Cold Gas in Galaxy Outflows

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with

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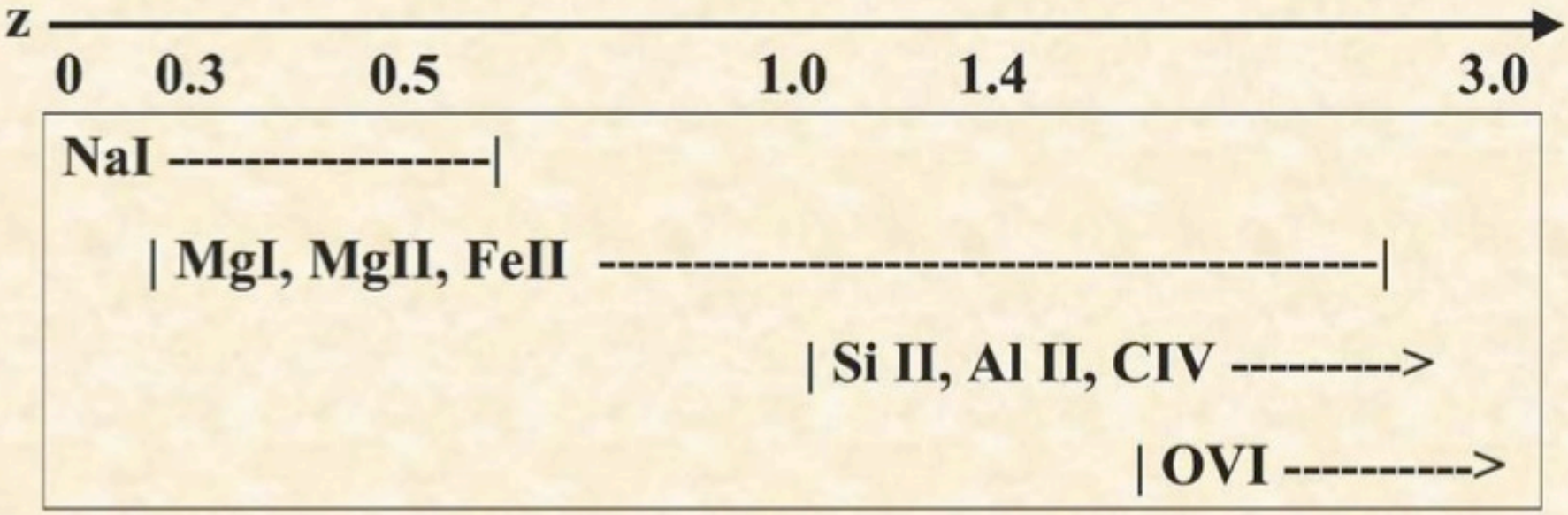
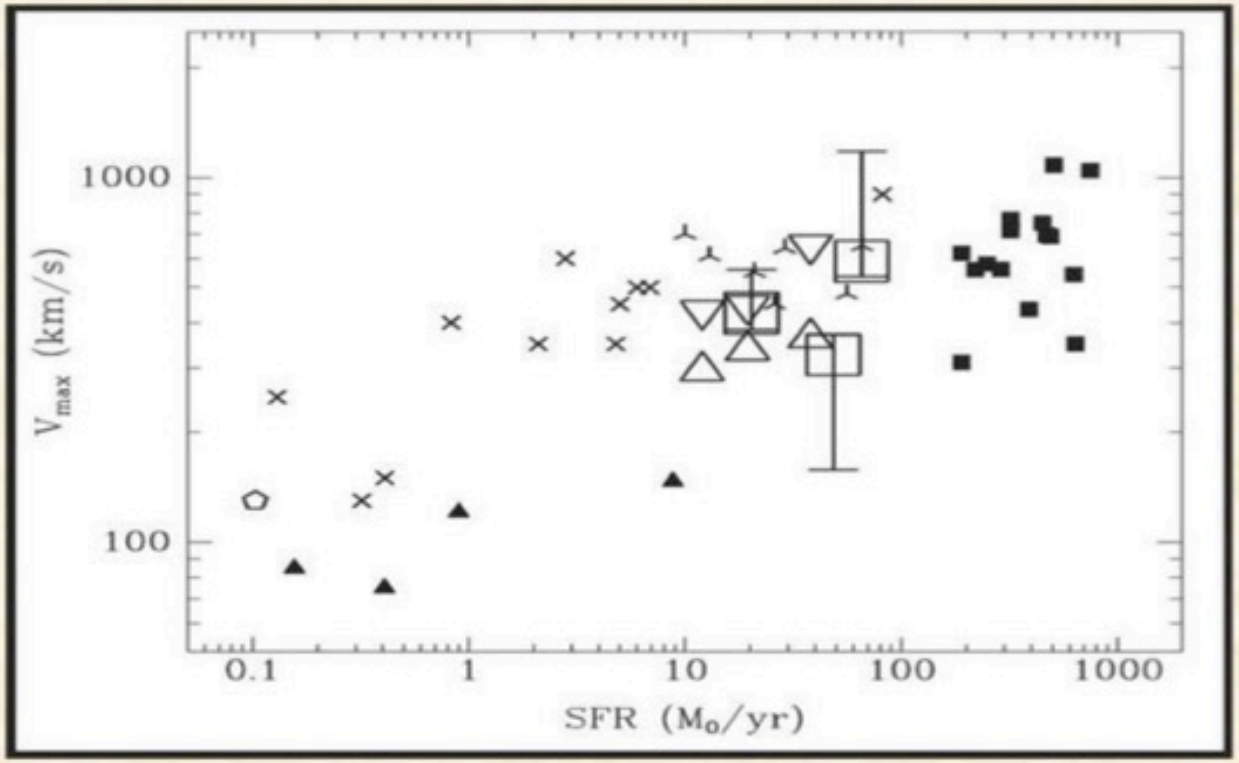
M82

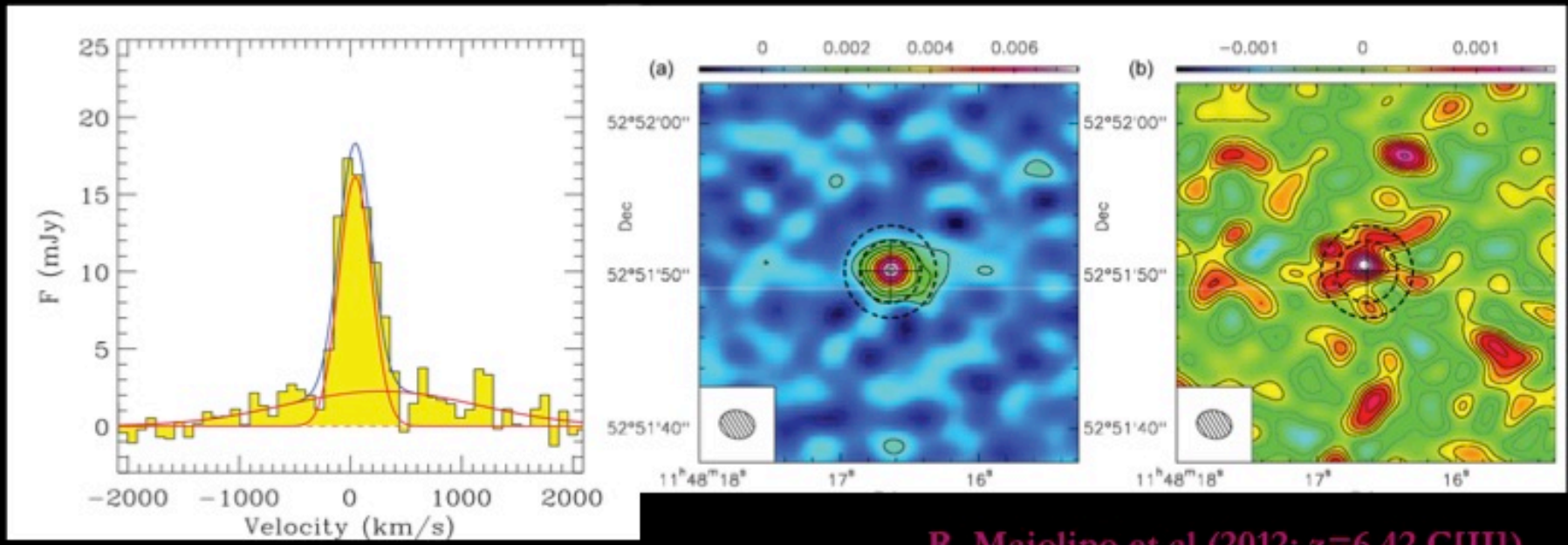
Lines Accessible through the Atmosphere



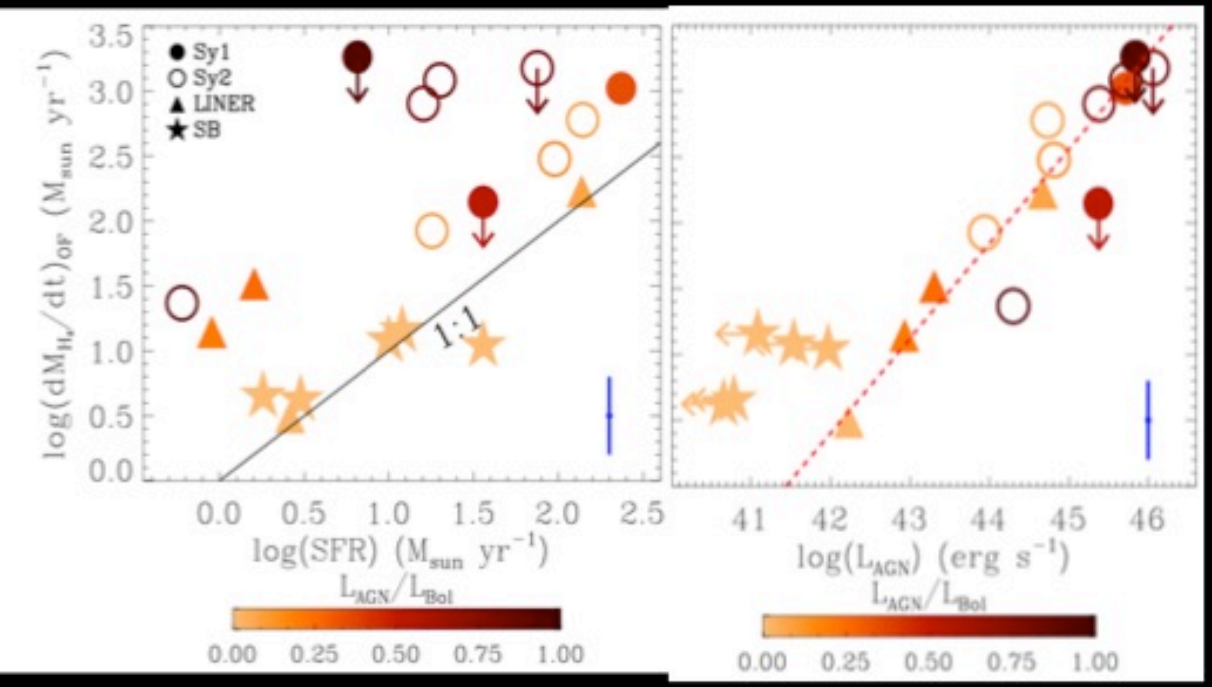


Martin (2005)

CO and CII observations

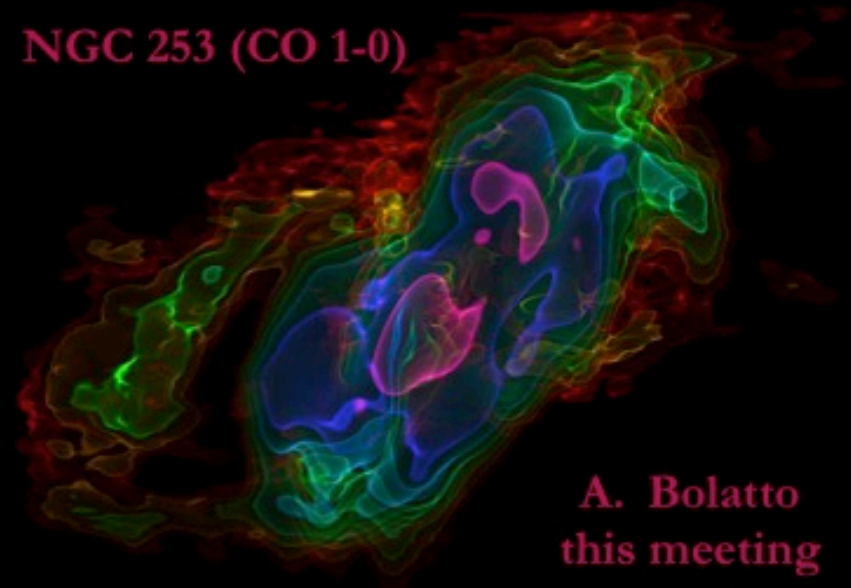


R. Maiolino et al (2012; z=6.42 C[II])

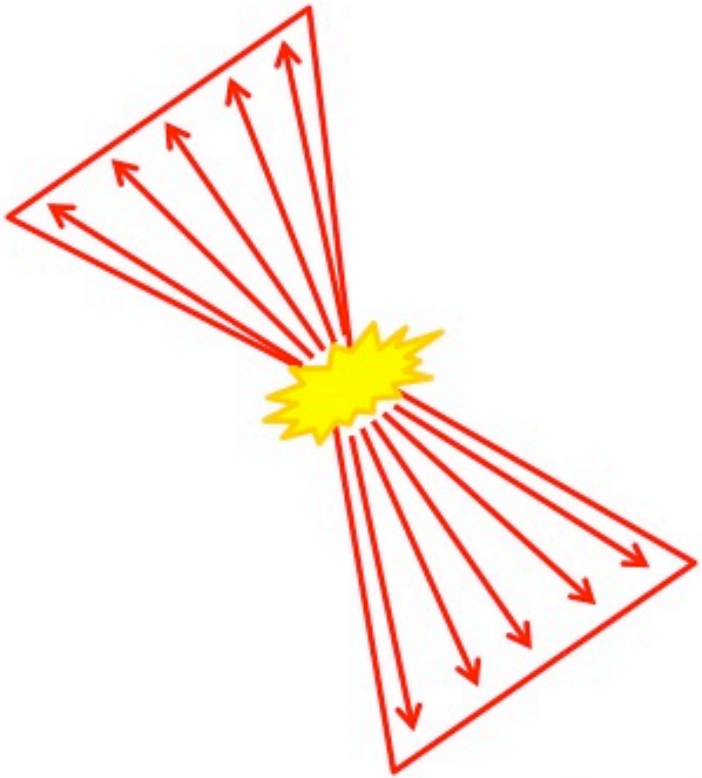


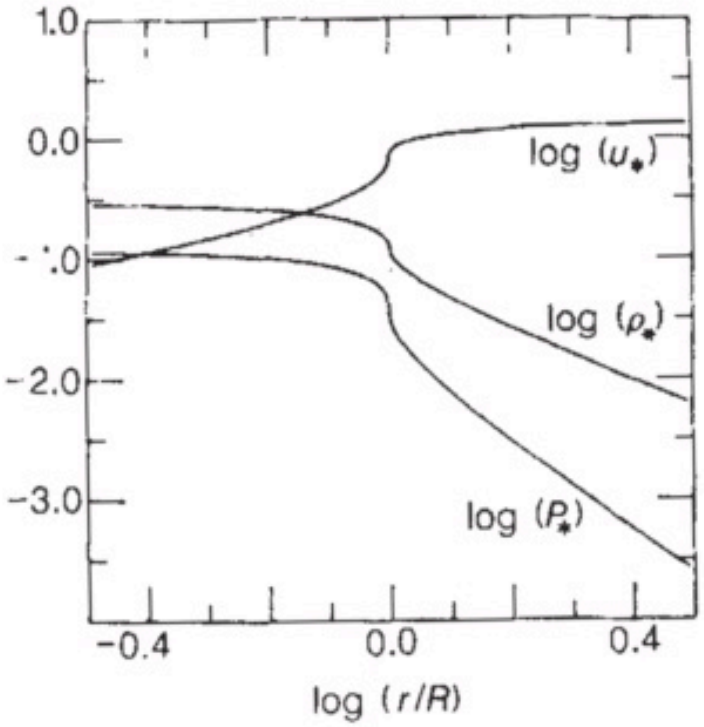
C. Cicone et al (2014; CO 1-0)

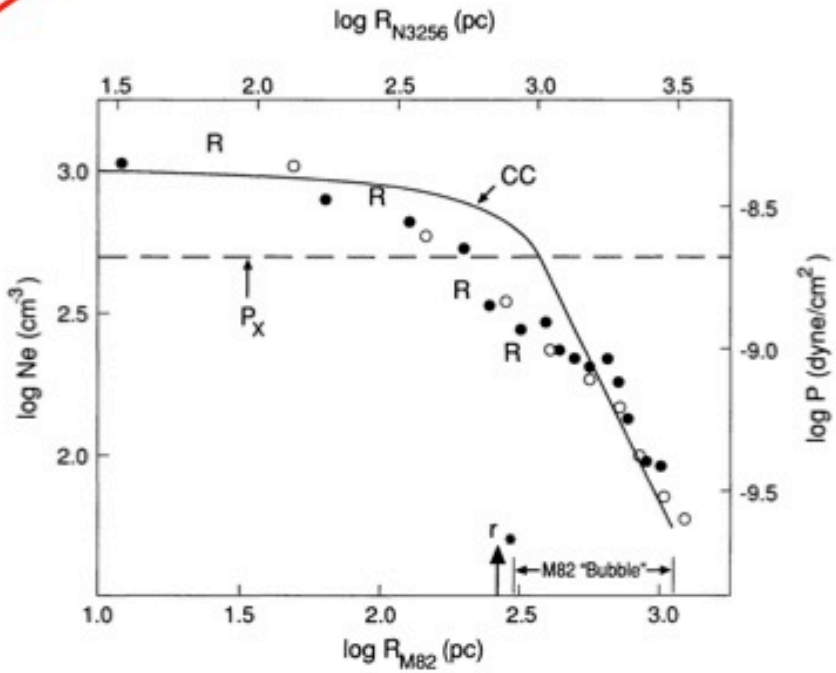
NGC 253 (CO 1-0)



