Modeling Turbulence in the Intracluster Medium

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With
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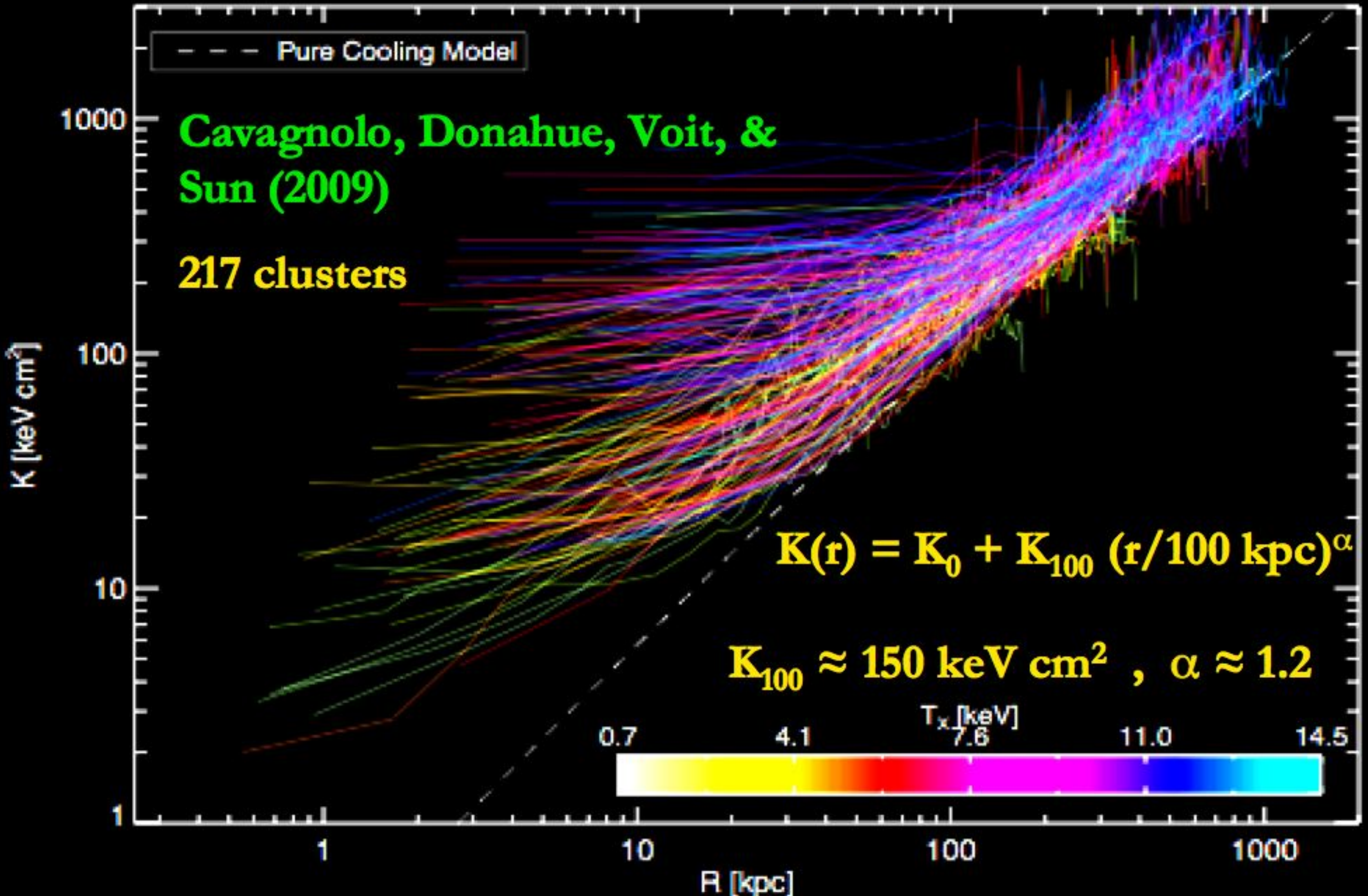
Chandra Entropy Profiles



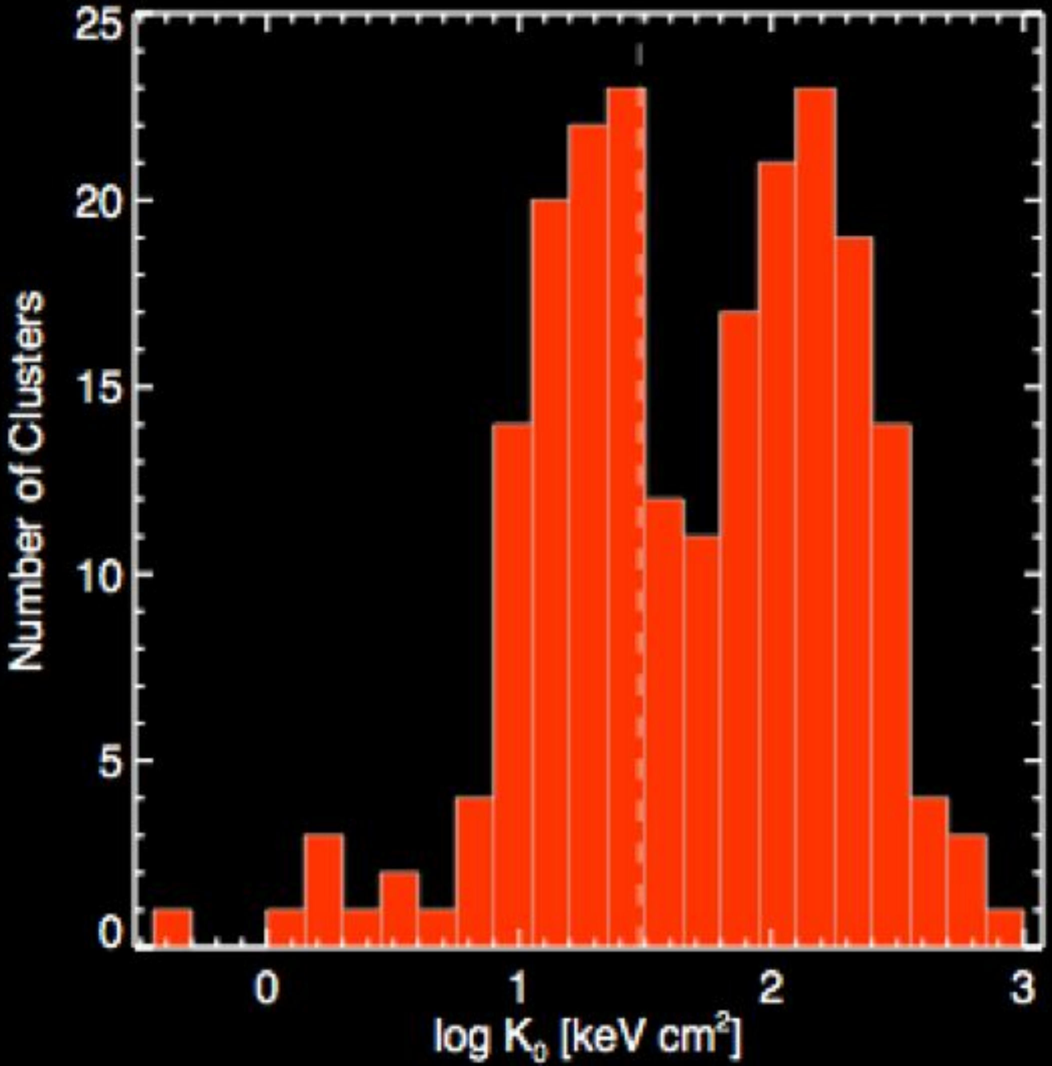
Cavagnolo, Donahue, Voit, & Sun (2009)

217 clusters

$$K(r) = K_0 + K_{100}\,(r/100\ \mathrm{kpc})^{\alpha}$$

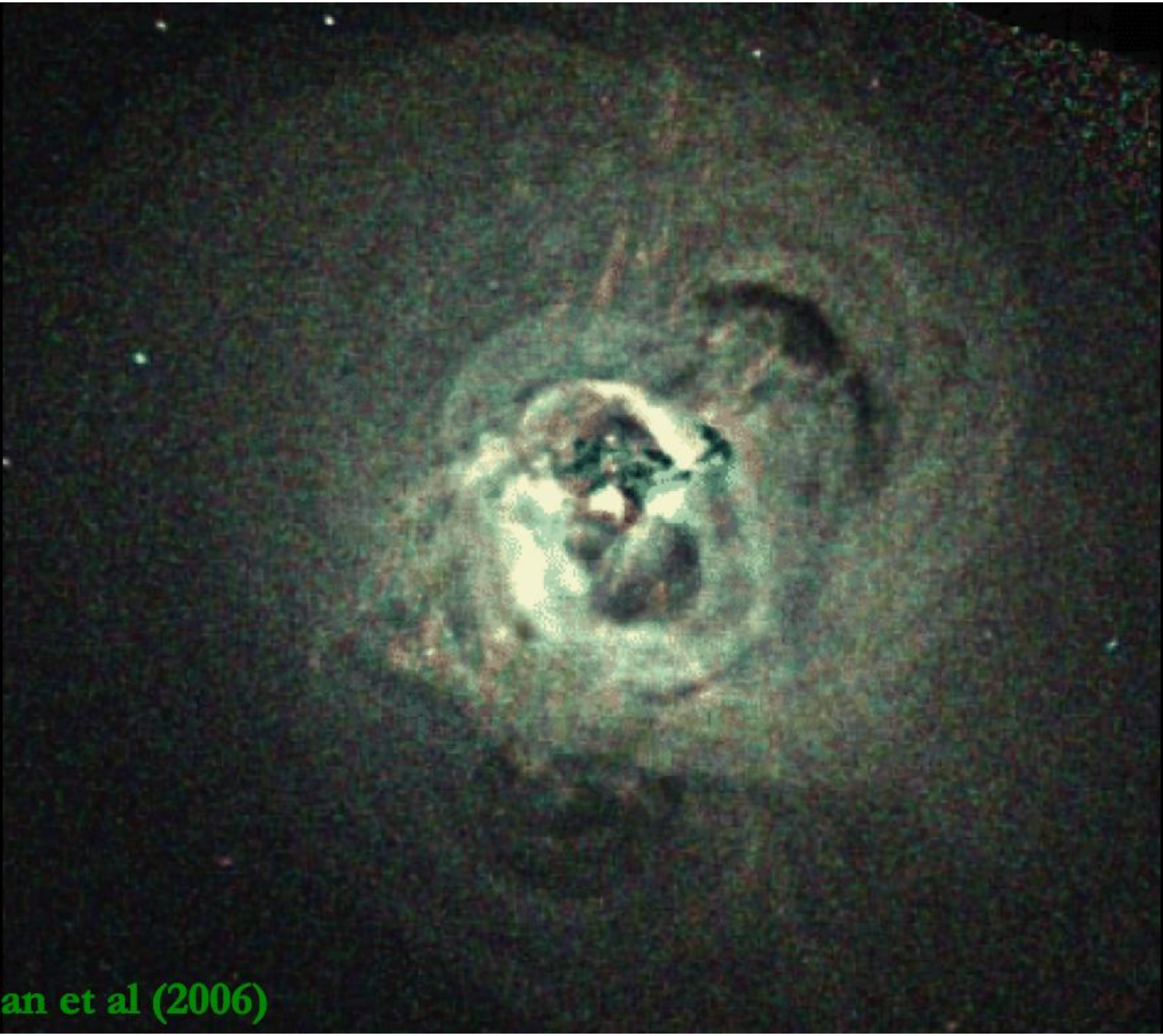
$$K_{100} \approx 150\ \mathrm{keV\ cm^2}\ ,\ \ \alpha \approx 1.2$$

Central Entropy Distribution



Distribution of K_0 is bimodal with deficit at K_0 ~ 40-50 keV cm^2 corresponding to a cooling time ~ 1 Gyr

Cavagnolo et al. (2009)



Fabian et al (2006)

Simulation setup

FLASH3, AMR

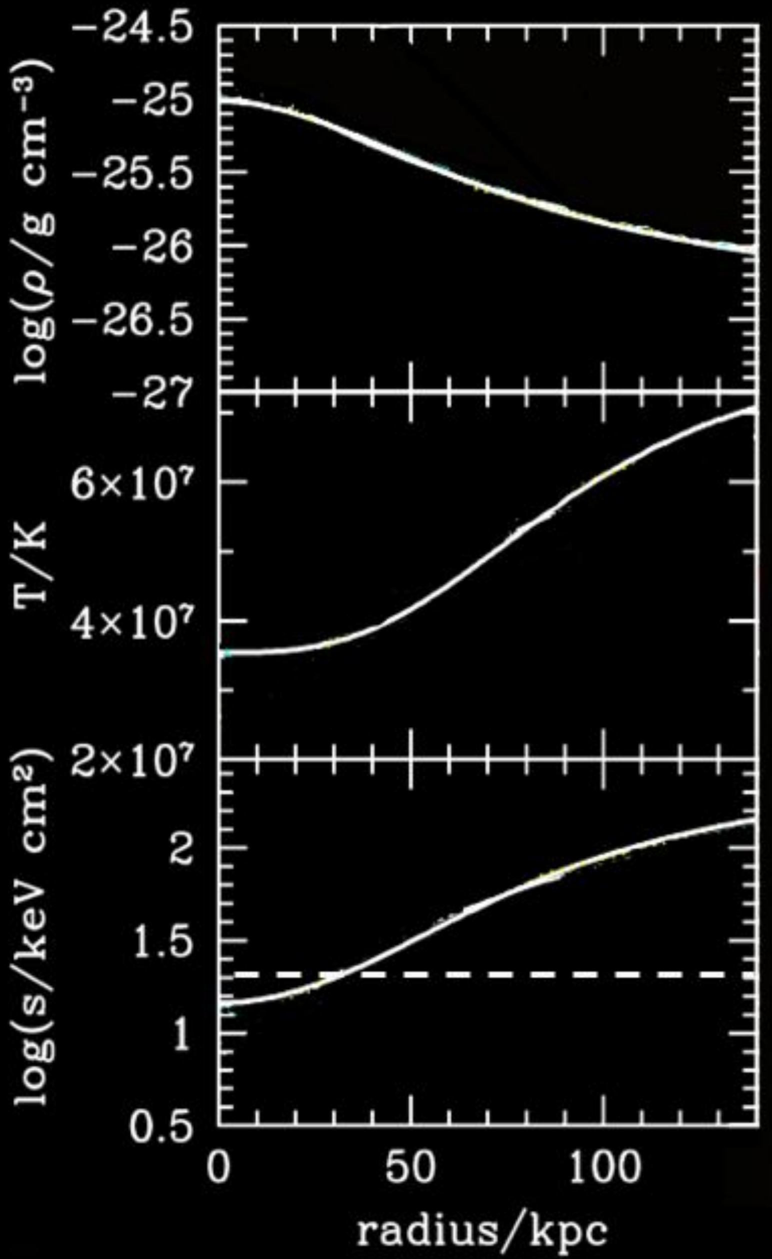
initially hydrostatic cluster, modeled after Perseus, static gravity

5 levels of refinement (3-6), 1024^3 eff. res., (650 kpc)^3 box

radiative cooling by thermal bremsstrahlung

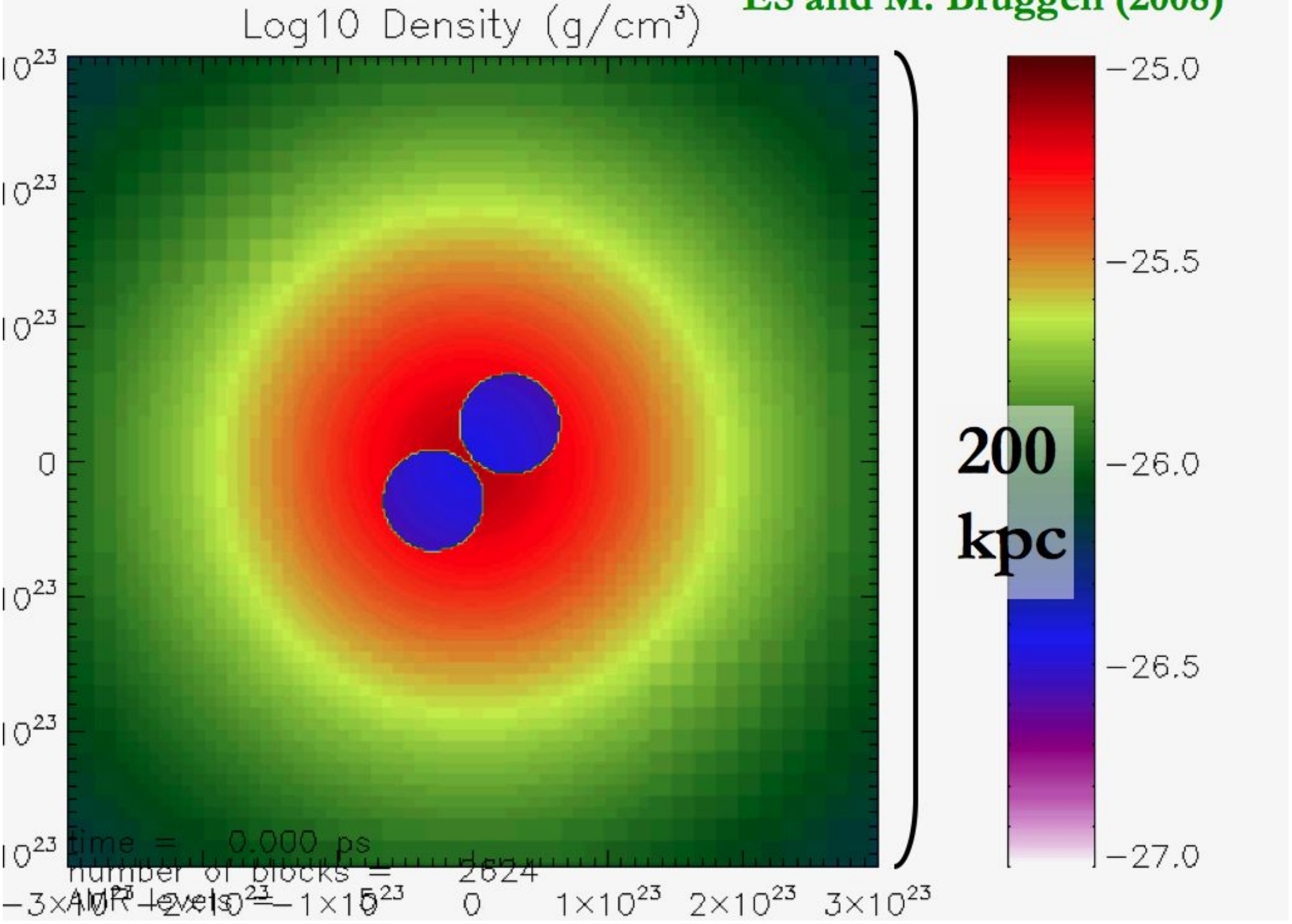
bubbles are produced by injection of energy into spherical regions

Saguaro cluster (4096core cluster at ASU)



