Jet-Mode AGN Feedback
(LOFAR prospects)

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and LOFAR TEAM
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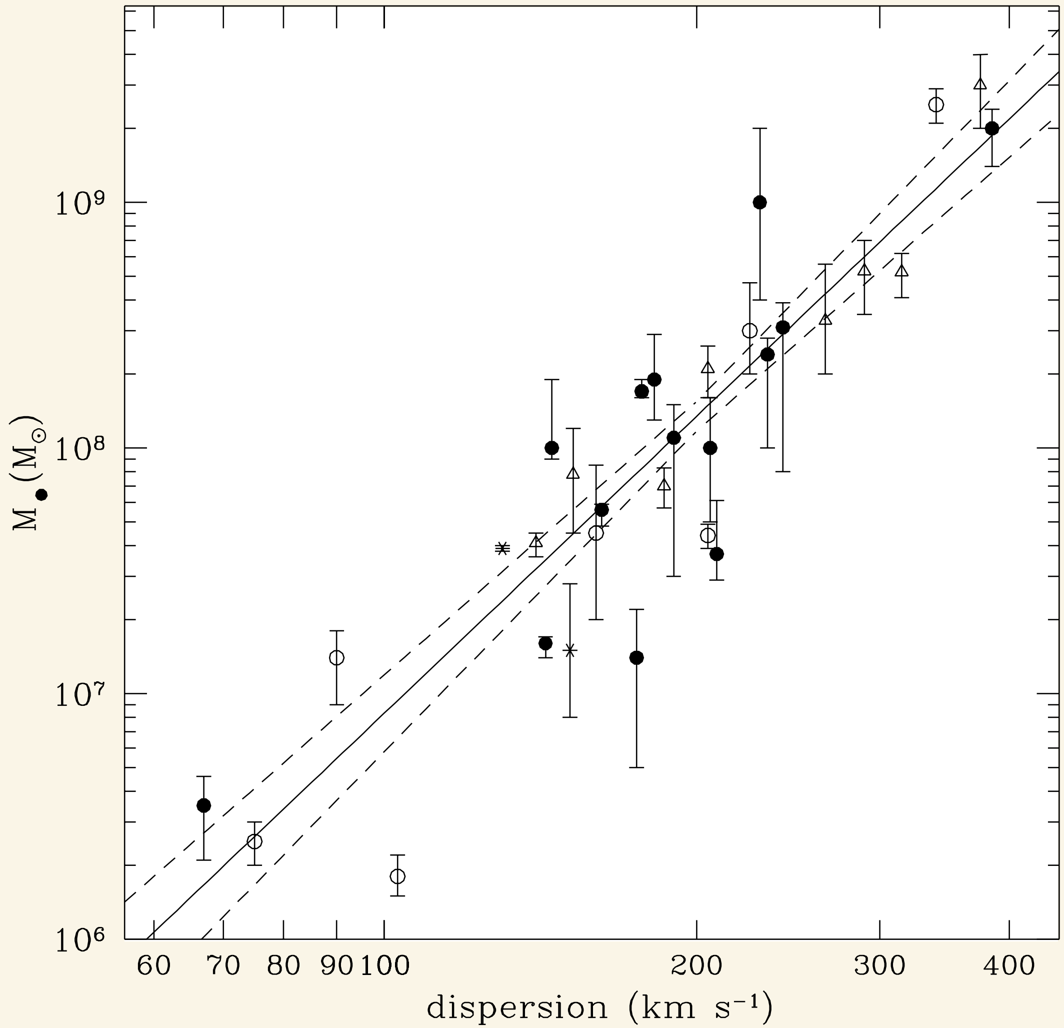
Michael Wise (ASTRON)

AGN Feedback and Galaxy Formation

- Important for galaxy formation: “what role do the BHs have in shaping the galaxies around them”.
- Observationally, the BH masses scale with the bulge masses: the "Magorrian relation” (Magorrian et al. 1998, Tremaine et al. 2002, Mullaney et al. 2012).

AGN Feedback and Galaxy Formation



Tremaine et al. 2002

AGN Feedback and Galaxy Formation

- Important for galaxy formation: "what role do the BHs have in shaping the galaxies around them".
- Observationally, the BH masses scale with the bulge masses: the "Magorrian relation" (Magorrian et al. 1998, Tremaine et al. 2002, Mullaney et al. 2012).
- The cooling flow problem (Fabian 1994, Fabian 2012).
- How cooling is truncated in massive galaxies (Scannapieco & Oh 2004, Di Matteo, Springel & Hernquist 2005, Croton et al. 2006, Bower, McCarthy & Benson 2008, Dubois et al. 2013, Sijacki et al. 2014, Rosas-Guevara et al. 2015)

Outline of the talk

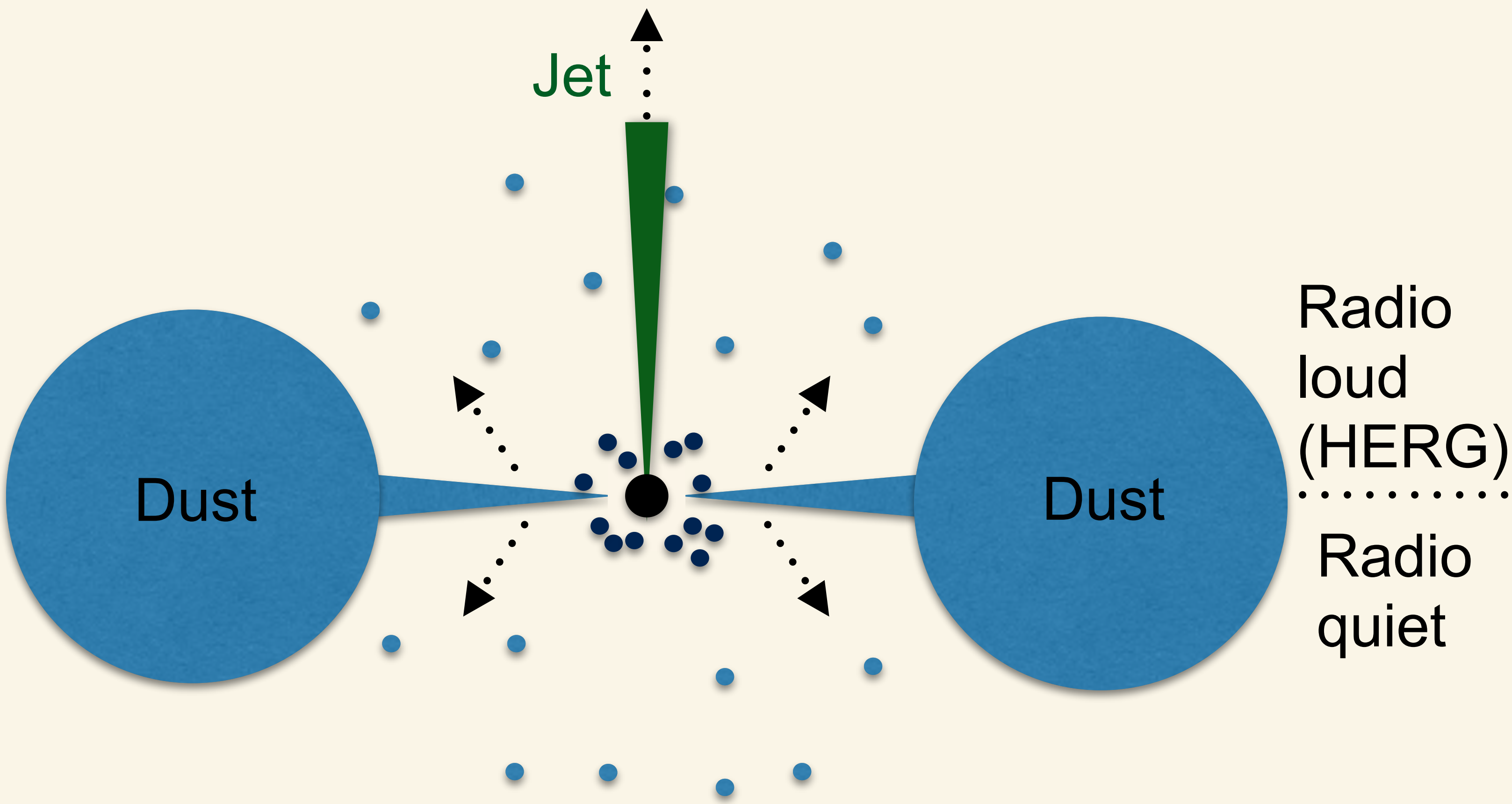
- AGN Feedback: radiative-mode and *jet-mode AGN feedback*
- Galaxy clusters; cooling flows; X-ray cavities; balancing cooling with jet-mode feedback (X-ray view)
- Scaling relation between mechanical power (derived using X-ray cavities) and radio power
- Next generation of low frequency radio telescopes and the prospect for high-z studies

AGN Feedback

- Radiative (QSOs)-mode AGN feedback:
  - BH accretion operating at Eddington limit ($L_{\rm acc} \sim 0.1 L_{\rm Edd}$) ➔ radiatively efficient AGN
  - In high-z systems (most effective at $z = 2 - 3$)
  - Feedback by moving cold gas around using galactic winds?
    - Evidence from galactic outflows: from RG (e.g., Nesvadba et al. 2011), quasars (Chartas et al. 2007), starburst galaxies (Alexander et al. 2010)
    - Caveats: hard to separate star formation winds from AGN driven winds, and high level of obscuration.
      - see the review of Fabian 2012 ("Observational evidence of AGN Feedback")

