Shocks in 2D and 3D: Implications for shattering of accelerated gas clouds

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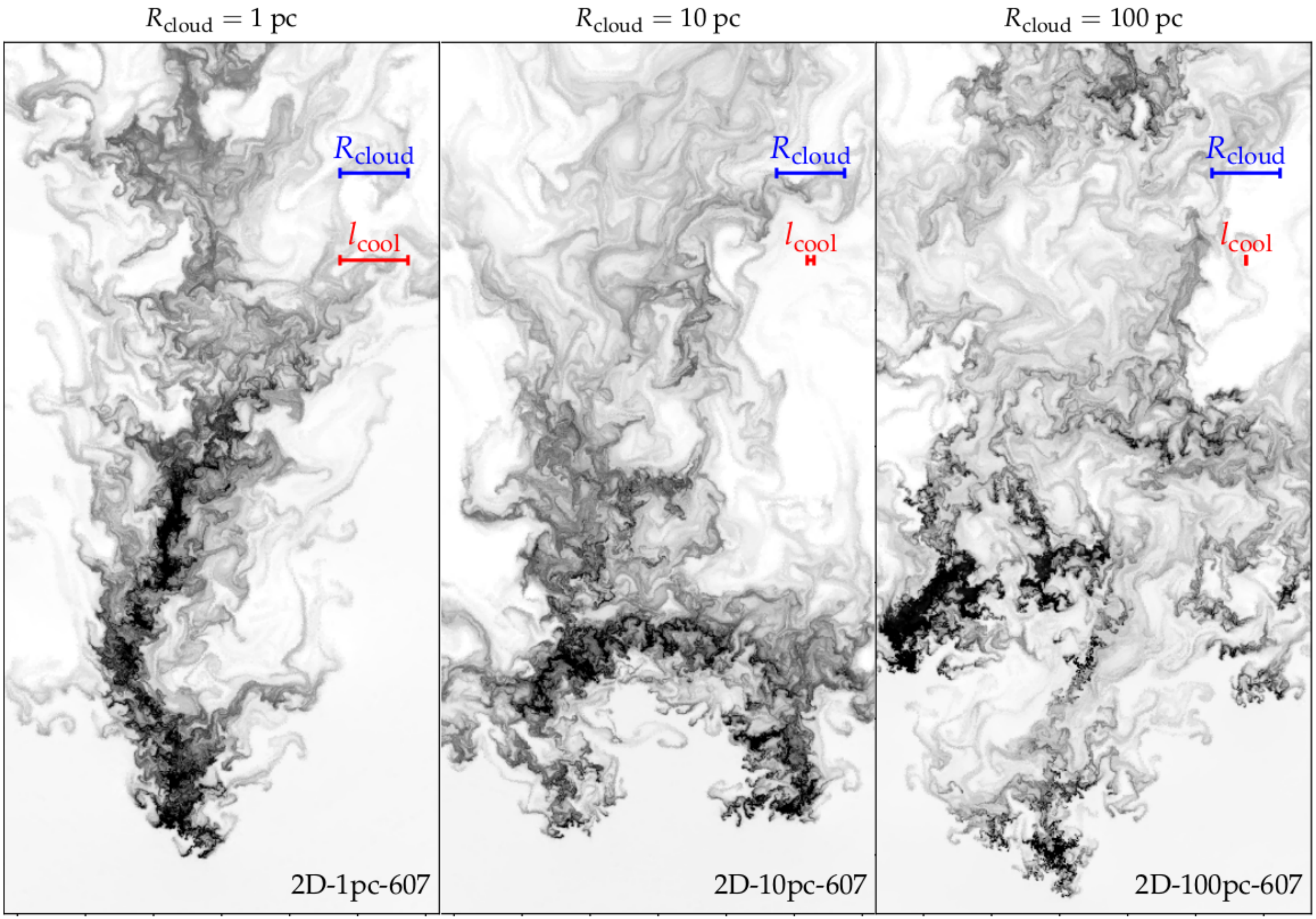
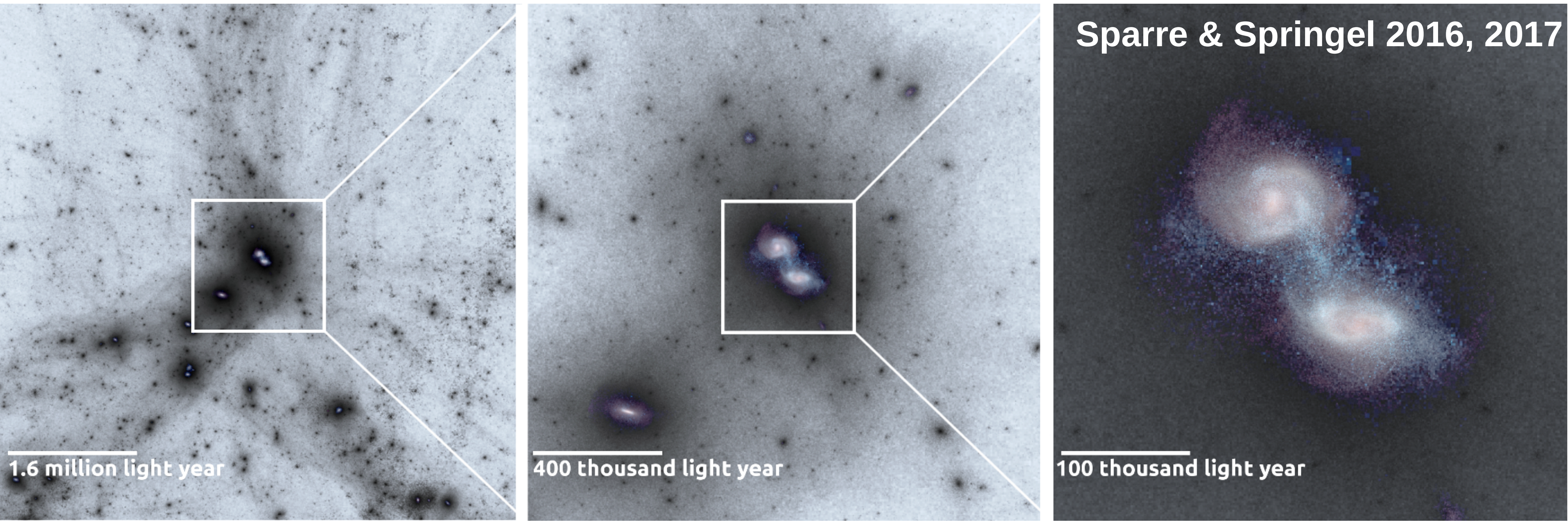


Cosmological simulations



Cosmological simulations resolve the cosmological large-scale structure and the 50-100 pc structure of galaxies.

