The physics of AGN feedback in clusters of galaxies

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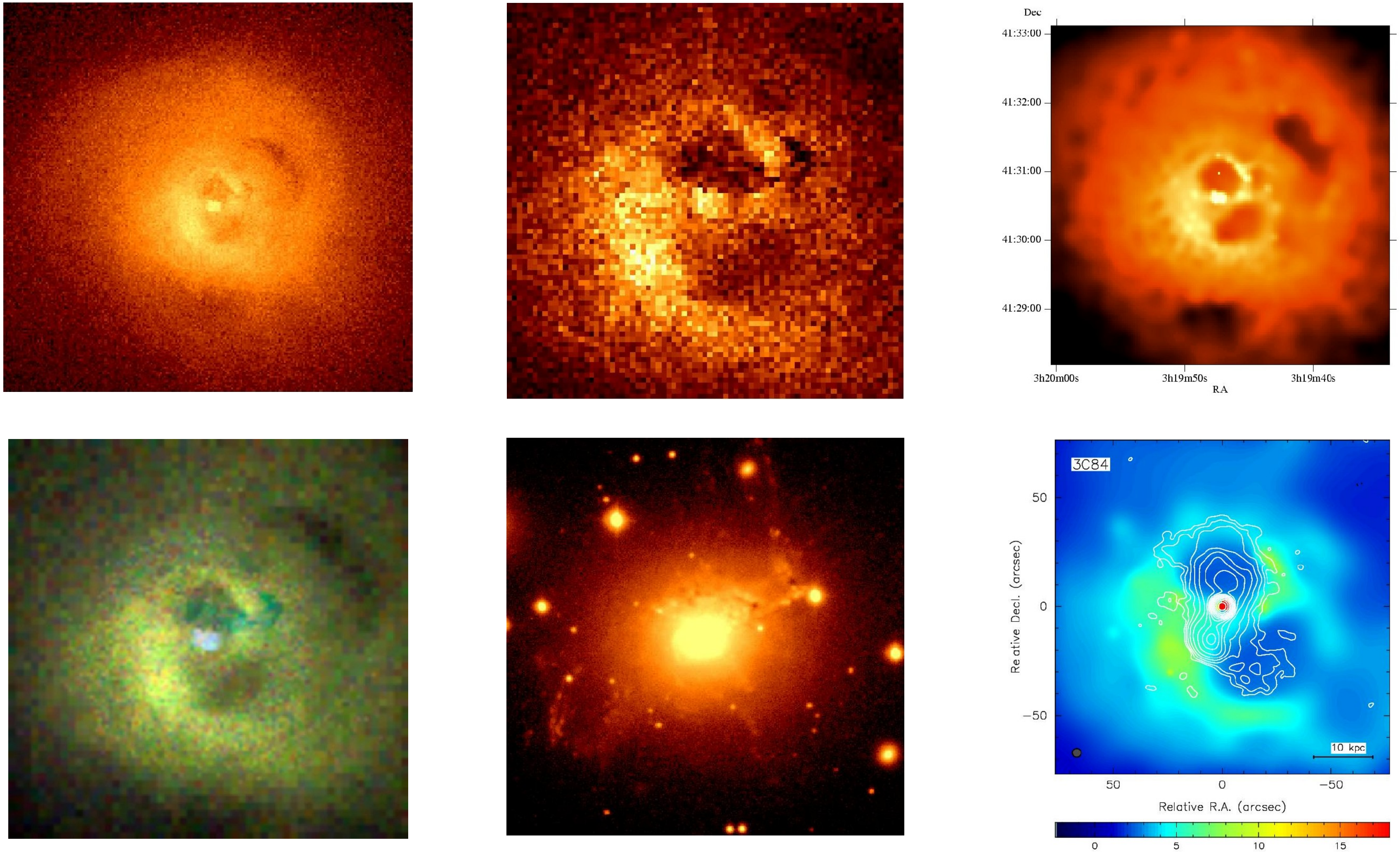
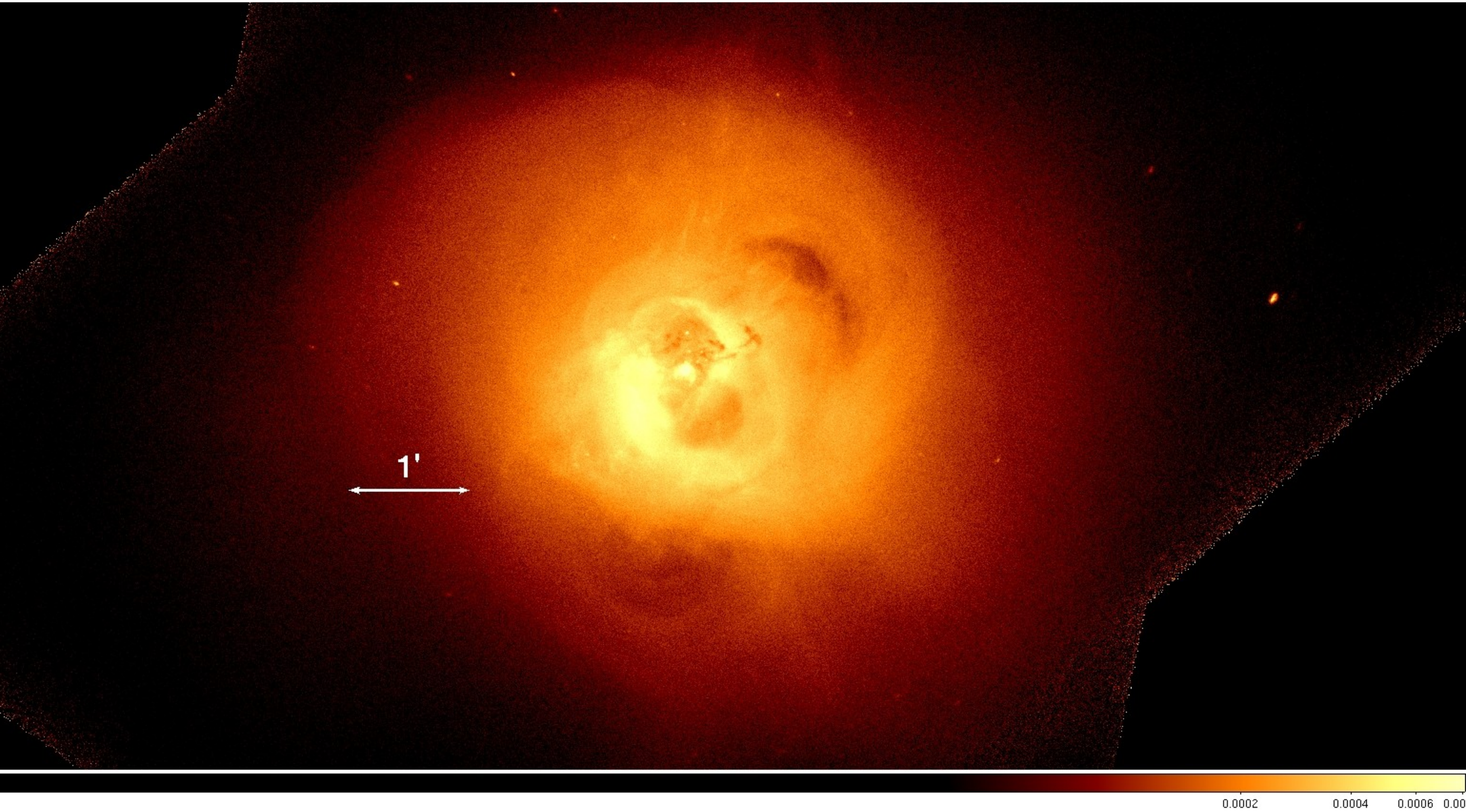
JACOBS
UNIVERSITY

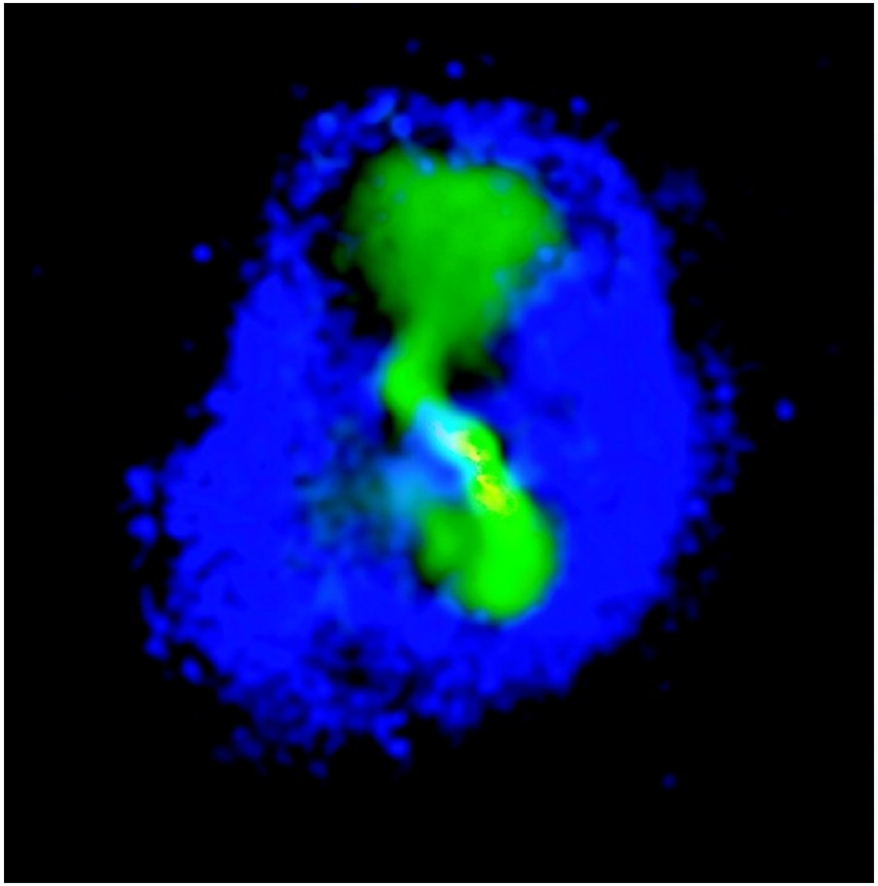
Perseus

Fabian et al (2000 MNRAS 318 L65)

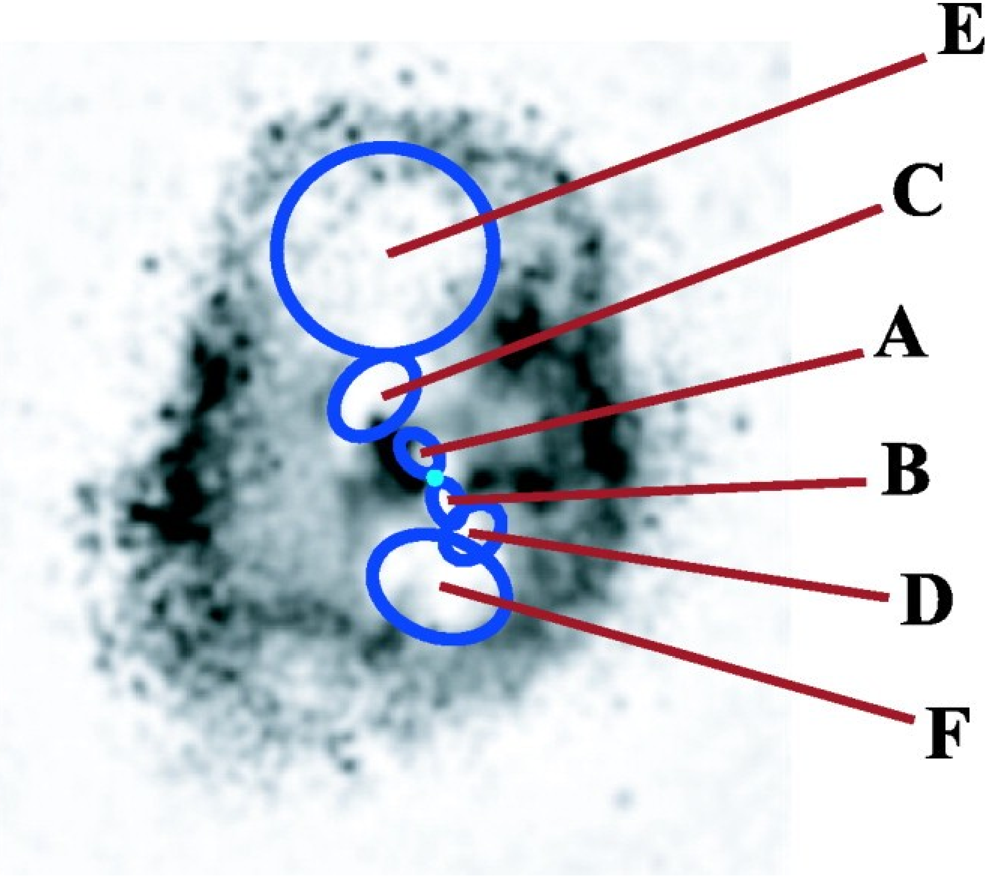




Slide from Bill Forman



green: 330 MHz
yellow: 1.4 GHz
blue: Chandra (227 ks)



