Multiphase gas in CGM: onset & structure

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Outline

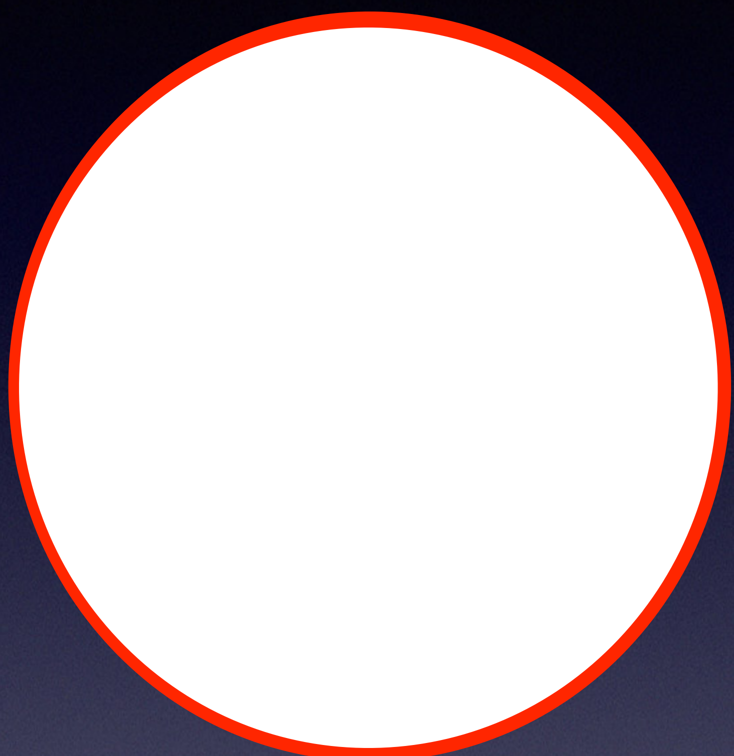
- Two independent problems: (i) *production*; (ii) *structure*

- Production: $t_{cool}/t_{ff}<10$ in HSE (galaxy clusters); seeding and growth in MP outflows (see Max Gronke's talk)

- What is structure (spatial, temporal, phase) of cold gas in turbulent CGM? An open question

Part I: production via TI in HSE

Condensation due to TI



hydrostatic equilibrium: $dp/dr = -\rho g$
gravity due to dark matter

heating~cooling at every radius
(to explain lack of cooling flows)

Emergent principle: condensation happens only when $t_{cool}/t_{ff} \lesssim 10$

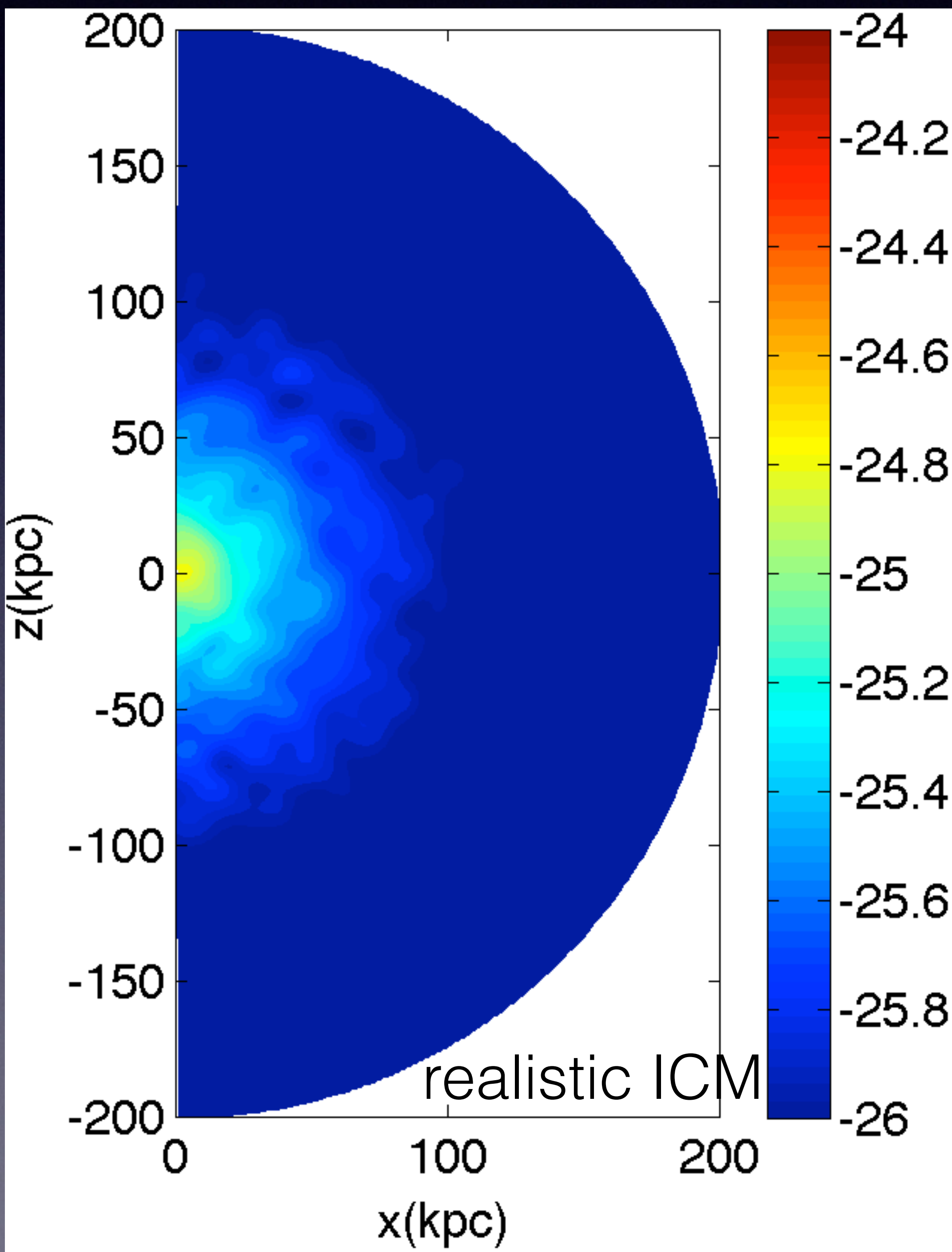
$$t_{\rm TI} \approx t_{\rm cool} = \frac{1.5 n k_B T}{n_e n_i \Lambda[T]}$$

$$t_{\rm ff} = \sqrt{\frac{2r}{g(r)}}$$

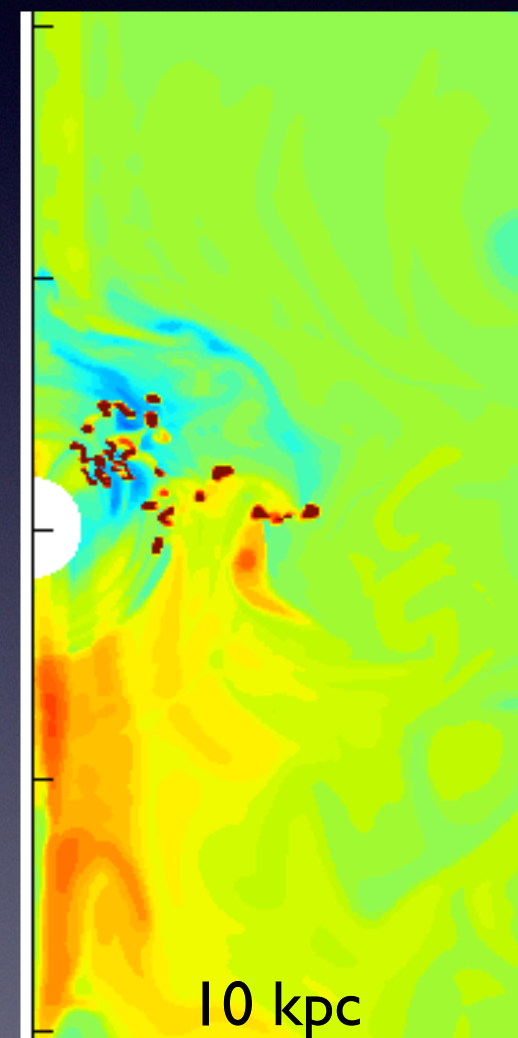
Idealised cluster sims.

