Title: Magnetic fields and cosmic rays in cosmological simulations

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Collection/Series: Cosmic Ecosystems

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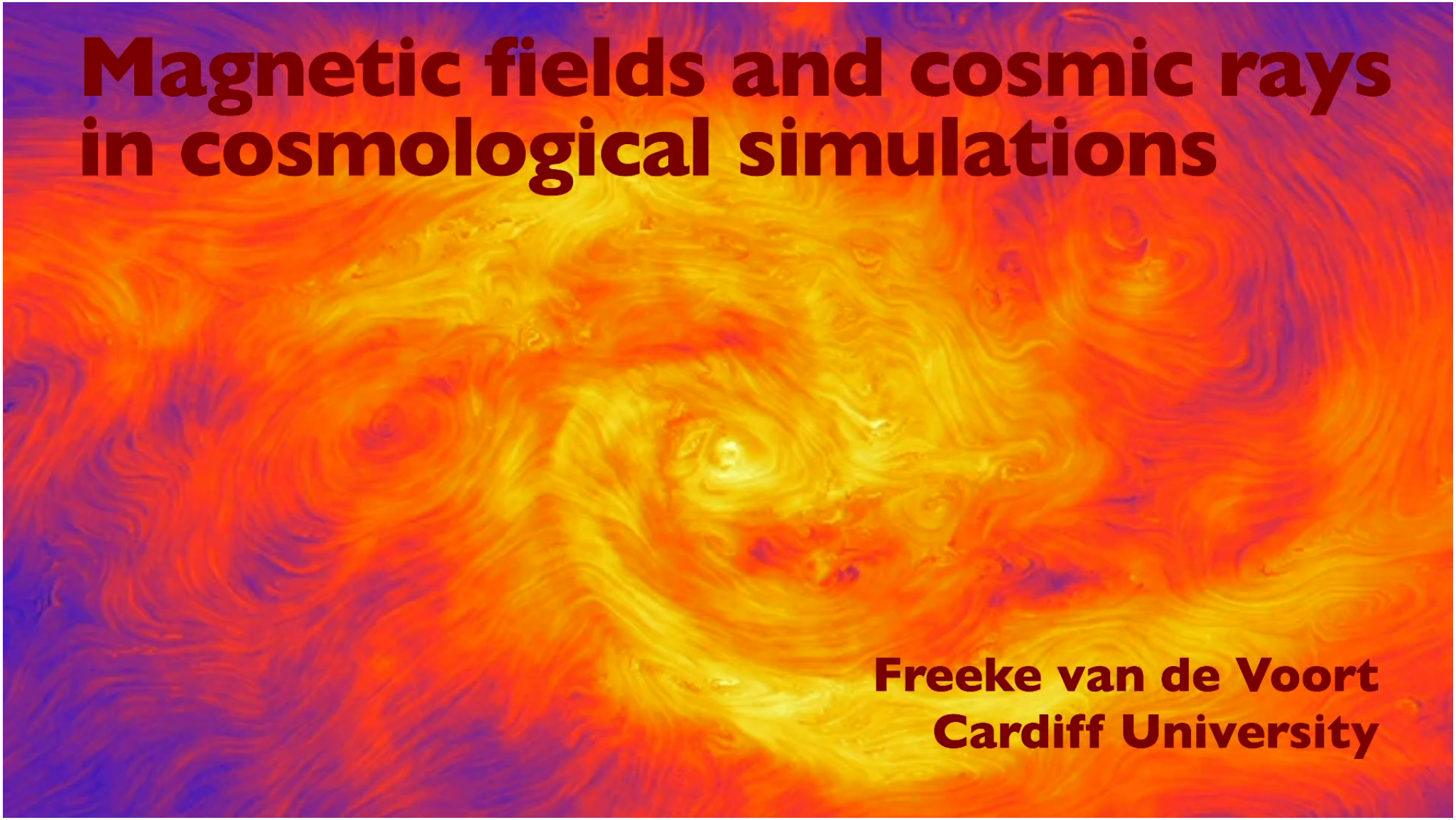
Abstract:

Using zoom-in cosmological simulations, I will discuss some of the physical and observable properties of the circumgalactic medium (CGM). I will focus on non-thermal physical processes and how they impact the galactic ecosystem. The presence of magnetic fields and feedback from relativistic cosmic rays changes the flow of gas in the CGM, affecting the efficiency of outflows driven by stars or supermassive black holes as well as the turbulence-driven mixing in the CGM. This also affects our simulations' predictions for neutral hydrogen and metal ions, observable through 21 cm emission and quasar absorption lines. I will show how these effects of magnetic fields and cosmic rays vary across a wide range in halo mass, from dwarf galaxies to galaxy groups.

Magnetic fields and cosmic rays in cosmological simulations



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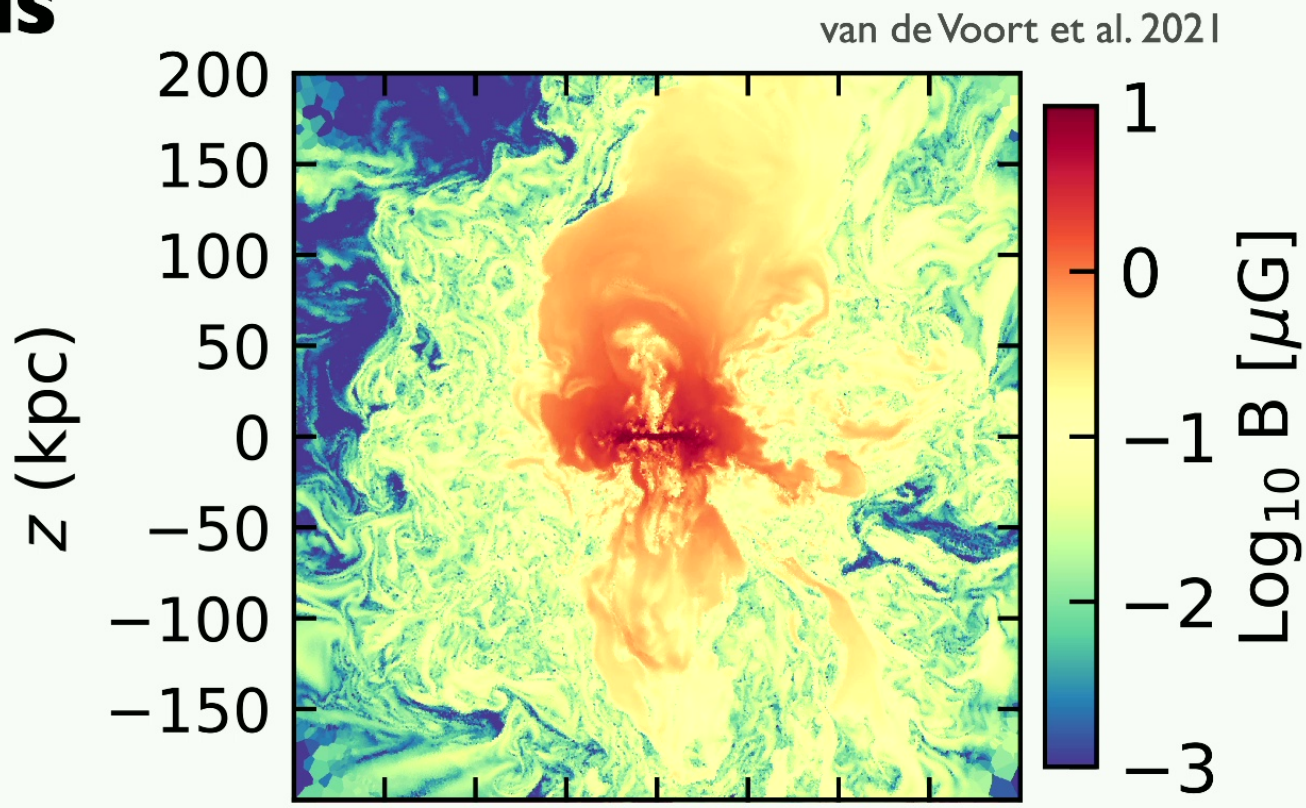
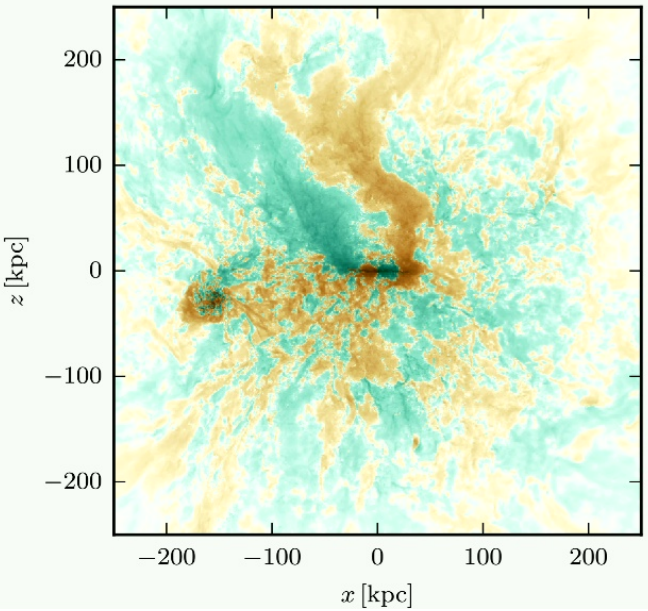
Magnetic fields