A characteristic scale for cold gas

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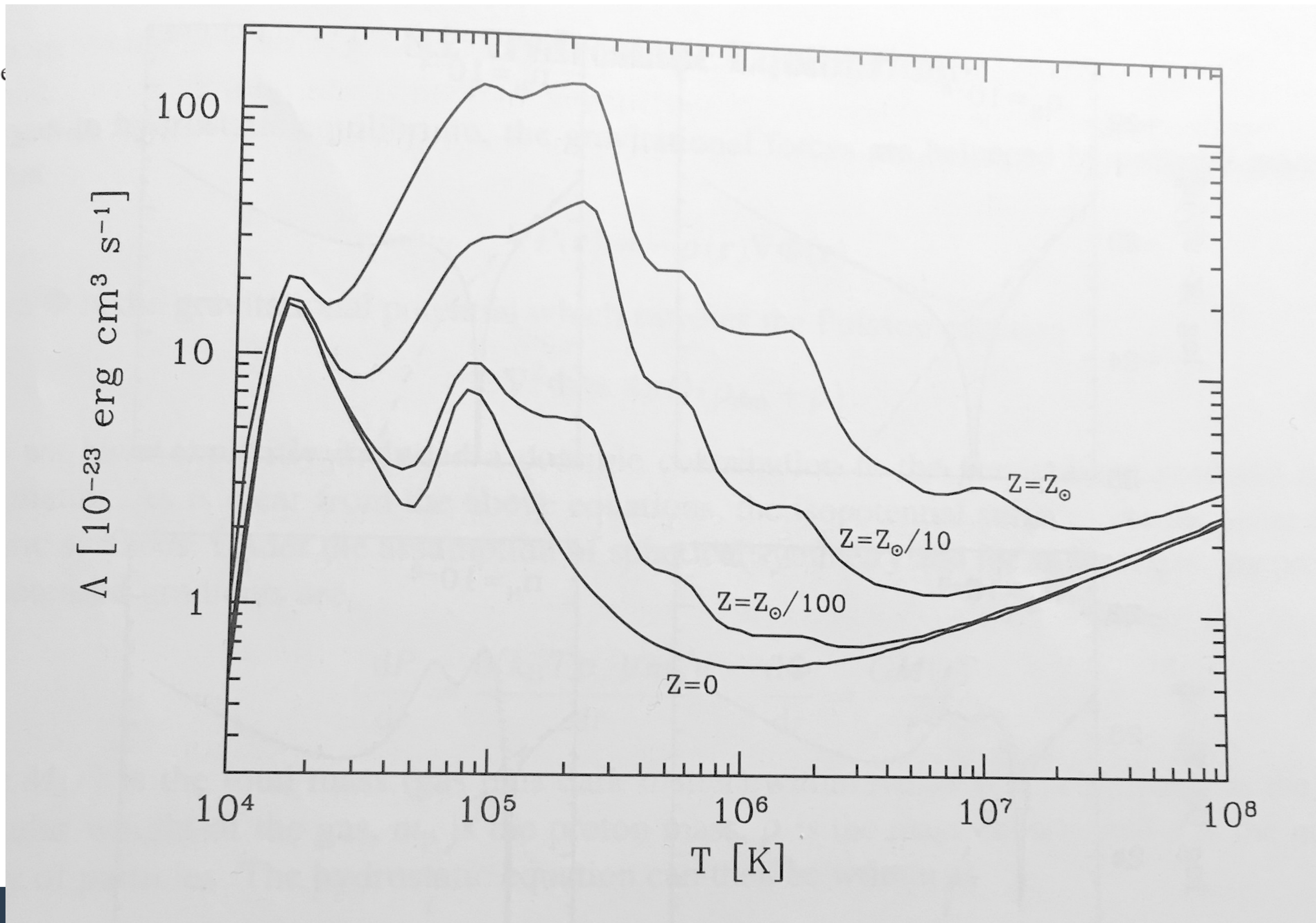
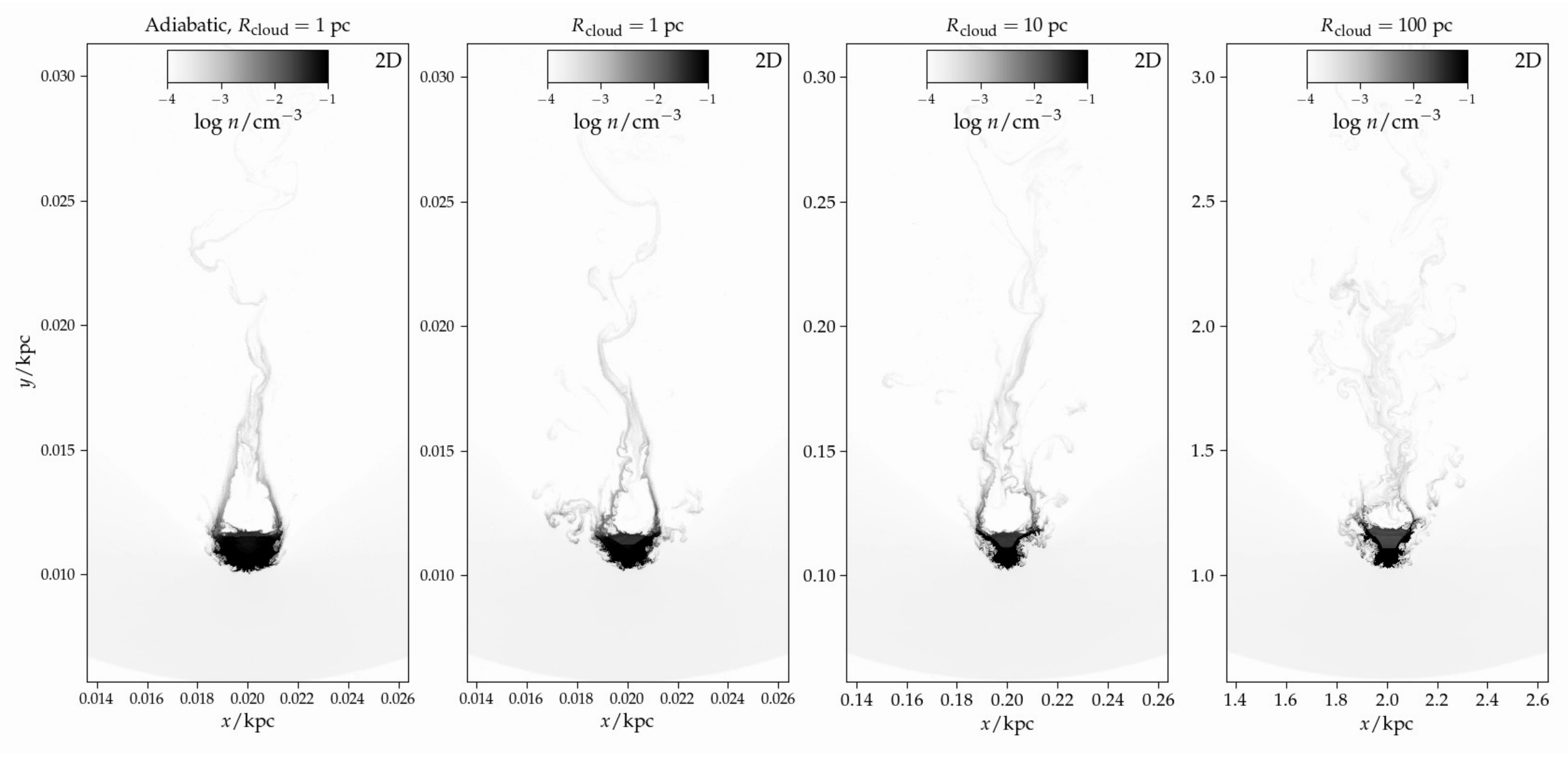
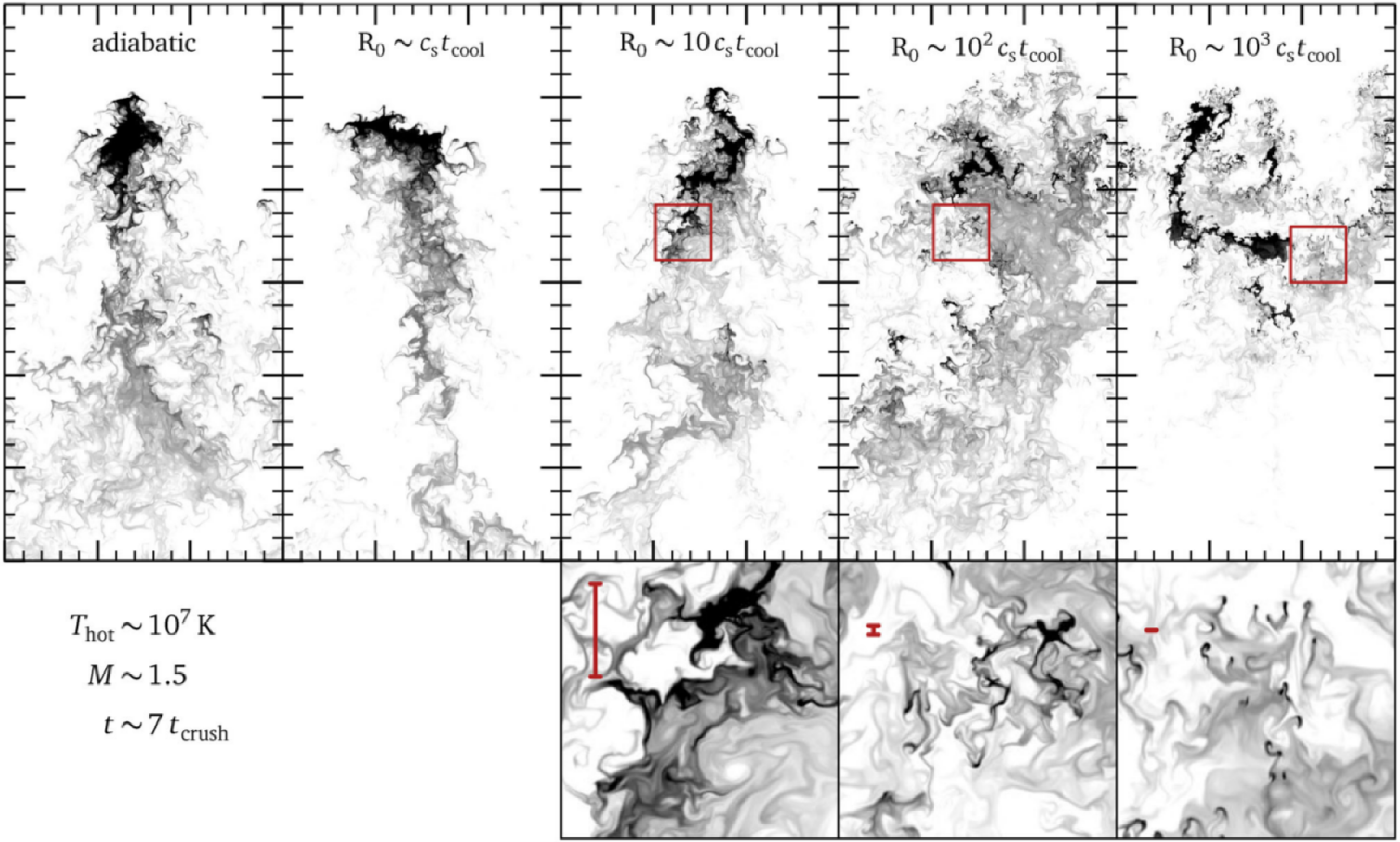




