Modeling of Turbulence in Starbursting Galaxies

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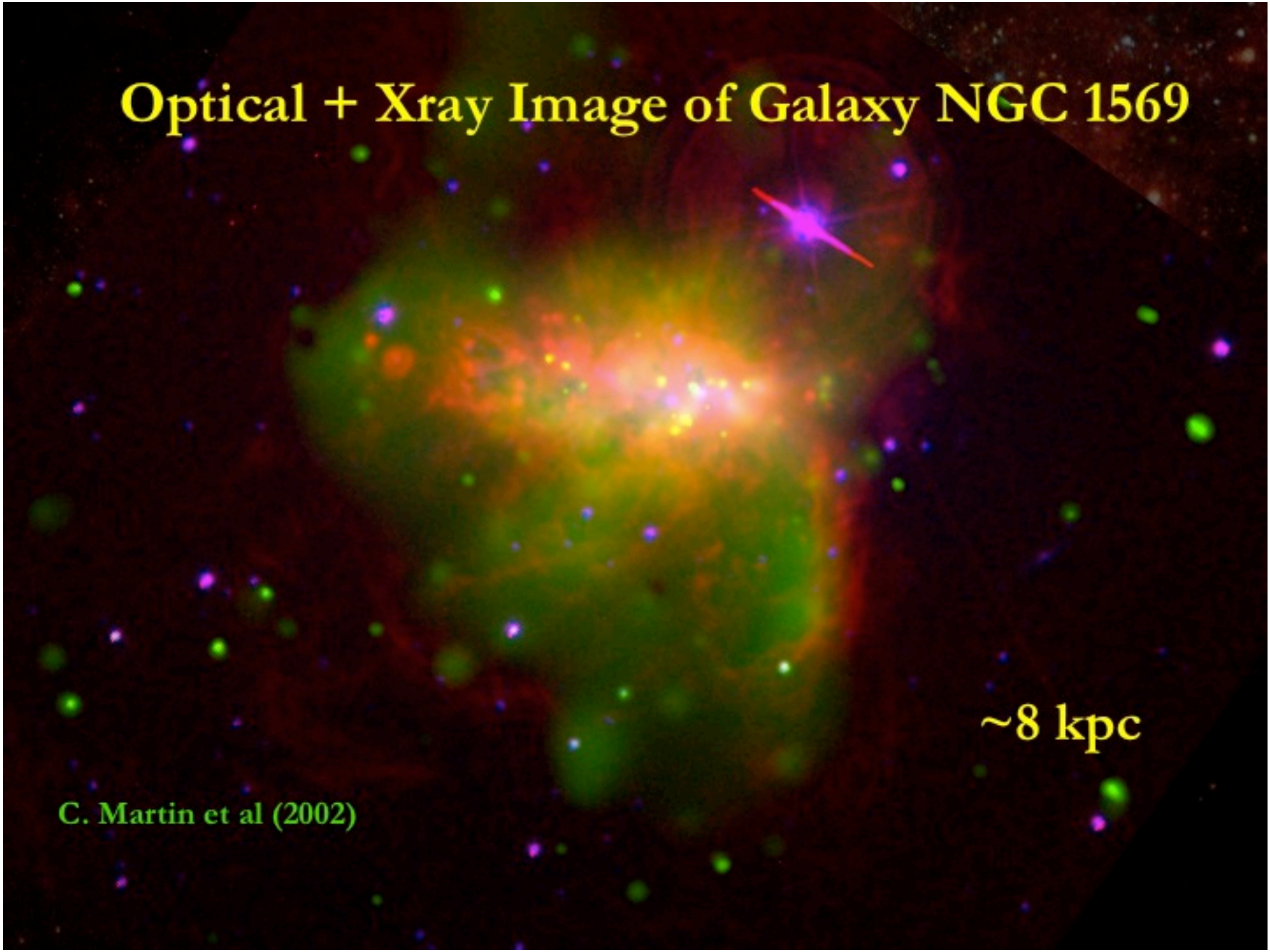
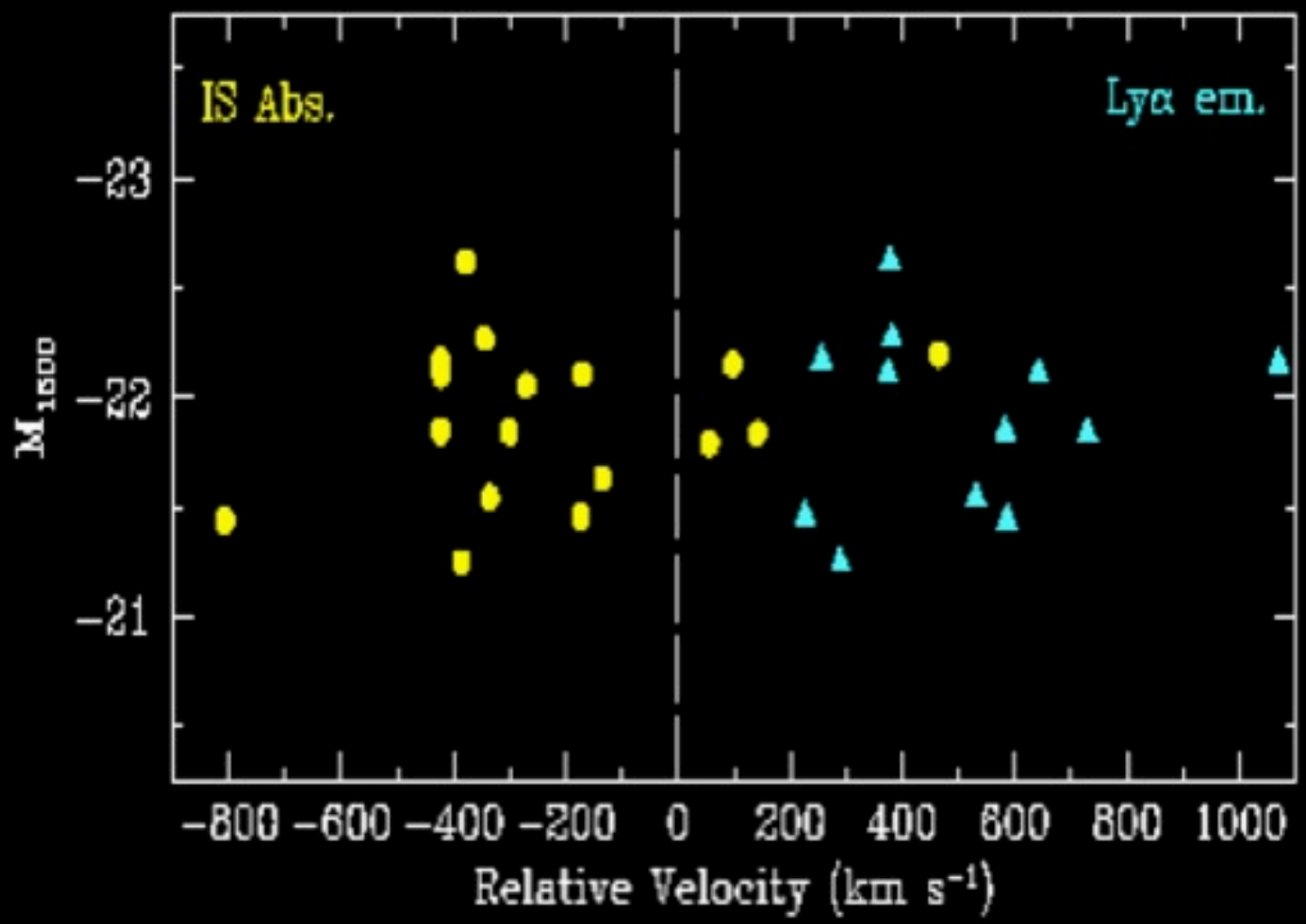
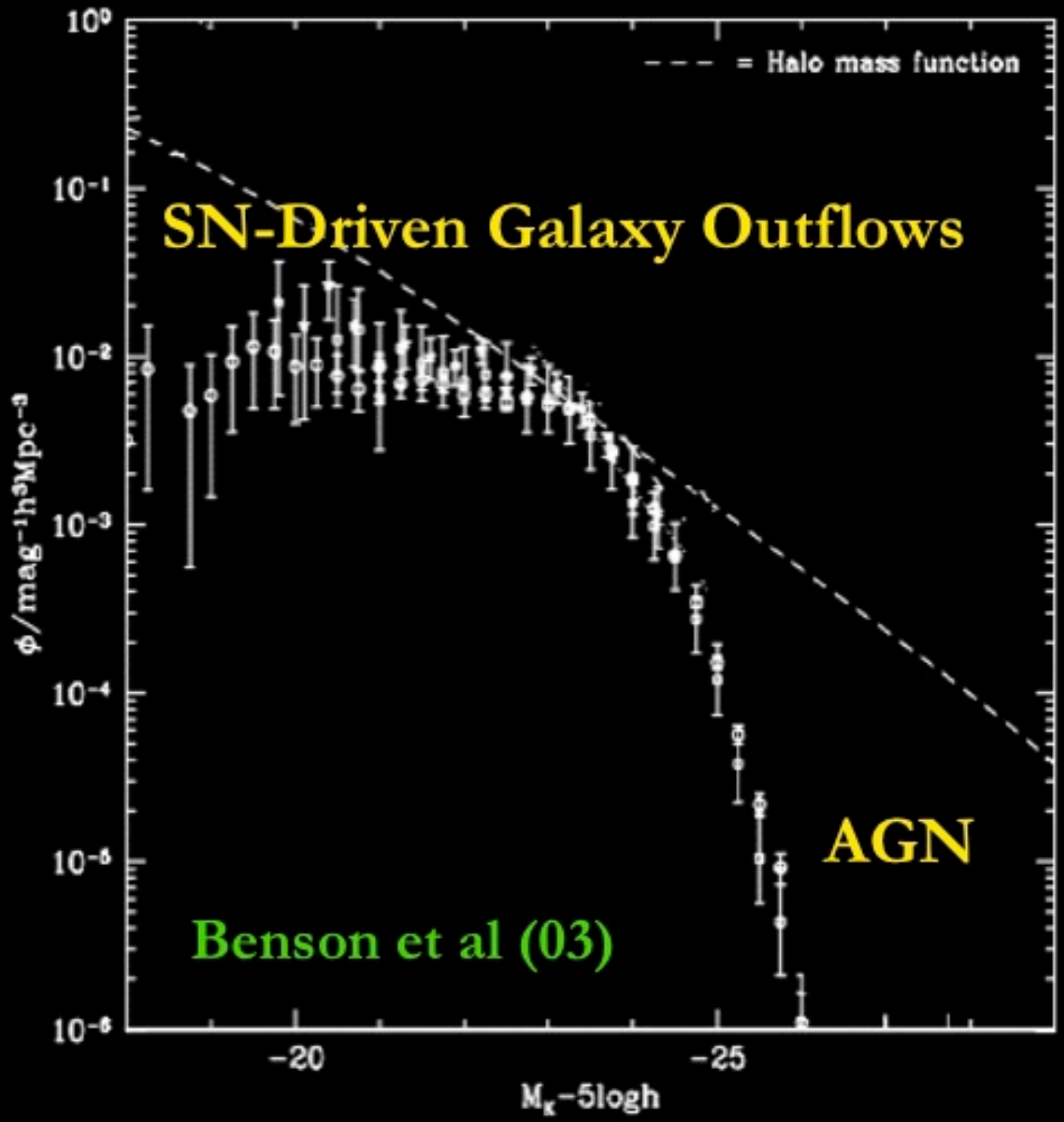
I. Starbursting Galaxies & Turbulence

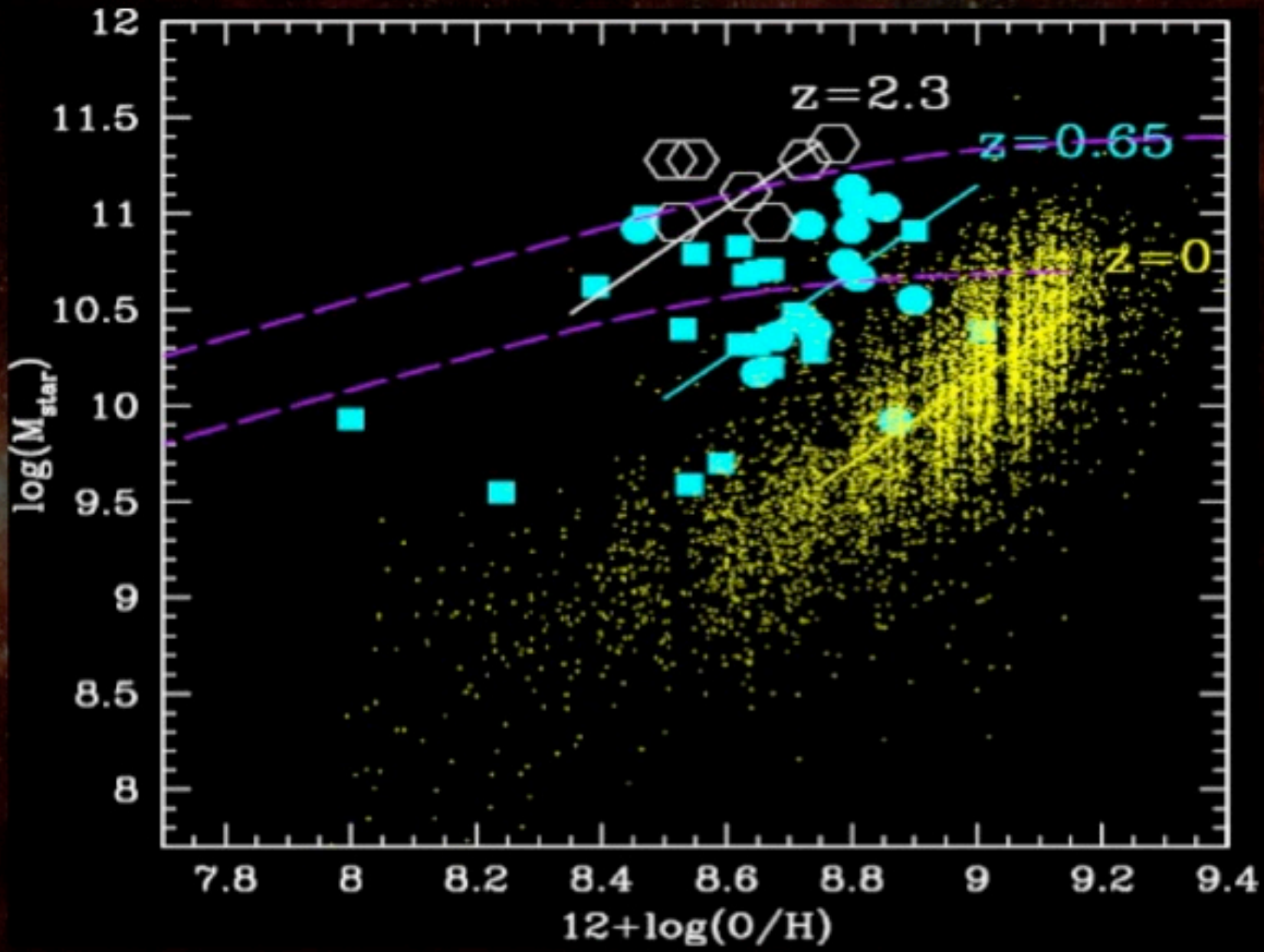

Optical + Xray Image of Galaxy NGC 1569
~8 kpc
C. Martin et al (2002)

