Galaxy clusters:

Laboratories for extreme plasma physics

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Michigan State University

University of Michigan
September 28, 2014

Galaxy clusters:
Laboratories for extreme plasma physics

Primary collaborators:
- Eric Hallman (Tech-X)
- Greg Meece (MSU)
- Sam Skillman (Stanford)
- Britton Smith (Edinburgh)
- Mark Voit (MSU)

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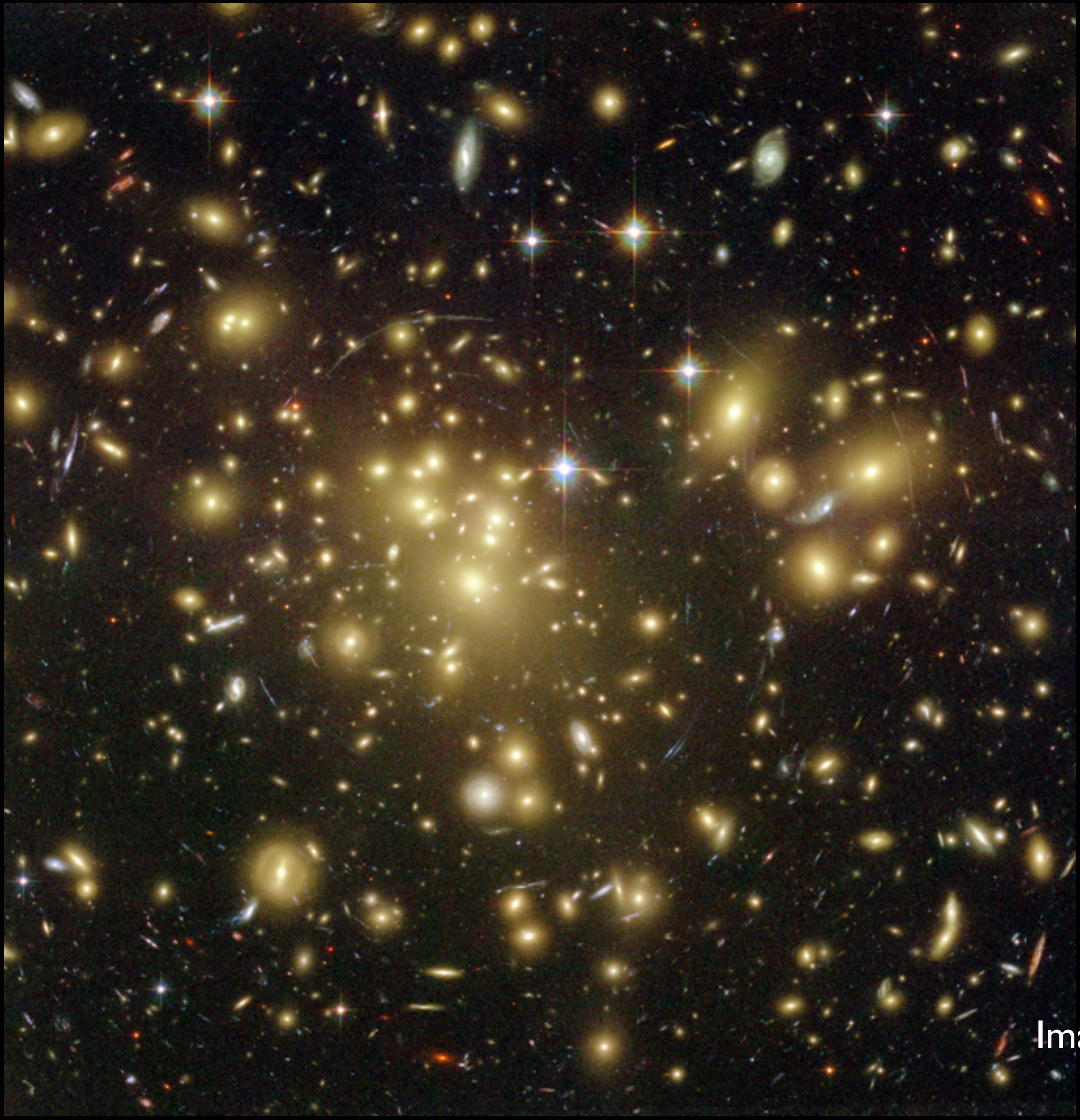
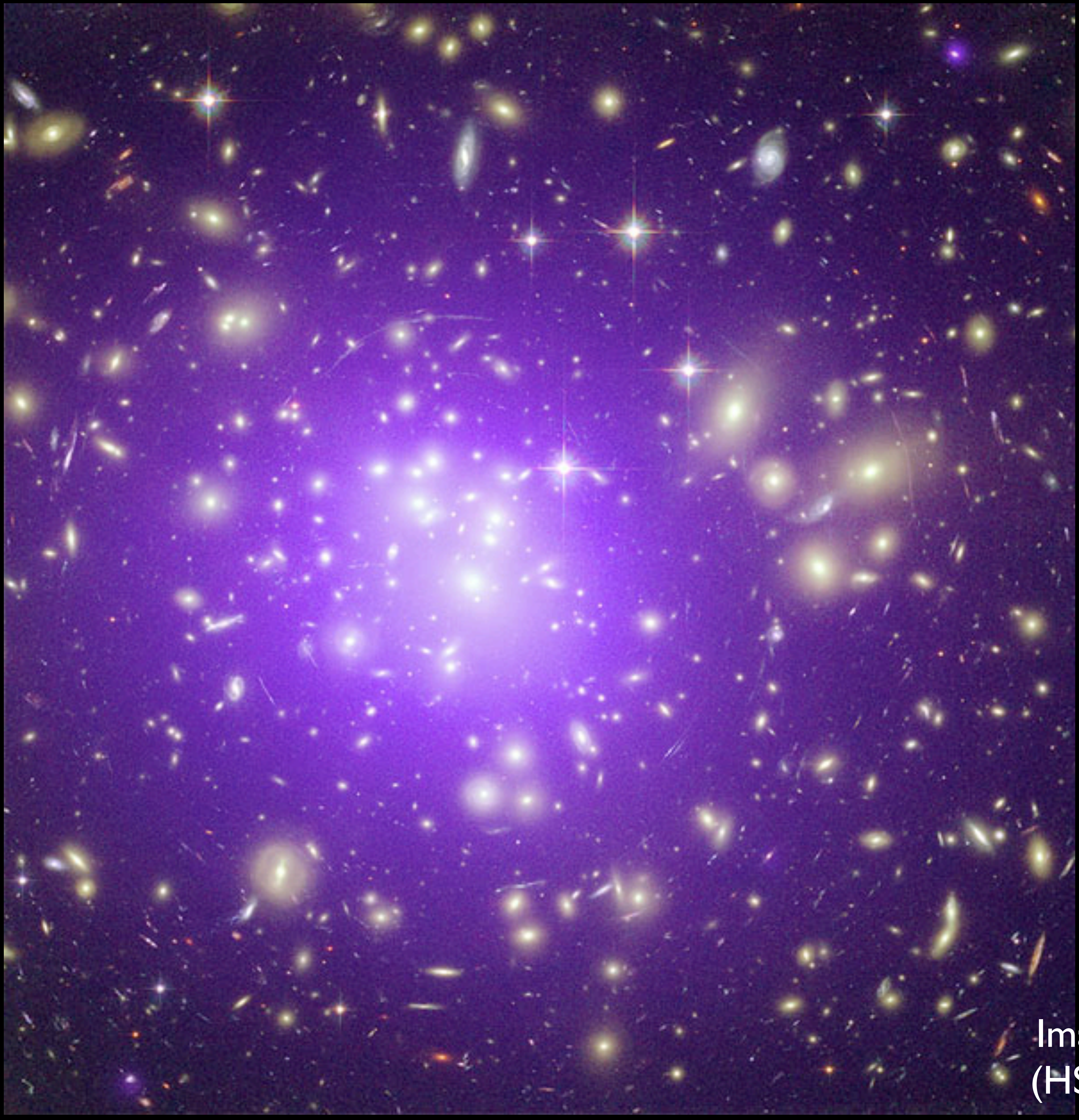
Galaxy clusters

- Massive + virialized
- “Closed box”
- $n(M,z)$: cosmology!



Abell 1689
Image c/o NASA
(HST)



Abell 1689
Image c/o NASA
(HST + Chandra)

Galaxy clusters

- Massive + virialized
- "Closed box"
- n(M,z): cosmology!

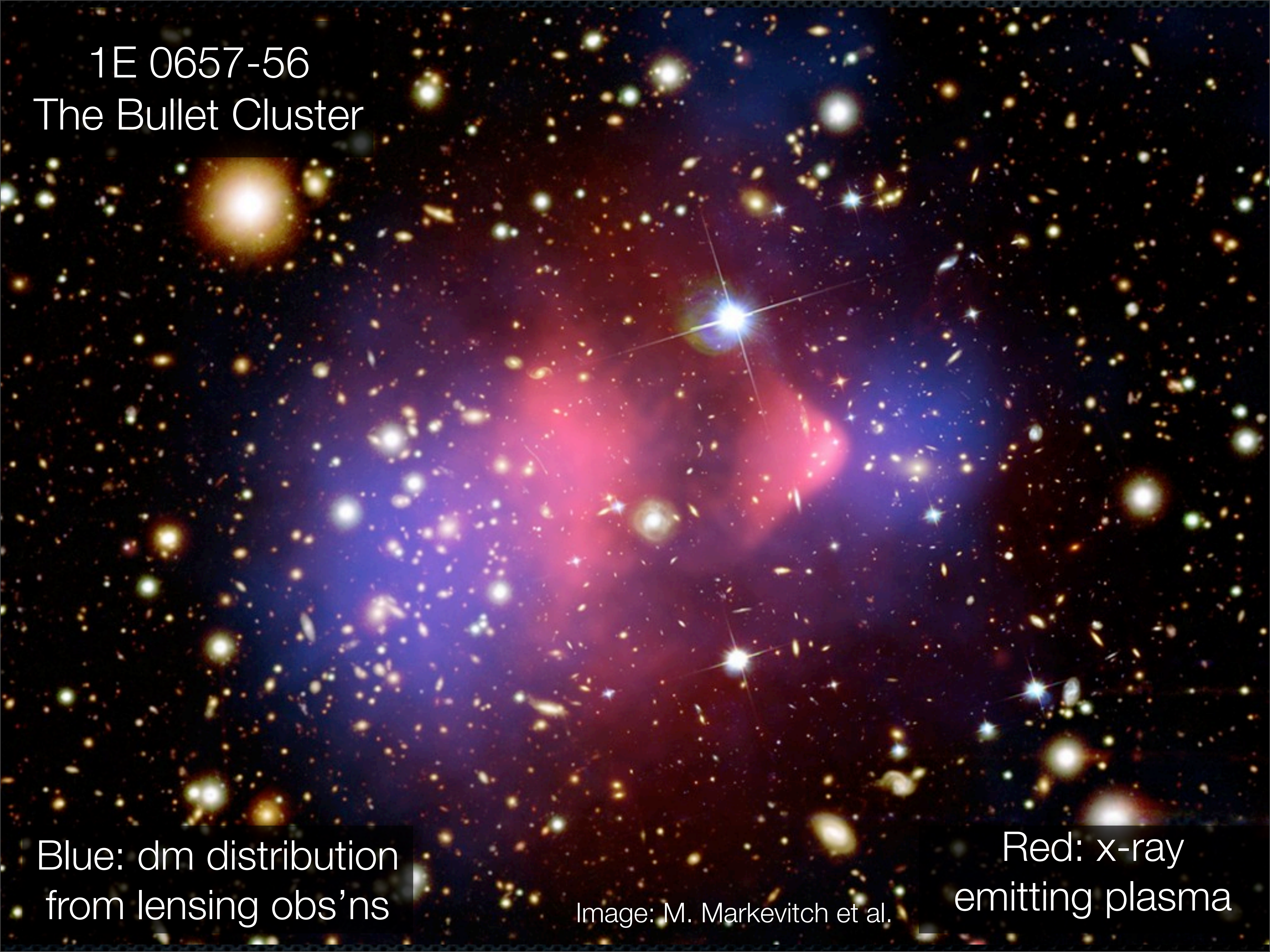
Theory: useful scaling relationships!

Galaxy clusters

- Massive + virialized
- "Closed box"
- n(M,z): cosmology!

Theory: useful scaling relationships!

however...



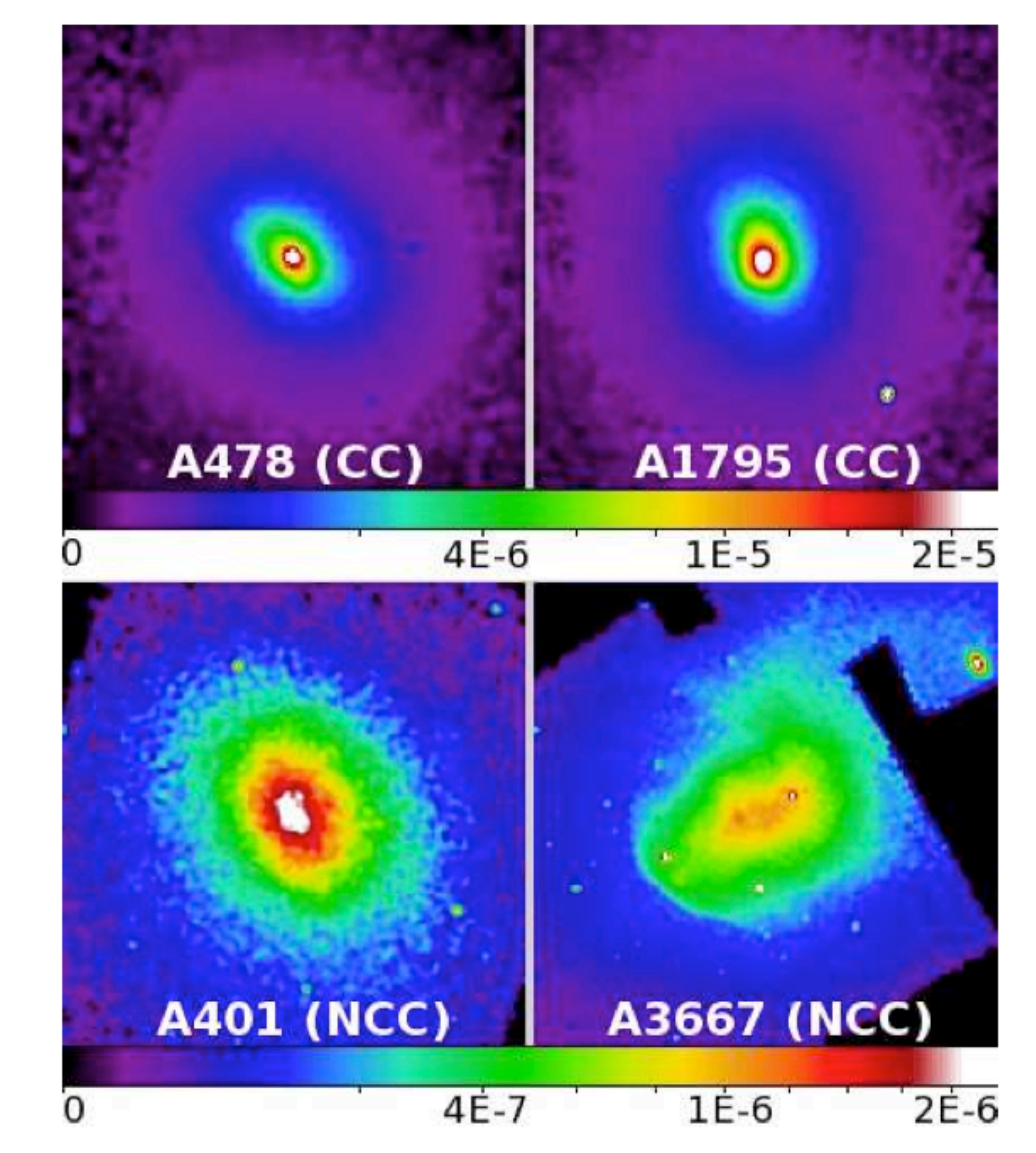
1E 0657-56
The Bullet Cluster

Blue: dm distribution from lensing obs'ns

Red: x-ray emitting plasma

Image: M. Markevitch et al.

Cool core vs. non-cool-core clusters



From Henning et al. 2009, ApJ, 697, 1597

Cosmological complications

- Cluster dynamics: mergers, turbulence, bulk flows (sloshing), lack of hydrostatic equilibrium
- asphericity
- Extracluster gas
- Non-thermal component of ICM (cosmic rays, B-fields, conduction)
- ICM cooling/heating (star formation, AGN)
- Sample selection

Exciting astrophysics!

- Cluster dynamics: mergers, turbulence, bulk flows (sloshing), lack of hydrostatic equilibrium
- asphericity
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- ~~Sample selection~~

Today: extreme plasma physics!

- Cluster dynamics: mergers, turbulence, bulk flows (sloshing), lack of hydrostatic equilibrium
- asphericity
- Extracluster gas
- Non-thermal component of ICM (cosmic rays, B-fields, conduction)
- ICM cooling/heating (star formation, AGN)
- ~~Sample selection~~

Radio relics as tracers of galaxy cluster evolution

Skillman et al. 2013, ApJ, 765, 1

including Eric Hallman (Tech-X), Jack Burns (Boulder), Britton Smith (Edinburgh), Hao Xu (UCSD), Hui Li (LANL), Matt Turk (NCSA/UIUC)

What is a radio relic?

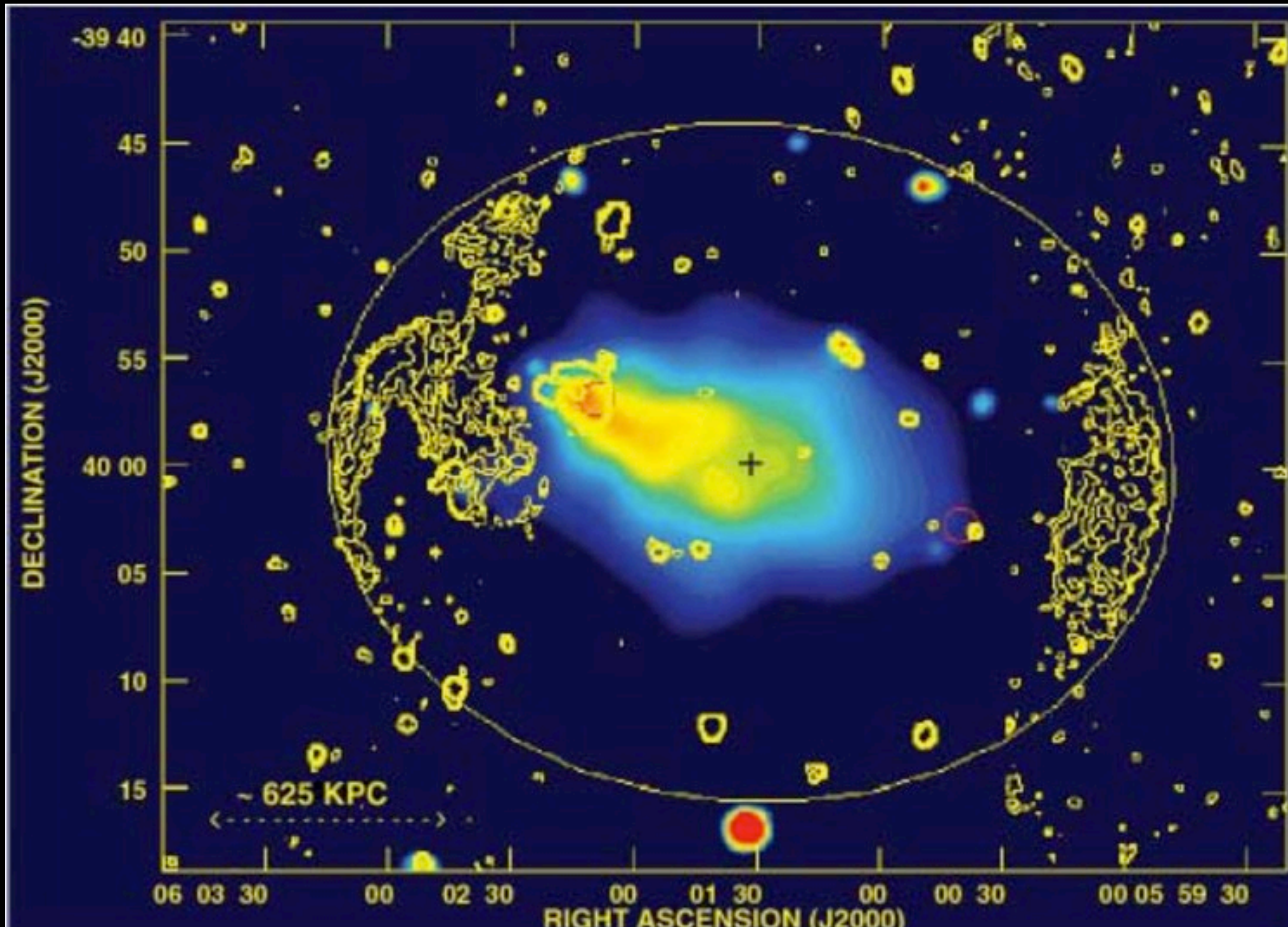
Text

Science AAAS

Giant Ringlike Radio Structures Around Galaxy Cluster Abell 3376
Joydeep Bagchi, *et al.*
Science **314**, 791 (2006);
DOI: 10.1126/science.1131189

Giant Ringlike Radio Structures Around Galaxy Cluster Abell 3376

Joydeep Bagchi,[1*] Florence Durret,[2] Gastão B. Lima Neto,[3] Surajit Paul[4]



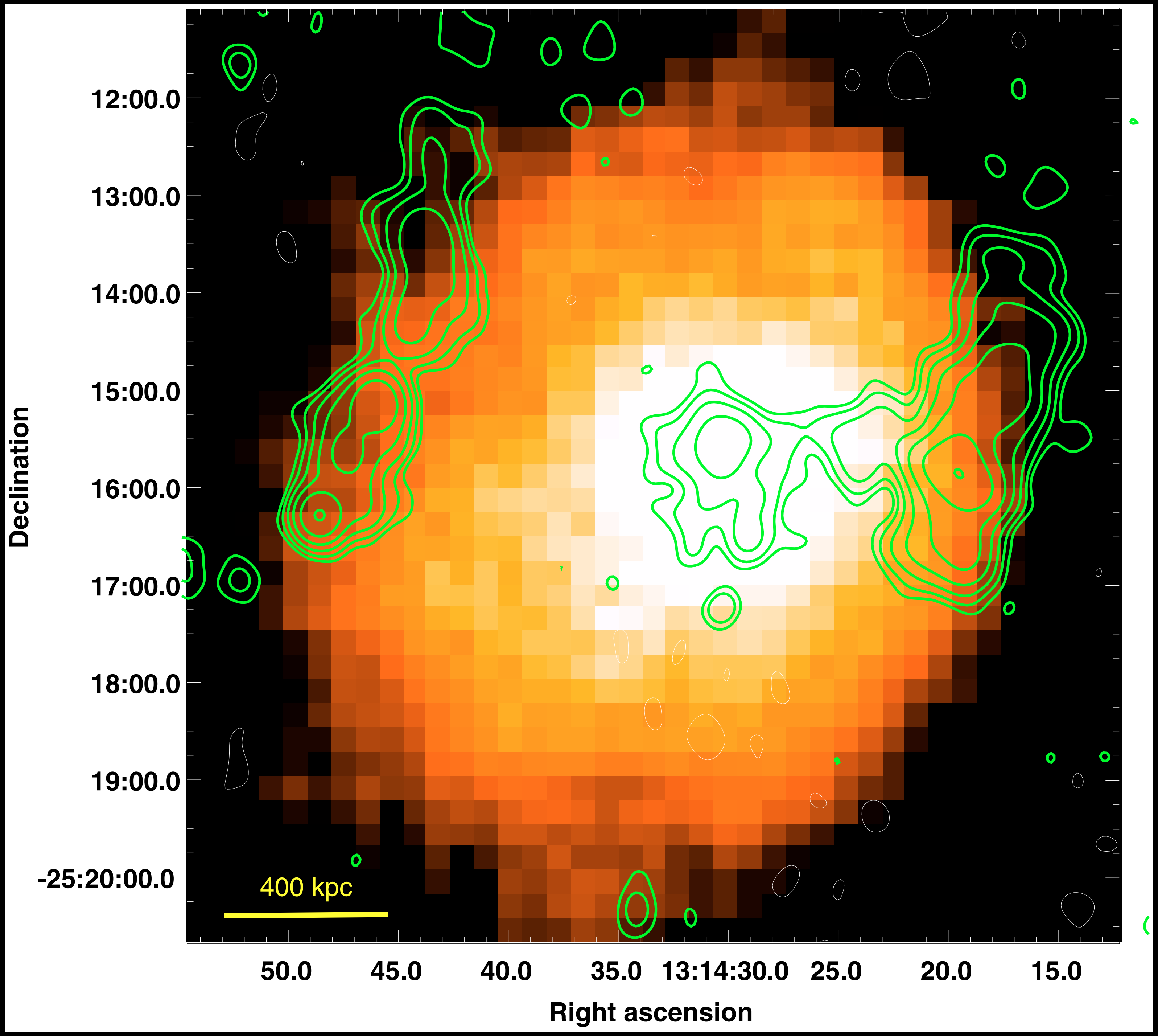
A&A 463, 937–947 (2007)
DOI: 10.1051/0004-6361:20065961