Adiabatic, $R_{\rm cloud} = 1$ pc
$R_{\rm cloud} = 1$ pc
$R_{\rm cloud} = 10$ pc
$R_{\rm cloud} = 100$ pc
2D
$\log n\,/\,{\rm cm}^{-3}$
−4 −3 −2 −1
$y\,/\,$kpc
$x\,/\,$kpc
0.010 0.015 0.020 0.025 0.030
0.014 0.016 0.018 0.020 0.022 0.024 0.026
0.10 0.15 0.20 0.25 0.30
0.14 0.16 0.18 0.20 0.22 0.24 0.26
1.0 1.5 2.0 2.5 3.0
1.4 1.6 1.8 2.0 2.2 2.4 2.6

A cloud interacting with a hot wind



Take-away messages from McCourt:

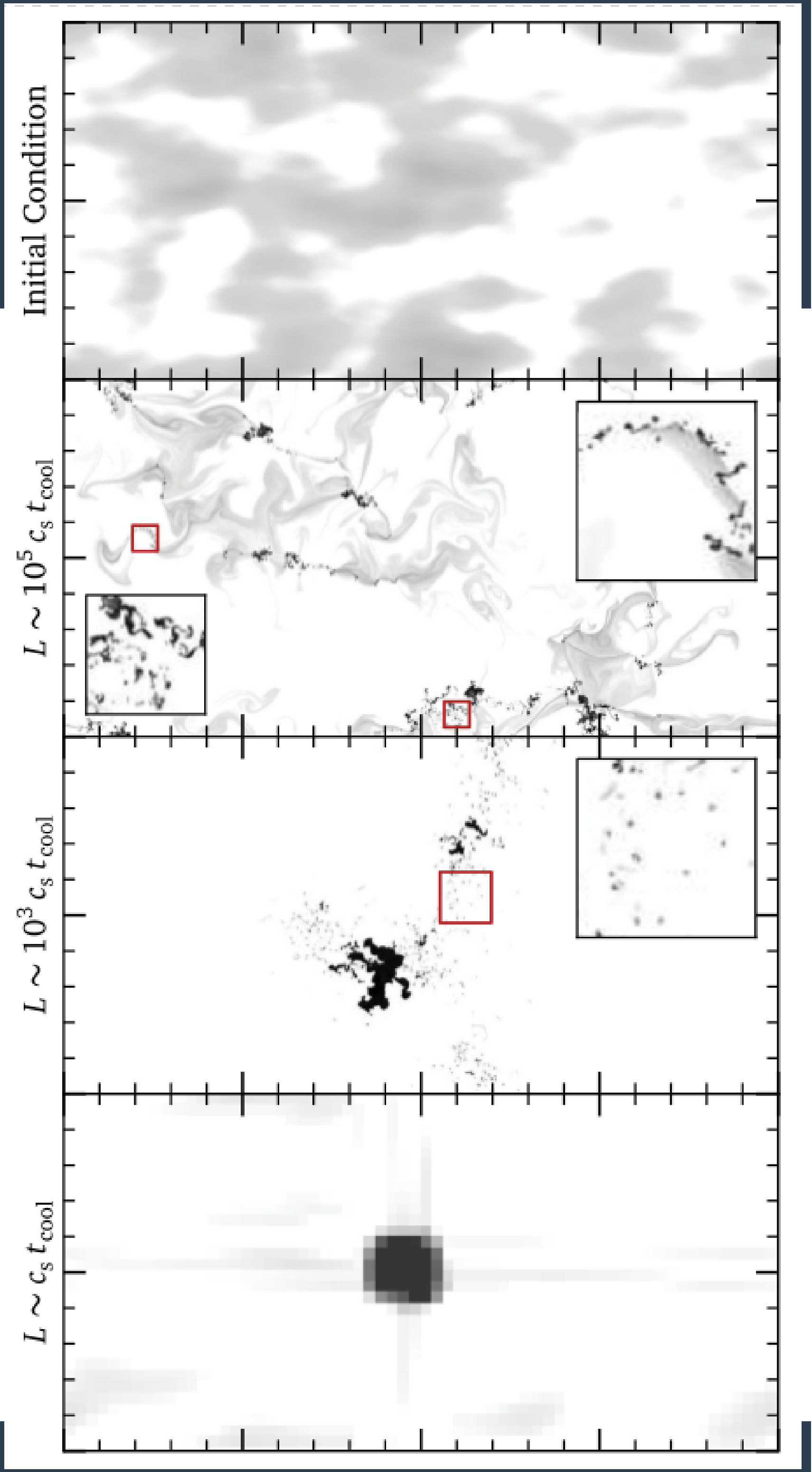
- Clouds larger than $c_s t_{cool}$ "shatter" into smaller clouds.

