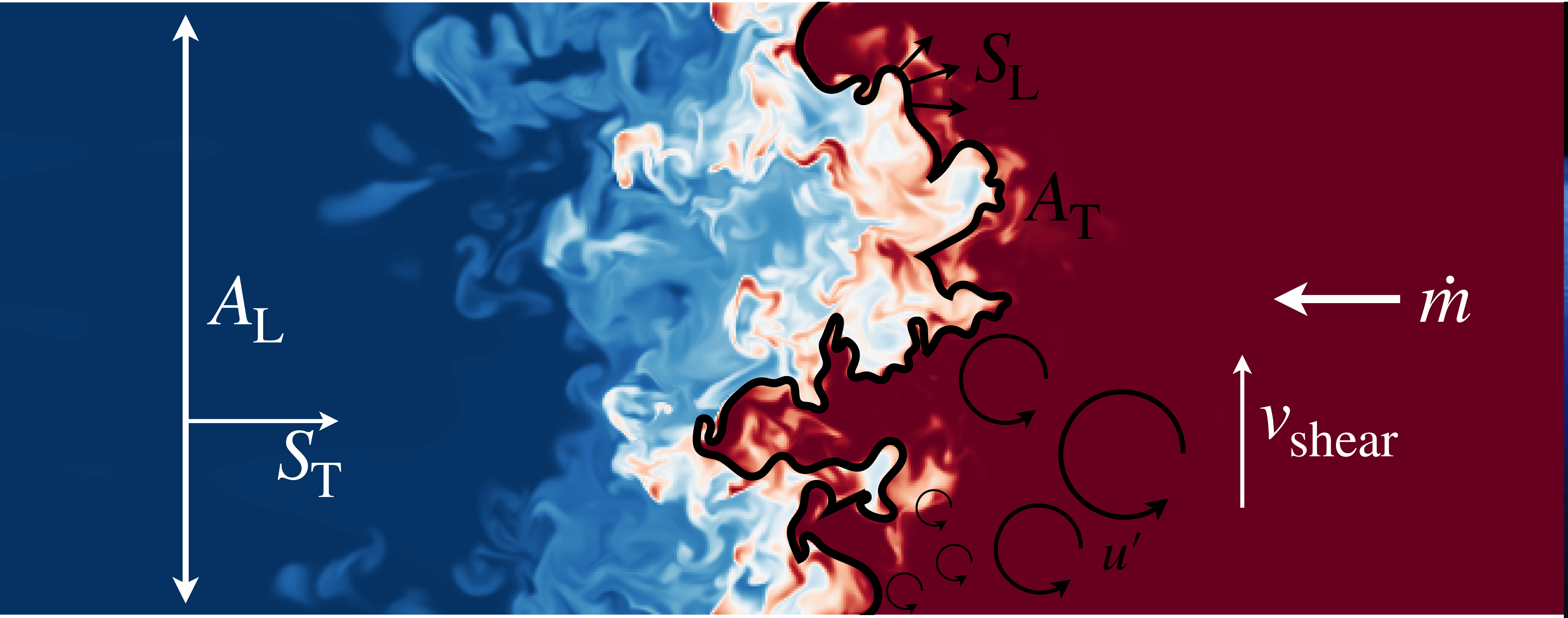
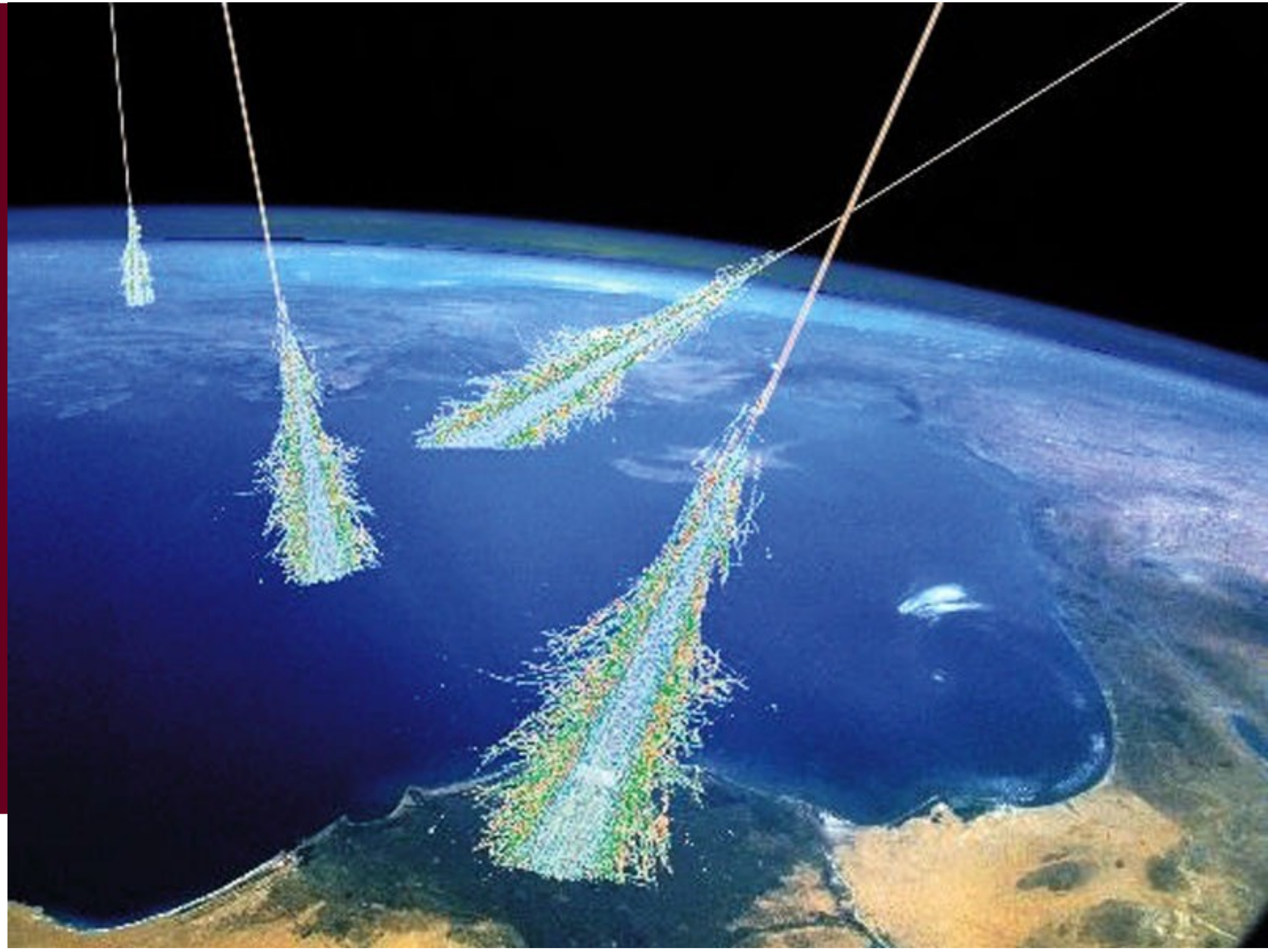


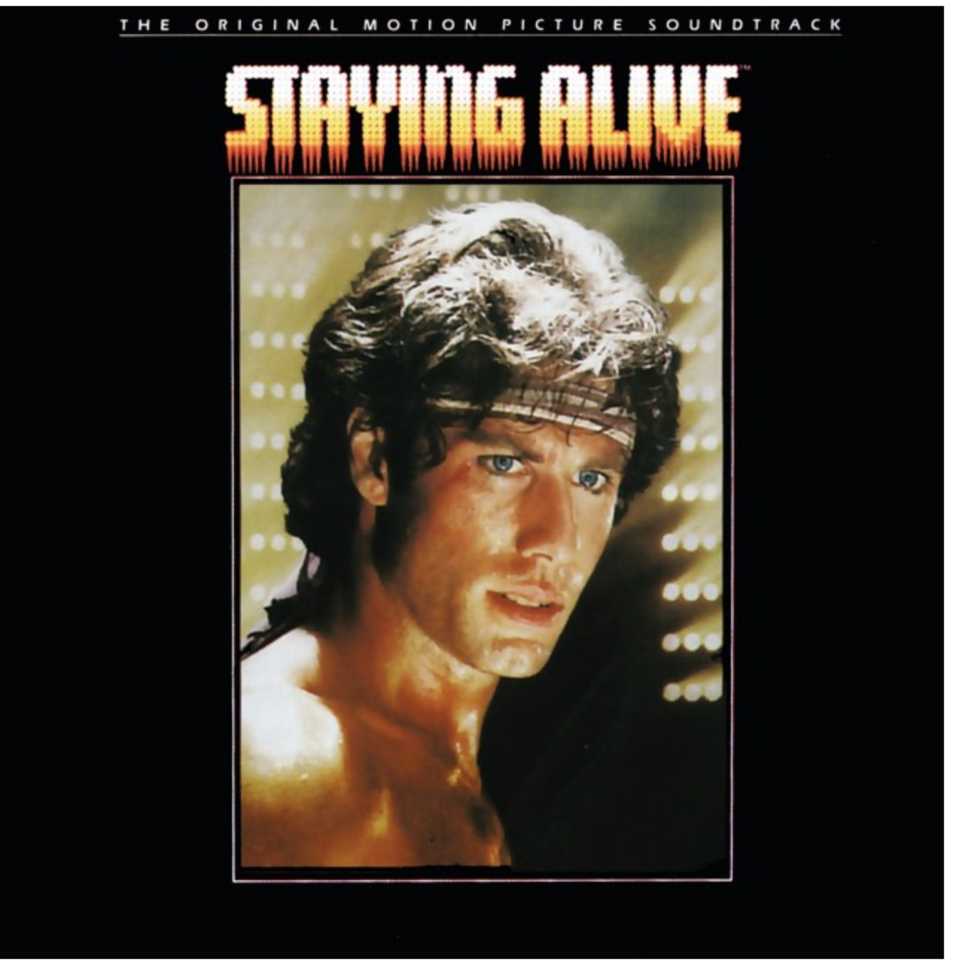


Gas Clouds and Cosmic Rays

Peng Oh (UCSB)

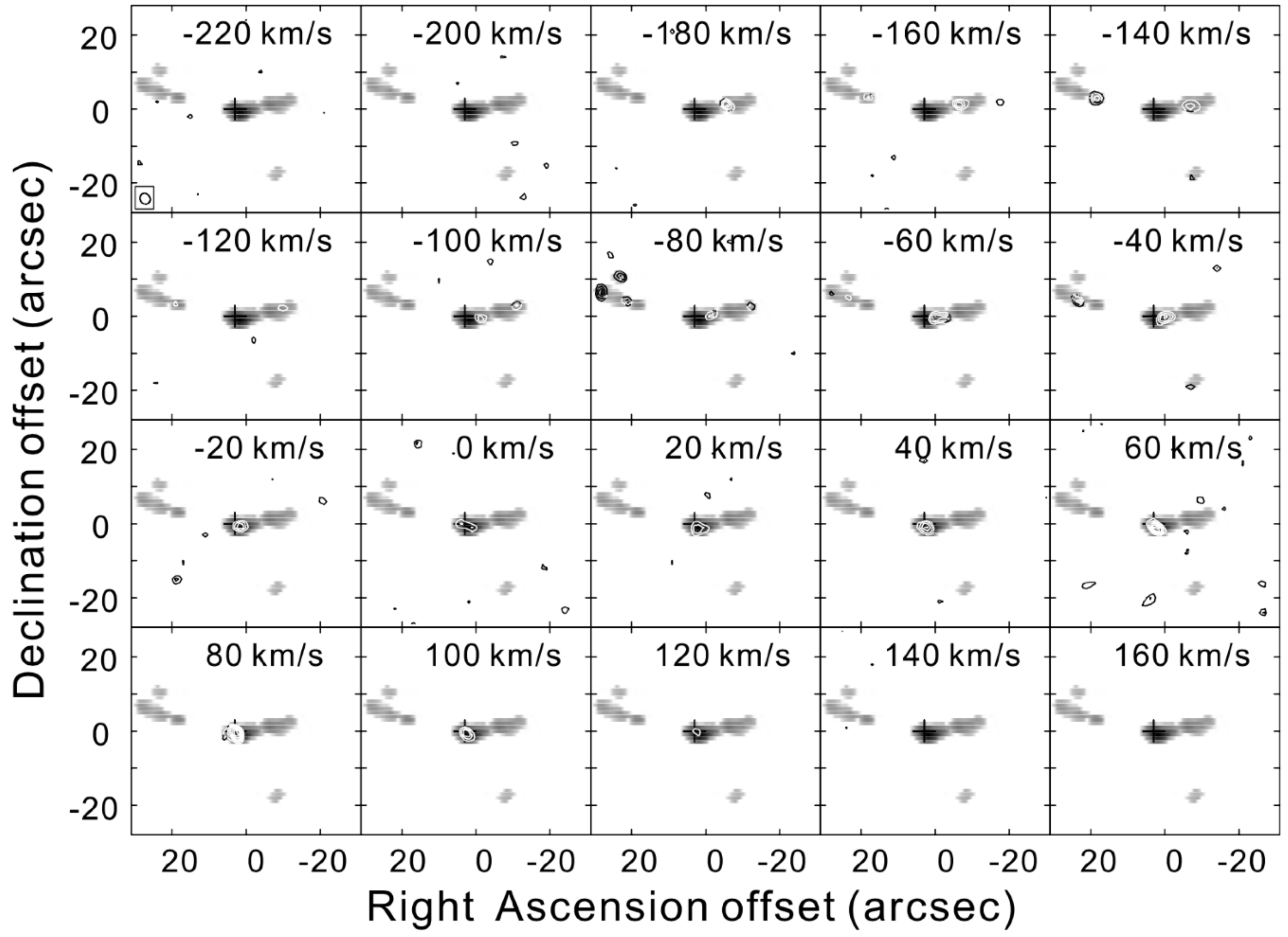
Cloudy with a Chance of Rain: Accretion Braking of Cold Clouds

Tan, Oh & Gronke 2022, in prep

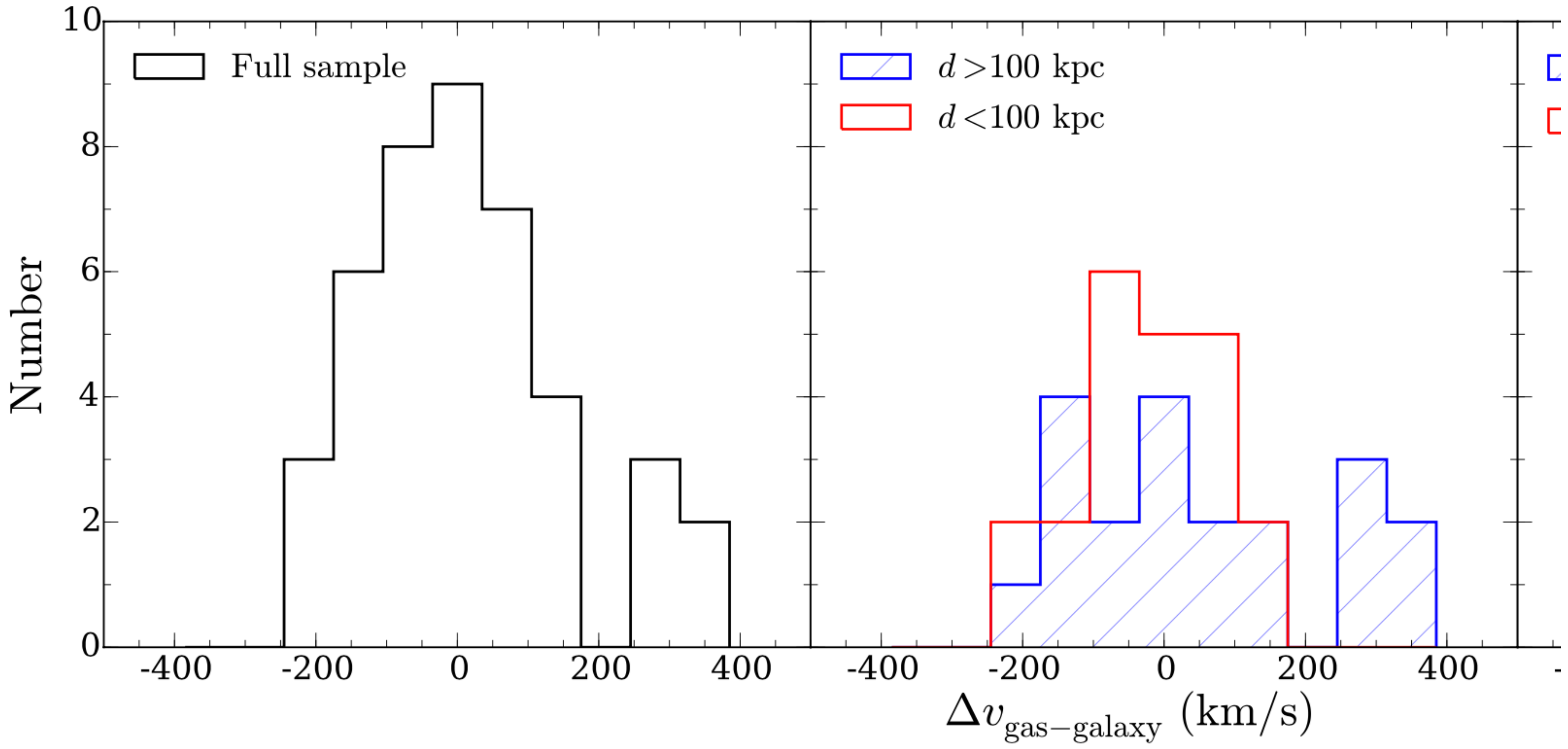


How do Falling Cluster Filaments Survive?

And why is their infall sub-virial?



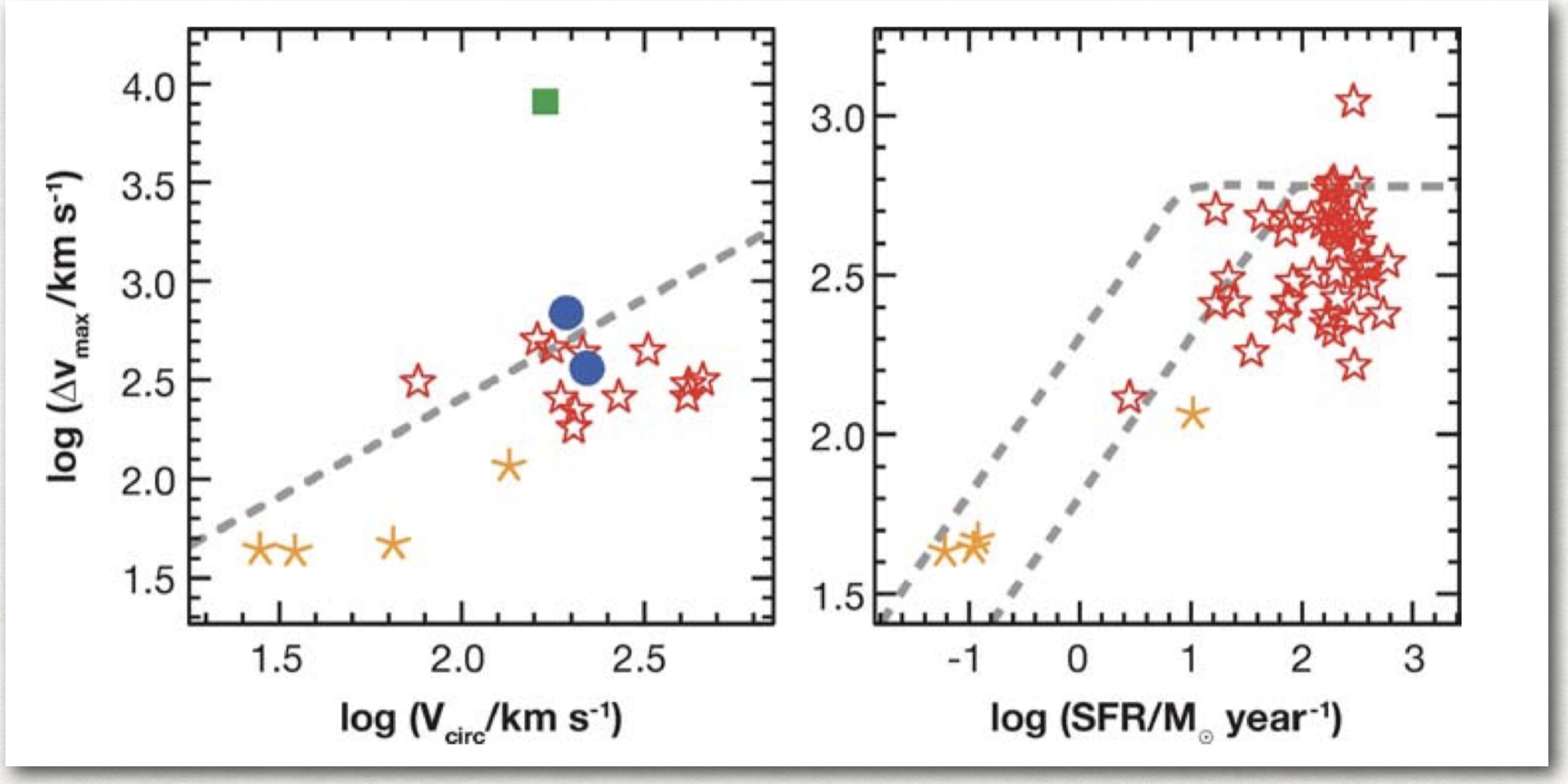
Perseus A, molecular gas velocity offsets Lim+08



Zahedy+19

Same problem with LRGs… velocity dispersions are only ~ 60% of expected

IN GALAXIES, WE SEE OUTFLOWING COLD GAS



Veilleux et al 2005

Most feedback mechanisms accelerate hot gas, but we can (mostly) only see cold gas

CLOUD SURVIVAL IN WINDS LOOKS HARD

B-fields help prolong life but clouds still die (Cottle+20)