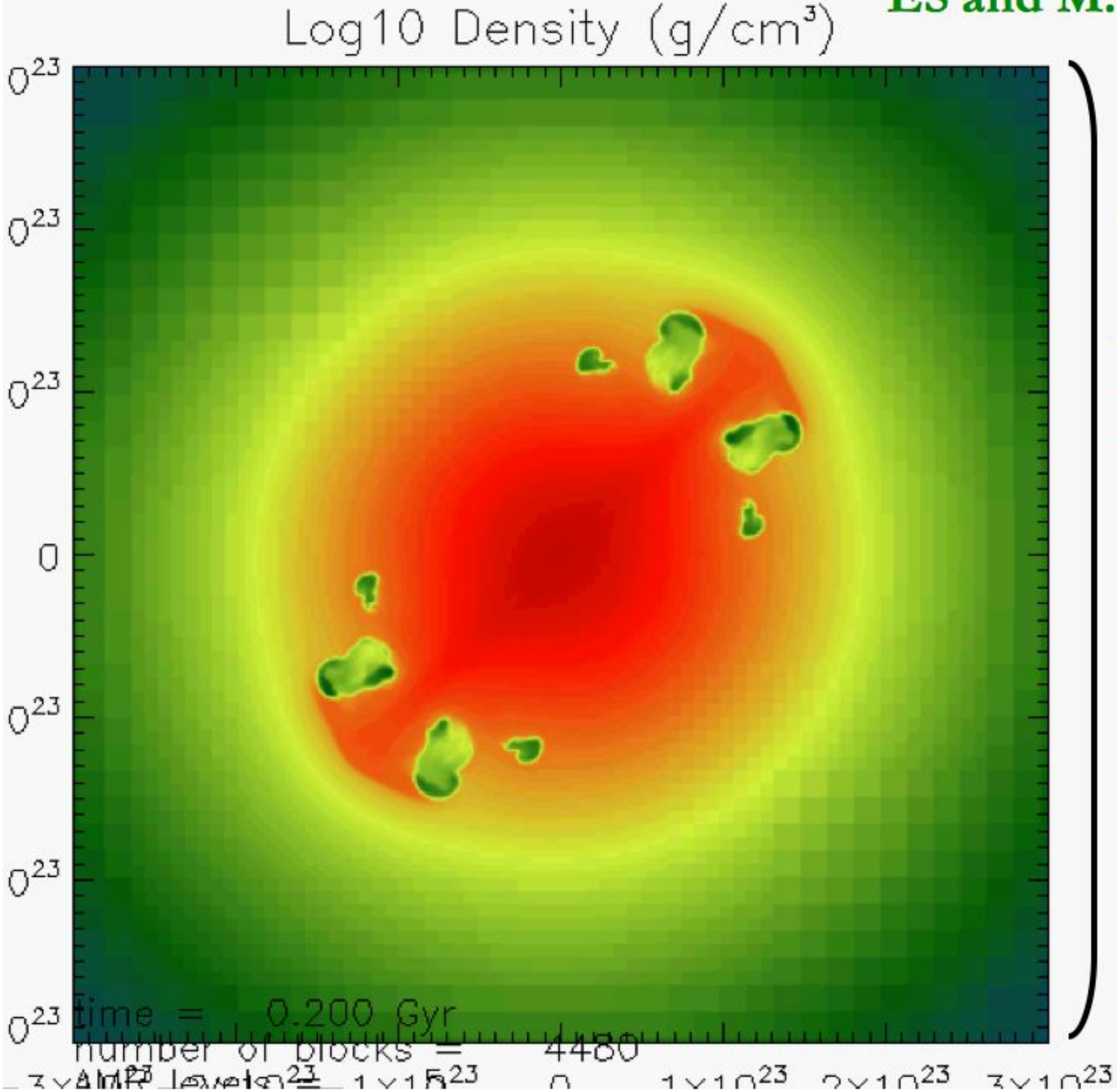
ES and M. Bruggen (2008)

ES and M. Bruggen (2008)



200 kpc

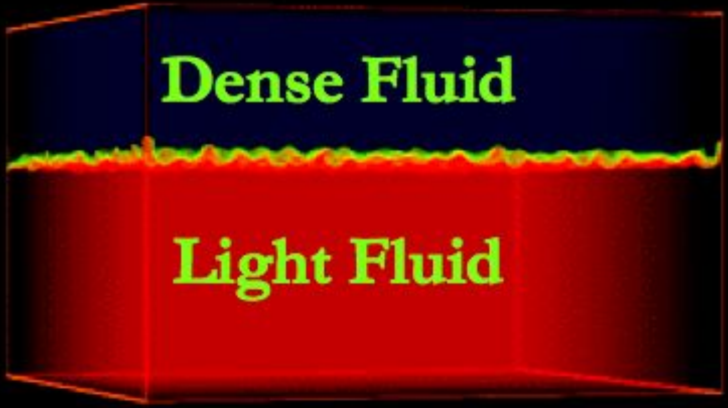
ES and M. Bruggen (2008)



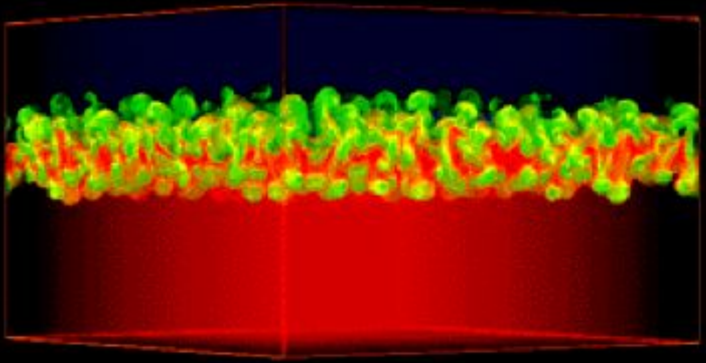
SEE ALSO:
Robinson et al '05
Reynolds et al '05
Bruggen '05

200 kpc

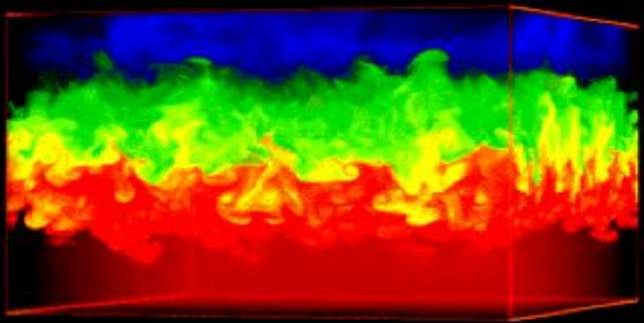
Rayleigh Taylor Instability



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

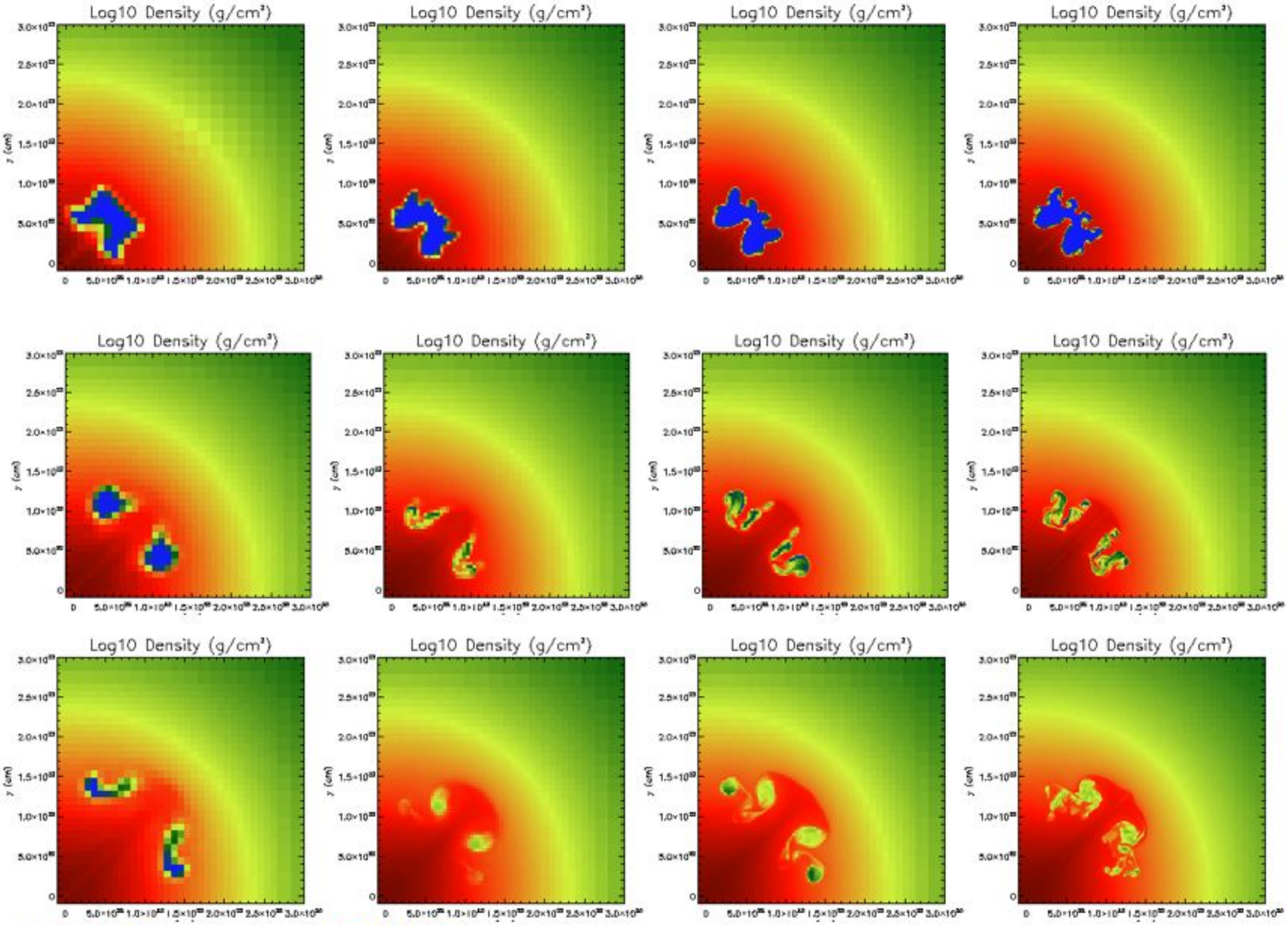


$$A_i = \frac{\bar{\rho}_+ - \bar{\rho}_-}{\bar{\rho}_+ + \bar{\rho}_-} .$$



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

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



ES and M. Bruggen (2008)

Ionized Medium

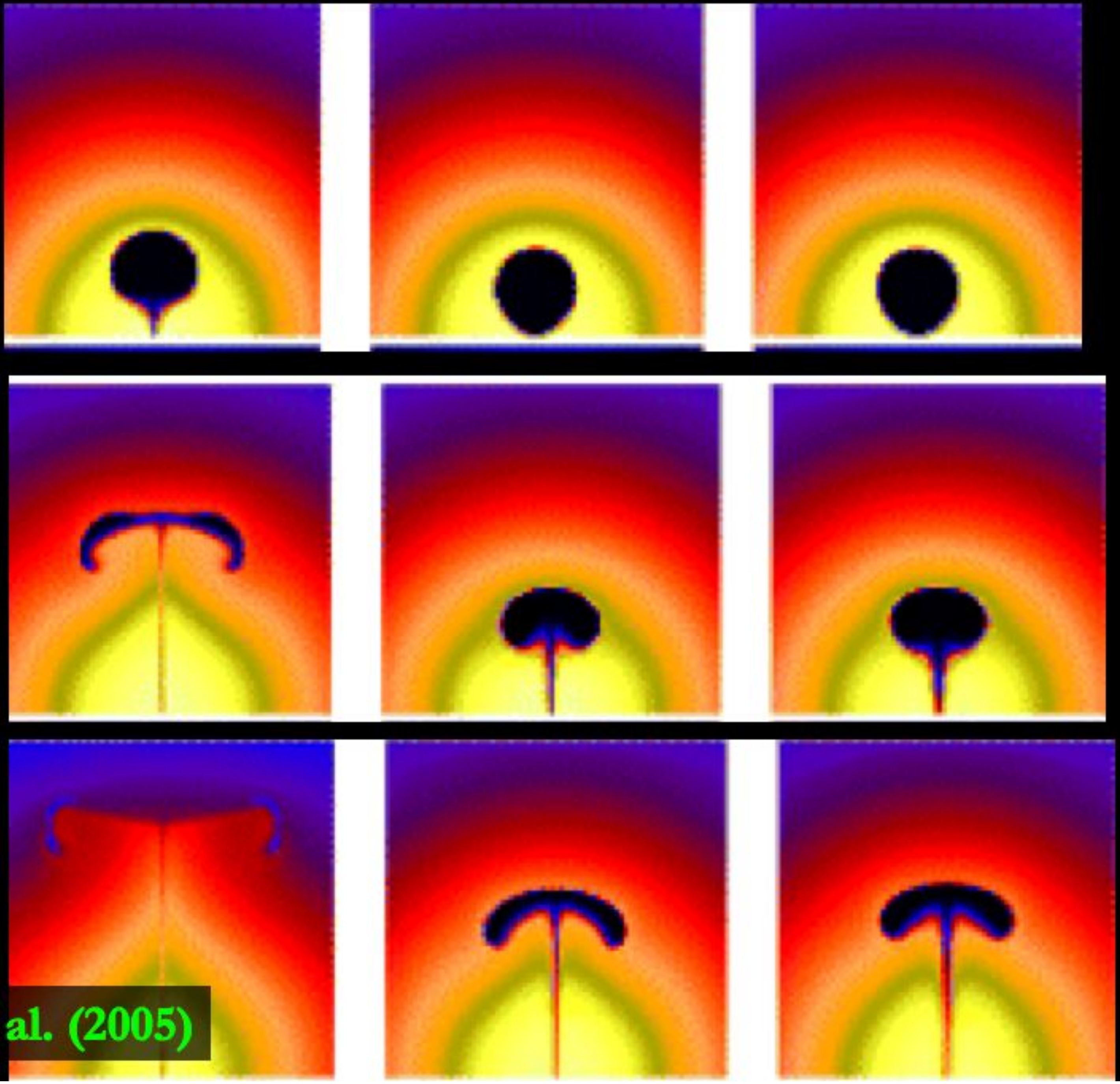
viscosity $\propto V_i \lambda_i$

V_i = Velocity of ions

$$\lambda_i = 1/[n\,\pi\,(e^2/3kT)^2]$$

Spitzer $\nu \approx 20$ kpc × 1000 km/s $n_{-3}^{-1}\,T_8^{5/2}$

viscous bubble evolution



Reynolds et al. (2005)

Ionized Medium

viscosity $\propto V_i \lambda_i$

V_i = Velocity of ions

$$\lambda_i = 1/[n\,\pi\,(e^2/3kT)^2]$$

$$\nu \approx 20\ \text{kpc} \times 1000\ \text{km/s}\ n_{-3}^{-1}\,T_8^{5/2}$$

$$\lambda_{I,B} = (m\,v_i\,/eB)$$

$$\nu \approx 10^{10}\ \text{cm}\ (T_8^{1/2}/B_{\mu G}) \times 1000\ \text{km/s}\ \ T_8^{1/2}$$

Subgrid Turbulence

$\vec{v}$

ρ

T

$P(\rho,T)$

$\vec{v}$

$\bar{\rho}$ L

$\bar{T}$ K

$P(\bar{\rho},K,\bar{T})$

ES & M. Bruggen (2010)

Fluid Equations For Supersonic Turbulence

Thermal +
Turbulent

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} .$$

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

ES & M. Bruggen (2009)