AGN Feedback

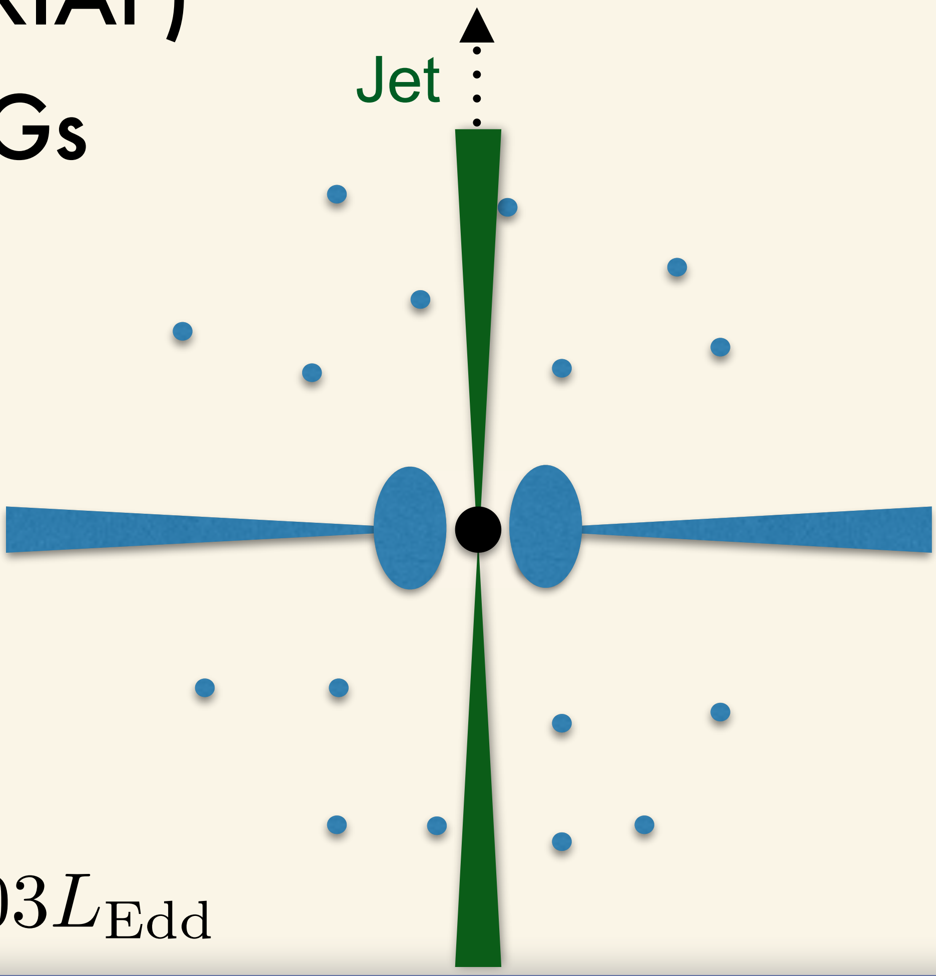
- Radiative mode: radiatively driven wind



$L_{\text{acc}} \sim 0.1 L_{\text{Edd}}$

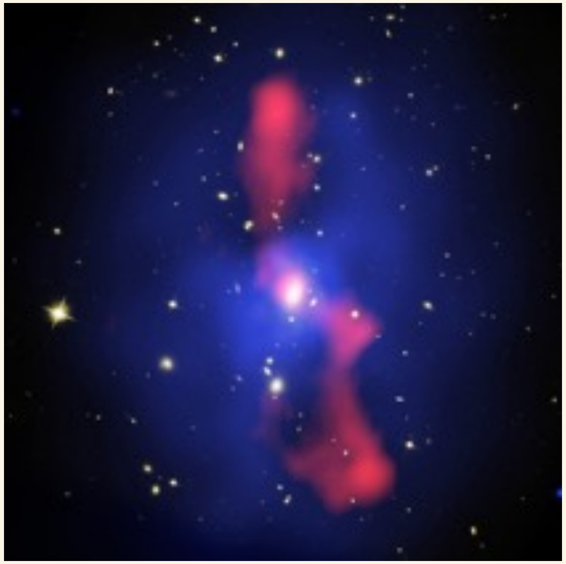
AGN Feedback

- Jet mode: kinetically driven flow dominates (ADAF/RIAF)
- FRI; LERGs



$L_{\mathrm{acc}} \sim 0.003 L_{\mathrm{Edd}}$

AGN Feedback

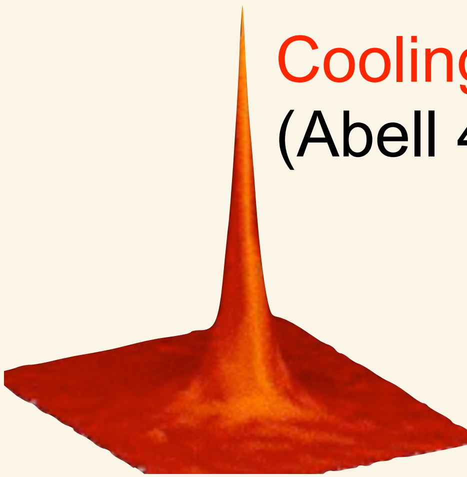


- Radio-mode AGN feedback:
  - At present epoch
  - In galaxies with hot halos → massive systems
  - The BH is accreting well below Eddington limit
  - Powerful jets (feedback by radio jets/lobes).
    - The observational evidence for radio mode feedback: bubbles or cavities discovered by Chandra in the ICM of many nearby systems

Cooling Flow Clusters

X-ray Surface Brightness →

Cooling Flow
(Abell 478)

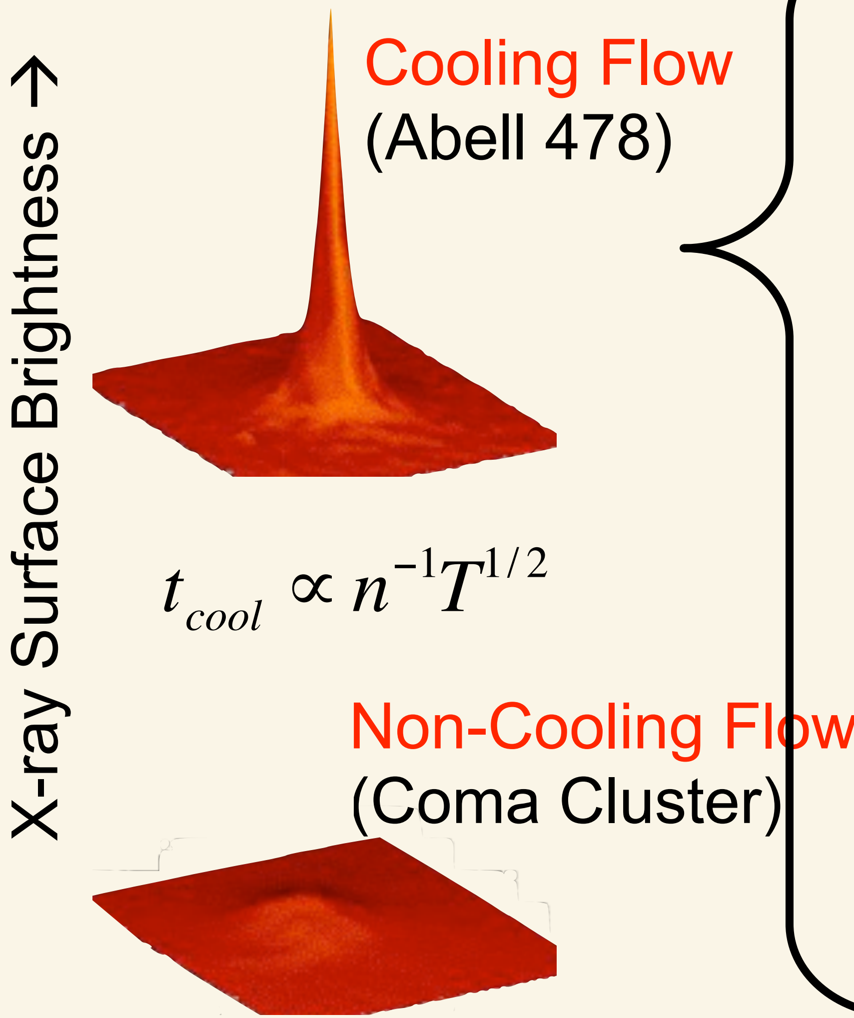


$$t_{cool} \propto n^{-1} T^{1/2}$$

Non-Cooling Flow
(Coma Cluster)

(www-xray.ast.cam.ac.uk)

Cooling Flow Clusters



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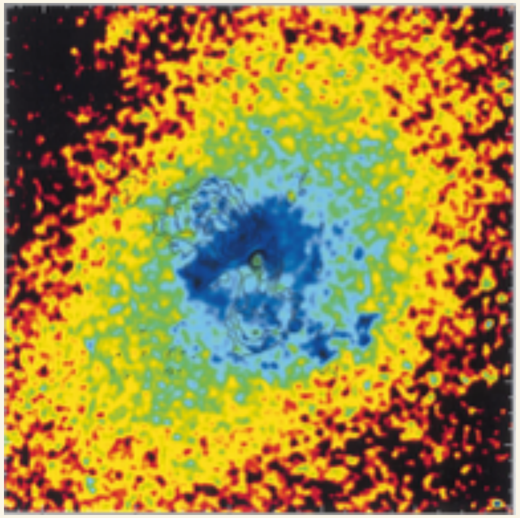
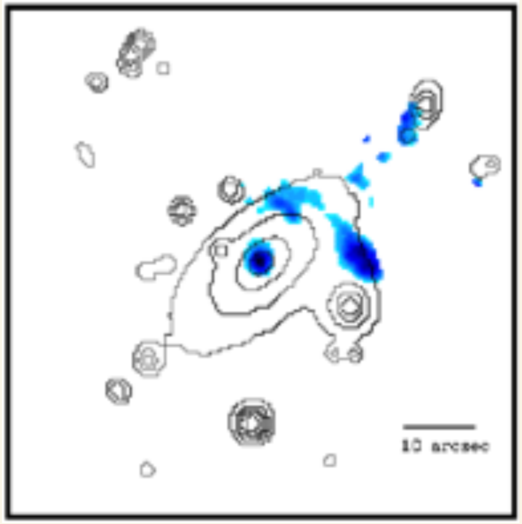
Abell 2597



Koekemoer et al. (1999)

Abell 1068



McNamara et al. (2004)

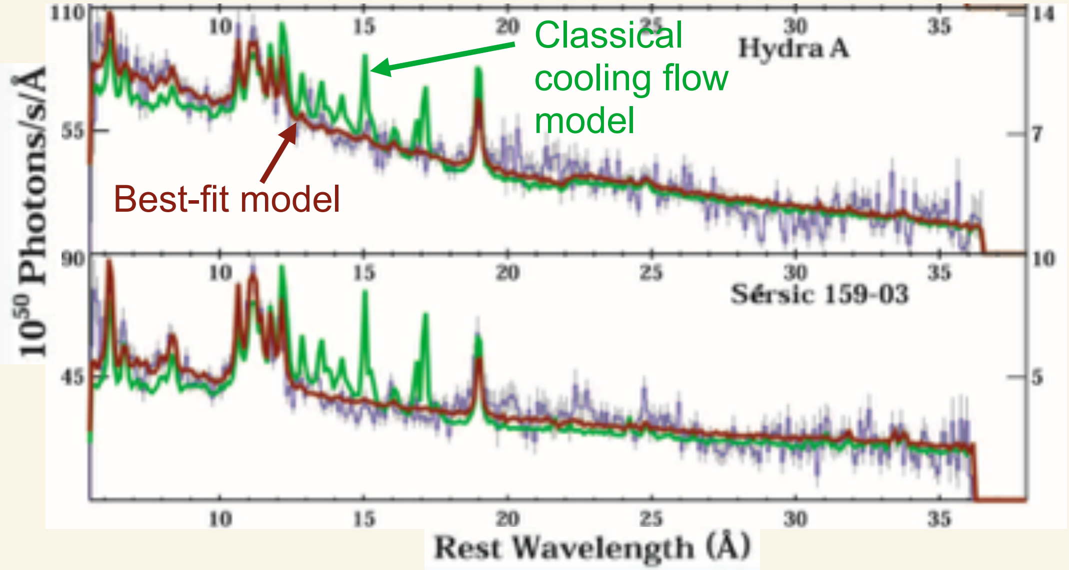
The New X-ray Observatories

(xmm.vilspa.esa.es)

