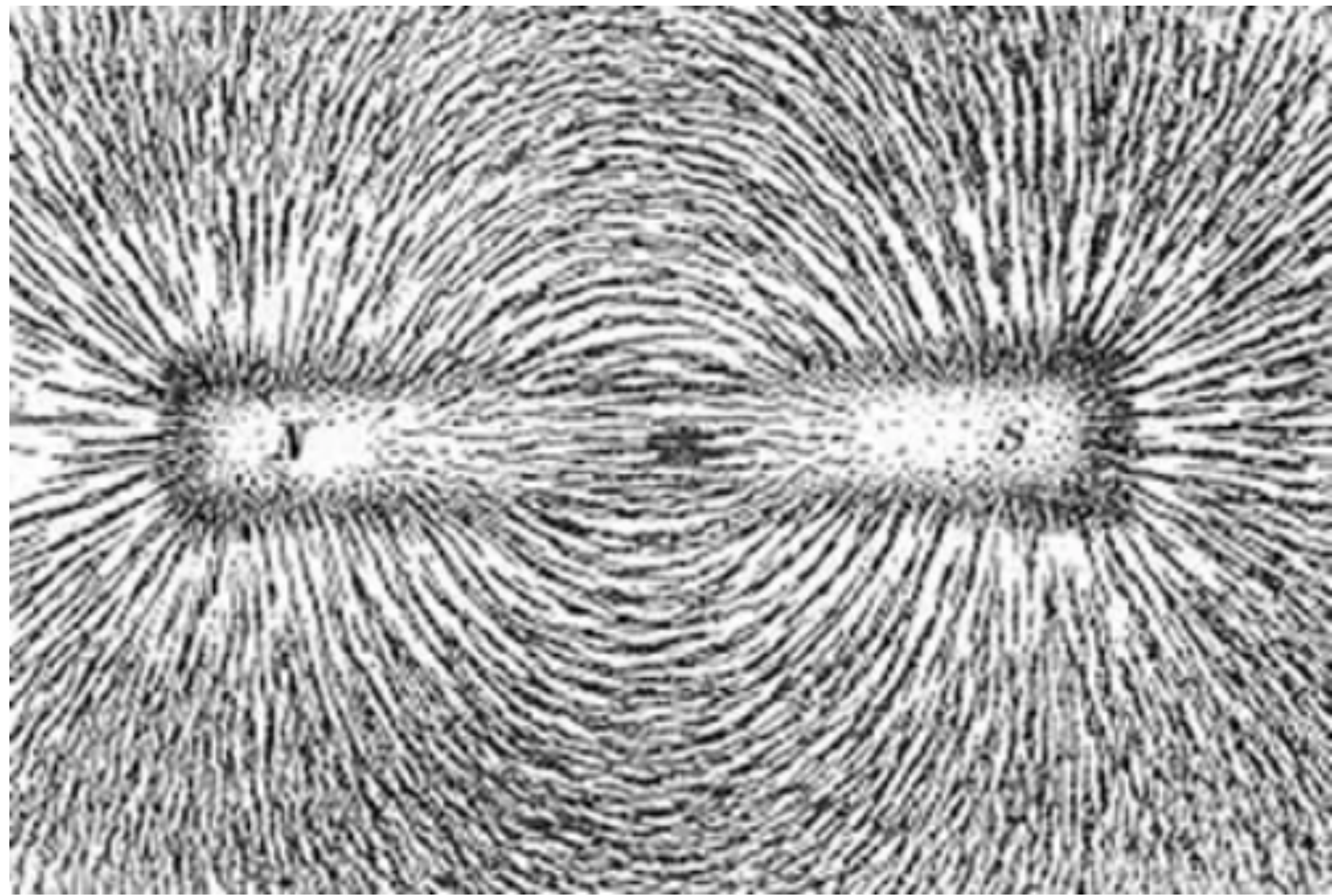
Non-thermal Processes in the CGM

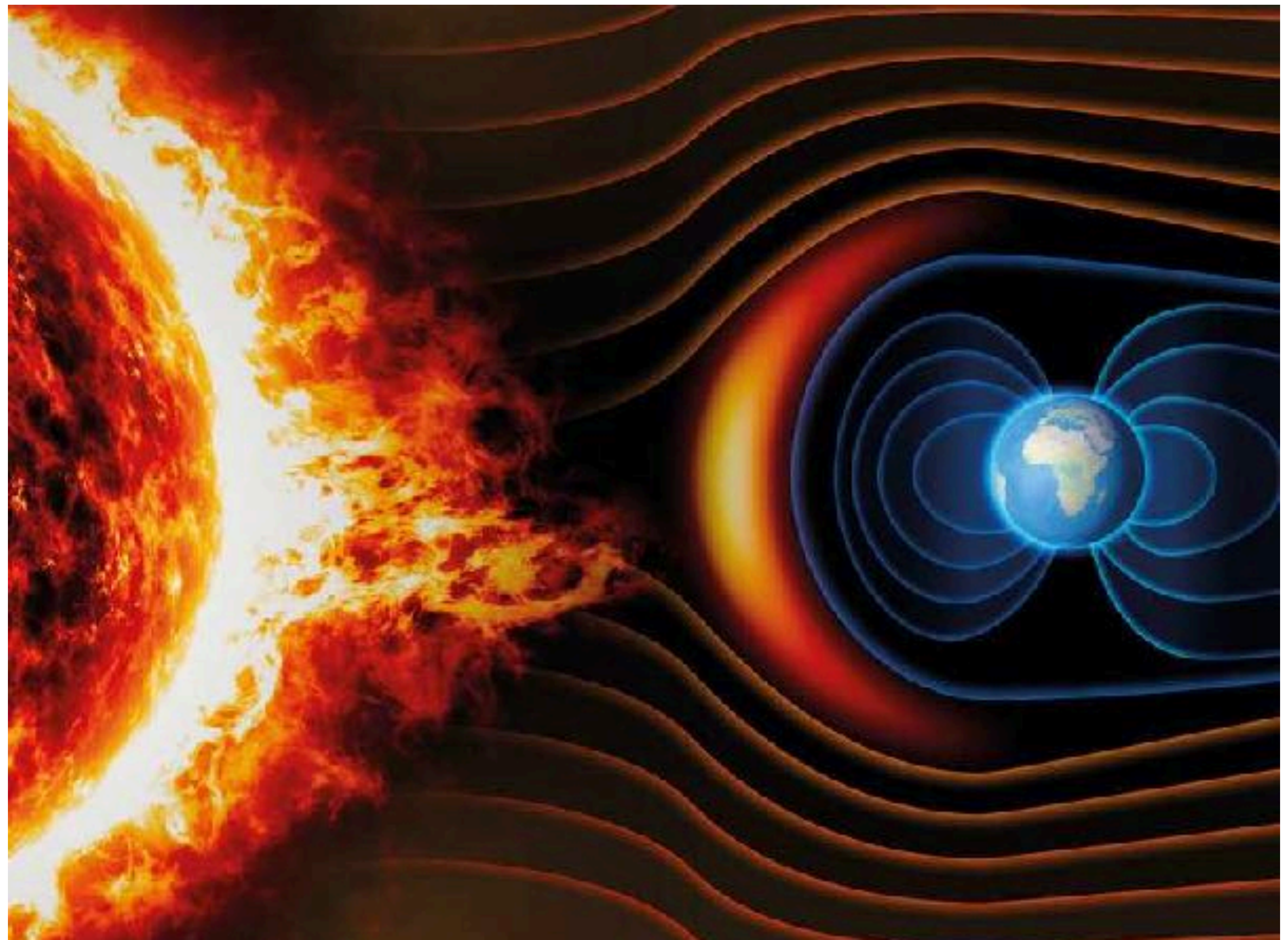


Peng Oh (UC Santa Barbara)

Non-thermal Processes: the Last Refuge of Scoundrels?

Cosmic Rays

Turbulence



Magnetic Fields

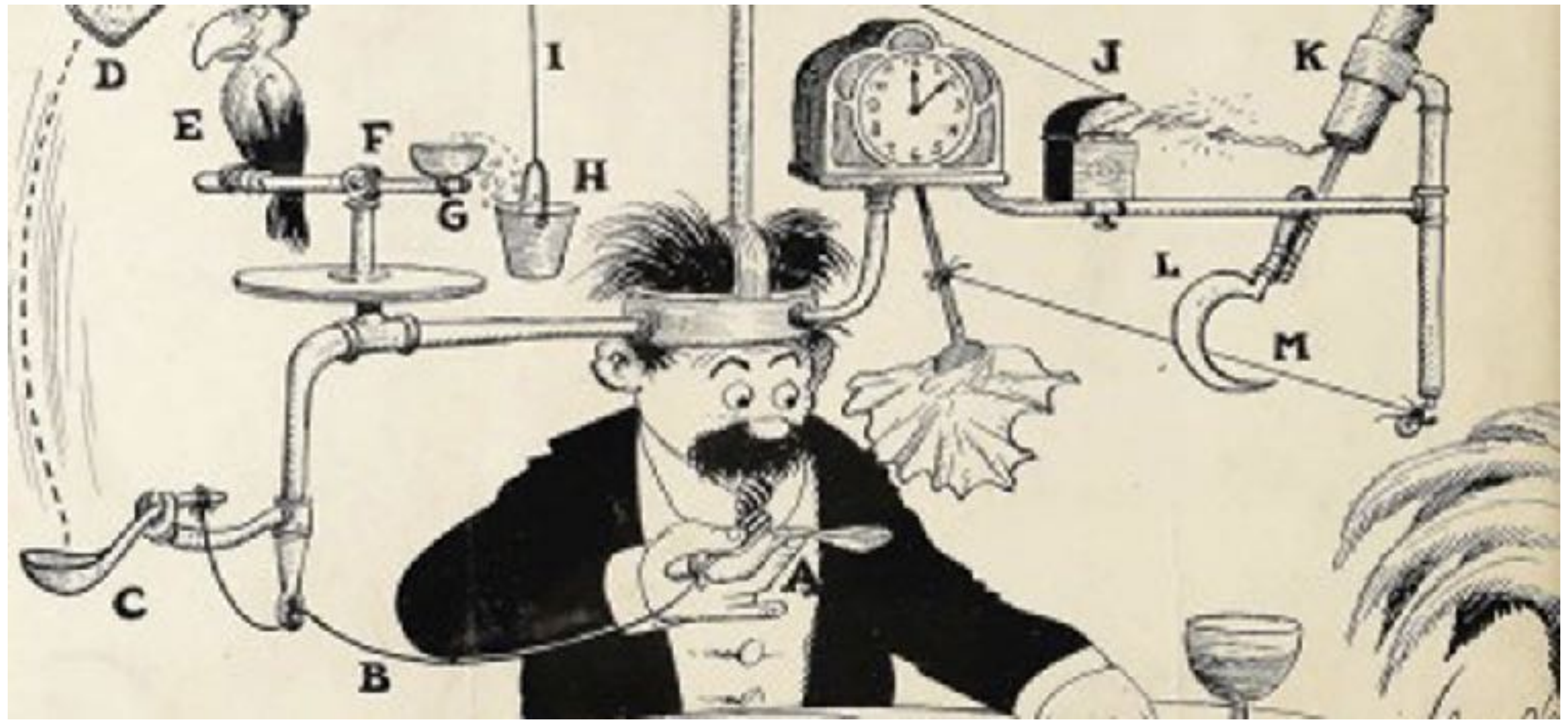
Why care about life non-thermal?

1. Democracy

In ISM, $P_{gas} \sim P_{\mathrm{B}} \sim P_{\mathrm{turb}} \sim P_{CR}$ WHY???

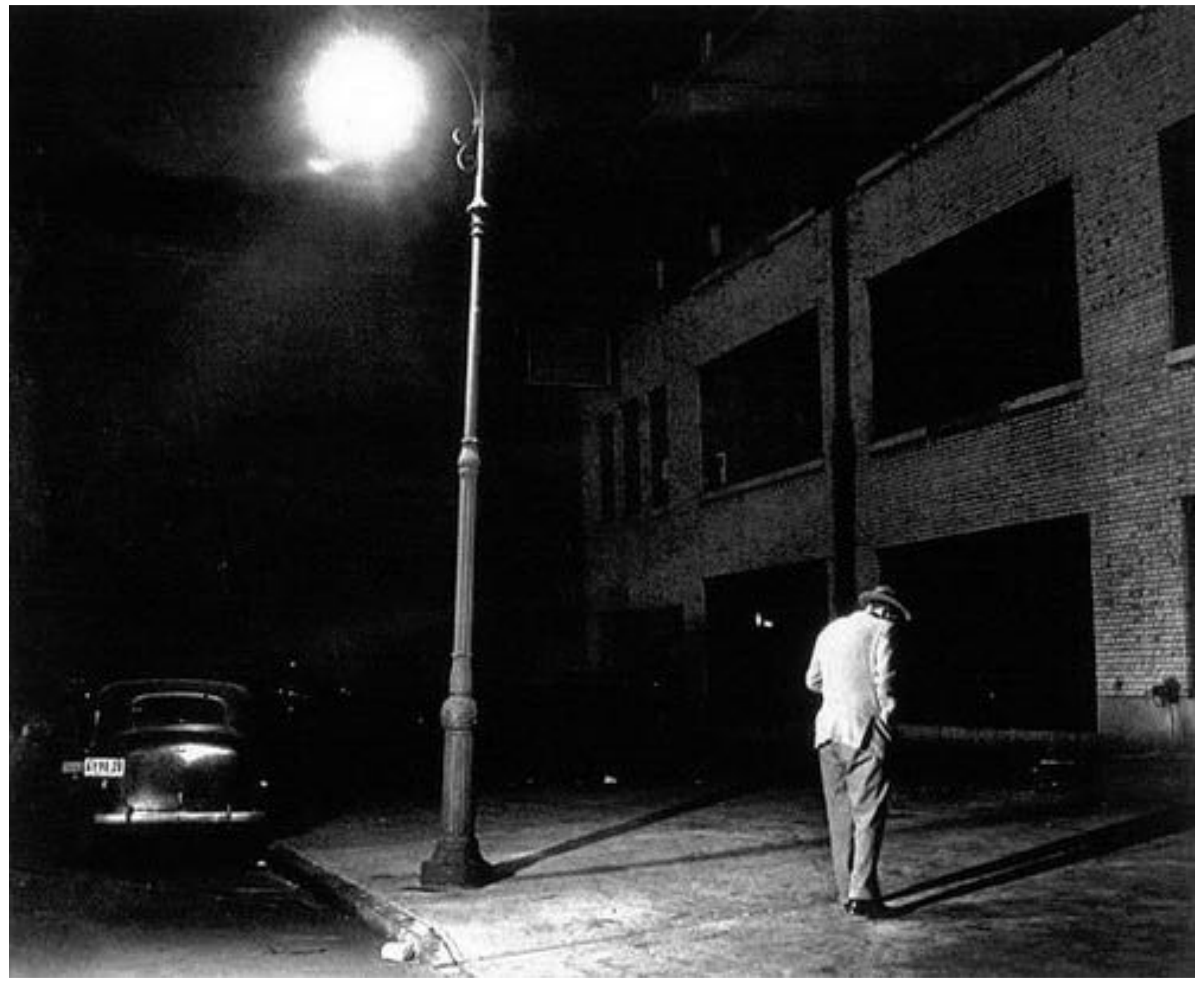
In galaxy clusters (ICM) $P_{gas} \gg P_{\mathrm{B}}, P_{\mathrm{turb}}, P_{CR}$

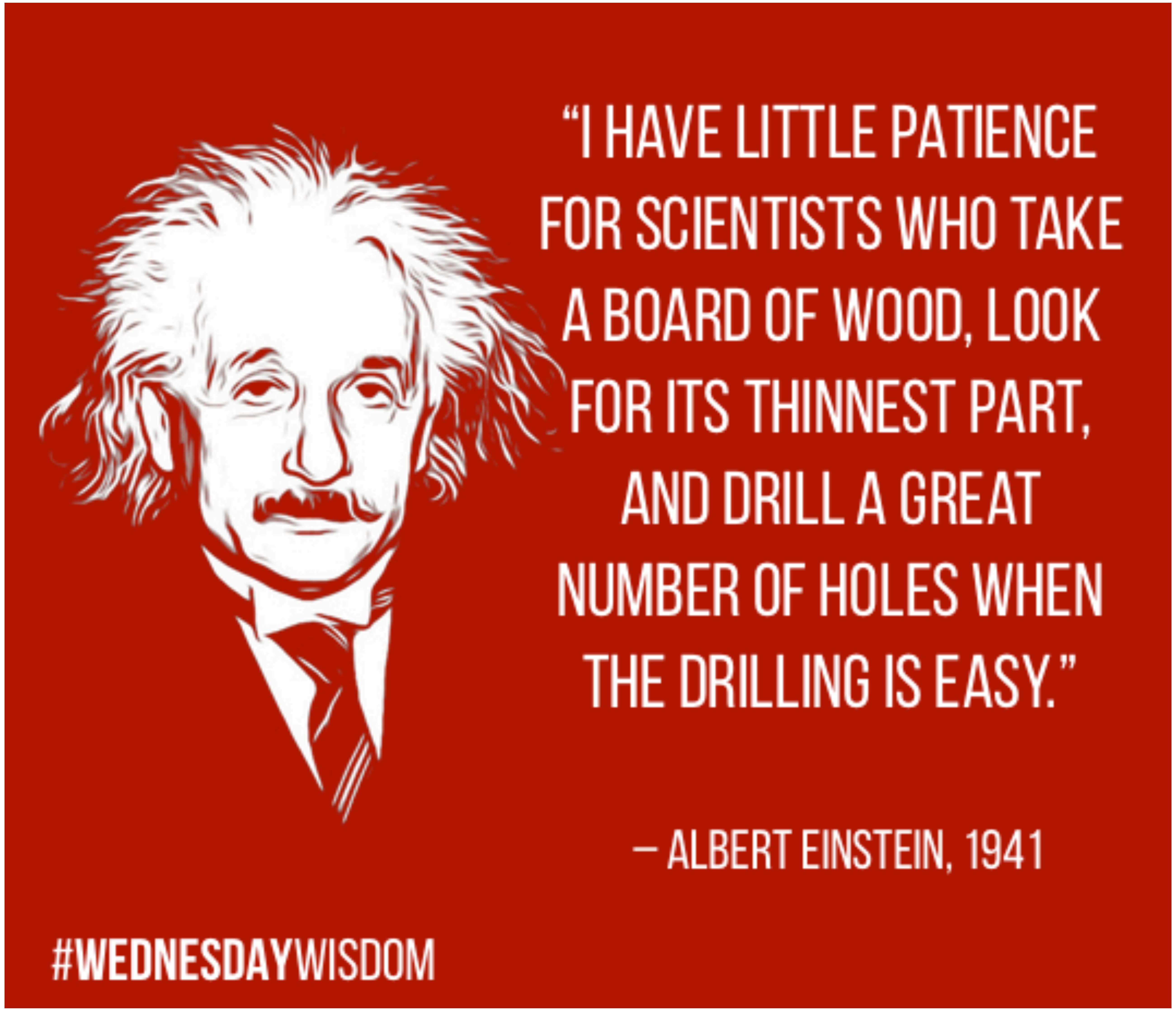
In CGM, ?????



2. Rich Physics

General Approach





"I HAVE LITTLE PATIENCE FOR SCIENTISTS WHO TAKE A BOARD OF WOOD, LOOK FOR ITS THINNEST PART, AND DRILL A GREAT NUMBER OF HOLES WHEN THE DRILLING IS EASY."

– ALBERT EINSTEIN, 1941

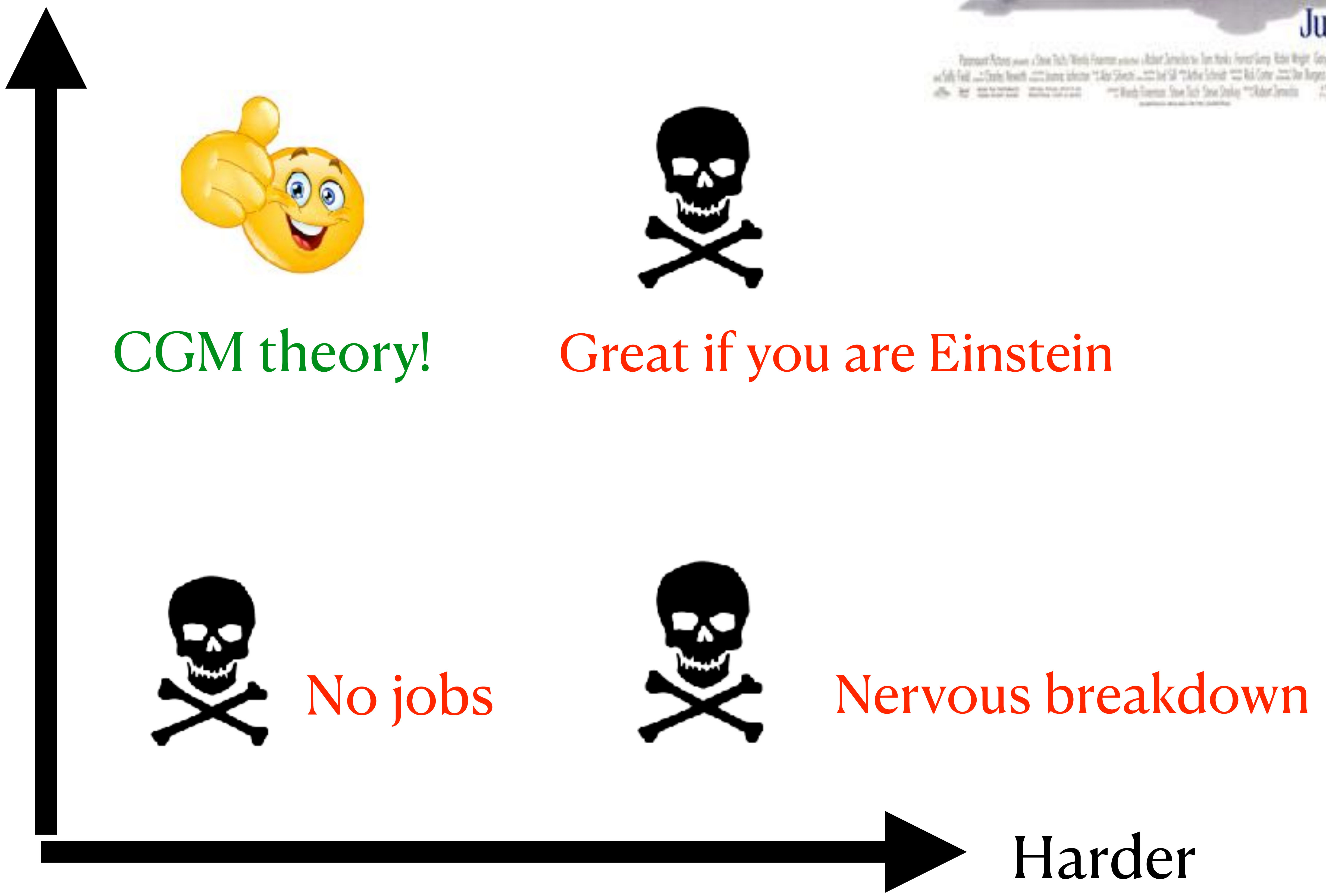
#WEDNESDAYWISDOM

Hmm…that's exactly
what I do for a living.

It is better to be lucky than to be smart

And the CGM is a good place to get lucky!

More interesting



CGM theory!

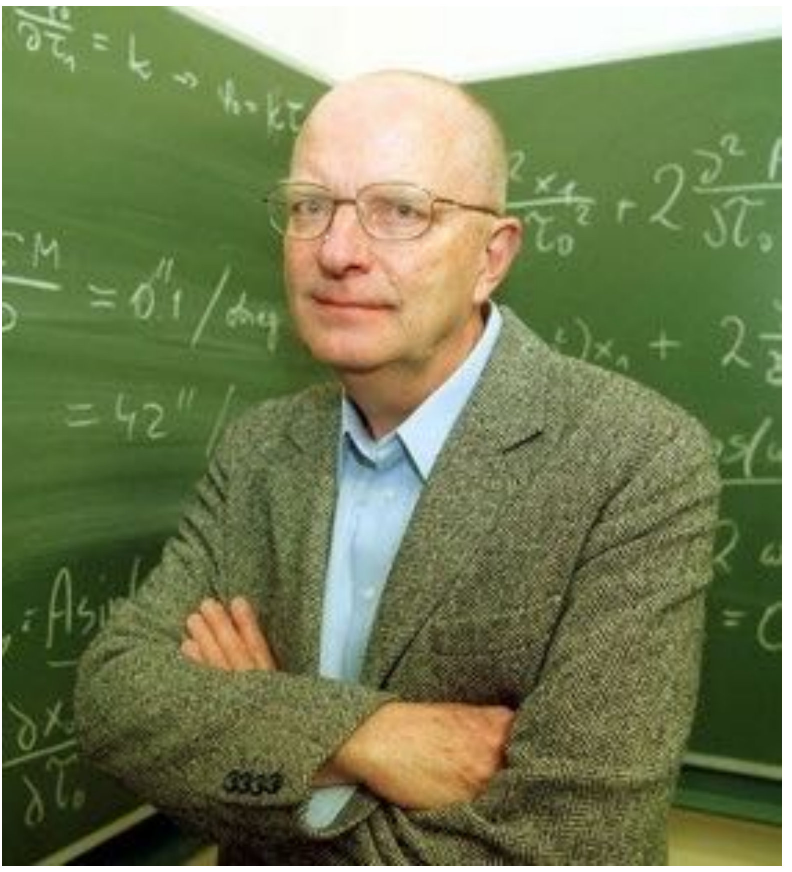
Great if you are Einstein

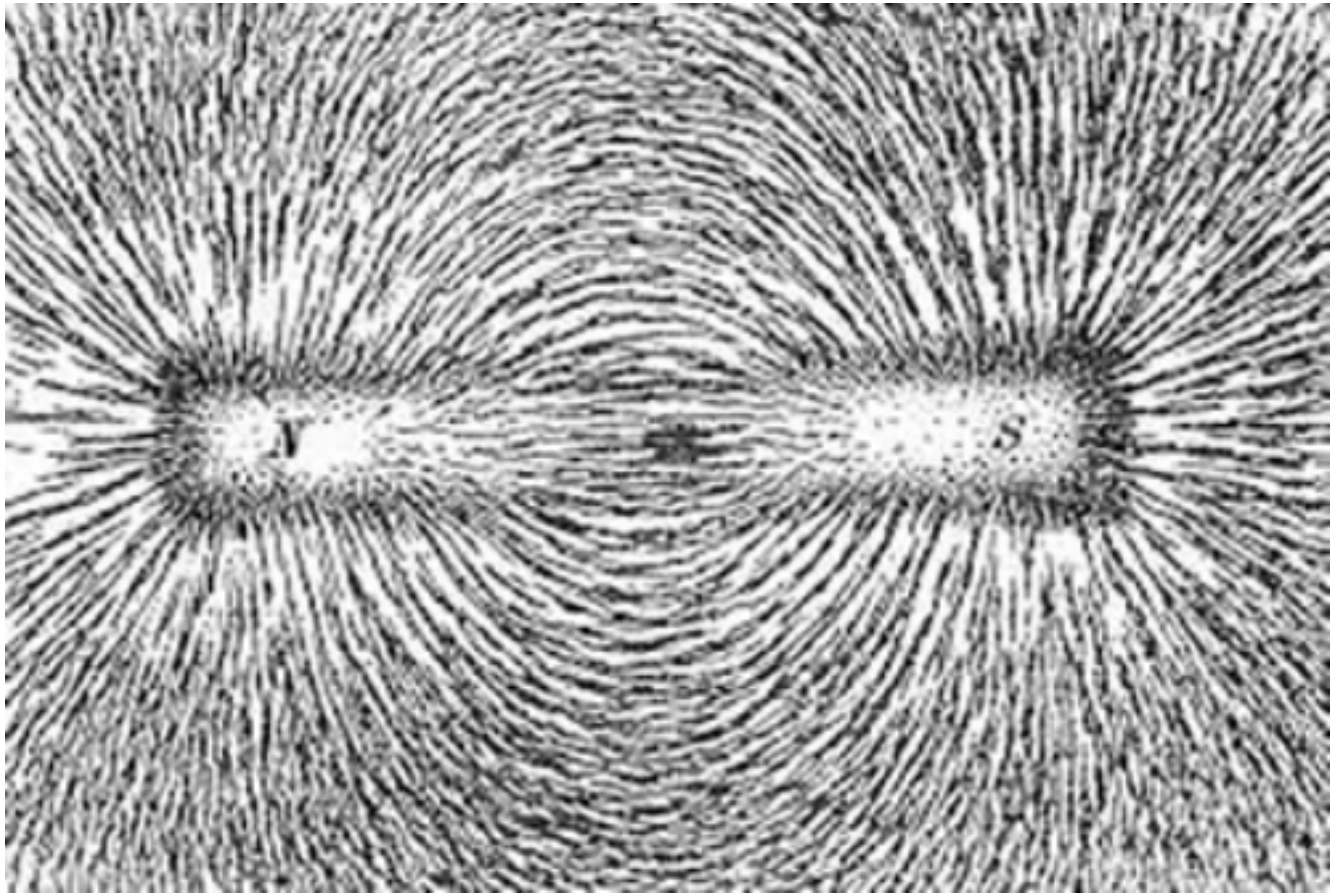
No jobs

Nervous breakdown

Harder

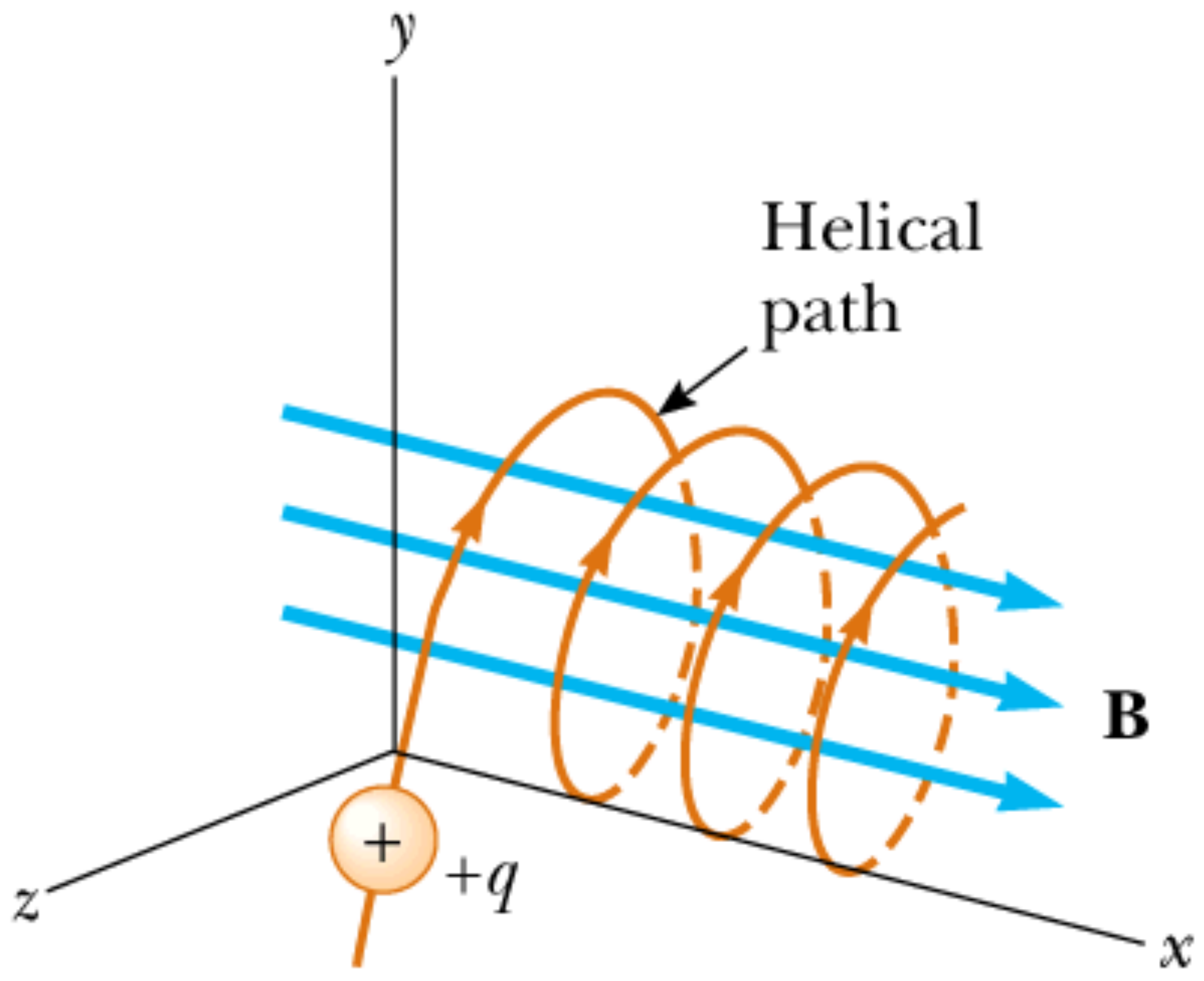
“A lot of people confuse difficult with interesting.”
— Bohdan Paczynski





Magnetic Fields

Why care about magnetic fields?

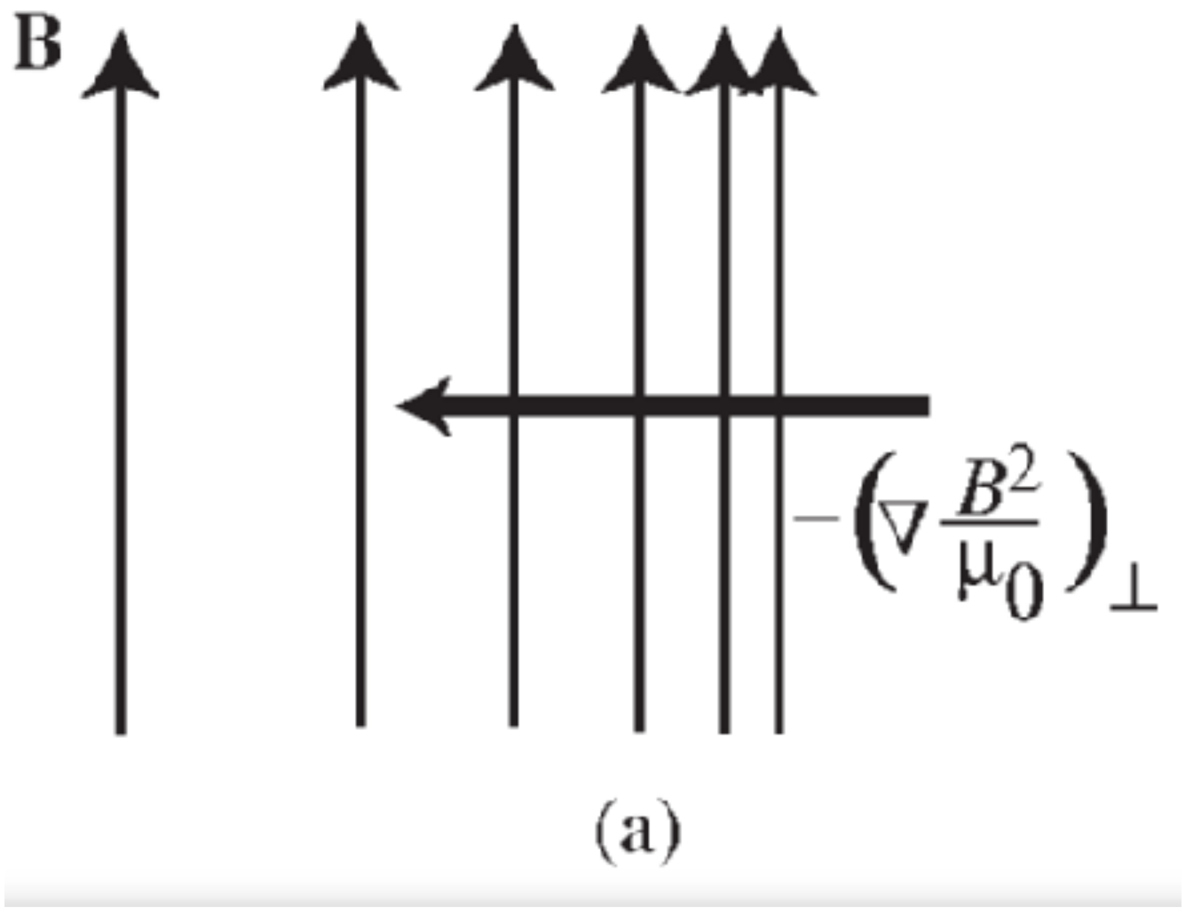


1. Anisotropic Transport

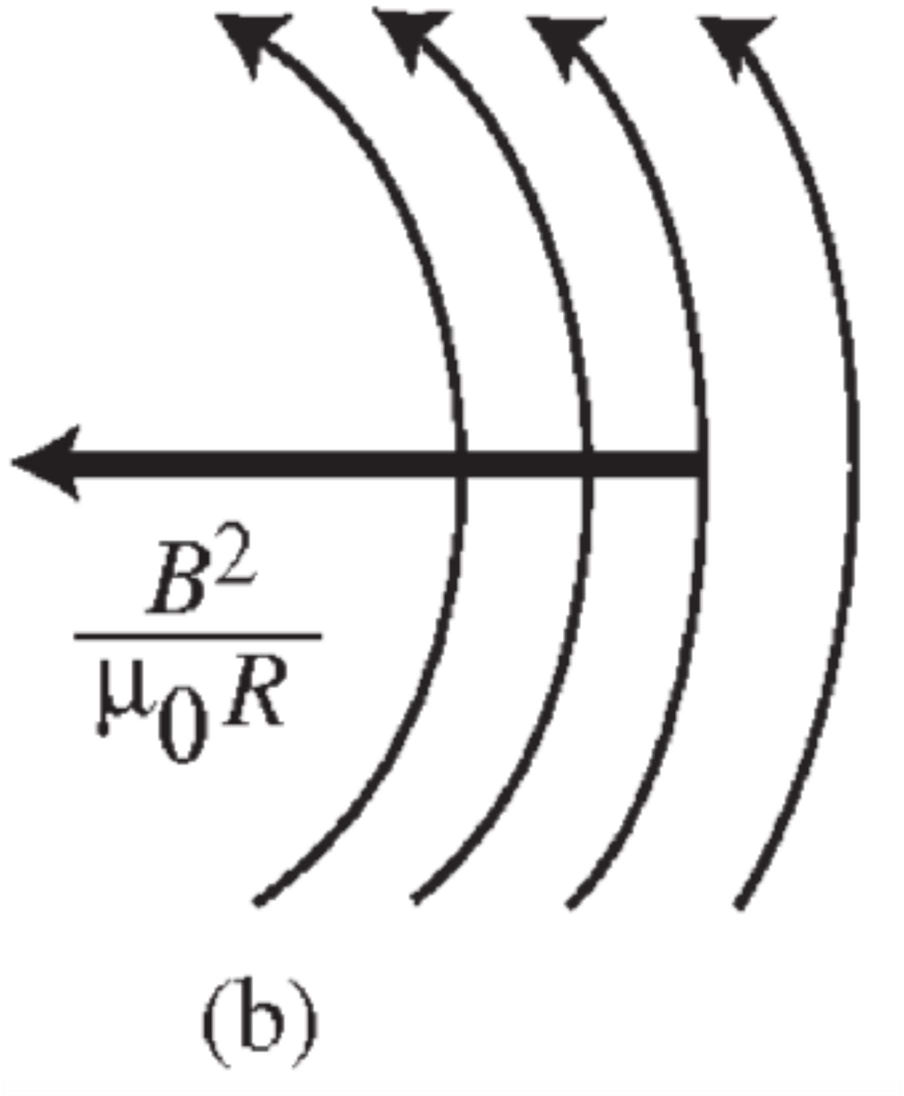
Of particles, momentum, heat…

2. MHD forces

Magnetic pressure
(B-fields don't like to
squeeze)