total energy = 10^{61} erg

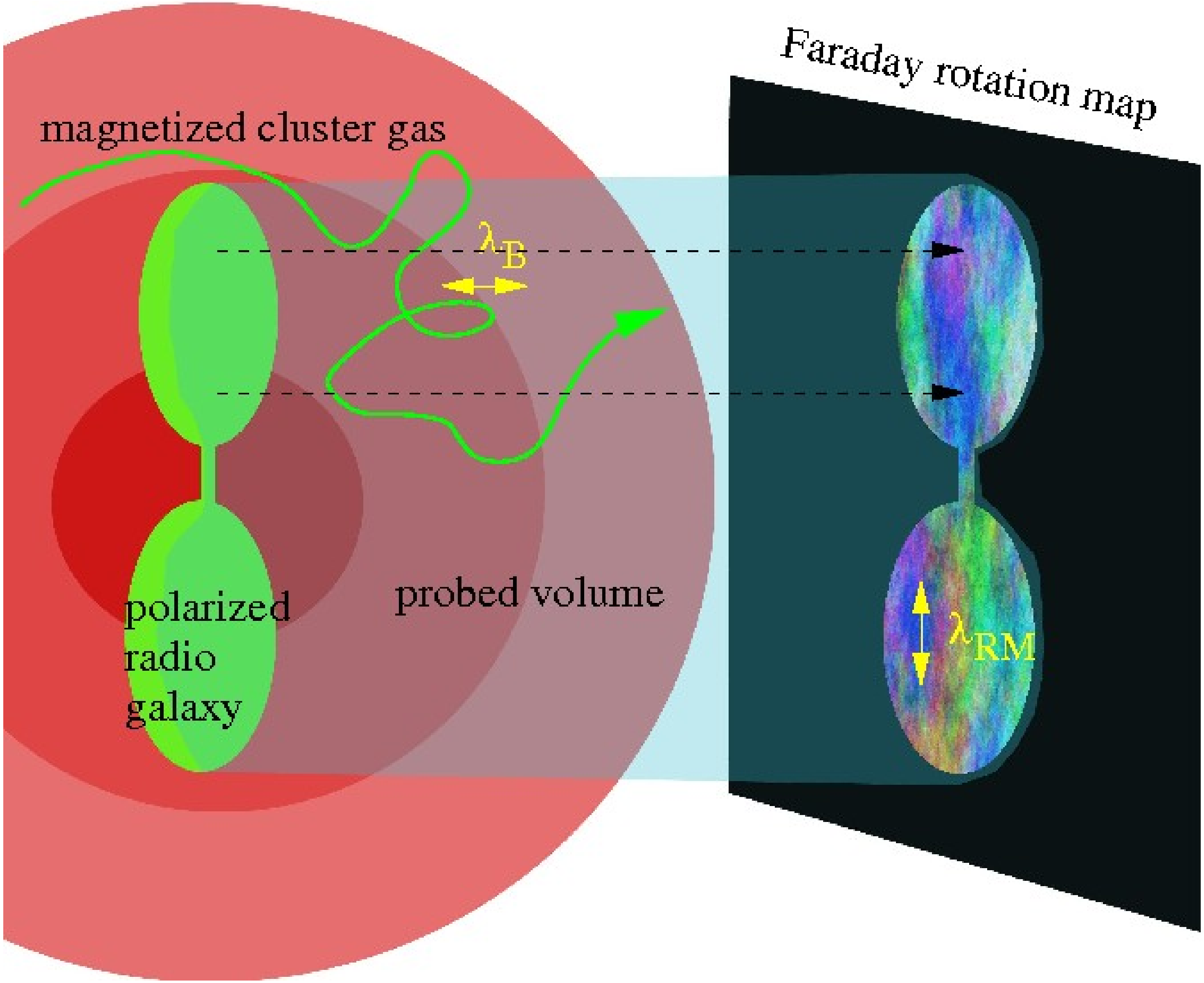
bubbles stay intact for long times

Wise et al. 2007

Evidence for turbulence in clusters

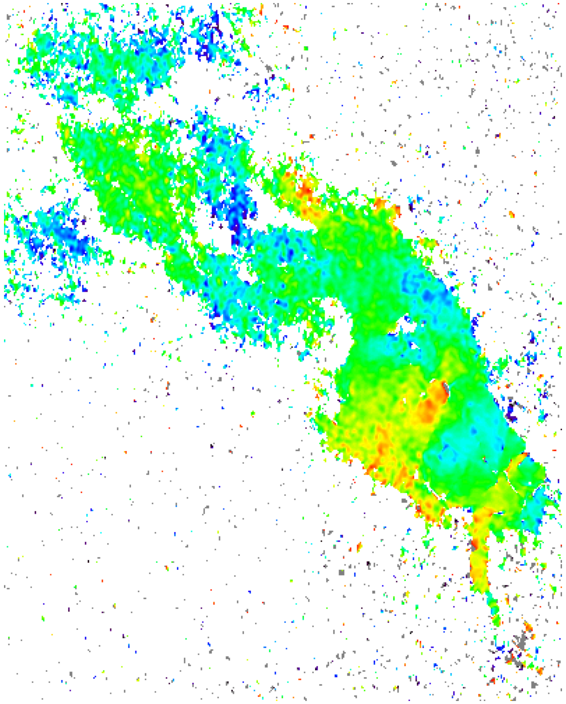
- metal profiles in clusters (e.g. Simionescu et al. 2008, Rebusco et al. 2006)
- lack of resonant scattering in 6.7 keV Fe line in Perseus (Churazov et al. 2004)
- Faraday rotation maps (e.g. Enßlin & Vogt 2003)
- non-thermal emission in clusters (e.g. Brunetti & Lazarian 2007)

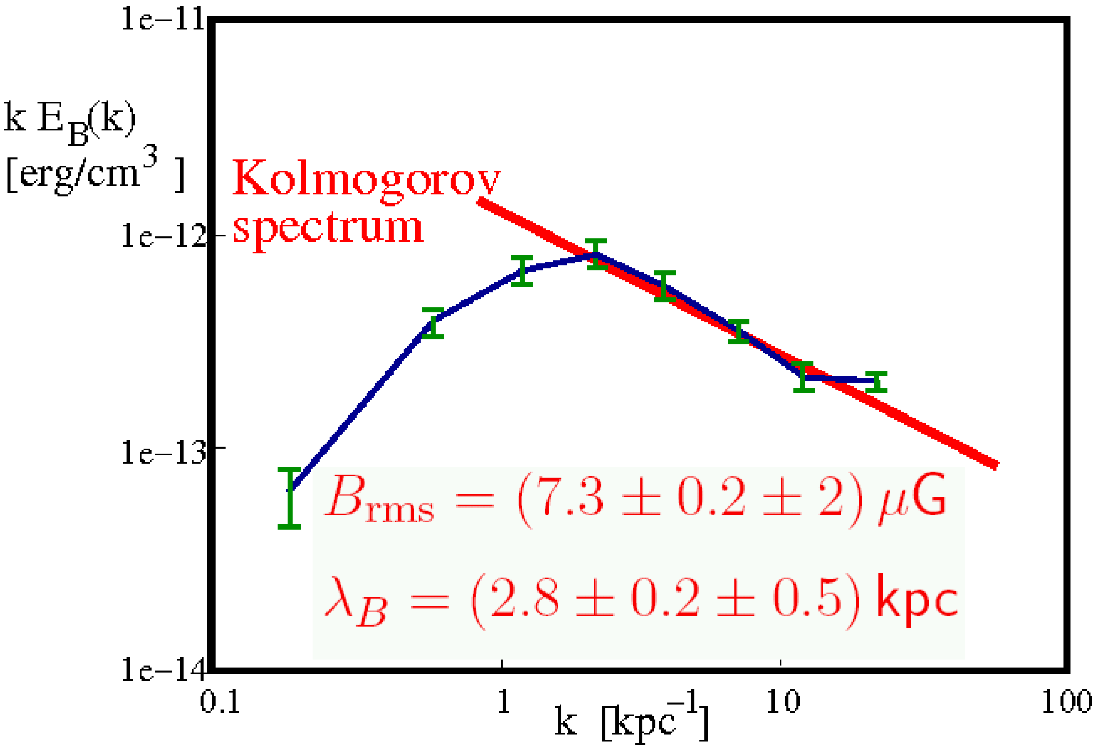
Faraday rotation



Slide from T. Enßlin

Faraday rotation





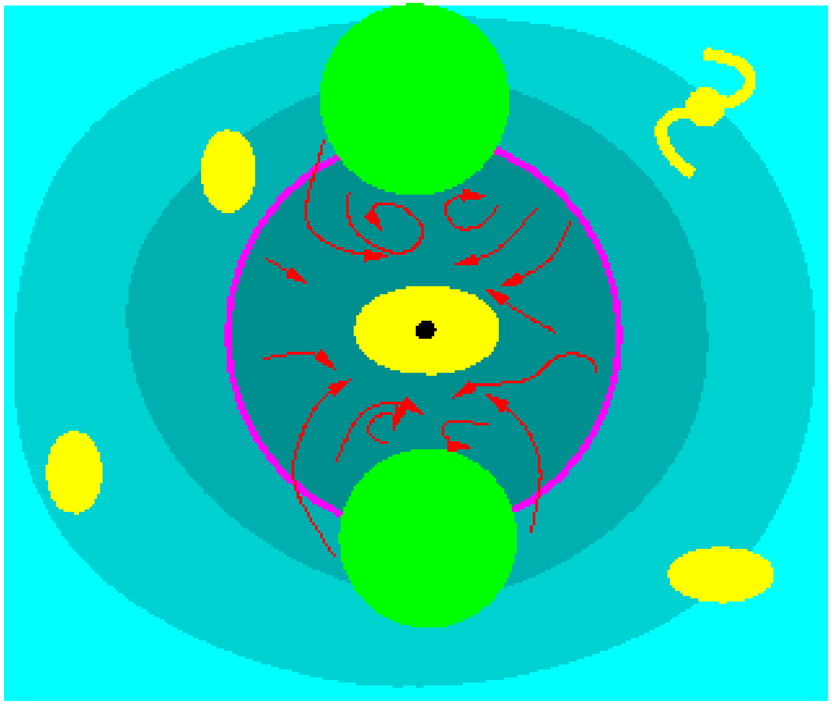
Maximum likelihood power spectrum estimate using 3-d window, assuming statistical isotropy, div B = 0.

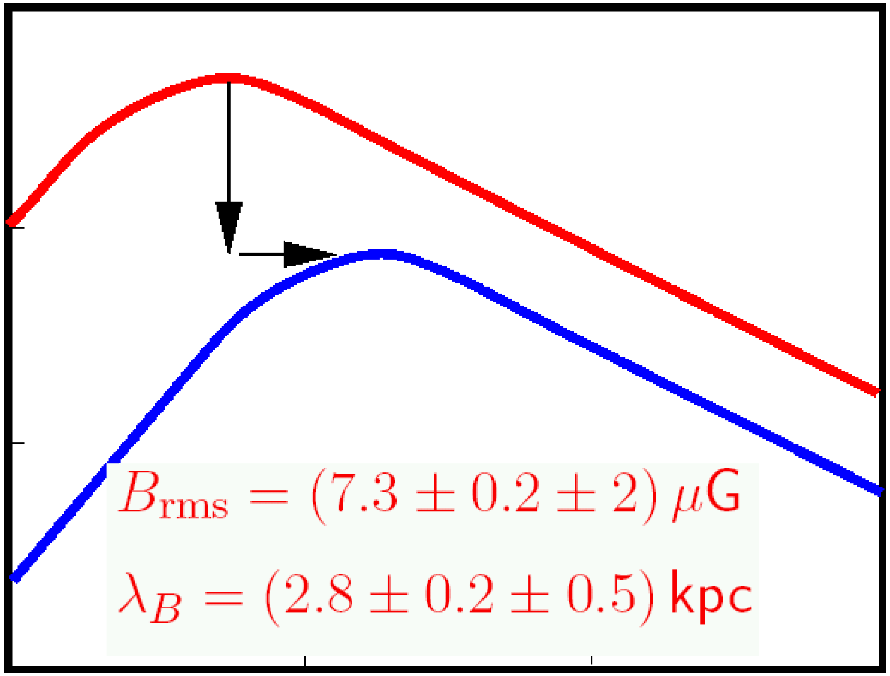
Enßlin & Vogt (2003), Vogt & Enßlin (2005)

Slide from T. Enßlin

Faraday rotation

cluster cool core





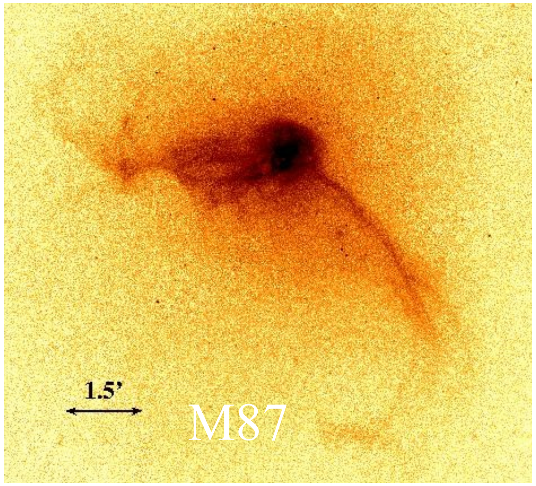
$$B_{\rm rms} = (7.3 \pm 0.2 \pm 2)\,\mu\text{G}$$

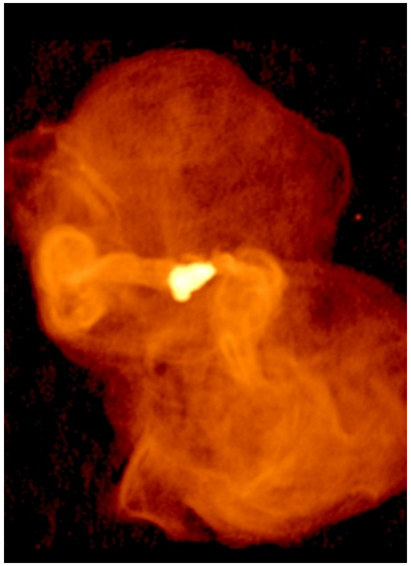
$$\lambda_B = (2.8 \pm 0.2 \pm 0.5)\,\text{kpc}$$

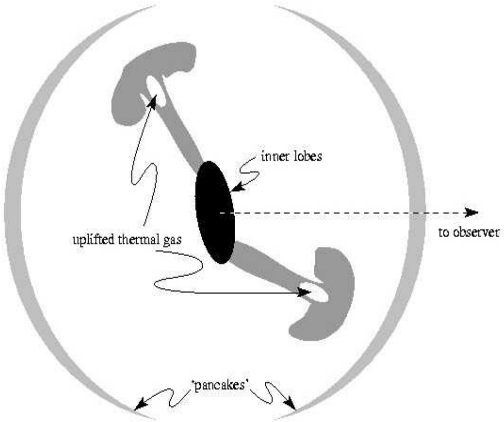
Hydro turbulence induced by buoyantly raising radio bubbles has the right strength & length-scale to drive observed magnetic turbulence (Enßlin & Vogt 2006)

