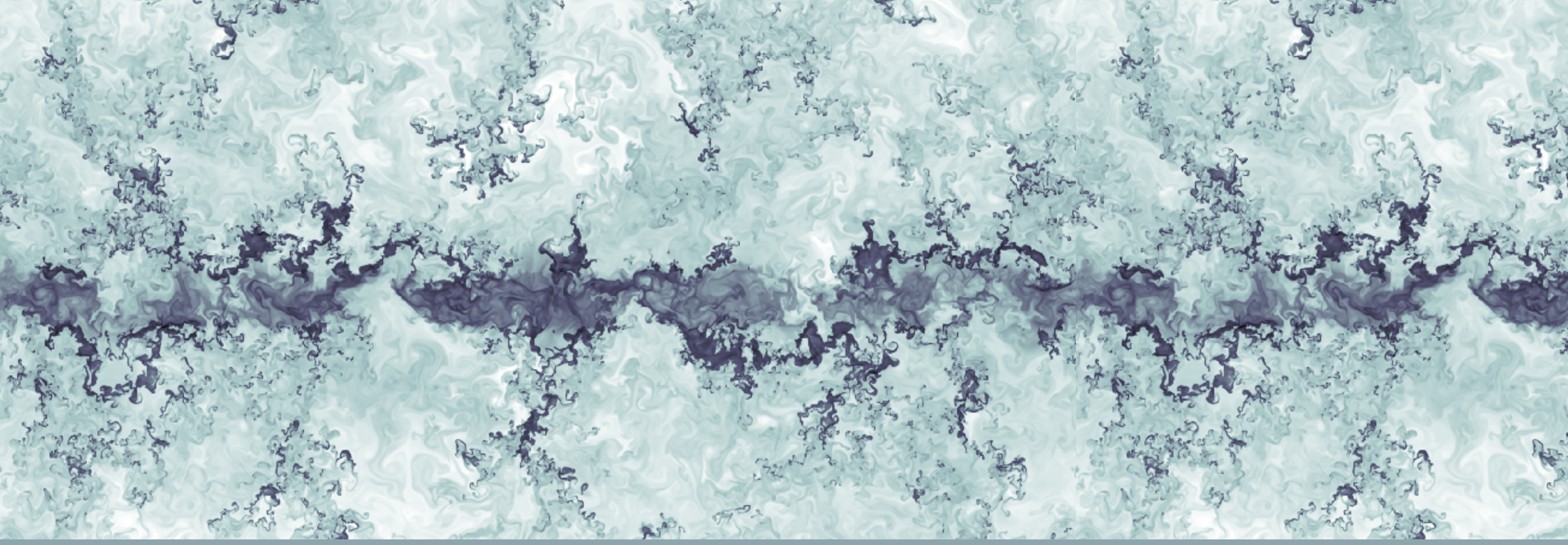


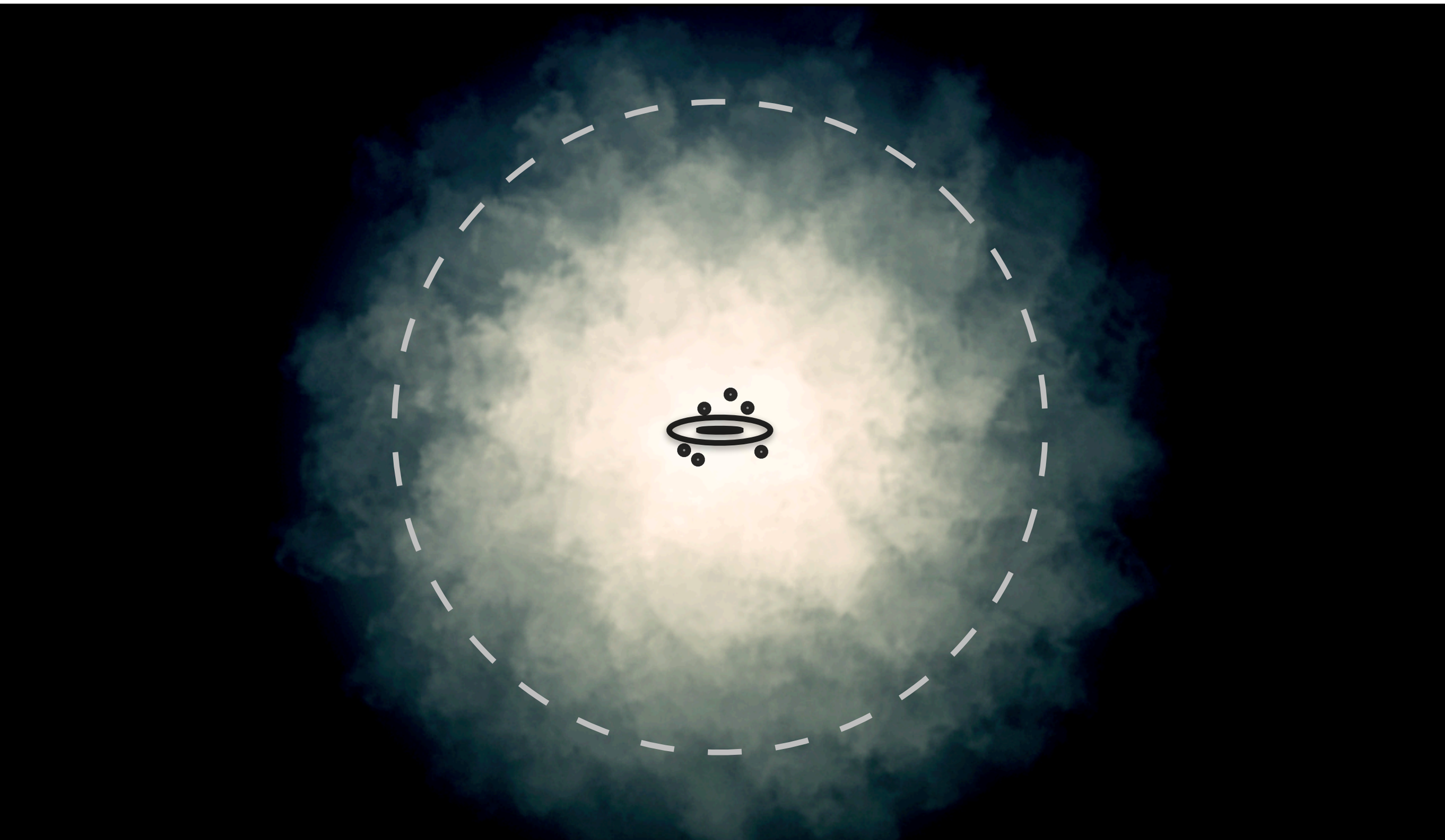
The Impact of **Cosmic Rays** on **Thermal Instability** in the Circumgalactic Medium

IRYNA **BUTSKY**

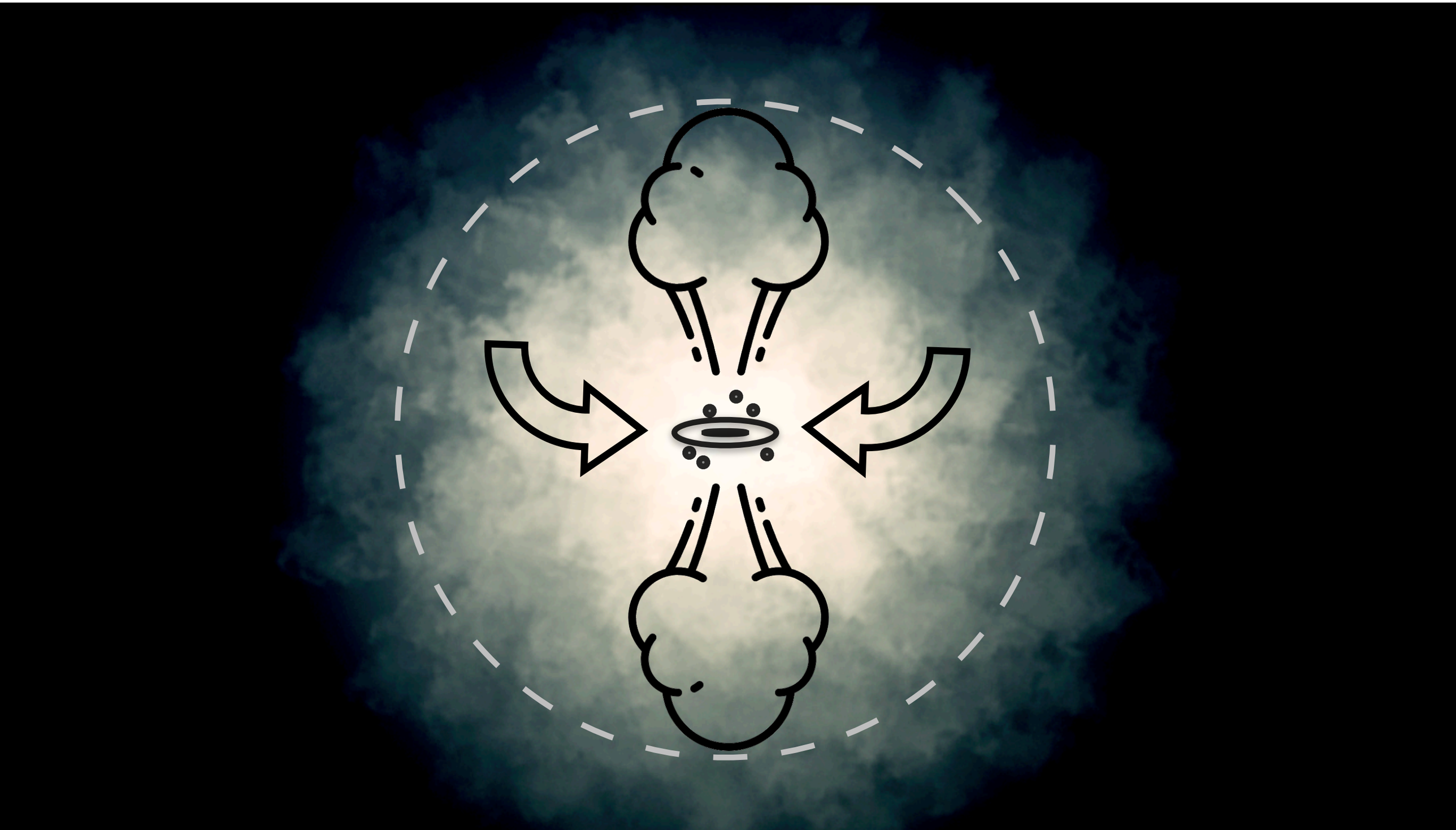
Drummond **Fielding**, Chris **Hayward**,
Cameron **Hummels**, Tom **Quinn**, Jess **Werk**

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

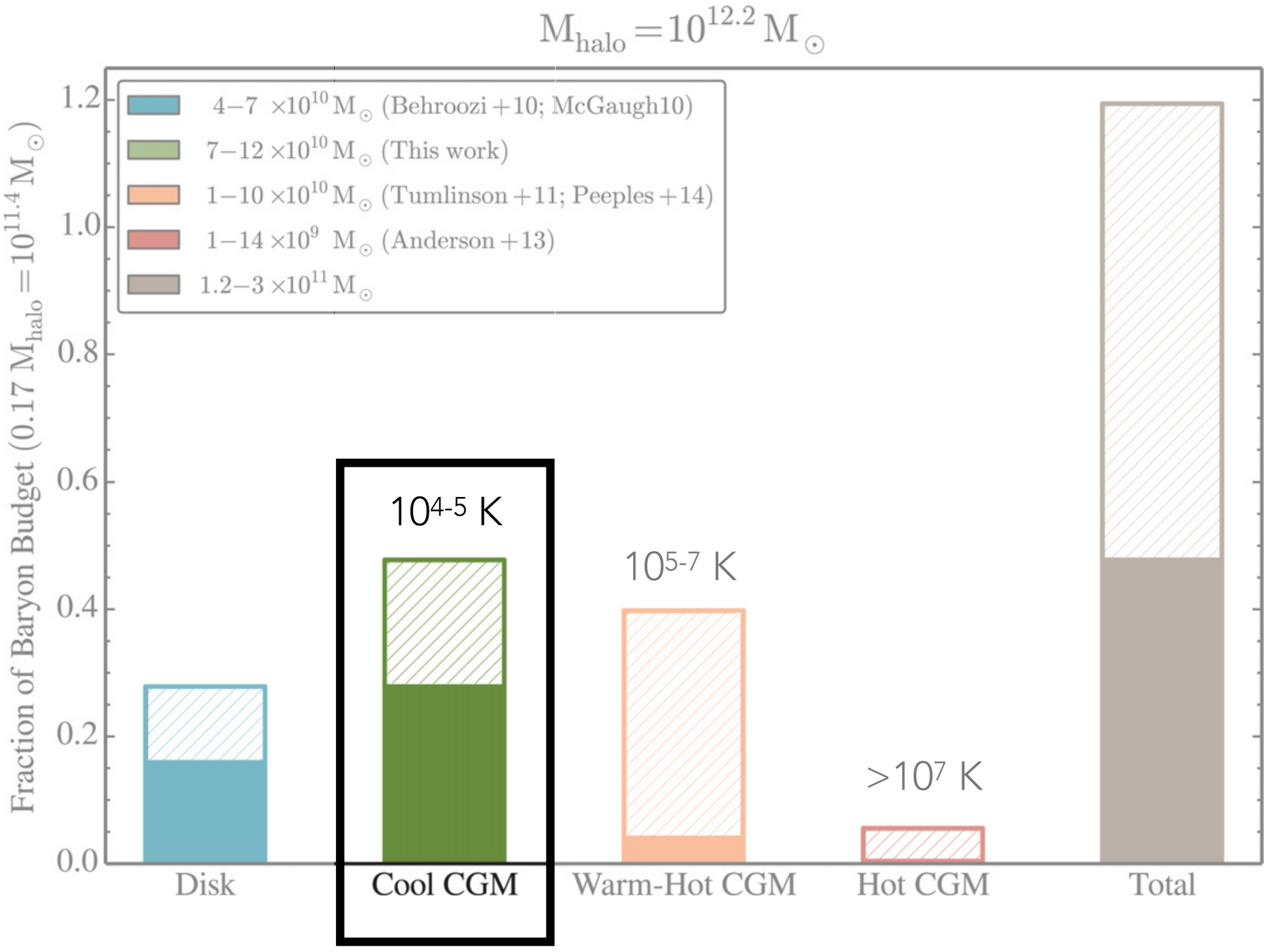
The Circumgalactic Medium (CGM)



The Circumgalactic Medium (CGM)



