Thermal Stability with Cosmic Ray Heating

I. Bottlenecks (Tsung, Oh & Jiang 2022)
II. Global Balance (Tsung, Oh & Bustard in prep)
III. In-Situ thermal instability (Tsung, Oh & Bustard in prep)

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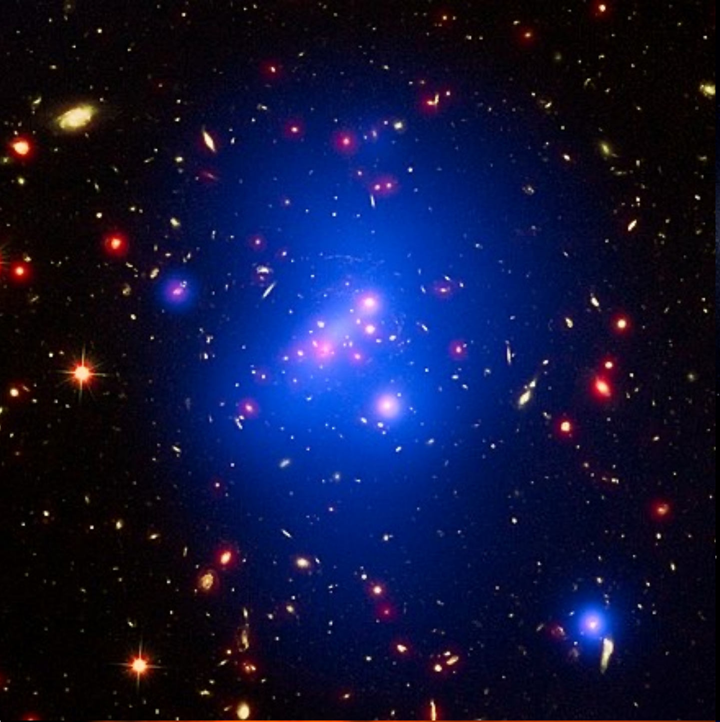
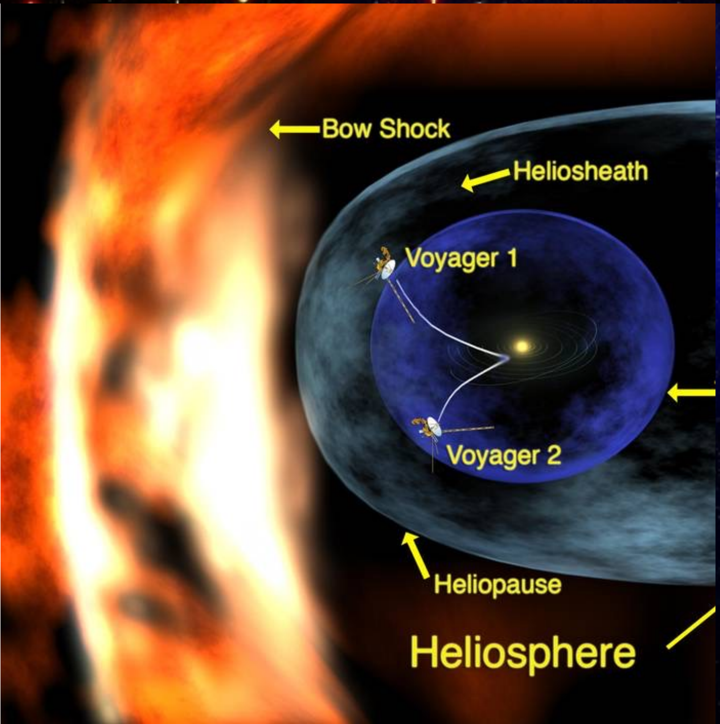
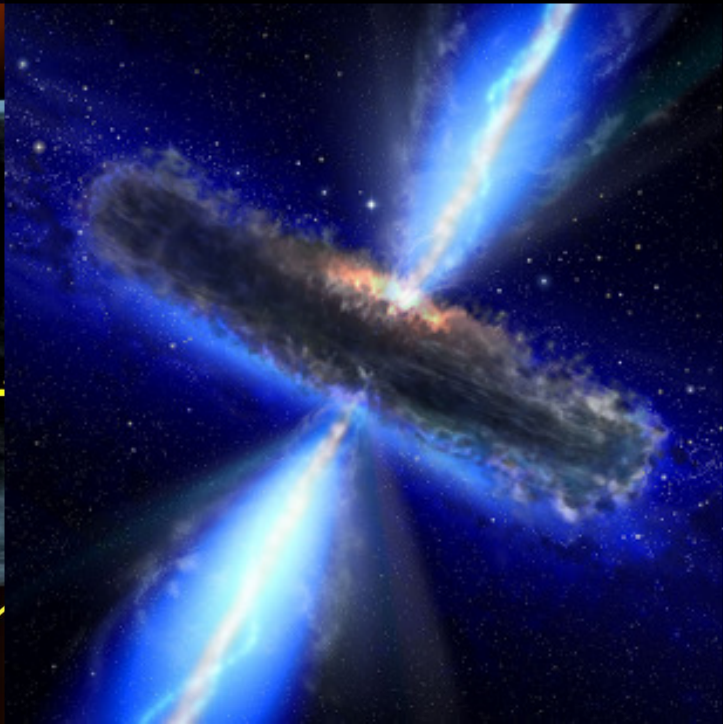
6th ICM workshop Copenhagen

XSEDE
Extreme Science and Engineering
Discovery Environment







Cosmic rays?

- Everywhere
- Observable in radio and gamma rays
- No radiative loss
- $\gamma_c = \frac{4}{3} < \frac{5}{3}$

COSMIC RAY FEEDBACK HEATING OF THE INTRACLUSTER MEDIUM

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ABSTRACT

Self-regulating active galactic nuclei (AGN) feedback in the cool cores of galaxy clusters plays central role in solving the decades-old cooling flow problem. While there is consensus that AGN provide most if not all of the energy needed to offset radiative losses in the intracluster medium (ICM) and prevent catastrophically large star formation rates, one major problem remains unsolved – how is the AGN energy thermalized in the ICM and what are the effective black hole feeding rates in realistic systems? We perform a suite of three-dimensional magneto-hydrodynamical (MHD) adaptive mesh refinement simulations of AGN feedback in a cool core cluster including cosmic ray (CR) physics. CRs are supplied to the ICM via collimated AGN jets and subsequently disperse in the magnetized ICM via streaming, and interact with the ICM via hadronic, Coulomb, and streaming instability heating. We find that CR transport is an essential model ingredient needed for AGN feedback to self-regulate, at least within the context of the physical model considered here. When CR streaming is neglected, the suppression of CR mixing with the ICM by magnetic fields significantly reduces ICM heating, which leads to cooling catastrophes. In the opposite case, when CR streaming is included, CRs come into contact with the ambient ICM and efficiently heat it, which results in globally stable atmospheres. Moreover, the dynamical state and intermittency of the central AGN are dramatically altered when CR streaming is present – while the AGN is never in a completely off-state, it is more variable, and the atmosphere goes through cycles characterized by low gas velocity dispersion interspersed with more violent episodes. We find that CR streaming heating dominates over the heating due to Coulomb and hadronic processes. Importantly, in simulations that include CR streaming, CR pressure support in the central 100 kpc is very low and does not demonstrably violate observational constraints. On the contrary, when CR streaming is neglected, CR energy is not spent on the ICM heating and CR pressure builds up to the level that is in disagreement with the data. Overall, our models demonstrate that CR heating is a viable channel for the thermalization of AGN energy in clusters, and likely also in elliptical galaxies, and that CRs play an important role in determining AGN intermittency and the dynamical state of cool core atmospheres.

8/18/22

Tsun Hin Navin Tsung

What Cosmological Sims Tell Us…

CRs can be a strong source of feedback in galaxies and clusters!

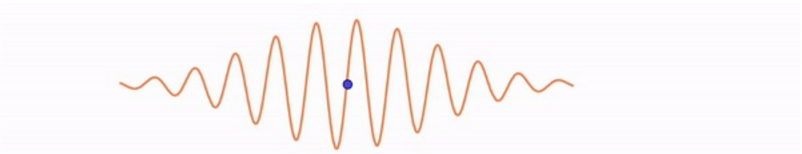
- CR pressure can drive outflows
- CR heating can suppress cooling flow

I. Bottlenecks

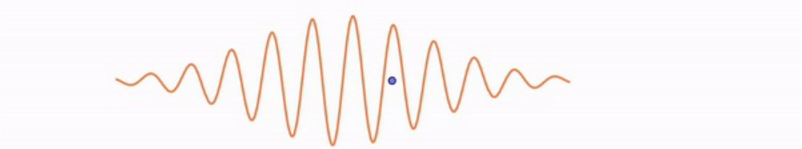
CR transport and confinement

Self-confinement
E < 300 GeV

CR streaming



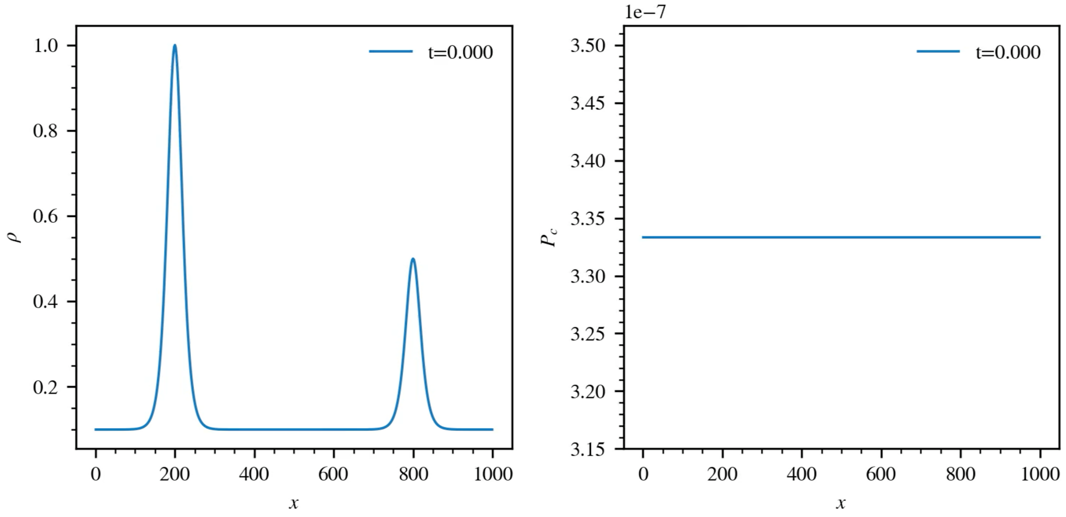
CR streaming + diffusion



- CR excite magnetic waves through the streaming instability if there is **CR anisotropy** (CR pressure gradient)
- Causes CRs to **advect at $\boldsymbol{v_A}$** with the magnetic waves down CR pressure gradient (streaming)
- CR **heats the gas at $-\boldsymbol{v_A}\nabla \boldsymbol{P_c}$**
- Scattering rate $\nu \sim \Omega\left(\frac{\delta B}{B}\right)^2$
- Slippage is captured by **diffusion correction**
- $\boldsymbol{F_c} = \gamma_c E_c(\boldsymbol{v} + \boldsymbol{v_s}) - \kappa\, \hat{b}\hat{b} \cdot \nabla P_c$

