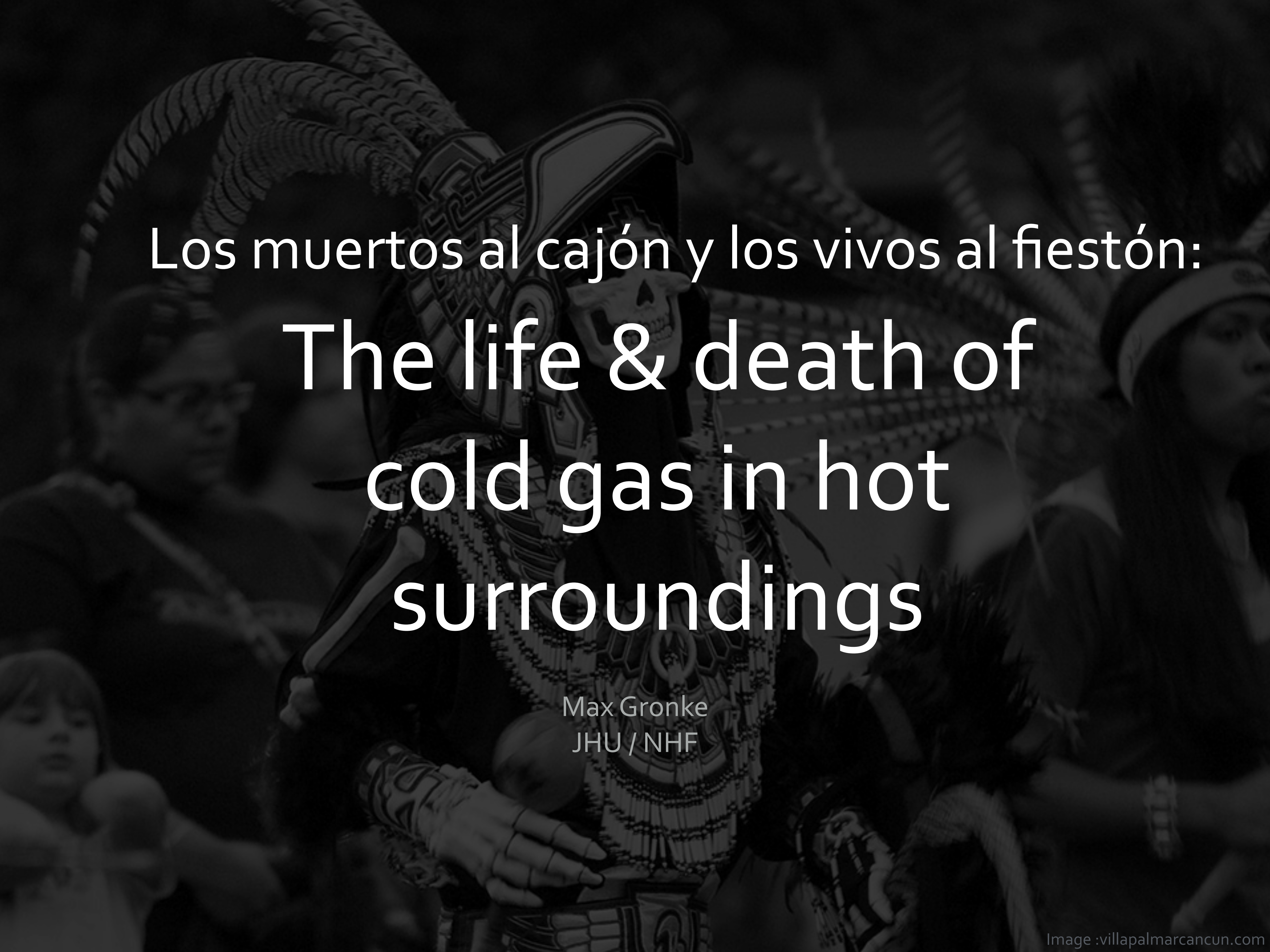


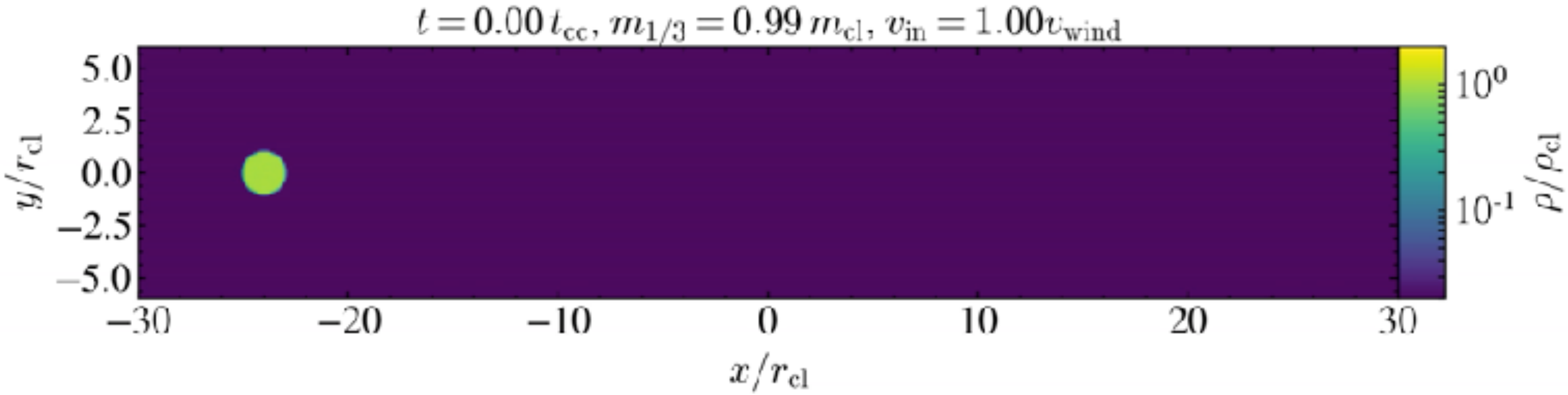
Los muertos al cajón y los vivos al fiestón:

The life & death of cold gas in hot surroundings

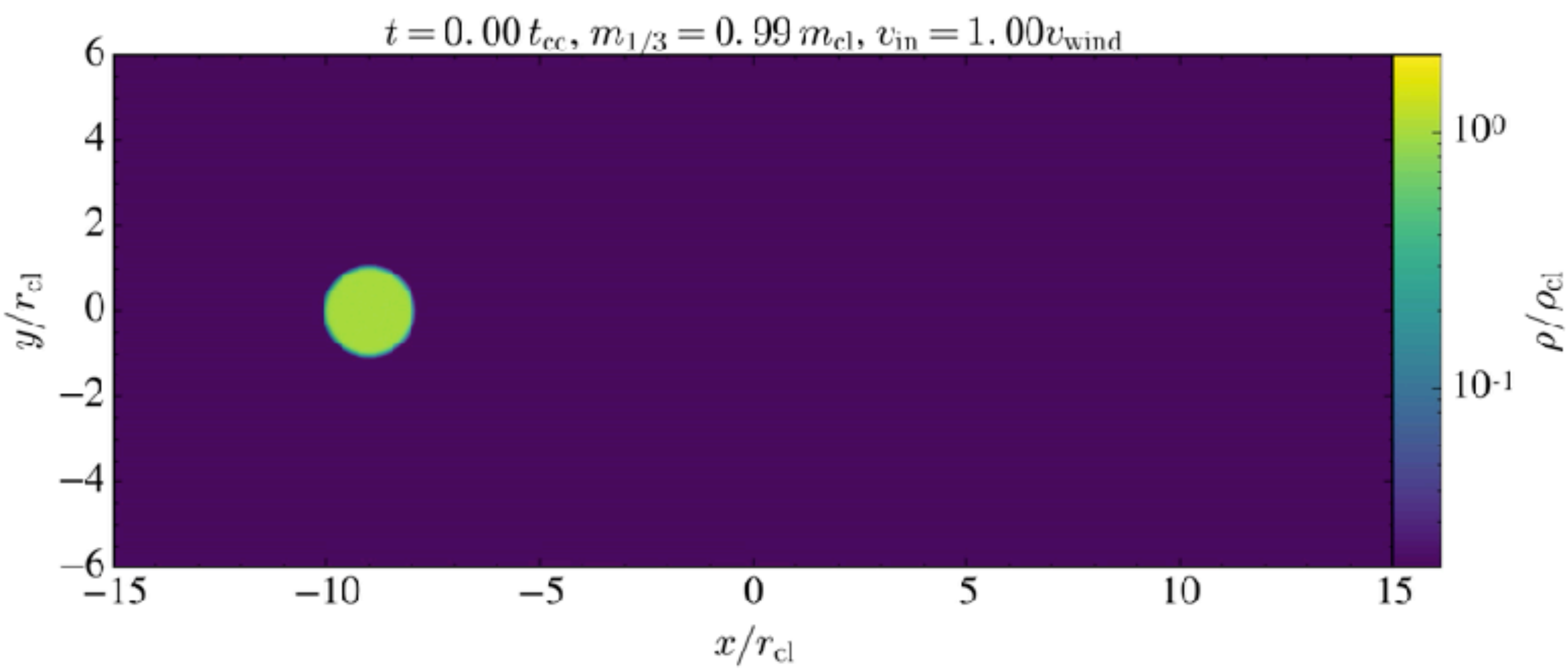
Max Gronke
JHU / NHF

Cajón or fiestón?

$$t_{\rm cool,mix}/t_{\rm cc} = r_{\rm cl,crit}/r_{\rm cl} \sim 8$$



$$t_{\rm cool,mix}/t_{\rm cc} = r_{\rm cl,crit}/r_{\rm cl} \sim 0.08$$



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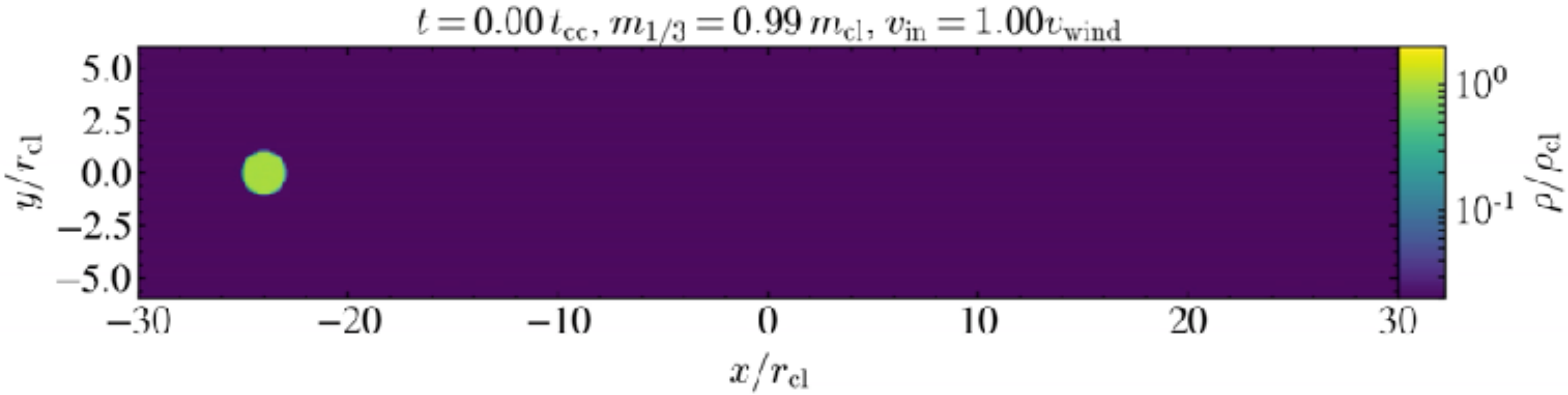

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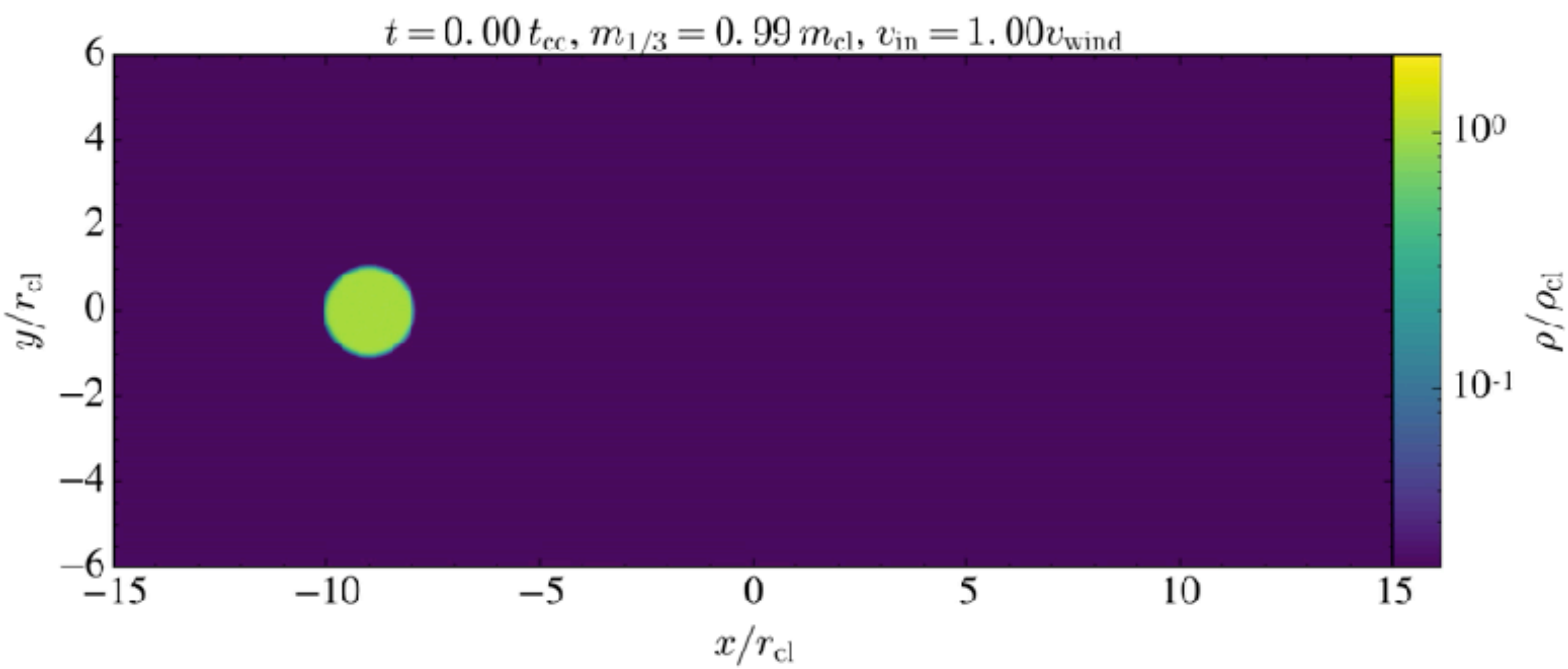

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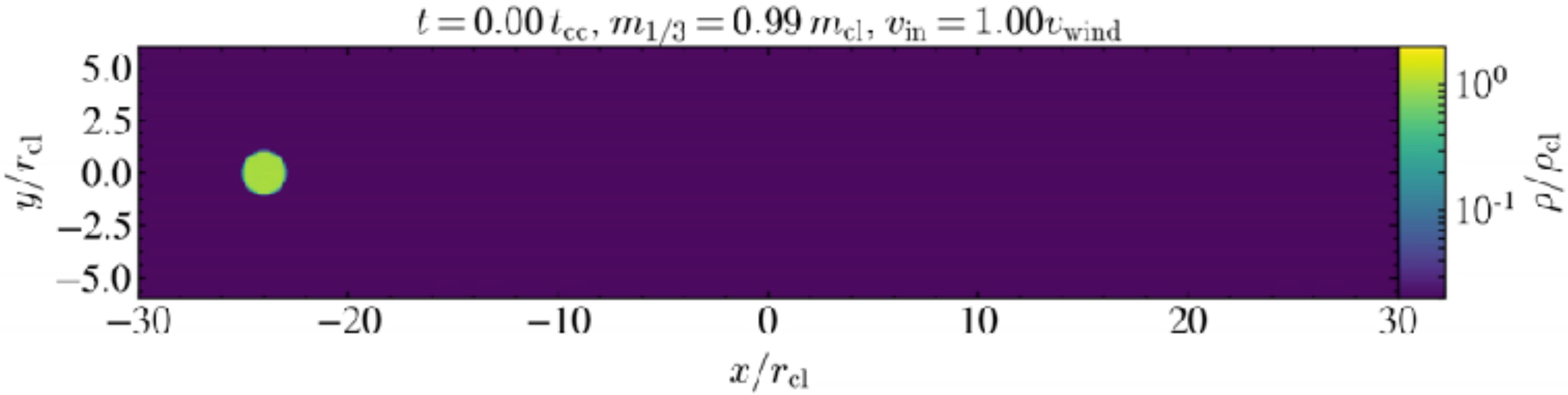
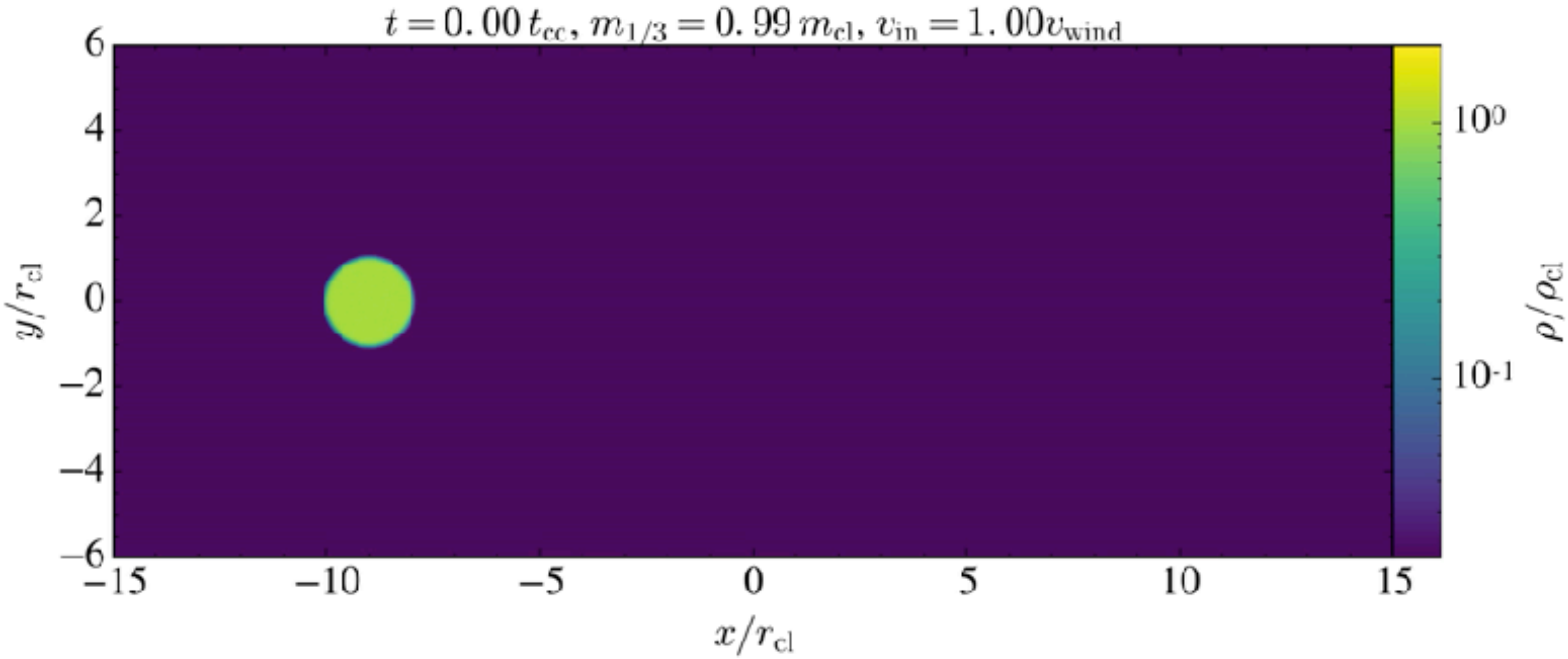
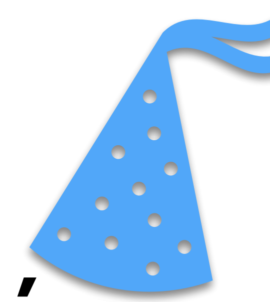


→ **cajón**

$$t_{\mathrm{cool,mix}}/t_{\mathrm{cc}} = r_{\mathrm{cl,crit}}/r_{\mathrm{cl}} \sim 0.08$$





→ **fiestón**

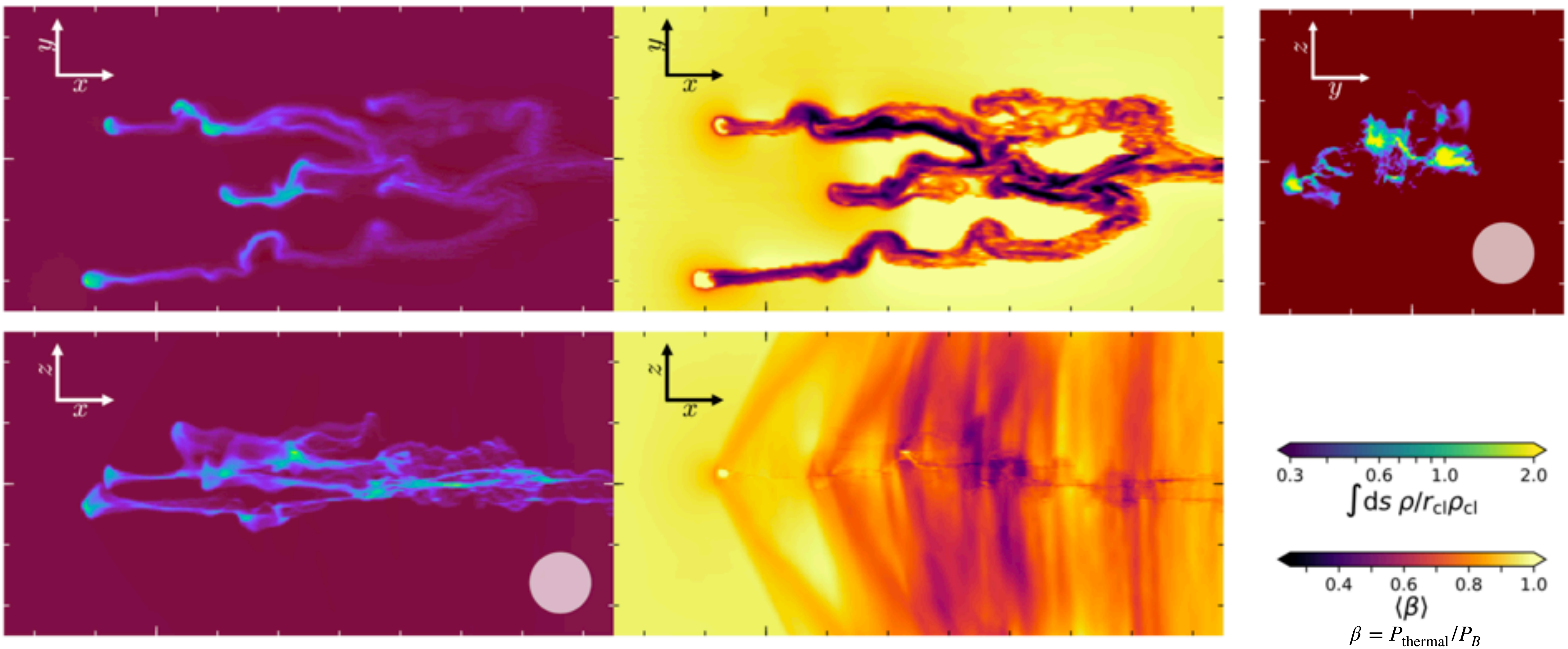
(fuel SF, tracer for outflows, ...)

→ As seen in Prateek's talk. This talk's focus: implications, long-term evolution.

MG & Oh (2020)

Magnetic compression

$$\chi \equiv \rho_{\rm cl}/\rho_{\rm hot} \sim 100, \beta_{\rm cl} \sim \beta_{\rm wind} \sim 1$$



→ Non-thermally supported cloud

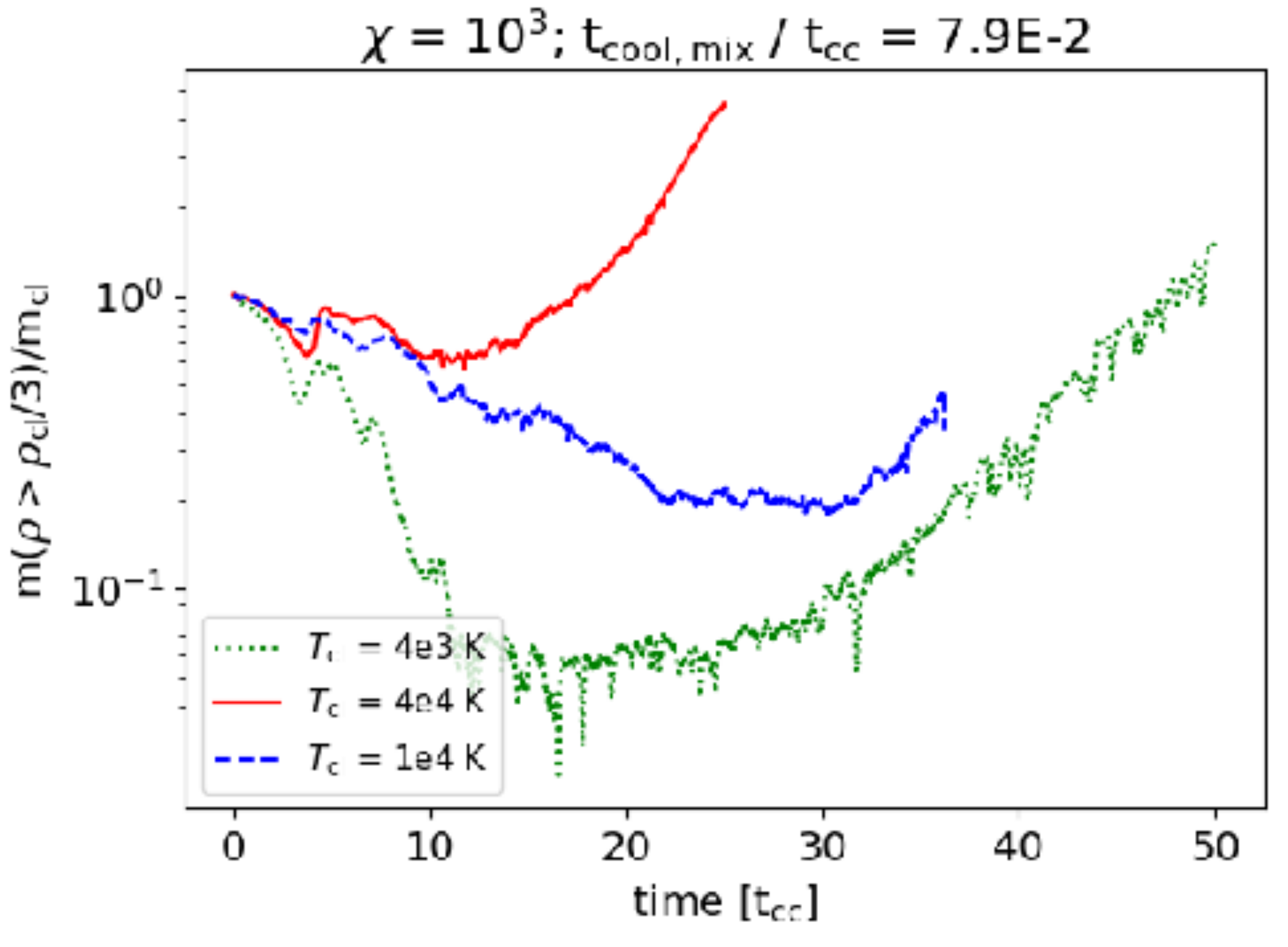
(as seen in observations? Werk et al. 2014; larger scale sims, Nelson et al. 2020)

Implications of cooling supported survival:

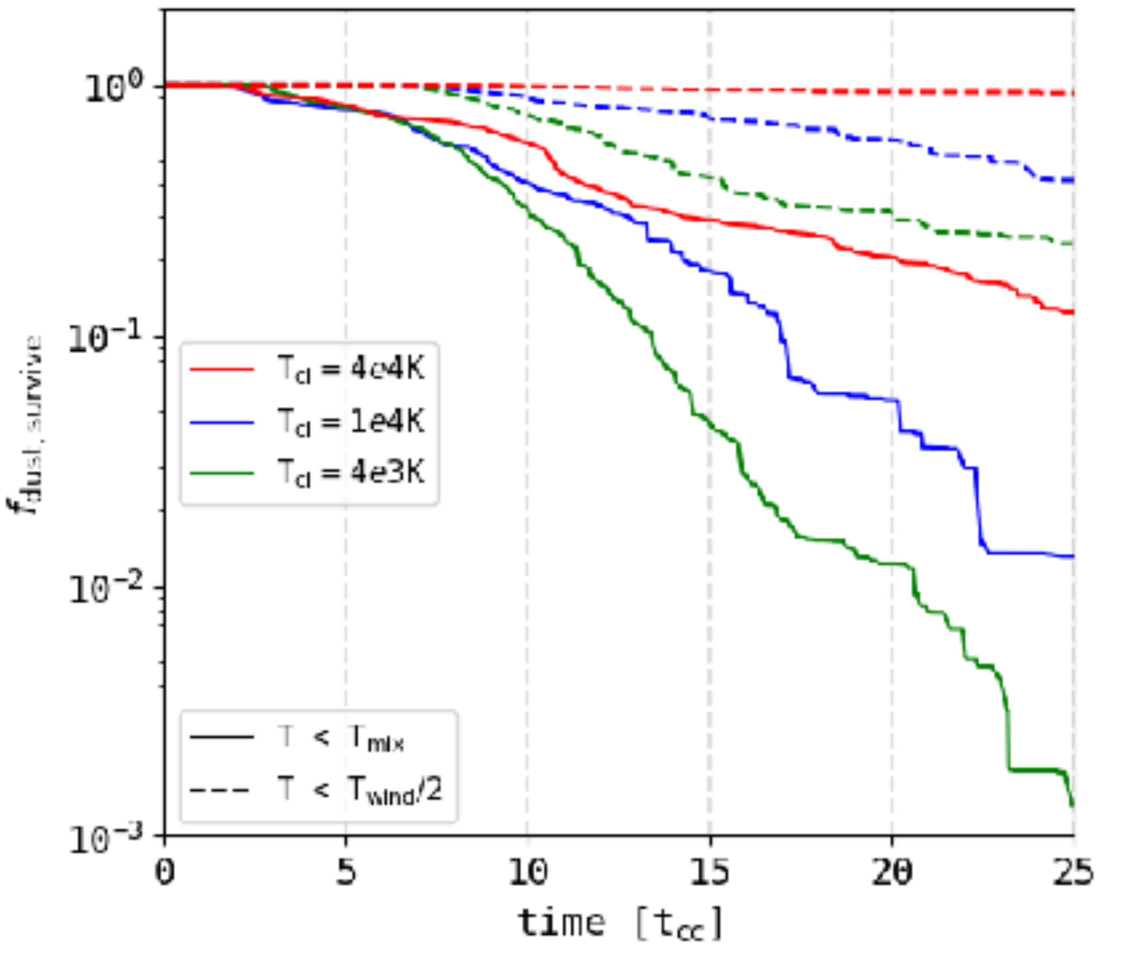
Molecular outflows

Ryan Farber
(University of Michigan)

Mass Growth



Dust Survival



→ Molecules & dust *can* survive *but* surviving fraction depends strongly on details of dust destruction.

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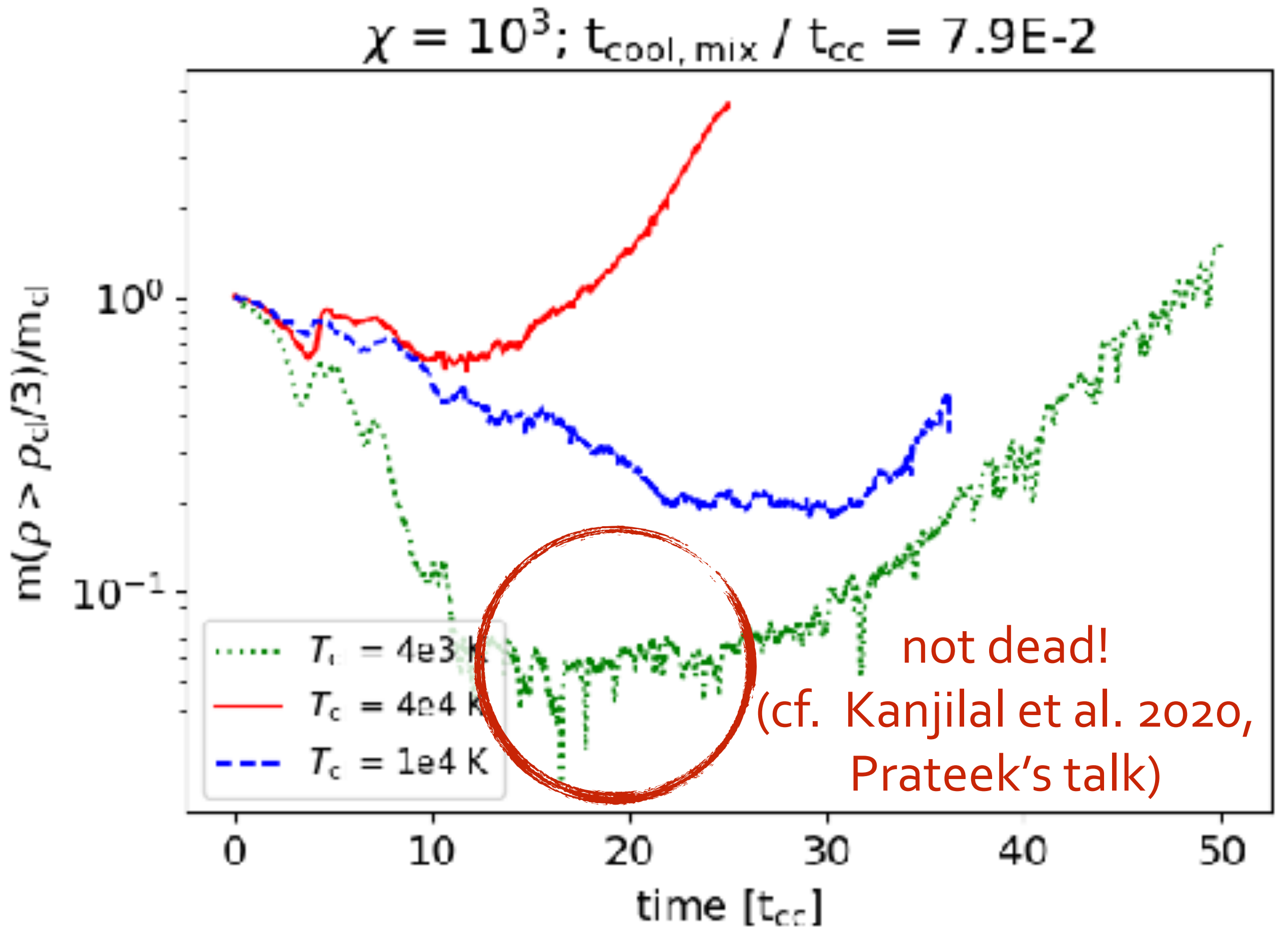

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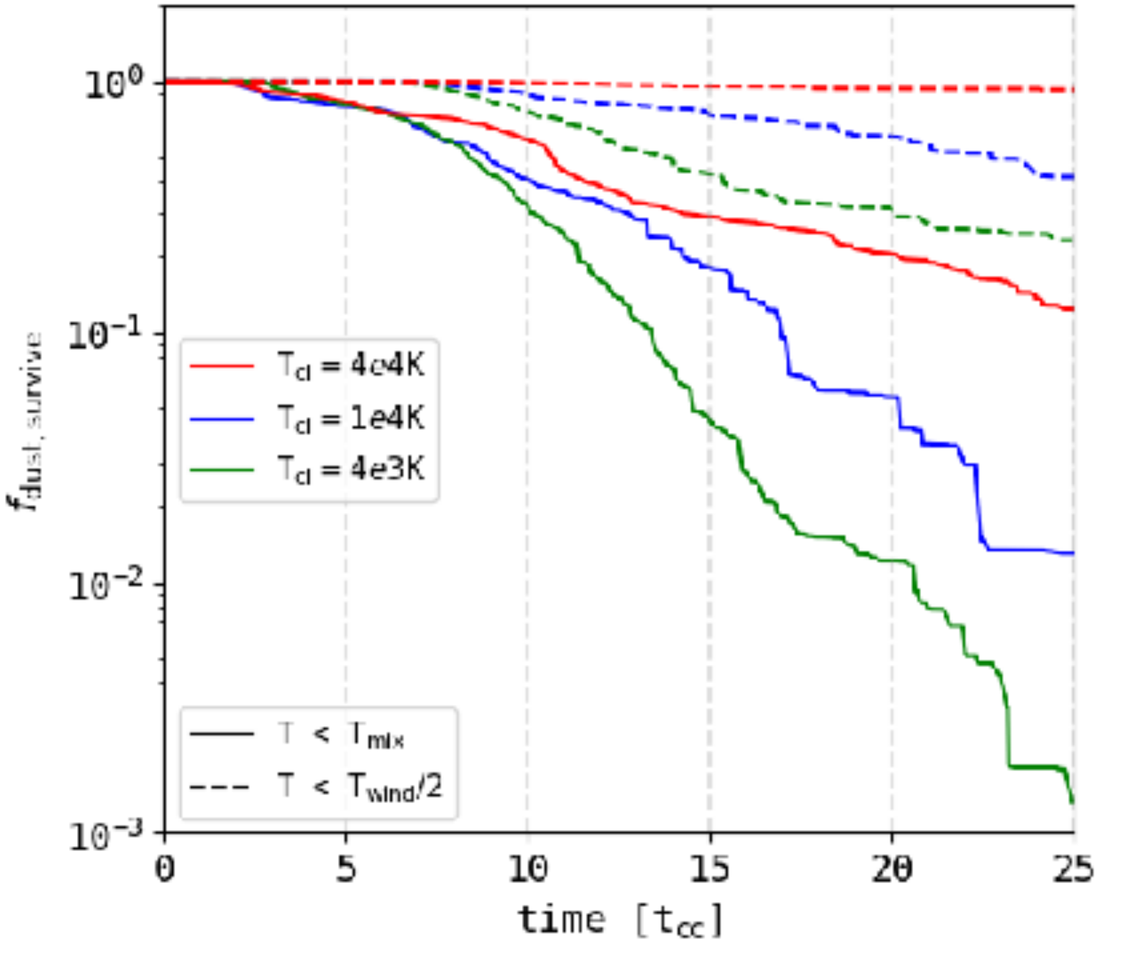

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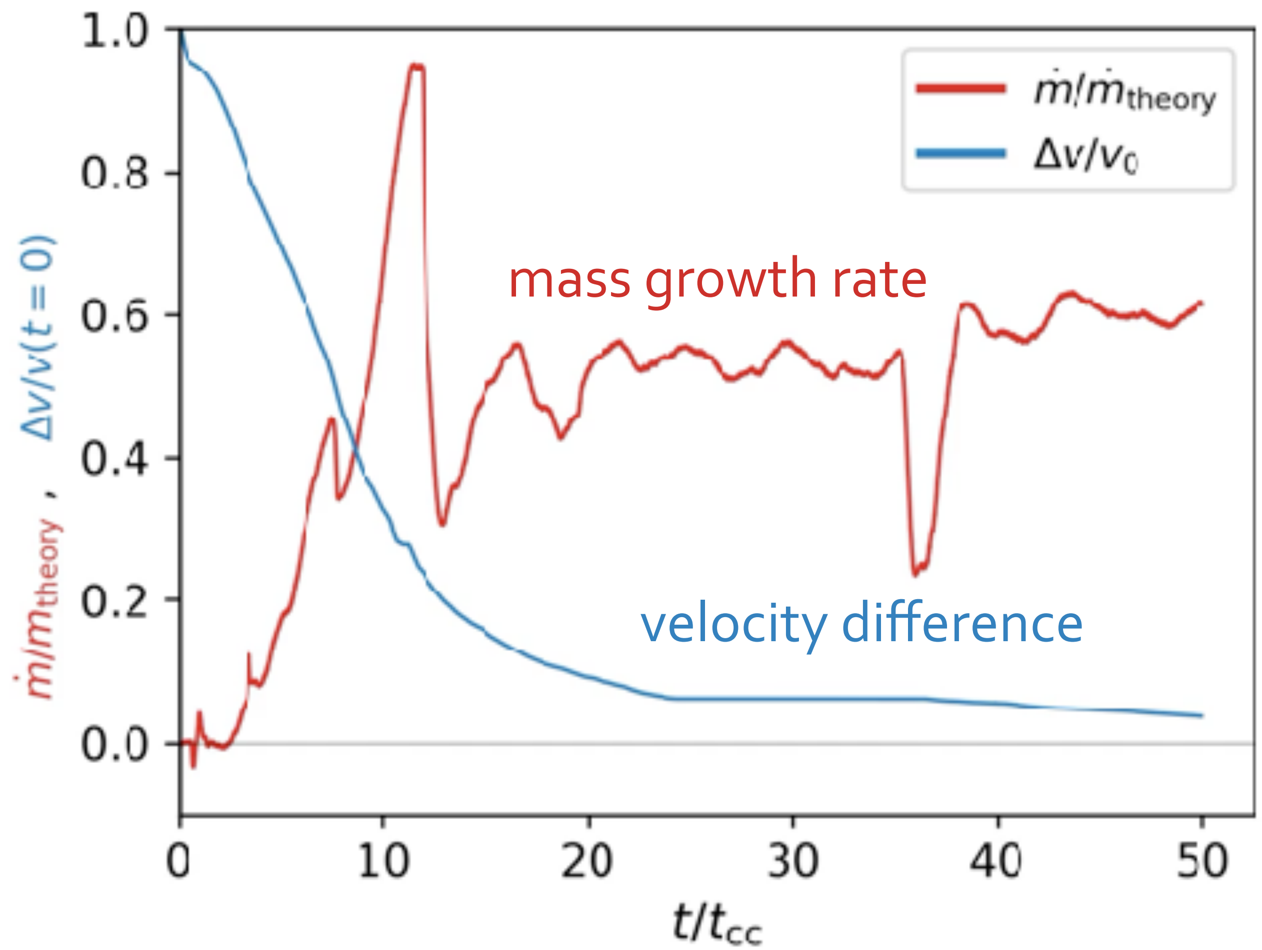
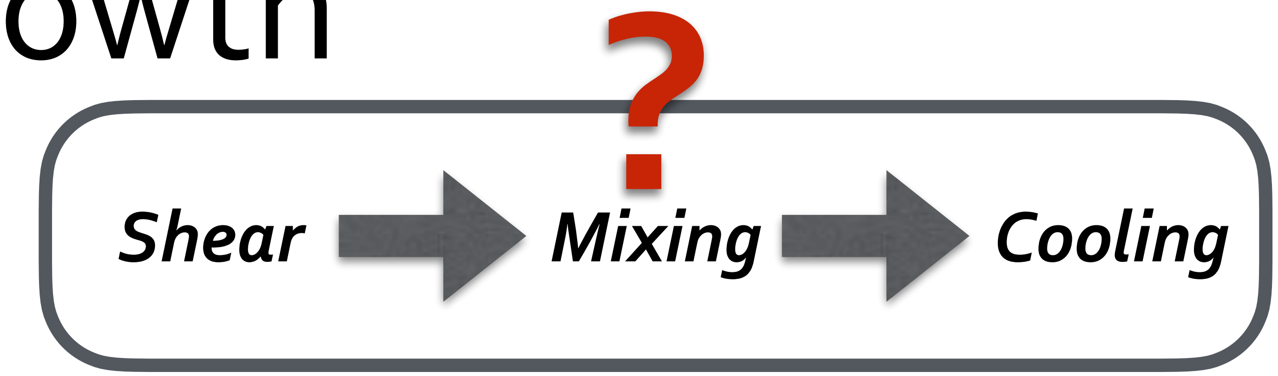
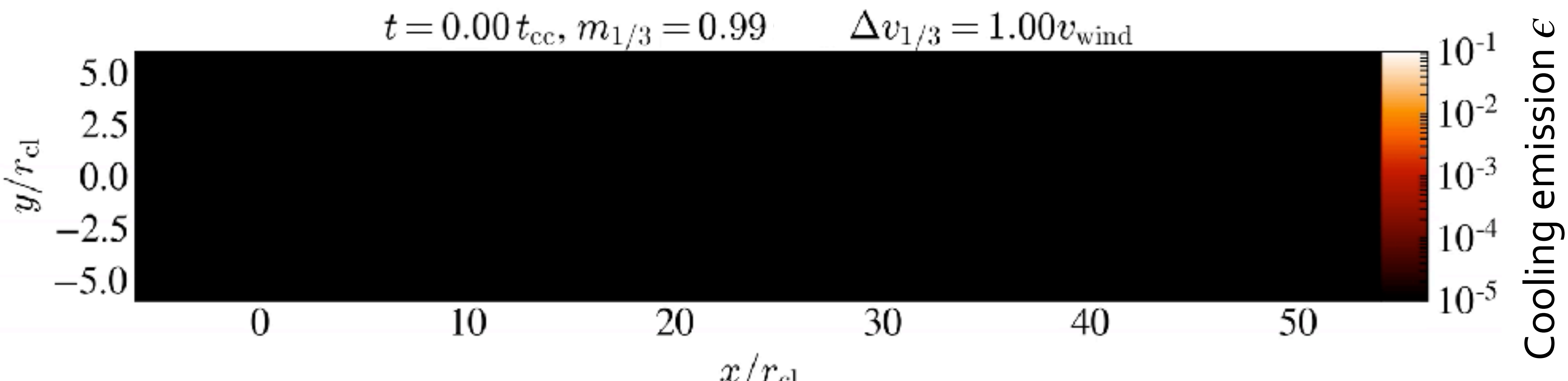
Implications of cooling supported survival:

Continuous mass growth

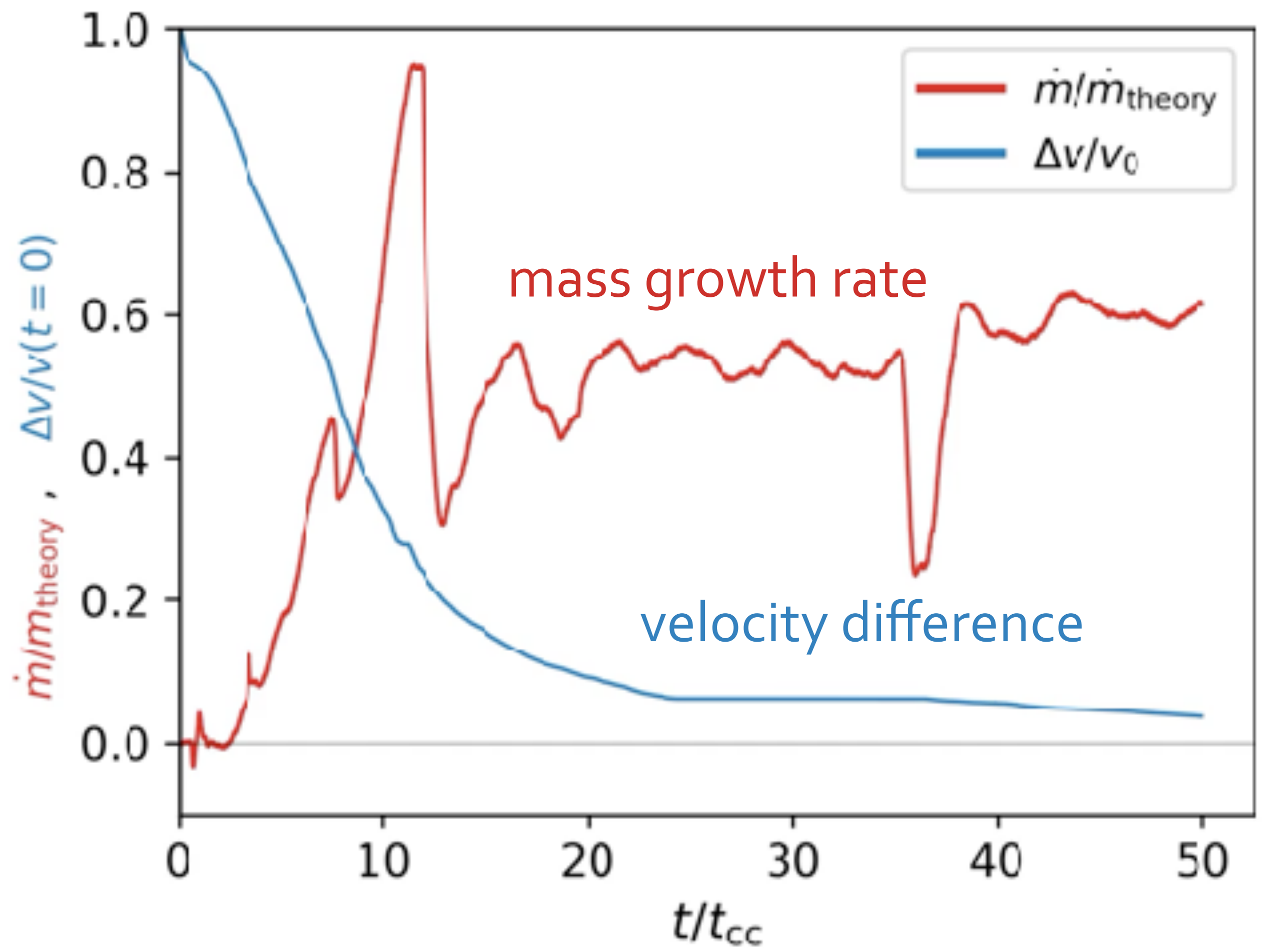


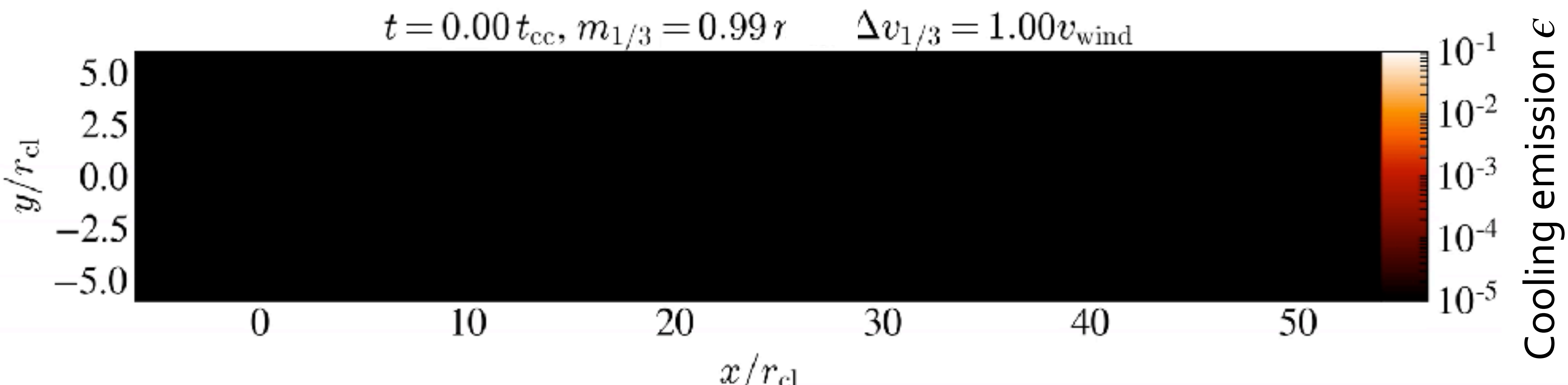




MG & Oh (2020a,b)

Continuous mass growth





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MG & Oh (2020a,b)

