# Cosmic Ray Transport, Energy Loss, and Influence in the Multiphase ISM

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Reference: Bustard and Zweibel 2021, ApJ 913, 106
(https://arxiv.org/abs/2012.06585)

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# Cosmic Ray Confinement

Extrinsic Turbulence (E > 300 GeV)

- Cosmic rays scatter off waves in a turbulent cascade
- Propagation is diffusive along magnetic field lines
- Cosmic rays *don't* transfer energy to gas

Self-confinement (E < 300 GeV)

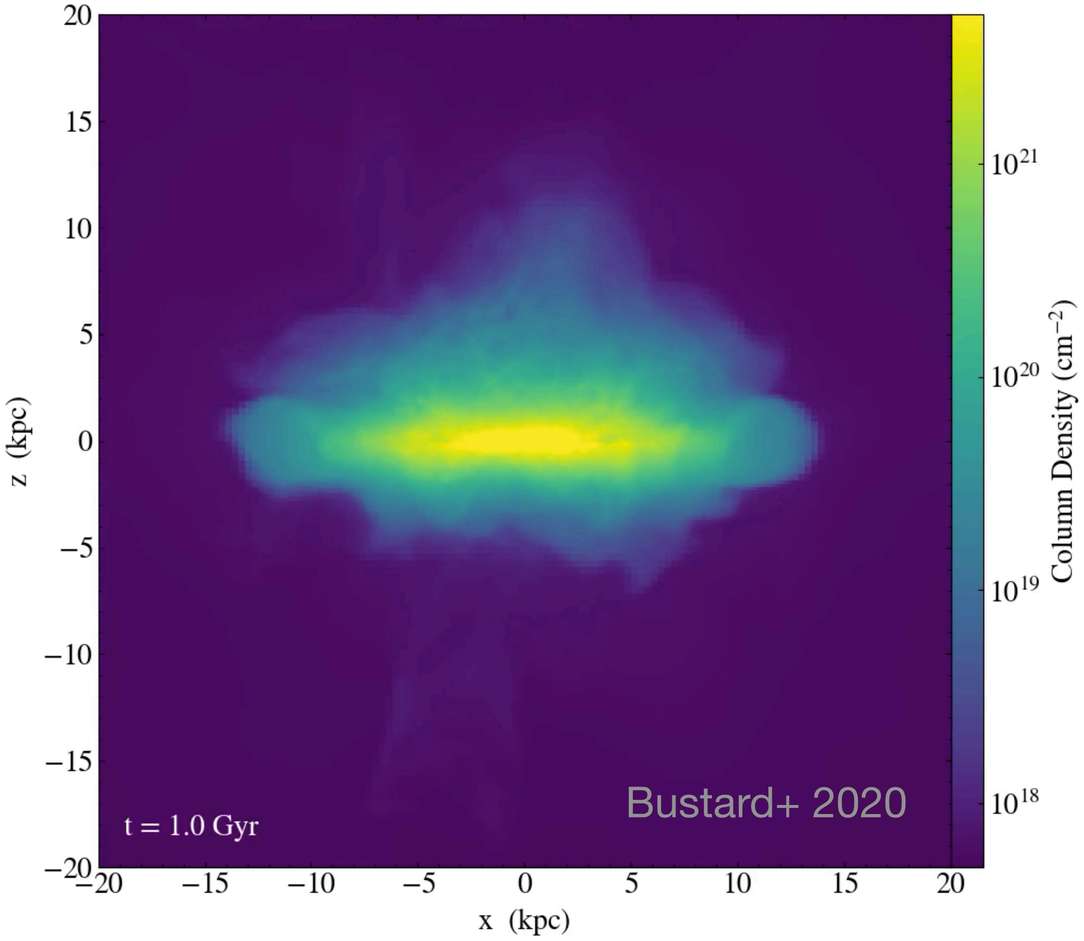
- Cosmic rays scatter off waves driven by a resonant **streaming** instability
- Propagation is at ~ Alfven speed

$$v_A^{ion} = \frac{B}{\sqrt{4\pi\rho_{ion}}}$$

- Cosmic rays *do* transfer energy to the gas

**Confinement leads to finite cosmic ray scale heights**

$$\nabla P_{CR}$$



CR-driven winds displace gas from galaxies, regulating star formation*

*See e.g. Ipavich 1975, Breitschwerdt+ 1991, Everett+ 2008, Uhlig+ 2012, Hanasz+ 2013, Salem and Bryan 2014, Ruszkowski+ 2017, Farber+ 2018, Mao and Ostriker 2018, Chan+ 2019, Buck+ 2020, Hopkins+ 2020, 2021, Yohan and Dubois 2020, Quataert+ 2021*

Cosmic rays help drive outflows to large distances

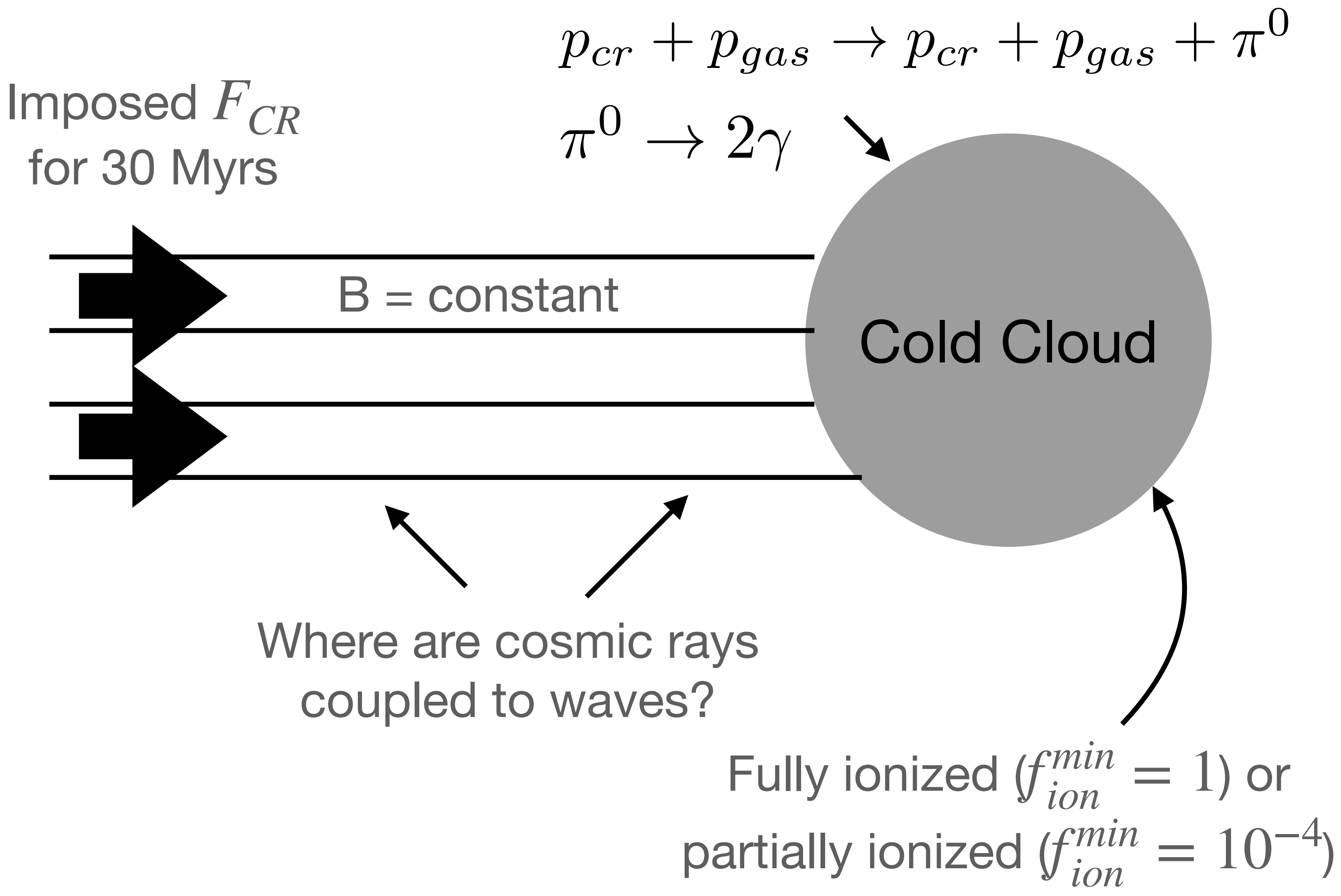
Cosmic rays accelerate and pressurize cold clouds in the CGM

Cosmic rays modify thermal instability/ precipitation

. . .

Sensitive to when, where, and how cosmic rays scatter, transfer energy + momentum, etc.

