

A Galaxy in the Making

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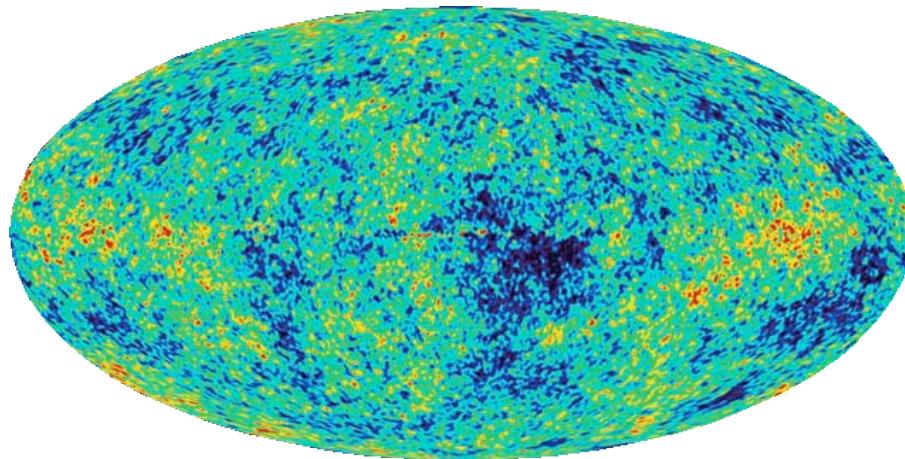
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Chamonix, 3 July 2009

A well defined IC problem



Dunkley et al. (2008)

The standard cosmological model is a success on large scales

Matter & energy content of the Universe + geometry

Cosmological

Parameters :

$$\Omega_m = 0.24$$

$$\Omega_\Lambda = 0.76$$

$$\sigma_8 = 0.80$$

$$h = 0.72$$

$$\begin{aligned} \frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f - \nabla \Phi \cdot \nabla_u f &= 0 \\ \frac{\partial \rho_b}{\partial t} + \nabla \cdot (\rho_b \mathbf{u}) &= 0 \\ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \cdot \mathbf{u} &= -\nabla \Phi - \frac{\nabla p}{\rho_b} \\ \frac{\partial \varepsilon}{\partial t} + \mathbf{u} \cdot \nabla \varepsilon &= -\frac{p}{\rho_b} \nabla \cdot \mathbf{u} \\ p &= (\gamma - 1) \varepsilon \rho_b \\ \nabla^2 \Phi &= 4\pi G \left[\int f d^3 u + \rho_b \right] \end{aligned}$$

Vlasov : dark matter, stars

Continuity : gas

Euler : gas

Energy : gas

Equation of state : gas

Poisson : everything

Everything we need to know/model & **HOW WELL** we know how to do it :

- **Initial conditions:**

→ WMAP observations make it a well def. pb. in the LCDM paradigm

- **Collisionless fluid:** Cold Dark Matter & star particles

→ Vlassov-Poisson : **we know how to do that**

- **Collisional fluid:** gas heated & cooled radiatively

(atomic, molecular)

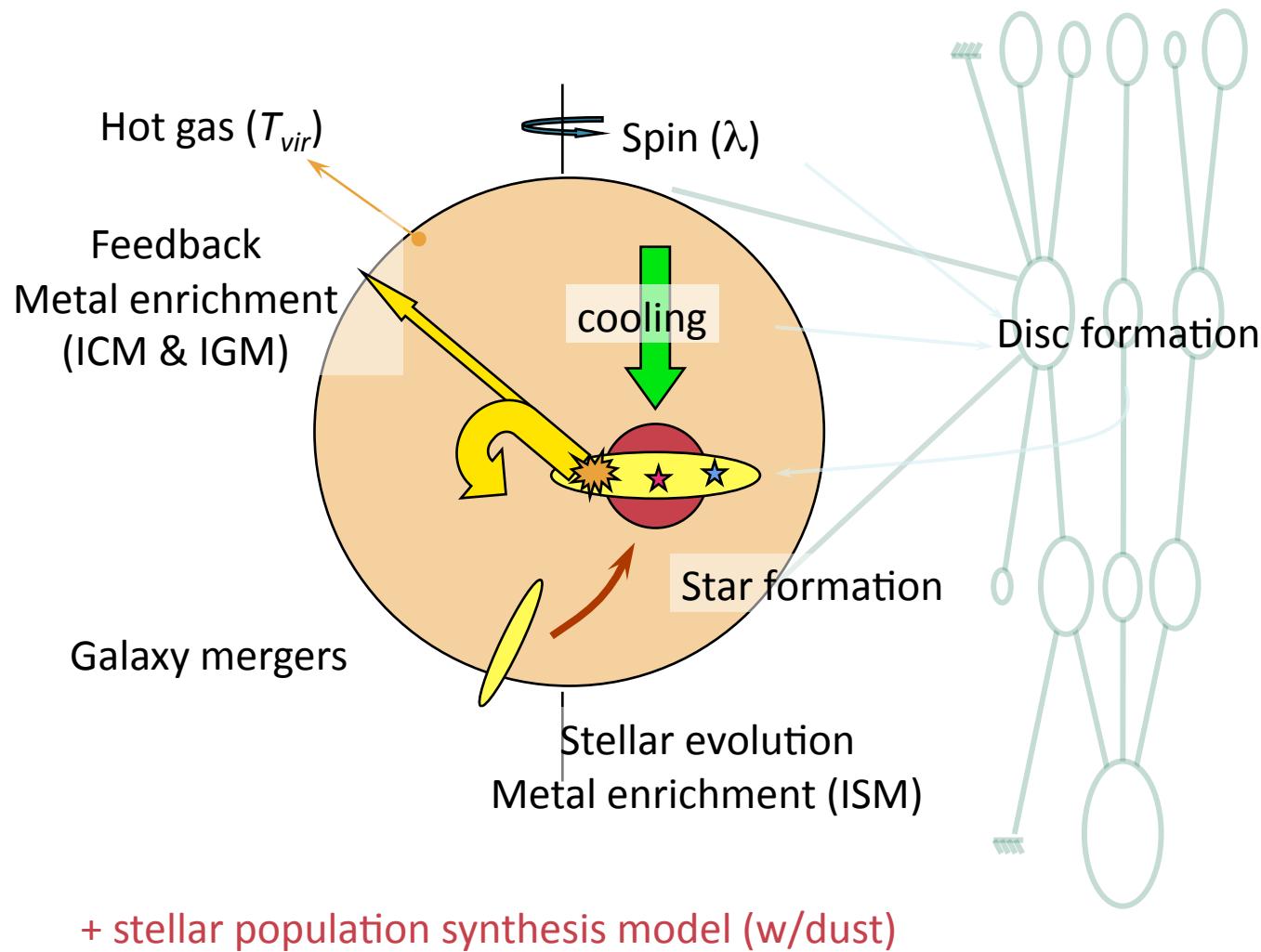
→ Euler-Poisson + homogeneous cooling & heating + chemistry: **we sort of know** (with light elements (no stars))

- **BUT Additional physics:** star formation and feedback

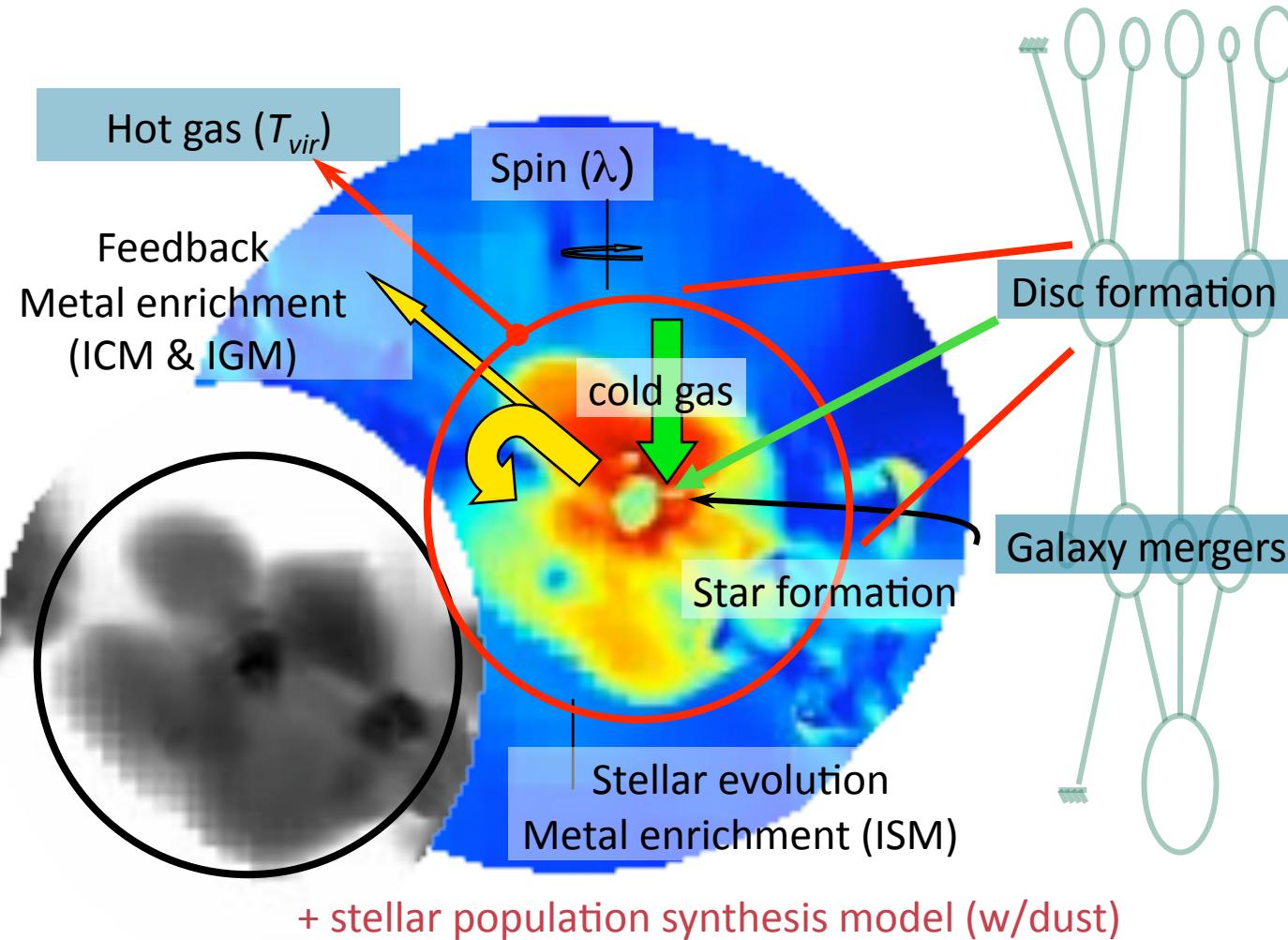
on the surrounding gas

→ Supernovae, turbulence, black hole growth, jets, MHD, accurate radiative transfer, chemistry of heavy elements, dust...
we don't understand how to model this at all (yet)!

Semi-Analytic Galaxy Models



... vs hydro simulation



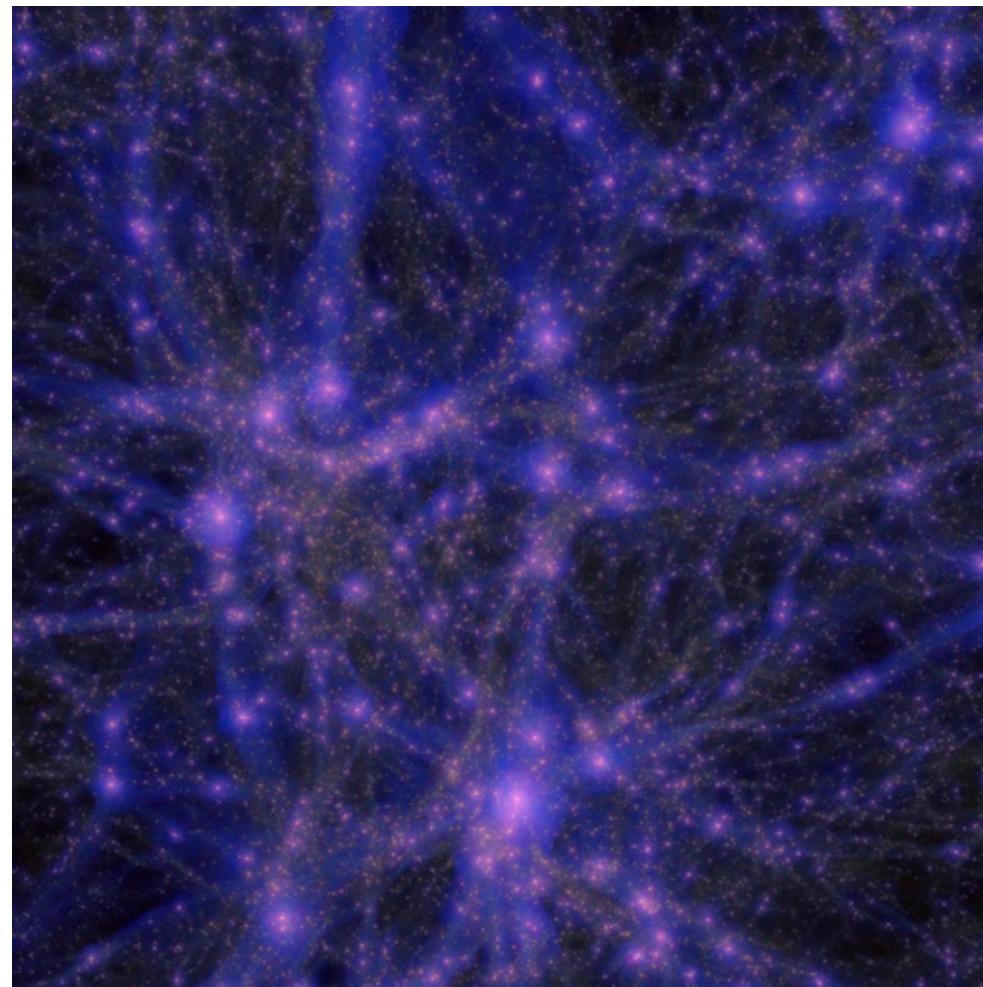
State of the Art Cosmological Simulation