[Sharma et al. 2012]

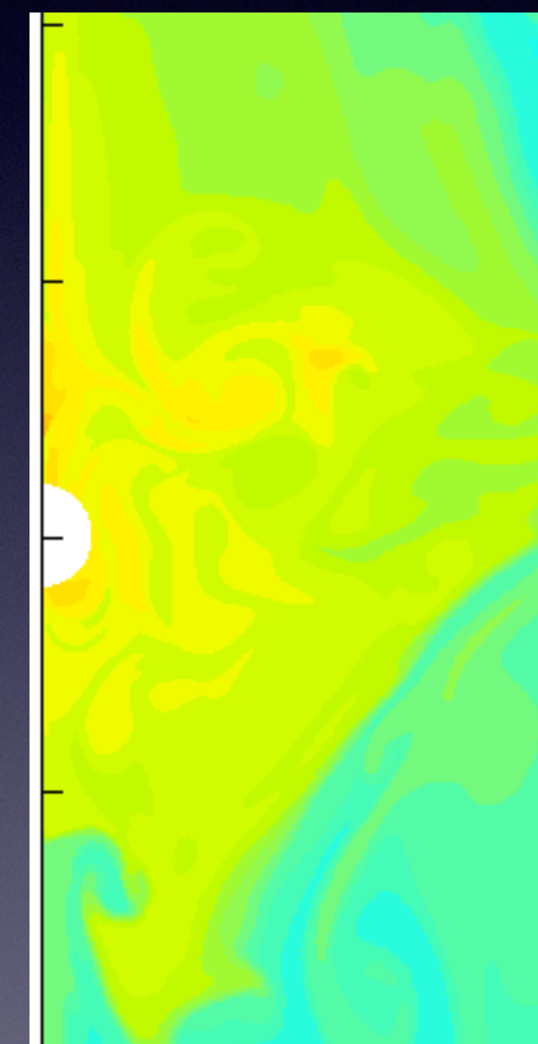
$\mathrm{Log}_{10}\,\rho$ (g cm^{-3})



multiphase
if $t_{cool}/t_{ff} < 10$



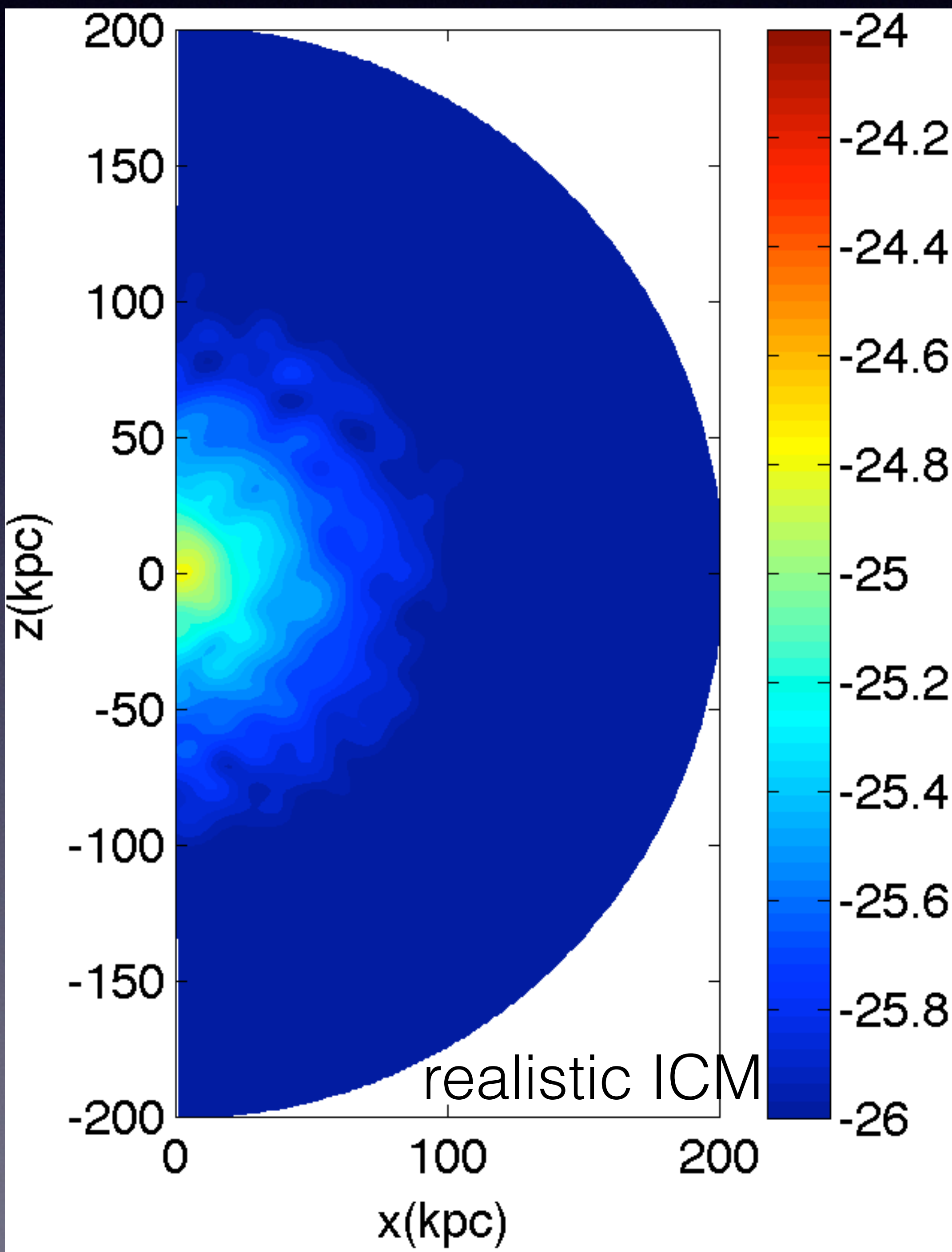
only hot phase
if $t_{cool}/t_{ff} > 10$



Idealised cluster sims.