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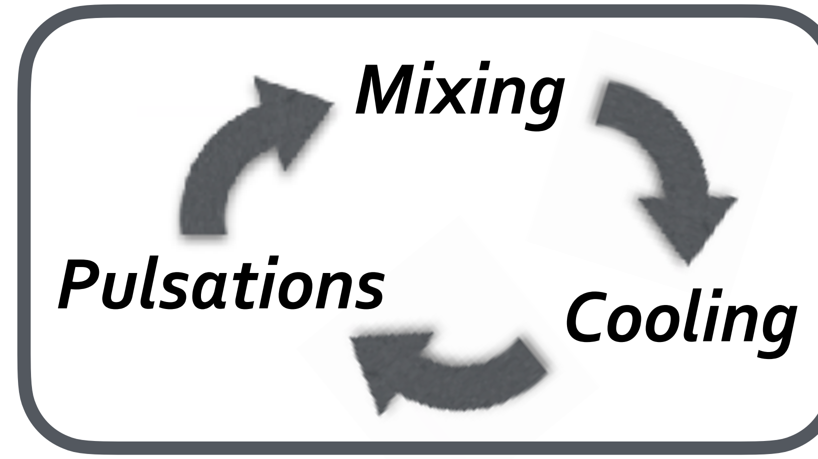

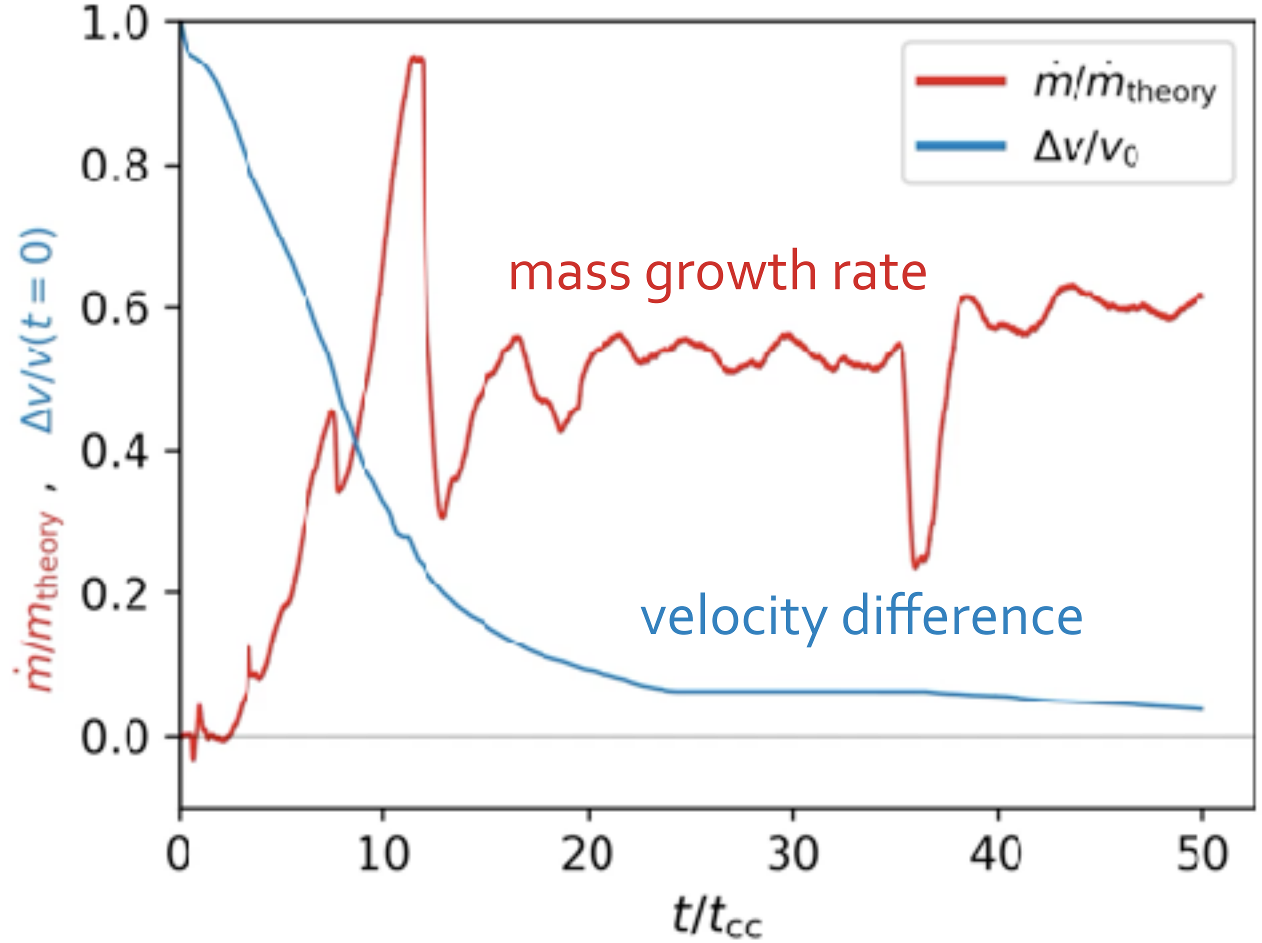

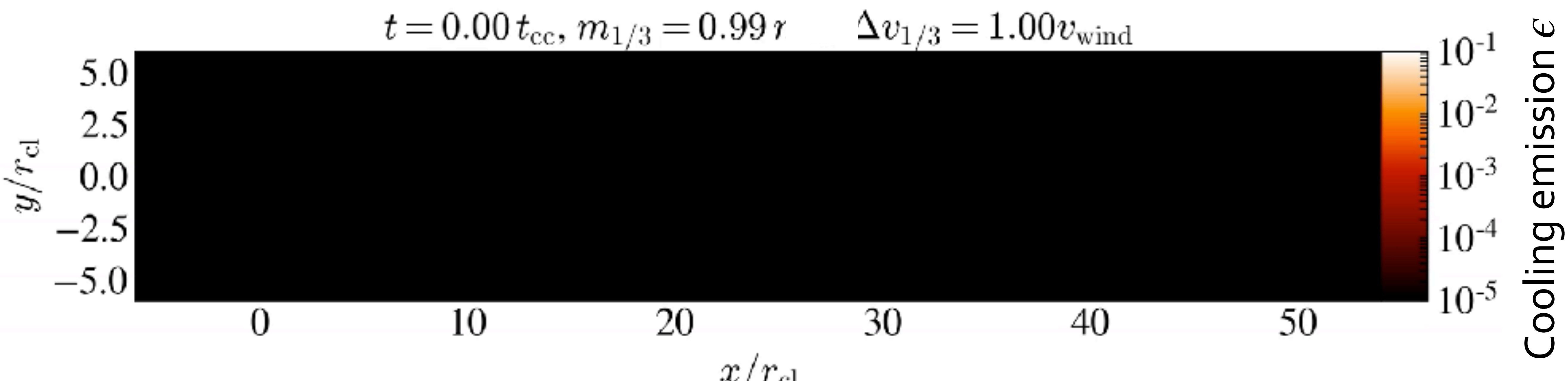

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MG & Oh (2020a,b)

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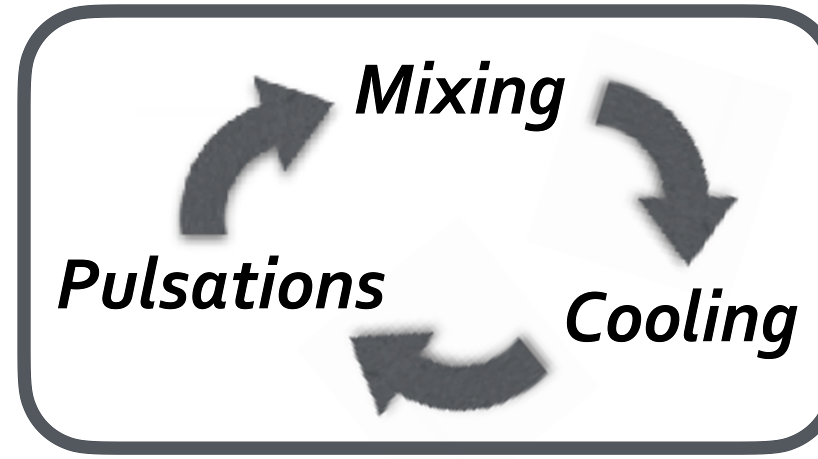
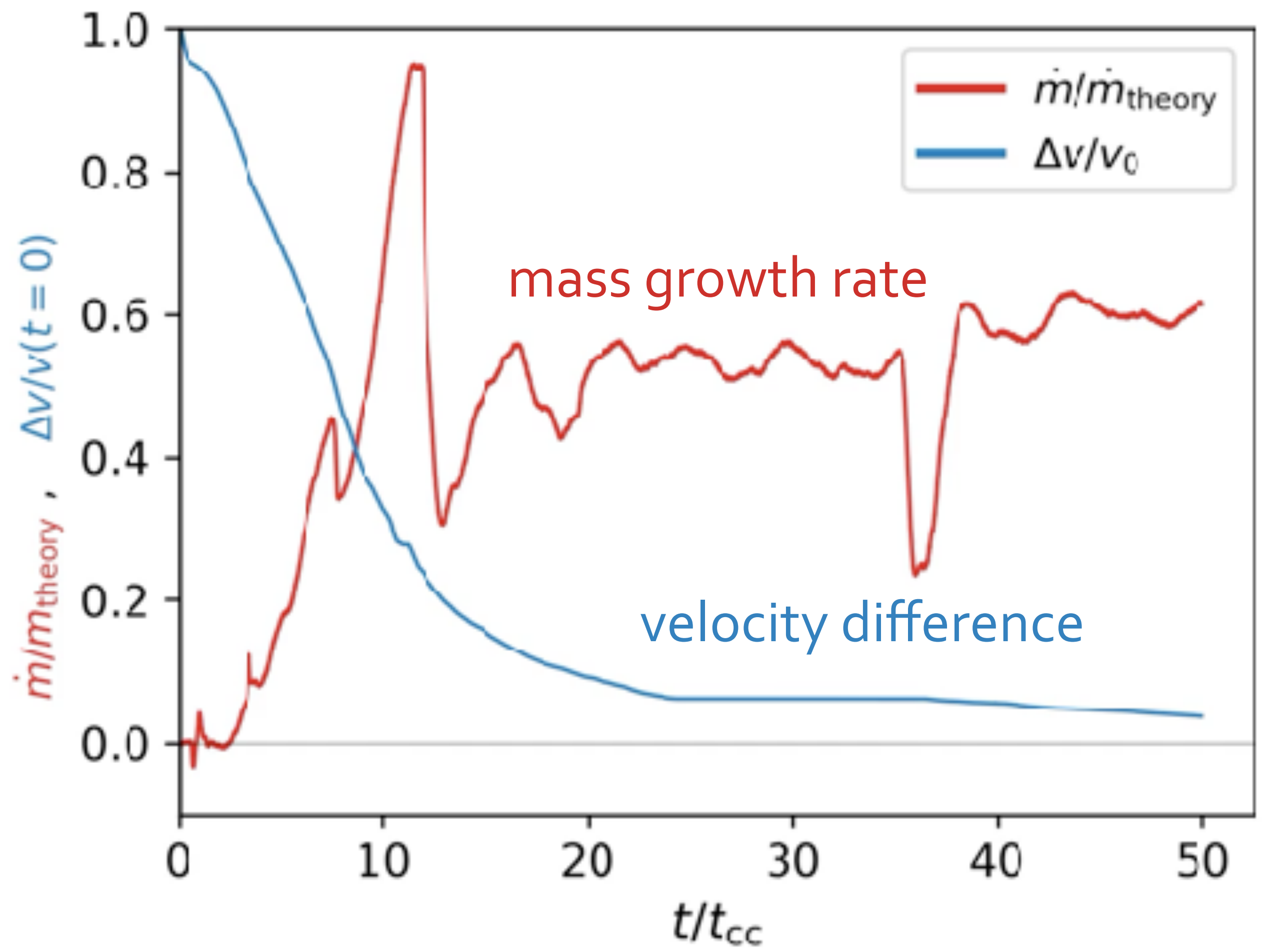


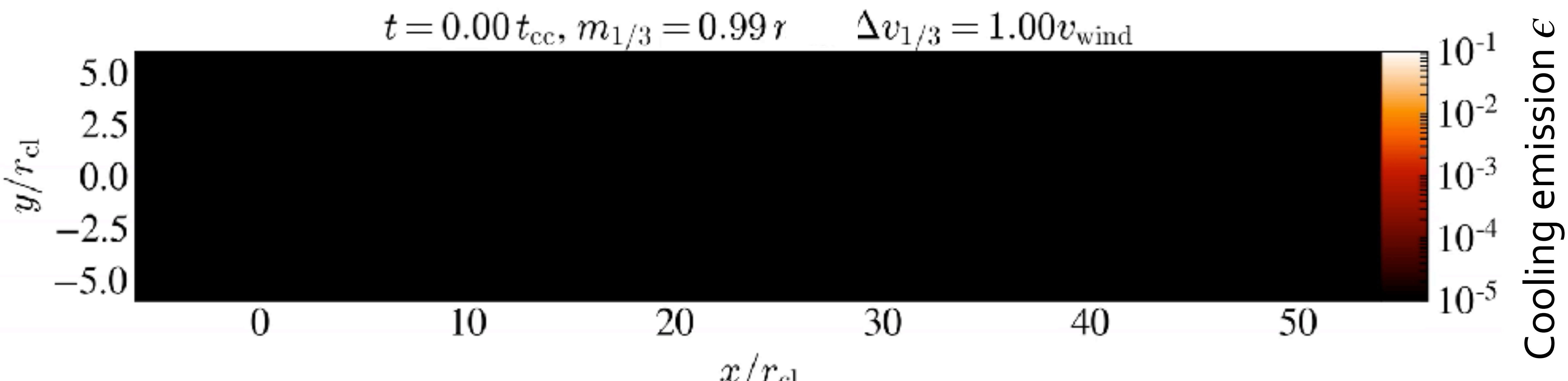


Converged mass growth rate

(resolving $\min(c_s t_{cool})$)

$$\dot{m}_{\text{theory}} \sim c_{\text{s,cold}} \text{Area}_{\text{cold}} \rho_{\text{hot}} (t_{\text{sound-cross}}/t_{\text{cool}})^{1/4}$$

$\rightarrow M_{\text{cold,CGM}} \sim \int \dot{m}\,\mathrm{d}t \sim M_*$ by galactic winds



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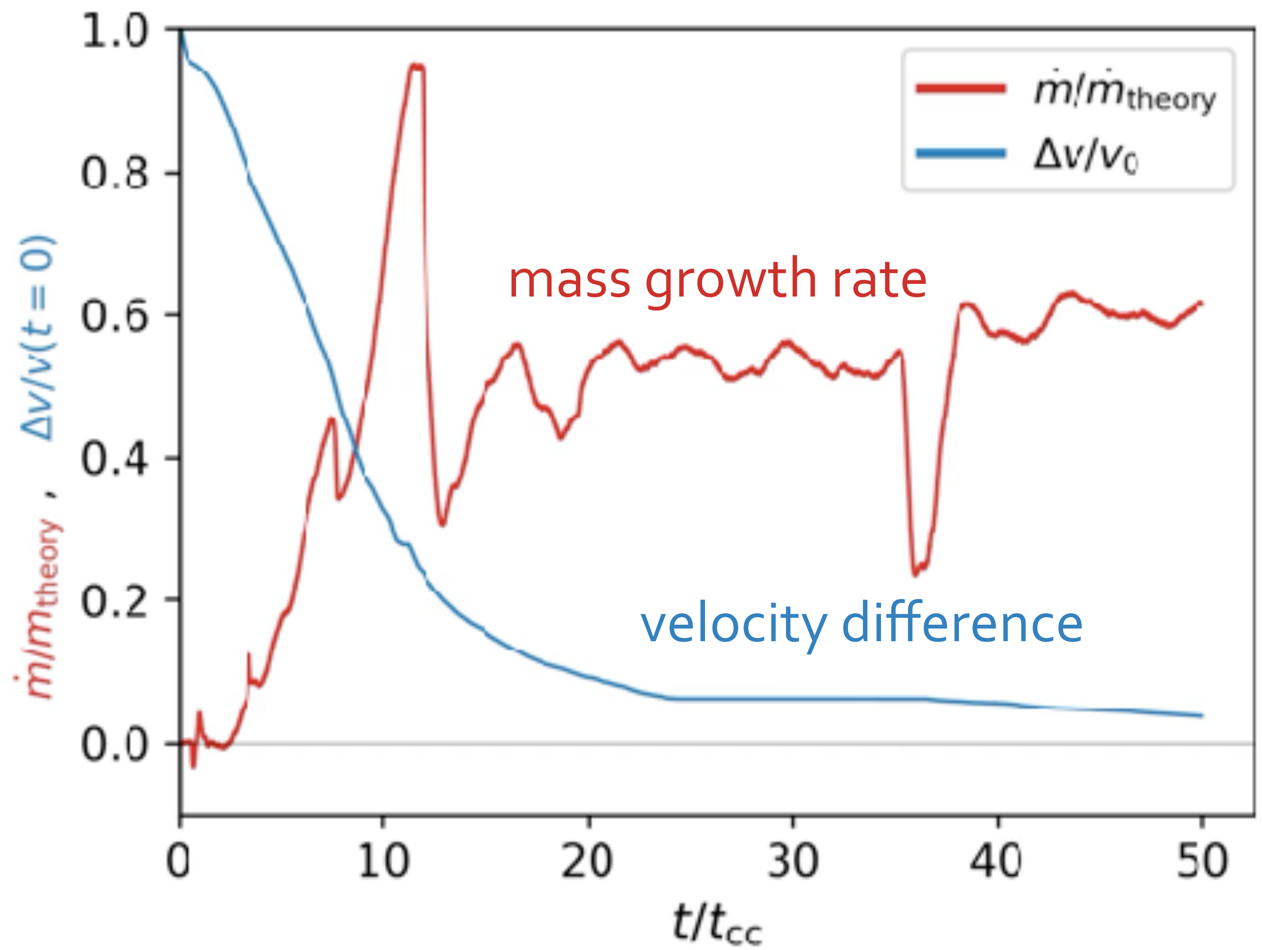

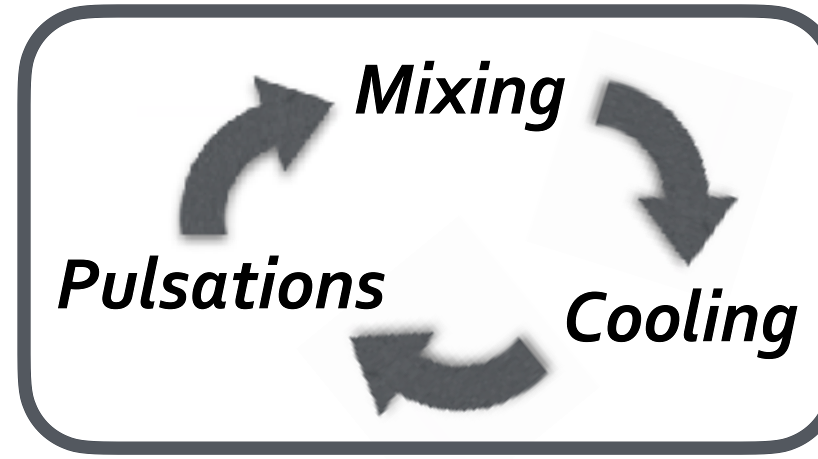

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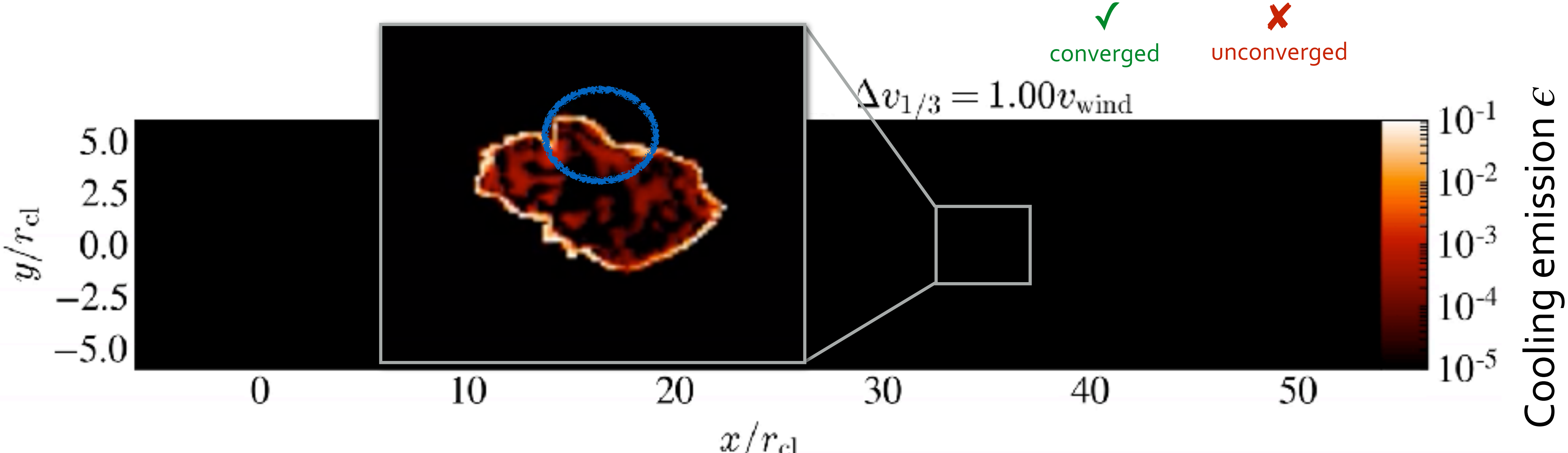
but

one-cell thick emission layer!

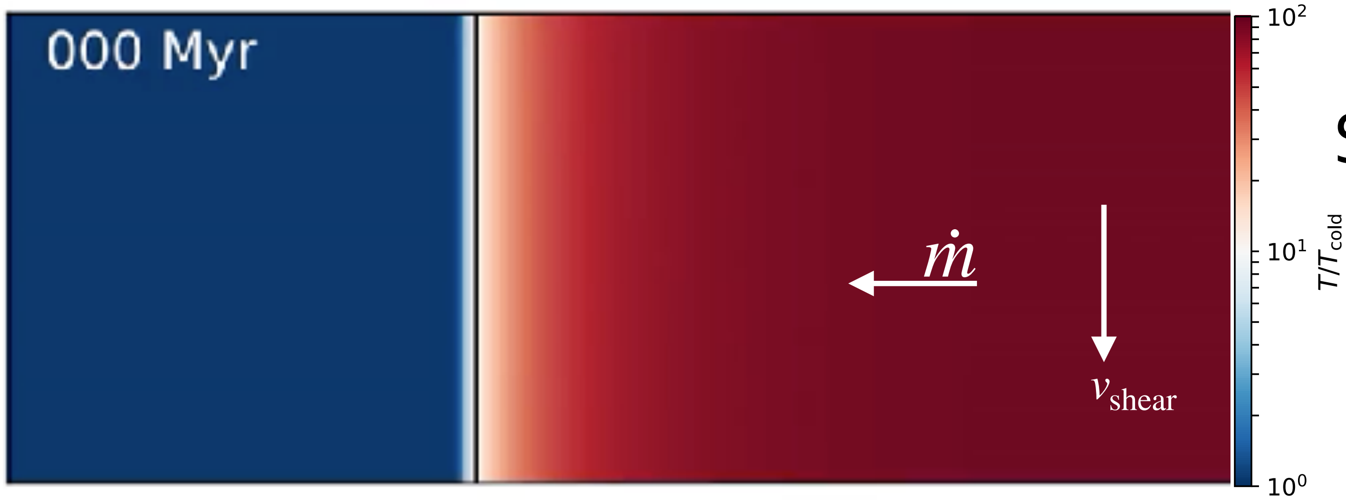
$(\dot{m} \propto L \sim \epsilon V)$

✓ converged ✘ unconverged



Tan, Oh, MG (2020)

Zooming in on turbulent mixing layers



Consistent 3D results

Seemingly converged mass growth rate

Brent Tan (UCSB)

also see Fielding et al. (2020) & Drummond's great talk!

Tan, Oh, MG (2020)

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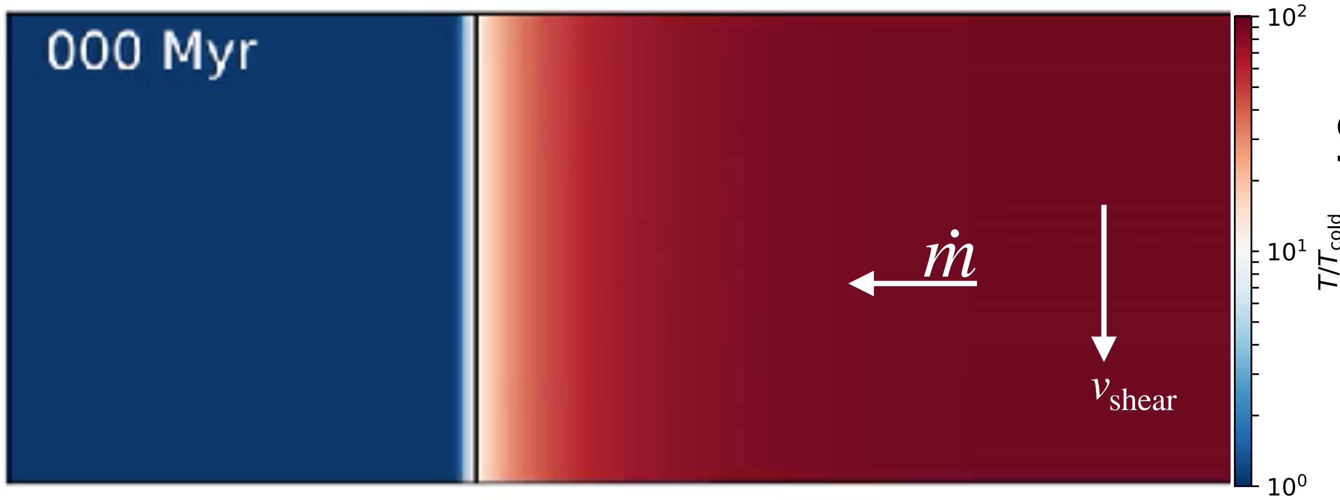

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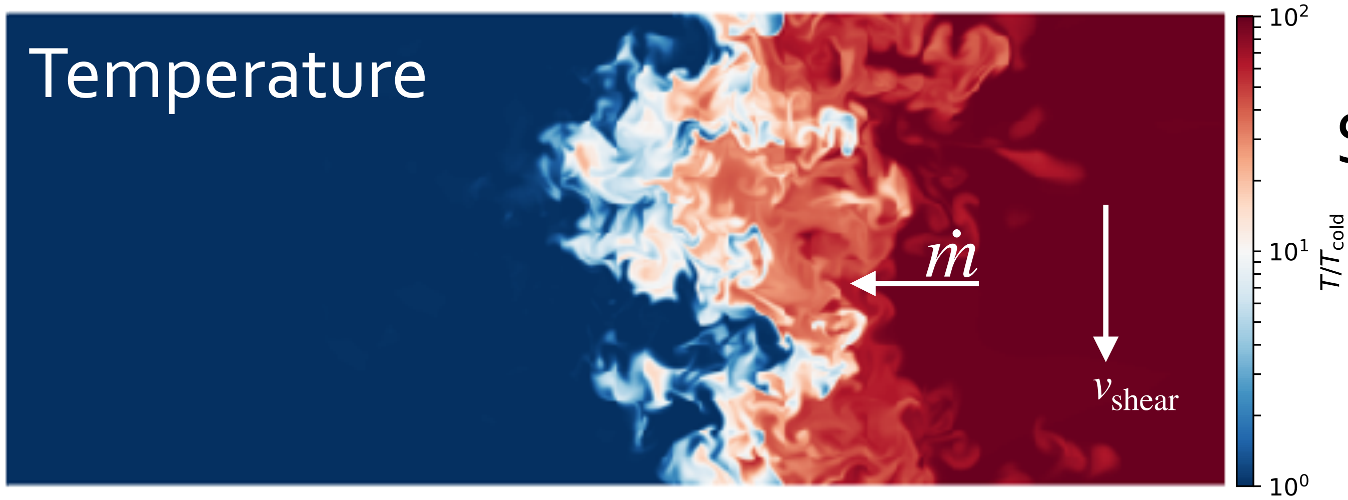

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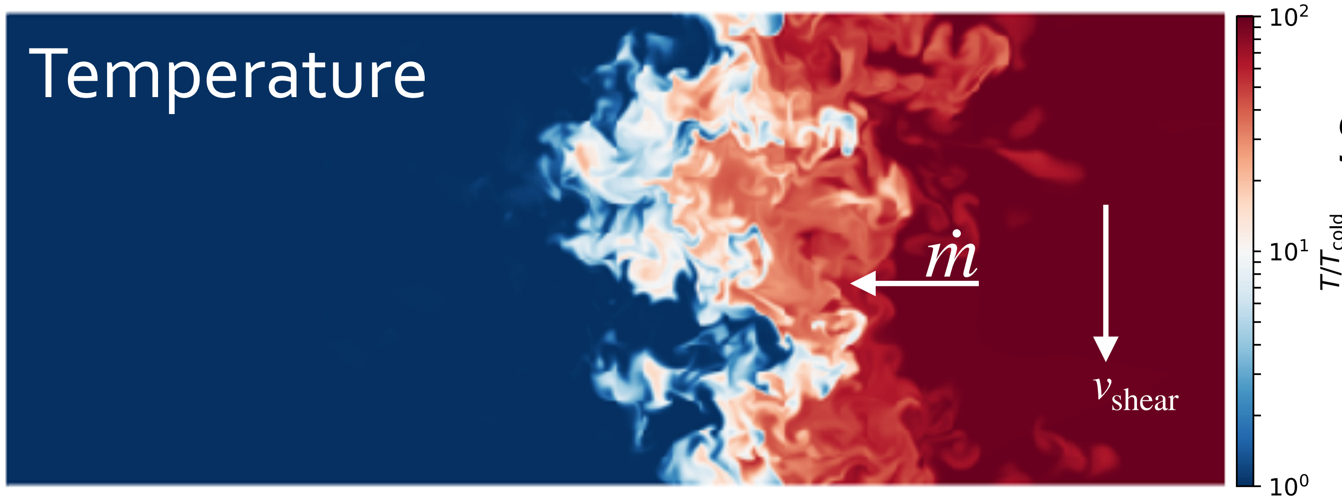

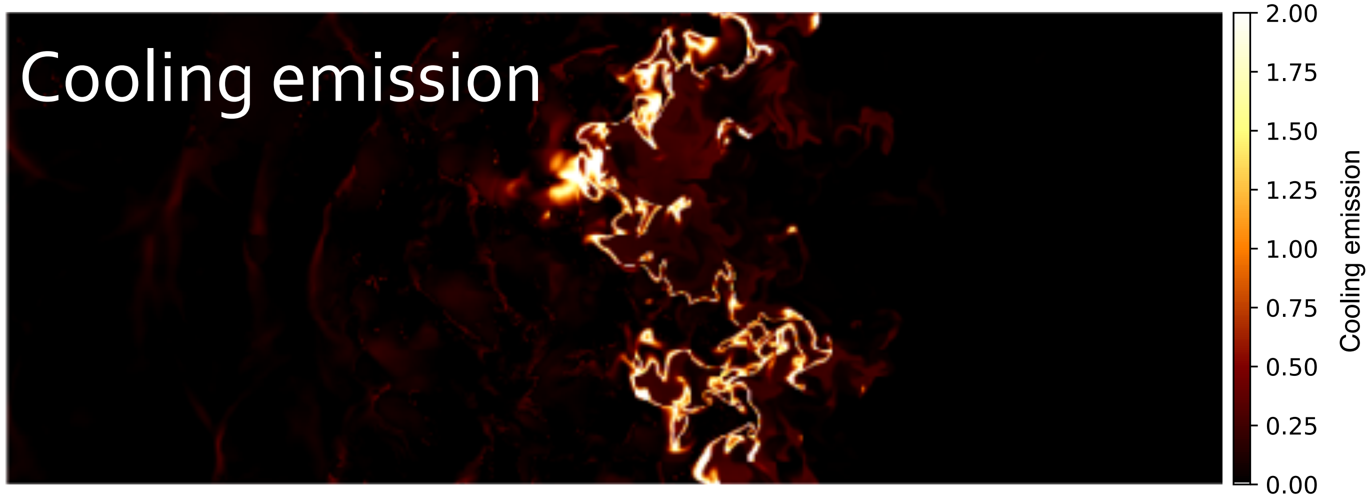

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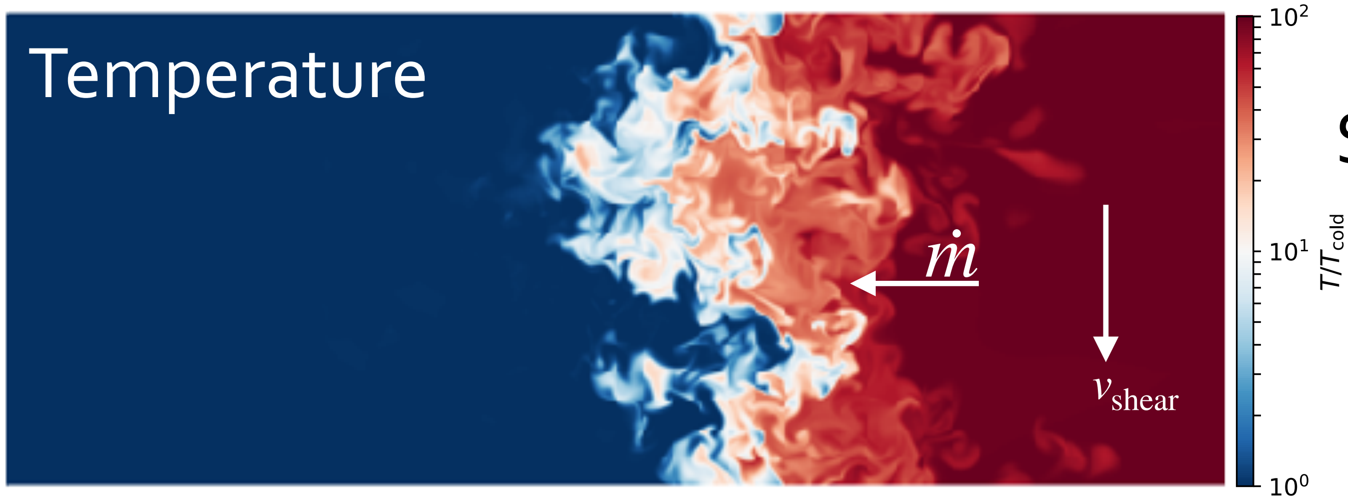
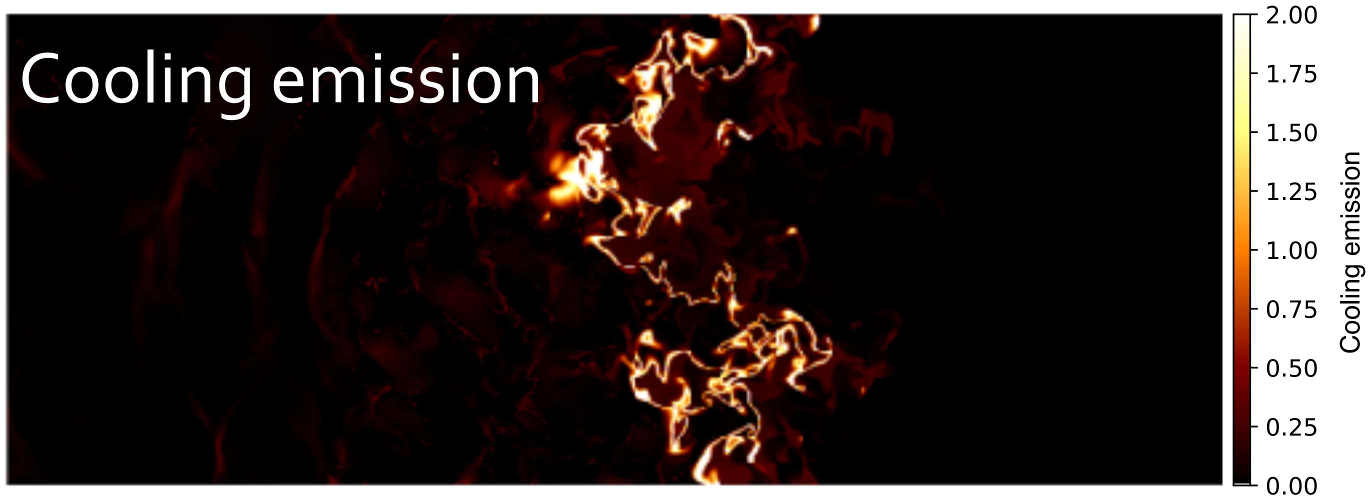
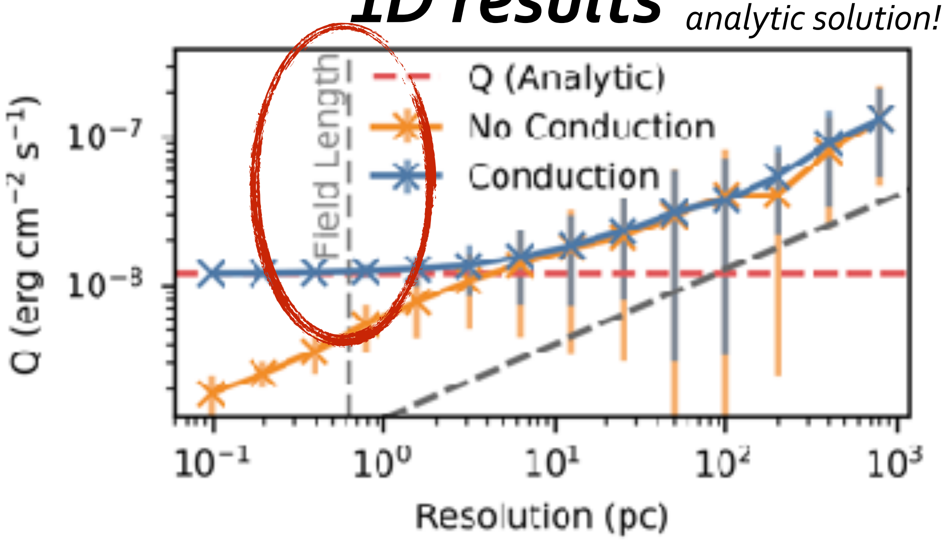




1D results

wide range & analytic solution!



$\lambda_{\rm F} \sim (D_{\rm cond.} t_{\rm cool})^{1/2}$

Consistent 3D results

Seemingly converged mass growth rate

but

one-cell thick emission layer!

$(\dot{m} \propto L \sim \epsilon V)$

✓ converged vs. ✗ unconverged

because of unresolved Field length

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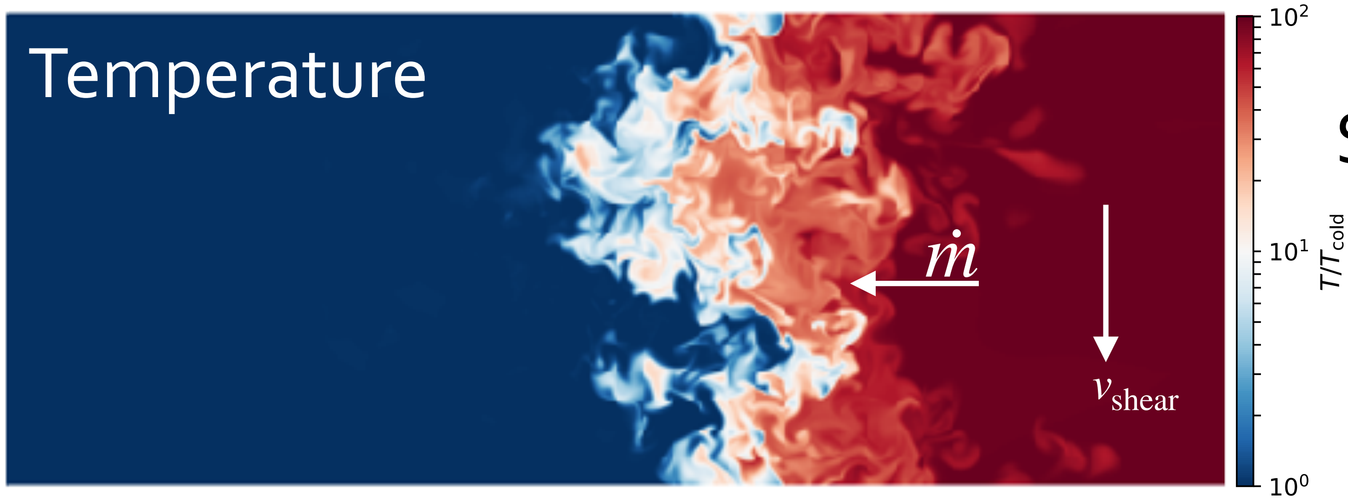

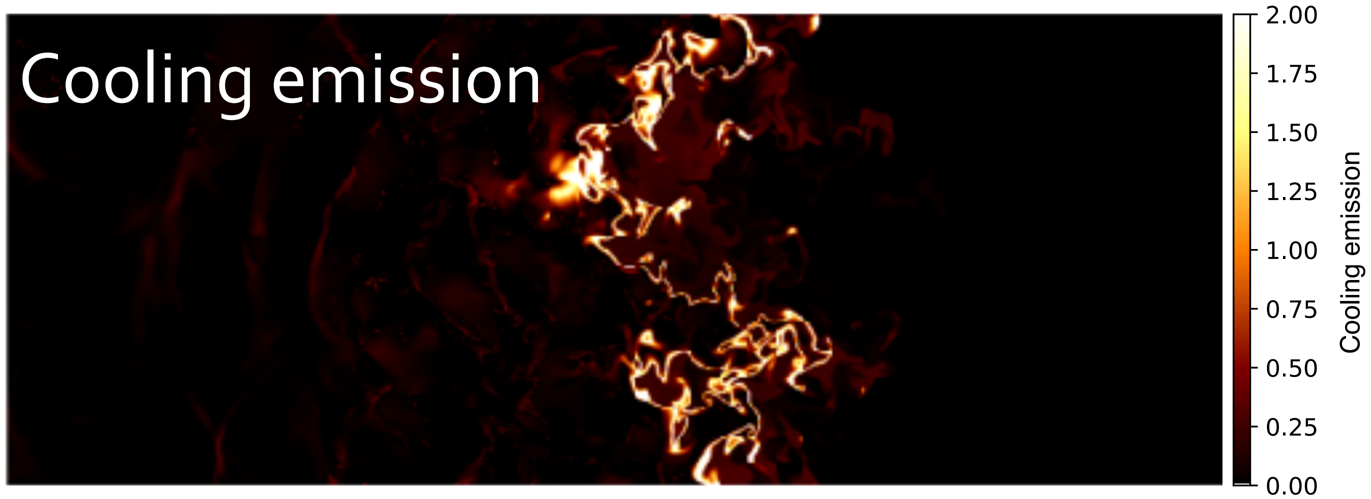

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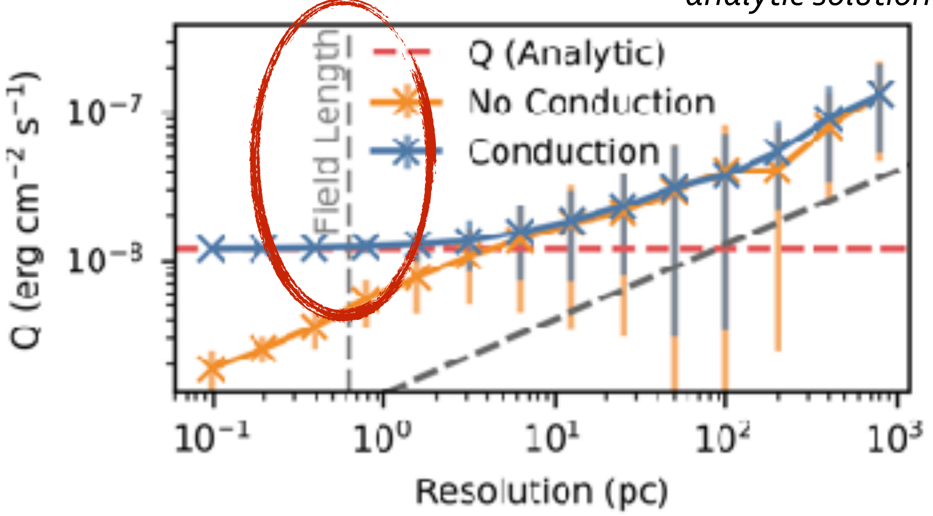

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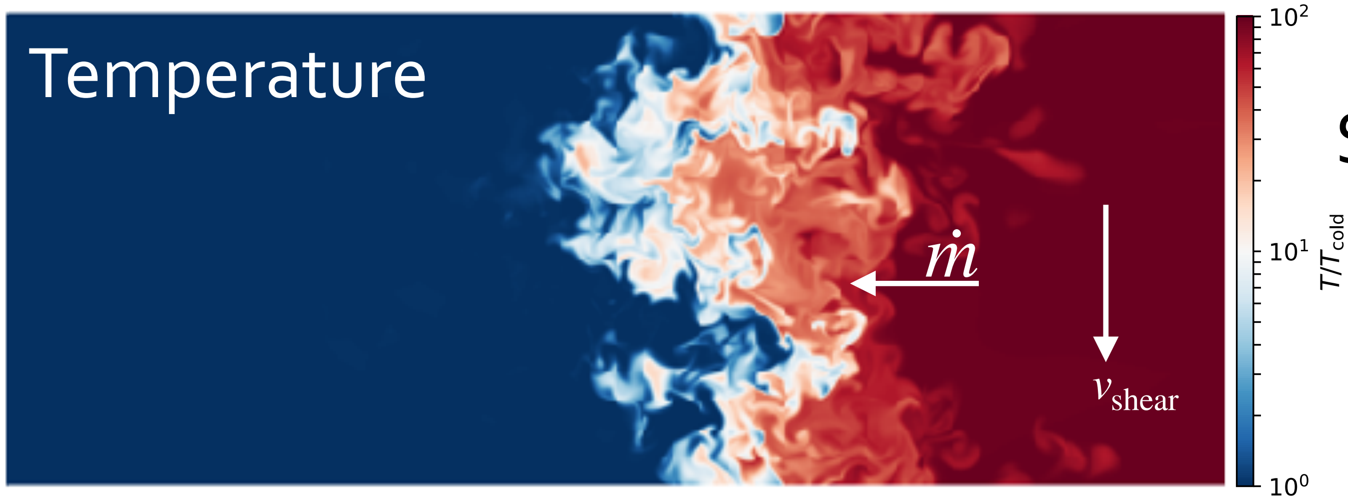
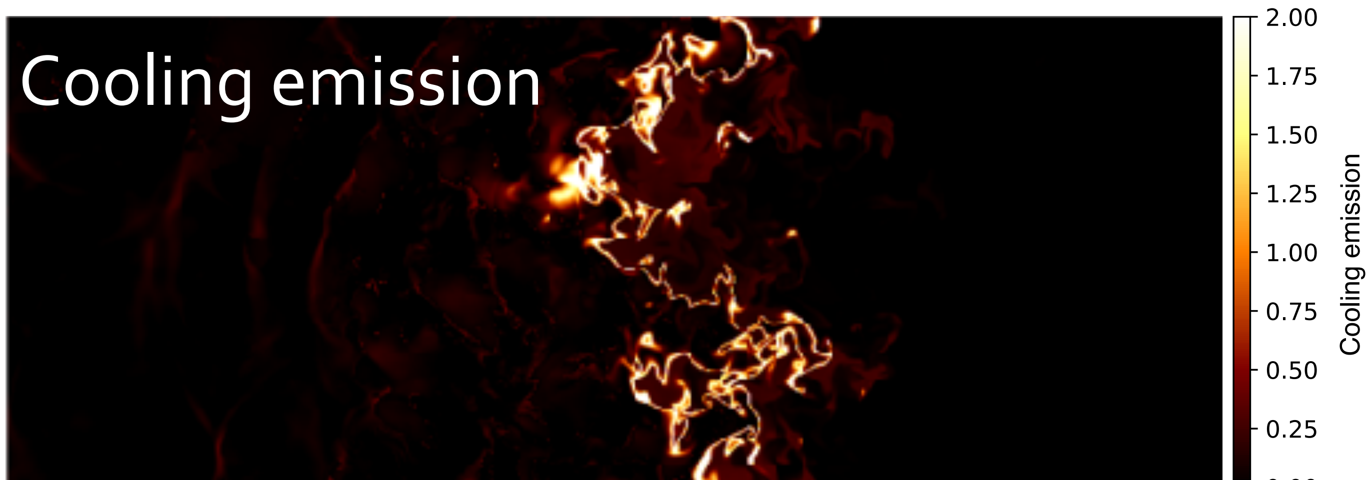
Why $\propto c_{\rm s,cold} \ll c_{\rm s,hot}$?

