AGN feedback in galaxy clusters and groups: state-of-the-art and recent advances

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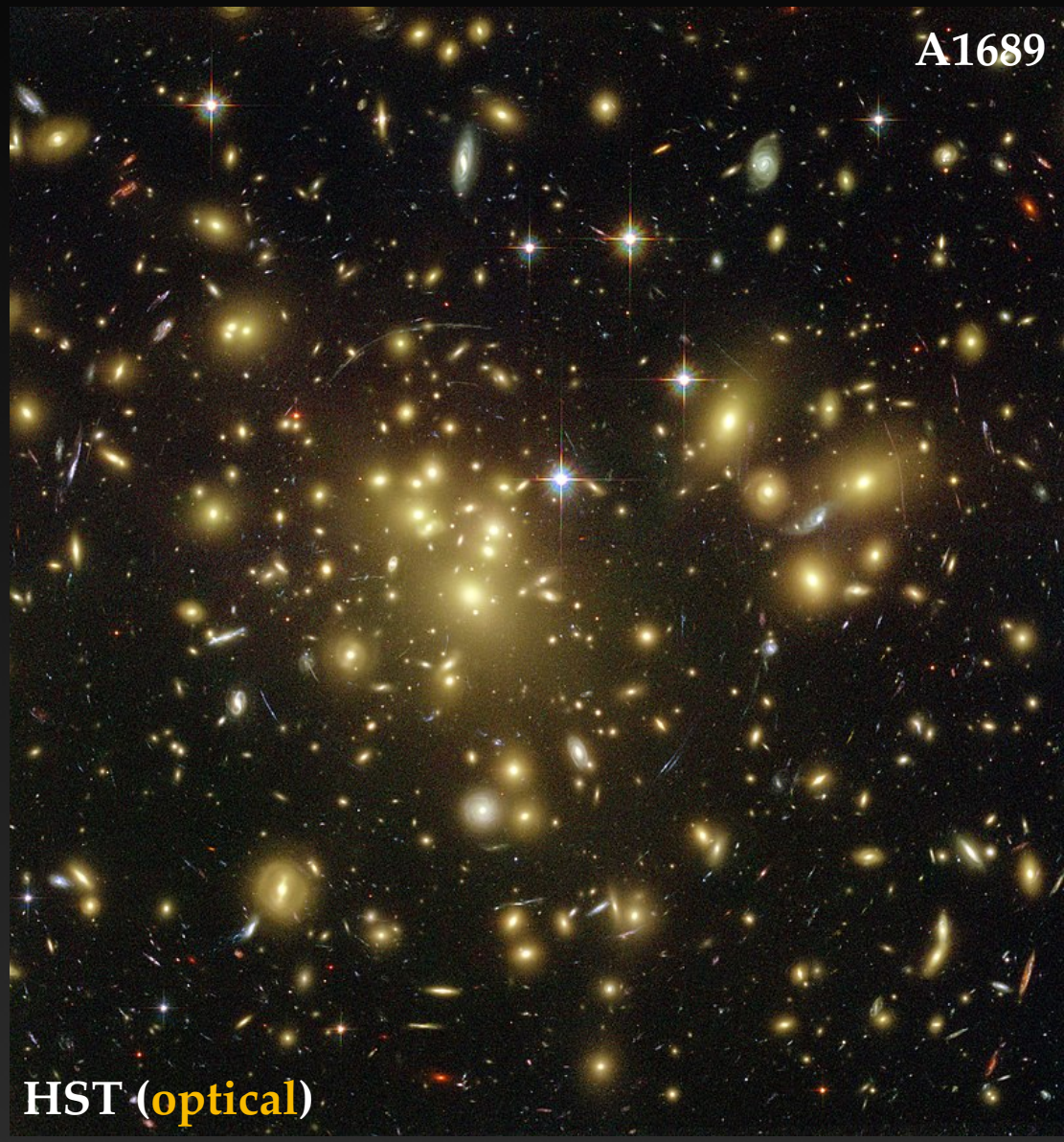
Overview

- Brief introduction: a multi-wavelength view of galaxy clusters and groups;
- The cooling flow problem: the need for AGN feedback;
- The power of X-ray and radio observations;
- Galaxy clusters: state of the art and open questions;
- What's missing in galaxy groups?
- Recent advances in the lower-mass regime;
- Surveys as a tool to study AGN feedback in groups;
- Open questions and conclusions;

Galaxy clusters and groups: a multi-wavelength picture

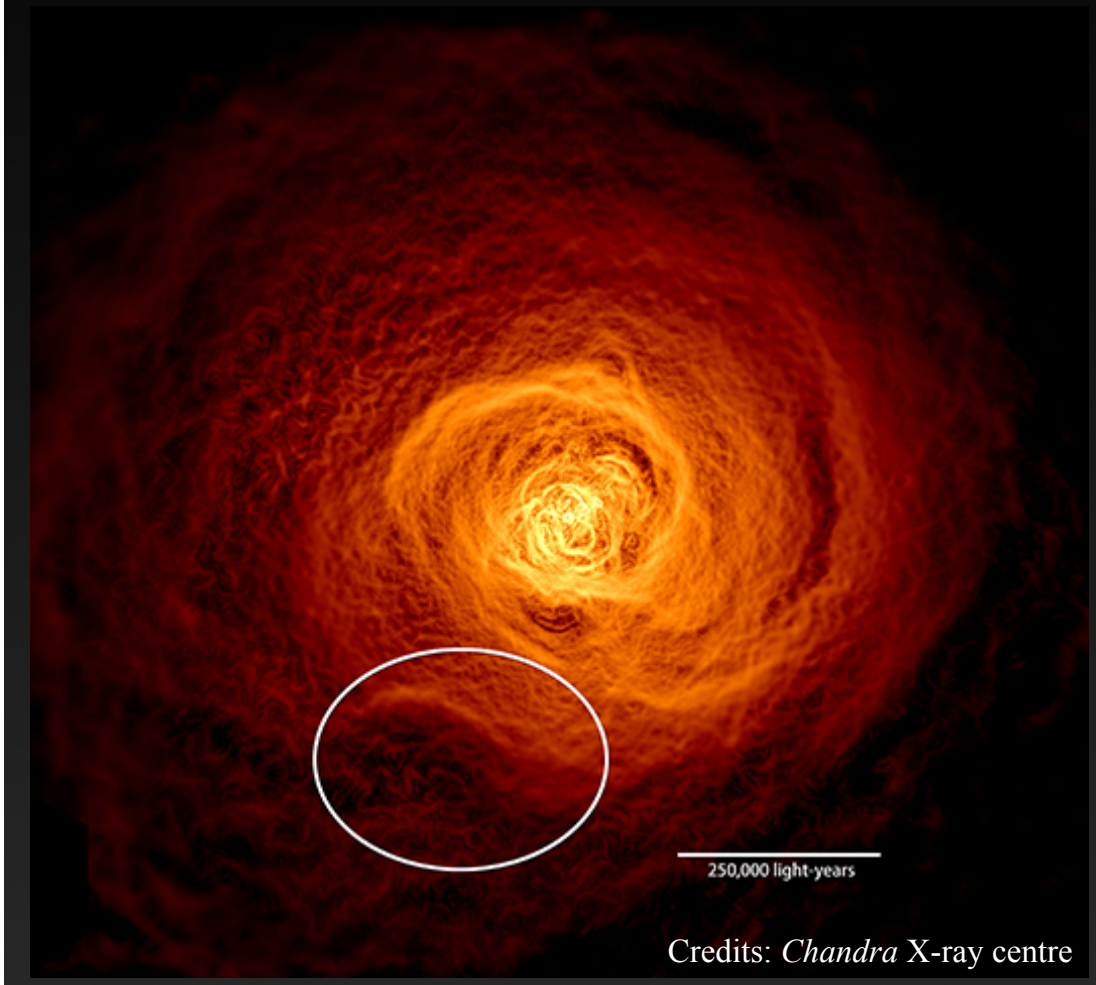
- Largest structures in the Universe™;
- $10^{13} < M_{\odot} < 10^{15}$
- Essential for cosmology: number density, dark matter (DM) perturbations etc.;
- Can contain 10s (groups) to 1000s (clusters) galaxies;
- >80% of the total mass is dark matter;
- Often dominated by a central Brightest Cluster Galaxy (BCG);



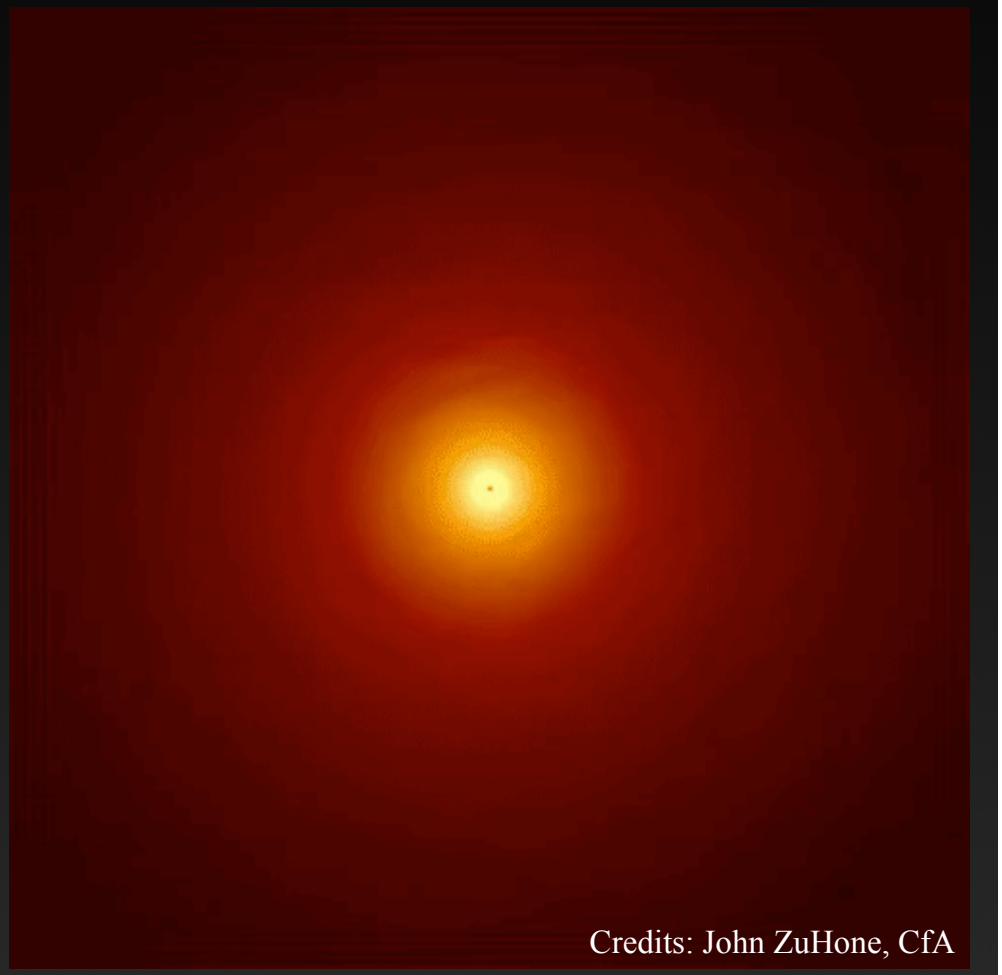
Galaxy clusters and groups: a multi-wavelength picture

- Permeated by 10^7 - 10^8 K plasma (Intra-Cluster Medium, ICM);
- The ICM is constantly cooling through Bremsstrahlung and line emission;
- X-ray observations give us information about the ICM thermal emission;
- Gas temperature, density, entropy, pressure, cooling time;
- Shocks, cold fronts, X-ray depressions, sloshing, mergers;

Galaxy clusters and groups: a multi-wavelength picture

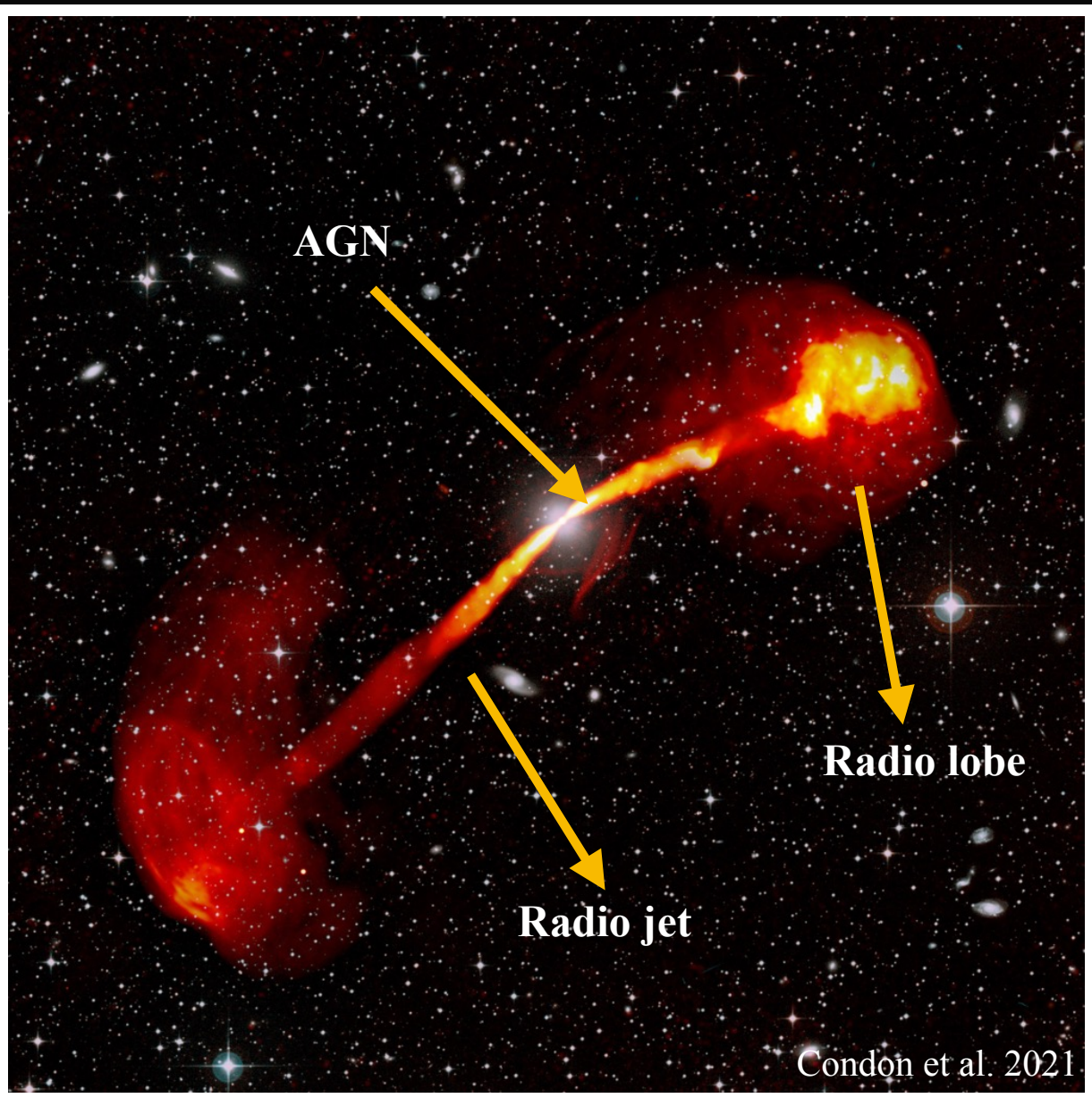


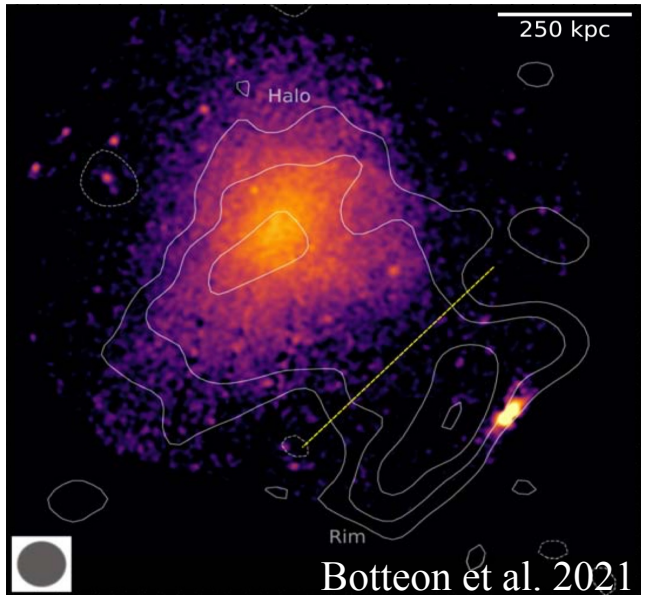
Credits: *Chandra* X-ray centre

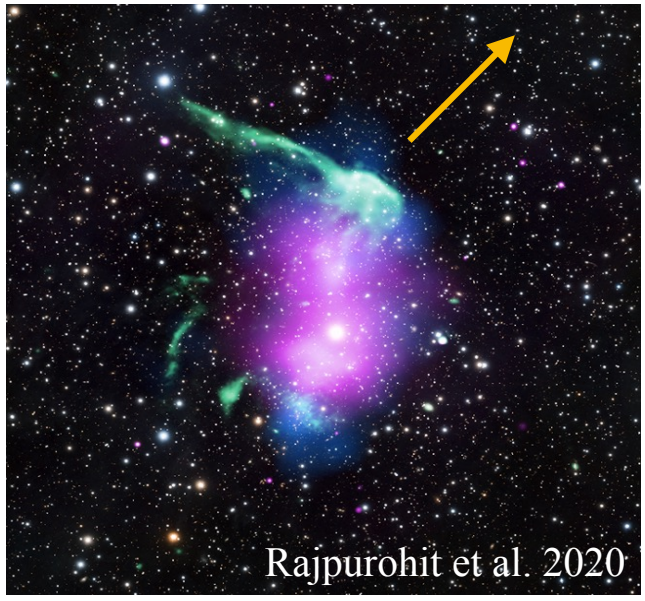


Credits: John ZuHone, CfA

Galaxy clusters and groups: a multi-wavelength picture







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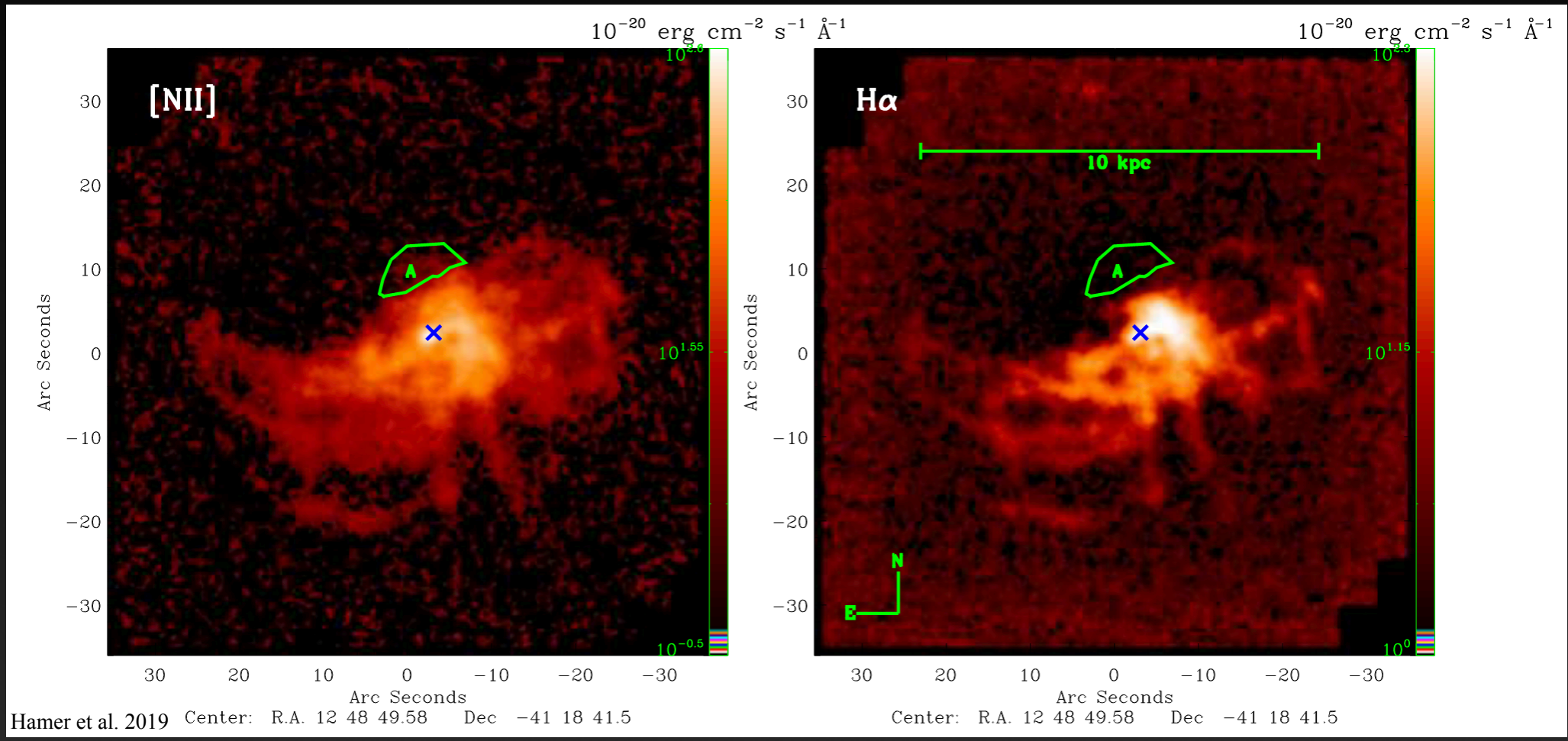
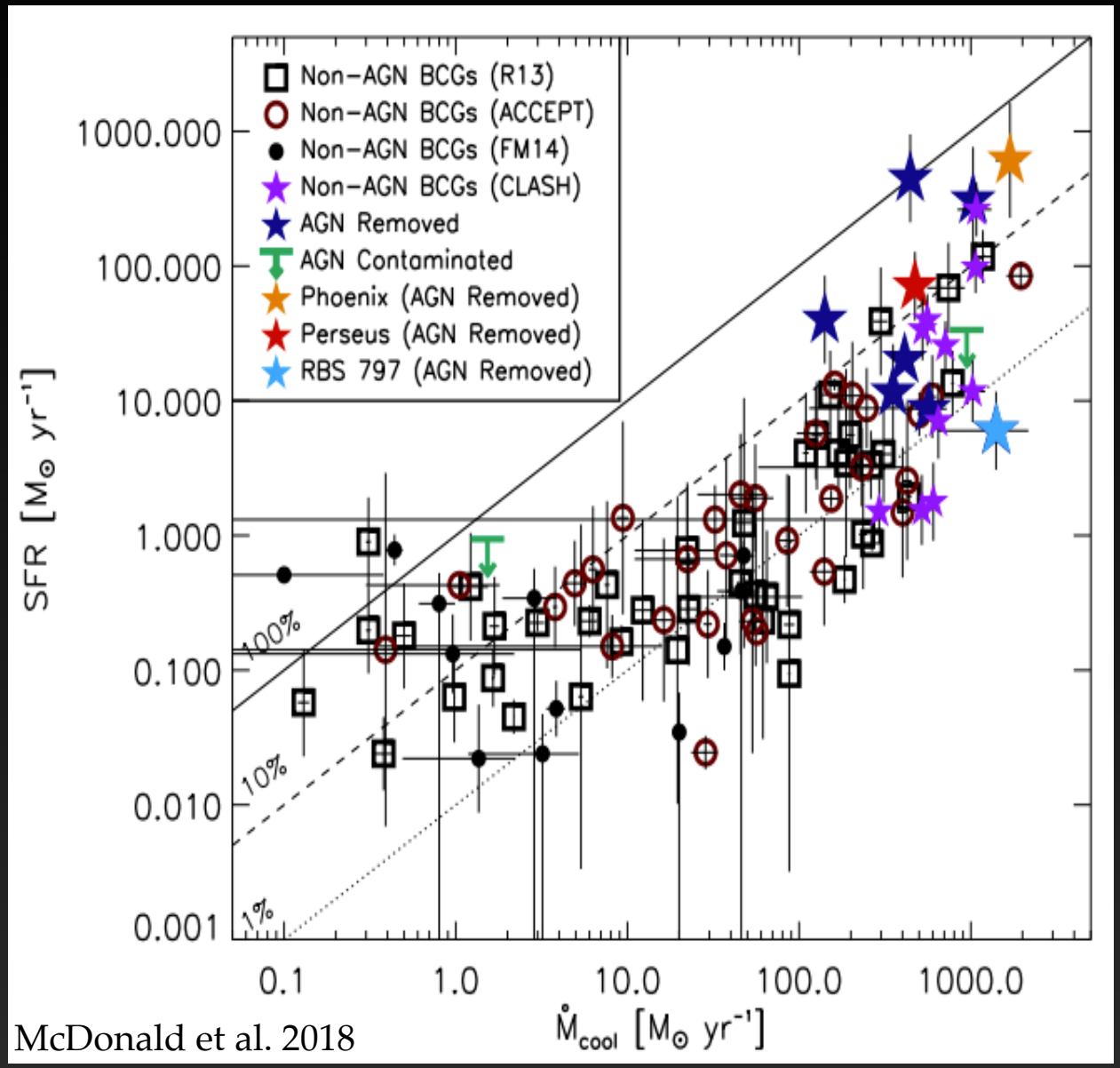