A. Bolatto
this meeting

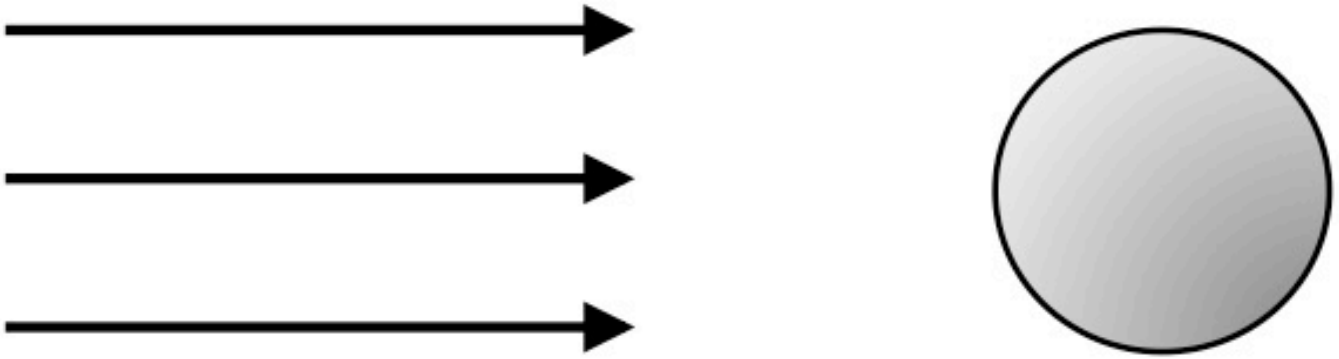






Heckman et al (1990) (See also, Heckman et al 1995; Ott et al 2005; Strickland & Heckman 2009; Yukita et al 2012)

Driving of Cold Clouds by a hot Wind



Cooling + Conduction

(Set Aside Radiation Pressure, B-fields)

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0,$$

$$\rho [\partial_t \boldsymbol{u} + (\boldsymbol{u} \cdot \nabla) \boldsymbol{u}] = -\nabla p,$$

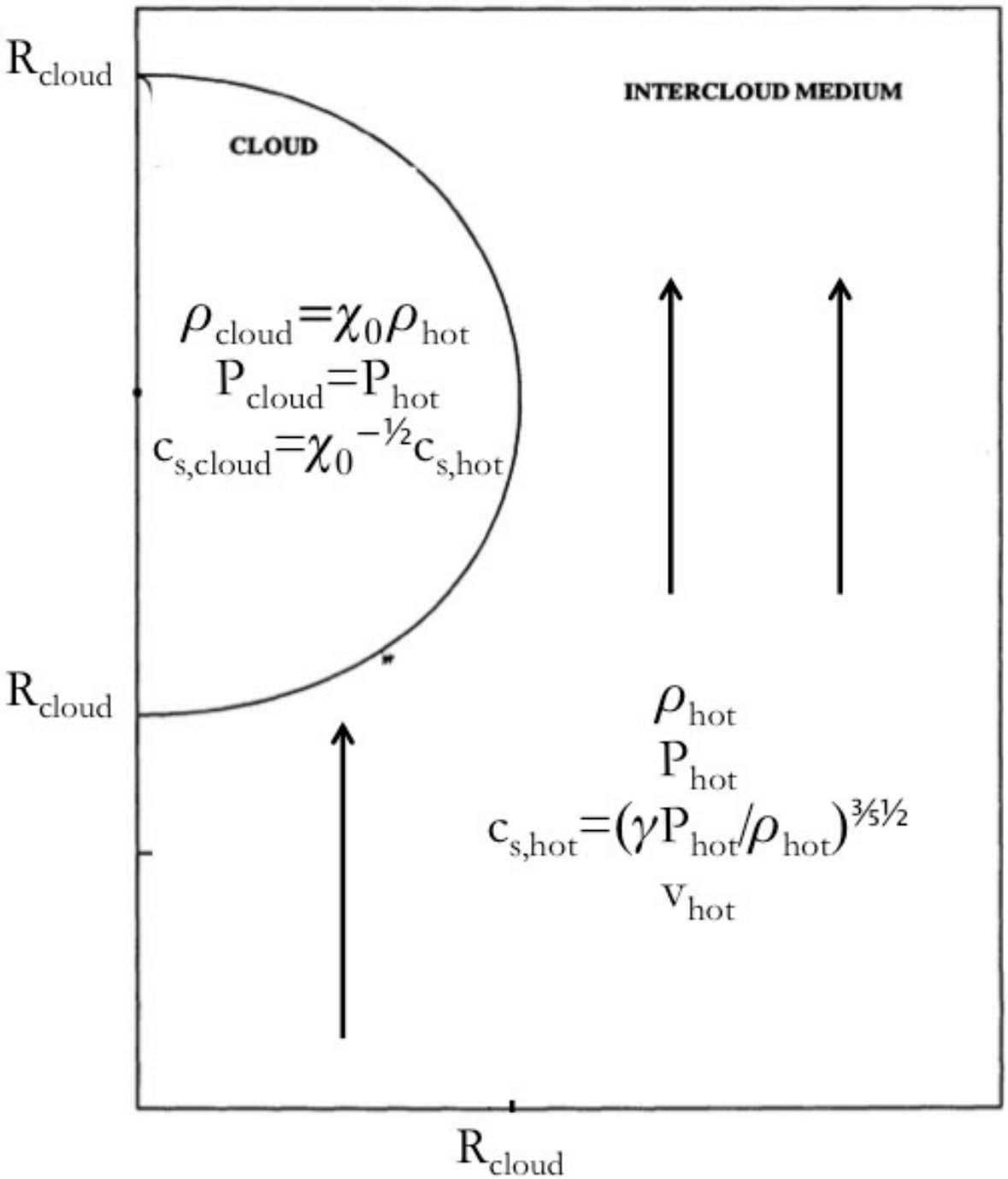
$$\partial_t E + \nabla \cdot [E \boldsymbol{u}] = -\nabla \cdot (p \boldsymbol{u}) - n^2 \Lambda(T) + \nabla \boldsymbol{q},$$

$$\mathbf{q} = \min \begin{cases} \kappa(T) \nabla T & \text{Spitzer} \\ 0.34 n_e k_{\mathrm{B}} T c_{\mathrm{s,e}} & \text{saturated} \end{cases}$$

$$\boldsymbol{x} \longrightarrow \alpha \boldsymbol{x}, \qquad \boldsymbol{t} \longrightarrow \alpha \boldsymbol{t}, \qquad \text{and} \qquad \rho \longrightarrow \rho / \alpha.$$

If we consider lengths in terms of cloud sizes only column density, v, & T matter

Klein, McKee, & Colella (1994)



$$t_{cc} \equiv \frac{\chi_0^{1/2} R_{\rm cloud}}{v_{\rm hot}}$$

Three time scales

1. cloud-crushing time $$t_{\rm cc} = \frac{\chi_0^{1/2} R_{\rm c}}{v_{\rm hot}}$$

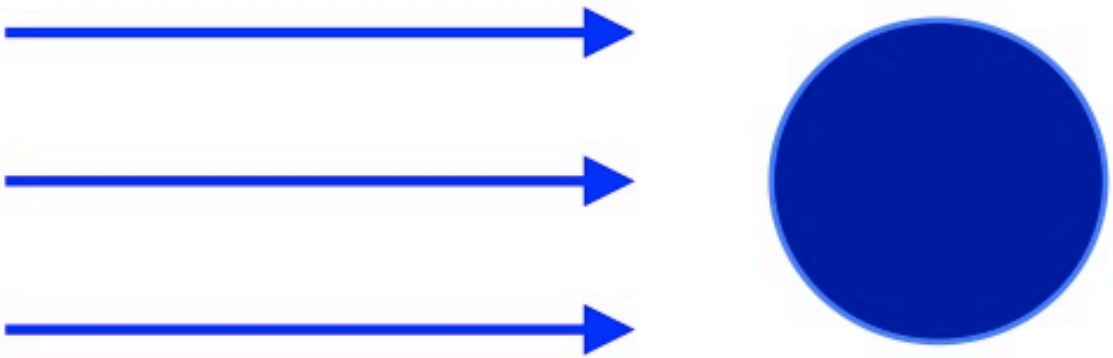
2. cooling time $$t_{\rm cool} \equiv [3/2 n_{\rm c} k_{\rm B} T_{\rm ps} / (\Lambda(T_{\rm ps}) n_{\rm e,c} n_{\rm i,c})]$$

3. Kelvin-Helmholtz time

$$t_{\rm KH} \approx 5(R_{\rm c}/v_{\rm h})[1 + 4(\gamma - 1) M_{\rm c}^2]^{1/2}$$

Velocity Evolution

$$v_{\rm cloud}(t) = t \, \frac{\pi {R_{\rm cloud}}^2 {v_{\rm hot}}^2}{\frac{4\pi}{3} {R_{\rm cloud}}^3 \chi_0}$$



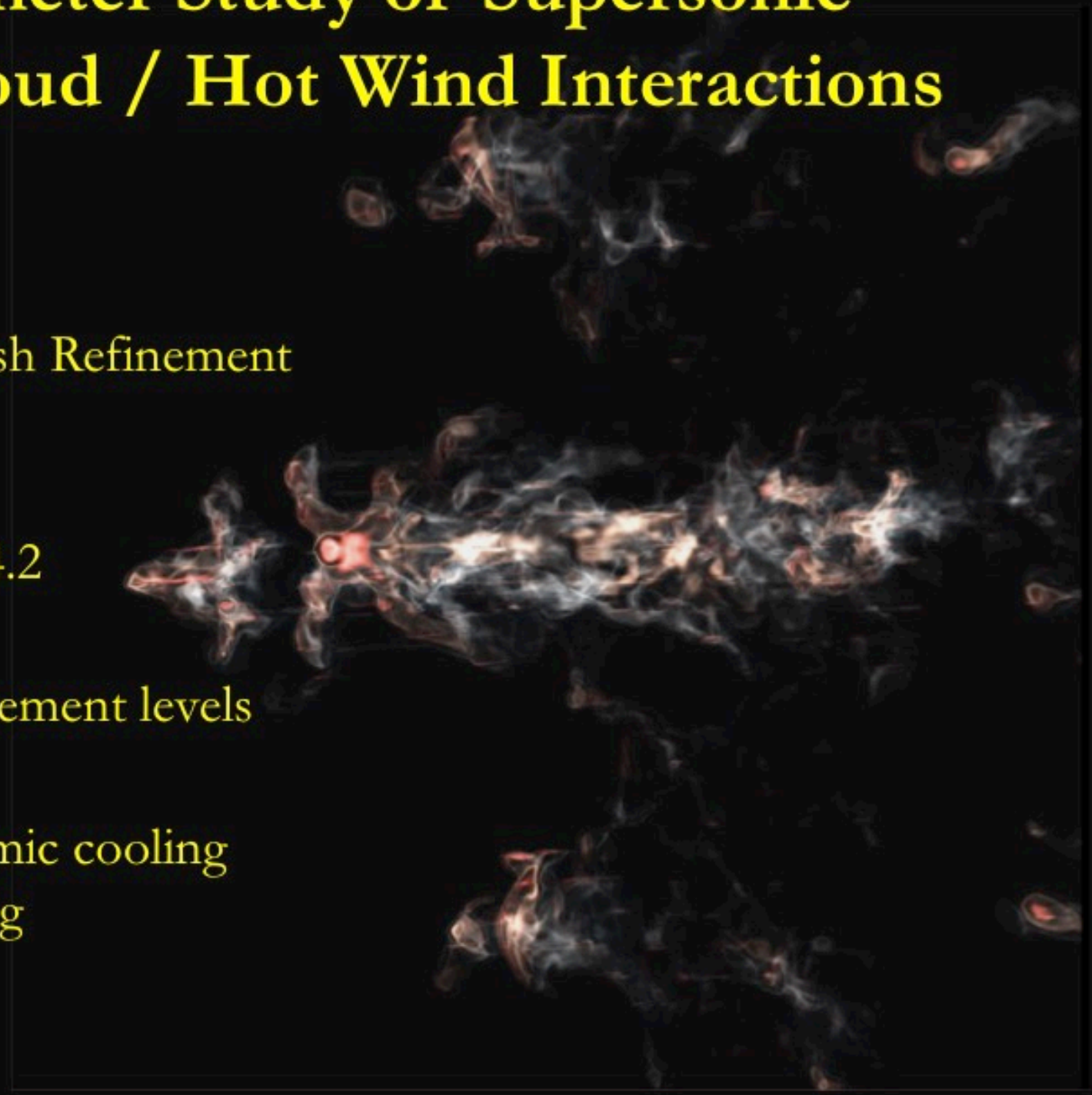
$$= t/t_{\rm cc} \, \frac{3 v_{\rm hot}}{4 \chi_0^{1/2}}$$

Cold clouds should always be shredded before acceleration.

What about supersonic case?

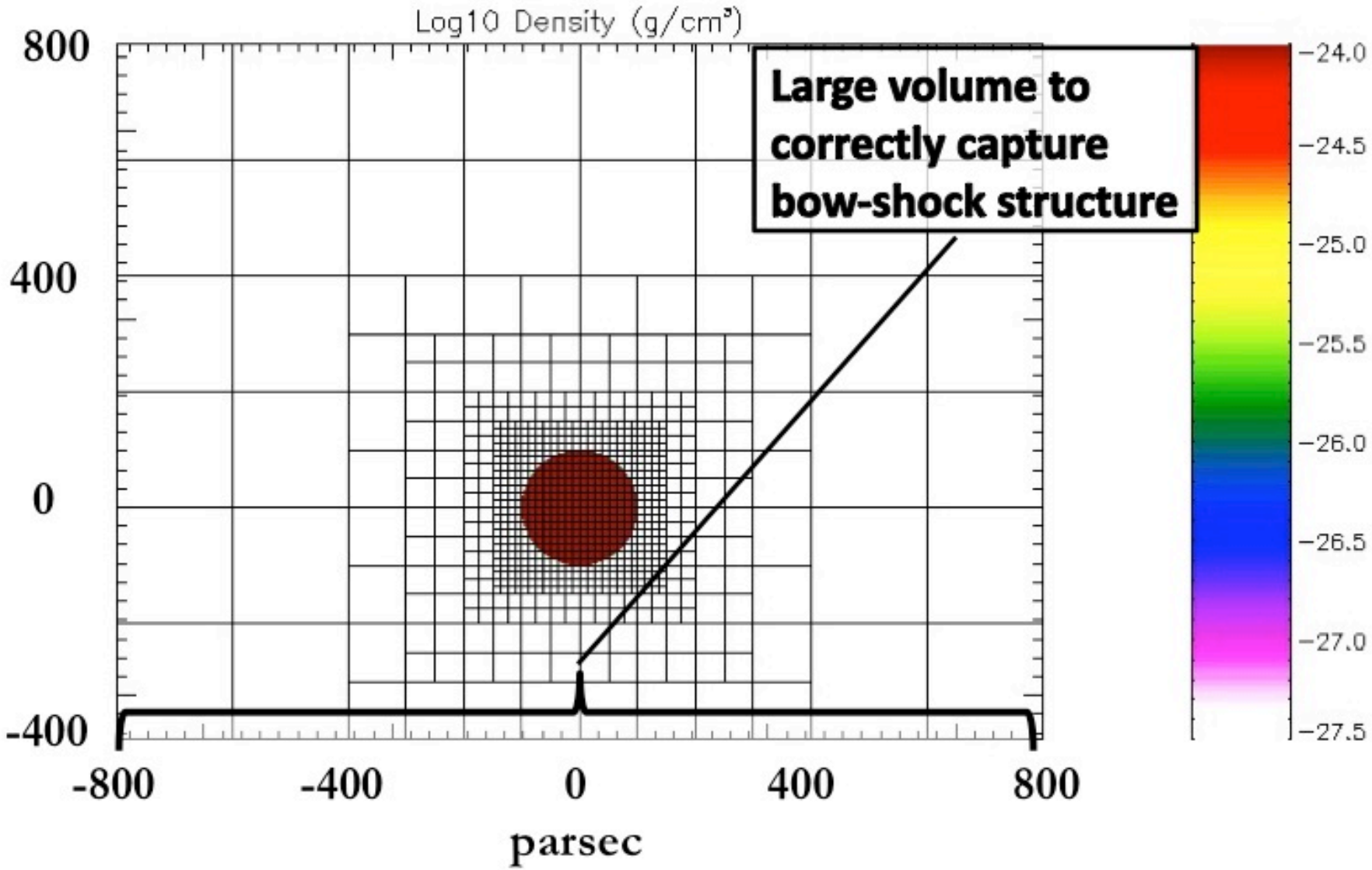
ES & M. Bruggen (2015)

Parameter Study of Supersonic Cold Cloud / Hot Wind Interactions



- 3D Adaptive Mesh Refinement Simulations
- FLASH Code, v4.2
- 4 additional refinement levels
- Equillibrium atomic cooling with subcyling

