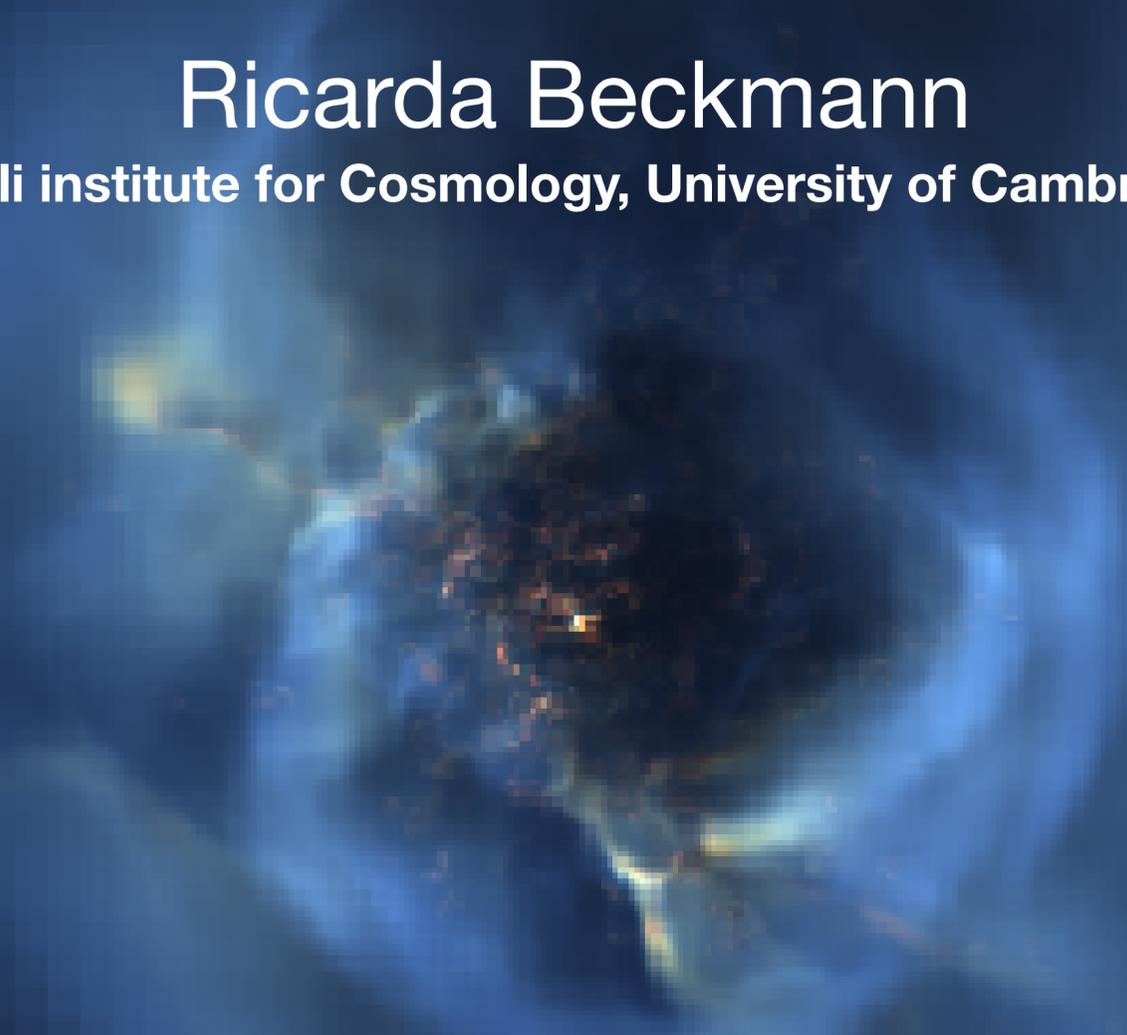


# Cosmic rays and the multi-phase gas in clusters

Ricarda Beckmann

Kavli institute for Cosmology, University of Cambridge

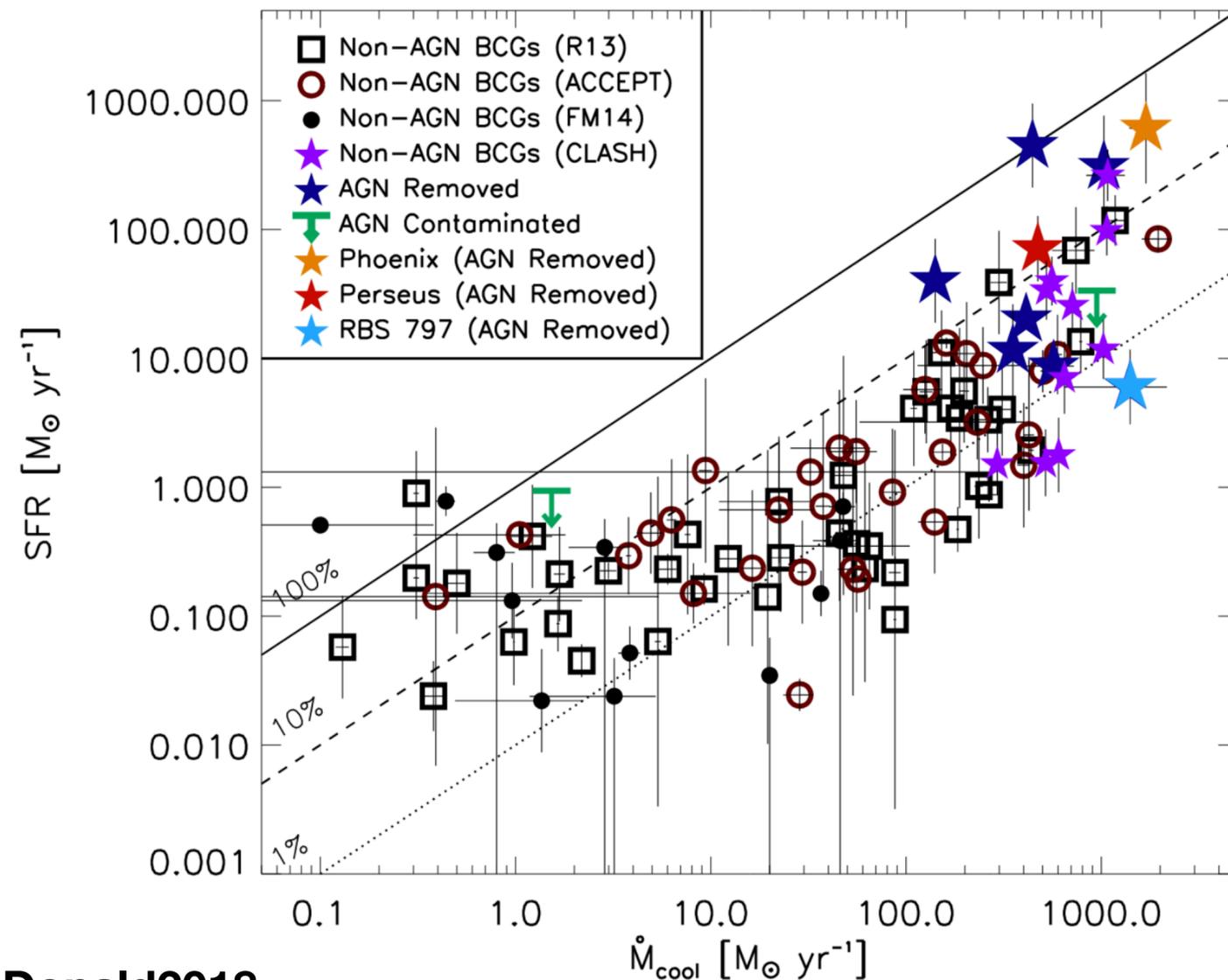


Work done in collaboration with **Yohan Dubois**, Pierre Guillard, Philippe Salomé, and the rest of the LYRICS collaboration, Paris, France