- Gas in (the outer parts) of galaxy might be in a different physical state than revealed by cosmological simulations.

These results are based on 2D simulations. My work:

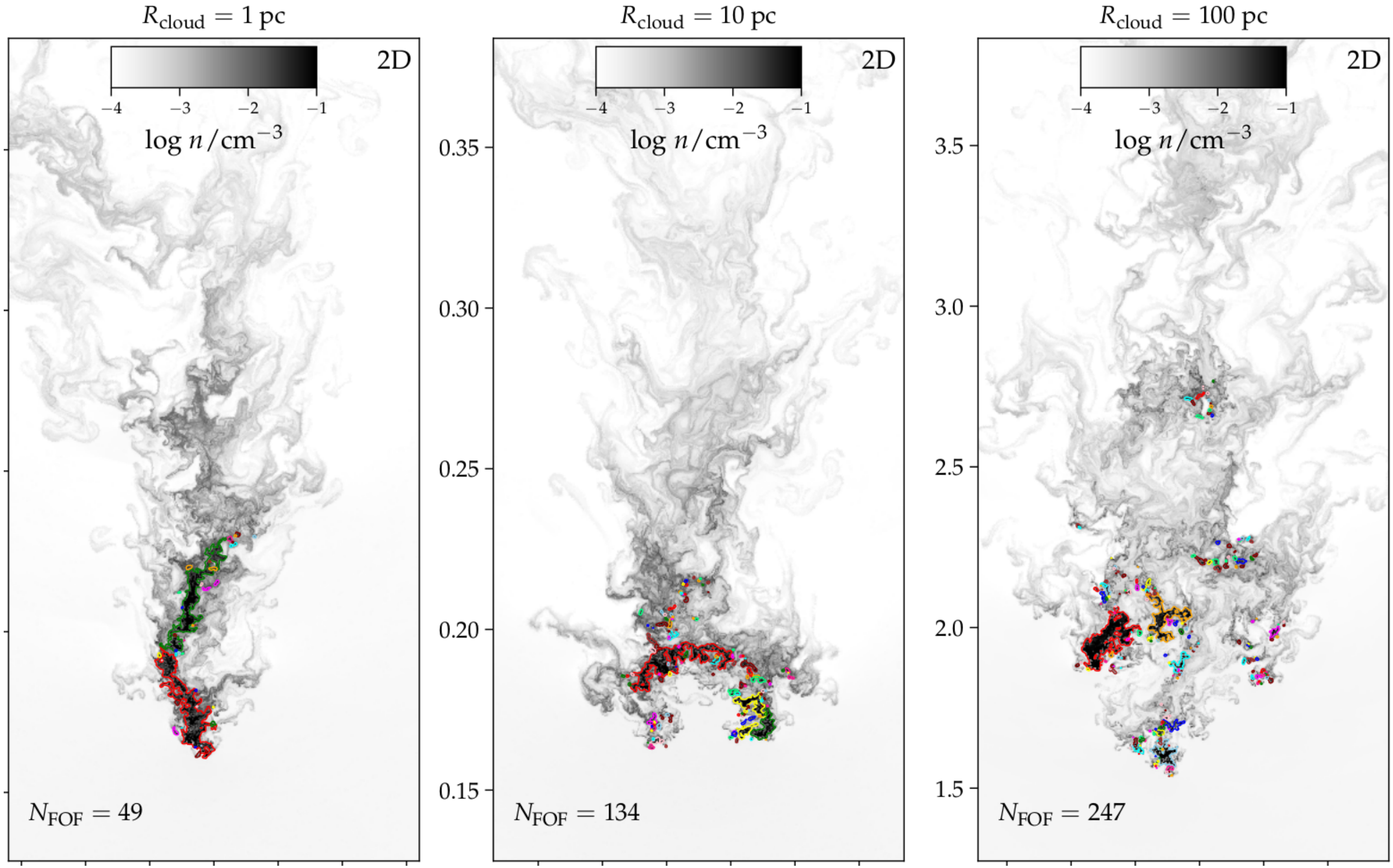
1) quantify fragmentation

2) 3D runs



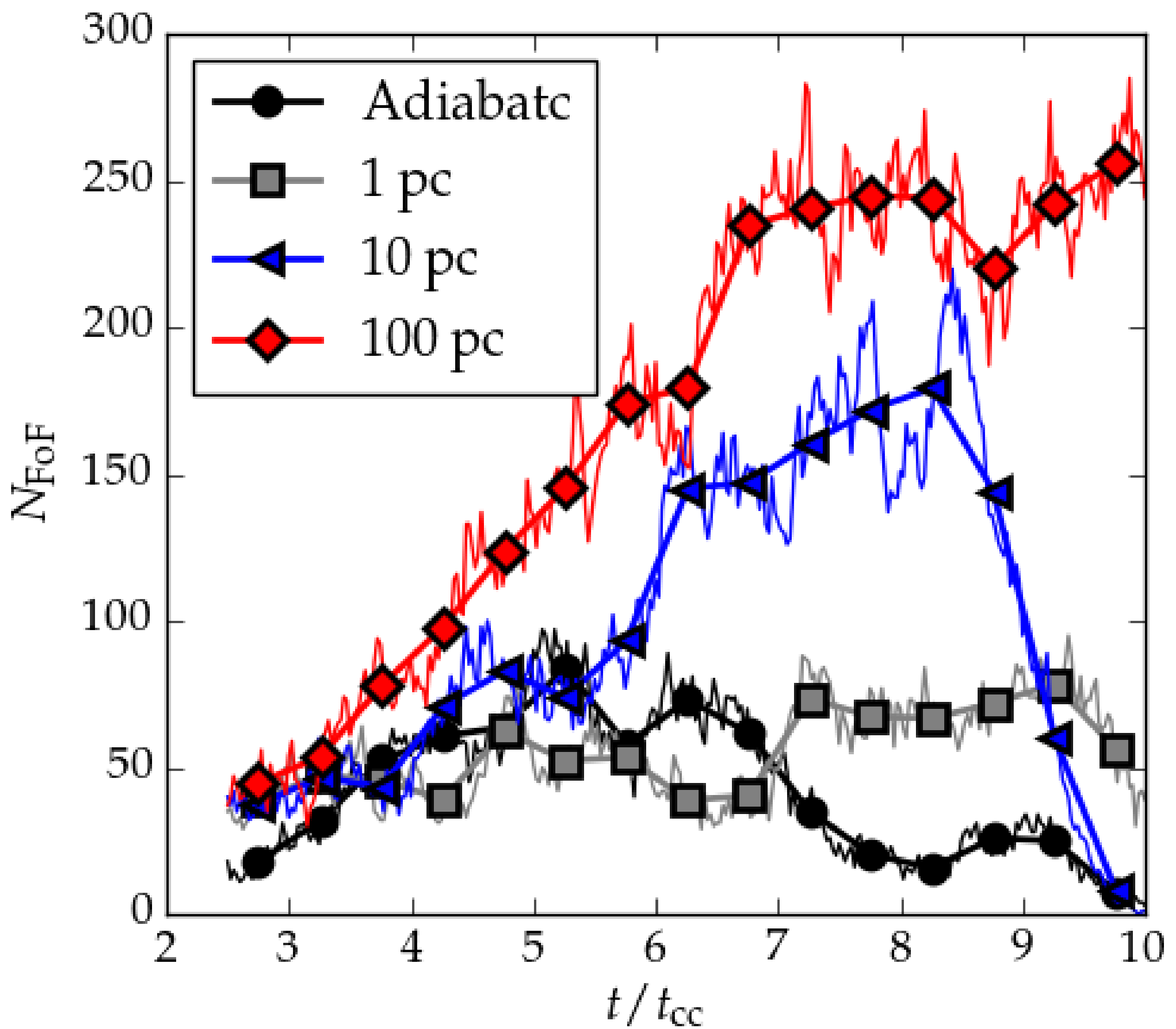
Quantifying the fragmentation

Friends-of-Friends analysis



MS, Pfrommer, Vogelsberger in prep.

Clouds larger than $c_s t_{cool}$ fragment



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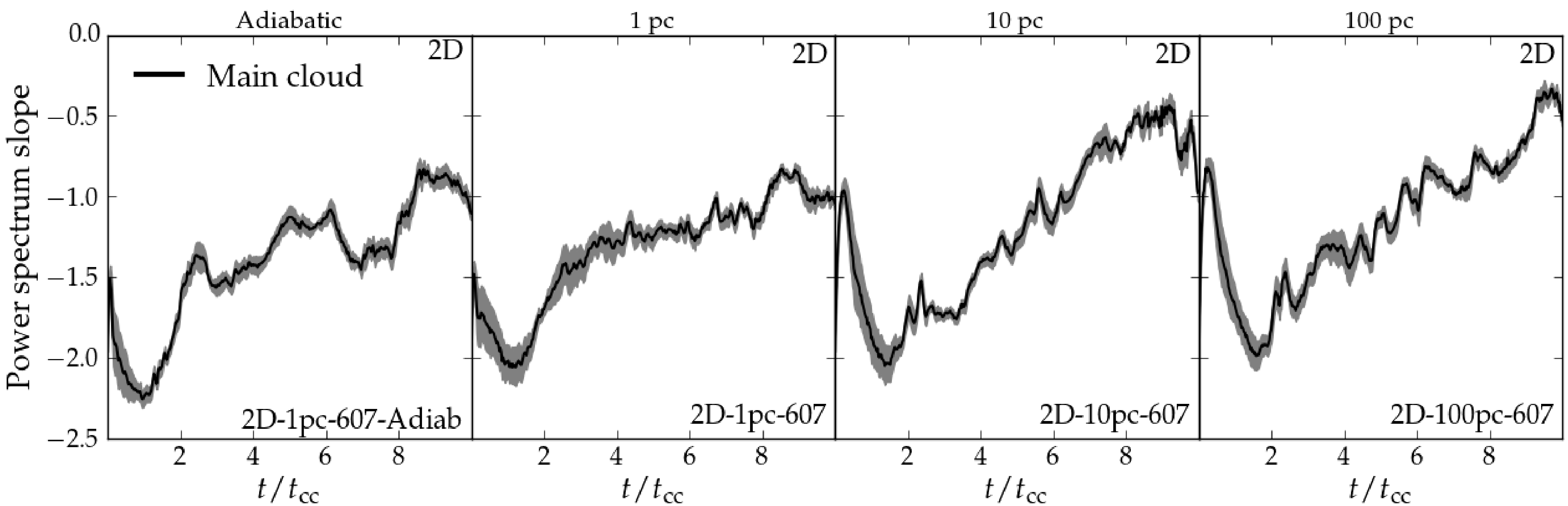
A shallow power spectrum is seen for clouds larger than $c_s t_{cool}$

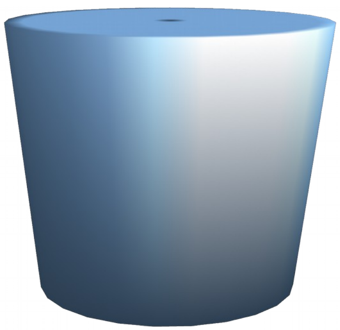


- **We have reproduced the McCourt results, and quantified the fragmentation.**

Two vs. three dimensions

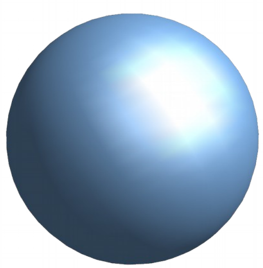
Potential flow solutions

A *potential flow* with div $\mathbf{v} = 0$ and curl $\mathbf{v} = \mathbf{0}$