Basic reason

Acceleration time:

$$t_{\rm acc} \sim \left(\frac{\rho_{\rm c}}{\rho_{\rm h}}\right) \frac{R}{v_{\rm h}}$$

is longer than destruction time

$$t_{\rm cc} \sim \left(\frac{\rho_{\rm c}}{\rho_{\rm h}}\right)^{1/2} \frac{R}{v_{\rm h}}$$

$$\frac{t_{\rm acc}}{t_{\rm cc}} \sim \left(\frac{\rho_h}{\rho_c}\right)^{1/2}$$

independent of cloud size

Entrainment in trouble: cool cloud acceleration and destruction in hot supernova-driven galactic winds

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ABSTRACT

Efficient thermalization of overlapping supernovae within star-forming galaxies may produce a supernova-heated fluid that drives galactic winds. For fiducial assumptions about the timescale for cloud shredding from high-resolution simulations (which neglect magnetic fields), we show that cool clouds with temperature from $T_c \sim 10^2$–10^4 K seen in emission and absorption in galactic winds cannot be accelerated to observed velocities by the ram pressure of a hot wind. Taking into account both the radial structure of the hot flow and gravity, we show that this conclusion holds over a wide range of galaxy, cloud and hot wind properties. This finding calls into question the prevailing picture whereby the cool atomic gas seen in galactic winds is entrained and accelerated by the hot flow. Given these difficulties with ram pressure acceleration, we discuss alternative models for the origin of high-velocity cool gas outflows. Another possibility is that magnetic fields in cool clouds are sufficiently important that they prolong the cloud's life. For $T_c = 10^3$ K and 10^4 K clouds, we show that if conductive evaporation can be neg

respectively, than the v

to reach those seen in

Marinacci+12,Armillotta+16, Gronke & Oh (2018,2020), Li+20, Sparre+20, Kanjilal+21, Abruzzo+22

Mixing + cooling works

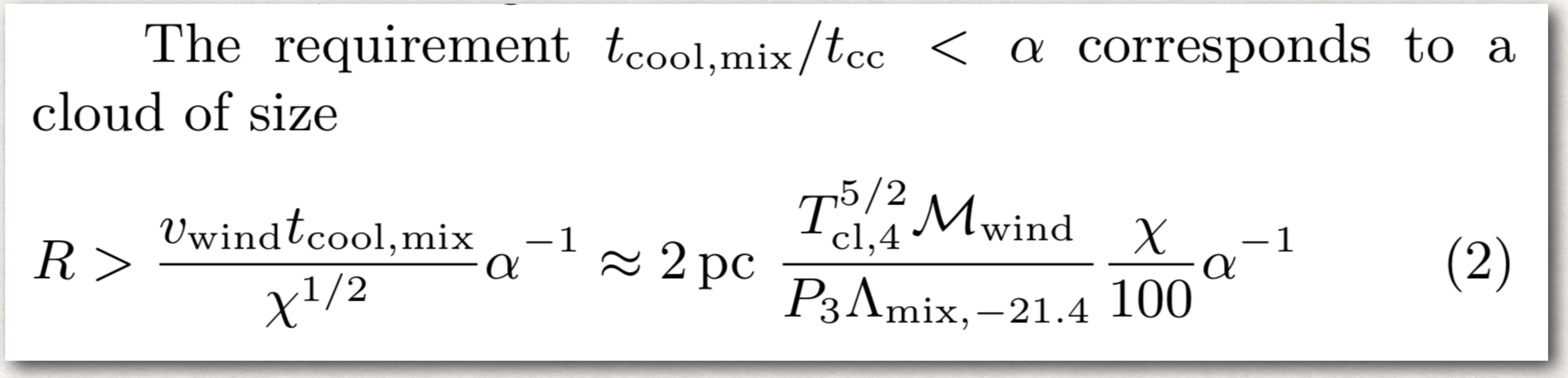
Don't think about Sailing $F = \rho v^2 A$

Think about a car crash

$$F = \frac{dp}{dt} = m\dot{v} + \dot{m}v = 0$$

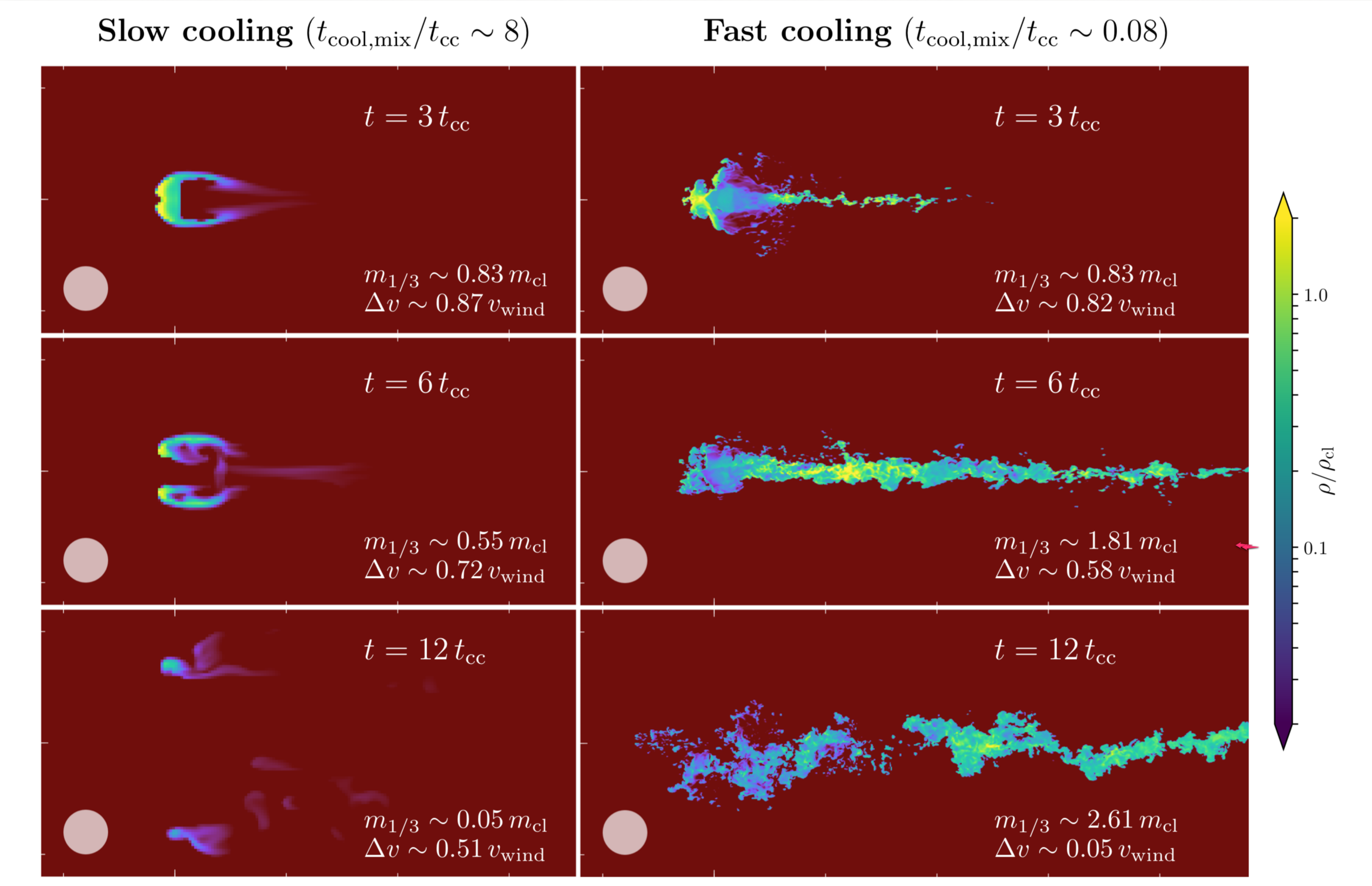
$$\Rightarrow a = \frac{\dot{m}}{m} v$$

Works if mixed gas can cool



The requirement $t_{\rm cool,mix}/t_{\rm cc} < \alpha$ corresponds to a cloud of size

$$R > \frac{v_{\rm wind} t_{\rm cool,mix}}{\chi^{1/2}} \alpha^{-1} \approx 2\,{\rm pc}\, \frac{T_{\rm cl,4}^{5/2} \mathcal{M}_{\rm wind}}{P_3 \Lambda_{\rm mix,-21.4}} \frac{\chi}{100} \alpha^{-1} \qquad (2)$$



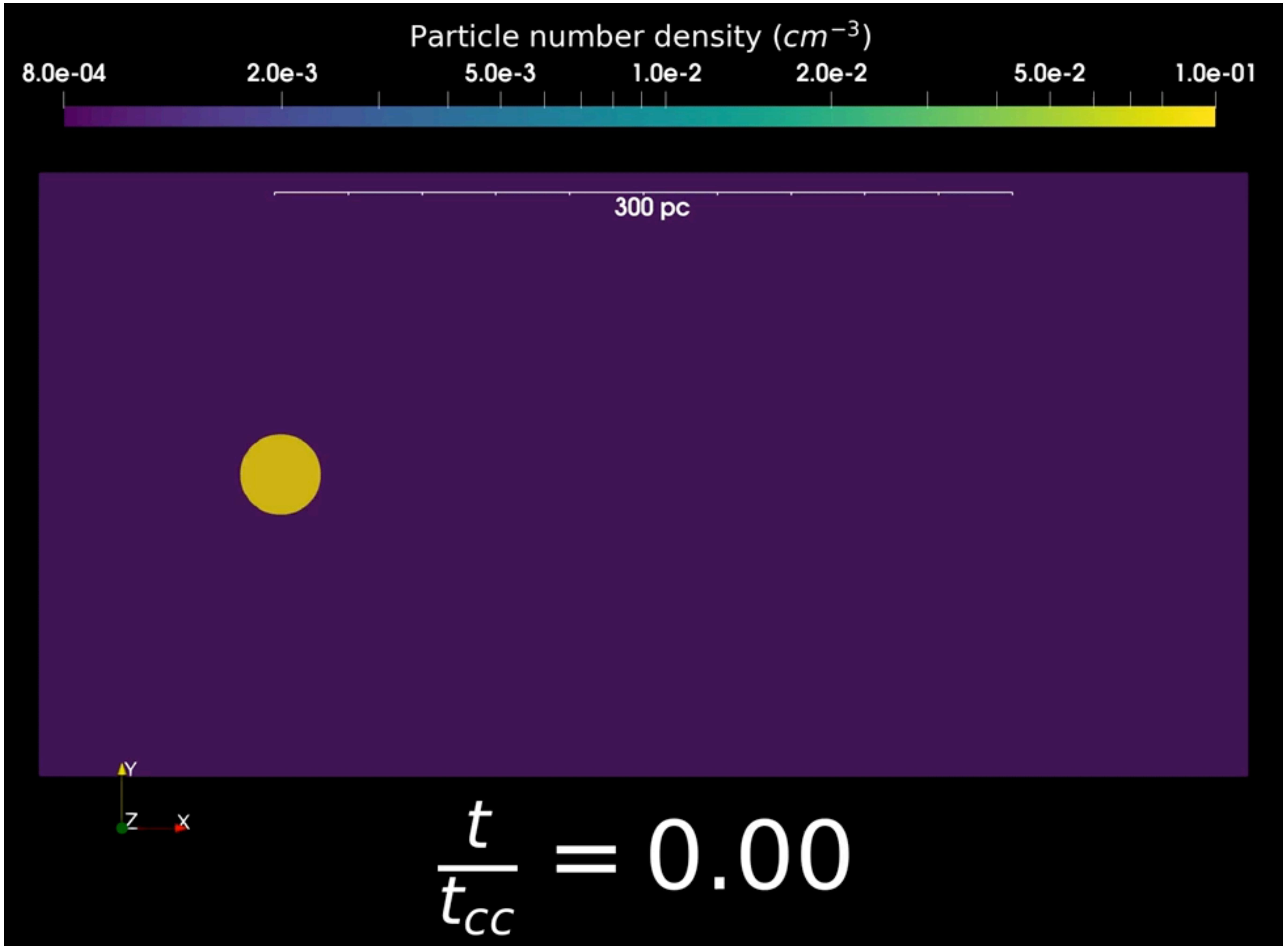
3D ATHENA sims. Mach number 1.5 winds.

Gronke & Oh 2018

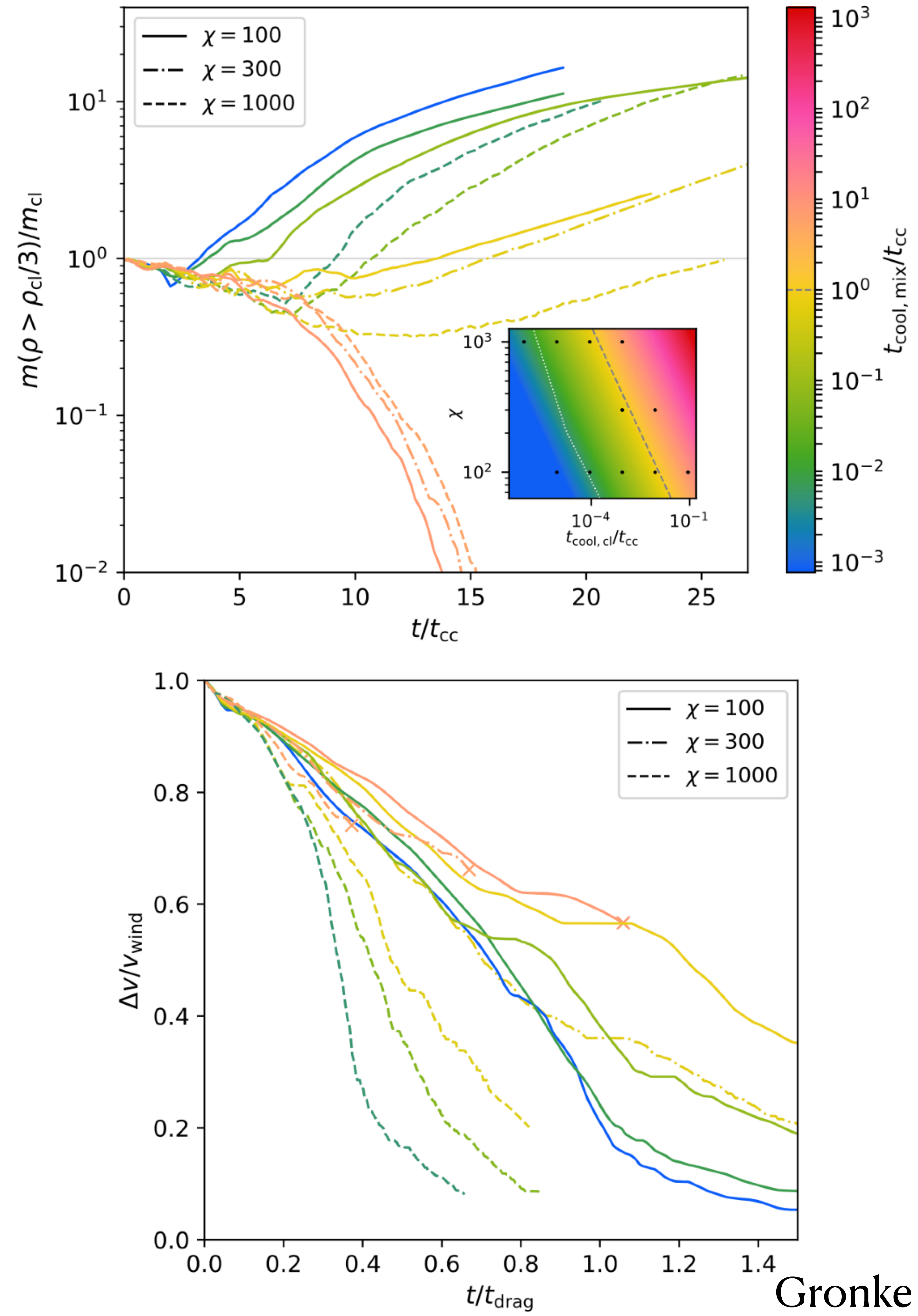
Cold gas grows in mass (from hot gas cooling out) and becomes comoving (since hot gas has high momentum)

Mass growth is highest when cloud is entrained

Often clouds 'rise from the dead'



Kanjilal+21

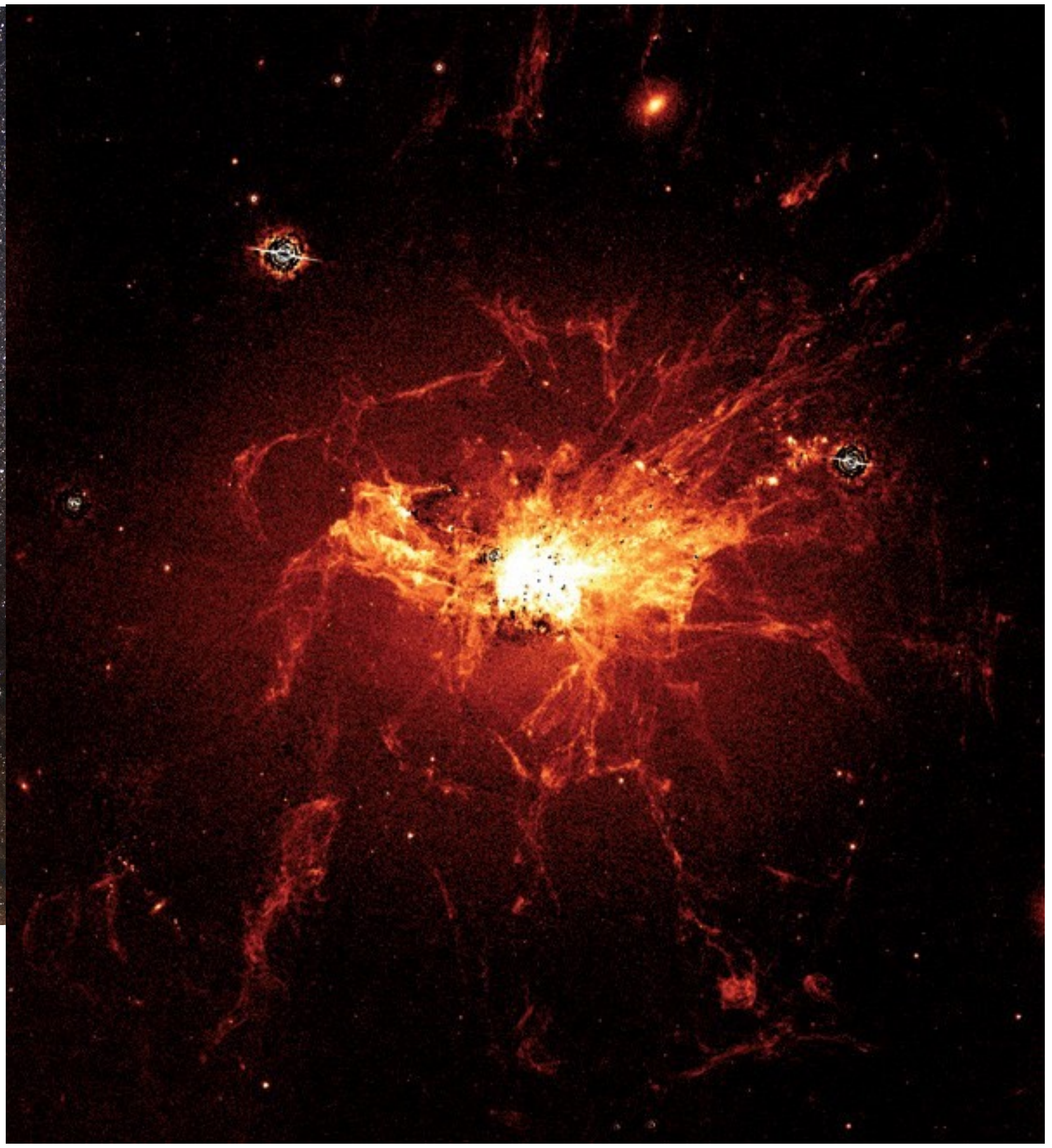


Gronke & Oh 2018

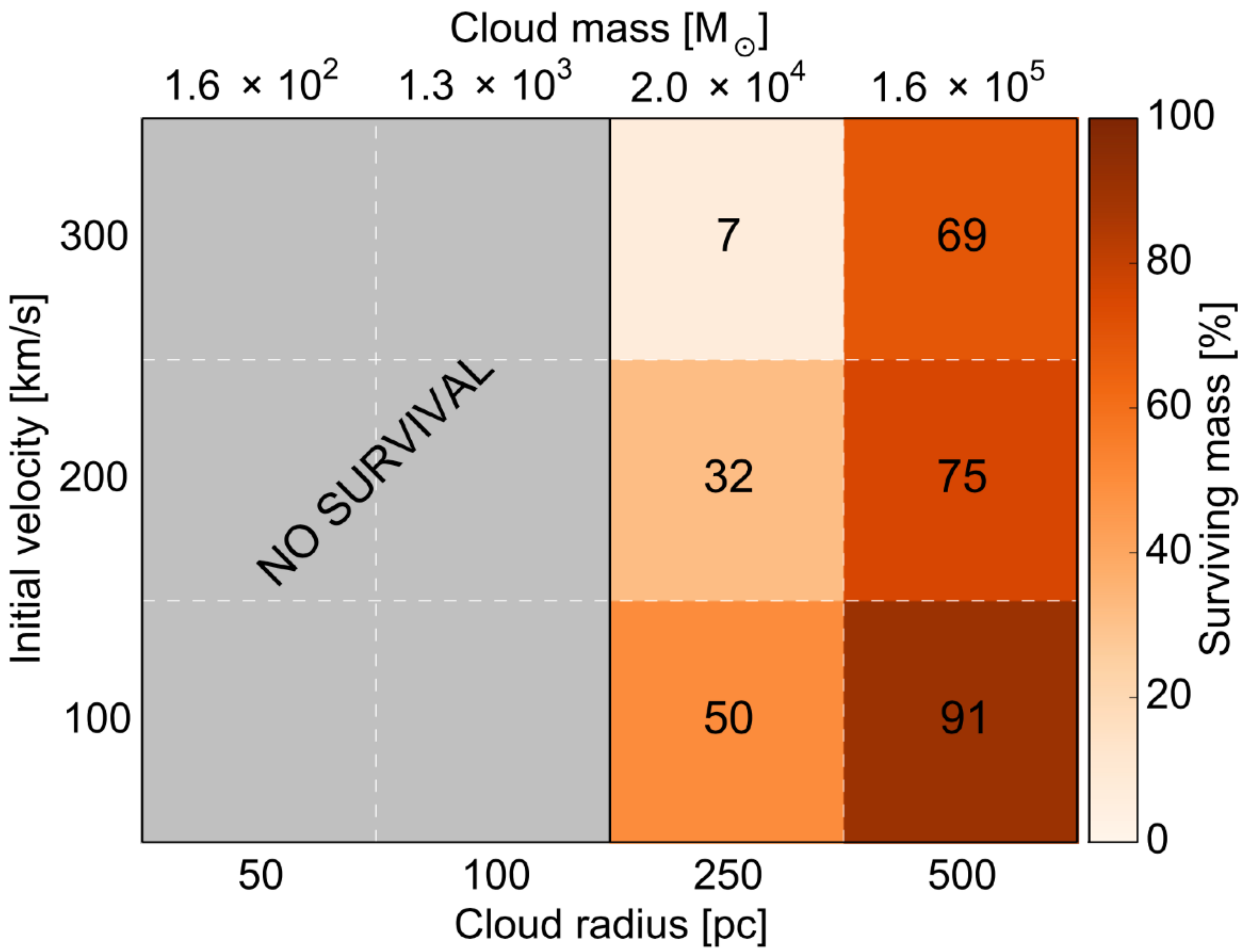
How about infall, rather than outflow…

Just reverse the velocity vector,right?

