Simulations of Galaxy Cluster Radio Relics: Probes of Plasma Physics

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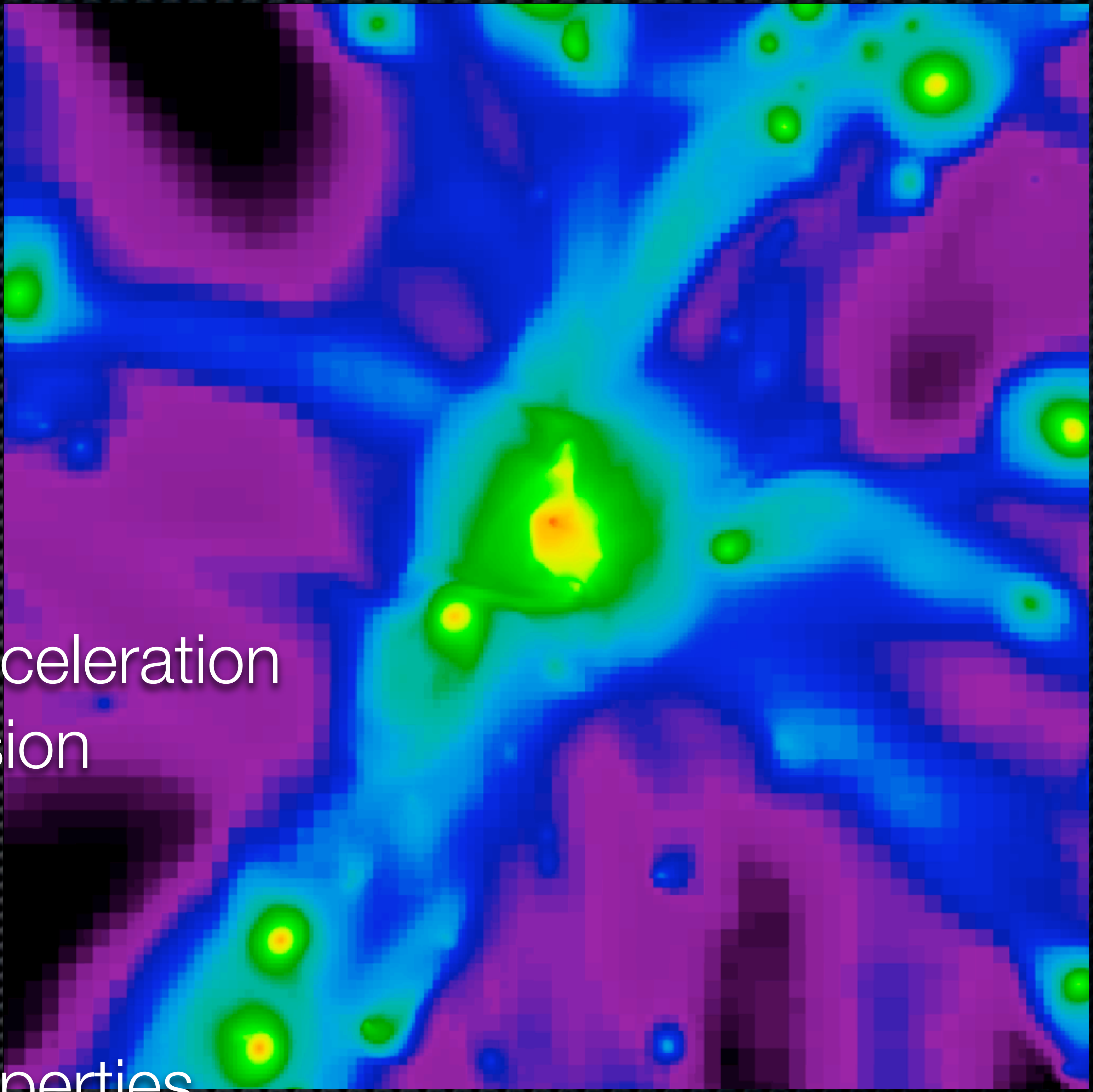
http://arxiv.org/abs/1006.3559

Outline



- Motivation
- Methods
  - Shock Finding
  - Diffusive Shock Acceleration
  - Synchrotron Emission
  - Simulations
- Results
  - Global Properties
  - Individual Halo Properties
- Ongoing Work
- Conclusions

Motivation

What is a radio relic?

- Diffuse radio emission
- Extended nature
- Exterior of cluster environment
- Moderately steep spectral shape
  - $S_\nu \propto \nu^{-\alpha} \quad \alpha \approx 1$
- Associated with disturbed galaxy clusters
- Not associated with any radio point sources or AGN

O … ics

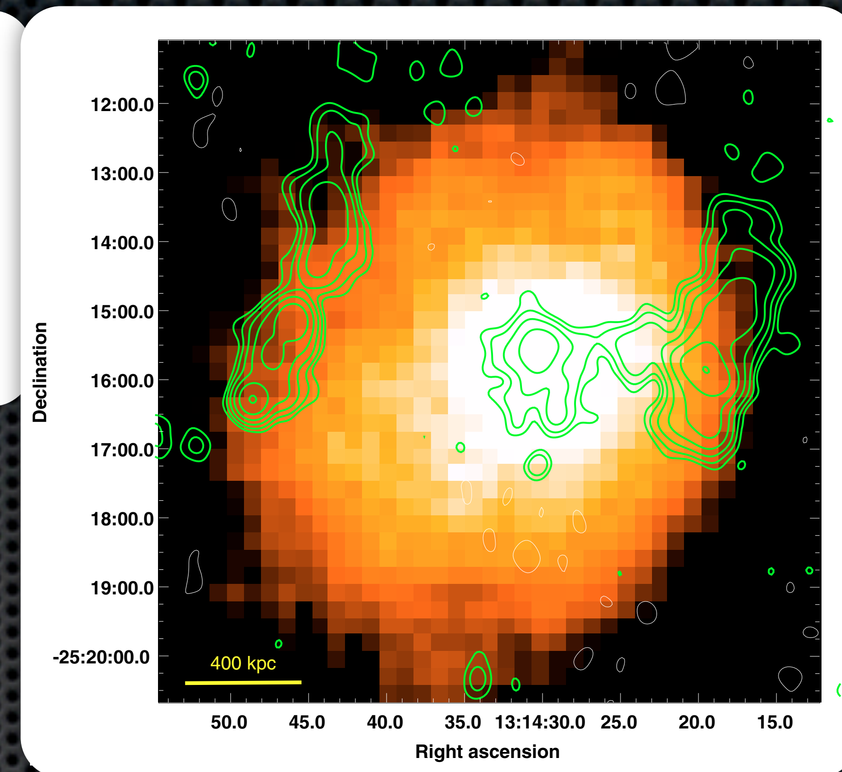
A&A 463, 937–947 (2007)
DOI: 10.1051/0004-6361:20065961

Astronomy & Astrophysics

GMRT radio halo survey in galaxy clusters at $z = 0.2$–0.4★

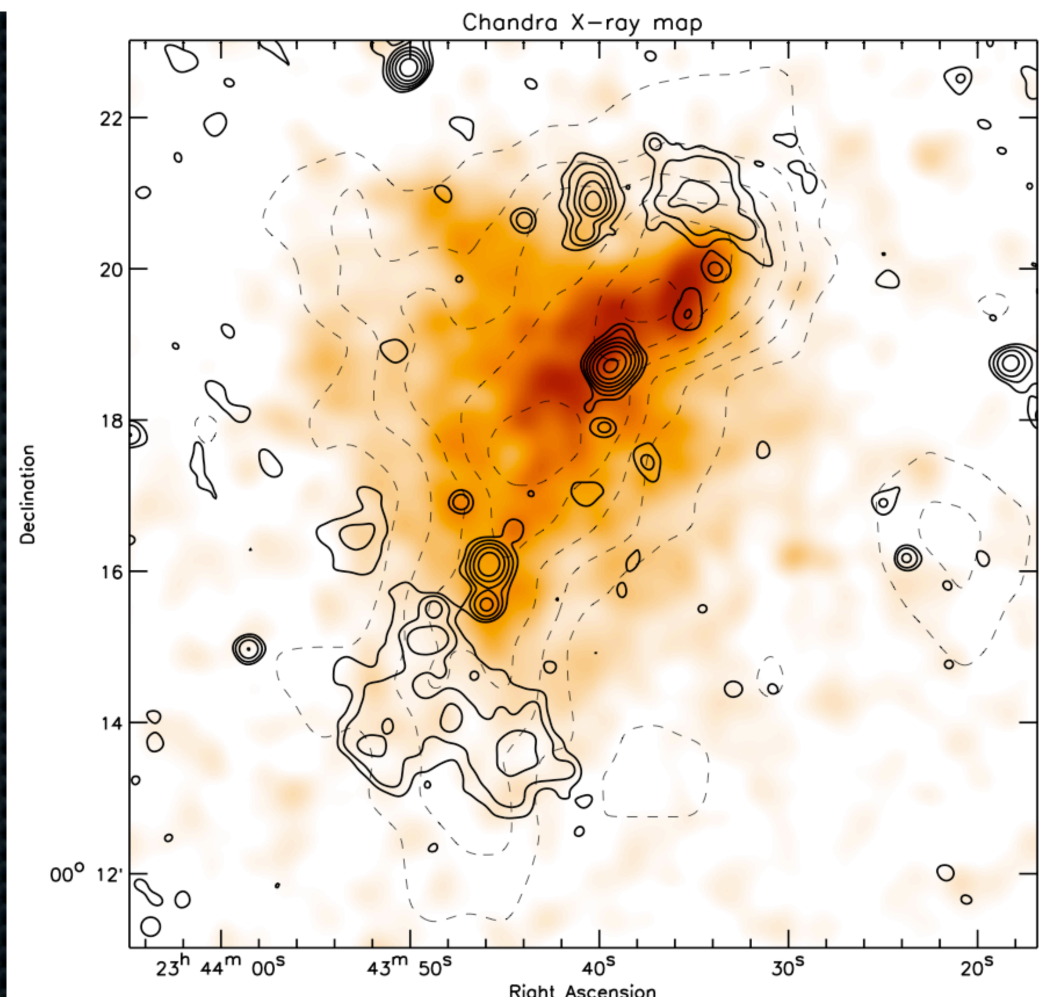
I. The REFLEX sub-sample

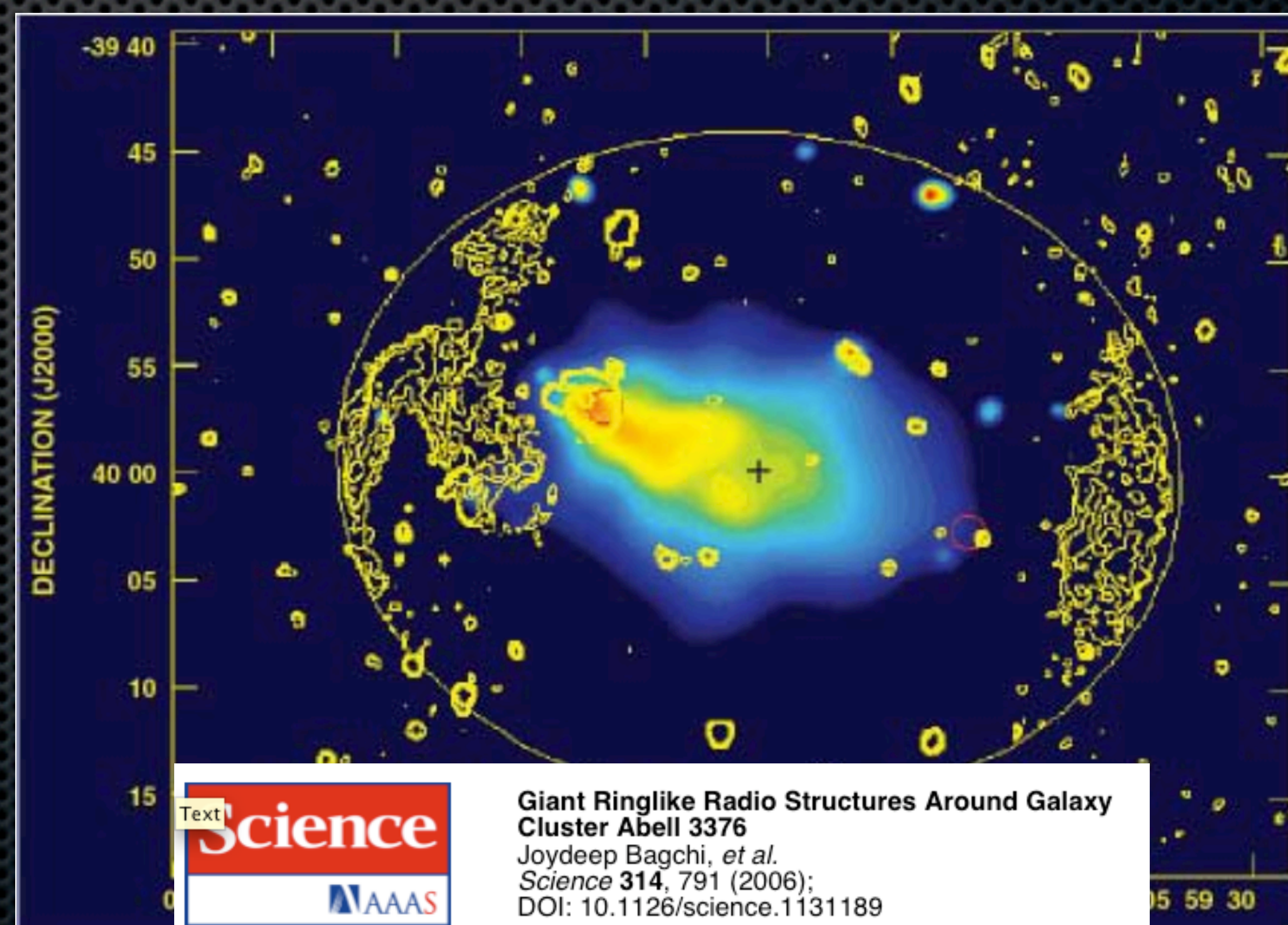
T. Venturi[1], S. Giacintucci[1,2,3], G. Brunetti[1], R. Cassano[1,3], S. Bardelli[2], D. Dallacasa[1,3], and G. Setti[1,3]



Radio observations of ZwCl 2341.1+0000: a double radio relic cluster

R. J. van Weeren[1], H. J. A. Röttgering[1], J. Bagchi[2], S. Raychaudhury[3], H. T. Intema[1], F. Miniati[4], T. A. Enßlin[5], M. Markevitch[6], and T. Erben[7]





