CRexit

How Cosmic Rays affect Cold Cloud Condensation in the CGM

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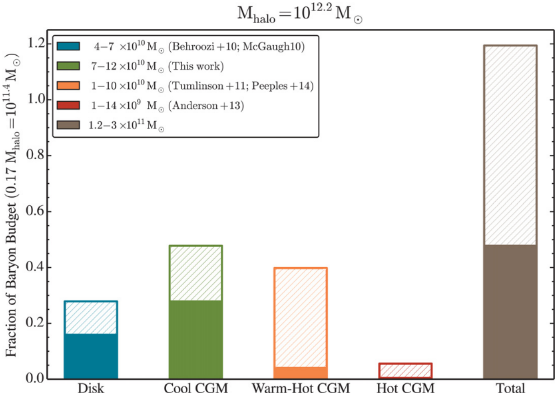
CGM & Cosmic Rays

- CGM contains large amounts of cold gas: potential fuel for star formation
- Possible origin: cold gas condensates in CGM via thermal instability



Werk et al (2014)

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- Observations: cold gas is out of pressure equilibrium with hot gas
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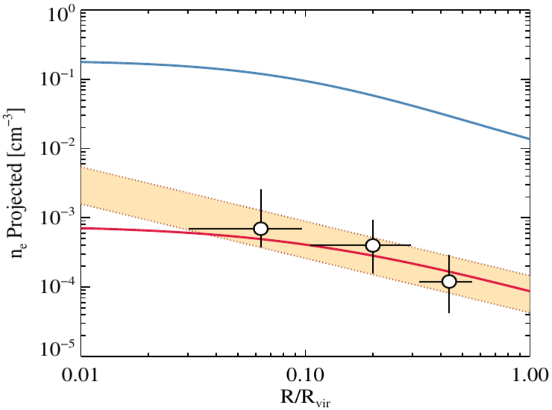

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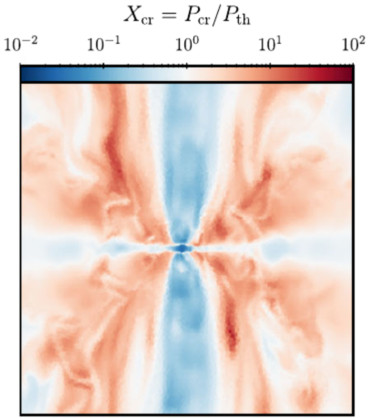

Thomas et al. (2023)

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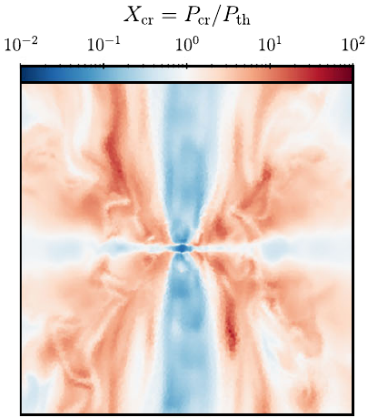
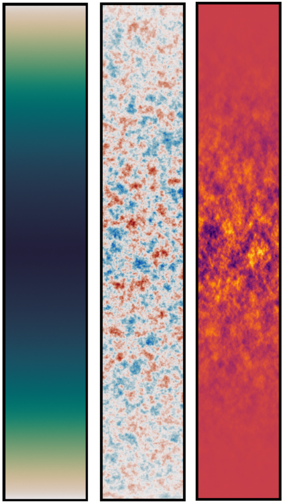
- **How do Cosmic Rays affect cold gas condensation in the CGM?**



Thomas et al. (2023)

