Dynamics of a turbulent, multiphase medium (via Zoom) 😭😭😭

Max Gronke
Max Planck Institute for Astrophysics

The multiphase ICM

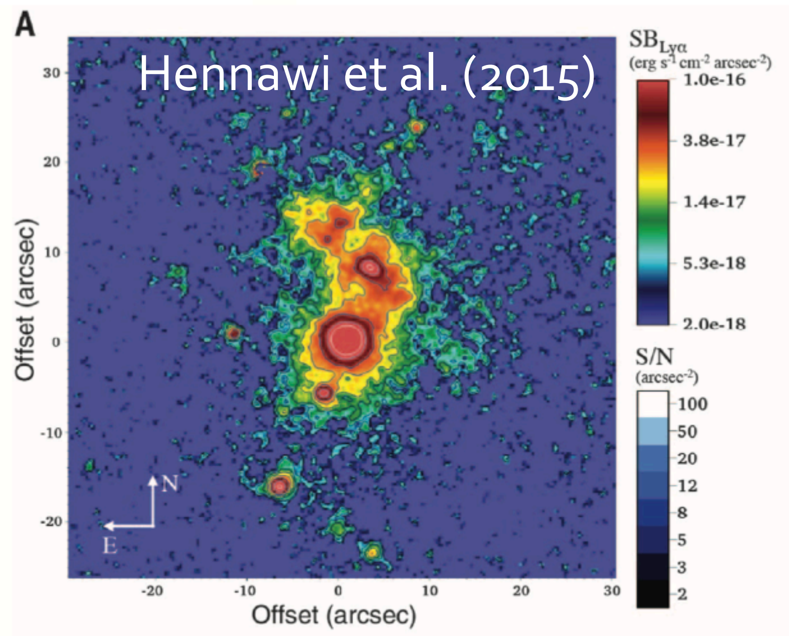
Fabian et al. (2008)

Under which conditions does a multiphase ICM develop?

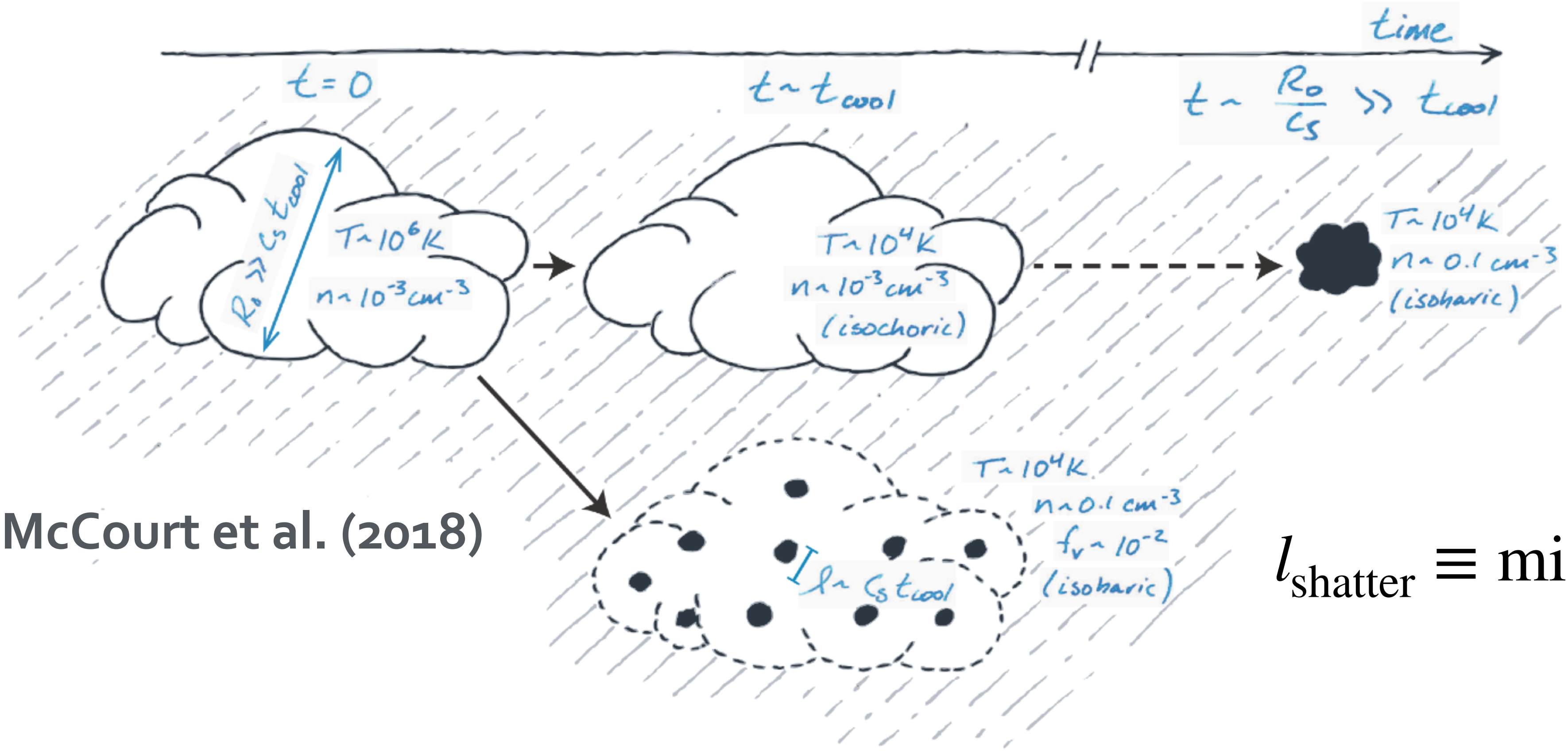
What are the characteristics of the multiphase ICM?
(this talk)

The “shattering” scale

From observations: $f_\mathrm{A} \sim 1, f_\mathrm{V} \ll 1$

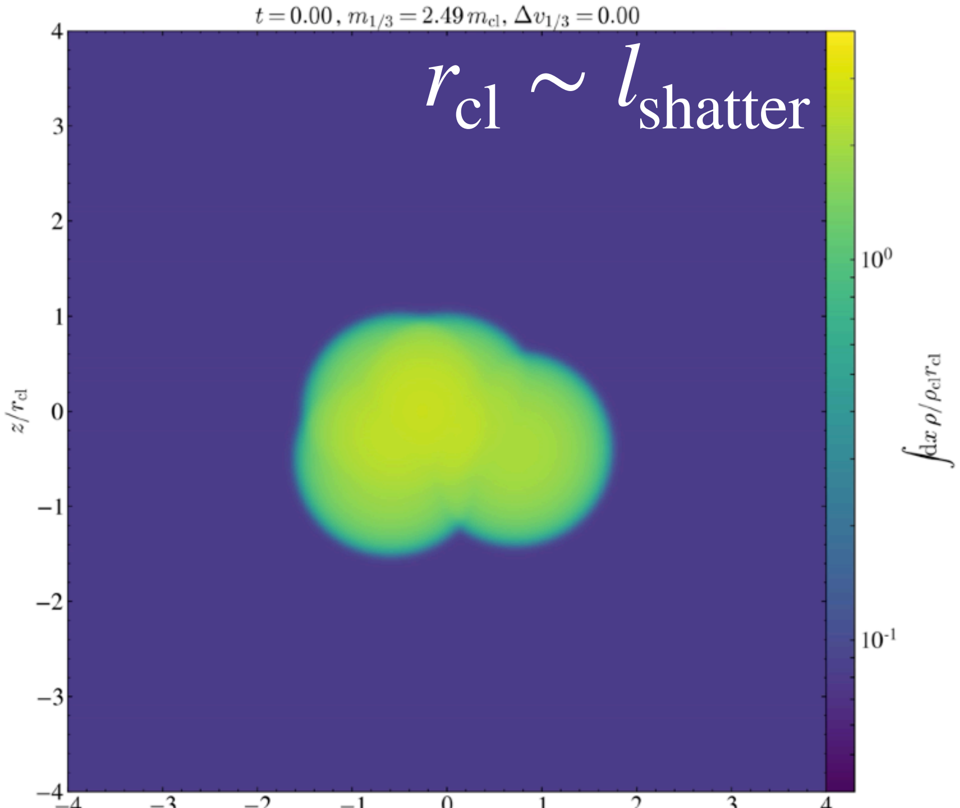


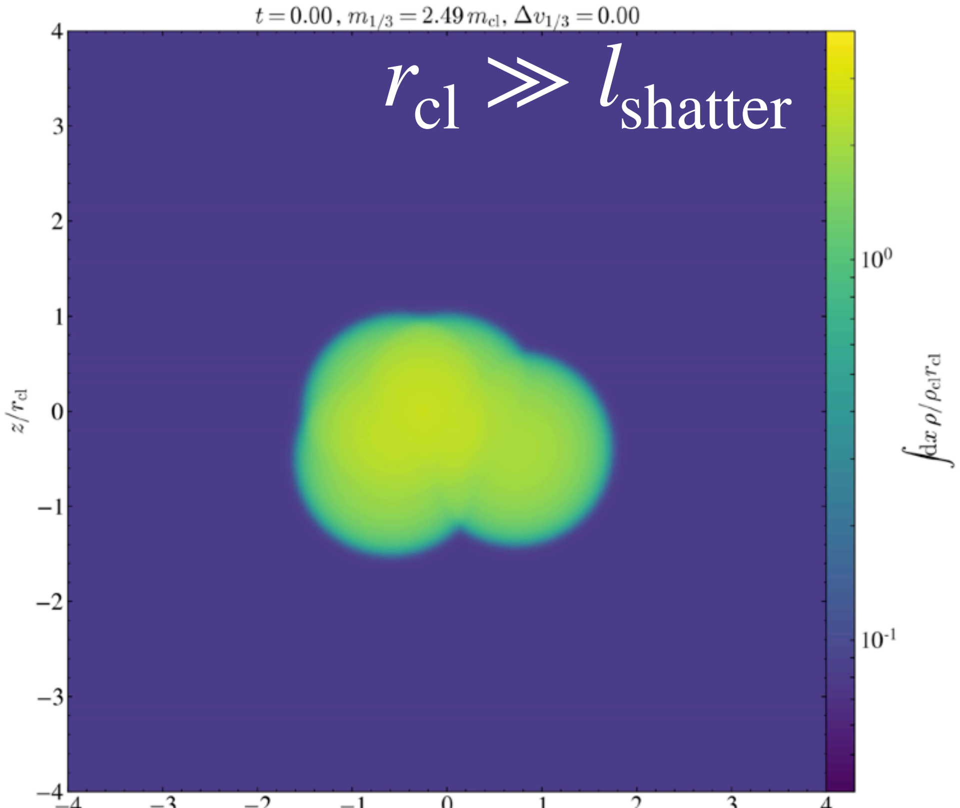
Hennawi et al. (2015)



McCourt et al. (2018)

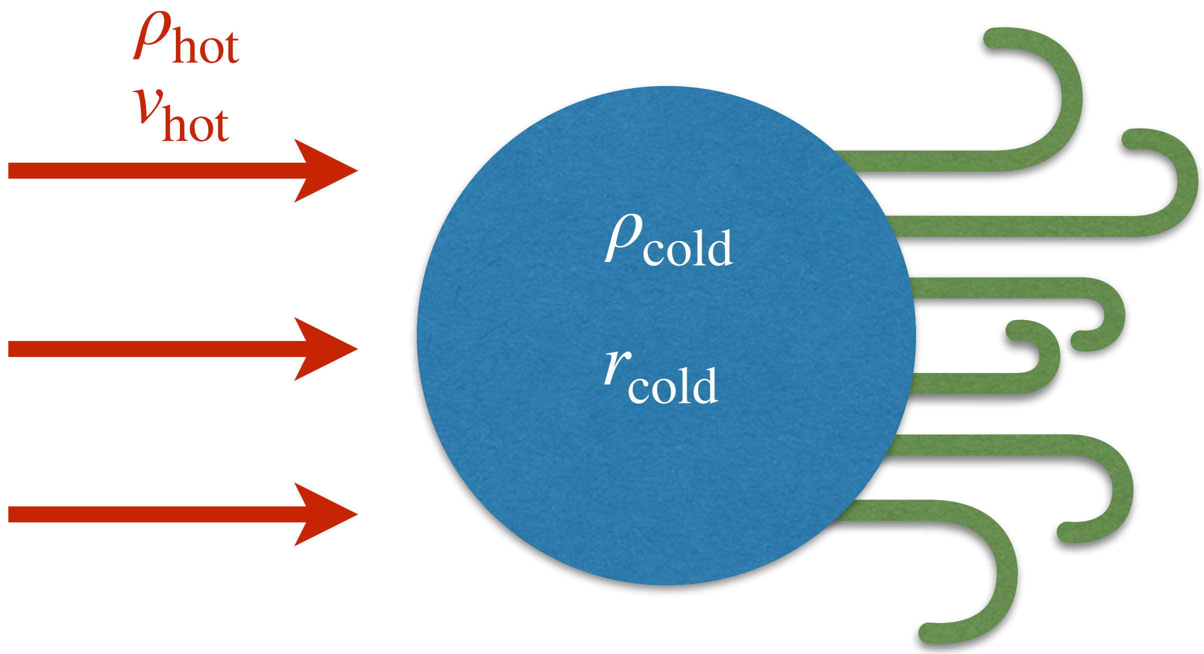
$$l_\mathrm{shatter} \equiv \min(c_\mathrm{s} t_\mathrm{cool}) \sim 0.1 n_1^{-1}\,\mathrm{pc}$$





