Simulating Turbulence in galaxies and galaxy clusters

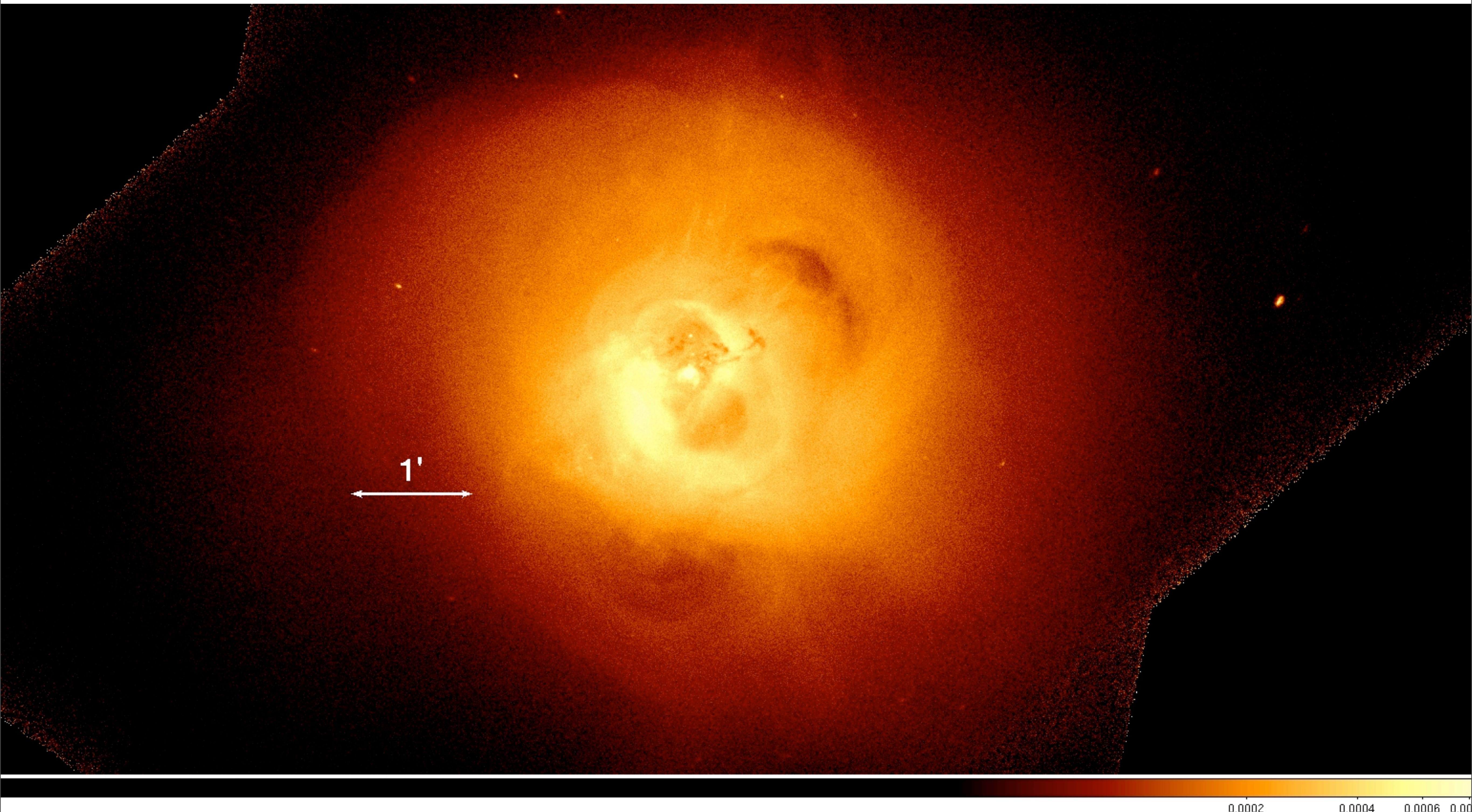
Marcus Brüggen (Jacobs University Bremen)

with help by

Evan Scannapieco (ASU)
Sebastian Heinz
Mitch Begelman
Aurora Simionescu

JACOBS
UNIVERSITY

1 Mio seconds Chandra exposure of Perseus



Slide from Bill Forman

Cool cores

peak in X-ray surface brightness coincident with drop in entropy

$$t_{\mathrm{cool}} \propto \frac{T}{n\,\Lambda}$$

$\Lambda \propto T^0$ at around 1 keV

$$t_{\mathrm{cool}} \propto T^2$$

at constant P -> cooling catastrophe

Fe XVII and other lines from 1 keV gas not present

soft X-rays are missing throughout entire cooling flow volume

Why and how is cooling of gas below $T_{vir}/3$ suppressed?

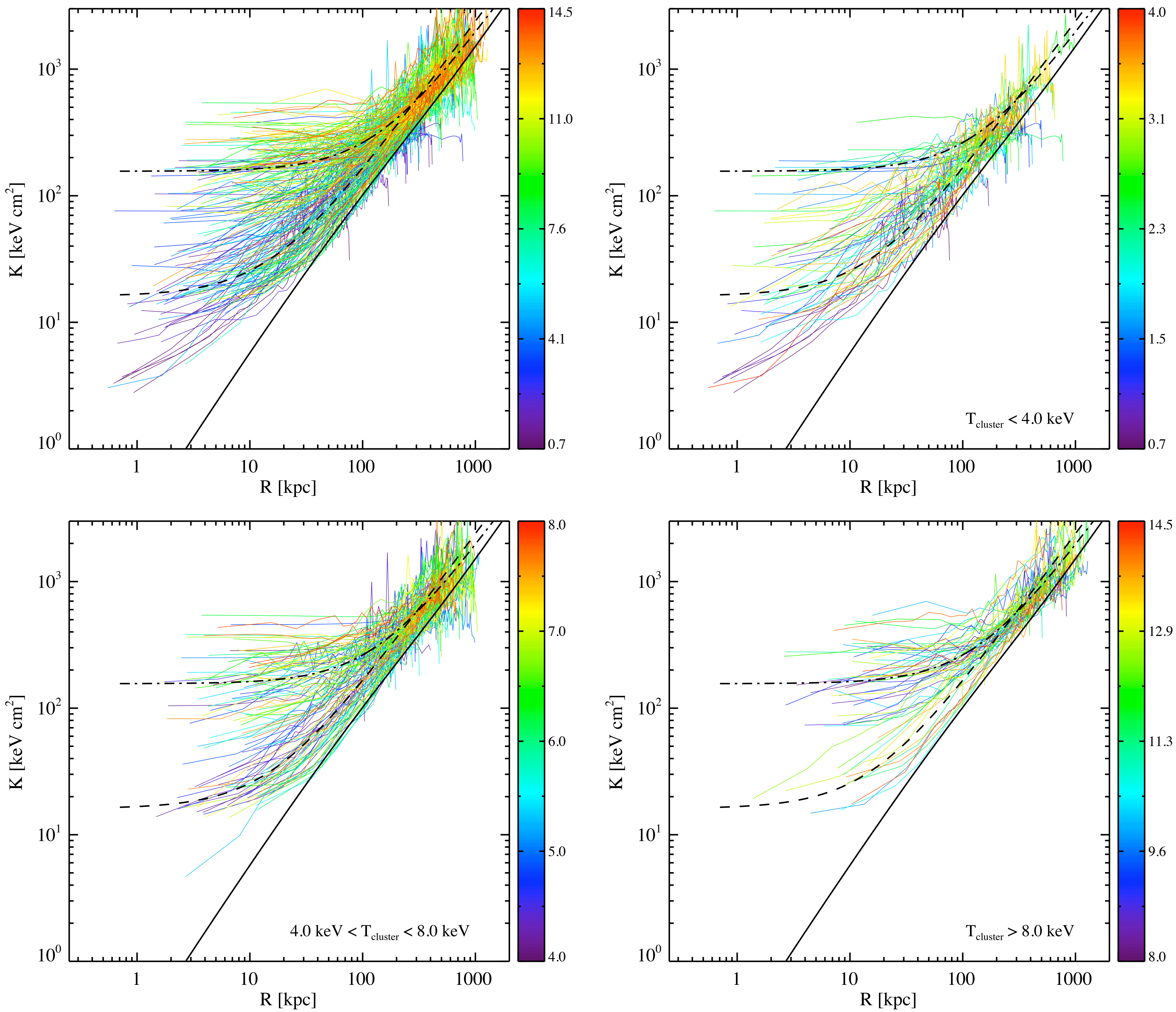


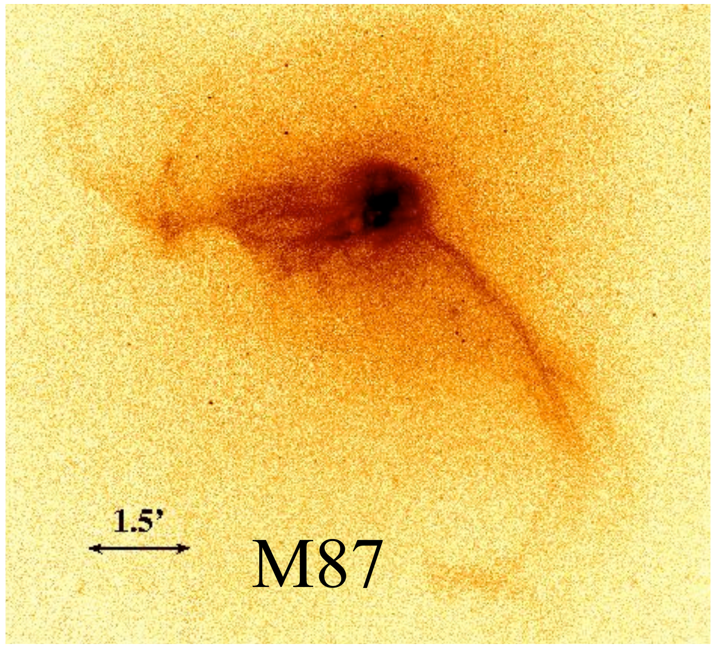
FIG. 5.— Composite plots of entropy profiles for varying cluster temperature ranges. Profiles are color-coded based on average cluster temperature. Units of the color bars are keV. The solid line is the pure-cooling model of Voit et al. (2002), the dashed line is the mean profile for clusters with $K_0 \leq 50$ keV cm^2, and the dashed-dotted line is the mean profile for clusters with $K_0 > 50$ keV cm^2. *Top left:* This panel contains all the entropy profiles in our study. *Top right:* Clusters with $kT_X < 4$ keV. *Bottom left:* Clusters with 4 keV $< kT_X <$ 8 keV. *Bottom right:* Clusters with $kT_X > 8$ keV. Note that while the dispersion of core entropy for each temperature range is large, as the kT_X range increases so to does the mean core entropy.

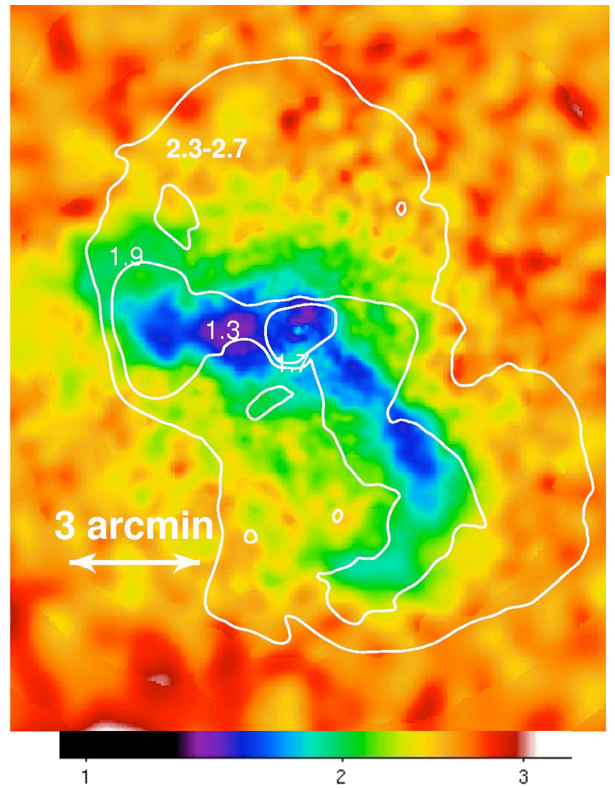
Cavagnolo et al. 2009

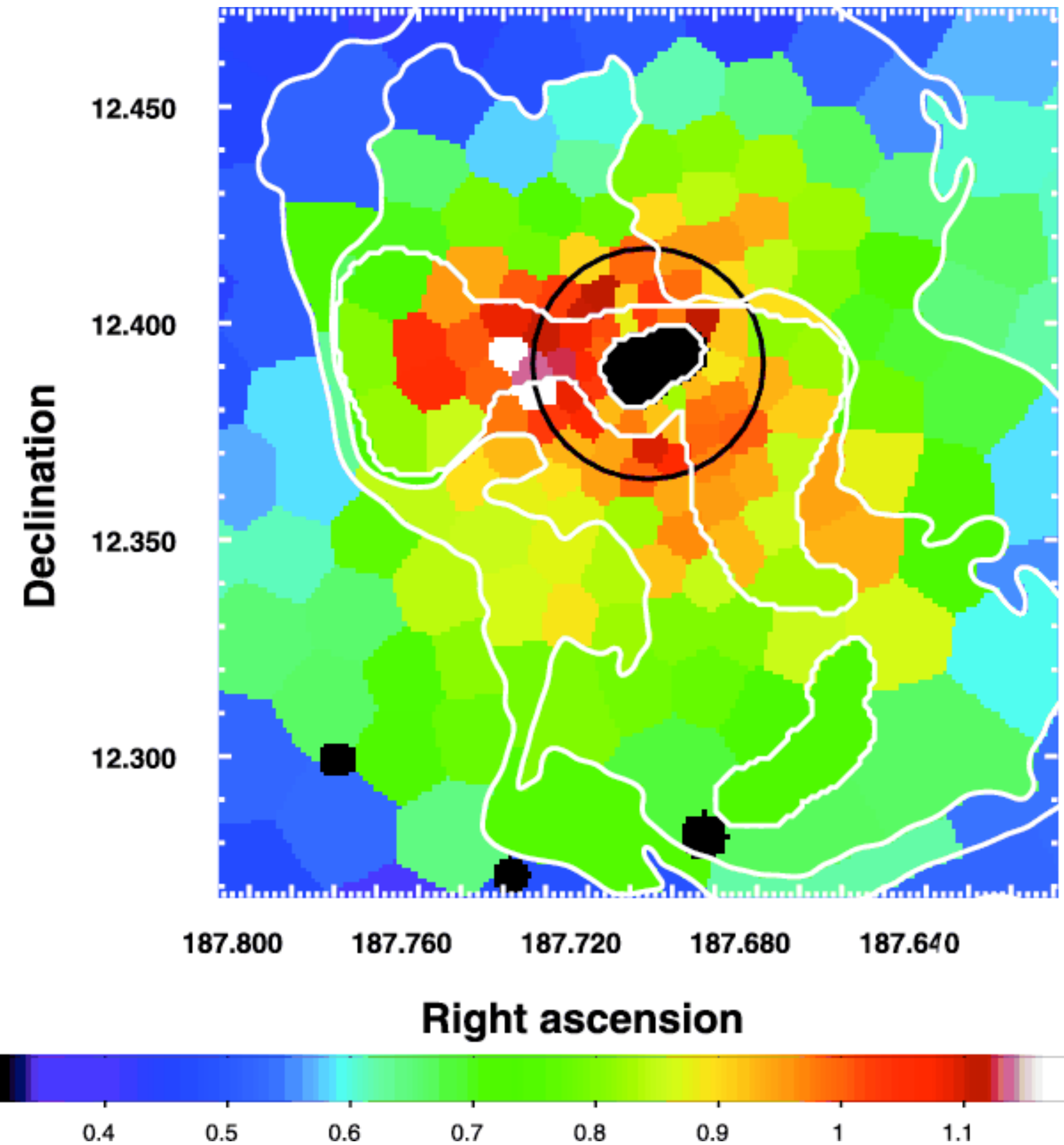
Issues

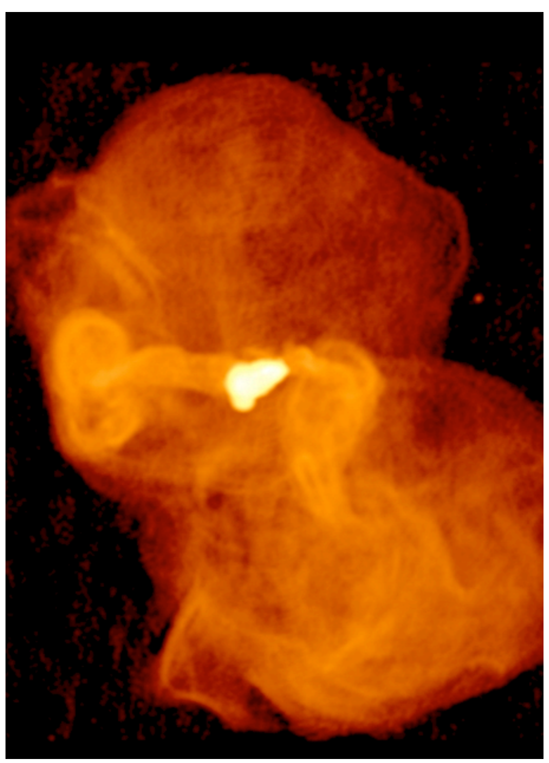
- Radiative cooling mostly balanced by heating?
- Requires continuous gentle distributed heat
- Balance has been locked in since z=0.4 (Bauer 05)
- Process must work over >10^3 in L_X and > 10 in kT
- probably looking for a single process
- here looking at AGN heating
- coupling of energy from AGN to surrounding gas is not easy
- impedance mismatch (tiny heat source in large volume)
- transport processes important

M87: Chandra-XMM-VLA View



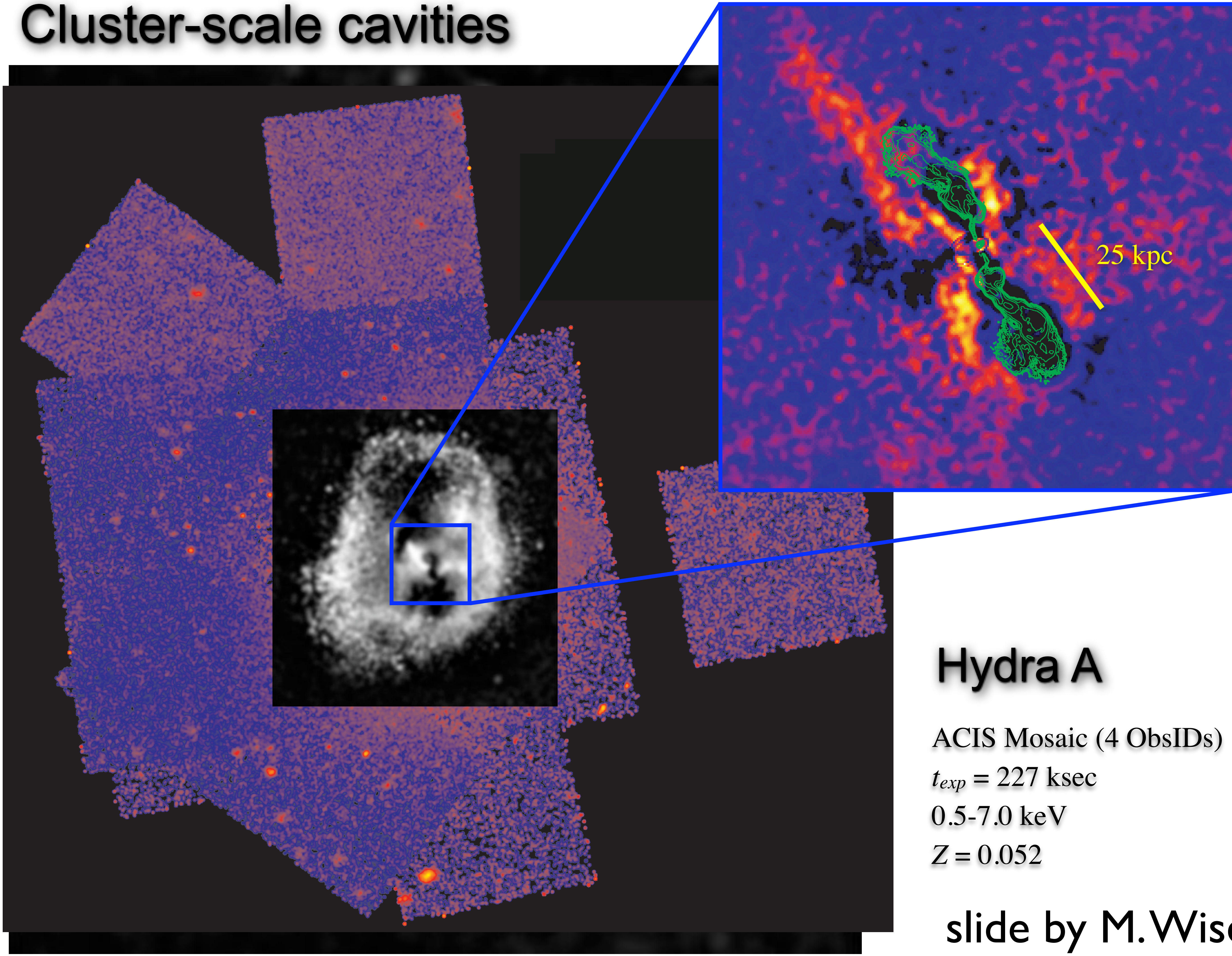






Simionescu, Böhringer, Brüggen, Finoguenov (2006)

