

# Into the Storm: Variable Gusts, Intracluster Squalls & Intermittent Downpours

Preliminary Results from Romulus Groups and Clusters

**ARIF BABUL**  
**UNIVERSITY OF VICTORIA**

**Michael Tremmel (Yale)**  
**Tom Quinn (U of Washington)**  
**Urmila Chadayammuri (Yale/CfA)**  
**Seoyoung Lyla Jung (Victoria)**  
**Douglas Rennehan (Victoria)**  
**Daisuke Nagai (Yale)**



# The ROMULUS Simulations

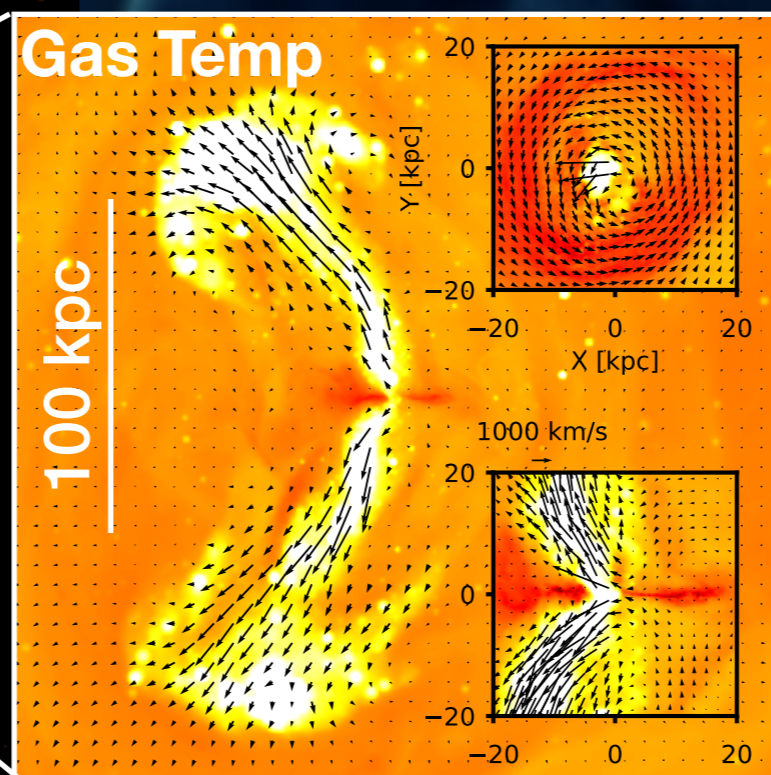
**Certified organic, free-range, locally grown supermassive black holes**

- ✓ Early Seeding in low mass halos
- ✓ Self-consistent and physically motivated dynamics, growth, and feedback
- ✓ Shown to make realistic  $M < 1.E+12 M_{\text{sun}}$  galaxies in detailed sense (zoom and cosmological boxes)
- ✓ **Organic  $M > 1.E+12 M_{\text{sun}}$  systems**
- ✓ **No hormones or additives**
- ✓ Naturally produces large-scale outflows

**ROMULUSC**  
 $10^{14} M_{\text{sun}}$  Galaxy Cluster  
Tremmel+2019

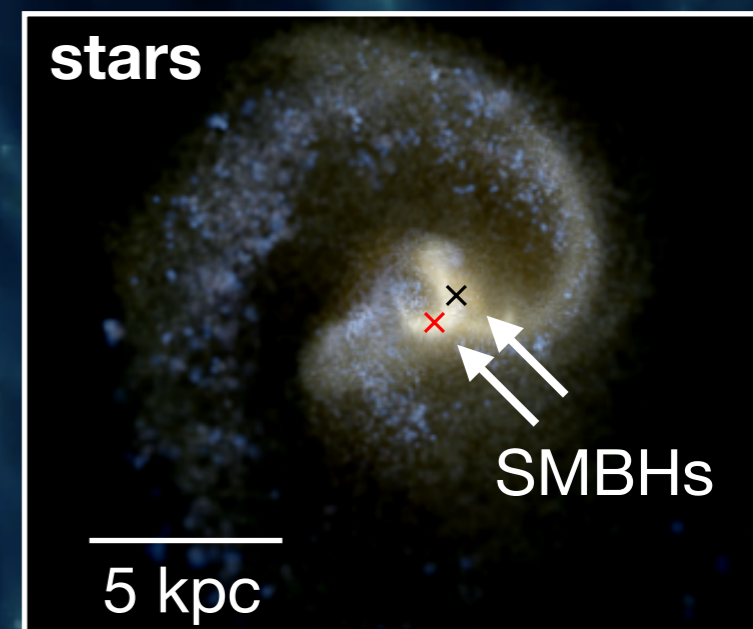
**ROMULUSC++**  
 $10^{13.5-15} M_{\text{sun}}$

**ROMULUS25**  
25 Mpc Volume  
Tremmel+ 2017



**CHANGA**

Resolution:  
250 pc (grav)  
50 pc (hydro)  
 $\sim 1e5 M_{\text{sun}}$





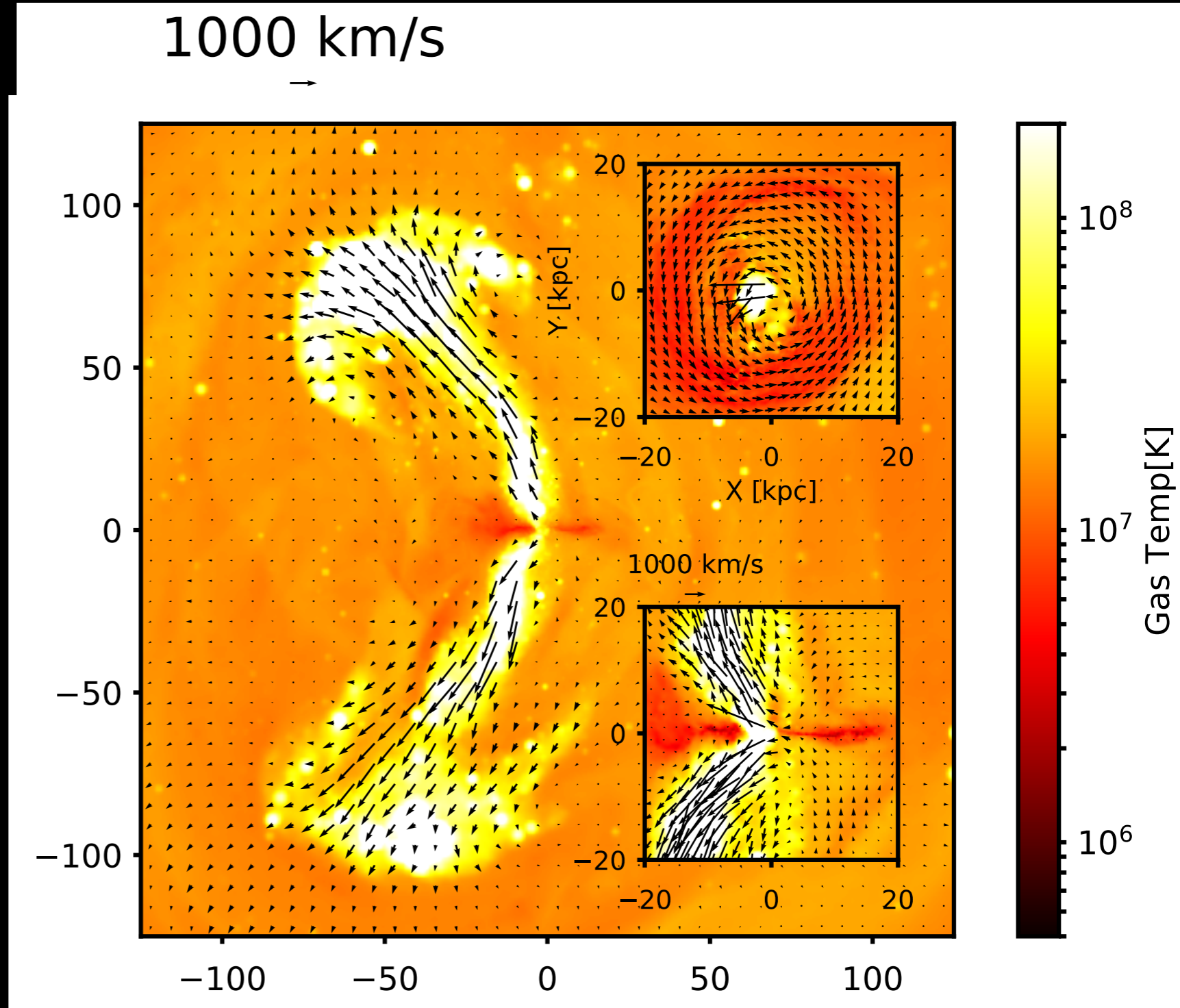
# Isotropically injected, thermally driven outflow

**0.2%** mass-energy transferred **thermally** to surrounding gas

Sub-grid model **not optimized** for  $M_{\text{halo}} > 1e12 M_{\text{sun}}$

Overcooling is avoided due to

- spatial (250 pc) and time ( $10^3$ - $10^4$  yrs) resolution for SMBH and gas.
- Brief cooling shutoff ( $10^3$ - $10^4$  yrs)
- Outflows launched from 100 pc scales