Astronomy & Astrophysics

GMRT radio halo survey in galaxy clusters at $z = 0.2–0.4^{\star}$

I. The REFLEX sub-sample

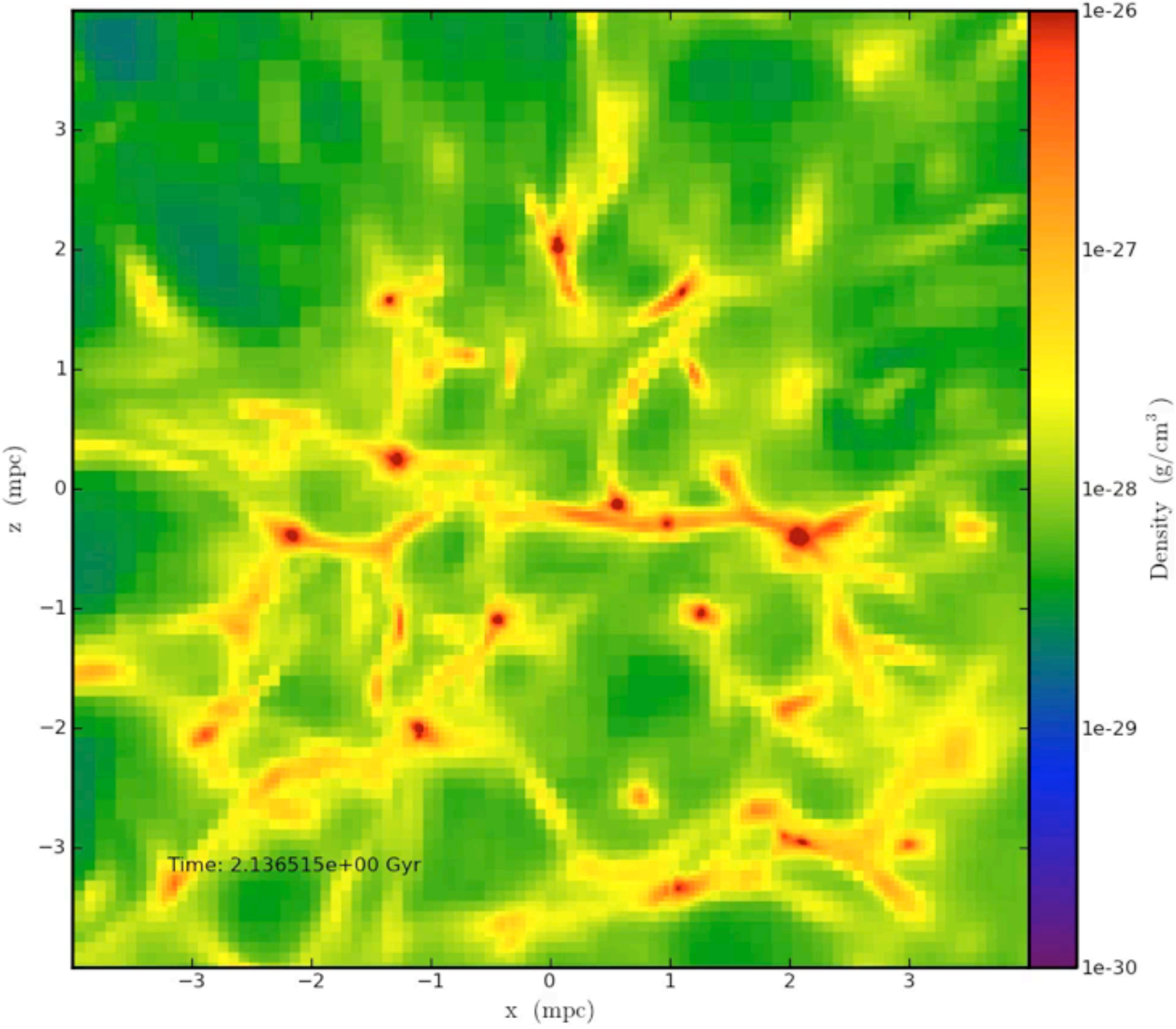
T. Venturi[1], S. Giacintucci[1,2,3], G. Brunetti[1], R. Cassano[1,3], S. Bardelli[2], D. Dallacasa[1,3], and G. Setti[1,3]



What produces radio relics?

Cosmological shocks

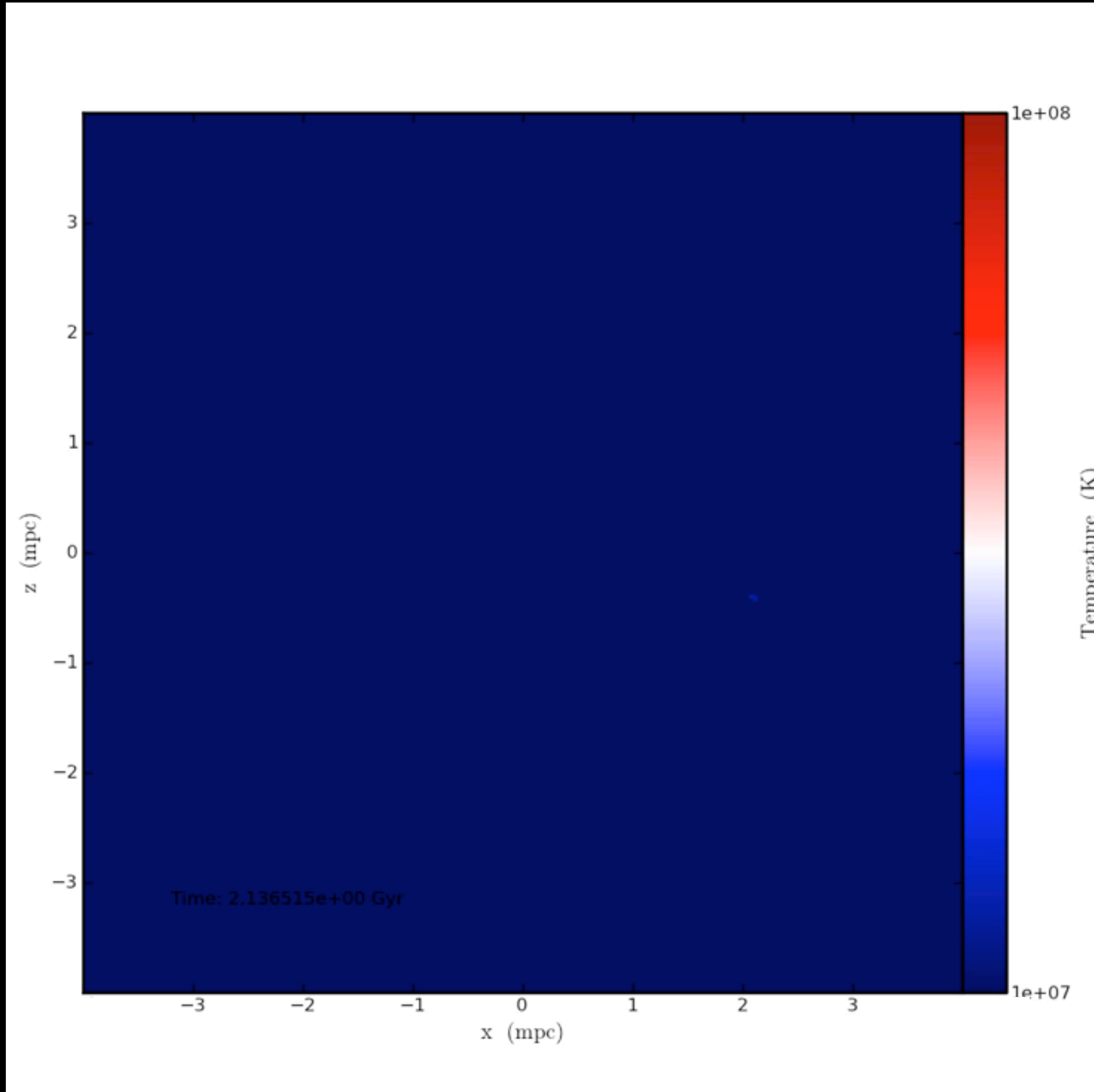
- Heat the intergalactic medium
- Produce cosmic rays!
- Observed in gamma ray (ions) and radio (e^-)



Gas Density

FOV
8 Mpc

10^8 K



Gas Temperature

10^7 K

FOV
8 Mpc

$$\frac{dP(\nu_{obs})}{d\nu} = 6.4 \times 10^{34} erg\ s^{-1}\ \ Hz^{-1} \frac{A}{\mathrm{Mpc}^2} \frac{n_e}{10^{-4}\mathrm{cm}^{-3}}$$
$$\frac{\xi_e}{0.05} (\frac{\nu_{obs}}{1.4GHz})^{-s/2} \times (\frac{T_2}{7keV})^{3/2}$$
$$\frac{(B/\mu G)^{1+(s/2)}}{(B_{CMB}/\mu G)^2 + (B/\mu G)^2} \Psi(\mathcal{M})$$

post-shock electron rho, T

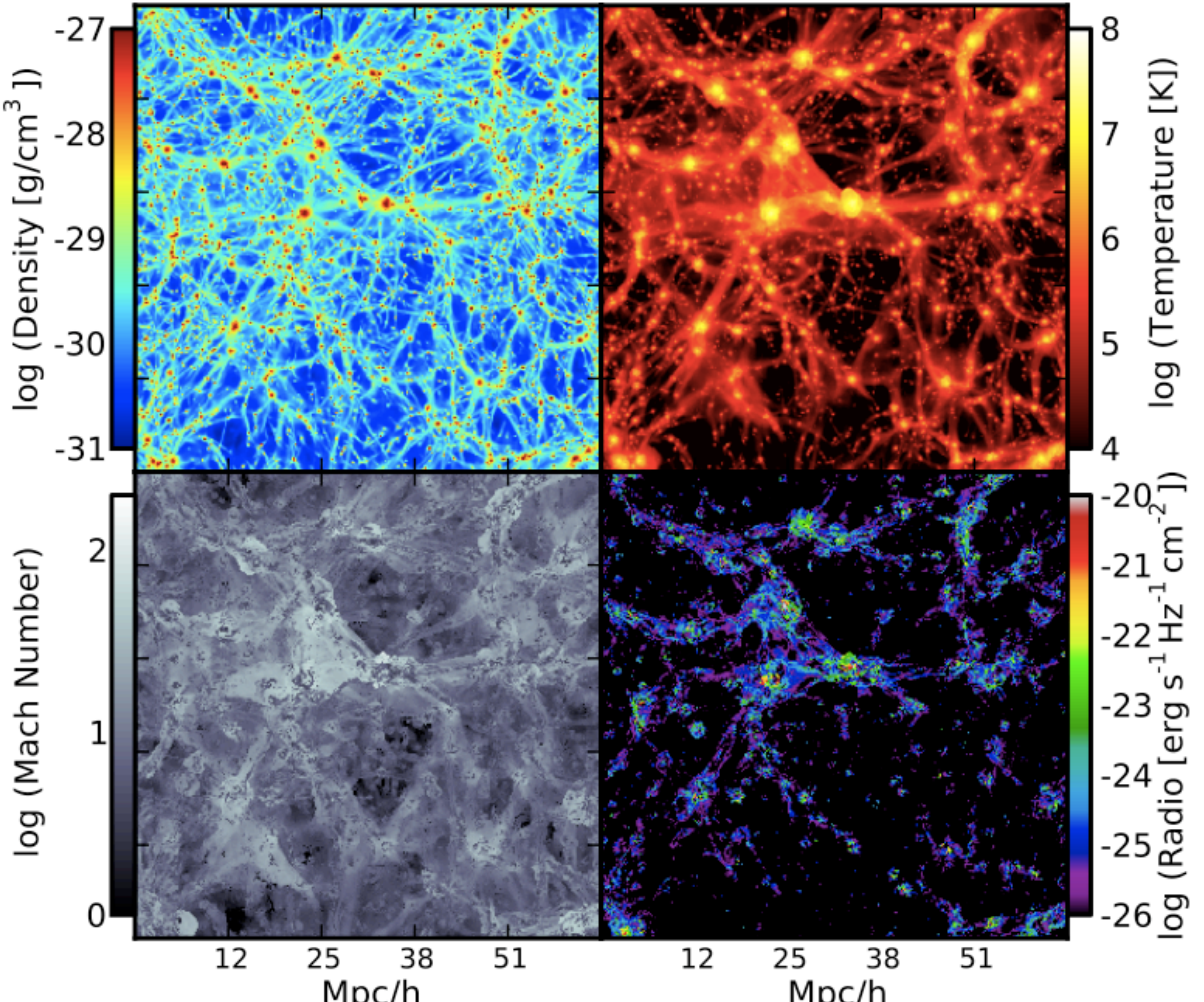
Area of shock

$$\frac{dP(\nu_{obs})}{d\nu} = 6.4 \times 10^{34} erg\ s^{-1}\ Hz^{-1} \frac{A}{\mathrm{Mpc}^2} \frac{n_e}{10^{-4}\mathrm{cm}^{-3}} \frac{\xi_e}{0.05} (\frac{\nu_{obs}}{1.4GHz})^{-s/2} \times (\frac{T_2}{7keV})^{3/2} \frac{(B/\mu G)^{1+(s/2)}}{(B_{CMB}/\mu G)^2 + (B/\mu G)^2} \Psi(\mathcal{M})$$

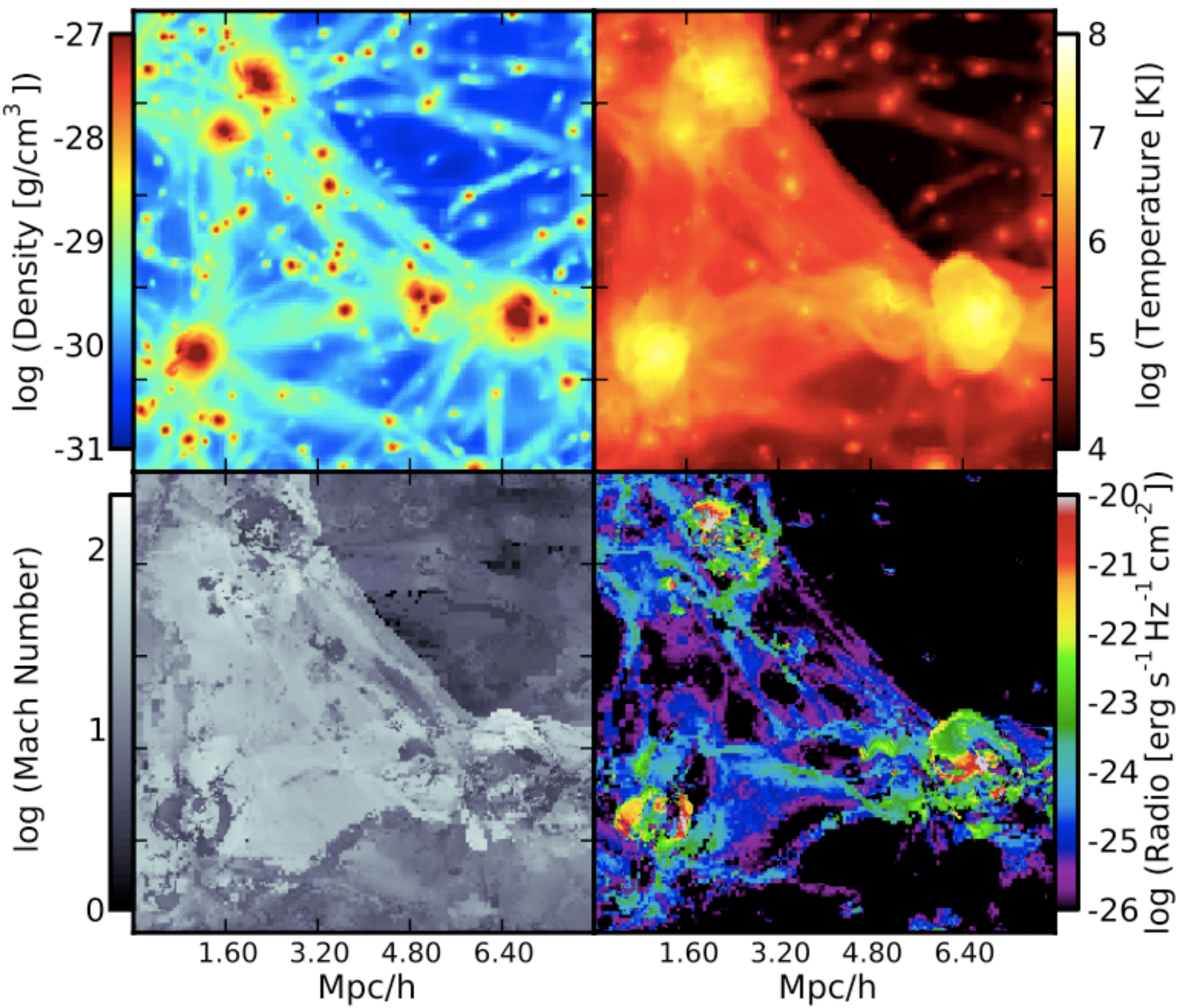
Electron acceleration efficiency

Magnetic fields

Acceleration efficiency as f(Mach)



log (Density [g/cm^3])
-27
-28
-29
-30
-31
log (Temperature [K])
8
7
6
5
4
log (Mach Number)
2
1
0
log (Radio [erg s^{-1} Hz^{-1} cm^{-2}])
-20
-21
-22
-23
-24
-25
-26
12
25
38
51
Mpc/h
12
25
38
51
Mpc/h


log (Density [g/cm3])
-27
-28
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-30
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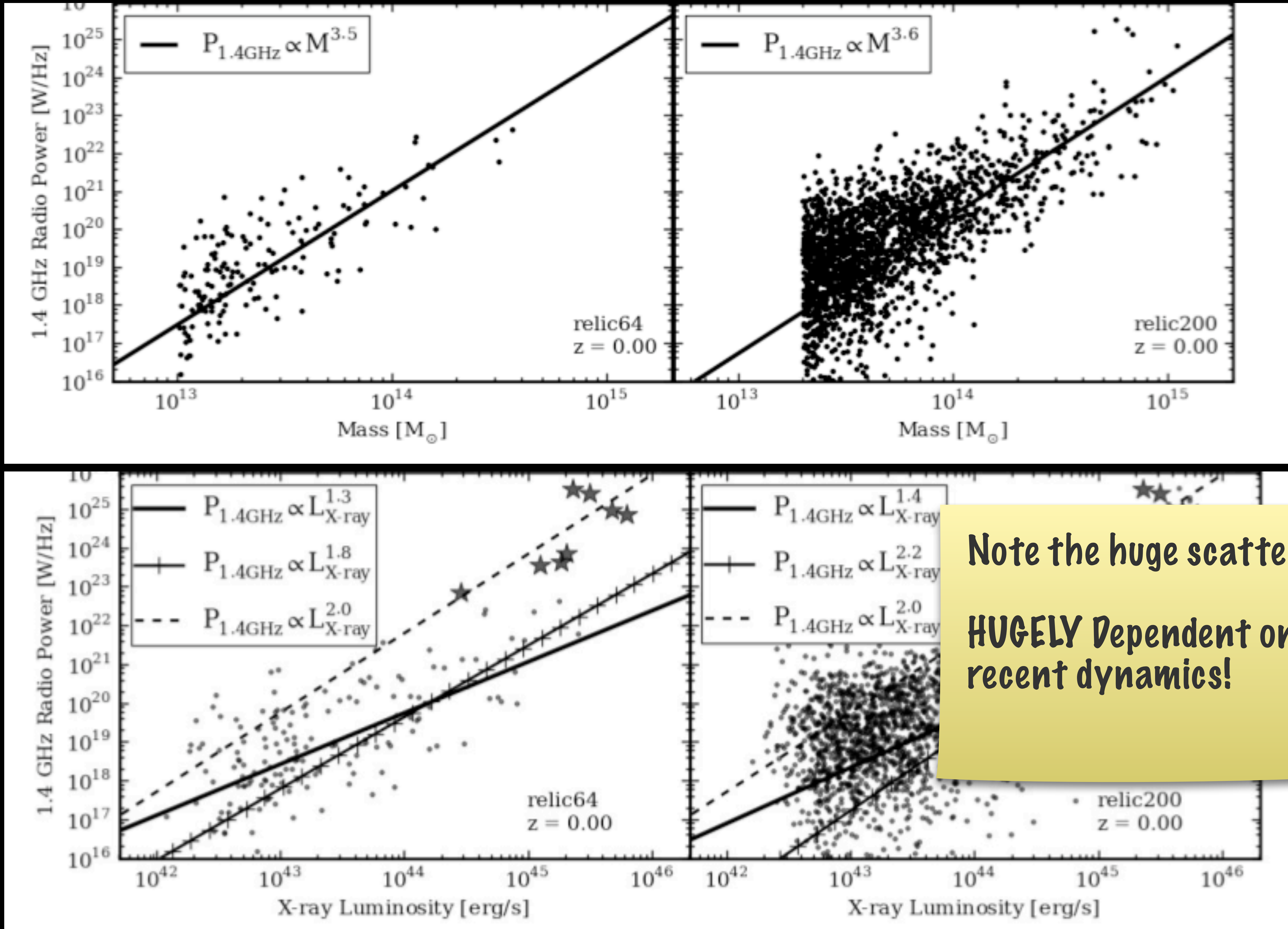
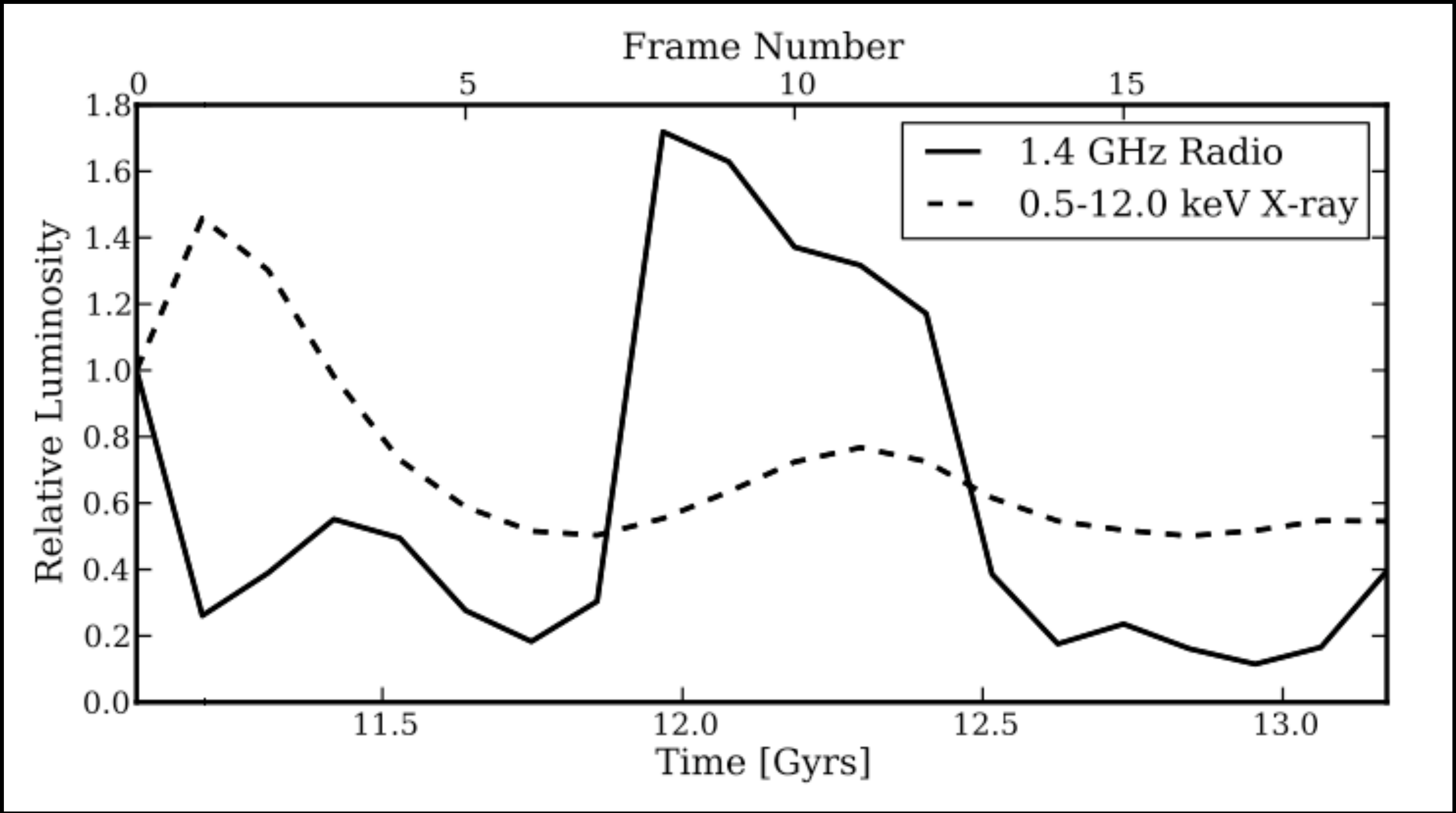
8
7
6
5
4
log (Mach Number)
2
1
0
log (Radio [erg s-1 Hz-1 cm-2])
-20
-21
-22
-23
-24
-25
-26
1.60
3.20
4.80
6.40
Mpc/h
1.60
3.20
4.80
6.40
Mpc/h