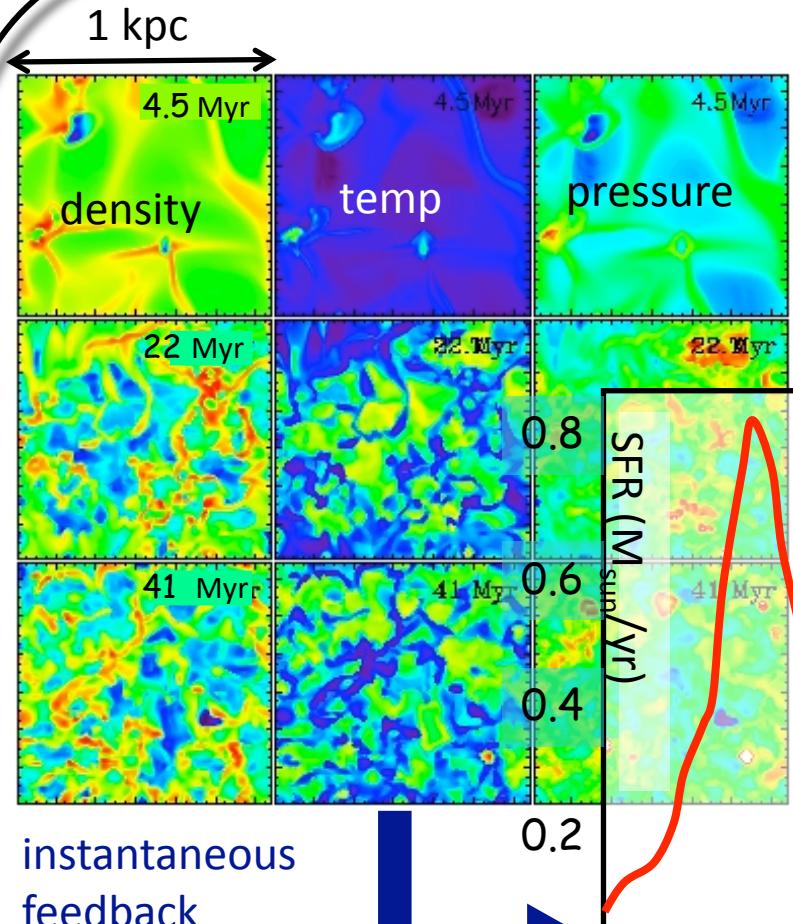
~ 1 billion
DM particles
~1 billion cell
root grid
(3 -6 AMR levels)



~ 1.5 kpc
physical
resolution

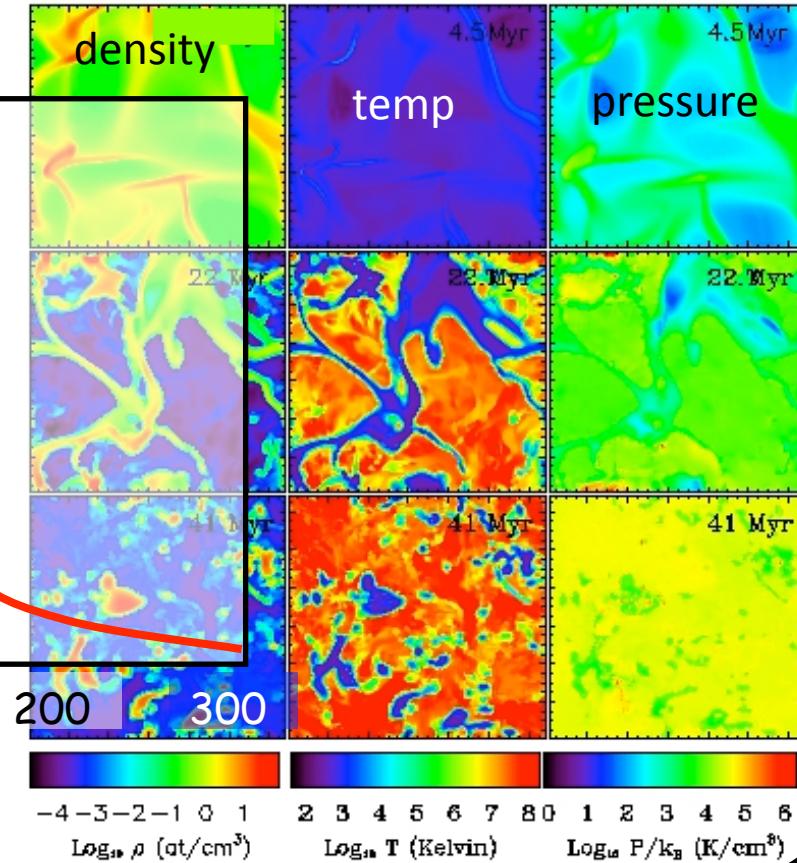
$50h^{-1}$ Mpc





What if let supernovave explode in same cell as where stars form?

non-instantaneous feedback



Slyz, Devriendt, Bryan, Silk (2005)

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Numerical implementation in Springel & Hernquist 2003

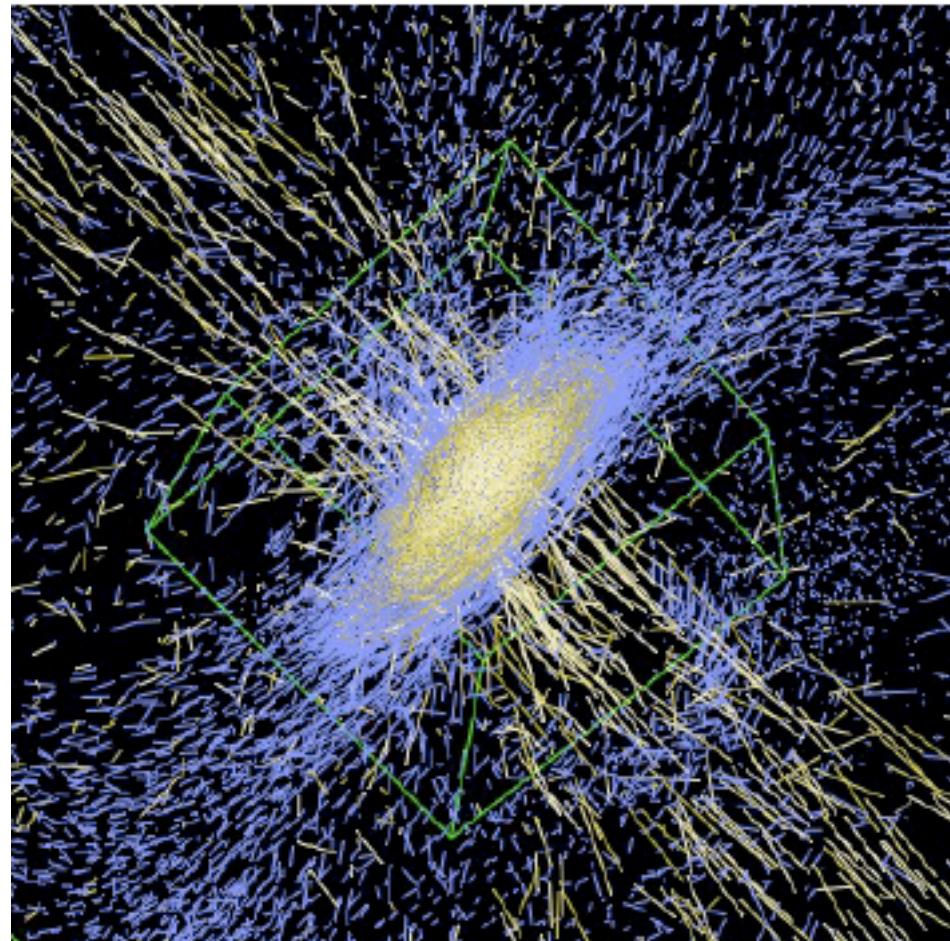
During timestep Δt a gas particle is added to the wind if a uniformly distributed random number out of the interval (0,1) falls below

$$p_w = 1 - \exp \left[-\frac{\eta(1 - \beta)x\Delta t}{t_*} \right]$$

Then modify velocity of gas particle:

$$\mathbf{v}' = \mathbf{v} + v_w \mathbf{n}$$

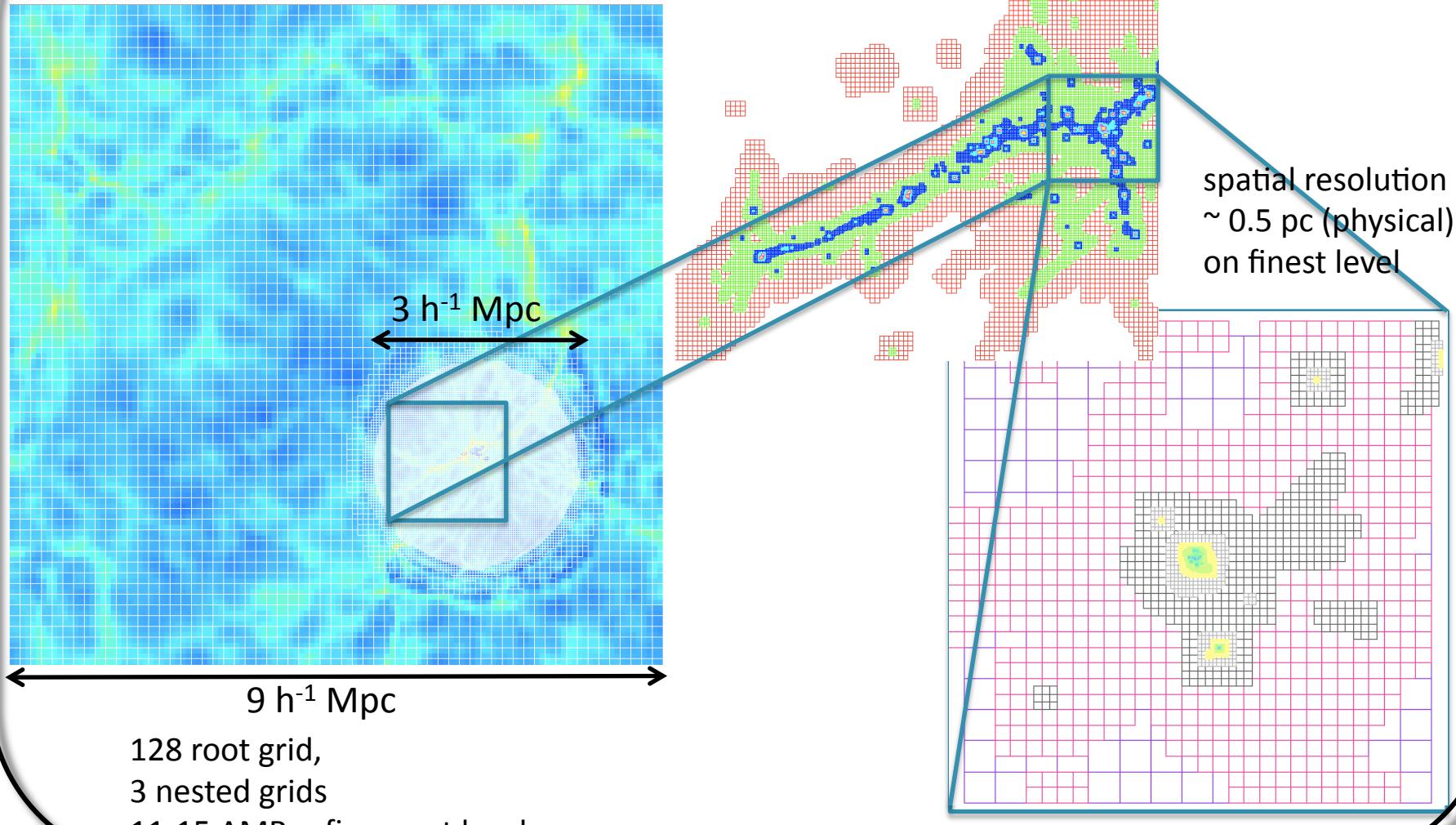
Where \mathbf{n} is either random direction on unit sphere (isotropic wind) or is along the rotation axis of a spinning object



DECOUPLE spawned wind particle for a brief time (max 50 Myr)
from hydrodynamic Interactions

AMR « resimulations » ...