**RomulusC z = 0.5**

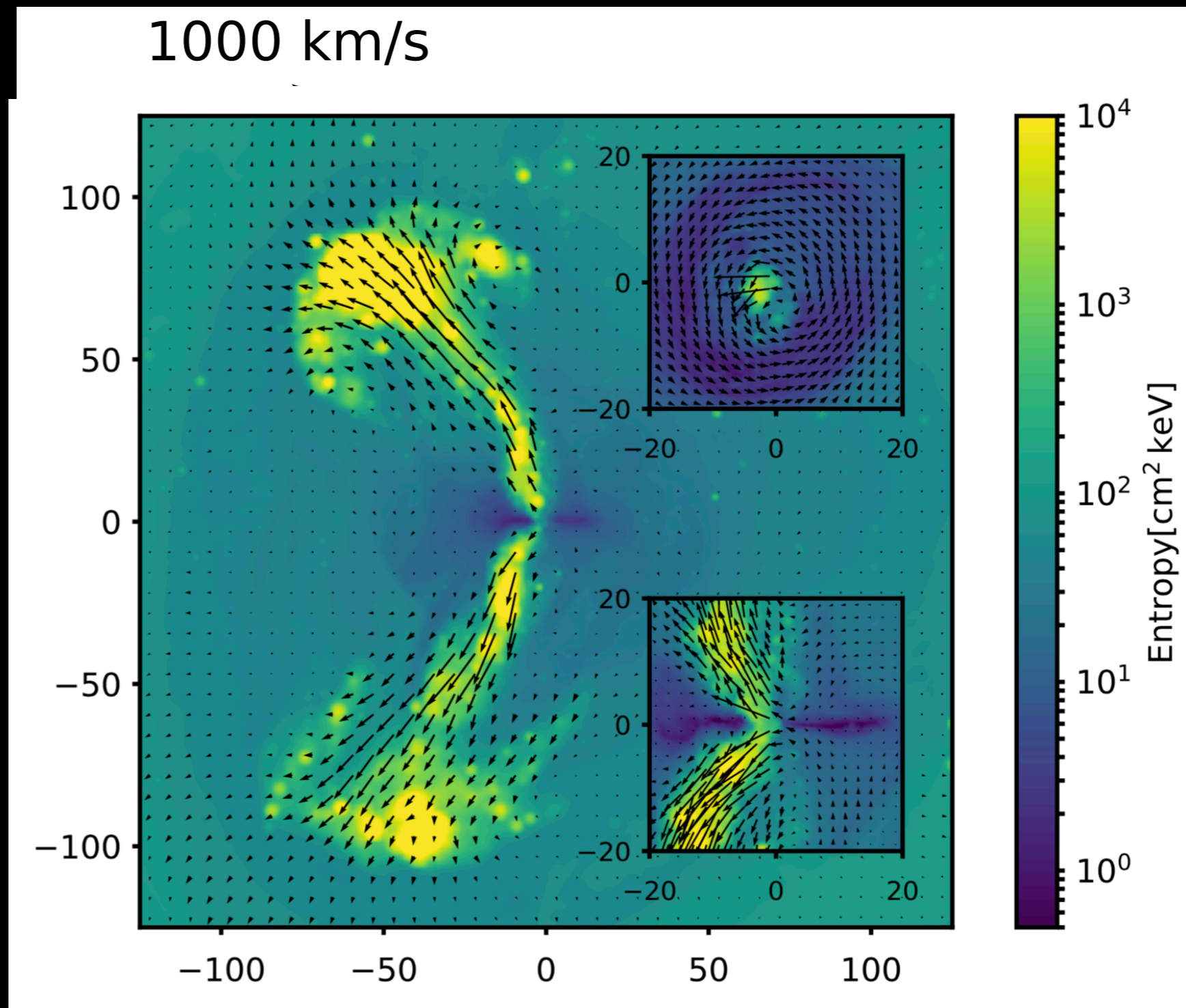
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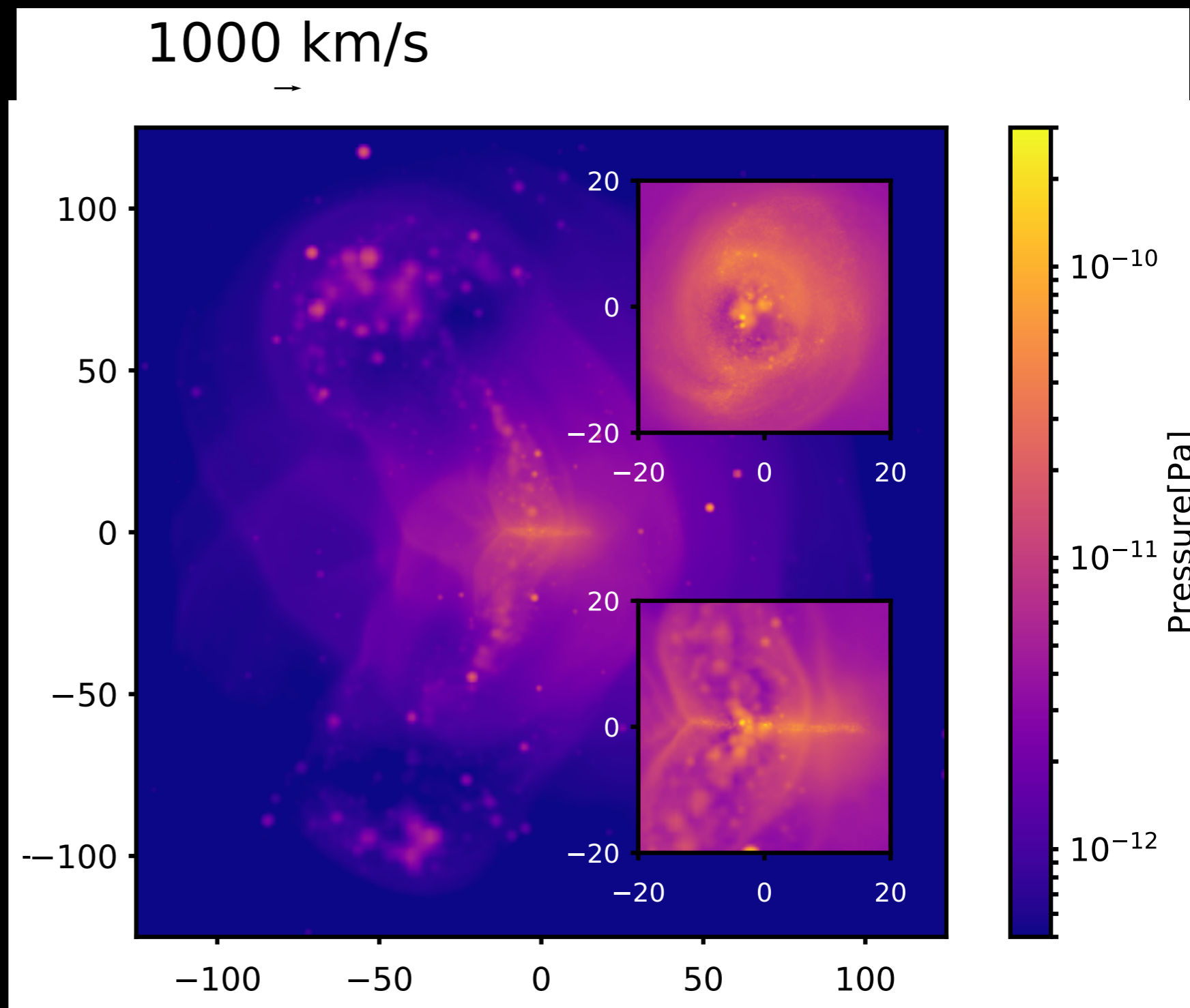
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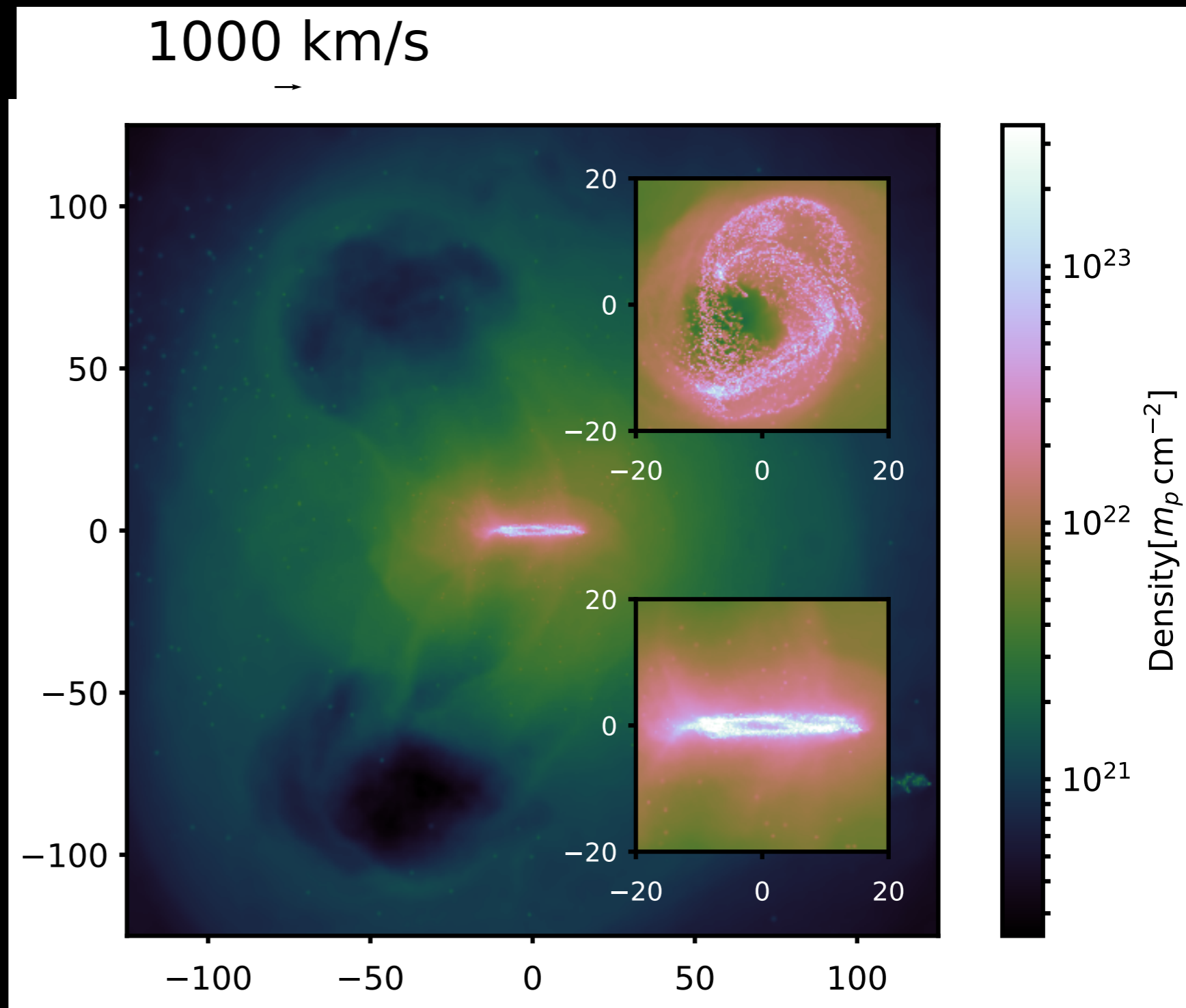
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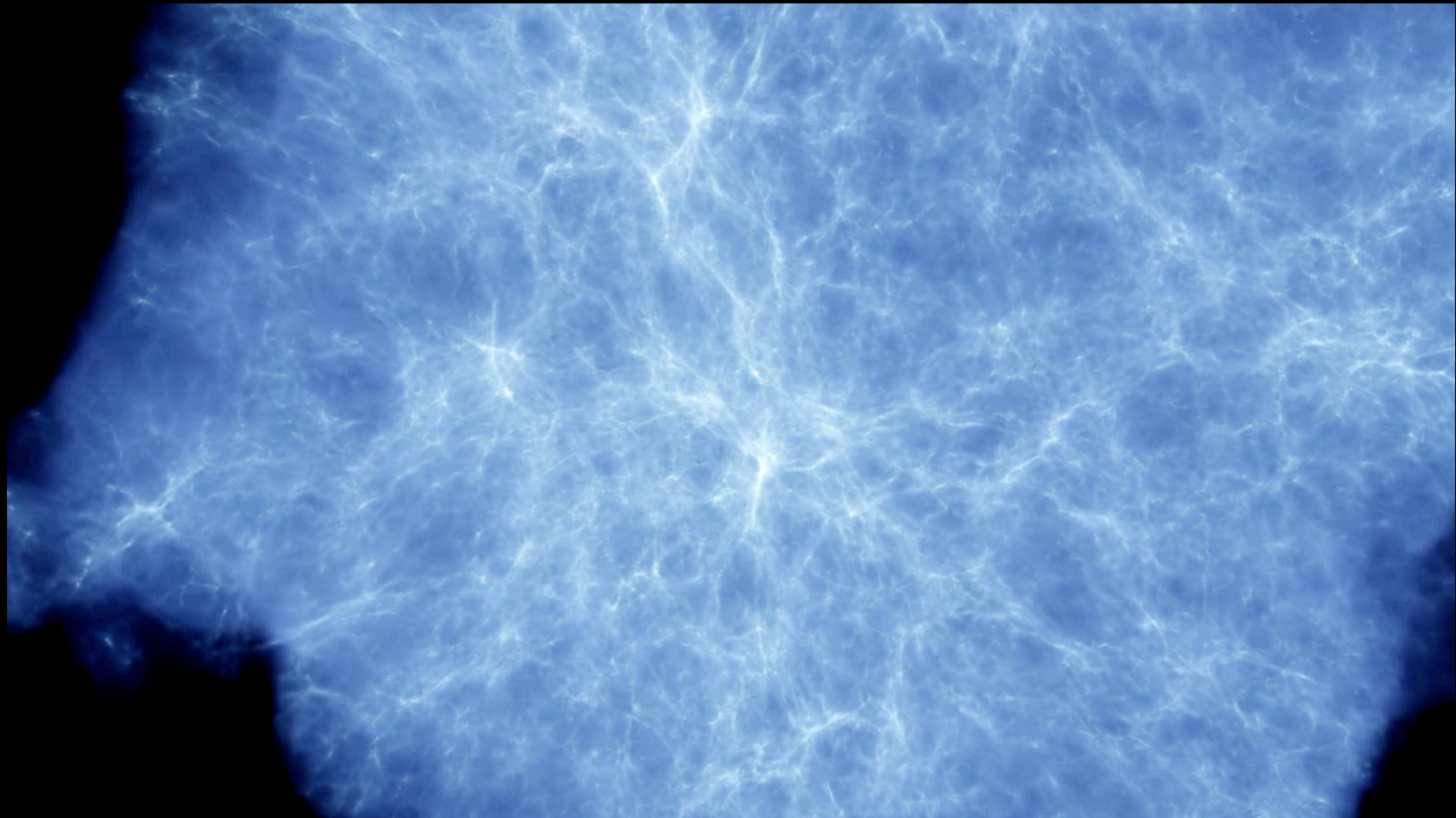


# The Rich Physics of Groups and Clusters

## Romulus25, RomulusC, RomulusC+...

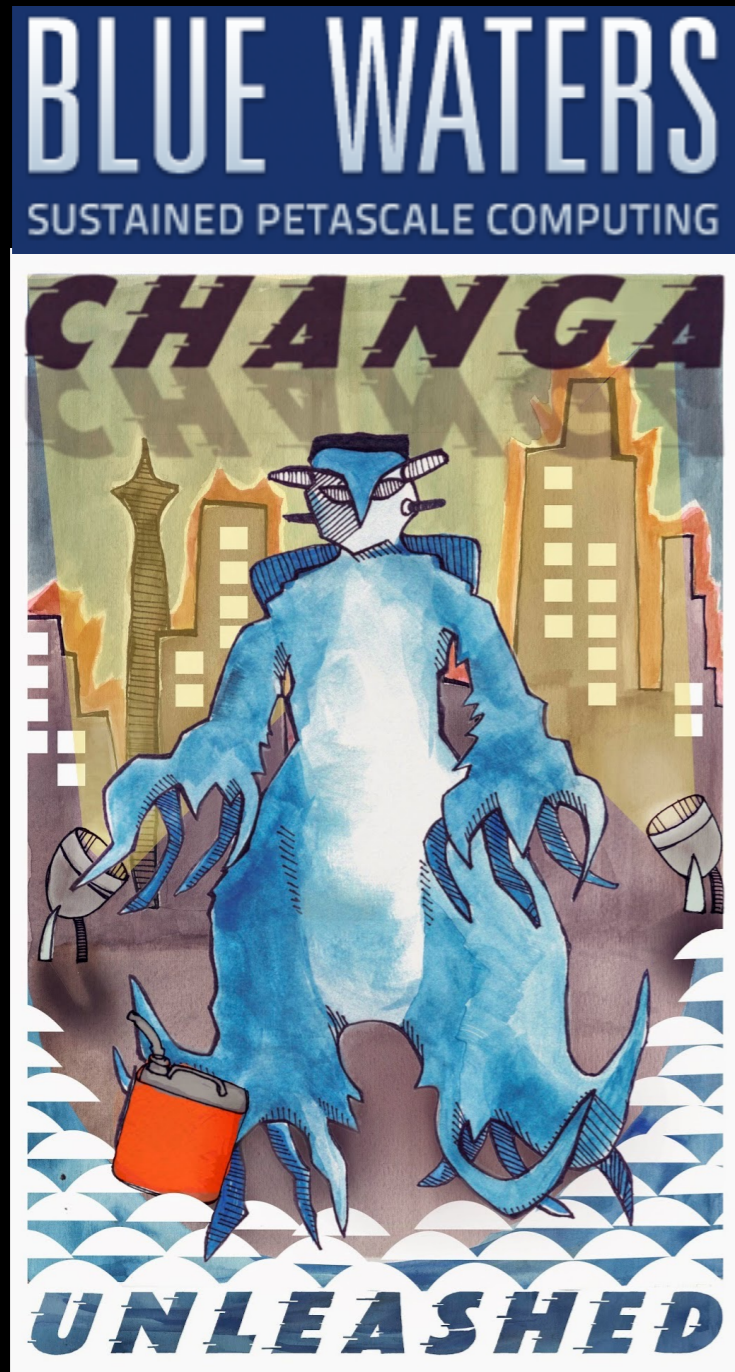
**Resolution:** 250 pc (grav), 50 pc (hydro),  $3.4e5/2.1e5 M_{\text{sun}}$  (DM/gas)

**Systems:** 33 groups ( $2e12 < M_{\text{vir}} < 2e13$ ), 1 ( $M_{\text{vir}}=1.5e14 M_{\text{sun}}$ ) + 2 More



RomulusC Gas Density

Introducing RomulusC:  $M_{200}=1.1e+14 M_{\text{sun}}$  ;  $R_{200} = 1.02 \text{ Mpc}$   
The highest resolution cosmological hydro simulation of a cluster to date



Zoom-In Simulation  
 $M_{\text{vir}}(z=0) = 1.5e14 M_{\text{sun}}$

Stars

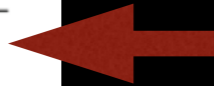
Chadayammuri+2019 (19XX.XXXX)  
Tremmel+2019 (1806.01282)  
Tremmel+2017



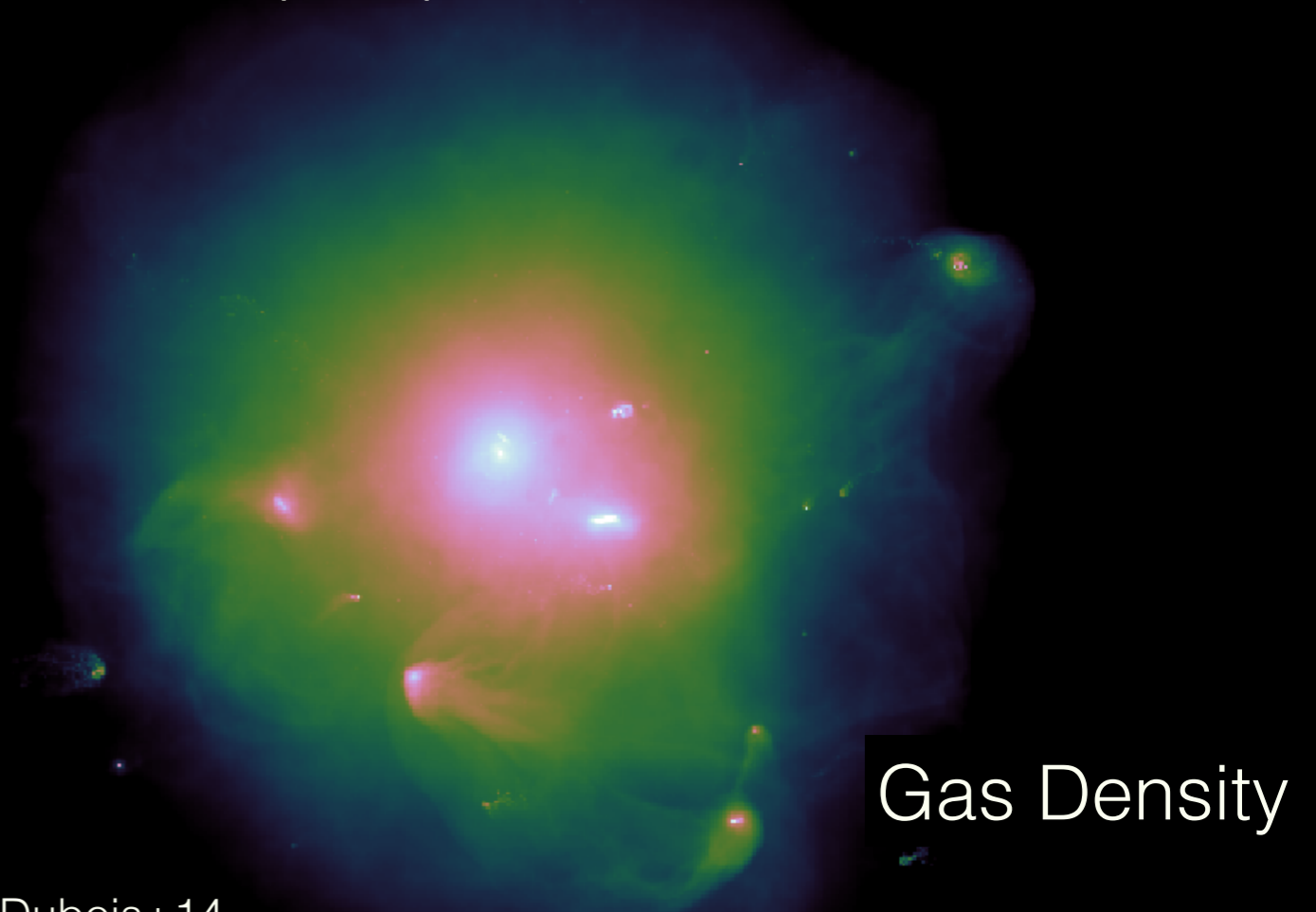
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Name	Spatial Res. <sup>a</sup> kpc	$M_{DM}$ $M_{\odot}$	$M_{gas}$ $M_{\odot}$
<b>RomulusC</b>	0.25	$3.4 \times 10^5$	$2.1 \times 10^5$
TNG300 <sup>b</sup>	1.5	$7.9 \times 10^7$	$7.4 \times 10^6$
TNG100 <sup>b</sup>	0.75	$5.1 \times 10^6$	$9.4 \times 10^5$
TNG50 (in progress <sup>c</sup> )	0.3	$4.4 \times 10^5$	$8.5 \times 10^4$
Horizon-AGN <sup>d</sup>	1	$8.0 \times 10^7$	$1.0 \times 10^7$
Magneticum <sup>e</sup>	10	$1.3 \times 10^{10}$	$2.9 \times 10^9$
Magneticum <sup>e</sup> high res	3.75	$6.9 \times 10^8$	$1.4 \times 10^8$
Magneticum <sup>e</sup> ultra high res	1.4	$3.6 \times 10^7$	$7.3 \times 10^6$
C-EAGLE <sup>f,g</sup>	0.7	$9.6 \times 10^6$	$1.8 \times 10^6$
EAGLE <sup>g</sup> (50, 100 Mpc)	0.7	$9.6 \times 10^6$	$1.8 \times 10^6$
Omega500 <sup>h</sup>	5.4	$1.6 \times 10^9$	$2.7 \times 10^8$
MACSIS <sup>i</sup>	5.9	$5.7 \times 10^9$	$1.0 \times 10^9$
BAHAMAS <sup>j</sup>	5.9	$5.7 \times 10^9$	$1.0 \times 10^9$
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Zoom-In Simulation  
 $M_{\text{vir}}(z=0) = 1.5e14 M_{\text{sun}}$