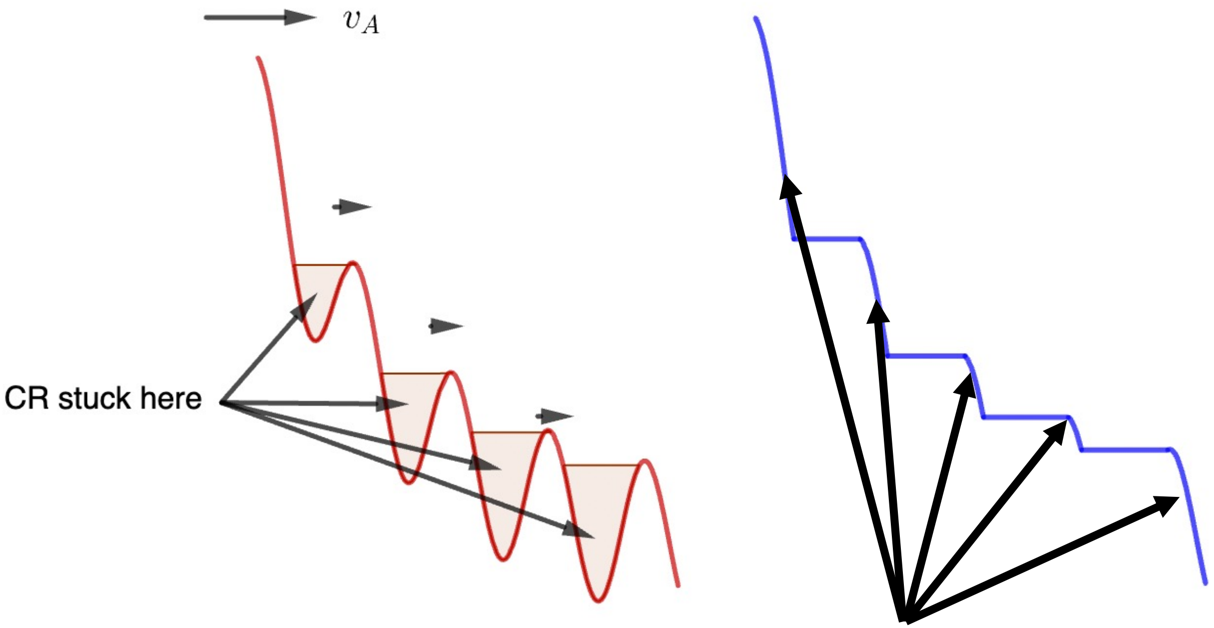
$P_c(v + v_A) \gg \kappa \nabla P_c$ (Streaming dominated)

CR flux



Density

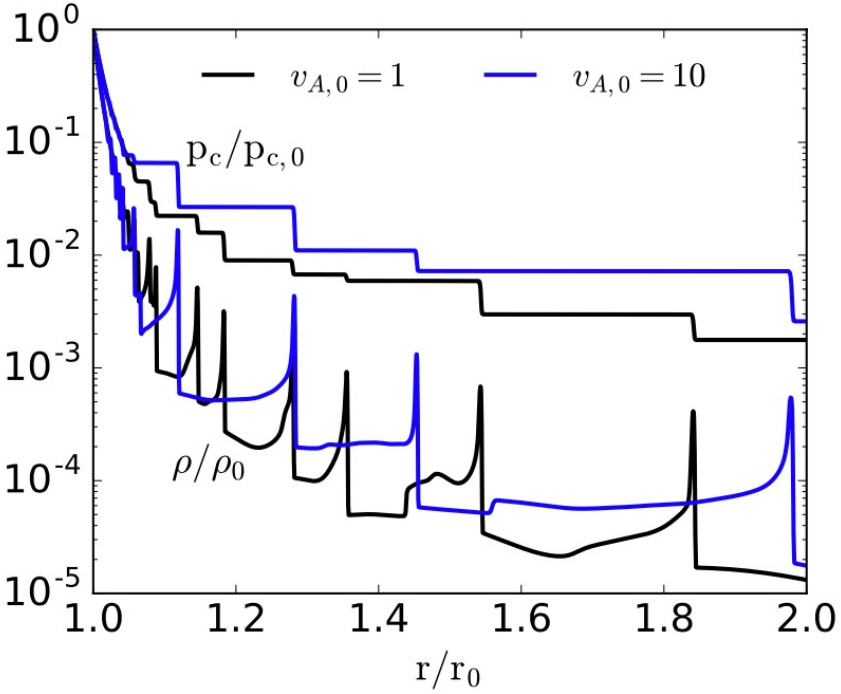
Cosmic Ray Pressure



$P_c = (v + v_A)^{-4/3}$
(Skilling 71, Wiener+13)

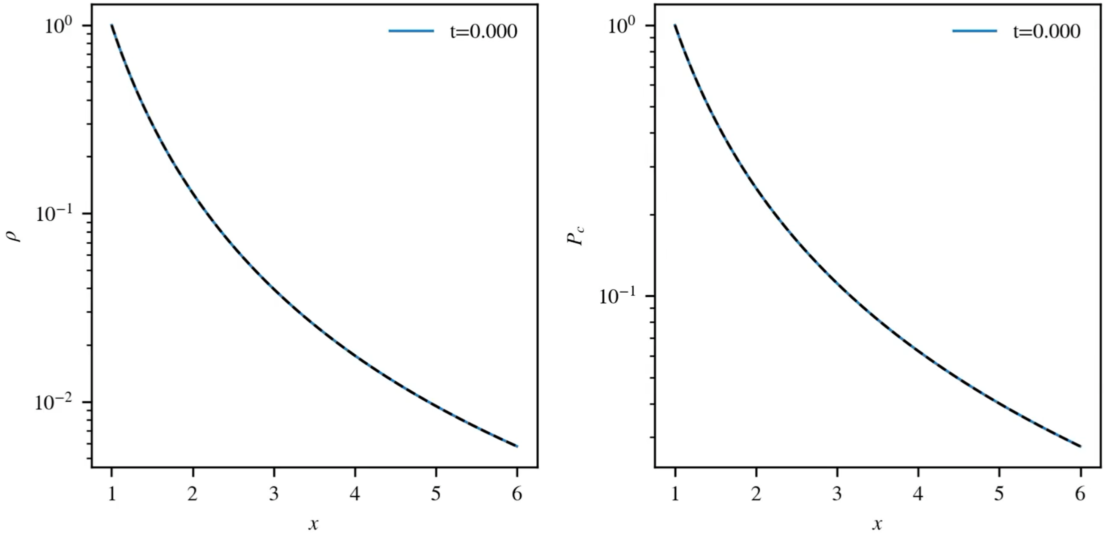
Where would you find bottlenecks?

Galactic Winds

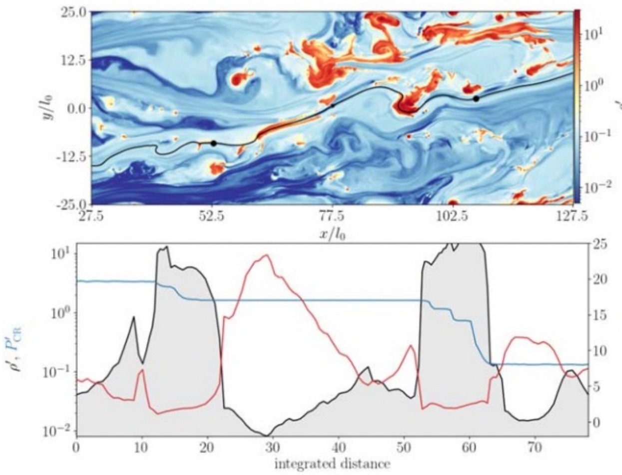


Quataert, Jiang & Thompson 2021

CR acoustic instability

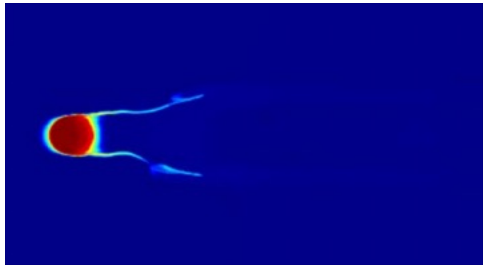


Tsung, Oh & Jiang 2022



Cold clouds acceleration

Huang, Jiang & Davis 2022

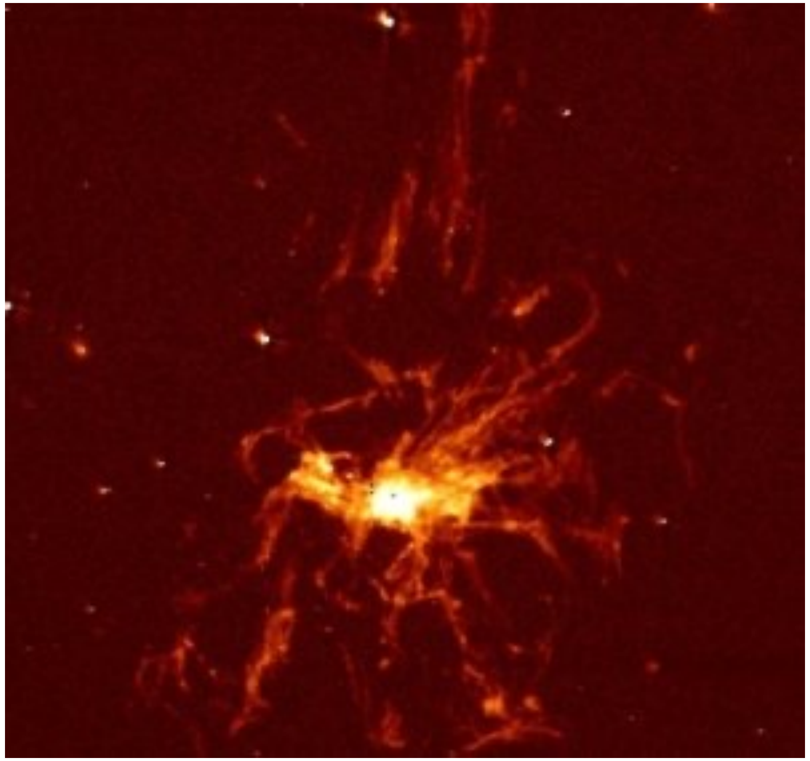


Bruggen & Scannapieco 2020

(for related work, see also Wiener+2019)

