

The dynamical impact of cosmic rays in Milky Way-like galaxies

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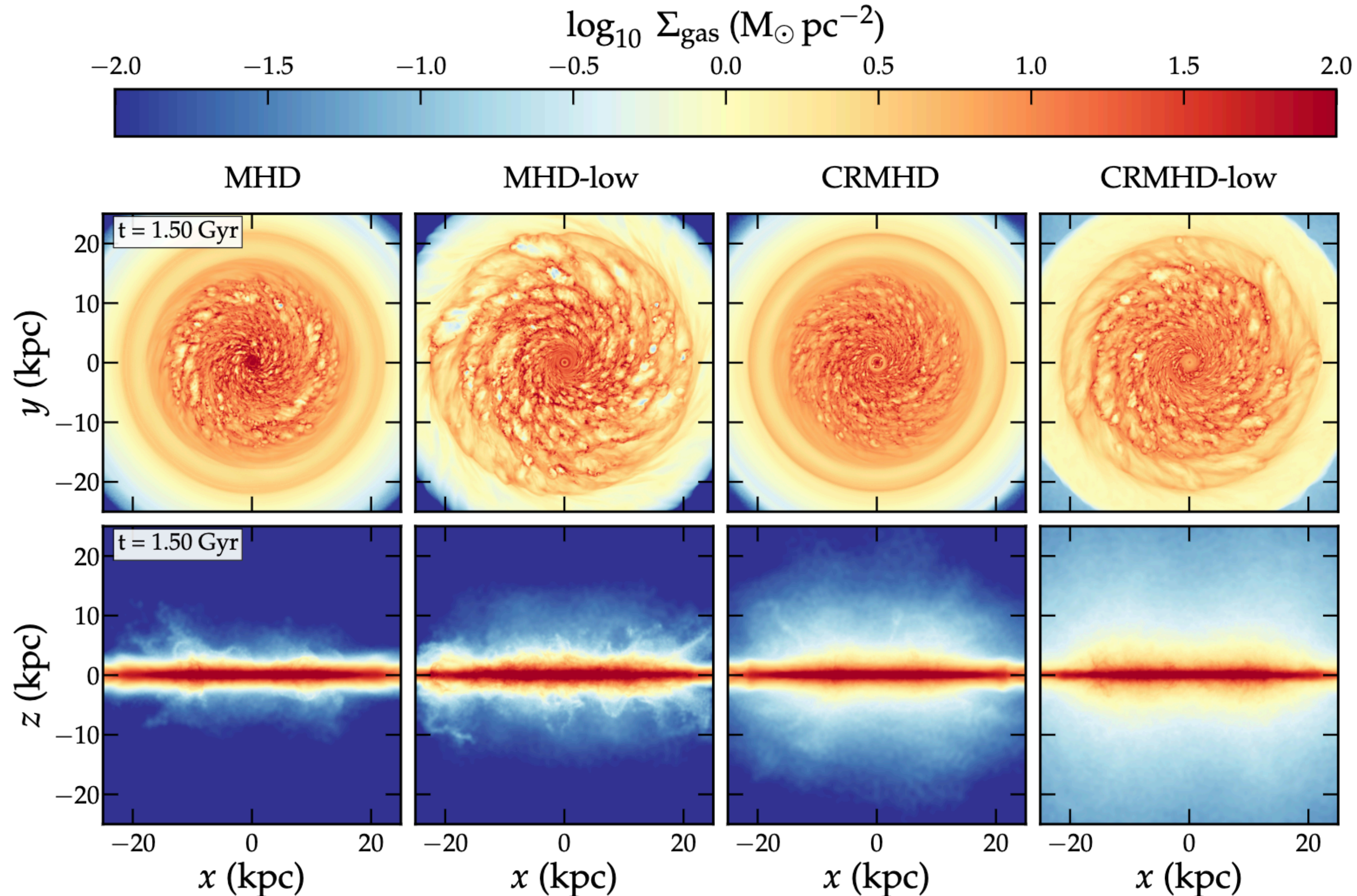
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ZENTRUM FÜR
ASTRONOMIE