- *XMM-Newton*
  - High spectral resolution and effective area

  ➔ Signatures of cooling not present at expected levels

The New X-ray Observatories



Peterson et al. (2003)

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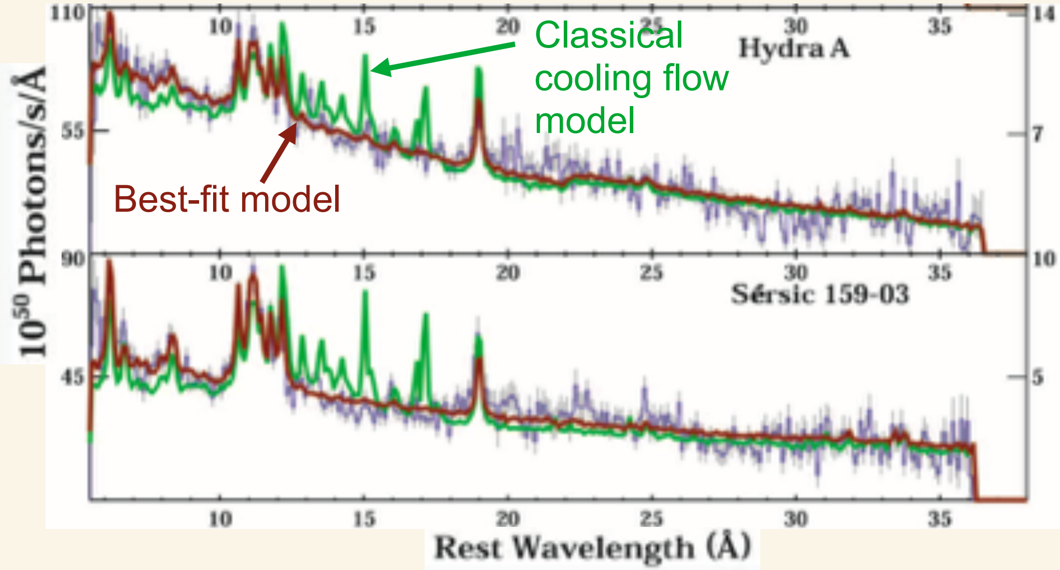

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  - High spatial resolution
  - ➔ Revealed strong coupling between AGN and ICM

(chandra.harvard.edu)

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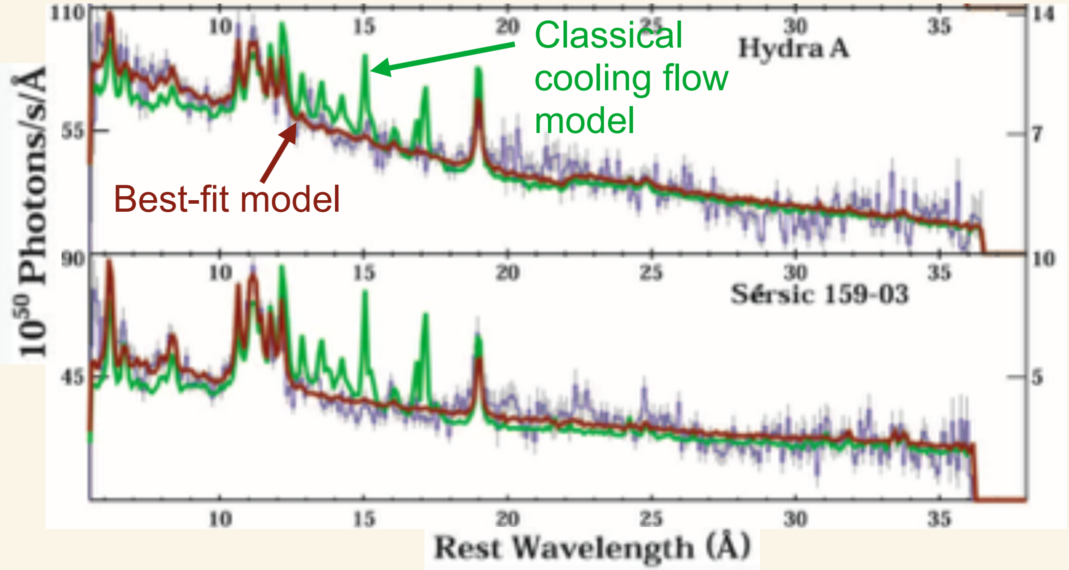

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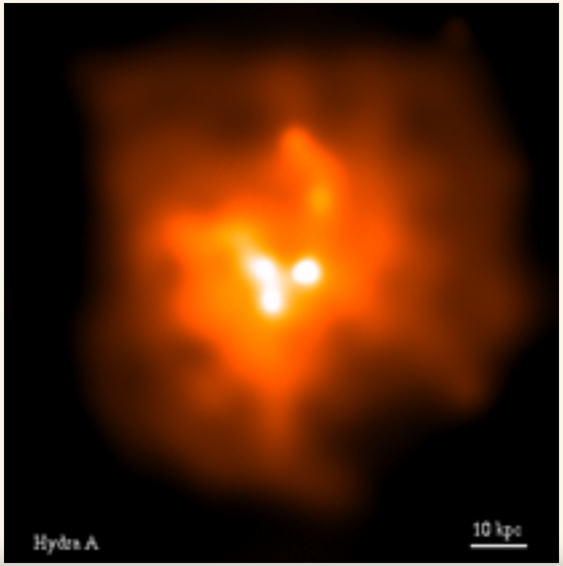

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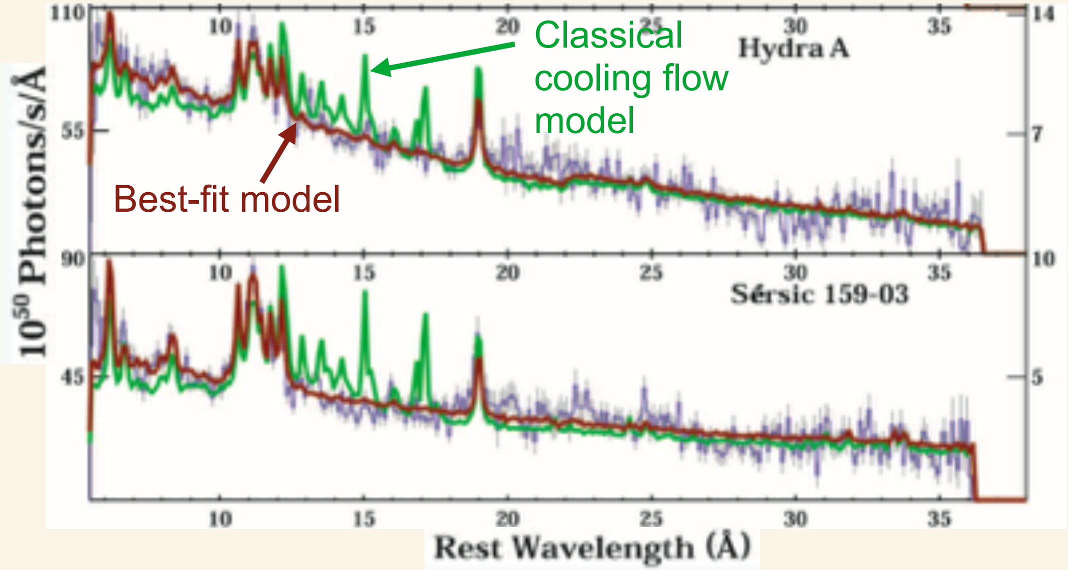

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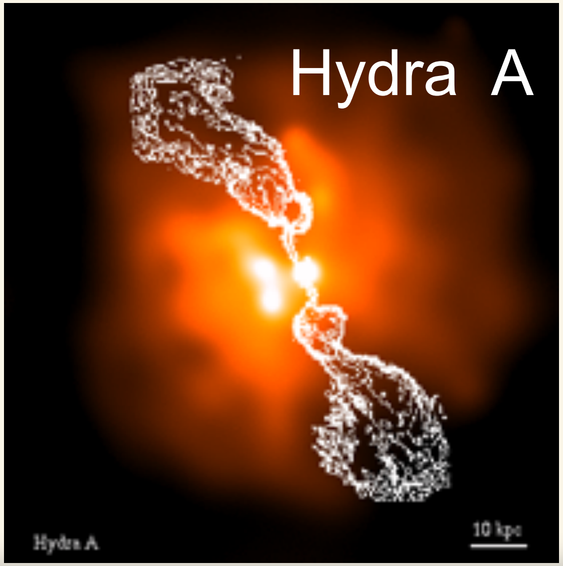
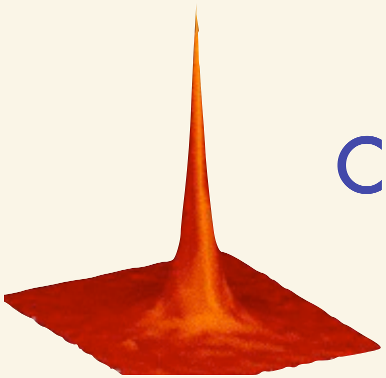


Feedback Schematic



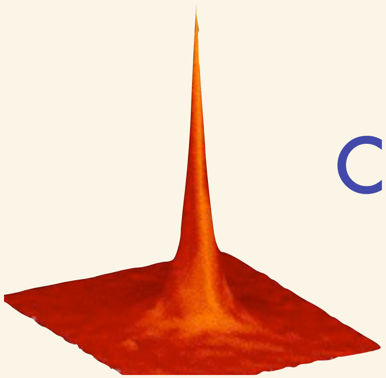
Cooling

L_{ICM}

ICM

Gas condensation

Feedback Schematic



Cooling

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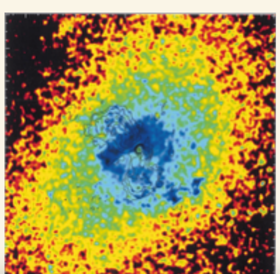
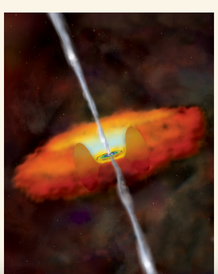
Gas condensation