High Redshift Outflows

M. Pettini et al (2001)

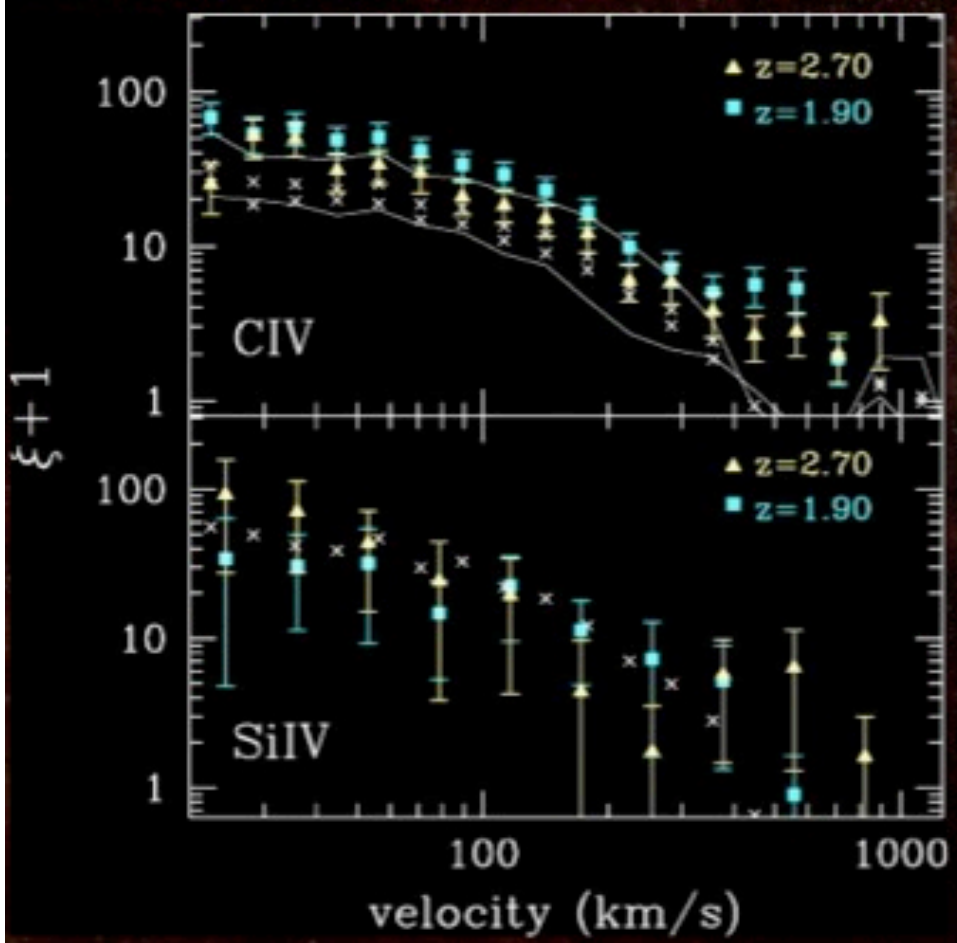


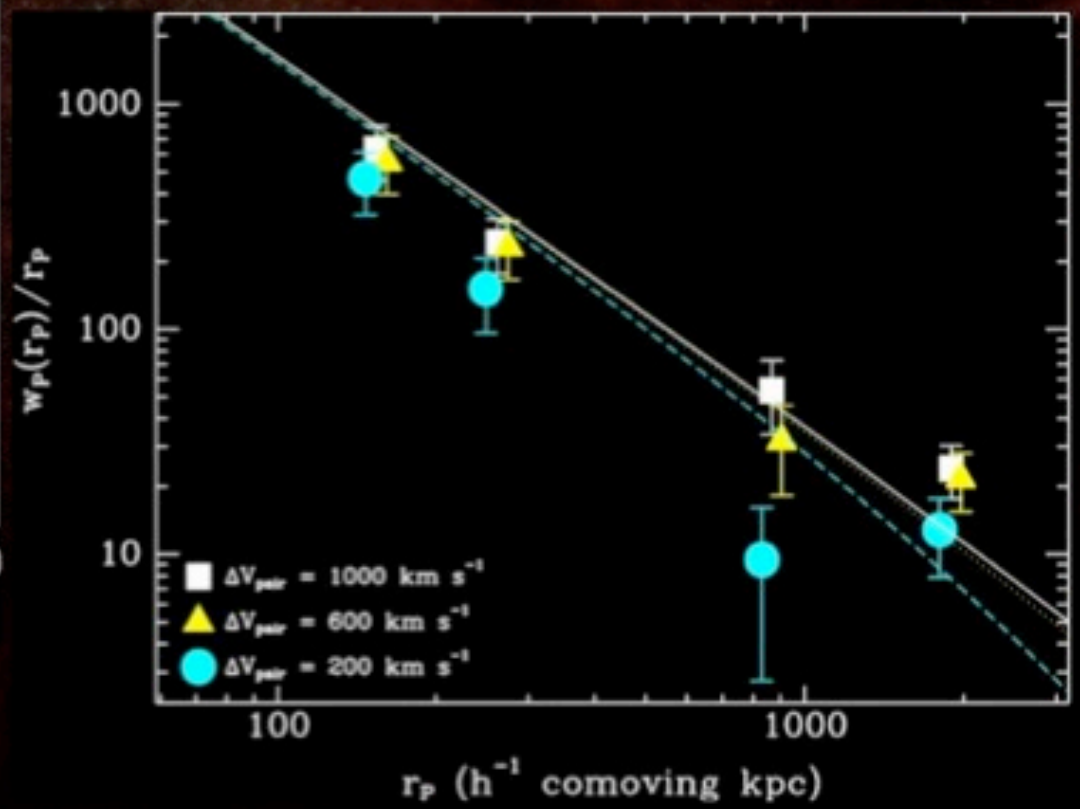

= Halo mass function
SN-Driven Galaxy Outflows
AGN
Benson et al (03)
ϕ/mag^{-1}h^{3}Mpc^{-3}
M_K−5logh
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
−20
−25



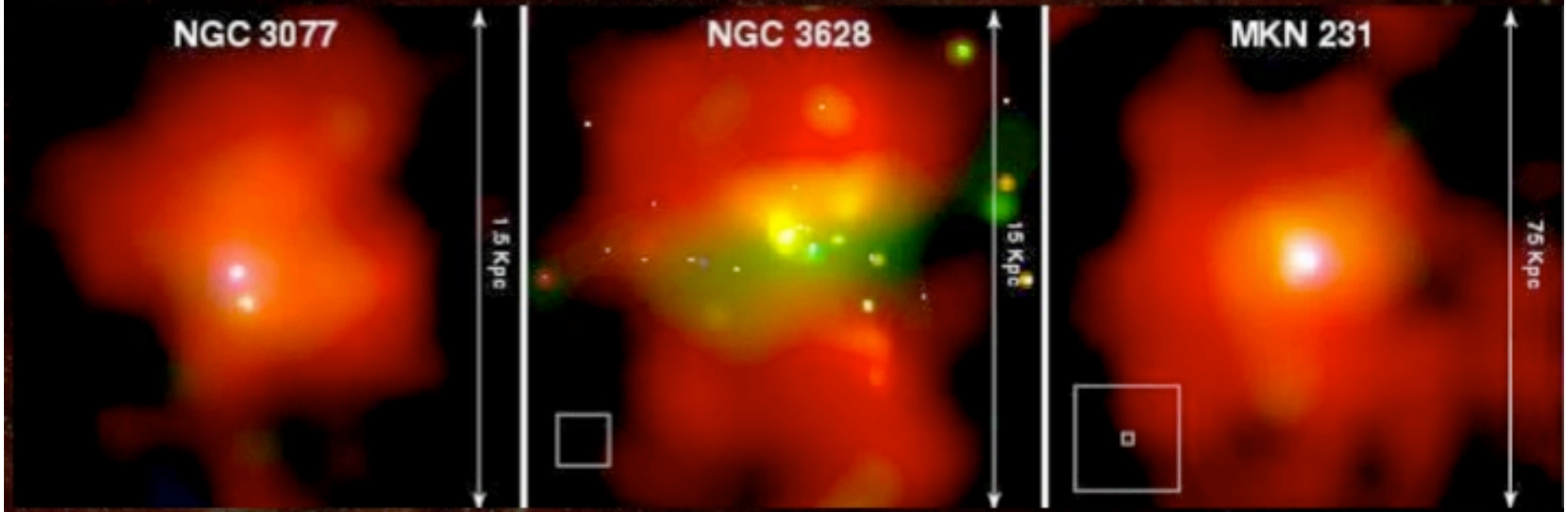
Tremonti et al. (2004); Bell et al. (2003); Liang et al. (2005)

ES, Pichon, Aracil, Petitjean, Thacker, Pogosyan, Bergeron& Couchman (2006)





Martin, ES, Ellison, Hennawi, Djorgovski, & Fournier (2010)

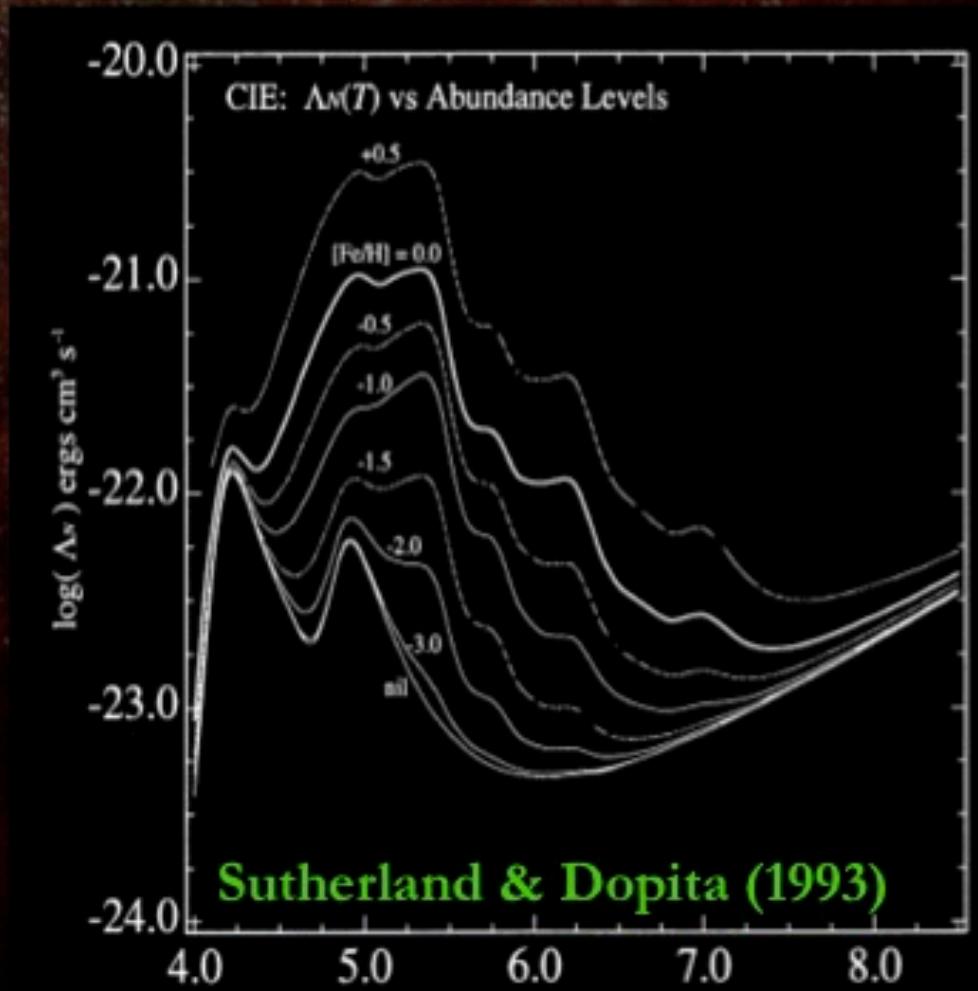


(Grimes et al. 2005)

Outflows are a generic features of galaxies with $\Sigma_\star \geq 0.1\ M_\odot\ yr^{-1}\ kpc^{-2}$ (Heckman 2001)

Supernovae & Cooling

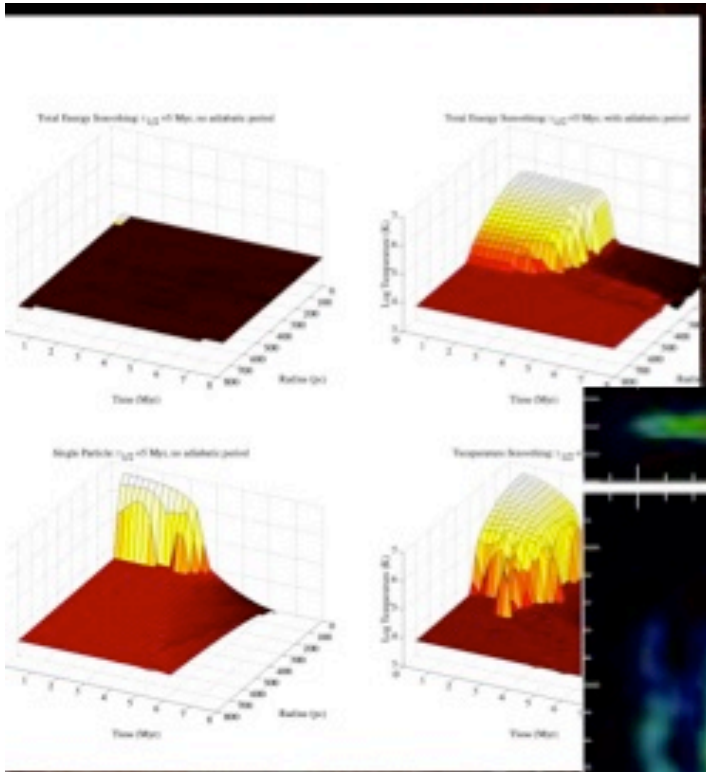
~3 pc



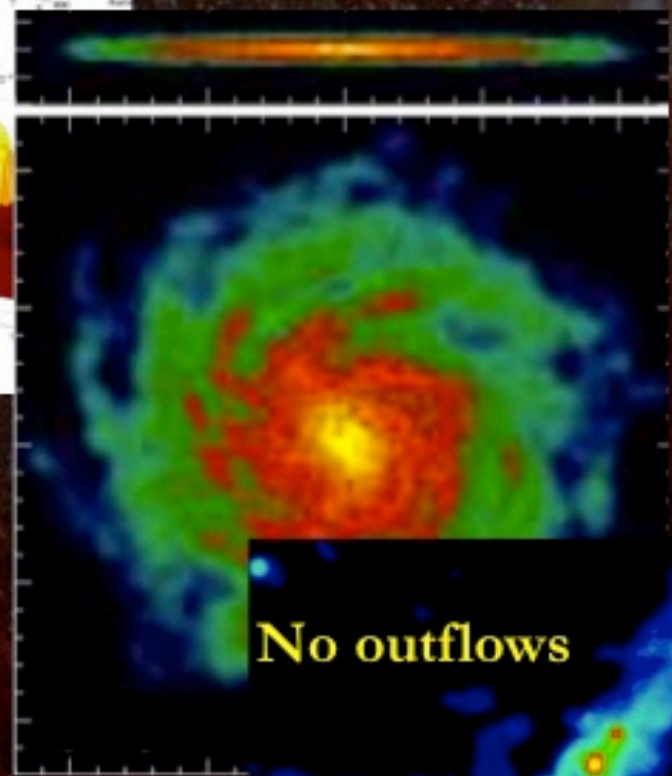
Log T

Cooling times ~ 3000 years

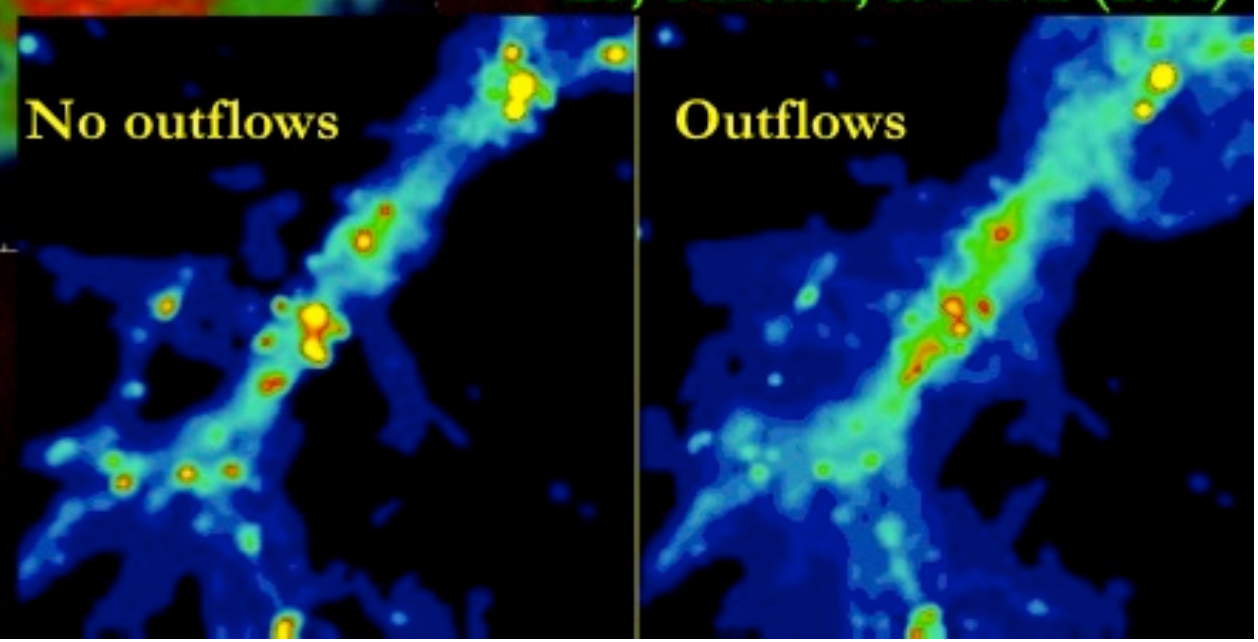
Modeling Outflows



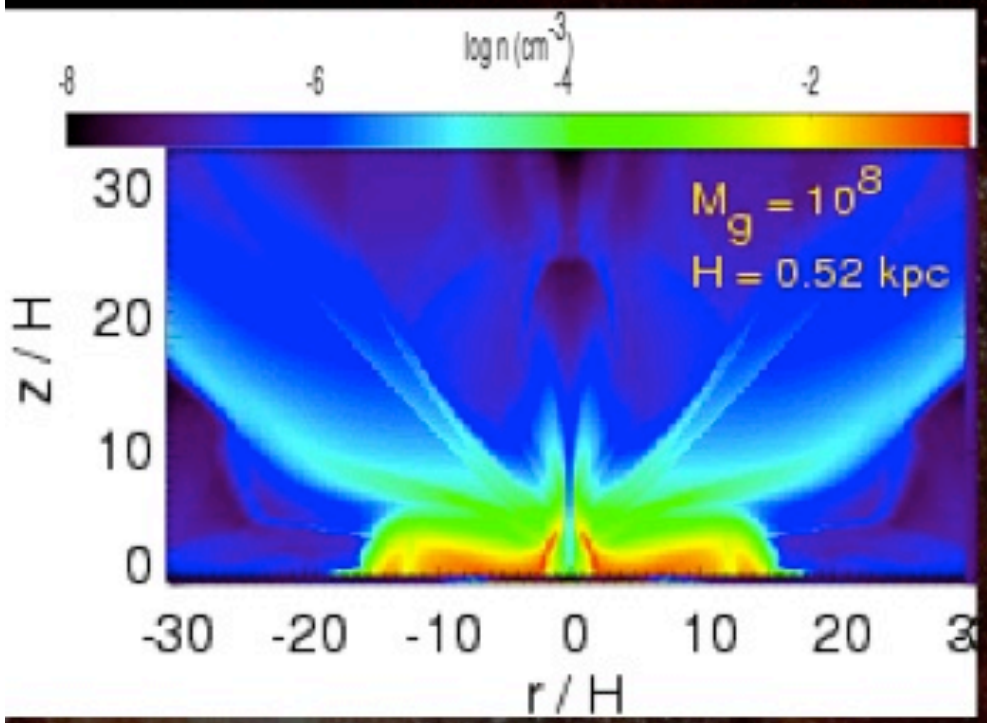
Thacker & Couchman (2000)