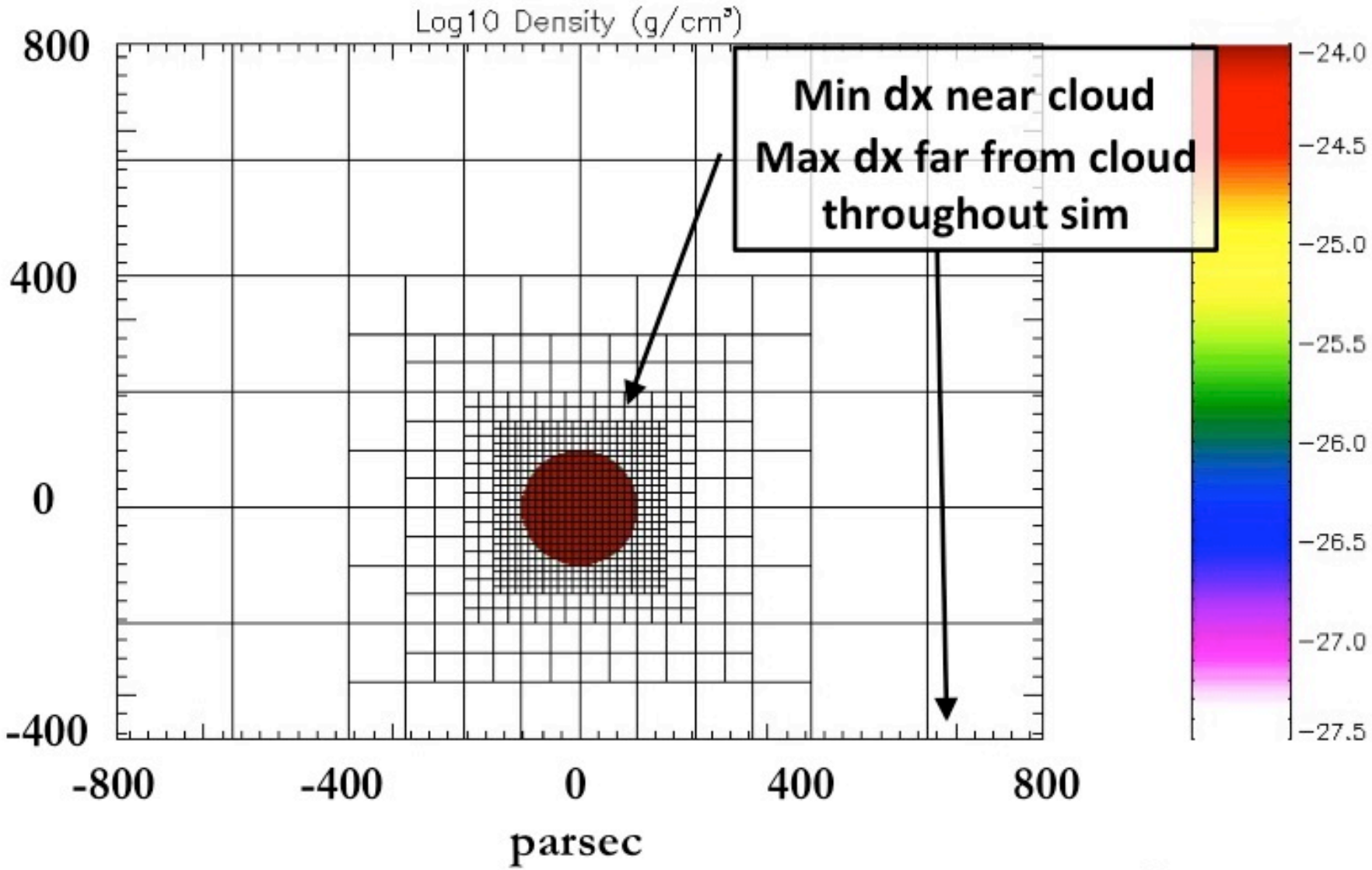
Simulation Setup



R_{cloud}=100 pc, V=16R_{cloud}×16R_{cloud}×12R_{cloud}

ES & M. Bruggen (2015)

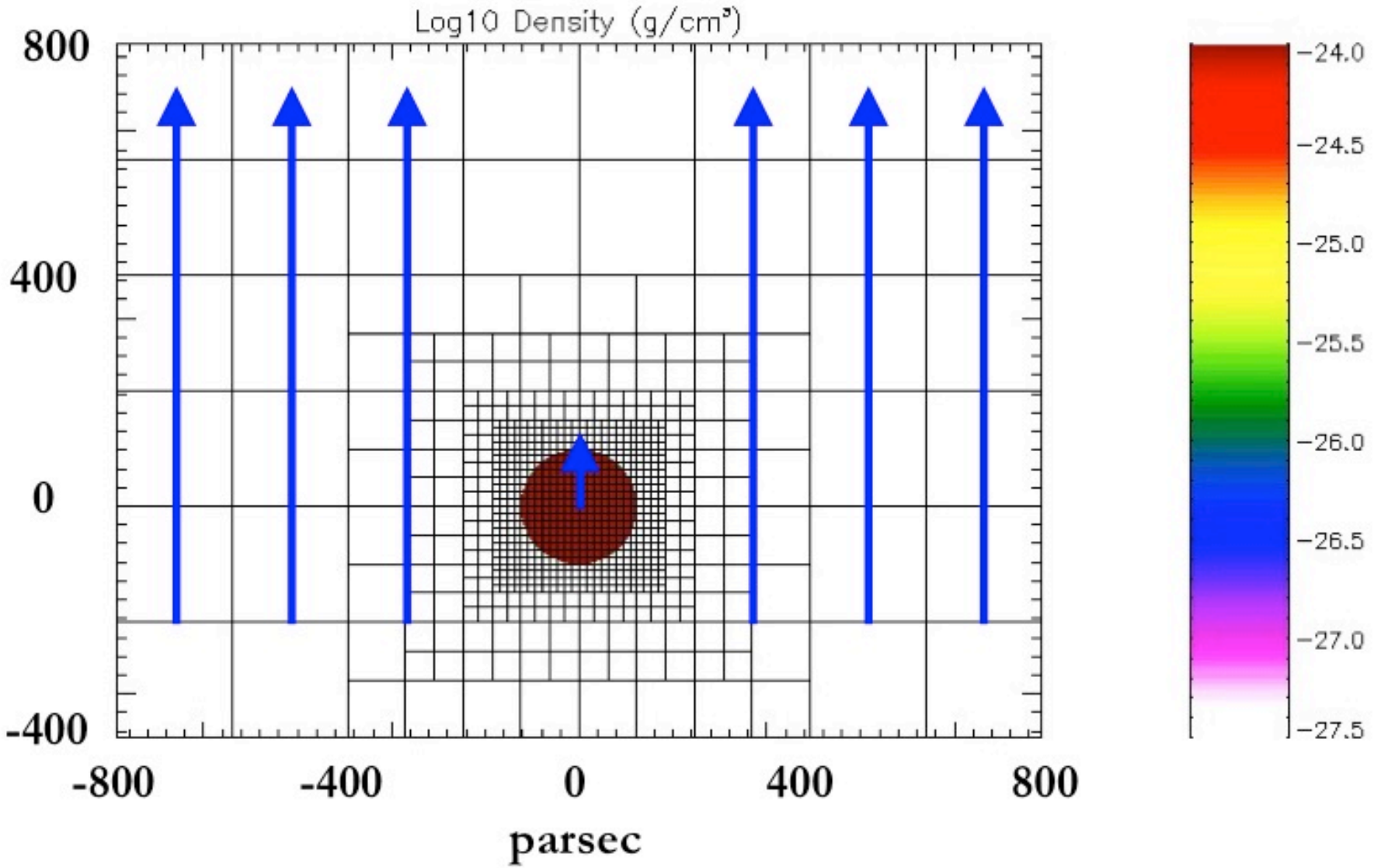
Simulation Setup



R_{cloud}=100 pc, $dx_{min}=R_{cloud}/64$

ES & M. Bruggen (2015)

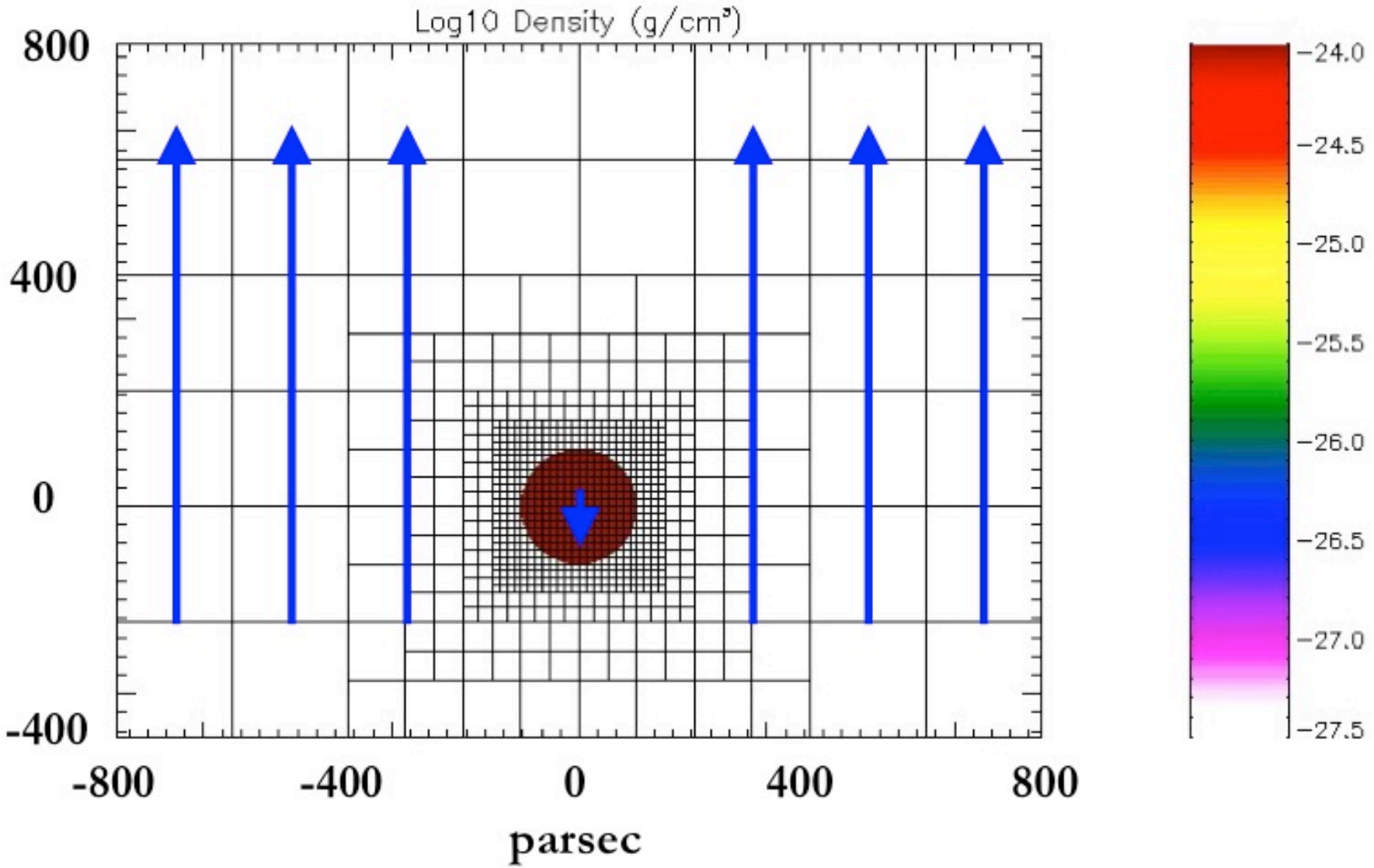
Simulation Setup



Frame change once per t_{cc}

ES & M. Bruggen (2015)

Simulation Setup



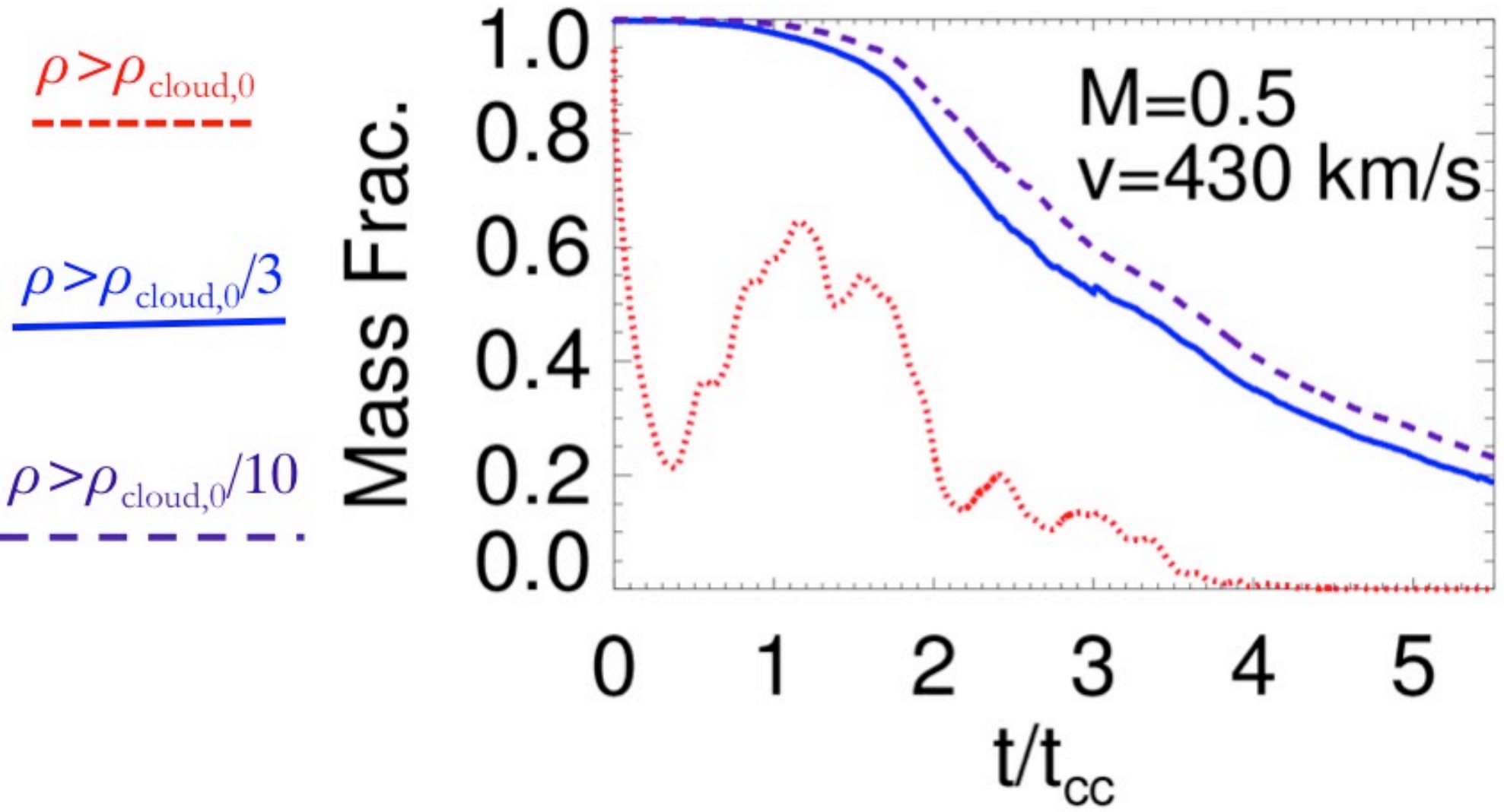
Frame change once per t_{cc}

ES & M. Bruggen (2015)

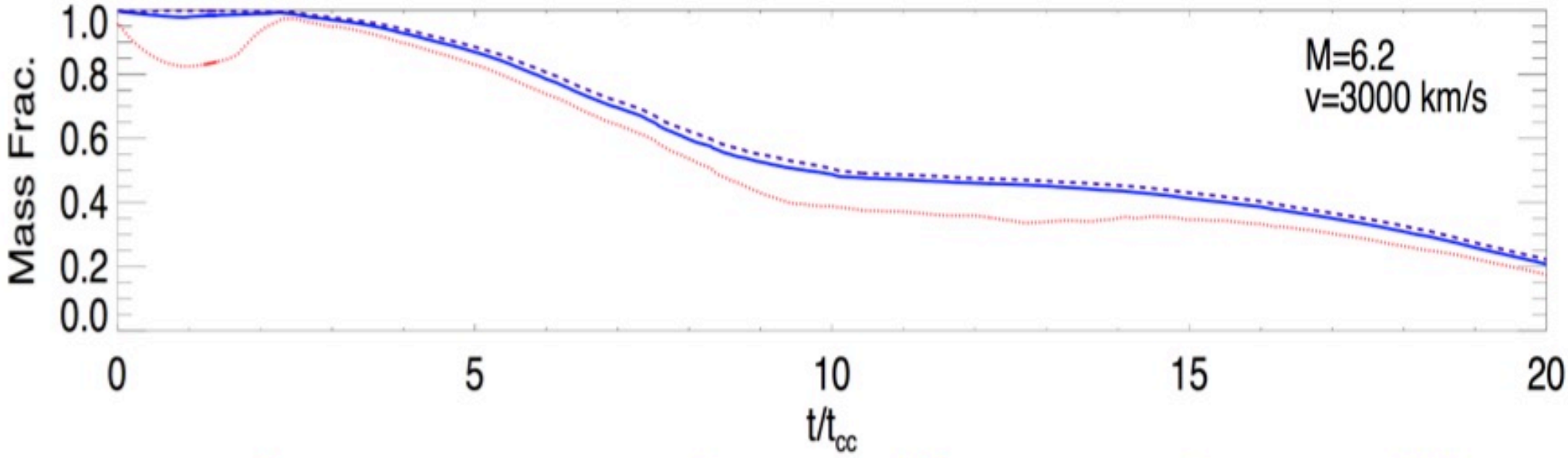
Simulation Parameters

Name	$M_{\rm hot}$	$r/R_\star$	n/n_0	ϵ/β	$v_{\rm hot}$ km s^{-1}	$T_{\rm hot}$ 10^6 K	χ_0	$M_{\rm cloud}$	$t_{\rm cc}$ Myr/100pc
M0.5v430	0.5	0.9	0.8	0.2	430	30	3000	28	12.5
M1v480	1.0	1.0	0.4	0.1	480	10	1000	32	6.4
M1v860	1.0	1.0	0.4	0.3	860	30	3000	57	6.2
M1v1500	1.0	1.0	0.4	0.9	1500	100	10000	100	6.5
M3.8v1000	3.8	1.1	0.2	0.1	1000	3	300	66	1.7
M3.5v1700	3.5	1.1	0.2	0.4	1700	10	1000	110	1.8
M3.6v3000	3.6	1.1	0.2	1.1	3000	30	3000	200	1.8
M6.5v1700	6.5	1.9	0.05	0.3	1700	3	300	110	1.0
M6.2v3000	6.2	1.9	0.05	1.0	3000	10	1000	200	1.0
M11.4v3000	11.4	2.6	0.03	0.9	3000	3	300	200	0.56