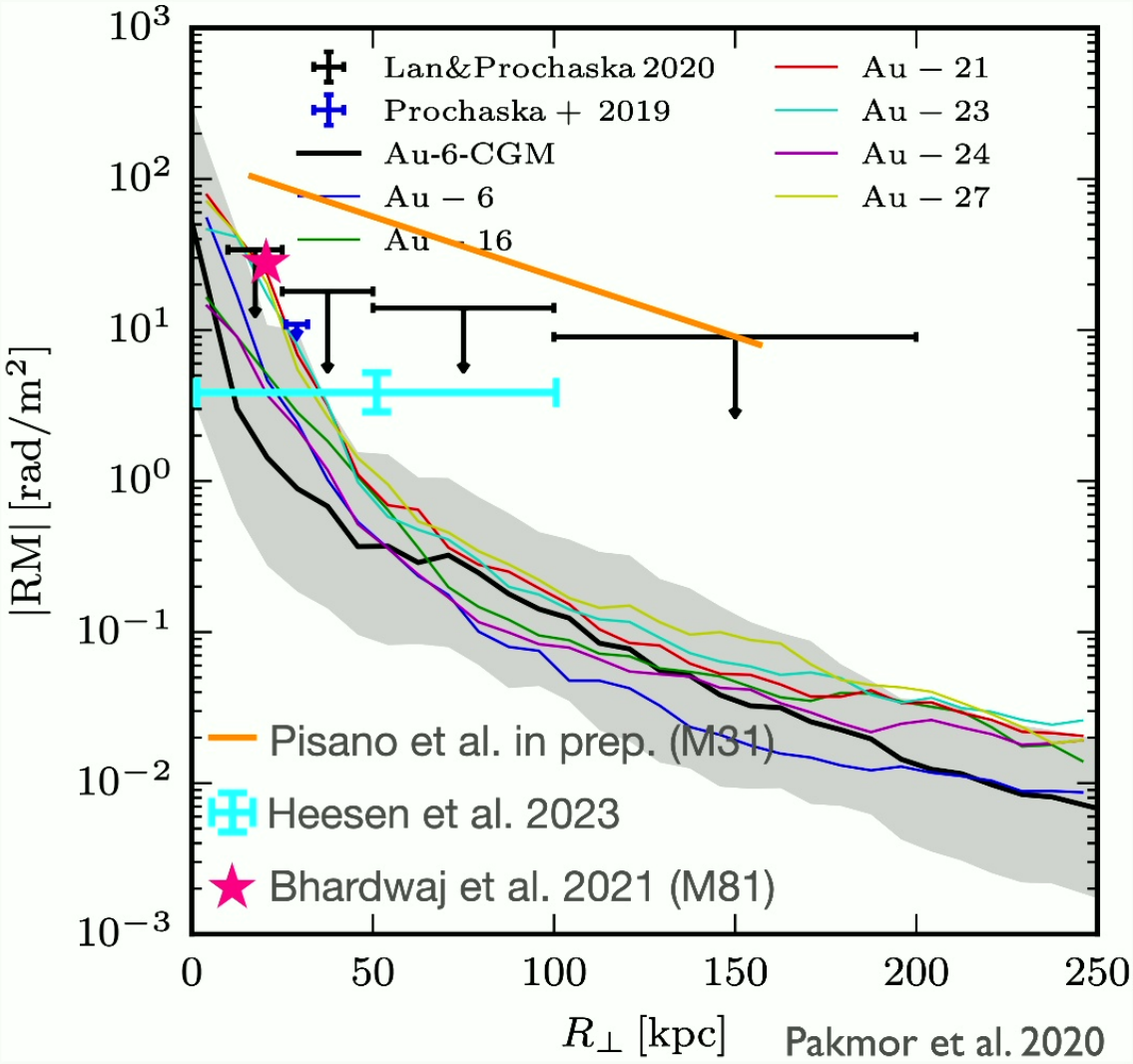


- Magnetic field strengths are highest in the polar direction, pushed out by outflows. Field strengths can be up to 1 μG, but in most of the volume are 0.01-0.1 μG.