Star formation

Accretion onto BH





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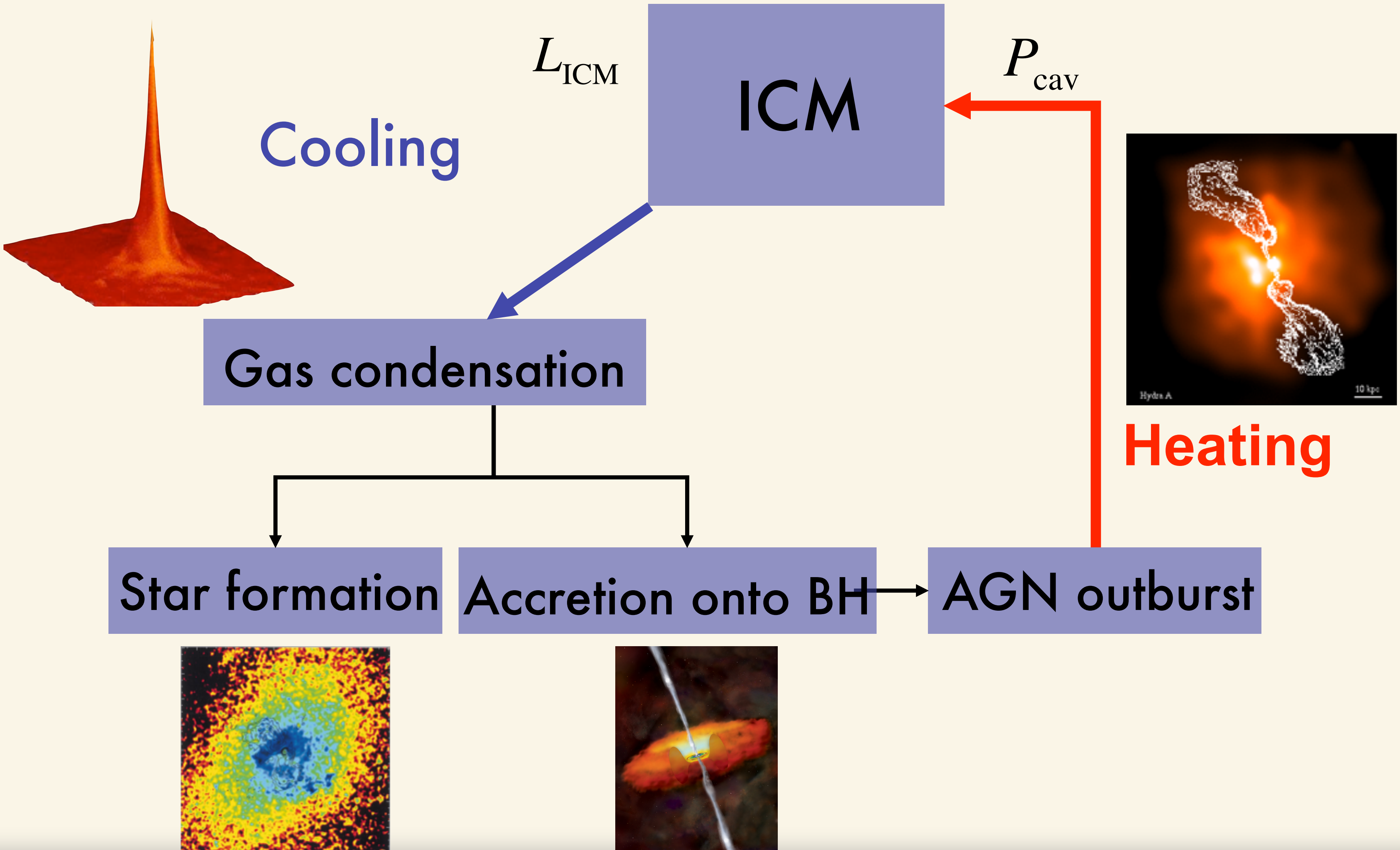
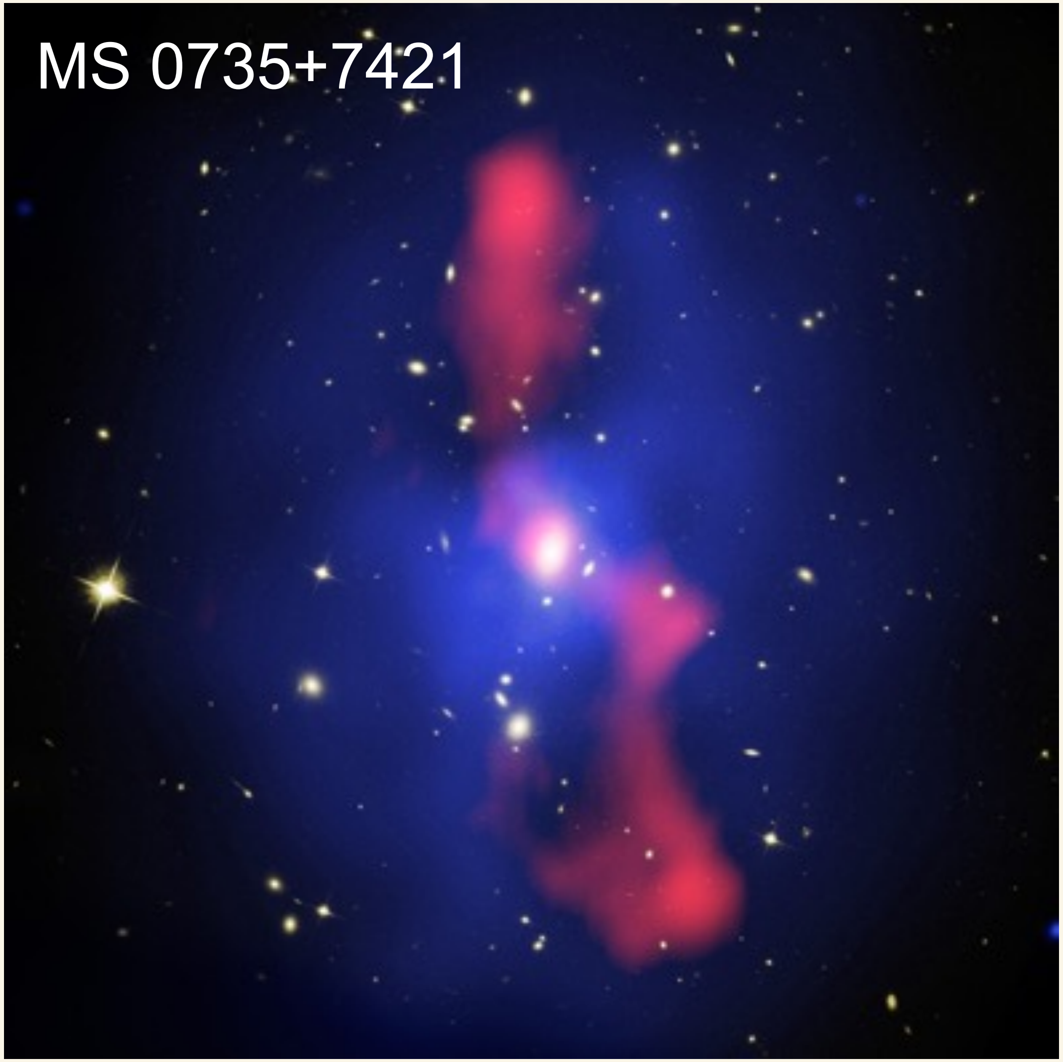


Regulating Cooling Flow Clusters

- Non-AGN heating: conduction (e.g., Voigt & Fabian 2004); sloshing (Markevitch & Vikhlinin 2001, ZuHone et al. 2010, Lagana et al. 2010)
- Heating by AGN:
    - X-ray bubbles, shocks, sound waves, mixing (McNamara & Nulsen 2007, 2012; Fabian 2012, Soker et al. 2015)
    - Cosmic rays (e.g., Gou & Oh 2008; Ensslin 2011, Wiener et al. 2013, Pfrommer 2013);
    - Convective core (Binney & Tabor 1993; Sharma et al. 2009)
- However, many details of AGN heating are still poorly understood (e.g., Banerjee & Sharma 2014, Wagh et al. 2014, Hillel & Soker 2014, Gaspari et al. 2013, Li & Bryan 2014, Soker et al. 2015)



X-ray data (McNamara et al. 2005); **327 MHz VLA radio data** (Bîrzan et al. 2008)

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credit: X-ray: NASA/CXC/SAO/E.Bulbul, et al.

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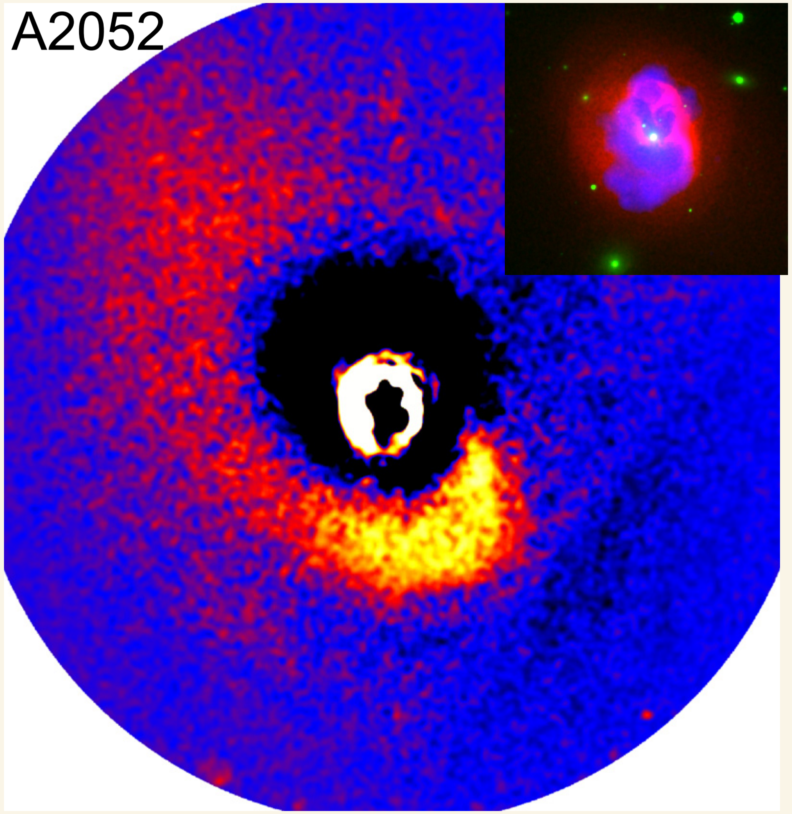

Blanton et al. 2011

What Do the Cavities Tell Us?