The Rhea-simulations of Milky Ways

Arepo: Springel (2010),
Weinberger et al. (2020)
CRs: Pfrommer et al. (2017)
Streaming: Wiener et al. (2013),
Buck et al. (2020)

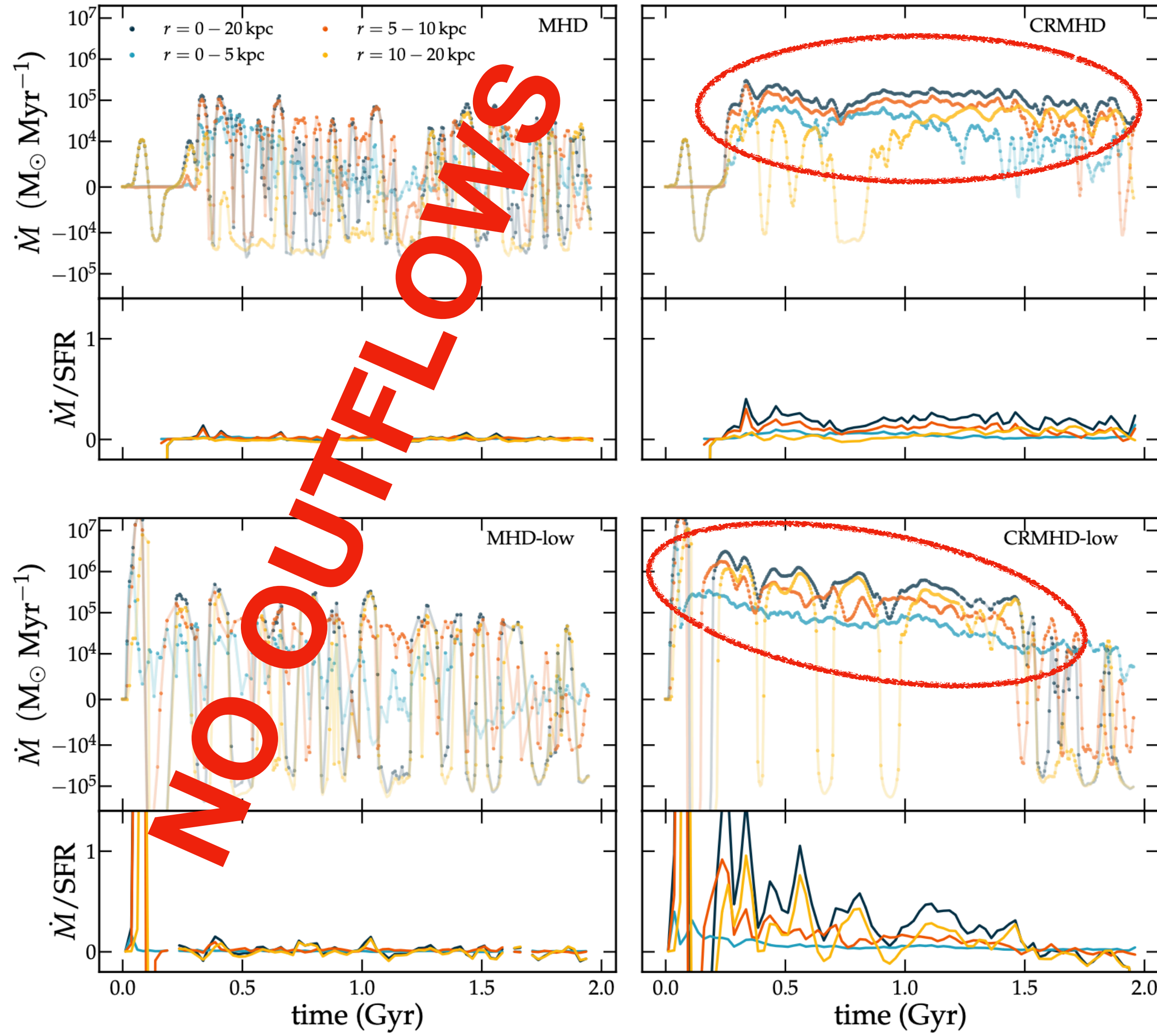


- Isolated, Milky Way-like galaxies
- $10^{12} \text{ M}_{\odot}$ halo mass
- CRs: advection + anisotropic diffusion ($\kappa = 4 \cdot 10^{28} \text{ cm}^2 \text{ s}^{-1}$), emulate streaming losses
- B-field strength: 3nG (“-low”) or $3\mu\text{G}$
- Evolved for 2 Gyr