MG & Oh (2020)

The “survival length”



Destruction timescale

$$t_{\rm destroy} \sim \chi^{1/2}\frac{r_{\rm cold}}{v_{\rm hot}} \ll t_{\rm drag} \sim \chi\frac{r_{\rm cold}}{v_{\rm hot}}$$

with $\chi \equiv \dfrac{\rho_{\rm cold}}{\rho_{\rm hot}}$

Mixed gas properties

$$T_{\rm mix} \sim \sqrt{T_{\rm hot}T_{\rm cold}}$$
$$n_{\rm mix} \sim \sqrt{n_{\rm hot}n_{\rm cold}}$$

Begelman & Fabian (1990)

Cooling time of *mixed* gas

$$\Rightarrow t_{\rm cool,mix} \sim 10 t_{\rm cool,cold}\frac{\chi}{100}\frac{\Lambda(T_{\rm mix})/\Lambda(T_{\rm cold})}{0.1}$$

Require $t_{\rm cool,mix} < t_{\rm destroy}$ ***for cold gas survival!***

MG & Oh (2018,2020)

$$\Updownarrow$$

$$r_{\rm cold} > r_{\rm crit} \equiv \frac{v_{\rm hot}t_{\rm cool,mix}}{\chi^{1/2}}$$
$$\approx 2\,{\rm pc}\frac{T_{\rm cold,4}\mathscr{M}}{P_3\Lambda_{\rm mix,-21.4}}\frac{\chi}{100}$$

$T_{\rm cold,4} \equiv T_{\rm cold}/(10^4\,{\rm K})$
$\Lambda_{\rm mix,-21.4} \equiv \Lambda(T_{\rm mix})/(10^{-21.4}\,{\rm erg\,cm^3\,s^{-1}})$
$P_3 \equiv nT/(10^3\,{\rm cm^{-3}\,K})$
$\mathscr{M} \equiv v_{\rm hot}/c_{\rm s,hot}$

“Shattering” versus “survival”

Shattering leads naturally to droplets of $r \sim l_{\rm shatter} \equiv \min(c_s t_{\rm cool})$ and $f_A \sim 1, f_V \ll 1$ as supported by observations.

vs.

Only big clumps with $t_{\rm cool,mix}/t_{\rm destroy} < 1 \Leftrightarrow r > r_{\rm crit}$ will survive.

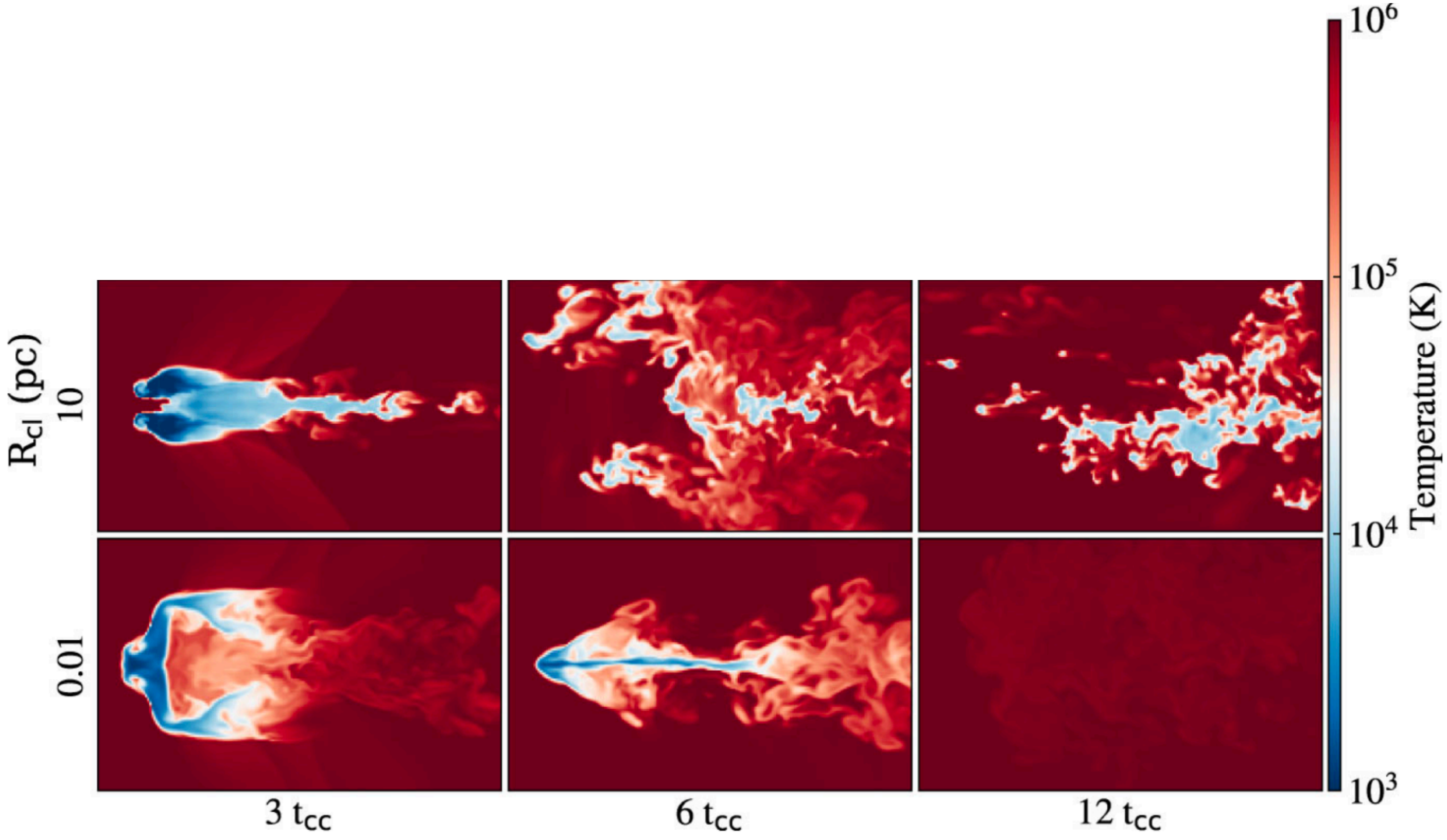
(a little detour)

→*What about the molecular phase?*

Intermezzo: what about colder phases?

Farber & MG (2021)

Molecular gas survival



$$t_{\rm cool,max} < t_{\rm cc}$$

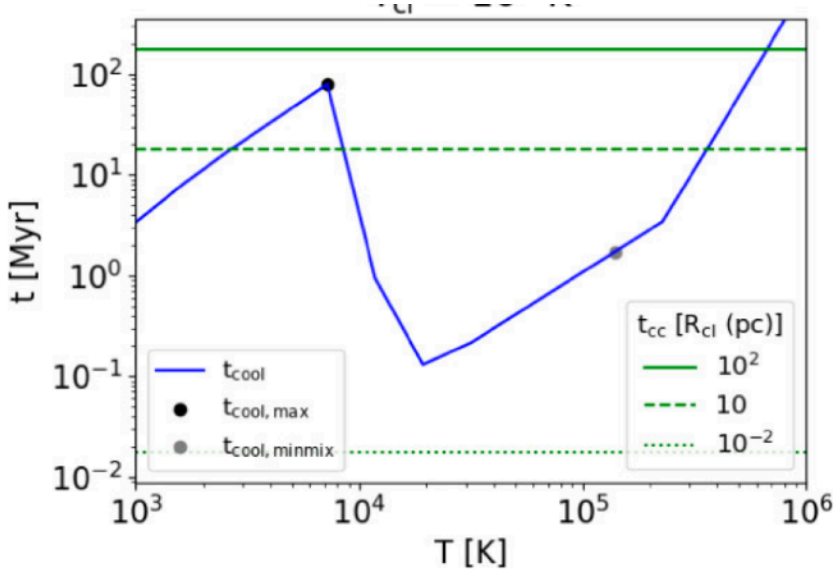
→ $T < 10^4$ K gas survives

$$t_{\rm cool,mix} < t_{\rm cc}$$

→ $T \sim 10^4$ K gas survives

$$t_{\rm cool,mix} > t_{\rm cc}$$

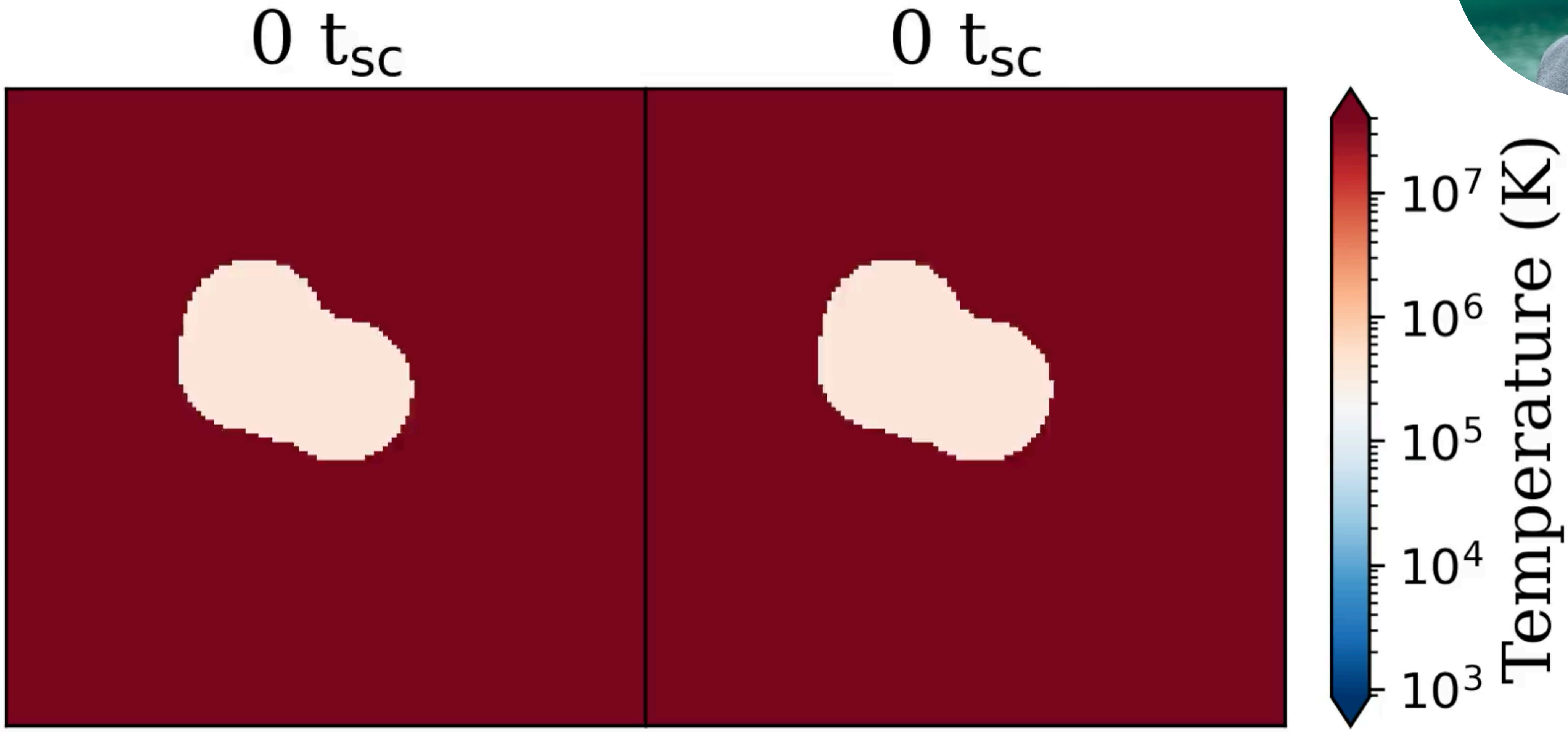
→ $T \sim 10^4$ K gas dies



Intermezzo: what about colder phases?

