To shatter, or not to shatter?

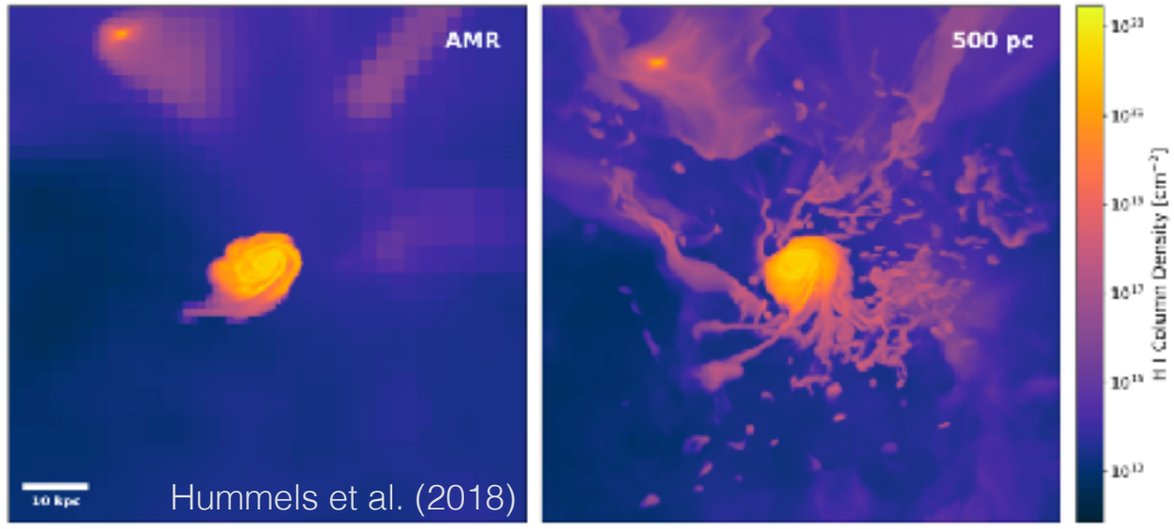
The search for a converged model of the CGM

or: What happens to a gas potato in the CGM?

MaxGronke
Hubble fellow/UCSB

with PengOh

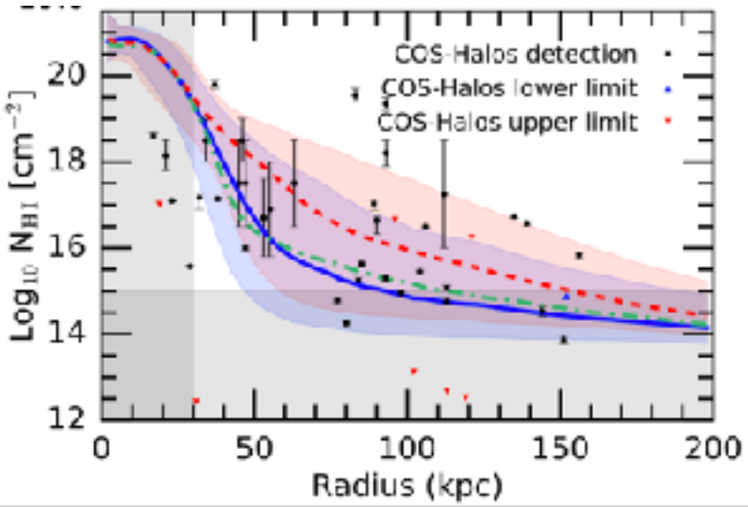
The issue of non-convergence



Hummels et al. (2018)

dian column density value, primarily in the interior 40 kpc (about half the virial radius). However, the entire median H I column density profile is boosted at all impact parameters for our highest-resolution (500 pc) simulation, increasing observed H I column densities by a factor of two throughout the halo. No convergence in this behavior is seen, suggesting that additional EHR will lead to even larger observed H I column densities.

also see
Faucher-Giguère et al. (2016)
Peeples et al. (2018)
Suaresh et al. (2018)



…as seen in Freeke's talk!

+ multiple observations suggesting small-scale structure.

e.g., Rauch et al. (1999), Rigby et al. (2002), Shaye et al. (2007), Lau et al. (2015), Churchill et al. (2003), Crighton et al. (2015), Lan et al. (2017)…

standard simulation with only mass refinement. However, the median neutral hydrogen column density is much higher in the 1 kpc spatially refined simulation, by up to 1.6 dex. The H I column density could potentially increase even further, because the results are not yet converged. The scatter between H I sightlines is large in all simulations, especially

van de Voort et al. (2018)

Hindering comparison to observations:

(mis)match due to model or numerics?

The road to convergence

1. What is the characteristic scale of cold gas in the CGM?

2. Can we (soon) resolve it?

Yes

Great!

No

Subgrid model?

"Schwerbelastungskörper"

Two scales in this talk:

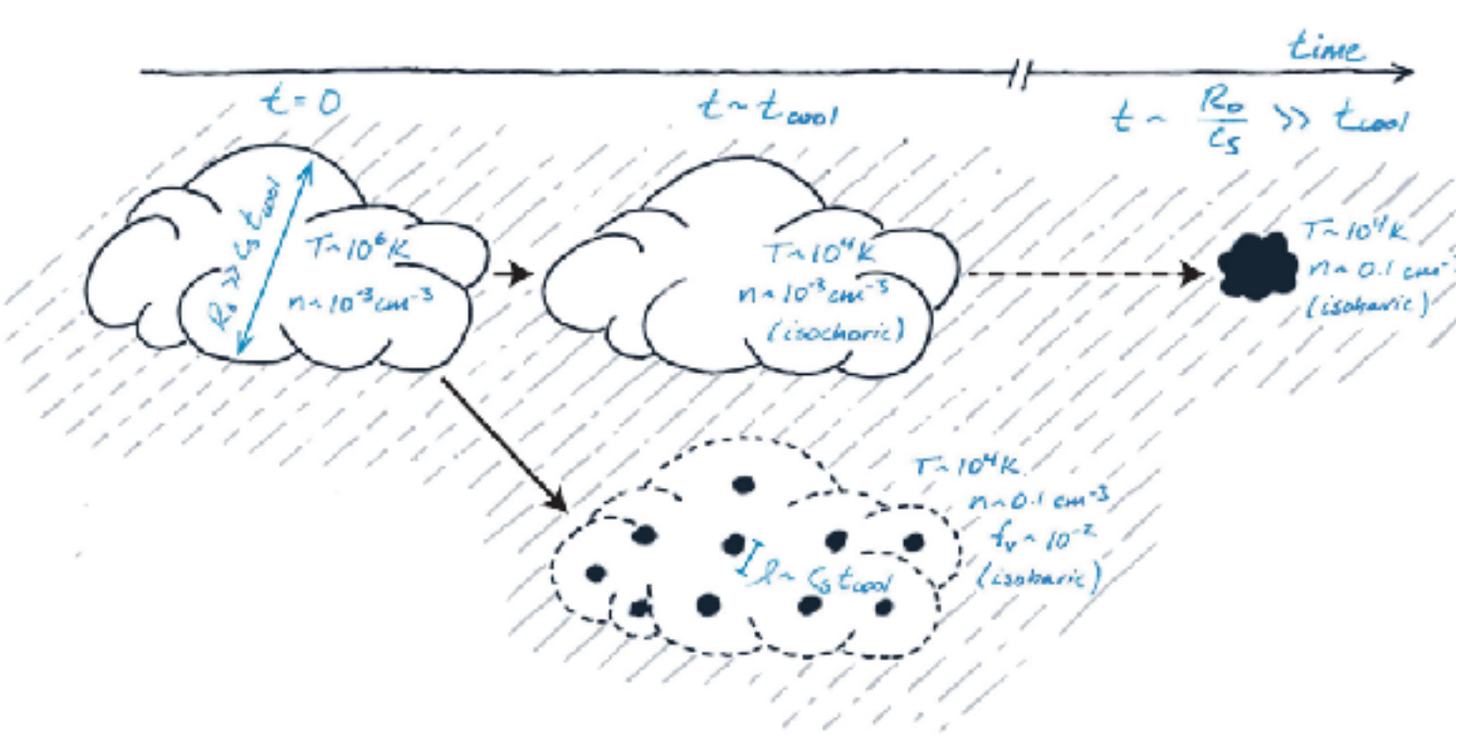
(a) ***shattering*** scale

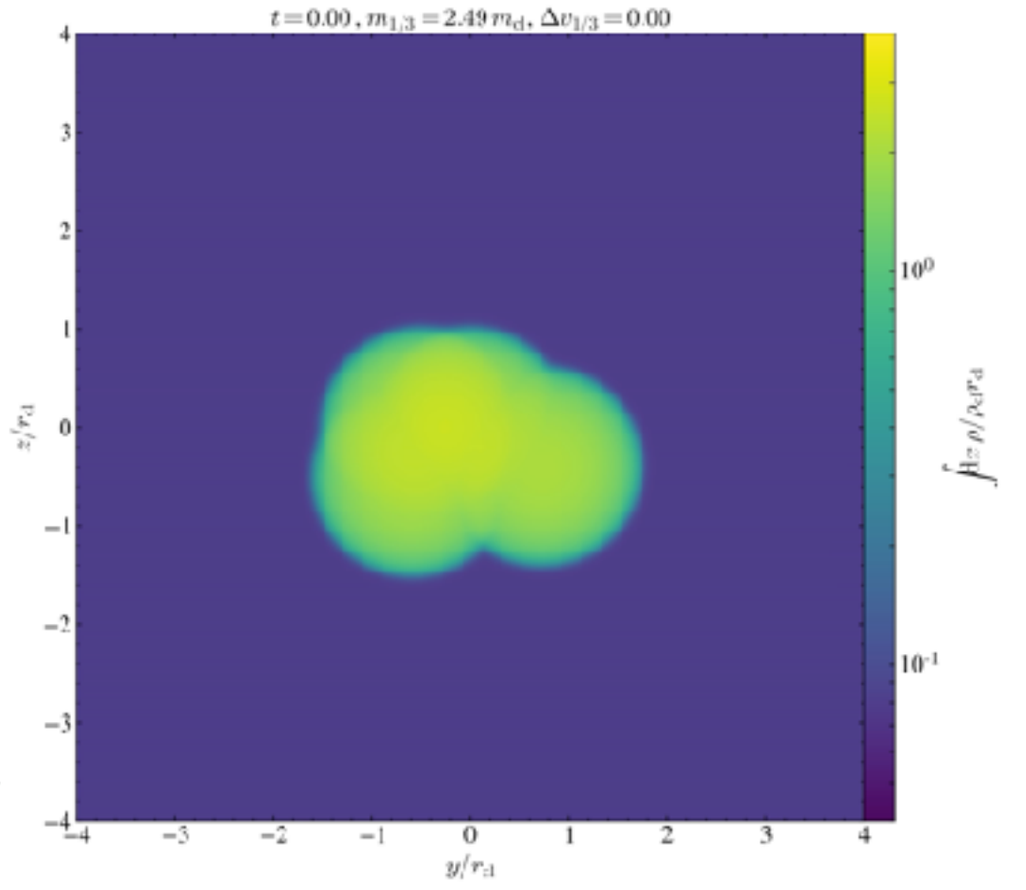
(b) ***survival*** length

(a) shattering scale

A characteristic scale for cold gas

Michael McCourt,[1★†] S. Peng Oh,[1★] Ryan O'Leary[2] and Ann-Marie Madigan[2,3]