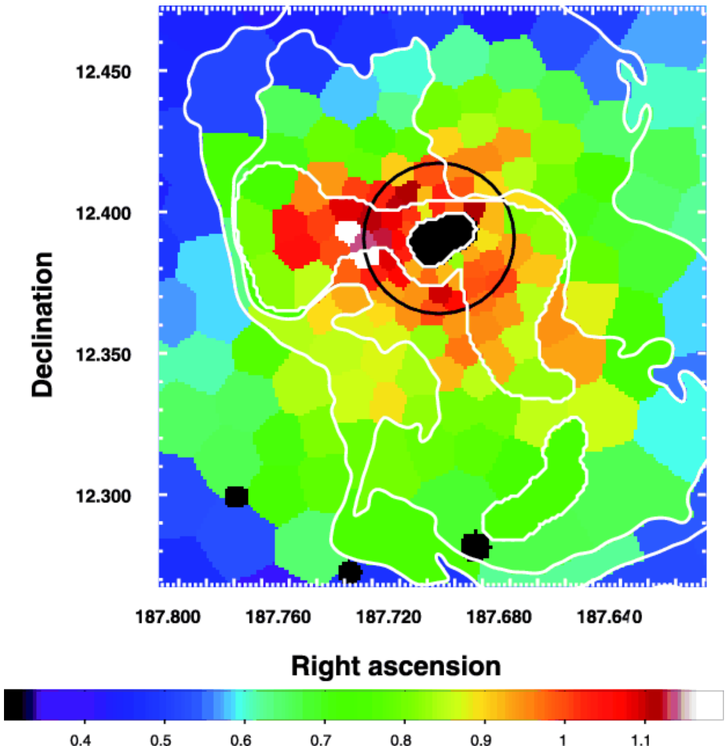
Slide from T. Enßlin

M87



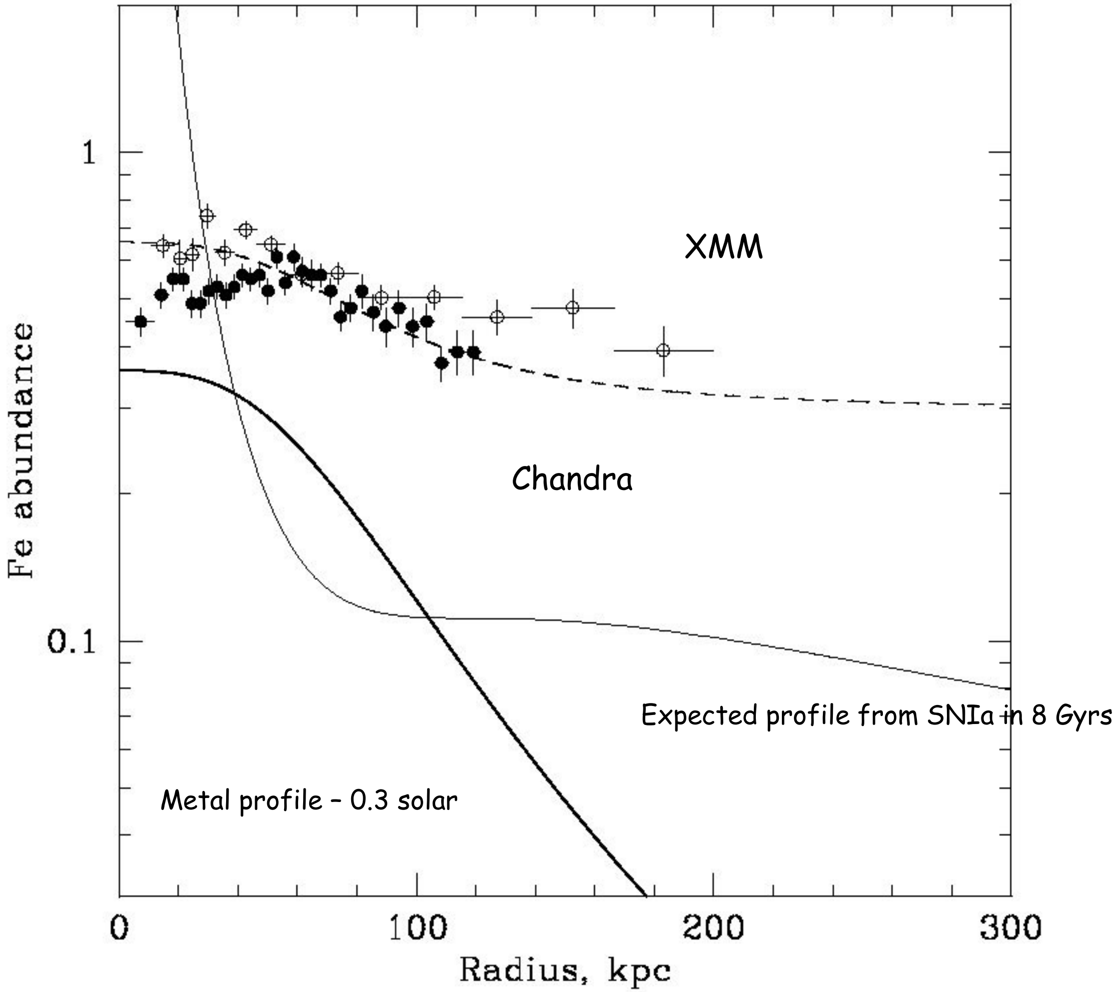






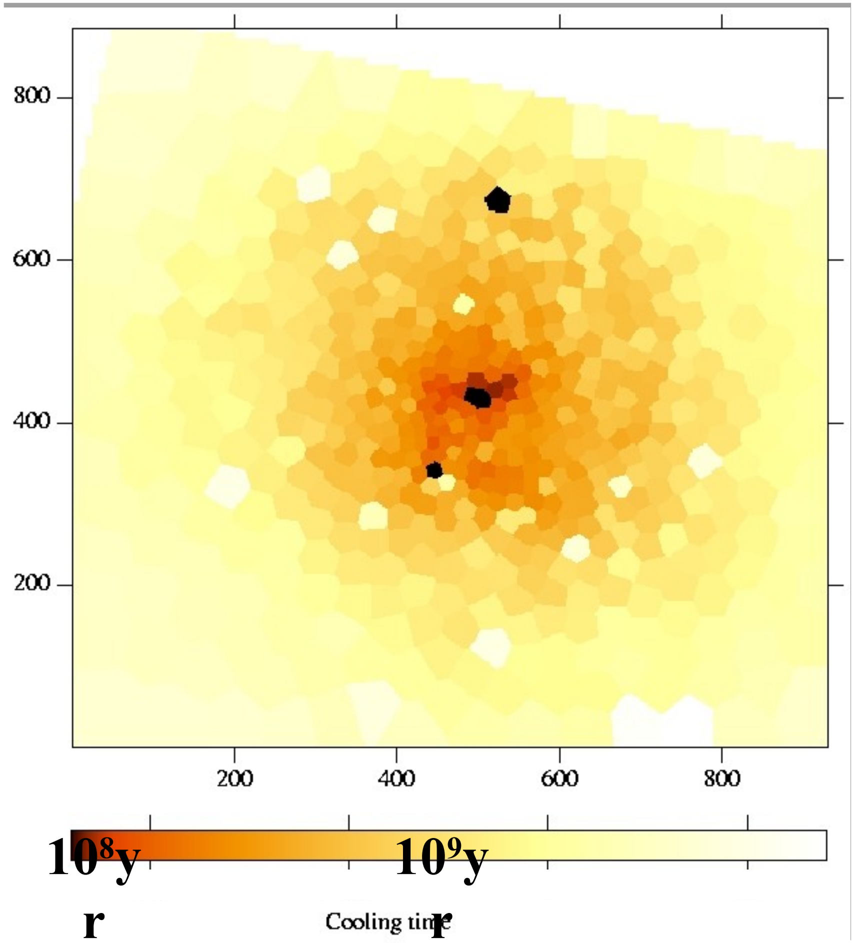
Simionescu, Böhringer, Brüggen, Finoguenov (2006)

Metals in Perseus

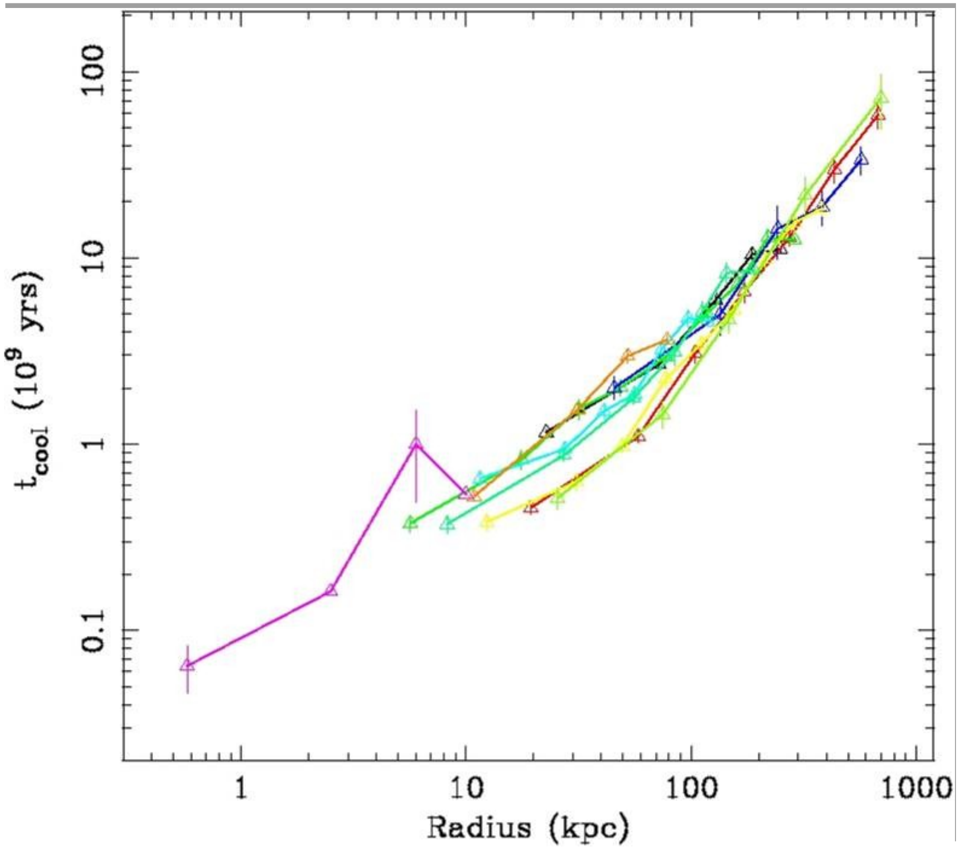


Rebusco et al., MNRAS 359, 1041 (2005)

Cooling time



Perseus cluster



Other clusters
Voigt & Fabian 2003

The ICM may be turbulent

Rayleigh-Taylor unstable bubbles induce turbulence

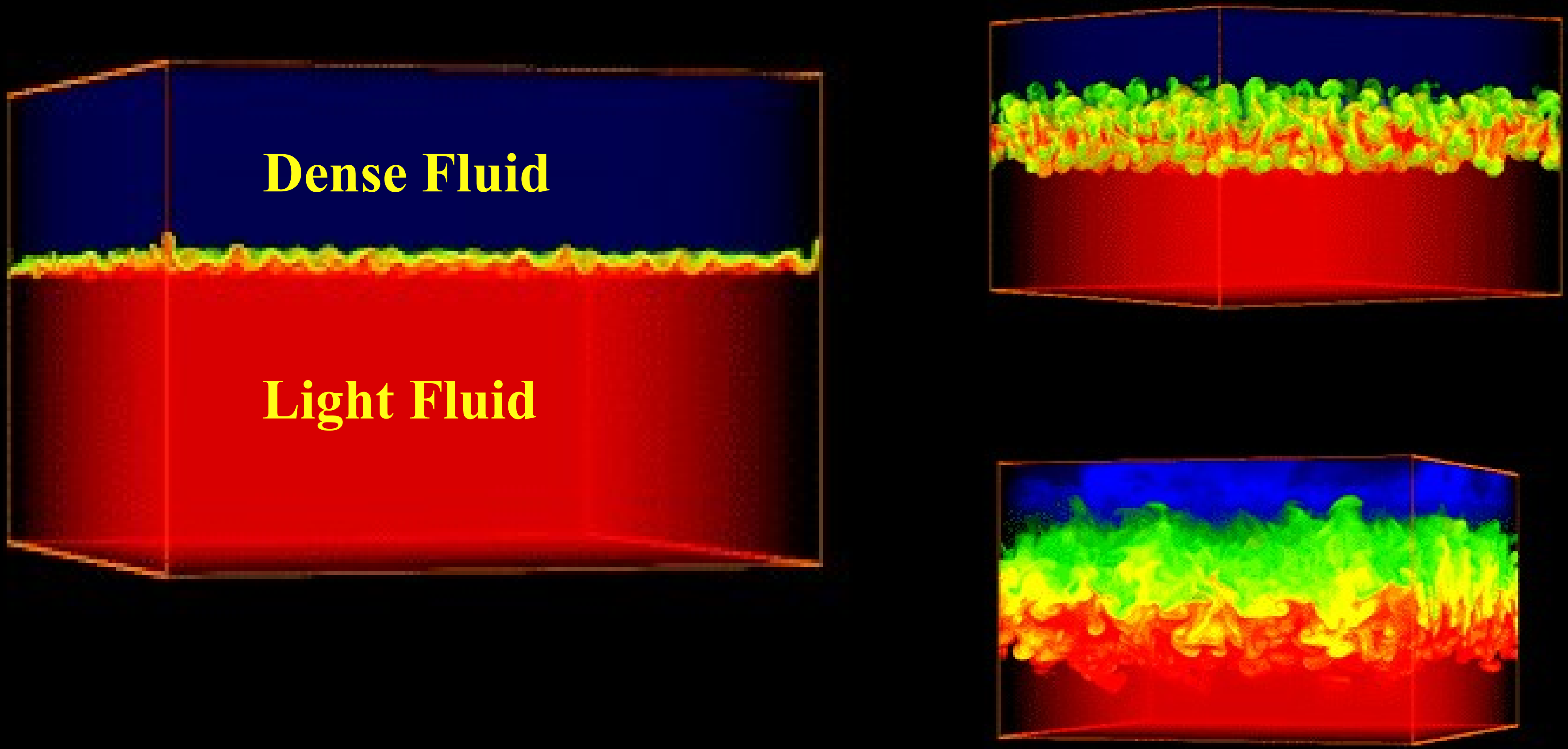
AGN-blown bubbles stay intact for long times

Rayleight-Taylor instabilities cannot be simulated for Re > 10000

Main Question:

How much turbulence do bubbles produce in the ICM
and what does this turbulence
do to the bubbles?

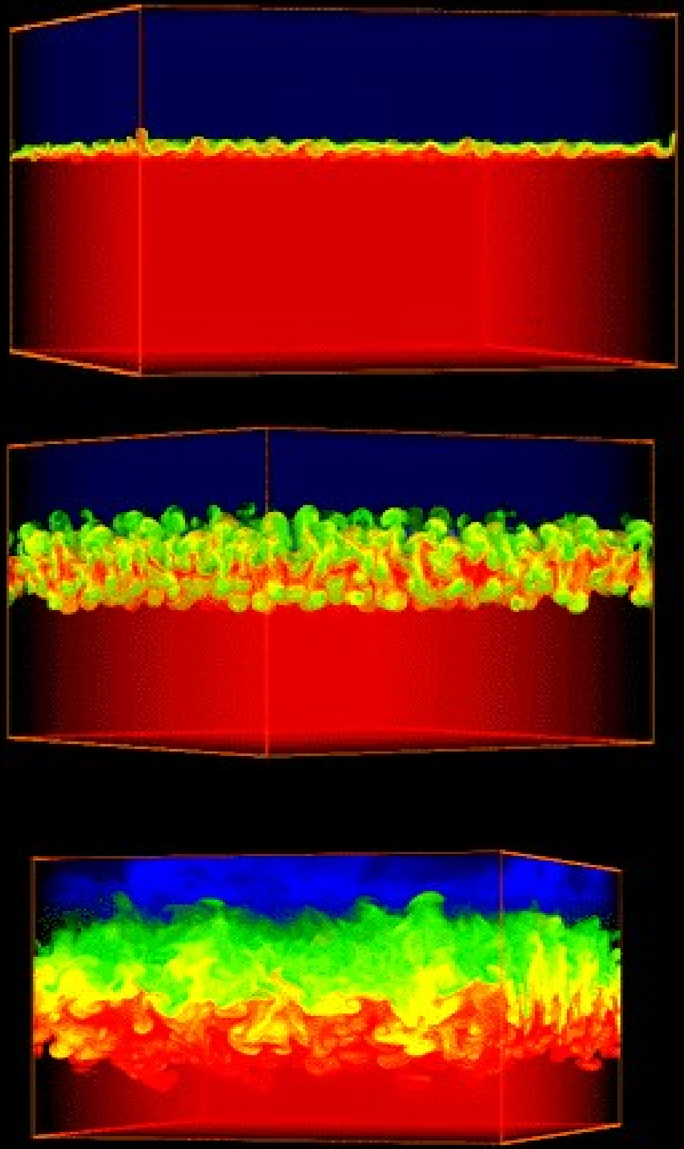
Rayleigh Taylor Instability



Rayleigh Taylor Instability

$$h_b = \alpha_b A_o g t^2$$

$$A_i = \frac{\bar{\rho}_+ - \bar{\rho}_-}{\bar{\rho}_+ + \bar{\rho}_-}$$



Dimonte & Tipton Â06 Turbulence Model

based on buoyancy-drag models for RT and RM instabilities: **self-similar, conserves energy, preserves Galilean invariance, works with shocks**