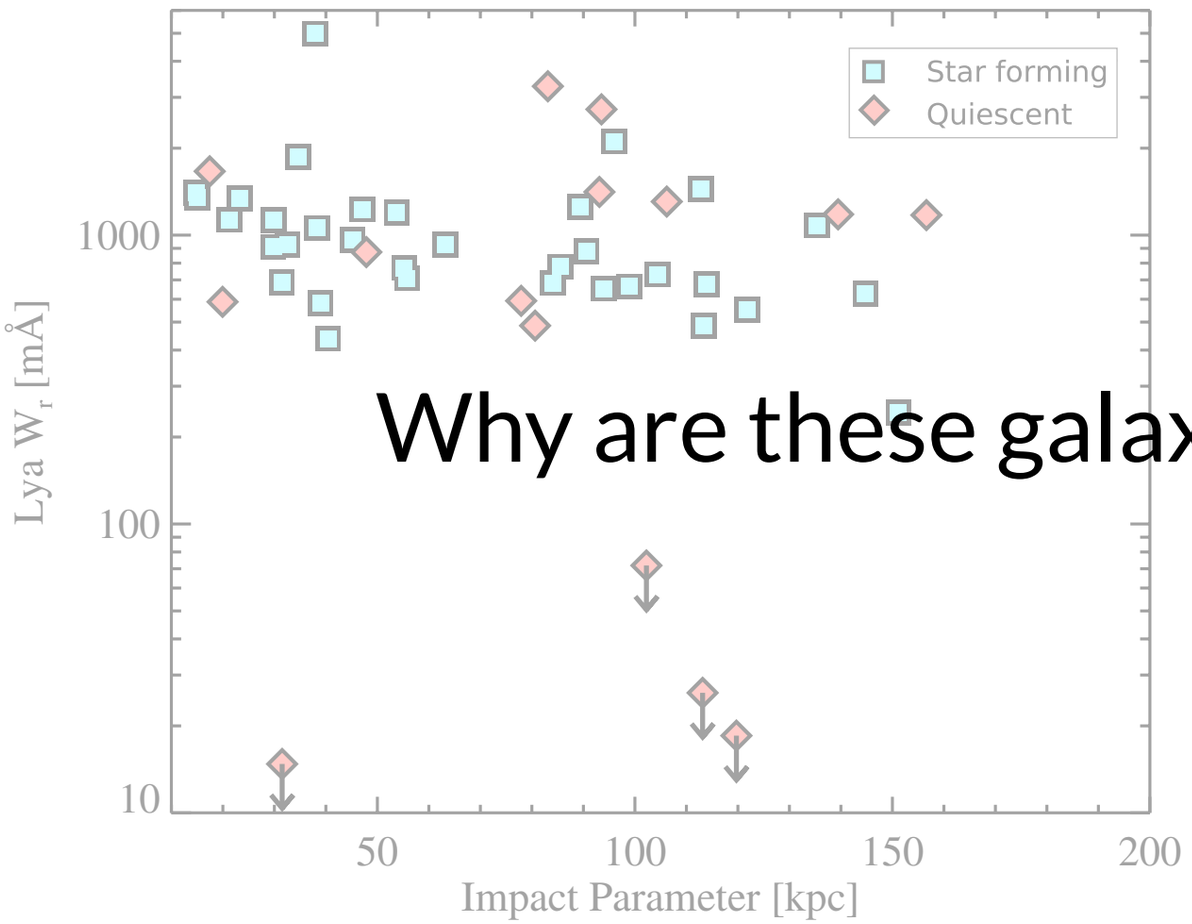
COOL CGM GAS COMPRISES 25-45% OF GALACTIC BARYONS



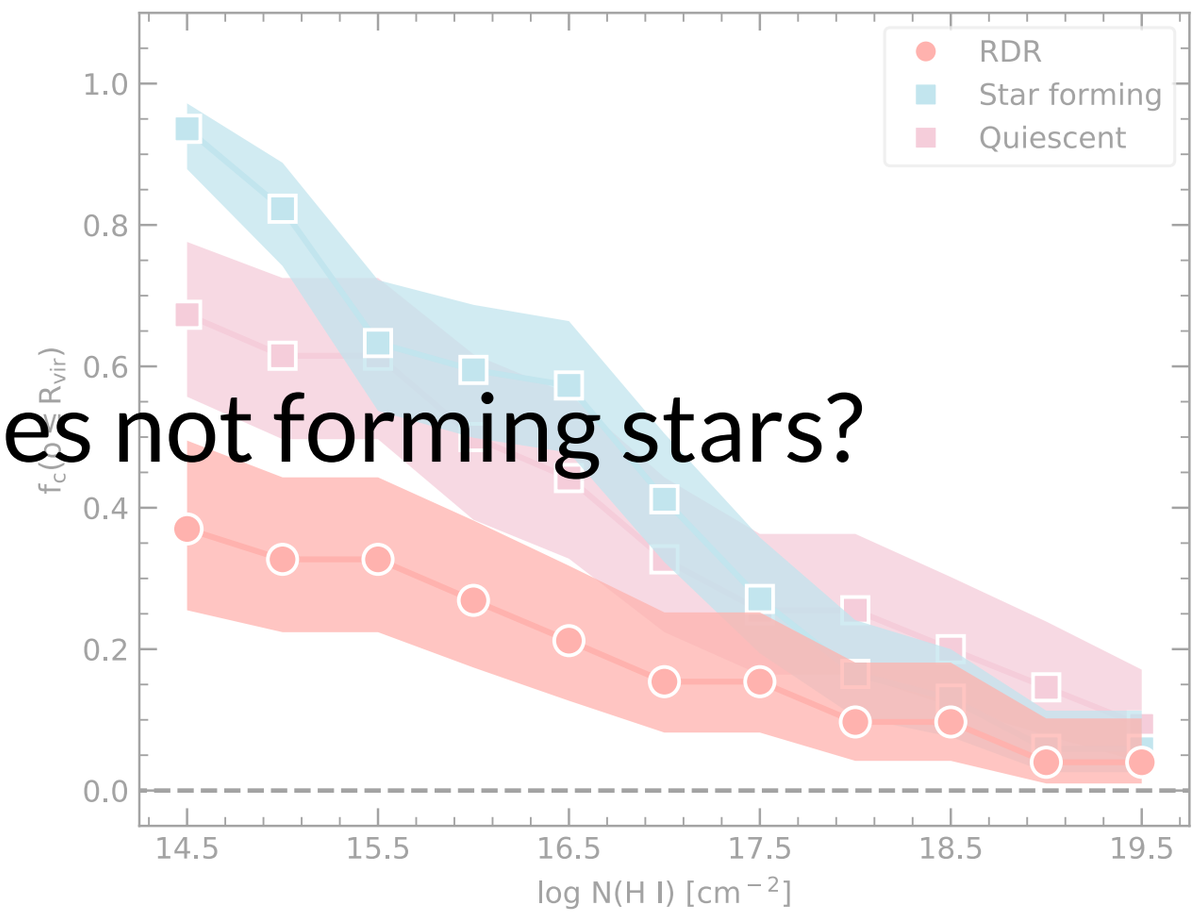
Werk et al. 2014

Quiescent galaxies have **massive reservoirs of cold gas** in their CGM

Thom+ 2012

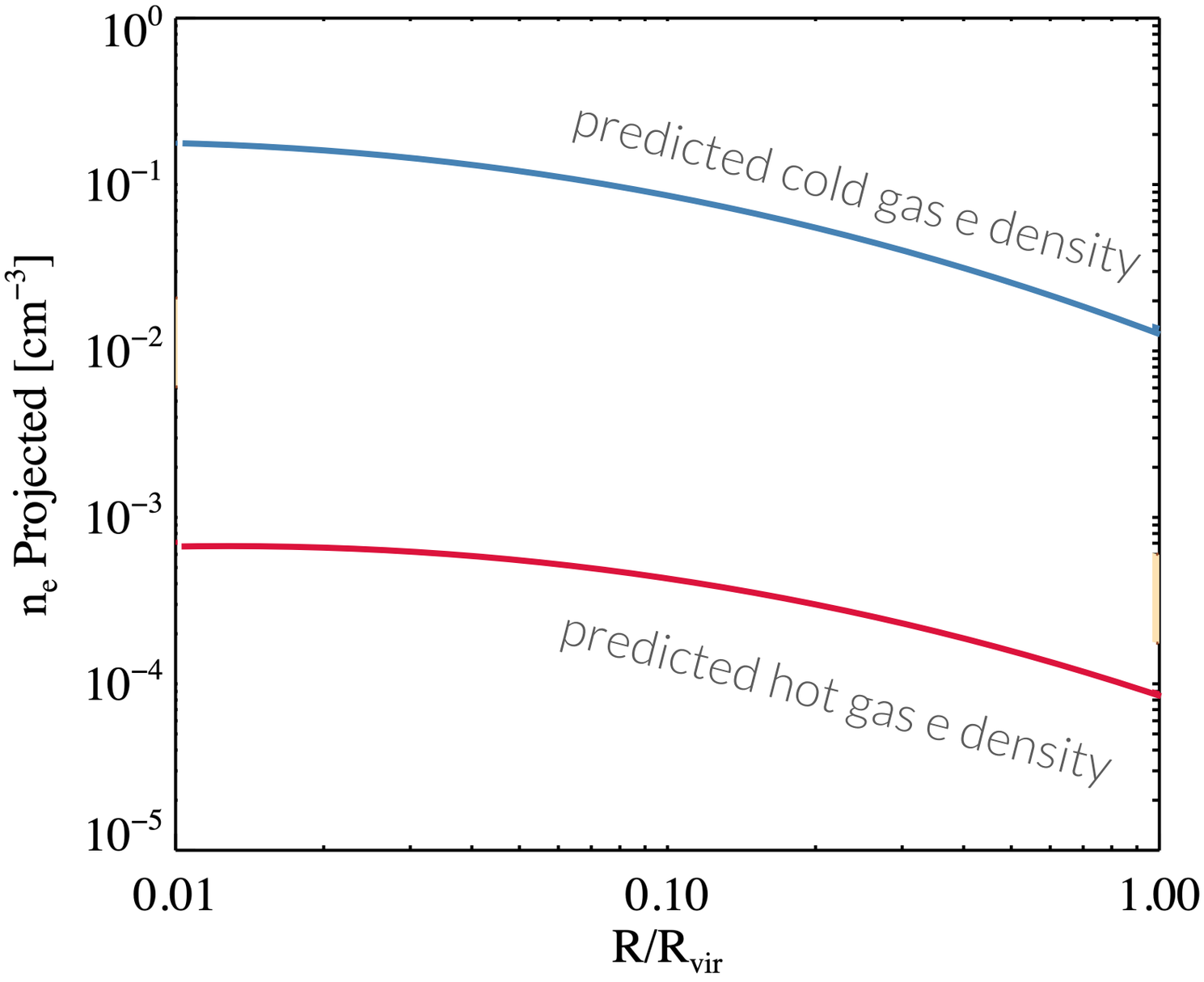


Berg+ 2019



Why are these galaxies not forming stars?

Cold CGM gas appears to be **out of** thermal pressure **equilibrium**



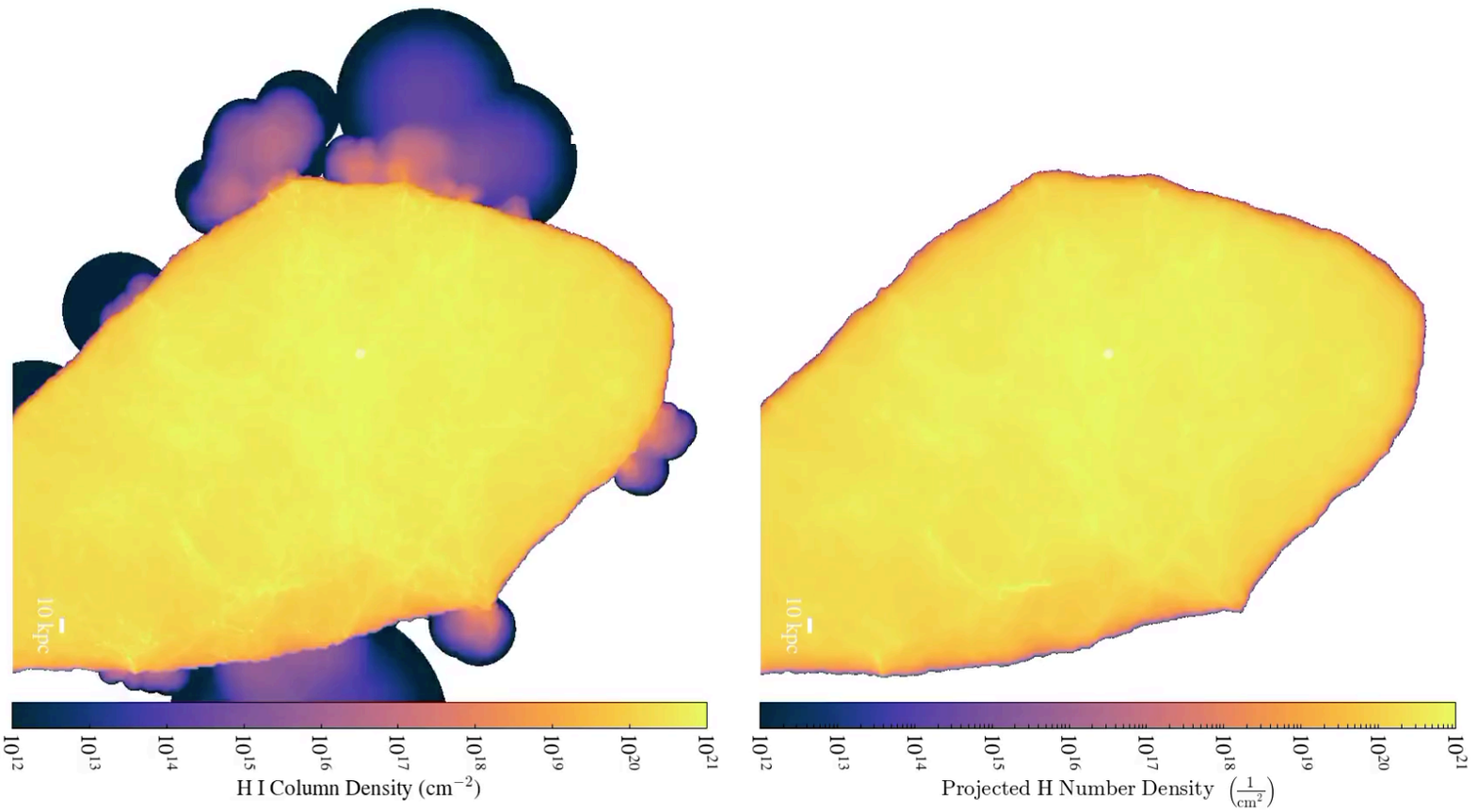
Maller and Bullock 2004, Werk et al. 2014

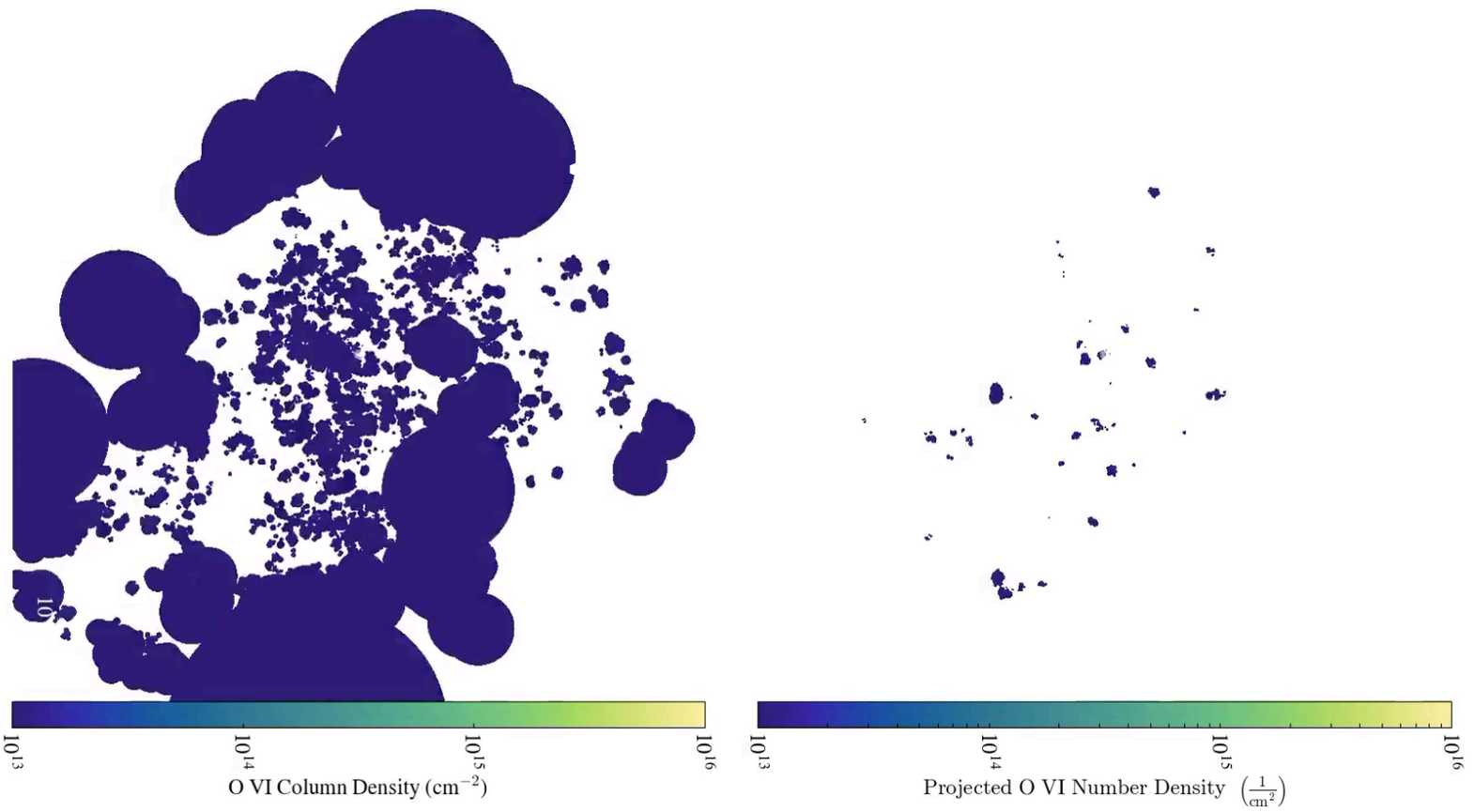
Is cold gas really out of **pressure** equilibrium?

