

The role of **AGN feedback** in galaxy clusters for the last 10 billion years

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Featuring the work by:

C. Rhea (former MSc student, now PhD student)

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A. Richard-Laferrière (former MSc student, now Cambridge Gates scholar)

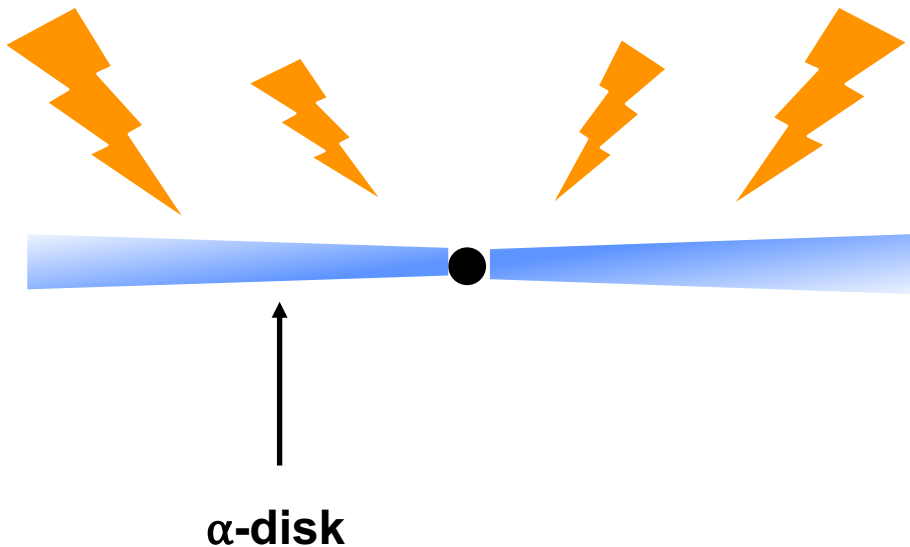
3C84/NGC1275 (Perseus cluster of galaxies). JHL/MLGM/MPL.

Conclusion:

**Black hole jets have a profound impact on galaxies
(based on **observations**)**

Black Hole Feedback

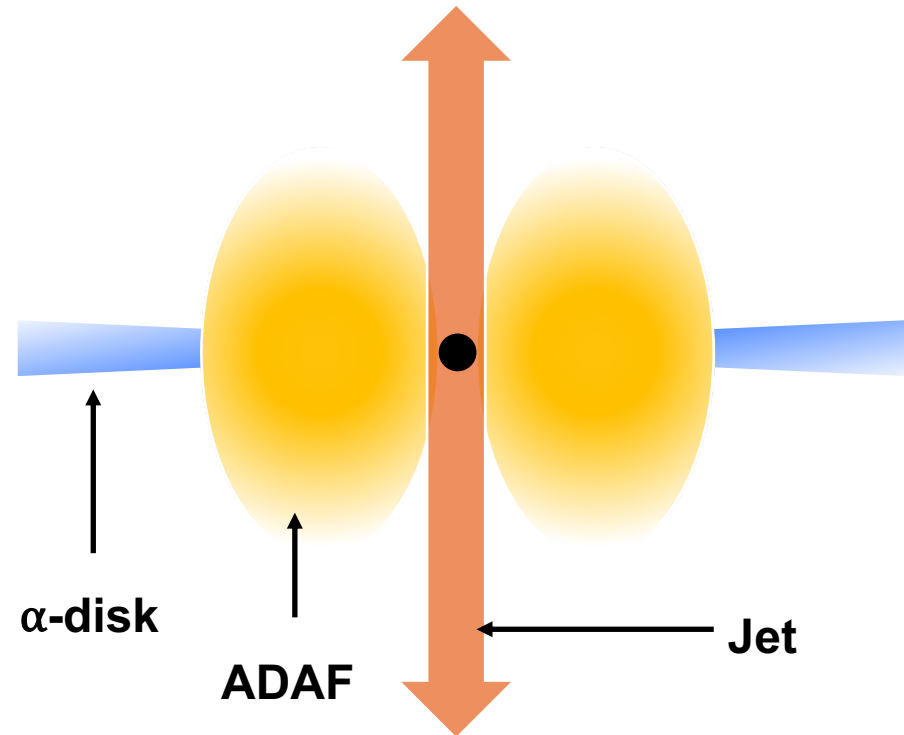
Quasar-mode



Radiatively-**efficient** ($M_{\text{BH}} \gg 1\% M_{\text{Edd}}$)