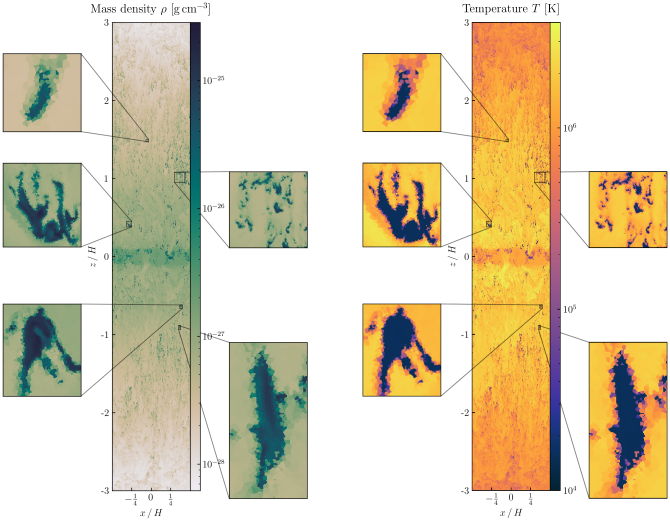
Simulation setup

- Patch of CGM gas, $30 \times 30 \times 180$ kpc
- Iso-cooling density profile
- Realistic cooling (CRISP)
- Heating mechanism to balance cooling **on average**
- Seed density perturbations via initial **turbulent velocity field** $(X_\mathrm{t} = 0.3)$
- Initial **turbulent magnetic field** $(X_\mathrm{b} = 0.01)$



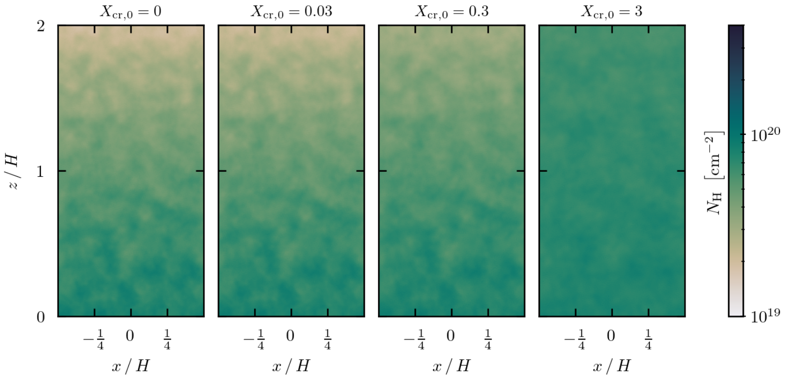
Cold cloud condensation

- Without CRs
- Multiphase CGM
- Cold, dense clouds condense from hot ambient medium
- Various shapes, sizes, masses, and thermodynamic properties



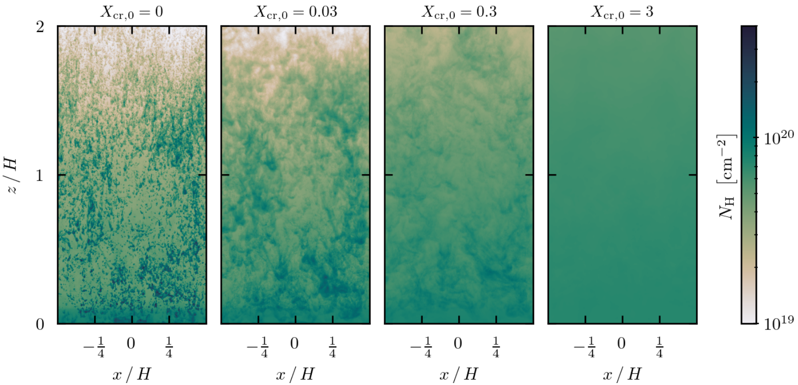
Advective CR transport

- CRs pressure as constant fraction of thermal pressure: $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$
- CRs only advect with gas flow



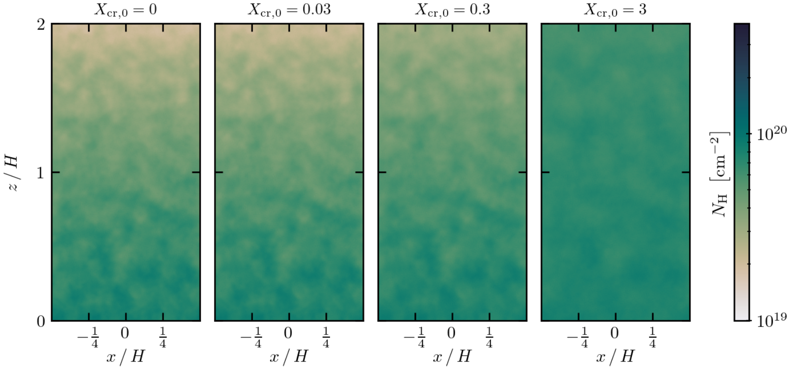
Advective CR transport

- CRs pressure as constant fraction of thermal pressure: $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$
- CRs only advect with gas flow
- Additional non-thermal pressure hinders collapse
- Advective CRs: launching sites of winds, supernova remnants, ...
- **Not the realistic CR transport scenario for CGM**