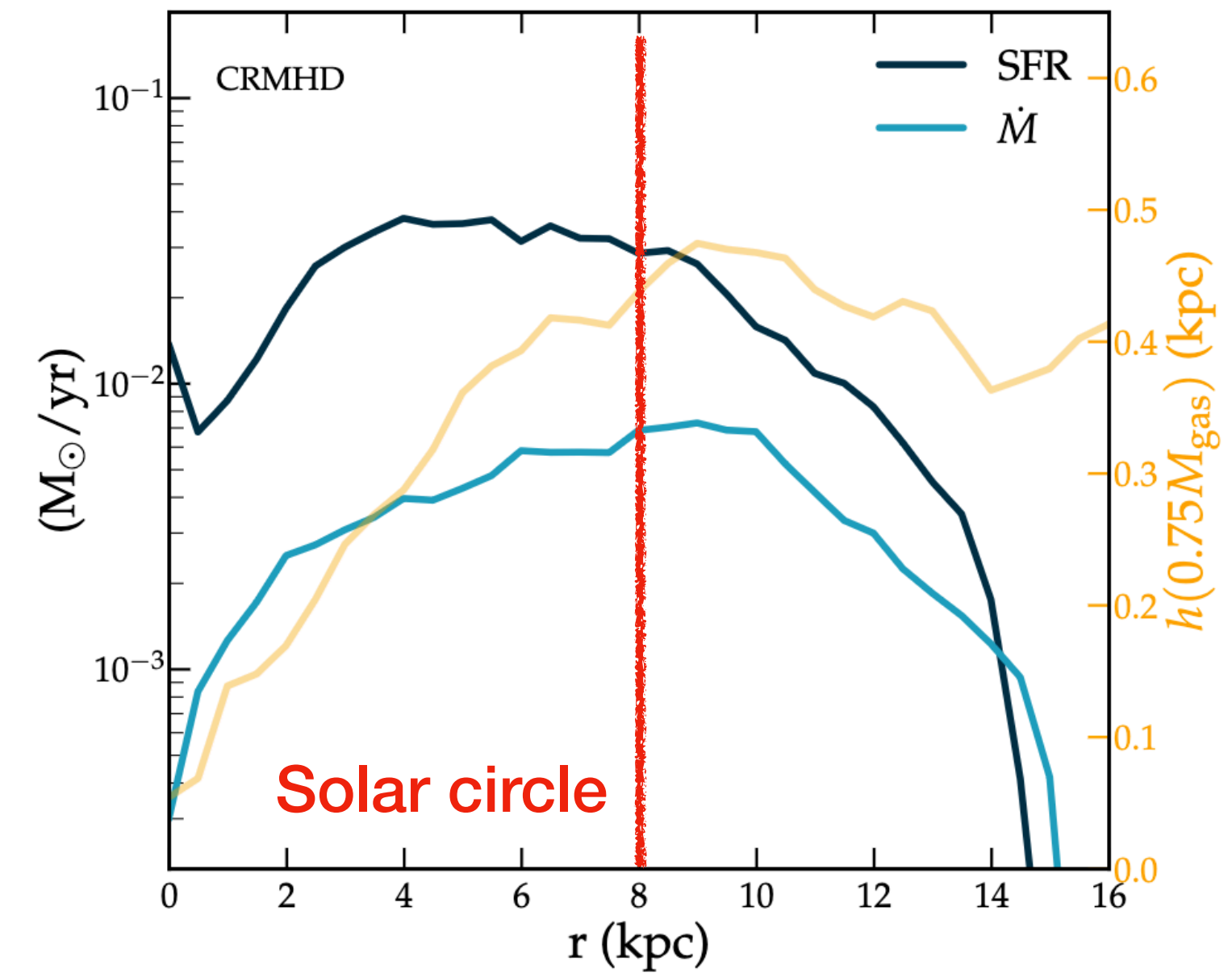
CR driven outflows

No CRs

CRs