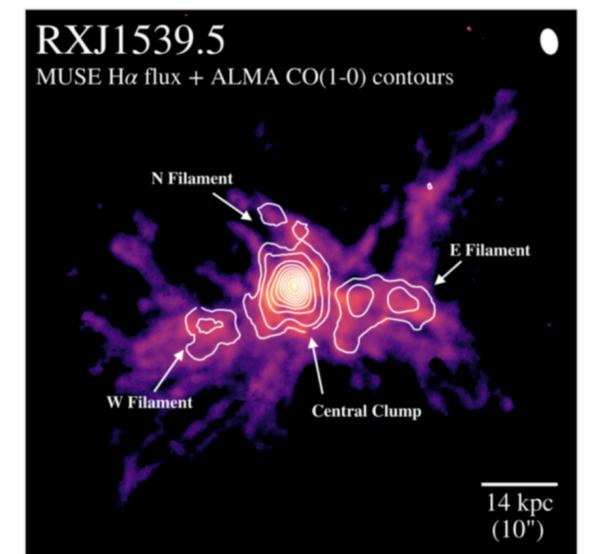
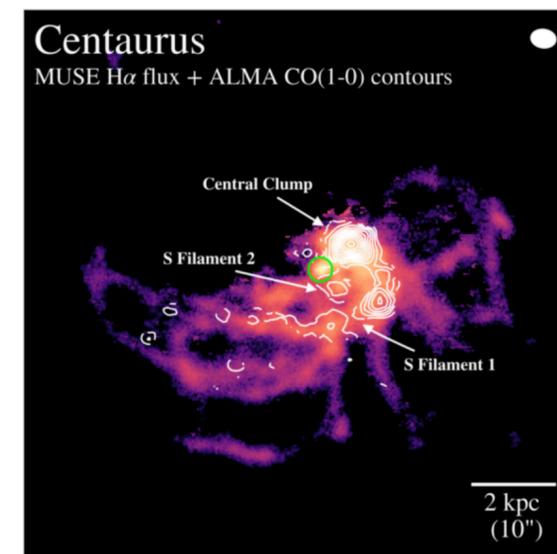
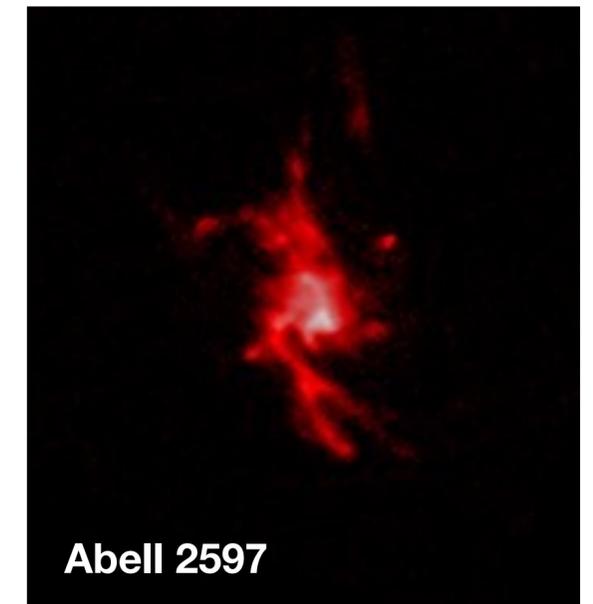
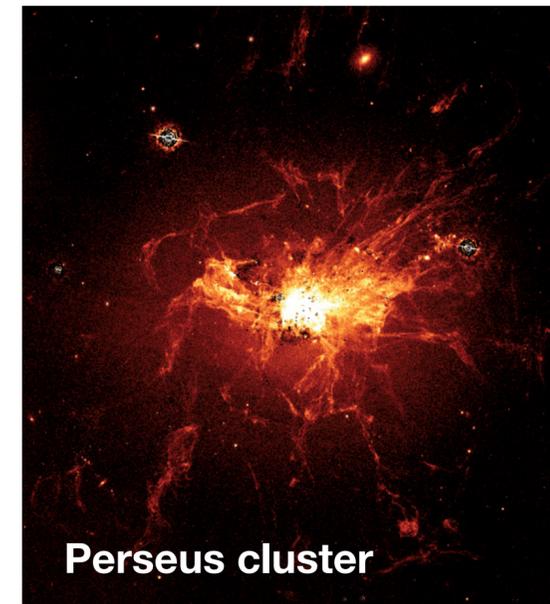
# Two sides of the cooling flow problem