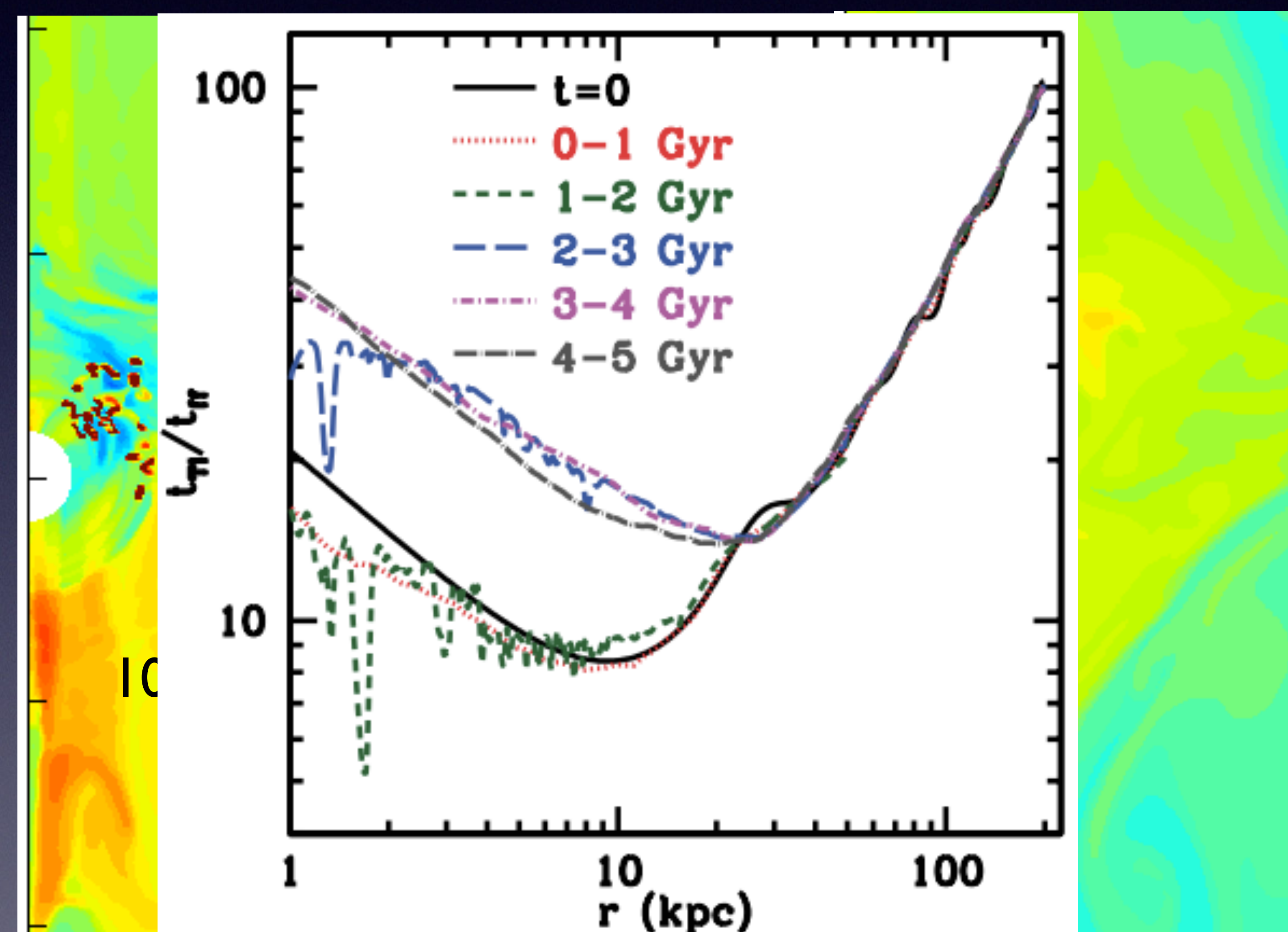
[Sharma et al. 2012]

$\text{Log}_{10}\ \rho$ (g cm^{-3})

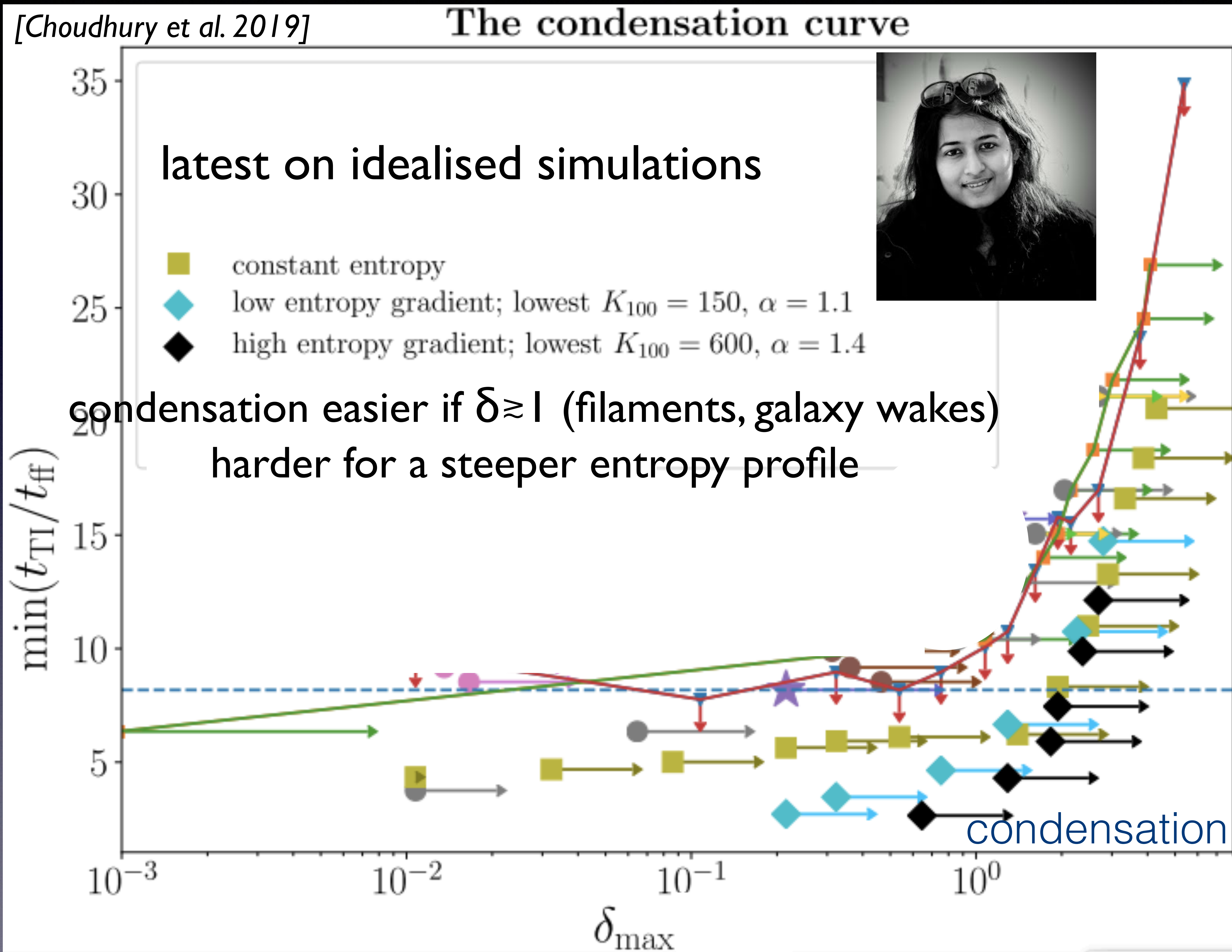


multiphase if $t_{cool}/t_{ff} < 10$

only hot phase if $t_{cool}/t_{ff} > 10$



excess gas from core condenses & $t_{cool}/t_{ff} \gtrsim 10$


[Choudhury et al. 2019]
The condensation curve
latest on idealised simulations
constant entropy
low entropy gradient; lowest $K_{100} = 150$, $\alpha = 1.1$
high entropy gradient; lowest $K_{100} = 600$, $\alpha = 1.4$
condensation easier if δ≳1 (filaments, galaxy wakes)
harder for a steeper entropy profile
condensation
$\min(t_{\rm TI}/t_{\rm ff})$
$\delta_{\rm max}$
35
30
25
20
15
10
5
10^{-3}
10^{-2}
10^{-1}
10^{0}