Farber & MG (in prep)

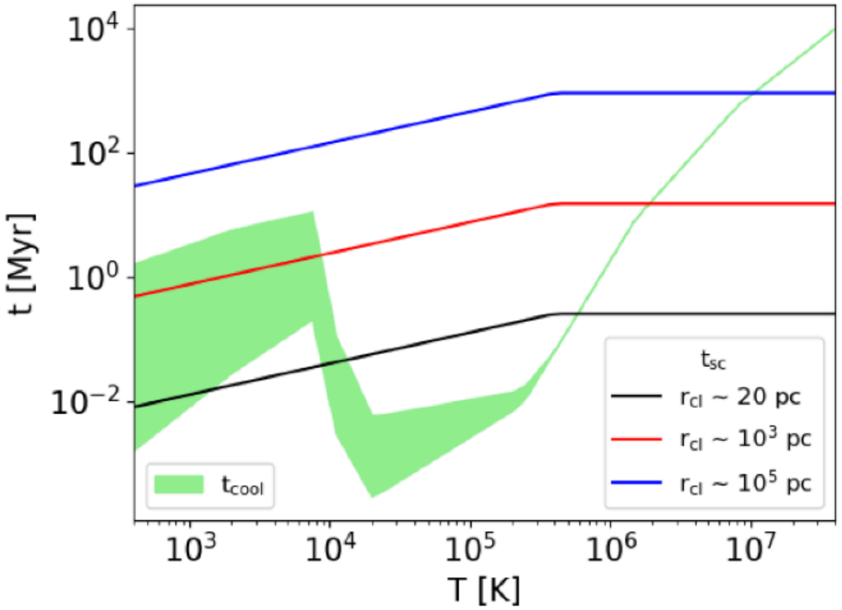
Molecular shattering



$r > \min(c_s t_{\mathrm{cool}})_{T\sim10^4\,\mathrm{K}} \rightarrow T \sim 10^4\,\mathrm{K}$ shattering

$r > \min(c_s t_{\mathrm{cool}})_{T<10^4\,\mathrm{K}} \rightarrow T < 10^4\,\mathrm{K}$ shattering

(mainly due to fast rotations)



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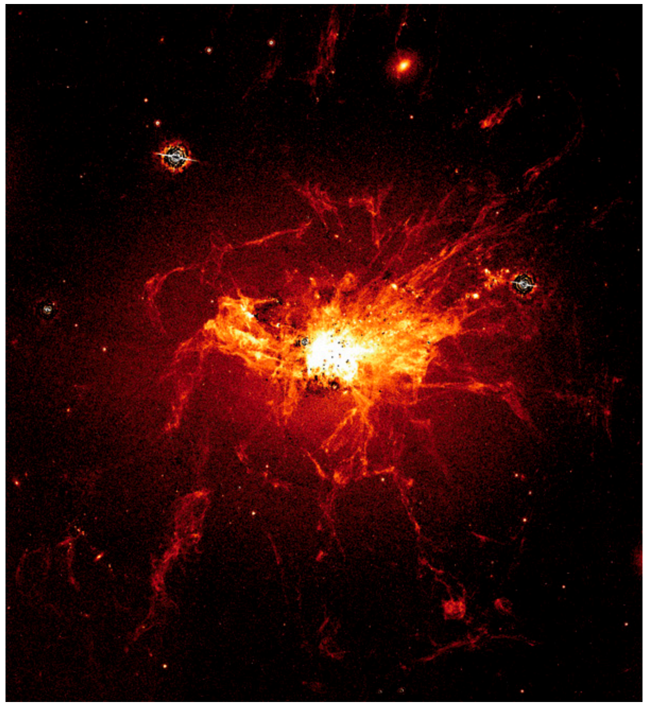
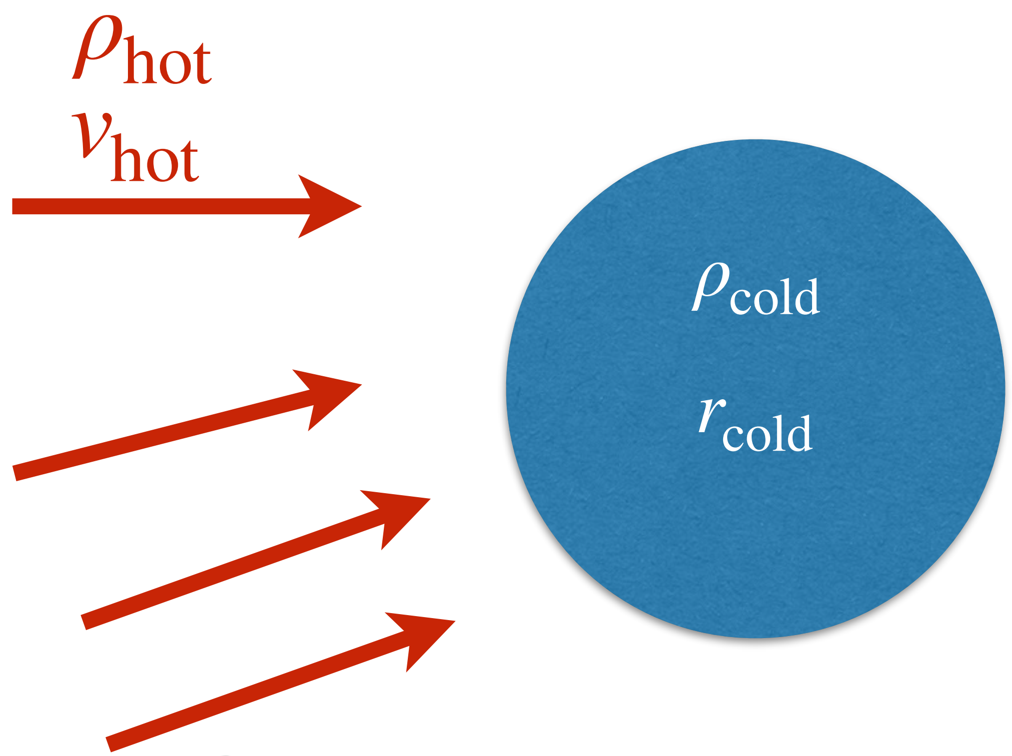


→ ***What about the molecular phase?***

↳ similar (but different) criteria for colder phase.