Radio-mode

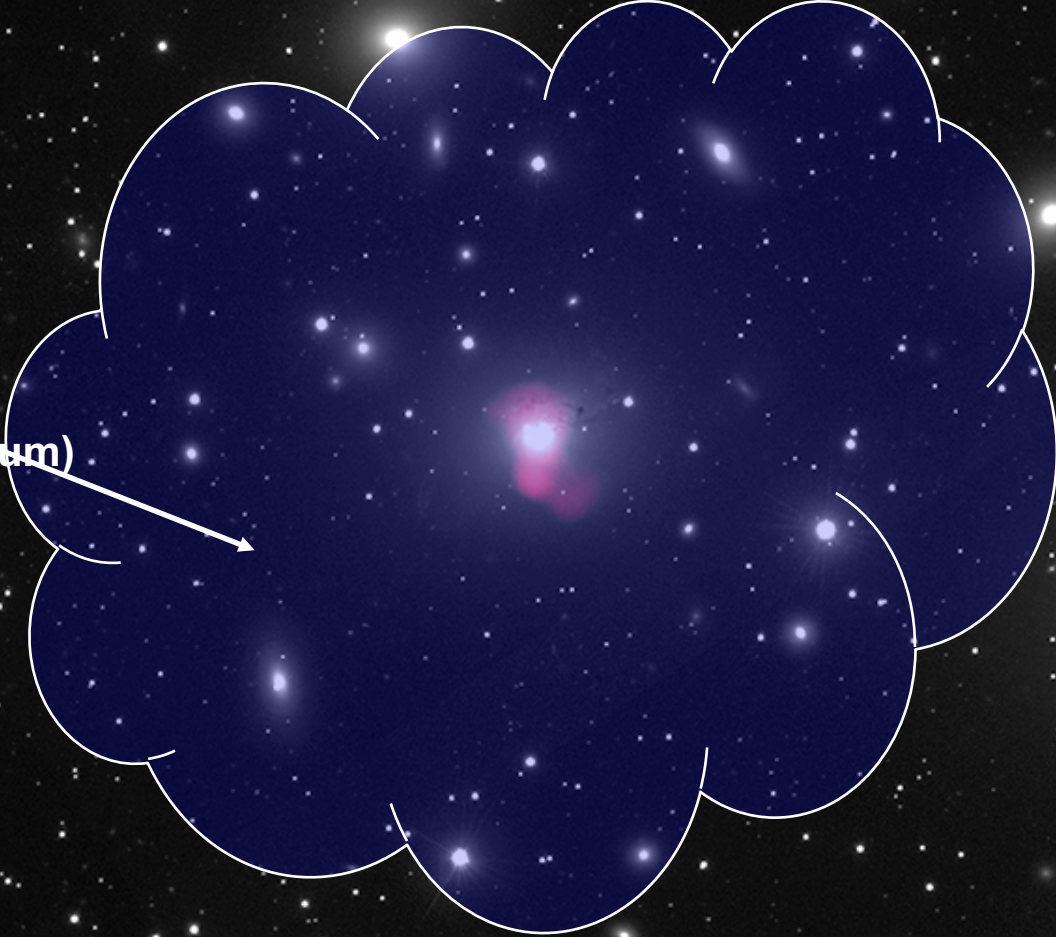
jet-mode/maintenance-mode/mechanical-mode/
kinetic-mode



Radiatively-**inefficient** ($M_{\text{BH}} \ll 1\% M_{\text{Edd}}$)