$$\nabla \cdot \mathbf{v} = \frac{1}{\rho}\frac{\partial\left[\rho v_\rho\right]}{\partial \rho} + \frac{1}{\rho}\frac{\partial v_\phi}{\partial \phi},$$

$$\nabla \times \mathbf{v} = \frac{1}{\rho}\left[\frac{\partial\left[\rho v_\phi\right]}{\partial \rho} - \frac{\partial v_\rho}{\partial \phi}\right]\hat{\mathbf{z}},$$

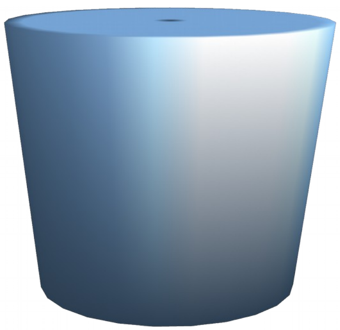


$$\nabla \cdot \mathbf{v} = \frac{1}{r^2}\frac{\partial\left[r^2 v_r\right]}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial\left[v_\theta \sin\theta\right]}{\partial \theta},$$

$$\nabla \times \mathbf{v} = \frac{1}{r}\left[\frac{\partial\left[r v_\theta\right]}{\partial r} - \frac{\partial v_r}{\partial \theta}\right]\hat{\varphi},$$

Potential flow solutions

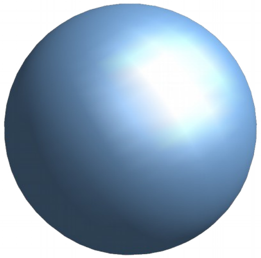
A *potential flow* has div **v** = 0 and curl **v** = 0