1) Star formation rates are much lower than one would expect from cooling rates

2) Multiphase gas with a striking morphology forms in the cluster centre



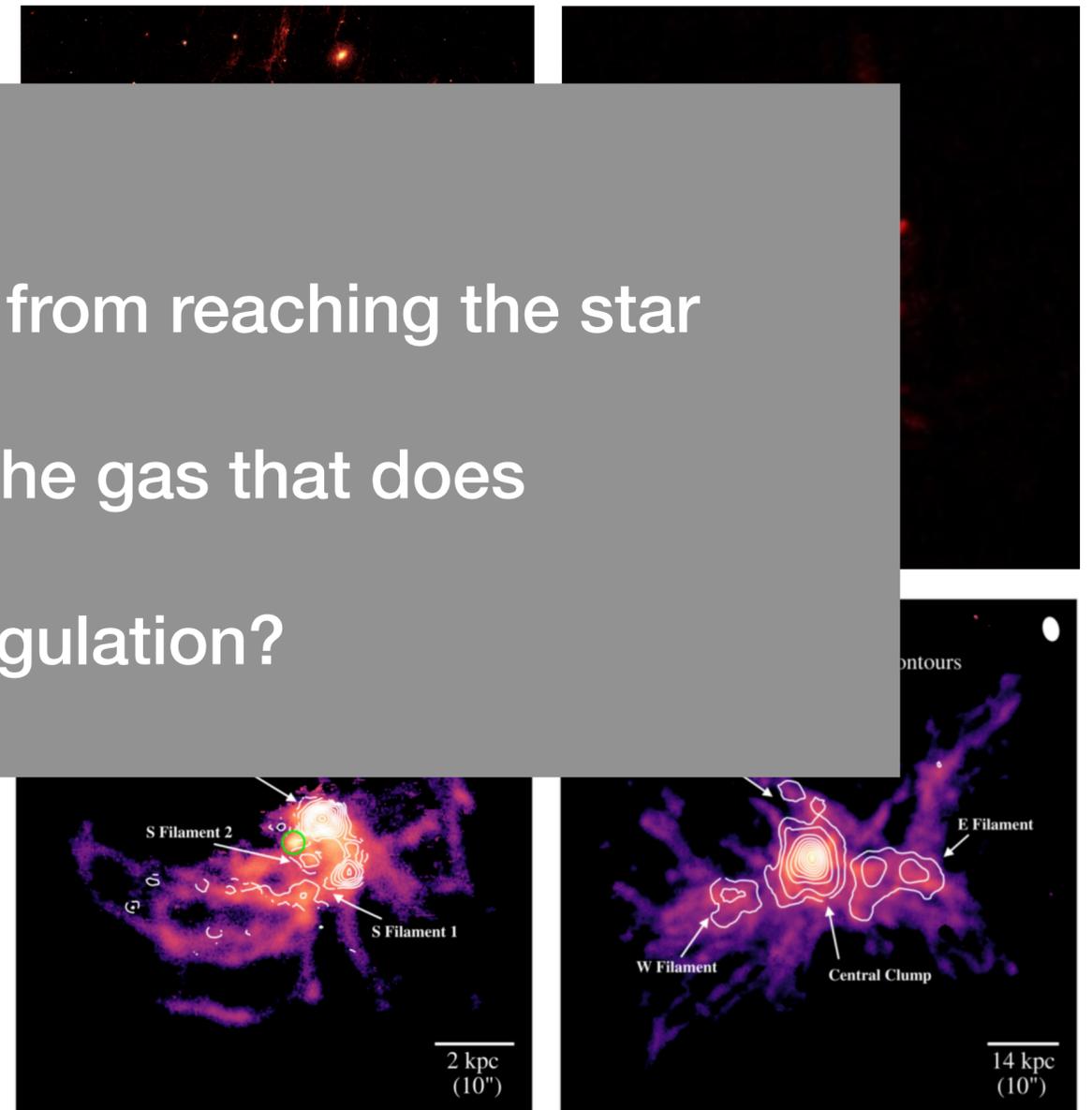
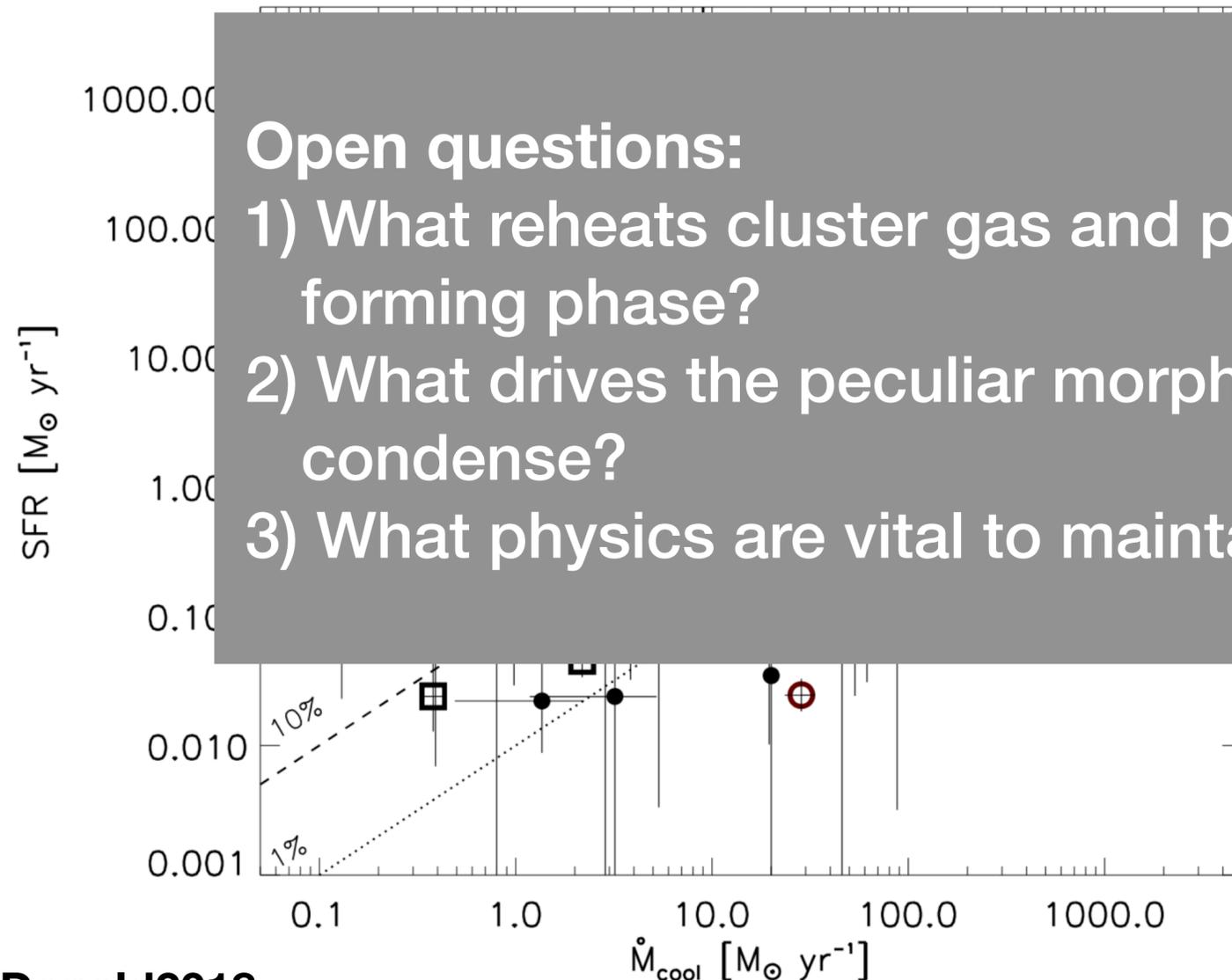
McDonald2018