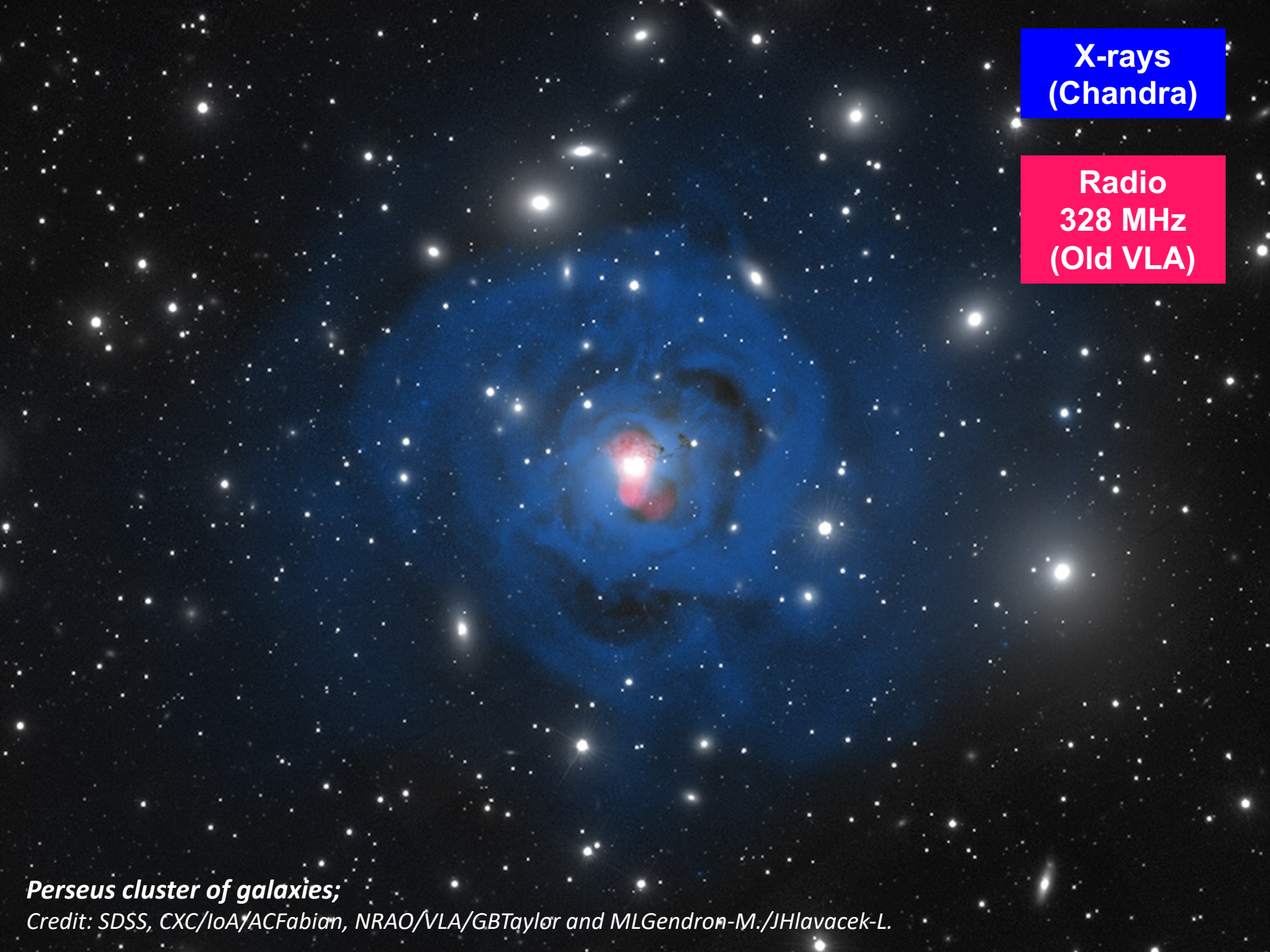
**Radio
328 MHz
(Old VLA)**

**Hot X-ray halo
(intracluster medium)**



Perseus cluster of galaxies ($z = 0.018$)

Credit: VLA, Taylor/Blundell; SDSS, CXC/loA/ACFabian.

A deep-field astronomical image of the Perseus cluster of galaxies. The background is a dense field of stars. In the center, there is a bright, glowing blue and white region, which is the intracluster medium (ICM) as seen in X-ray and radio wavelengths. The blue color represents the X-ray emission from the hot gas, and the white color represents the radio emission from the synchrotron radiation produced by relativistic electrons in the same gas. The central region is surrounded by a diffuse, blue, cloud-like structure. The overall image is a composite of different wavelengths, showing the complex structure of the galaxy cluster.