THE ASTROPHYSICAL JOURNAL, 518:603–612, 1999 June 20

A CLUSTER MERGER AND THE ORIGIN OF THE EXTENDED RADIO EMISSION IN ABELL 3667

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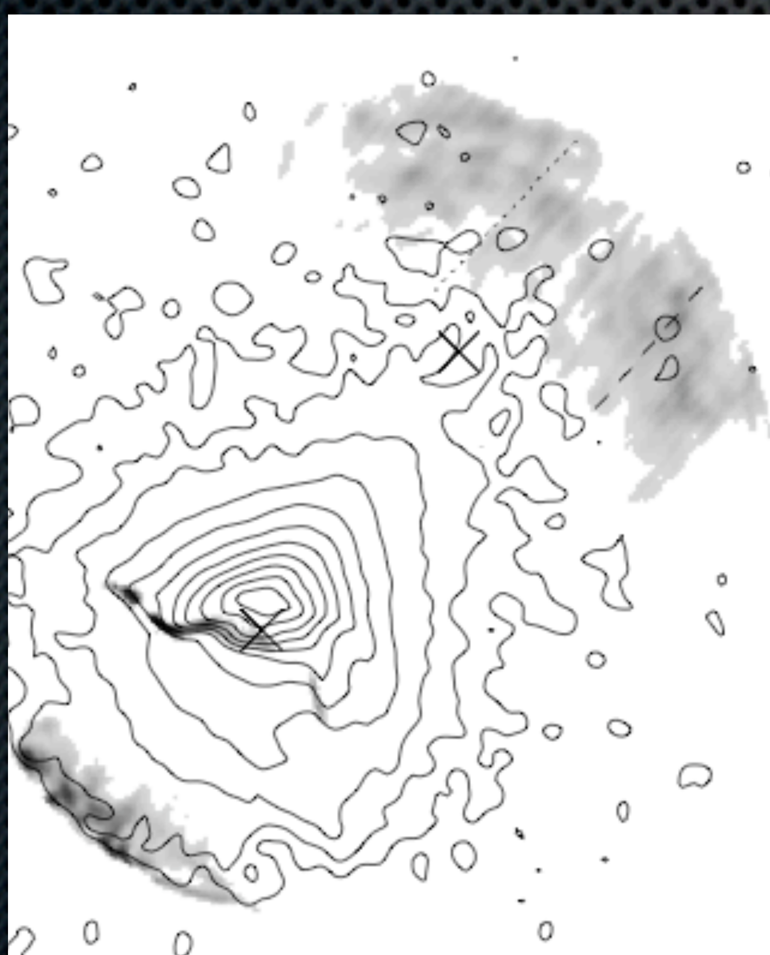
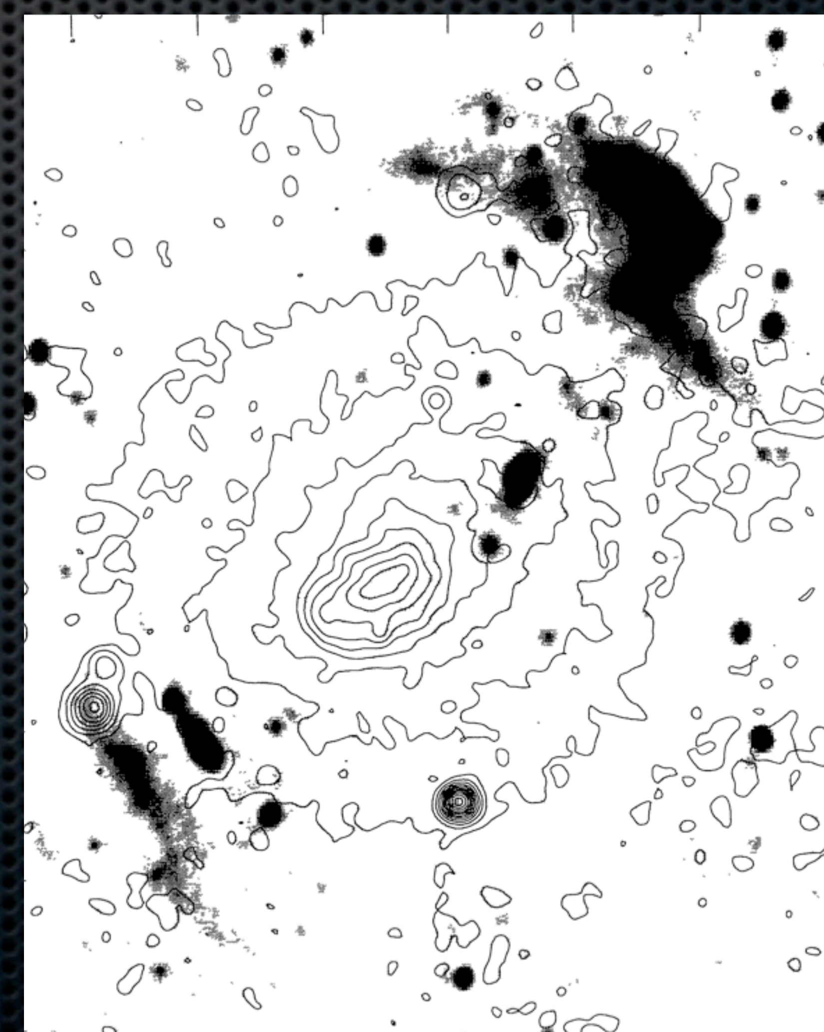


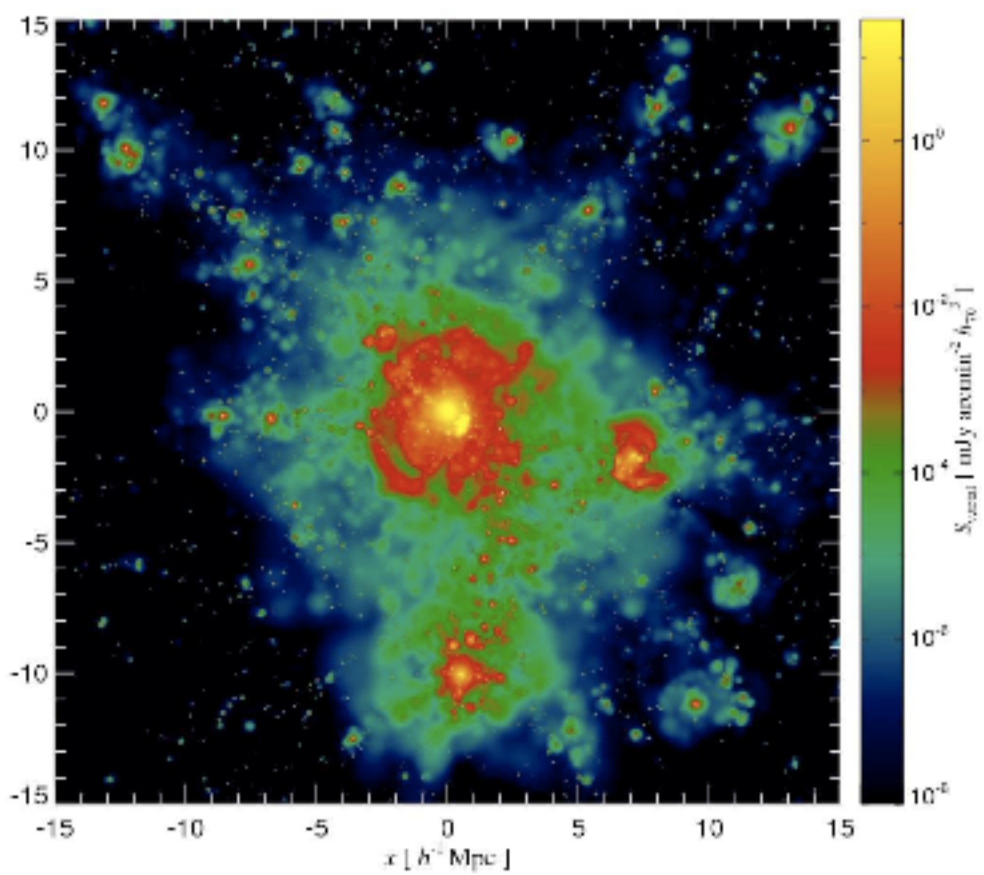
Abell 3667
???



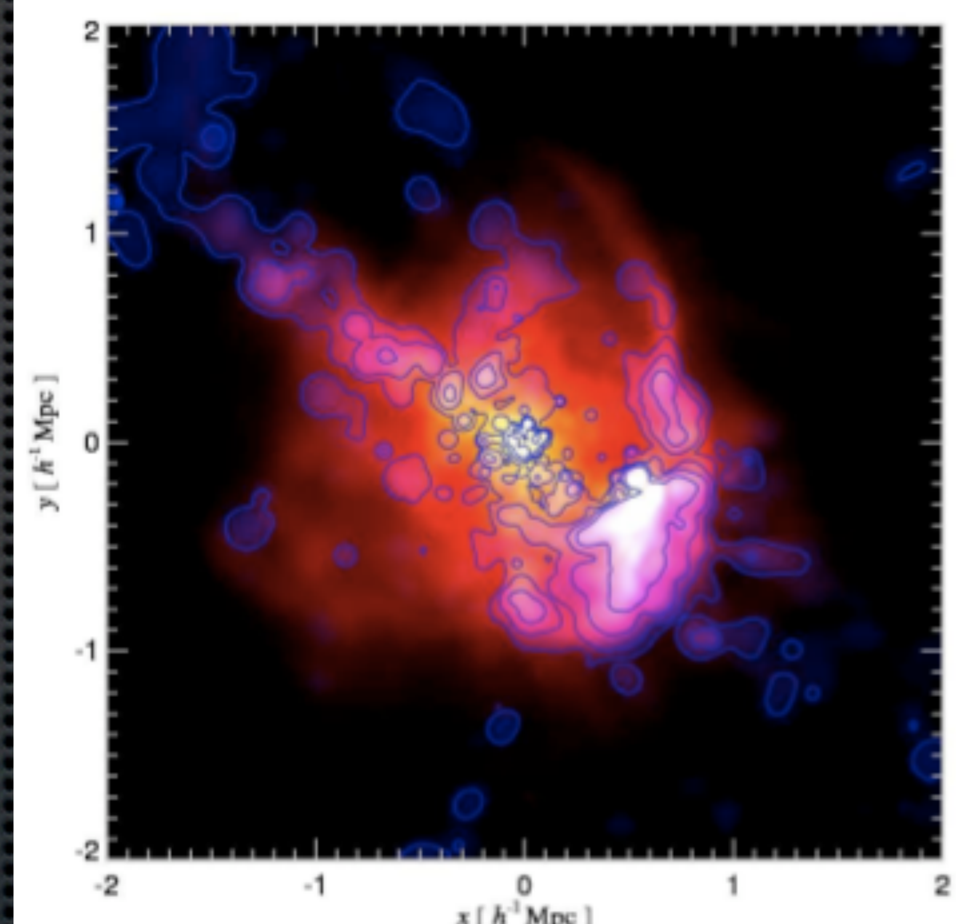
Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission

Christoph Pfrommer,[1]★ Torsten A. Enßlin,[2]★ Volker Springel[2]★
[1]*Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario, M5S 3H8, Canada*
[2]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, Postfach 1317, 85741 Garching, Germany*

Total radio synchrotron emission, 150 MHz:



Radio Gischt at shocks



Exploring the magnetized cosmic web through low frequency radio emission

N. Battaglia[1,2]★, C. Pfrommer[2], J. L. Sievers[2], J. R. Bond[2], T. A. Enßlin[3]
[1]*Department of Astronomy and Astrophysics, University of Toronto, 50 St. George st., Toronto ON, M5S 3H4,*
[2]*Canadian Institute for Theoretical Astrophysics, 60 St. George st., Toronto ON, M5S 3H8*
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Mon. Not. R. Astron. Soc. **391,** 1511–1526 (2008) doi:10.1111/j.1365-2966.2008.13955.x

Diffuse radio emission from clusters in the MareNostrum Universe simulation

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[1] *Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany*
[2] *Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany*
[3] *Grupo de Astrofísica, Universidad Autónoma de Madrid, Cantoblanco, 28039 Madrid, Spain*
[4] *Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*

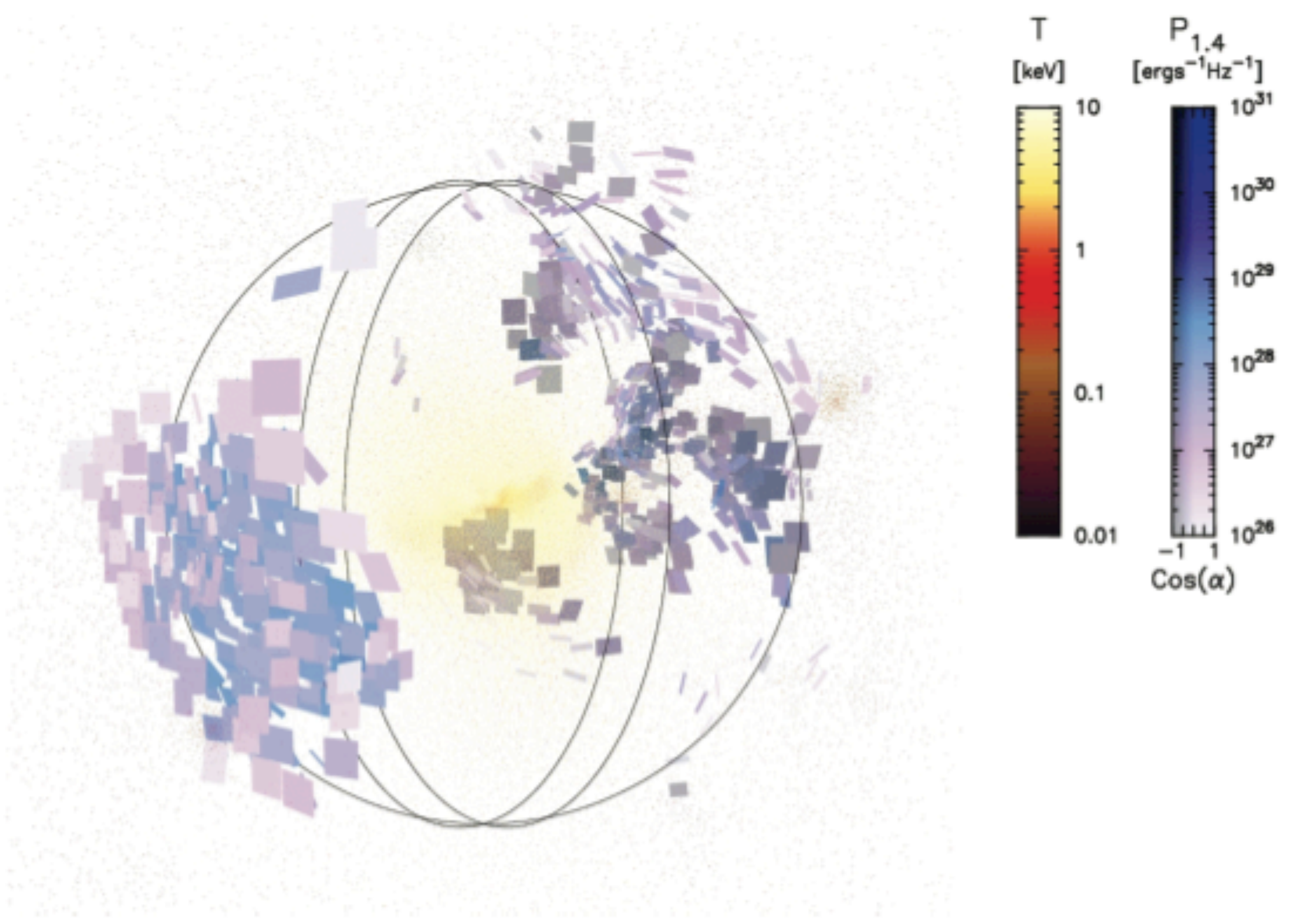
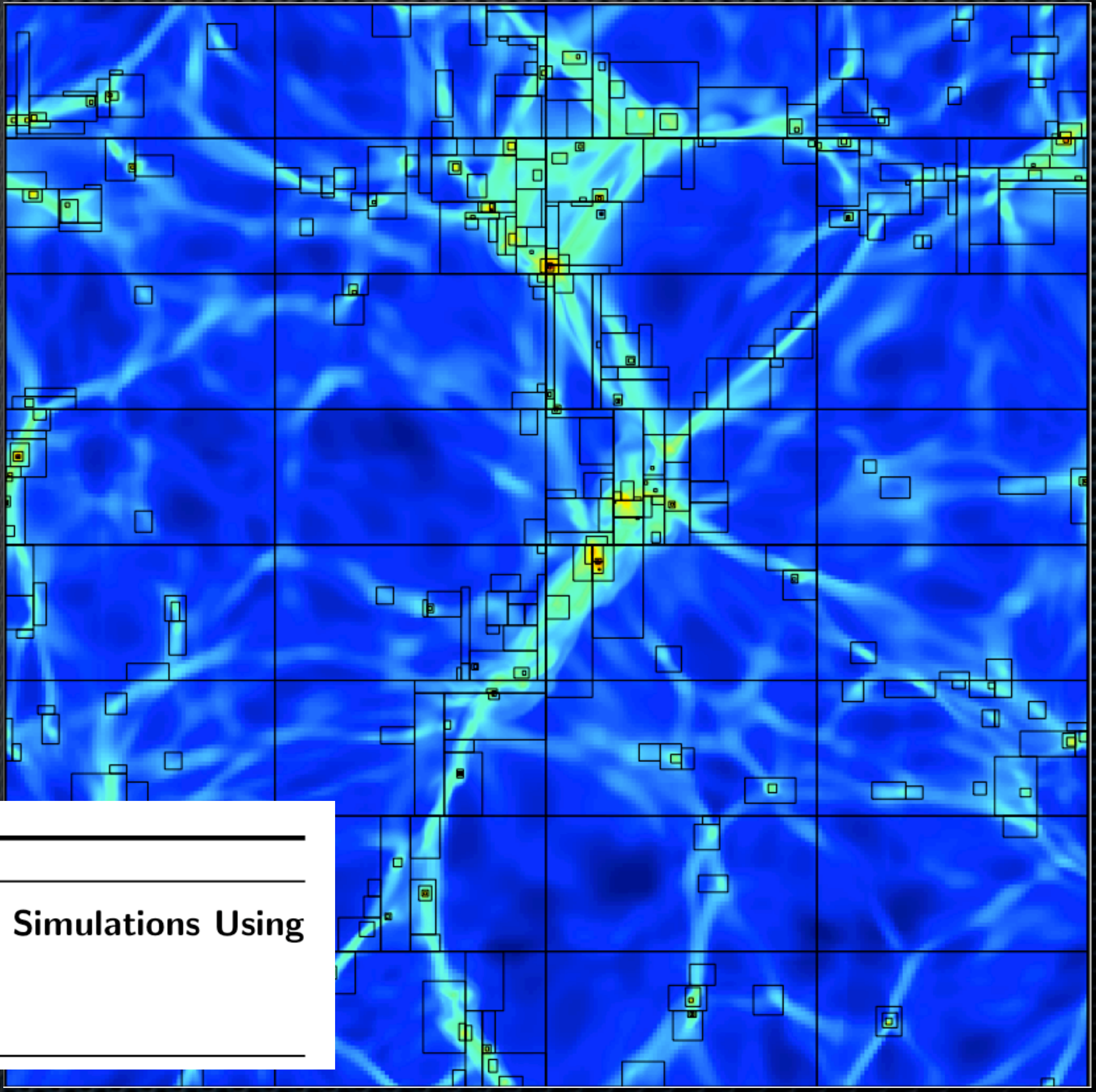


Figure 5. A textbook example of a double relic found in the MareNostrum Universe simulation.

