Study of Cosmic Rays Transport around Young Protostars

Impact of in-situ CR acceleration on hydrogen ionization

RAMSES SNO 2025

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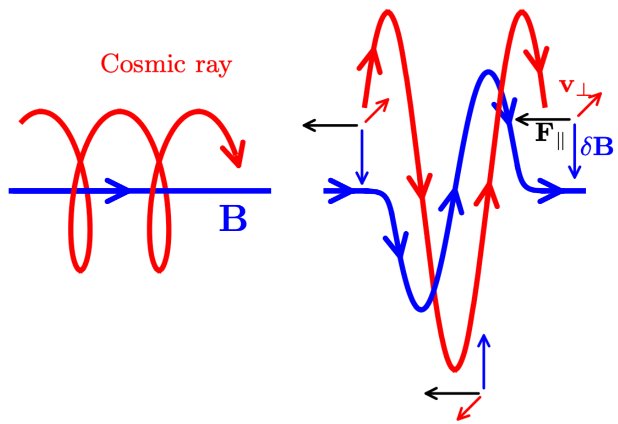
Credit: JWST

Cosmic rays (CRs)

- Proton + Electron + Heavy Nuclei
- Propagate along magnetic field lines
- Energy equipartition ($E_{\rm CR} \simeq E_{\rm th} \simeq E_{\rm turb} \simeq E_{\rm mag}$) in the ISM



Ruszkowski and Pfrommer 2023

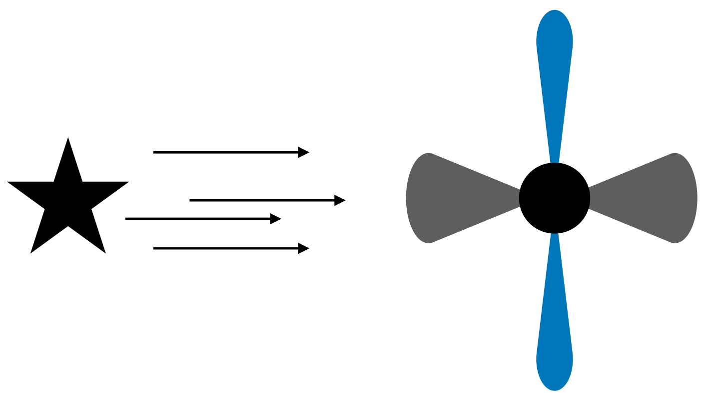
Cosmic rays (CRs)

- Proton + Electron + Heavy Nuclei
- Propagate along magnetic field lines
- Energy equipartition ($E_{\rm CR} \simeq E_{\rm th} \simeq E_{\rm turb} \simeq E_{\rm mag}$) in the ISM
- Low energy (MeV - GeV) CR is the main source of ionization in embedded protostar regions (Padovani et al. 2009, 2018, 2022, 2024).

H_2 ionization by CRs around protostars

What we thought before

- Uniform background ionization rate: $\zeta_{H_2} \sim 10^{-17} s^{-1}$
- We assumed external sources (OB stars, Supernovae … etc.)



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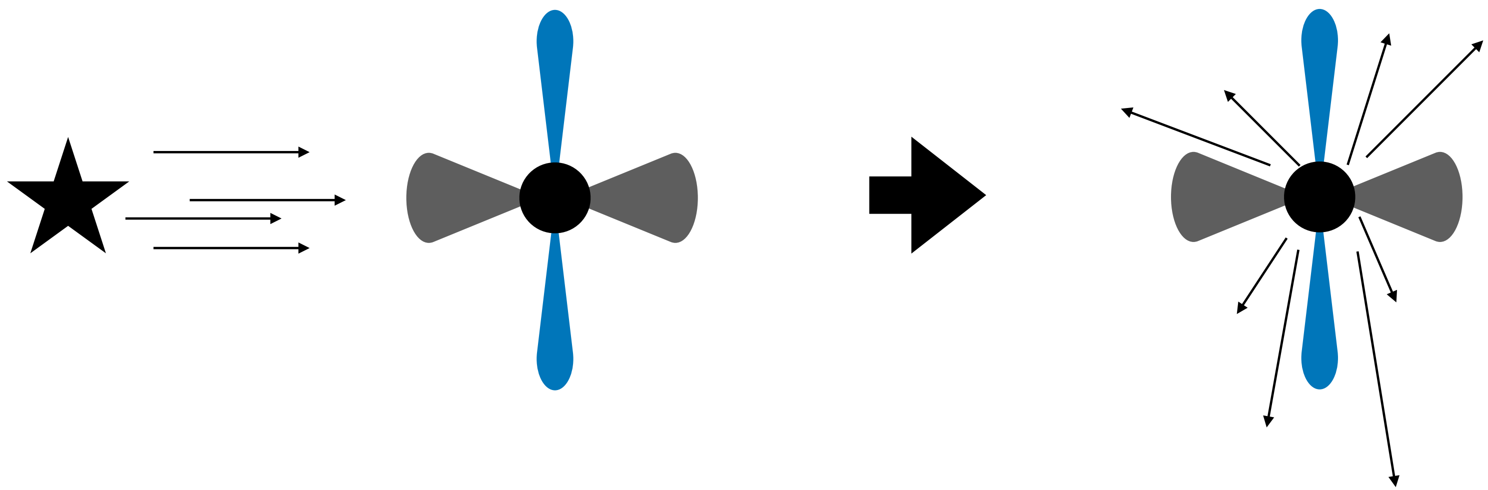