HVCs



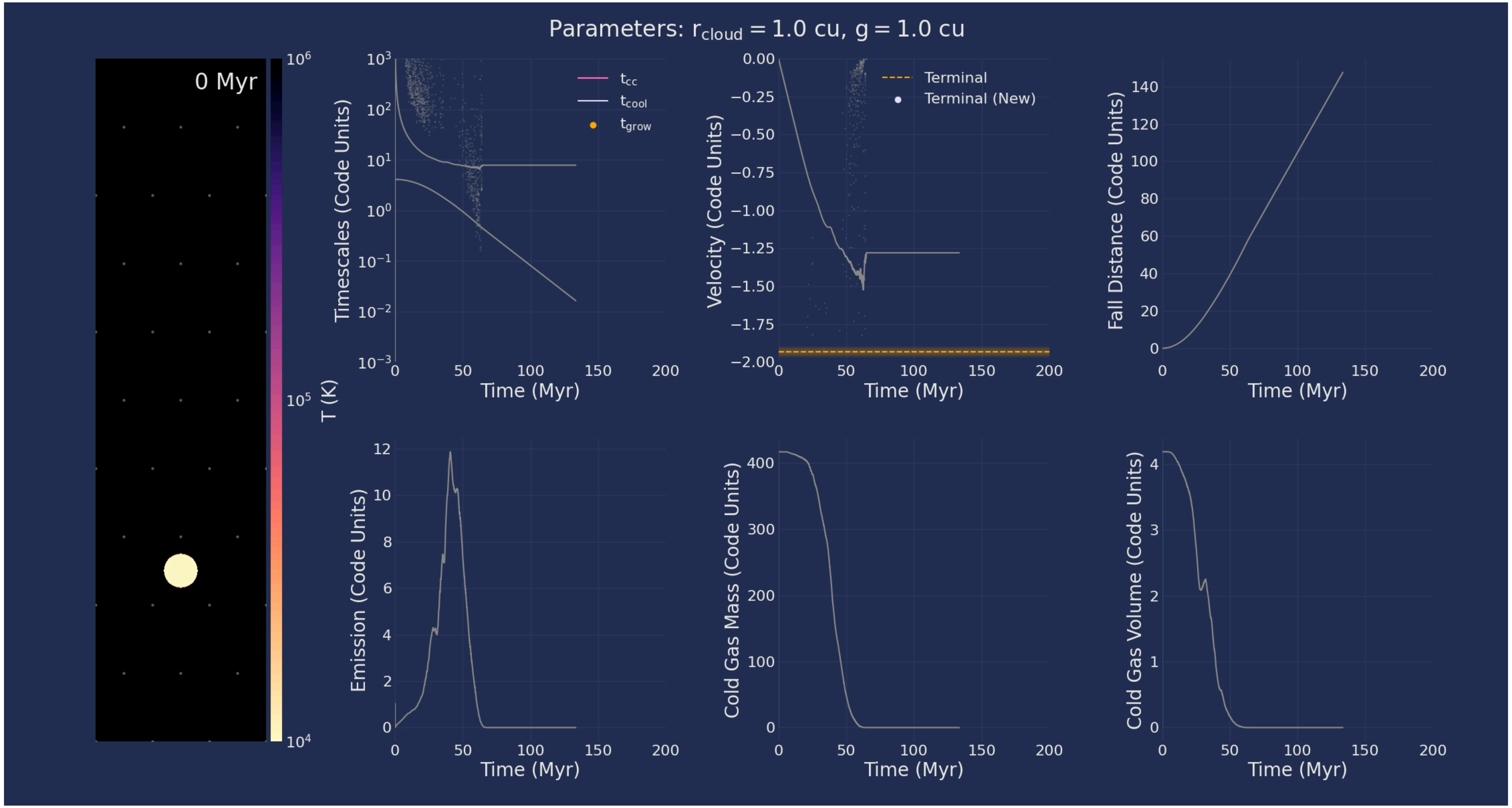
Cluster Filaments



Armillotta+17

Often modelled with wind tunnels

It doesn’t work

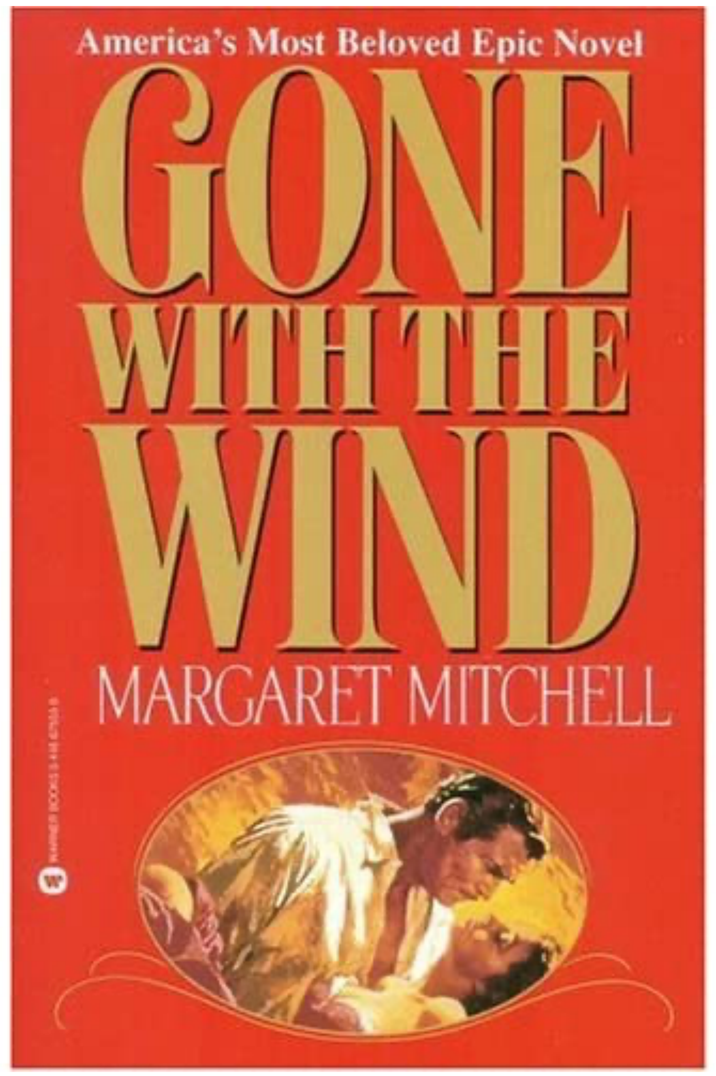


Cloud falling in

isothermal atmosphere

$$t_{\mathrm{cool,mix}} \ll t_{\mathrm{cc}}$$

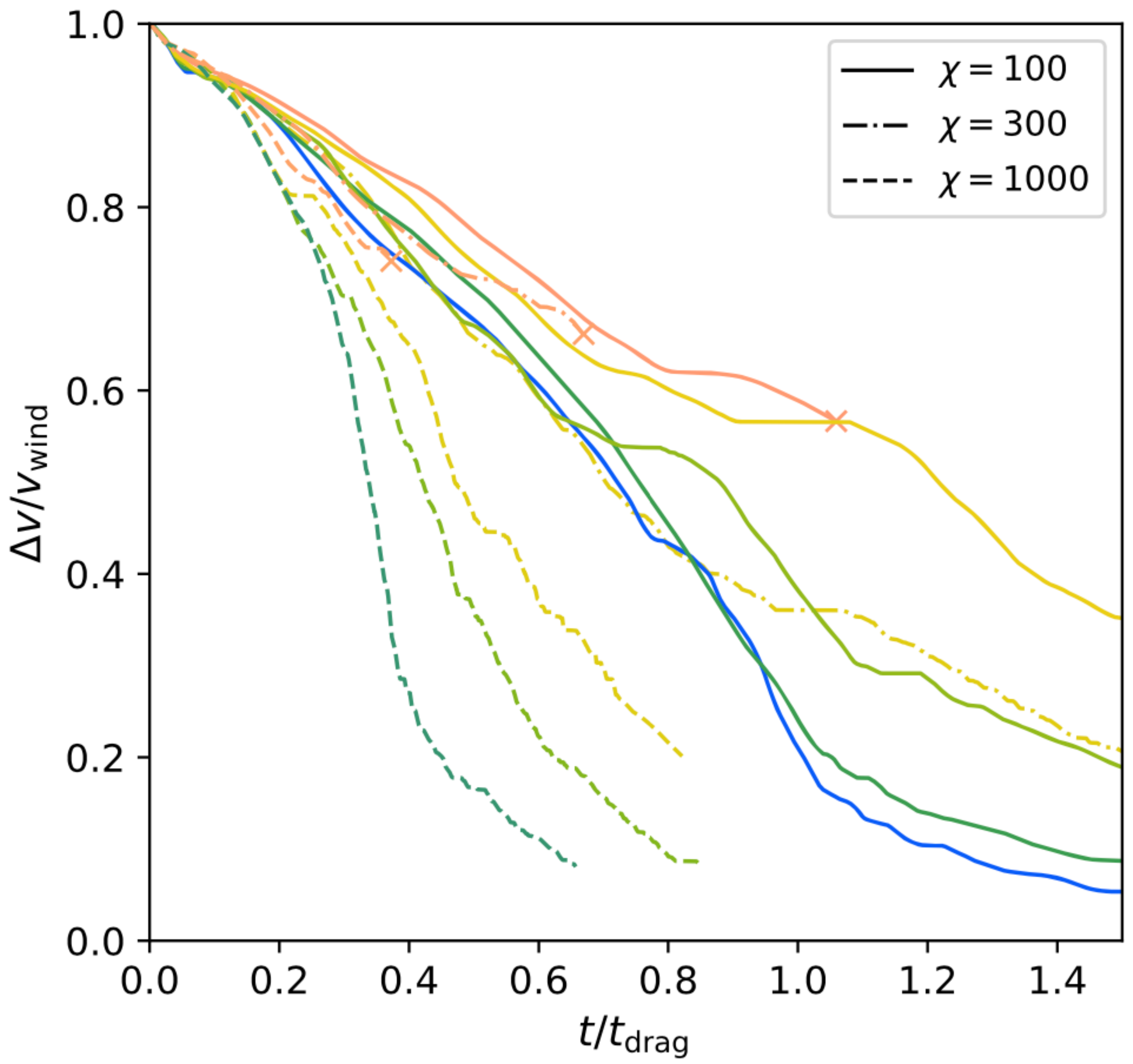
It dies



Why?

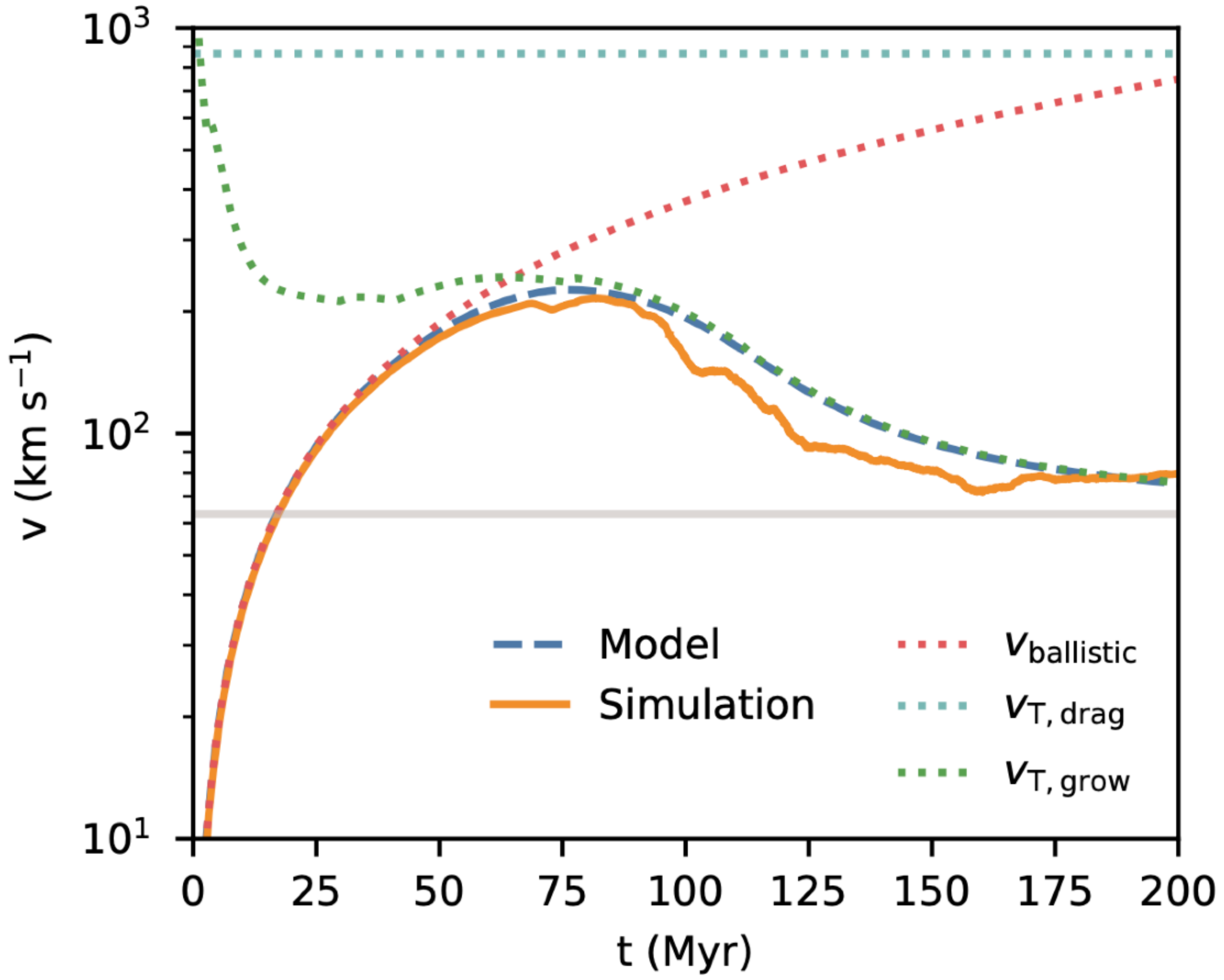
The cloud never entrains. It falls like a rock.

Cloud in a wind



Cloud destruction slows down with time

Falling Cloud

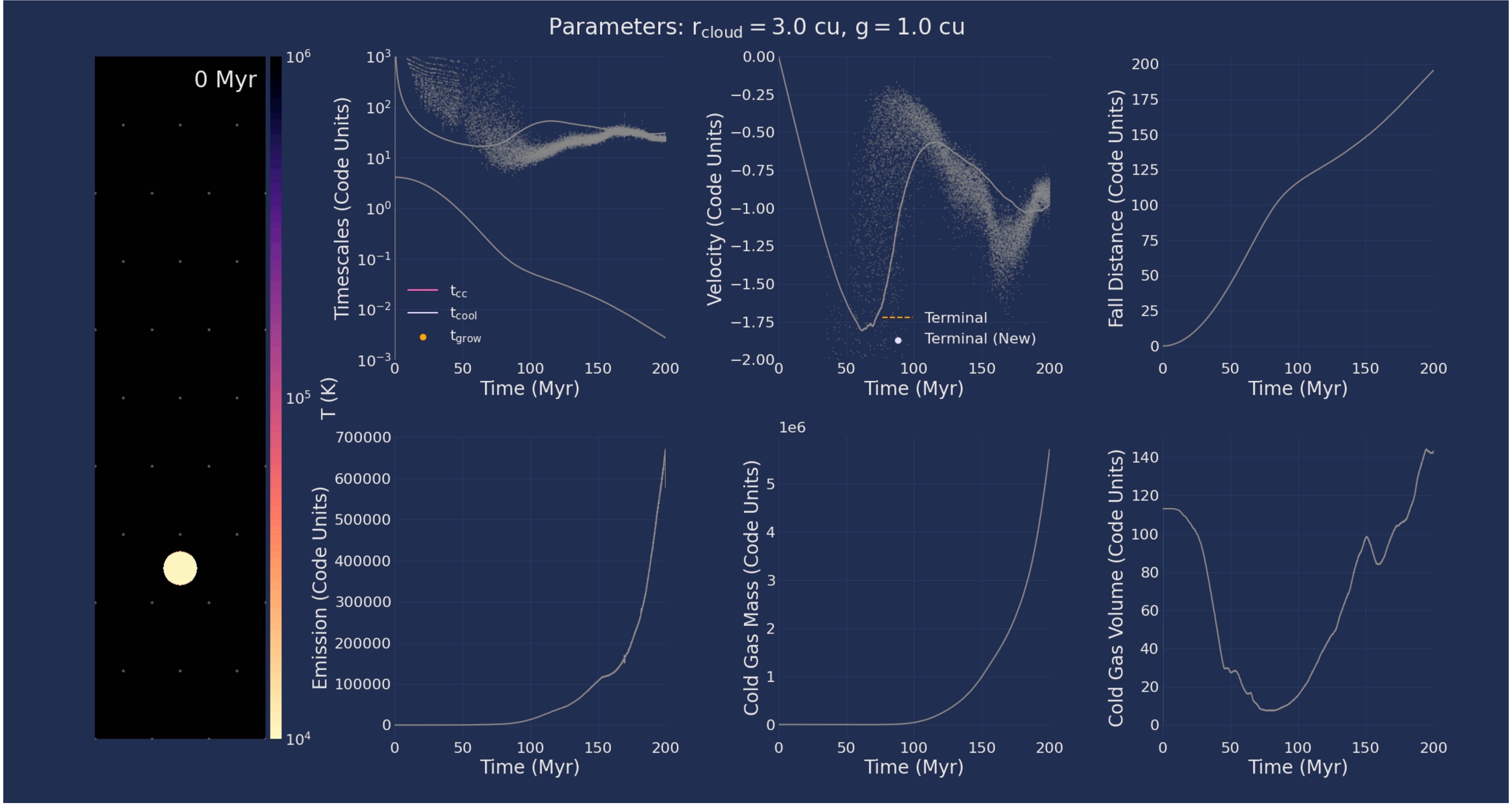


Cloud destruction gets worse with time

Things are going to get a lot worse before they get worse.