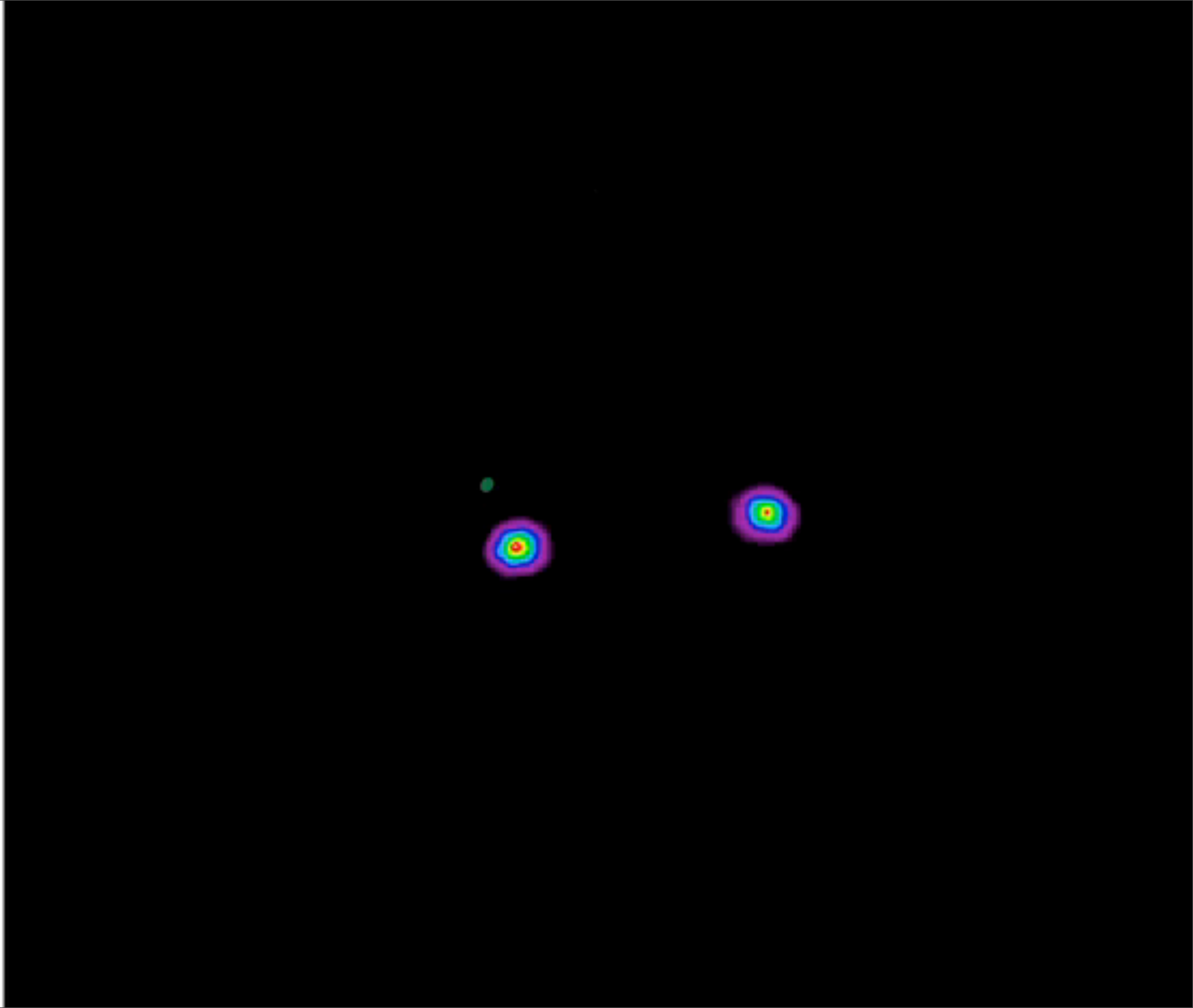


Note the huge scatter!

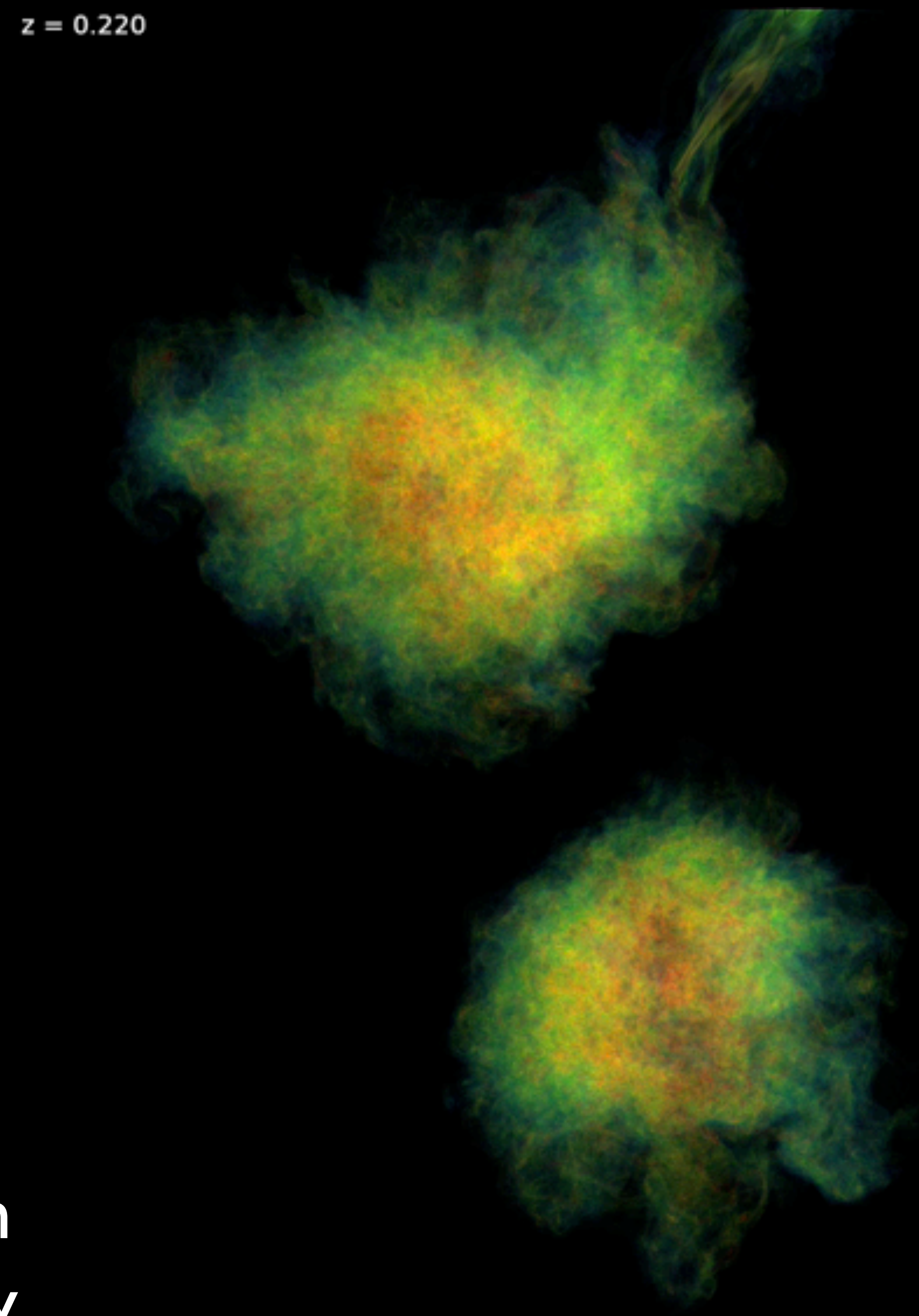
HUGELY Dependent on recent dynamics!



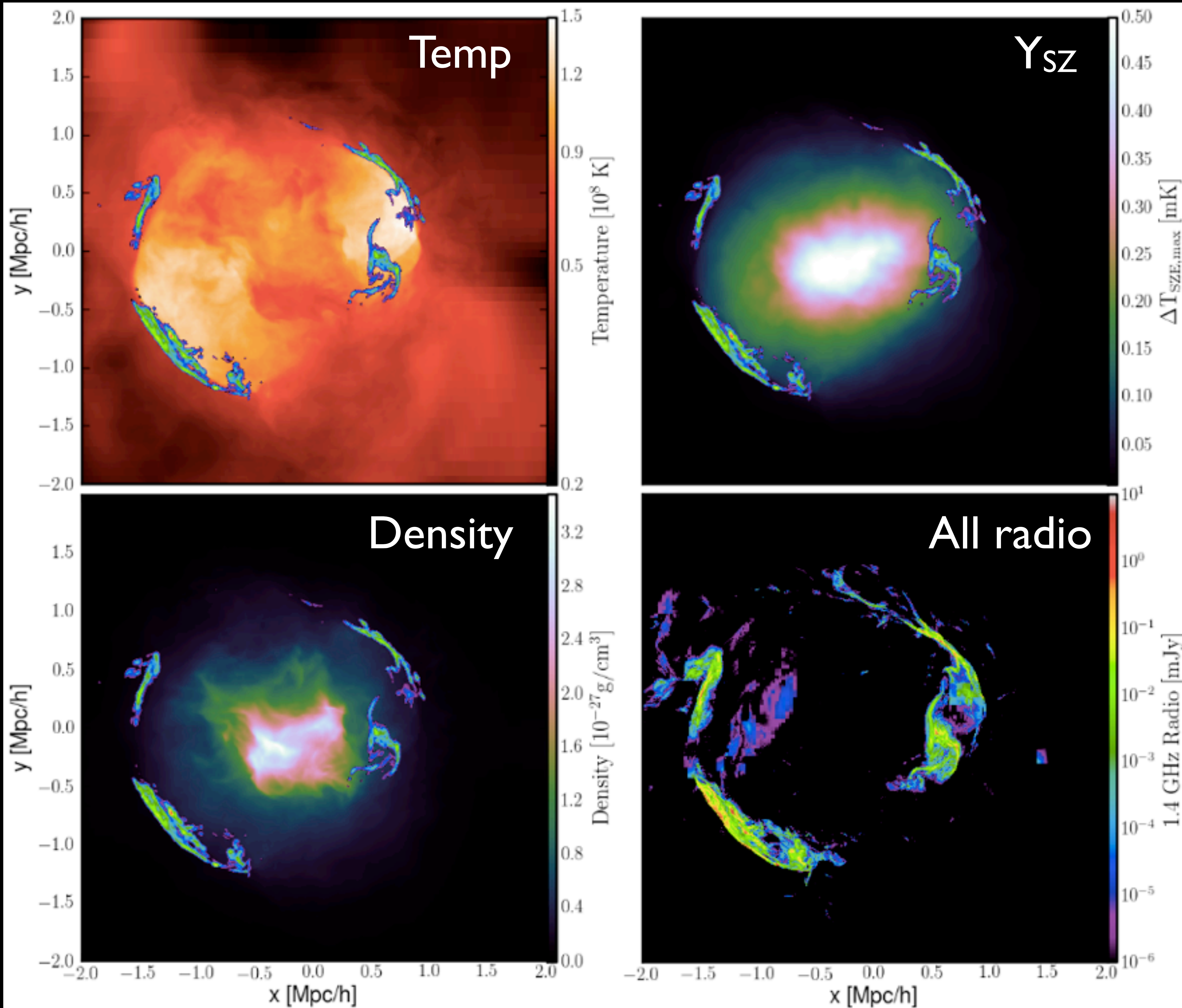
Frame Number
0
5
10
15
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Relative Luminosity
1.4 GHz Radio
0.5-12.0 keV X-ray
11.5
12.0
12.5
13.0
Time [Gyrs]

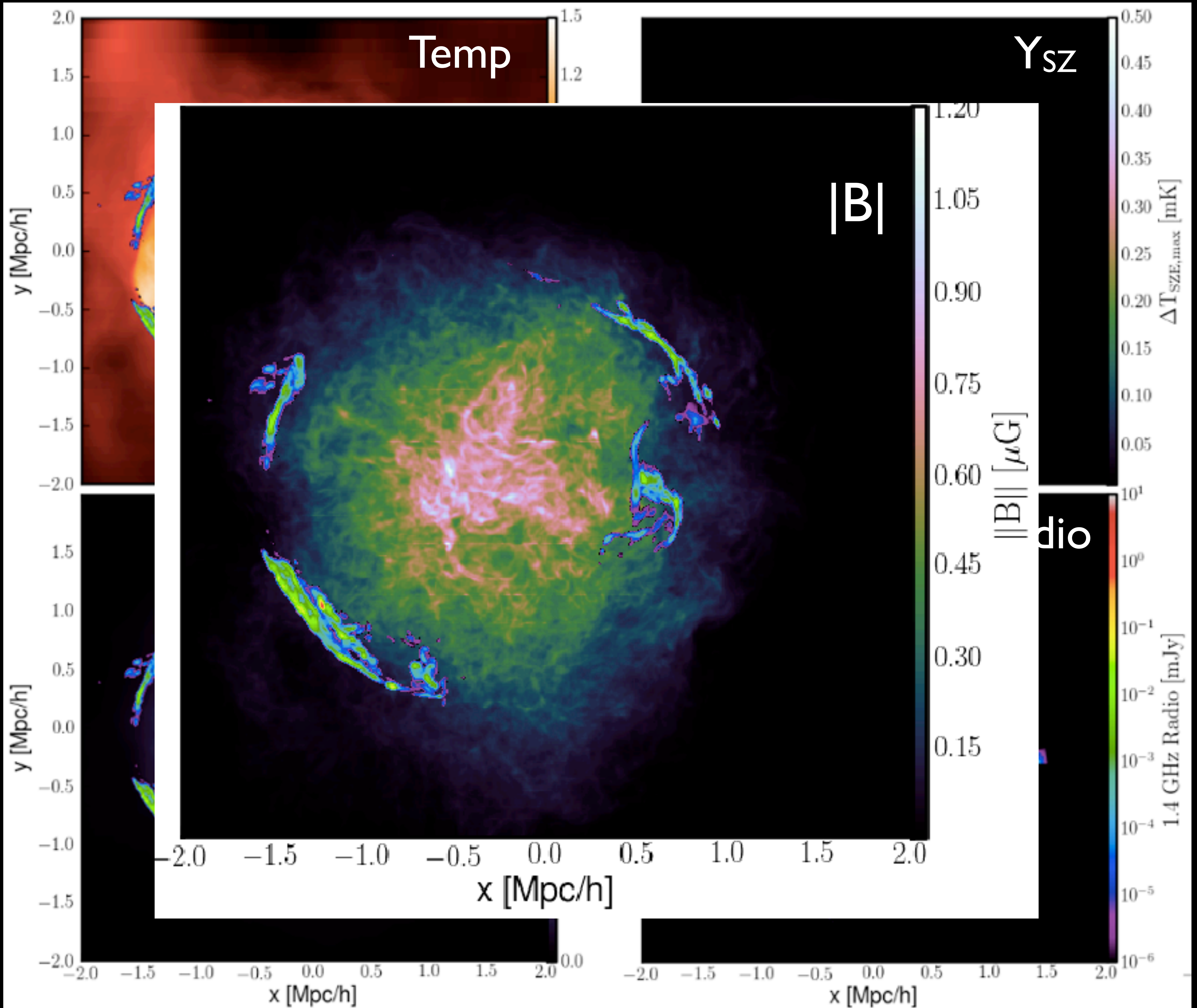


Inclusion of MHD into galaxy cluster simulations: more realistic relics!



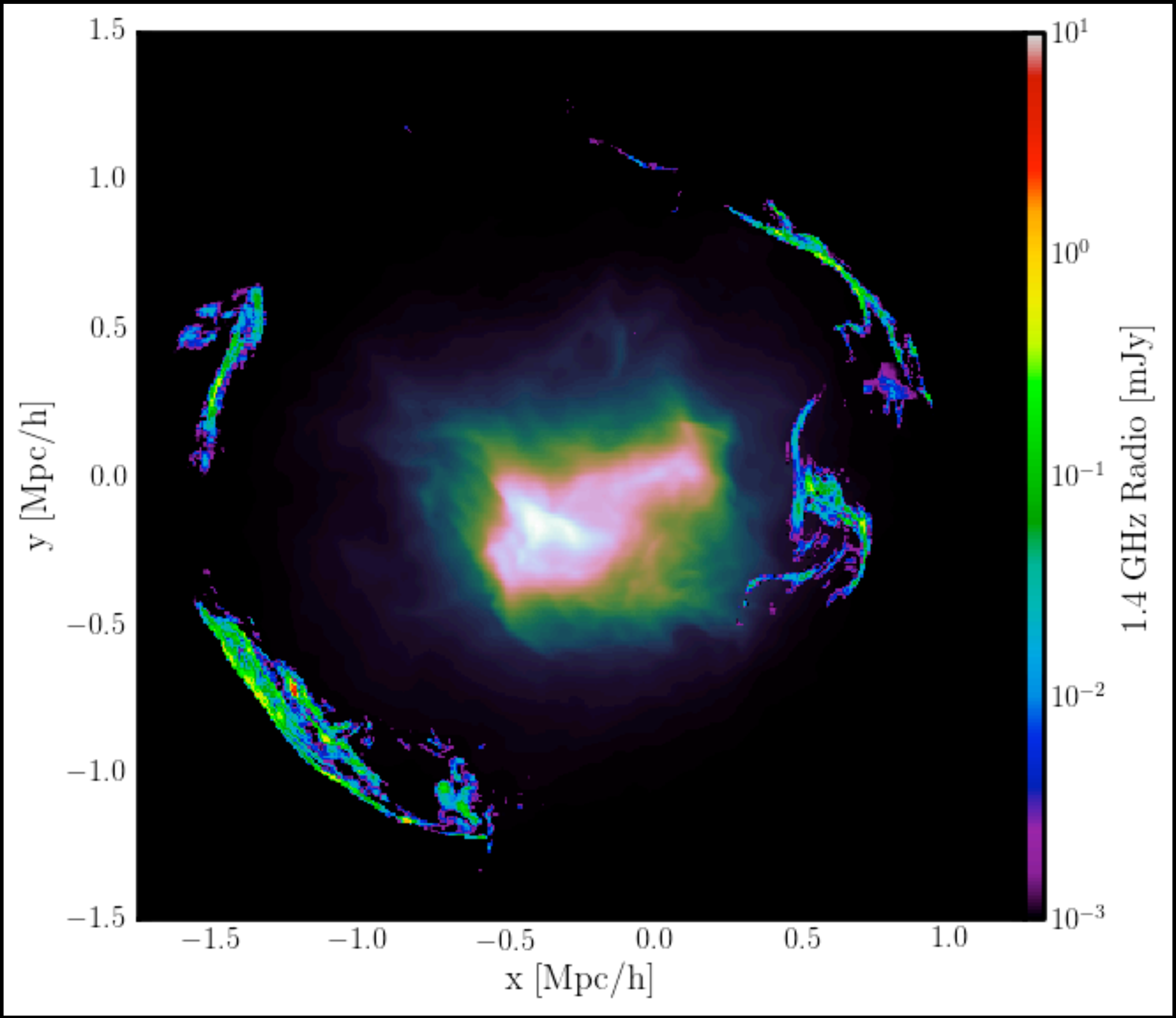
Inject B-fields at z=3.0 from AGN, follow merger history


Temp
Y_SZ
Density
All radio
Temperature [10^8 K]
ΔT_SZE,max [mK]
Density [10^-27 g/cm^3]
1.4 GHz Radio [mJy]
y [Mpc/h]
x [Mpc/h]

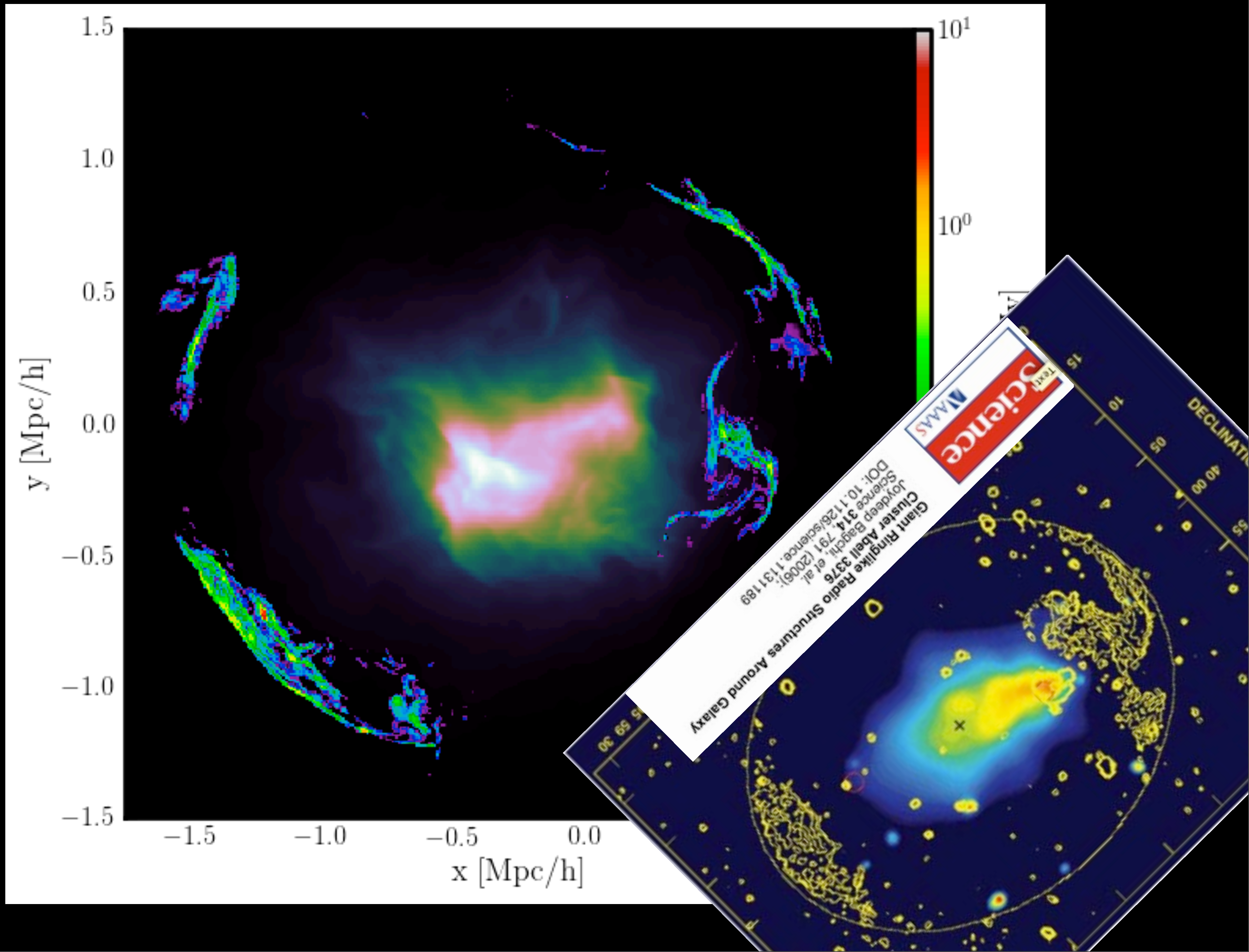


Temp
Y_SZ
|B|
||B|| [μG]
dio
x [Mpc/h]
y [Mpc/h]
ΔT_SZE,max [mK]
1.4 GHz Radio [mJy]