Hamer et al. 2019

The cooling flow problem



McDonald et al. 2018

- Bremsstrahlung emission

$$J_{X,T} \propto n_e^2 \, T^{1/2}$$

- In more relaxed systems, the core is colder and denser
- We expect a cooling flow and the trigger of high SFR in central galaxies
- Most clusters lie below the 10% line

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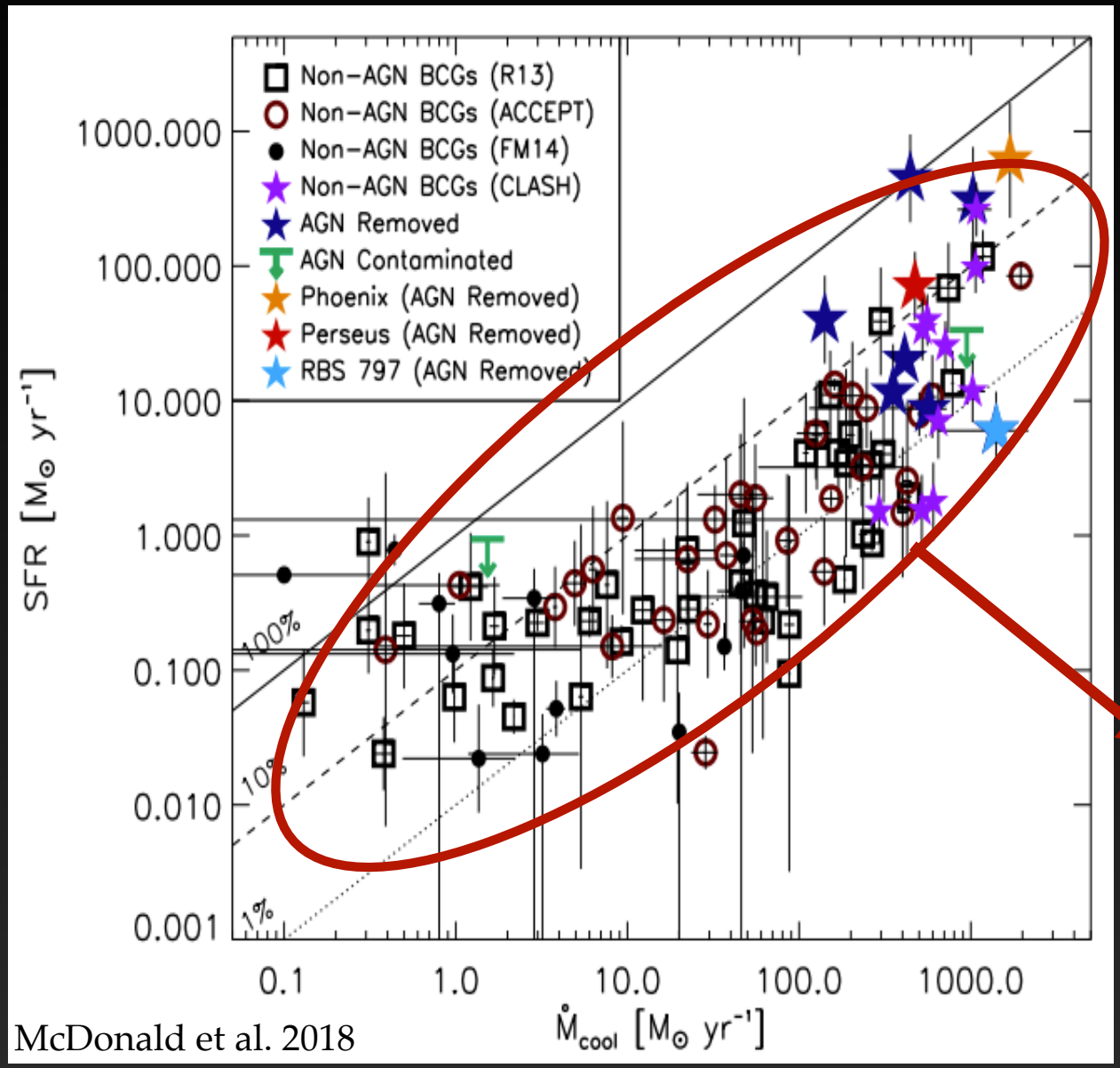

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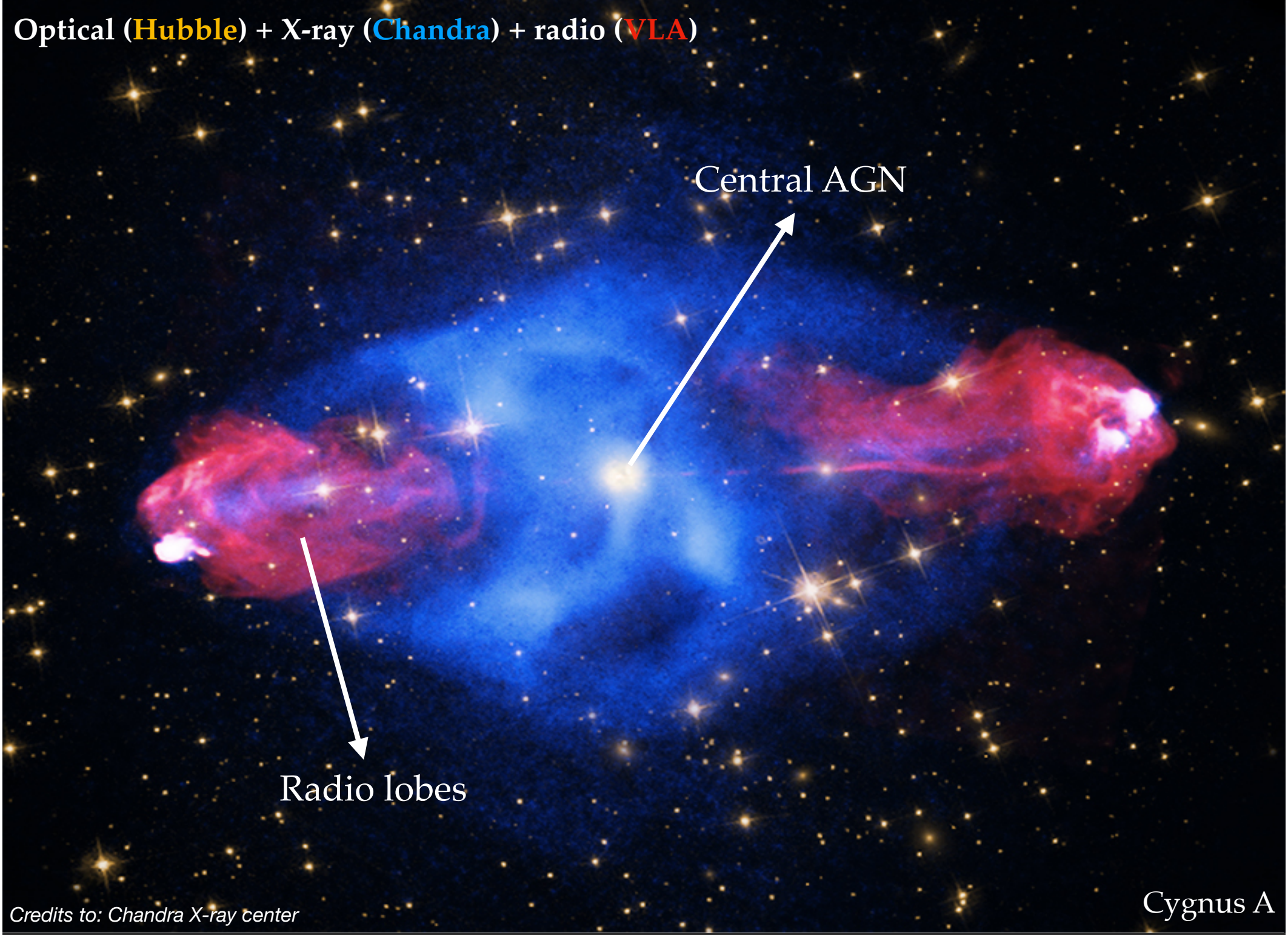
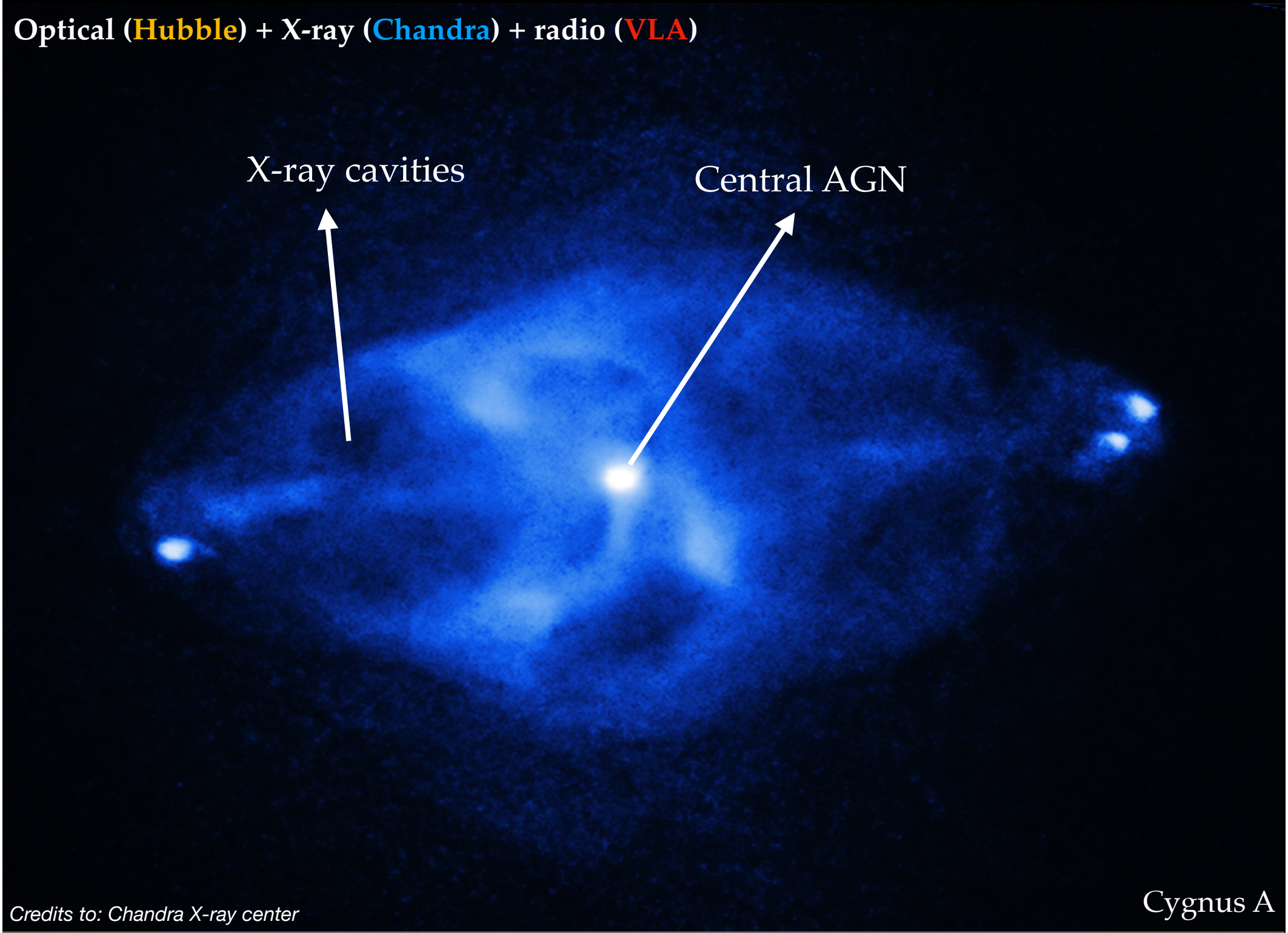
Something is quenching the ICM radiative losses


Optical (Hubble) + X-ray (Chandra) + radio (VLA)
Central AGN
Radio lobes
Credits to: Chandra X-ray center
Cygnus A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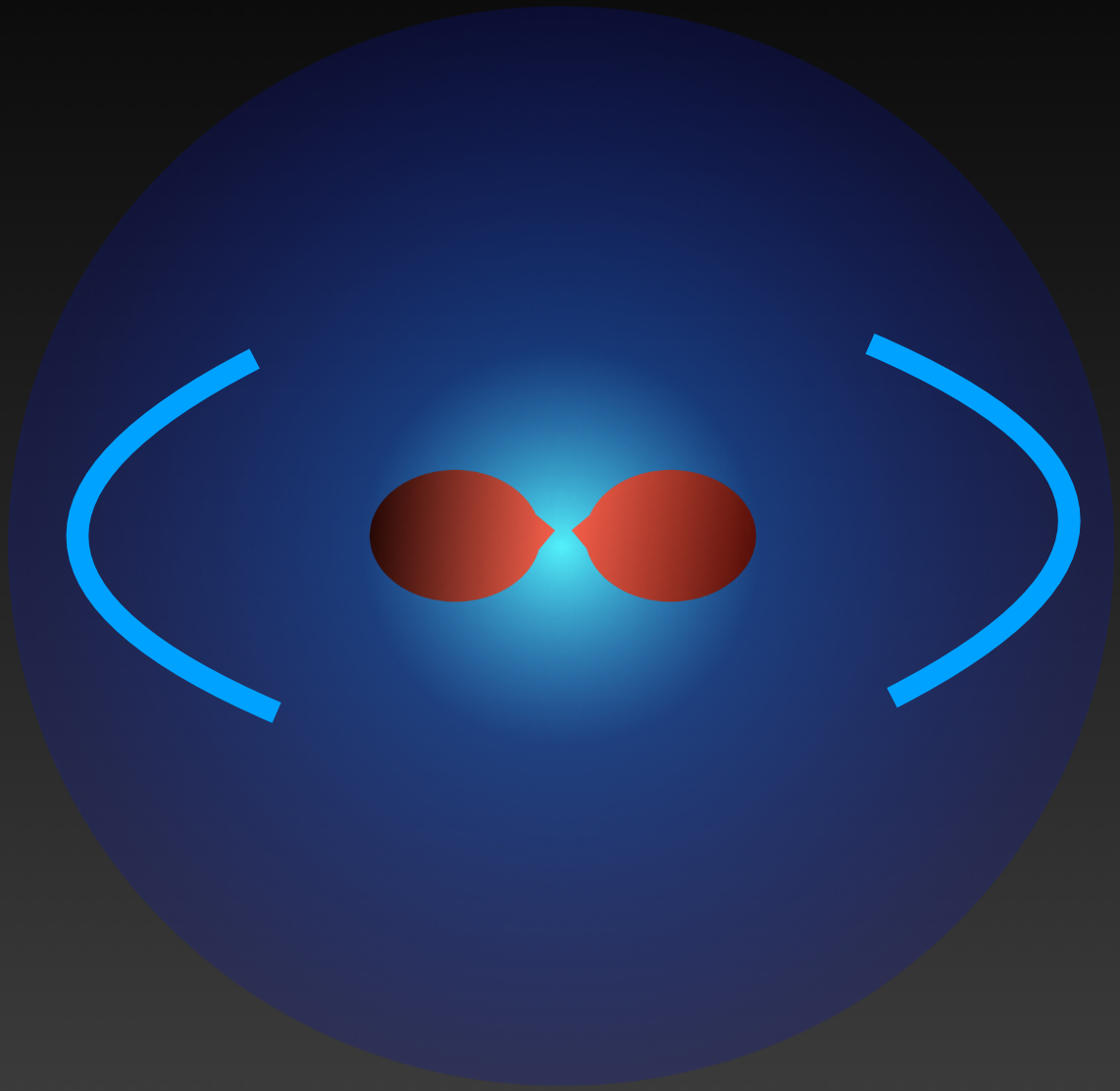
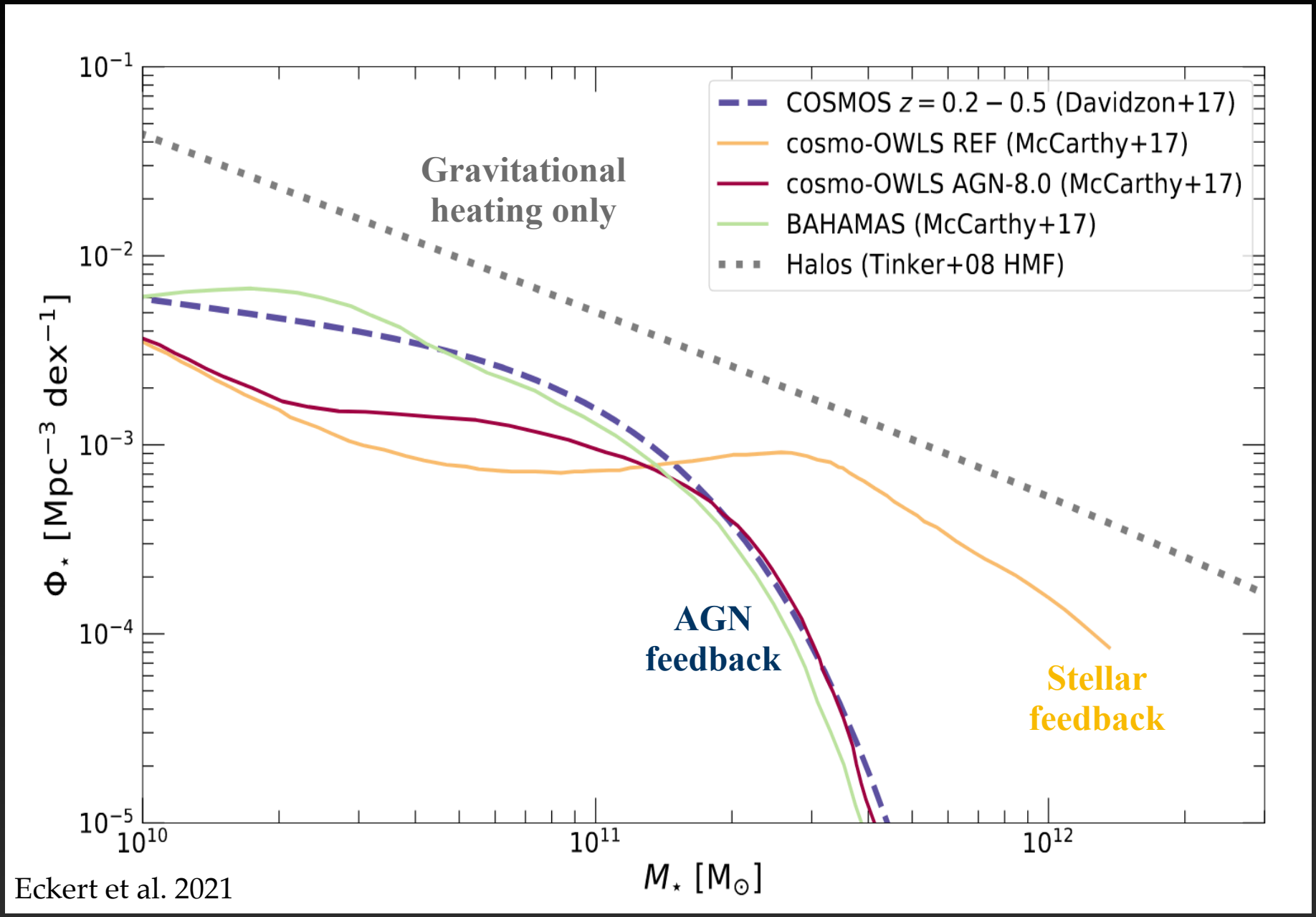
AGN feedback in galaxy clusters



- In the absence of an heating source, the ICM should cool and condense;
- The availability of fuel for the SMBH switches the AGN on;
- Shocks and mechanical feedback heats the ICM: the atmosphere expands;
- Cooling slows down, the AGN switches off;
- Repeat!