H_2 ionization by CRs around protostars

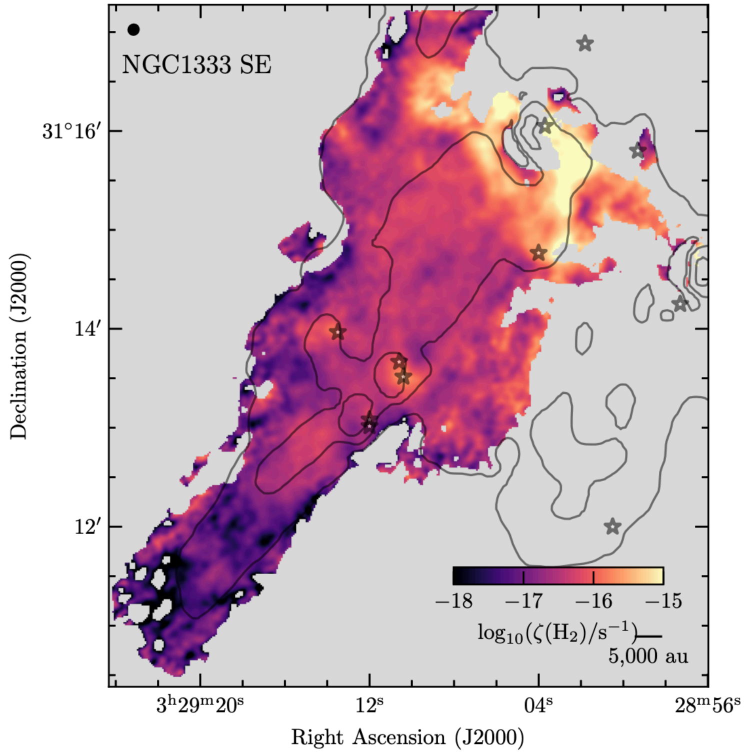
Recent observations

- Uniform background ionization rate: $\zeta_{H_2} \sim 10^{-17} s^{-1}$
- We assumed external sources (OB stars, Supernovae … etc.)

⬇

- Inhomogenous distribution of ionization rate
- External sources + **Internal sources (local)** Padovani et al. 2009, 2021
- $DCO^+(J=3\text{-}2)$, $H^{13}CO^+(J=3\text{-}2)$ $\Rightarrow \zeta_{H_2}$ Cabedo et al. 2023; Pineda et al. 2024