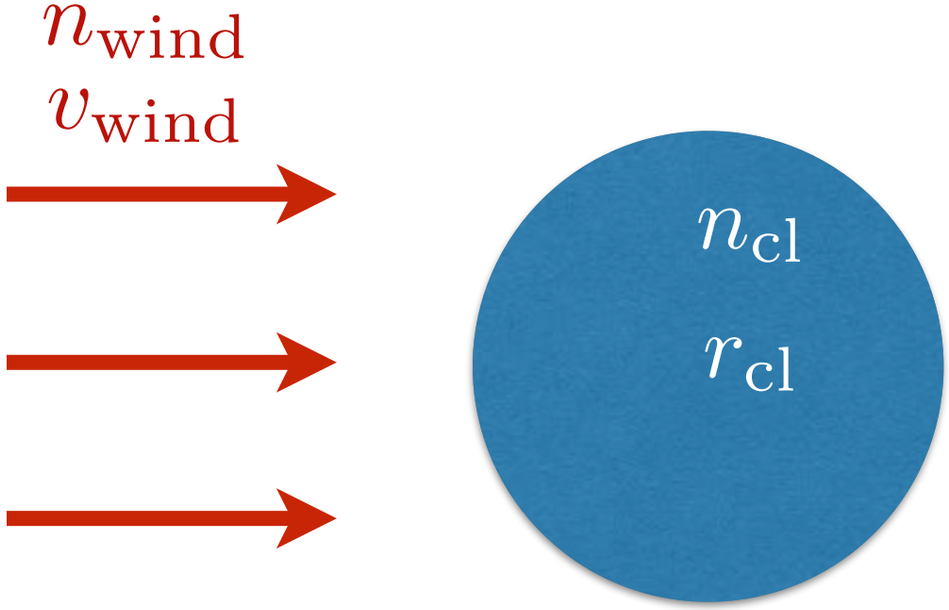


…as also seen in Cameron's talk.

$$l_{\text{shatter}} \sim \min(c_s t_{\text{cool}}) \sim 0.1\,(n/\text{cm}^{-3})^{-1}\,\text{pc}$$

Problem: will droplets survive?

Cloud survival in a hot medium



Destruction time

$$t_{\rm cc} \sim \chi^{1/2} \frac{r_{\rm cl}}{v_{\rm wind}}$$

$$\text{with } \chi \equiv \frac{n_{\rm cl}}{n_{\rm wind}}$$

Acceleration time

$$t_{\rm drag} \sim \chi \frac{r_{\rm cl}}{v_{\rm wind}}$$

$$\chi \equiv \frac{n_{\rm cl}}{n_{\rm wind}} \sim \frac{T_{\rm wind}}{T_{\rm cl}} \gtrsim 100 \Rightarrow t_{\rm drag} \gg t_{\rm cc} \Rightarrow$$ Cloud destroyed quickly!

but if $t_{\rm cool,mix} < t_{\rm cc}$ cloud will survive!

MG & Oh (2018)

↓

cooling time of *mixed* gas ($T_{\rm mix} \sim \sqrt{T_{\rm cl} T_{\rm wind}}$)

Begelman & Fabian (1990)

(b) survival length

Require $t_{cool,mix} < t_{cc}$ for cold gas survival

reminder: $t_{\rm cc} \sim \chi^{1/2} \dfrac{r_{\rm cl}}{v_{\rm wind}}$

$$r_{\rm cl} > r_{\rm cl,crit} \equiv \frac{v_{\rm wind} t_{\rm cool,mix}}{\chi^{1/2}} \approx 2\,{\rm pc}\ \frac{T_{\rm cl,4}^{5/2}\mathcal{M}_{\rm wind}}{P_3 \Lambda_{\rm mix,-21.4}} \frac{\chi}{100}$$

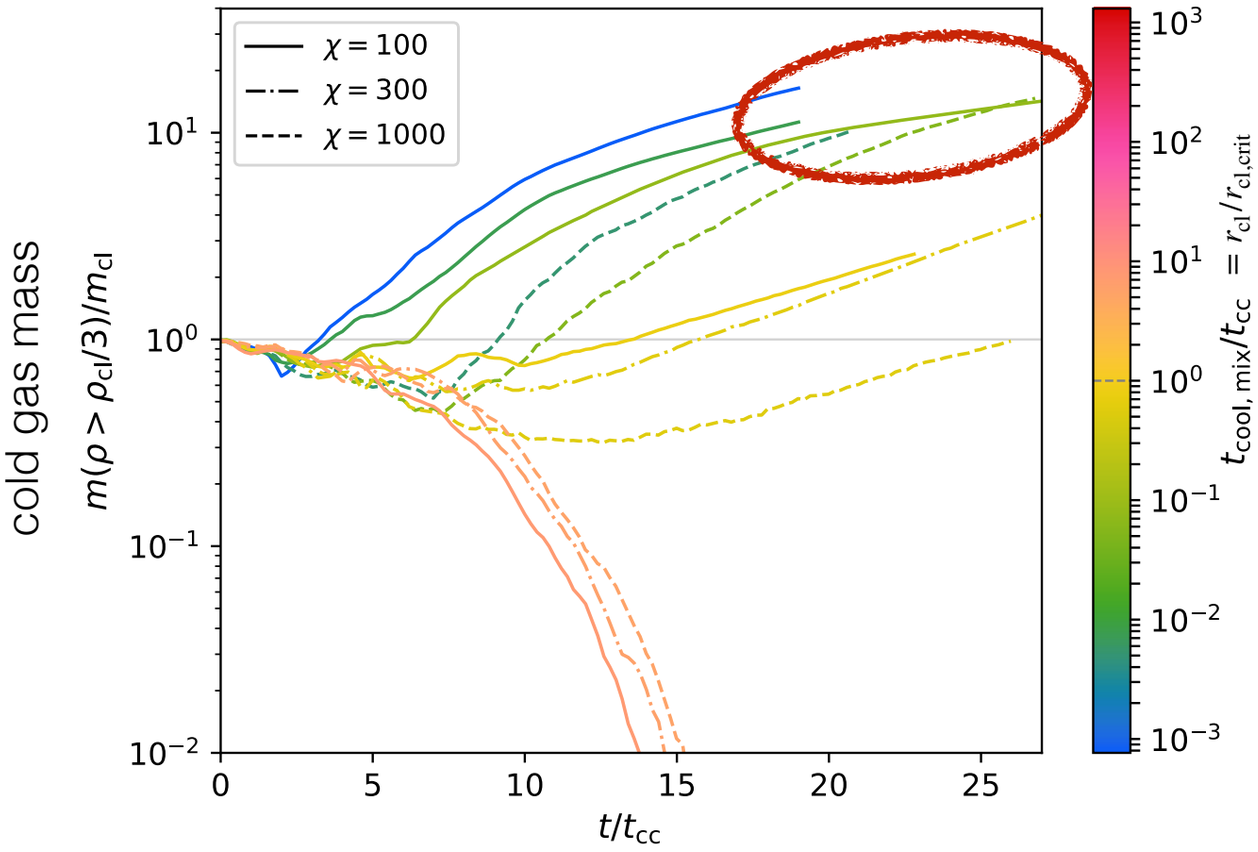
$T_{\rm cl,4} \equiv (T_{\rm cl}/10^4\,{\rm K})$

$P_3 \equiv nT/(10^3\,{\rm cm^{-3}\,K})$

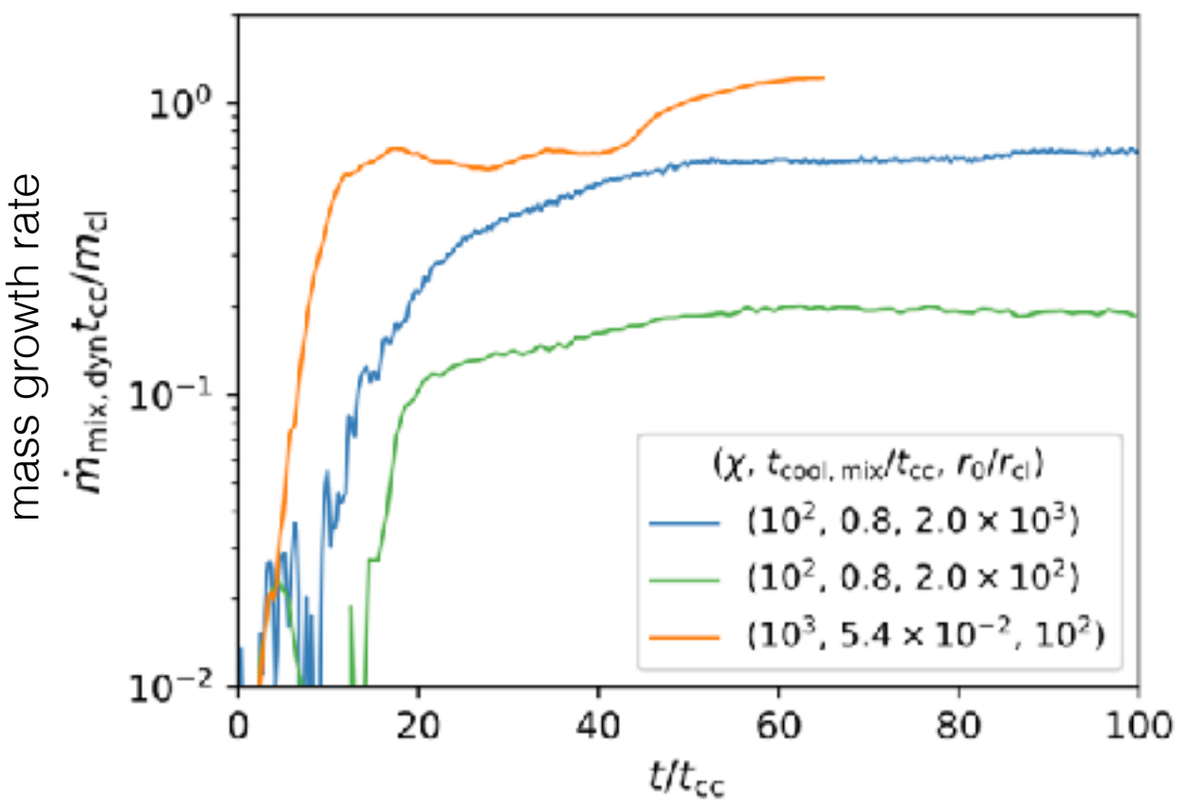
$\Lambda_{\rm mix,-21.4} \equiv \Lambda(T_{\rm mix})/(10^{-21.4}\,{\rm erg\,cm^3\,s^{-1}})$