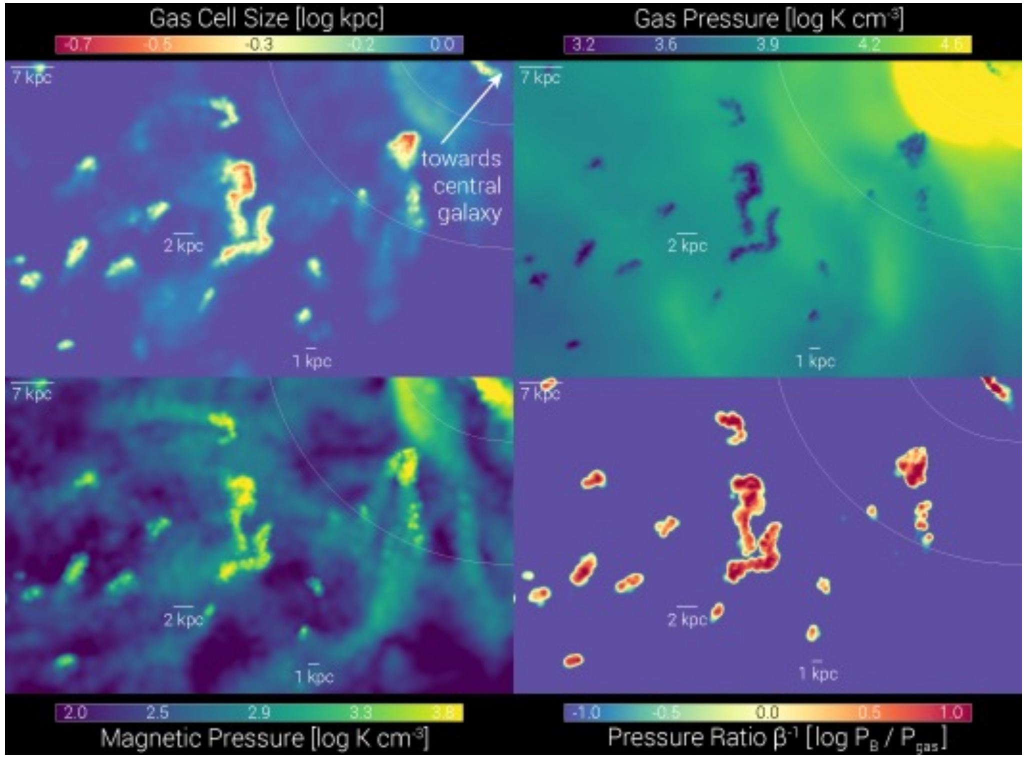
Plenty of cold clouds…

H-alpha filaments



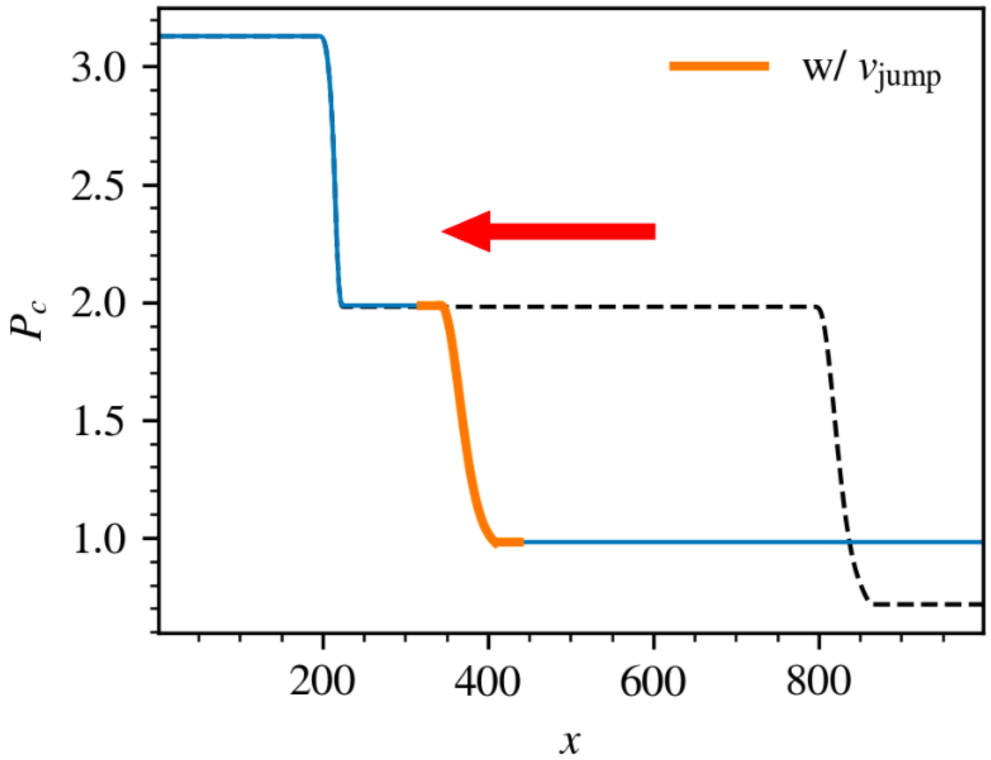
Fabian+2003

Cold gas @ cosmological sims



Nelson+2020

Cold gas is dynamically moving… What about the bottlenecks then?