Cluster-scale cavities

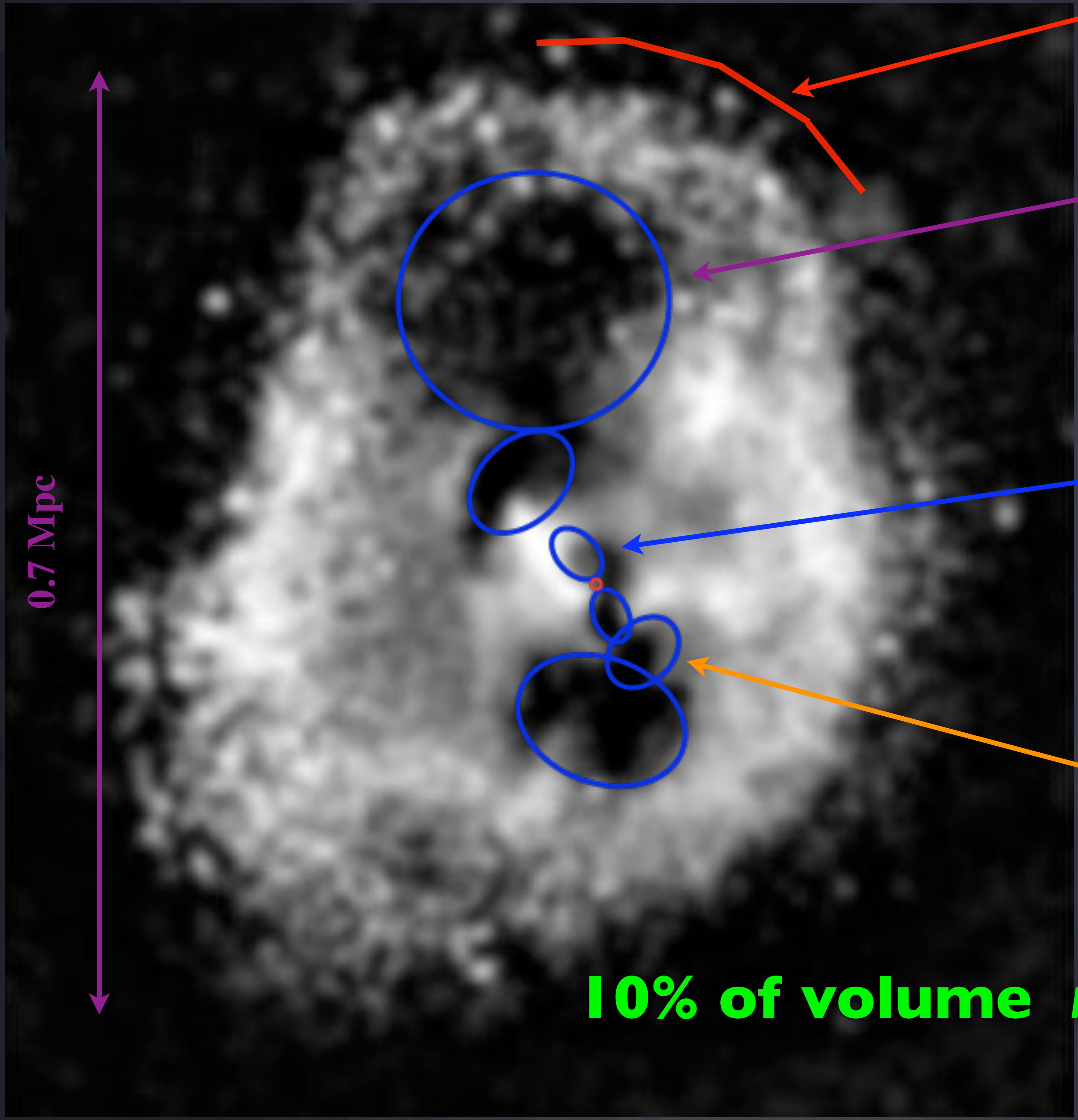


Hydra A

ACIS Mosaic (4 ObsIDs)
t_{exp} = 227 ksec
0.5-7.0 keV
Z = 0.052

slide by M. Wise

Hydra A



slide by M. Wise

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)

The ICM may be turbulent

Rayleigh-Taylor unstable bubbles induce turbulence

AGN-blown bubbles stay intact for long times

Rayleigh-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?

Dimonte & Tipton ‘06 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

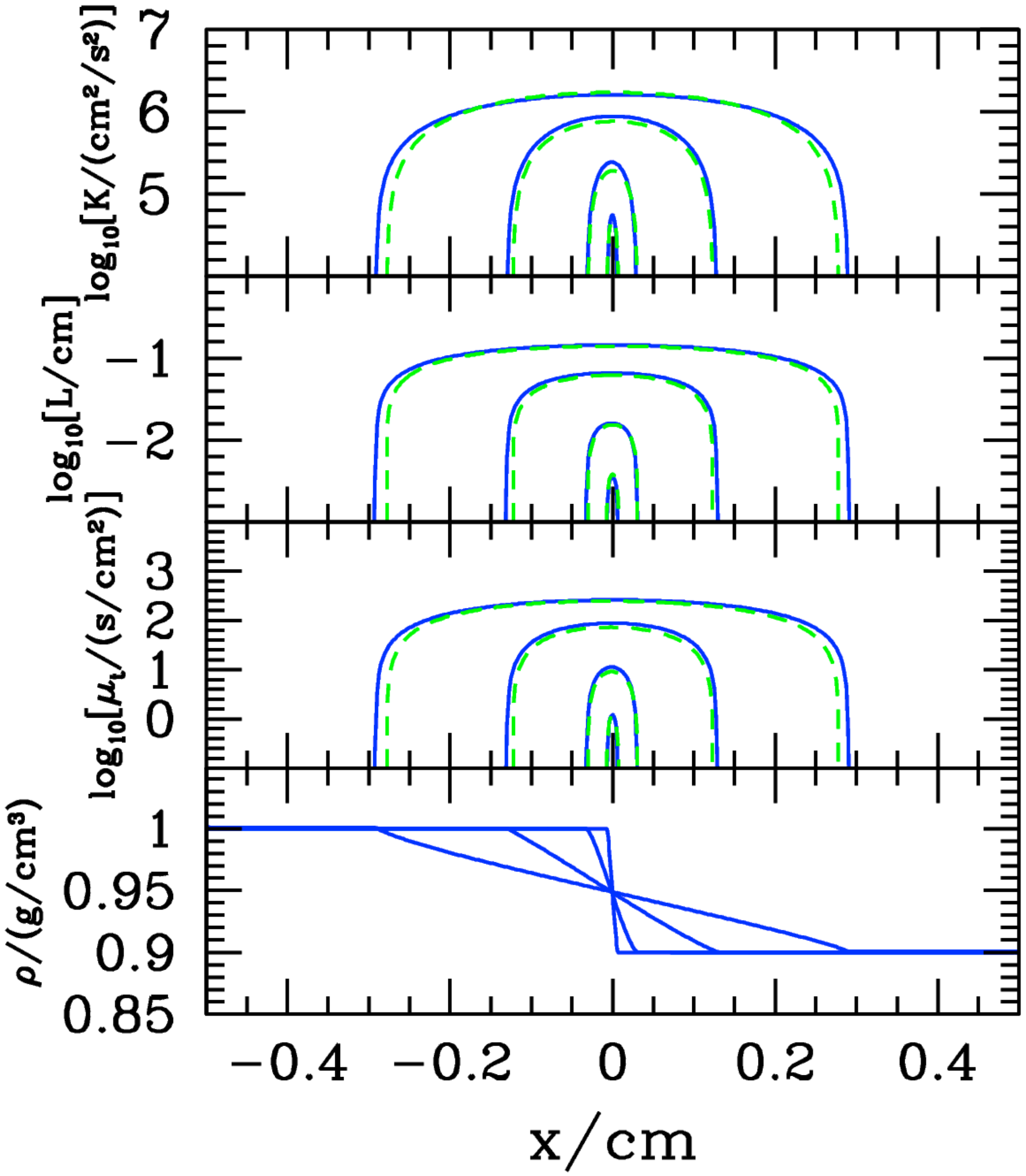
leading order in expansion around mean velocity: mean quantities are modified by presence of