Pineda et al. 2024

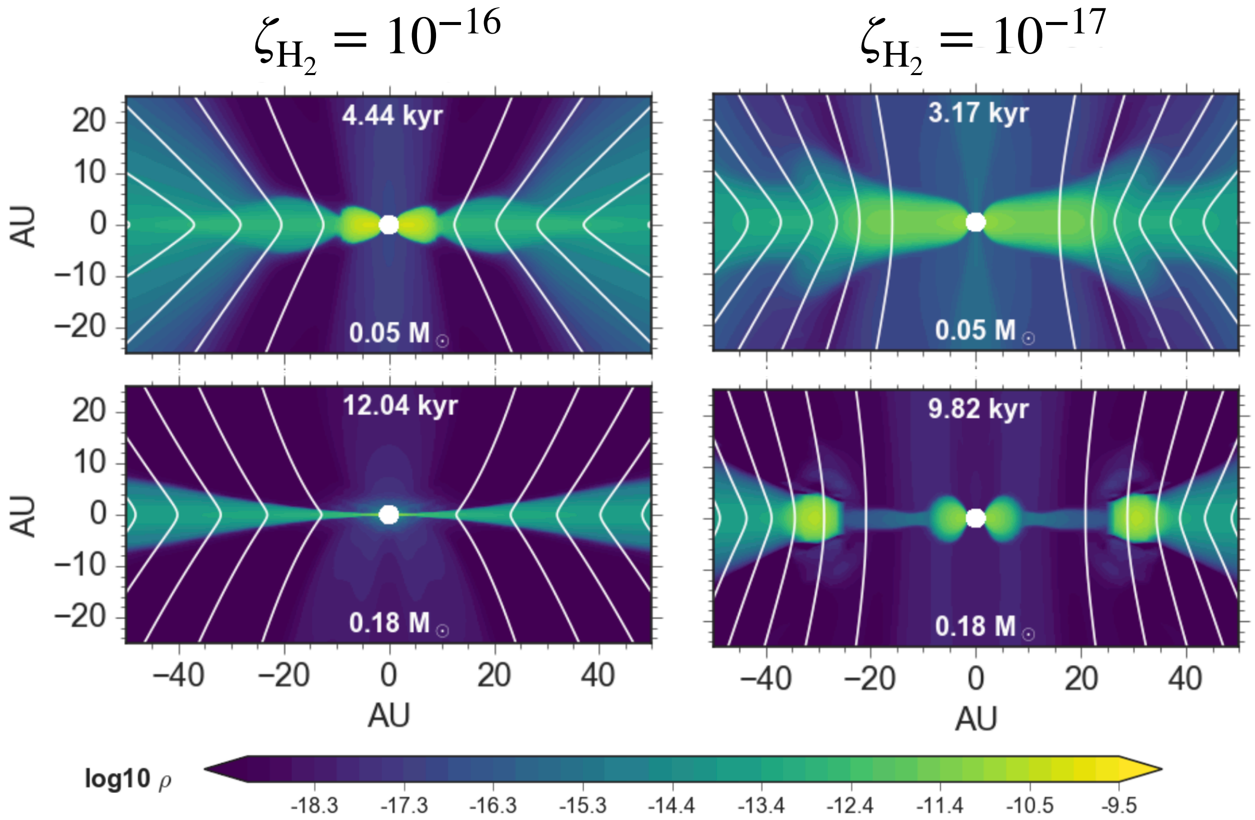


H_2 ionization by CRs around protostars

State of the art in protostellar disk simulations

High ζ_{H_2}

Gas **coupled** to B-field



Low ζ_{H_2}

Gas **decoupled** from B-field

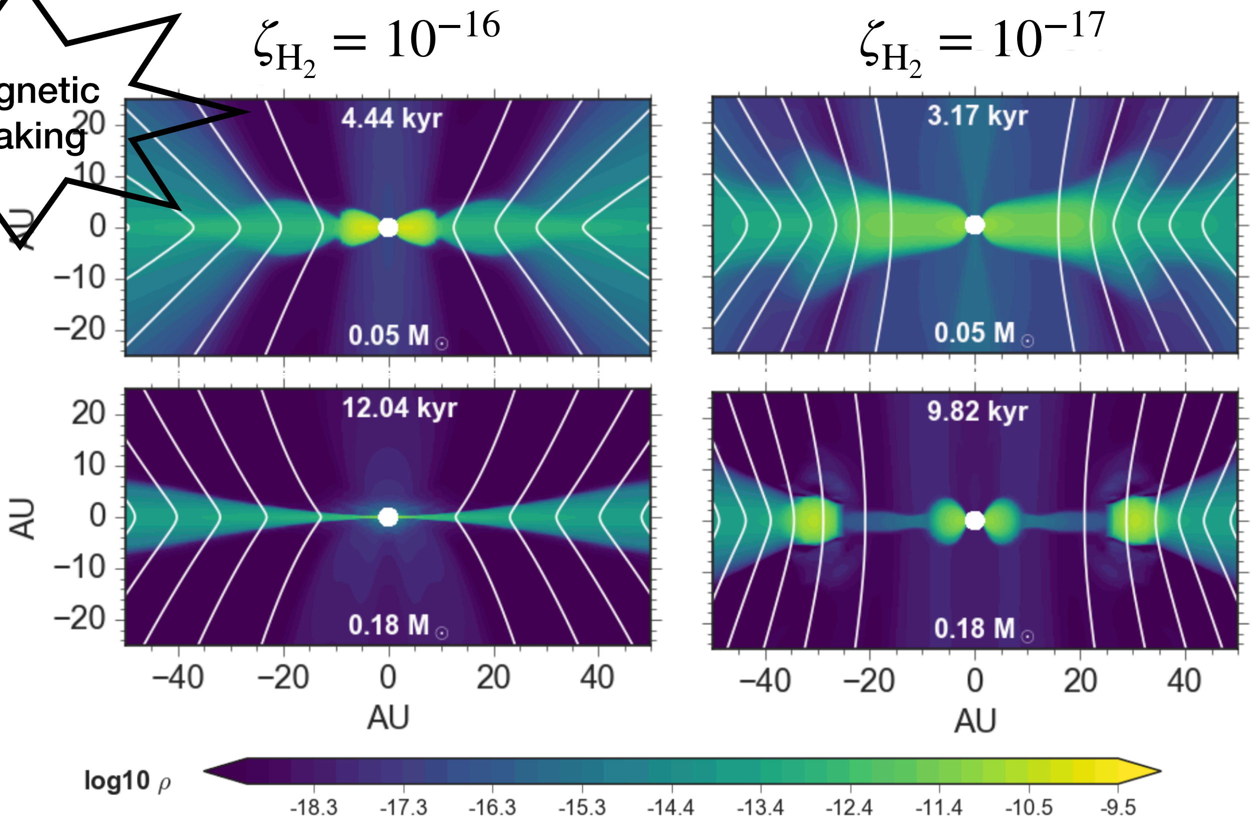
Kuffmeier et al. 2020

H_2 ionization by CRs around protostars

State of the art in protostellar disk simulations

Magnetic Braking

High ζ_{H_2} | **Low** ζ_{H_2}
Gas **coupled** to B-field | Gas **decoupled** from B-field
MHD | **NiMHD**
Small disk | **Large** disk



Kuffmeier et al. 2020

Project Goals

Study of Cosmic Ray Transport around Young Protostars

1. How do CRs propagate in protostellar environments?
2. What role does in-situ CR acceleration play?
3. How does CR distribution affect ionization and MHD coupling?