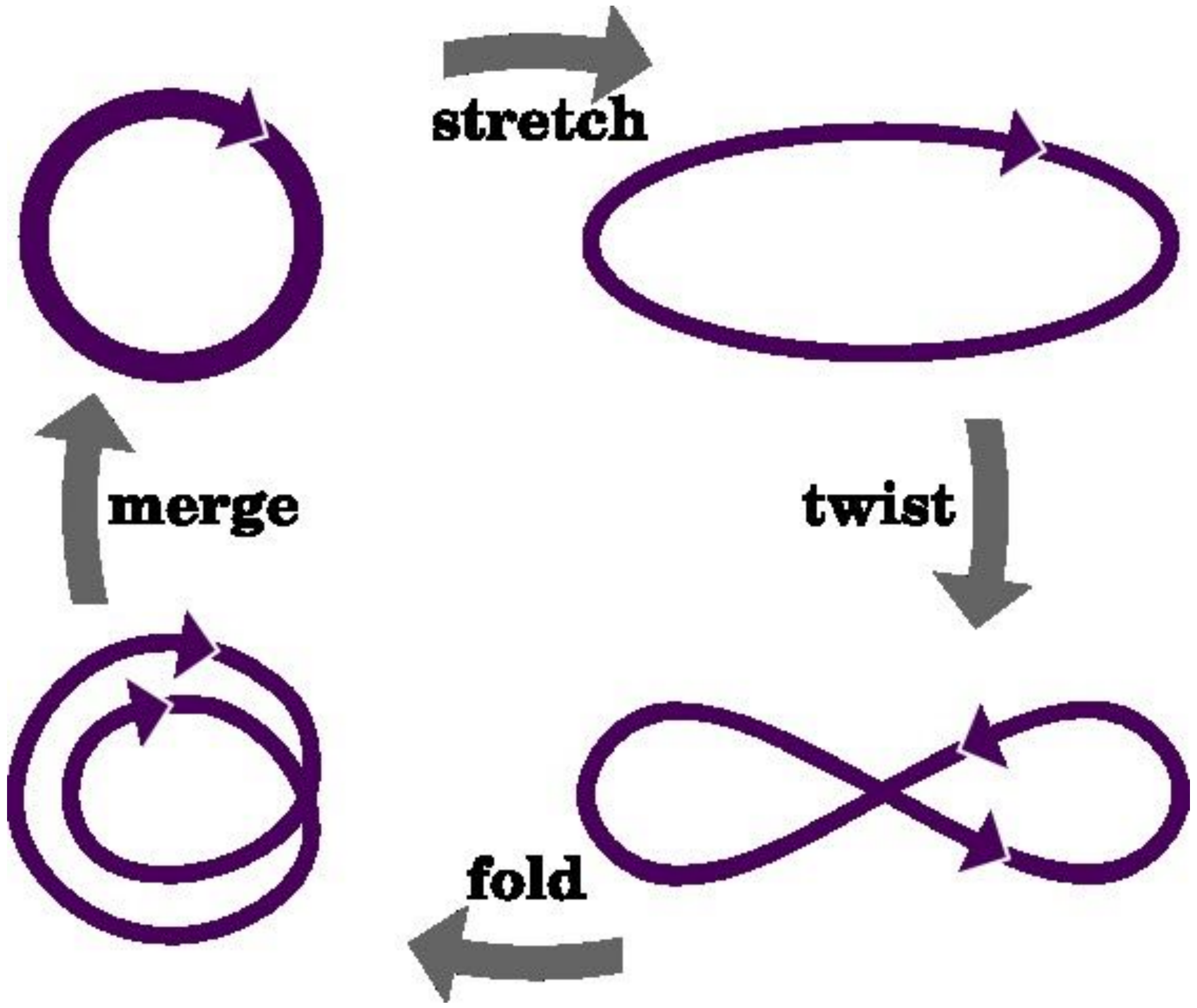


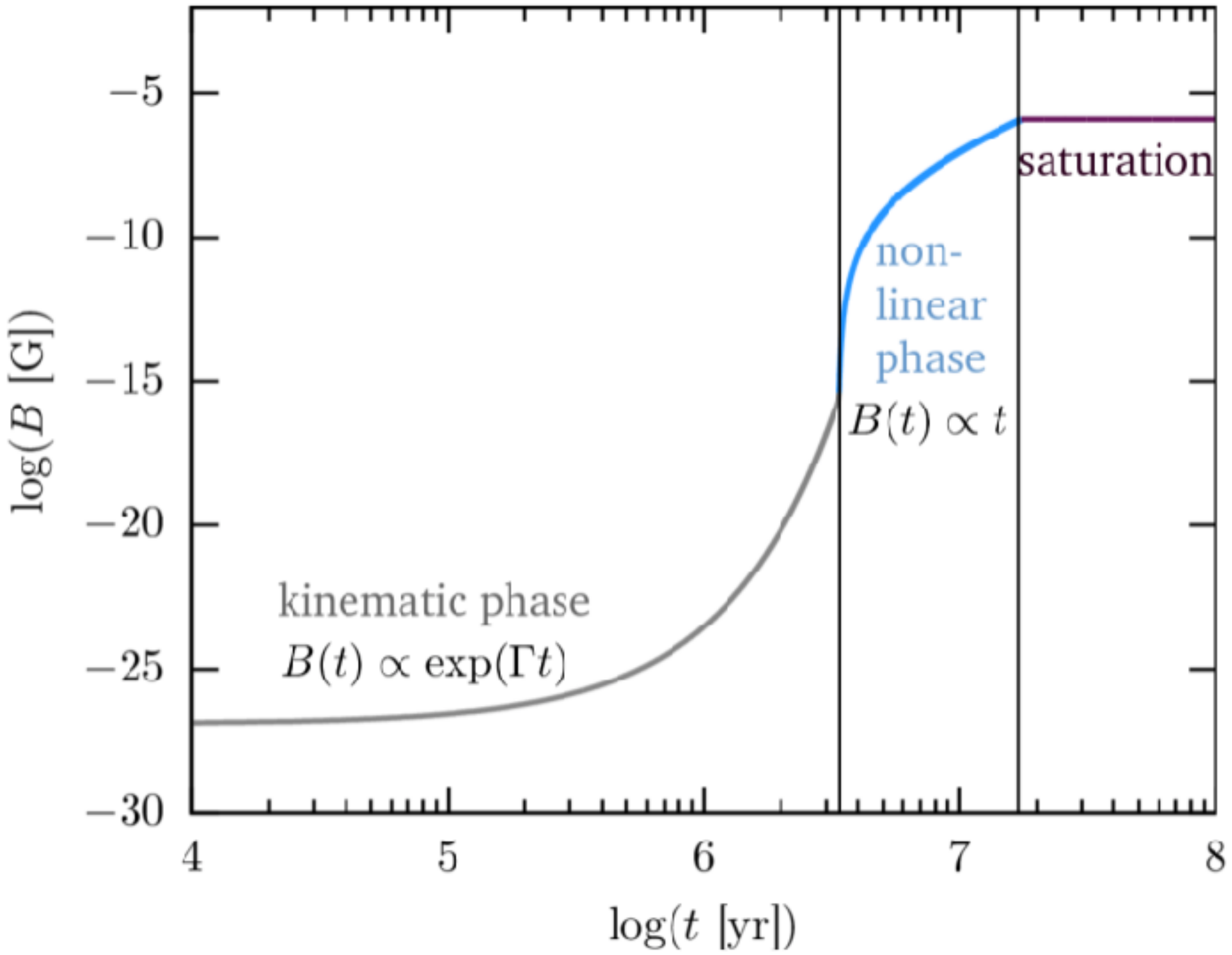
Magnetic tension
(B-fields don't like
to bend)



B-fields grow in many ways

Turbulent dynamo is probably most relevant to CGM



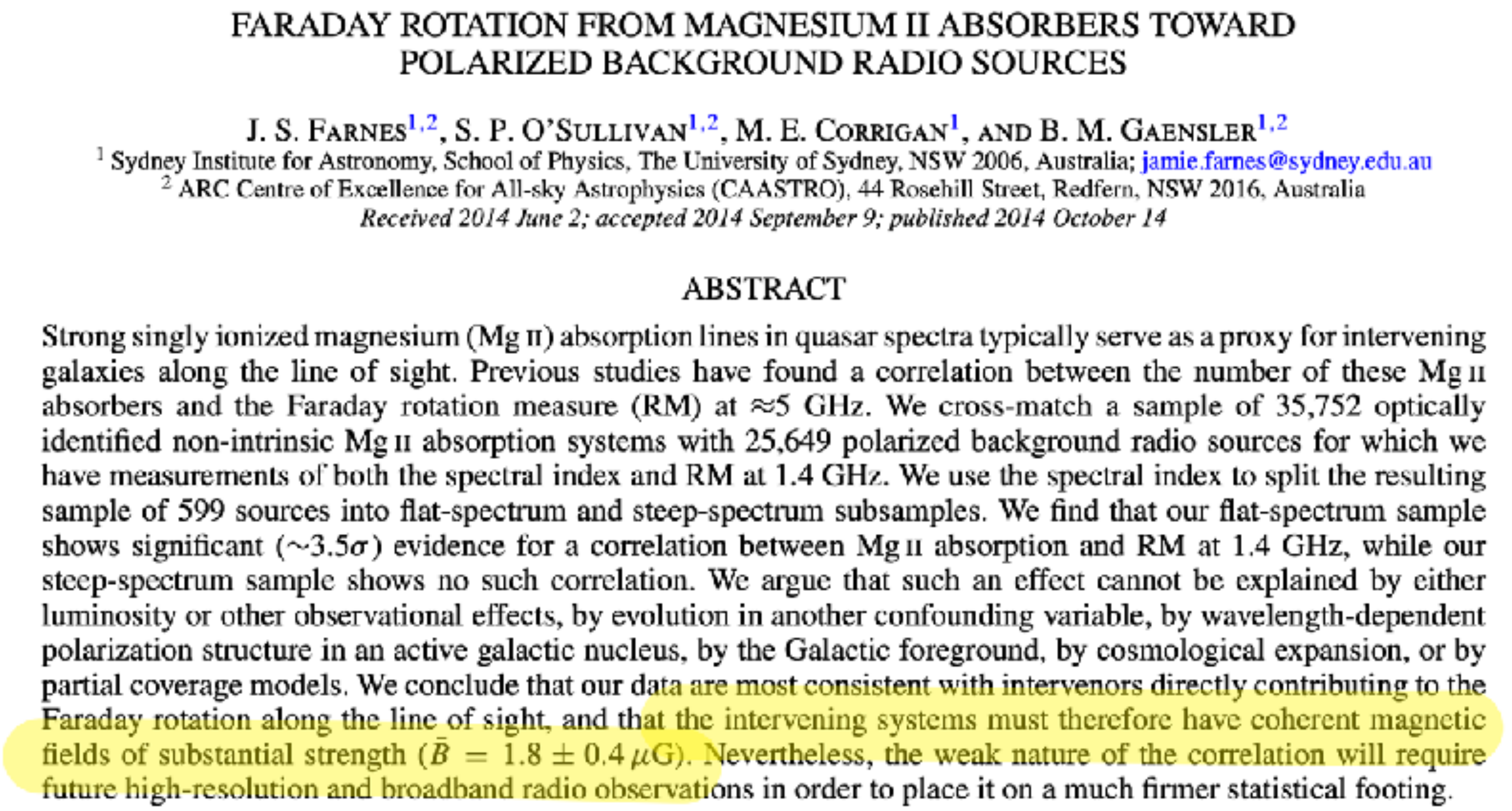


Saturates
when reaches
equipartition
with turbulence

Fig credit: J. Schober

What is the B-field in the CGM?

Constraints very uncertain…

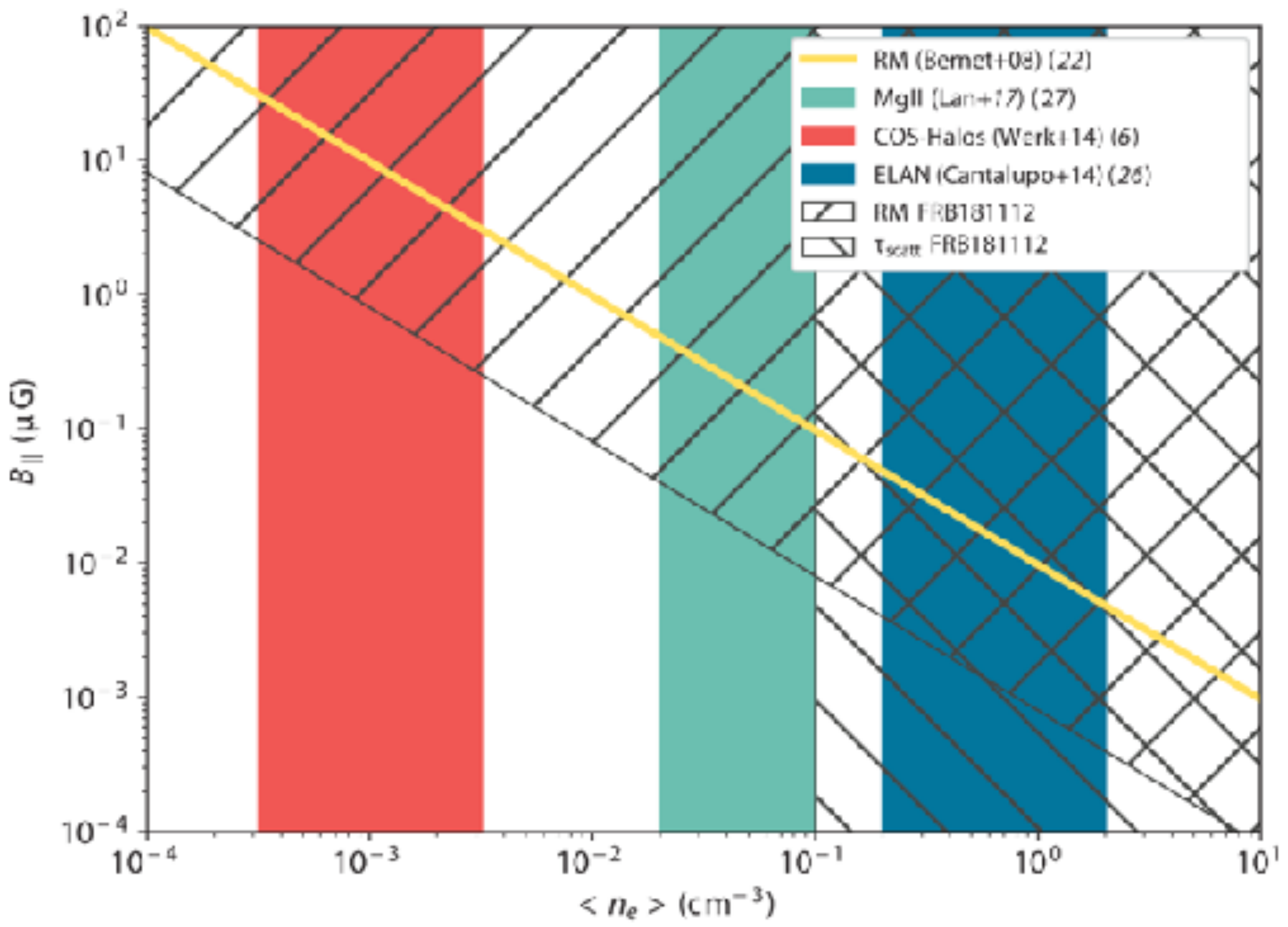


FARADAY ROTATION FROM MAGNESIUM II ABSORBERS TOWARD
POLARIZED BACKGROUND RADIO SOURCES

J. S. Farnes[1,2], S. P. O'Sullivan[1,2], M. E. Corrigan[1], and B. M. Gaensler[1,2]
[1] Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia; jamie.farnes@sydney.edu.au
[2] ARC Centre of Excellence for All-sky Astrophysics (CAASTRO), 44 Rosehill Street, Redfern, NSW 2016, Australia
Received 2014 June 2; accepted 2014 September 9; published 2014 October 14

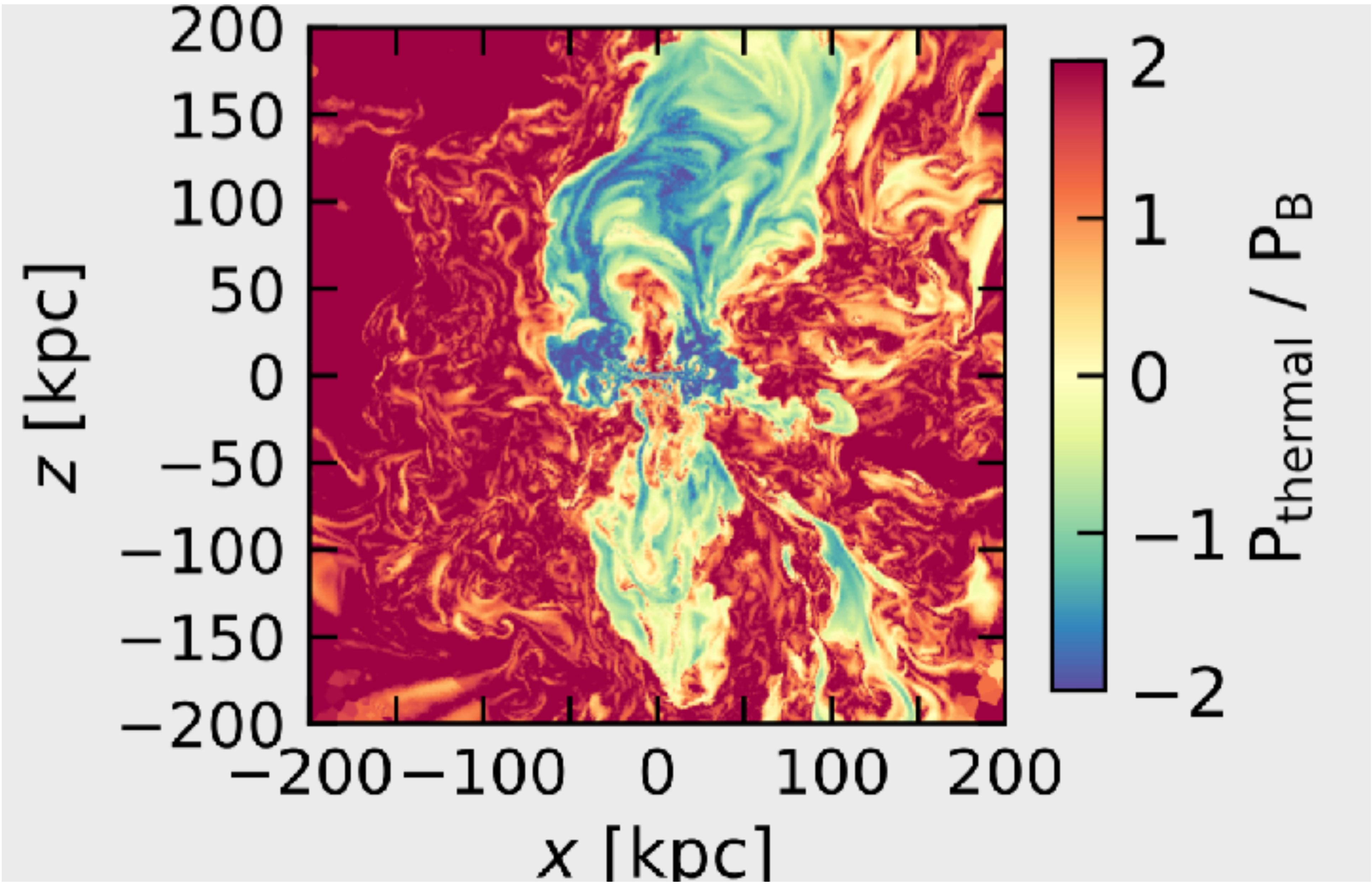
ABSTRACT

Strong singly ionized magnesium (Mg II) absorption lines in quasar spectra typically serve as a proxy for intervening galaxies along the line of sight. Previous studies have found a correlation between the number of these Mg II absorbers and the Faraday rotation measure (RM) at ≈5 GHz. We cross-match a sample of 35,752 optically identified non-intrinsic Mg II absorption systems with 25,649 polarized background radio sources for which we have measurements of both the spectral index and RM at 1.4 GHz. We use the spectral index to split the resulting sample of 599 sources into flat-spectrum and steep-spectrum subsamples. We find that our flat-spectrum sample shows significant ($\sim 3.5\sigma$) evidence for a correlation between Mg II absorption and RM at 1.4 GHz, while our steep-spectrum sample shows no such correlation. We argue that such an effect cannot be explained by either luminosity or other observational effects, by evolution in another confounding variable, by wavelength-dependent polarization structure in an active galactic nucleus, by the Galactic foreground, by cosmological expansion, or by partial coverage models. We conclude that our data are most consistent with intervenors directly contributing to the Faraday rotation along the line of sight, and that the intervening systems must therefore have coherent magnetic fields of substantial strength ($\bar{B} = 1.8 \pm 0.4\,\mu$G). Nevertheless, the weak nature of the correlation will require future high-resolution and broadband radio observations in order to place it on a much firmer statistical footing.



Prochaska+20

Parts of CGM could be magnetically dominated



van der Voort+20

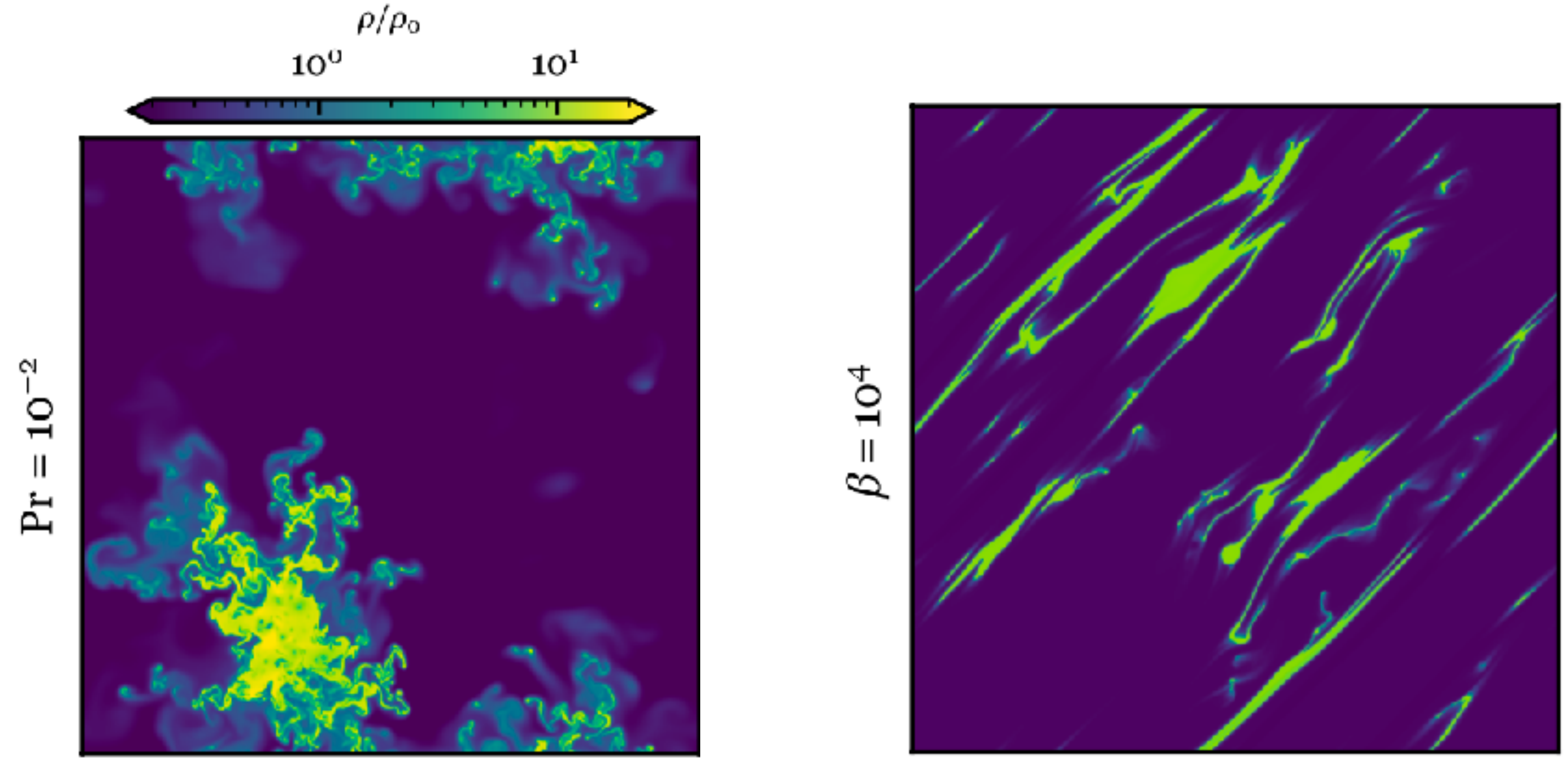
Sims:

$\beta \ll 1$

in biconical outflows!

Some CGM implications

1. Very different cloud morphology



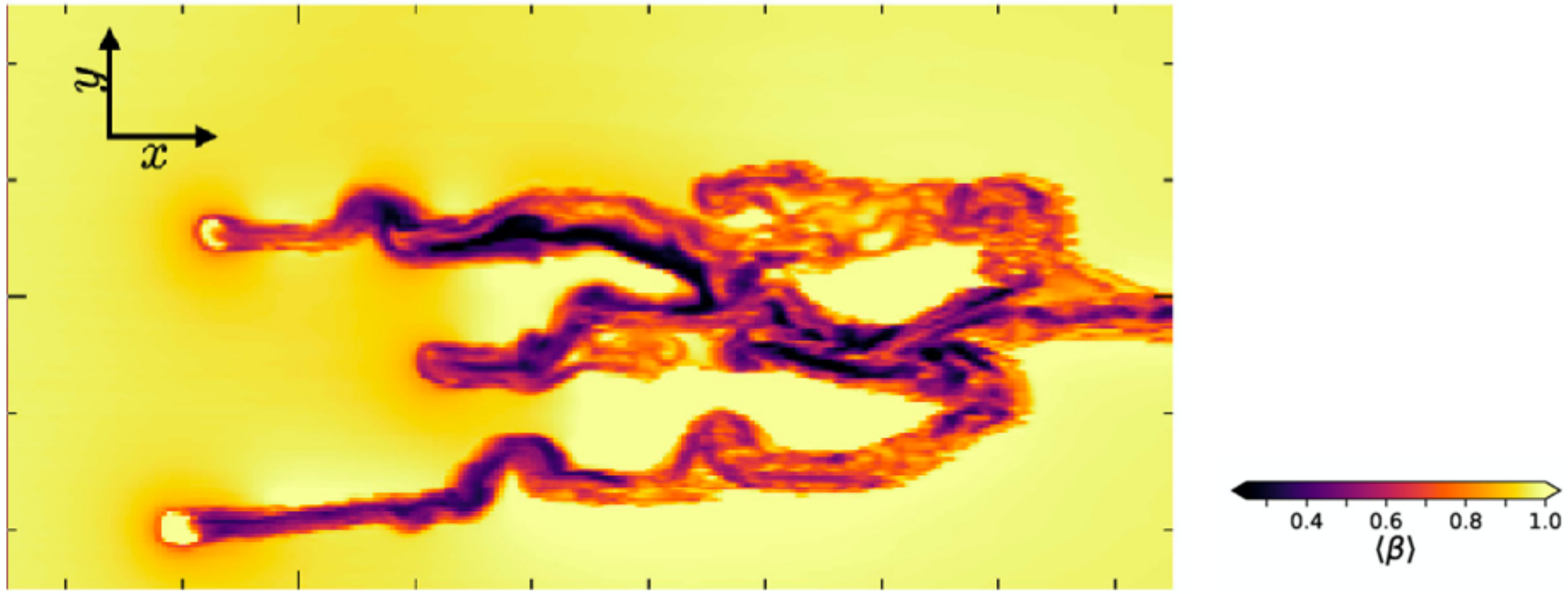
Hydro

MHD

$$\beta = \frac{P_{\rm gas}}{P_{\rm B}}$$

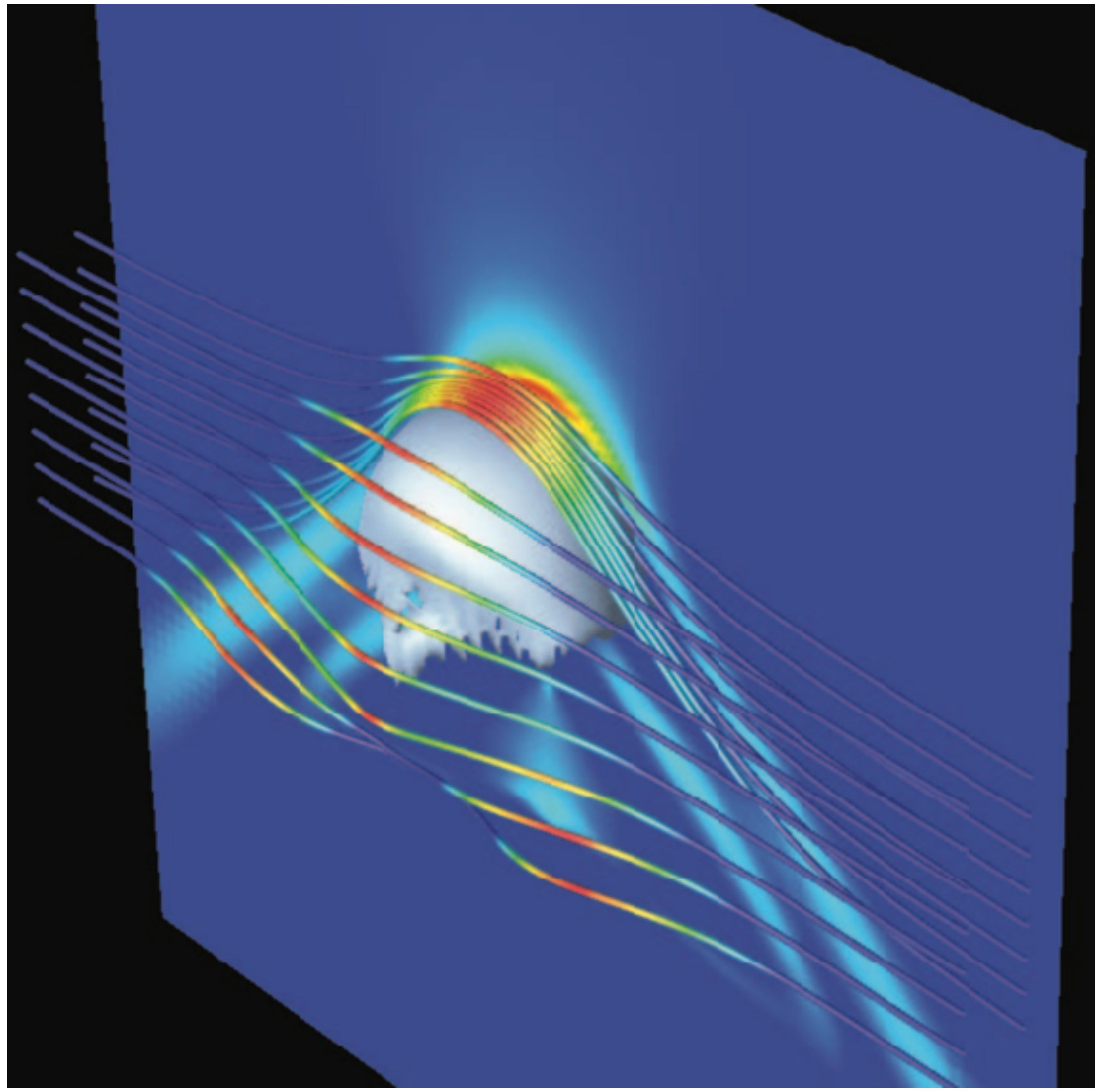
Jennings & Li 2020

2. Magnetic pressure support in cold gas



Gronke & Oh 2020

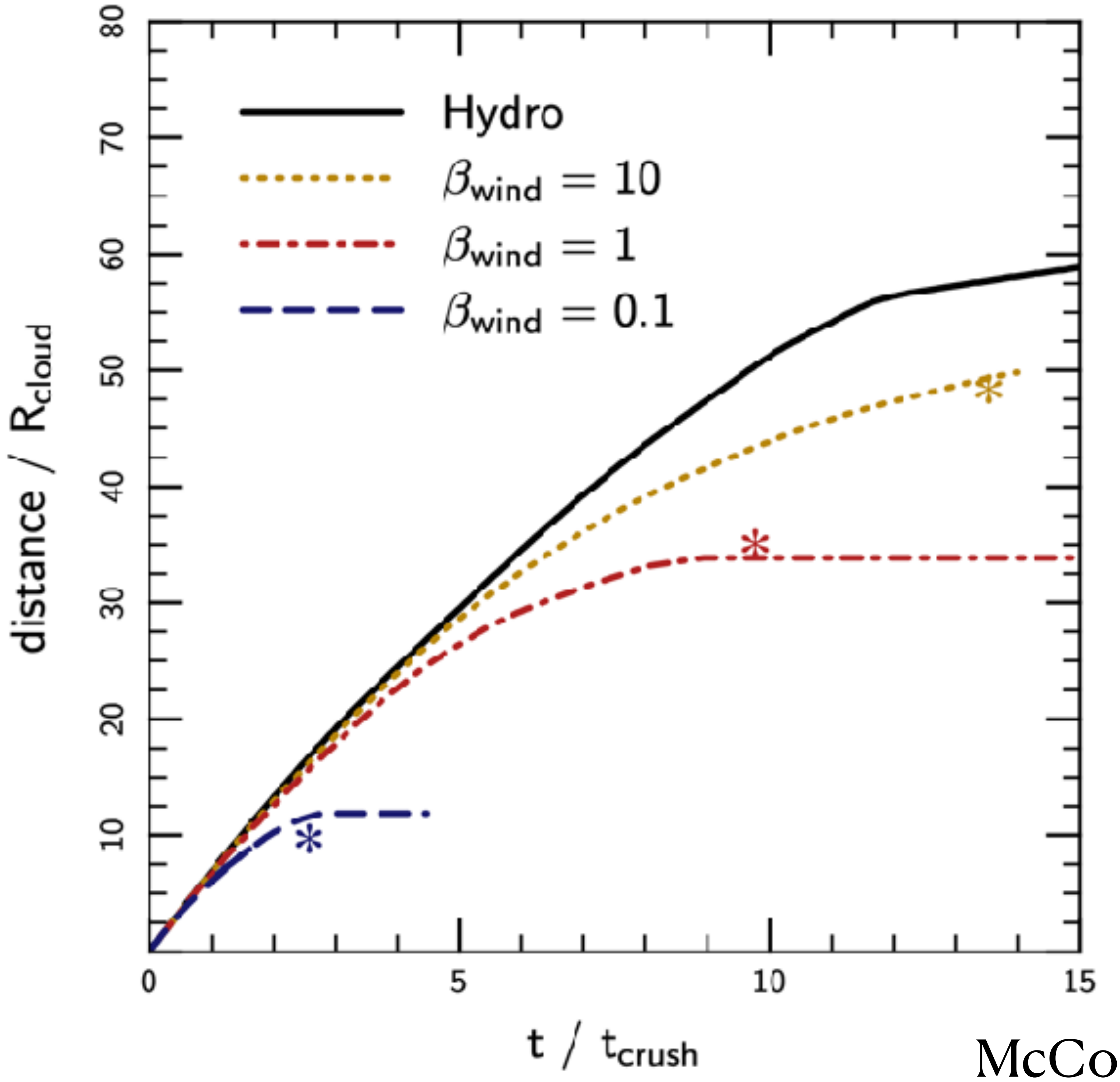
3. Magnetic draping can suppress hydro instabilities (via magnetic tension)



Dursi & Pfrommer 2008

Distance travelled before cold gas comoves with hot wind

Shorter distance means better coupling



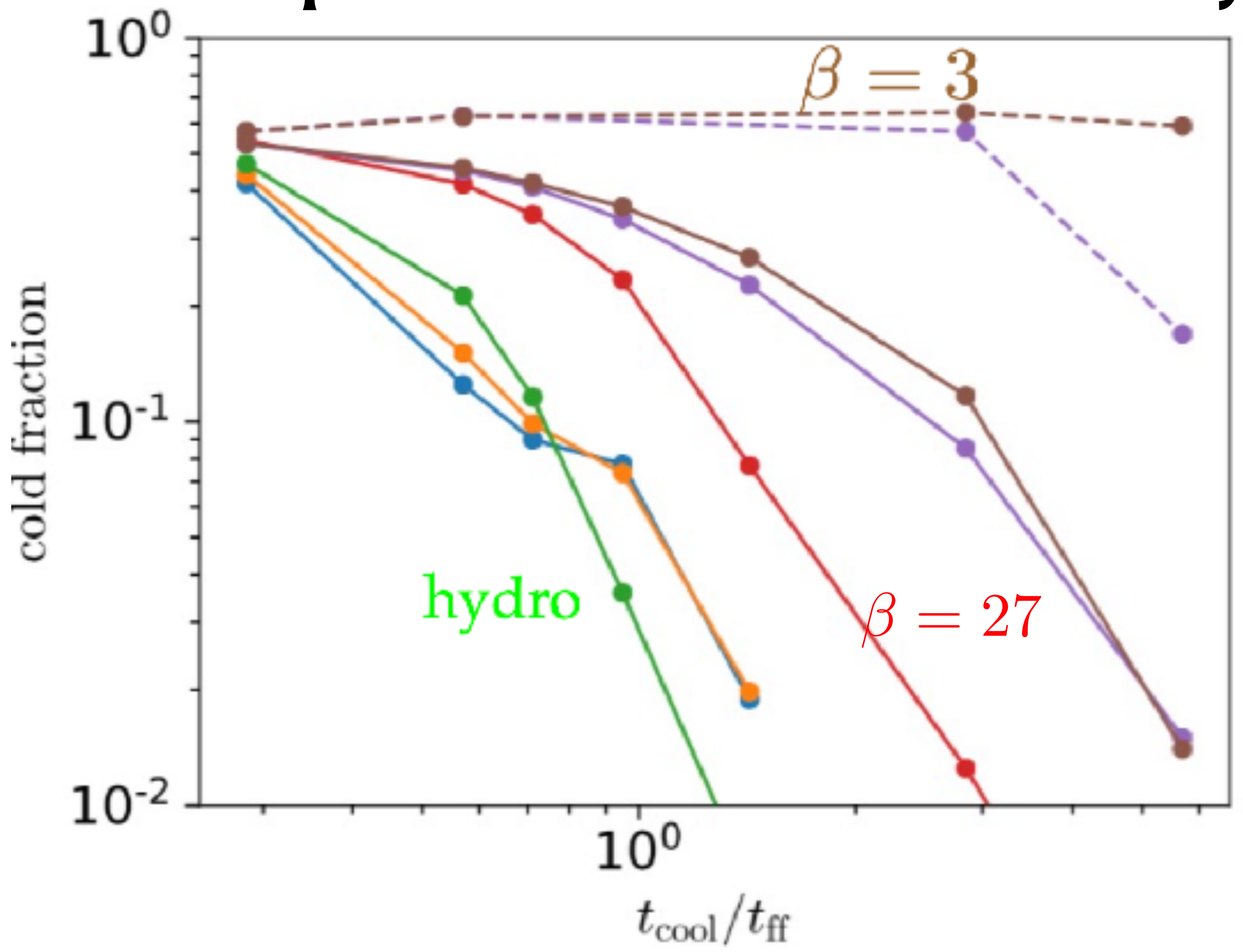
McCourt+15

4. Magnetic drag increases momentum coupling of hot and cold phases

Ji+18

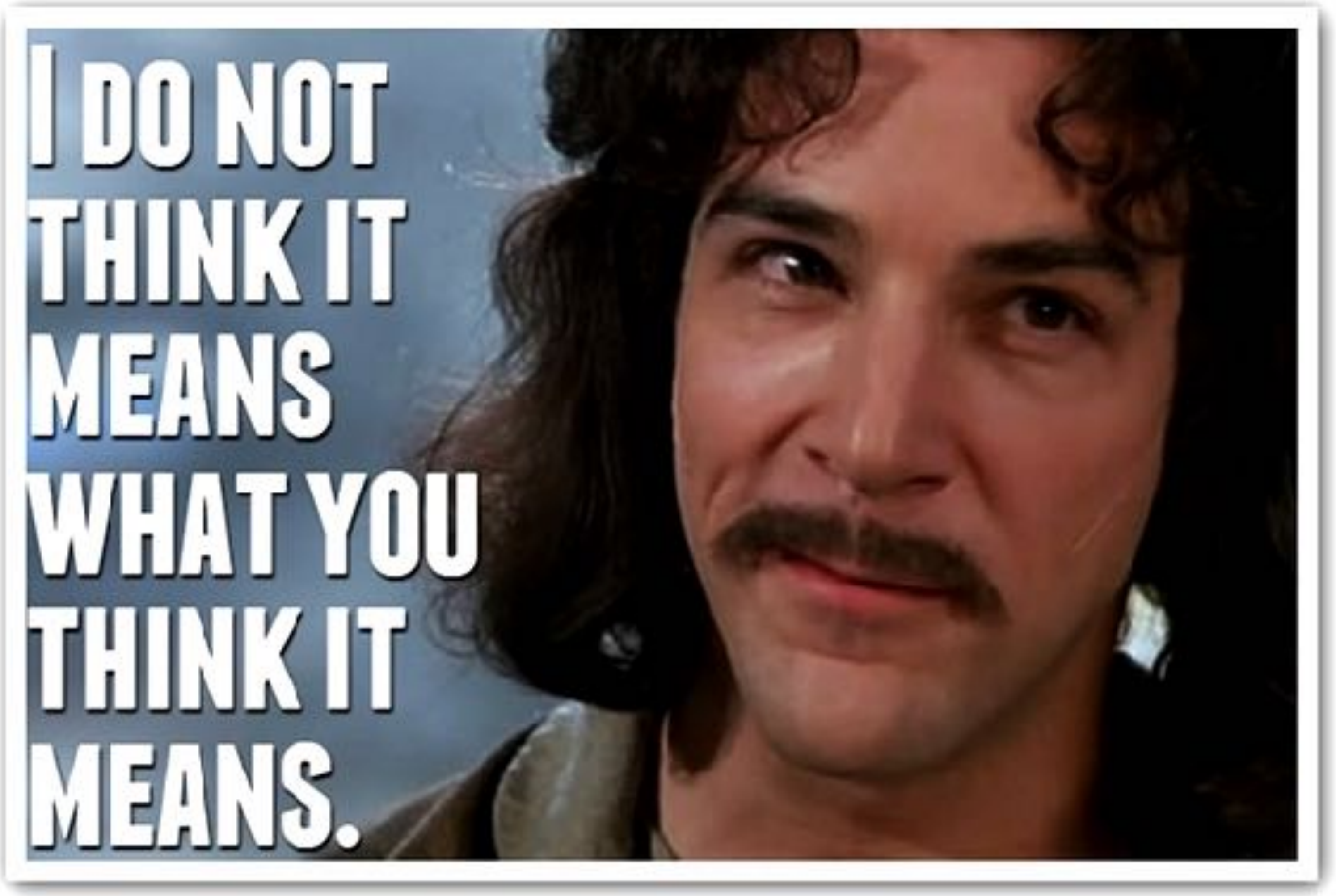
MHD forces can still surprise you

Example: Thermal instability with gravity + MHD



B-fields change threshold $\frac{t_{\rm cool}}{t_{\rm ff}}$ for a multiphase medium

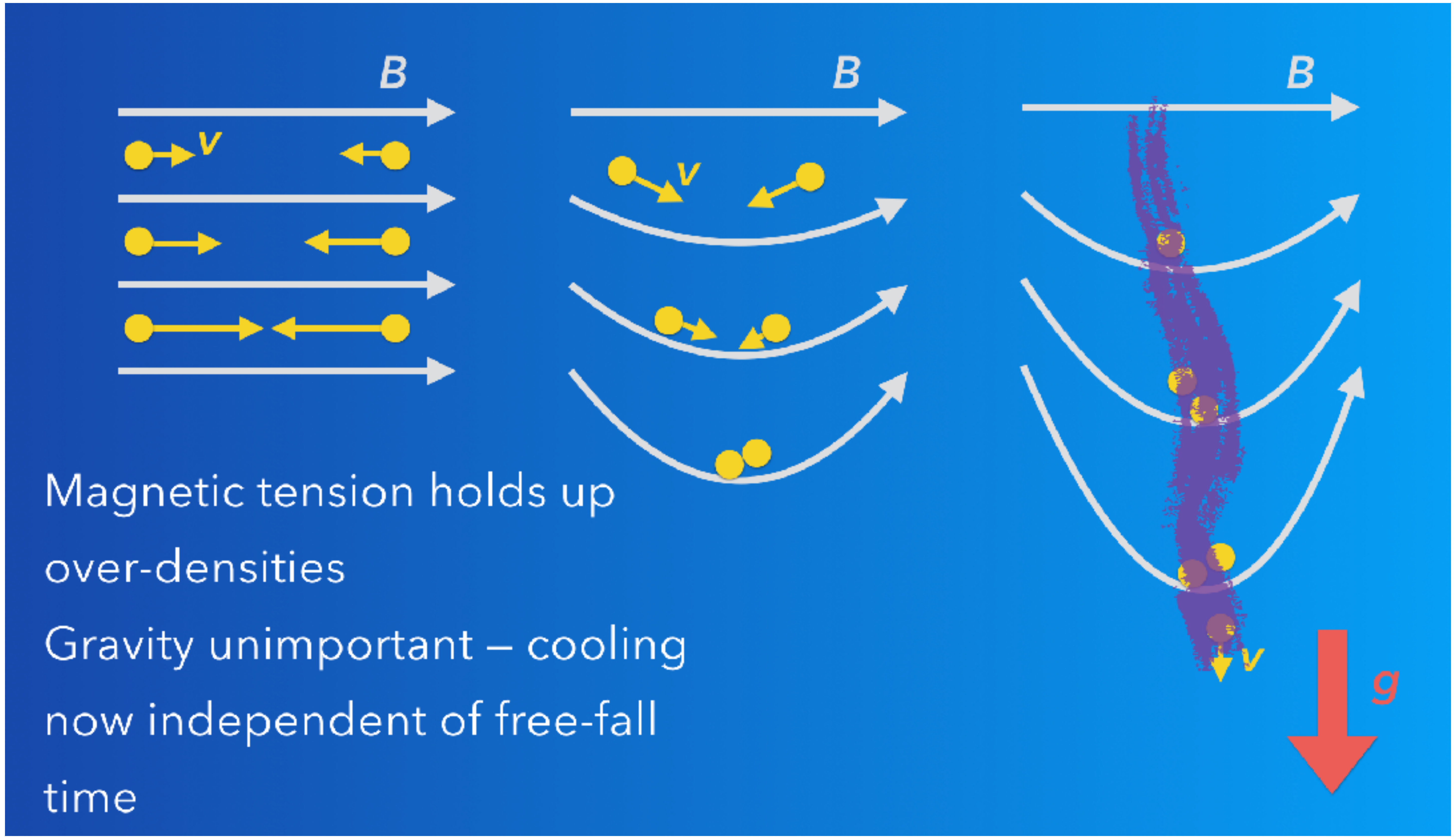
Can be independent of $\frac{t_{\rm cool}}{t_{\rm ff}}$



Even very weak fields matter

Because you must compare perturbed forces, not background forces

So far, so good.