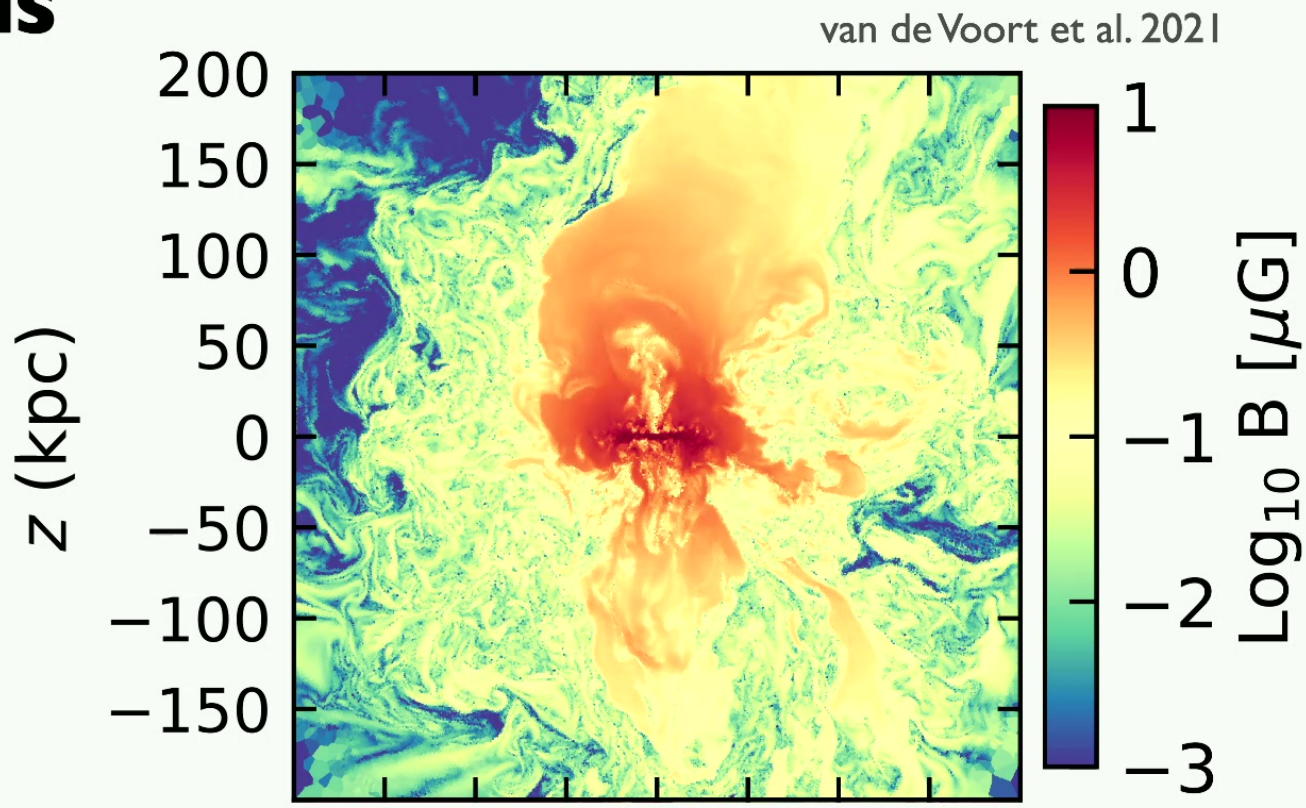
Rotation measure

- Faraday rotation of polarised background sources can constrain magnetic fields in the CGM. So far, our simulations are consistent with observations.





Magnetic fields



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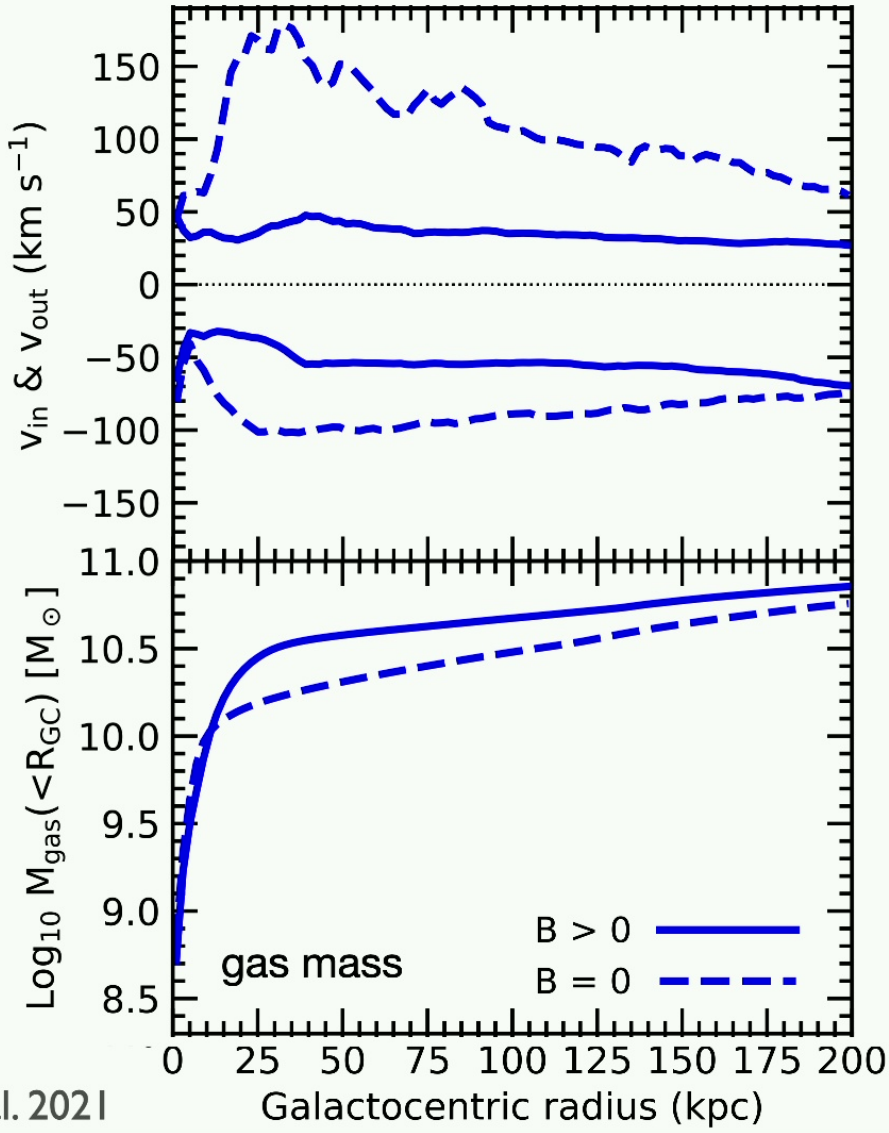
Effect of B fields

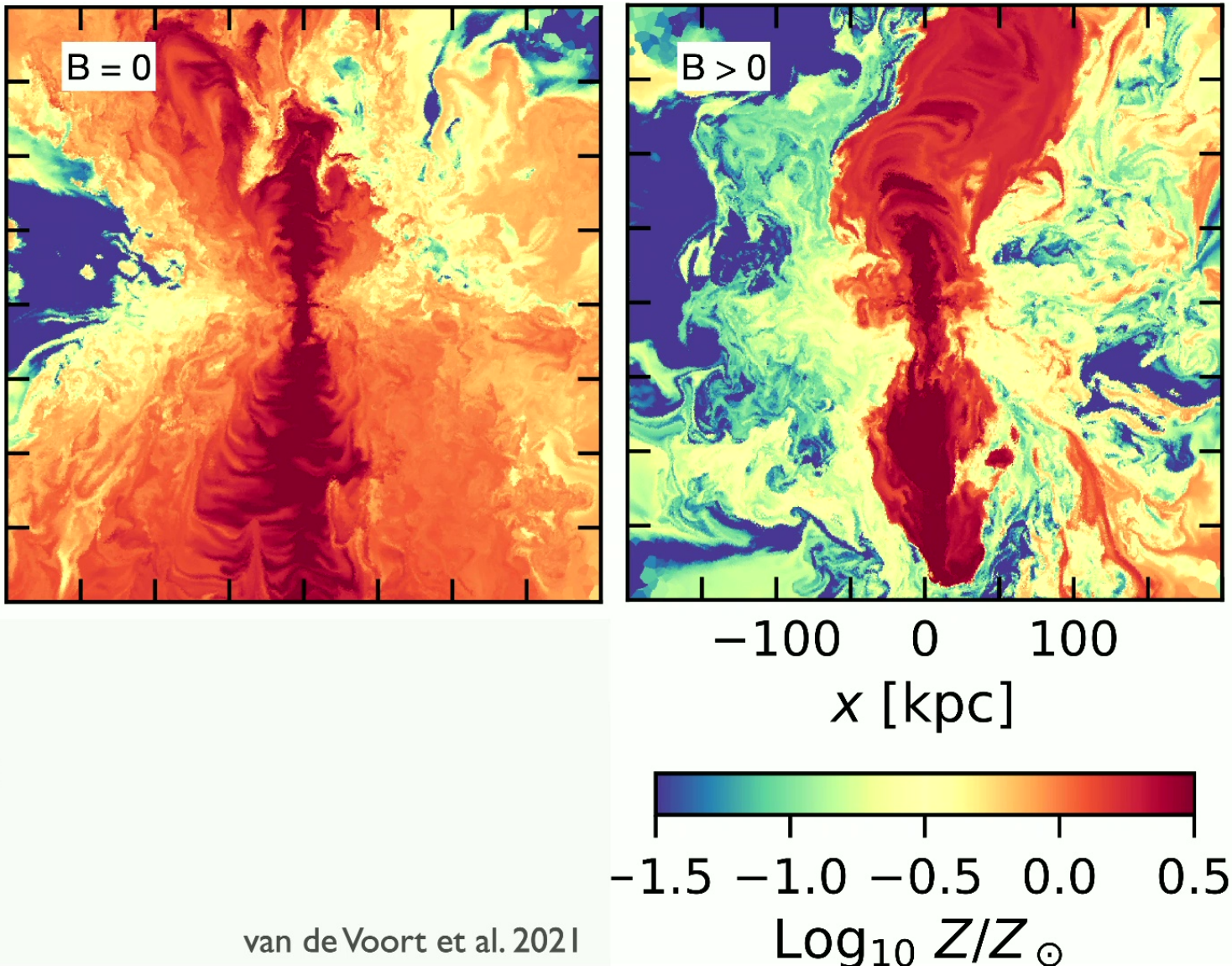
- The (absolute) outflow and inflow velocities are smaller with magnetic fields, so we get weaker inflows and outflows (and a higher CGM baryon fraction).
- The baryon fraction in the halo are higher when magnetic fields are included.
- Gas and metals are transported to beyond the halo's viral radius more efficiently without magnetic fields.
- The differences only disappears at large distances, around a Mpc.