Tsung, Oh & Jiang 2022

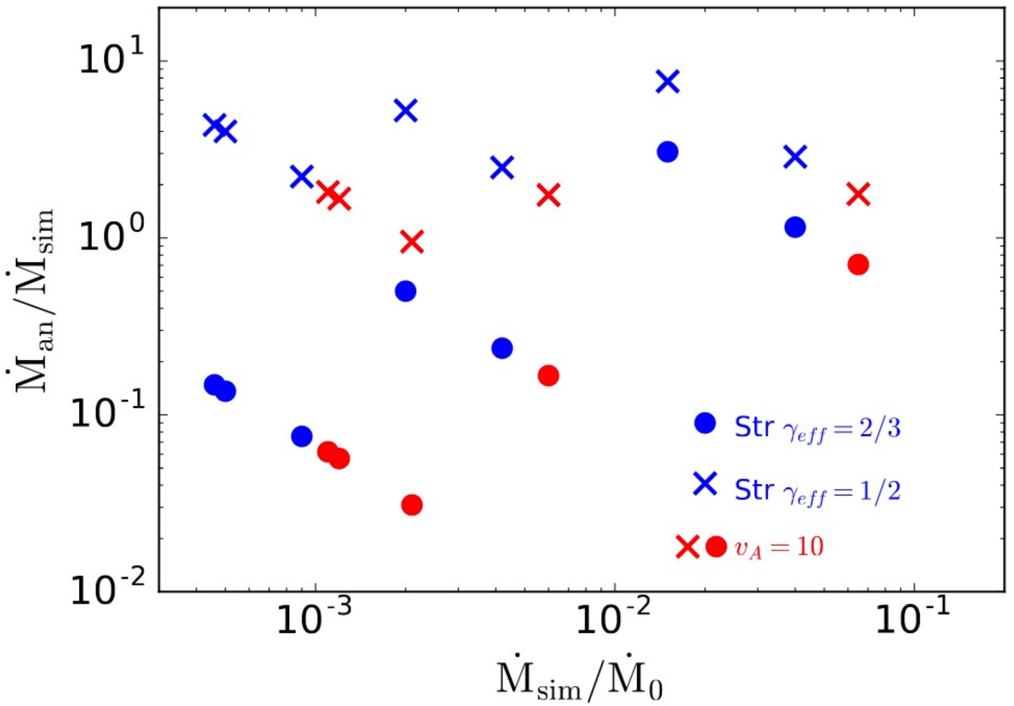
$P_c \propto (v + v_A)^{-4/3}$ ✗

$$P_c \propto \left(v + v_A - v_{\rm bump}\right)^{-4/3}.$$ ✓

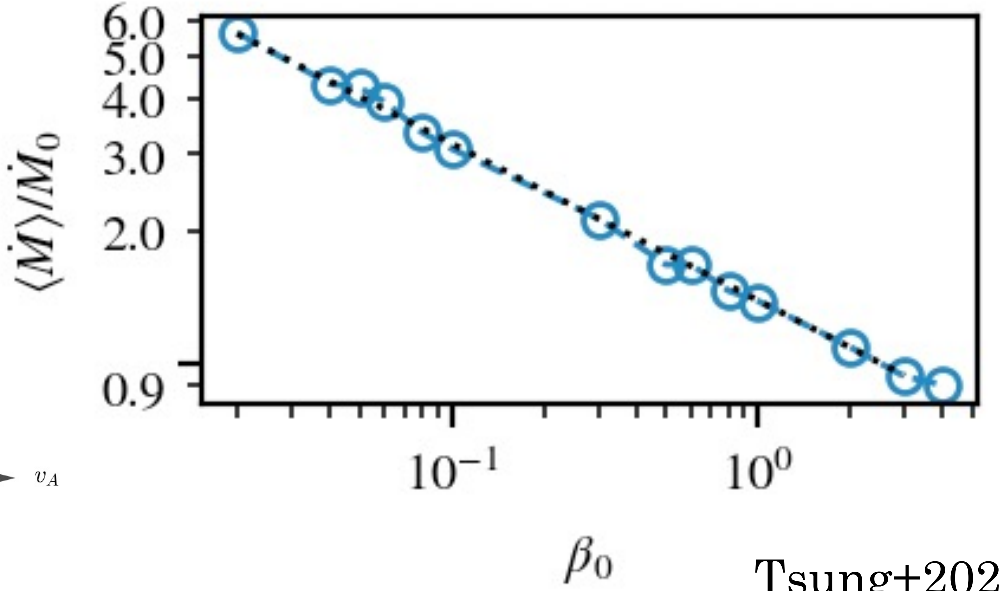
- If $v_{\rm bump} \to v + v_A$,

Bottleneck suppressed

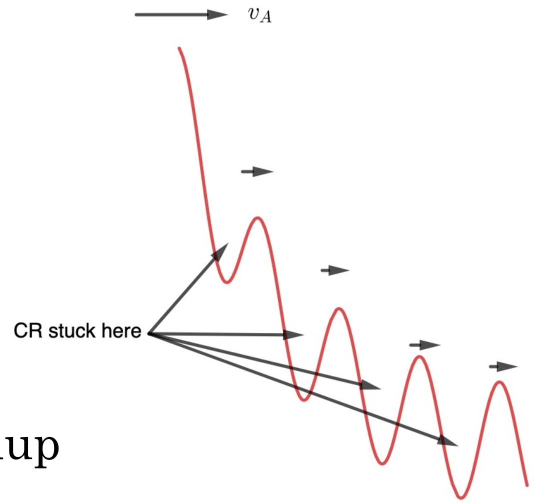
Bottlenecks can enhance mass outflow



Quataert+2021



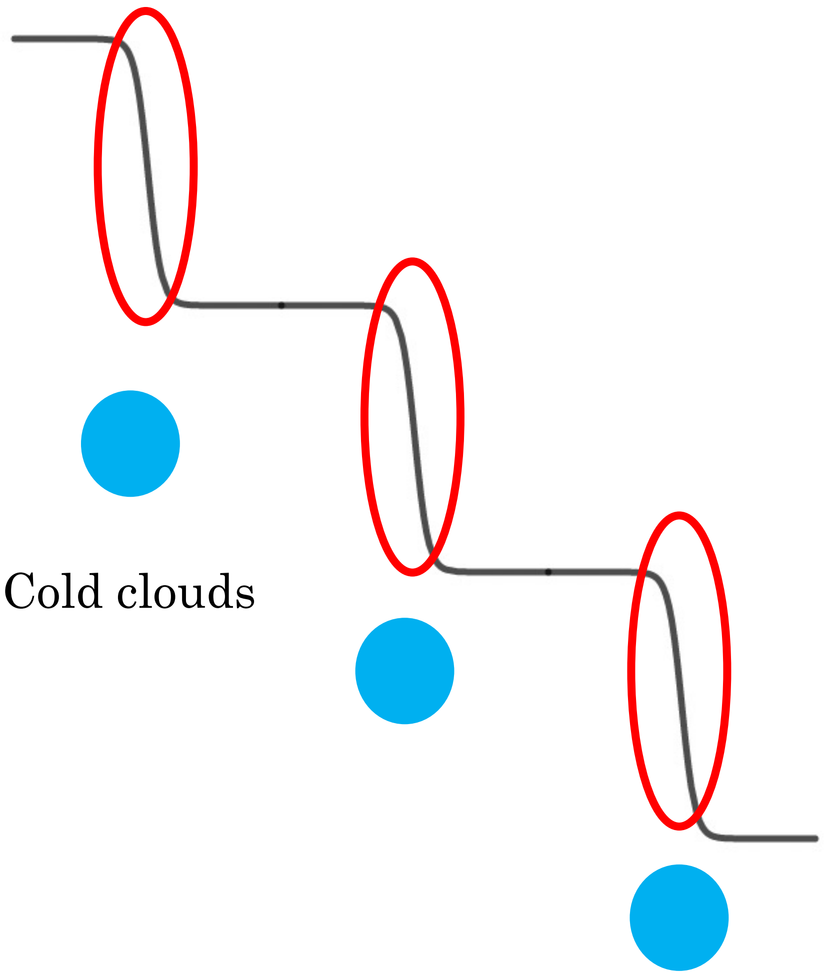
Tsung+2022



- Bottlenecks causes greater pressure buildup

II. Global Balance

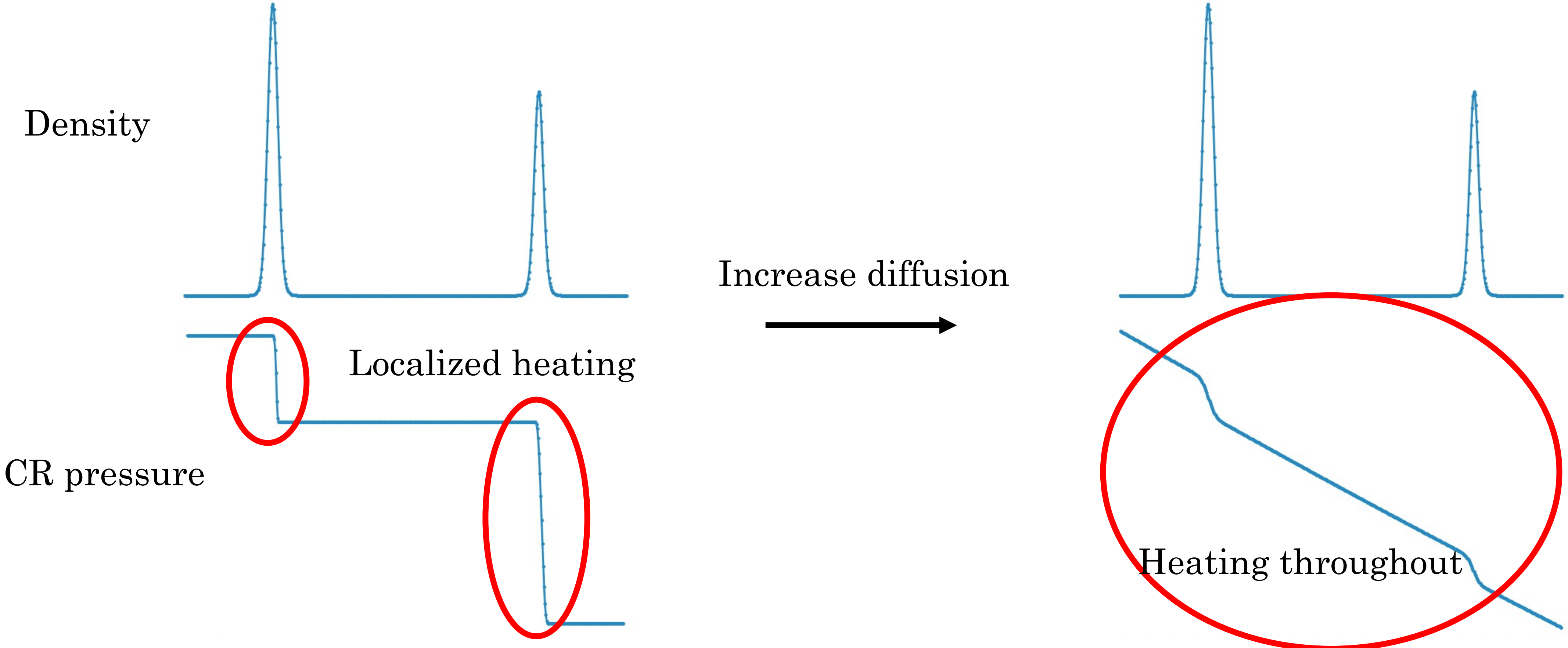
Bottlenecks redistributes CR heating and pressure forces

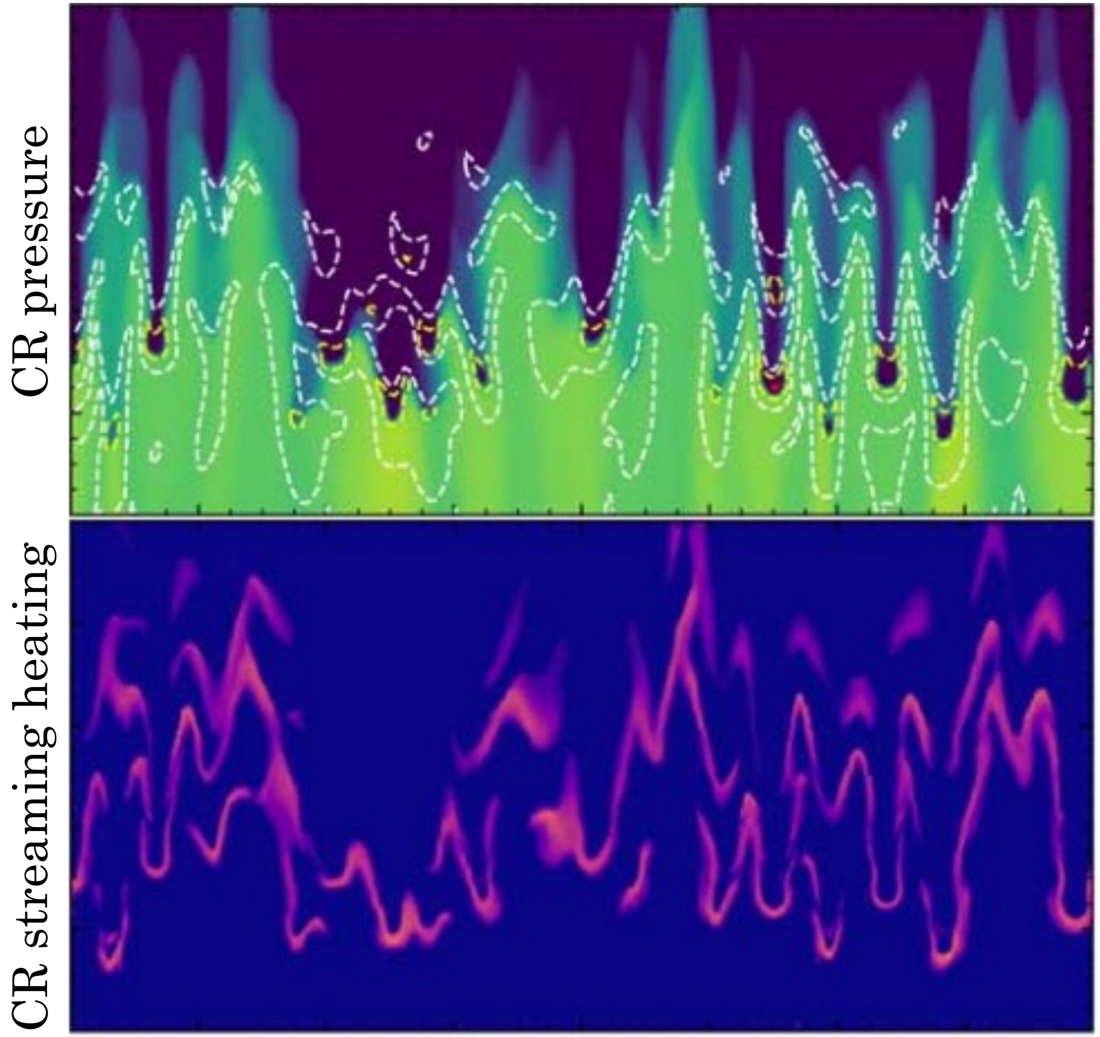


- CR heating $-v_A \nabla P_c$, CR pressure force ∇P_c
- Only heating and forcing at the jumps, not plateau
- Jumps occurs at cold clouds, where cooling is strong
- No heating on the hot gas