Complicated by multiphase structure (possibly sub-grid)



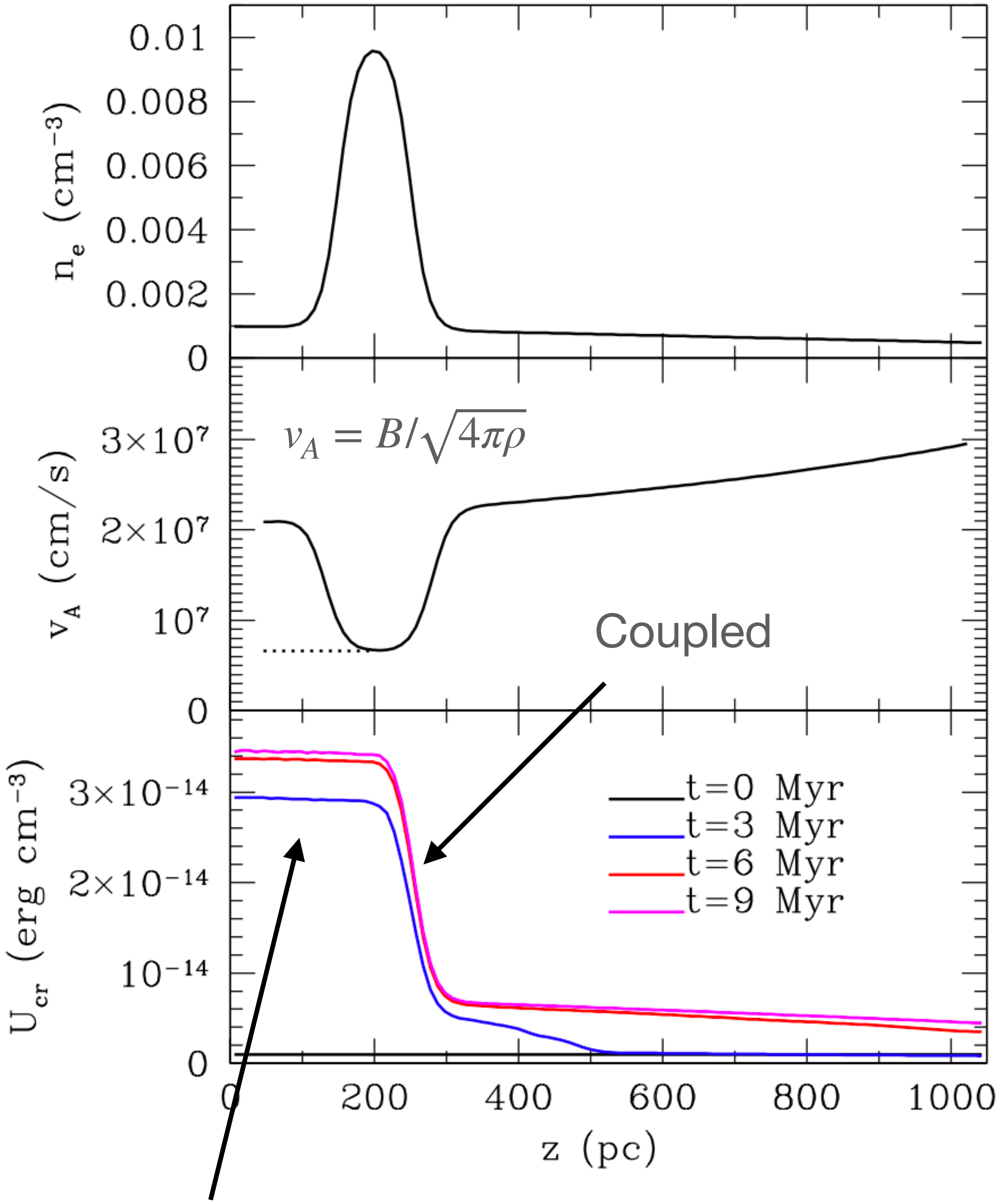
### MHD Simulations w/Athena++

- Evolve cosmic ray energy $E_{cr}$ and flux $F_{cr}$ using two-moment technique borrowed from radiative transfer *(Jiang and Oh 2018)*
- *Transport*: Streaming at $v_A^{ion}$, diffusion due to ion-neutral damping (following *Hopkins+ 2021)*
- “Collisionless” energy loss + hadronic and Coulomb collisions included

# Self-Confinement and Bottlenecks

*Kulsrud and Pearce 1969, Skilling 1971, Kulsrud 2005, Zweibel 2017, Wiener+ 2017, 2019*

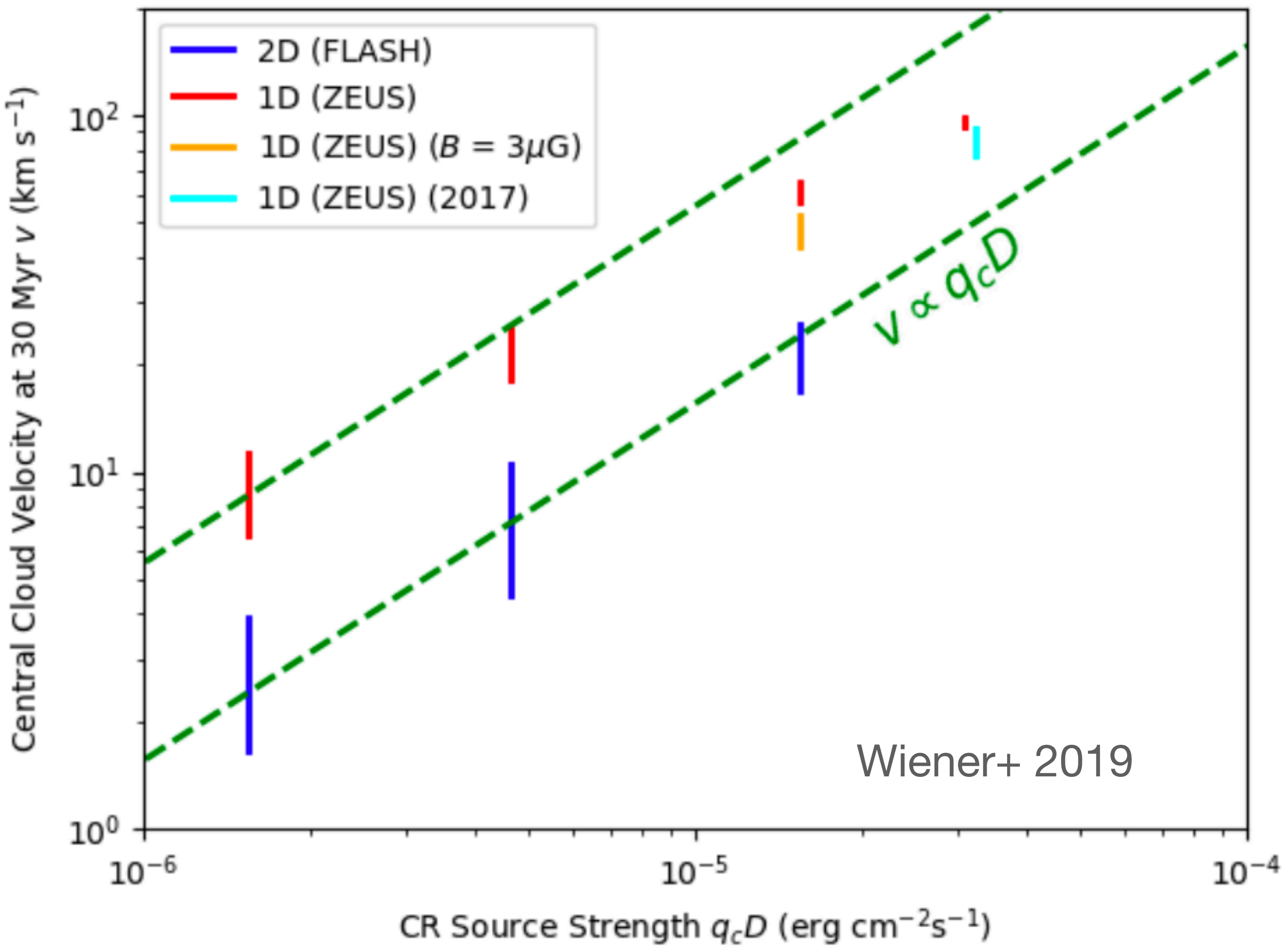
- **When $\nabla P_{CR} \neq 0$, resonant streaming instability excites forward-traveling Alfven waves**
  - $v_{st} = \dfrac{B \cdot \nabla P_{CR}}{|B \cdot \nabla P_{CR}|} v_A^{ion}$
  - Alfven wave damping heats the gas ("collisionless" energy loss)
    - $dE_{CR}/dt \sim - v_A^{ion} \cdot \nabla P_{CR}$
    - $dE_g/dt \sim v_A^{ion} \cdot \nabla P_{CR}$
  - Tightly coupled CRs trace density perturbations: $P_{cr} \sim v_A^{-4/3} \sim \rho^{2/3}$
- **If $\nabla P_{CR} = 0$, no waves are excited**
  - Cosmic rays free-stream
  - This situation arises at density inhomogeneities! "Free-zones" — *Skilling (1971)*