ES & M. Bruggen (2015)



ES & M. Bruggen (2015)

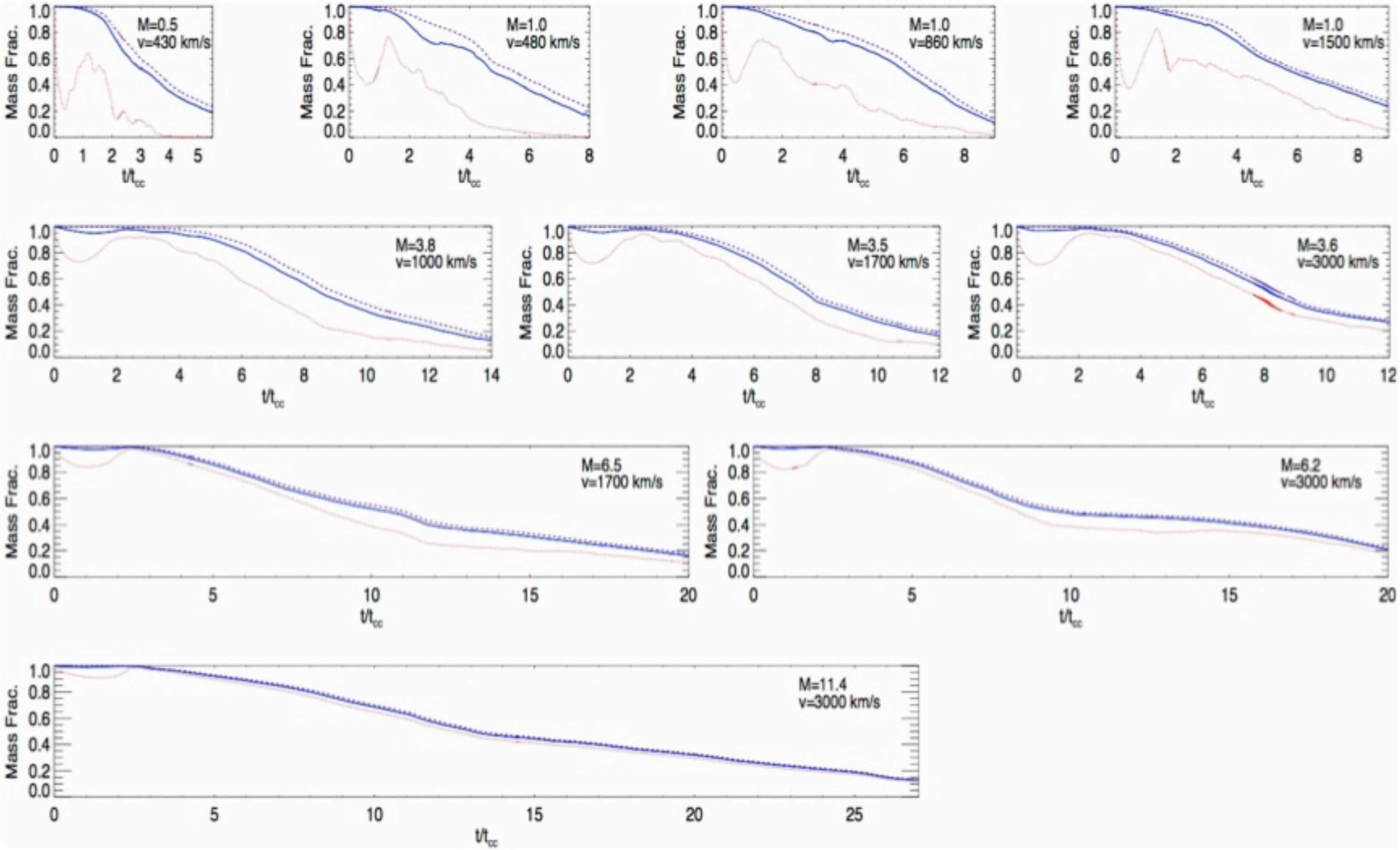


$\rho > \rho_{\mathrm{cloud},0}$

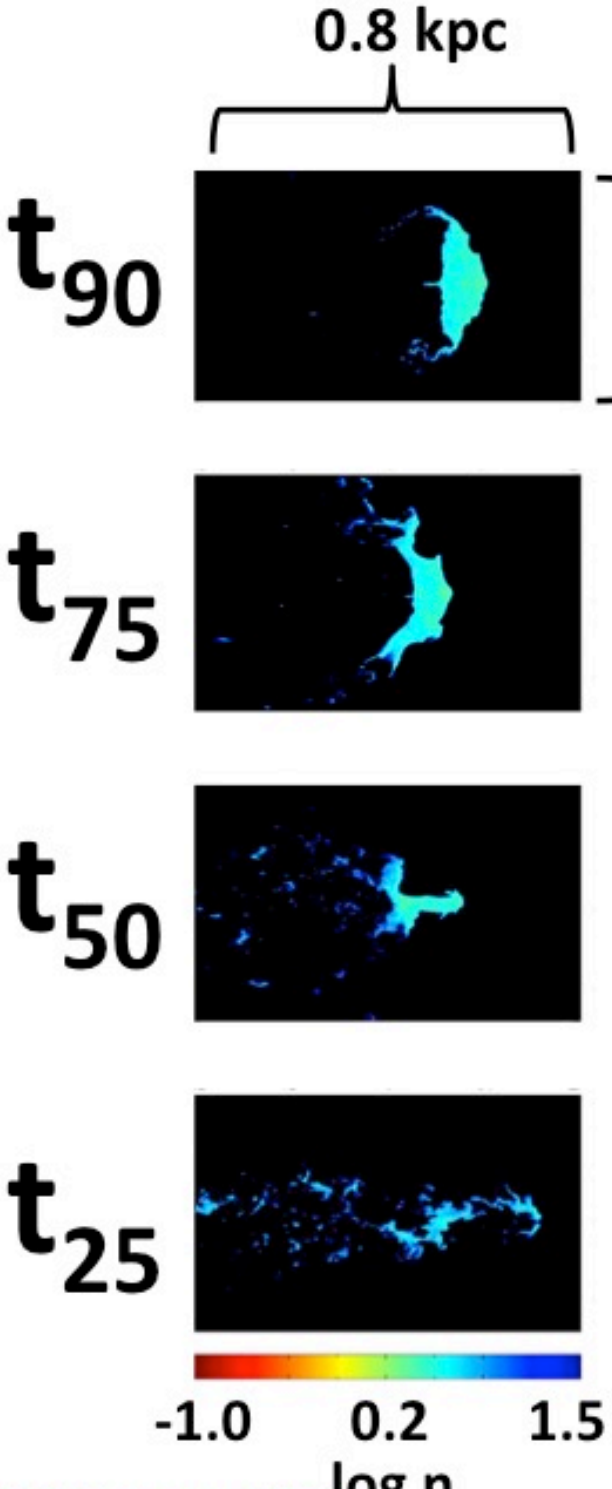
$\rho > \rho_{\mathrm{cloud},0}/3$

$\rho > \rho_{\mathrm{cloud},0}/10$

ES & M. Bruggen (2015)



ES & M. Bruggen (2015)



Log n slices: M=0.5 v=430

90% Mass above $rho_0/3$

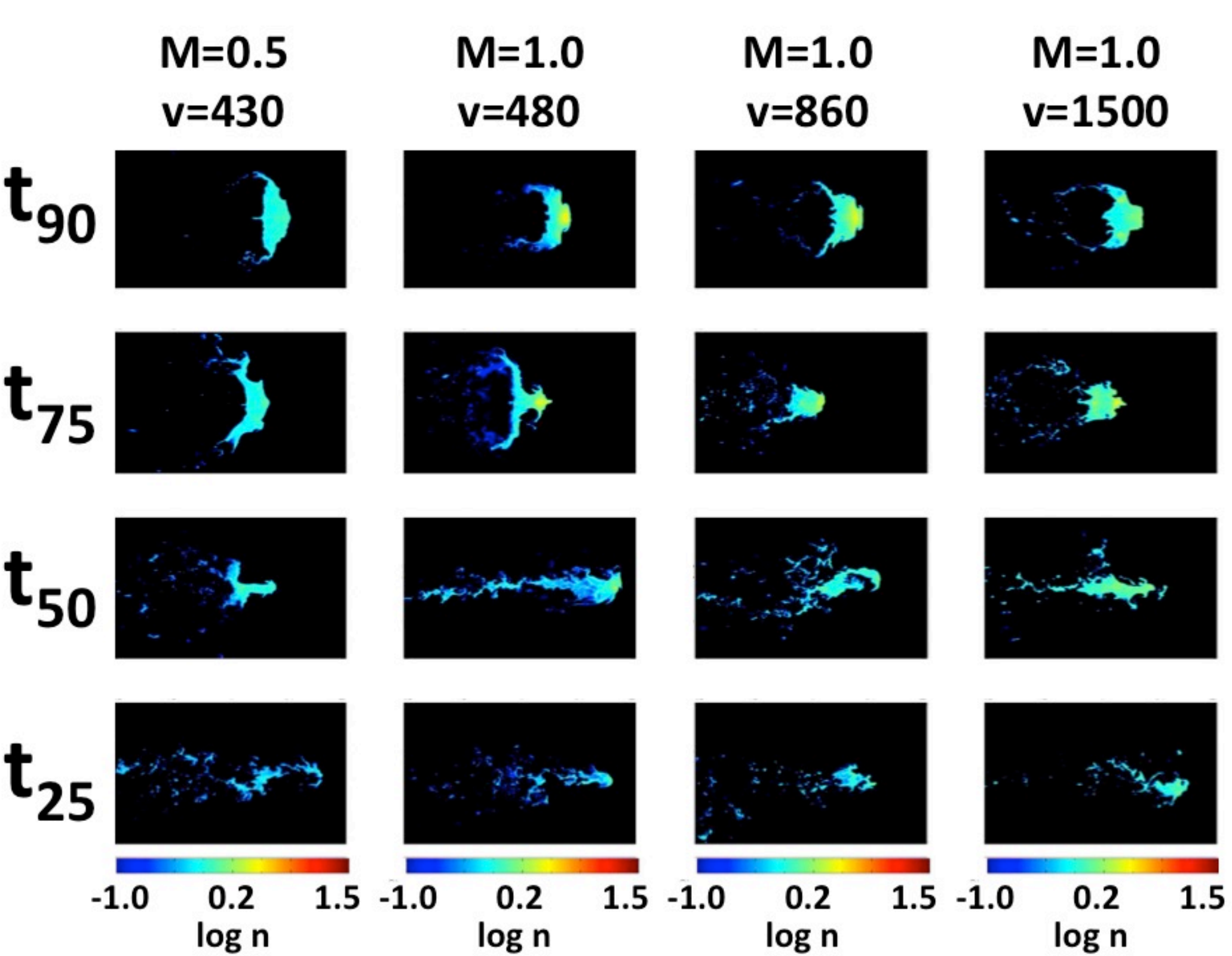
75% Mass above $rho_0/3$

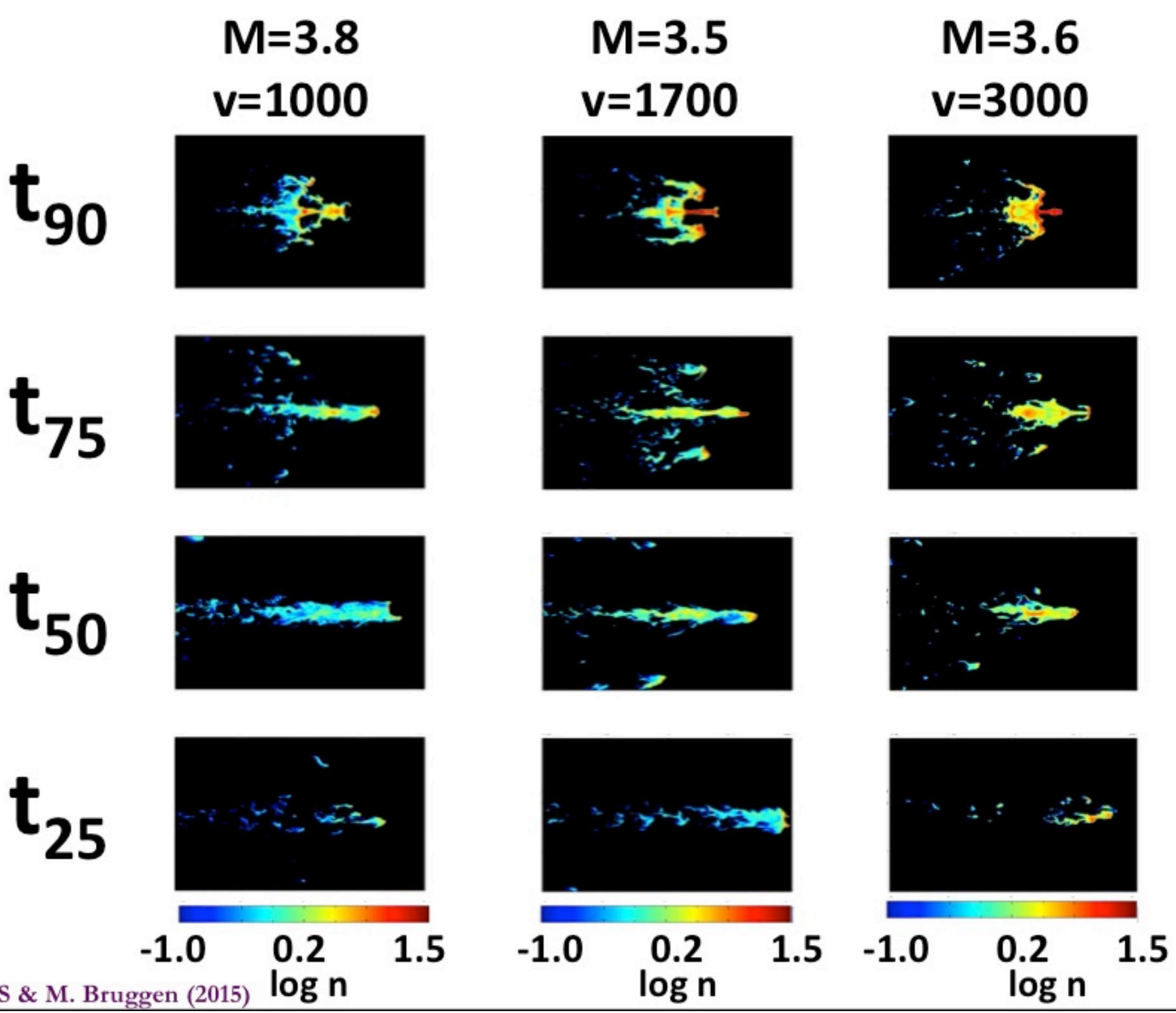
50% Mass above $rho_0/3$

25% Mass above $rho_0/3$

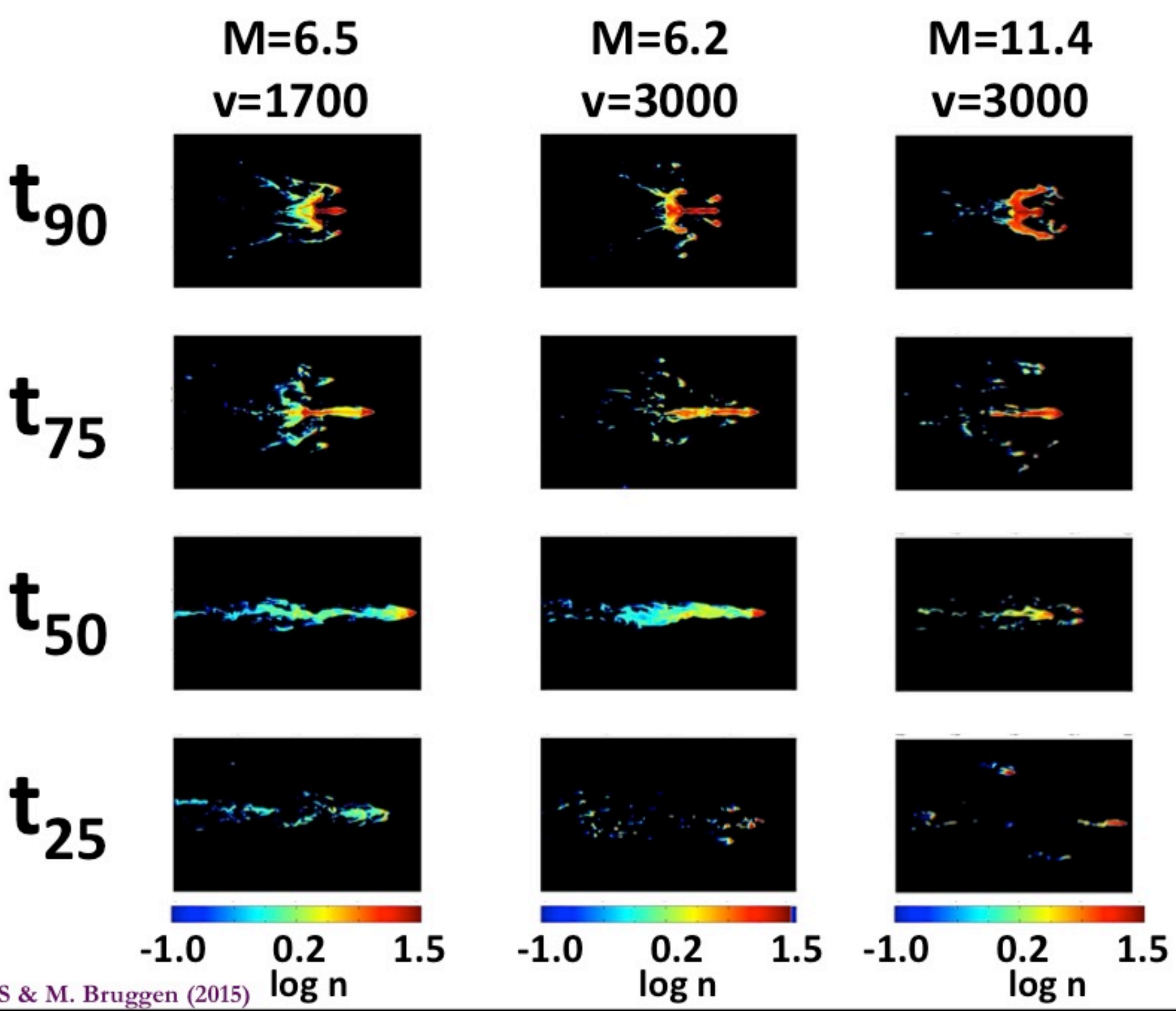
ES & M. Bruggen (2015)

