantage of good stellar mass resolution of ~20,000 $M_{\odot}$

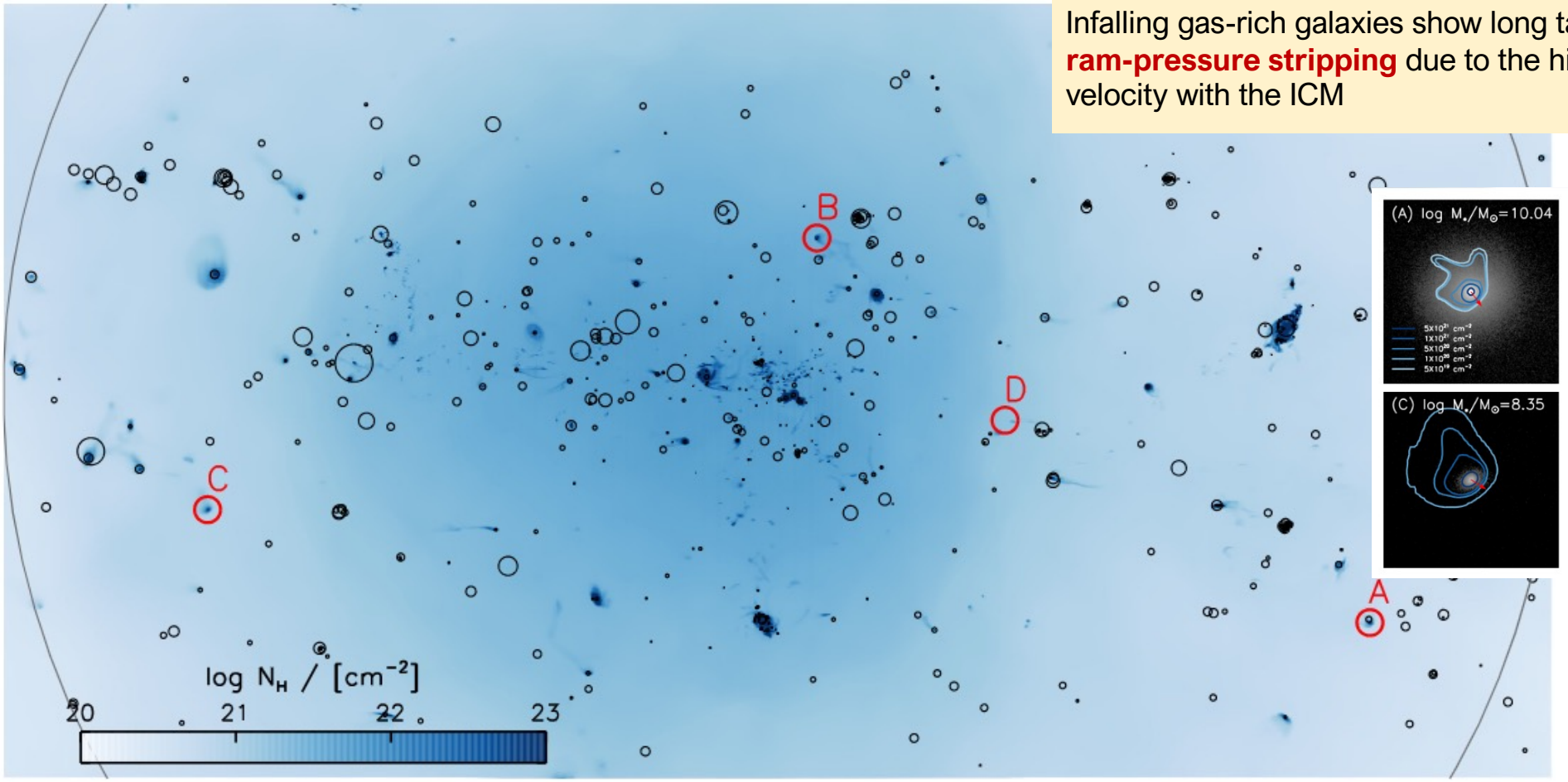
Origin of diffuse lights in cluster (Jeon+ 2025, submitted)