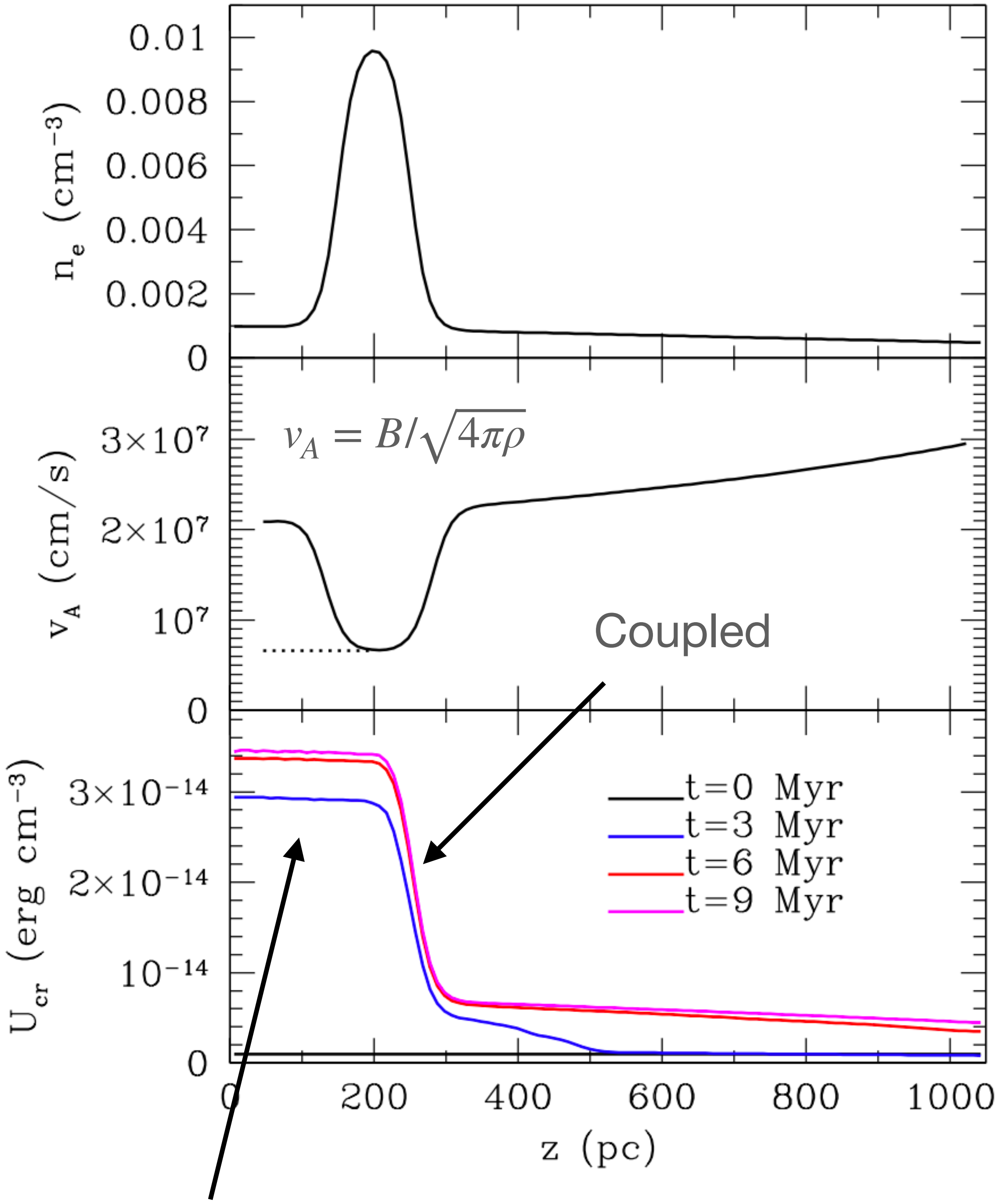


Wiener+ 2017

# Self-Confinement and Bottlenecks

*Kulsrud and Pearce 1969, Skilling 1971, Kulsrud 2005, Zweibel 2017, Wiener+ 2017, 2019*





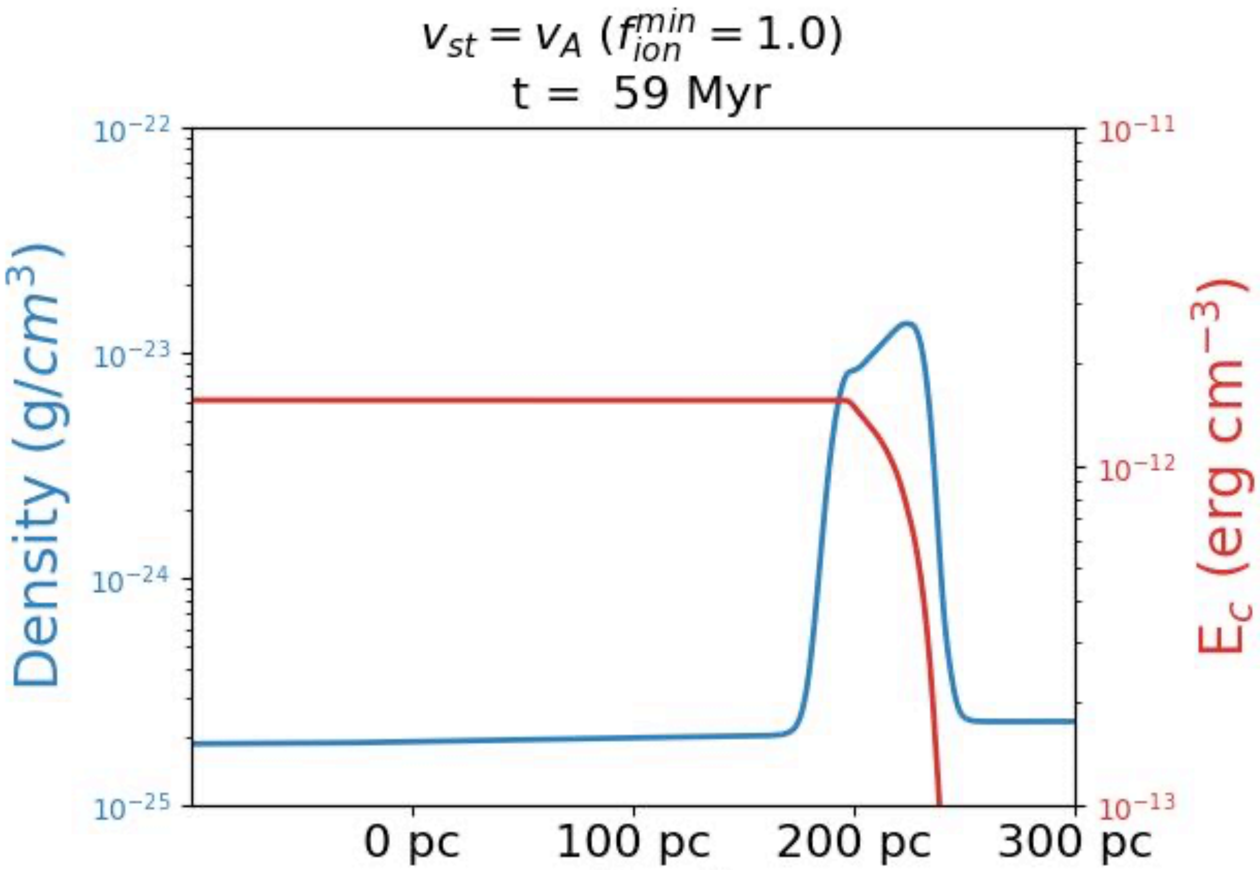
Uncoupled

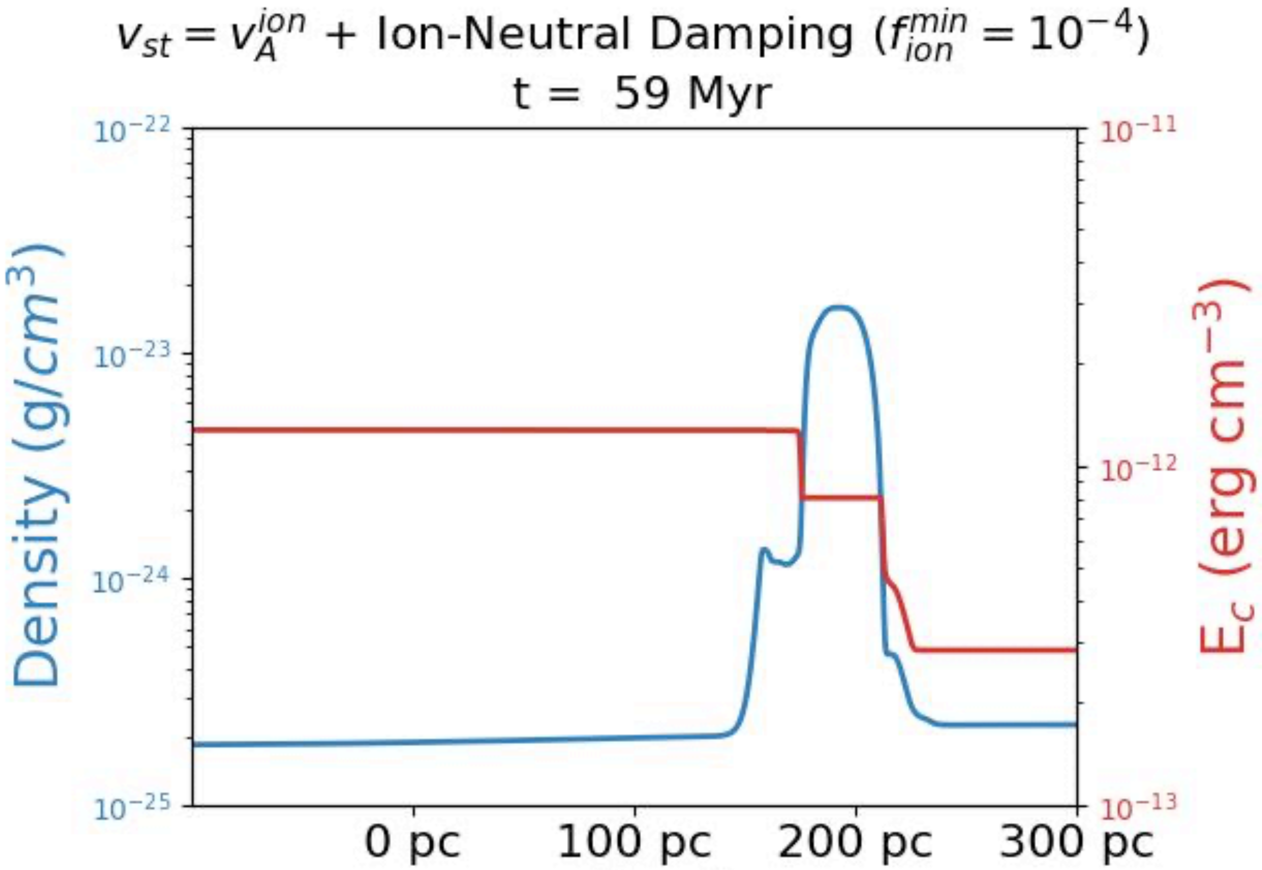
Wiener+ 2017

- **If $\nabla P_{CR} = 0$, no waves are excited**
  - Cosmic rays free-stream
  - This situation arises at density inhomogeneities! “Free-zones” — *Skilling (1971)*