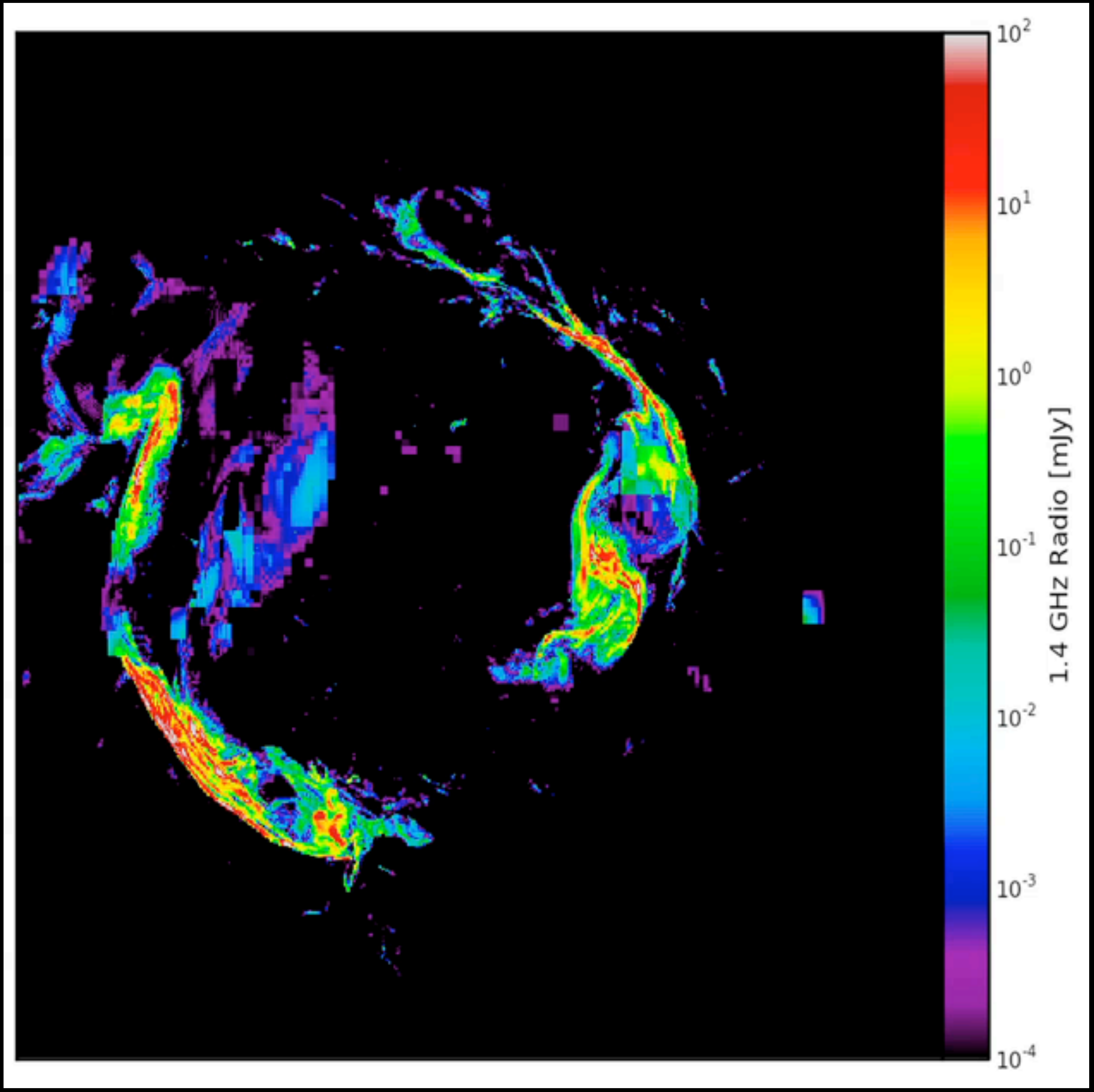
Combined X-ray and radio emission



Combined X-ray and radio emission

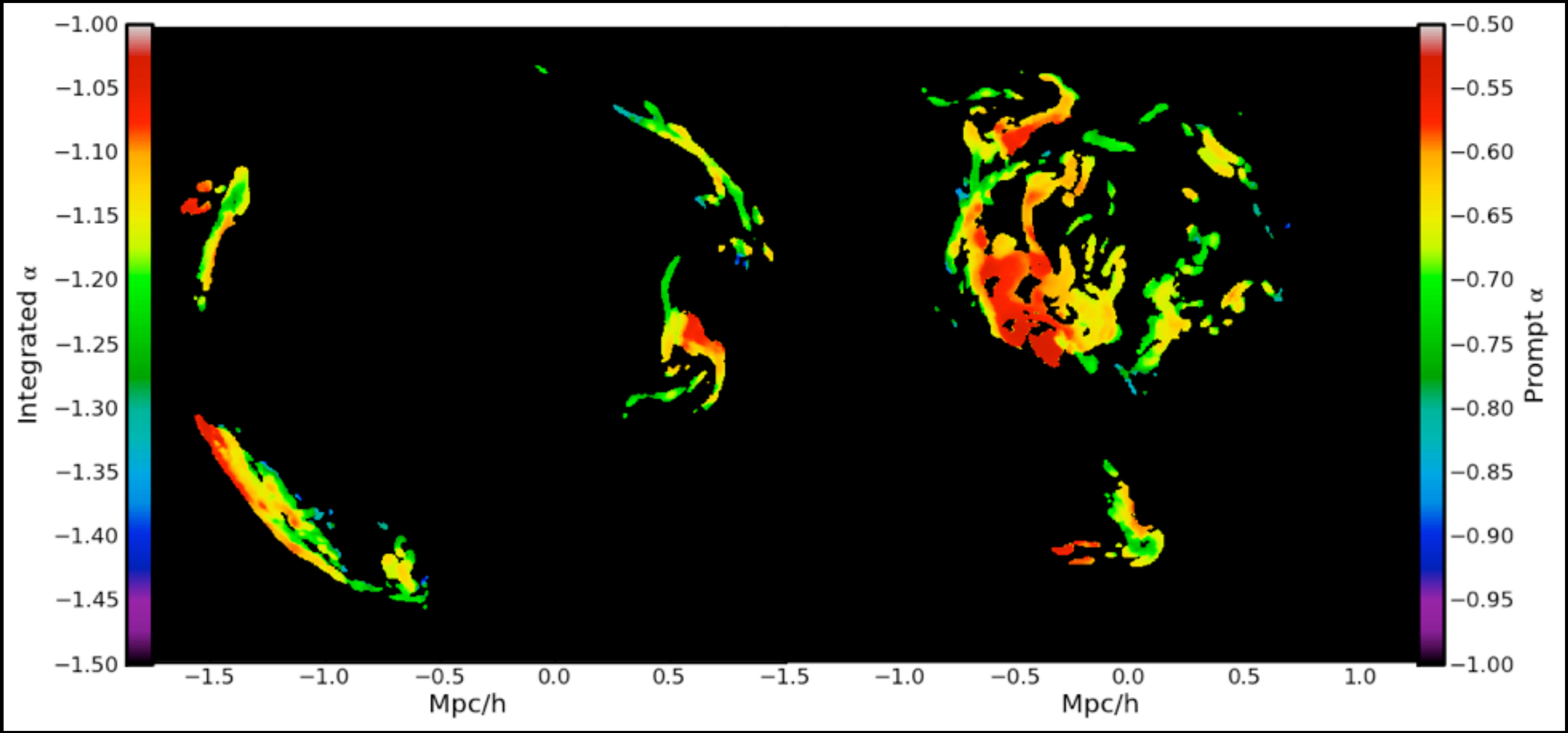


Appearance depends strongly on viewing angle!



Spectral index

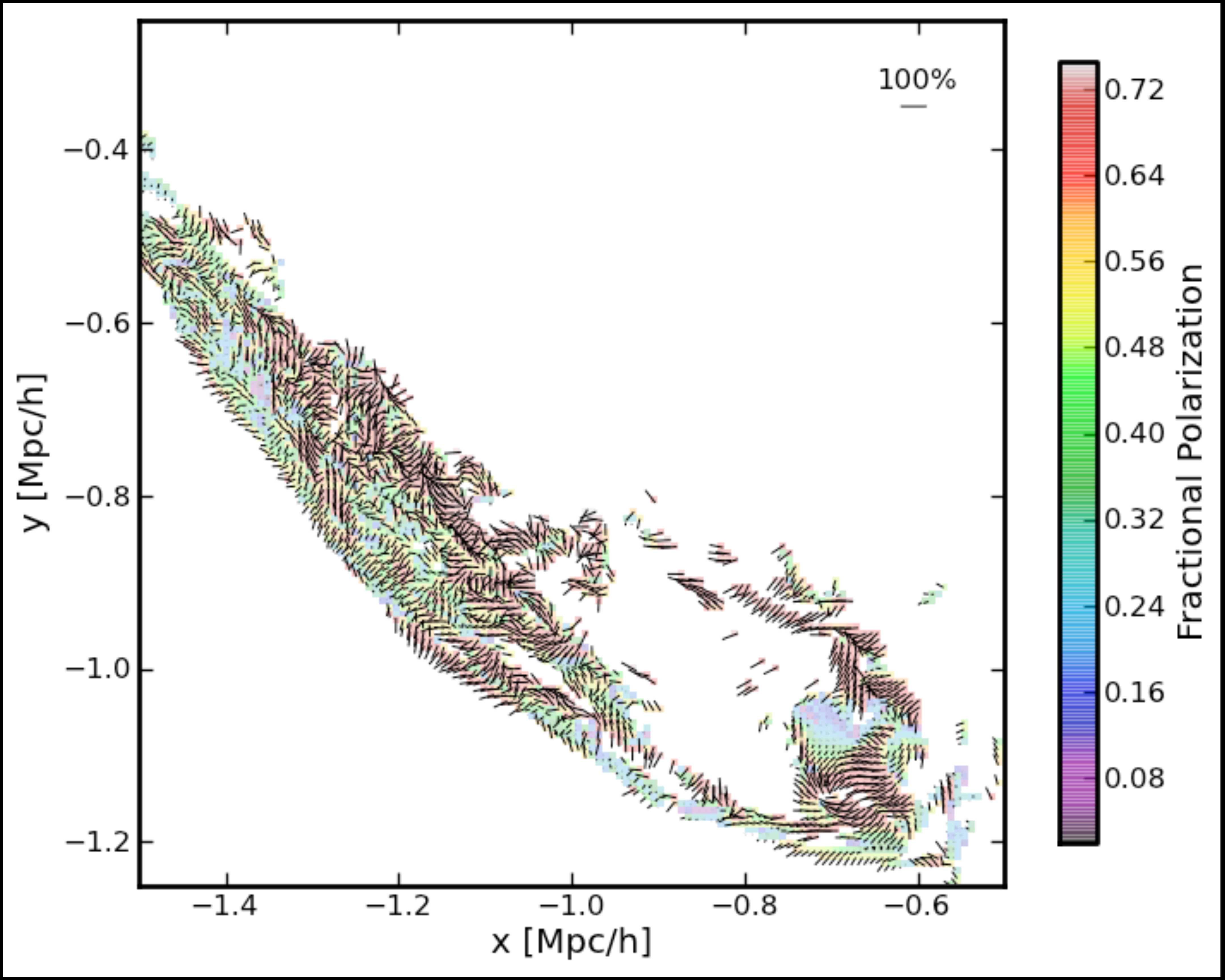
Between 300 MHz - 1.4 GHz



Edge on

Face on

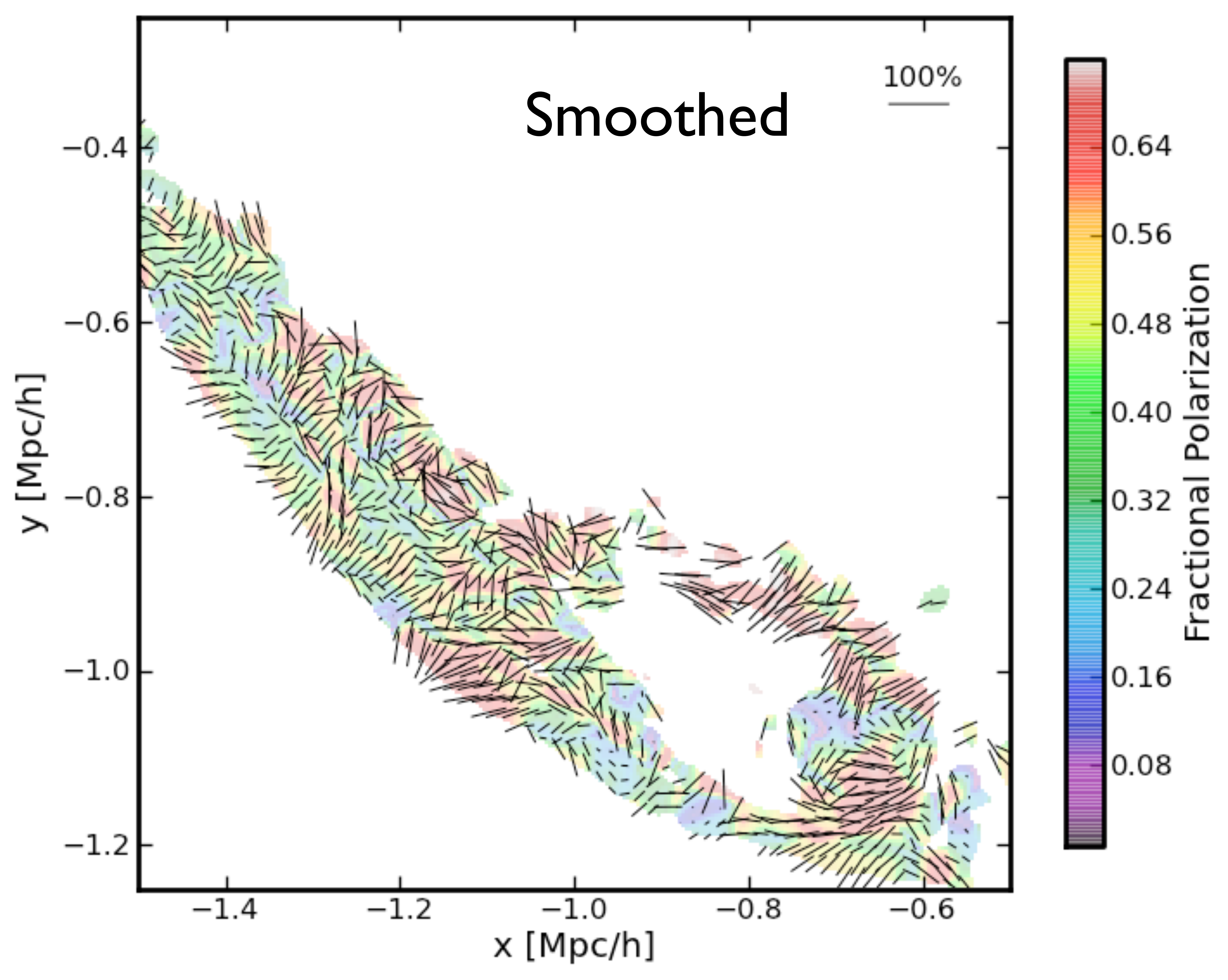
Polarization - edge on



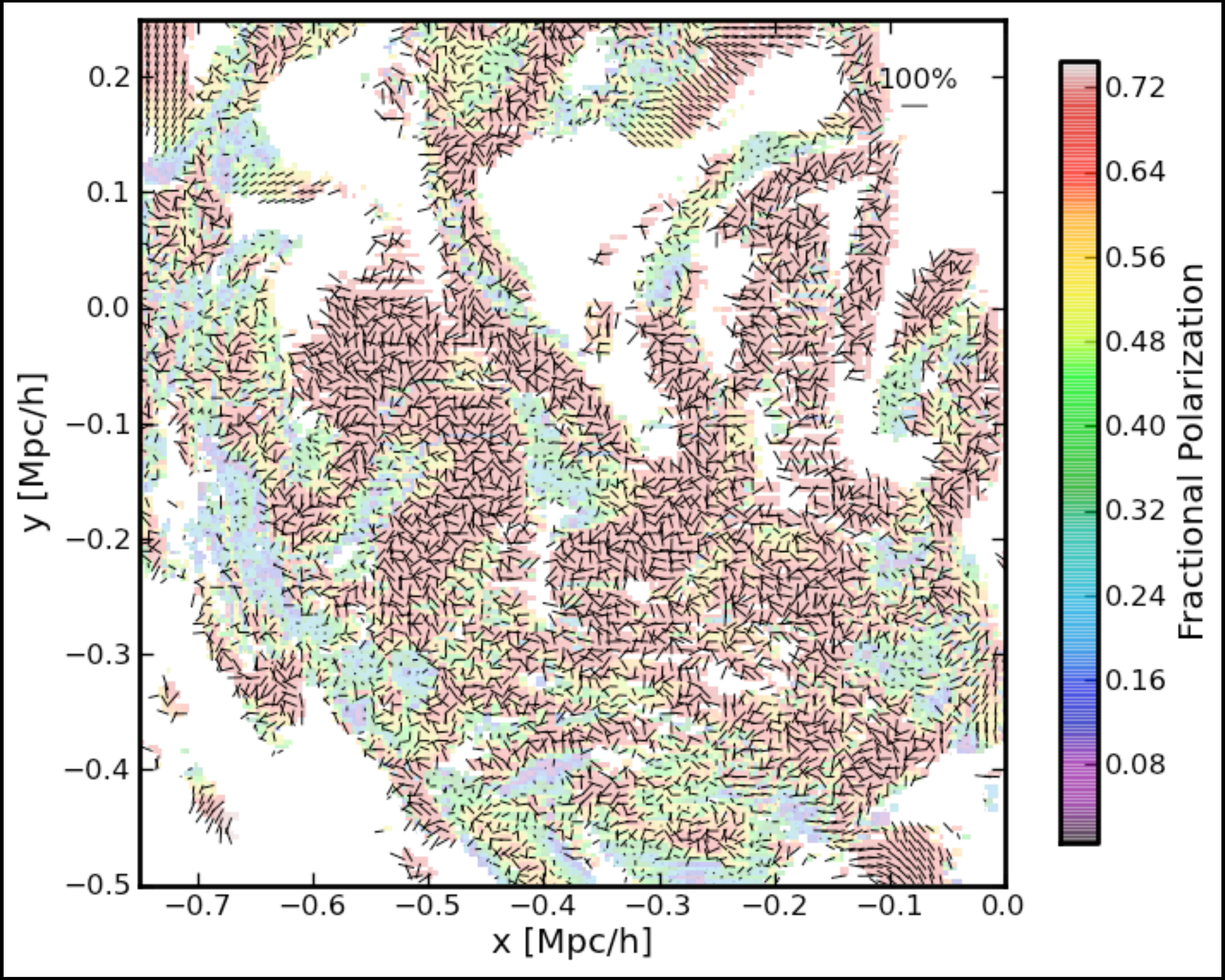
(E-vectors)

Polarization - edge on

(E-vectors)

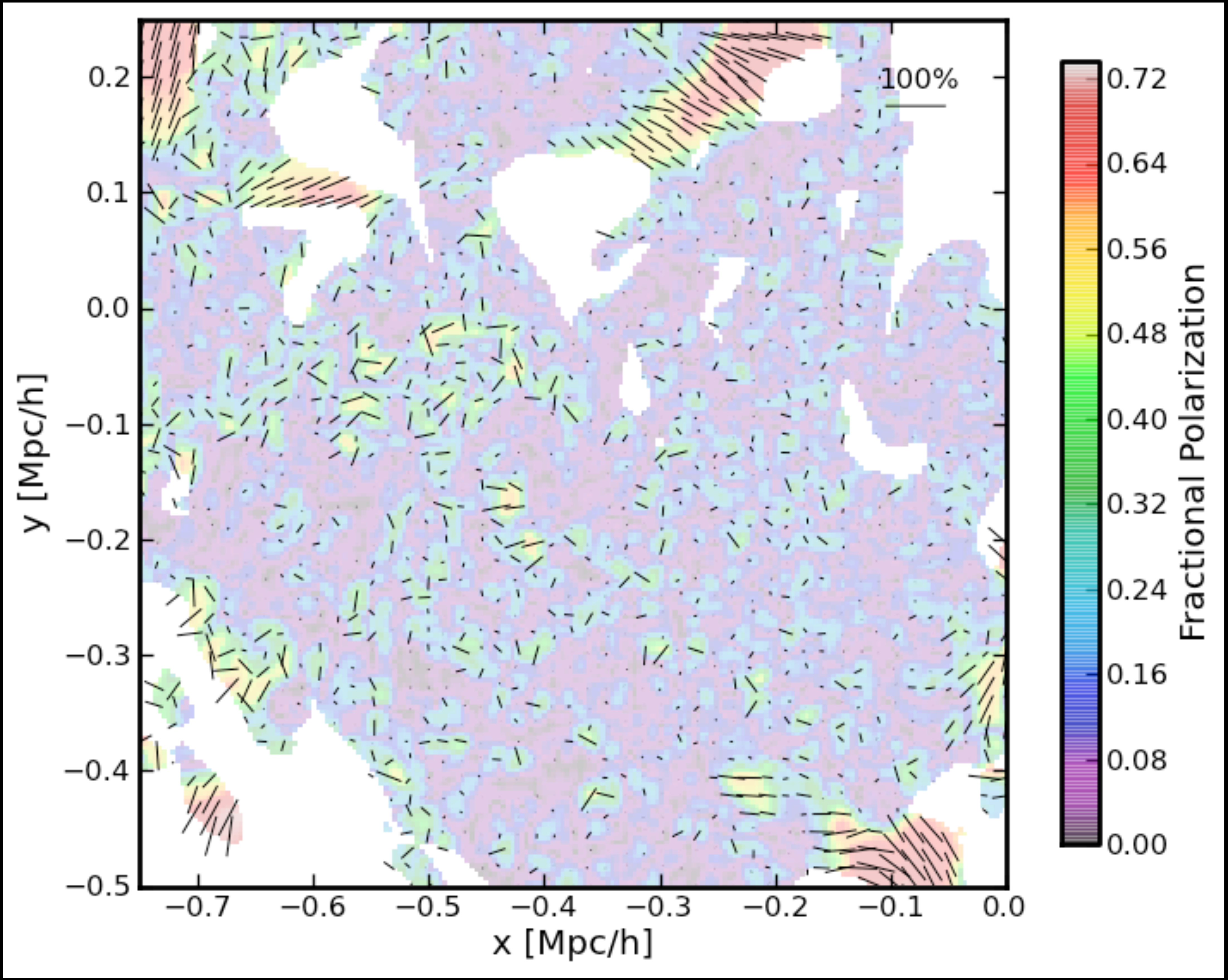


Polarization - face on



Polarization - face on

Smoothed

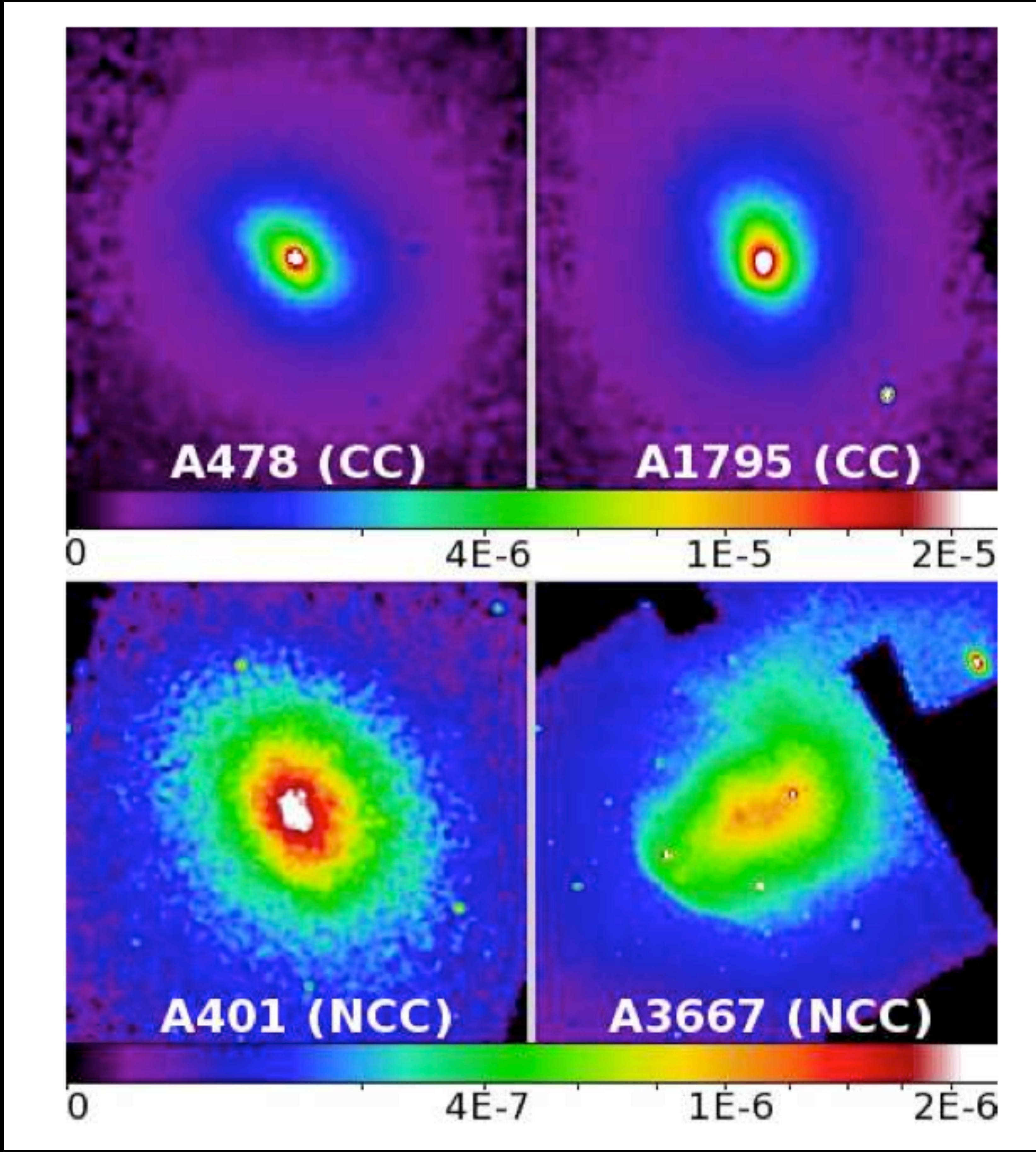


Radio relics...