MG & Oh (2018,19)

Clouds > $r_{cl,crit}$ will survive and ***grow***



in CC85 wind…



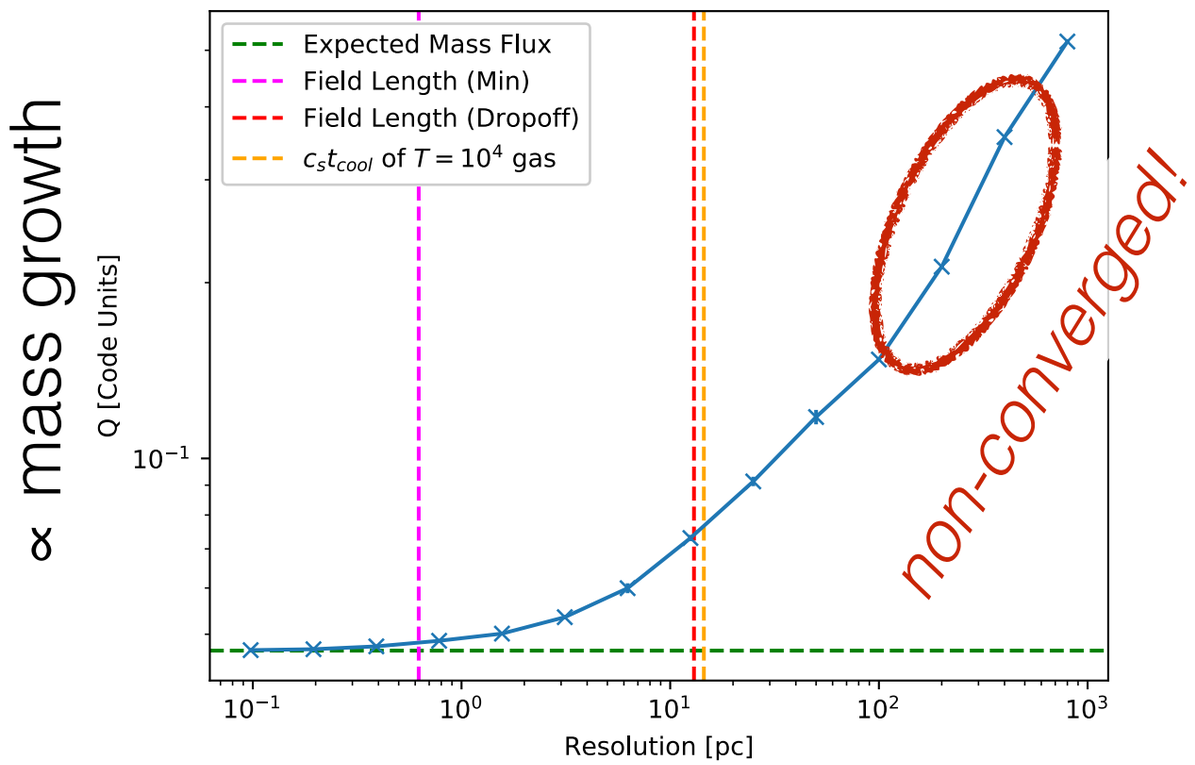
$$M_{\rm cold,CGM} \sim \int {\rm d}t \dot{m}_{\rm wind} \sim \beta M_*$$

(cold gas transported to CGM comparable to stellar mass of galaxy; mote work with more realistic wind profiles required)

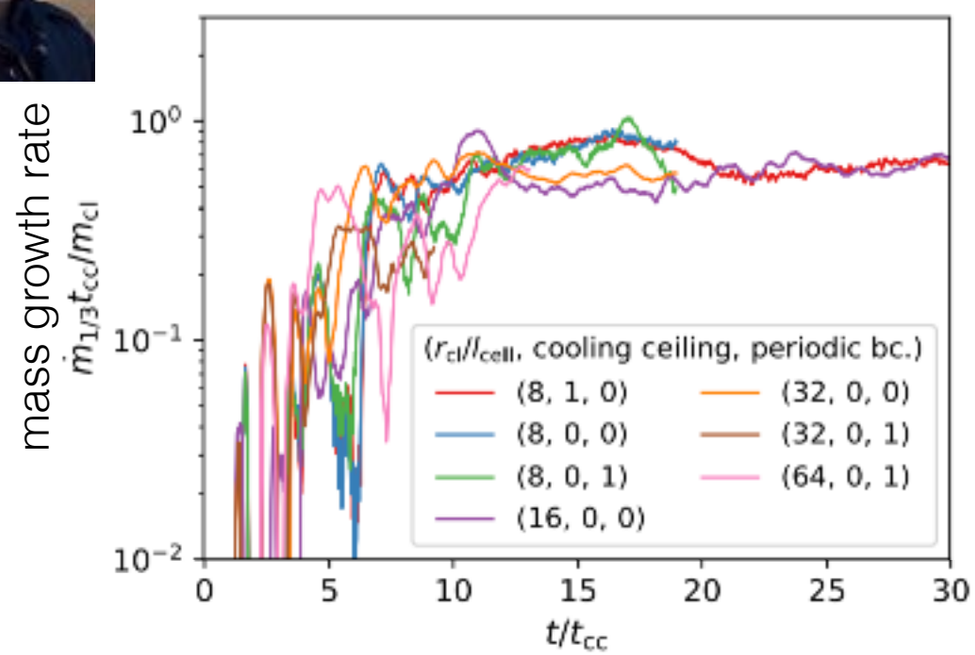
What about (c) the Field length?

i.e., is the $r_{cl} > r_{cl,crit}$ mass growth converged in our sims?