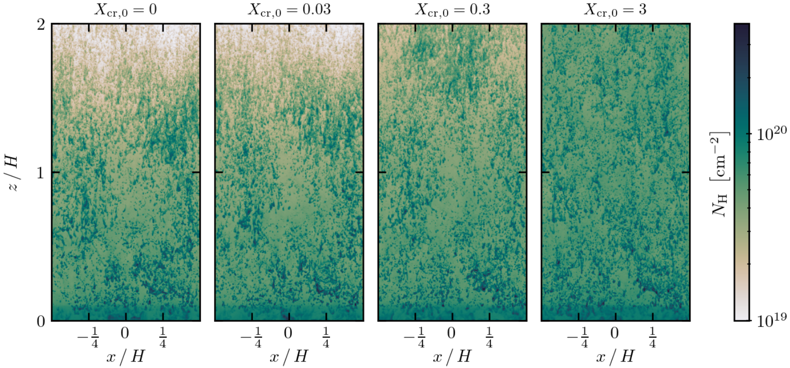
2-moment CR transport

- CRs can move relative to the gas
- Motion along magnetic field lines
- 2-moment: evolution equations for CR energy and CR flux

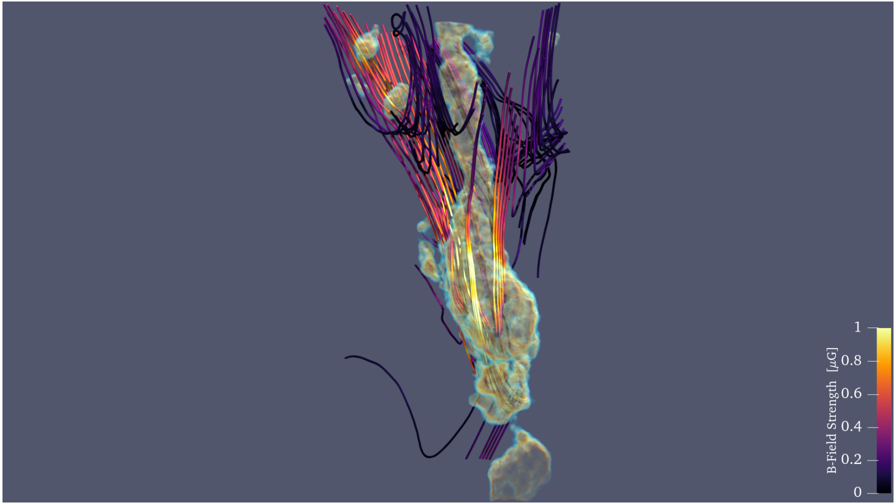


2-moment CR transport

- CRs can move relative to the gas
- Motion along magnetic field lines
- **Realistic transport: minimal impact of CRs on cloud condensation**