- are from mergers
- Emission primarily from gas at low ρ, very high T
- correlate well with jumps in T, S_x, SZ
- We find reasonable spectral indices, magnetic field behavior (when compared to observed relics)

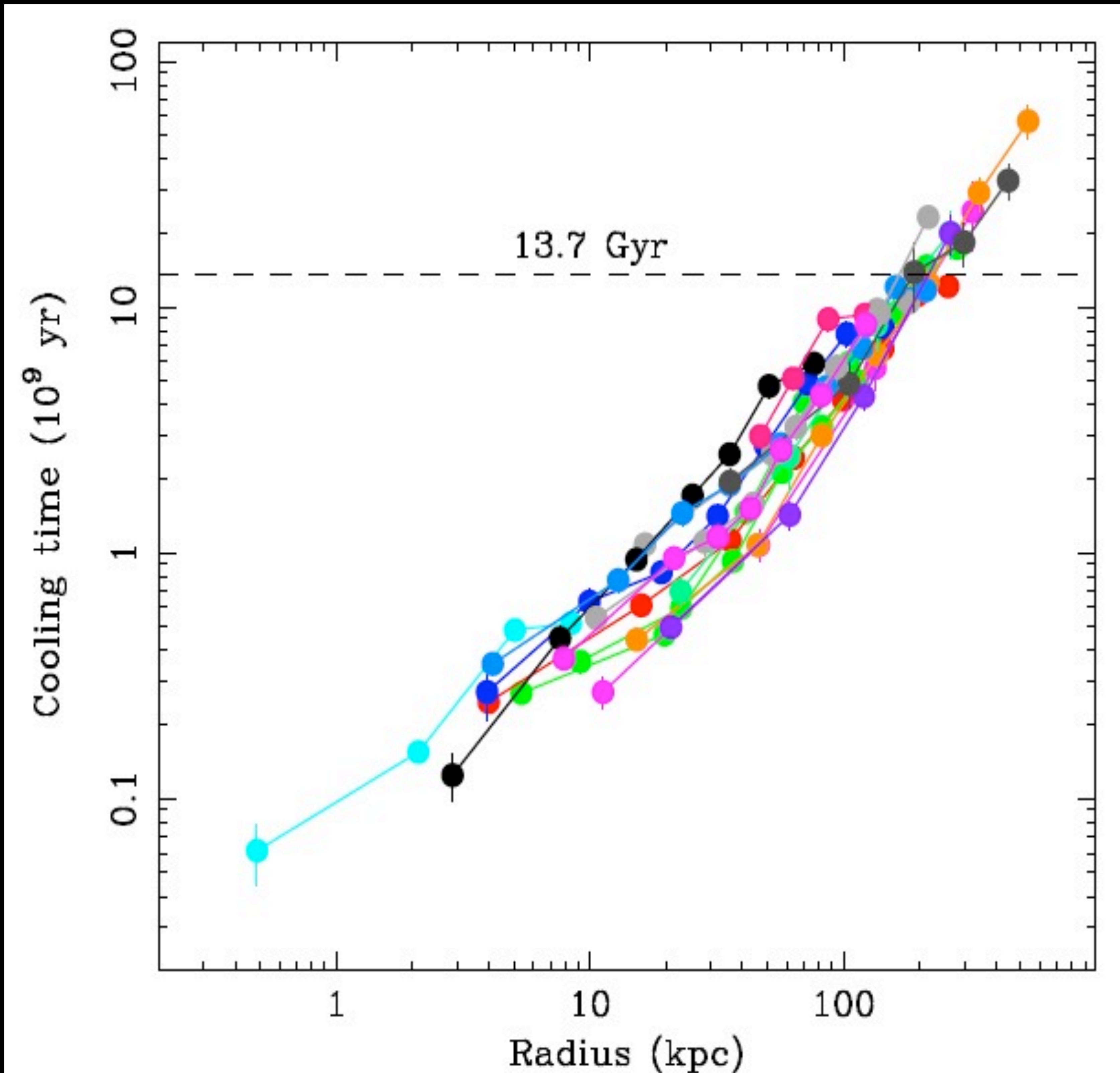
Understanding galaxy cluster cores

Cool core vs. non-cool-core clusters



From Henning et al. 2009, ApJ, 697, 1597

The cool core problem



Peterson & Fabian
2006

How to heat the cluster core?

- Merger shocks/turbulence/sound waves
- Cold clump accretion
- Supernova feedback
- Cosmic rays
- Thermal conduction
- AGN feedback (of various sorts)
- (probably many more ideas)

How to heat the cluster core?

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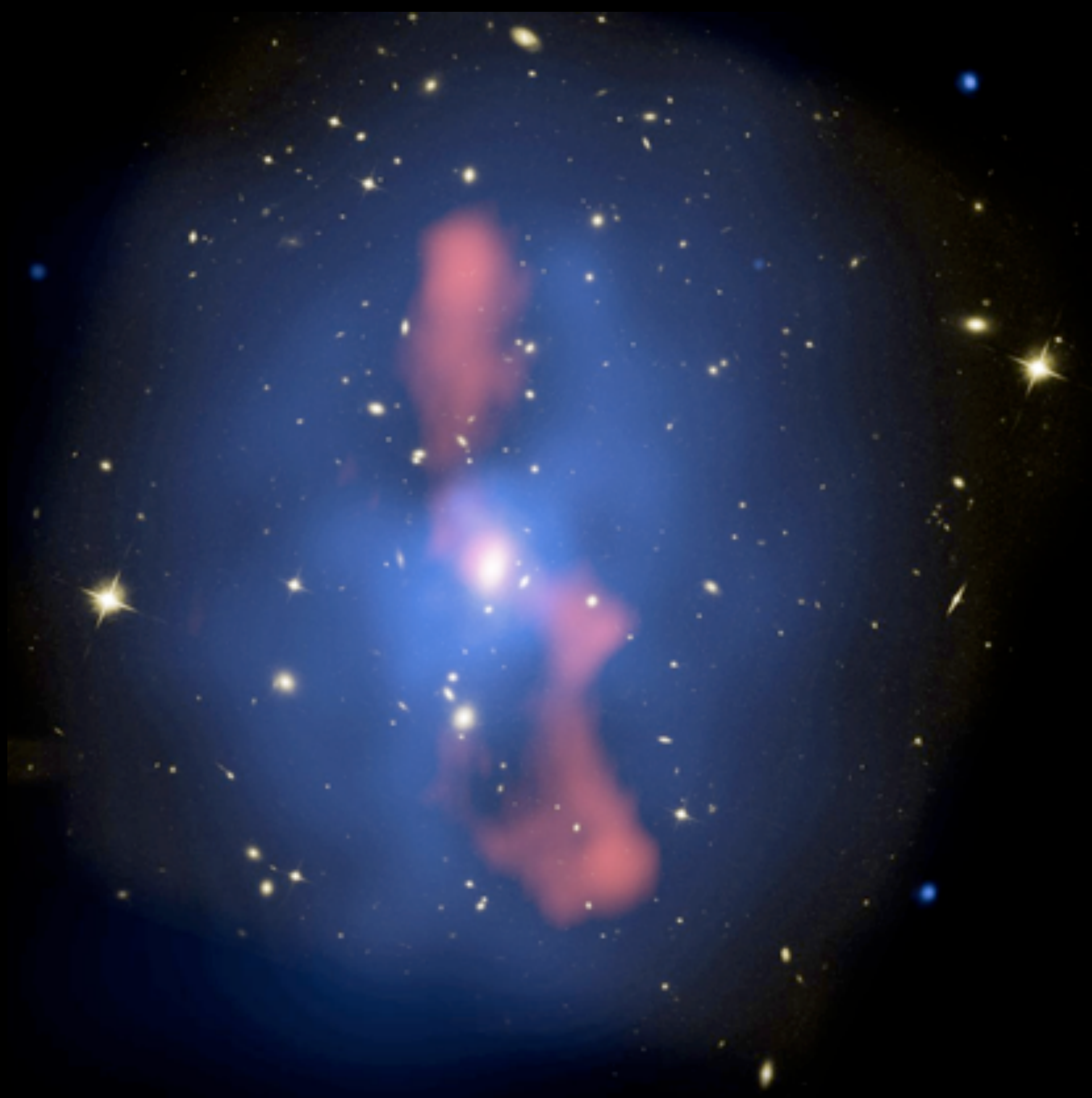
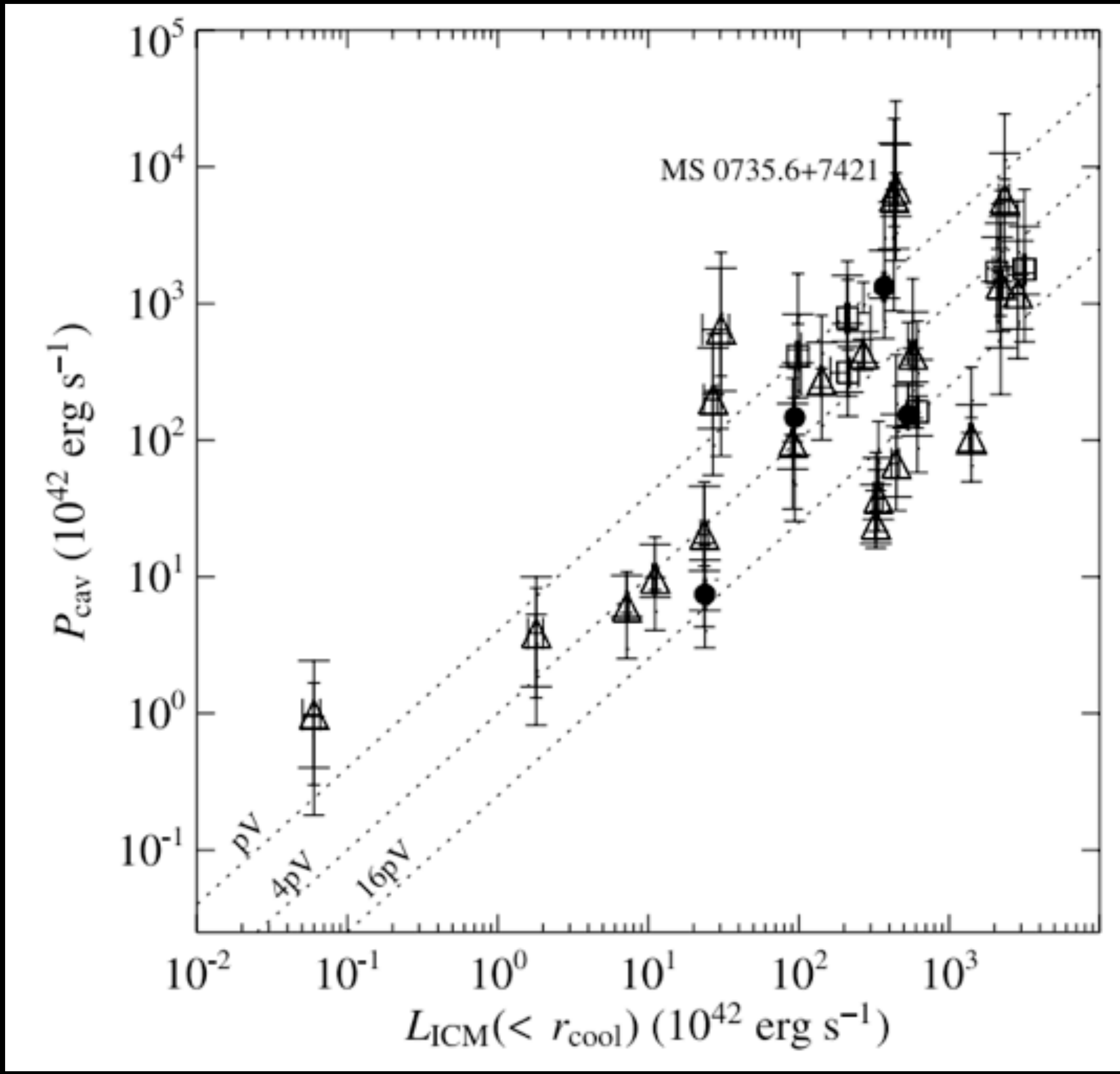
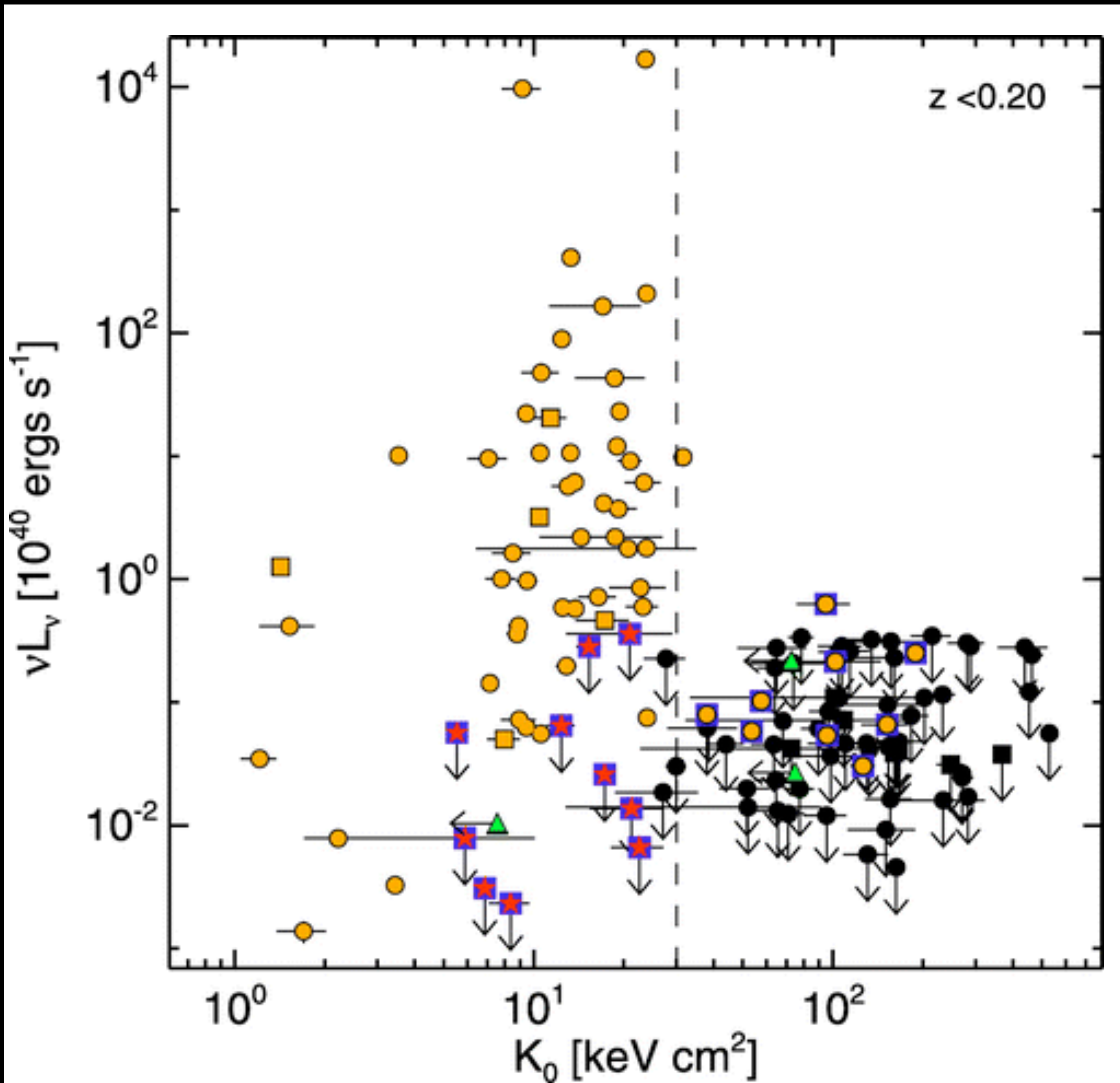


McNamara+



Rafferty+ 2006

Cluster entropy and AGN radio activity

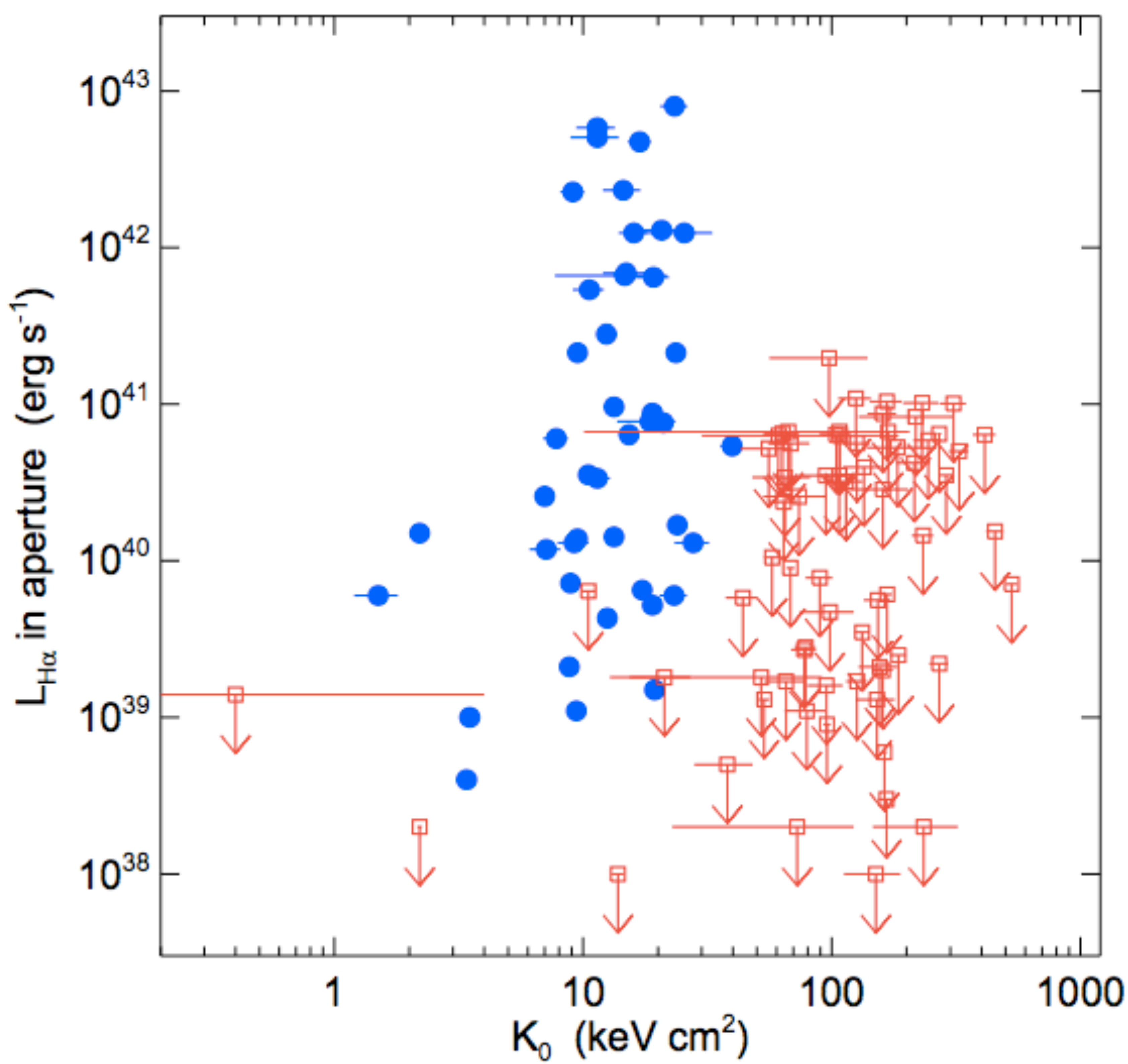


Cavagnolo+ 2008

note:

$K = k_b T n_e^{-2/3}$

Cluster entropy and H-alpha emission



Detection

Upper limit

X-axis:
central entropy

Voit & Donahue 2014,
arXiv: 1409.1601

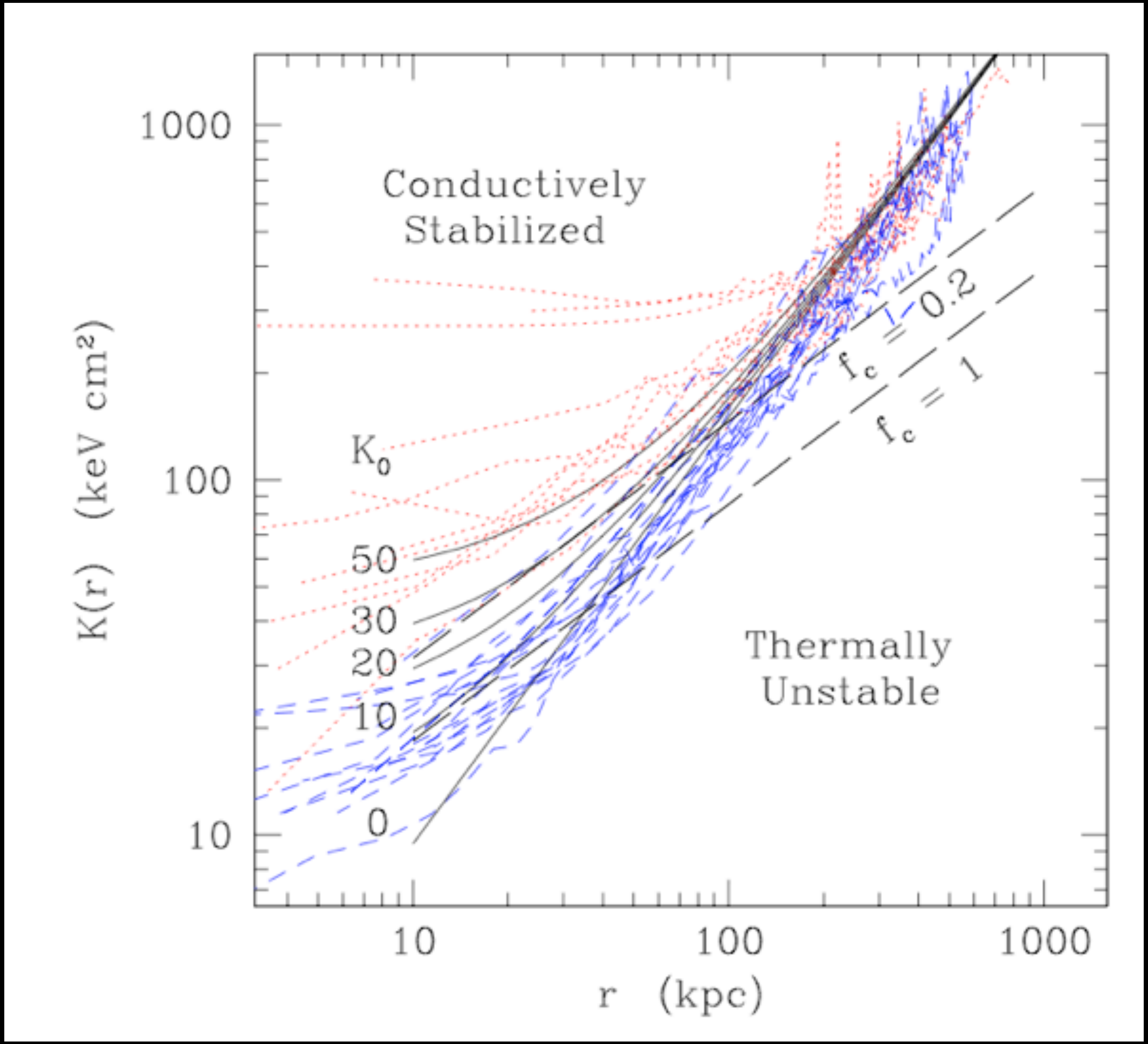
What regulates the (possibly stable) multiphase medium that feeds the AGN?