# Transport

# 1D Simulations


$v_{st} = v_A$ ($f_{ion}^{min} = 1.0$)
t = 59 Myr


$v_{st} = v_A^{ion}$ + Ion-Neutral Damping ($f_{ion}^{min} = 10^{-4}$)
t = 59 Myr

## Fiducial Parameters

Cloud radius: $r_c = 10\text{pc}$

Cloud density: $n_c \approx 10\text{cm}^{-3}$

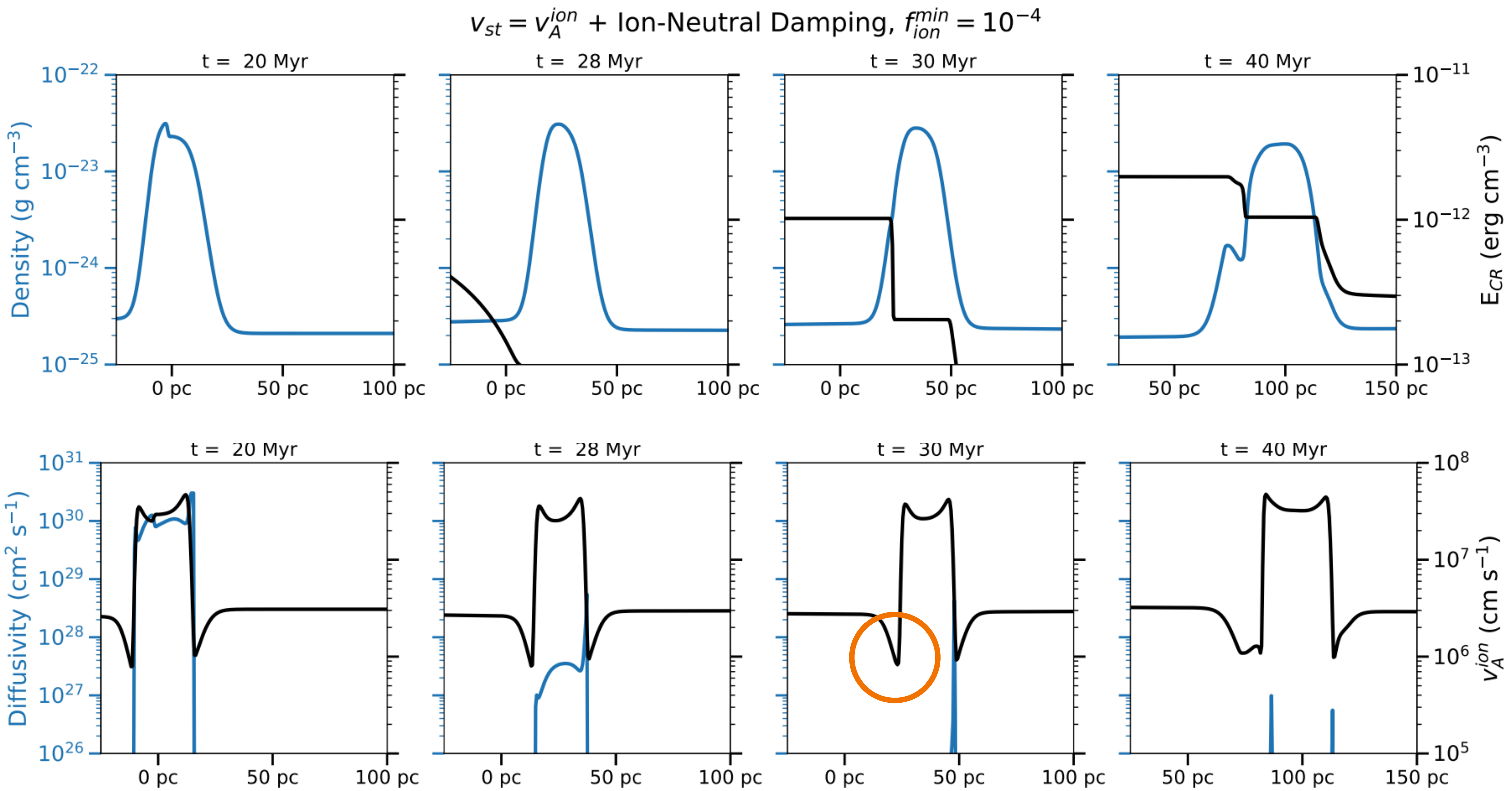
Magnetic field: $B \approx 5\mu G$

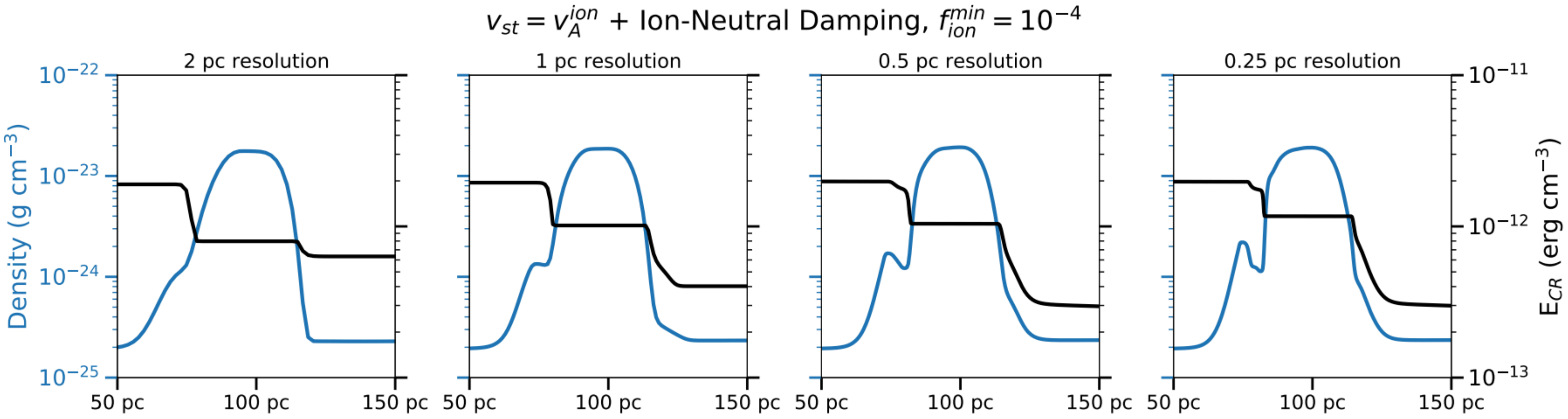
Interface width: $t_c = 5\text{pc}$

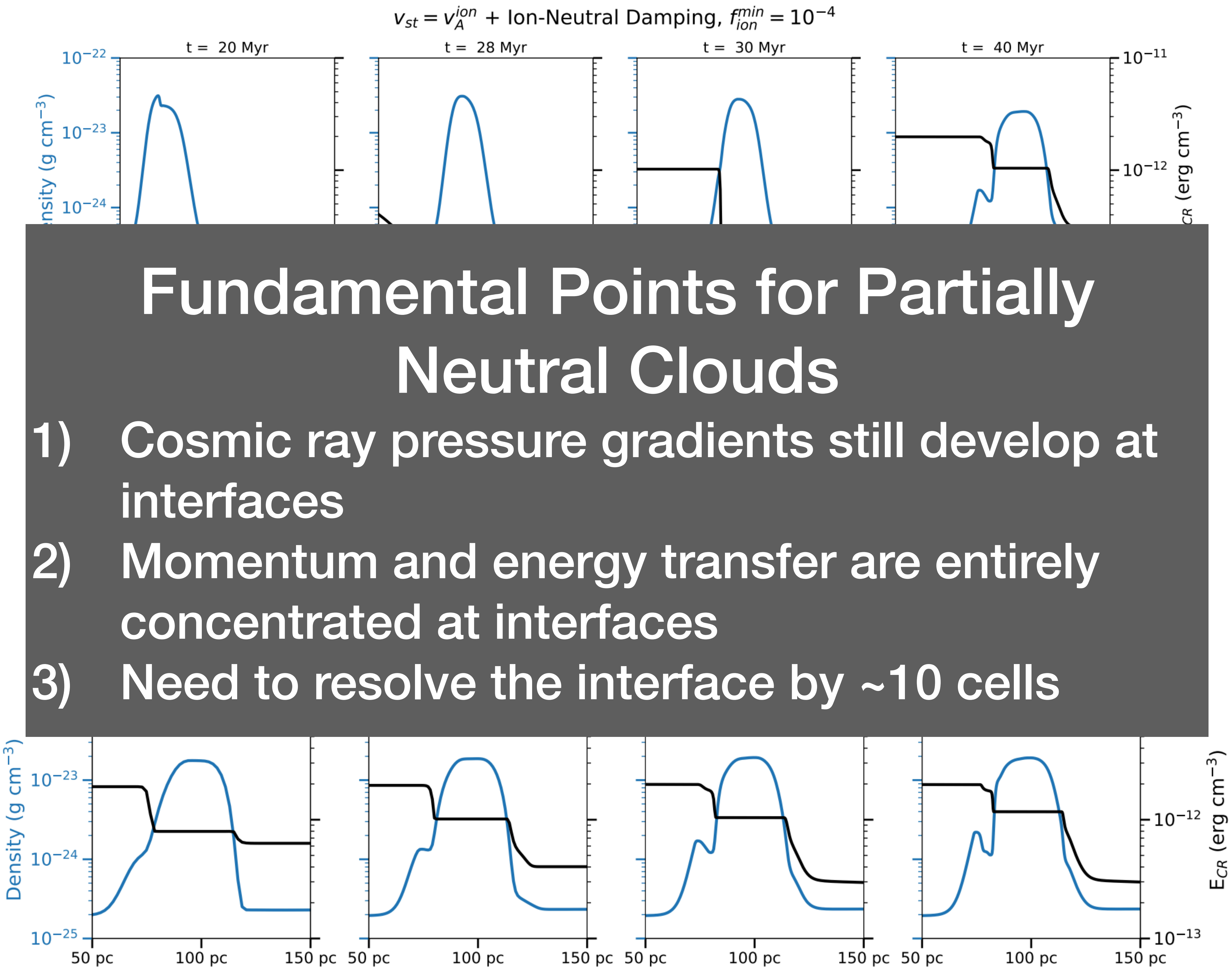
Plasma beta: $\beta = P_g / P_B \approx 1.6$