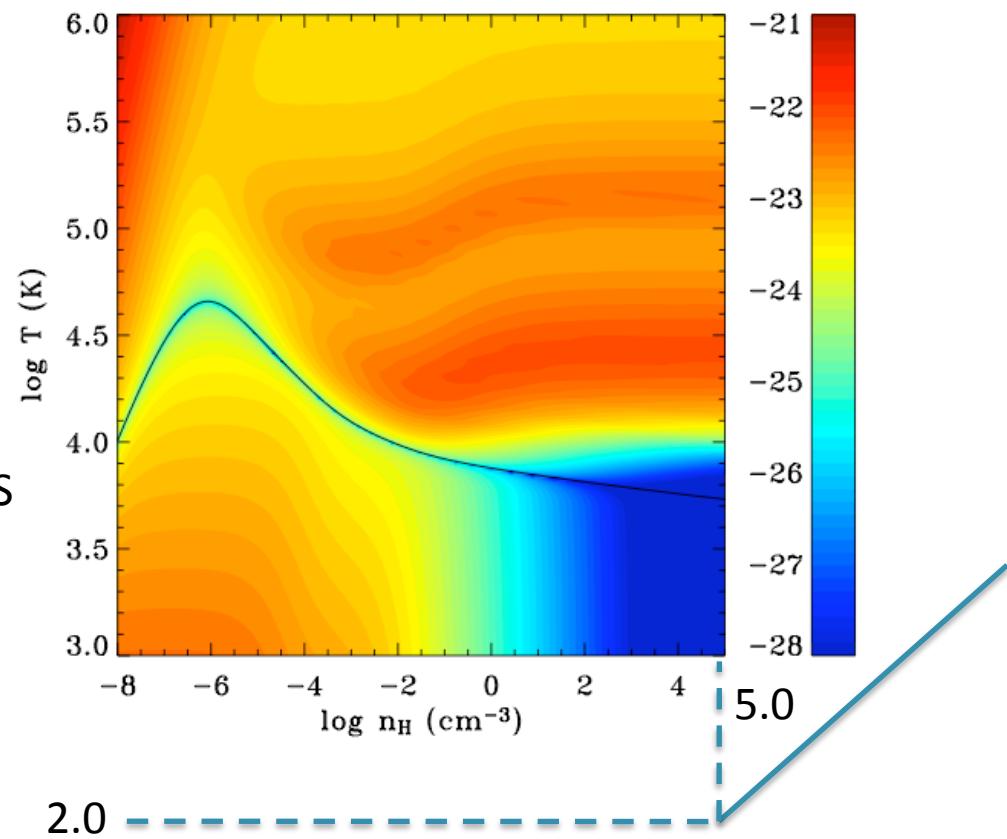
with RAMSES (Teyssier 2002)



Radiative Cooling

Metal dependent
Cooling + Heating
Rate (in the presence
of UV radiation)

Switch to polytropic EOS
to ensure no numerical
fragmentation at finest
refinement level



Model for Star Formation

$$\text{if } \rho_g > \rho_0 \quad \rightarrow \quad \dot{\rho}_* = \frac{\rho_g}{t_*(\rho_g)}$$

$$\rho_0 = 10^5 \text{ atoms/cm}^3$$

$$t_* = t_0 \left(\frac{\rho_g}{\rho_0} \right)^{-1/2}$$

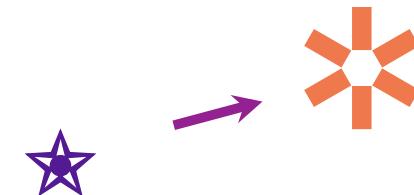
Choose t_0 so that have $\sim 2\%$ star formation efficiency per free fall time

(Krumholz & Tan 2005)

$$m_* = 167 M_{\text{sun}}$$

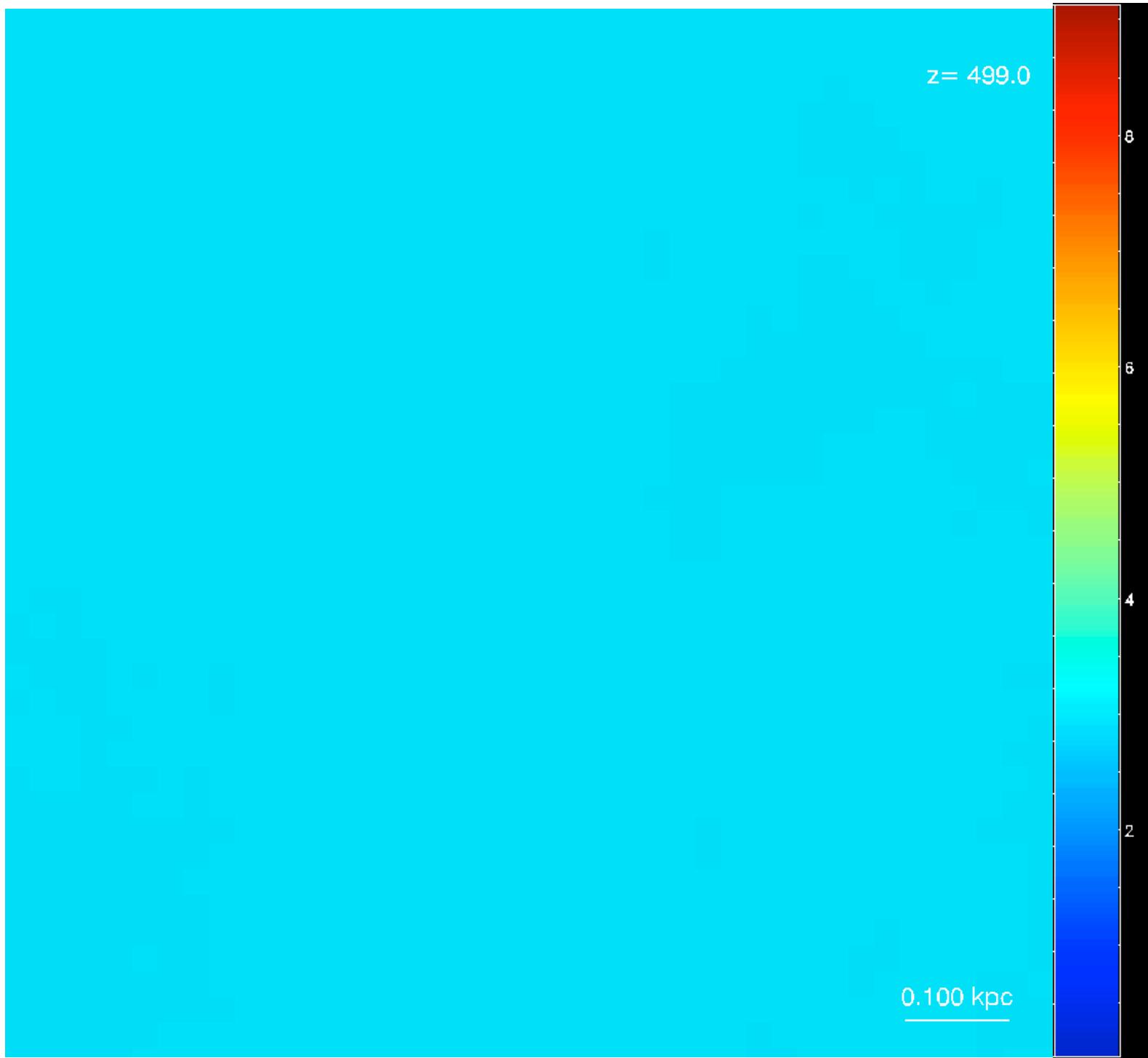
Model for supernovae feedback

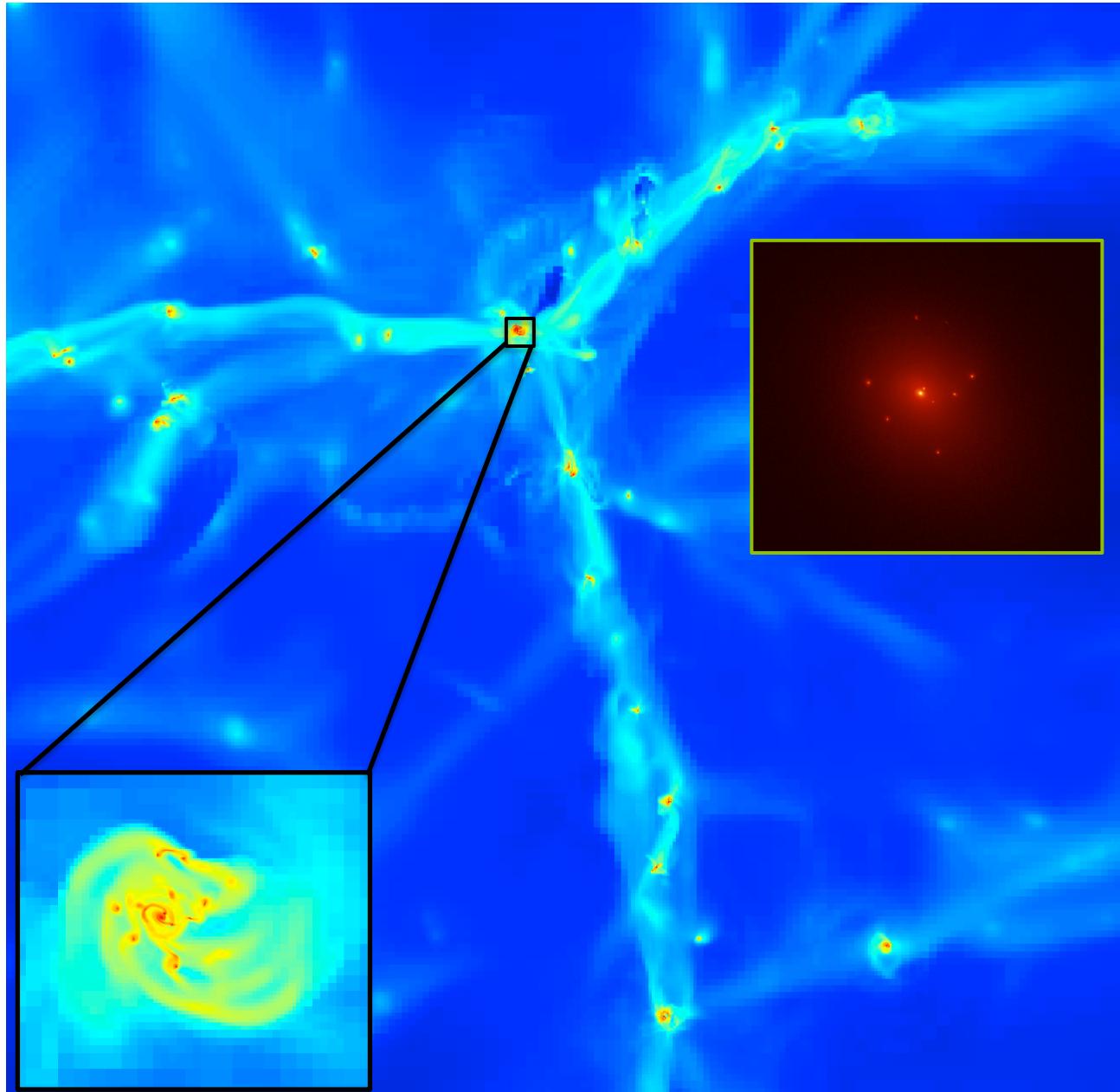
Thermal pulse
with
10 Myr delay



~ 1 supernovae/star particle
for Salpeter IMF

Produce metals that are advected as a passive scalar &
incorporated into cooling and heating routine