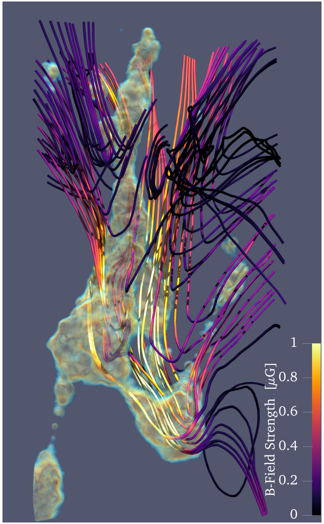


Cosmic Ray motorway



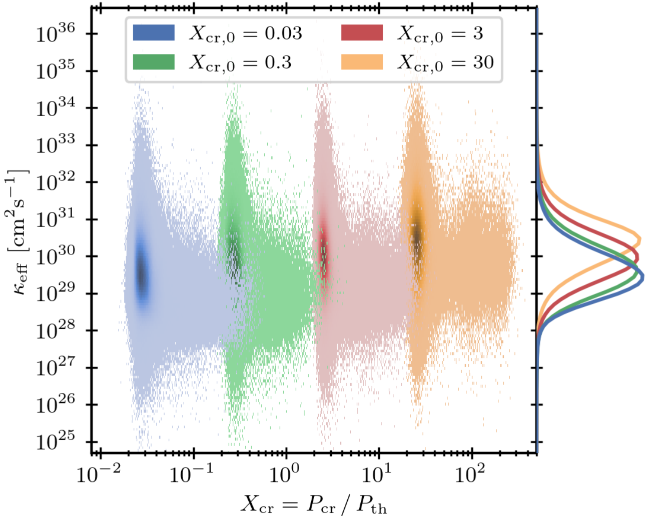
Cosmic Ray motorway

- Magnetic field topology of randomly chosen cloud
- **Field lines open up pathway for CRs to escape**



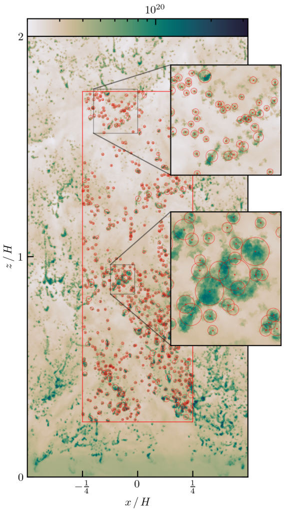
CR diffusion coefficient

- effective CR diffusion coefficient
  $\kappa_{\text{eff}} = f_{\text{cr}} \, / \, (\boldsymbol{b} \cdot \nabla \varepsilon_{\text{cr}})$
- Results from combined transport of streaming and diffusion



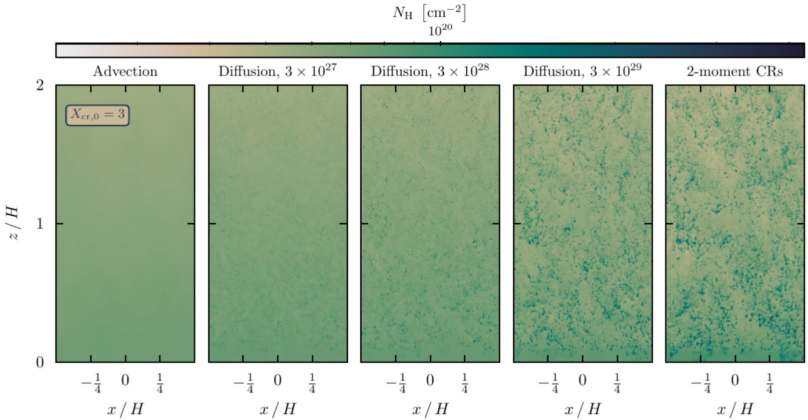
CRexit - Timescales

- $t_{\rm cr} = r_{\rm cloud}^2 \,/\, \kappa_{\rm eff,cr}$
  Defines the timescale of CRs to travel 1 $r_{\rm cloud}$, i.e. to escape the cloud
- $t_{\rm collapse} \approx t_{\rm cool}$ (no self-gravity)
  Defines the collapse timescale of a cloud
- If $t_{\rm cr} \lesssim t_{\rm collapse}$: CRs escape to quickly to apply sufficient pressure support against collapse



CRexit - Varying CR transport speed

- Slow CR transport: Cloud condensation is suppressed
- Fast CR transport: Minimal impact of CRs on cloud collapse