Zooming in on turbulent mixing layers





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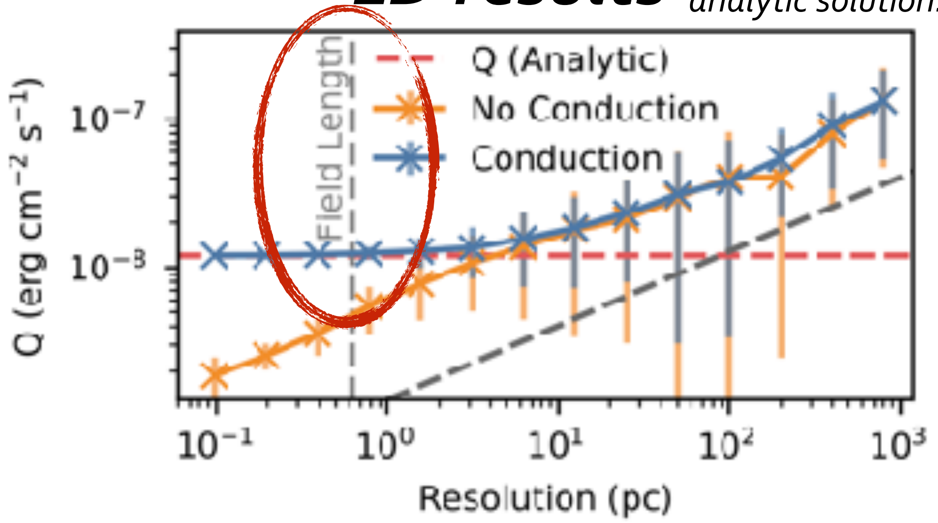
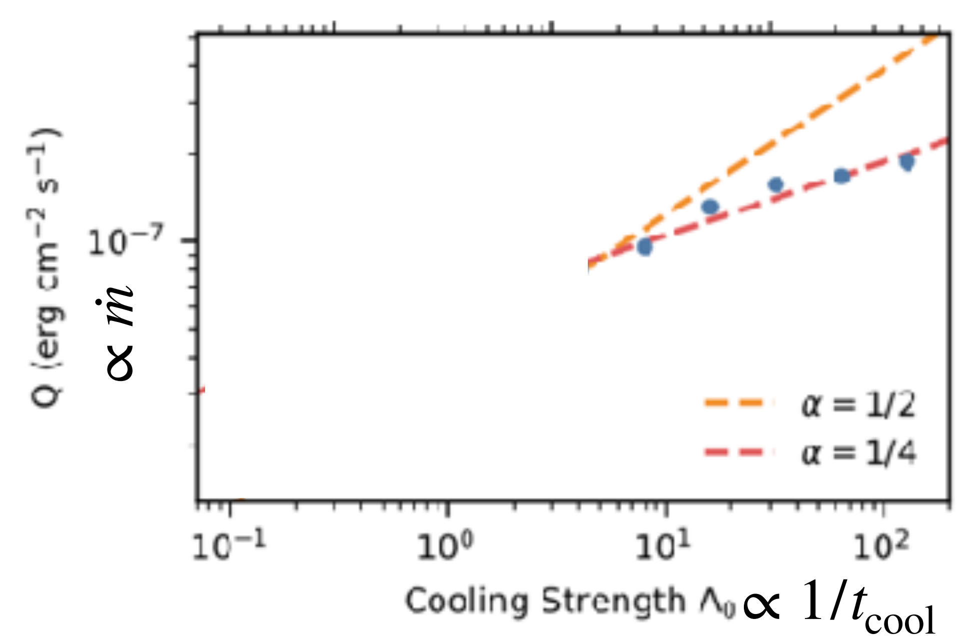


$\lambda_{\rm F} \sim (D_{\rm cond.}t_{\rm cool})^{1/2}$



Tan, Oh, MG (2020)

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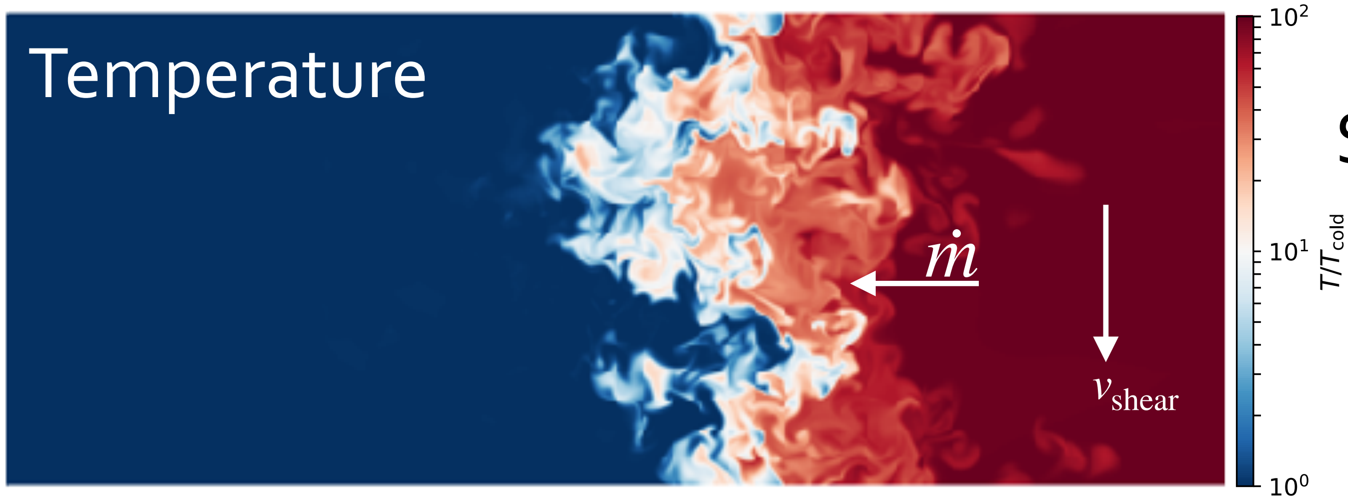

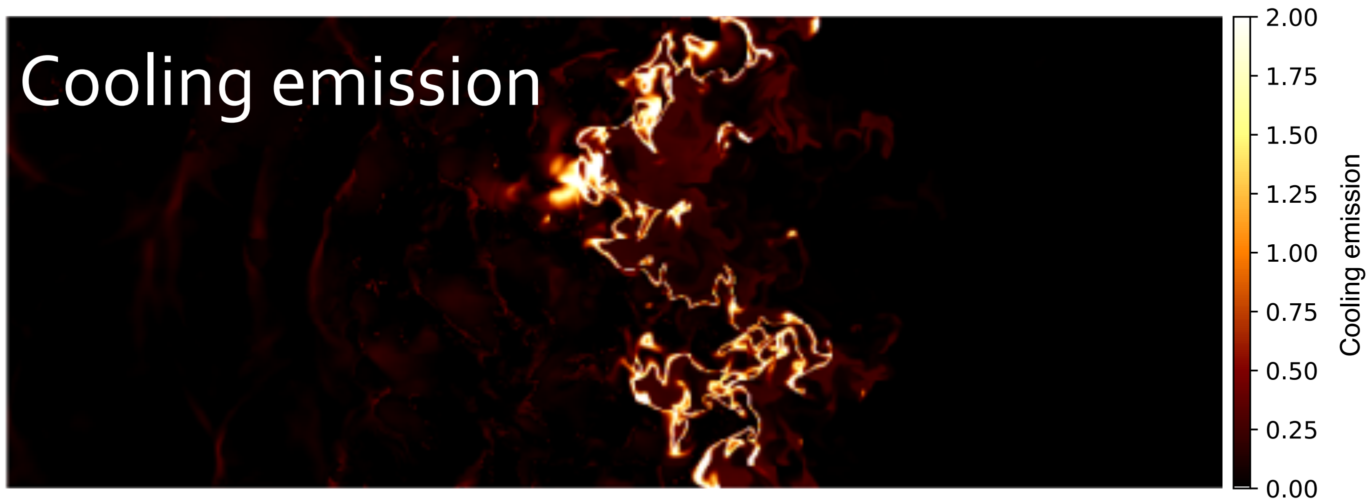

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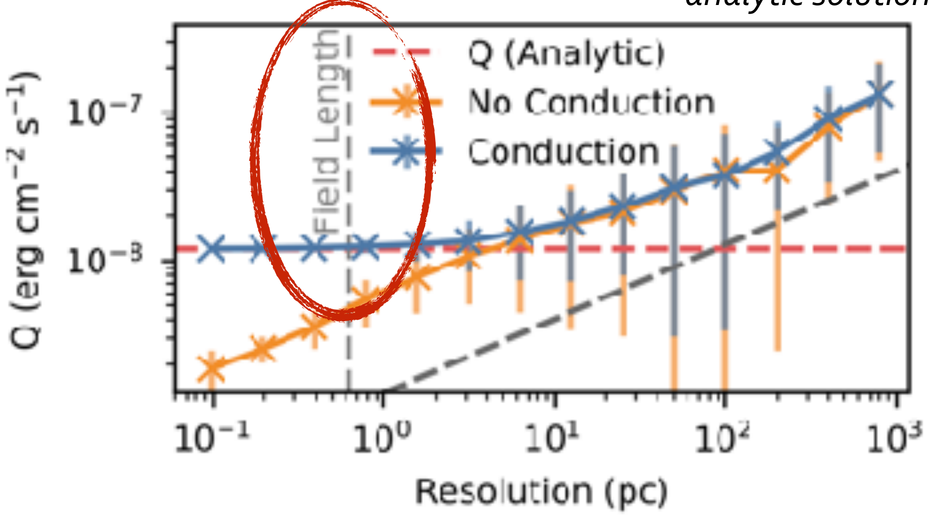

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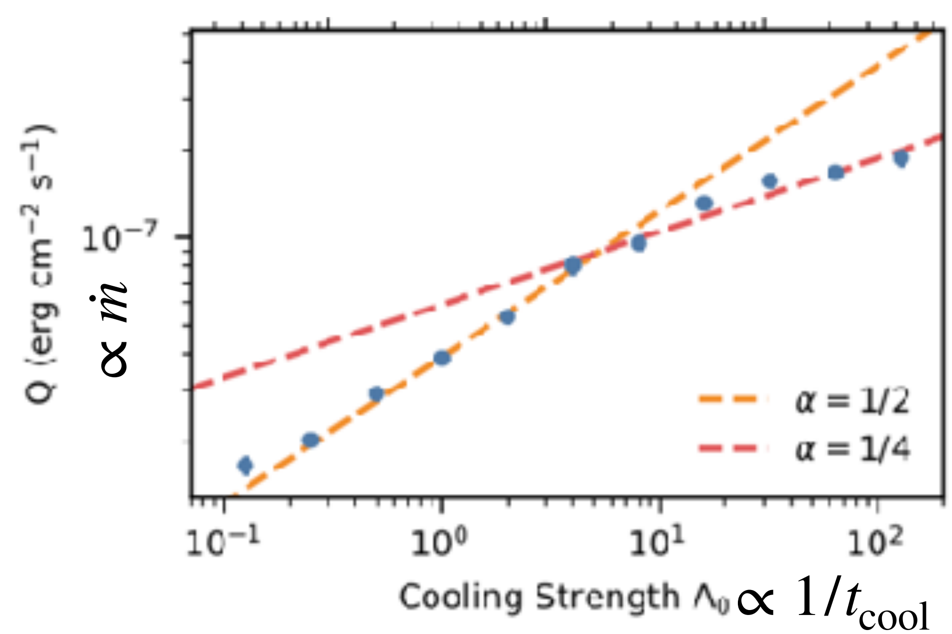
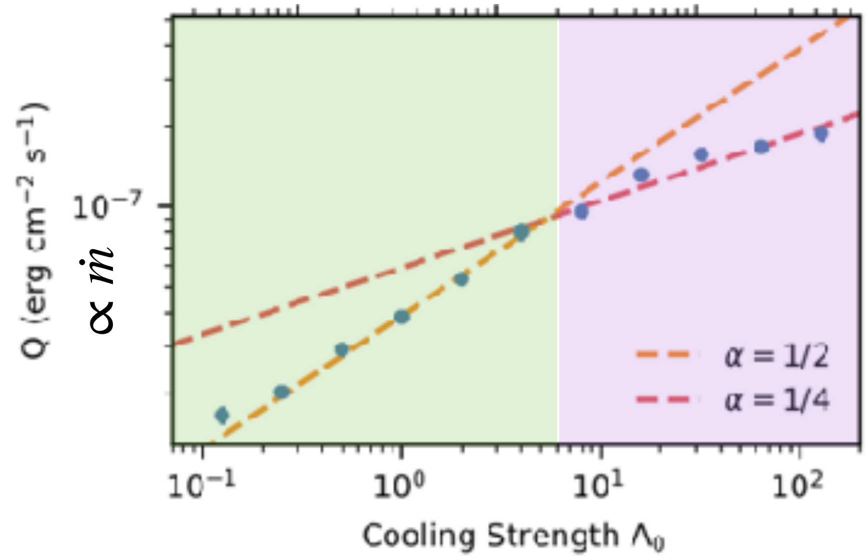
Why $\propto t_{\rm cool}^{-1/4}$?? And $\propto t_{\rm cool}^{-1/2}$???

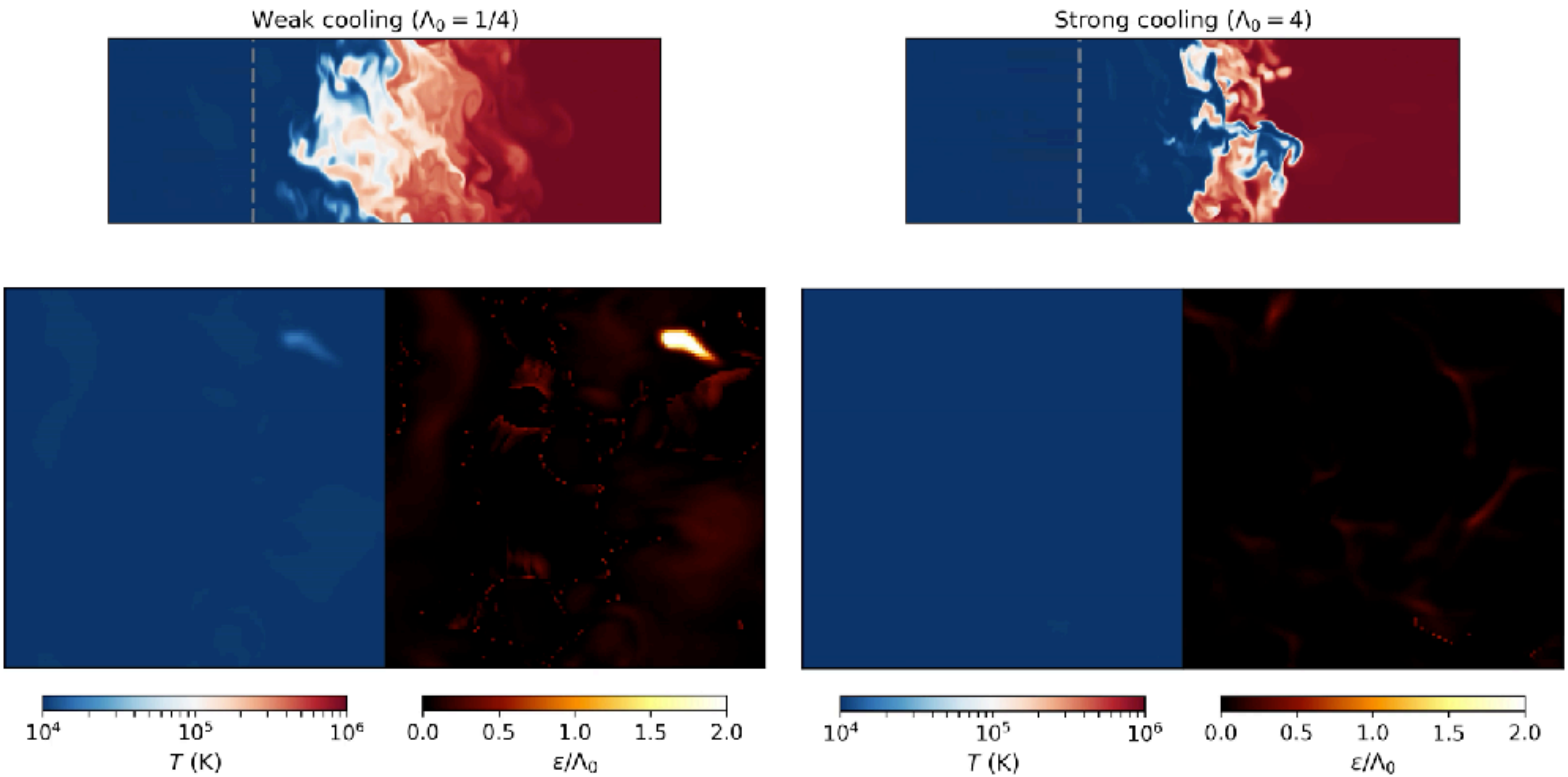
(cf. Ji et al. 2019)



Two different cooling regimes

Tan, Oh, MG (2020)





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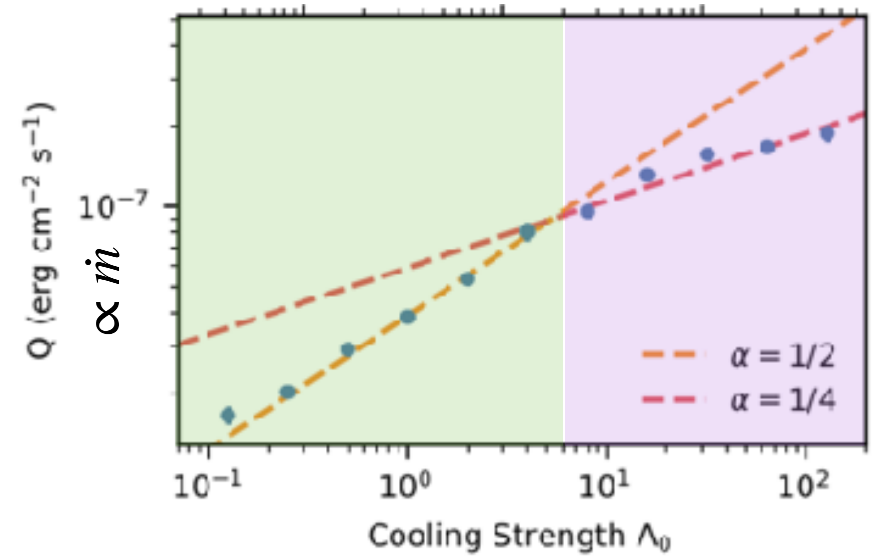
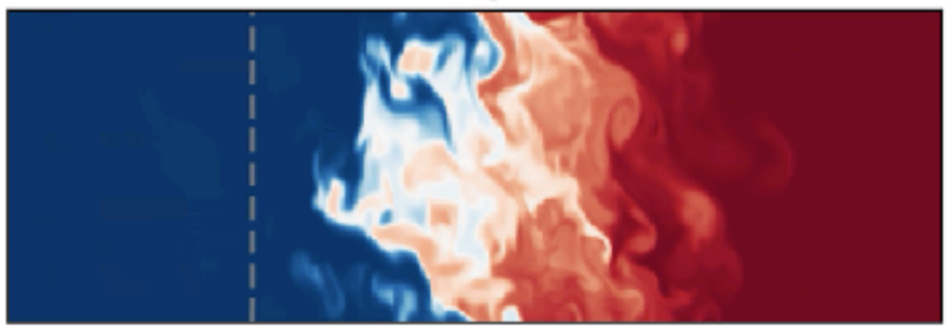
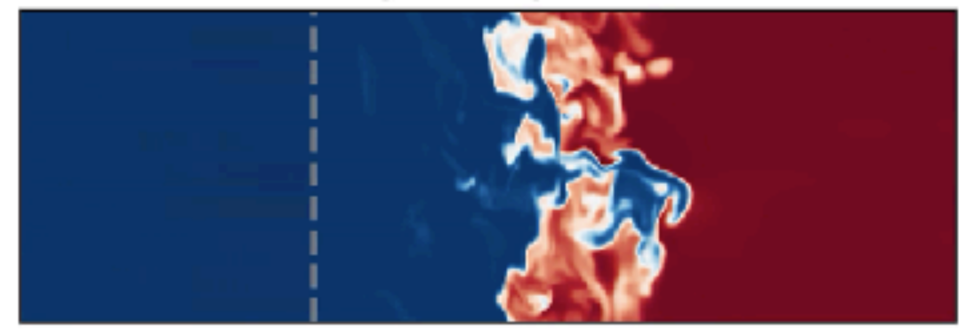
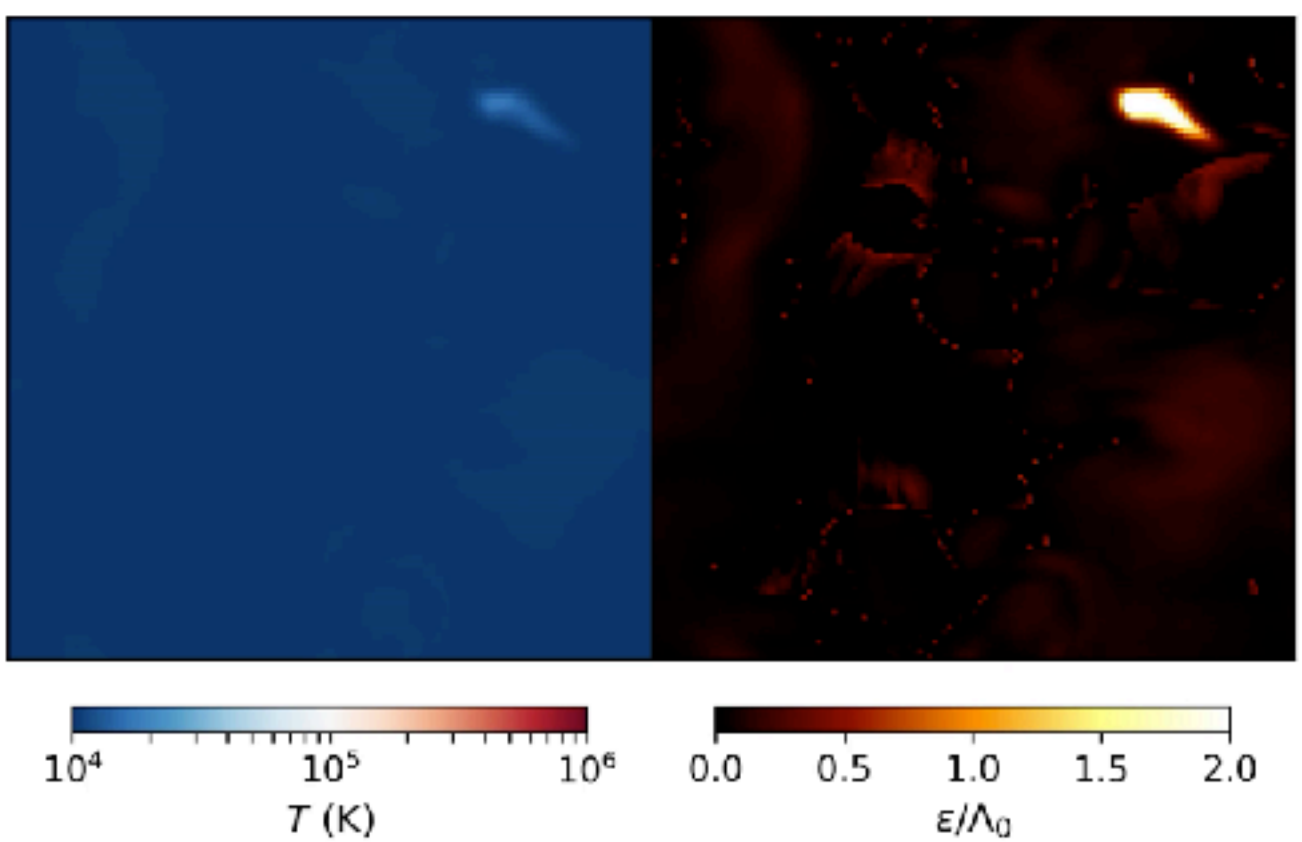


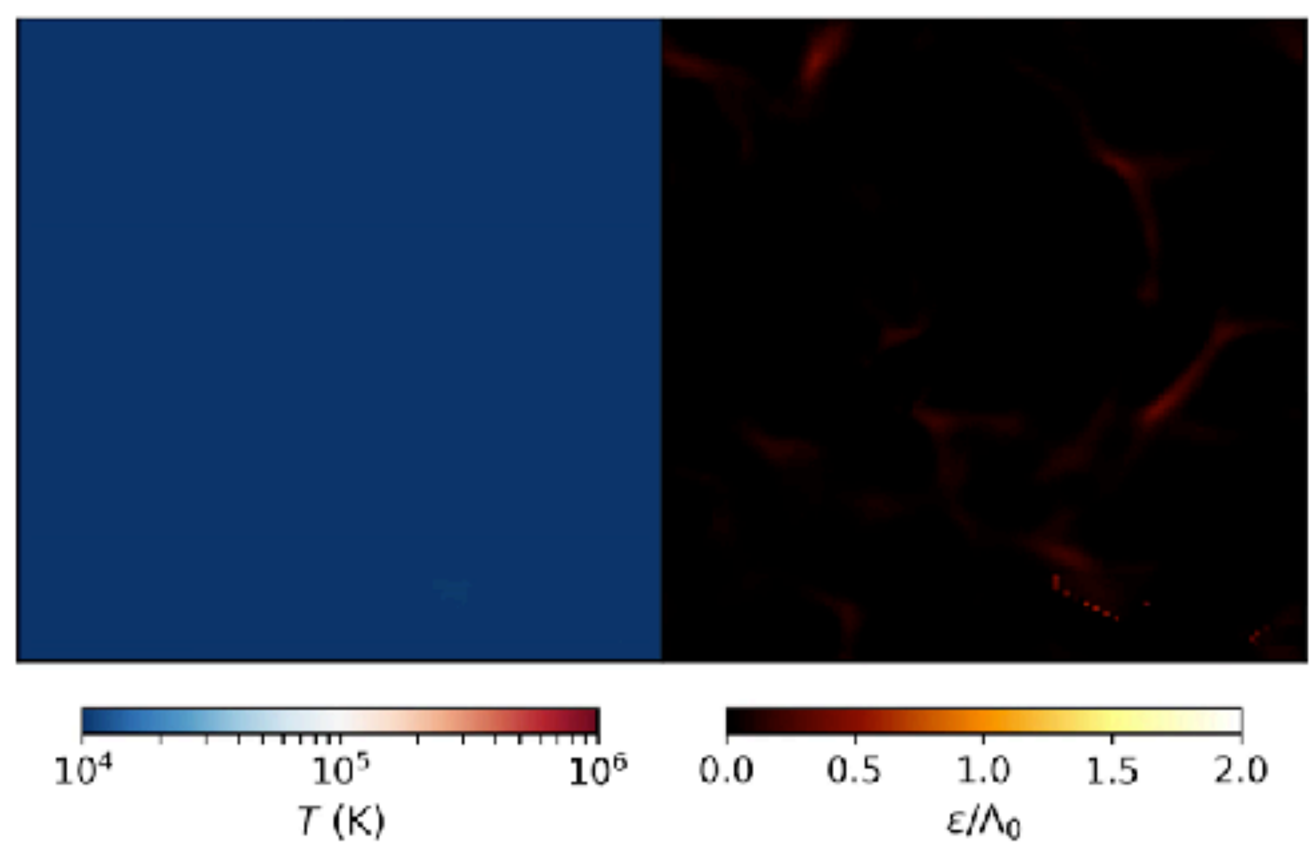
Weak cooling ($\Lambda_0 = 1/4$)



Strong cooling ($\Lambda_0 = 4$)

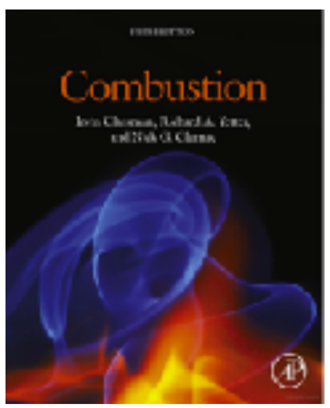






Fuel & oxidizer instead of hot & cold gas: Tan, Oh, MG (2020)

Insights from turbulent combustion



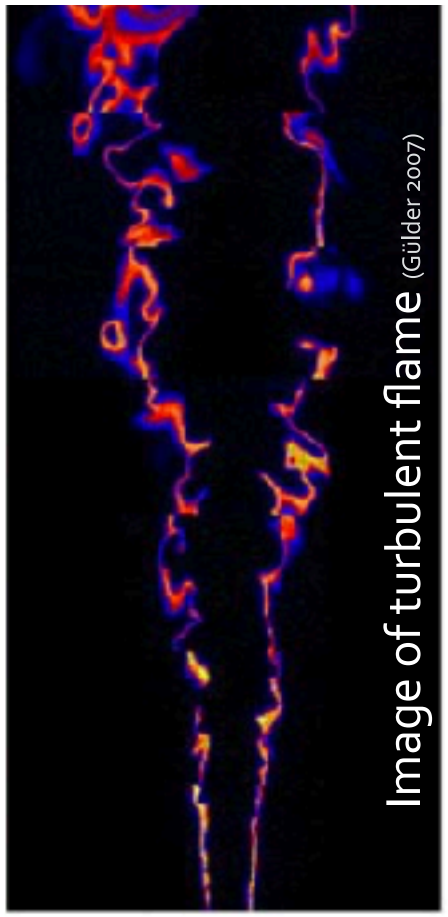


Image of turbulent flame (Gülder 2007)

Fuel & oxidizer instead of hot & cold gas:

Tan, Oh, MG (2020)

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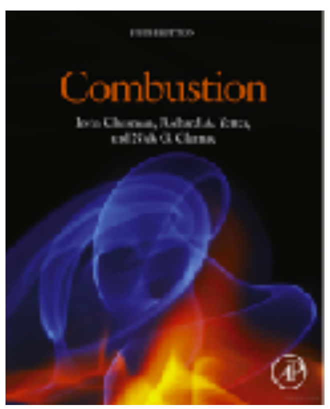

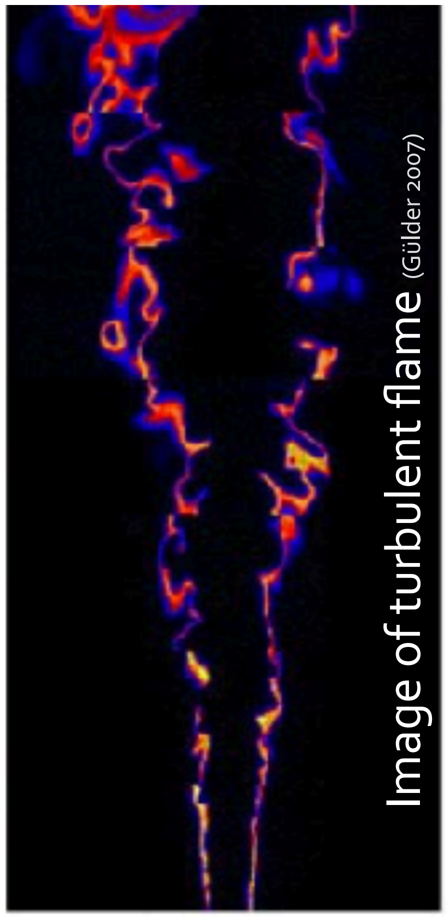

ZEITSCHRIFT FÜR ELEKTROCHEMIE
UND ANGEWANDTE PHYSIKALISCHE CHEMIE

Z. f. Elektroch. Bd. **46.** November 1940. Nr. 11 (S. 601—652).

DER EINFLUSS DER TURBULENZ AUF DIE FLAMMENGESCHWINDIGKEIT IN GASGEMISCHEN.

Von *Gerhard Damköhler.*

(Bericht aus dem Institut für Motorenforschung der Luftfahrtforschungsanstalt Hermann Göring, Braunschweig.)

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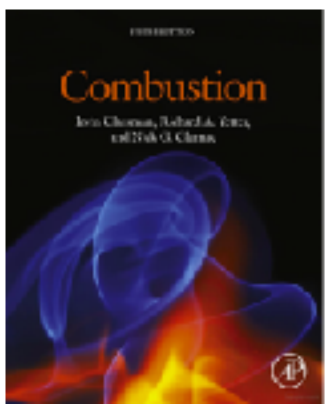
Tan, Oh, MG (2020)

Insights from turbulent combustion



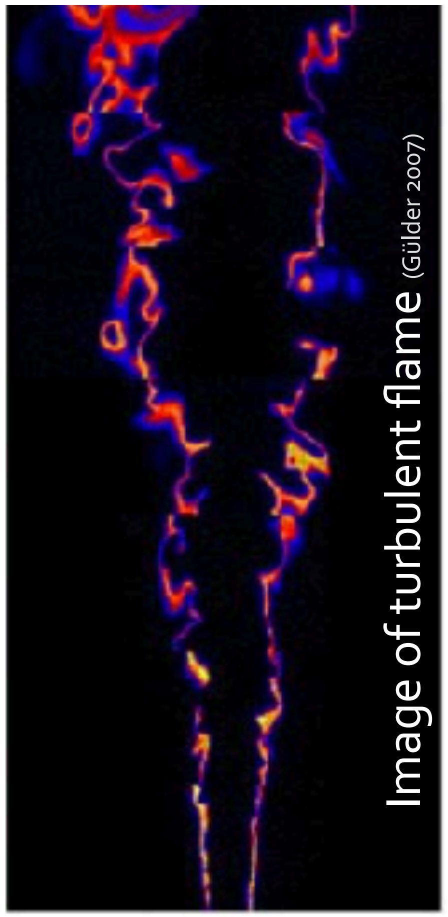


Image of turbulent flame (Gülder 2007)

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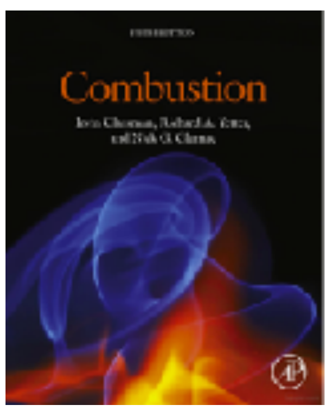

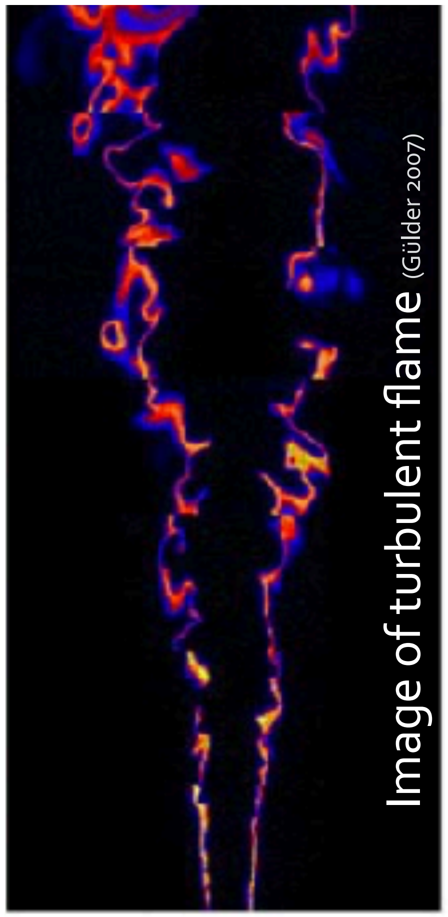

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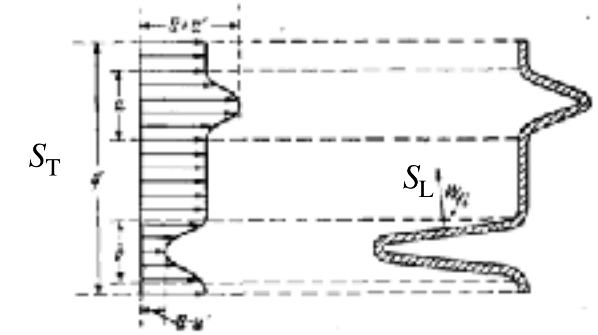

Fig. 16.

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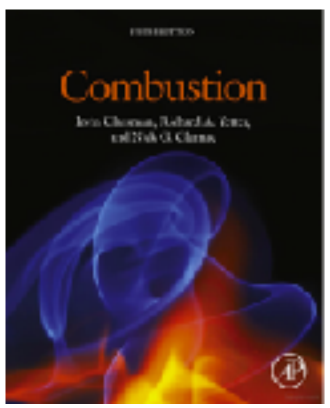

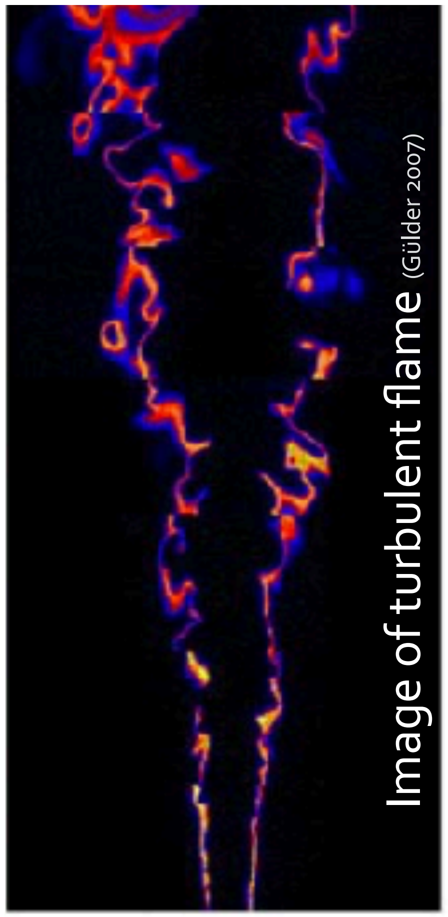

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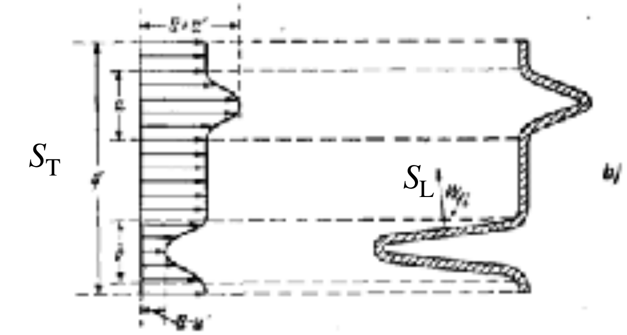

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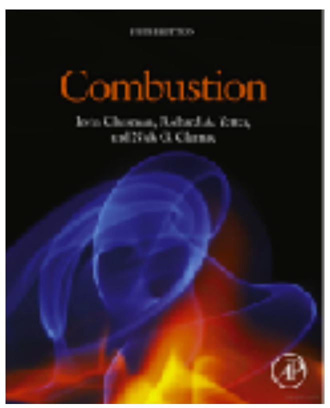

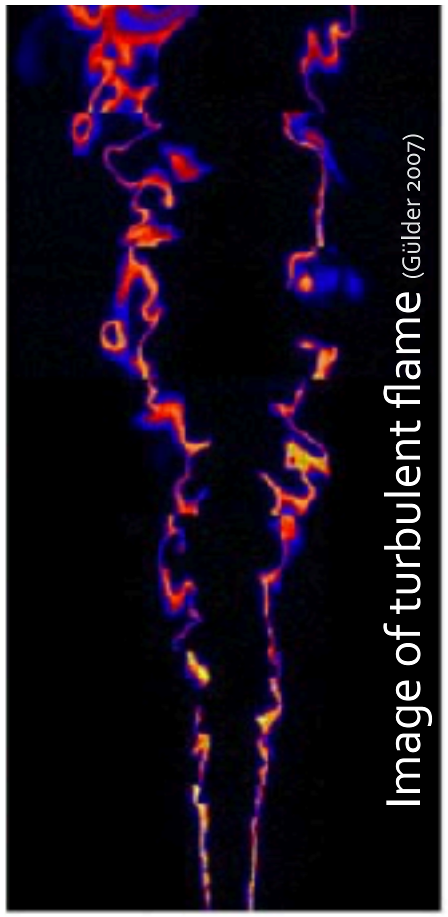

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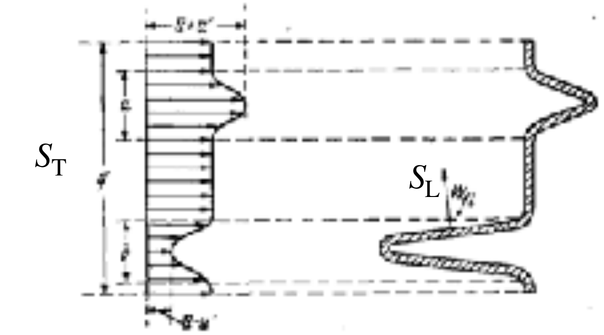

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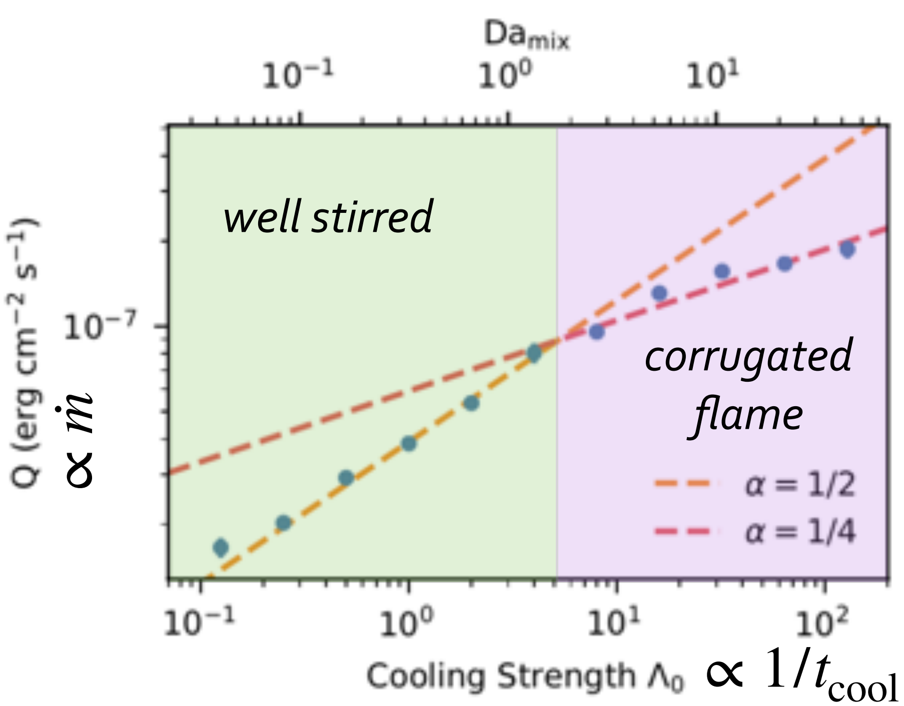
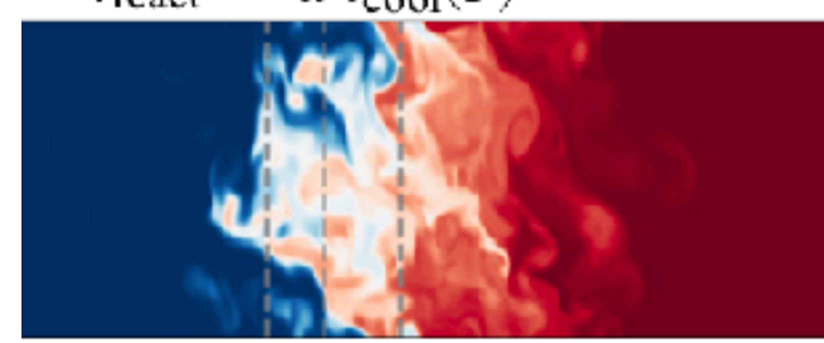
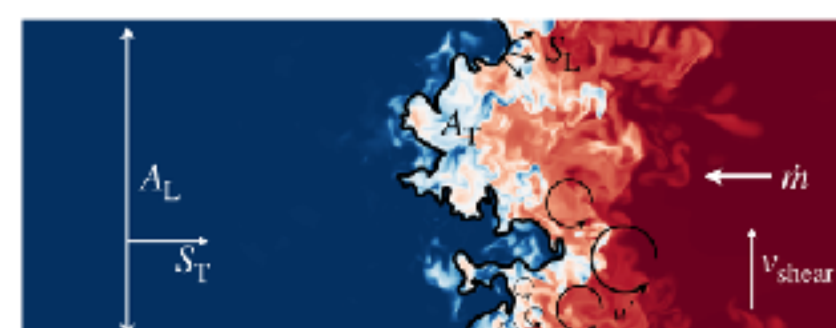


$\mathrm{Da} < 1 \rightarrow$ well stirred
(straight flamefront)



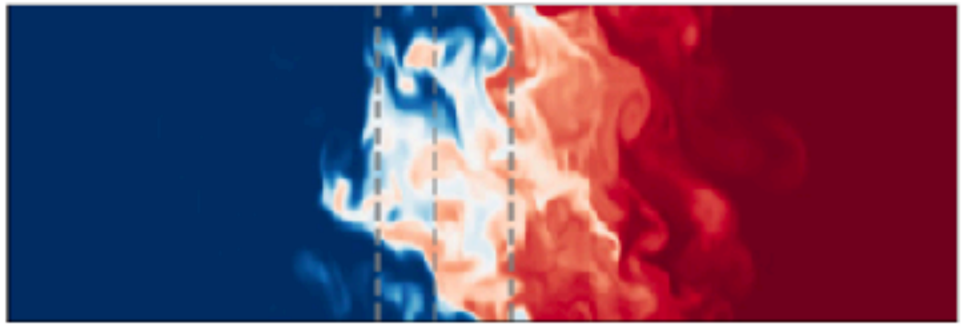
$\mathrm{Da} > 1 \rightarrow$ corrugated flame
(wrinkled flamefront)



Two different ~~cooling~~ burning regimes

$$\dot{m} \sim \rho_{\text{hot}} A_{\text{cold}} S_{\text{T}}$$

well stirred



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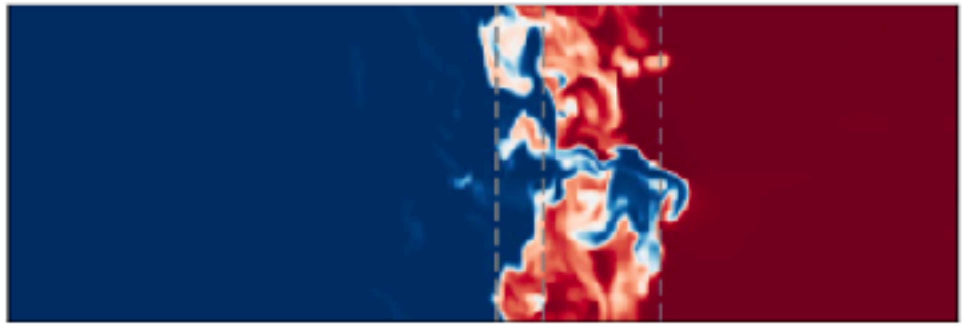

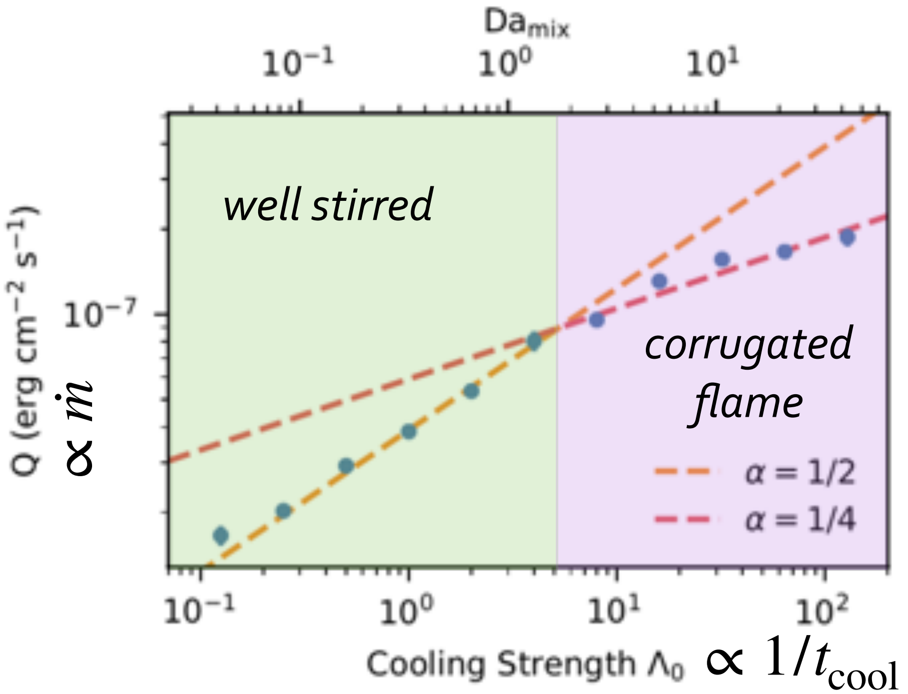

Tan, Oh, MG (2020)

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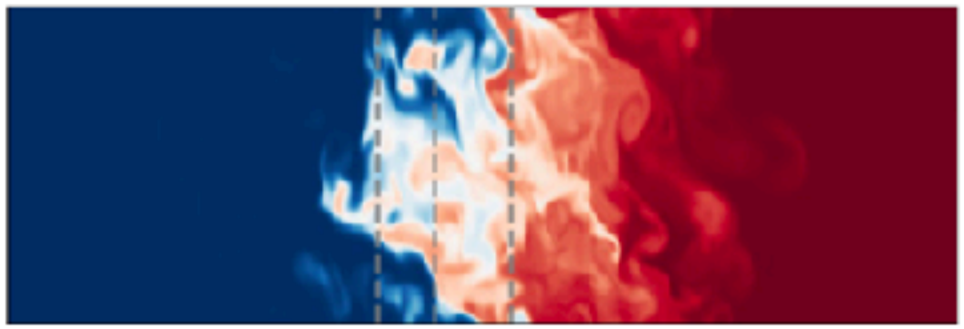
$$\dot{m} \sim \rho_{\rm hot} A_{\rm cold} S_{\rm T} \propto S_{\rm T} \approx (D_{\rm turb}/\tau_{\rm react})^{1/2} \sim (u'L/\tau_{\rm react})^{1/2}$$

Turbulent diffusion coefficient $D_{\rm turb} \sim u'L$

well stirred



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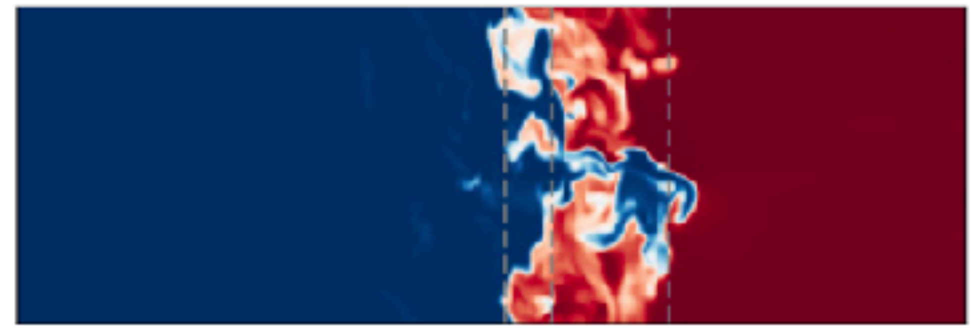

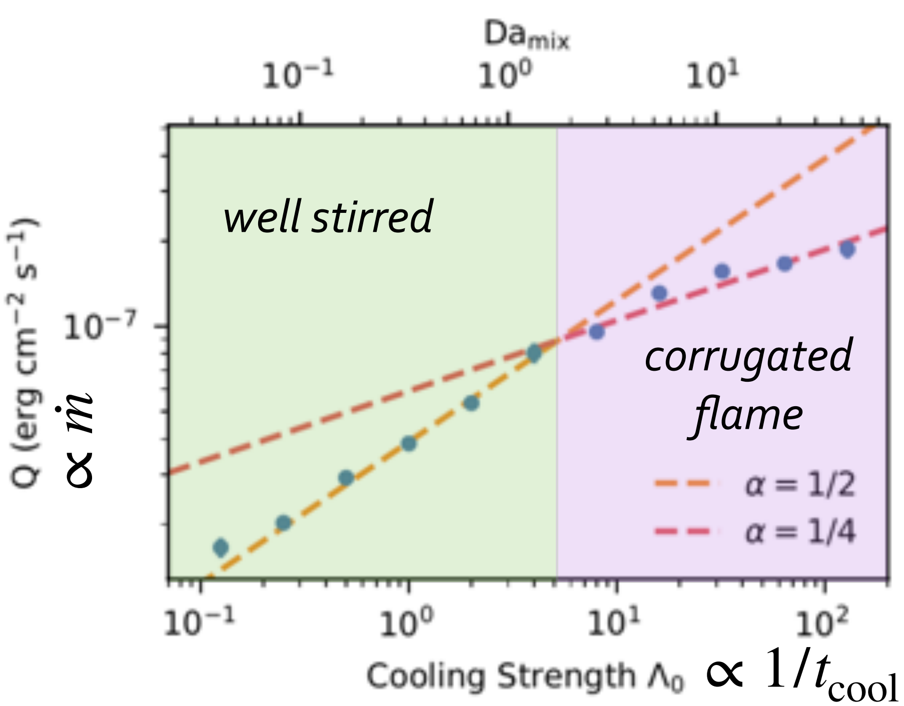

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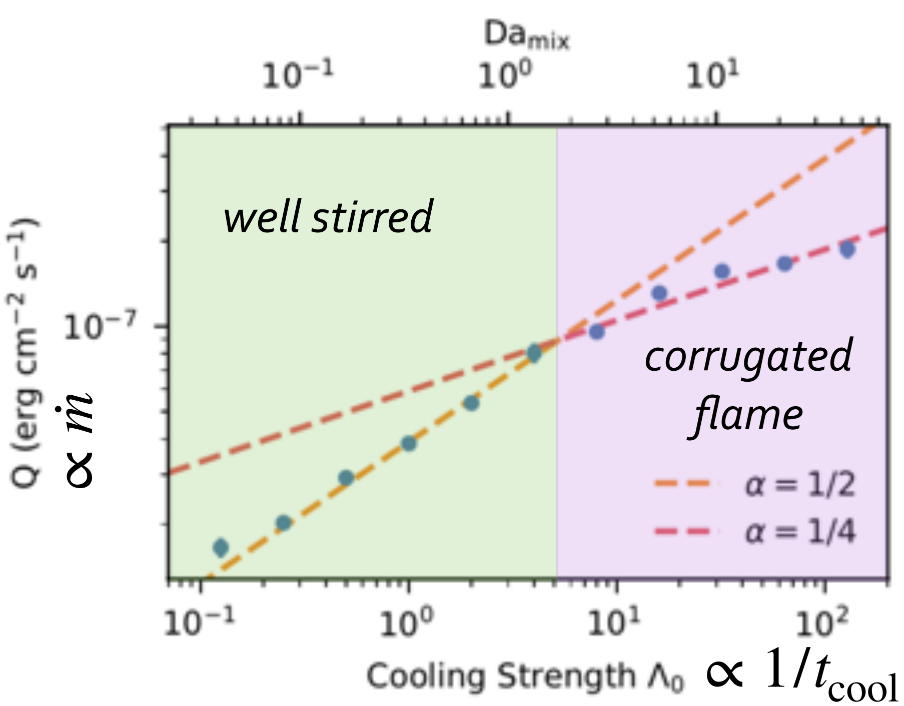
Turbulent diffusion coefficient
$D_{\rm turb} \sim u'L$

well stirred | *corrugated flame*

$$\tau_{\rm react} \sim t_{\rm cool}$$
$$\Rightarrow \dot{m} \propto (u'L/t_{\rm cool})^{1/2} \propto t_{\rm cool}^{-1/2}$$