— Lily Tomlin —

There's still hope



Decelerates via mixing with hot gas

Reaches lower terminal velocity than with ram pressure!

vanishes when no acceleration

$$\frac{d(mv)}{dt} = \dot{m}v + \cancel{\dot{v}m} = mg - \frac{1}{2}C_0\rho_{\rm hot}v^2A$$

Accretion Drag

Hydrodynamic Drag

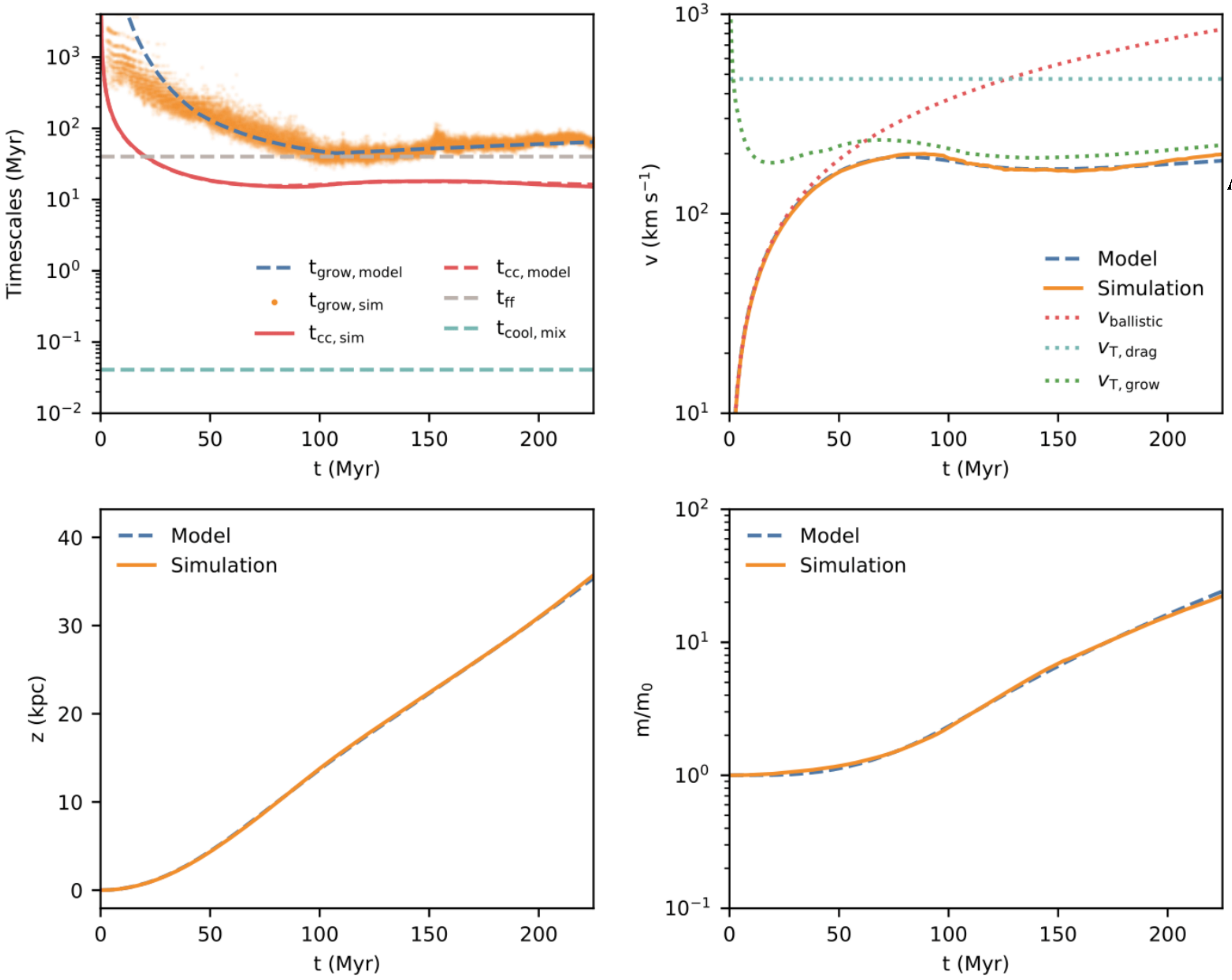
Hydro drag dominates: $v_{\rm T,drag} = \sqrt{\frac{2mg}{\rho_{\rm hot}C_0A}} \simeq \sqrt{\frac{2\chi Rg}{C_0}}$

Accretion drag dominates: $v_{\rm T,cool} = \frac{mg}{\dot{m}} \sim gt_{\rm grow}$

$t_{\rm grow}$ well understood from wind tunnel studies

Cloud Falling in Constant Background

Compare against Analytic Model



Hydro drag terminal velocity

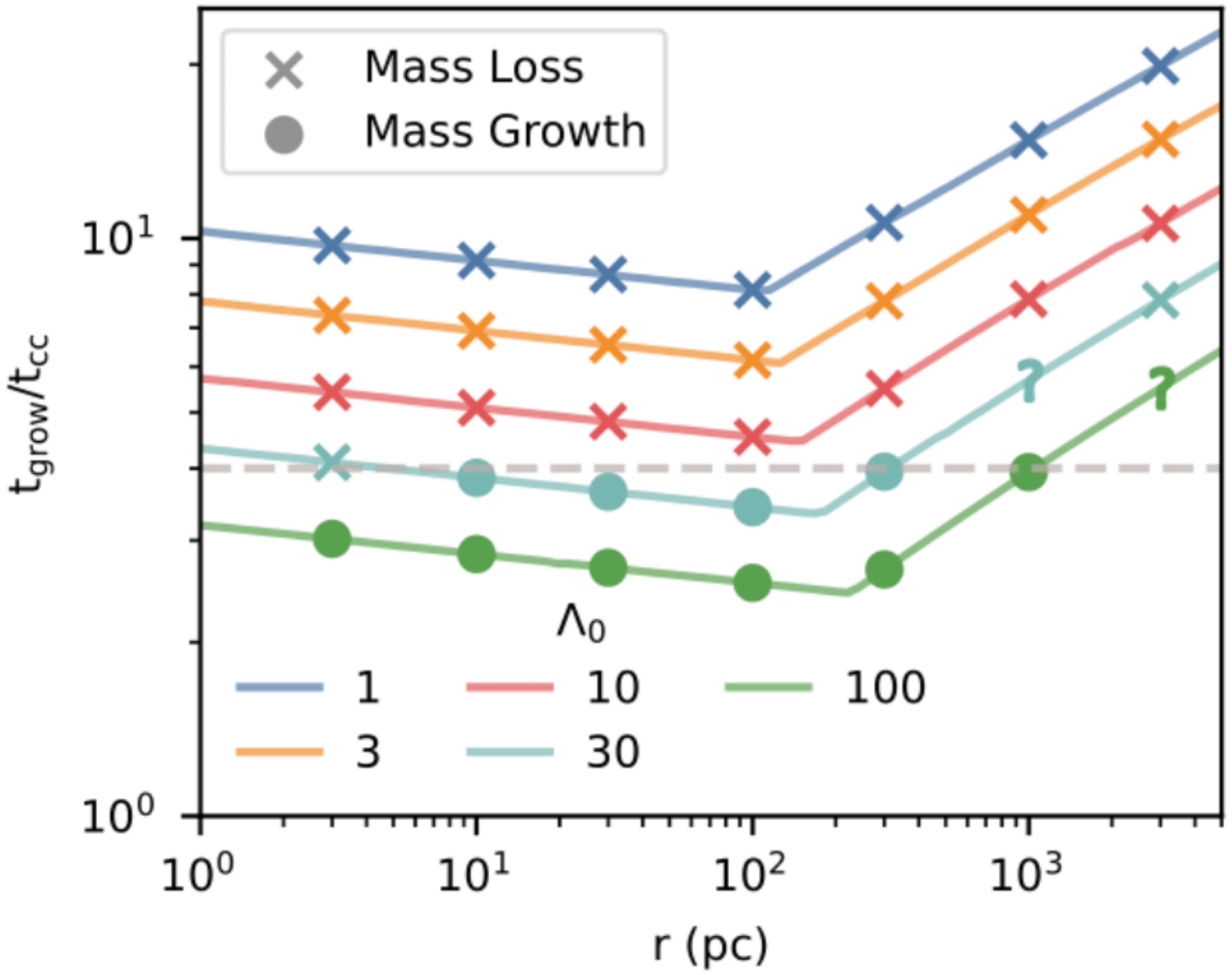
Accretion drag terminal velocity

Model matches sims very well.

Survival Criterion

Cloud must grow faster than it's destroyed

$$t_{\rm grow} < 4t_{\rm cc}$$



For falling cloud in constant background, cloud size does NOT matter!

Different from wind tunnel

$$t_{\rm cool,mix} < t_{\rm cc} \Rightarrow r > r_{\rm crit} \sim \frac{v_{\rm wind} t_{\rm cool,mix}}{\sqrt{\chi}}$$

Equivalent to:

$$t_{\mathrm{cool,mix}} < 0.1\,\mathrm{Myr}\left(\frac{g}{10^{-8}\,\mathrm{cm/s^2}}\right)^{-4/5}$$

$$P > 3000\,\mathrm{k}_B\,\mathrm{K\,cm^{-3}}\left(\frac{g}{10^{-8}\,\mathrm{cm/s^2}}\right)^{4/5}$$

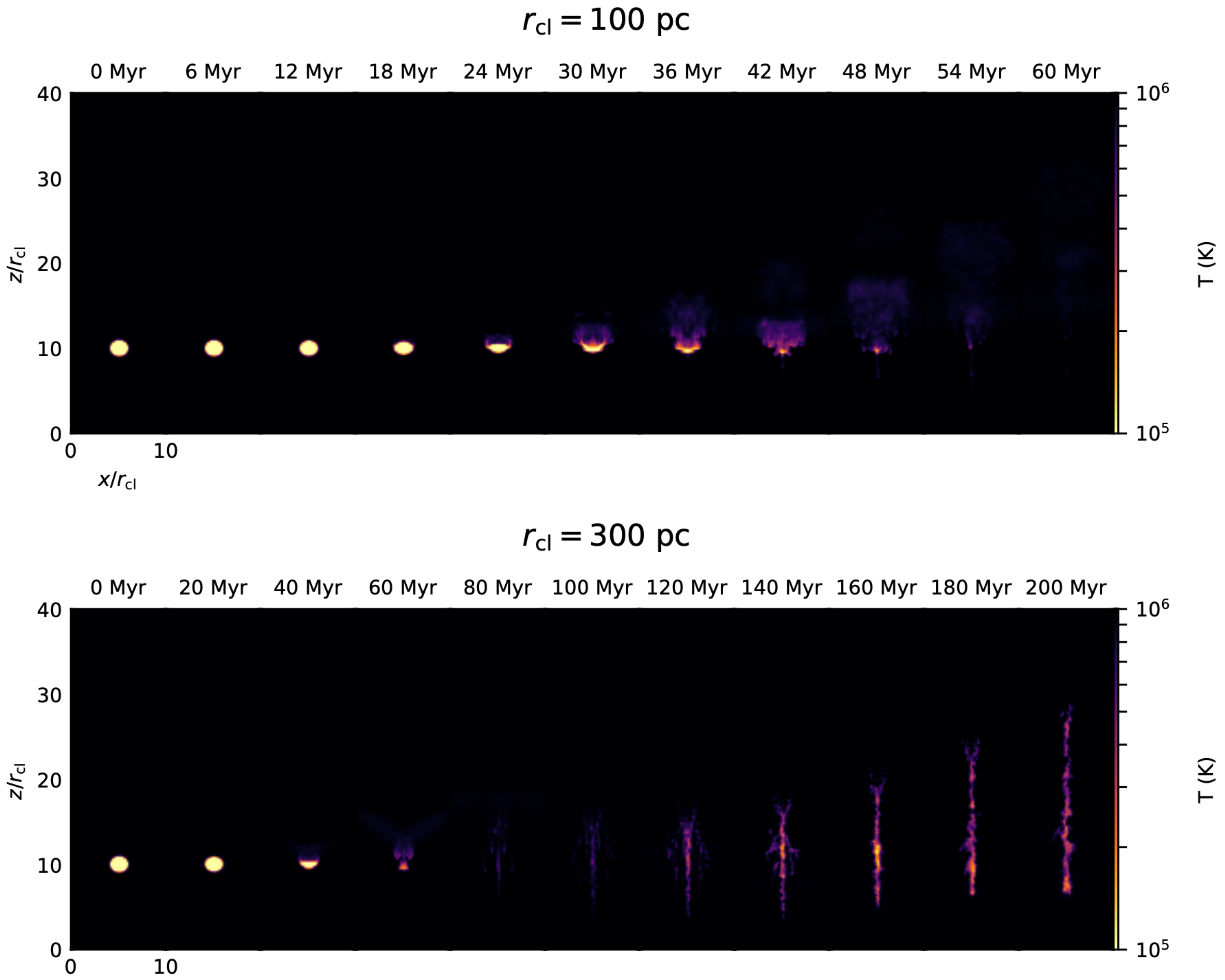
$$\frac{t_{\mathrm{cool,hot}}}{t_{\mathrm{ff}}} < 1$$ in planar geometry (just like thermal instability!)

Accretion braking is efficient where thermal instability takes place

So, the cold gas you make in TI survives

In Stratified Halo, size does matter

You have to survive famine before you can feast



Cloud must be big enough to survive until reach dense inner halo, where it can grow

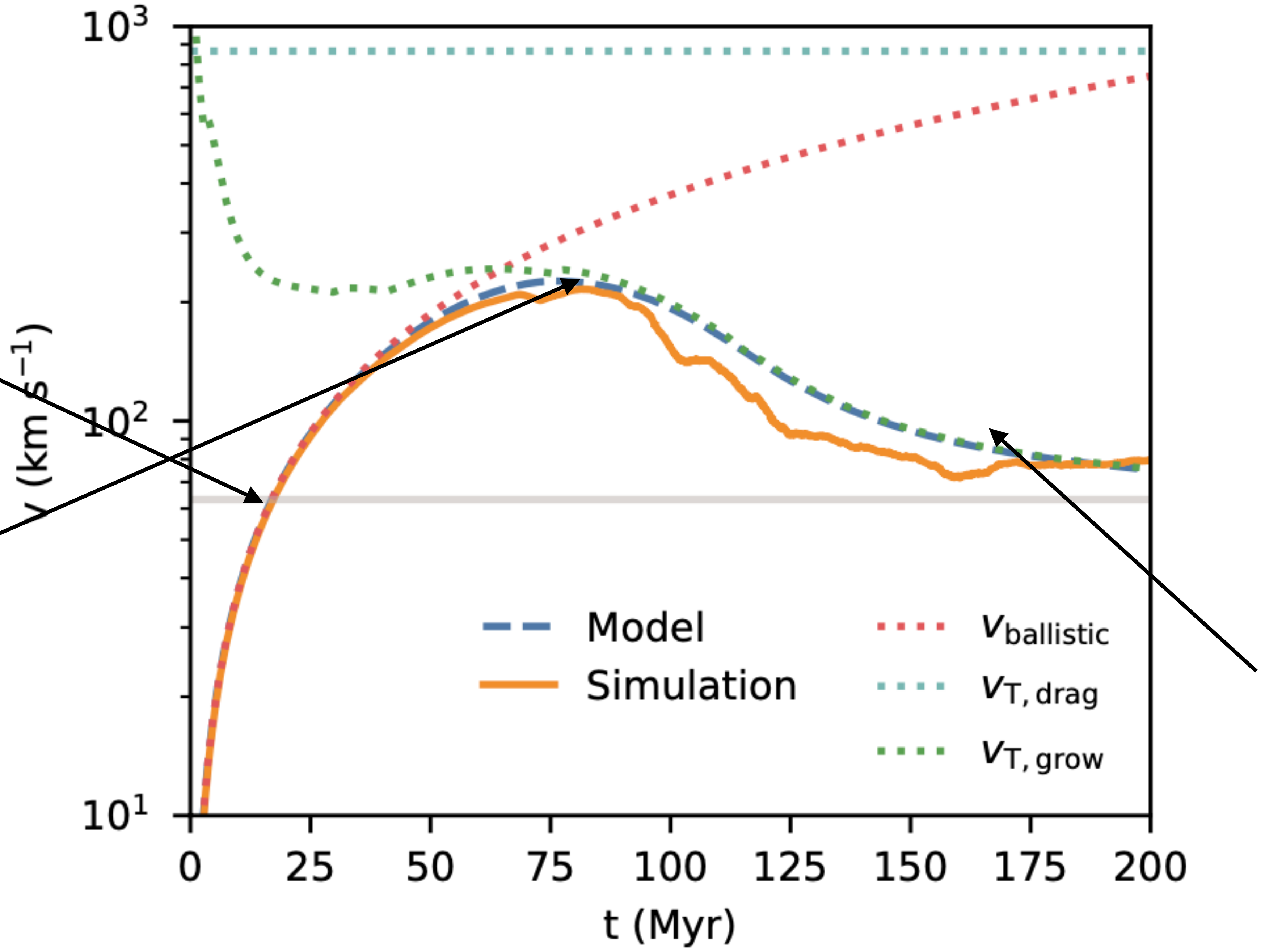
$$\frac{t_{\rm cc}}{t_{\rm ff}} > \alpha \sim 7$$

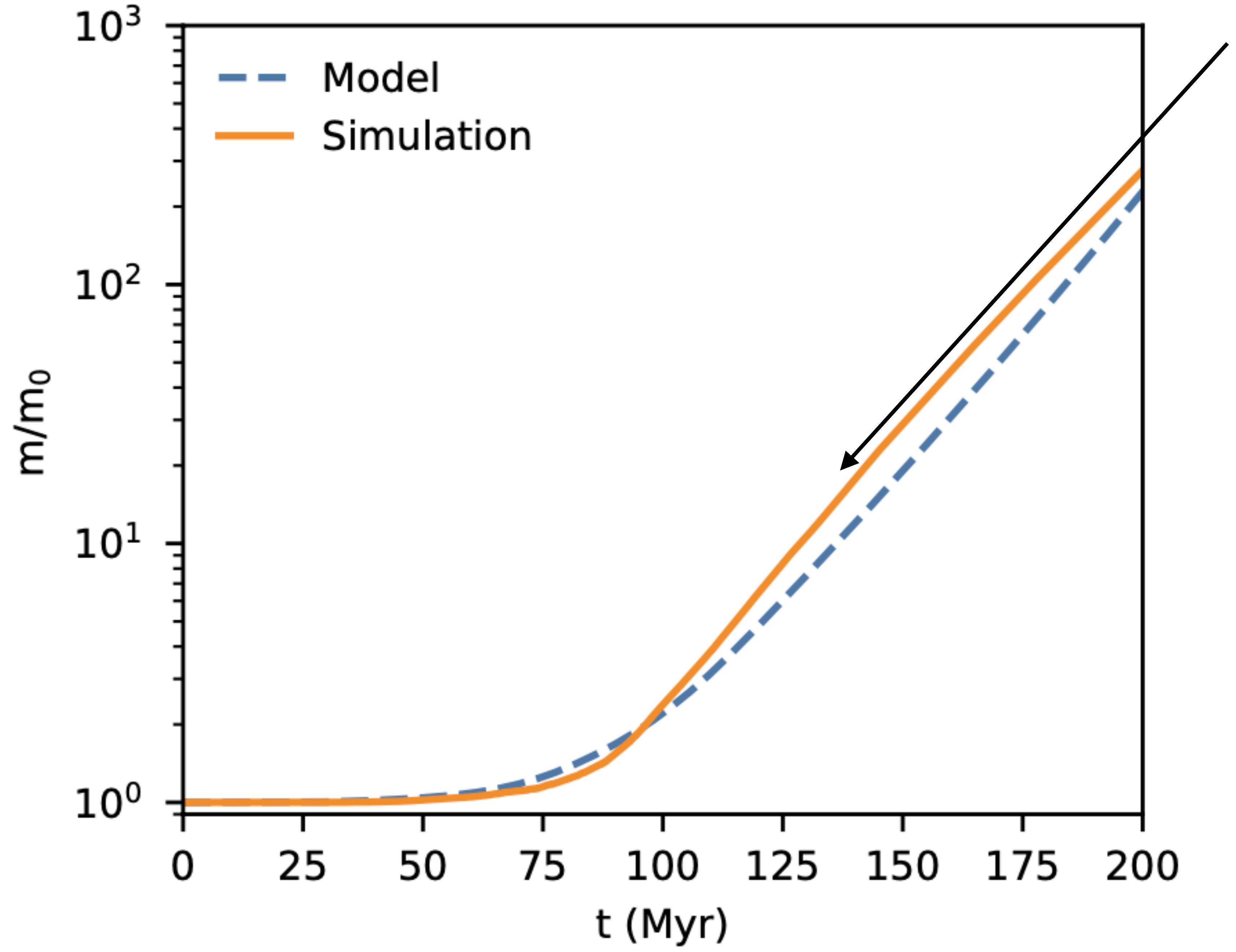
Falls ballistically

in low density CGM

Reaches dense region:

the parachute opens!