→ ***What is the relevant length scale in a <u>turbulent</u> environment?***

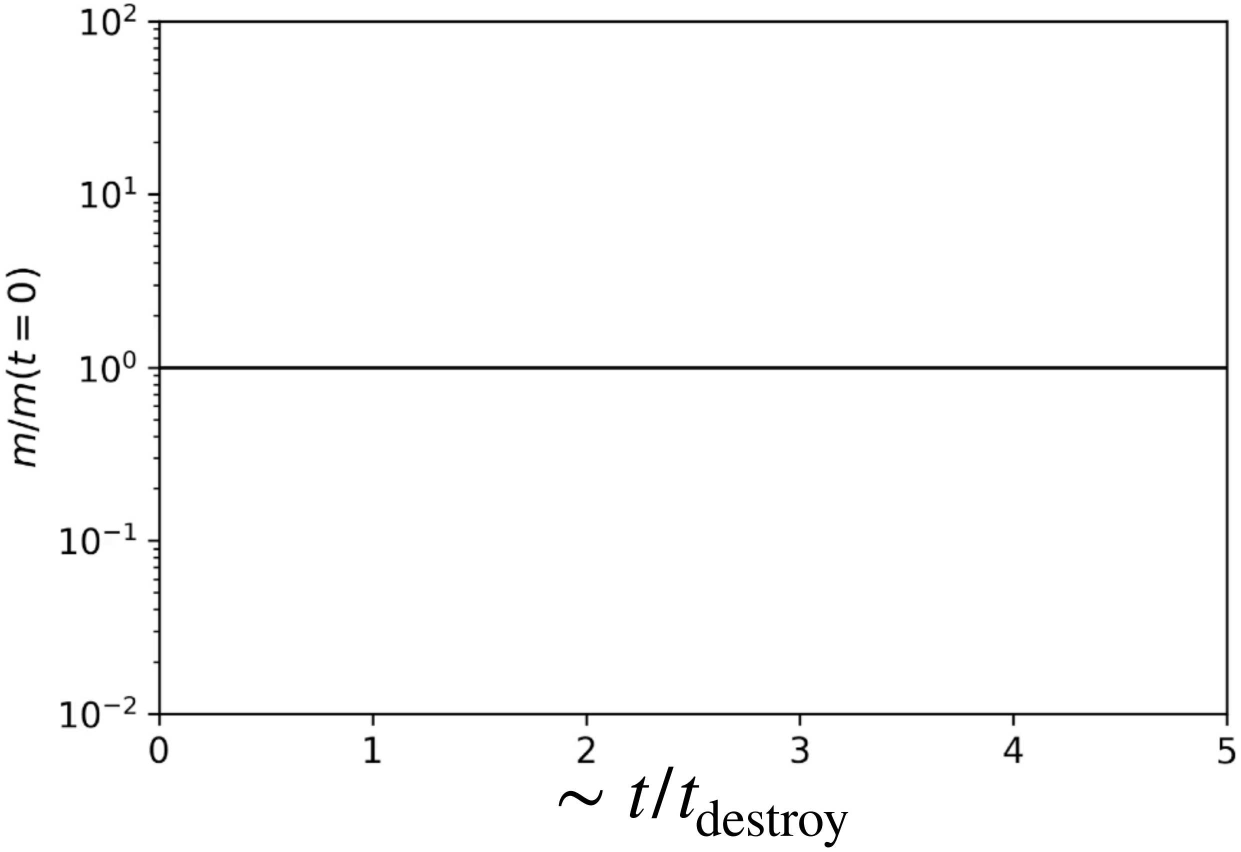
Cold gas survival in turbulent media

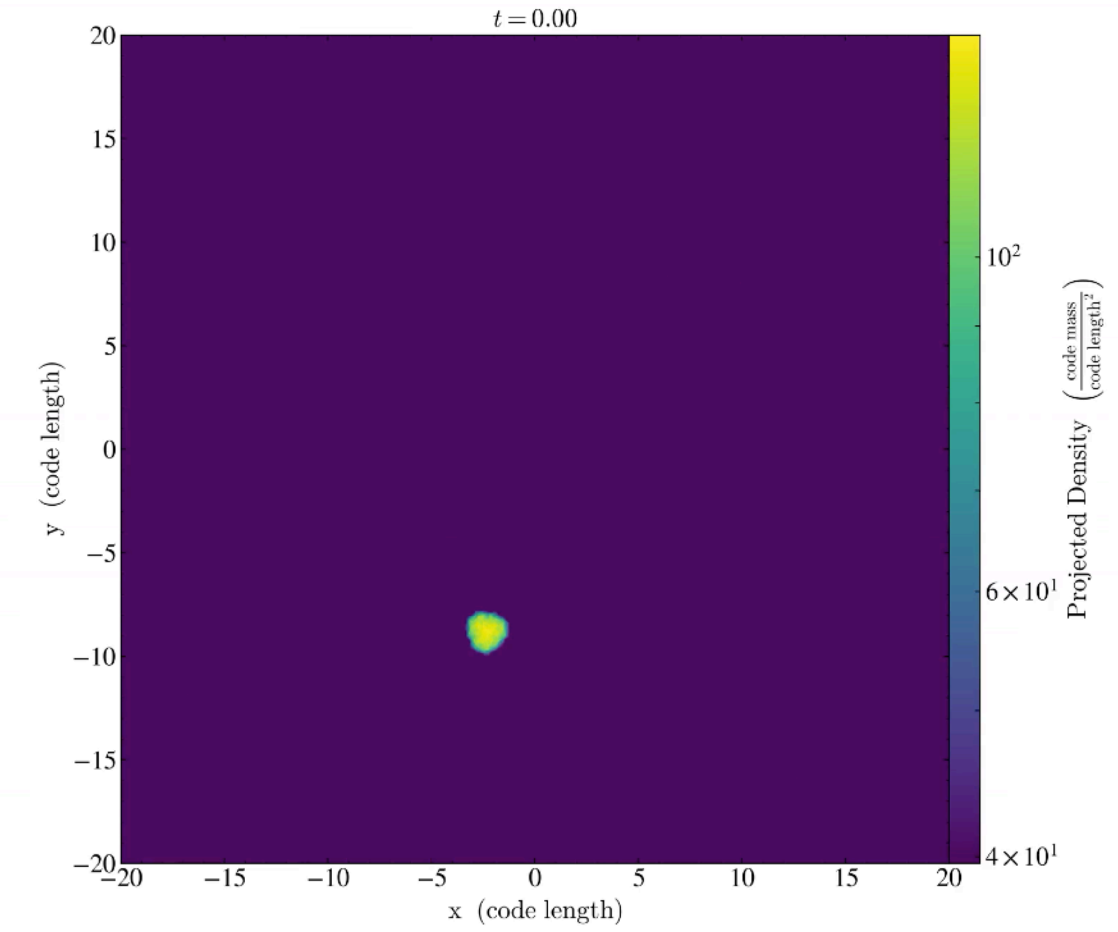


Destruction timescale

$$t_{\rm destroy} \sim \chi^{1/2} \frac{r_{\rm cold}}{\bar{v}_{\rm hot}}$$

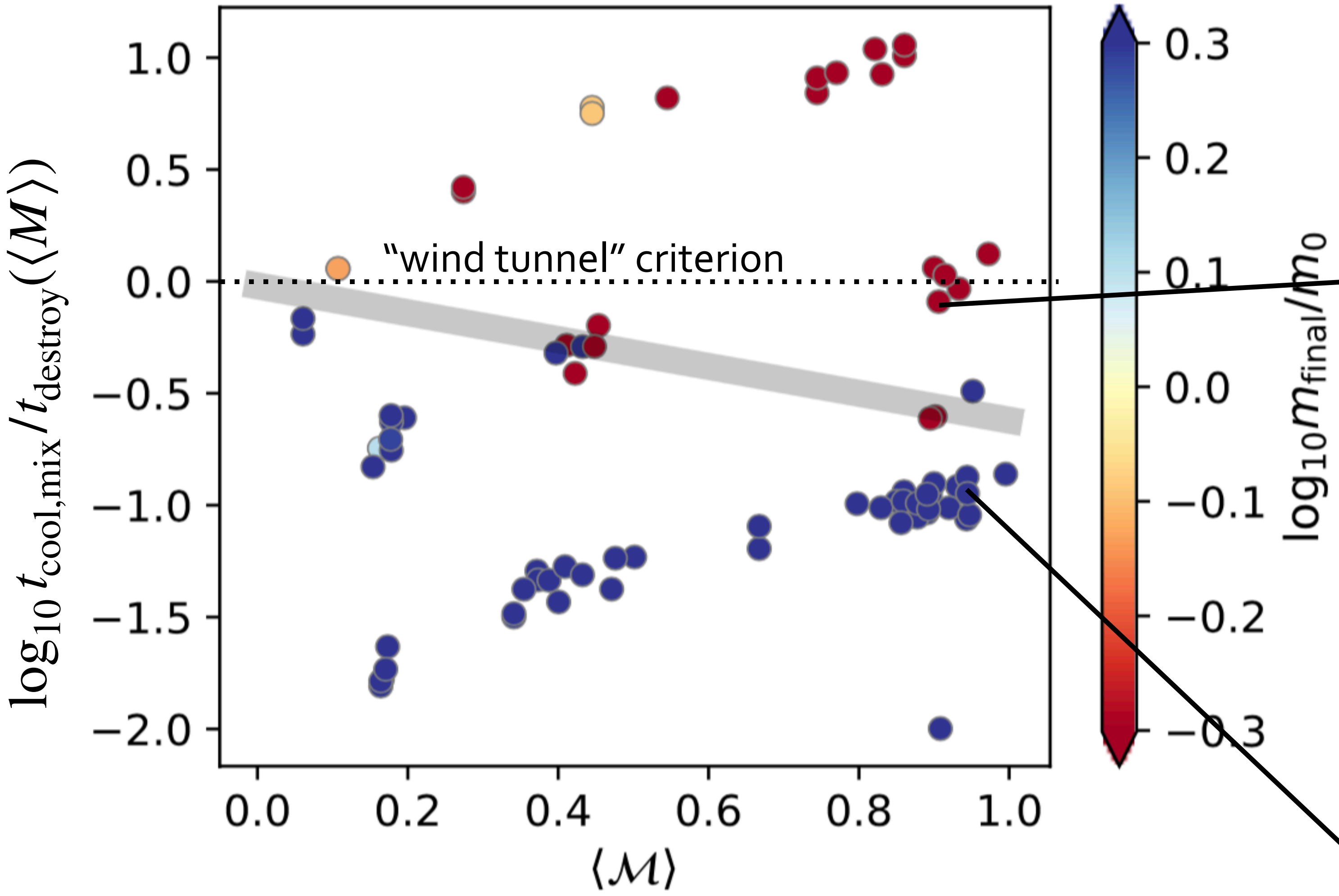
$$\text{with } \chi \equiv \frac{n_{\rm cold}}{n_{\rm hot}}$$



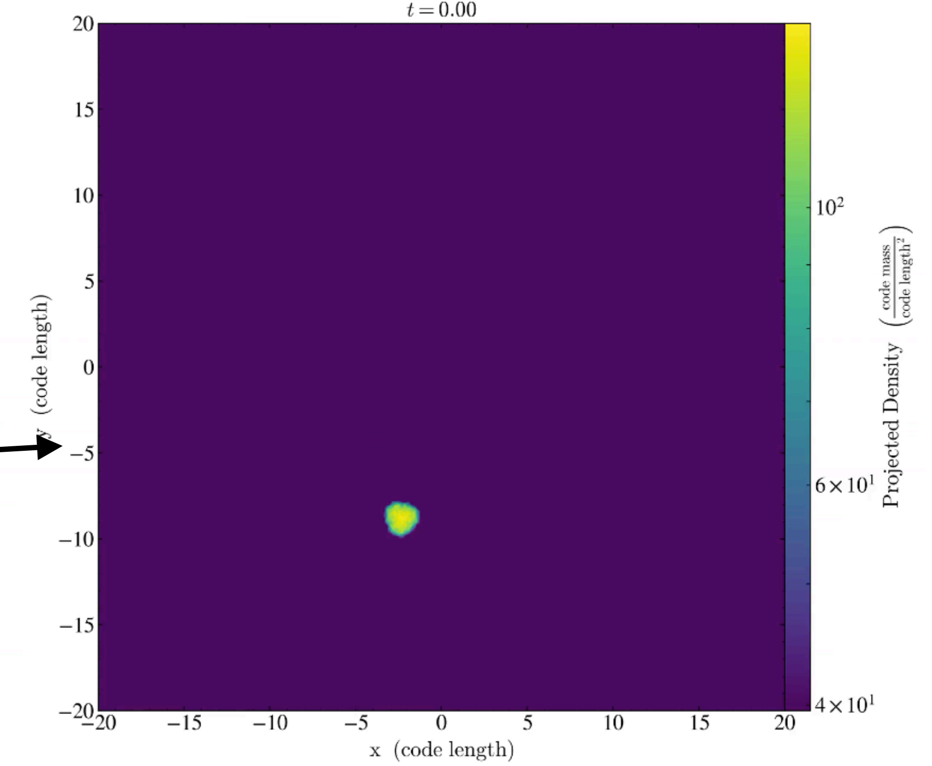


MG, Oh, Ji, Norman (2022)

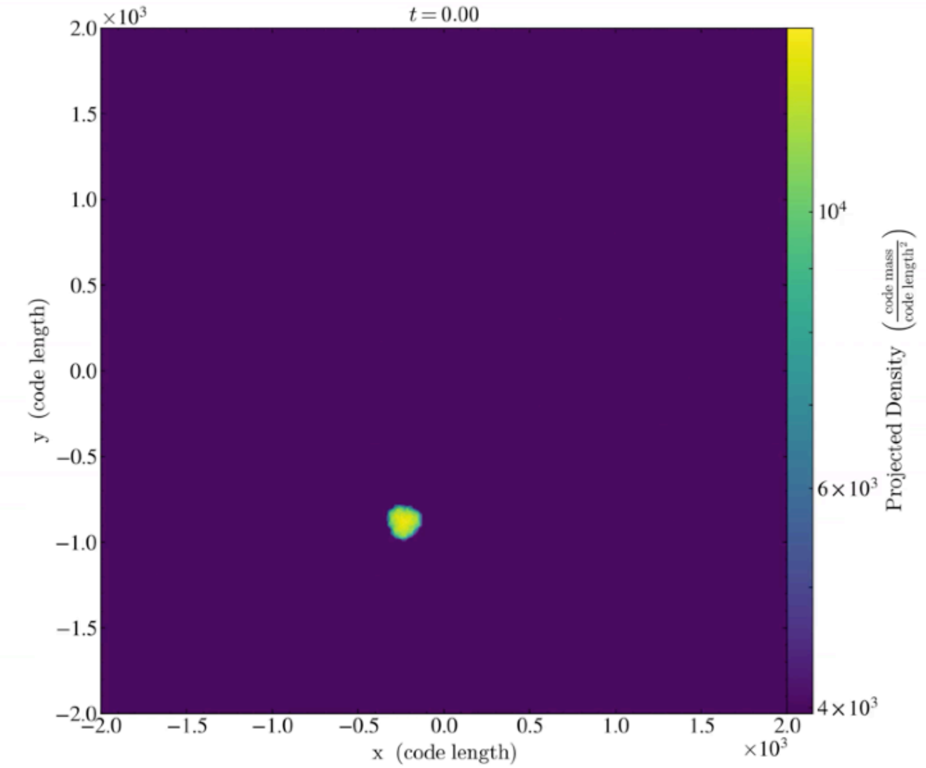
Survival criterion for turbulent multiphase media



$t_{\rm cool,mix}/t_{\rm destroy} \sim 1$

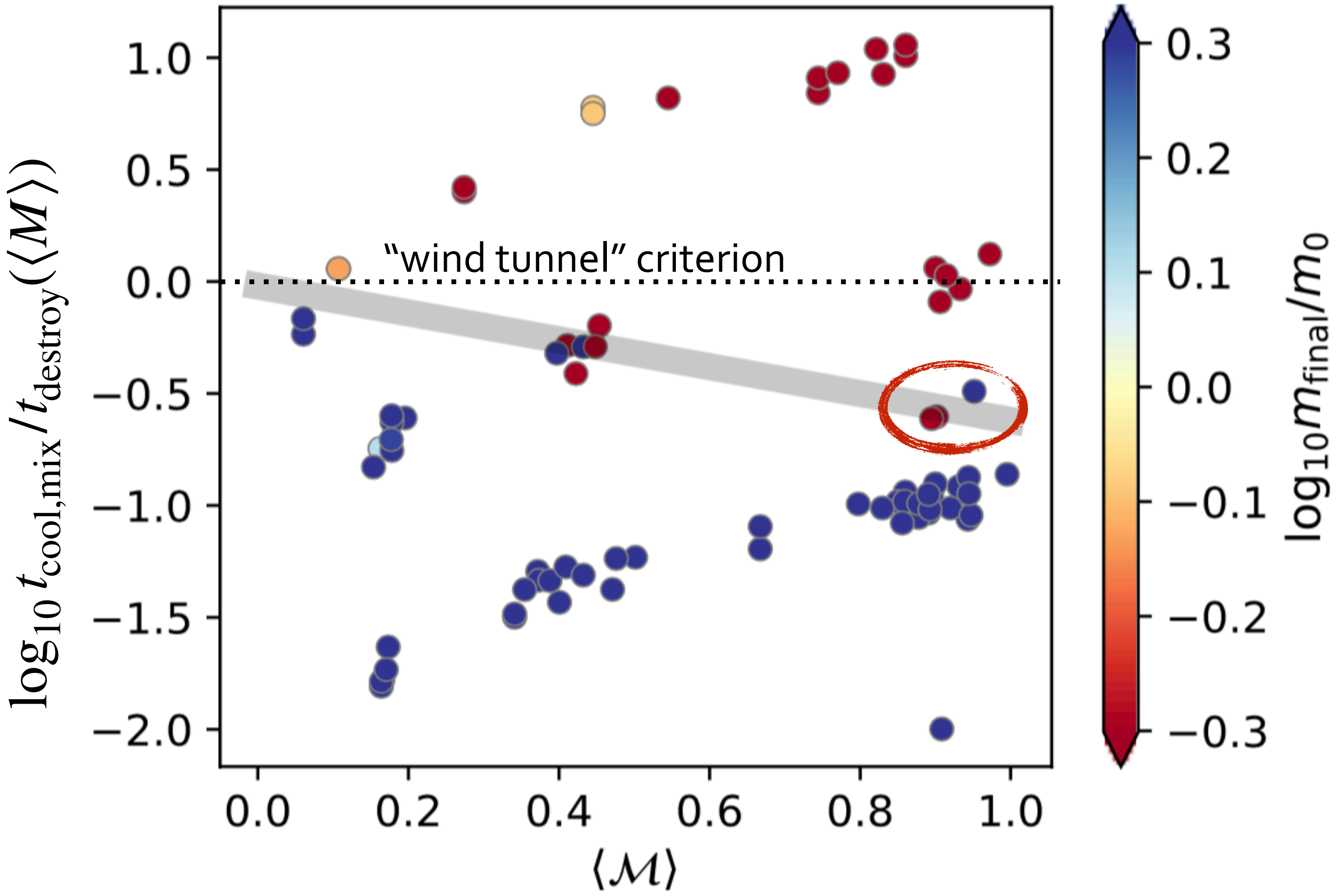


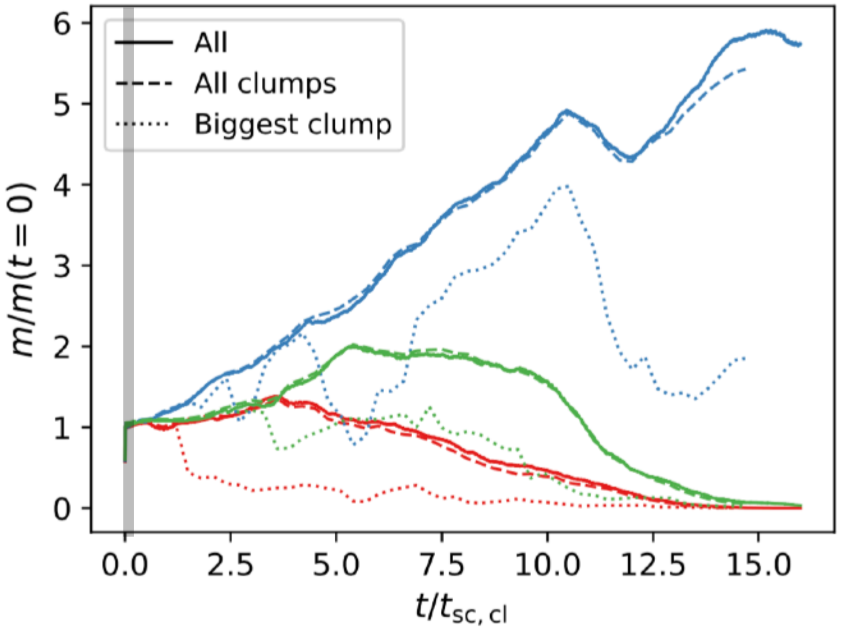
$t_{\rm cool,mix}/t_{\rm destroy} \sim 0.1$