**Simplifying assumptions:** No gravity, no radiative cooling, $P_{cr}/P_g \sim 1$ regime

# Cosmic Rays and Cold Clouds (Bustard + Zweibel 2021)





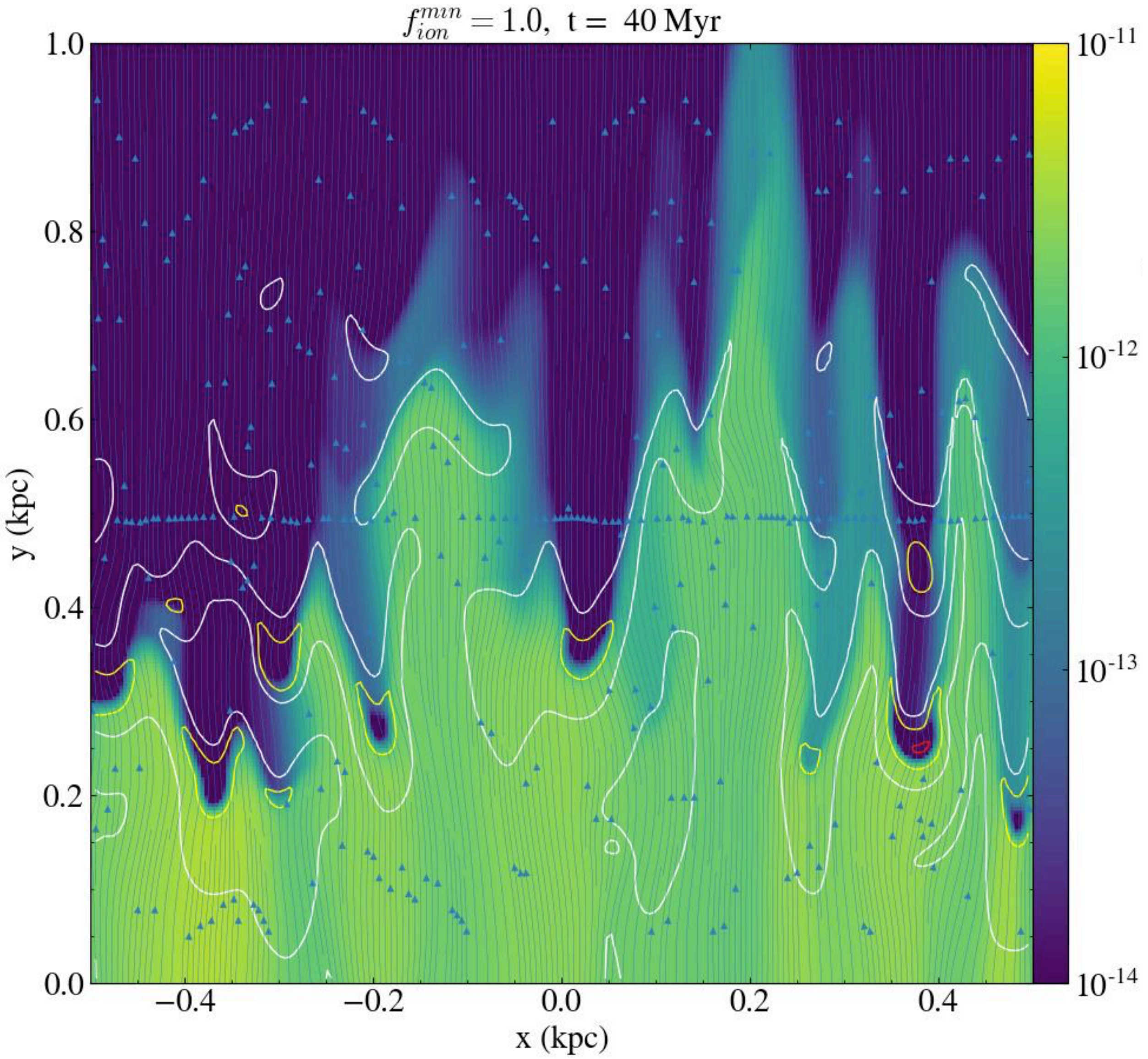


$v_{st} = v_A^{ion}$ + Ion-Neutral Damping, $f_{ion}^{min} = 10^{-4}$

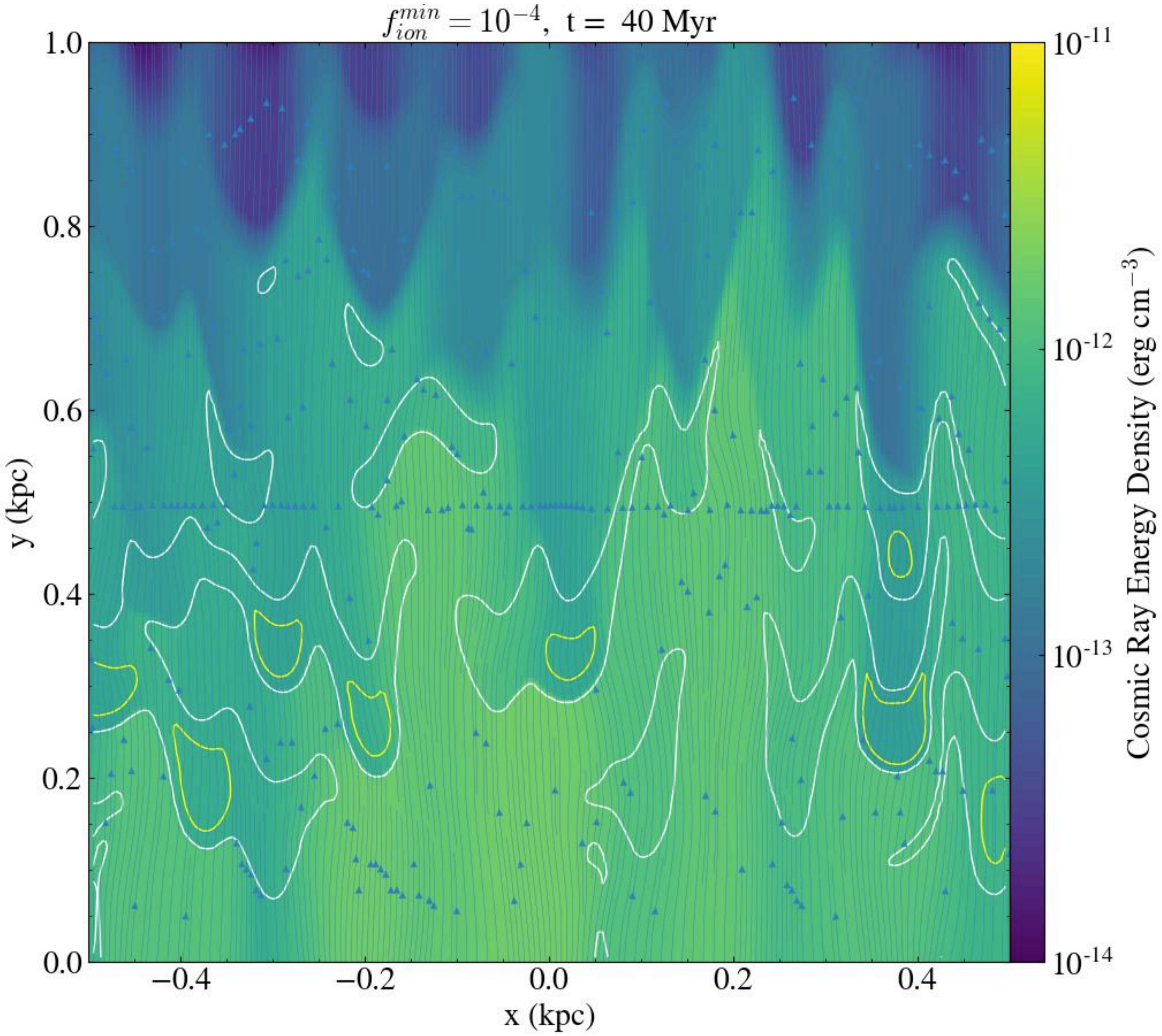
# Fundamental Points for Partially Neutral Clouds