K = Turbulent KE , L= Turbulent Length Scale

$$\frac{\partial \bar{\rho} K}{\partial t} + \frac{\partial \bar{\rho} K \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_K}\frac{\partial K}{\partial x_j}\right) - R_{i,j}\frac{\partial \tilde{u}_i}{\partial x_j} + S_K$$

turb. diffusion

work associated with turbulent stress

source term with RM and RT contributions

$$\frac{\partial \bar{\rho} L}{\partial t} + \frac{\partial \bar{\rho} L \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_L}\frac{\partial L}{\partial x_j}\right) + \bar{\rho} V + C_C \bar{\rho} L \frac{\partial \tilde{u}_i}{\partial x_i},$$

turb. diffusion

growth of eddies through turb. motion

growth of eddies through motion in mean flow

$$S_K = \bar{\rho} V \left[C_B A_i g_i - C_D \frac{V^2}{2} \right], \qquad \mu_T = C_\mu \bar{\rho} L V, \qquad V \equiv \sqrt{2K}$$

buoyancy

drag

turb. viscosity

turb. velocity

Modified fluid equations

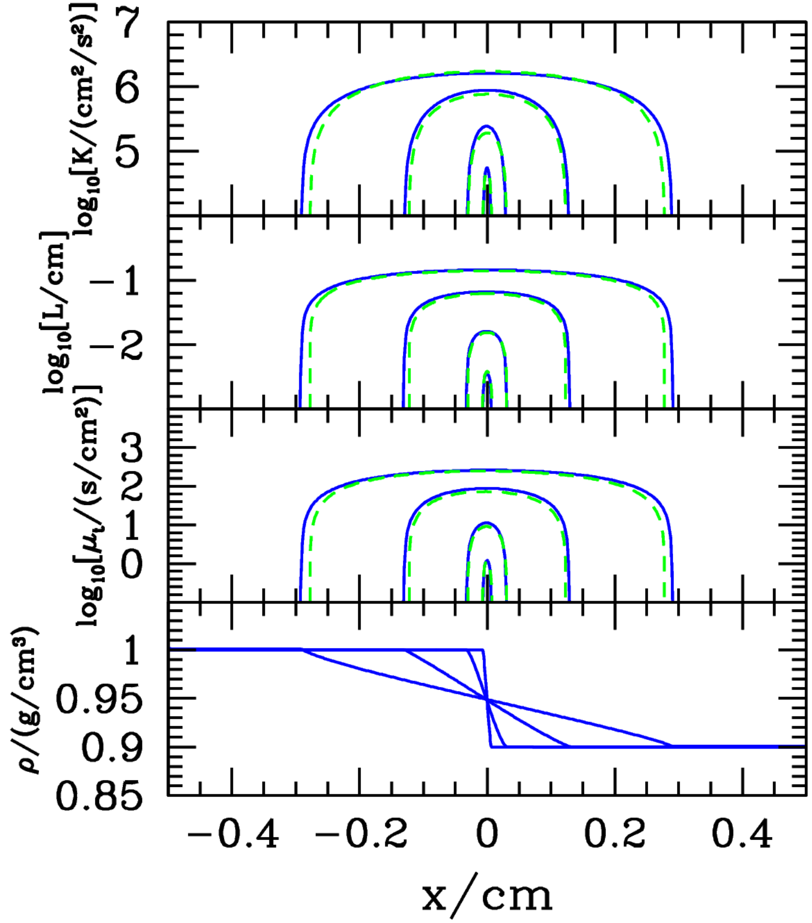
leading order in expansion around mean velocity: mean quantities are modified by presence of

1. Reynolds stress R
2. Turbulent viscosity, mu
3. Source term S_K

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} - \frac{\partial R_{i,j}}{\partial x_j}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho E u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_E}\frac{\partial E}{\partial x_j}\right) - \frac{\partial P u_j}{\partial x_j} - S_K$$

Rayleigh-Taylor Shock Tube Test from DT06



solid: simulation
dashed: analytic

$$L(x,t) = L(t,0)[1 - x^2/h(t)^2]^{1/2}$$

$$K(x,t) = K(t,0)[1 - x^2/h(t)^2]$$

$$h(t) = \alpha A(0) t^2$$

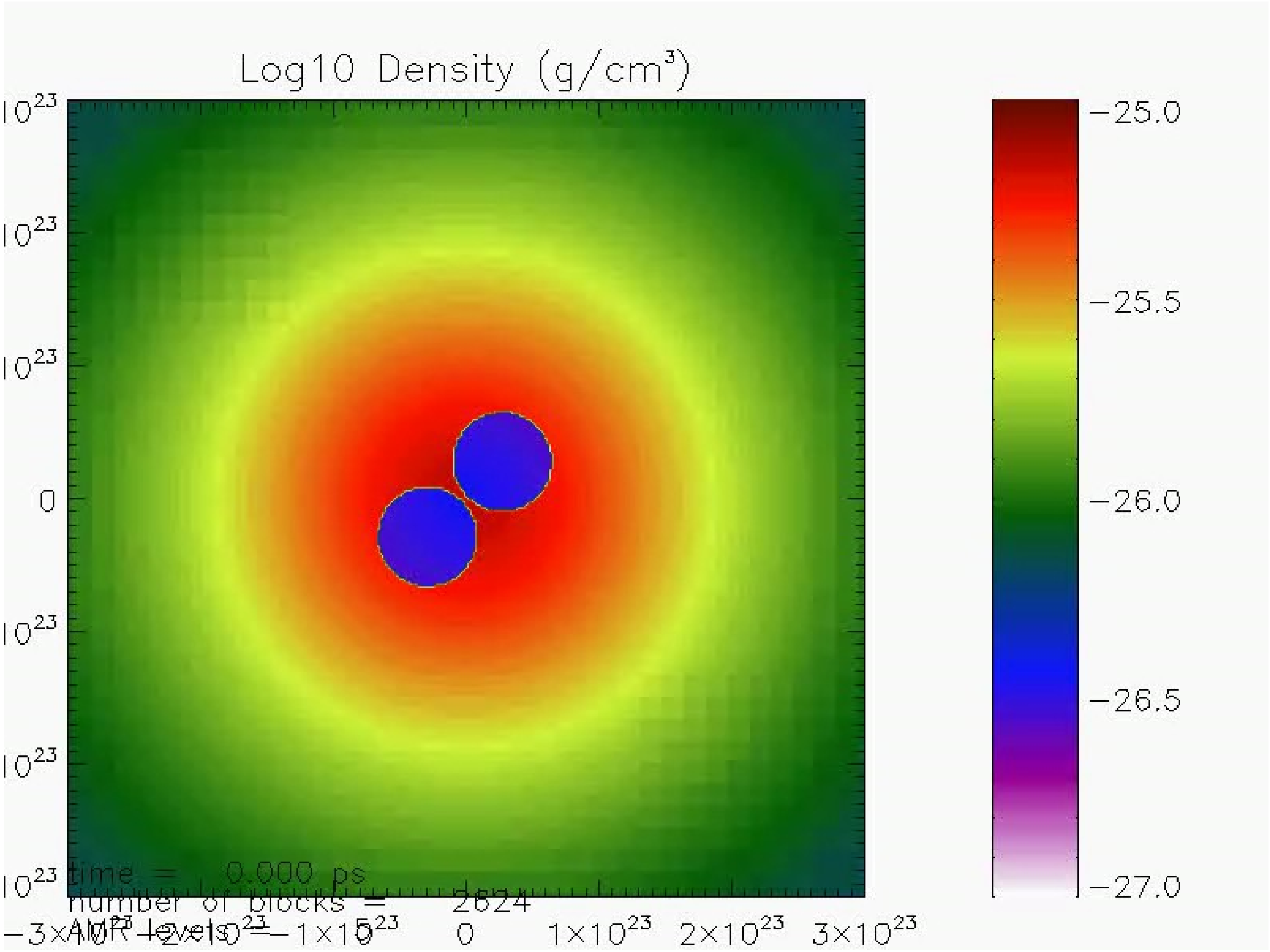
$$L(t,0) = h(t)/2$$

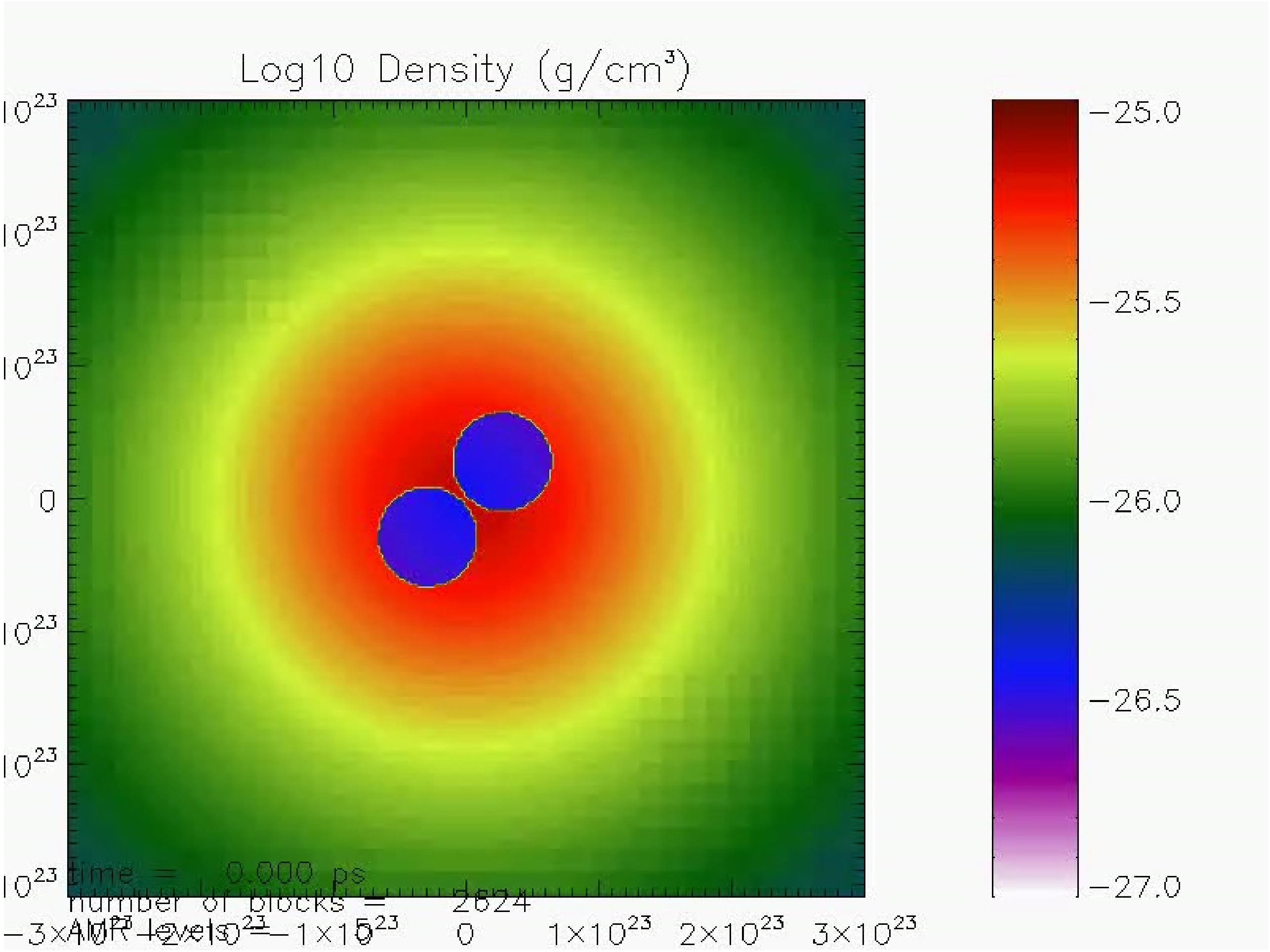
$$K(t,0) = (dh/dt)^2/2$$

K, L and mu increase as t^2 -> rapid mixing between materials

Simulation setup

- numerical implementation in FLASH3.0 framework
- Equations for K and L are evolved explicitly (with addl. timestep constraint)
- momentum and energy equation modified by source term, Reynolds tensor and turbulent viscosity
- initially hydrostatic cluster, static gravity
- 5 levels of refinement (3-6), 1024^3 eff. res., (650 kpc)^3 box
- bubbles are produced by
  (a) evacuation in pressure equilibrium
  (b) injection of energy into spherical regions (Sedov-type), r = 10 kpc
- metal injection proportional to light distribution
- metal fraction in each cell represented by mass scalar
- radiative cooling by thermal bremsstrahlung


Log10 Density (g/cm³)
time = 0.000 ps
number of blocks = 2624
AMR levels = 5
−3×10²³
−2×10²³
−1×10²³
0
1×10²³
2×10²³
3×10²³
−25.0
−25.5
−26.0
−26.5
−27.0


Log10 Density (g/cm³)
10²³
10²³
10²³
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10²³
10²³
10²³
−3×10²³
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−1×10²³
0
1×10²³
2×10²³
3×10²³
time = 0.000 ps
number of blocks = 2624
AMR levels = 5
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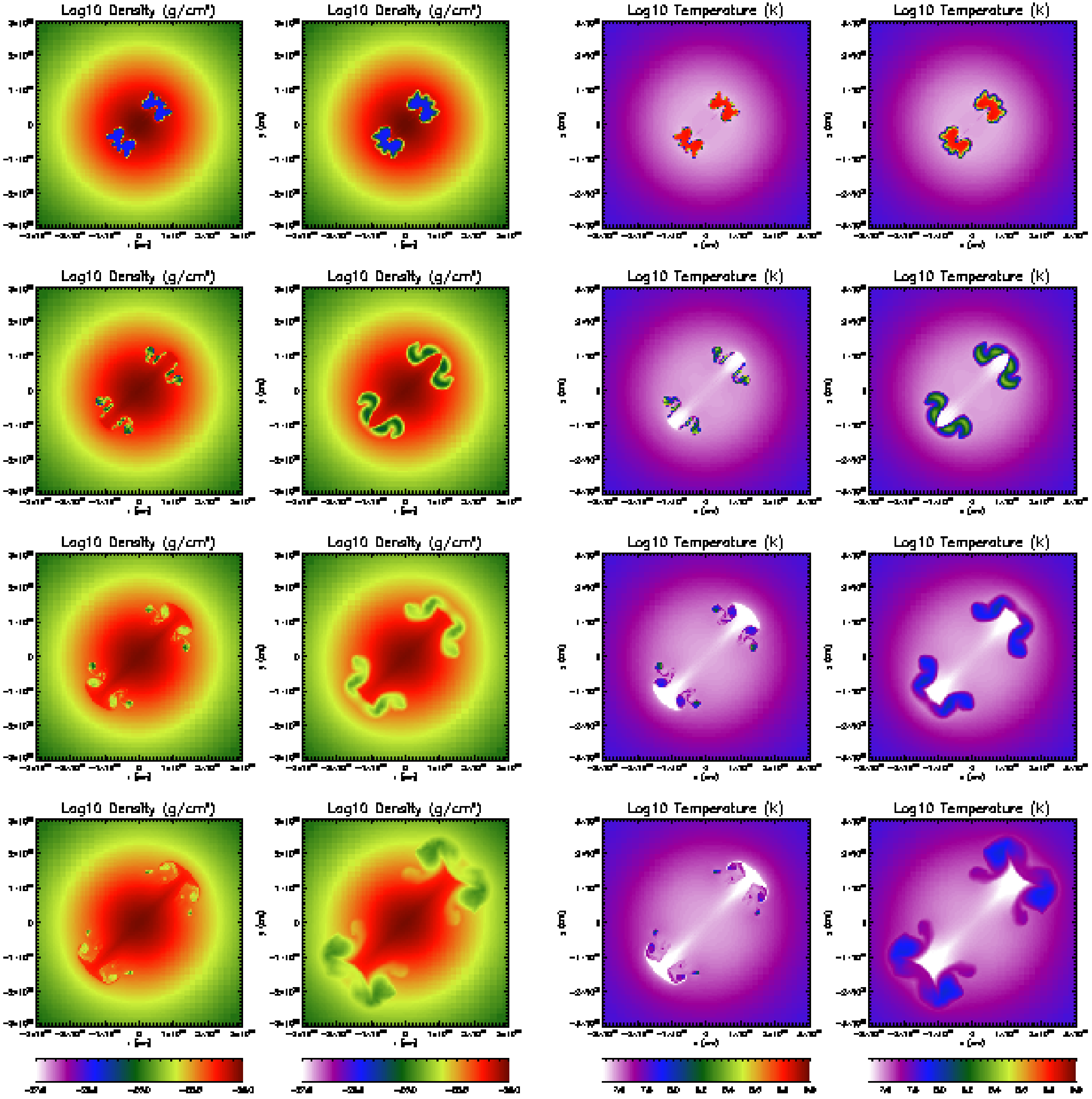
−25.5
−26.0
−26.5
−27.0



