Unified Modeling of Galaxy Populations in Clusters

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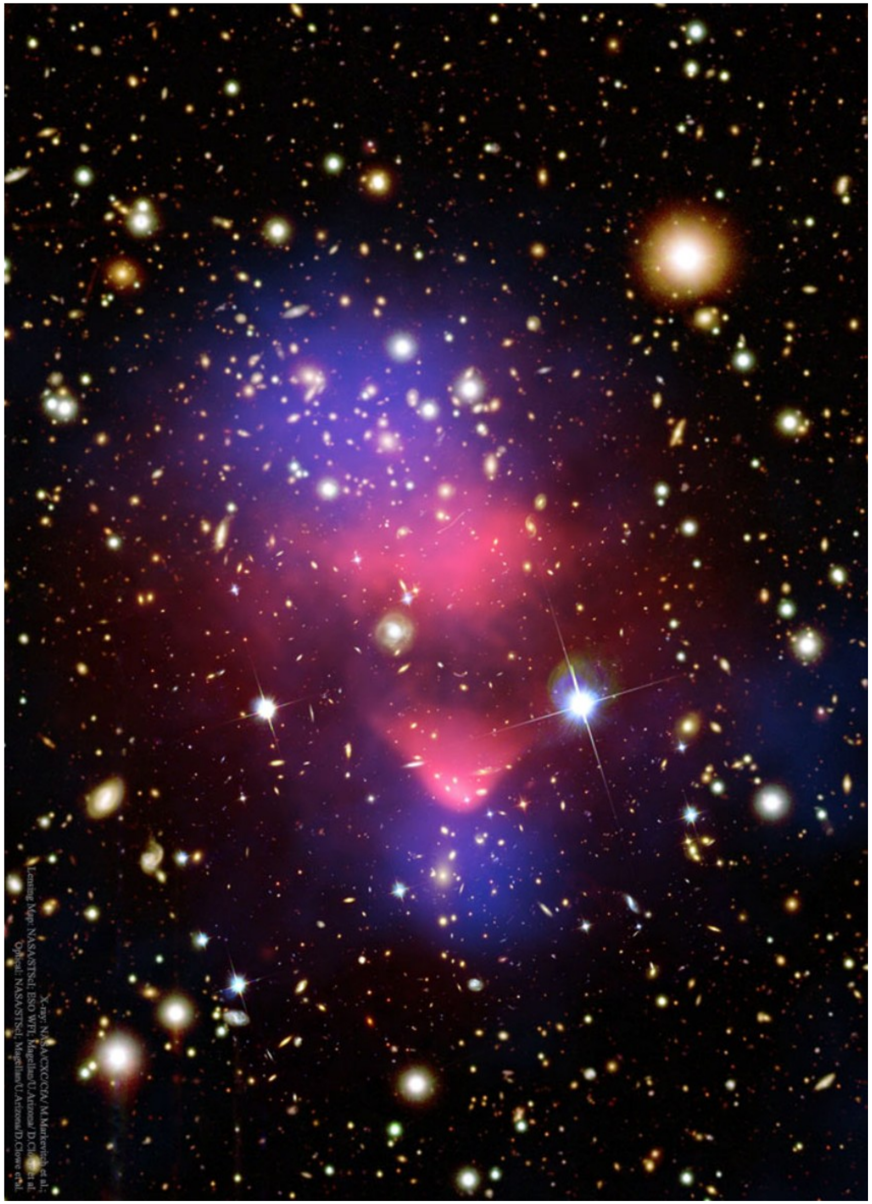
Outline

- Scientific background (Why it matters)
- The Galaxy Clustering Problem (Why Blue Waters)
- Charm++ and ChaNGa (Key Challenges)
- Recent results (Accomplishments)

Clusters: the science

- Largest bound objects in the Universe
- Visible across the entire Universe
- Baryonic content is observable
- “Closed box” for galactic evolution



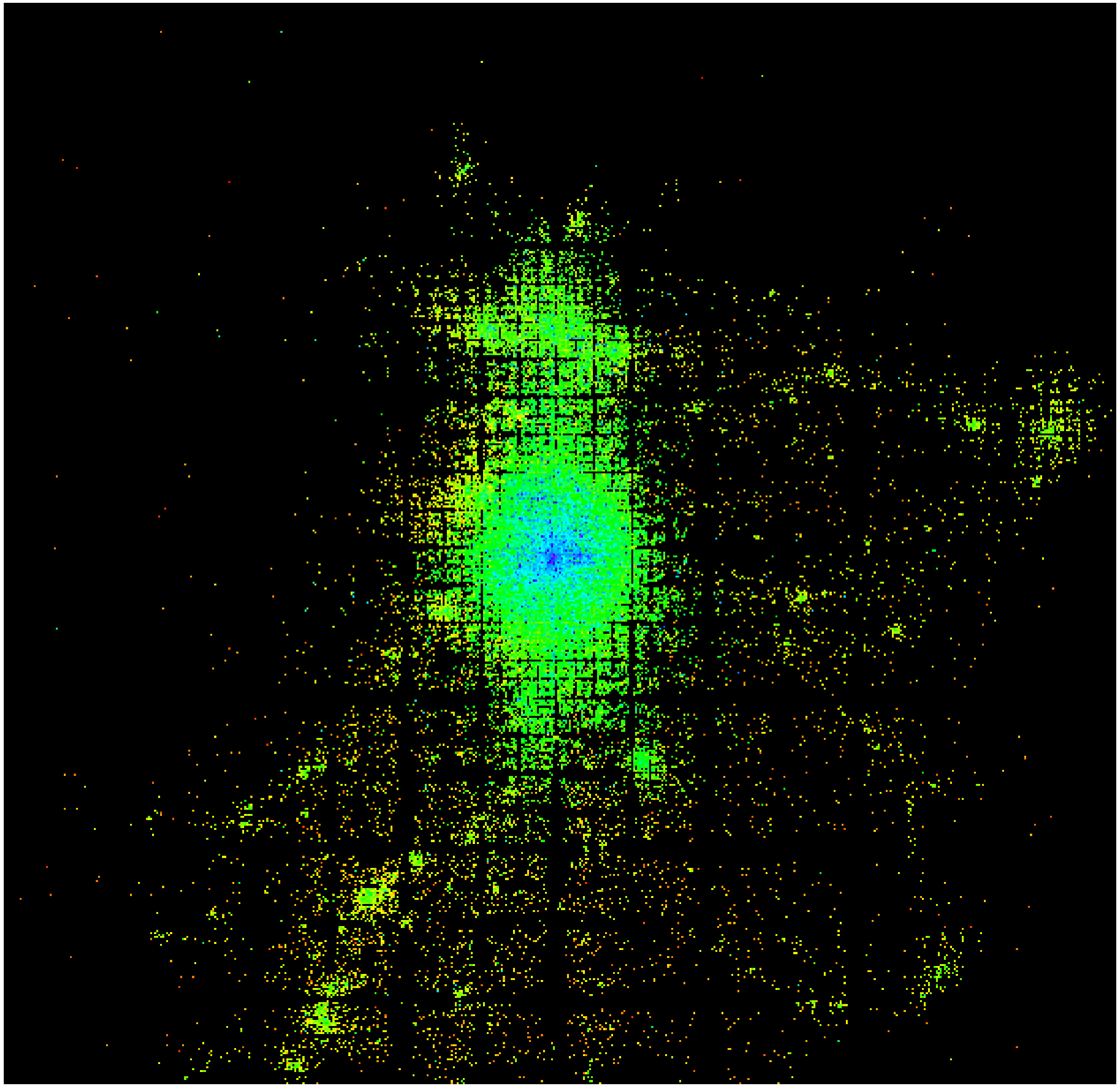
Clusters: the challenge

- Good models of stellar feedback
- Good models of AGN (black hole) feedback
- Hydrodynamic instabilities require good algorithms
- Resolution: 10^5 Msun particles in 10^{15} Msun object
- Highly “clustered” computation

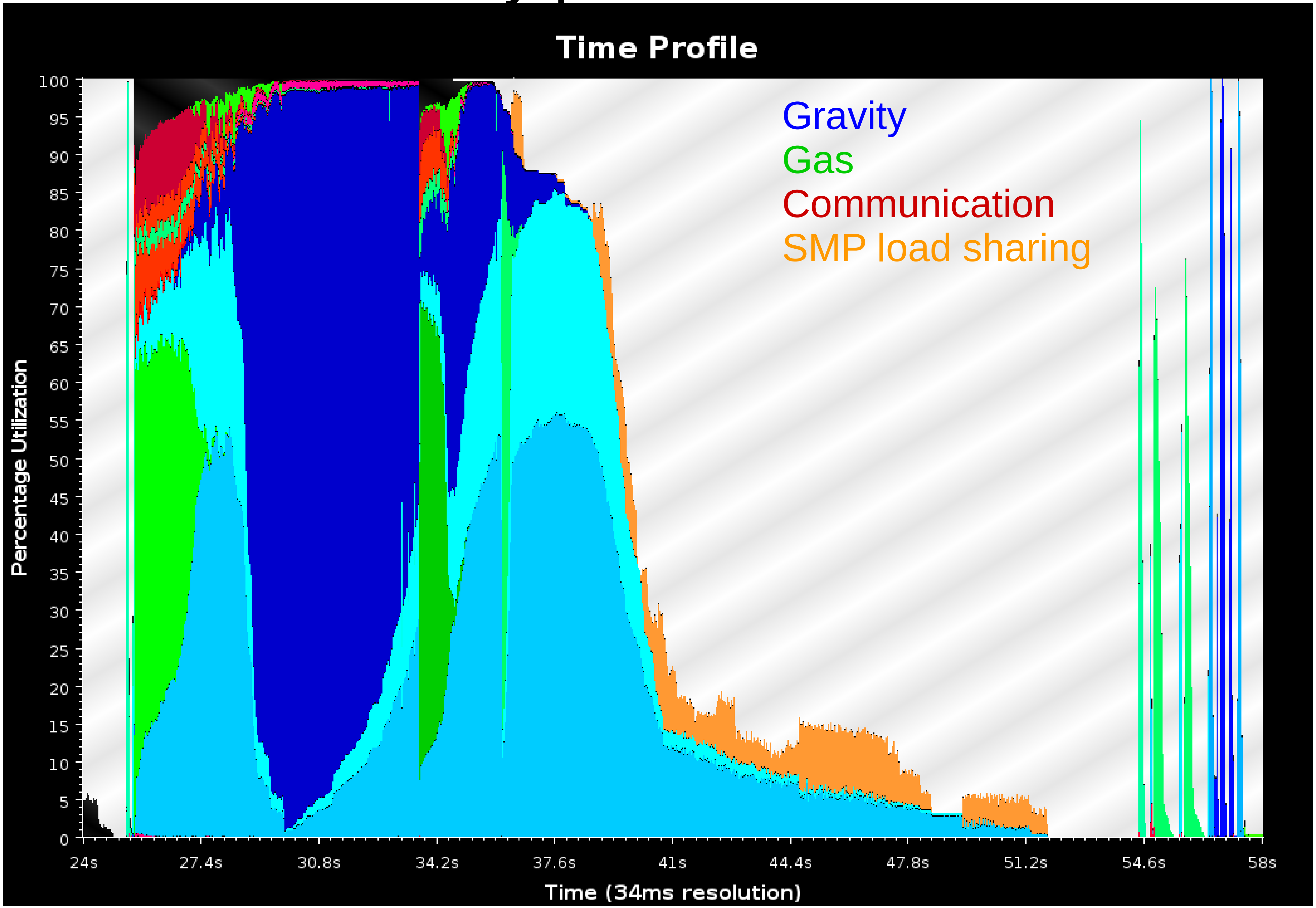
Clustered/Multistepping Challenges

- Computation is concentrated in a small fraction of the domain
- Load/particle imbalance
- Communication imbalance
- Fixed costs:
  - Domain Decomposition
  - Load balancing
  - Tree build