Magnetic tension holds up over-densities

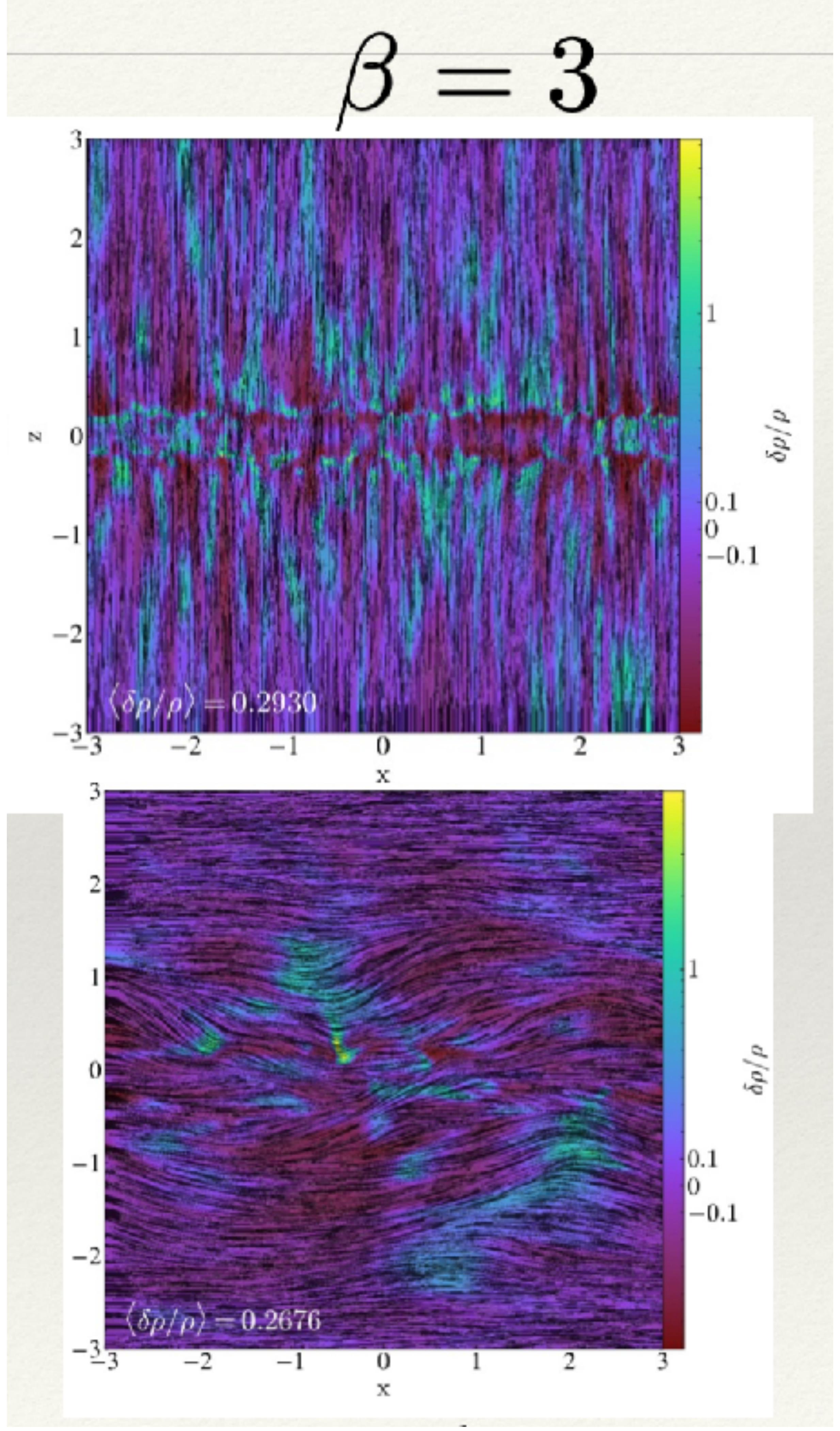
Gravity unimportant – cooling now independent of free-fall time

Ji+18

here's the weird thing...

horizontal and vertical fields give the same cold gas mass!

even though they look very different

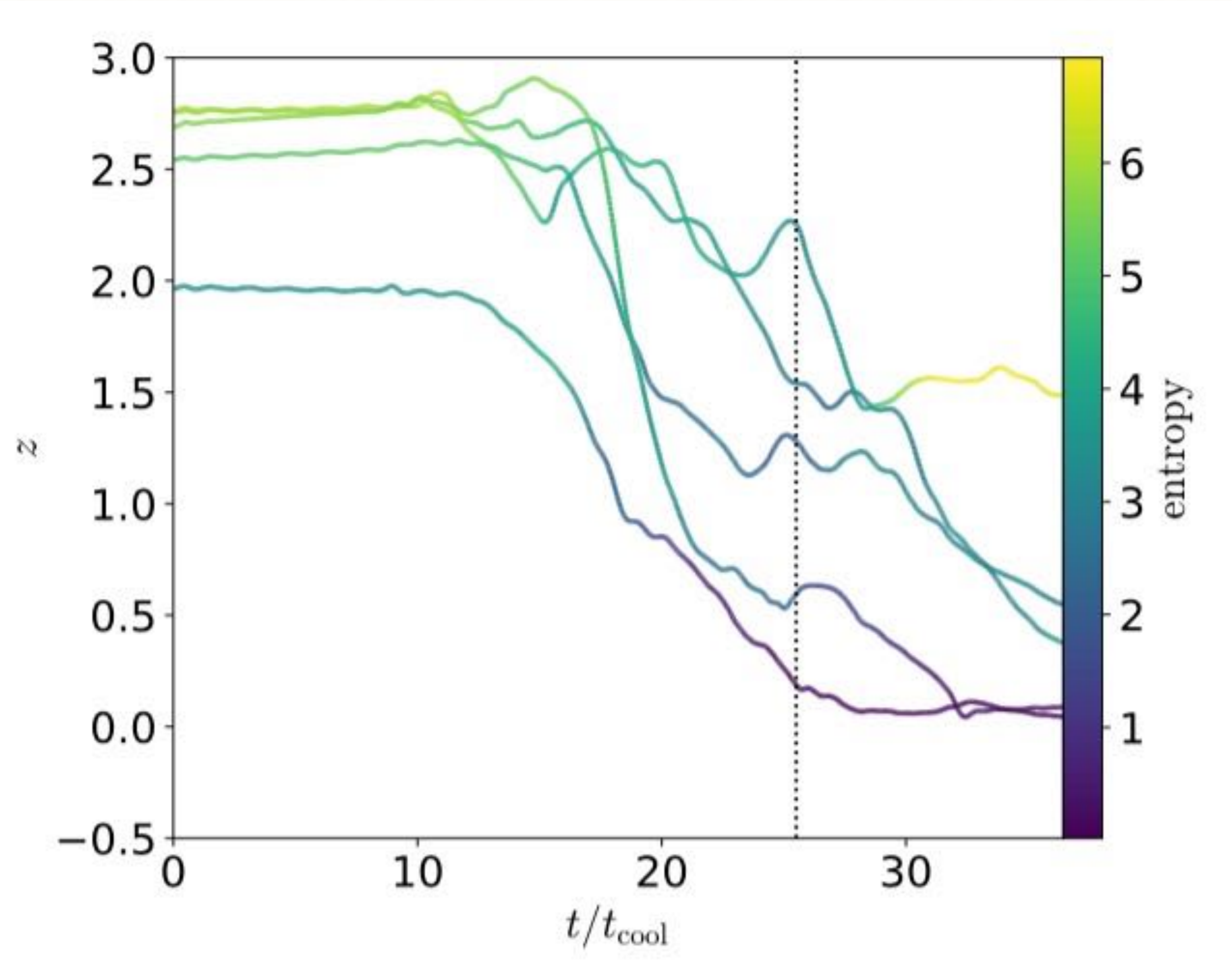


vertical field

$$\frac{\delta\rho}{\rho} = 0.29$$

horizontal field

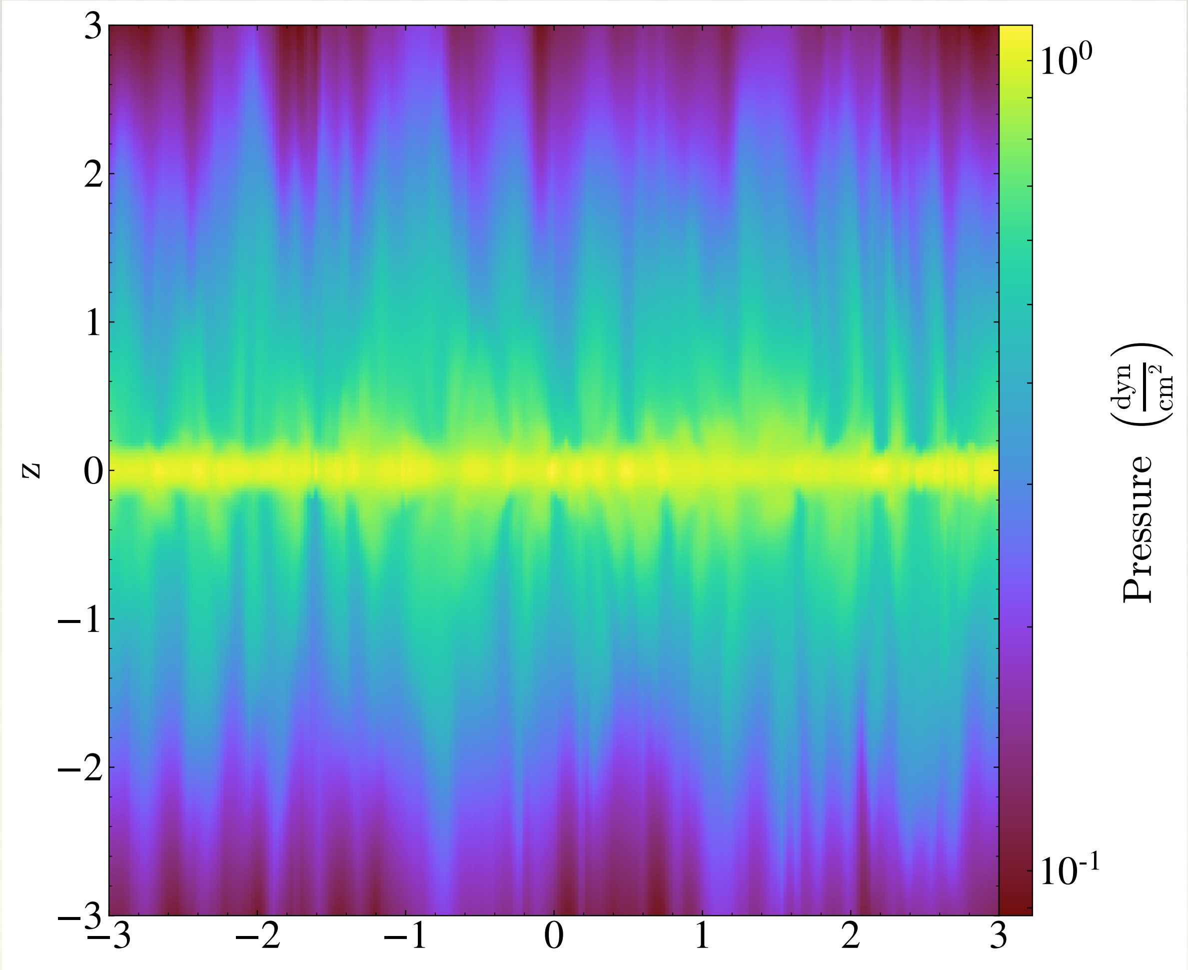
$$\frac{\delta\rho}{\rho} = 0.27$$



$$\beta = 3$$

Particles also don’t move!
Buoyancy also suppressed

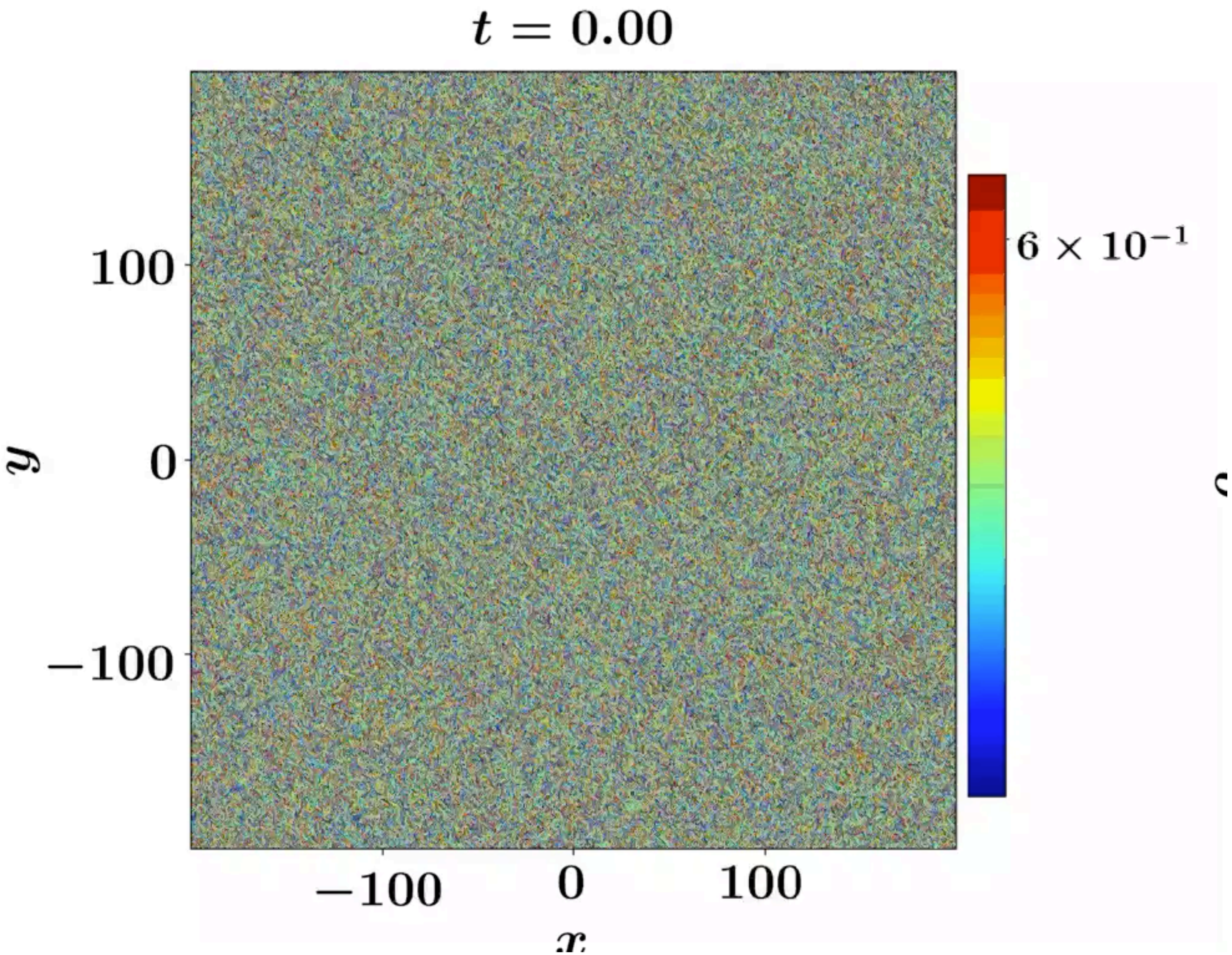
Supported by high pressure regions …which develop because of confining tension




low
high
low

Here's another head-scratcher

Outcome of thermal instability w/ B-fields. Solitons??



Jiang & Oh 2021

Turbulence

When I meet God, I’m going to ask him two questions: why relativity? And why turbulence? I really believe he’ll have an answer for the first.

—Werner Heisenberg

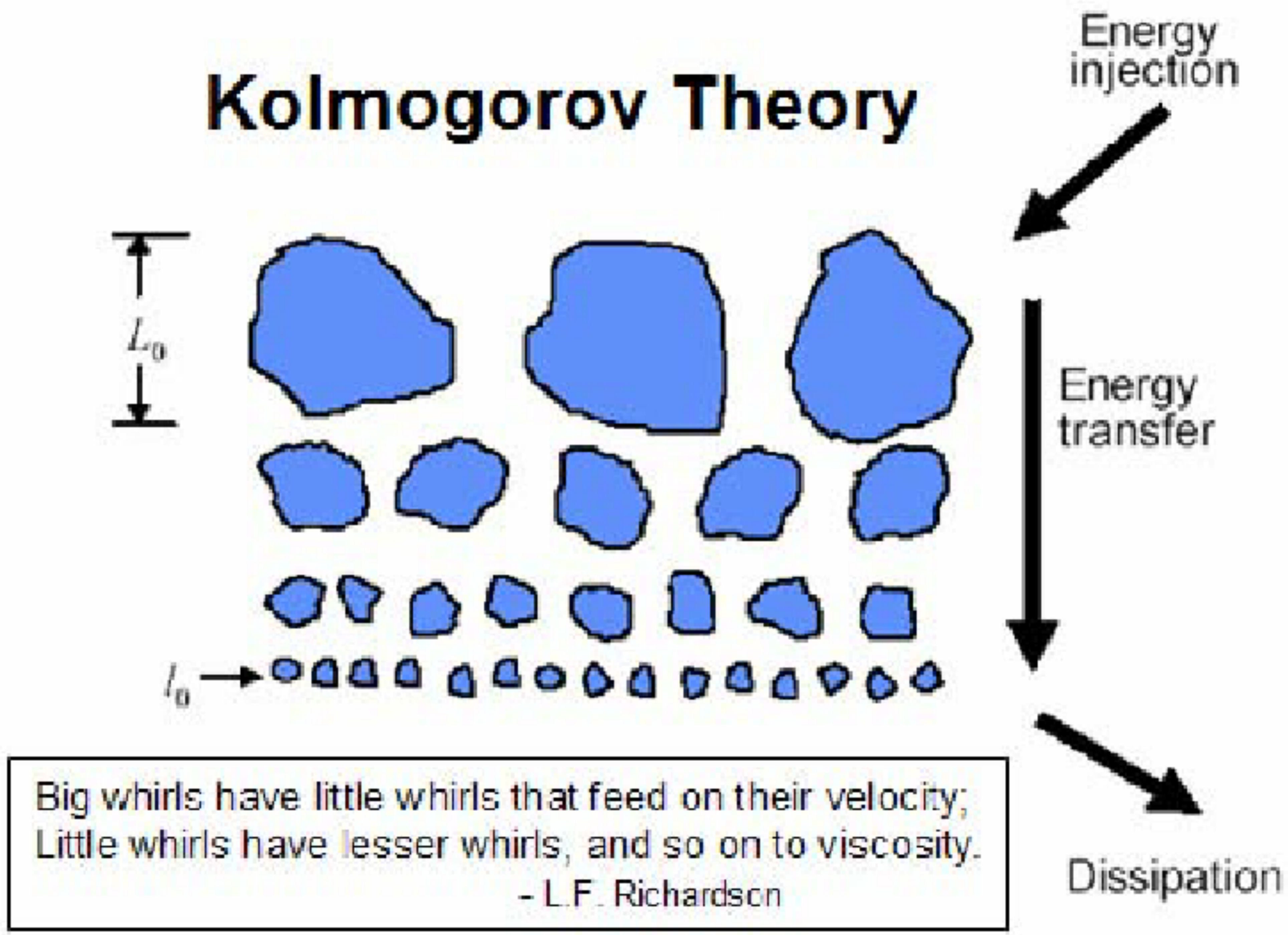
What's Turbulence?

…more than just non-thermal motions

- energy cascades (usually from large to small scales)
- comes from non-linear term in hydro equations $v \cdot \nabla v$
- Incompressible hydro: Kolmogorov turbulence

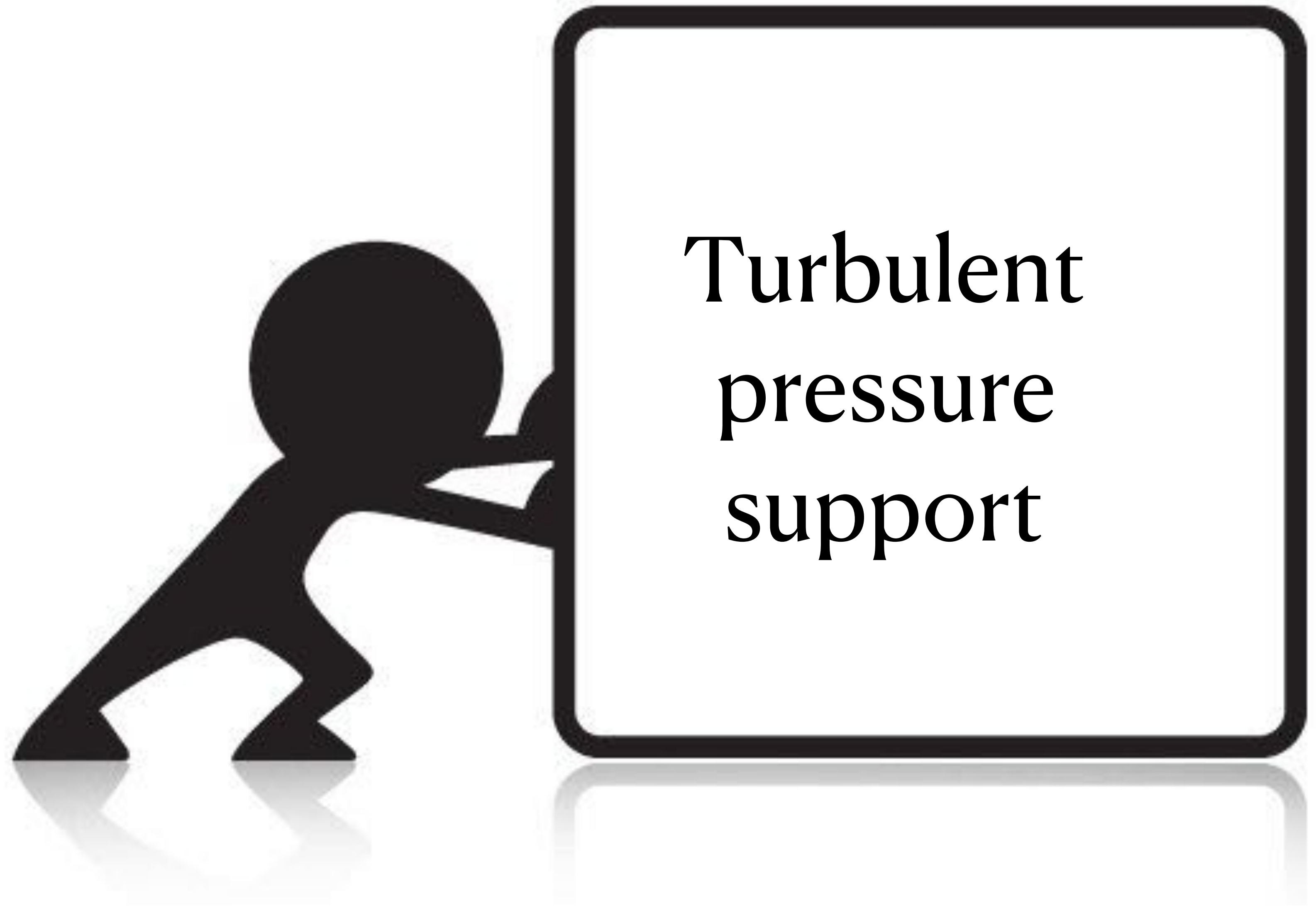
$$\frac{E_{\rm kinetic}}{t_{\rm eddy}} \sim \frac{\rho v^3}{l} \sim {\rm const}$$

More to life than Kolmogorov:
compressible turbulence (jump directly to small scales!),
MHD (3 independent cascades!),
stratified turbulence (vertical motions suppressed)…
decaying turbulence, etc



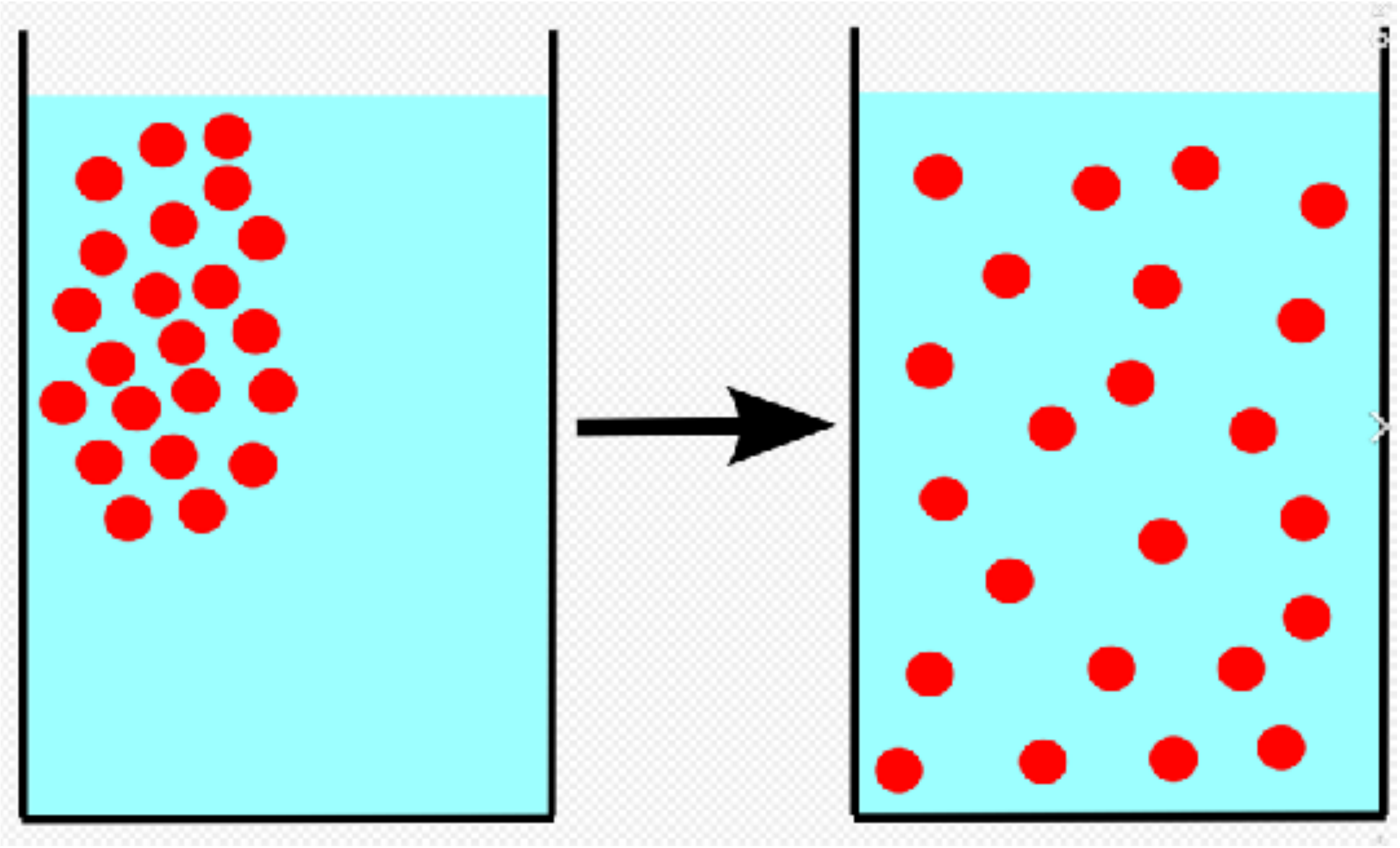
Big whirls have little whirls that feed on their velocity;
Little whirls have lesser whirls, and so on to viscosity.
- L.F. Richardson

Why should you care about turbulence?

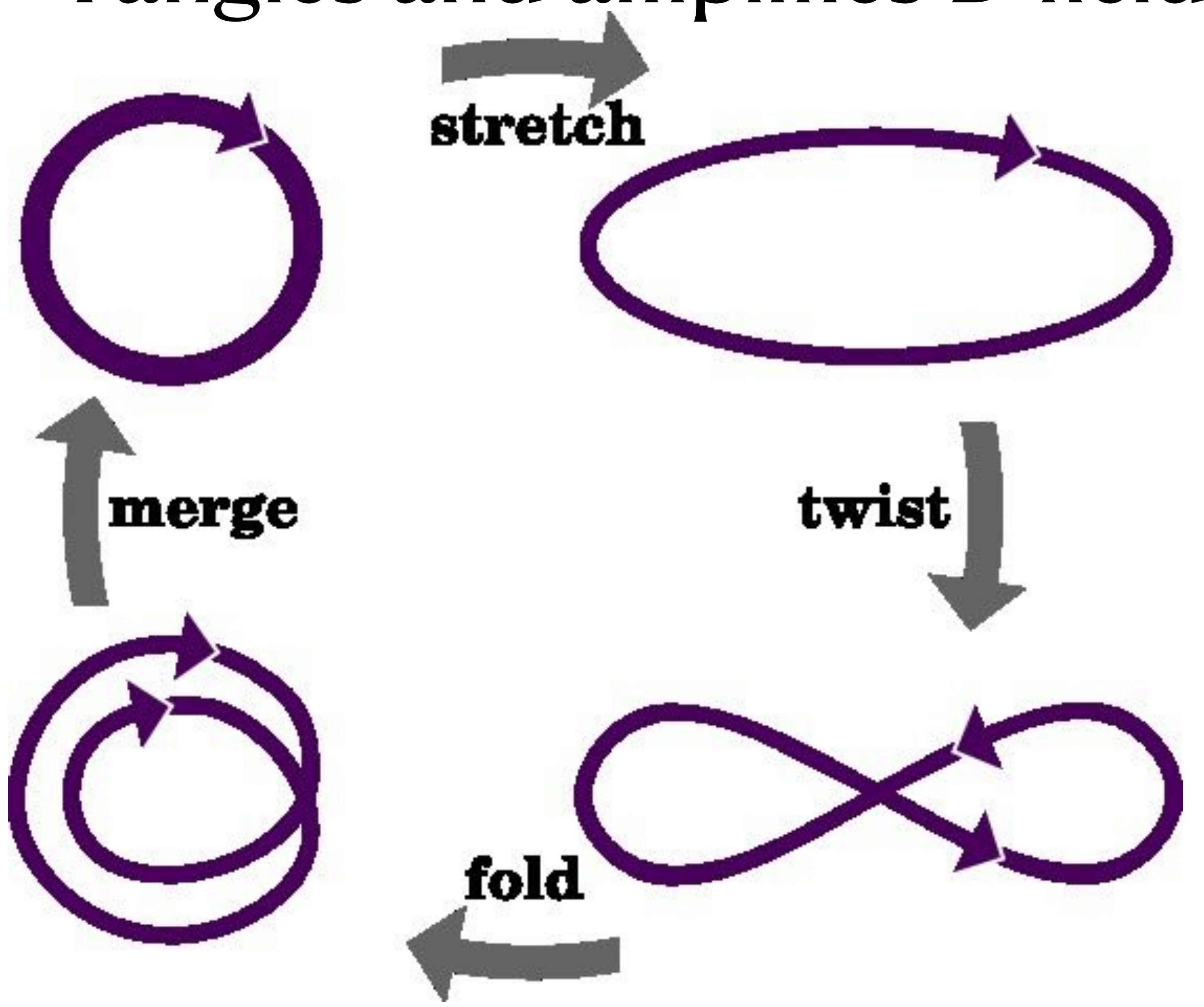


Turbulent pressure support

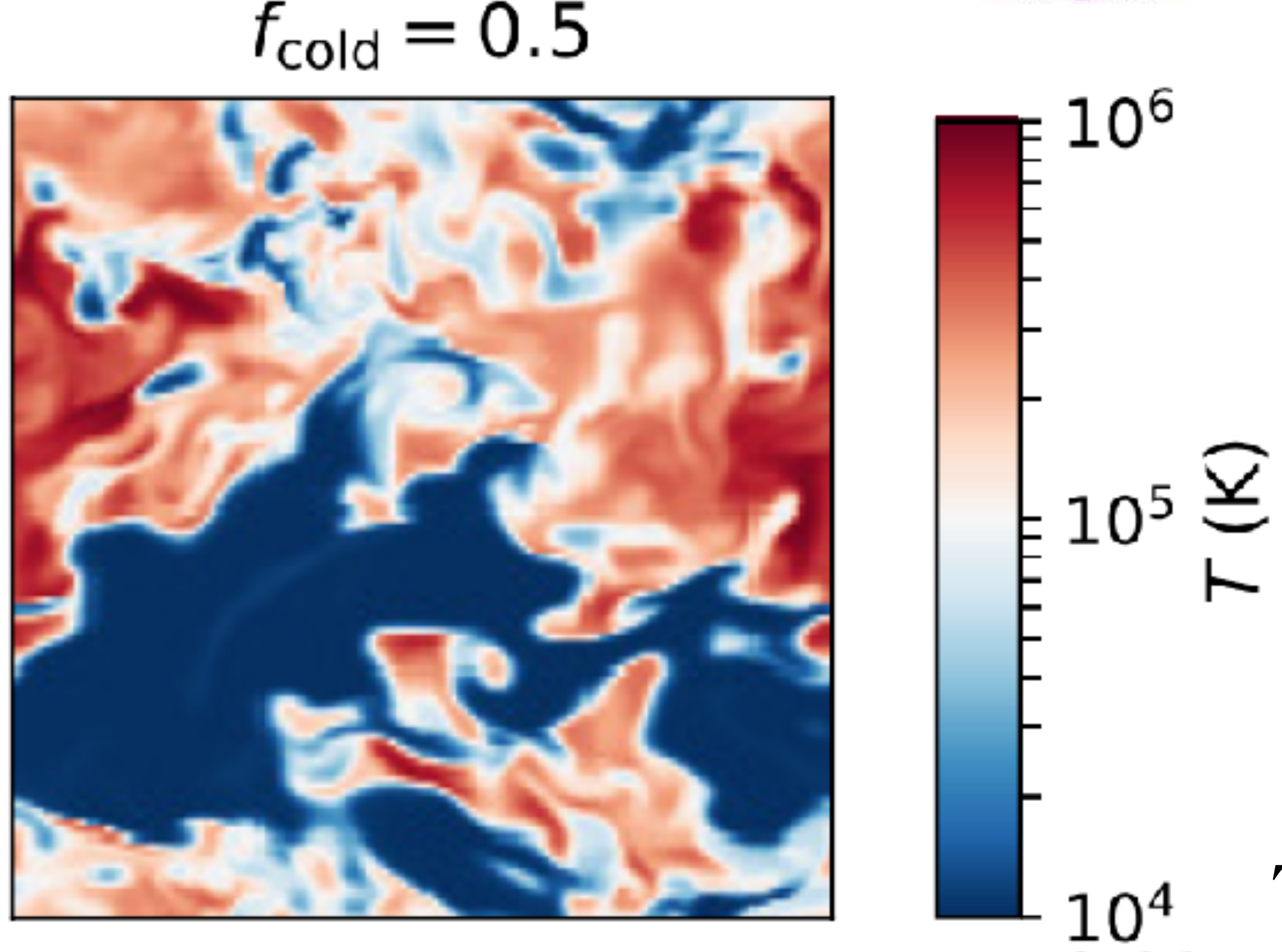
Diffuses (metals, entropy ...)