Cosmic rays **alter ionization state** in the CGM

MHD + cosmic rays

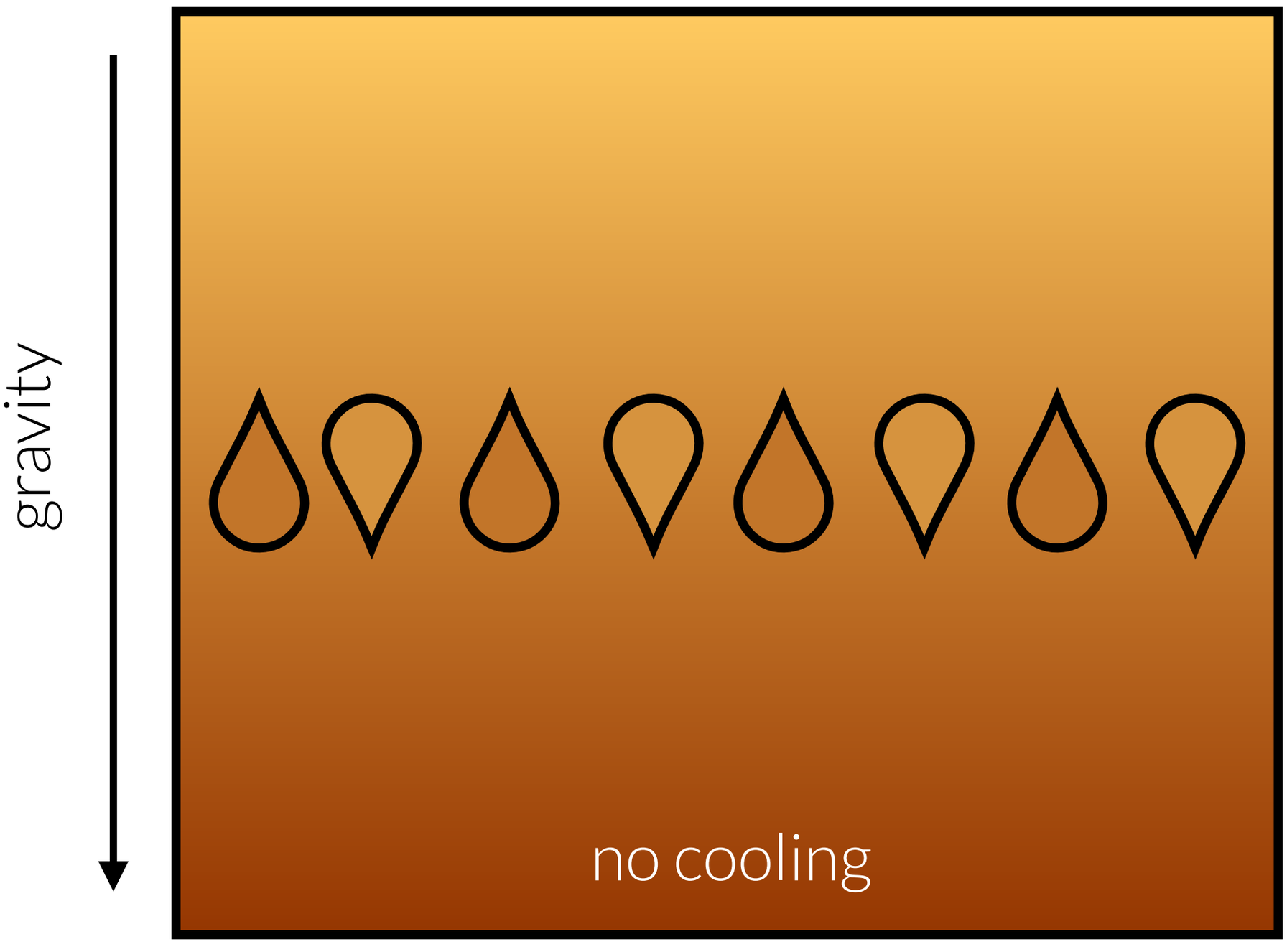
MHD - only



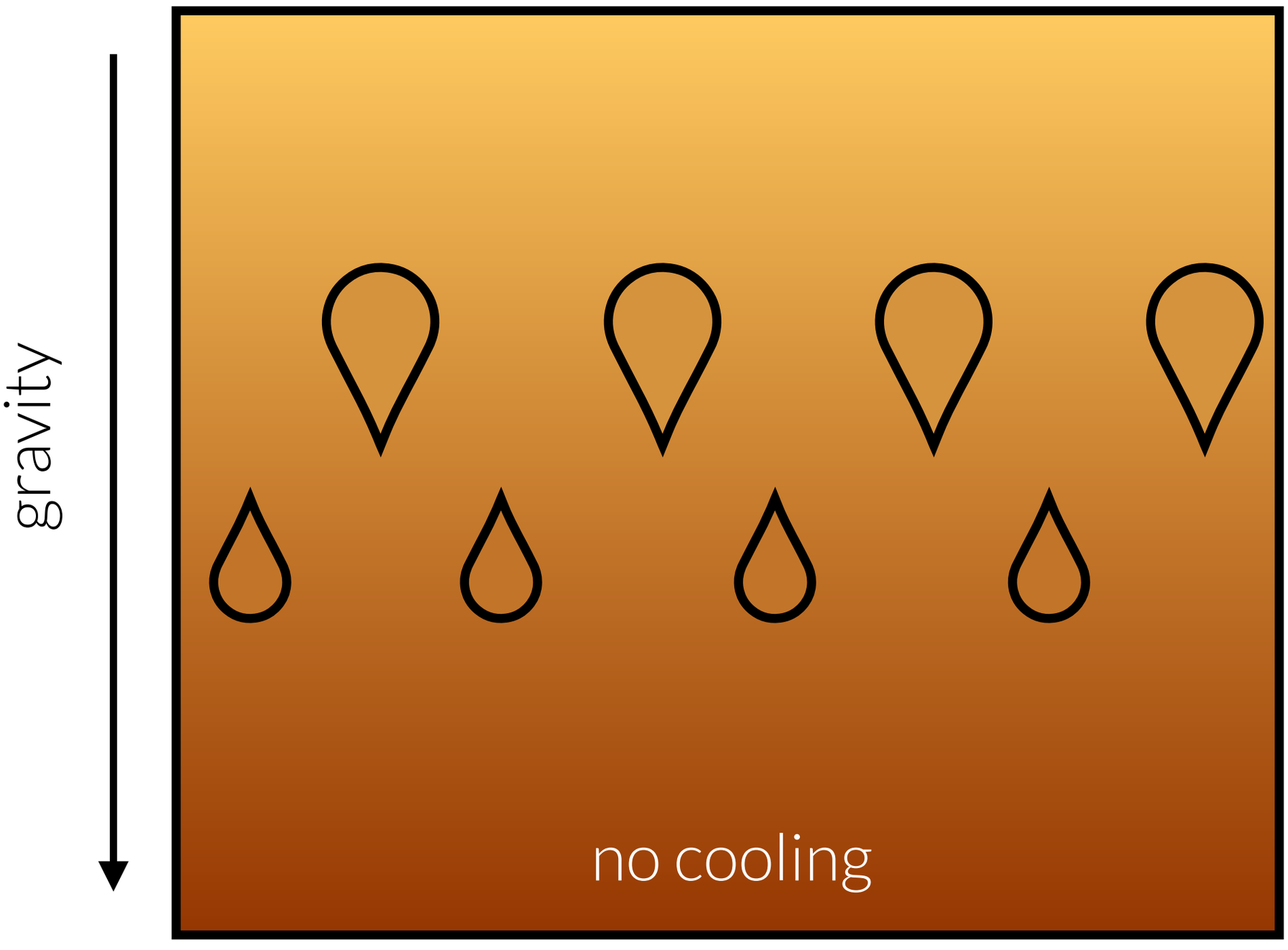


Movie credit: Cameron Hummels and the FIRE Collaboration

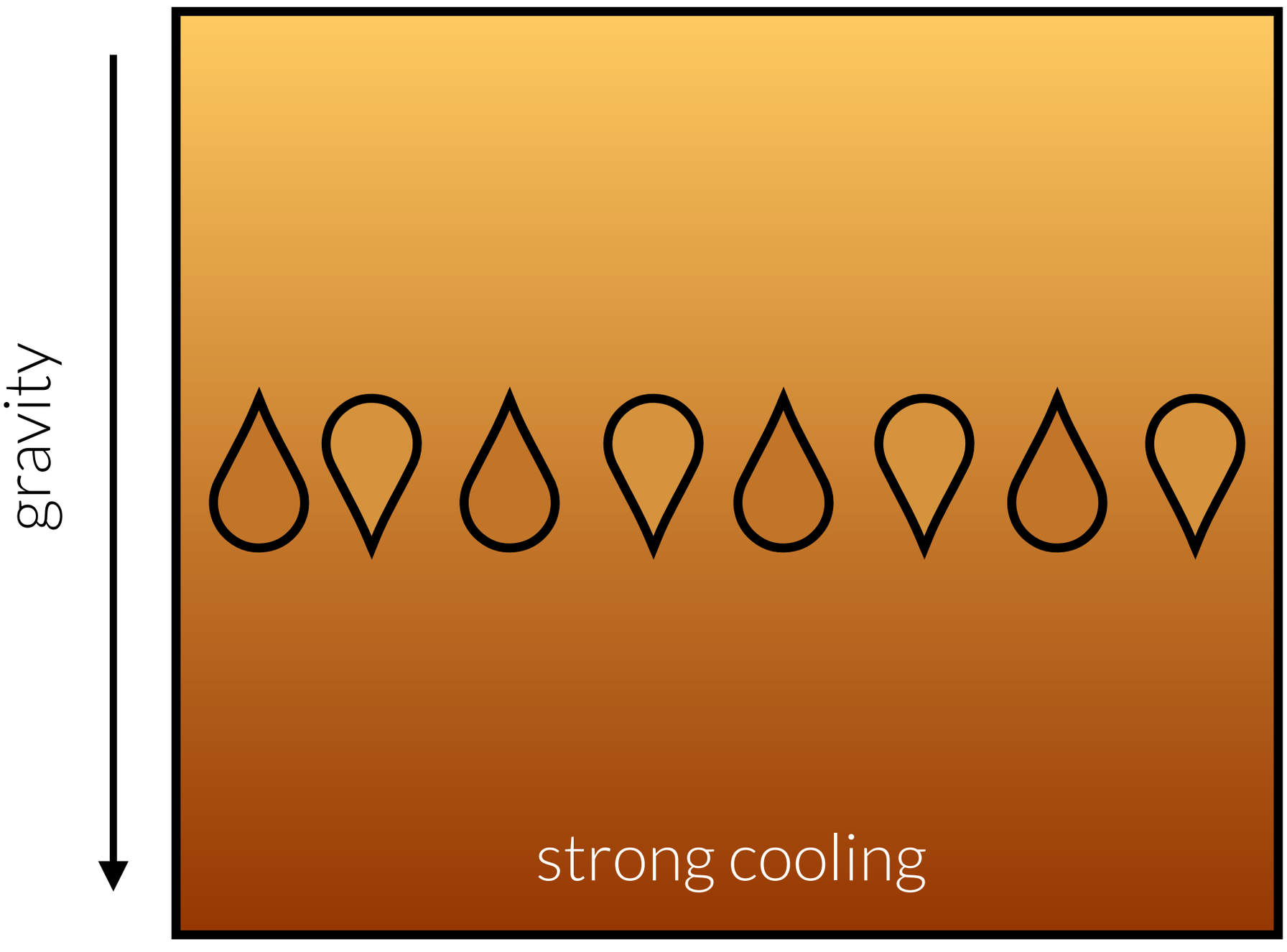
Thermal instability in a stratified plasma



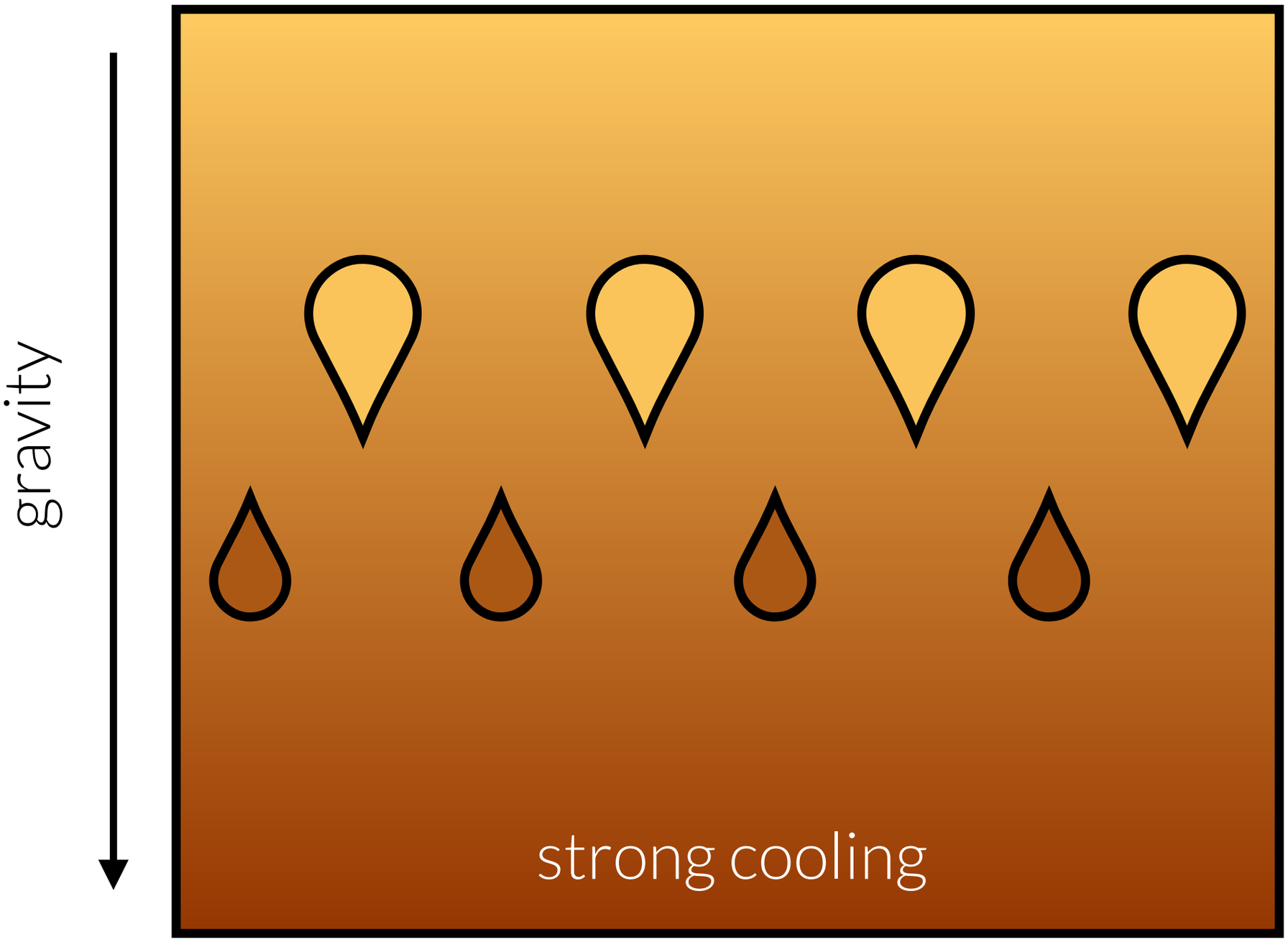
Thermal instability in a stratified plasma