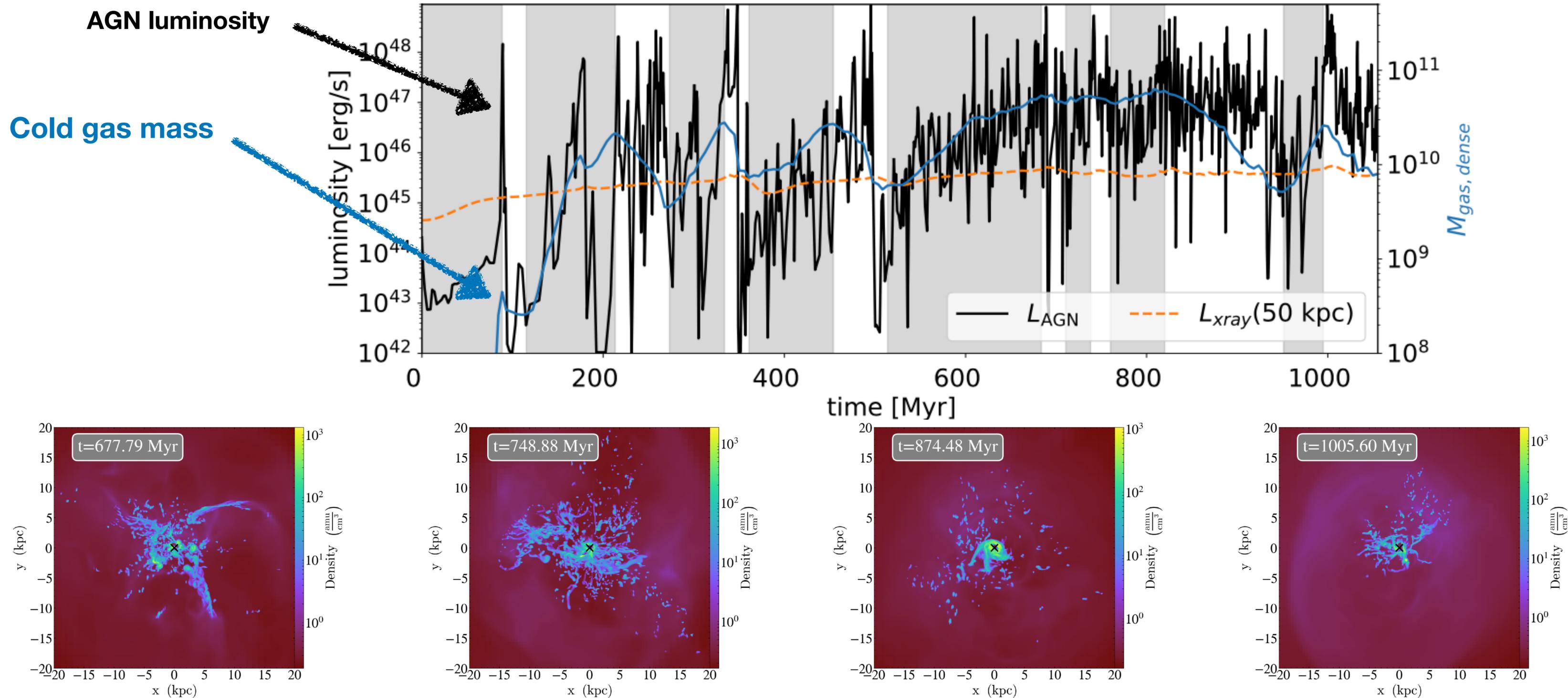
# Two sides of the cooling flow problem

1) Star formation rates are much lower than one would expect from cooling rates

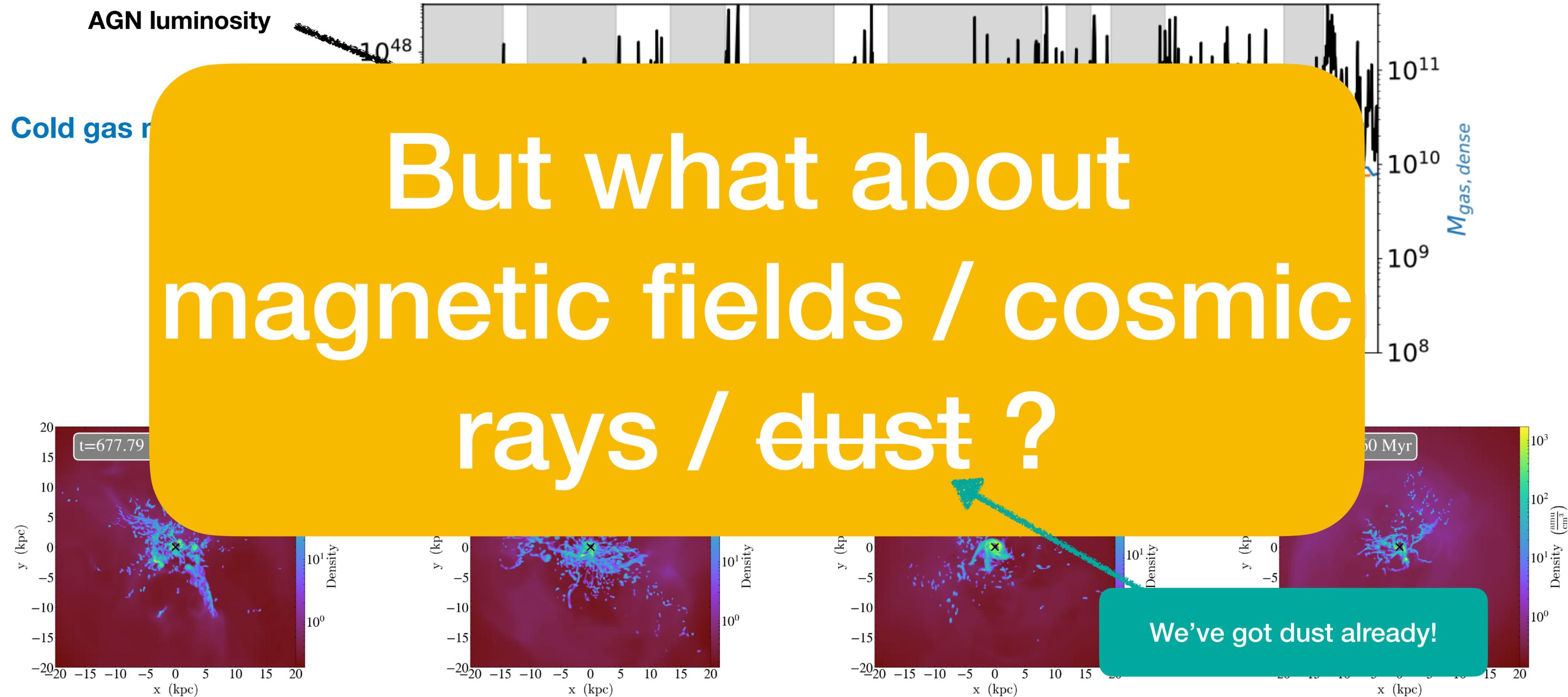
2) Multiphase gas with a striking morphology forms in the cluster centre



# A spin-driven AGN jet self-regulates cluster cooling flows and produces a wide range of gas morphologies.



A spin-driven AGN jet self-regulates cluster cooling flows and produces a wide range of gas morphologies.



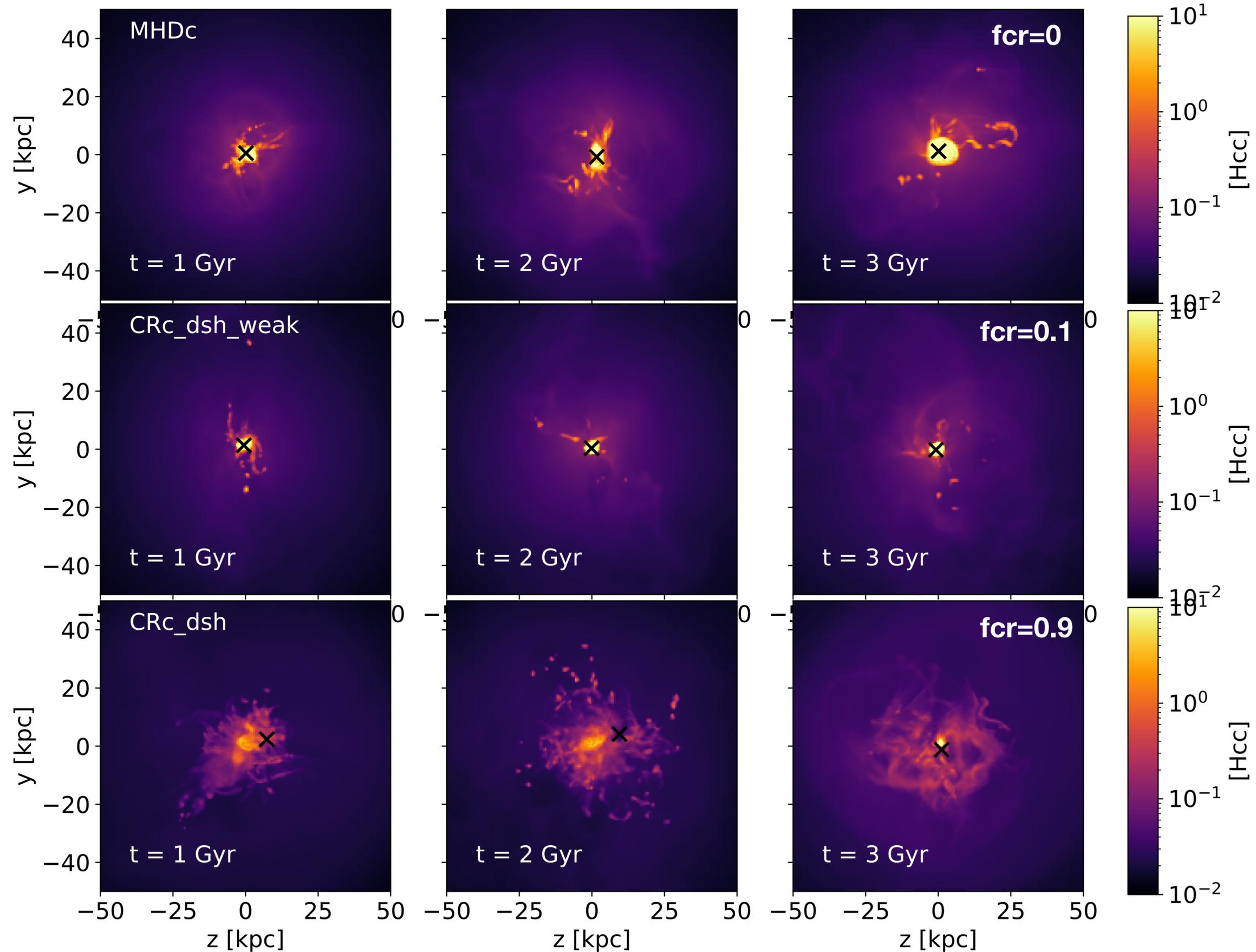
# Multiphase gas, magnetic fields and cosmic rays