1D cooling layer. Credit: Brent Tan



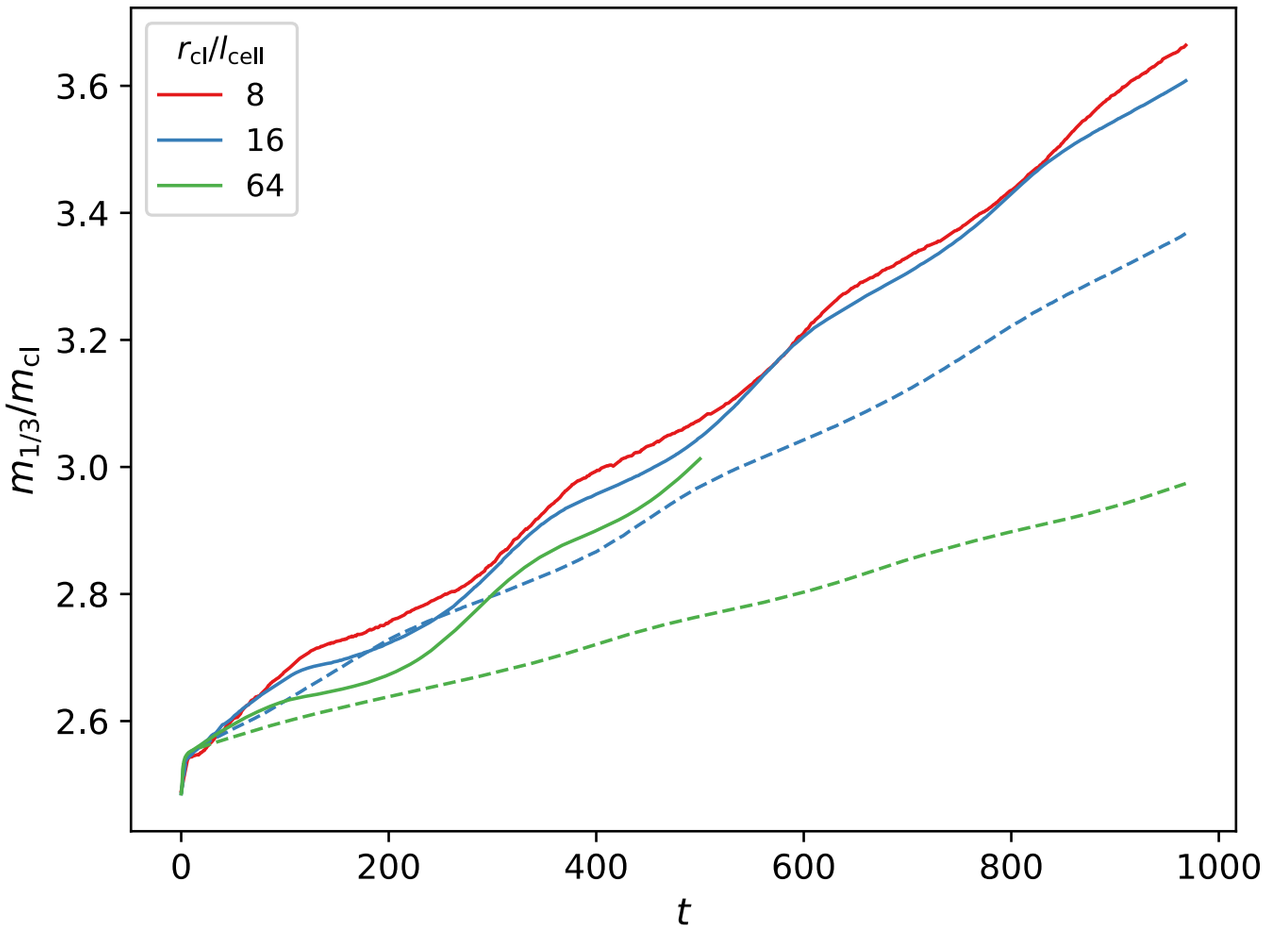
3D windtunnel

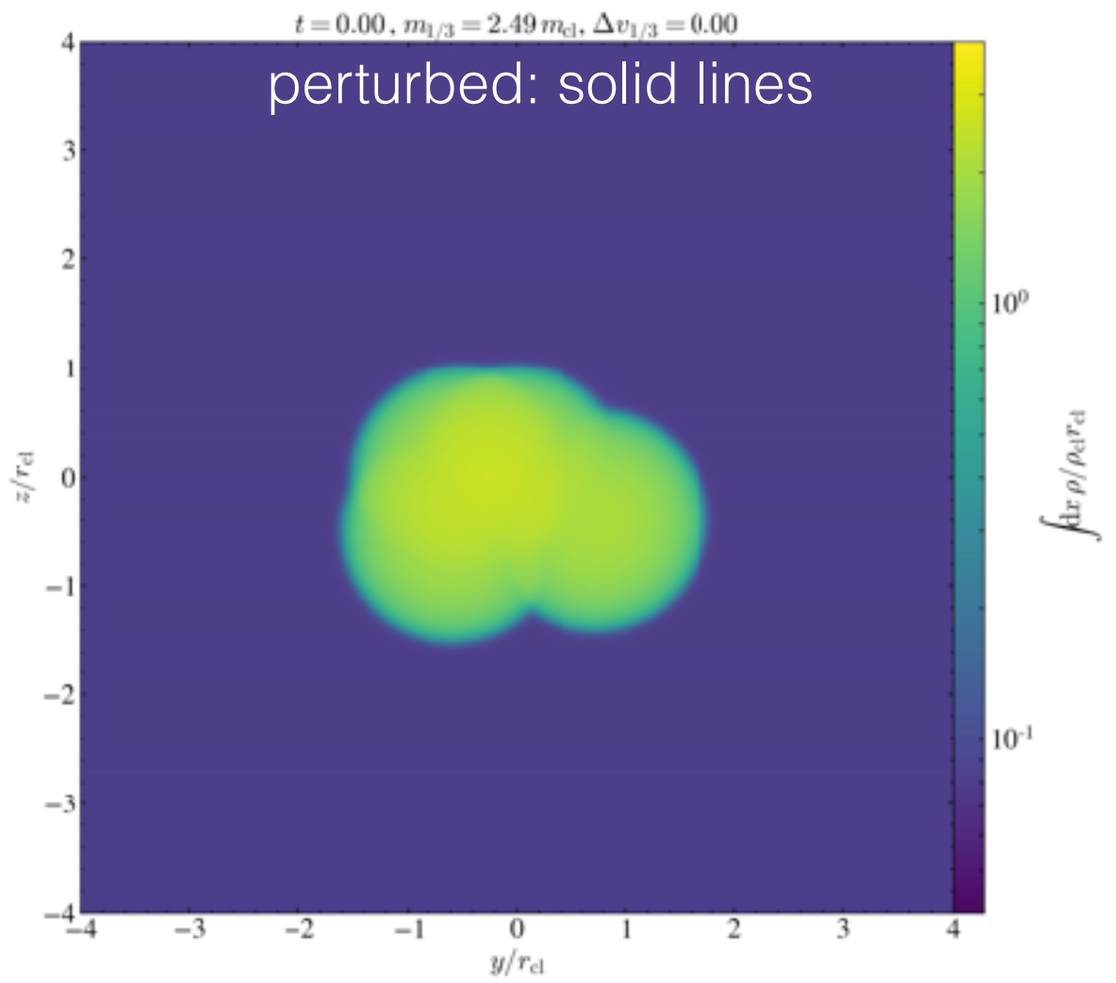


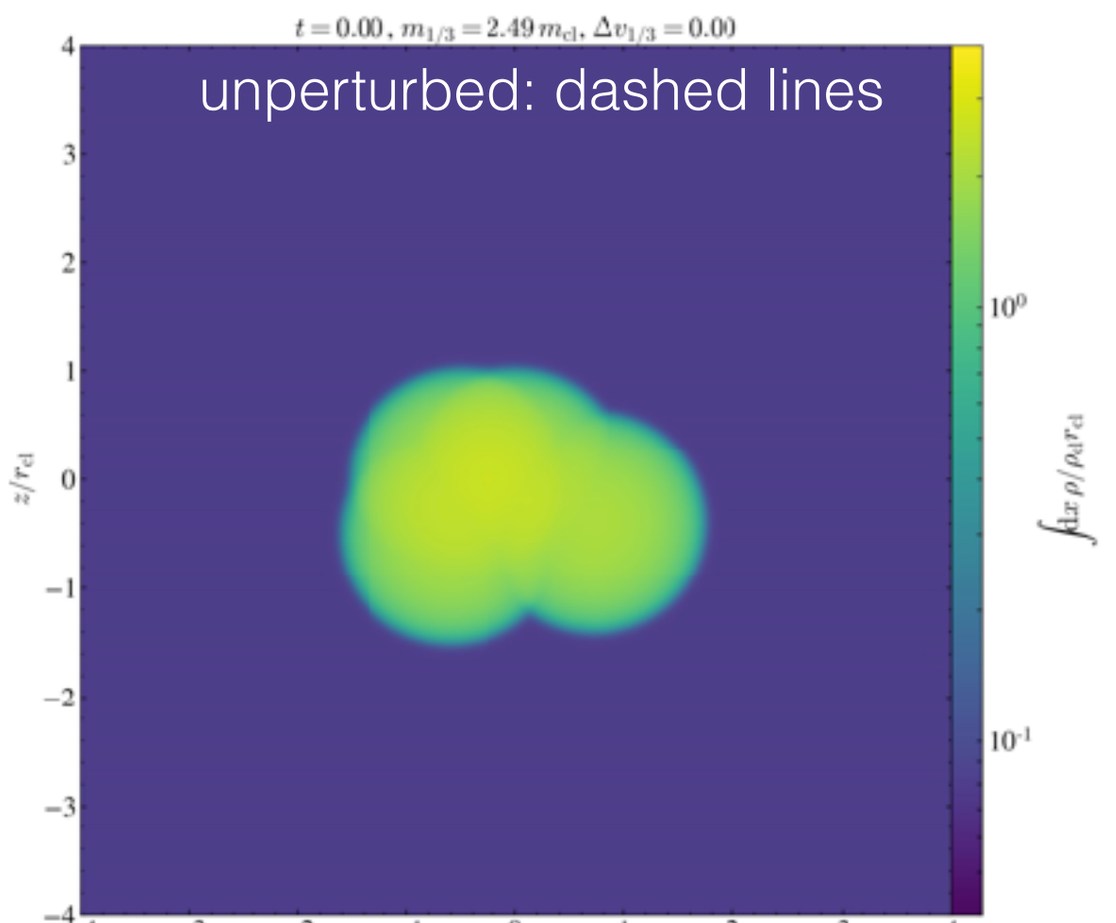
***Dynamics* responsible for convergence.** →*Drummond's talk.*

Pulsations and convergence

…of cooling induced mass growth.







Short recap: $l_{shatter}$ versus $r_{cl,crit}$

$$l_{\rm shatter} \sim \min(c_{\rm s} t_{\rm cool}) \sim 0.1\,(n/{\rm cm}^{-3})^{-1}\,{\rm pc}$$

$$r_{\rm cl,crit} \sim 2\,\frac{T_{\rm cl,4}^{5/2}\mathscr{M}}{P_3\Lambda_{\rm mix,-21.4}}\frac{\chi}{100}\,{\rm pc}$$

$$\frac{r_{\rm cl,crit}}{l_{\rm shatter}} \sim 10\mathscr{M}\frac{\chi}{100}\left(\frac{\Lambda(T_{\rm cl})/\Lambda(T_{\rm mix})}{0.1}\right)$$

Idea: while cooling, $l_{shatter}$ emerges naturally

subgrid model required?

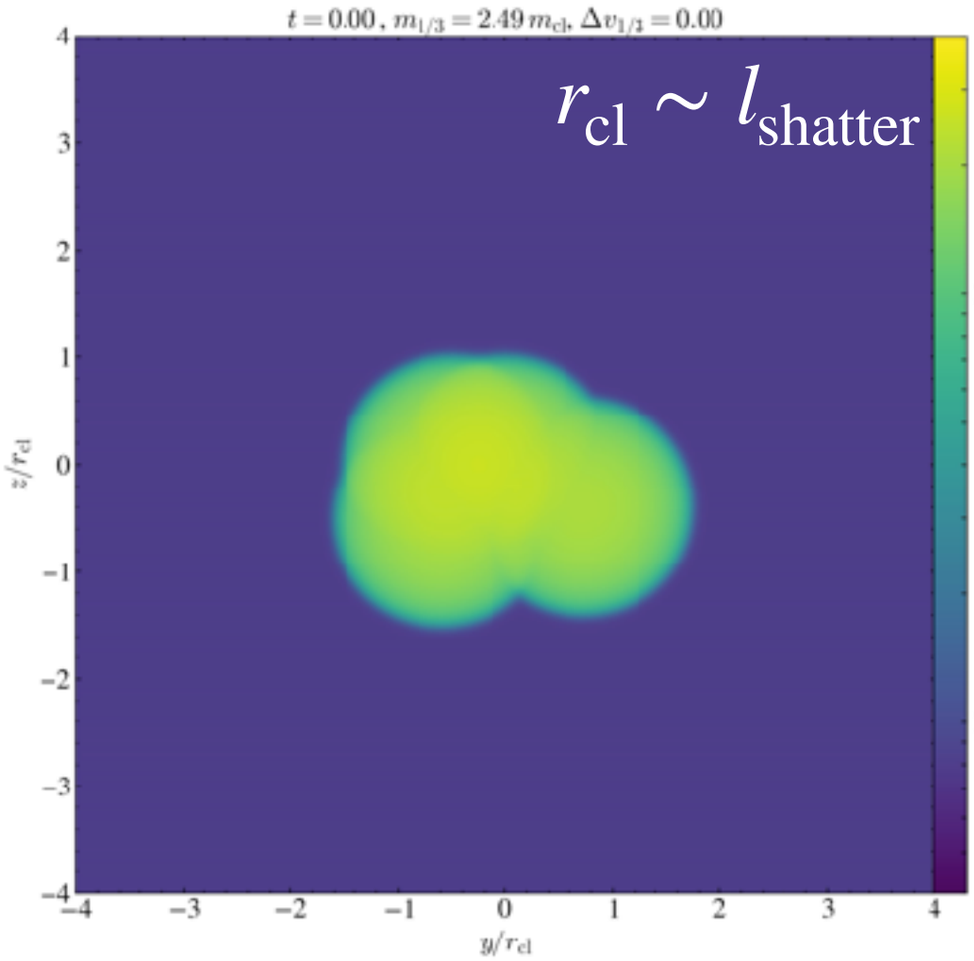
Idea: cold gas < $r_{cl,crit}$ gets washed away