1) Cosmic ray pressure gradients still develop at interfaces
2) Momentum and energy transfer are entirely concentrated at interfaces
3) Need to resolve the interface by ~10 cells

## Assuming Fully Ionized Gas

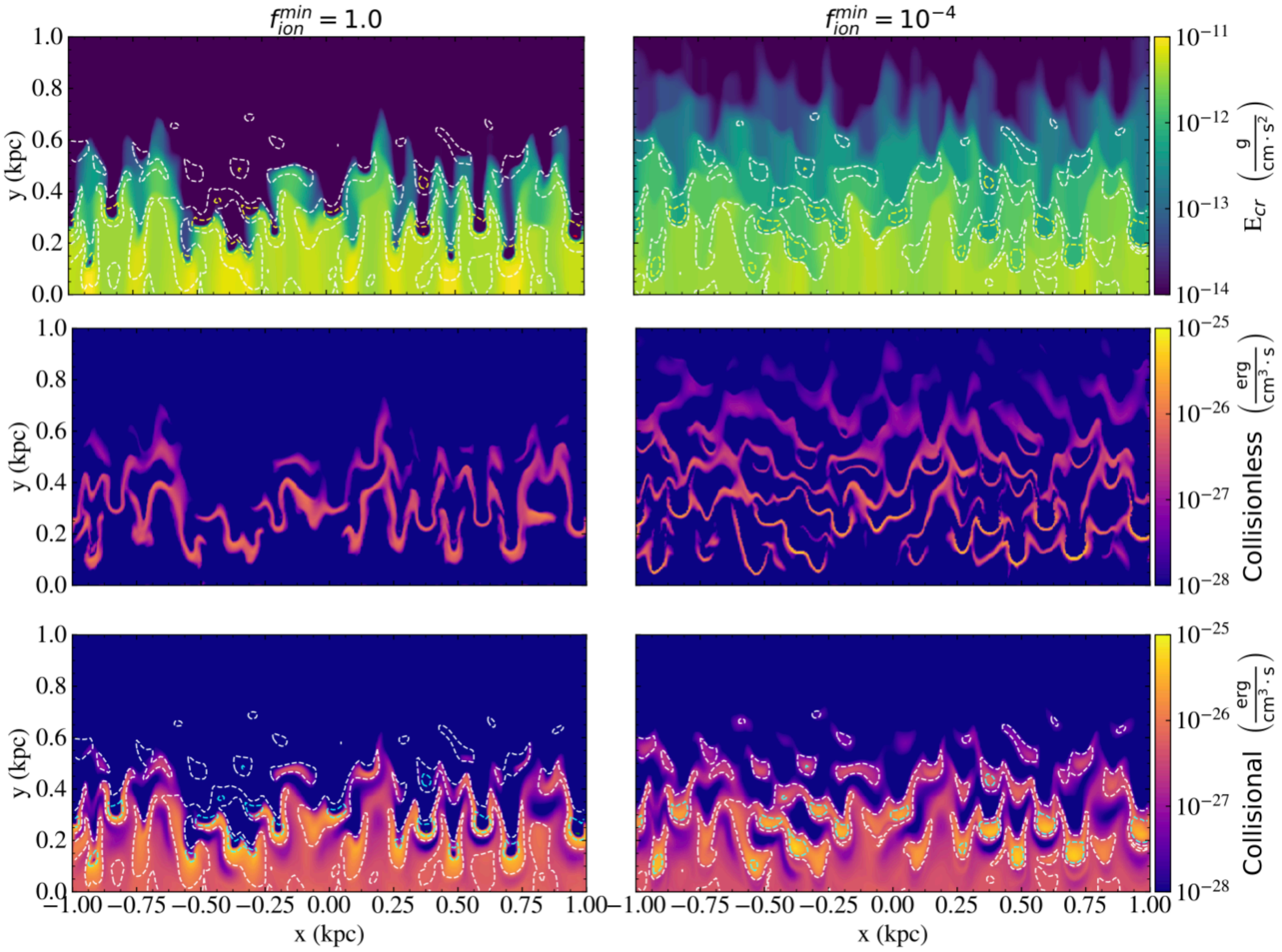


## Ionization-Dependent Transport



# Energy Loss

# Cosmic Rays and Cold Clouds (Bustard + Zweibel 2021)



$\propto v_A \cdot \nabla P_{cr}$

$\propto nE_{cr}$

Assuming fully ionized

Collisionless energy transfer is **distributed throughout the cloud**

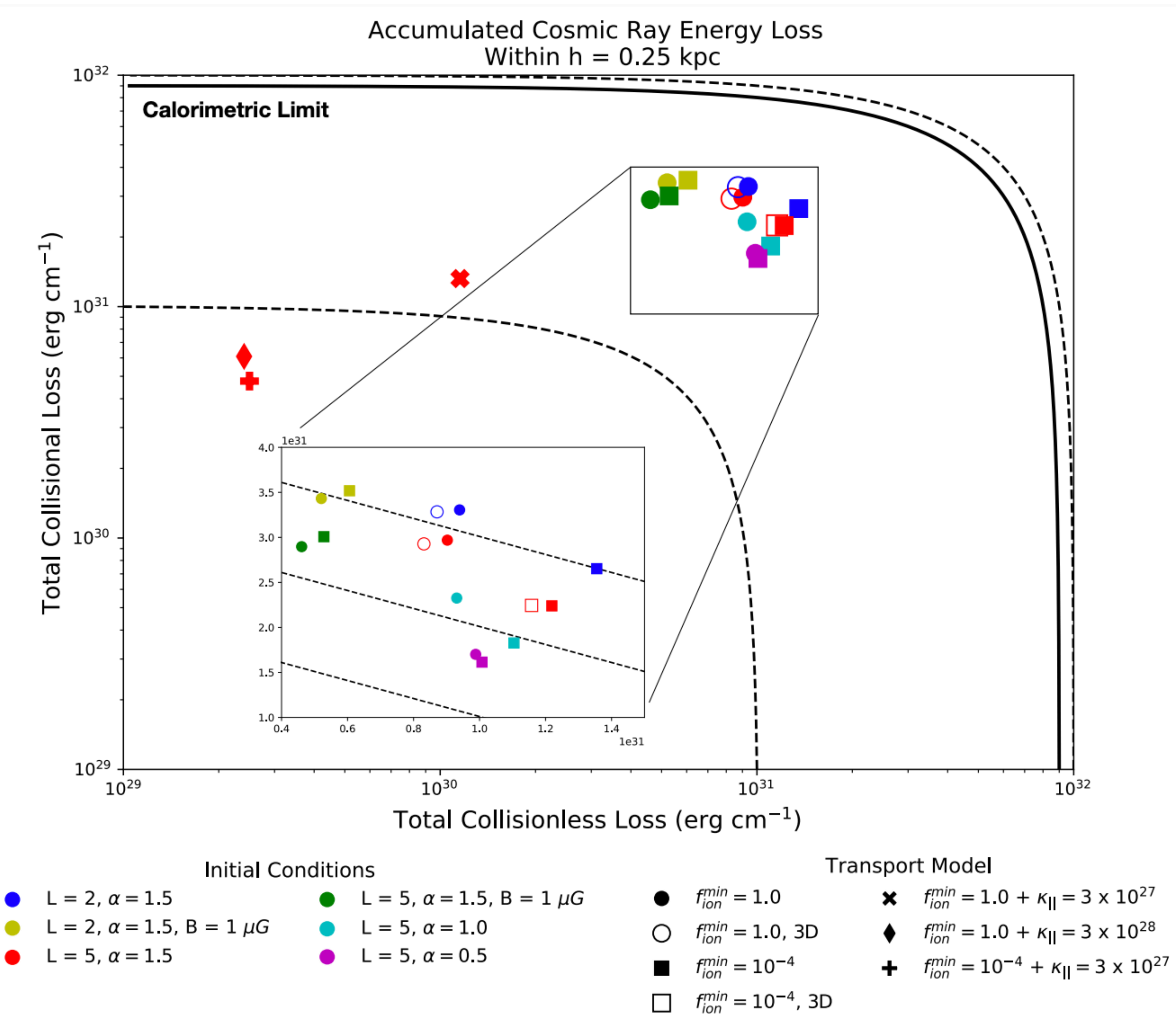
Collisions are biased towards **cloud interfaces**

Varying ionization

Collisionless energy transfer is **focused at cloud interfaces**

Collisions are biased towards **cloud interiors**

# Cosmic Rays and Cold Clouds (Bustard + Zweibel 2021)



Fast transport in partially neutral clouds doesn't greatly affect the **total** energy loss