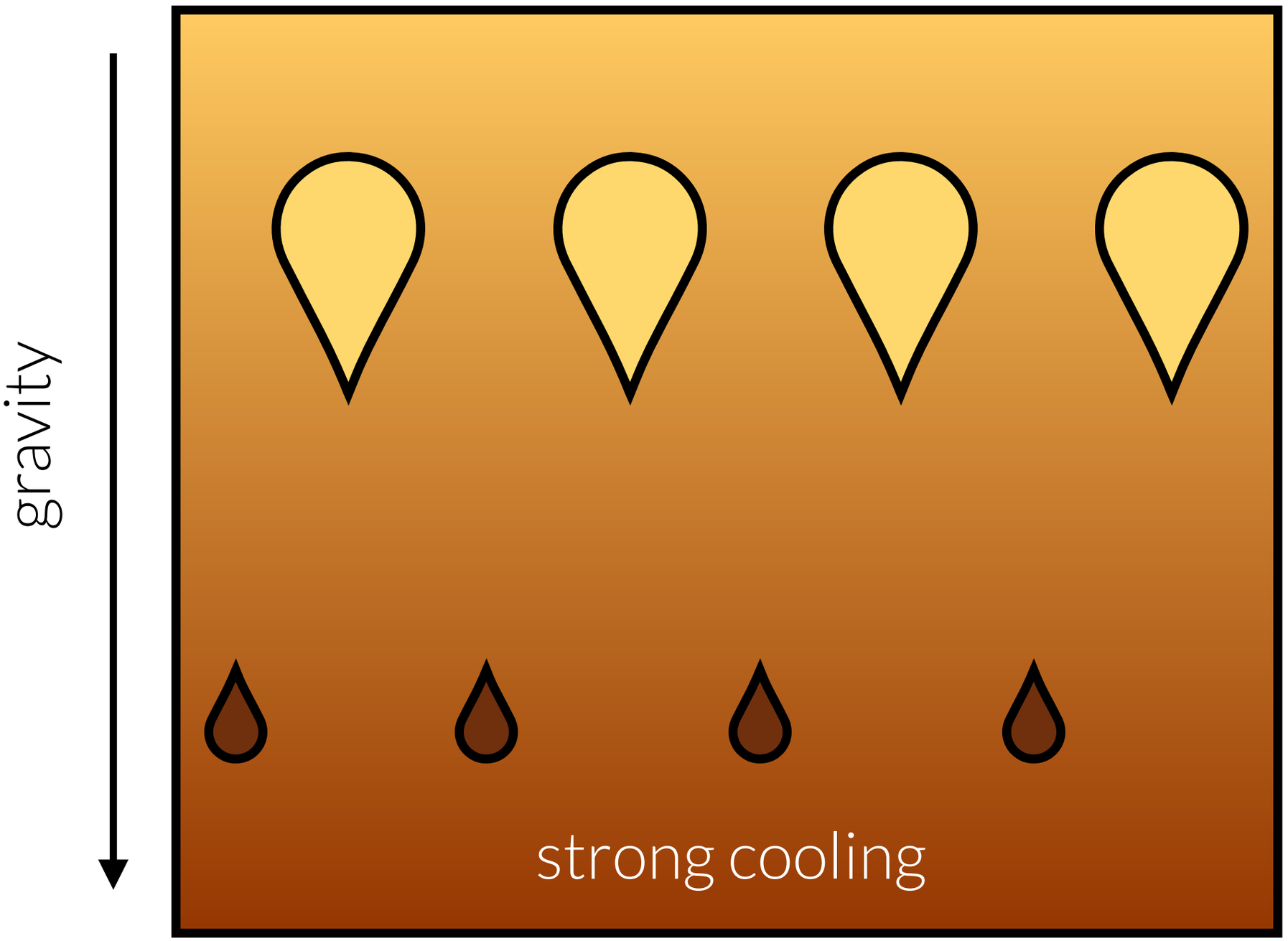
Thermal instability in a stratified plasma



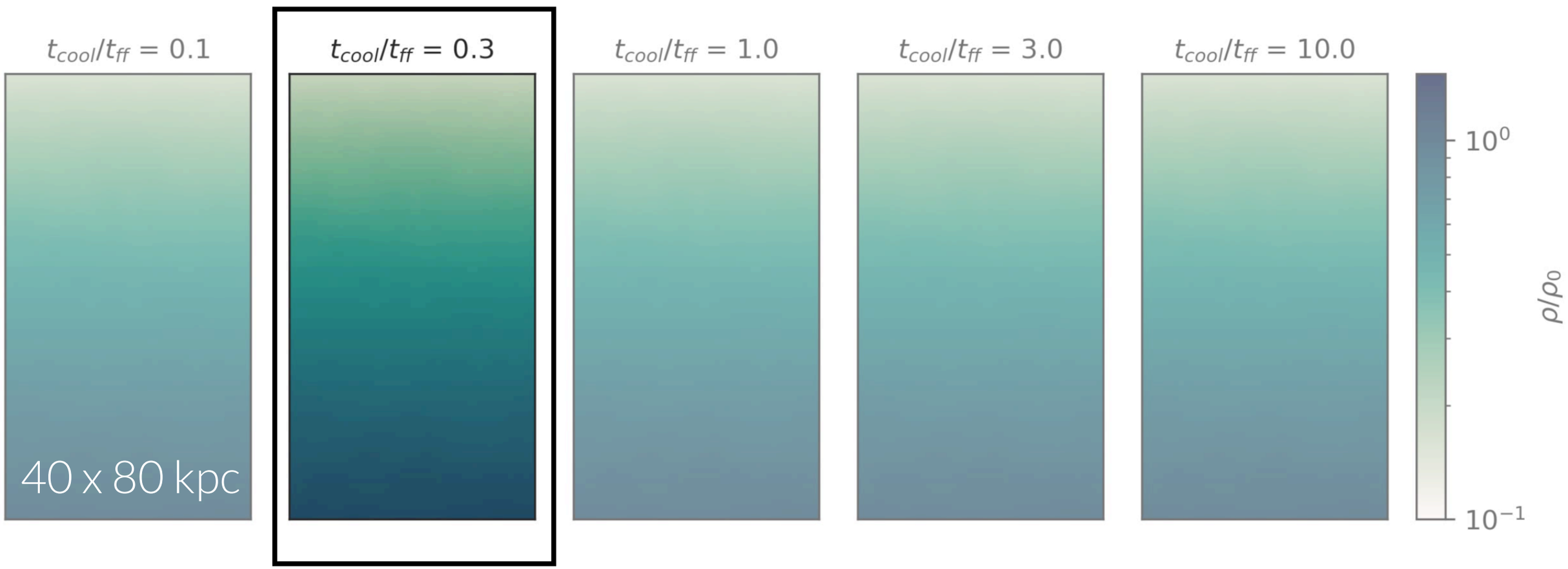
Thermal instability in a stratified plasma



Thermal instability in a stratified plasma



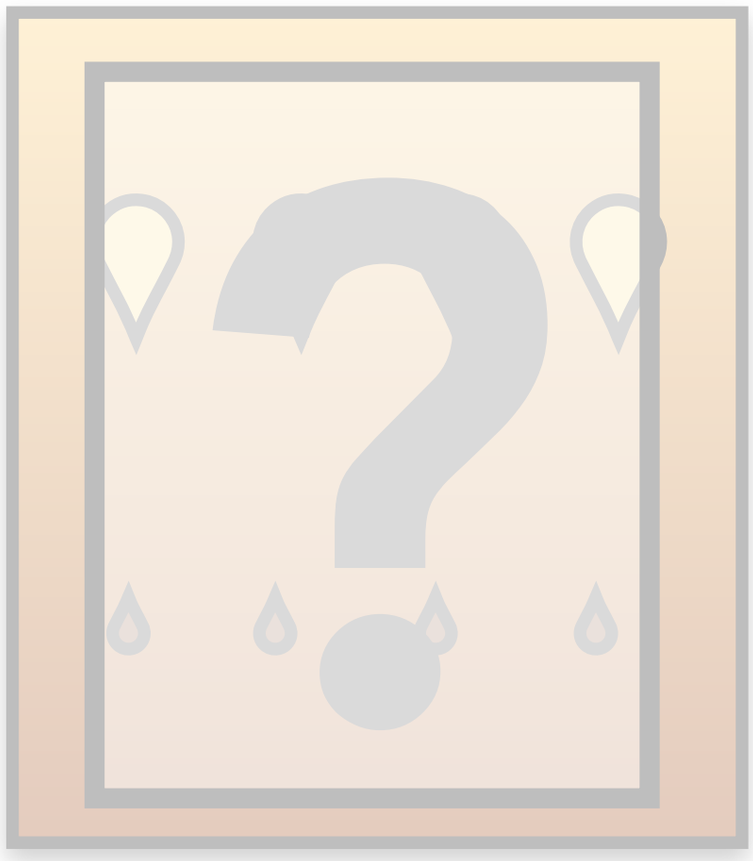
Thermal instability **without** cosmic rays