Load distribution

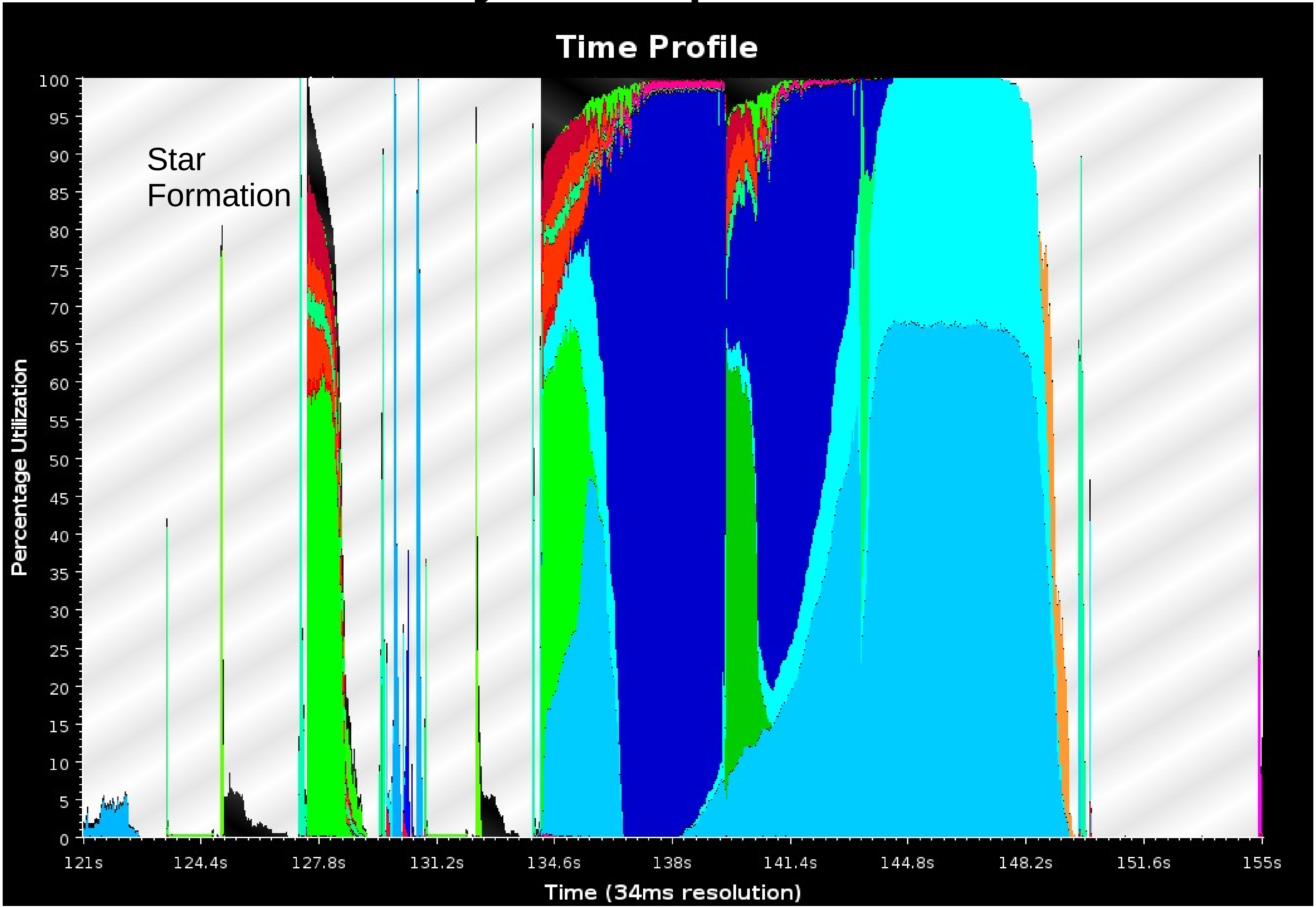


LB by particle count



29.4 seconds

LB by Compute time



15.8 seconds

Charm Nbody GrAvity solver

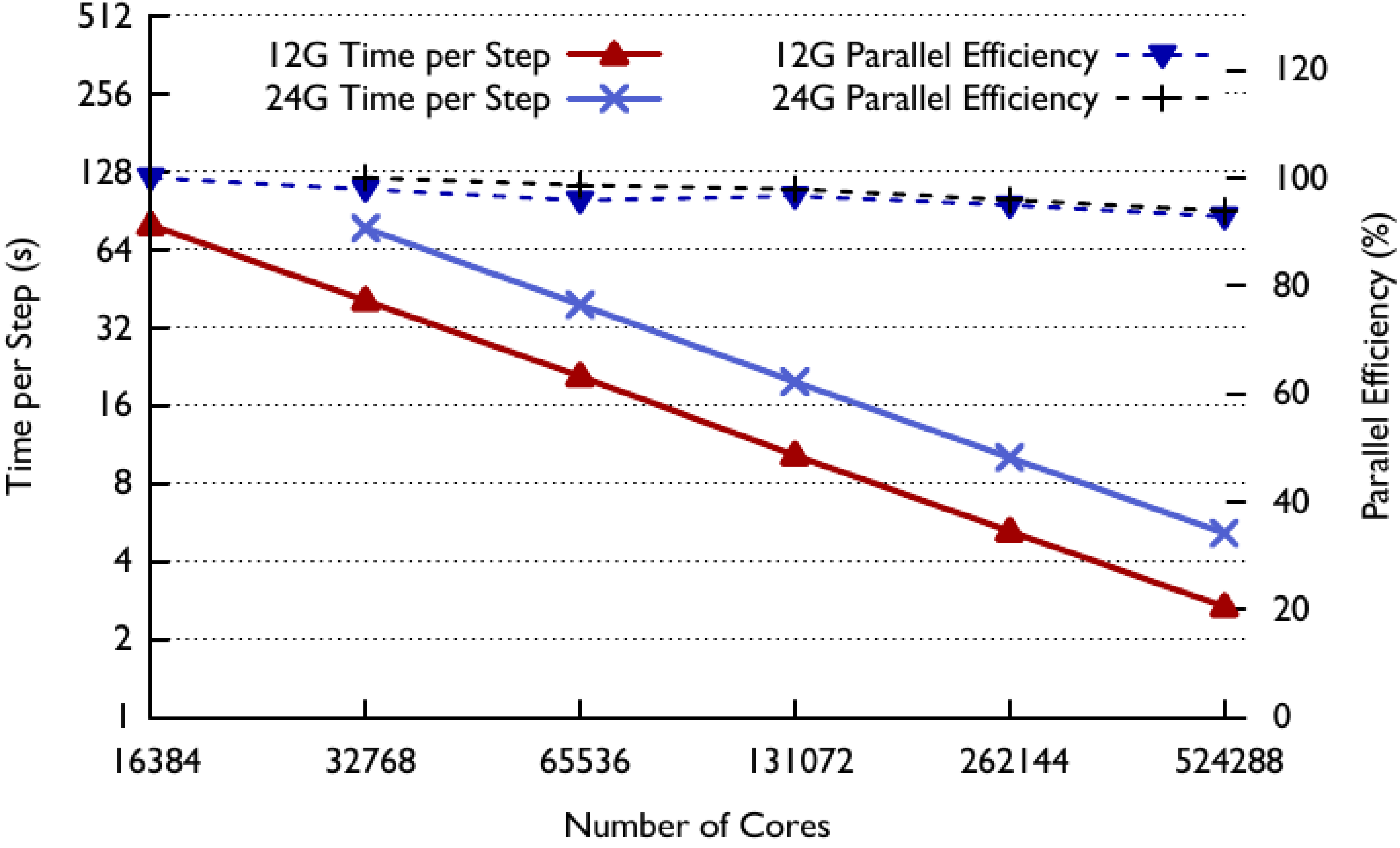
- Massively parallel SPH
- SNe feedback creating realistic outflows
- SF linked to shielded gas
- SMBHs
- Optimized SF parameters

Menon+ 2014, Governato+ 2014

Charm++

- C++-based parallel runtime system
  - Composed of a set of globally-visible parallel objects that interact
  - The objects interact by asynchronously invoking methods on each other
- Charm++ runtime
  - Manages the parallel objects and (re)maps them to processes
  - Provides scheduling, load balancing, and a host of other features, requiring little user intervention

Scaling to .5M cores



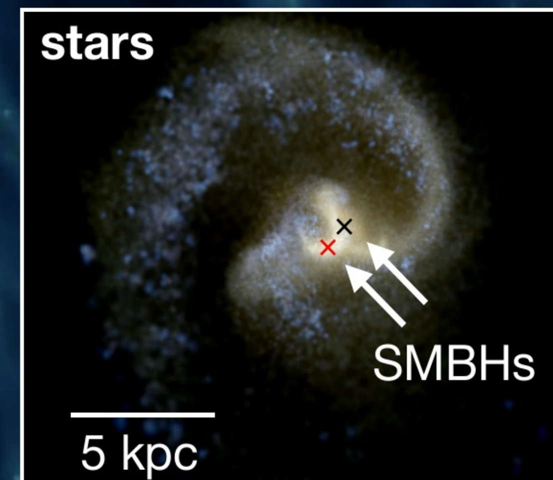
The ROMULUS Simulations

CHANGA

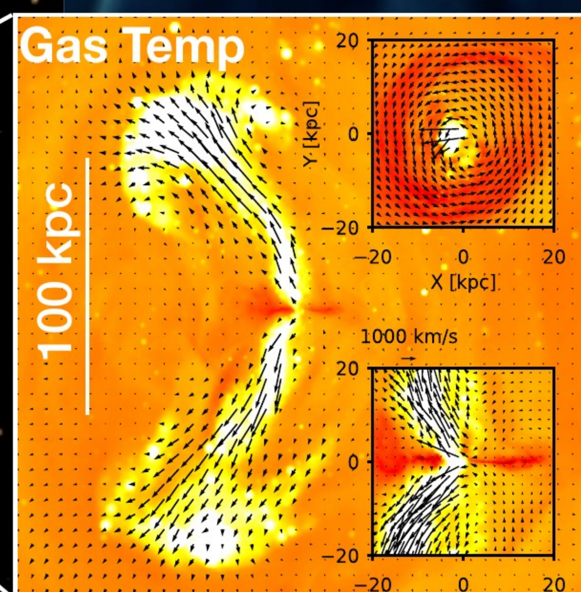
Certified organic, free-range, locally grown supermassive black holes

- ✓ Early Seeding in low mass halos
- ✓ Self-consistent and physically motivated dynamics, growth, and feedback
- ✓ Naturally produces large-scale outflows
- ✓ **No unnecessary additives or assumptions**

ROMULUS25
25 Mpc Volume
Tremmel+ 2017
(gas temp)

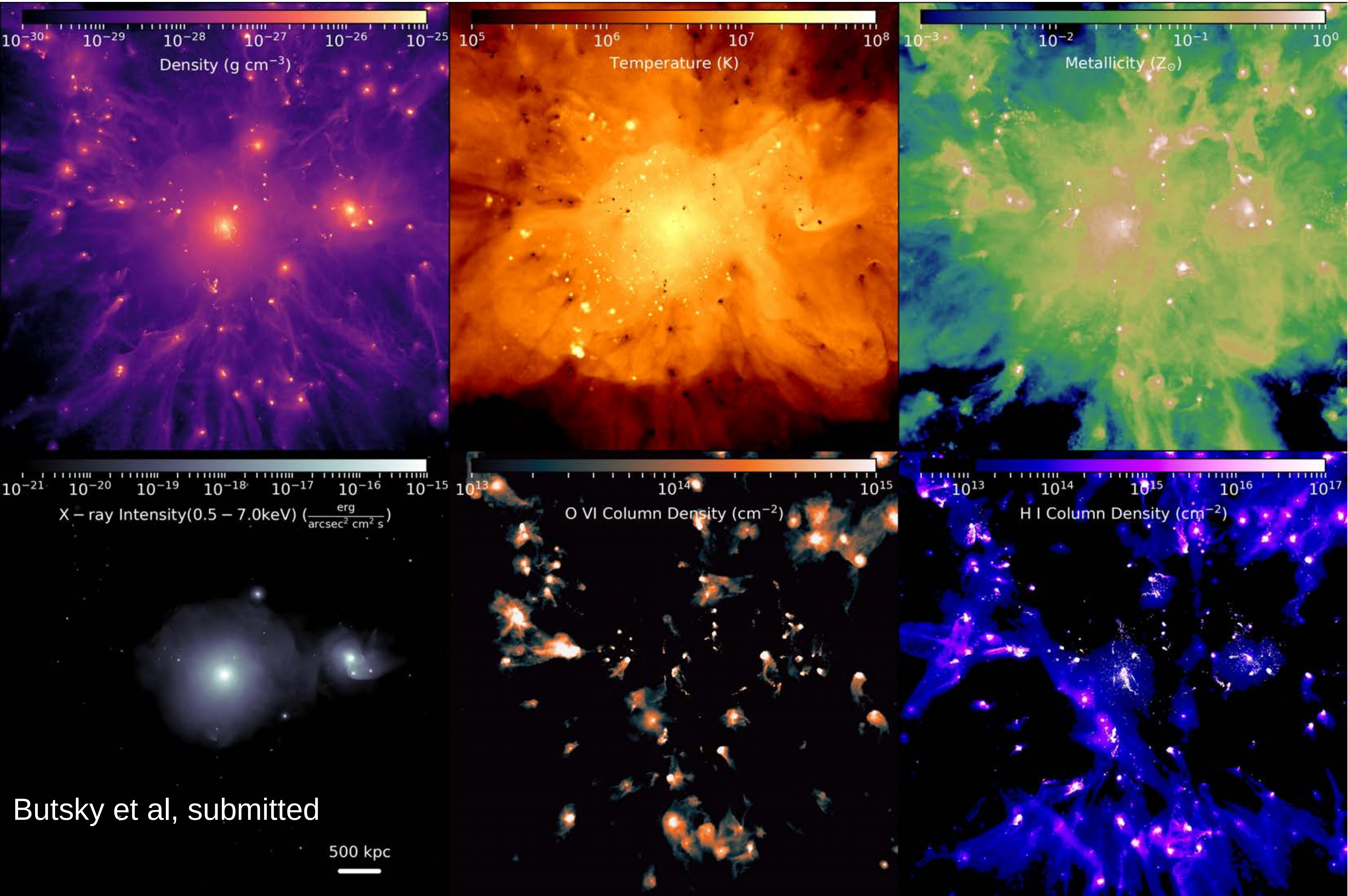


ROMULUSC
10^{14} M_{sun} Galaxy Cluster
Tremmel+ 2019
(stars, uvj colors)