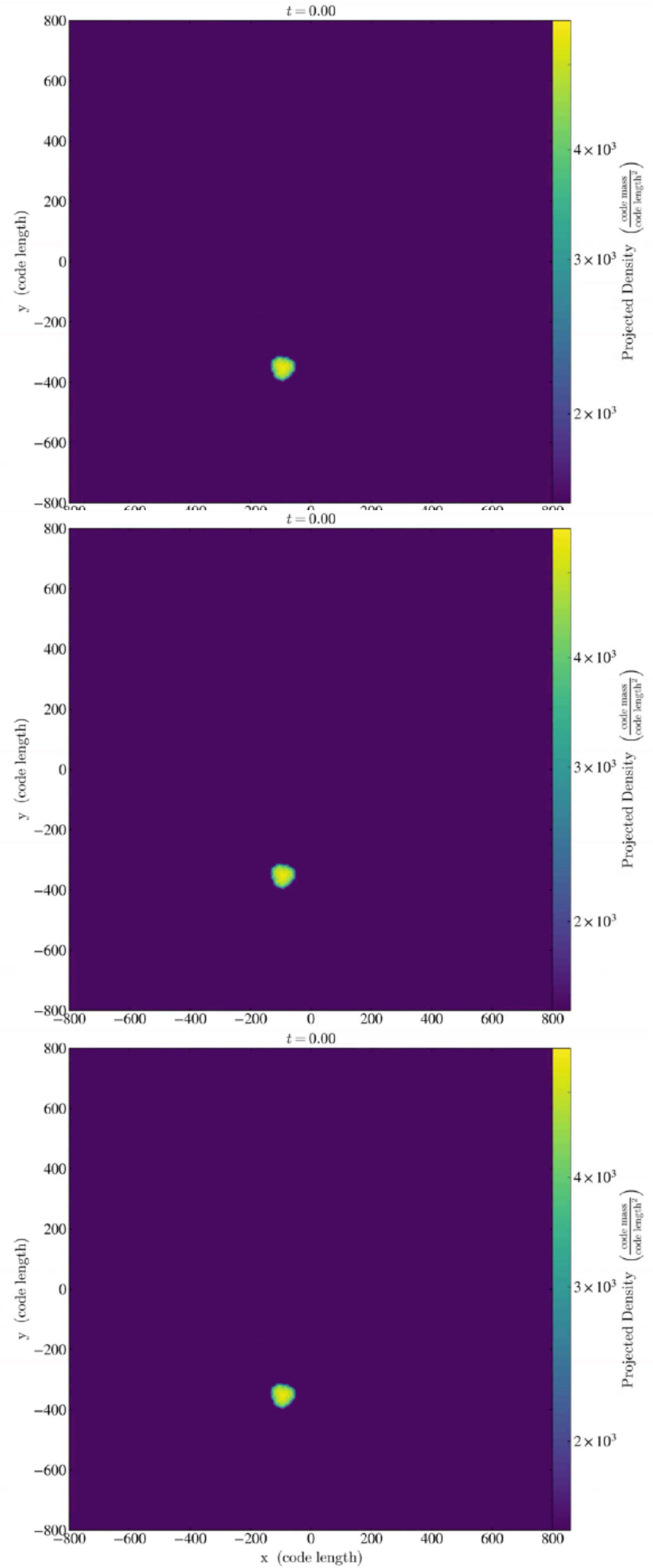
→ $t_{\rm cool,mix}/t_{\rm destroy} \lesssim 1$ *approximately works also in turbulent media.*

Survival criterion for turbulent multiphase media





Big clumps ($\gtrsim r_{\rm crit}$) at all times required for survival!



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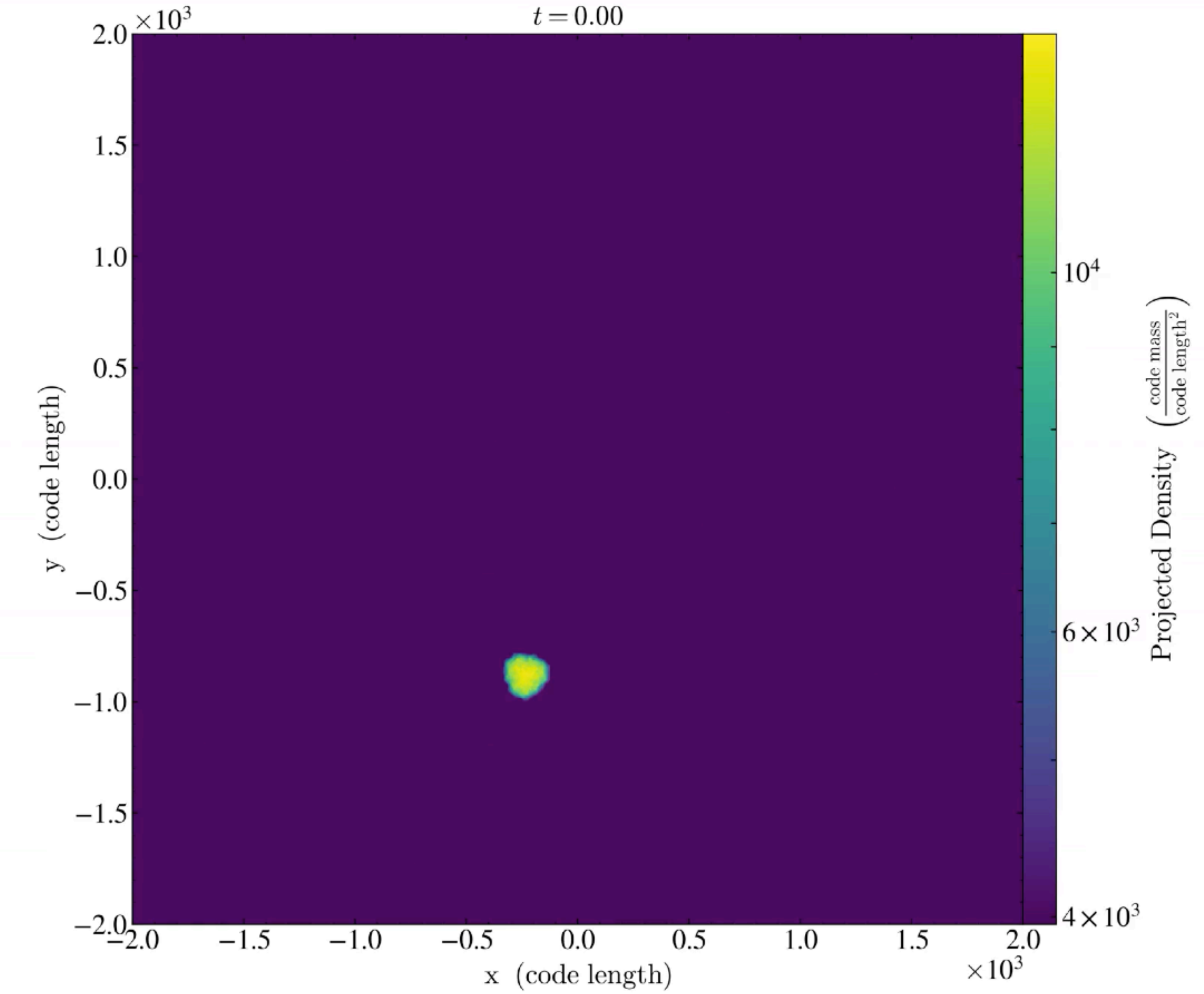

Big “core” & many droplets!
→The best of both worlds!

“Shattering” versus “survival”

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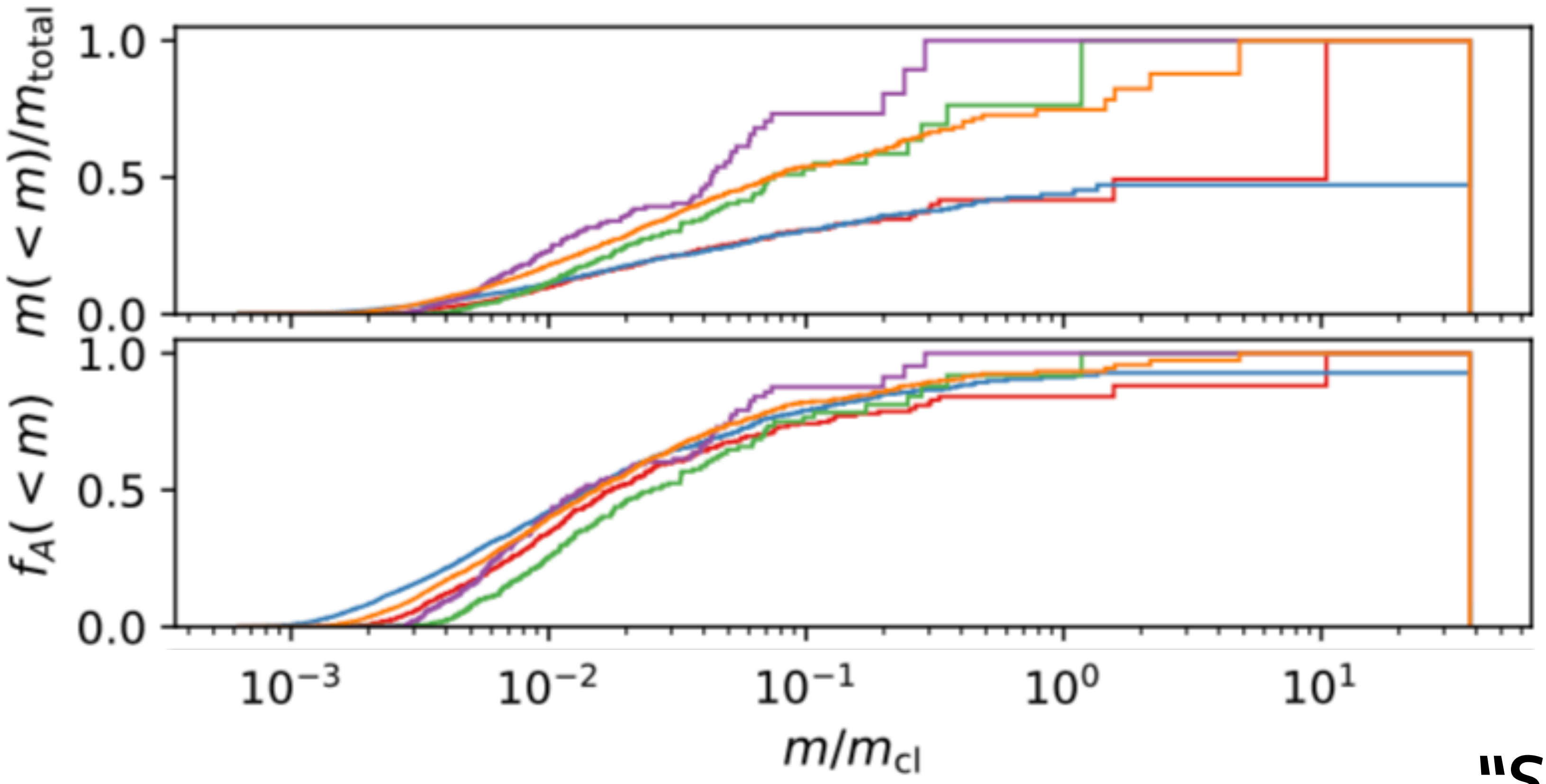
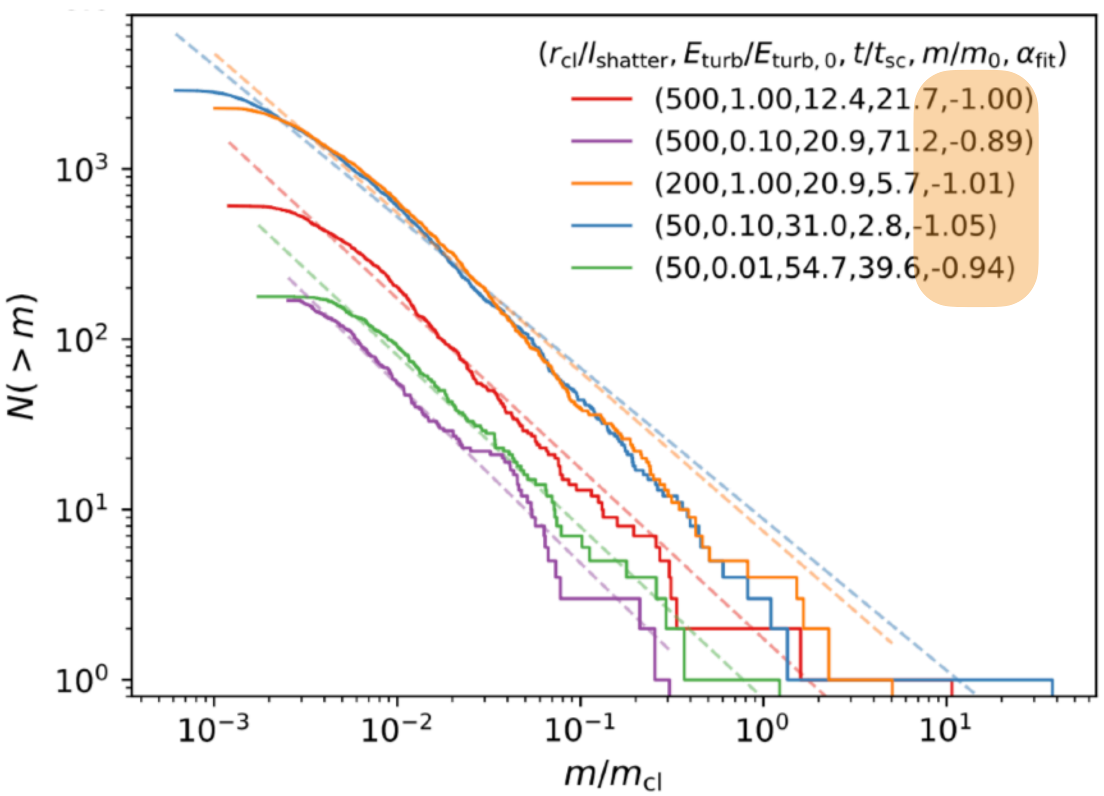