Gas Density

Marinacci+17, Dubois+14,  
 Bocquet+16, Armitage+18,  
 Schaye+15, Shirasaki+ 18,  
 Barnes+17, Wu+ 15,  
 McCarthy+17

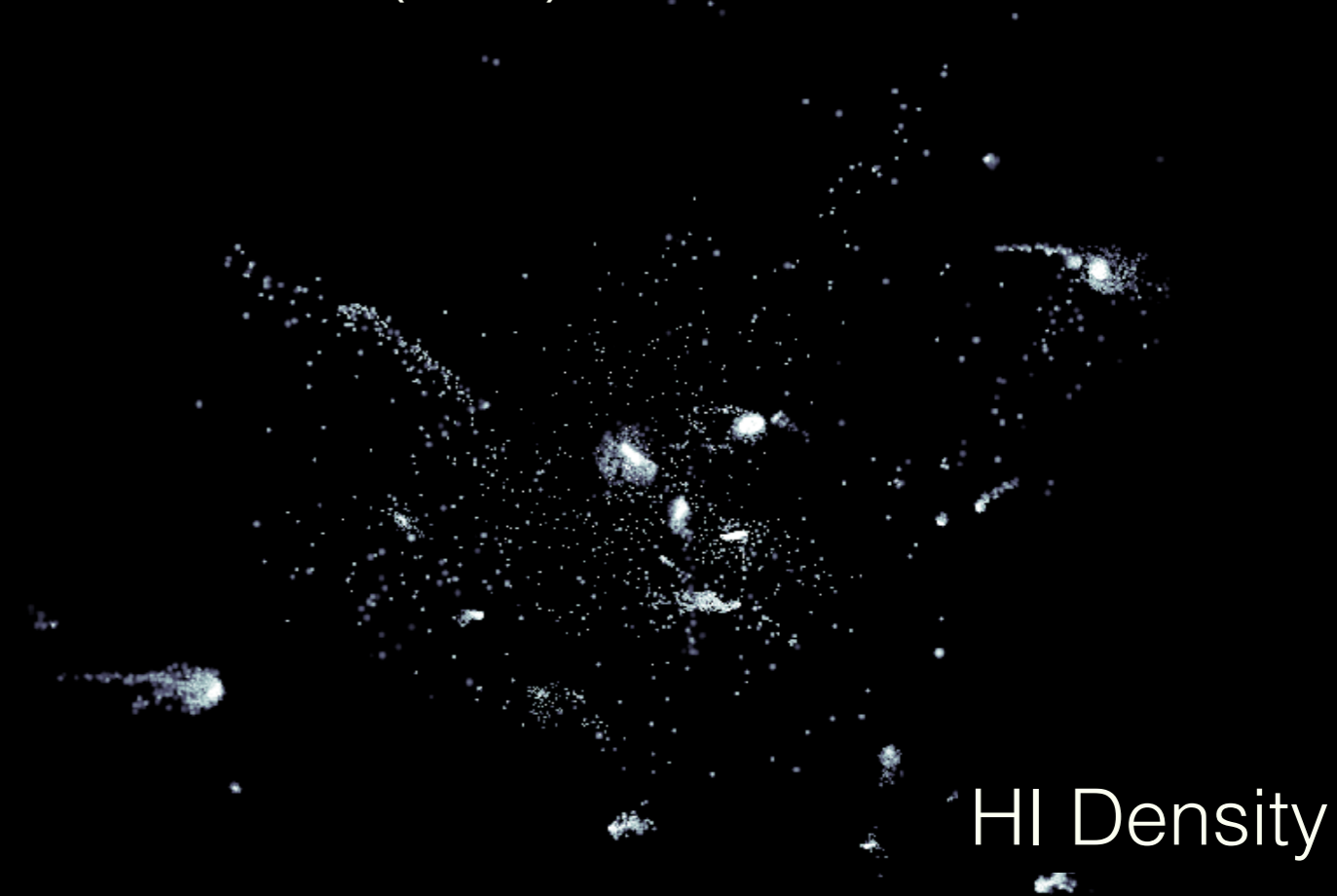
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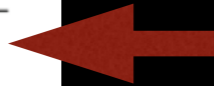
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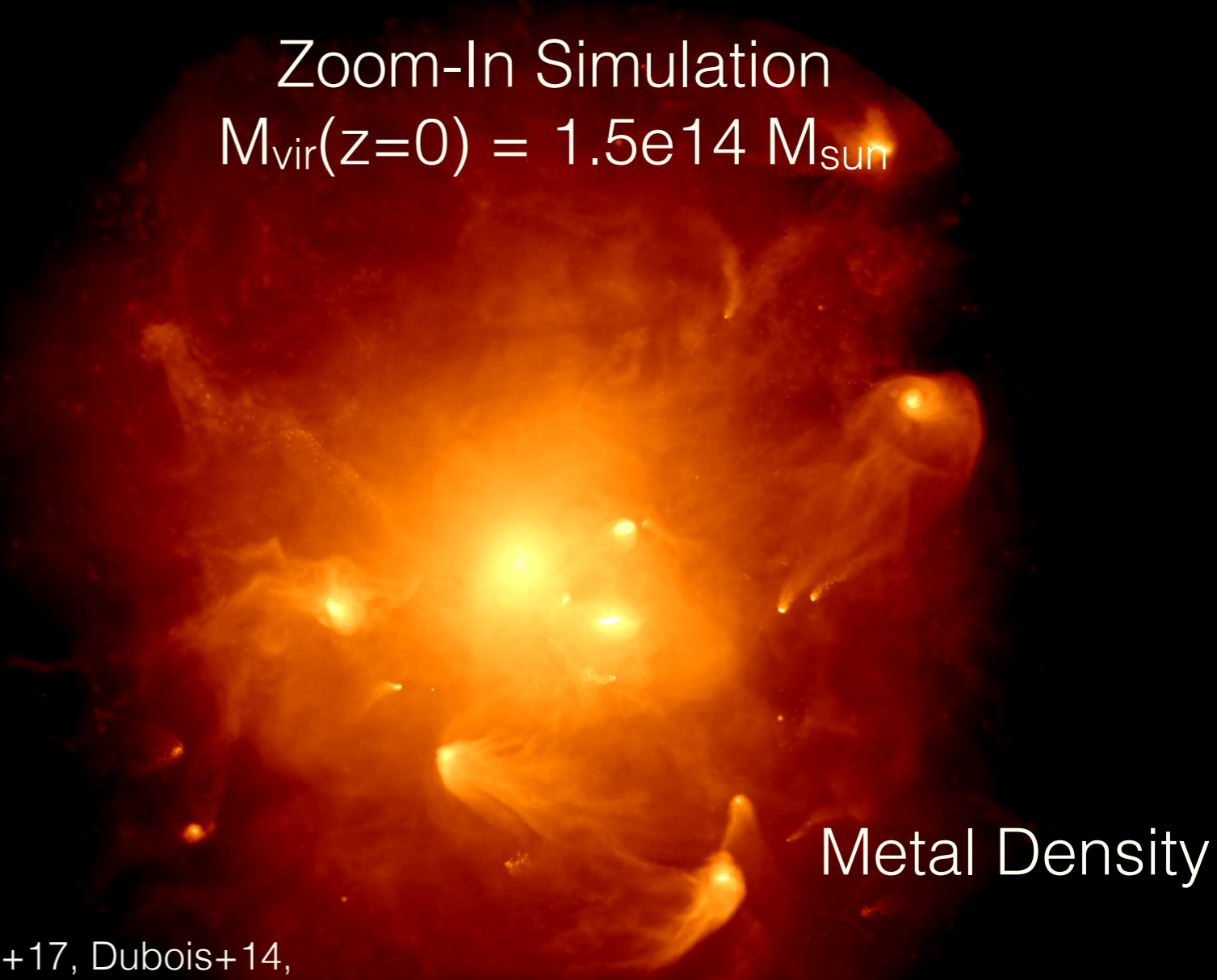


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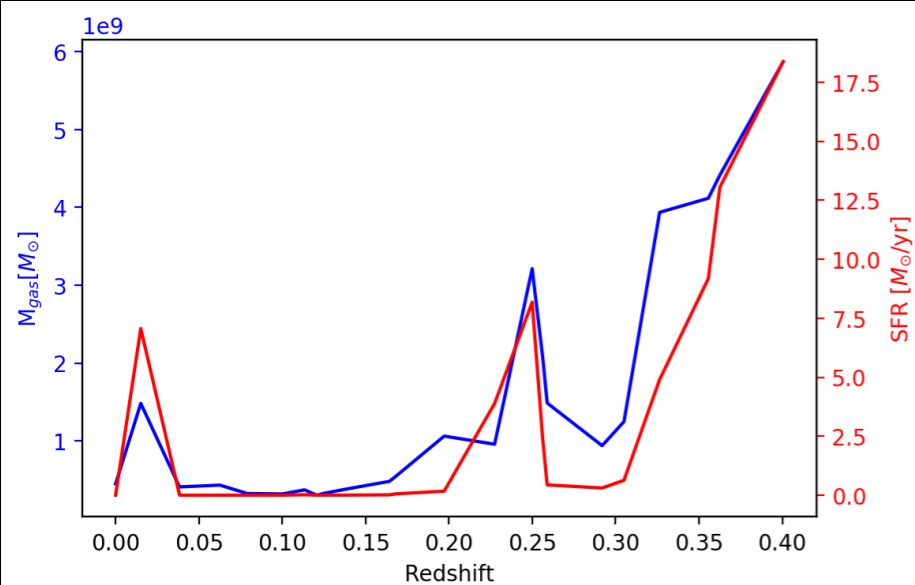
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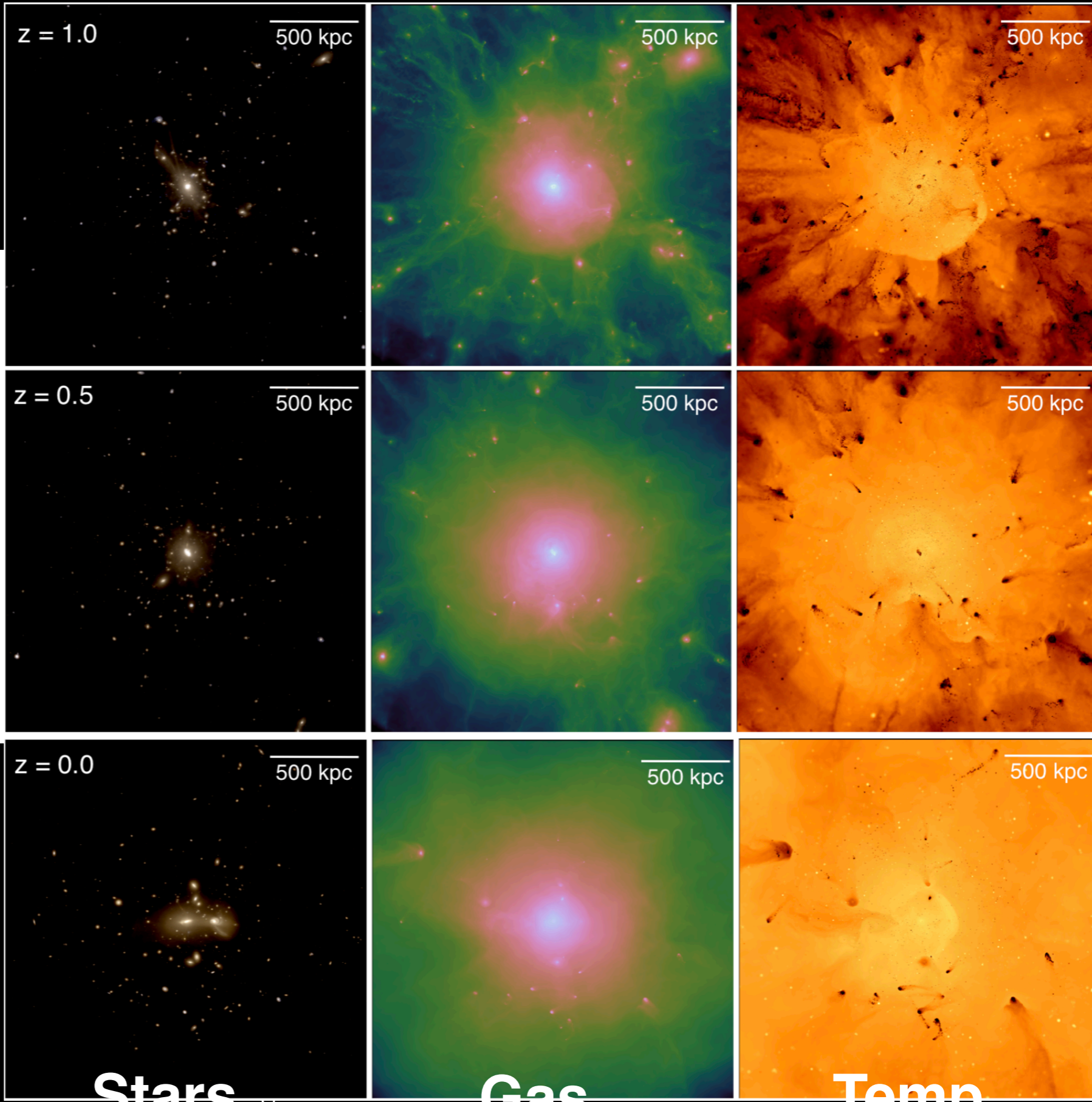
Metal Density