AGN luminosity is split into kinetic (jet) energy and cosmic ray energy, conserving energy and preserving the self-regulation mechanism

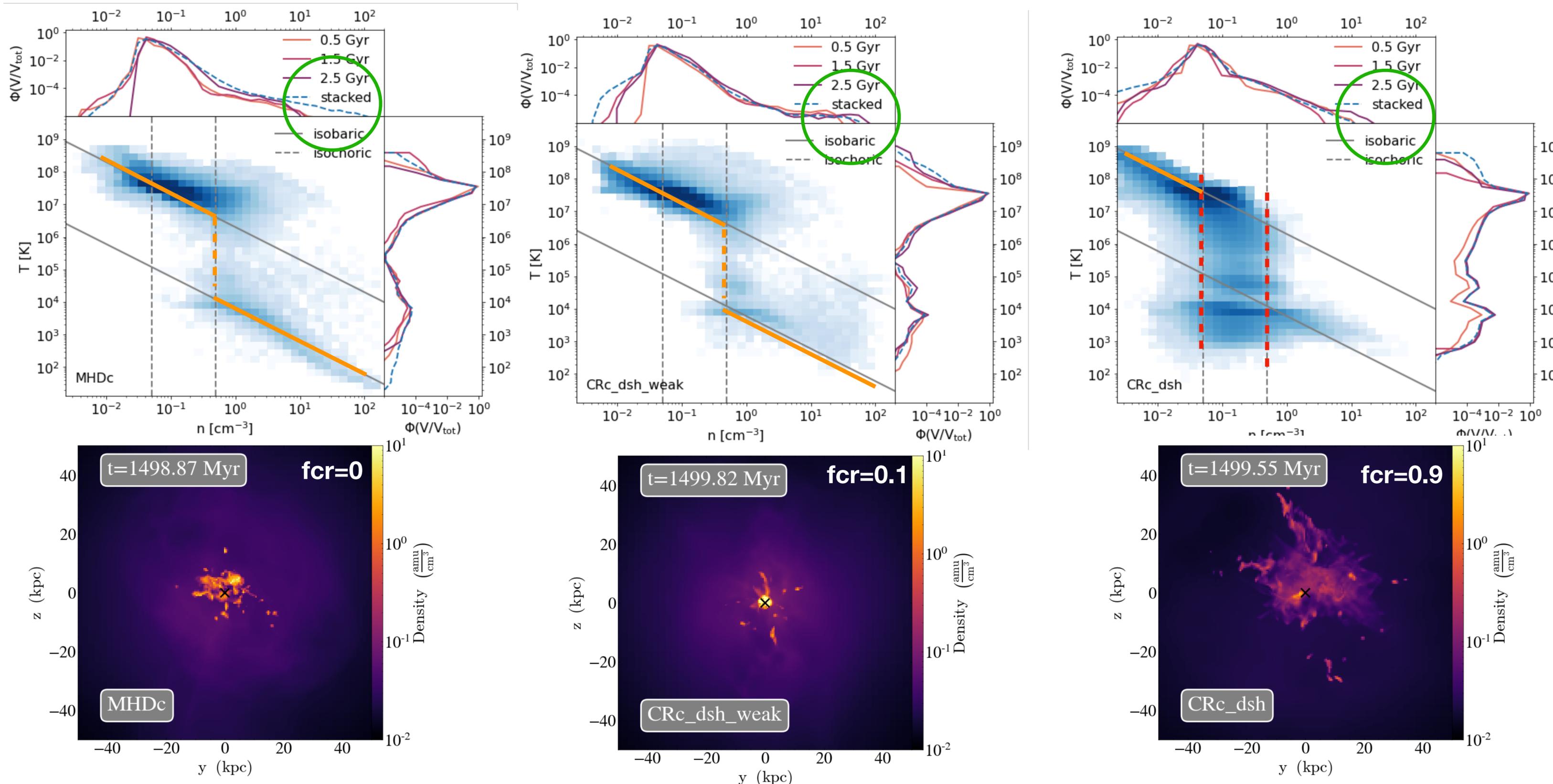
$$L_{\text{AGN}} = \epsilon_f \epsilon_r \dot{M}_{\text{BH}} c^2$$

$$L_{\text{kin}} = (1 - f_{\text{CR}}) L_{\text{AGN}}$$

$$L_{\text{CR}} = f_{\text{CR}} L_{\text{AGN}}$$



# Cooling in CR dominated gas



# Cooling flows over time

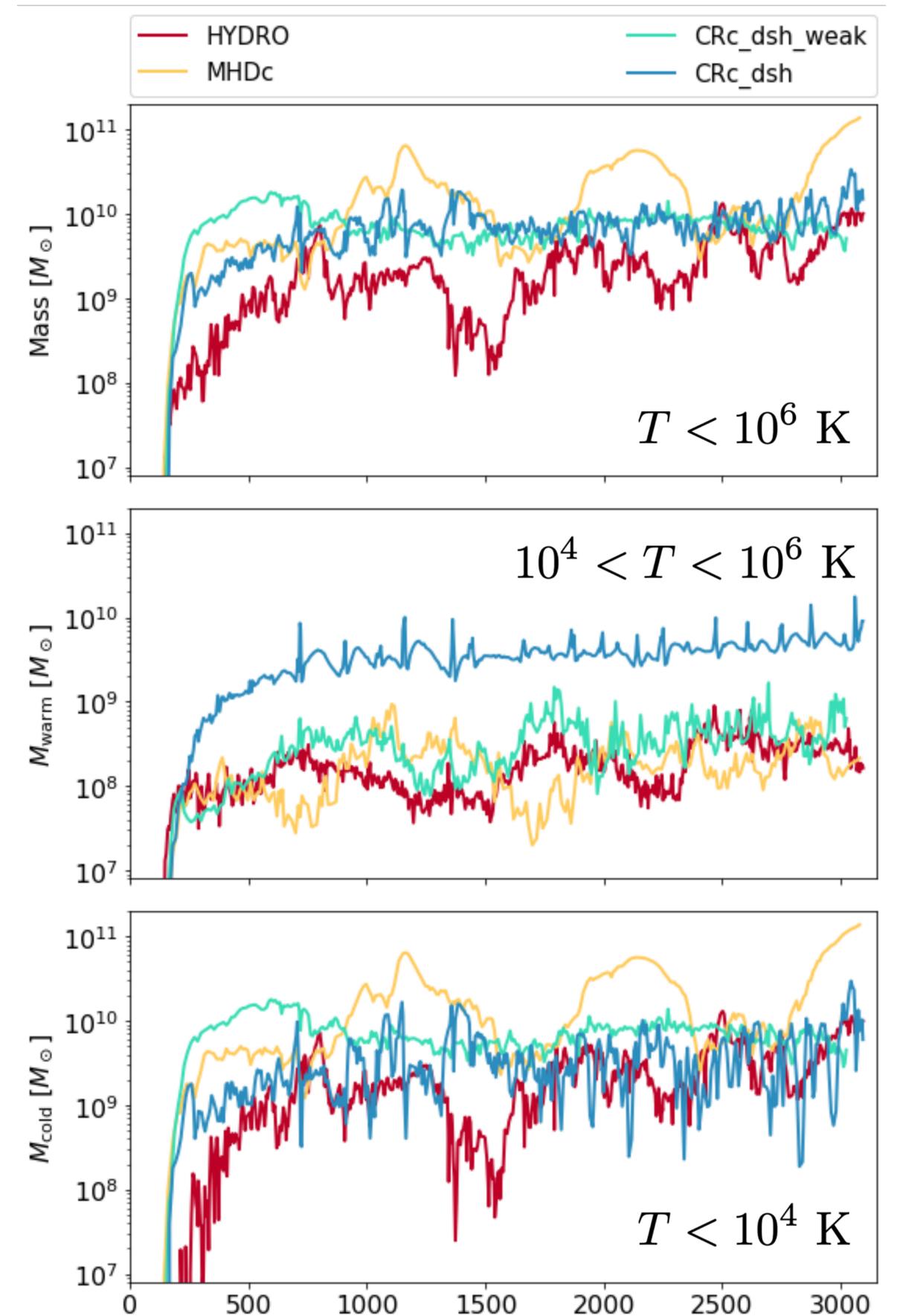
Magnetic fields enhance thermal instability (compare blue/green to yellow)