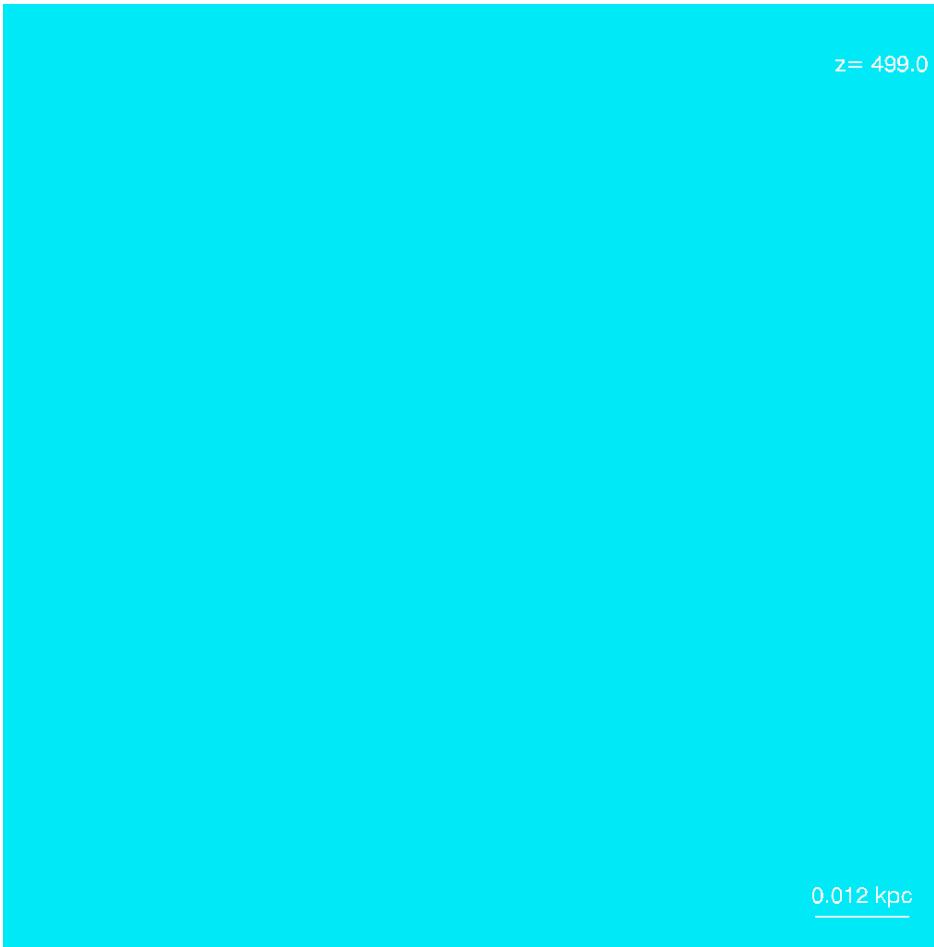
Gas Density



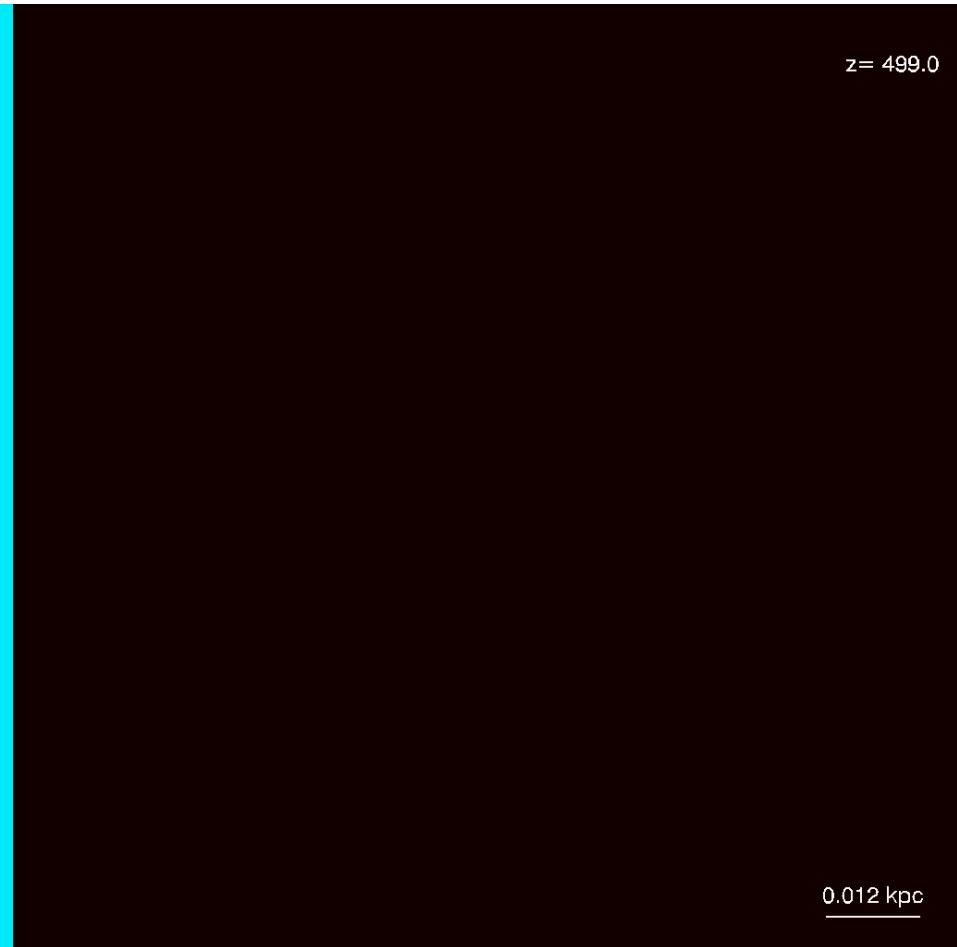
Gas Temperature



Gas Density



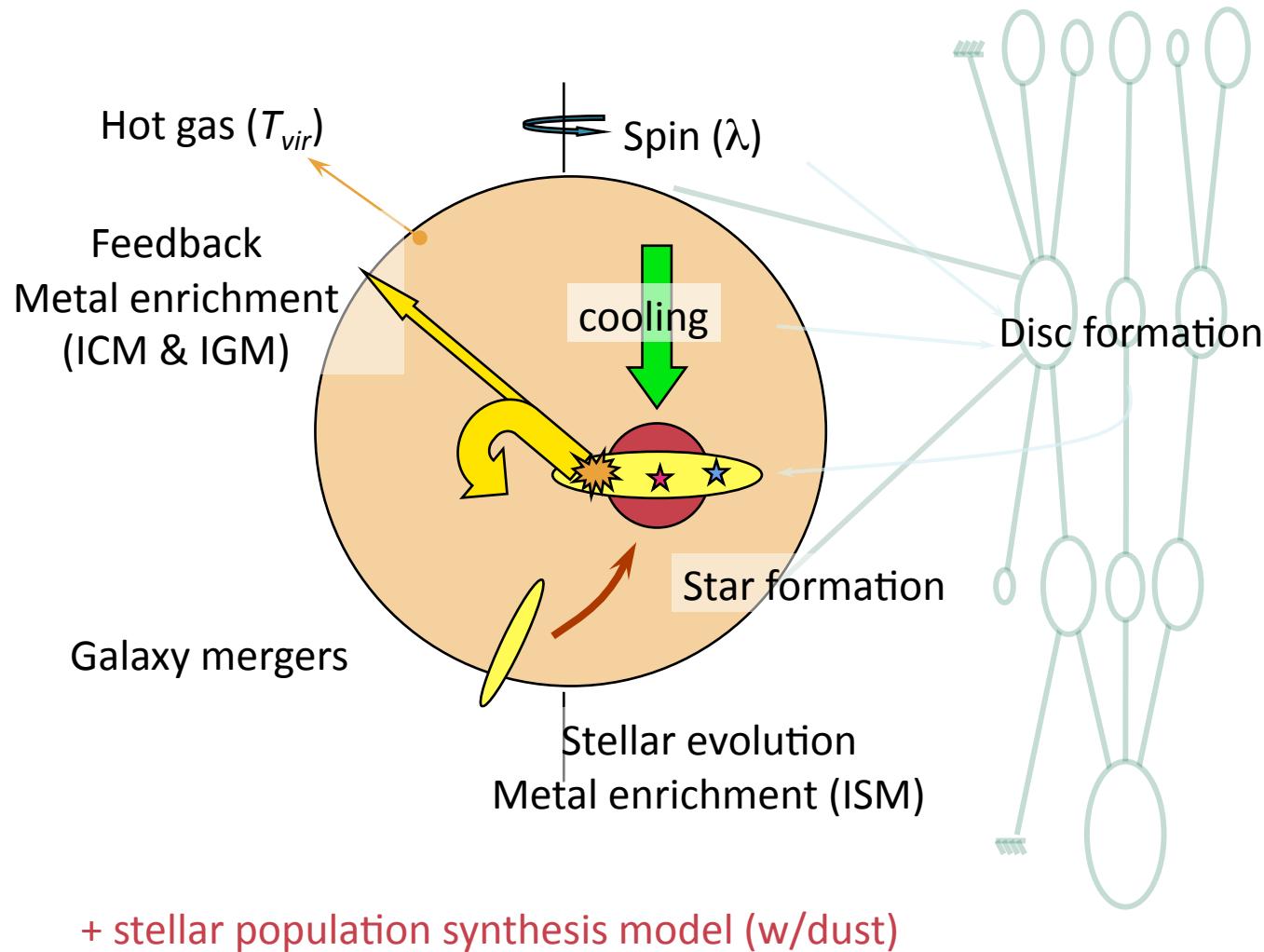
Star Density

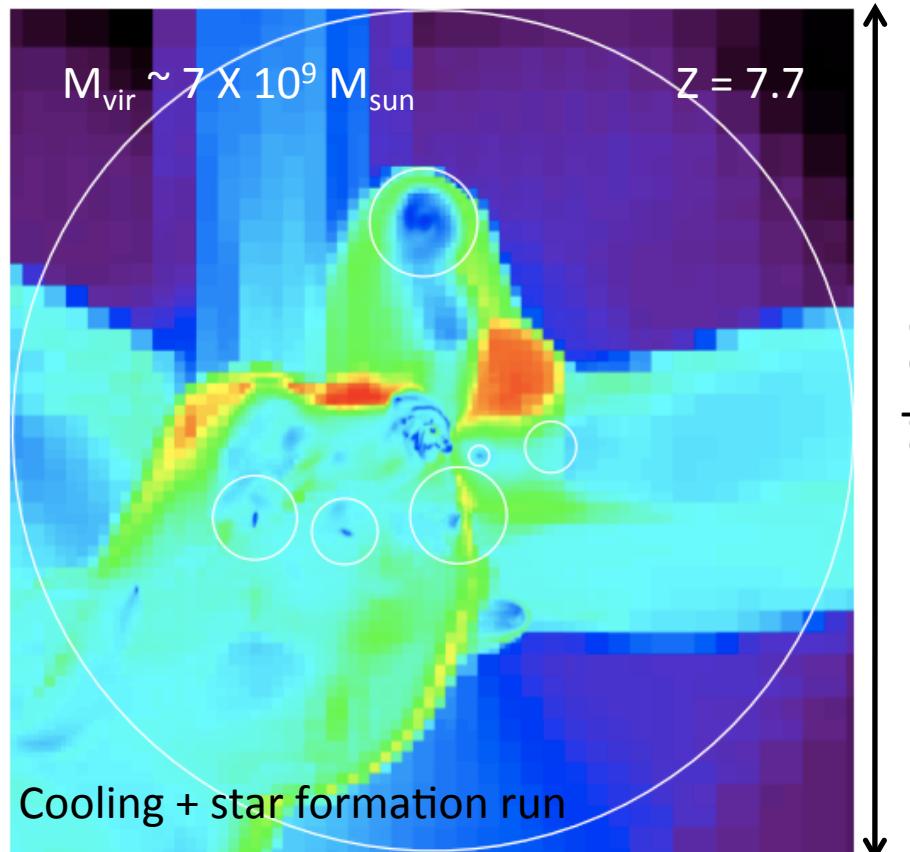
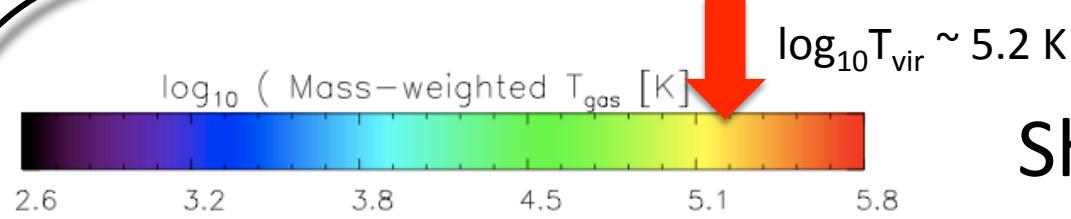


0.012 kpc

0.012 kpc

Traditional picture (White & Rees 1978)



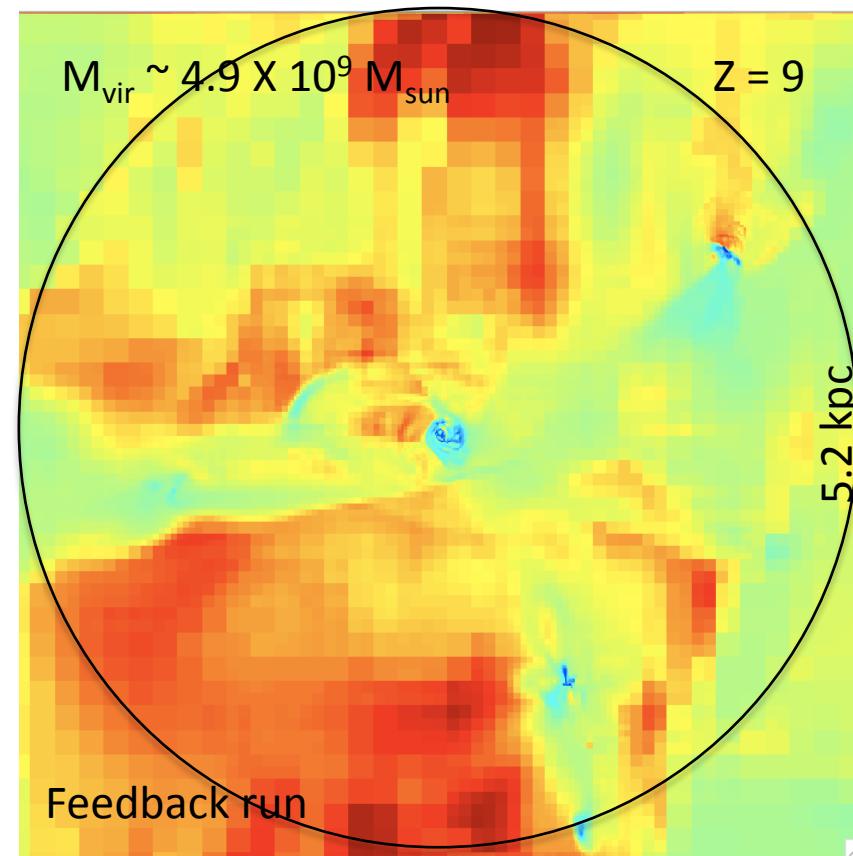
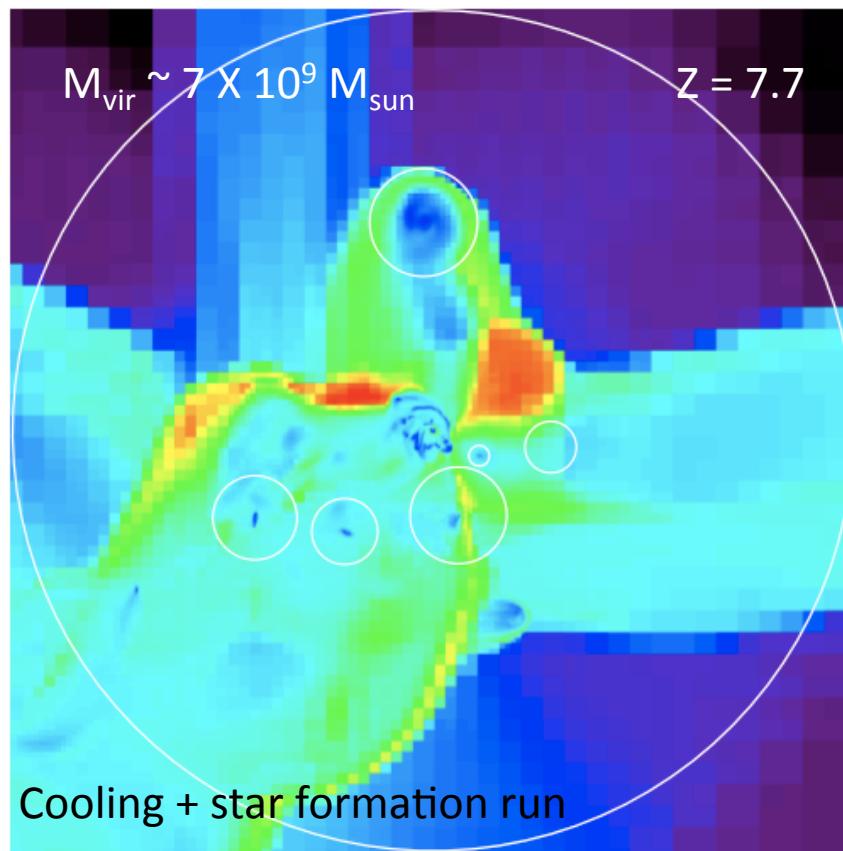
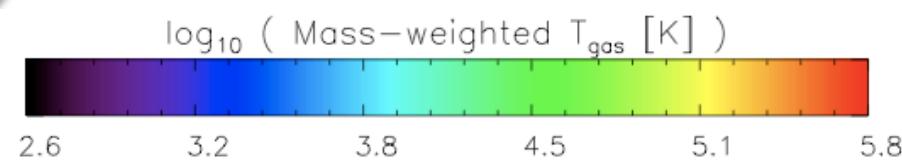


Shock heating?