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

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

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

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

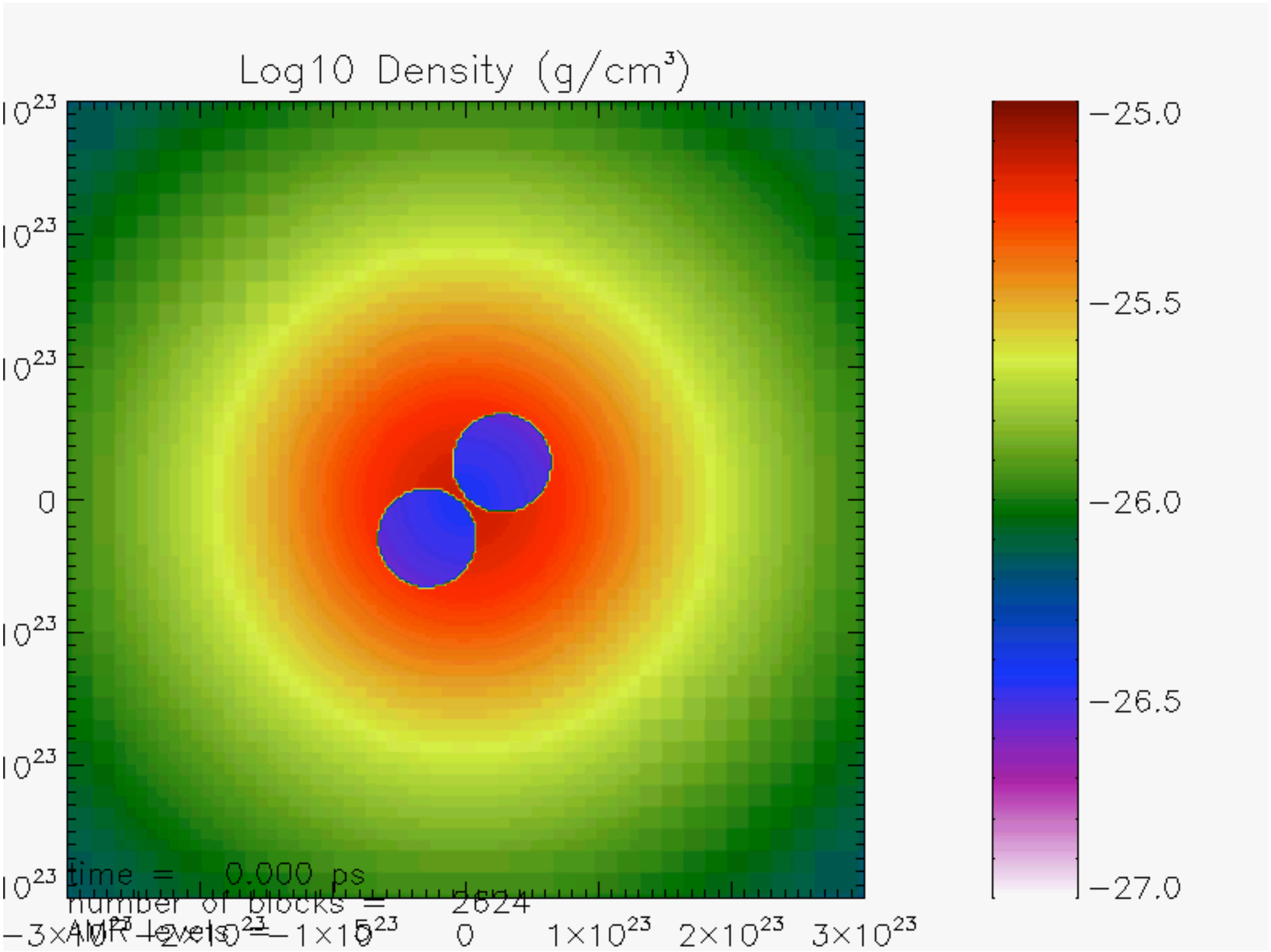
$$L(t,0) = h(t)/2$$

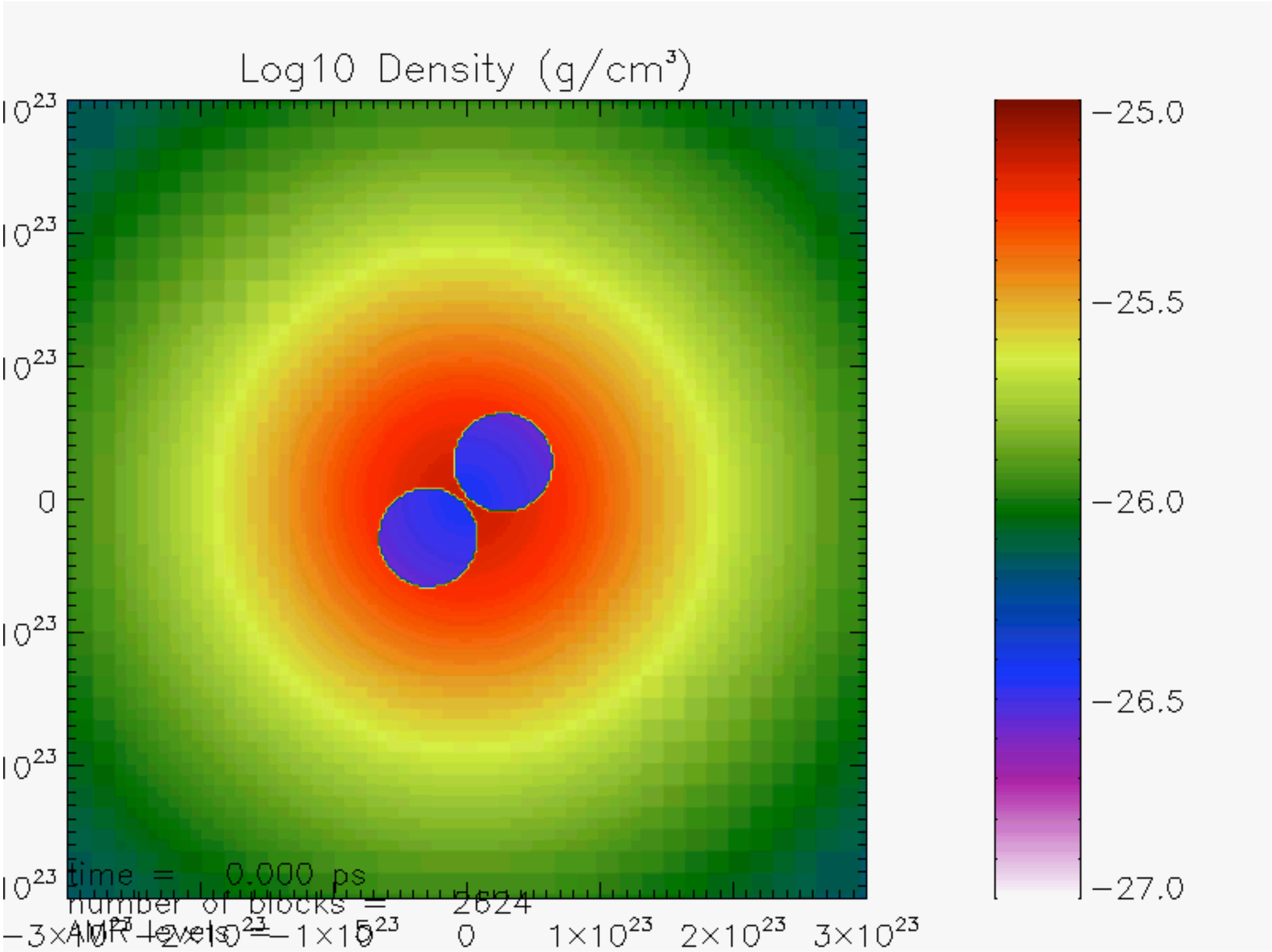
$$K(t,0) = (dh/dt)^2/2$$

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

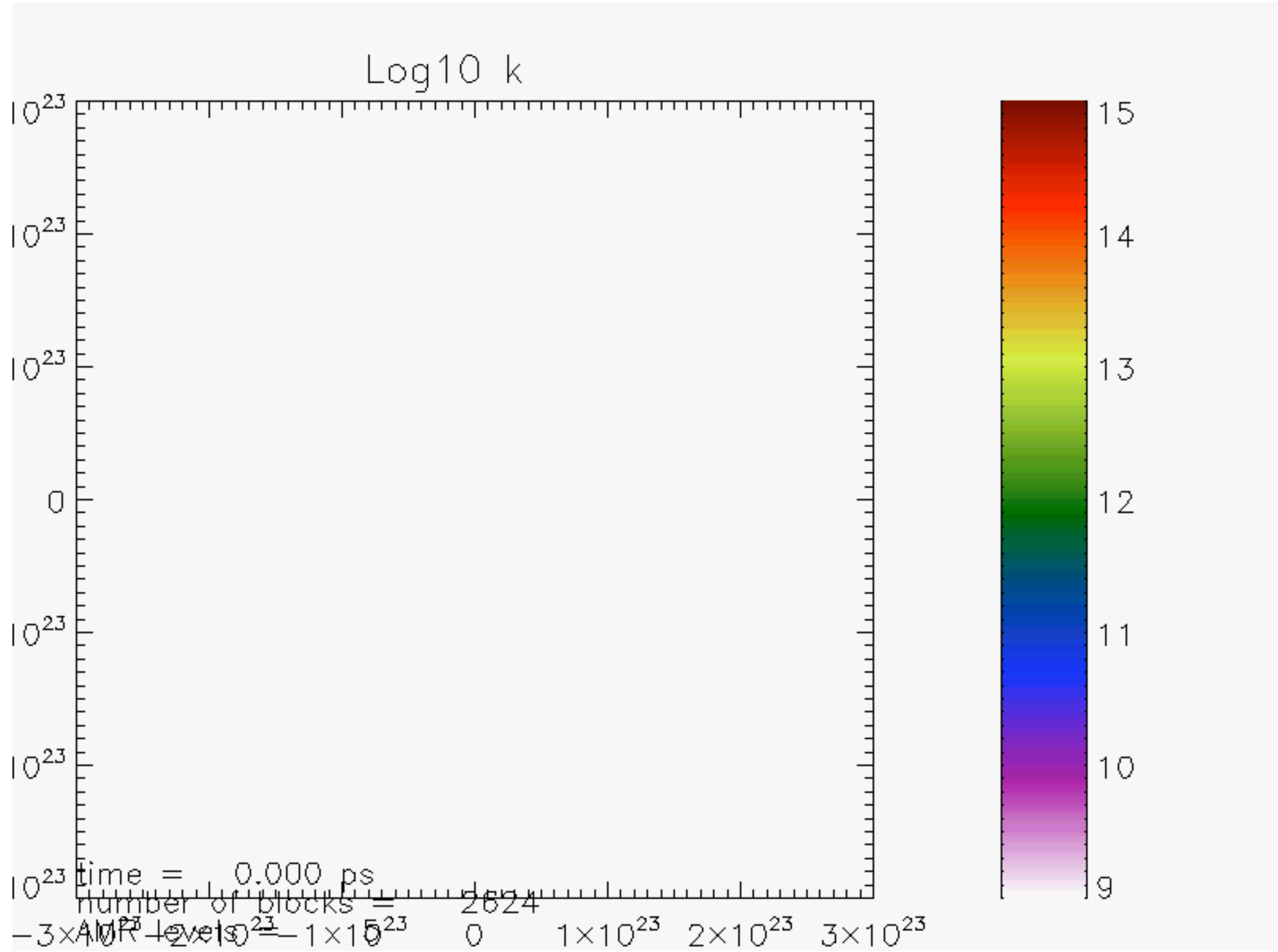
Simulation setup

- 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

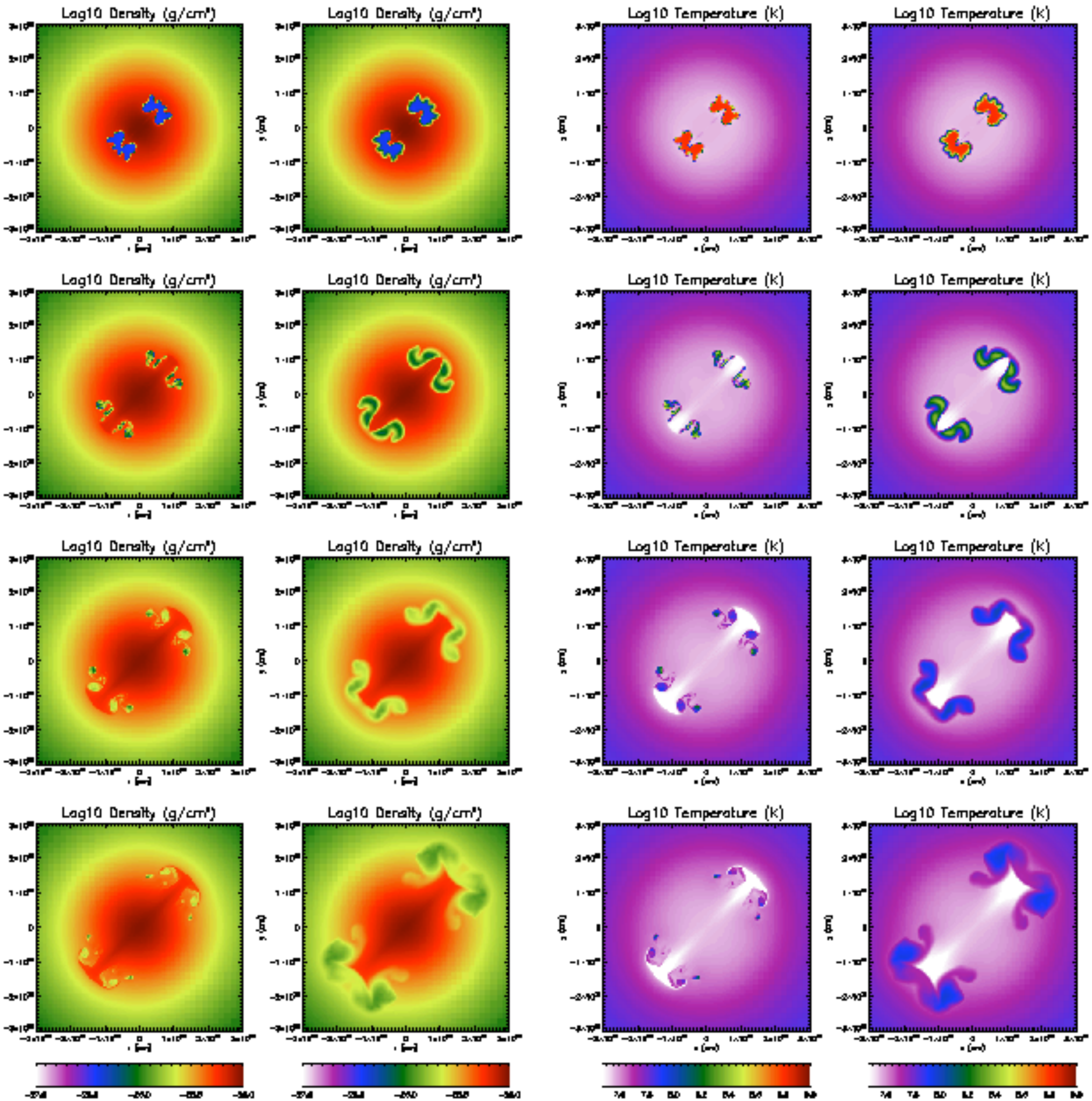

Log10 Density (g/cm³)
−25.0
−25.5
−26.0
−26.5
−27.0
time = 0.000 ps
number of blocks = 2624
AMR levels = 5
0
1×10²³
2×10²³
3×10²³



Log10 Density (g/cm³)
time = 0.000 ps
number of blocks = 2624
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
0
1×10^23
2×10^23
3×10^23
15
14
13
12
11
10
9

DAES-k



50 Myr

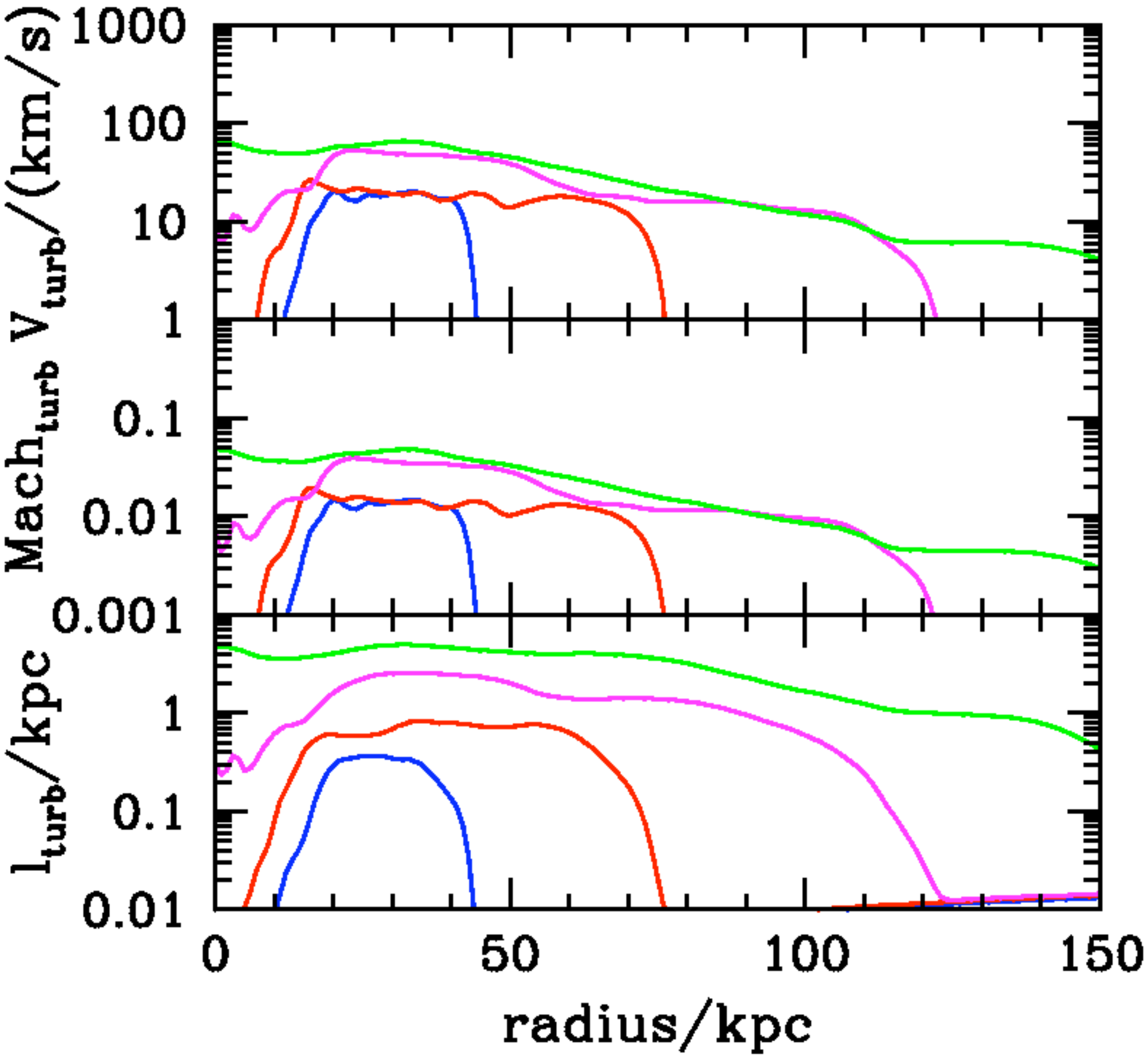
100 Myr

150 Myr

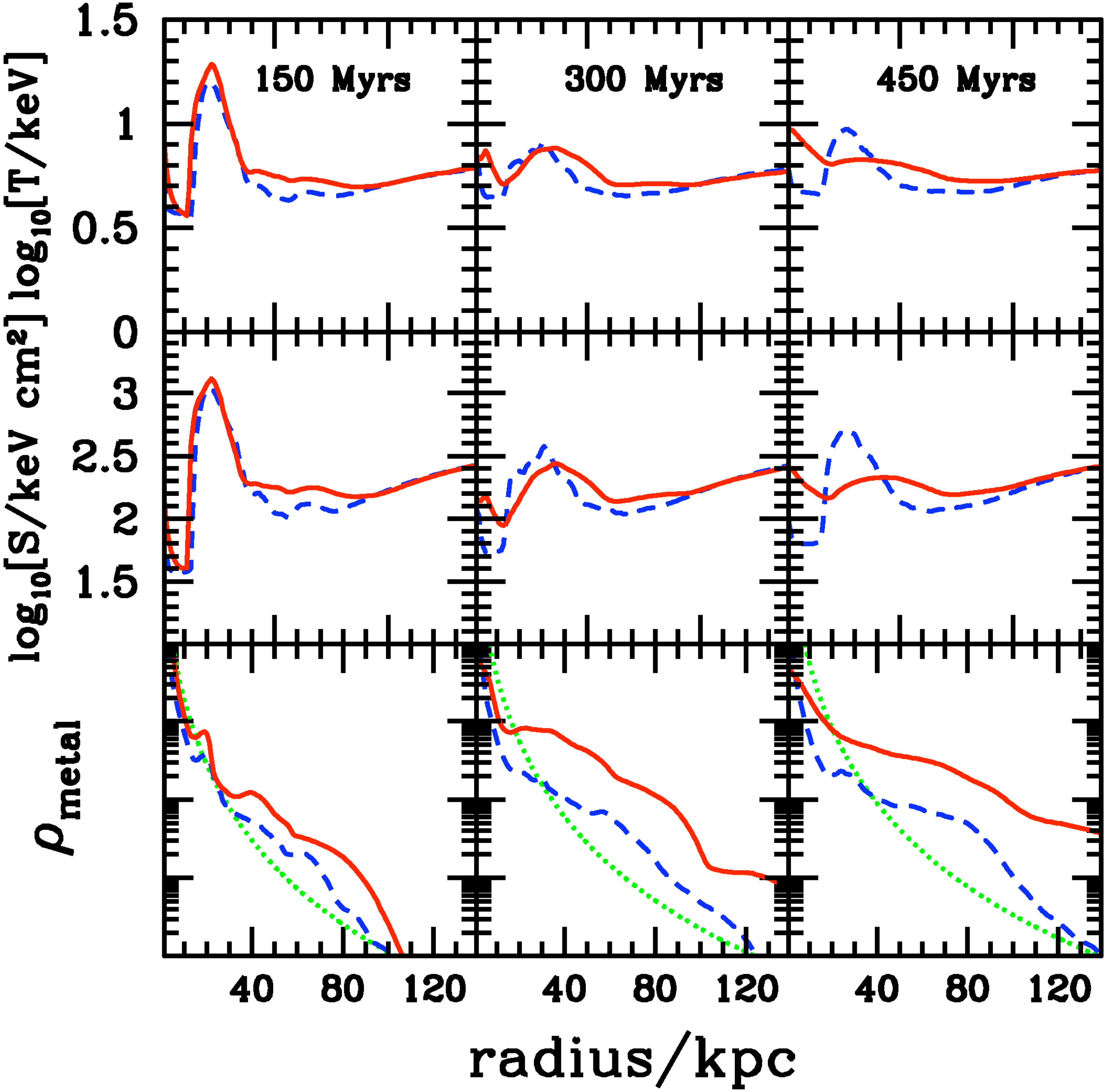
200 Myr

with subgrid

with subgrid



turb_profile_AE

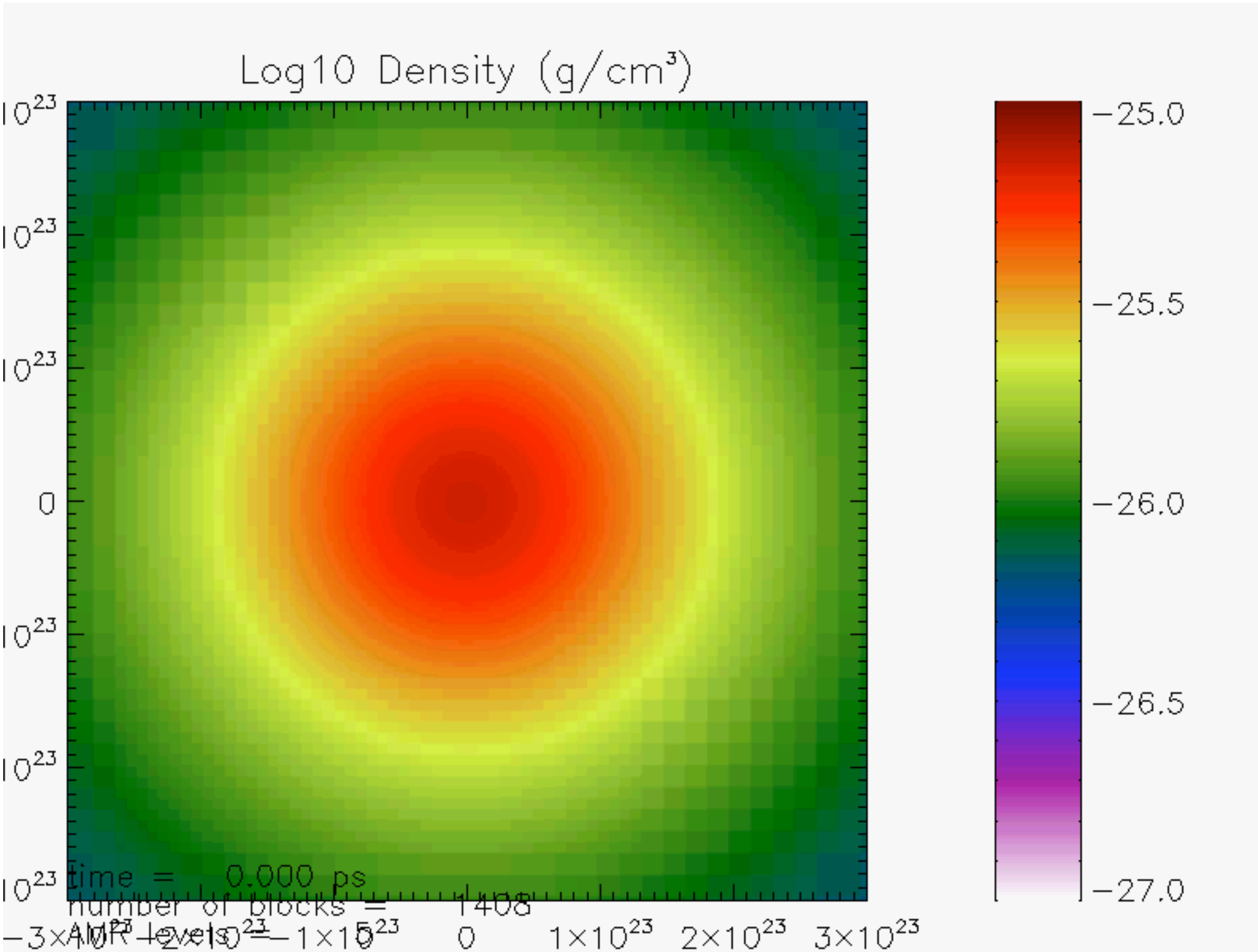


T increase not due to turbulent dissipation but mixing

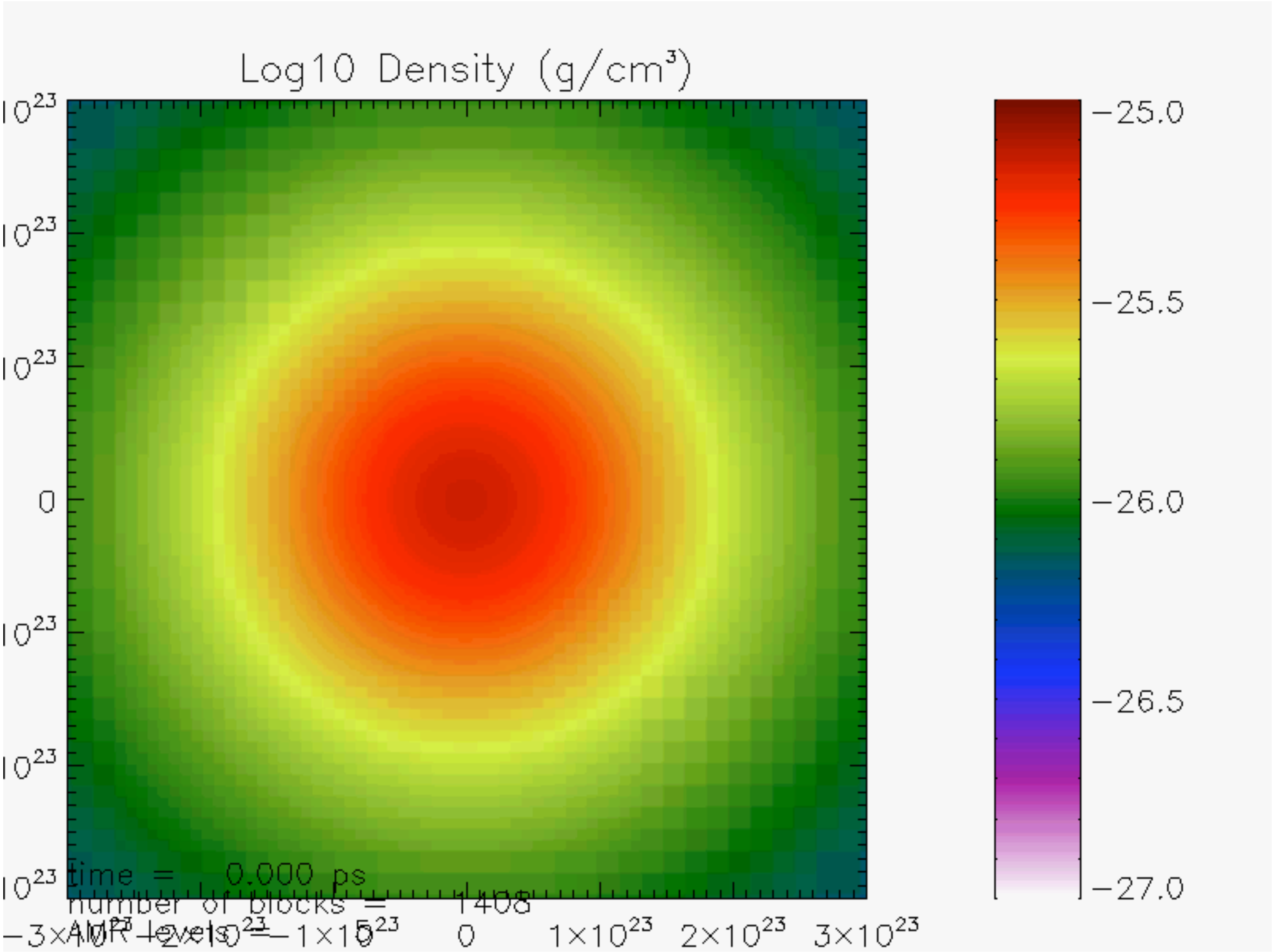
red: with subgrid
blue: w/o subgrid
green: no bubbles