1-D model for CGM

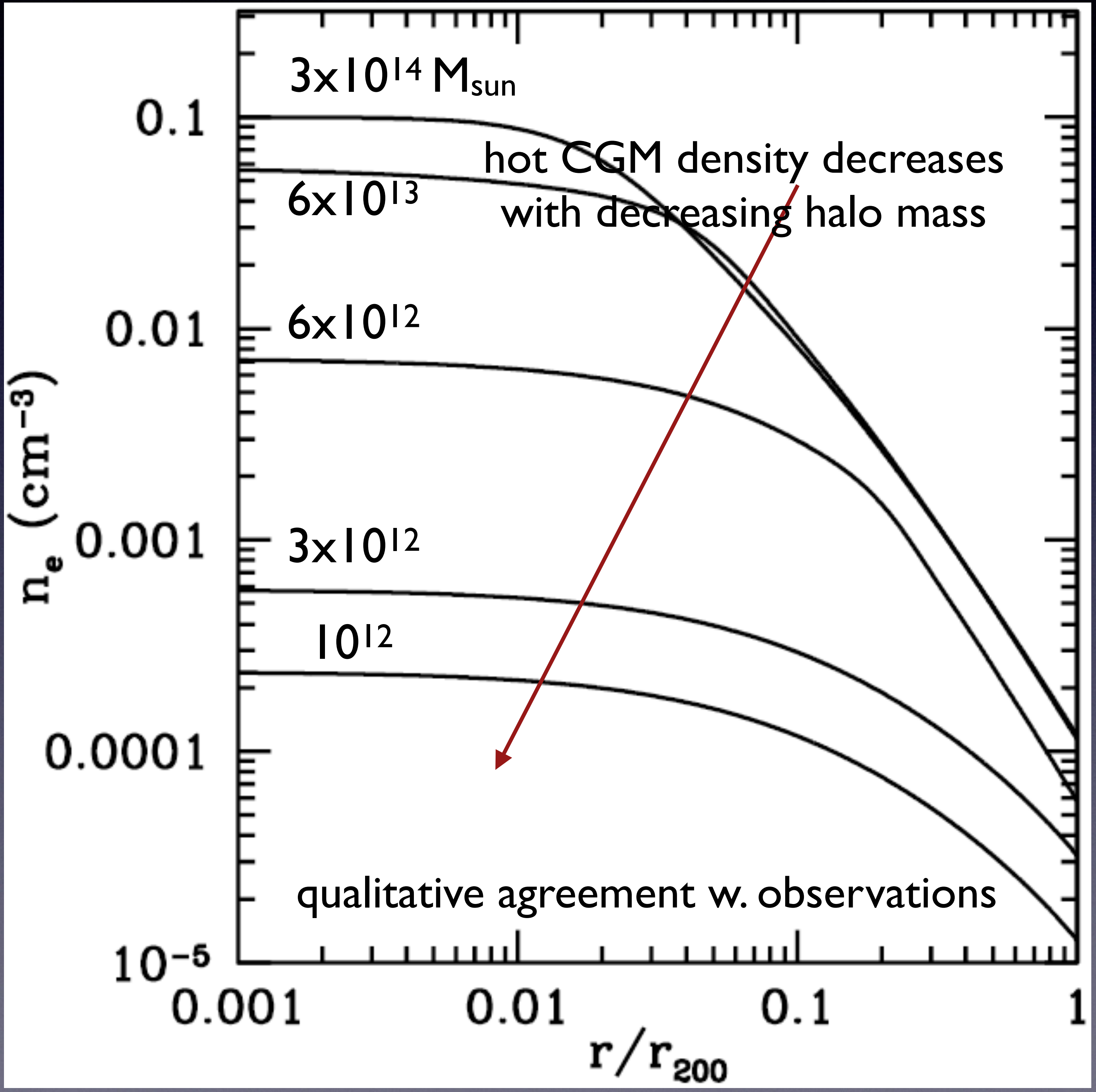
[Sharma et al. 2012]

"universal" gas profile close to r_{200}

integrate inward w. hydrostatic eq.
calculate t_{cool}/t_{ff}
if $t_{cool}/t_{ff} < 10$, introduce core

upper limit on core density in thermal eq.

=> very dilute & large Galactic halo



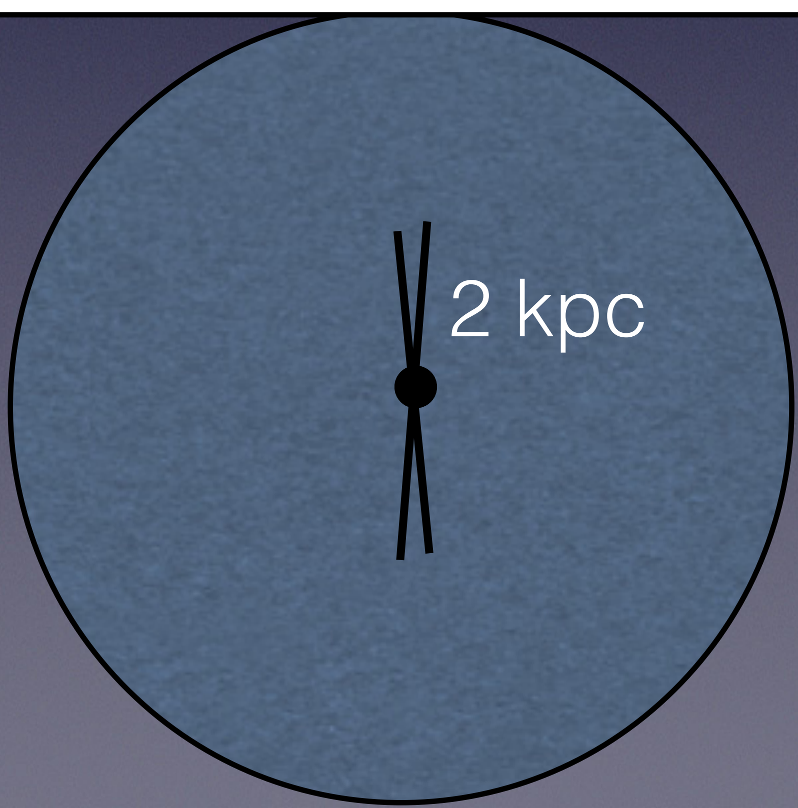
AGN jet-ICM sims.