50 Myr

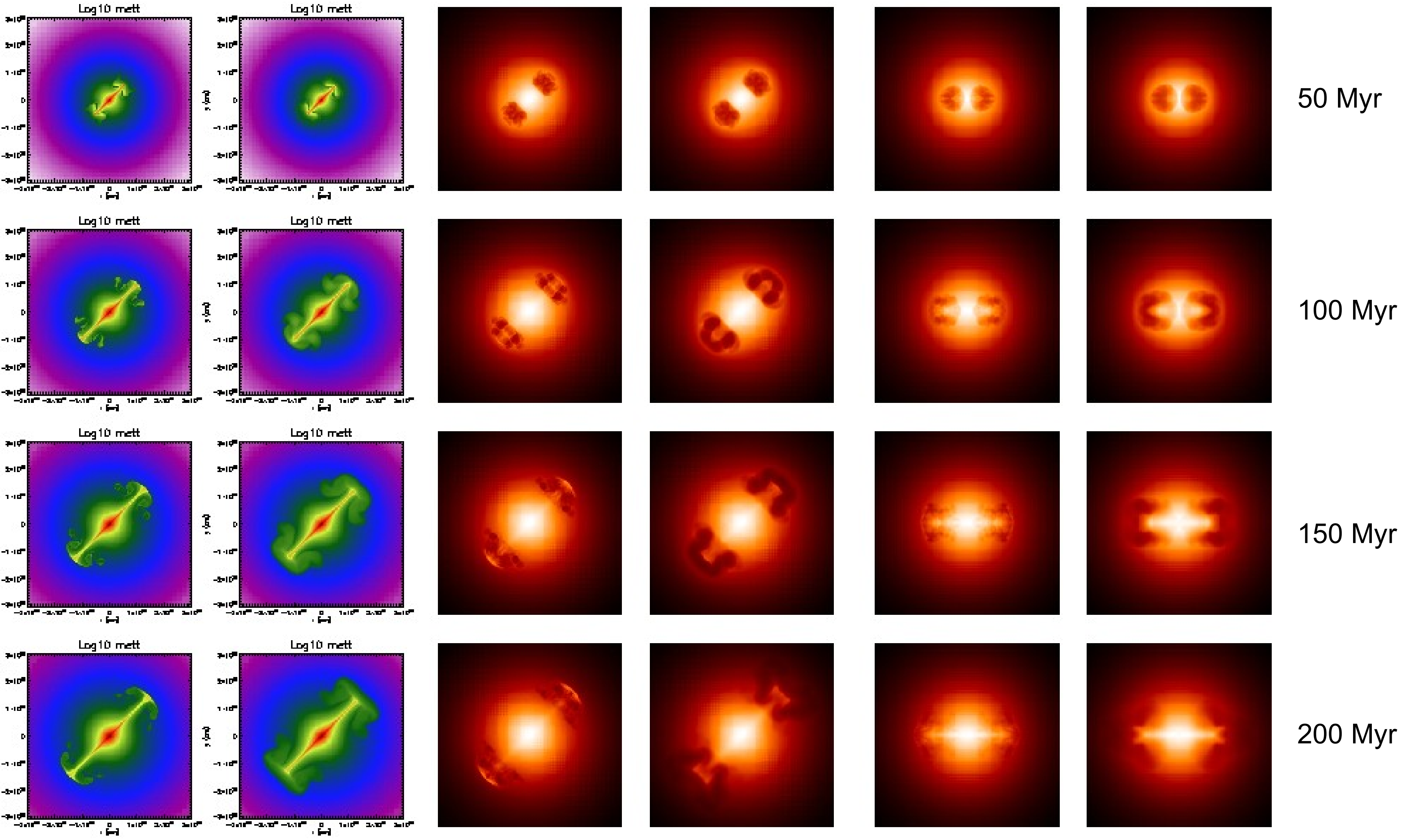
100 Myr

150 Myr

200 Myr

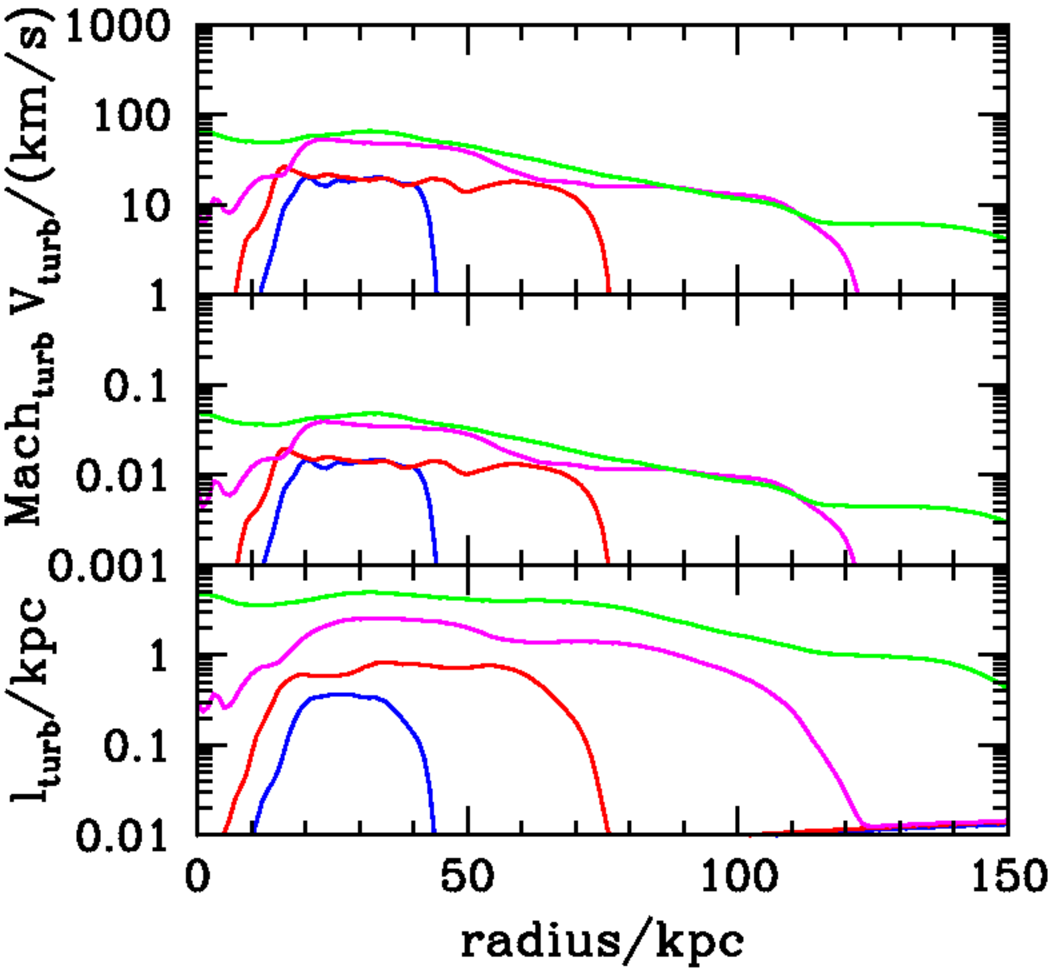
with subgrid

with subgrid

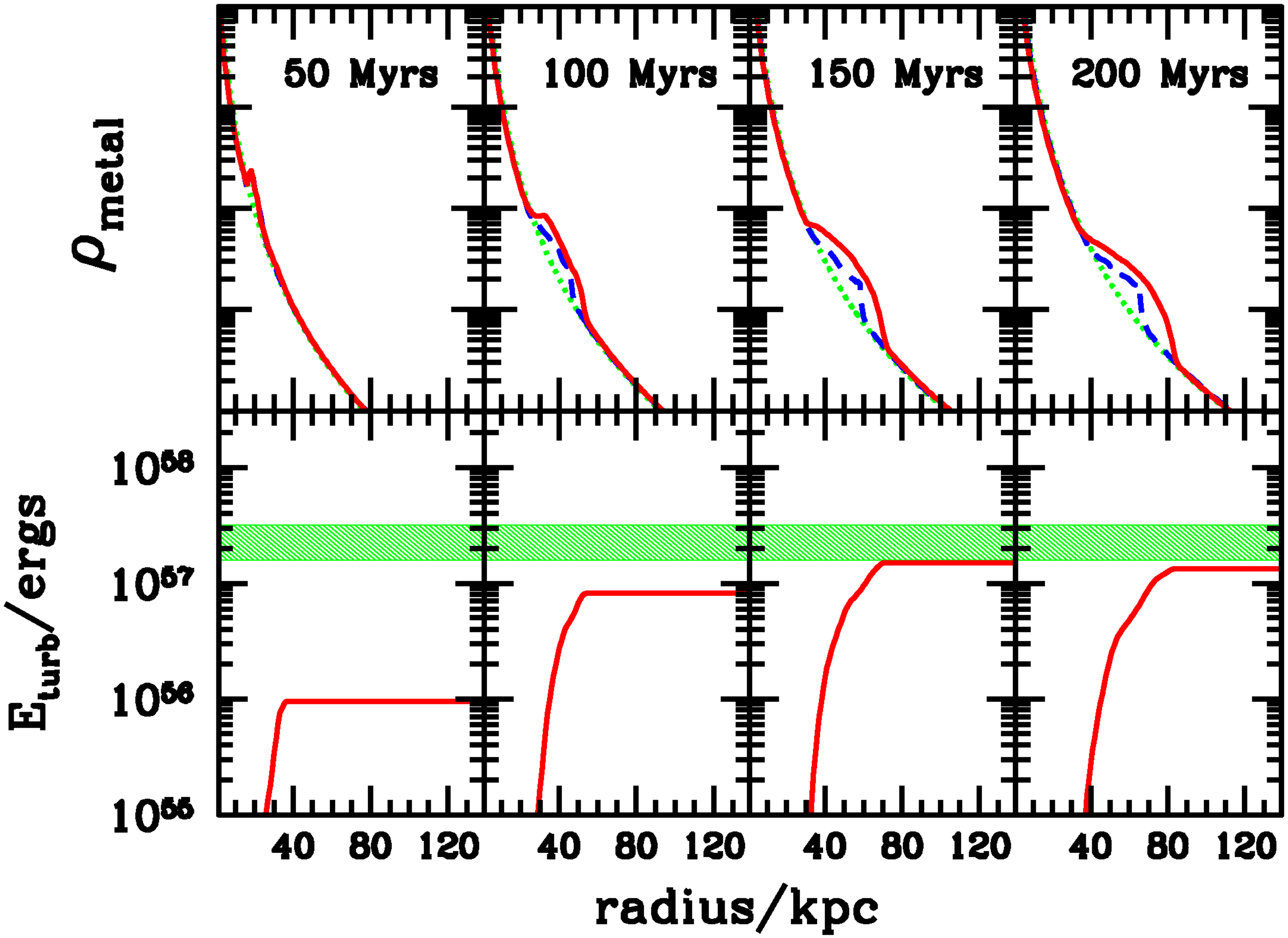


metals

X-ray emission



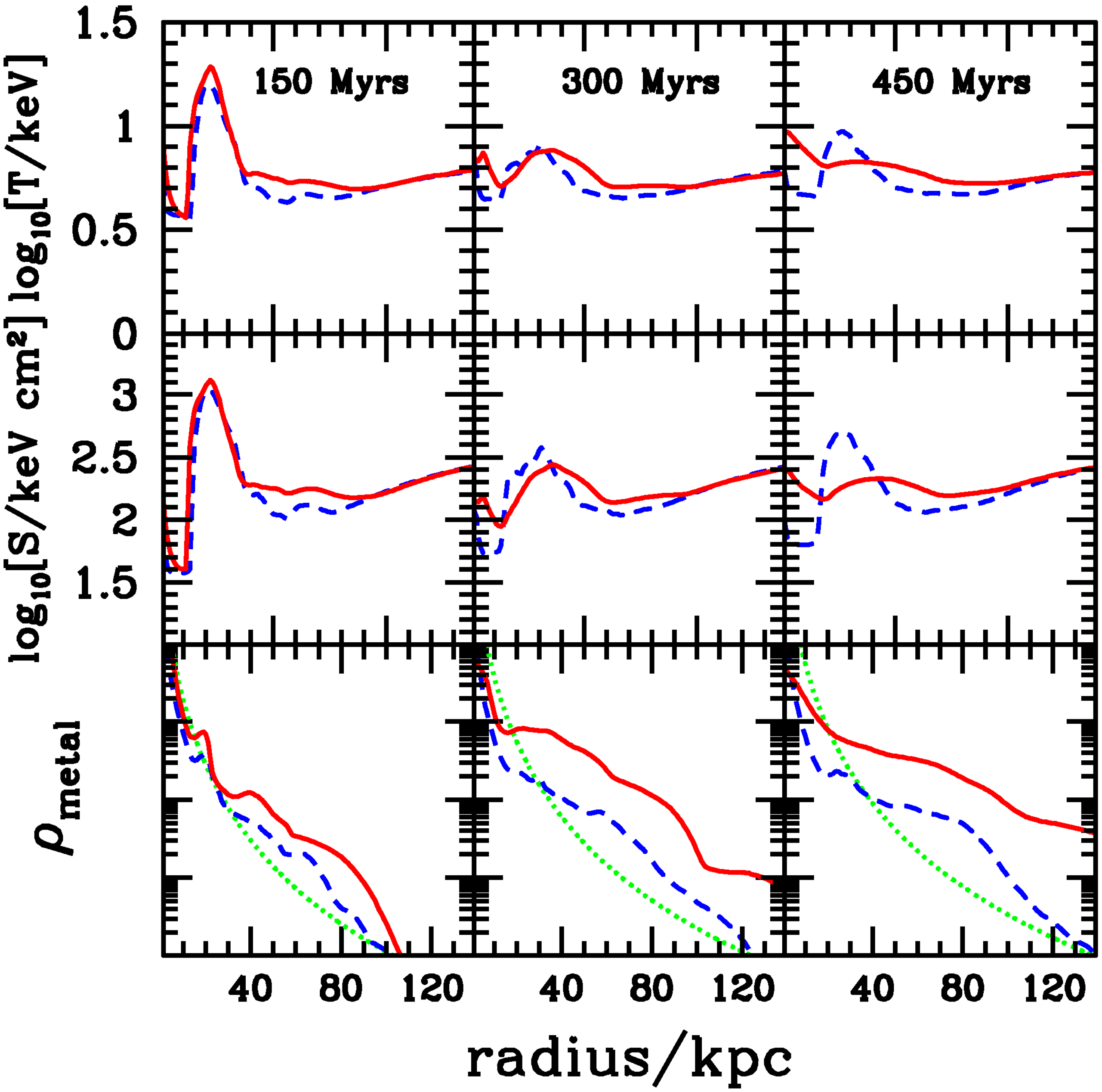
turb_profile_AE



red: subgrid
blue: w/o subgrid

1-2% of E_buoy

radialES



T increase not due to turbulent dissipation but mixing

red: with subgrid
blue: w/o subgrid
green: no bubbles

periodic evacuated bubble run

radialER