ES & M. Bruggen (2015)


M=0.5
v=430
M=1.0
v=480
M=1.0
v=860
M=1.0
v=1500
t90
t75
t50
t25
-1.0
0.2
1.5
log n
-1.0
0.2
1.5
log n
-1.0
0.2
1.5
log n
-1.0
0.2
1.5
log n

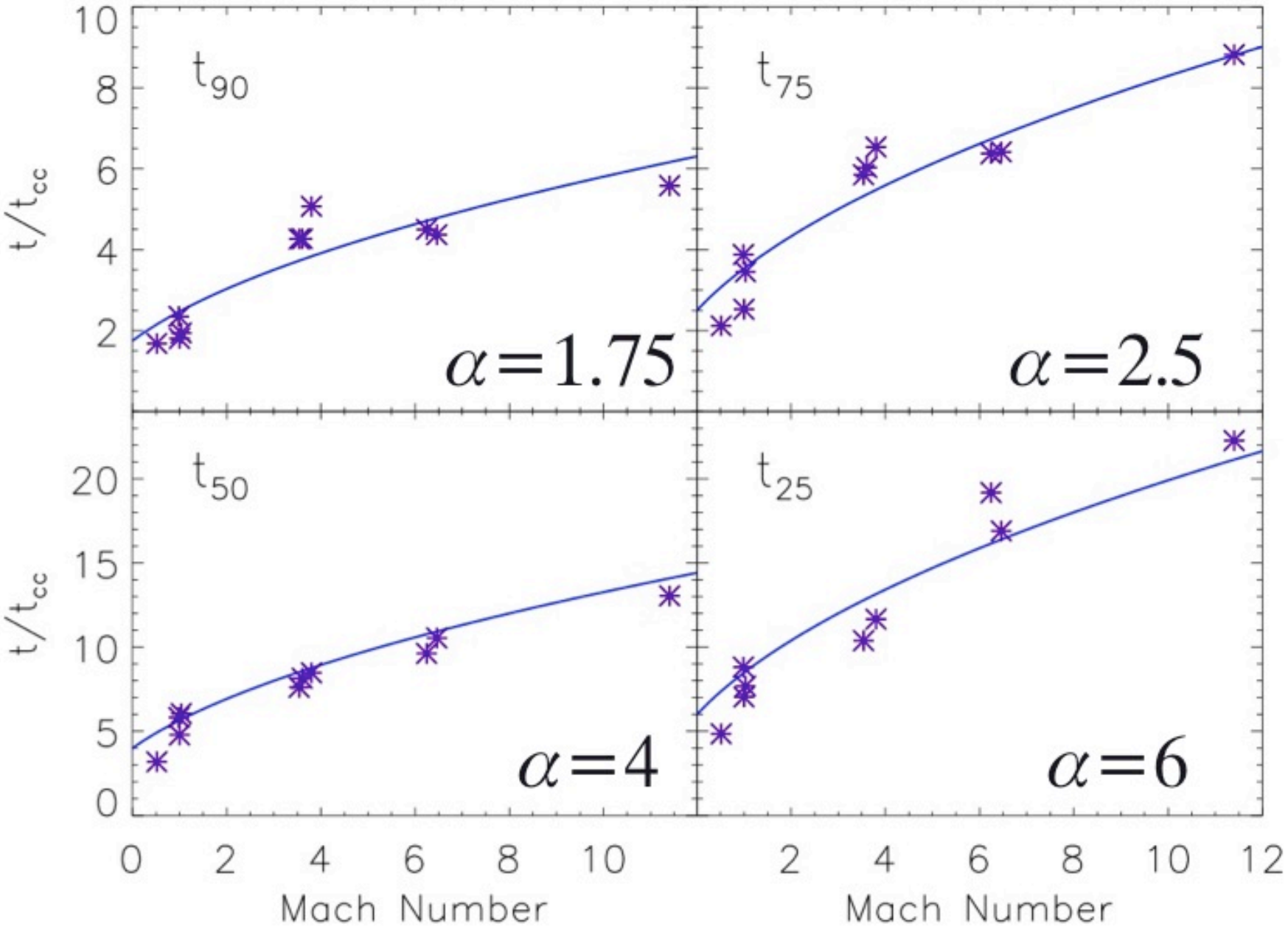


ES & M. Bruggen (2015)



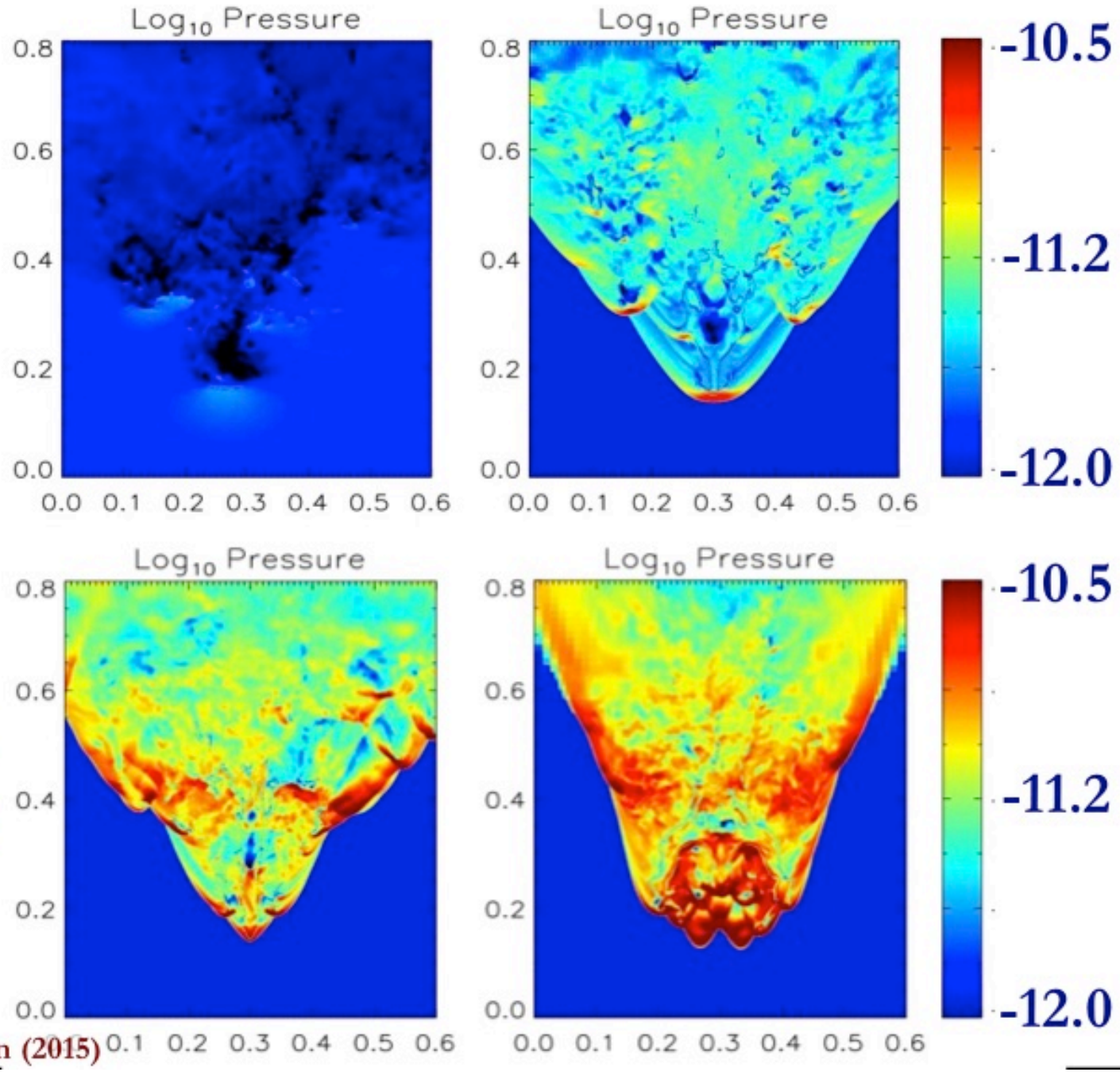
ES & M. Bruggen (2015)

$$t = \alpha t_{cc} \sqrt{1 + M_{hot}}$$

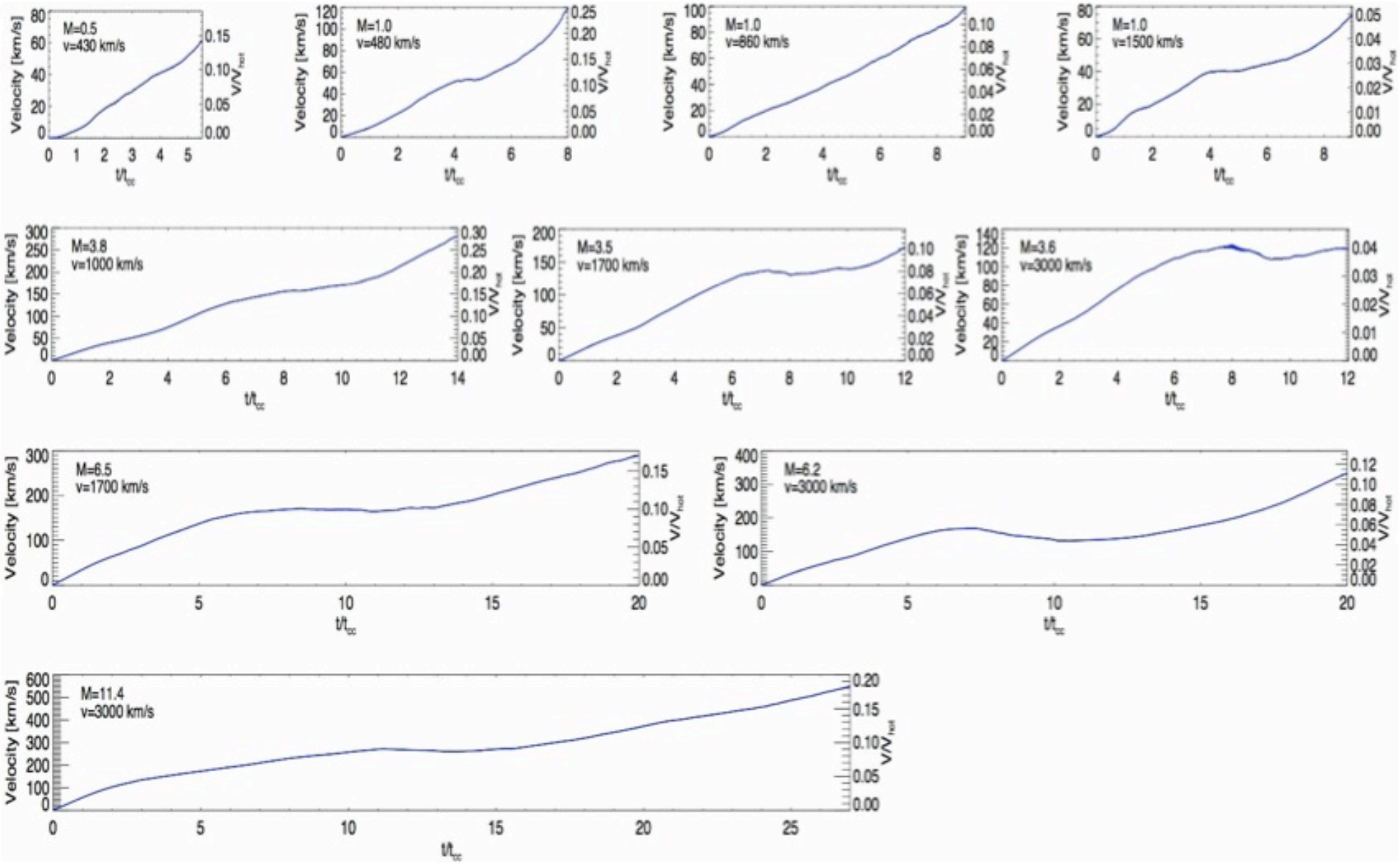


ES & M. Bruggen (2015)

Log Pressure at 6 t_{cc}



ES & M. Bruggen (2015)



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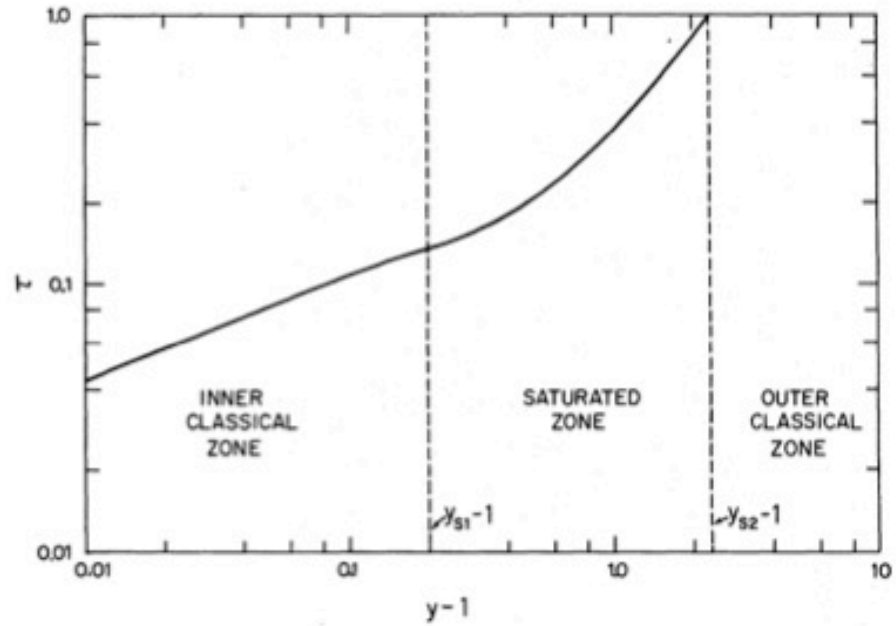
What about thermal conduction?