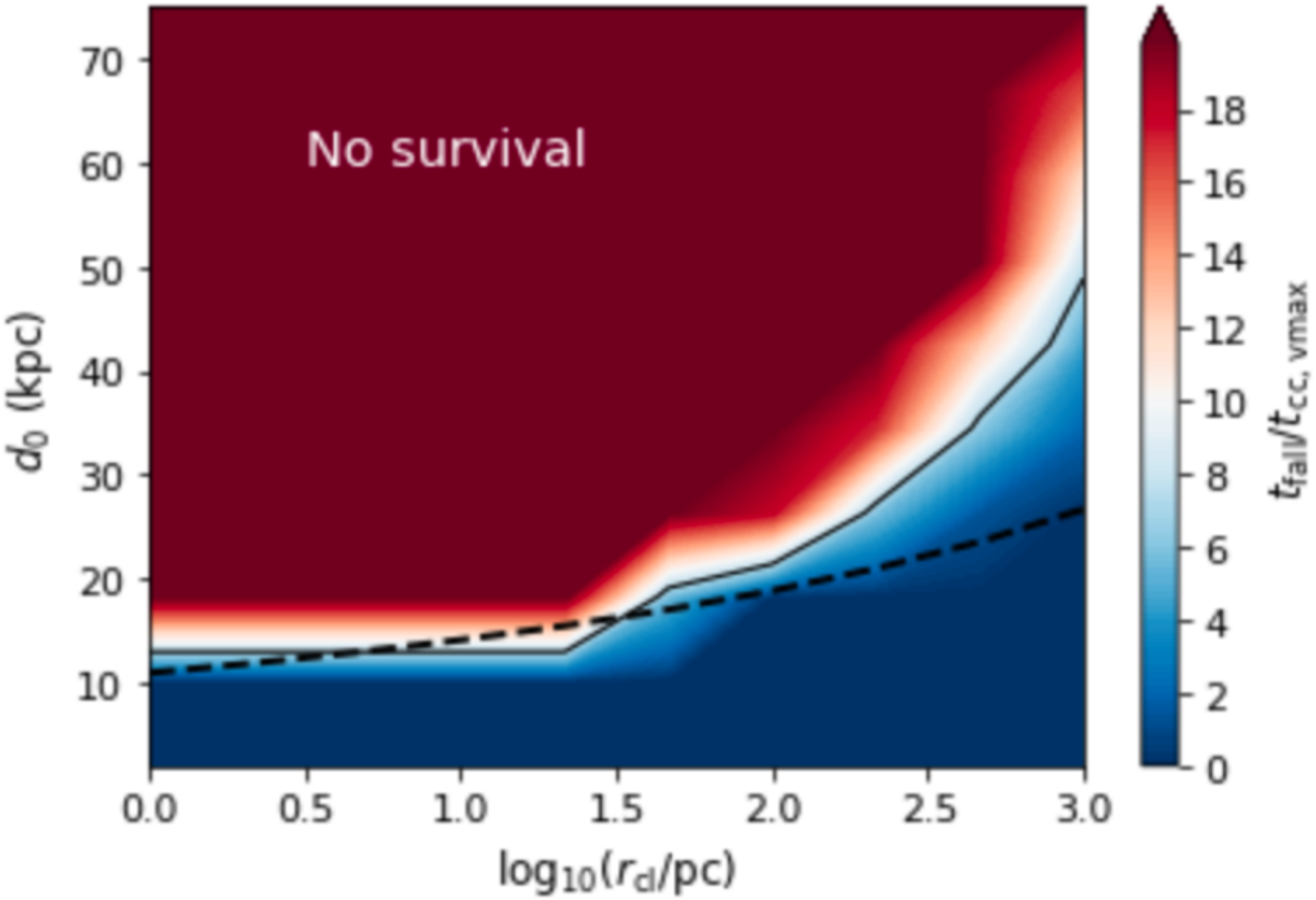
Decelerates

to terminal

velocity

and grows

in mass



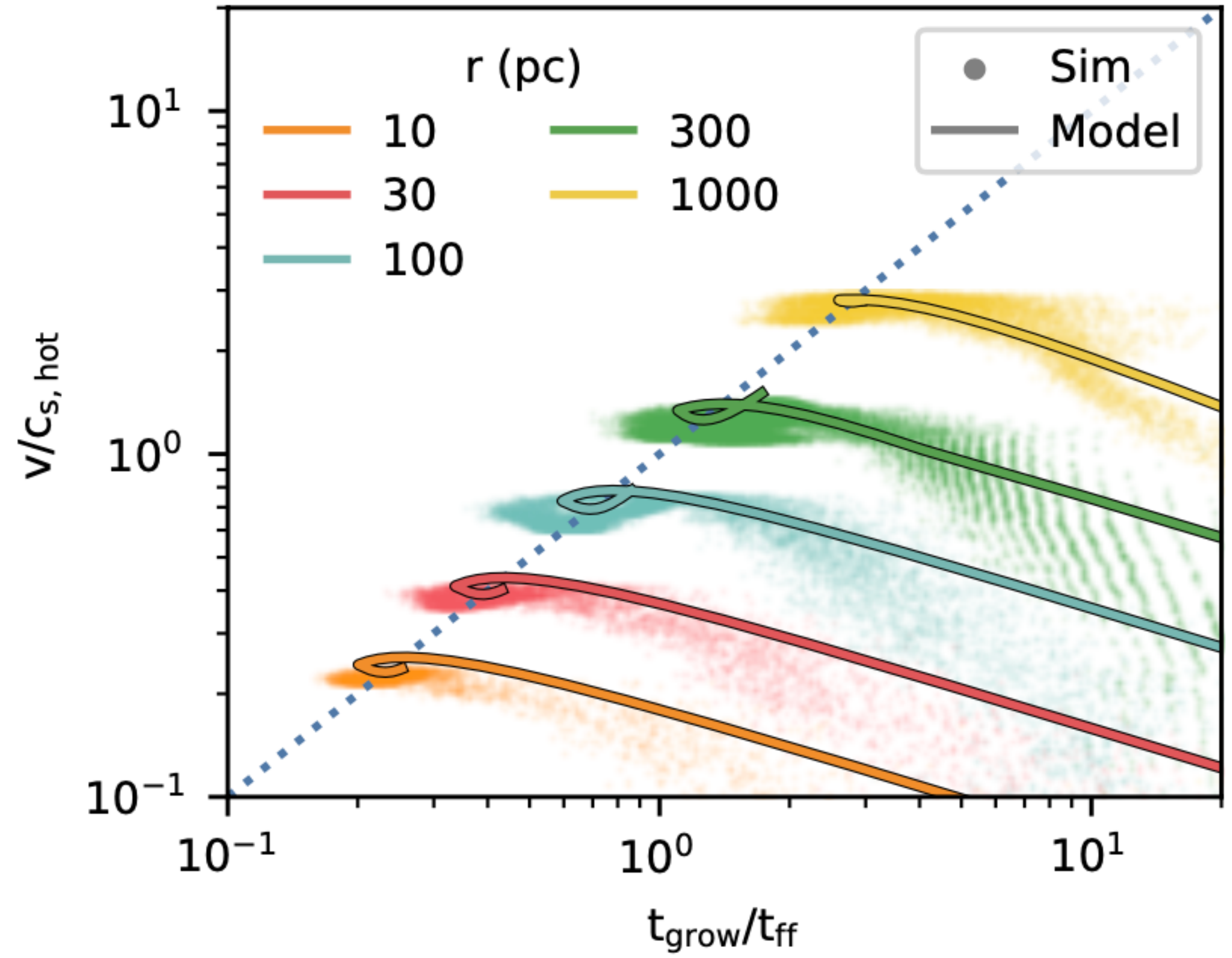
Near Milky Way (< 10 kpc), clouds of any size can survive and grow

Clouds falling from CGM need fat reserves until they reach the food shelter

Subvirial infall

If the parachute opens, you fall slowly

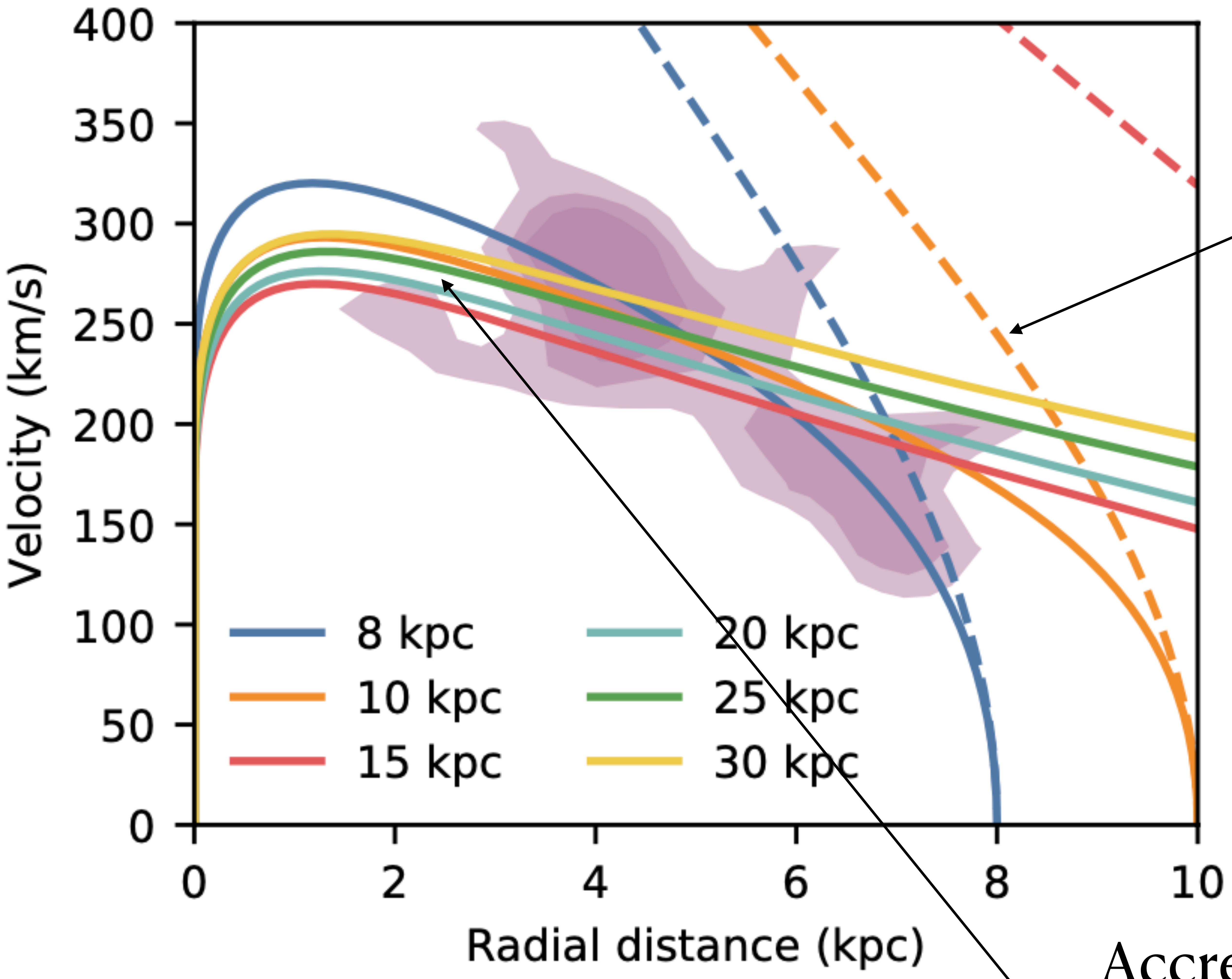
$$v_\mathrm{T} \sim g t_\mathrm{grow} \sim \left(\frac{v_\mathrm{vir}}{t_\mathrm{ff}}\right) t_\mathrm{grow} \Rightarrow \frac{v_\mathrm{T}}{v_\mathrm{vir}} \sim \frac{t_\mathrm{grow}}{t_\mathrm{ff}} < 1$$



Small clouds fall more slowly

And grow more in mass

Fits infall velocities in Perseus A



Standard models: need to fine-tune drop height

Accretion induced braking: velocities independent of drop height

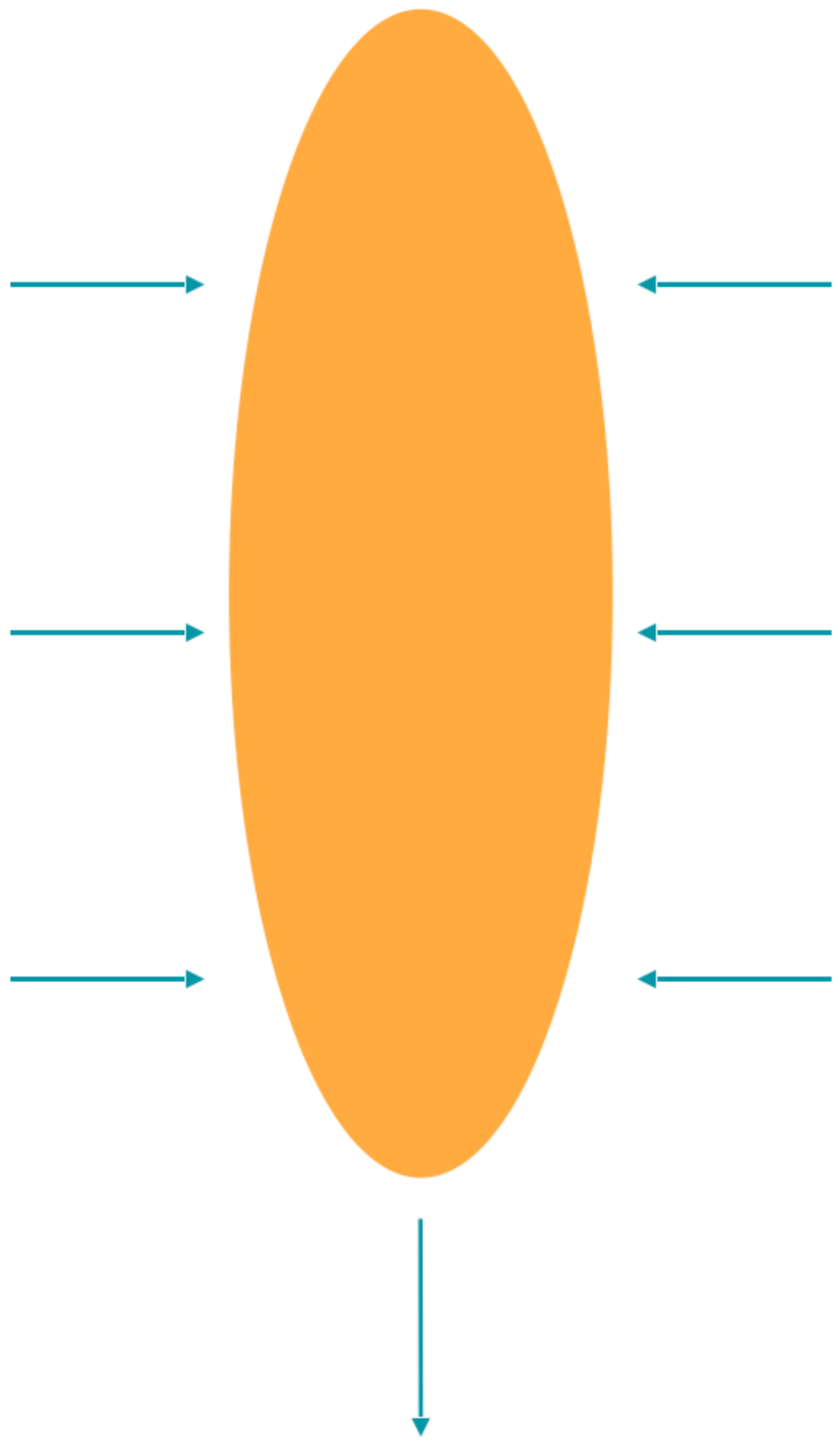
Bottom Line

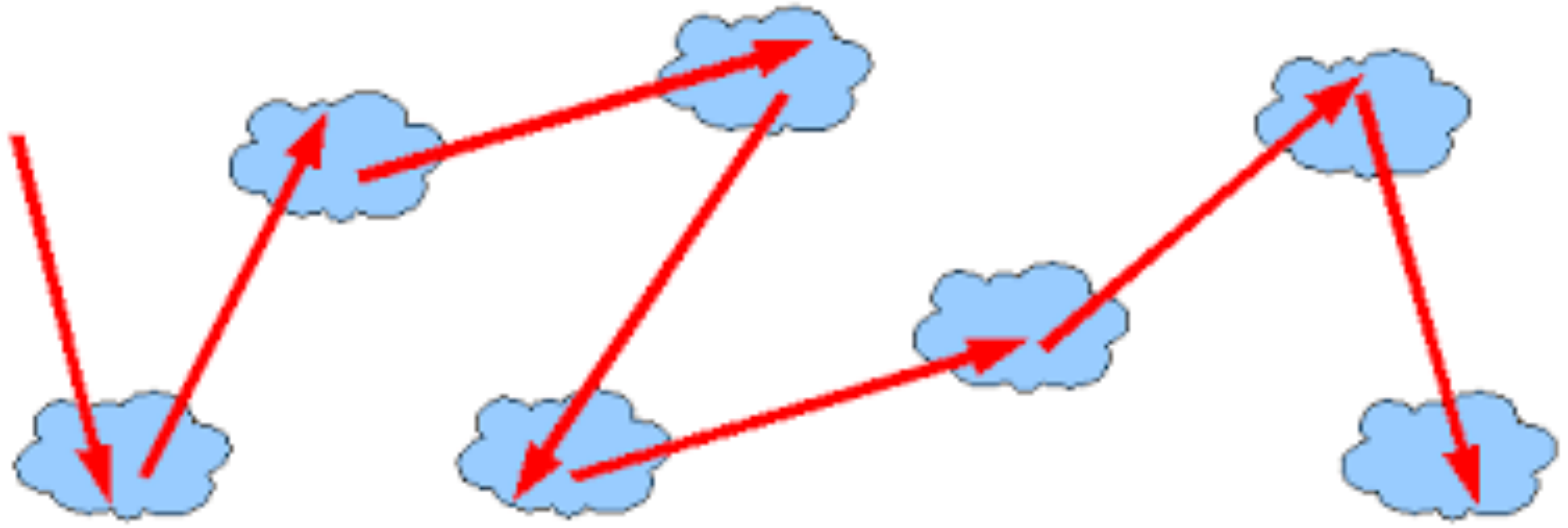
Mix to Decelerate!

- Accretion induced drag is stronger than hydrodynamic drag
- To survive, growth must beat destruction $t_{\rm grow} < t_{\rm cc}$
- Need short cooling times near halo center

- New, subvirial terminal velocity $v_{\rm T} \sim g t_{\rm grow}$

$$\frac{v_{\rm T}}{v_{\rm vir}} \sim \frac{t_{\rm grow}}{t_{\rm ff}} < 1$$



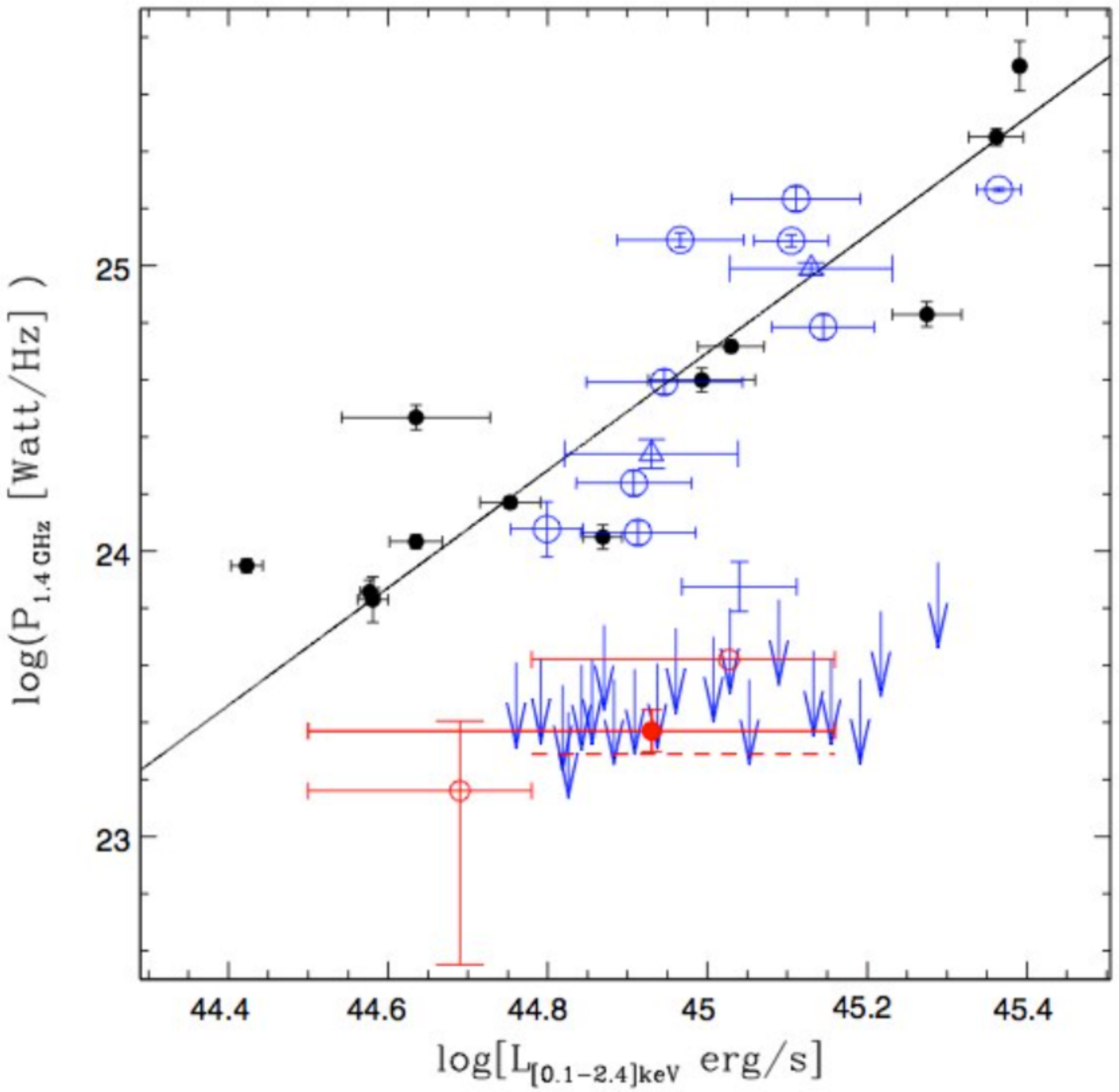


Turbulent Reacceleration of Cosmic Rays

Bustard & Oh 2022a submitted,

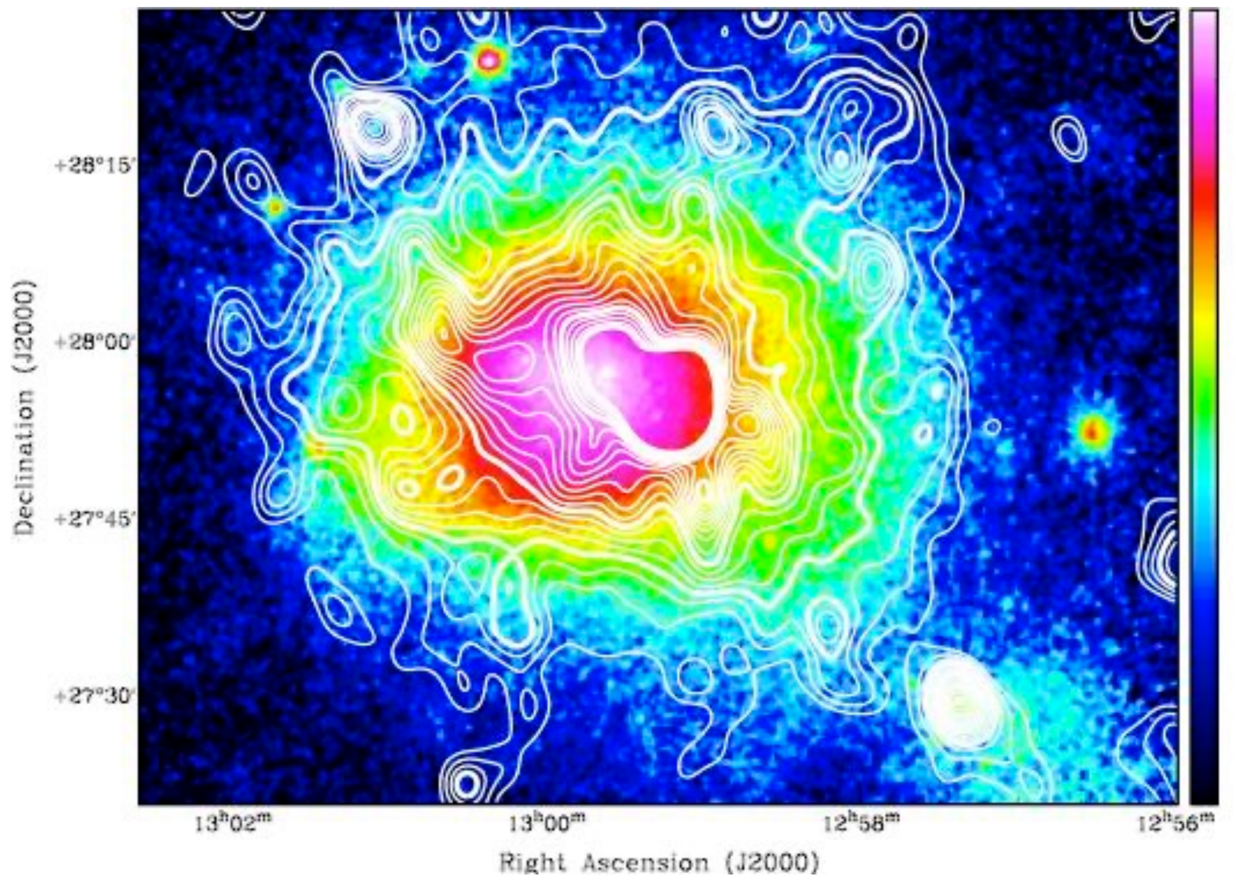
Bustard & Oh 2022b, in prep

Radio Halos: CR turbulent reacceleration in action



Brown et al 2011
Brunnetti et al 2009

They are either ON
or OFF



ON: recent or ongoing merger

OFF: Stacked images show faint emission (Brown et al 2011)