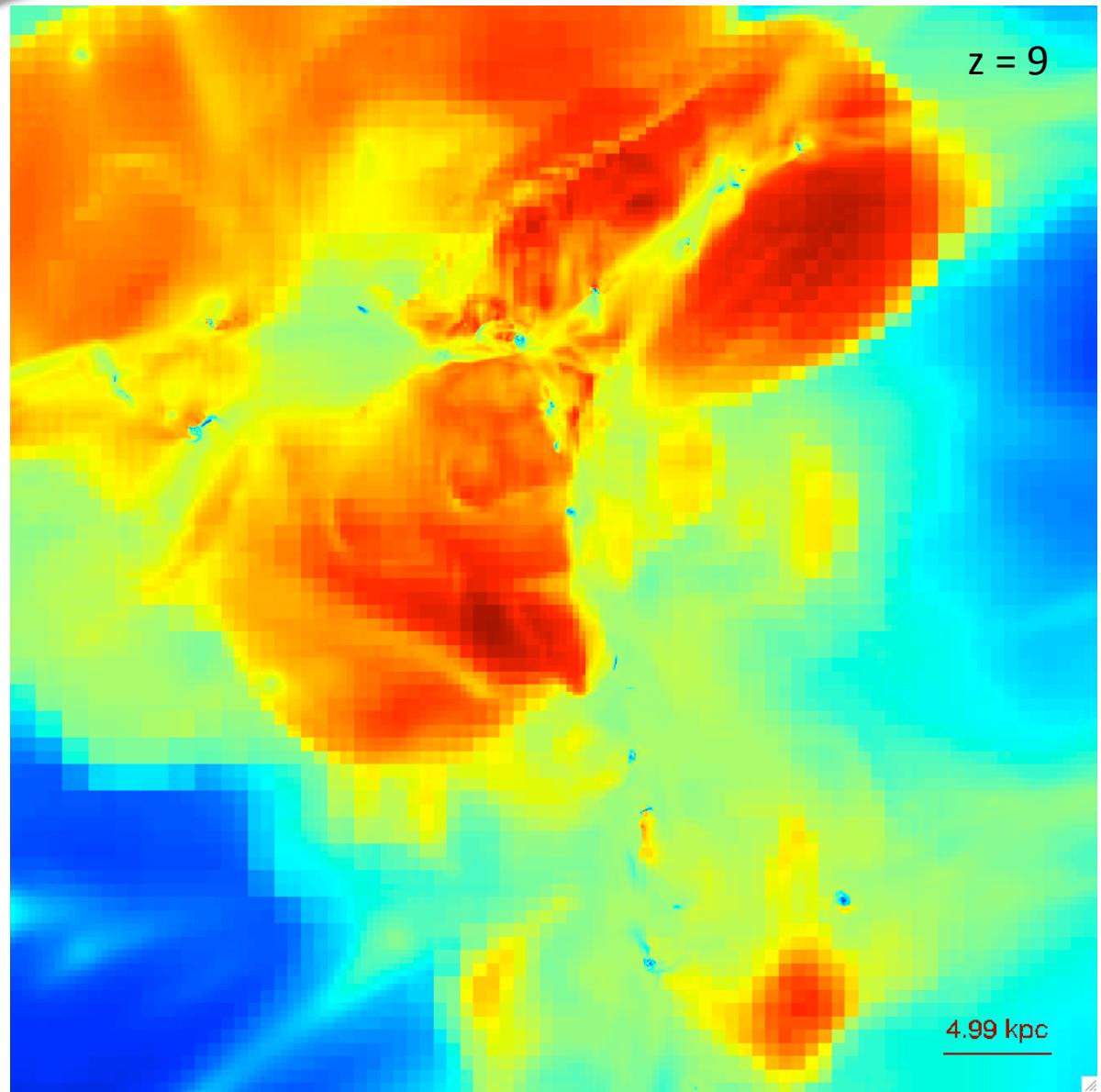
$M > \text{few} \times 10^{11} M_{\odot}$ ----> shock heating

$M < \text{few} \times 10^{11} M_{\odot}$ ----> cold flows

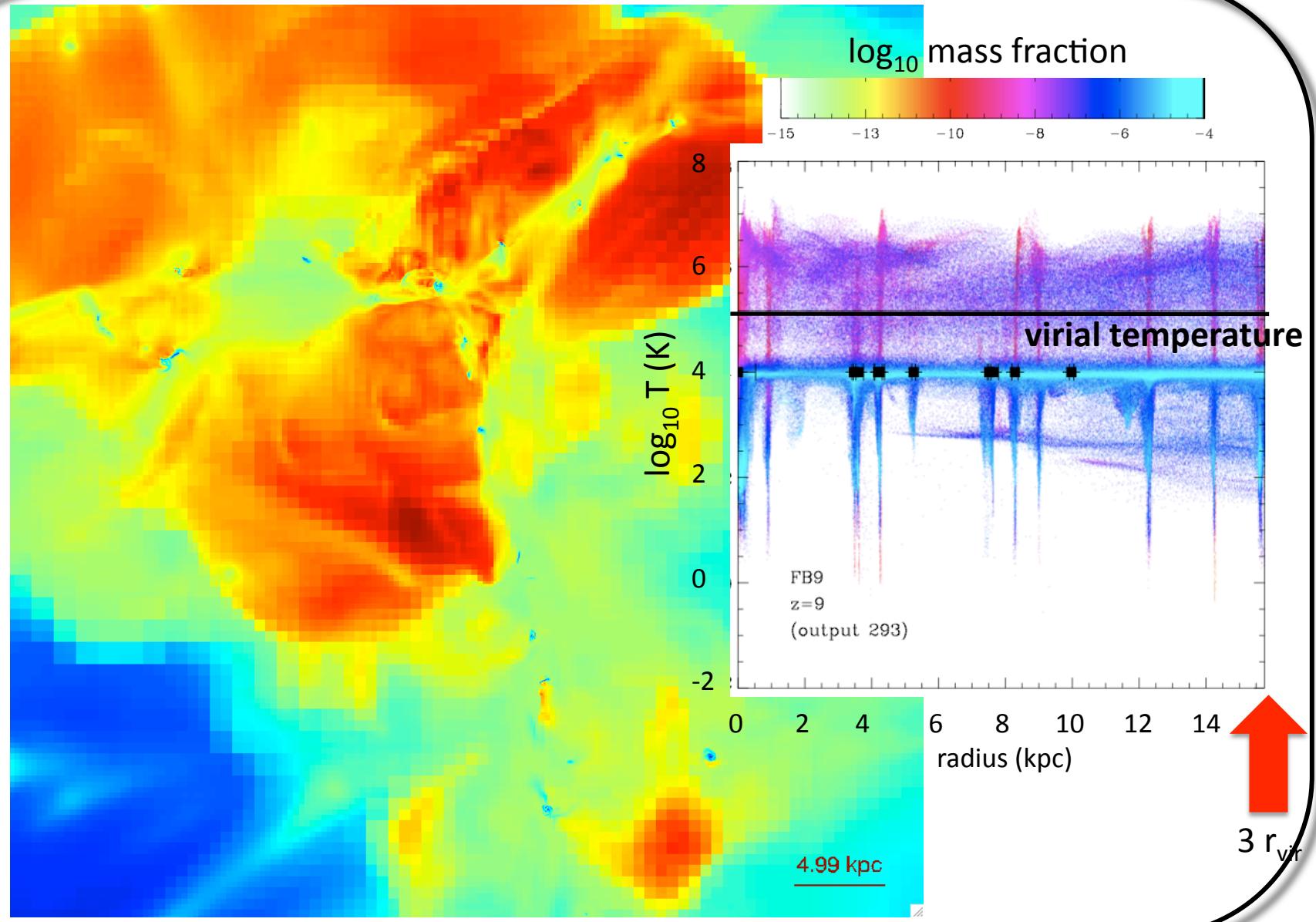
Birnboim & Dekel 2003, Ocvirk et al. 2008



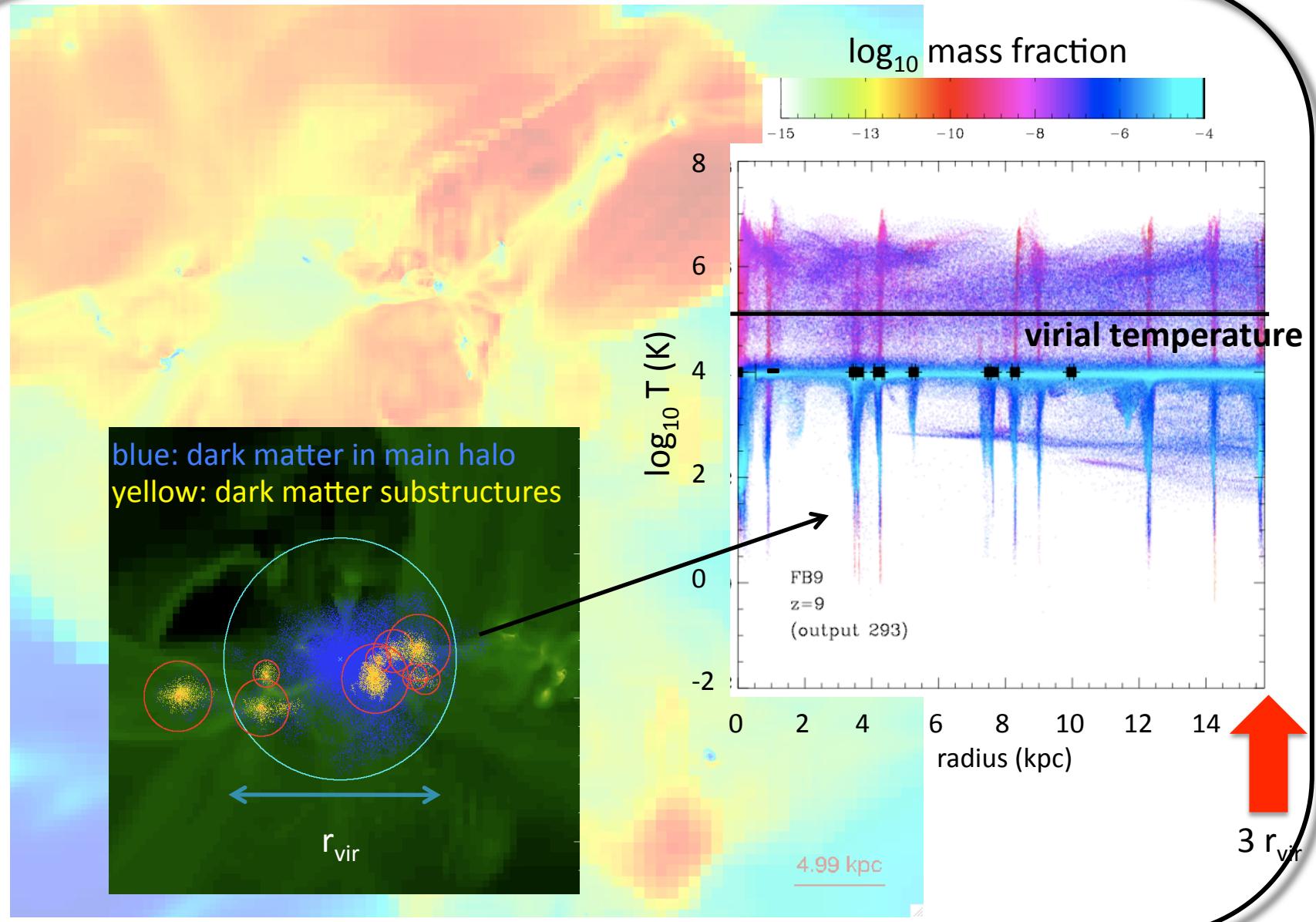
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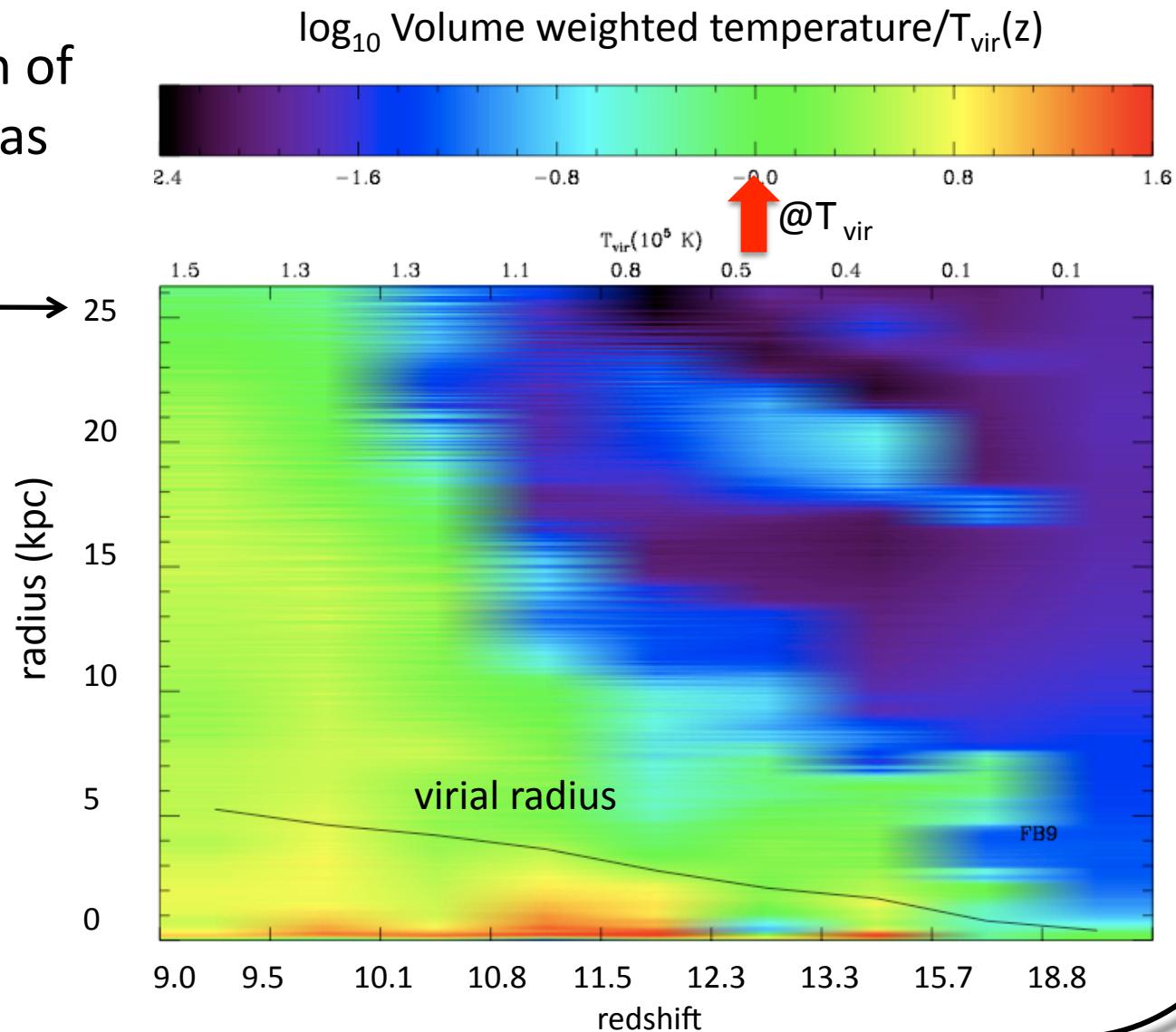
Chamonix, 3 July 2009