periodic evacuated bubble run

radialER

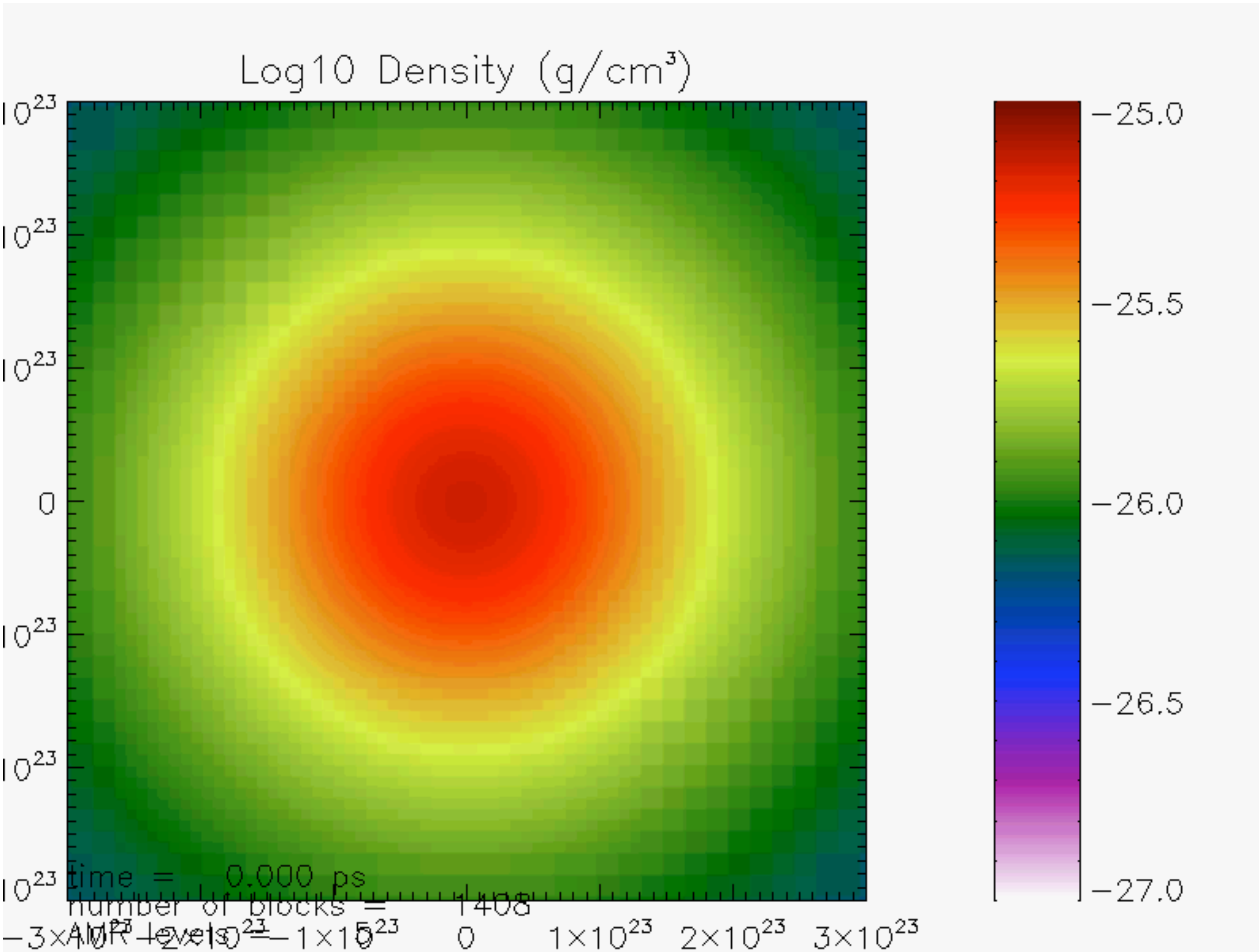

Log10 Density (g/cm³)
time = 0.000 ps
number of blocks = 1408
AMR levels = 5
0
1×10²³
2×10²³
3×10²³
−25.0
−25.5
−26.0
−26.5
−27.0

NASS



Log10 Density (g/cm³)
10²³
10²³
10²³
0
10²³
10²³
10²³
time = 0.000 ps
number of blocks = 1408
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

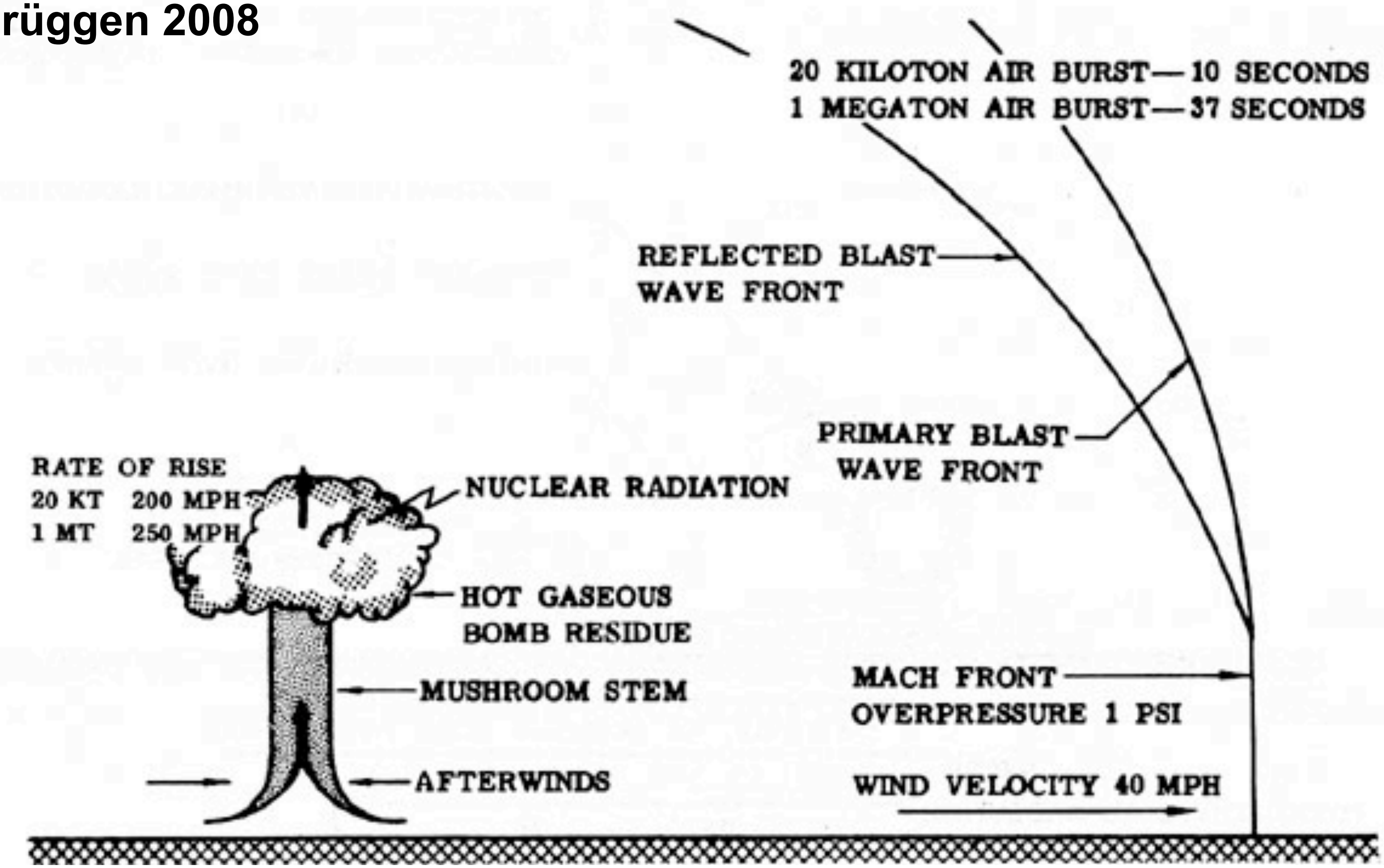
NASS

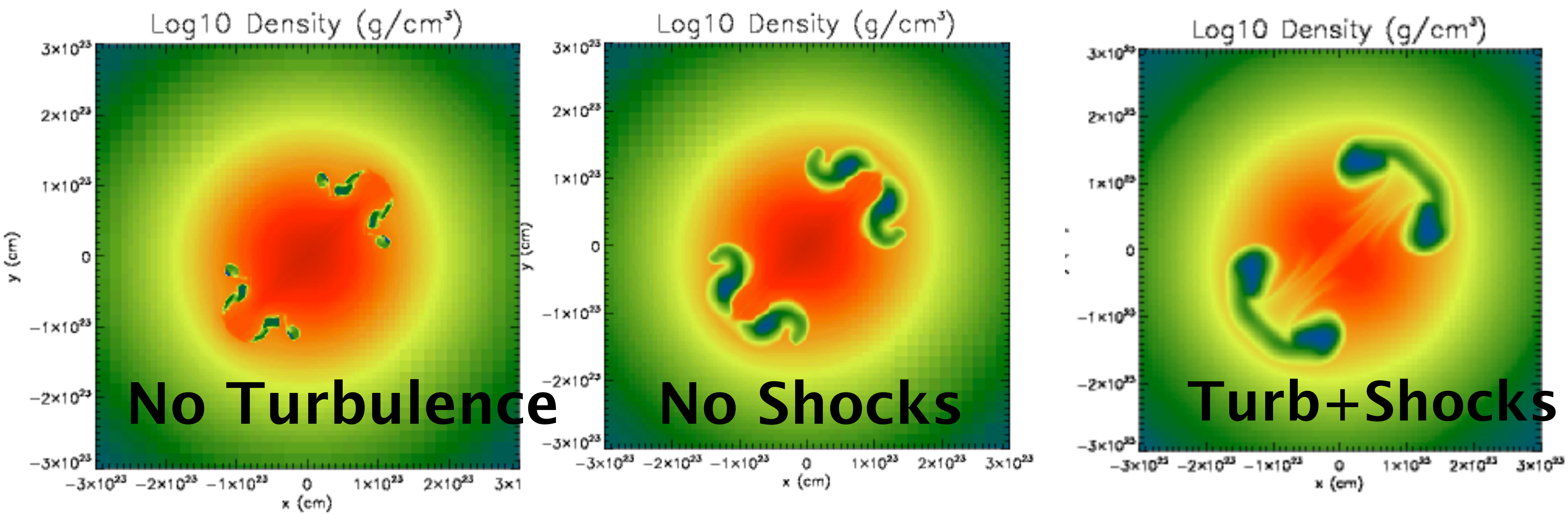


Log10 Density (g/cm³)
time = 0.000 ps
number of blocks = 1408
AMR levels = 5
0
1×10²³
2×10²³
3×10²³
−25.0
−25.5
−26.0
−26.5
−27.0

DASS

Scannapieco & Brüggen 2008



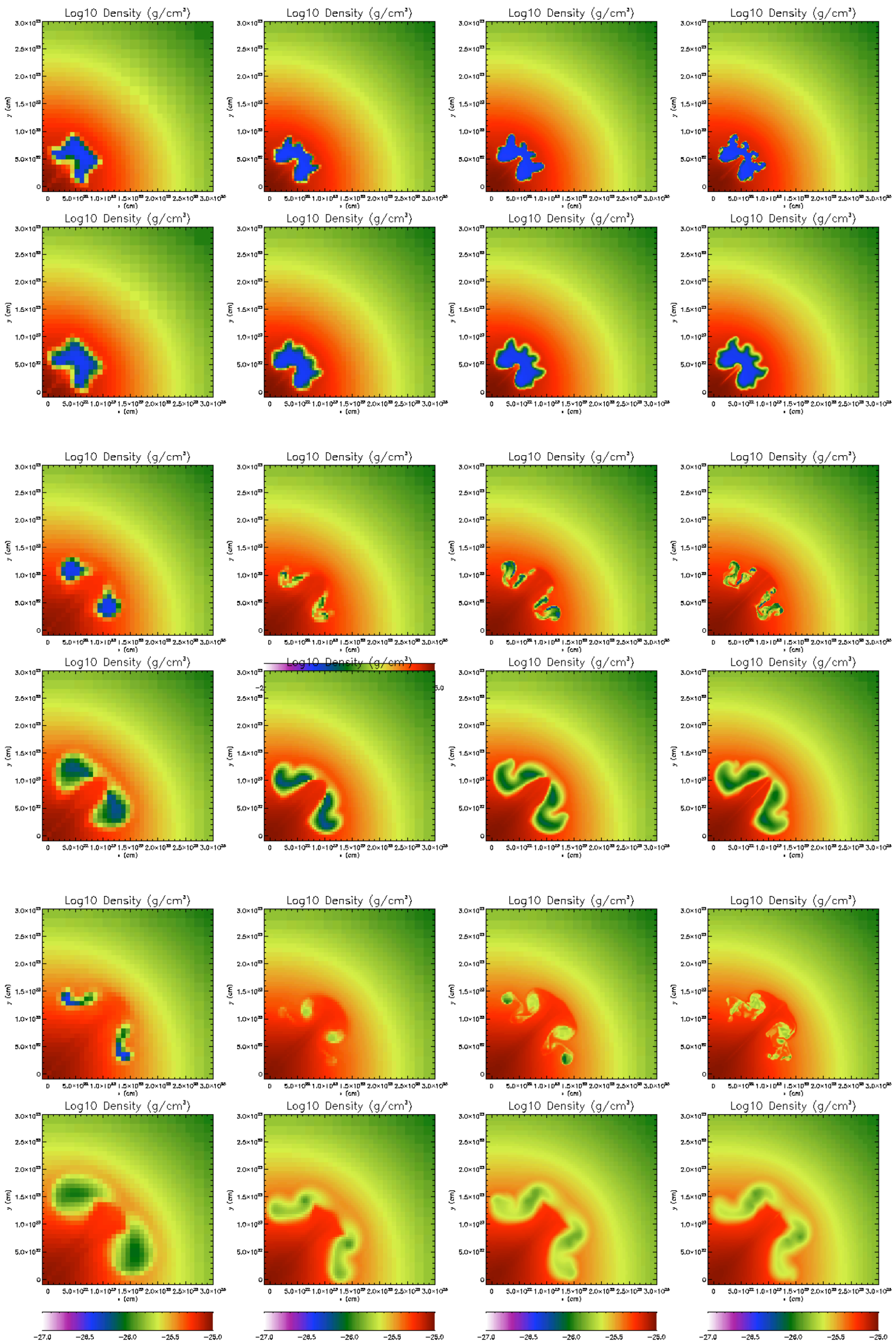


Dependence on resolution

subgrid

subgrid

subgrid



refinement level 3 4 5 6

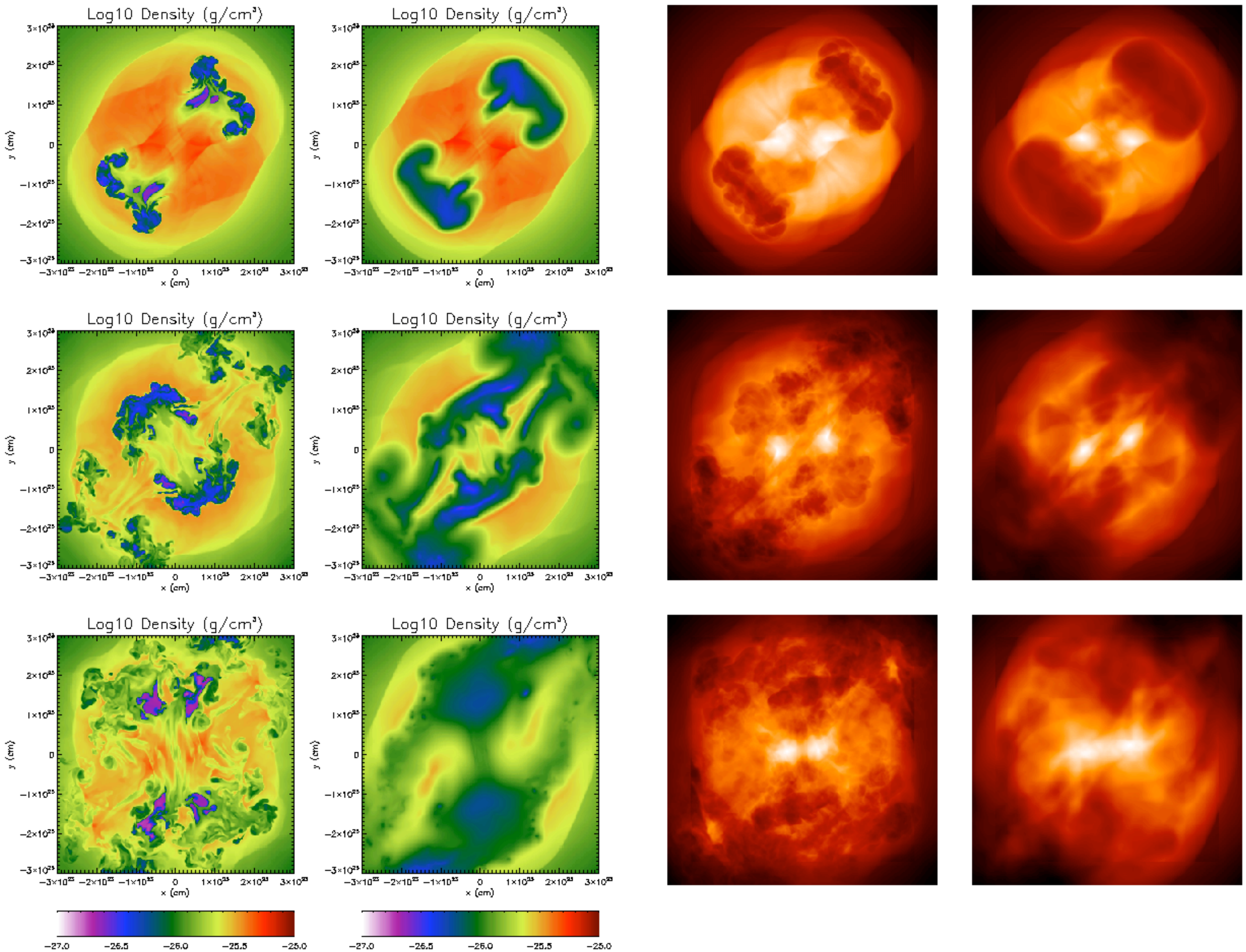
$$\lambda_{\max} = 4\pi(\nu^2 A/g)^{1/3}$$