The need for AGN feedback



Eckert et al. 2021

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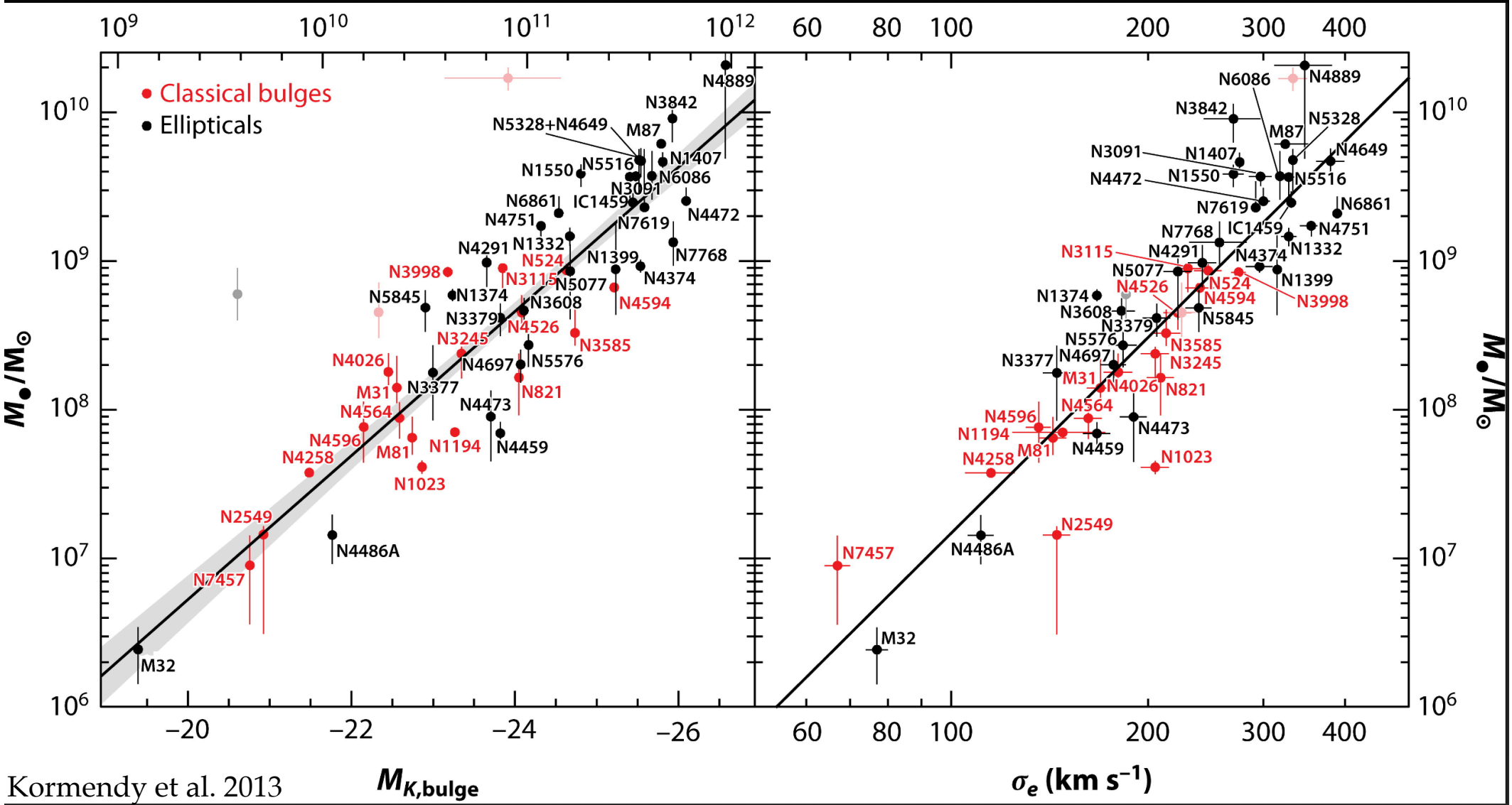
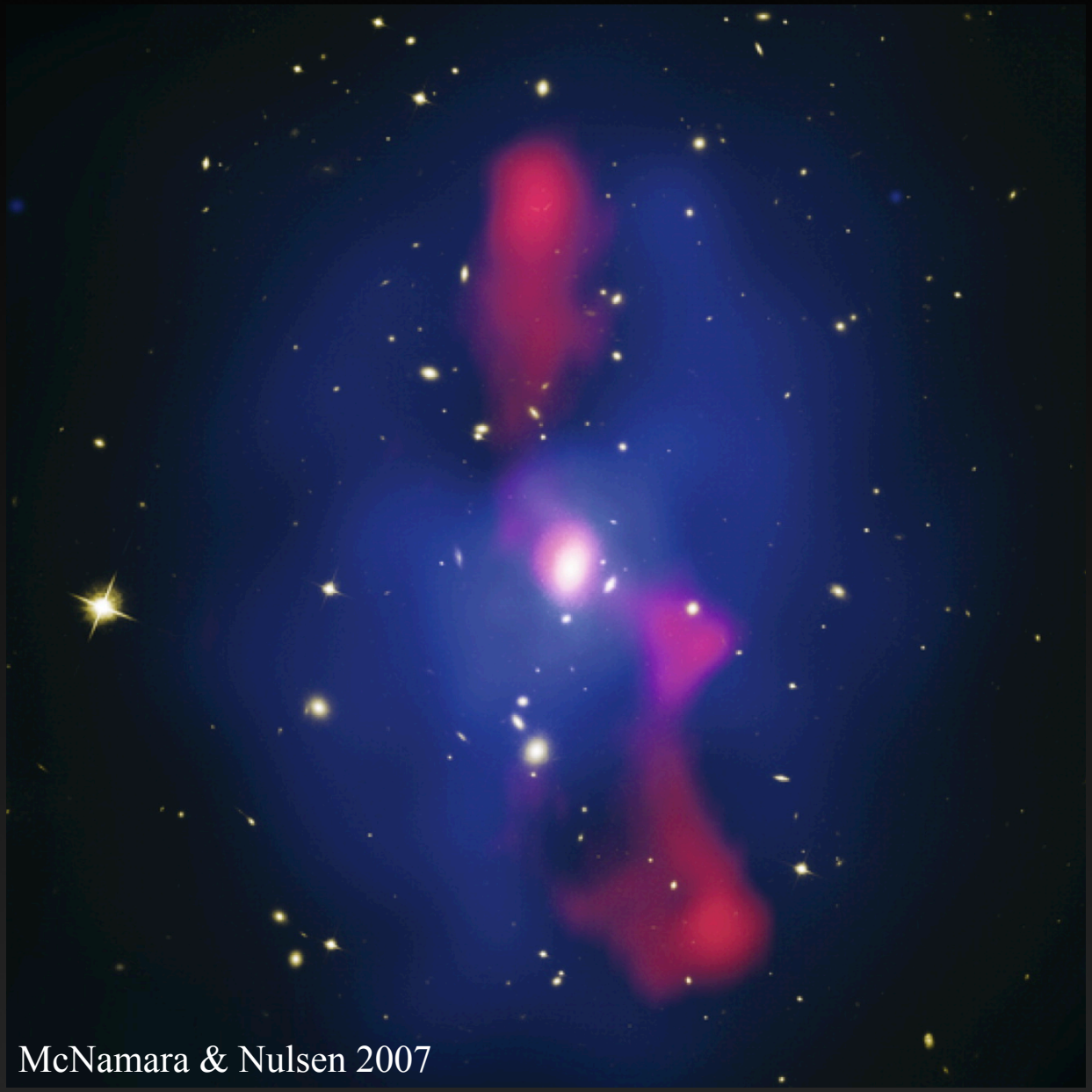
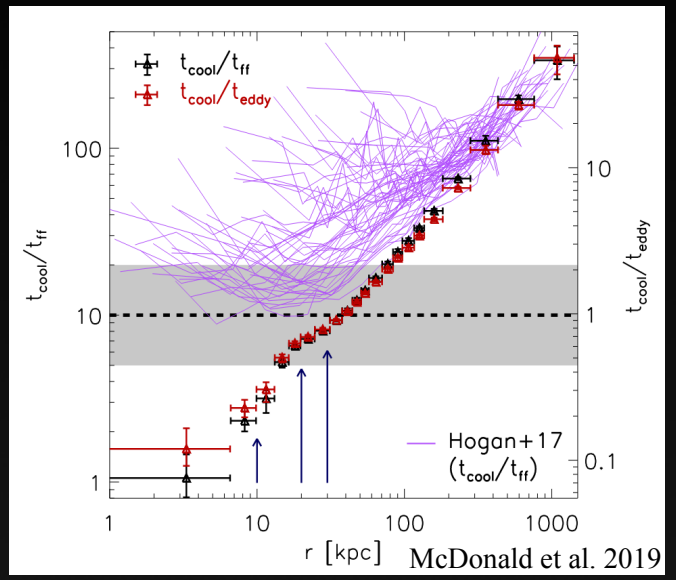


Kormendy et al. 2013

Observations of galaxy clusters





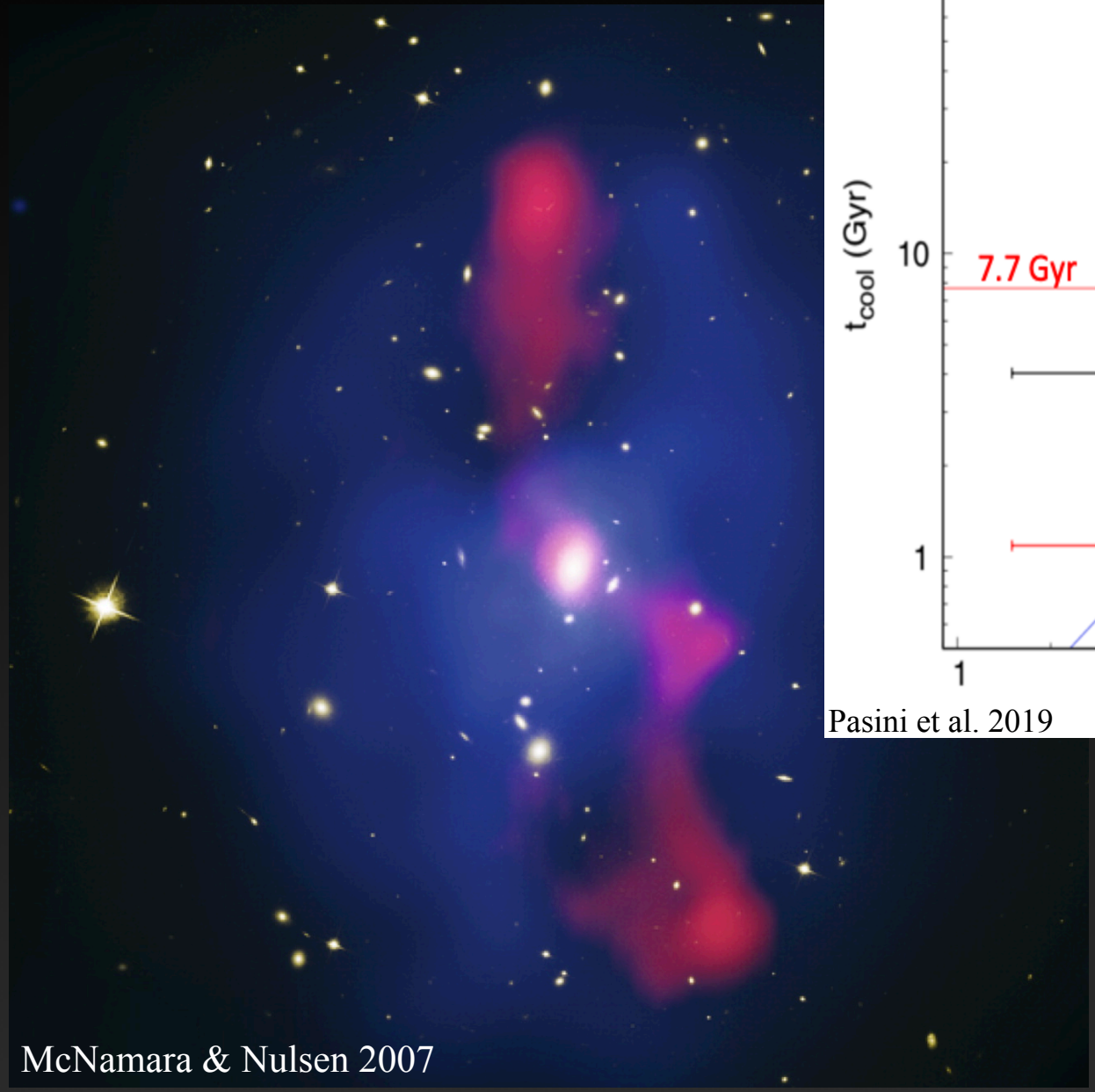
Cavity power:

$$P_{cav} = \frac{4pV}{t_{cav}}$$

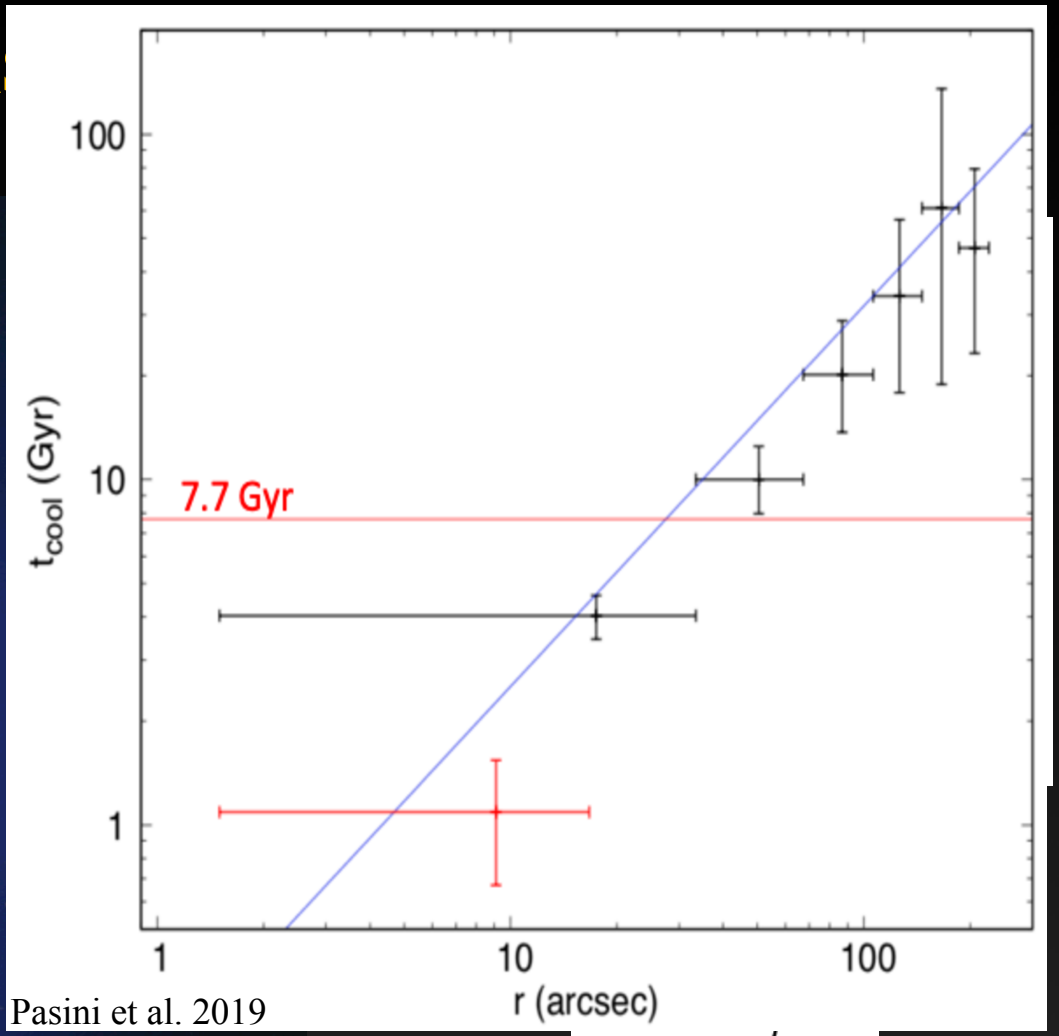
With:

$$E_{cav} = \frac{\gamma}{\gamma - 1} pV = 4pV$$

Observations



McNamara & Nulsen 2007



Pasini et al. 2019

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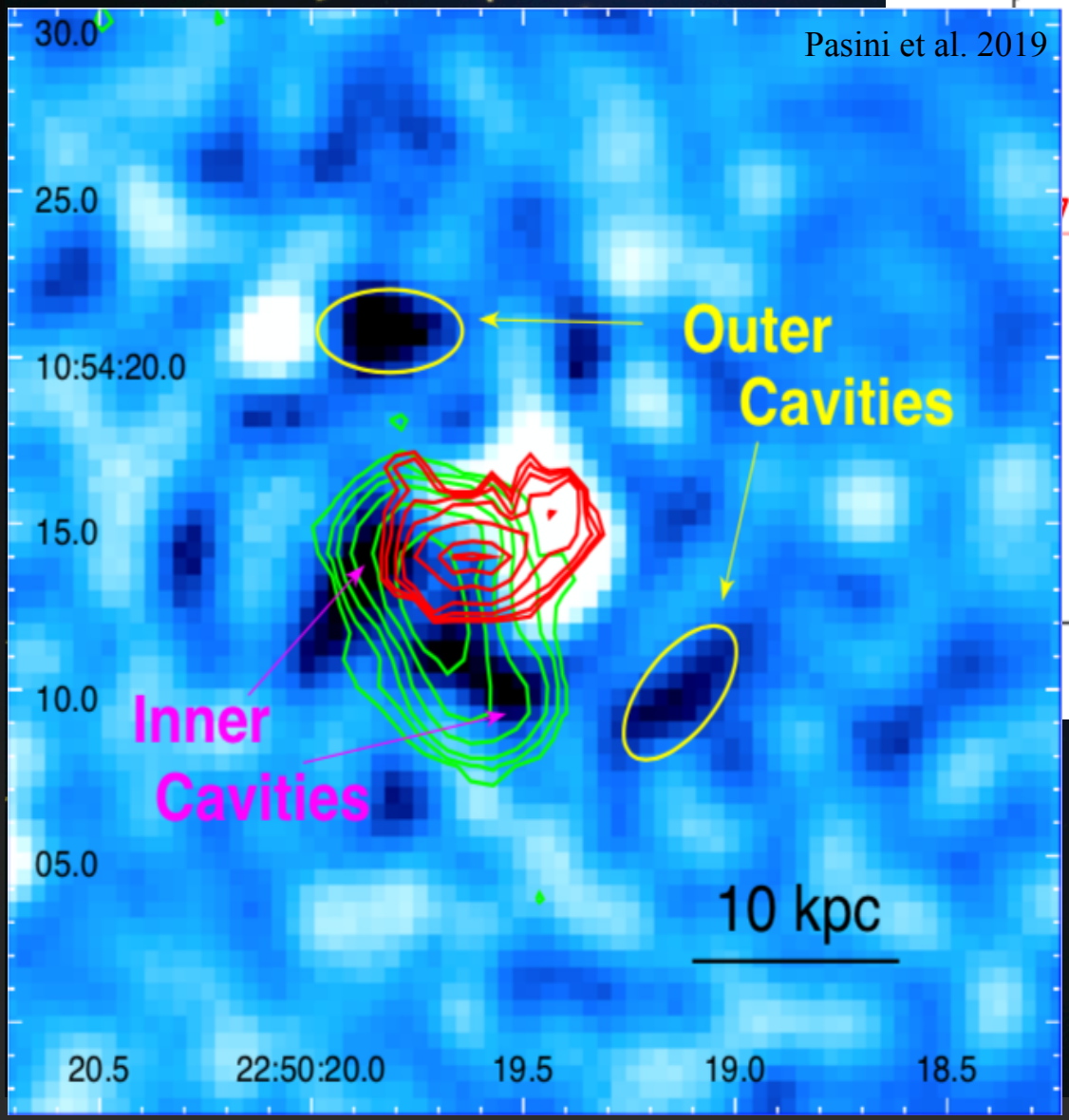

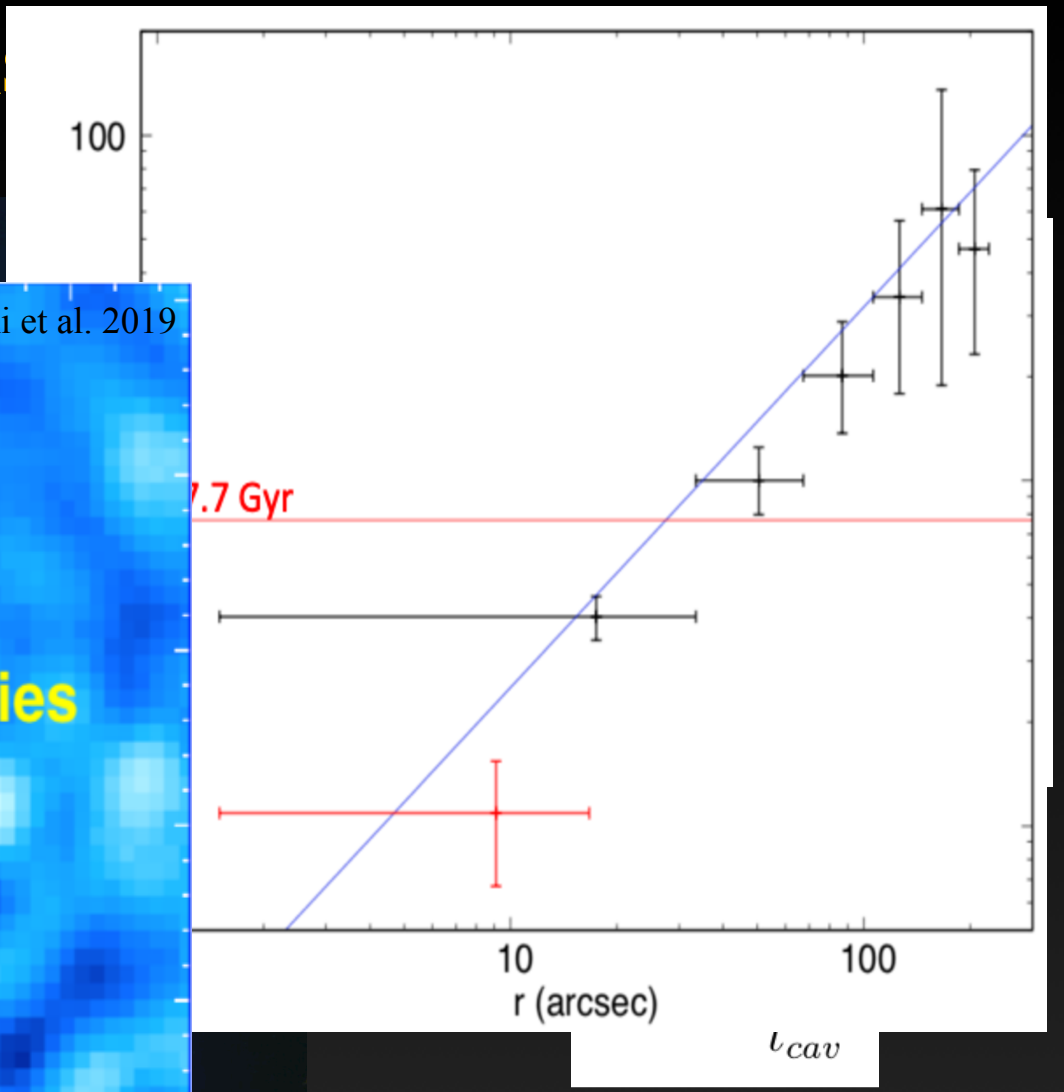

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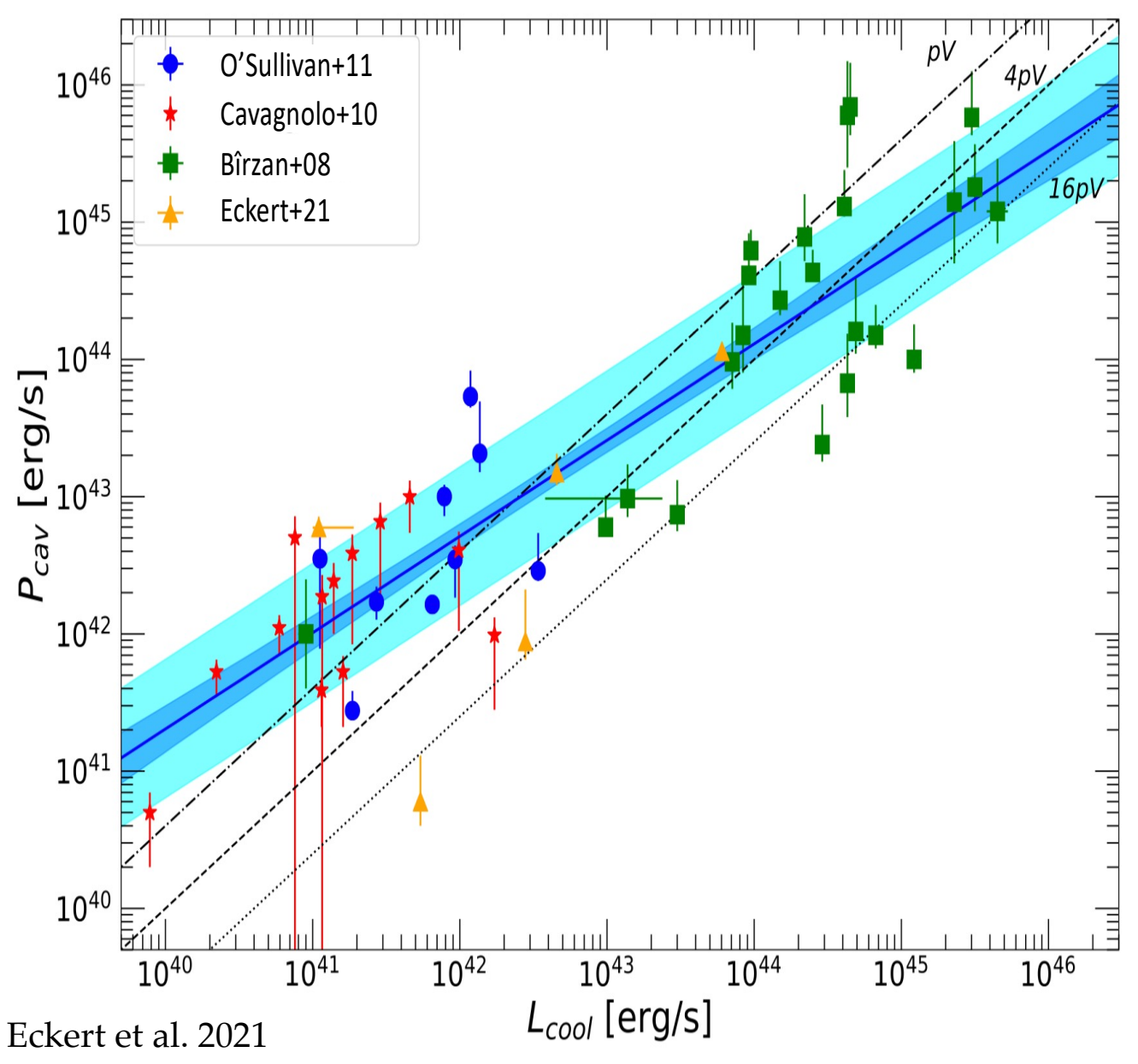
Cavity power - cooling correlation



