



Radiation-Magneto-HydroDynamics simulations of cosmic ray feedback:

The role of cosmic rays in the evolution of galaxies

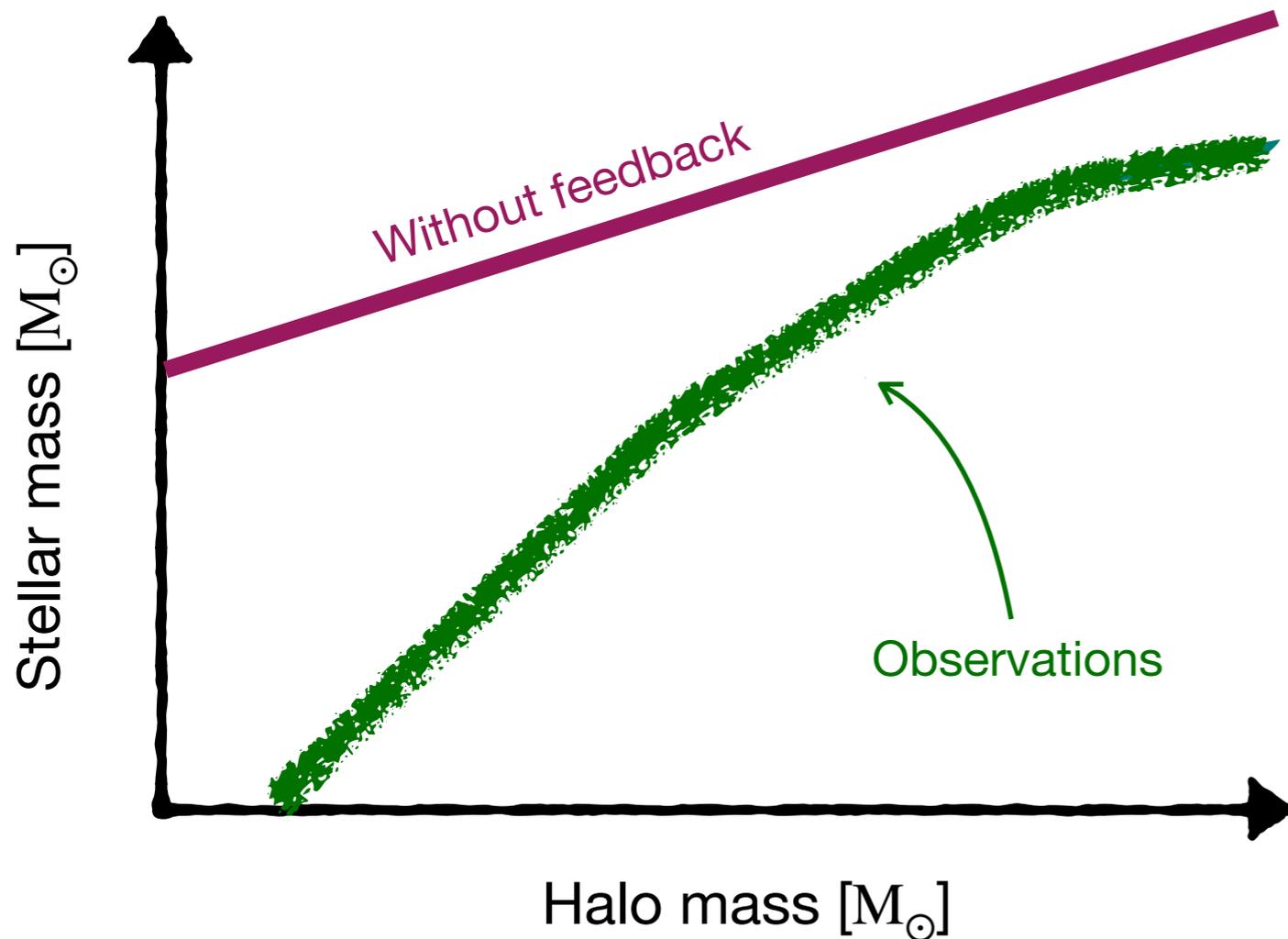
Marion Farcy

Joakim Rosdahl - Yohan Dubois



Feedback in numerical simulations

Realistic treatment of the feedback in numerical simulations
=> regulate star formation and reproduce observations



Feedback channels:

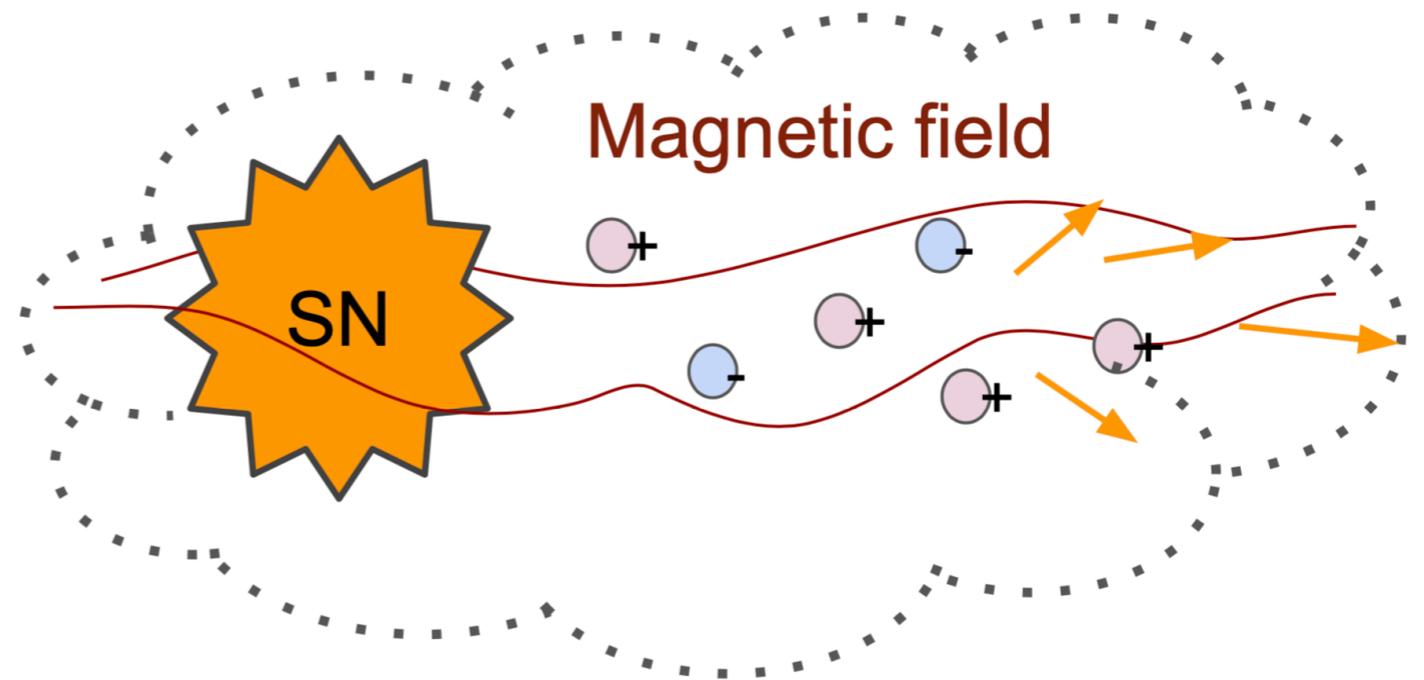
- Supernova explosion
- Radiation pressure
- Stellar winds
- Photo-ionisation heating
- Active galactic nuclei
- Cosmic rays

...

CRs as a source of feedback

Cosmic Rays:

- ★ Mainly protons with $\varepsilon \sim \text{GeV}$
- ★ Accelerated in SN shock waves
- ★ Advected with gas and diffused along magnetic field lines



Uncertain CR parameters:

CR energy $\simeq 10\%$ SN energy

$$10^{27} \lesssim \kappa \lesssim 10^{29} \text{ cm}^2/\text{s}$$

$$\vec{\mathcal{F}}_{\text{CR}} \propto \kappa \vec{b} \left(\vec{b} \cdot \vec{\nabla} P_{\text{CR}} \right)$$

CR flux $\vec{\mathcal{F}}_{\text{CR}}$ is proportional to the diffusion coefficient κ , the magnetic unit vector \vec{b} , and the CR pressure gradient $\vec{b} \cdot \vec{\nabla} P_{\text{CR}}$.

Provide an extra pressure gradient
 Leak out from dense to more diffuse regions
 Heat the gas through collisions or streaming losses



Disrupt ISM clouds
 Alter the star formation rate
 and the CGM gas properties

How and to what extent do **CRs**
regulate **galaxy evolution**?

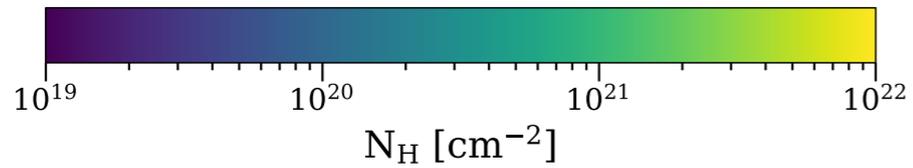
1. Code & setup
2. Impact of CRs on the galactic gas
3. Effect of CRs on star formation
4. Outflows and their temperature phases
5. Sensitivity of the results with the unknown diffusion coefficient



- ★ **Radiation** propagation and its interaction with gas (*Rosdahl et al 2013, Rosdahl & Teyssier 2015*)
- ★ **MHD** with **CRs** implemented as a fluid (*Fromang et al 2006, Dubois & Commerçon 2016*)
- ★ **CR diffusion** ($\kappa = 10^{28} \text{ cm}^2 \text{ s}^{-1}$) and **advection** (*Dubois & Commerçon 2016, Dubois et al 2019*)
- ★ Local **star formation** efficiency depending on the thermo-turbulent gas properties (*Federrath & Klessen 2012, Kimm et al 2017*)
- ★ Mechanical **feedback** injecting the correct amount of momentum or energy regardless of the resolution (*Kimm & Cen 2014, Kimm et al 2015*)