[Prasad et al. 2015]

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = S_\rho$$ mass

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p - \rho \nabla \Phi + S_\rho v_{\rm jet} \hat{\mathbf{r}}$$ momentum

$$\frac{p}{\gamma - 1} \frac{d}{dt} \ln(p/\rho^\gamma) = -n^2 \Lambda$$ internal energy



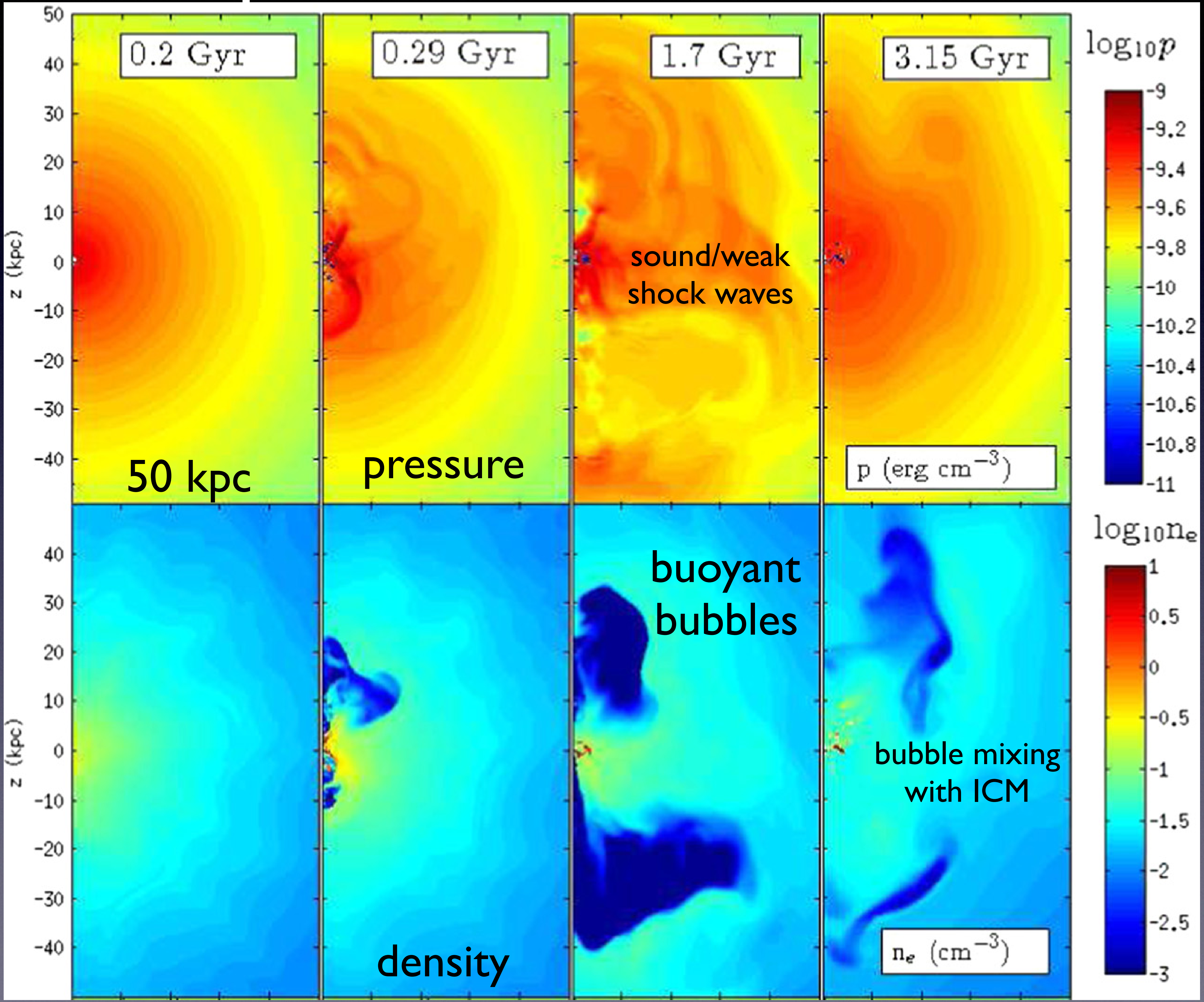
source term applied in a small bipolar cone at the center: opening angle of 30^0, size 2 kpc

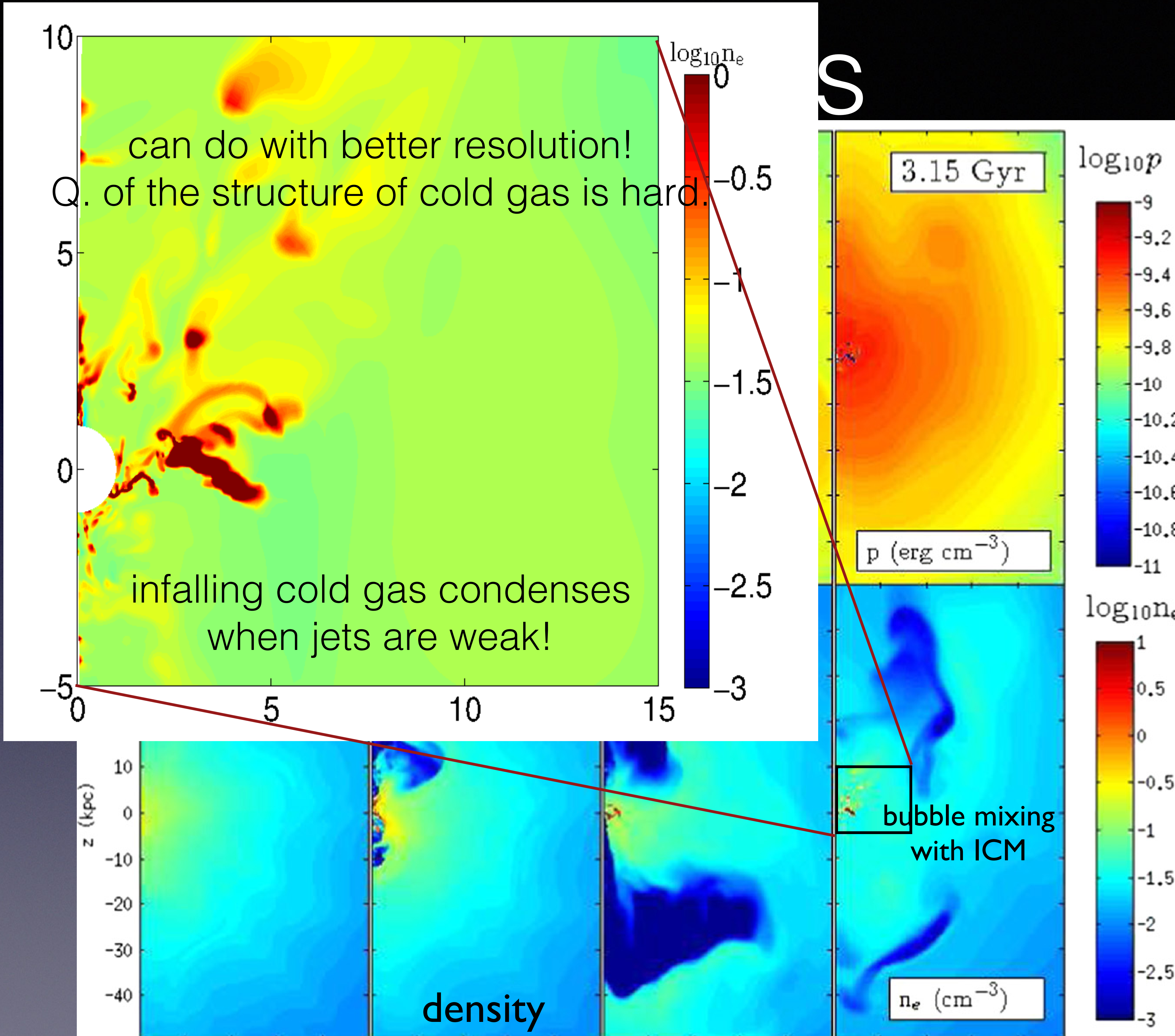
$$\dot{M}_{\rm jet} v_{\rm jet}^2 = \epsilon \dot{M}_{\rm acc} c^2$$