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

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

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

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



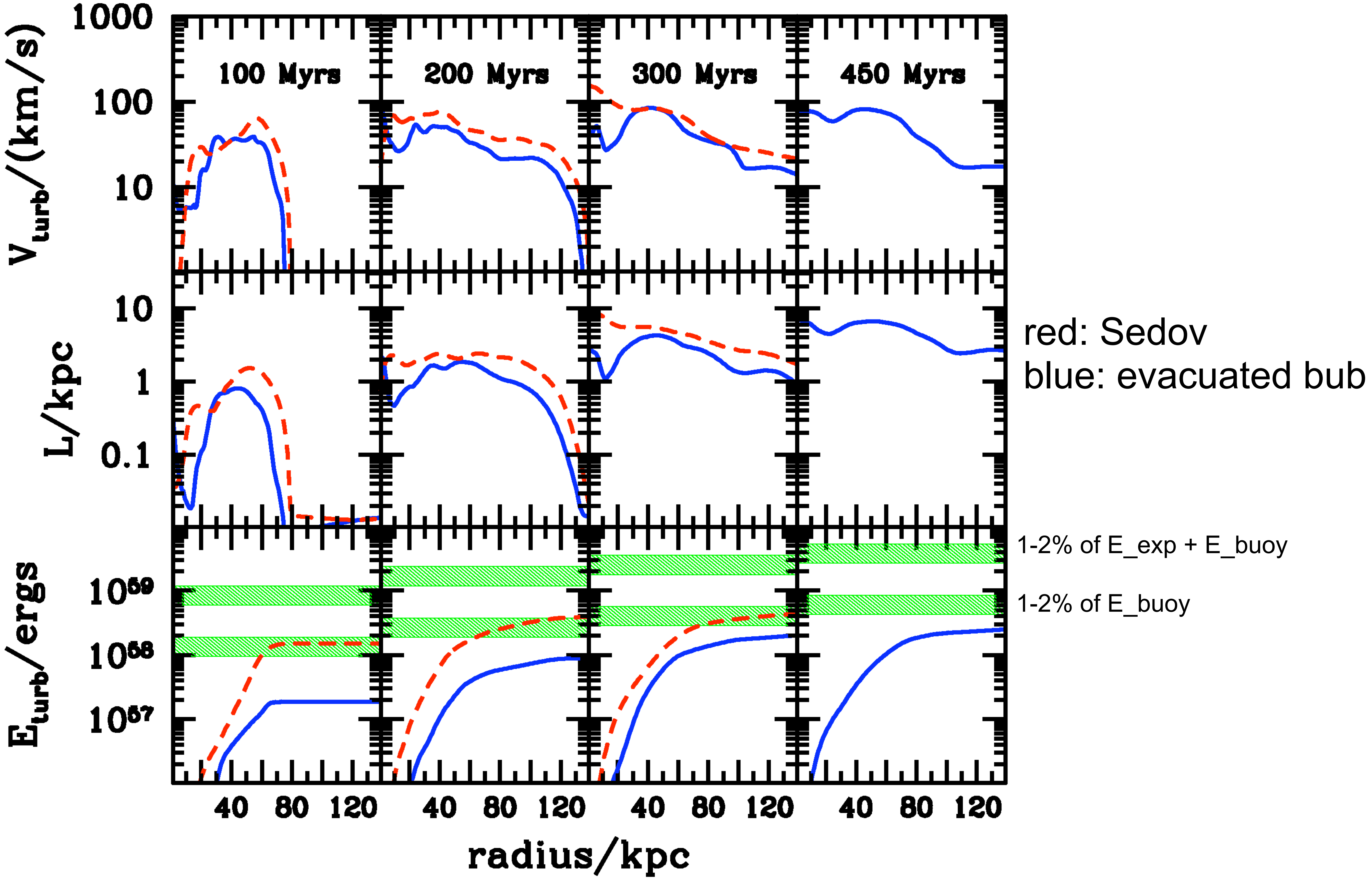
100 Myr

200 Myr

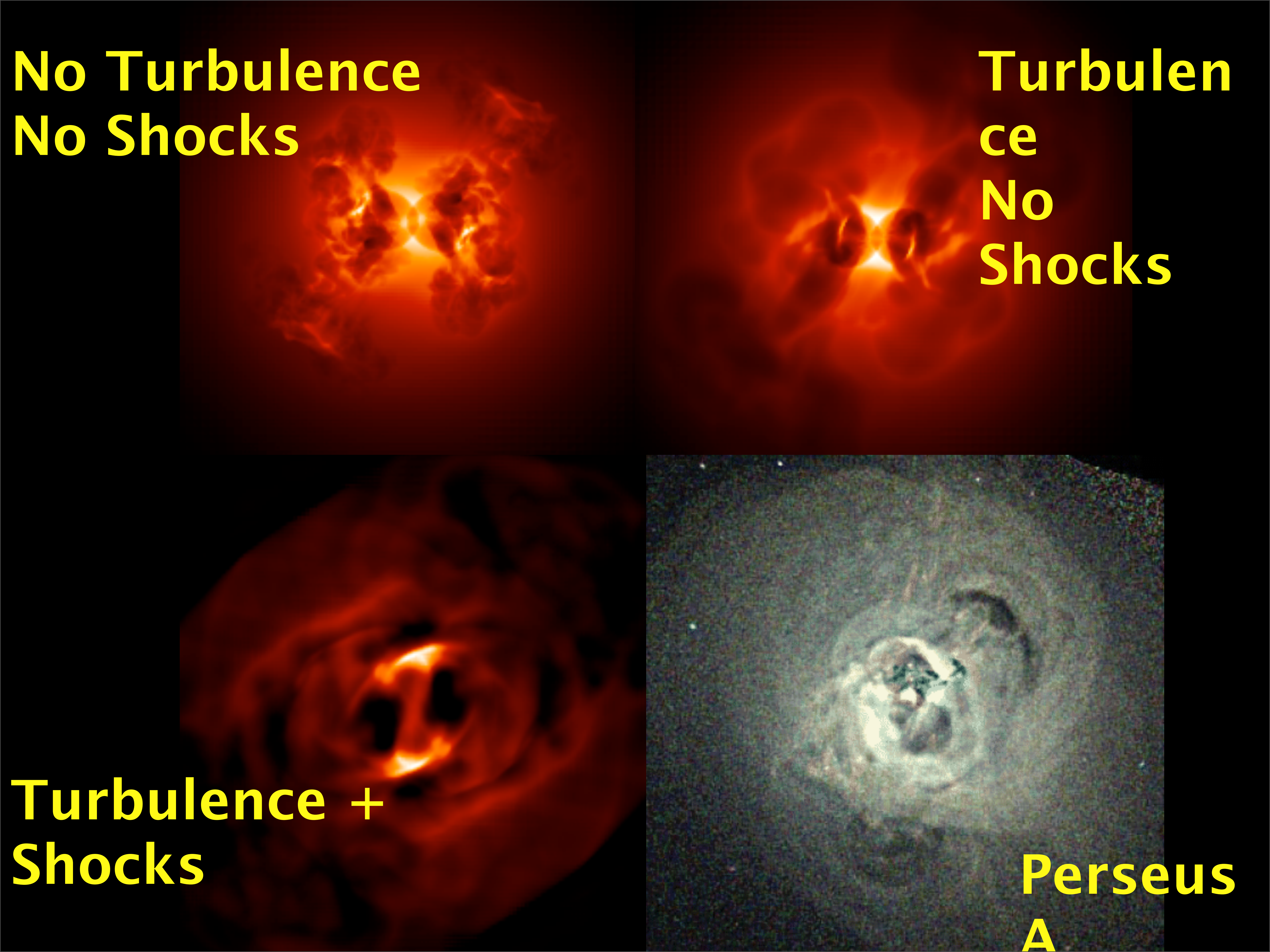
300 Myr

periodic Sedov bubble run

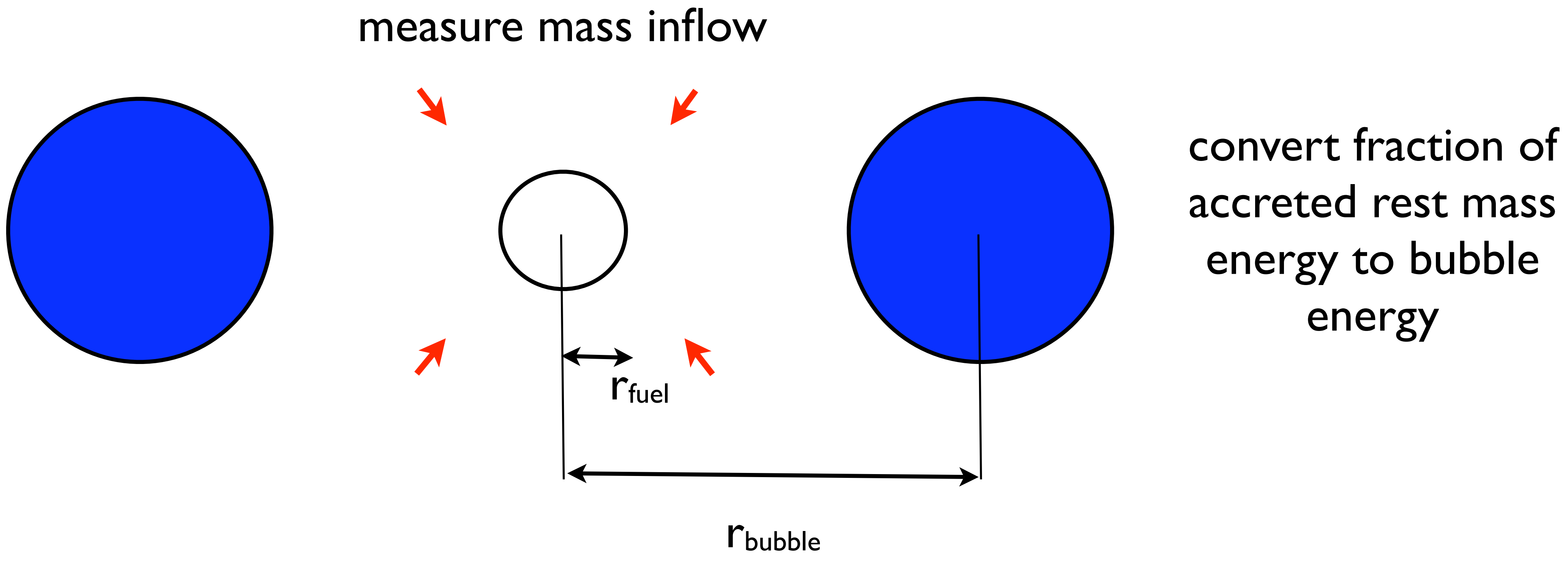
periodic mean shock

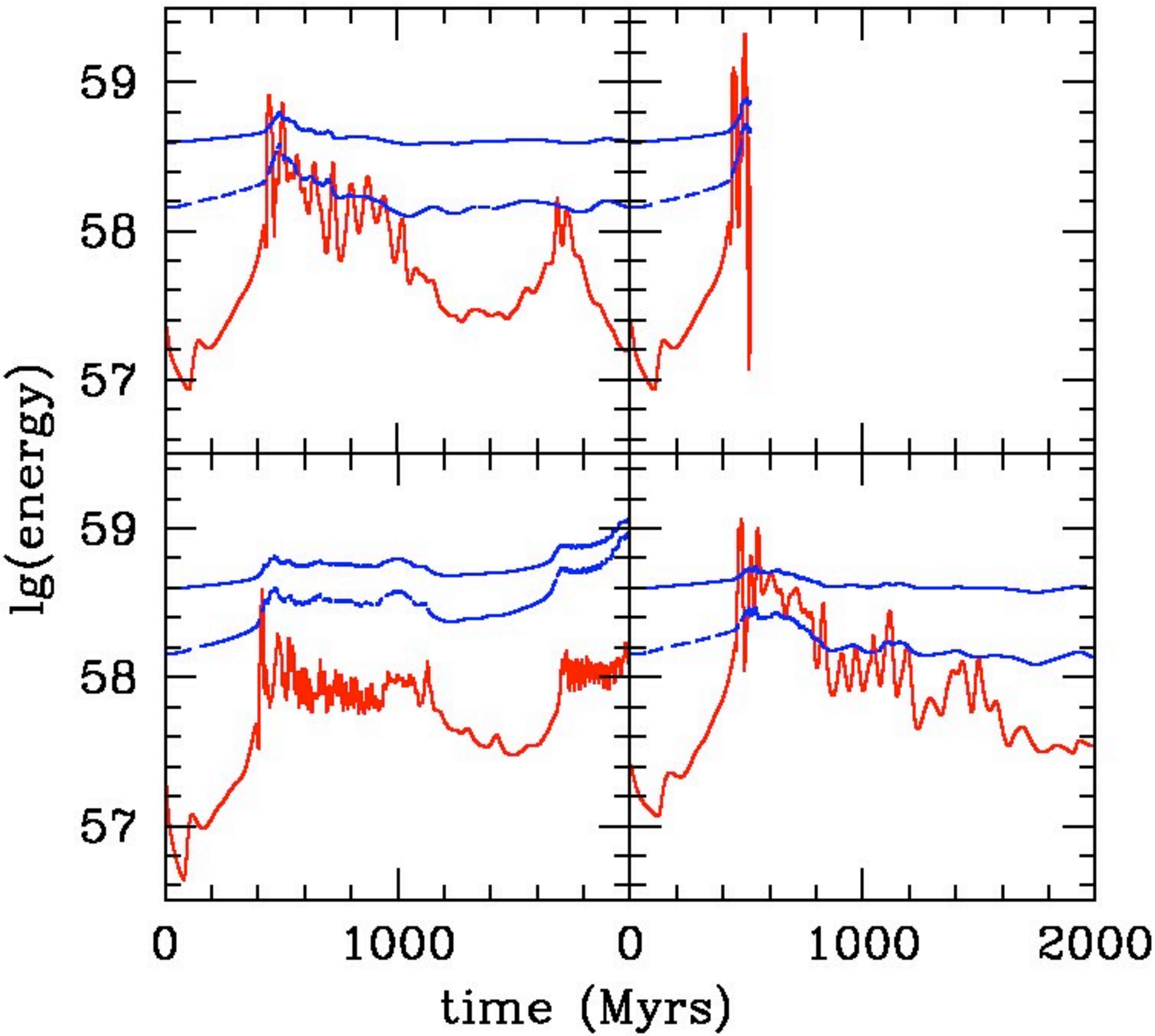

100 Myrs
200 Myrs
300 Myrs
450 Myrs
1000
100
10
10
1
0.1
V_{turb}/(km/s)
L/kpc
E_{turb}/ergs
10^{59}
10^{58}
10^{57}
40
80
120
radius/kpc
red: Sedov
blue: evacuated bub
1-2% of E_exp + E_buoy
1-2% of E_buoy

radialTR

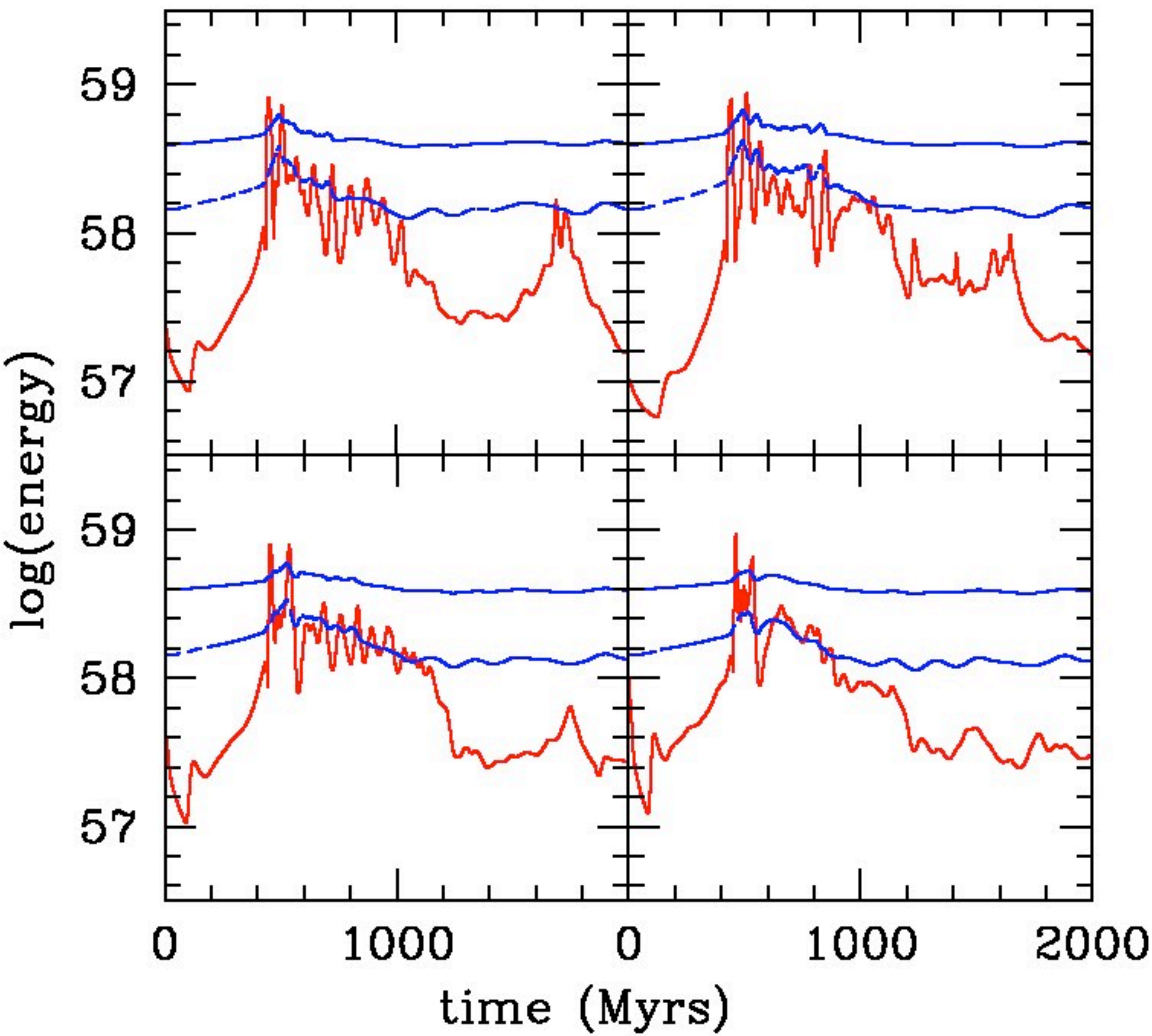

No Turbulence
No Shocks
Turbulen
ce
No
Shocks
Turbulence +
Shocks
Perseus
A

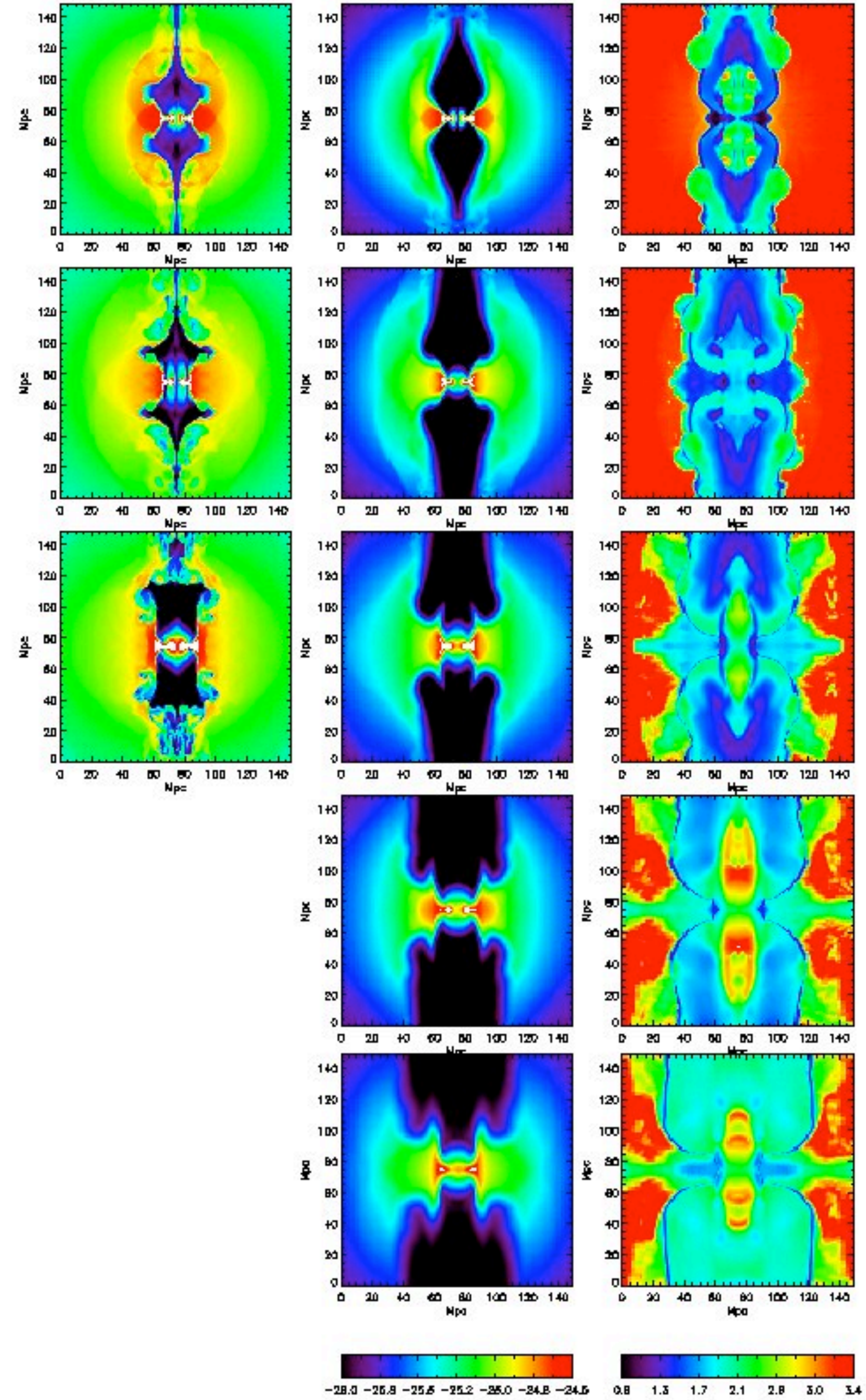
So how do you get the AGN to self-regulate?