# Overall cluster evolution:



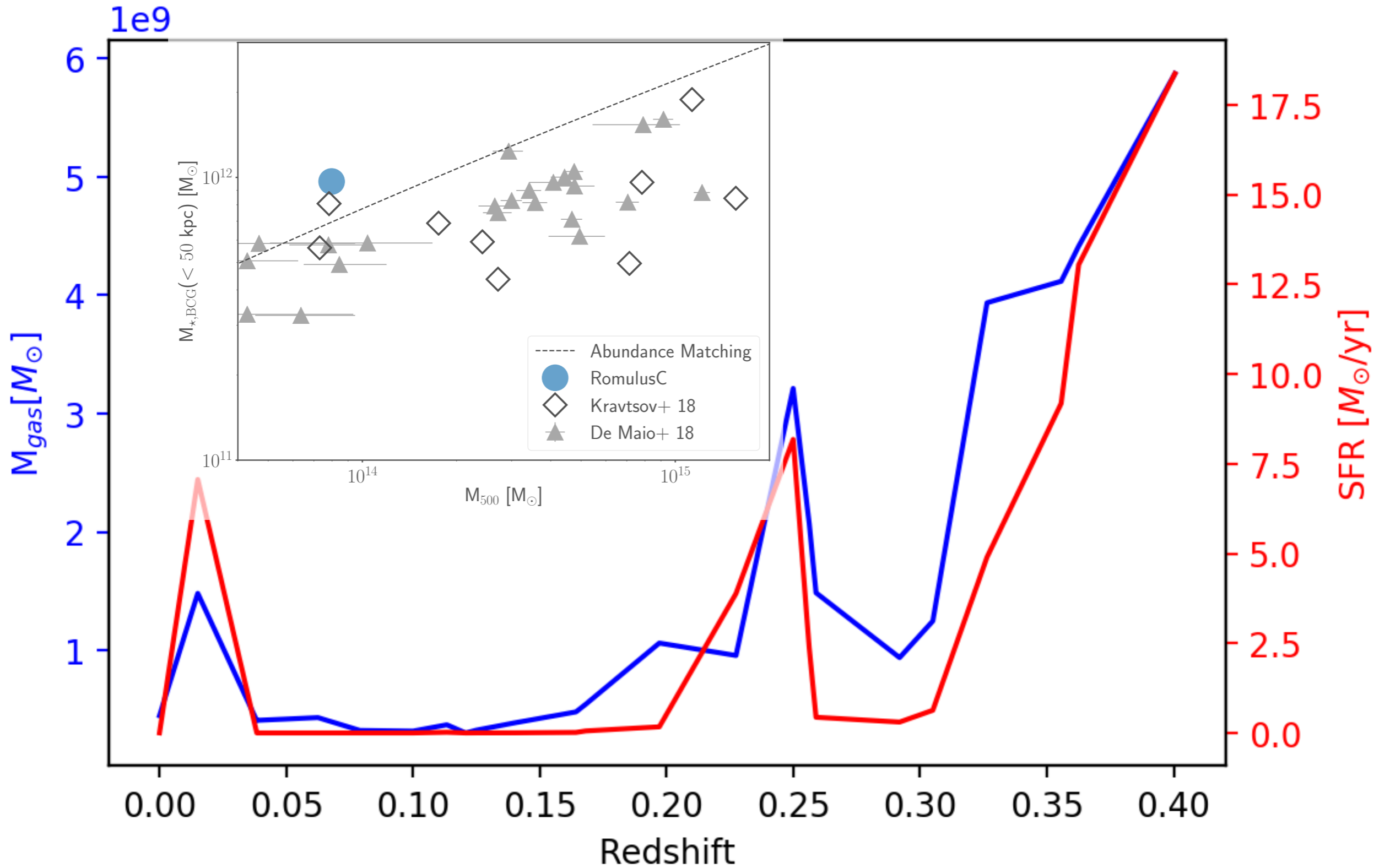
BCG experiences a merger.  
 Close (<50 kpc) pass at 11.7 Gyrs  
 Final galaxy merger is ongoing to z=0



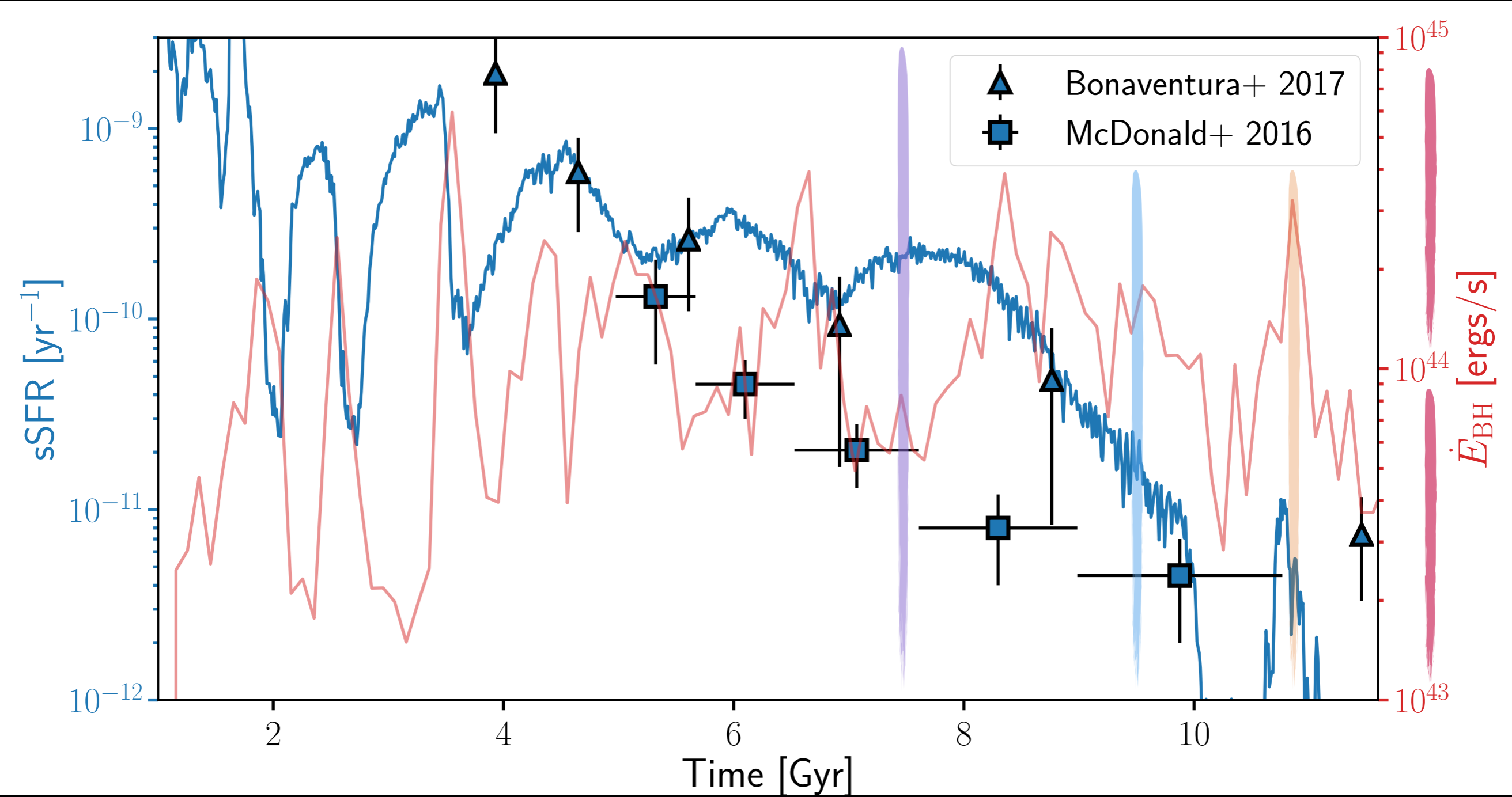
**Stars**      **Gas**      **Temp**



# RomulusC BCG Properties

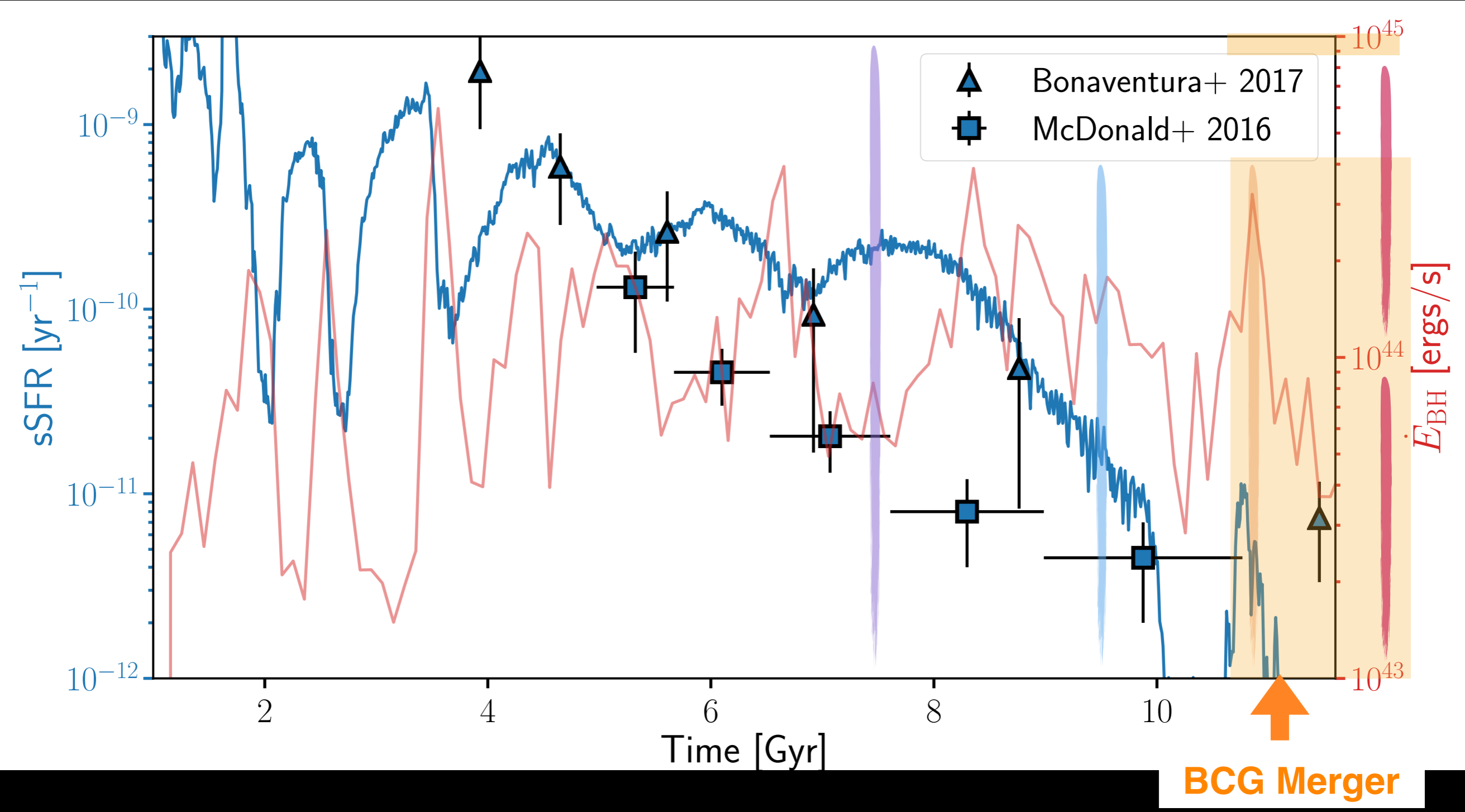


# AGN Activity and Quenching of Brightest Cluster Galaxy

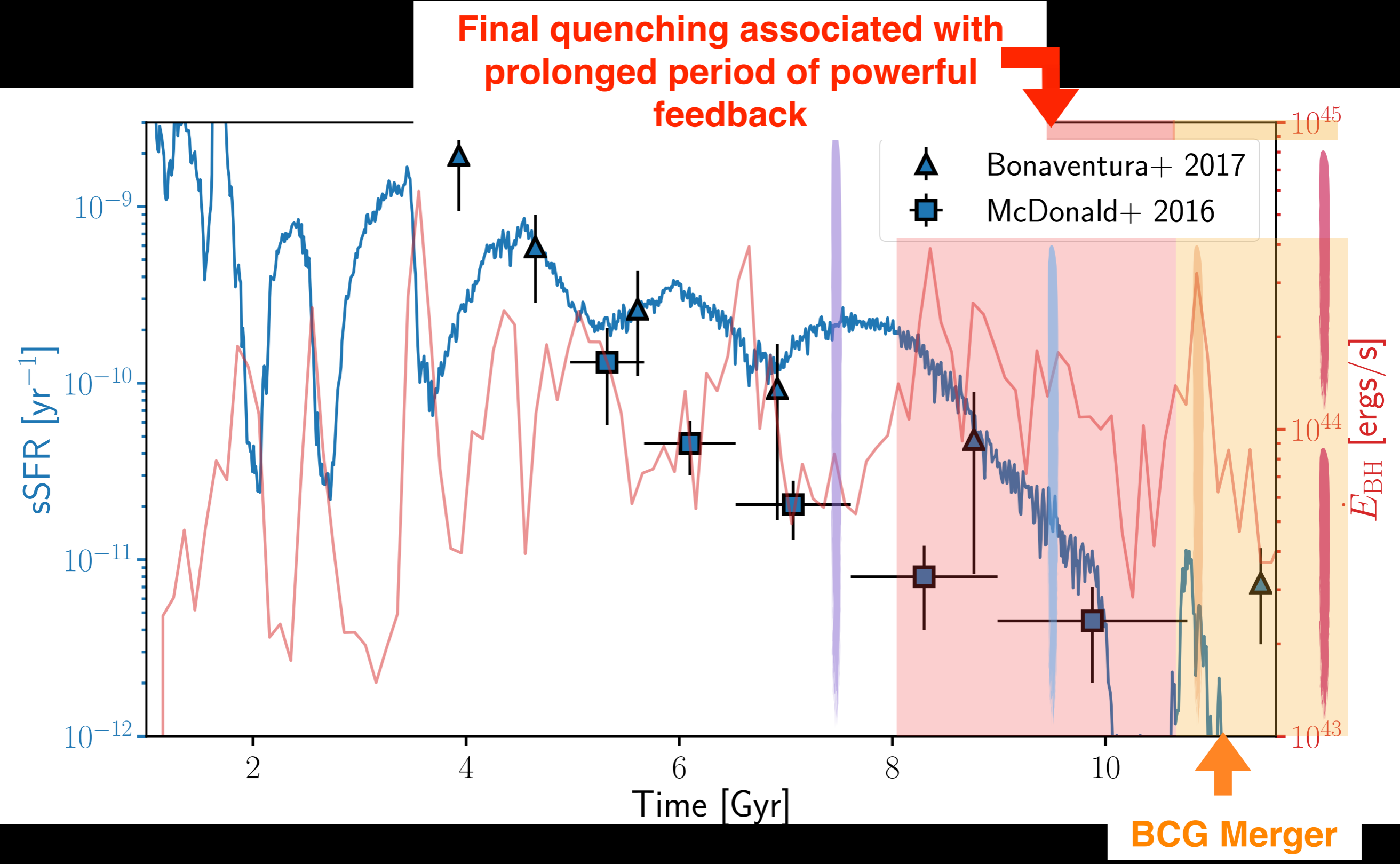




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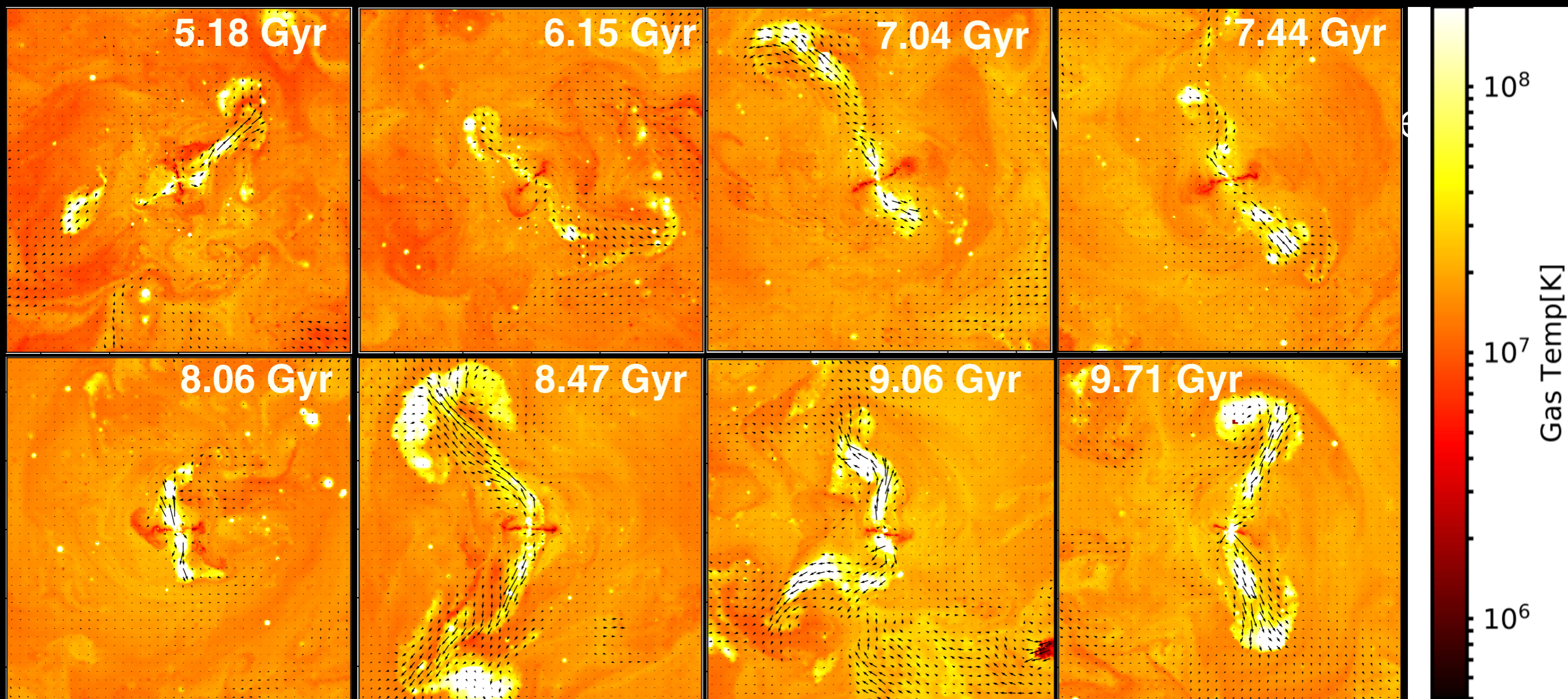


# AGN Activity and Quenching of Brightest Cluster Galaxy



Outflows are ubiquitous over the simulation lifetime

Outflows are collimated by disk and ICM pressure, flow to  $> 0.1 R_{200}$  and constantly wobble primarily due to pre-existing channels and ICM weather.