Eckert et al. 2021

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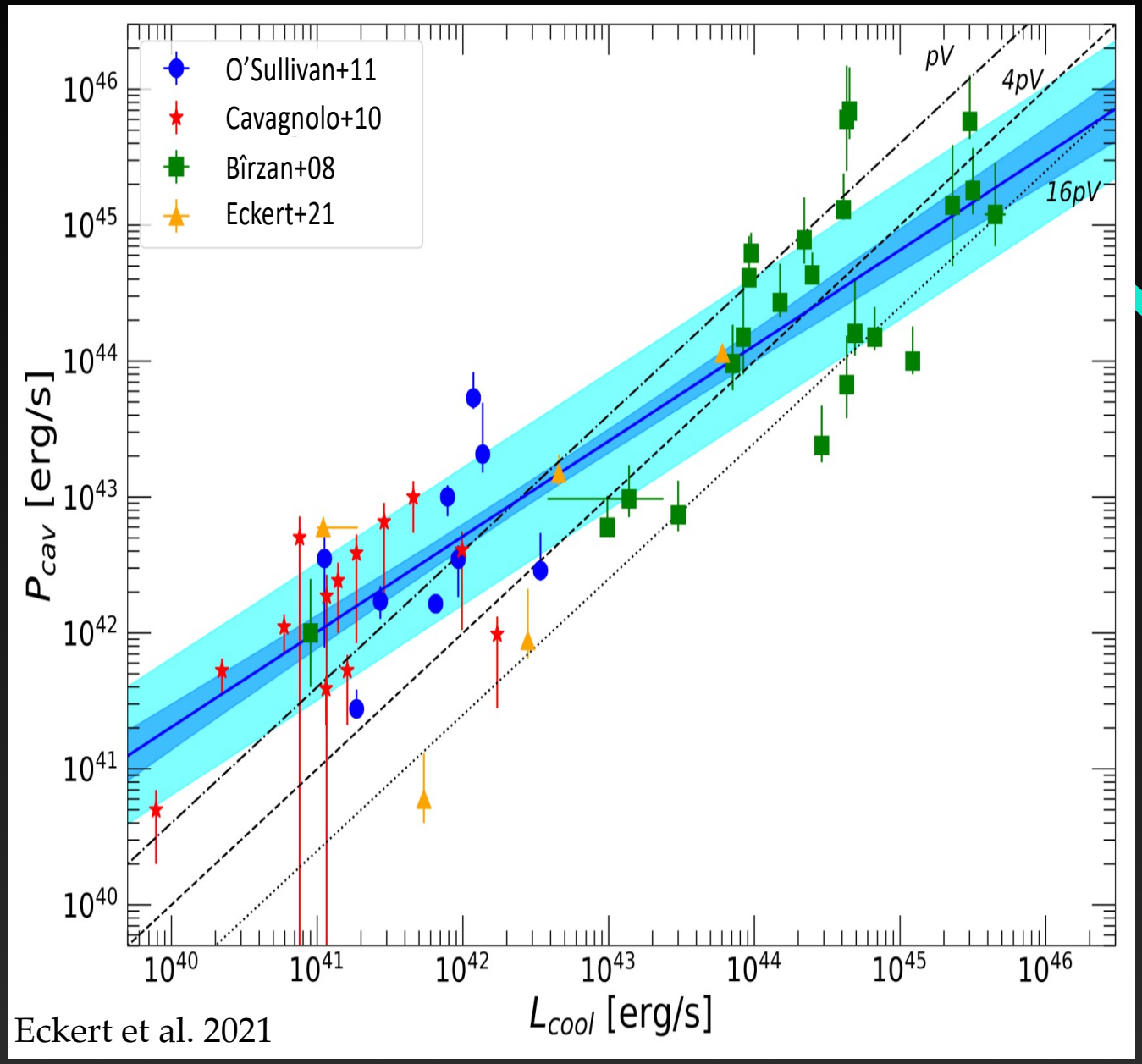

Eckert et al. 2021

ICM radiative losses are counterbalanced by heating provided by the AGN

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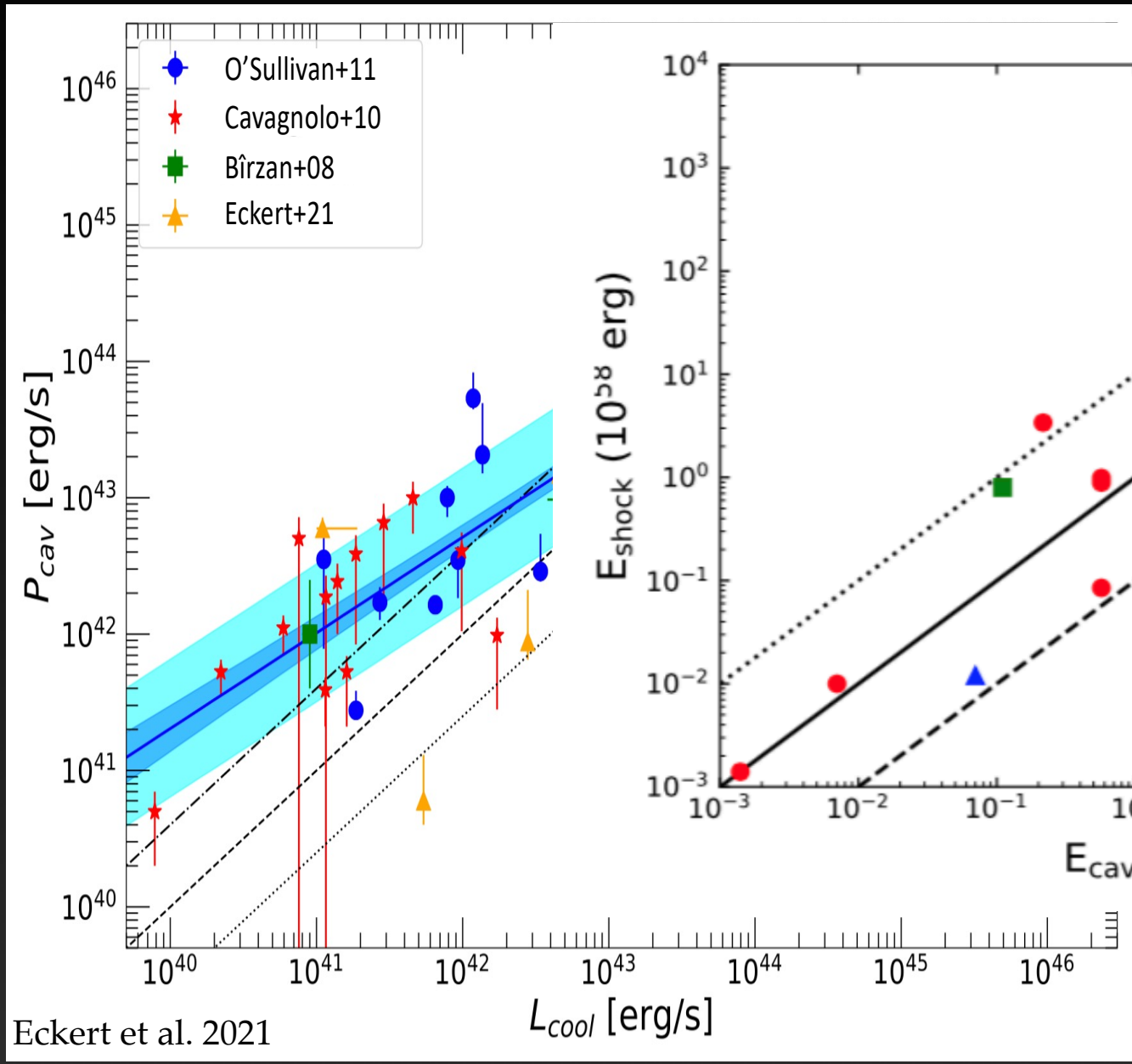
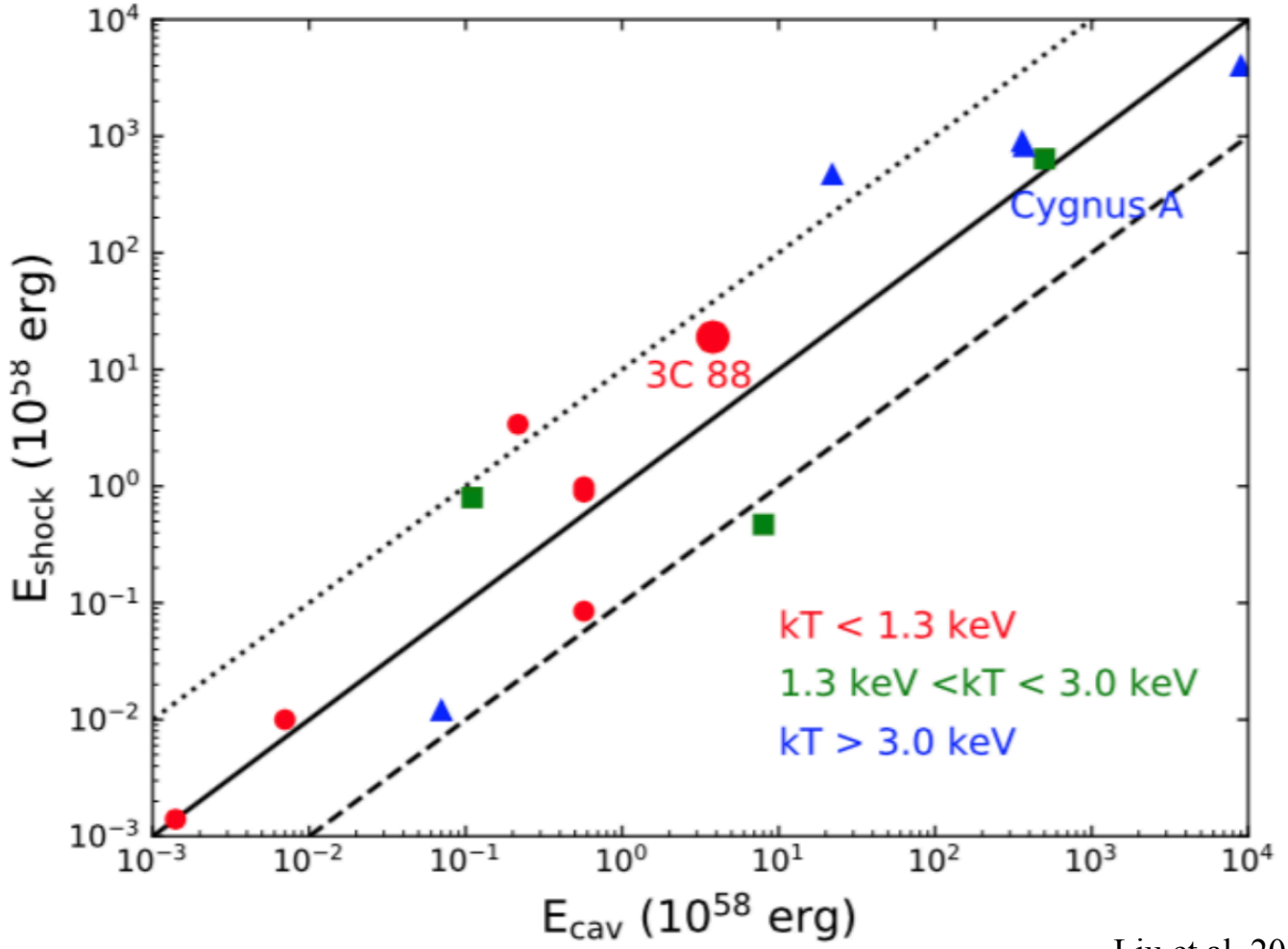
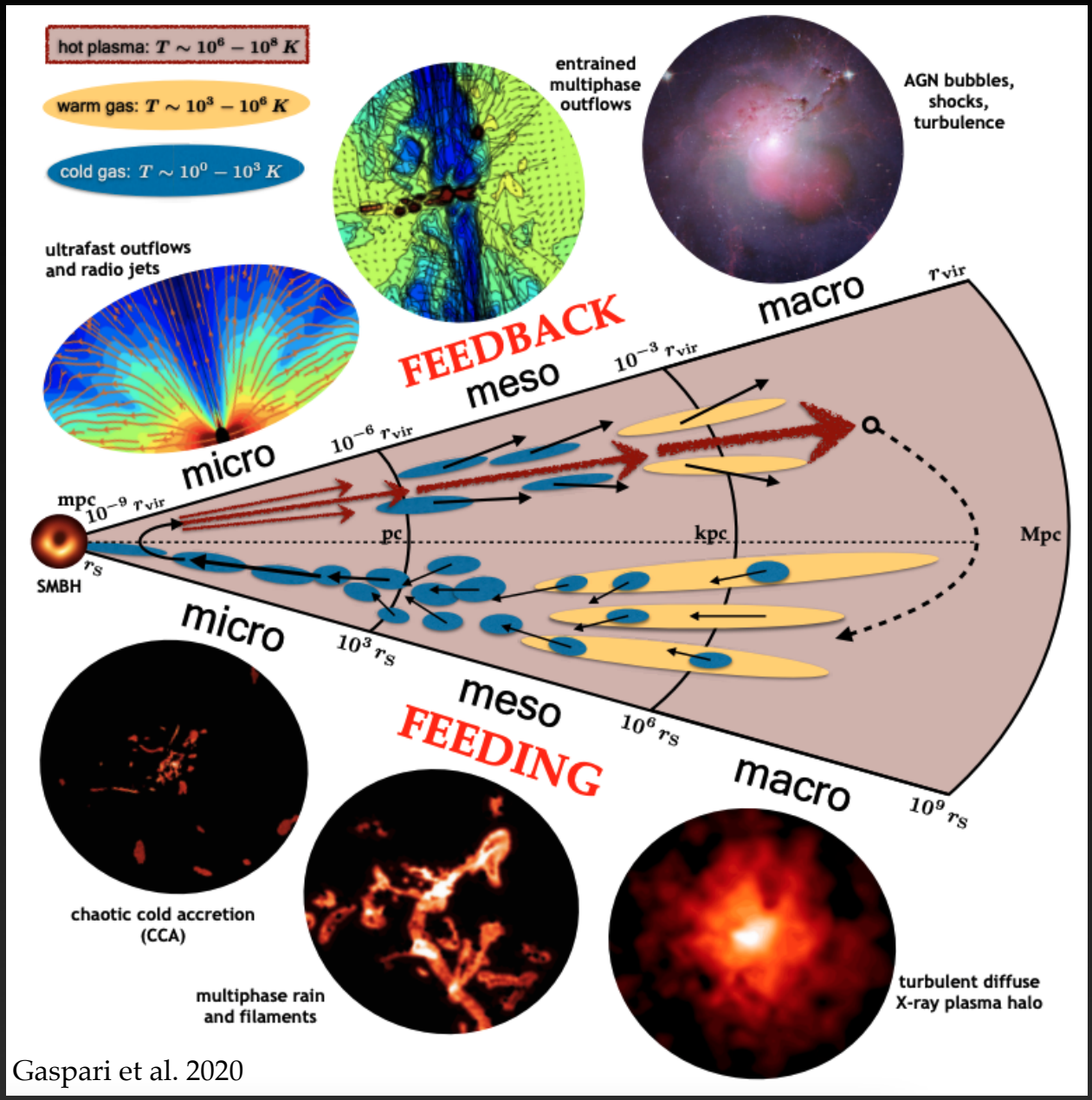


Eckert et al. 2021



Liu et al. 2019

AGN feedback in galaxy clusters: state of the art



Gaspari et al. 2020

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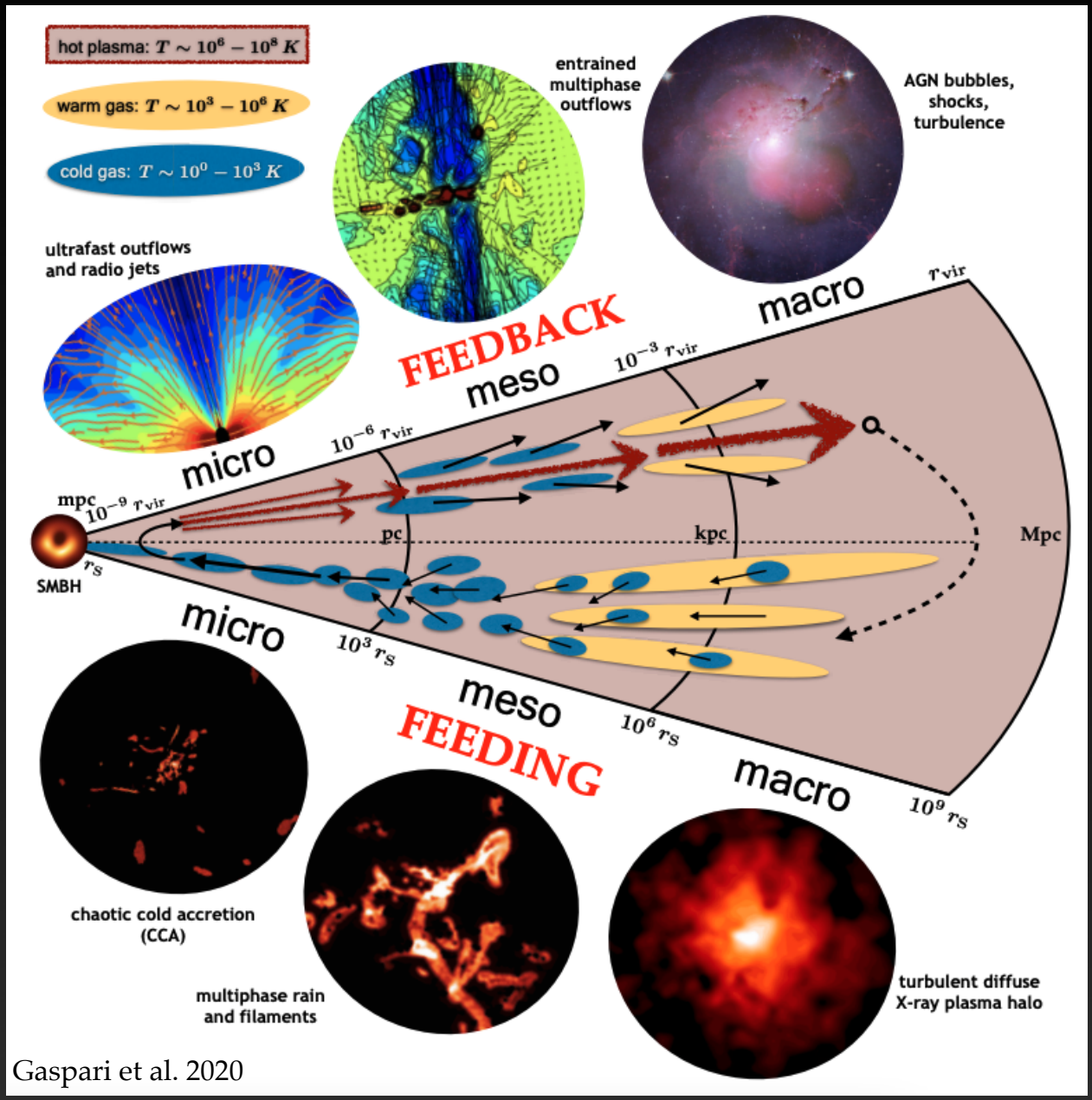

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<u>Many questions still to be answered:</u>

- Is this picture valid over the entire mass range of clusters and groups?
- What does it take to break the feeding/feedback cycle?
- Does the AGN duty cycle hold over the entire Hubble time?
- How is the feedback energy deposited onto the ICM?