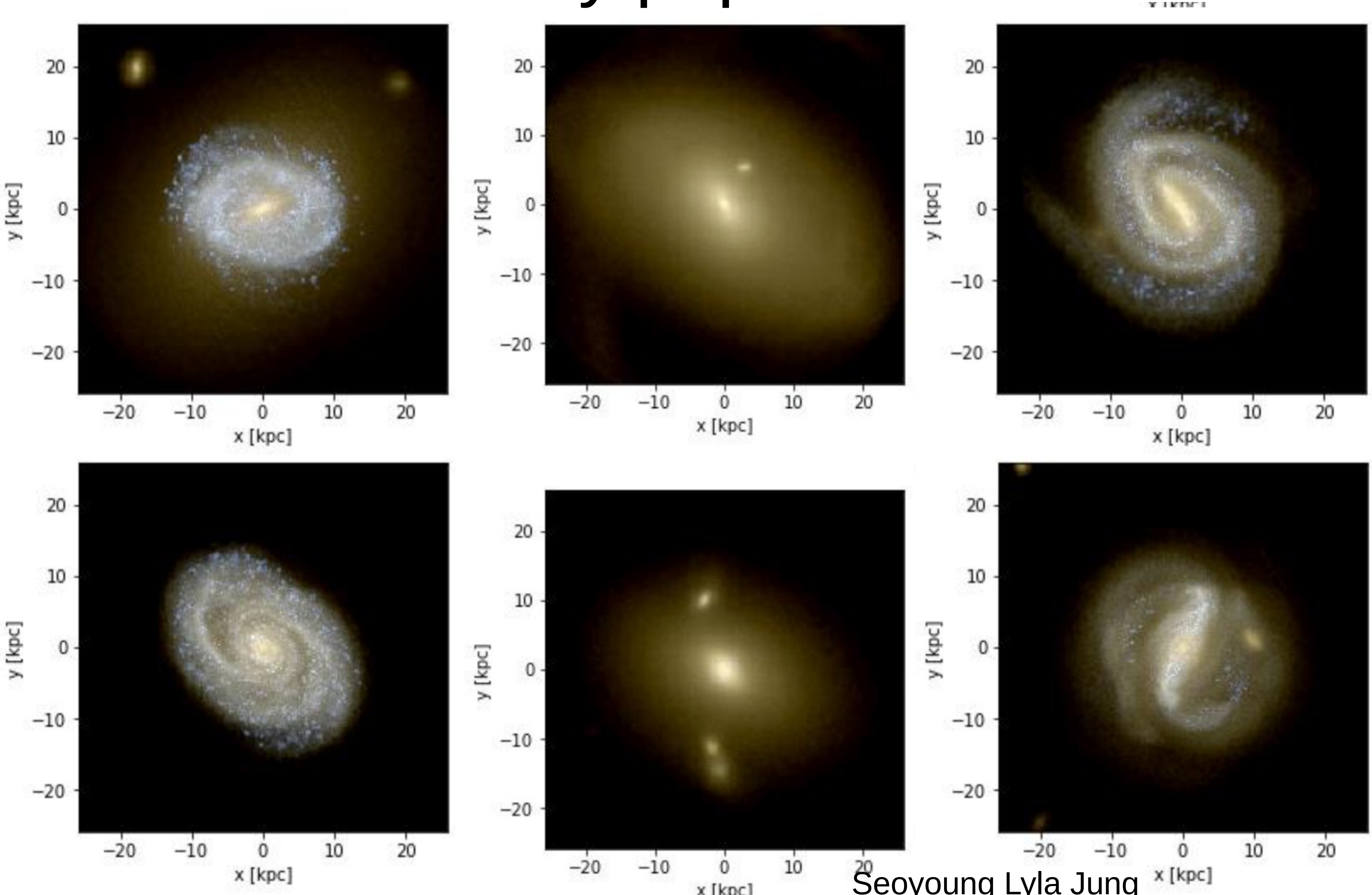


Resolution:
250 pc (grav)
50 pc (hydro)
~1e5 M_{sun}

Galaxy Cluster Observables

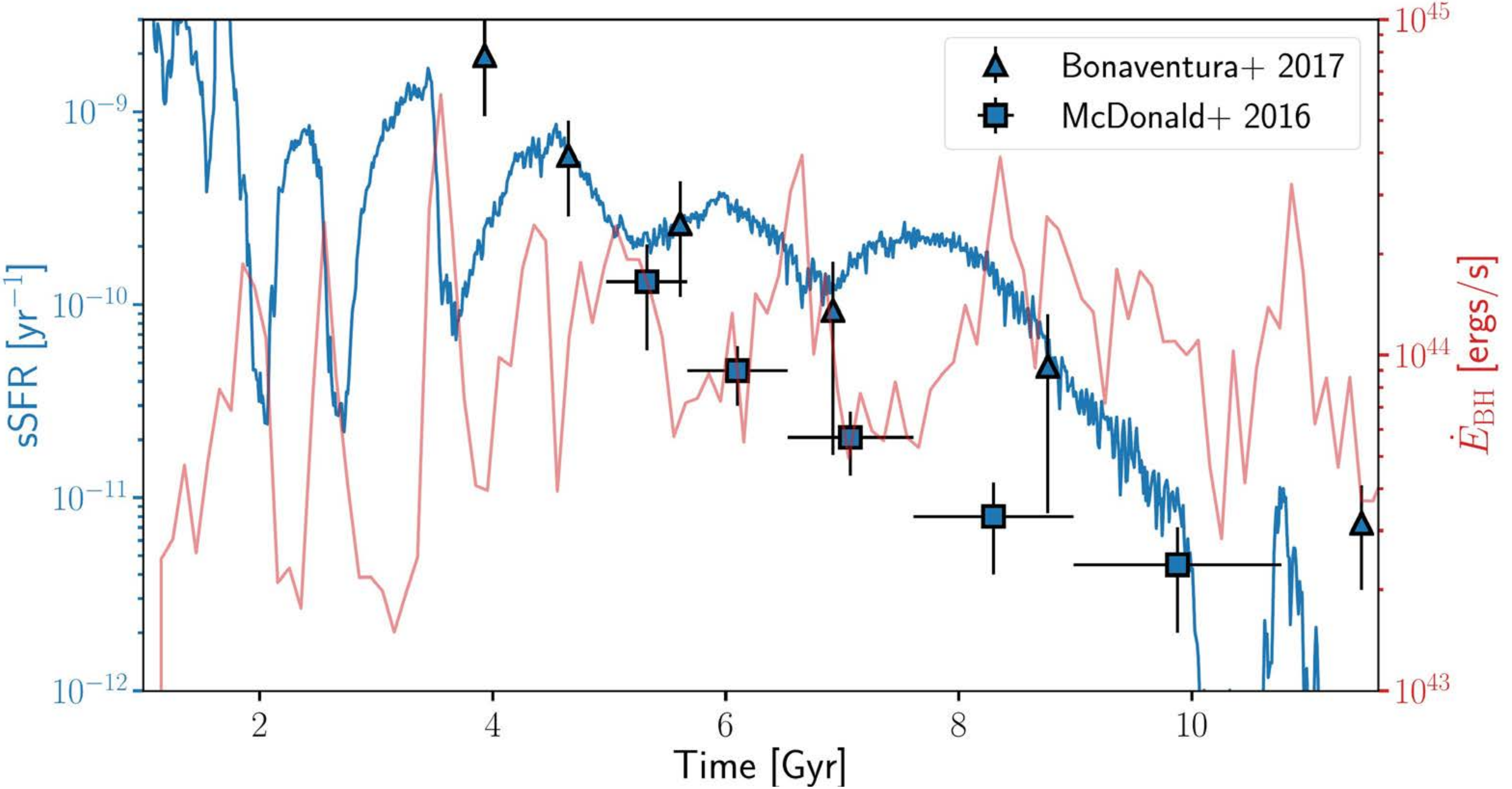


Galaxy populations



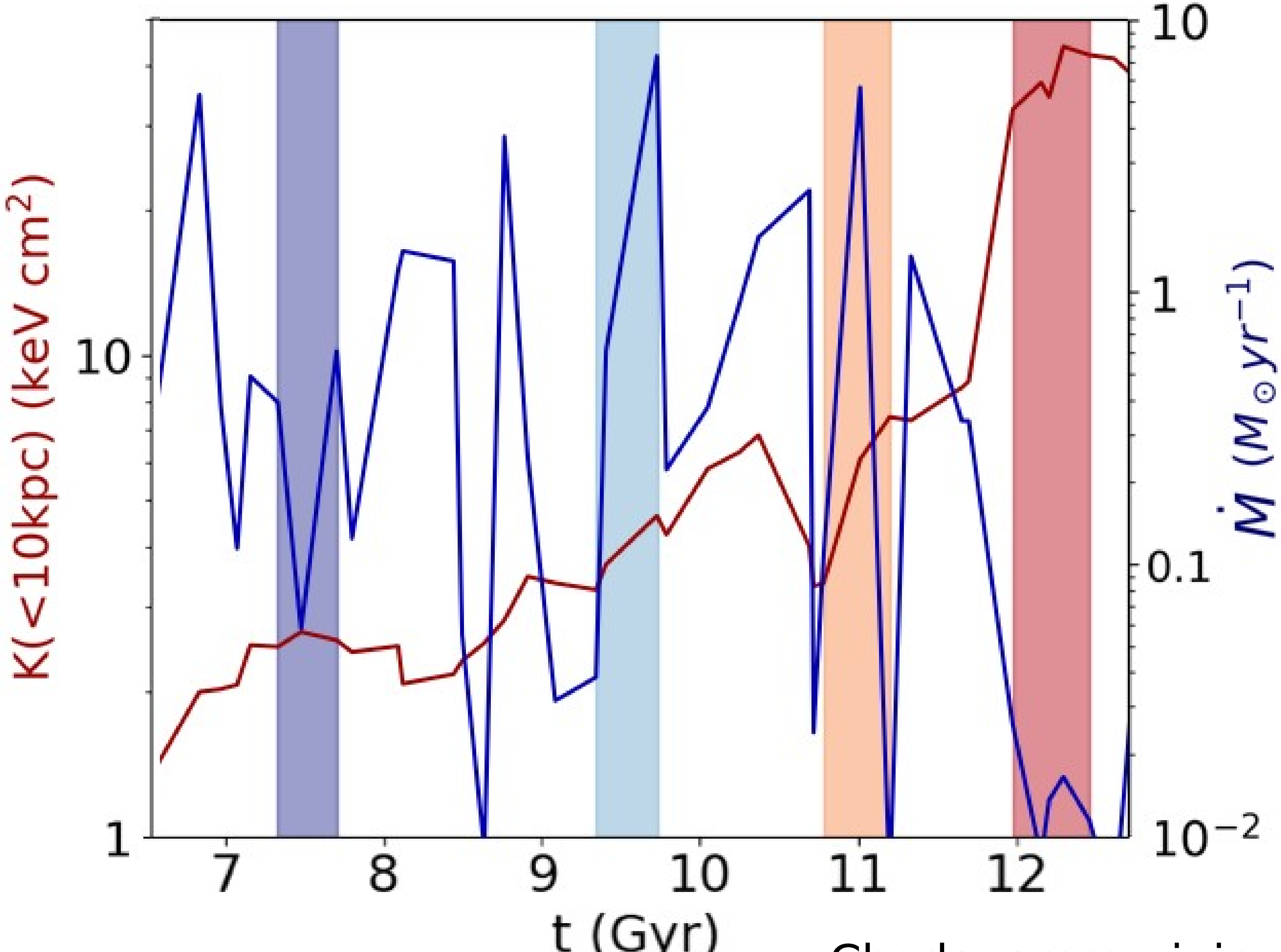
Seoyoung Lyla Jung

Outflows and Quenching



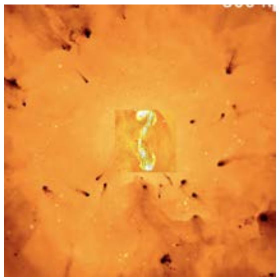
Chadayammuri, in prep

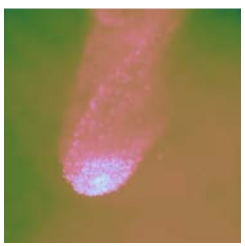
AGN feedback and Non/Cool Cores

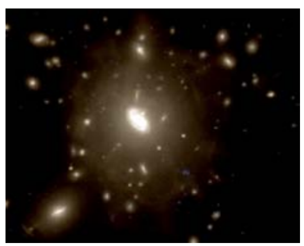


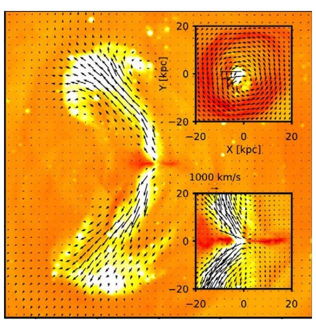
Chadayammuri, in prep

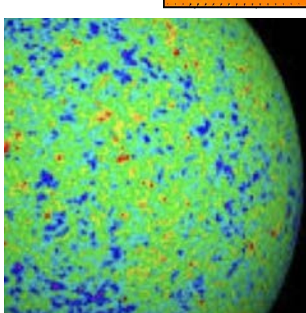
Exploring the physics of groups & clusters in a holistic manner