Tangles and amplifies B-fields



Heats

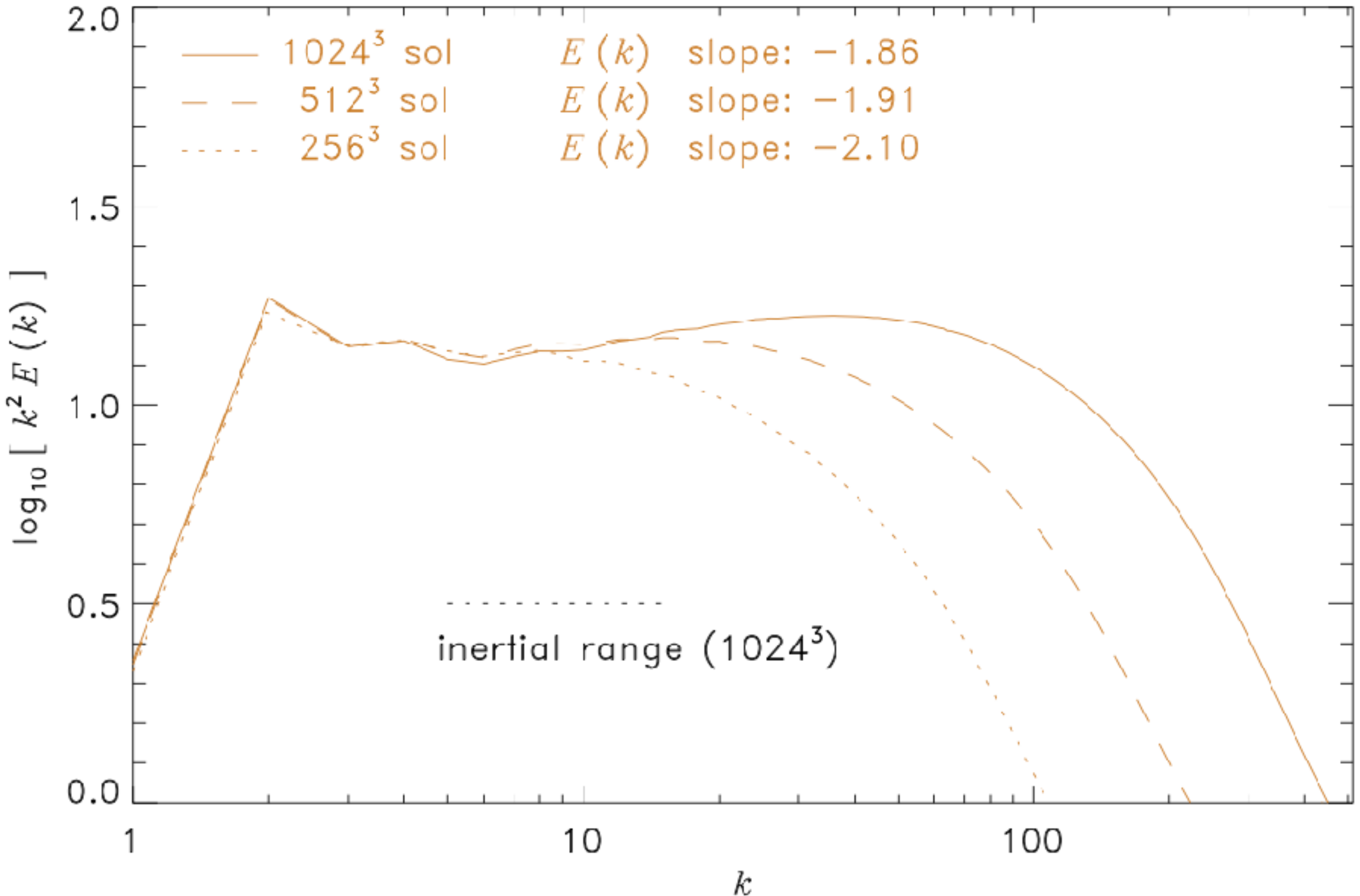


Changes multi-phase structure

Tan+20

An Inconvenient Truth

We barely resolve turbulence in our sims

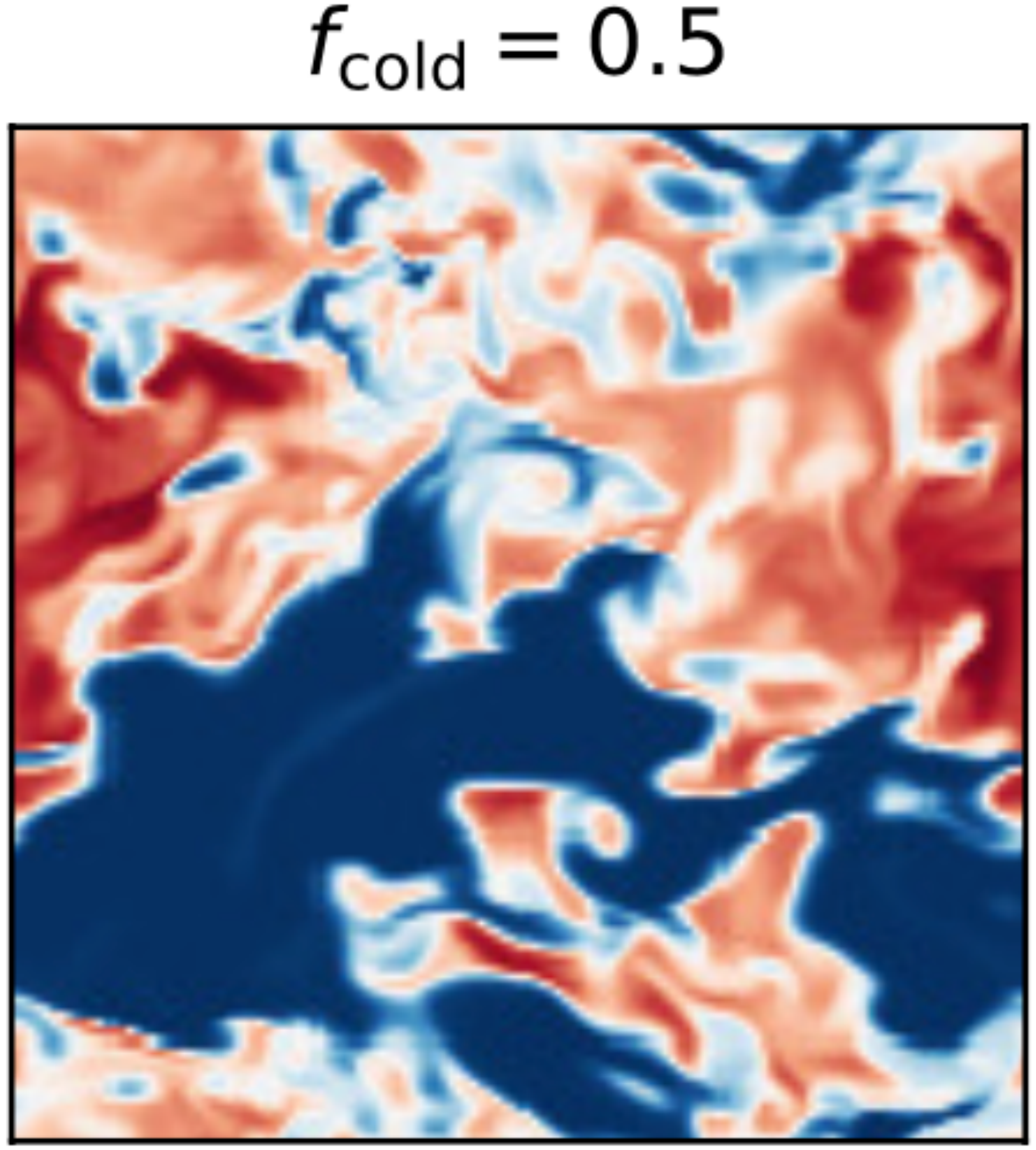


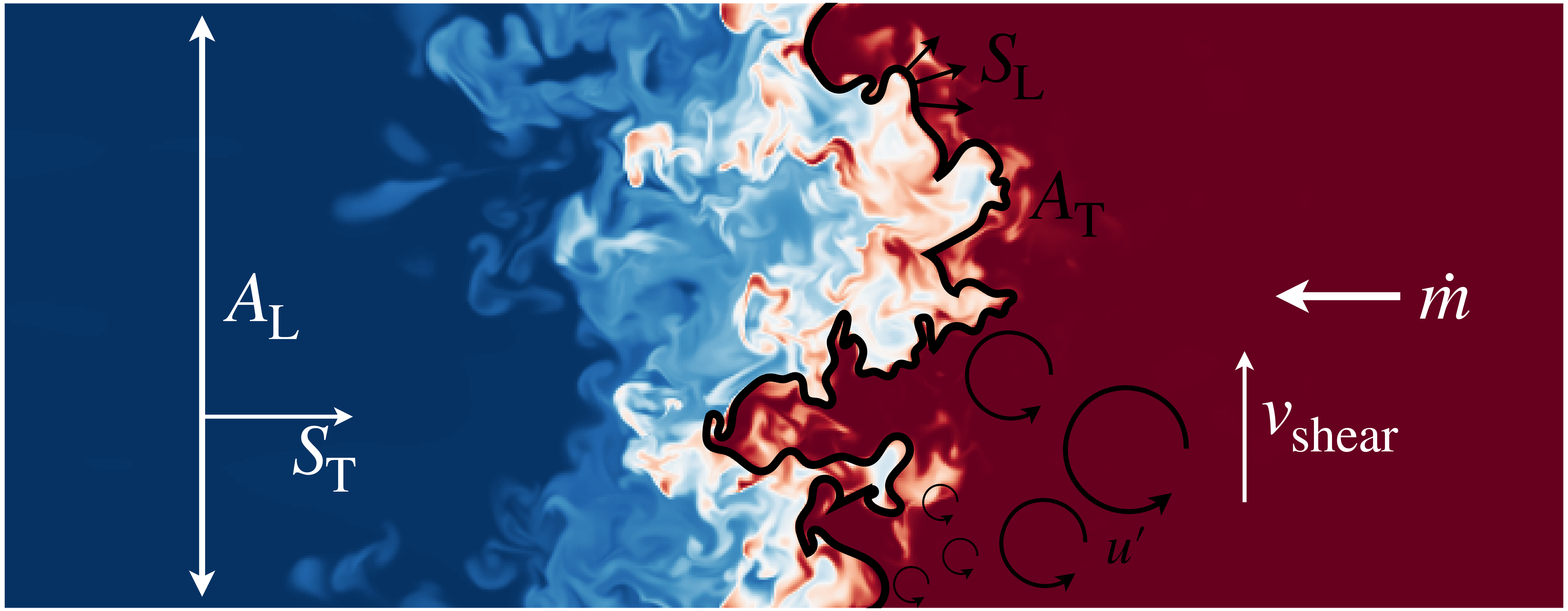
Federrath+2010

we're stirring honey...

Numerical viscosity extends up to ~ 20-30 times the grid scale

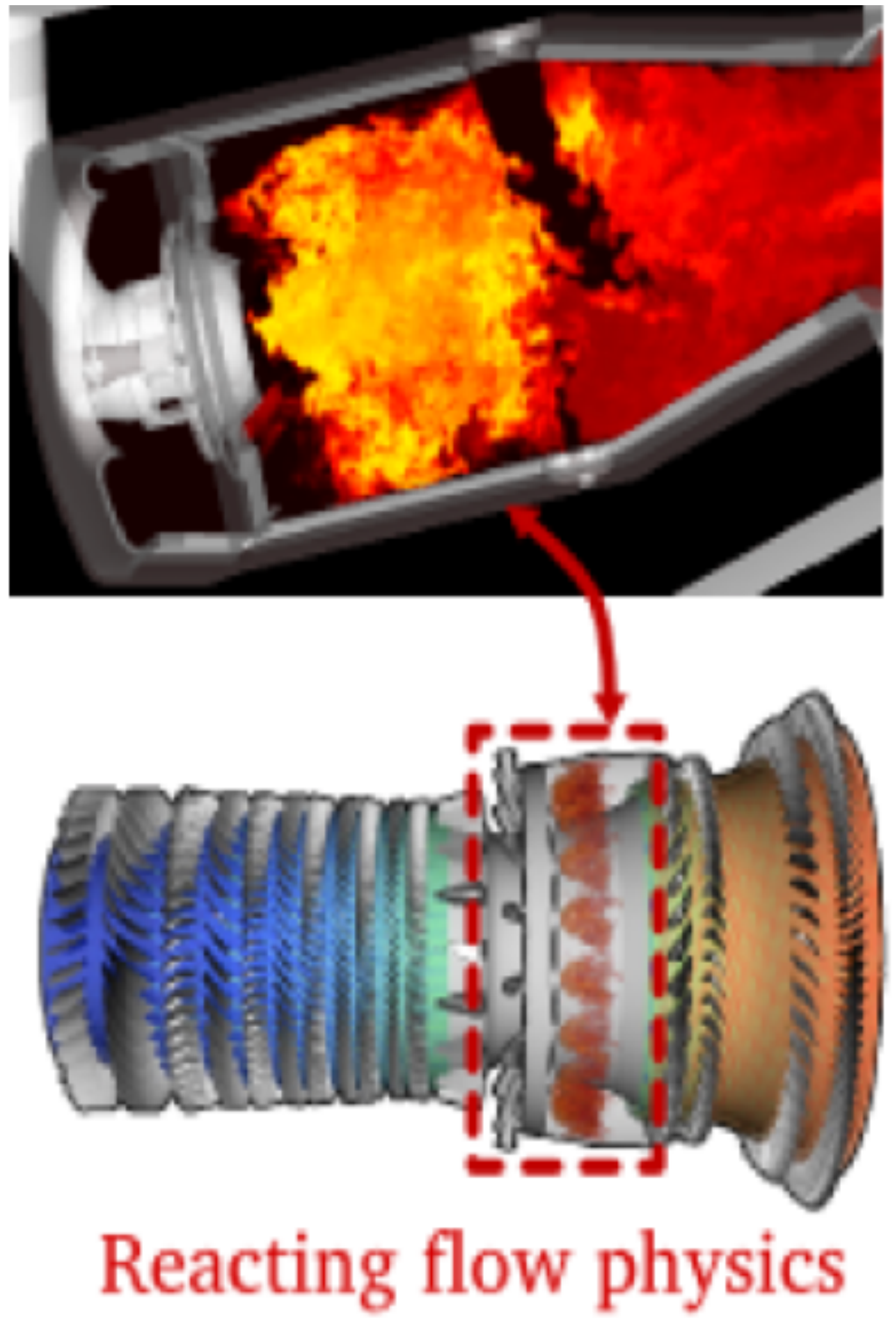
Turbulence & Radiative Cooling

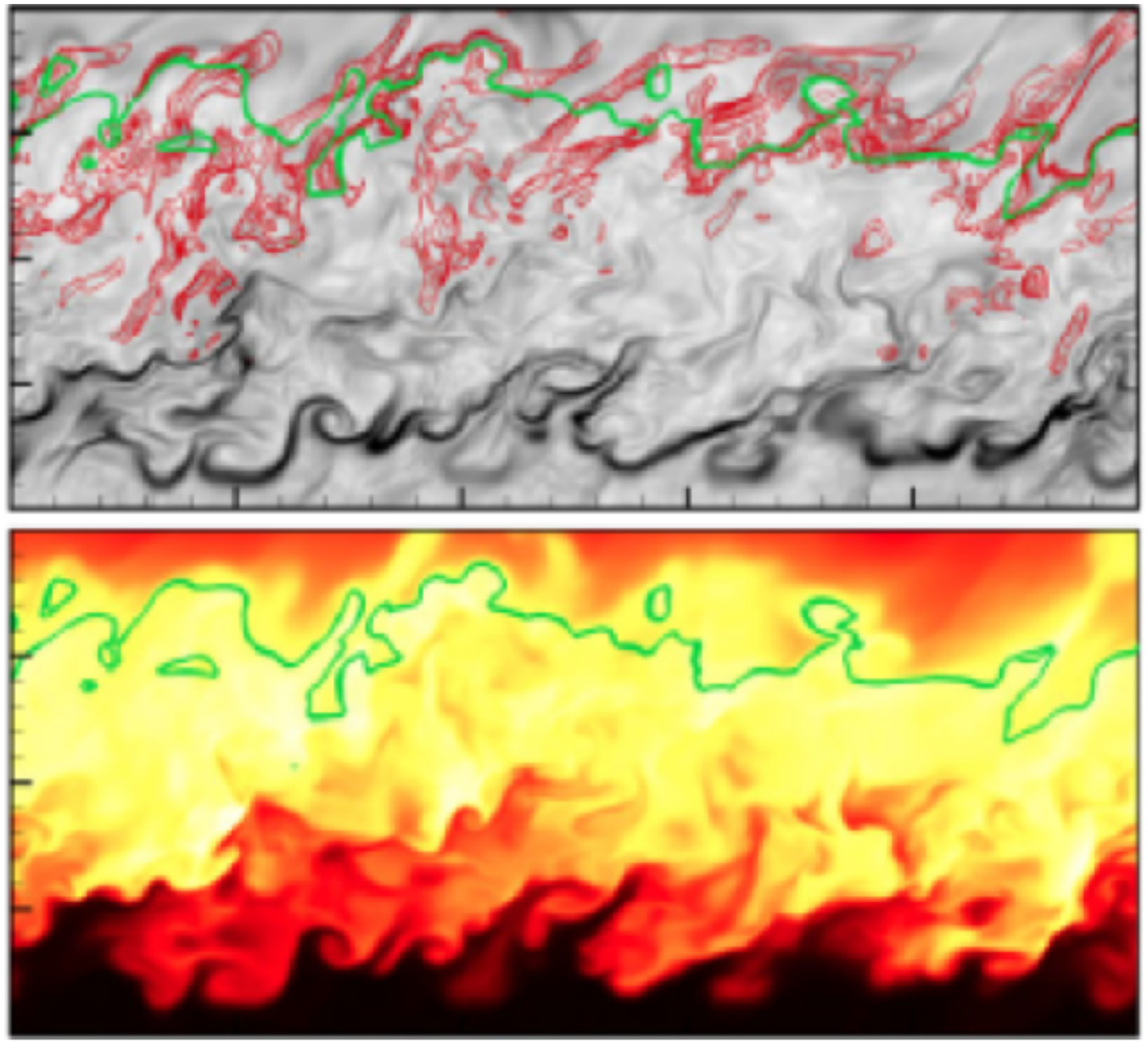




This..

Brent Tan





looks like this

Radiative Mixing Layers: Insights from Turbulent Combustion

Brent Tan[1]★, S. Peng Oh[1], and Max Gronke[1,2]†
[1] *University of California - Santa Barbara, Department of Physics, CA 93106-9530, USA*
[2] *Department of Physics & Astronomy, Johns Hopkins University, Bloomberg Center, 3400 N. Charles St., Baltimore, MD 21218, USA*

Two highlights

Details of microscopic heat transfer between phases not important

Not sensitive to numerical diffusion

Don't need to resolve Field length

Effective cooling: geometric mean of elastic and inelastic collision times $\tilde{\tau}_{\rm cool} \sim \sqrt{\frac{L}{u'} t_{\rm cool}}$

Just like conduction

$$\lambda_{\rm F} \sim \sqrt{\frac{\kappa T}{n^2 \Lambda(T)}} \sim \sqrt{\lambda_e v_e t_{\rm cool}}$$

or radiative transfer

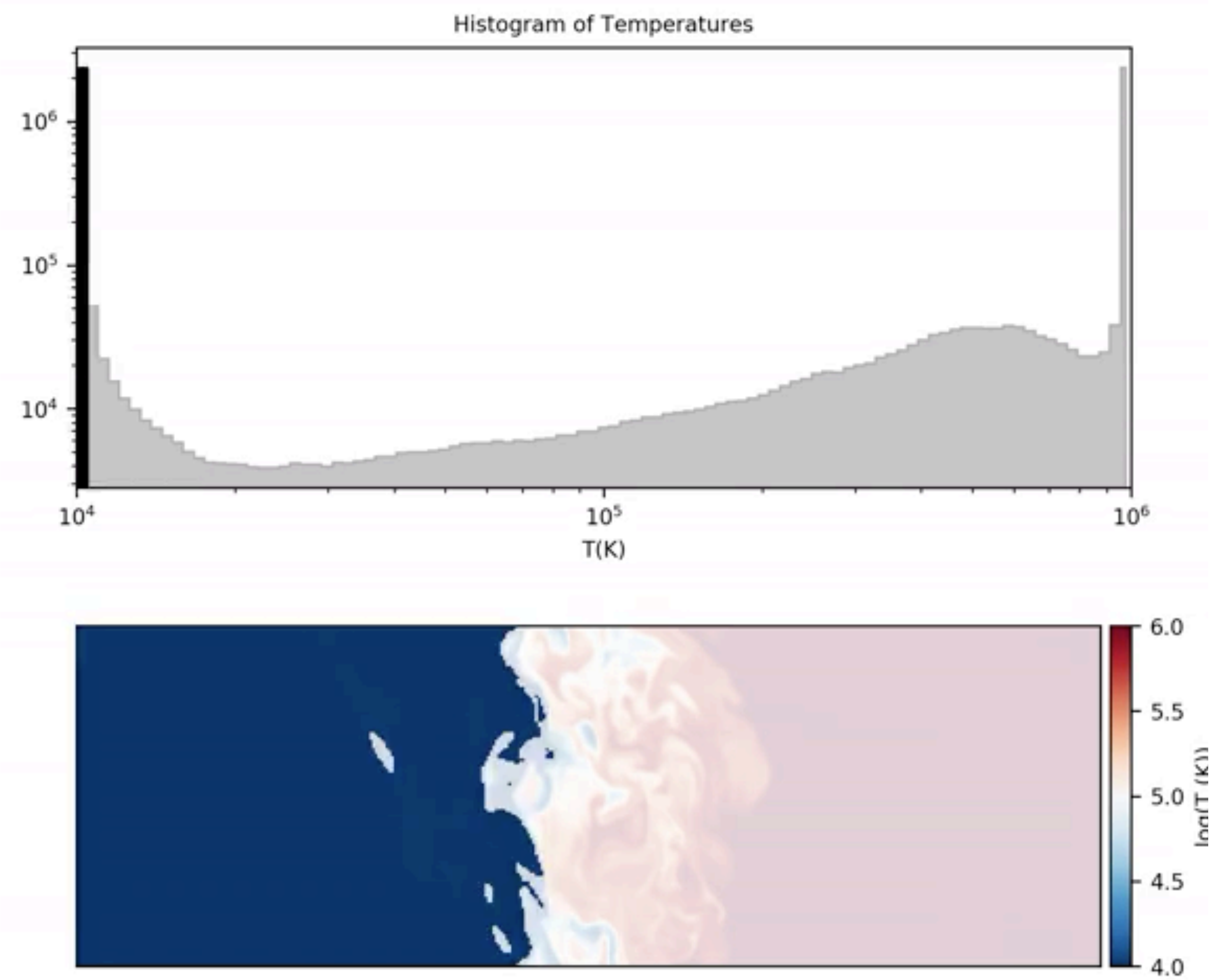
$$\tau_* \sim \sqrt{\tau_a \tau_s}$$

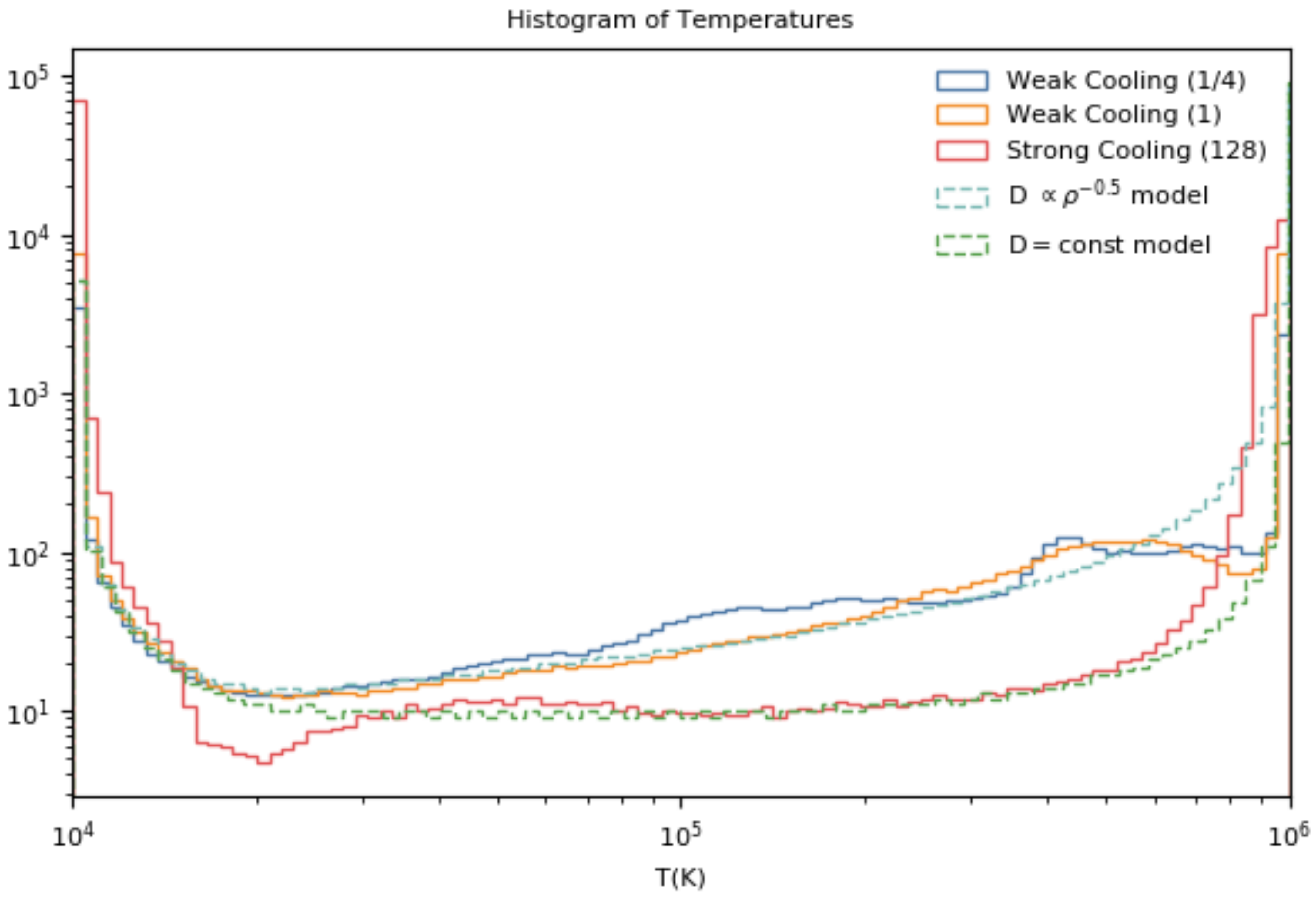
Tan+21 in prep

You want a subgrid model...

Analytic model for temperature PDFs

Input: cooling time, turbulent diffusivity

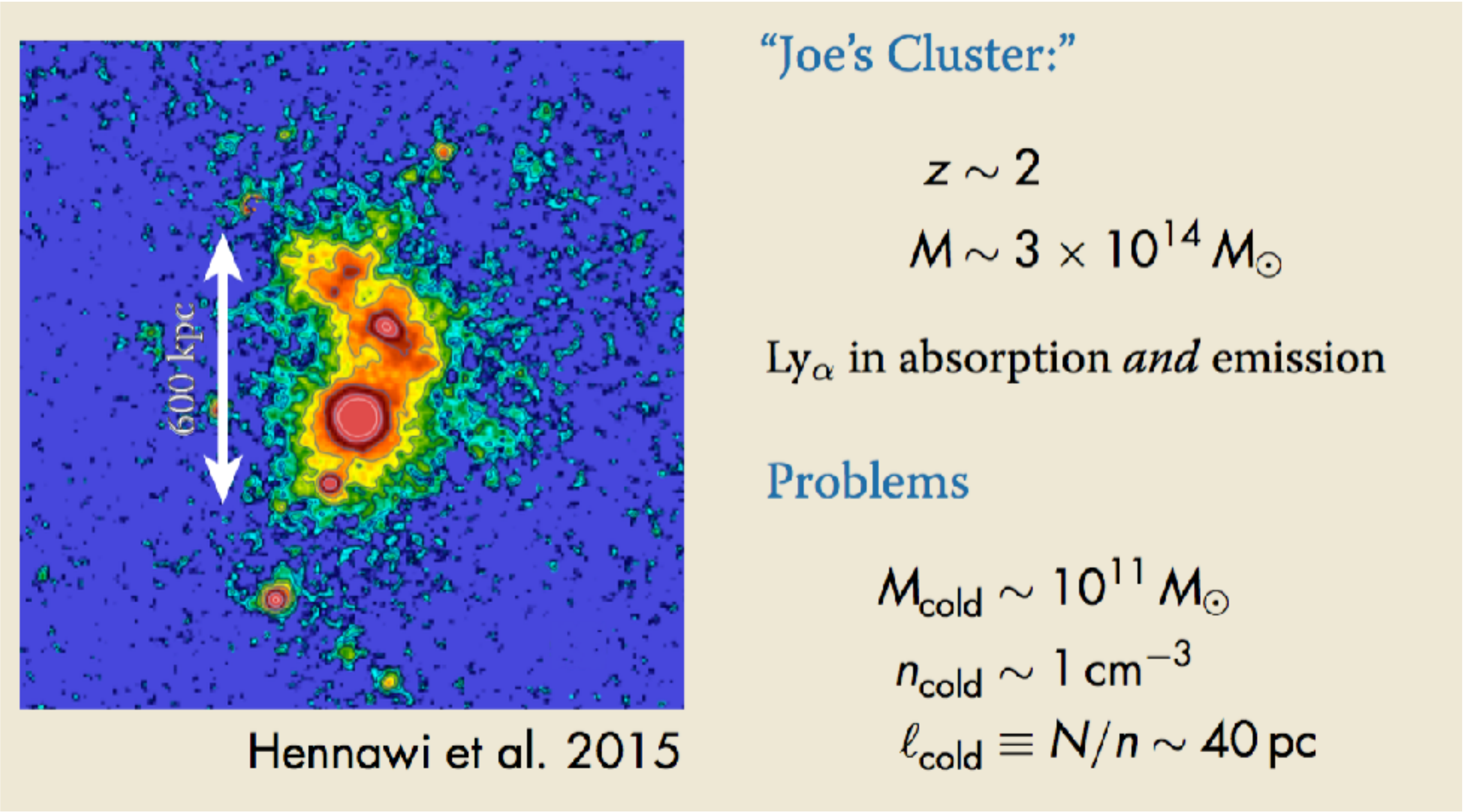




By density or emission weighting, get absorption/emission line ratios from analytic model which matches sims

‘Foggy’ cold gas is observationally driven

Theorists are just catching up...



Hennawi et al. 2015

“Joe’s Cluster:”

$z \sim 2$

$M \sim 3 \times 10^{14}\, M_\odot$

Ly$_\alpha$ in absorption *and* emission

Problems

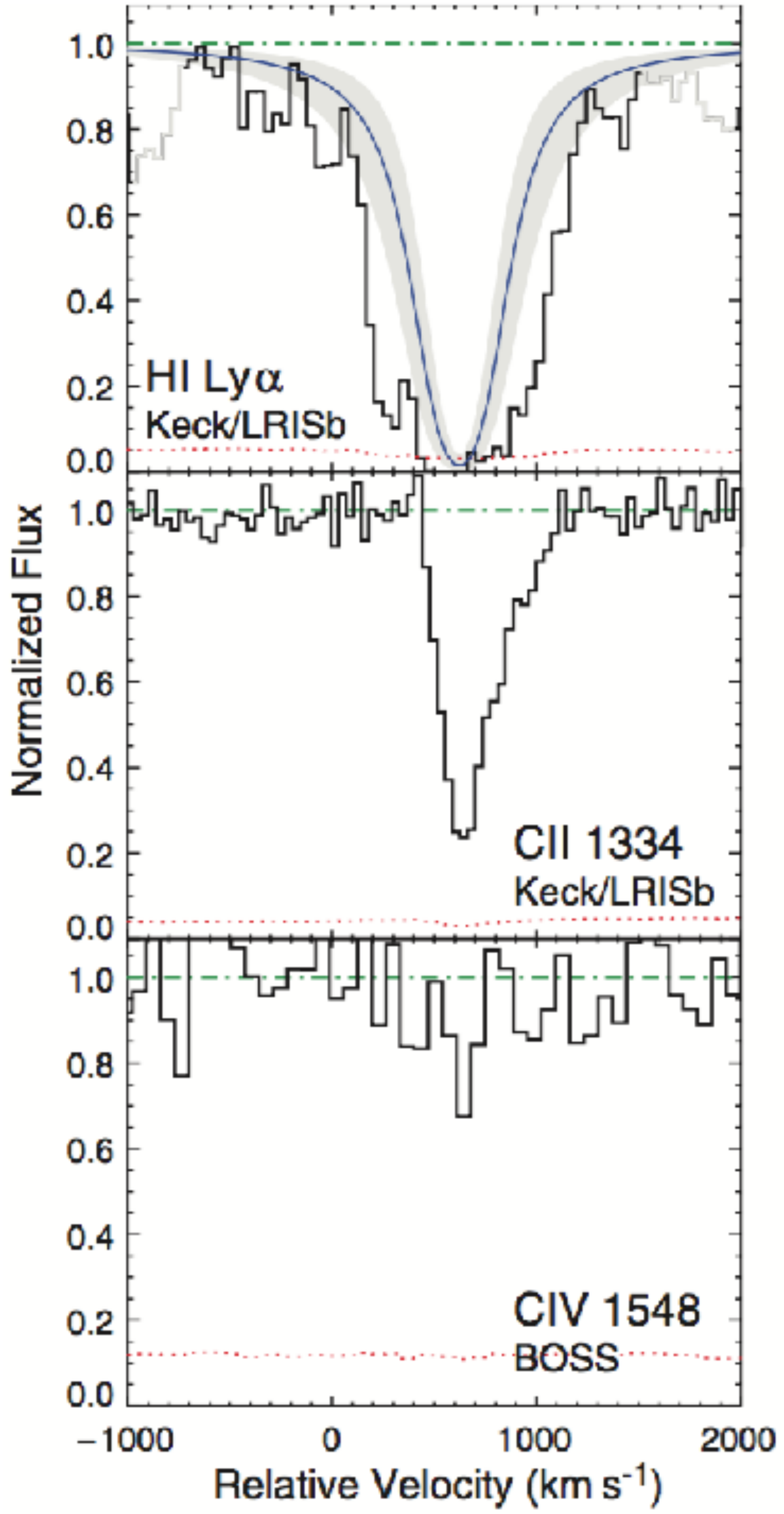
$M_{\rm cold} \sim 10^{11}\, M_\odot$

$n_{\rm cold} \sim 1\ {\rm cm}^{-3}$

$\ell_{\rm cold} \equiv N/n \sim 40\ {\rm pc}$

Highly
suprathermal
line widths

$\mathcal{M} \sim 100\,!$



Large area covering fraction $f_A \sim 1$
despite low volume filling fraction $f_V \sim 10^{-4}$
Need a very thin shell which surrounds the halo??

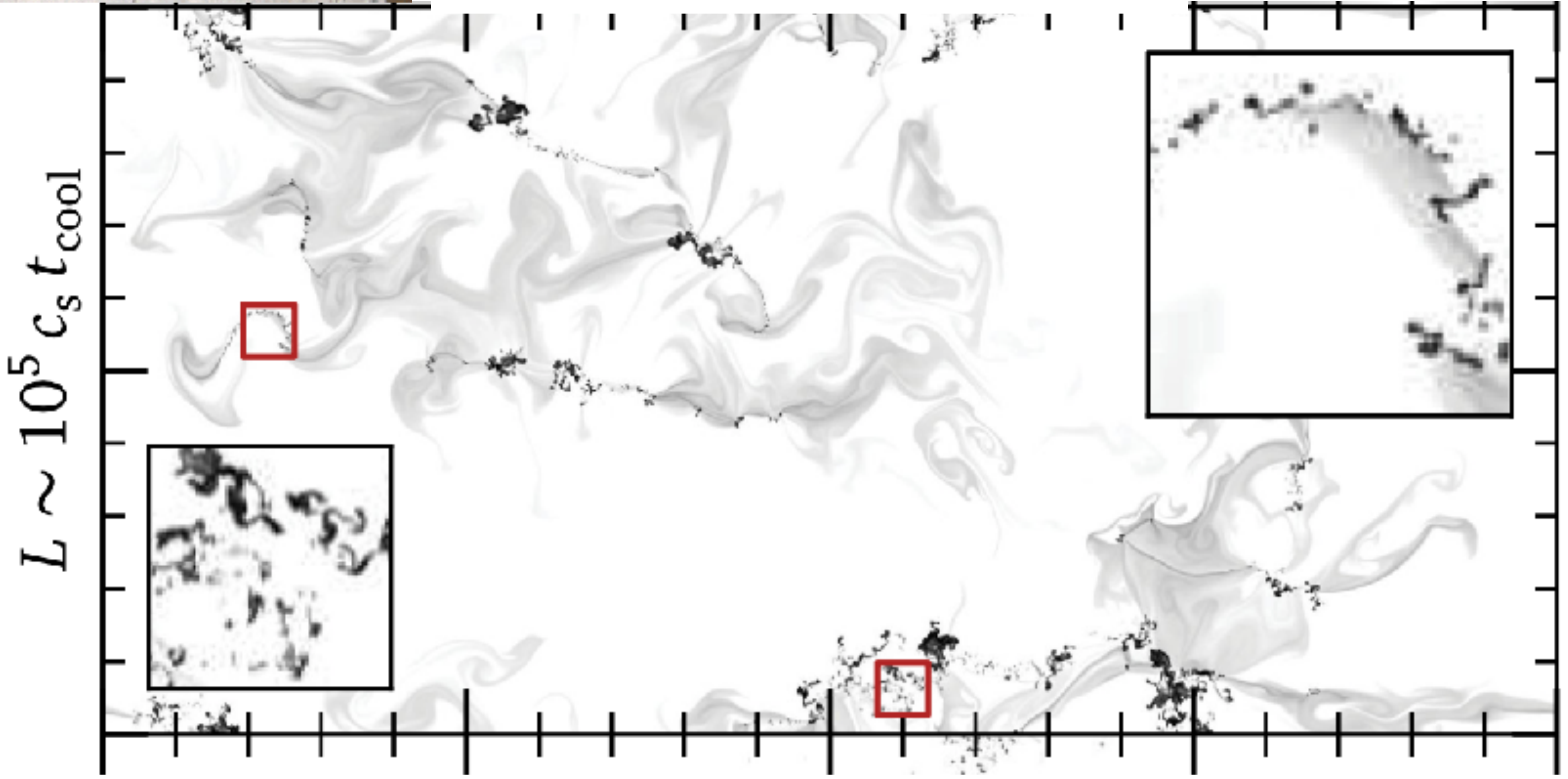
All makes sense if have a fog: intersect *many* cloudlets along line of sight

Mike vs. Max

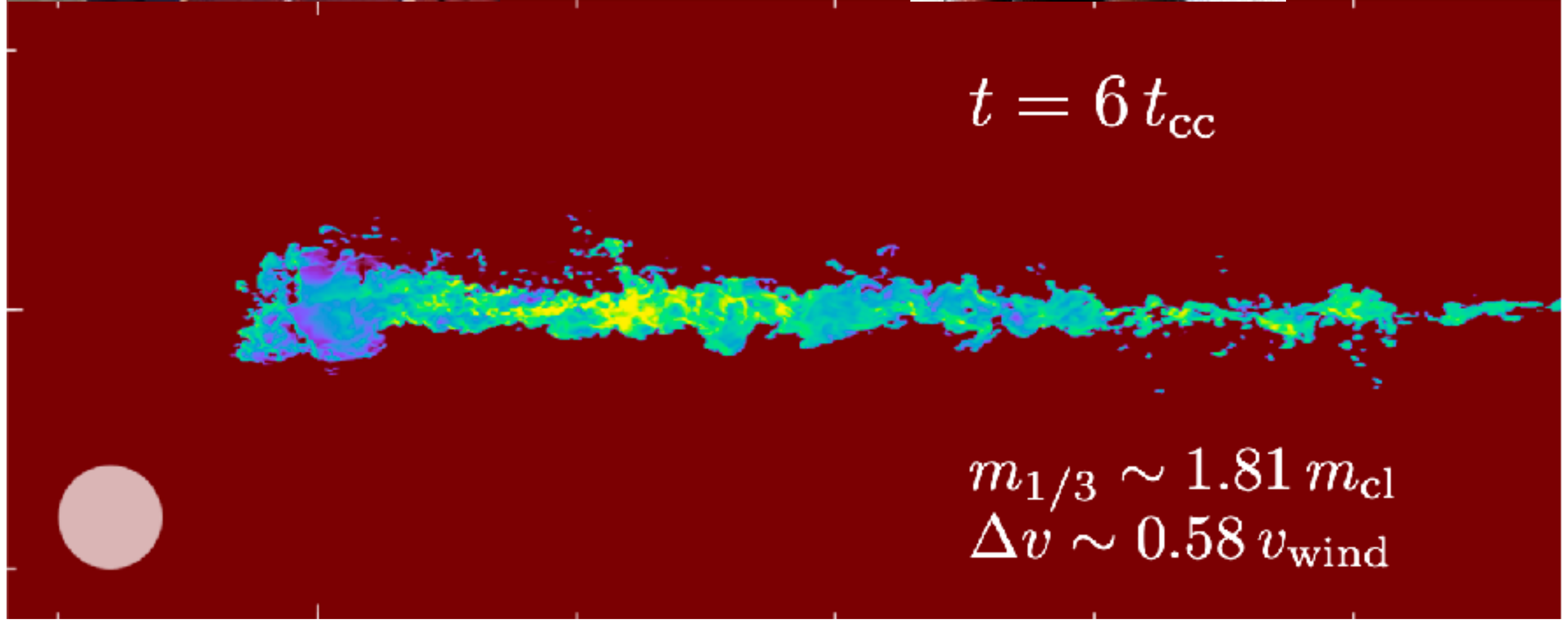
OK, you still want to talk sizes

Mike McCourt

Max Gronke



McCourt+2018



Gronke & Oh 2018

Typical size $\lambda_{\rm Mc} \sim c_s t_{\rm cool} (T \sim 10^4 K)$

Trash talk:'Big clouds will just shatter'

Minimum size $\lambda_{\rm G} \sim c_s t_{\rm cool,mix} (T \sim 10^5 K) \gg \lambda_{\rm Mc}$

Trash talk: 'Mist will just dissolve'

Who is right?