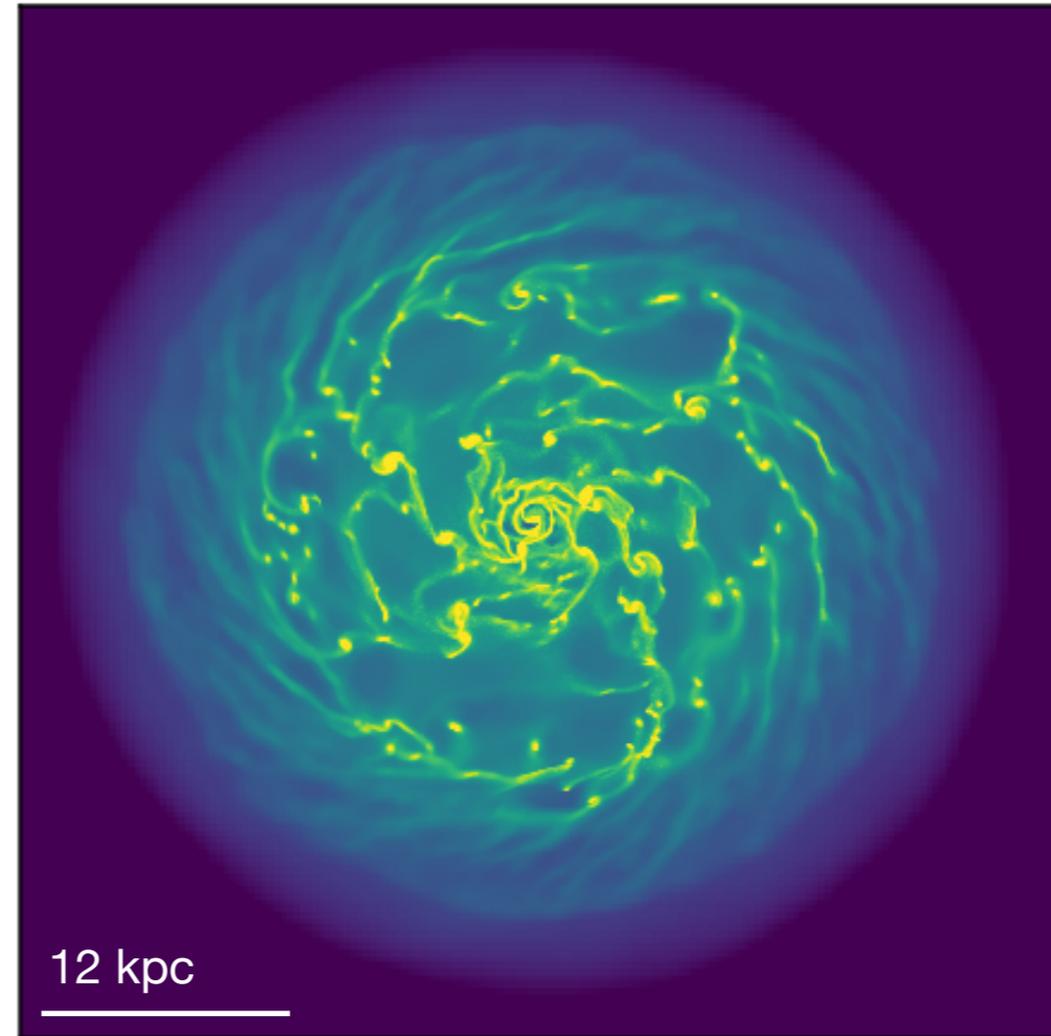
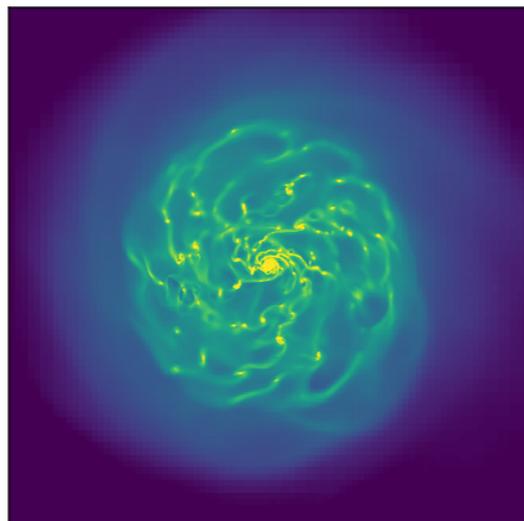
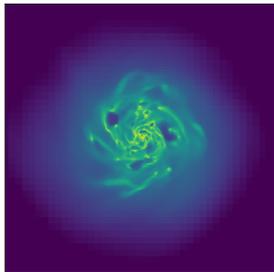
Idealised galaxies

Milky-Way mass galaxy



Intermediate mass galaxy

Low mass galaxy



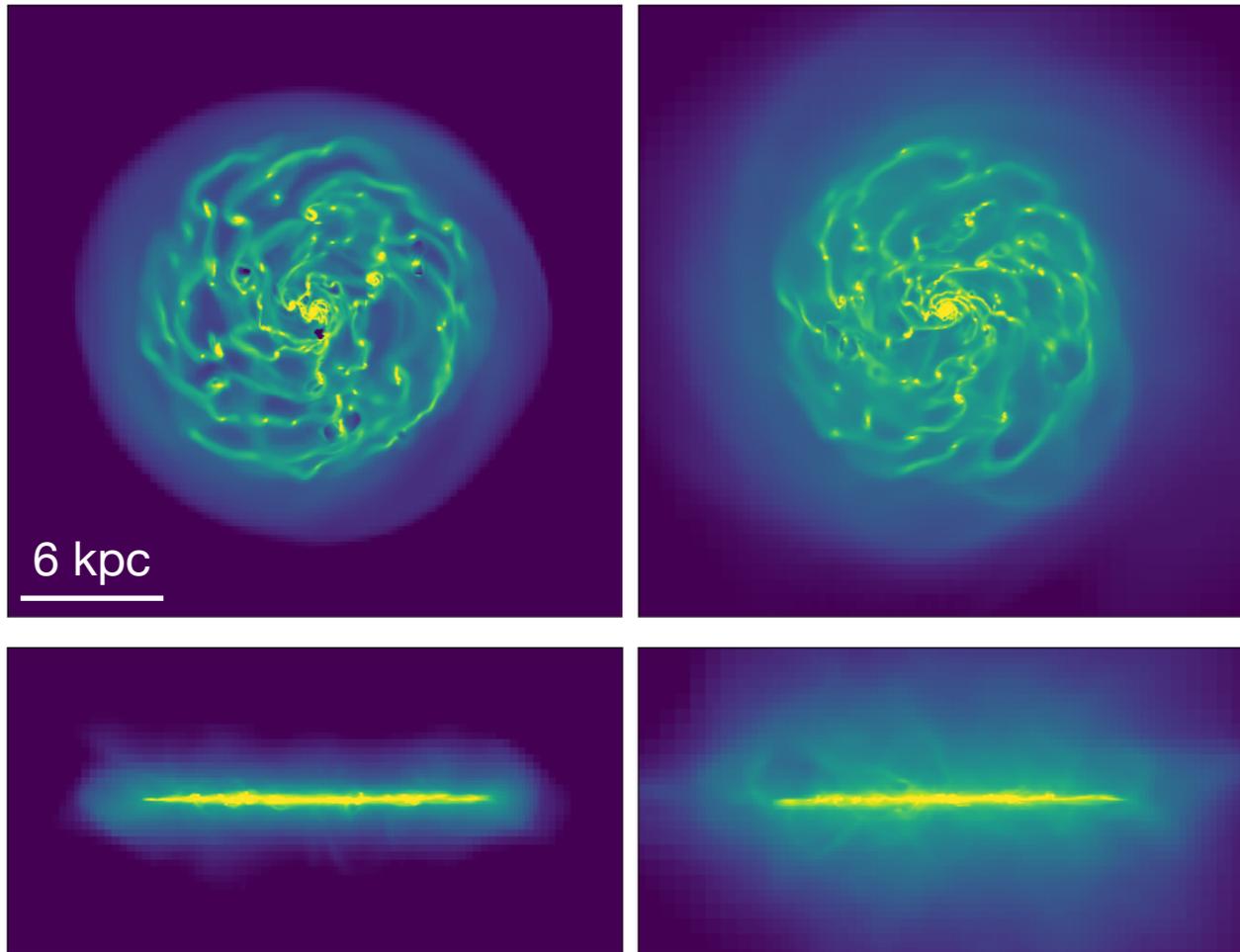
Galaxy type	$M_{\text{disk}} [M_{\odot}]$	$M_{\text{halo}} [M_{\odot}]$	$R_{\text{vir}} [\text{kpc}]$	$L_{\text{box}} [\text{kpc}]$	$\Delta x_{\text{max}} [\text{pc}]$
Low mass	3.5×10^8	10^{10}	41	150	9
Intermediate mass	3.5×10^9	10^{11}	89	300	9
Milky-Way mass	3.5×10^{10}	10^{12}	192	600	18

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Impact of CRs on the galactic gas

Without CRs

With CRs



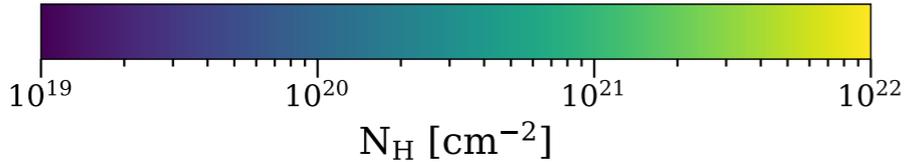
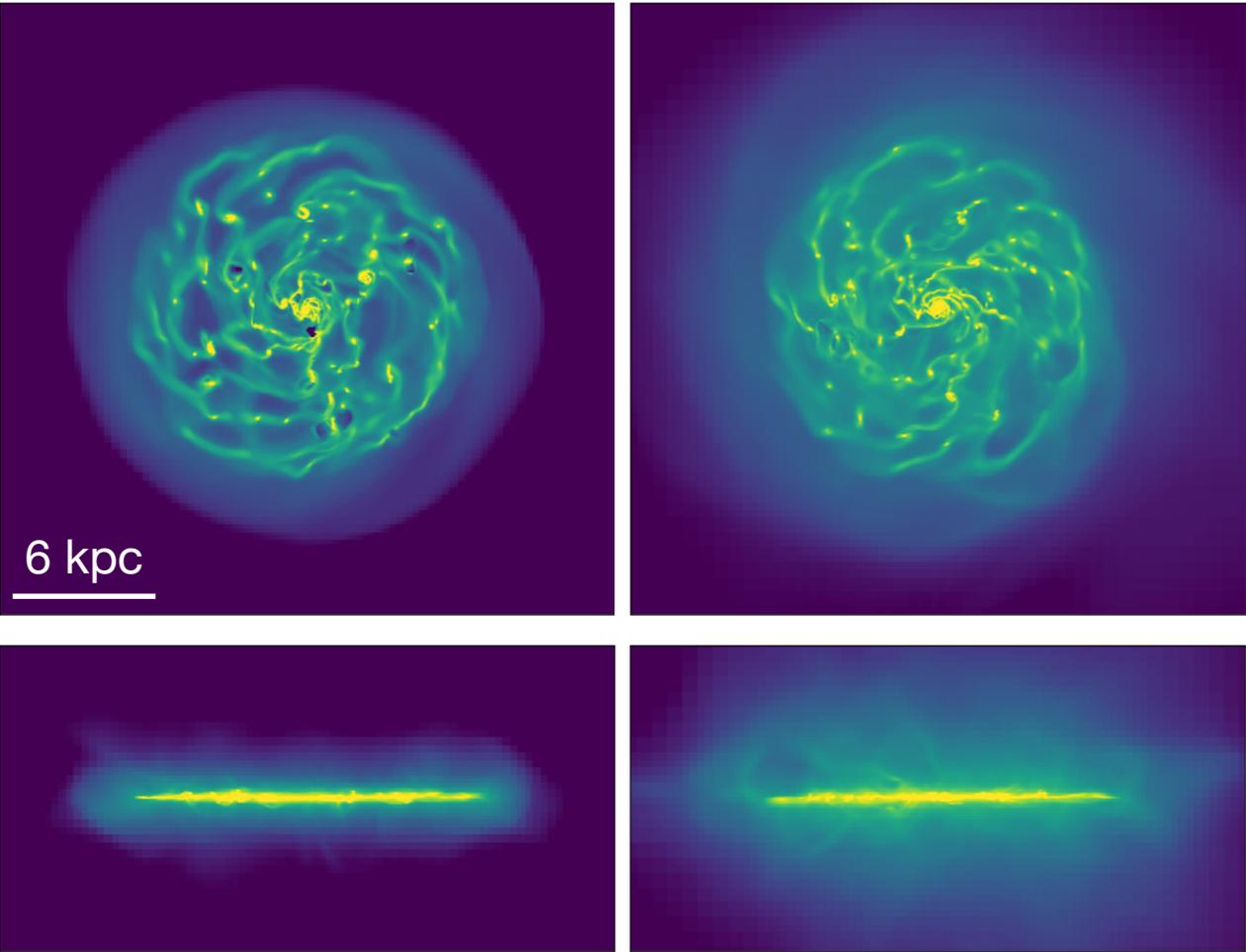
Intermediate mass galaxy