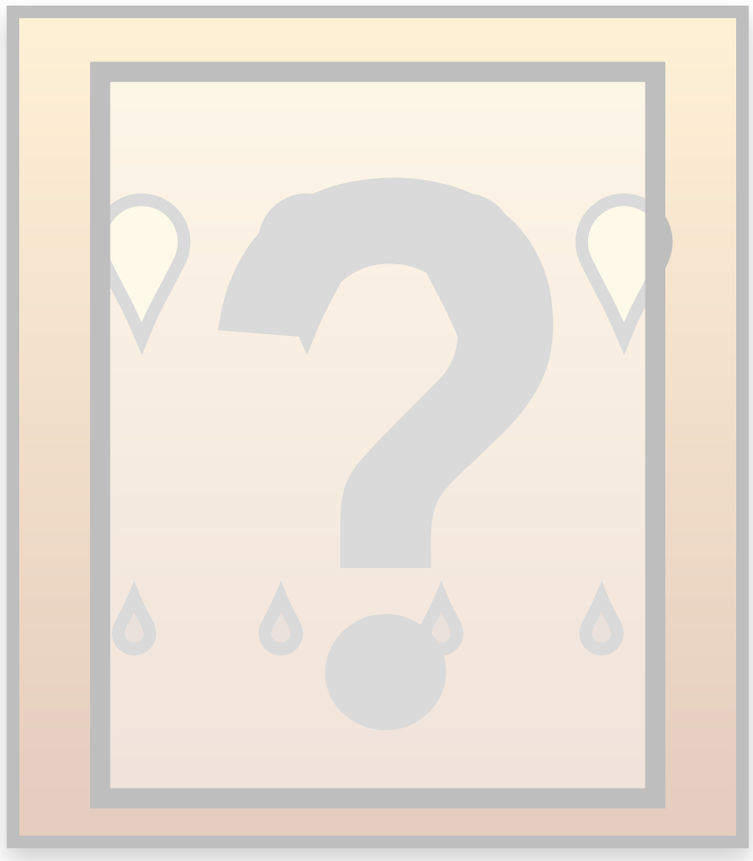


Cosmic Rays and Thermal Instability

pressure

transport

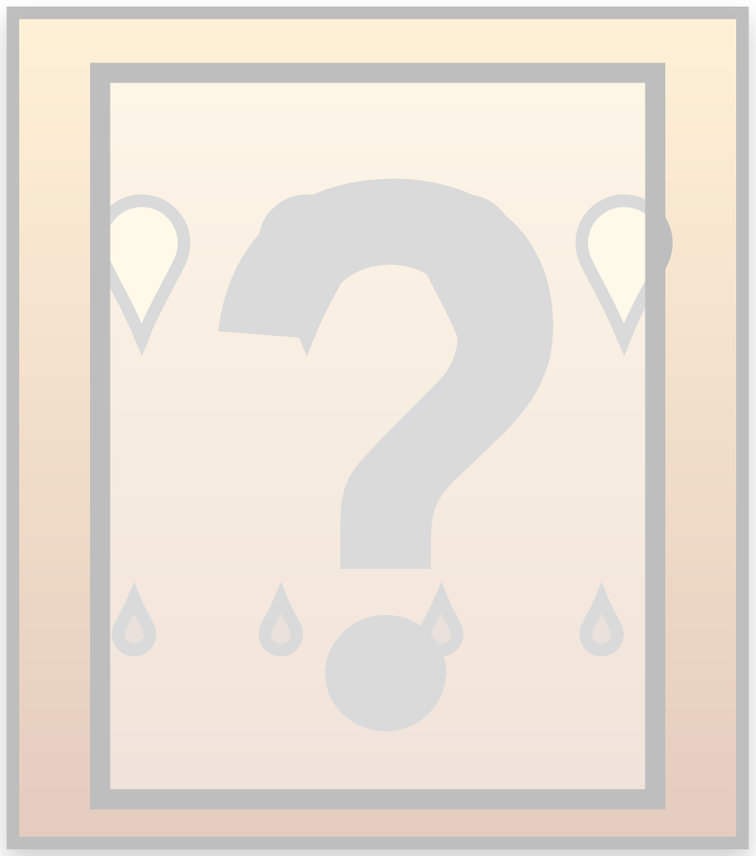




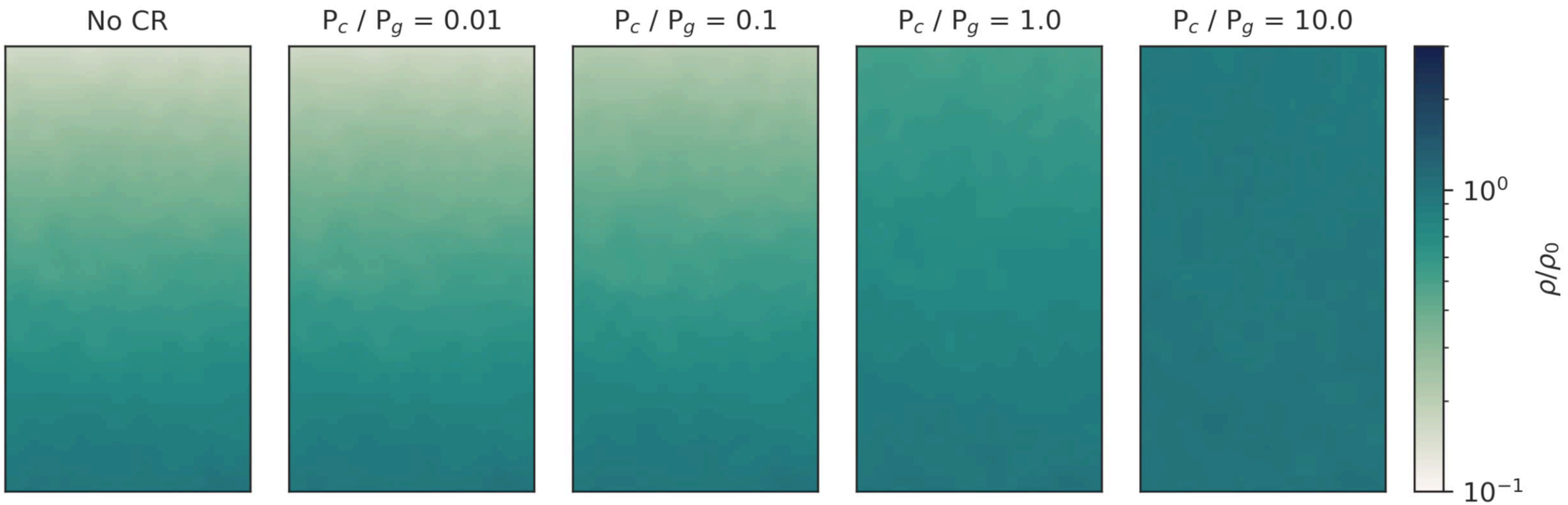
Cosmic Rays and Thermal Instability

pressure

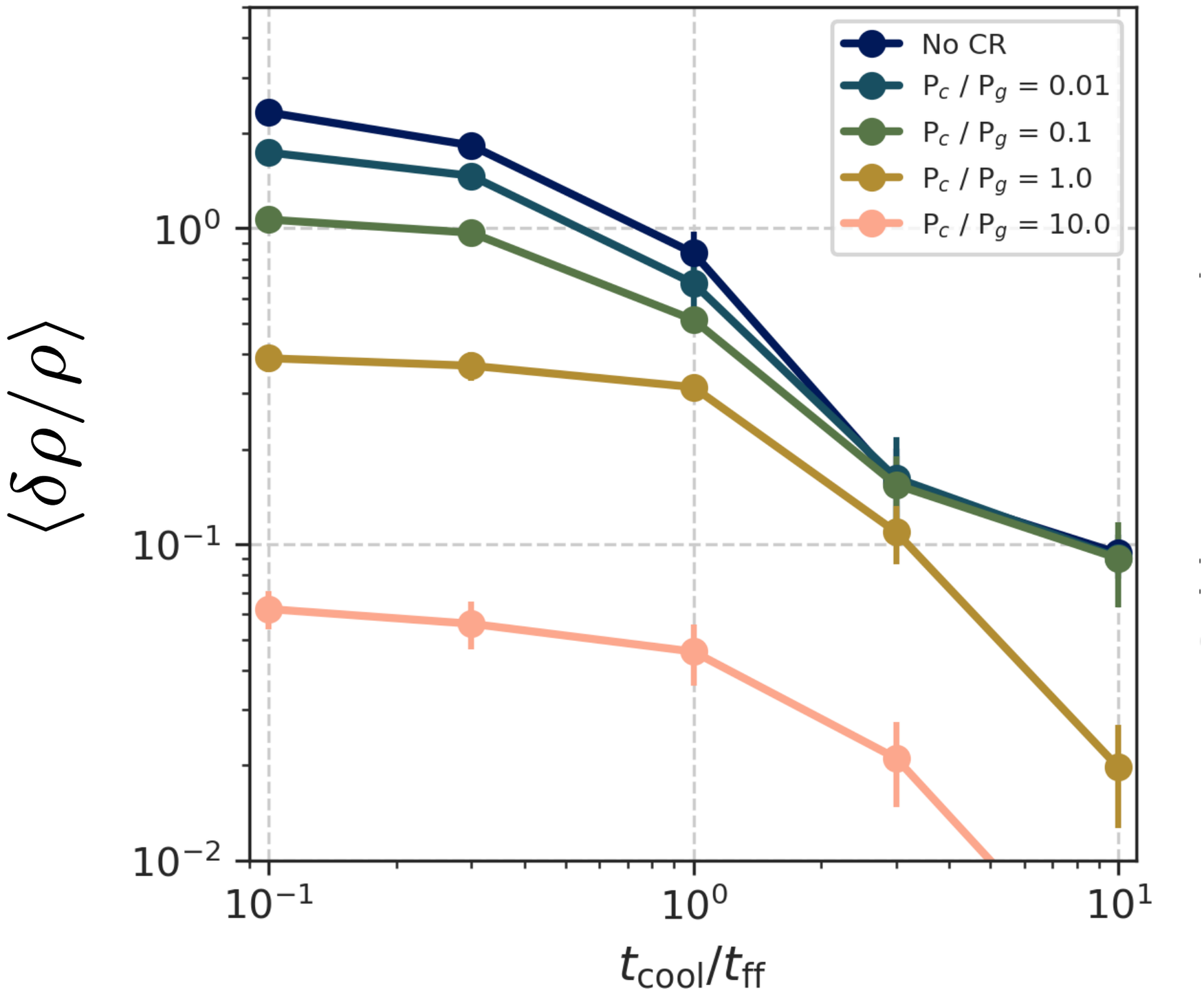
transport



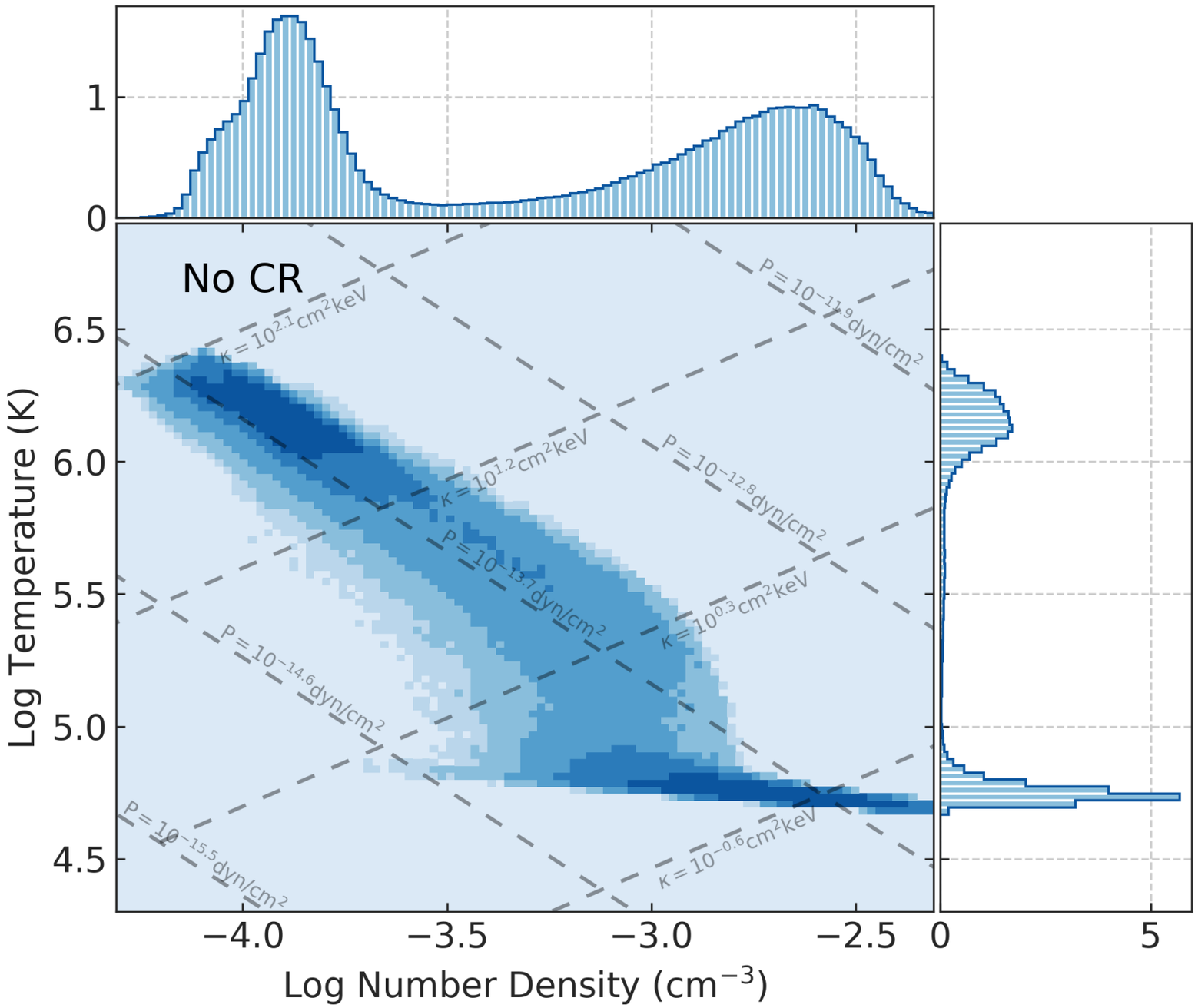
Cosmic ray pressure decreases **cold gas density**



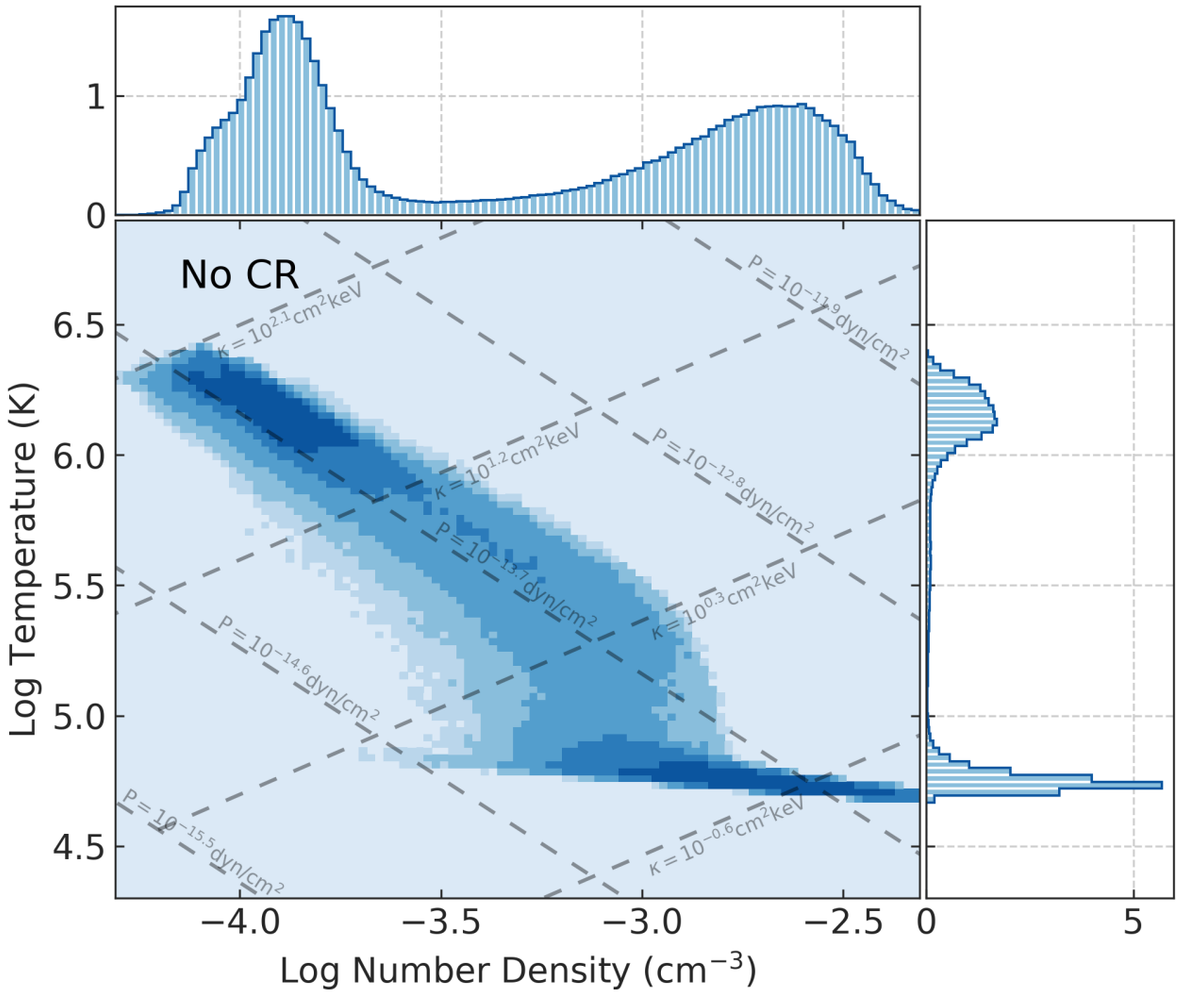
Cosmic ray pressure washes out **density fluctuation**

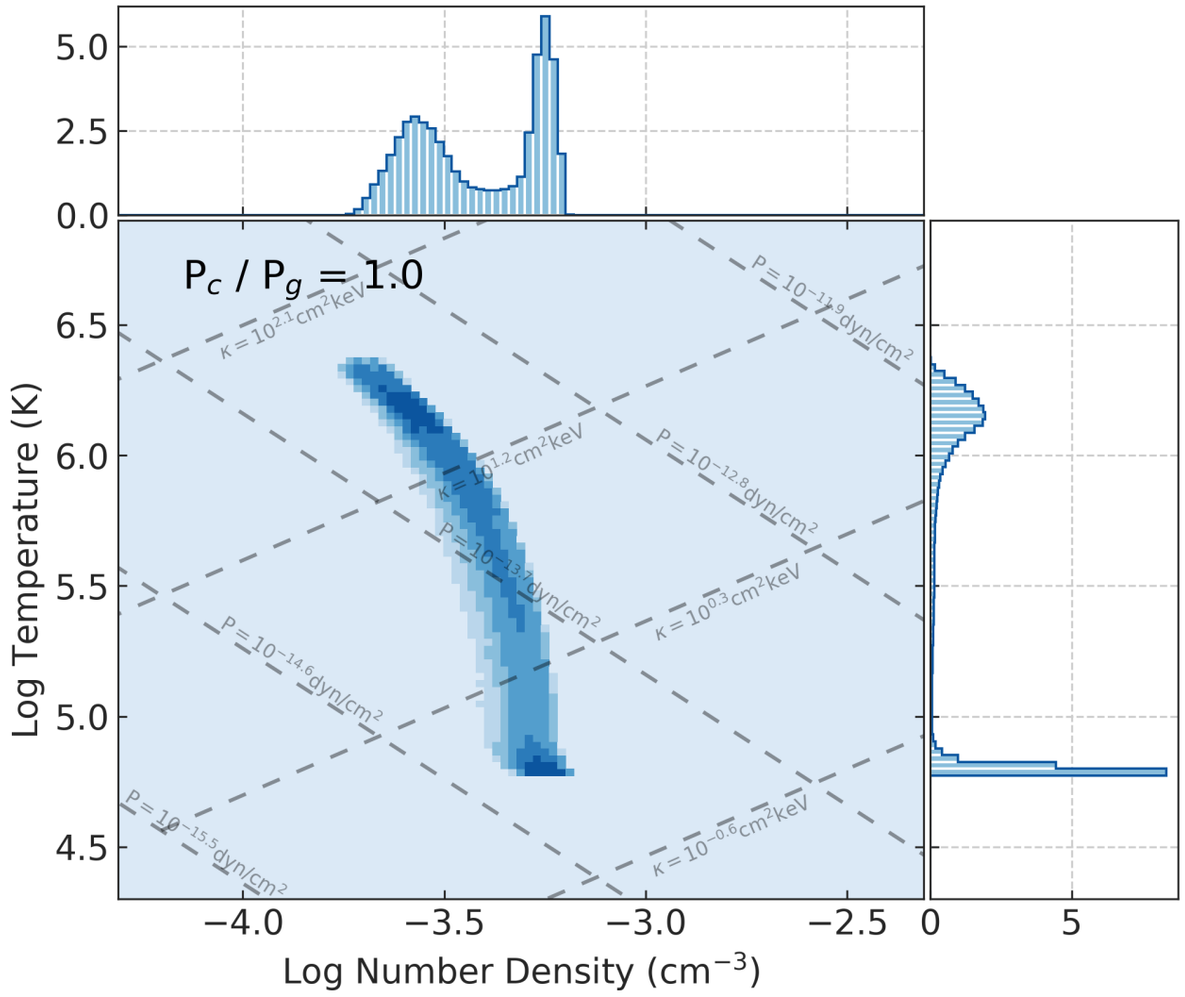


Without cosmic rays, gas cools in thermal pressure equilibrium (**isobarically**)

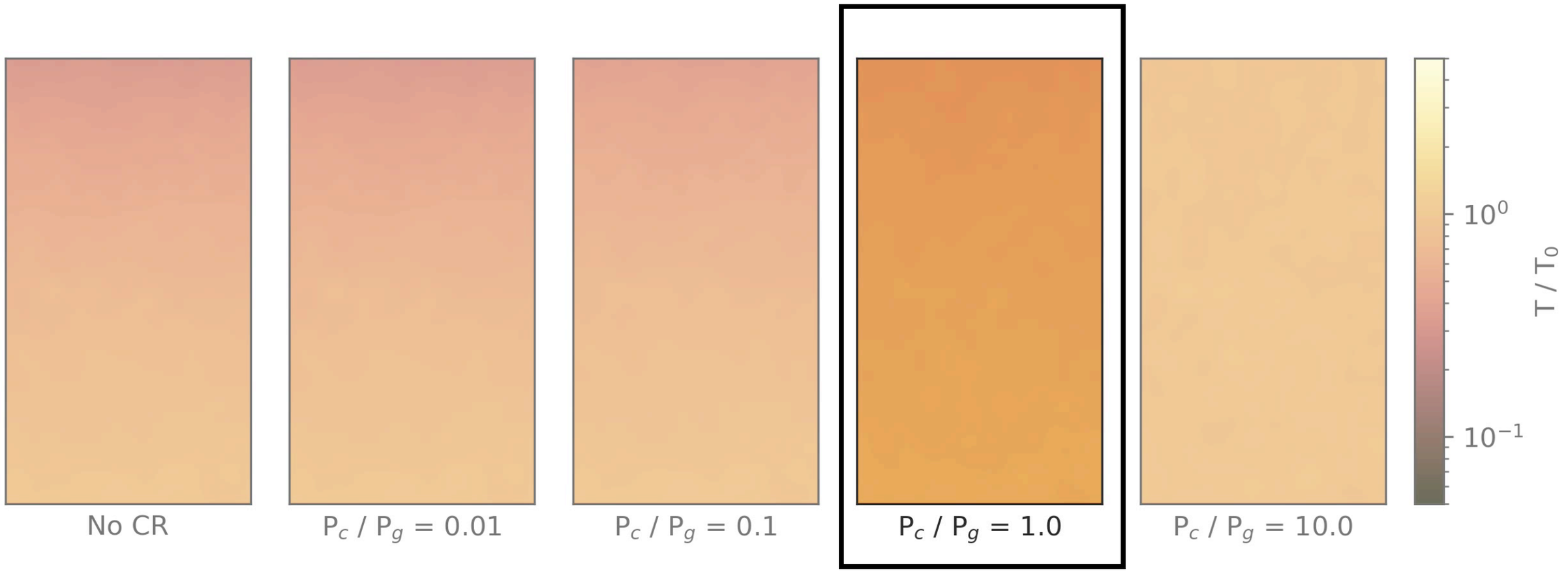


With high cosmic ray pressure, gas cools at constant density (**isochorically**)