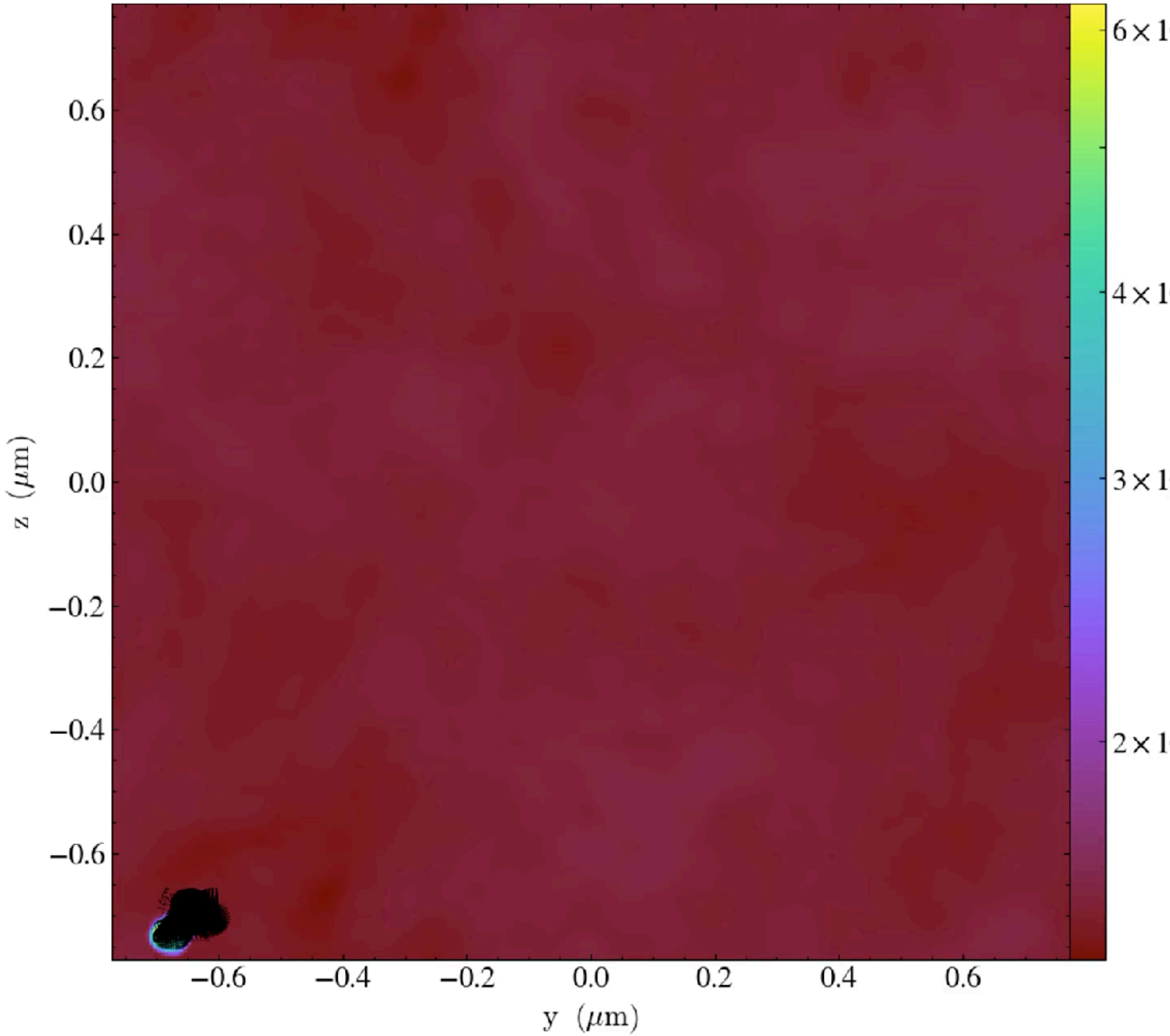
Both?

Instead of this...

Do this.

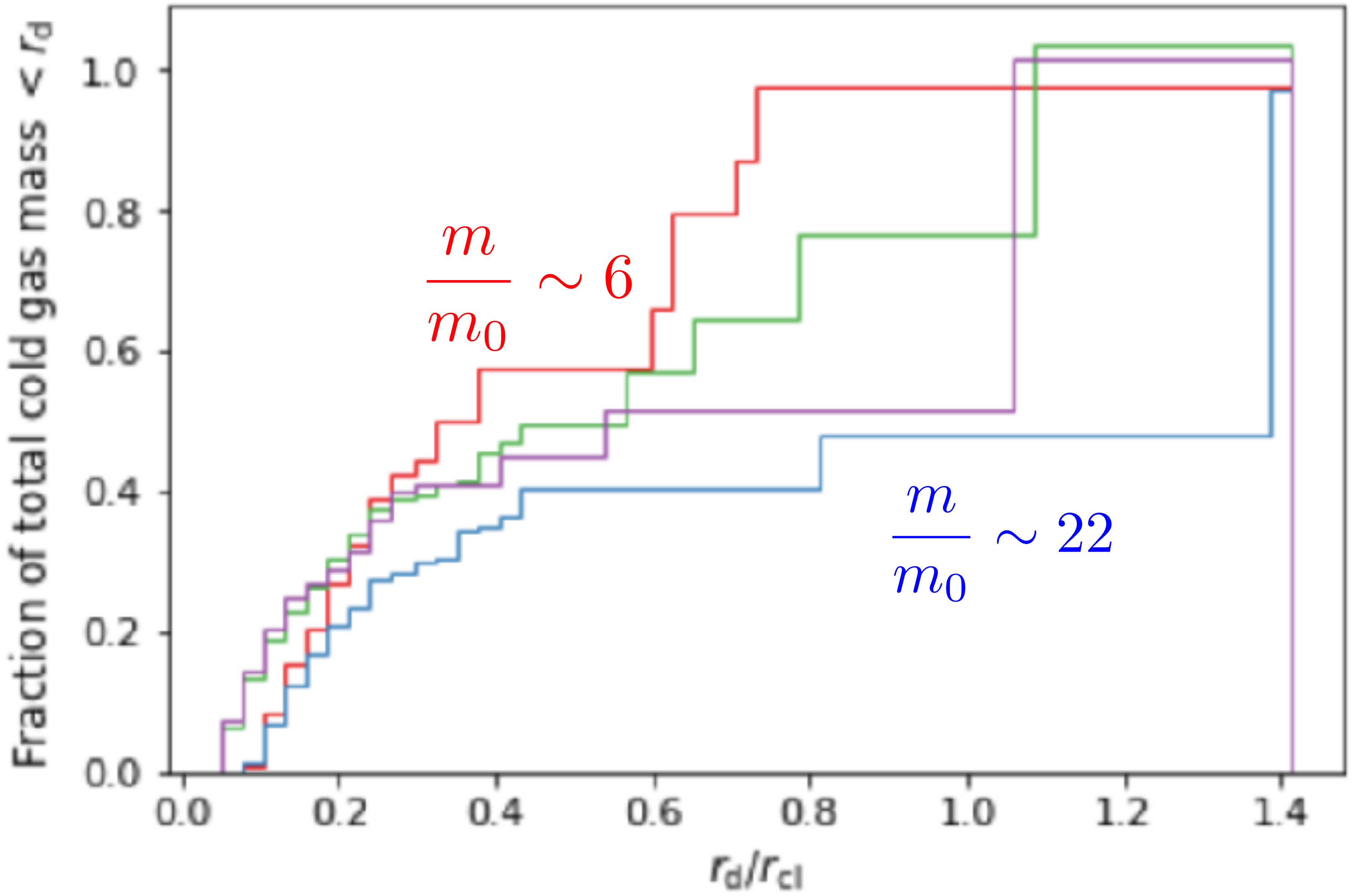
Laminar Flow

Turbulent Flow



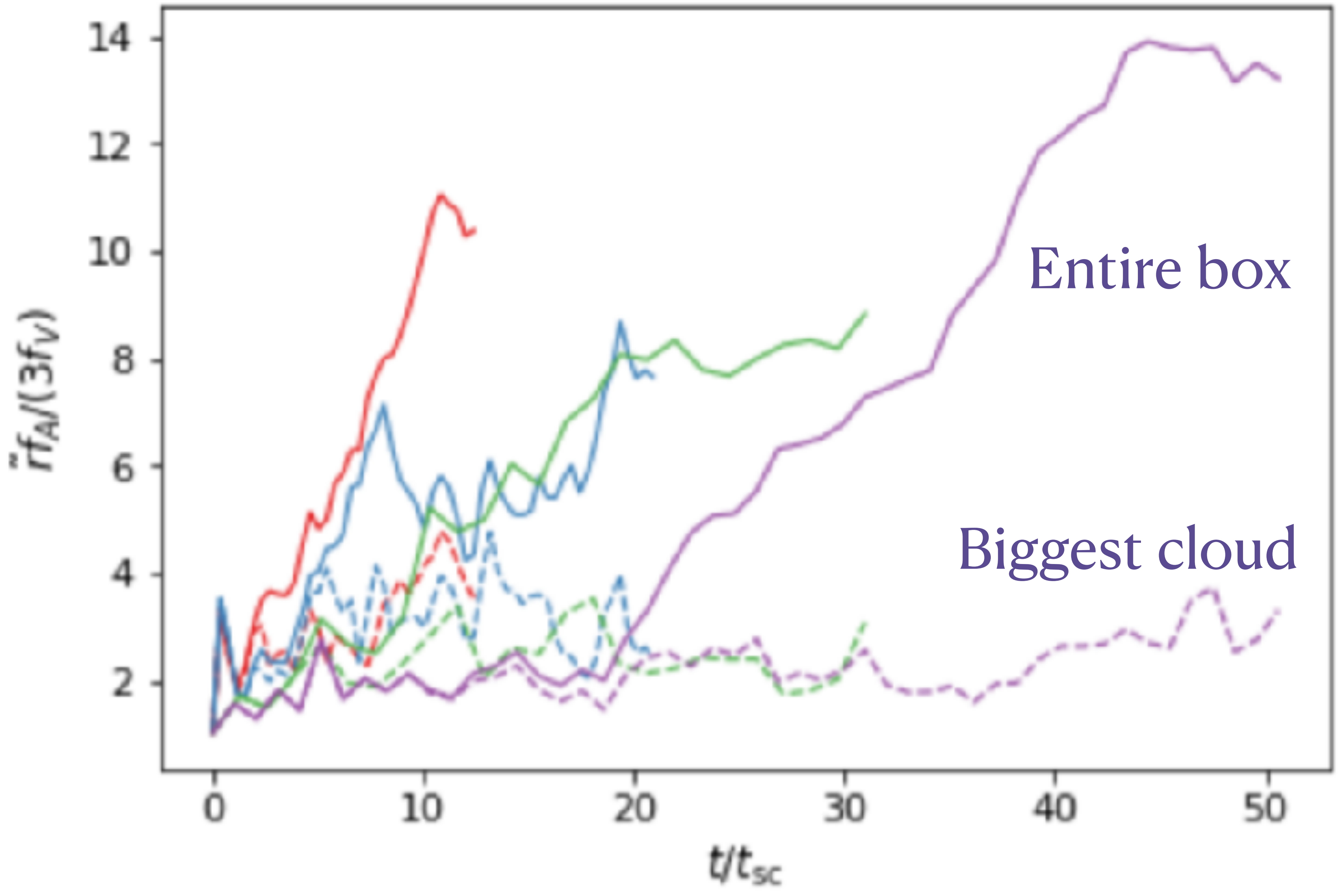
Gronke & Oh 2021

Lots of cool features



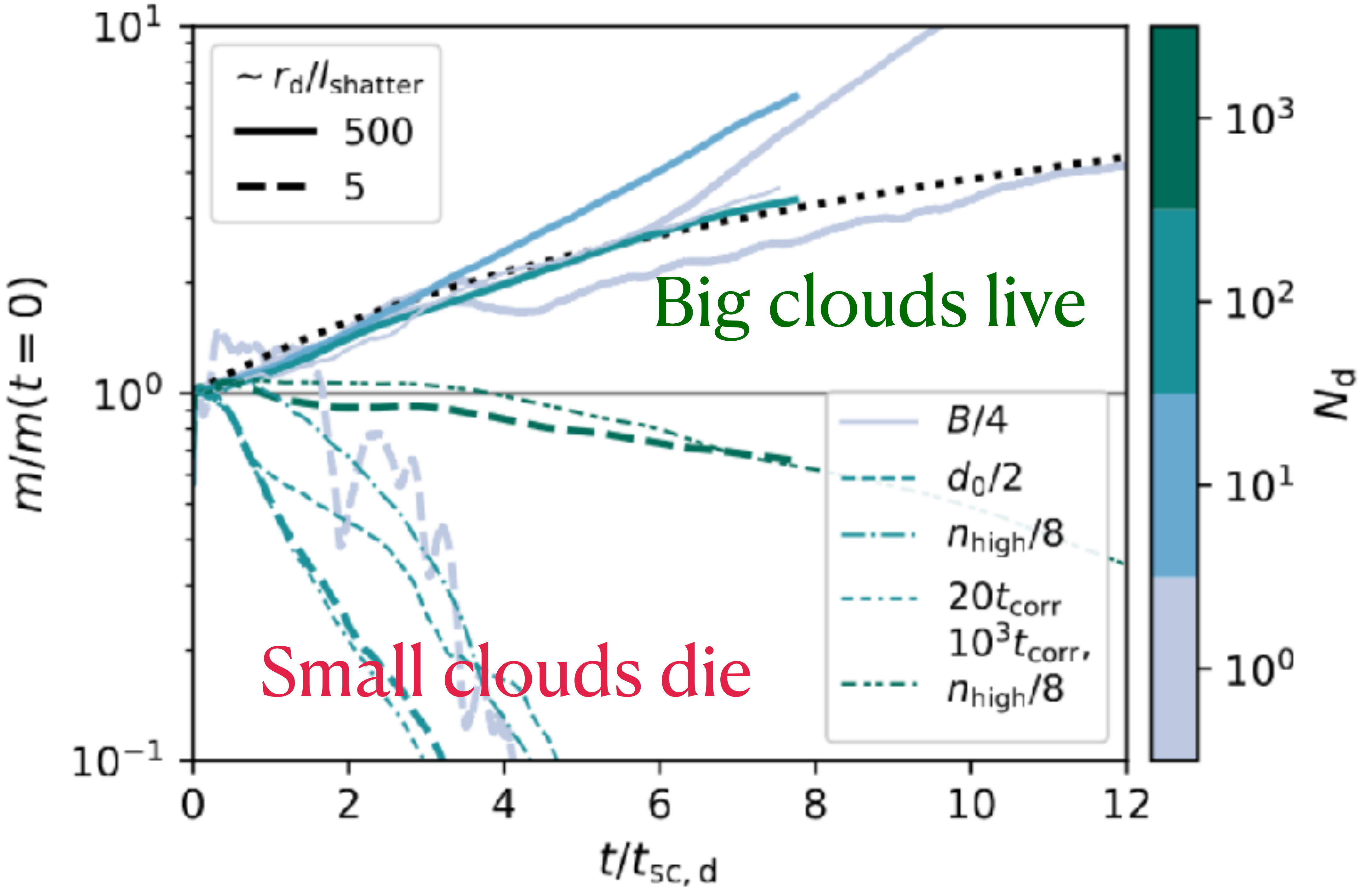
Mass broadly distributed across range of scales

(~1/2 in a big cloud, ~ 1/2 in much smaller clouds)



But area dominated by small cloudlets

Along a random line of sight, you are *much* more likely to pierce the ‘fog’ than a ‘cloud’



Big clouds live

Small clouds die

Large clouds are *required* for survival

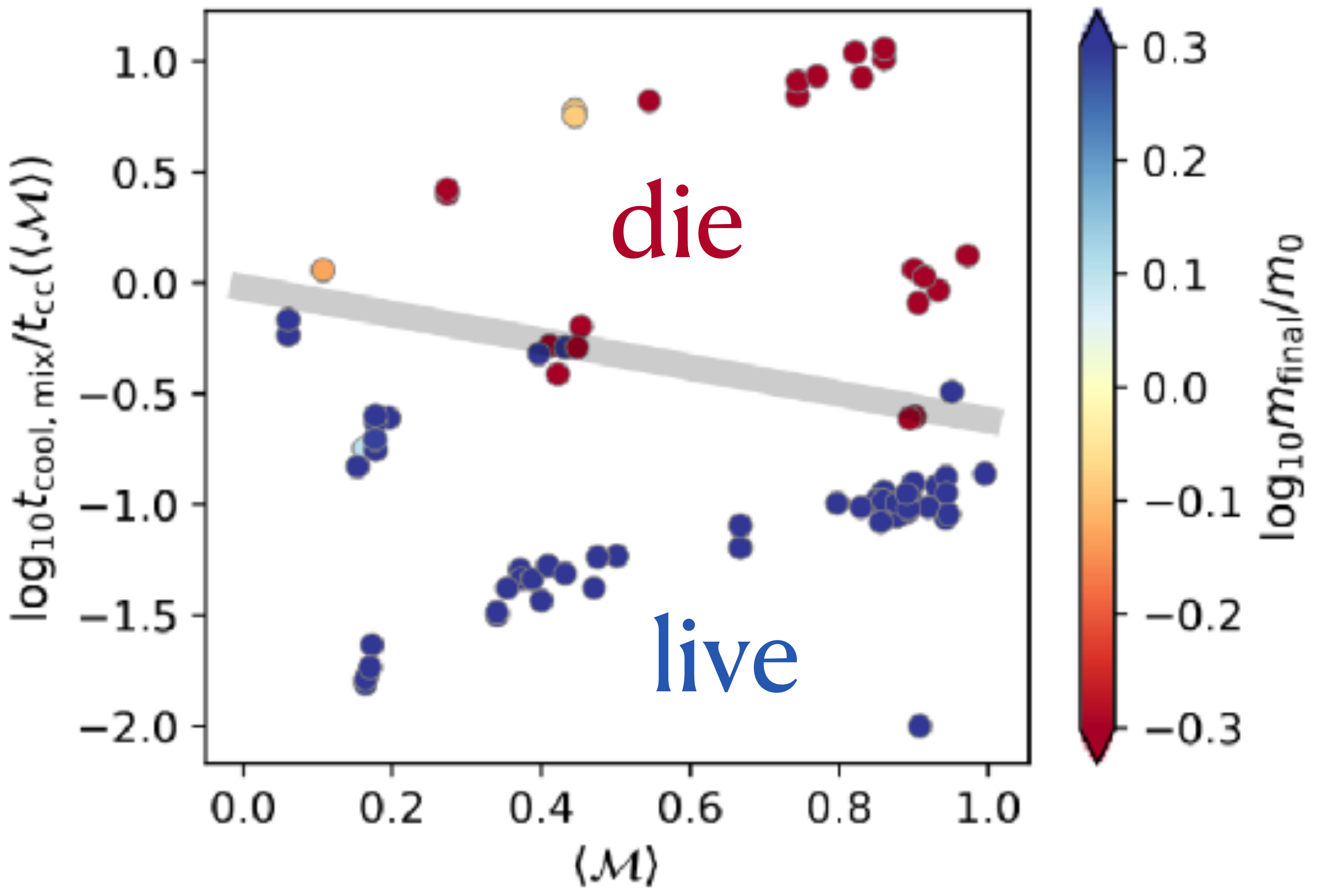
Equivalent mass in small droplets doesn't work

Coagulation too slow to ensure survival

Growth roughly fits analytic models

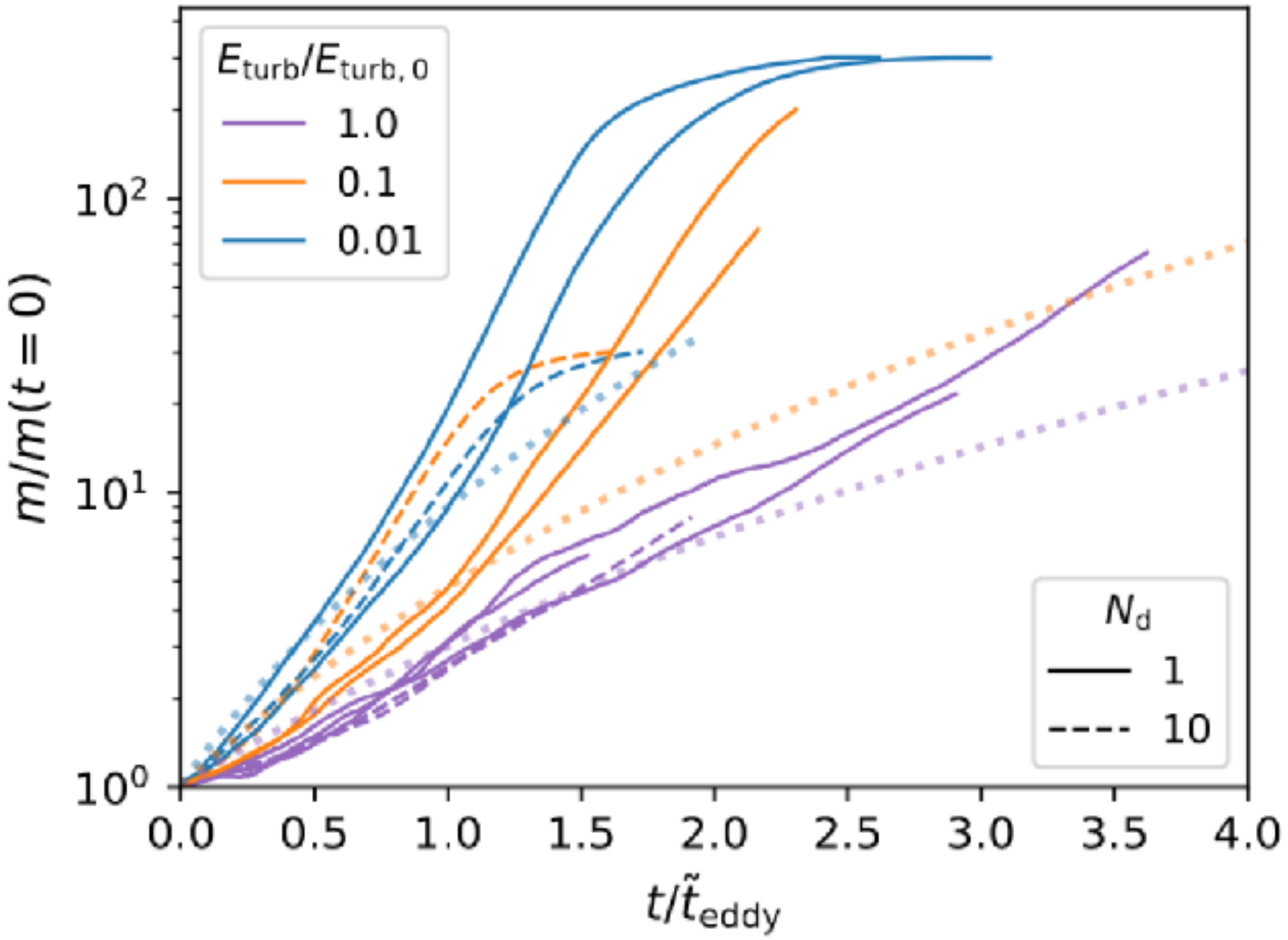
but transition to exponential growth when small clouds dominate area

Mass threshold similar to wind problem (Gronke & Oh 2018)



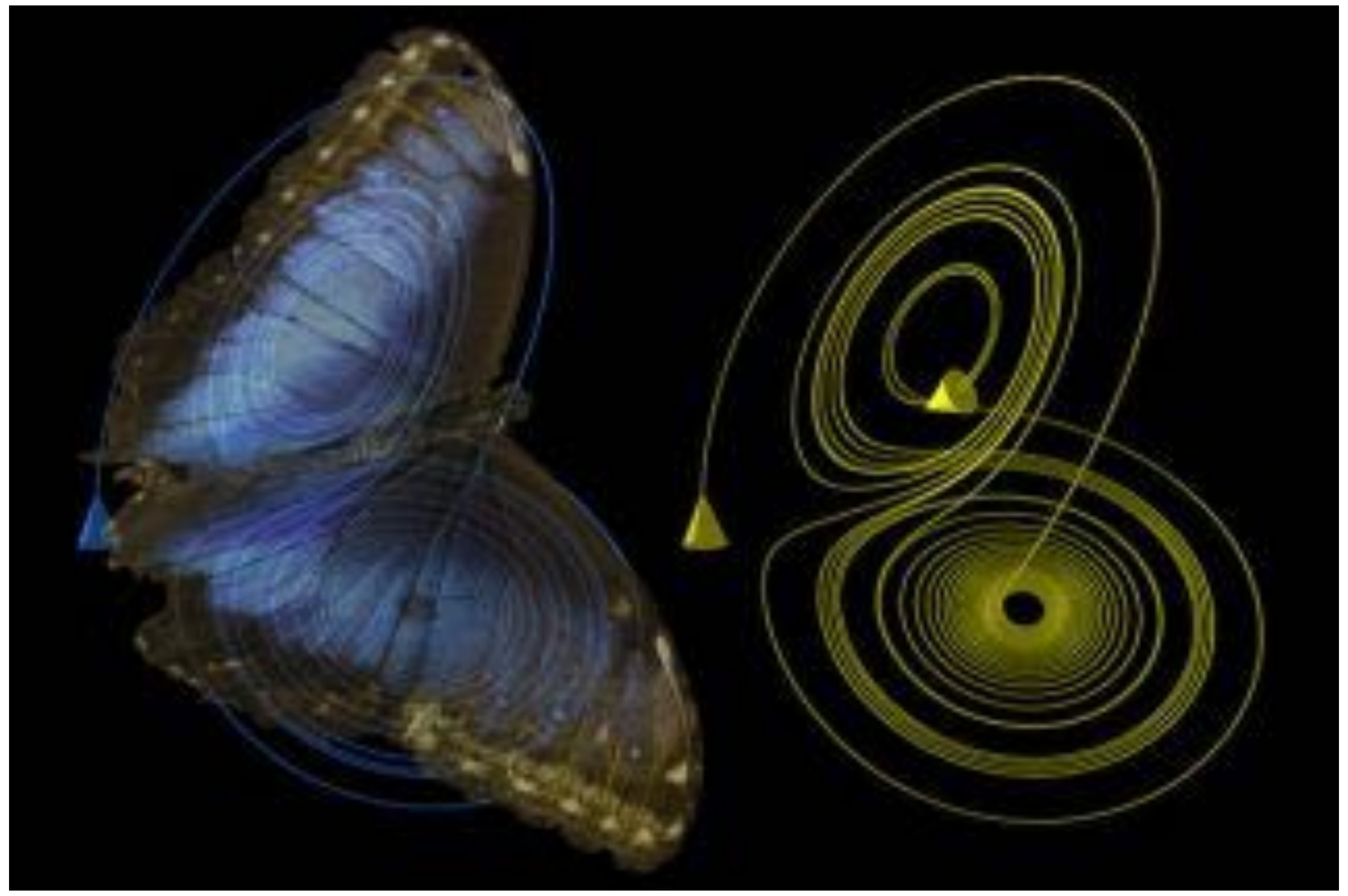
die

live

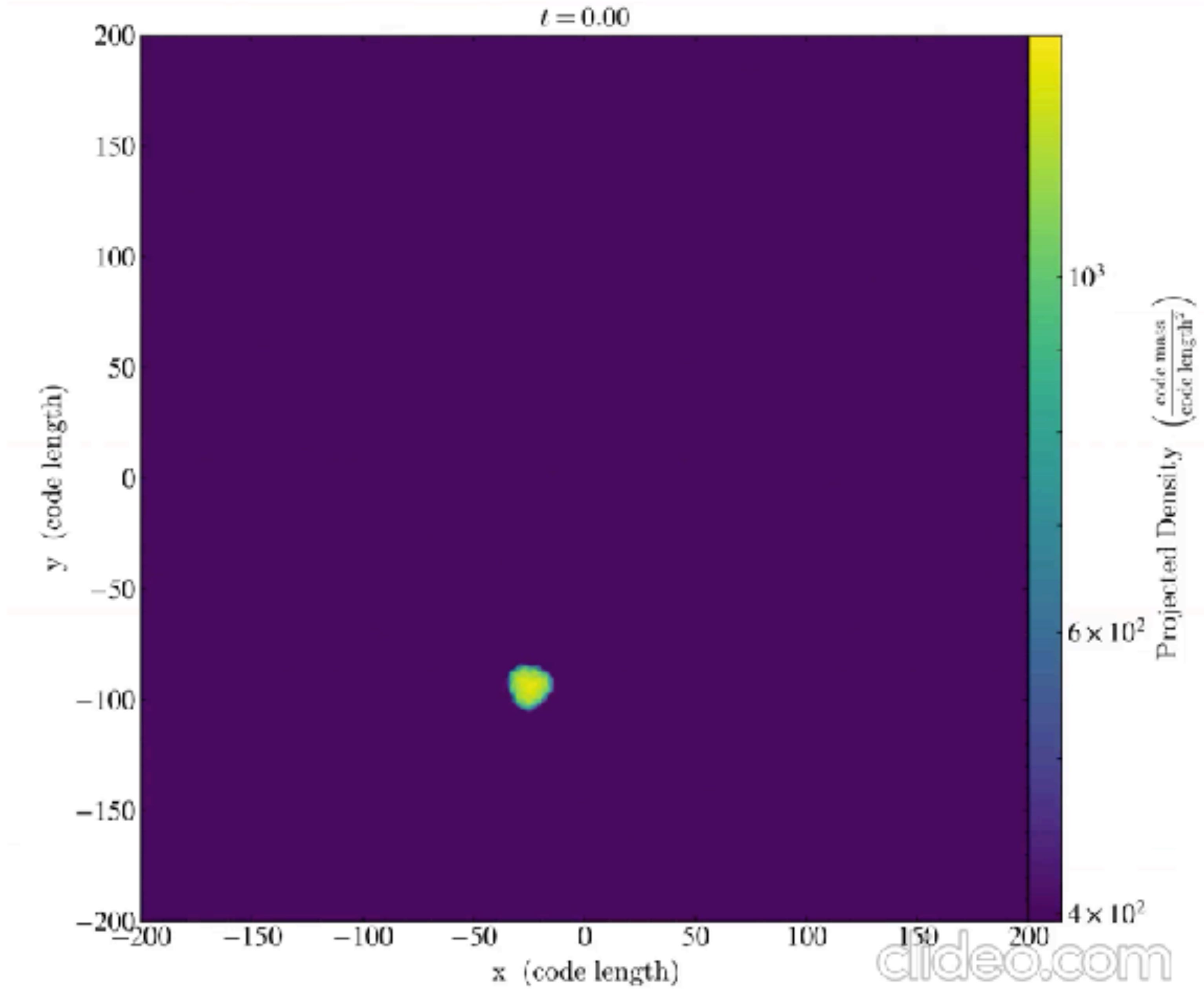


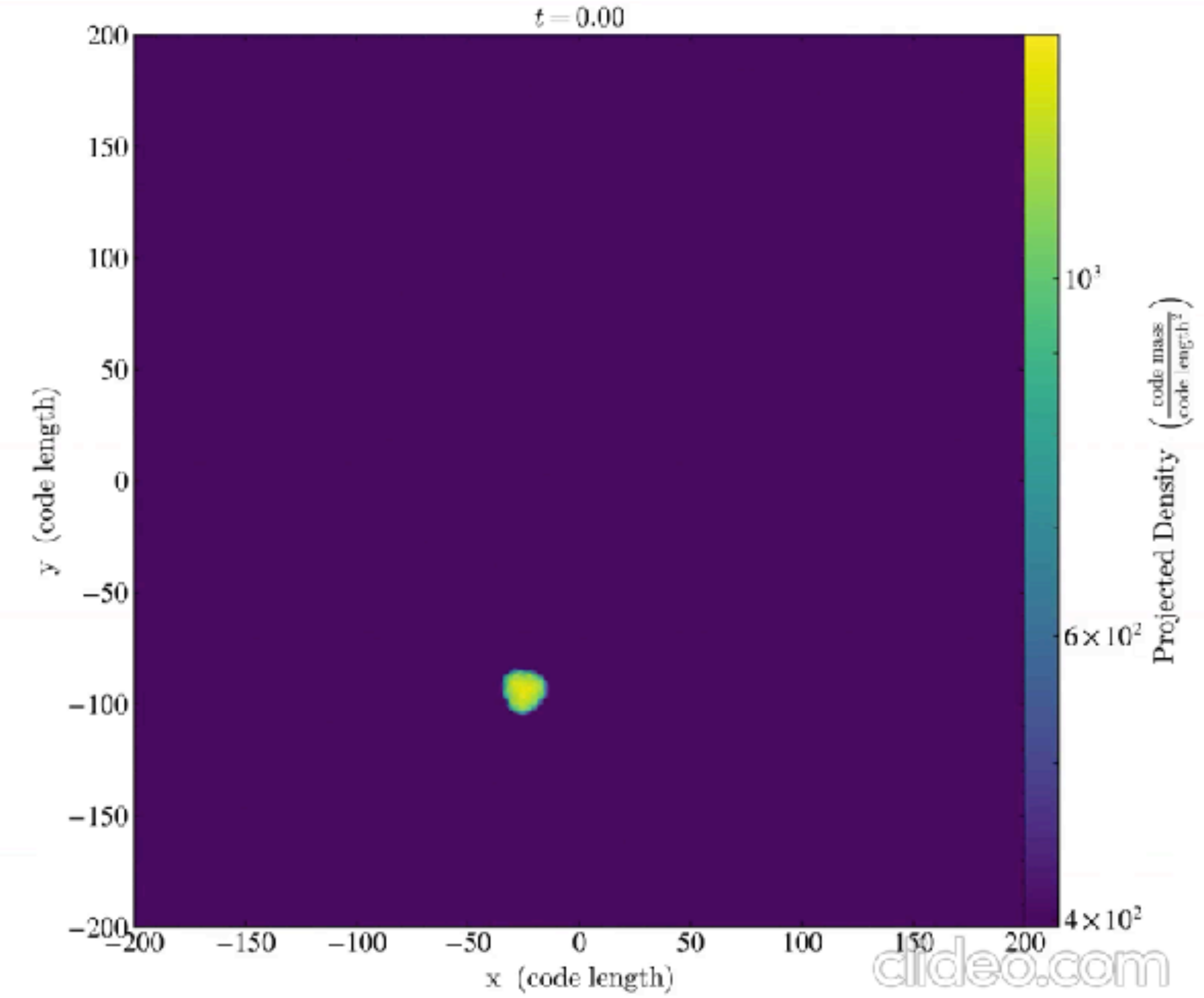
Outcome is highly stochastic

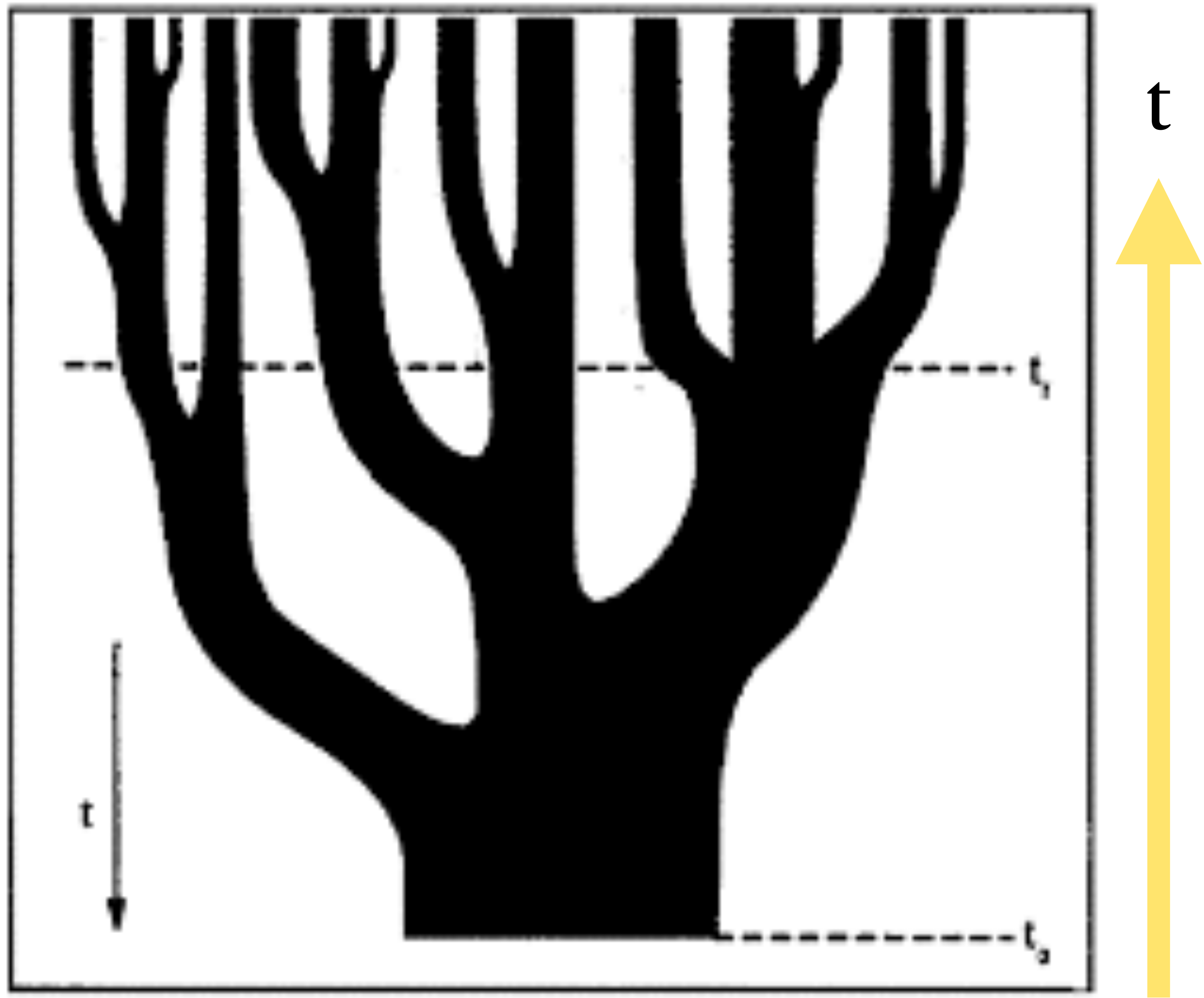
… a lot of 'cosmic variance'



Need to ensemble average!



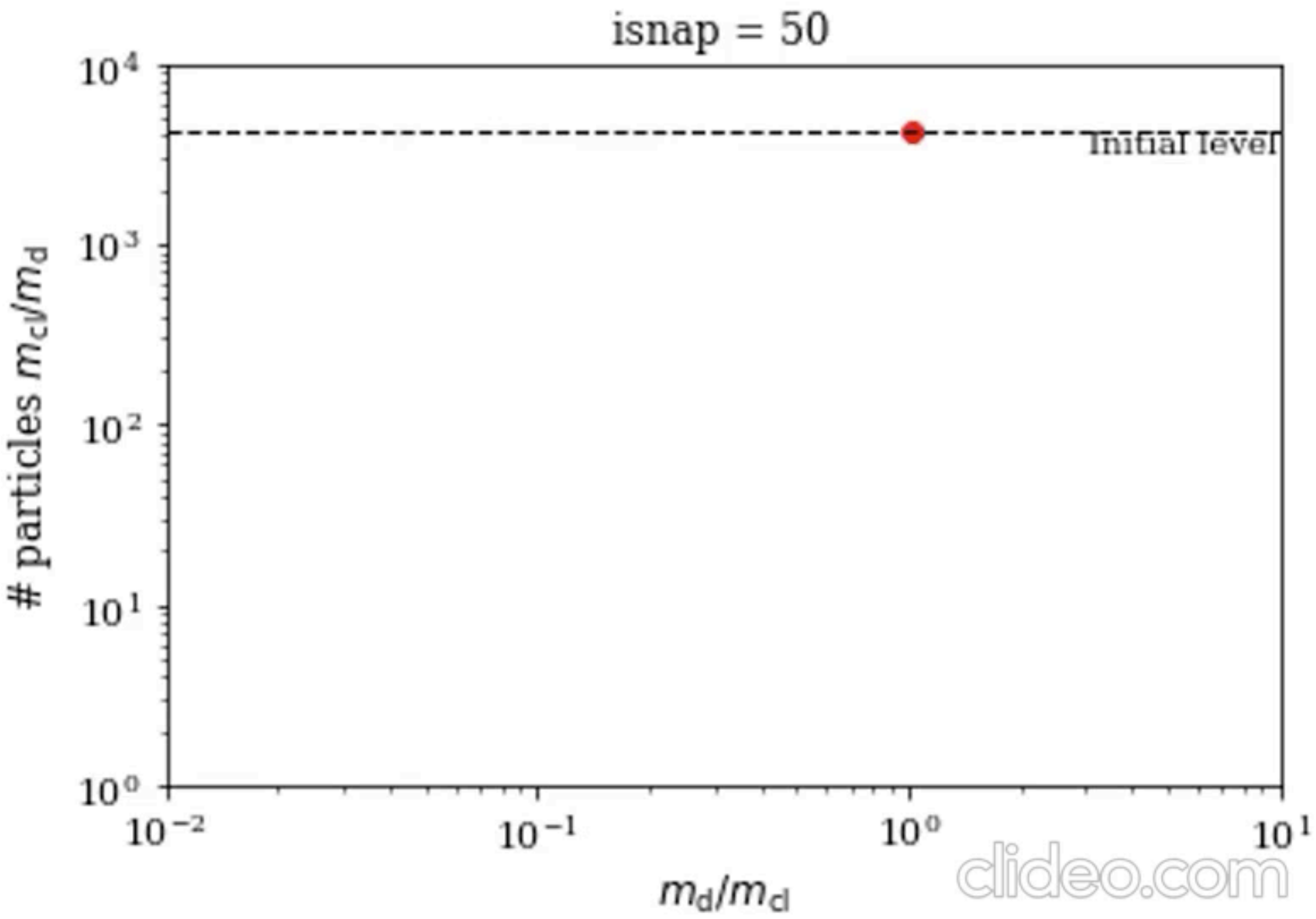




Monte-Carlo approach ('shattering' tree) probably useful

Invert merger tree

The Nerd Version



Continuous growth and breakup on all scales

The Hollywood Version

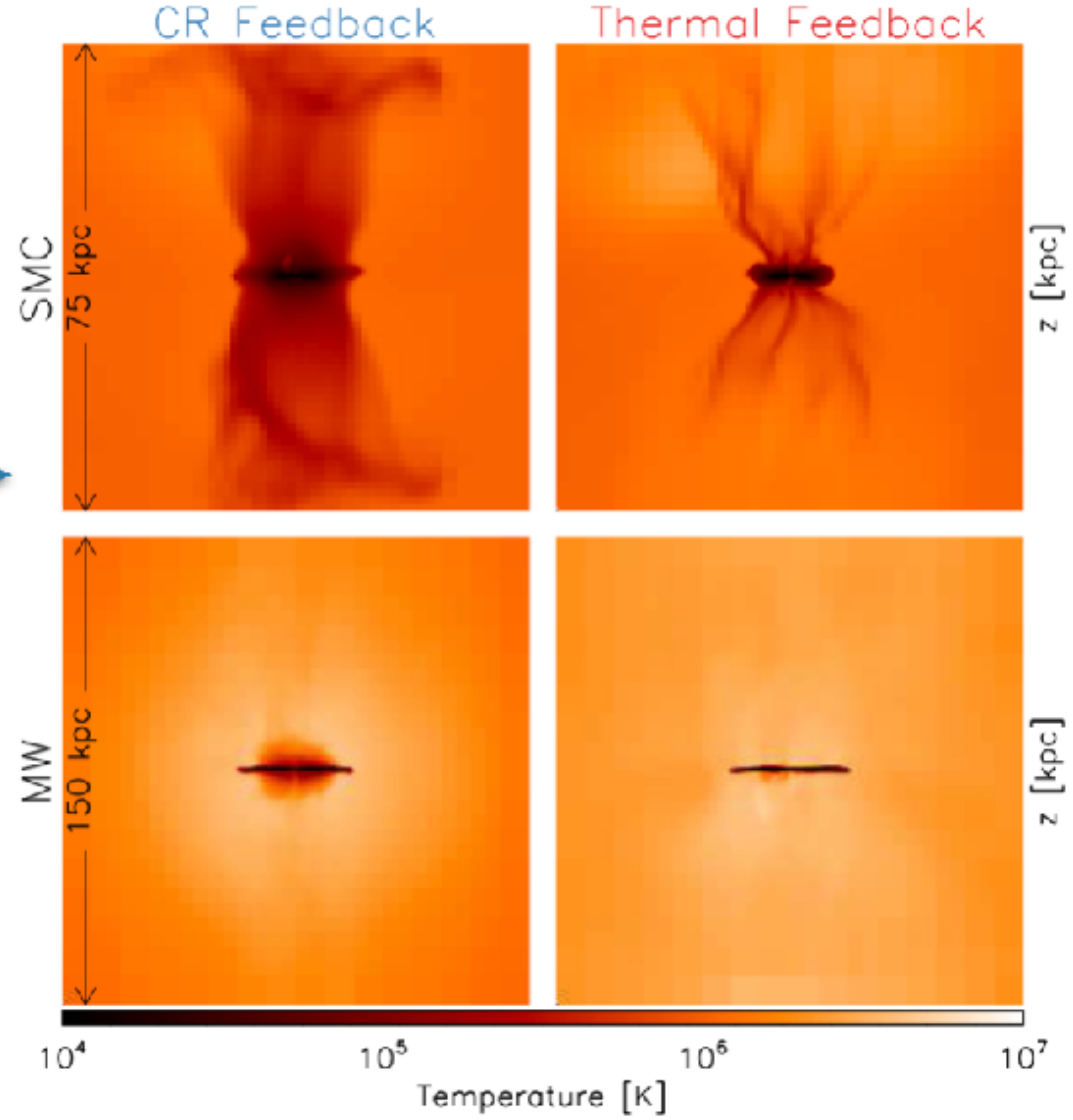
The big cloud...