$$M_{\text{halo}} = 10^{11} M_{\odot}$$

Impact of CRs on the galactic gas

Without CRs

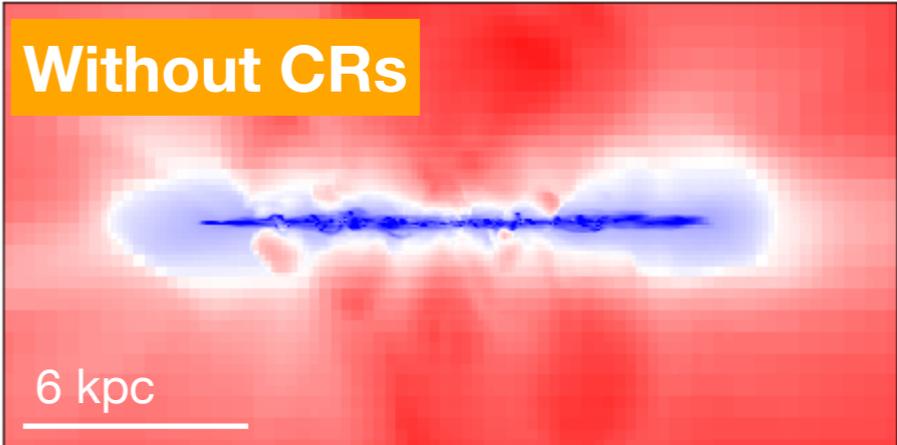
With CRs



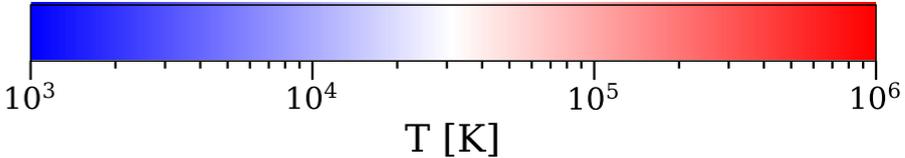
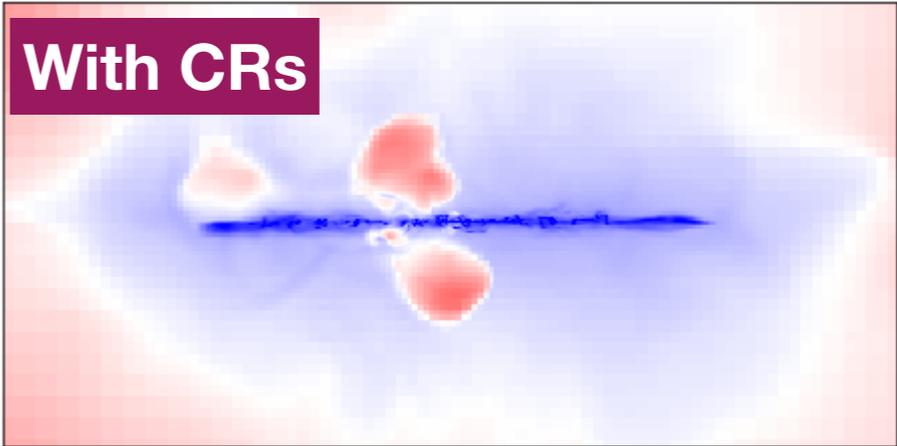
Intermediate mass galaxy

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Without CRs

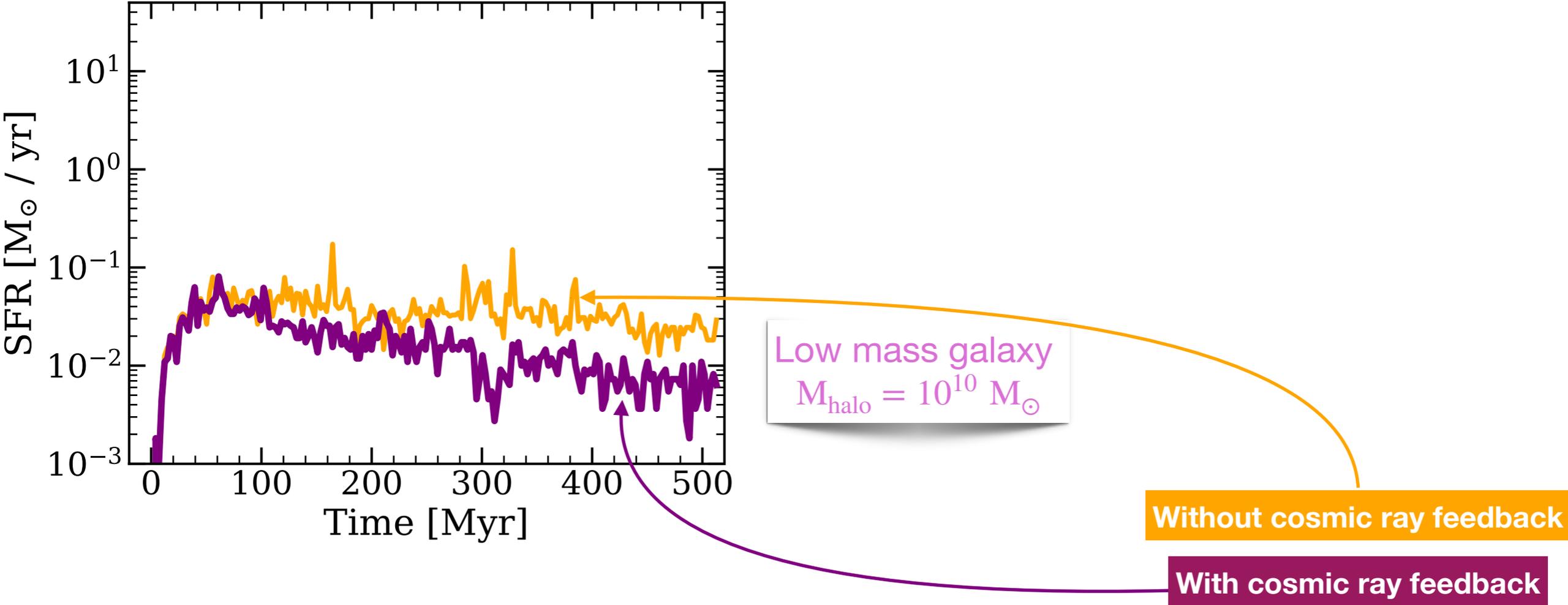


With CRs

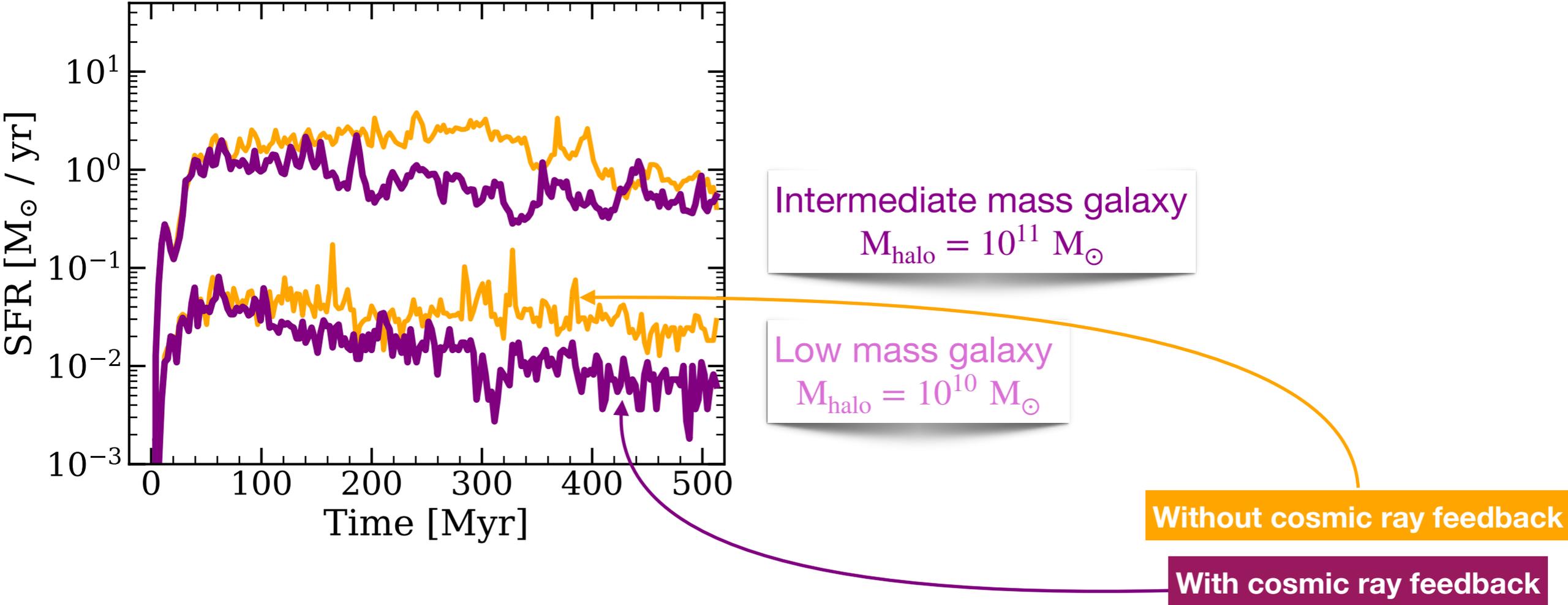


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3. **Effect of CRs on star formation**
4. Outflows and their temperature phases
5. Sensitivity of the results with the unknown diffusion coefficient