Methods

enzo

- Adaptive Mesh Refinement (AMR) Hydrodynamics
- Dark Matter N-Body -- Particle-Mesh Method
- Piecewise Parabolic Method (PPM) & Zeus Finite Difference



yt
amr data analysis

SciPy08 conference proceedings

Analysis and Visualization of Multi-Scale Astrophysical Simulations Using Python and NumPy

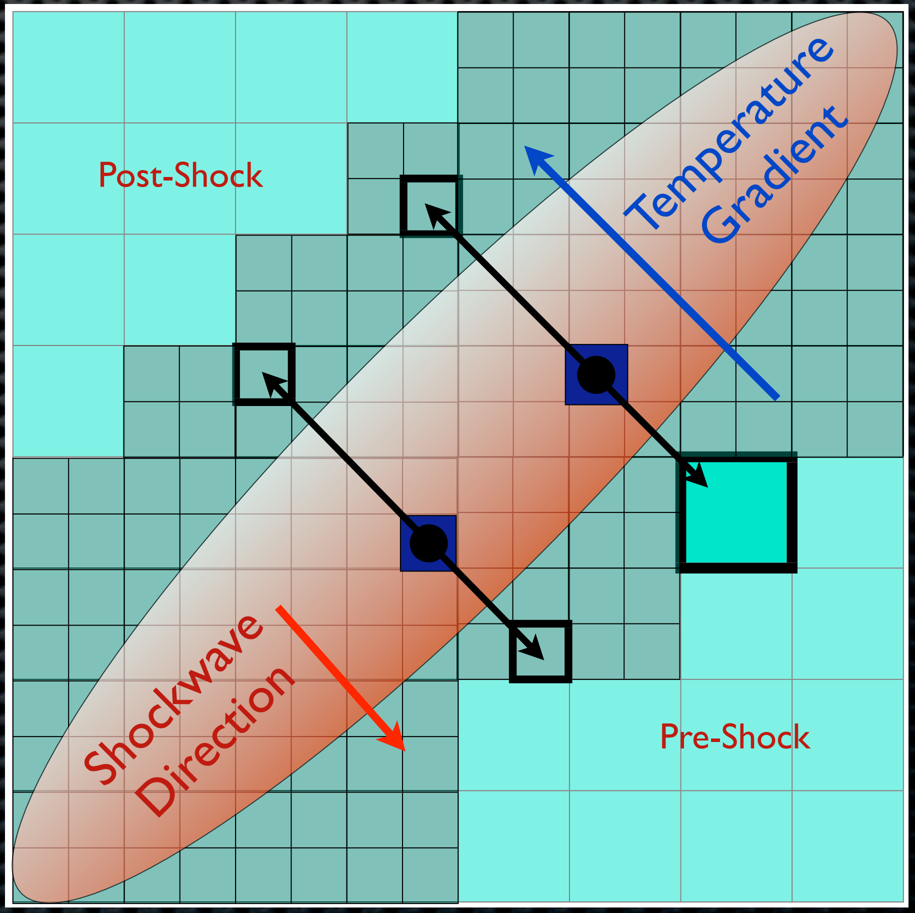
Matthew Turk (mturk@slac.stanford.edu) – *KIPAC / SLAC / Stanford*, USA

Shock Finding & Characterizing

$$\nabla \cdot \vec{v} < 0$$
$$\nabla T \cdot \nabla S > 0$$
$$T_2 > T_1$$
$$\rho_2 > \rho_1,$$

$$\frac{T_2}{T_1} = \frac{(5\mathcal{M}^2 - 1)(\mathcal{M}^2 + 3)}{16\mathcal{M}^2},$$

- Converging Gas
- Entropy increases across shockwave
- Rankine-Hugoniot Jump Conditions
- Set minimum temperature to 10^4K



Cosmic Rays: Diffusive Shock Acceleration

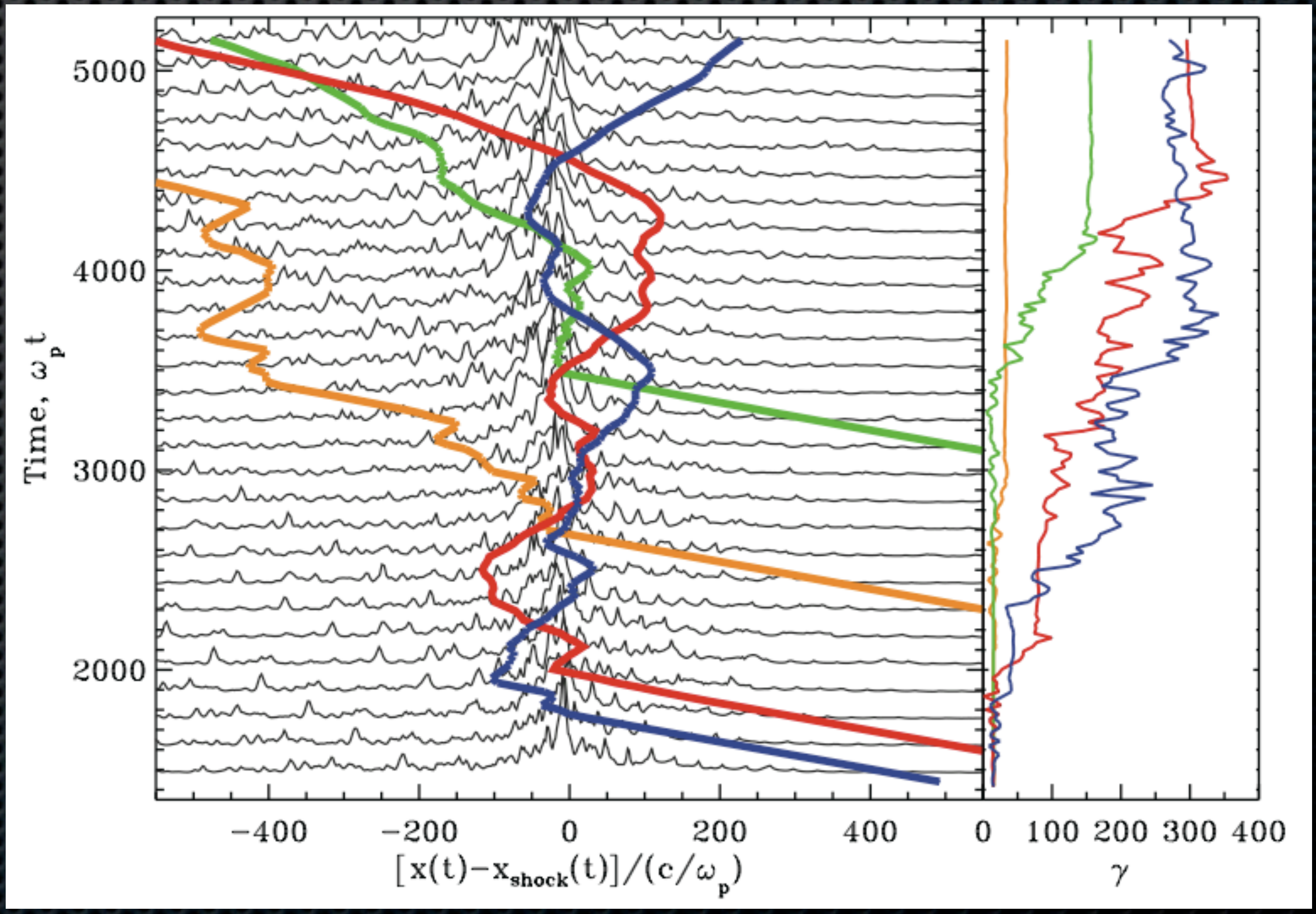
- First-order Fermi acceleration at shock fronts
- Kinetic Energy of the shock ⟶ Cosmic Rays
- What efficiency does this have?

$$N(E) \propto E^{-\delta}$$

$$\delta = 2\frac{\mathcal{M}^2 + 1}{\mathcal{M}^2 - 1} + 1$$

$$\alpha = (\delta - 1)/2$$

Anatoly Spitkovsky (2008)



Synchrotron Emission

Mon. Not. R. Astron. Soc. **375,** 77–91 (2007) doi:10.1111/j.1365-2966.2006.11111.x

Radio signature of cosmological structure formation shocks

Matthias Hoeft★ and Marcus Brüggen★
International University Bremen, Campus Ring 1, 28759 Bremen, Germany

$$n_E(E) \equiv \frac{\mathrm{d}n_\mathrm{e}}{\mathrm{d}E} = \begin{cases} n_\mathrm{e}\, C_\mathrm{spec}\, \frac{1}{m_\mathrm{e}c^2}\, \tilde{e}^{-s} \left(1 - \frac{\tilde{e}}{\tilde{e}_\mathrm{max}}\right)^{s-2} & : \quad \tilde{e} < \tilde{e}_\mathrm{max} \\ 0 & : \quad \text{elsewhere} \end{cases},$$

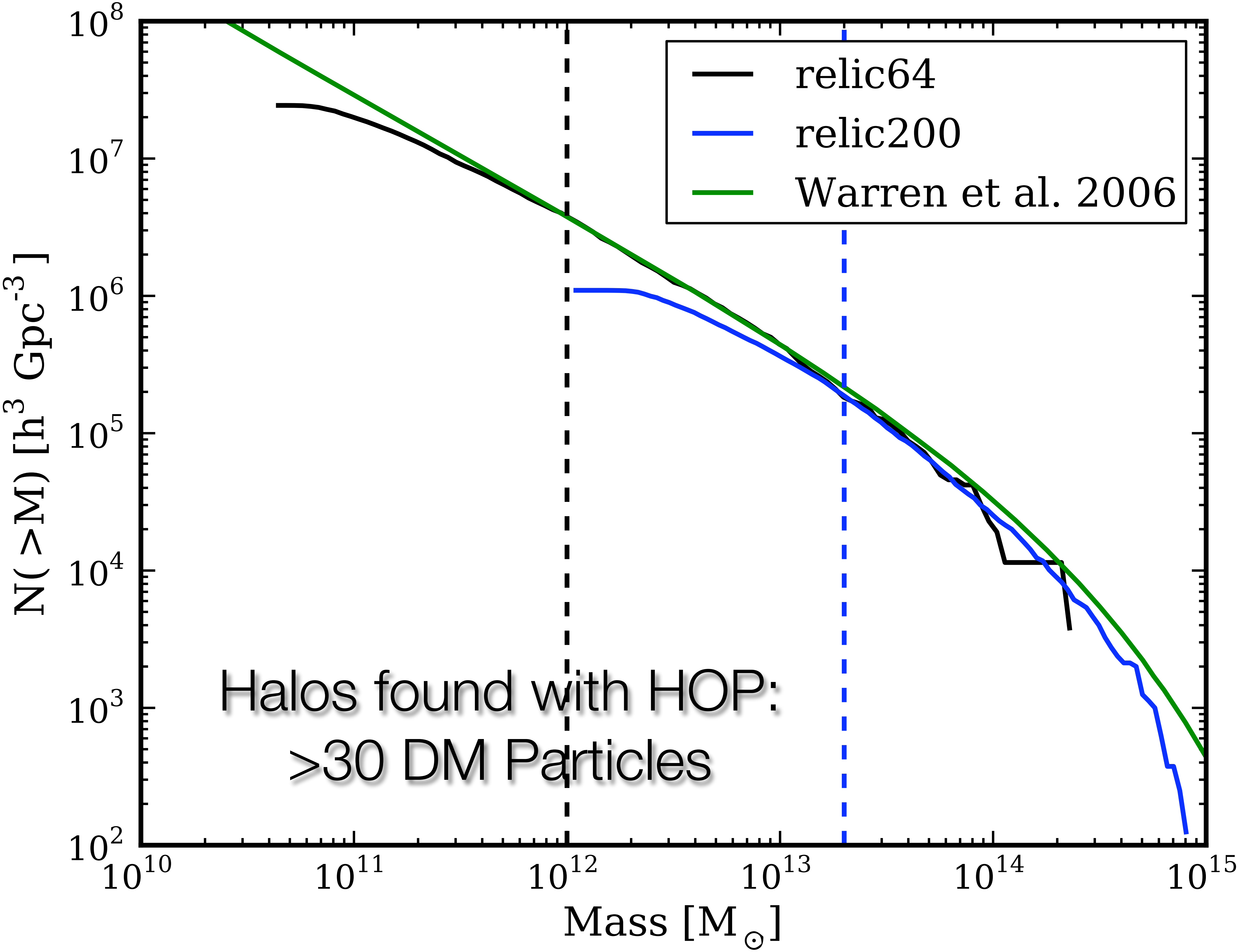
$$r = \rho_2/\rho_1$$

$$s = \frac{r+2}{r-1}$$

$$\begin{aligned} \frac{\mathrm{d}P(\nu_\mathrm{obs})}{\mathrm{d}\nu} &= A\, n_\mathrm{e}\, C^p_\mathrm{spec}\, C_\mathrm{sync} \left(\frac{B}{\mu\mathrm{G}}\right)^{s/2} \left(\frac{1.4\,\mathrm{GHz}}{\nu_\mathrm{obs}}\right)^{s/2} \frac{\sqrt{u_\mathrm{d}}}{C_\mathrm{cool}} \frac{1}{C_\Psi}\, \Psi(\mathcal{M}) \\ &= 6.4 \times 10^{34}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}\, \frac{A}{\mathrm{Mpc}^2} \frac{n_\mathrm{e}}{10^{-4}\,\mathrm{cm}^{-3}} \frac{\xi_\mathrm{e}}{0.05} \left(\frac{\nu_\mathrm{obs}}{1.4\,\mathrm{GHz}}\right)^{-s/2} \\ &\times \left(\frac{T_\mathrm{d}}{7\,\mathrm{keV}}\right)^{3/2} \frac{(B/\mu\mathrm{G})^{1+(s/2)}}{(B_\mathrm{CMB}/\mu\mathrm{G})^2 + (B/\mu\mathrm{G})^2}\, \Psi(\mathcal{M}) \end{aligned}$$

The Simulations

- *relic64*
  - $(64\ \mathrm{Mpc}/h)^3$ Volume
  - 256^3 Root Grid
  - Up to 6 levels of refinement
  - 3.9 kpc/h Peak Resolution
  - DM Mass $1.96 \times 10^9 h^{-1} M_\odot$
  - ~300,000 cpu hours on 256 cpus
- *relic200*
  - $(200\ \mathrm{Mpc}/h)^3$ Volume
  - 256^3 Root Grid
  - Up to 5 levels of refinement
  - 24.4 kpc/h Peak Resolution
  - DM Mass $6.23 \times 10^{10} h^{-1} M_\odot$
  - ~100,000 cpu hours on 128 cpus