If there is large CR diffusion

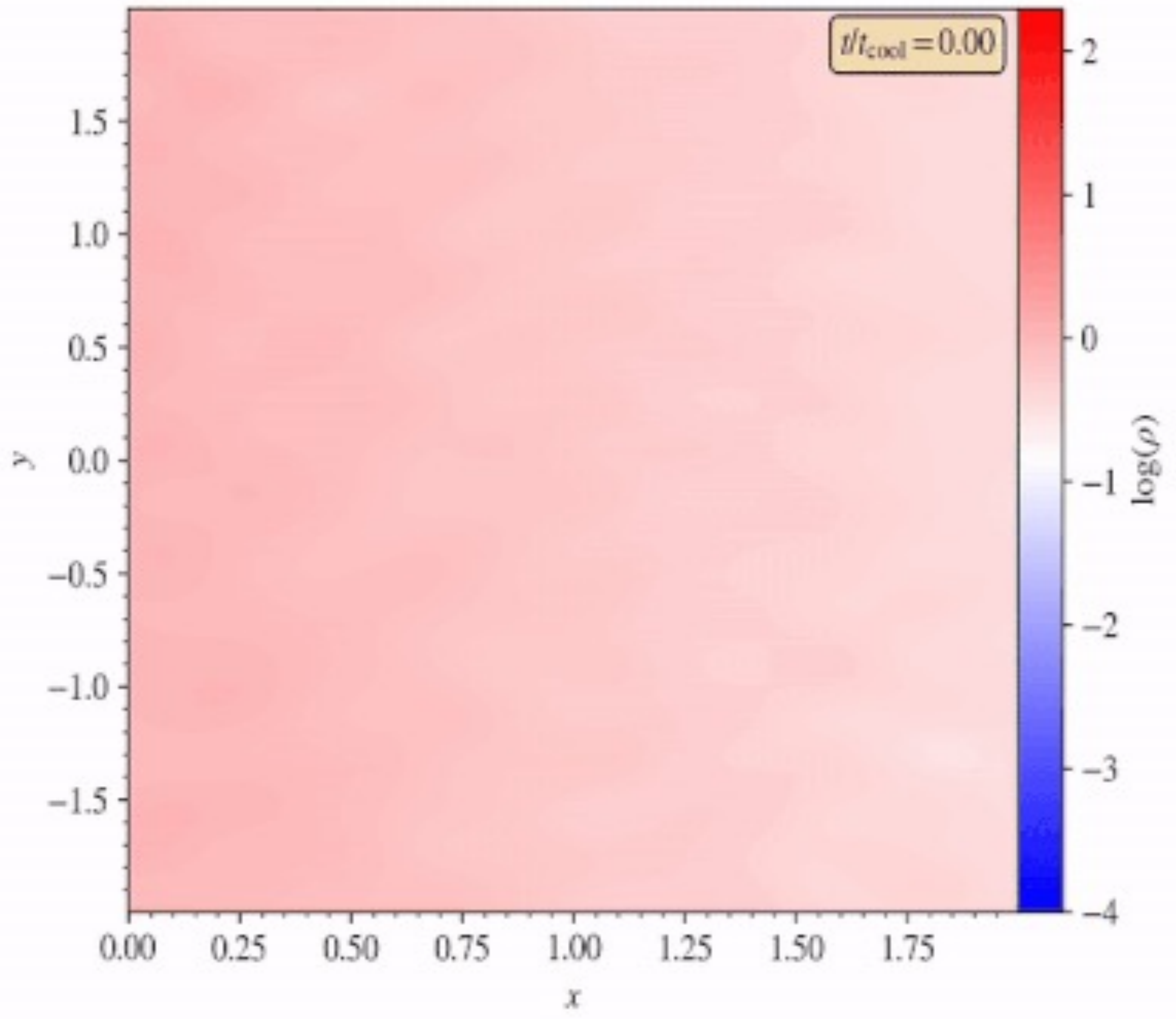
- When $\kappa \nabla P_c > P_c(v + v_A)$ (Diffusion dominated)





Bustard & Zweibel 2020

- For stationary clouds, bottlenecks do form, and heating is concentrated at the clouds (Bustard & Zweibel 2020)
- Question: In an environment where cold gas can move around with dynamics, what would the bottleneck do to CR heating and hence on its prospect in sustaining a self-regulated cycle?
- What kind of setup do we want: Ideally where cold gas can be formed and evolve self-consistently, with one setup having a staircase and the other doesn't

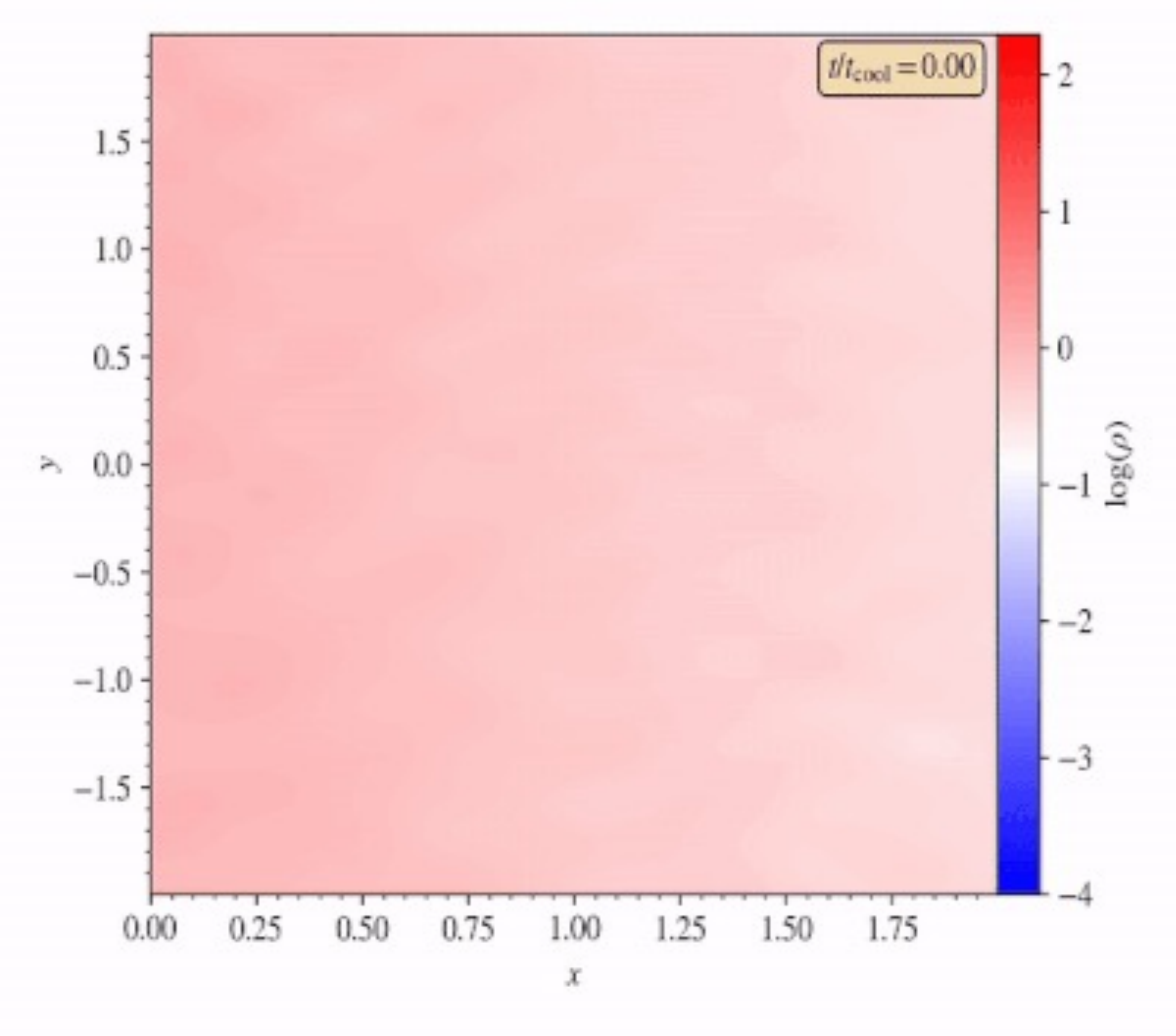


- Ingredients:
  - Cold clouds in stratified medium
  - CR with streaming heating

- Begin with a two-fluid stratified thermal instability setup
- Produce cold gas from thermal instability
- CRs evolved with the two-moment method

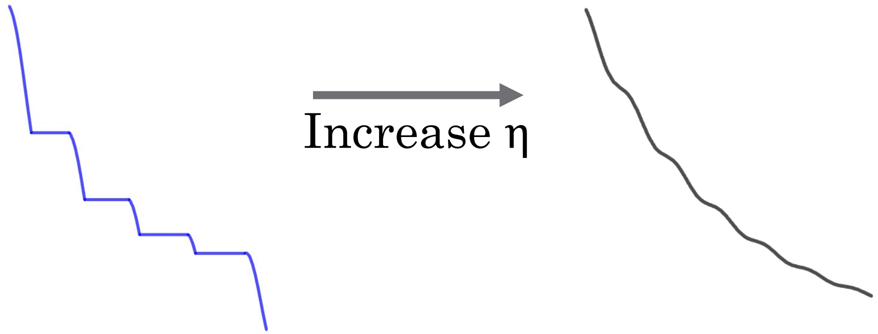
- Two kinds of heating:
  1. $H = \langle \rho^2 \Lambda \rangle$ (Magic heating, McCourt+2012)
  2. CR heating $-v_A \nabla P_c$

- After reaching a certain cold mass fraction, cut away $H = \langle \rho^2 \Lambda \rangle$
- Observe how CR heating rate is distributed and evolve