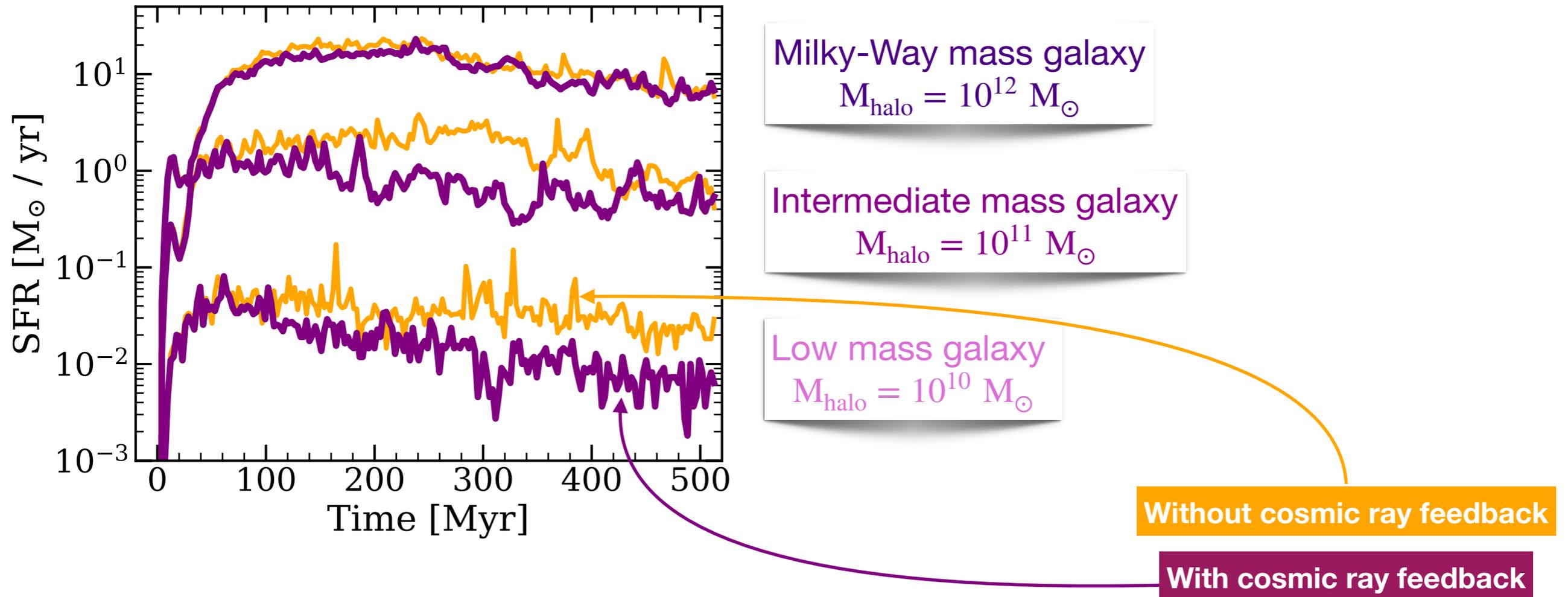
Effect of CRs on star formation



Effect of CRs on star formation



Effect of CRs on star formation



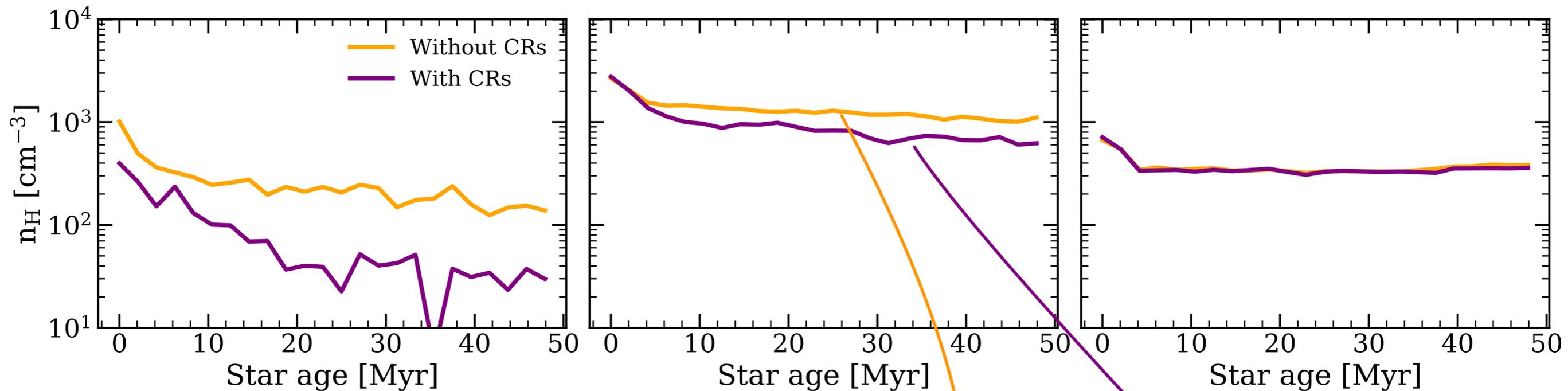
- ★ Star formation is impacted by the addition of CRs for the two dwarf galaxies
- ★ The effect of CRs in reducing the SFR \searrow when the galaxy mass \nearrow

Effect of CRs on star formation

Low mass galaxy

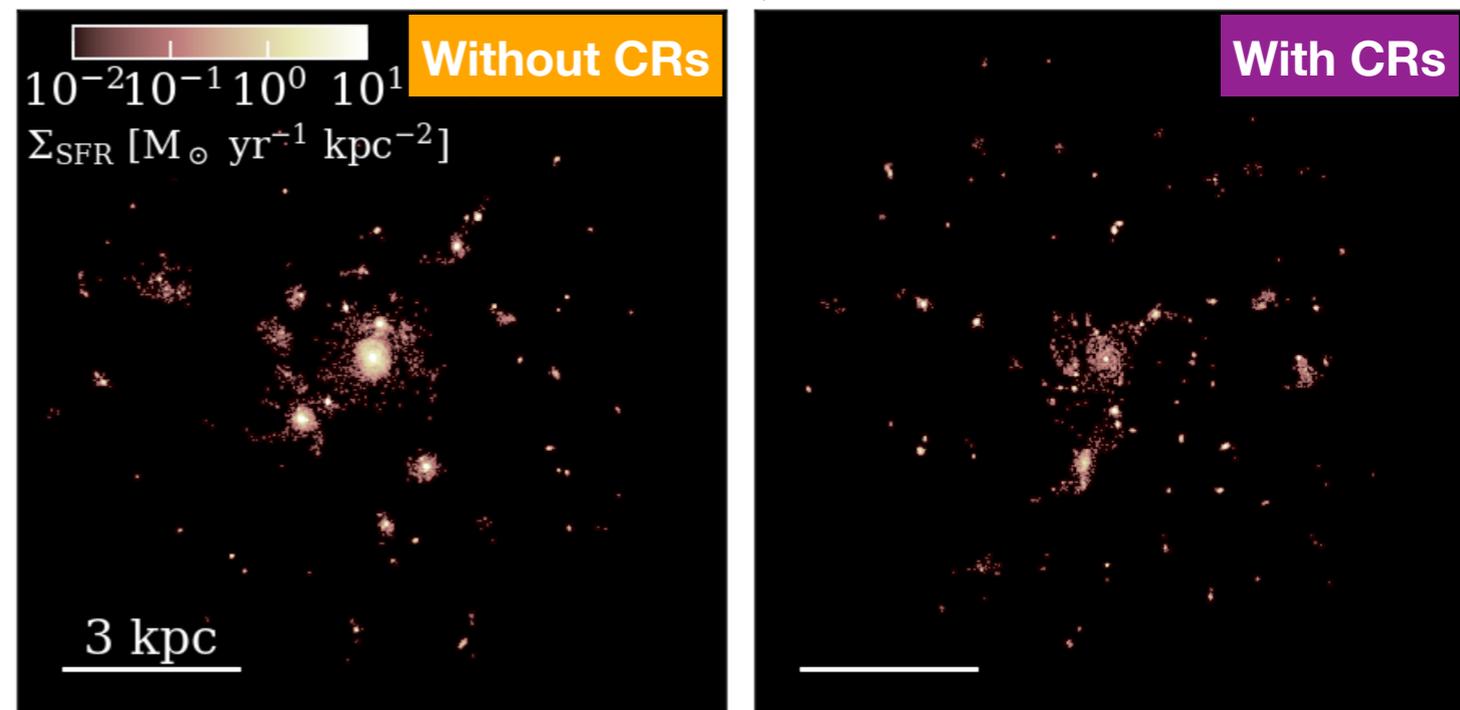
Intermediate mass galaxy

Milky-Way mass galaxy



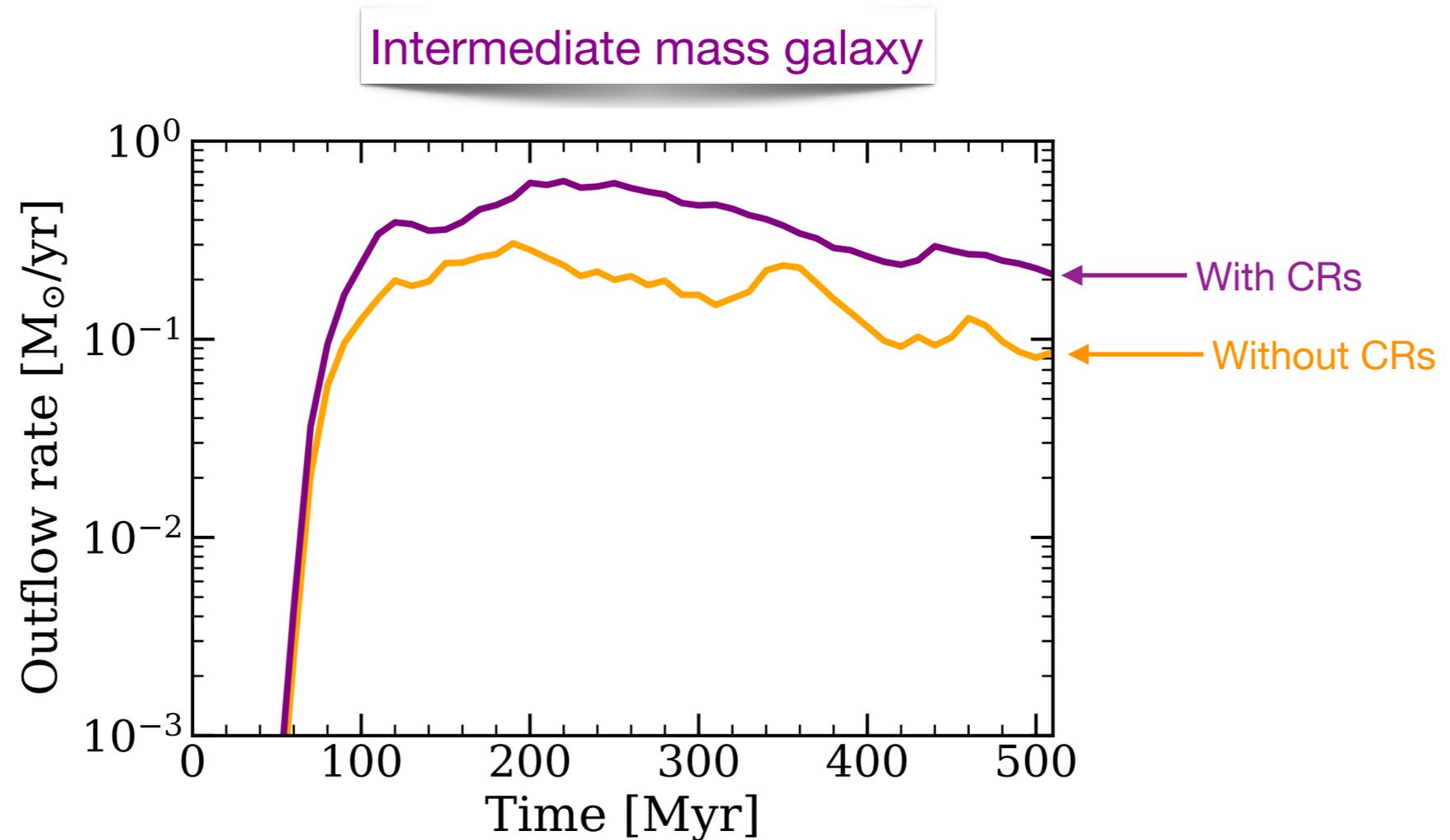
★ CRs smooth the ISM gas distribution
 -> stars form and explode in more diffuse environments

★ Less numerous and massive star formation clumps with CR feedback



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5. Sensitivity of the results with the unknown diffusion coefficient