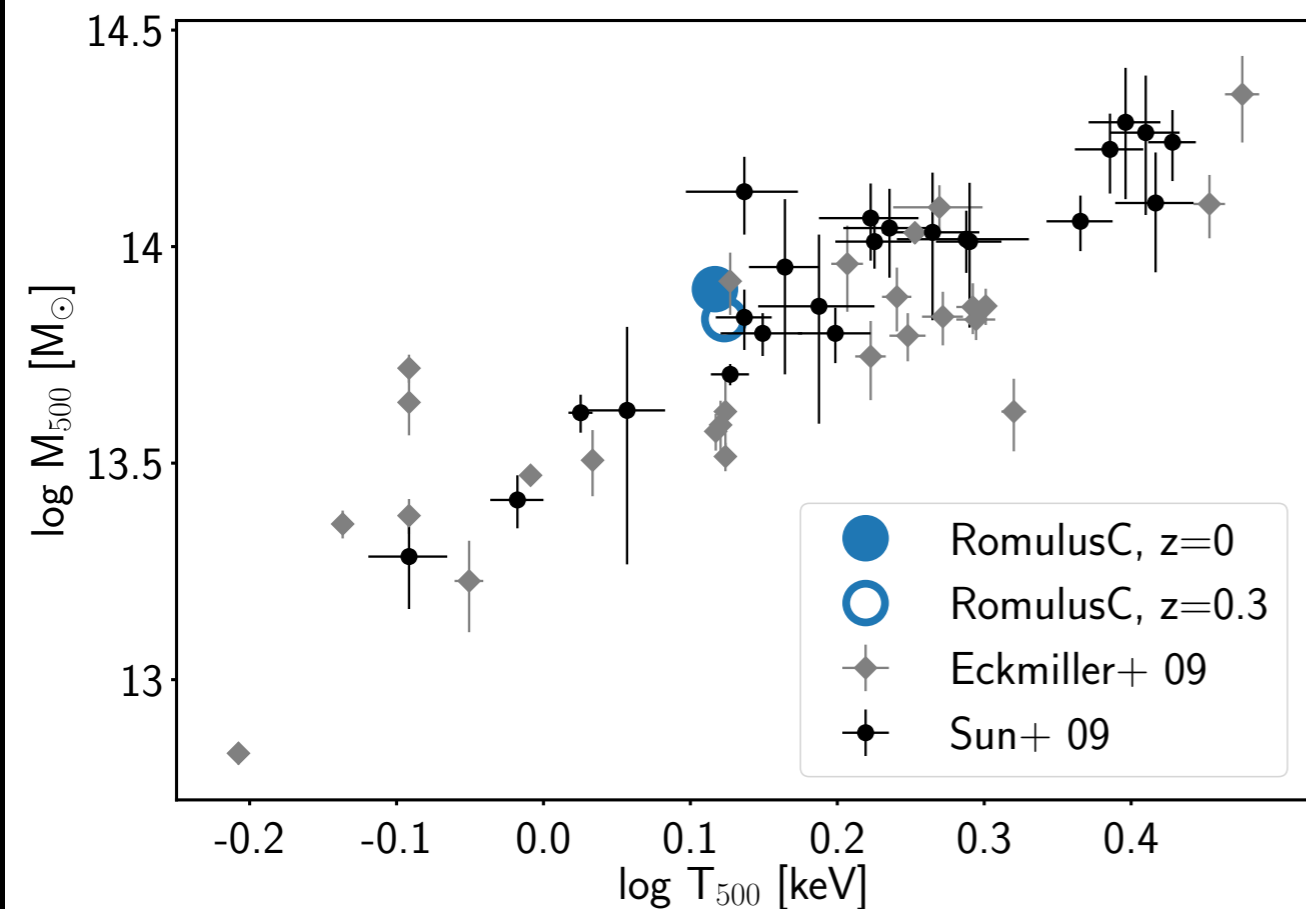




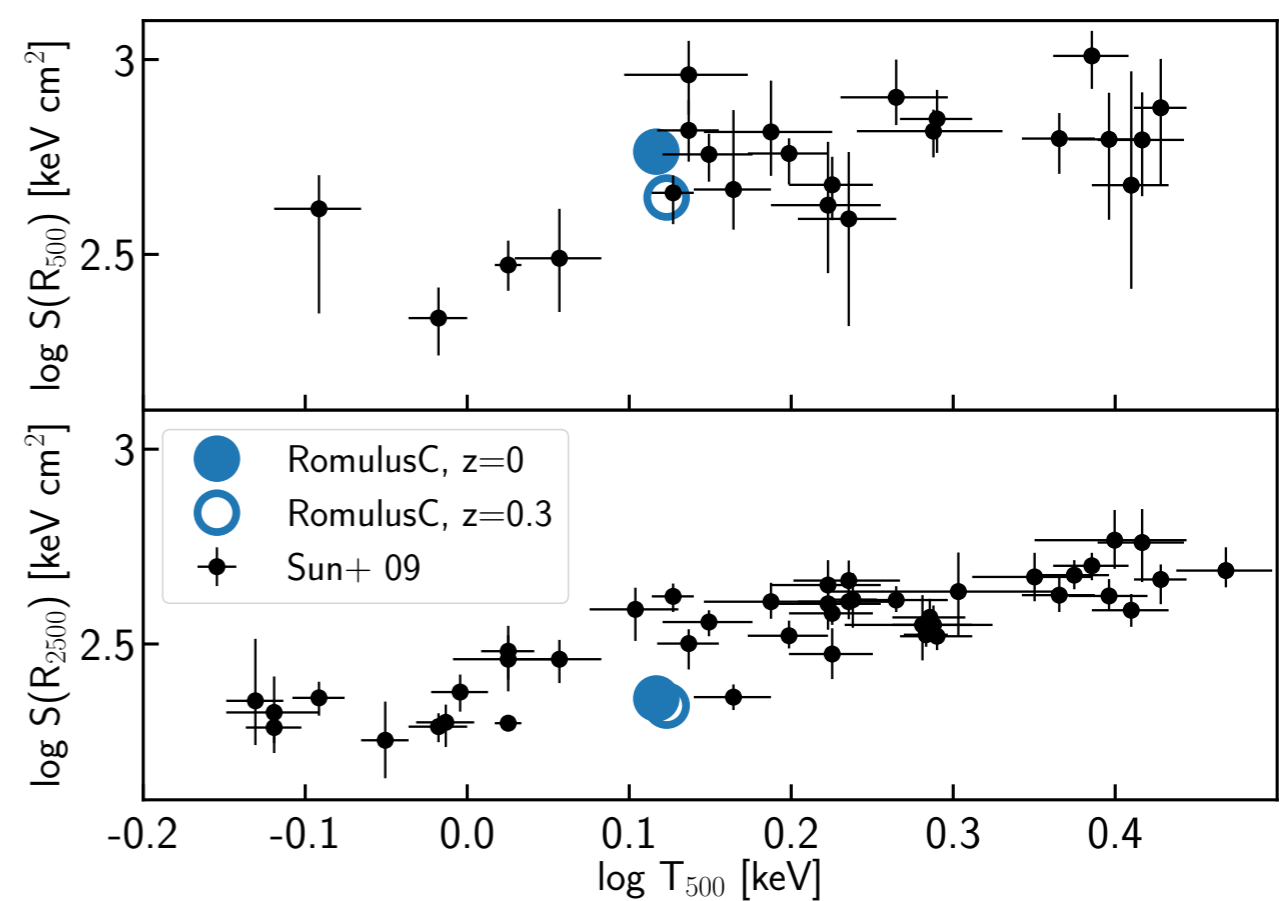
# Global ICM Properties

RomulusC lies on observed  $M_{500}$ - $T_{500}$ - $S_{500}$  relations

$M_{500}$ - $T_{500}$

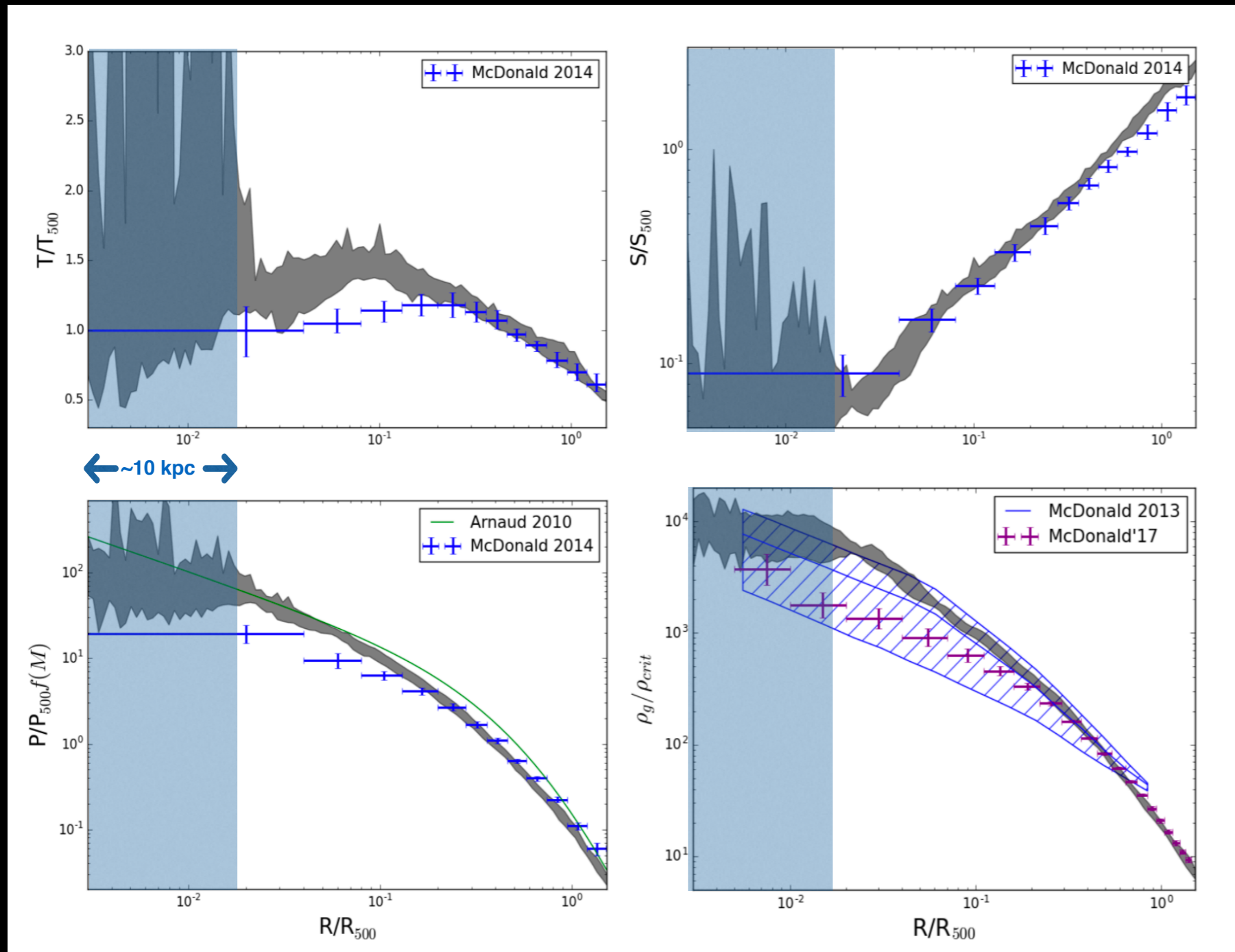


$S(R_{500,2500})$ - $T_{500}$



# Global ICM Properties

## Radial profiles over $z=0.3-0.5$ : cool core cluster



Arnaud+'10 and McDonald+'13,14:  
**obs. cool cores**

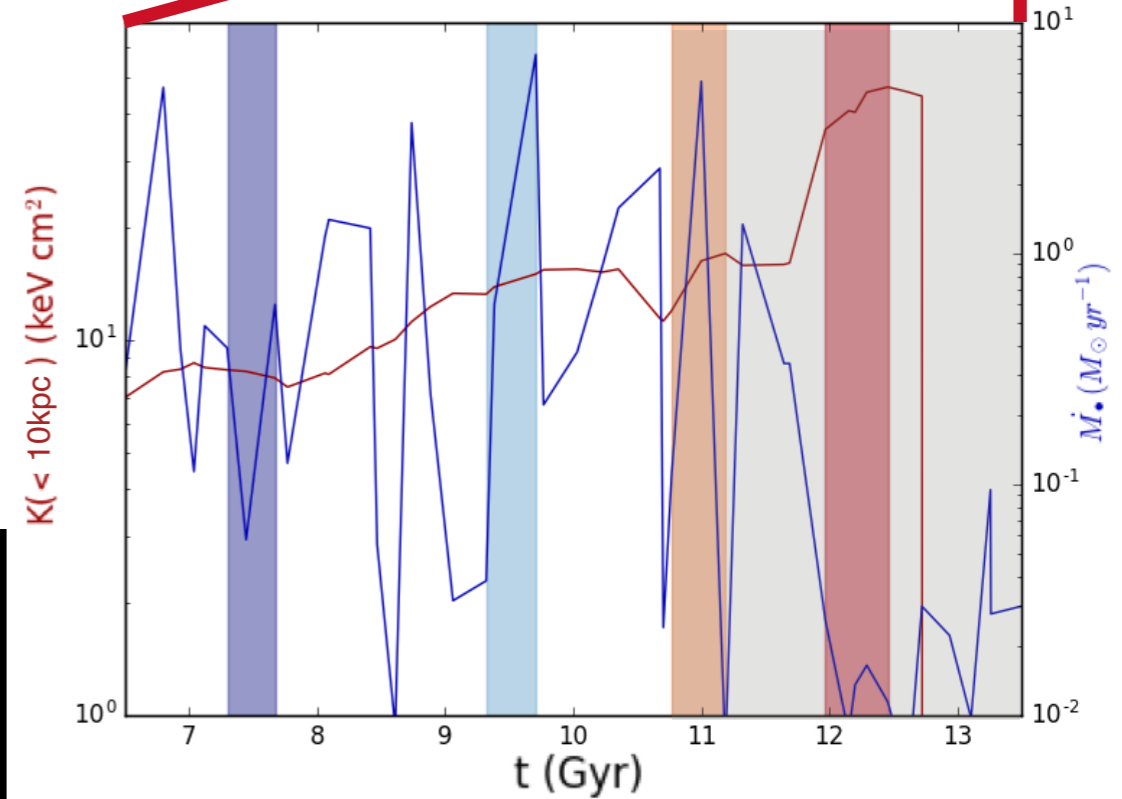