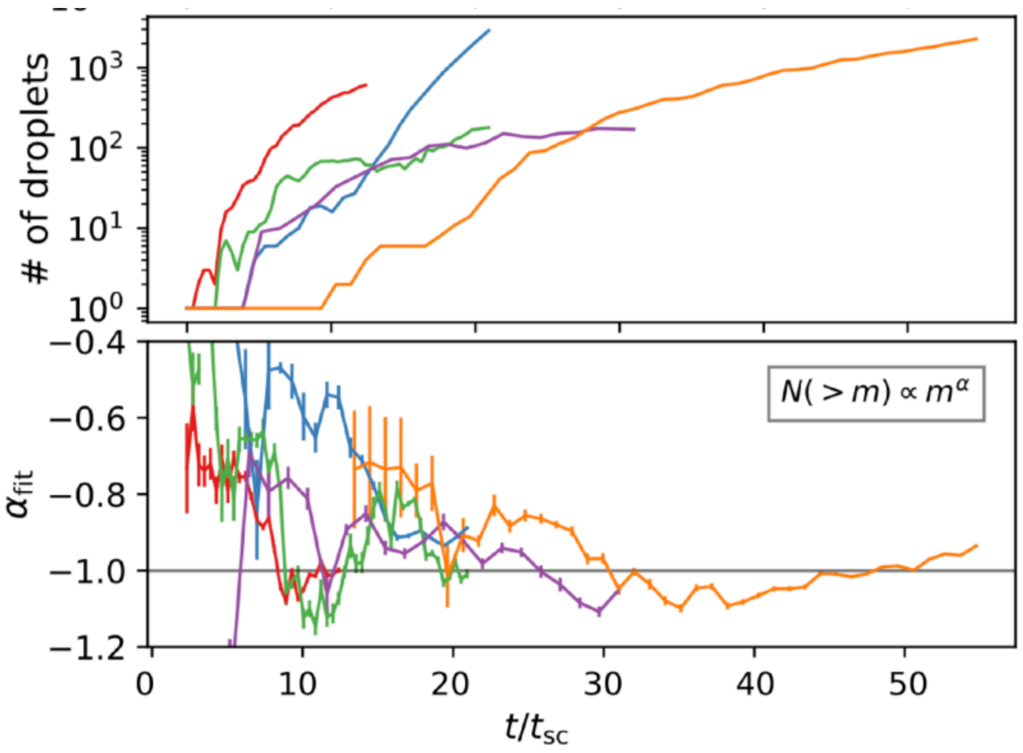
Mass can be dominated by some big clumps areal covering fraction is dominated by small clumps

“Starfleet” morphology

Mass can be dominated by some big clumps areal covering fraction is dominated by small clumps

Mass distribution of droplets

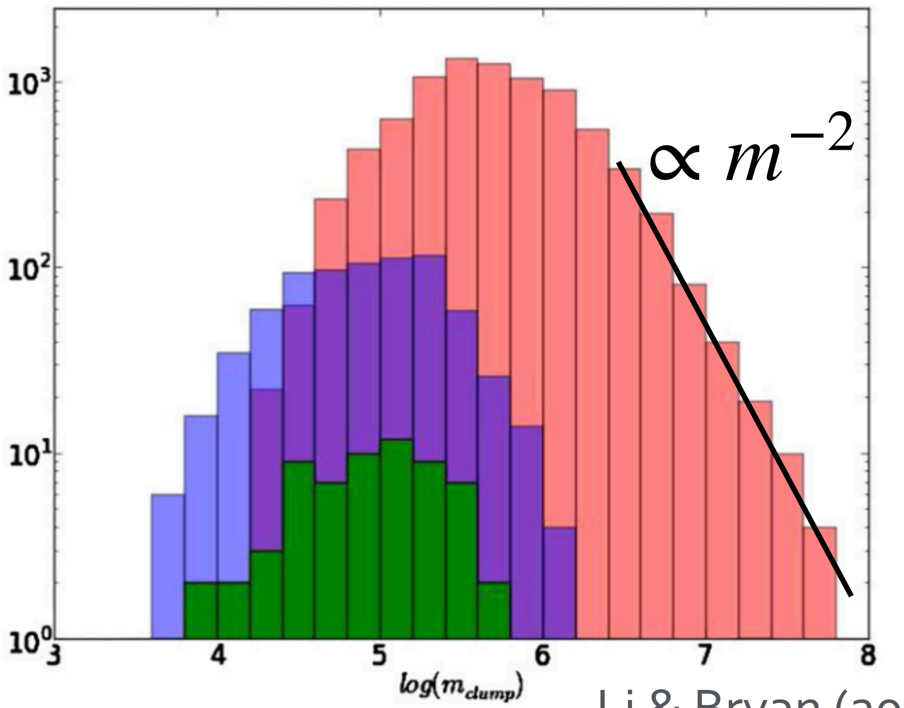




Power-law droplet mass distribution with $N(>m) \propto m^{-1}$.

→ Scale free & equal mass per log bin!

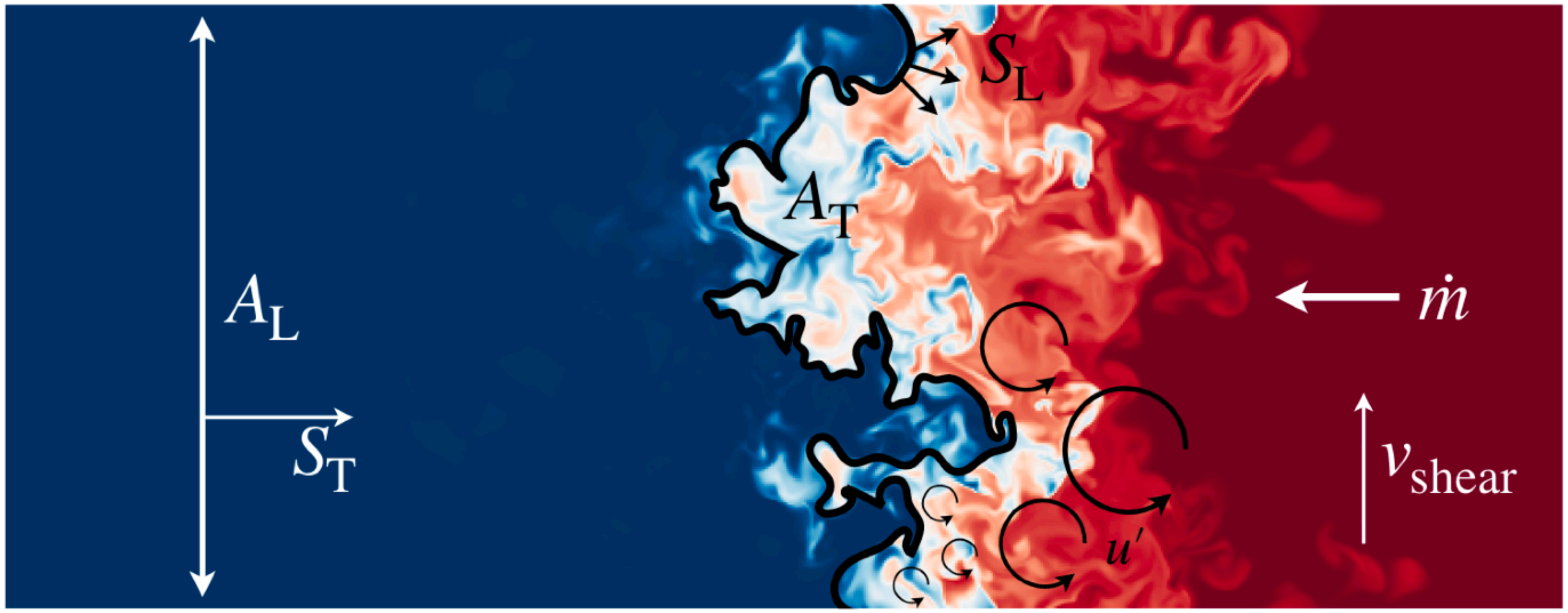
Also seen in larger scale sims of the ICM!



Li & Bryan (2014)

Tan, Oh & MG (2021)

Mass transfer rate



(random walk argument)

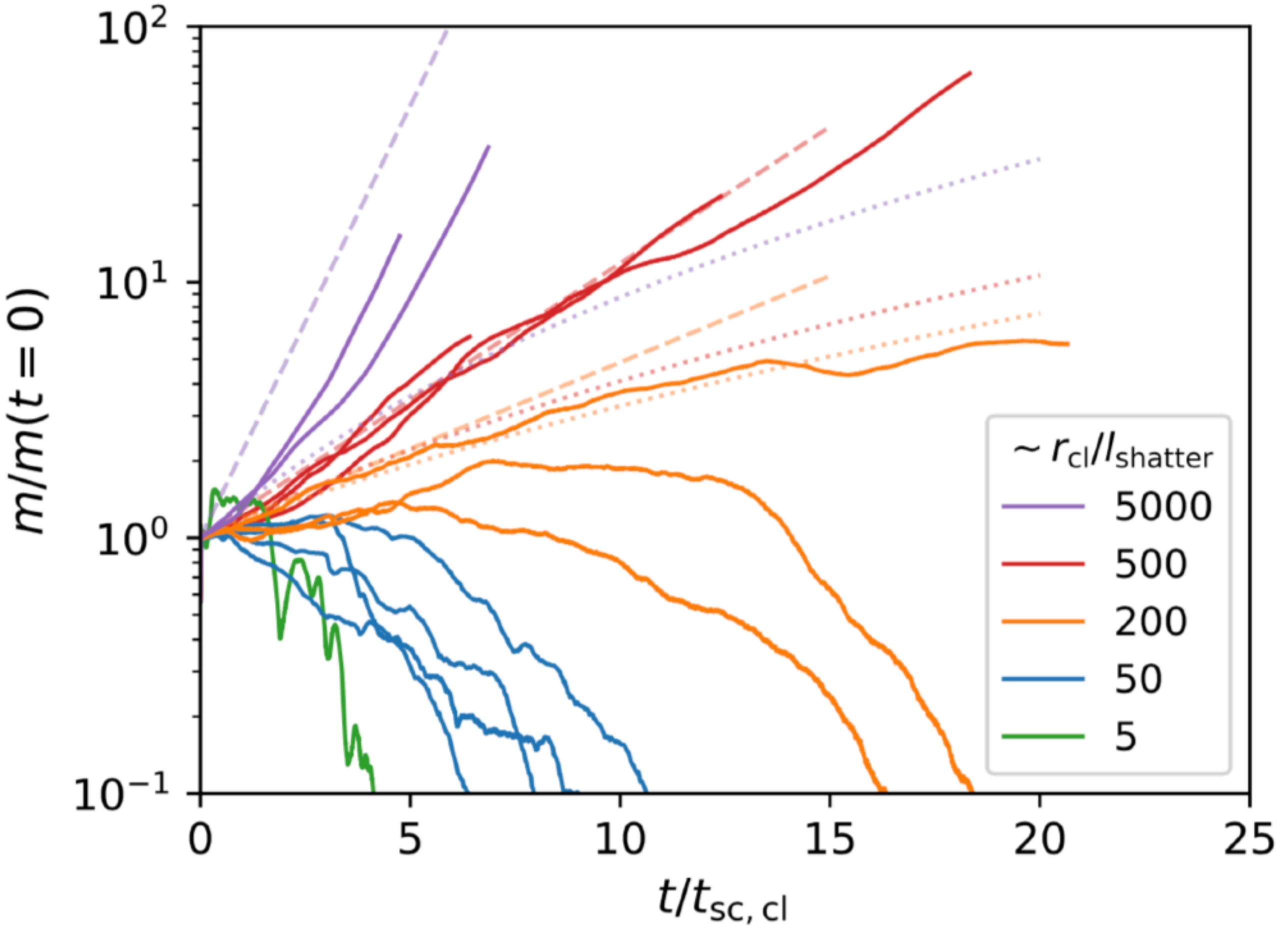
- Turbulent diffusion $\lambda(t_{\rm cool}) \sim (D_{\rm turb} t_{\rm cool})^{1/2} \sim (u' L t_{\rm cool})^{1/2}$
- Only fraction of gas $f_{\rm cool} \sim \lambda(t_{\rm cool})/L$ mixes and cools
- Whole eddy cools in $\tilde{\tau}_{\rm cool} \sim f_{\rm cool}^{-1} t_{\rm cool} \sim (t_{\rm cool} L/u')^{1/2}$