Cosmic ray physics

CR transport equation

Rosdahl et al. 2025

$$\frac{\partial E_{\rm cr}}{\partial t} + \nabla \cdot \boldsymbol{F}_{\rm cr} = \underbrace{v \cdot (\nabla \cdot P_{\rm cr})}_{\text{Advection}} + Q - \Lambda_{\rm cr} E_{\rm cr}$$

$$\frac{1}{\tilde{c}^2}\frac{\partial \boldsymbol{F}_{\rm cr}}{\partial t} + \nabla \cdot P_{\rm cr} = \underbrace{-\,\mathrm{D}_{\rm cr}^{-1}}_{\text{Diffusion}} \cdot [\boldsymbol{F}_{\rm cr} - \underbrace{\boldsymbol{v} \cdot (E_{\rm cr} + P_{\rm cr})}_{\text{Advection}}]$$

$\mathrm{D}_{\rm cr}$: Diffusion coefficient, $\tilde{c}$: Reduced speed of light (RSOL)

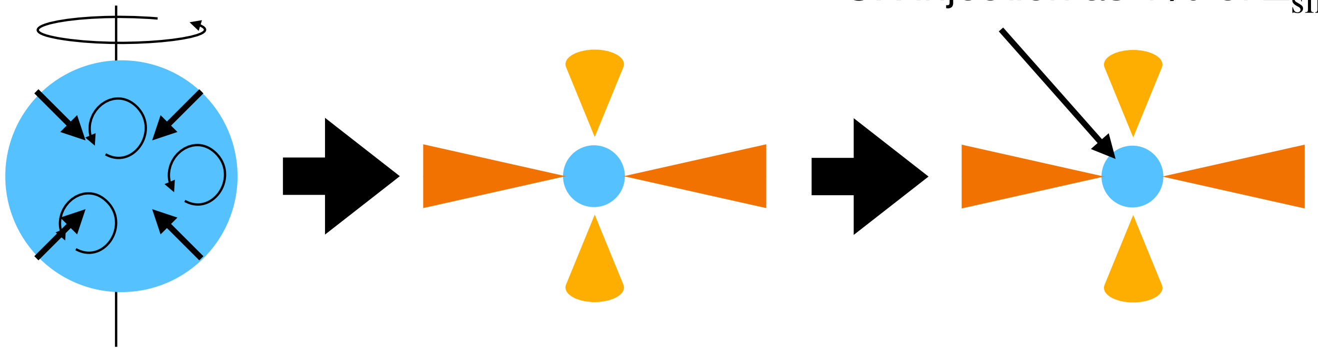
CR cooling

Guo et al. 2008, Fitz Axen et al. 2024

$$\Lambda_{\rm cr} = 7.51 \times 10^{-16}(1 + 0.22\mathrm{n}_e + 0.125 f_{\rm neut}) n_{\rm H}$$

Simulation strategy

Dense core simulation



1. Single CR energy approximation

For simplicity: 2. Decoupling the gas and the CRs -> **No momentum exchange**

3. CR ionization rate calculated by **post-processing**

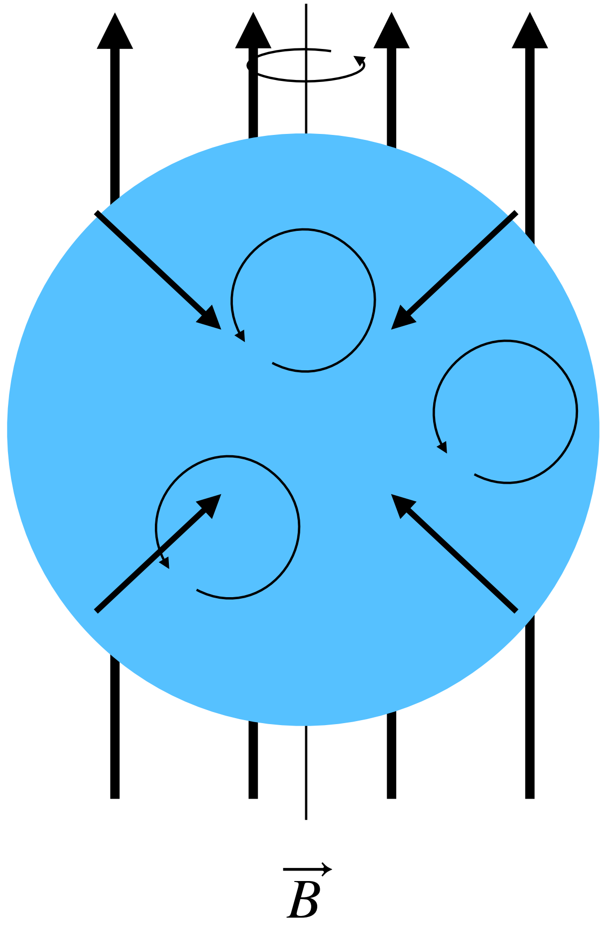
$$\zeta_{H_2} = v_p n_c \epsilon^{-1} L_{\rm ion}$$

Padovani et al. 2020; Armillotta et al. 2021

- v_p: Proton velocity
- n_c: CRs number density
- ϵ: Averagy energy lost by each proton per ionization event
- $L_{\rm ion}$: Proton loss function