- Spitzer/saturated conduction
- 4 additional refinement levels
- Equilibrium atomic cooling/subcy

$$n = 1/cm^{-3}$$

M=6E4 Msun



(Cowie & McKee 1976, McKee & Cowie 1977)

(see also Marcolini et al 2005; Orlando et al 2005, 2006, 2008; Recchi & Hensler 2007)

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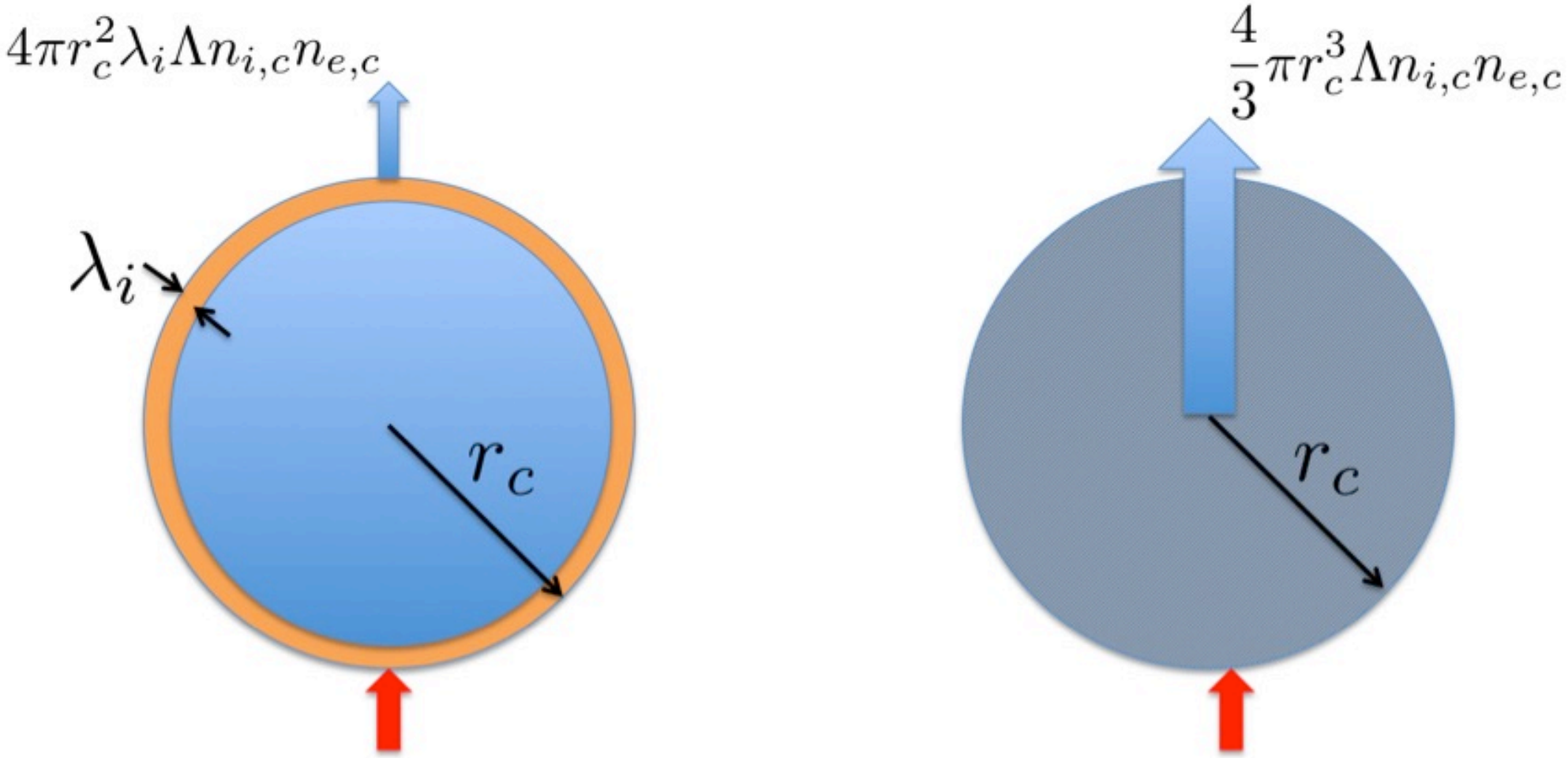
What about thermal conduction?

Large column density

Small column density



$4\pi r_c^2 \cdot 5.5 c_s n_e k T$

$4\pi r_c^2 \cdot 5.5 c_s n_e k T$

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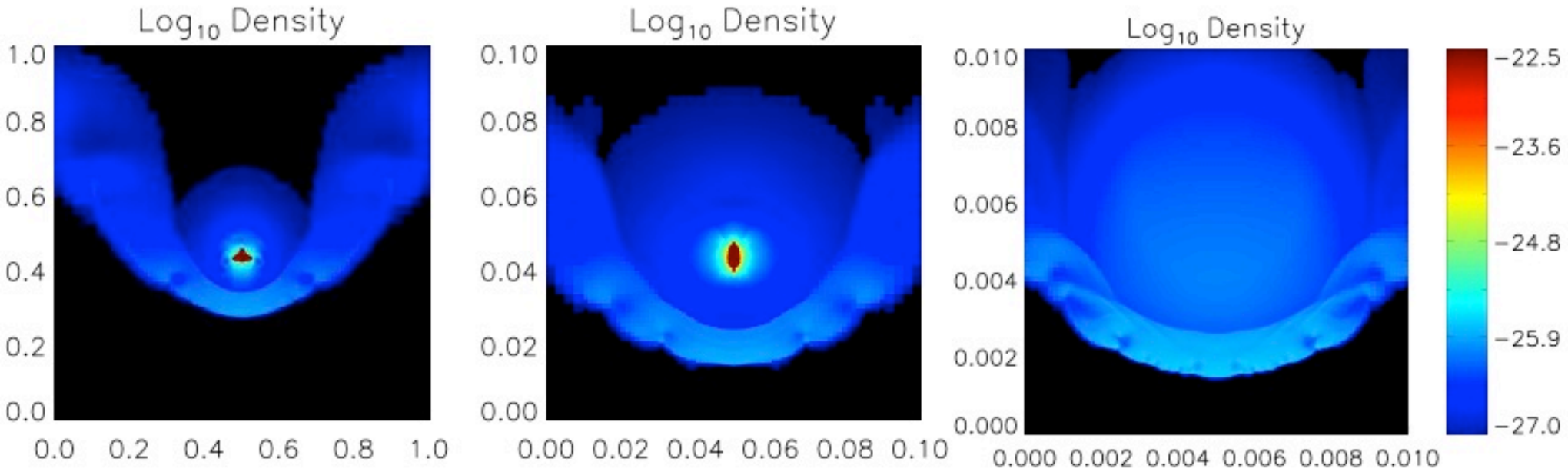
Effect of Column Density



Electron mean free path > cloud radius

$$\lambda_{\rm i} n_{\rm i,c} = 1.3 \times 10^{18} {\rm cm}^{-2} T_7^2$$

If column density is less -> heat deposited over entire cloud

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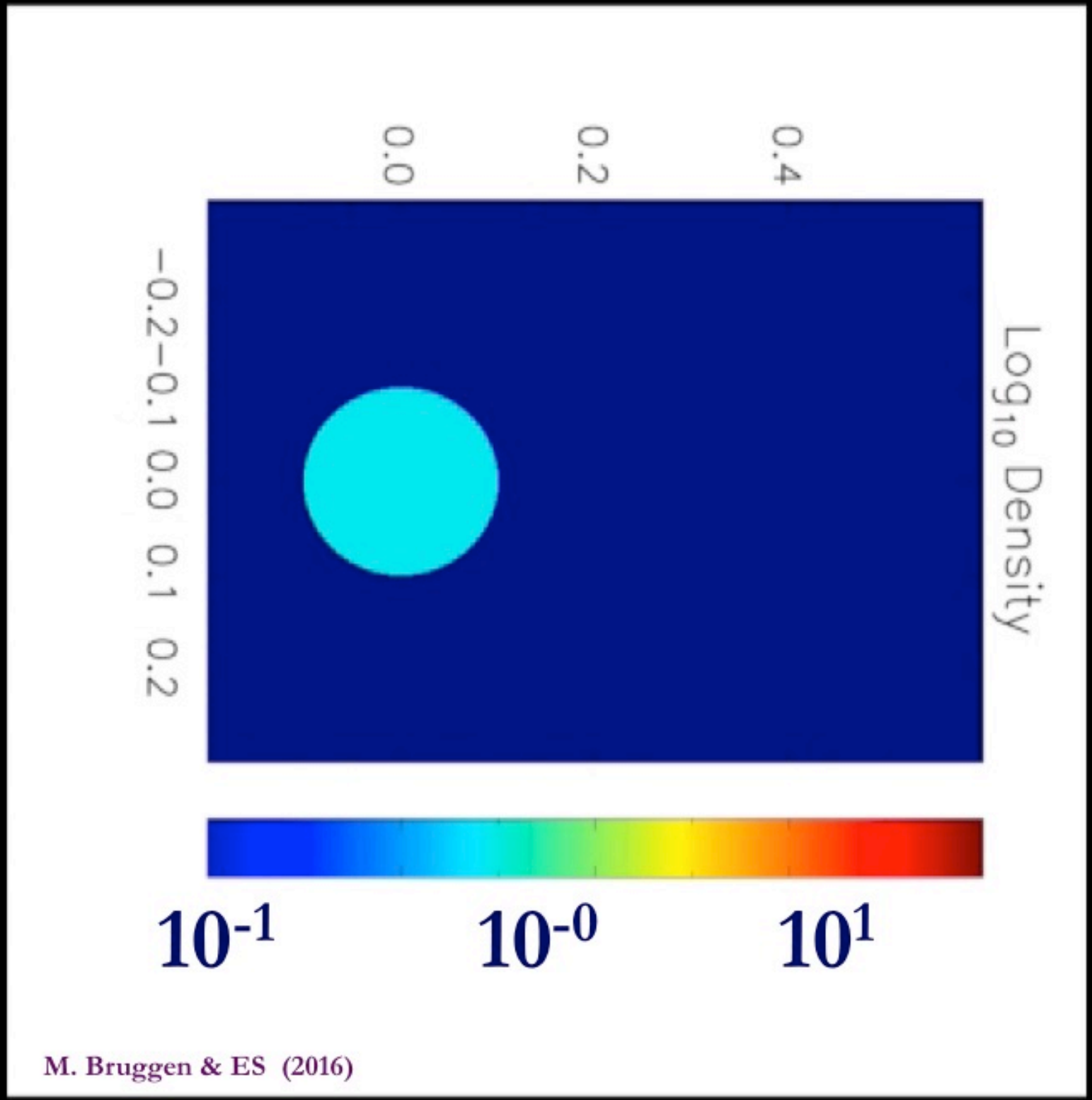
0.0
0.2
0.4
−0.2−0.1 0.0 0.1 0.2
Log10 Density
10-1
10-0
101
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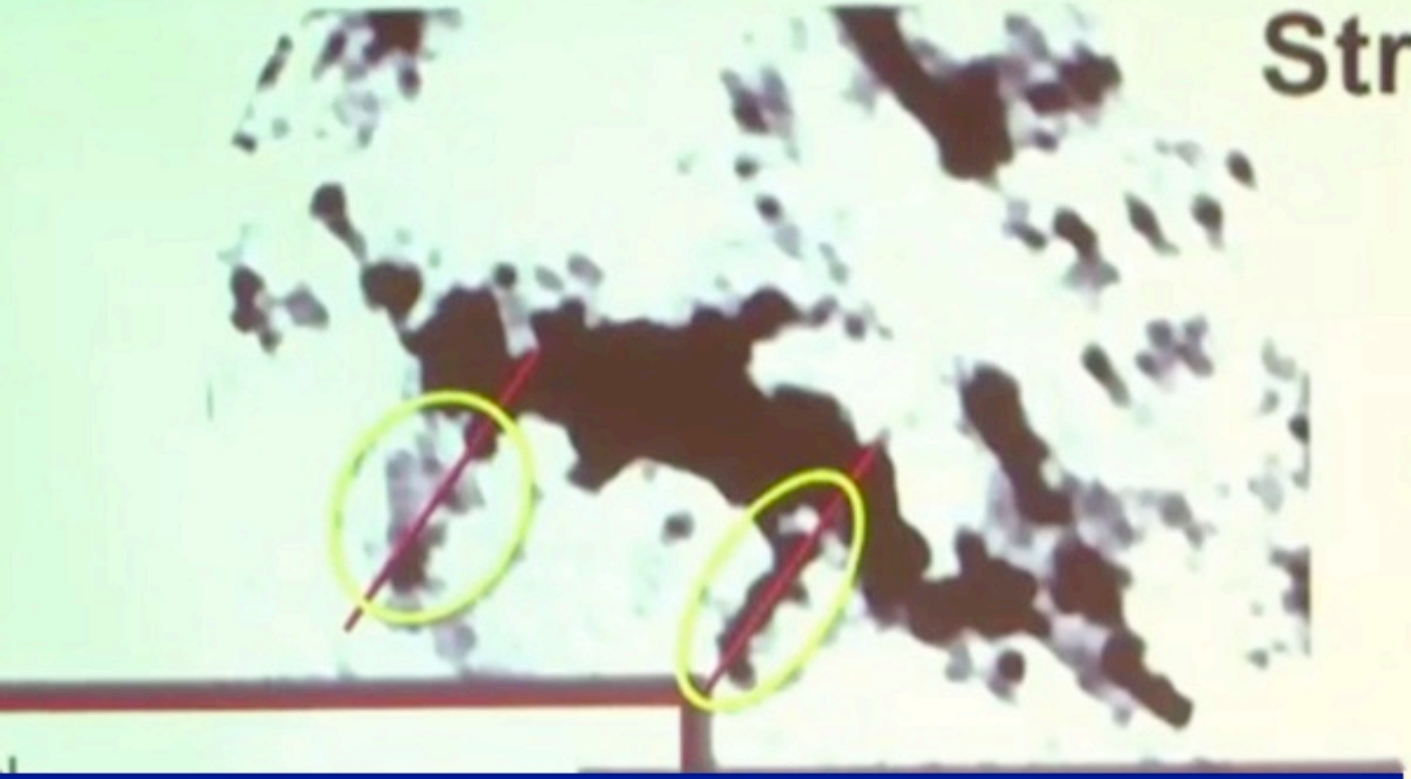
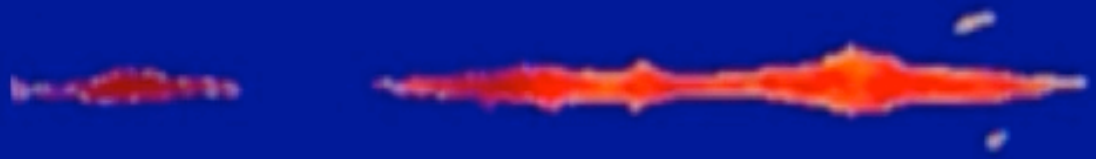
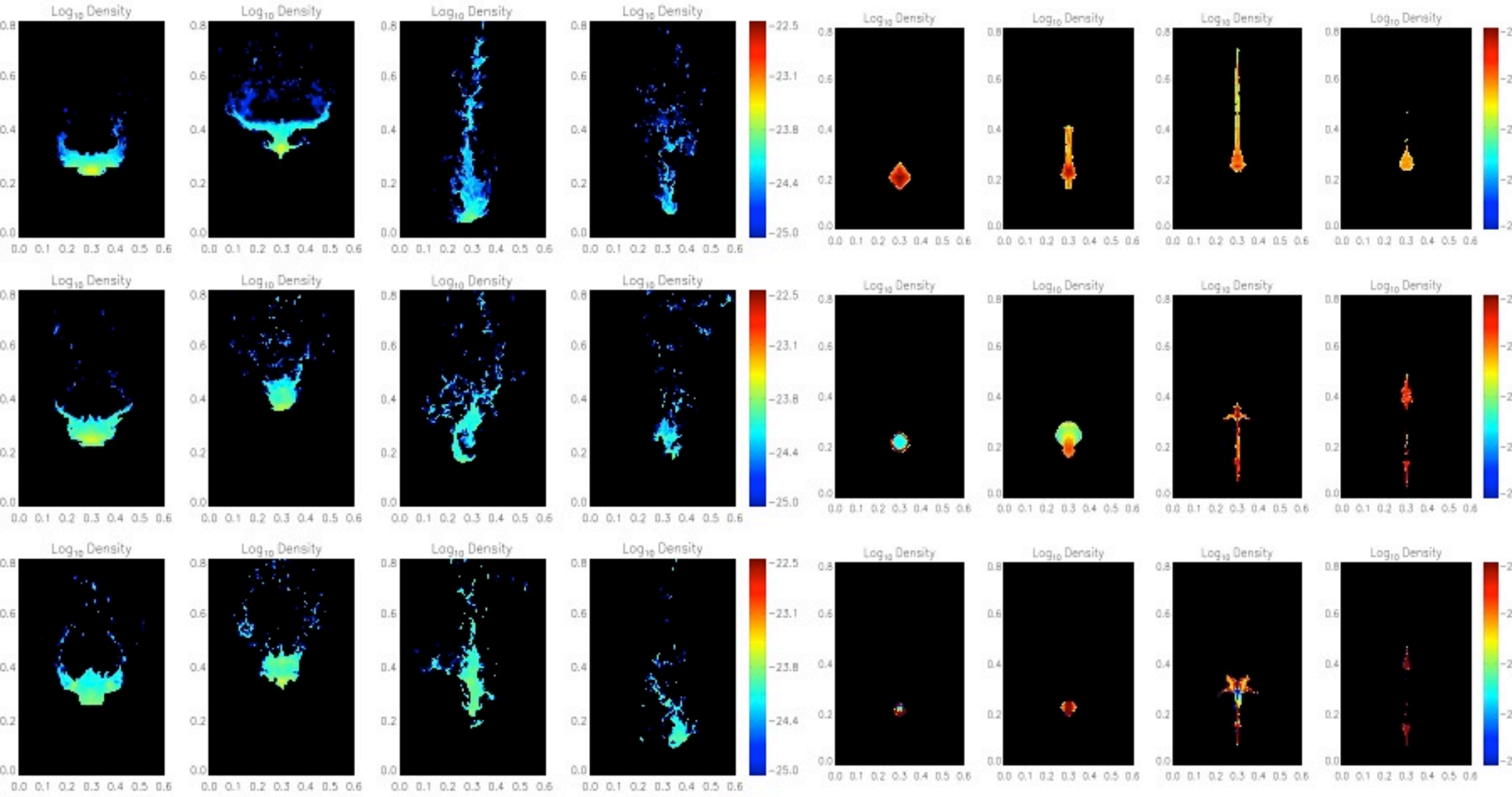
Streamers



- Brightest streamer is barely resolved implying width < 30 pc
- Line width is ΔV~100 km/s implying very turbulent motions
- This is not self-gravitating gas!
- Optically thin mass: 10^6 $M_\odot$
- ~250 pc in length



Comparison of M=1 Runs



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Evolution has nothing to do with the KH instability!