There's actually two kinds

Resonant and non-resonant

- **Resonant:** (transit-time damping)

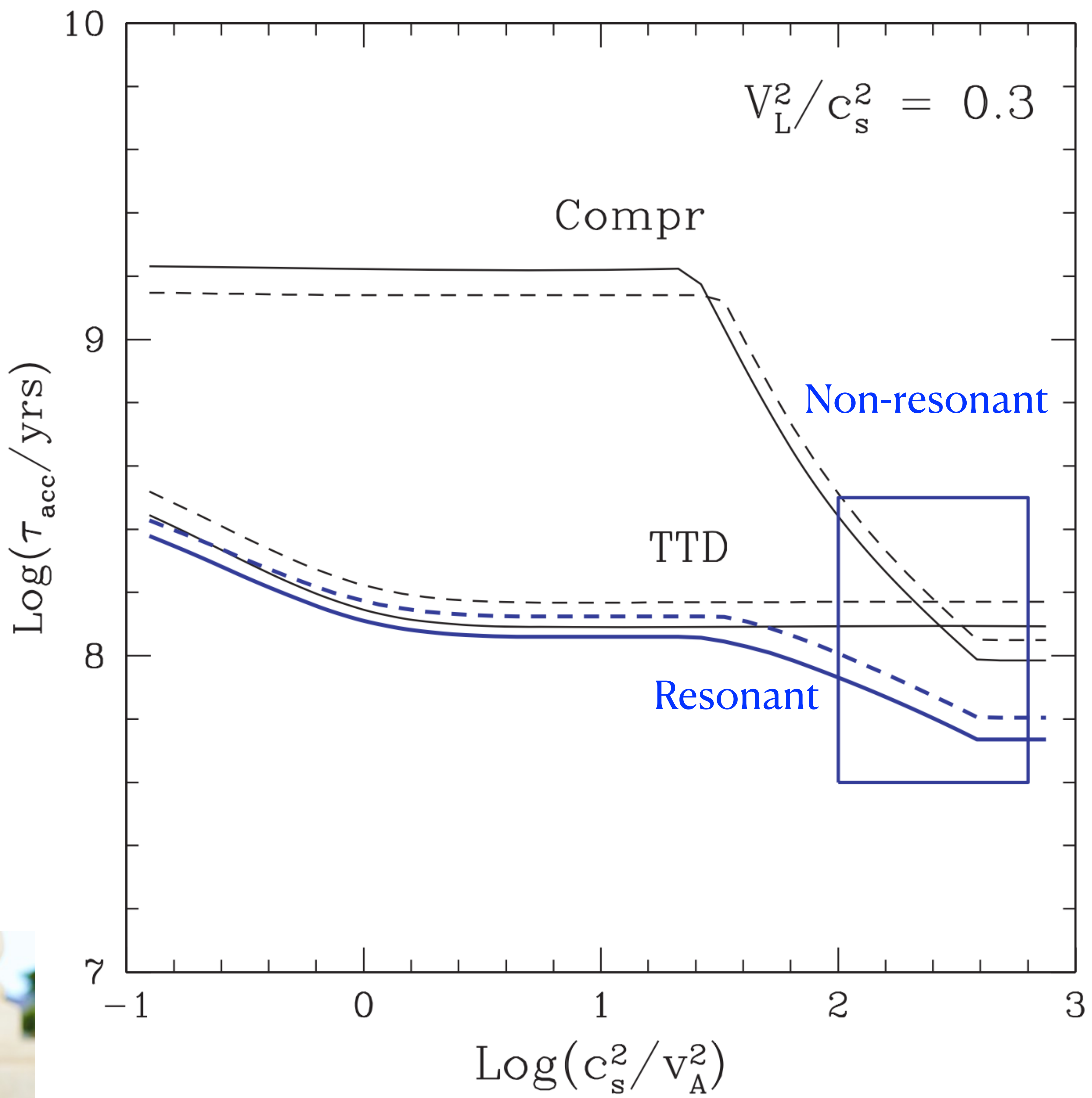
  — small scale resonance between wave period and particle transit time $\omega = k_{\|} v_{\|}$

- characteristic scale: damping scale of fast modes

- Sensitive to uncertain fast mode power spectrum slope and damping

- Complicated. Impossible to simulate. The glamor boy.

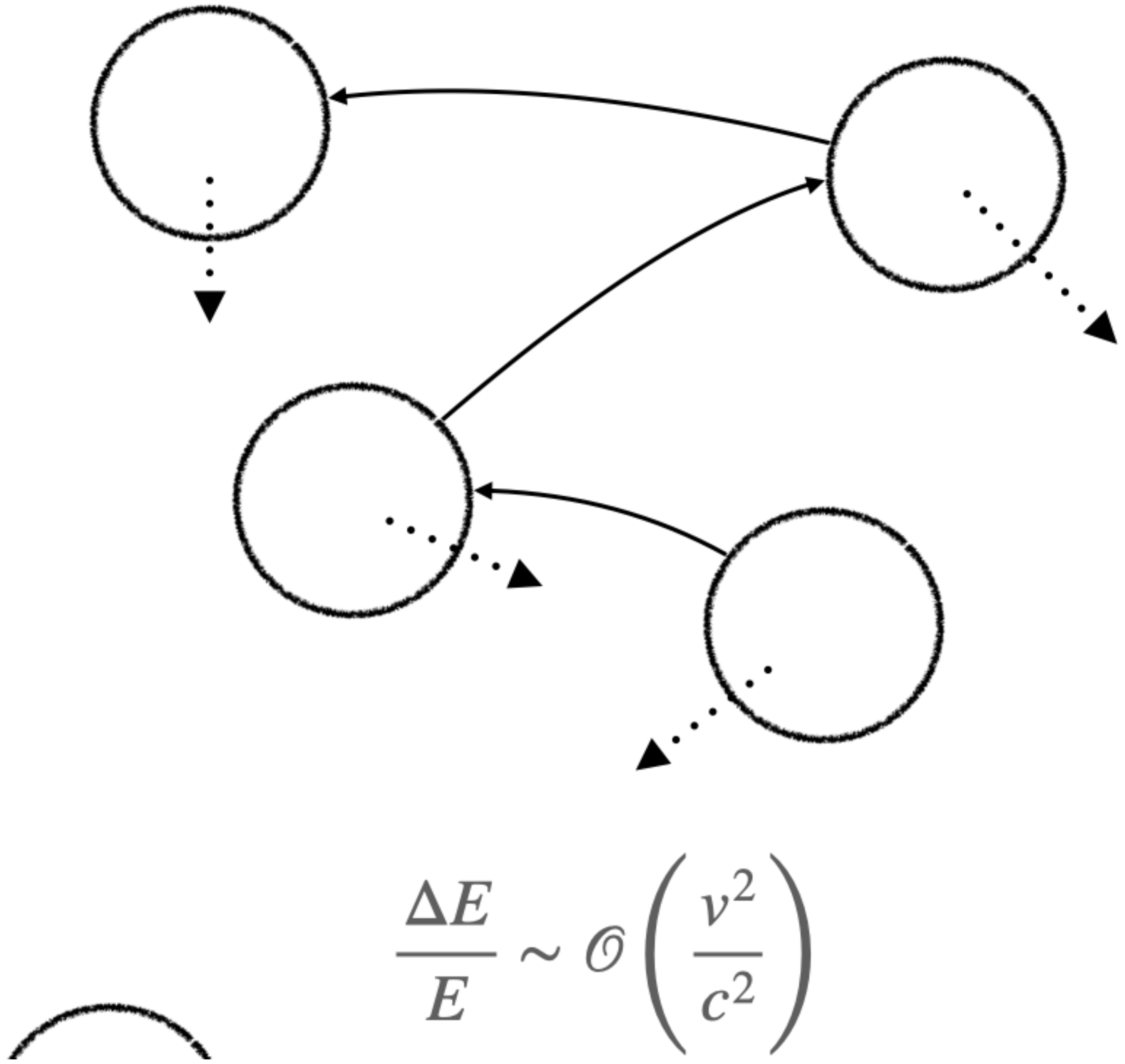
- Also needed in our galaxy to scatter E> 300 GeV cosmic rays



Brunetti & Lazarian 2007

- **Non-resonant:** Large scale Fermi-II acceleration, in presence of diffusion
- Characteristic scale: outer eddy scale
- CRs get energy from compression, then diffuse out
- Simple, robust.
- Analytic estimates never tested in hydro sims! Neglected. The unwanted child.

Turbulent Reacceleration
(2nd order Fermi)



$$\frac{\Delta E}{E} \sim \mathcal{O}\left(\frac{v^2}{c^2}\right)$$

Motivation

- Test analytic predictions for non-resonant reacceleration in modern hydro sims.
- What is the effect of **CR streaming** on acceleration?
- What is the **backreaction** of CR reacceleration on MHD turbulence?

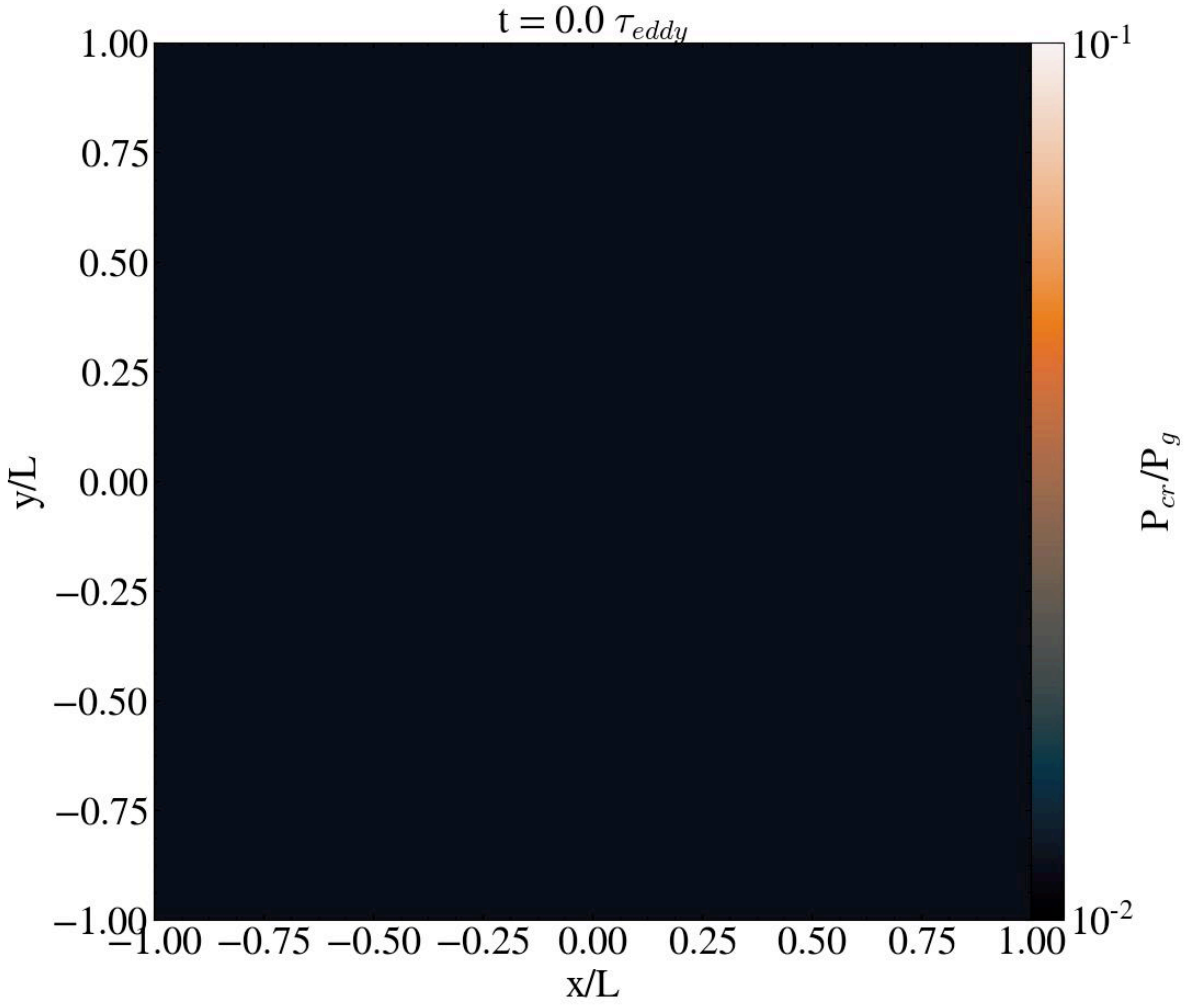
The Setup

3D Athena MHD simulations

Driven compressive, subsonic turbulence

Field-aligned CR diffusion + streaming

2 moment CR code (Jiang & Oh 2018)



Diffusive Acceleration

Sims match canonical expectations (Ptuskin 1988)

Growth peaks when

$$t_{\rm sc} \sim t_{\rm diffuse} \Rightarrow \kappa \sim 0.2 L_0 v_{\rm ph}$$

This is lifetime of compression

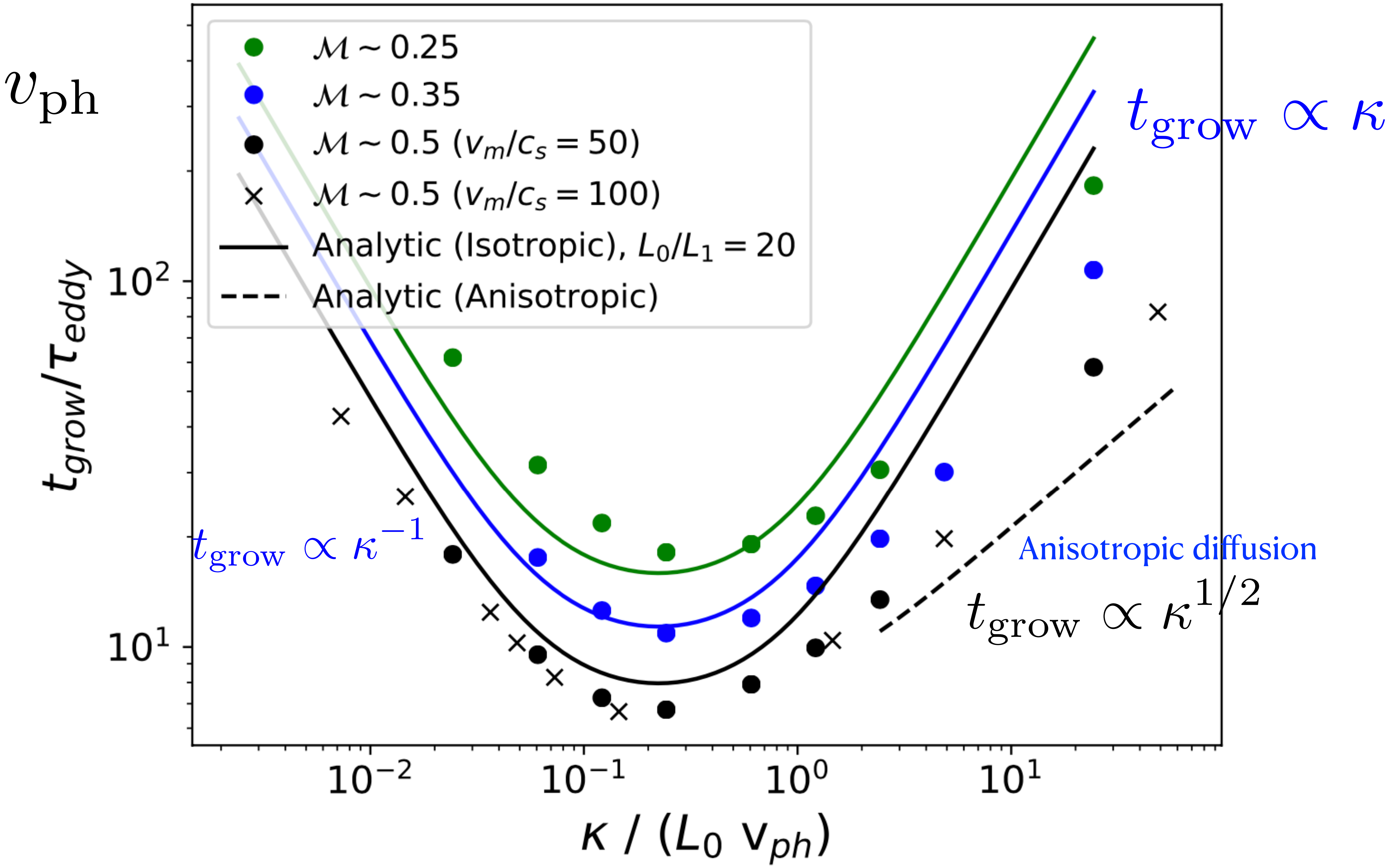
(not $t_{\rm eddy}$)

With anisotropic diffusion,

CRs trapped longer — acceleration

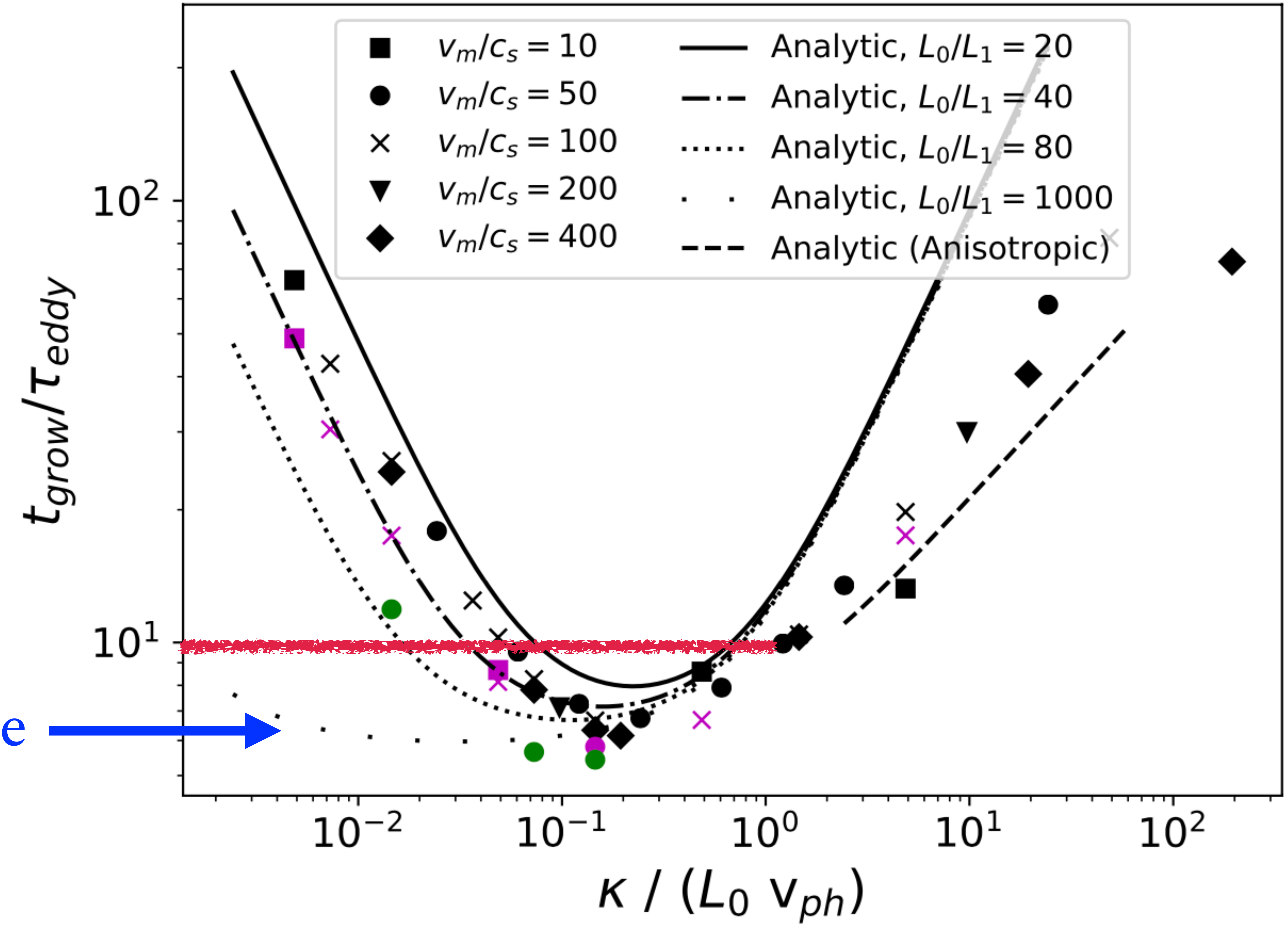
more efficient

(Chandran & Maron 2004)