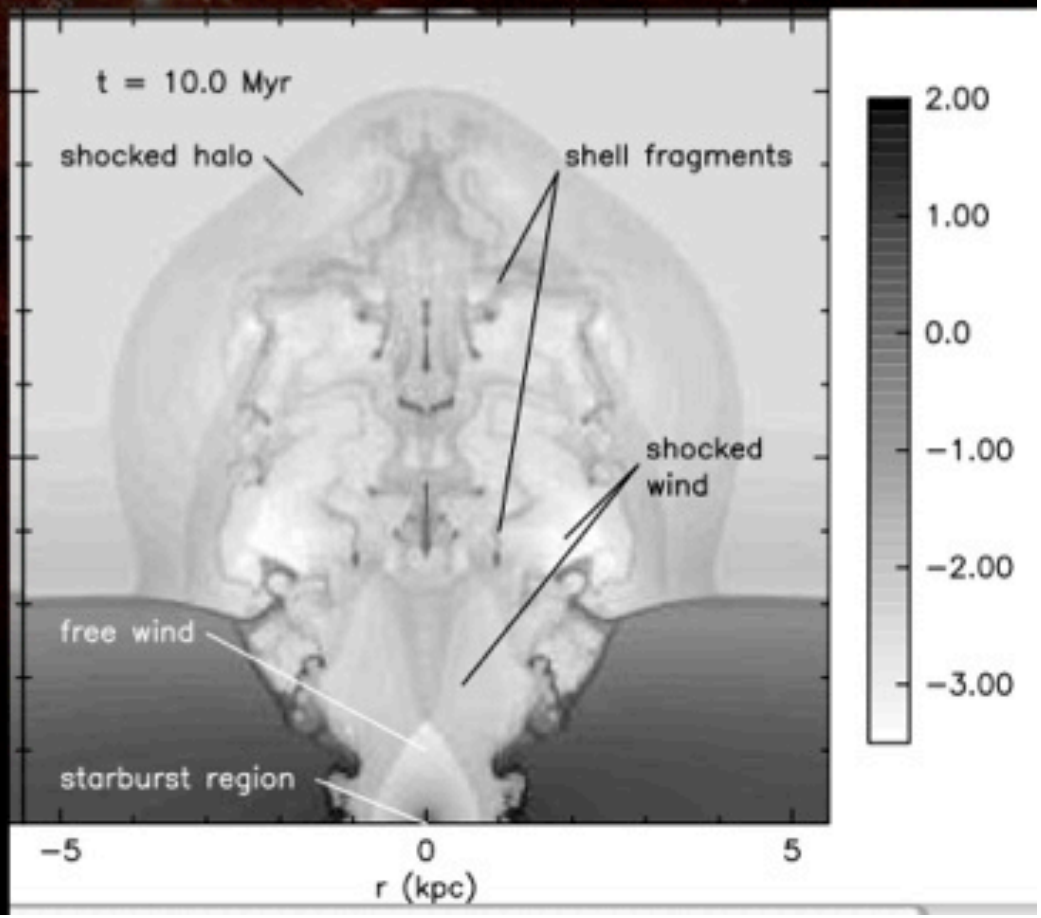
Springel & Hernquist (2003)



ES, Thacker, & Davis (2001)

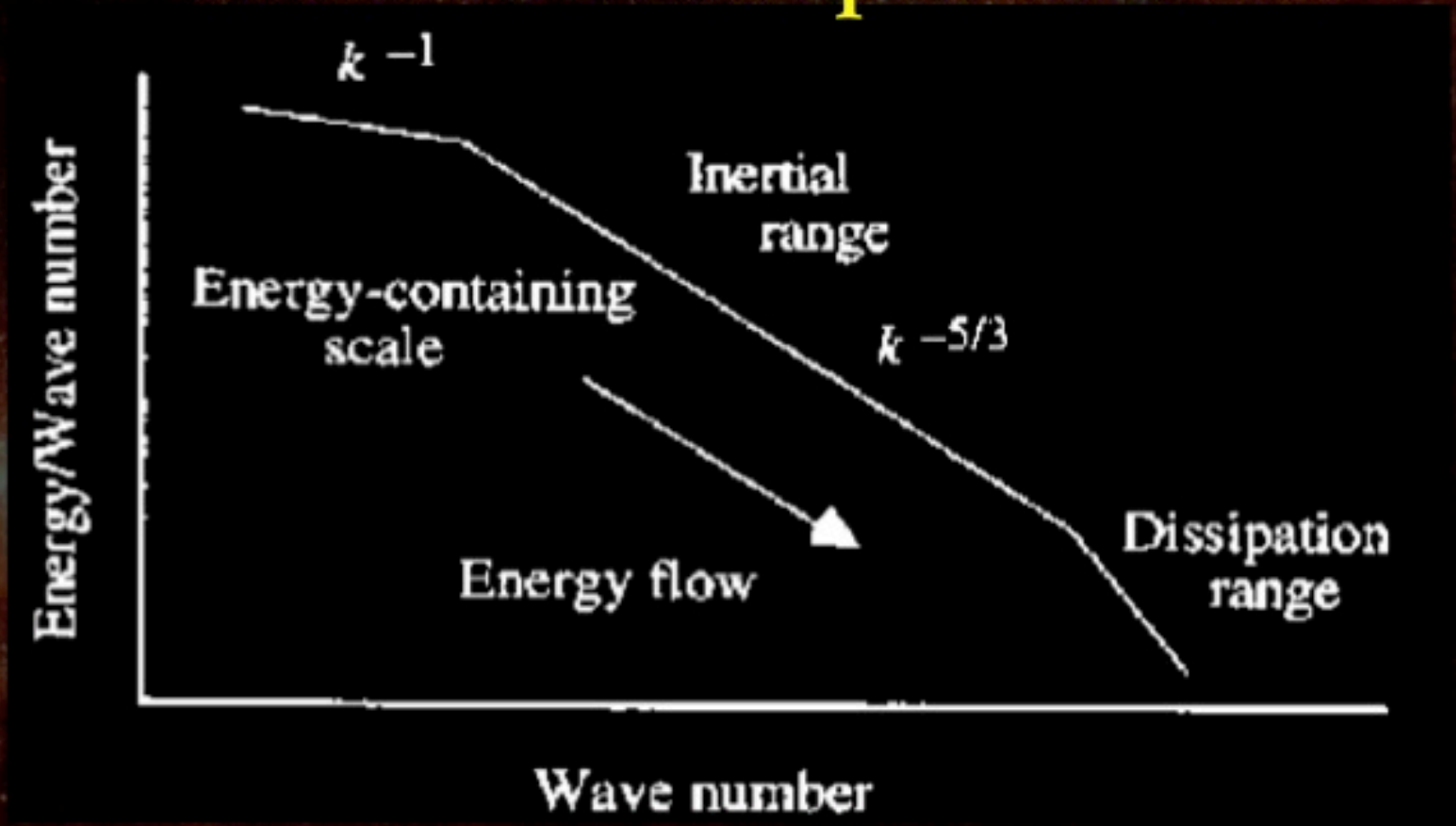


MacLow & Ferrara (1999)



Strickland & Stevens (2000)

Turbulent Dissipation Scale



Ionized Medium

Spitzer :

$L \approx 10^{-2}$ ly

Neutral Medium

Ambipolar Diffusion :

$L \approx 10^{-3}$ ly

Supersonic Turbulence

$\vec{V}$

ρ

T

$P(\rho,T)$

Cooling Time/
Homogeneous composition

Turbulent Decay of Energy
Turbulent Mixing

ES & M. Bruggen (2010)

II. Starbursting Outflows
& Subgrid Turbulence Models
ES & M. Bruggen (2010)

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 <u>everywhere.</u>

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

ES & M. Bruggen (2010)

$\dot{E}_{\rm mech}$

$$\Sigma_{\rm SFR} = 2.5 \times 10^{-4} \frac{M_\odot}{{\rm yr\,kpc}^2} \left(\frac{\Sigma_{\rm gas}}{10^6 M_\odot {\rm kpc}^{-2}} \right)^{1.5}$$

$$\frac{dN_{\rm OB}}{dN} = AN^{-\beta}$$

1 SN per 150 $M_\odot$

10 SNe or greater $M_{\rm bubble} = 2\ M_\star$

All K, $L = R_{\rm bubble}$

ES & M. Bruggen (2010)

Fluid Equations For Supersonic Turbulence

K = Turbulent KE , L= Turbulent Length Scale

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

turb. diffusion

$$-\rho V C_D \frac{\max(V - V_0, 0)^2}{L}$$

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

turb. diffusion

growth of eddies
through motion in mean flow

$$\mu_T = C_\mu \bar{\rho} L V, \qquad V \equiv \sqrt{2K}$$

turb. viscosity

turb. velocity

ES & M. Bruggen (2010)

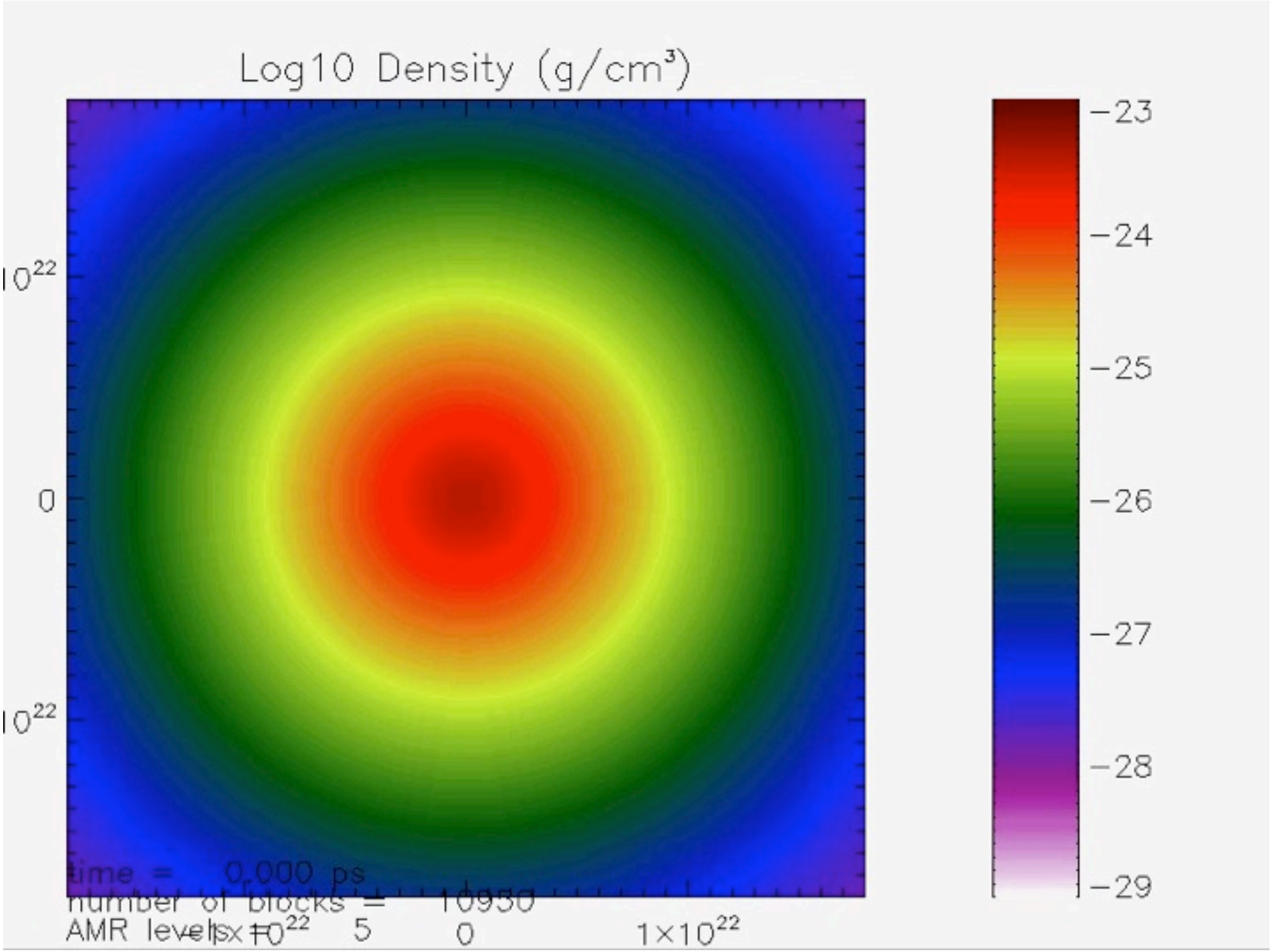
Fluid Equations For Supersonic Turbulence

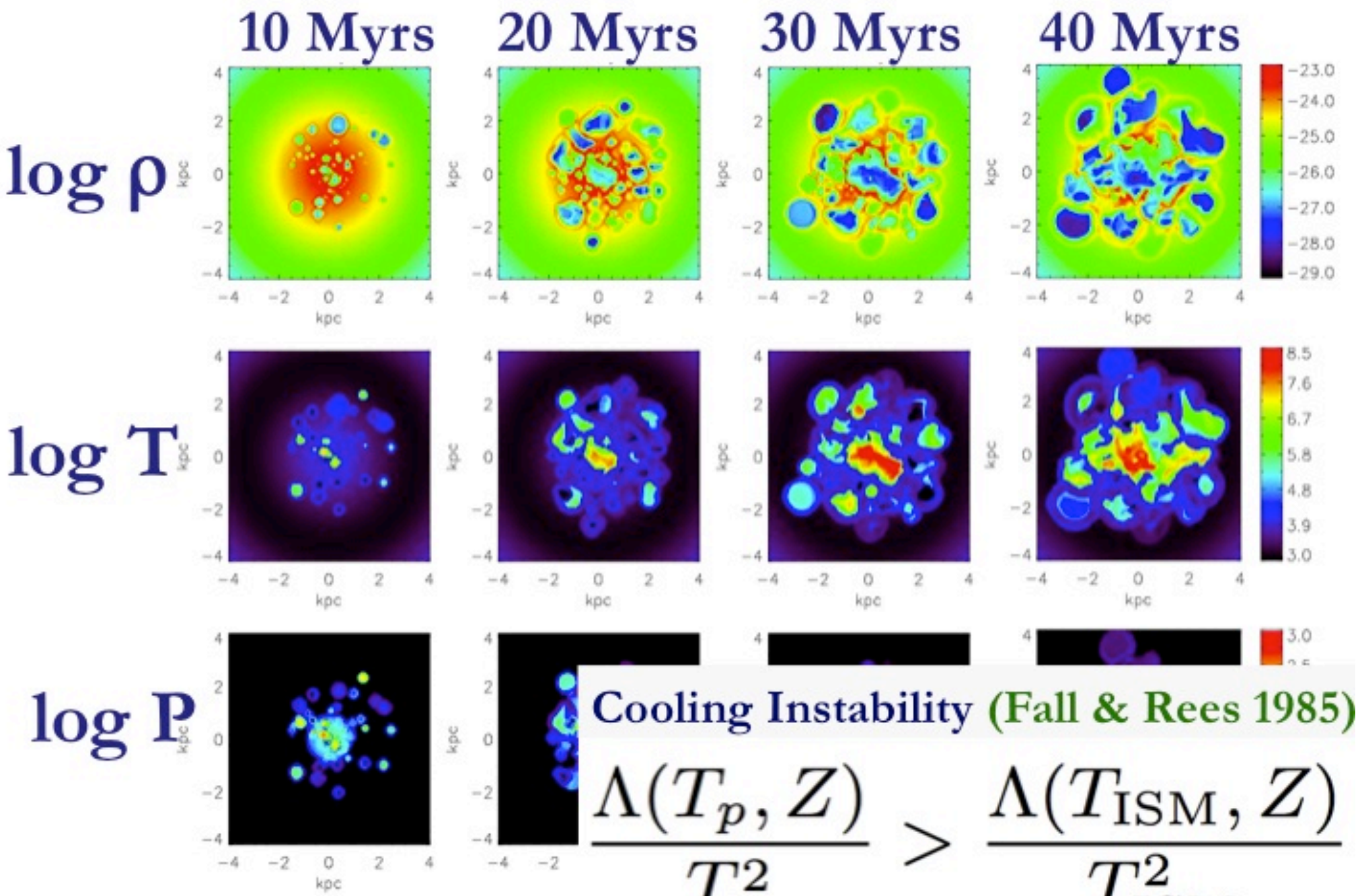
Thermal +
Turbulent

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

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

ES & M. Bruggen (2010)