Evaporation Time

Energy to evaporate material off

$$\frac{1}{2}\dot{m}c_{\rm evap}^2 = -\eta_{\rm h}\frac{3c_{\rm ps}^2}{2\gamma}\rho_{\rm h}v_{\rm h}\pi R_{\rm c}^2$$

Heat impinging onto cloud

$$\tilde{\dot{m}} \equiv \frac{\dot{m}}{m}t_{\rm cc} = -A\chi_0^{1/2}$$

$$\mathrm{A} \approx 0.01$$

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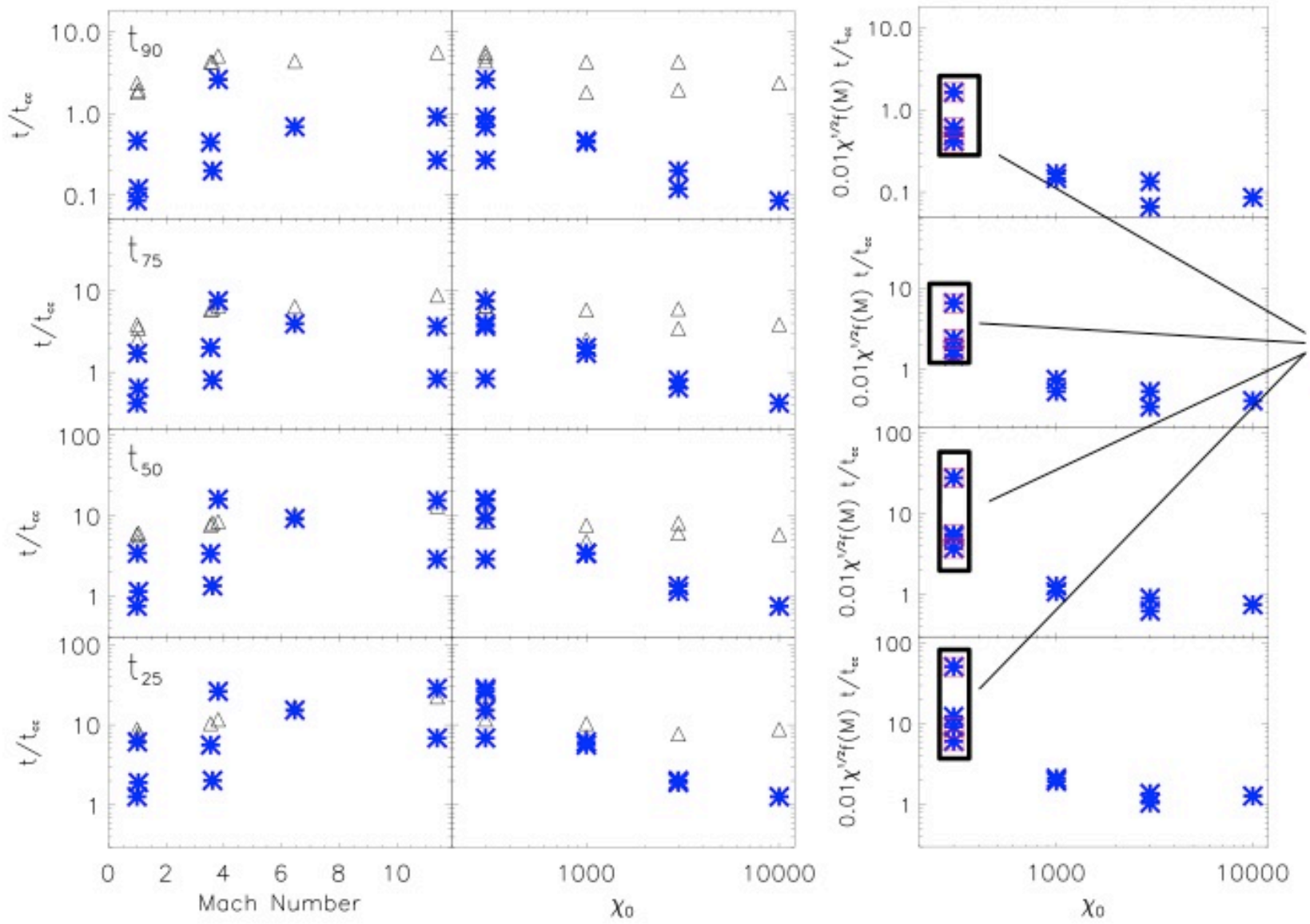

Time for cloud to reach 90%, 75%, 50%, and 25% of its original. Triangles are from previous runs not including the effect of conduction.

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Outliers

The outliers are the runs for which radiative cooling in the evaporative flow is significant.

Including optically cooling in the flow surrounding the cloud

$$\frac{t_{\rm evap}}{t_{\rm cc}} \equiv \frac{-1}{\dot{\tilde{m}}} = \frac{1}{\mathbf{A}\quad \chi_0^{1/2}} \frac{2g}{\sqrt{1+4g}-1}$$

$$g = 3.5\Lambda_{-22}\left(\frac{f_{\rm c}}{0.5}\right)\left(\frac{A}{0.01}\right)\left(\frac{n_{\rm c}R_{\rm c}}{3\times10^{20}{\rm cm}^{-2}}\right)\left(\frac{3\times10^6 K}{T_{\rm evap}}\right) M \left(\frac{1000}{\chi_0}\right)^{1/2}.$$

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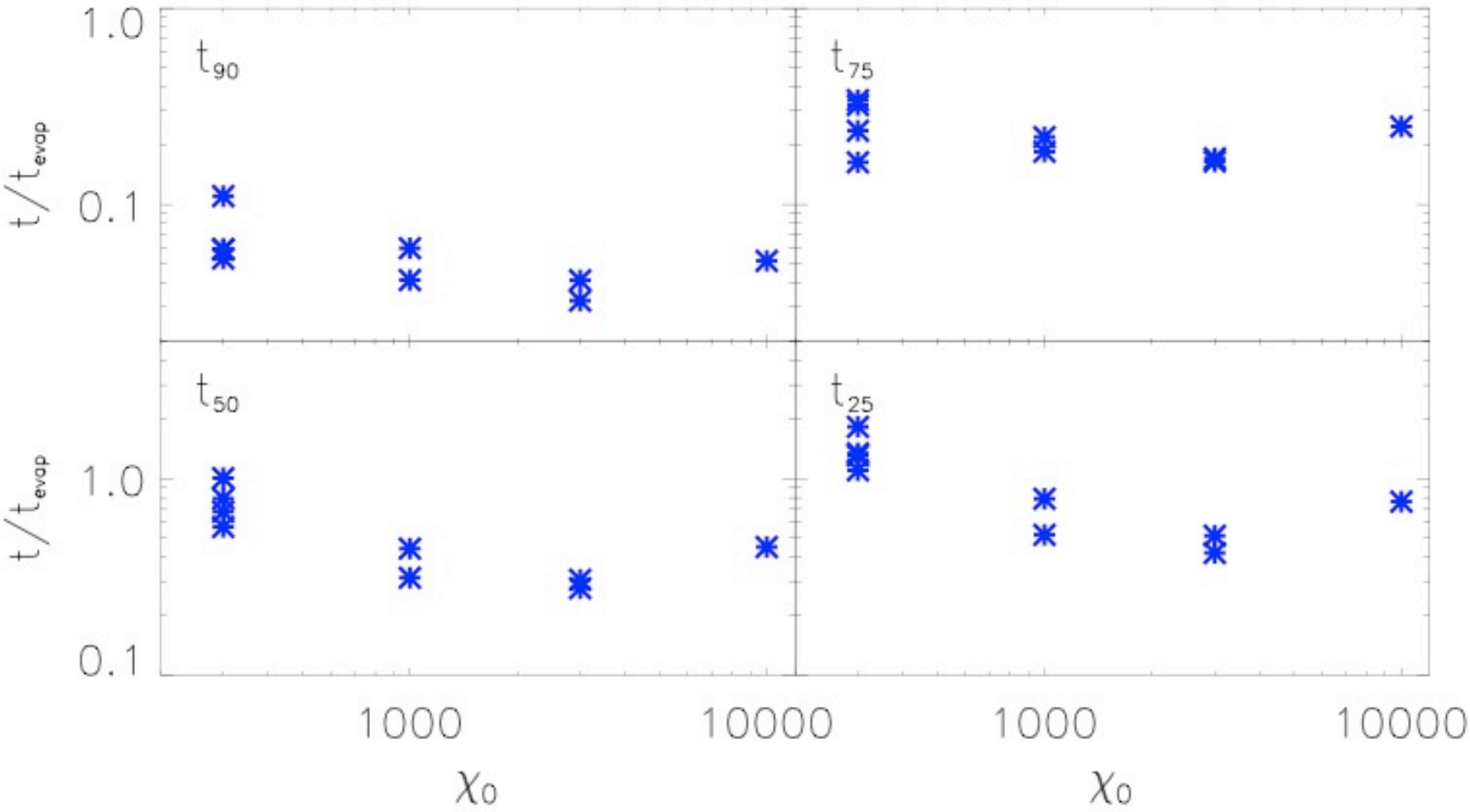
Survival time



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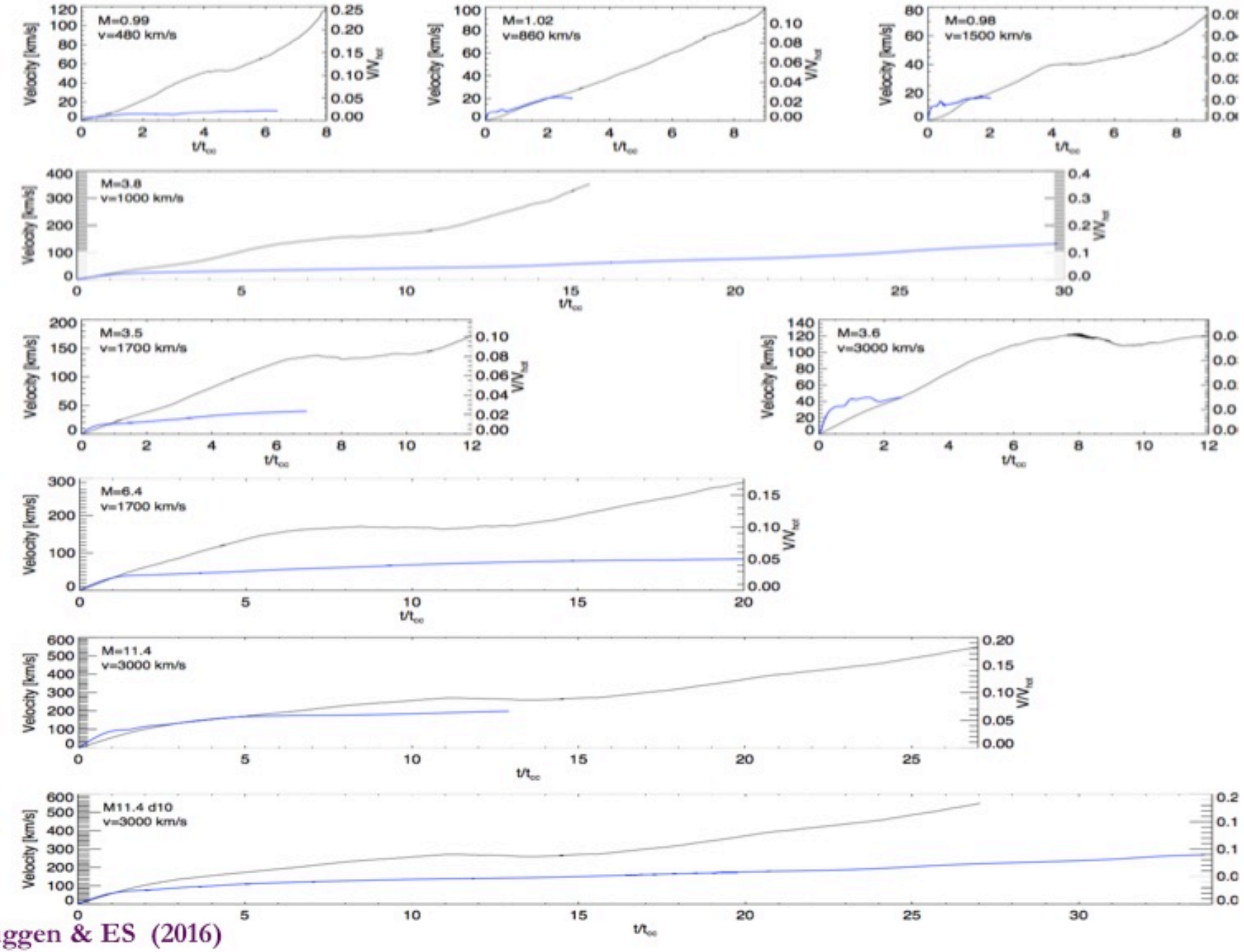
Velocity evolution



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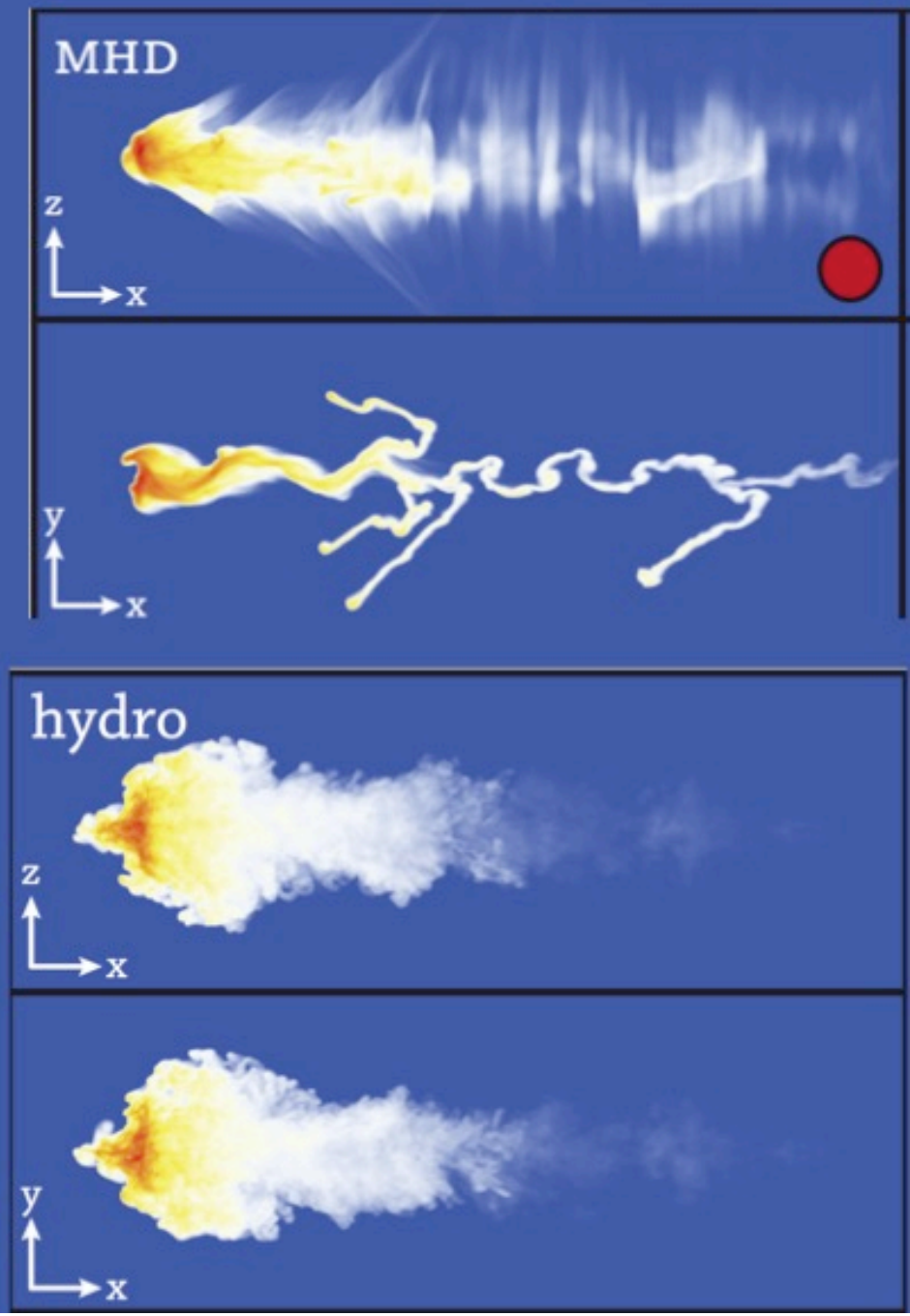
Magnetic Fields