- Enthalpy gives estimate of energy required to create them
- Buoyancy arguments allow estimate of age (confirm with ASTRO-H?)
- Used together, we can estimate the AGN mechanical power

From the X-ray data:
Measure p, V

$$E_{cav} = pV + \frac{1}{\gamma - 1} pV, \; \gamma = \frac{4}{3}$$

Ages: t_{cav} (t_{buoy})

$$P_{cav} = E_{cav} / t_{cav}$$

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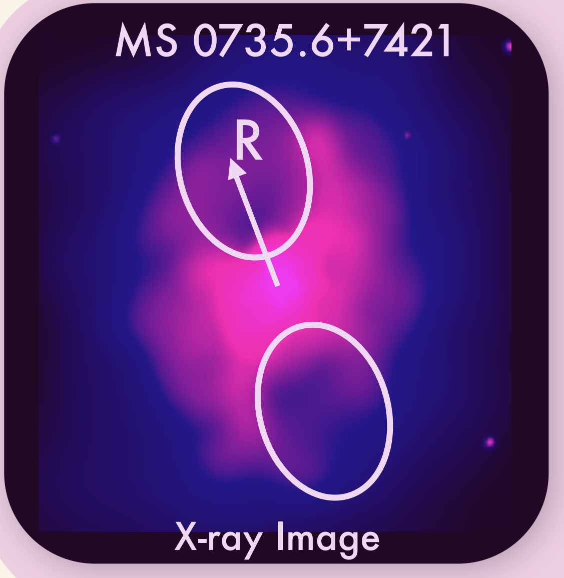

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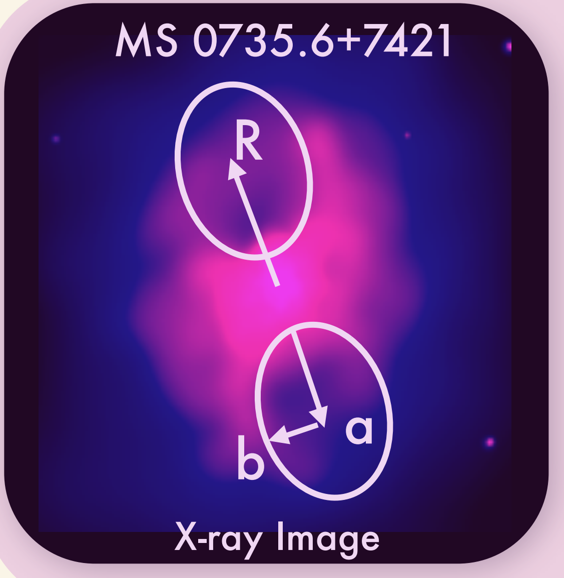

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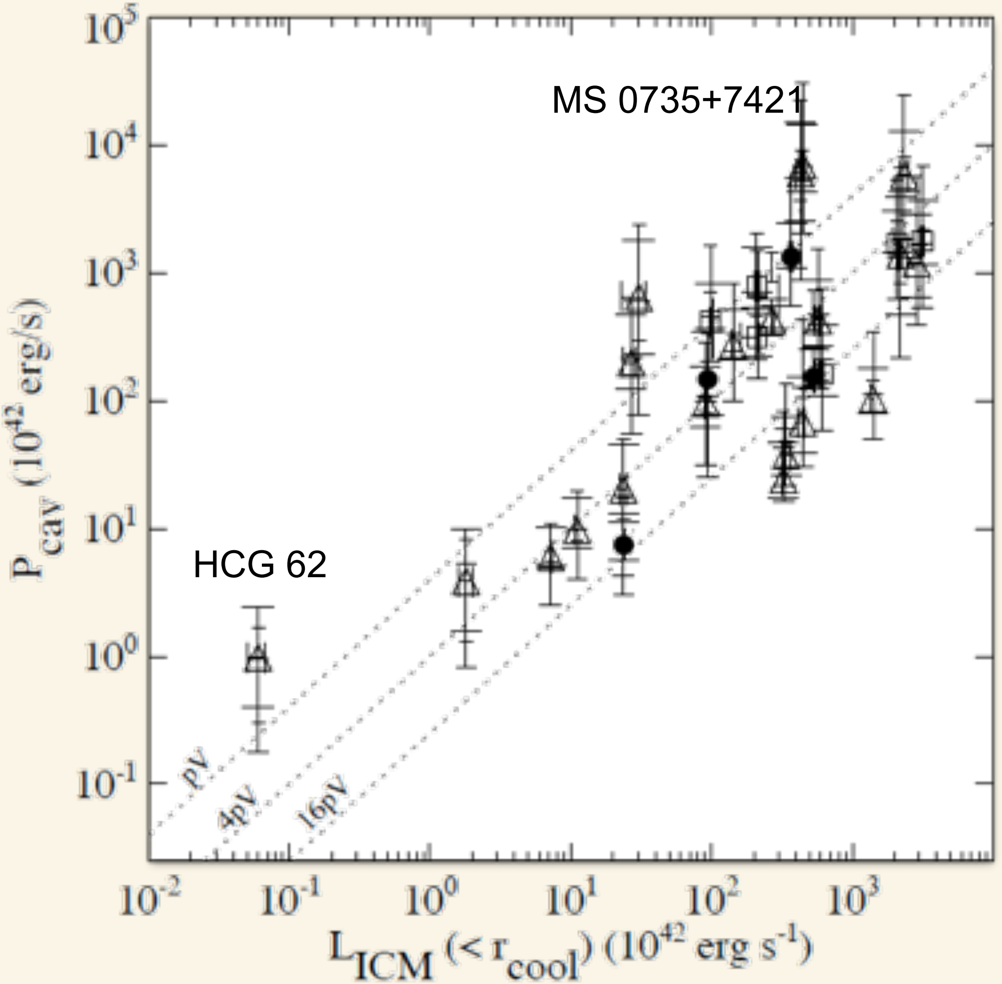
Heating with Jet-mode Feedback

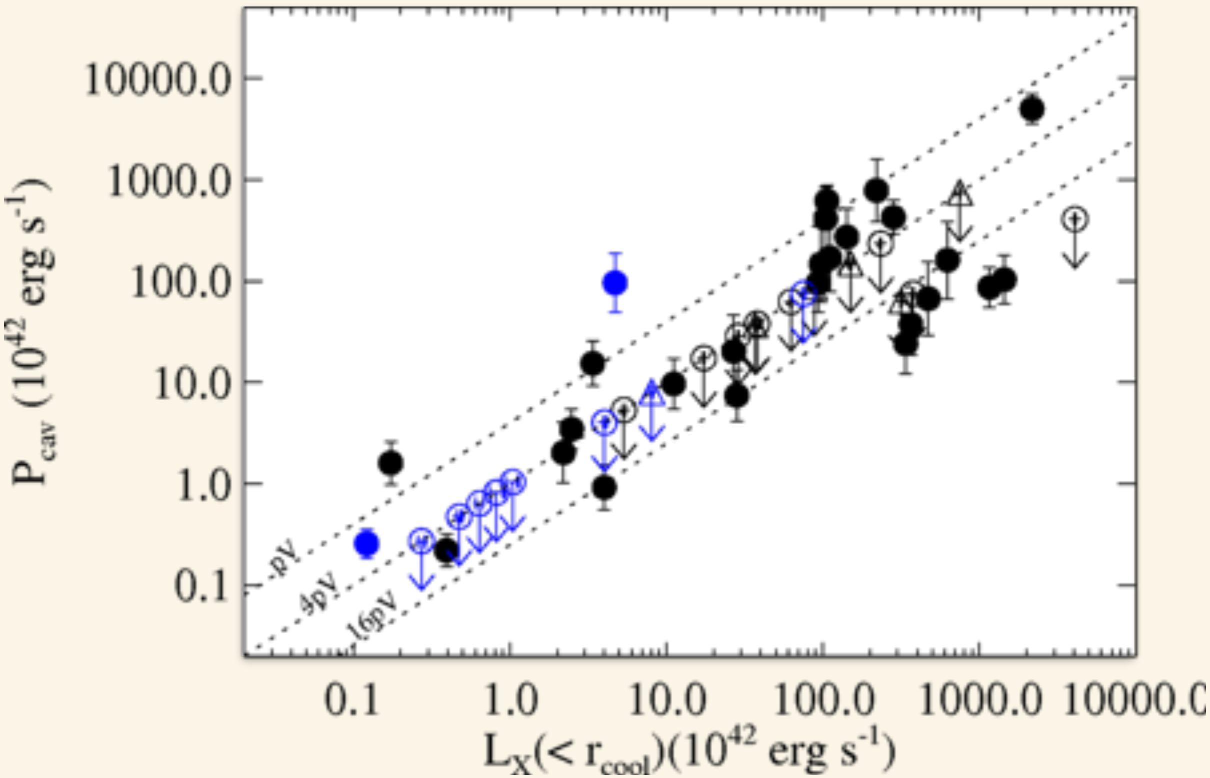


Rafferty et al. (2006)

- Samples of systems with cavities from Chandra archive (Bîrzan et al. 2004; Dunn et al. 2004, 2005; Rafferty et al. 2006)
- Complete samples, roughly 65% of cooling flow clusters have detected cavities (Bîrzan et al. 2012; see also Dunn et al. 2006, Fabian 2012, Panagoulia et al. 2014)

Heating with Jet-mode Feedback

Bîrzan et al. (2012)



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Radio and X-ray: Complementary Data

- X-ray data (e.g., Rafferty et al. 2006):
  - Measure *p*, *V*
  - $E_{cav} = pV + \frac{1}{\gamma - 1} pV, \; \gamma = \frac{4}{3}$
  - Ages: t_{cav} (t_{buoy})
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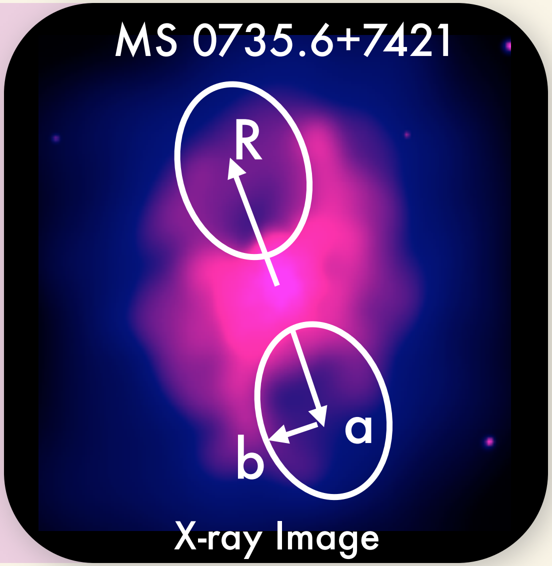
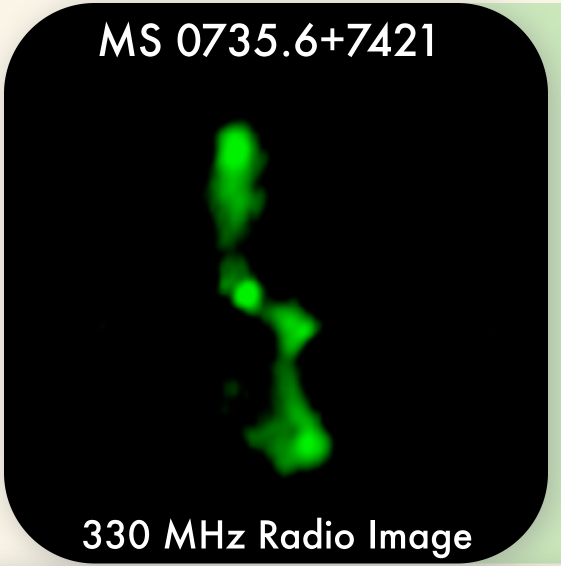