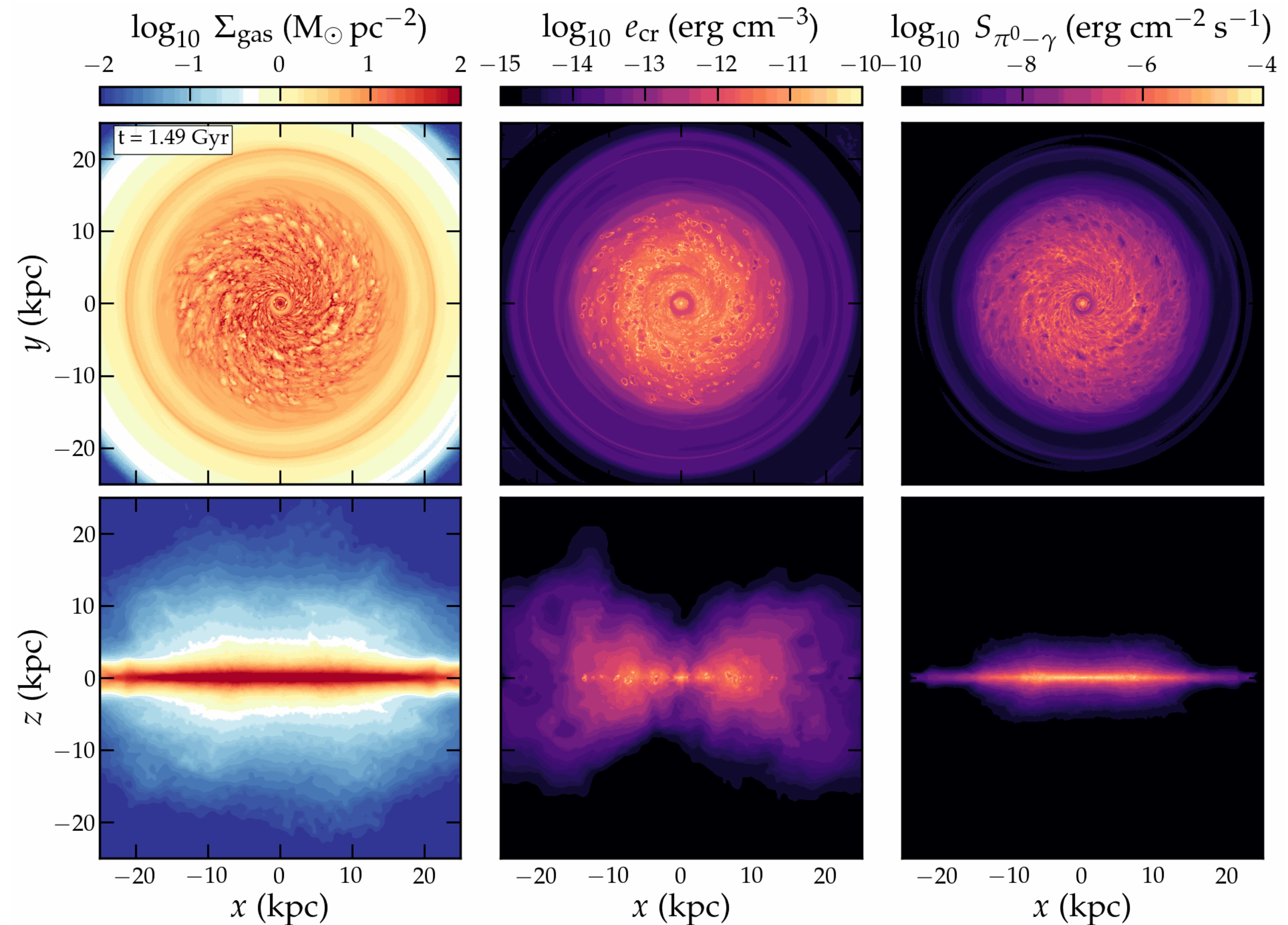
No outflows without CRs