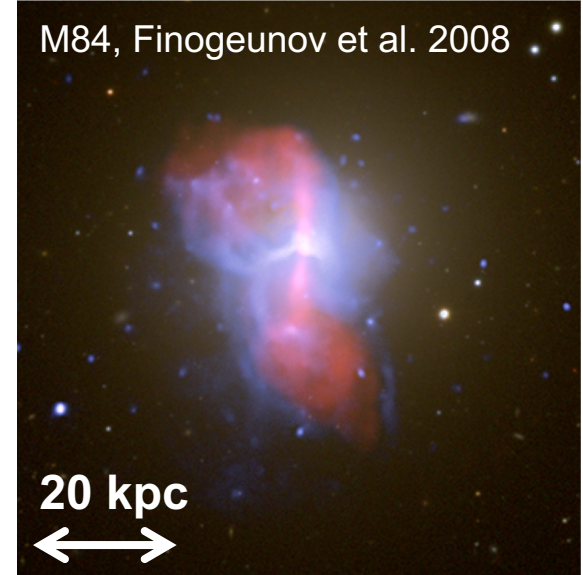
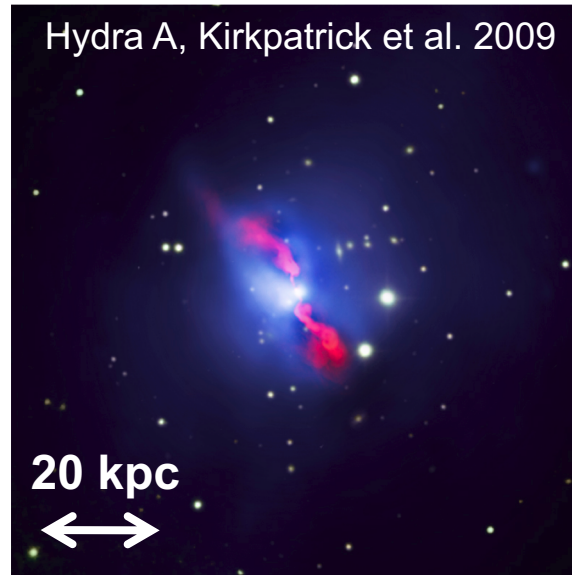
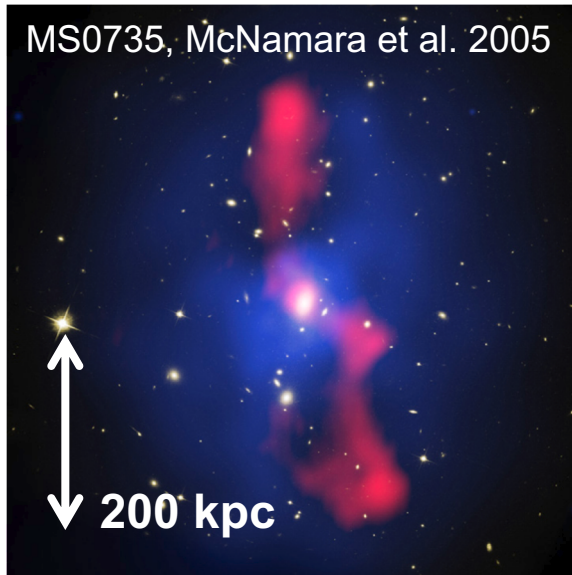
**X-rays
(Chandra)**

**Radio
328 MHz
(Old VLA)**

Perseus cluster of galaxies;

Credit: SDSS, CXC/loA/ACFabian, NRAO/VLA/GBTaylor and MLGendron-M./JHlavacek-L.

What do black hole jets do to galaxies?



→ Jet-mode AGN feedback is a **fundamental** process in massive galaxies.