- Radio data:
  - $L_{radio}\Big|_{10\ \mathrm{MHz}}^{10000\ \mathrm{MHz}} = f(\alpha_{330}^{1400}, S_{330})$
  - ν_{break} for lobes
  - Synchrotron ages: $t_{syn} = f(B, \nu_{break})$

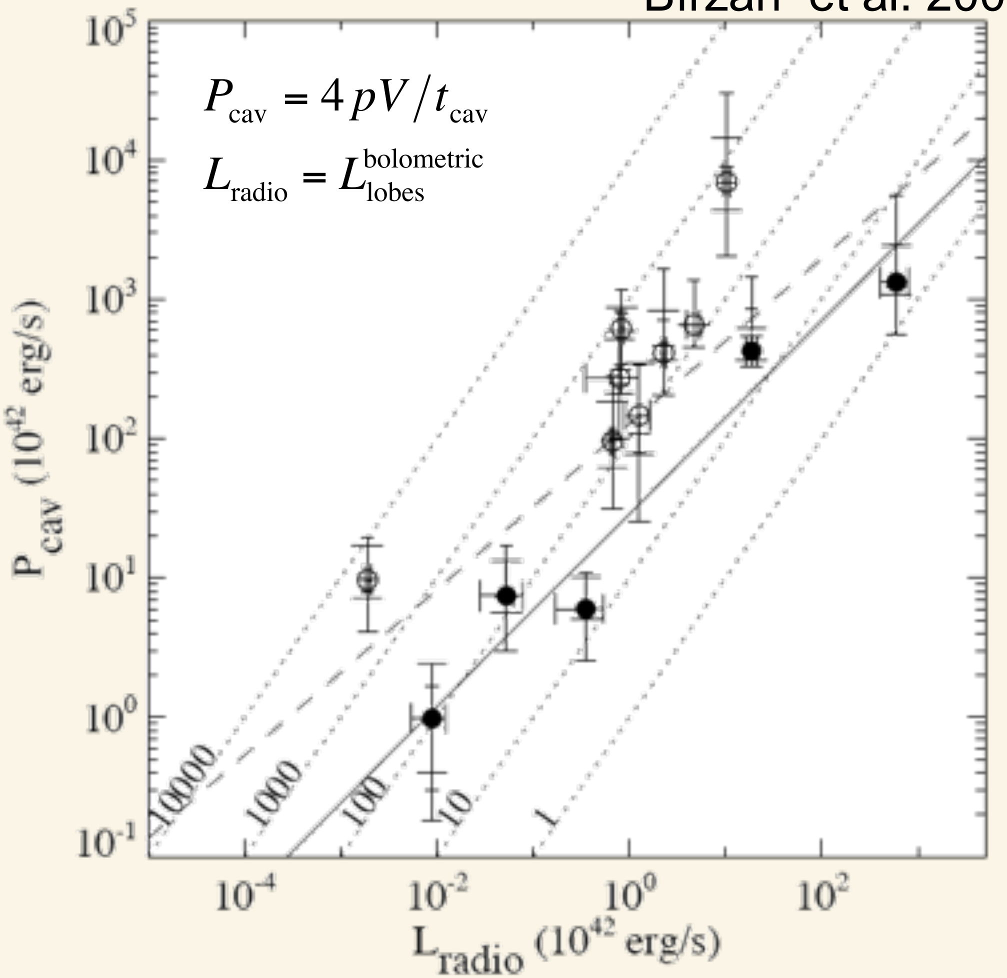
Jet Mode Scaling Relations

- 24 systems from Chandra Data Archive which show X-ray cavities (0.0035 < z < 0.545).
- VLA observations at 330 MHz 1.4 GHz, 4.5 GHz and 8.5 GHz.
- There is a large range in efficiencies.

⇨ Older cavities generally have lower efficiencies (possibly due to entrainment).

- Accounting for spectral aging gives tighter scaling relation.
- See also Cavagnolo et al. 2010, Merloni & Heinz 2007, Daly et al. 2012, Antognini et al. 2012, Godfrey & Shabala 2013.

Bîrzan et al. 2008



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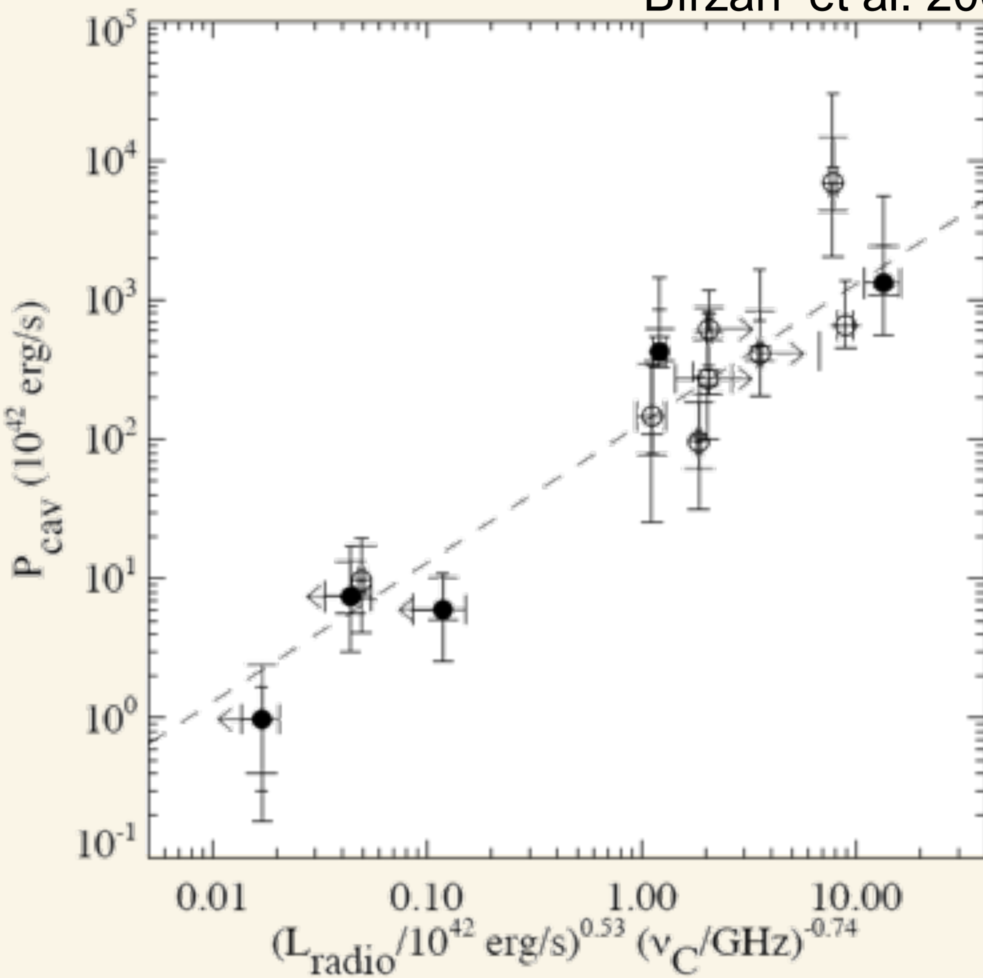

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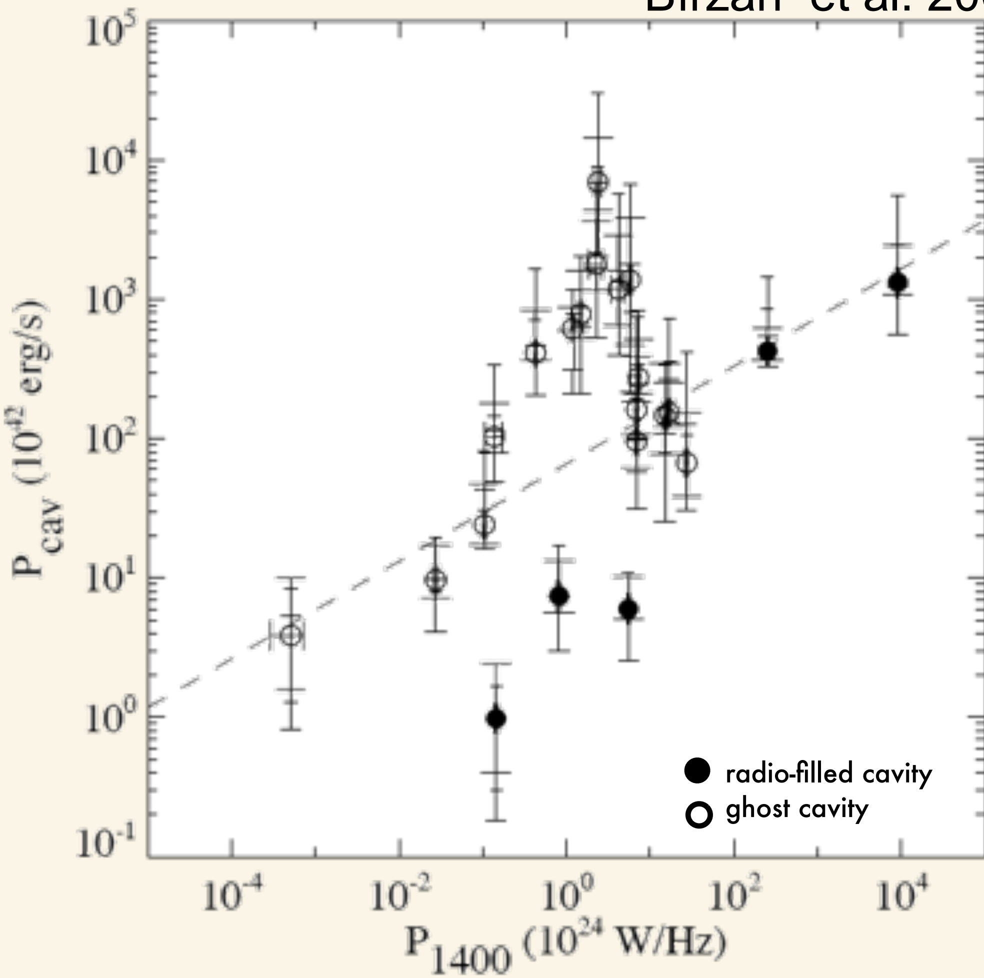