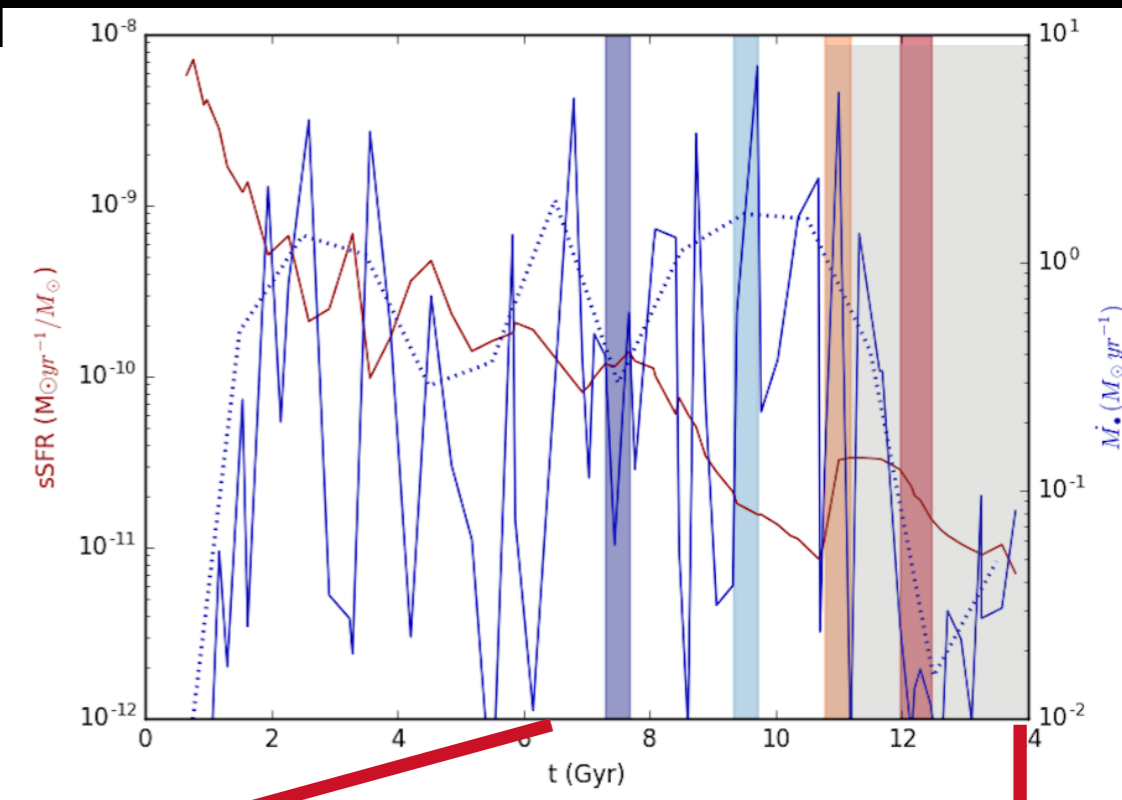
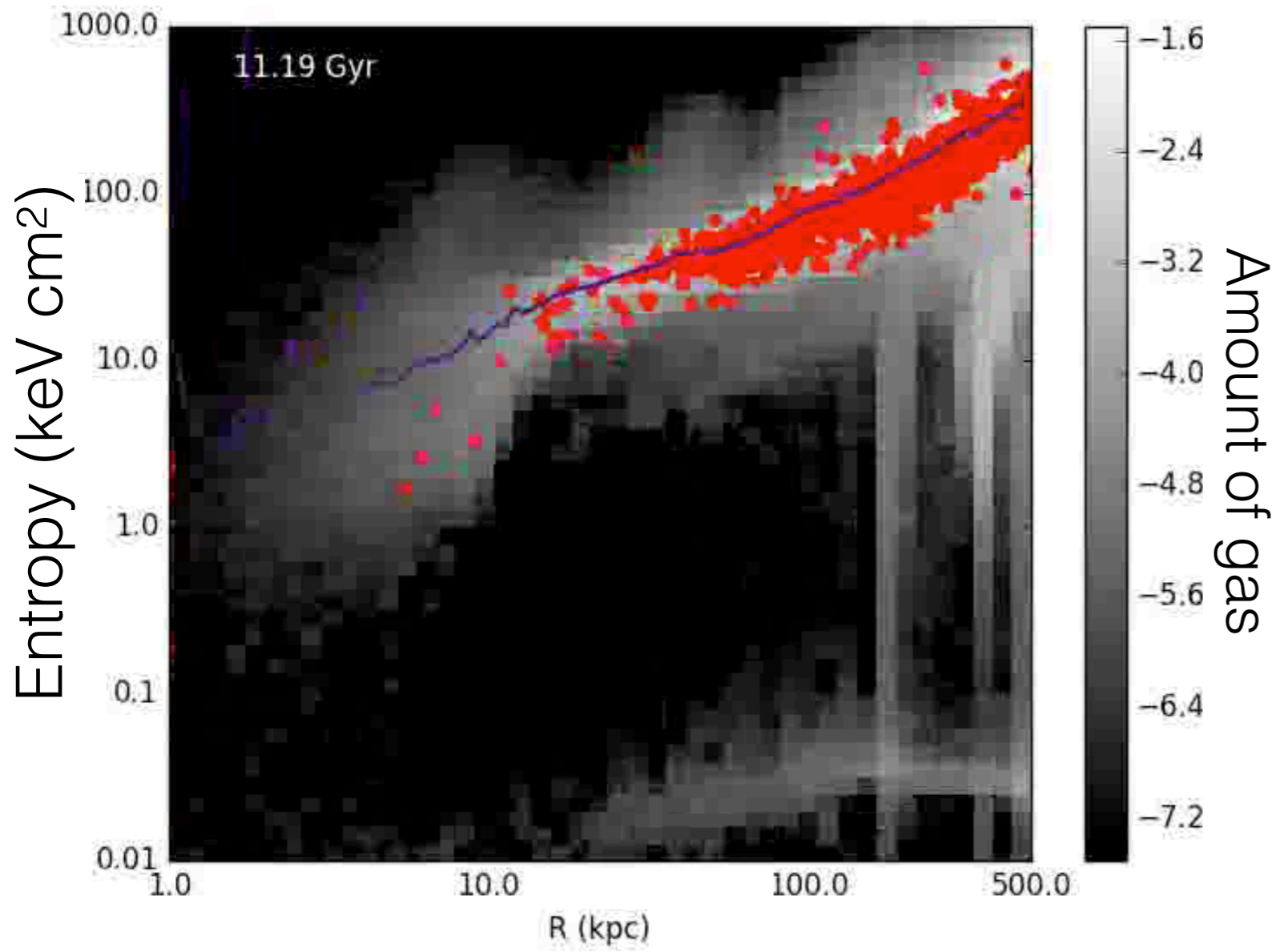
McDonald +'17:  
**all clusters**

**Arnaud+ clusters**  
are closer in mass  
to Romulus C;  
**McDonald+ are**  
more massive.

# Multiphase Intracluster Medium?

AGN heated particles rise and settle at 30-500 kpc

AGN stabilizes central entropy at  $\sim 10 \text{ keV cm}^2$

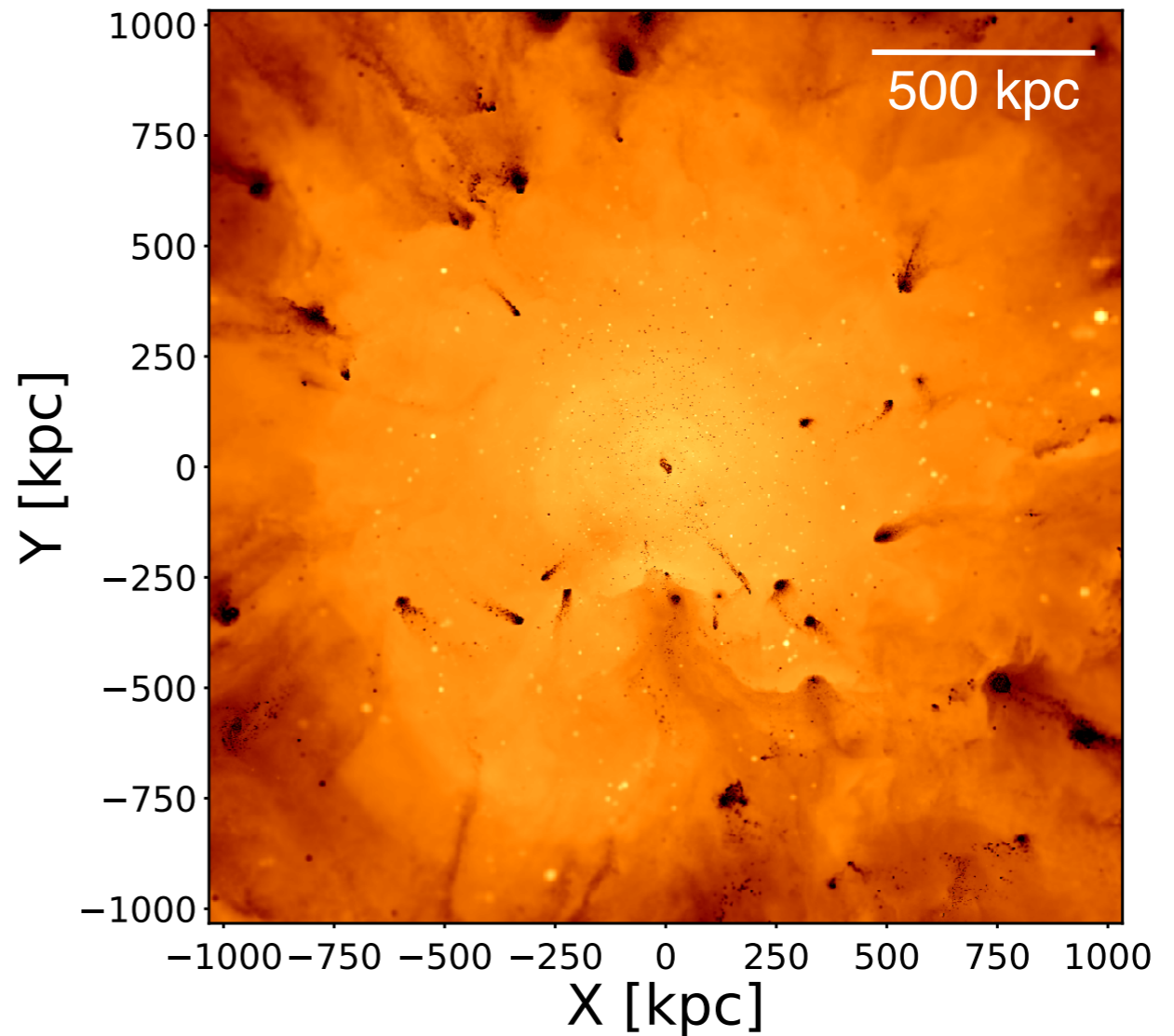
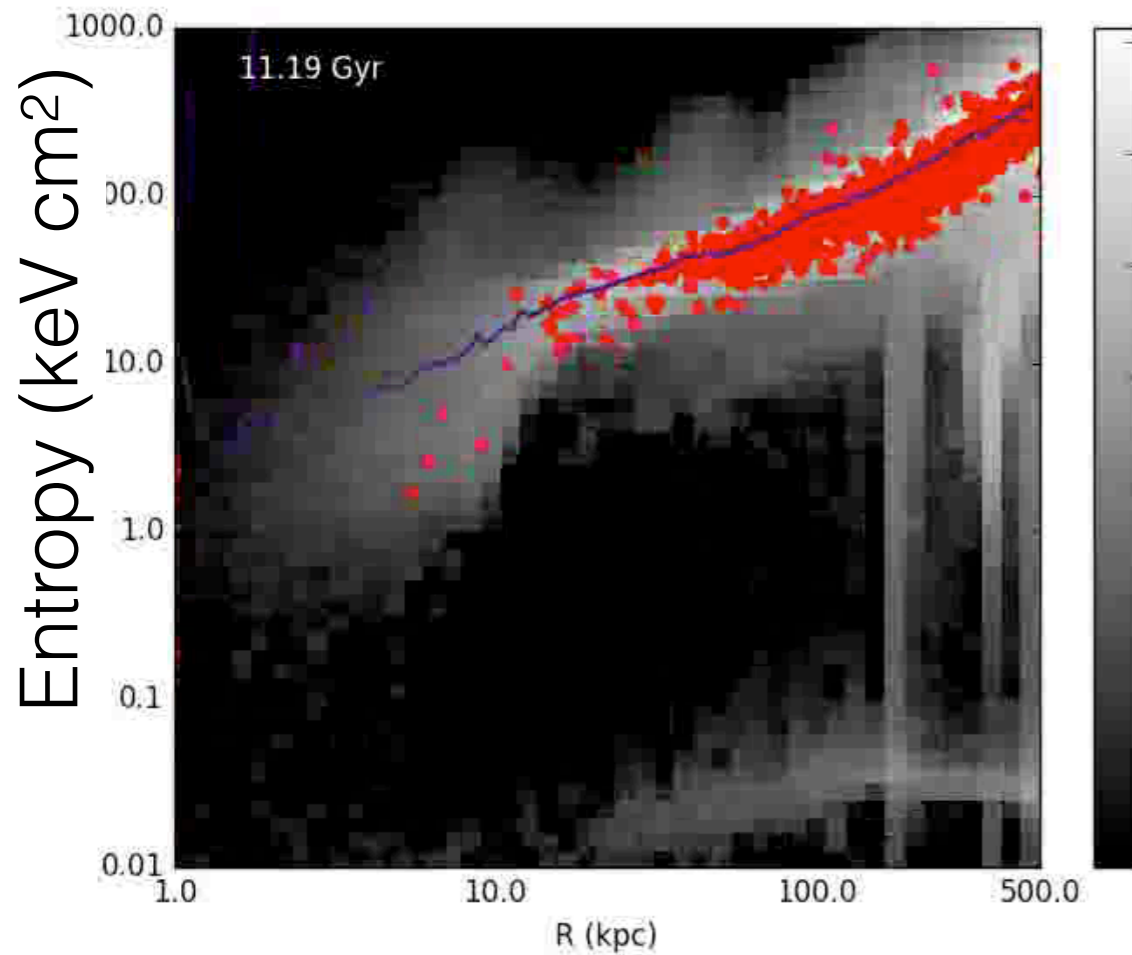