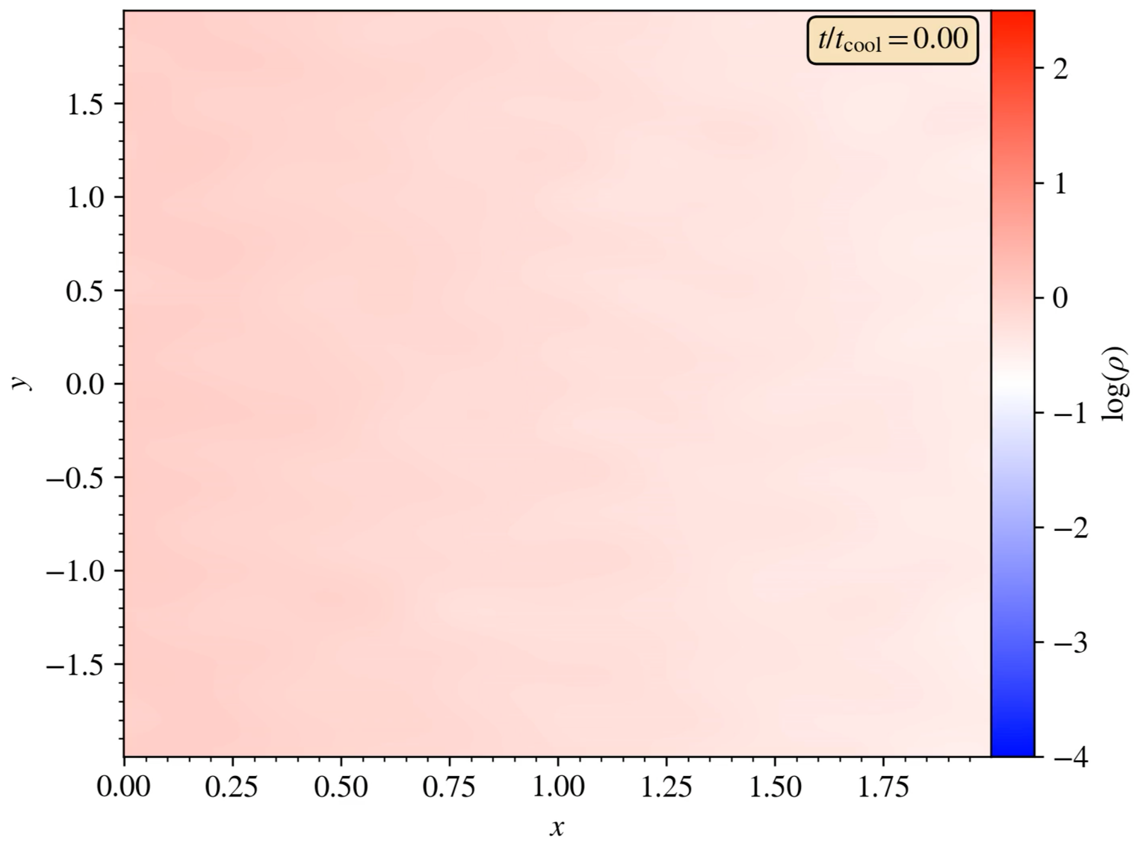
- $\eta = \frac{\kappa}{v_A L_c}$

- Bottleneck staircase can be switched on and off by changing η



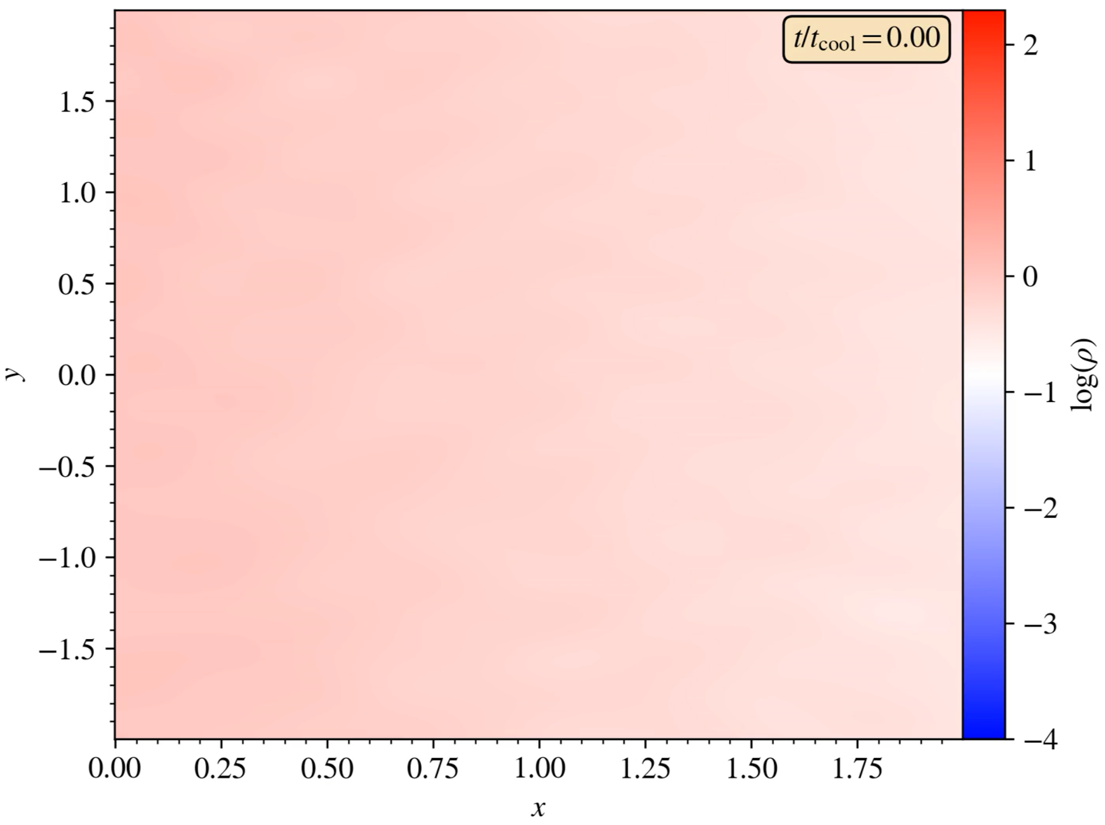
Diffusion smoothed

$P_c/P_g \approx 1, \beta \approx 100, \eta \approx 1, t_{\rm cool}/t_{\rm ff} \approx 0.68$

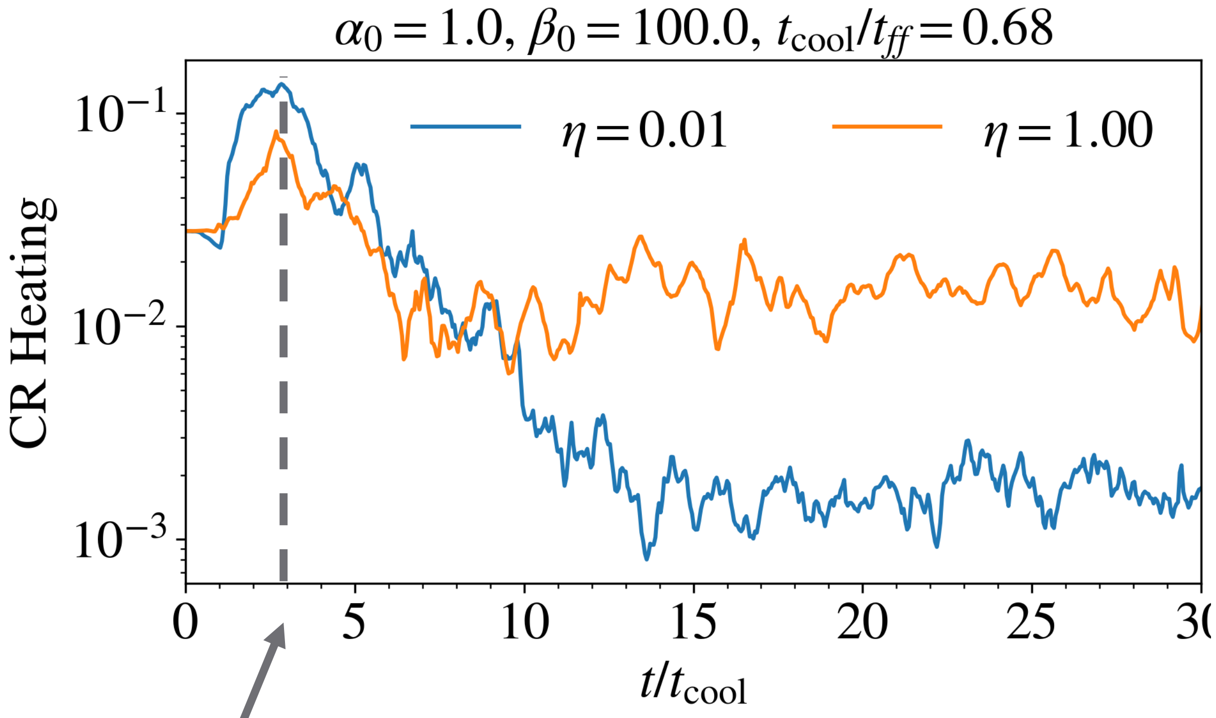


Low diffusion

$P_c/P_g \approx 1, \beta \approx 100, \eta \approx 0.01, t_{\rm cool}/t_{\rm ff} \approx 0.68$



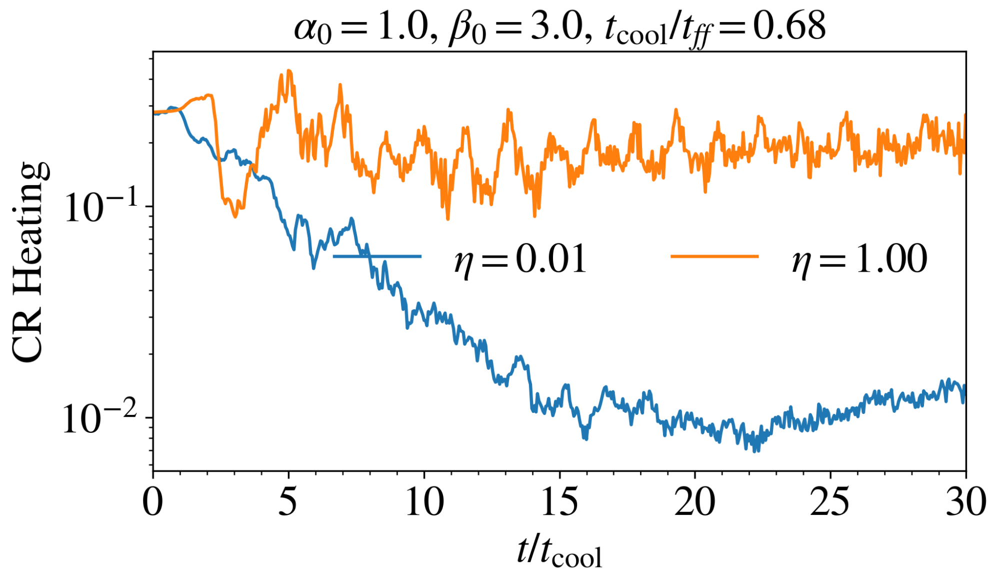
CR heating rate



Tsung, Oh, Bustard 2022(In prep)