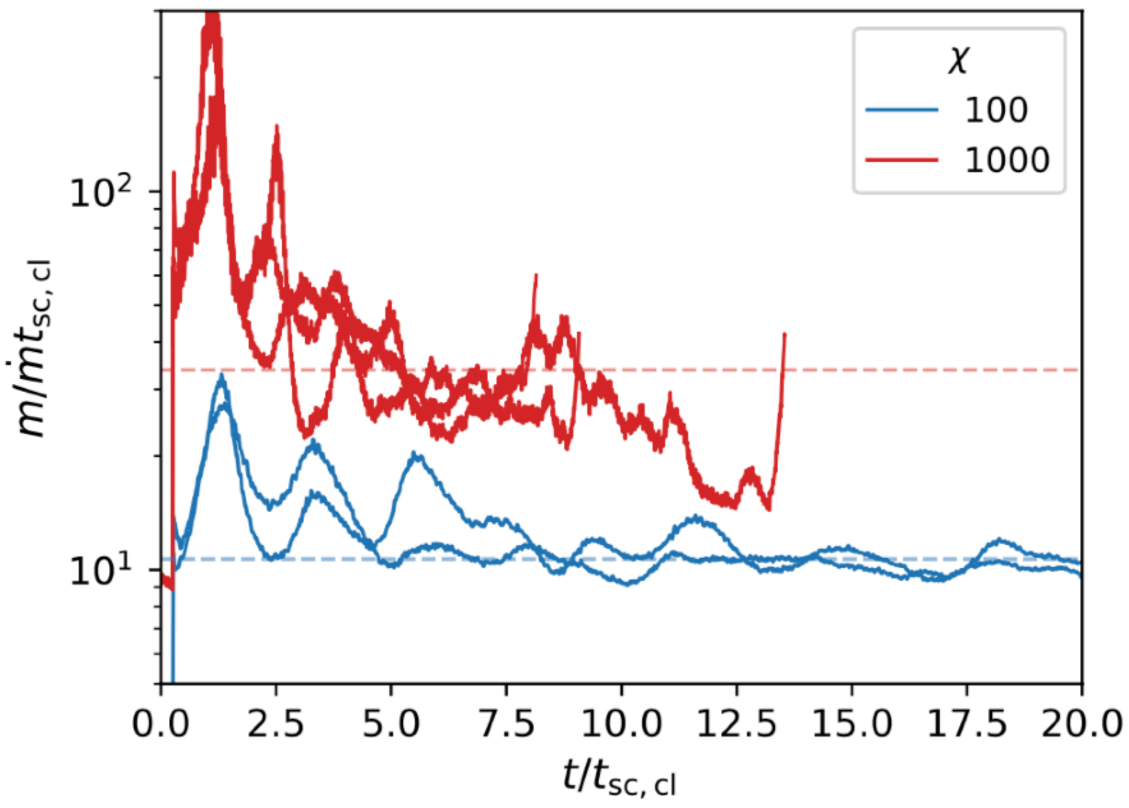
$\Rightarrow$effective cooling time $\tilde{\tau}_{\rm cool} \sim (t_{\rm cool} t_{\rm eddy})^{1/2} \sim (t_{\rm cool} L/u')^{1/2}$

Implications

- outer scale resolved, resolving individual front ($\sim \lambda_F$) not necessary for converged $\dot{m}$
- match scalings understood from turbulent combustion theory
- backed up by experimental data (Gülder 1994)

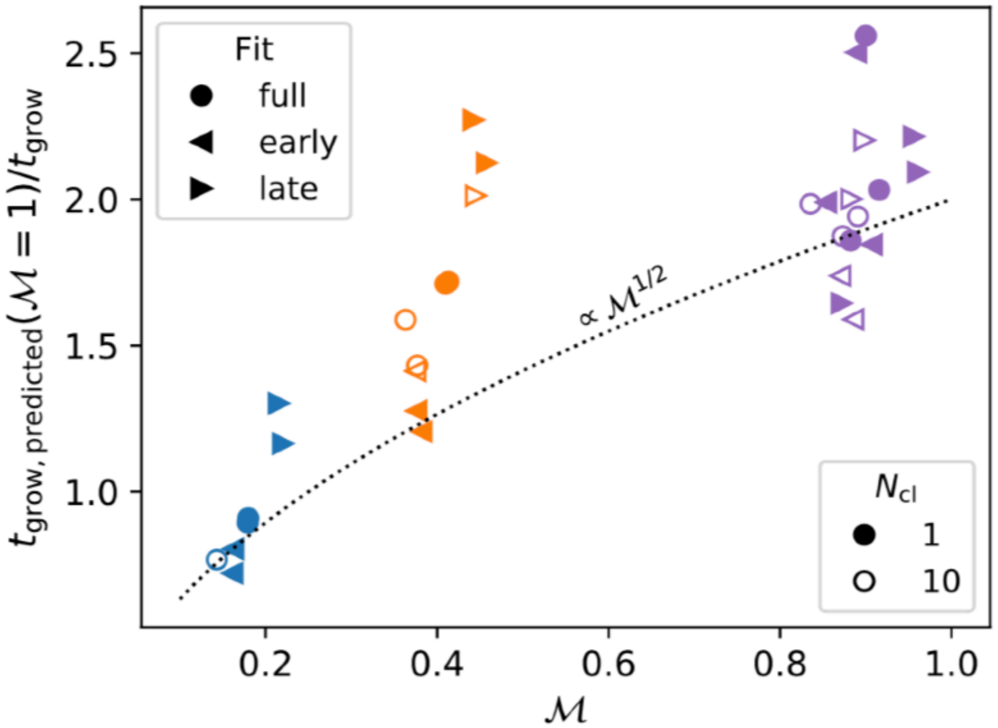
Mass transfer rate





effective cooling time

$$\tilde{\tau}_{\rm cool} \sim (t_{\rm cool} t_{\rm eddy})^{1/2} \sim (t_{\rm cool} L/u')^{1/2}$$

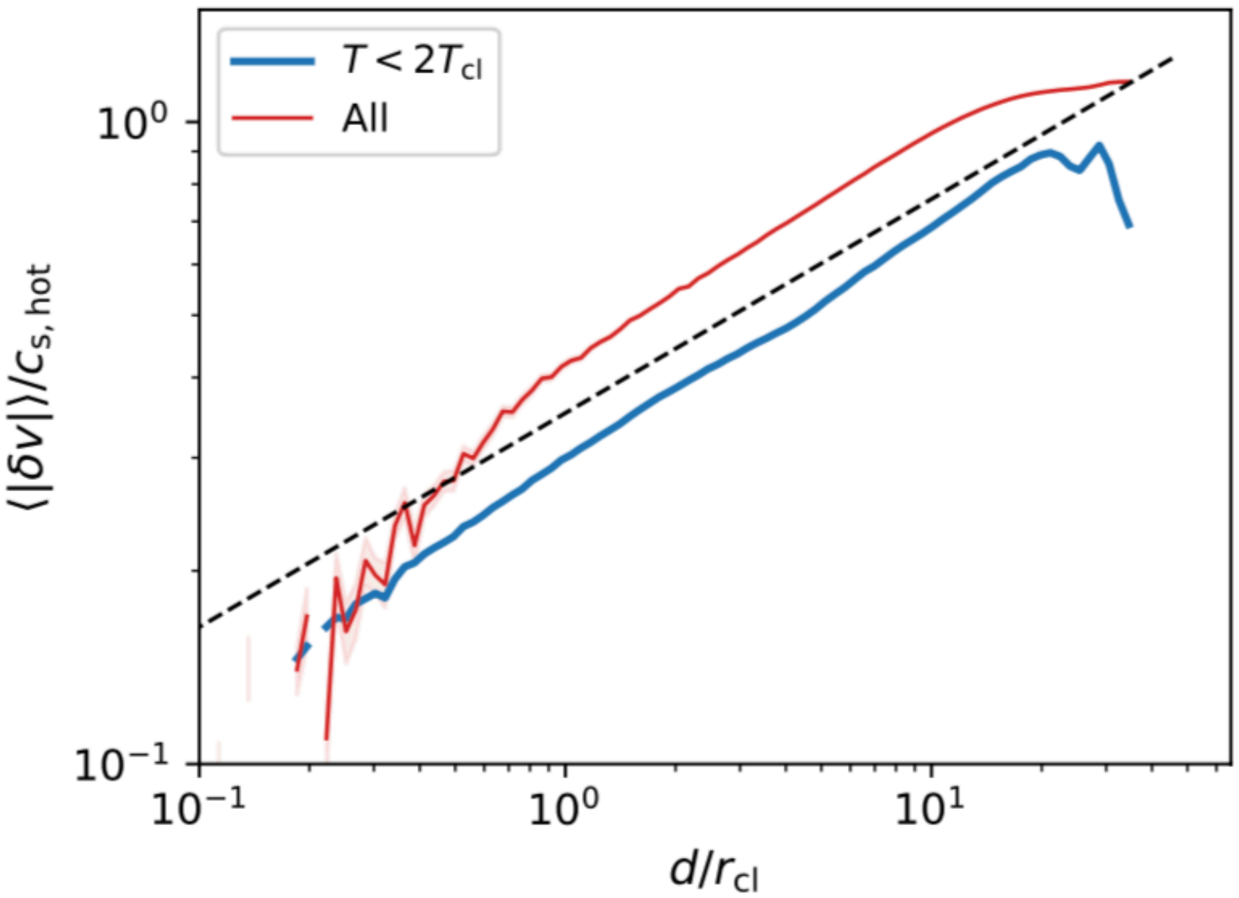


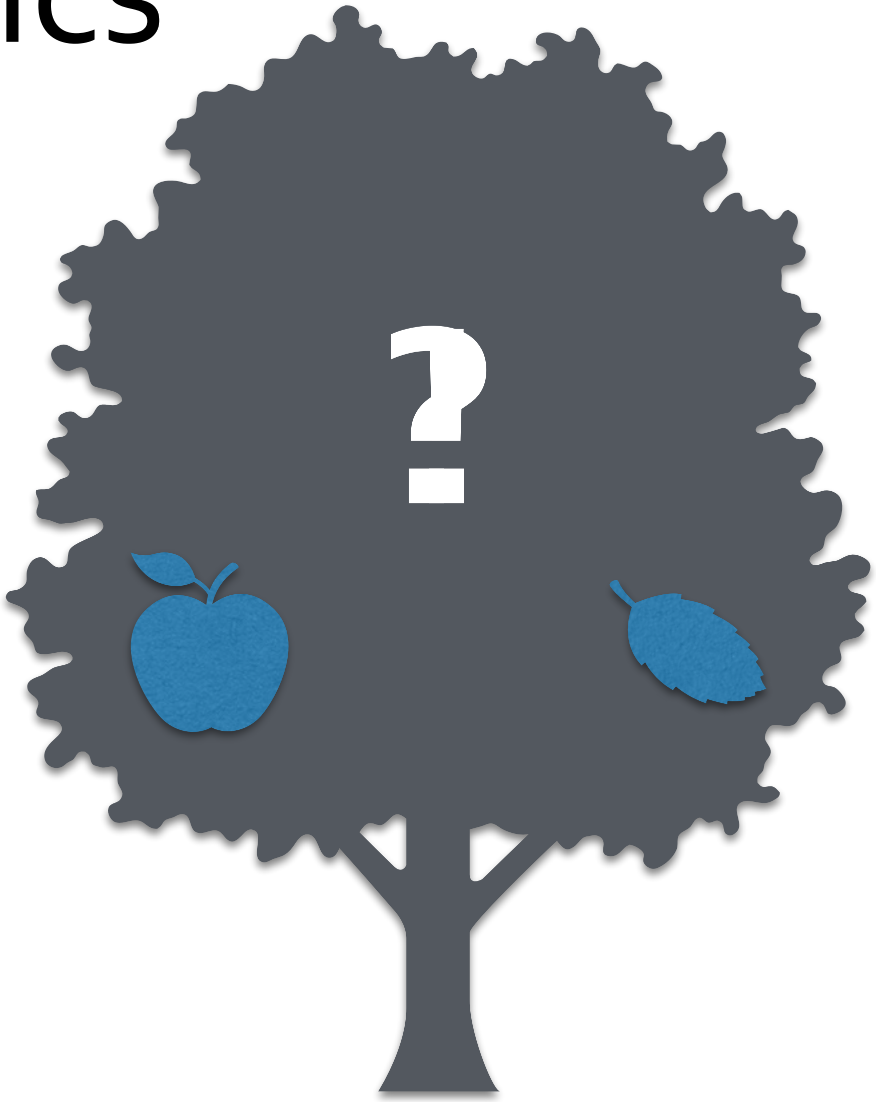
(cf. Yuan's, Mateusz' talks)