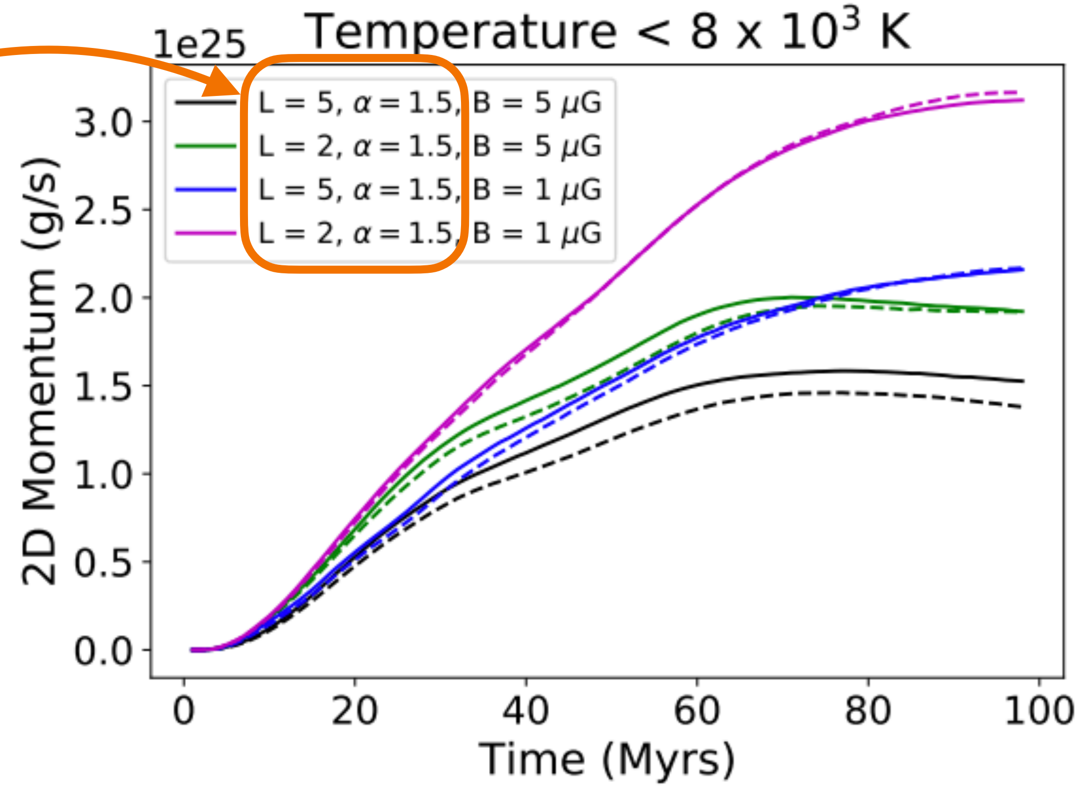
- Additional diffusivity in diffuse, ionized gas will decrease gamma-ray emission — possibly necessary for simulations to match Fermi-LAT luminosities of external galaxies *(Chan+ 2019, Hopkins+ 2021)*

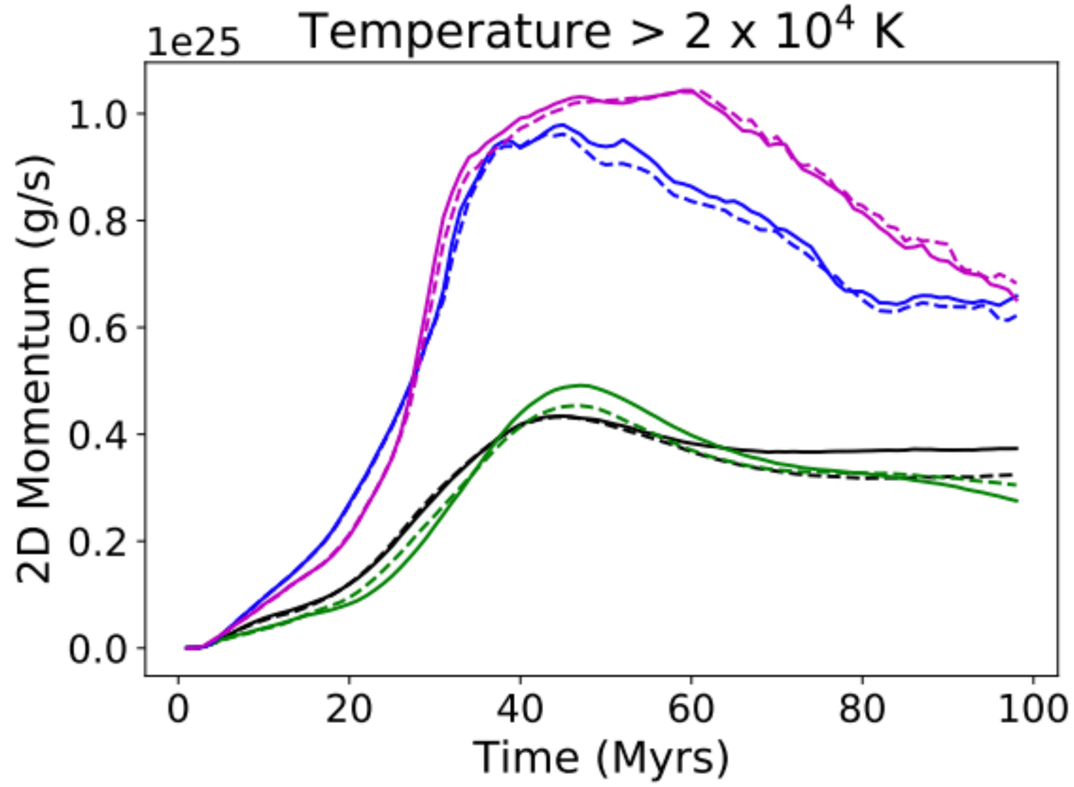
# Influence

# Implications for Wind Driving

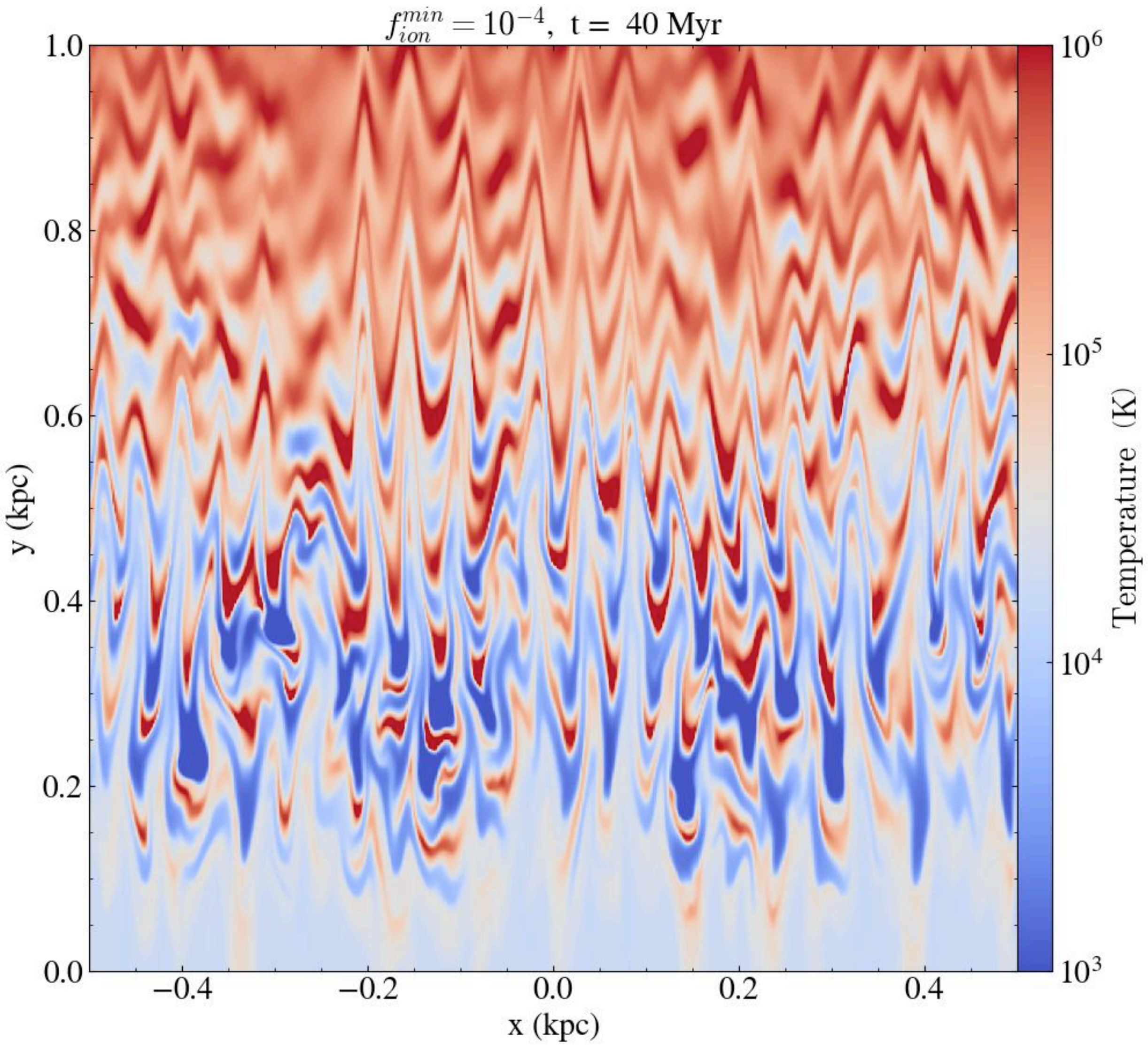
- Solid lines (fully ionized) and dashed lines (varying ionization) are pretty similar!
  - Because interfaces instigate bottlenecks, even partially neutral clouds can be accelerated
- Results are more sensitive to magnetic field strength