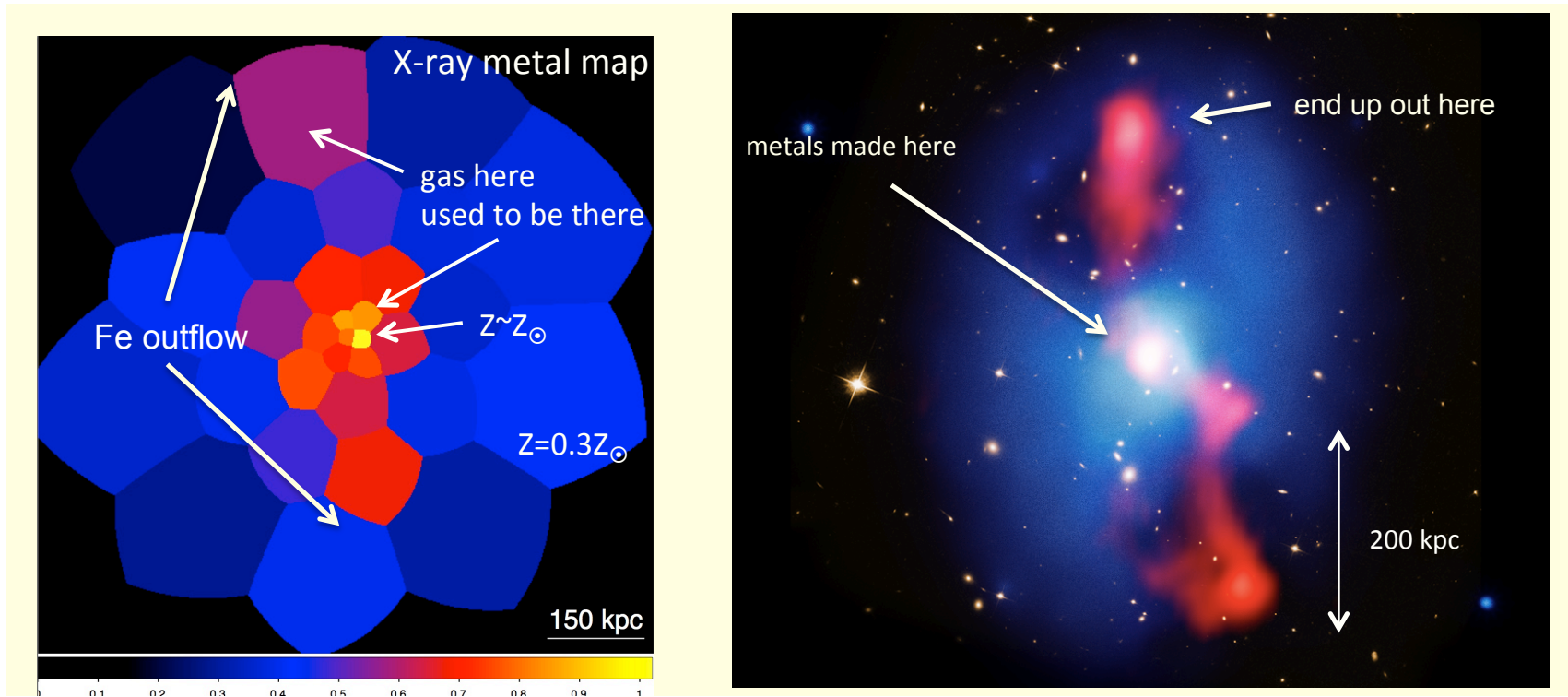
→ Jets are powerful:

$E_{\text{cavity}} = 10^{60}$ ergs; $P_{\text{cavity}} = 10^{44-45}$ erg/s; $t_{\text{buoyancy}} = 10^{7-8}$ yrs; Size ≈ 25 [10-200] kpc

→ Quenching: without jets, the hot halos around massive galaxies would cool and form powerful starbursts (suppress by orders of magnitude).

Birzan et al. 2004, Rafferty et al. 2006, Dunn & Fabian 2006, 2008, Dunn et al. 2010, Birzan et al. 2008, Cavagnolo et al. 2010, Dong et al. 2010, Hlavacek-L. et al. 2012, Hlavacek-L. et al. 2013, Hlavacek-L. et al. 2015, Panagoulia et al. etc.