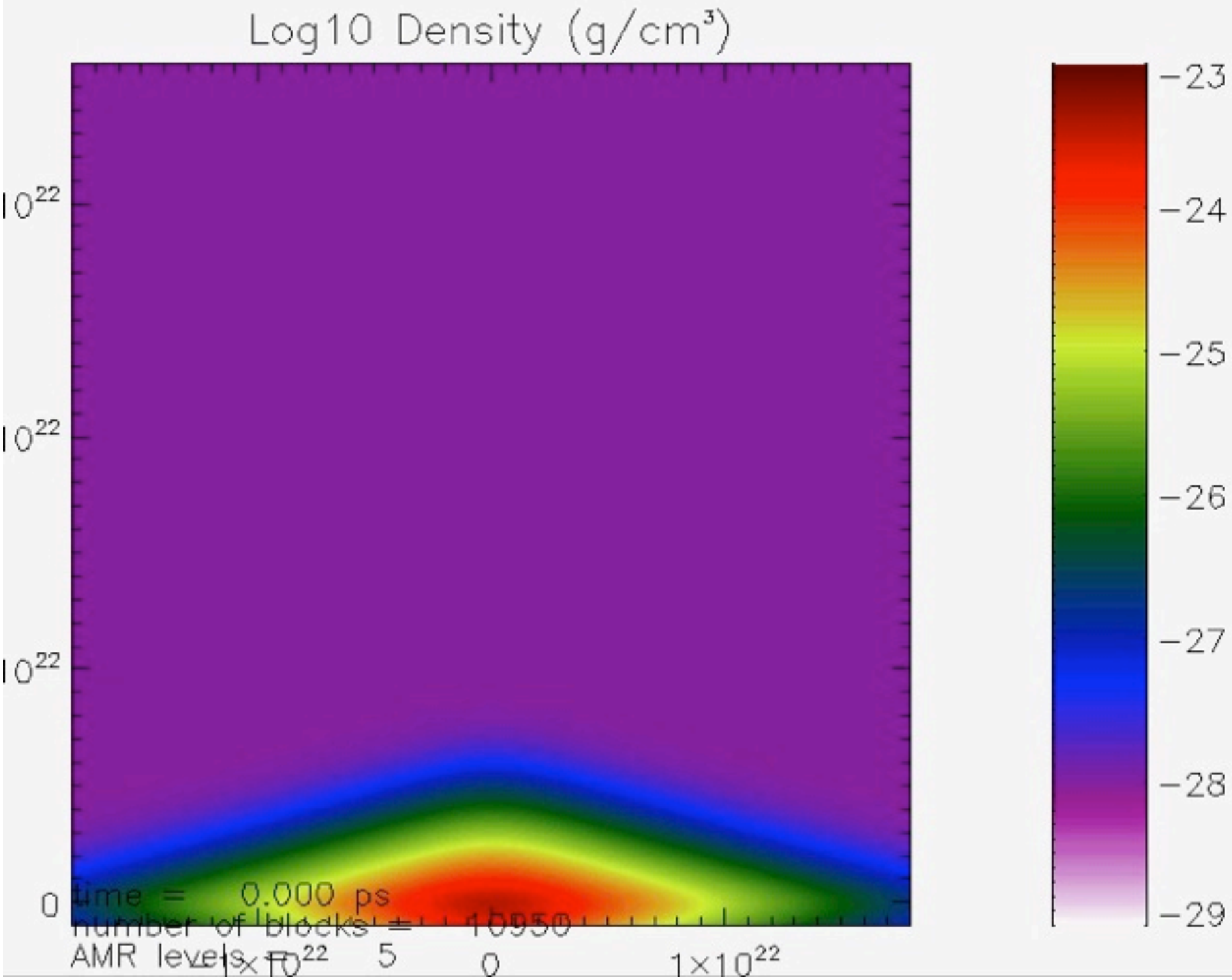

Log10 Density (g/cm³)
−23
−24
−25
−26
−27
−28
−29
10²²
0
10²²
time = 0.000 ps
number of blocks = 10930
AMR levels = 5
0
1×10²²

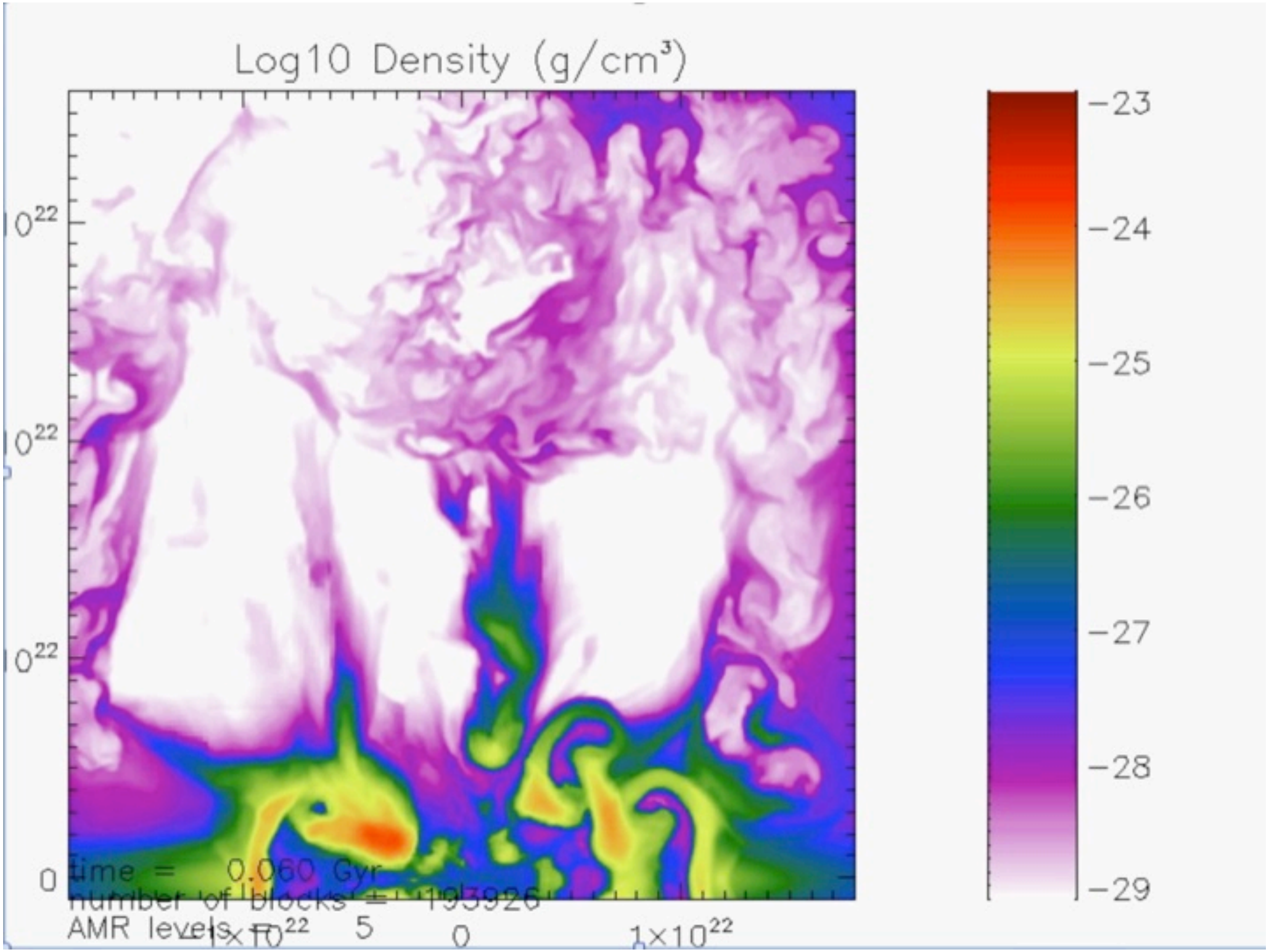


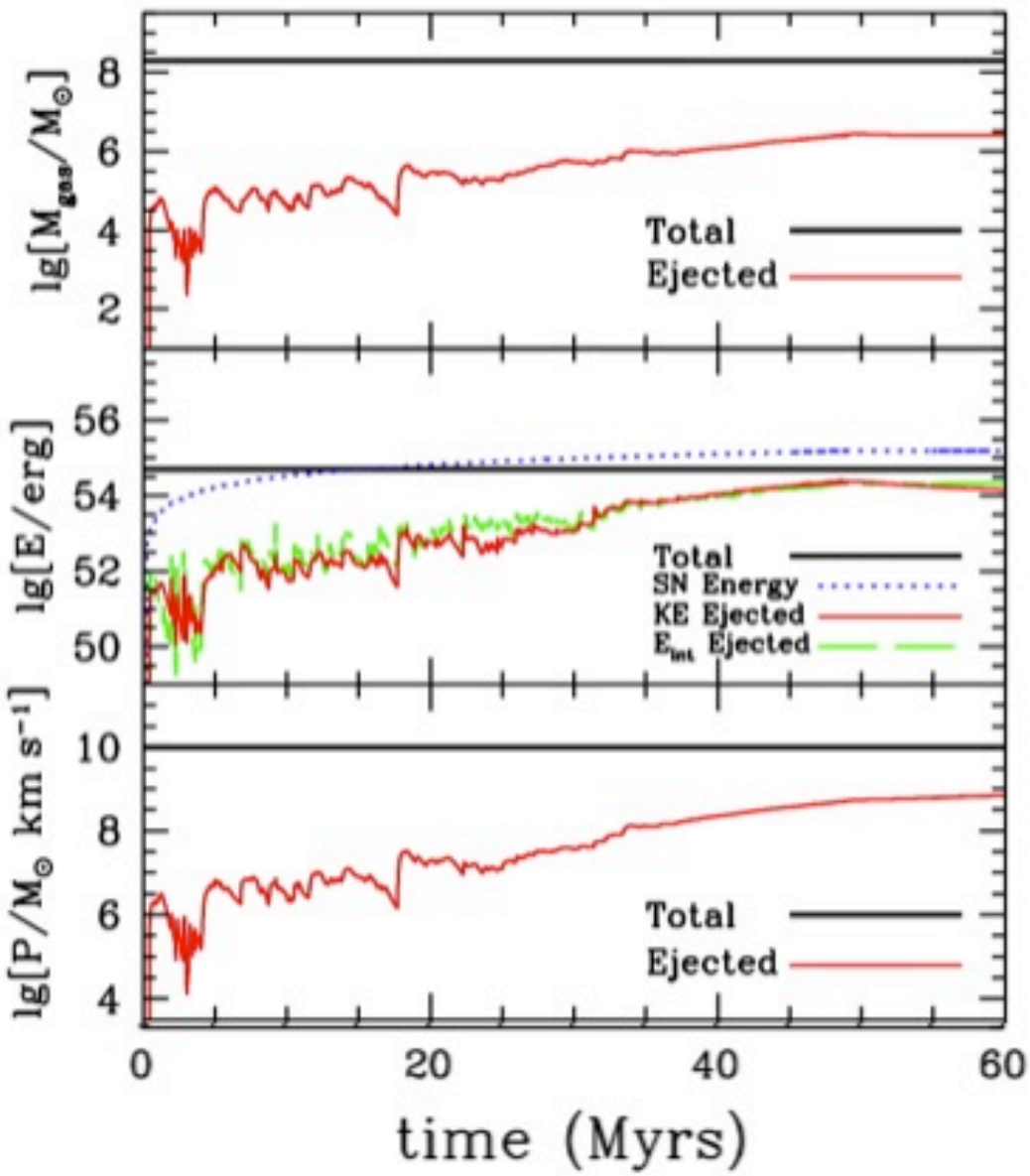
Cooling Instability (Fall & Rees 1985)

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

ES & M. Bruggen (2010)


Log10 Density (g/cm³)
10^22
10^22
10^22
0
time = 0.000 ps
number of blocks = 10950
AMR levels = 5
−1×10^22
0
1×10^22
−23
−24
−25
−26
−27
−28
−29


Log10 Density (g/cm³)
−23
−24
−25
−26
−27
−28
−29
10²²
10²²
10²²
0
time = 0.060 Gyr
number of blocks = 193926
AMR levels = 5
−1×10²²
0
1×10²²



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

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

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

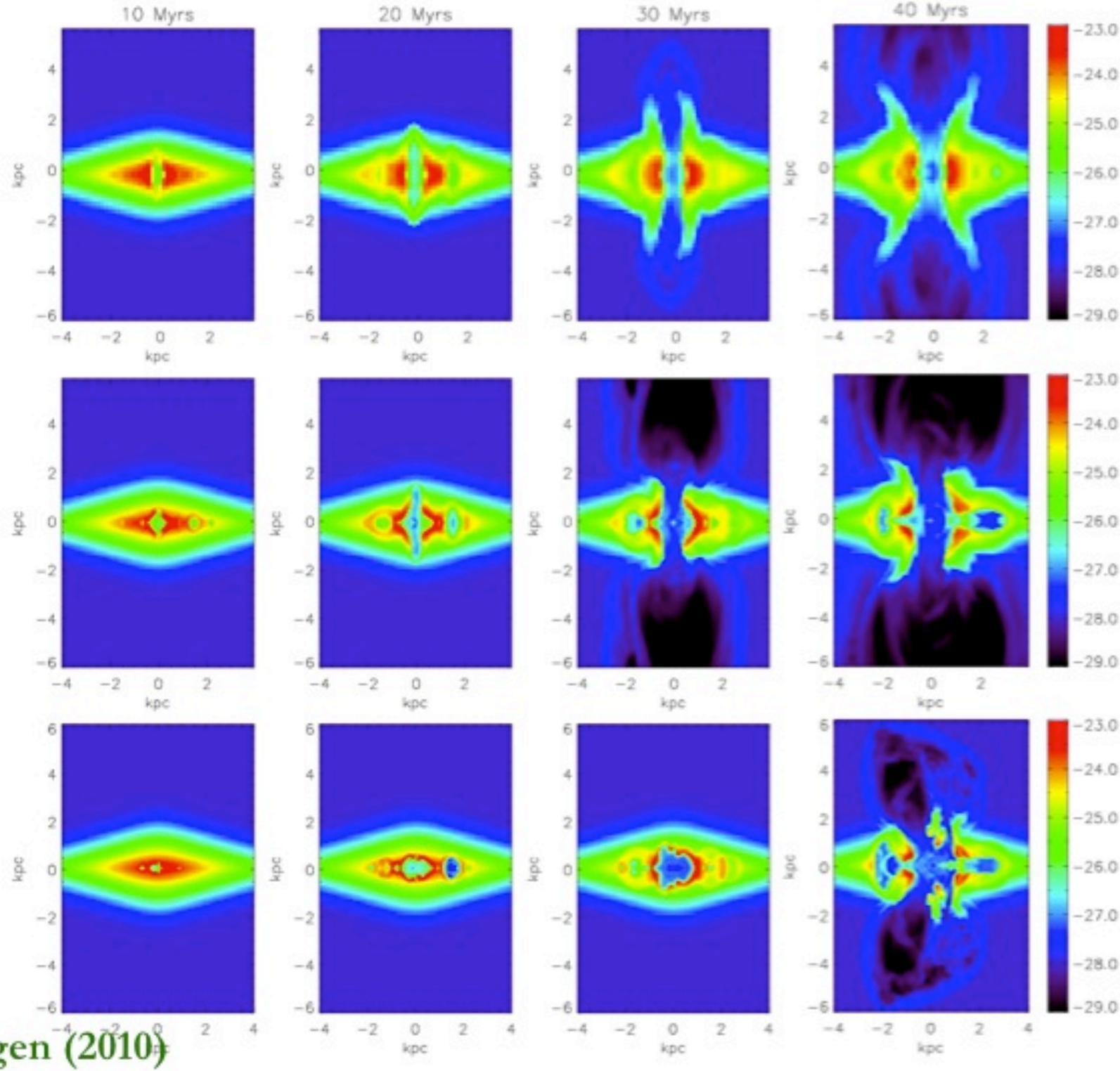
$V_{ej} \approx 50$ km/s

ES & M. Bruggen (2010)

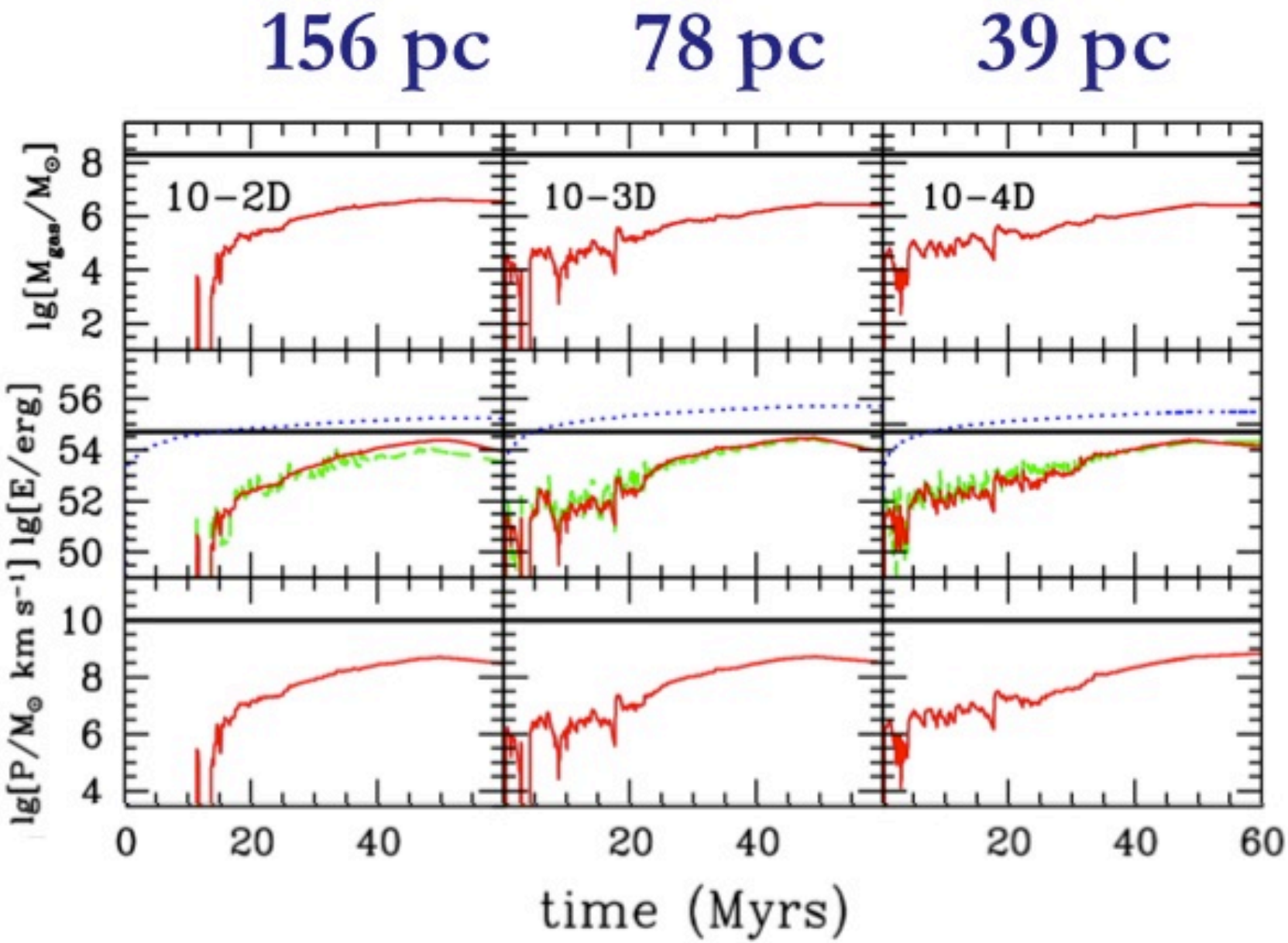
log ρ
156 pc

log ρ
78 pc

log ρ
39 pc



ES & M. Bruggen (2010)