Ordered

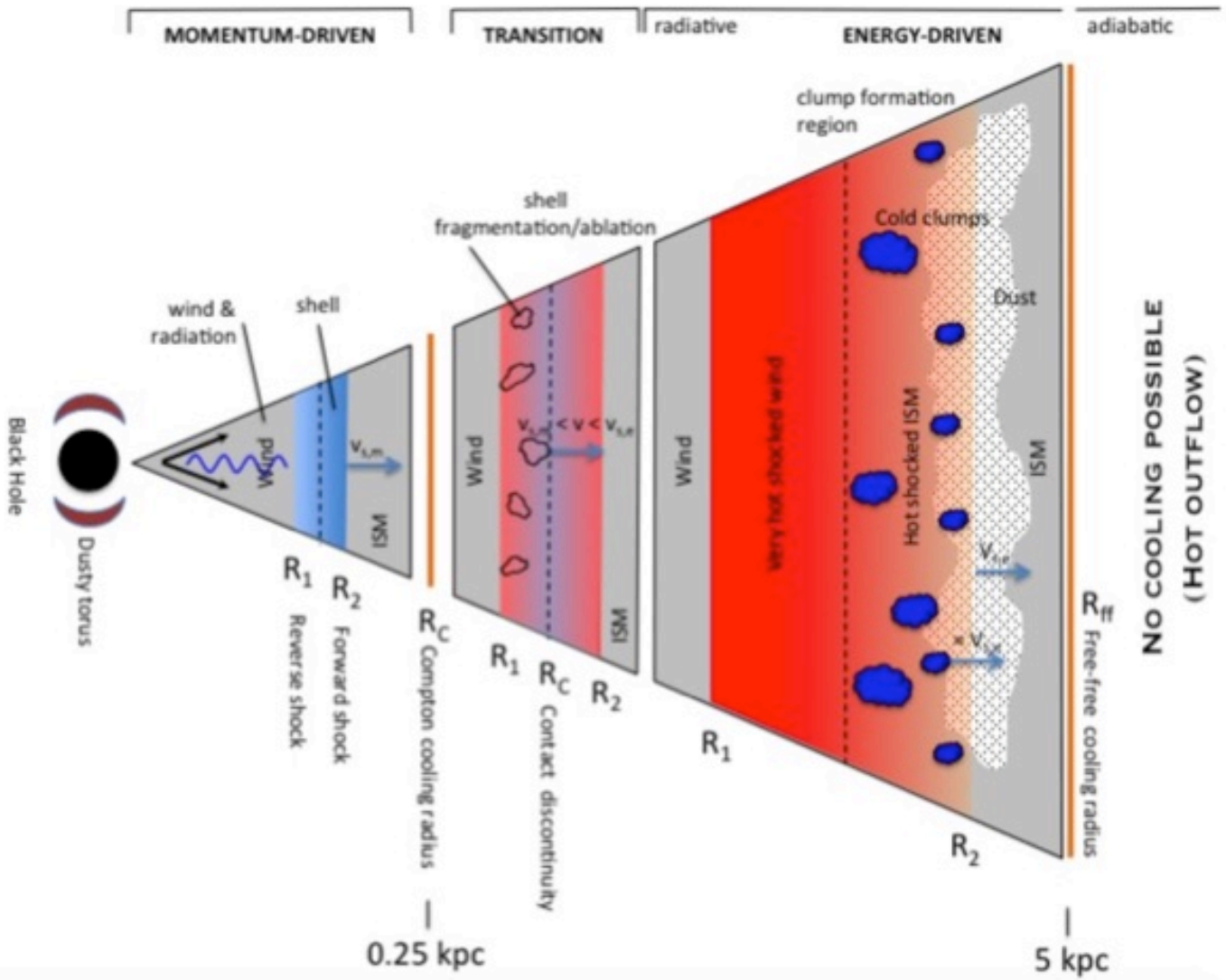
Tangled

Anisotropic Conduction



(Mc Court. et al 2015, et al. see also, Mac Low et al 1994; Gregori et al 1999, 2000; Fragile et al 2005; Orlando et al 2008; Shin et al 2008, Banda-Barragan et al. 2015)

What about condensing out of the Flow?



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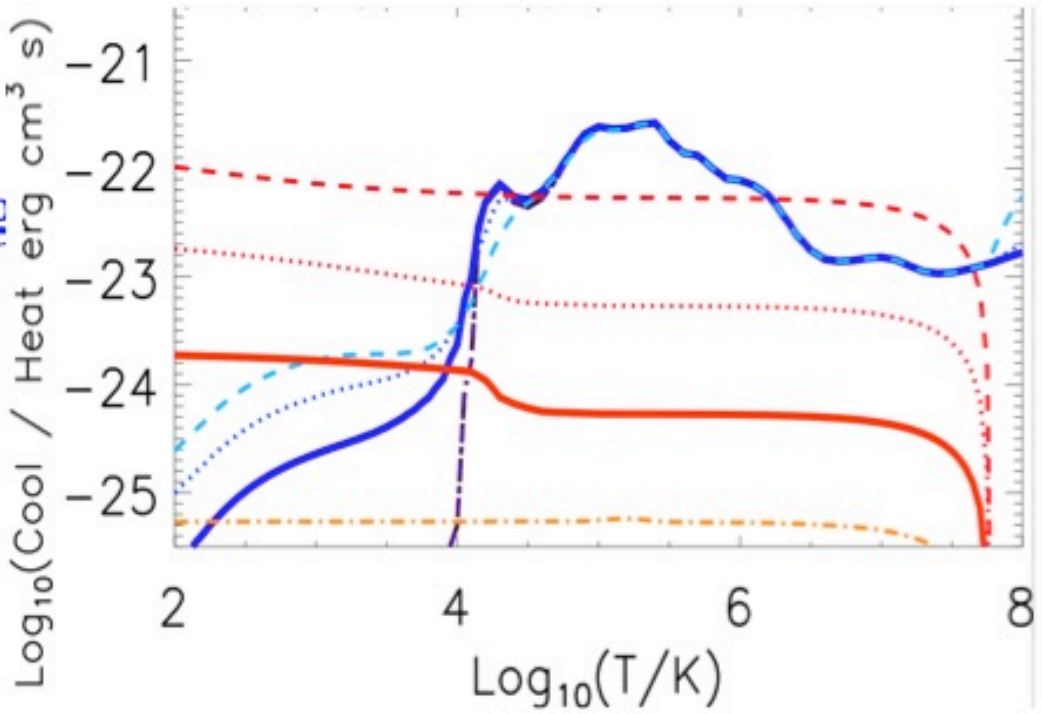
see also Wang (1995); Efstathiou (2000); Silich et al. 2003, Tenorio-Tagle et al. (2007); Thompson et al. (2016)

Clouds condensing from outflow

- FLASH Code, v4.2
- 512^3 box (1kpc, at 1kpc)
- Conduction, cooling heating
  (Gnedin & Hollon 2012)
- 2.2 x10^7 K, 60 cm^{-3}
- Dust cooling + destruction



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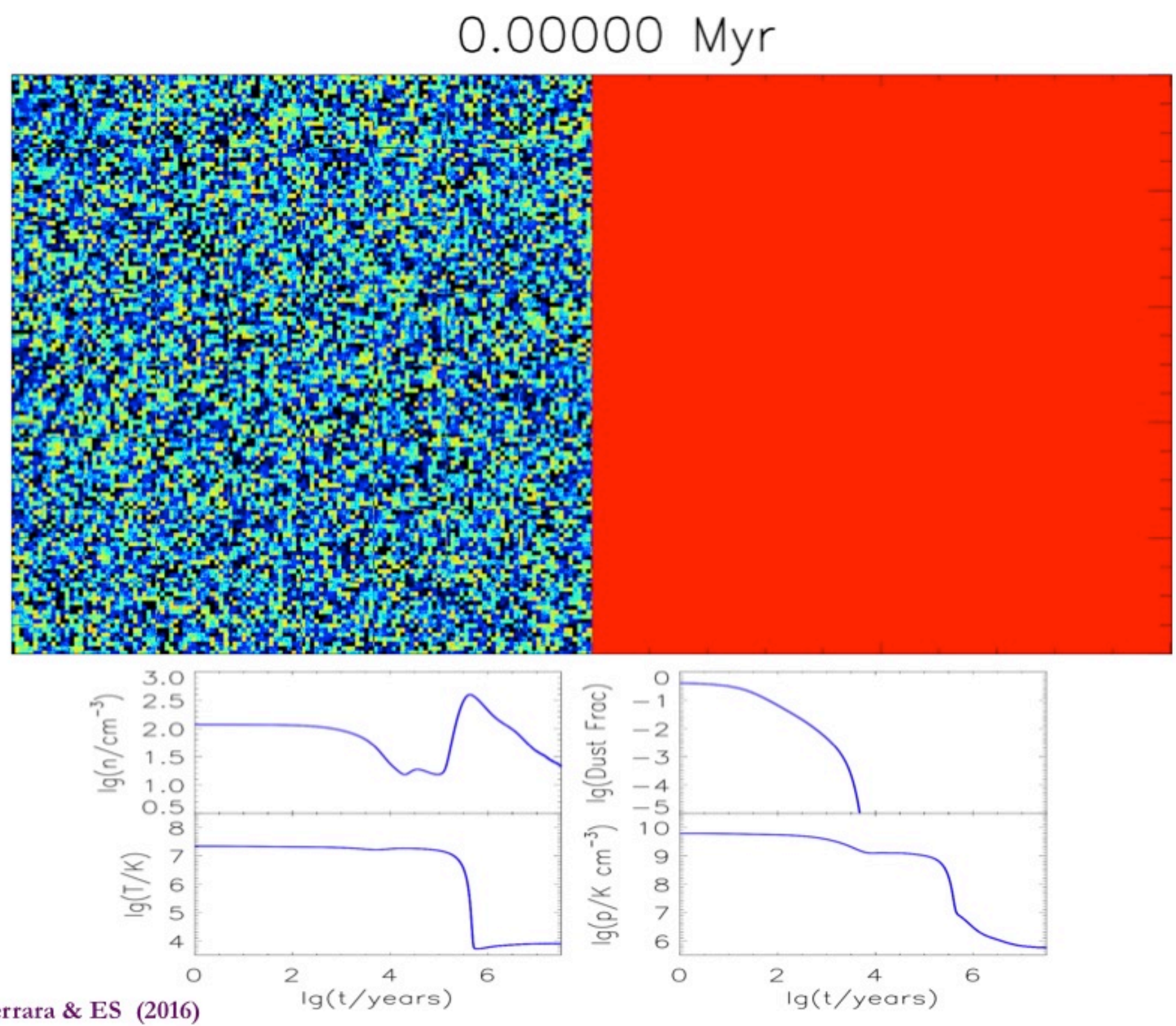
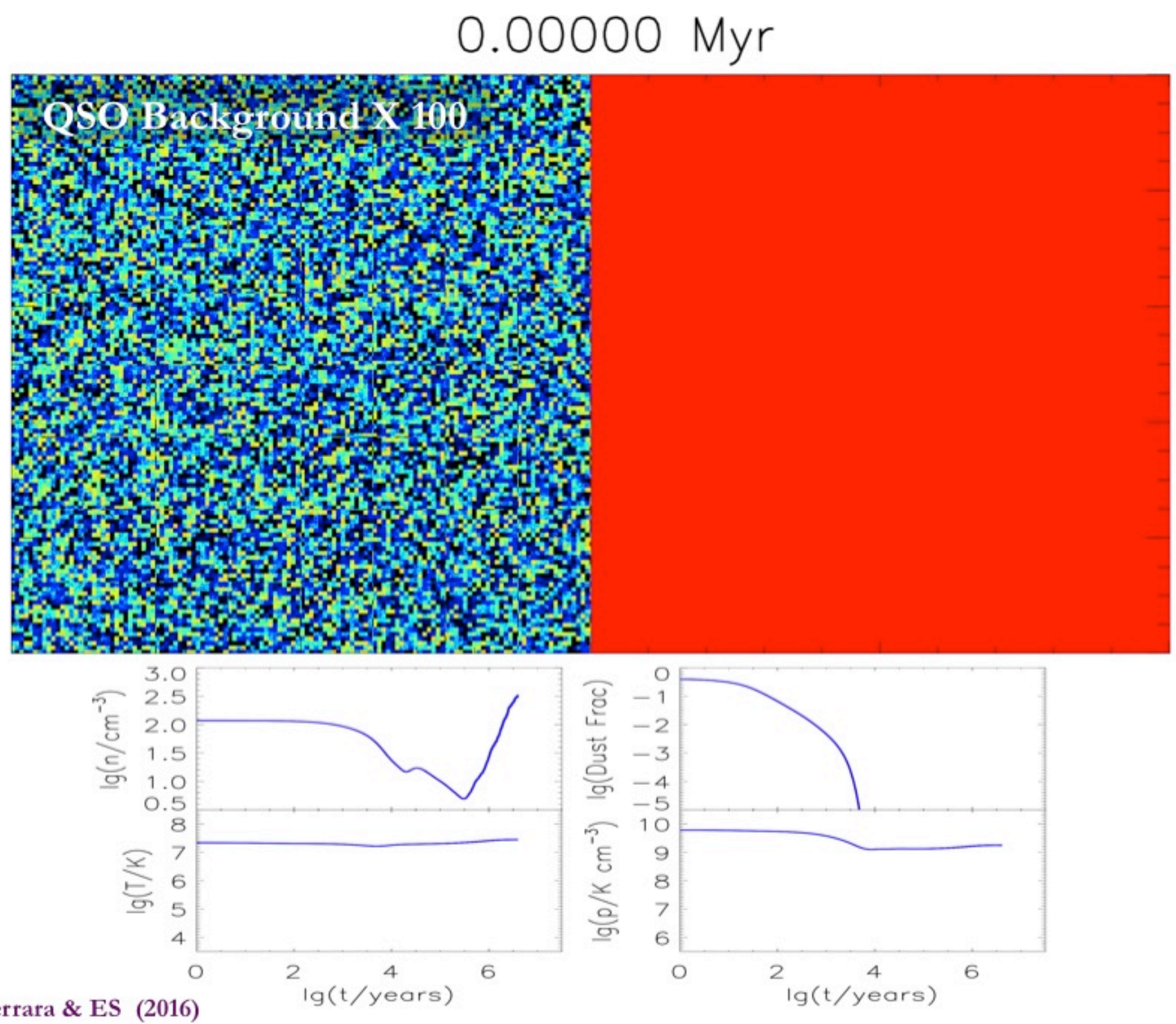


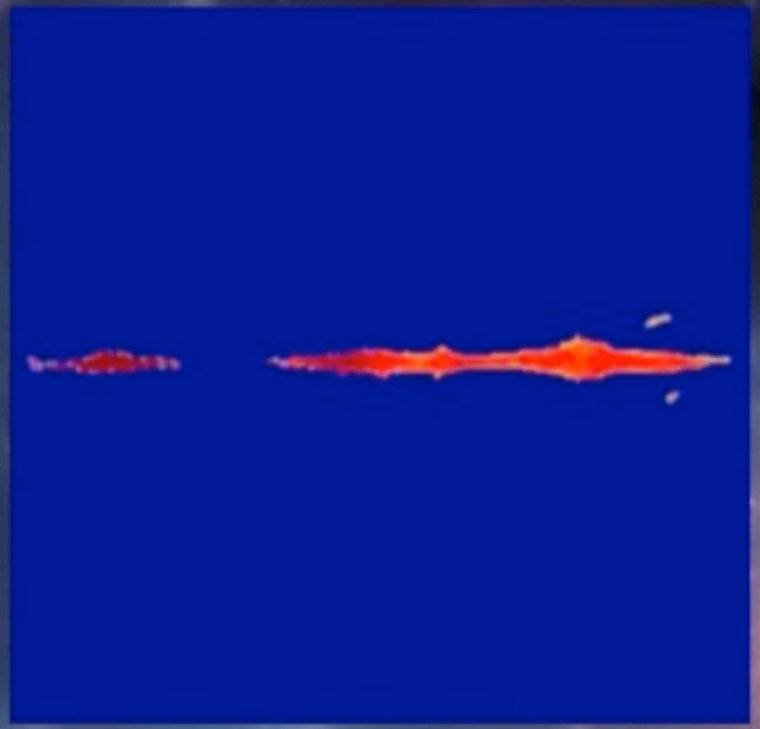
A. Ferrara & ES (2016)

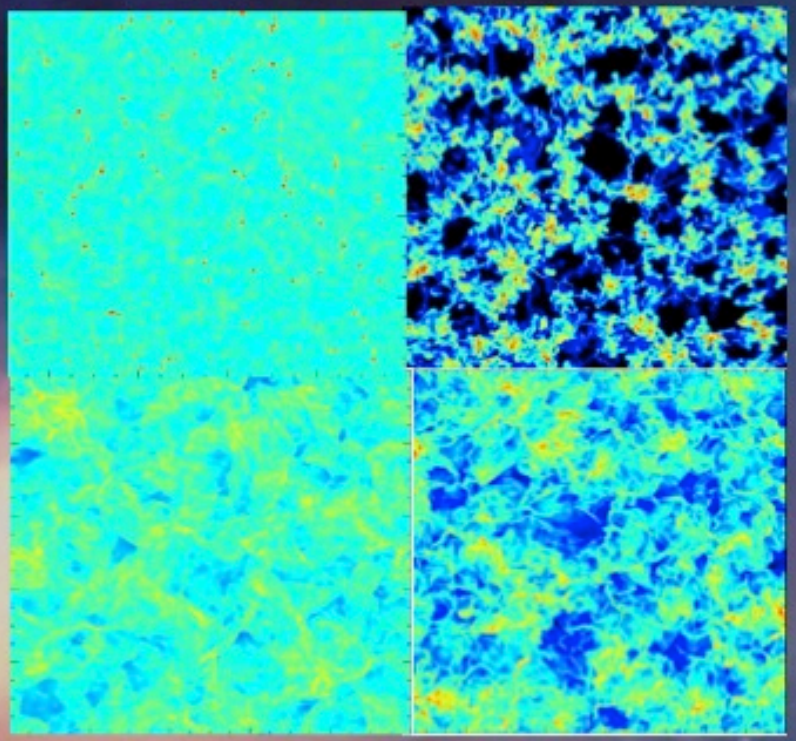


A. Ferrara & ES (2016)

Conclusions

I. $$t = \alpha t_{\rm cc} \sqrt{1 + M_{\rm hot}}$$

II. 

III. 

IV. THANKS!

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