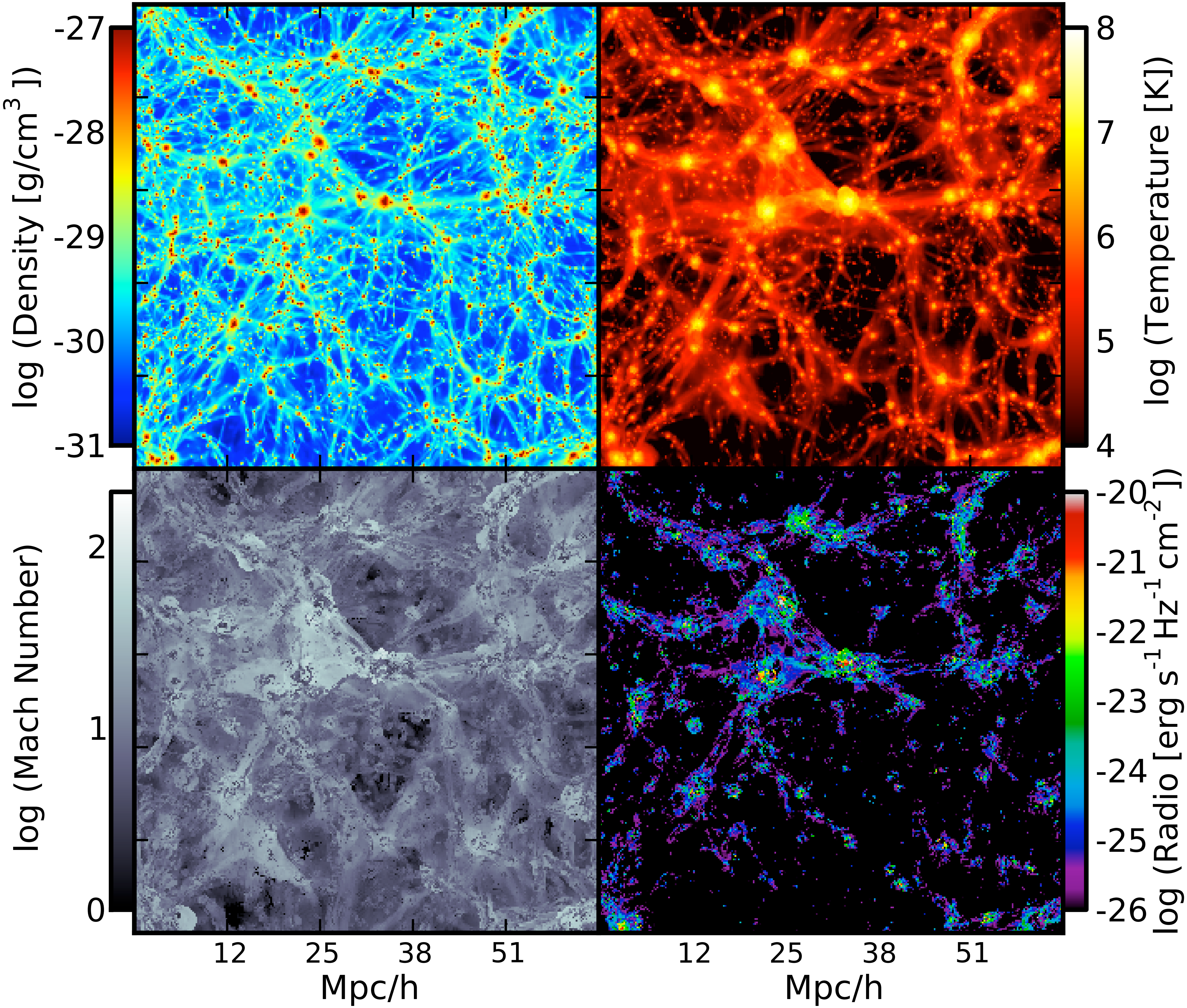


relic64
relic200
Warren et al. 2006
Halos found with HOP:
>30 DM Particles
N(>M) [h^3 Gpc^{-3}]
Mass [M$_\odot$]
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}

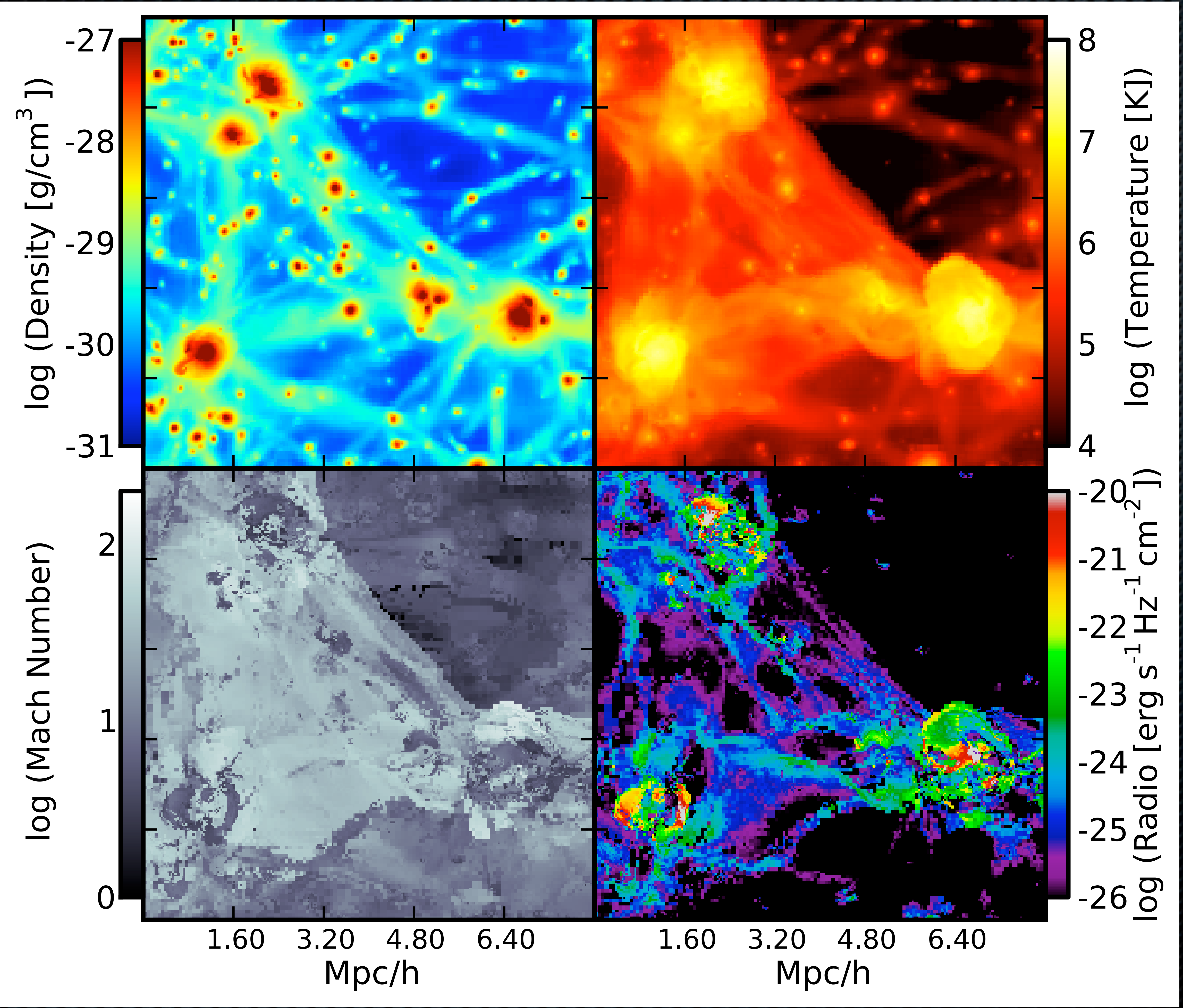
Global Properties of Radio Emission

Full Box Projections

$$P_z(x, y) = \frac{\int w(x, y, z) v(x, y, z) dz}{\int w(x, y, z) dz}$$

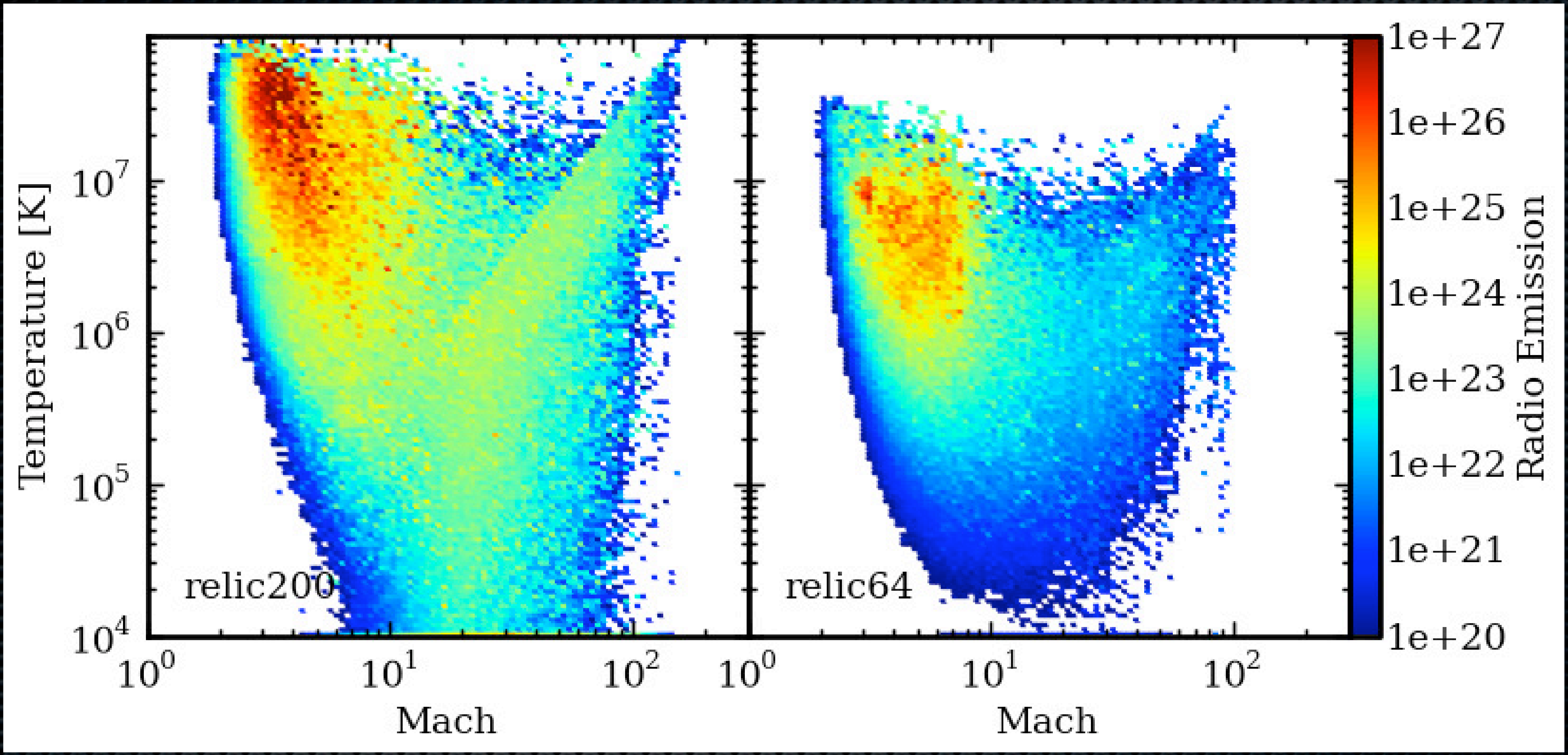


-27
-28
-29
-30
-31
log (Density [g/cm3])
8
7
6
5
4
log (Temperature [K])
2
1
0
log (Mach Number)
-20
-21
-22
-23
-24
-25
-26
log (Radio [erg s-1 Hz-1 cm-2])
12
25
38
51
Mpc/h
12
25
38
51
Mpc/h



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
1.60
3.20
4.80
6.40
Mpc/h
1.60
3.20
4.80
6.40
Mpc/h