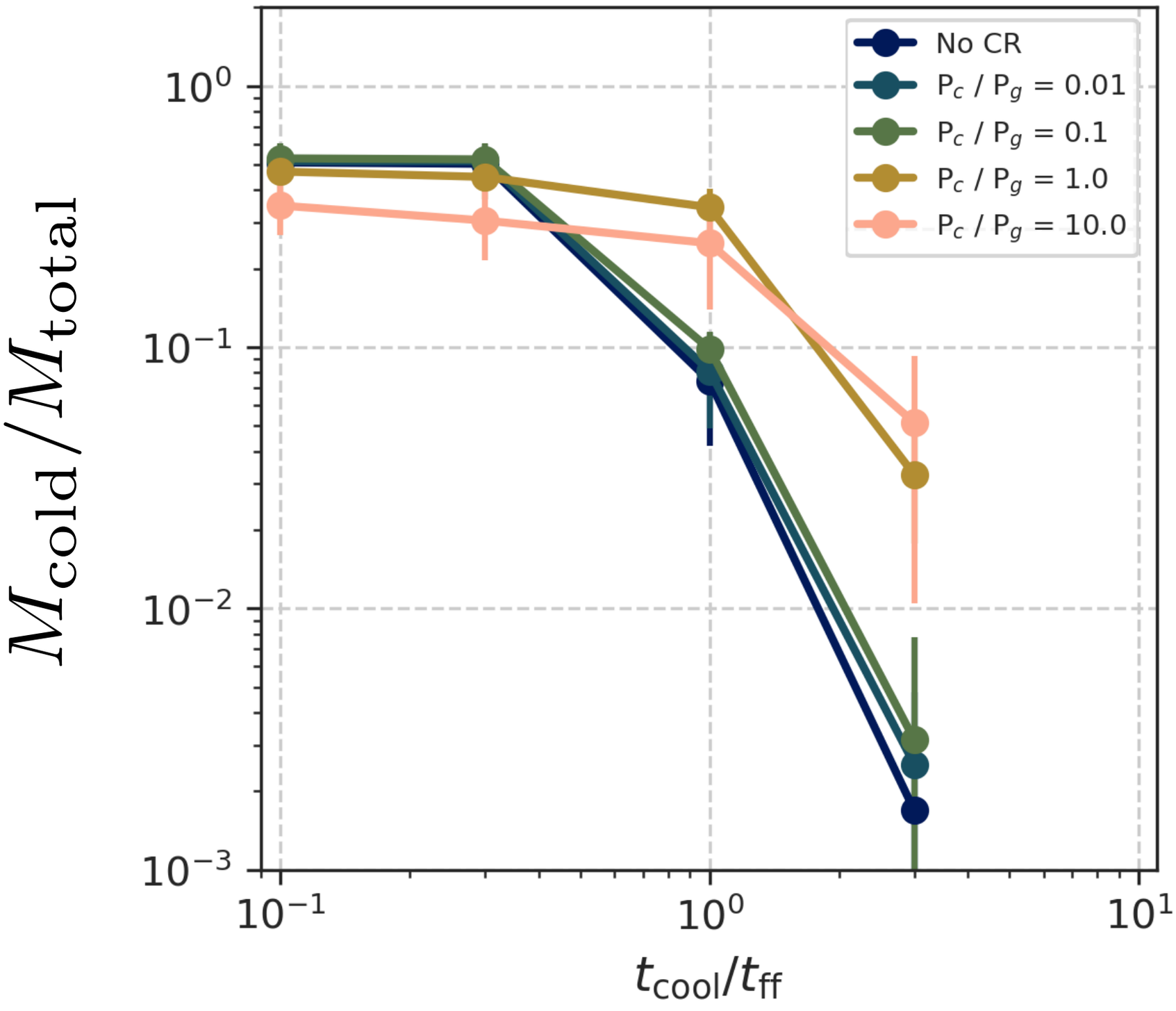


Cold gas **temperature is independent** of cosmic ray pressure

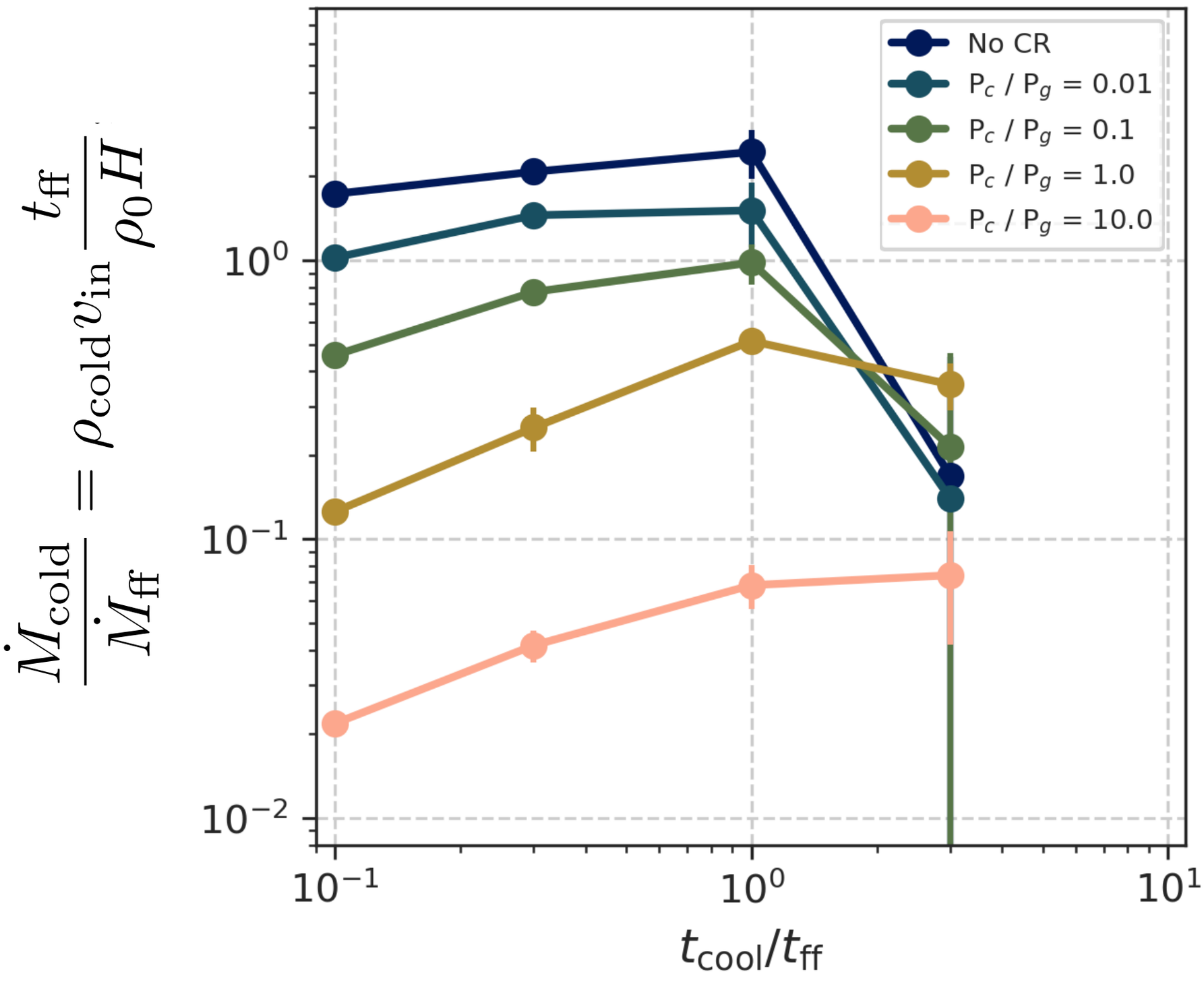


Cold gas temperature is set by the shape of the **cooling curve**, which is an approximation to atomic physics and insensitive of cosmic ray pressure