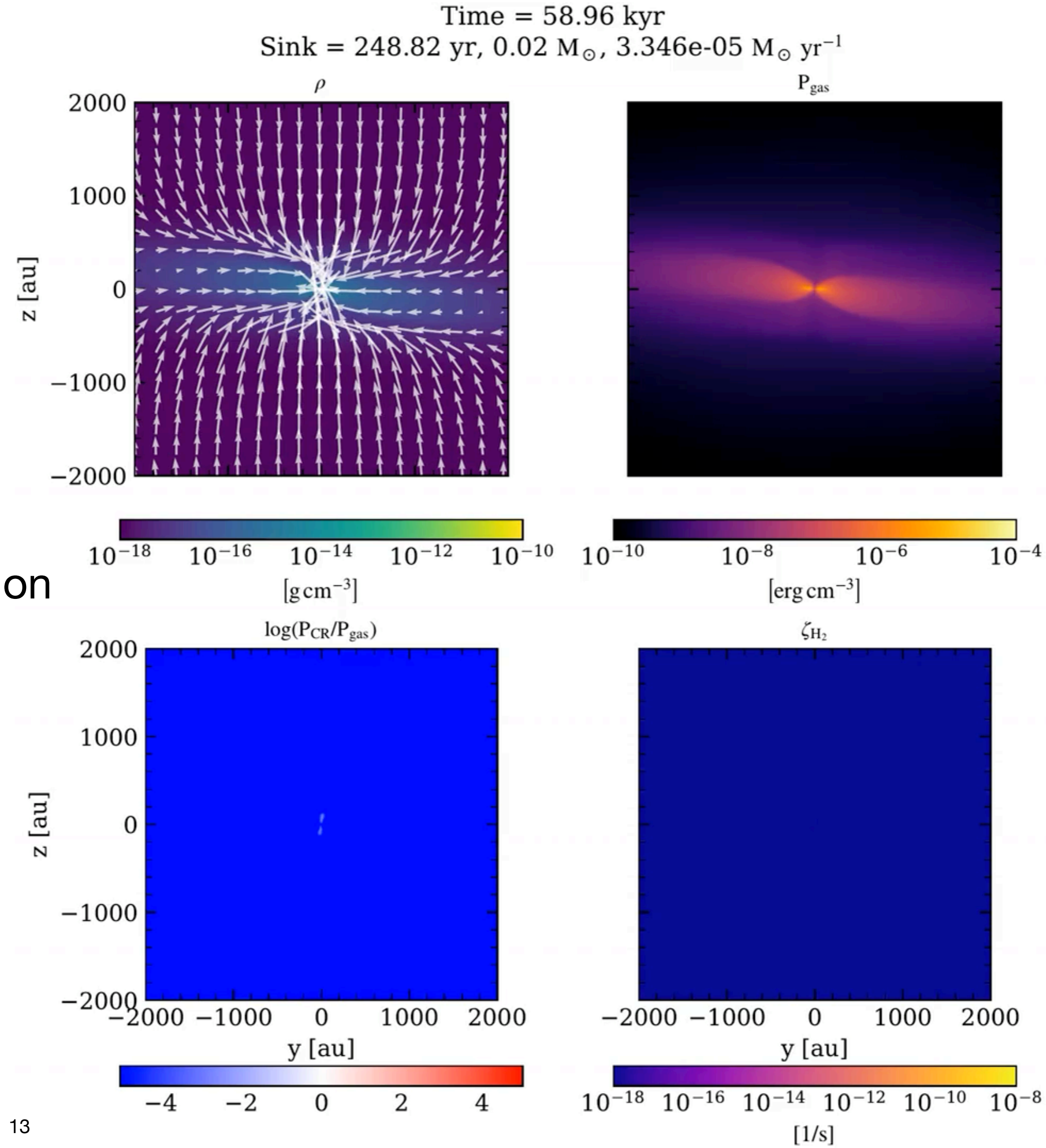
Simulation setup
One solar mass isolated collapse

- NiMHD (Only Ambipolar diffusion)
- $D_{\rm CR} = 10^{24}{\rm cm}^2{\rm s}^{-1}$, $\tilde{c} = 10^{-3}c$
- $M = 1{\rm M}_\odot, T = 10\,{\rm K}$
- $\alpha = E_{\rm rot}/E_{\rm grav} = 0.4$
- $\beta = E_{\rm thermal}/E_{\rm grav} = 0.04$
- $\mu =$ Mass to flux ratio = 3.3
- $\Delta_{\rm x} =$ ~ 1AU (Levels = 6 - 14)



Simulation results
Preliminary

- Code works well.
- Evolved 65 Kyr
- 96 cores + ~ 3 months (200,000 CPU hours) on the PSMN cluster @ ENS de Lyon
- CRs propagate along the MHD outflow, building high CR pressure.