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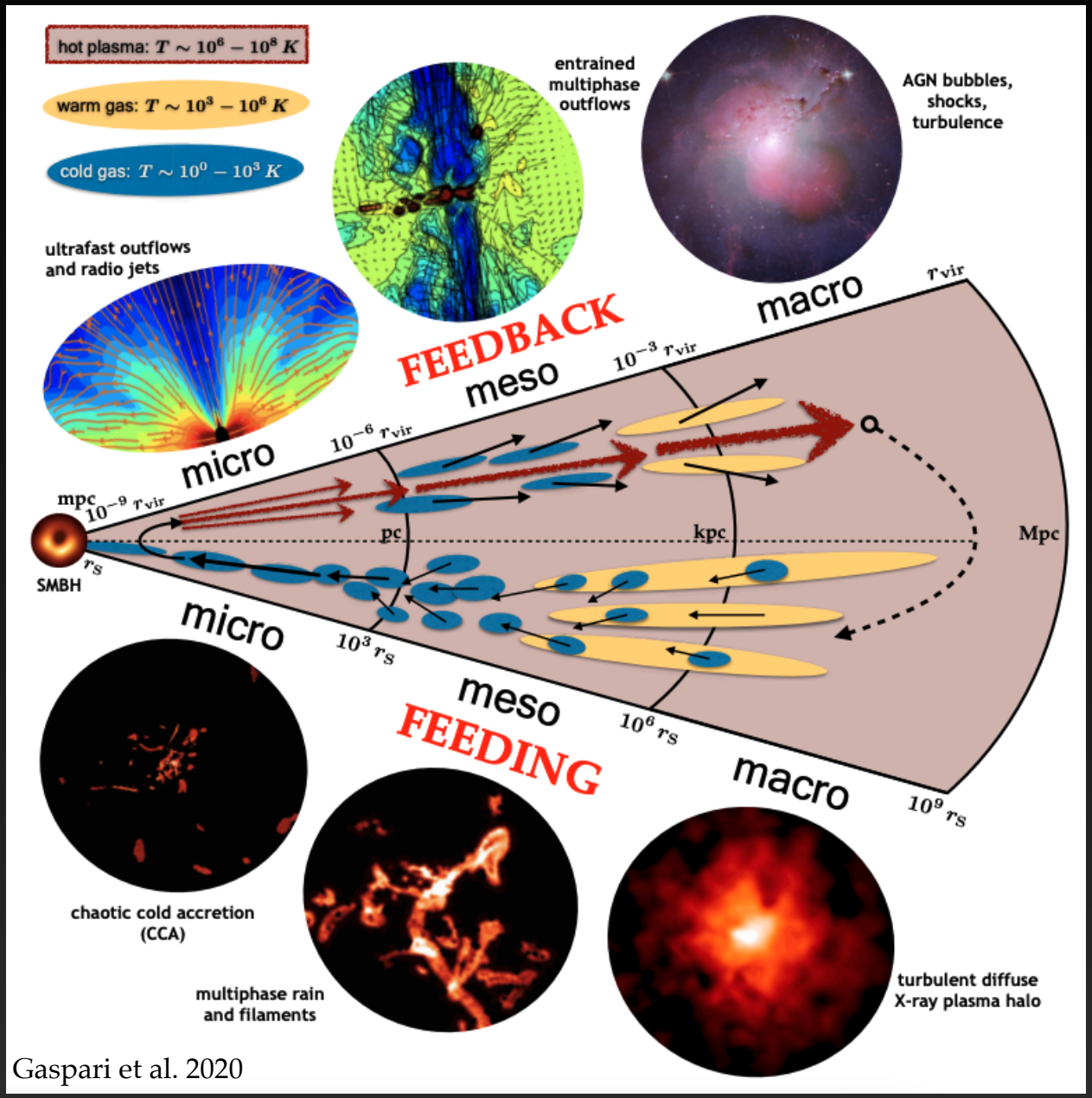

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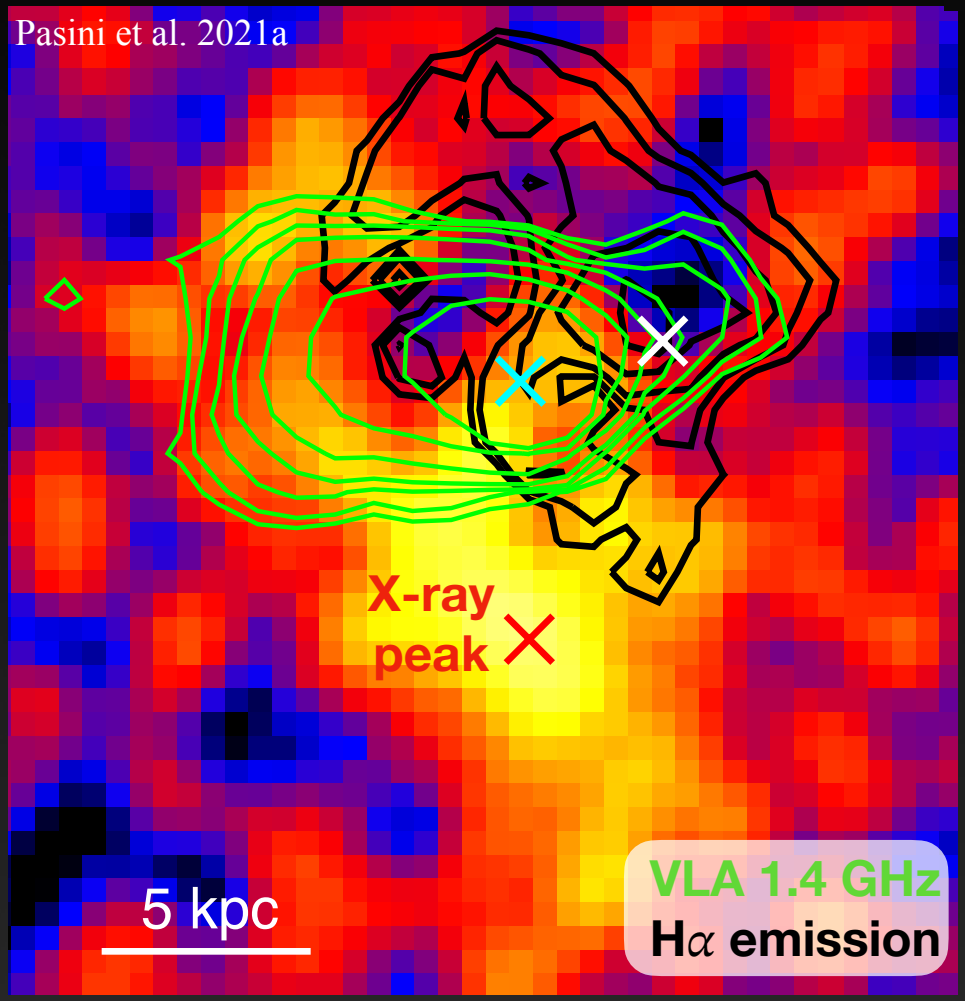
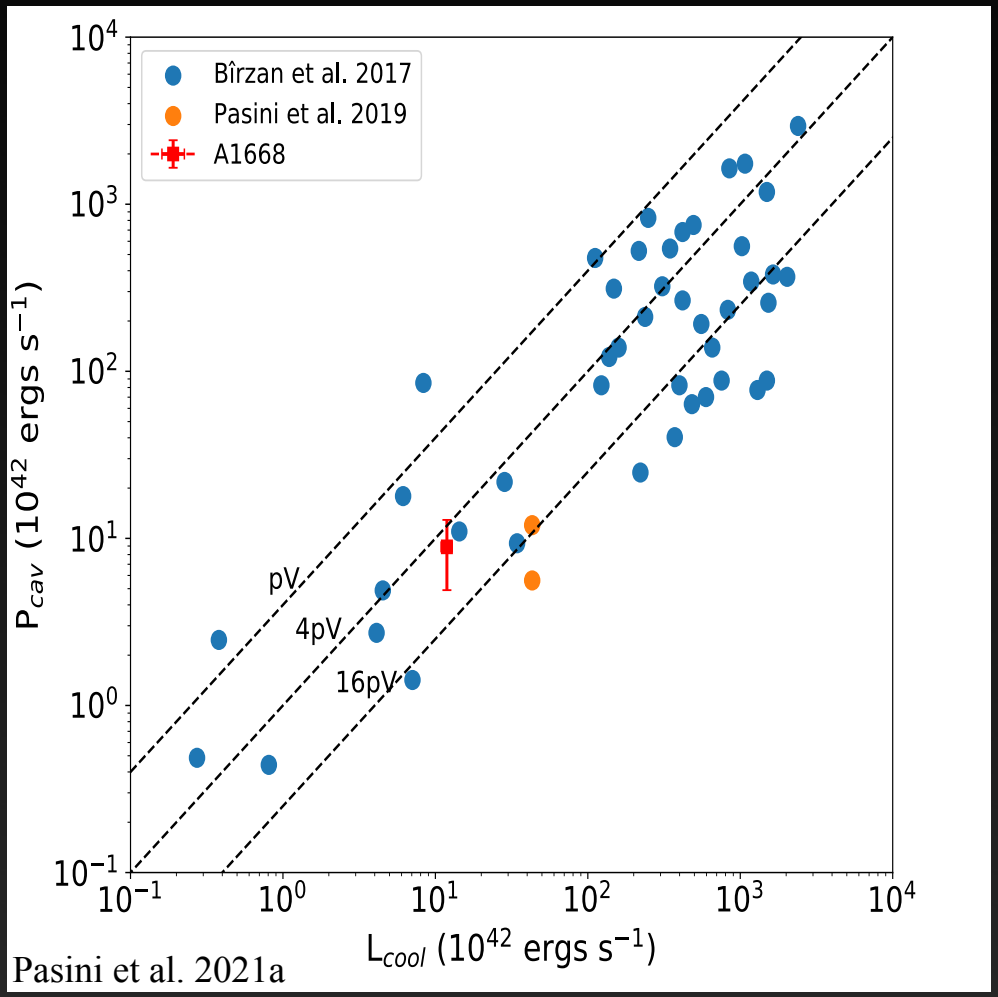
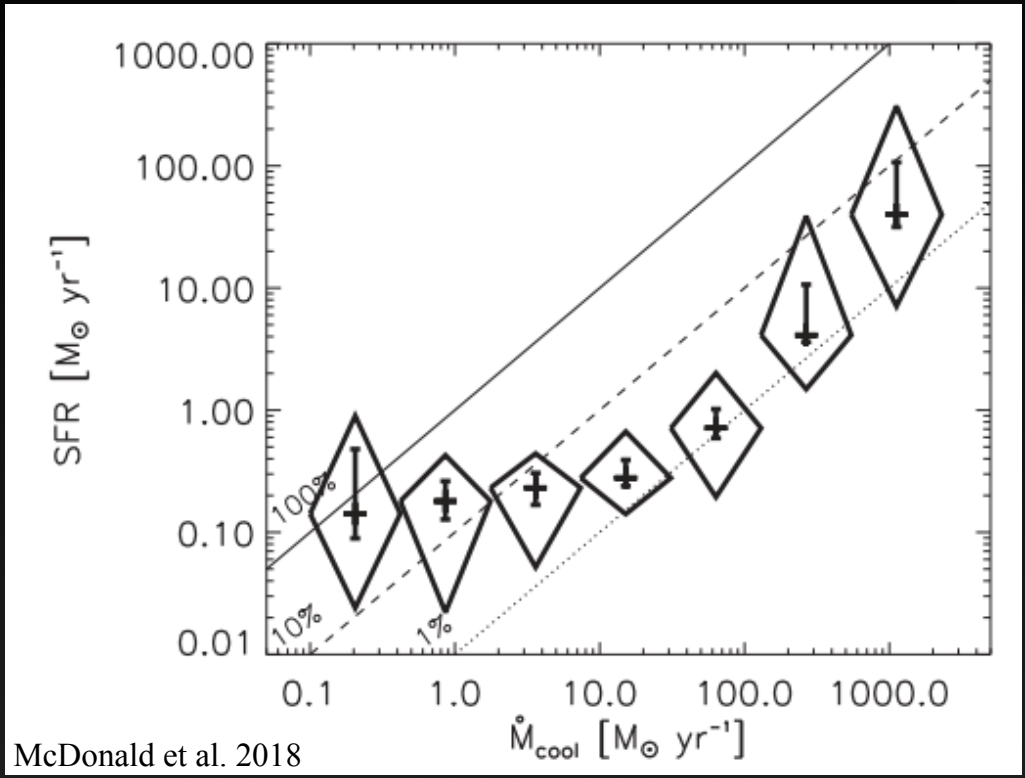
How strong is the ICM-AGN connection?





Recent advances: triggering of SFR, shock heating, feeding valve...



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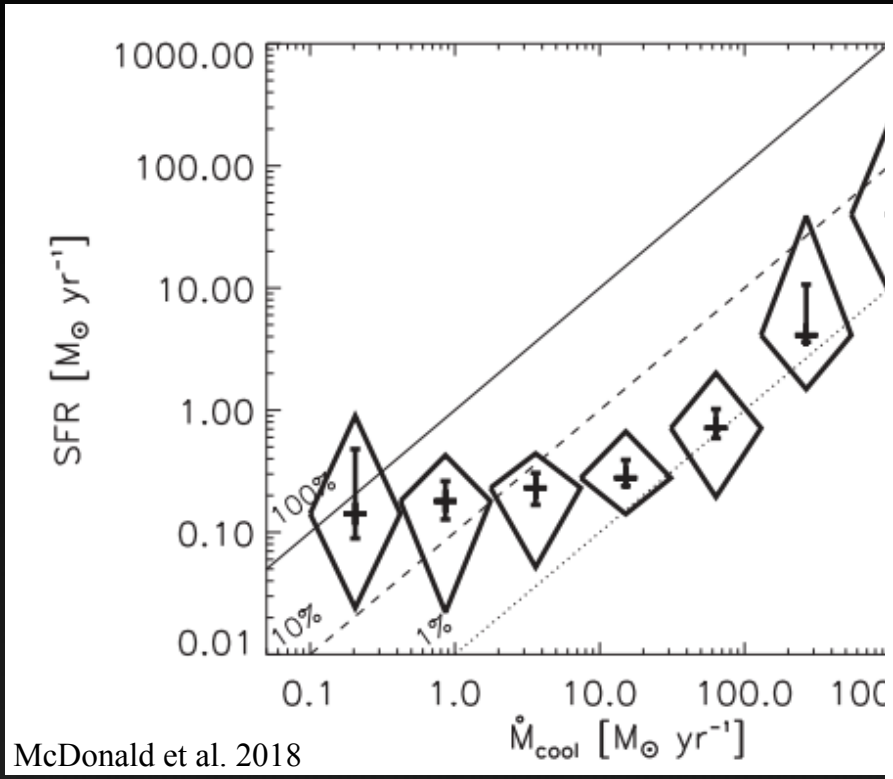

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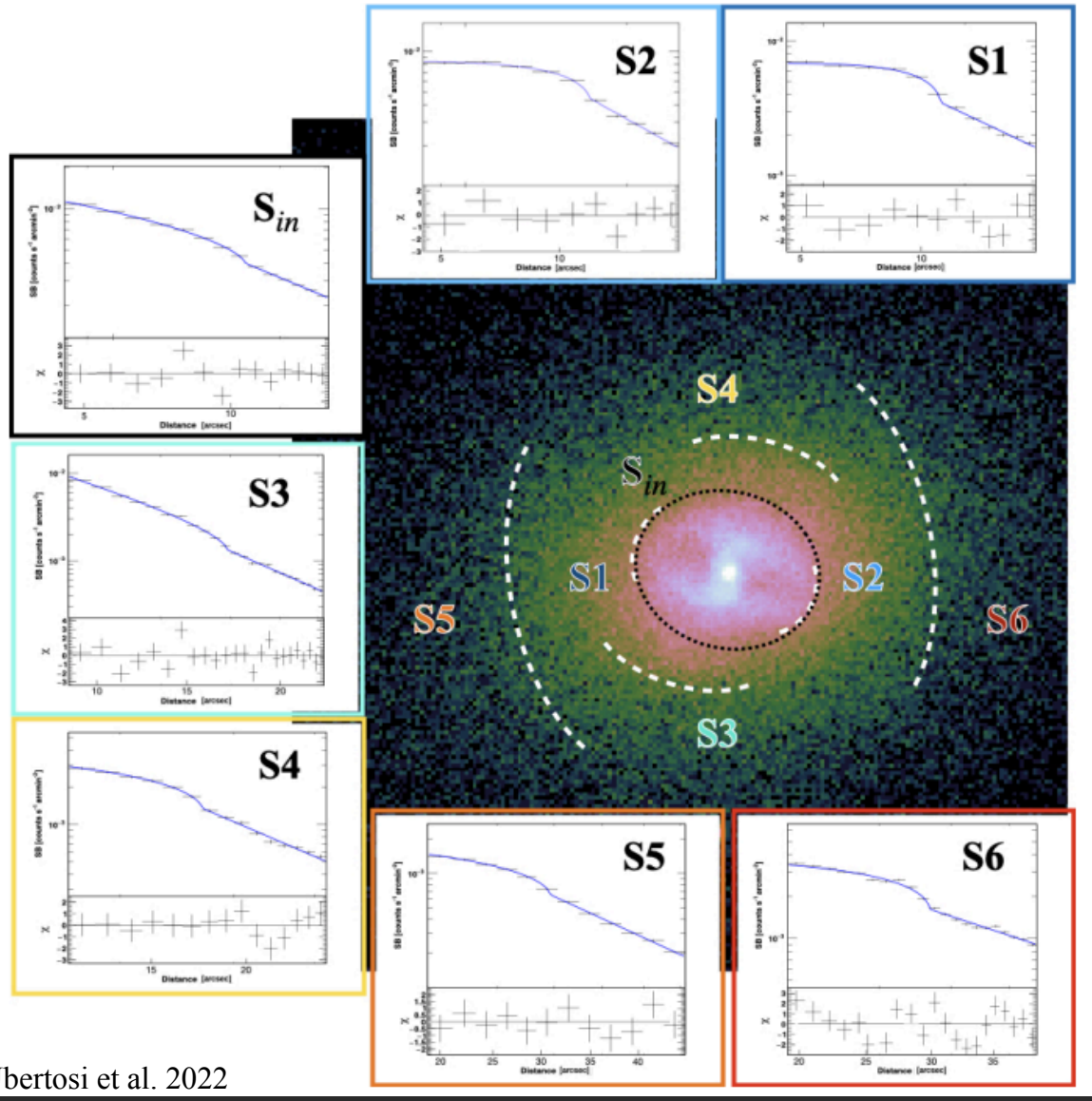

Ubertosi et al. 2022

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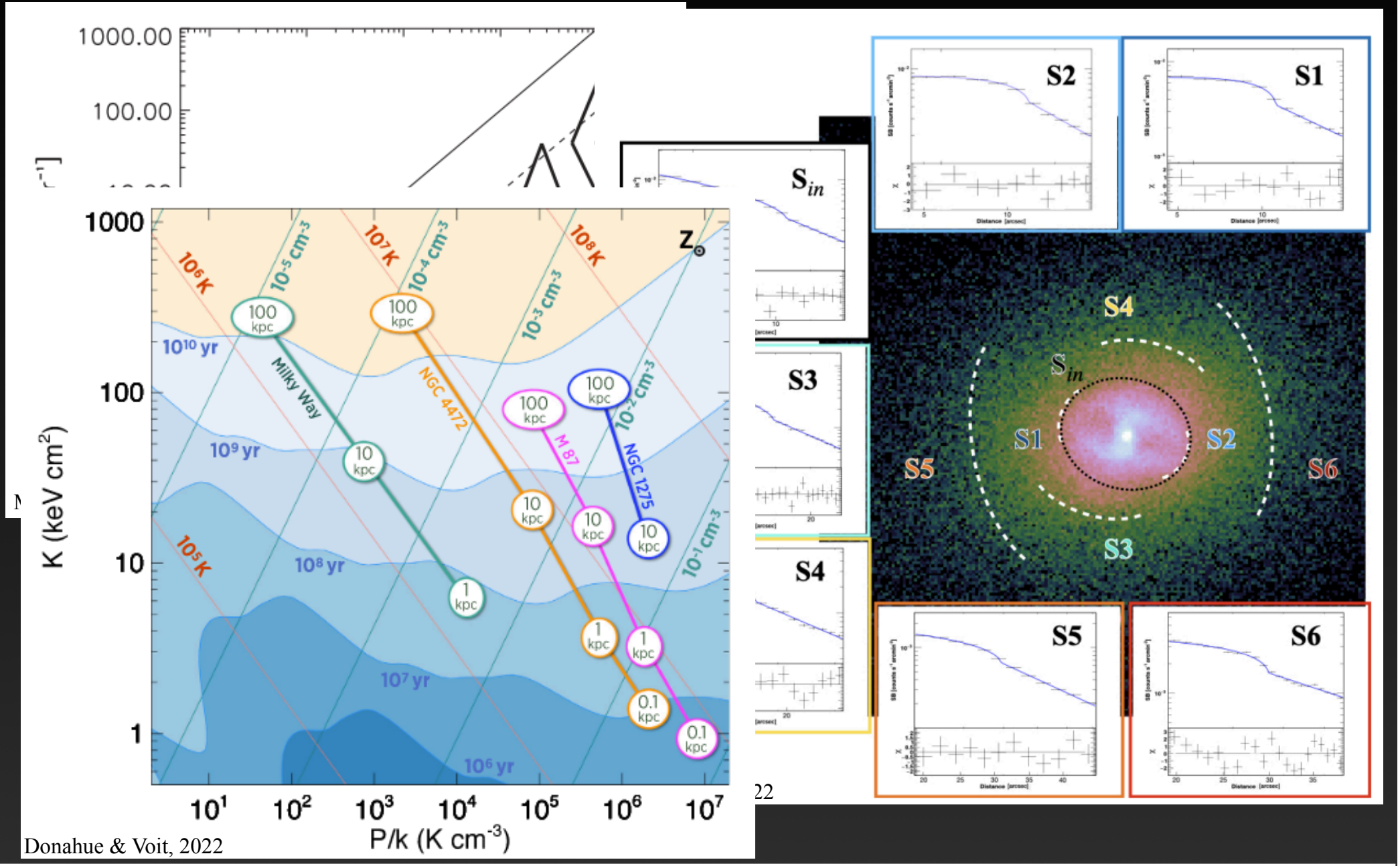
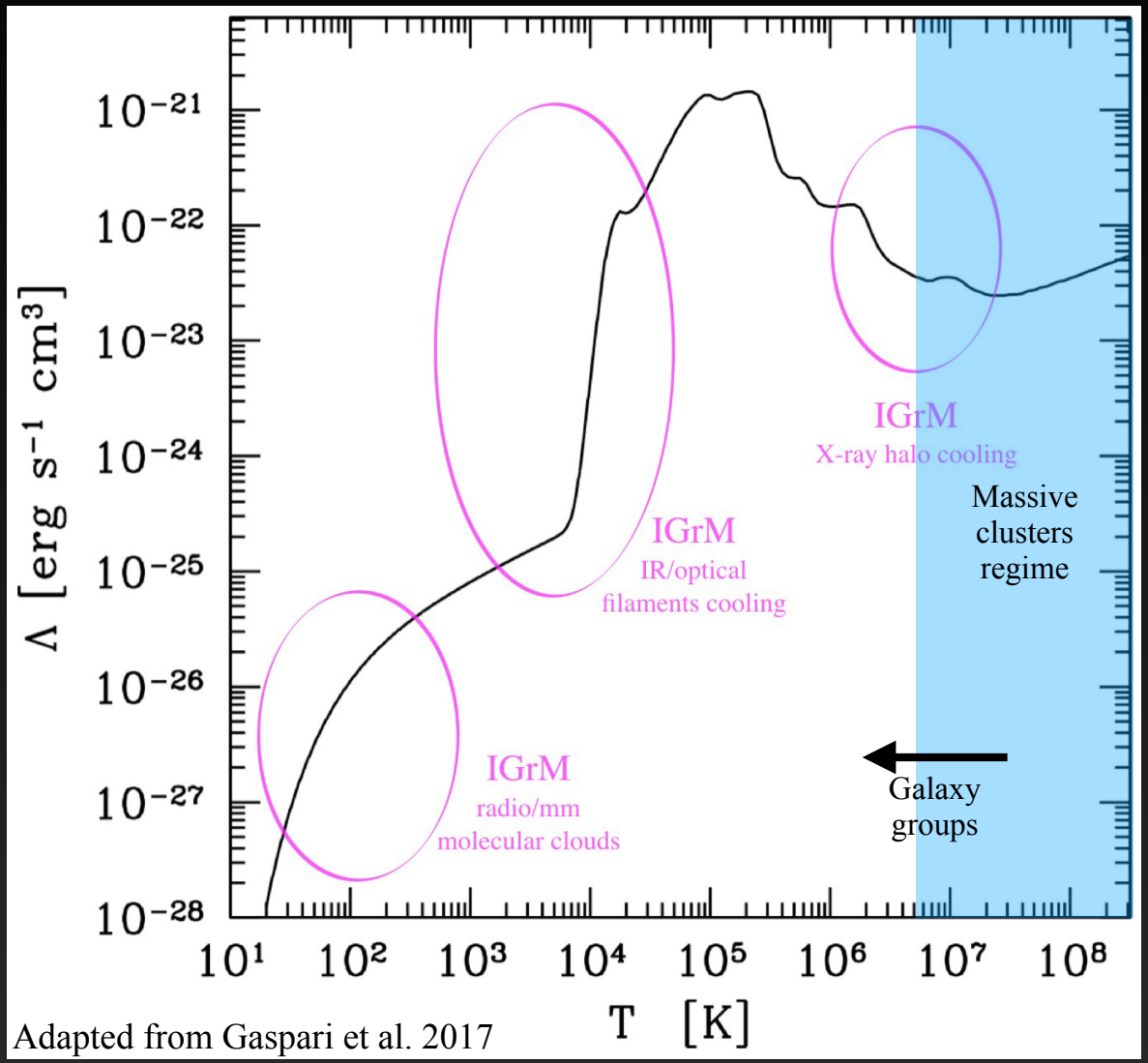


Donahue & Voit, 2022

What about galaxy groups?