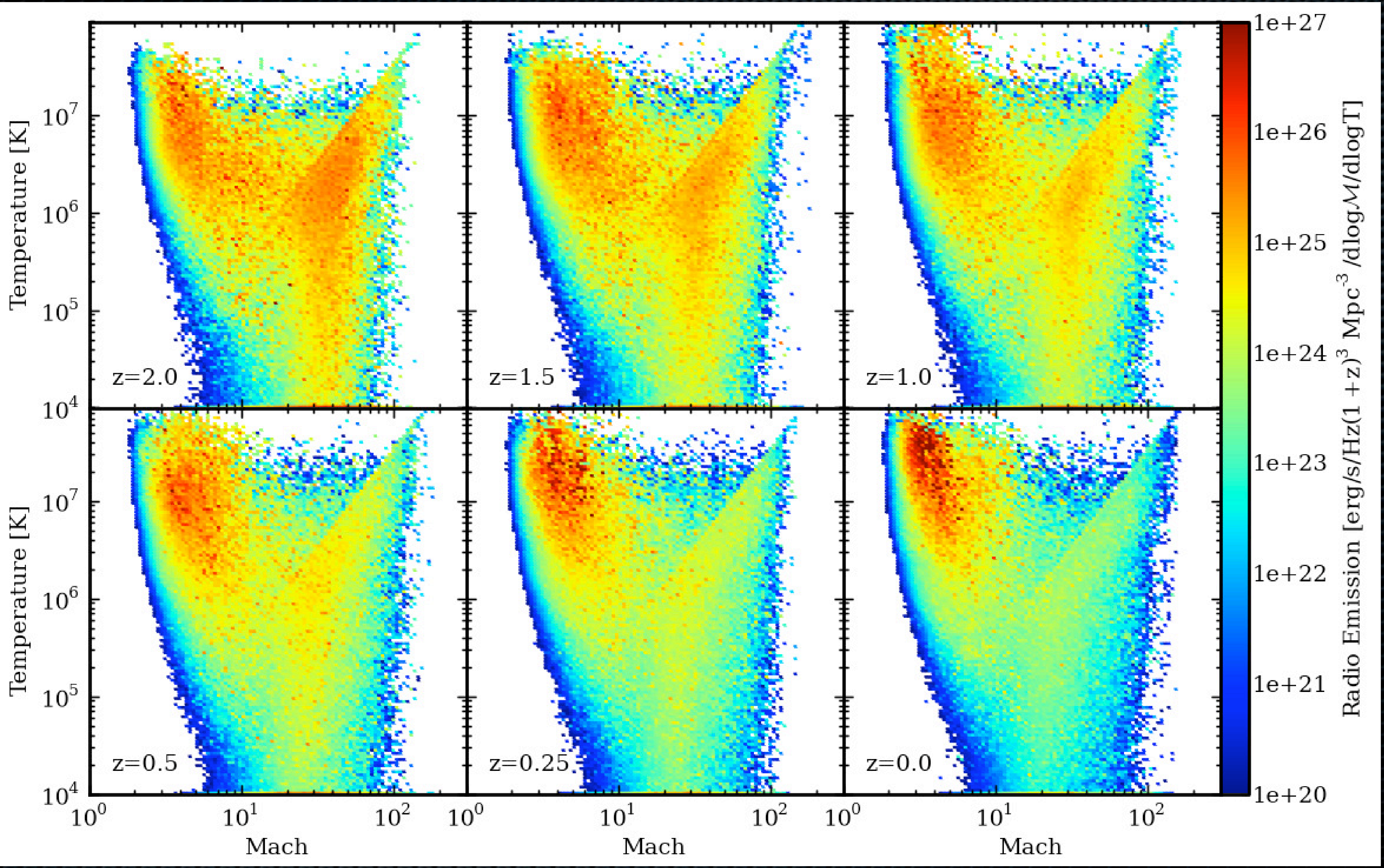
Phase Diagrams



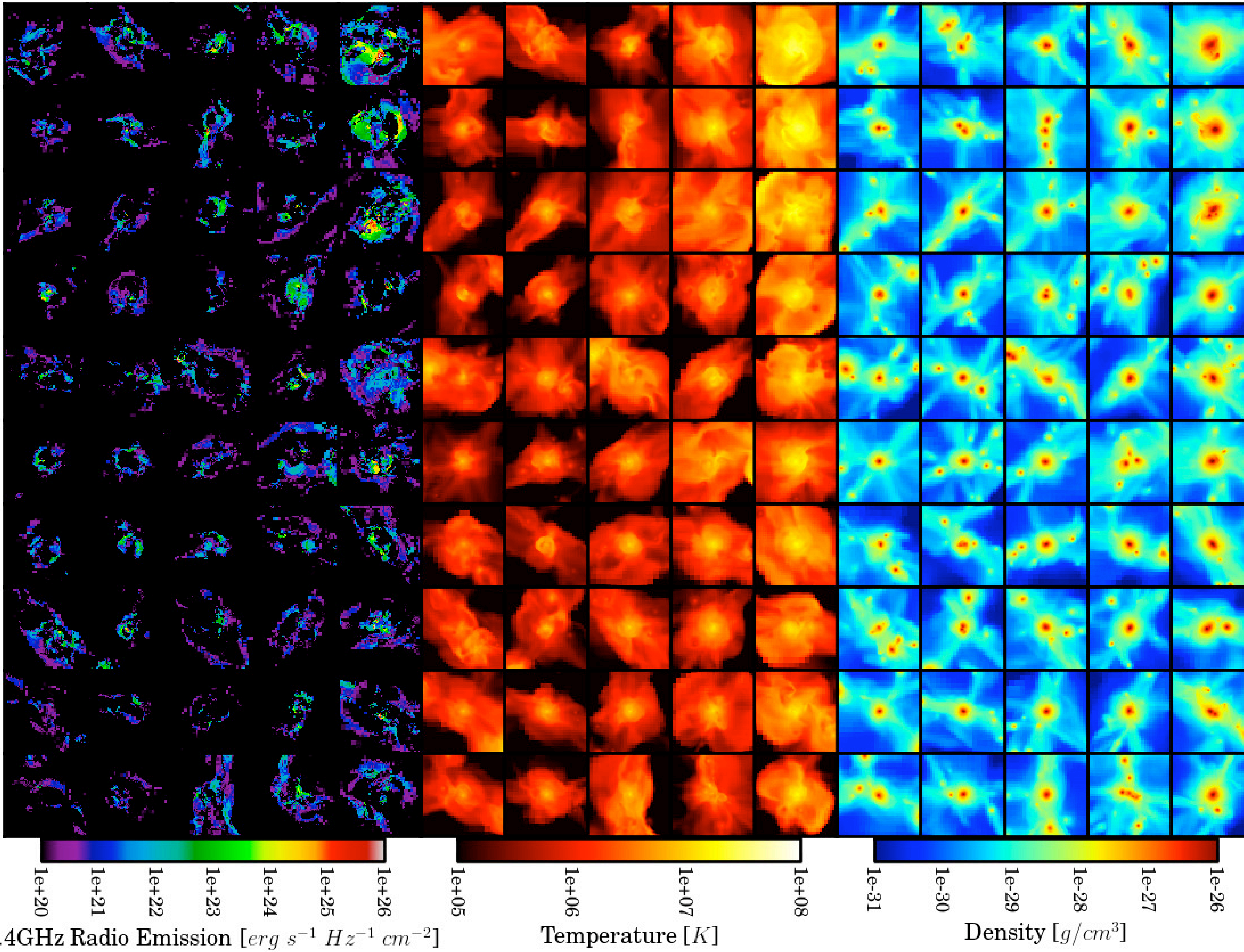
Temperature - Mach

==> Merger Shocks Dominate

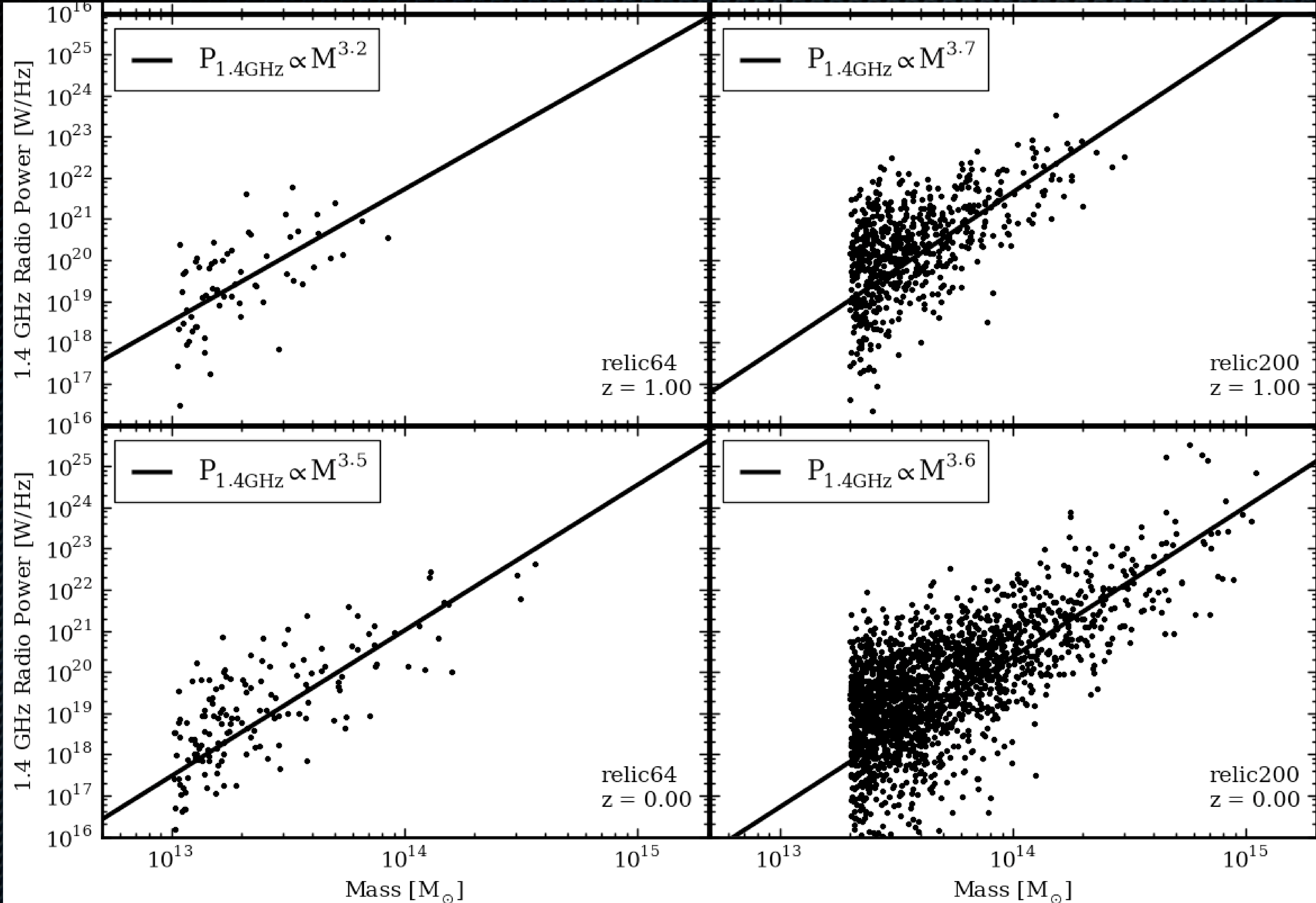
==> Clear Accretion Shock Signature


Temperature [K]
Mach
z=2.0
z=1.5
z=1.0
z=0.5
z=0.25
z=0.0
Radio Emission [erg/s/Hz(1 +z)^3 Mpc^-3 /dlogM/dlogT]
1e+27
1e+26
1e+25
1e+24
1e+23
1e+22
1e+21
1e+20

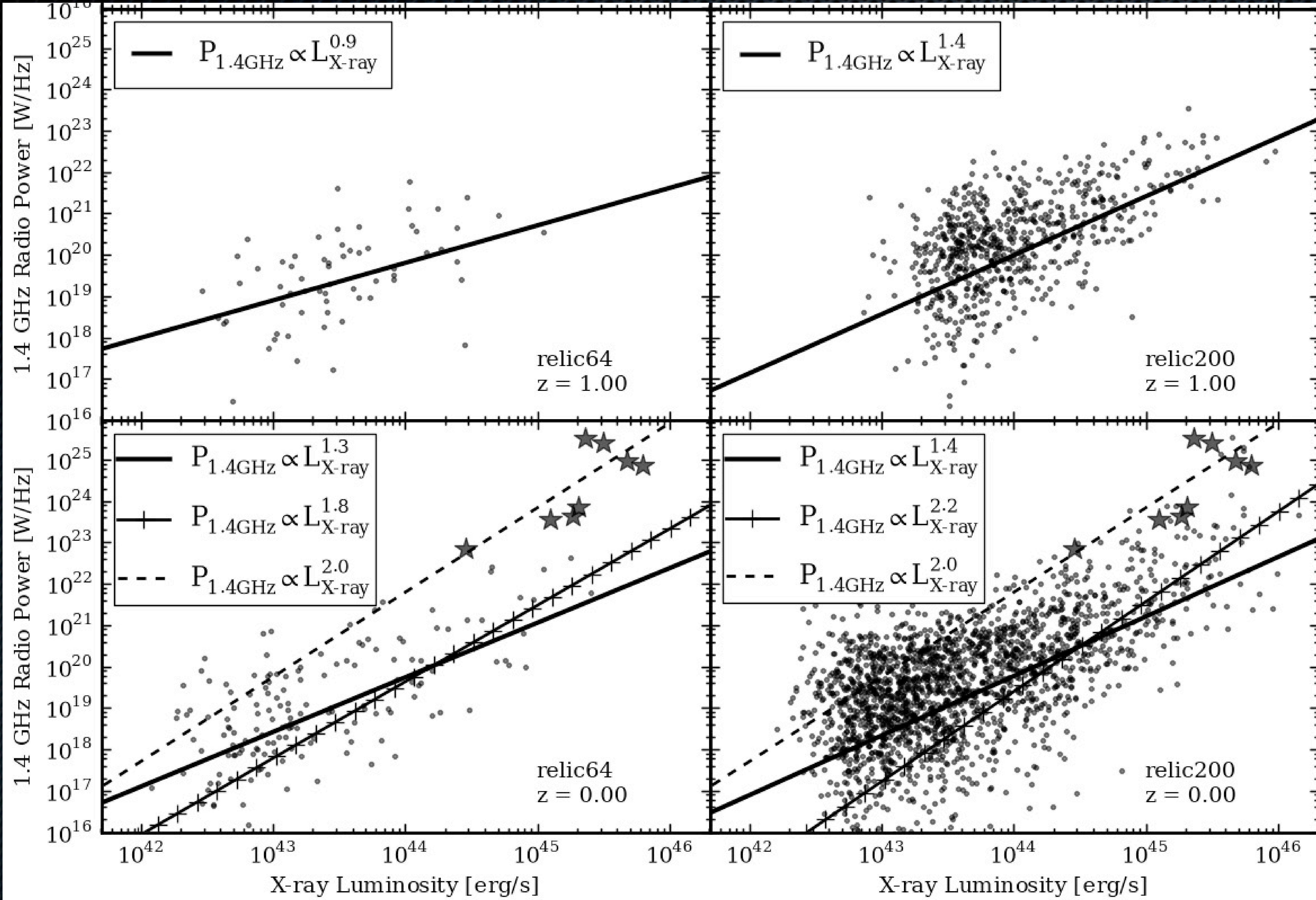
Individual Halo Properties



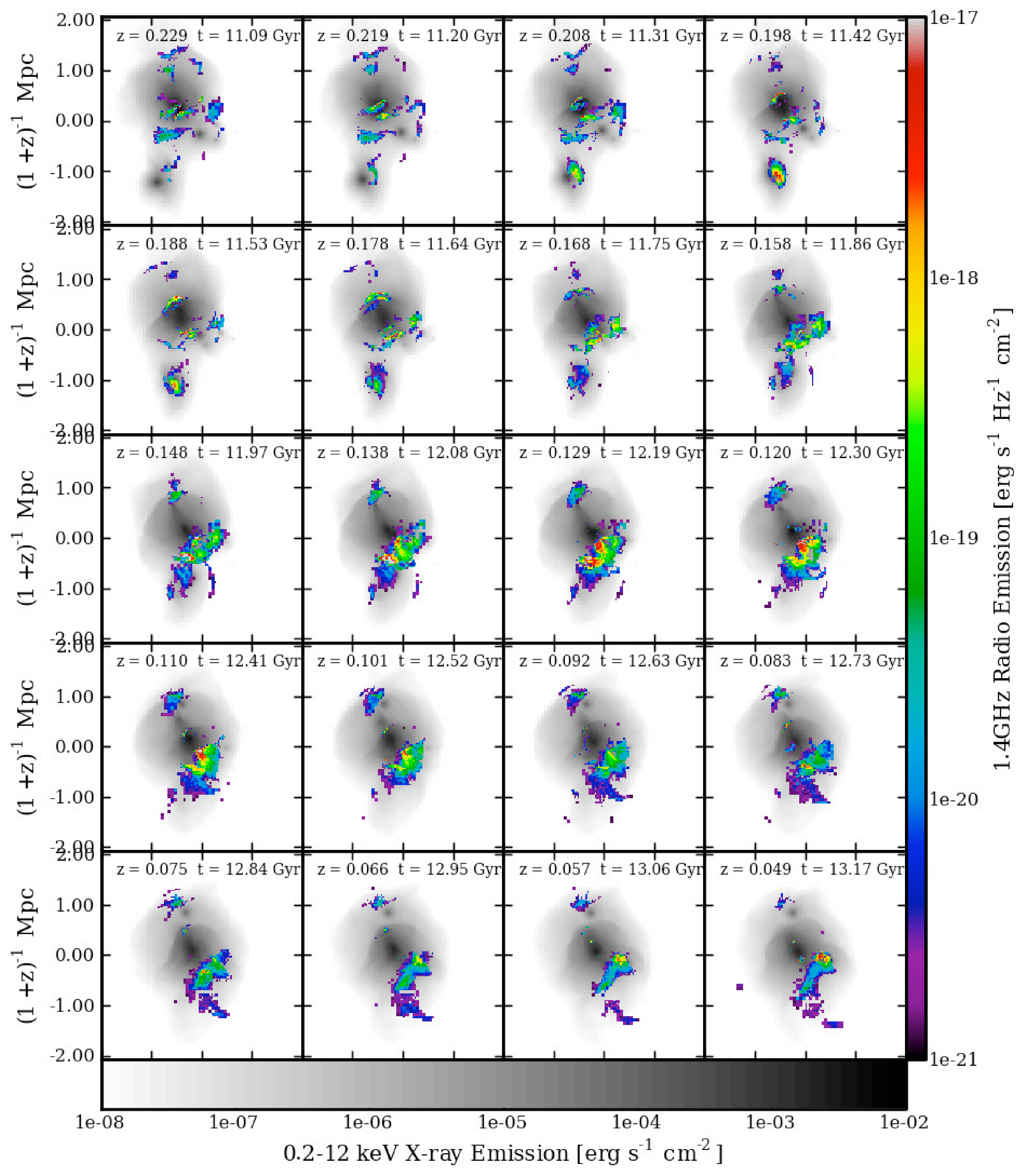
1e+20
1e+21
1e+22
1e+23
1e+24
1e+25
1e+26
1.4GHz Radio Emission $[erg\ s^{-1}\ Hz^{-1}\ cm^{-2}]$
1e+05
1e+06
1e+07
1e+08
Temperature $[K]$
1e-31
1e-30
1e-29
1e-28
1e-27
1e-26
Density $[g/cm^3]$