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

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

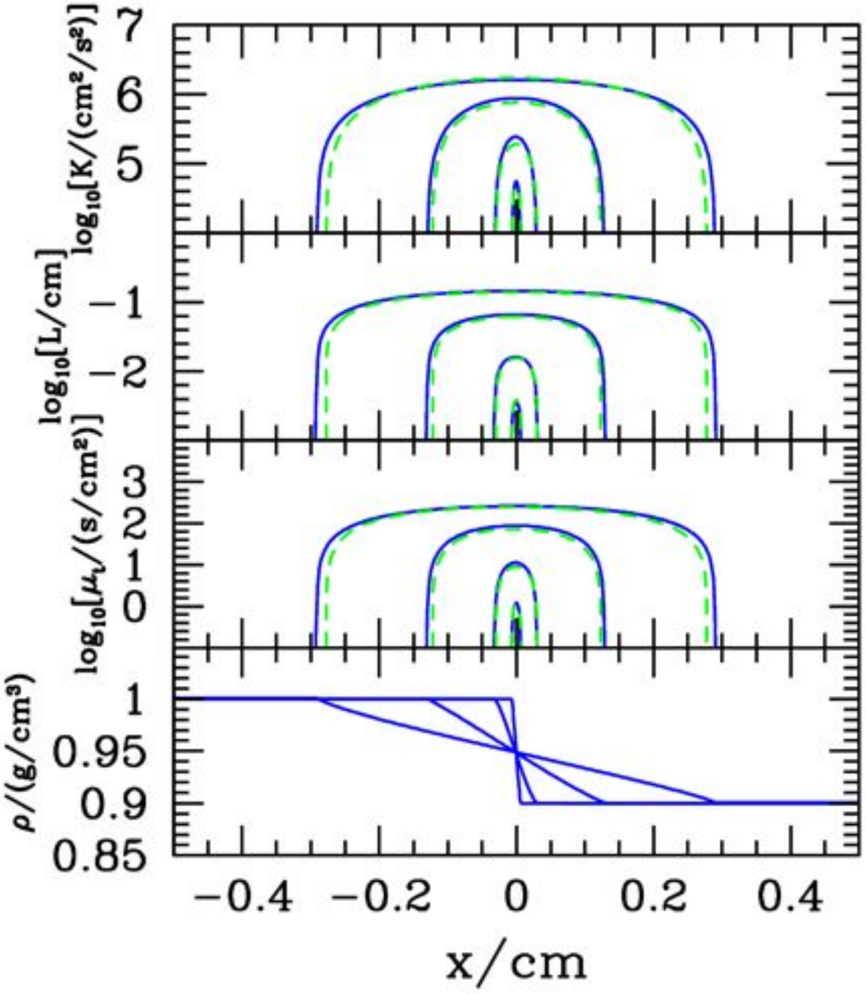
buoyancy

drag

turb. viscosity

turb. velocity

Rayleigh-Taylor Shock Tube Test



solid: simulation
dashed: analytic

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

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

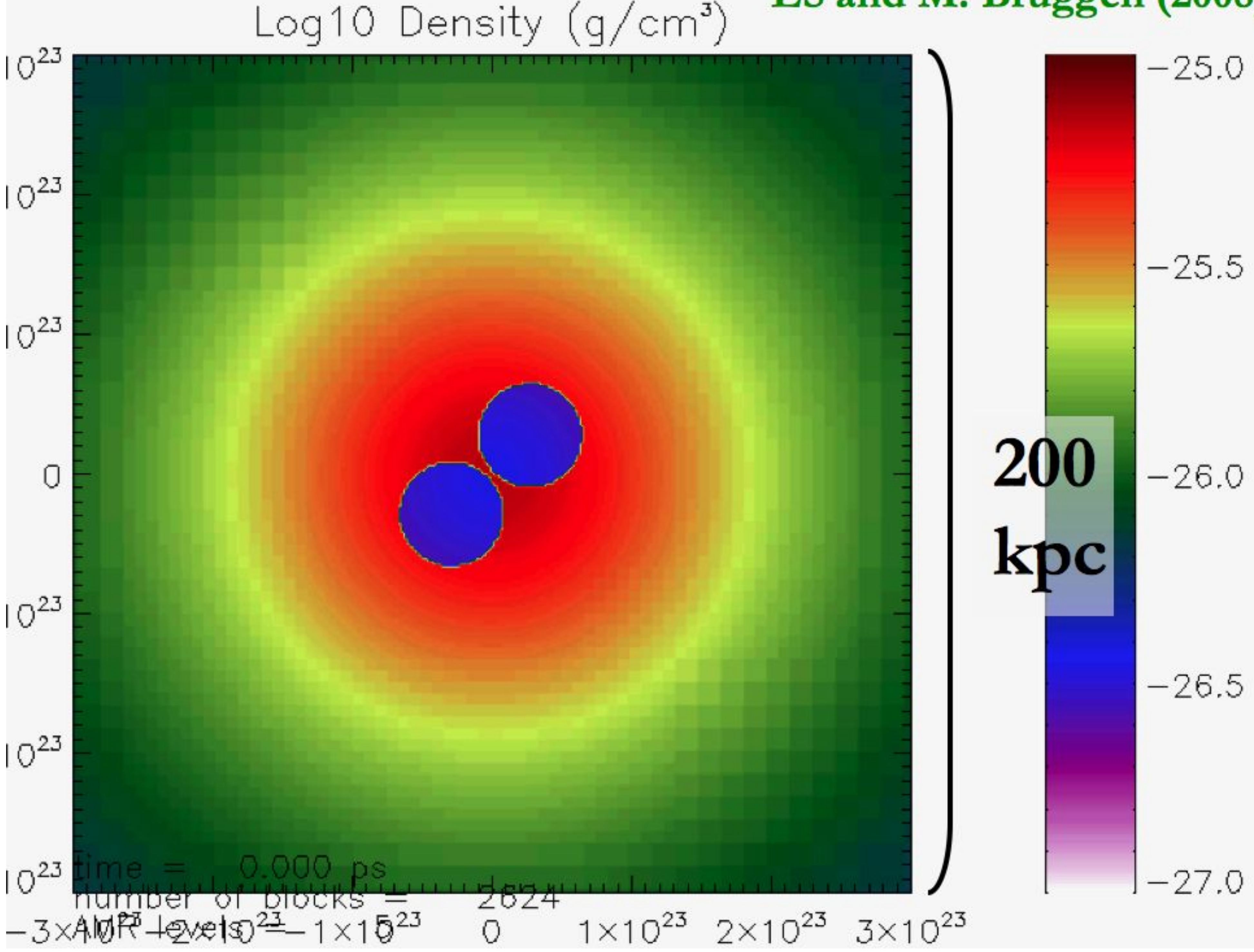
$$h(t) = \alpha A(0) t^2$$

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

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

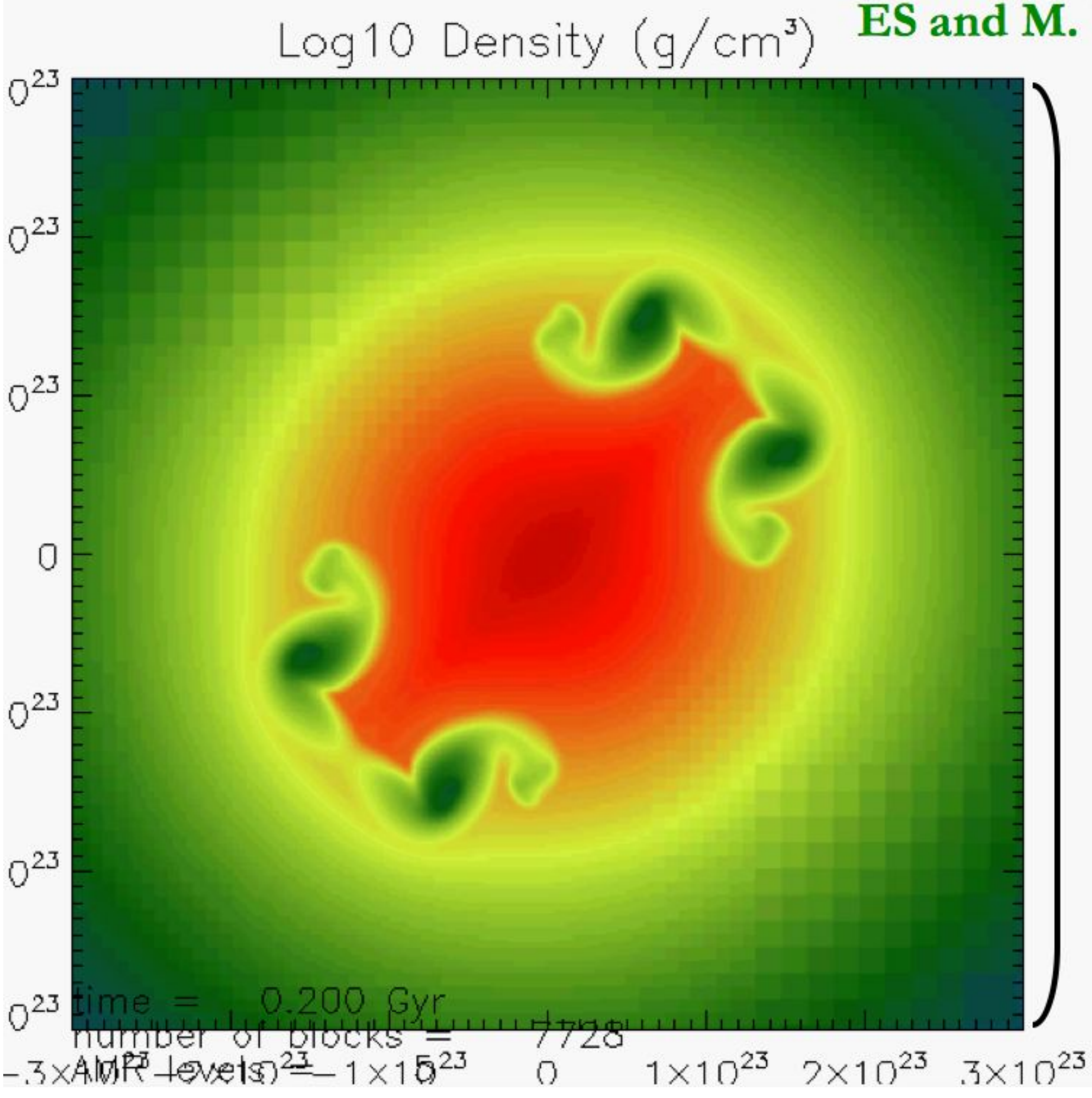
ES and M. Bruggen (2008)

ES and M. Bruggen (2008)



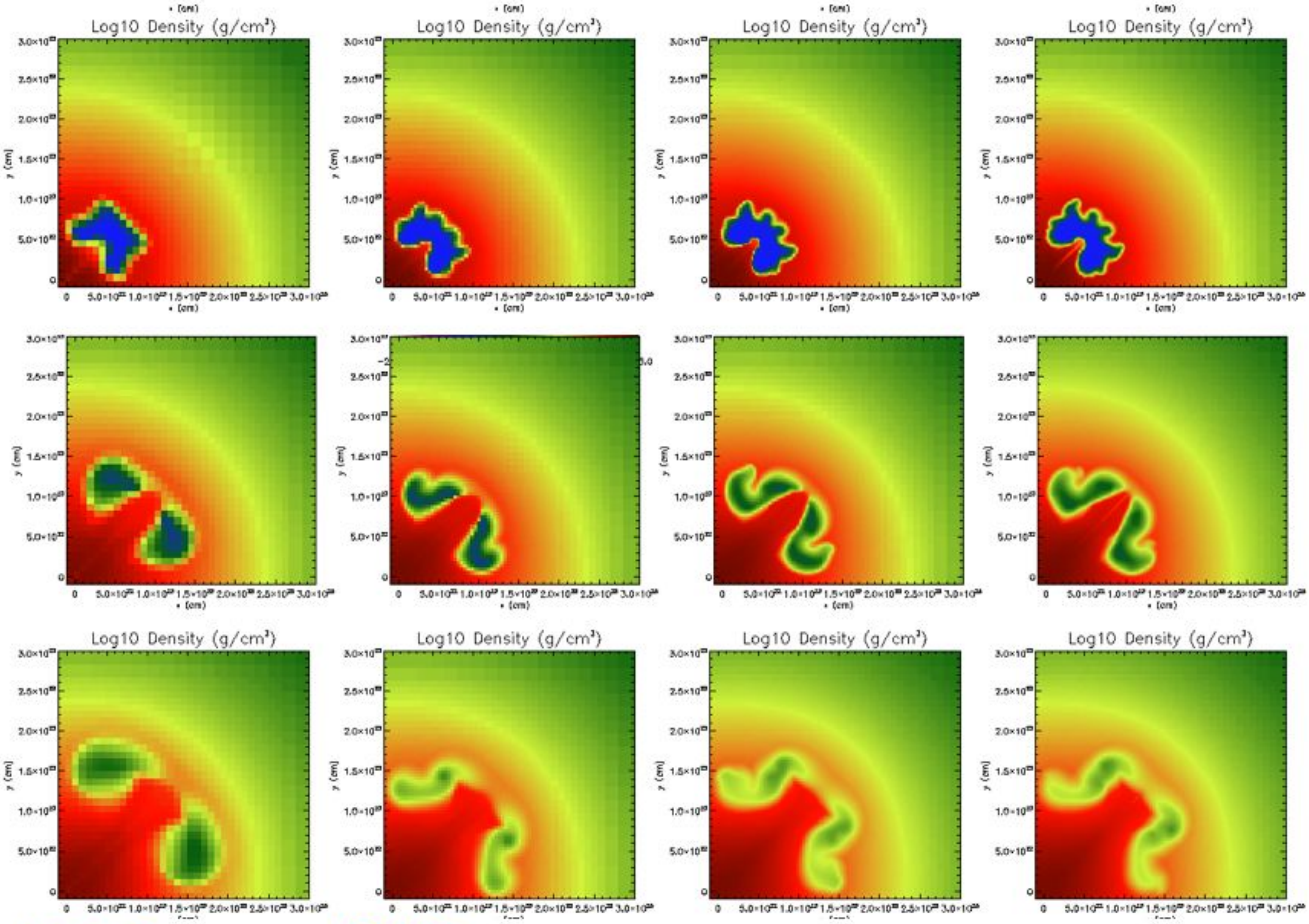
200 kpc

ES and M. Bruggen (2008)



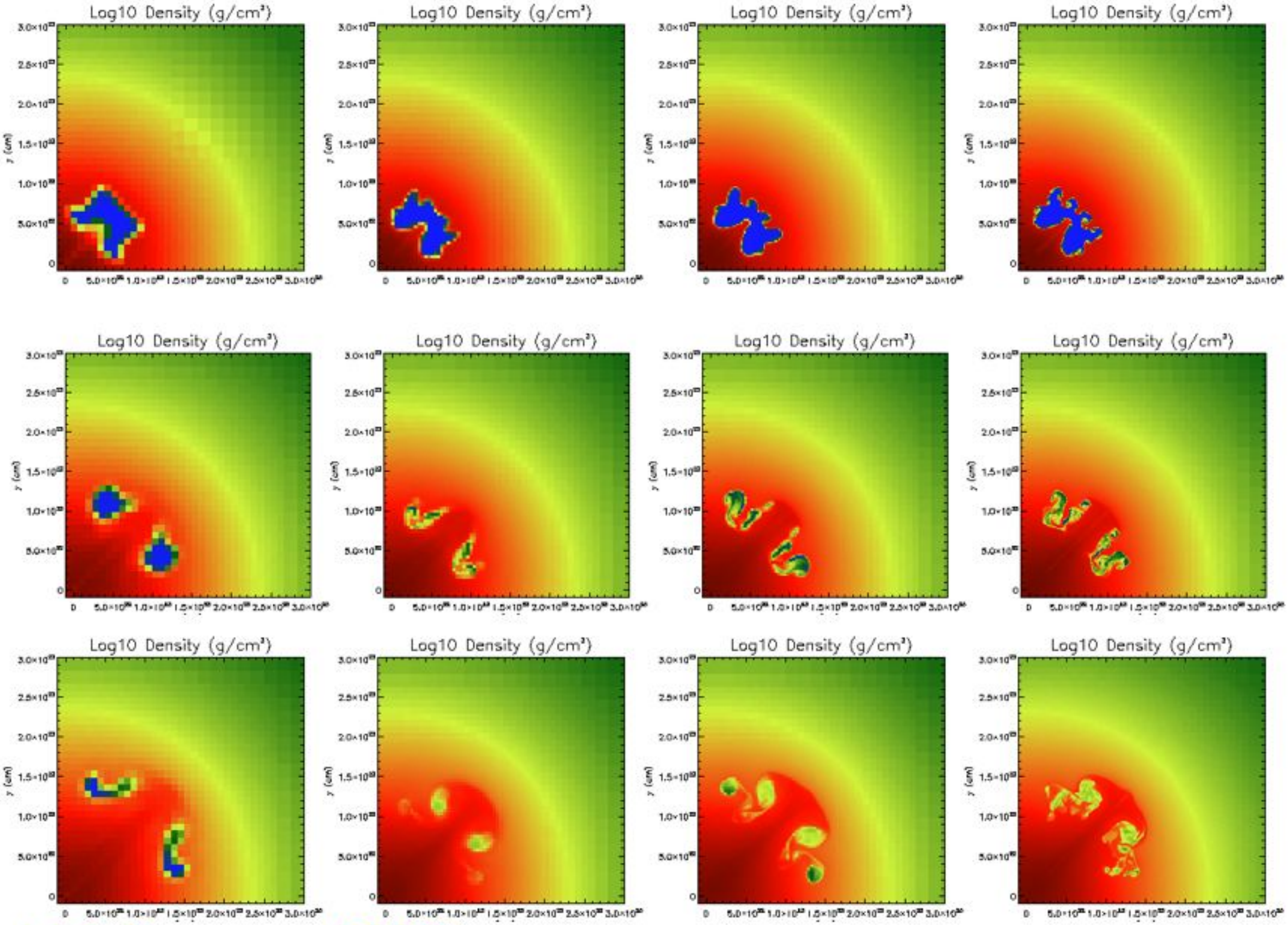
200 kpc

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



ES and M. Bruggen (2008)

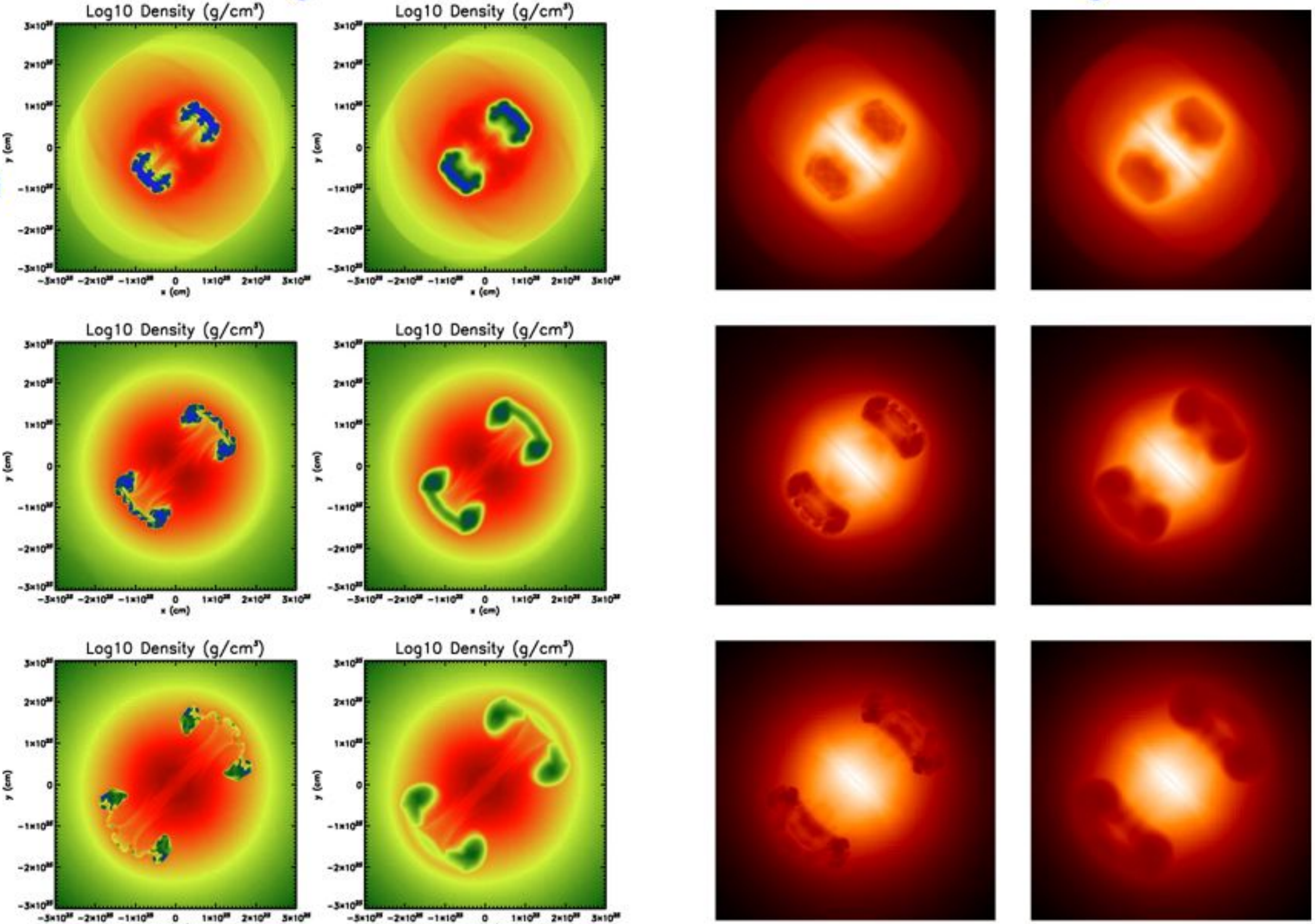
Dependance on Resolution $\lambda_{\max} = 4\pi(\nu^2 A/g)^{1/3}$



ES and M. Bruggen (2008)