van de Voort et al. 2021

Effect of B

- Metals mix less throughout the CGM with magnetic fields resulting in more metal-poor halo gas.
- Because of changes in the outflow direction near the disc or because of lower velocity dispersion or suppression of instabilities in the CGM?



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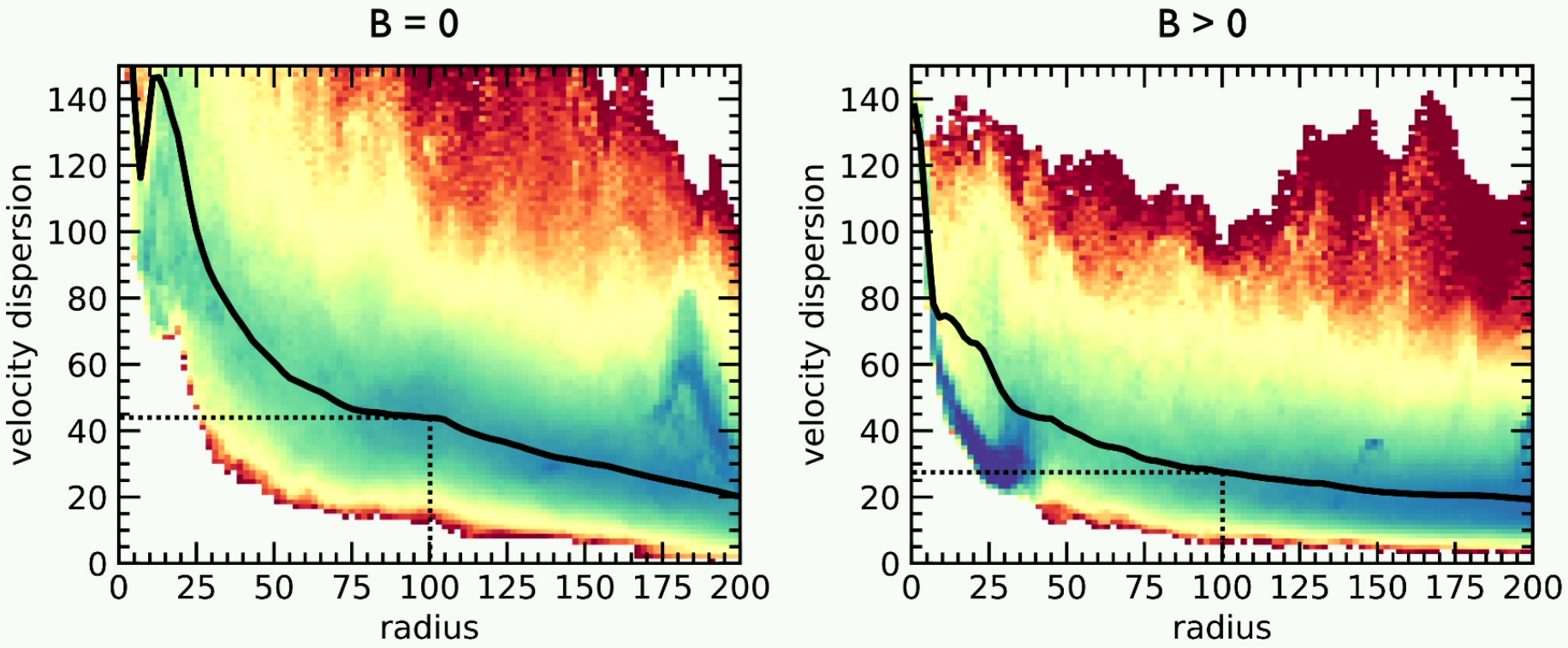
Velocity dispersion depends on B fields

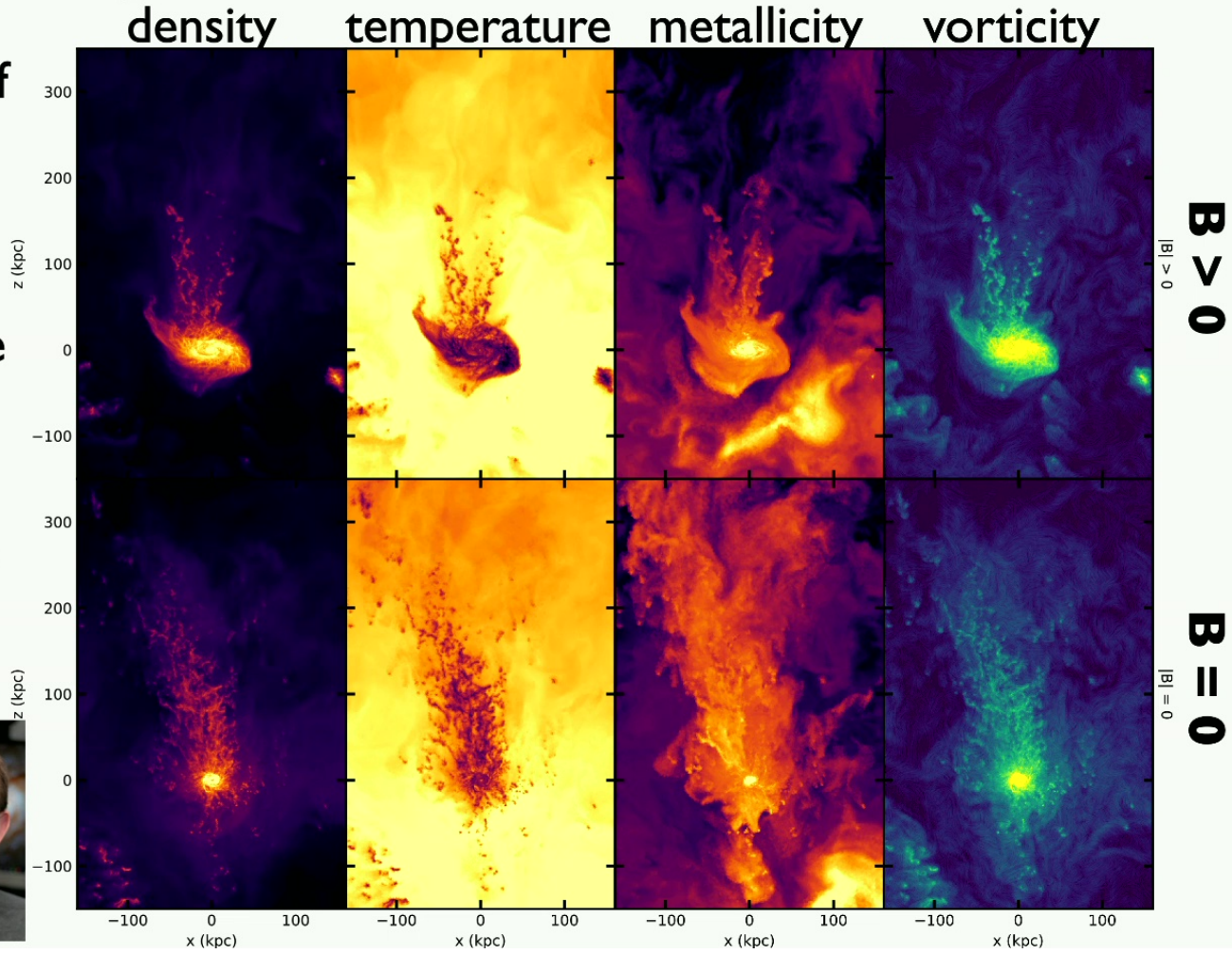
- The velocity dispersion is lower with B fields, causing reduced metal mixing and subsequent differences in cooling.