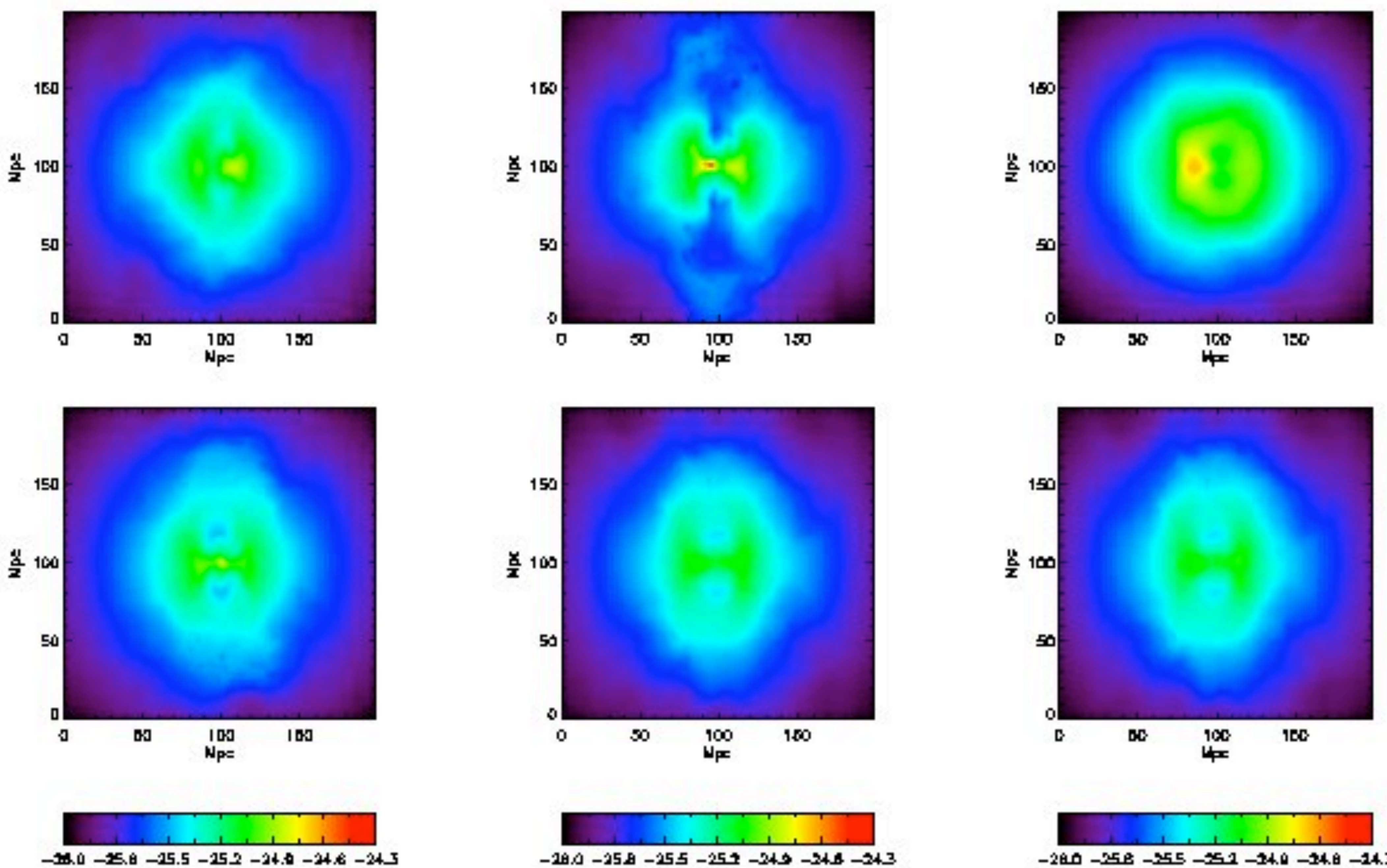


59
58
57
59
58
57
lg(energy)
0
1000
0
1000
2000
time (Myrs)


59
58
57
log(energy)
0
1000
2000
time (Myrs)


Mpc
−26.0 −25.8 −25.6 −25.2 −25.0 −24.8 −24.6
0.8 1.3 1.7 2.1 2.6 3.0 3.4

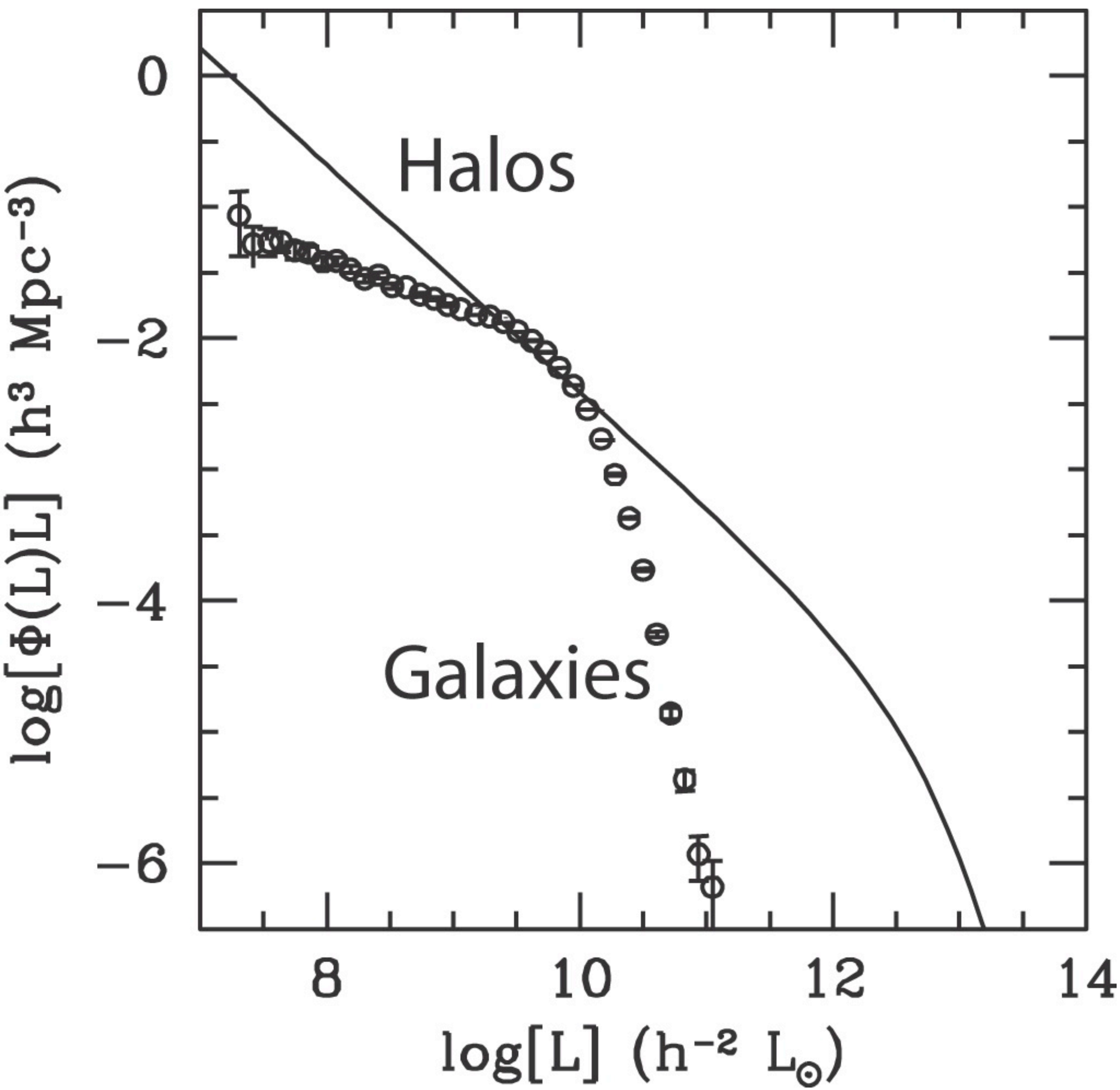
Slices of density after 1.5 Gyr



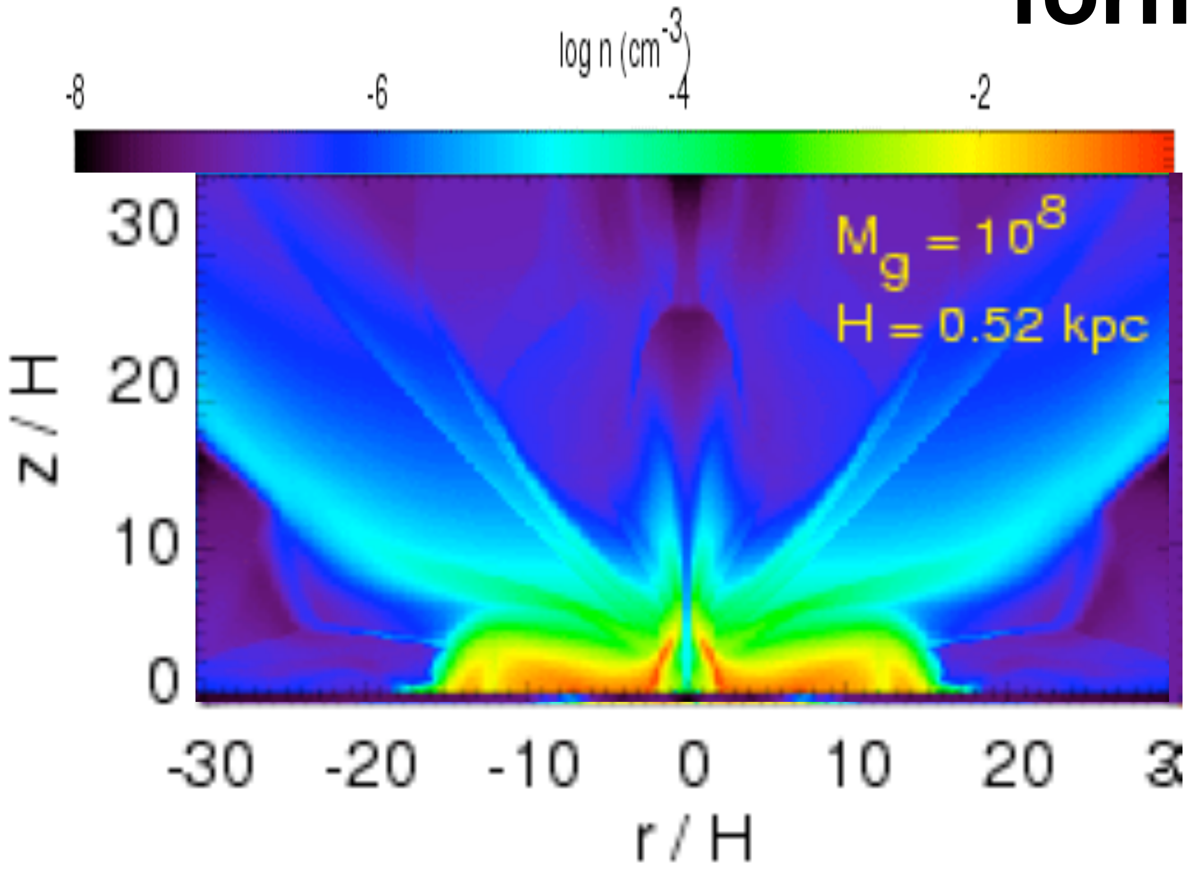
vary geometry

vary energy

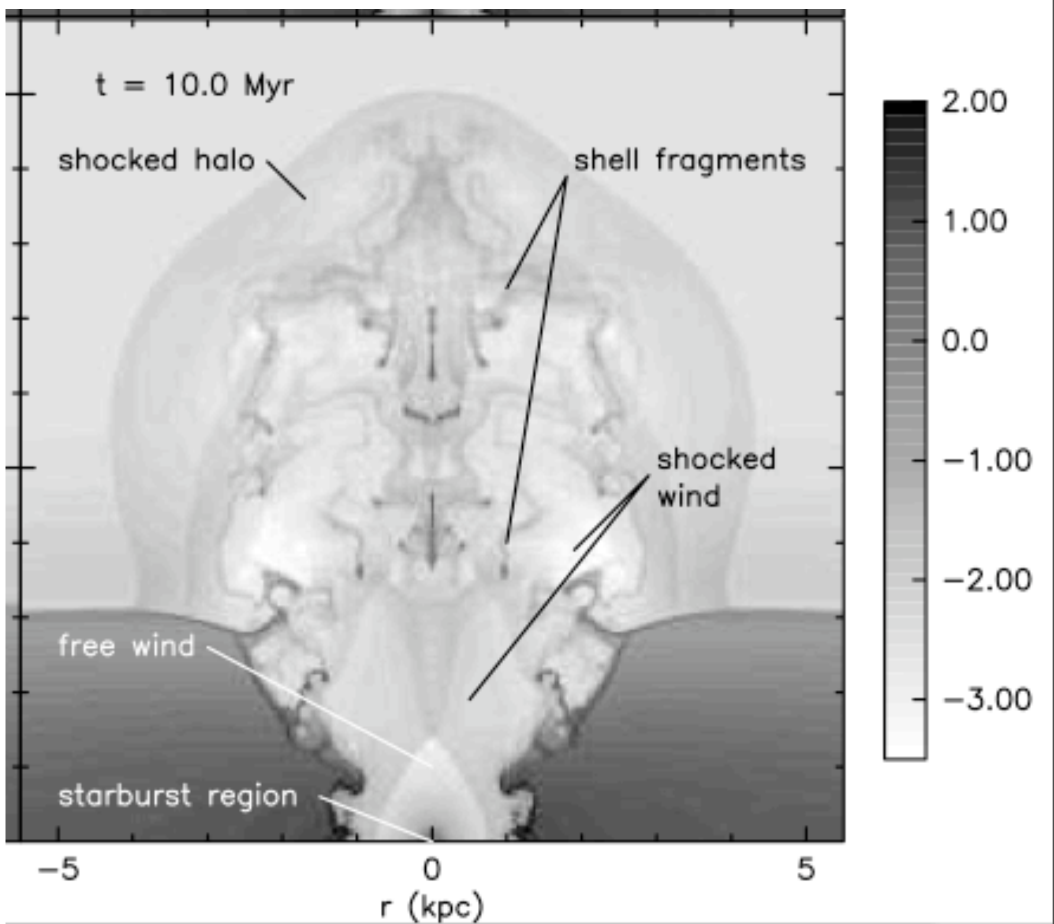
Now to the other end of the mass function...

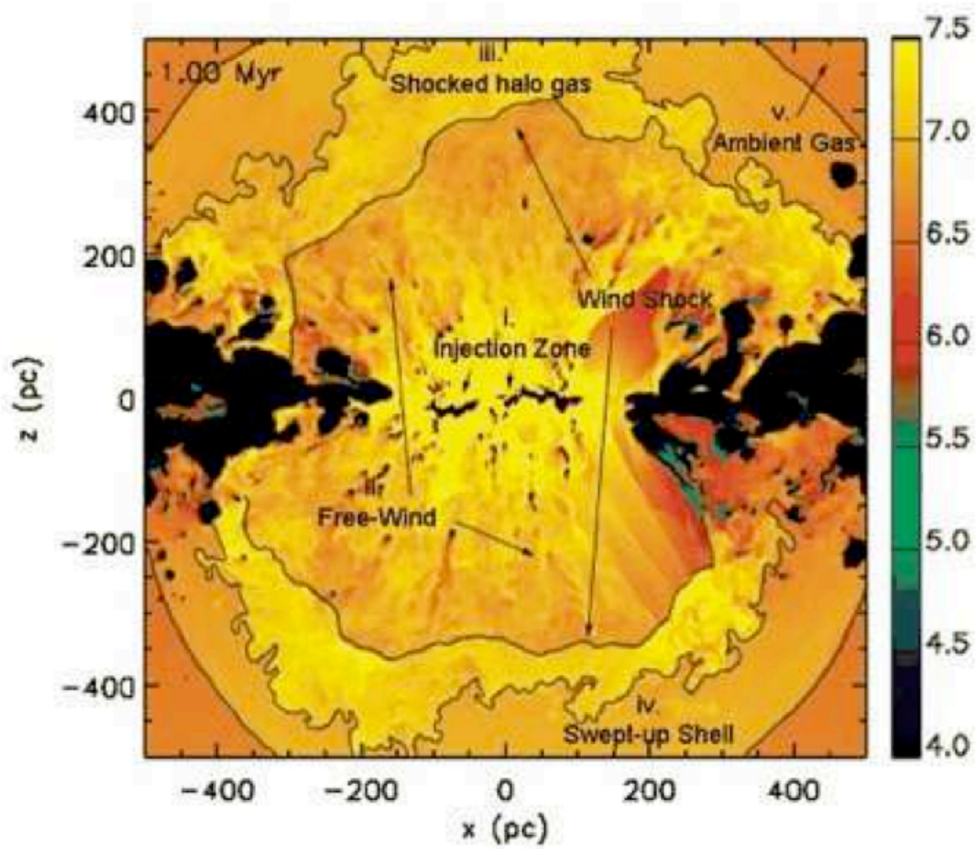


Star-burst driven outflows play a key role in structure formation



MacLow & Ferrara (1999)





Cooper et al. (2008)

Strickland & Stevens (2000)

FLASH3.0, AMR
initially hydrostatic galaxy, modeled after NGC 1569
4 levels of refinement, 39 parsec res., 25 x 25 x 30 kpc box
Atomic radiative cooling everywhere.