Outflows and their temperature



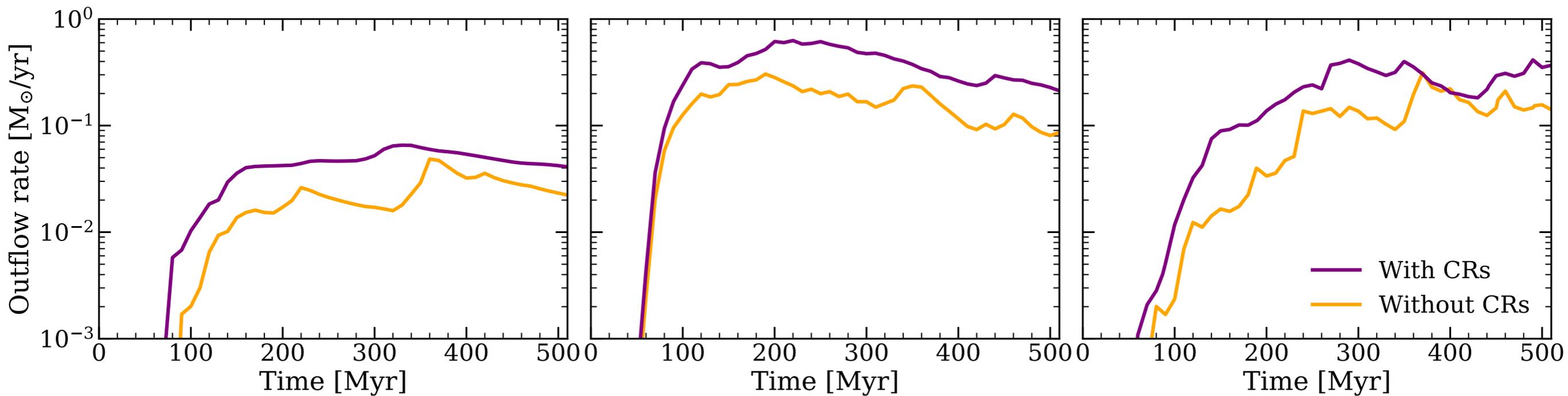
★ More outflows when cosmic ray feedback is added

Outflows and their temperature

Low mass galaxy

Intermediate mass galaxy

Milky-Way mass galaxy



- ★ More outflows when cosmic ray feedback is added
- ★ Similar effect at any galaxy mass

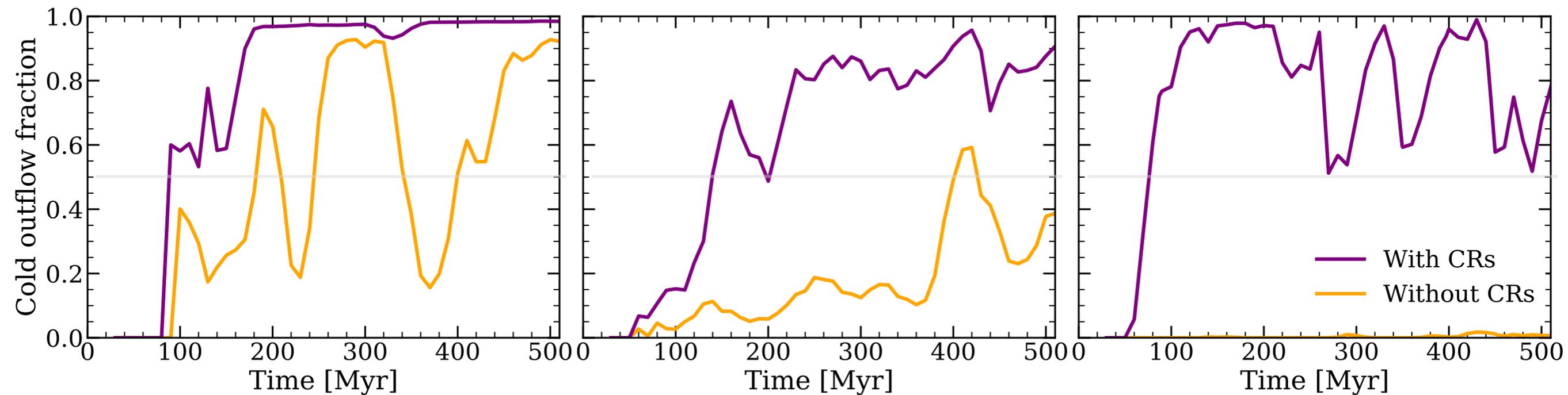
Outflows and their temperature

Fraction of cold outflows with $T < 10^5$ K

Low mass galaxy

Intermediate mass galaxy

Milky-Way mass galaxy



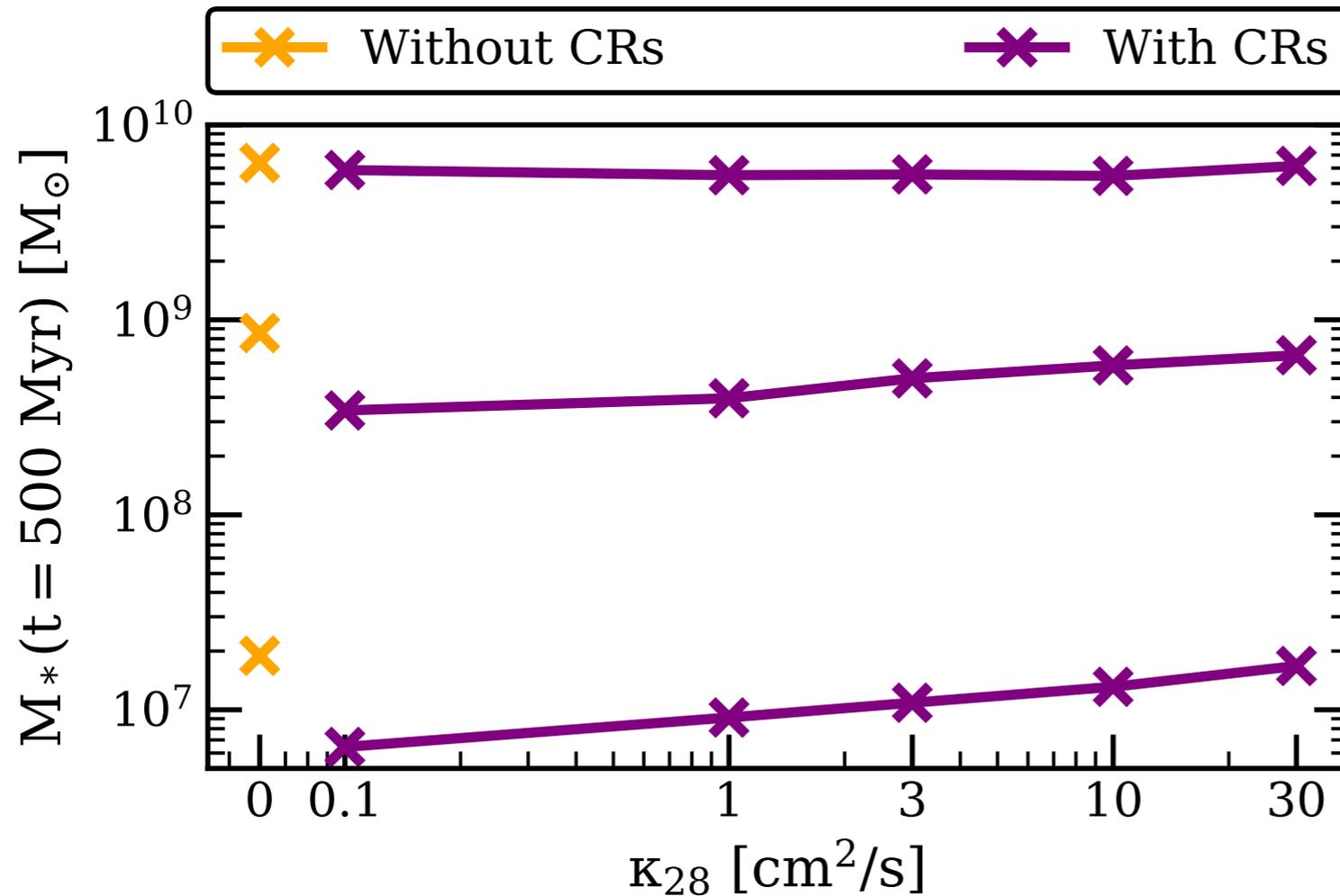
★ Cosmic rays => much more cold outflowing gas

★ Without cosmic rays => cold fraction of outflowing gas ↘ with galaxy mass

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Sensitivity of the results with the unknown diffusion coefficient

$$\kappa_{28} = \kappa \times 10^{28} \text{ cm}^2/\text{s}$$



Milky-Way mass galaxy
 $M_{\text{halo}} = 10^{12} M_\odot$

Intermediate mass galaxy
 $M_{\text{halo}} = 10^{11} M_\odot$

Low mass galaxy
 $M_{\text{halo}} = 10^{10} M_\odot$

Range of values derived from γ -ray luminosity
 or spallation products measurements

Without CRs

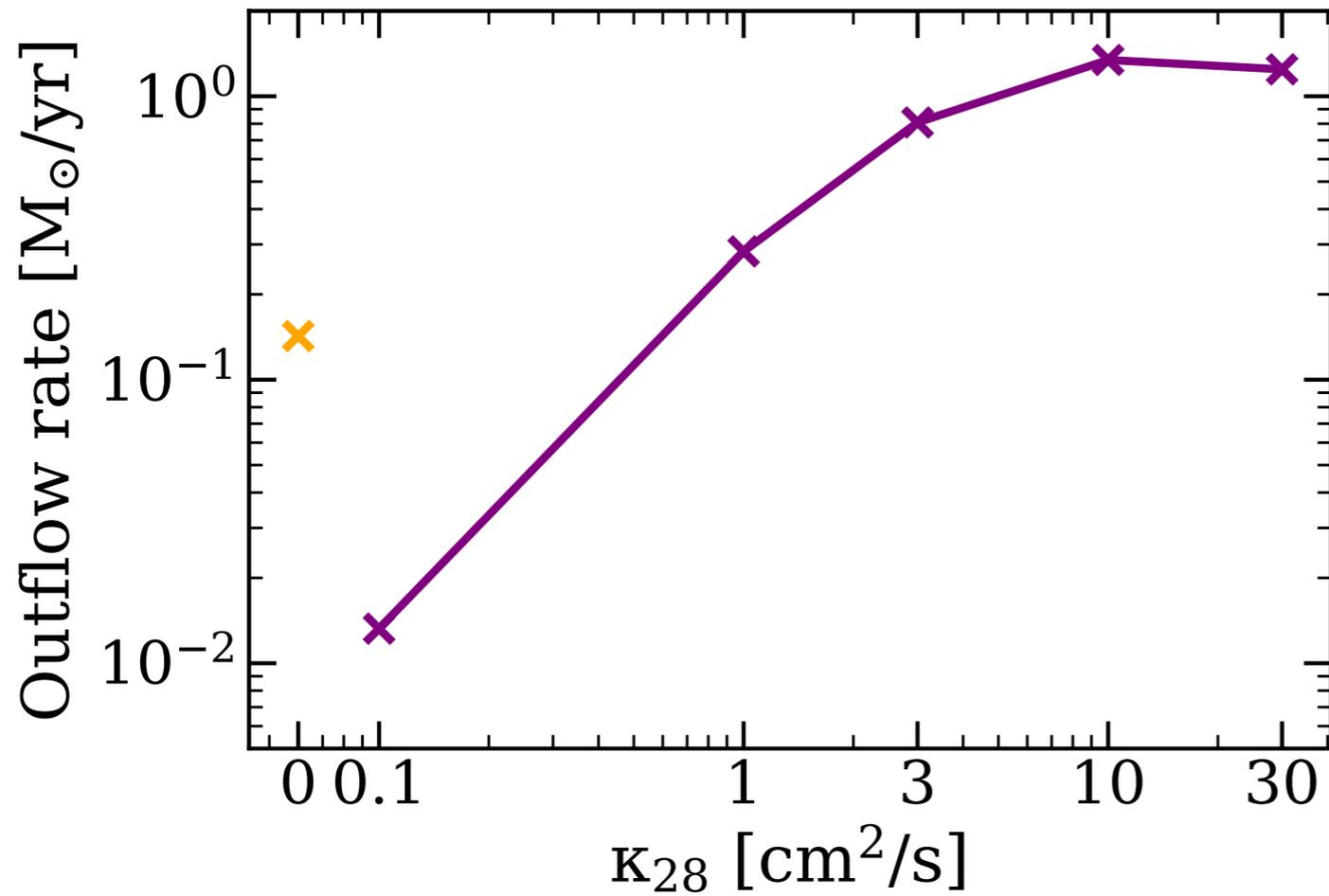
$\kappa \searrow \Rightarrow \text{CRs } t_{\text{confinement}} \nearrow$