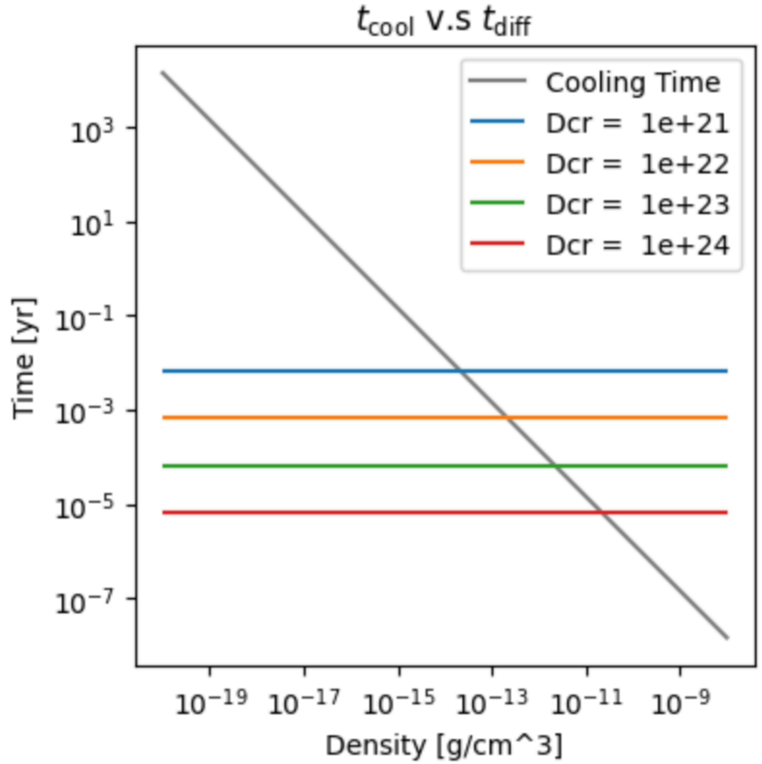
Discussion

Diffusion coefficient (D_{CR})

- The CR diffusion coefficient is highly uncertain in star-forming regions since we cannot observe the CRs in these regions (Nishio et al. 2025).
- Local CR diffusion speed > c, when D_{CR} is too large.
- The value of D_{CR} roughly scales as

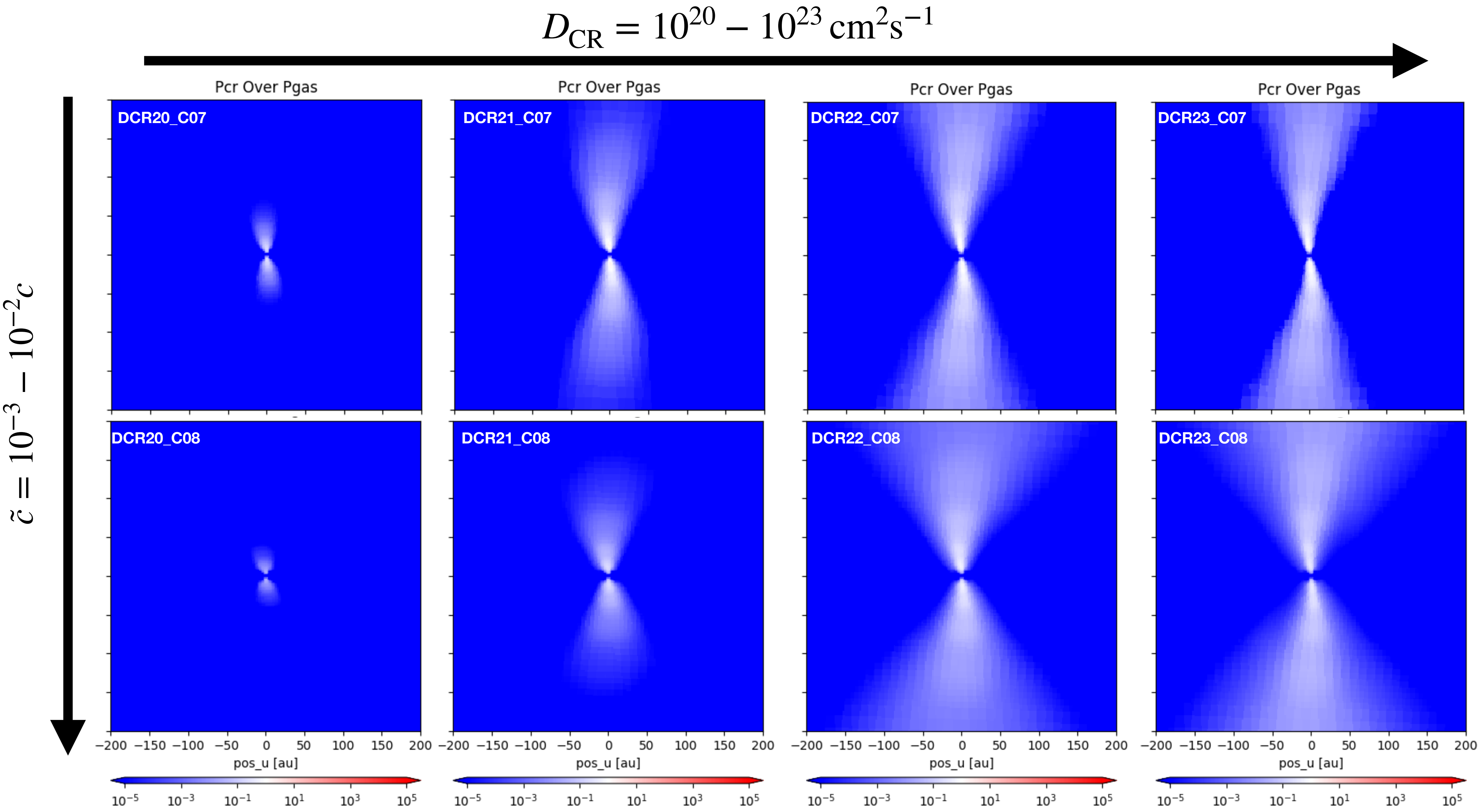
$$D_{\mathrm{CR}} = 7 \times 10^{20} \left(\frac{E}{1\mathrm{MeV}} \right)^{0.5} \mathrm{cm}^2\mathrm{s}^{-1}.$$ Droge et al. 1999