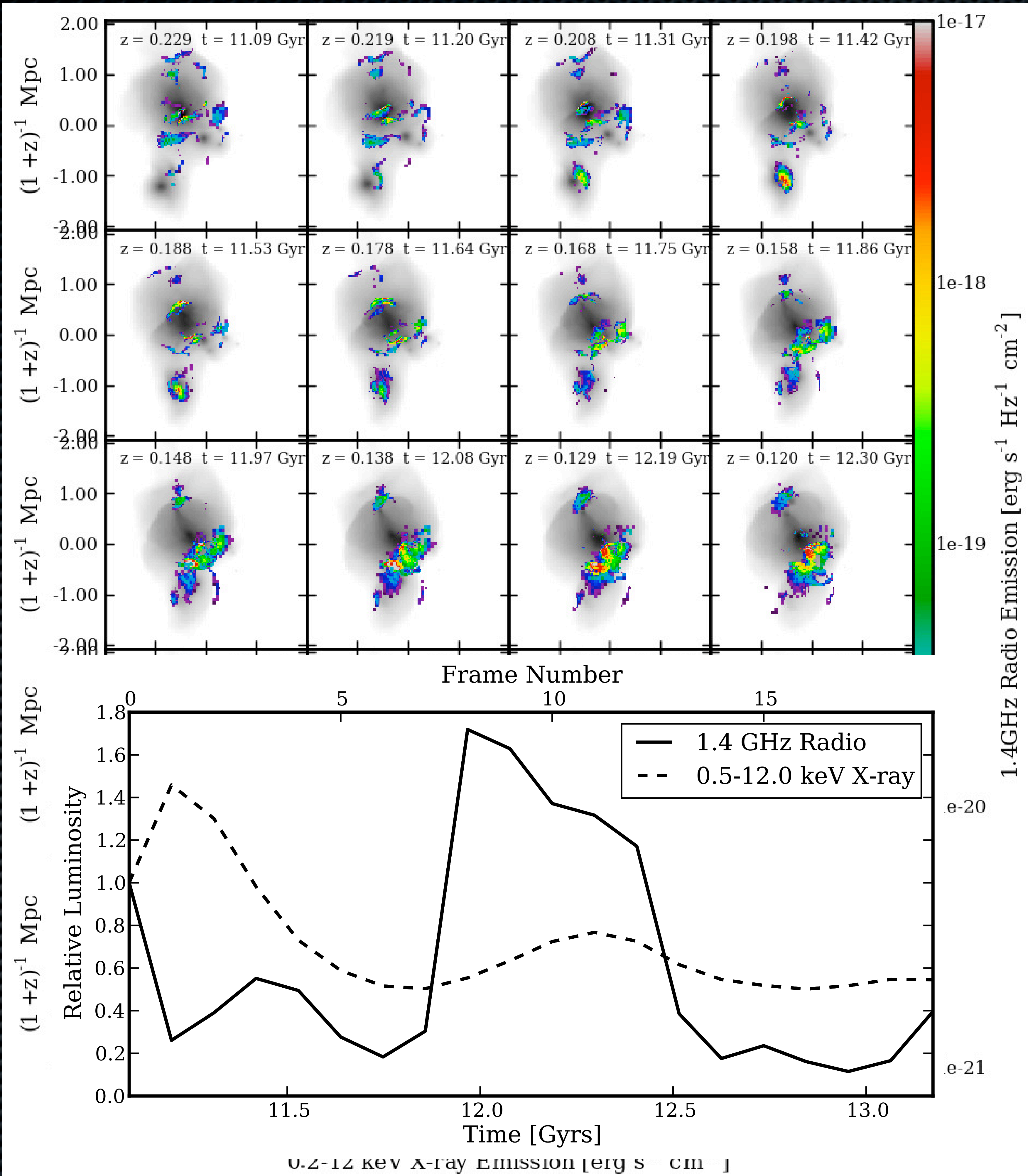


$P_{1.4GHz} \propto M^{3.2}$
relic64
z = 1.00
$P_{1.4GHz} \propto M^{3.7}$
relic200
z = 1.00
$P_{1.4GHz} \propto M^{3.5}$
relic64
z = 0.00
$P_{1.4GHz} \propto M^{3.6}$
relic200
z = 0.00
1.4 GHz Radio Power [W/Hz]
Mass [$M_\odot$]



1.4 GHz Radio Power [W/Hz]
$P_{1.4GHz} \propto L_{X\text{-ray}}^{0.9}$
relic64
z = 1.00
$P_{1.4GHz} \propto L_{X\text{-ray}}^{1.4}$
relic200
z = 1.00
$P_{1.4GHz} \propto L_{X\text{-ray}}^{1.3}$
$P_{1.4GHz} \propto L_{X\text{-ray}}^{1.8}$
$P_{1.4GHz} \propto L_{X\text{-ray}}^{2.0}$
relic64
z = 0.00
$P_{1.4GHz} \propto L_{X\text{-ray}}^{1.4}$
$P_{1.4GHz} \propto L_{X\text{-ray}}^{2.2}$
$P_{1.4GHz} \propto L_{X\text{-ray}}^{2.0}$
relic200
z = 0.00
X-ray Luminosity [erg/s]
X-ray Luminosity [erg/s]


z = 0.229 t = 11.09 Gyr
z = 0.219 t = 11.20 Gyr
z = 0.208 t = 11.31 Gyr
z = 0.198 t = 11.42 Gyr
z = 0.188 t = 11.53 Gyr
z = 0.178 t = 11.64 Gyr
z = 0.168 t = 11.75 Gyr
z = 0.158 t = 11.86 Gyr
z = 0.148 t = 11.97 Gyr
z = 0.138 t = 12.08 Gyr
z = 0.129 t = 12.19 Gyr
z = 0.120 t = 12.30 Gyr
z = 0.110 t = 12.41 Gyr
z = 0.101 t = 12.52 Gyr
z = 0.092 t = 12.63 Gyr
z = 0.083 t = 12.73 Gyr
z = 0.075 t = 12.84 Gyr
z = 0.066 t = 12.95 Gyr
z = 0.057 t = 13.06 Gyr
z = 0.049 t = 13.17 Gyr
(1 +z)^-1 Mpc
2.00
1.00
0.00
-1.00
-2.00
1.4GHz Radio Emission [erg s^-1 Hz^-1 cm^-2]
1e-17
1e-18
1e-19
1e-20
1e-21
1e-08
1e-07
1e-06
1e-05
1e-04
1e-03
1e-02
0.2-12 keV X-ray Emission [erg s^-1 cm^-2]

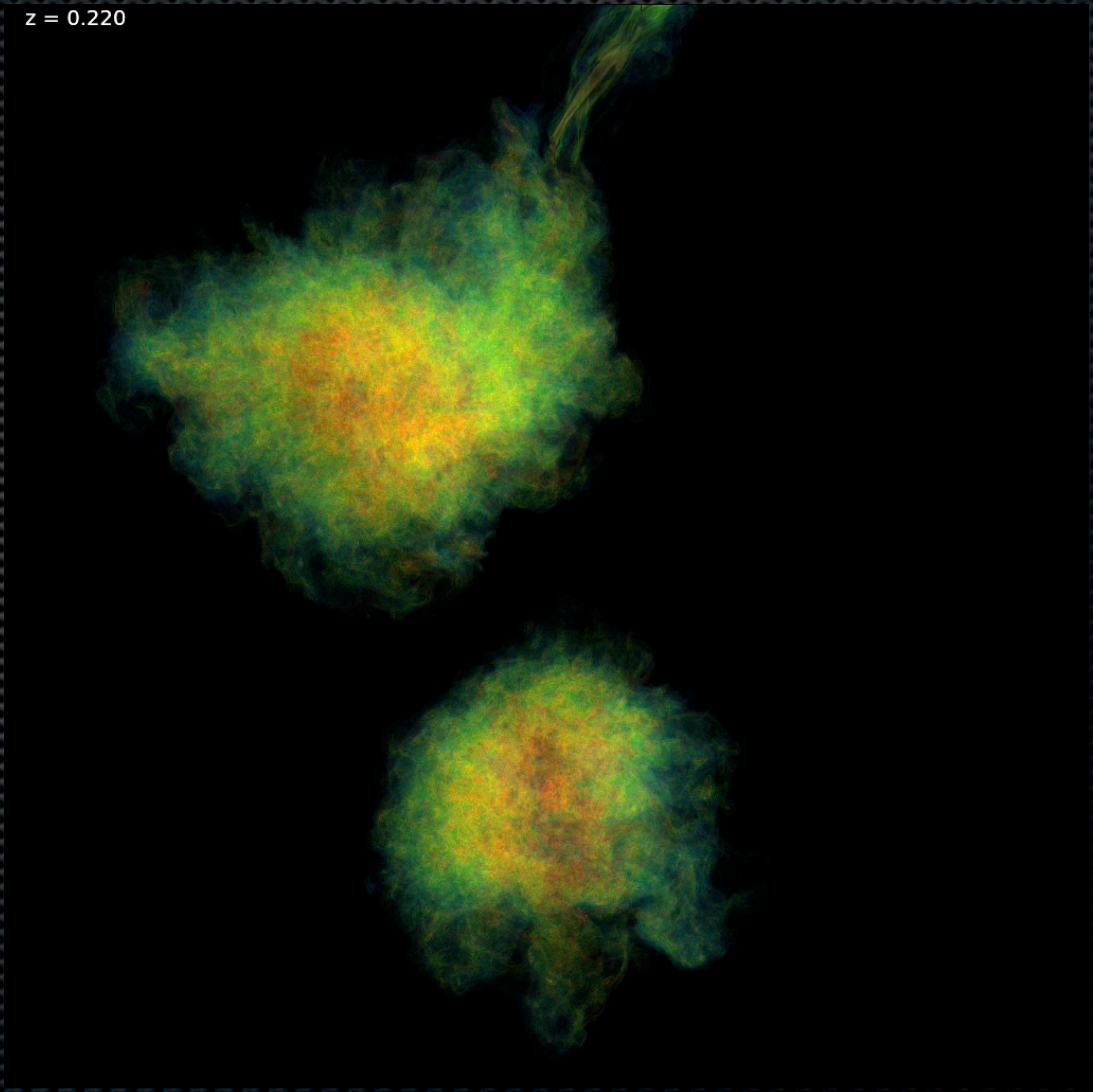

z = 0.229 t = 11.09 Gyr
z = 0.219 t = 11.20 Gyr
z = 0.208 t = 11.31 Gyr
z = 0.198 t = 11.42 Gyr
z = 0.188 t = 11.53 Gyr
z = 0.178 t = 11.64 Gyr
z = 0.168 t = 11.75 Gyr
z = 0.158 t = 11.86 Gyr
z = 0.148 t = 11.97 Gyr
z = 0.138 t = 12.08 Gyr
z = 0.129 t = 12.19 Gyr
z = 0.120 t = 12.30 Gyr
(1 +z)^-1 Mpc
1.4GHz Radio Emission [erg s^-1 Hz^-1 cm^-2]
Frame Number
Relative Luminosity
Time [Gyrs]
1.4 GHz Radio
0.5-12.0 keV X-ray

Conclusions

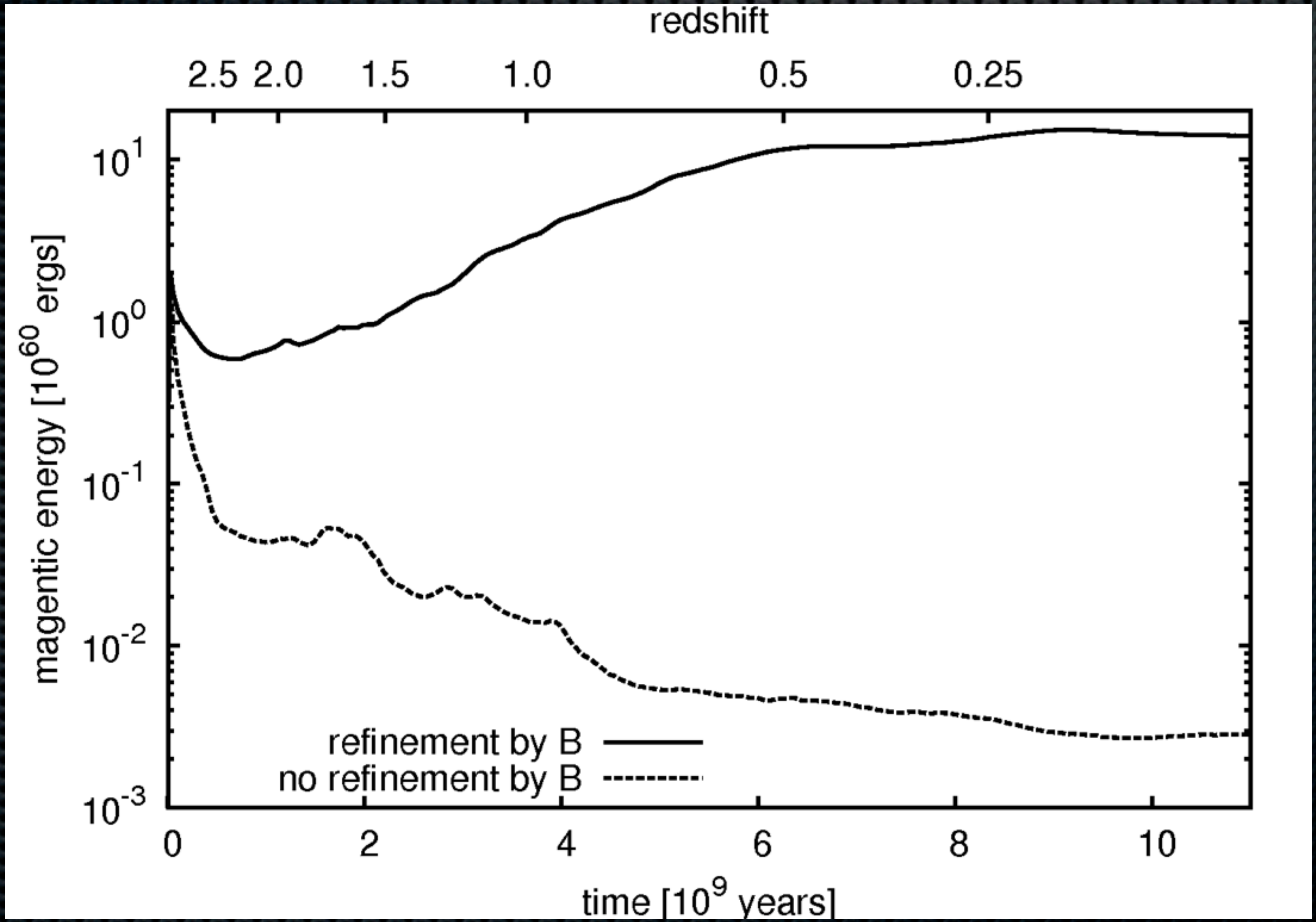
- Global Properties
  - Emission primarily from hot, dense gas, associated with merger shocks
  - Redshift evolution of accretion shocks imprint cosmology
- Individual Halo Properties
  - General scaling relationships with Mass, X-ray Luminosity
  - Large scatter suggests merger state very important