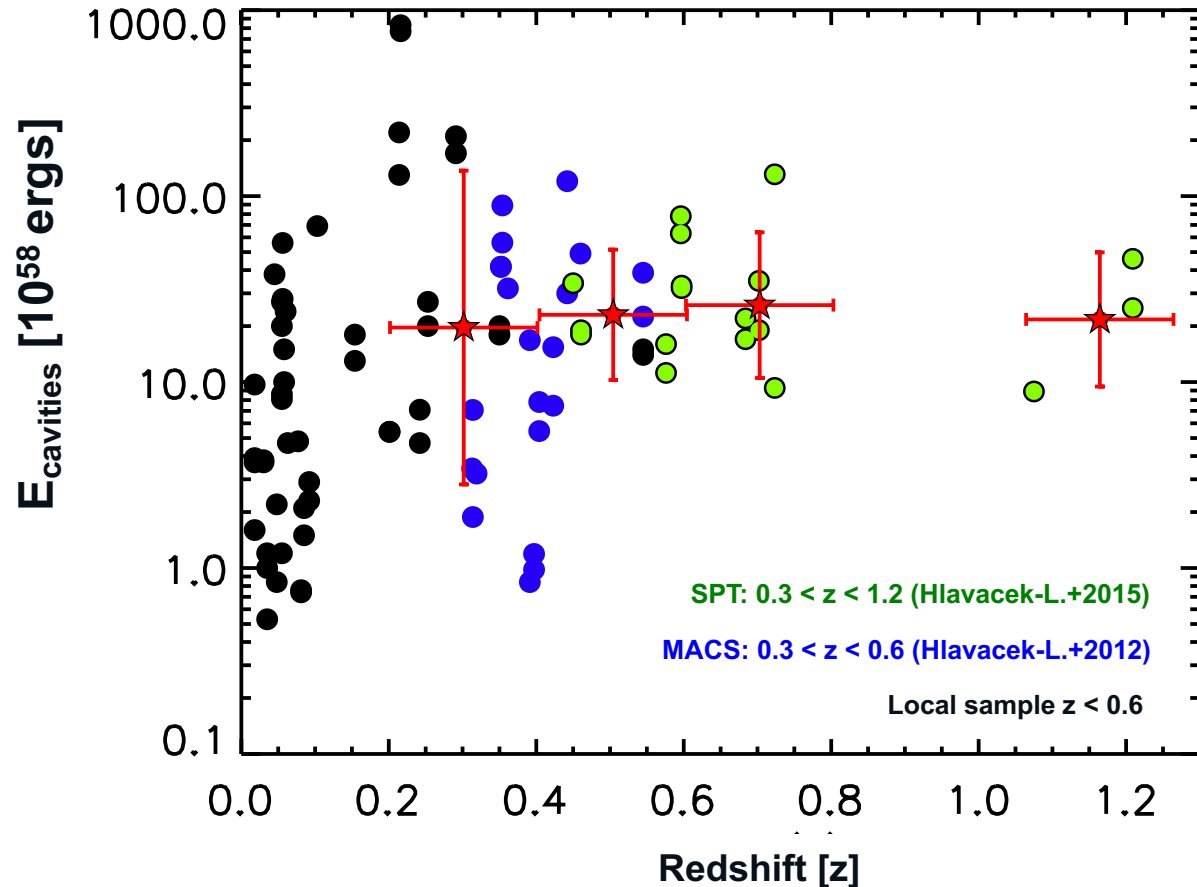
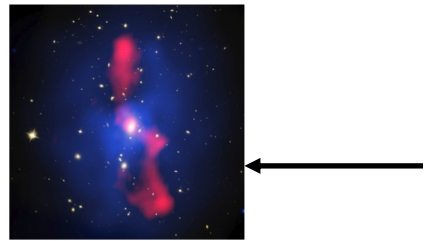
What do black hole jets do to galaxies?



- Jets drive metals out of galaxies (ex. hundreds of kpc).
- ALMA: Jets drive molecular gas outflows of 200-400 km/s (10^9 - 10^{10} M_⊙) on galaxy scales (similar to quasar driven winds).

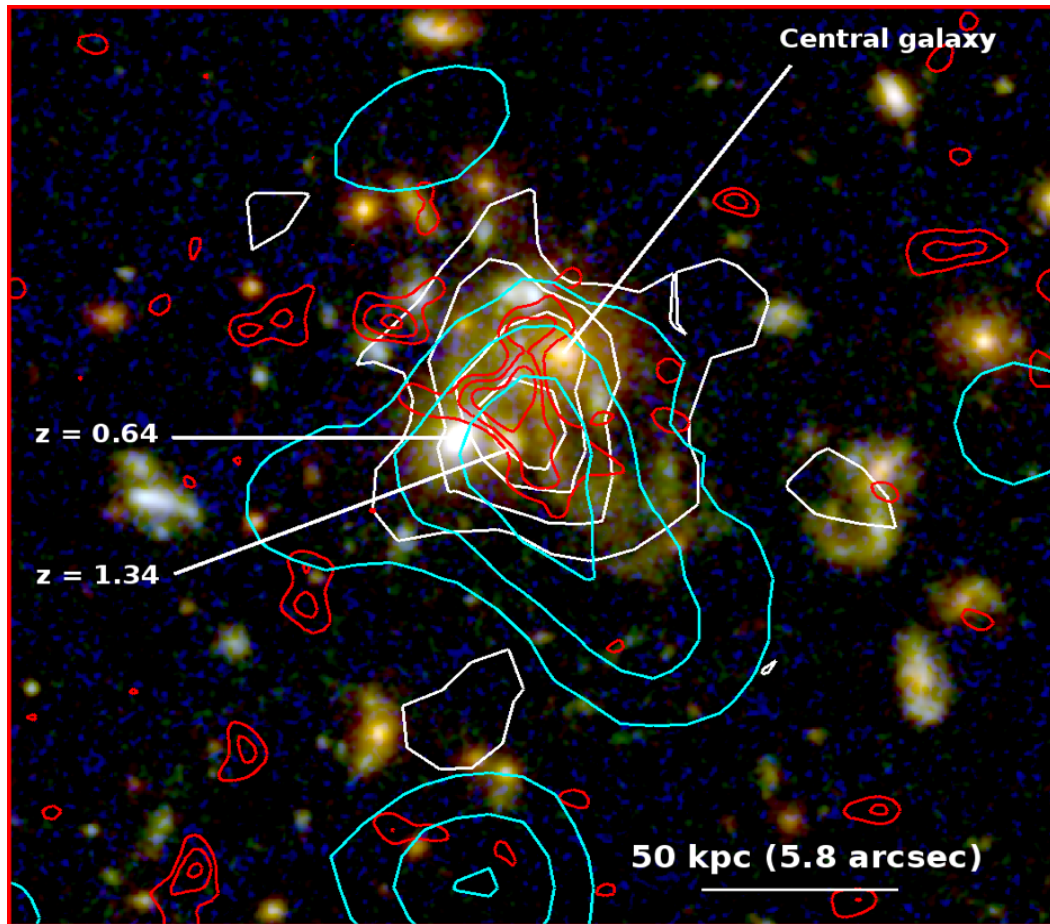
Kirkpatrick et al. 2009, 2011; McNamara et al. 2009, 2012; Hlavacek-Larrondo et al. 2011., as well as the work by McNamara, Russell, Tremblay and collaborators.