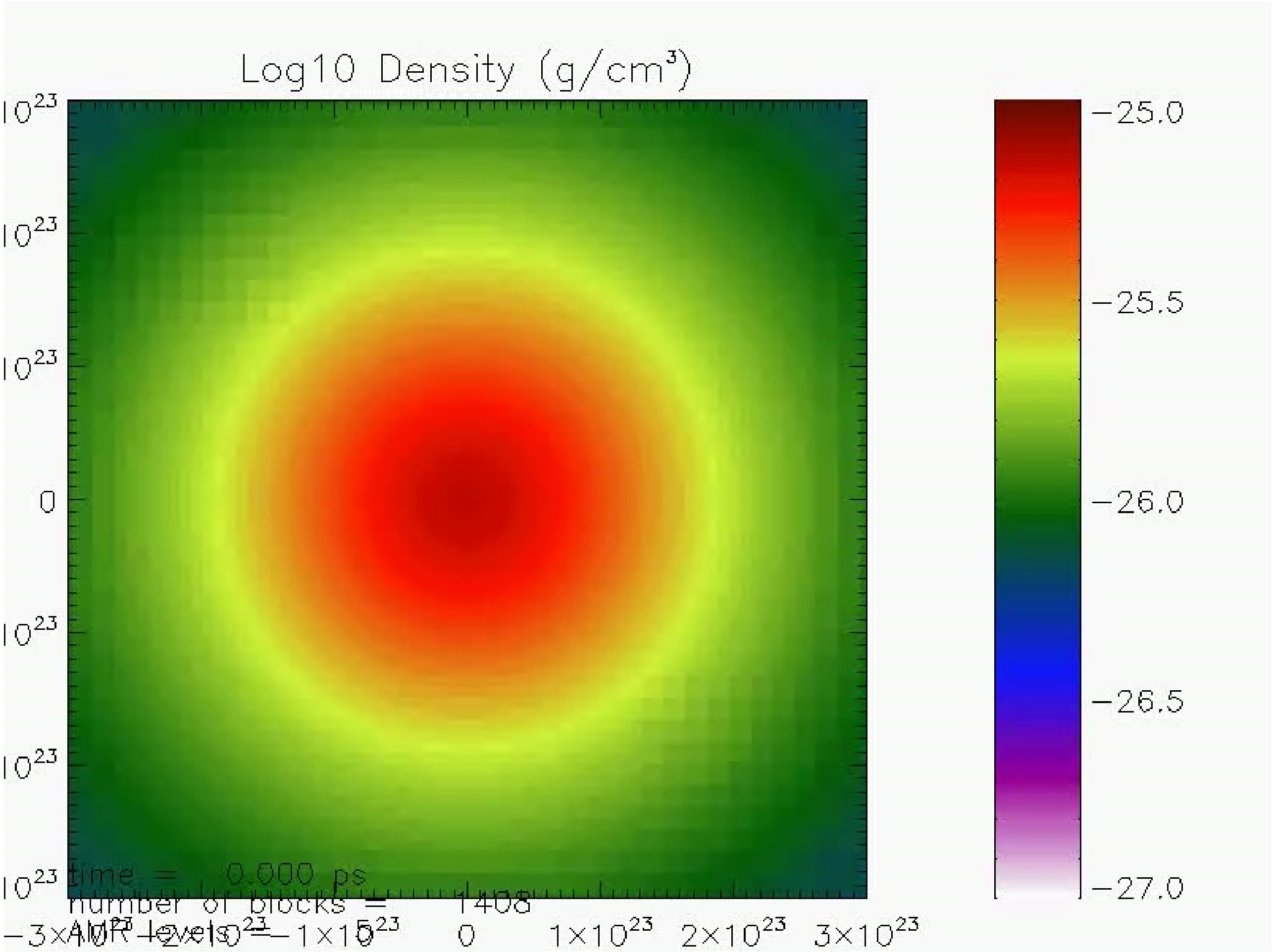
In pure hydro run, bubbles fragment after single pressure scale height.

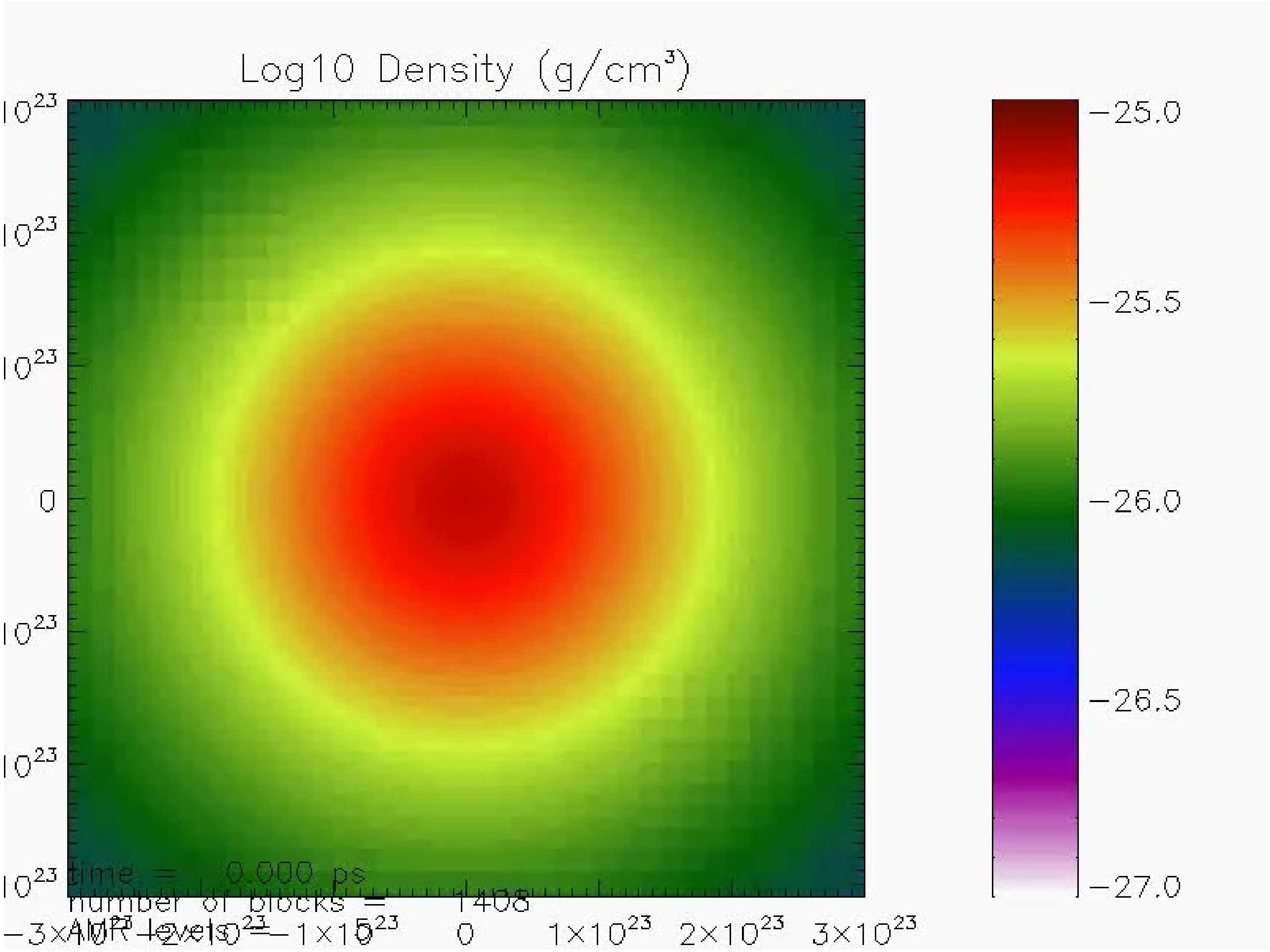
Dominant unstable modes are set by grid resolution.

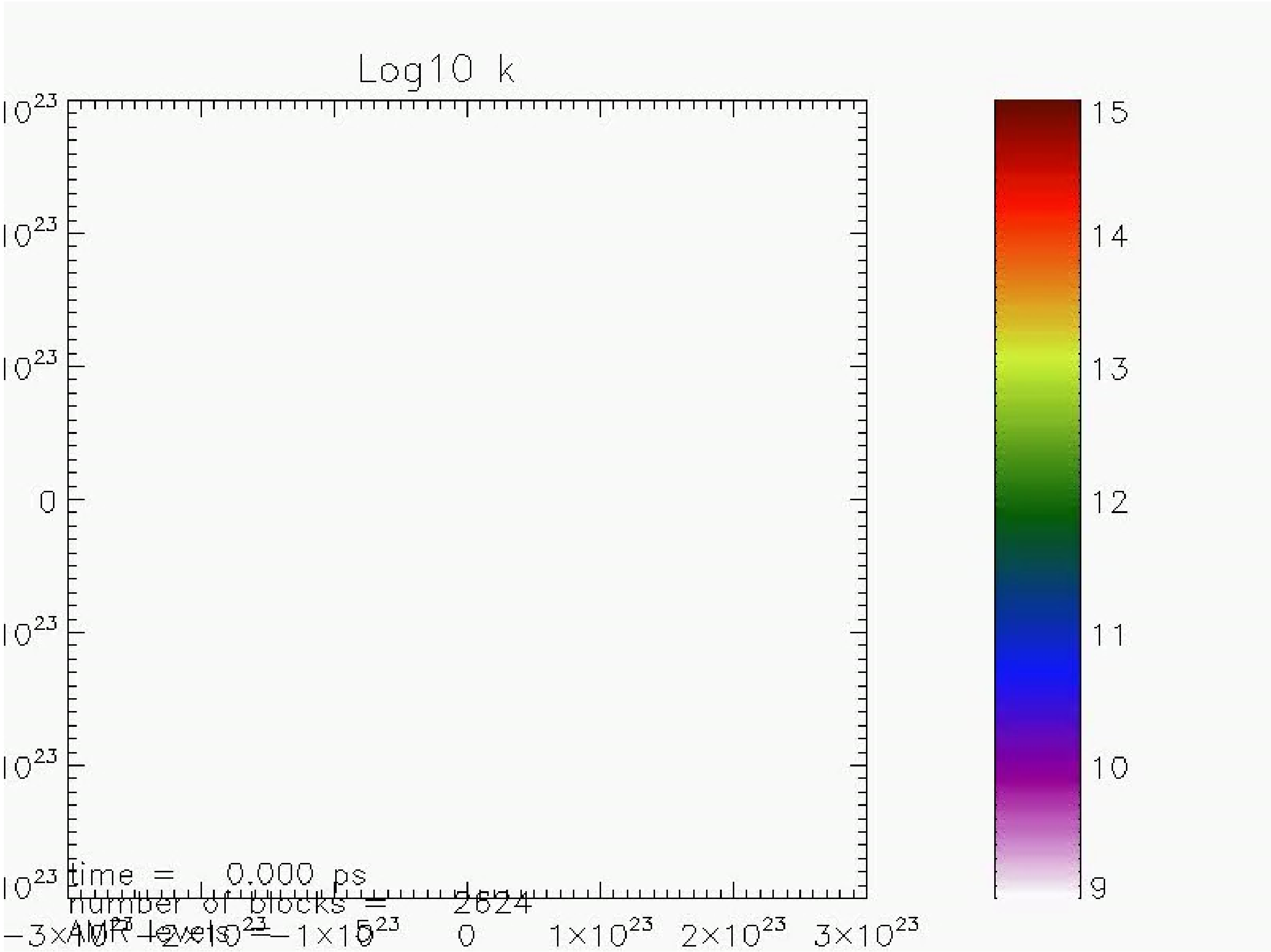
Subgrid models captures growth of modes that the grid cannot resolve.

It smears out the interface between bubble and ambient medium and keeps the bubbles intact.

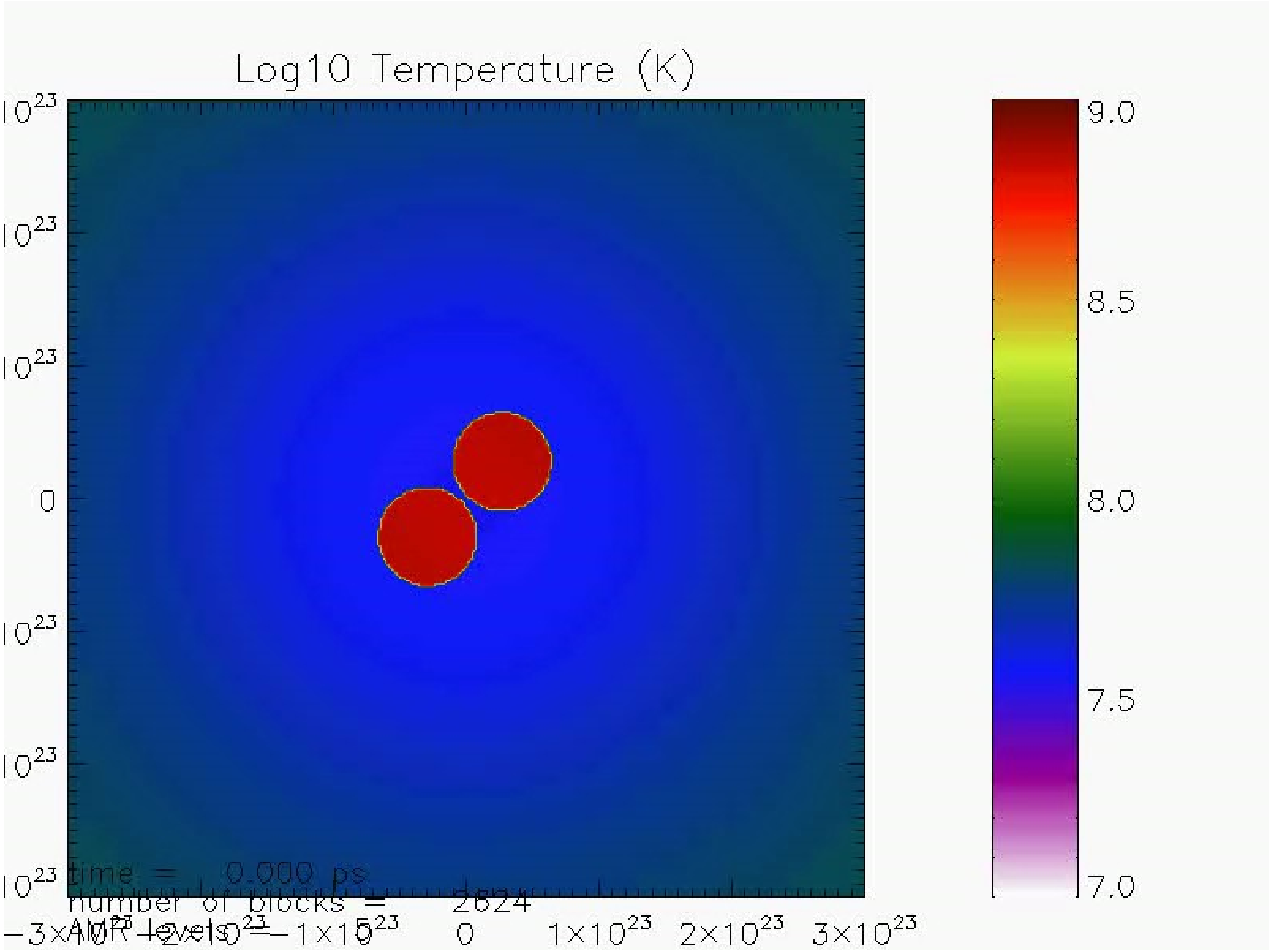
Metal transport is enhanced.