Density Slices

X-ray



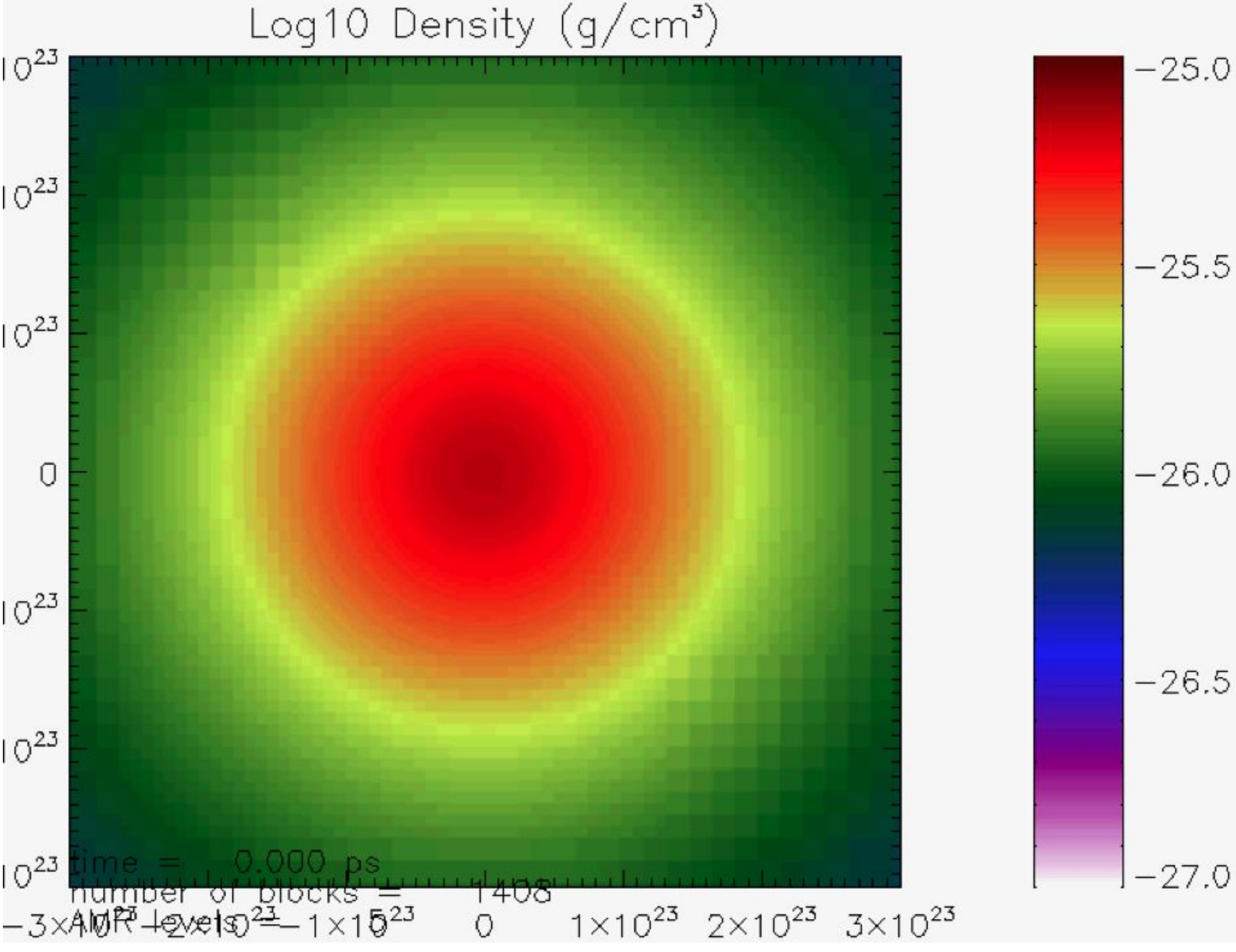
50 Myrs

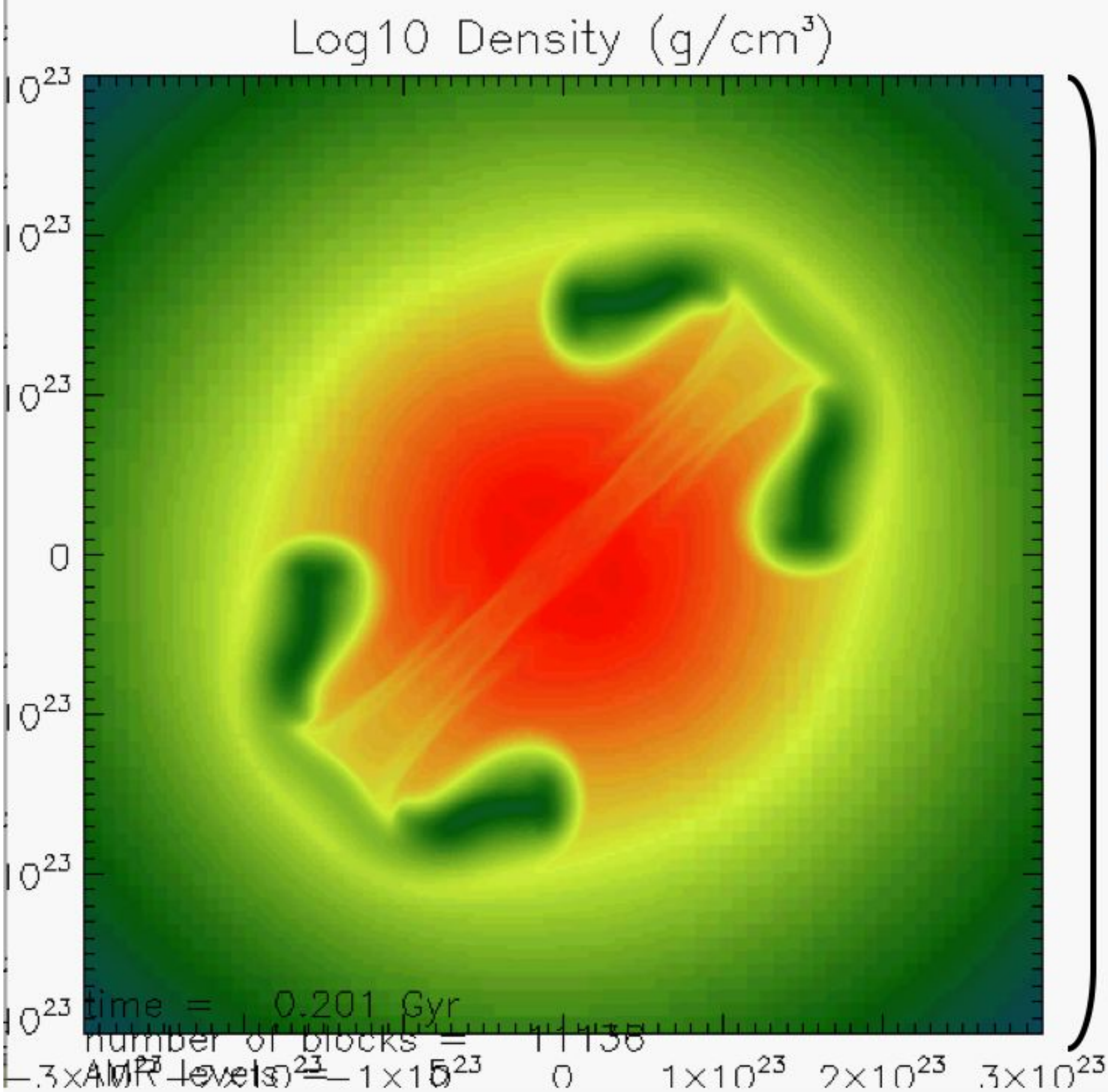
100 Myrs

150 Myrs

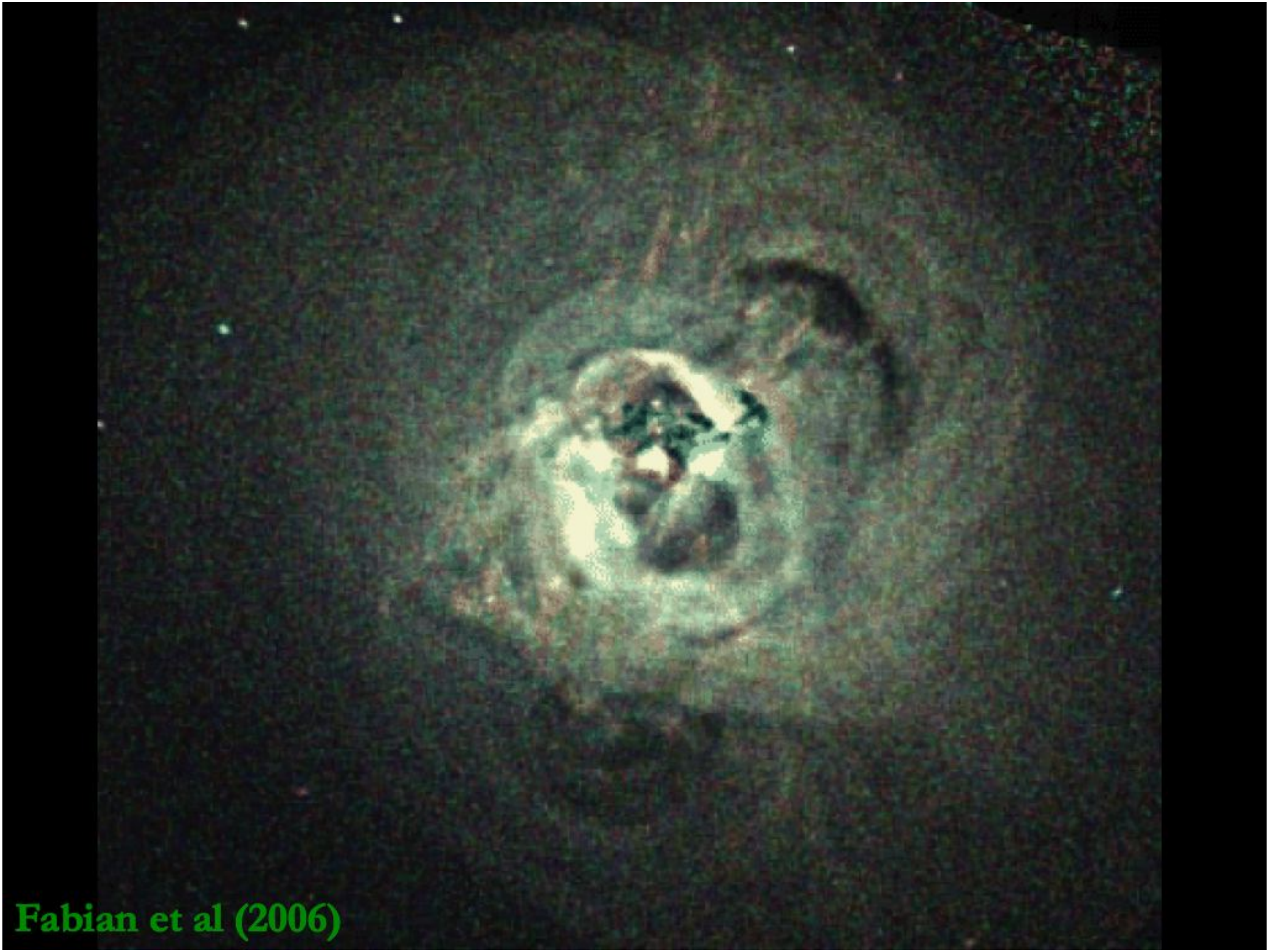
No Turb. **Turbulence** **No Turb.** **Turbulence**

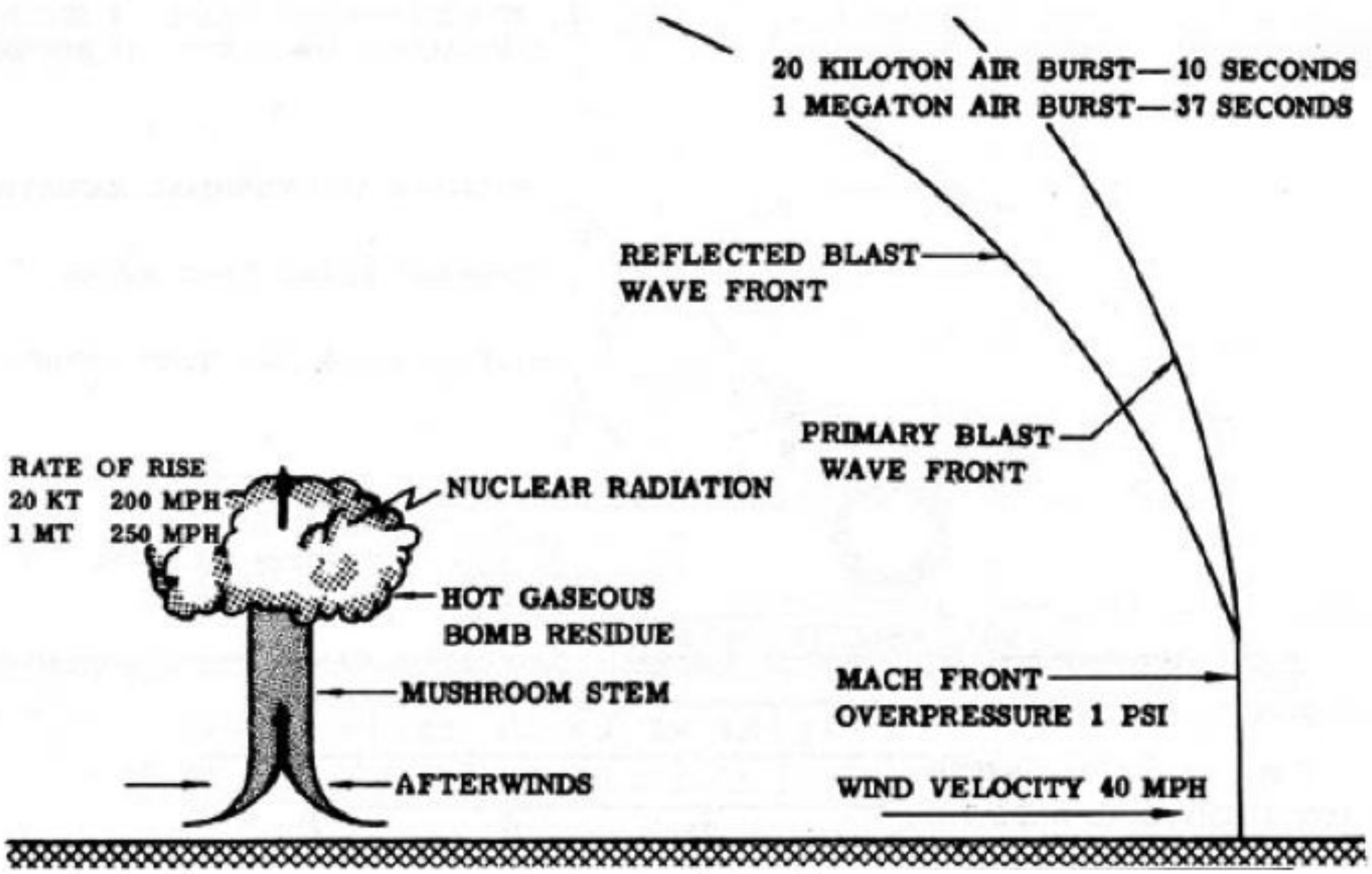
ES and M. Bruggen (2008)

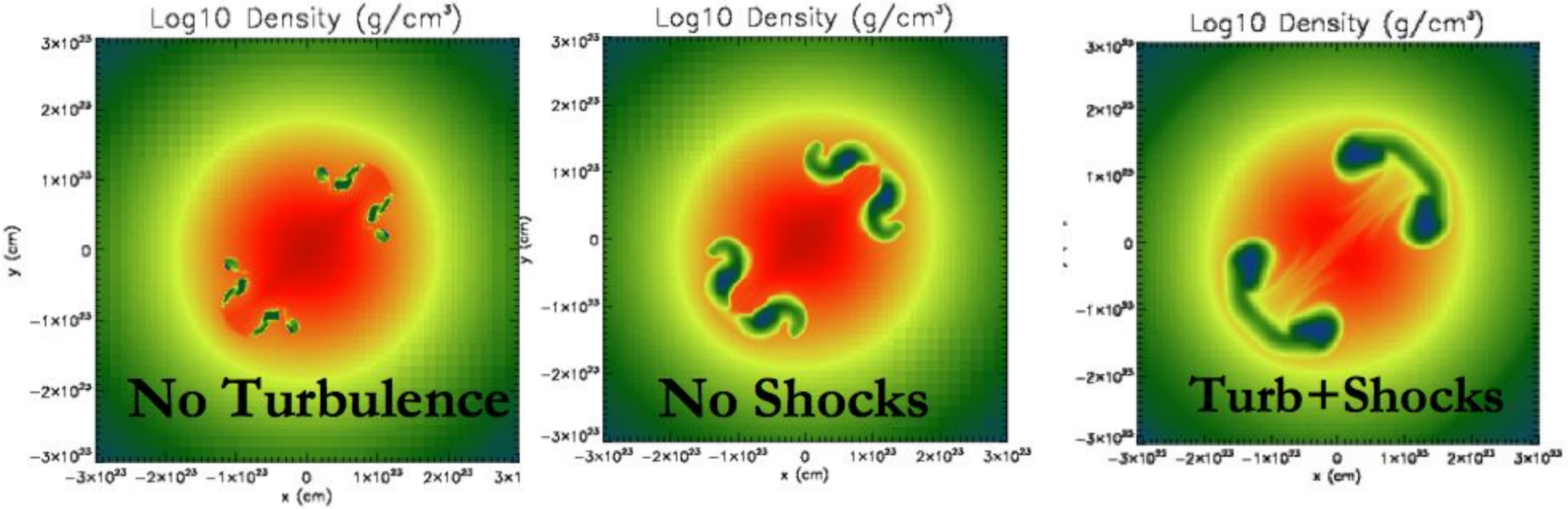

Log10 Density (g/cm³)
−25.0
−25.5
−26.0
−26.5
−27.0
10^23
10^23
10^23
0
10^23
10^23
10^23
time = 0.000 ps
number of blocks = 1408
AMR levels = 5
−3×10^23
−2×10^23
−1×10^23
0
1×10^23
2×10^23
3×10^23

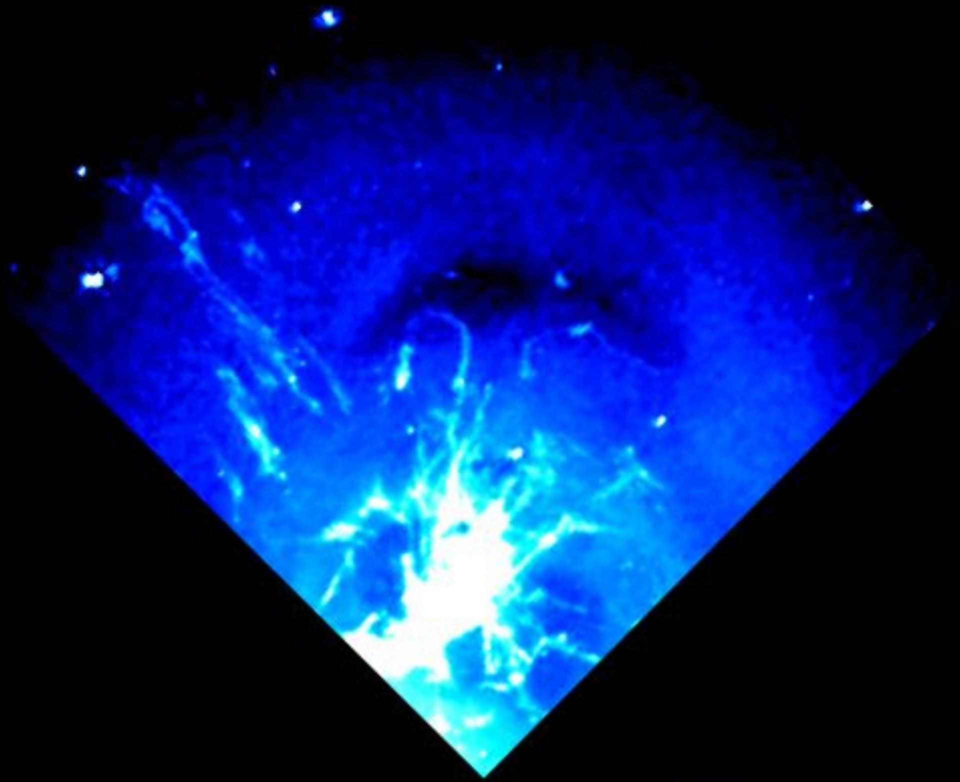

Log10 Density (g/cm³)
10^23
10^23
10^23
0
10^23
10^23
10^23
time = 0.201 Gyr
number of blocks = 11136
AMR levels = 5
−3×10^23
−2×10^23
−1×10^23
0
1×10^23
2×10^23
3×10^23

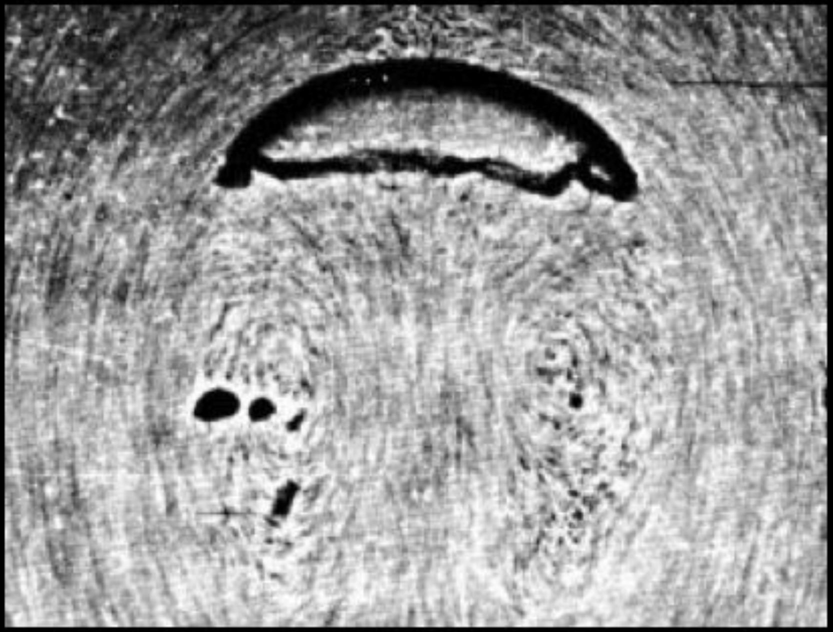
200 kpc

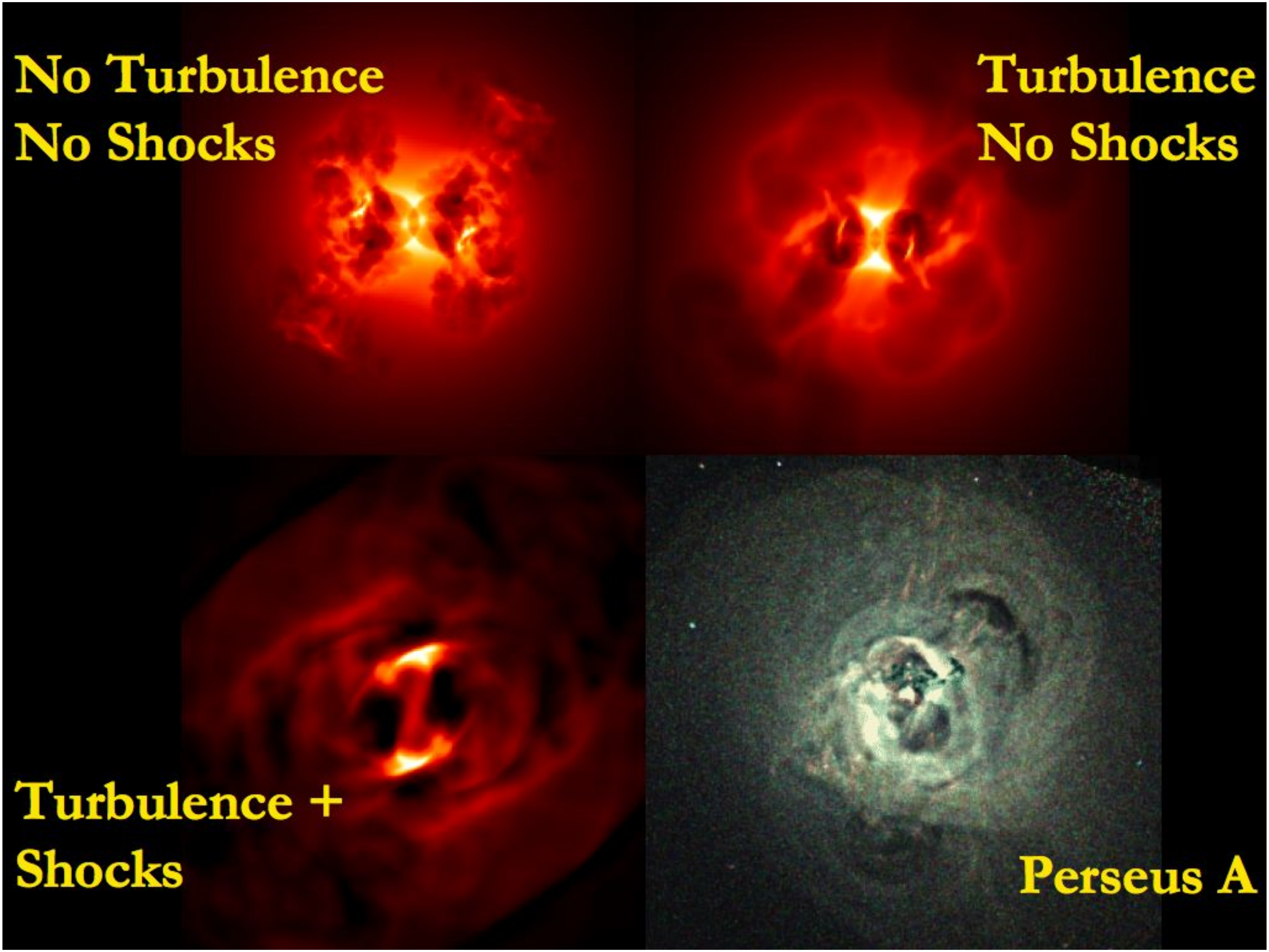

Fabian et al (2006)