Scaling Relation Applications

- Studies of how jet-mode heating balance cooling for large samples of galaxies (e.g., Best et al. 2006,2007, Magliocchetti & Bruggen 2007, Hart et al. 2009, Ma et al. 2013).
- Studies of accretion mechanisms (e.g., Sun 2009)
- Studies of the cosmic evolution of AGN feedback to a redshift of $z \sim 1.2$ (e.g., Smolcic et al 2009, Danielson et al. 2012, Simpson et al. 2013)
- Study of the effect of feedback on X-ray selected groups (e.g., Giodini et al. 2010)
- Study of the kinetic power of a sample of quasars at $z \sim 2$ (e.g., Nesvadba et al. 2011)
- To infer the AGN jet power where cavities are not visible in X-ray data (e.g., Ogrean et al. 2010, Morganti et al. 2015)

Present studies up to z=0.5

- No evolution in AGN feedback studies (Bauer et al. 2005, Hlavacek-Larrondo et al. 2012);
  - Only one systematic study using cavities up to $z = 0.5$, but only for the most massive clusters (Hlavacek-Larrondo et al. 2012 using MACSs sample)
- No cool core in 400 SD ROSAT survey (Vikhlinin et al. 2007)
- However, high-z universe cannot be study easier with current X-ray instruments
  - Chandra resolution limits detectable size
  - Cosmological dimming
  - Small field of view not good for surveys
- Caveats for high-z studies:
  - redshift evolution for cool core systems (smaller at high-z)?
  - some high-z systems might have a bright quasar at the center

AGN Feedback at High Redshift

- No evolution in jet-mode AGN feedback studies up to $z = 1.3$ (e.g., Simpson et al. 2013), keeping the heating/cooling balance as in the local universe (Best et al. 2006):
  - Most of the jet-mode AGN feedback studies rely on radio scaling relations (Lehmer et al. 2007, Smolcic et al. 2009, Danielson et al. 2012, Ma et al. 2013)
- It is important to understand if the local scaling relations apply to higher redshifts, especially given the evolution of AGN population with redshift (e.g., Willman et al. 2008)
- With new instruments (LOFAR, SKA, eROSITA) the feedback from low luminosity RL AGNs (LERGs) can be studied using deep fields (e.g., COSMOS, XMM/LSS, NEP, LOFAR Peerl Survey)

New Era of Radio Telescopes

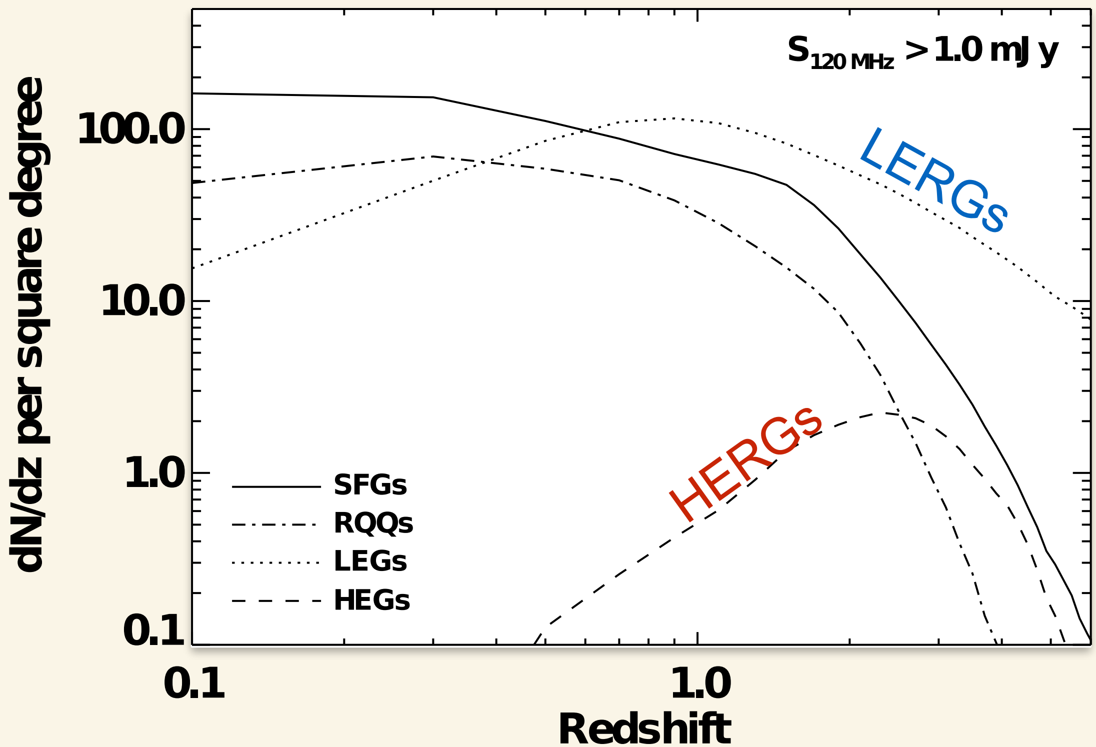
- LOFAR (the LOw Frequency ARray):
- Currently 46 stations located throughout Europe (37 in the Netherlands, 6 in Germany, 1 in UK, Sweden, France)
- Low Band: 10-80 MHz
- High Band: 120-240 MHz

Credit: http://kaira.sgo.fi

What Can LOFAR Add?

- All-sky surveys (plus targeted observations) – new measurements of lobes at 140 MHz:
  - Better constraints on energetically dominant low-frequency-emitting elections
  - Better constraints on break frequency and spectral age
  - Better understanding of cavity and lobe content
  - Improve and expand the scaling relations
- Deep, small-area surveys at low frequencies:
  - Probe fainter LERGs in cluster environments
  - Better understanding of jet-mode feedback at higher redshifts

Evolution of AGN Population

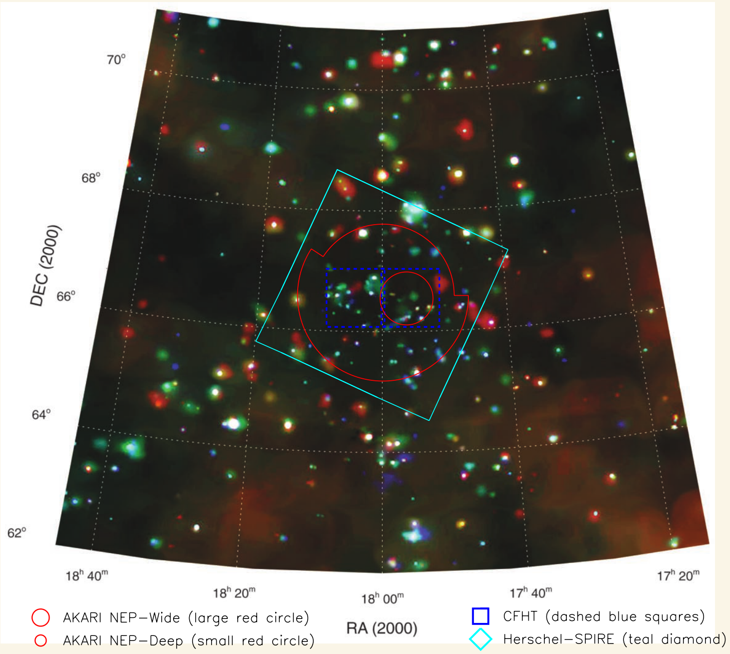


Credit: Philip Best (adapted from Willman et al. 2008)

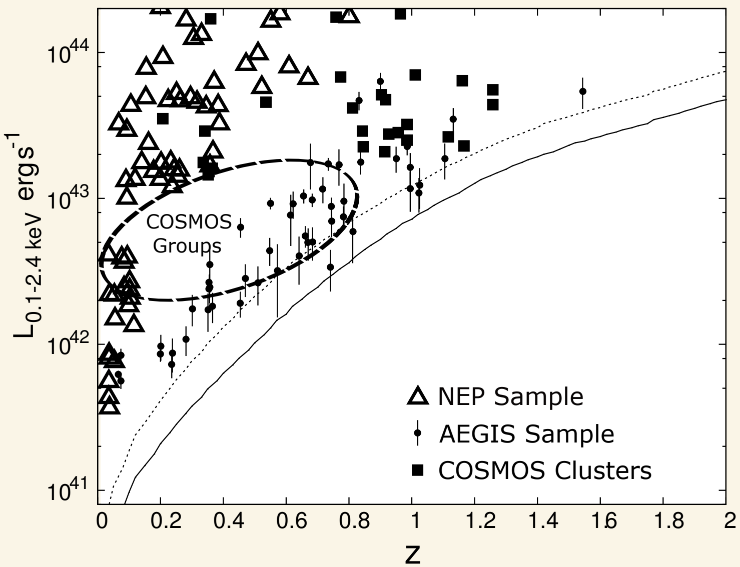
- LOFAR's advantages:
  - low frequencies more sensitive to steep-spectrum and higher-redshift systems, and
  - large field of view suitable for surveys
- Many LERGs can be detected at $z > 1$ by LOFAR

AGN Feedback in X-ray detected clusters

- NEP RASS: 64 clusters out to $z = 0.8$ in an area of 87.4 deg^2 (Gioia et al. 2003, Henry et al. 2006); NEPW: 5.4 deg^2 (< LOFAR beam at 120 MHz); NEPD: 0.67 deg^2
- COSMOS: 72 clusters/groups out to $z = 1.2$ in an area of 2 deg^2 (Finoguenov et al. 2007)
- XMM/LSS: 66 clusters out to $z = 1.5$ in an area of 6 deg^2 (Adami et al. 2011)