ES & M. Bruggen (2010)

Simulations of Mixing in Supersonic Turbulence

We use the FLASH code with modified "Stir unit" for flow and scalar driving. Periodic simulation box, 512^3 cells

Turbulent flows:

-Driven and maintained by a solenoidal external force at large scales $1 \leq k/2\pi \leq 2$

-Amplitude of the force adjusted to obtain 6 Mach numbers from 0.9 to 6

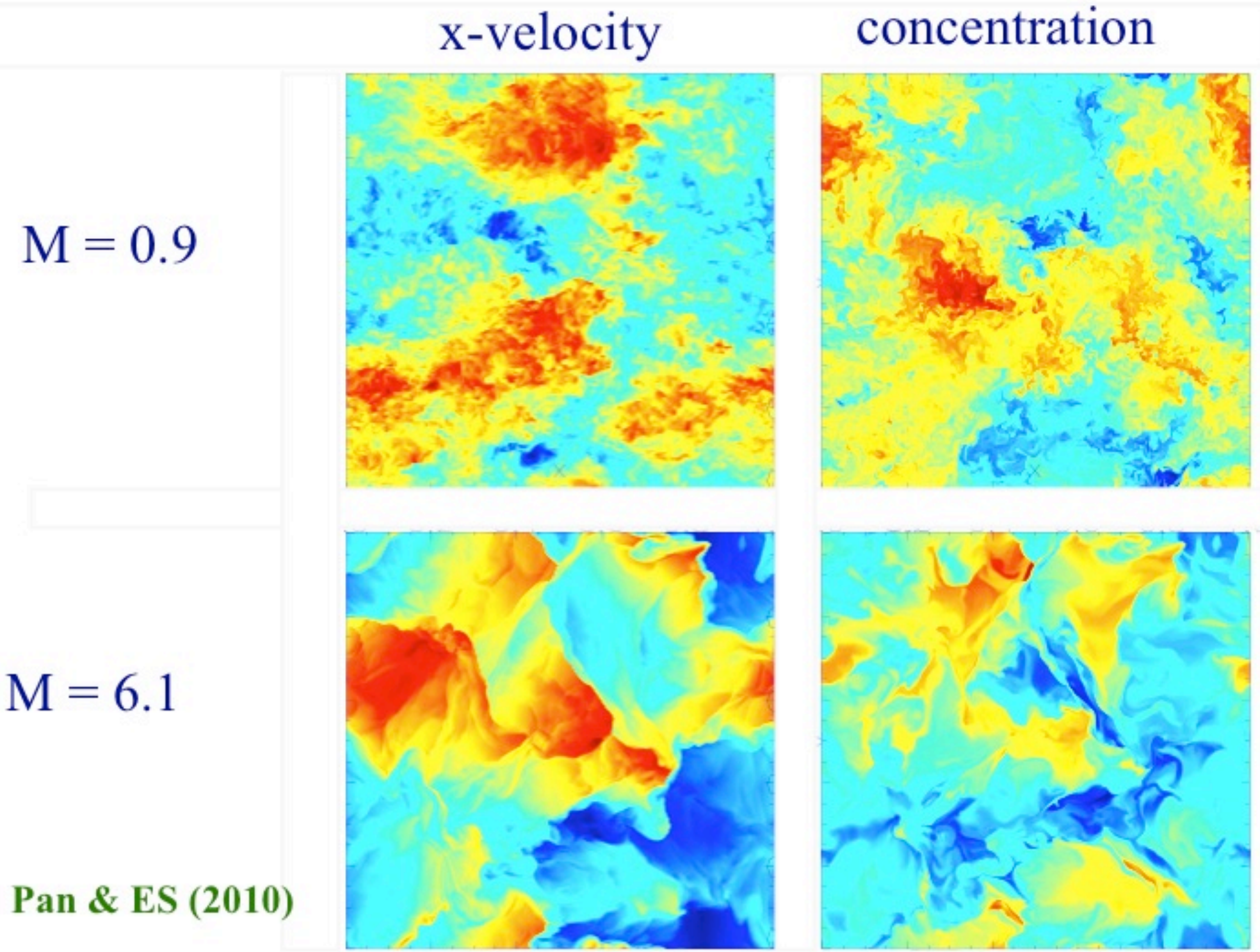
-Isothermal equation of state.

Passive scalars:

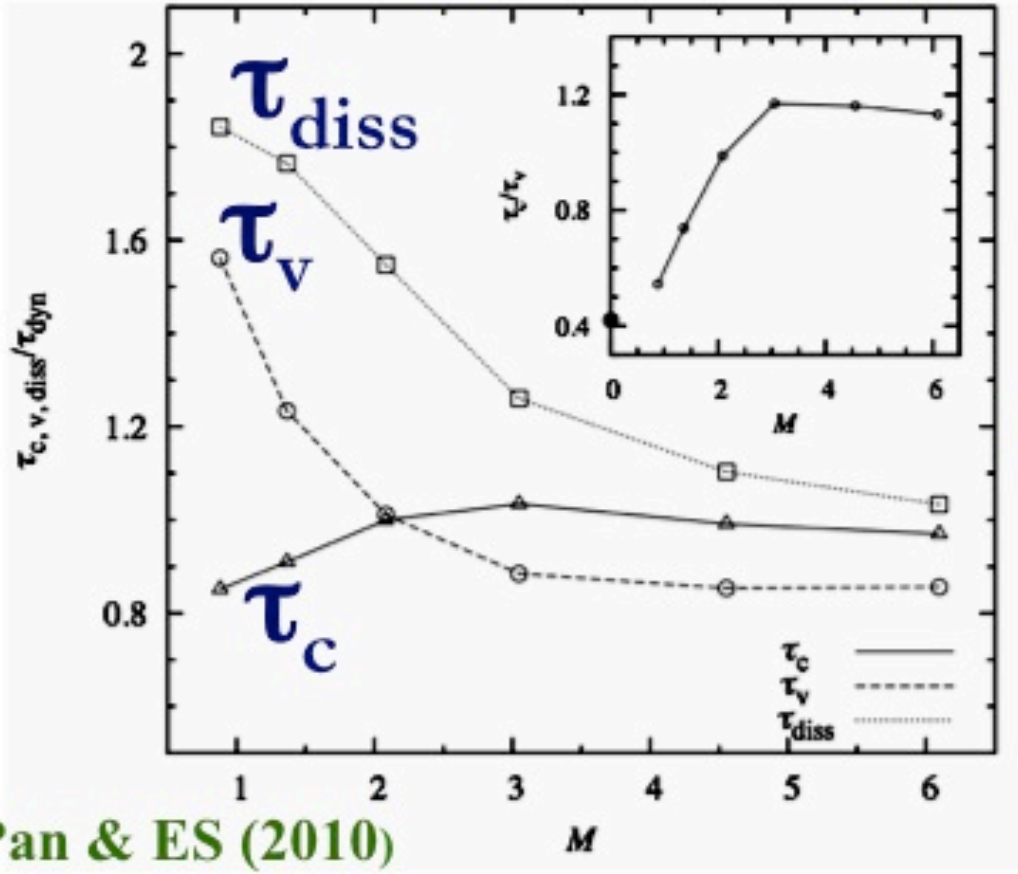
-Same driving scheme used representing new sources of pollutants at large scales.

-Three independent scalars evolved in each flow to achieve accurate statistical measurements.

Pan & ES (2010)


x-velocity
concentration
M = 0.9
M = 6.1
Pan & ES (2010)

Mixing and Energy Dissipation Timescales



Pan & ES (2010)

- Energy dissipation rate increases with M, shocks
- Mixing rate decreases with M compressible modes are less efficient at producing scalar structures at small scales

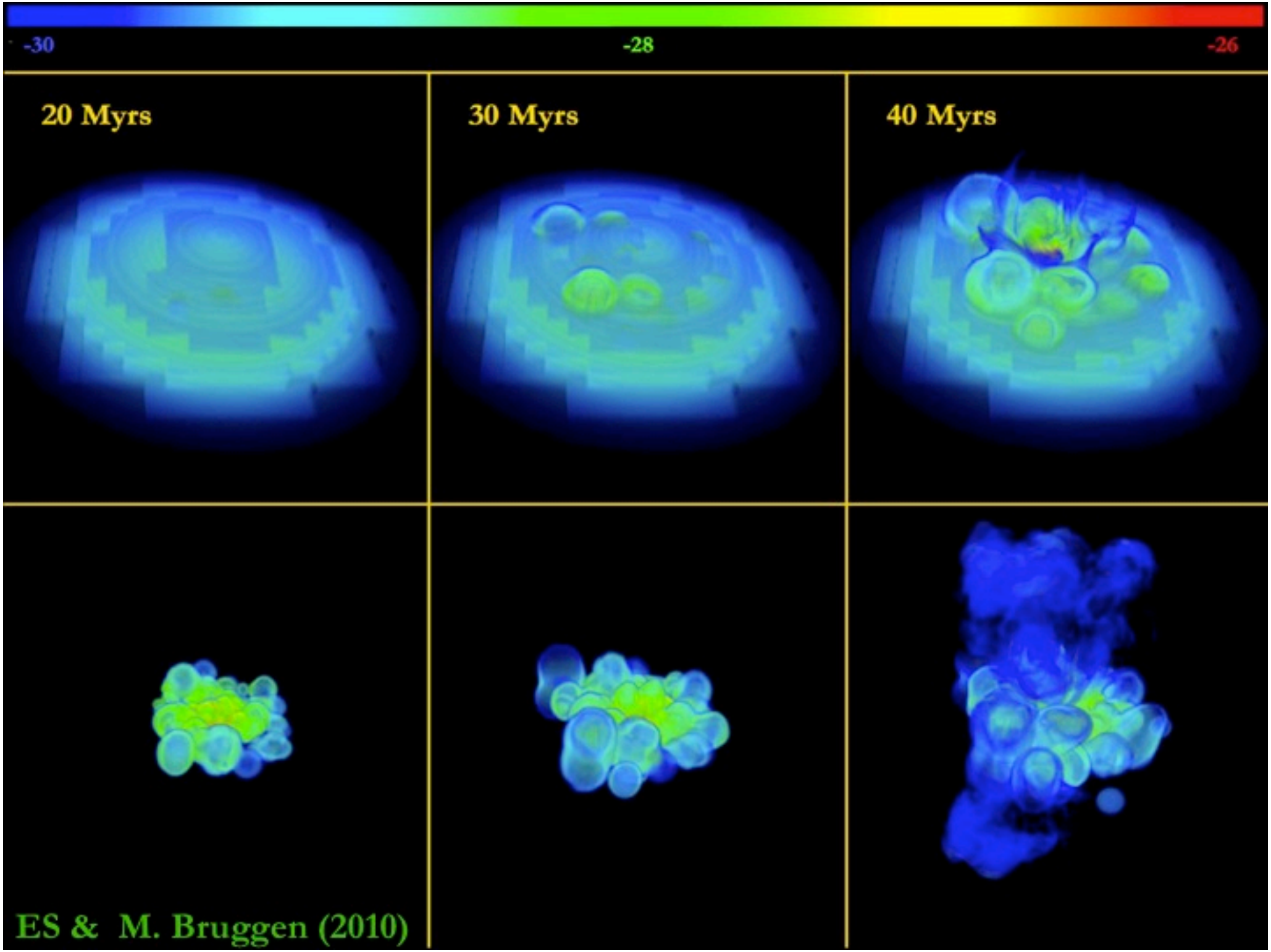
1. Kinetic energy contained in compressible modes first increases with M and then saturates at 1/3 for M>3, corresponding to equipartition.
2. pdV work has significant contribution (15-35%) to the conversion of kinetic energy to thermal energy.

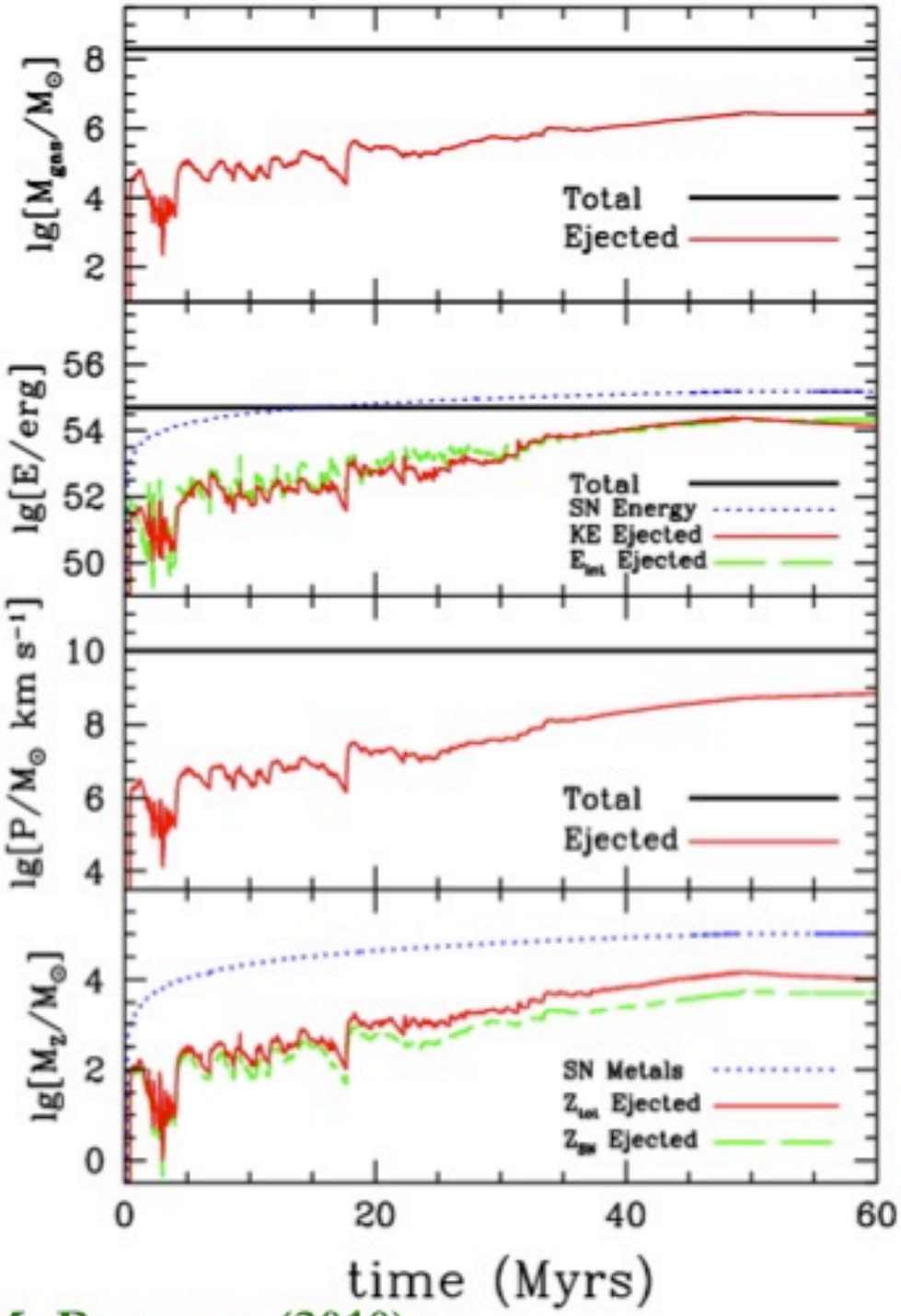
Fluid Equations For Supersonic Turbulence

$$\frac{\partial \rho F_r}{\partial t} + \frac{\partial \rho F_r u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_F}\frac{\partial F_r}{\partial x_j}\right)$$

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

ES & M. Bruggen (2010)