Cosmic ray pressure can **increase cold mass fraction**

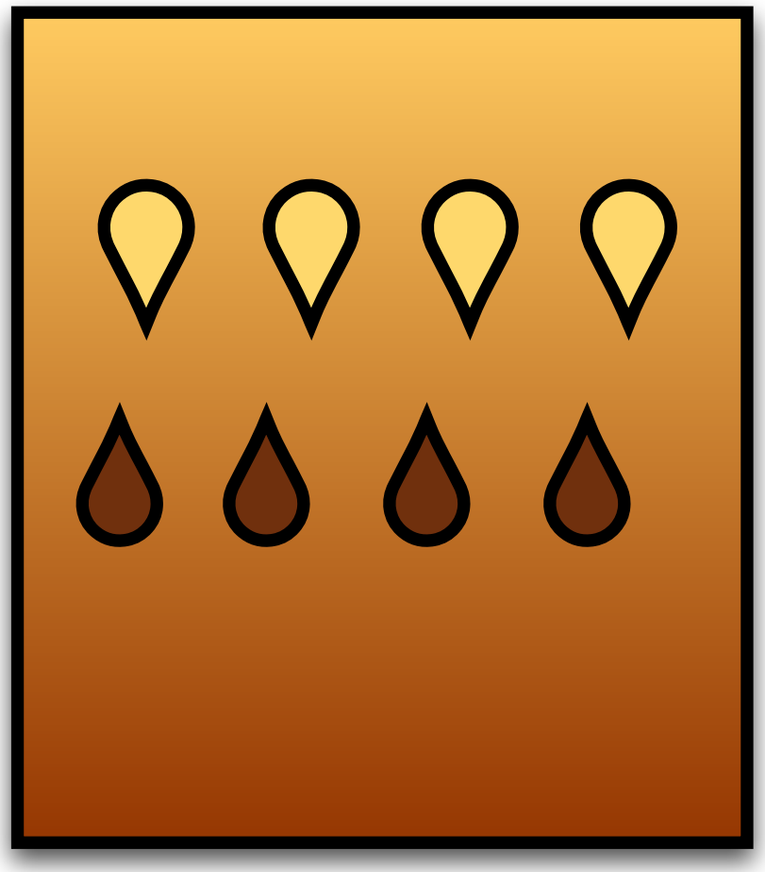


Cosmic ray pressure **decreases cold mass flux**



Cosmic Rays and Thermal Instability

pressure

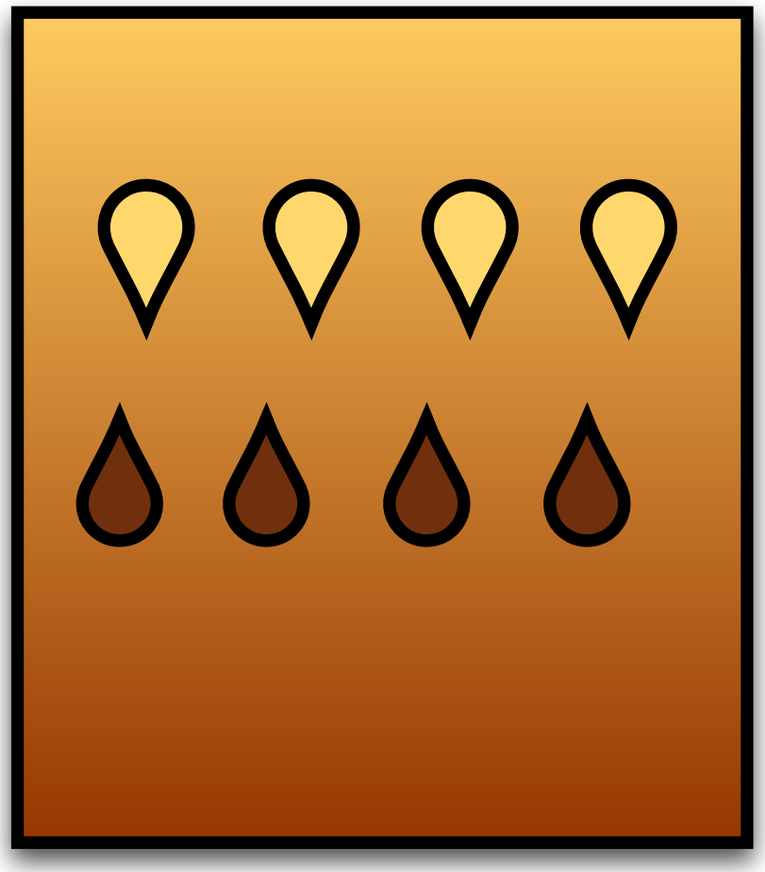


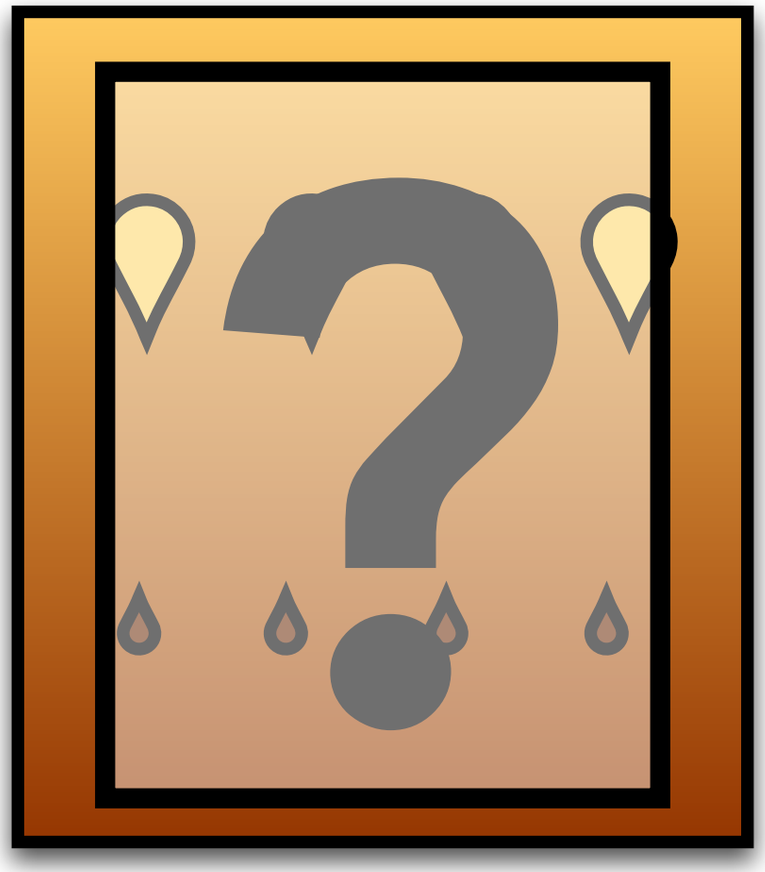
transport

Cosmic Rays and Thermal Instability

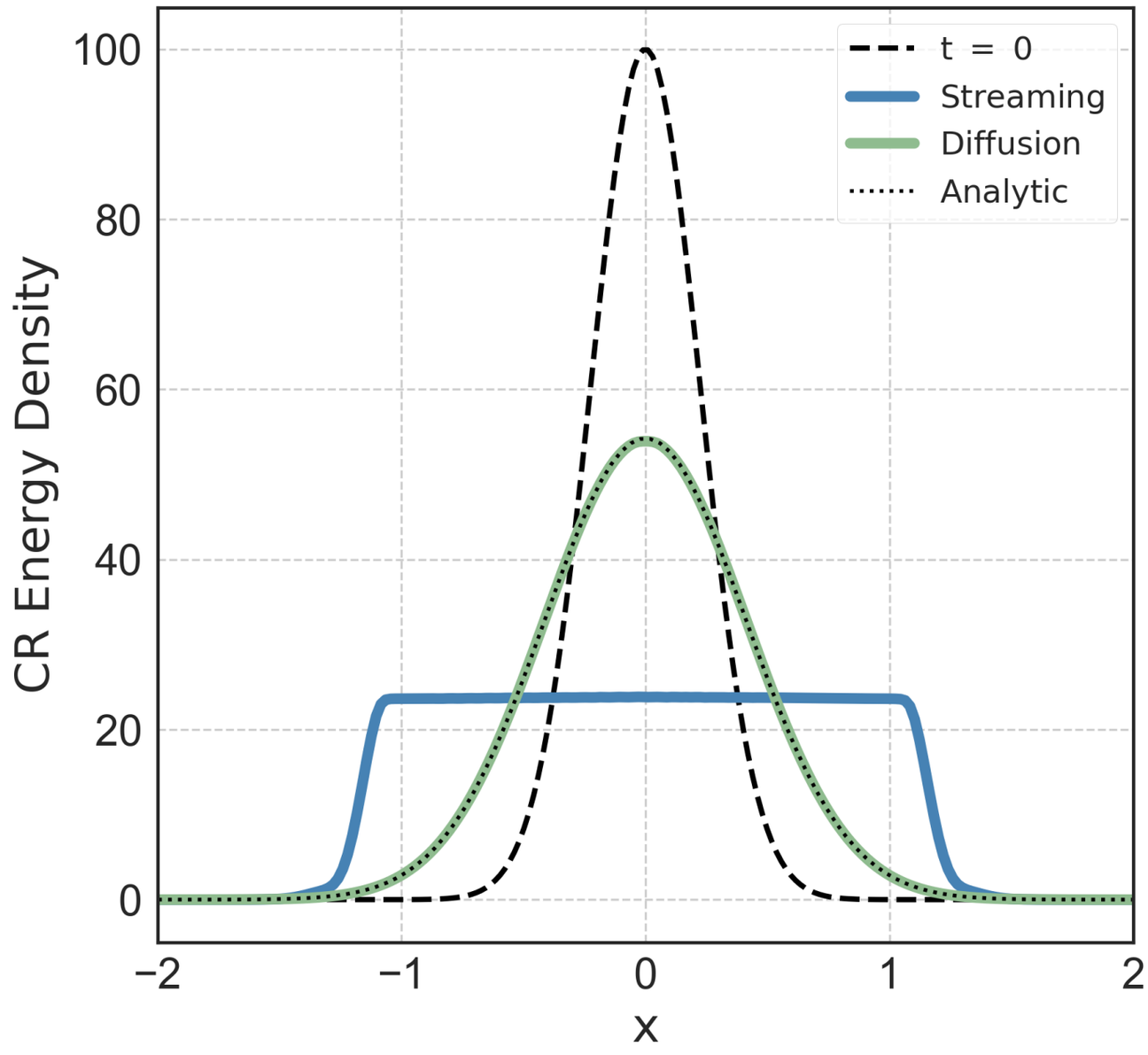
pressure

transport



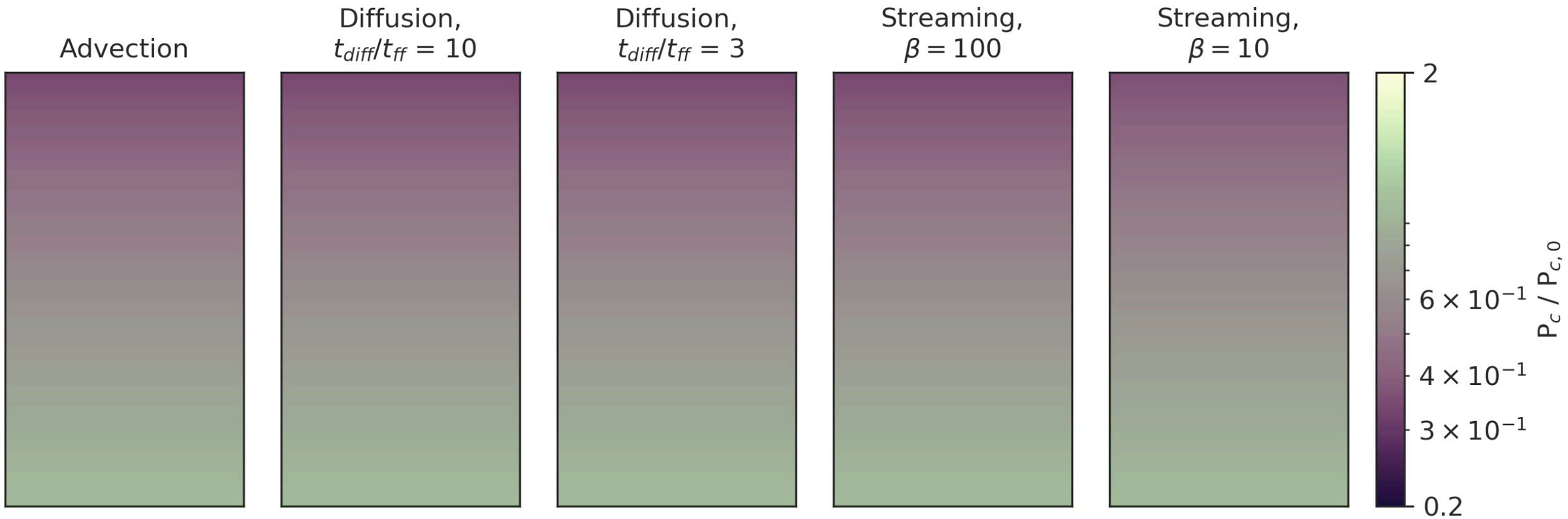


Cosmic ray transport: **streaming** and **diffusion**



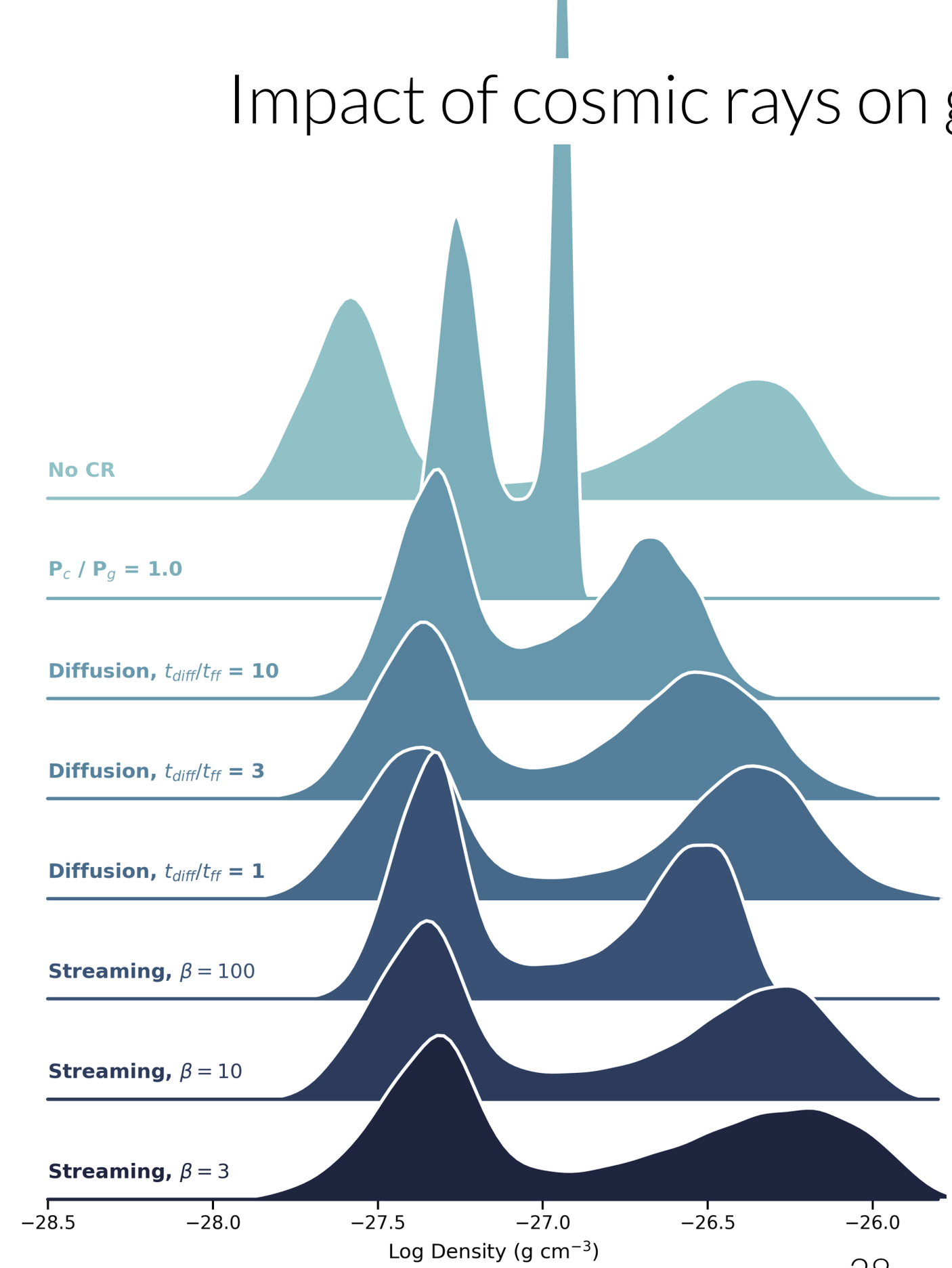
Cosmic rays move **down** their energy gradient, **along** magnetic field lines

Impact of cosmic ray transport



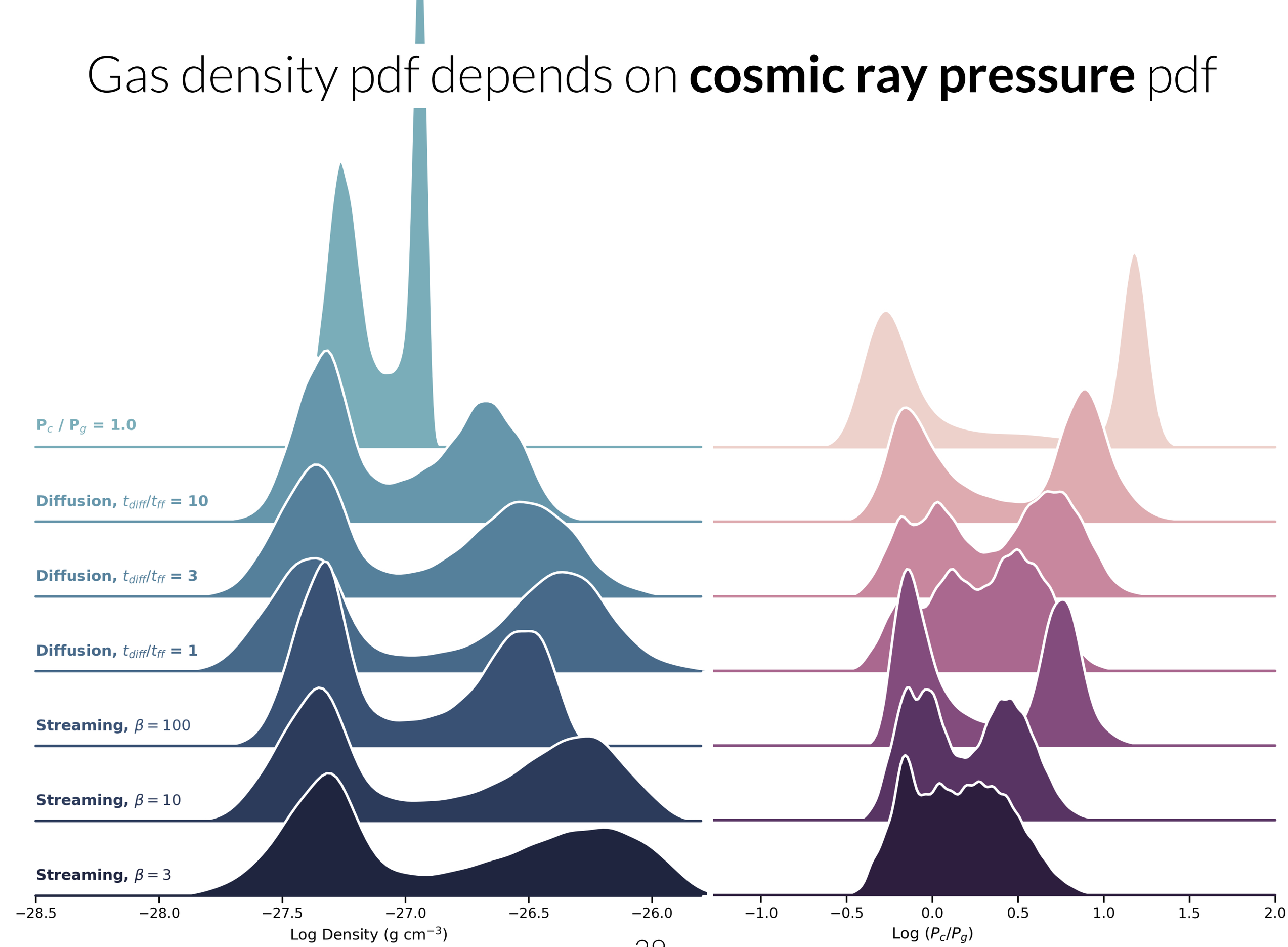
Cosmic ray transport redistributes cosmic ray pressure **from** high concentrations (in **cold gas**) **to** low concentrations (in **hot gas**)

Impact of cosmic rays on gas **density profiles**

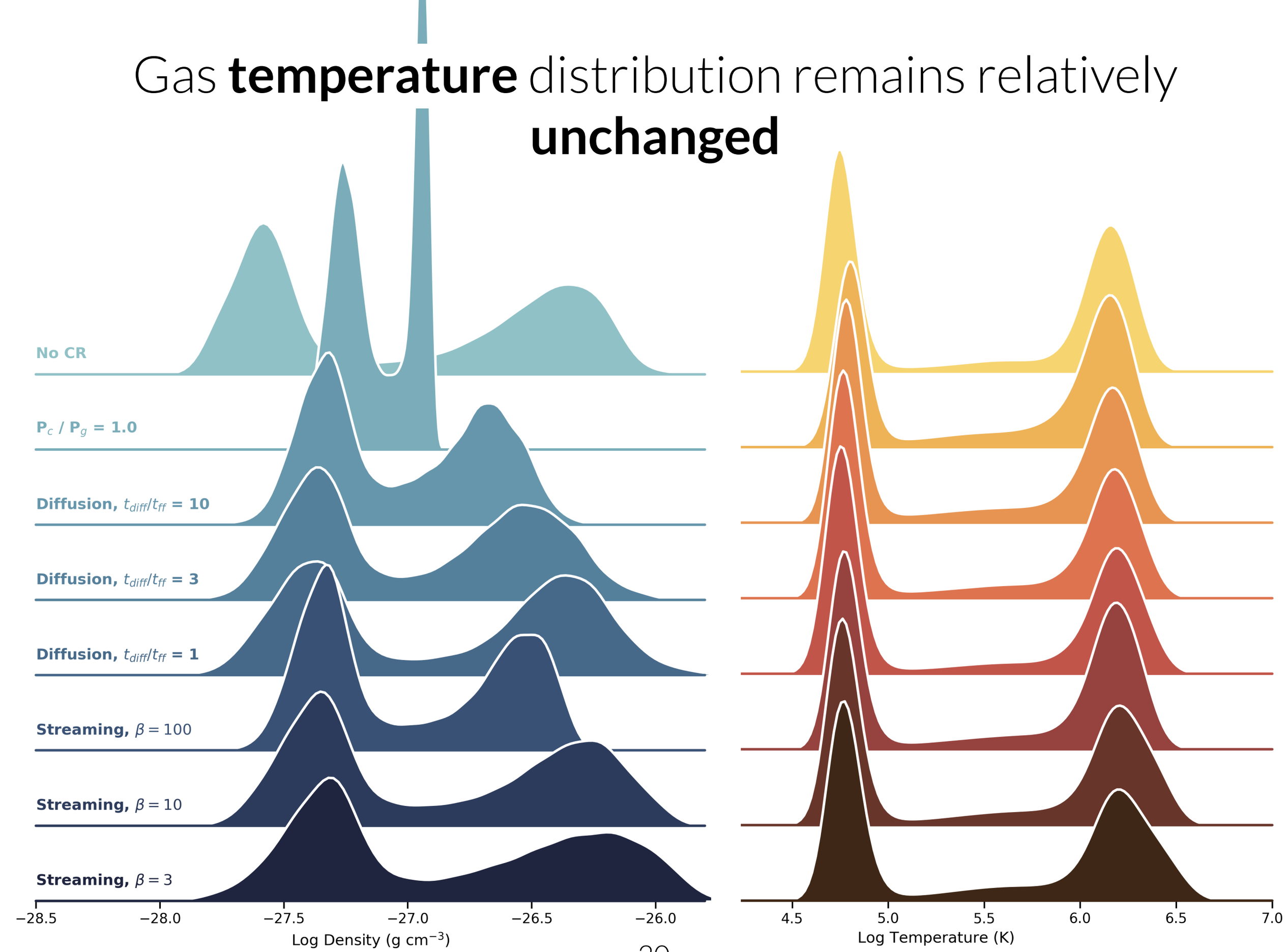


Simulations with cosmic ray transport have density distributions in between those of simulations **without cosmic rays** and simulations with cosmic rays but **without cosmic ray transport**