- Also, be careful of the CR diffusion timescale and the CR cooling timescale.
- CR @ 100 MeV, $D_{\mathrm{CR}} \sim 10^{22}\mathrm{cm}^2\mathrm{s}^{-1}$



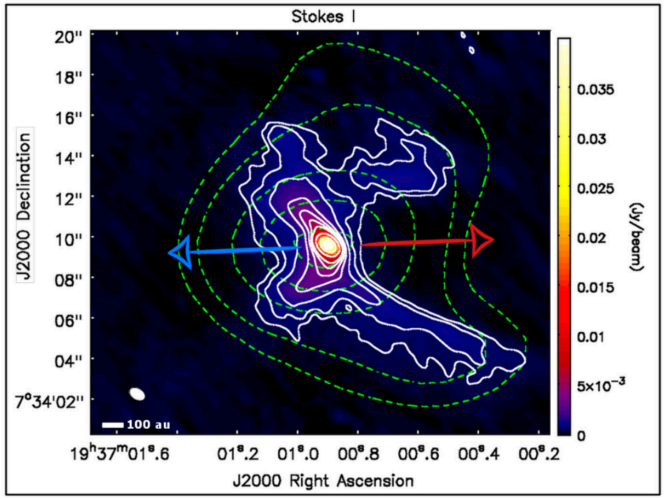
Discussion
Reduced speed of light, RSOL ($\tilde{c}$)

- $\tilde{c}$ must be chosen carefully in the simulation (Jiang & Oh 2018; Rosdahl et al., 2025)
- Evolve CR at the speed of light is computationally expensive
- Keep updating $\tilde{c}$ based on hydro speed (Rosdahl et al. 2025) $c \geq \tilde{c} \geq v_{\mathrm{MHD}}$
- Be careful to check local CR diffusion speed (Hopkins et al. 2021) $c \geq \tilde{c} \geq D_{\mathrm{CR}}/\ell_{\mathrm{CR}}$

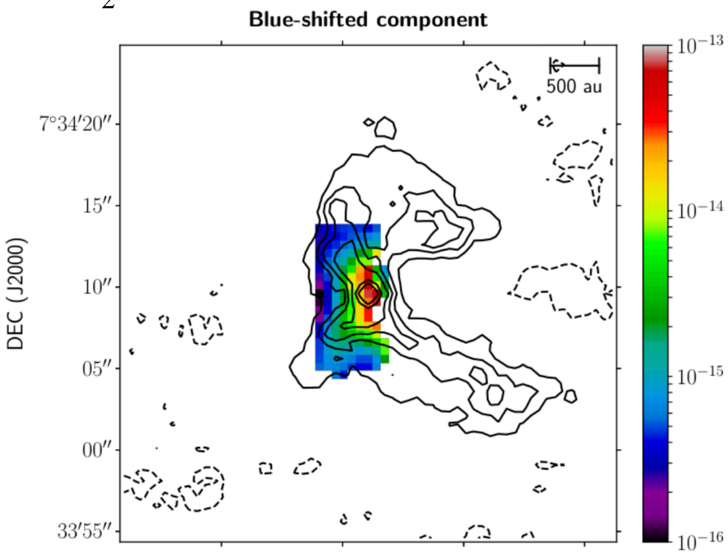

$D_{\mathrm{CR}} = 10^{20} - 10^{23}\ \mathrm{cm^2 s^{-1}}$
$\tilde{c} = 10^{-3} - 10^{-2} c$
Pcr Over Pgas
DCR20_C07
DCR21_C07
DCR22_C07
DCR23_C07
DCR20_C08
DCR21_C08
DCR22_C08
DCR23_C08
pos_u [au]

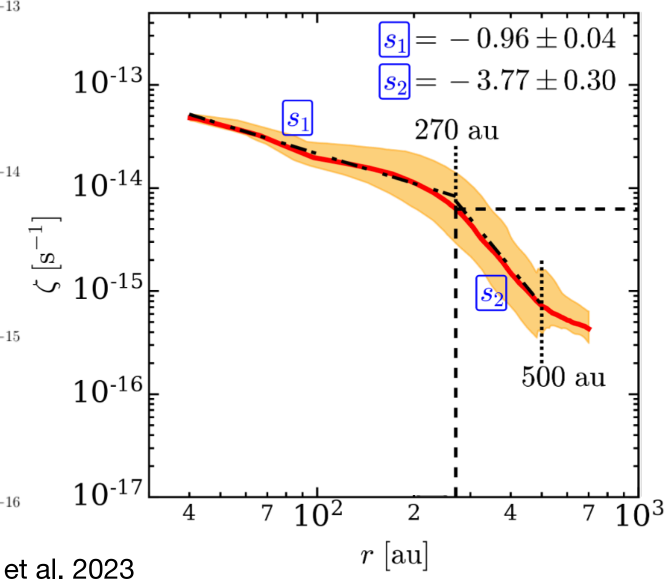
B335 protostar

- No Keplerian disk > 10 AU -> Magnetic braking or Young age? (Yen et al. 2015)
- No evidence of ion-neutral decoupling at scales > 100 AU (Yen et al. 2018)
- High ionization rate at r < 1000 AU -> MHD (Cabedo et al. 2023)
- DCO+(J=3-2), H13CO+(J=3-2) ⇒ ζ_{H_2}