Conduction in the intracluster medium

with Britton Smith (Edinburgh), Mark Voit, David Ventimiglia (MSU), Sam Skillman (Stanford/KIPAC)

Smith et al. 2013, ApJ, 778, 152

Conduction may be important in regulating cluster cores



Voit et al. 2008, ApJL, 681, L5

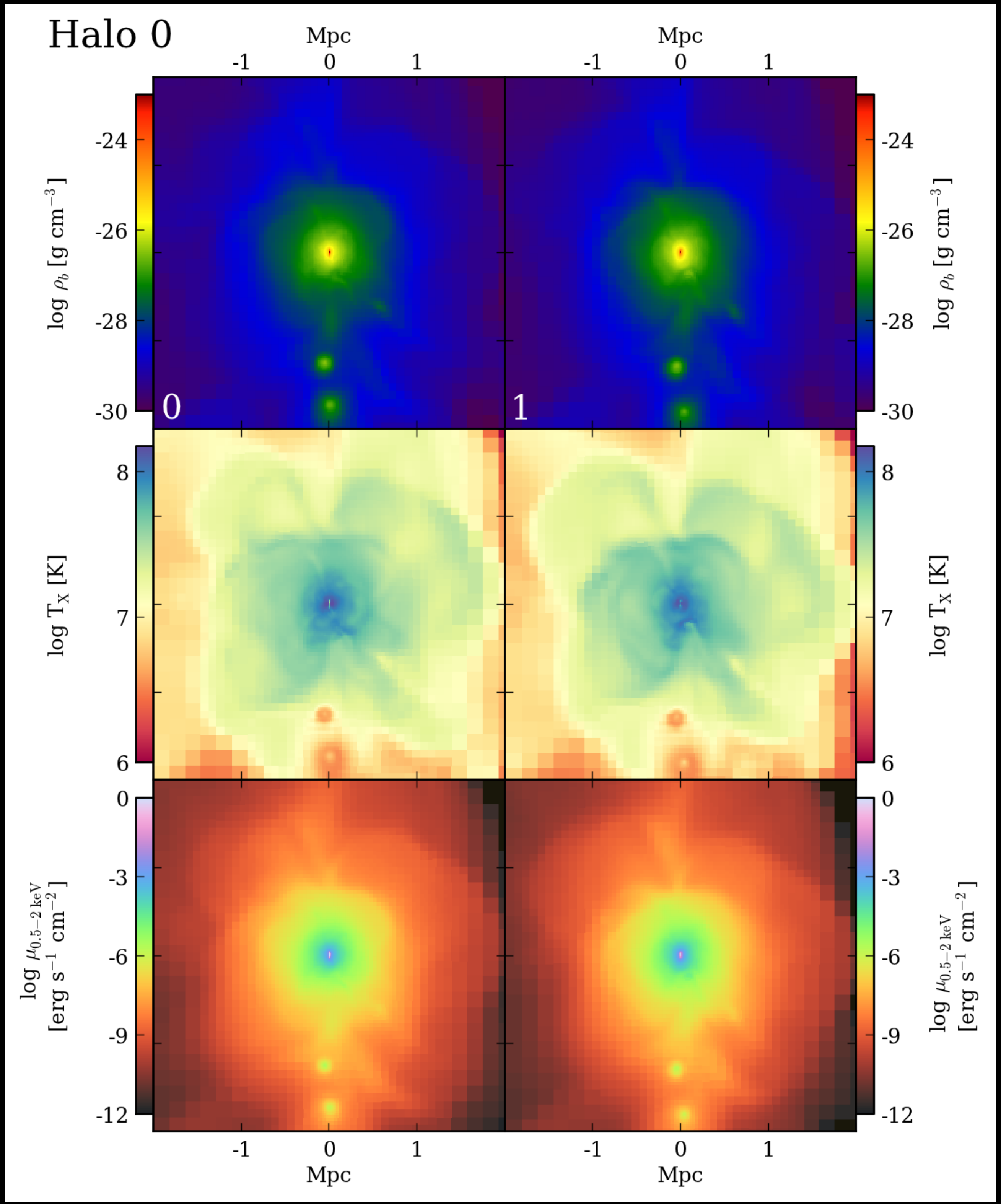
$$\lambda_F \equiv \left[\frac{T\kappa(T)}{n^2\Lambda(T)}\right]^{1/2} = 4\,\mathrm{kpc}\,\left[\frac{K}{10\,\mathrm{keV\,cm^2}}\right]^{3/2} f_c^{1/2}$$

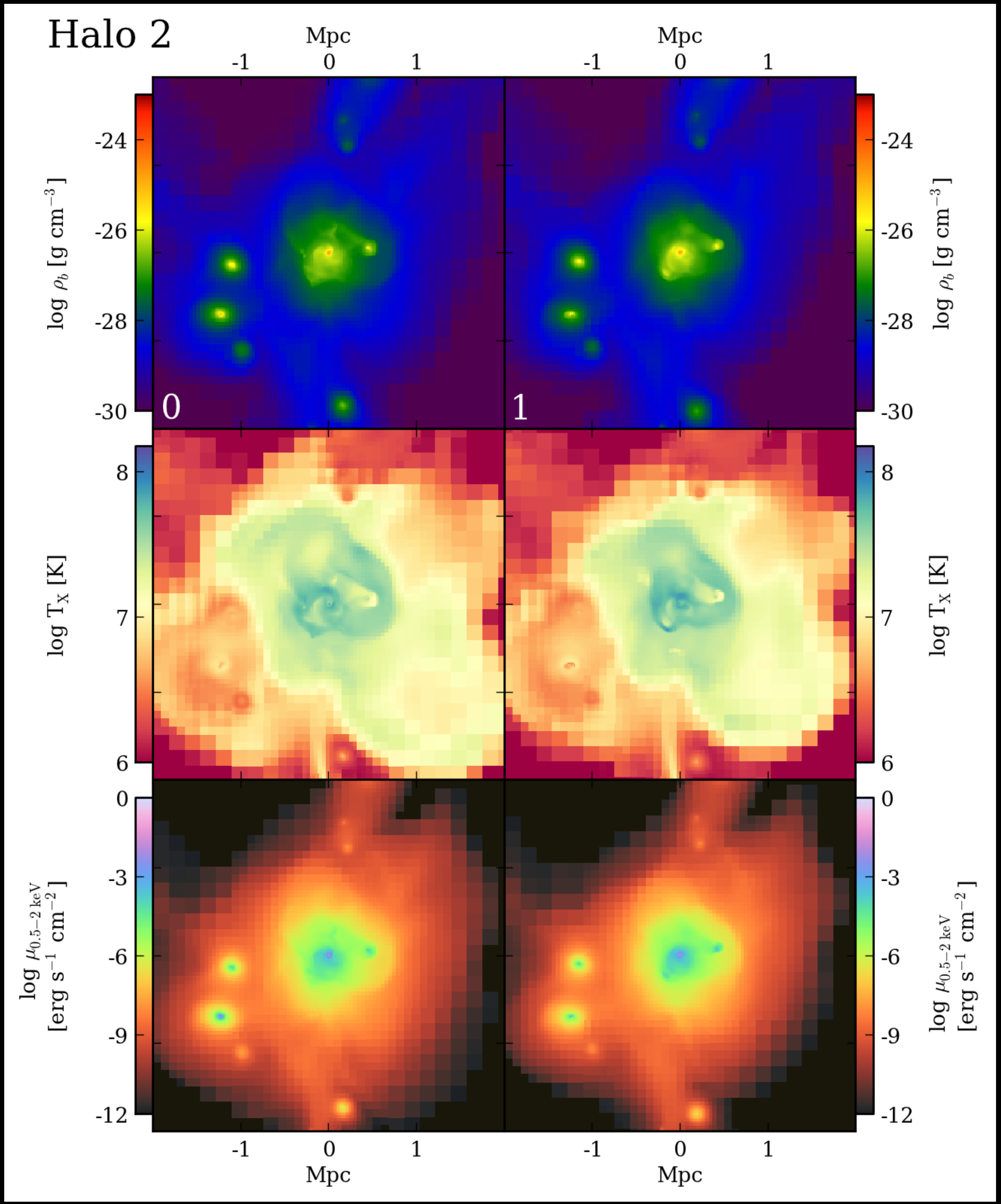
A study of conduction in the ICM

- AMR simulations of cluster formation
- N-body + hydro, cooling, star formation and thermal feedback (no AGN yet!)
- **Isotropic** conduction with f_{sp} = 0, 0.01, 0.1, 0.33, 1
- 10 individual clusters run, identical except for f_{sp}.

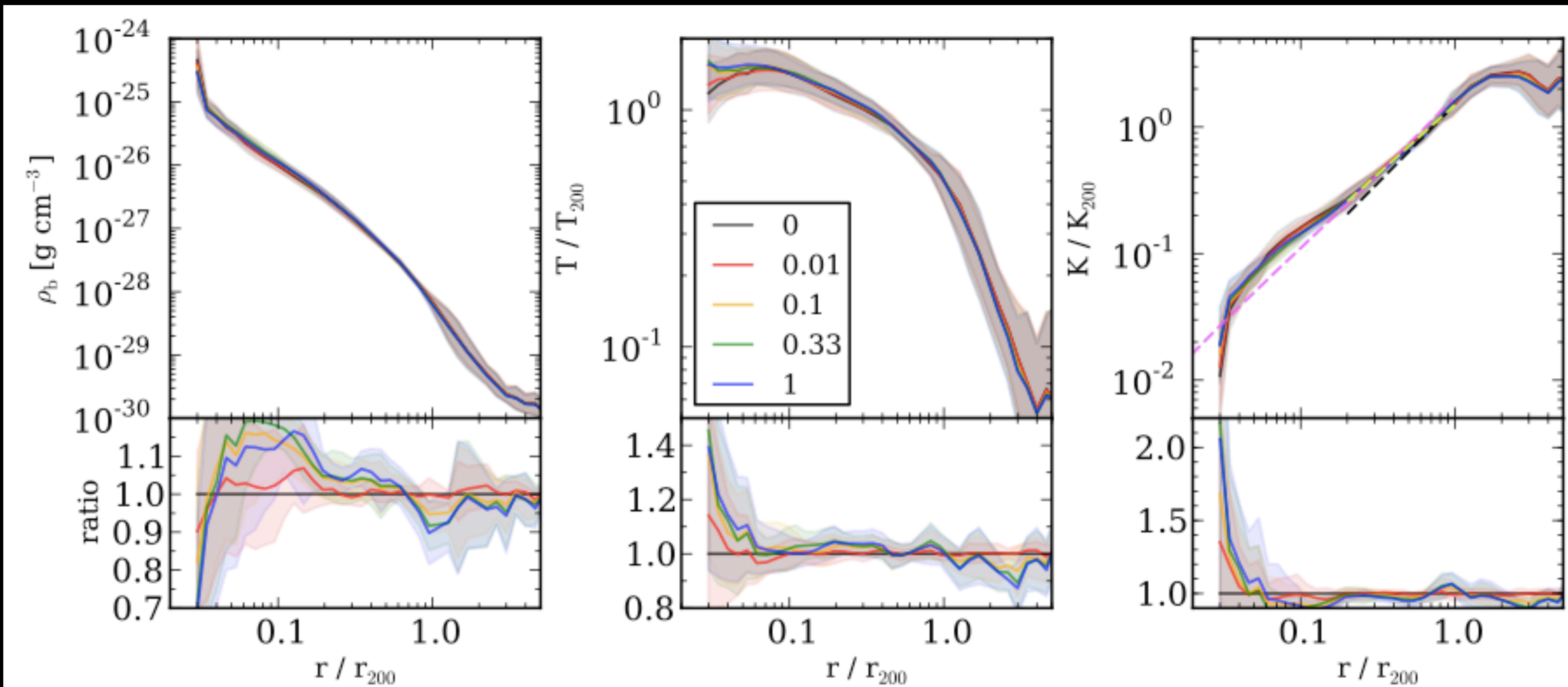
Smith, O'Shea et al. 2013

Is conduction observable?