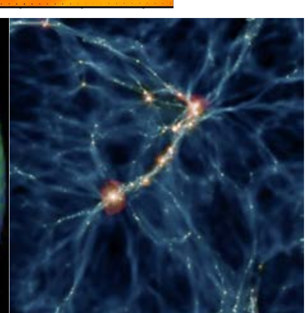












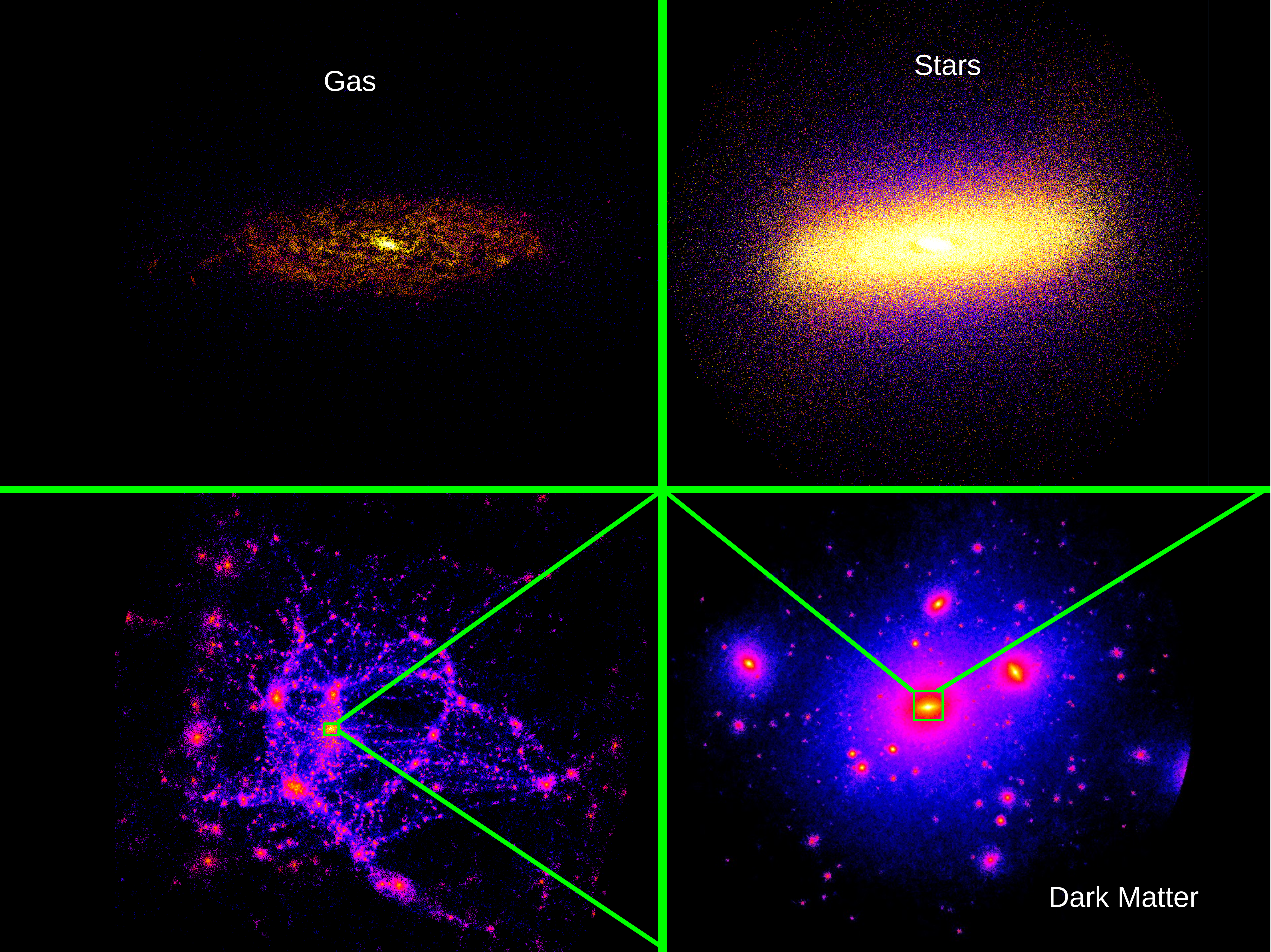
- Diffuse gas properties
  - Baryon fraction, entropy profile
  - CC/NCC dichotomy & mergers
- Evolution of Cluster galaxies
  - Quenching & morphology changes
- AGN/BH evolution & dynamics
  - Merger rates & LISA
  - Feedback mode & duty cycles
- Cosmology: LSS/CMB tension
  - Stellar, gas, dark matter dynamics
  - Hydrostatic bias

Take Aways

- Galaxy Clusters are hard:
  - Scale is set by galactic (i.e. star formation) physics
  - Orders of magnitude larger than galaxies
  - Computational effort is spatially concentrated.
  - (Probably should include MHD/cosmic rays)
- But now clusters are doable
  - Capability machines
  - Advanced load balancing techniques
  - First “holistic” simulations of galaxy clusters

Acknowledgments

- NSF ITR
- NSF Astronomy
- NSF SSI
- NSF XSEDE program for computing
- BlueWaters Petascale Computing
- Blue Waters PAID Program
- NASA HST
- NASA Advanced Supercomputing


Gas
Stars
Dark Matter

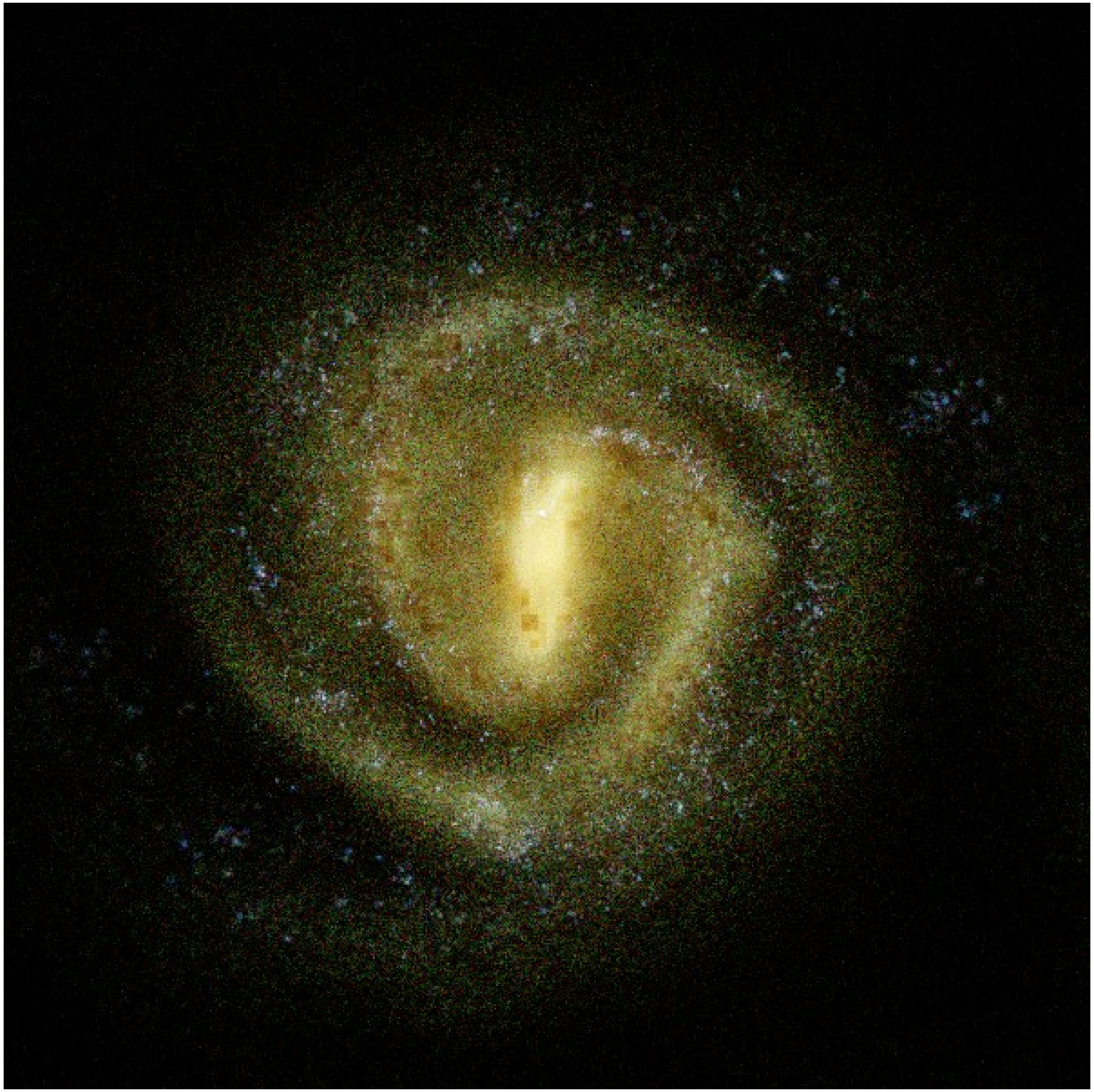
Modeling Star Formation: it's hard

- Gravitational Instabilities
- Magnetic Fields
- Radiative Transfer
- Molecular/Dust Chemistry
- Driven at large scales: differential rotation
- Driven at small scales: Supernovea and Stellar Winds
- Scales unresolvable in cosmological simulations

Resolution and Subgrid Models

- Maximize Simulation Resolution
  - Capture tidal torques/accretion history (20+ Mpc)
  - Adapt resolution to galaxy (sub-Kpc, 10^5 Msun)
- Capture Star Formation in a sub-grid model
  - Stars form in high density environments
  - Supernovea/stellar winds/radiation regulate star formation
  - Mitigate issues with poor resolution (overcooling)
  - Tune to match present day stellar populations