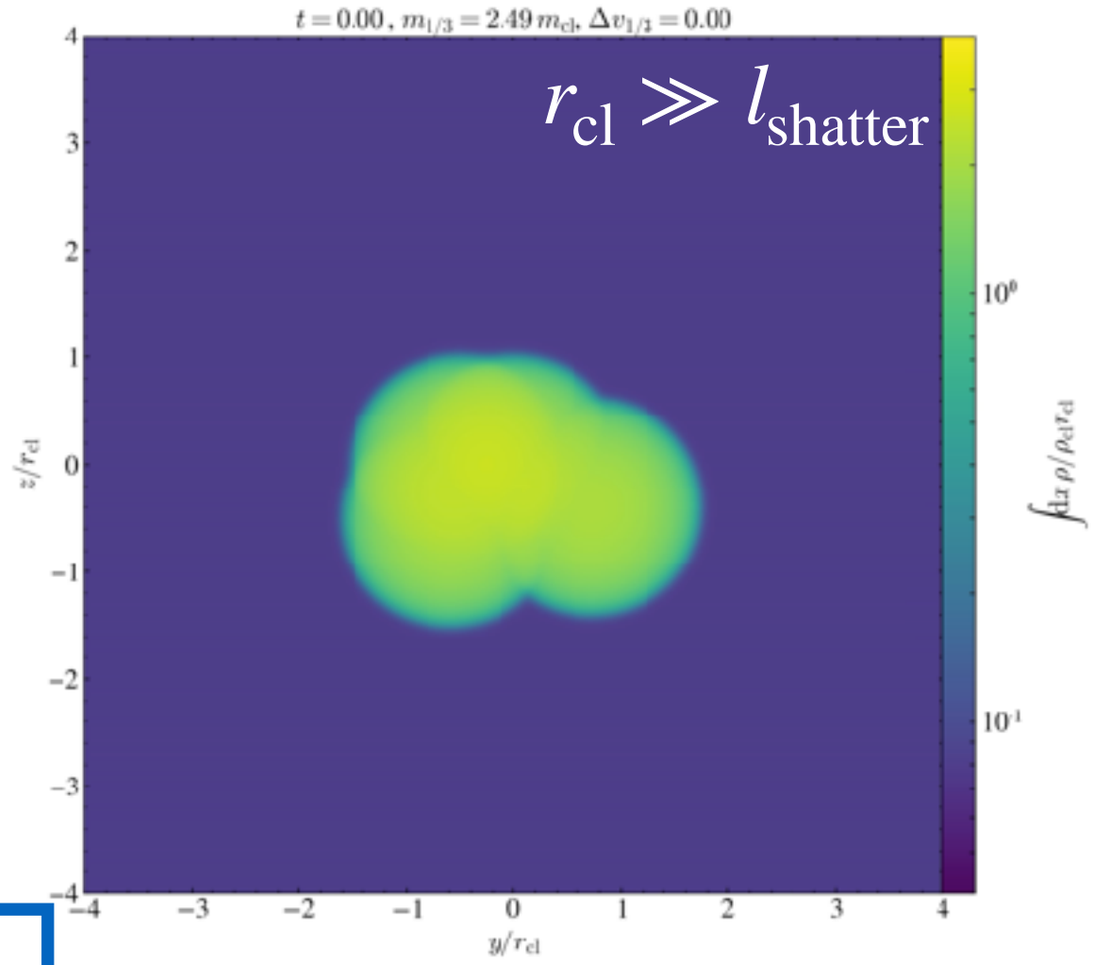
resolving (soon) feasible?

→ relevant for initial question.

…but how are the two scales related? → universal setup.

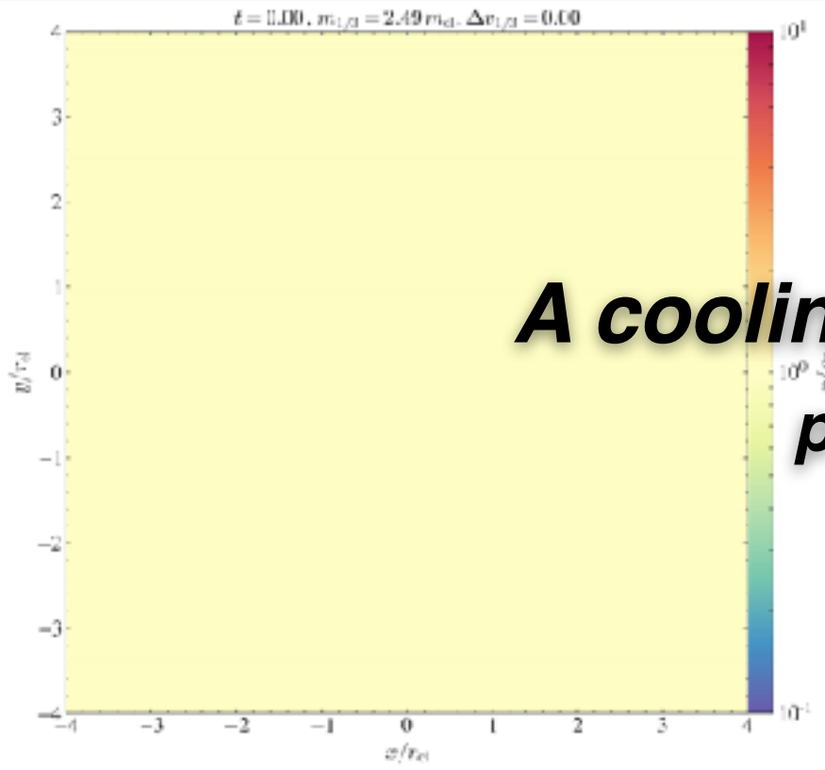
When does shattering occur? (in 3D)



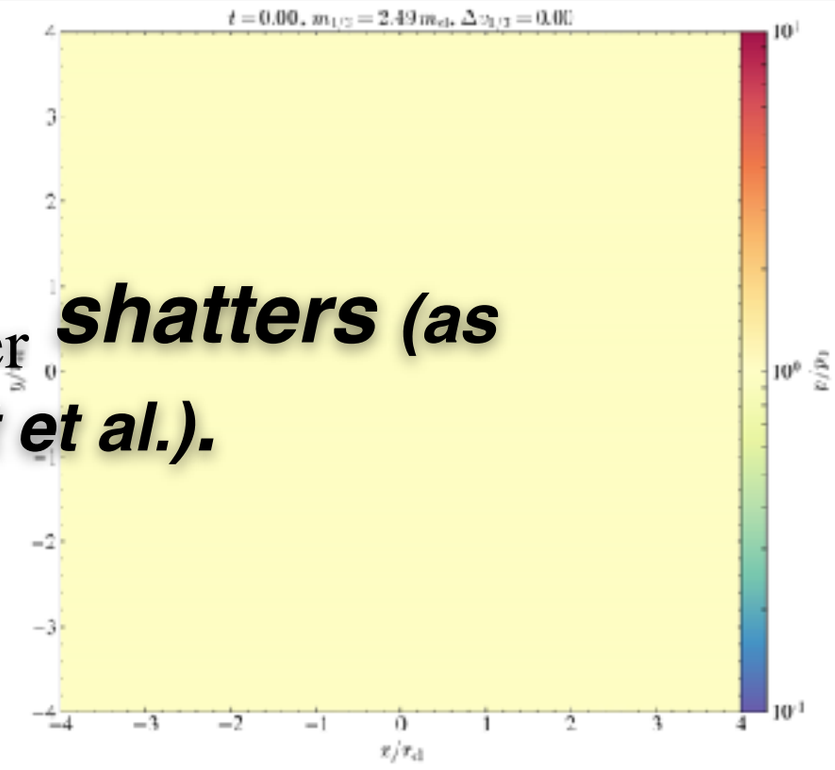


density (projection)

$\chi_{\rm initial} \sim 100,$
$T_{\rm cl} \sim 10^5 \longrightarrow 10^4\,{\rm K}$