Strong cosmic rays consistently produce warm gas (blue)



Weak cosmic rays prevent over-condensation into cold gas (compare green to yellow)



# Distribution of CR in the cluster

$$\eta = \frac{P_{\text{cr}}}{P_{\text{therm}}}$$

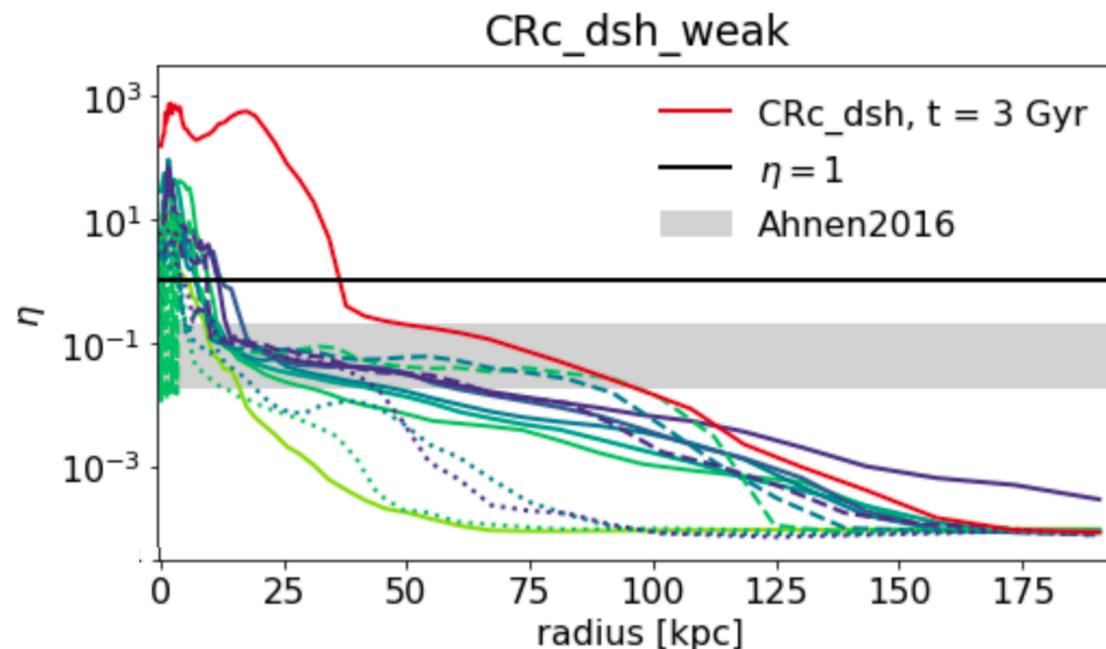
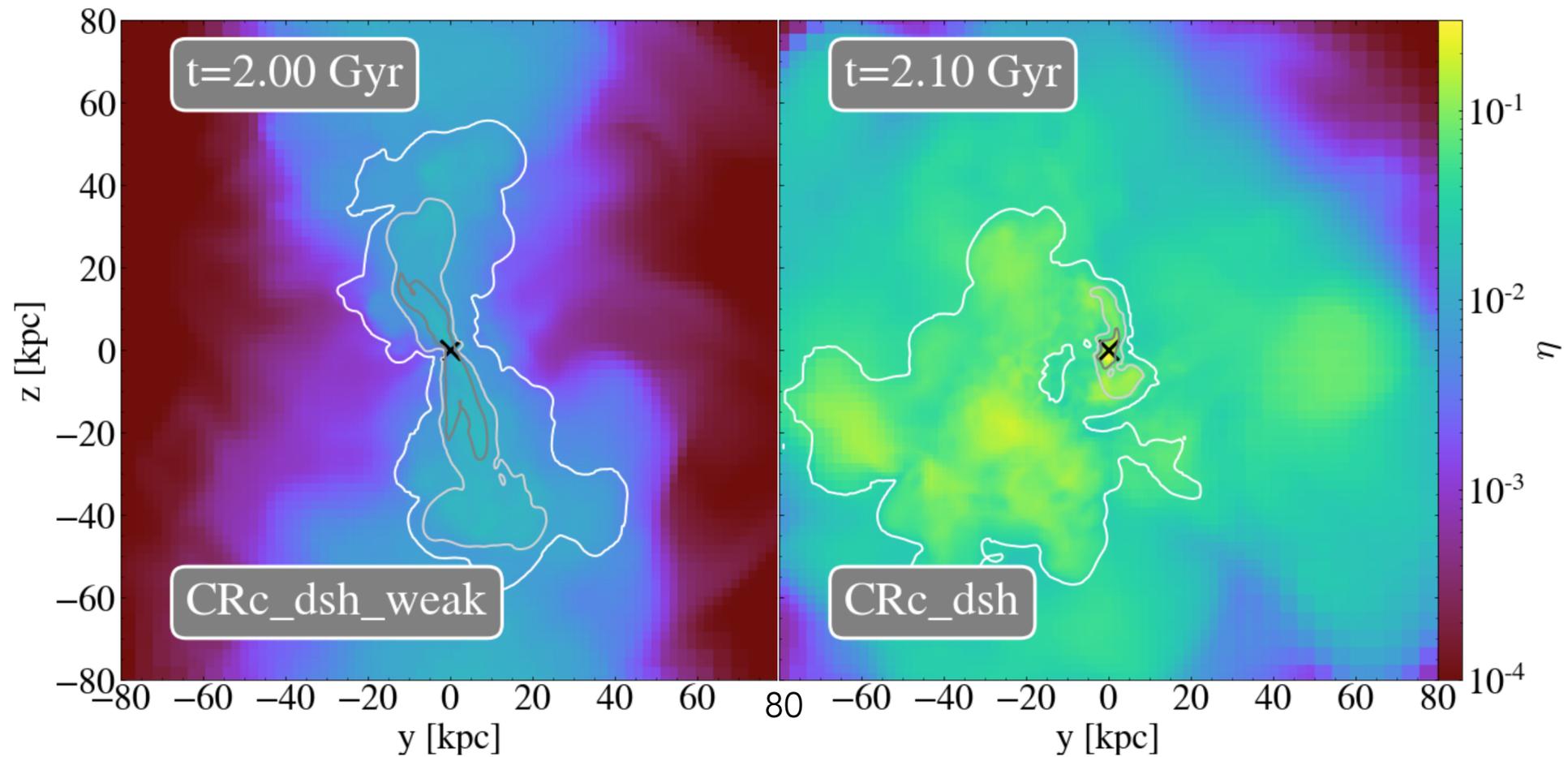
For high eta, total gas pressure is dominated by cosmic rays