Component	Parameter	Value
gas	$a_{\rm gas}$	0.7 kpc
	$b_{\rm gas}$	0.2 kpc
	$M_{\rm gas}$	$2 \times 10^8 M_\odot$
	SFR	$0.17\ M_\odot/\rm yr$
	$Z_{\rm gas}$	$0.25\ Z_\odot$
gas+stellar	$a_{\rm disk}$	0.7 kpc
potential	$b_{\rm disk}$	0.2 kpc
	$M_{\rm disk}$	$3 \times 10^8 M_\odot$
DM halo	$r_{\rm DM}$	2 kpc
	v_c	35 km/s

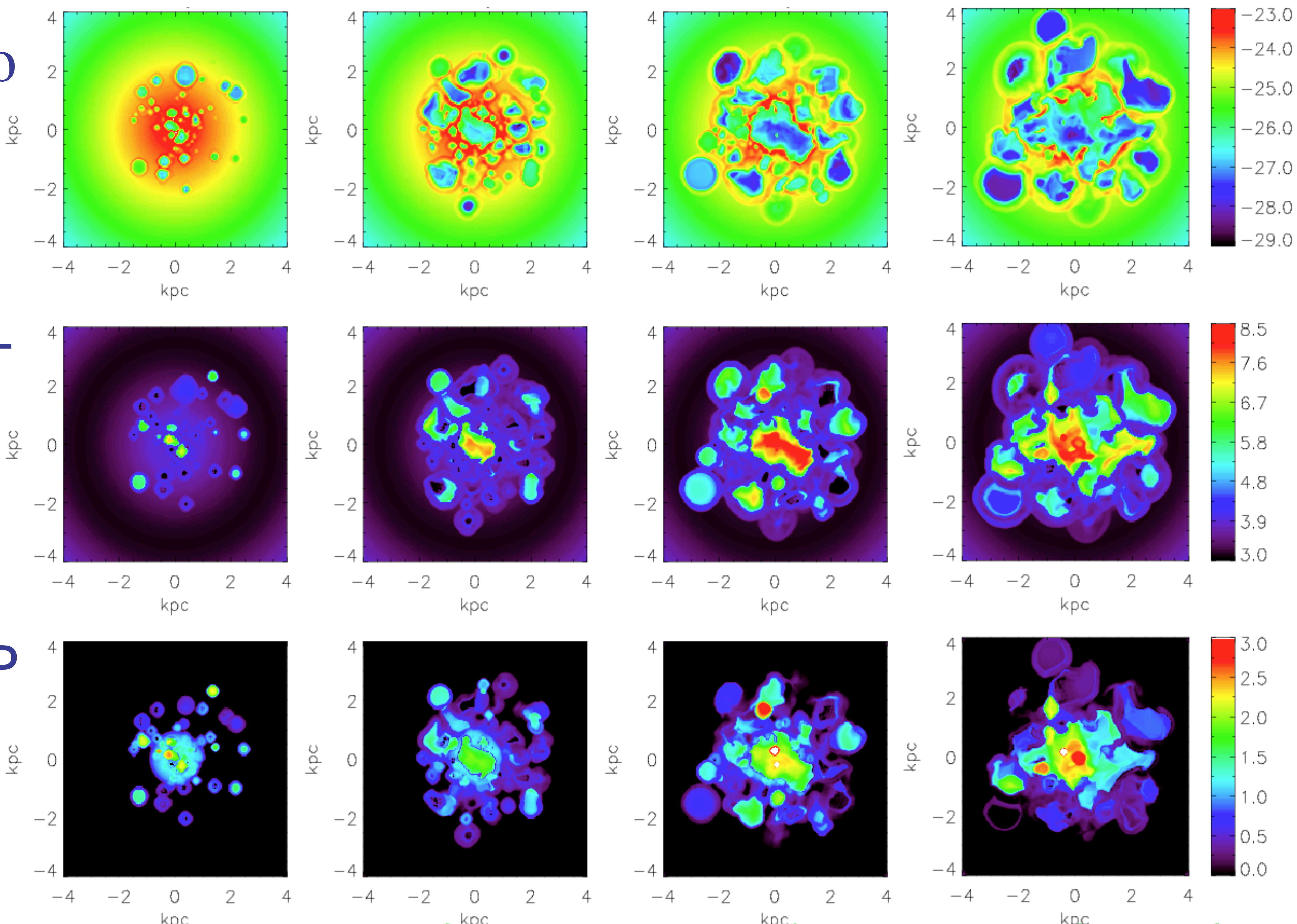
Scannapieco & M. Bruggen (2010)

10 Myrs 20 Myrs 30 Myrs 40 Myrs

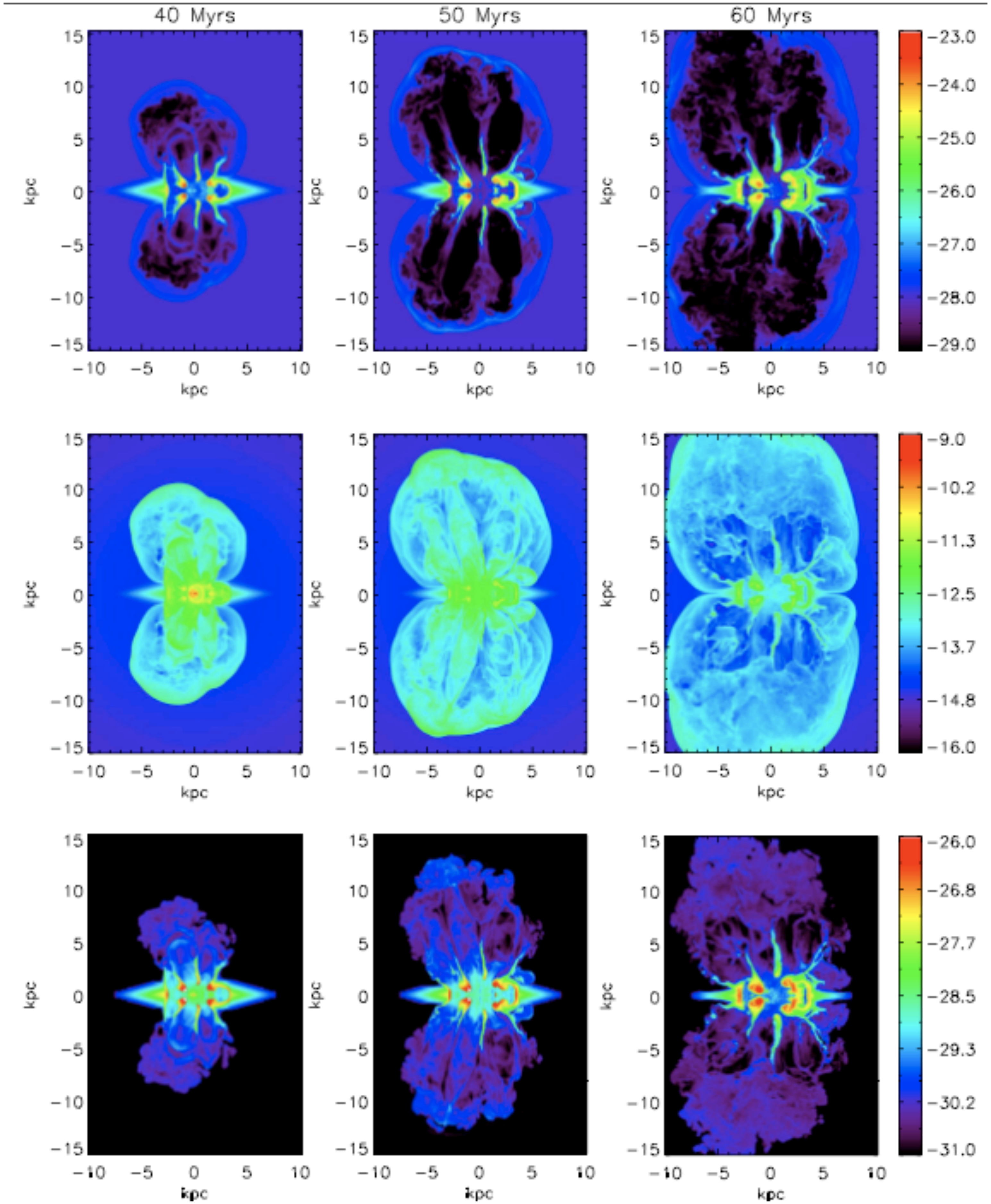
log ρ

log T

log P



Scannapieco & Brüggen (2010)



40 Myrs
50 Myrs
60 Myrs
kpc
-23.0
-24.0
-25.0
-26.0
-27.0
-28.0
-29.0
-9.0
-10.2
-11.3
-12.5
-13.7
-14.8
-16.0
-26.0
-26.8
-27.7
-28.5
-29.3
-30.2
-31.0

Turbulence "avoids" dense regions

$$t_{\rm decay} \propto L/\sqrt{2K} \propto \rho^{-1}/\sqrt{\rho^{-1}} \propto \rho^{-1/2}$$

Cooling Instability (Fall & Rees 1985)

$$\frac{\Lambda(T_p, Z)}{T_p^2} > \frac{\Lambda(T_{\rm ISM}, Z)}{T_{\rm ISM}^2}$$

At Z=0.1 solar this is the case for T > 3 x 10^5 K. In the presence of turbulence

$$\frac{\Lambda(T_p, Z)}{T_p^2(1 + K_p/E_p)^2} > \frac{\Lambda(T_{ISM}, Z)}{T_{\rm ISM}^2(1 + K_{\rm ISM}/E_{\rm ISM})^2},$$

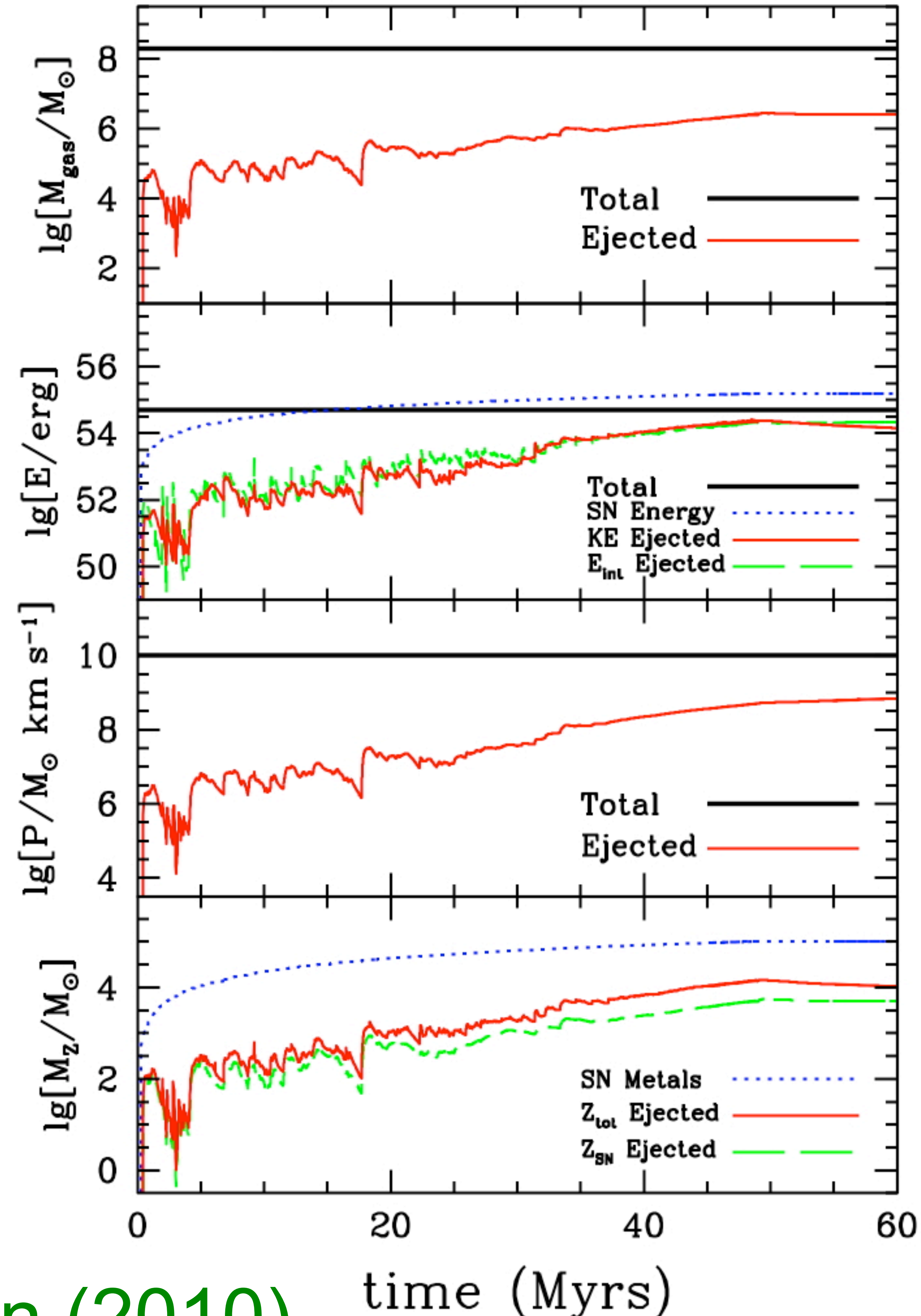
$M_\star = 8\times10^6 M_\odot$

$\approx 8\times10^6 M_{Ej}$

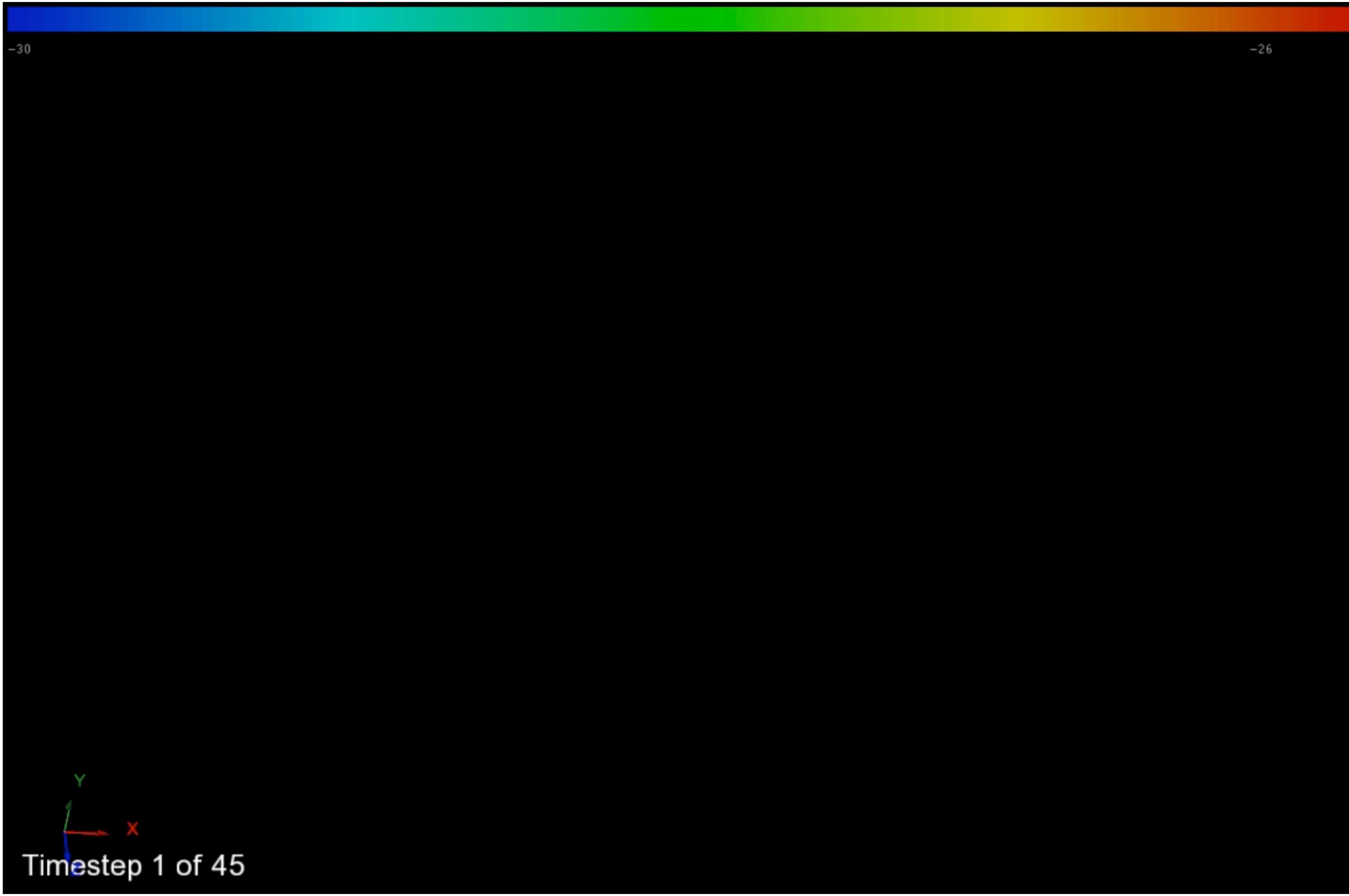
$E_{SN} < E_{total\text{-}ej}$

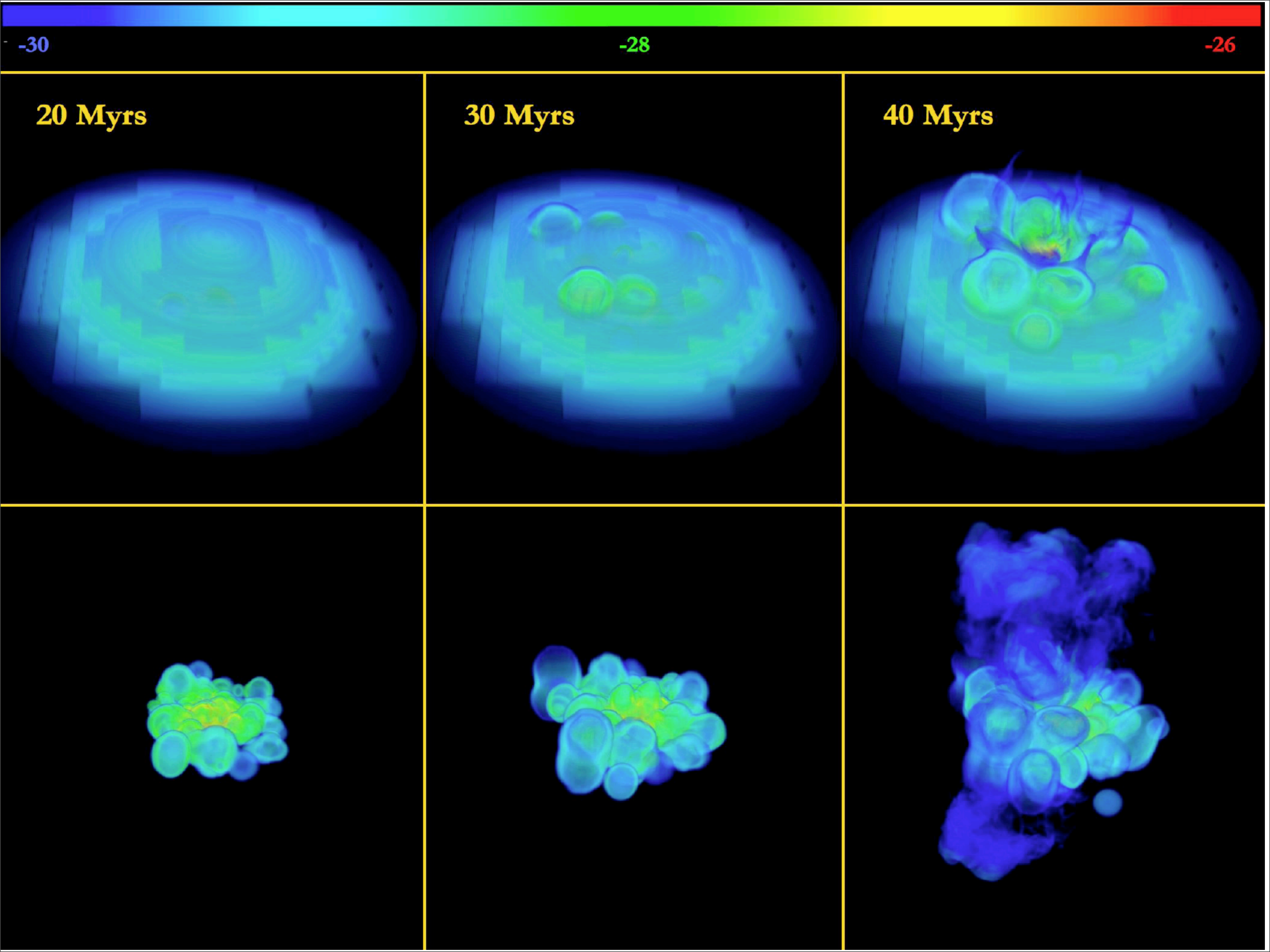
$V_{ej} \approx 50$ km/s

Most metals retained / Most ejected metals are from SNe



Scannapieco & Brüggen (2010)