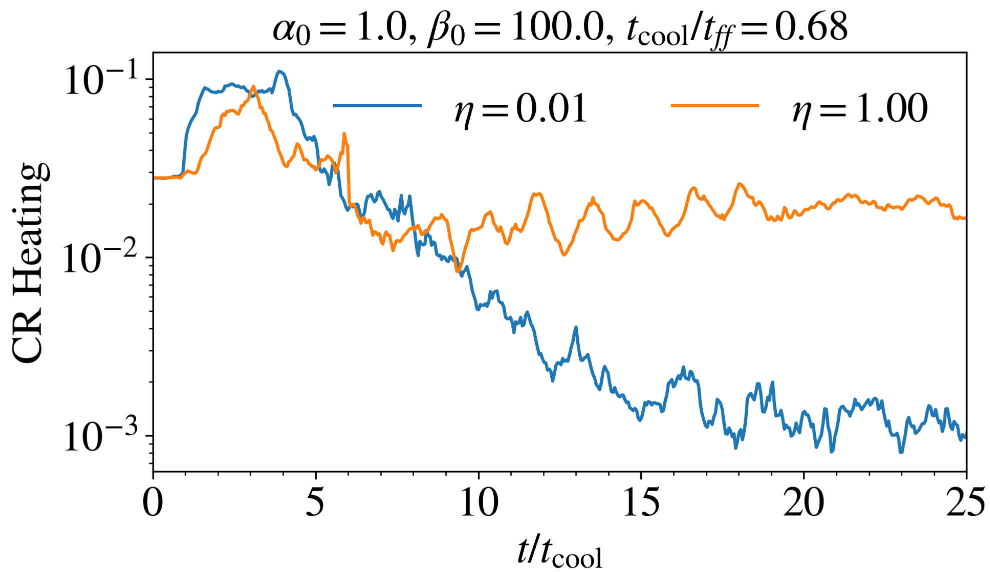
Magic heating cut off

Stronger B-field



Higher resolution

High diffusion



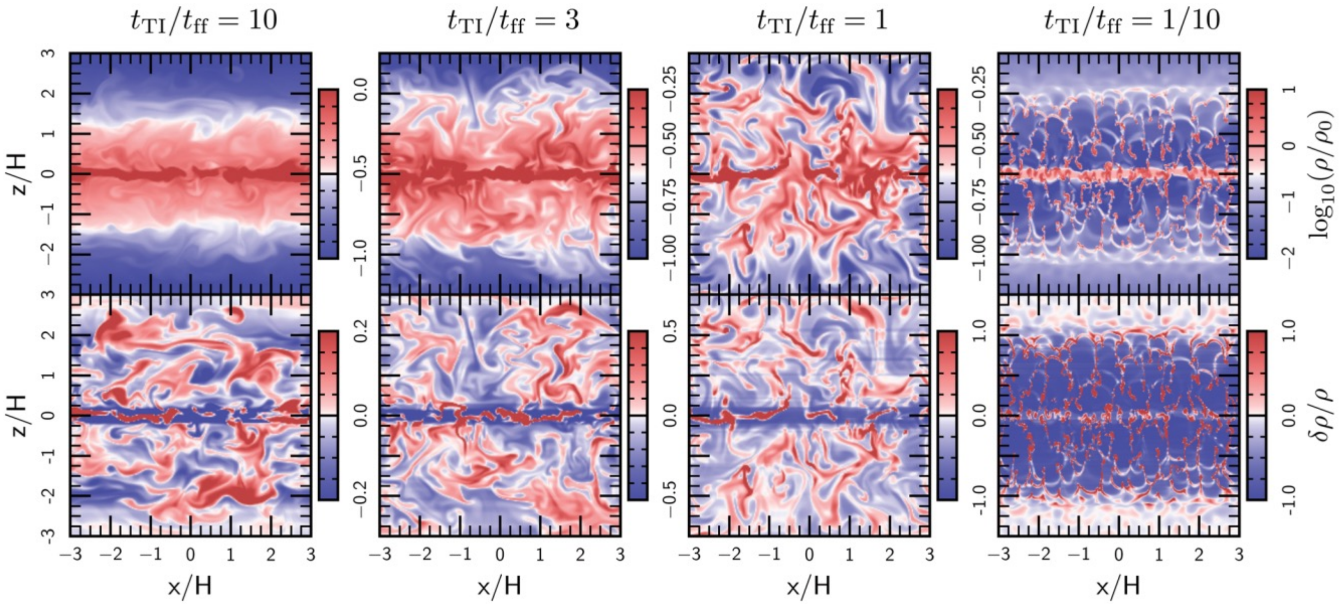
Some further work

- How does the staircase survive in turbulent medium?
- Currently running a set of 3D simulations
- Wider parameter study

- Bottom line: We believe the staircase could destabilize the atmosphere by redistribution of CR heating

III. In-Situ Thermal Instability

Thermal Instability with CR

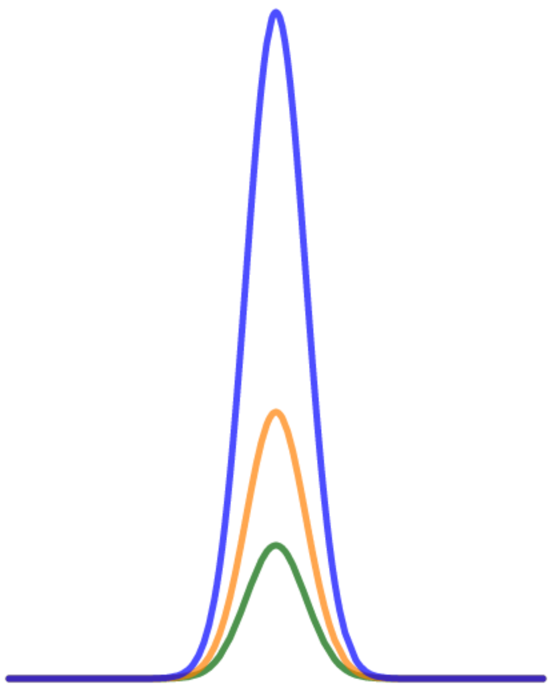


- McCourt, Sharma, Quataert, Parrish 2012
- Sharma, McCourt, Quataert, Parrish 2012
- Gaspari, Ruszkowski, Sharma 2012
- Sharma+2012
- Gaspari, Ruszkowski, Oh2013
- Voit, Bryan, O'Shea, Donahue 2015
- Yang & Reynolds 2016
- Ji, Oh, McCourt 2016
- Li, Ruszkowski, Bryan 2017
- Li, Ruszkowski, Tremblay 2018
- Choudury+2019
- Butsky+2020 (CR)

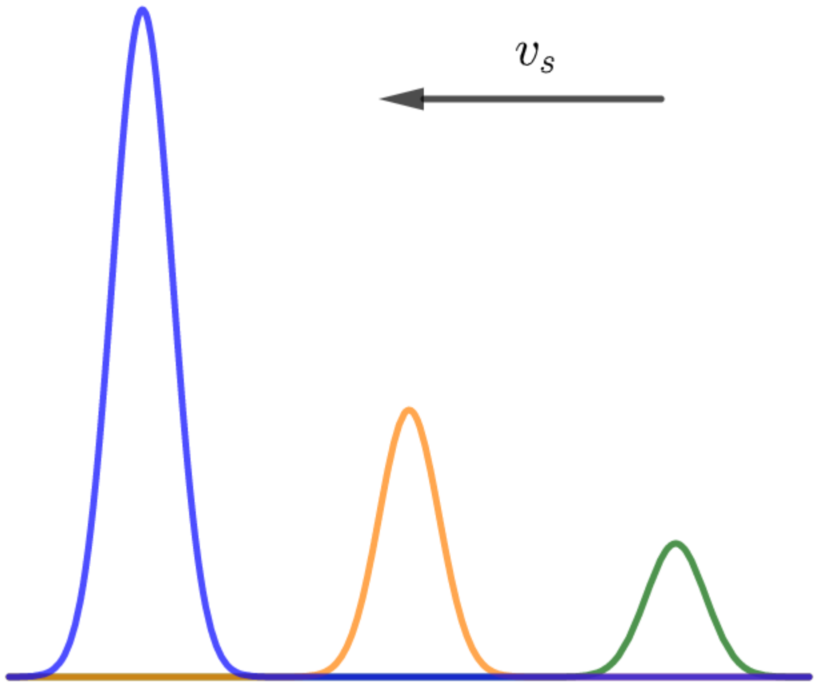
Again? Isn't the story completed??

What's new if $B \parallel g$?

No CR

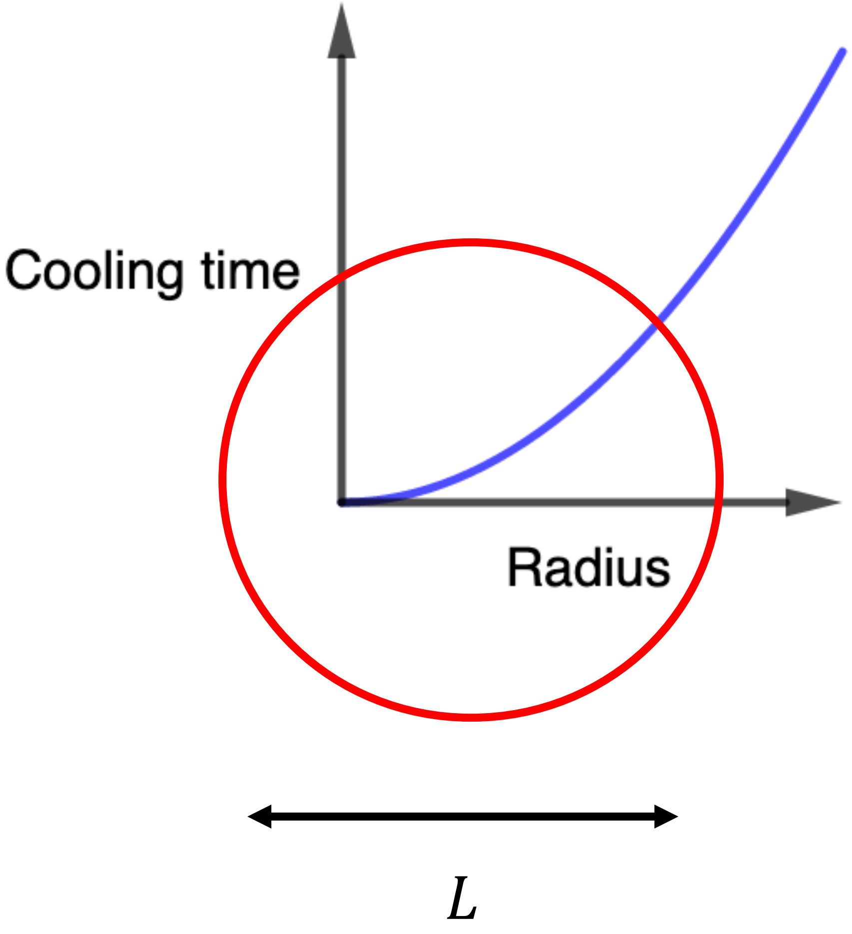


With CR (Kempski+ 2020)