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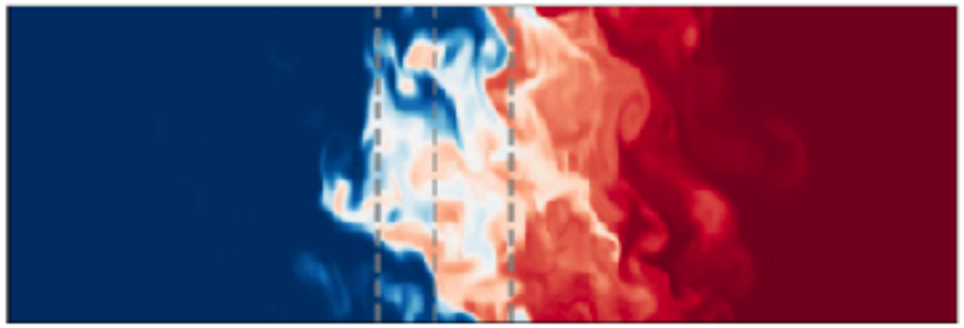

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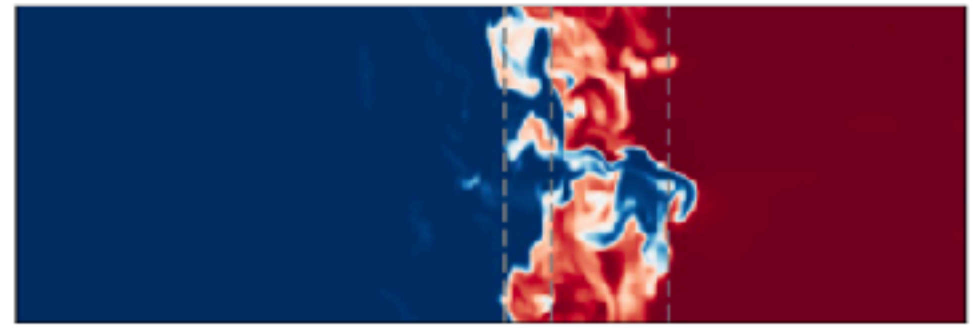

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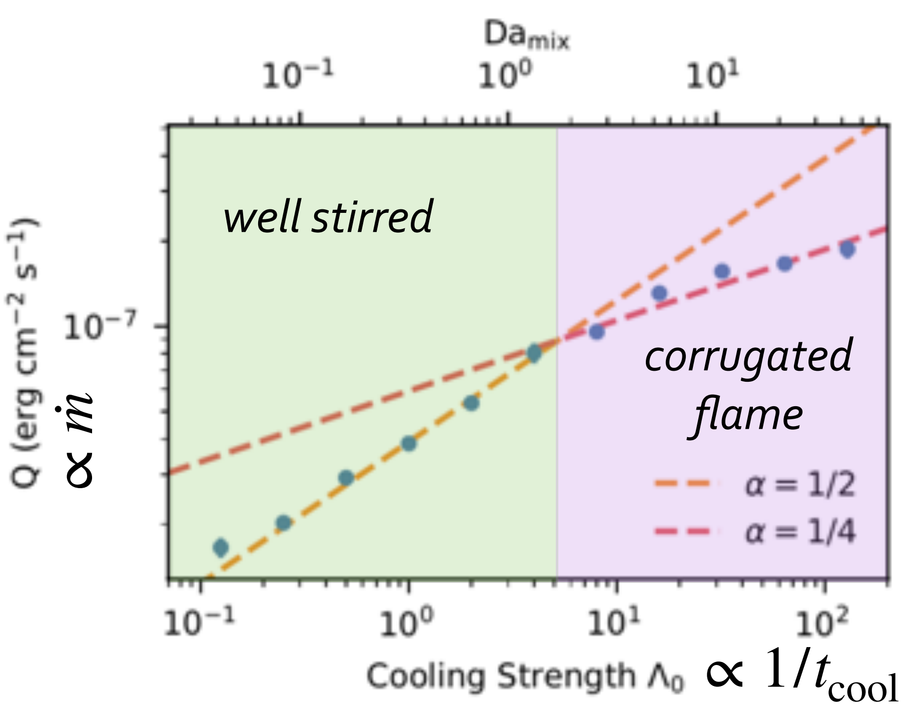

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Turbulent diffusion coefficient
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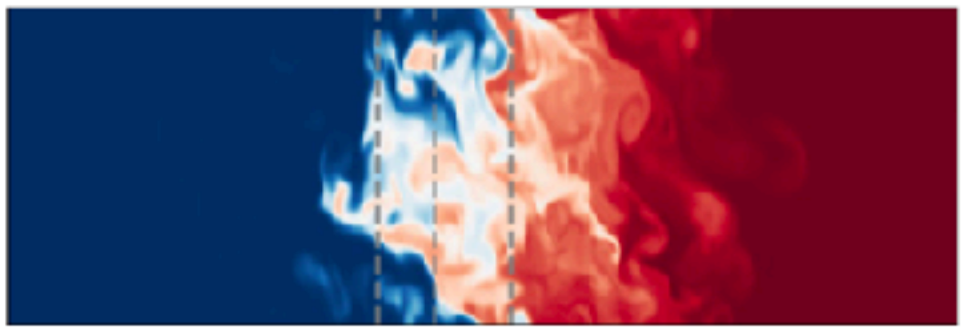

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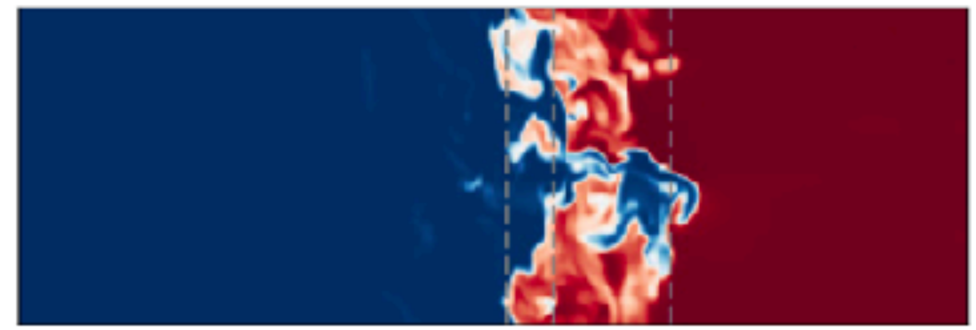

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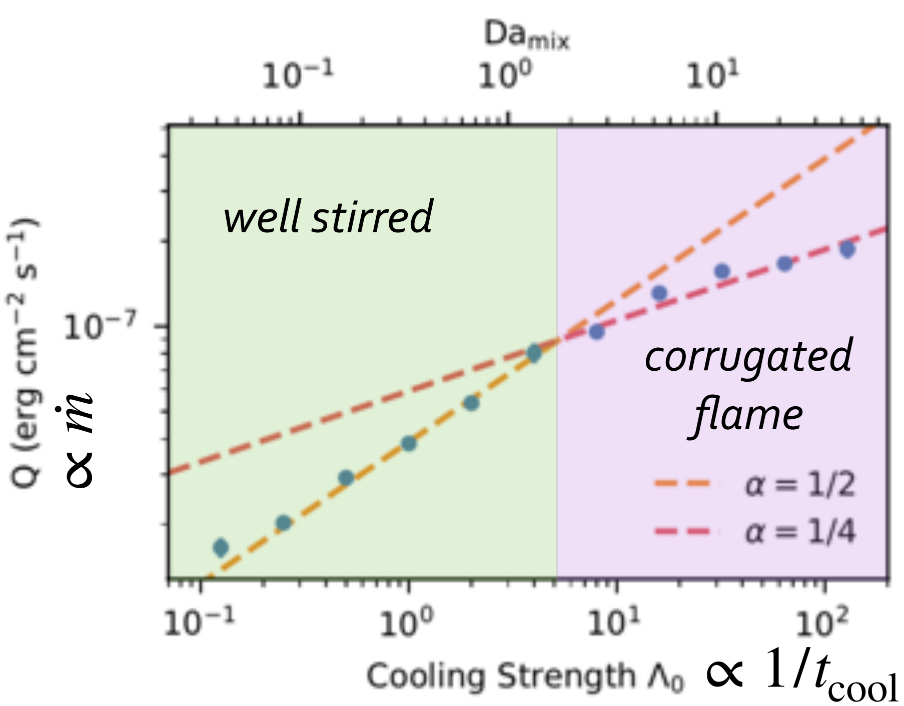

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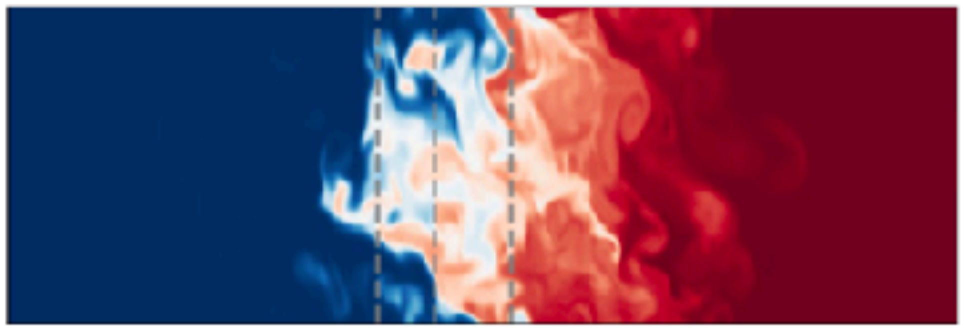

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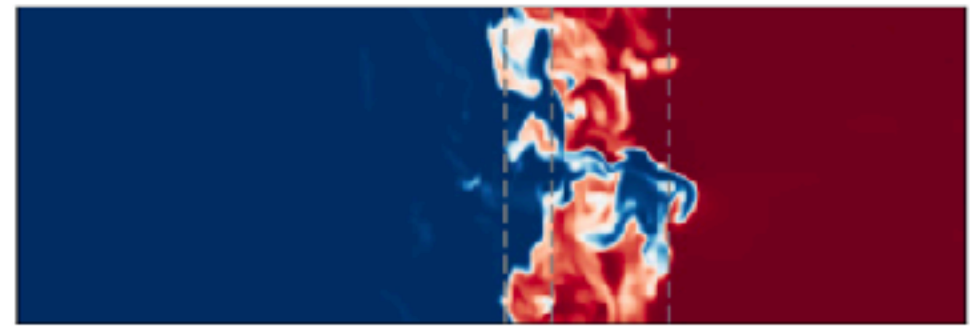

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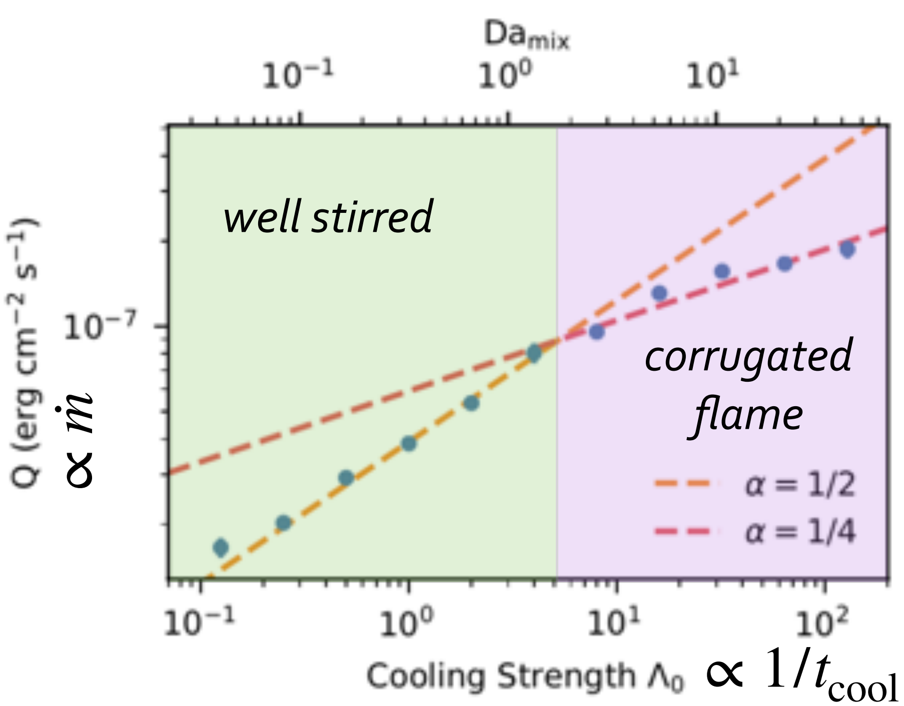

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Tan, Oh, MG (2020)

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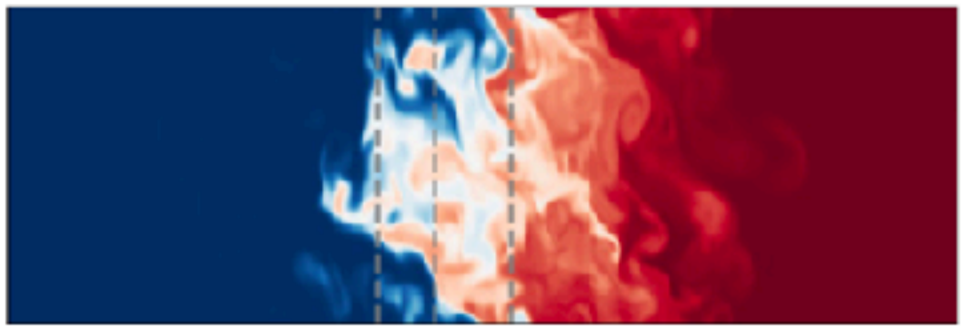

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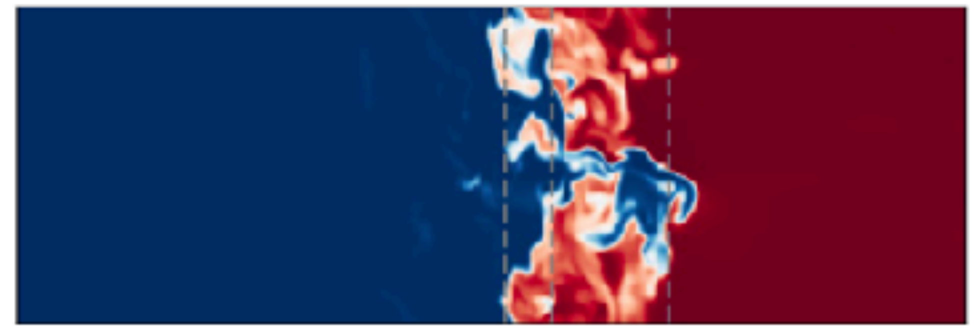

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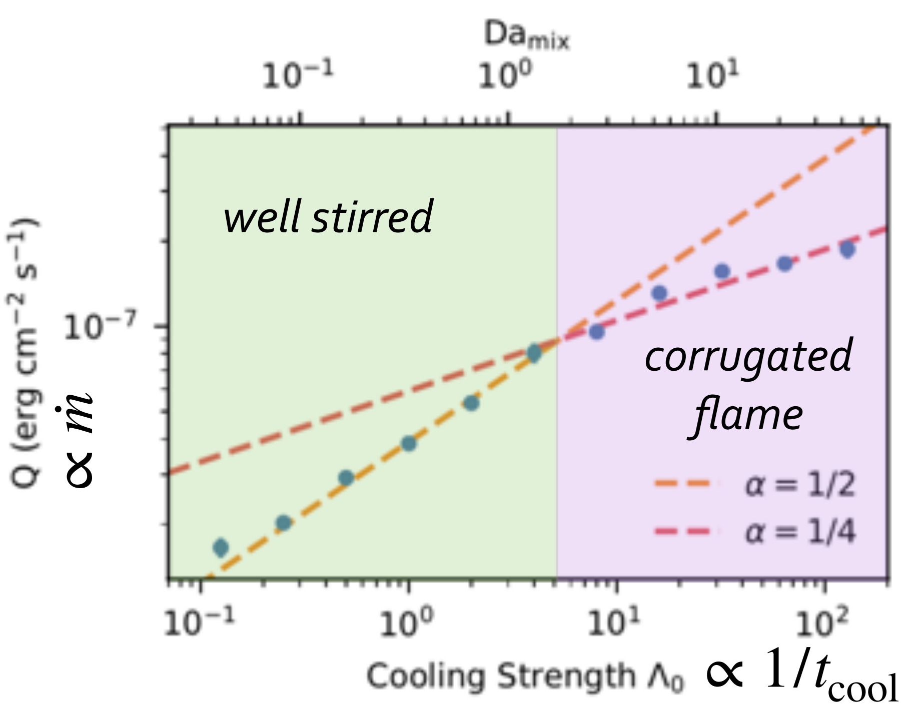

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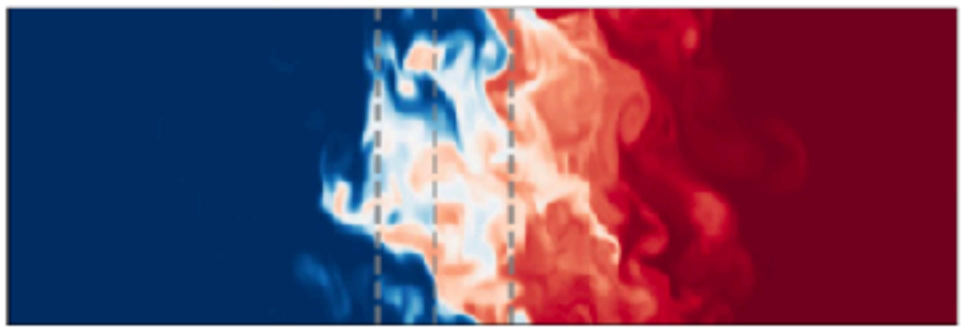

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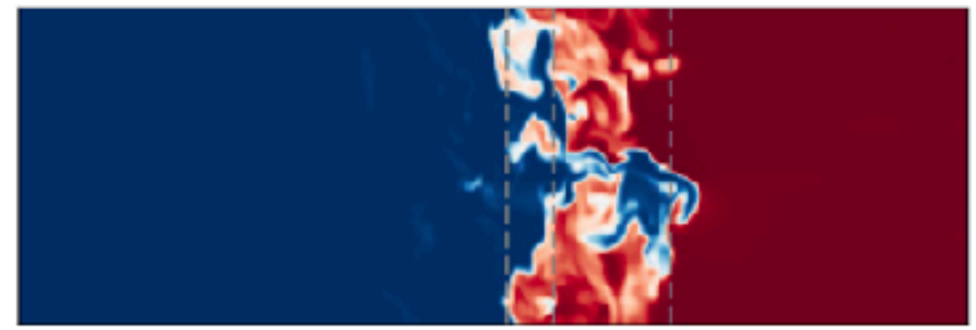

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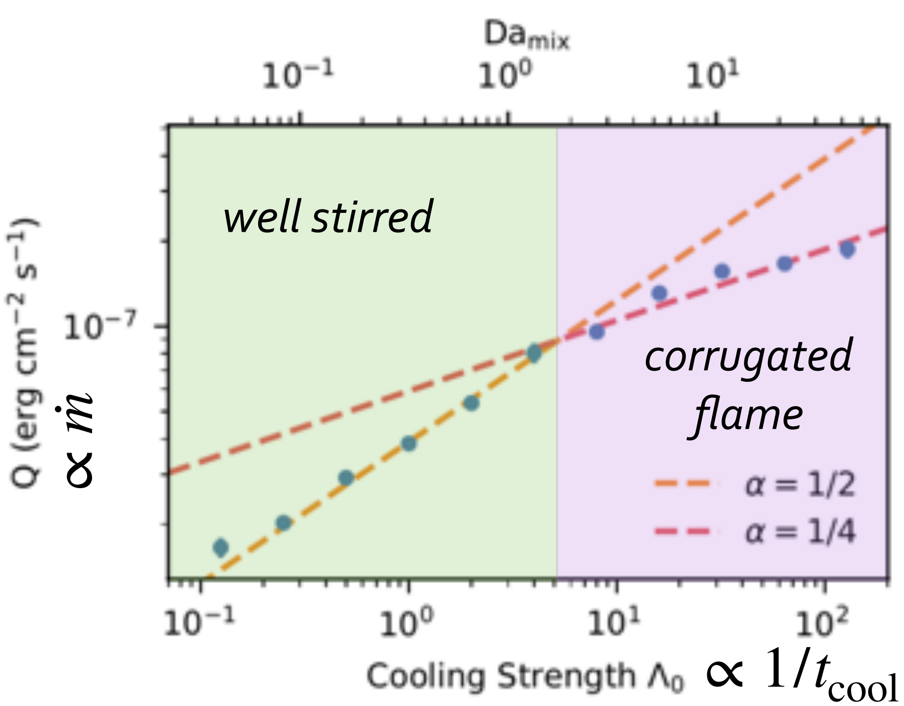

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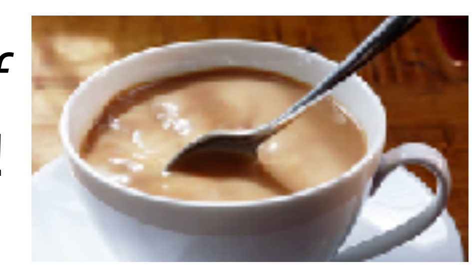
$$\left.\begin{array}{l} D_{\rm num} \ll D_{\rm turb} \\ \tau_l \sim l/v_l \propto l^{2/3} \end{array}\right\}$$

(Kolmogorov spectrum)

Cooling set by *rate of mixing on outer scale*!



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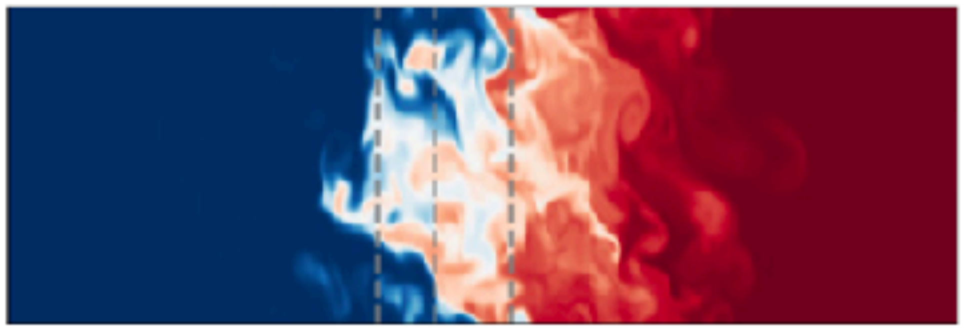
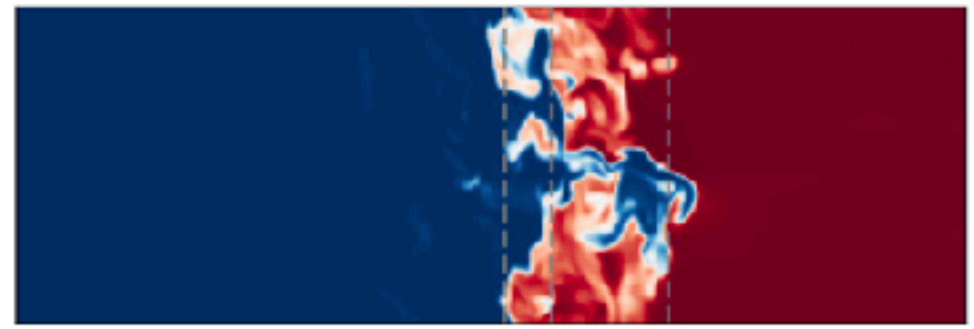
$D_{\rm turb} \sim u' L$

well stirred



$$\tau_{\rm react} \sim t_{\rm cool}$$
$$\Rightarrow \dot{m} \propto (u' L/t_{\rm cool})^{1/2} \propto t_{\rm cool}^{-1/2}$$

corrugated flame

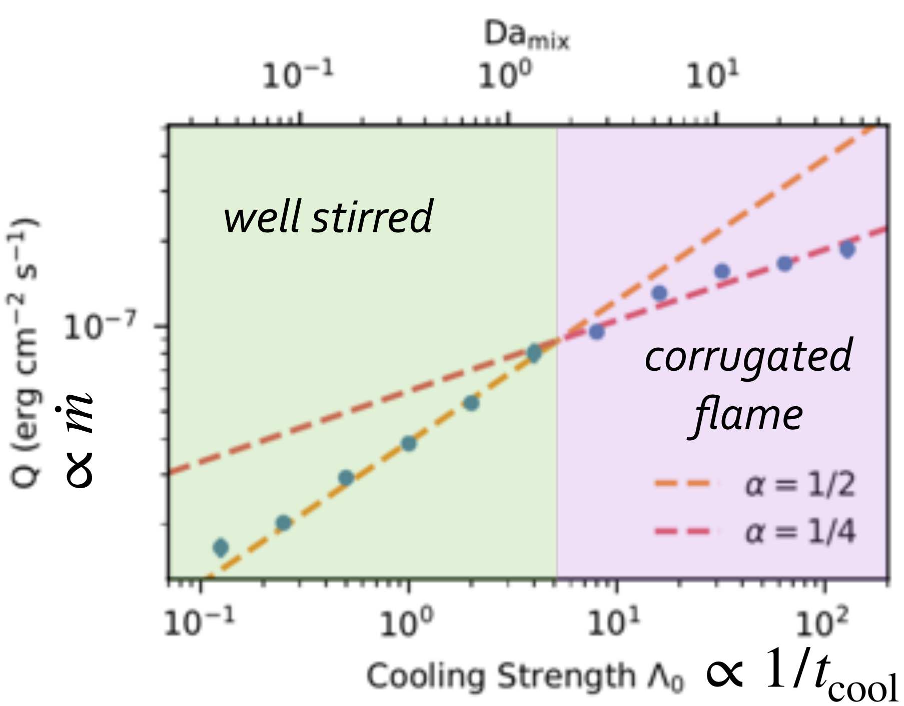


$$\tau_{\rm react} \sim \lambda_{\rm F,turb}/u'$$
$$\Rightarrow \dot{m} \propto (u')^{3/4} (L/t_{\rm cool})^{1/4}$$
$$\sim u' (L/u' t_{\rm cool})^{1/4} \propto t_{\rm cool}^{-1/4}$$

$\mathrm{Da} = L/u' t_{\rm cool}$

"Turbulent Field length"
$\lambda_{\rm F,turb} \sim (D_{\rm turb} t_{\rm cool})^{1/2}$
(vs $\lambda_{\rm F} \sim (D_{\rm cond.} t_{\rm cool})^{1/2}$)

Gülder (1991) scaling $S_{\rm T} \sim u' \mathrm{Da}^{1/4}$ fits to experimental data!

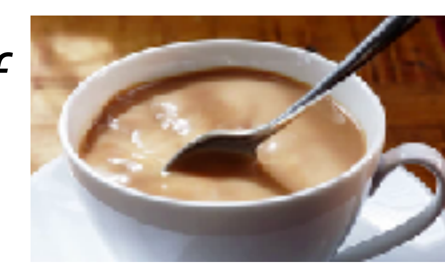


Initial questions

1. Convergence

$$\left.\begin{array}{l} D_{\rm num} \ll D_{\rm turb} \\ \tau_l \sim l/v_l \propto l^{2/3} \end{array}\right\}$$ Cooling set by *rate of mixing on outer scale*!

(Kolmogorov spectrum)



2. $\dot{m} \propto c_{\rm s,cold} \ll c_{\rm s,hot}$?

Shear: $u' \sim L/t_{\rm KH} \sim v_{\rm shear} \chi^{-1/2} \sim \mathcal{M}_{\rm hot} c_{\rm s,cold}$

$t_{\rm KH} \sim \chi^{1/2} L/v_{\rm shear}$

$\mathcal{M}_{\rm hot} \sim 1$ common in CGM

3. Scalings ✓

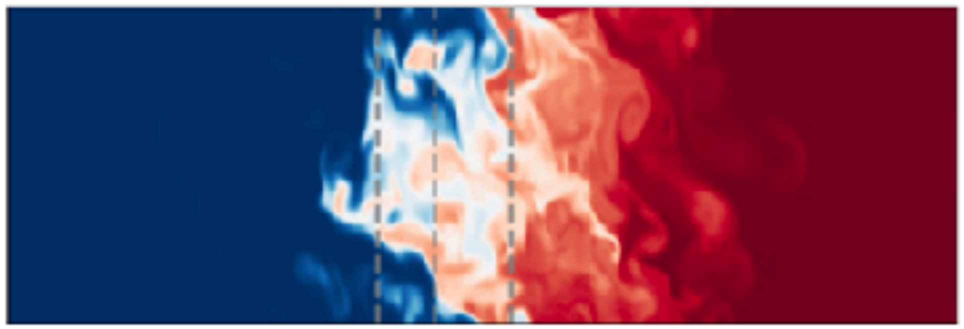
Tan, Oh, MG (2020)

Two different ~~cooling~~ burning regimes

$$\dot{m} \sim \rho_{\rm hot} A_{\rm cold} S_{\rm T} \propto S_{\rm T} \approx (D_{\rm turb}/\tau_{\rm react})^{1/2} \sim (u' L/\tau_{\rm react})^{1/2}$$

Turbulent diffusion coefficient $D_{\rm turb} \sim u' L$

well stirred



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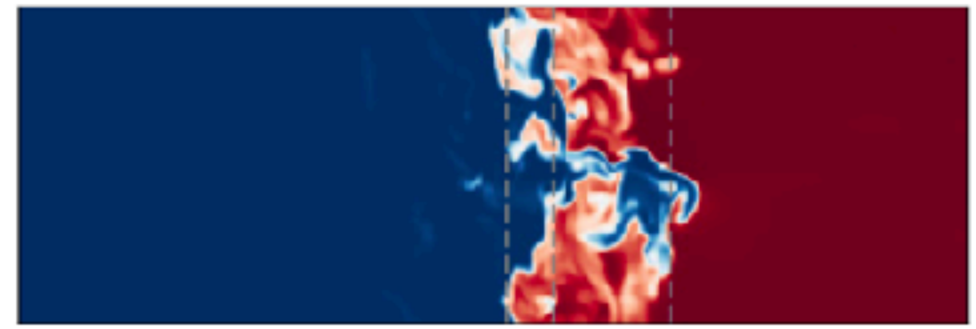
corrugated flame



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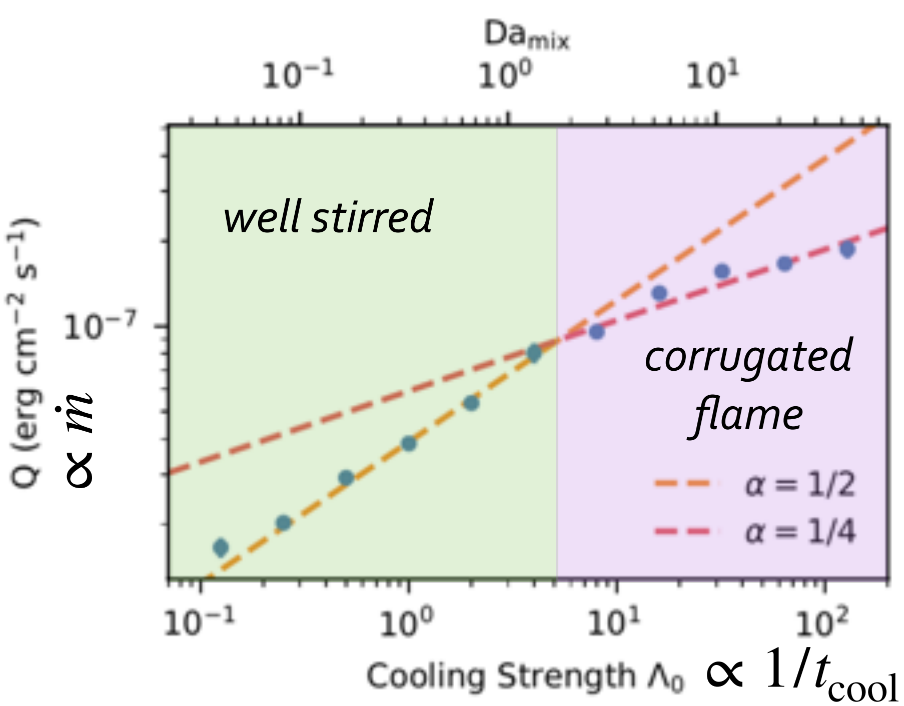

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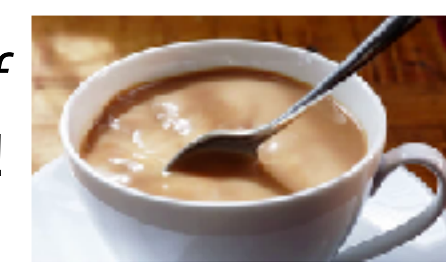

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Pulsations: Cold front (=mass) moving at $c_{\rm s,cold} \sim u'$

3. Scalings ✓

Cool things you can do with the model

Scalings for mass & momentum transfer

$u' \to Q$

$$v_{\rm in} \approx 10\,{\rm km\,s^{-1}}\,\mathcal{M}_{\rm turb}^{1/2} P_2^{-1} \left(\frac{L}{100\,{\rm pc}}\right)^{1/2} \left(\frac{t_{\rm cool,cold}}{0.03\,{\rm Myr}}\right)^{-1/2} \qquad (56)$$

for the Da < 1 'well stirred' (slow cooling) regime, and

$$v_{\rm in} \approx 8\,{\rm km\,s^{-1}}\,\mathcal{M}_{\rm turb}^{3/4} P_2^{-1} \left(\frac{L}{100\,{\rm pc}}\right)^{1/4} \left(\frac{t_{\rm cool,cold}}{0.03\,{\rm Myr}}\right)^{-1/4} \qquad (57)$$

for the Da > 1 'corrugated flame' (fast cooling) regime. Here, $P_2 \equiv$

Shearing layer u'

$$u' \approx 50\,{\rm km\,s^{-1}}\,\mathcal{M}^{4/5} \left(\frac{c_{s,c}}{15\,{\rm km\,s^{-1}}}\right)^{4/5} \left(\frac{t_{\rm cool,cold}}{0.03\,{\rm Myr}}\right)^{-0.1}, \qquad (58)$$

Tan, Oh, MG (2020)

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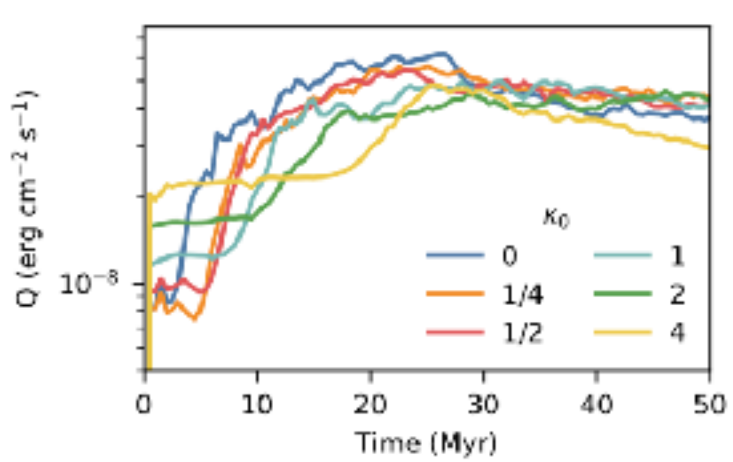
Resolution requirement for larger scale simulations

(resolving $\lambda_{\rm F}$ *not* necessary)



Tan, Oh, MG (2020)

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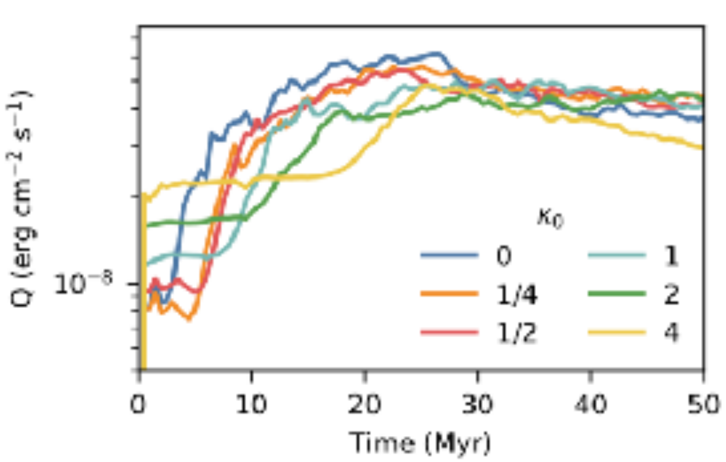
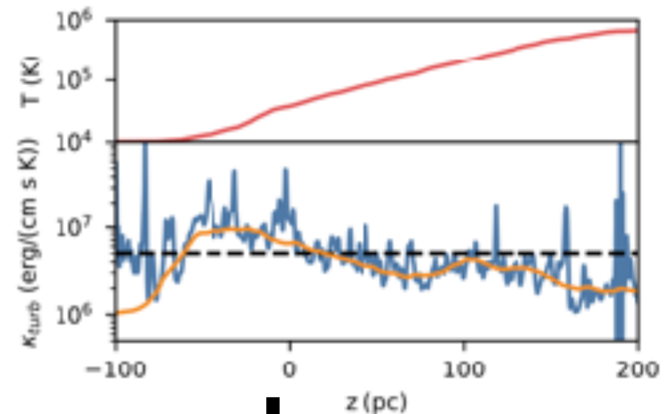
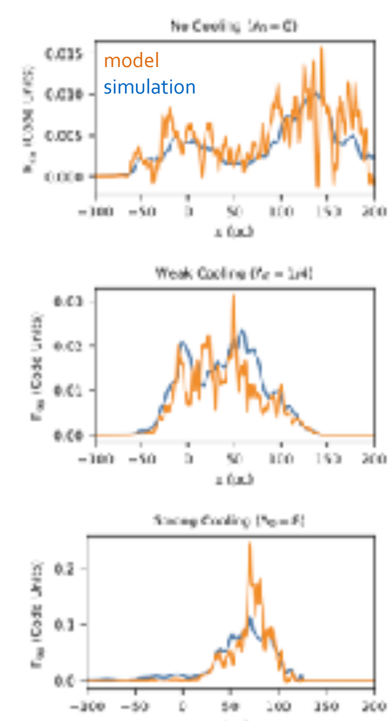
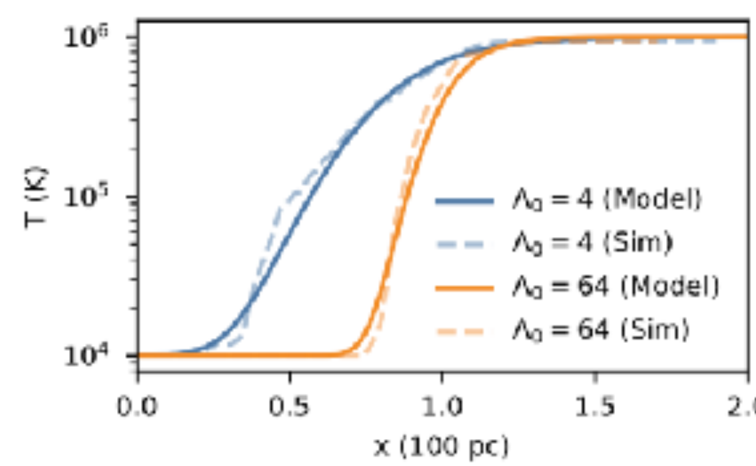


Mixing length model

Calibrate $D_{\rm turb}$ from adiabatic sim



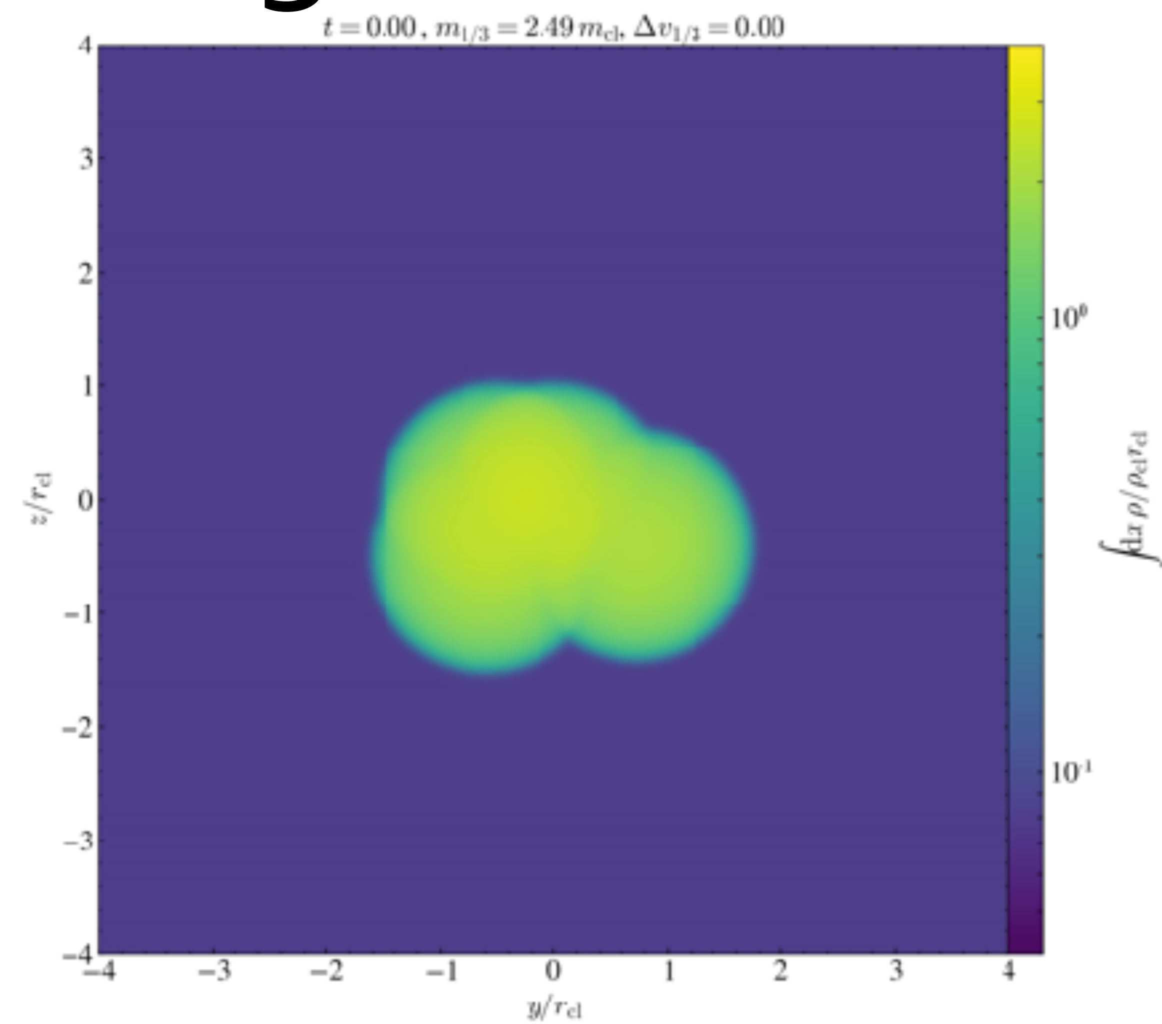


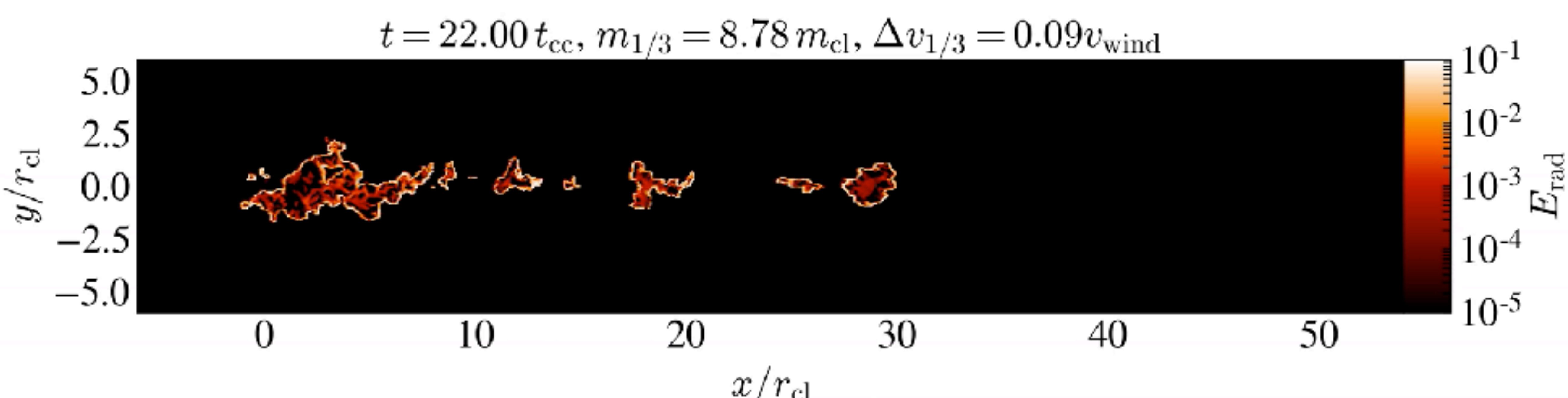


Observables (OVI, ...)

Back to: pulsations & mass growth

What are the requirements for pulsations?