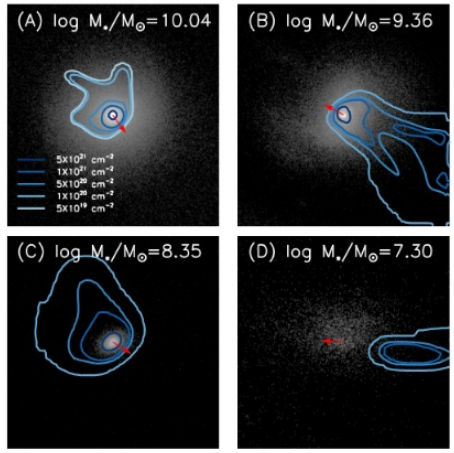


- ~70% of BCG + ICL stars has been accreted through stripping and disruption of external satellites, while ~30% produced as in-situ stellar formation.

Infalling galaxies with gaseous tails

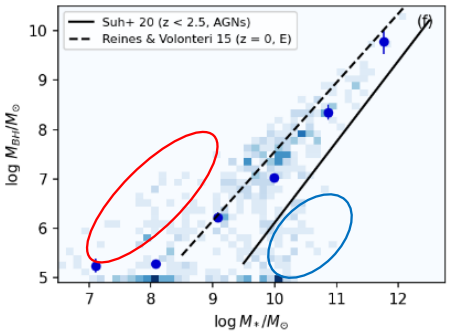
Infalling gas-rich galaxies show long tails driven by **ram-pressure stripping** due to the high relative velocity with the ICM



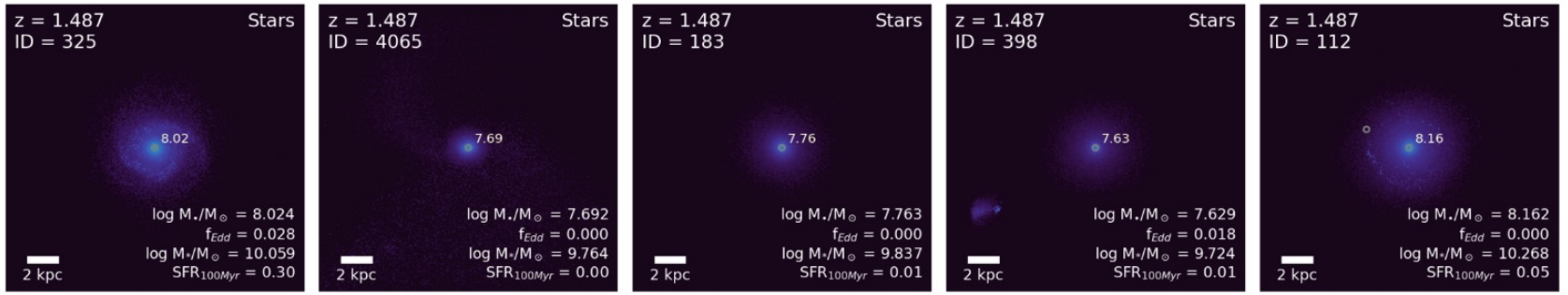


Han+ 2025

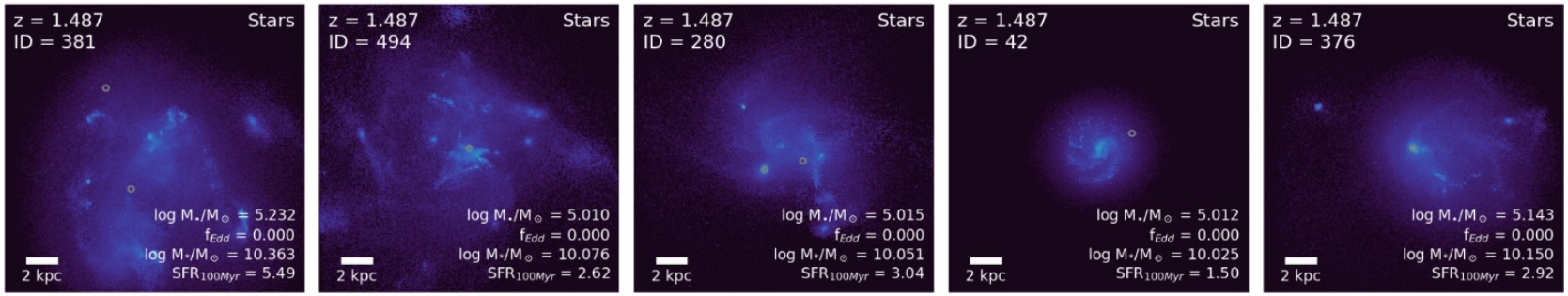
Diversity of galaxy morphology and black hole mass (WIP)