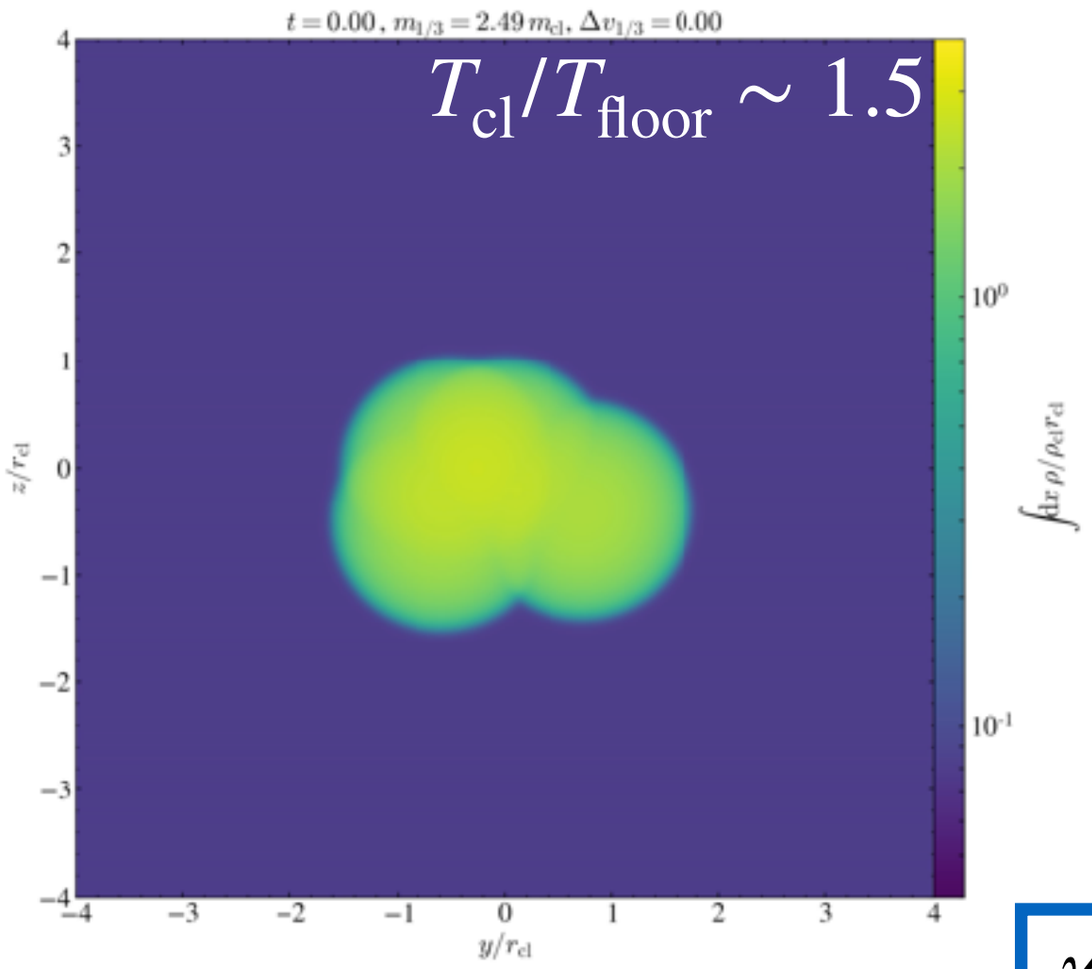


pressure (slice)



A cooling cloud $\gg l_{\rm shatter}$ shatters (as predicted by McCourt et al.).

When does shattering occur? (in 3D)



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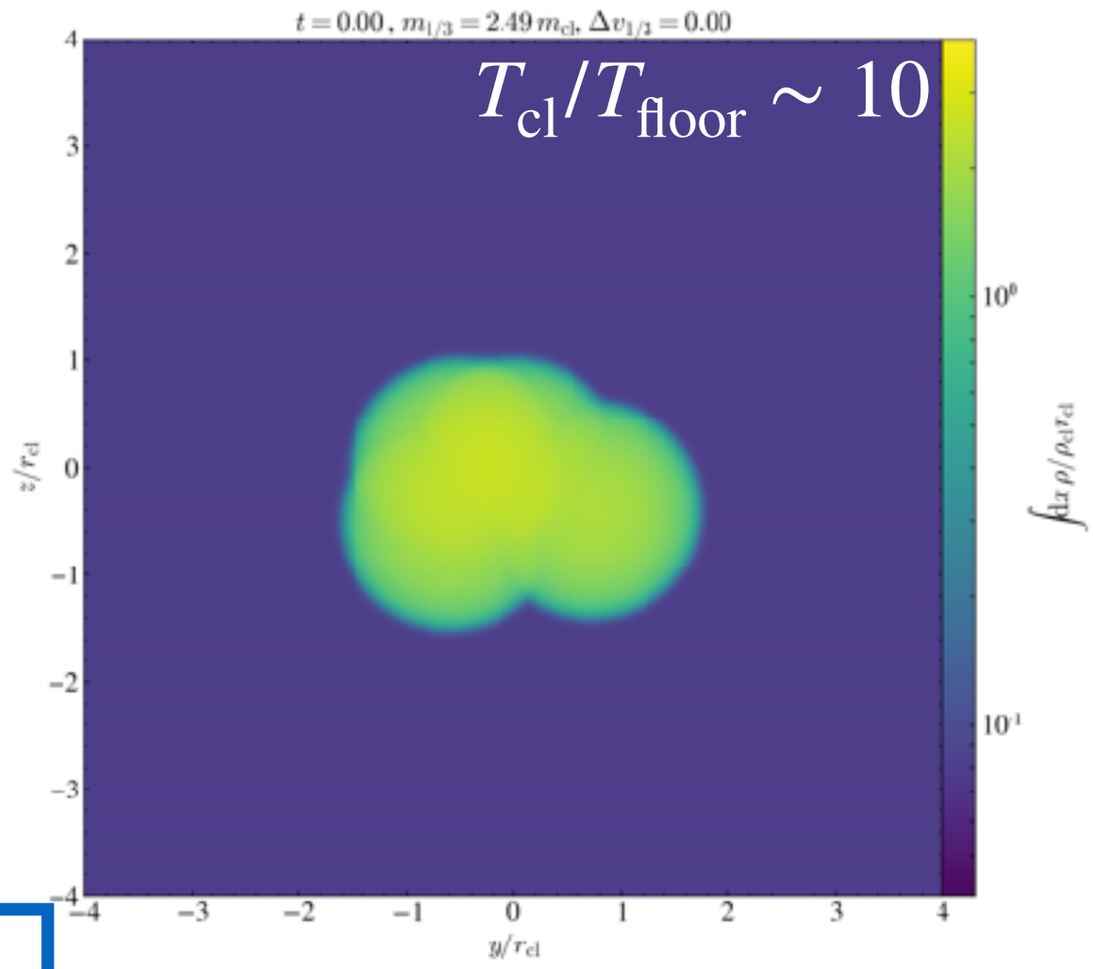
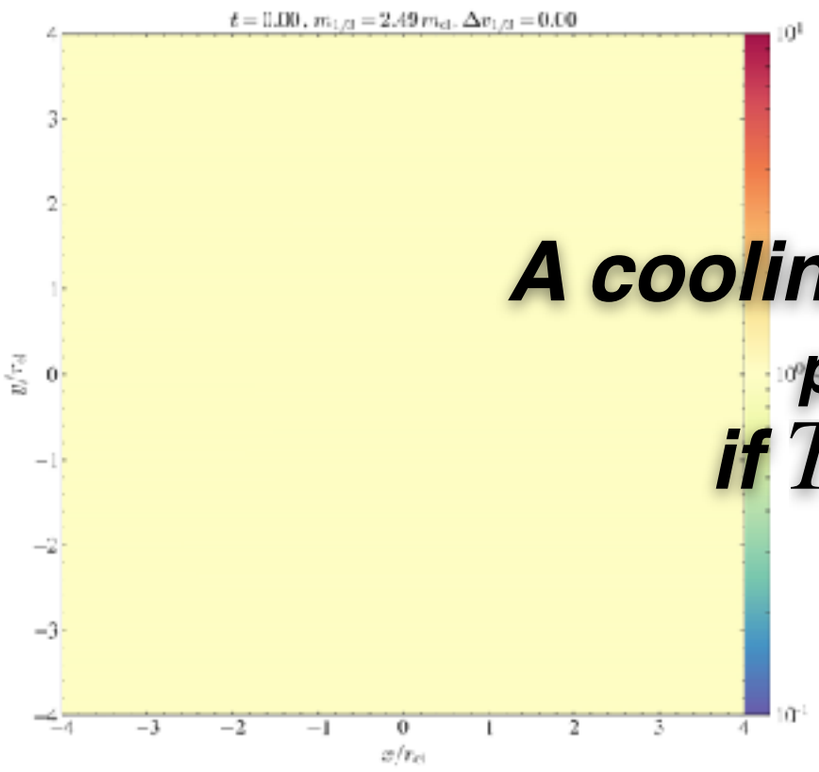
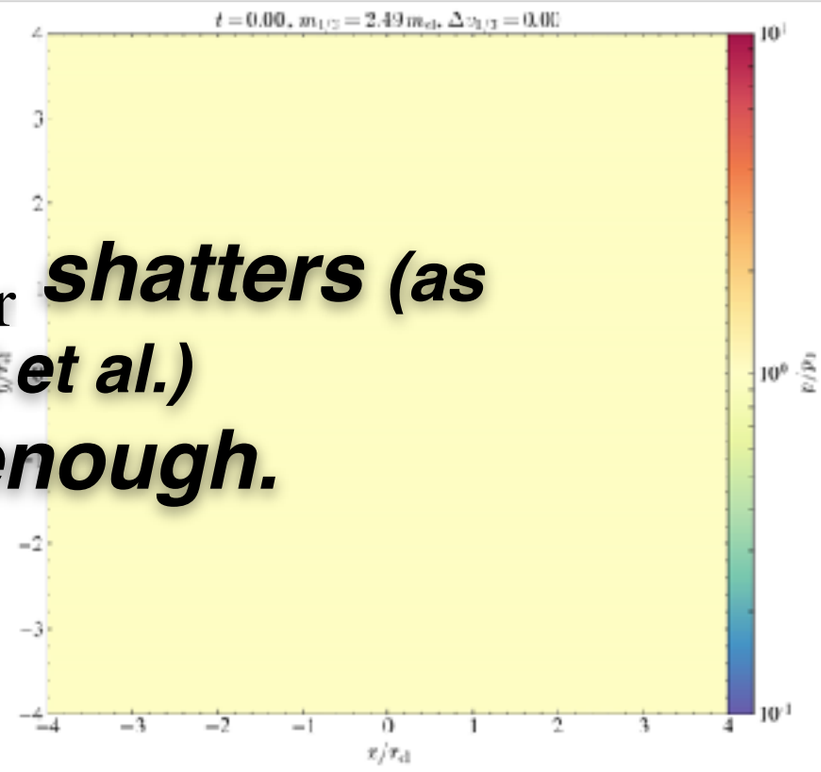