Back to: pulsations & mass growth

MG & Oh (2020)

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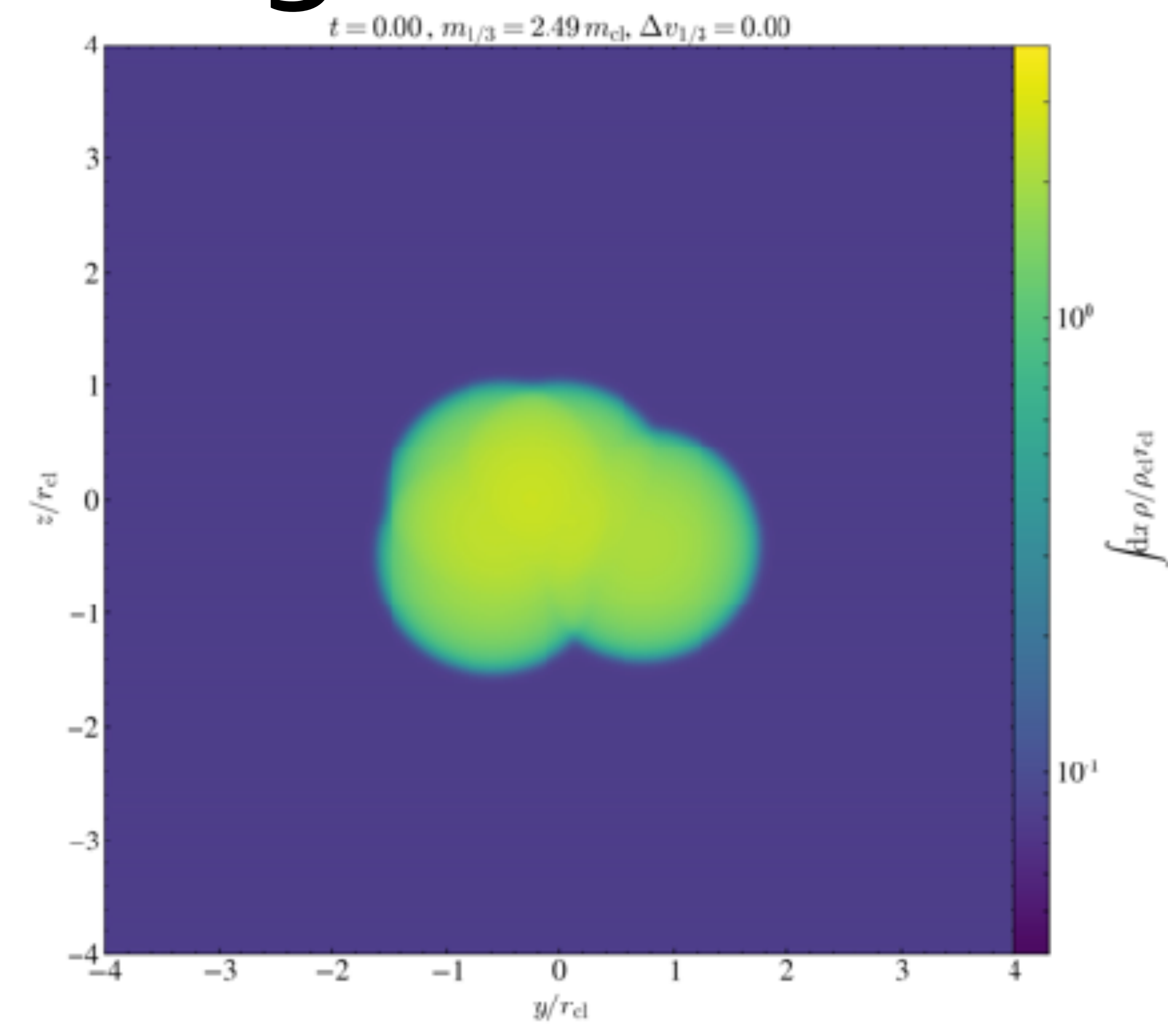
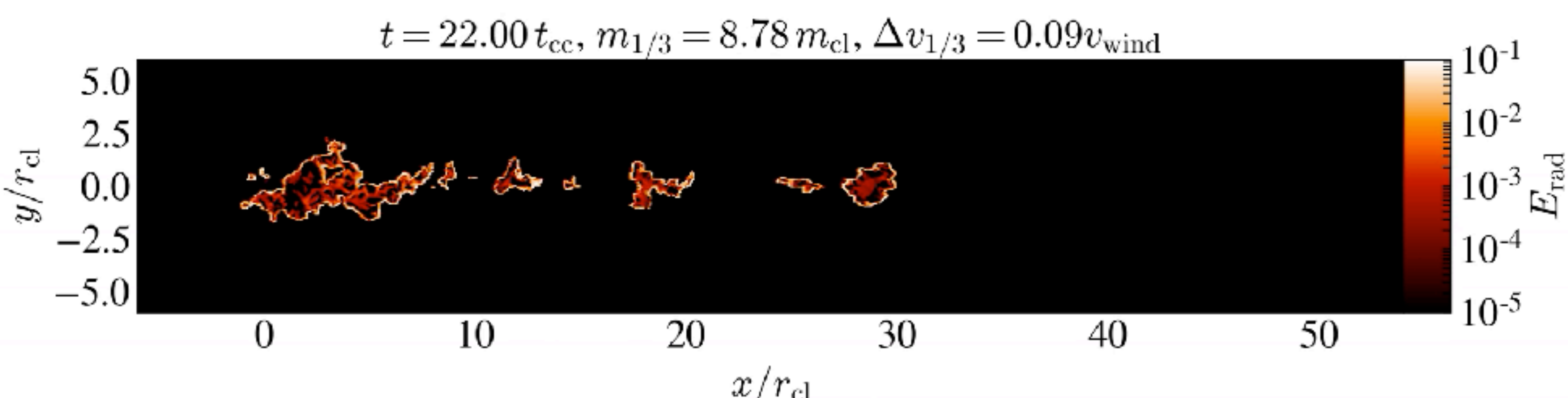
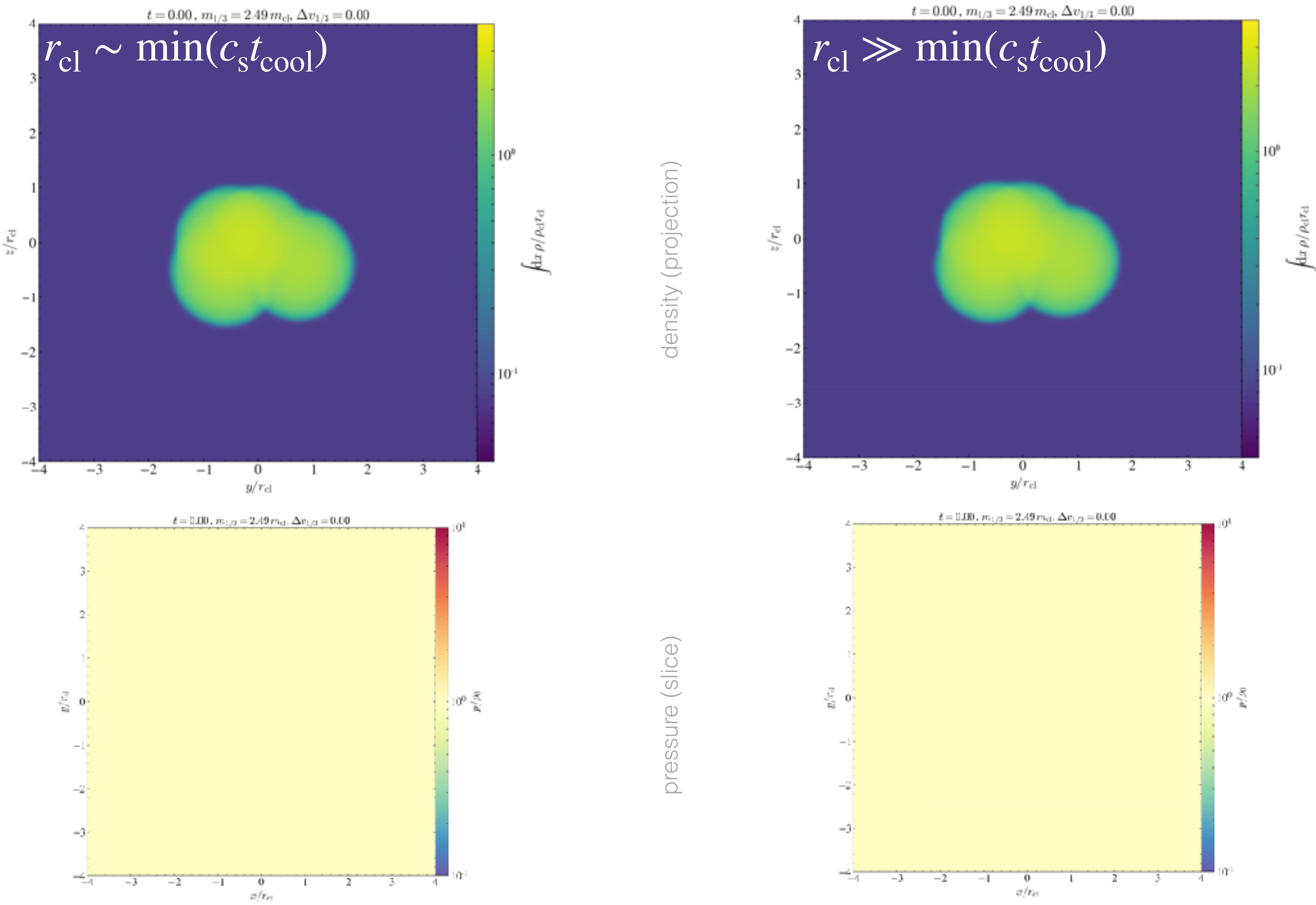




Requirements for pulsations: size

MG & Oh (2020)



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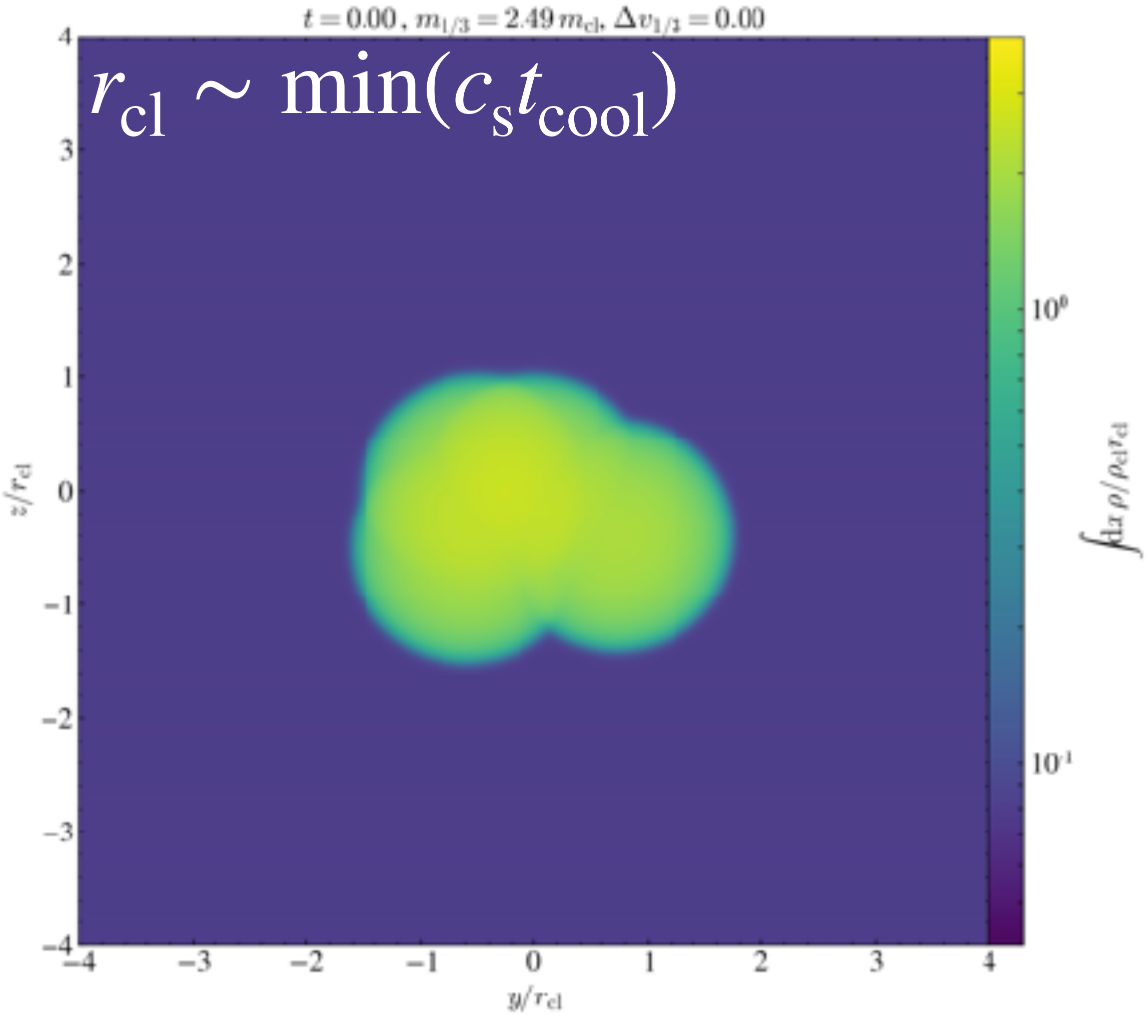
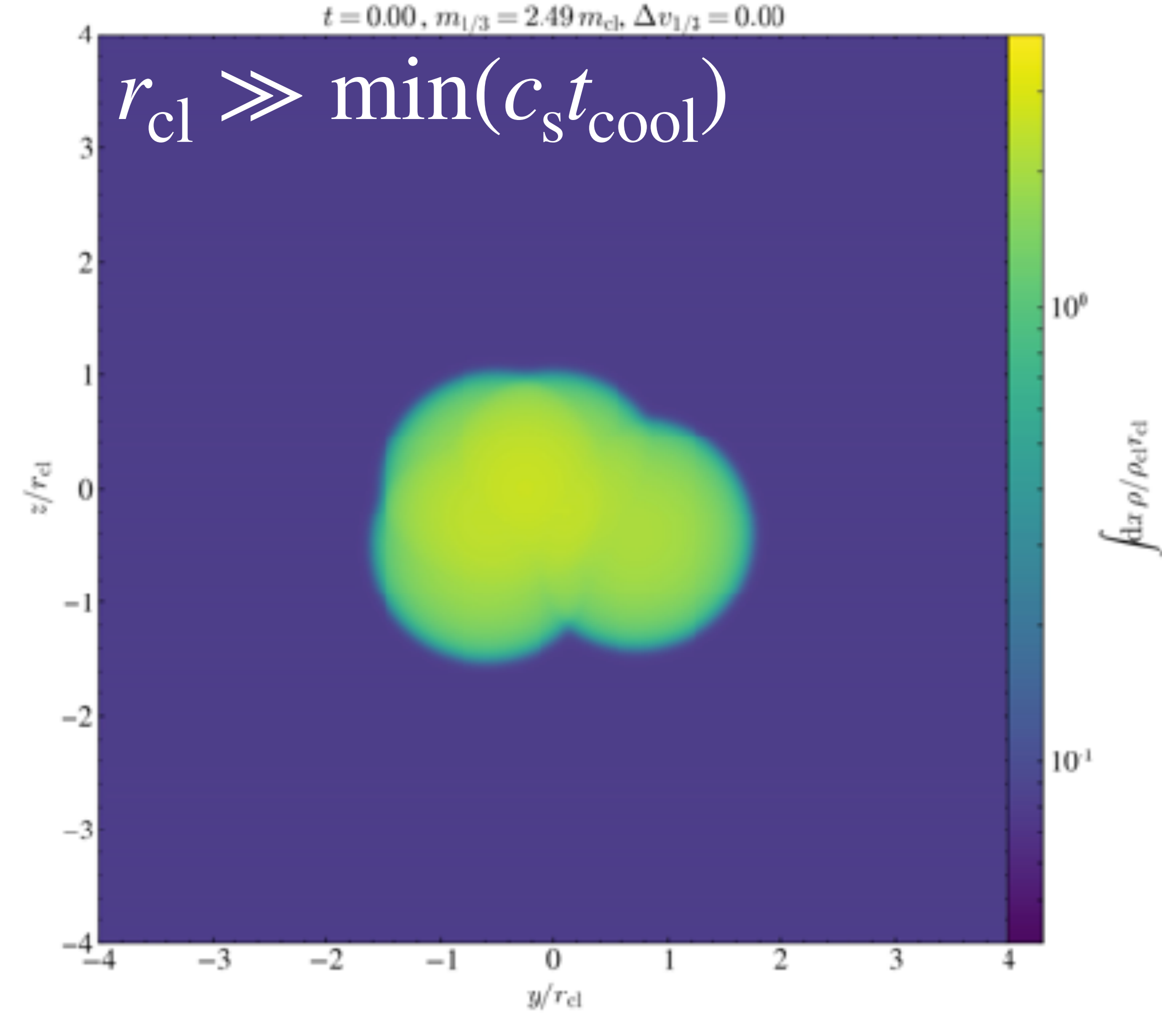
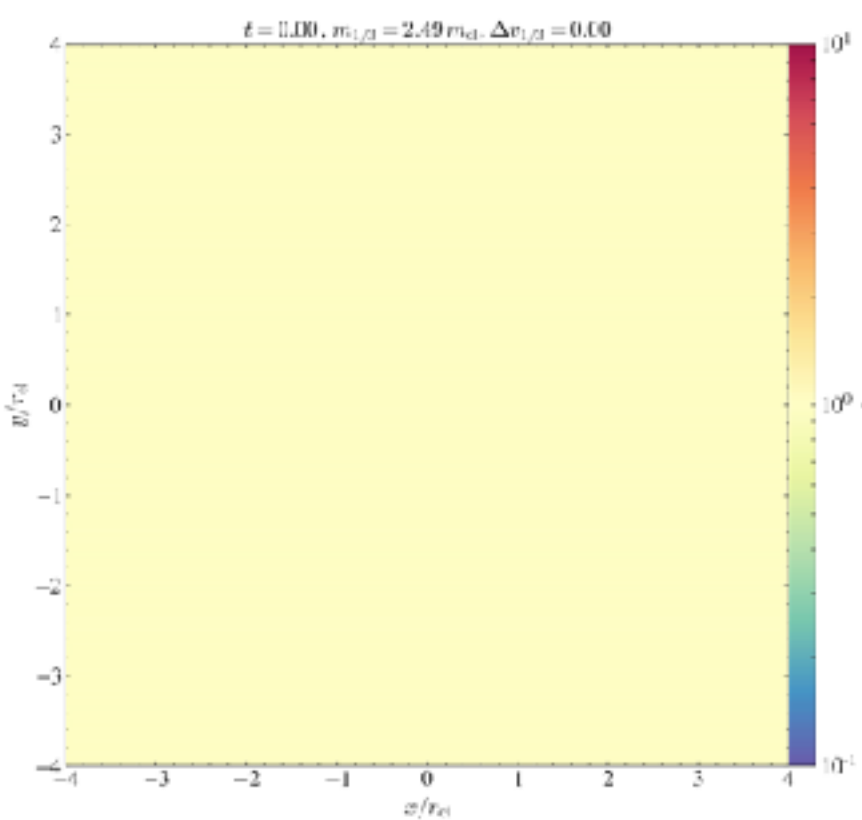


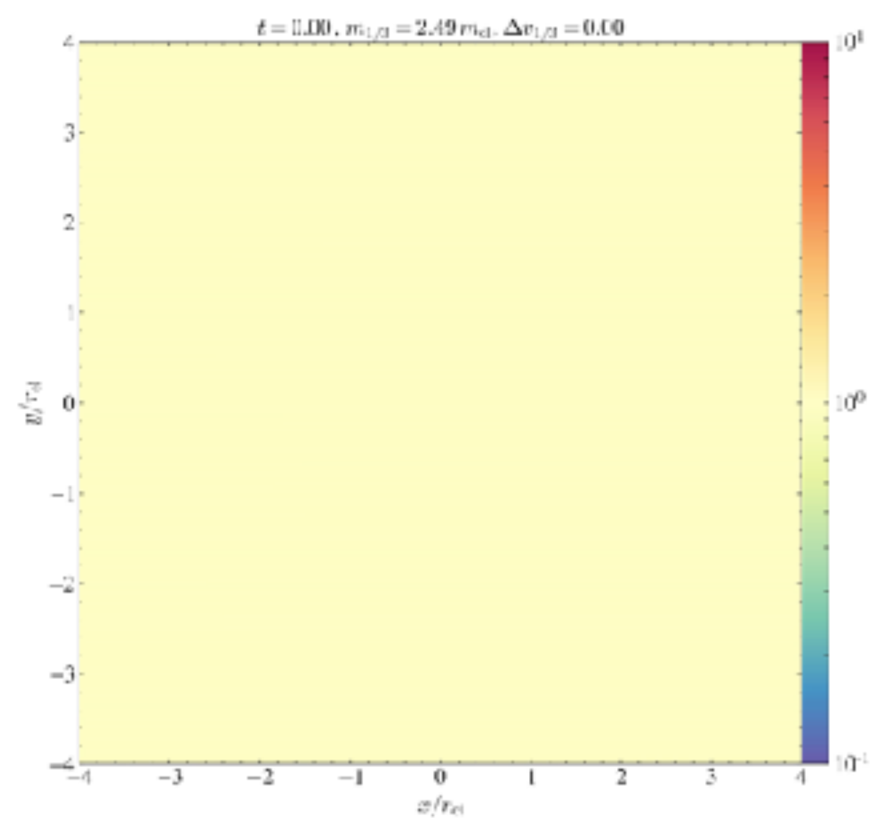


density (projection)

Needs to be out of sonic contact.



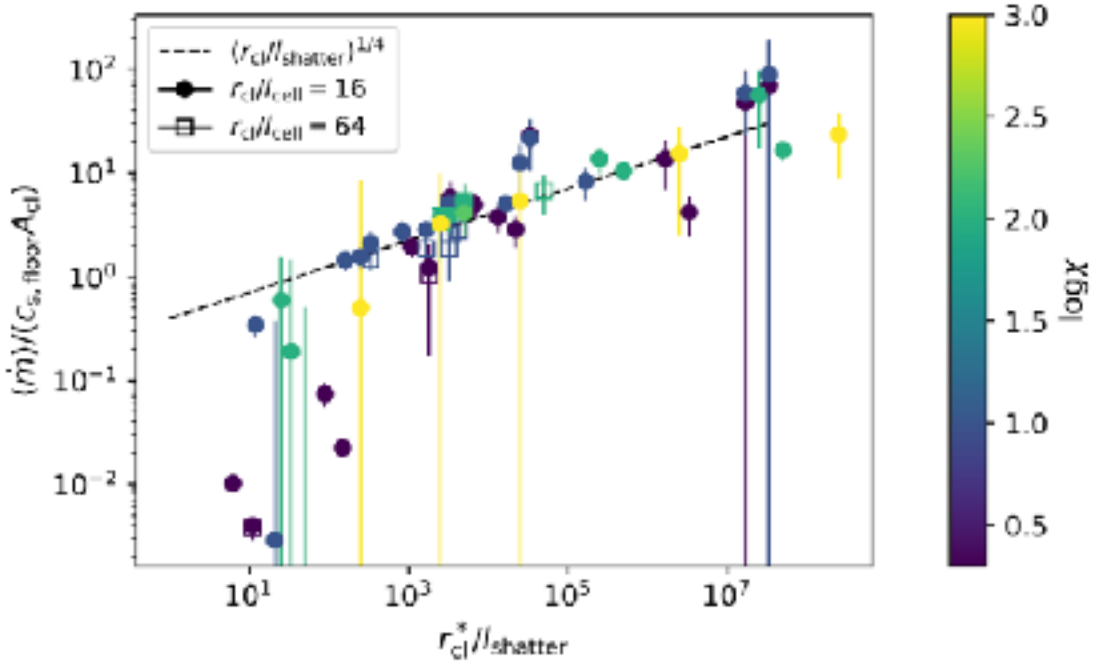
pressure (slice)



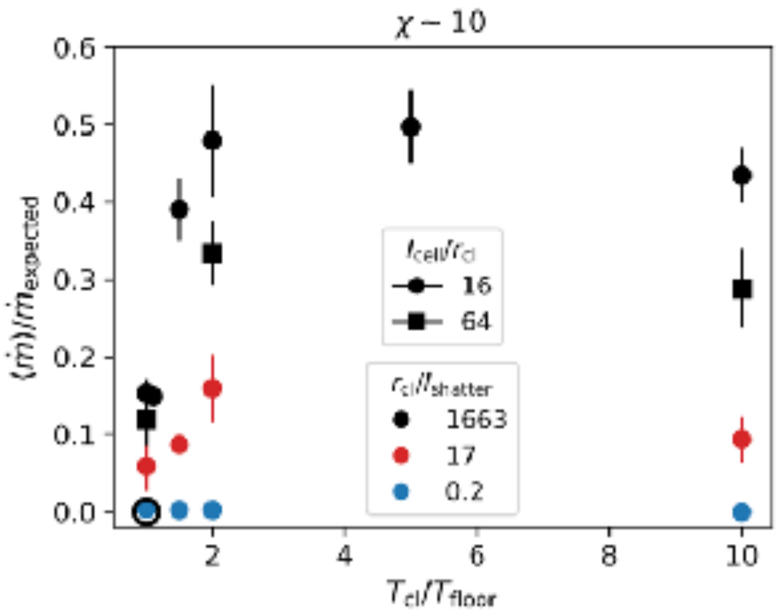
Requirements for pulsations

Large enough cloud

$(r_{\rm cl} > l_{\rm shatter} \equiv \min(c_{\rm s} t_{\rm cool}))$



Initial perturbation $\delta P/P \gtrsim 0.5$



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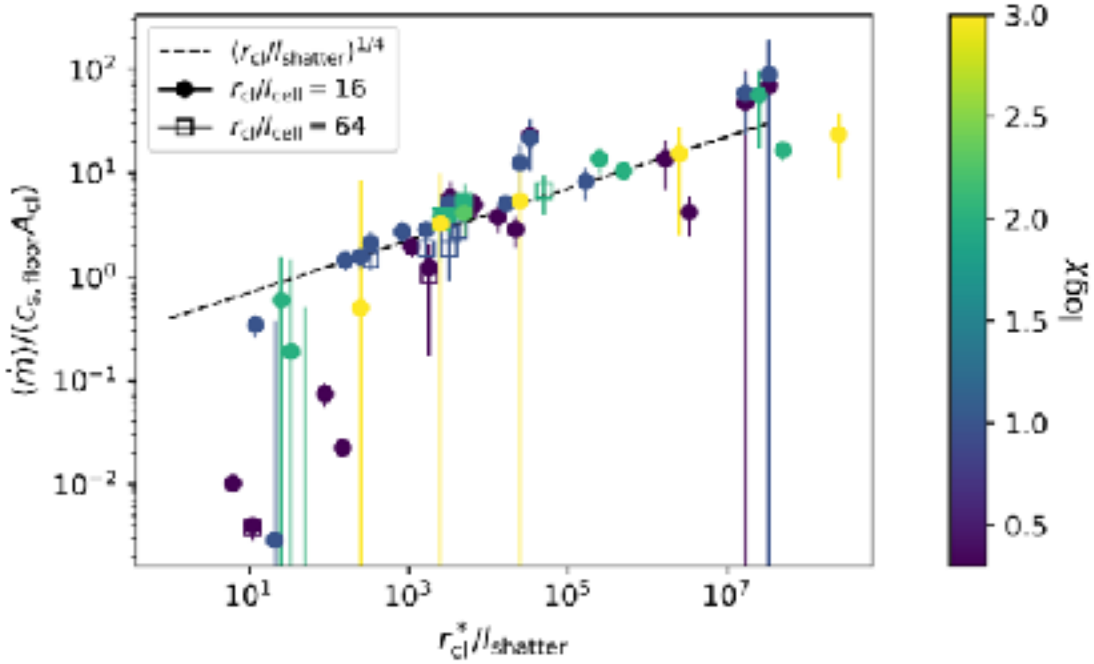

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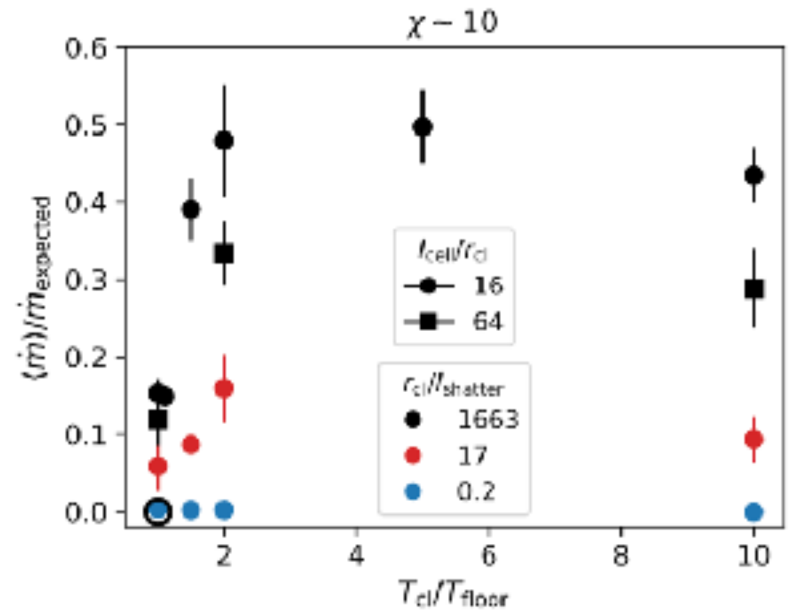
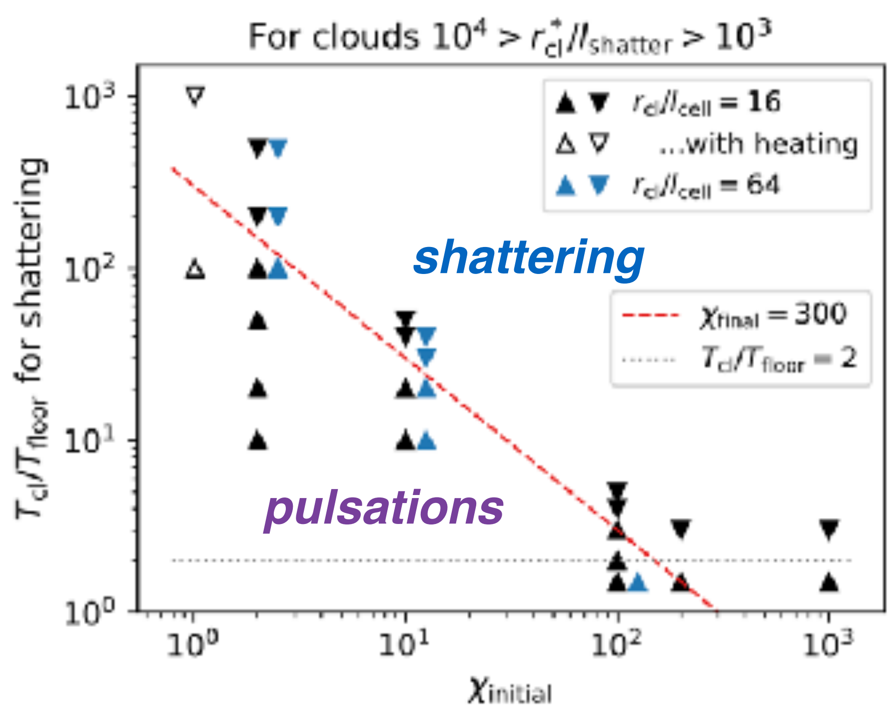


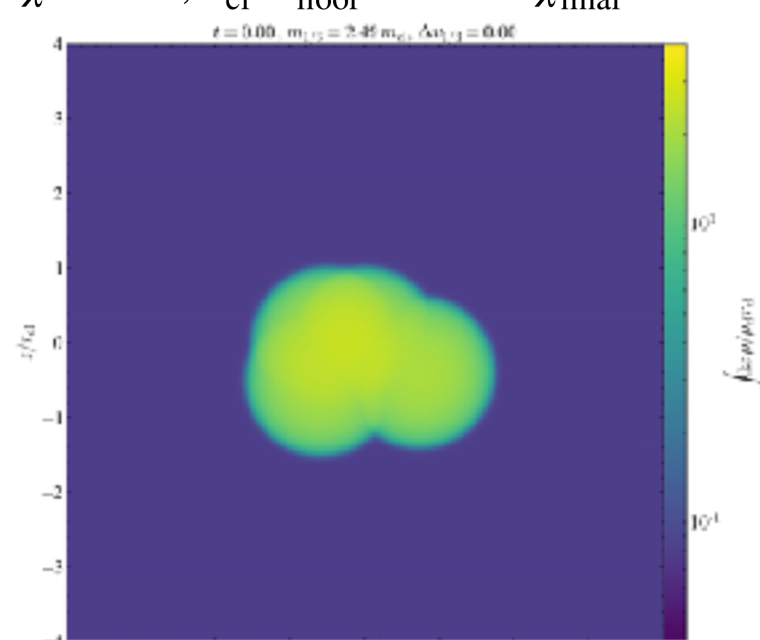


(but see Das et al. 2020!)

...but not too large

$(\chi_{\rm final} \equiv \chi T_{\rm cl}/T_{\rm floor} \lesssim \chi_{\rm crit} \sim 300)$

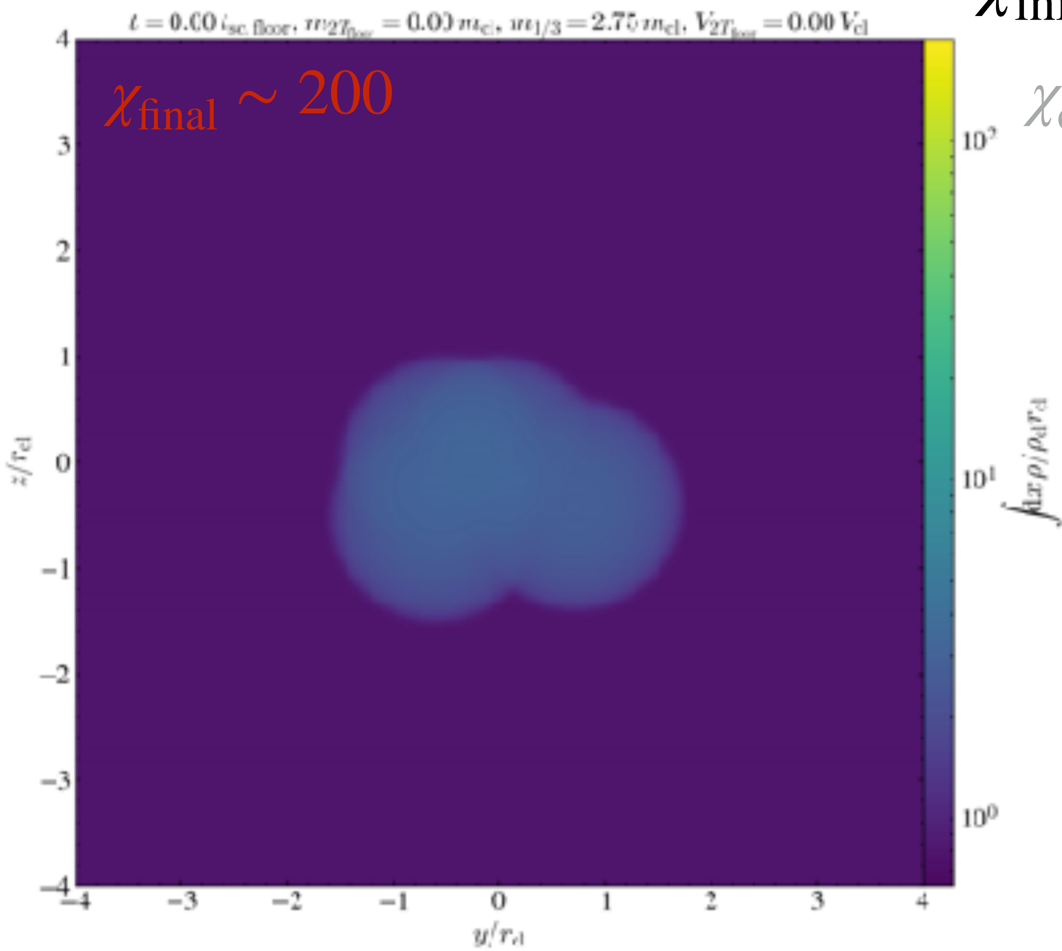
$\chi \sim 100, T_{\rm cl}/T_{\rm floor} \sim 10 \Rightarrow \chi_{\rm final} \sim 10^3$



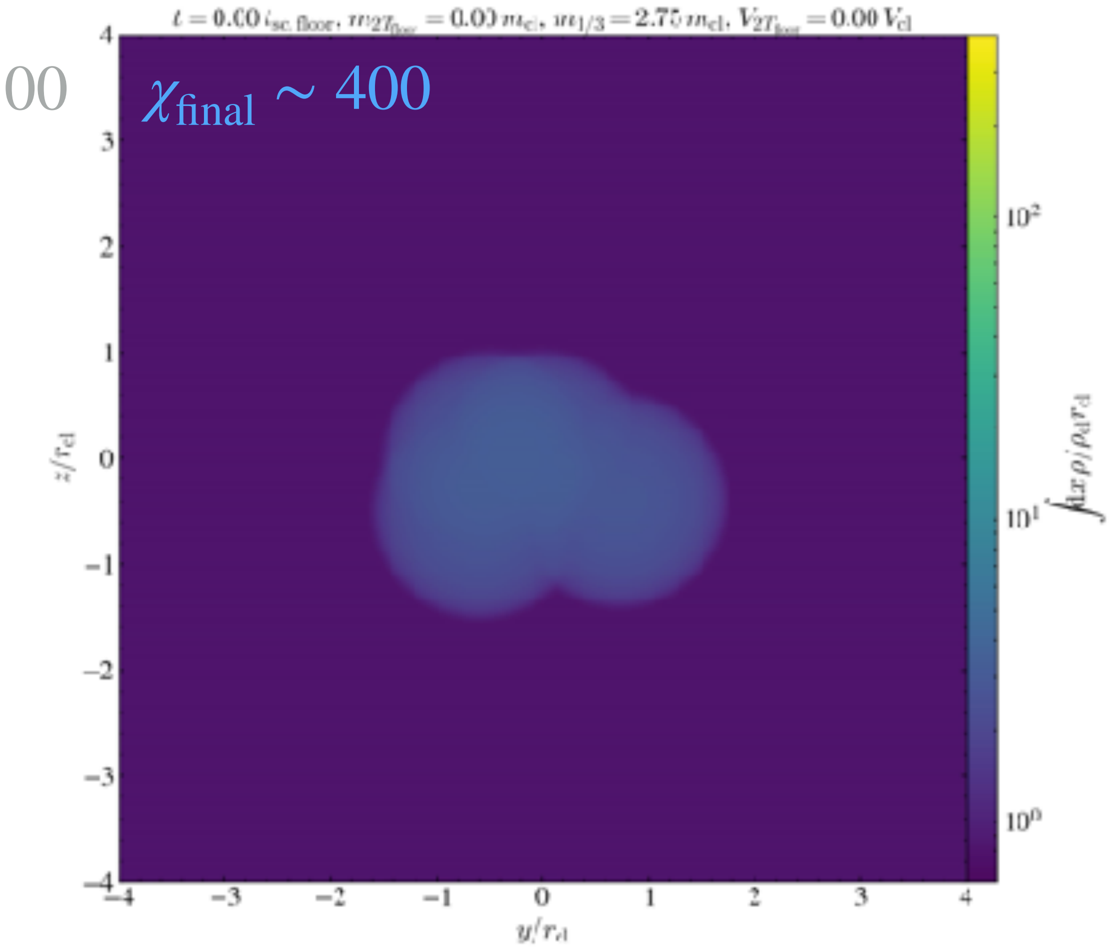
MG & Oh (2020)

"Magical" boundary at $\chi_{\rm final} \sim \chi_{\rm crit}$

$\chi_{\rm initial} \sim 100$



$\chi_{\rm crit} \sim 300$



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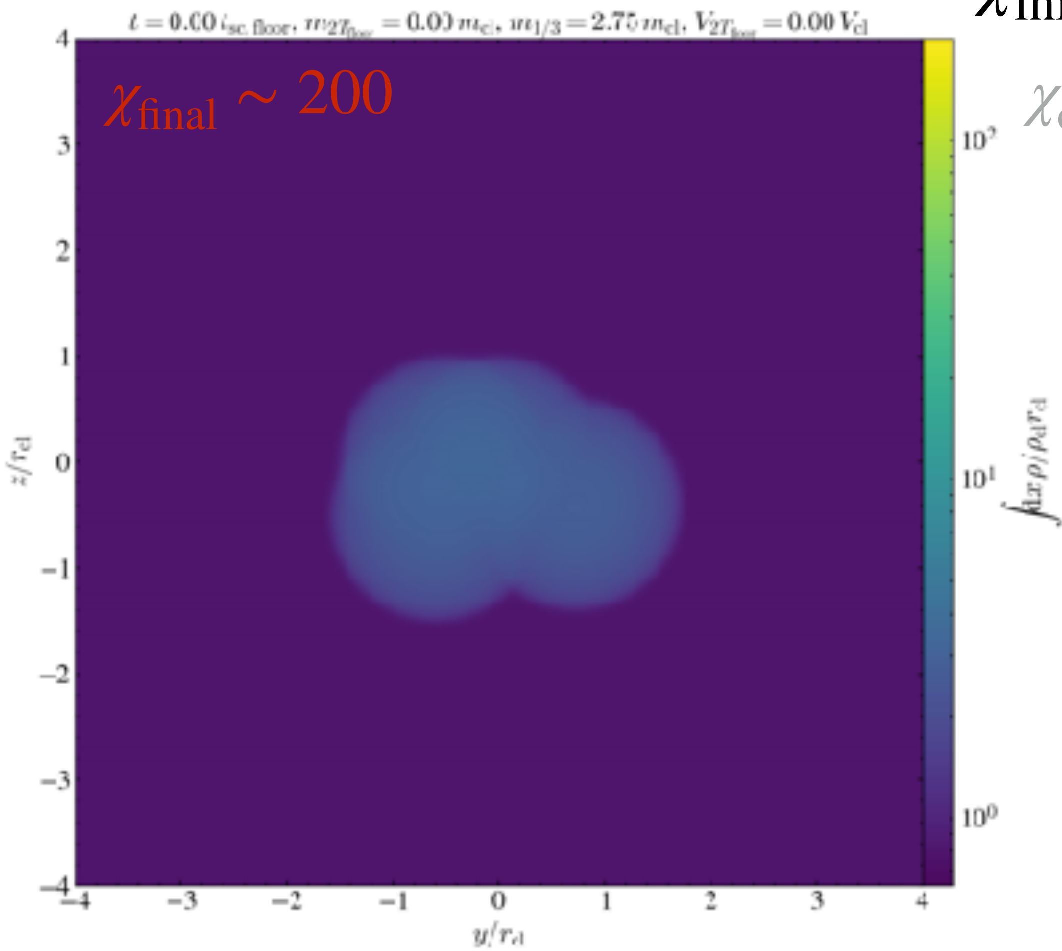

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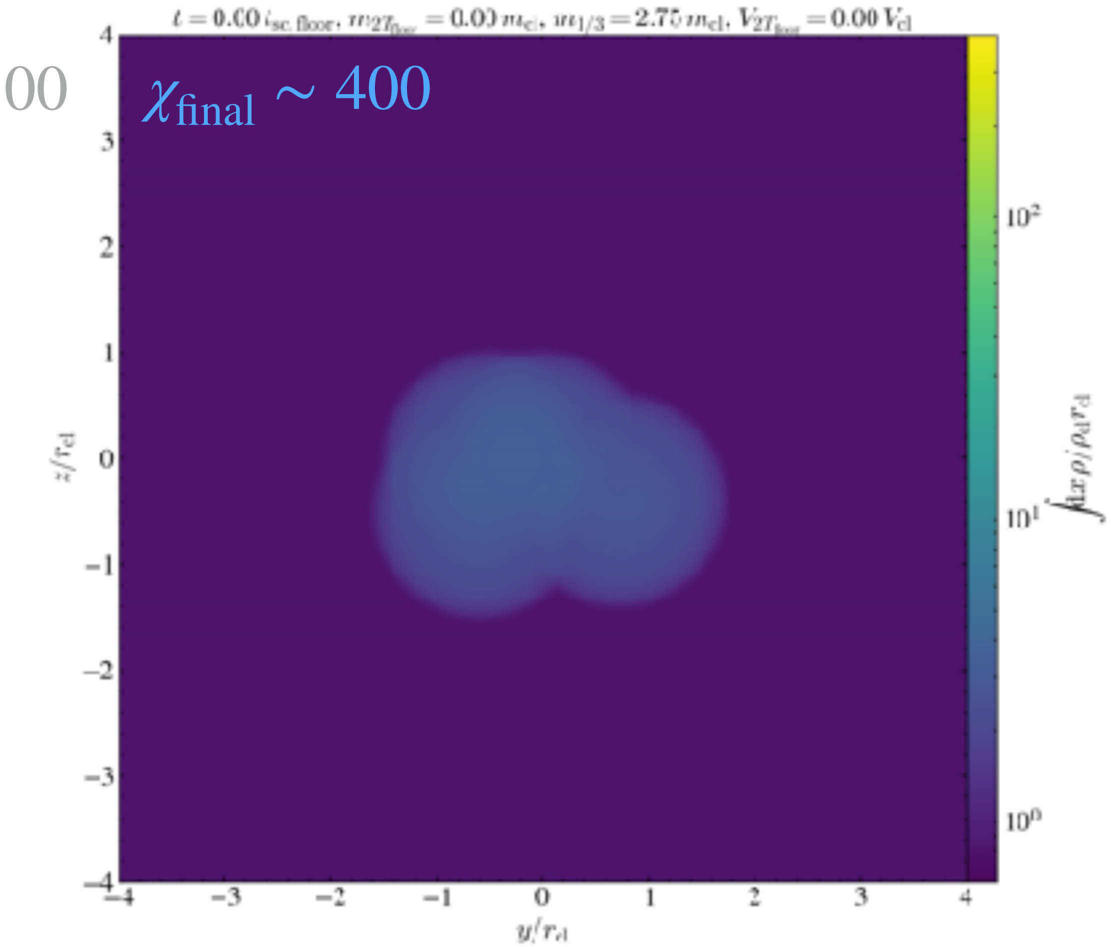

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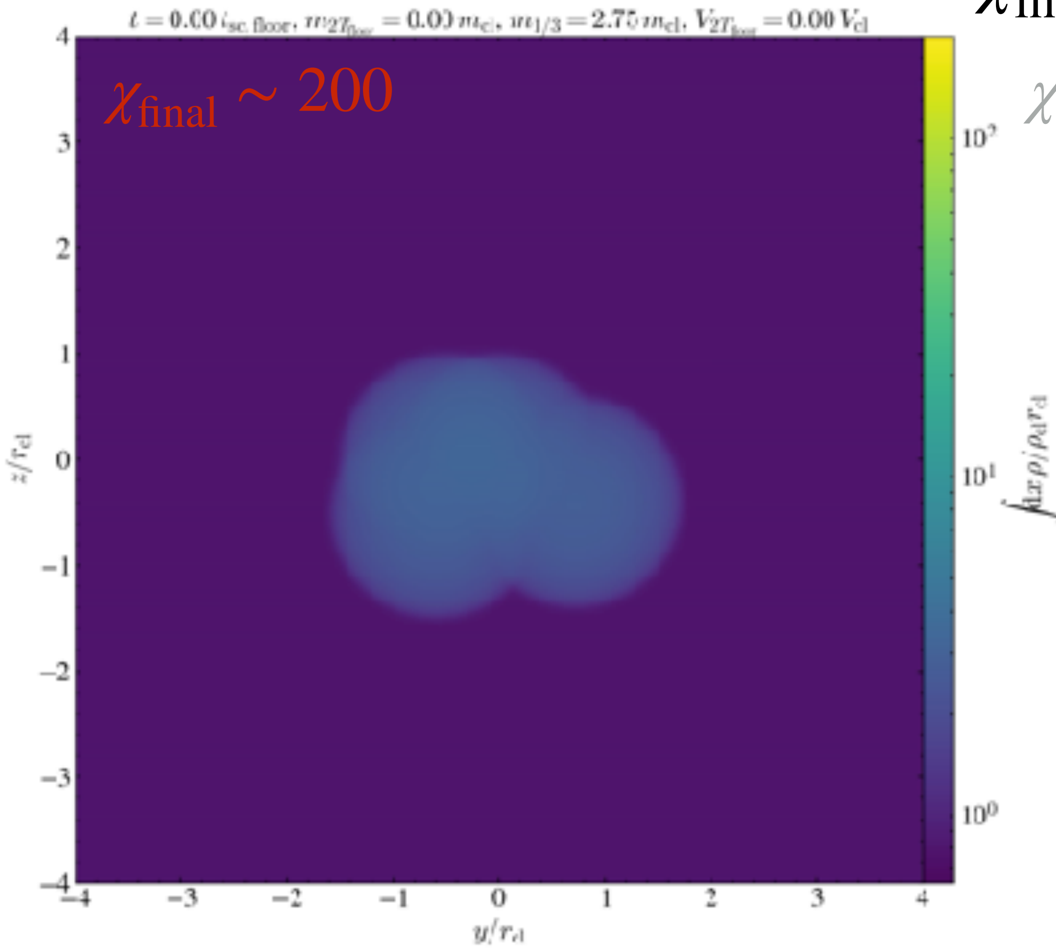

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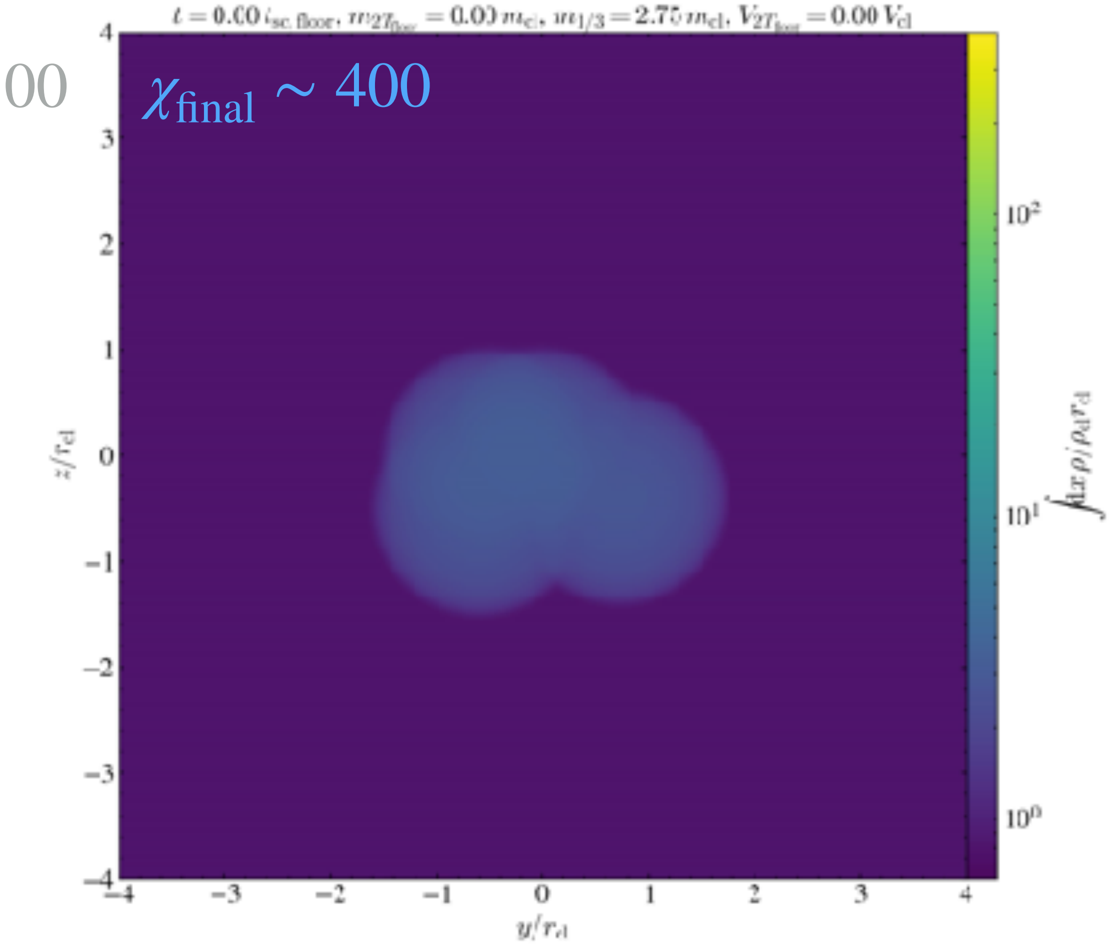

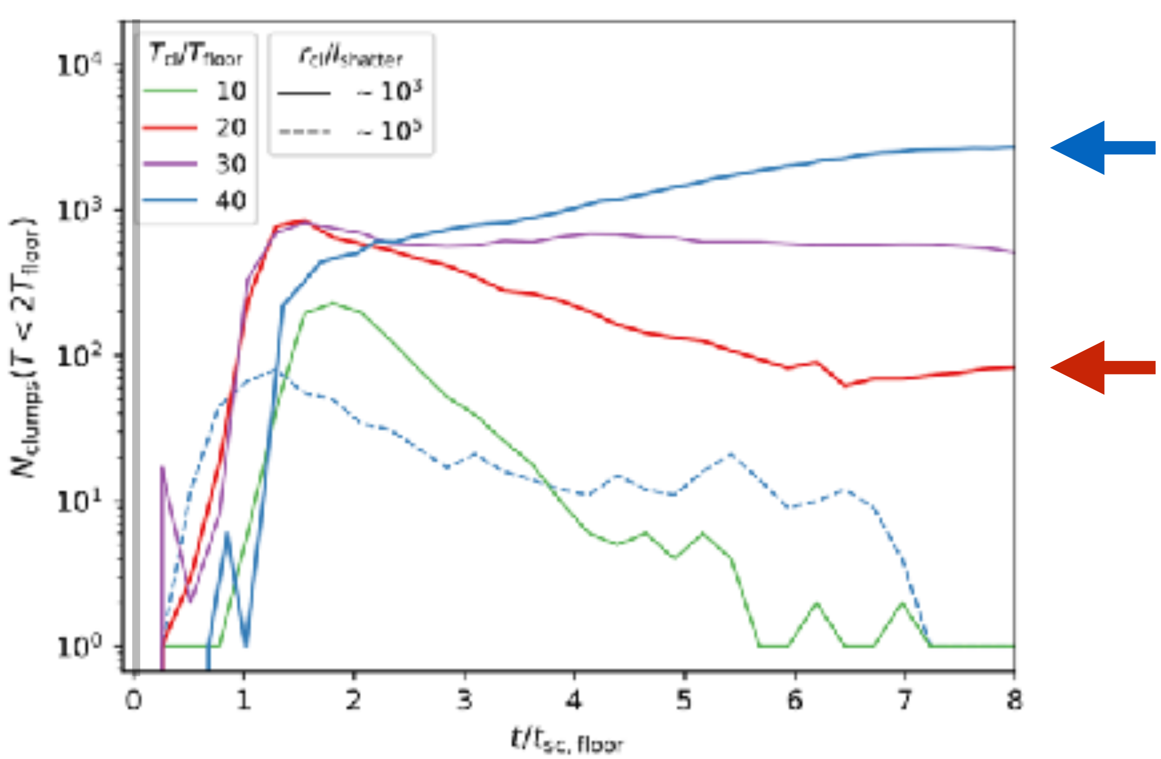

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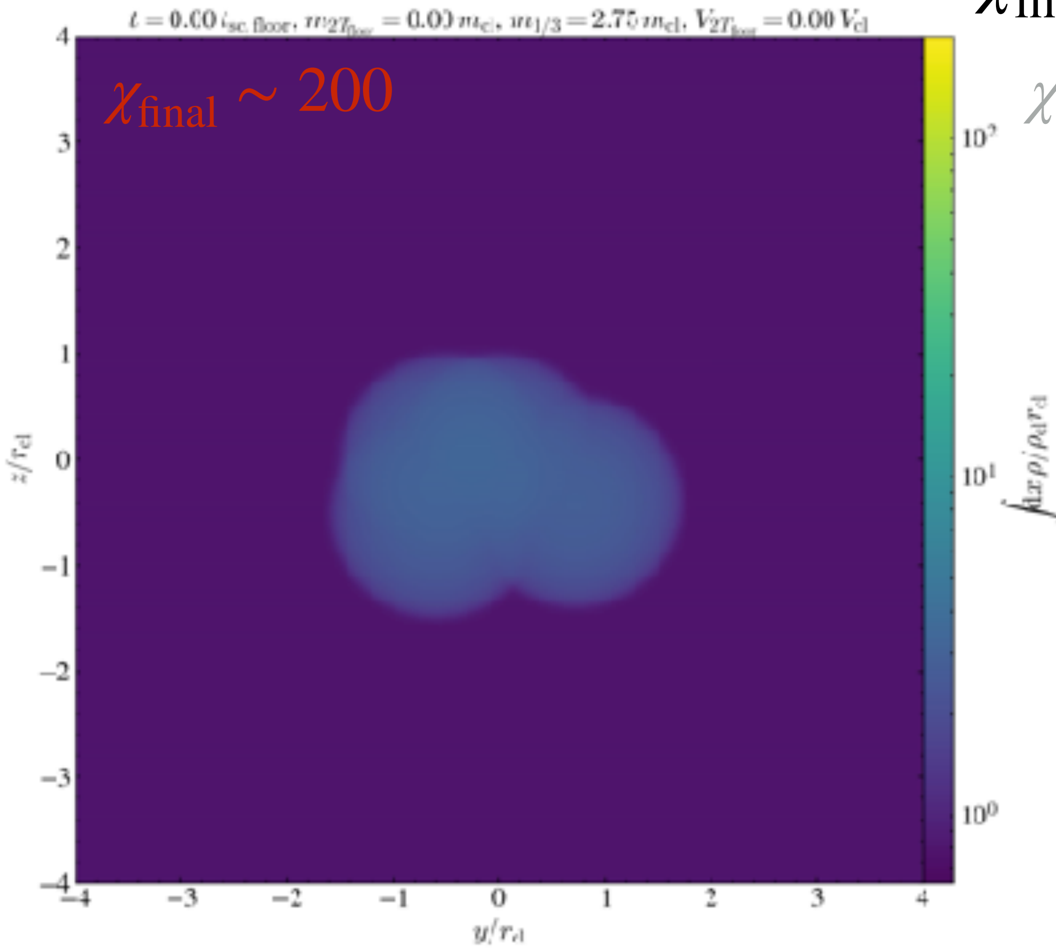