f_{BH} (=M_{BH}/M_*) ~ 1%



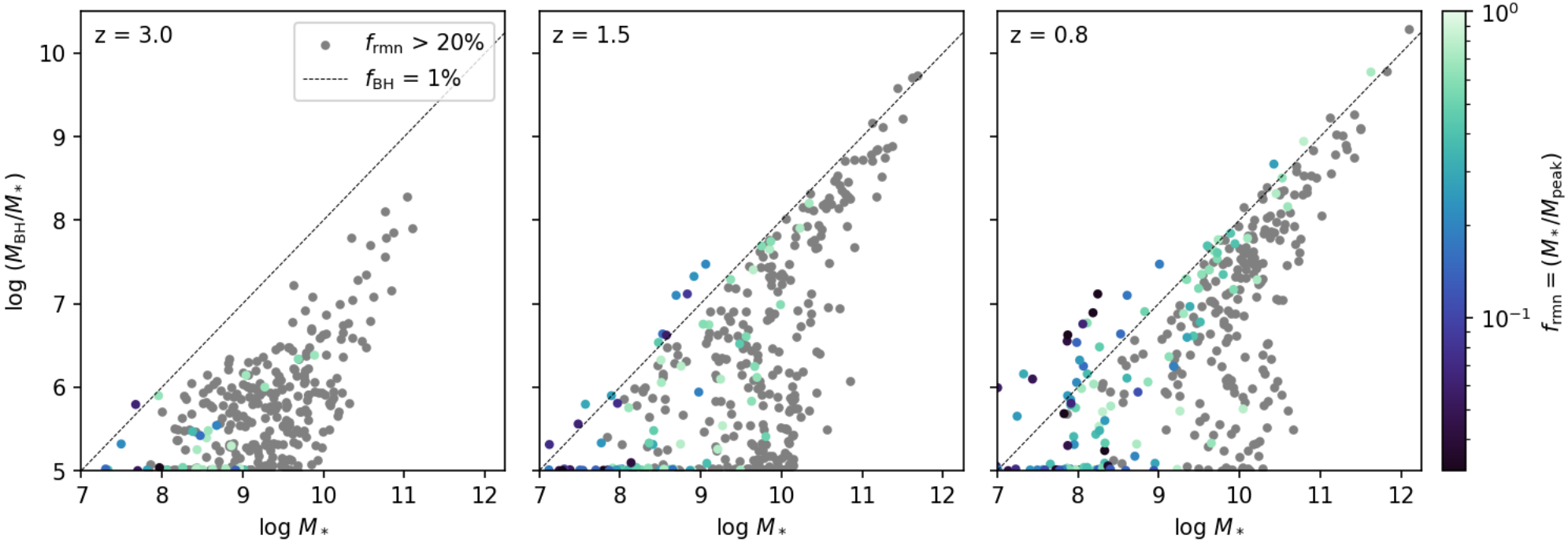
f_{BH} ~ 0.01% (“Undermassive”)



- The large variation of black hole to galaxy mass ratio is related to the galaxy morphology

Origin of “overmassive” black holes in NC (WIP)