Adapted from Gaspari et al. 2017

In galaxy groups, line emission significantly contributes to the cooling of the IGrM

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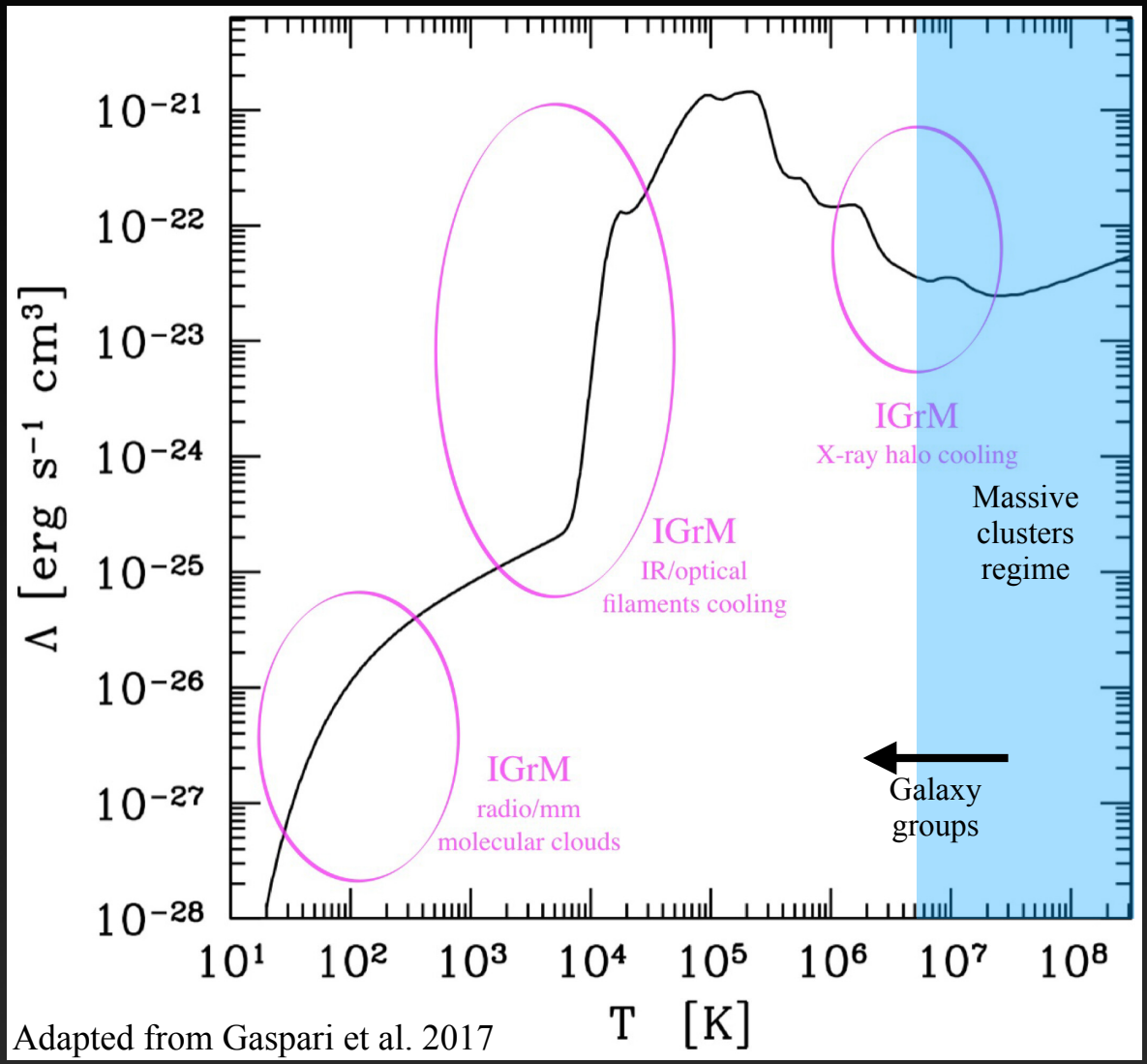

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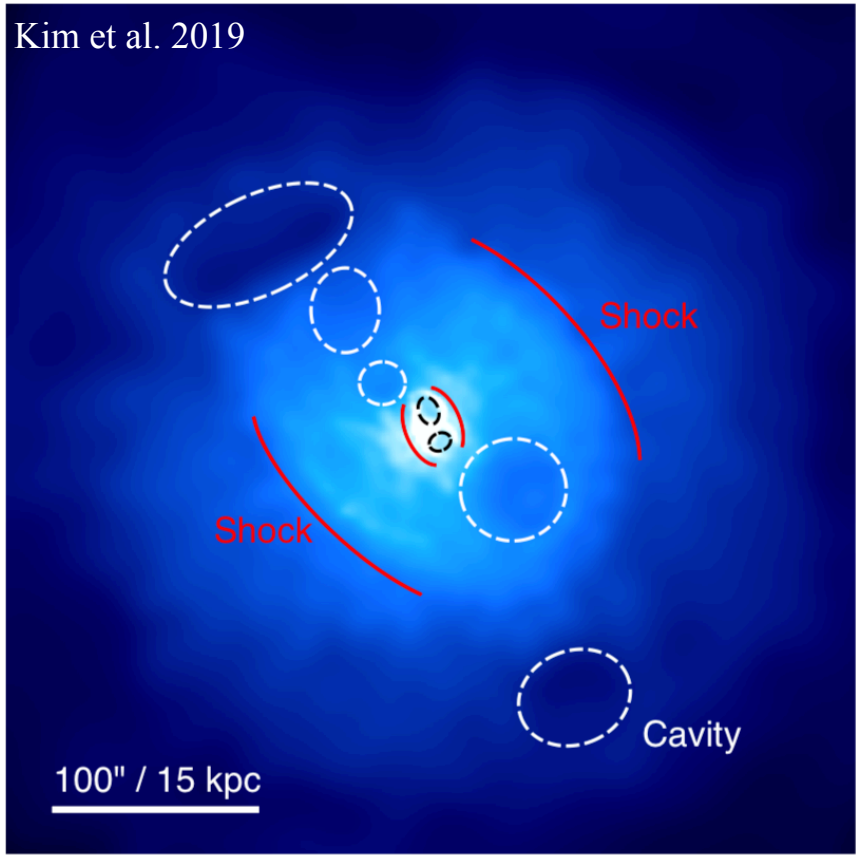

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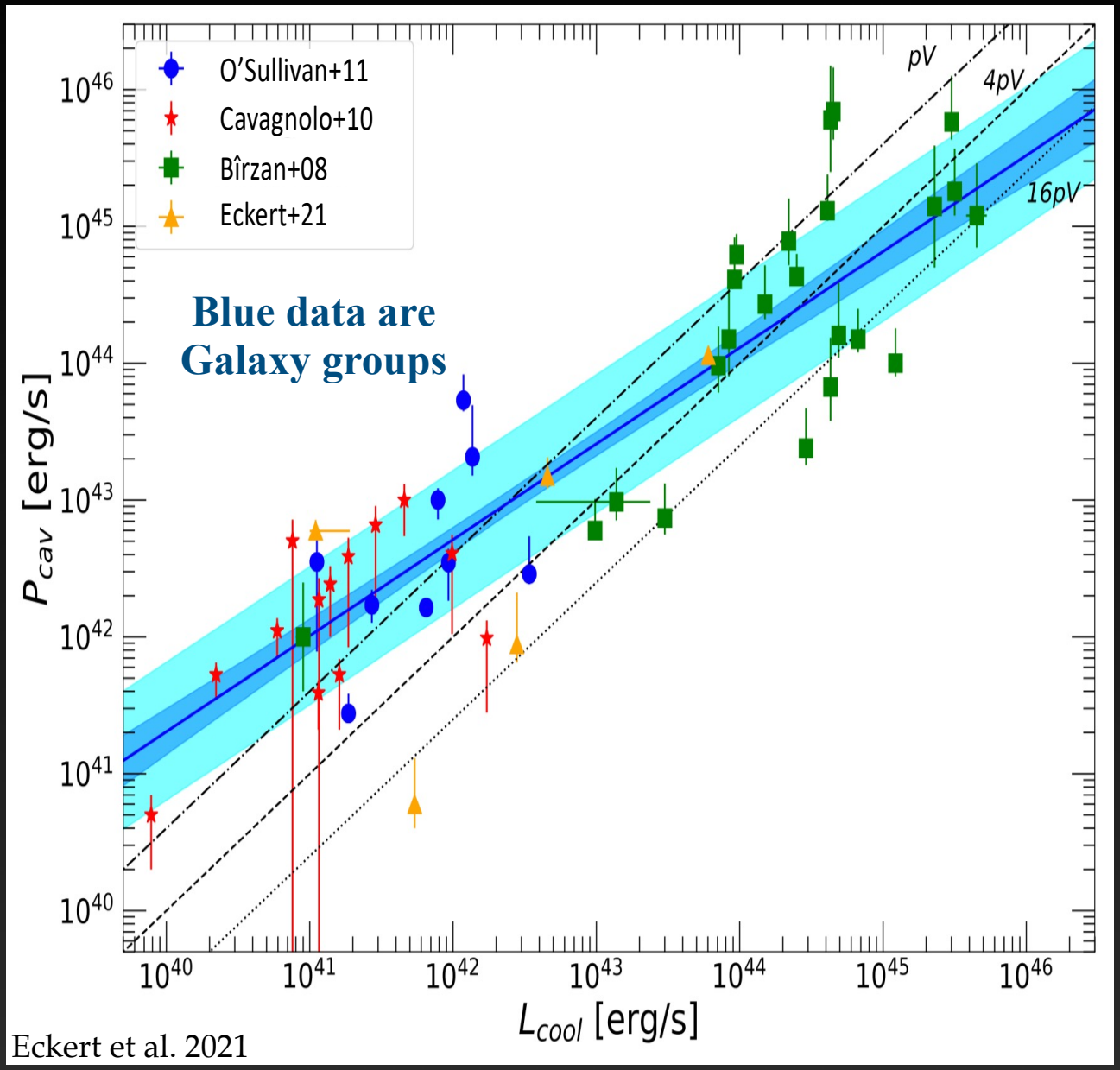

Eckert et al. 2021

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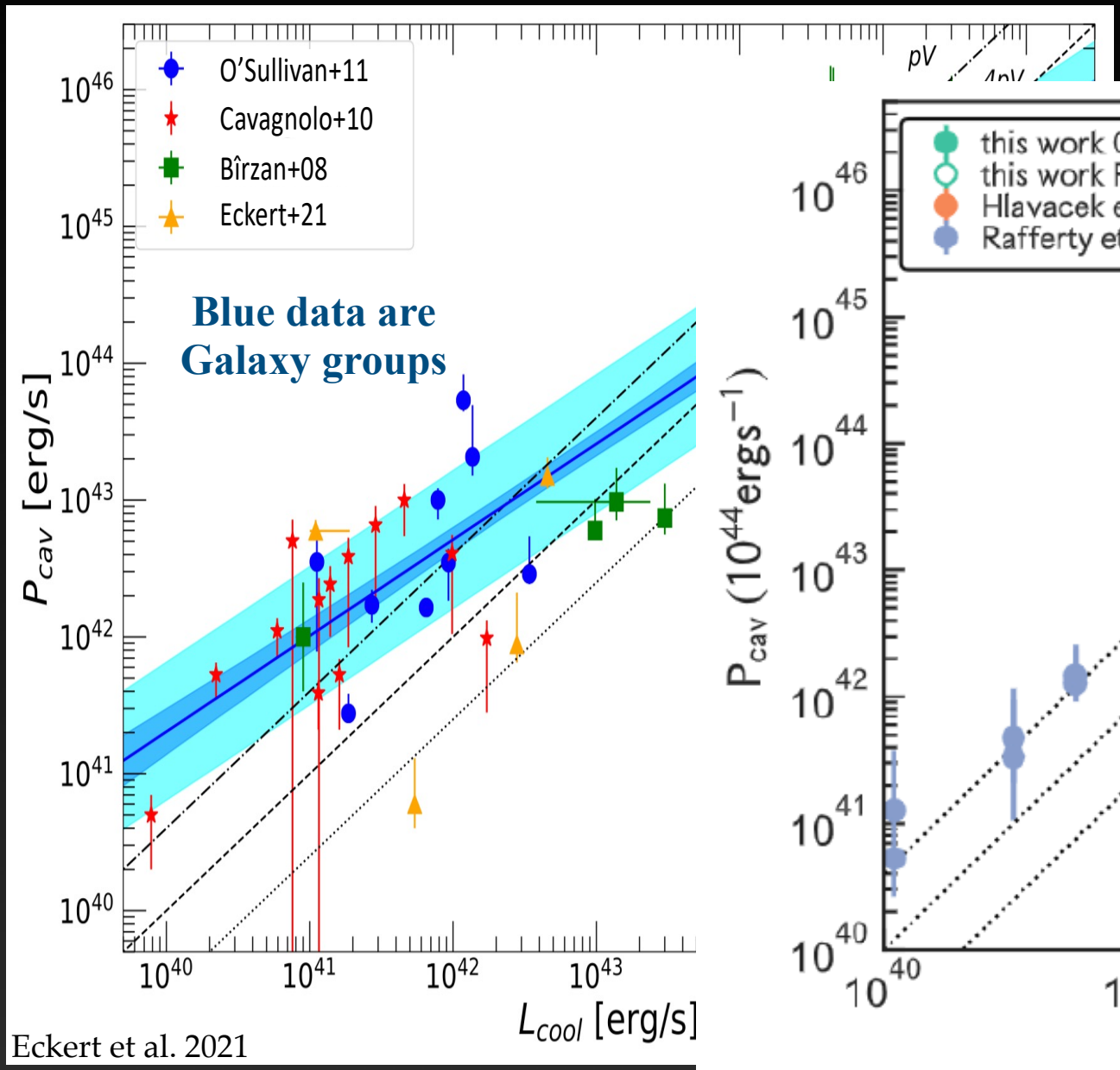

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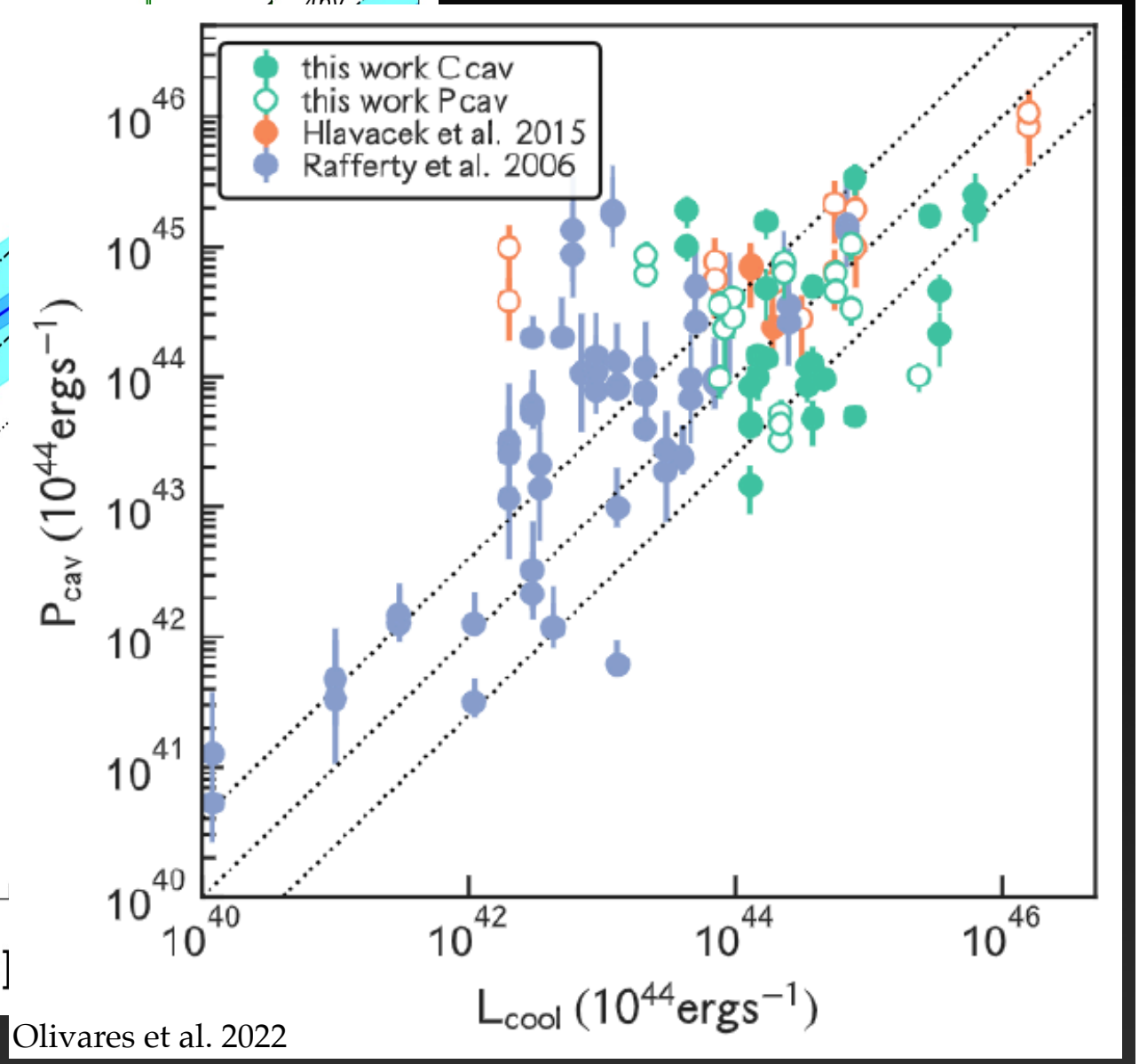

Olivares et al. 2022

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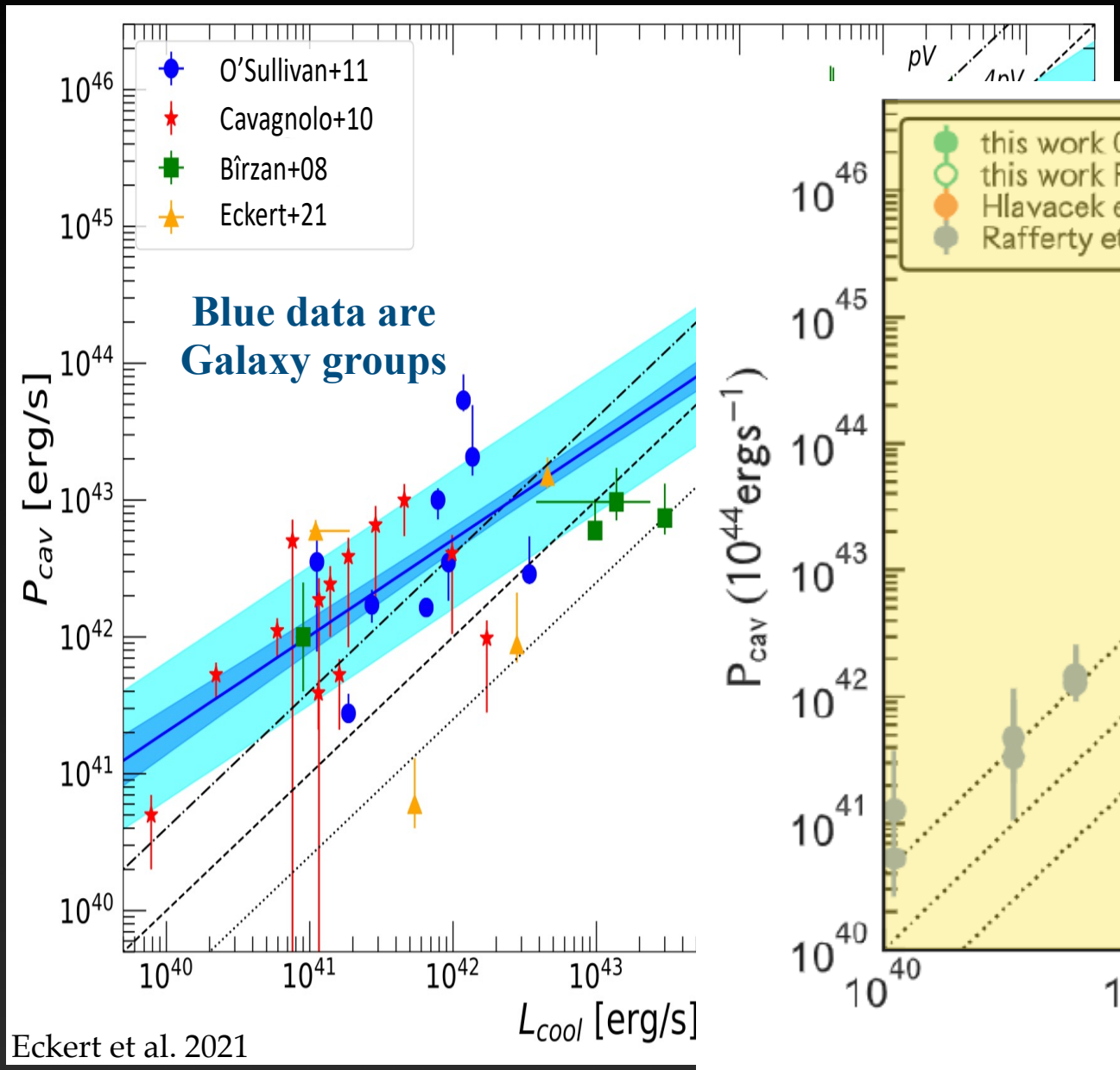