For $\kappa \ll L_0 v_{\mathrm{ph}}$

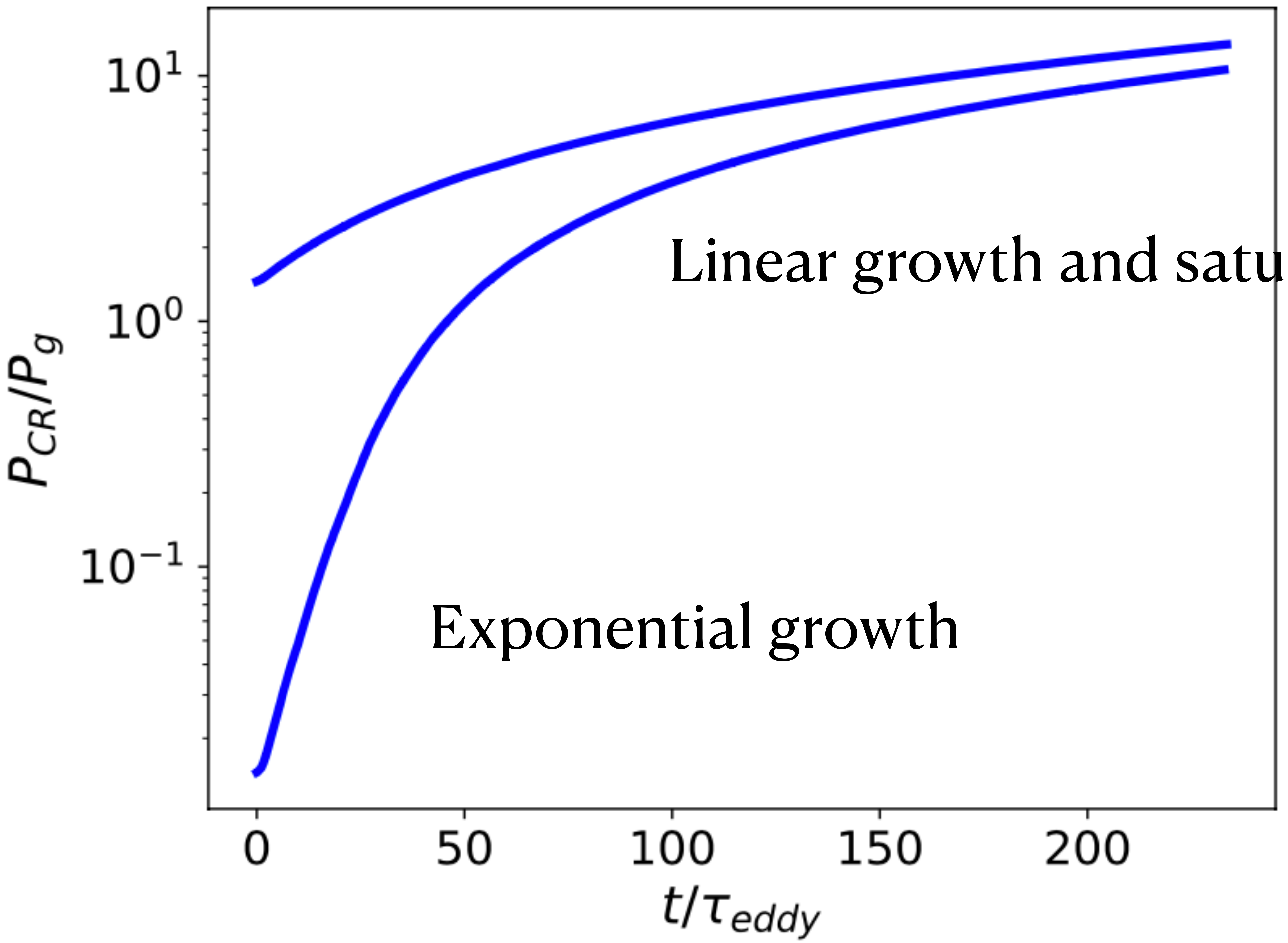
smaller eddies accelerate CRs better —resolution dependent, need more inertial range



analytics with full inertial range →

Over 3 decades in $\frac{\kappa}{L_0 v_{\mathrm{ph}}}$ we have $t_{\mathrm{grow}} \sim 5 - 10 \ \ t_{\mathrm{eddy}}$

Similar to turbulent dynamo

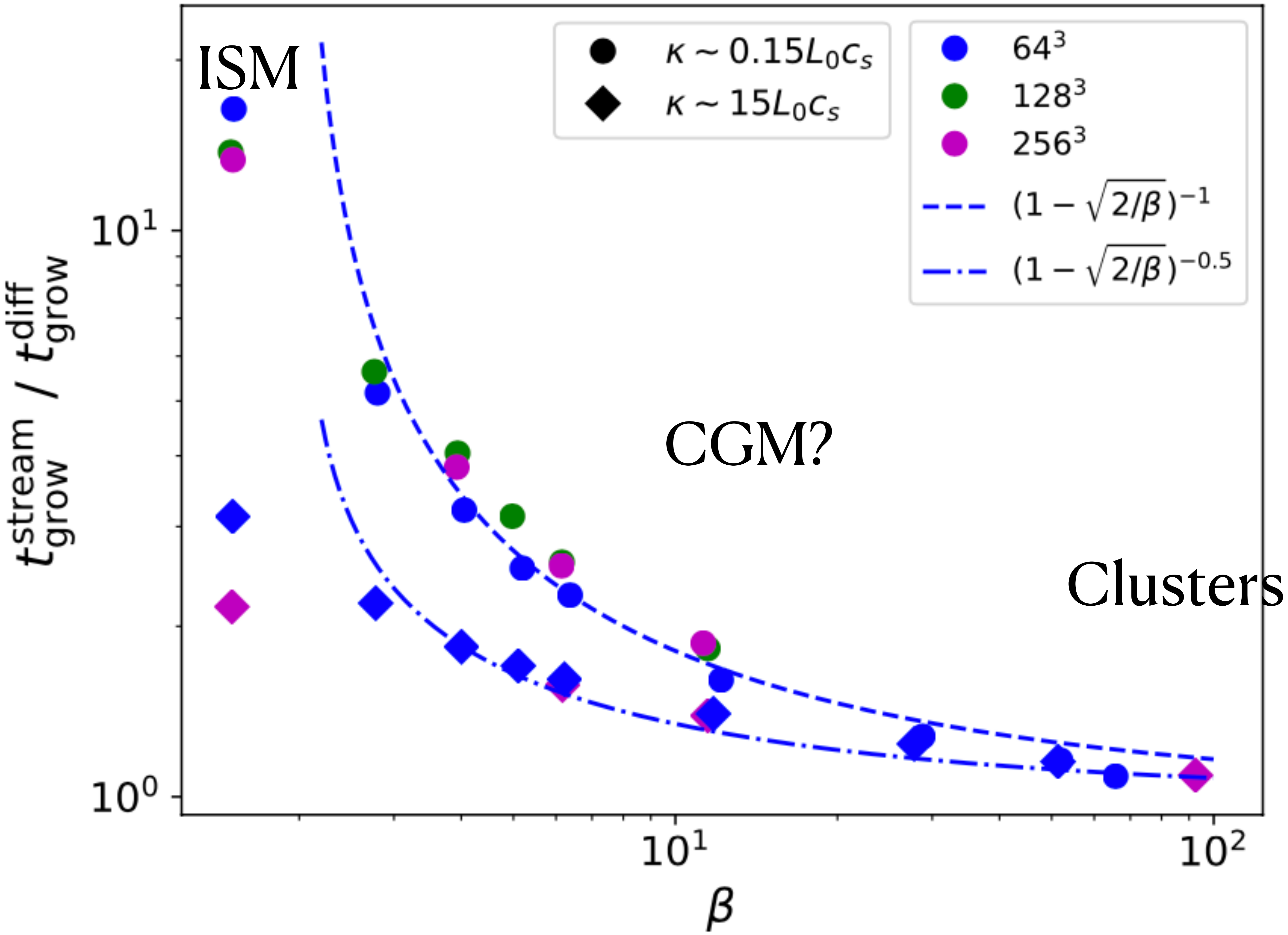


Linear growth and saturation

Exponential growth

Streaming Slows Things Down

Acceleration is weak for strong B-fields (fast streaming)



It's just because of streaming losses, right?

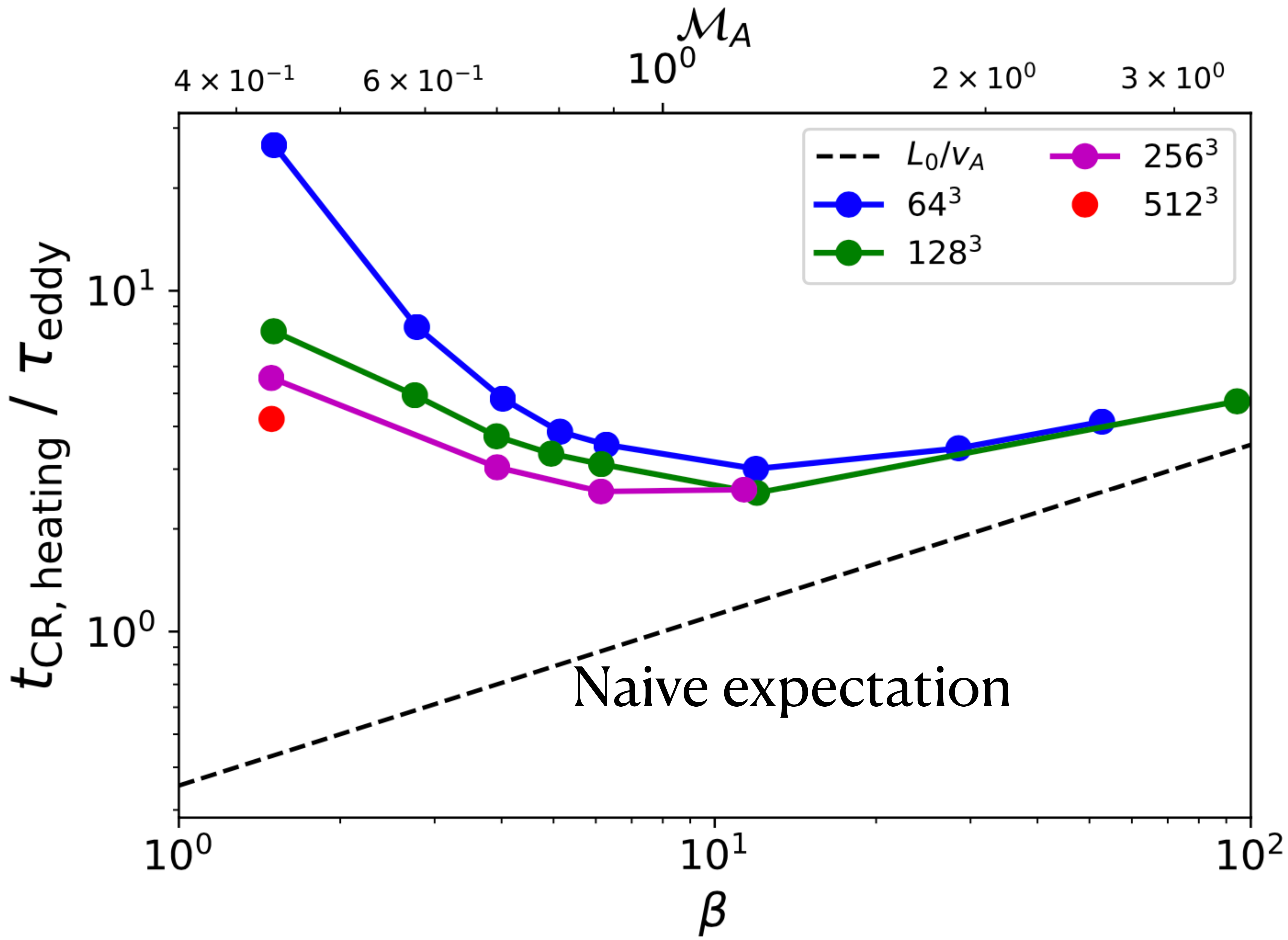
$$v_{\rm A} \cdot \nabla P_c$$

No, it's bcos of phase shifts due to streaming

$$F_c \propto P_c \quad \text{(streaming)}$$

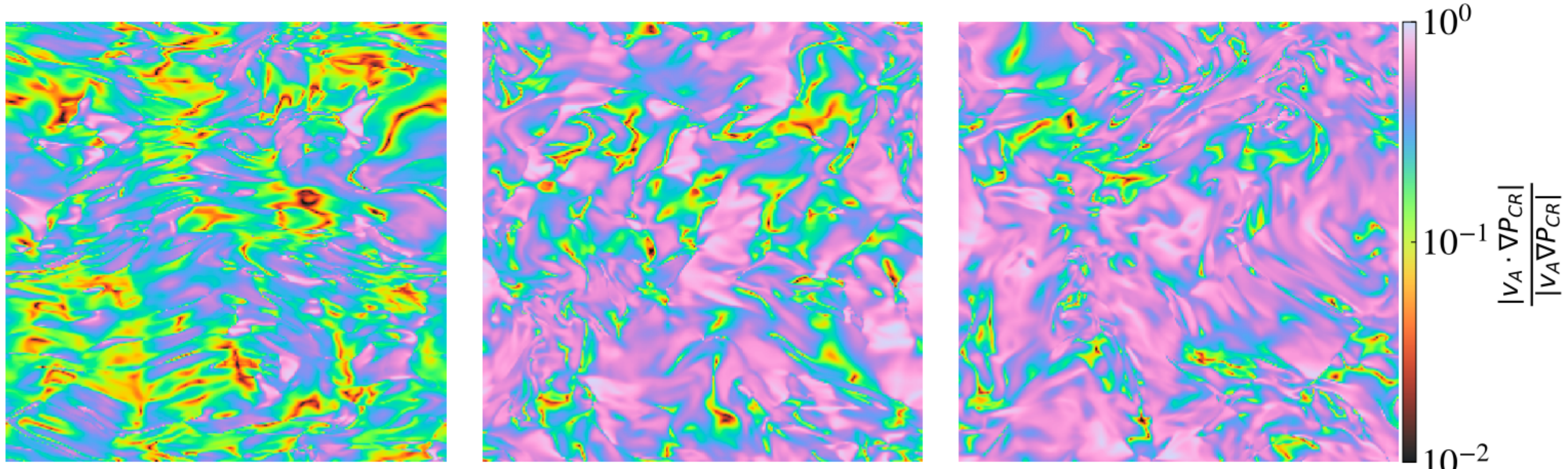
$$F_c \propto \nabla P_c \quad \text{(diffusion)}$$

Heating is almost independent of B-field!



Misalignment between B-fields and compression when B-fields are strong

$$v_A \cdot \nabla P_c$$



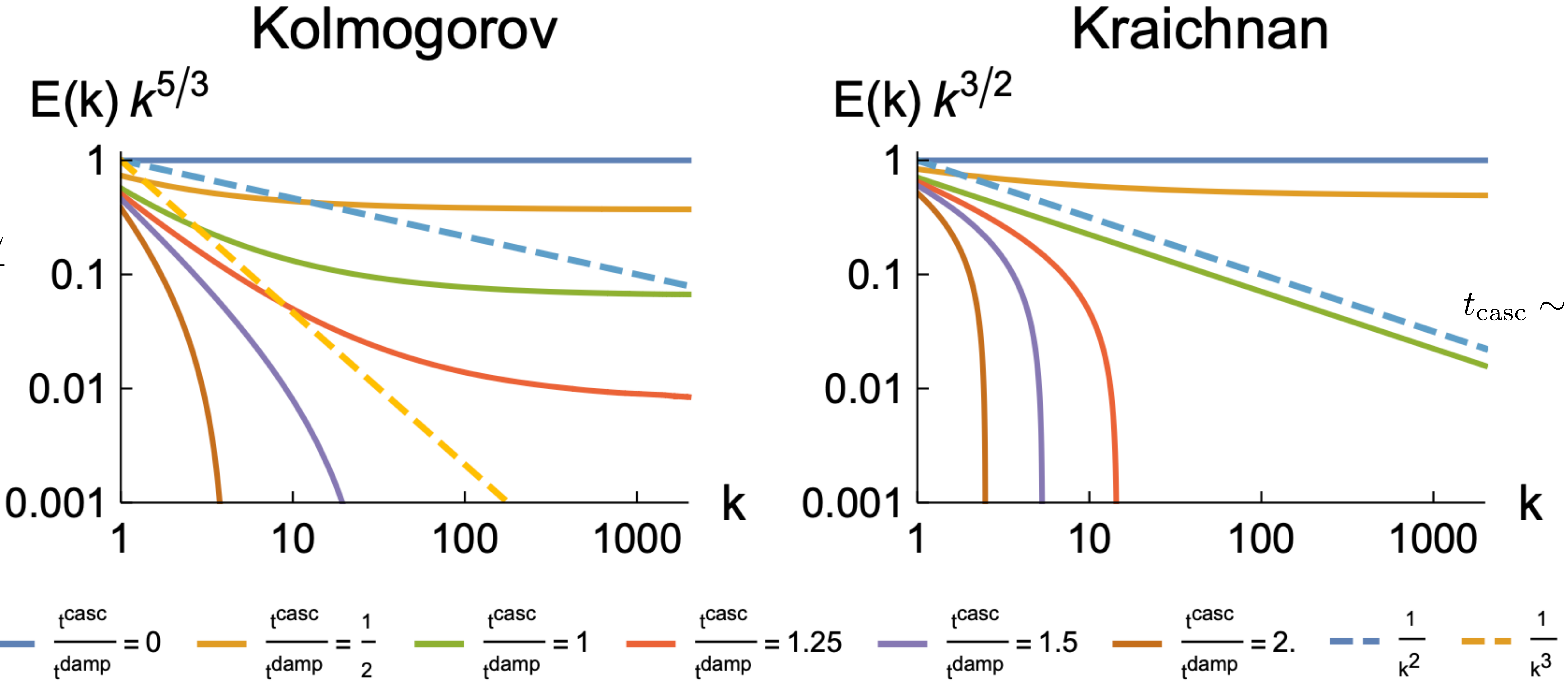
Resolution dependent

Effect missing in large scale sims

Cosmic Rays Damp Turbulence

$$\epsilon\ \delta(k-k_{\mathrm{L}}) = \frac{\partial}{\partial k}F(k) + \Gamma(k)E(k)$$

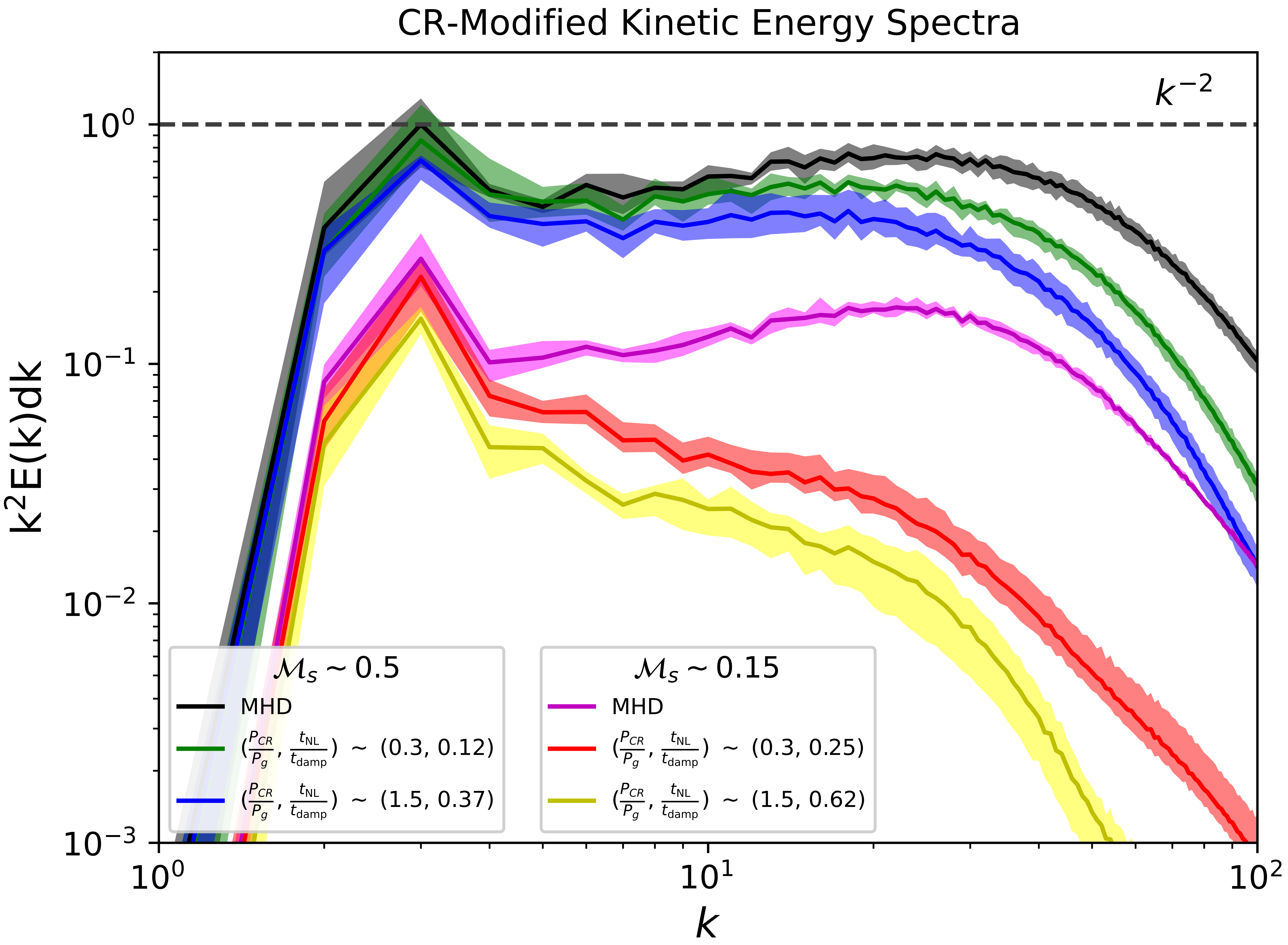
$$t_{\mathrm{casc}} \sim \frac{L}{v}$$



$$t_{\mathrm{casc}} \sim \frac{Lv_{\mathrm{ph}}}{v^2}$$

Depends on ratio of cascade time to damping time $t_{\mathrm{damp}} \sim \rho v^2 \max\left(\frac{\mathrm{t_{grow}}}{\mathrm{P_{CR}}}, \frac{1}{\tilde{\epsilon}}\right) \sim \max\left(\mathrm{M_c^2 t_{grow}}, \mathrm{t_{inject}}\right)$