\Rightarrow more interactions with gas
 \Rightarrow more SF suppression

Sensitivity of the results with the unknown diffusion coefficient

Milky-Way mass galaxy

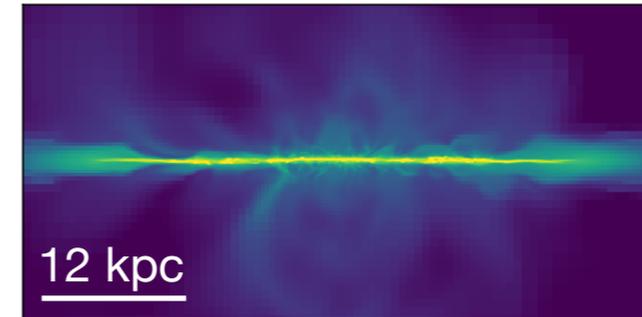
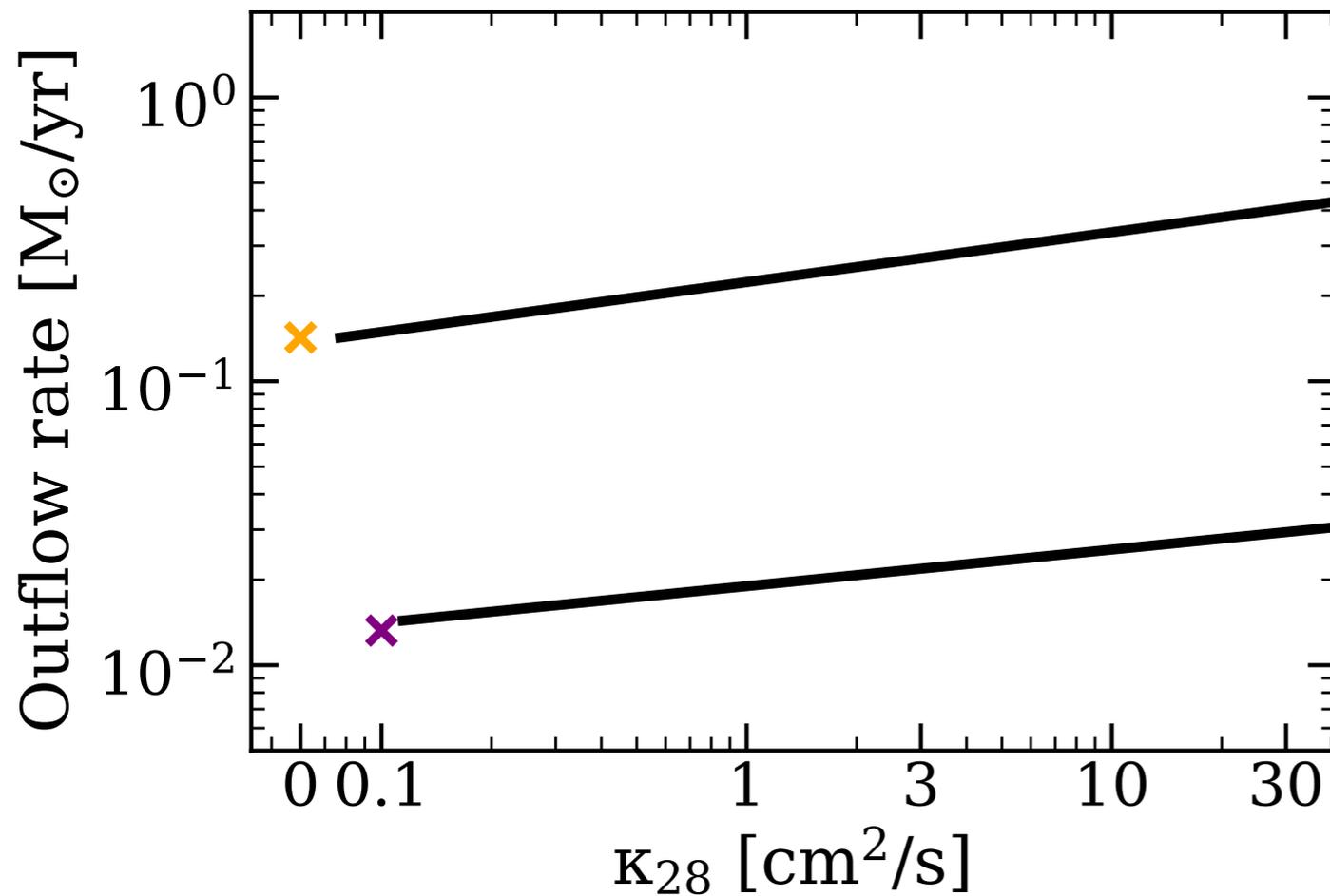
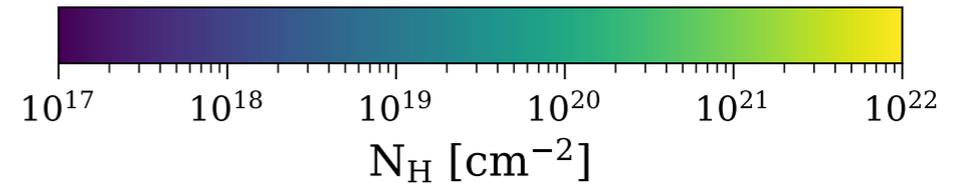
$$\kappa_{28} = \kappa \times 10^{28} \text{ cm}^2/\text{s}$$



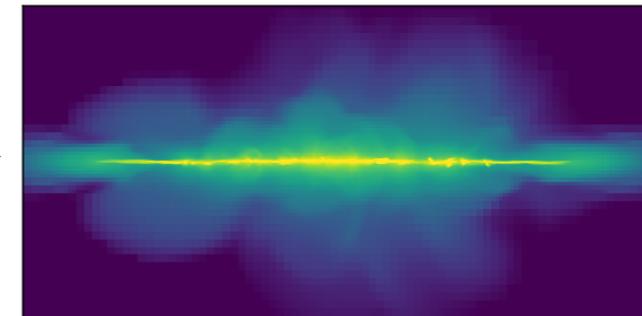
Sensitivity of the results with the unknown diffusion coefficient

Milky-Way mass galaxy

$$\kappa_{28} = \kappa \times 10^{28} \text{ cm}^2/\text{s}$$



noCR



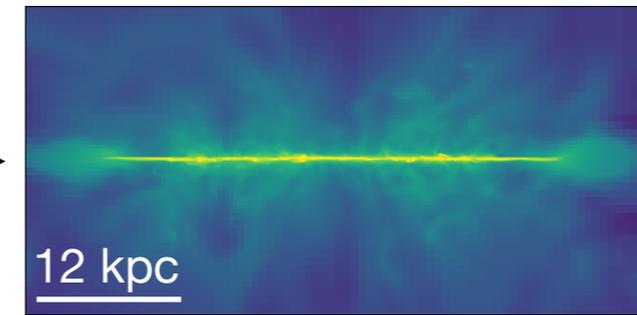
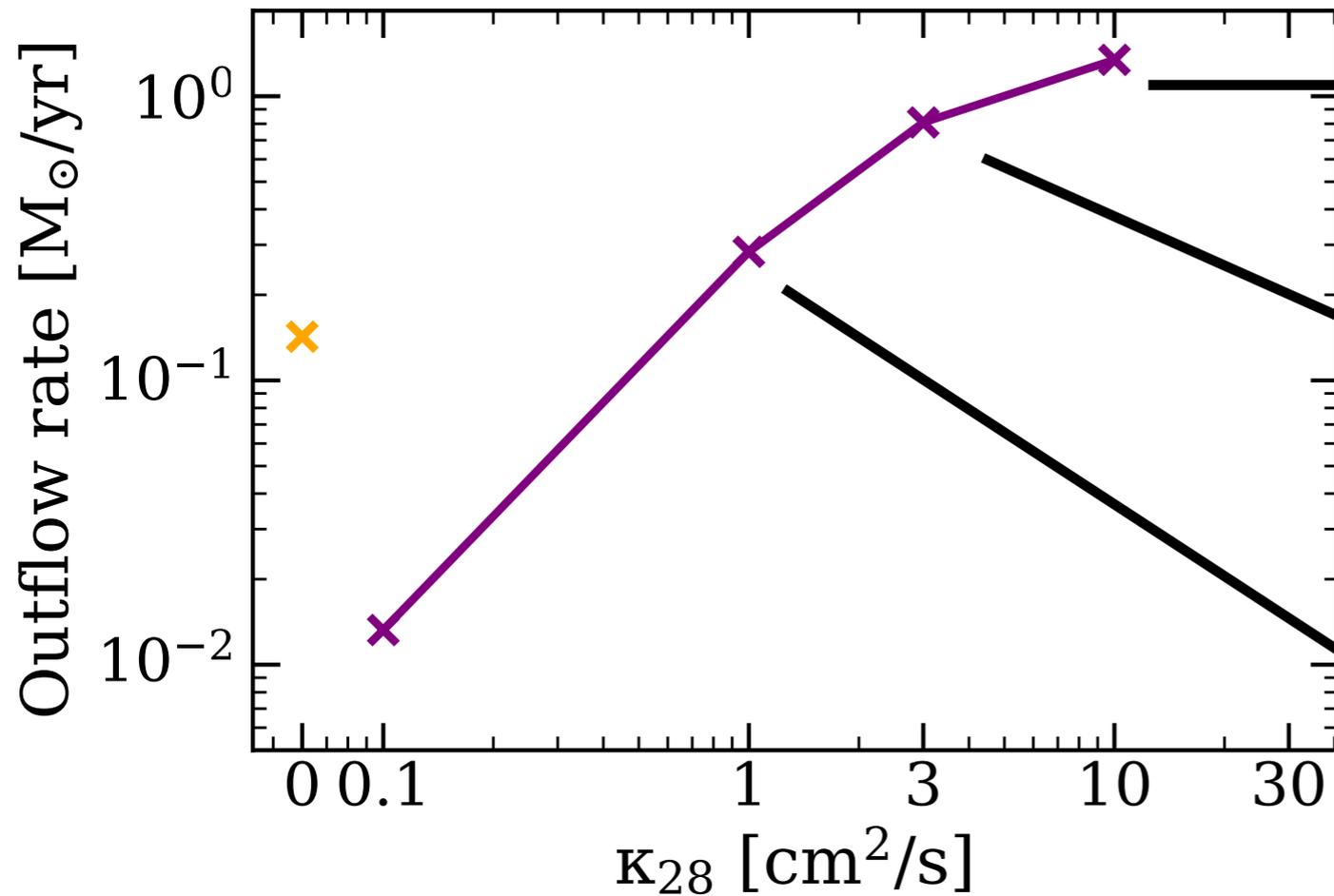
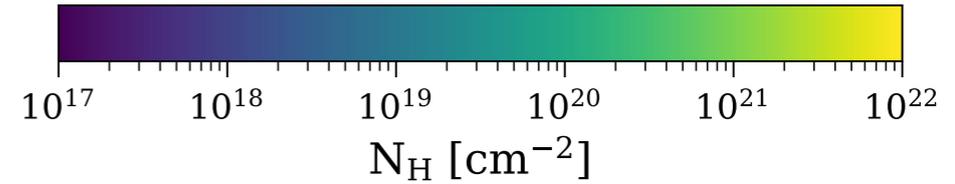
$\kappa_{28} = 0.1$