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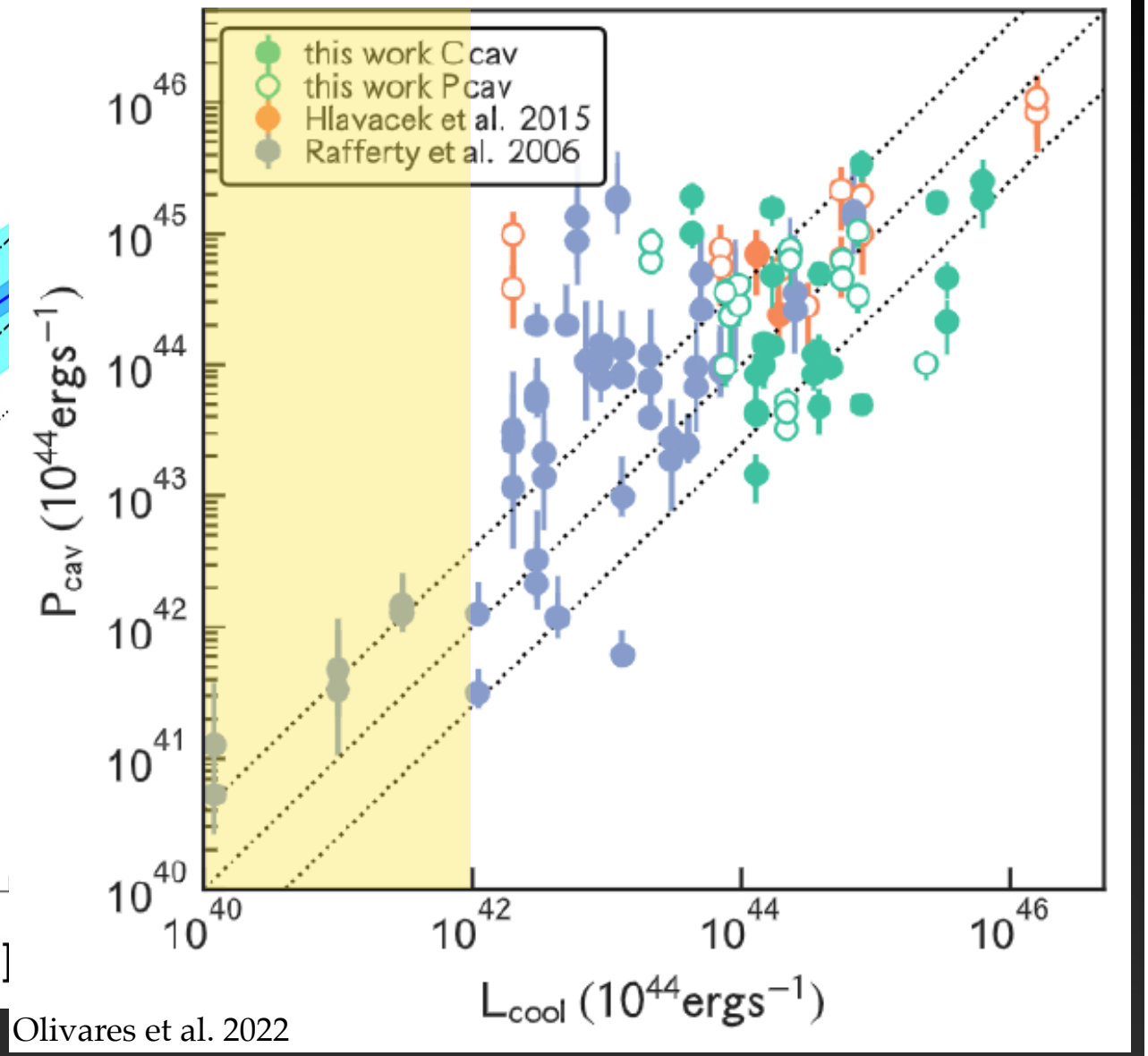

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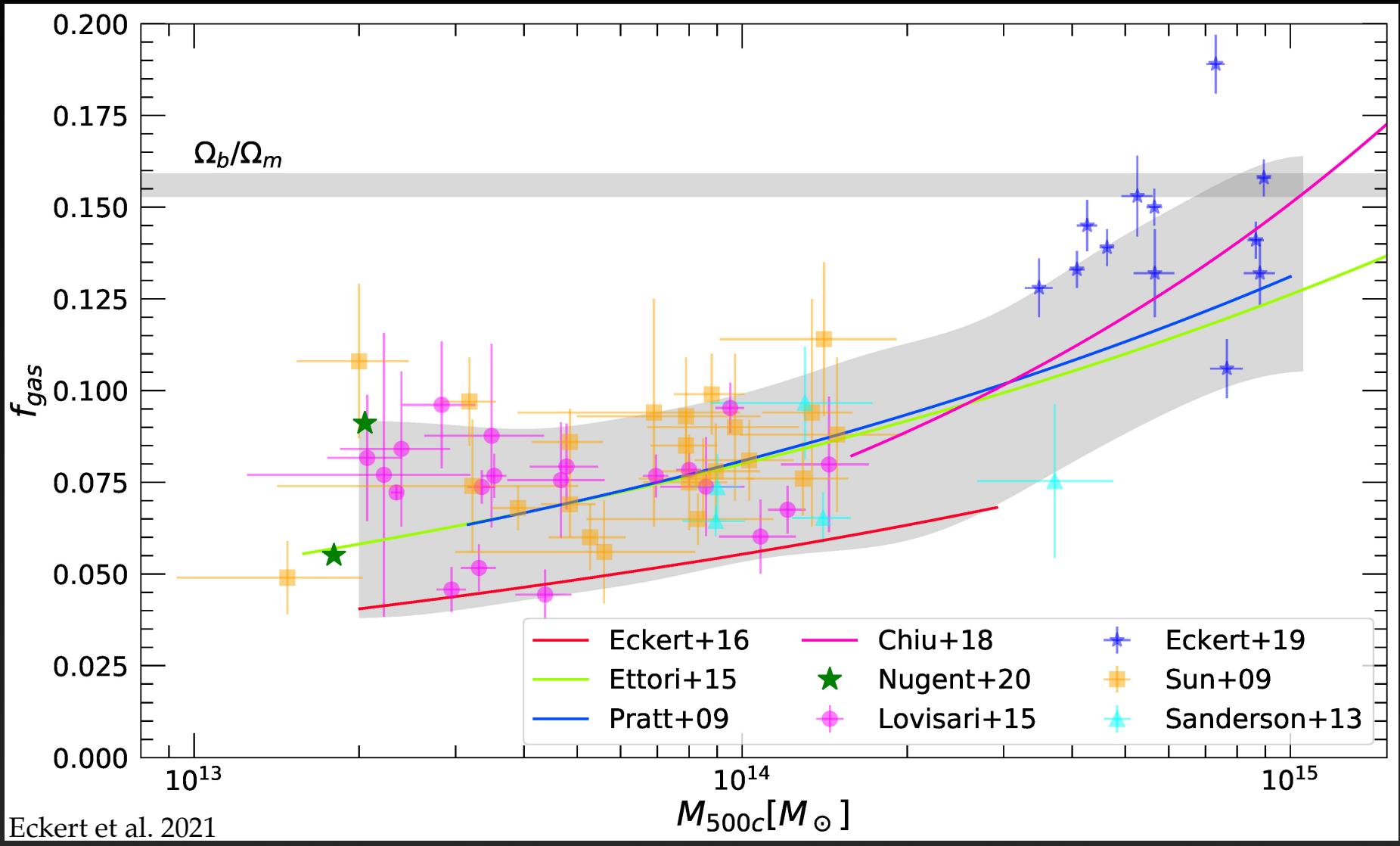

Eckert et al. 2021

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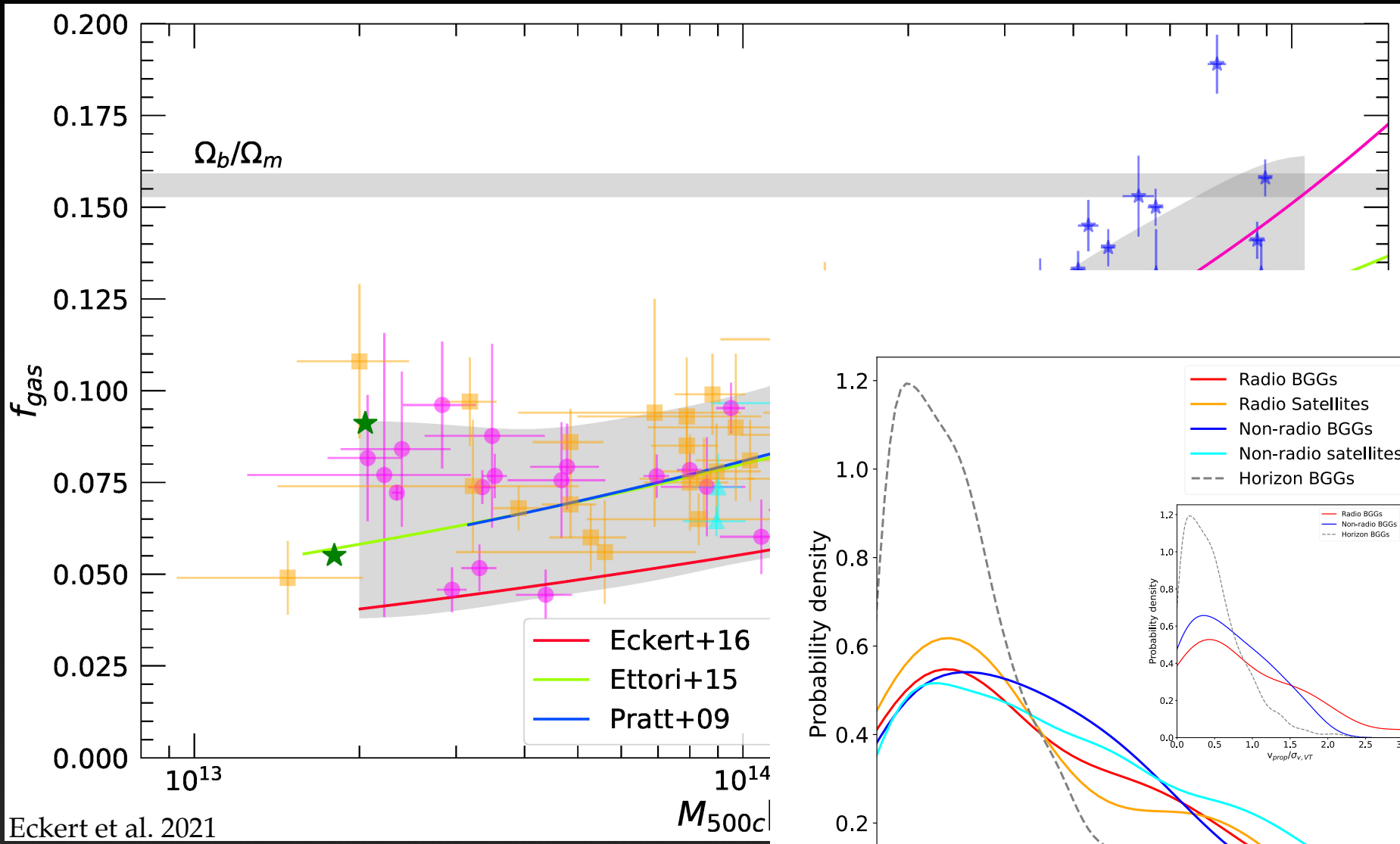
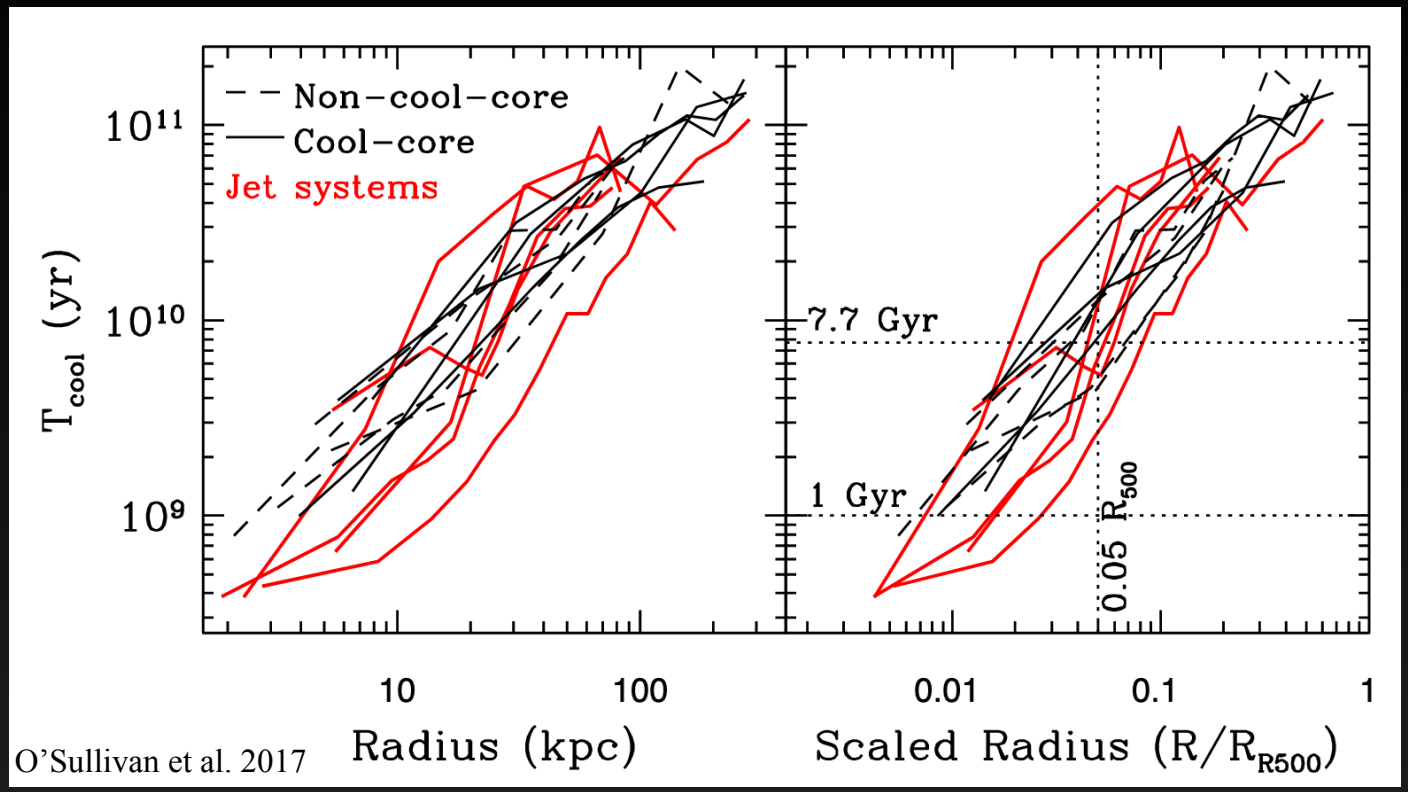


Eckert et al. 2021

Pasini et al. 2021b

AGN feedback in galaxy groups: recent advances



O'Sullivan et al. 2017

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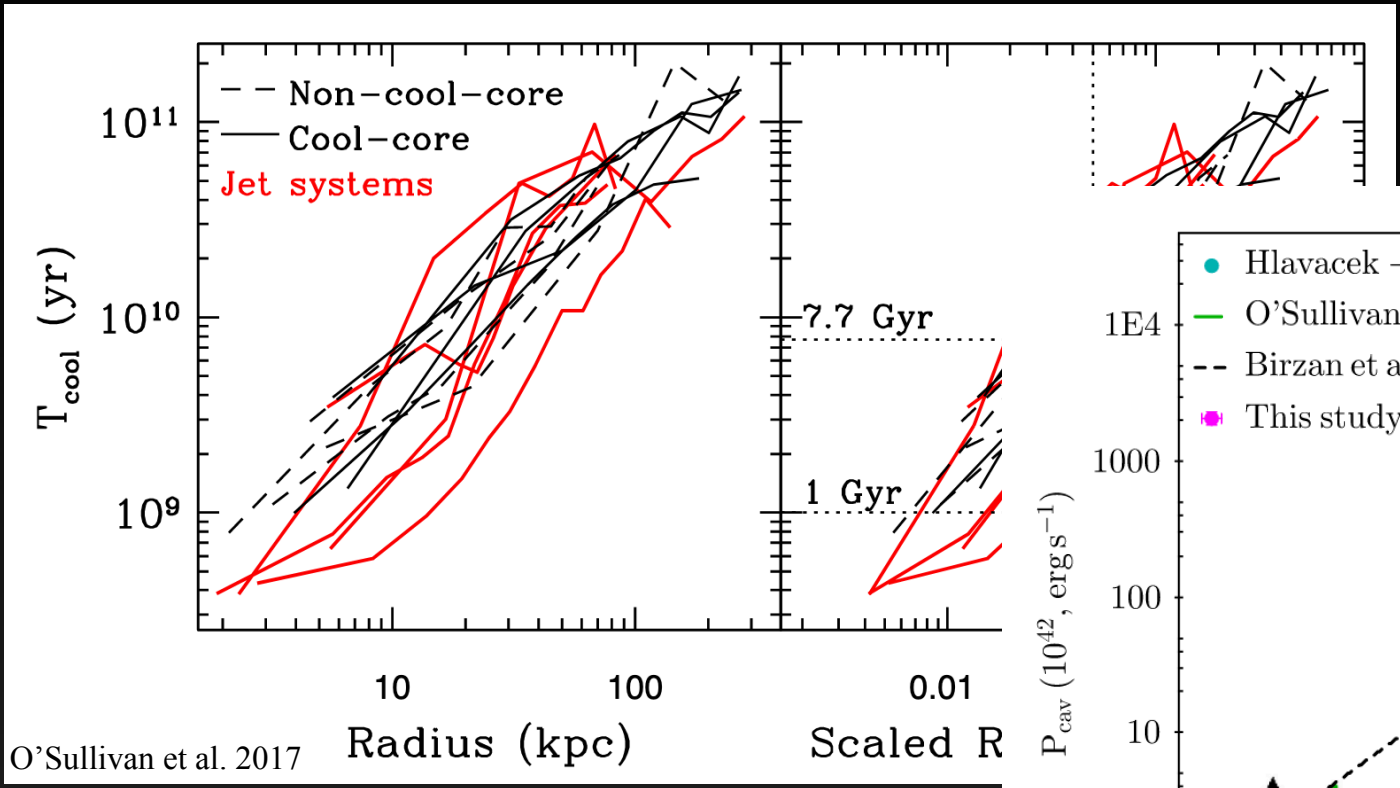

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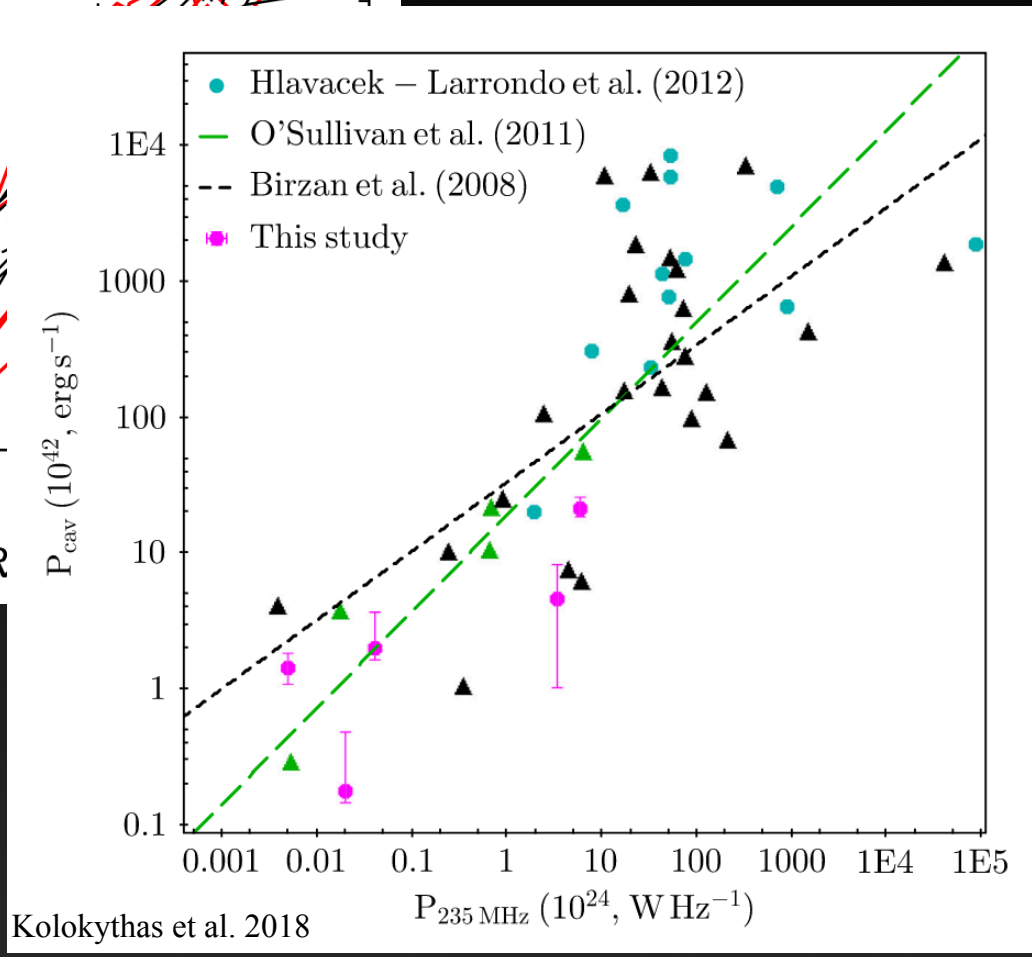
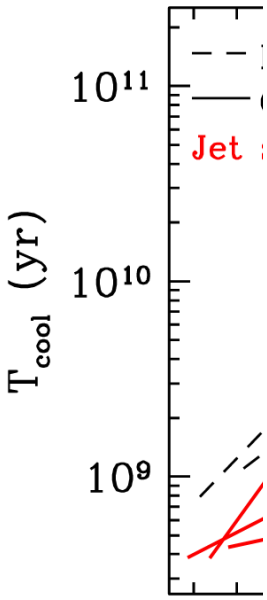
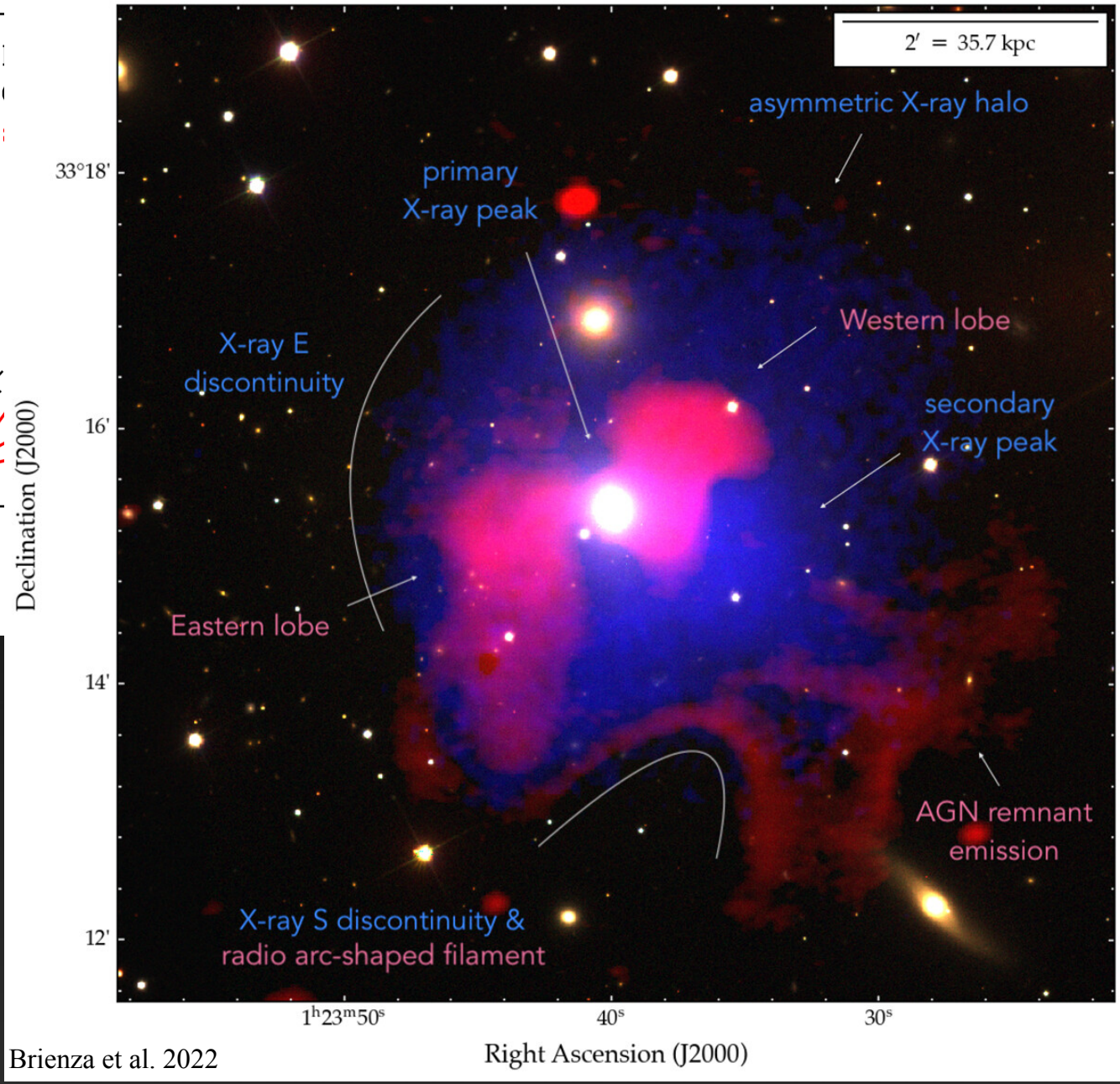