$$v_\rho = v_{\text{inject}}\left(1 - \frac{R^2}{\rho^2}\right)\cos\phi,$$

$$v_\phi = -v_{\text{inject}}\left(1 + \frac{R^2}{\rho^2}\right)\sin\phi,$$

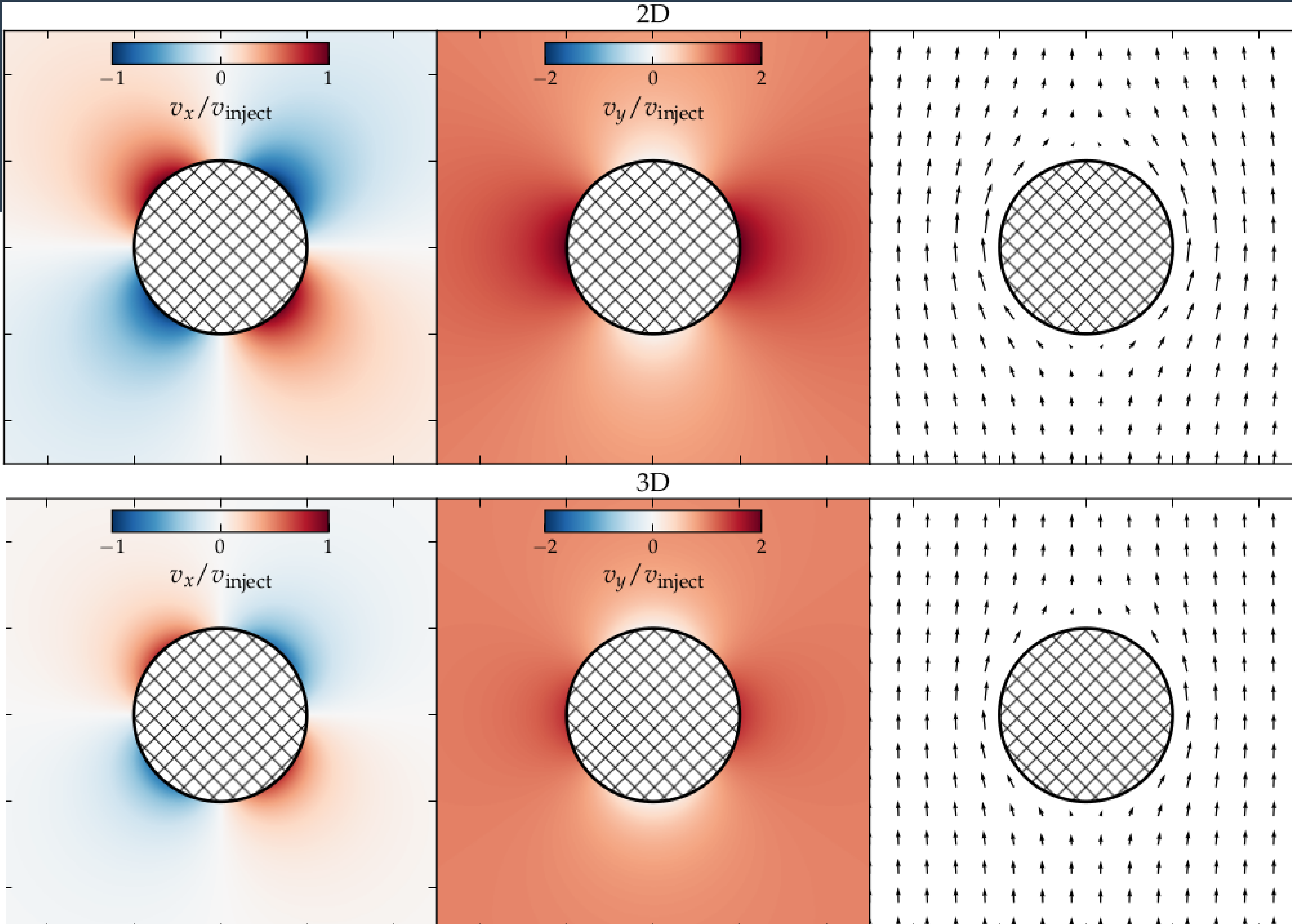
$$v_z = 0$$



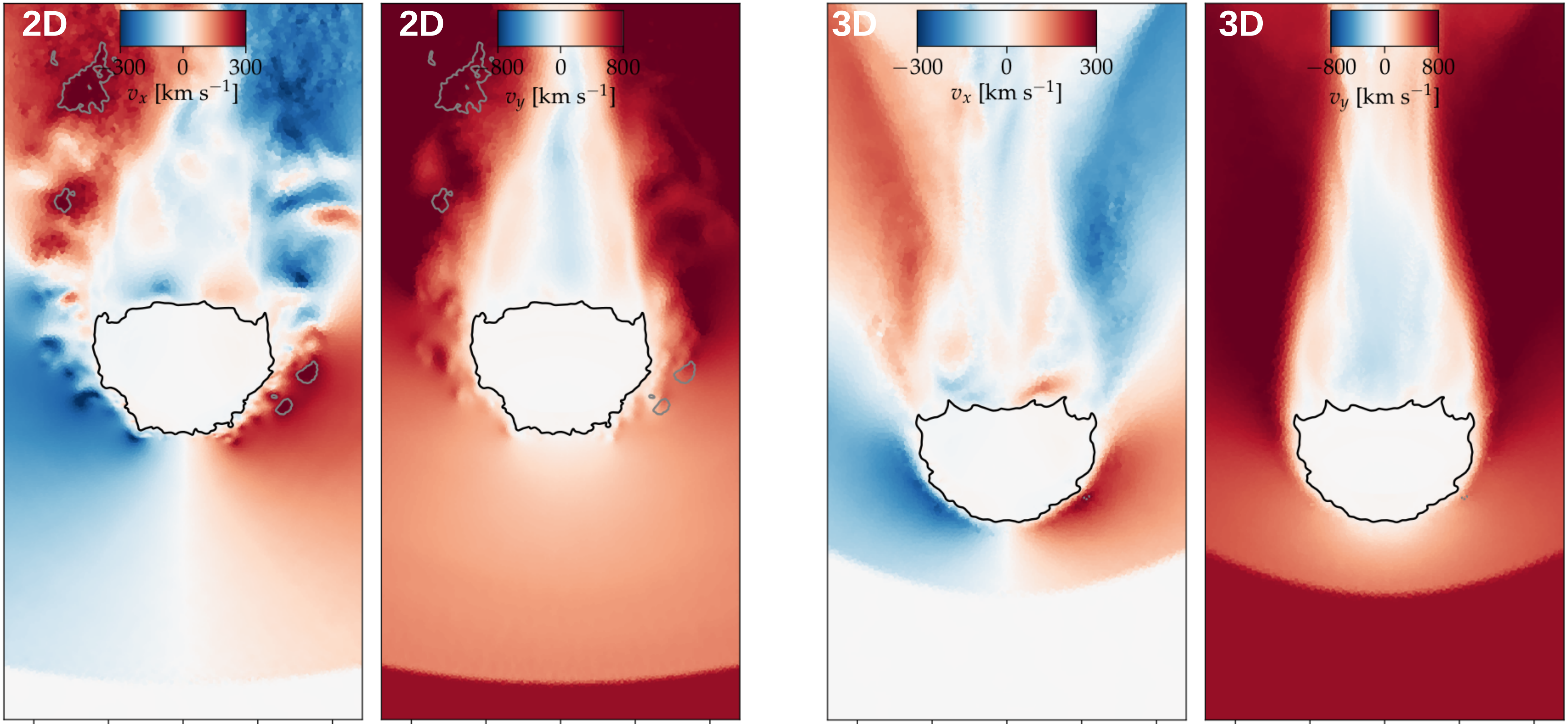
$$v_r = v_{\text{inject}}\left(1 - \frac{R^3}{r^3}\right)\cos\theta,$$