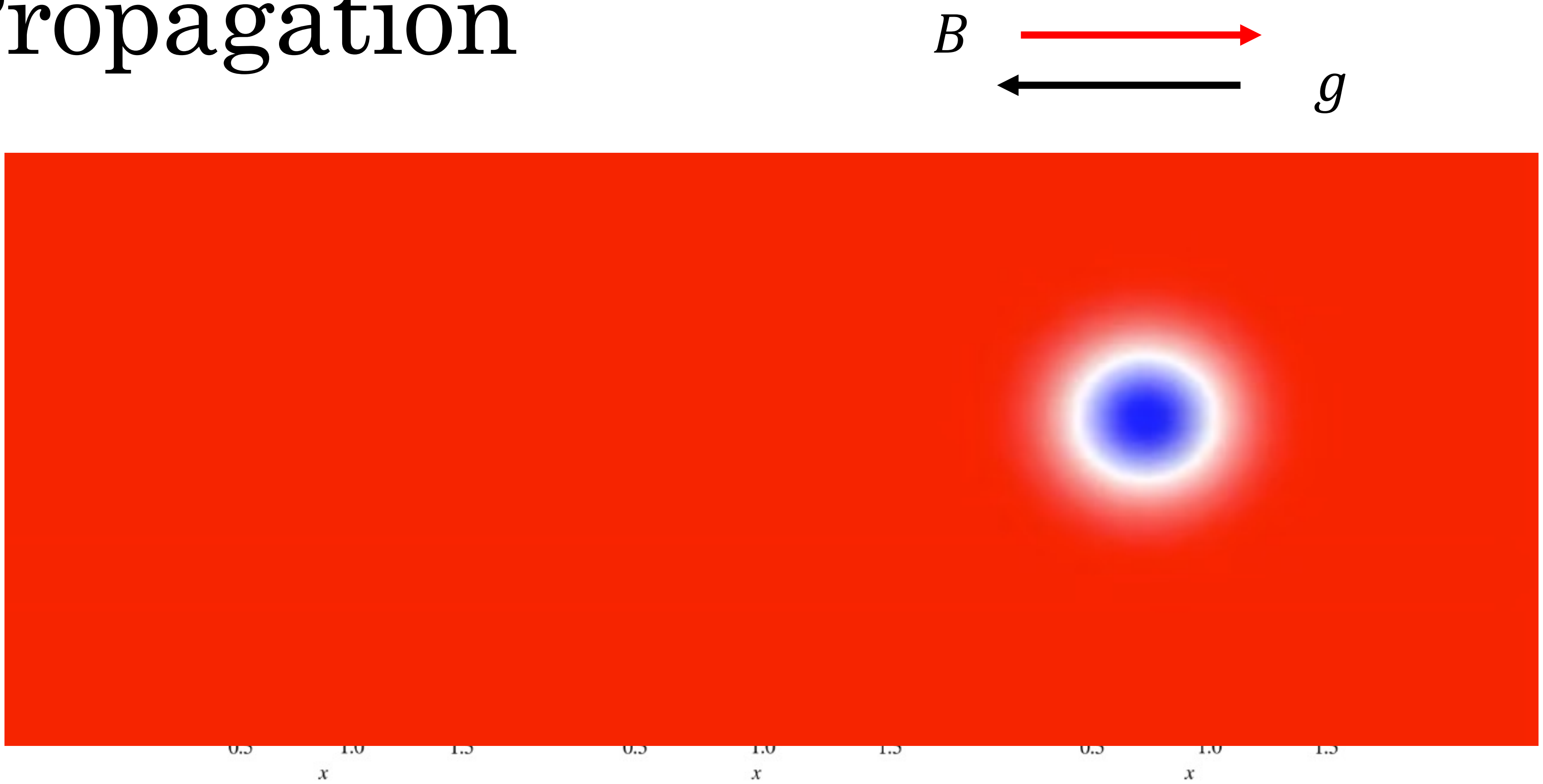
- CR heating can cause thermal modes to propagate

What can CRs do?



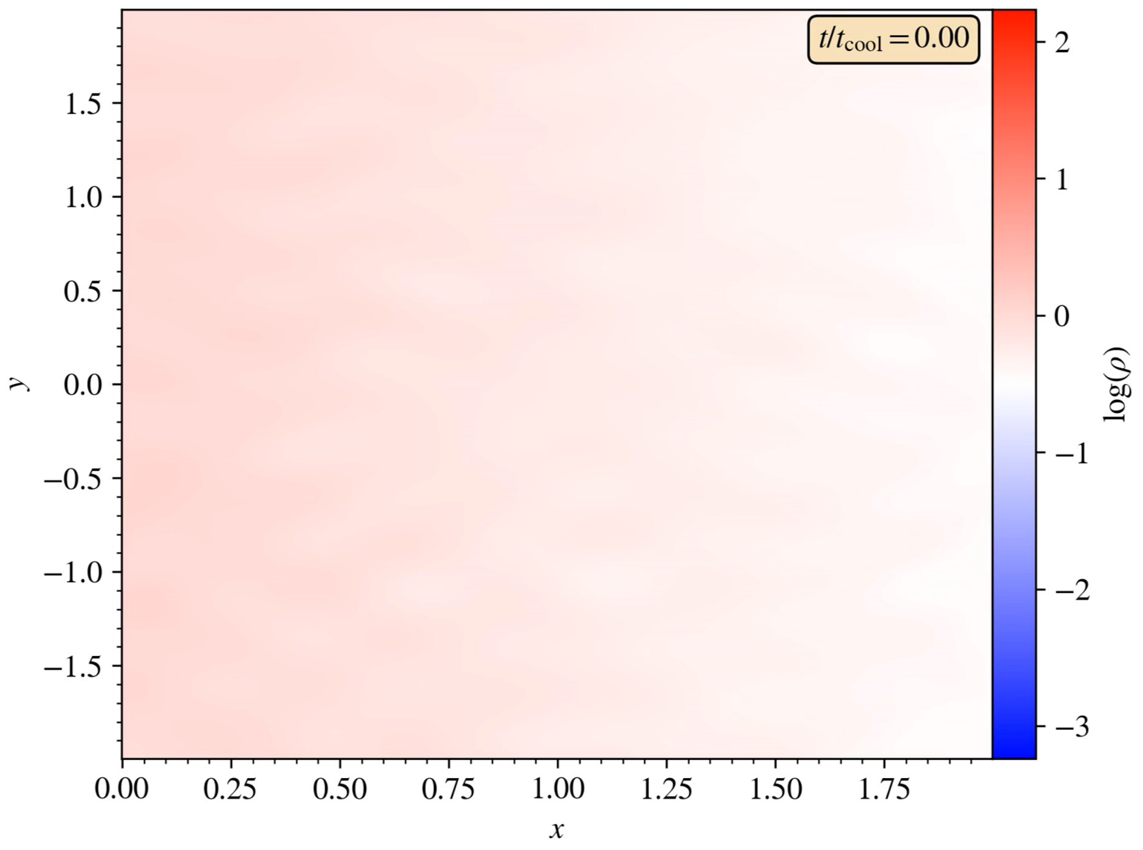
- Propagation of modes sets a time limit on how much time it can grow to nonlinear amplitudes
- Crossing time $t_{cross} \sim L/v_A$
- What happens when $\theta = \frac{t_{cool}}{t_{cross}} > 1$?

Propagation



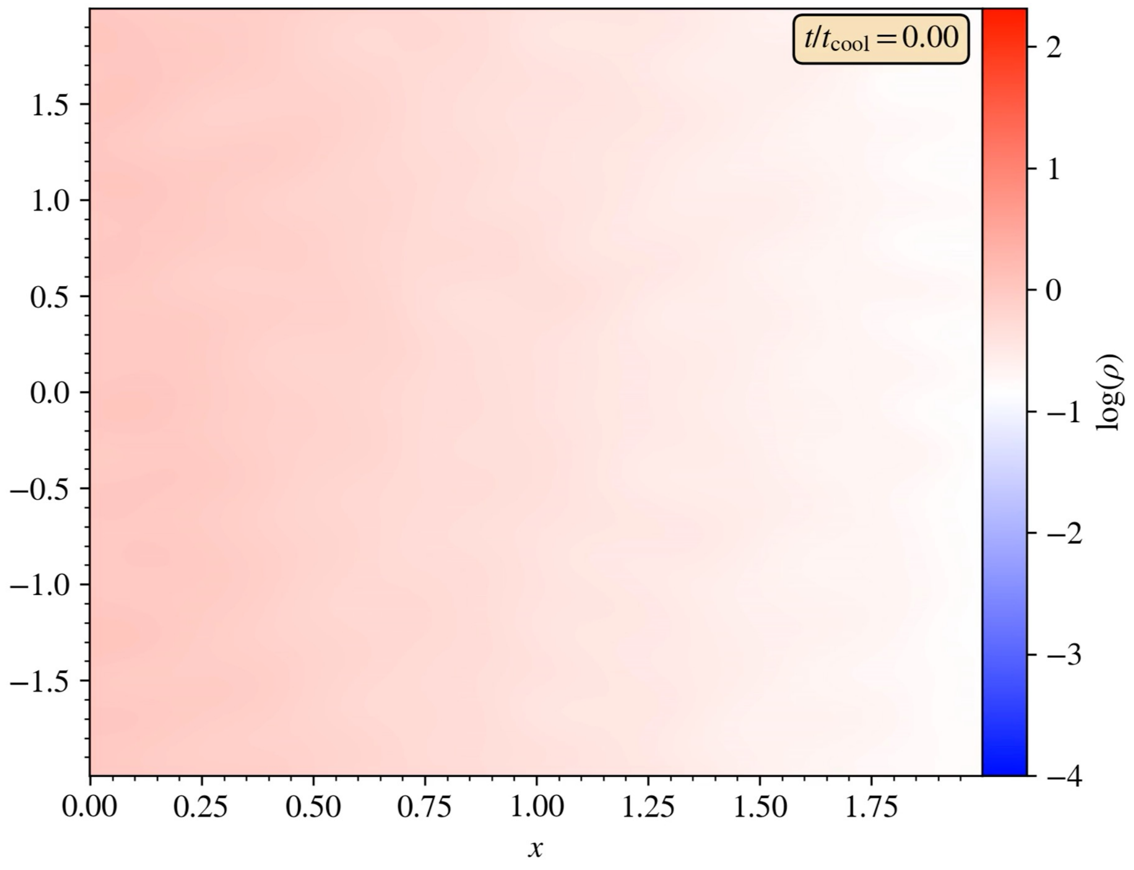
- Thermal modes do propagate under the effect of the CRs

$\frac{P_c}{P_g} \approx 1, \beta \approx 3, \eta \approx 0.01, \frac{t_{\text{cool}}}{t_{\text{ff}}} \approx 2.28$



$\frac{t_{\text{cool}}}{t_{\text{cross}}} \approx 1$

No CR $\beta \approx 3, \frac{t_{\text{cool}}}{t_{\text{ff}}} \approx 2.28$



Summary

- CR streaming dominated transport gives rise to the bottleneck effect.
- CR pressure buildup from the bottlenecks can contribute to increase in mass outflow rate
- The bottleneck staircase redistributes CR heating so that most of the heating goes into the cold clouds, which is then quickly radiated away. Heating of the hot gas is inefficient.
- CR heating can cause thermal entropy modes to propagate, thereby causing suppression in cold gas formation if $t_{\text{cool}}/t_{\text{cross}}$ approaches and exceeds 1.
- Behavior of the bottleneck staircase in a turbulent field is poorly understood, future study could reveal the role bottlenecks play in a dynamic and turbulent ICM and CGM environments.