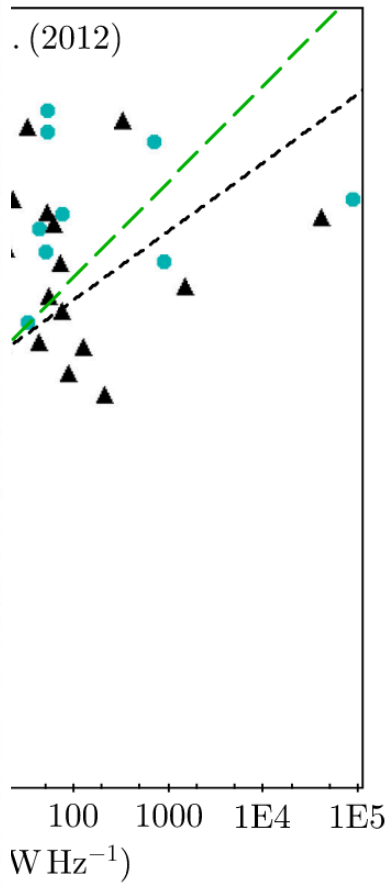
Kolokythas et al. 2018

AGN feedback in galaxy groups: recent advances

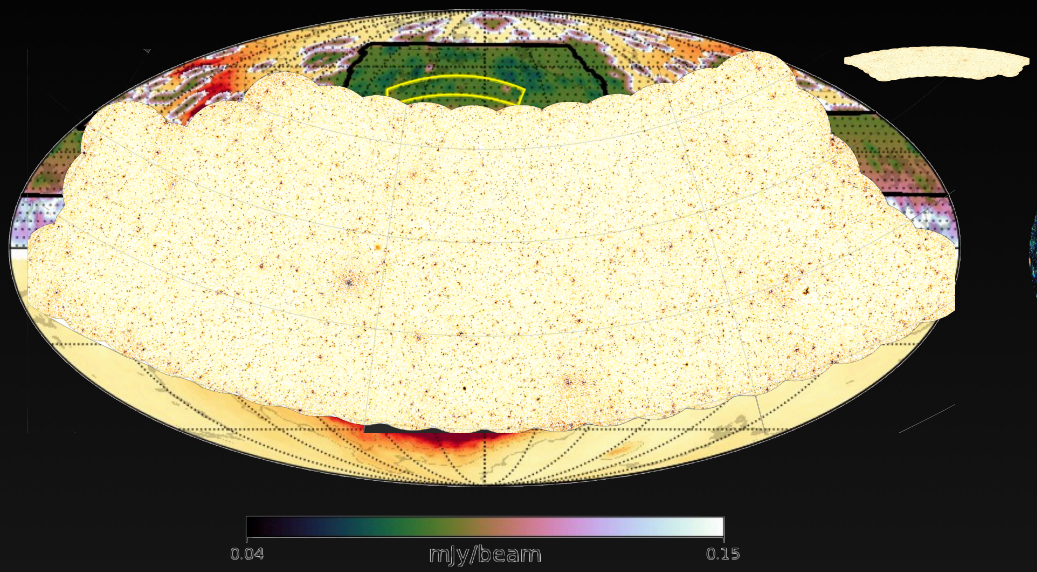




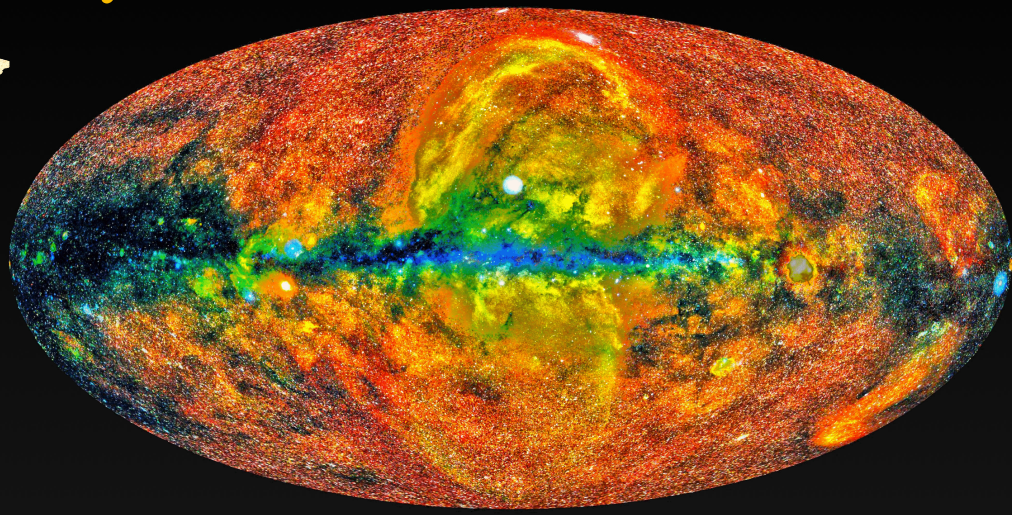
Brienza et al. 2022



The survey era



LoLSS, de Gasperin et al. 2021

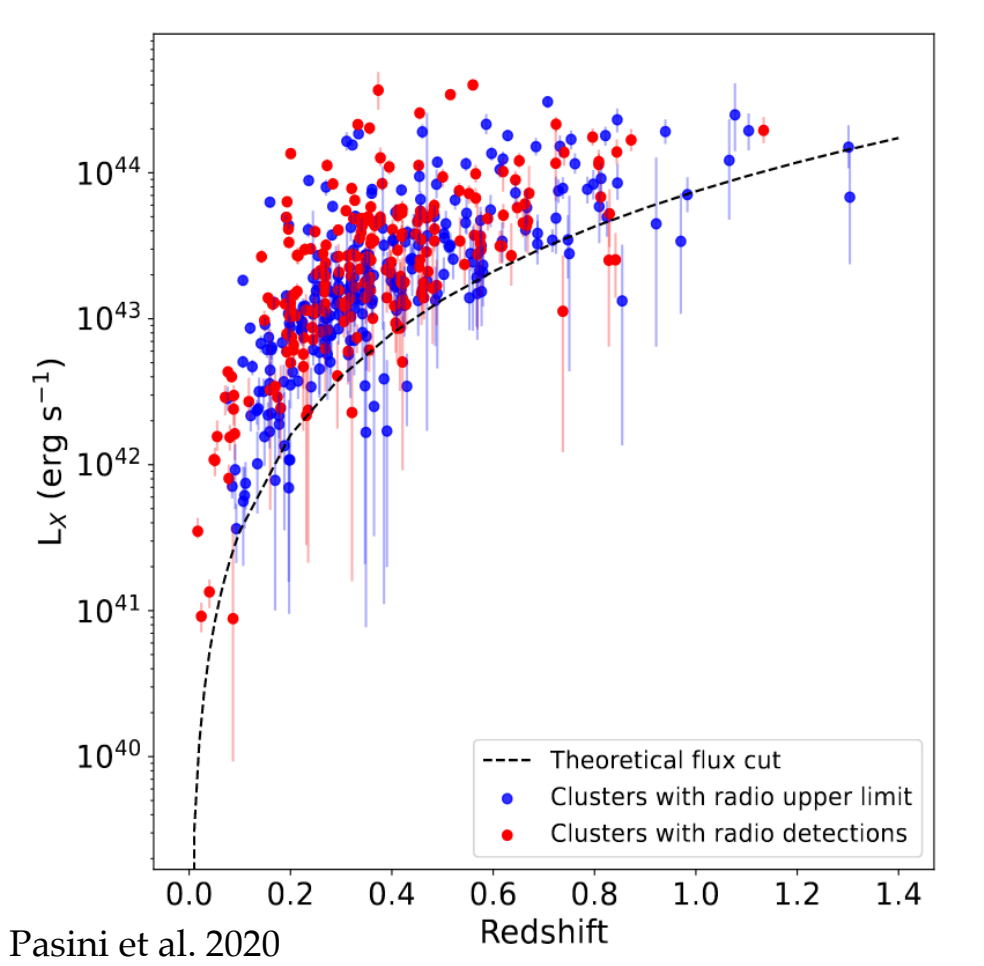


eRASS, image from press release, Sanders et al.

Samples of thousands of systems for which we can have available X-ray and radio observations

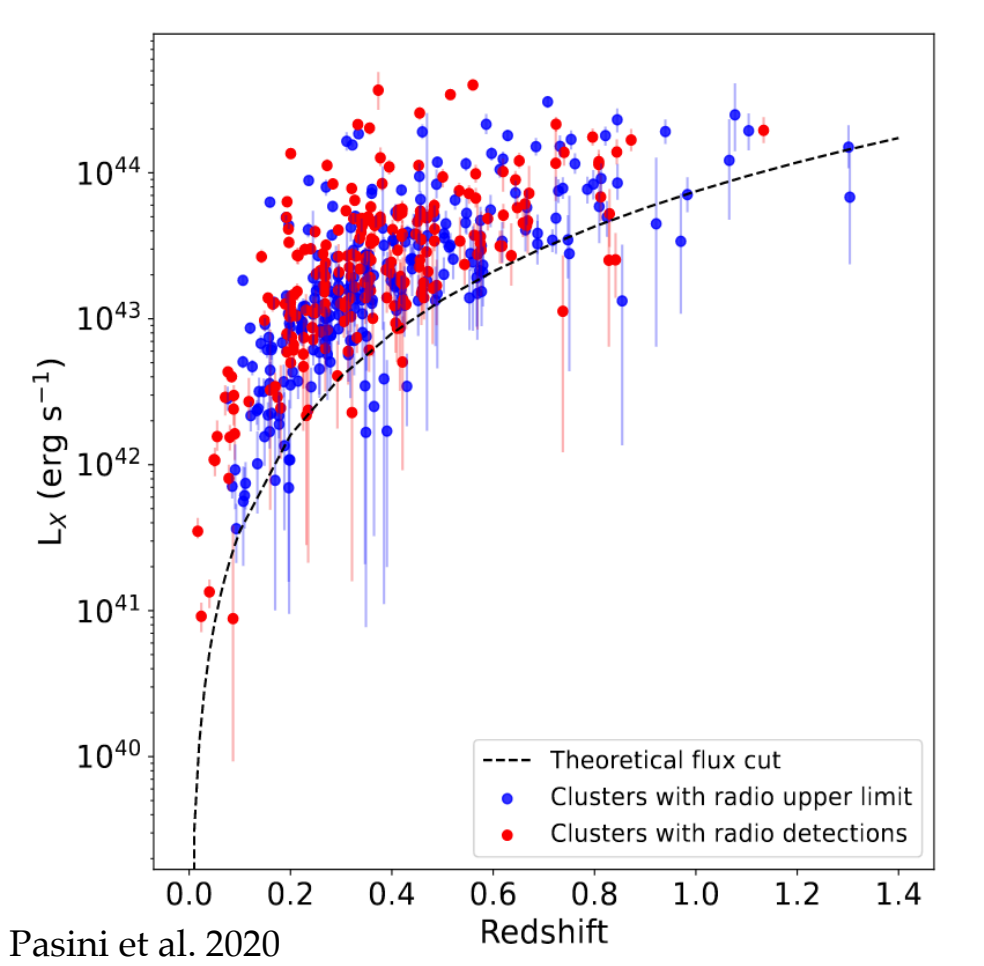
The combination of new-generation surveys and modern simulations is essential to address open questions

The power of surveys

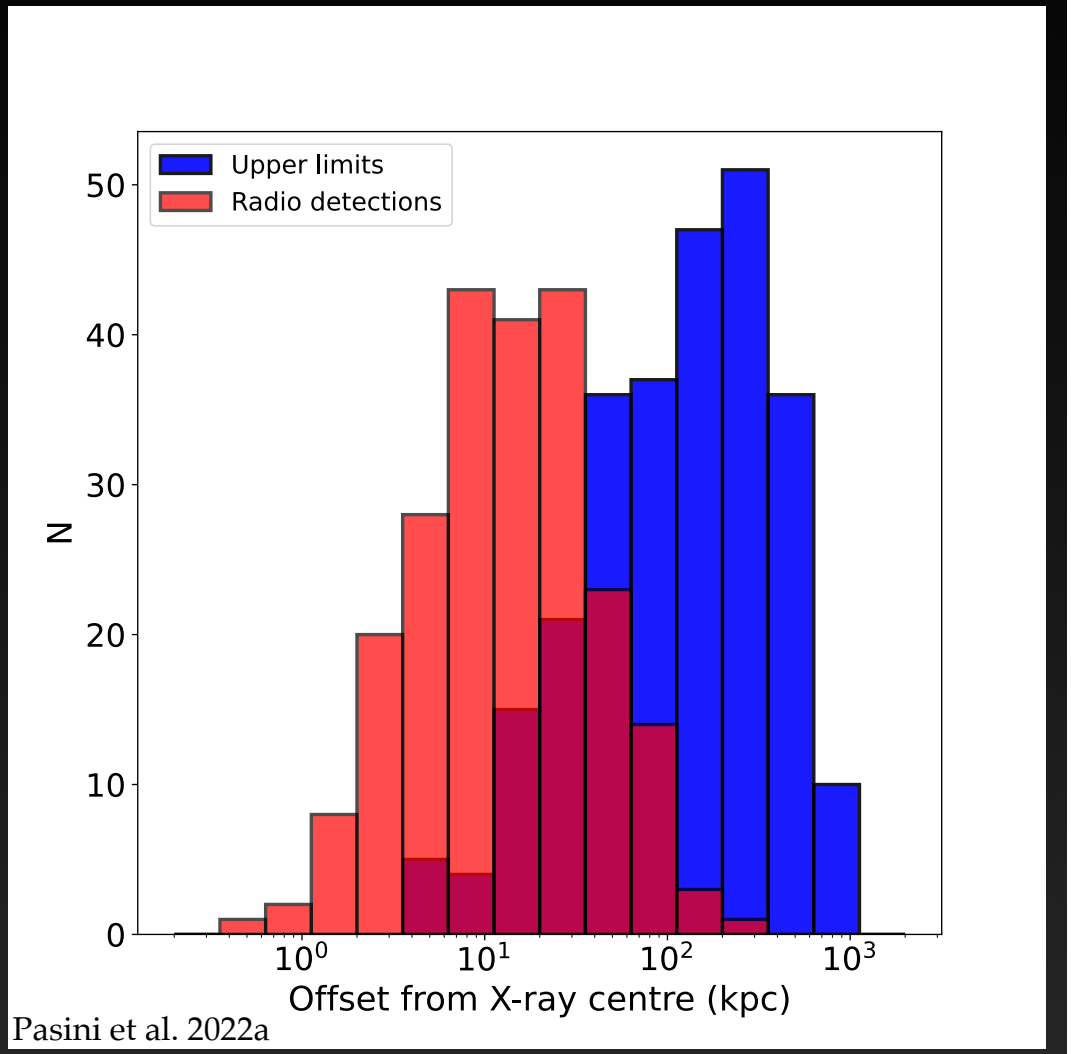


Pasini et al. 2020

The power of surveys

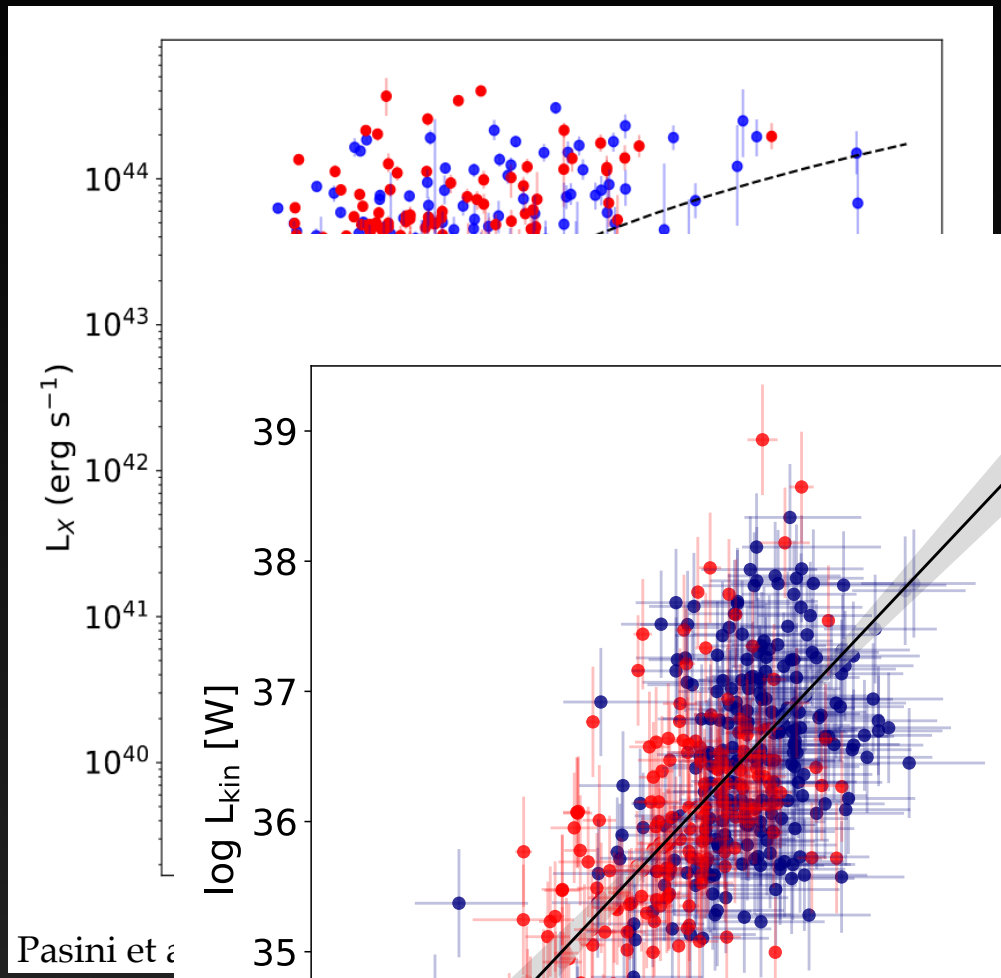


Pasini et al. 2020



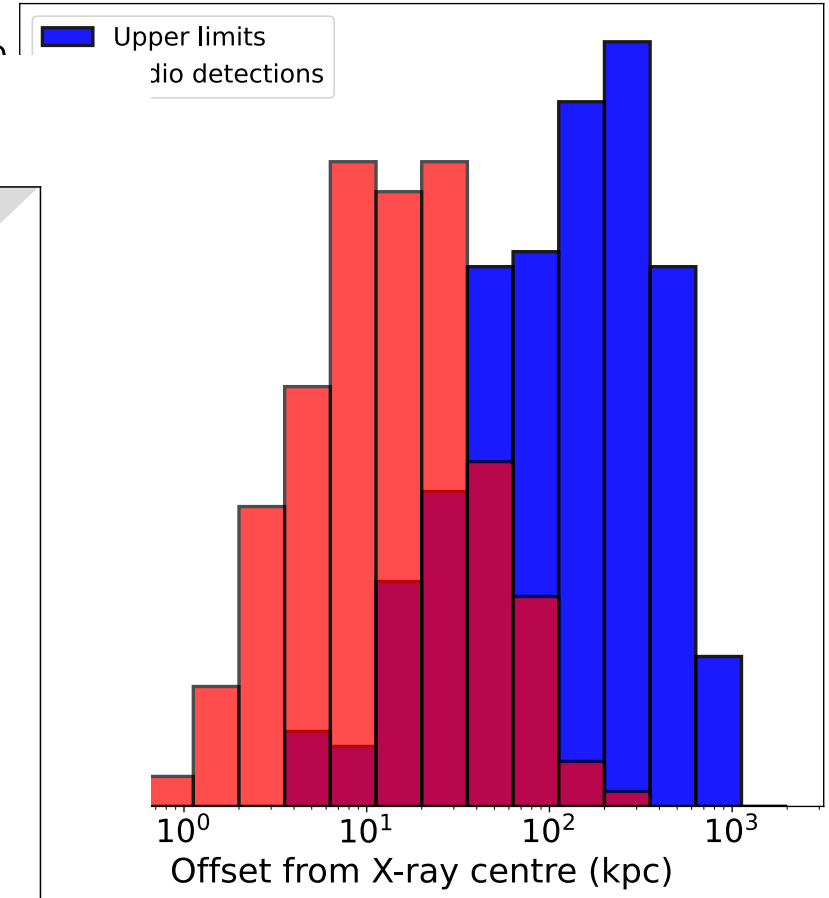
Pasini et al. 2022a

The power of surveys



Pasini et a

Pasini et al. 2022a



AGN feedback: what's next?

Galaxy clusters

- We understand the physical details of cooling and the macro properties of the feedback cycle;
- We are able to reproduce the observations (with limits..);

↓

- Physical details of how heating energy is deposited onto the ICM;
- Evolution of AGN feedback over Hubble time;
- Reduce fine-tuning in simulations;

Galaxy groups

- We observe similar (macro-)processes with respect to massive clusters;
- We understand the 'general' behaviour;

↓

- Detailed X-ray/radio studies of a significant (i.e. representative) number of systems;
- Comparison with clusters and implementation into HD simulations;

Conclusions and take-away messages

- AGN feedback is an essential process in our Universe;
- Multi-wavelength observations of galaxy clusters and groups give us unique information about the interplay between thermal and non-thermal emission;
- In the higher mass regime, we need to shift the focus on the strength/duration of the feedback cycle;
- In the lower mass regime, we need to ‘catch up’ what it’s been done for clusters, to understand similarities and differences;