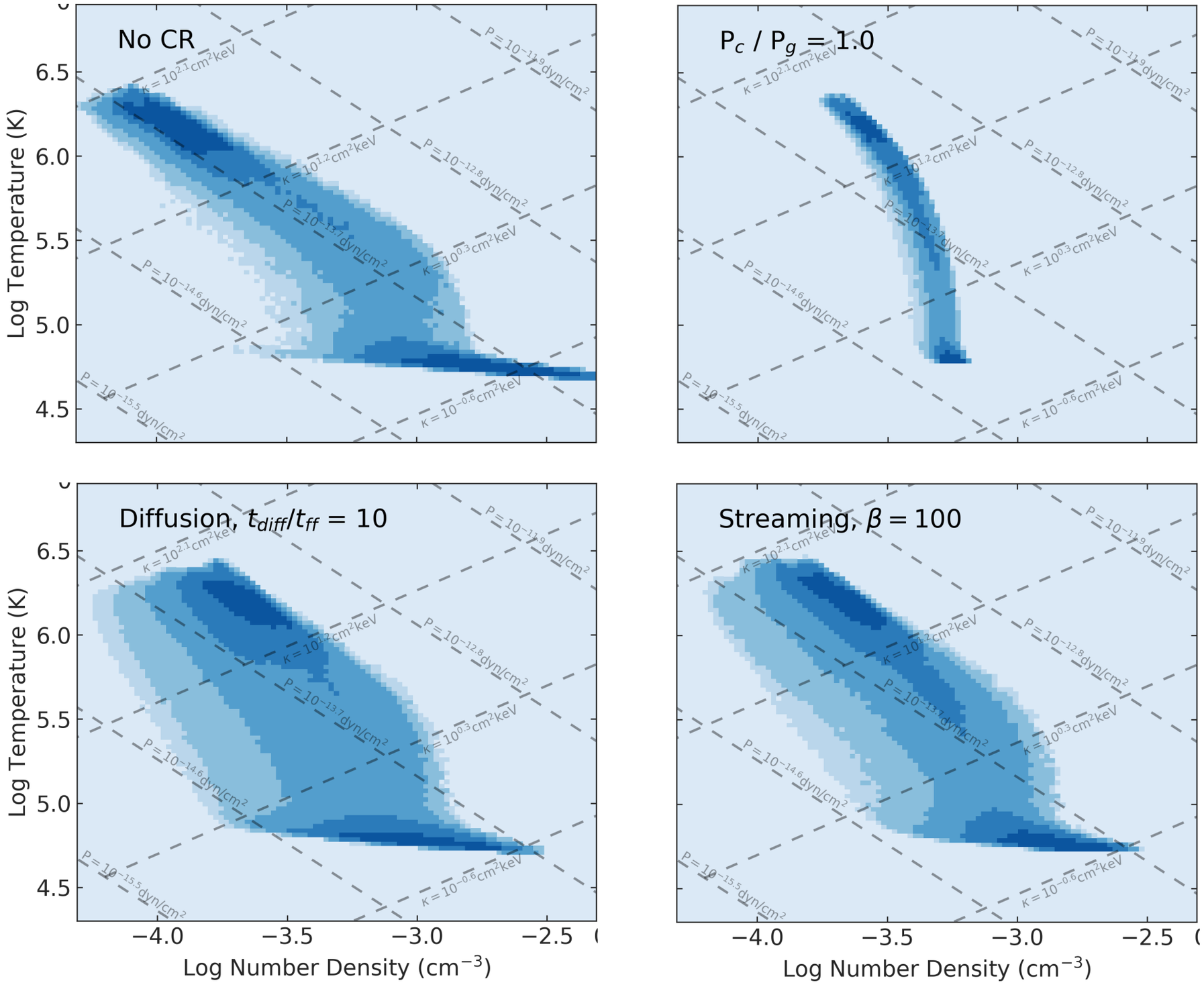
Gas density pdf depends on **cosmic ray pressure** pdf



Gas **temperature** distribution remains relatively **unchanged**



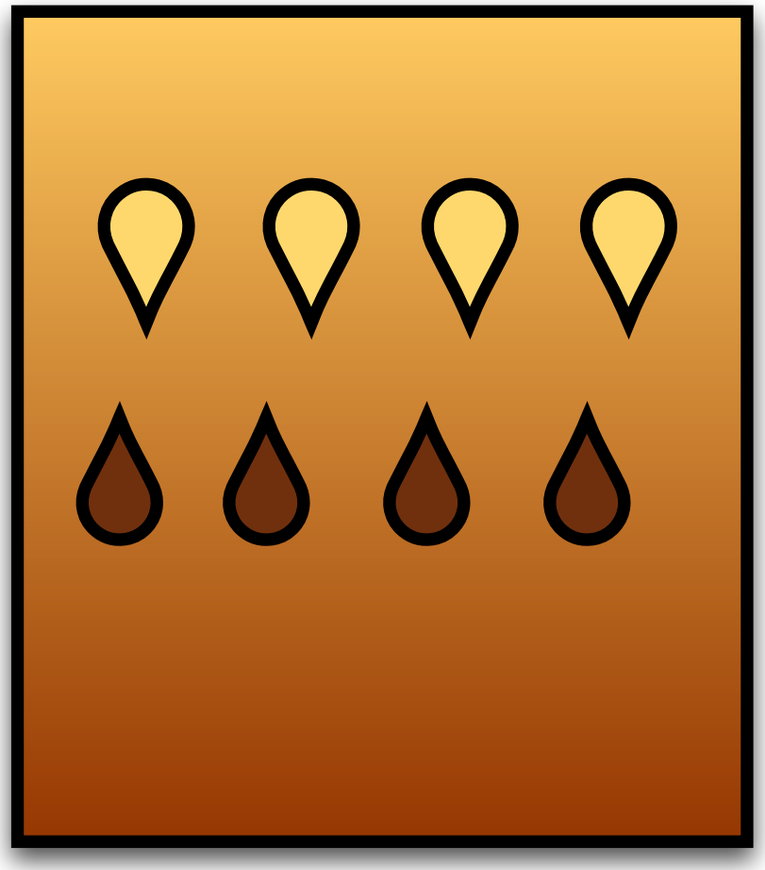
Cosmic ray transport **fills larger** density-temperature **phase space**

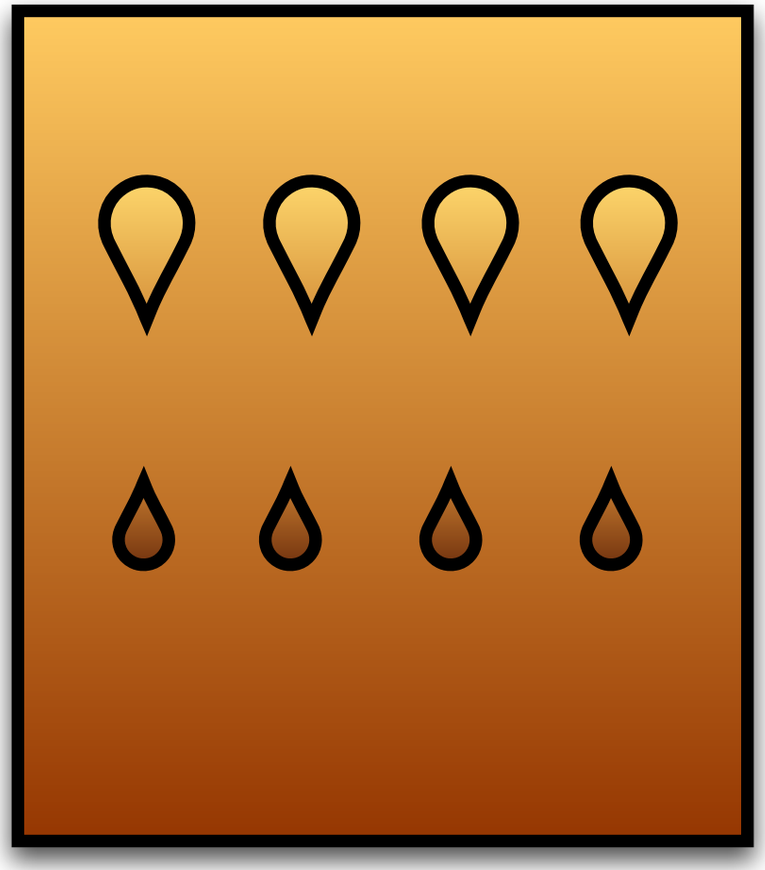


Cosmic Rays and Thermal Instability

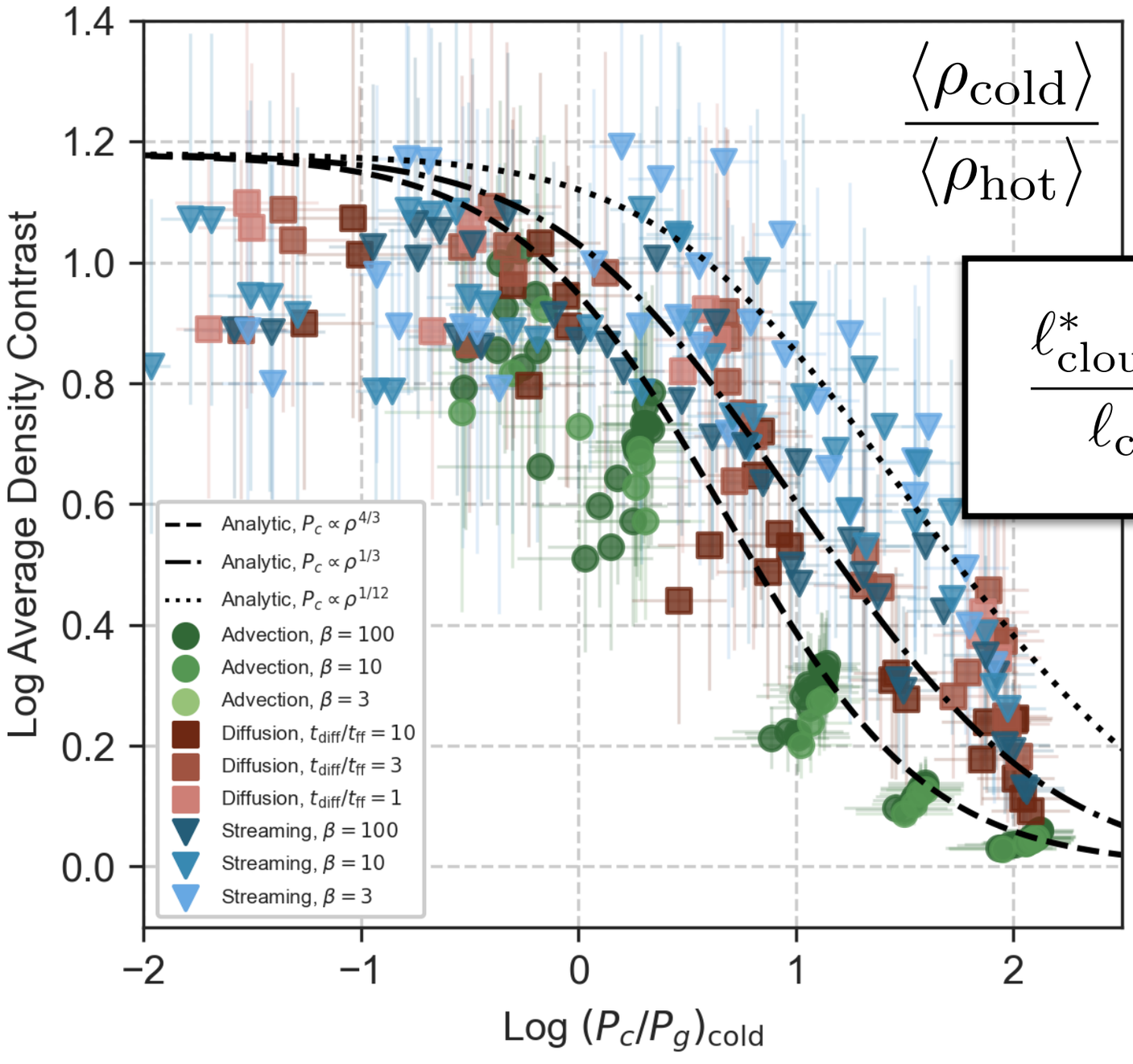
pressure

transport





Non-thermal pressure support **decreases cold gas density** and **increases size of cold clouds**



$$\ell_{\rm cloudlet} \sim \min(c_{\rm s} t_{\rm cool})$$

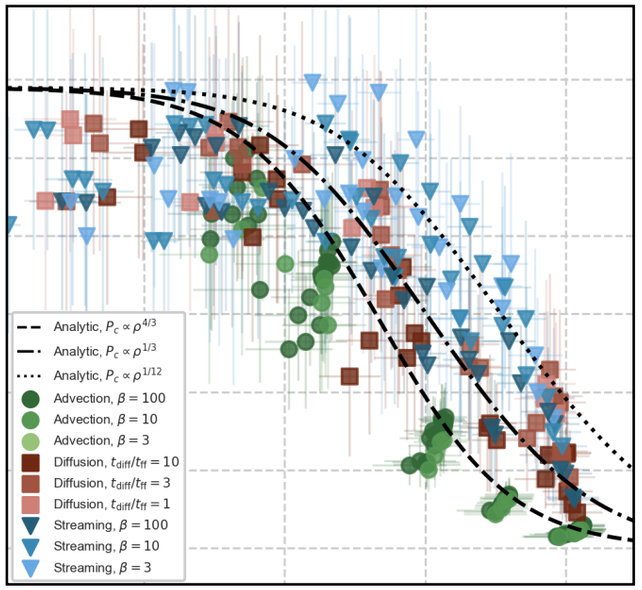
$$\frac{\ell^*_{\rm cloudlet,\eta\gg1}}{\ell_{\rm cloudlet}} \approx \Theta \left(\frac{\gamma_{\rm c,eff}}{\gamma} \eta_{\rm cold} \right)^{1/2}$$

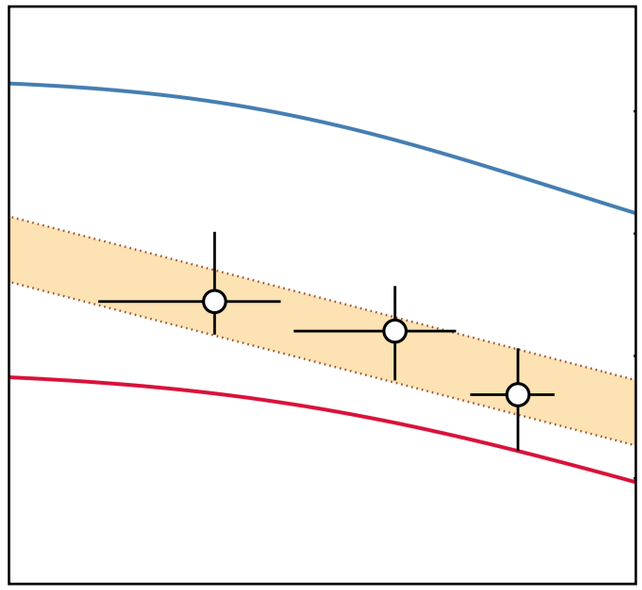
$$\Theta = T_{\rm hot}/T_{\rm cold}$$

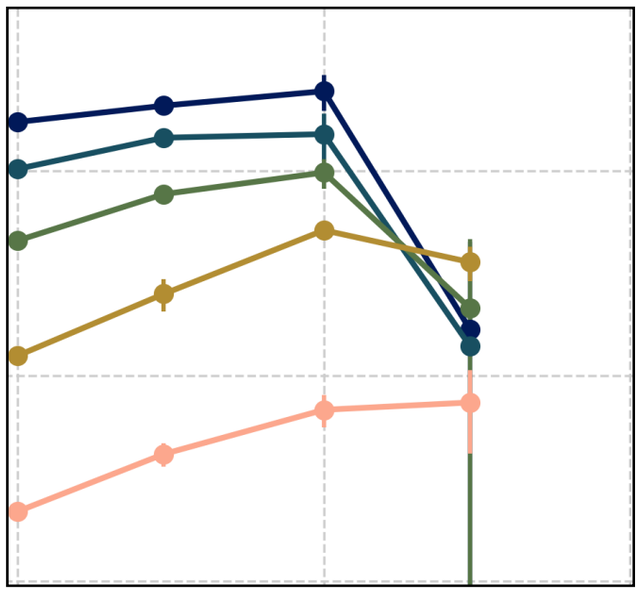
$$\eta = P_{\rm c}/P_{\rm g}$$

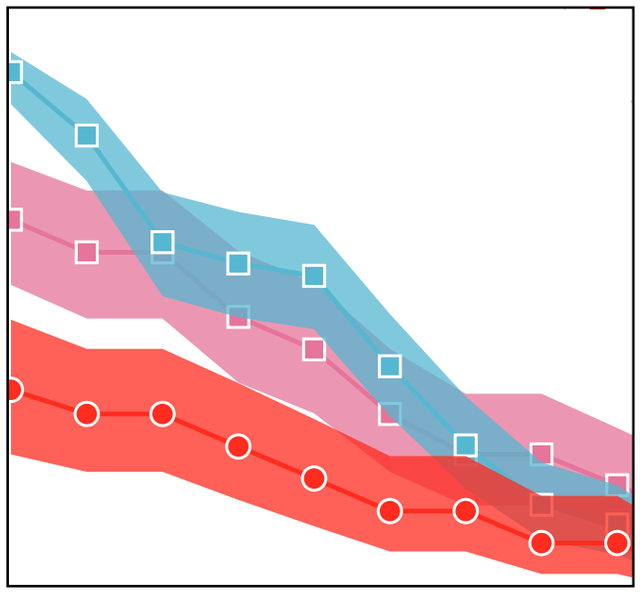
In summary, **accurate interpretations** of CGM observations **need to account for** the presence of **cosmic rays.**

for example, cosmic rays **decrease** cold gas density and **increase** cold cloud sizes









cosmic ray pressure can also **decrease** cold gas **accretion rates**