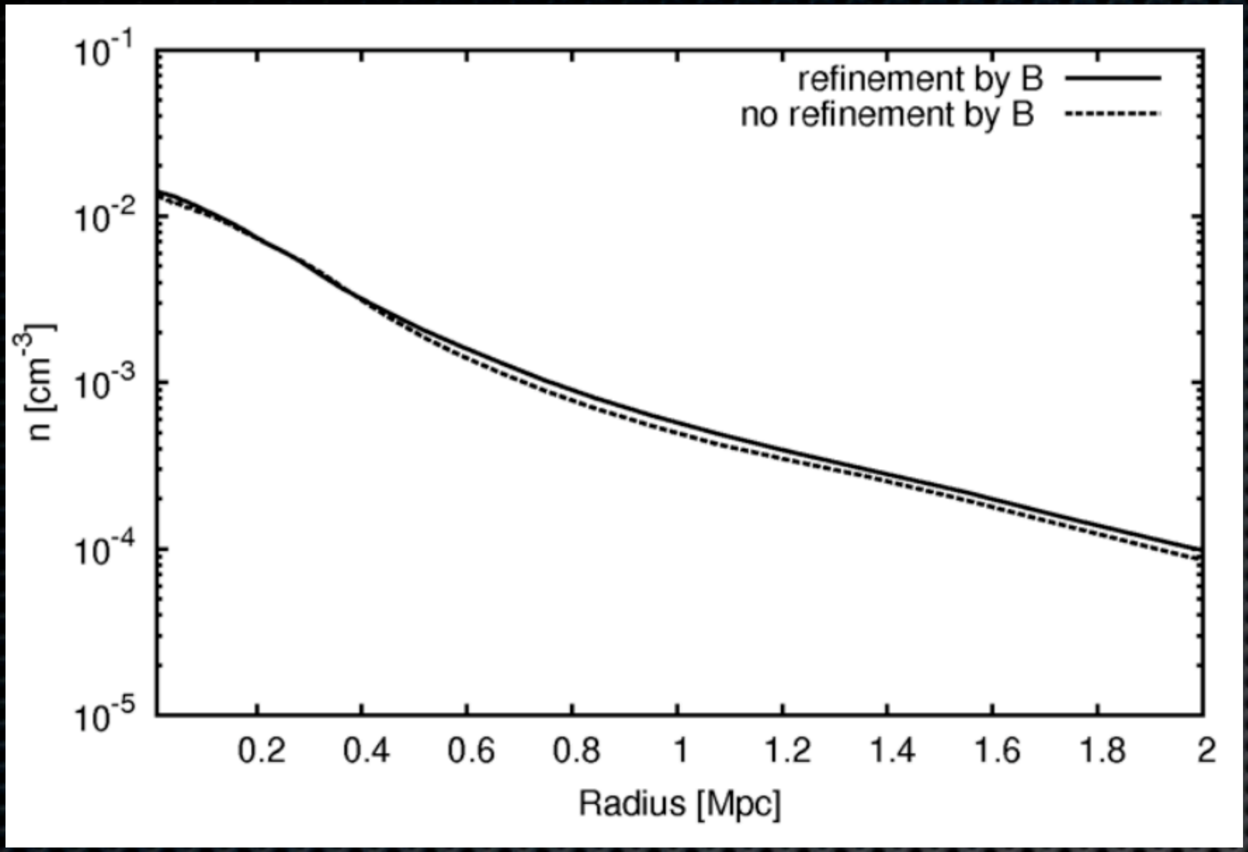
Initial Work witih MHD Enzo

- Collaboration with Hao Xu and Hui Li at LANL
- Inject B-fields at z=3.0 from AGN sources
- Follow Merger History

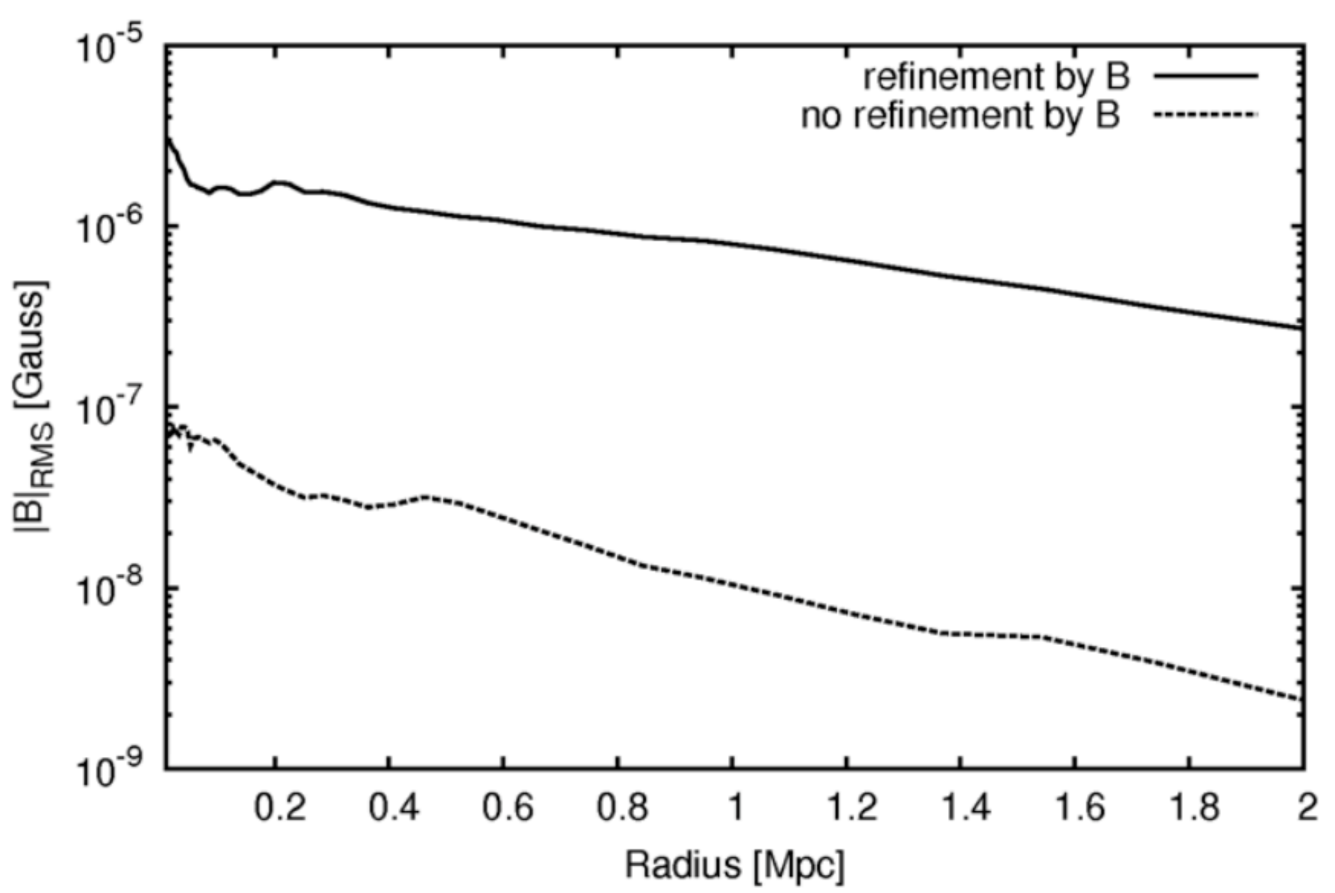


Refinement Refinement Refinement!

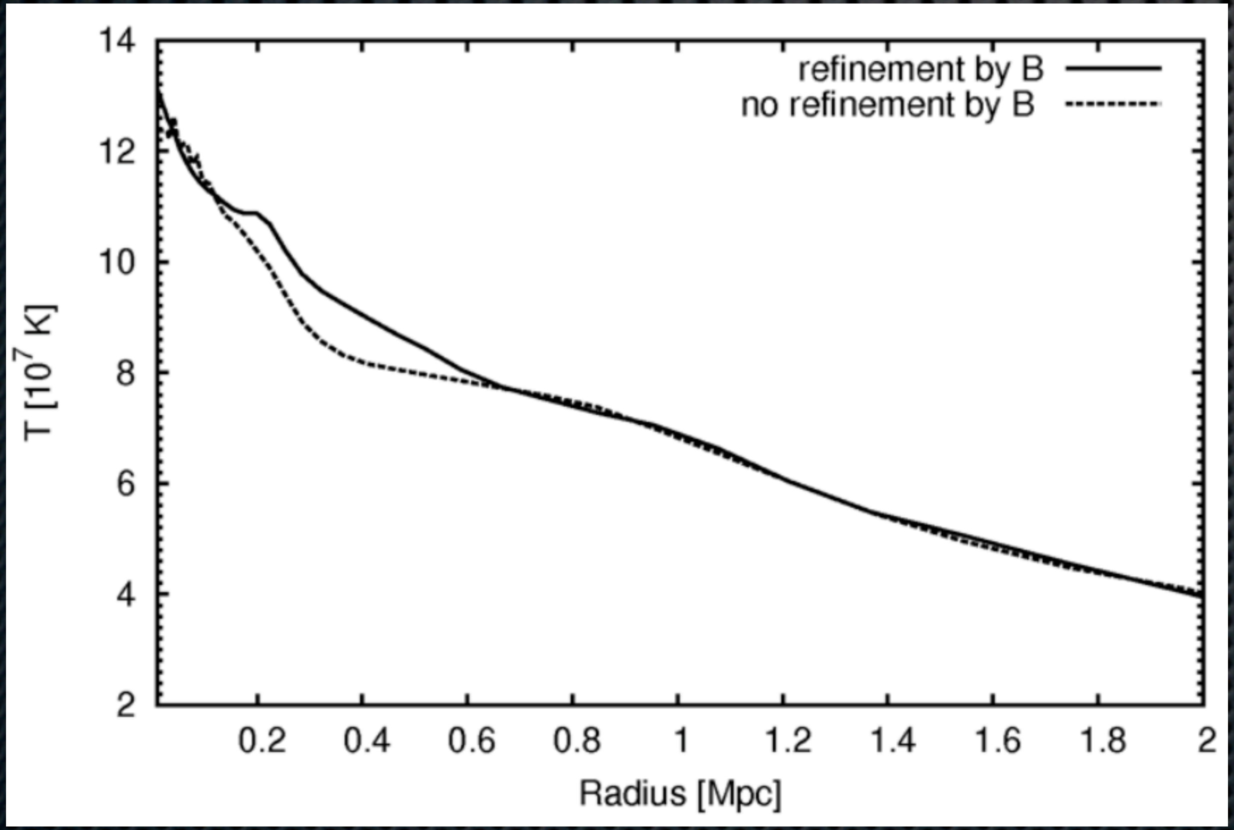




refinement by B
no refinement by B
n [cm^{-3}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Radius [Mpc]

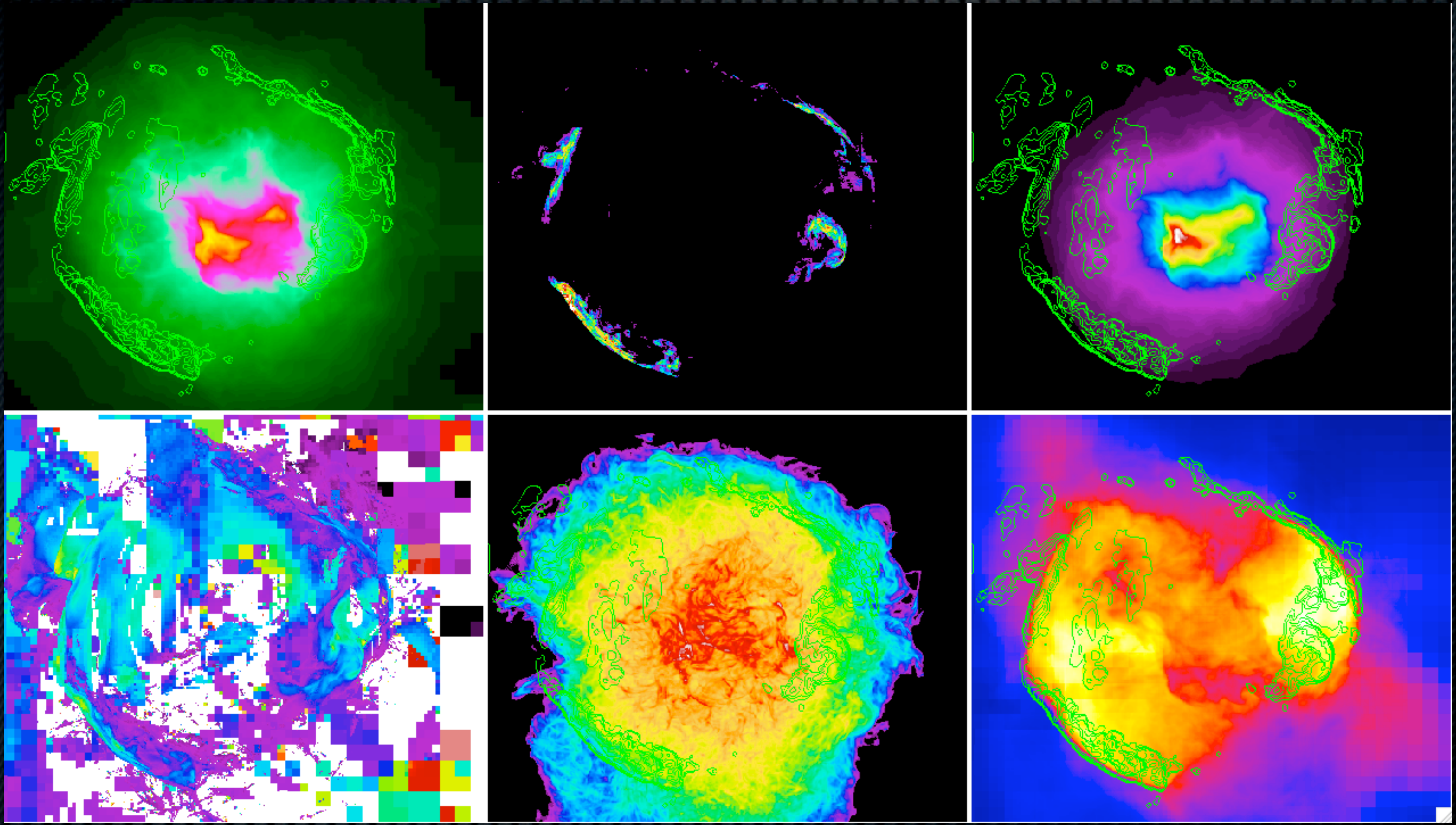


refinement by B
no refinement by B
$|B|_{RMS}$ [Gauss]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Radius [Mpc]