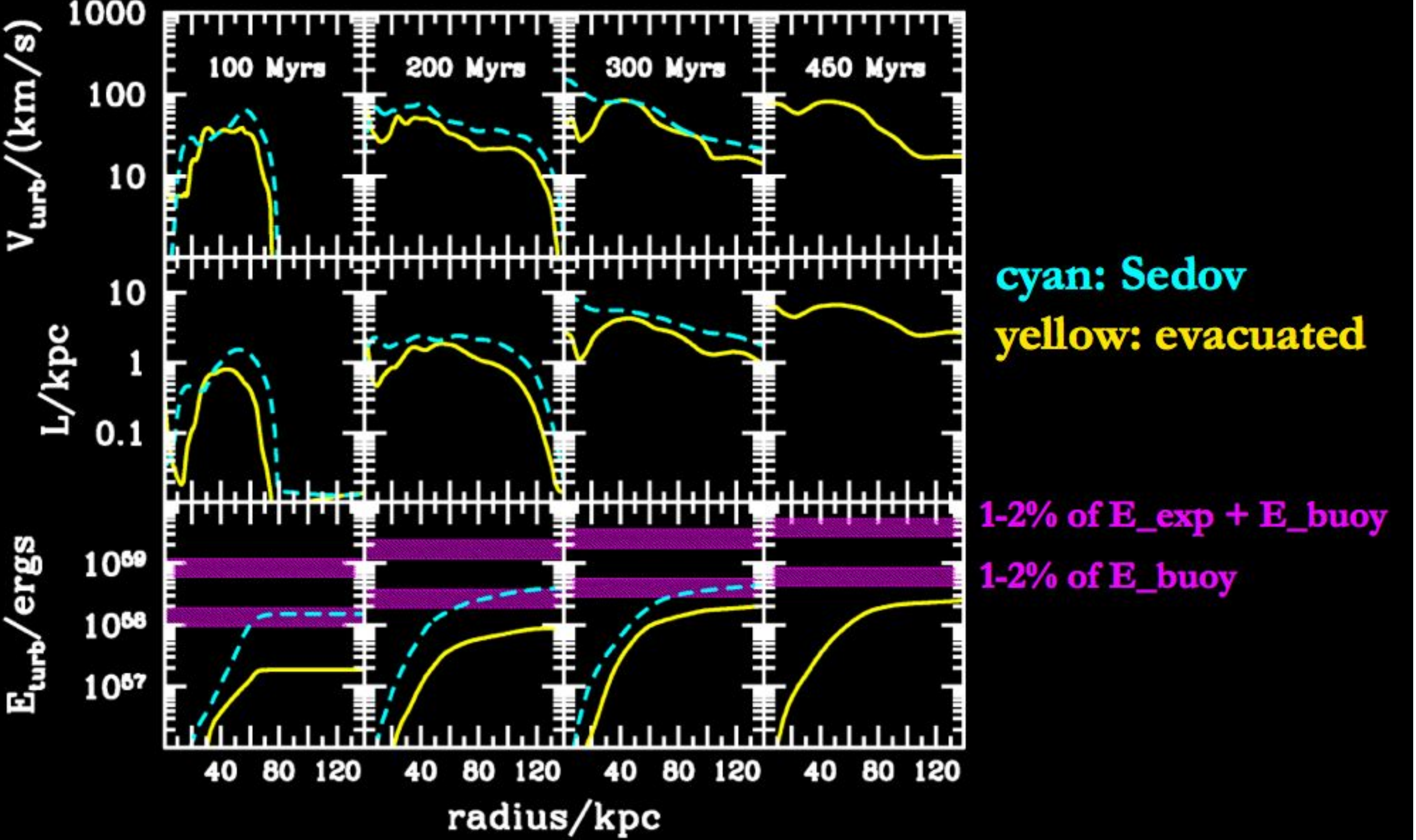

20 KILOTON AIR BURST— 10 SECONDS
1 MEGATON AIR BURST— 37 SECONDS
REFLECTED BLAST WAVE FRONT
PRIMARY BLAST WAVE FRONT
RATE OF RISE
20 KT 200 MPH
1 MT 250 MPH
NUCLEAR RADIATION
HOT GASEOUS BOMB RESIDUE
MUSHROOM STEM
AFTERWINDS
MACH FRONT
OVERPRESSURE 1 PSI
WIND VELOCITY 40 MPH


Log10 Density (g/cm³)
y (cm)
x (cm)
3×10²³
2×10²³
1×10²³
0
−1×10²³
−2×10²³
−3×10²³
3×1
No Turbulence
No Shocks
Turb+Shocks

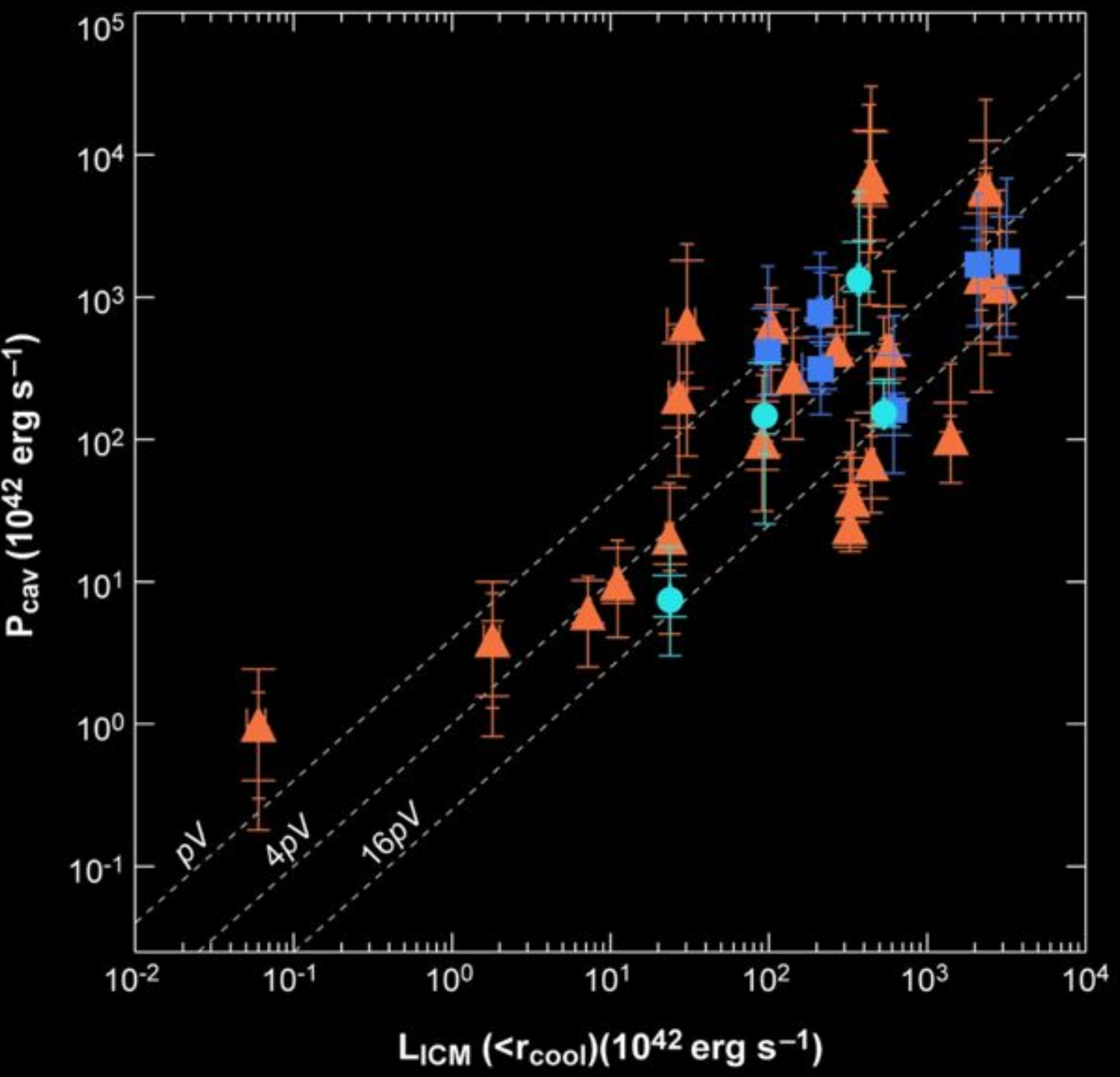





No Turbulence
No Shocks
Turbulence
No Shocks
Turbulence +
Shocks
Perseus A


100 Myrs
200 Myrs
300 Myrs
450 Myrs
V_{turb}/(km/s)
1000
100
10
L/kpc
10
1
0.1
E_{turb}/ergs
10^{69}
10^{68}
10^{67}
40
80
120
radius/kpc
cyan: Sedov
yellow: evacuated
1-2% of E_exp + E_buoy
1-2% of E_buoy

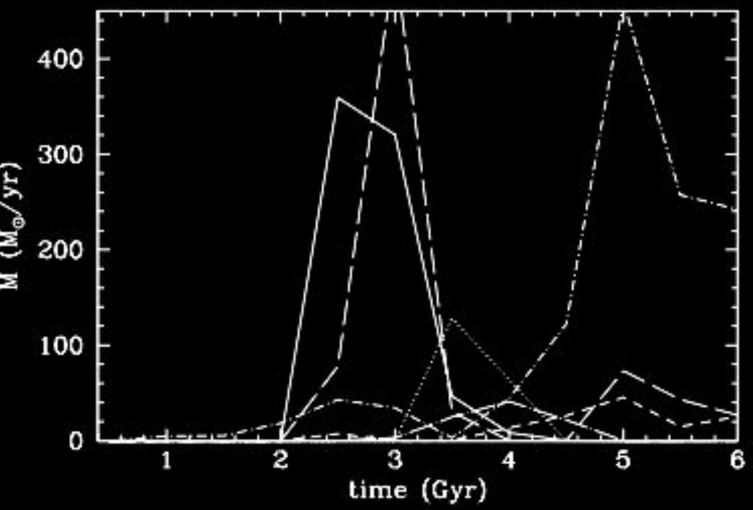
AGN Heating



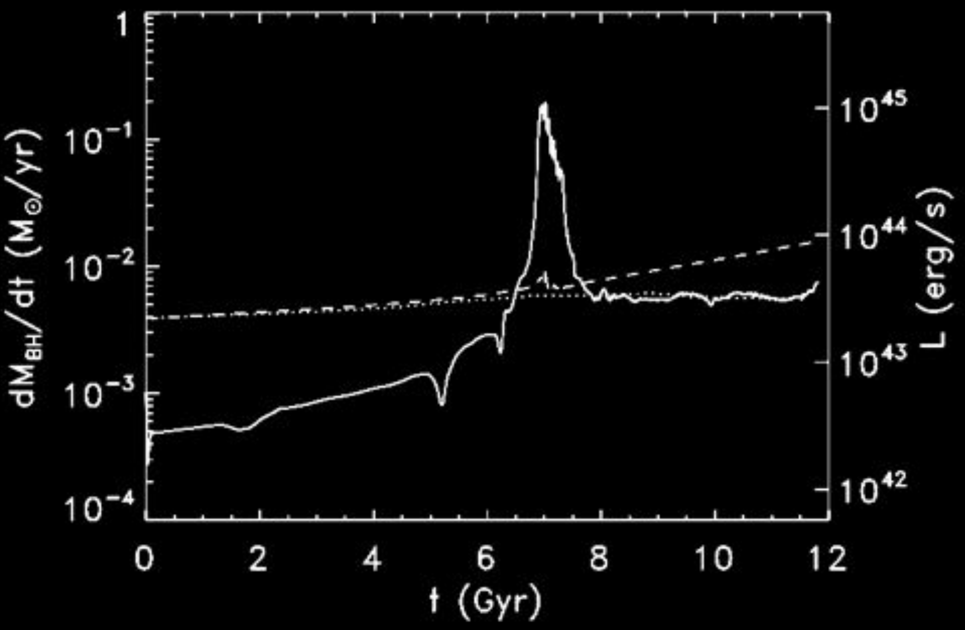
How Coupled?

Rafferty et al. (2006)

Brighenti & Mathews (2006)

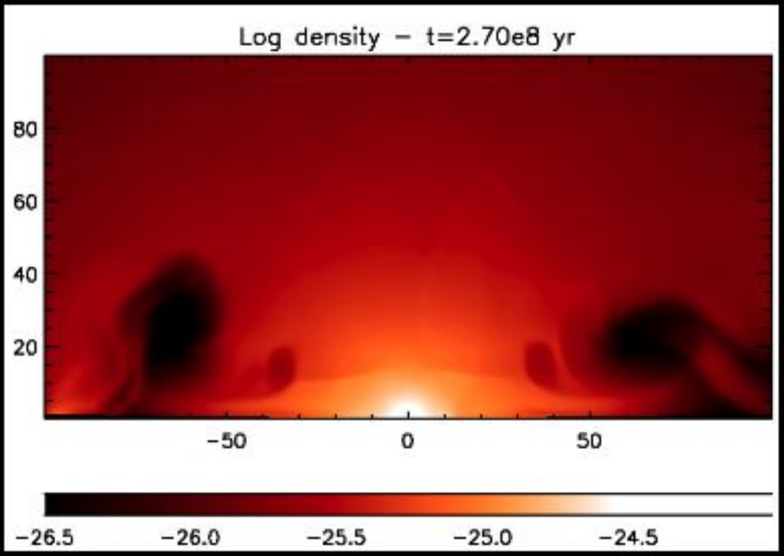


Cattaneo & Tessier (2008)



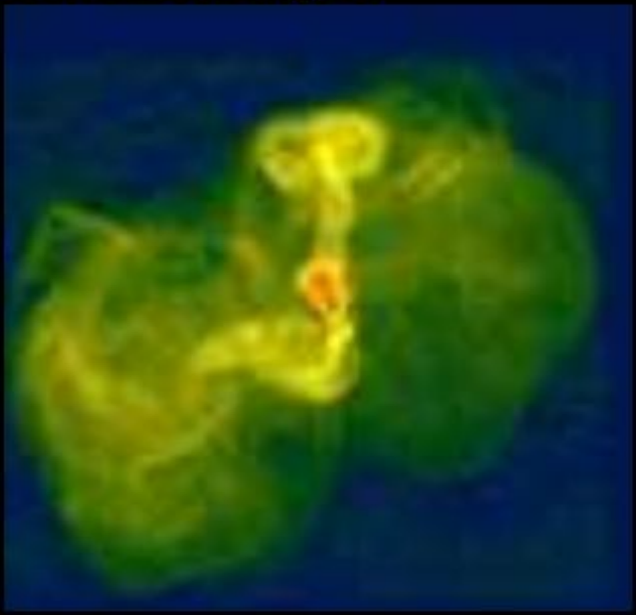
Yang, Ricker, & Sutter (Poster)

100 kpc



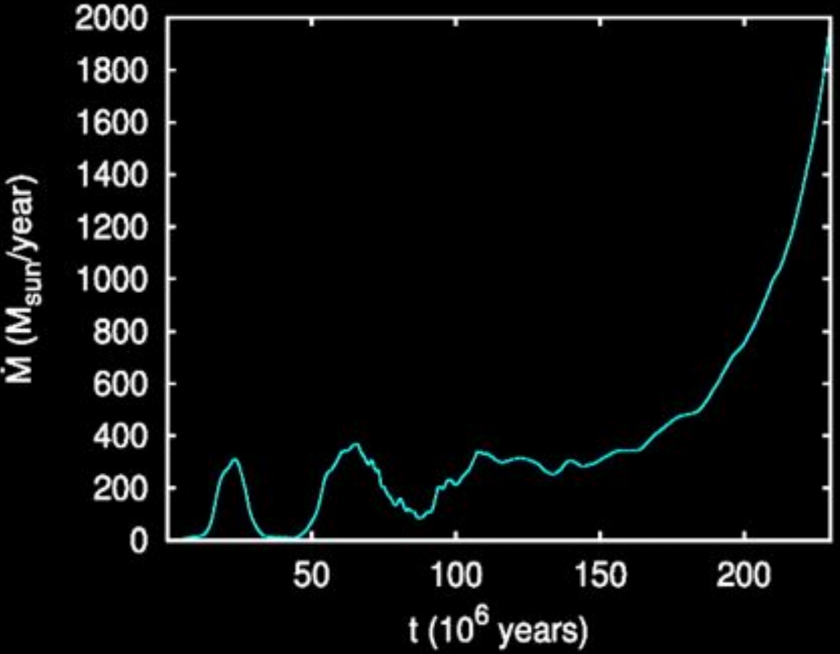
Bondi accretion within central 3.2 kpc.