Implications: kinematics

Velocity structure function (VSF)

$$\langle \delta v \rangle (d) = \langle v(r+d) - v(r) \rangle$$



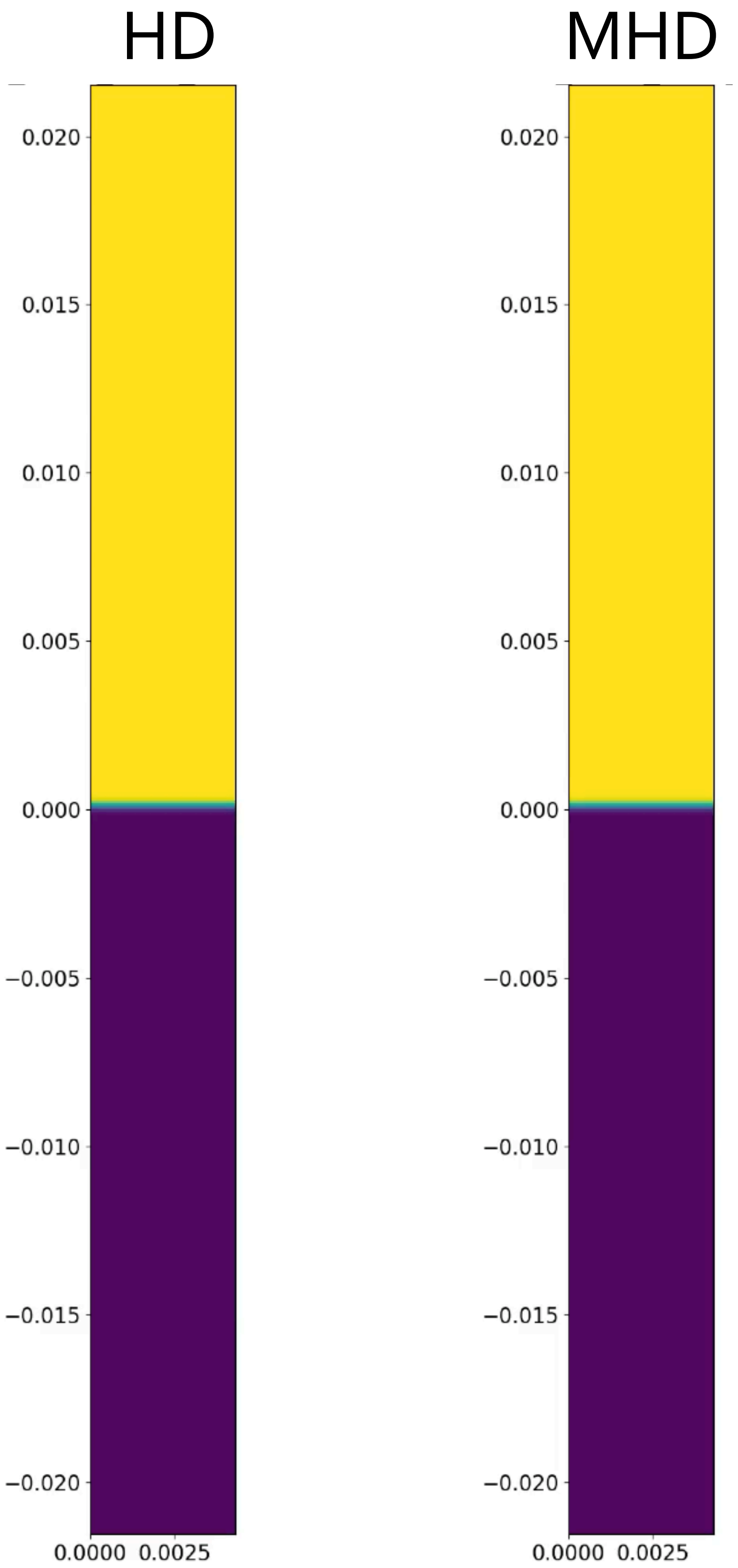


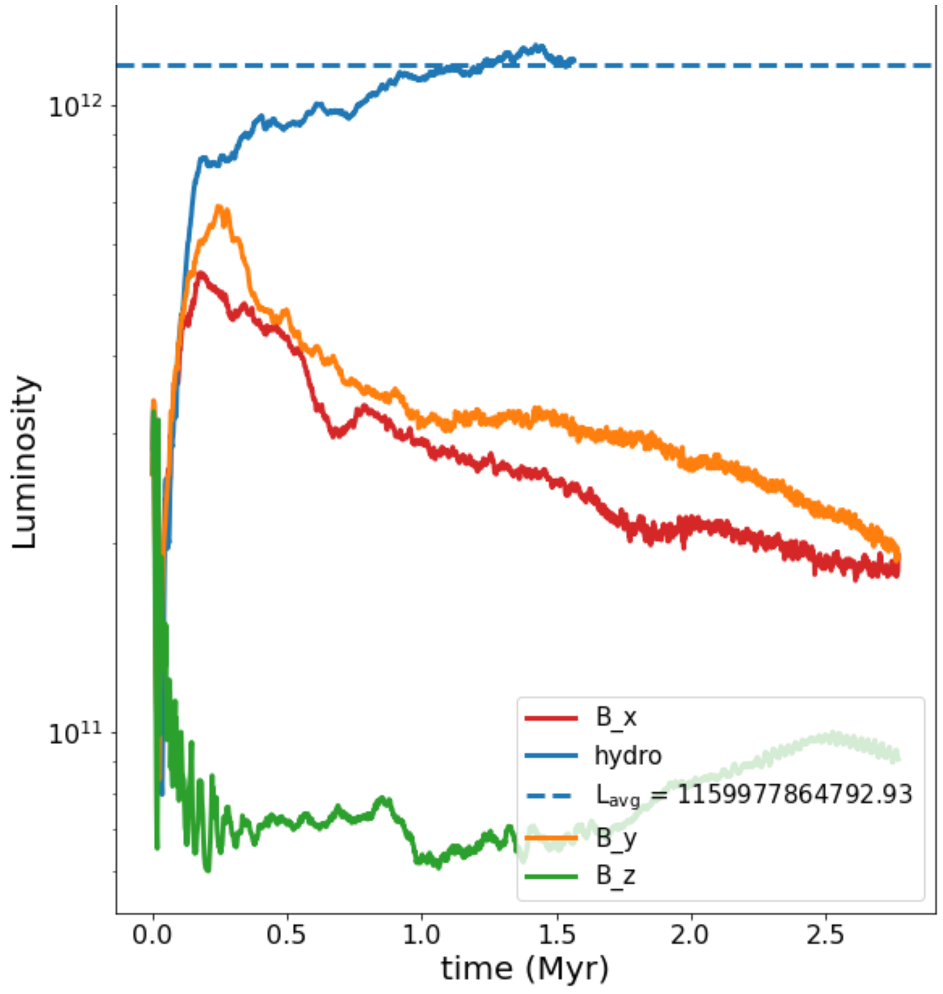
→ ***Cold gas well entrained, can be used to probe kinematics of hot gas.***

Mass growth of cold gas → momentum transfer!

(preliminary)

What about magnetic fields?





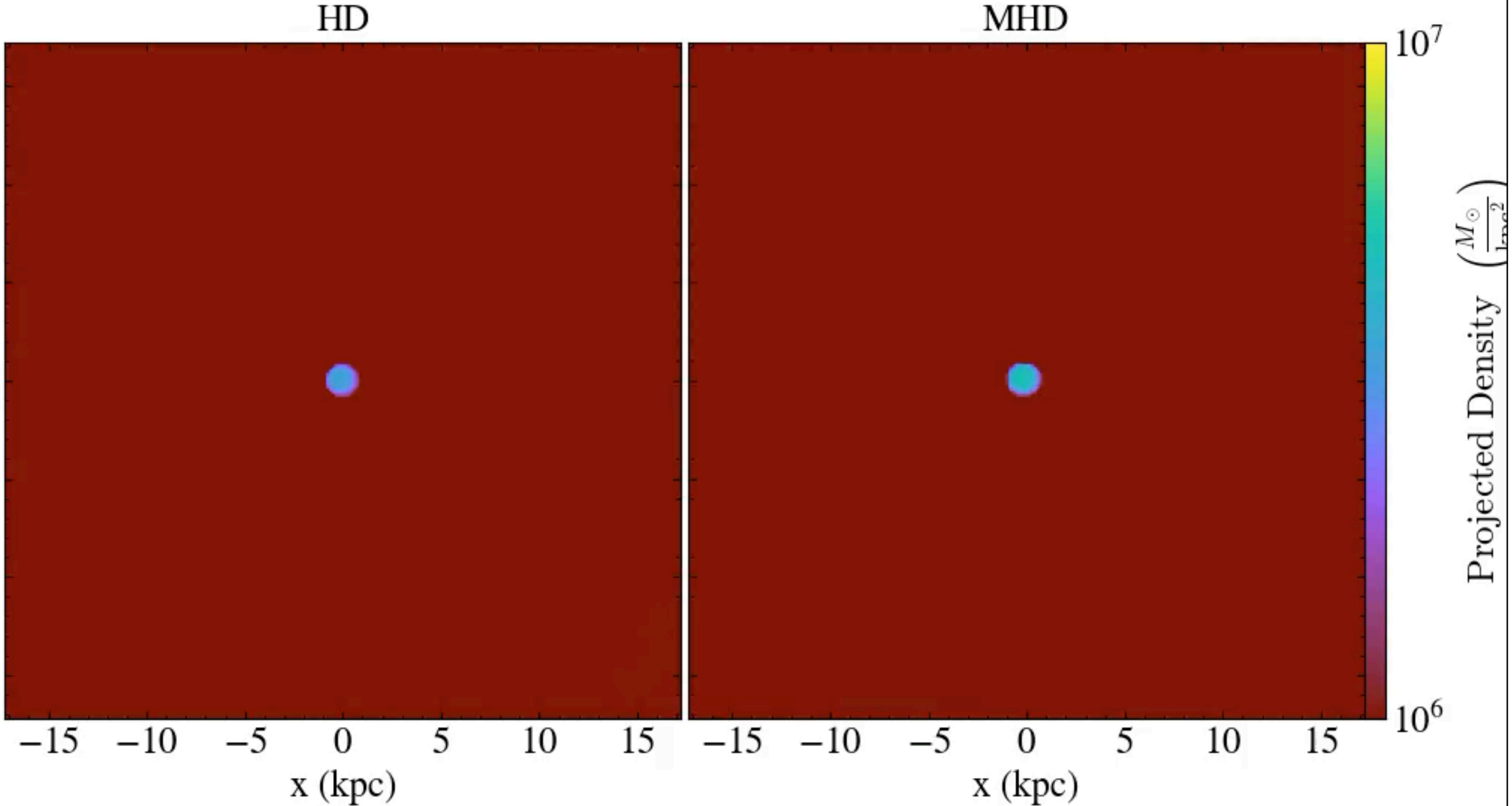
Hitesh Kishore Das

→ ***strongly suppress mixing!***

(see also, e.g., Ji et al. 2018)

(preliminary)

Multiphase MHD turbulence



Hitesh Kishore Das

→ similar survival criterion & mass transfer rate ***but*** very different morphology!

Summary: the dynamics of a turbulent, multiphase medium

- **Morphology**
  - cooling sets "shattering" scale $l_{\rm shatter} \sim \min(c_{\rm s} t_{\rm cool})$
  - cold gas survives in laminar or turbulent flows if $t_{\rm cool,mix}/t_{\rm destroy} < 1 \Leftrightarrow r > r_{\rm crit}$
  - In turbulence, "cold gas fleet" morphology with "mothership" ensured survival and $\mathrm{d}n/\mathrm{d}m \propto m^{-2}$ mass distribution
- **Mass transfer**
  - scalings from turbulent mixing layers & combustion theory $\tilde{\tau}_{\rm cool} \sim \sqrt{t_{\rm cool} L/u'}$ match multiphase simulations
  - effective growth leads to good kinematic coupling between the phases

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Skål!