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



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

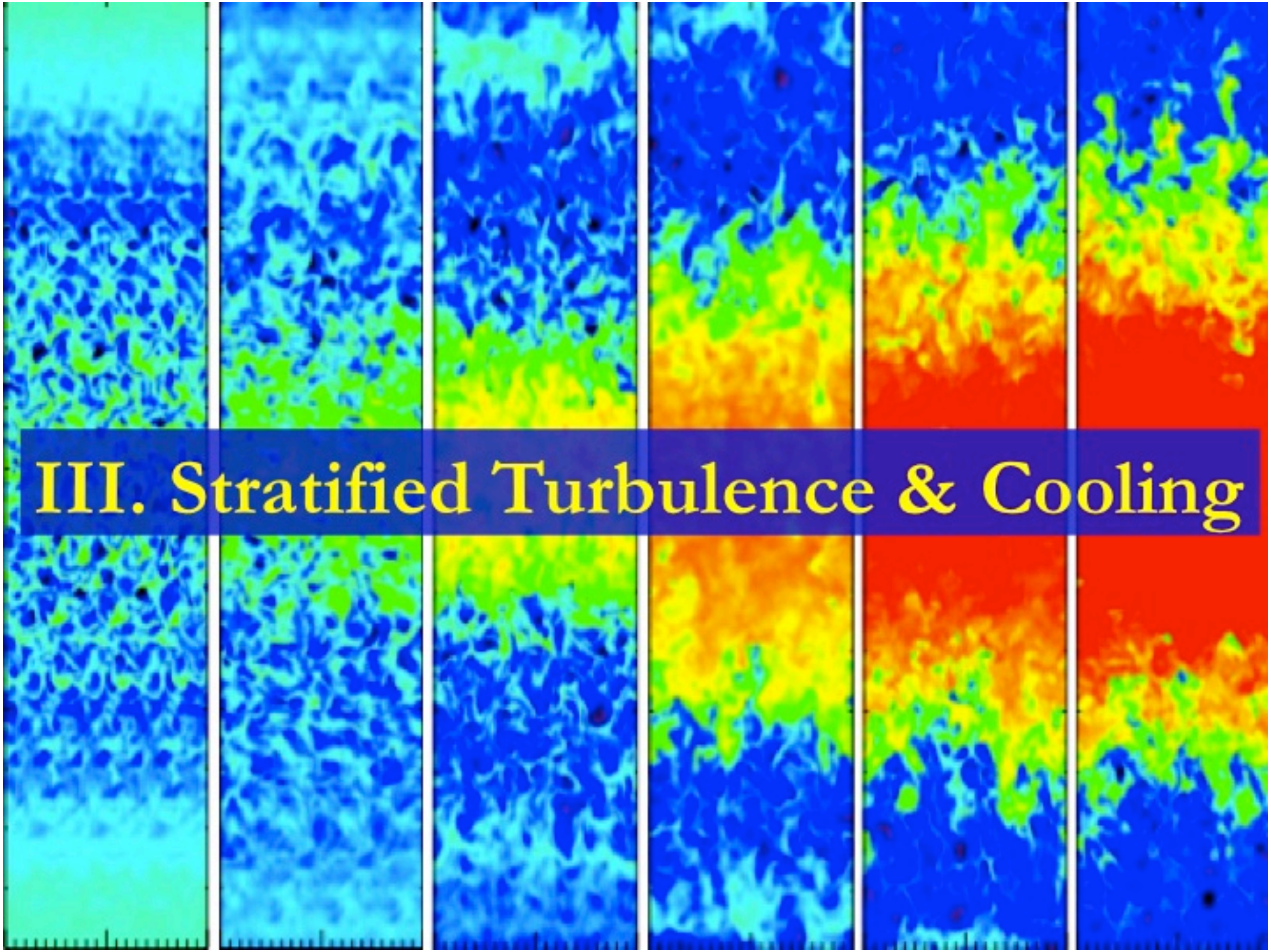
$\approx 8\times10^6 M_{Ej}$

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

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

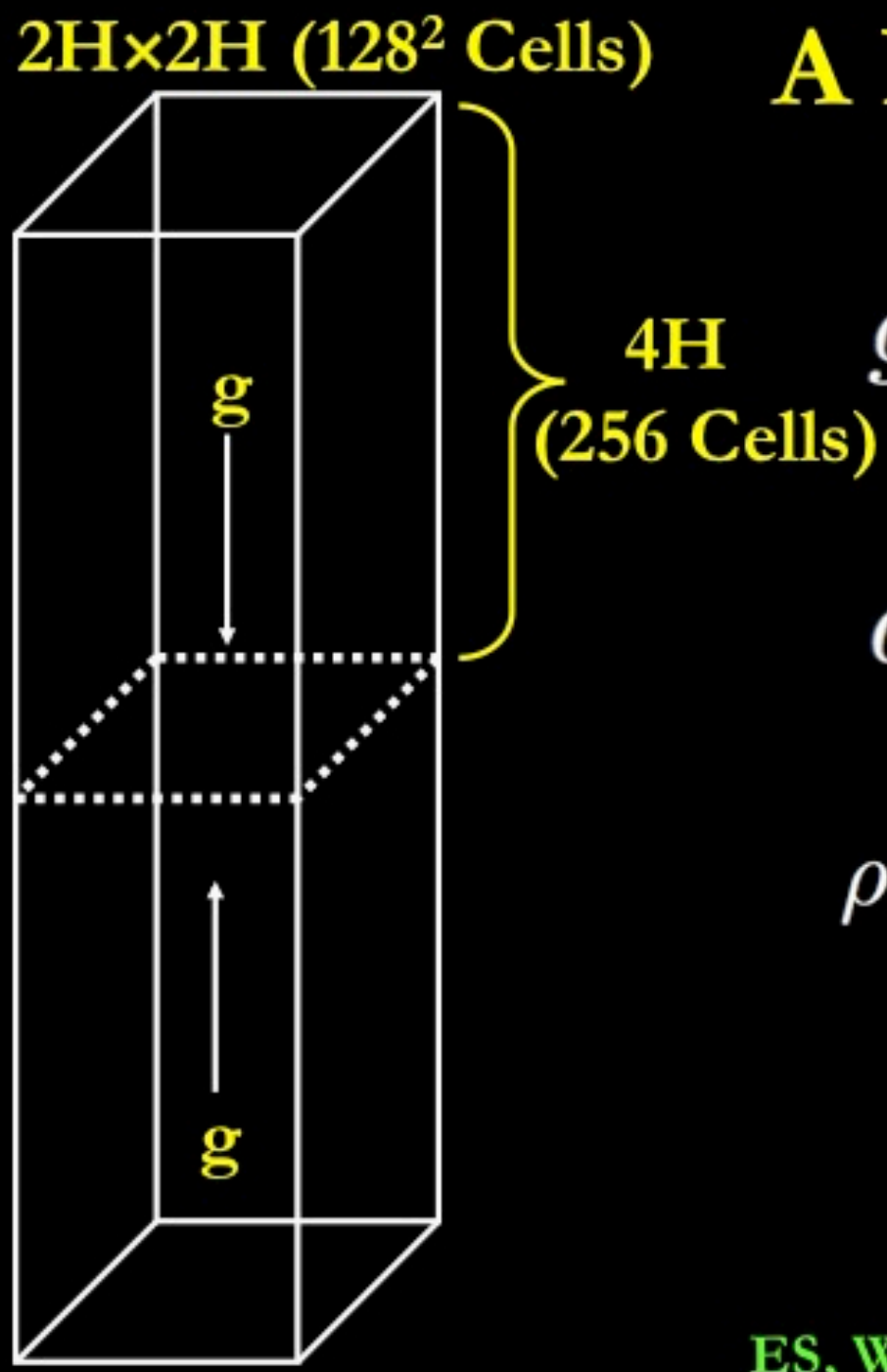
Most metals retained / Most ejected metals are from ongoing SNe

ES & M. Bruggen (2010)



III. Stratified Turbulence & Cooling

A Piece of a Galaxy



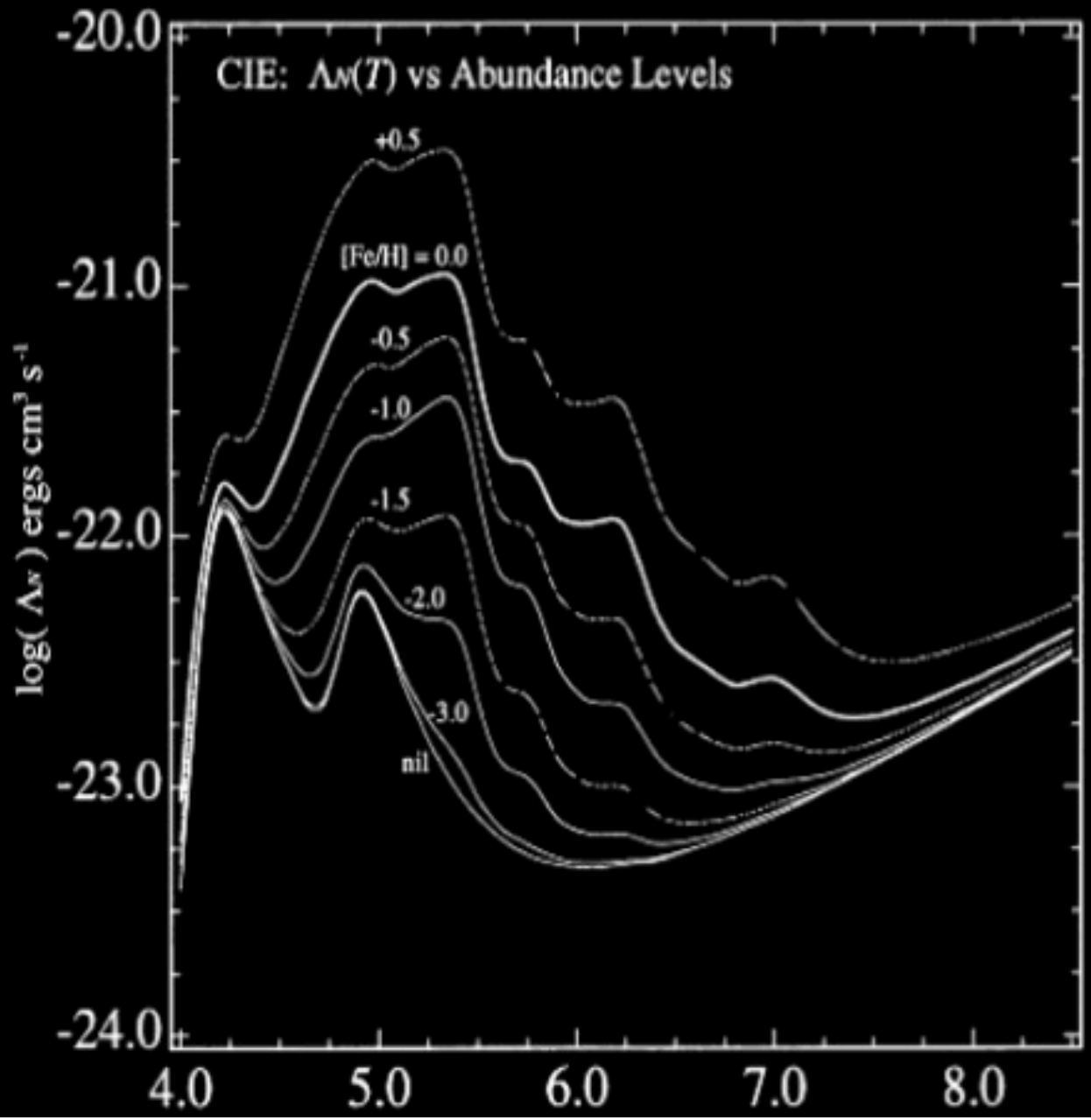
$$g = g_0 \frac{-z}{\sqrt{z^2 + a^2}}$$

$$a = H/2$$

$$\rho(z,t) = \rho_0 e^{-\left[\frac{(z^2+a^2)^{1/2}-a}{H}\right]}$$

ES, W. Gray, L. Pan(2012)

Radiative Cooling Rates in Interstellar Gas



What Equations do we Solve?

$$\frac{D\rho}{Dt} = 0,$$

$$\frac{D\rho u_i}{Dt} + \frac{\partial P}{\partial x_i} = \rho g_i + \boxed{\rho f_i e^{-\left[\frac{(z^2+a^2)^{1/2}-a}{H}\right]}},$$

$$\frac{D\rho E}{Dt} + \frac{\partial P u_j}{\partial x_j} = \rho \dot{E}_{\rm cool} + \rho \dot{E}_{\rm chem},$$

$$\frac{D\rho X_s}{Dt} = \rho A_s \dot{R}_s.$$

$$\mathcal{P}_{\rm f}(k)\left(\delta_{ij} - \frac{k_i k_j}{k^2}\right)\exp\left[-\frac{(t-t')}{t_{\rm f}}\right]$$ We stir at L= H/10

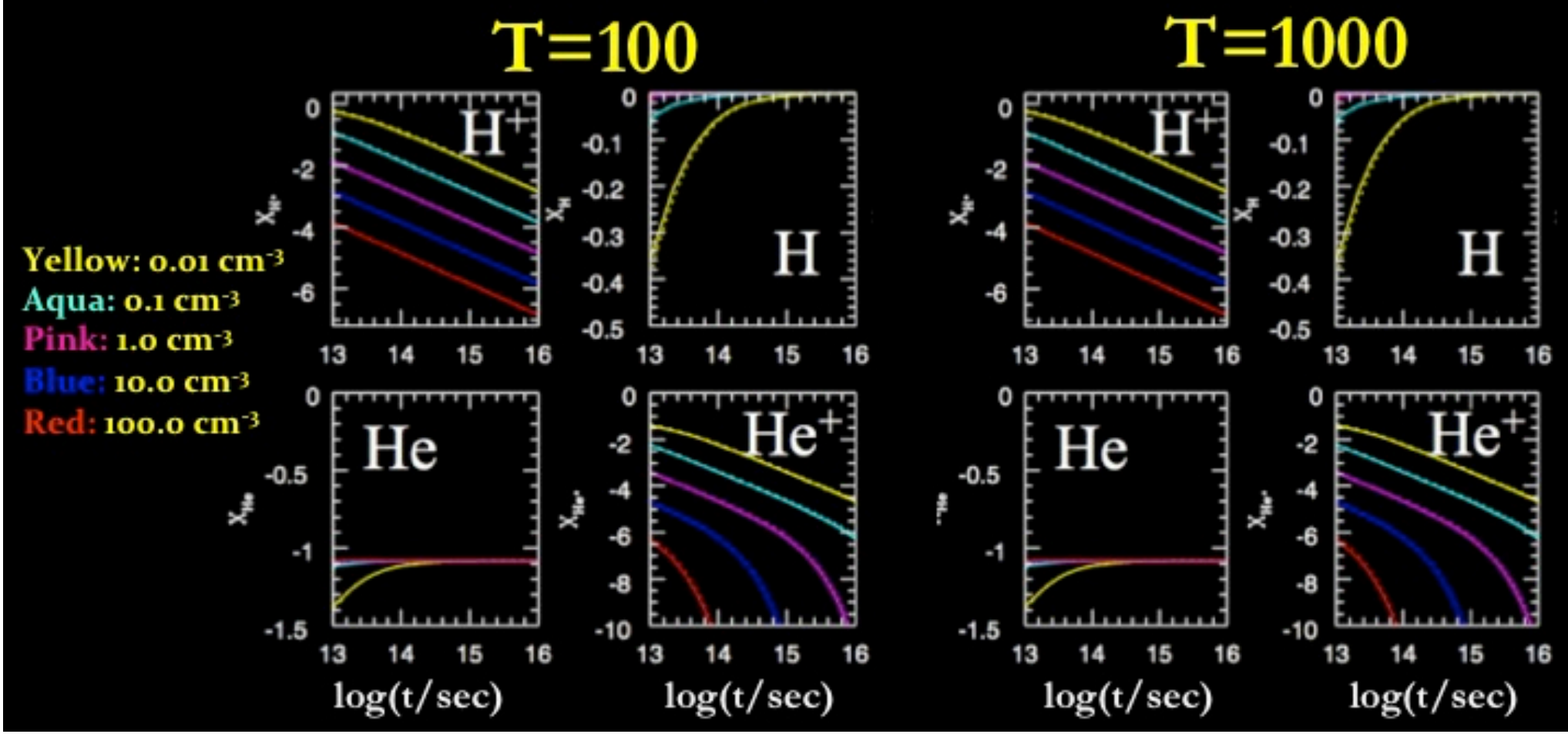
ES, W. Gray, L. Pan(2012)

Chemistry

7 Species (H, H^+, H^-, He, He^+, He^{++}, e^-), 14 Reactions

An implicit Runge-Kutta Method (4th order) evolve the species

Sub-cycles-- Run chemistry at smaller timesteps while still running simulation at hydrodynamic timescale



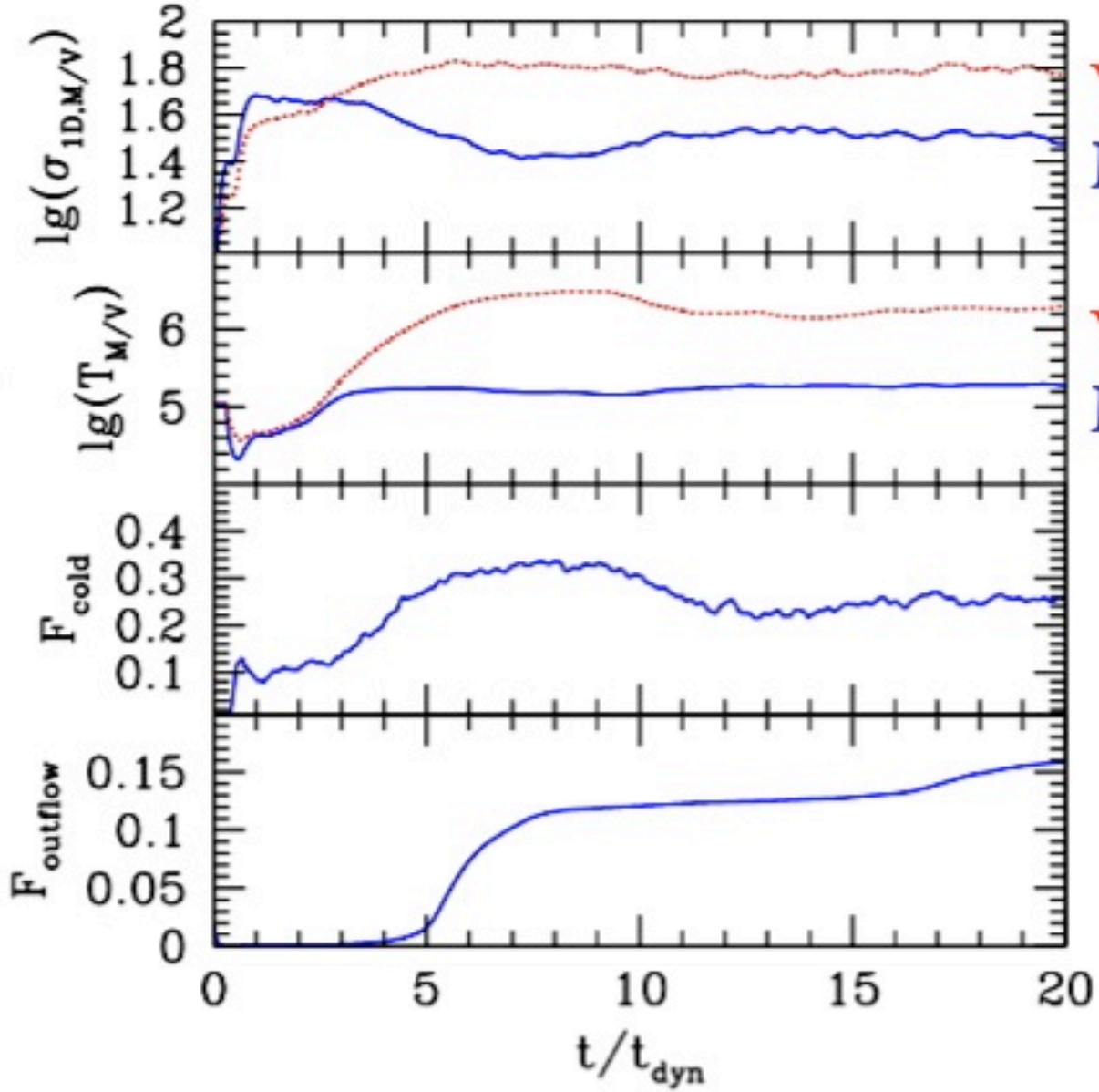
Evolution ($\sigma_{1D,M}$=34 km/s)

Velocity dispersion

Temperature

Cold Mass Fraction

Outflowing Fraction



Vol Ave.