..launches the droplets

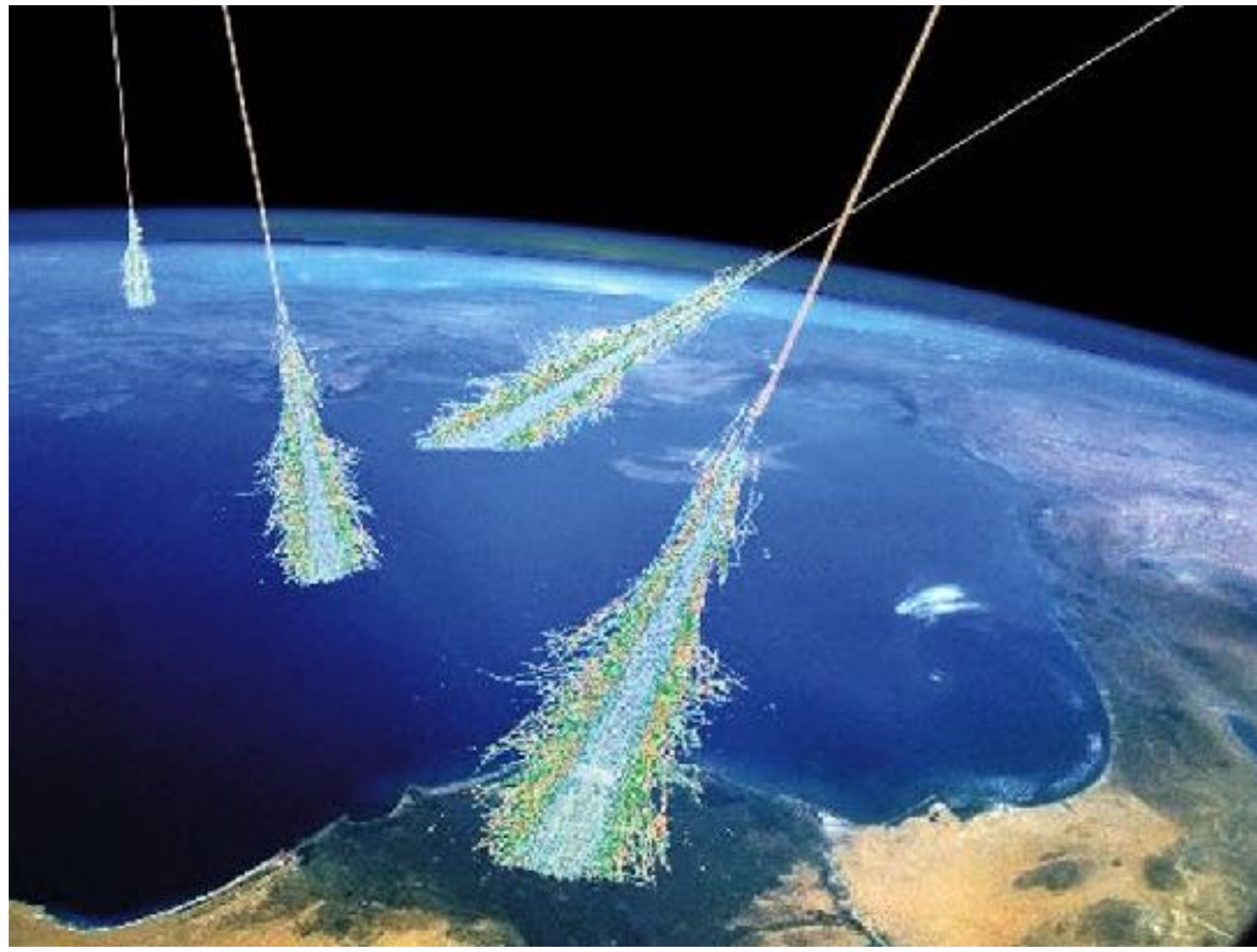
which do battle and get blown up

but the mothership survives and keeps launching more

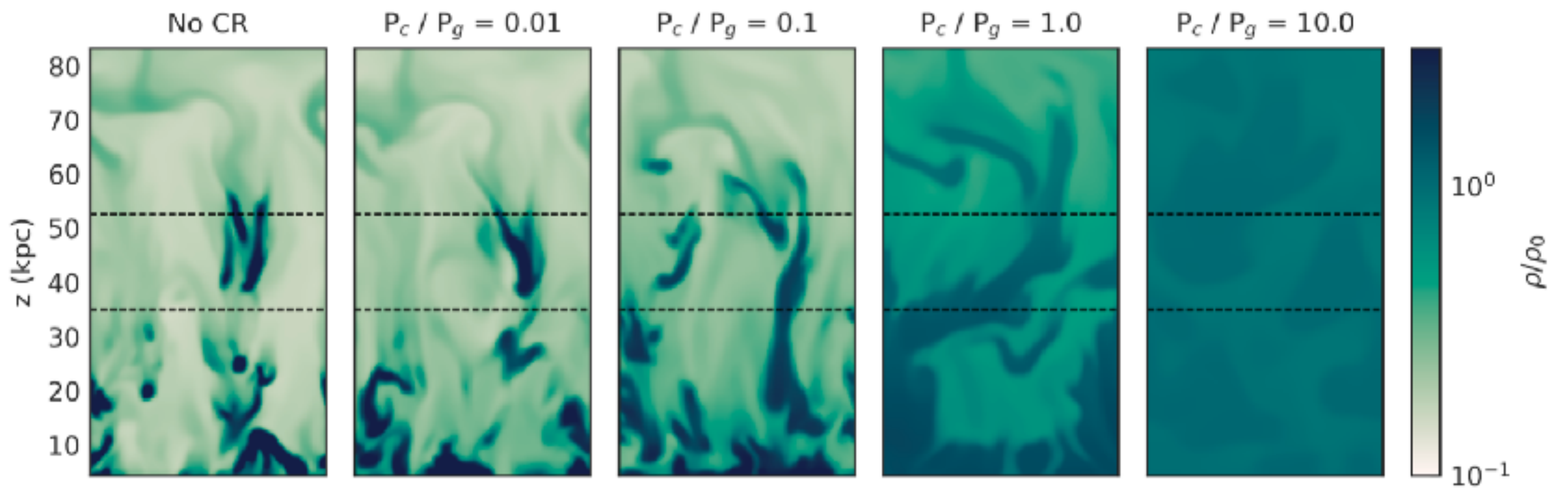
Cosmic Rays



Booth et al 2013

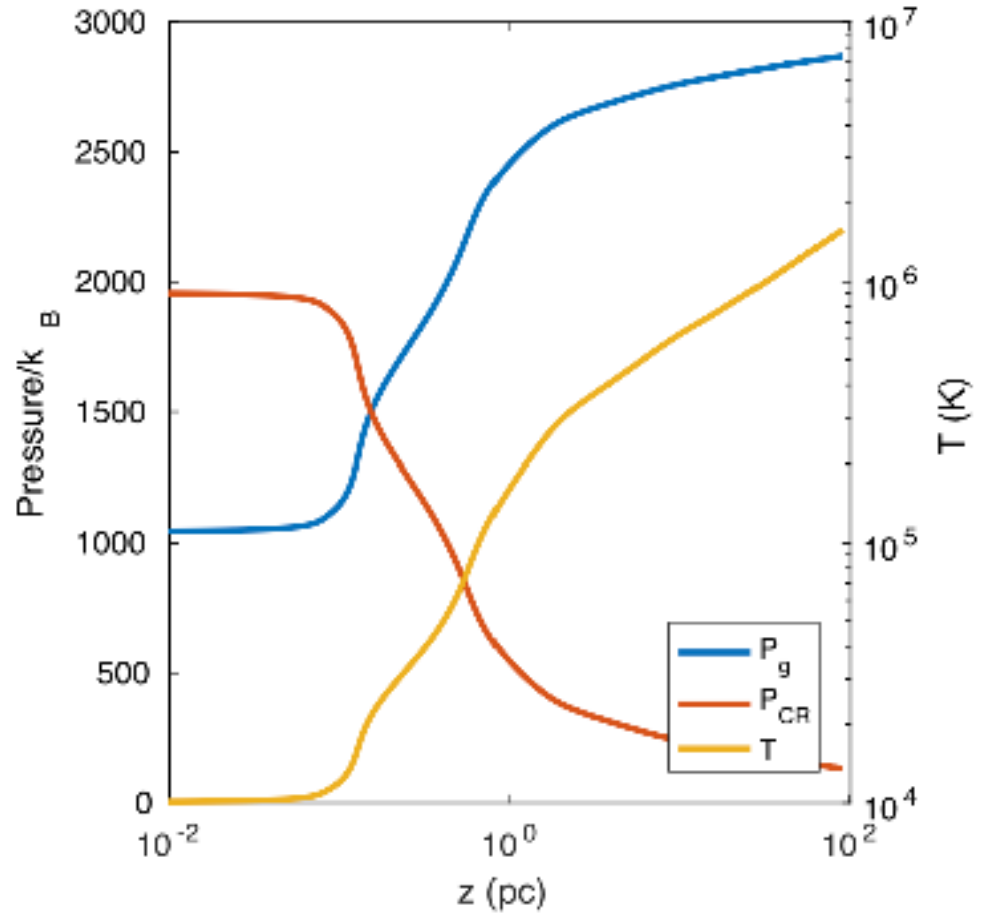


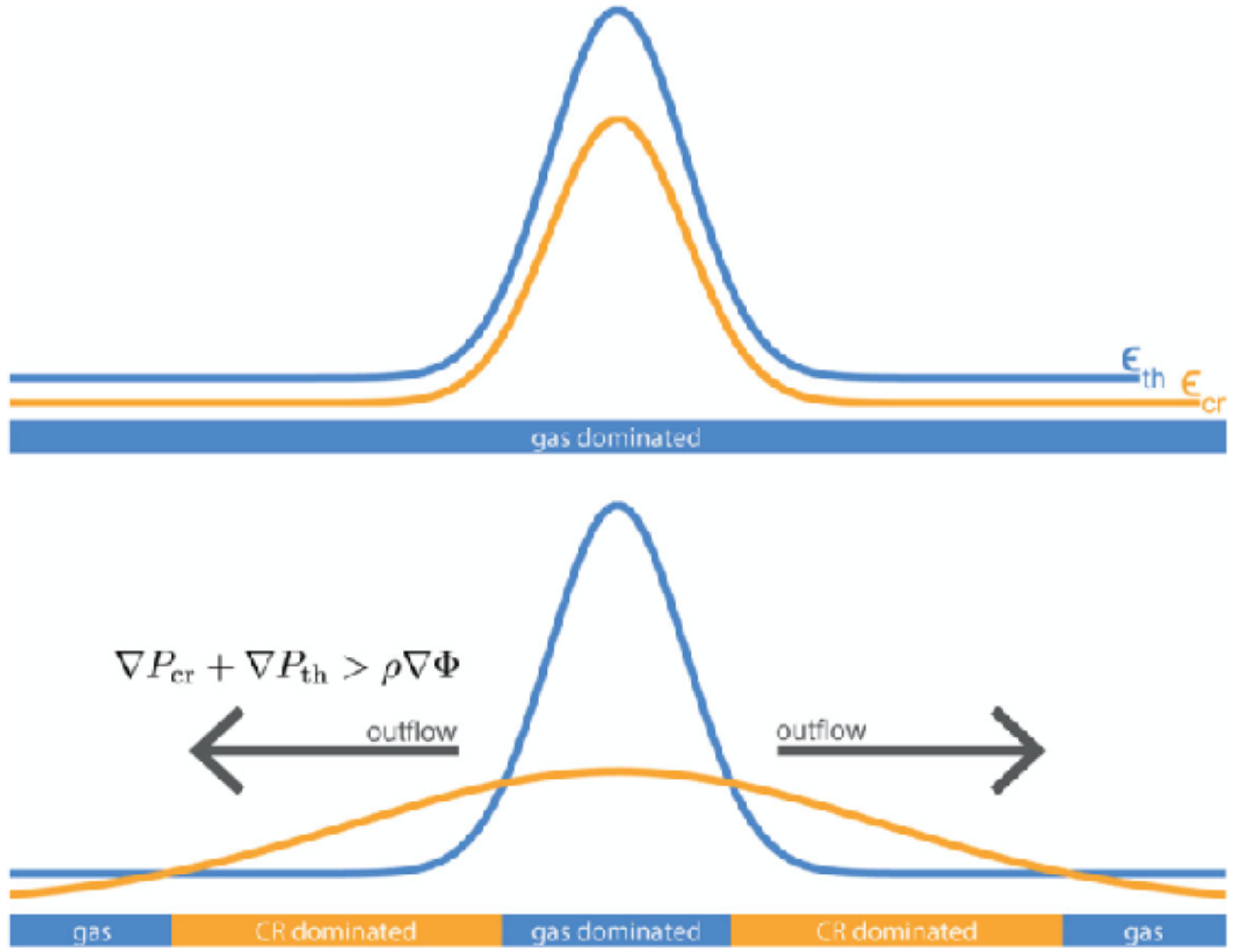
Why should you care about Cosmic Rays?



Butsky+20

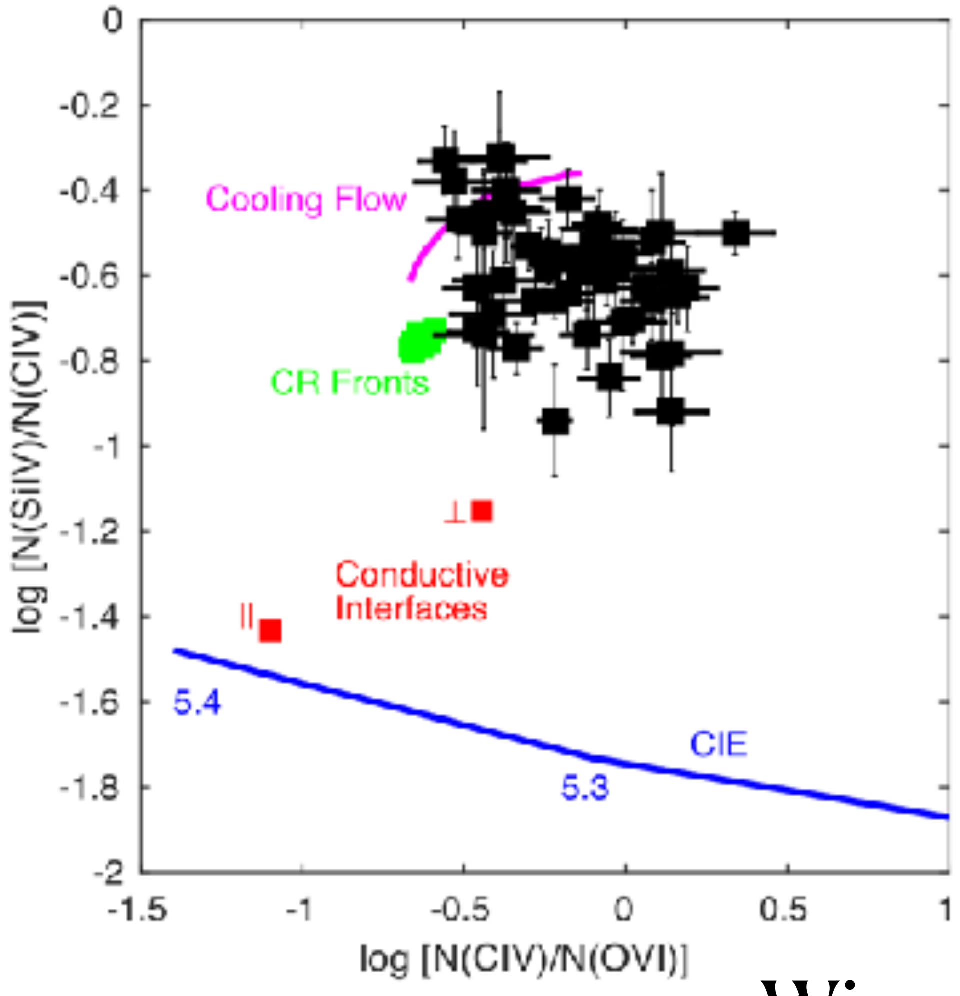
They provide non-thermal pressure support





They drive Galactic winds and dominate in the halo

Salem & Bryan 2014



Wiener+17

They heat and alter thermal interfaces

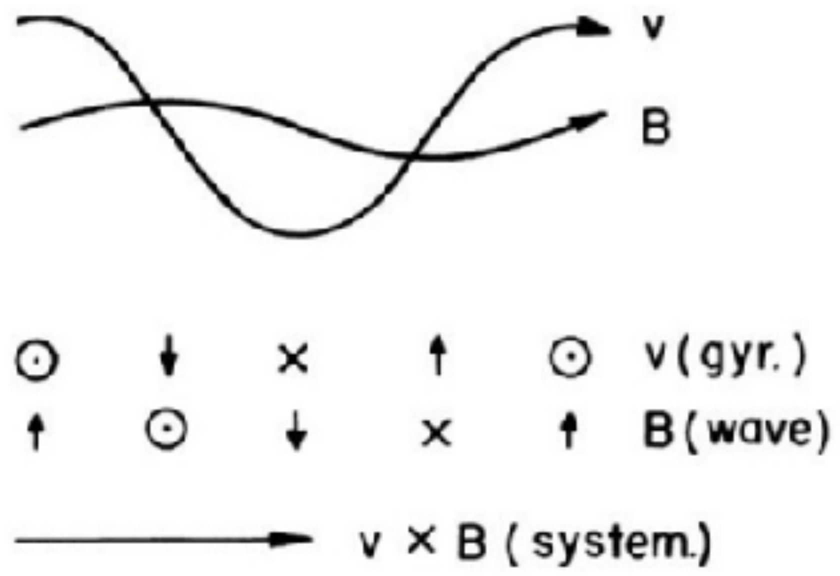
Cosmic Ray Physics in a Nutshell

See Zweibel 2013, 2017 for reviews and Ellen's talk on Thurs!

CRs are relativistic… but they live in our Galaxy for $\sim 3 \times 10^7 \mathrm{yr} \gg \dfrac{L_{\mathrm{gal}}}{c}$

Why??

They are **self-confined** by the streaming instability



Wentzel 1972

Steady Lorentz force

Scatter in pitch angle $\delta\theta \sim \pm \frac{\delta B}{B}$

Scatter off magnetic fluctuations

Random walk out

$$\lambda \sim r_{\mathrm{L}}/(\delta B/B)^2 \sim 1\,\mathrm{pc}$$

Can write two-fluid hydrodynamic equations.

CRs **stream** at Alfven velocity $v_A = \frac{B}{\sqrt{4\pi\rho}}$

As $\nabla P_{\rm c} \rightarrow 0$ CRs decouple and stream at speed of light

They can also **diffuse** relative to Alfven wave frame, with flux: $F_{\rm c} = -\kappa_{\|} \nabla P_c$

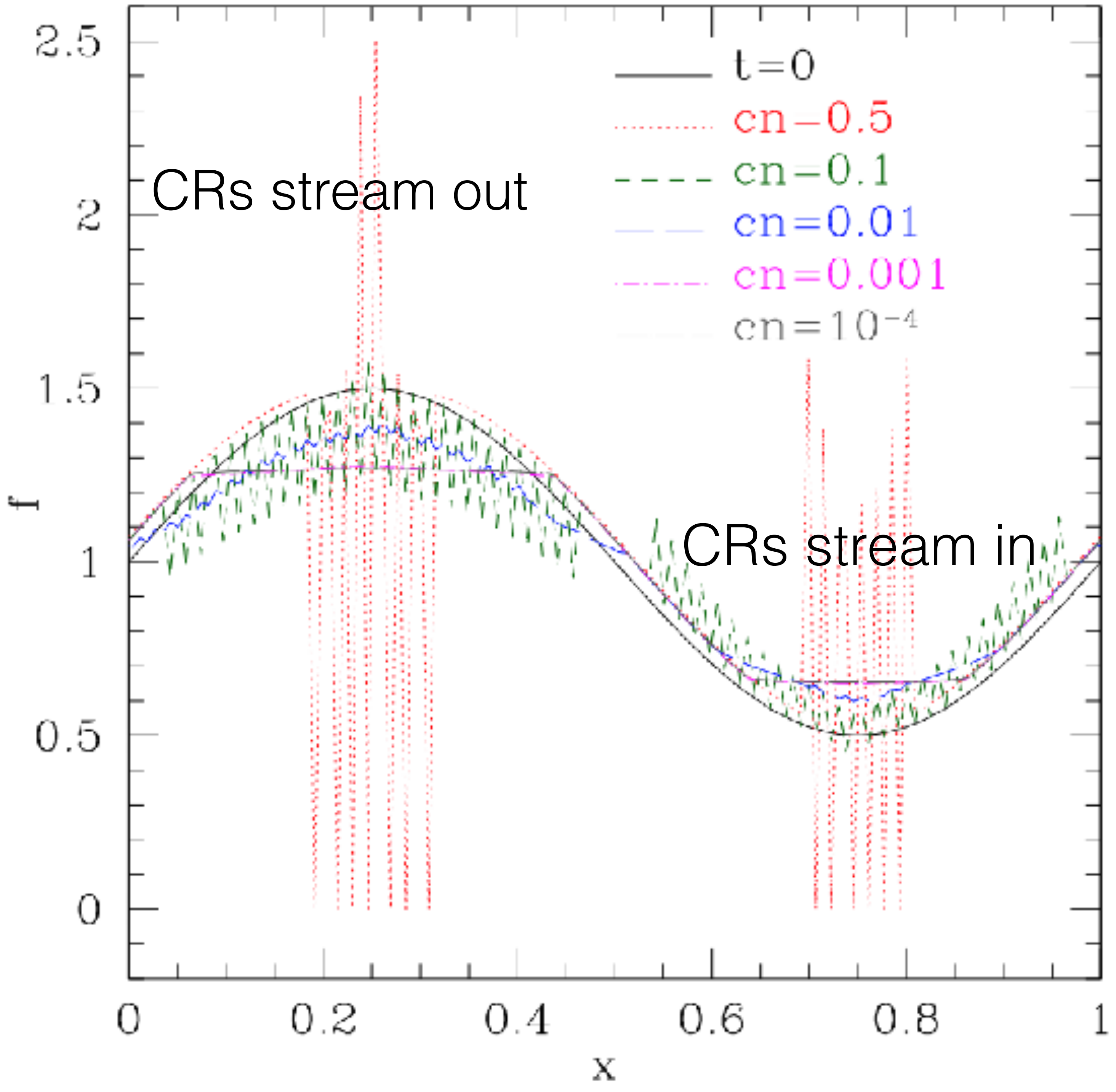
Tangled magnetic fields can also cause effectively diffusive behavior

CRs **push** gas with force ∇P_c

CRs **heat** gas at rate $v_{\rm A} \cdot \nabla P_c$

CRs are a relativistic fluid like photons

We should use radiative transfer methods on them



Sharma et al 2010

CRs can only stream down gradient: grid scale instabilities!

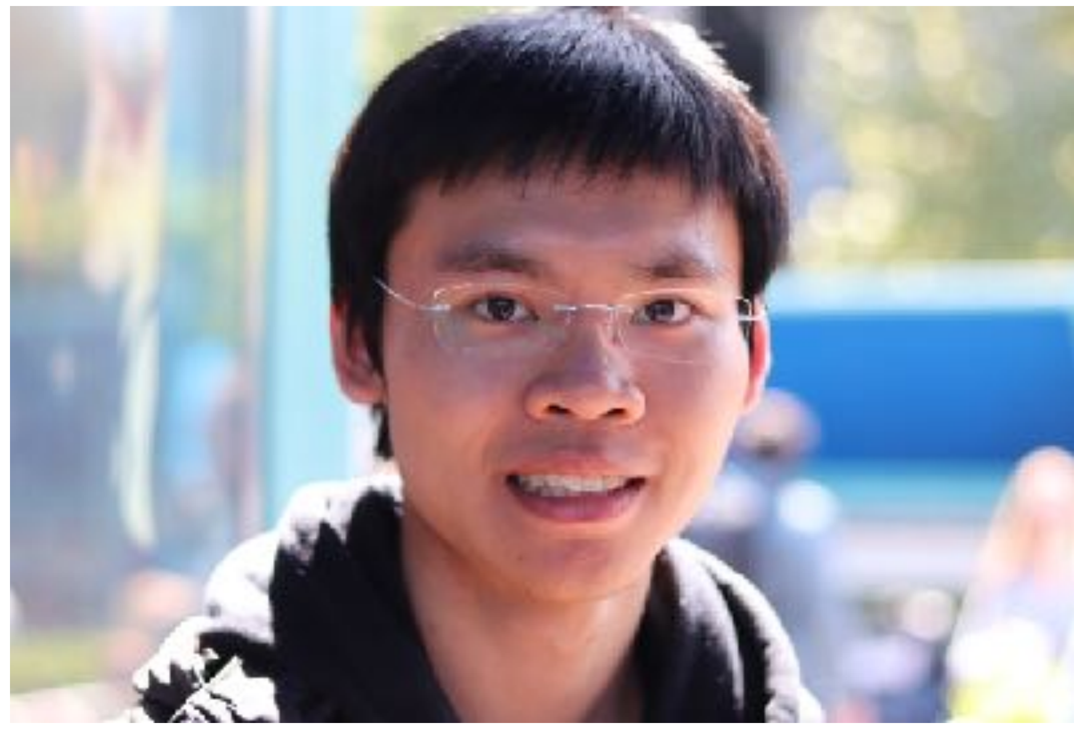
Have to add artificial diffusion: uncertain + expensive

Cured by two-moment method (Jiang & Oh 2018)

Enforces decoupling when $\nabla P_c \rightarrow 0$

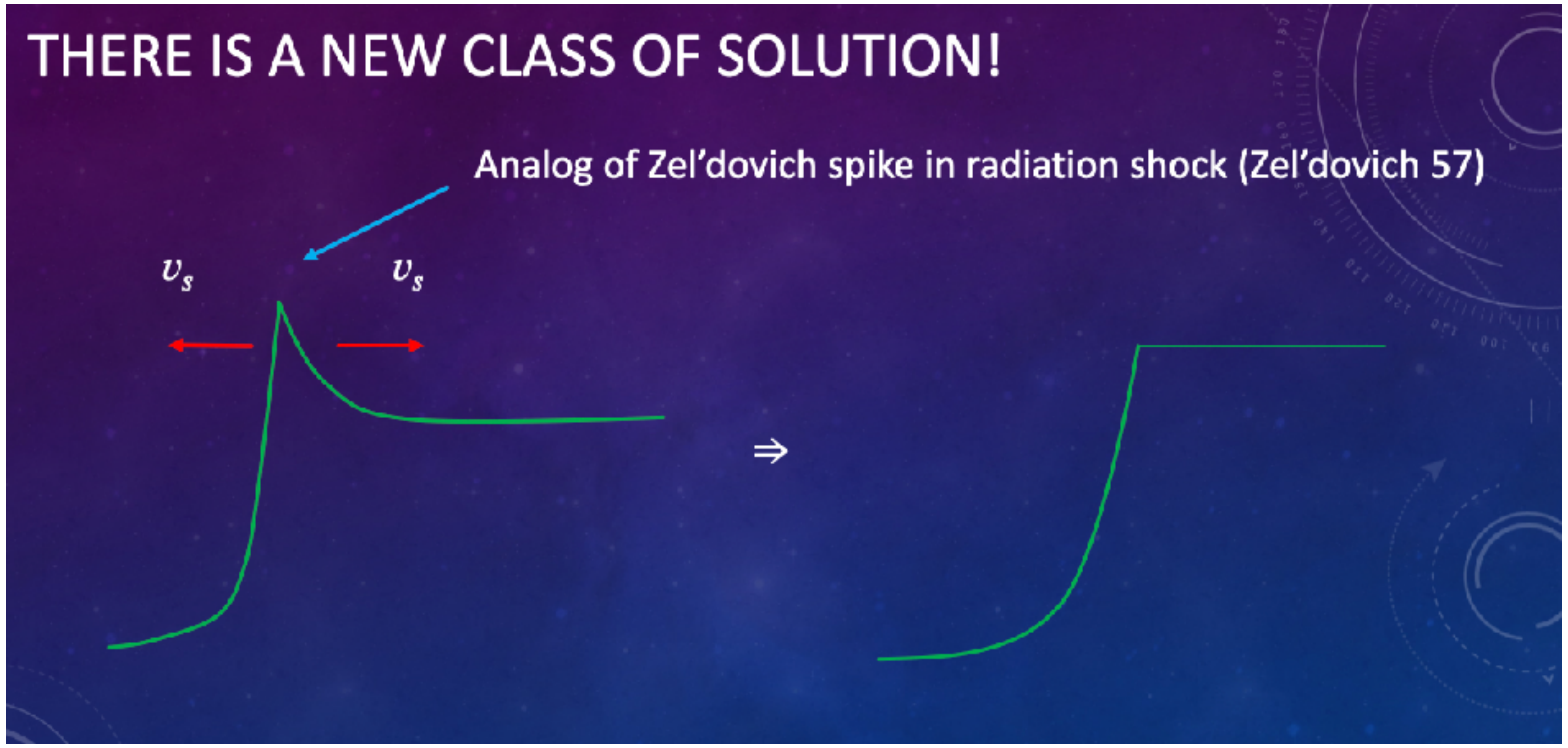
Streaming + diffusion is now standard

Tsung+20



CRs + shocks: most demanding test

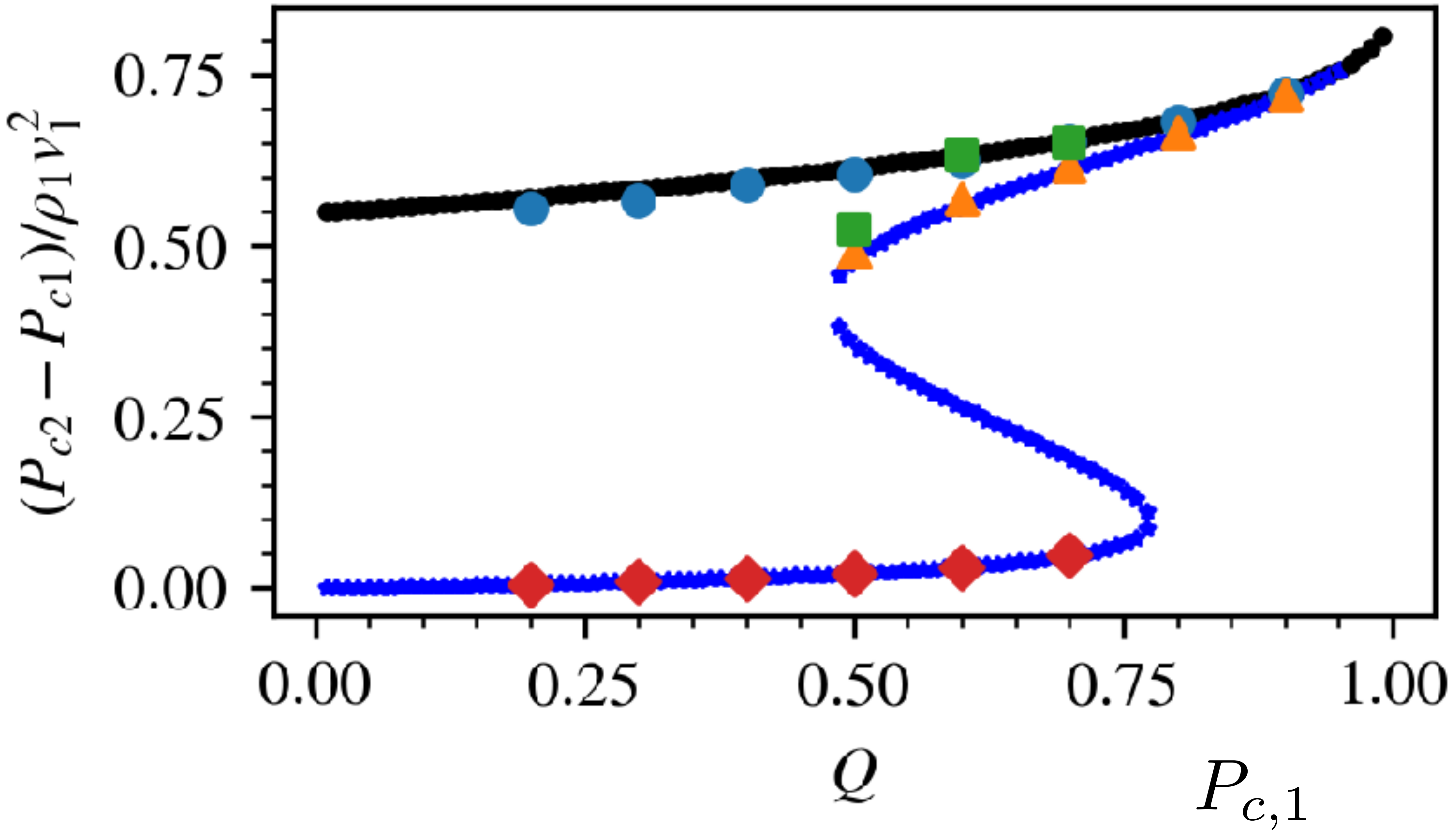
Previously impossible to simulate with streaming



THERE IS A NEW CLASS OF SOLUTION!

Analog of Zel'dovich spike in radiation shock (Zel'dovich 57)

$\beta = 1, \mathcal{M} = 20$



$$\frac{P_{c,1}}{P_{g,1} + P_{c,1}}$$

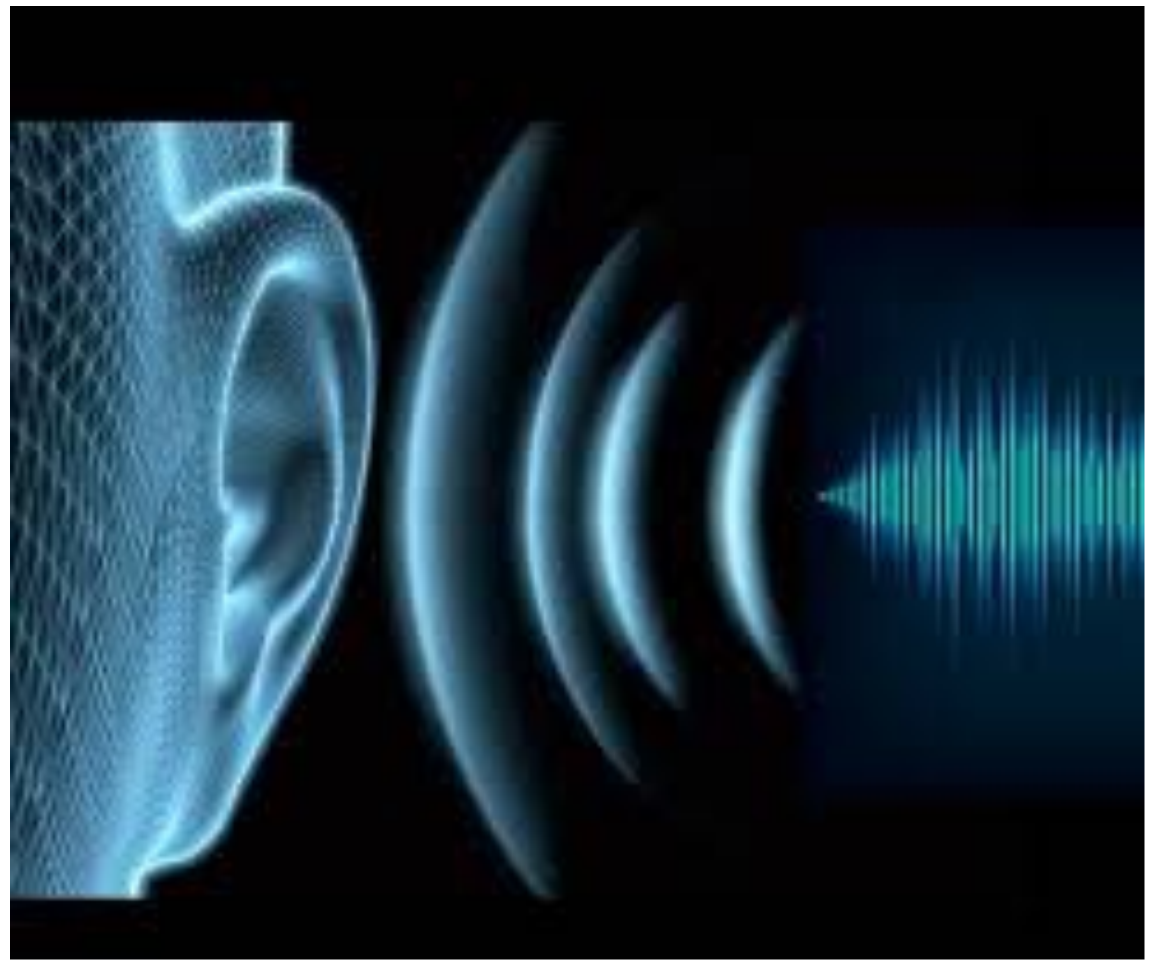
A very demanding test of numerics

CR shocks equilibration times are very long (1000's of diffusion times)

OK, we got our elephant gun. What else to go after?