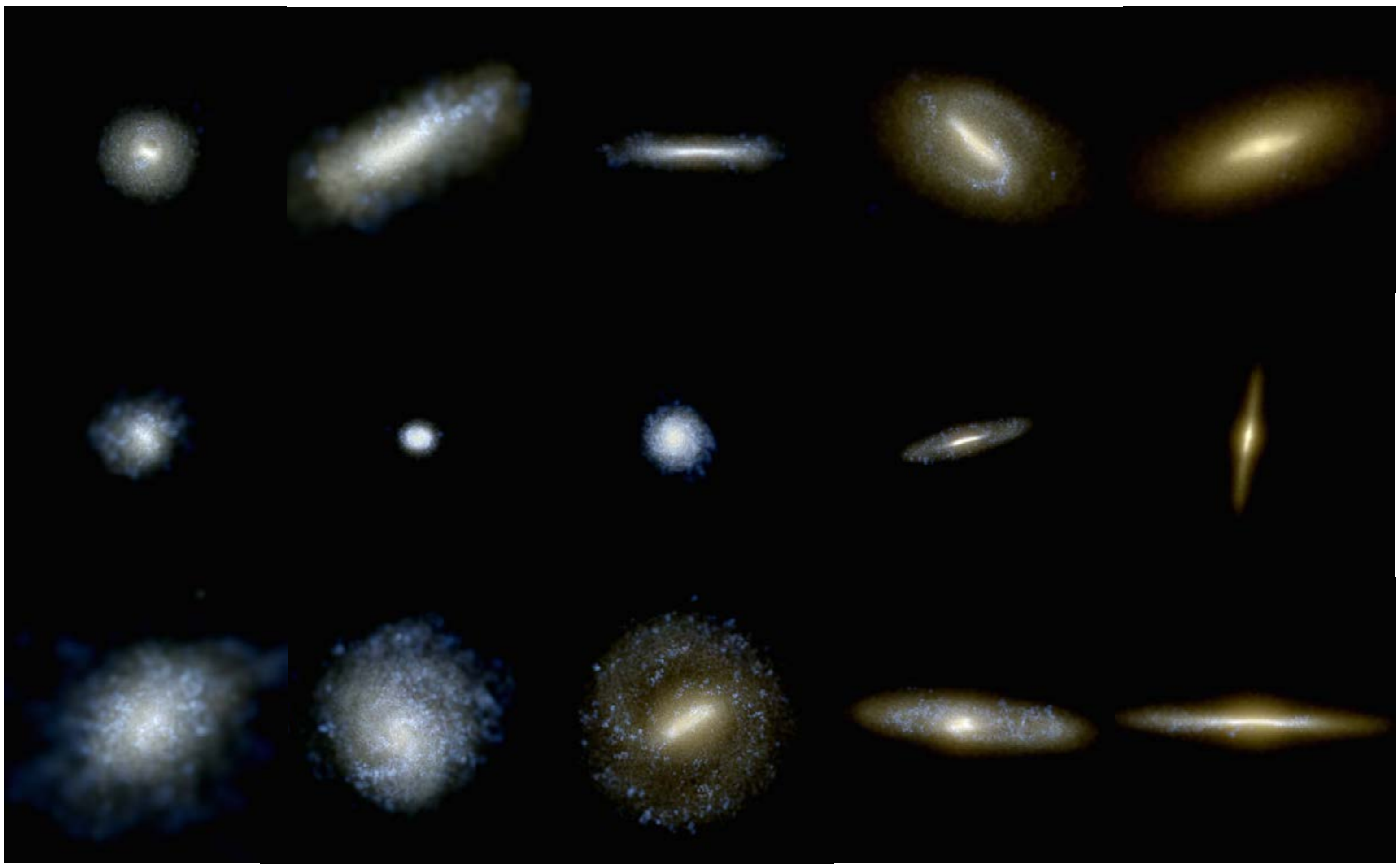
Previous PRAC: good morphologies



Danielle
Skinner

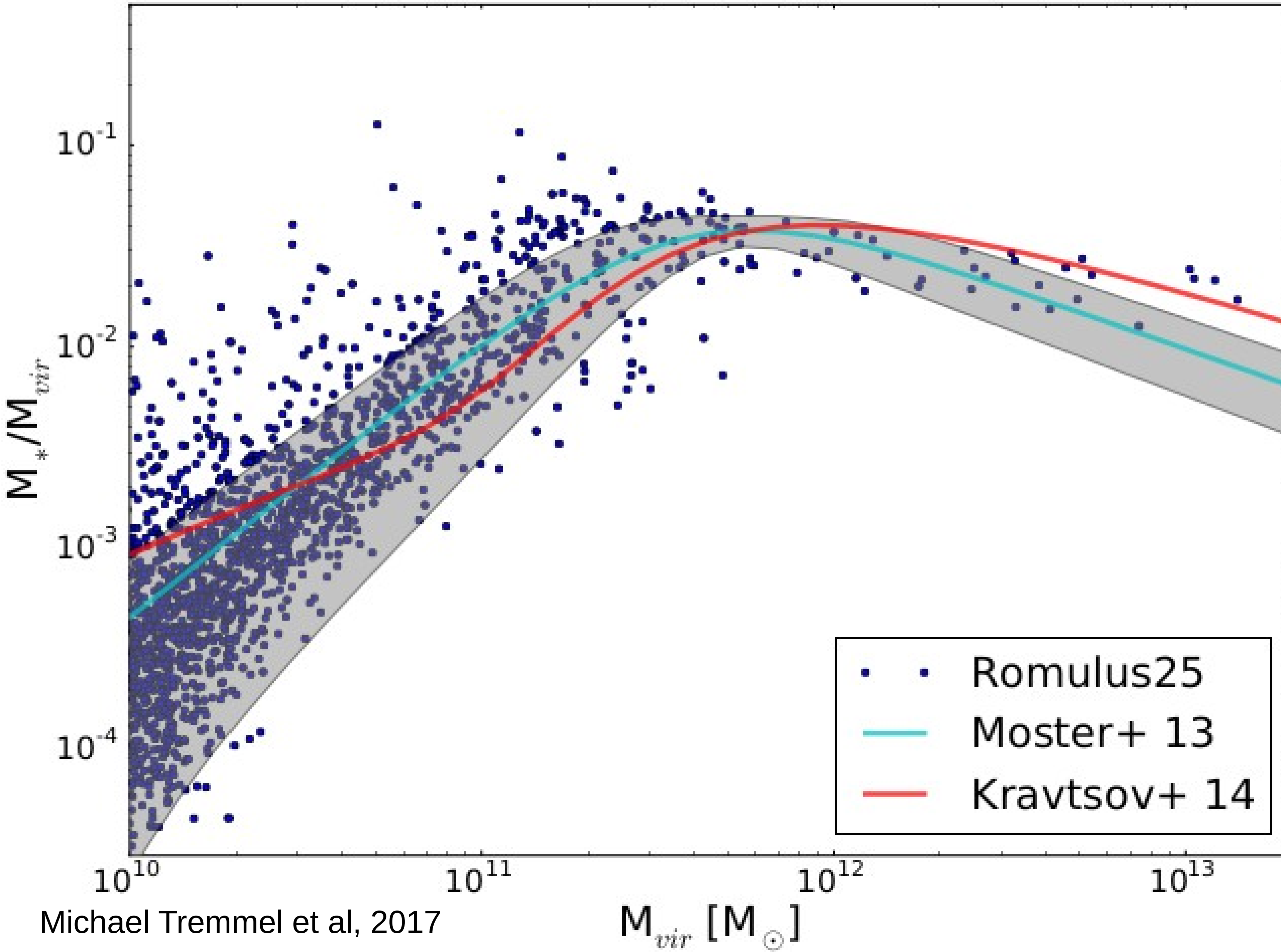
Good morphologies across a population

z = 3 z = 2 z = 1.2 z = 0.75 z = 0.5

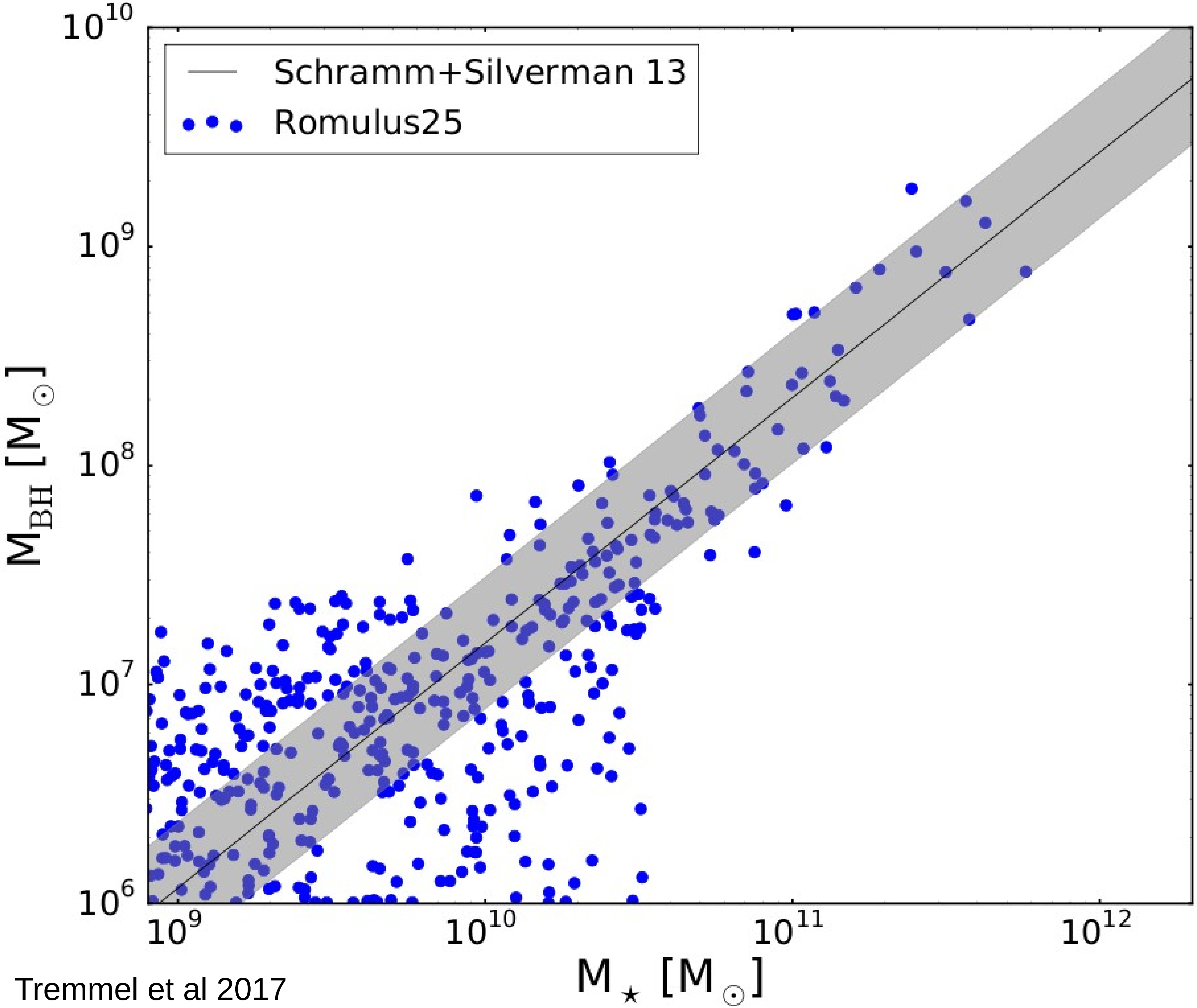


Black hole/AGN feedback

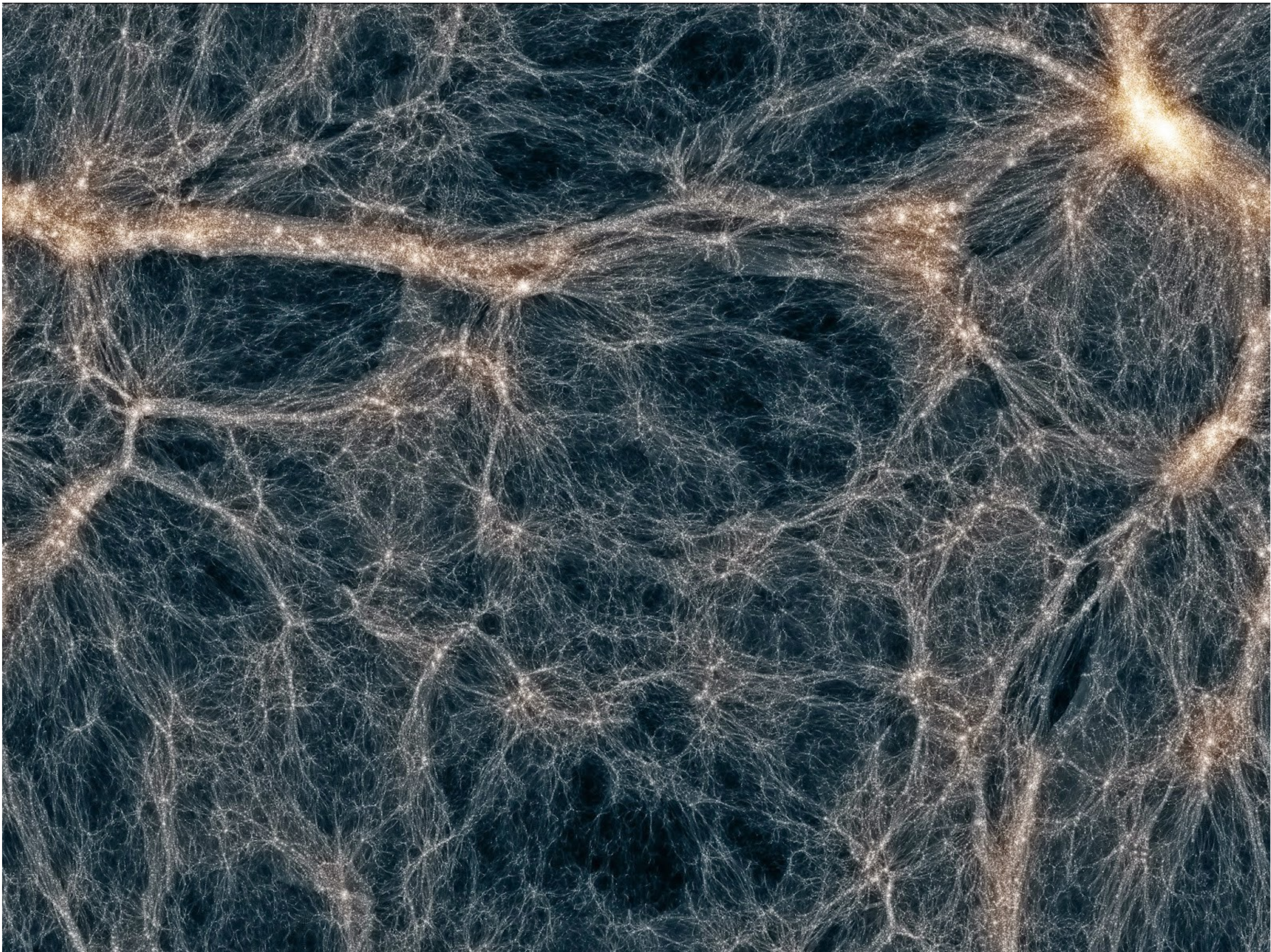
- Supernova feedback doesn't suppress star formation in massive galaxies
  - Modeling of more energetic feedback required
- Components of AGN modeling:
  - Seed (1e6 Msun) BH form in dense, low metallicity gas
  - BH grow from accreting gas, and release energy into the surrounding gas (Active Galactic Nuclei)
  - BH in merging galaxies sink to the center and merge (LIGO, eLISA)



Michael Tremmel et al, 2017



Tremmel et al 2017



Results: A cluster at unprecedented resolution

- Structure of the brightest cluster galaxy
- Other galaxies in the cluster environment
- The state of the intracluster medium

Introducing RomulusC

The highest resolution cosmological hydro simulation of a cluster to date

Name	Spatial Res.[a] kpc	M_{DM} $M_\odot$	M_{gas} $M_\odot$
RomulusC	0.25	3.39×10^5	2.12×10^5
TNG300[b]	1.5	7.88×10^7	7.44×10^6
TNG100[b]	0.75	5.06×10^6	9.44×10^5
TNG50 (in progress[c])	0.3	4.43×10^5	8.48×10^4
Horizon-AGN[d]	1	8.0×10^7	1.0×10^7
Magneticum[e]	10	1.3×10^{10}	2.9×10^9
Magneticum[e] high res	3.75	6.9×10^8	1.4×10^8
Magneticum[e] ultra high res	1.4	3.6×10^7	7.3×10^6
C-EAGLE[f,g]	0.7	9.6×10^6	1.8×10^6
EAGLE[g] (50, 100 Mpc)	0.7	9.6×10^6	1.8×10^6
Omega500[h]	5.4	1.56×10^9	2.7×10^8