Chadayammuri+ in prep



# Multiphase Intracluster Medium?

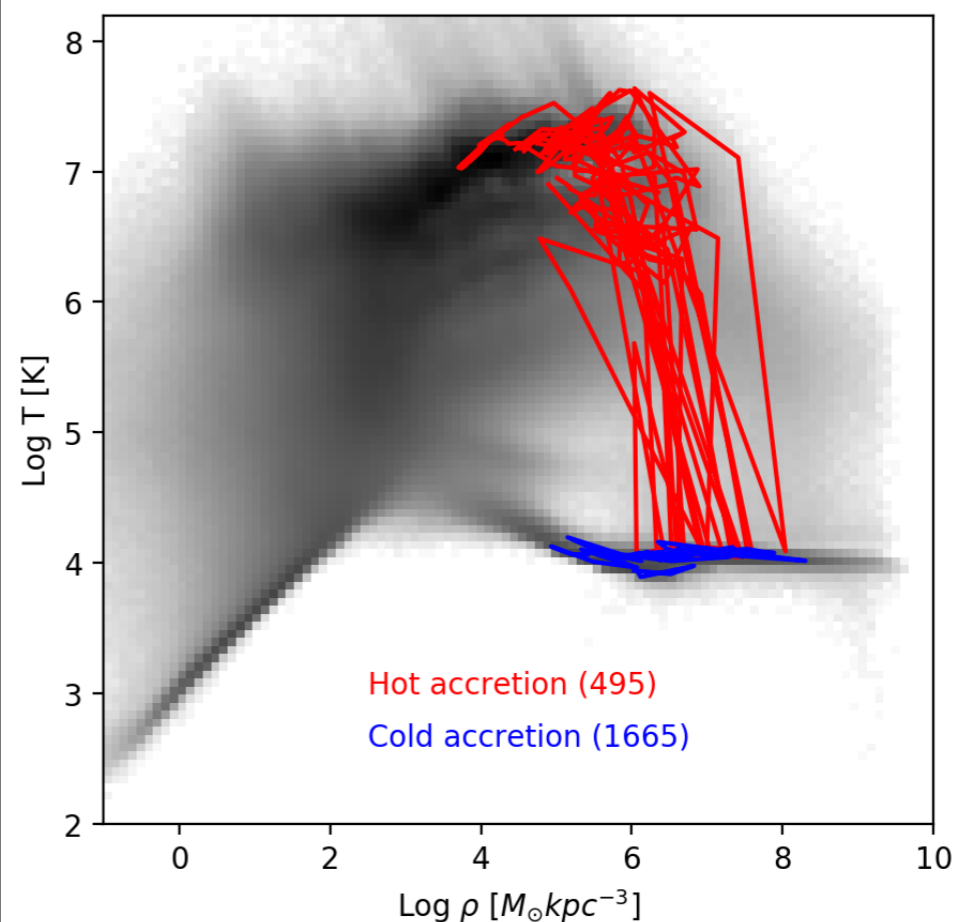
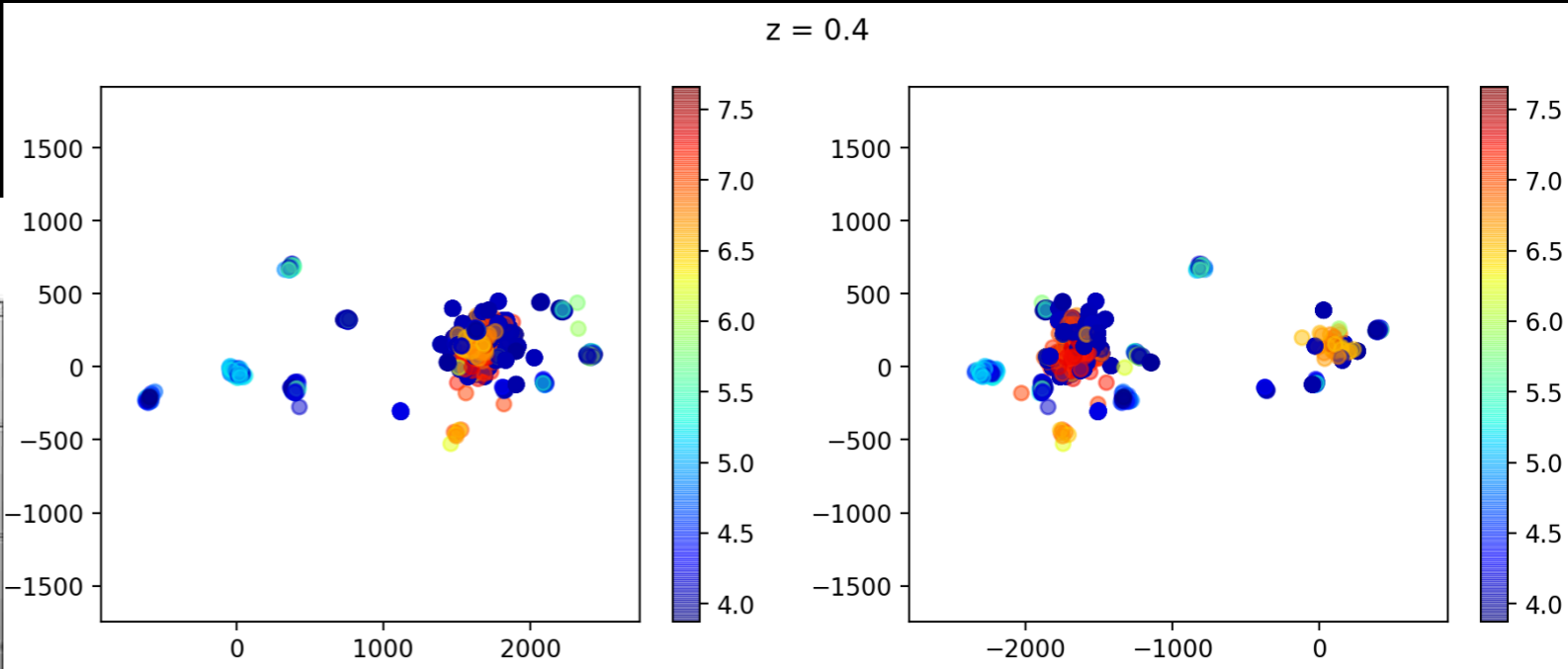
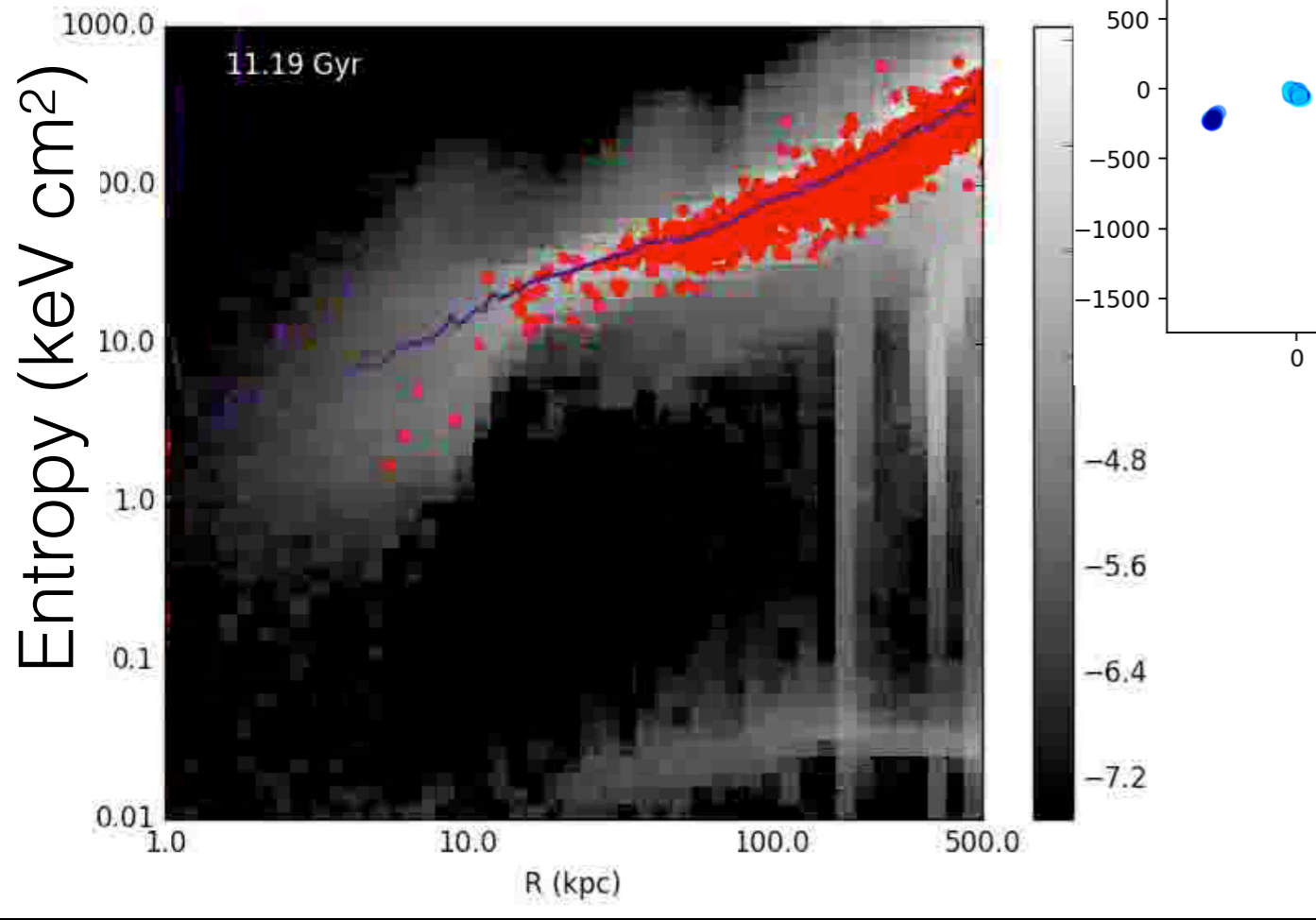
Gas with range of (low)  $K$  in the ICM — some is cold gas coming in from far. But we also see ICM cooling: cold clouds?



Chadayammuri+ in prep

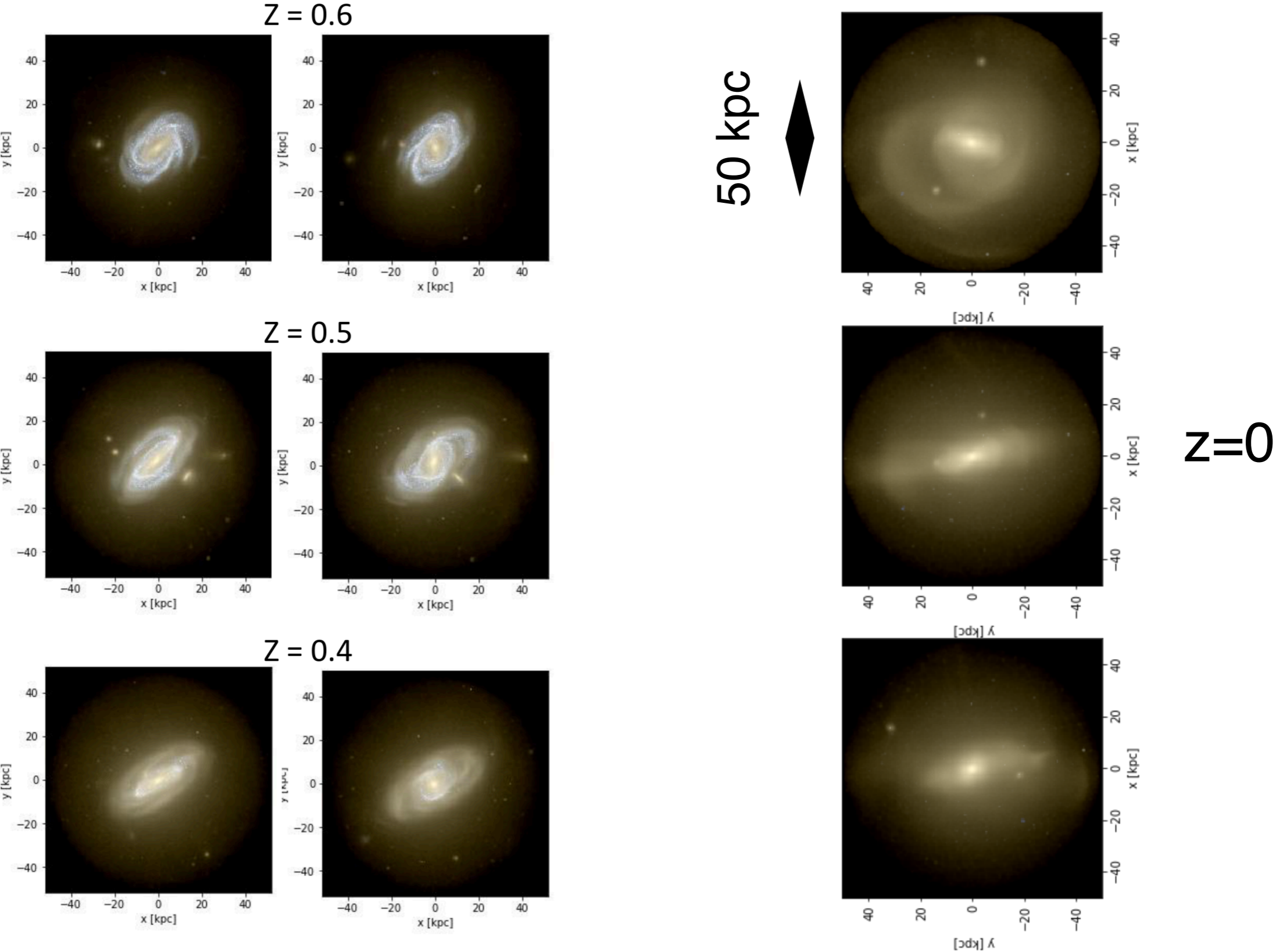
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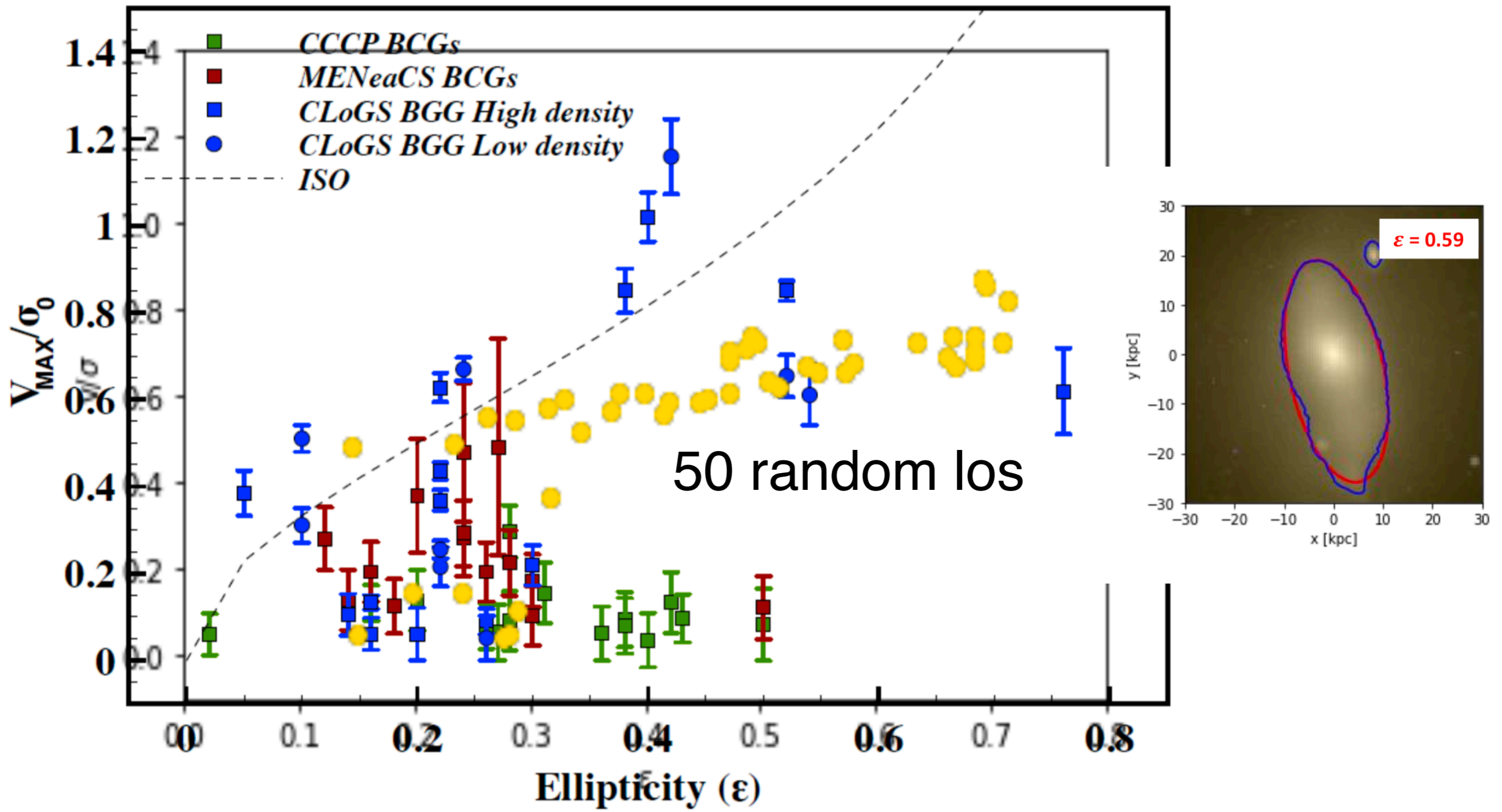
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# Quenching of the RomulusC BCG