Reminder: Jet energy is split into kinetic and CR energy

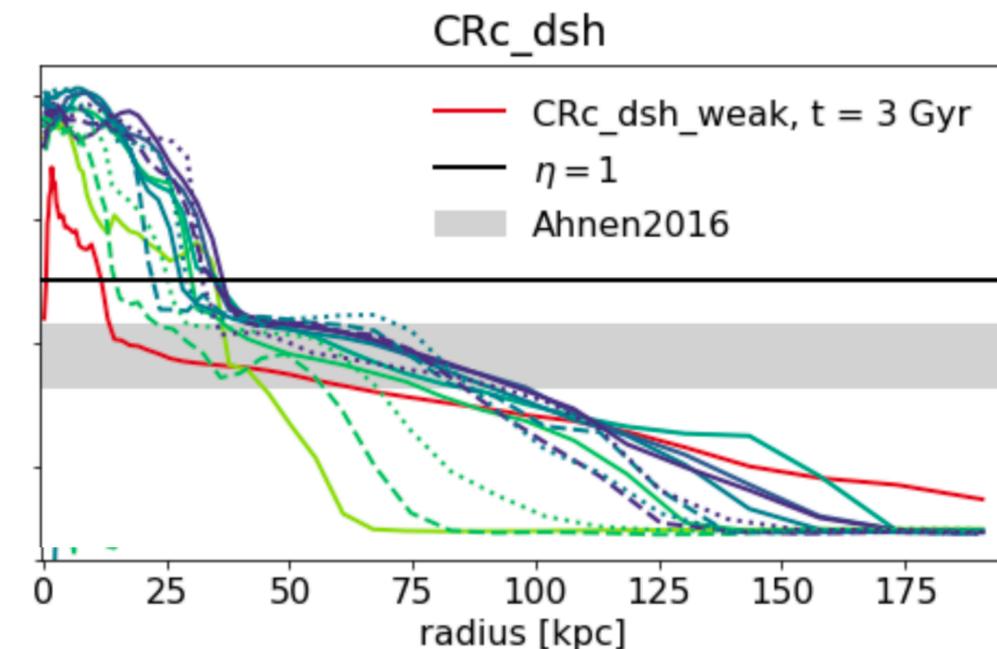
$$L_{\text{AGN}} = \epsilon_f \epsilon_r \dot{M}_{\text{BH}} c^2$$