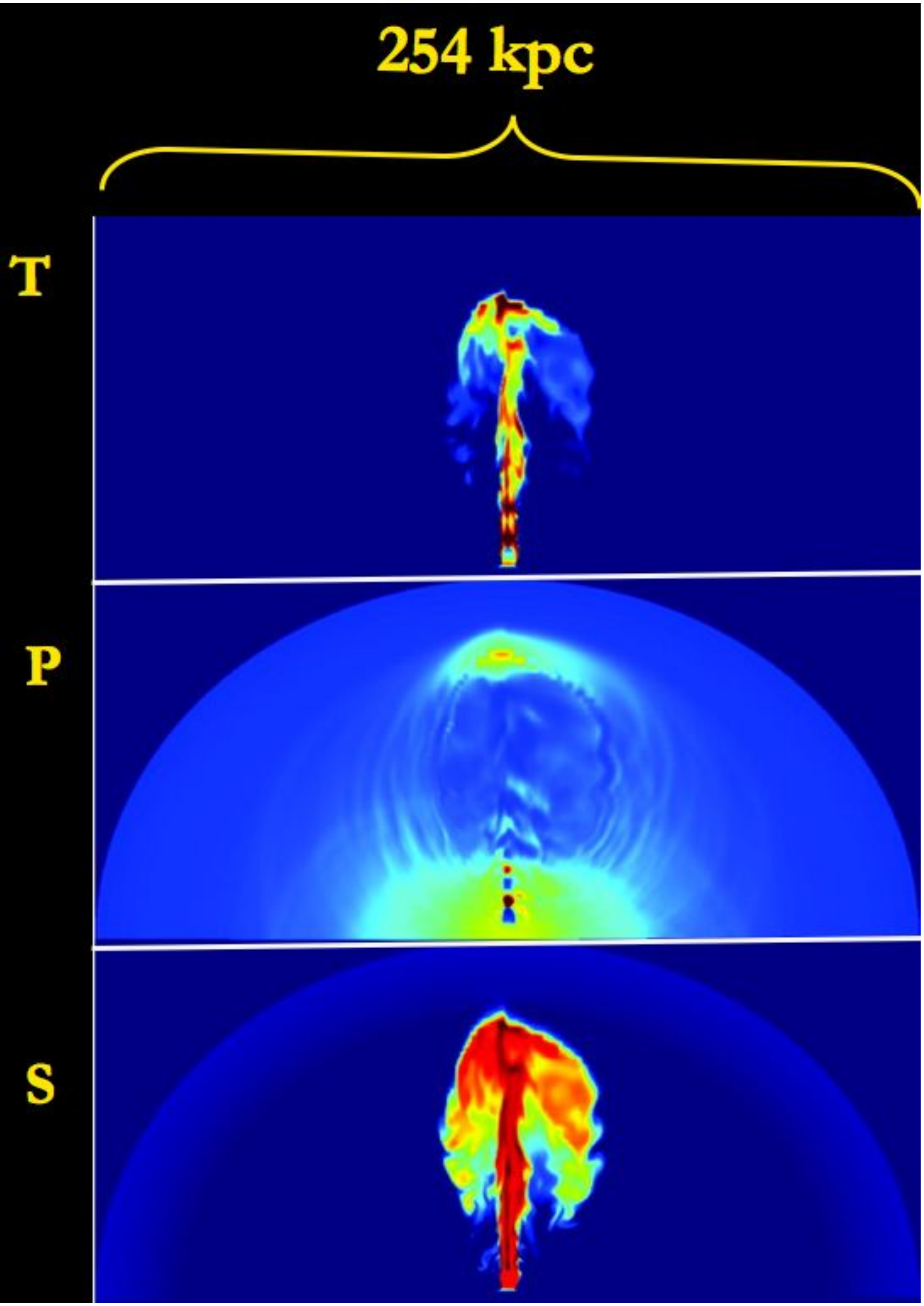
70 kpc



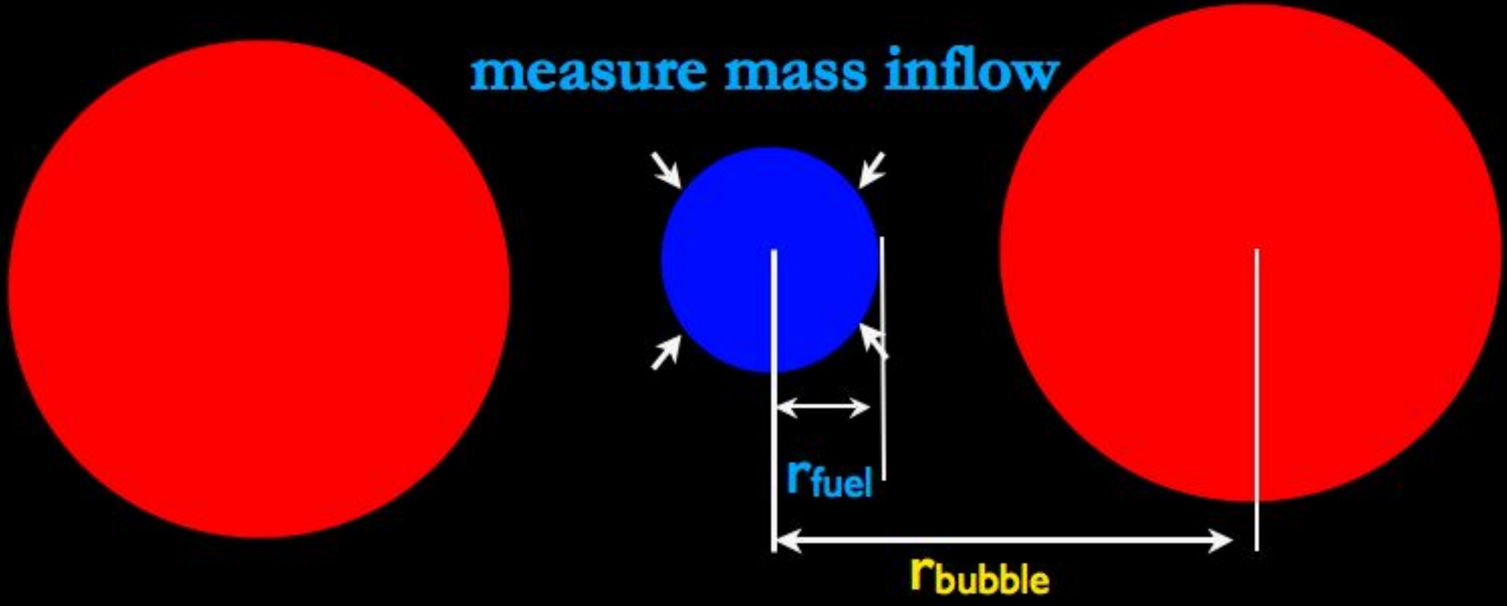
Vernaleo & Reynolds (2008)

Low-density channel prevents isotropic heating





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



measure mass inflow

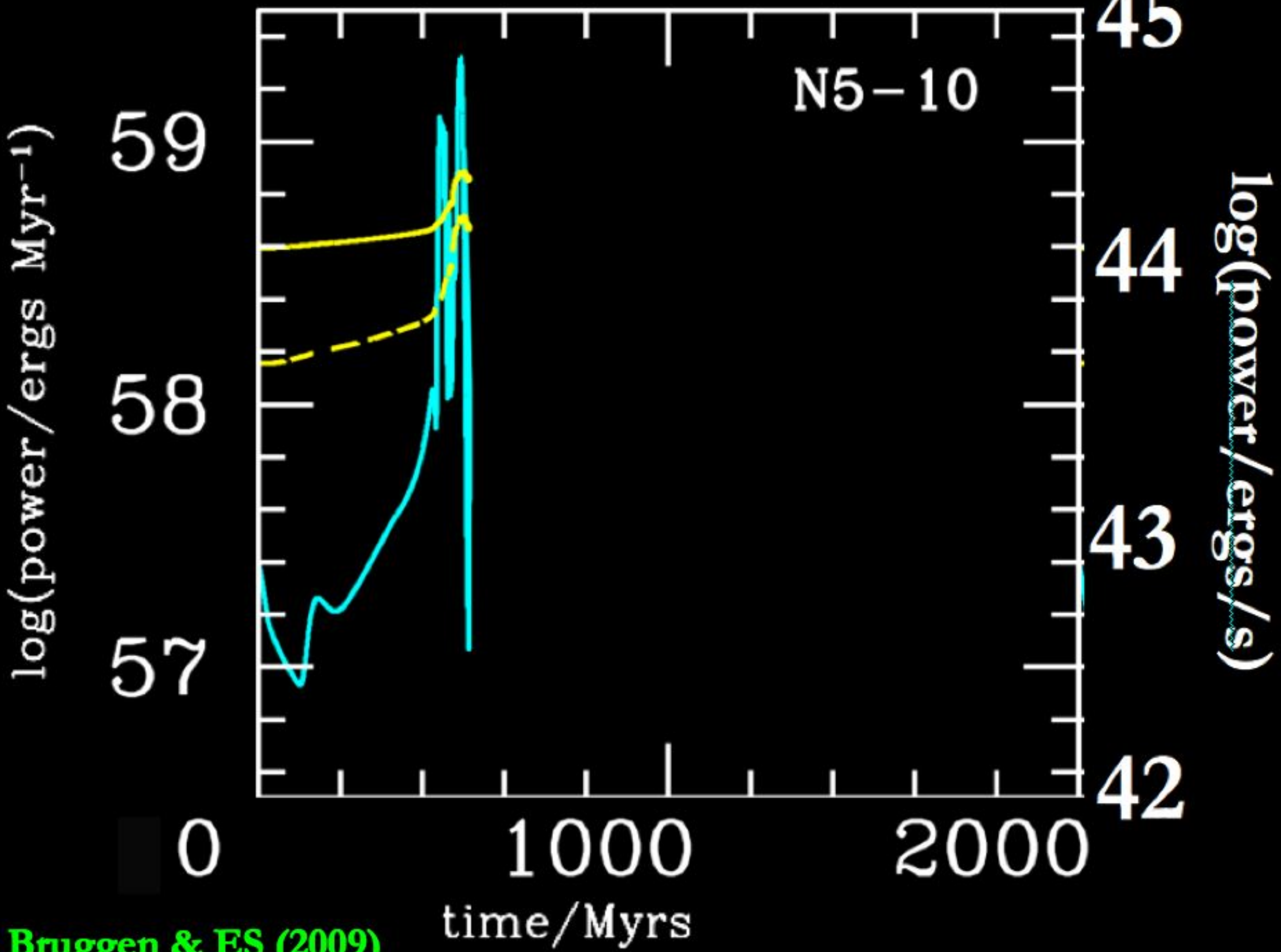
r_{fuel}

r_{bubble}

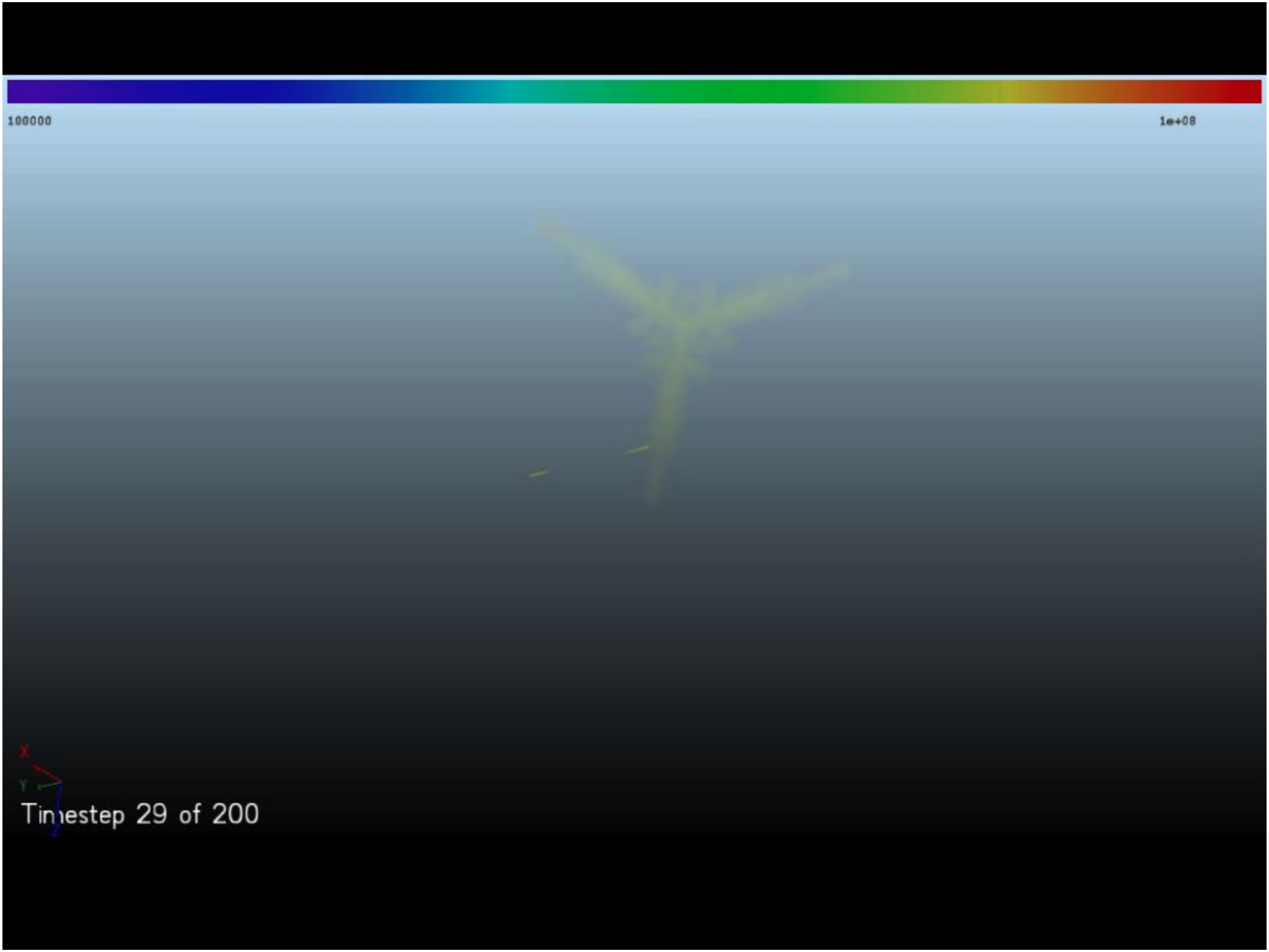
convert fraction of accreted rest
mass energy to bubble energy

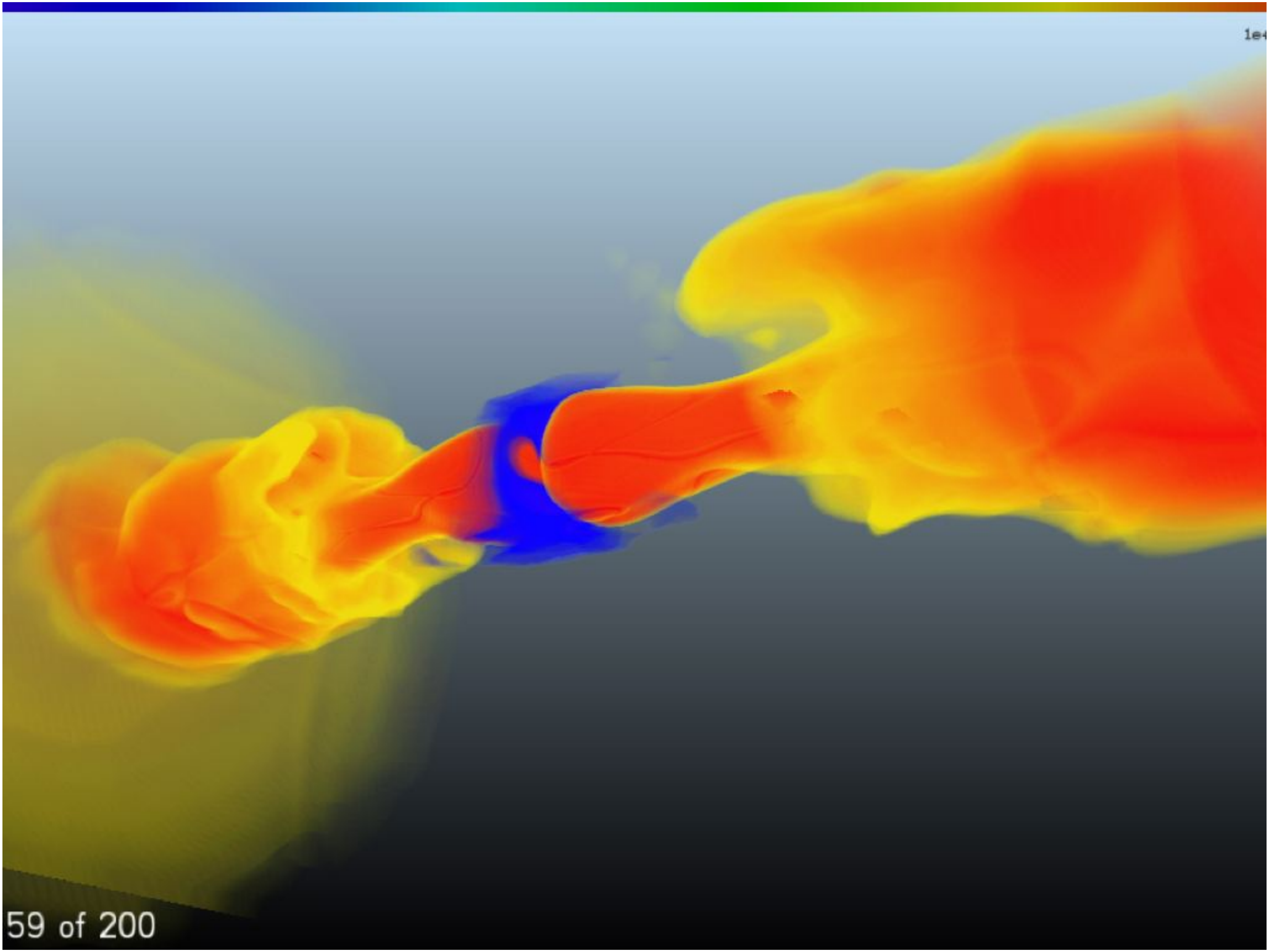
1.5×10^{-3} mc^2

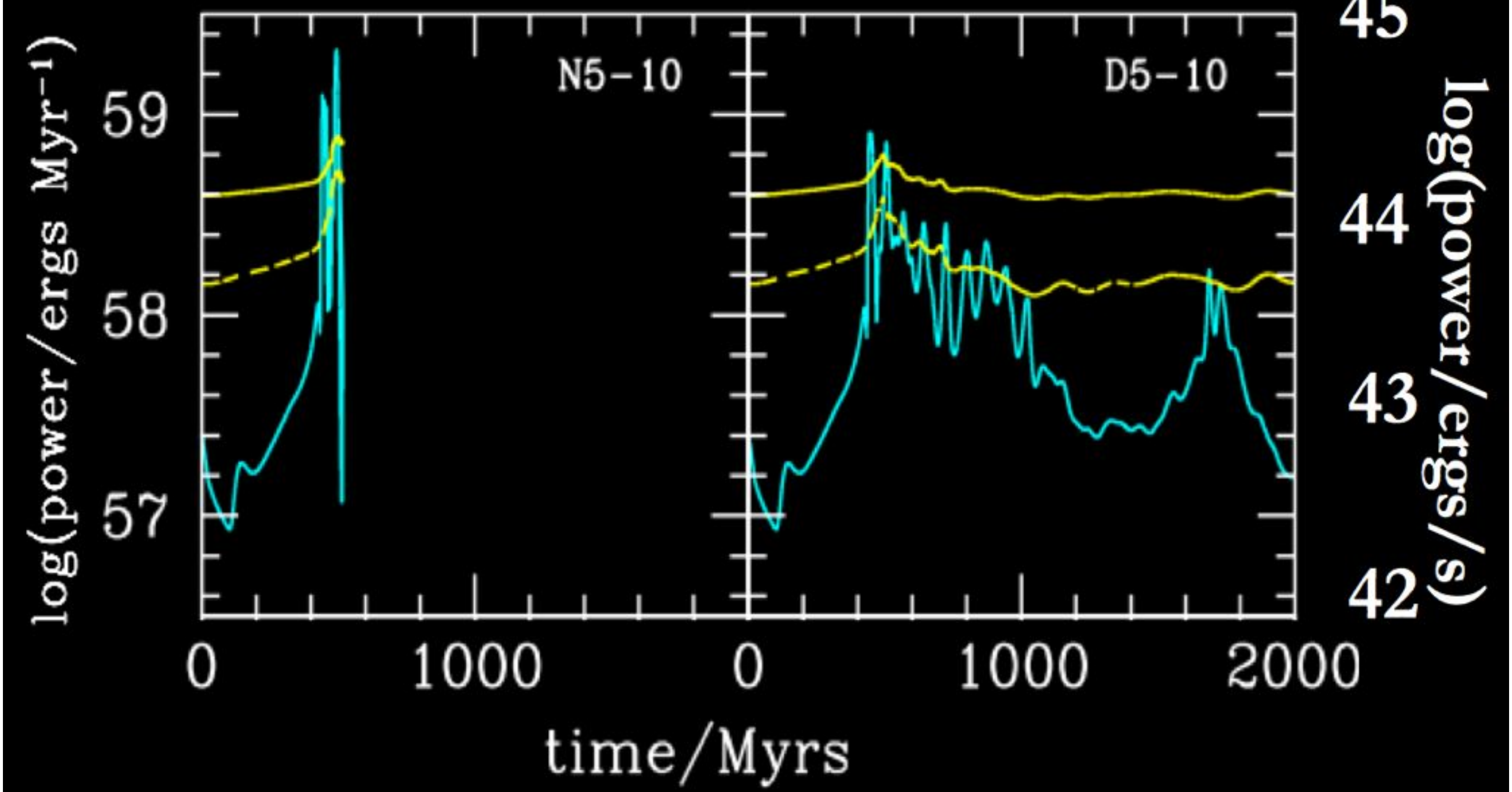
M. Bruggen & ES (2009)