Satellite stripping

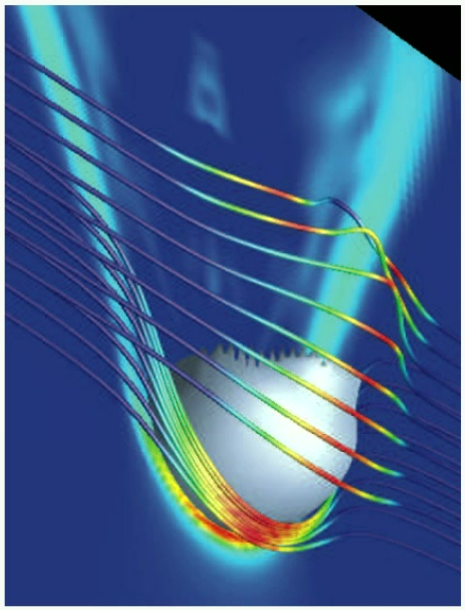
- Ram pressure stripping of the CGM of a galaxy in a 10^{13} M_{sun} group.
- Rotated such that negative z direction is the velocity direction of the satellite.
- Gas is stripped less easily with magnetic fields and it mixes less with the ambient halo gas.

Rintoul et al. 2025

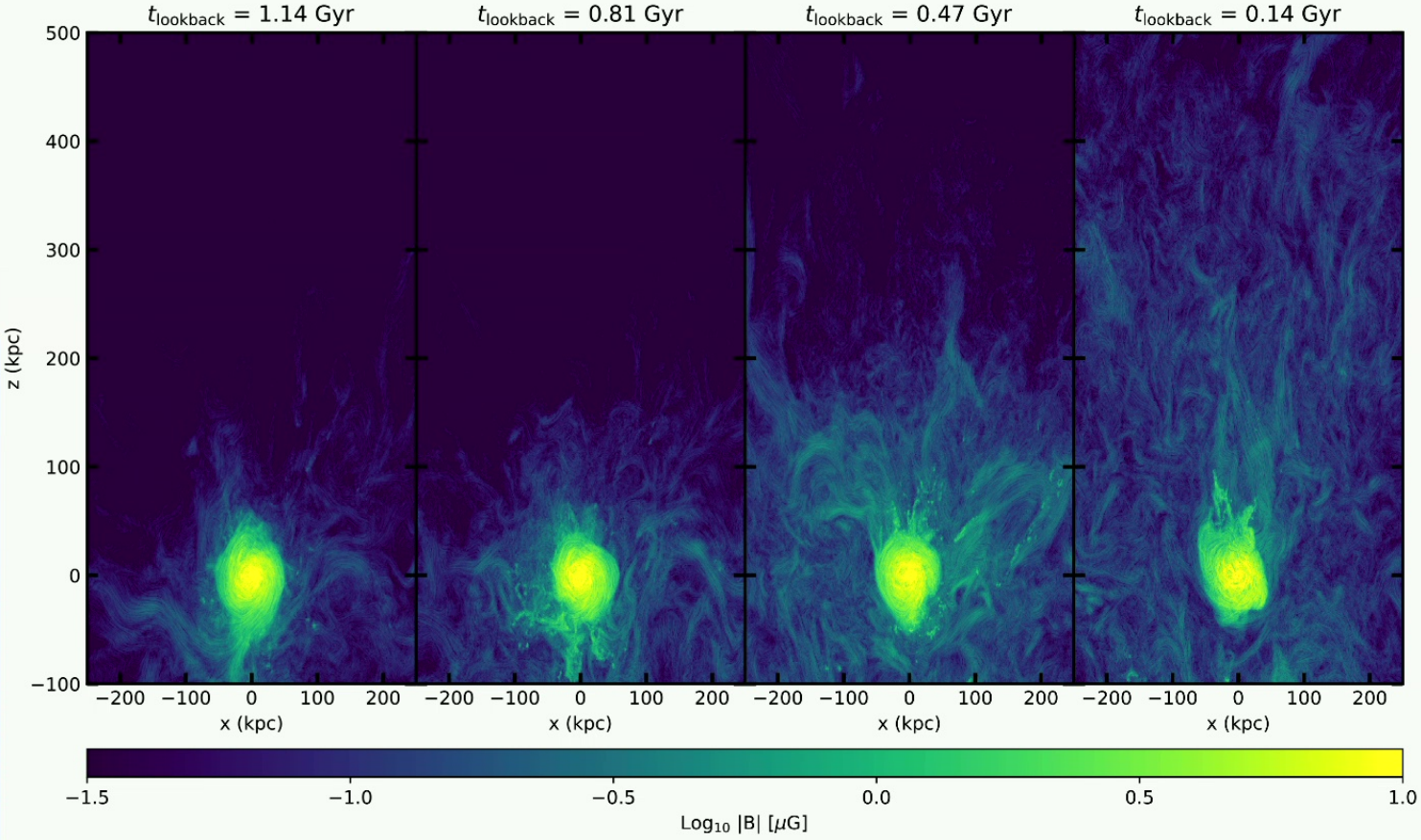


Magnetic draping

- Magnetic draping layer suppresses instabilities and mixing.