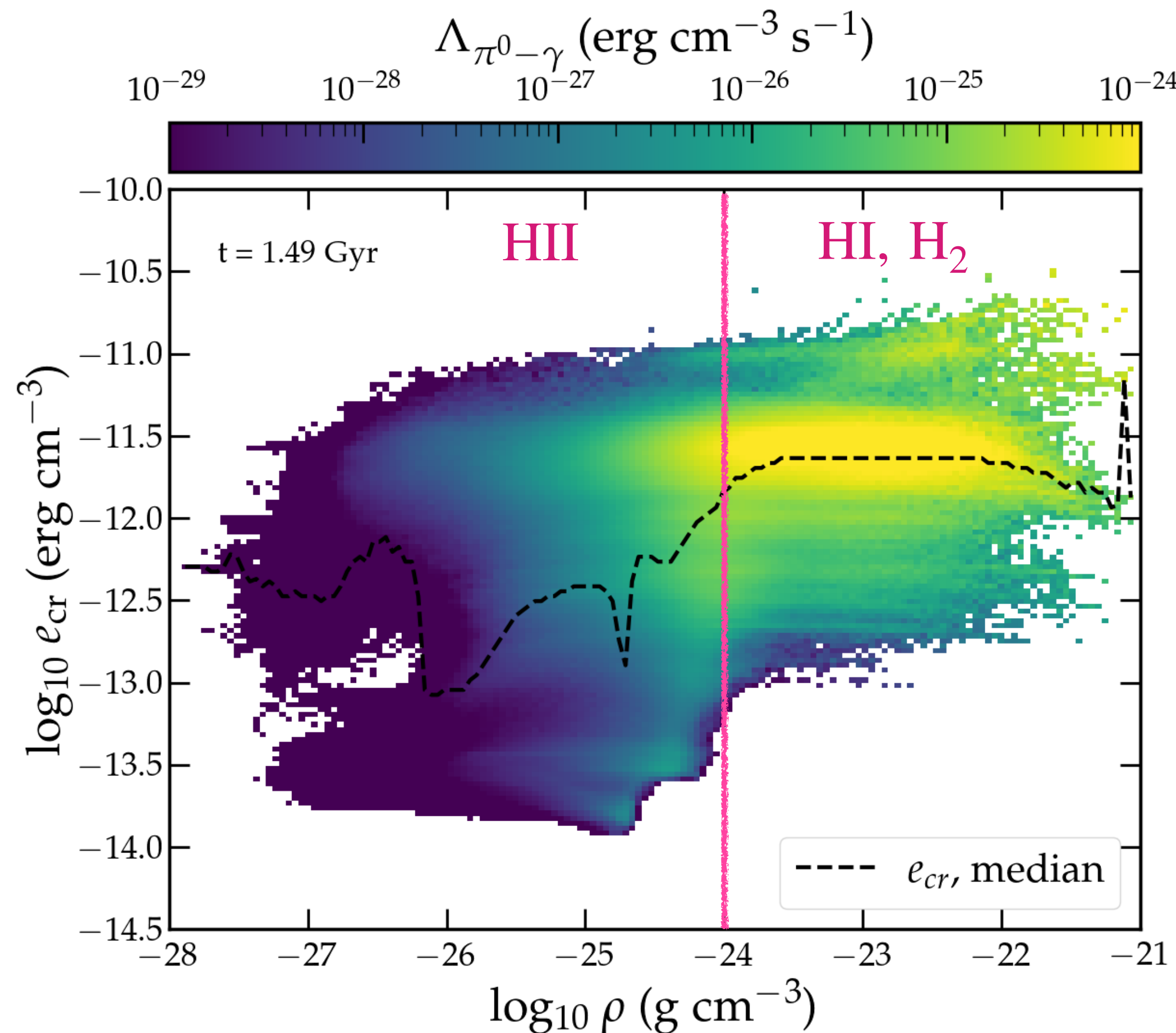
CRs launch outflows from the entire galactic disk