M. Bruggen & ES (2009)

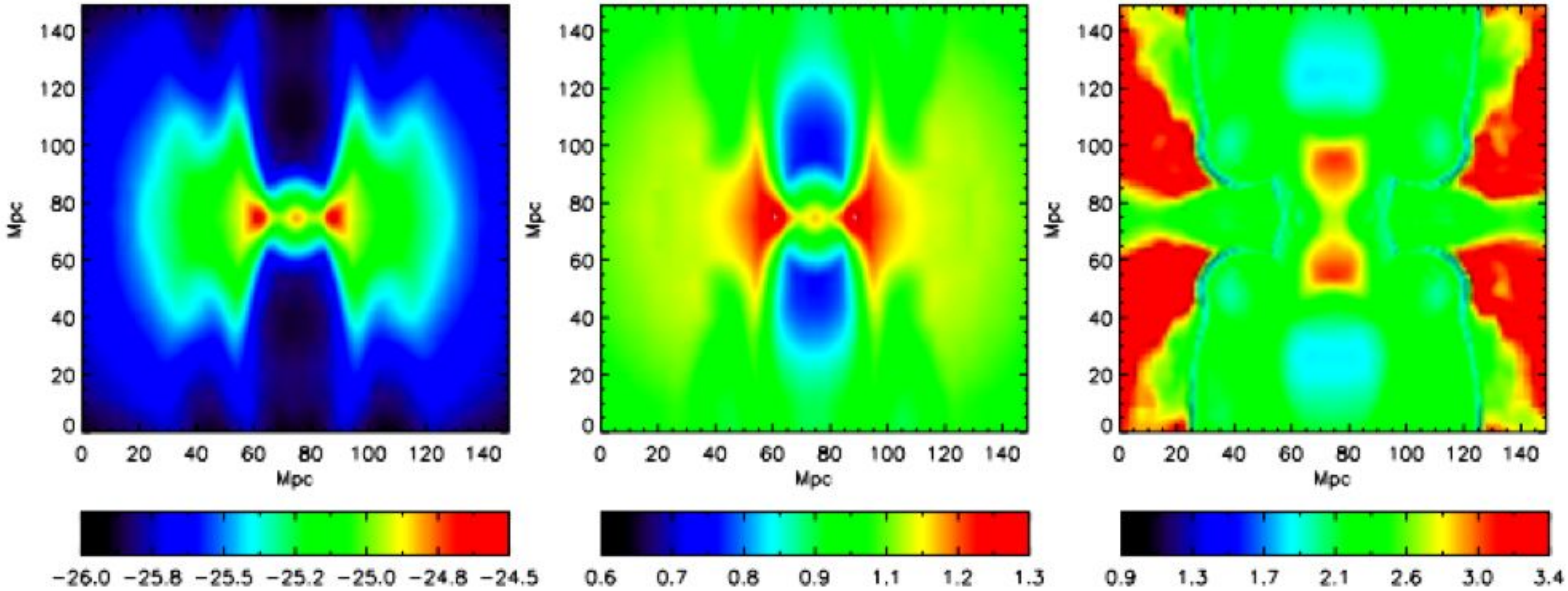

100000
1e+08
X
Y
Z
Timestep 29 of 200


1e
59 of 200



M. Bruggen & ES (2009)

600 Myrs



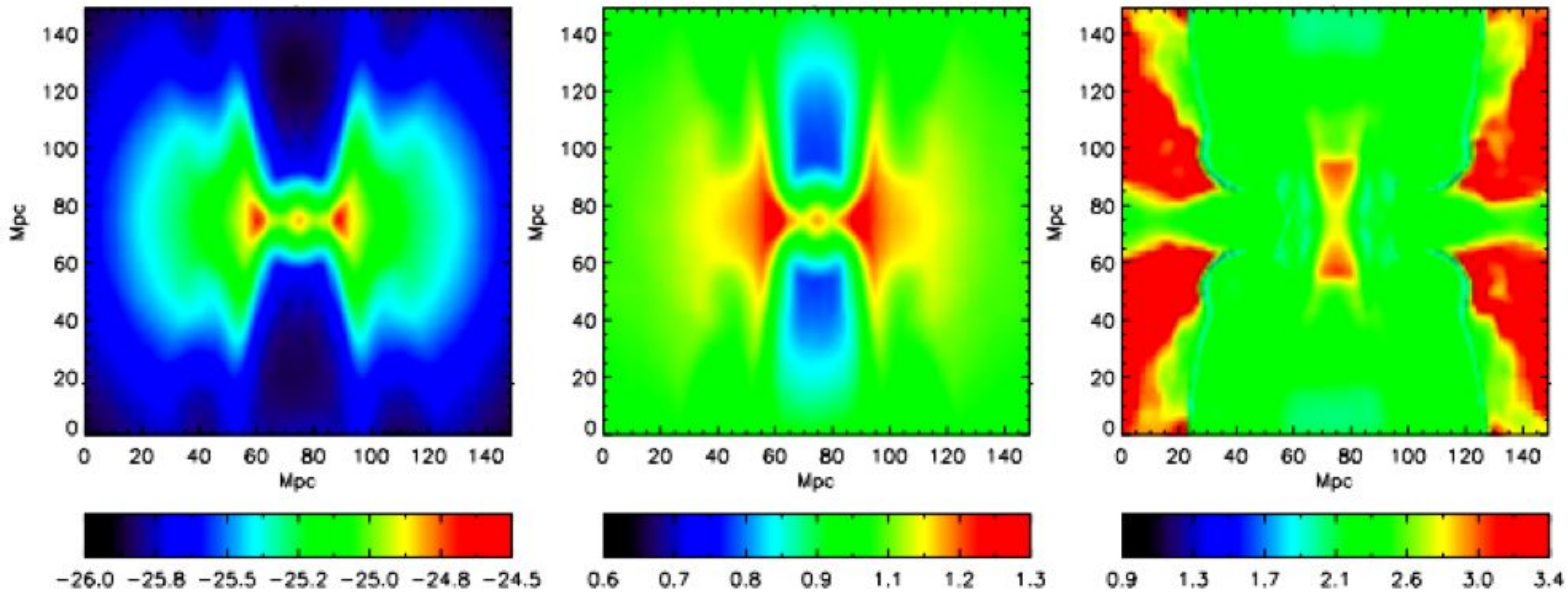
Density

Dynamical Time

Turbulent Diffusion Time

M. Bruggen & ES (2009)

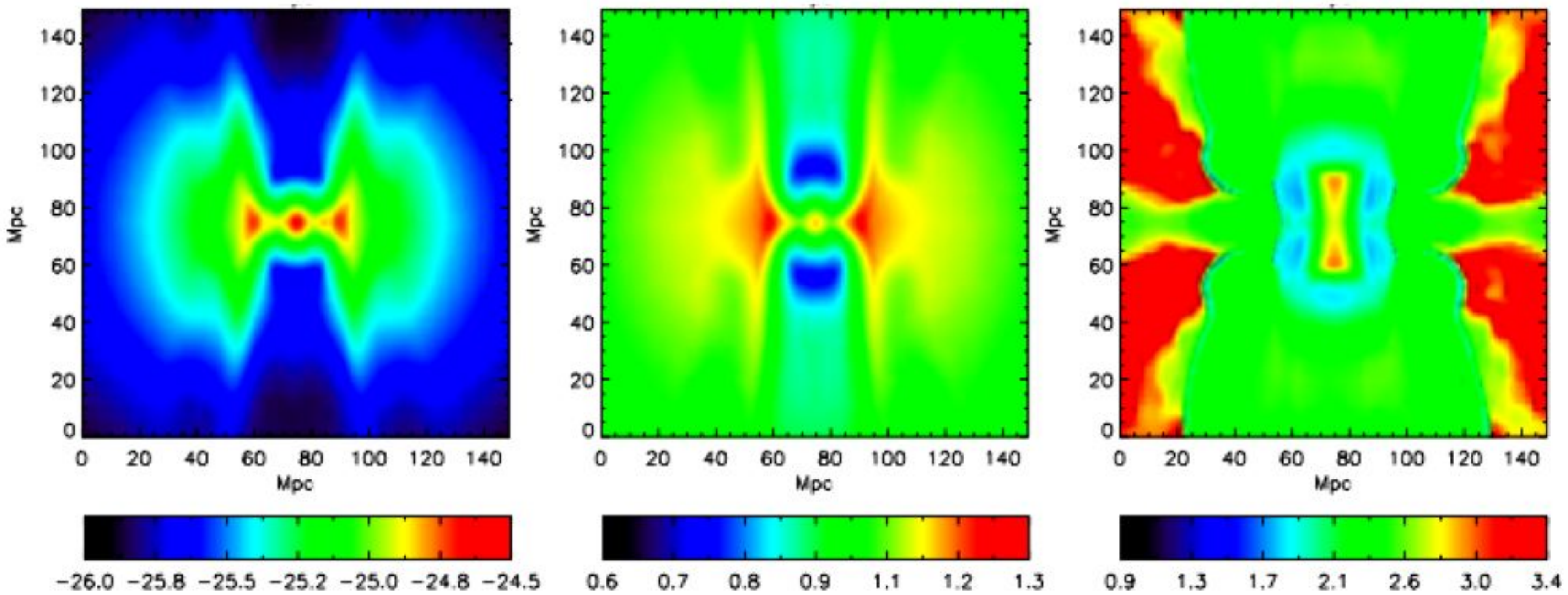
620 Myrs



Density **Dynamical Time** **Turbulent Diffusion Time**

M. Bruggen & ES (2009)

640 Myrs



Density

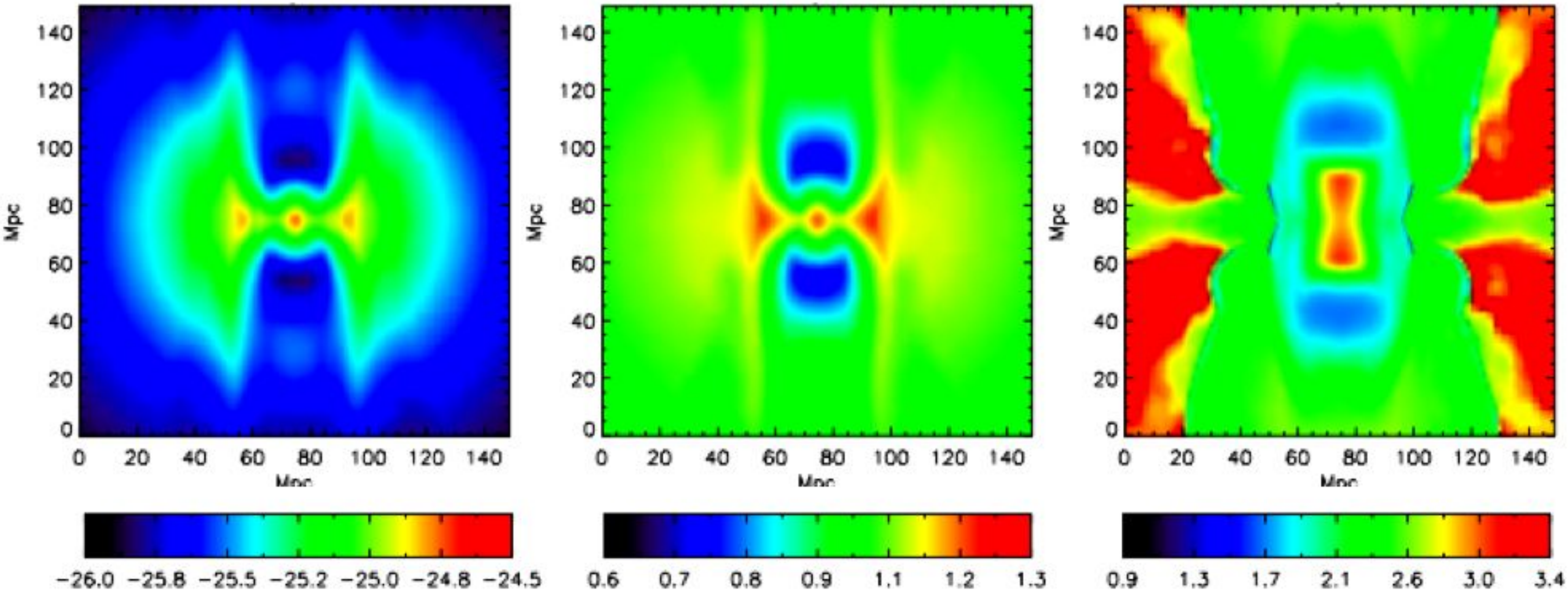
Dynamical Time

Turbulent Diffusion Time

M. Bruggen & ES (2009)

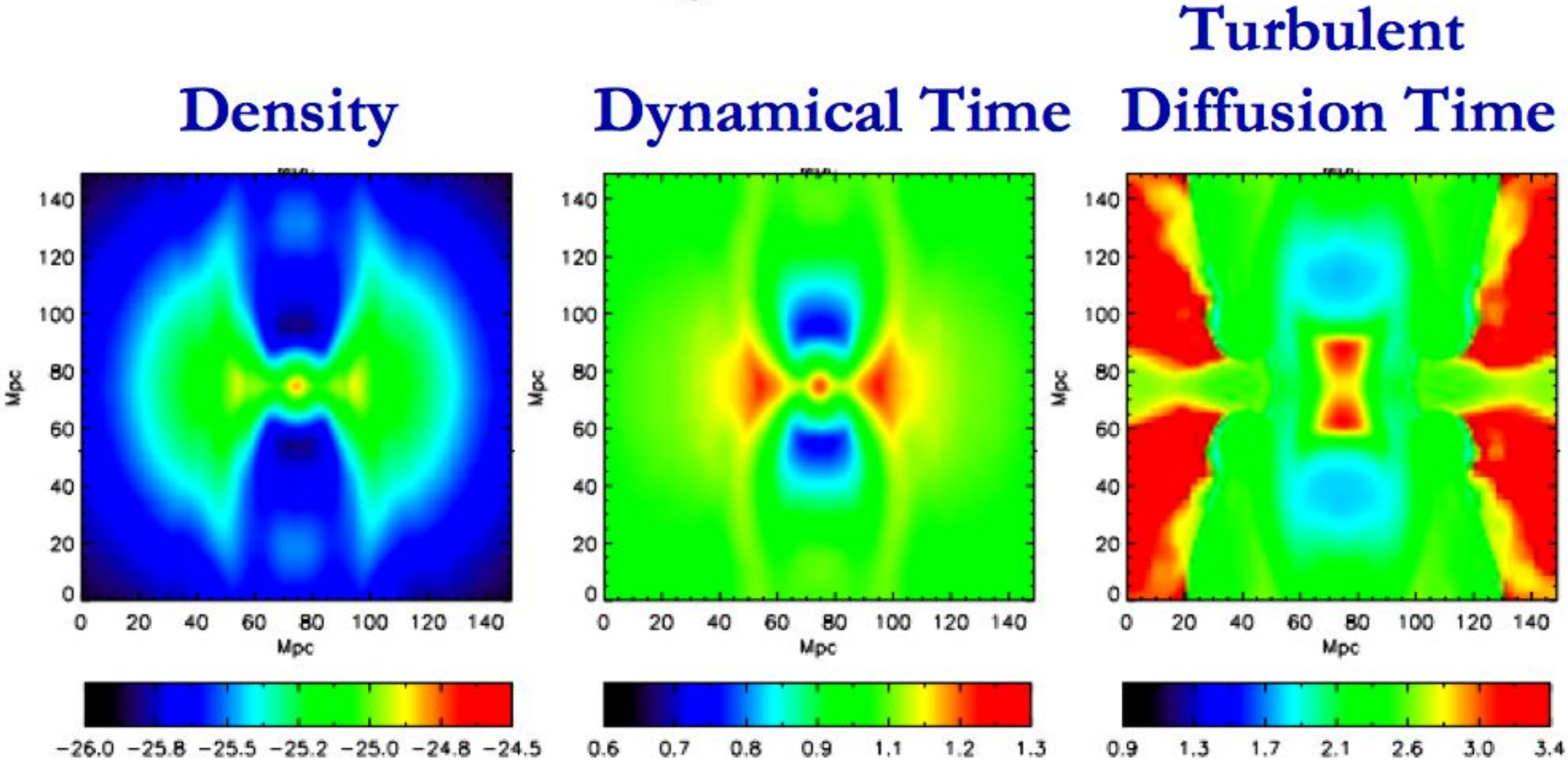
660 Myrs

Density **Dynamical Time** **Turbulent Diffusion Time**



M. Bruggen & ES (2009)

680 Myrs



Density

Dynamical Time

Turbulent Diffusion Time

M. Bruggen & ES (2009)

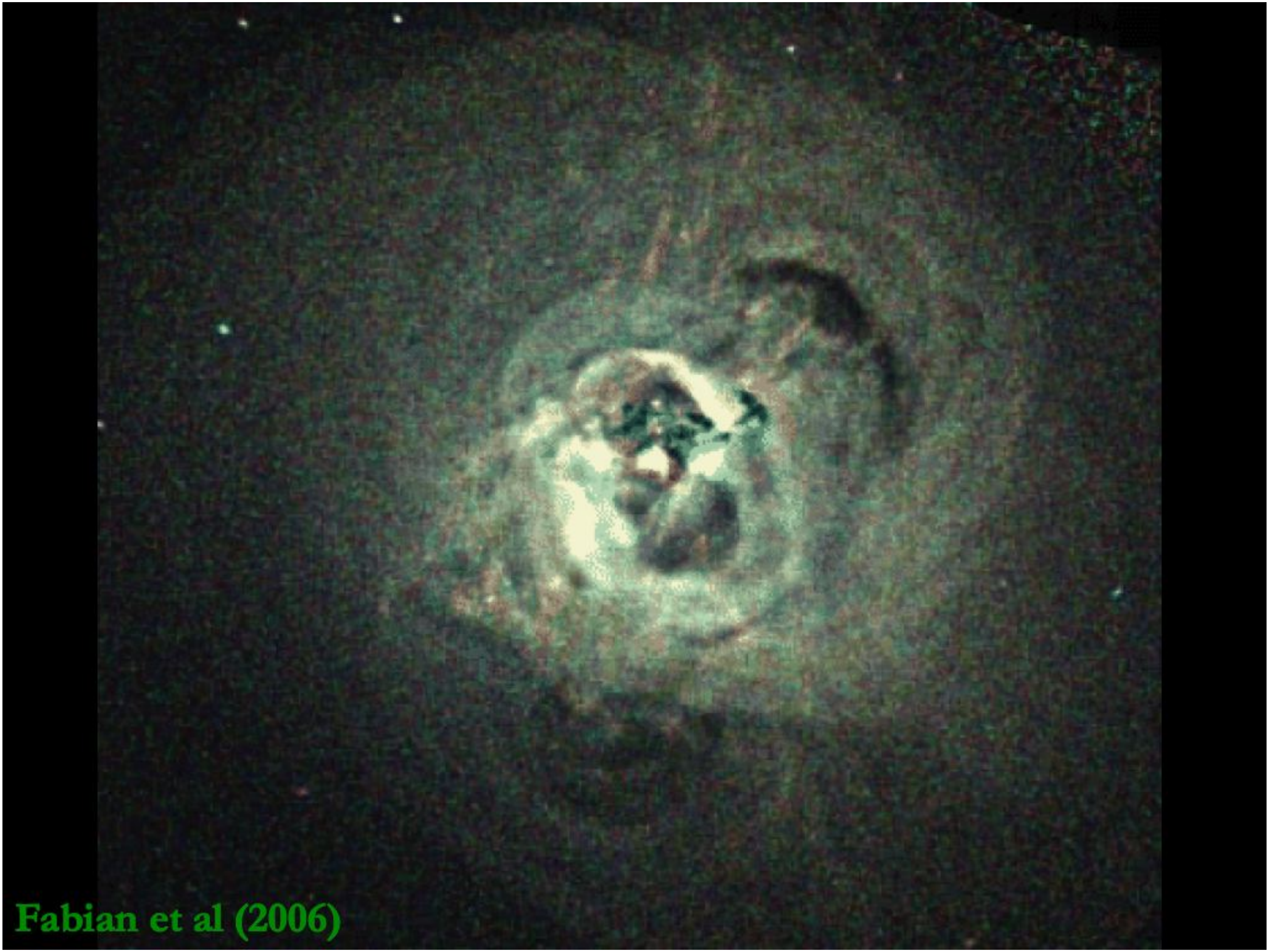
What Sets Duty Cycle?