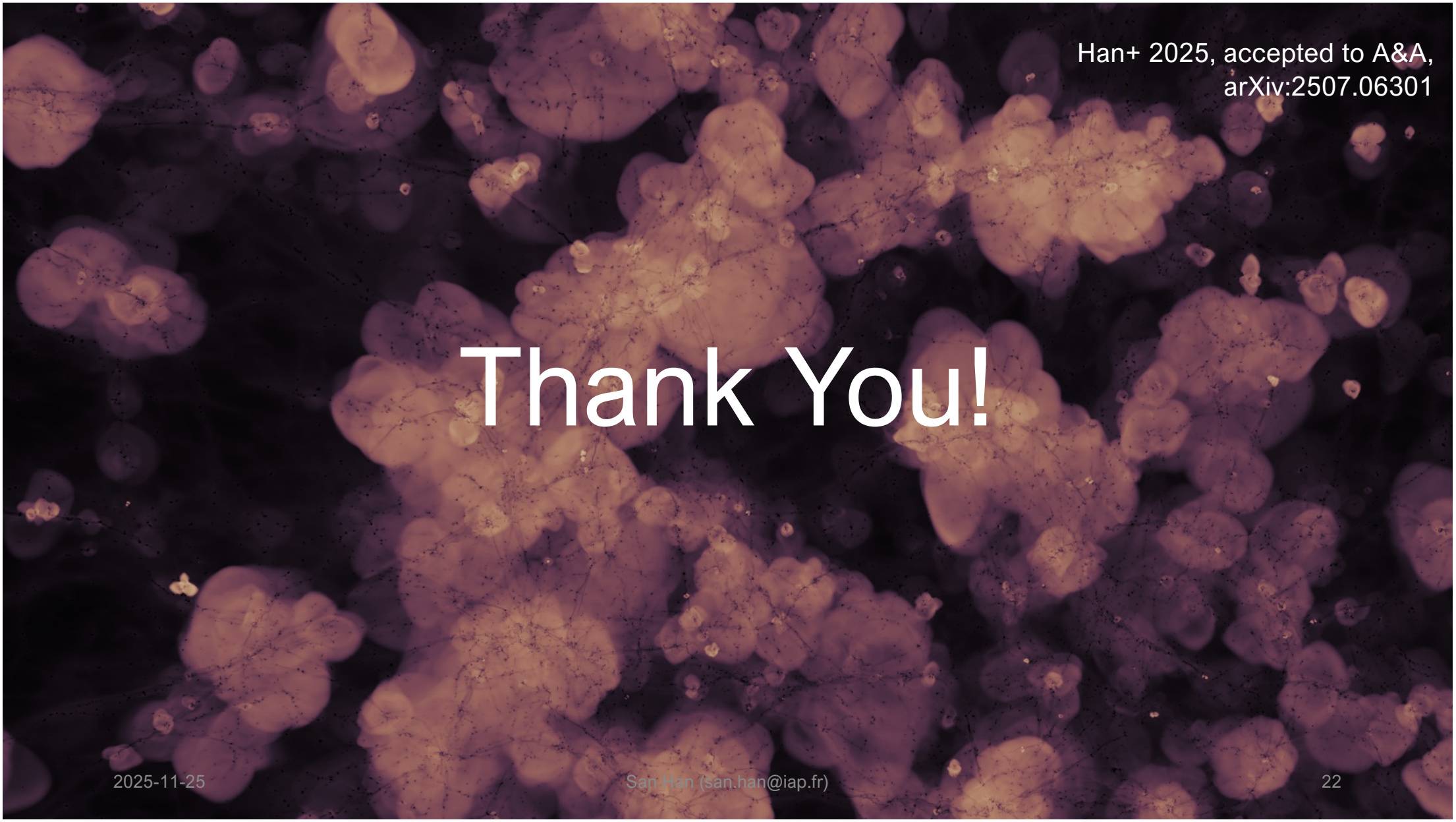
Color: remaining mass



- All of “overmassive” BHs (M_{BH} / M_* ~ 0.1) are related to the stellar mass loss.
- No intrinsically overmassive BHs are found in NC.

Summary

- We introduce **NewCluster**, a new high-resolution (~70pc) zoom-in simulation of a galaxy cluster (~5E14 M_{sol}) with up-to-date astrophysical prescriptions.
- NC provides a powerful sample to directly investigate the evolution of individual galaxies in dense environments, with the capability to resolve systems down to the dwarf regime.
- As an ongoing project, the simulation has now passed z=0.56, and are expected to reach z~0.4 by 2026 April.
- We welcome collaborators interested in working with the NC data!


Han+ 2025, accepted to A&A,
arXiv:2507.06301
Thank You!