Log10 Density (g/cm³)
−25.0
−25.5
−26.0
−26.5
−27.0
0
10²³
−3×10²³
−2×10²³
−1×10²³
0
1×10²³
2×10²³
3×10²³
time = 0.000 ps
number of blocks = 1408
AMR levels = 5

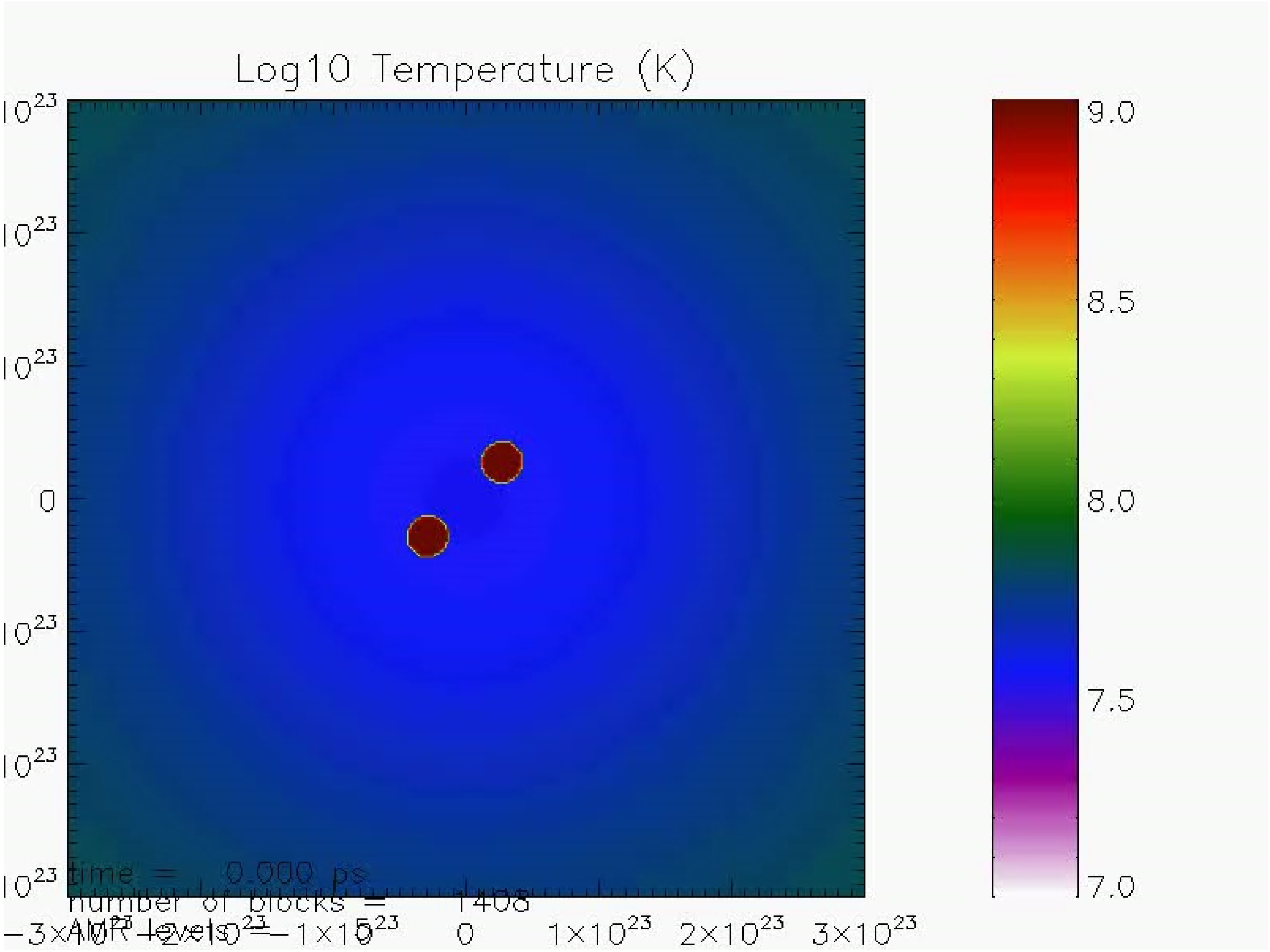

Log10 Density (g/cm³)
10^23
10^23
10^23
0
10^23
10^23
10^23
−3×10^23
−2×10^23
−1×10^23
0
1×10^23
2×10^23
3×10^23
time = 0.000 ps
number of blocks = 1408
AMR levels = 5
−25.0
−25.5
−26.0
−26.5
−27.0


Log10 k
time = 0.000 ps
number of blocks = 2624
AMR levels =
−3×10^23 −2×10^23 −1×10^23 0 1×10^23 2×10^23 3×10^23
0
15
14
13
12
11
10
9

DAES-k


Log10 Temperature (K)
10^23
10^23
10^23
0
10^23
10^23
10^23
−3×10^23
−2×10^23
−1×10^23
0
1×10^23
2×10^23
3×10^23
time = 0.000 ps
number of blocks = 2624
AMR levels =
9.0
8.5
8.0
7.5
7.0

DAES-temp

Log10 Temperature (K)
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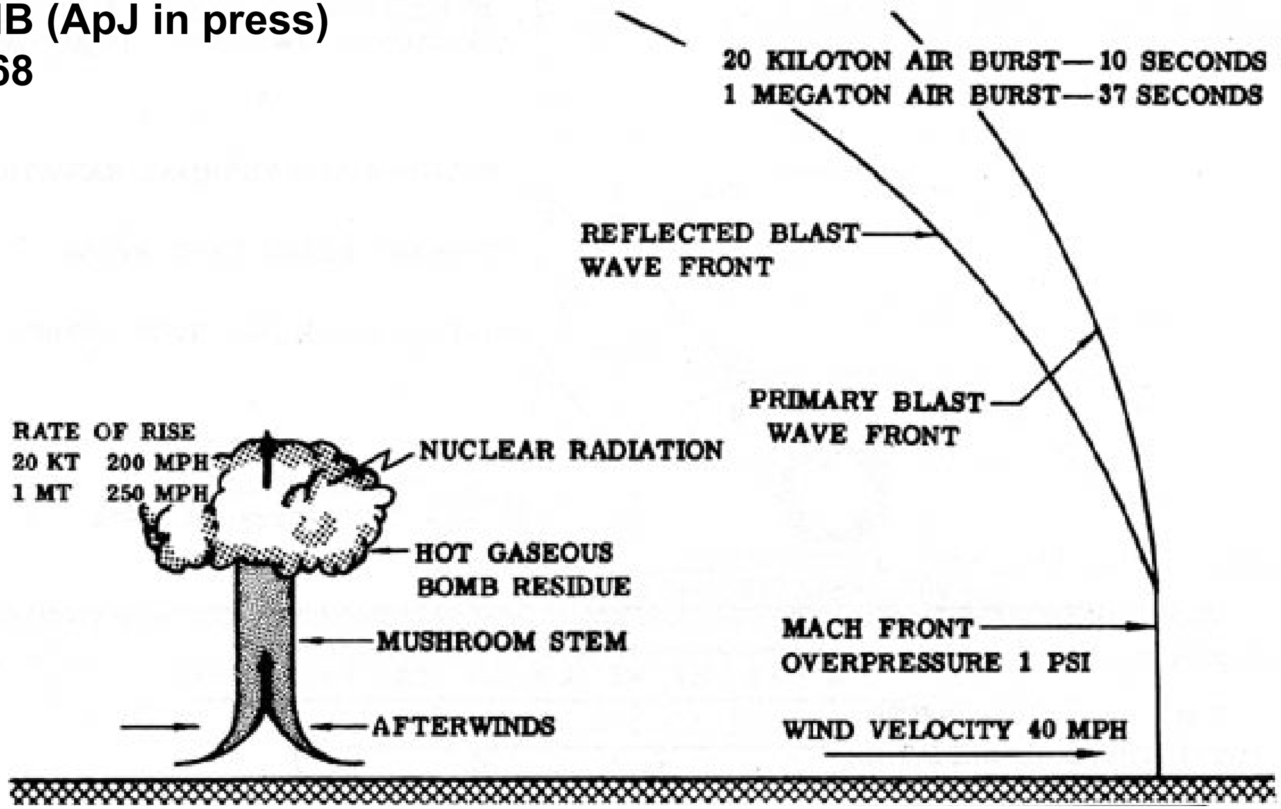
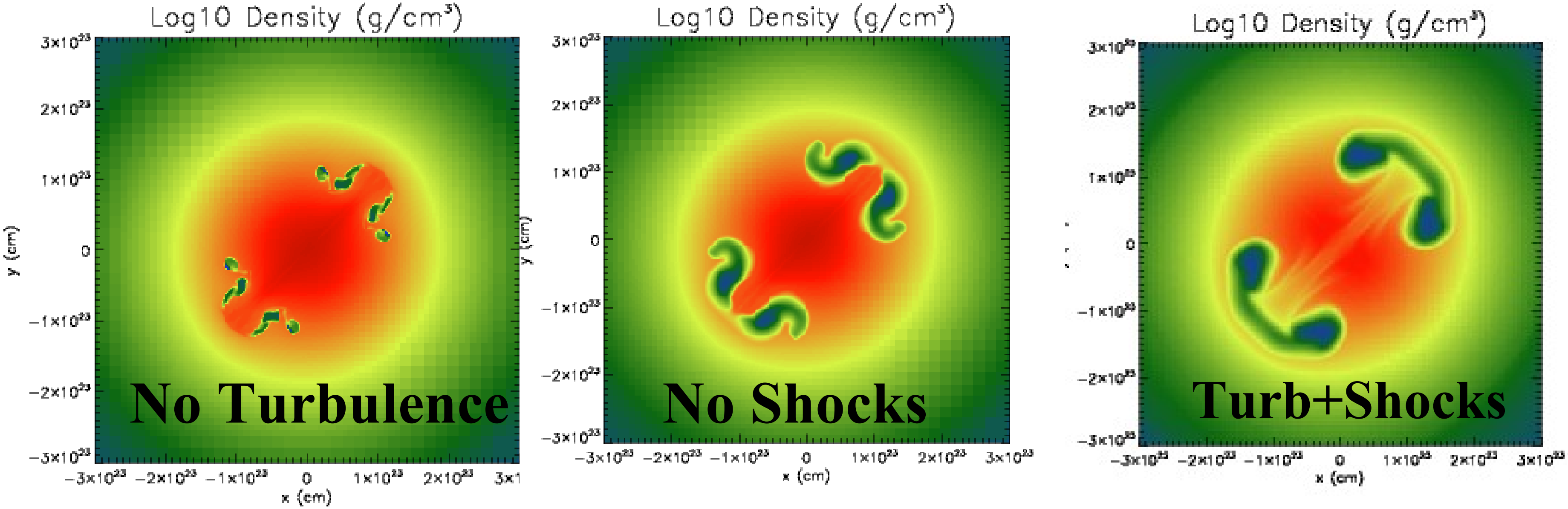
−2×10^23
−1×10^23
0
1×10^23
2×10^23
3×10^23
9.0
8.5
8.0
7.5
7.0