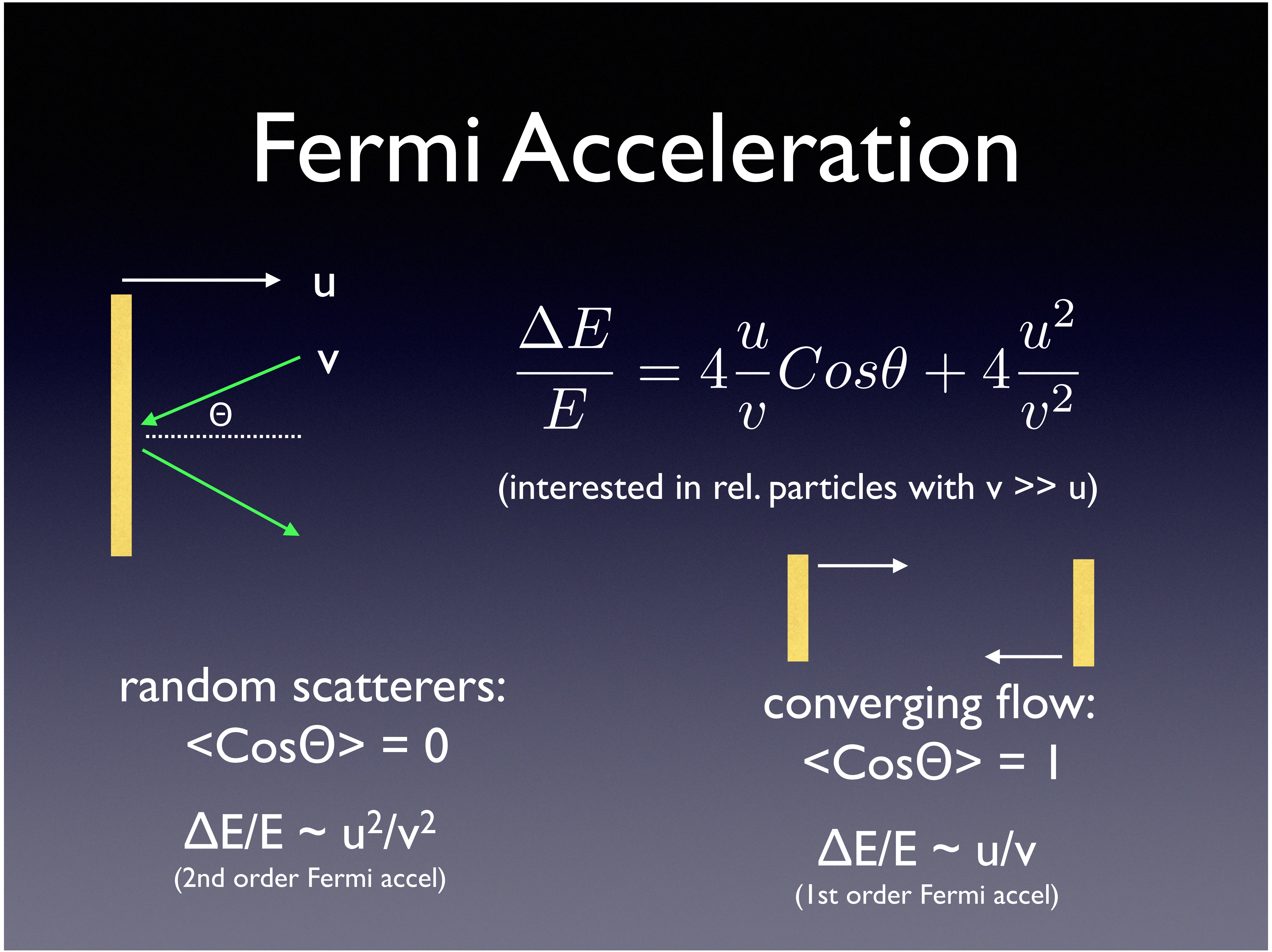
Turbulence!

Sound waves!



Just add Cosmic Rays and stir...

Where do CRs come from?



Fermi Acceleration

$$\frac{\Delta E}{E} = 4\frac{u}{v}Cos\theta + 4\frac{u^2}{v^2}$$

(interested in rel. particles with v >> u)

random scatterers:
$\langle Cos\Theta \rangle = 0$

$\Delta E/E \sim u^2/v^2$
(2nd order Fermi accel)

converging flow:
$\langle Cos\Theta \rangle = 1$

$\Delta E/E \sim u/v$
(1st order Fermi accel)

slide E. Quataert

Cosmic Rays+Turbulence: what happens?

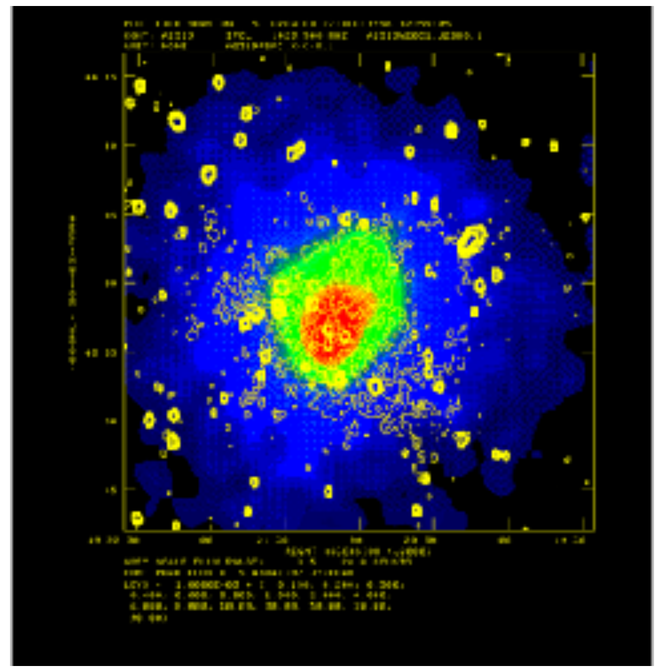
PLAYS WELL
WITH OTHERS

2nd order Fermi: the original. Faster than you think!

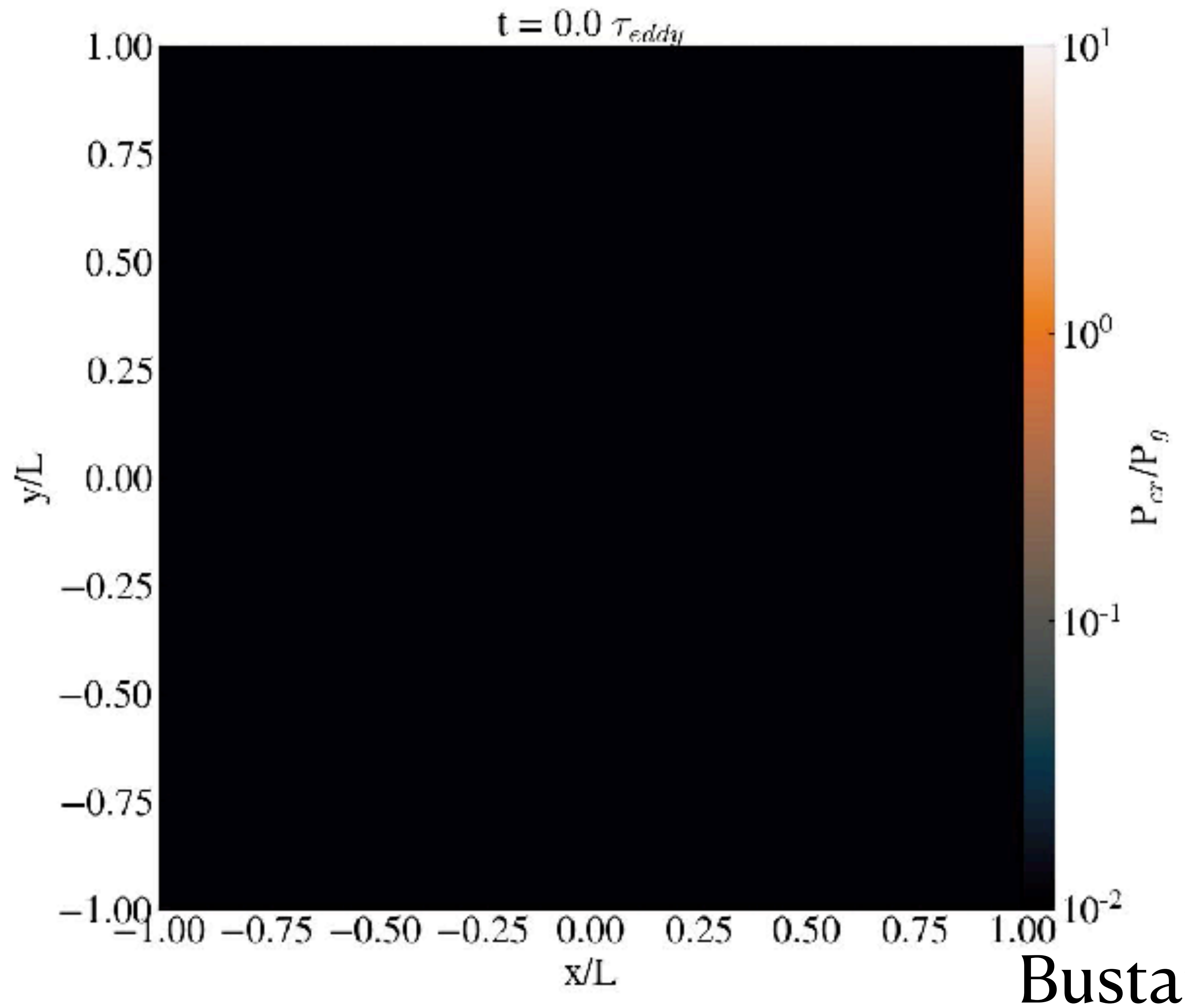
Resonant (transit time damping): large CR mfp, needs kinetic treatment, relevant to ICM

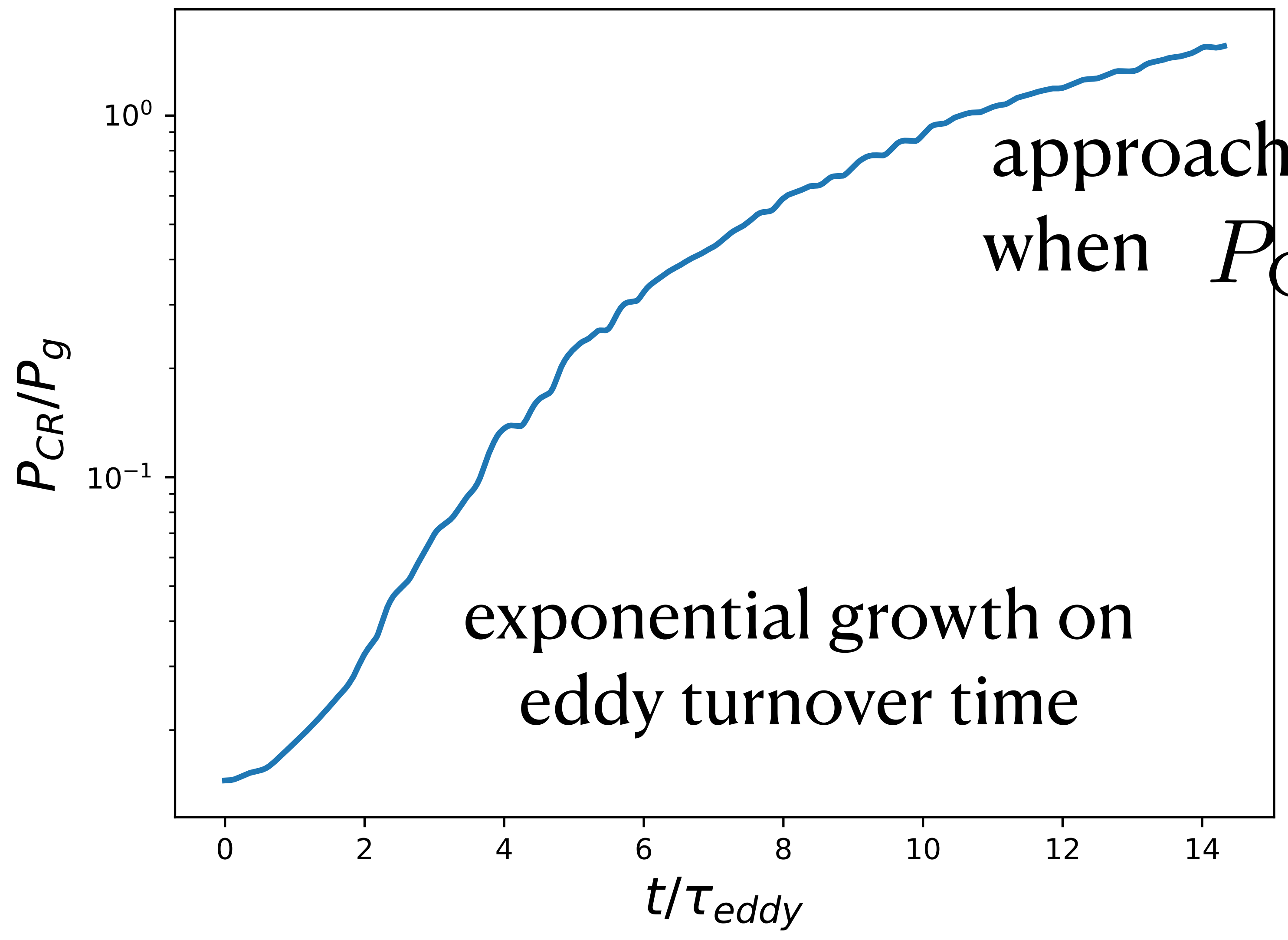
Non-resonant: small CR mfp, fluid approximation good, relevant to ISM + CGM

Neglected, not explored in simulations



cluster radio halos





approaches saturation when $P_{\rm CR} \sim P_{\rm gas}$?

exponential growth on eddy turnover time

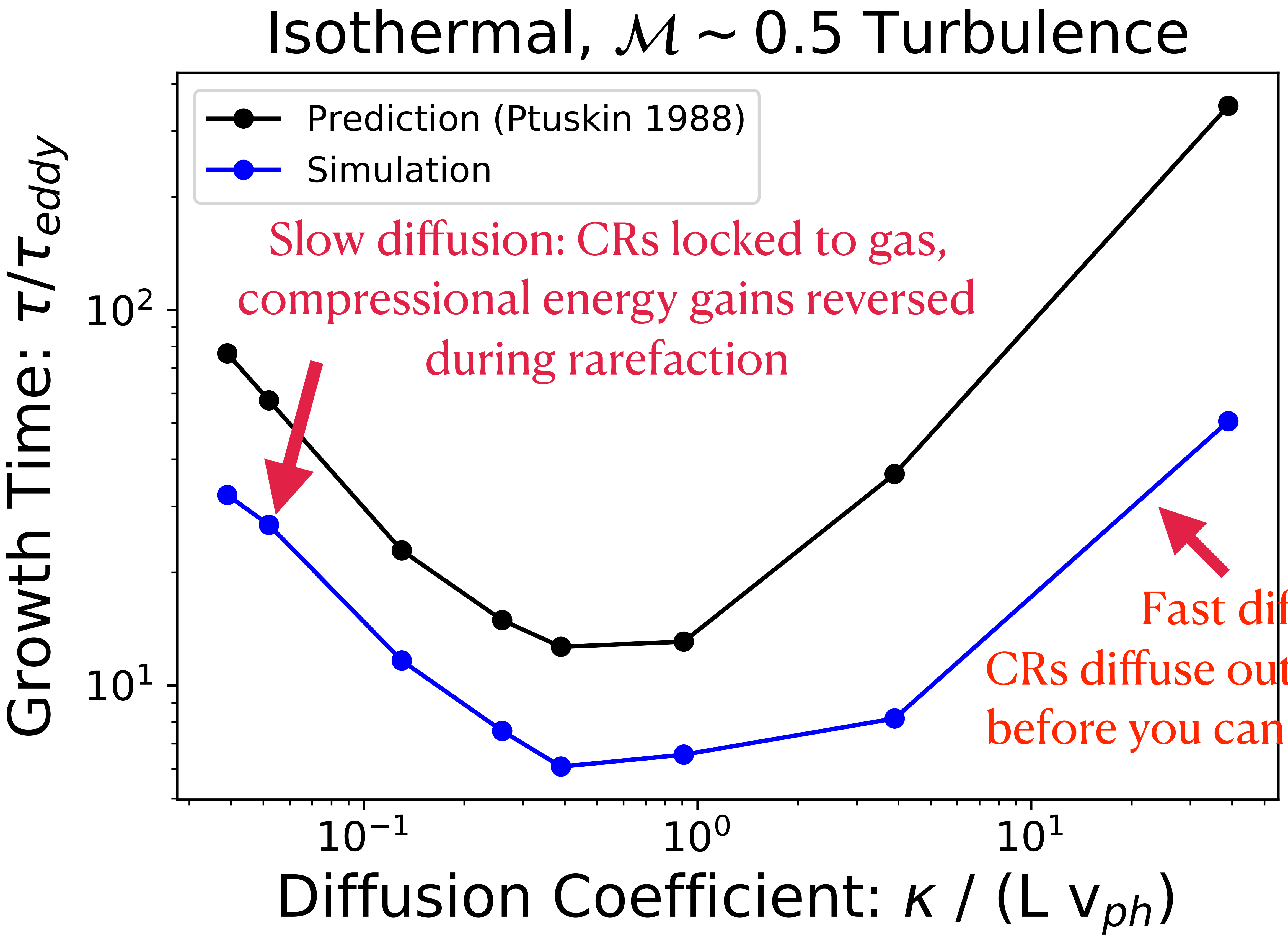
Turbulence accelerates the CRs!

Bustard & Oh 2021

Chad Bustard

There is a sweet spot for acceleration

It’s really just secular adiabatic heating



Slow diffusion: CRs locked to gas, compressional energy gains reversed during rarefaction

Fast diffusion: CRs diffuse out before you can squeeze them

Happens when

$$\kappa \sim 3 \times 10^{29} \mathrm{cm^2\,s^{-1}} \left(\frac{L}{10\,\mathrm{kpc}}\right) \left(\frac{v}{100\,\mathrm{km\,s^{-1}}}\right)$$

Close to Milky Way values! Coincidence?... **maybe not.**

Acceleration time is short

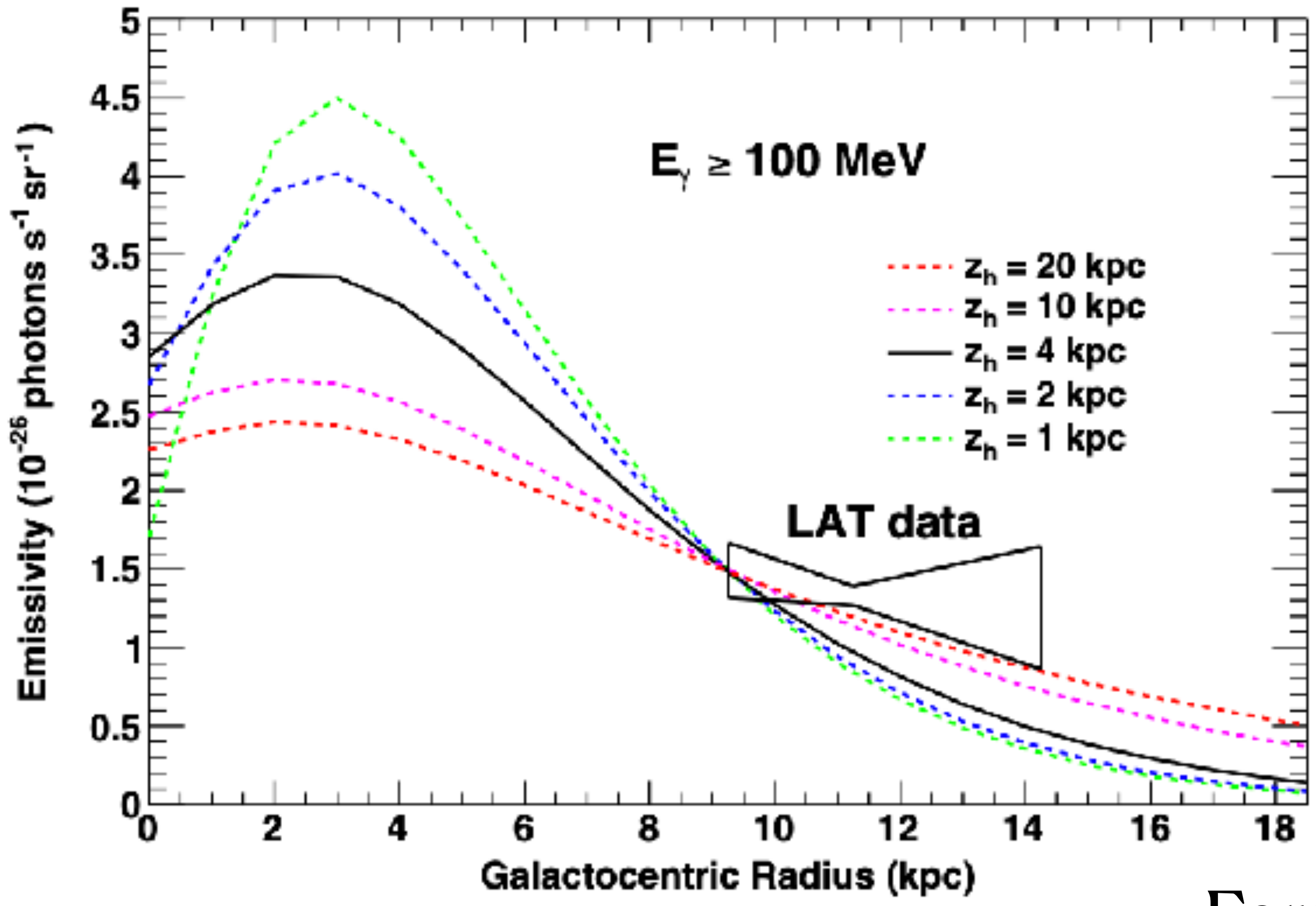
$$\tau_{\rm grow} \sim \tau_{\rm eddy} \sim 10^8\,\mathrm{yr} \left(\frac{L}{10\,\mathrm{kpc}}\right) \left(\frac{v}{100\,\mathrm{km\,s^{-1}}}\right)^{-1}$$

Bustard & Oh 2021

Nature *and* Nurture matter

CRs gain energy from turbulence in the halo

- CRs revived in halo — changing CR profile and wind solutions
- Turbulent 'dynamo' for CRs. Potentially enforces $P_{\rm CR} \sim P_{\rm gas}$?
- Affects gamma-ray luminosity vs. wind-driving, CR gradient problem, etc etc…

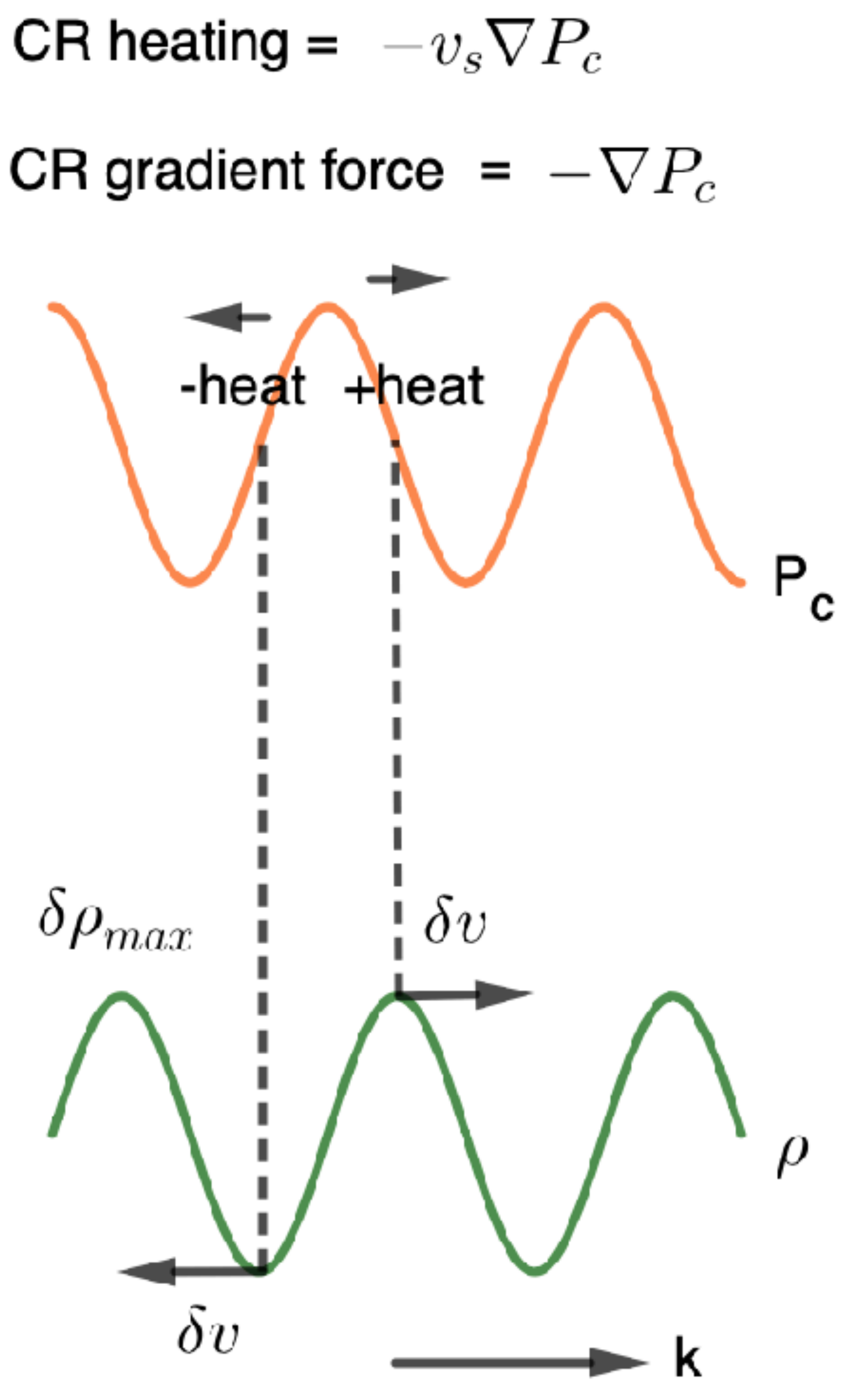


CR gradient problem: Cosmic Ray profile in Milky Way declines more slowly away from sources than expected from standard models

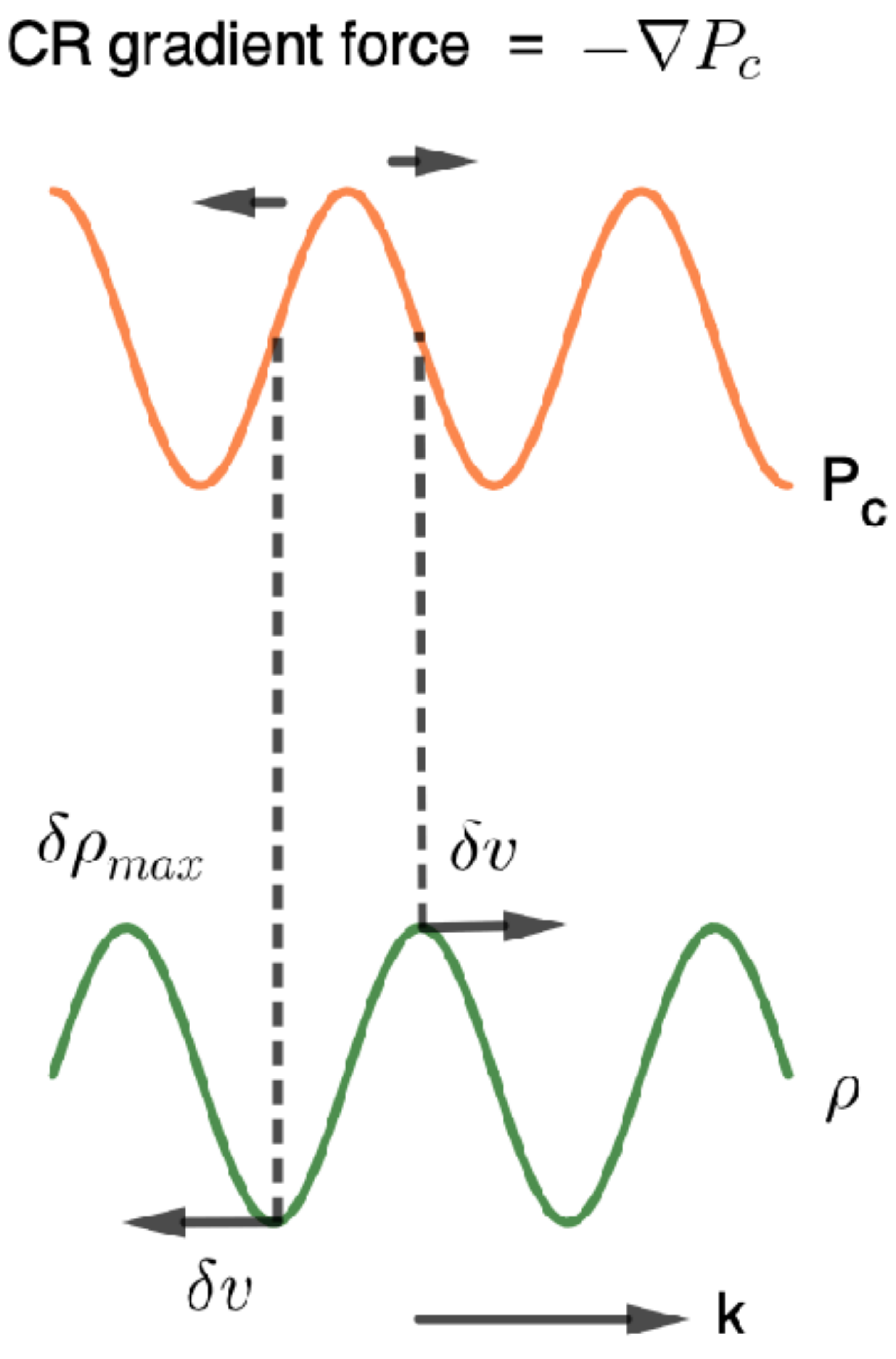
Fermi-Lat Collab (Ackermann+11)

CRs + Sound Waves: what happens?

- Sound waves are harmonic oscillator
- Direct driving: CRs provide forcing which can be in phase (growth) or out of phase (damping) Drury & Falle 1986
- Indirect driving: CR streaming heats gas which also changes gas pressure forces. Begelman & Zweibel (1994)



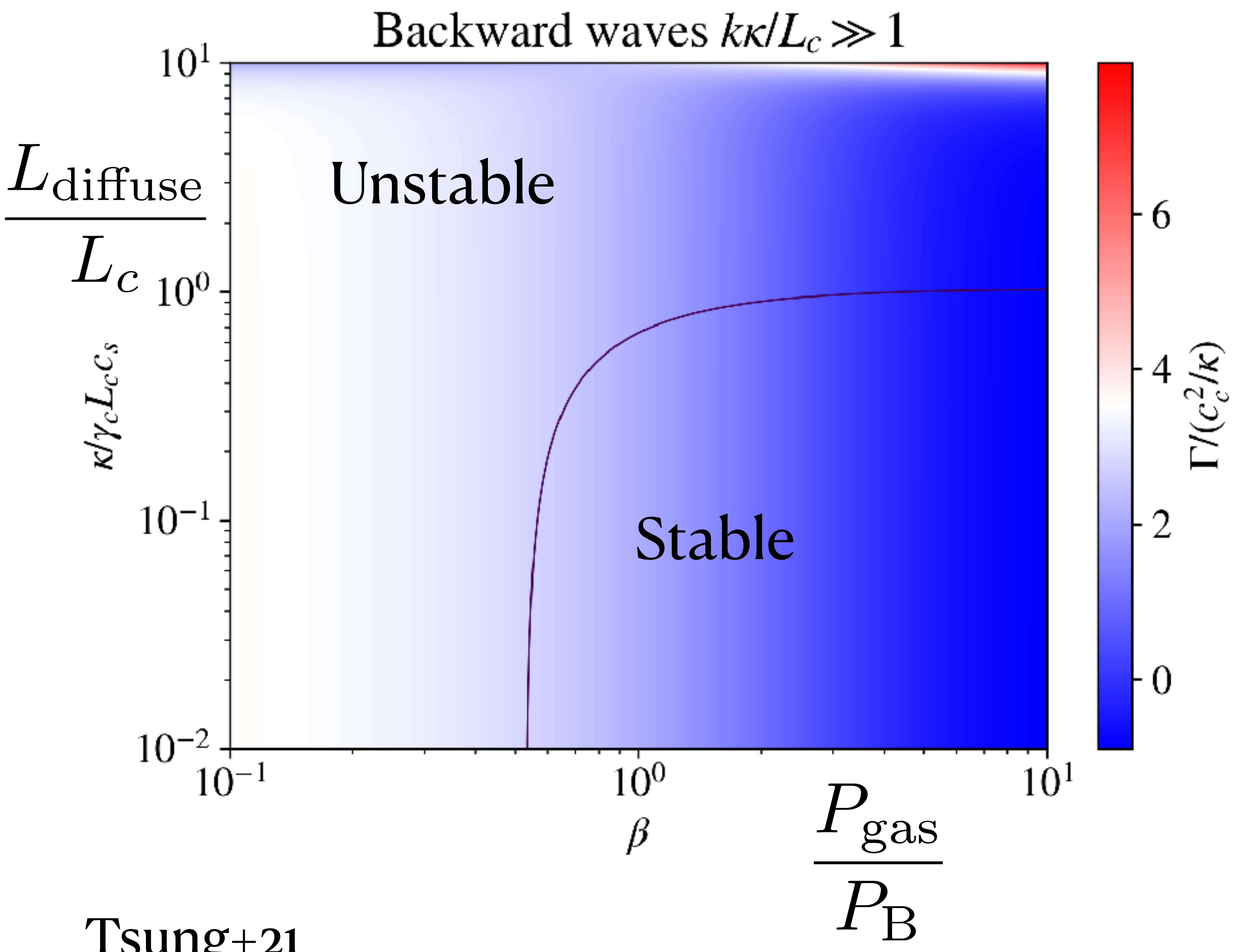
Sound Wave



Sound Wave

Growth time is short! (of order wave period)

Instability with streaming, diffusion + background gradient



Tsung+21

For instability:

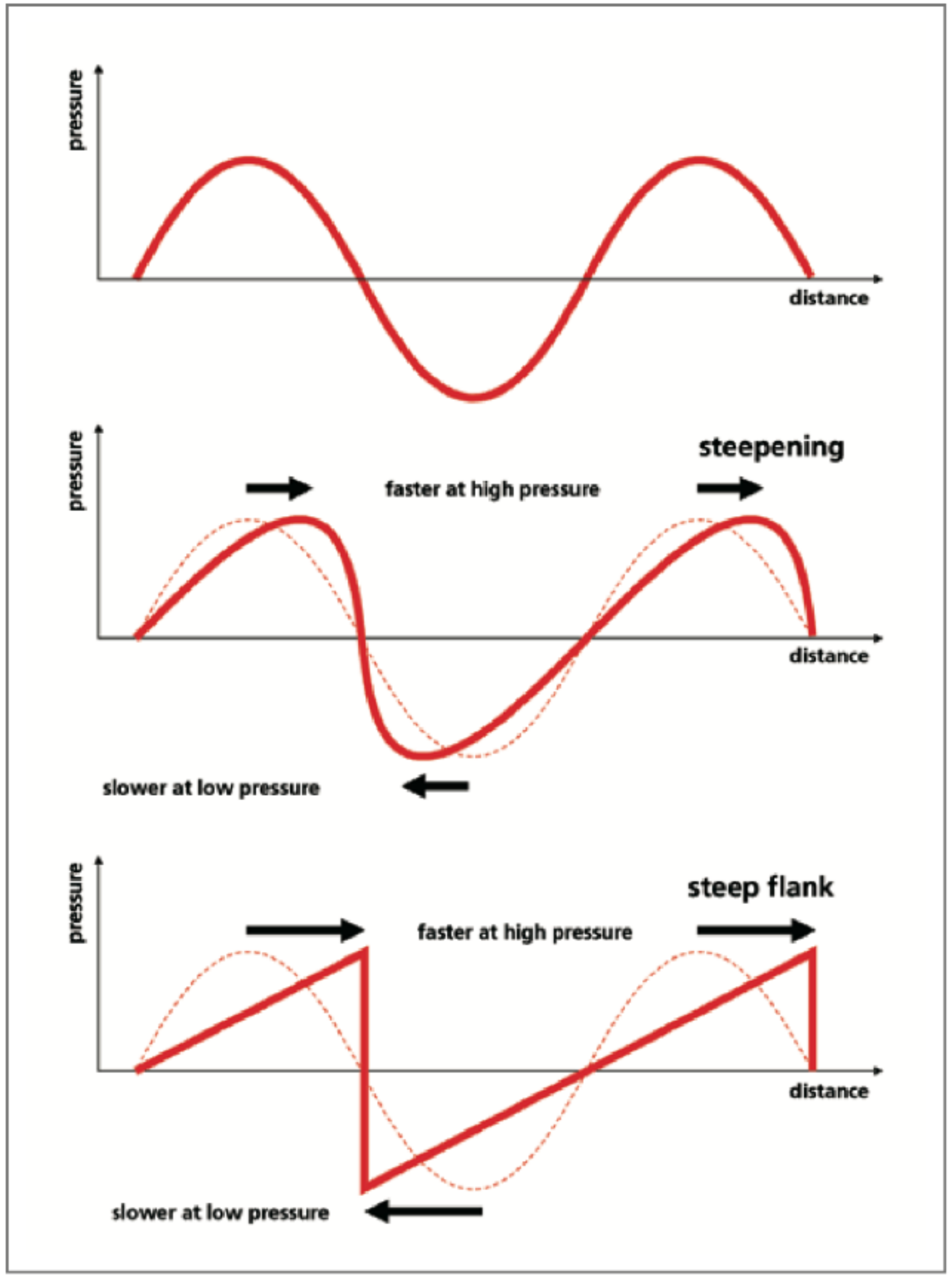
Short CR scale height (unstable regardless of B-field)

or

Strong B-fields (unstable regardless of CR scale height)

In very weak B-field (ICM) regime, potential CR instability driven by pressure anisotropy (Kempski & Quataert 2020)

What happens to a growing sound wave?



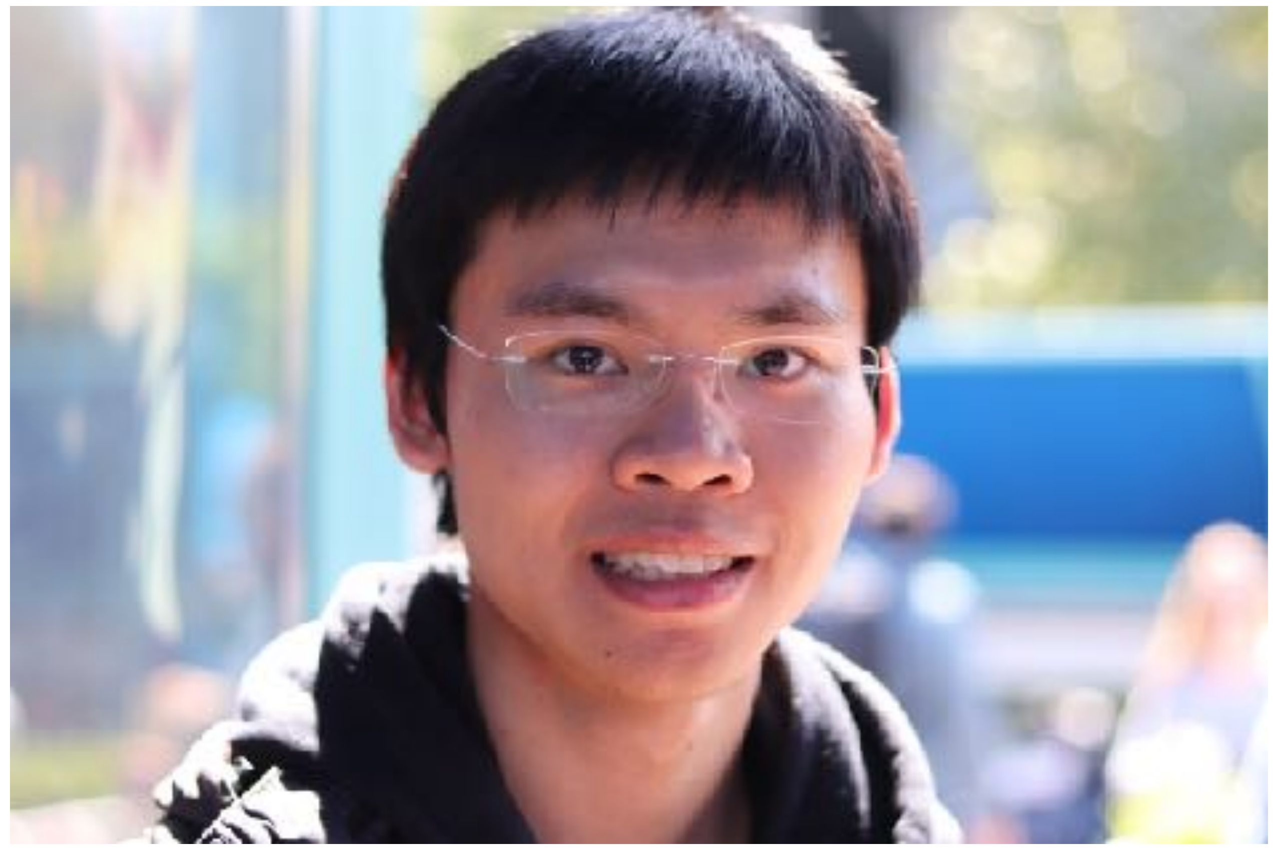
It goes non-linear, steepens and shocks

Figure from Storz 2007

Bring it On

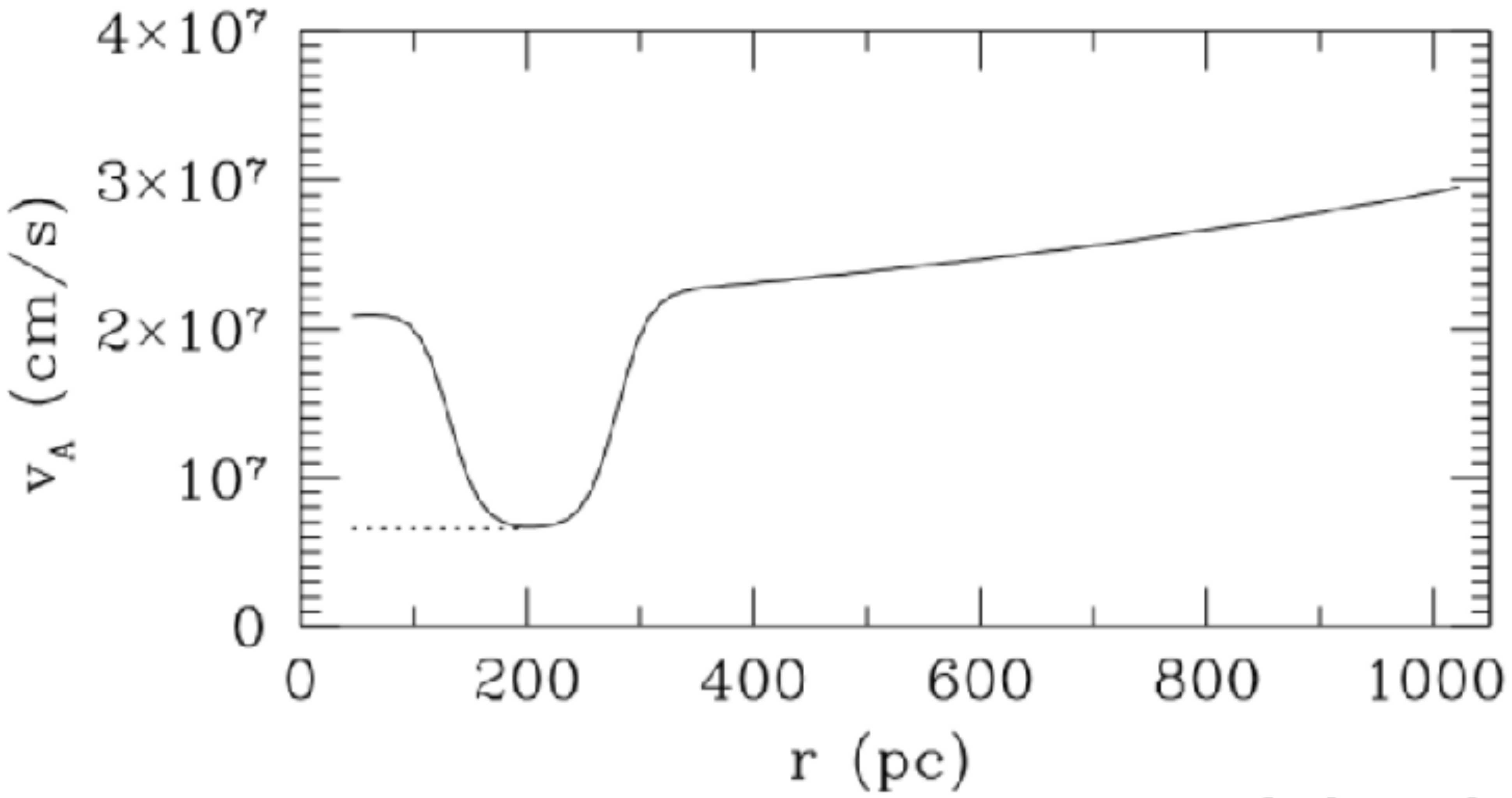
This staircase structure is new: has never been seen before in CR sims!