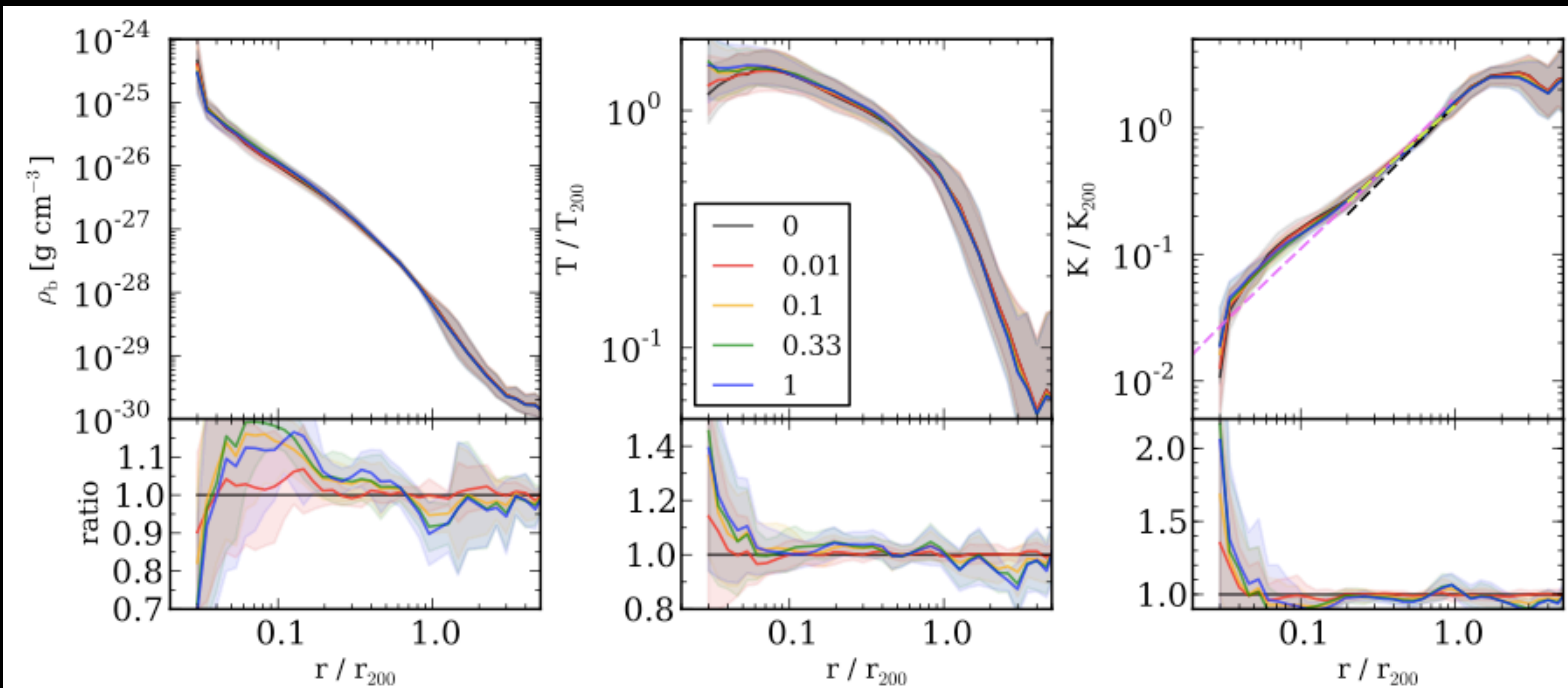


Radial profiles



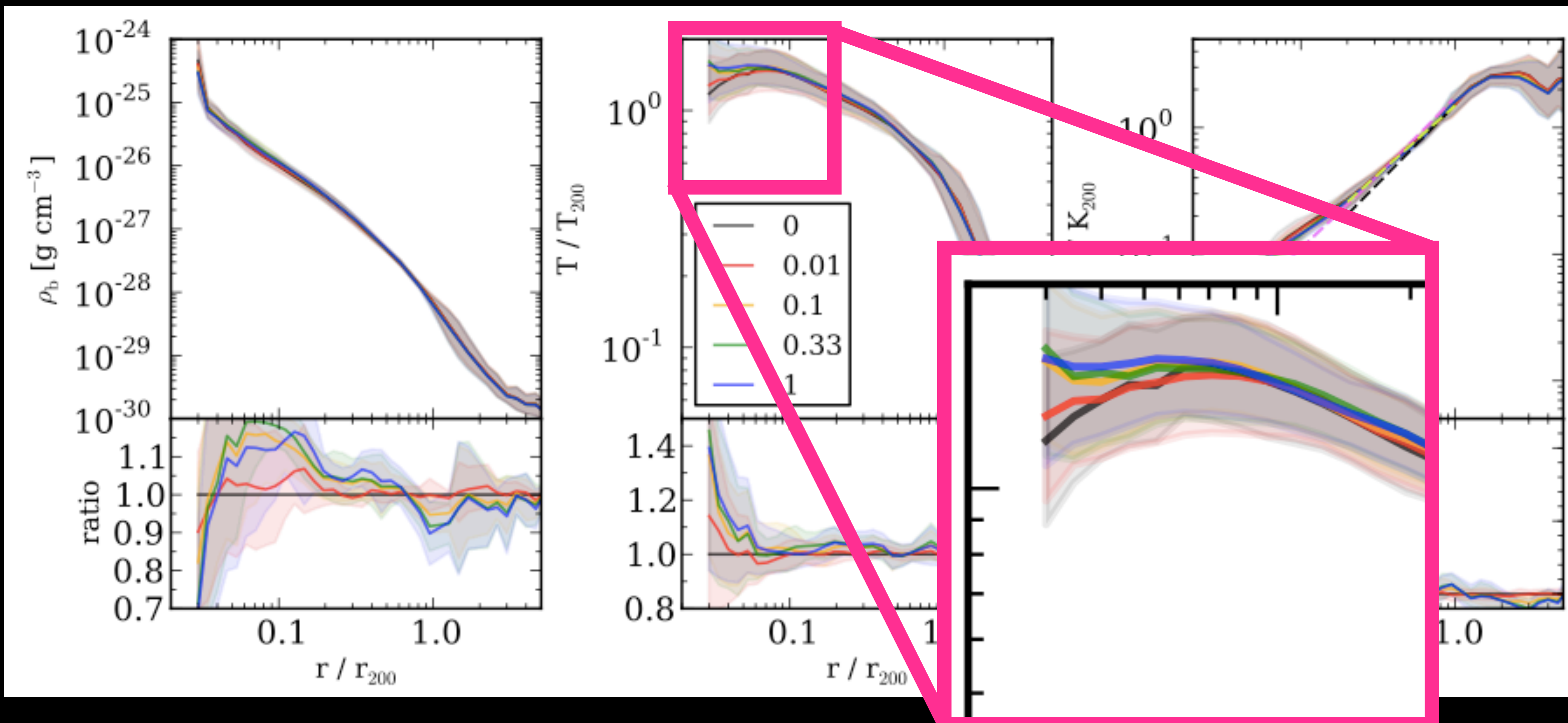
Density Temperature Entropy

Radial profiles



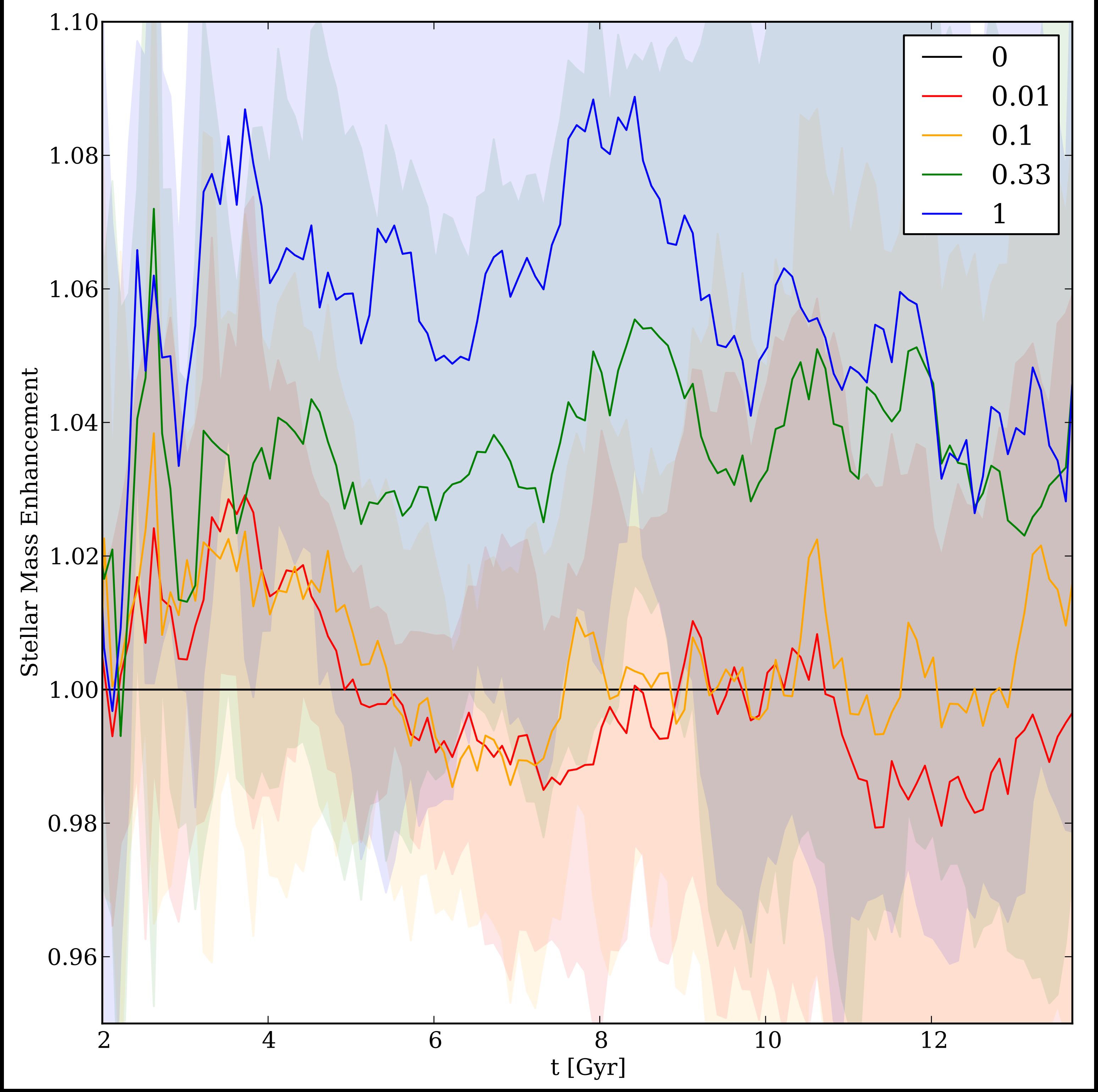
Density Temperature Entropy

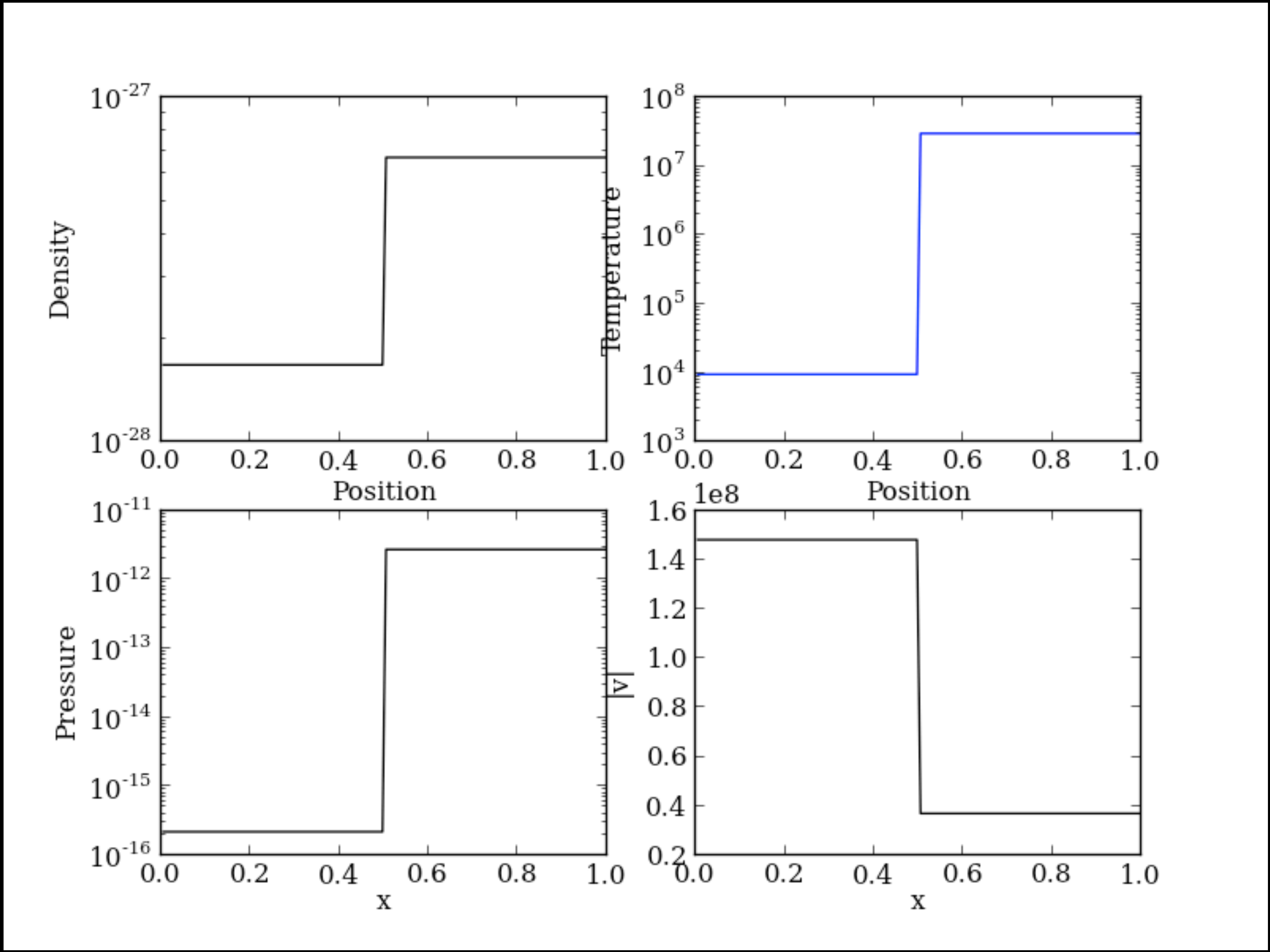
Radial profiles



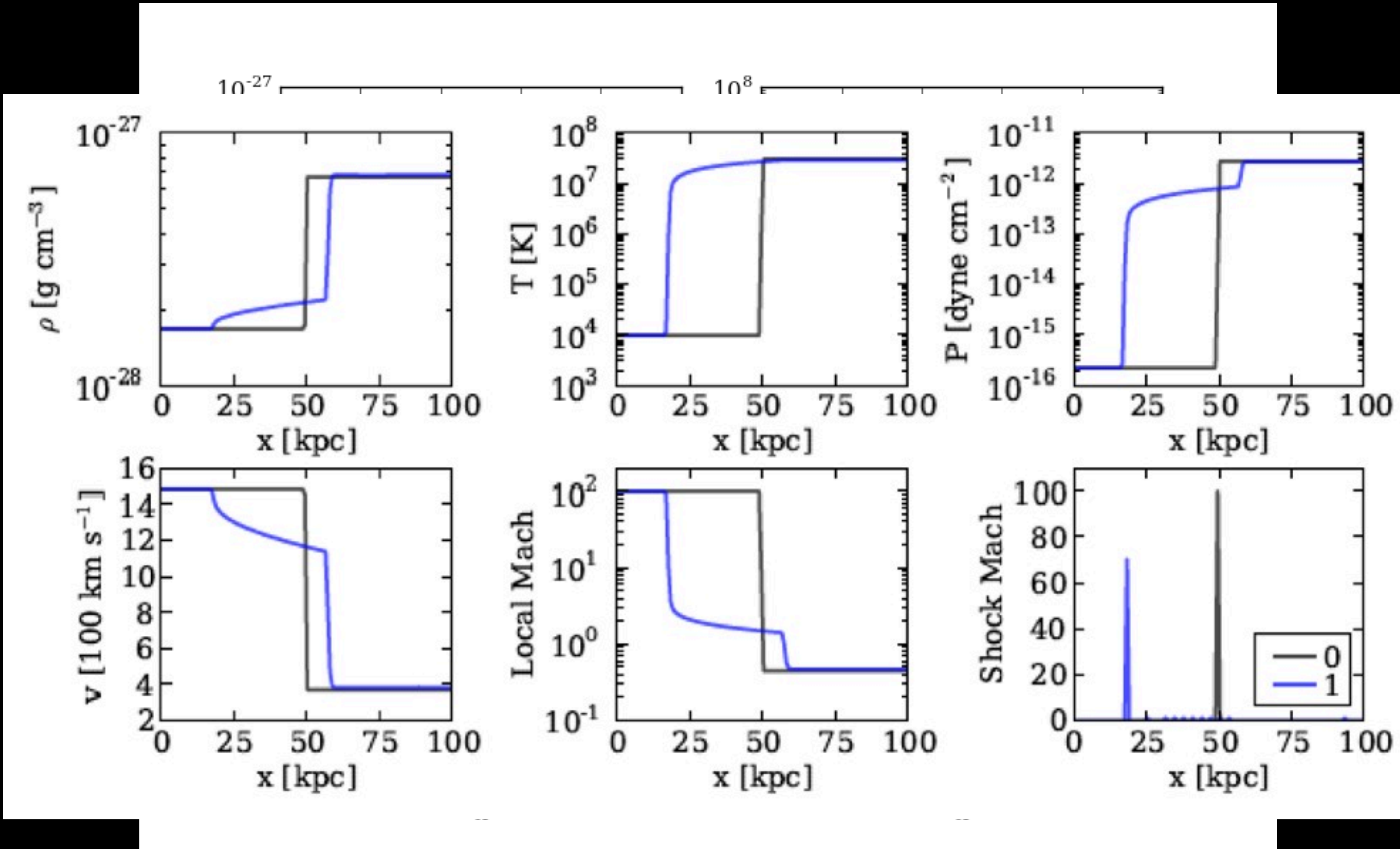
Density Temperature Entropy

Does conduction suppress star formation (i.e., gas cooling)?





Shafranov shocks!



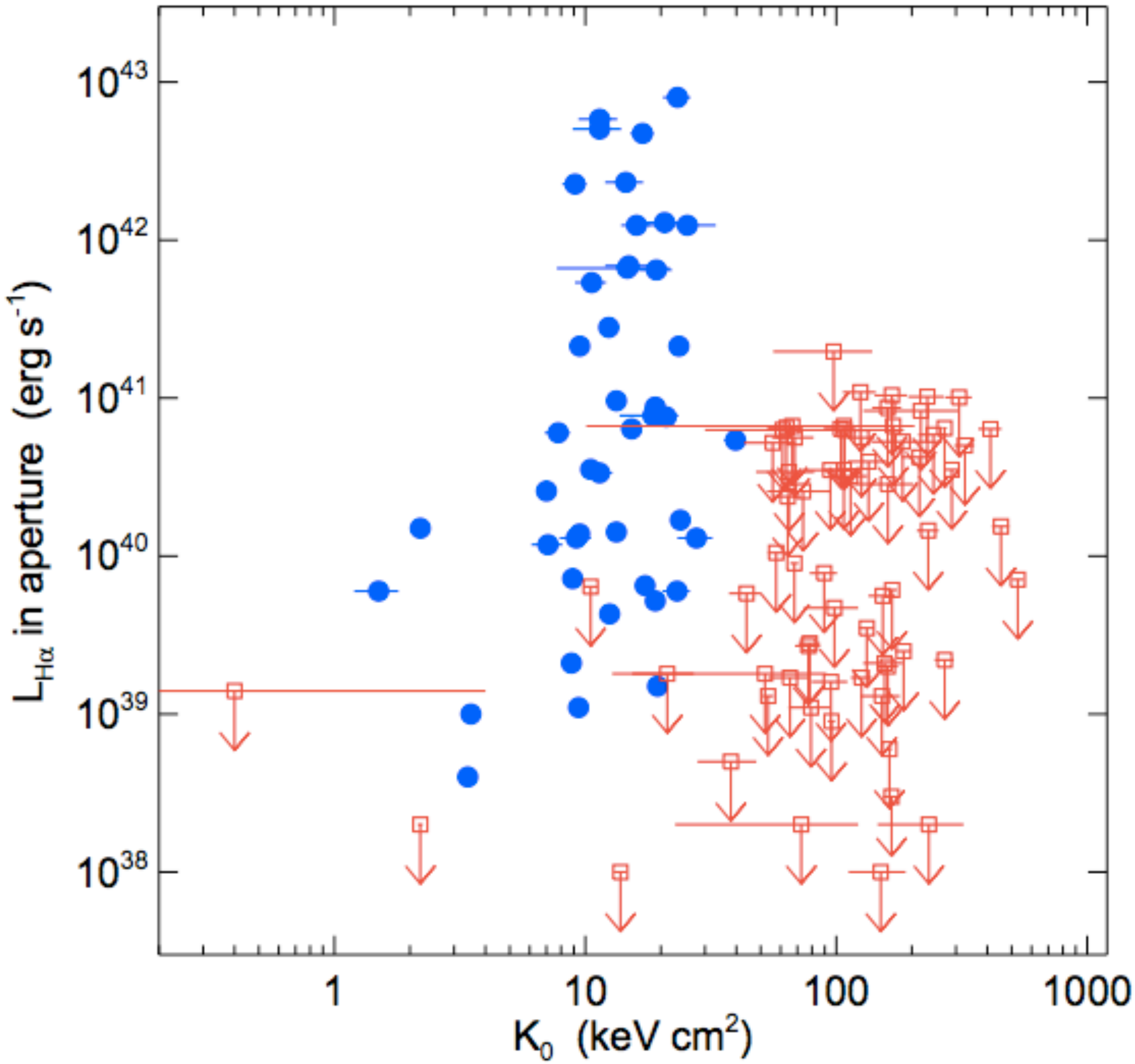
Shafranov shocks!

Conduction...

- increases T_{core} by 20-30% and makes them *slightly* puffier
- decreases temperature inhomogeneity in the ICM - questionable observable signature
- does not suppress gas cooling/condensation/star formation, and may even enhance it
- Different/more powerful feedback mechanisms (AGN?) required to remove core gas and suppress star formation

Can AGN feedback regulate the behavior of cluster cores?

Meece, O'Shea & Voit 2014, in prep.

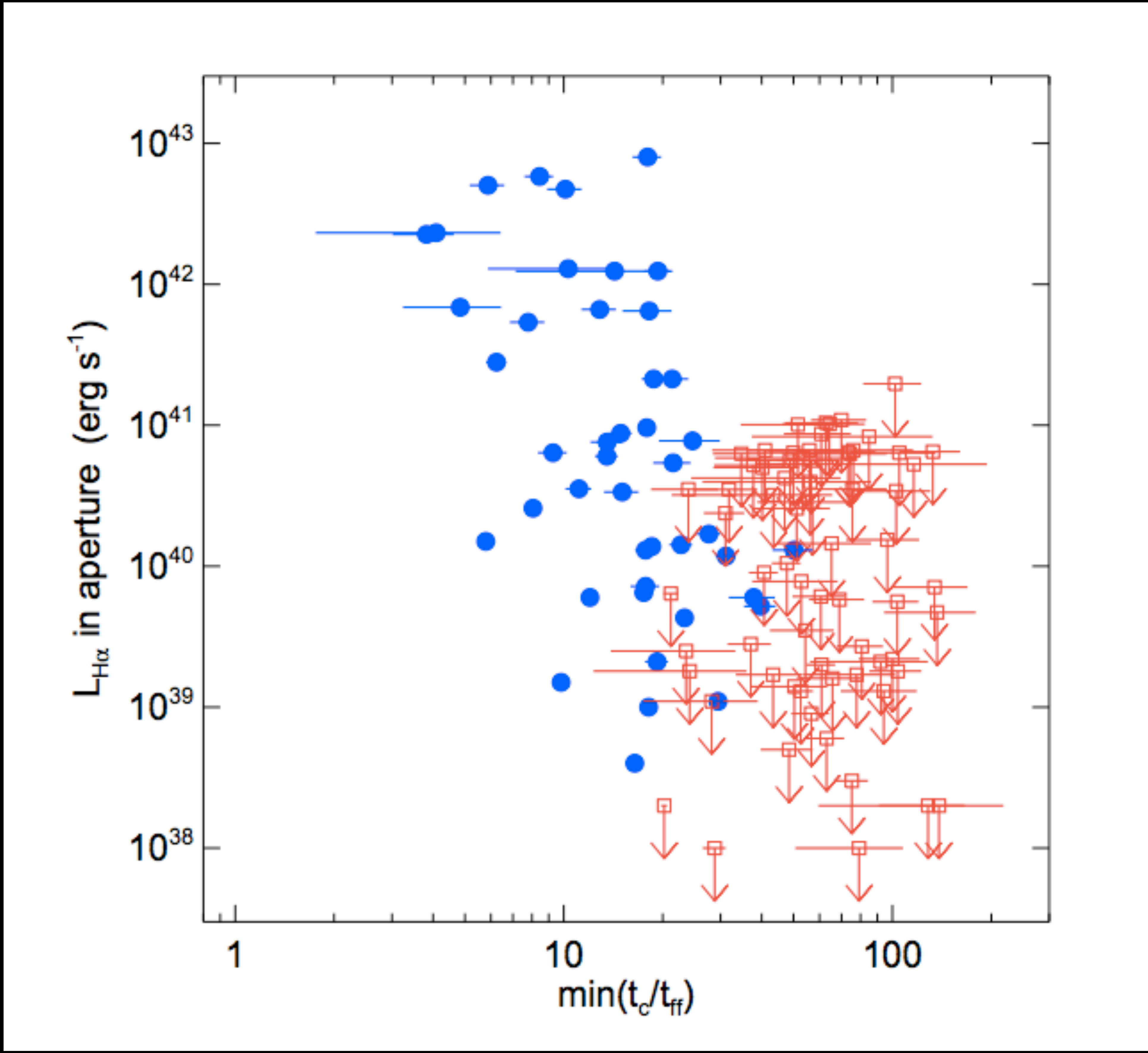


Detection

Upper limit

X-axis:
central entropy

Voit & Donahue 2014, arXiv: 1409.1601



Detection

Upper limit

X-axis:
$t_{cool}/t_{free\text{-}fall}$

Voit & Donahue 2014, arXiv: 1409.1601

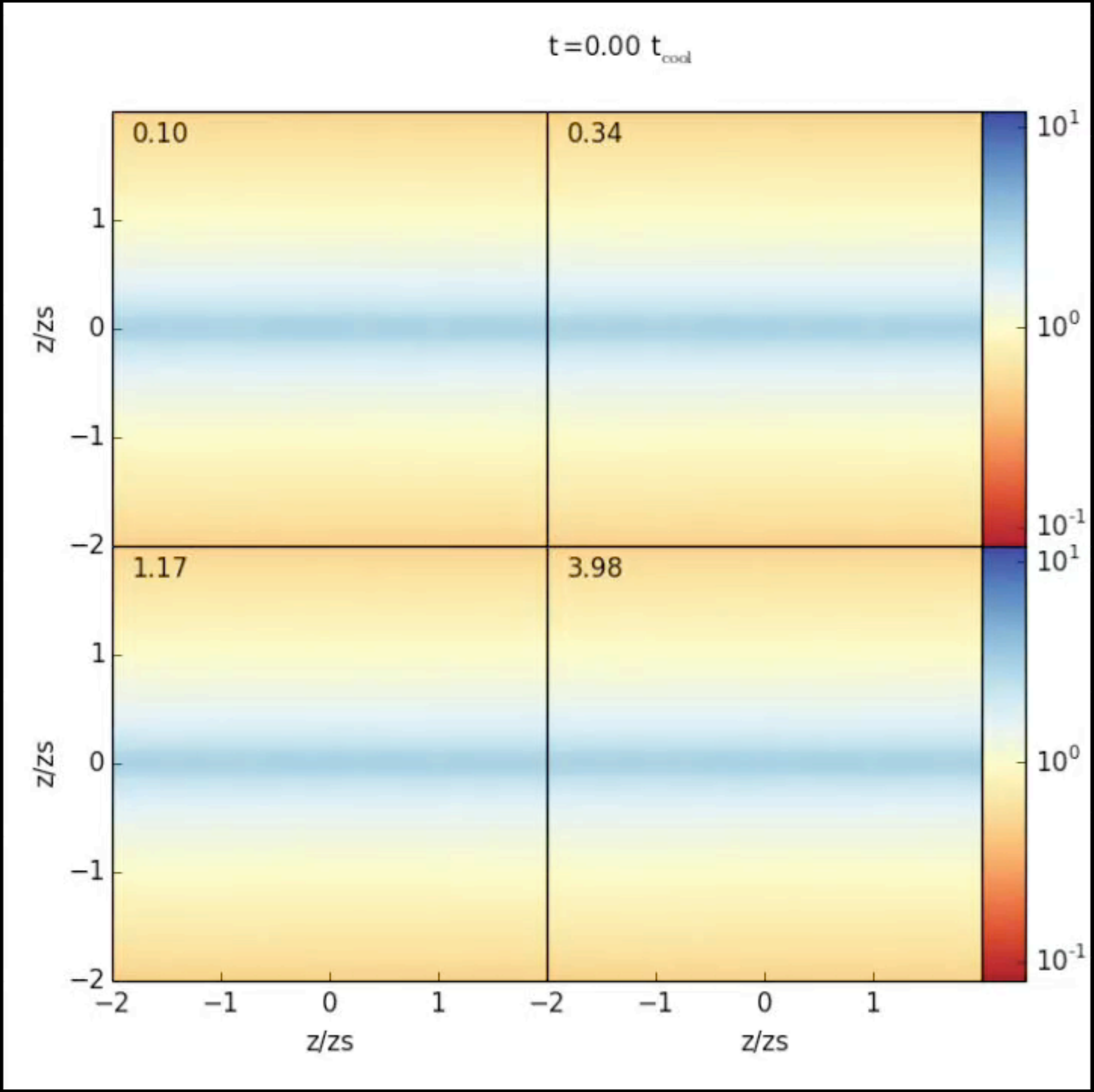
Simulations

- 2D cartesian/cylindrical, 3D spherical, imposed gravitational potential
- Control density, temperature structure of gas (isothermal, isentropic, $S(z) \sim z^a$, etc.)
- Heating balances cooling at every height
- Ratio of cooling time to dynamical time set at 1 scale height

Meece, O'Shea & Voit 2014, in prep.