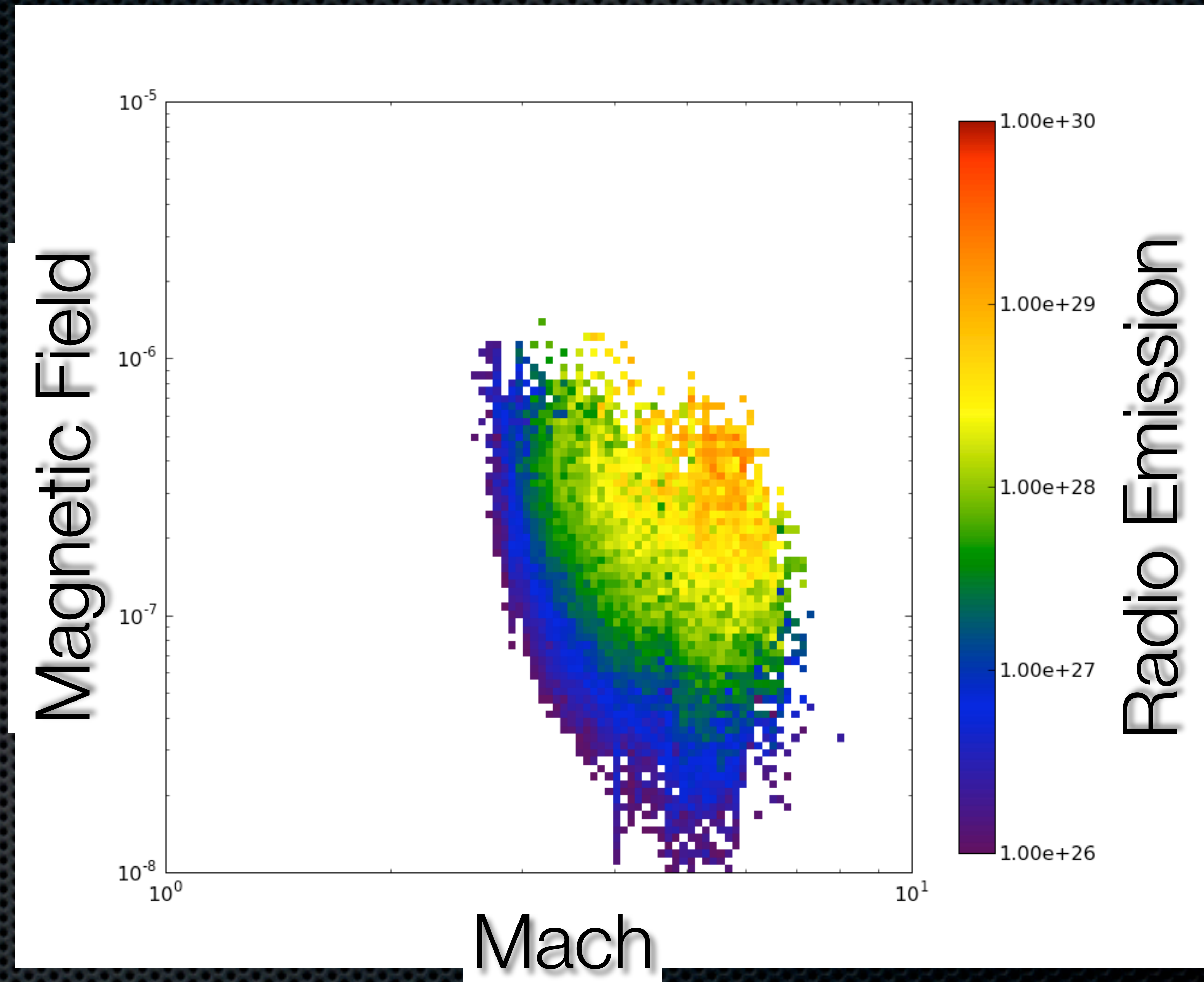


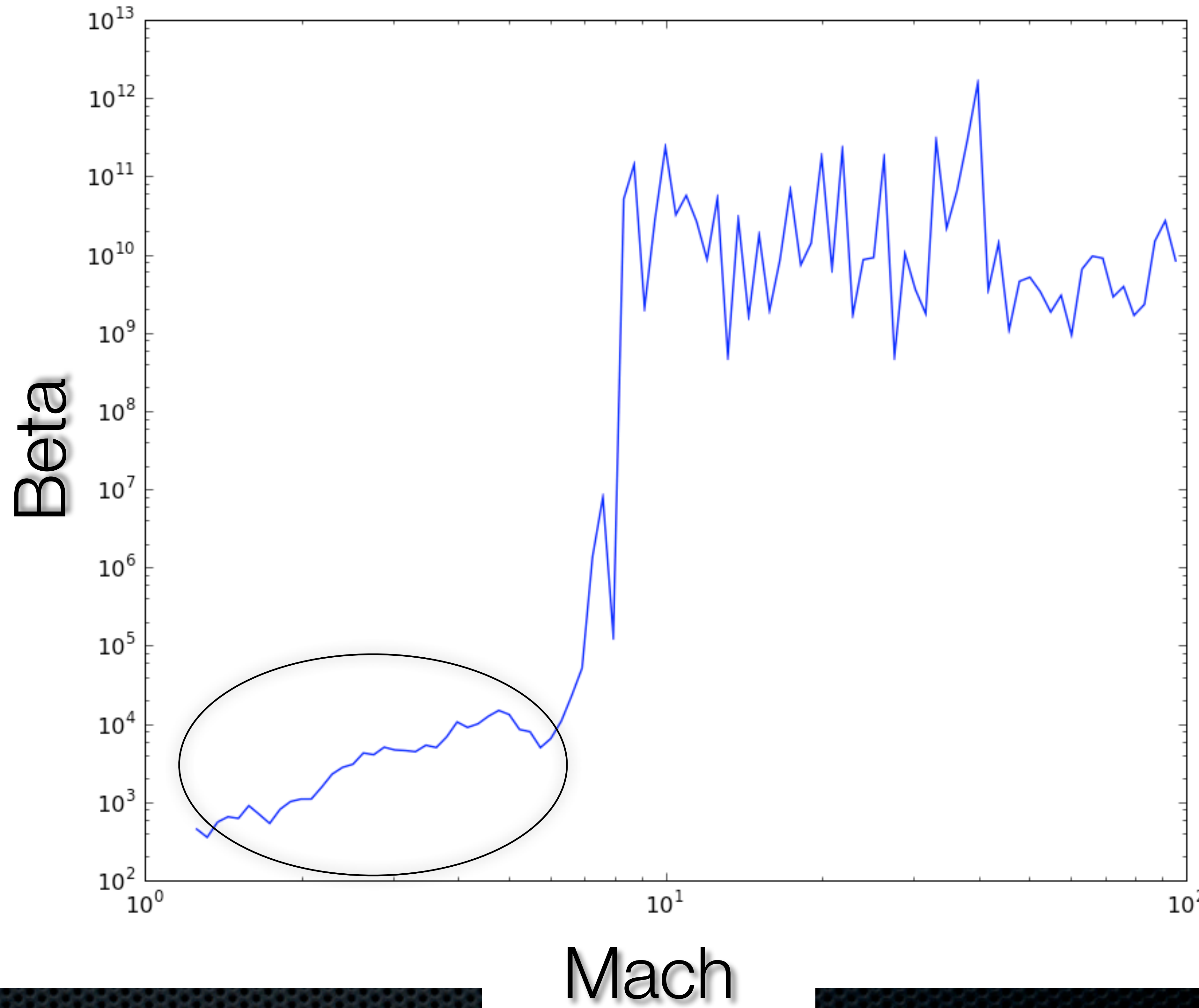
refinement by B
no refinement by B
T [10^7 K]
14
12
10
8
6
4
2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Radius [Mpc]

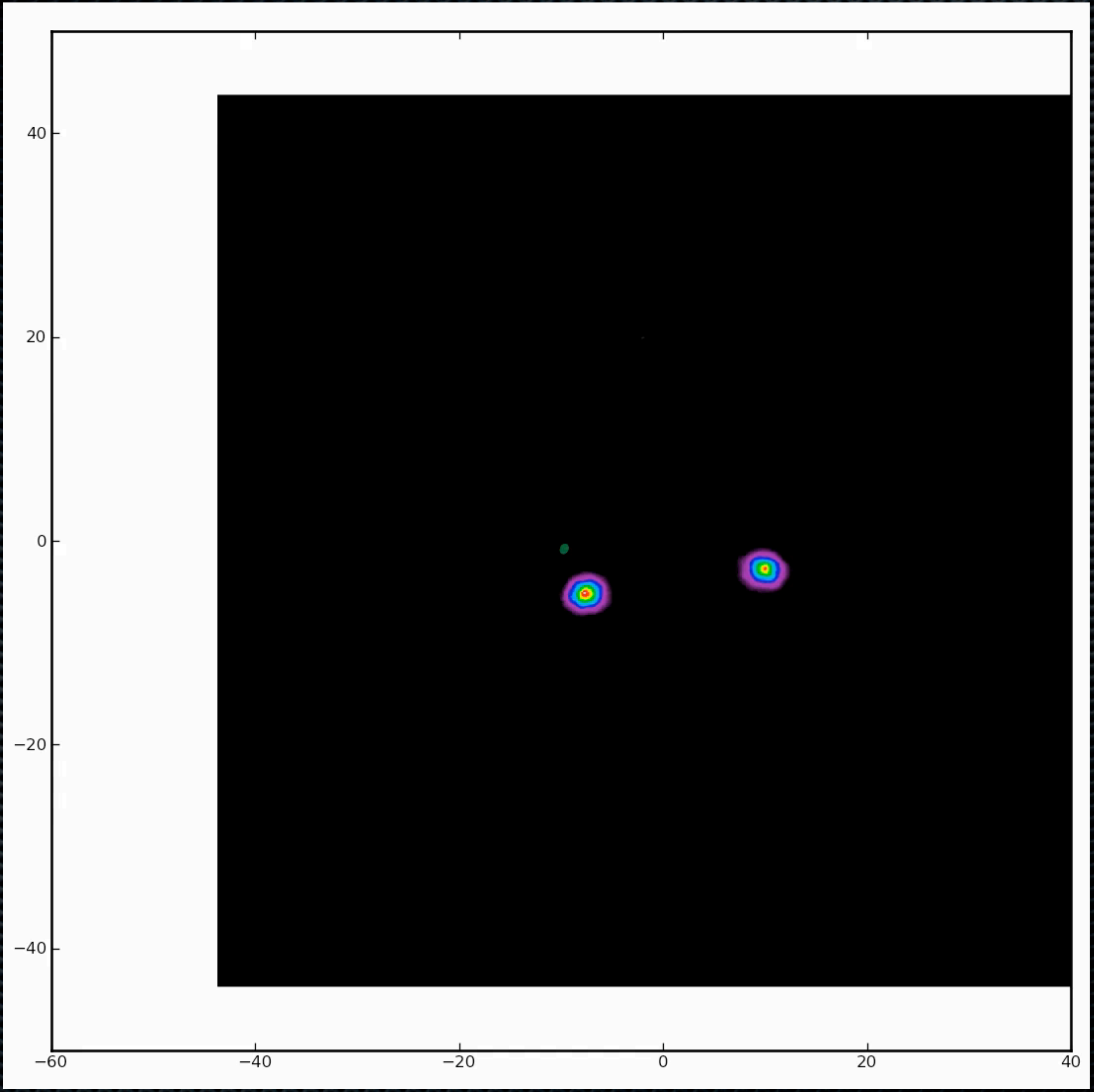
Preliminary Results

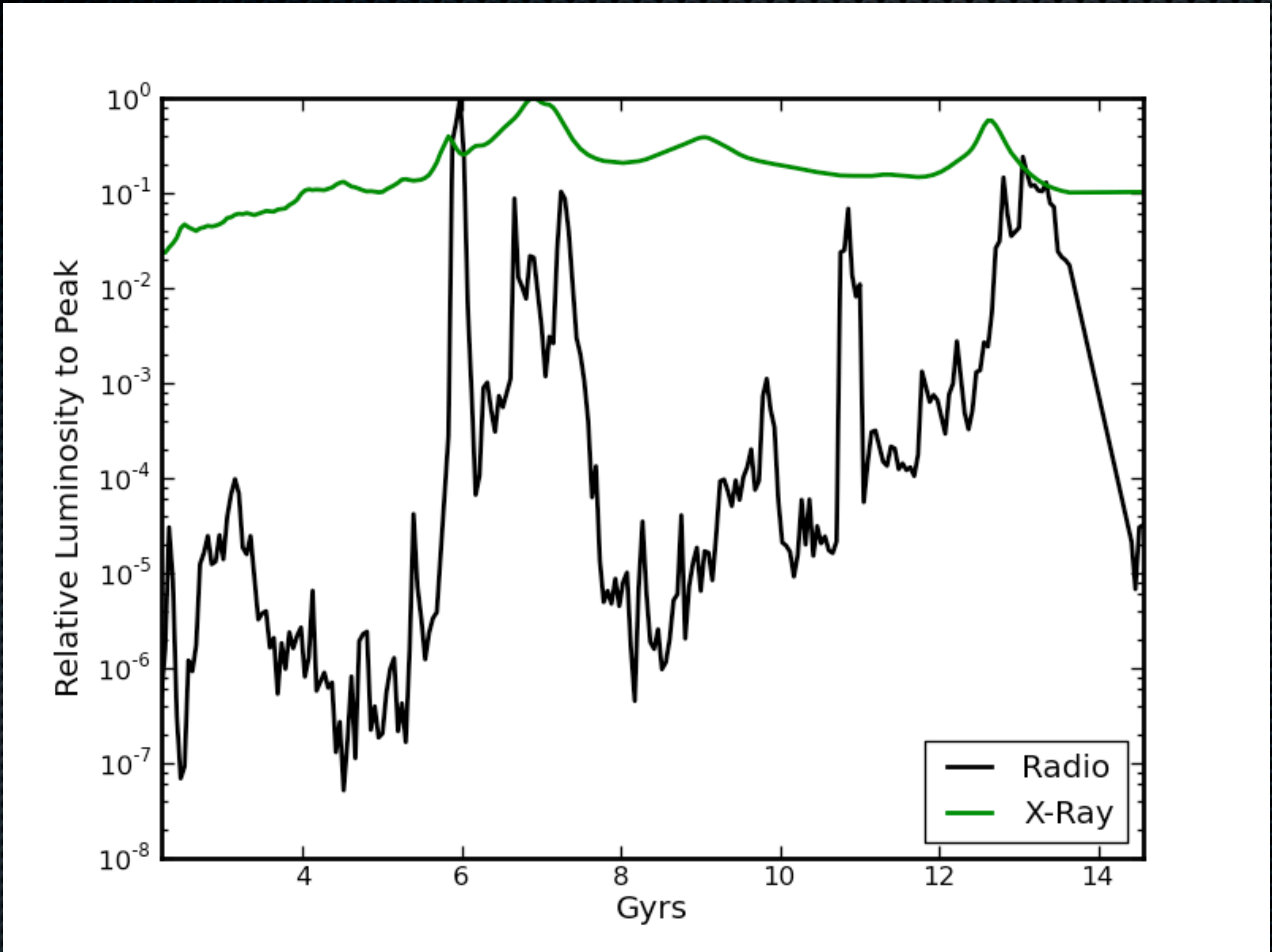


- Radio Emission from 0.1- 1 microGauss, Shock Mach numbers of 4-7

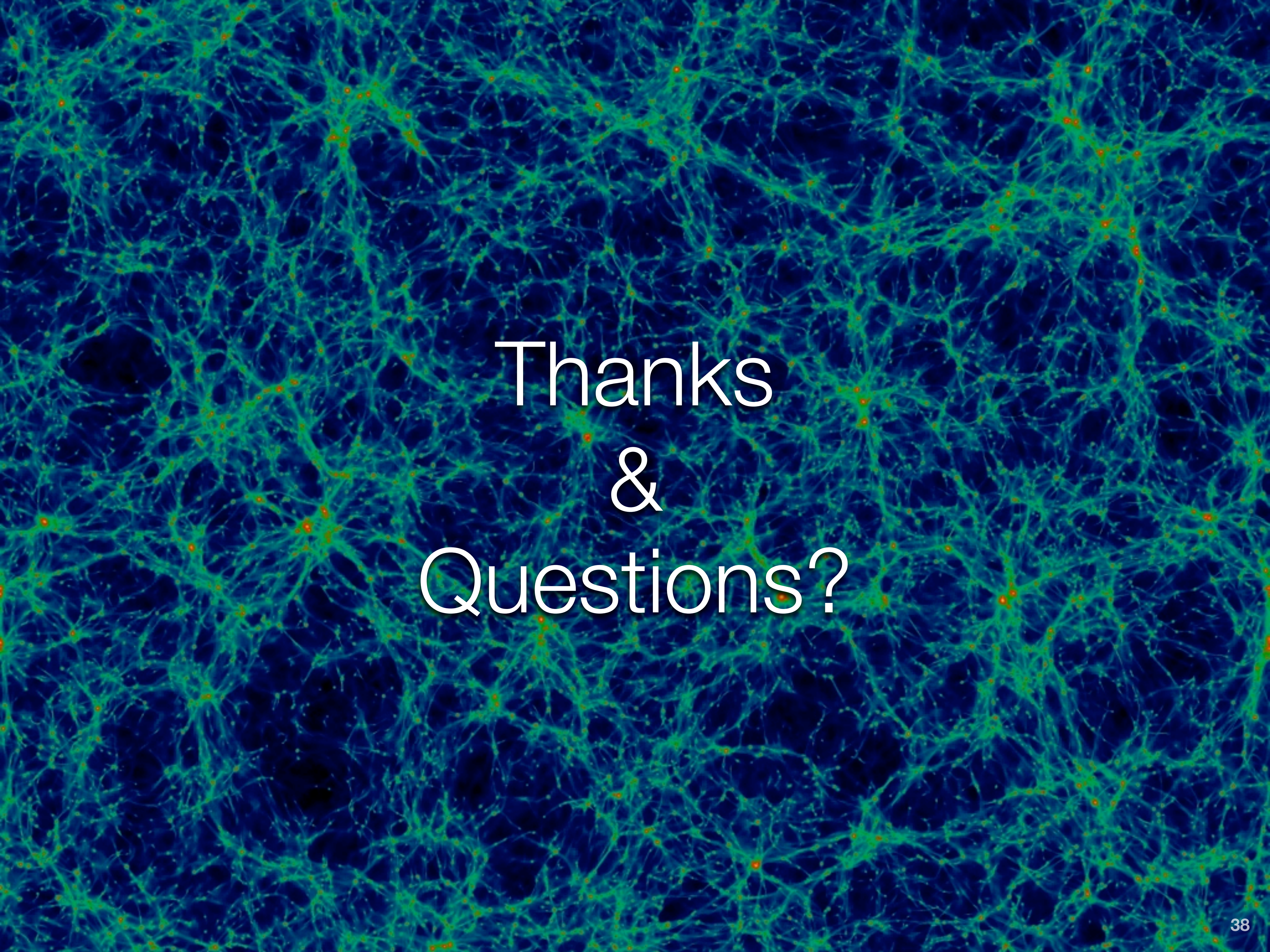



Beta
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{0}
10^{1}
10^{2}
Mach


40
20
0
−20
−40
−60
−40
−20
0
20
40



Relative Luminosity to Peak
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
4
6
8
10
12
14
Gyrs
Radio
X-Ray



Thanks
&
Questions?