$$\chi_{\rm initial} \sim 100,\quad r_{\rm cl} \gg l_{\rm shatter}$$

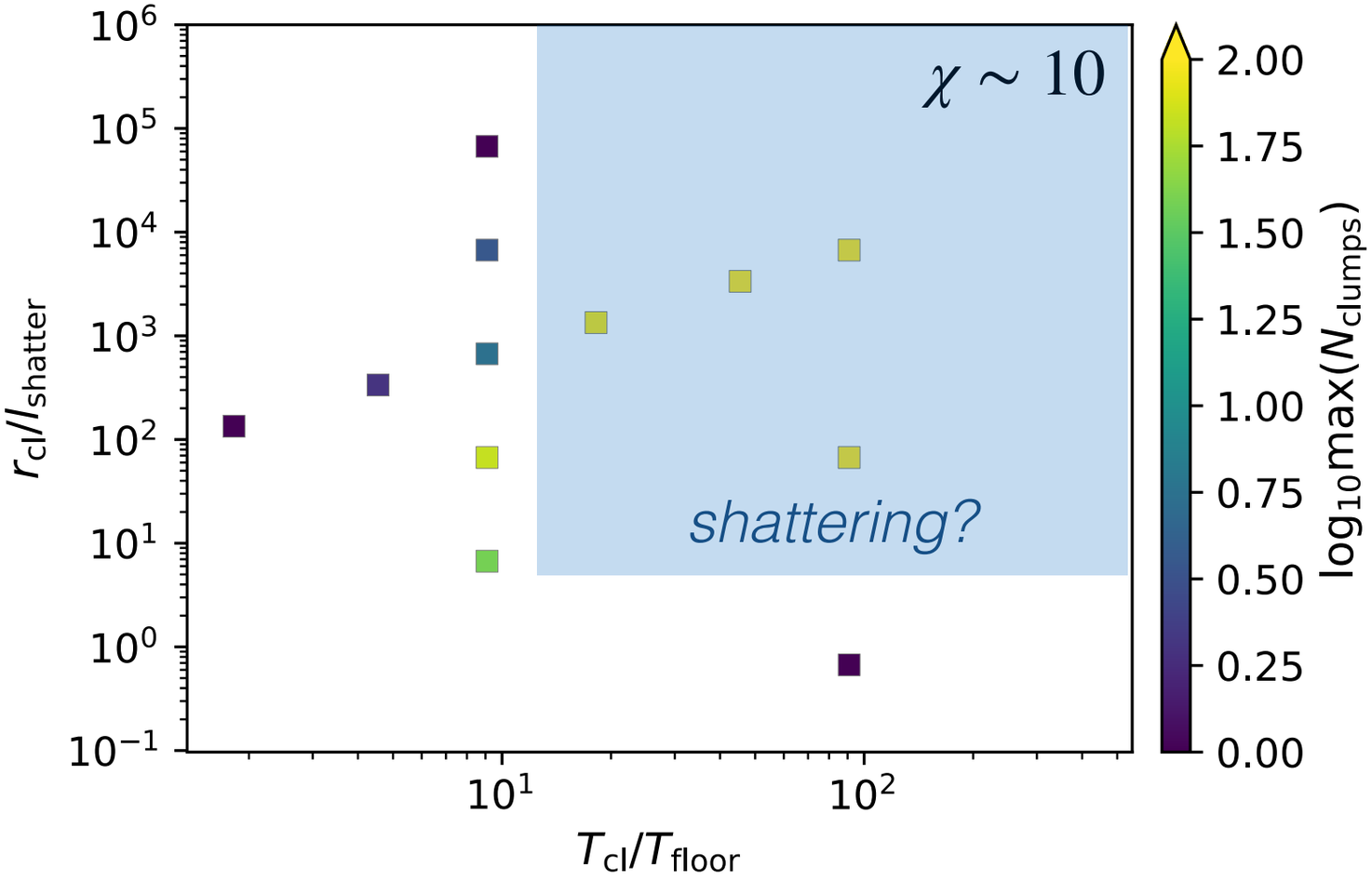


pressure slice



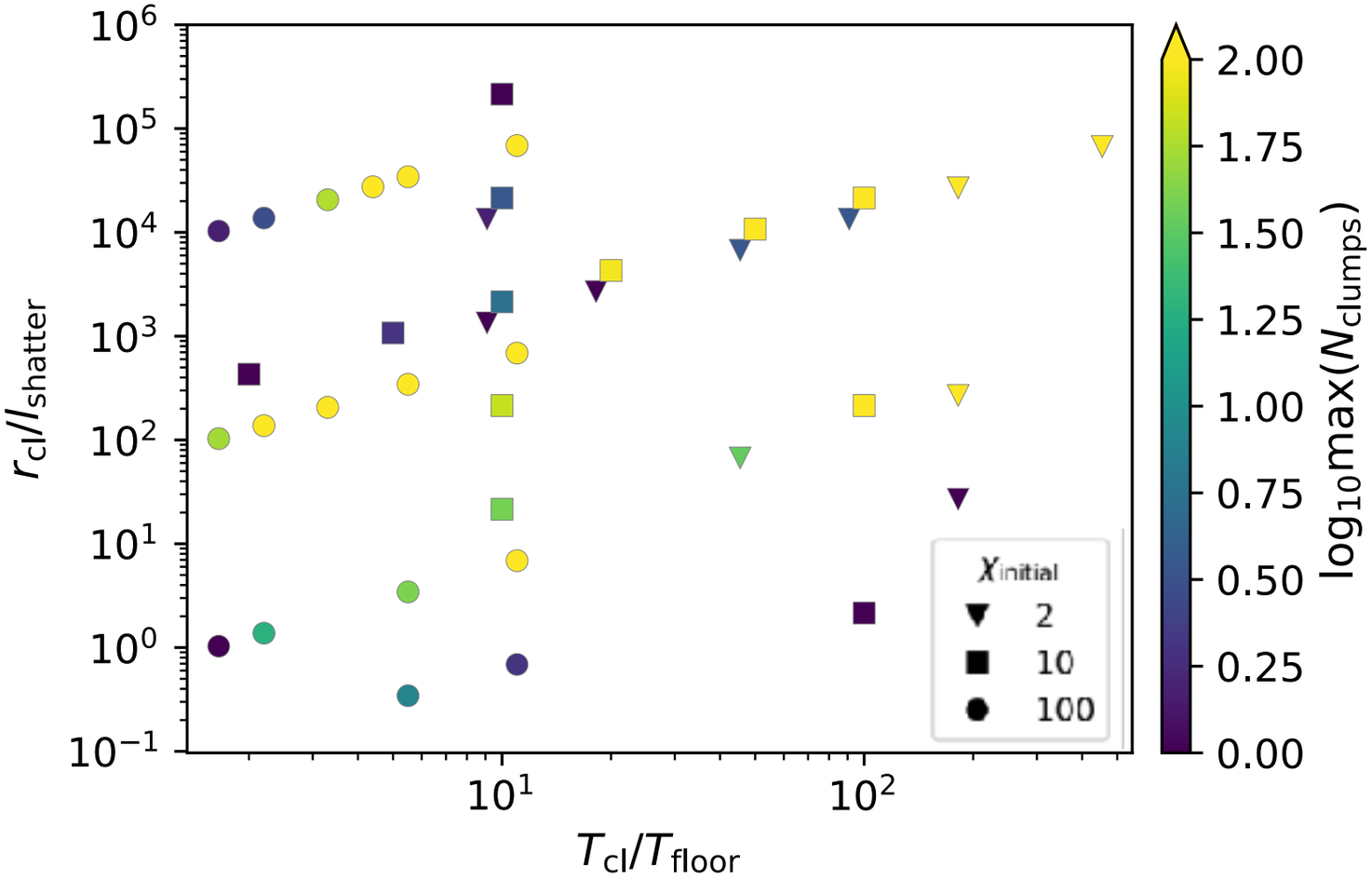
A cooling cloud $\gg l_{\rm shatter}$ shatters (as predicted by McCourt et al.) if $T_{\rm cl}/T_{\rm floor}$ is large enough.

Conditions of shattering



A cooling cloud $\gtrsim 10 l_{\rm shatter}$ ***shatters if*** $T_{\rm cl}/T_{\rm floor}$ ***is large enough.***