Gamma emission from CR protons

- Gamma emission from neutral pion decay of primary protons
- Calculated with CRAYON code, assumes steady-state
- Can see many details in the gamma emission - varies with position and time



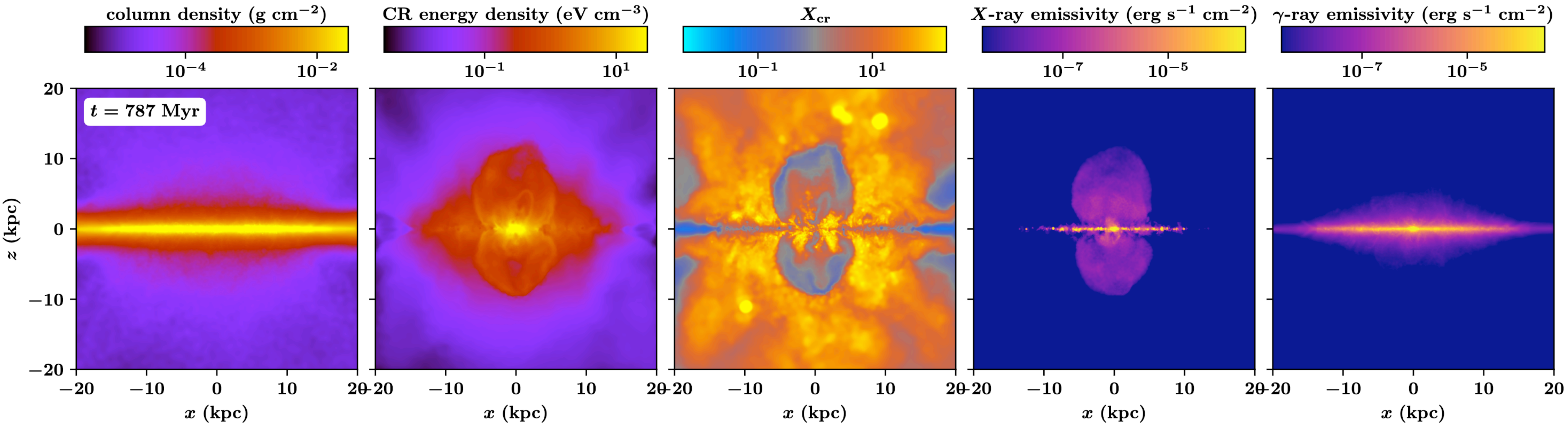
Gamma emission from CR protons



- Adiabatic CRs: $e_{\text{cr}} \propto \rho^{4/3}$
- Deviation due to **non-adiabatic interactions** and **fast diffusion**
 - (See e.g. Girichidis et al. 2024)
- Gamma rays show a big **dynamic range**, shining primarily in the **atomic phase**

“Fermi”/“eROSITA”-bubbles

The importance of details in the galactic center



- Periodically launched, short-lived (~ 20 Myr) outflows from the center
- Outflow bubbles visible in X-rays but not gamma rays \rightarrow due to missing leptonic gamma rays

Conclusions

- CRs can **launch outflows** from Milky Way galaxies
- Outflows are launched from the **entire disk**, but weak
- Gamma rays: big dynamic range + **strong time variations**
- CRs strongly **non-adiabatic** (diffusion, gamma rays, ...)
- Accurate MW potential → Fermi/eROSITA bubbles, short-lived outflows
 - Visible in X-rays but not in gamma rays, due to missing leptonic component