Zoom-In Simulation

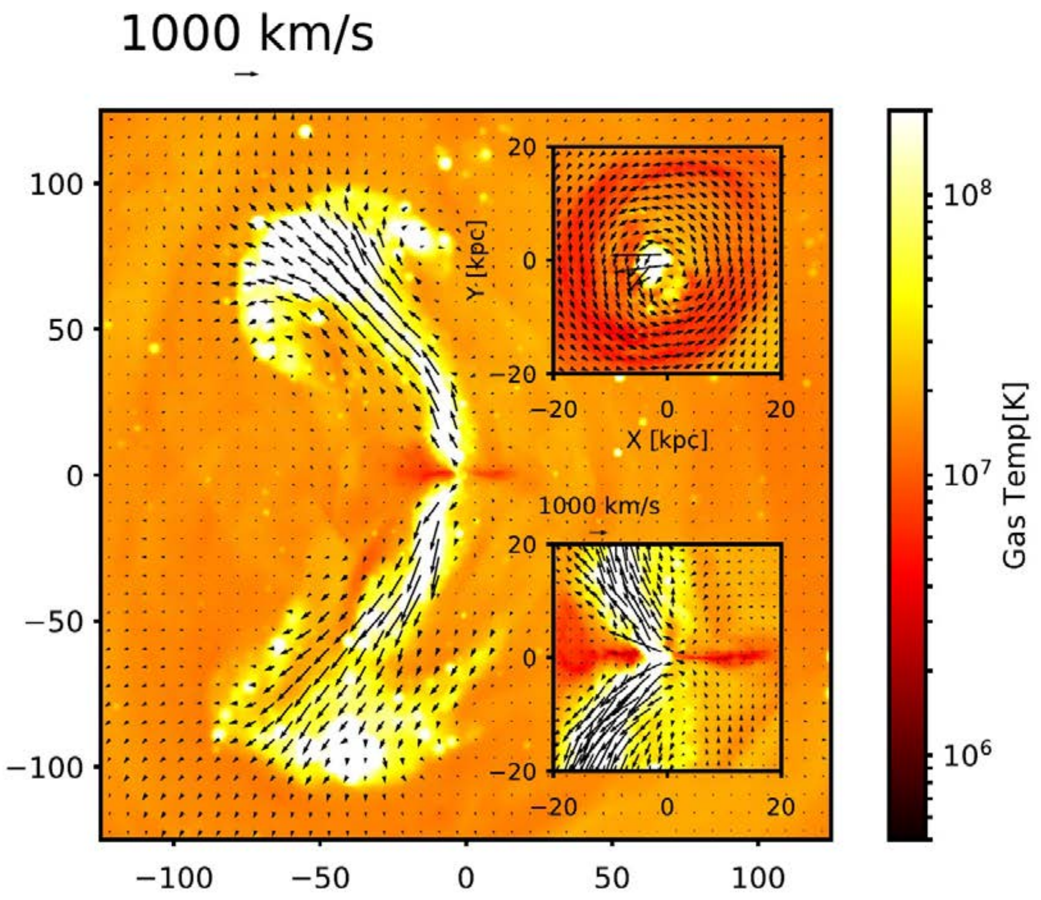
$M_{200}(z=0) = 1.5e14\ M_{sun}$

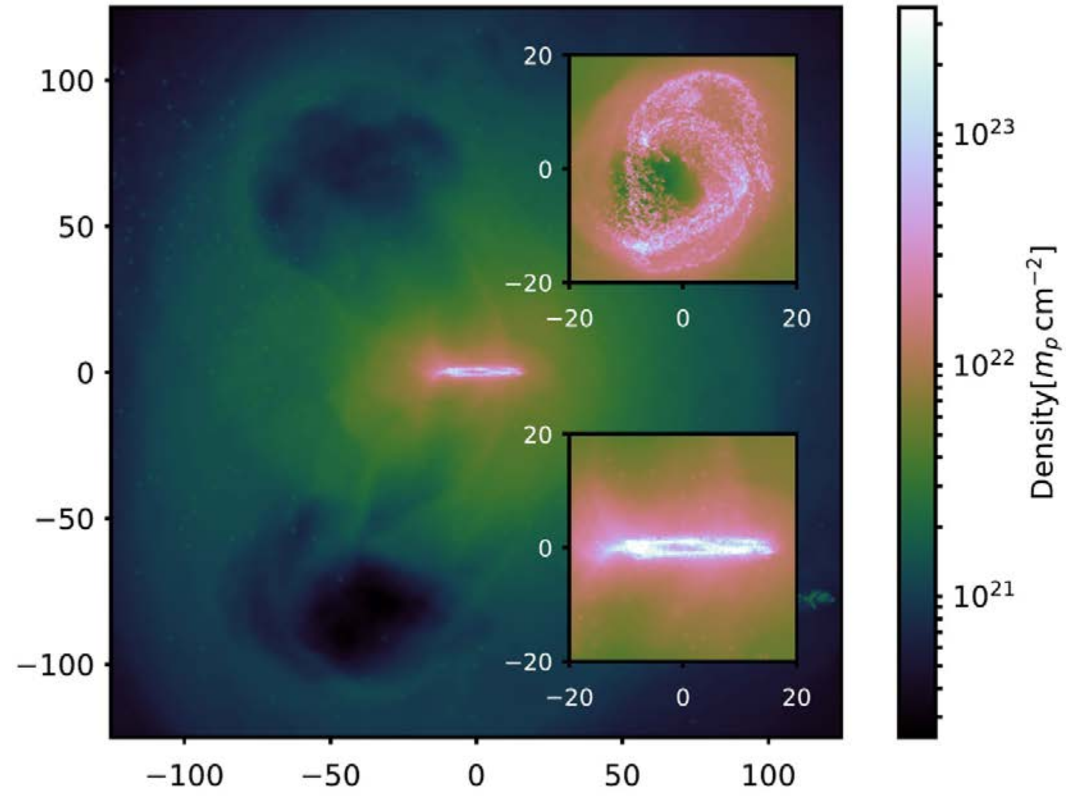
Resolution:

250 pc, 2e5 M_{sun}

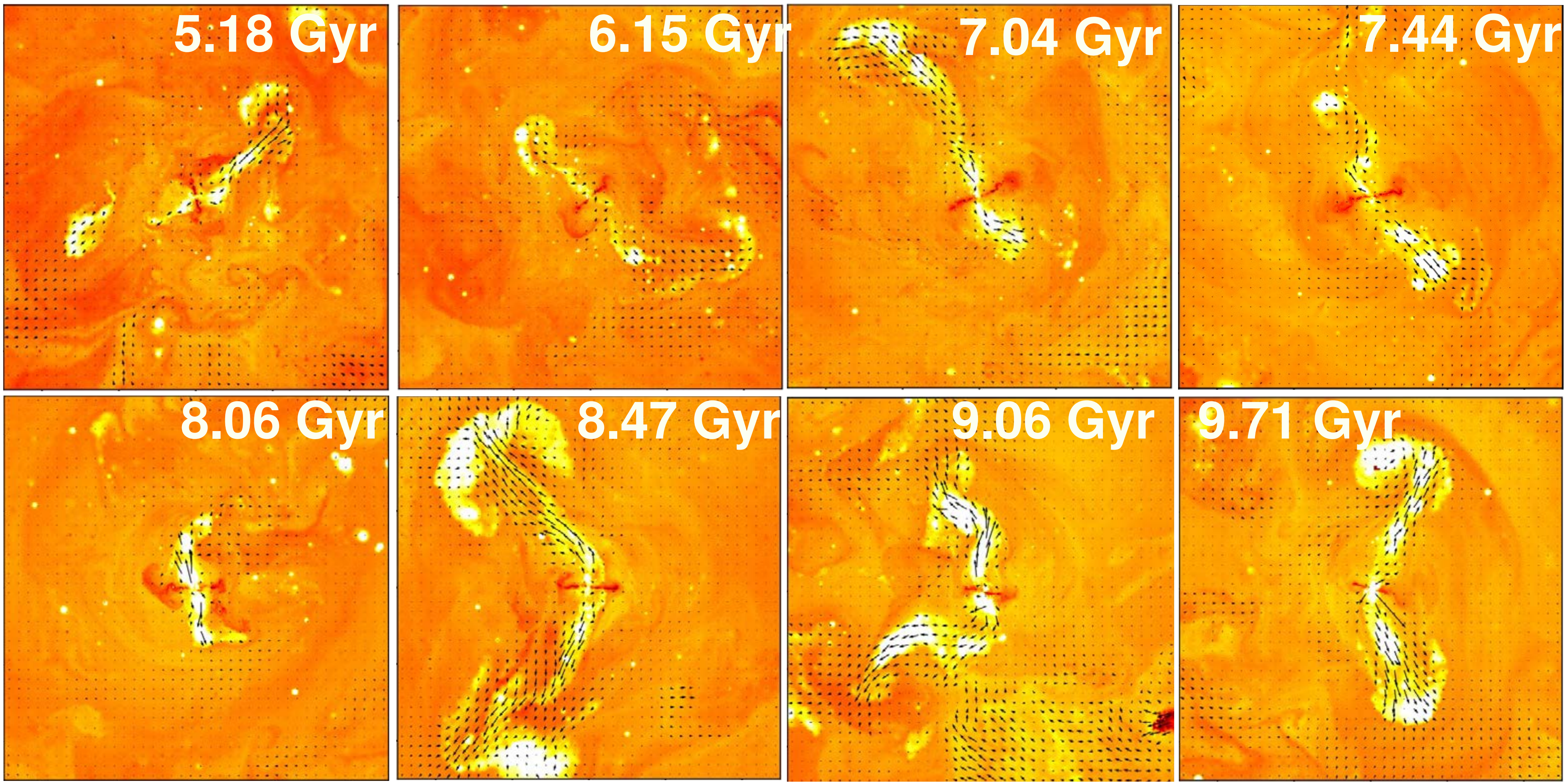
Marinacci+ 17, Dubois+ 14, Bocquet+ 16, Armitage+ 18, Schaye+ 14, Shirasaki+ 18