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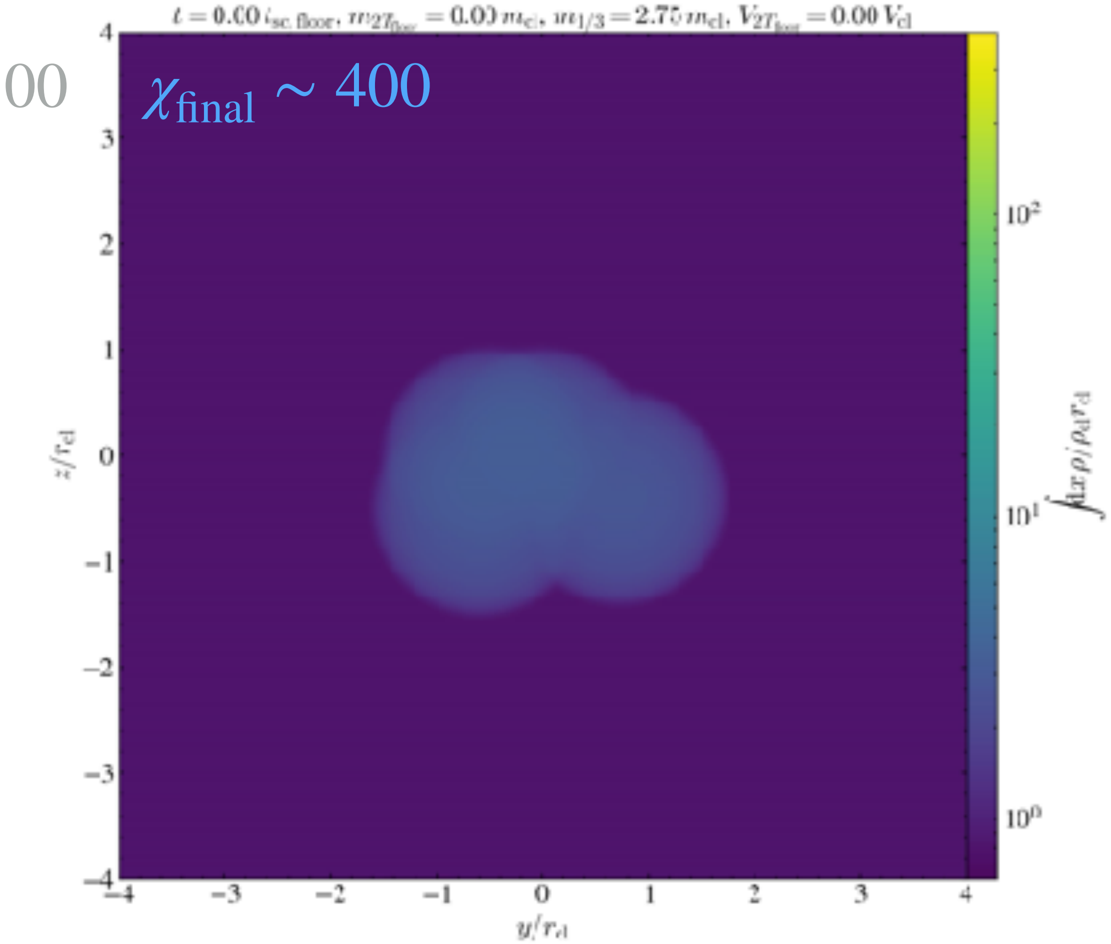

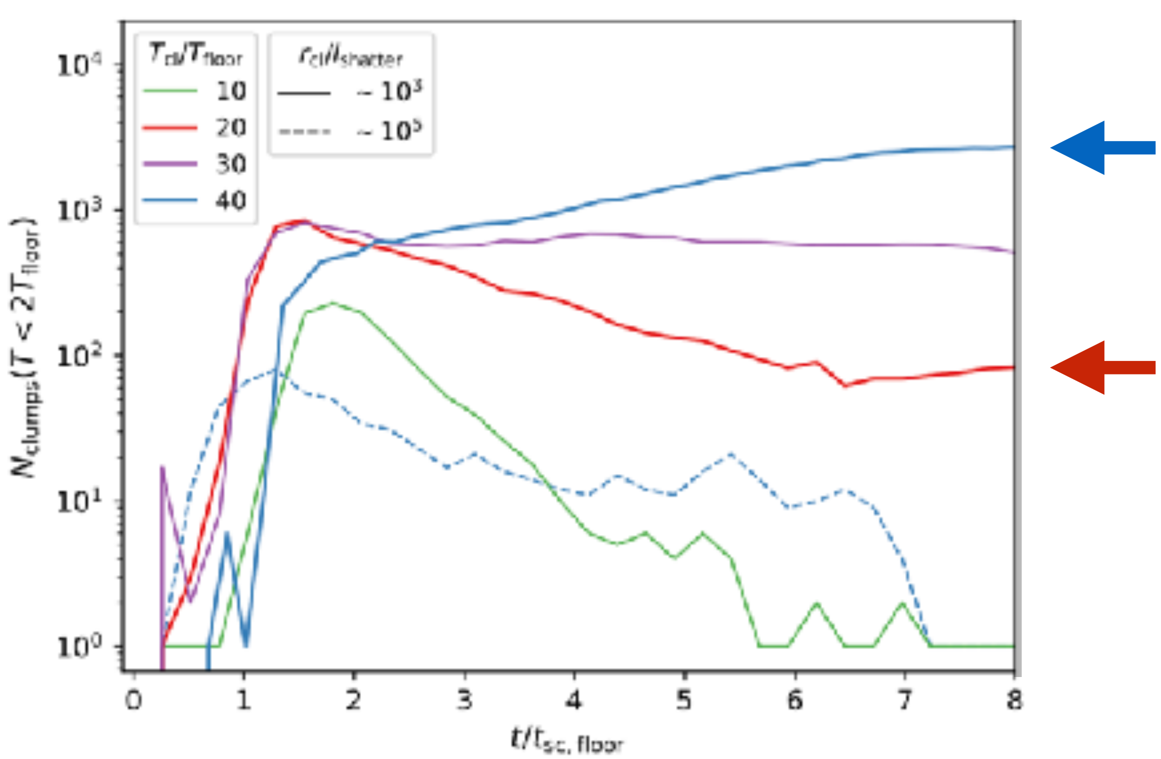

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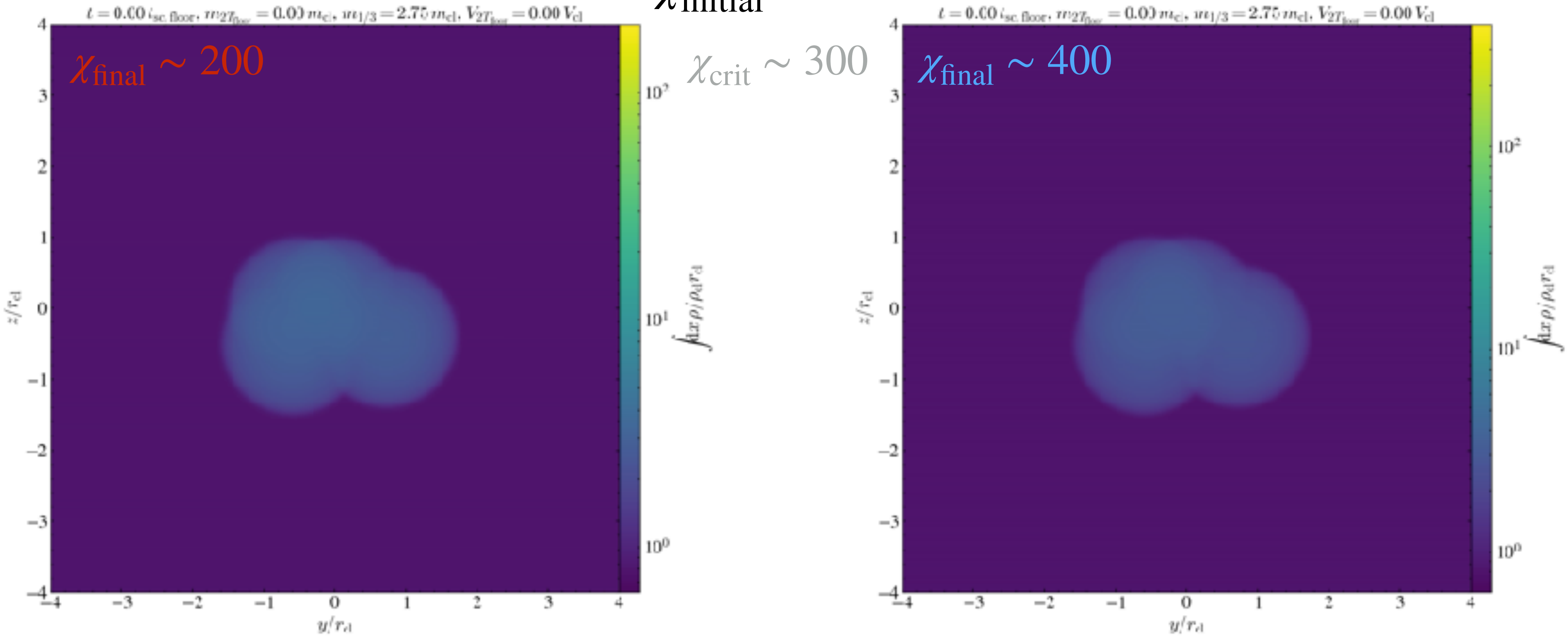
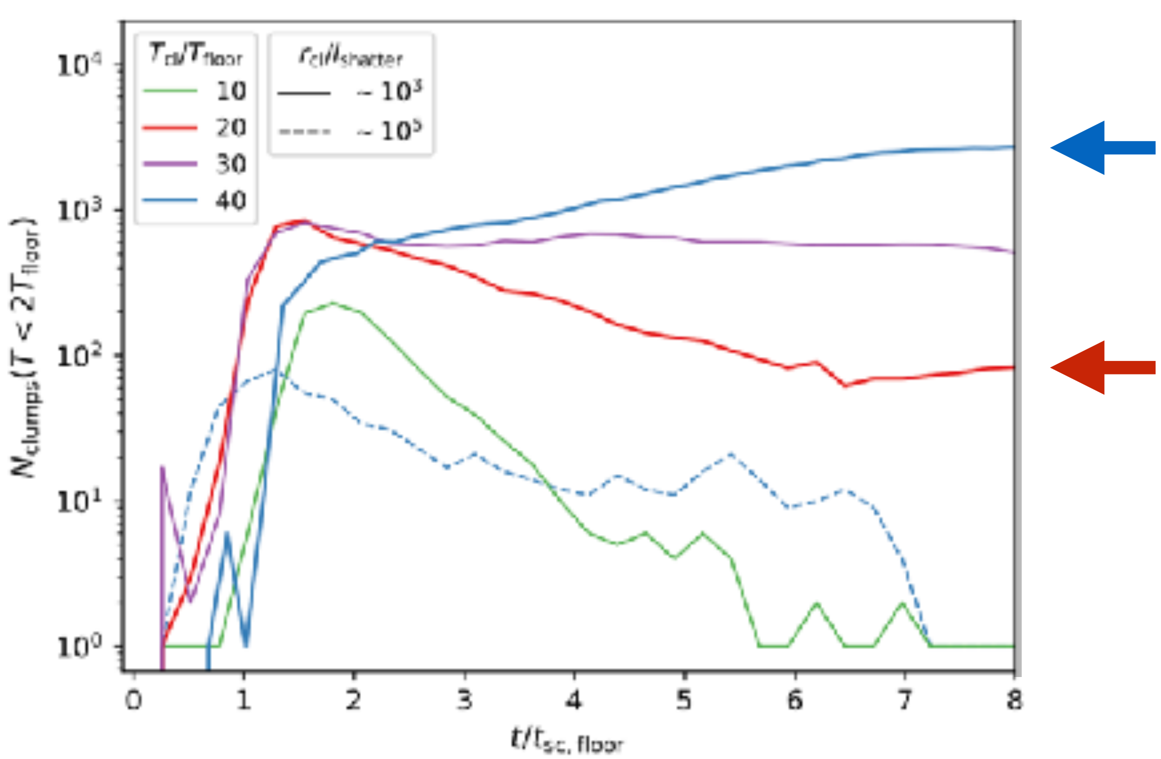
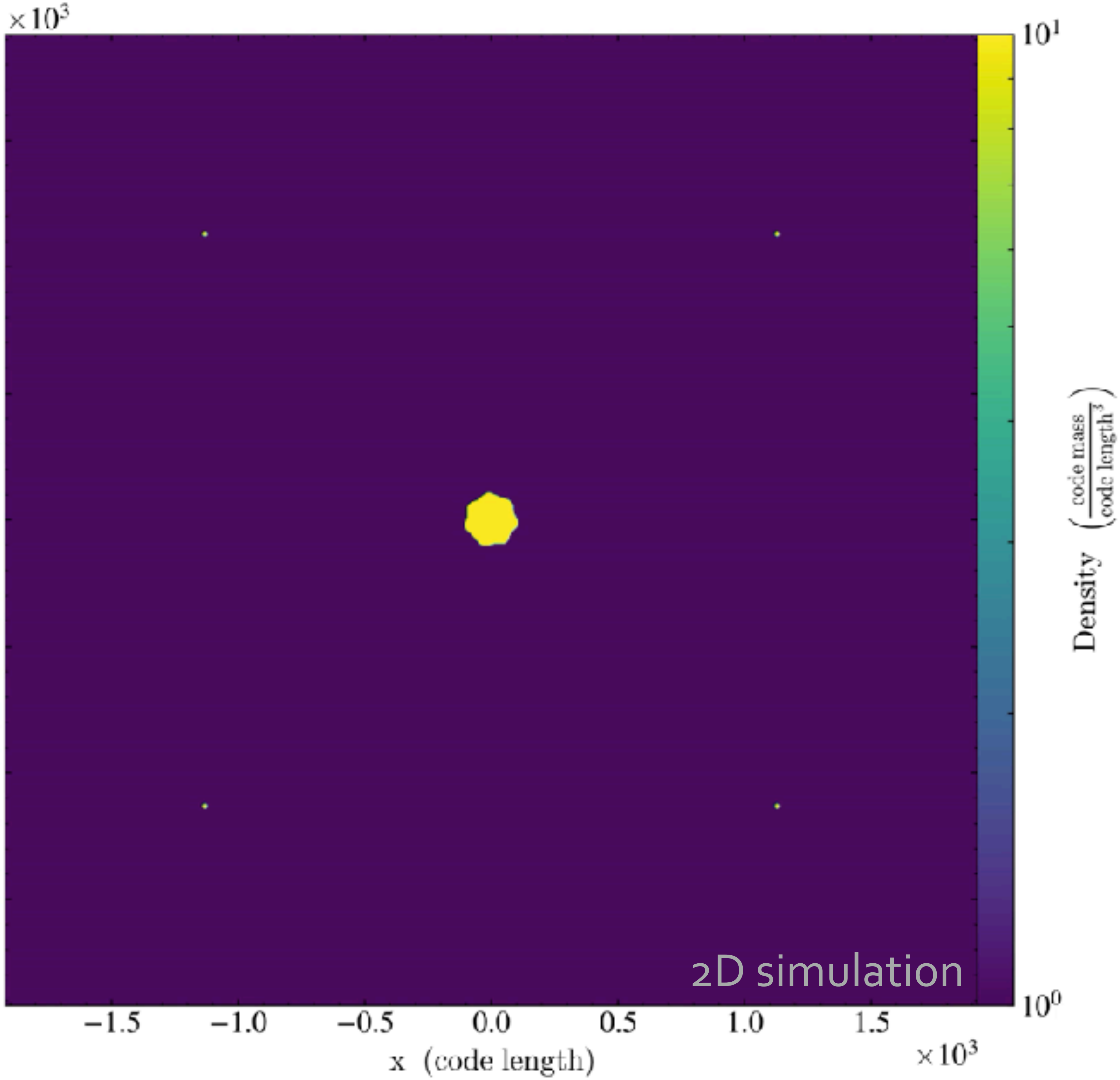




→*Competition between <u>fragmentation</u> and <u>coagulation</u>.*

What drives coagulation?



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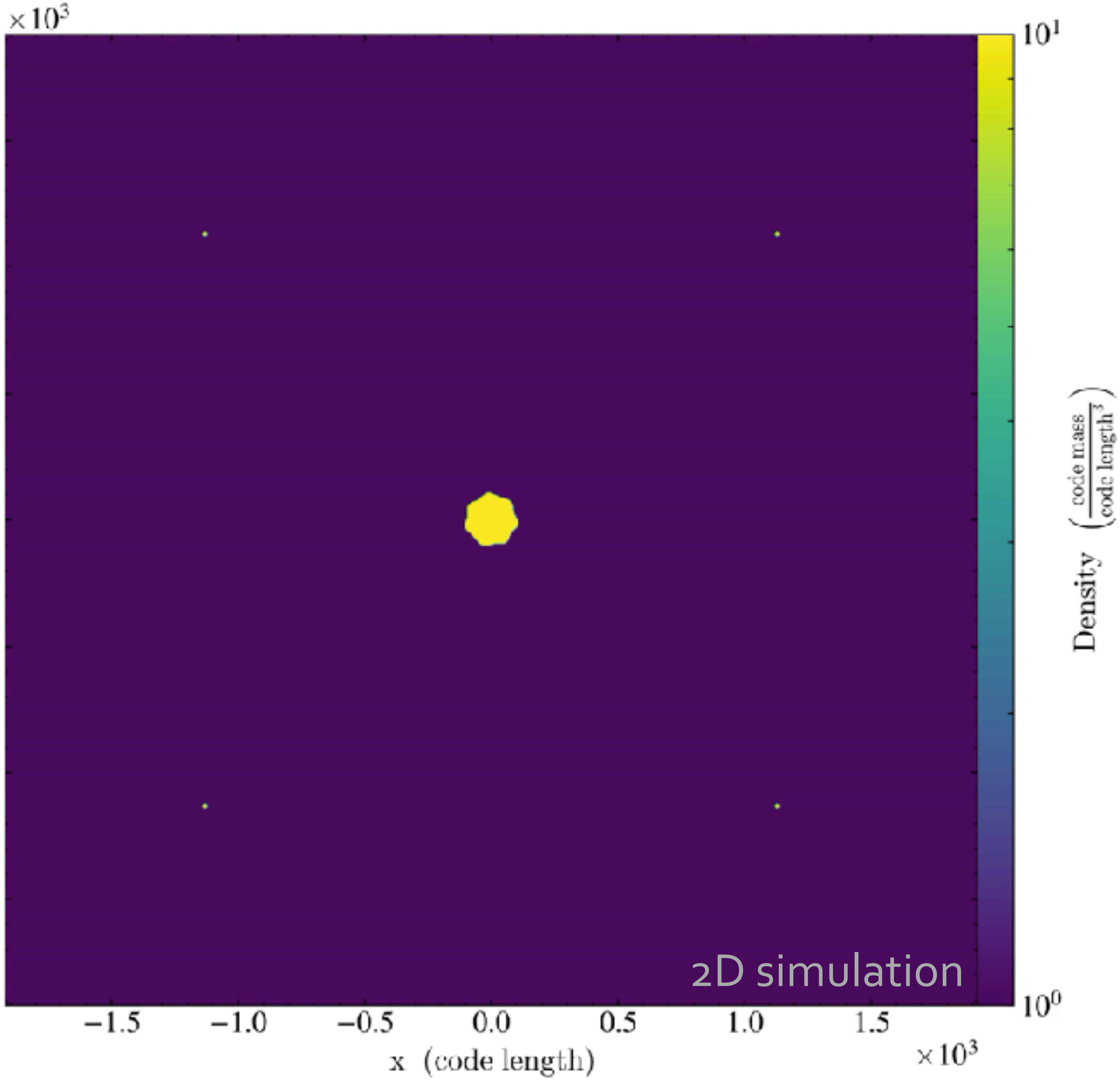

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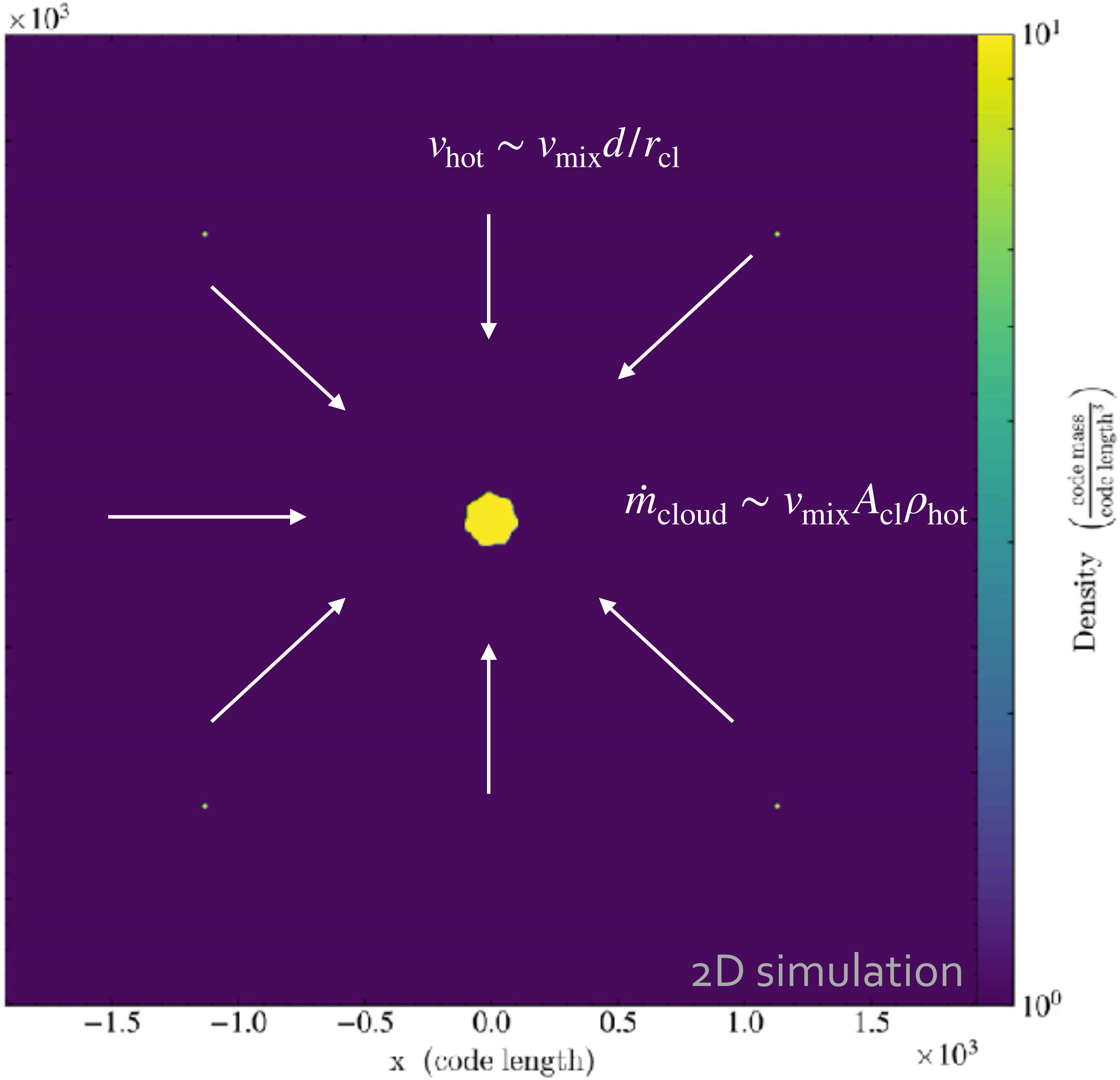

Cooling driven coagulation

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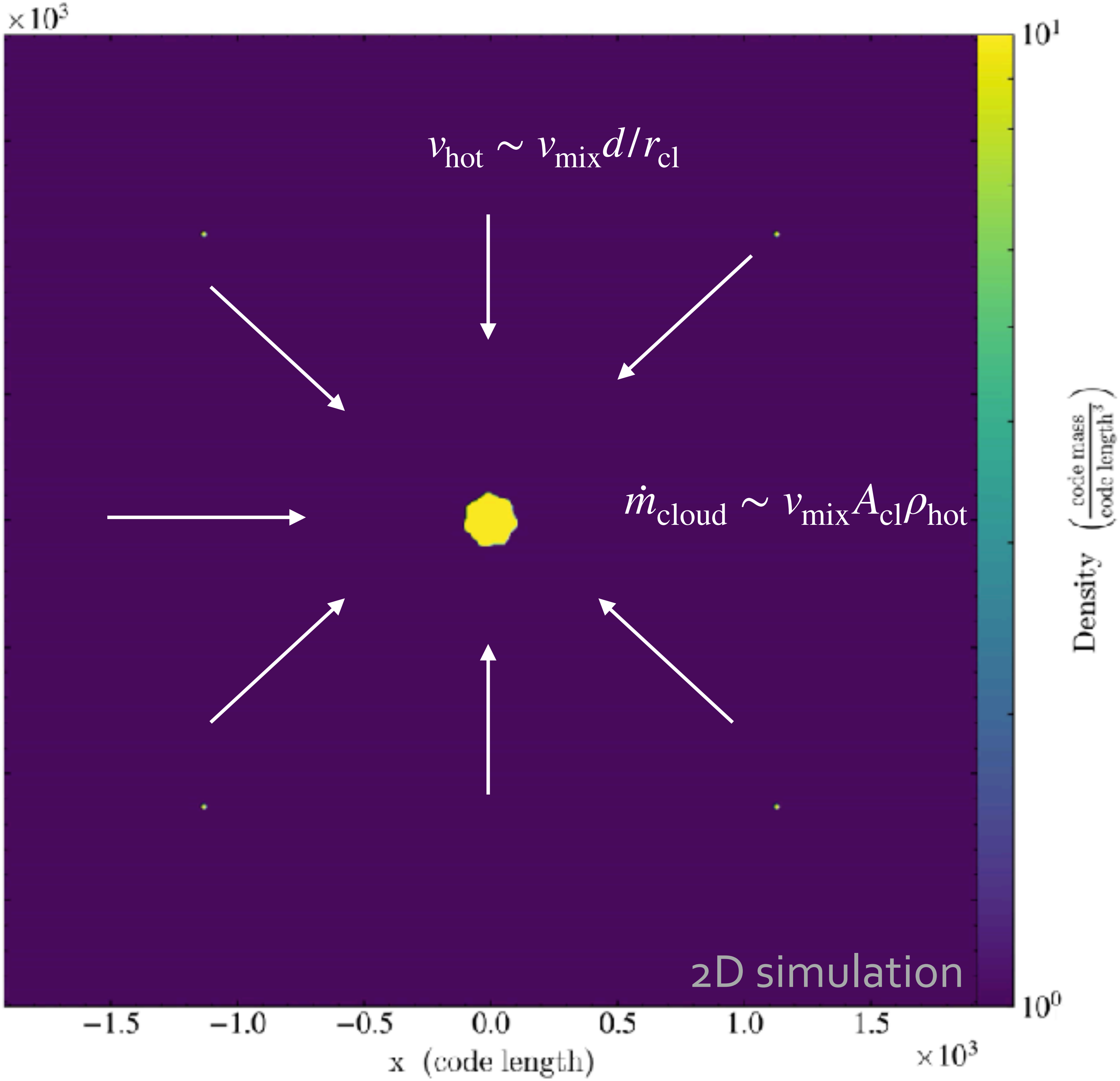

Cooling driven coagulation

"Shattering boundary"

$$\chi_{\rm final} \equiv T_{\rm cl}/T_{\rm floor} \chi_{\rm initial} \gtrsim \chi_{\rm crit}$$

$T_{\rm cl}/T_{\rm floor} \propto \delta P$

↳ "height of drop"

$t_{\rm grow,cloud} \equiv m/\dot{m} \propto \chi_{\rm initial}$

↳(relative) strength of cooling

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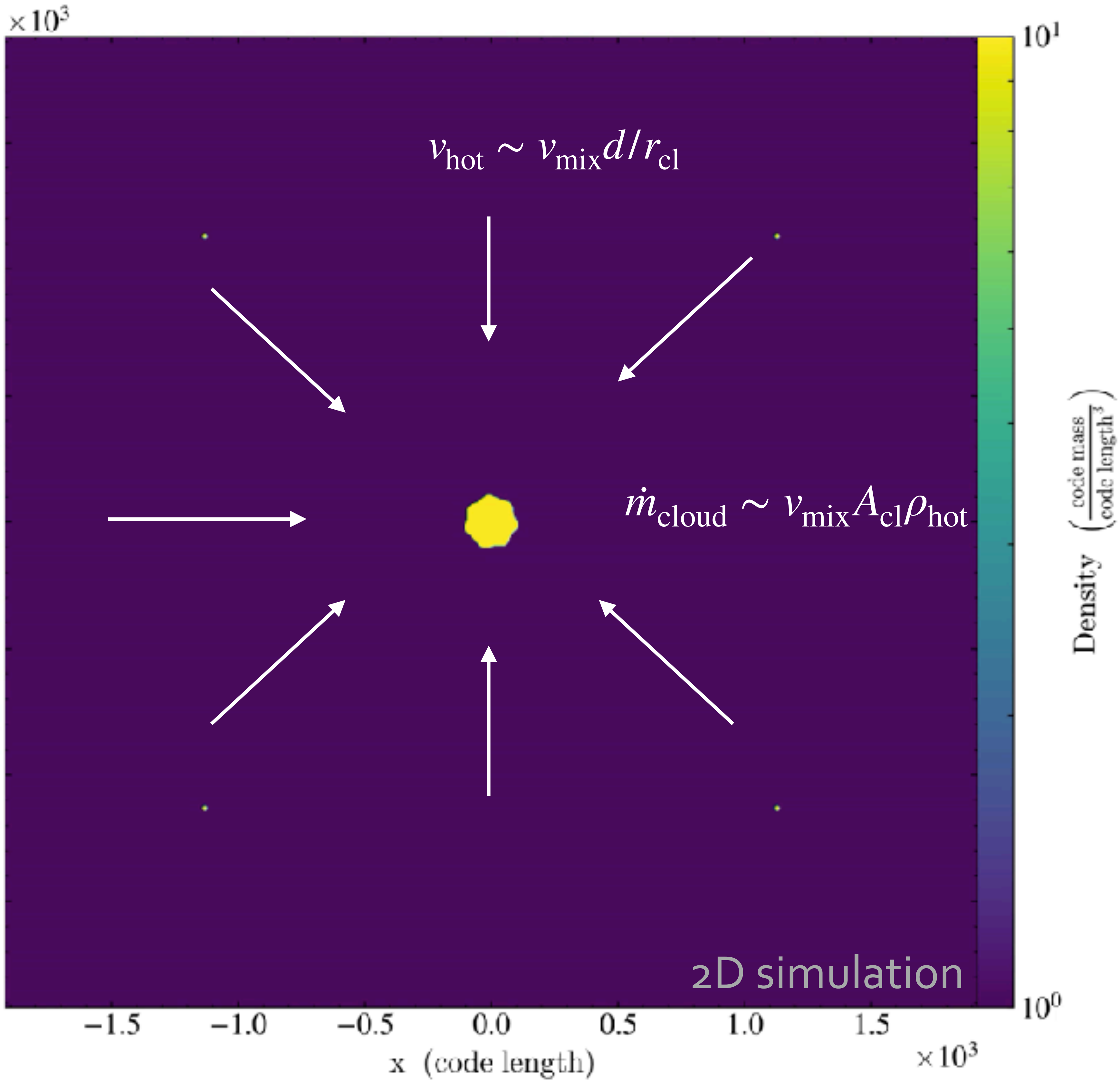

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Pressure ($\sim t_{\rm drag}$) or mass transfer ($t_{\rm grow,droplet}$)?

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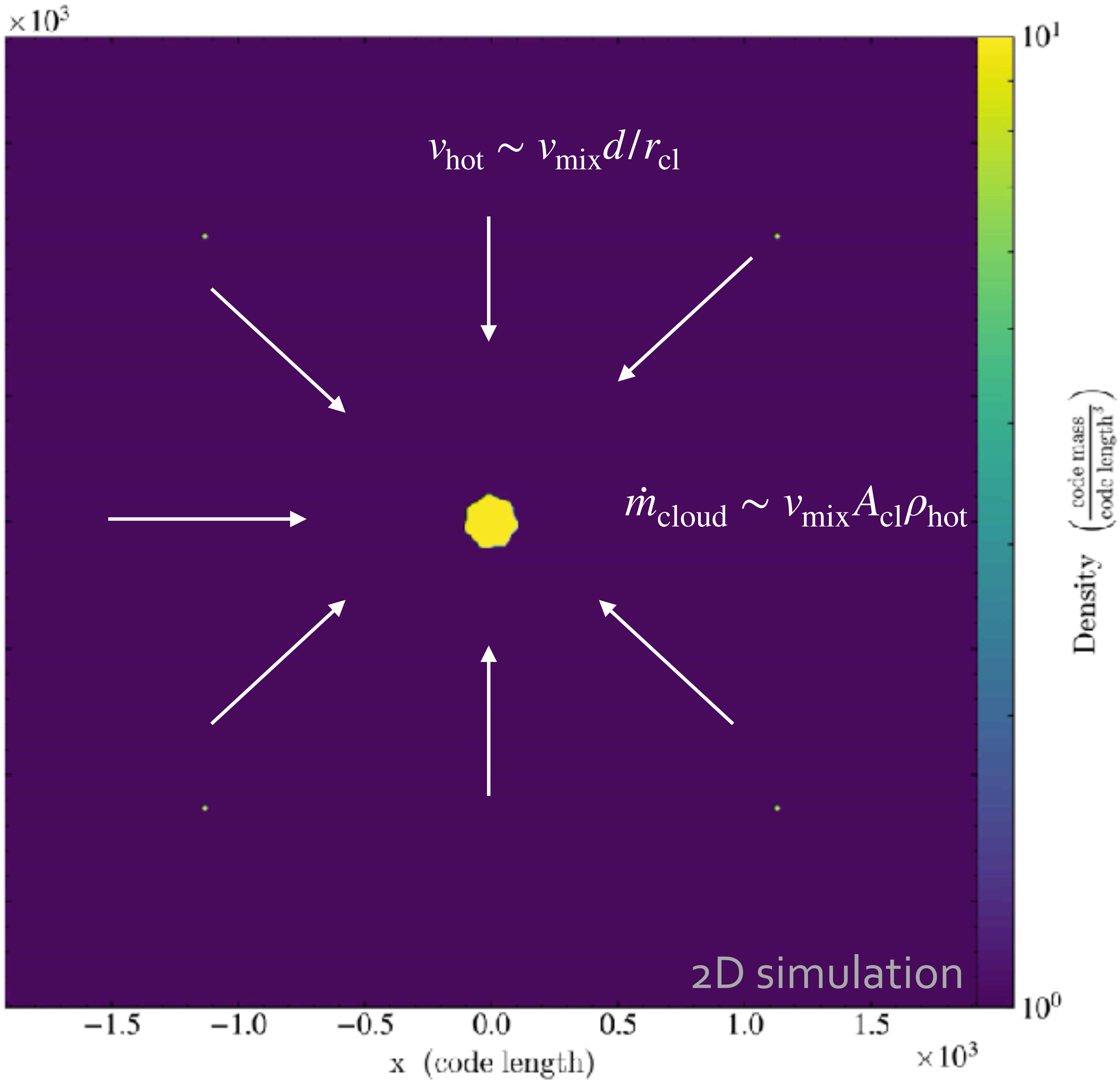

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Droplet acceleration

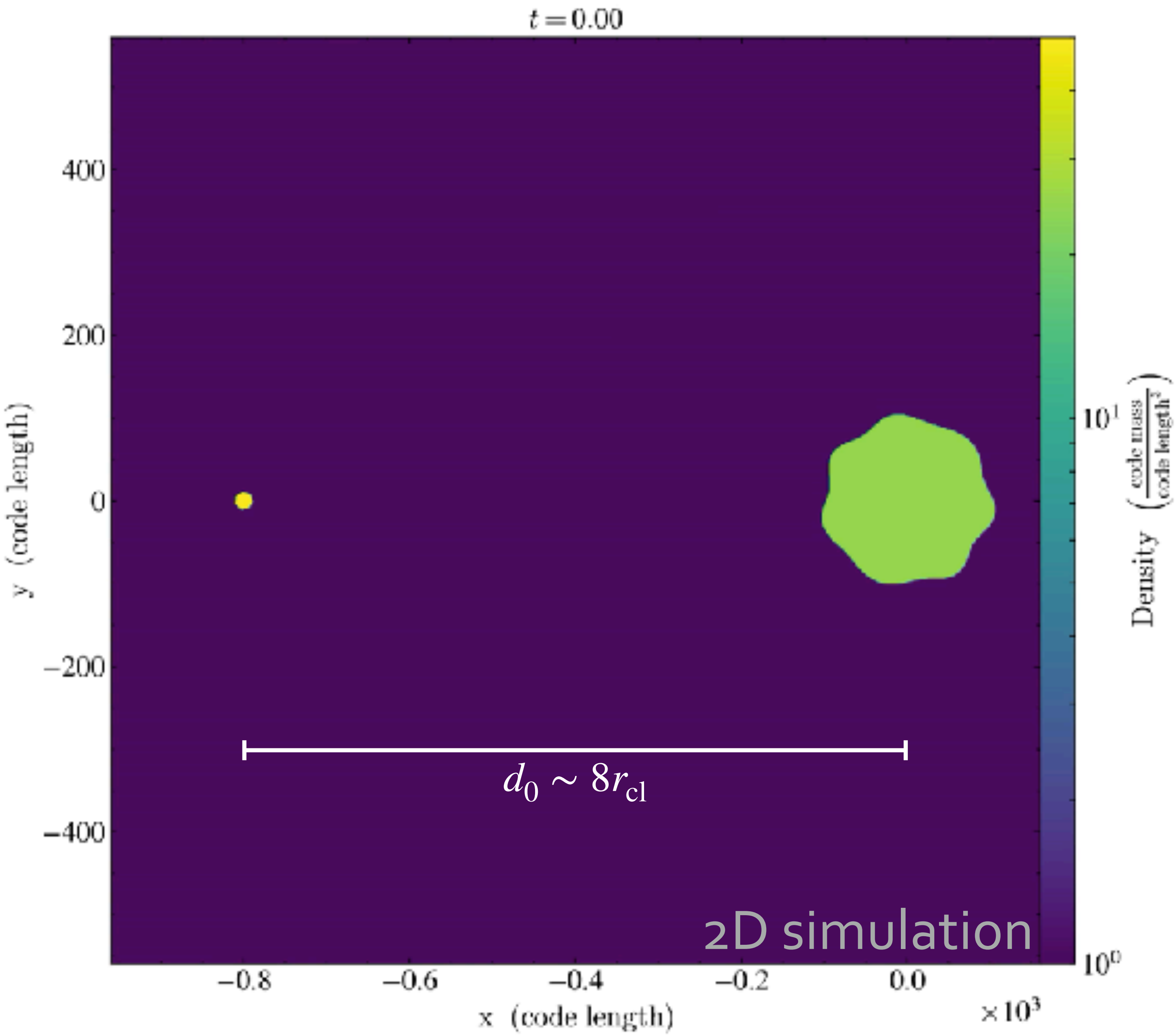
Pressure ($\sim t_{\rm drag}$) or mass transfer ($t_{\rm grow,droplet}$)?

$$\frac{t_{\rm drag}}{t_{\rm grow}} \sim \frac{\chi r_{\rm d}/v_{\rm hot}}{m/\dot{m}} \sim \frac{v_{\rm mix}}{v_{\rm hot}} \sim \frac{d}{r_{\rm cl}} \gg 1$$

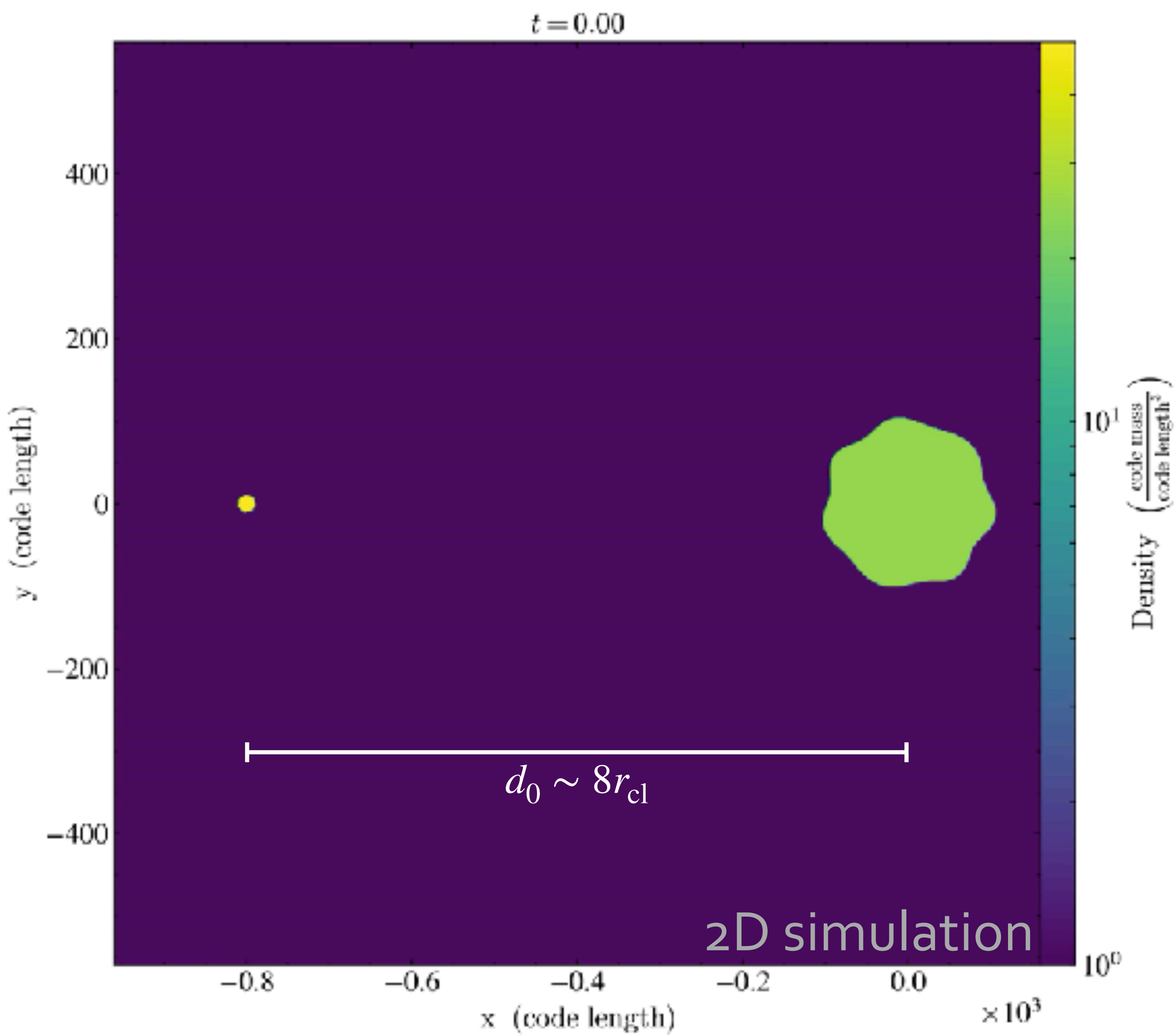
→mass transfer

(cf. MG & Oh 2018 for clouds)

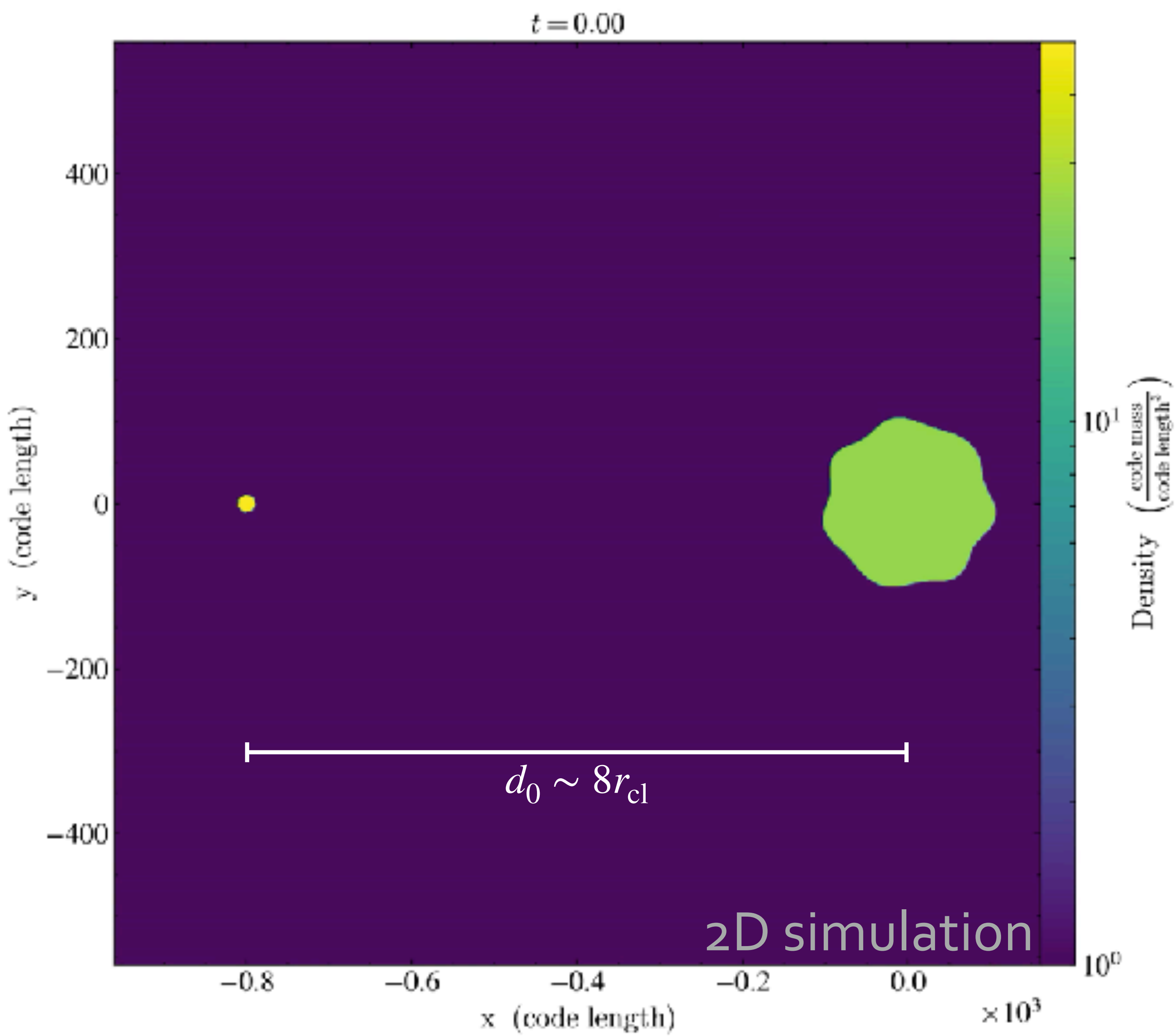
Fun with coagulation

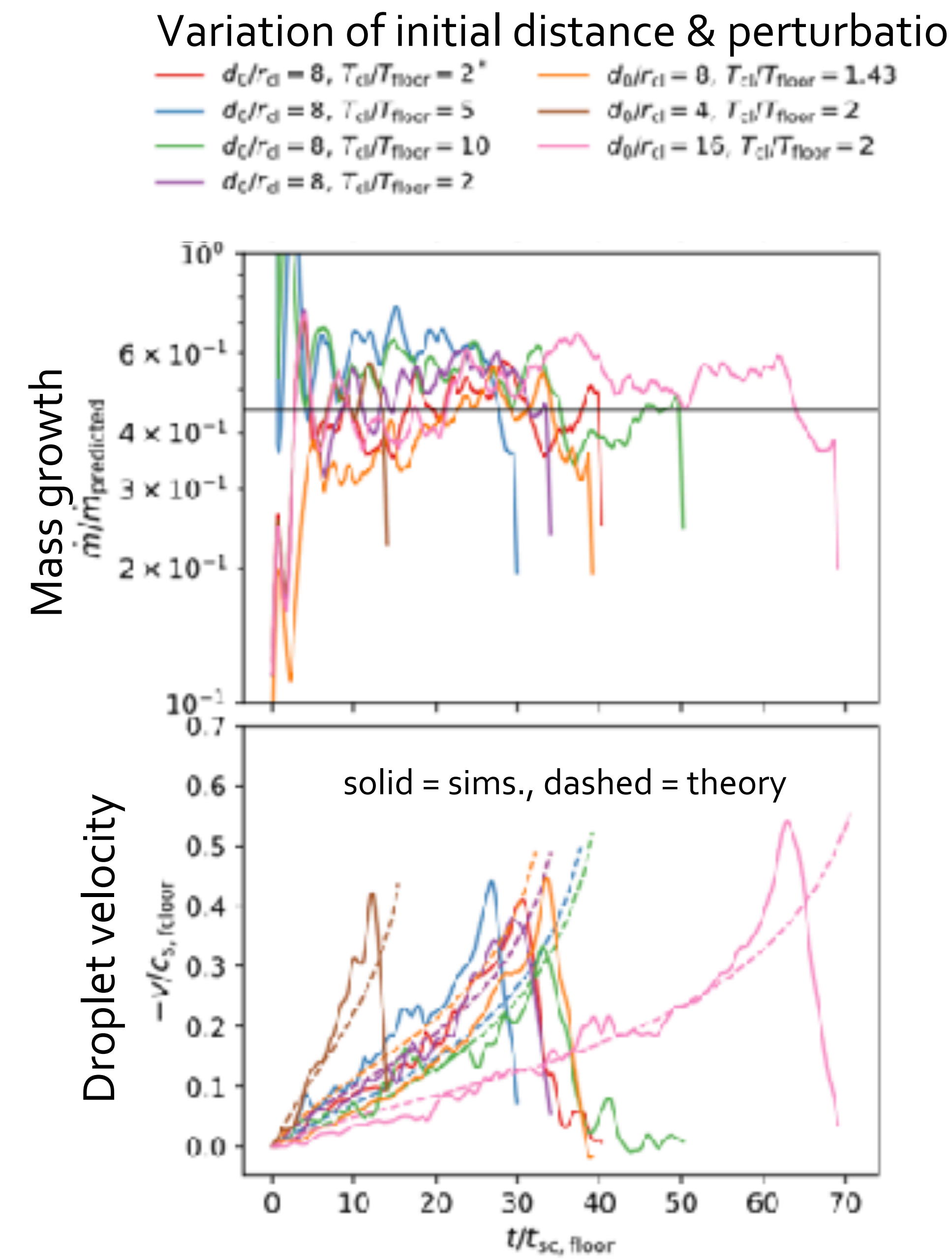


Fun with coagulation



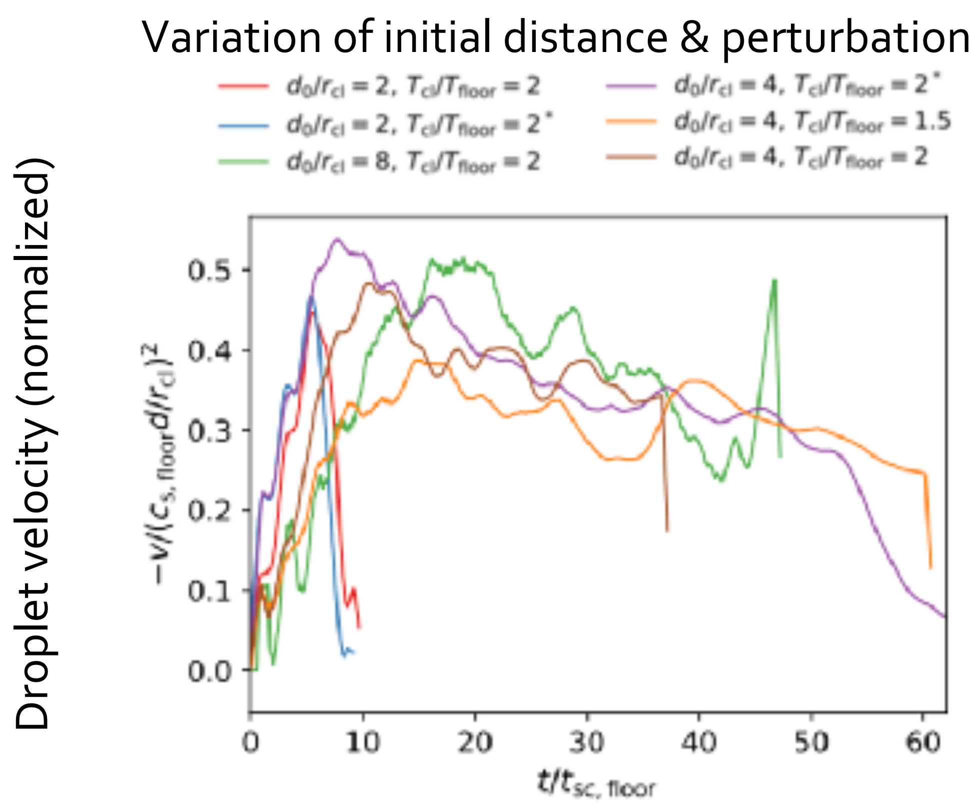
Fun with coagulation

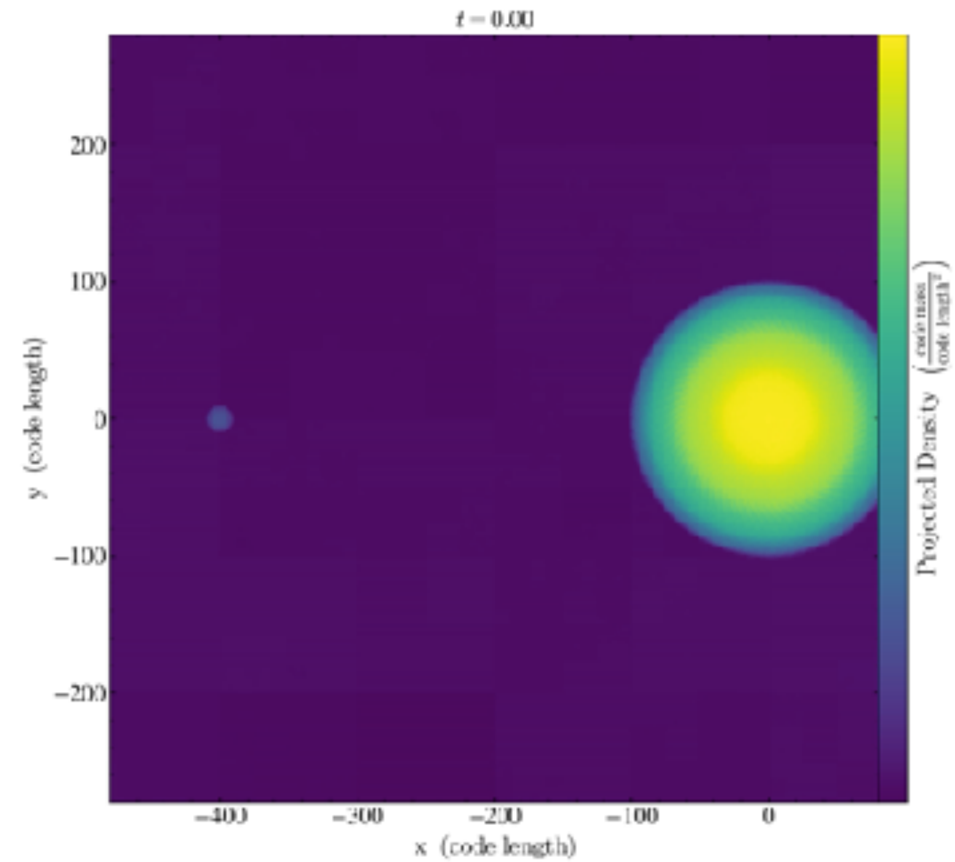


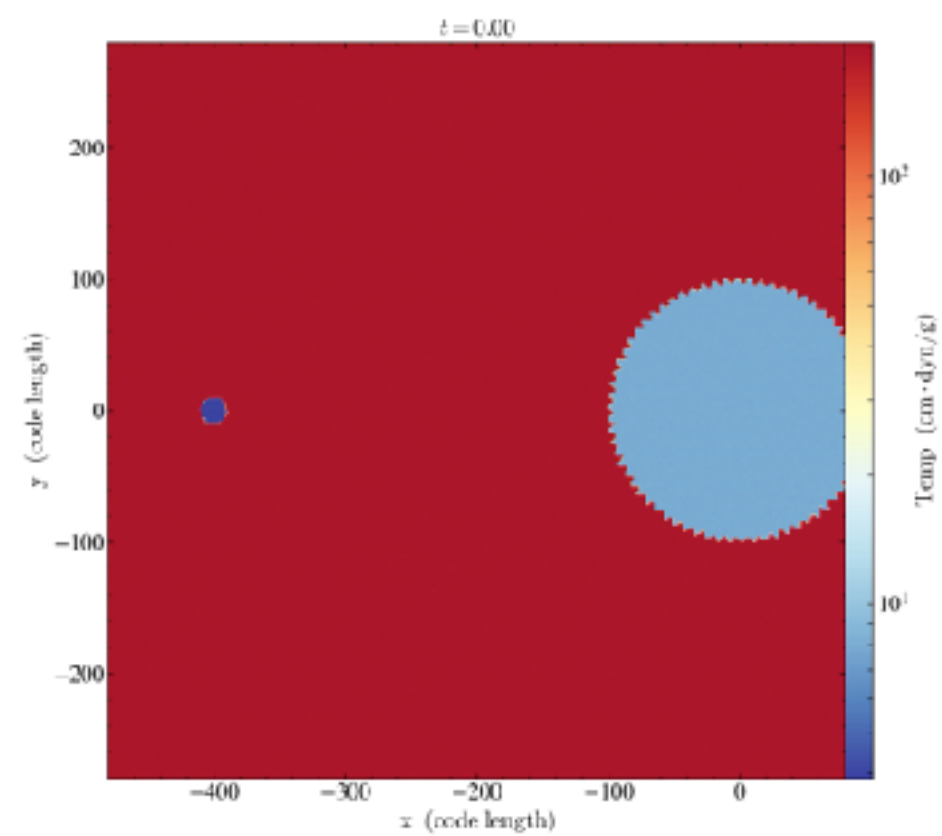


→Well modeled with cooling & entrainment scalings.