Maury et al. 2018

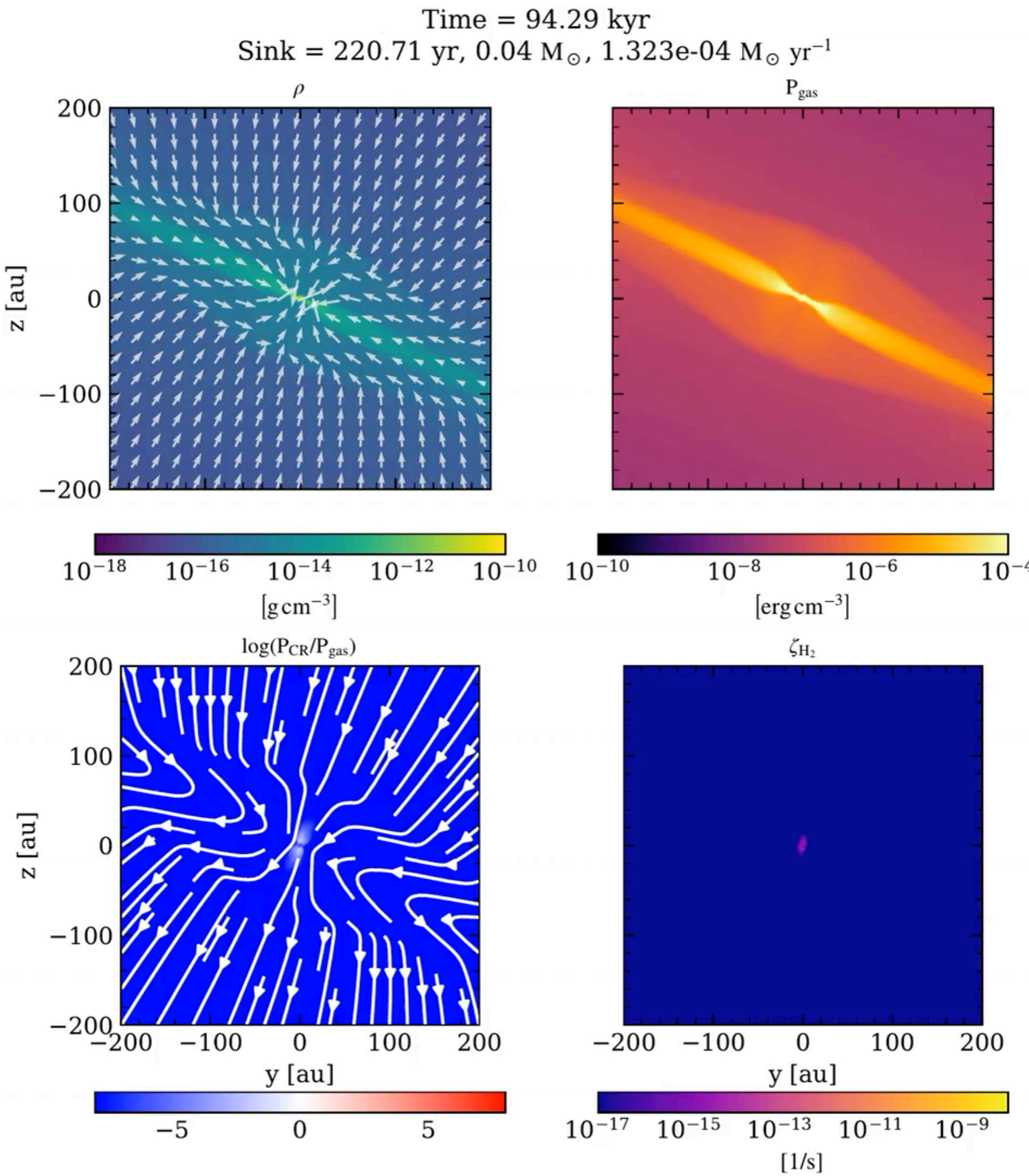




Cabedo et al. 2023

Simulation results
B335

- $M = 2.5M_{\odot}$
- $\alpha = 0.35$
- $\beta = 0.001$
- $\mu =$ Mass to flux ratio = 6.67
- $D_{\mathrm{CR}} = 10^{22}, \tilde{c} = 10^{-3}c$
- Cosmic rays create the high-pressure region, which is tilted relative to the rotation axis.
- $\zeta_{\mathrm{H_2}}$ reach $10^{-14}\mathrm{s}^{-1}$ around the protostar, consistent with observations.



Discussion
CR Ionization rate

- CR ionization rate can reach $10^{-14}\mathrm{s}^{-1}$ and is consistent with observations, while the typical background value is $10^{-17}\mathrm{s}^{-1}$
- The high CR ionization rate in the simulation matches the observation results.
- The resistivity table in RAMSES only reaches $10^{-16}\mathrm{s}^{-1}$ (Marchand et al. 2016).
- To ensure self-consistency, we need a new resistivity table for on-the-fly simulation with RAMSES.

Conclusions & Future Plan

- The value of the reduced speed of light needs to be chosen carefully in the star-forming regions.
- Local CR injection can lead to a high ionization rate around the protostar.
- Momentum exchange will be included.
- We will combine with local chemical and radiation with RAMSES-RT
- We need a new resistivity table due to the high CR ionization rate in the simulation