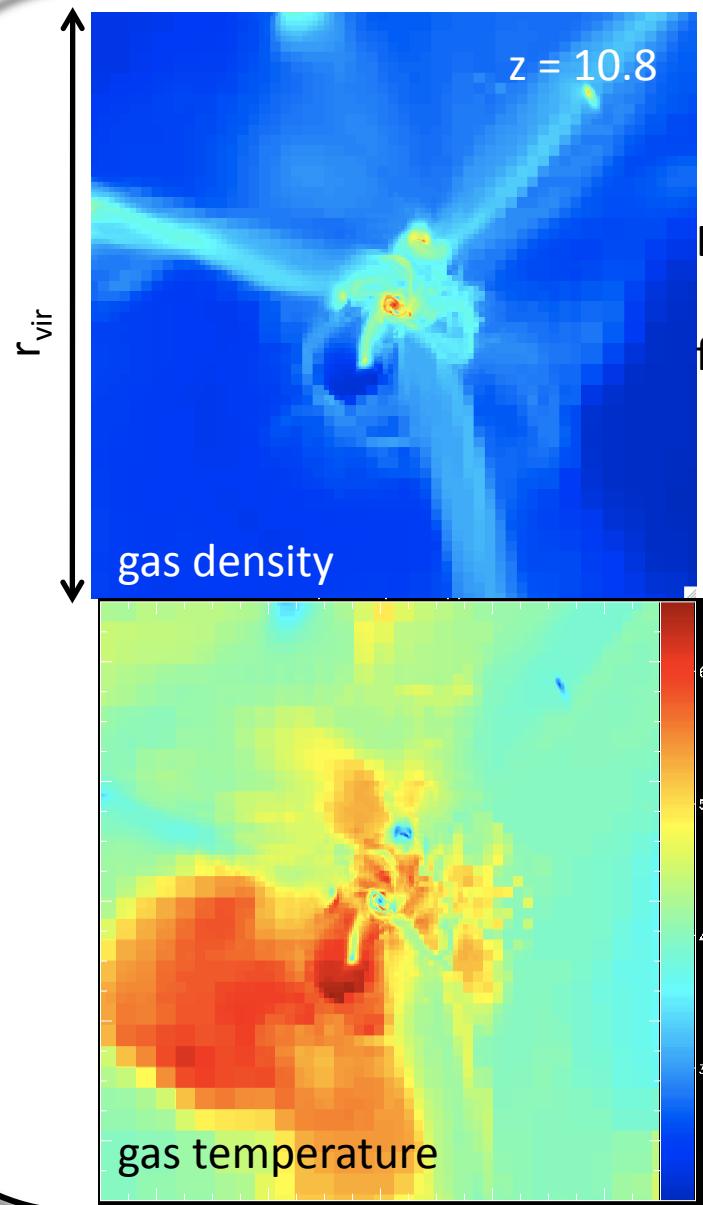


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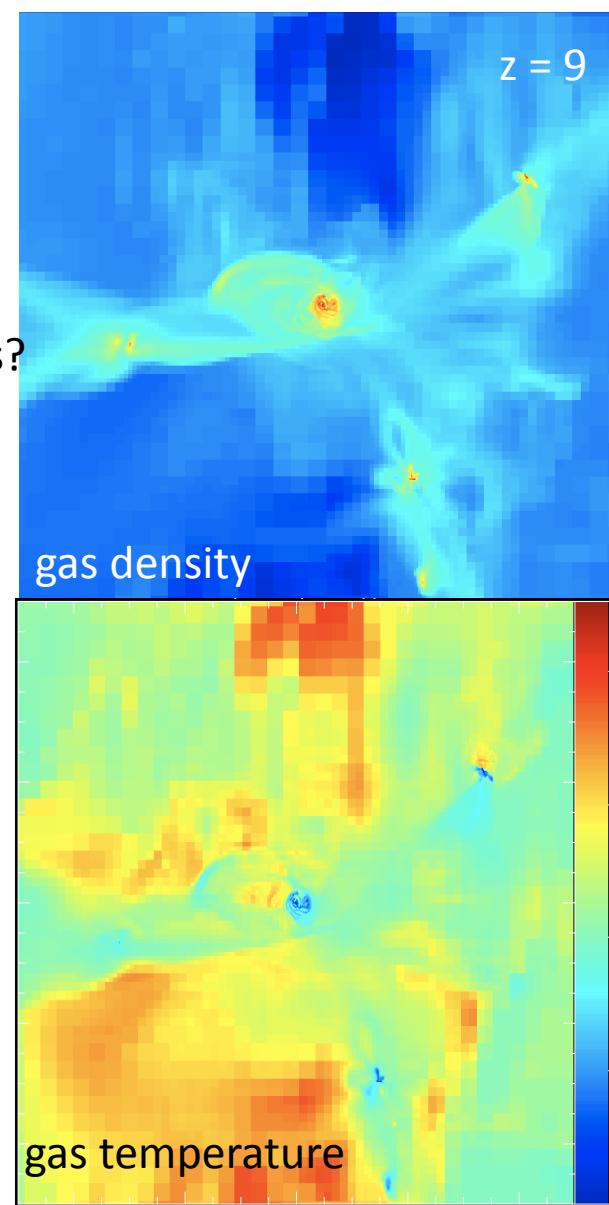
Time evolution of radius of hot gas

$\sim 5 r_{\text{vir}} \rightarrow 25$



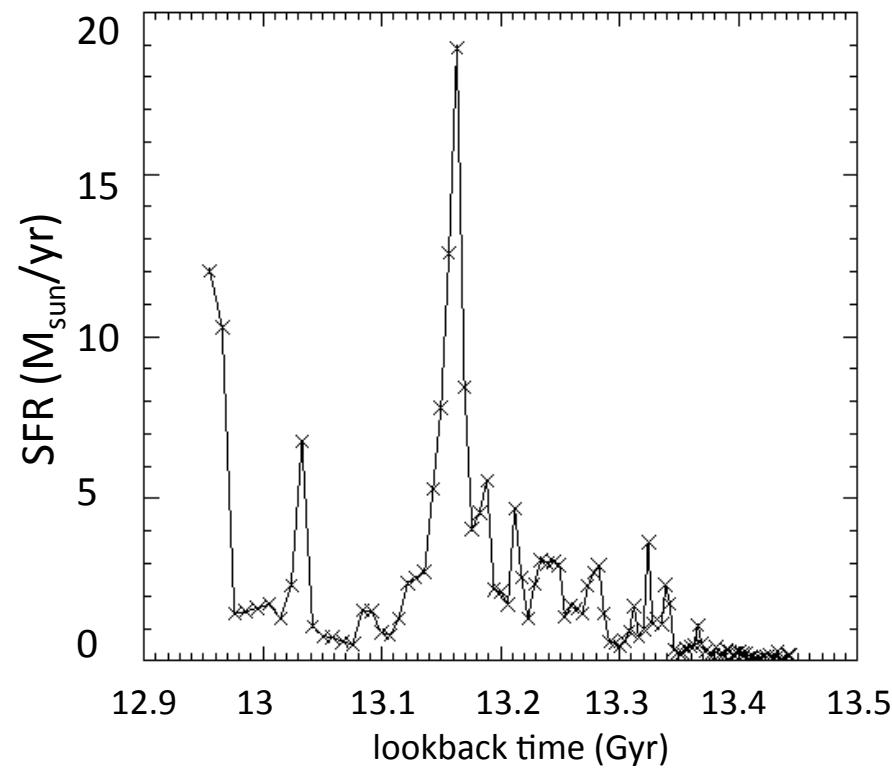


Break up
of
filaments?