Extra slides

More accurate coupling CR \leftrightarrow gas+B

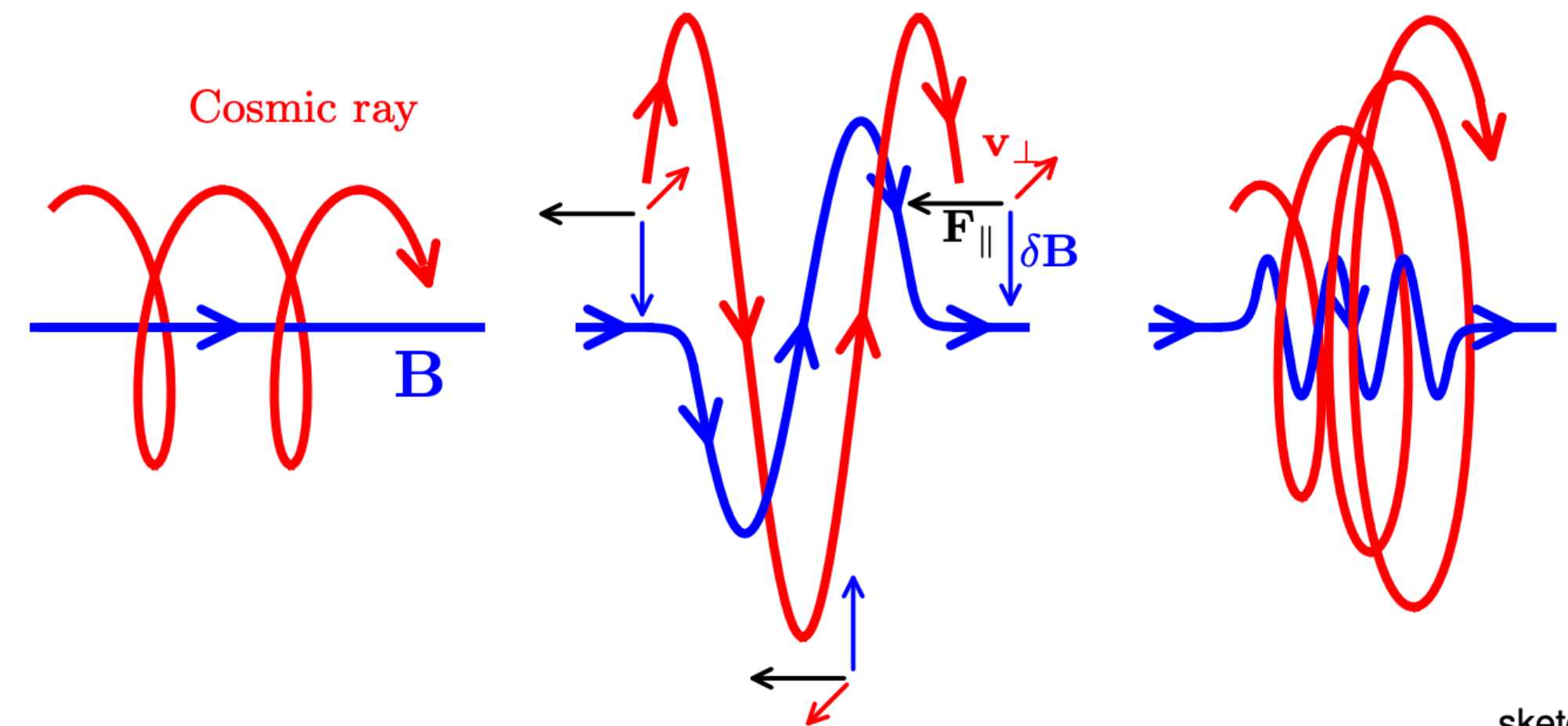
- CRs: back-reaction onto B-field, gyro-resonances
 \Rightarrow no simple diffusion
 \Rightarrow complex transport (E-transfer $E_{\text{cr}} \leftrightarrow E_{\text{mag}}$)
- Streaming instability (Kulsrud+1975)
- bulk of CRs streams with Alfvén speed, Alfvén heating
- equate growth and damping (Wiener+ 2013)