Different clump distributions

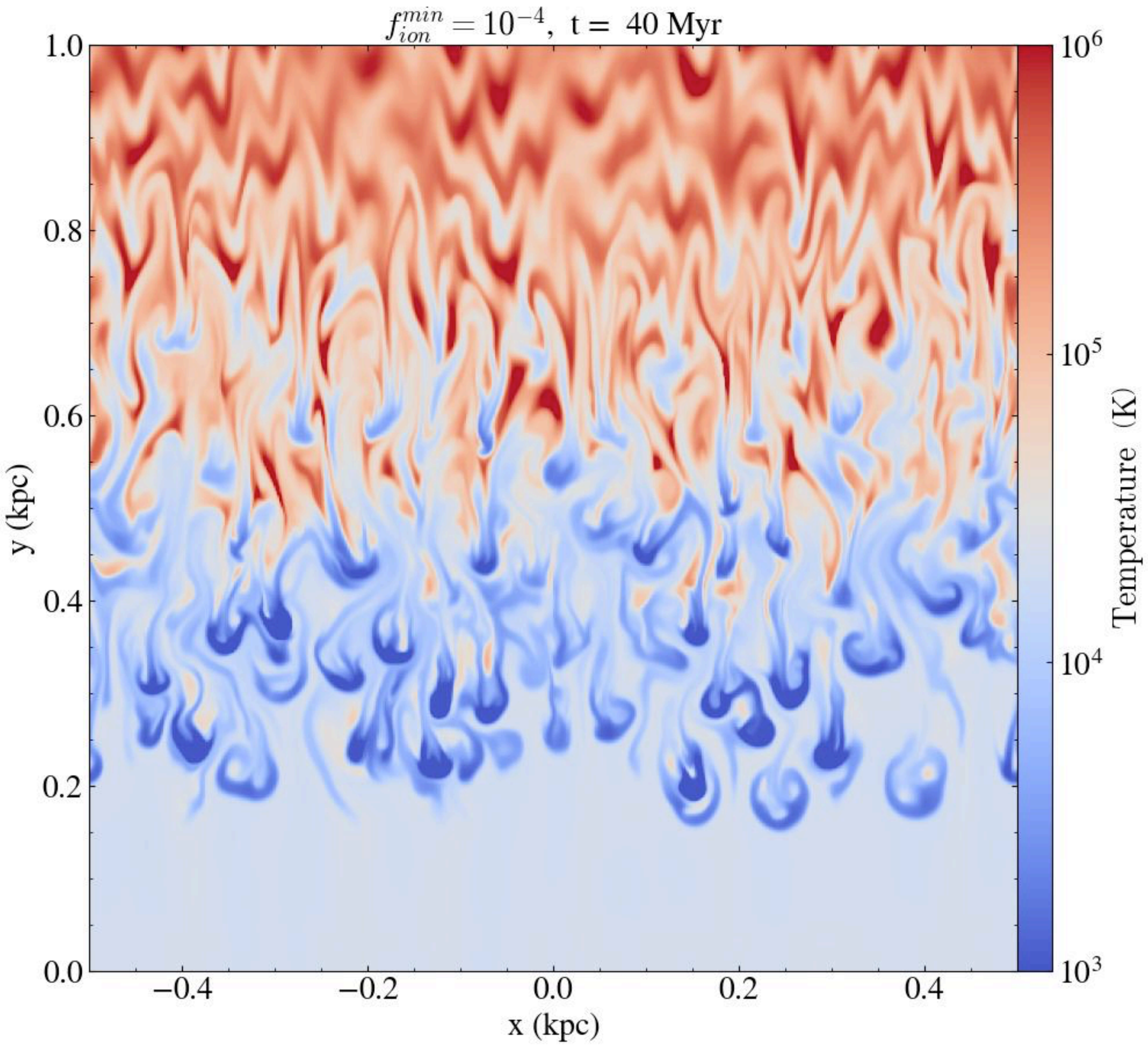




# Sensitivity to Magnetic Field Strength



$\beta \sim 1.6$ $B = 5\mu G$



$\beta \sim 40$ $B = 1\mu G$

- Perturbations drag magnetic field lines around the clouds, effectively **funneling CRs through under-dense channels of the ISM**, rather than into the clouds themselves
- CRs that "squeak through the cracks" **primarily push out the diffuse ionized gas**, rather than the cold clouds

# Conclusions

- Density irregularities in the multiphase ISM induce cosmic ray decoupling and collisionless and collisional losses

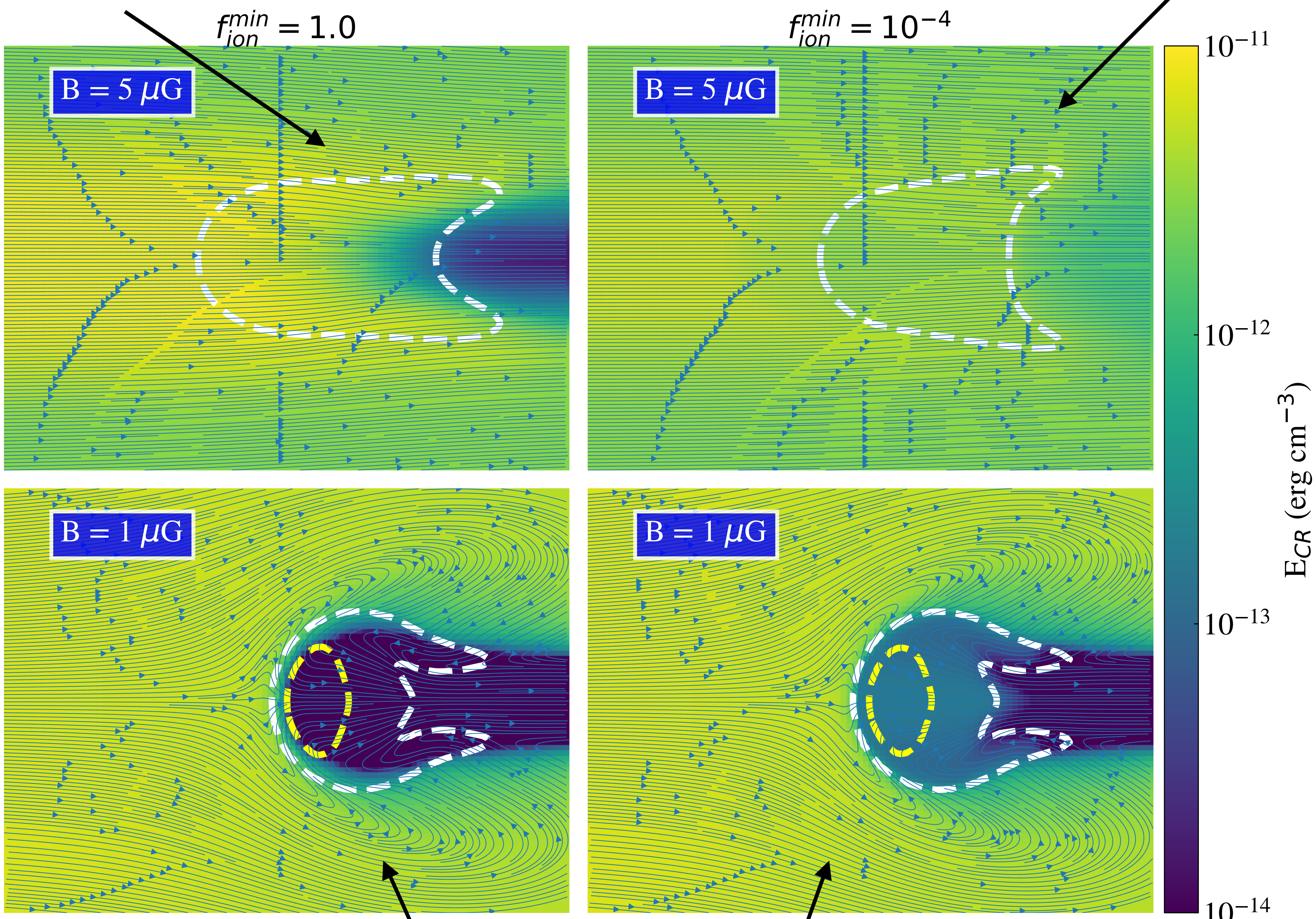
- When gas ionization is accounted for
    - Cosmic rays sample more of the ISM and lose more energy in cloud interiors
    - Less momentum is imparted to cold clouds, but only by a factor < a few
    - Cosmic ray influence is concentrated at the cloud interfaces

- Momentum transfer to clouds and spatial footprint of cosmic rays depend most sensitively on magnetic field strength/topology

- What if the clouds move in a turbulent flow? See poster: *Turbulent Reacceleration of Streaming Cosmic Rays: Fluid Simulations*, Chad Bustard and S. Peng Oh

# Additional Slides

# 2D Simulations of a Single Cloud



Cosmic ray pressure gradient stretches the cloud

Cosmic rays uniformly pressurize the cloud

Magnetic field warping pushes cosmic rays around the cloud

# Fast Transport in Partially Neutral Gas

**Ion-neutral collisions decouple ions and neutrals, damp Alfven waves, and cut off turbulent cascade** *(e.g. Kulsrud and Cesarsky 1971, Skilling 1971, Farber+ 2018, Xu and Lazarian 2017, Krumholz+ 2020)*

Streaming instability growth rate

$$\Gamma_{CR}(\gamma) \approx \frac{\pi}{4}\frac{\alpha-1}{\alpha}\Omega_0\frac{n_{CR}(>\gamma)}{n_i}\left(\frac{v_D}{v_A}-1\right) = \Gamma$$

Wave damping rate

$v_{st} > v_A$ needed to balance damping

$$\Gamma_{in} \approx 10^{-9} f_{neutral} T_{1000}^{1/2} \rho_{-24} \quad s^{-1}$$

**Plasma Alfven speed >> gas Alfven speed in partially neutral gas**

$$v_A^{ion} = \frac{v_A}{\sqrt{f_{ion}}}$$