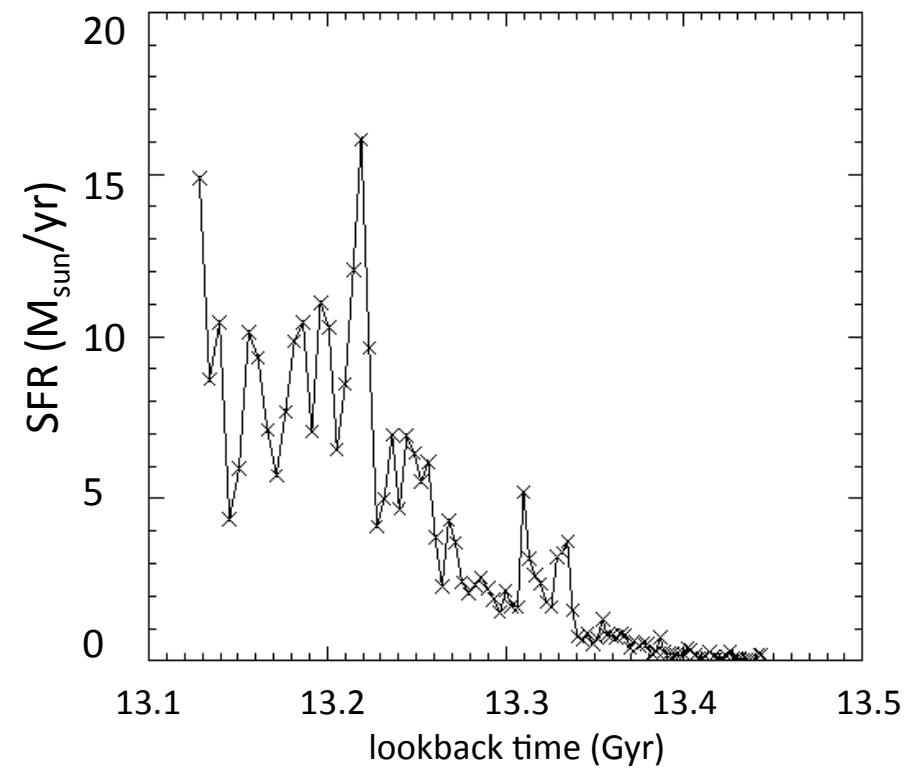


Star Formation Rate of main progenitor

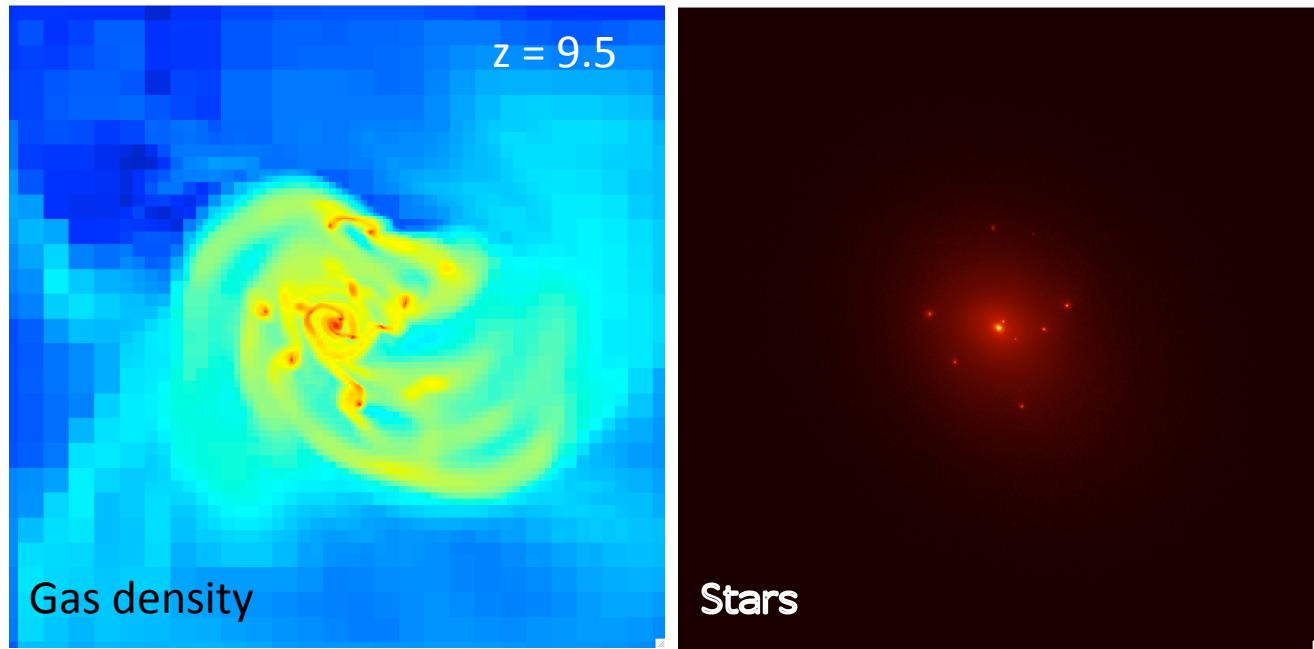
Cooling +star formation



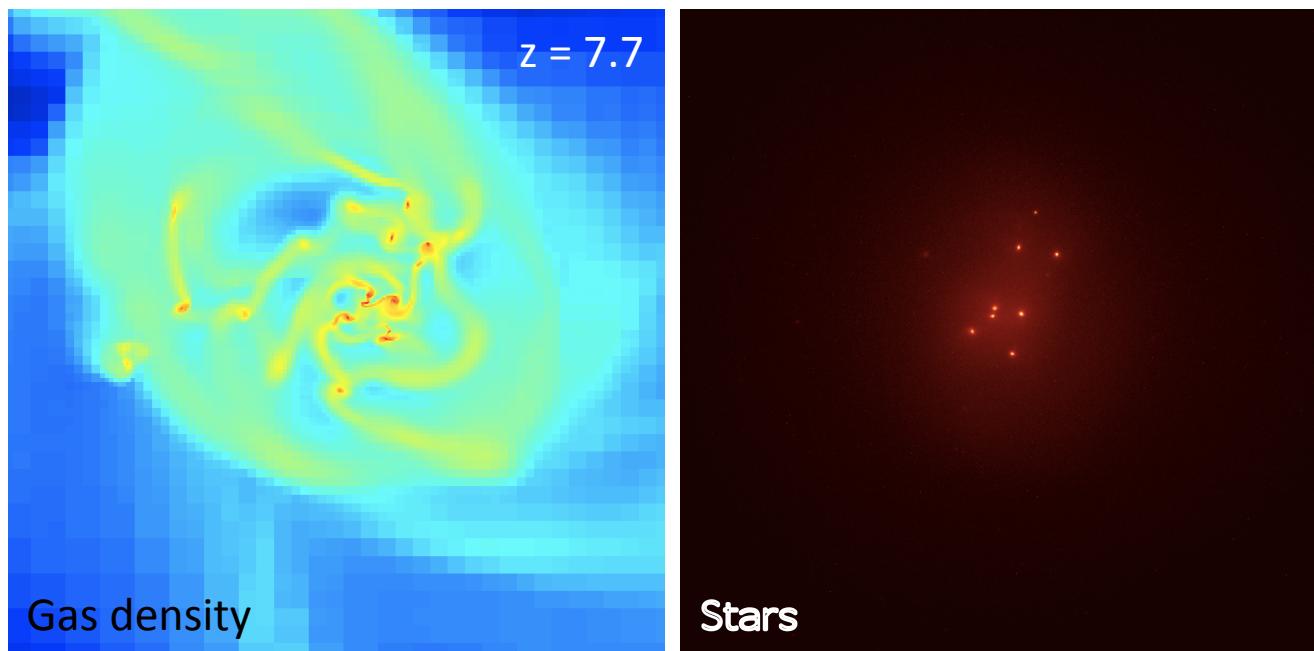
Cooling + star formation + supernovae fbk