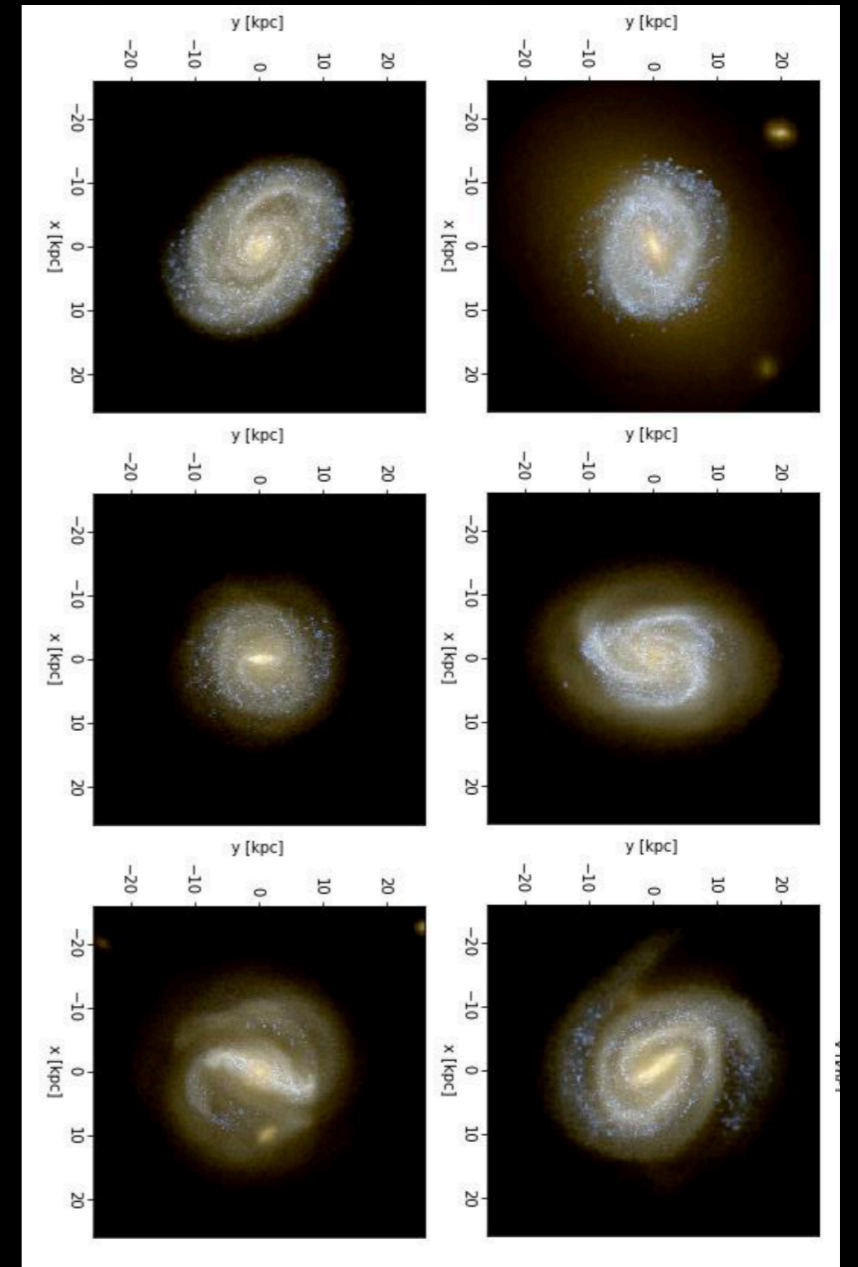
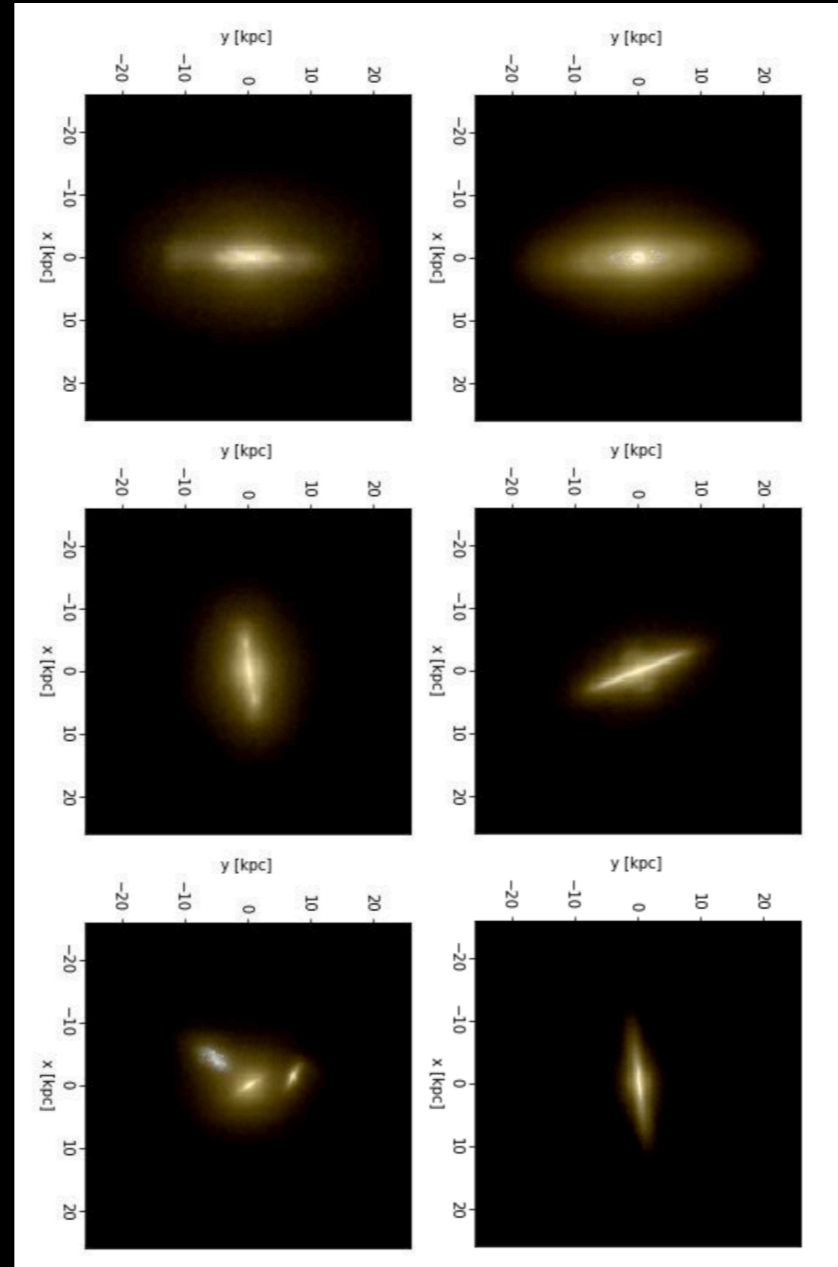
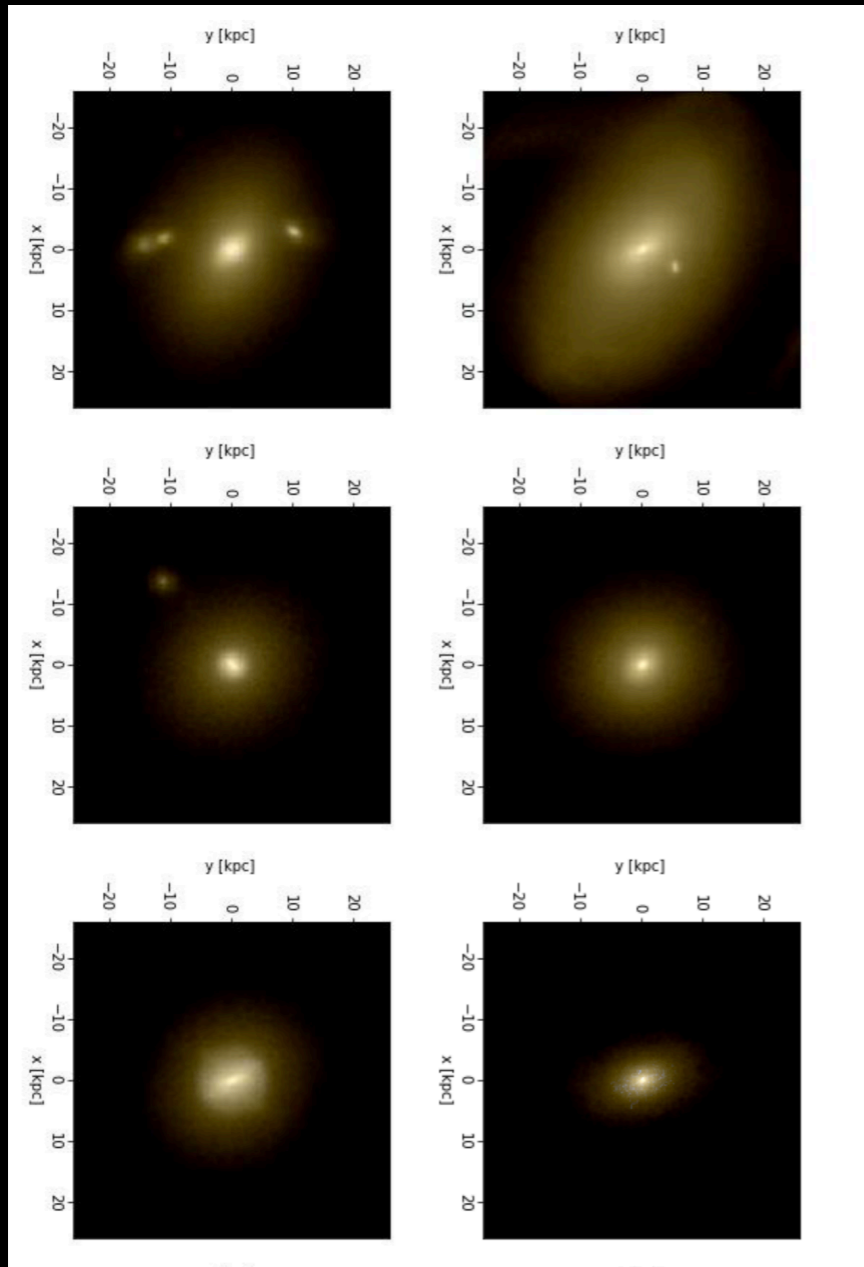


# RomulusC BCG Properties



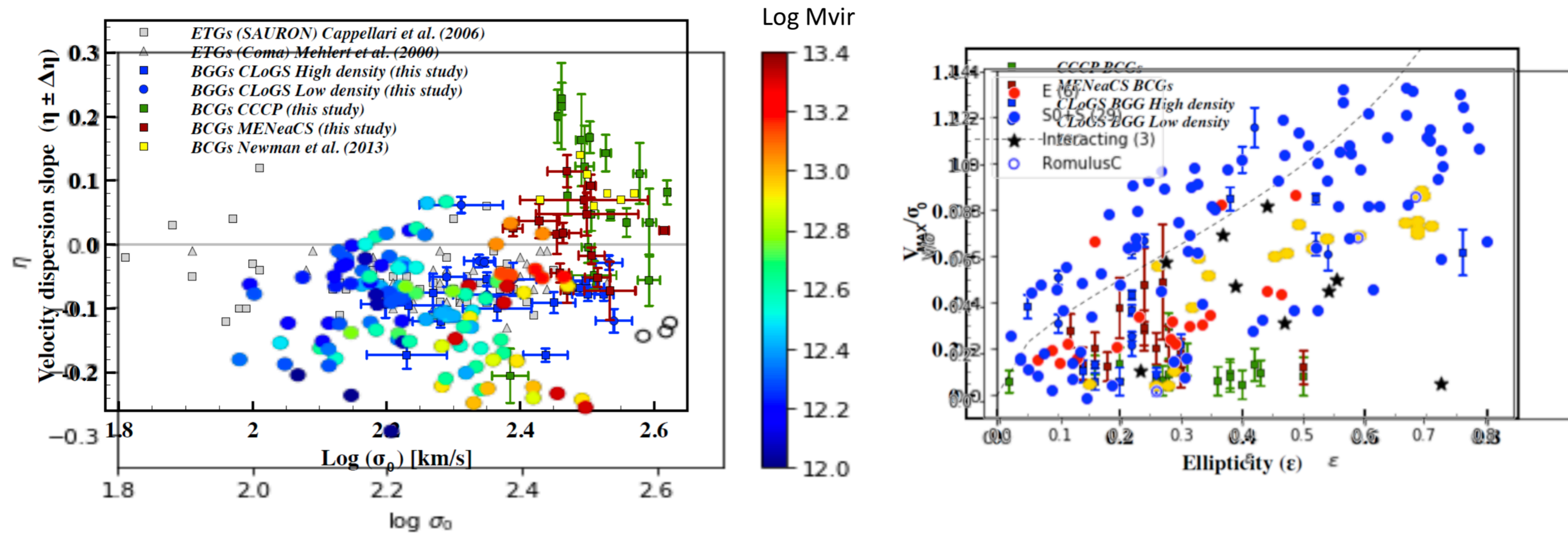
# BCG Properties

## Romulus25 — galaxy groups



# BCG Properties

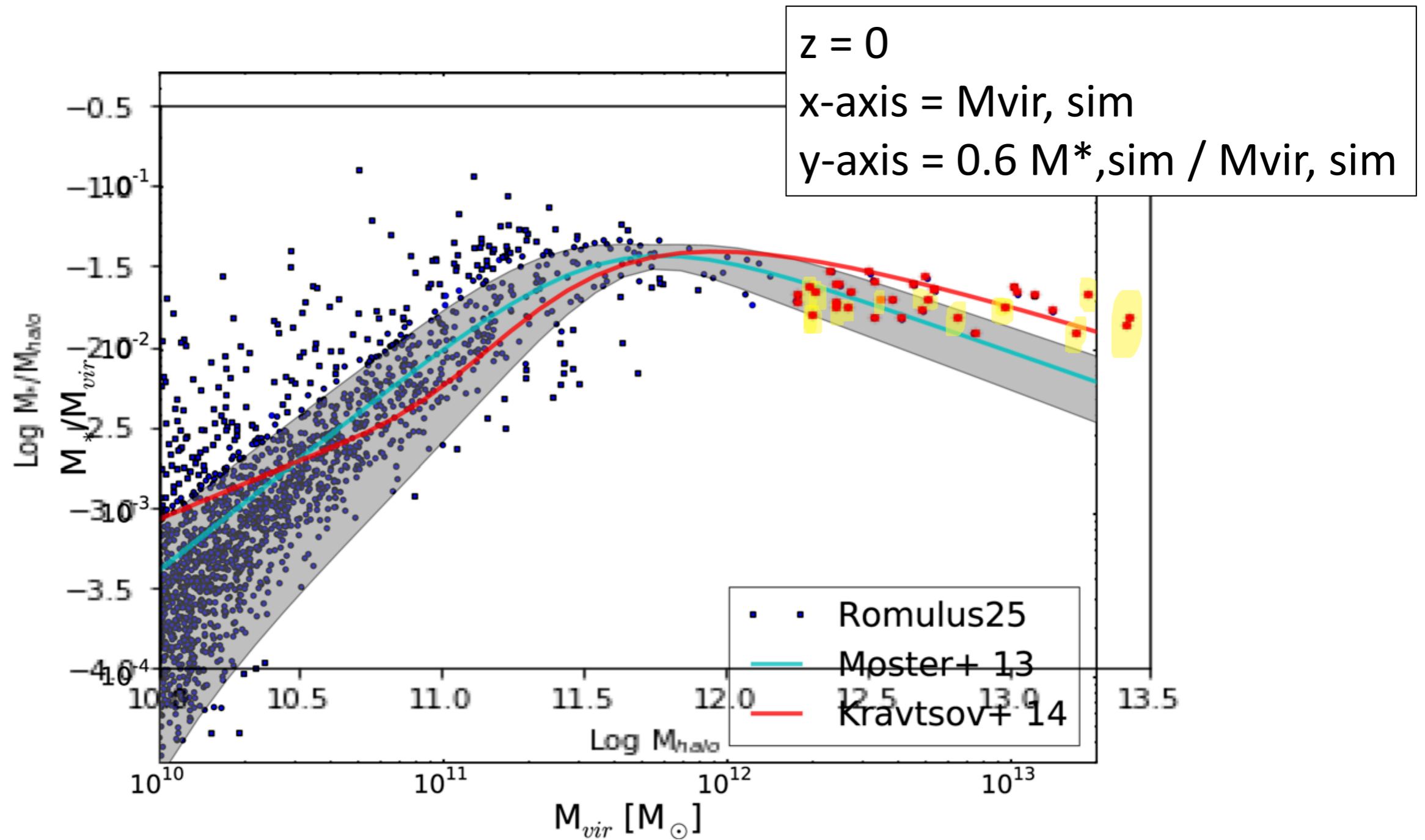
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# BCG Properties

## Romulus25 — galaxy groups



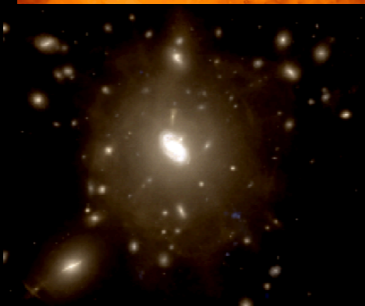
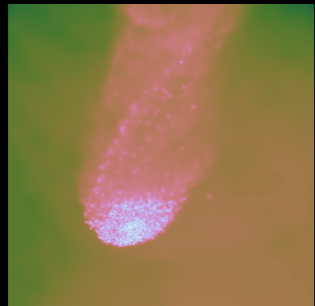
## Exploring the rich physics unfolding in groups & clusters in a holistic manner



### **Diffuse gas properties across hierarchy**

\*baryon fraction, entropy profile, cold/hot gas

\*CC/NCC dichotomy, impact of mergers



### **Evolution of central & satellite galaxies**

\*morphology, SFH & assembly of centrals,

\*quenching & morphology transformation

### **BH/AGN dynamics, growth/feedback**

\*centrals and satellites

\*feedback mode, duty cycles, AGN+SN

### **Cosmology: CMB/LSS tension**

\*stellar - gas- dark matter dynamics

\*probe hydrostatic bias as function of mass,  $z$