When is jet-mode AGN feedback important?



→ AGN feedback has been operating in clusters of galaxies for > 8 Gyrs, i.e. over half of the age of the Universe.

When is jet-mode AGN feedback important?



Starburst of $900 M_{\odot}/\text{yr}$ (!)

→ **WHITE**: Spitzer MIPS contours

→ **RED**: cold molecular gas (VLA CO 1-0)

→ **BLUE**: COOL X-RAY GAS



C. Rhea (PhD student)

→ Massive cluster of galaxies at $z = 1.7$ (universe 4 billion years old).

→ Cooling of hot X-ray halo is forming a starburst – feedback has failed!

Black hole jets impact strongly the **thermal gas/baryons in and around massive galaxies for the last 10 billion years.**

What else?

**X-rays
(Chandra)**

**Radio
328 MHz
(Old VLA)**

Jets from the central black hole

MINI-HALO (radio particles/Cosmic rays)

Perseus cluster of galaxies;

Credit: SDSS, CXC/IoA/ACFabian, NRAO/VLA/GBTaylor and MLGendron-M./JHlavacek-L.

**NEW JVLA Observations
270-430 MHz**

Radio filaments

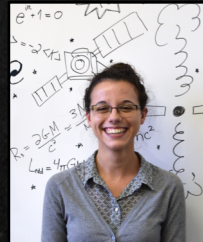
Loop

MINI-HALO (radio particles/Cosmic rays)