t_{cool}/t_{ff} = 0.1

t_{cool}/t_{ff} = 0.34

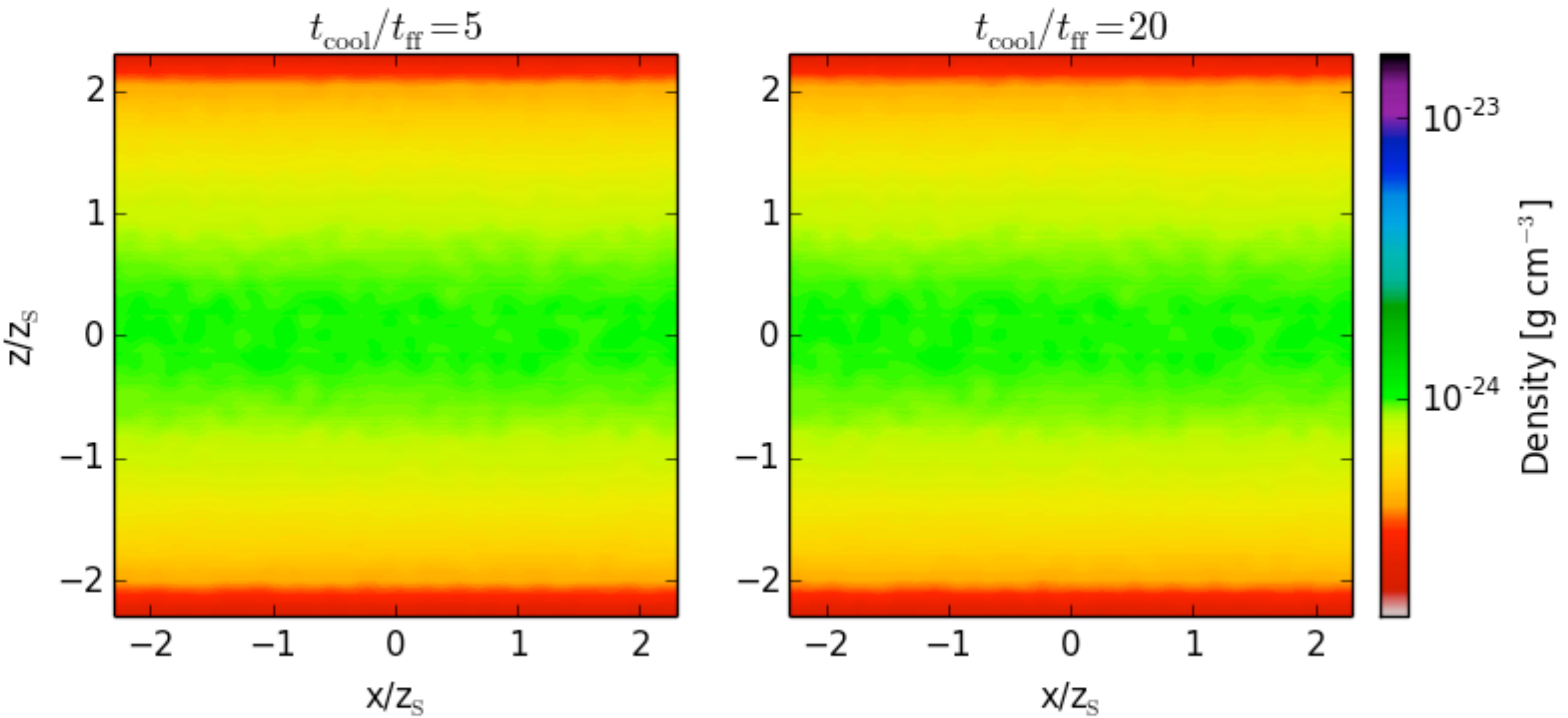


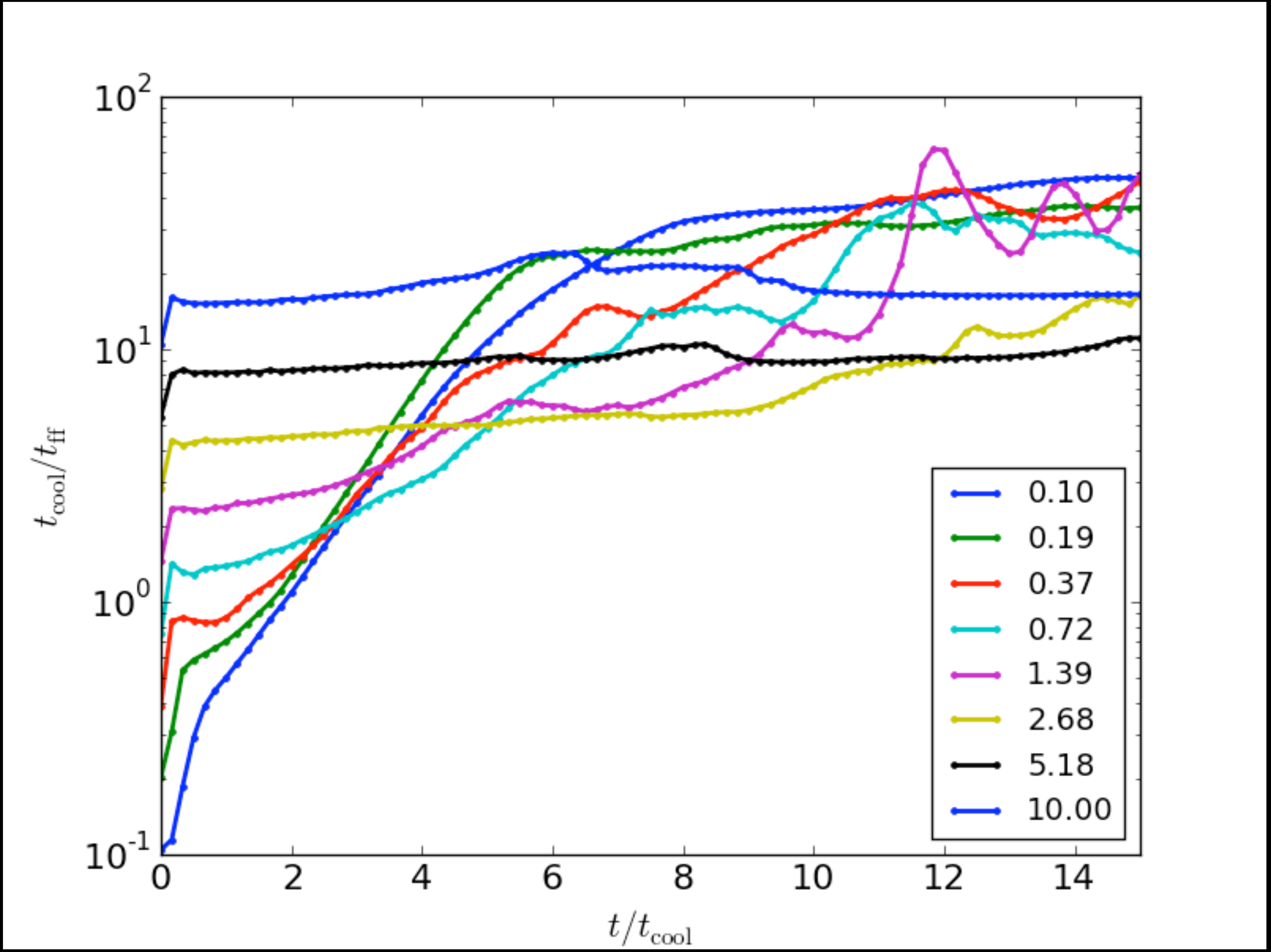
Colorbar: density

t_{cool}/t_{ff} = 1.17

t_{cool}/t_{ff} = 3.98

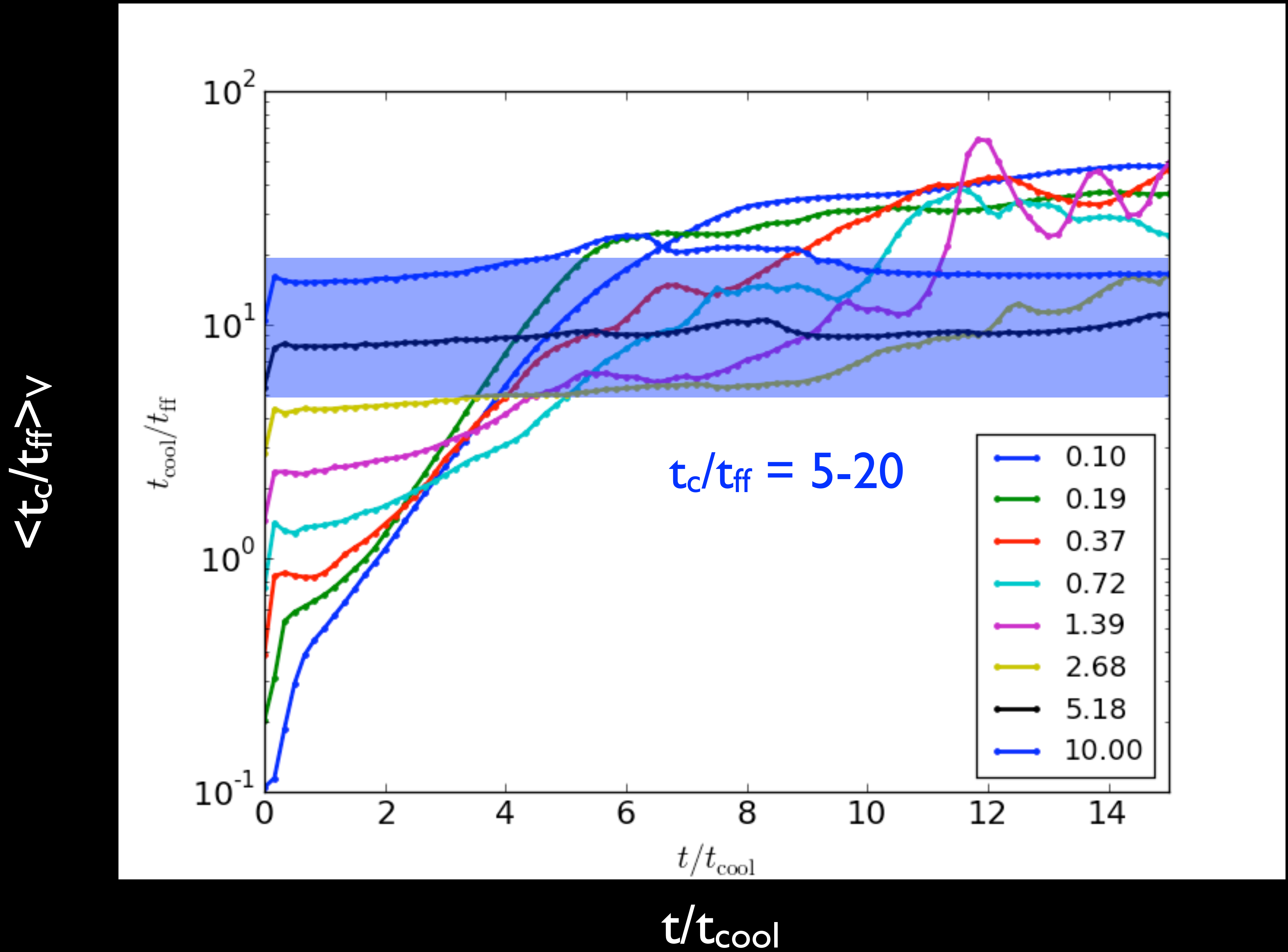
$t/t_{\mathrm{cool}} = 0.00$



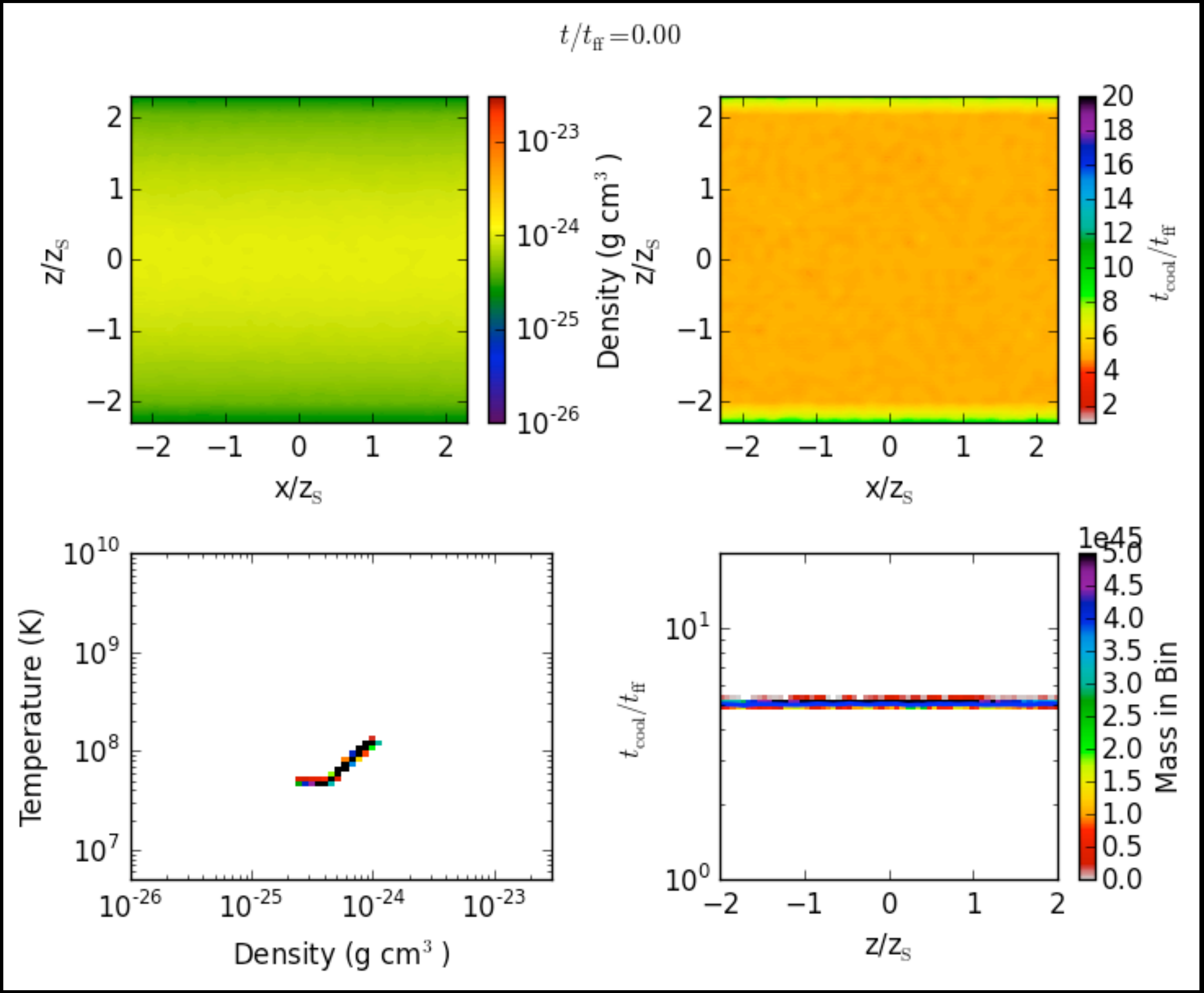


$<t_c/t_{ff}>_V$

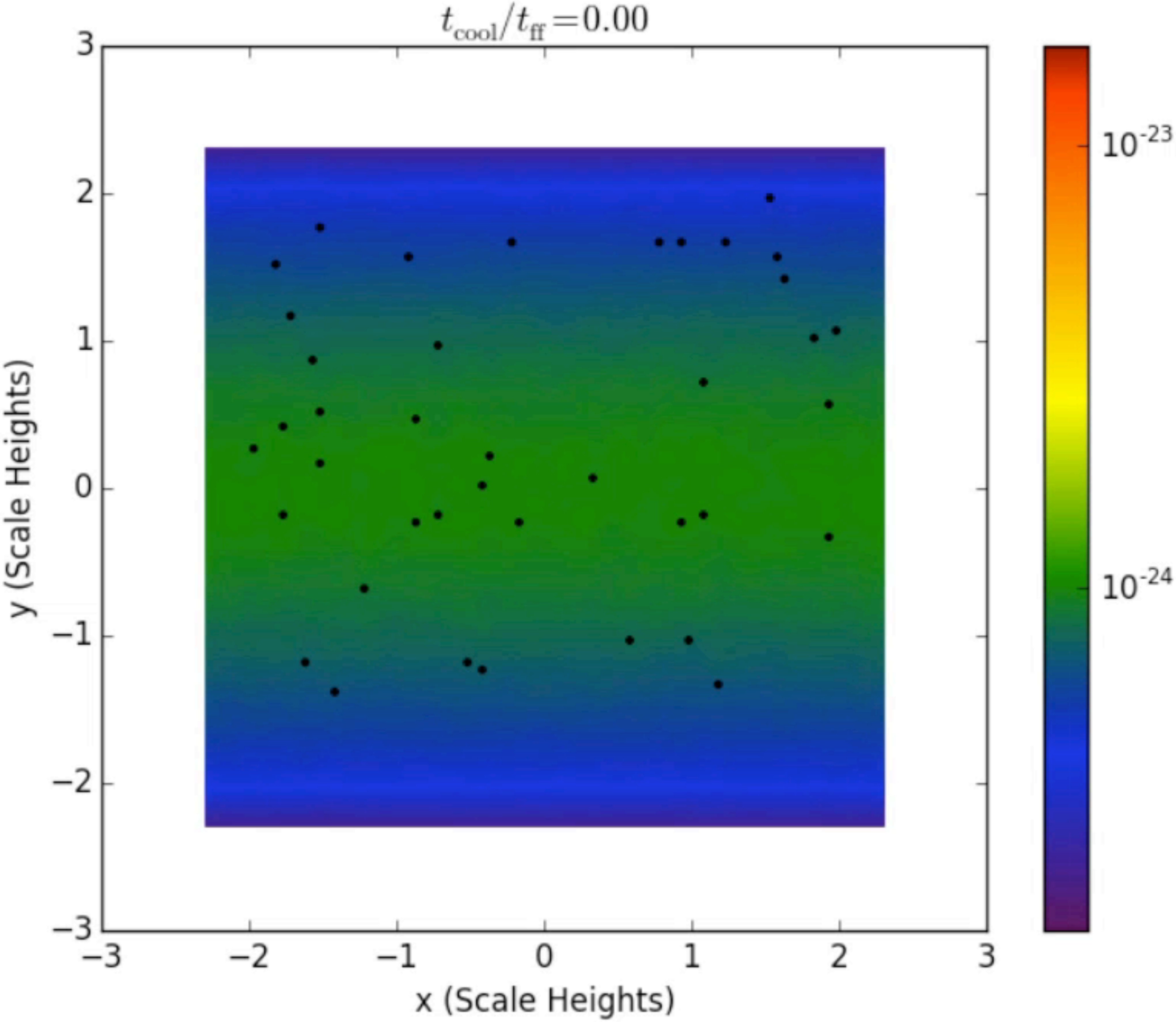
t/t_{cool}



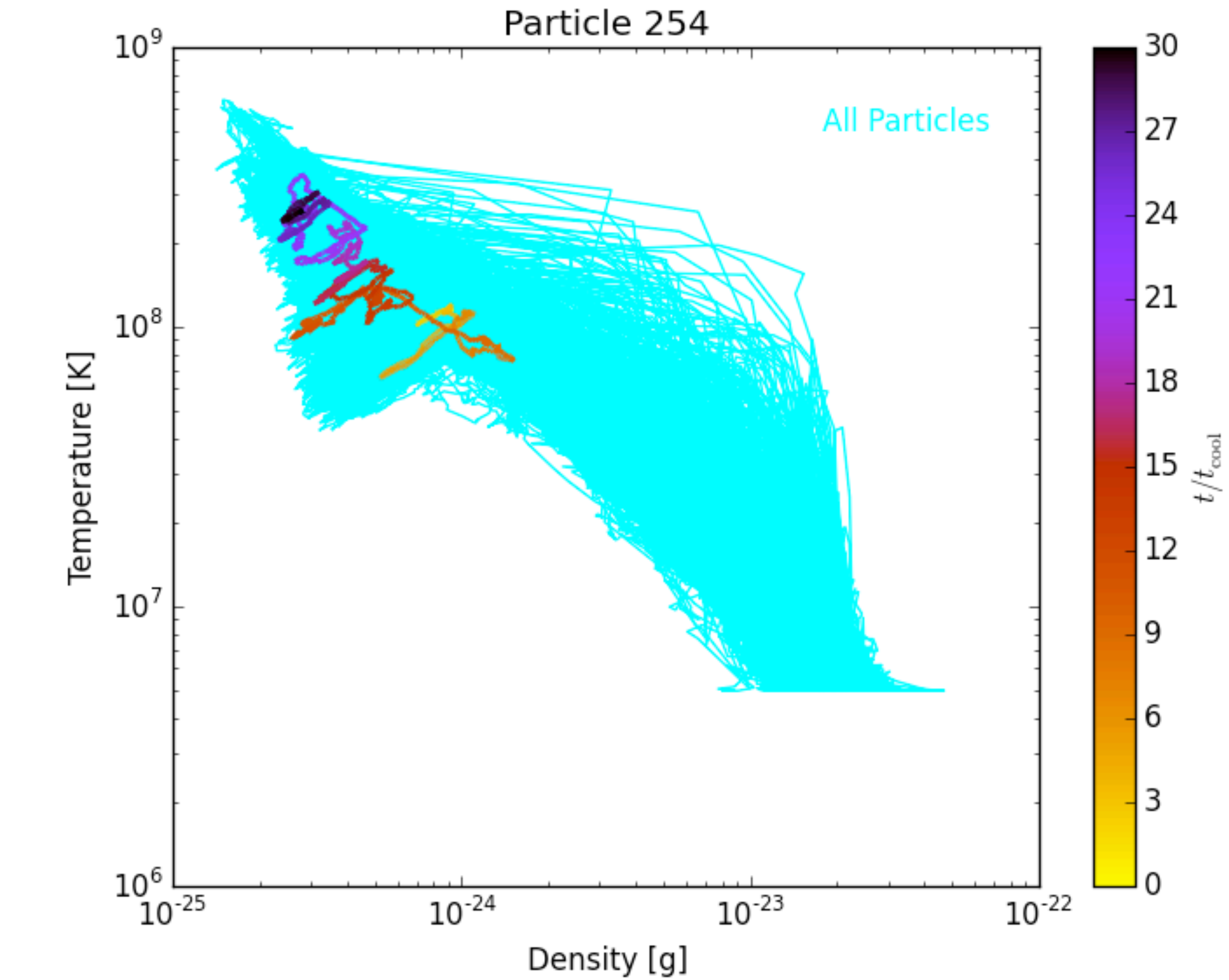
<tc/tff>v
t/tcool
$t_{\rm cool}/t_{\rm ff}$
$t/t_{\rm cool}$
tc/tff = 5-20
0.10
0.19
0.37
0.72
1.39
2.68
5.18
10.00



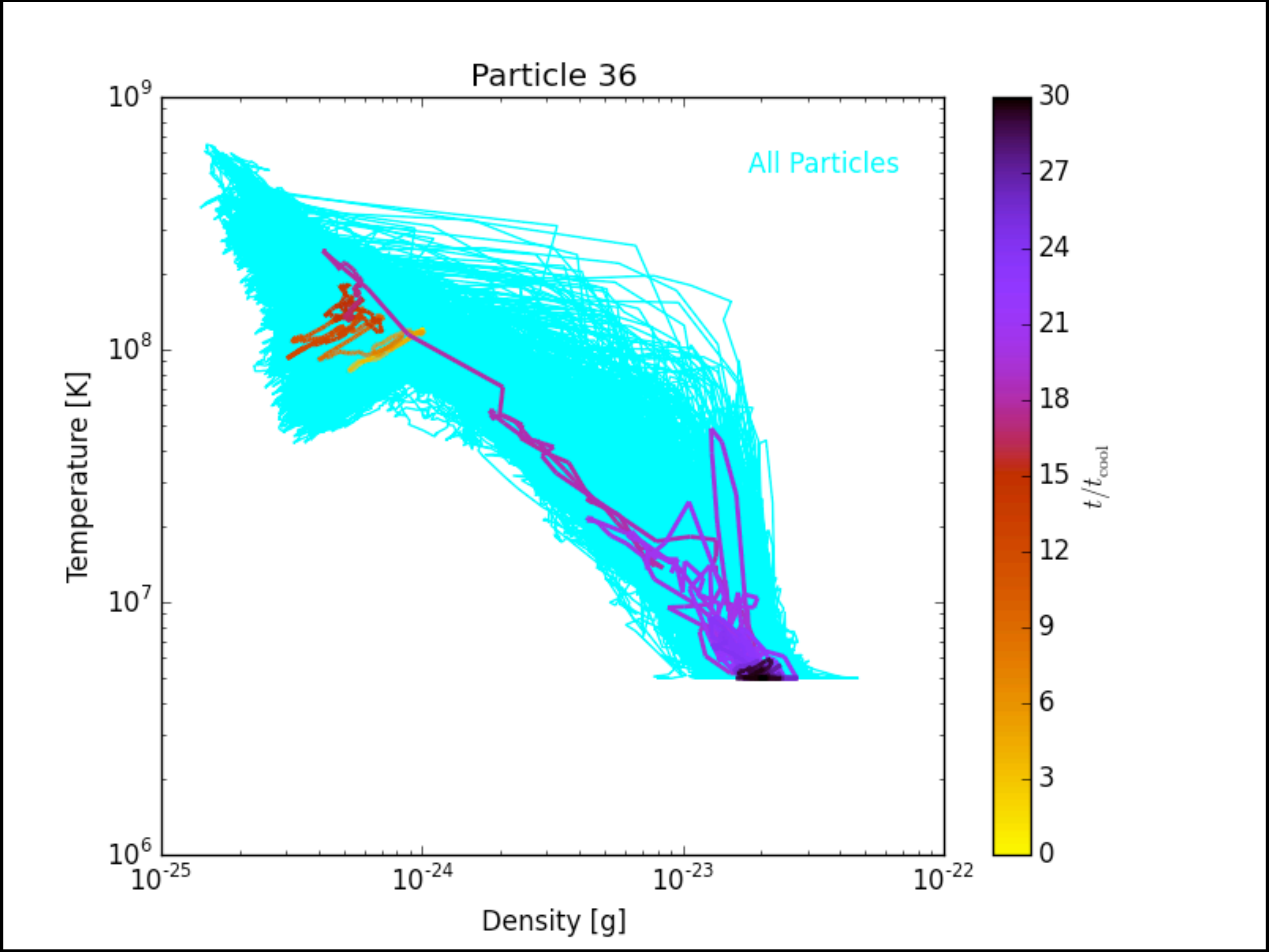
$t/t_{\rm ff} = 0.00$
z/z$_S$
x/z$_S$
Density (g cm^3)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$t_{\rm cool}/t_{\rm ff}$
Temperature (K)
Mass in Bin
1e45



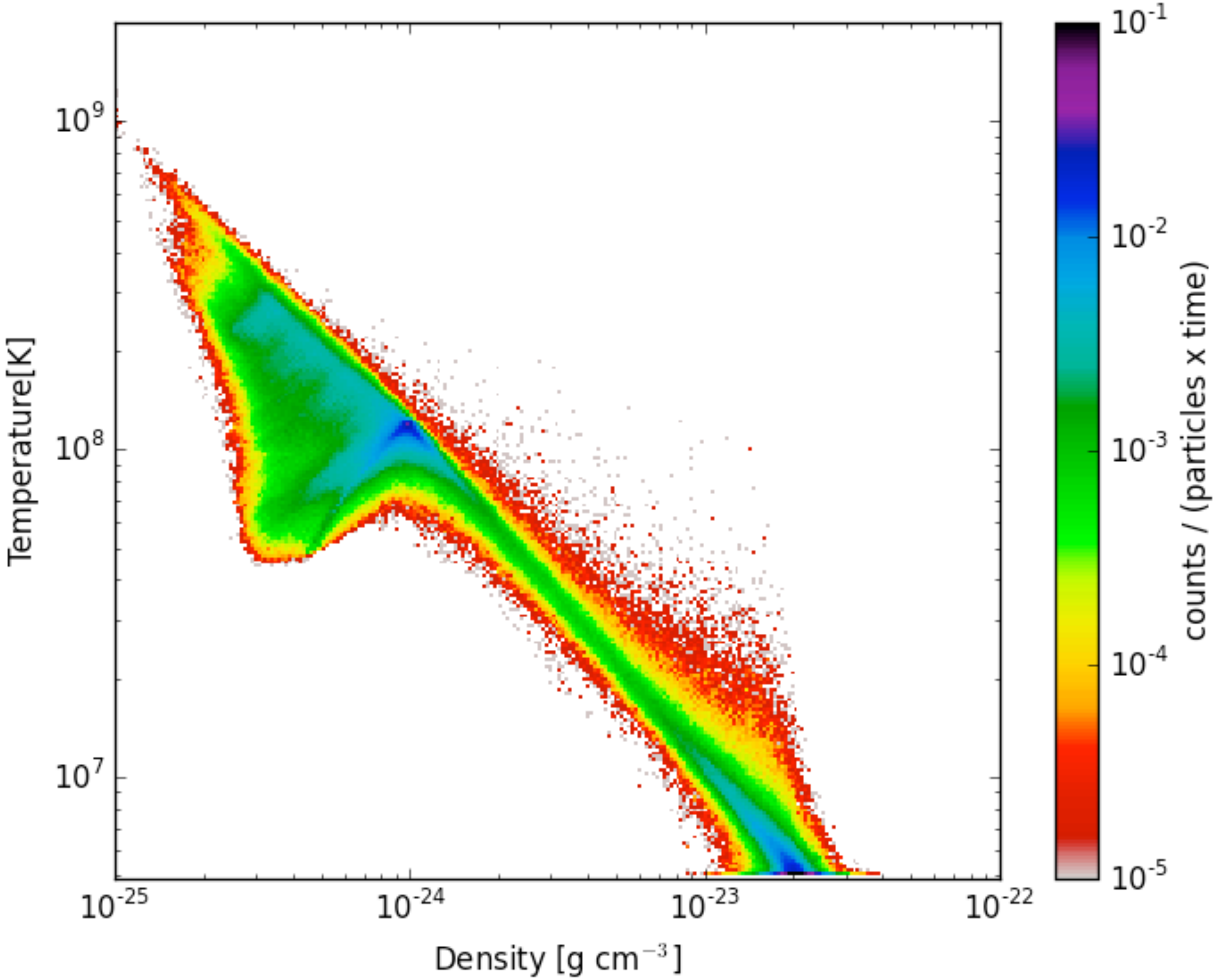
$t_{\rm cool}/t_{\rm ff} = 0.00$
y (Scale Heights)
x (Scale Heights)
3
2
1
0
−1
−2
−3
10^{-23}
10^{-24}



Particle 254
All Particles
Temperature [K]
Density [g]
10^{9}
10^{8}
10^{7}
10^{6}
10^{-25}
10^{-24}
10^{-23}
10^{-22}
$t/t_{\rm cool}$
30
27
24
21
18
15
12
9
6
3
0



Particle 36
All Particles
Temperature [K]
Density [g]
10^9
10^8
10^7
10^6
10^{-25}
10^{-24}
10^{-23}
10^{-22}
$t/t_{\rm cool}$
30
27
24
21
18
15
12
9
6
3
0



Temperature[K]
10^9
10^8
10^7
10^{-25}
10^{-24}
10^{-23}
10^{-22}
Density [g cm^{-3}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
counts / (particles x time)

Creation of a multiphase medium...

- can happen even in the presence of global thermal equilibrium in many circumstances
- depents primarily on the local ratio of cooling and free-fall times (t_{cool}/t_{ff} <~ 10)
- Less-stable situations trend to marginal stability (t_{cool}/t_{ff} ~ 10) very rapidly by ‘draining’ low-entropy gas.

Conclusions

- Cosmological structure formation naturally produces radio relics as a result of halo mergers
- MHD simulations of cluster evolution reproduce observable quantities well: spectral indices, polarization
- Conduction affects the intracluster medium, but not profoundly: very hard to observe differences!
- Gas that is in global thermal balance (heating = cooling) can still produce multiphase gas under the right conditions!

Thank you!