Simulation Results

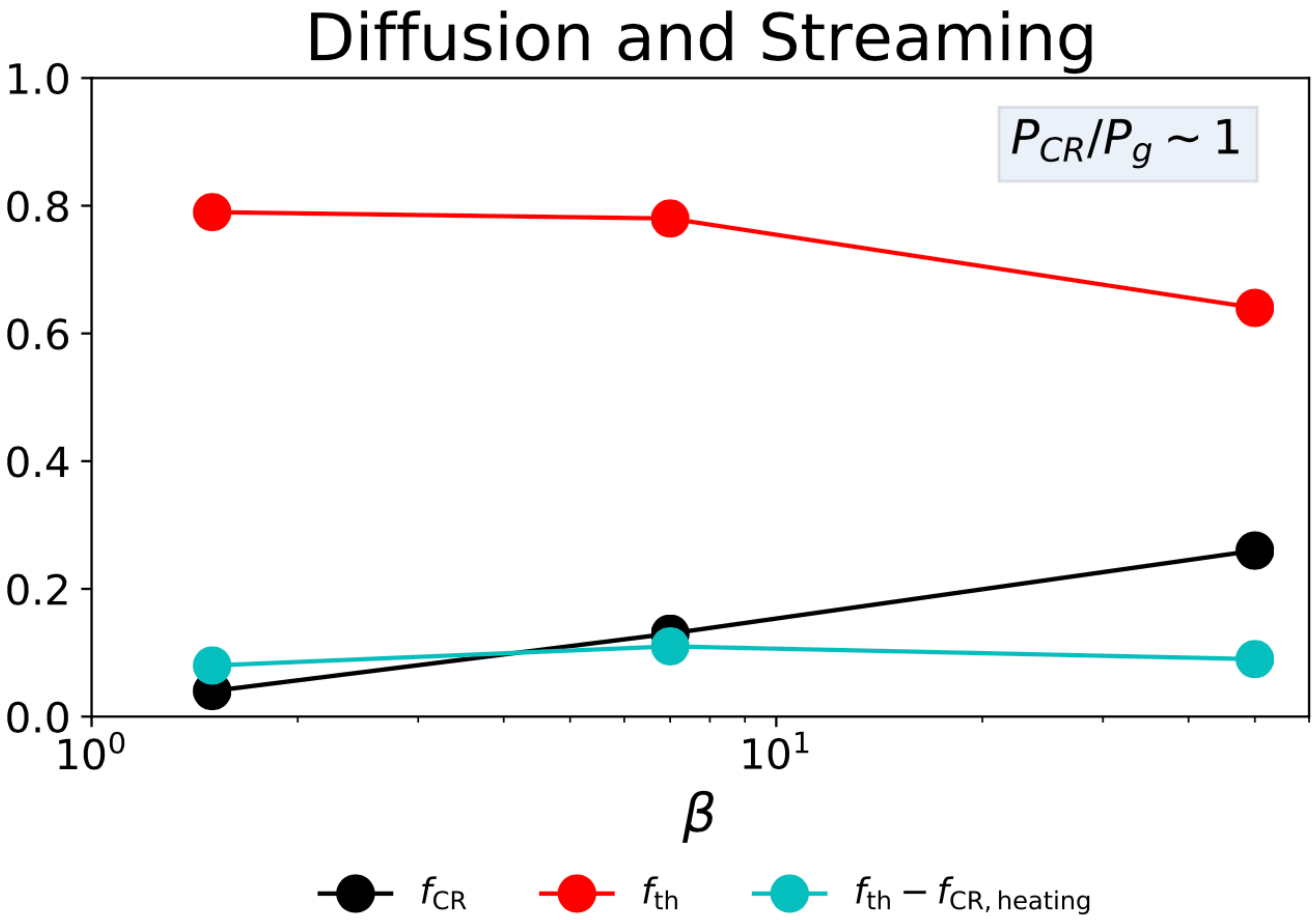


512^3 sims

Diffusion only

Clear signs of damping

— small scales get wiped out



With streaming, gas is mostly heated by CRs

— energy intercepted by CRs before reaching grid scale

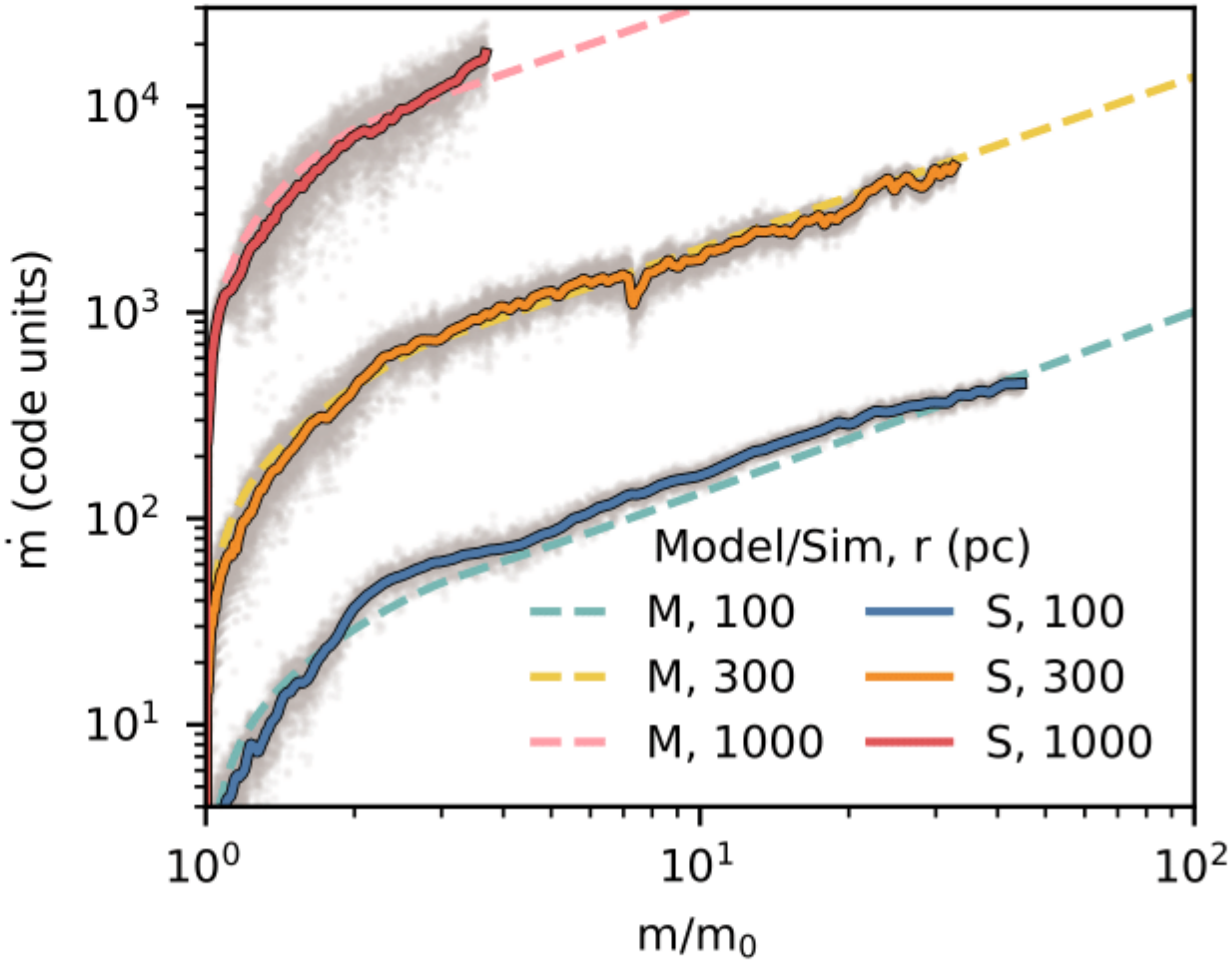
— turbulence damped on small scales.

Implications

- CRs have unusual form of viscosity — kill compressive modes on small scales
- `Divergence cleaning' — removes perturbations for thermal instability?
- Remove small scale fast modes needs to scatter CRs resonantly
- Damping maximized when $\mathcal{M}_{\rm s} < \dfrac{P_c}{P_{\rm tot}}$

Might not be important in ICM, but important in CGM

MASS GROWTH RATE

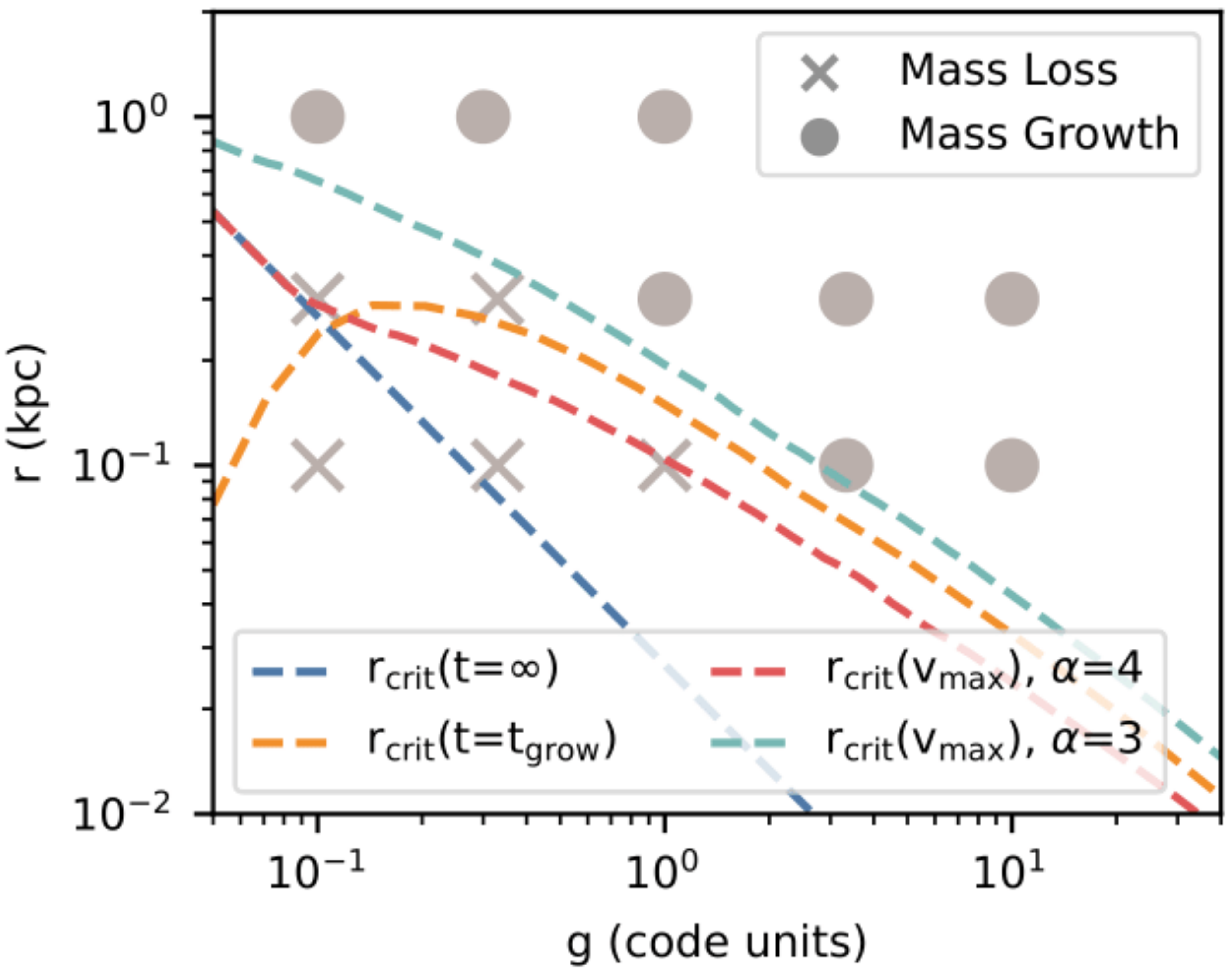


$$A_{\mathrm{cloud}} \approx A_{\mathrm{cloud},0} \left(\frac{m}{m_0}\right)^{\alpha}$$

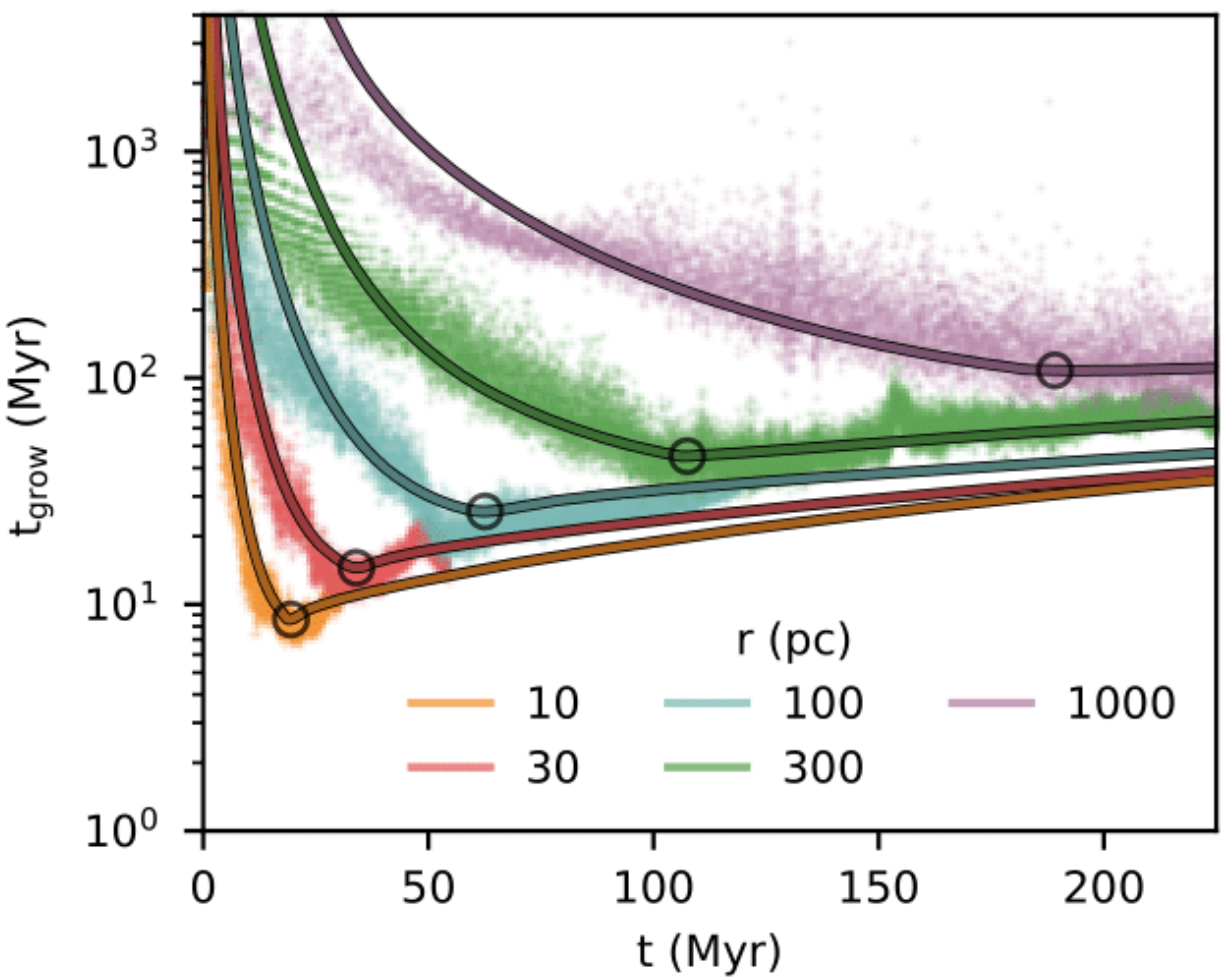
$\boxed{\alpha = 5/6}$

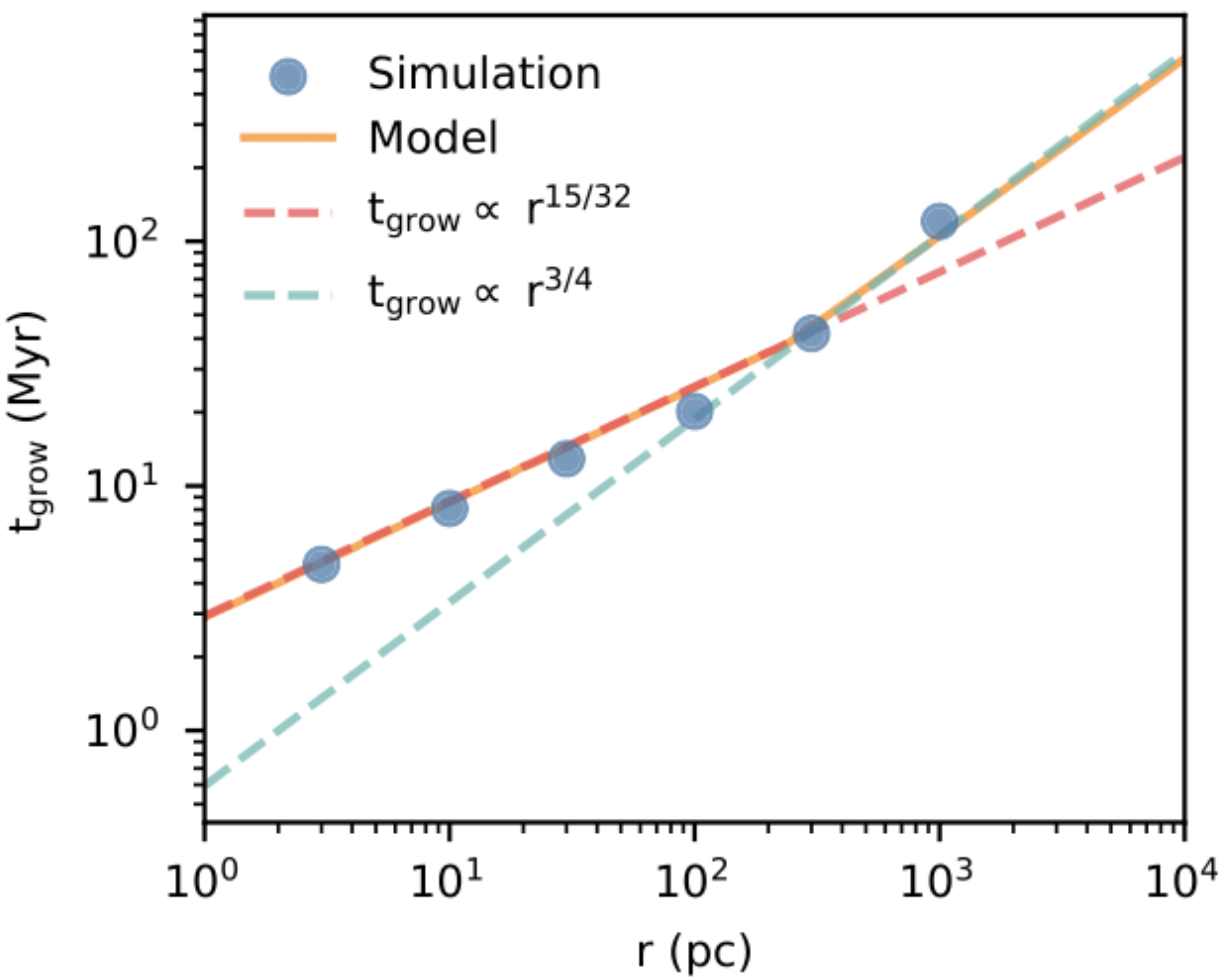
SURVIVAL: ISOTHERMAL HYDROSTATIC BACKGROUND

- Cooling time decreases as you fall
- Transition from non-growth to growth
- Need to survive until cooling time is short enough to grow



SCALINGS


t_{grow} (Myr)
10^0
10^1
10^2
10^3
0
50
100
150
200
t (Myr)
r (pc)
10
30
100
300
1000


Simulation
Model
$t_{grow} \propto r^{15/32}$
$t_{grow} \propto r^{3/4}$
t_{grow} (Myr)
10^0
10^1
10^2
10^0
10^1
10^2
10^3
10^4
r (pc)

For subsonic clouds

$$t_{\rm grow} = 40\,{\rm Myr}\left(\frac{10^{-8}\,{\rm cm/s^2}}{g}\right)^{3/8}\left(\frac{\chi}{100}\right)^{5/8}\left(\frac{r}{100\,{\rm pc}}\right)^{15/32}\left(\frac{t_{\rm cool}}{0.03\,{\rm Myr}}\right)^{5/32}$$

For supersonic clouds

$$t_{\rm grow} = 35\,{\rm Myr}\left(\frac{150\,{\rm km/s}}{c_{\rm s,hot}}\right)^{3/5}\left(\frac{\chi}{100}\right)\left(\frac{r}{100\,{\rm pc}}\right)^{3/4}\left(\frac{t_{\rm cool}}{0.03\,{\rm Myr}}\right)^{1/4}. \tag{28}$$