Edge

Edge

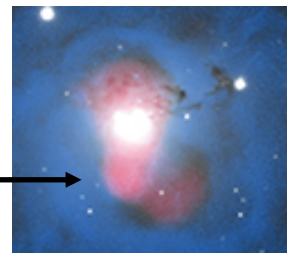
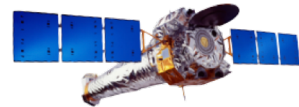
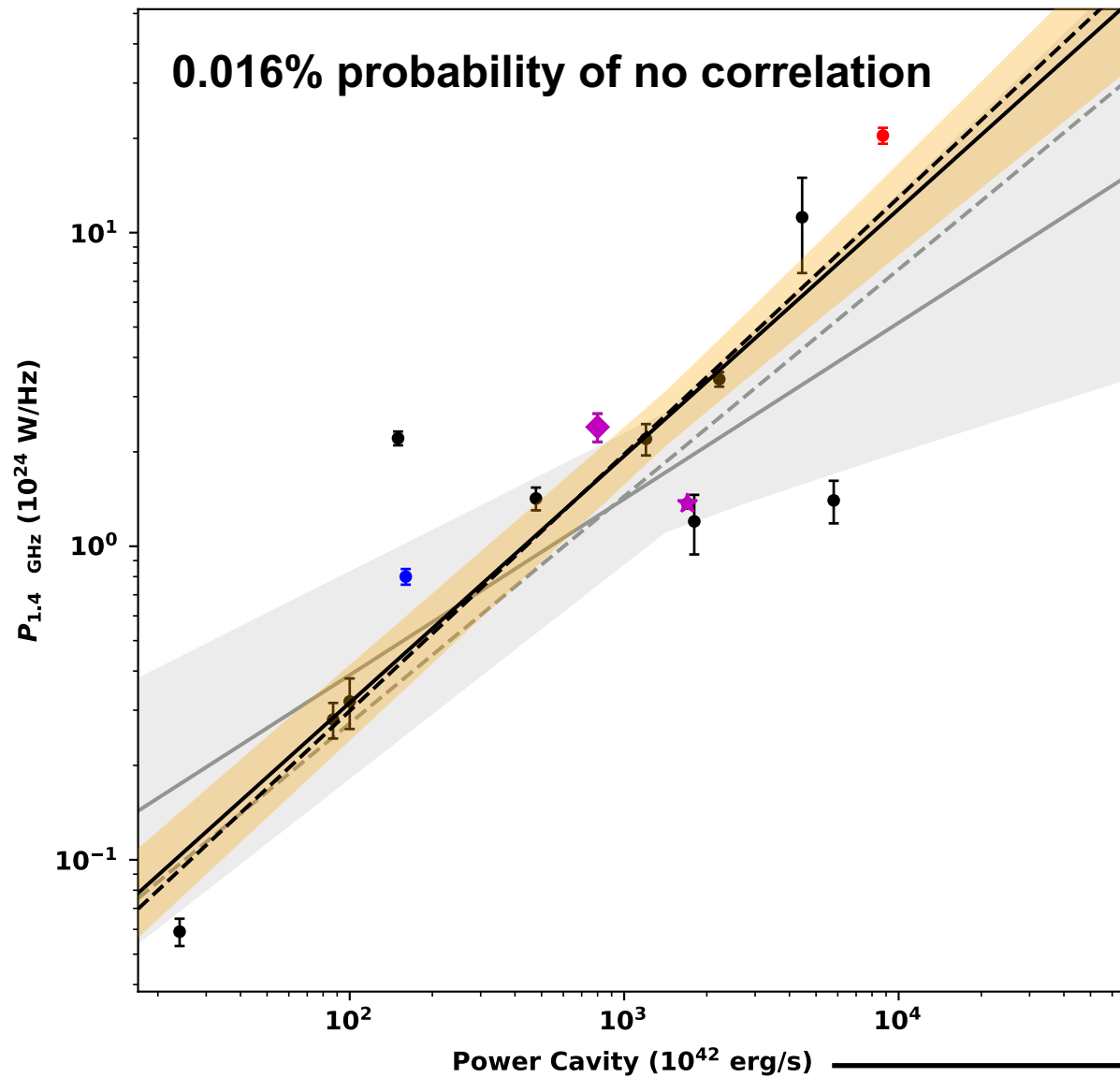
Plume



Black hole jets heat/energize the **thermal gas/baryons in
and around massive galaxies ...**

**Do black hole jets also heat/energize the **non-thermal
gas/cosmic rays?****

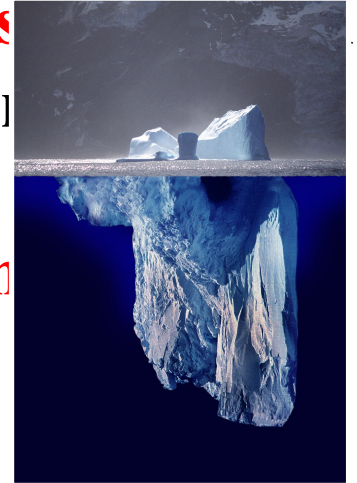
Black hole feedback and non-thermal gas



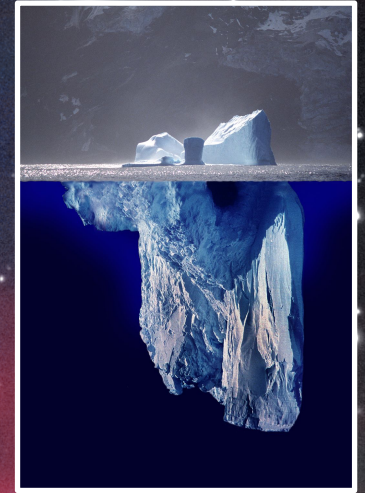
Take Home Points:

AGN Feedback in Galaxy Clusters

- Black hole jets impact strongly the **thermal gas** and around massive galaxies for the last 10 Gyr
- Black hole jets deposit **energetic particles/cosmic rays** and **magnetic fields** in and around galaxies.
- Black hole jets may also **keep these particles relativistic** for long time scales ($\gg 10^8$ yrs), thus impacting fundamental processes such as heating/star formation over longer time scales than initially thought.



The role of AGN feedback in galaxy clusters for the last 10 billion years



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