v_{jet}=0.1c, $\epsilon=6\times10^{-5}$, $r_{in,out}$=1, 200 kpc

robust to variations

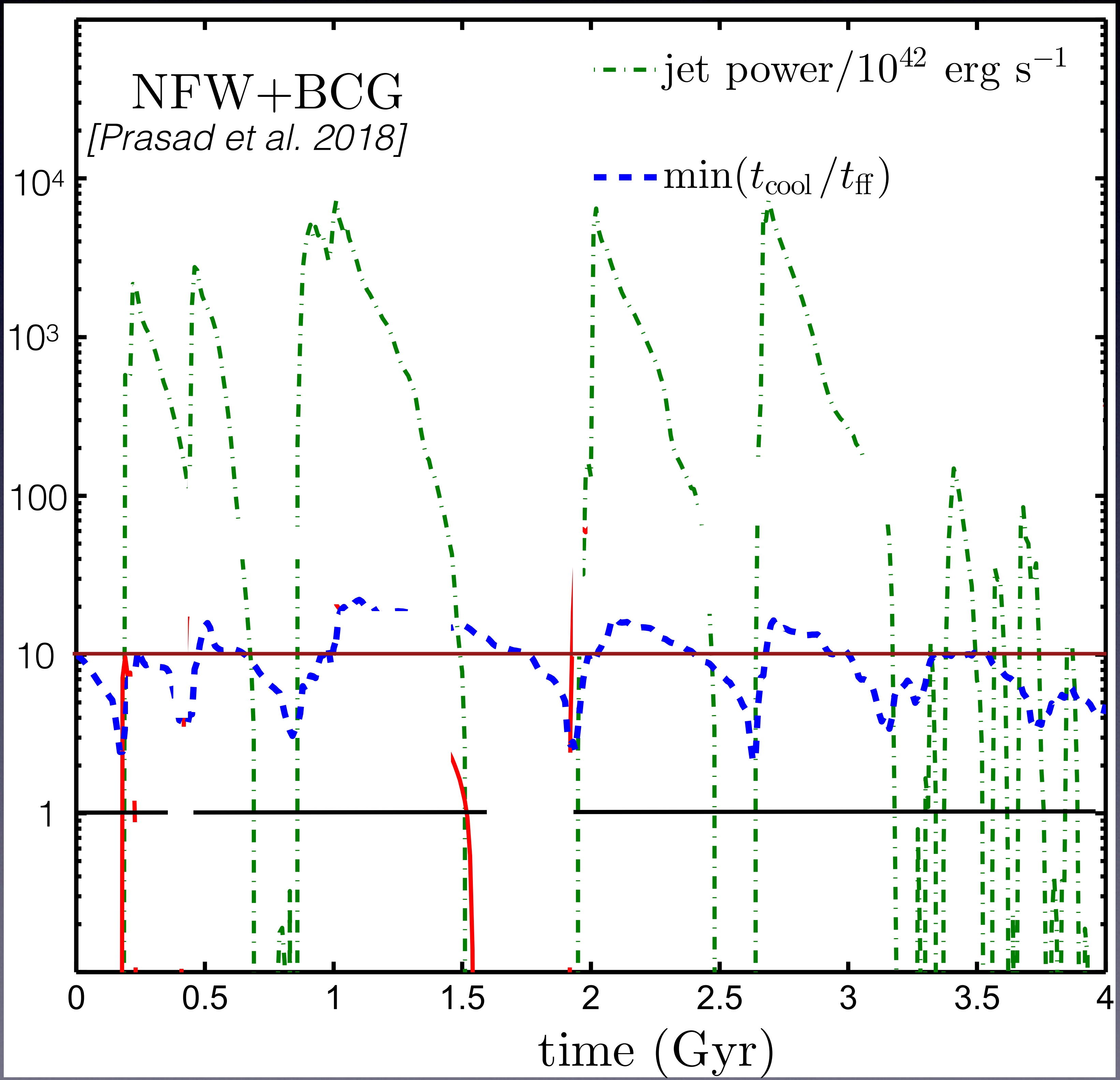
poloidal slices





can do with better resolution!
Q. of the structure of cold gas is hard.
infalling cold gas condenses
when jets are weak!
log10ne
3.15 Gyr
log10p
p (erg cm−3)
log10ne
ne (cm−3)
z (kpc)
bubble mixing
with ICM
density