- ★ Disk thicker, need to push gas denser than in the **noCR** case
- ★ $\kappa_{28} = 0.1$ -> counter-productive in launching winds

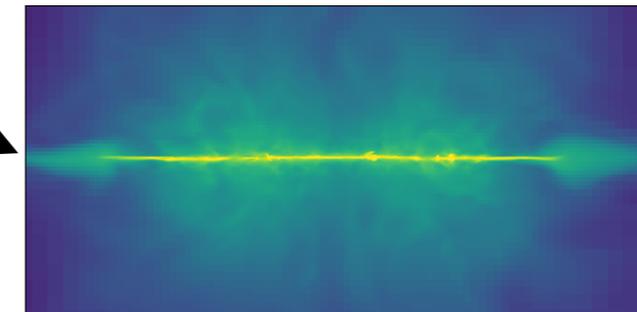
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Milky-Way mass galaxy

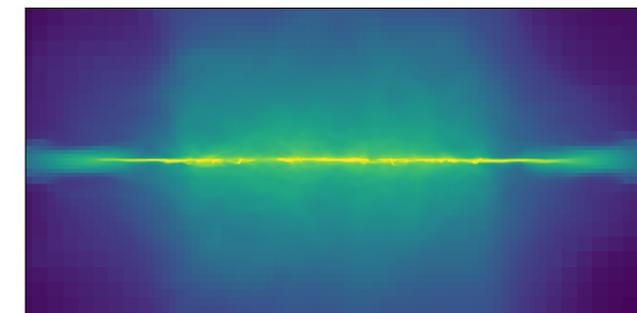
$$\kappa_{28} = \kappa \times 10^{28} \text{ cm}^2/\text{s}$$



$\kappa_{28} = 10$



$\kappa_{28} = 3$



$\kappa_{28} = 1$

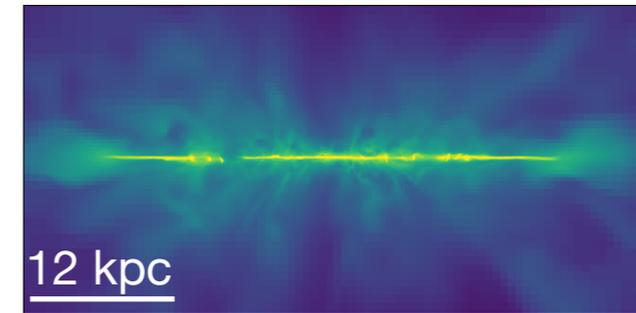
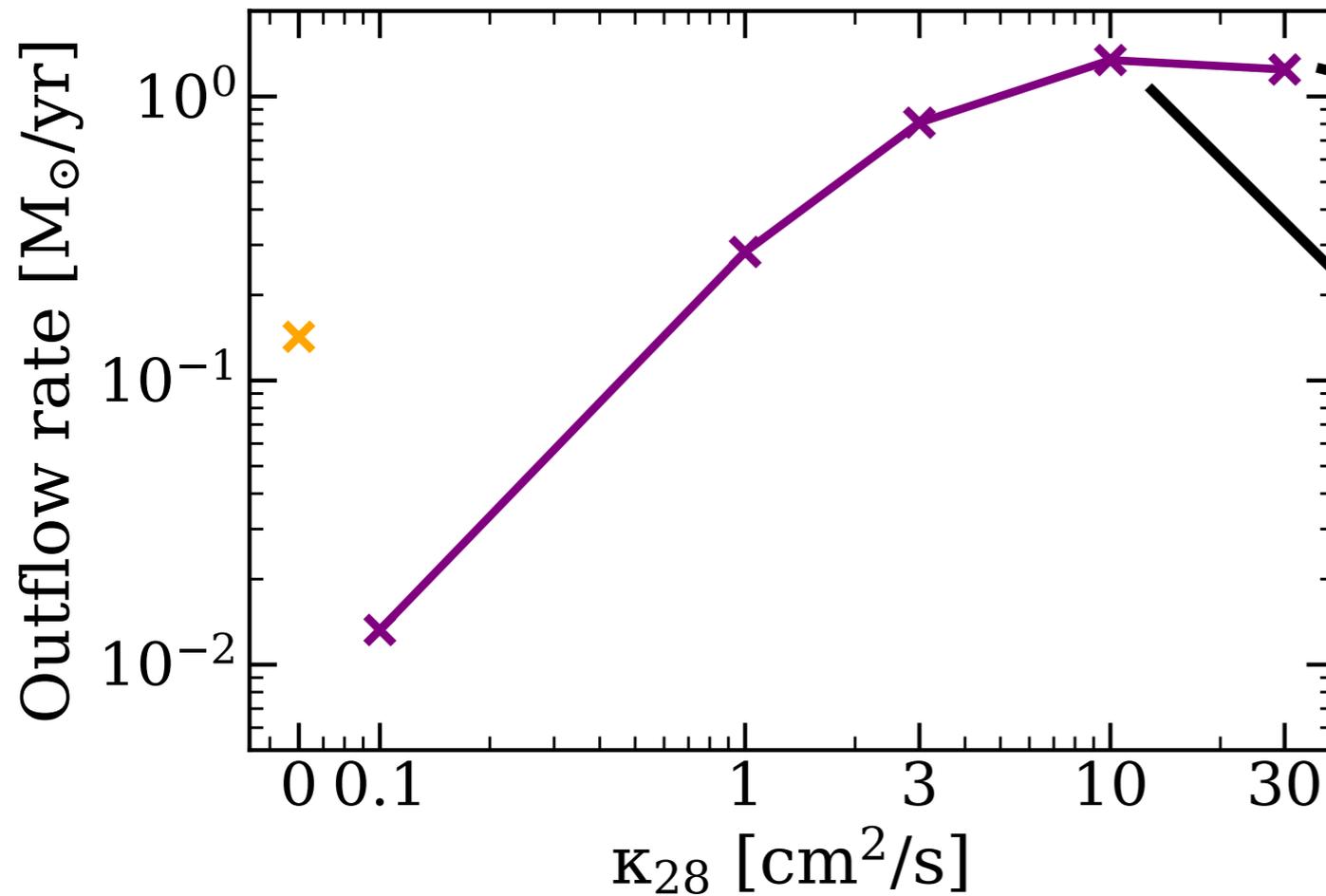
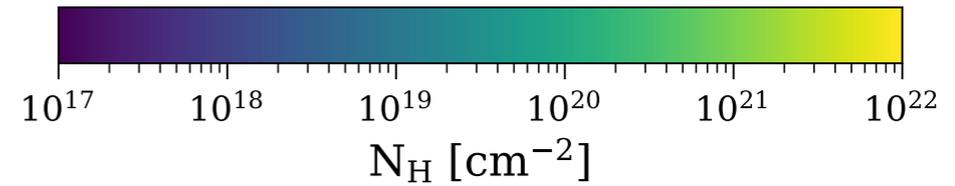
★ More and more extended gas distribution around the disk

★ $\kappa \nearrow \Rightarrow$ the outflow rate \nearrow

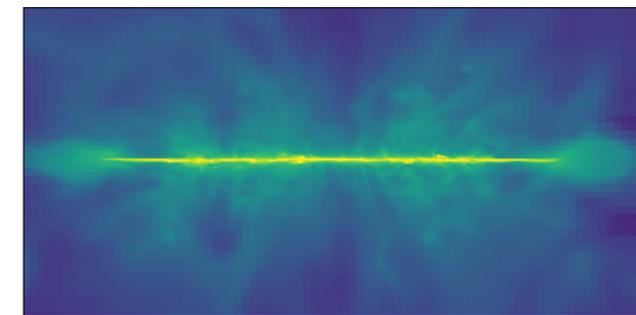
Sensitivity of the results with the unknown diffusion coefficient

Milky-Way mass galaxy

$$\kappa_{28} = \kappa \times 10^{28} \text{ cm}^2/\text{s}$$



$\kappa_{28} = 30$



$\kappa_{28} = 10$

- ★ Gas around the disk and in the outflows becomes more diffuse
- ★ $\kappa_{28} = 30 \rightarrow$ CR energy escapes too quickly to continue maintaining more outflows

CONCLUSIONS

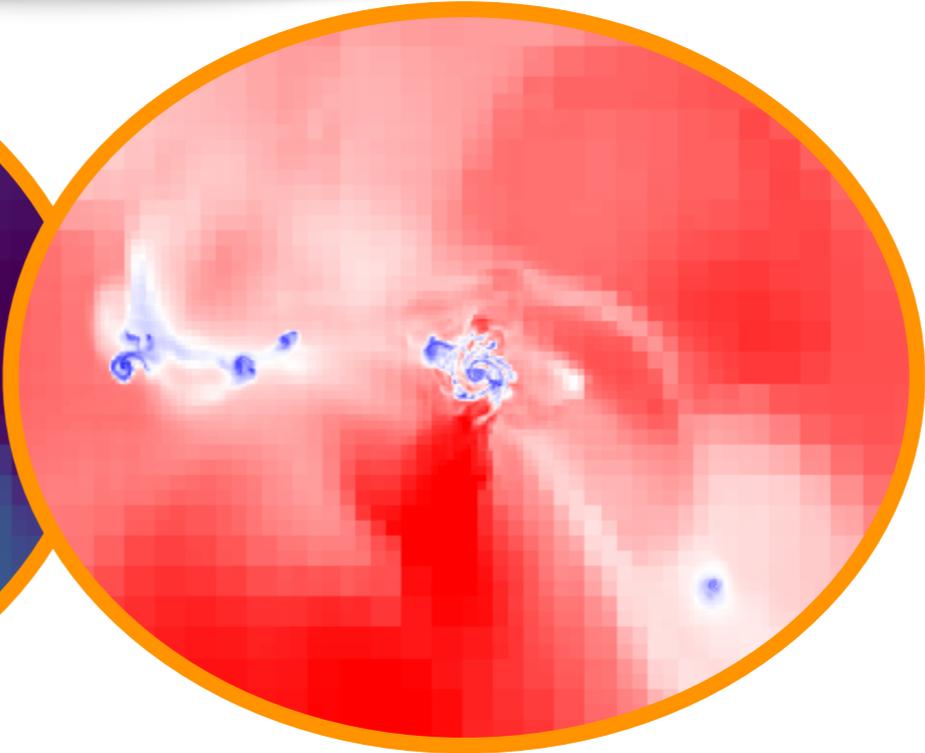
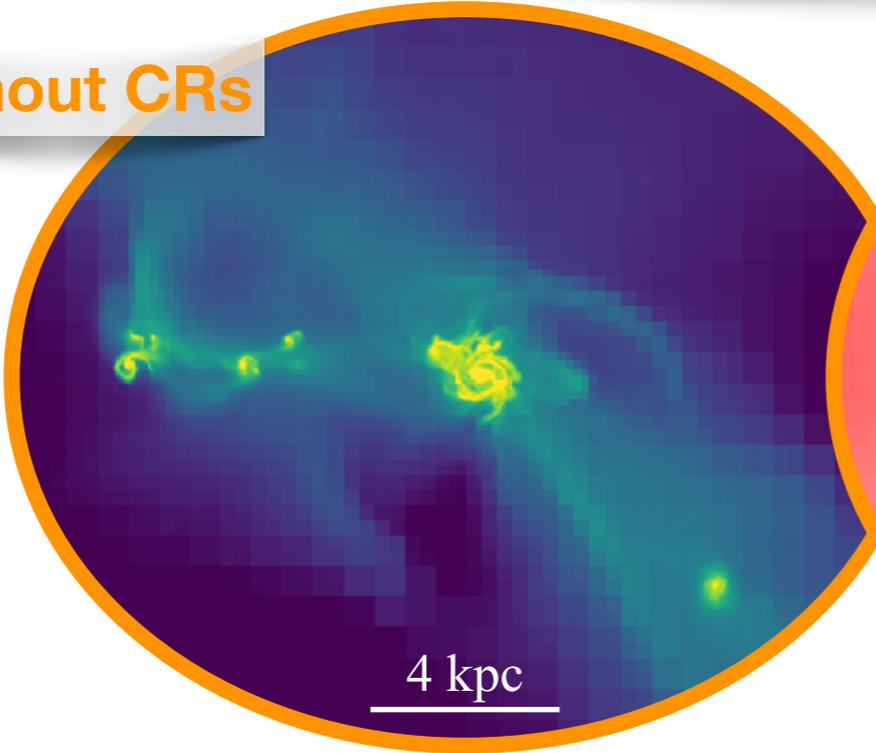
- CRs**
- ★ Produce a smoother gas distribution and a colder CGM
 - ★ Mildly alter the SFR for the two dwarf galaxies.
 - ★ Inefficient in suppressing SFR in a MW-mass galaxy, just as SN feedback
 - ★ Help driving more and colder outflows
 - ★ BUT results dependant on the CR parameters !