Outflows in the BCG

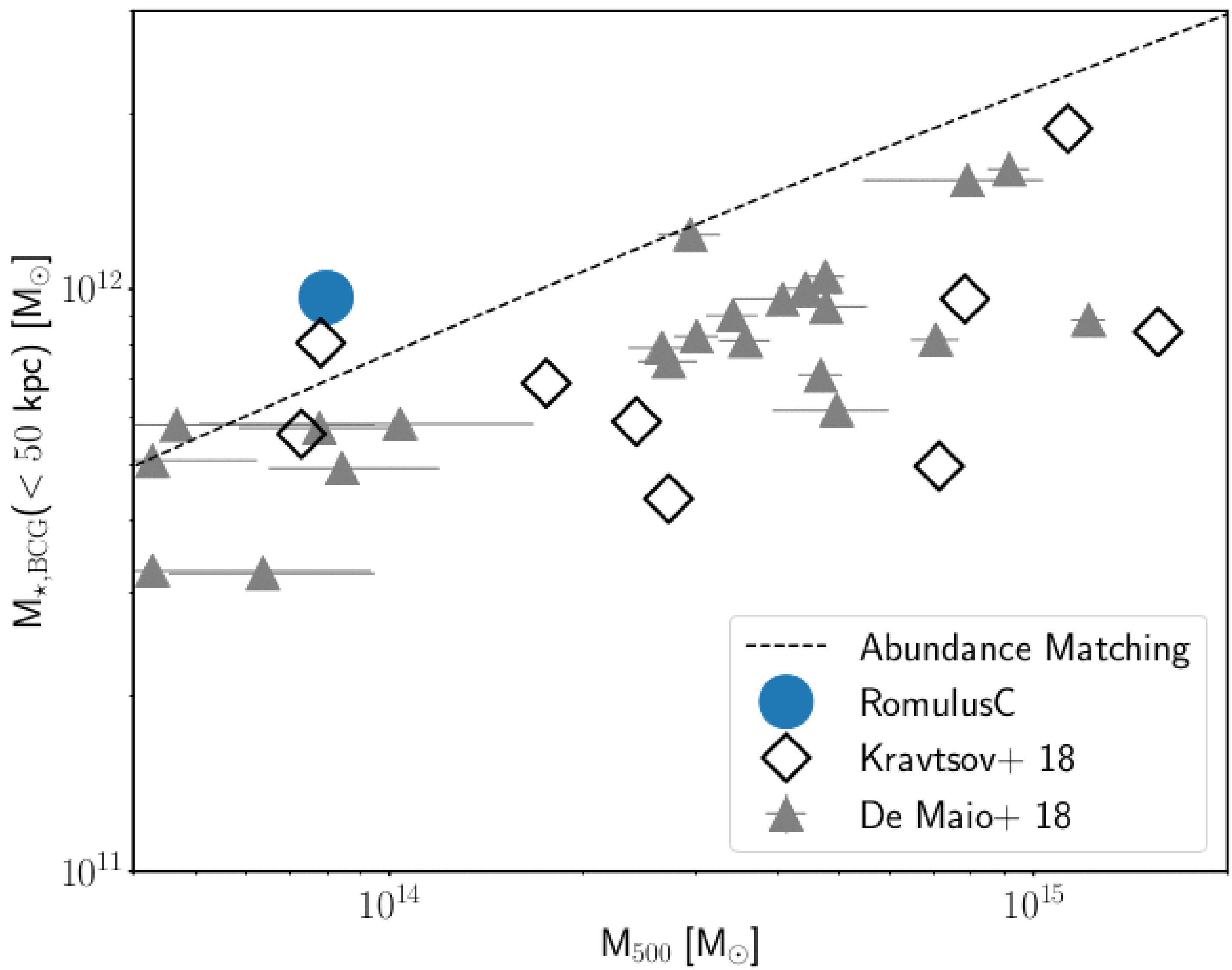




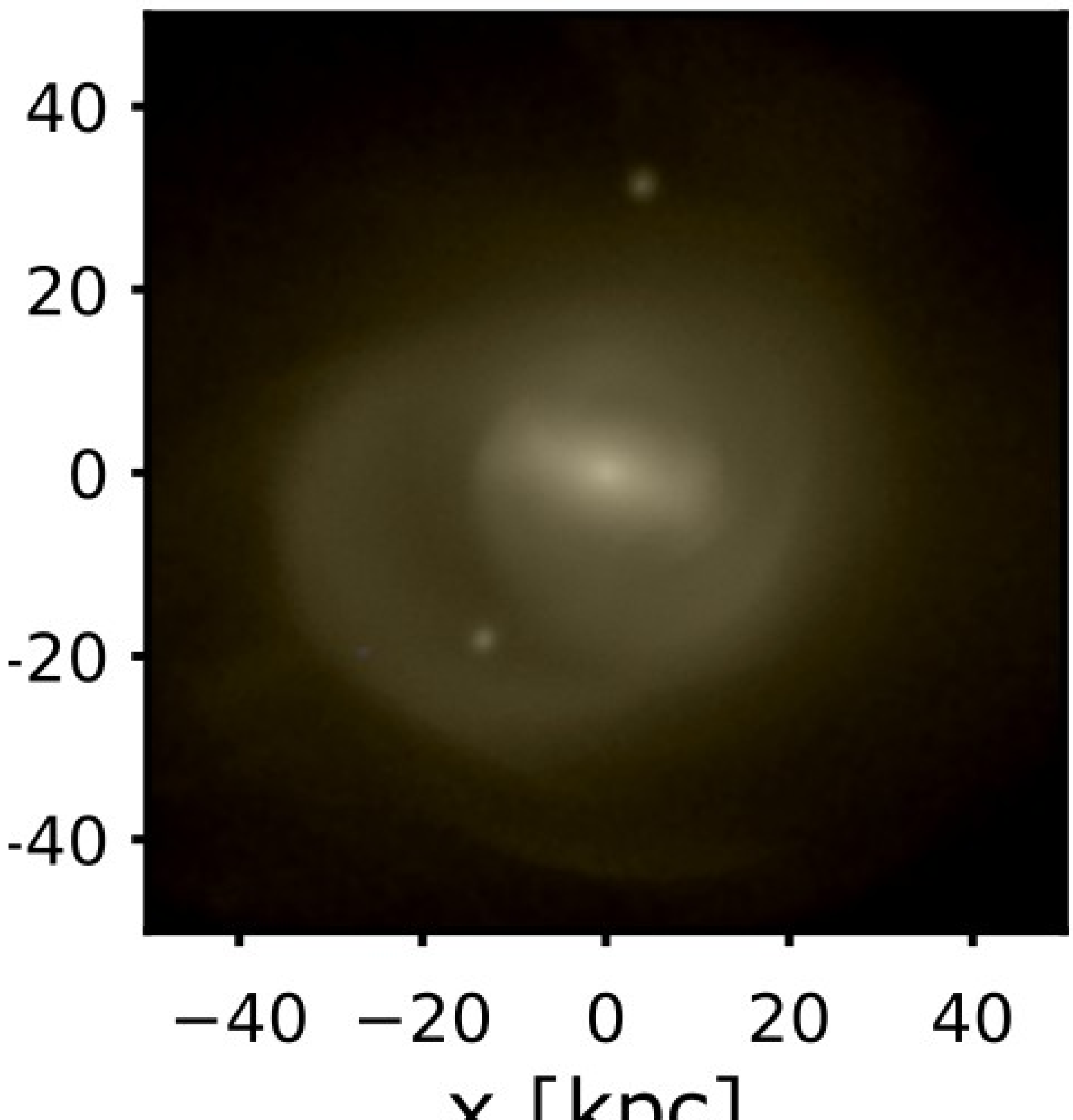
Winds are ubiquitous through time



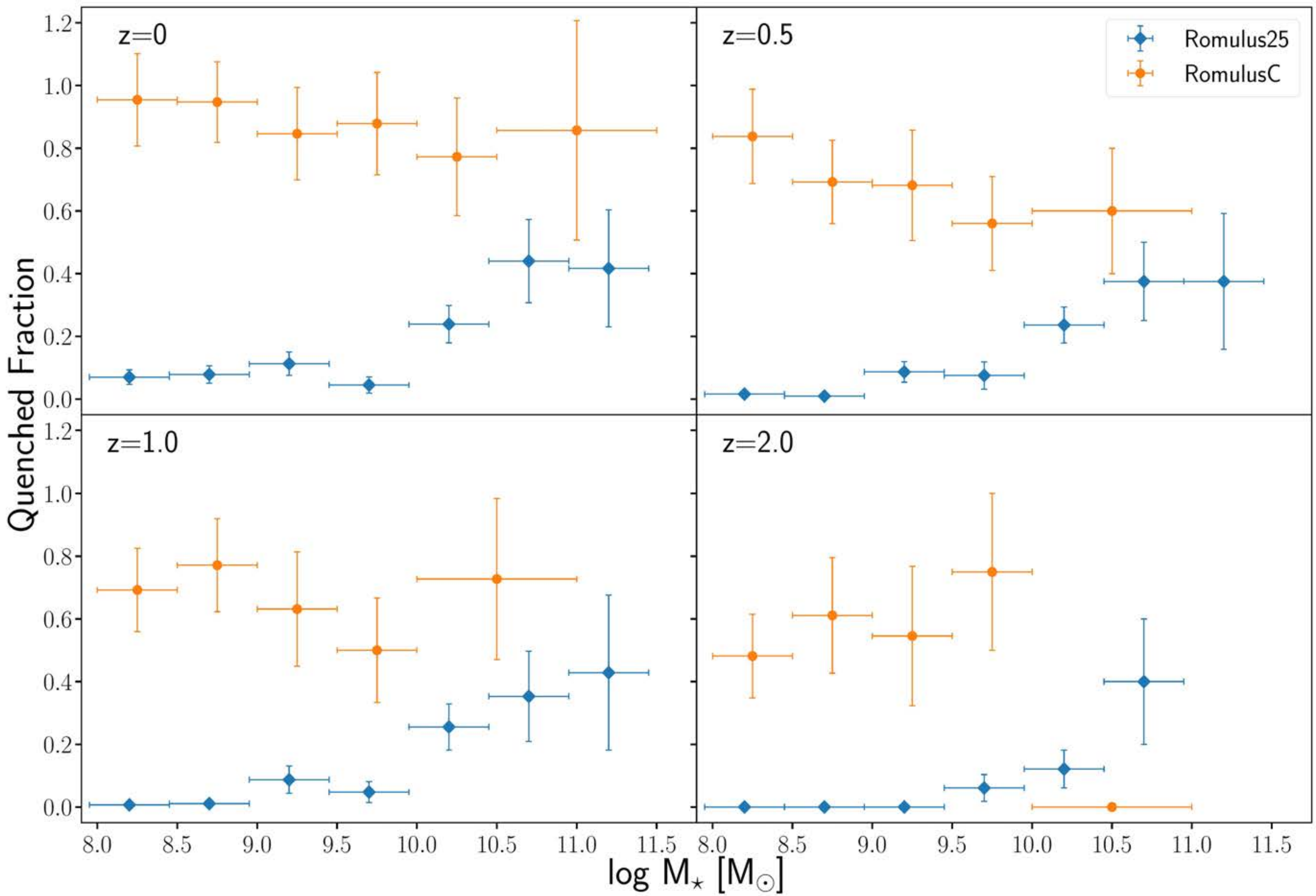
Stellar Mass



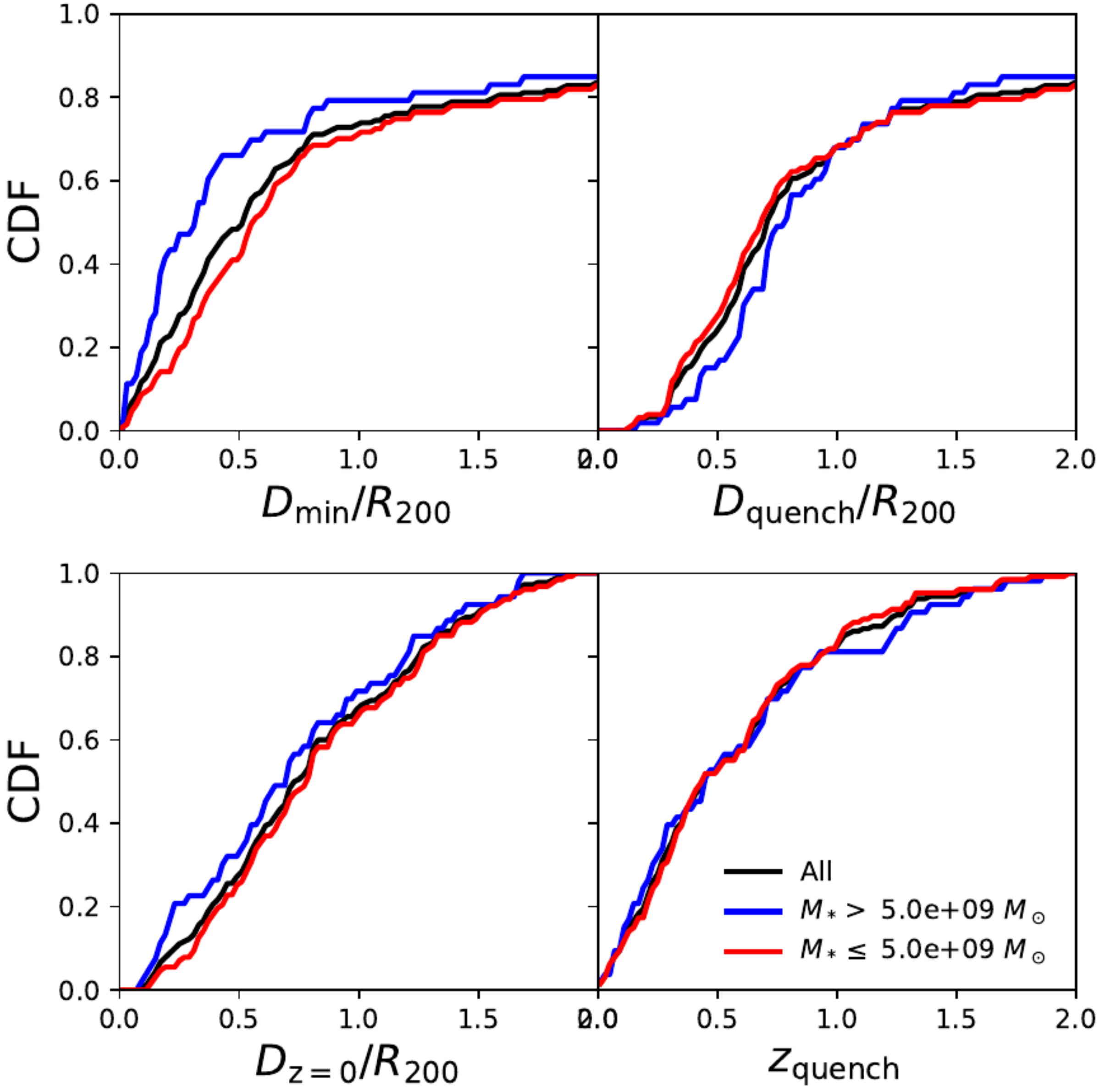
Morphology of BCG



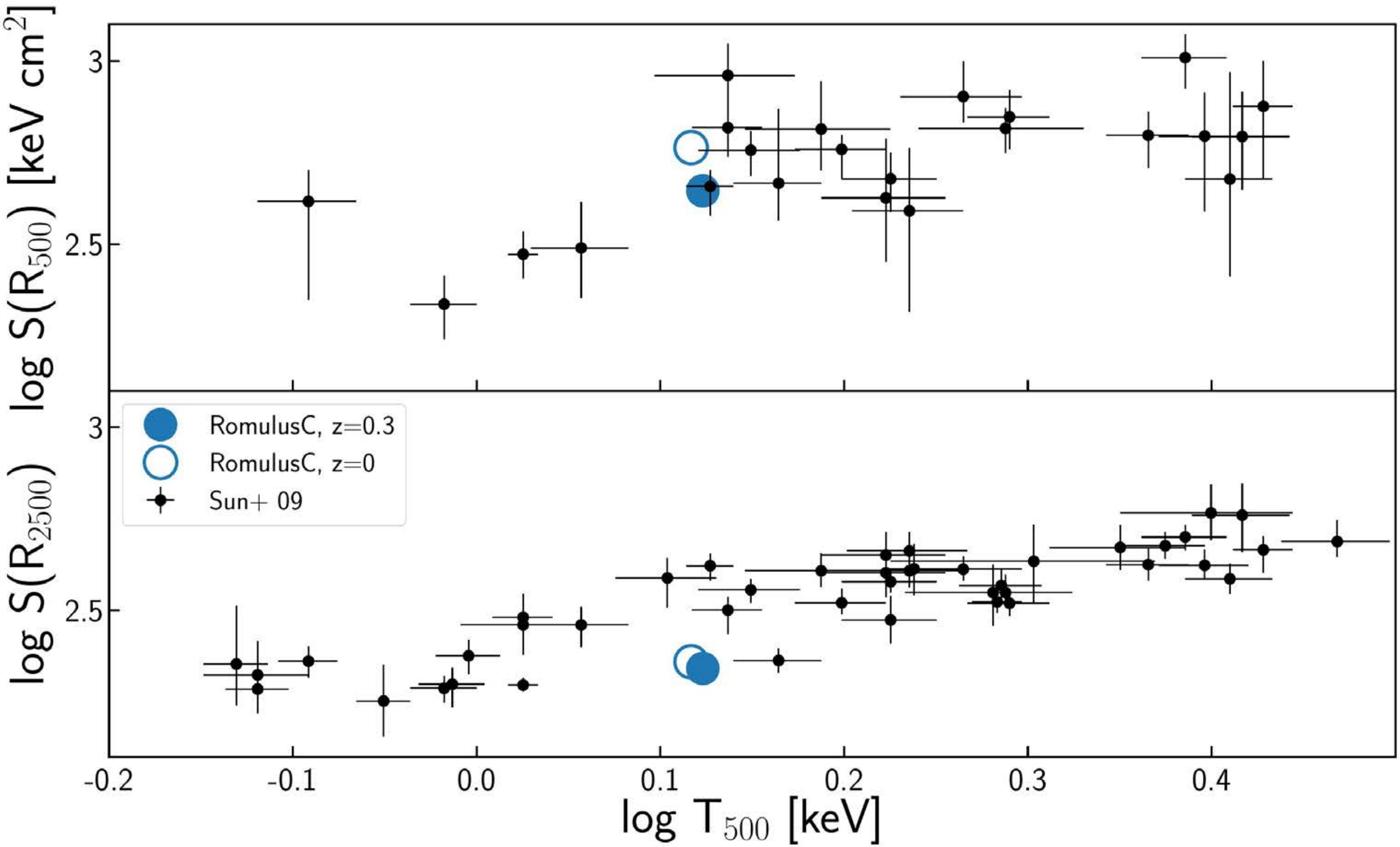
Quenching in the cluster



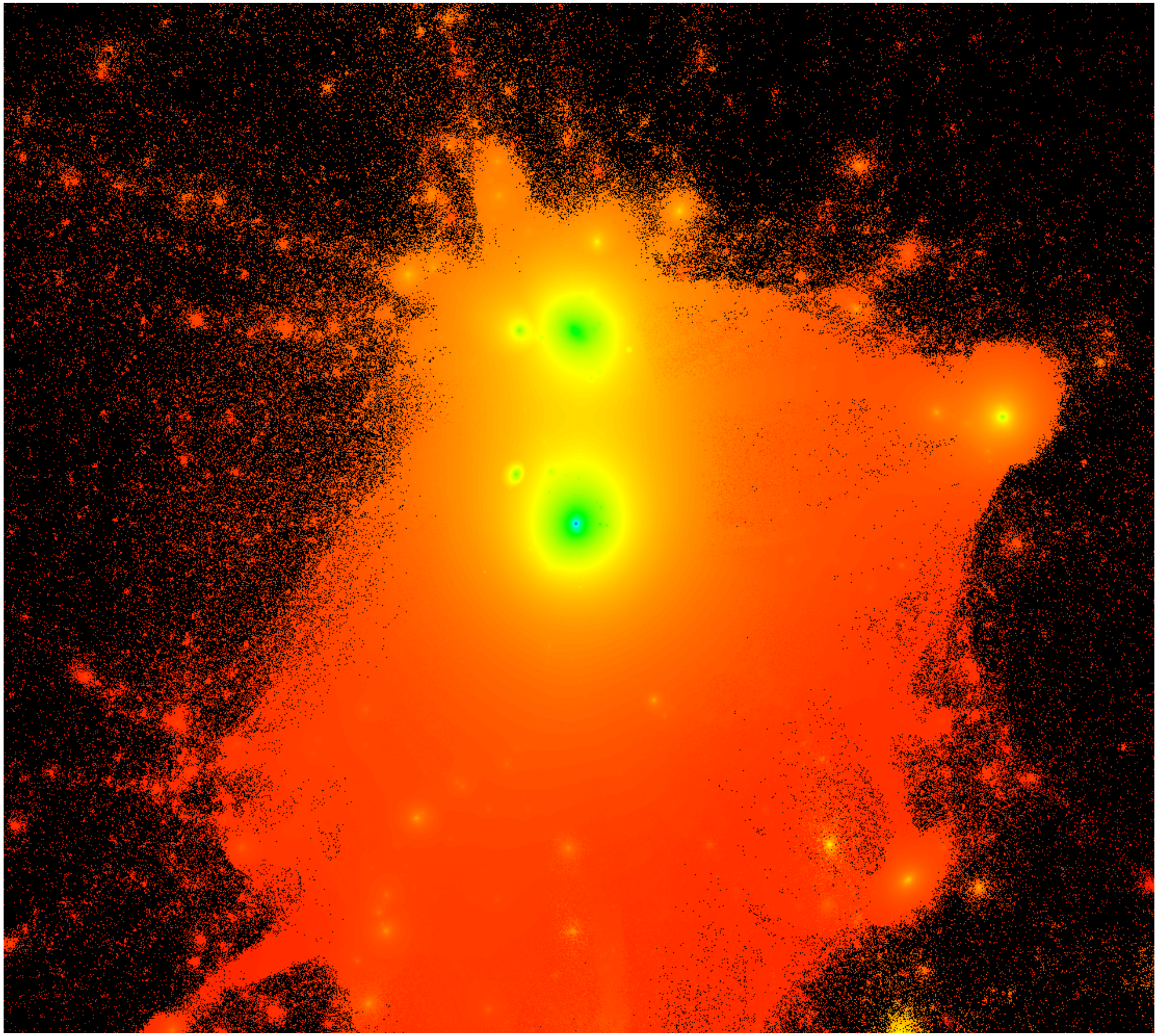
Quenching with radius



IntraCluster Medium

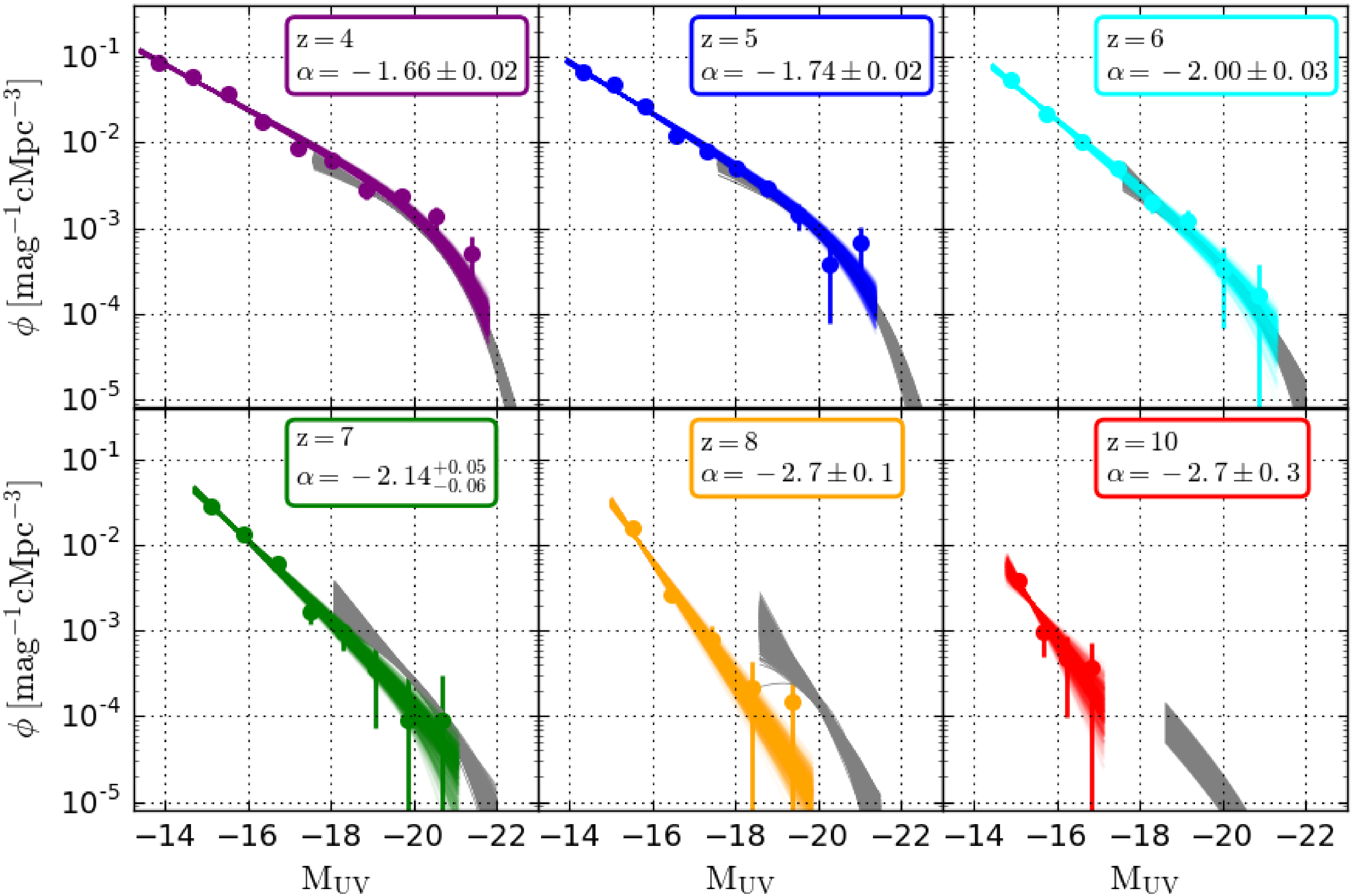


Zoomed Cluster simulation



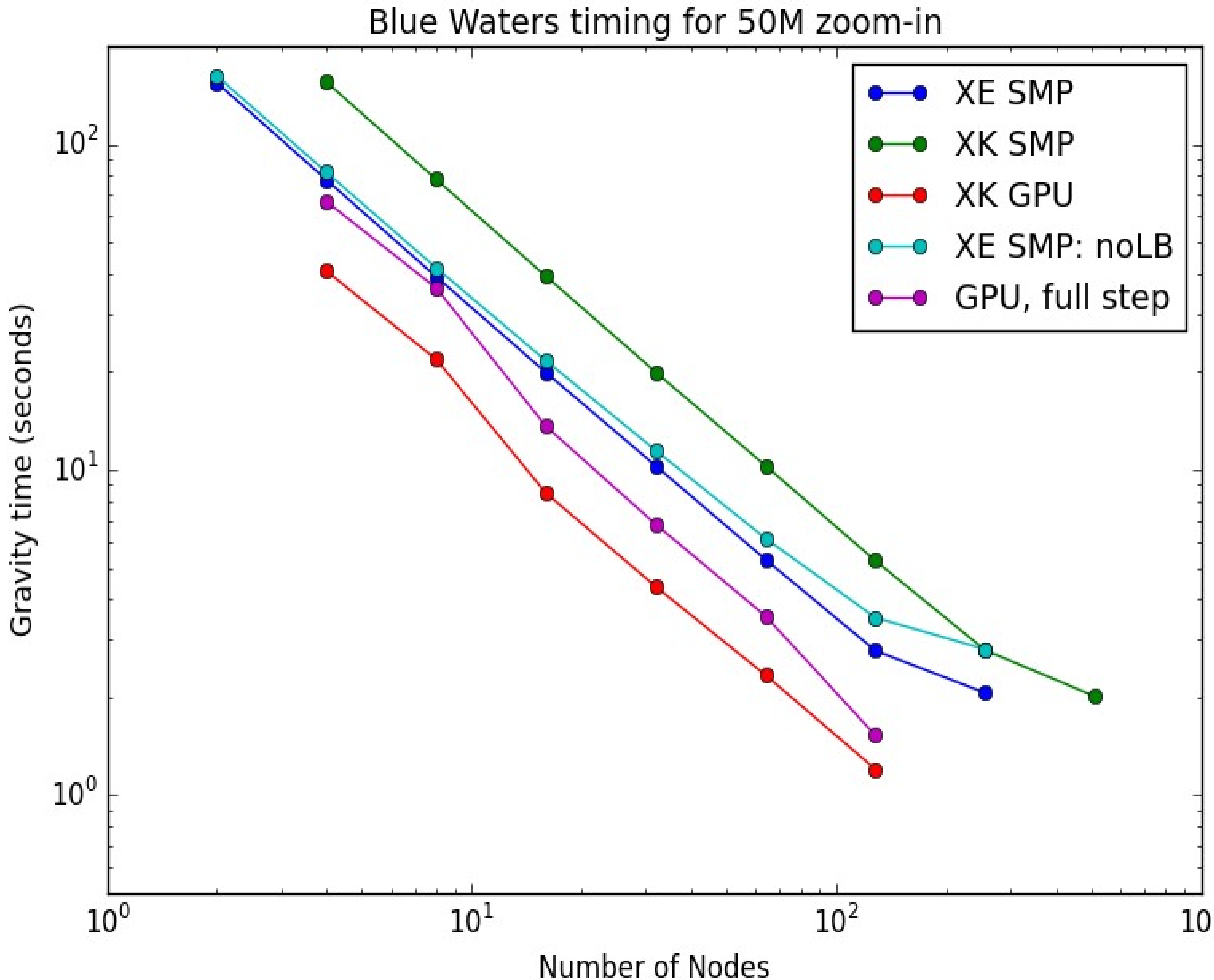
Luminosity Function

Anderson, et al 2016



PAID: ChaNGa GPU Scaling

- ChaNGa has a prelimary GPU implementation
- Goals of PAID:
  - Tesla → Kepler optimization
  - SMP optimization
  - Multistep Optimization
  - Load balancing
- Personnel:
  - Simon Garcia de Gonzalo, NCSA
  - Michael Robson, Harshitha Menon, PPL UIUC
  - Peng Wang, Tom Gibbs (NVIDIA)


Blue Waters timing for 50M zoom-in
XE SMP
XK SMP
XK GPU
XE SMP: noLB
GPU, full step
Gravity time (seconds)
Number of Nodes
10^0
10^1
10^2
10^3

PAID GPU Progress

- 2X speed up of main gravity kernel; 1.4X speedup of 2nd gravity kernel
  - Interwarp communication
  - Caching of multipole data
  - Higher GPU occupancy
  - Overall speedup of 60%
- SMP queuing of GPU requests
  - Reduced memory use, allowing more host threads
  - GPU memory management still an issue

Broader Impacts: Pre-Majors and Supercomputing

- UW Pre-Major in Astronomy Program:
  - Engage underrepresented populations in research early
  - Establish a cohort
  - Plug major leak in the STEM education pipeline
- Simulation data analysis is ideal for this research
  - Science and images are compelling
  - Similarity to Astronomical data reduction