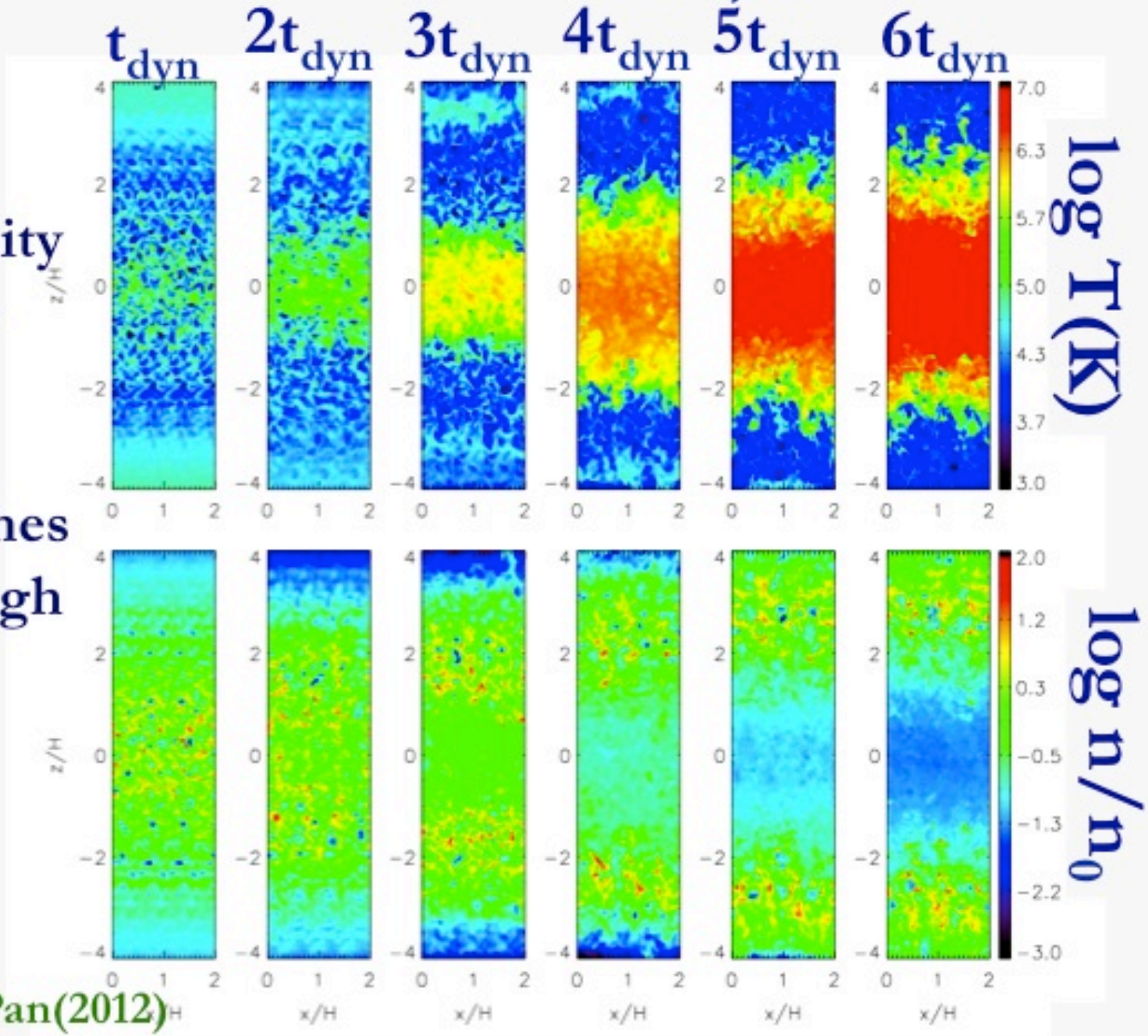
Mass Ave.

Vol Ave.

Mass Ave.

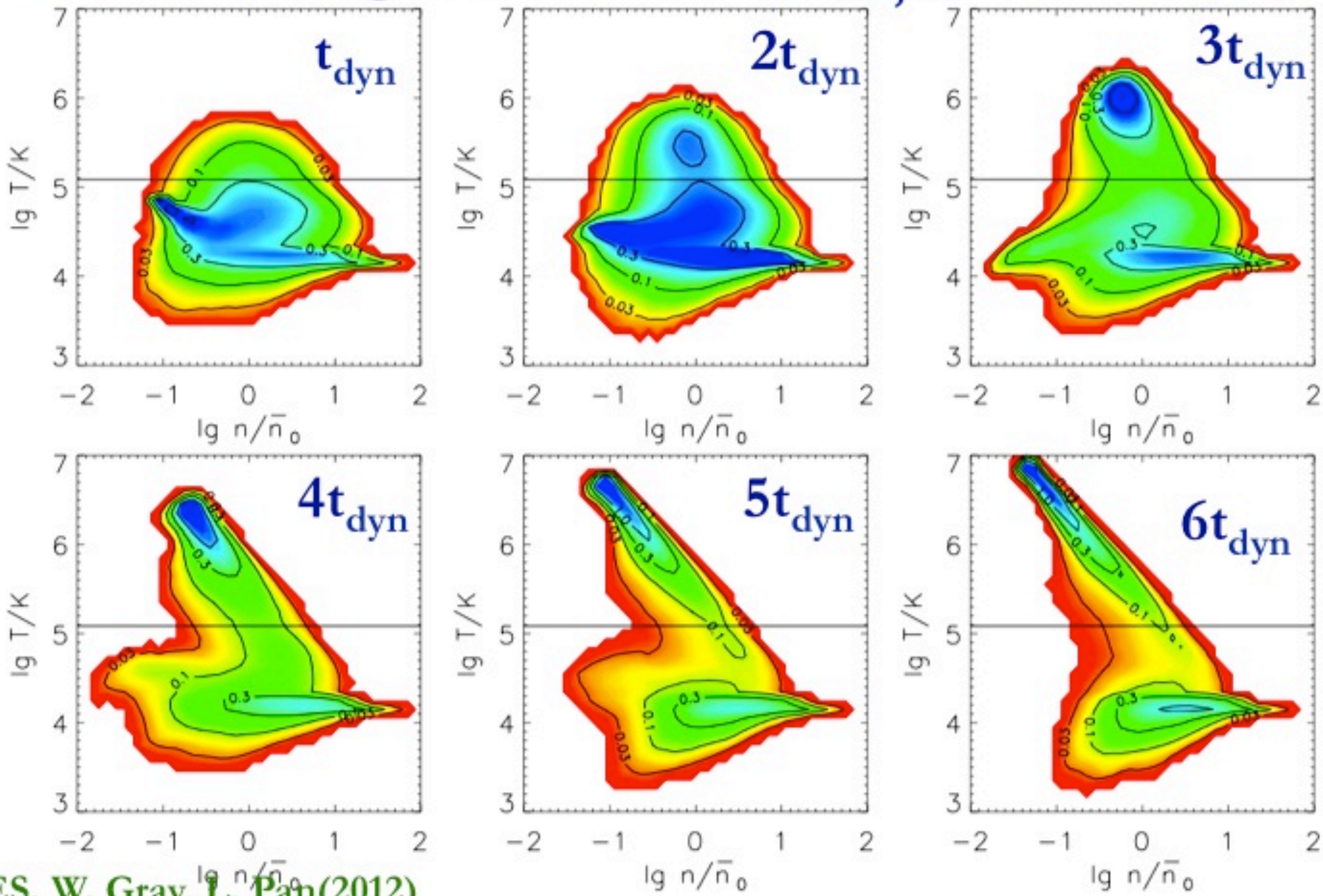
Temp & Dens Slices ($\sigma_{1D,M}$=34 km/s)

Hot low density gas builds up over many dynamical times, & pushes material to high latitudes



ES, W. Gray, L. Pan(2012)

Mass-Weighted PDF ($\sigma_{1D,M}$=34 km/s)

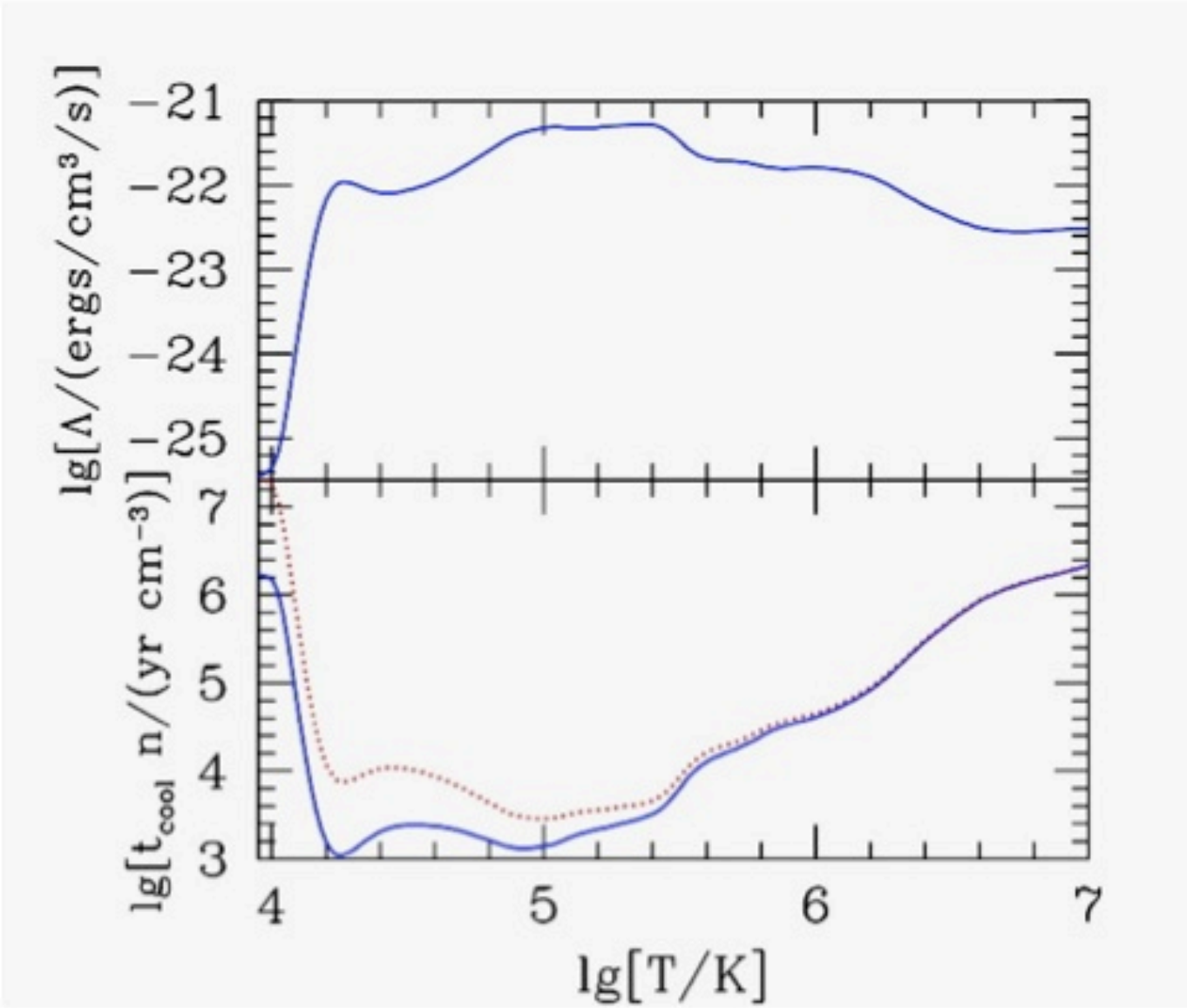


ES, W. Gray, L. Pan(2012)

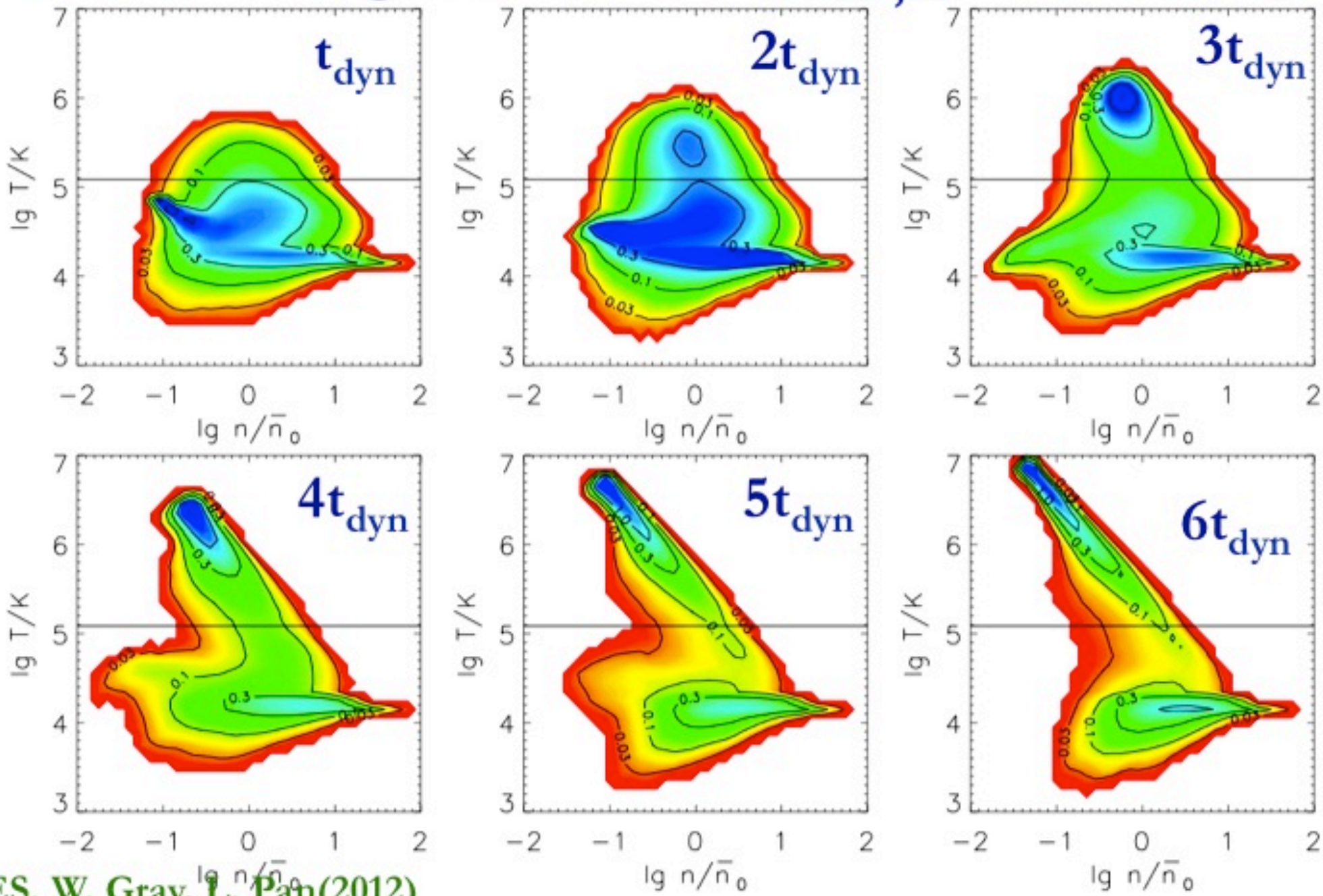
Radiative Cooling Rates in Interstellar Gas