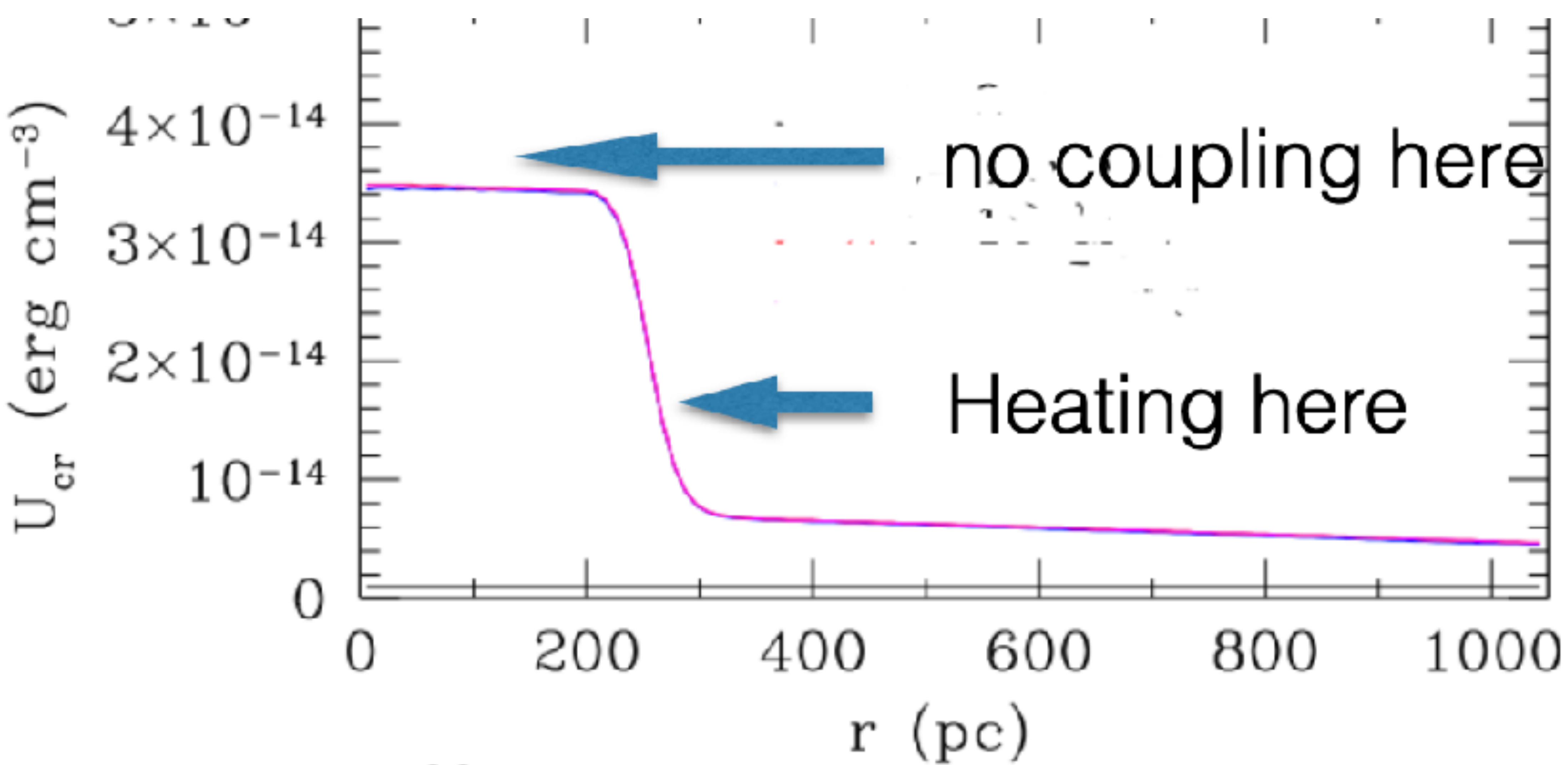
Weak shocks separated by uncoupled regions (free-streaming CRs)



Tsung+21

CR Staircase is due to 'bottleneck effect'





no coupling here

Heating here

Hydro turned off

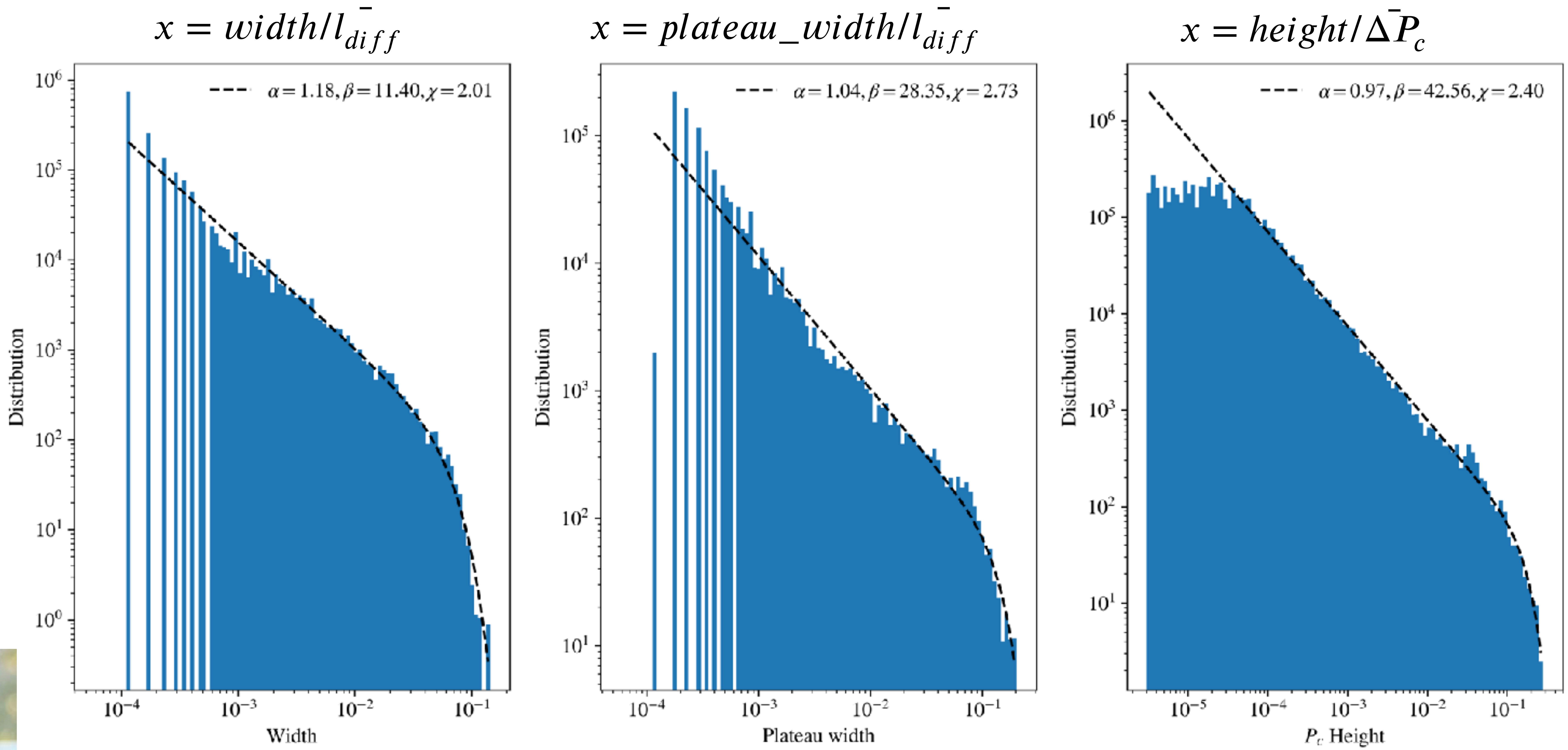
Wiener, Oh & Zweibel 2017 (see also Skilling 1971)

Minimum in Alfven speed ('bottleneck') causes CRs to decouple

System reaches a statistical steady state

Statistics

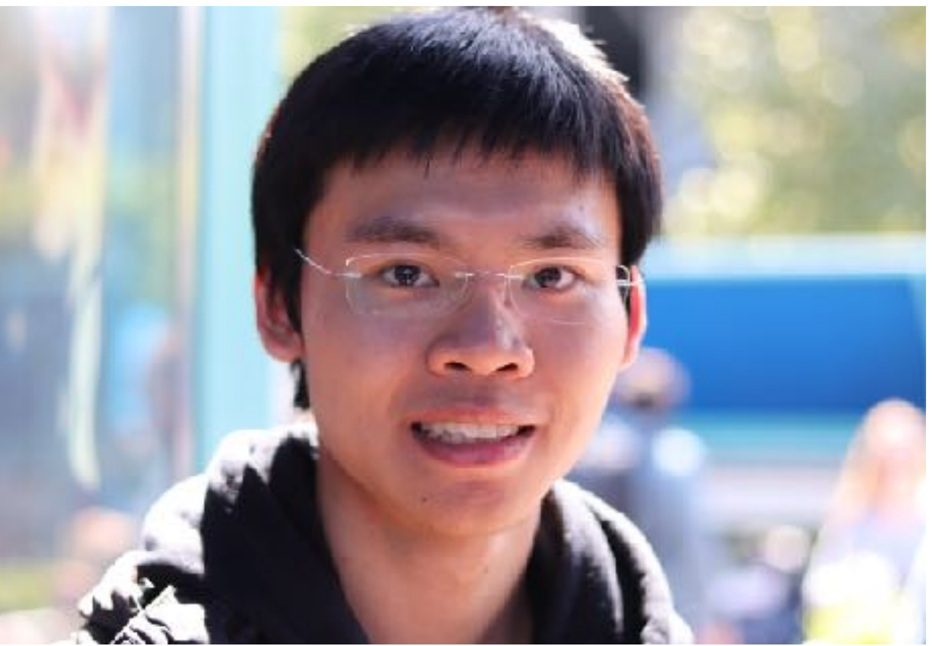
Fitting function $f \propto x^{-\alpha}\exp(-\left(\frac{x}{\beta}\right)^{\chi})$



$x = width/\bar{l}_{diff}$

$x = plateau\_width/\bar{l}_{diff}$

$x = height/\Delta\bar{P}_c$

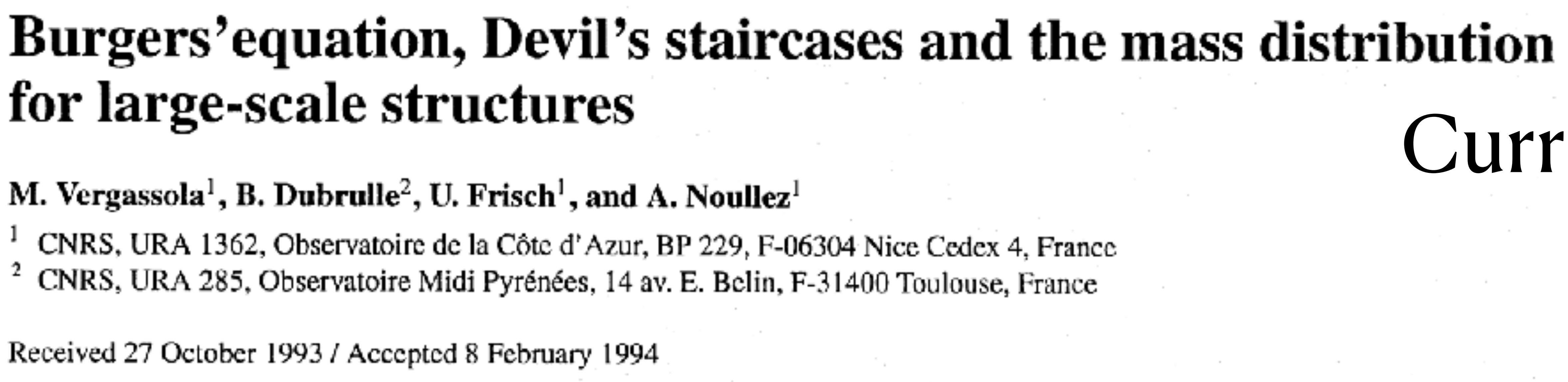


Distribution of widths and height follows a Schechter-like function!

Possible to understand characteristic lengthscales

Reminiscent of adhesion model!

Extension of Zeldovich approximation — solves Burger's equation



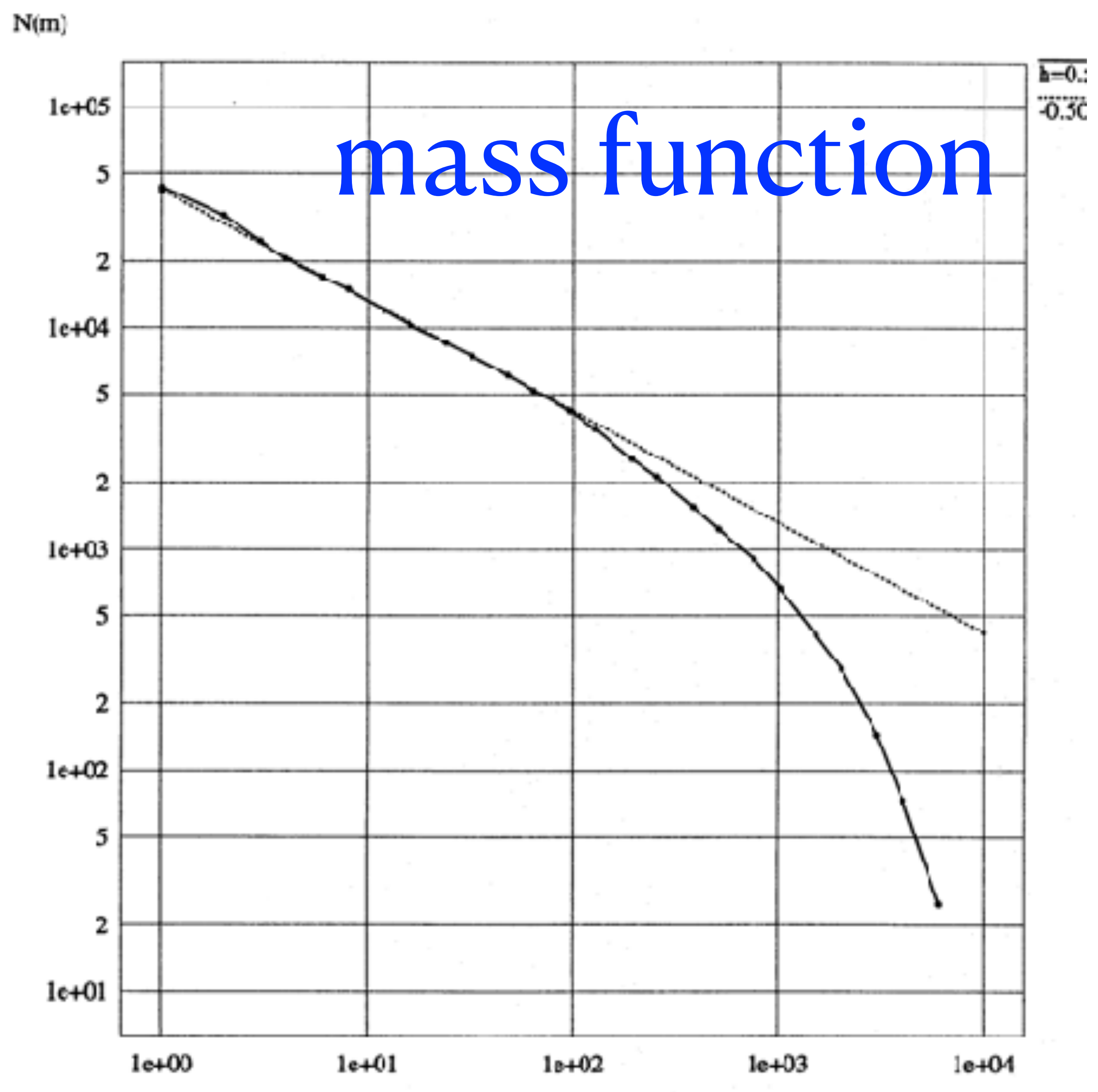
Burgers'equation, Devil's staircases and the mass distribution for large-scale structures

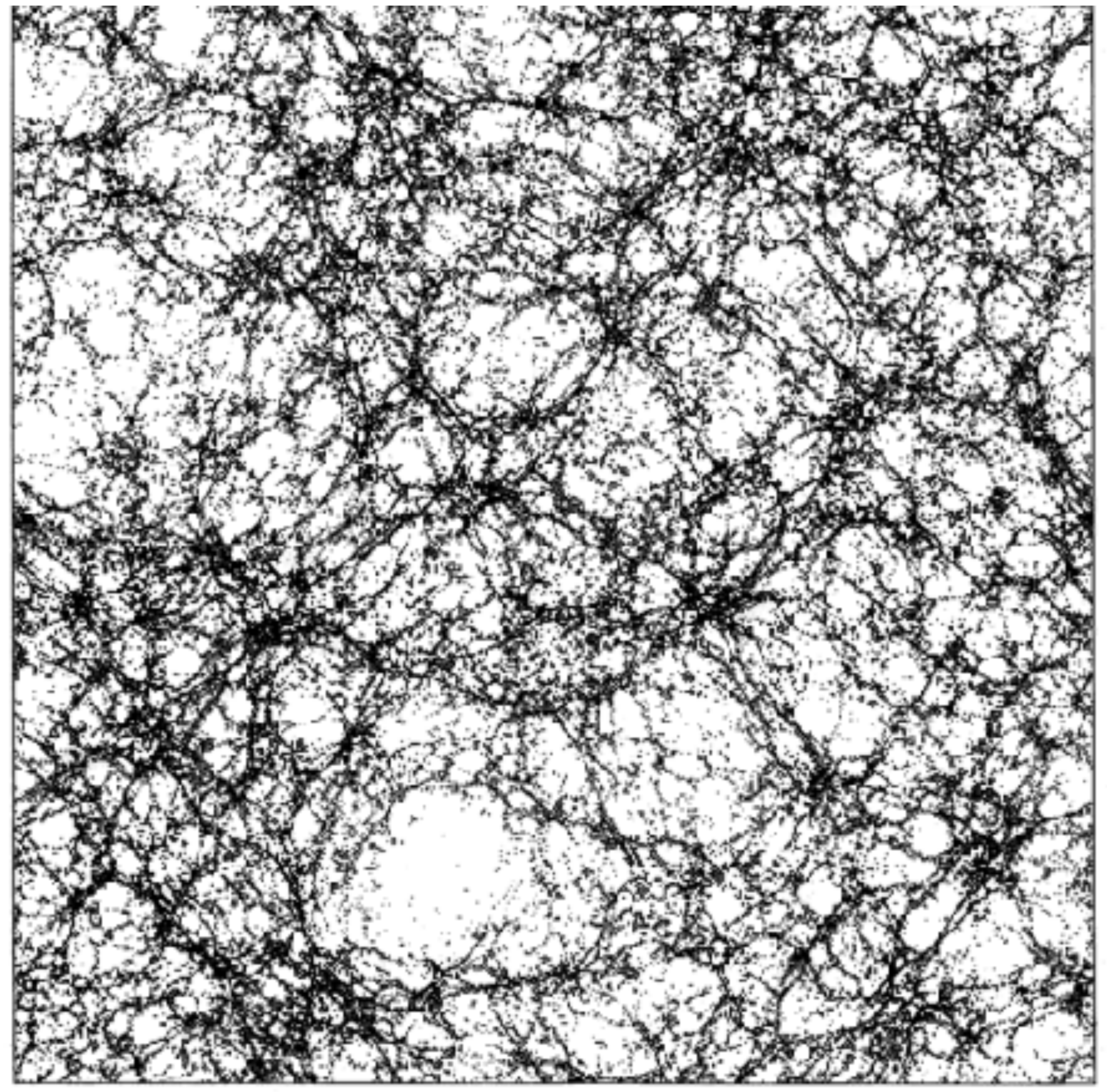
M. Vergassola[1], B. Dubrulle[2], U. Frisch[1], and A. Noullez[1]

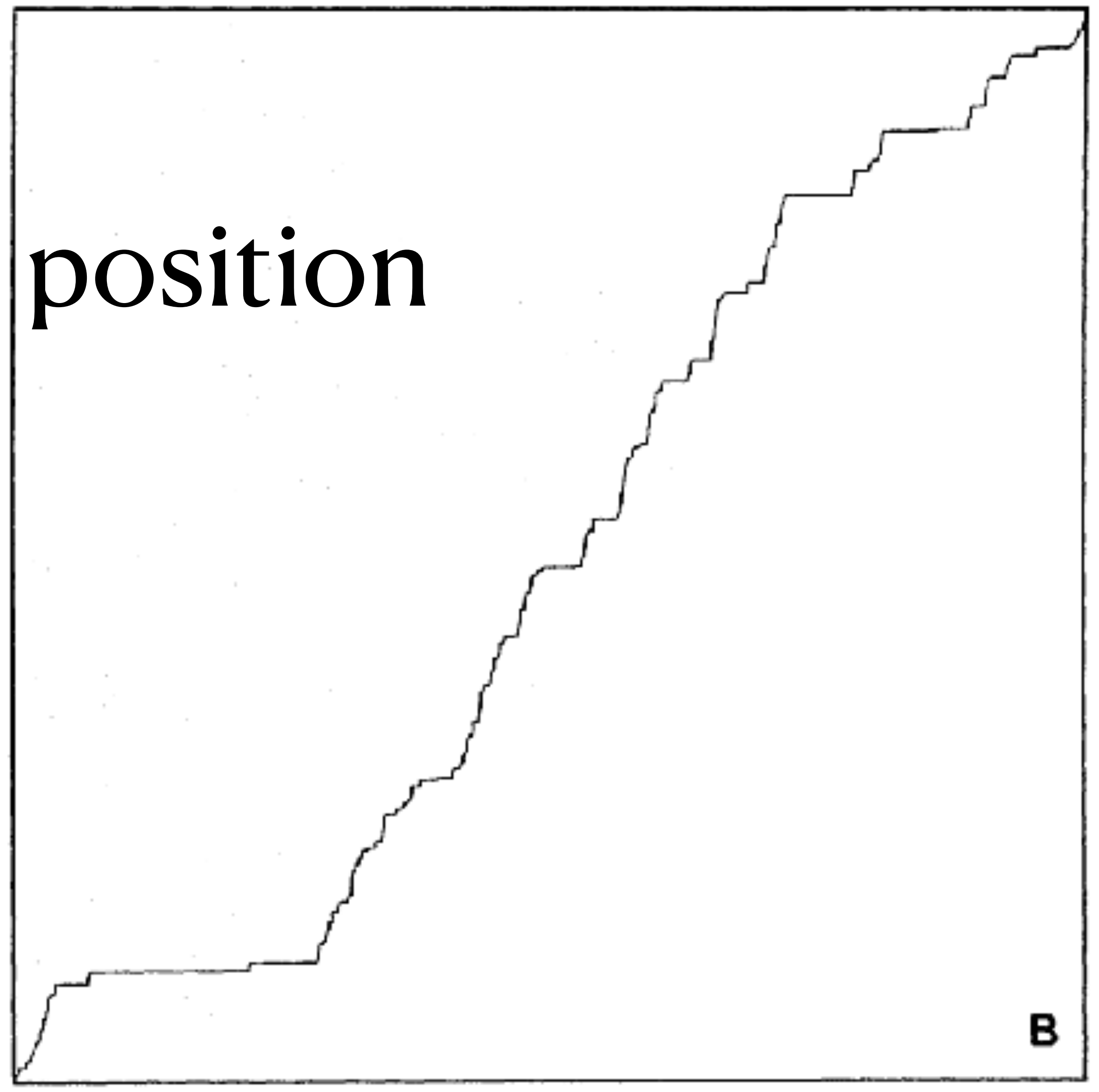
[1] CNRS, URA 1362, Observatoire de la Côte d'Azur, BP 229, F-06304 Nice Cedex 4, France
[2] CNRS, URA 285, Observatoire Midi Pyrénées, 14 av. E. Belin, F-31400 Toulouse, France

Received 27 October 1993 / Accepted 8 February 1994

Schechter-like mass function





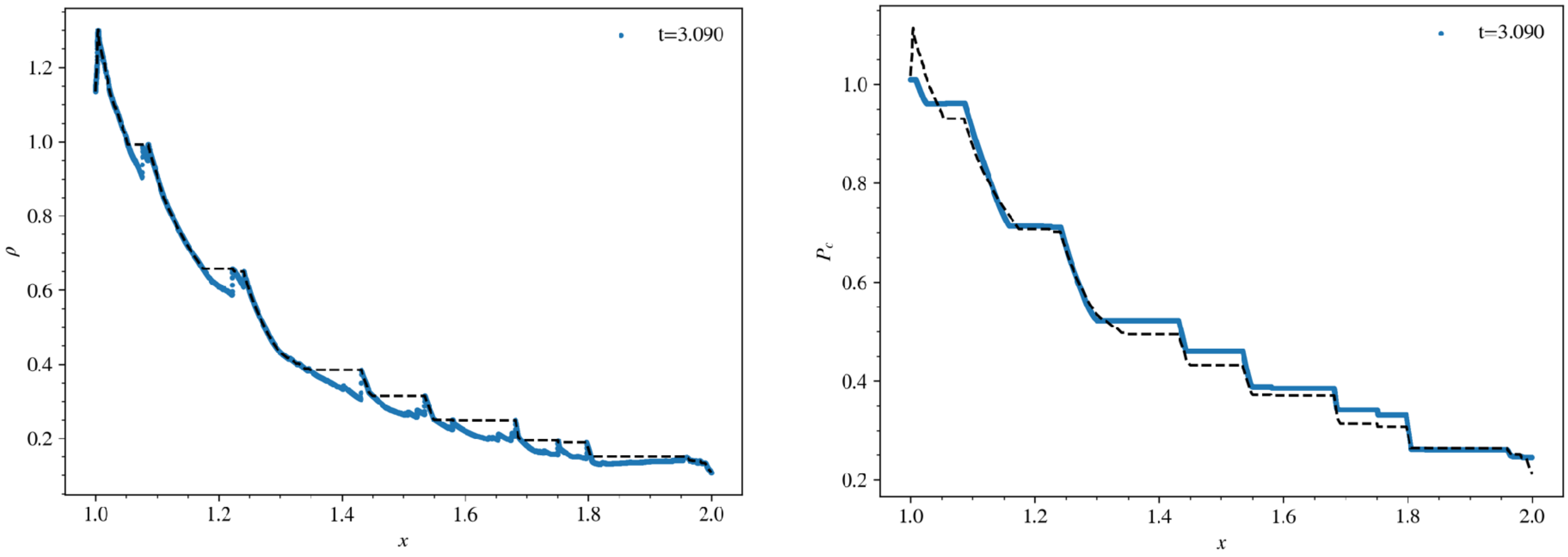


Lagrangian map is a "Devil's staircase" with fractal dimension

Reasonable density distribution!

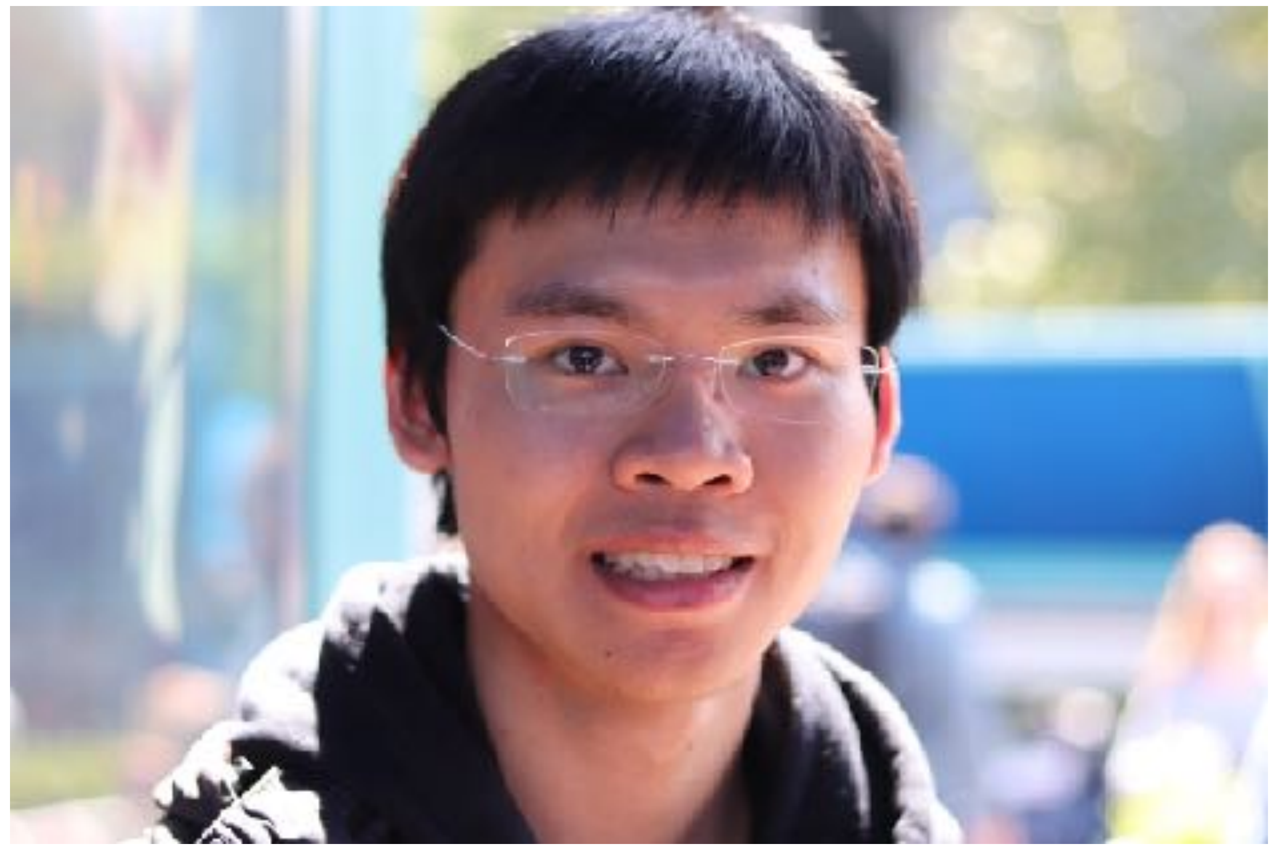
Many beautiful properties, with deep roots in Legendre transform

Scheme works well

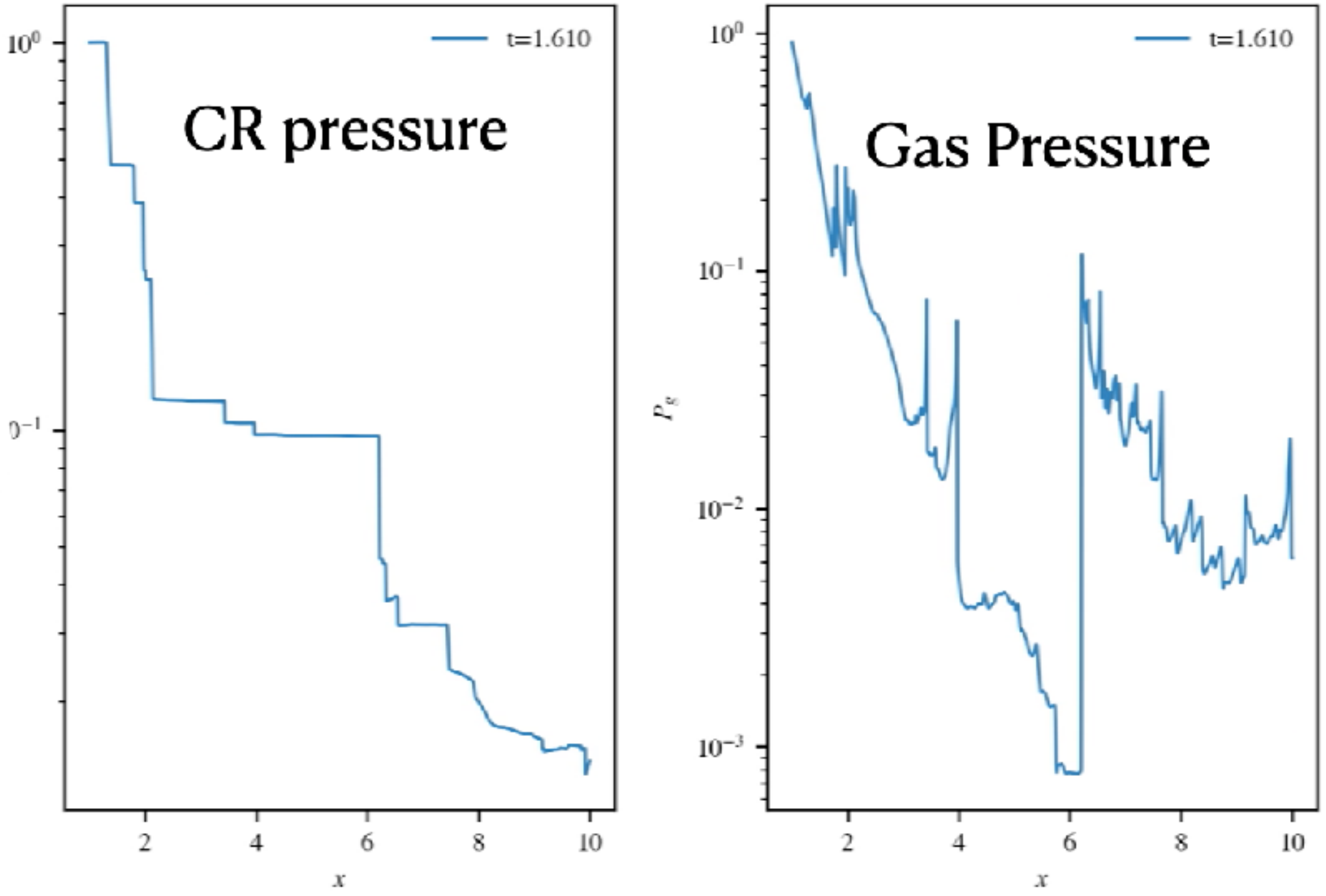


Black dotted line represents convex hull construction

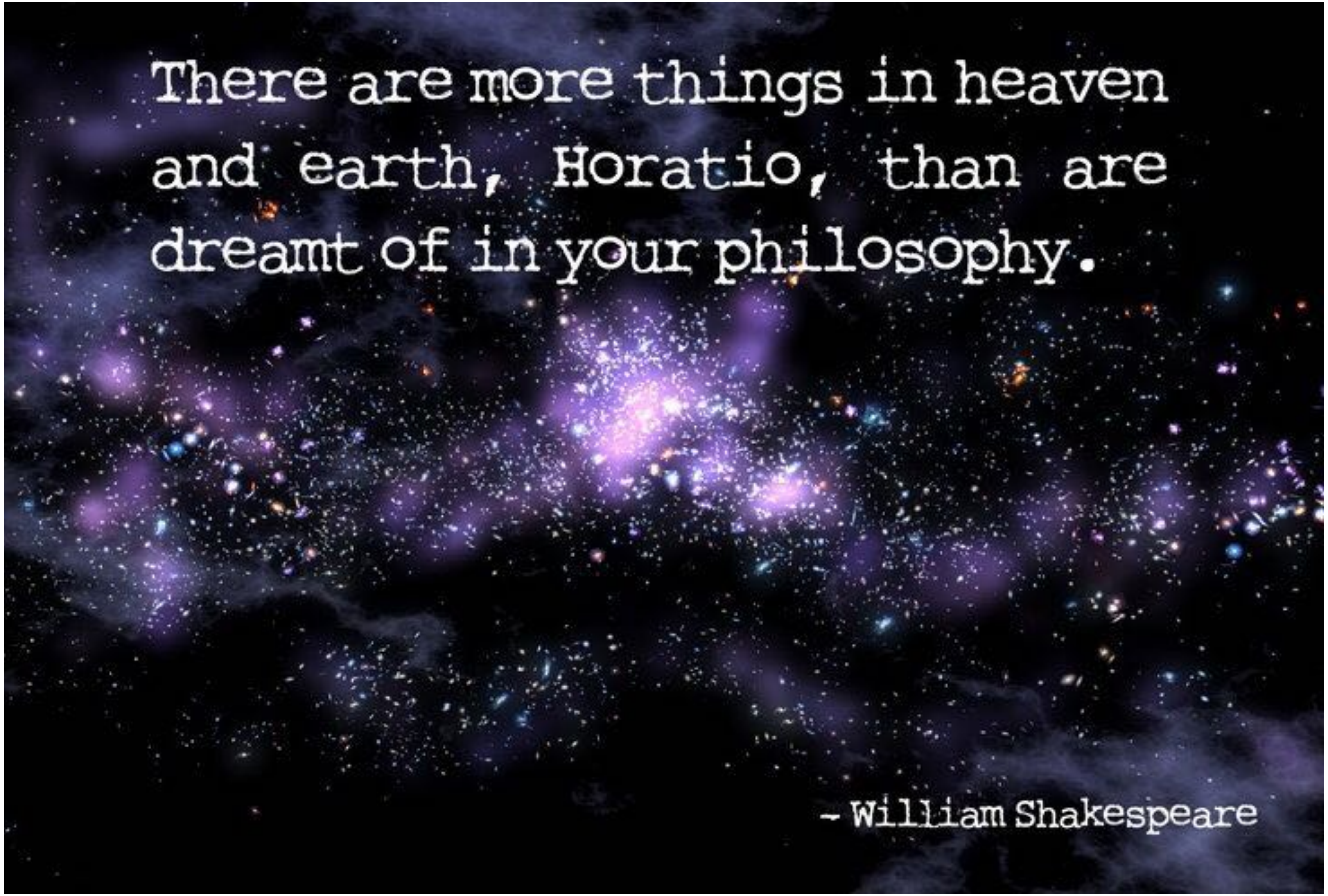
OK, so what?



- Time-averaged momentum and energy transfer appear unchanged
- But strong transient density and velocity fluctuations! (visible w/ FRBs?)
- **Strong spatial and temporal pressure fluctuations** — assuming a fixed pressure will be a poor approximation



Many cool and wacky surprises in store



There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.

- William Shakespeare