−30
−26
Y
X
Timestep 1 of 45



-30
-28
-26
20 Myrs
30 Myrs
40 Myrs

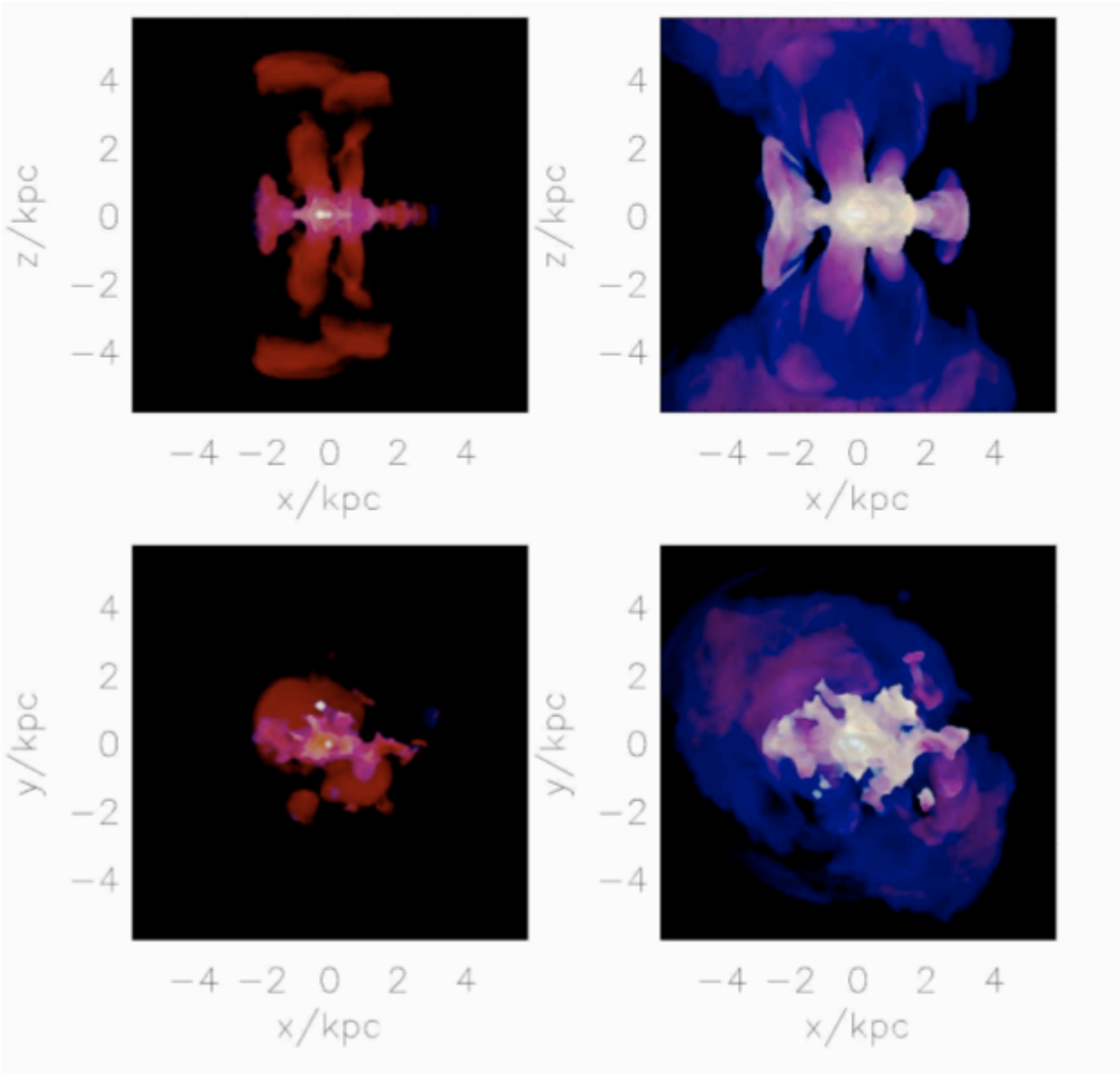
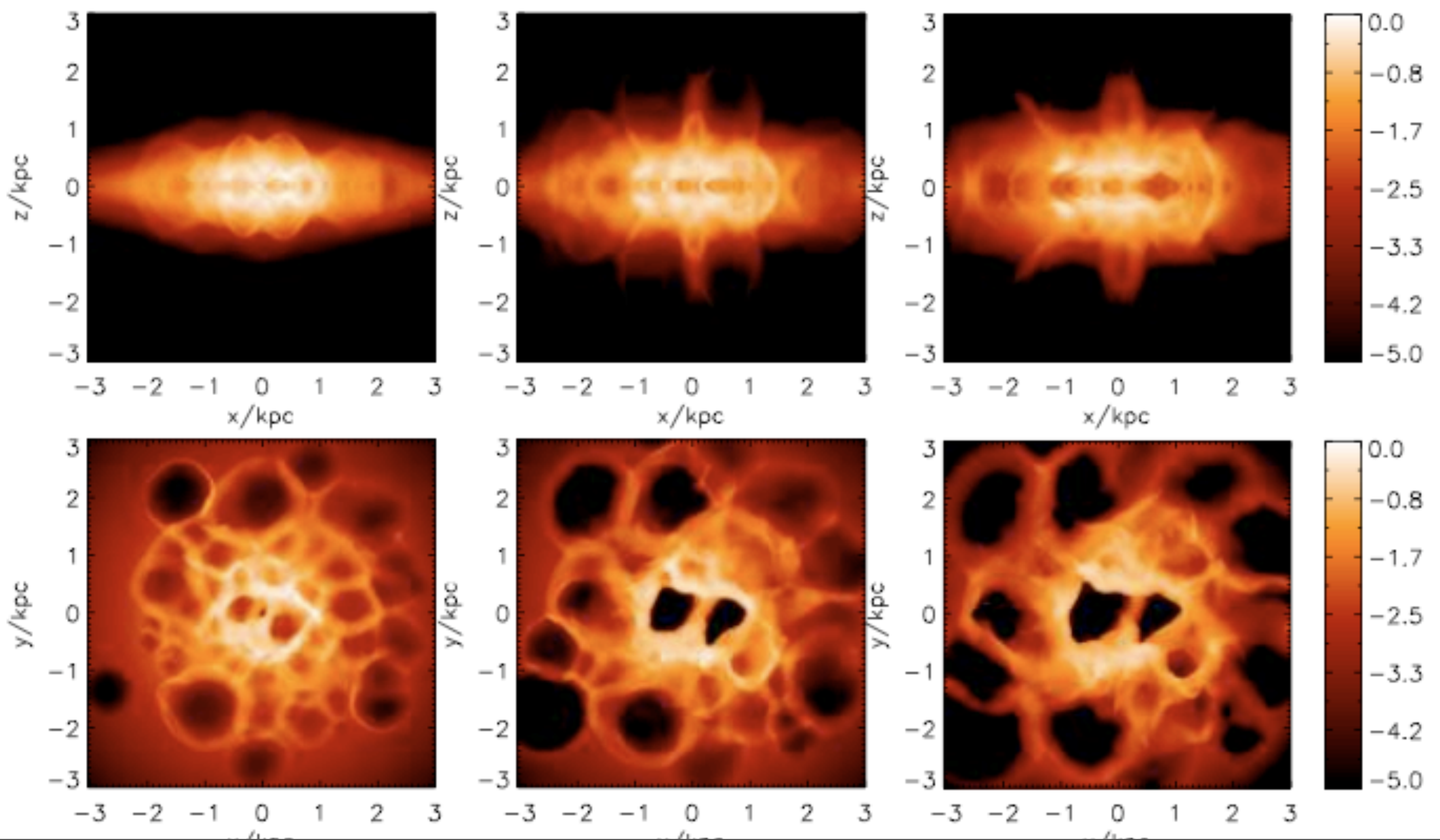


Figure 13. False colour maps of the logarithmic surface brightness in the soft (0.5-2 keV; red) and hard (2-10 keV; blue) X-ray bands in our fiducial simulation (7-4D) at 30 (left panels) & 40 Myrs (right panels). The top row shows a projection in the y-direction and the bottom row shows a projection in the z-direction, spanning the central 12×12 kpc.

- energy from SNe -> supersonic turbulence
- turbulence acts on scales > mfp but < resolution
- pockets of hot gas sweep up thick shells
- shells persist for long times because of cooling instability
- overlapping rarefied regions lead to central outflow
- outflow not caused by single bubble
- mass entrainment occurs in shear layer between hot wind and ISM
- soft x-ray: shocked material in disk
- hard x-ray: direct emission from wind

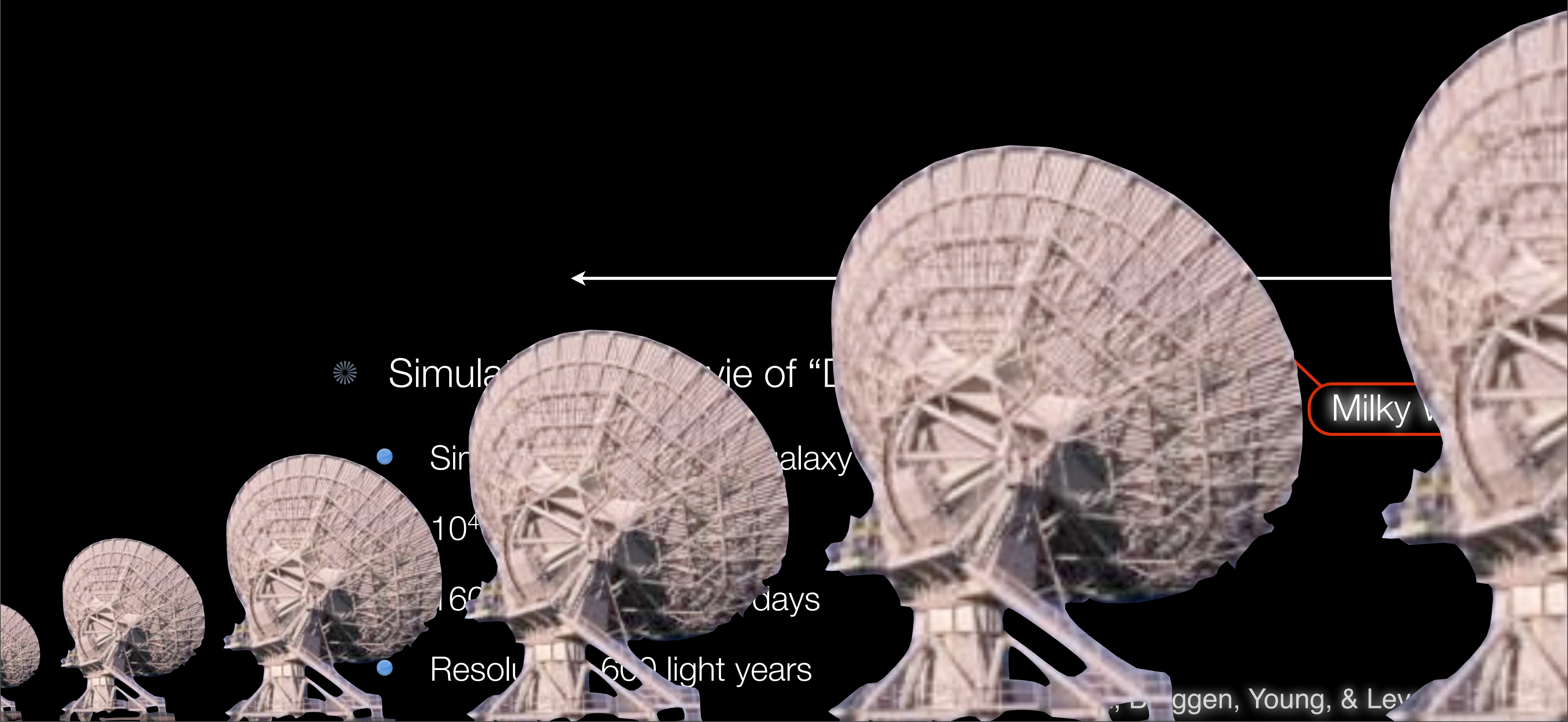


Interface: simulations/observations

- Simula… vie of "D…
  - Sir… alaxy
  - 10^4…
  - 16… days
  - Resolu… 60 light years

Milky W…

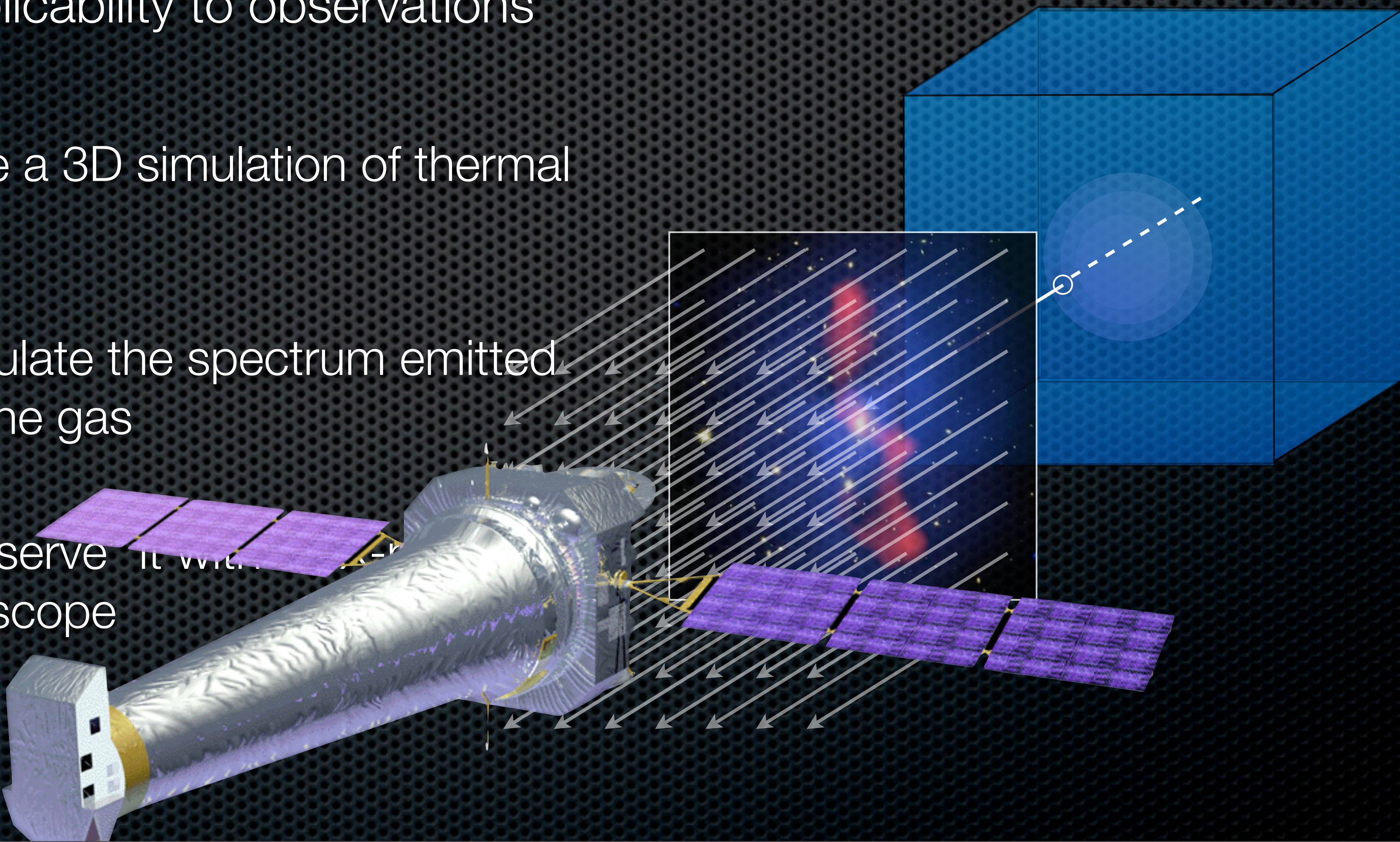
…, B… ggen, Young, & Lev…



Interface: simulations/observations

“A simulation is only as good as its applicability to observations”

1. Take a 3D simulation of thermal gas
2. Simulate the spectrum emitted by the gas
3. “Observe” it with [illegible] telescope



The Chandra view

- The neighborhood

Red: 0.3-2 keV, Green: 2-5 keV, Blue: 5-10 keV

  - S2 Cluster
    (Springel et al. 2001)
  - $10^{15} M_{\odot}$ Cluster
  - z_{start}=0.02

- The Jet:
  - W=10^{46} ergs s^{-1}
  - Run: 260 CPU days
  - Outburst: $3x10^{7}$ yrs
  - Resolution: 170 pc

450 kpc

Heinz, Brüggen, Young, & Levesque 2006

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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.

- Turbulence succeeds in reproducing a self-regulated AGN with duty cycles of 50-100 Myrs

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

- Galaxy outflows can be driven by collective motions even when cooling is included

- Outflow structure is determined by cooling instability rather than RT instability

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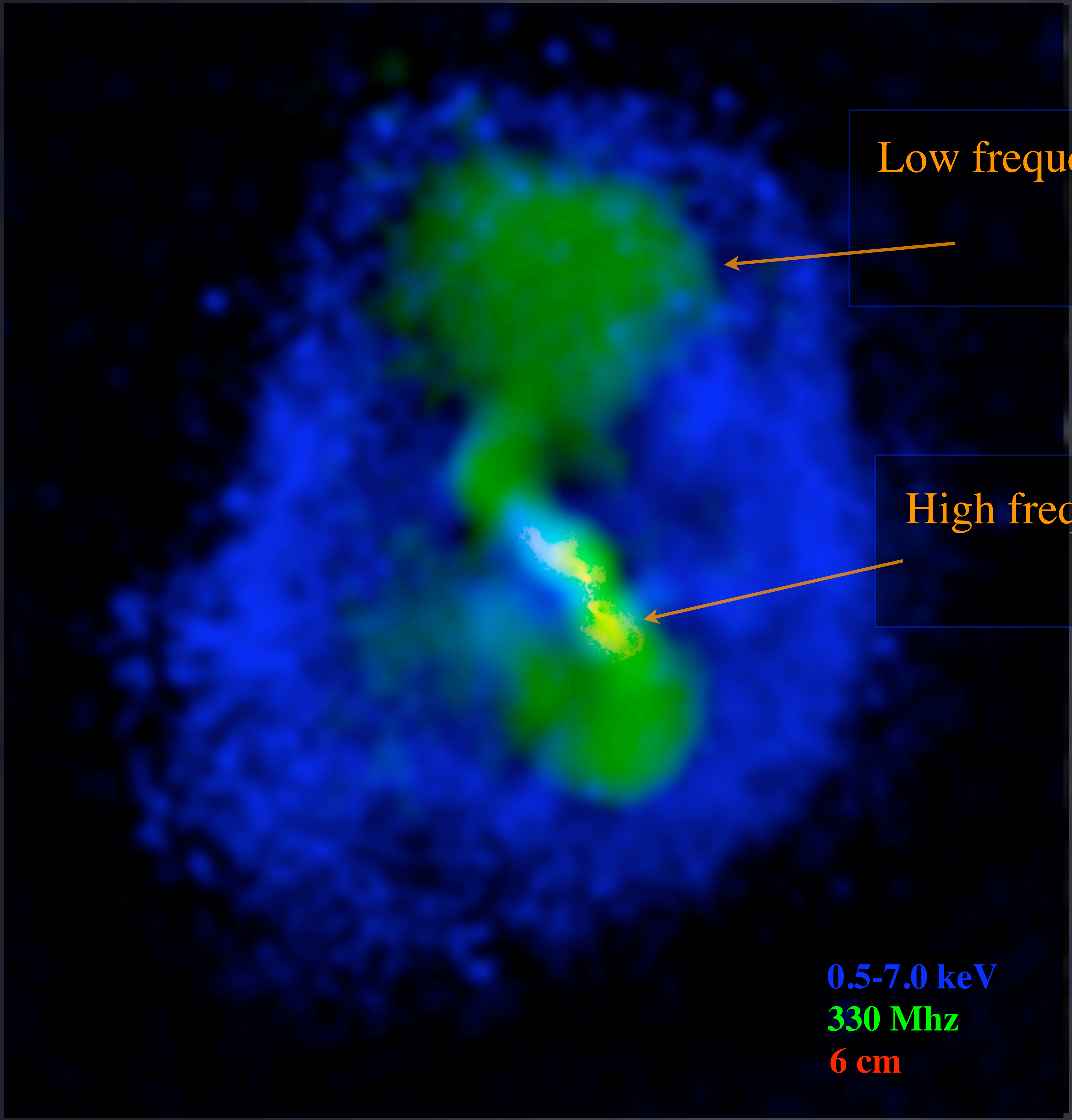
Low frequency



Low frequency ⇒ integrated history
$t > 200$ Myr

High frequency ⇒ recent activity
$t \sim 50$ Myr

Tracer of cavity energetics

slide by M. Wise