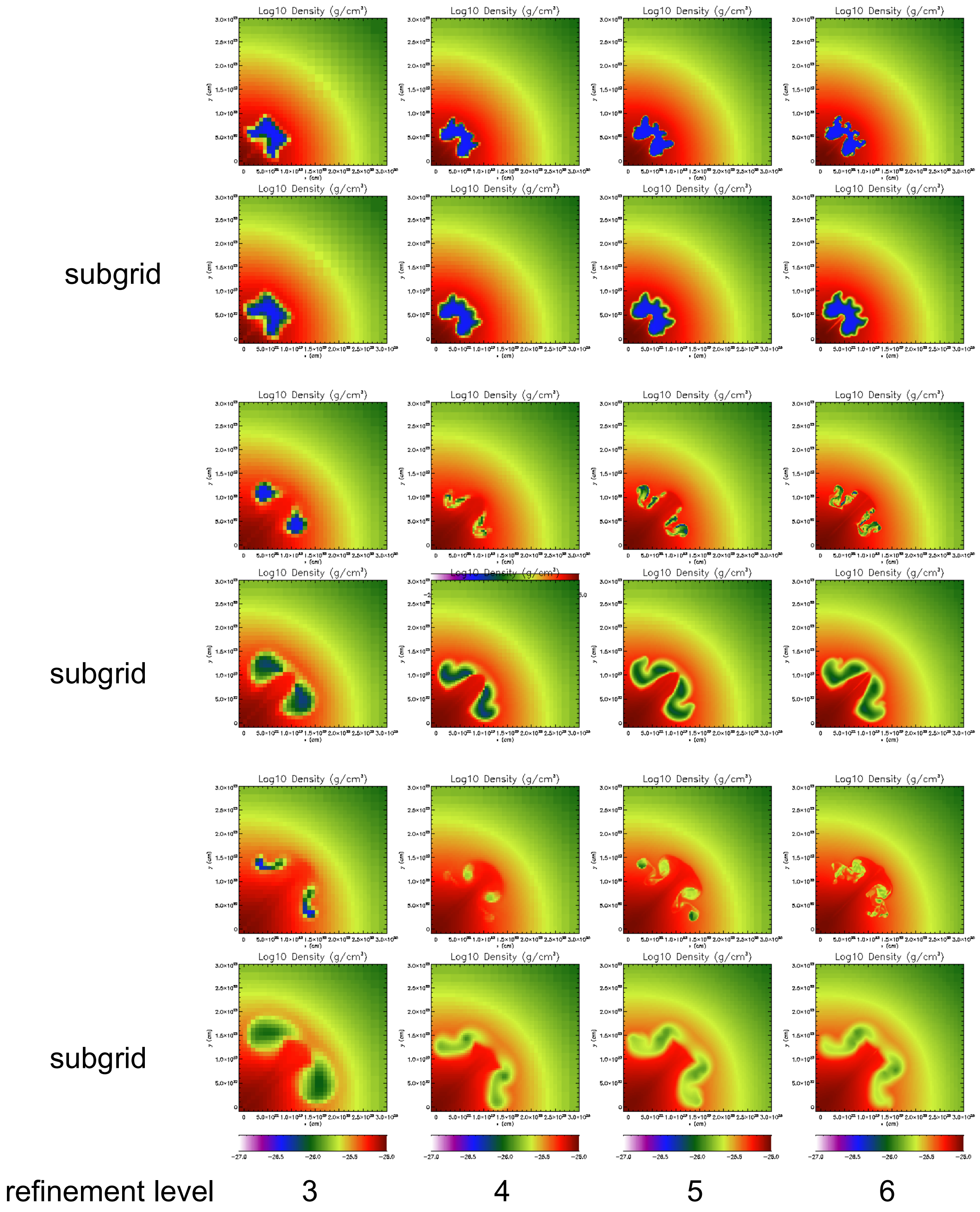
DASS-temp

Scannapieco & MB (ApJ in press)
astro-ph 0806.3268





Dependence on resolution



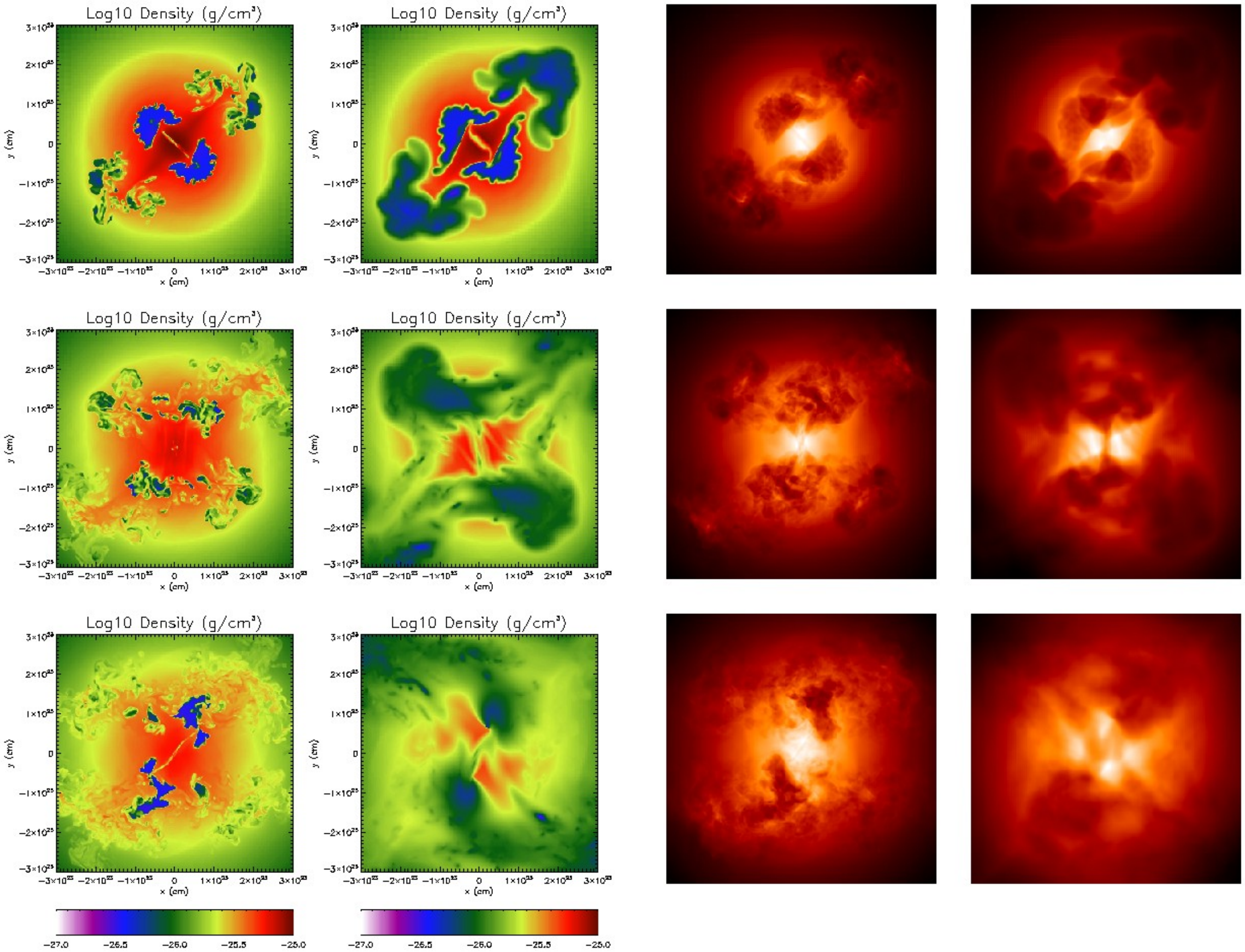
$$\lambda_{\max} = 4\pi(\nu^2 A/g)^{1/3}$$

$$\mathrm{Re} \sim 2000 - 5000$$

$$\nu \sim dv/\mathrm{Re} \sim 3\,\mathrm{km\,s^{-1}kpc}$$

$$\lambda_{\max} \sim 2\,\mathrm{kpc}$$

w/o subgrid with subgrid corresponding unsharp-masked X-ray images



150 Myr

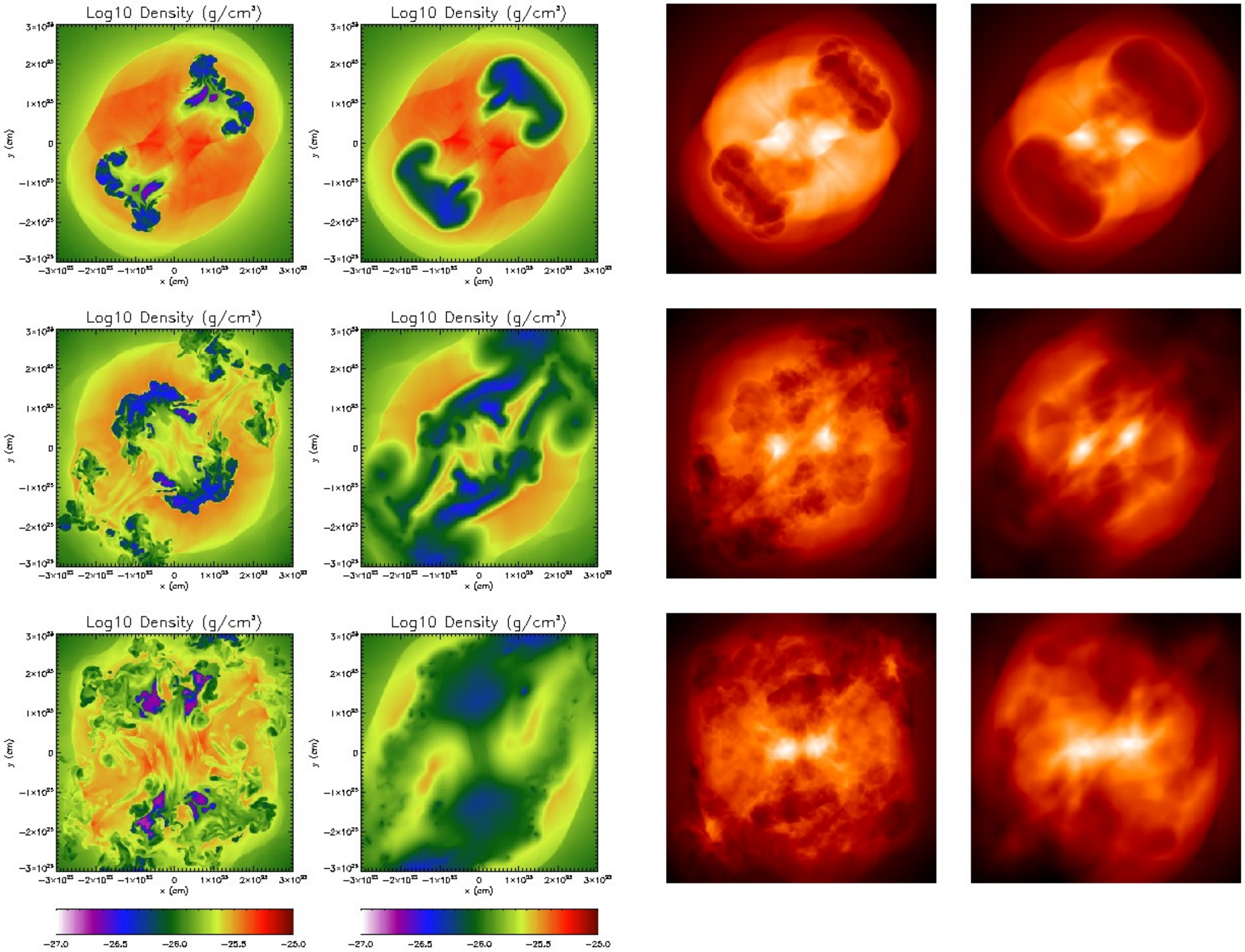
300 Myr

450 Myr

periodic evacuated bubble run

periodic mean

w/o subgrid with subgrid corresponding unsharp-masked X-ray images



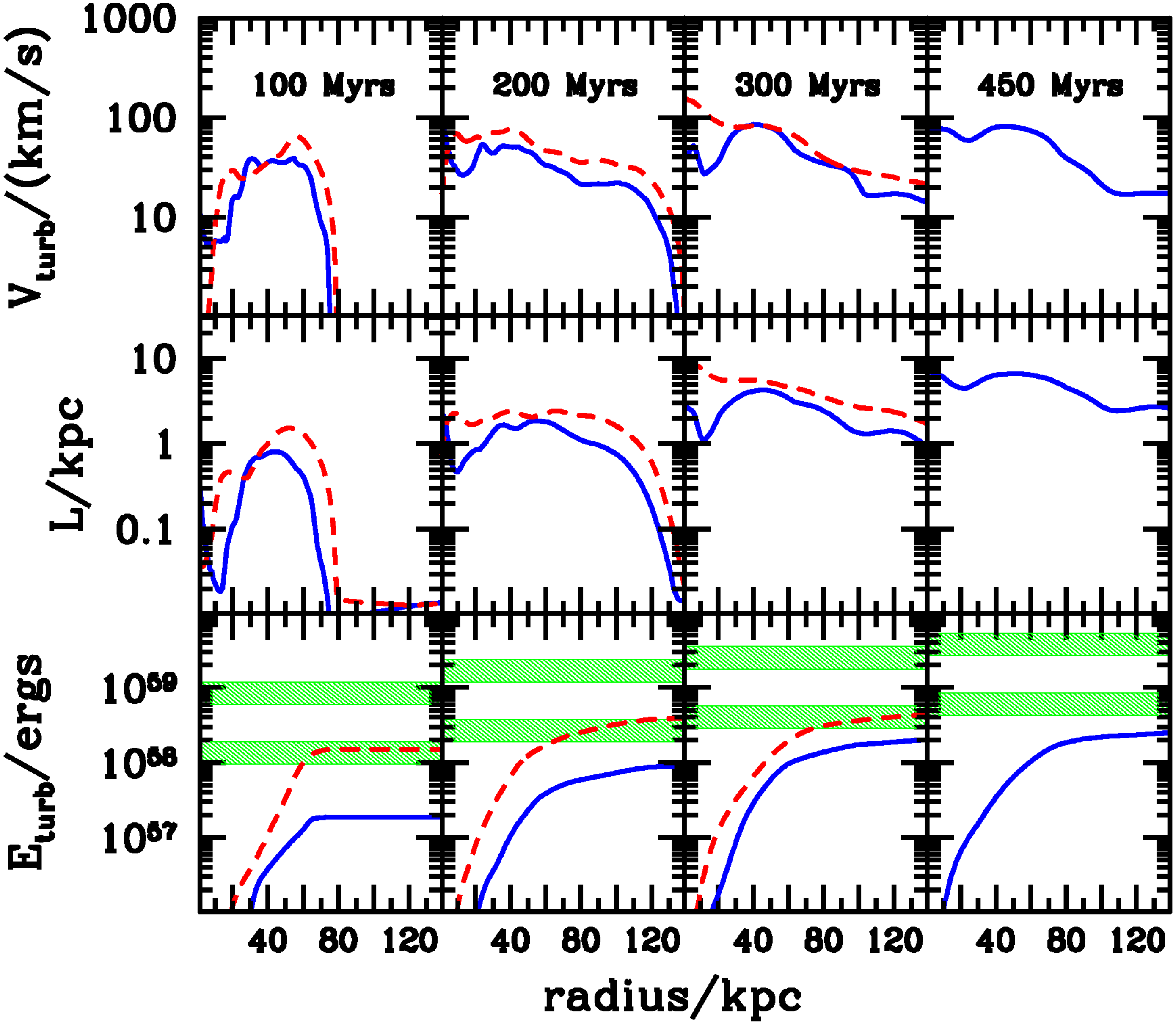
100 Myr

200 Myr

300 Myr

periodic Sedov bubble run

periodic mean shock



red: Sedov

blue: evacuated bub

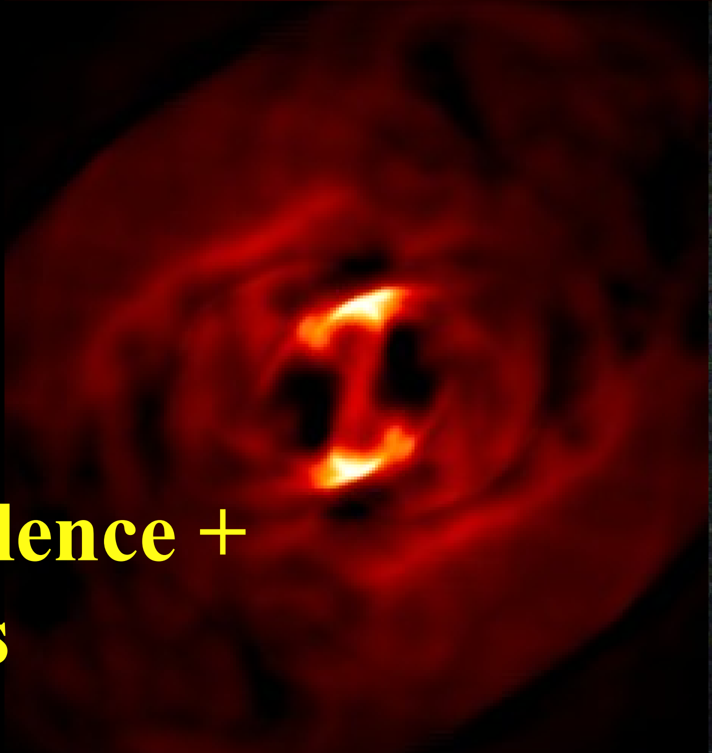
1-2% of E_exp + E_buoy

1-2% of E_buoy

radialTR

No Turbulence
No Shocks

Turbulence
No Shocks



Turbulence +
Shocks

Perseus A

Conclusions

- We tried a K-L subgrid model to study the RT and RM driven turbulence in galaxy clusters.

- RT and RM instabilities that drive the evolution of bubbles result in motions on many scales that are far below the resolution limit of current simulations. The superposition of unstable modes smears out the interface between bubbles and ambient medium and prevents break-up of bubbles. This mixing explains the appearance of X-ray cavities. Subgrid models are needed to capture this physics.

- Subgrid turbulence enhances metal transport in clusters; typical turbulent diffusivity: 500 km/s kpc - in line with observations of metal profiles in Perseus

- Turbulent energy is about 1% of total energy in bubbles available to heat the cluster. Subgrid turbulence plays no role in heating cool cores.

- Turbulent motions can be probed with Con-X.

- In simulations where RT and RM instabilities occur, proper treatment of subgrid physics can be essential!