Cooling Rate

Cooling Time

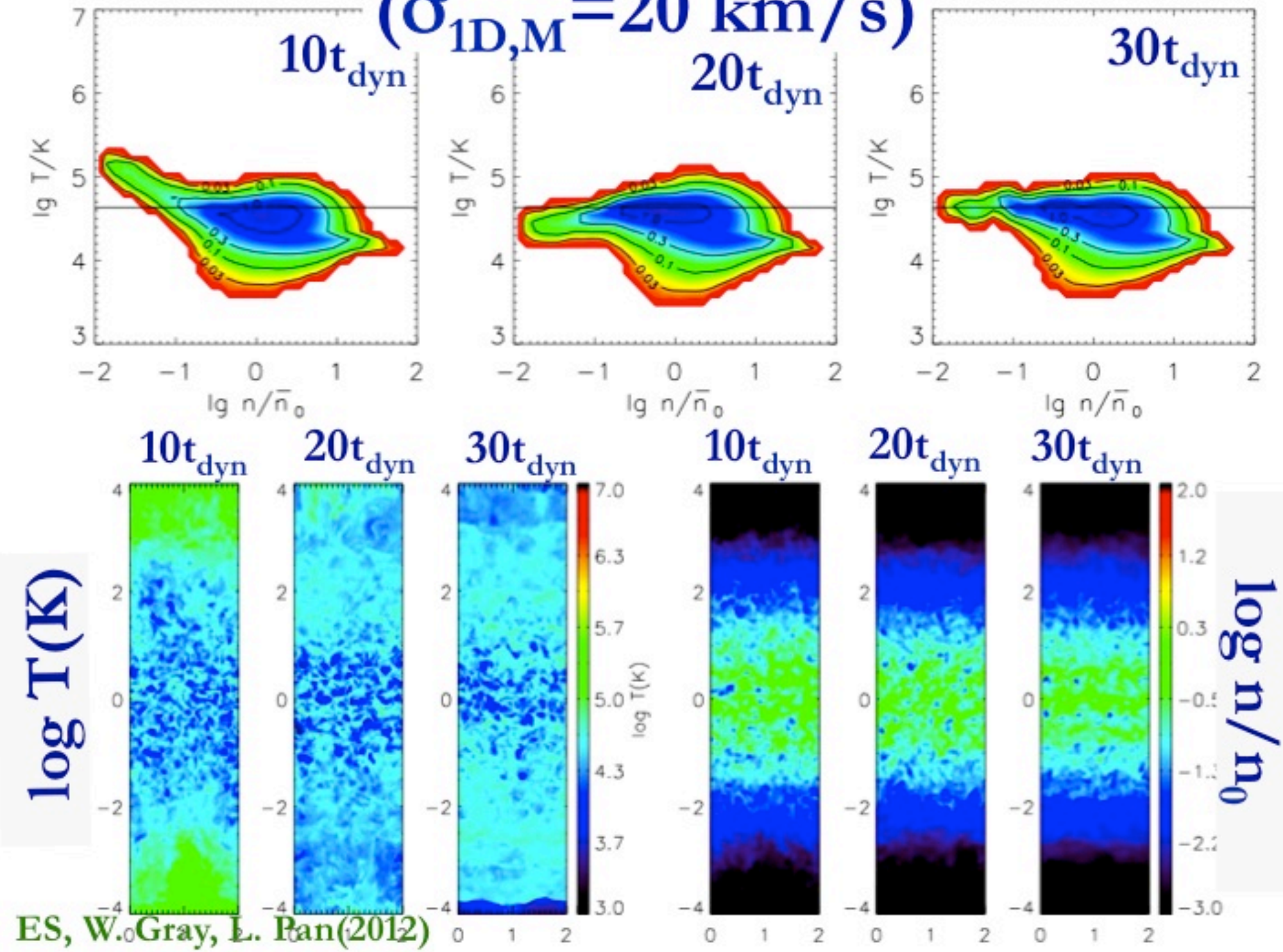


Mass-Weighted PDF ($\sigma_{1D,M}$=34 km/s)



ES, W. Gray, L. Pan(2012)

($\sigma_{1D,M}$=20 km/s)

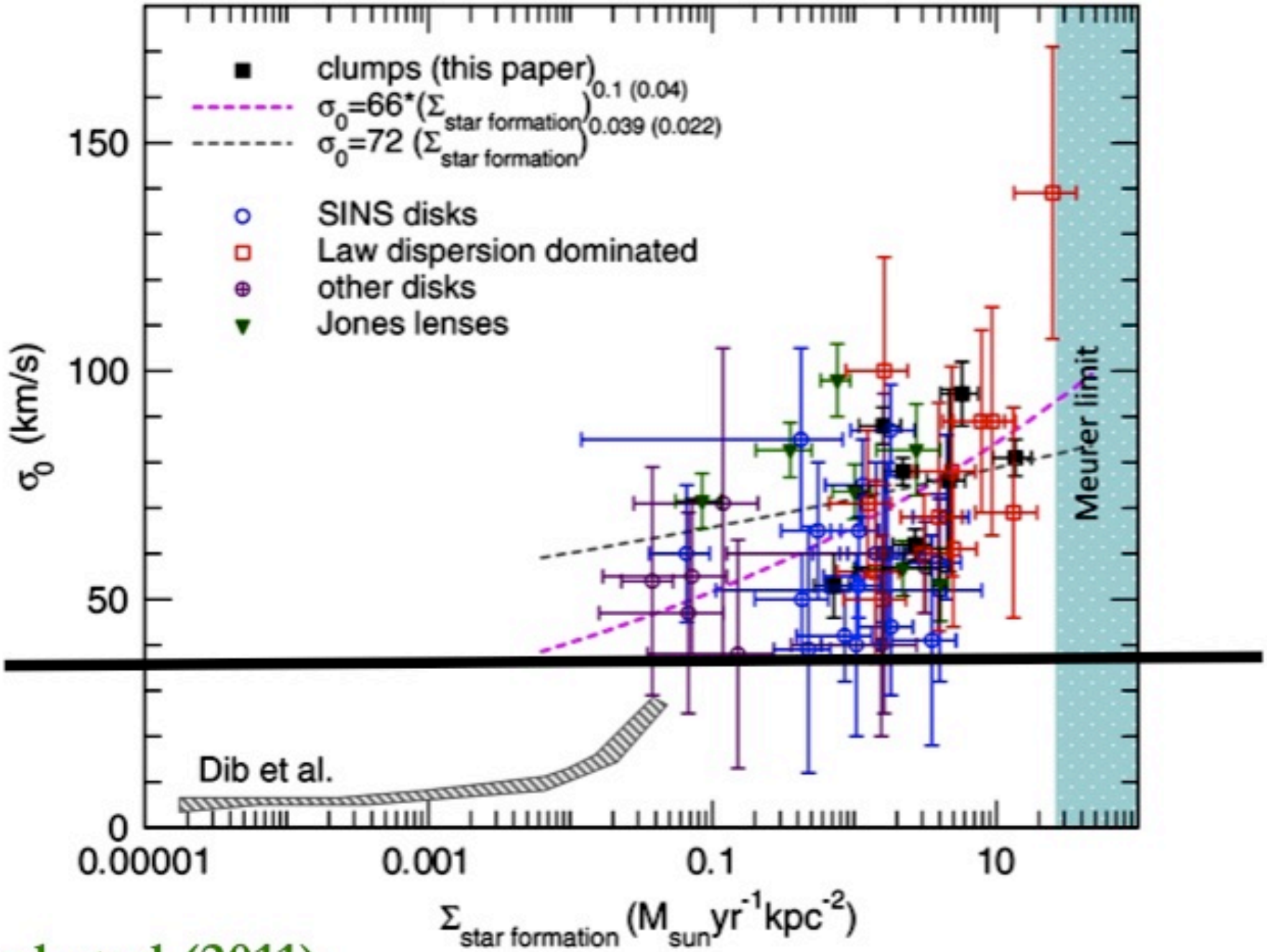


ES, W.Gray, L. Pan(2012)

Run Parameters

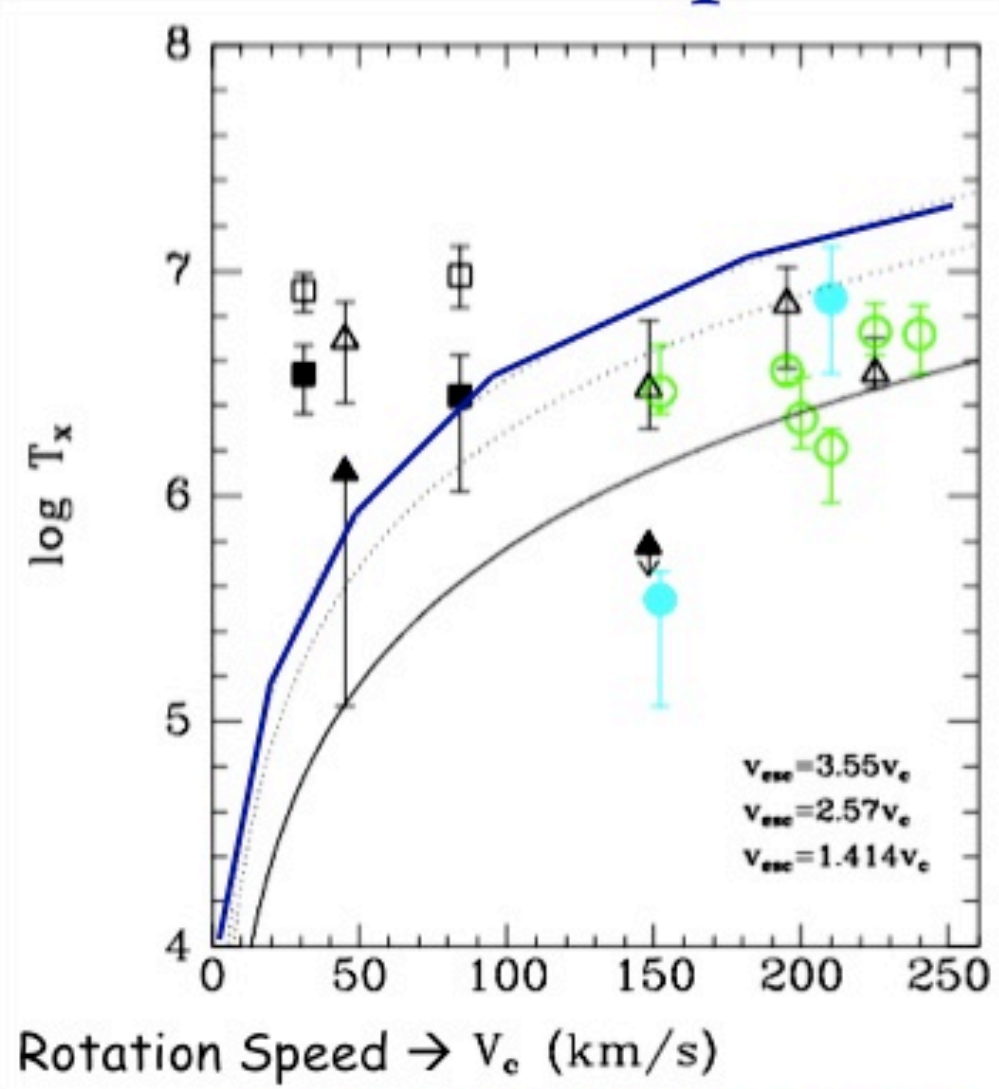
Name	$\bar{\sigma}_{1D,M}$ (km/s)	$\bar{\sigma}_{3D,M}$ (km/s)	$H\bar{n}^{(a)}$ ($M_\odot\,\mathrm{pc}^{-2}$)	$H/\Delta x$	t_{final} (t_{dyn})	F_{outflow}
S34	34	59	0.061	64	20	0.16
S20	20	35	0.0061	64	40	0.02
S29	29	50	0.018	64	20	0.01
S61	61	106	0.18	64	10	0.95
S35HR	35	60	0.061	96	12	0.27

ES, W. Gray, L. Pan(2012)



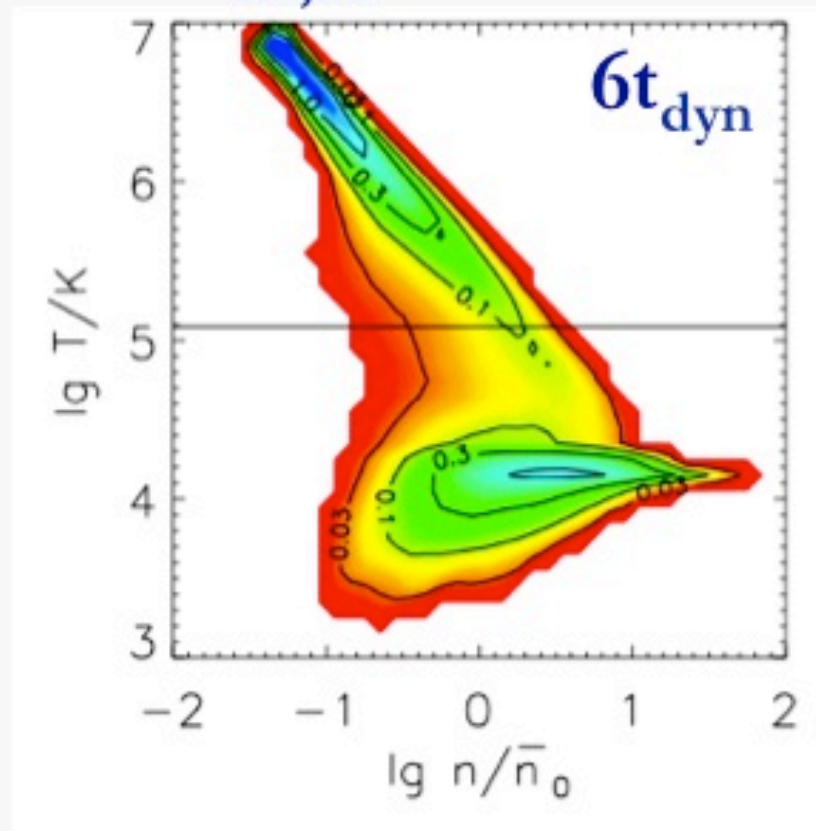
Genzel et al (2011)

Hot Gas Escapes from Dwarf Starbursts



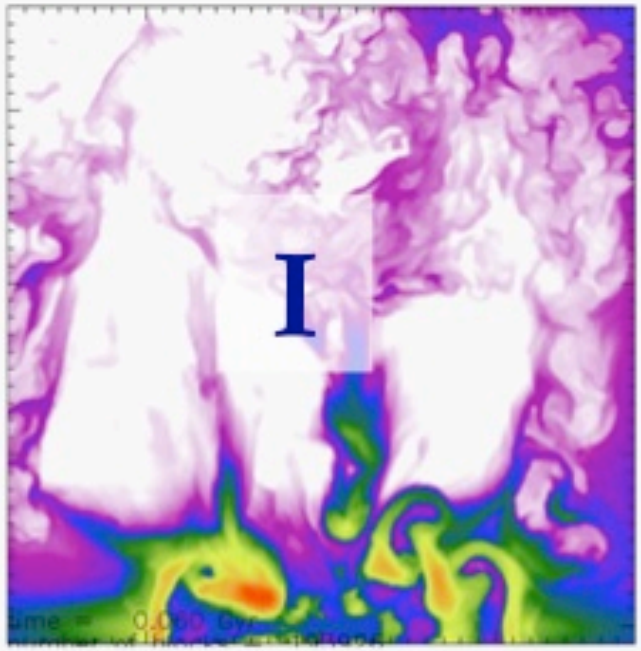
Martin (1999), Martin (2004)

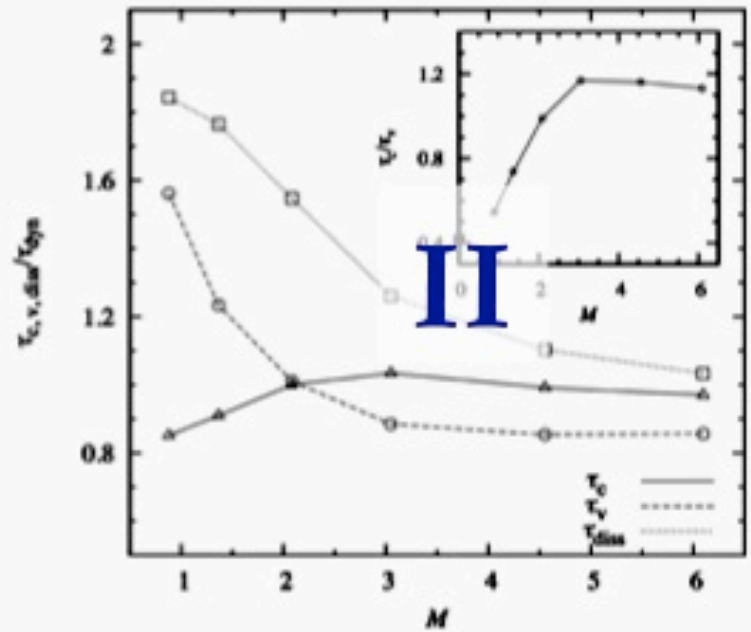
$\sigma_{1D,M}$=34 km/s

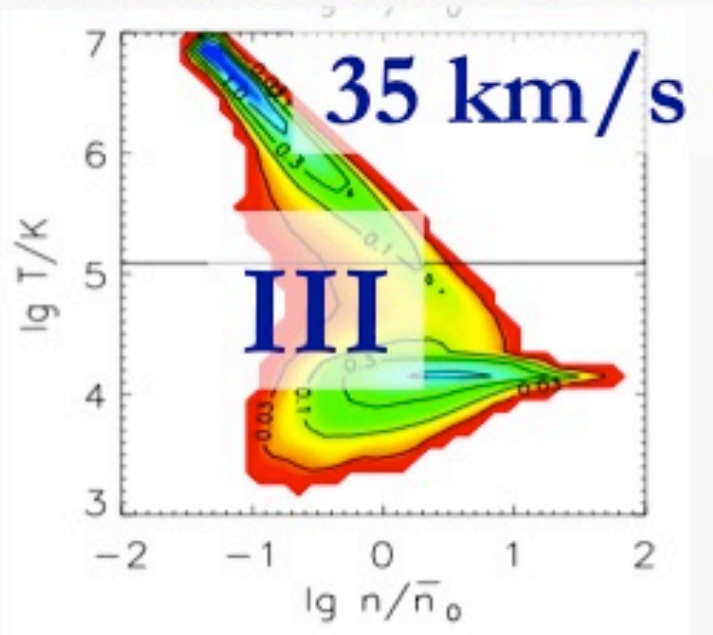


ES, W. Gray, L. Pan(2012)

Conclusions







IV
Thanks!