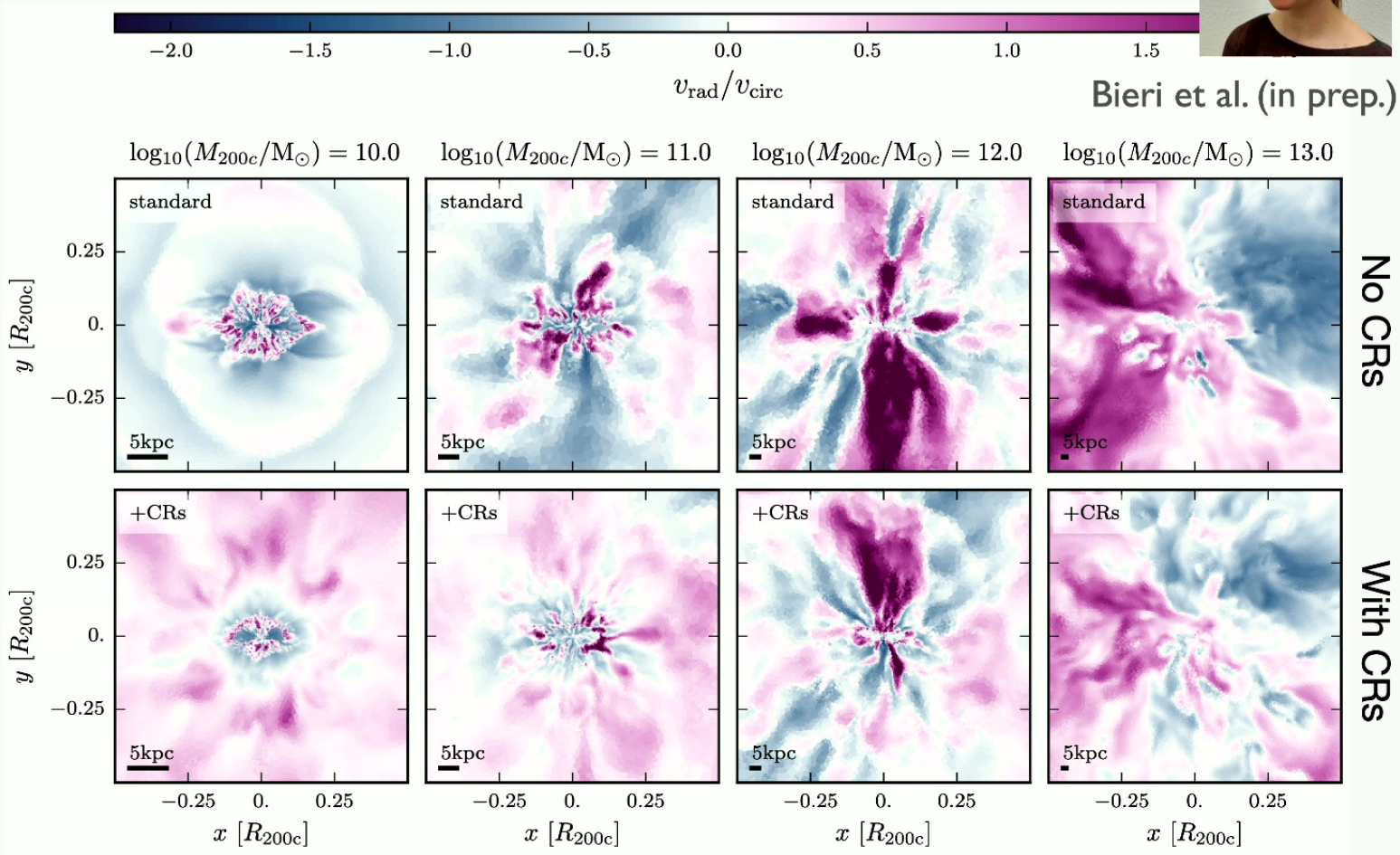
Dursi & Pfrommer 2008



Rintoul et al. 2025

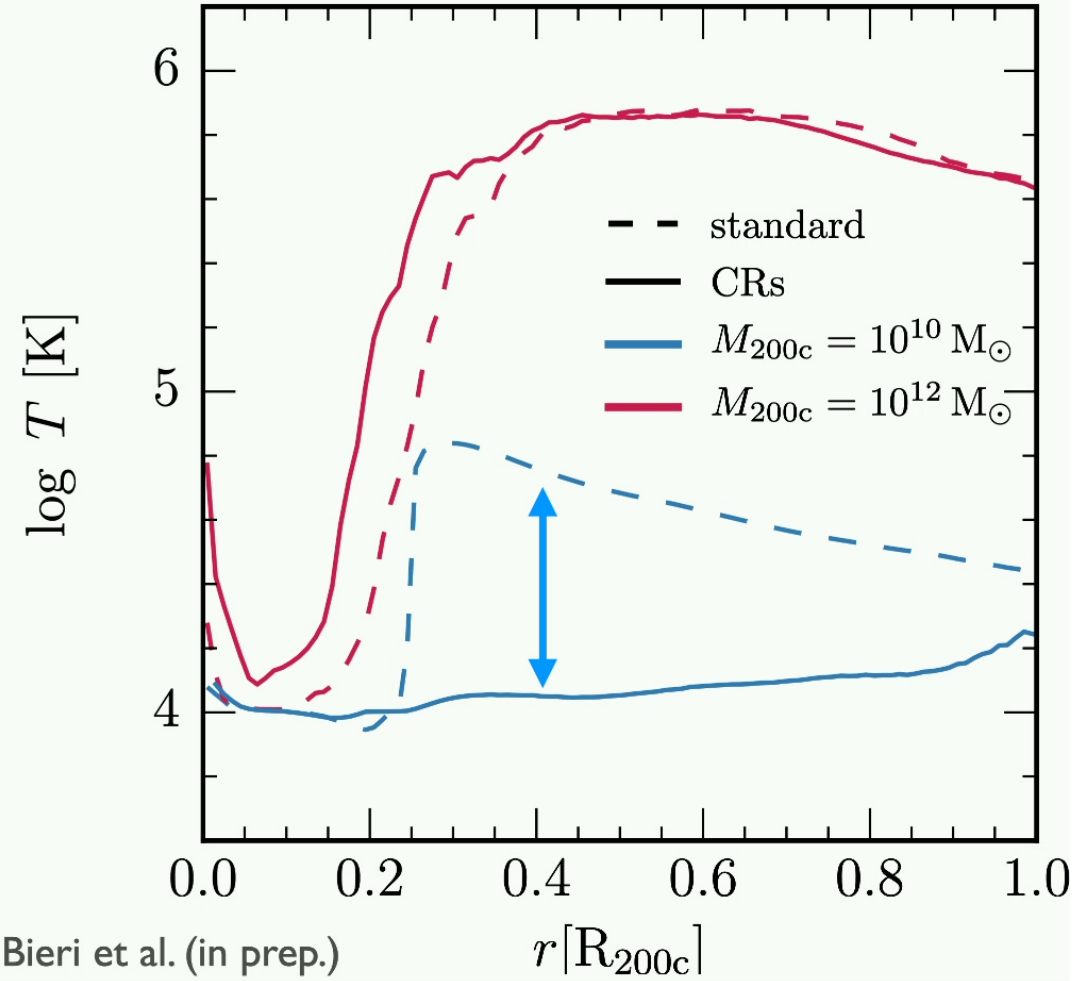
Cosmic ray feedback - radial velocity

- Higher mass outflow velocities in low-mass haloes with CRs.
- No clear effect in Milky Way-mass and more massive haloes.



Cosmic ray feedback - CGM properties

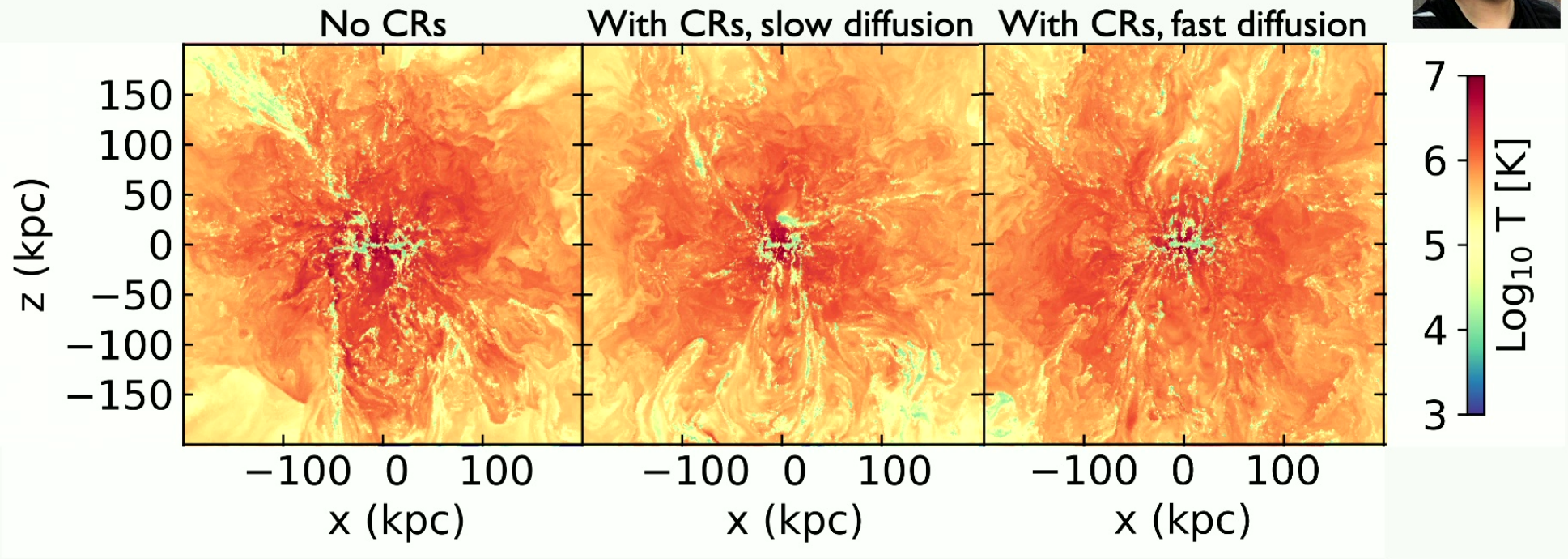
- Milky Way-mass halo unaffected by cosmic ray feedback (red curves).
- Dwarf galaxy halo has higher density (not shown) and lower temperature (blue curves).