Cool-core cycles



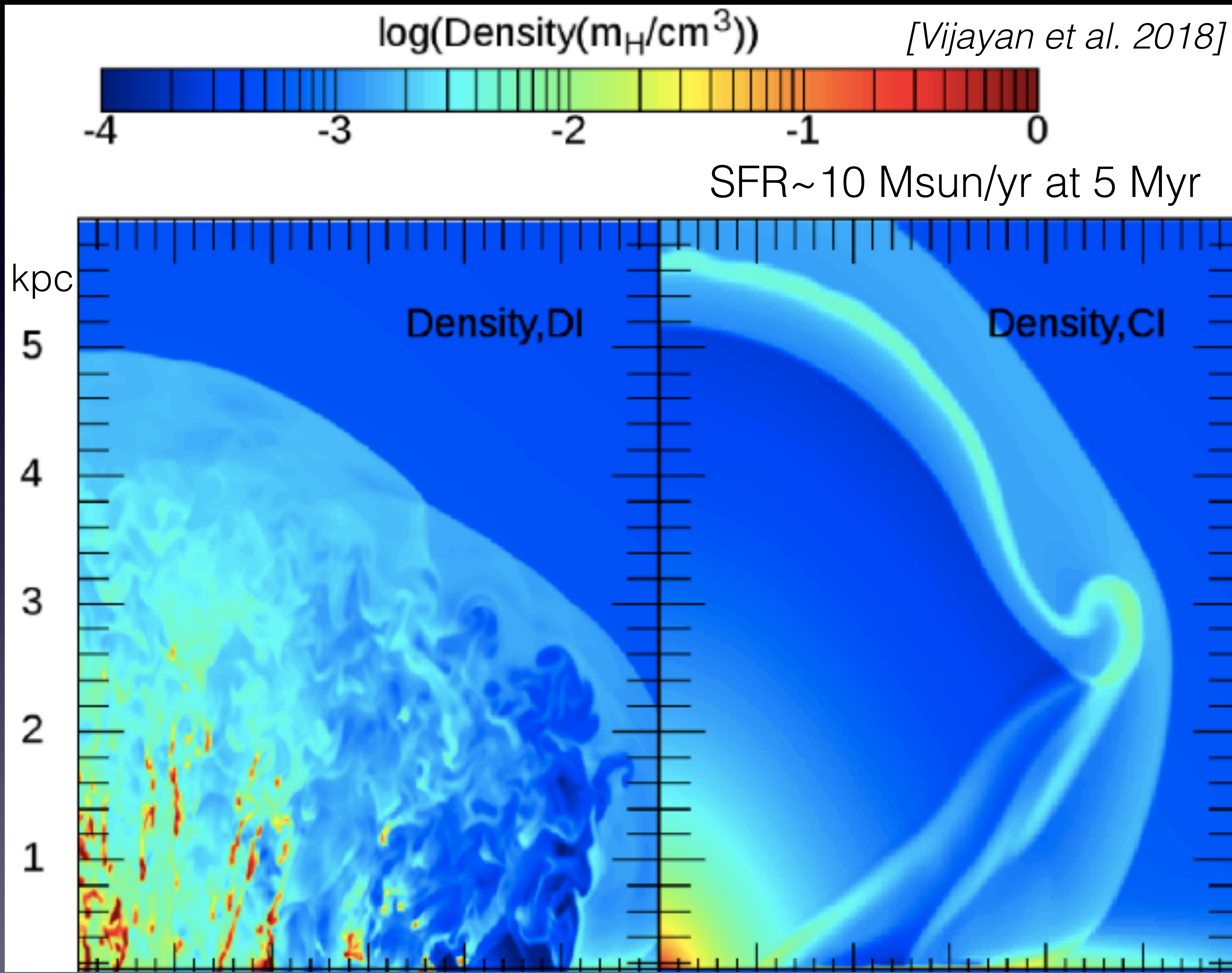
repeating cycles of cooling & heating

fewer cycles for higher ε

min(t_{cool}/t_{ff}) between a few and 20

huge variation in jet power

MP gas in galactic outflows



central injection doesn't give MP clouds

similar conclusions from Schneider et al. 2018

Where do cold clouds in galactic outflows come from in the first place? seeds needed to grow cold gas

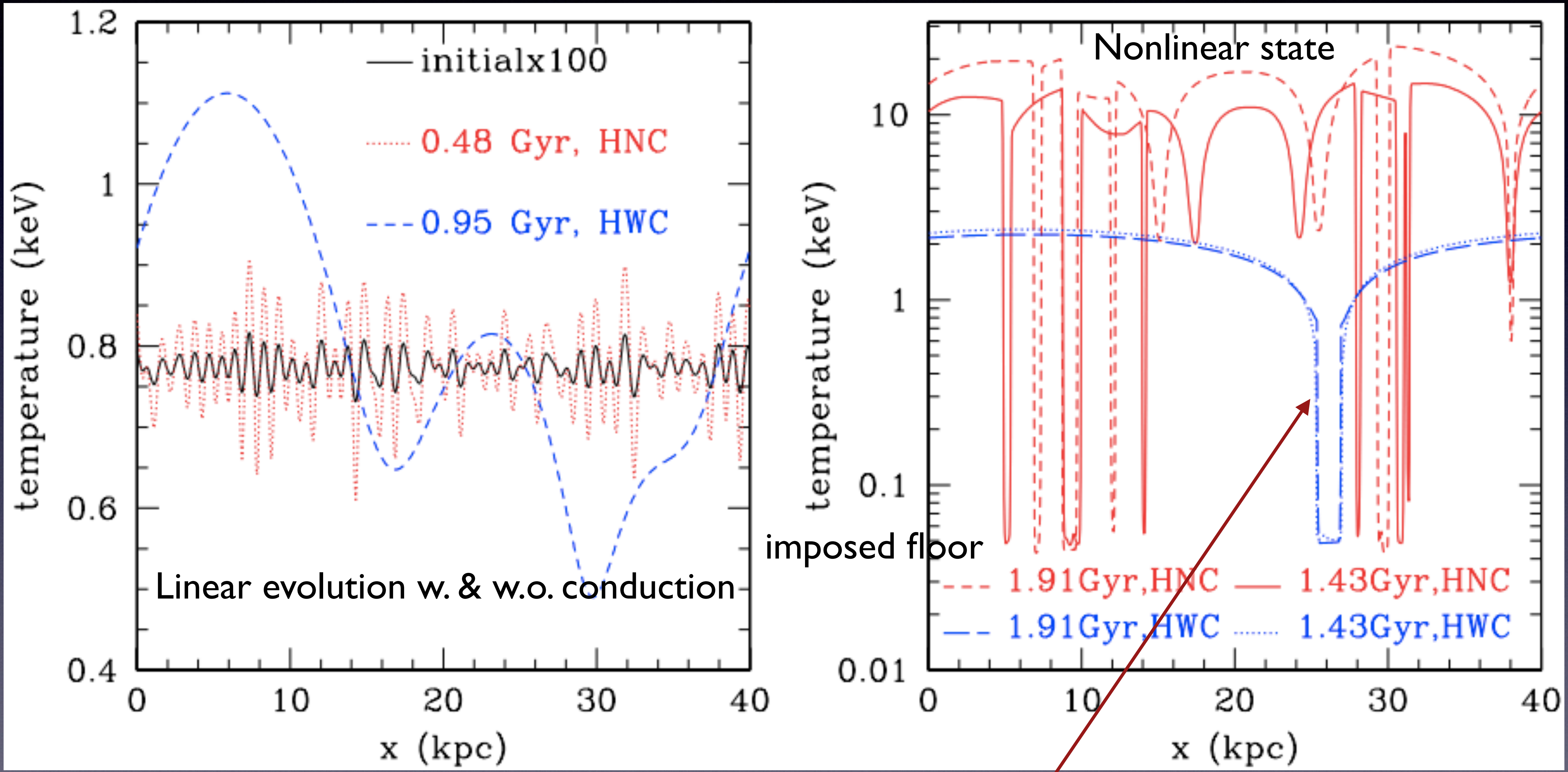
from multiple *SN spread throughout* disc throwing up cold clouds

Part II: structure of MP gas

What is the *structure* of cold gas once it is produced?
Presumably independent of *how* it is produced.

Nonlinear evolution of TI

[Sharma et al. 2010]



nonlinearly, dense regions *merge* (*not fragment as in a mist*!), forming a quasi-steady structure (see also Waters+Proga '19)

What happens in a realistic turbulent medium?