Coagulation in 3D

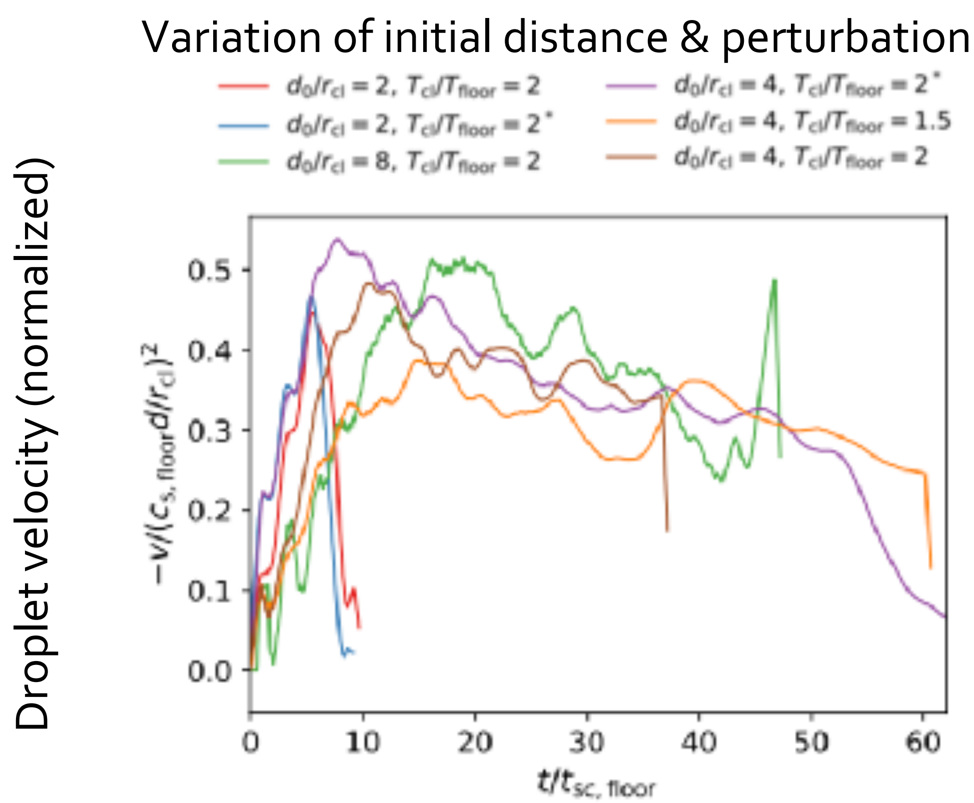


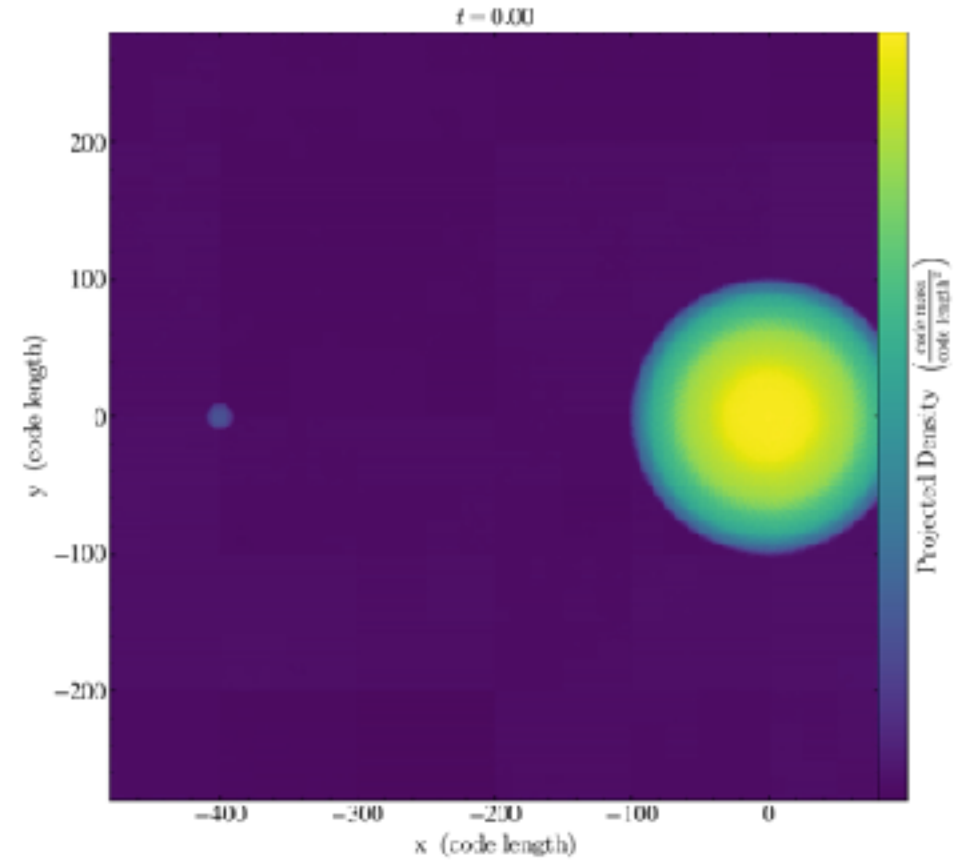


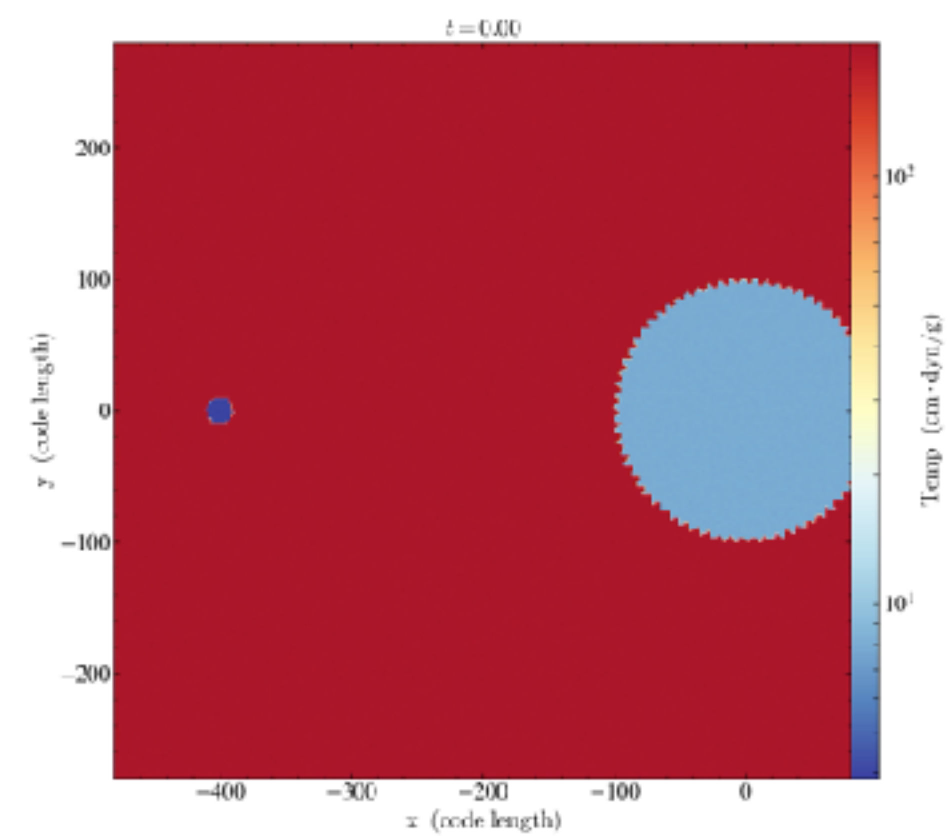


Works but $v_{\rm hot} \sim v_{\rm mix}(d/r_{\rm cl})^{\boxed{2}}$ → slower

Coagulation in 3D

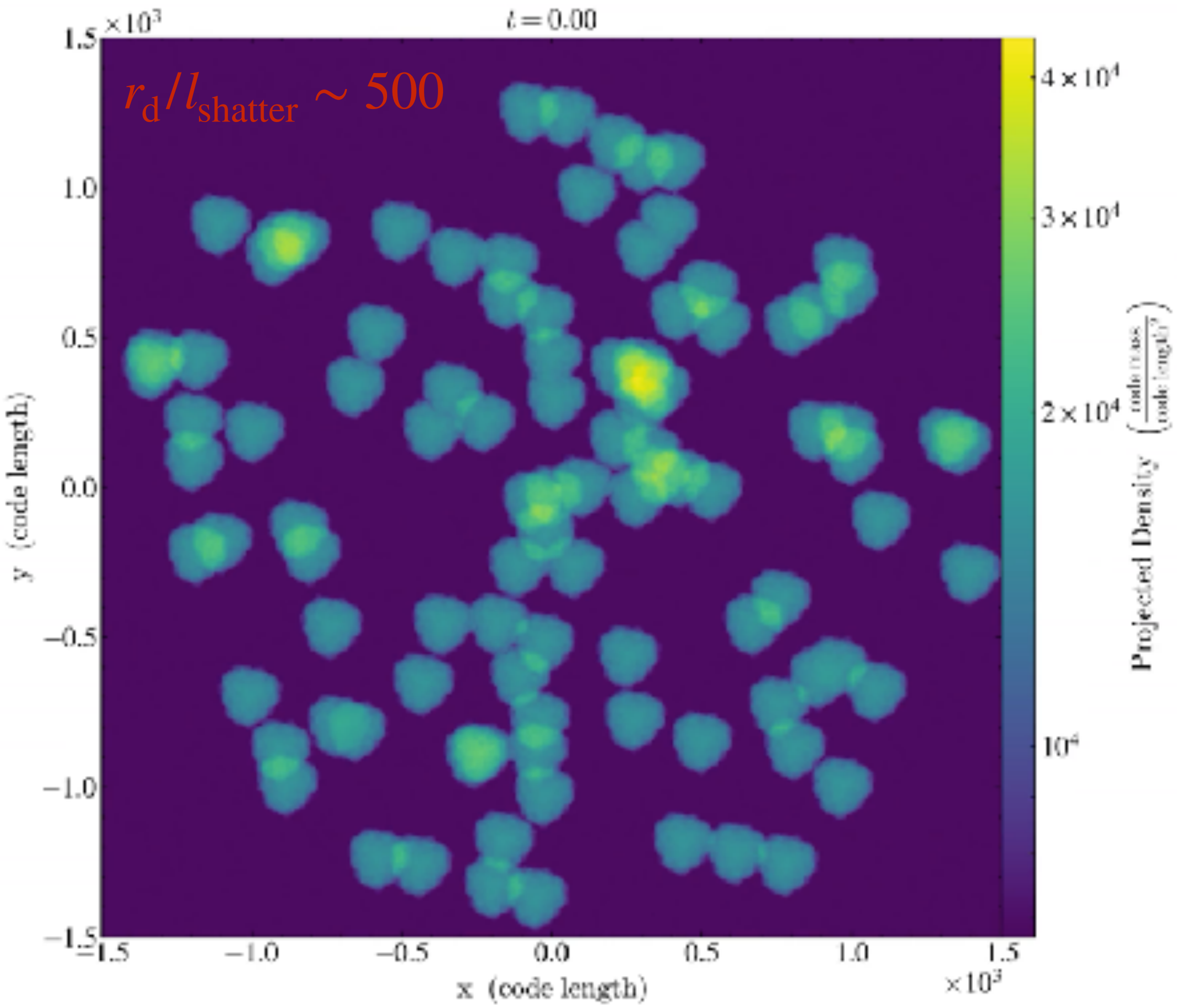






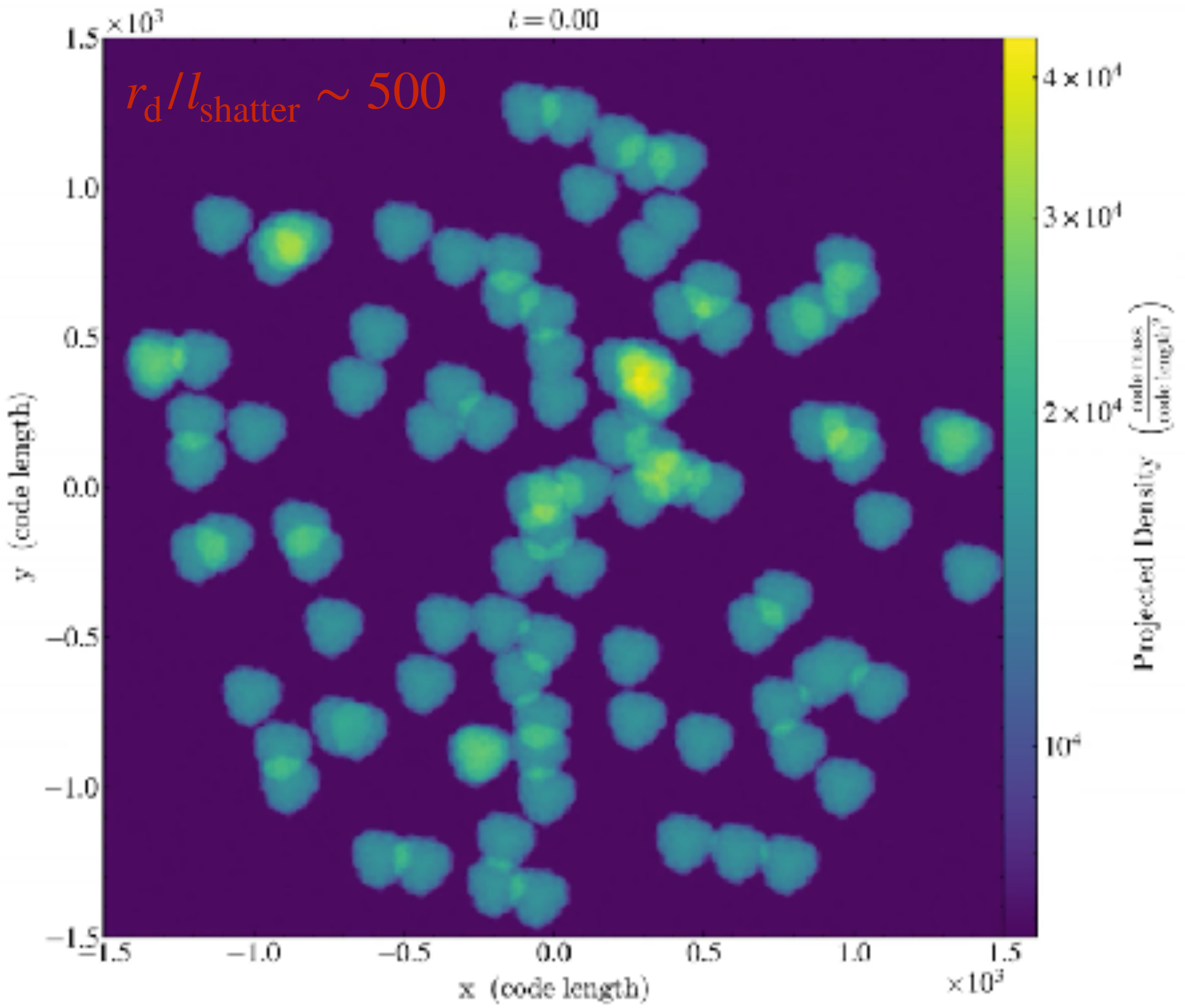
Works but $v_{\rm hot} \sim v_{\rm mix}(d/r_{\rm cl})^{\boxed{2}} \rightarrow$ slower

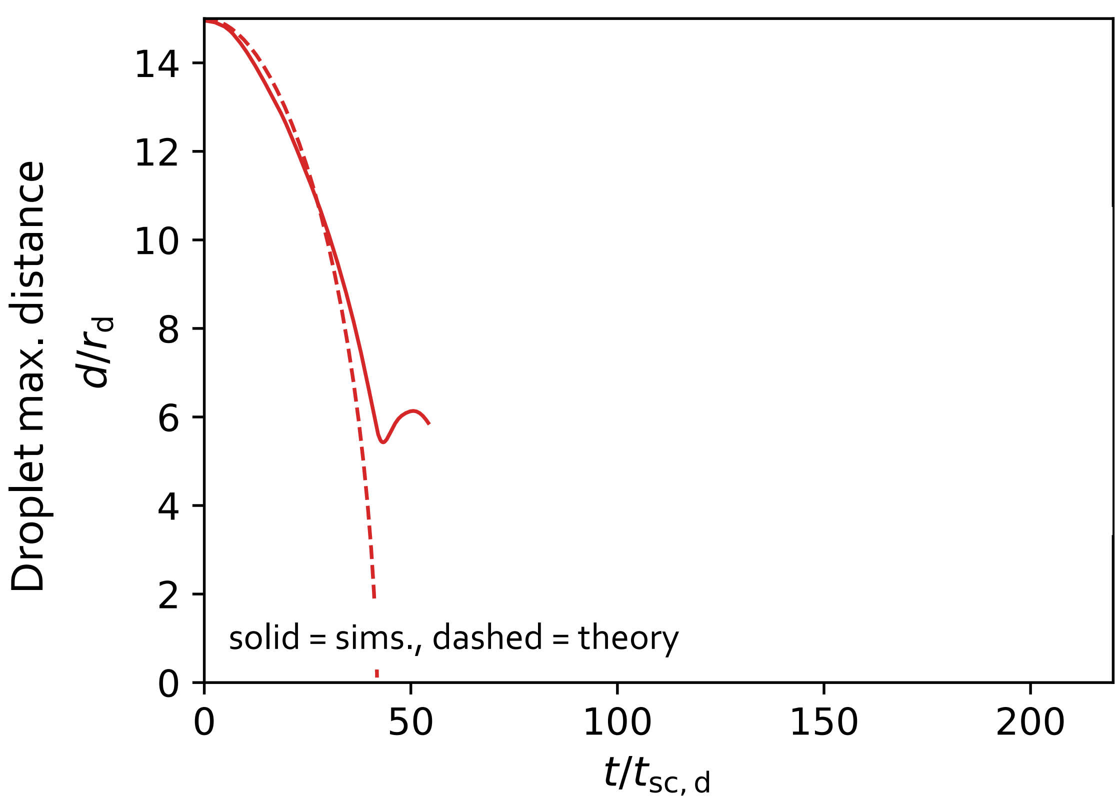
Many droplet coagulation (3D)



solid = sims., dashed = theory

Many droplet coagulation (3D)





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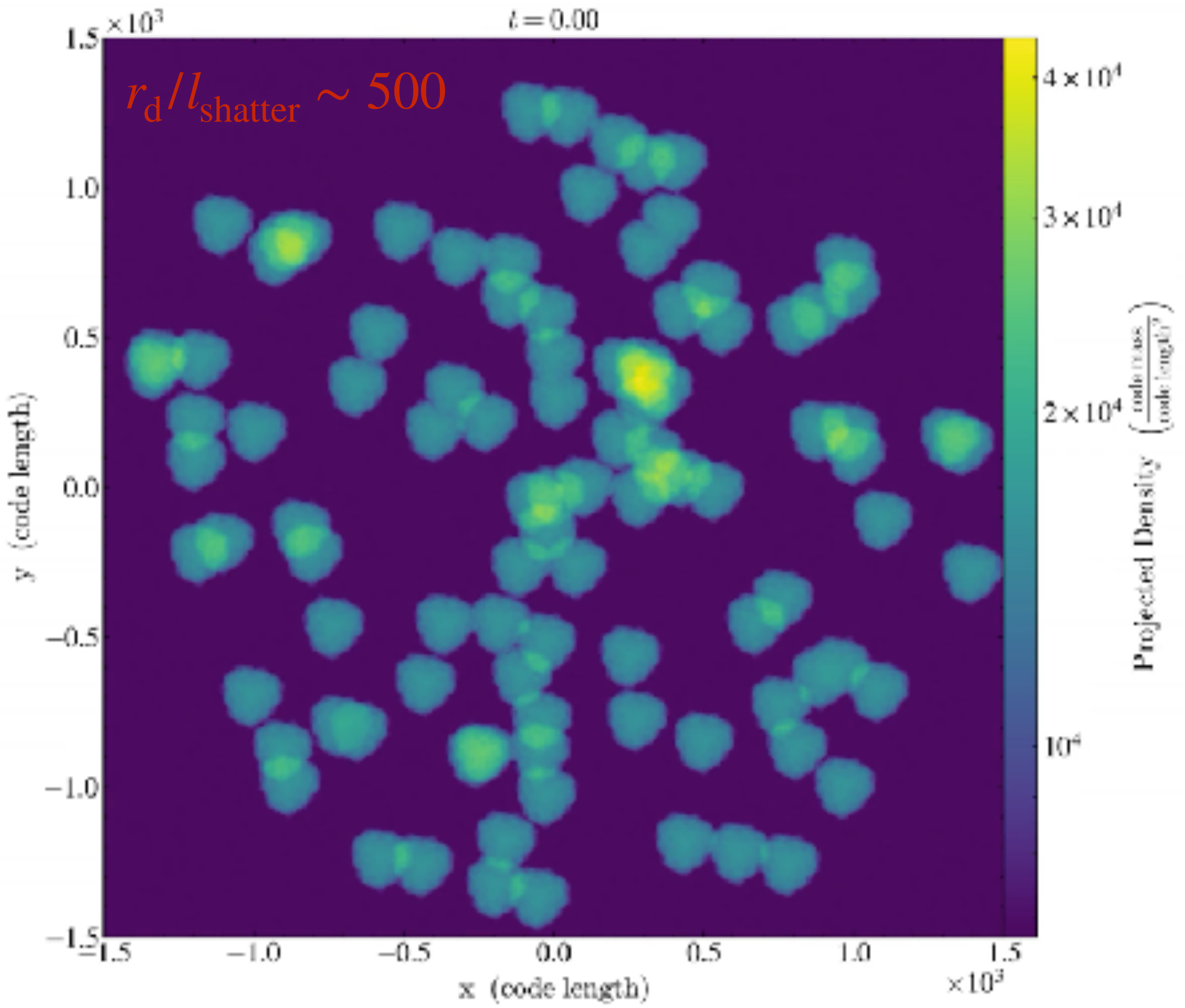
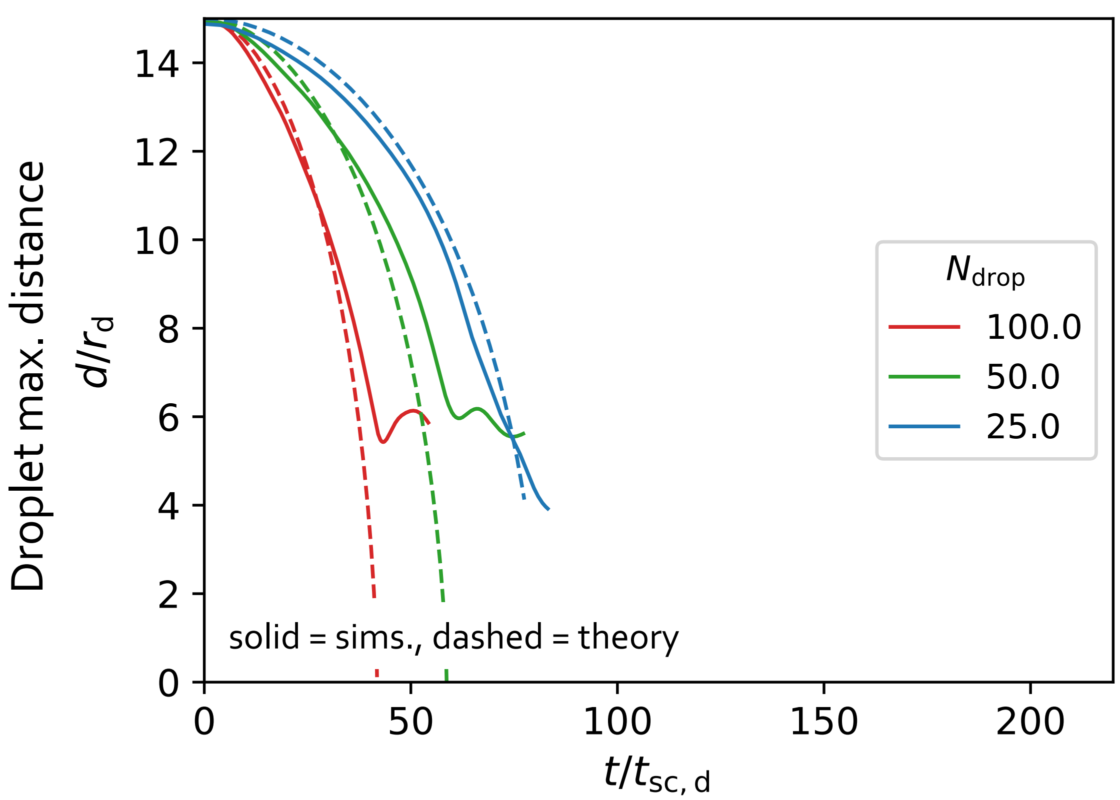
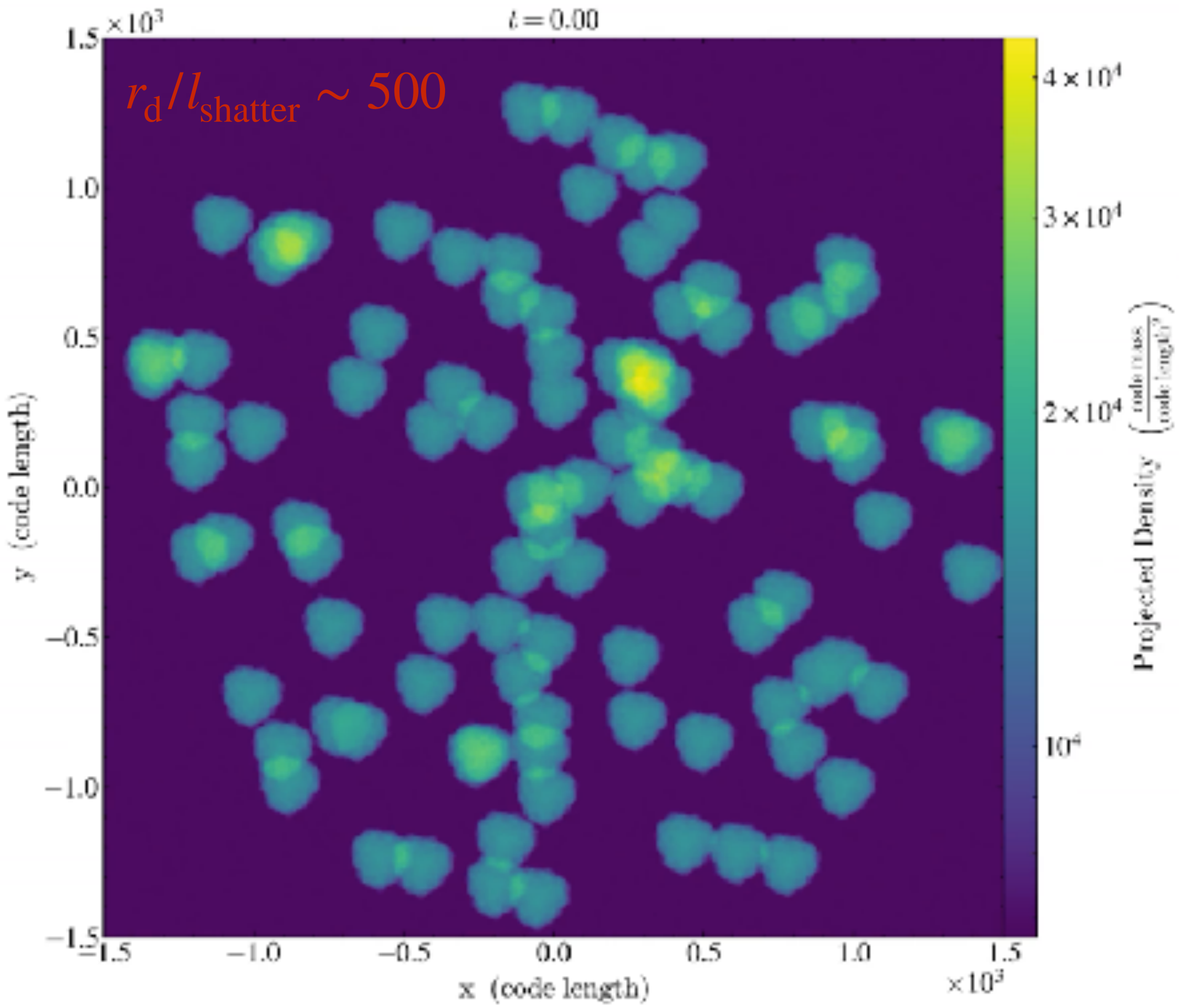
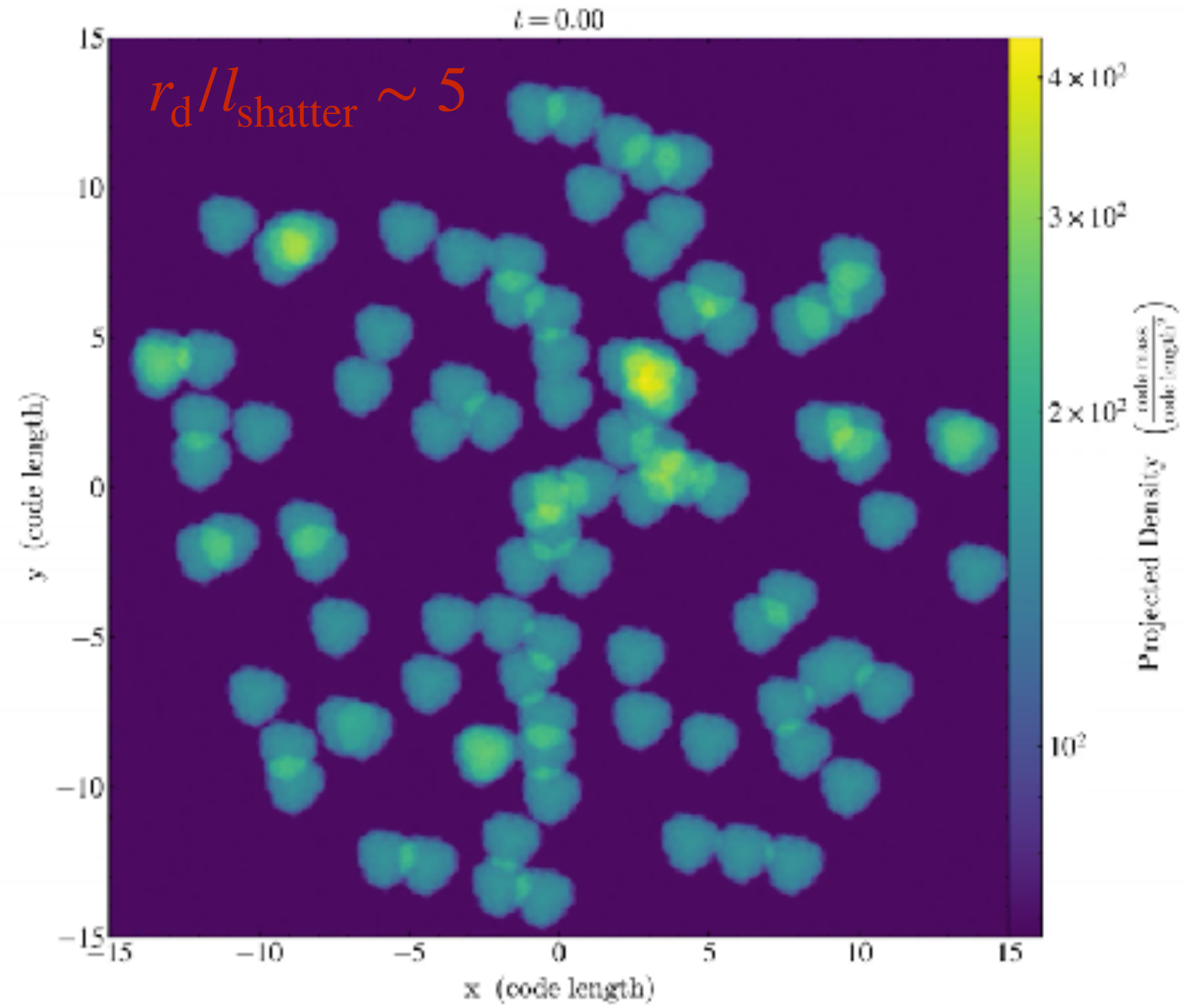
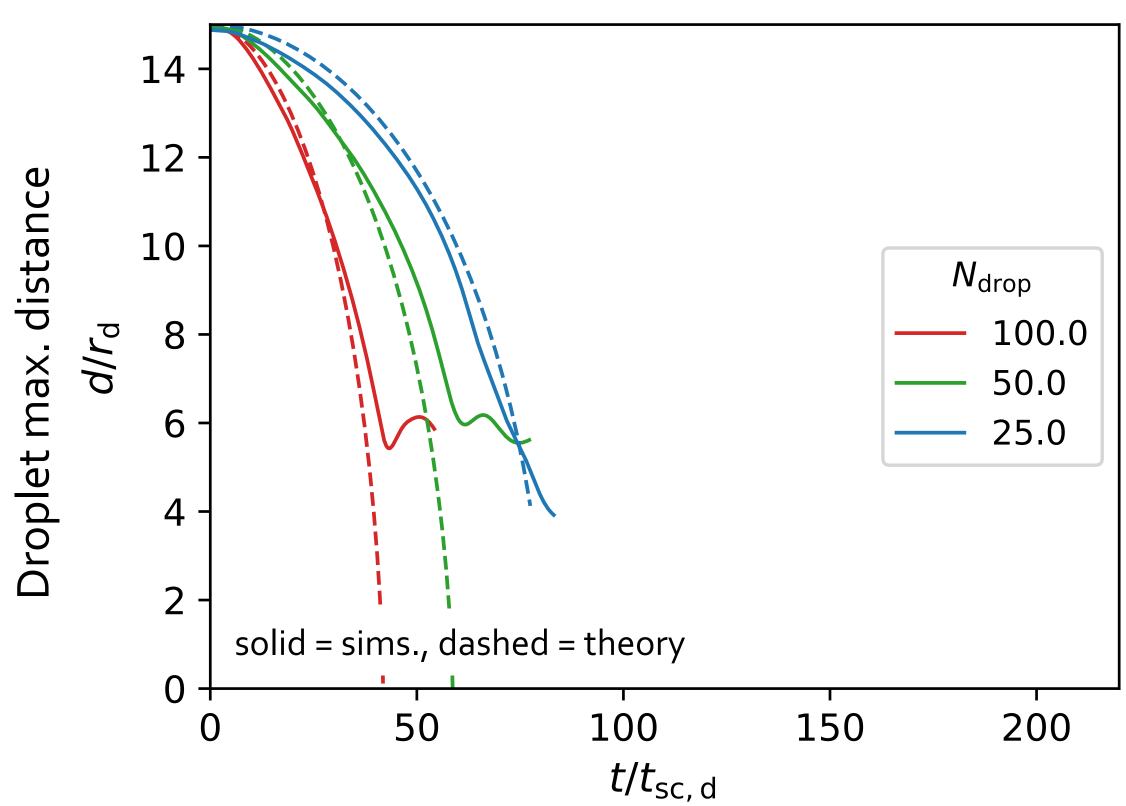




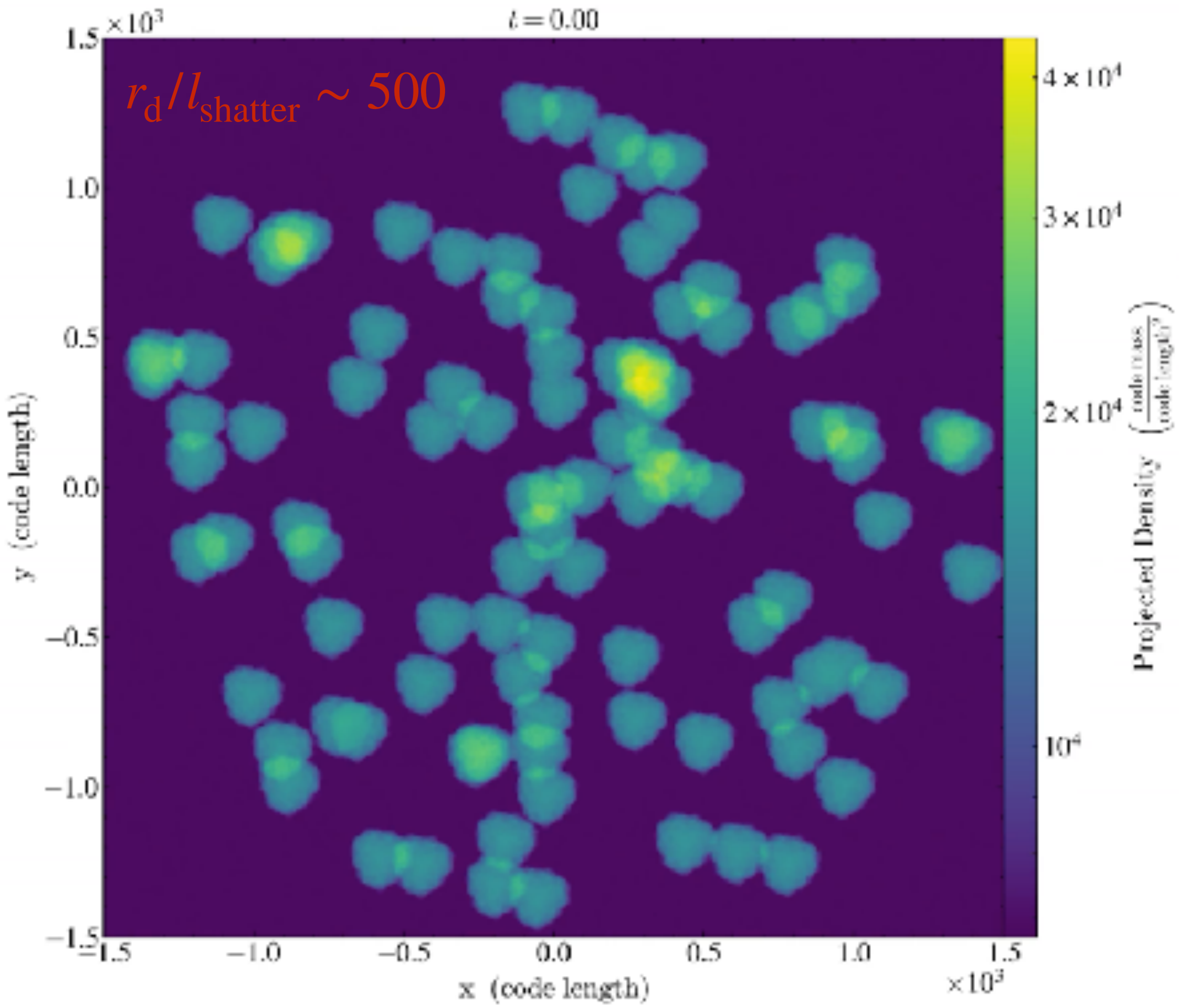
Many droplet coagulation (3D)