Bieri et al. (in prep.)

CGM temperature

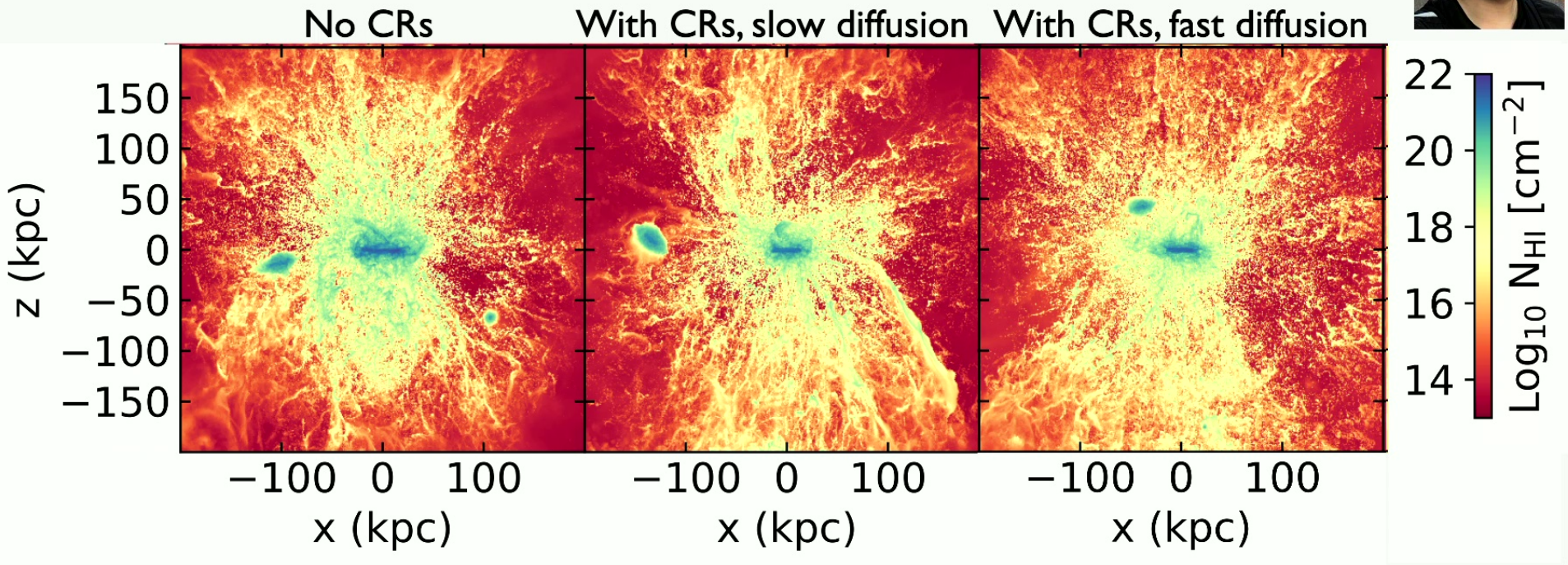
Hannington et al. (in prep.)



- Milky Way-mass halo with our fiducial cosmic ray model.
- No strong effect on CGM properties for this halo mass (10^{12} M_{sun}).

CGM HI column density

Hannington et al. (in prep.)



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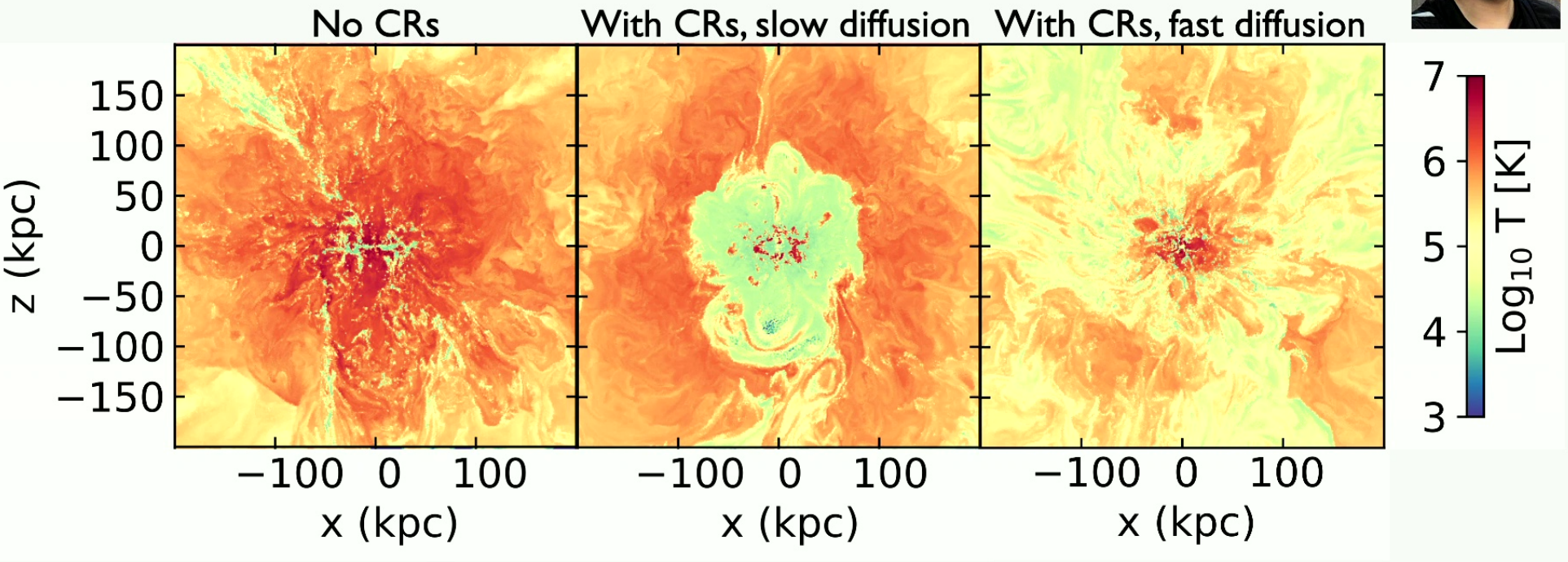
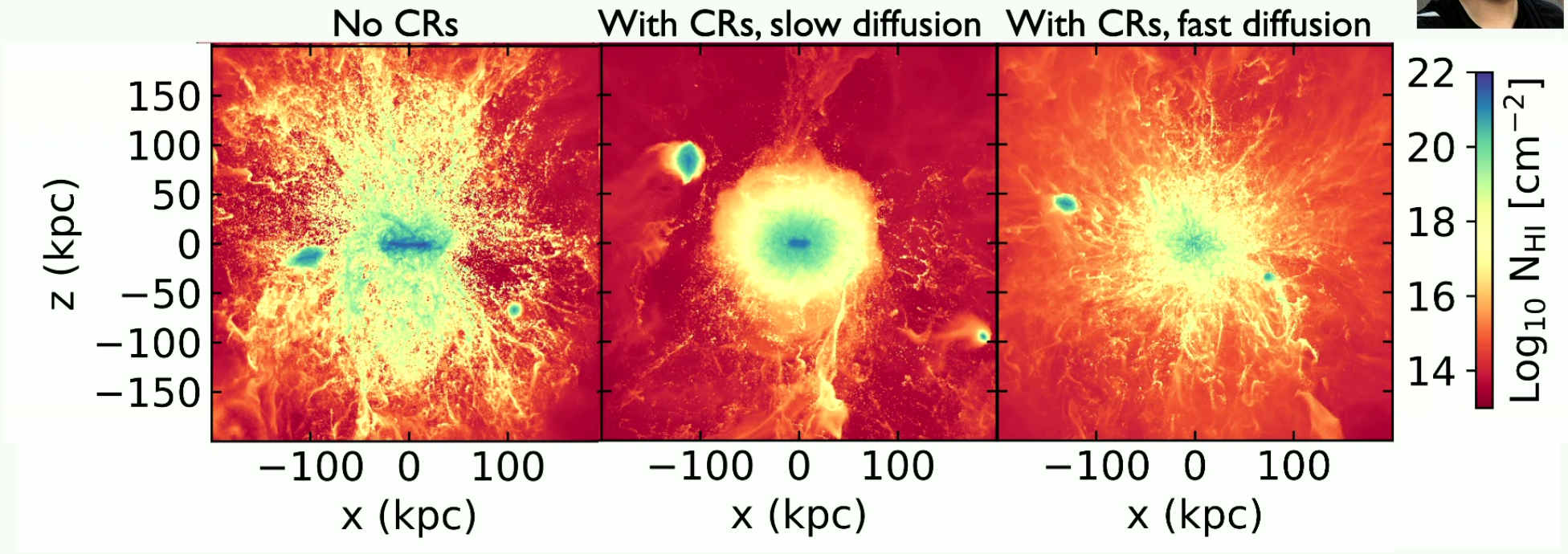