Idealised galaxies  **Cosmological zoom-in halo**

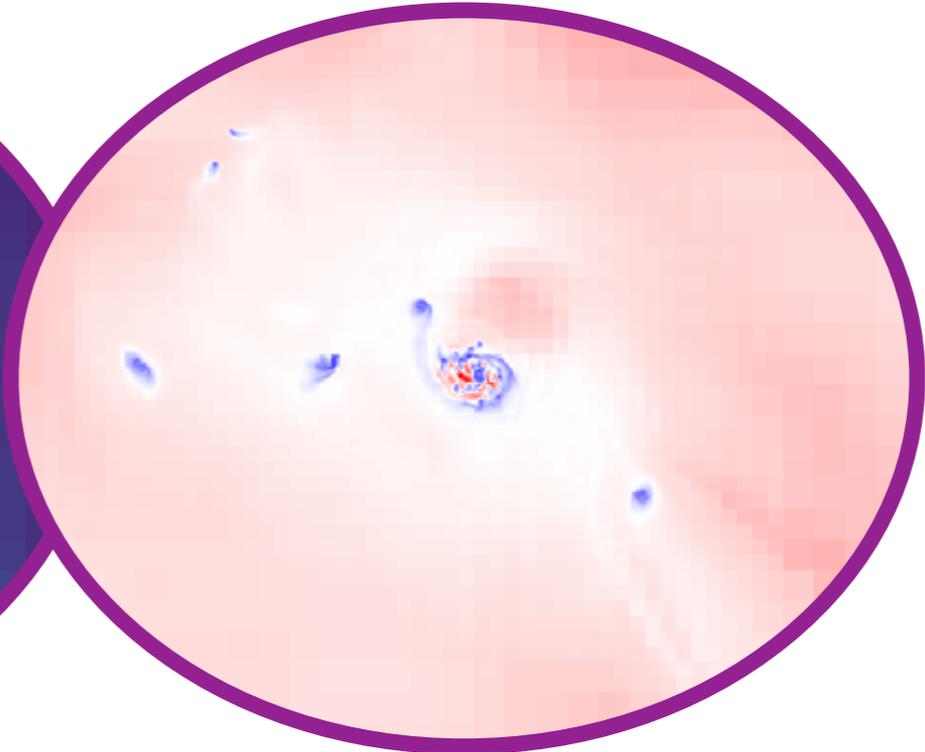
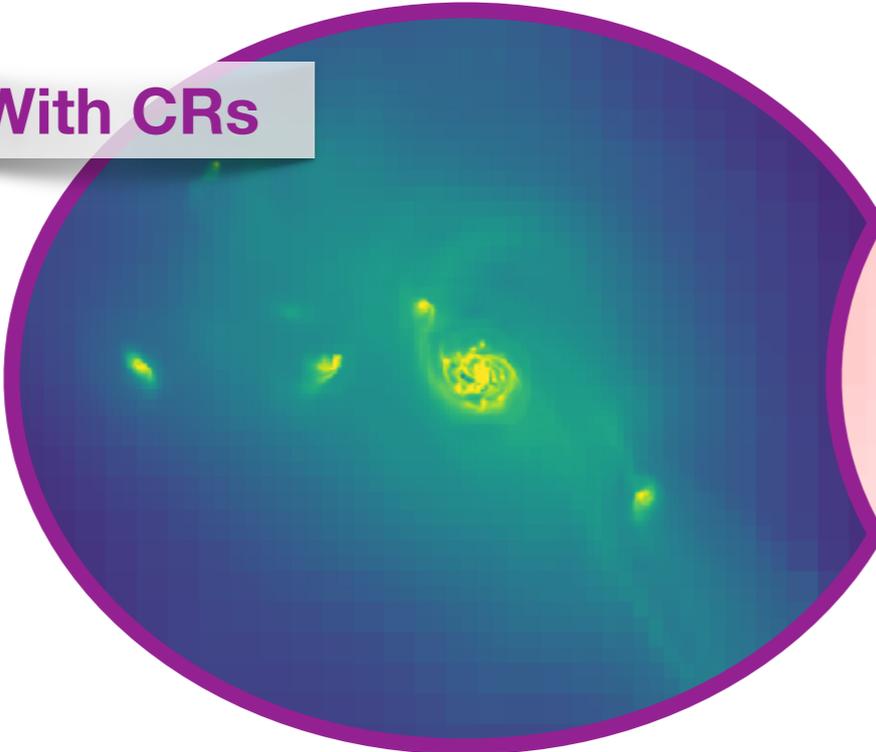
ONGOING WORK

At $z=5$: $M_{\text{halo}} = 1.5 \times 10^{10} M_{\odot}$

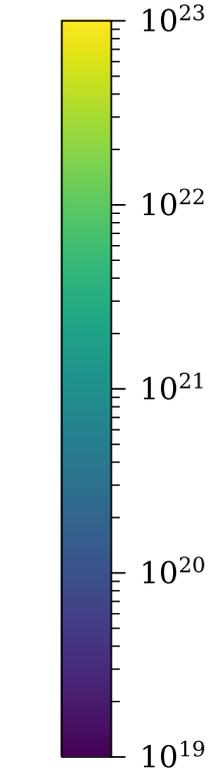
Without CRs



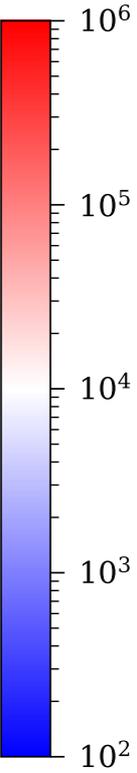
With CRs



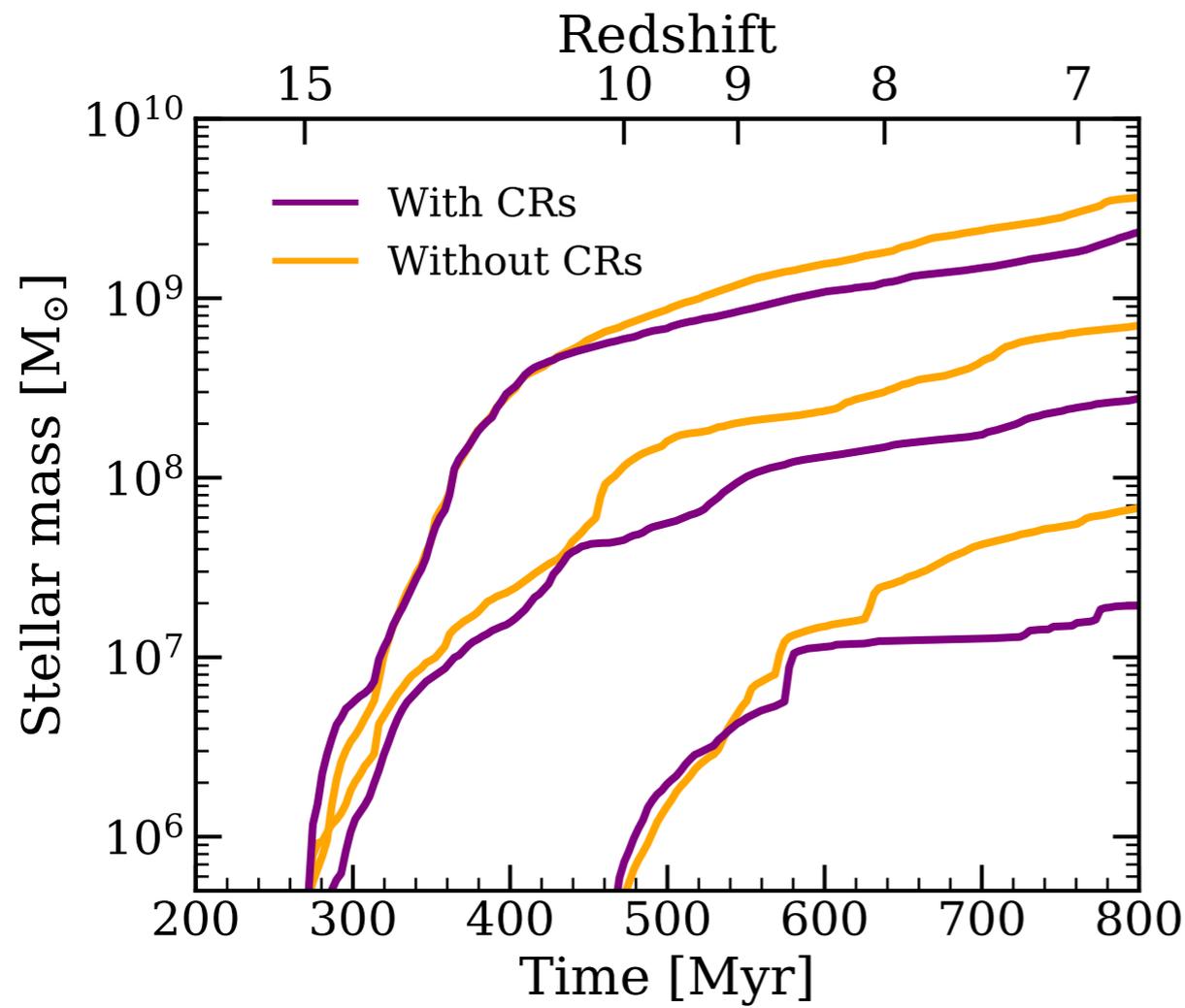
$N_{\text{H}} [\text{cm}^{-2}]$



$T [\text{K}]$



ONGOING WORK



At $z = 5$:

$$M_{\text{halo}} = 10^{11} M_{\odot}$$

$$M_{\text{halo}} = 1.5 \times 10^{10} M_{\odot}$$

$$M_{\text{halo}} = 2.6 \times 10^9 M_{\odot}$$

★ The effect of CRs in reducing the SFR ↘ when the galaxy mass ↗

CONCLUSIONS

CRs

- ★ Produce a smoother gas distribution and a colder CGM
- ★ Mildly alter the SFR for the two dwarf galaxies.
- ★ Inefficient in suppressing SFR in a MW-mass galaxy, just as SN feedback
- ★ Help driving more and colder outflows
- ★ BUT results dependant on the CR parameters !

Farcy, Rosdahl & Dubois in prep.

In a cosmological context:

- same SFR suppression effect
- smoother and colder gas

WIP

+ Want to investigate if CRs have an impact on the Epoch of Reionisation itself

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