Conditions of shattering



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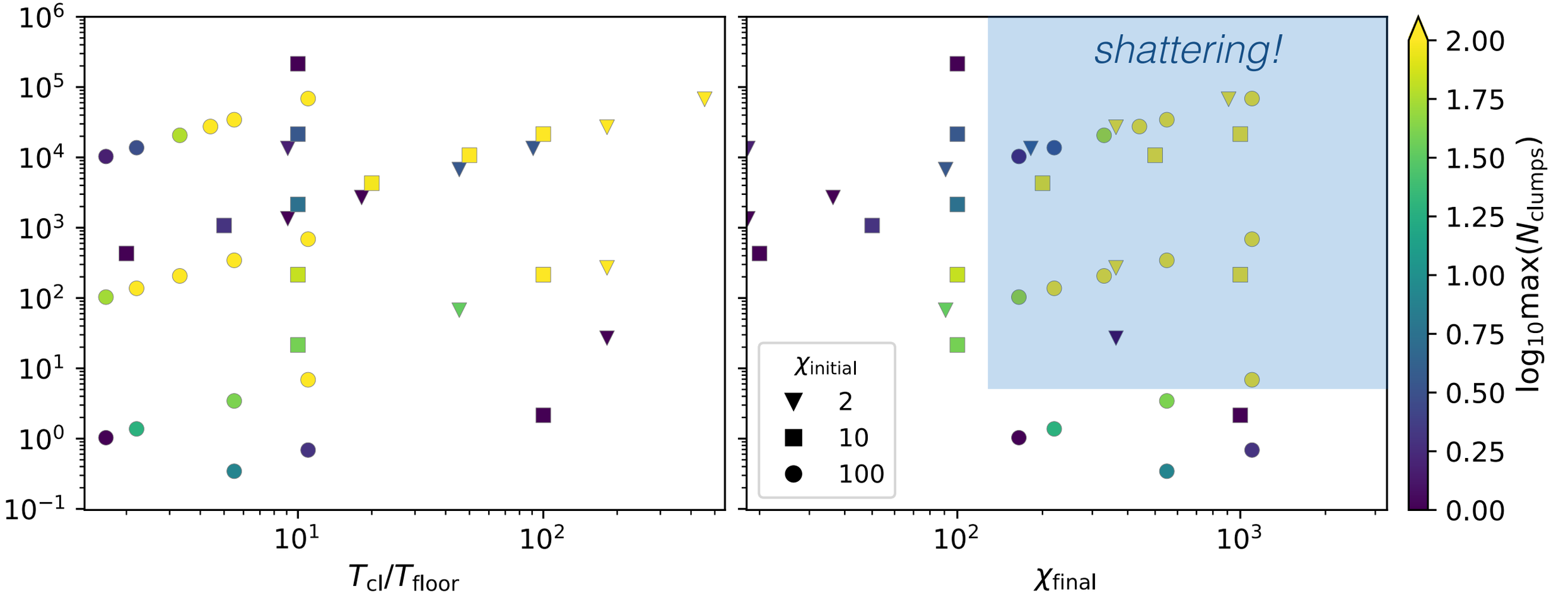
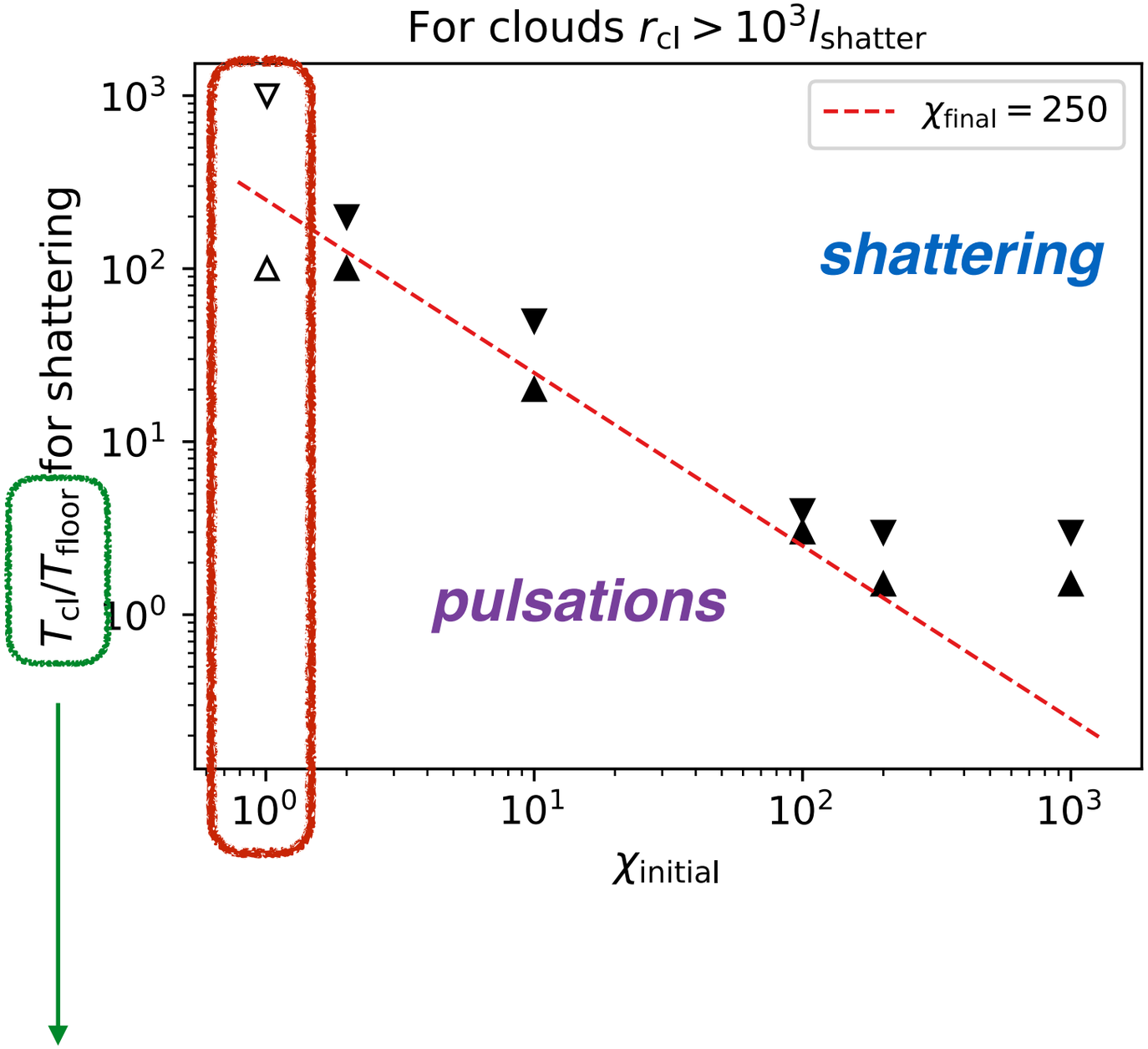
Conditions of shattering



A cooling cloud $\gtrsim 10 l_{\rm shatter}$ ***shatters***
if $\chi_{\rm final} \equiv T_{\rm cl}/T_{\rm floor}\chi_{\rm initial} \gtrsim 250.$

Conditions of shattering



can be related to $\mathscr{M}$ via shock jump conditions

Implications

Thermal instability:

only

$$T_{\rm hot} \gtrsim 2 \times 10^6\, K$$

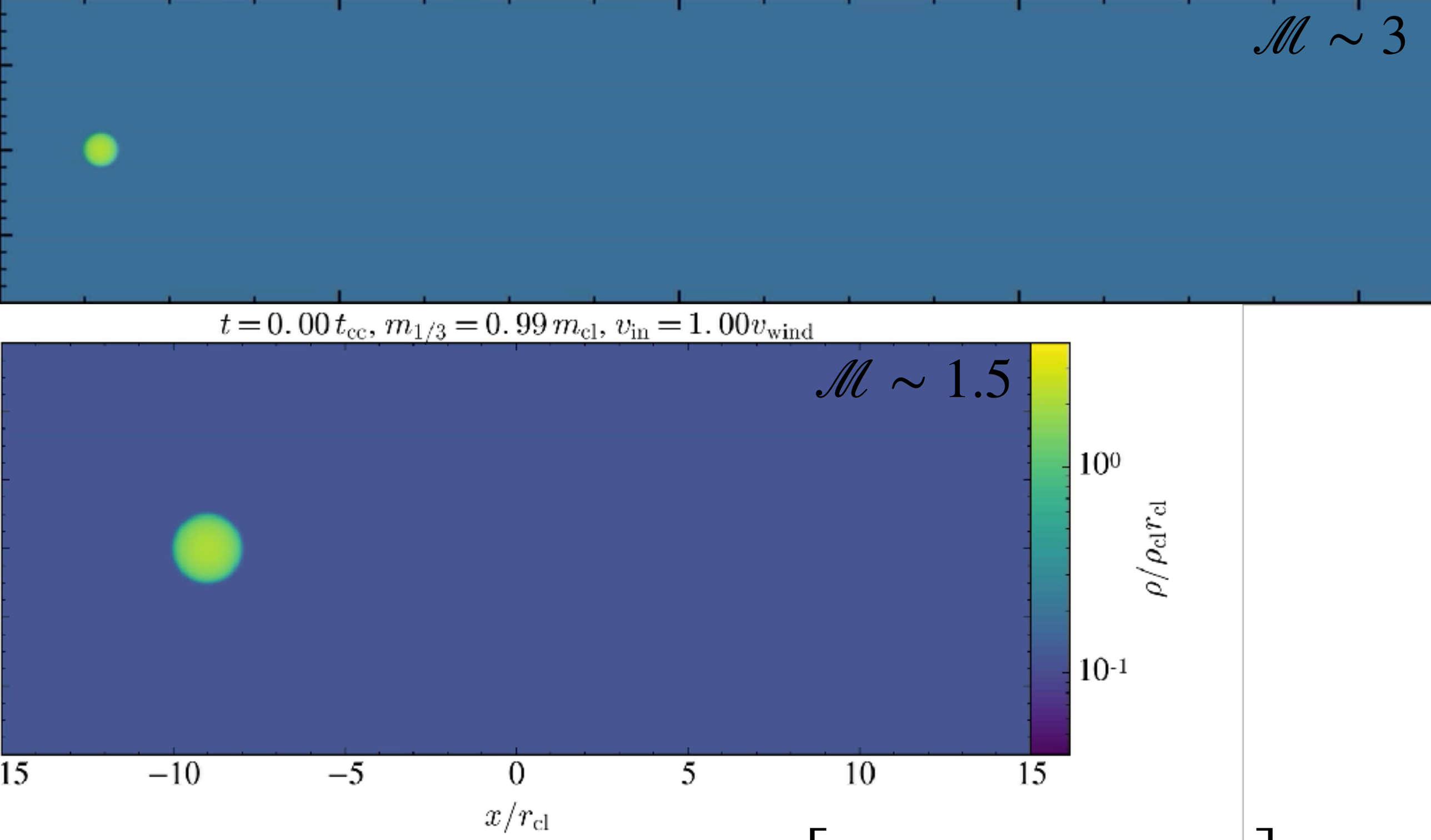
leads to "fog".

Galactic winds:

only clouds in

$$\mathscr{M}^2 \lesssim \frac{1}{2\gamma}\left[\frac{\chi_{\rm crit}}{\chi_{\rm initial}}(\gamma+1)-(\gamma-1)\right] \sim 4$$

wind survive "as a whole". Afterwards "dynamic coagulation effects" important.



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wind survive "as a whole". Afterwards "dynamic coagulation effects" important.

To shatter, or not to shatter?

Is the region big enough?

$$r_{\rm cl} \gtrsim 10 \min(c_{\rm s} t_{\rm cool}) \sim 1\,(n/{\rm cm}^{-3})^{-1}\,{\rm pc}$$

Yes

Does it cool a lot?

$$\chi_{\rm final} \equiv \chi T_{\rm cl}/T_{\rm floor} \gtrsim 250$$

shatters!

"dynamic coagulation effects"?

No

cools isochorically

gets destroyed on short timescale?

(damped) pulsations

Is it even bigger?

$$r_{\rm cl} \gtrsim r_{\rm cl,crit} \sim 20\,\frac{T_{\rm cl,4}^{5/2}\mathscr{M}}{P_2 \Lambda_{\rm mix,-21.4}}\,\frac{\chi}{100}\,{\rm pc}$$

Survives and grows!

Destroyed?