- Results are very different when Cosmic Ray energy losses to the magnetic field are not included: lower temperature gas supported by Cosmic Ray pressure.

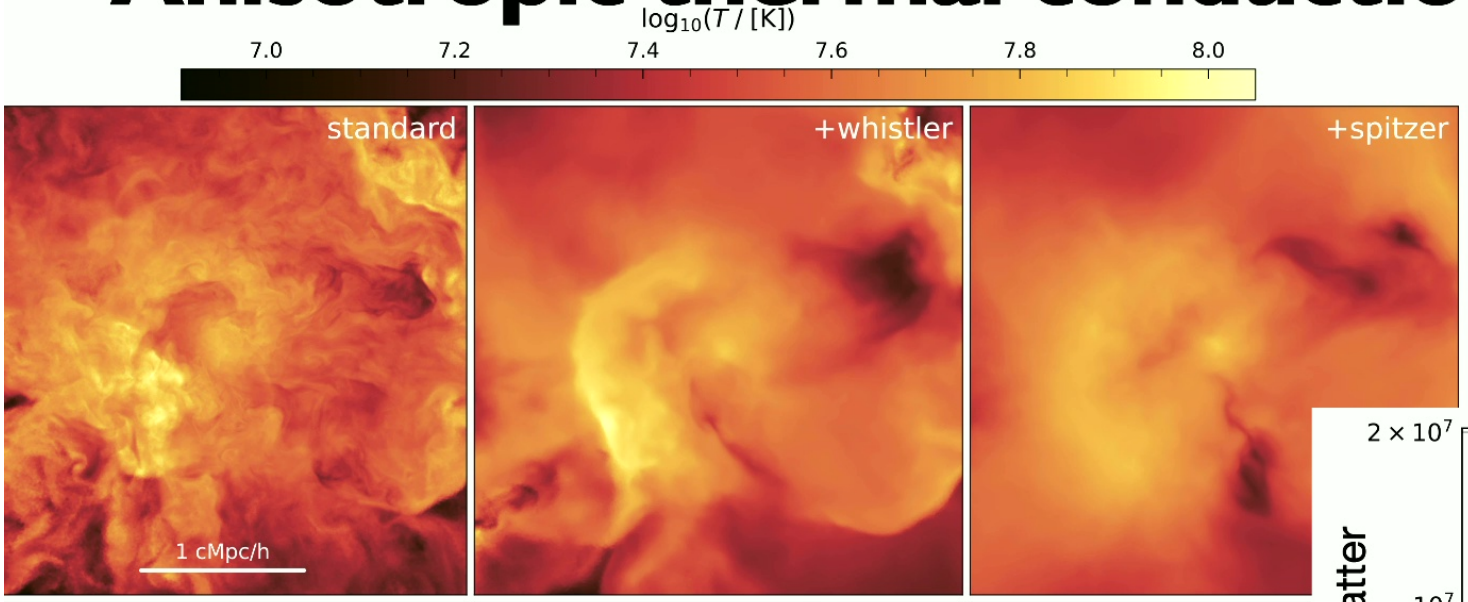
CGM HI column density

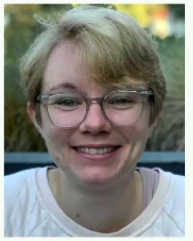
Hannington et al. (in prep.)



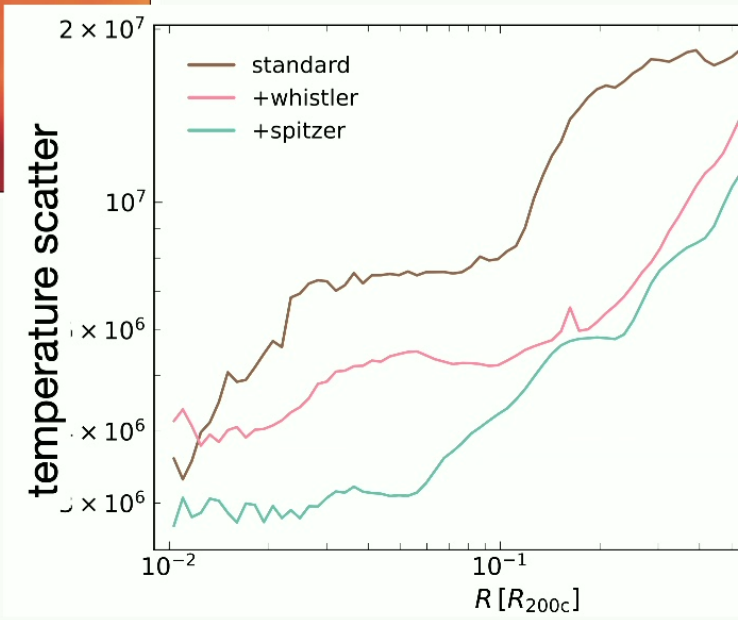
- Results are very different when Cosmic Ray energy losses to the magnetic field are not included: HI column density reduced in outer halo, possibly enhanced in inner halo.

Anisotropic thermal conduction





Talbot et al. 2025



- Less structure/scatter in the ICM temperature of galaxy cluster halo ($7 \times 10^{14}\ M_{sun}$) with anisotropic thermal conduction.

Summary

- Magnetic fields reduce gas mixing and slow down gas flows. Haloes consequently have higher gas fractions.
- Magnetic fields also reduce ram pressure stripping of satellite galaxies.
- Cosmic ray feedback can substantially change the CGM, but if the losses due to interactions with the magnetic fields are correctly modelled in our simulations, the effect is minimal for haloes with $M_{halo} > 10^{12}\ M_{sun}$.
- However, there is disagreement in the literature on the effects of magnetic fields and cosmic ray feedback.
- Thermal conduction may also play a role in the phase structure of the CGM.