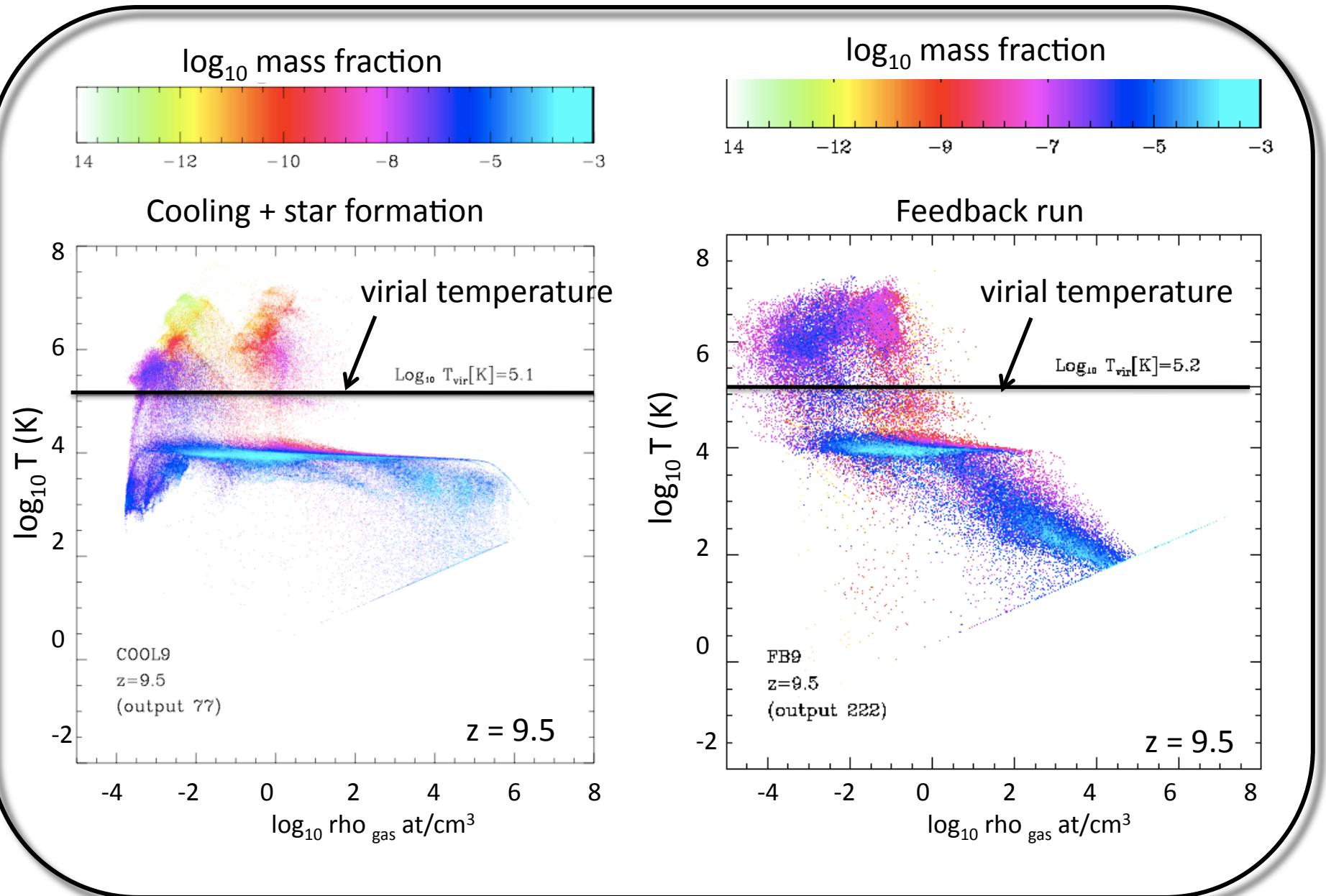


Feedback run

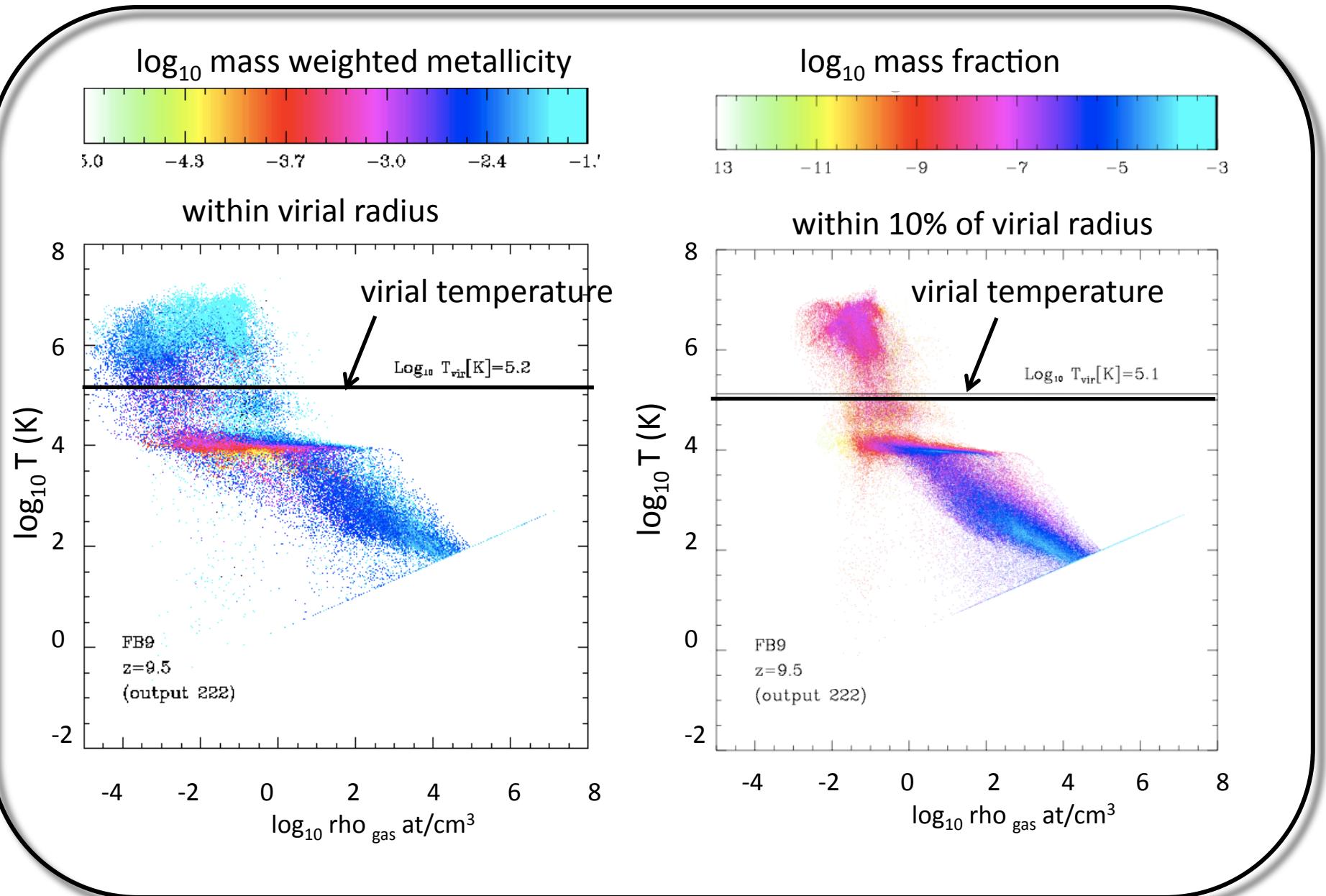


No Feedback run

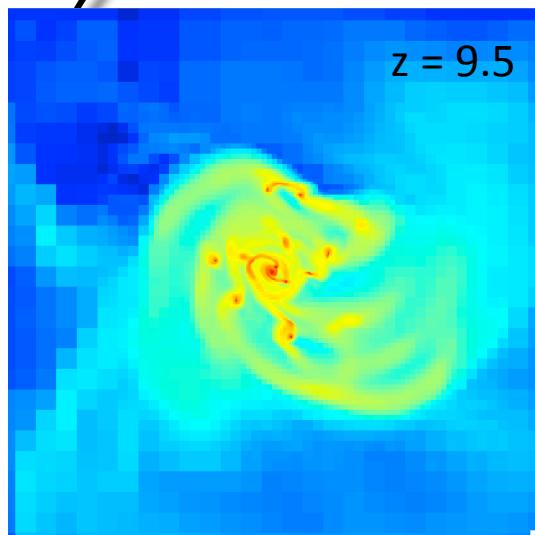




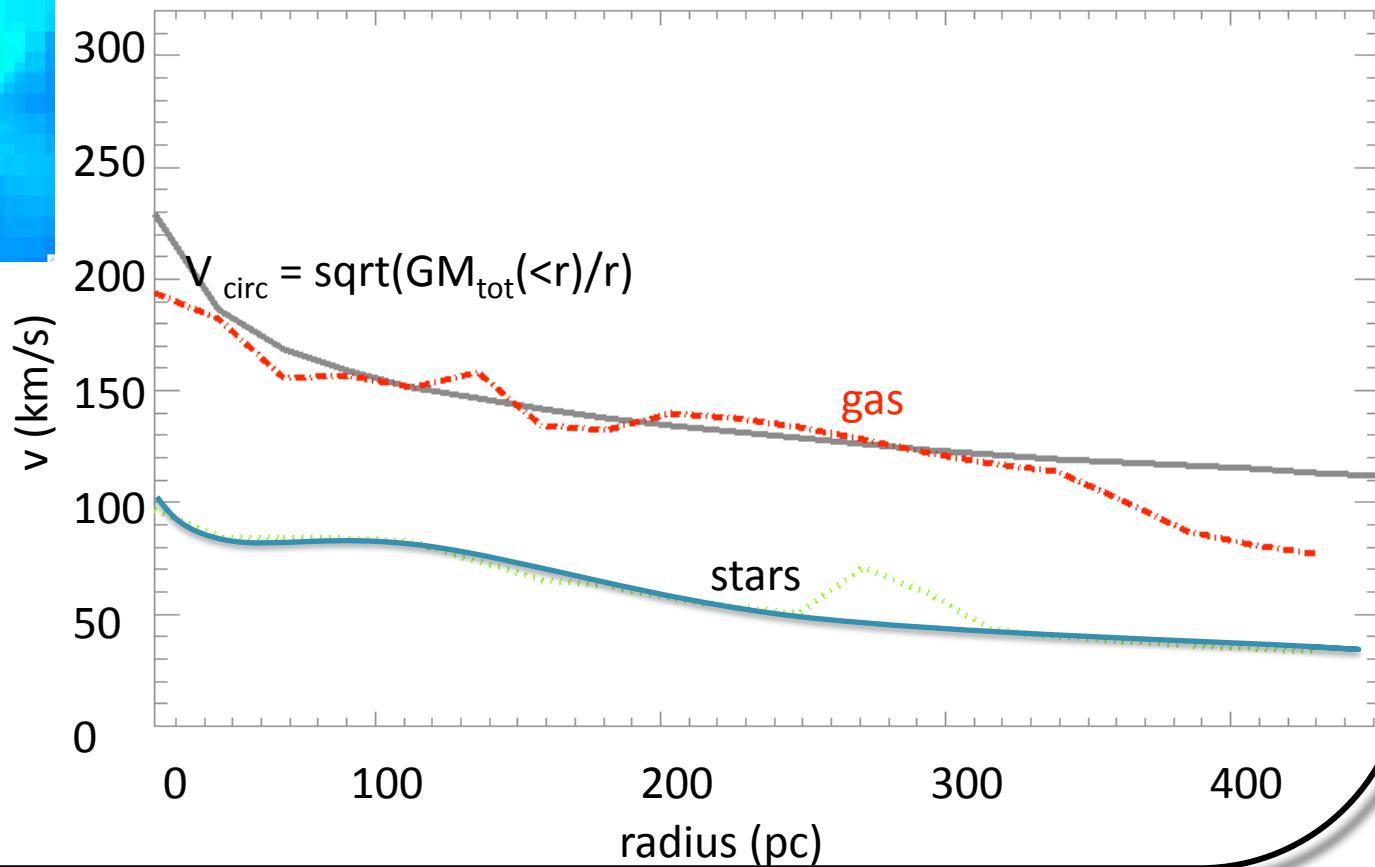
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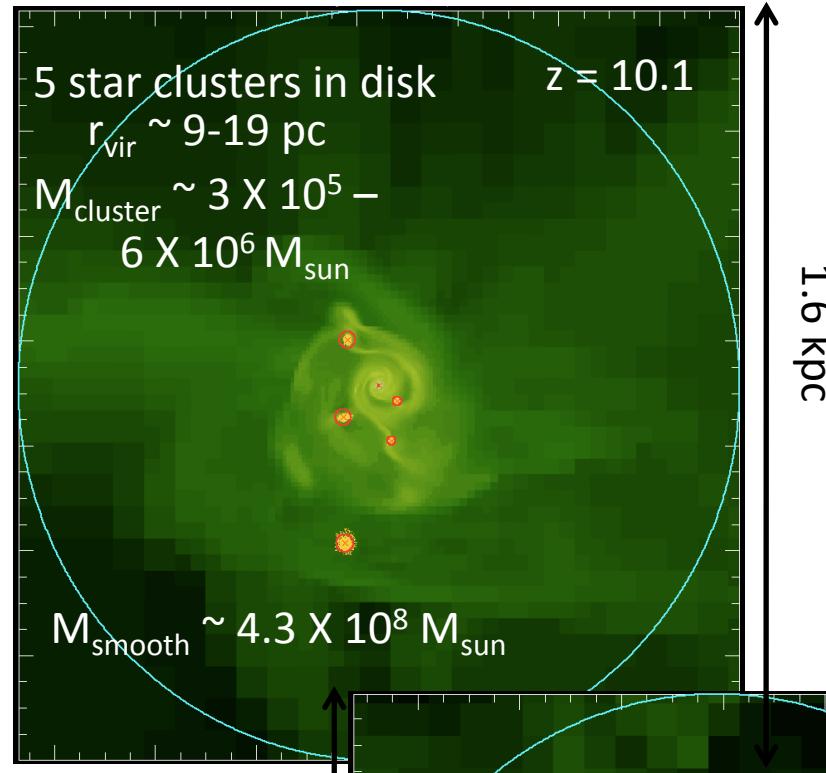
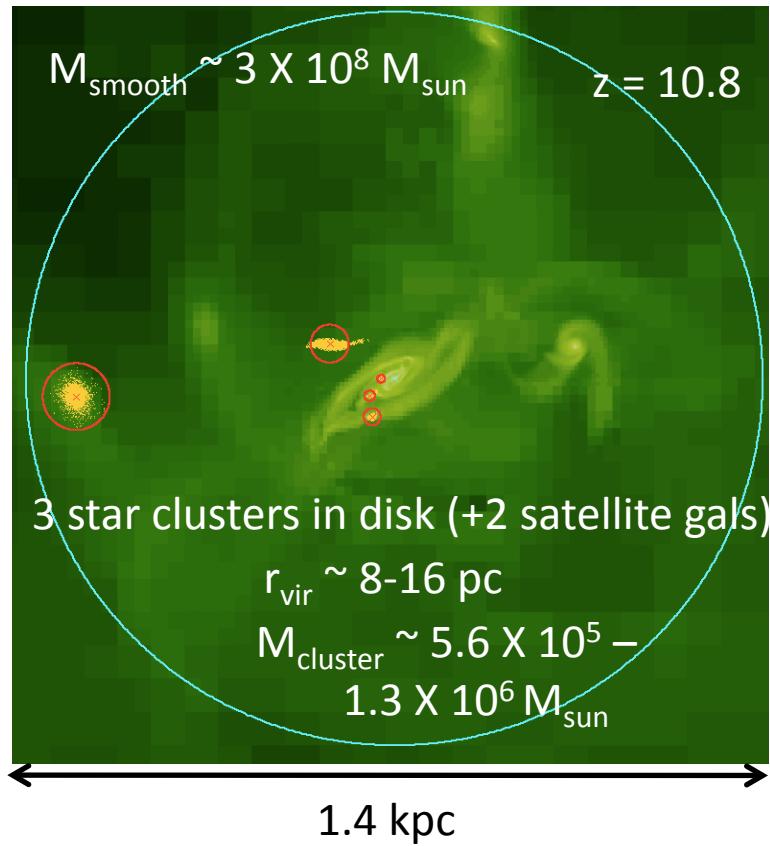


Disk Rotation Curves



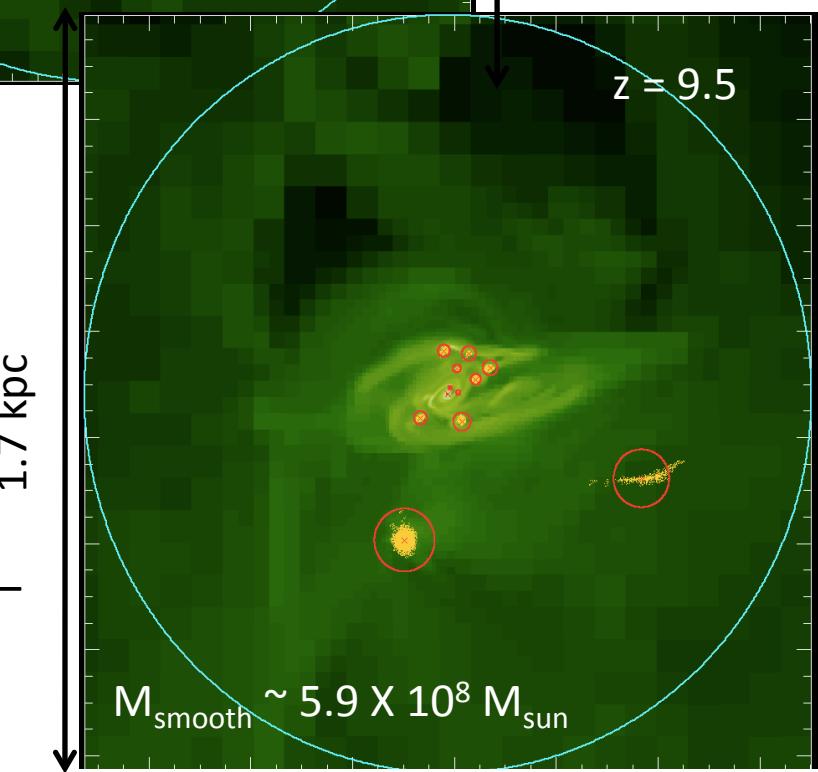
Gas rotationally supported within $\sim 10\%$ of virial radius



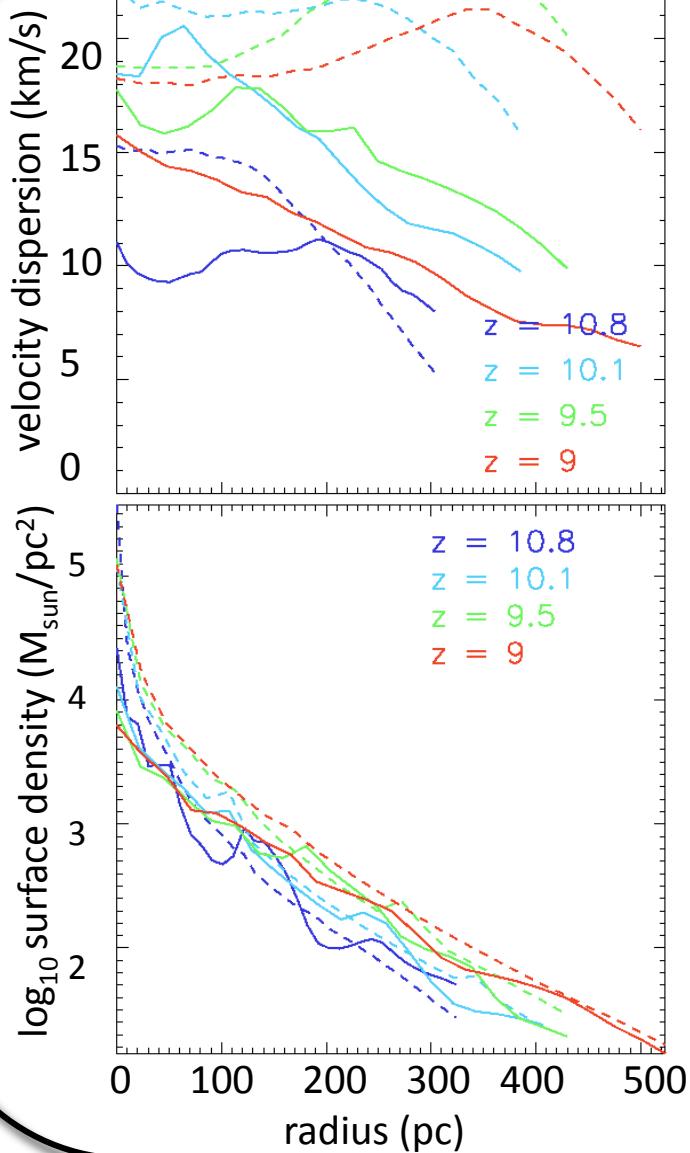


Measuring Star Cluster Properties

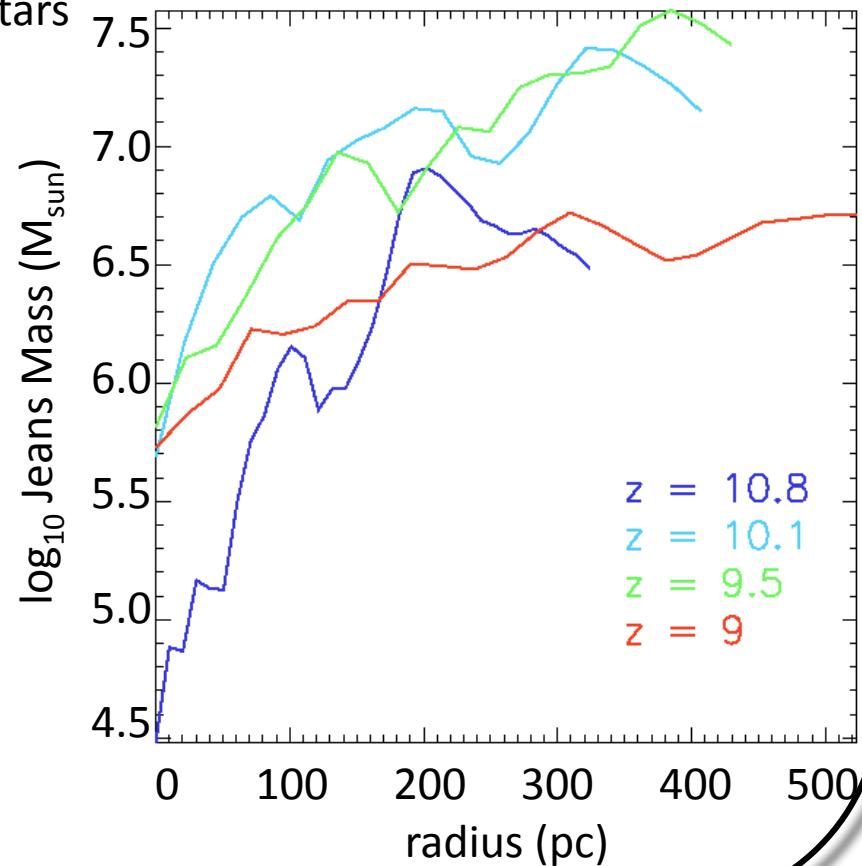
9 star clusters in disk
 (+2 satellite gals)
 $r_{\text{vir}} \sim 4-20 \text{ pc}$
 $M_{\text{cluster}} \sim 3.7 \times 10^4 - 7.9 \times 10^6 M_{\odot}$



Disk Fragmentation



solid: gas
dashed: stars



Conclusions

- 1) Star formation in high redshift galaxies happens under extreme conditions generating enormous winds reaching distances of few virial radii
- 2) Massive cluster formation seems to be an important mode of star formation