$$v_\theta = -v_{\text{inject}}\left(1 + \frac{R^3}{2r^3}\right)\sin\theta,$$

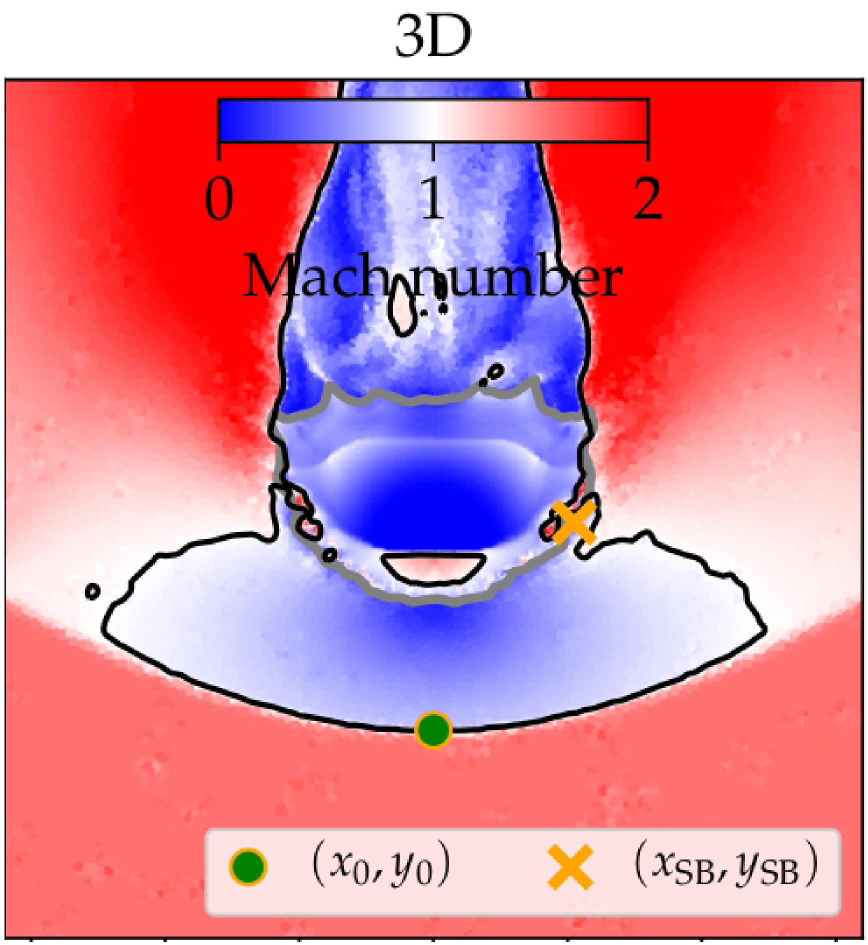
$$v_\varphi = 0,$$

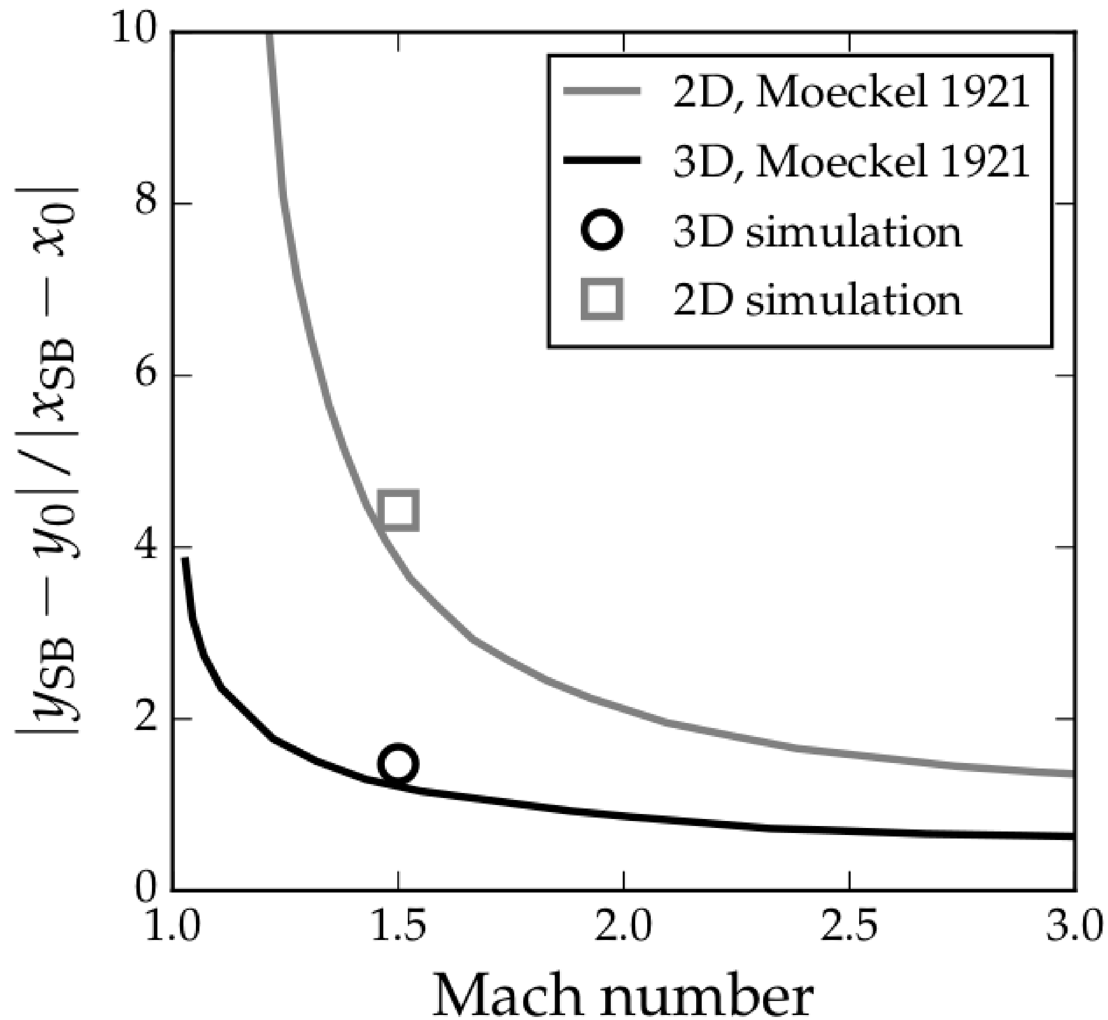

2D
−1 0 1
$v_x / v_{\rm inject}$
−2 0 2
$v_y / v_{\rm inject}$
3D
−1 0 1
$v_x / v_{\rm inject}$
−2 0 2
$v_y / v_{\rm inject}$