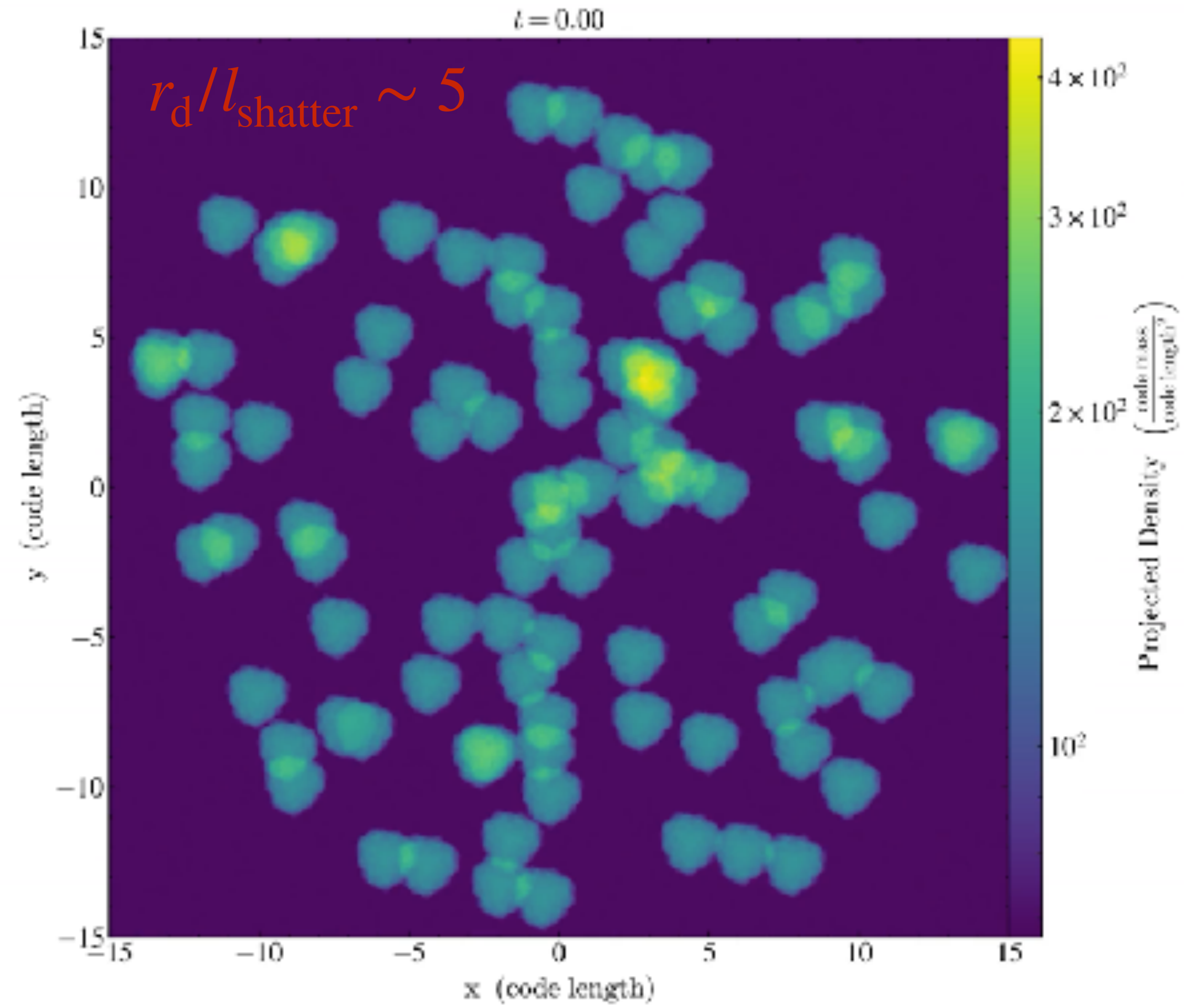


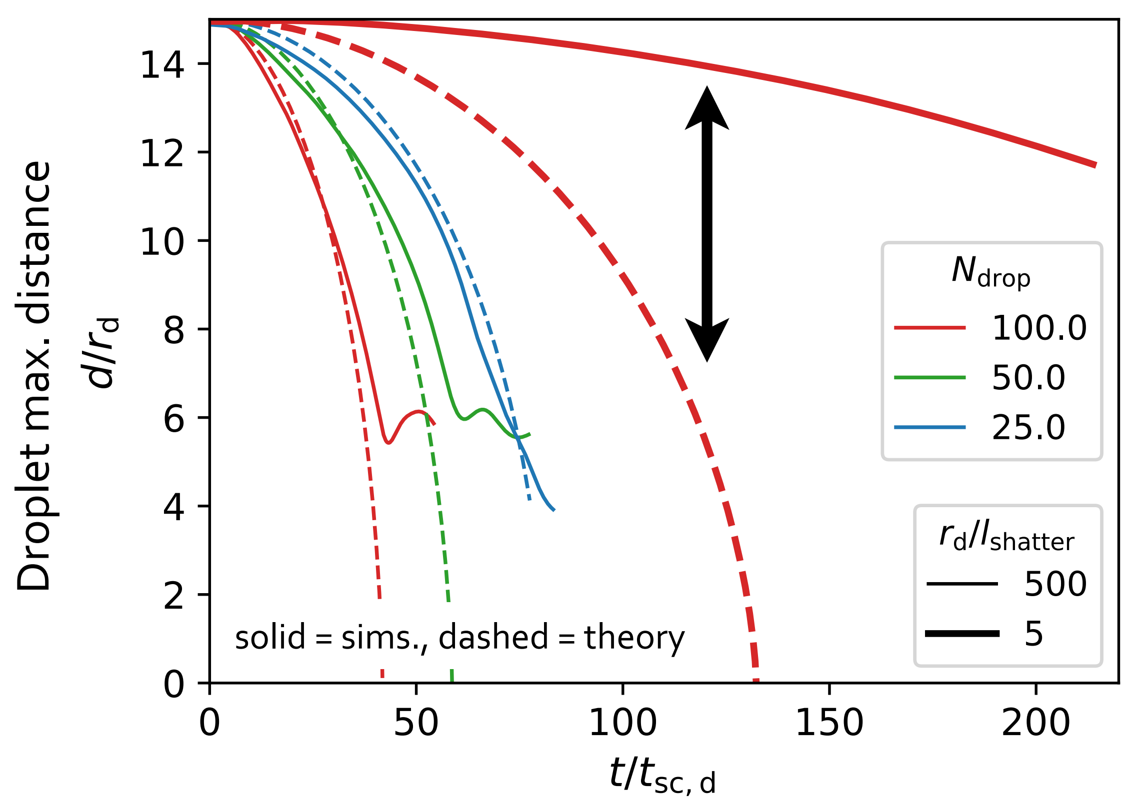




Many droplet coagulation (3D)







no pulsations

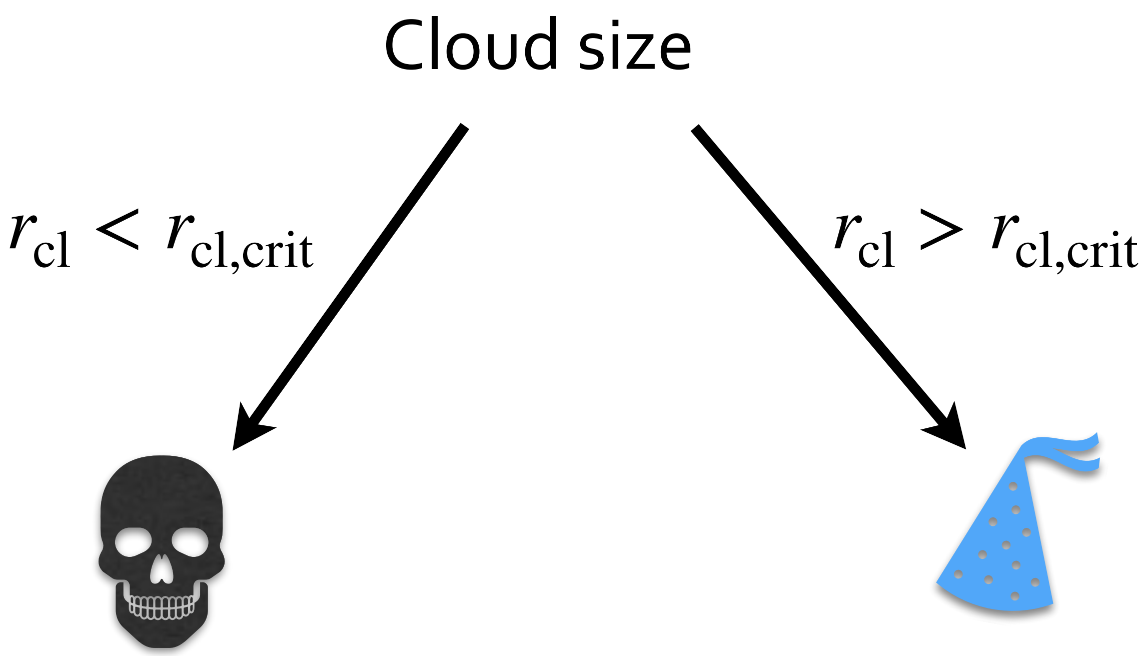
=

less cooling

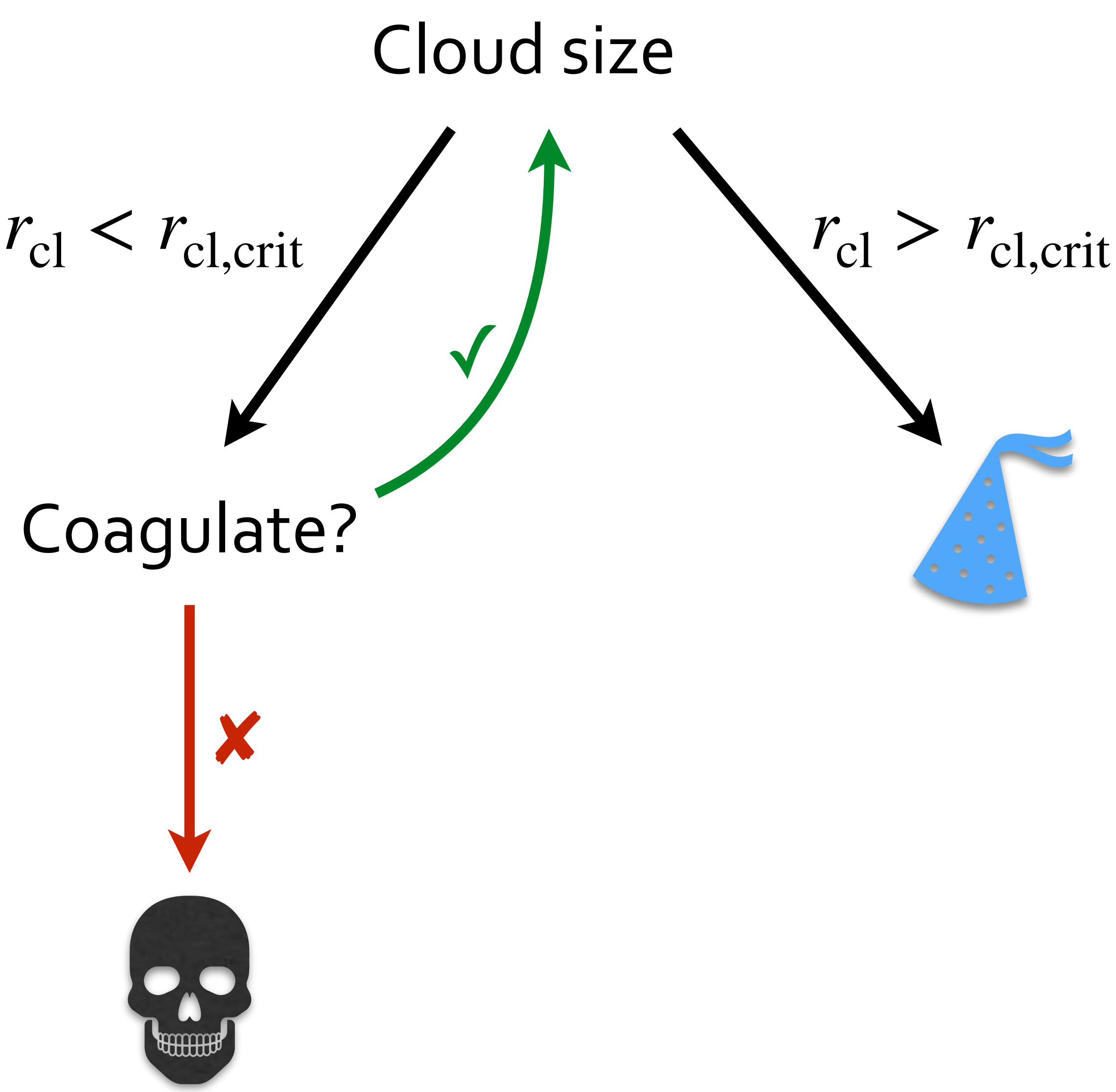
=

slower coagulation

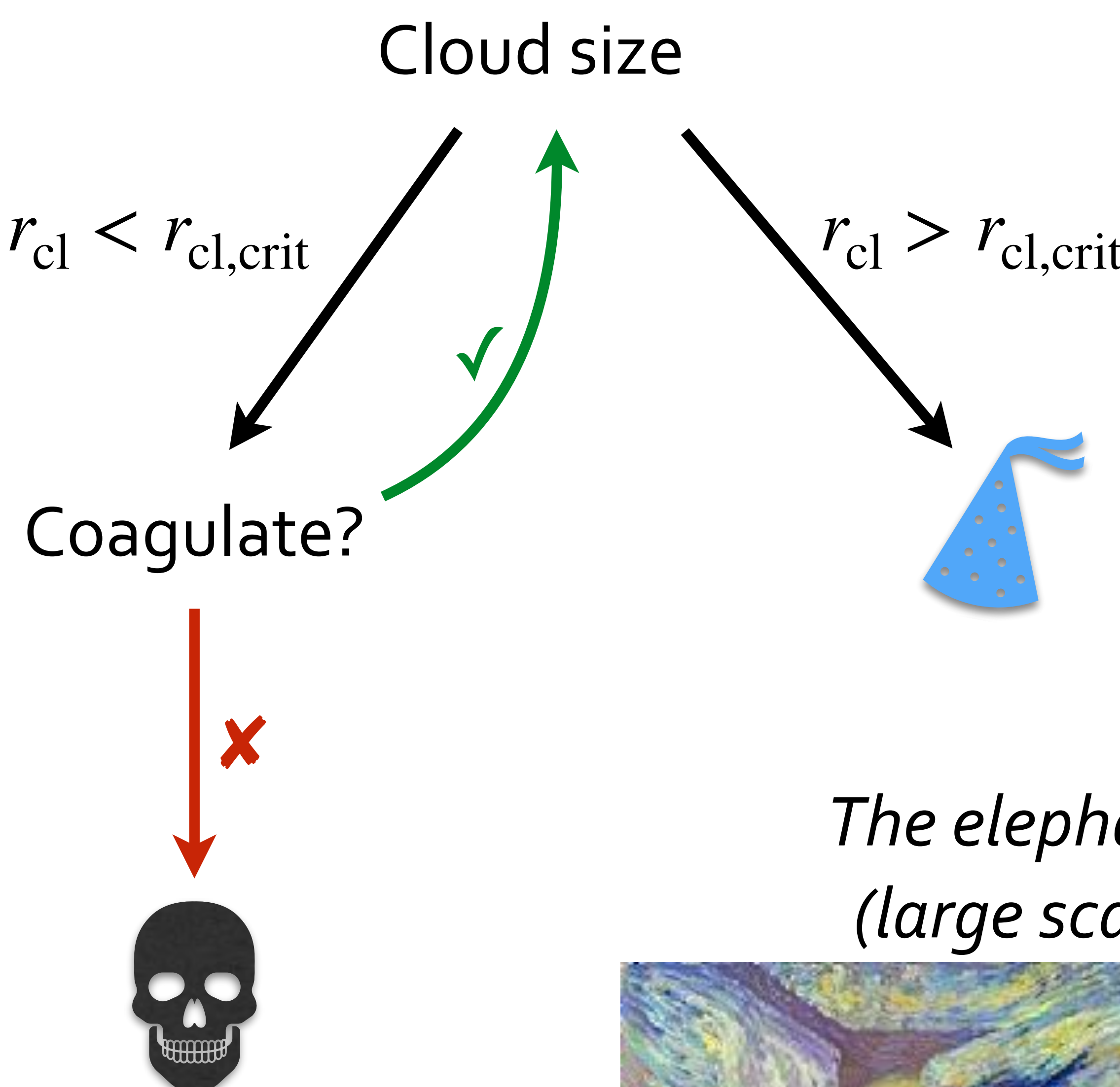
Can coagulation save the doomed?



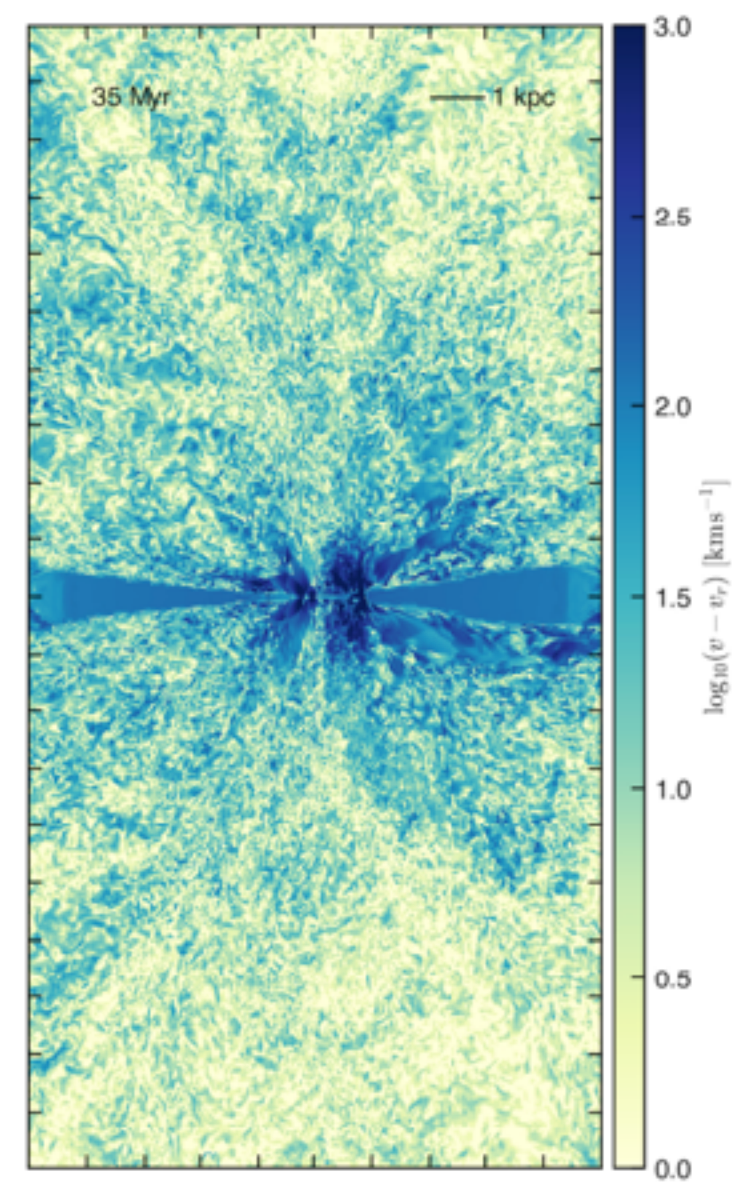
Can coagulation save the doomed?



Can coagulation save the doomed?



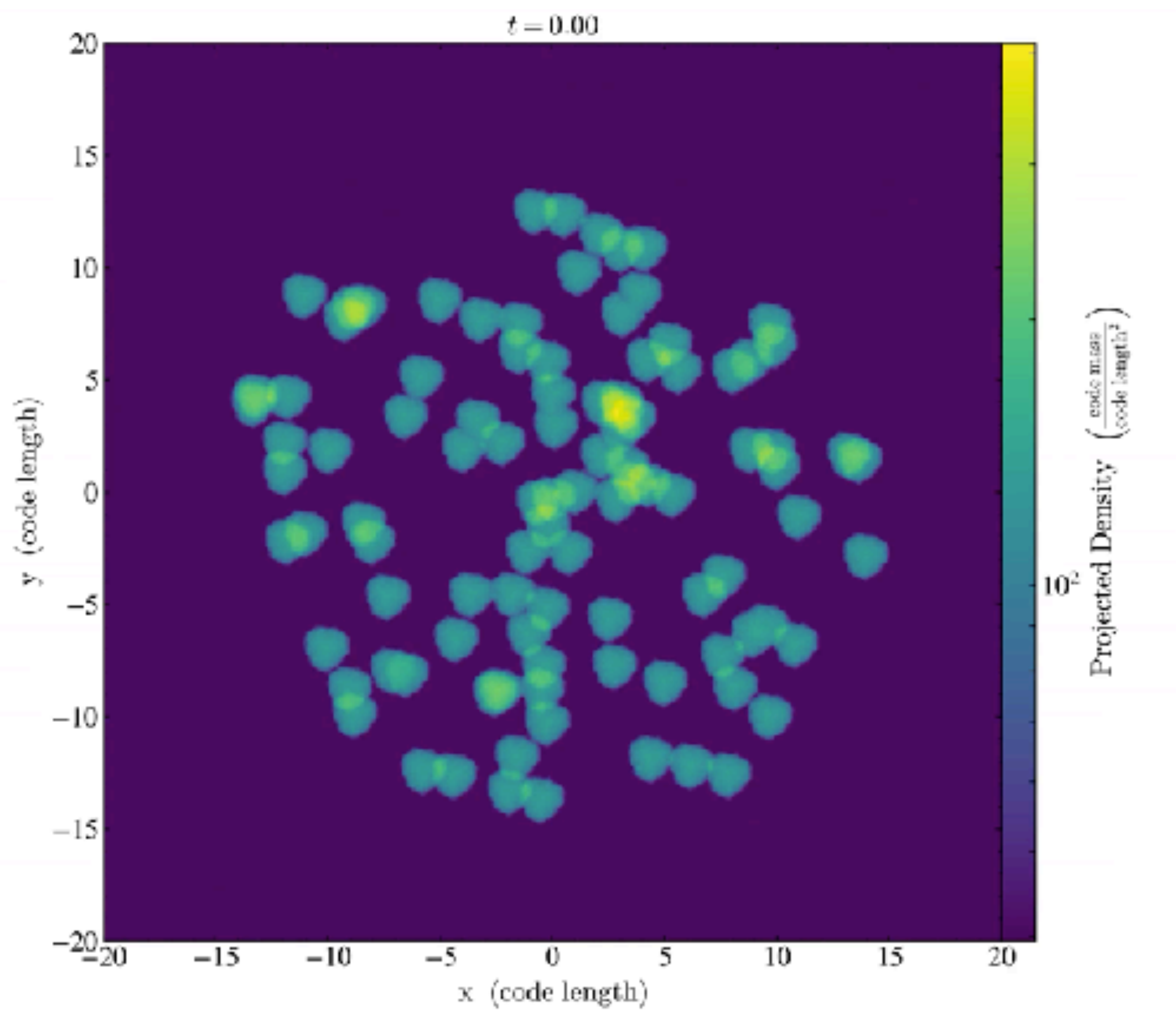
The elephant in the room:
(large scale) turbulence!

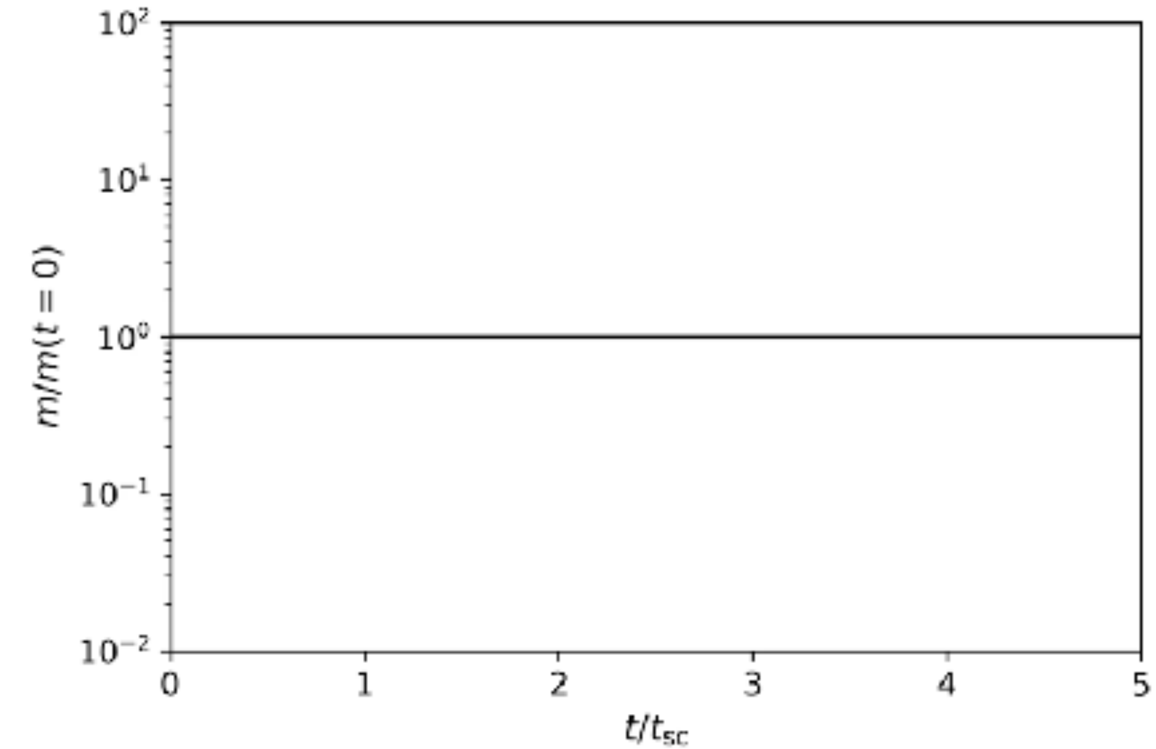


Schneider et al. (2020)

Can coagulation save the doomed?

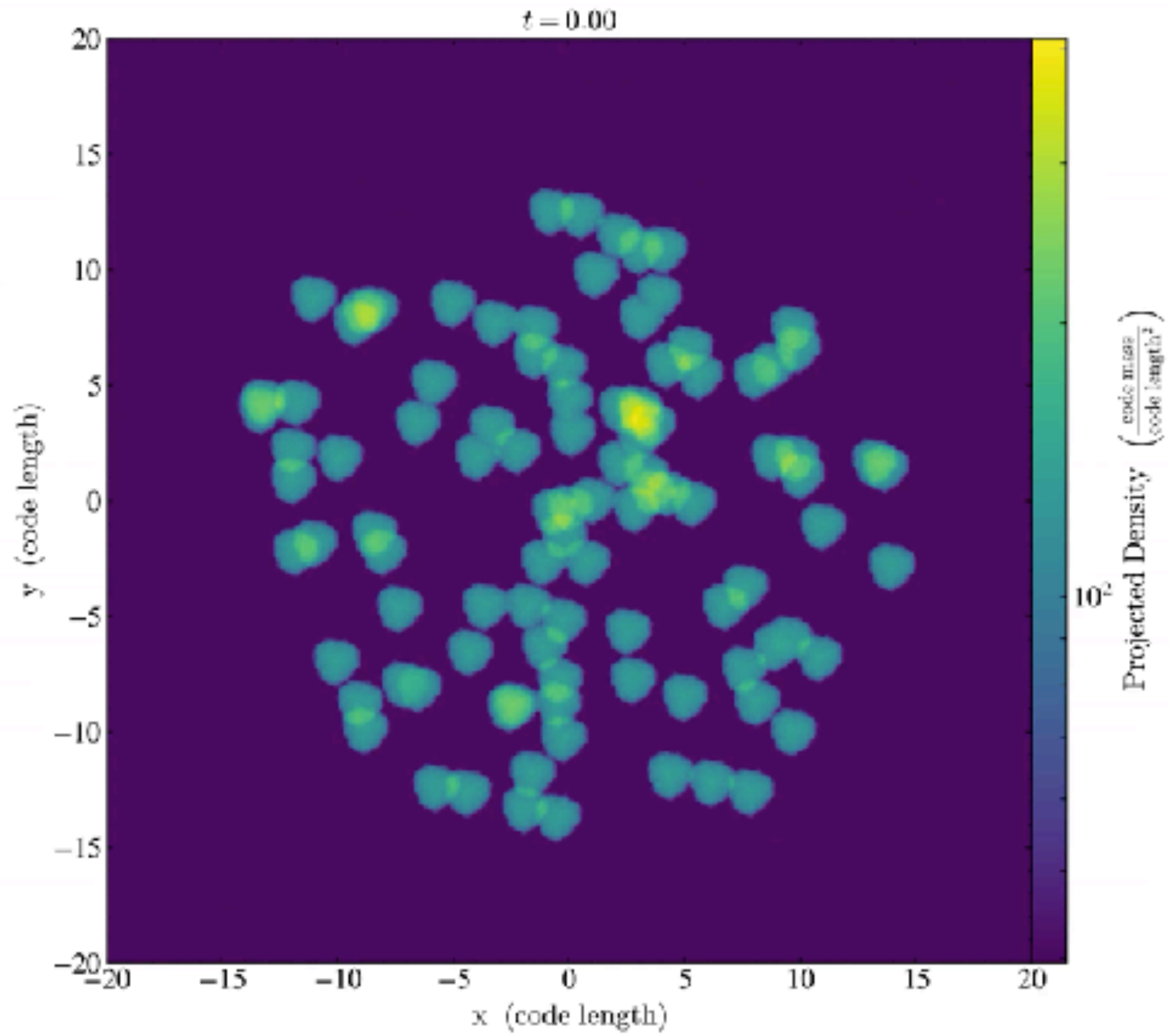
$\chi \sim 100, \mathscr{M}_{\rm turb} \sim 1, r_{\rm cl} \sim 0.5 r_{\rm cl,crit}$

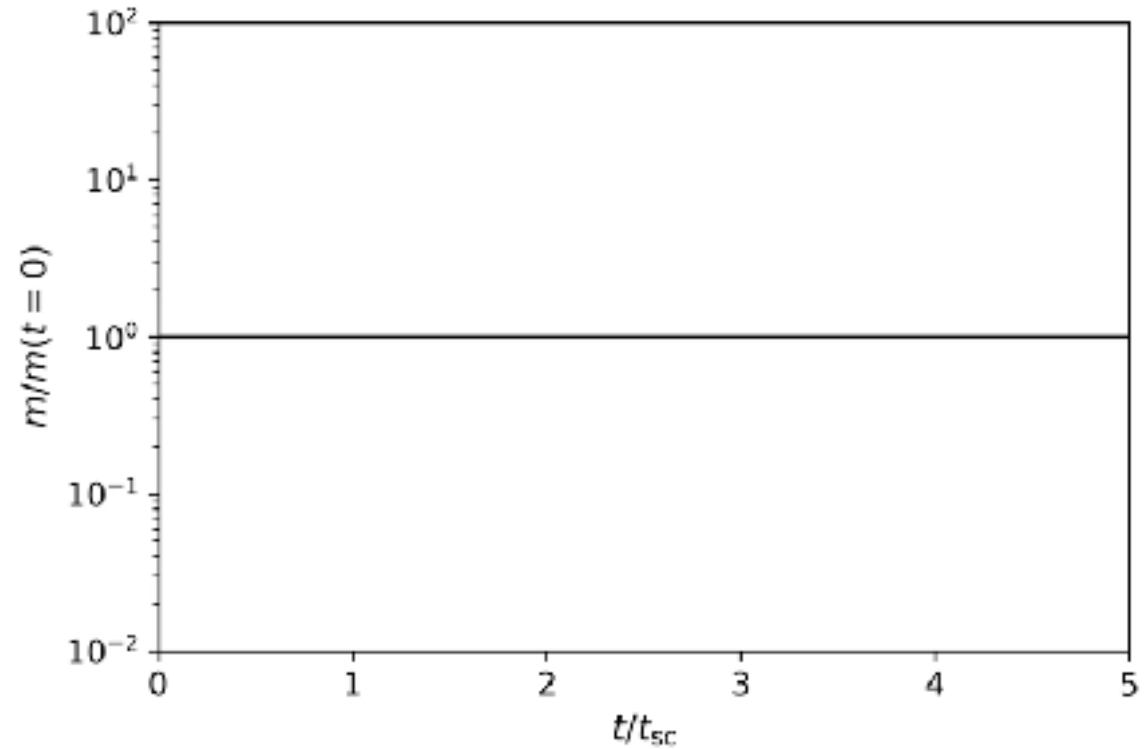




Can coagulation save the doomed?

$$\chi \sim 100, \mathscr{M}_{\mathrm{turb}} \sim 1, r_{\mathrm{cl}} \sim 0.5 r_{\mathrm{cl,crit}}$$





Can coagulation save the doomed?

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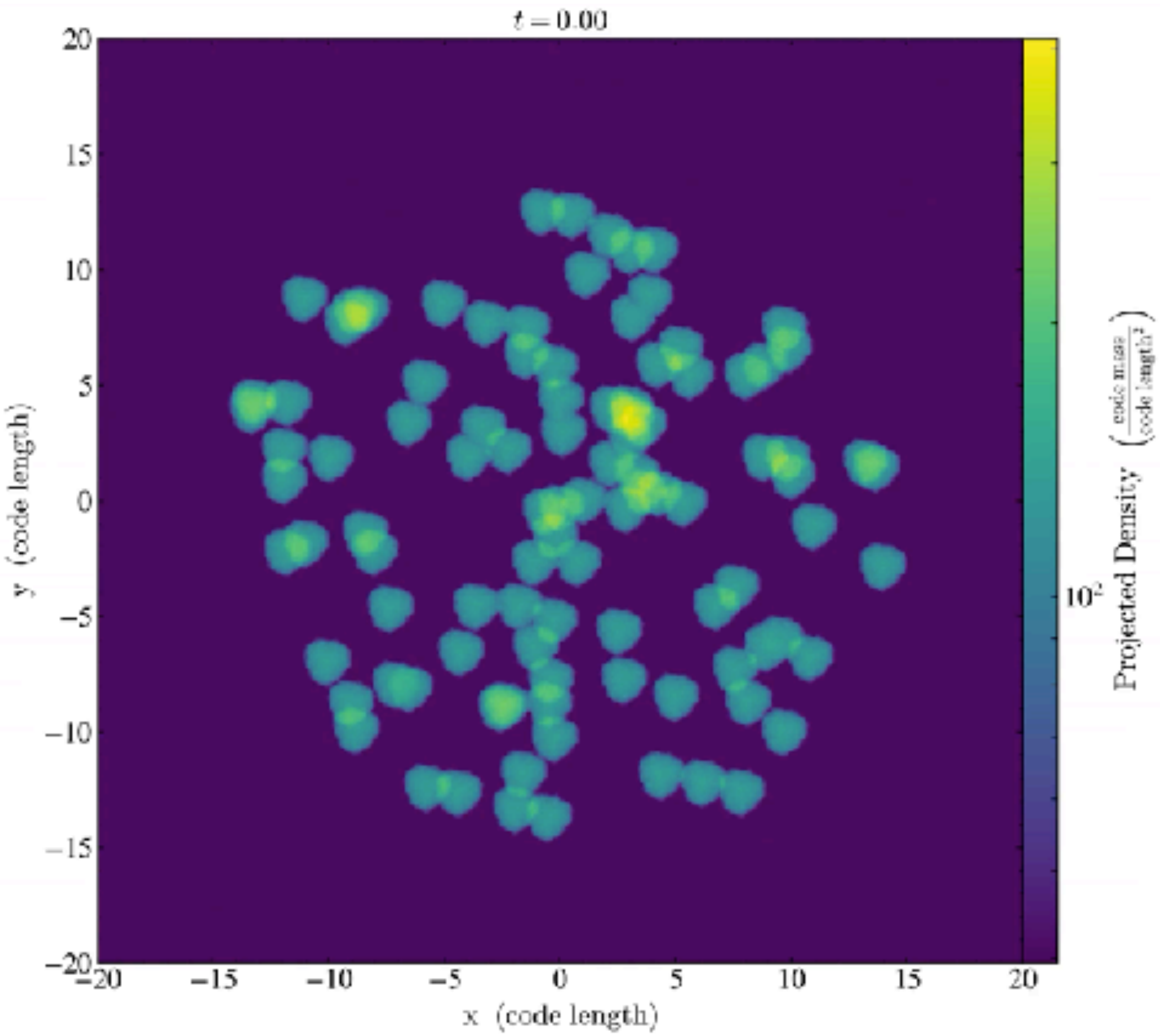
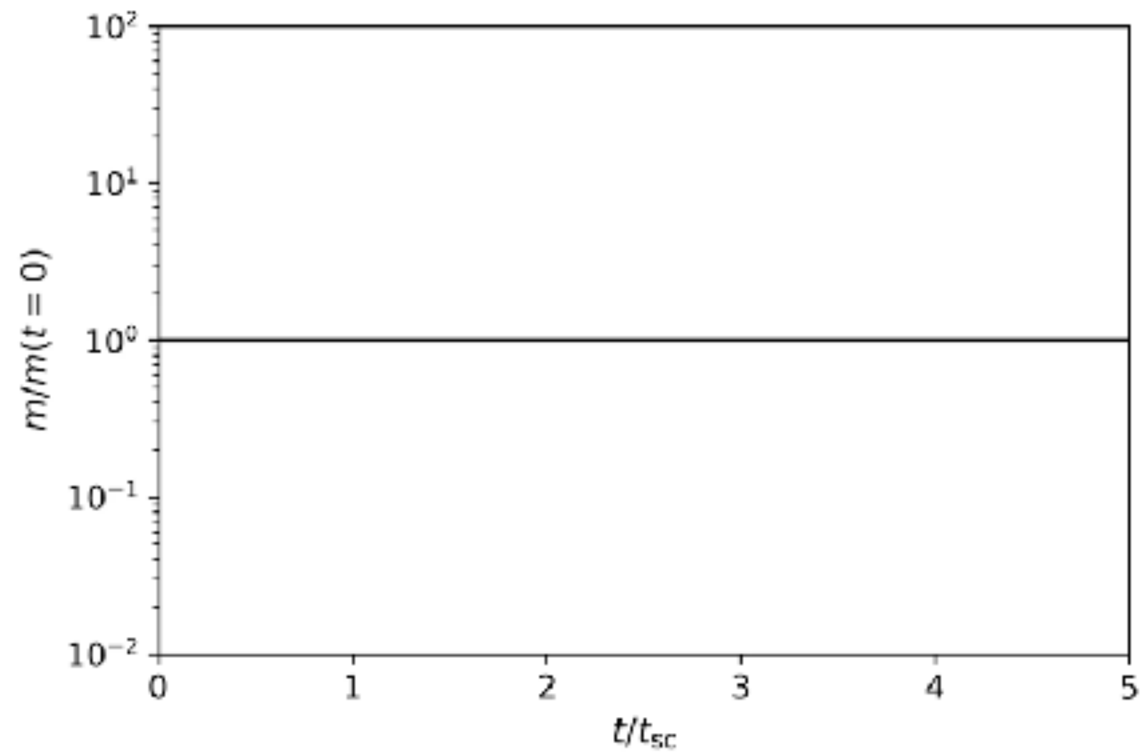
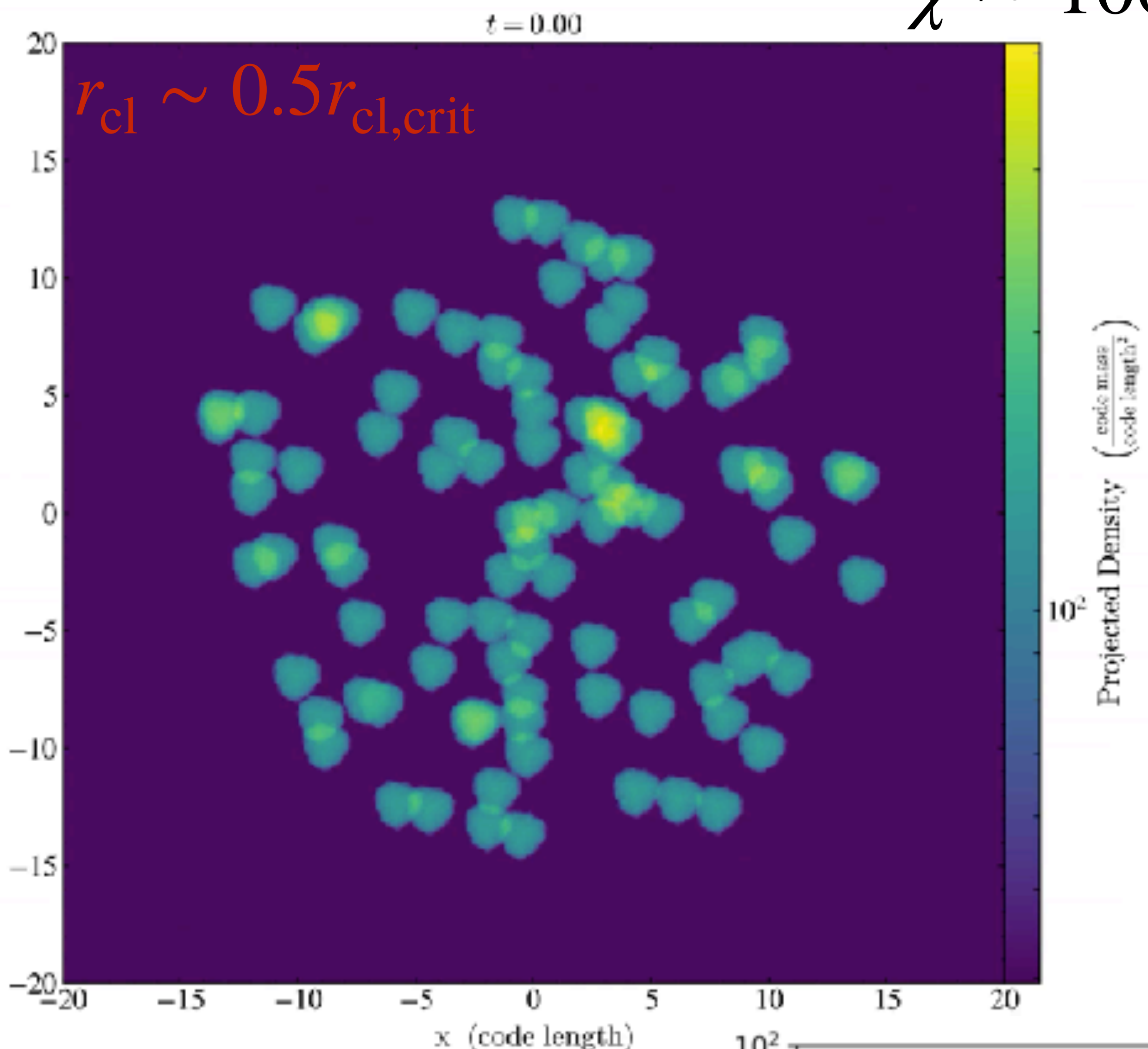


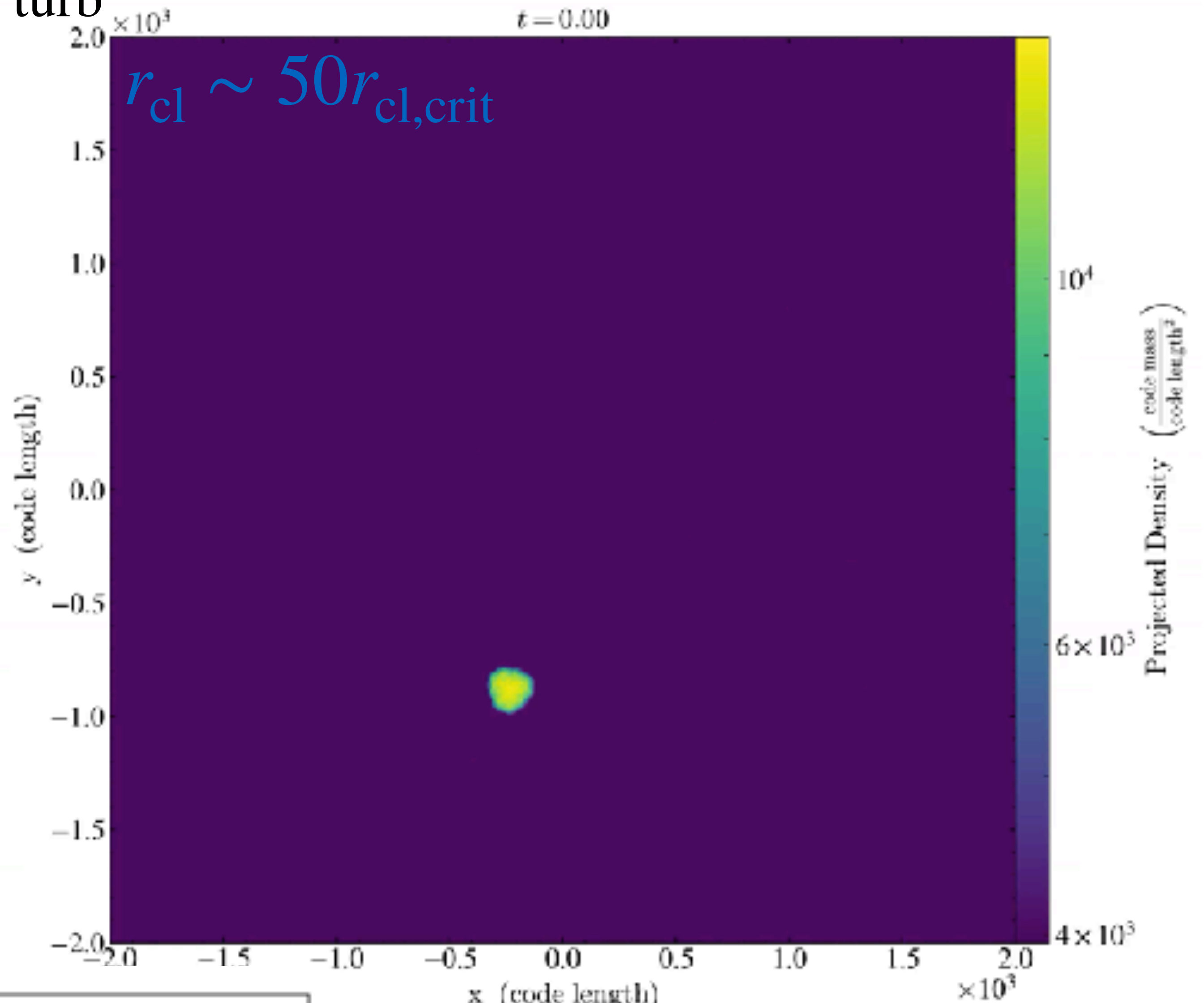


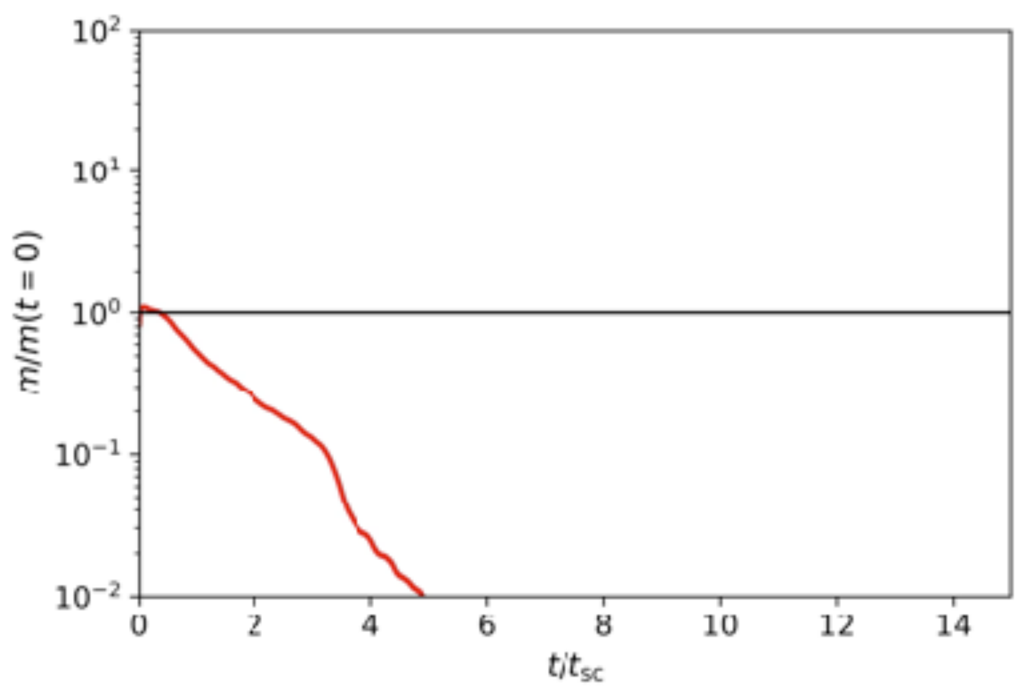
→ Only if $v_{\rm turb} \lesssim v_{\rm coag} \sim c_{\rm s,c}(\bar{d}/r_{\rm cl})^2$,i.e., only in quiescent regions.

So: cajón or fiestón?

$\chi \sim 100, \mathscr{M}_{\rm turb} \sim 1$







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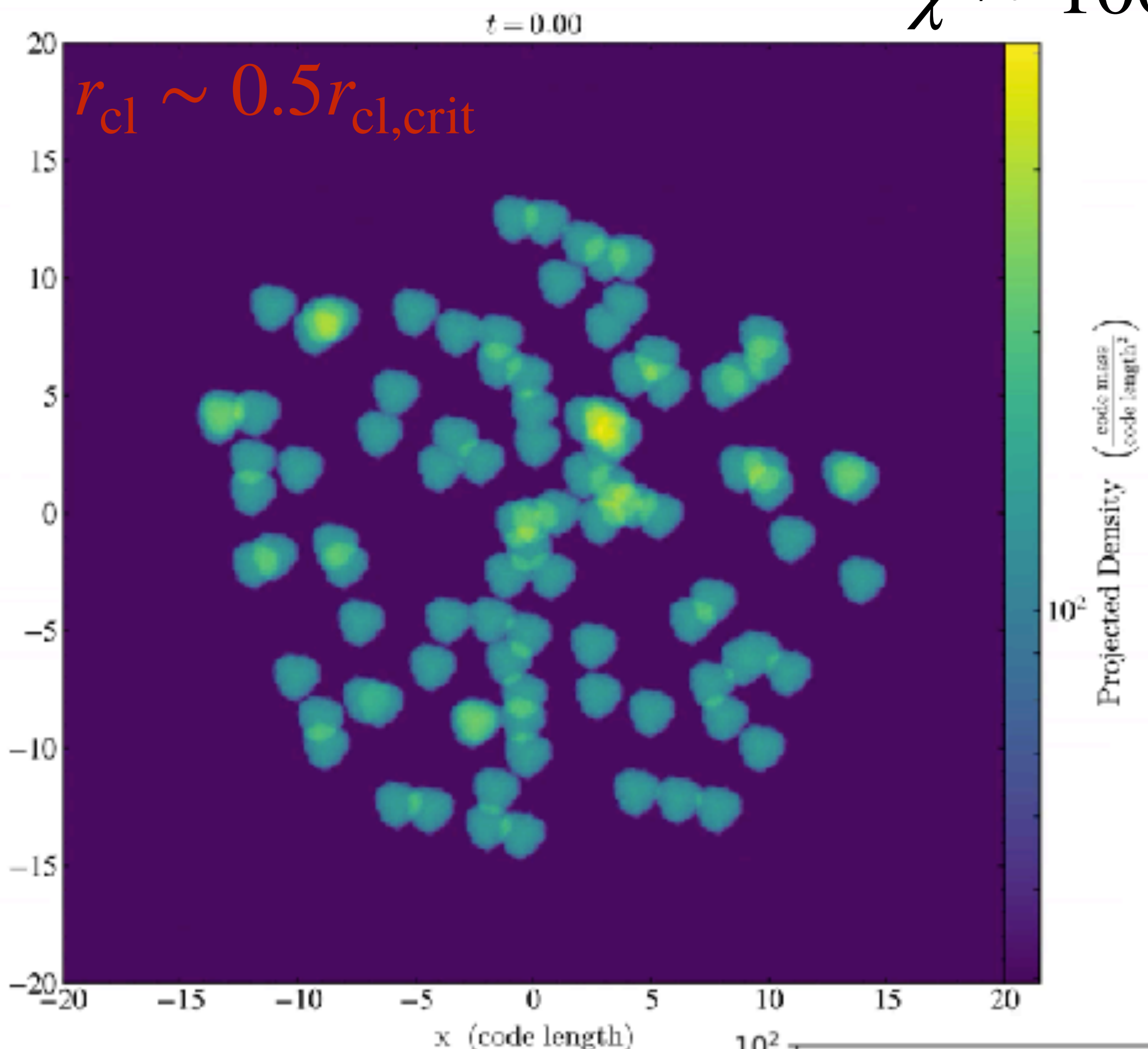

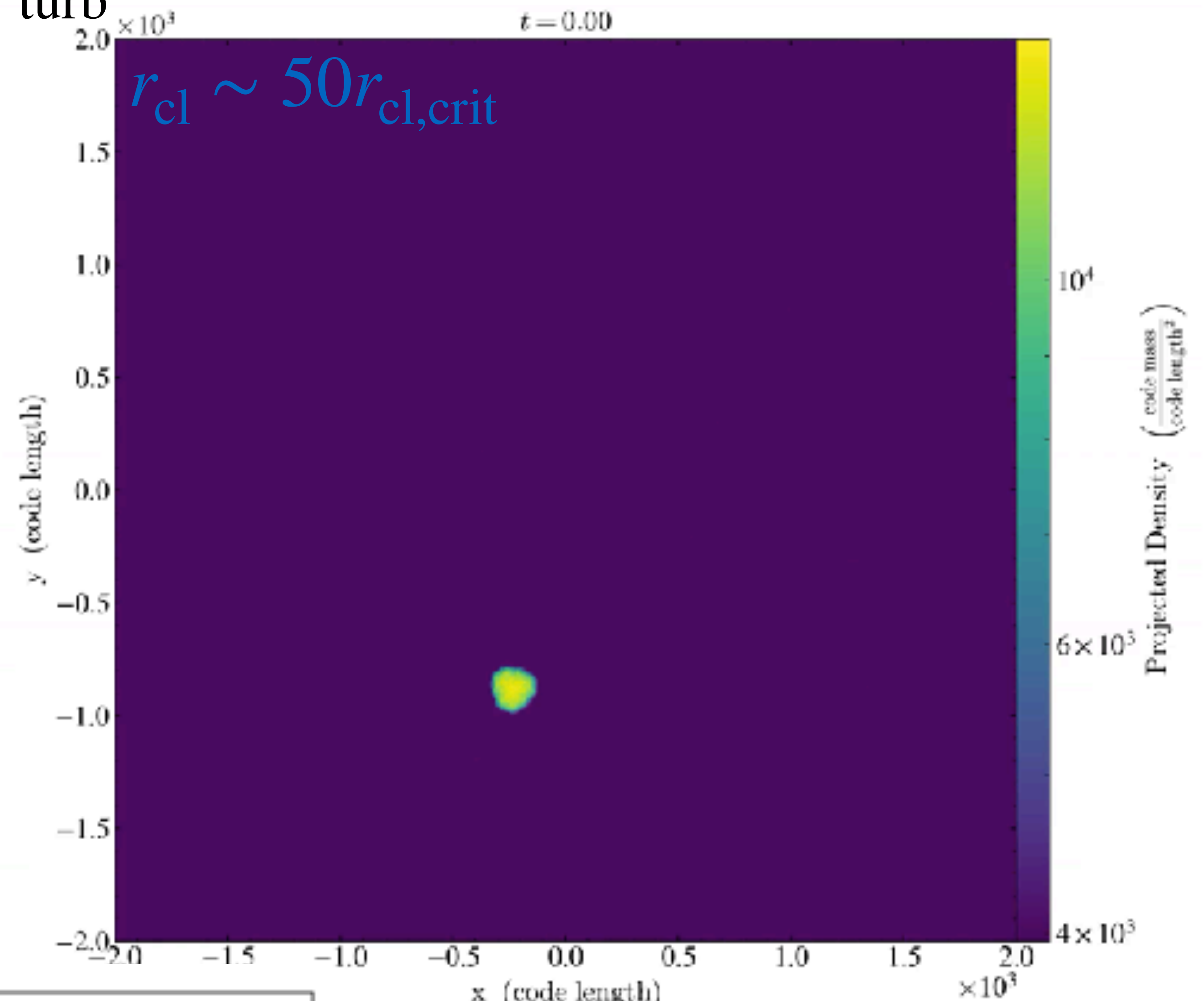

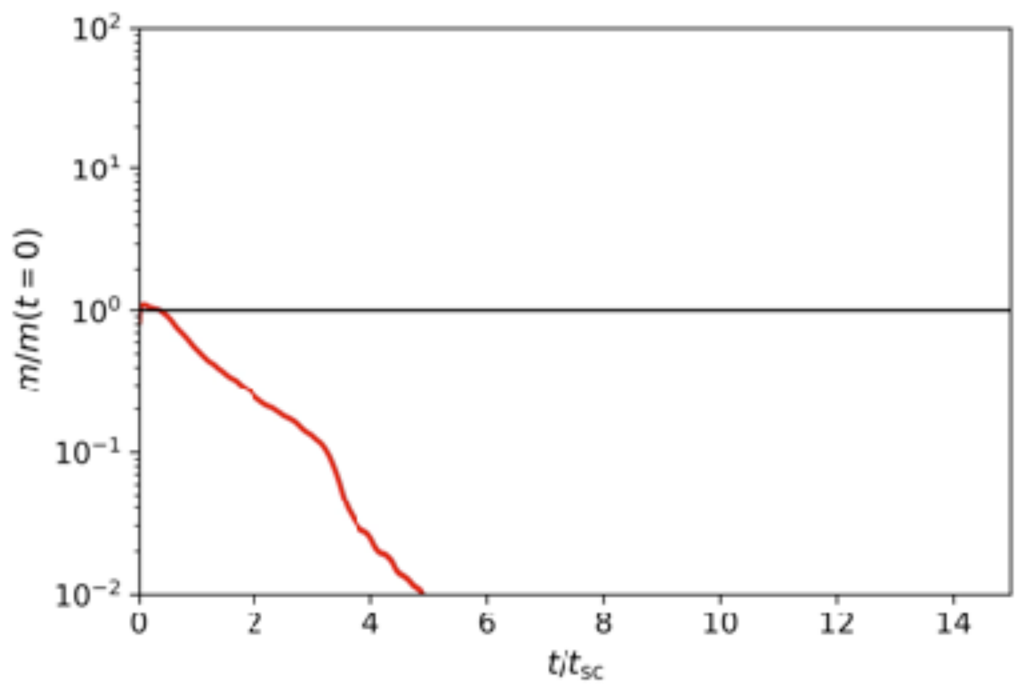

Take away points

$t_{\mathrm{cool,mix}}/t_{\mathrm{cc}} \lesssim 1 \Leftrightarrow r_{\mathrm{cl}}/r_{\mathrm{cl,crit}} \gtrsim 1$
survival criterion also in turbulent media.

Cooling induced mass growth has many implications and is backed up by theory & experiments of mature field of turbulent combustion.

Coagulation inefficient but sets barrier between shattering and pulsation.