$$\Gamma_{\text{growth}} = \Gamma_{\text{NLLD}} + \Gamma_{\text{in}}$$

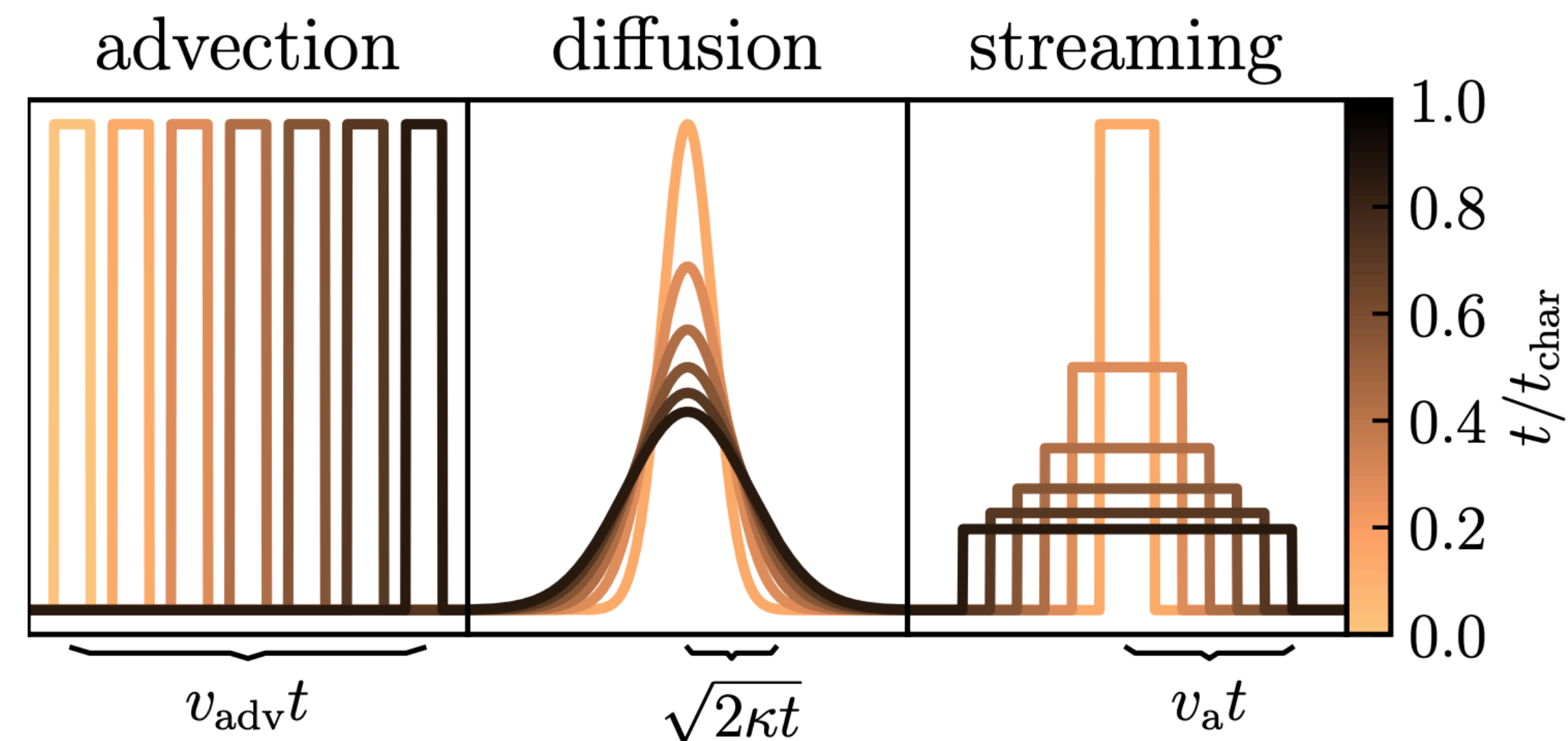
depend on effective turbulence model, effective B-field $\delta B/B$, fixed B spectrum

$$\Rightarrow H = -\mathbf{v}_A \cdot \nabla P_{\text{cr}}$$

- new self-consistent PIC models (Shalaby et al. 2021/2023)
- \Rightarrow many unknowns concerning
 - transport speeds
 - energy exchange



sketch: Jacob



More accurate coupling CR \leftrightarrow gas+B

- new approach in fluid approximation
- Thomas+ 2019,2021,2022:
 - follow CR energy AND energy in magnetic waves
 - averaged over p , given fixed spectrum