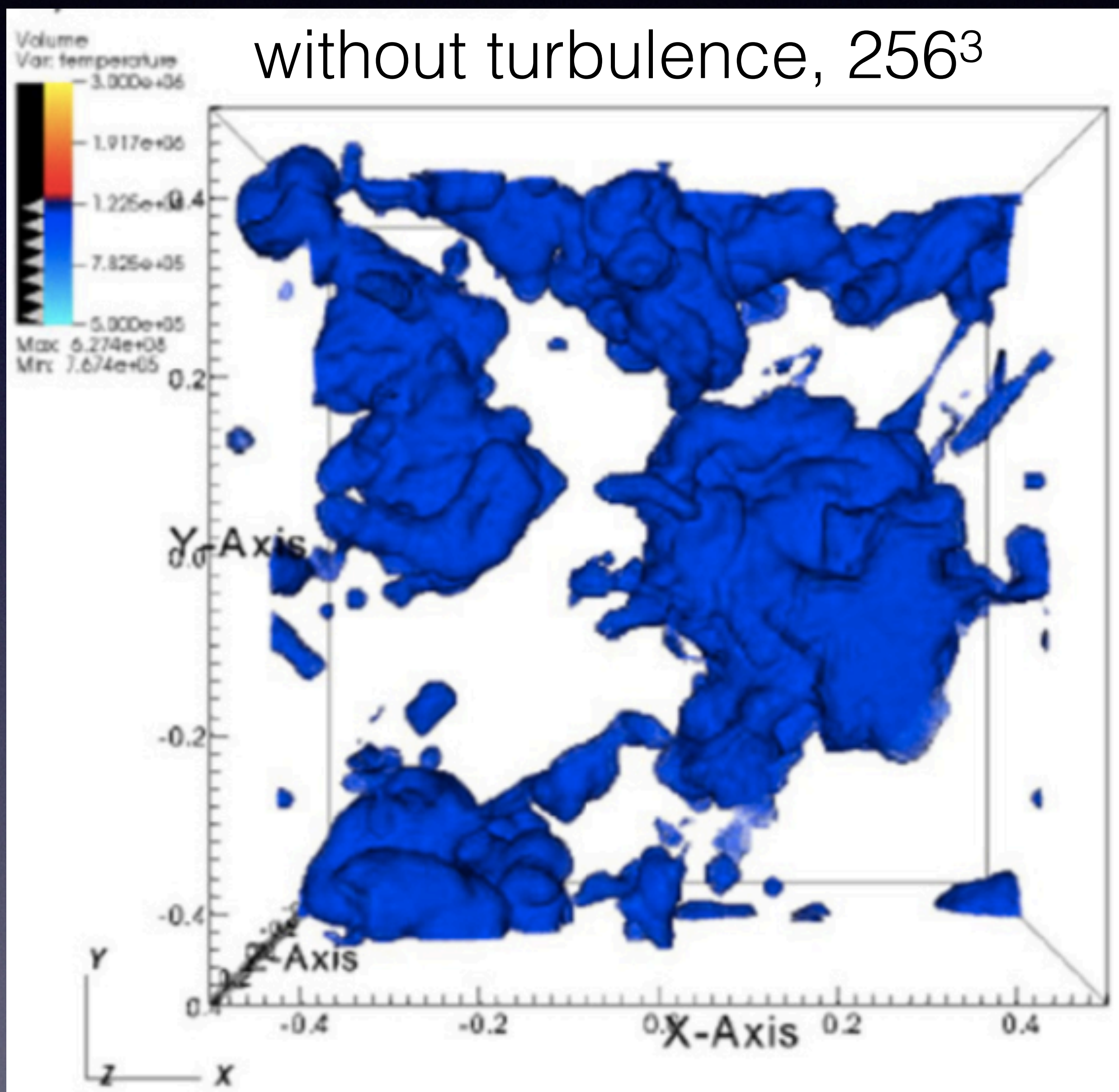
With turbulence?

CGM likely to be turbulent: see Eugene's talk

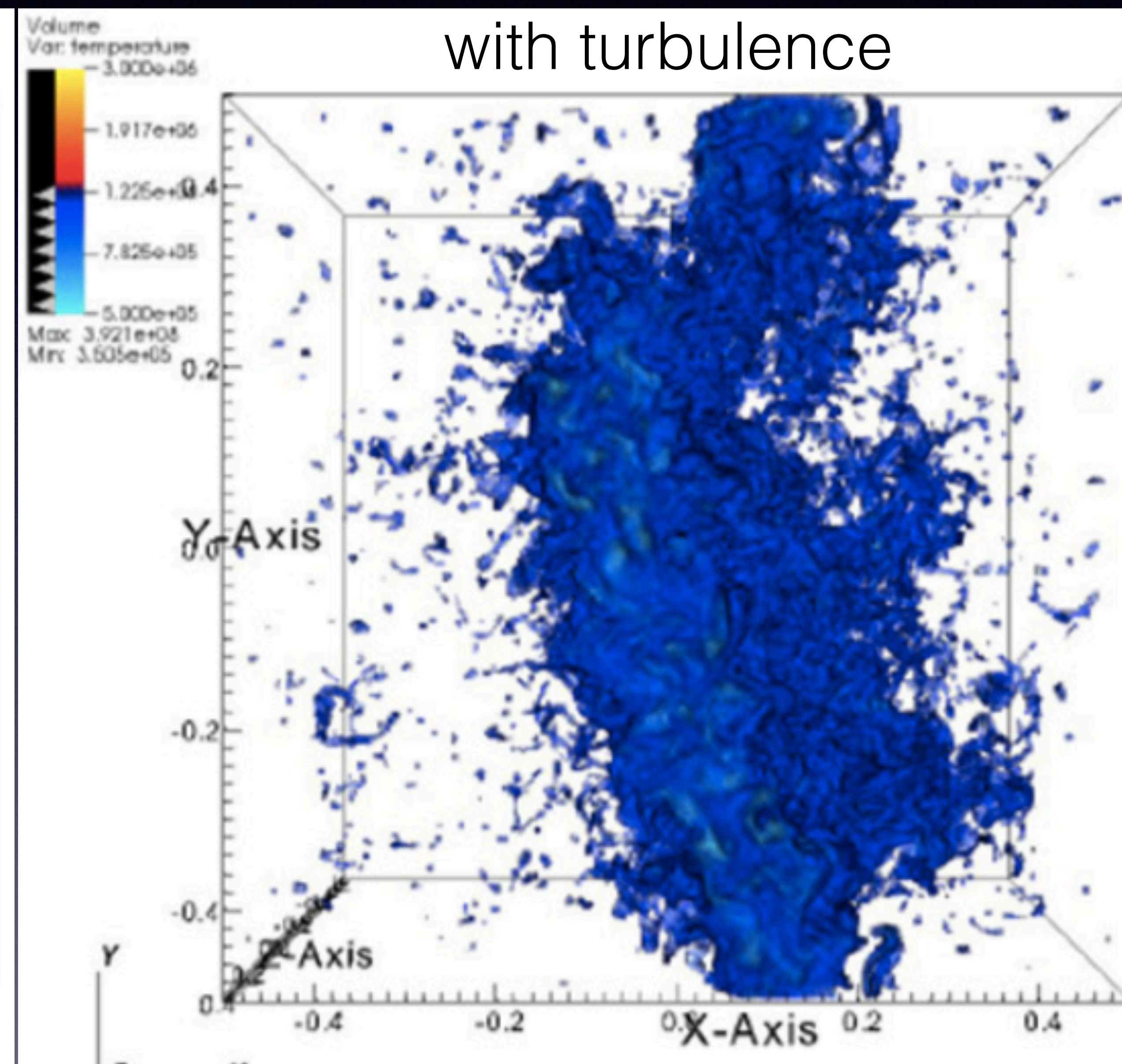
Volume rendering of cold structures

[Mohapatra & Sharma 2012]

without turbulence, 256^3



with turbulence



evolution without turbulence
shows nonlinear coalescence

turbulence determines structure of cold gas
MP gas is created & destroyed dynamically
variability in LOS properties of cold gas

Conclusions

- production of cold gas in HSE due to TI (t_{cool}/t_{ff})
- cold clouds thrown up by SN in disk can seed growth of MP gas via Gronke-Oh mechanism; need to study this in realistic setups
- nonlinear structure of cold gas not as well understood: coalesce in absence of driving, highly variable in presence of turbulence

Thank You!