$$L_{\text{kin}} = (1 - f_{\text{CR}}) L_{\text{AGN}}$$

$$L_{\text{CR}} = f_{\text{CR}} L_{\text{AGN}}$$

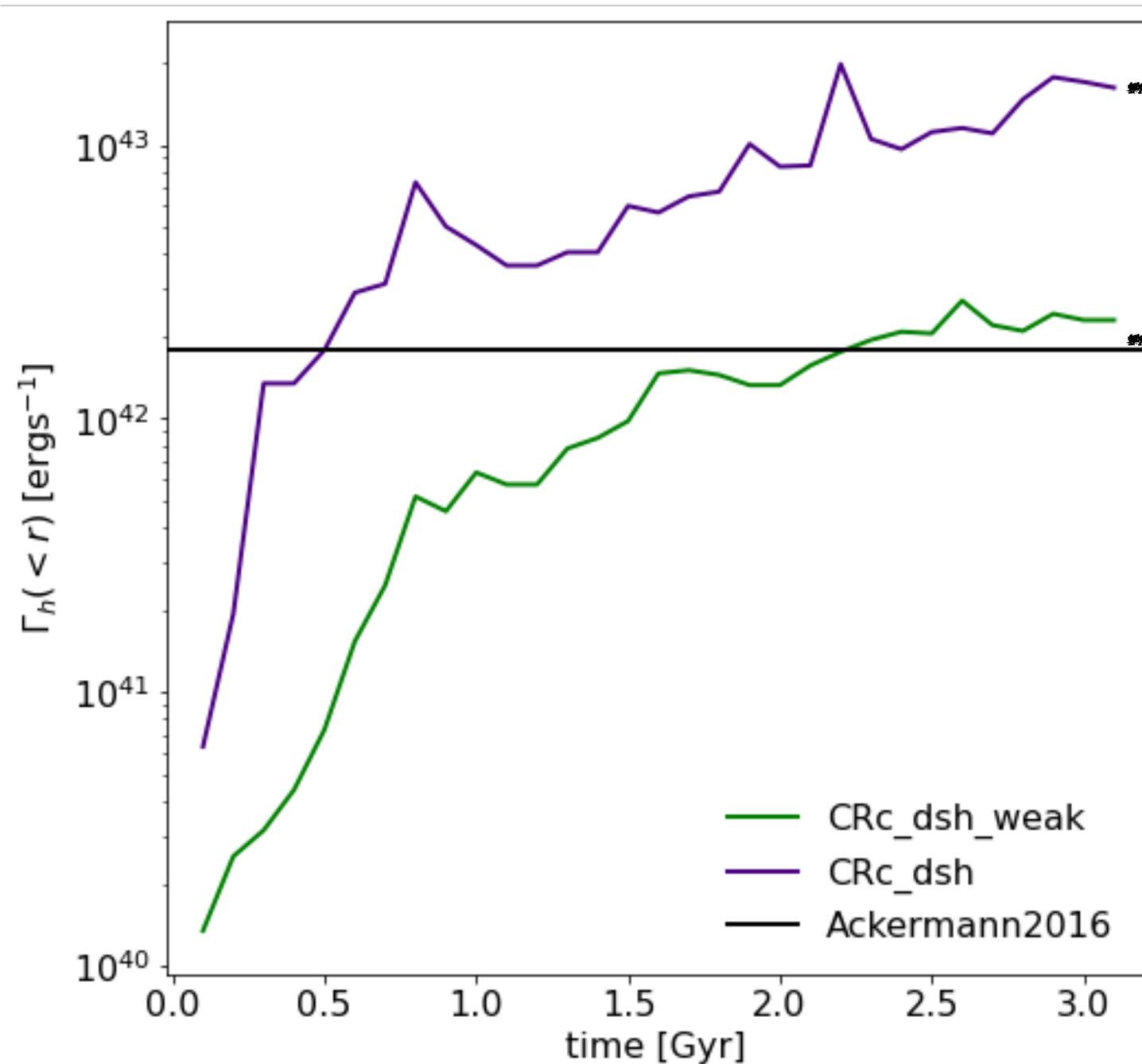


Weak CR & strong kinetic jet: CR remain within jet cone



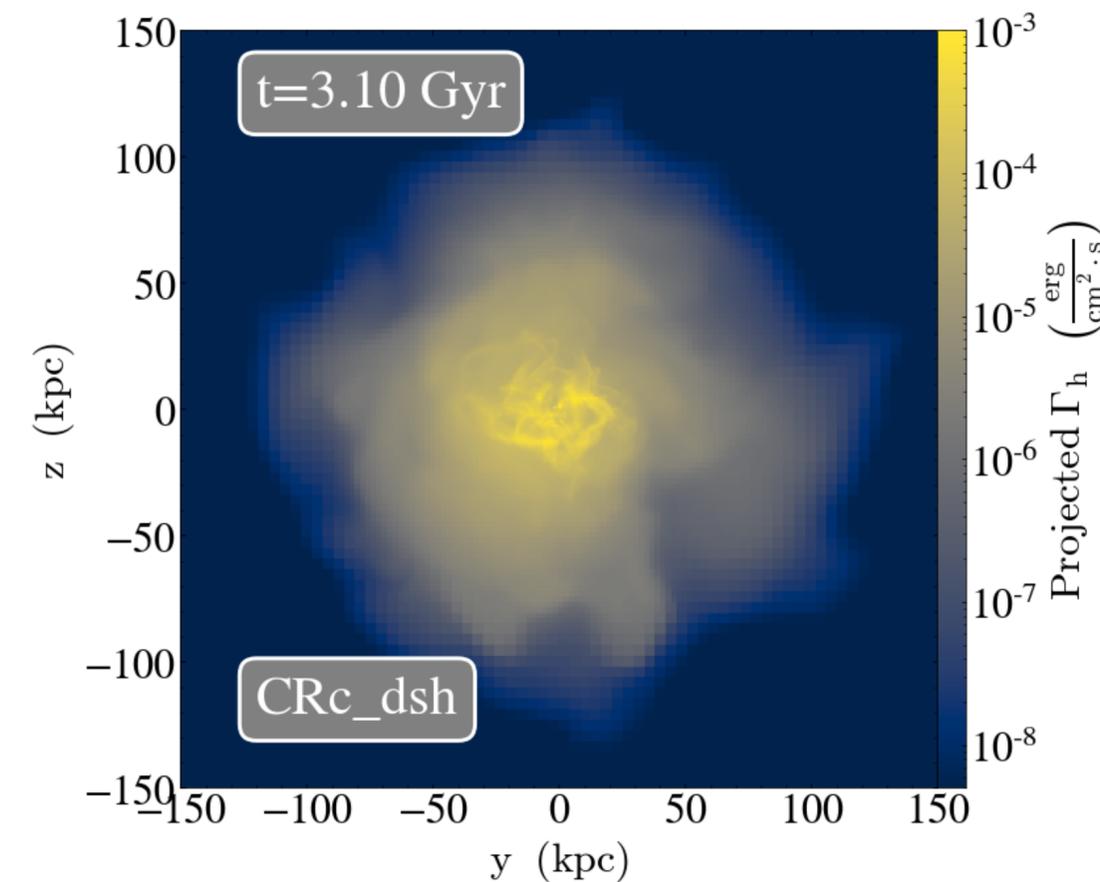
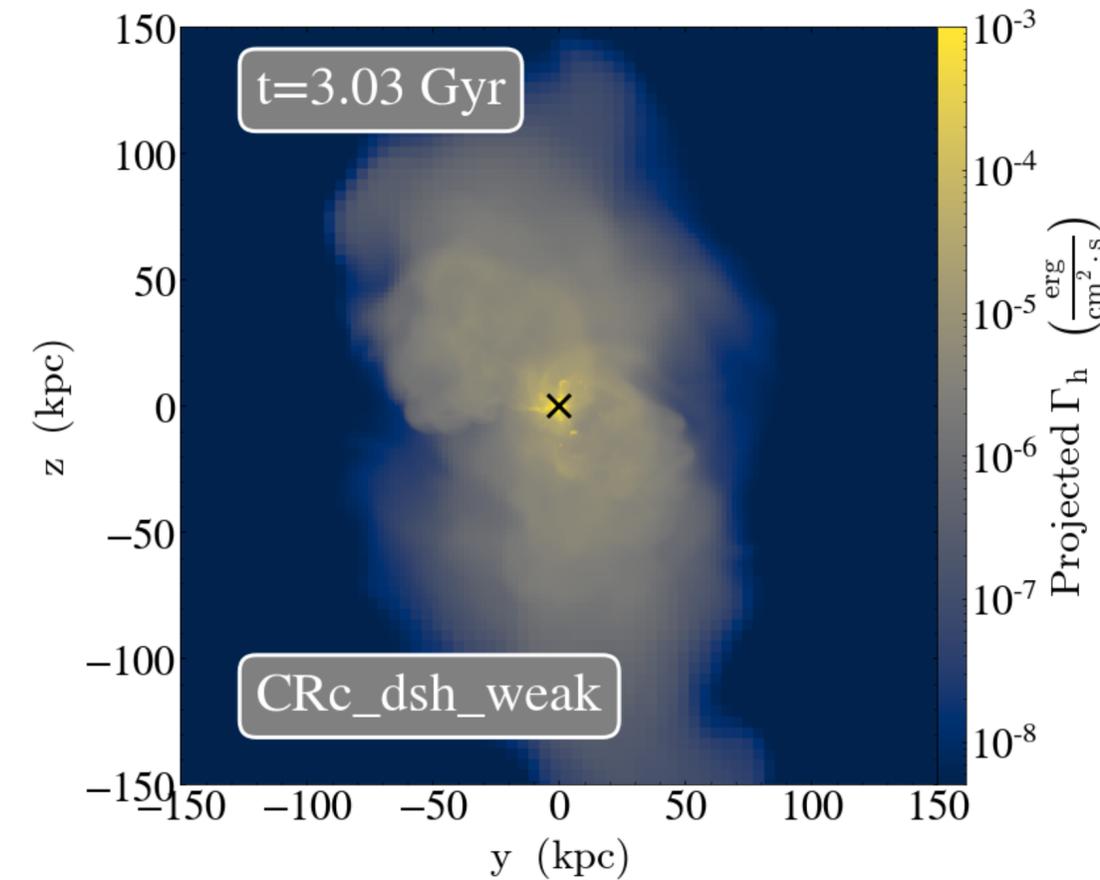
Strong CR & weak kinetic jet: CR are distributed isotropically

# Observational constraints: Gamma-ray emission



**90% jet energy in CR  
exceeds  
observational  
constraints**

**10% jet energy in CR  
broadly lies within  
observational  
constraints**



# Conclusions

## Cooling flow

Even a small fraction of CR in the jet offset magnetic field induced over-cooling and support long-term cluster self-regulation.

## Distribution of CR

CR only get distributed outside the jet cone for CR dominated jets, in which case they produce an extended, CR dominated core.

## Gas phase and cooling physics

CR dominated cores cool isochorically, producing an extended warm, diffuse nebula.

## Observational constraints

Self-regulating CR dominated jets produce gamma-ray emission that exceed observational constraints.



### Also includes:

- CR and the onset of thermal instability
- CR transport mechanisms and cooling flows
- Stochasticity of cooling flows and robustness of results
- All the gory details

# Advert: Cold clouds in hot galaxy clusters - Fred Jennings

coming soon

MNRAS 000, 1–12 (2015)

Preprint 26 September 2021

Compiled using L<sup>A</sup>T<sub>E</sub>X style file v3.0

## Shattering and growth of cold clouds in galaxy clusters: the role of radiative cooling, magnetic fields and thermal conduction

Fred Jennings,<sup>1,2\*</sup> Ricarda S. Beckmann,<sup>2,3</sup> Debora Sijacki<sup>2</sup> and Yohan Dubois<sup>3</sup>

<sup>1</sup>*Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, United Kingdom*

<sup>2</sup>*Institute of Astronomy, University of Cambridge, Madingley Rd, Cambridge CB3 0HA, United Kingdom*

<sup>3</sup>*Institut d'Astrophysique de Paris, UMR 7095, CNRS, UPMC Univ. Paris VI, 98 bis boulevard Arago, 75014 Paris, France*

Accepted XXX. Received YYY; in original form ZZZ

### ABSTRACT

Galaxy clusters, consisting of hundreds or thousands of individual galaxies in virial equilibrium, are known to comprise of a complex makeup of intra-cluster fluid, with multiphase gas filling the space around and between member galaxies. Notably they house extended cooling filaments, which are often observed to be accreting onto the supermassive black hole of the central galaxy in the cluster. The survivability of cold, dense gas that exists in the hot ( $\geq 10^8\text{K}$ ) medium within clusters of galaxies is an important open problem in astrophysics. Understanding how cold gas evolves in this medium, often travelling at a high relative speed in outflows or inflows, has important ramifications for cluster physics, most notably in the areas of accretion onto the central black hole, feedback, star formation, and cluster cooling. In this paper we perform (magneto-)hydrodynamical simulations of



**Cooling, magnetic fields, thermal conduction and more!**