$$t_{\rm duty} \approx l/v_{\rm turb}$$

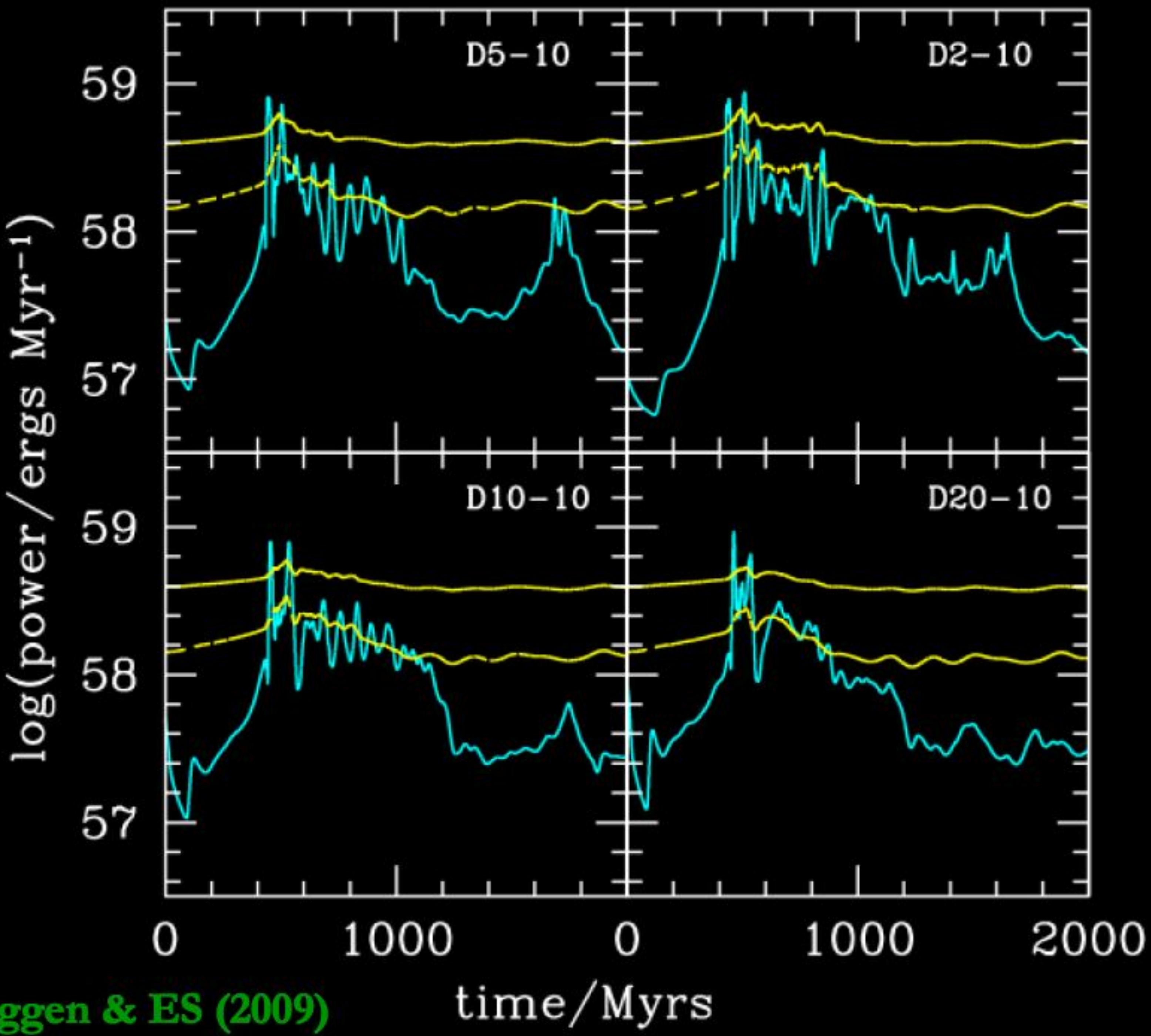
$$v_{\rm turb} = gl/c_s \approx c_s \frac{l}{r_0} \quad g = c_s^2 \frac{1}{\rho}\frac{d\rho}{dr} \equiv c_s^2/r_0$$

$$t_{\rm duty} \approx \frac{r_0}{c_s}$$

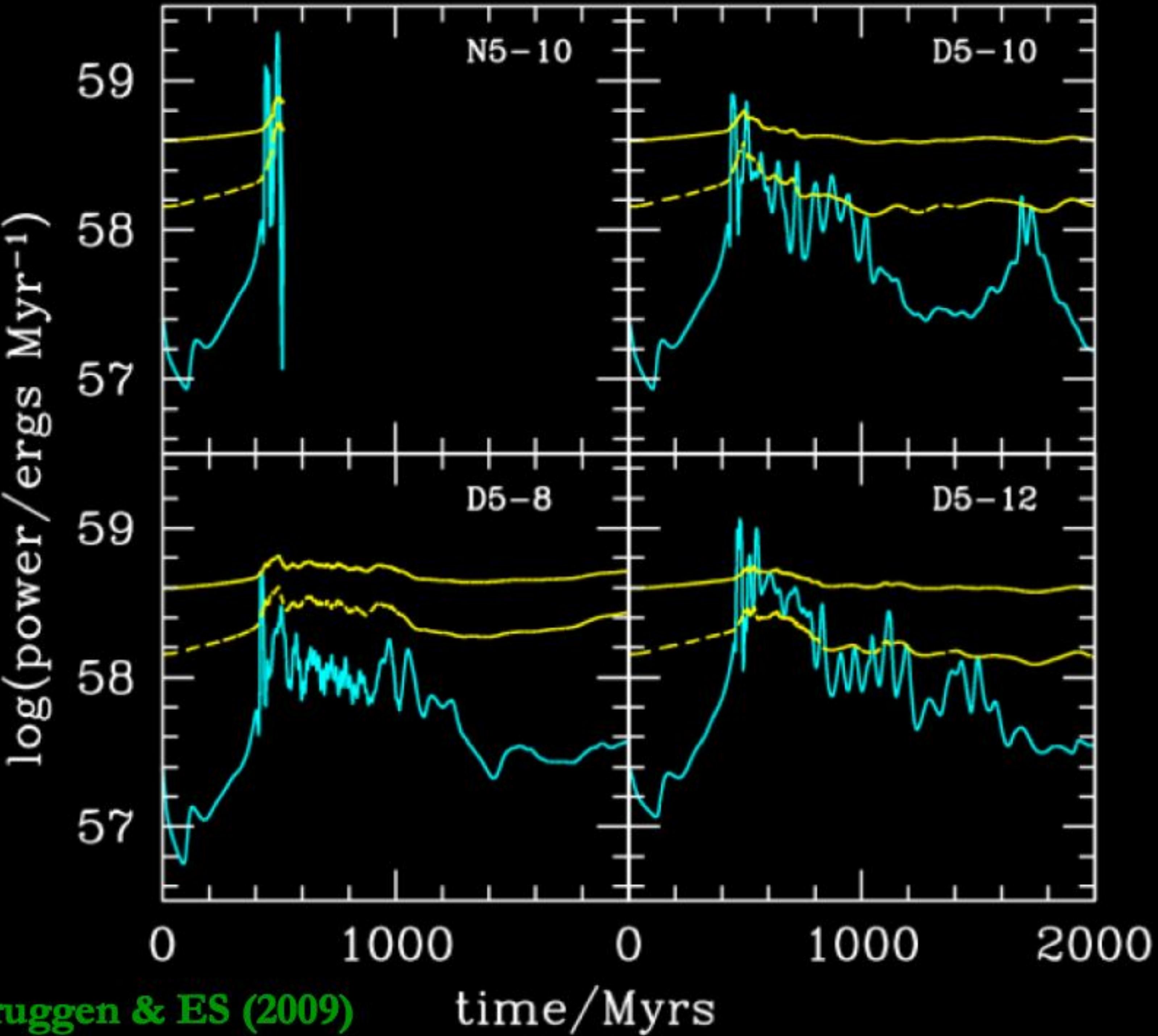
M. Bruggen & ES (2009)



Fabian et al (2006)

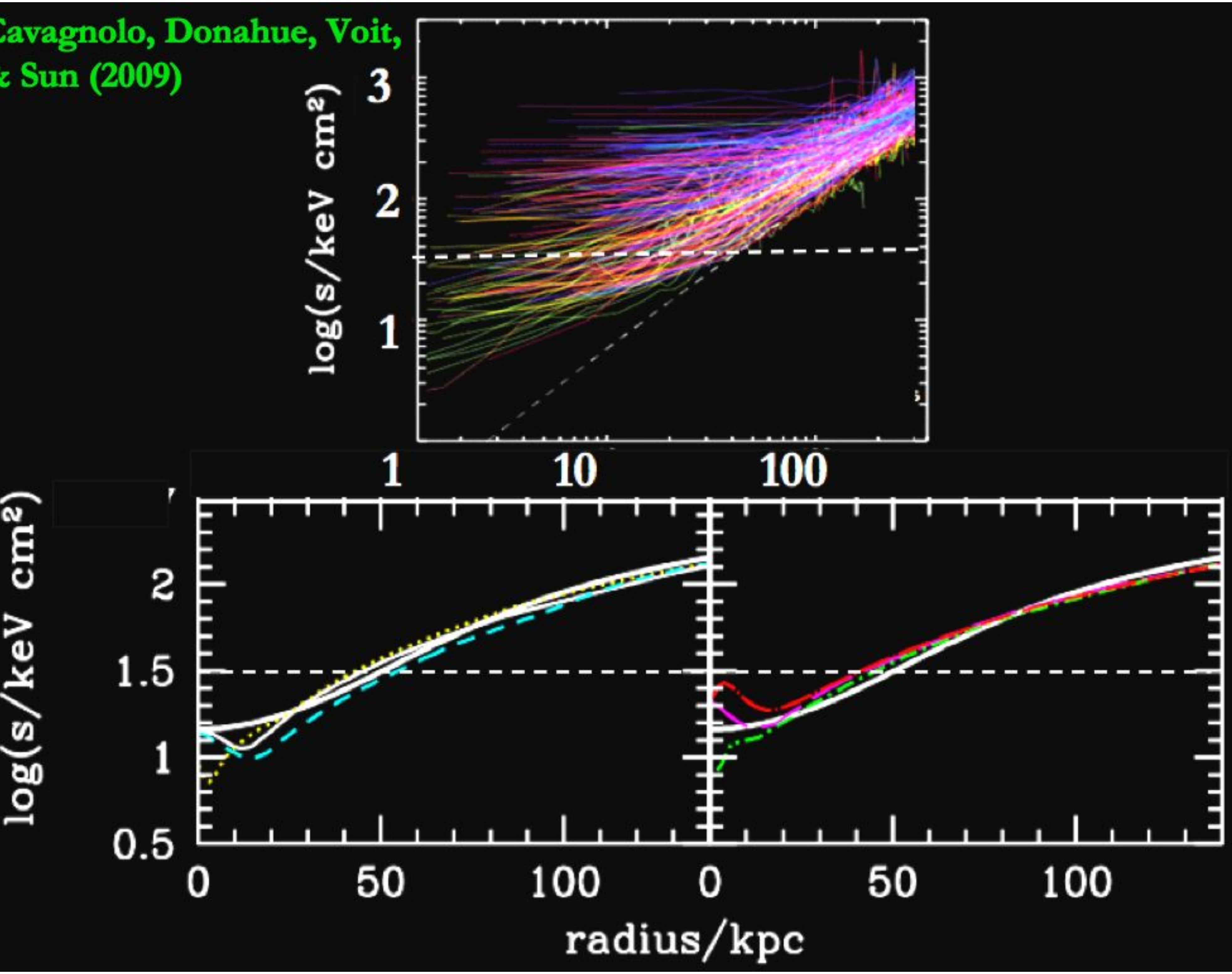


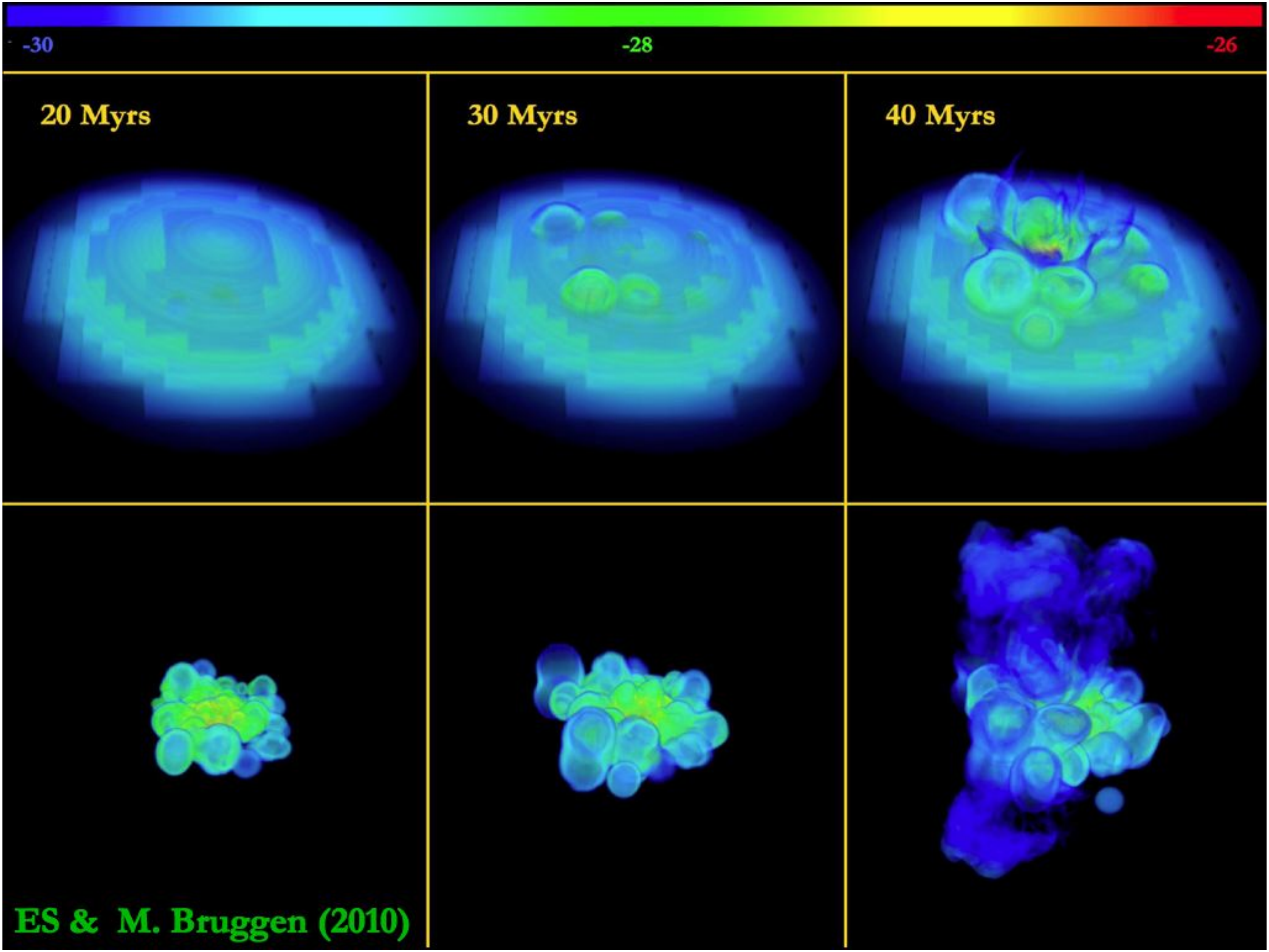
M. Bruggen & ES (2009)



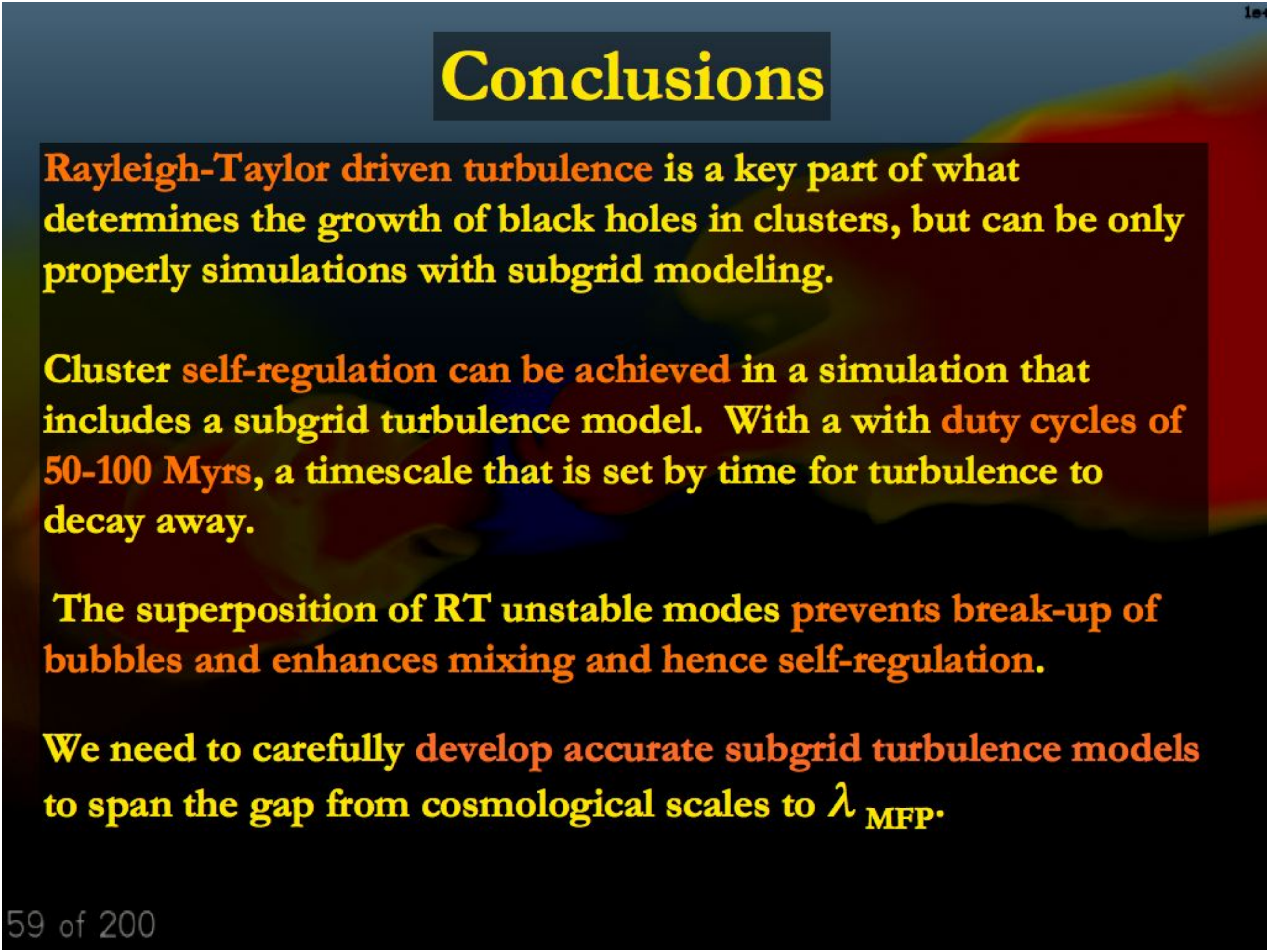
M. Bruggen & ES (2009)

Cavagnolo, Donahue, Voit, & Sun (2009)




-30
-28
-26
20 Myrs
30 Myrs
40 Myrs
ES & M. Bruggen (2010)

Conclusions



Rayleigh-Taylor driven turbulence is a key part of what determines the growth of black holes in clusters, but can be only properly simulations with subgrid modeling.

Cluster self-regulation can be achieved in a simulation that includes a subgrid turbulence model. With a with duty cycles of 50-100 Myrs, a timescale that is set by time for turbulence to decay away.

The superposition of RT unstable modes prevents break-up of bubbles and enhances mixing and hence self-regulation.

We need to carefully develop accurate subgrid turbulence models to span the gap from cosmological scales to λ_{MFP}.