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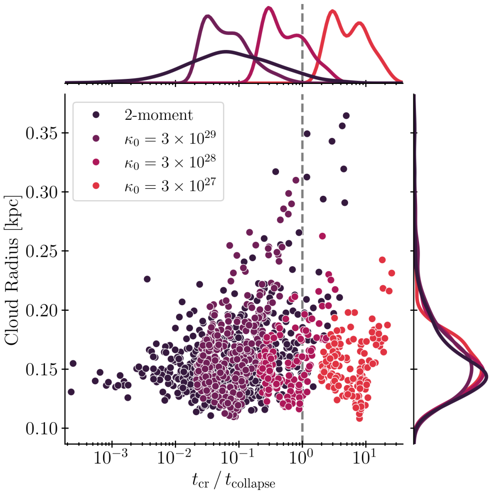
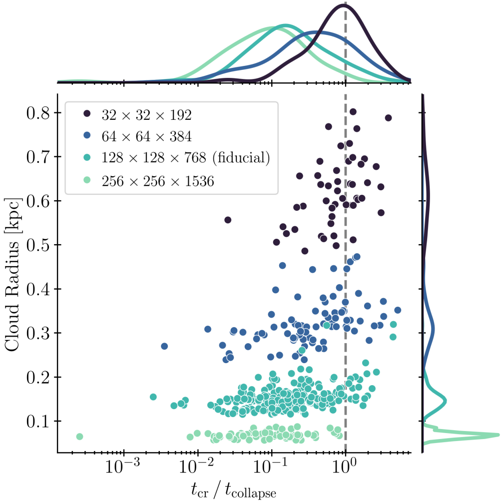


Resolution

- Setup with $X_{\mathrm{cr}} = 3$
- 2-moment CR transport
- Low resolution: larger clouds

  $\rightarrow t_{\mathrm{cr}} = r_{\mathrm{cloud}}^2 \,/\, \kappa_{\mathrm{eff,cr}}$ larger

  $\rightarrow$ **Larger fraction of CRs is trapped inside clouds**



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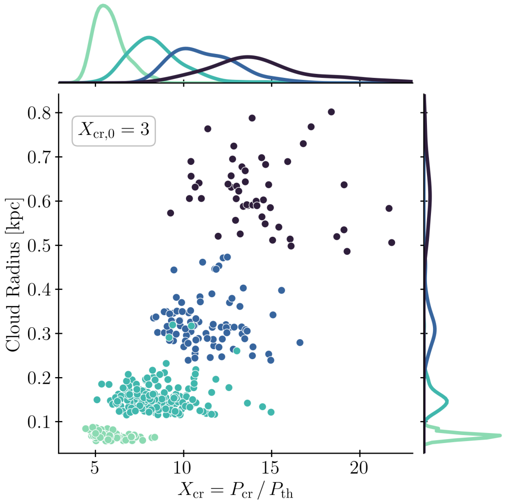
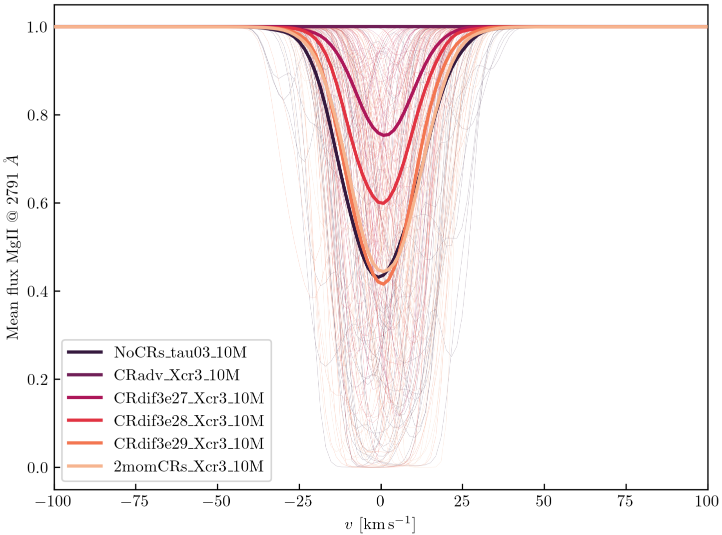
- CRs become less important with increasing resolution!



Coming soon: Observational implications

- Weber et al. (in prep)
- Probing CR transport with absorption line spectroscopy



Main Takeaways

When modelling CRs in the CGM:

- **Realistic CR transport is crucial** $\rightarrow t_{\mathrm{cr}}$
  Slow transport locks CRs inside clouds
- **Numerical resolution is crucial** $\rightarrow r_{\mathrm{cloud}}$
  Larger clouds retain CRs much longer