The velocity field in 2D and 3D



The standoff distance in 2D and 3D

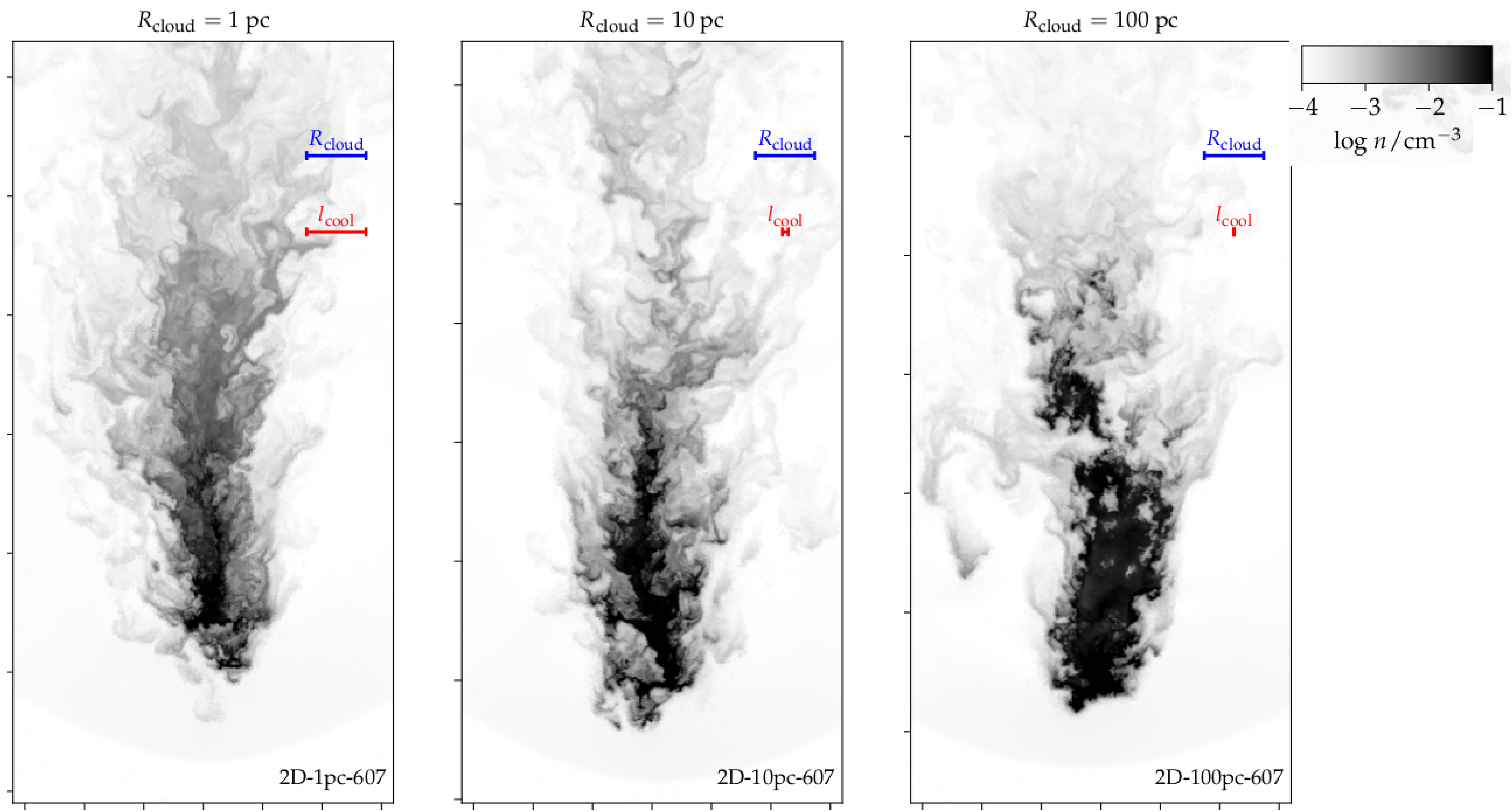




- **Standoff-distance is larger in 2D than in 3D**
- **Velocity around the cloud is largest in 2D.**

→ 3D is necessary

Shattering also occur in 3D!



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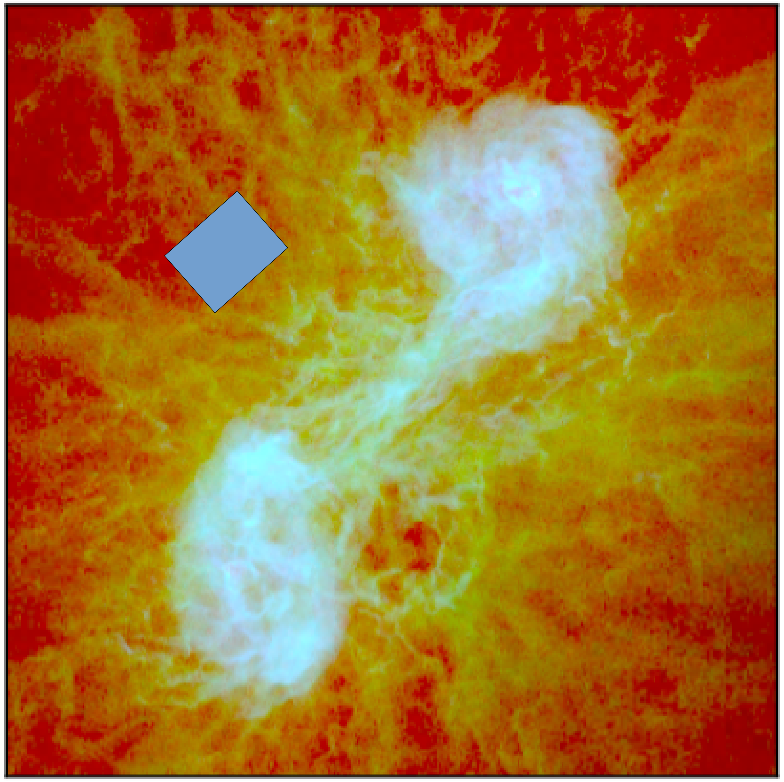
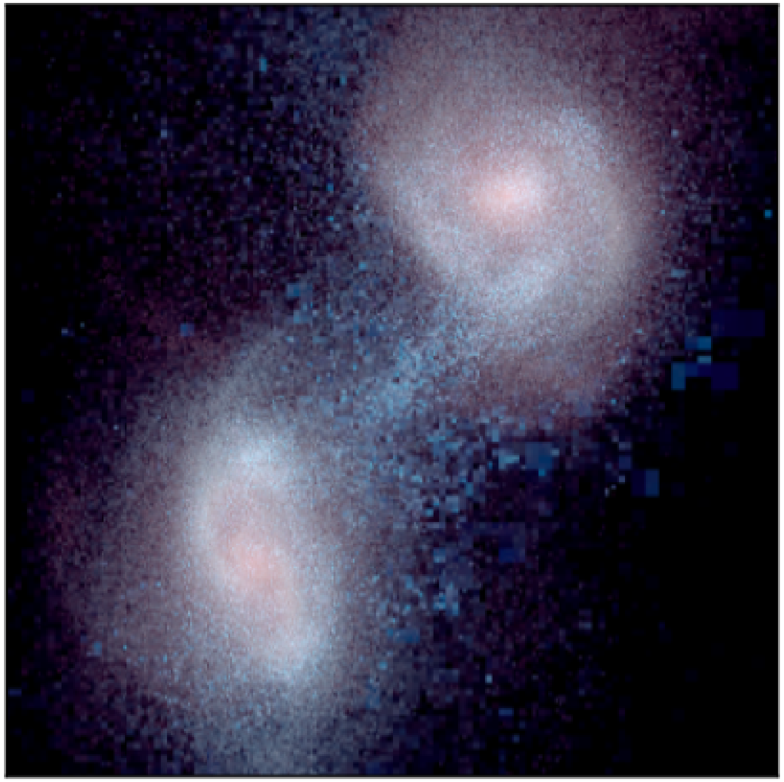
Future work

Next steps

- **Next steps: MHD, anisotropic thermal conduction.**
- **Link to cosmological simulations**

Conclusions

- 3D is necessary for a reliable treatment of bow shocks and the acceleration of cold clouds.

- Radiative cooling causes shattering of large clouds. Both in 2D and 3D. The gas in galaxy outskirts is probably in a different state than revealed by simulations.

- Next steps:
  MHD, anisotropic conduction. Cosmology.