Adapted from Voges et al. 2001



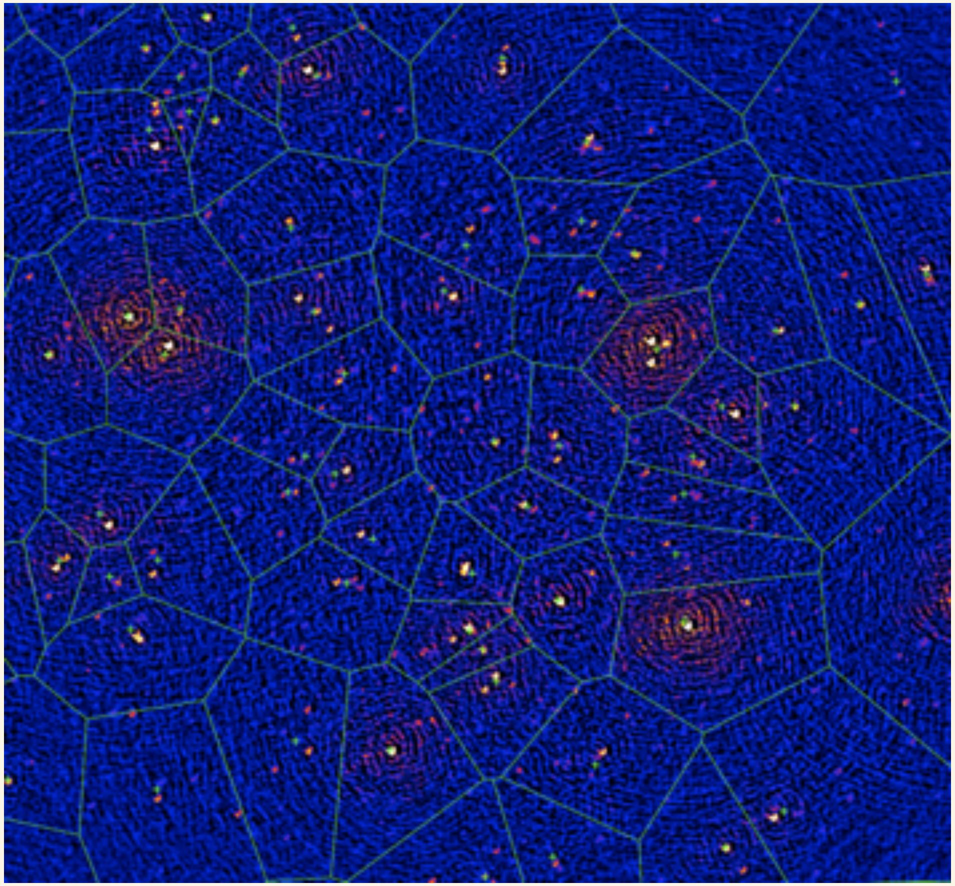
Adapted from Erfanianfar et al. 2013

Studying AGN Feedback using LOFAR

- Do the locally derived scaling relations apply to higher redshift, or do we need different relations for FRI/FRII?
  - Use LOFAR + X-ray data to estimate heating (from lobe sizes) and cooling rates in X-ray known clusters (in, e.g., NEP, COSMOS, XMM-LSS fields, LOFAR All Sky Survey data)
- To what redshift does AGN heating continue to balance cooling?
  - Deep, small-area surveys at low frequencies (NEPW, COSMOS)
  - Observe the so-called 1.4 GHz microJansky population (Padovani et al. 2009,2011)
    - Contribution from SFGs and RQ AGN becomes important (60% of all AGN are RQ at <0.1 mJy at 1400 MHz, Padovani et al. 2011)
  - Study AGN feedback using LOFAR data as proxy
- Are other radio sources (e.g., HERGs, RL QSOs) important for jet-mode feedback?
  - Radiative mode/Jet mode interplay (Churazov et al. 2005, Hlavacek-Larrondo et al. 2012, Russell et al. 2013, Short at al. 2010, Ragone-Figueroa et al. 2014, Pike et al. 2014)

Facet Calibration (HBA)

- Corrects for direction-dependent effects (DDEs) from ionosphere + errors in beam model (van Weeren et al. 2015)
- Loop over facets, performing self calibration on the facet calibrator
- From 30–100 facets needed to achieve thermal noise
- Implemented in the Factor package (Rafferty et al. in preparation)



NEP field at 150 MHz; Bîrzan et al. in prep.

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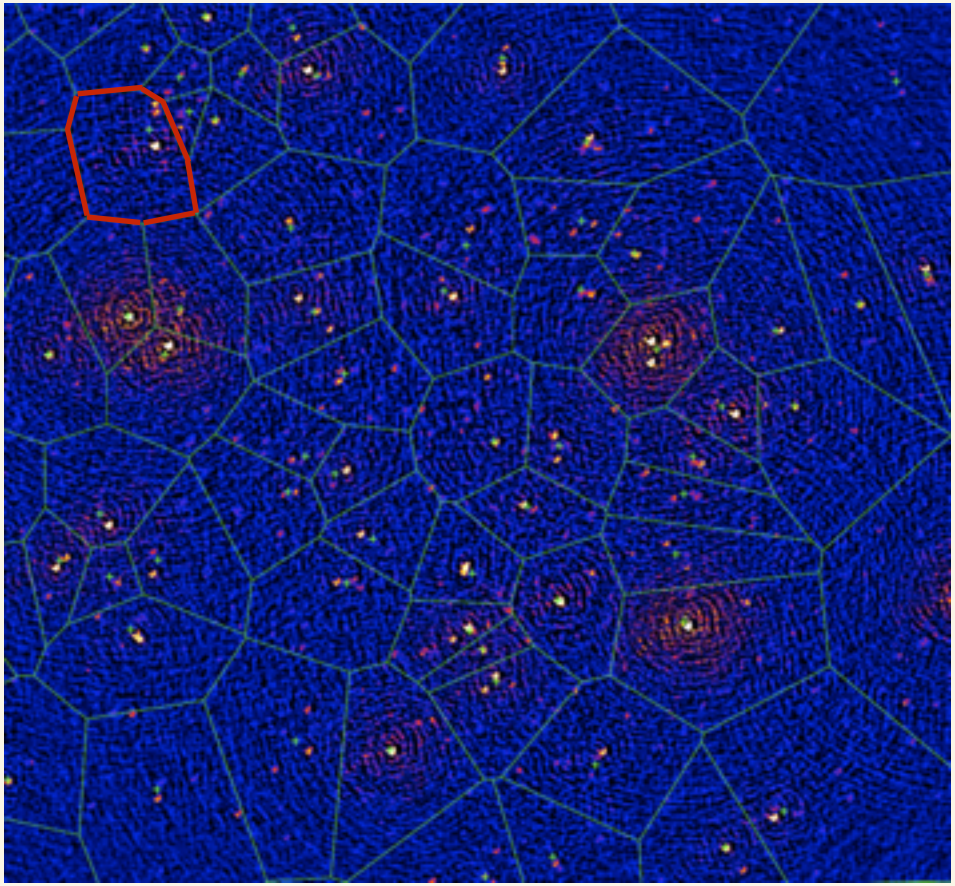

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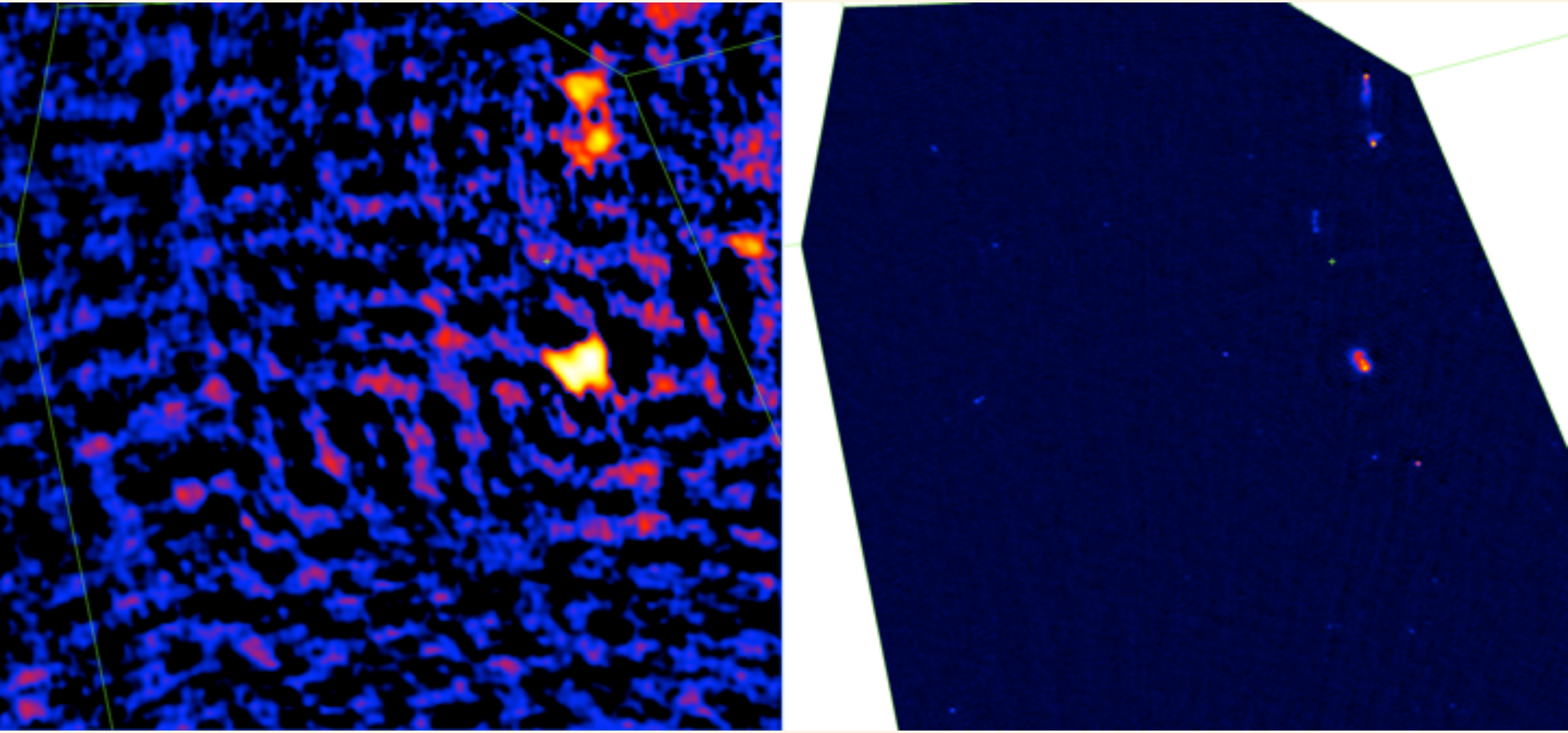
DDE improvements

- After DDE calibration, noise and resolution improve by factor of 5 or more:



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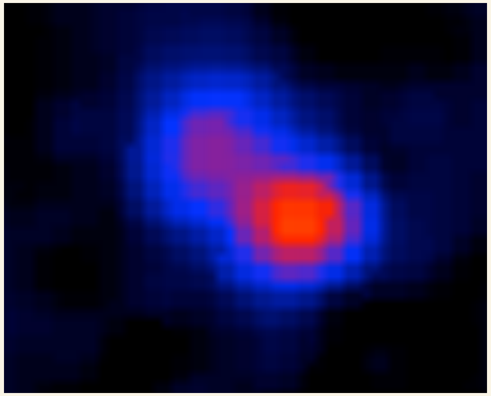
Example NEP Cluster

- RXJ1746.7+6639, cluster at z=0.386 (Henry et al. 2006, Gioia et al. 2003)
- Detected and resolved in LOFAR data at 142 MHz



142 MHz

- No radio detection in any other deep NEP images (1.4 GHz VLA: Branchesi et al.2006, Kollgaard et al. 1994, Brinkmann et al.1999), but does appear in VLSSr (unresolved)
- Spectral index ≈ 2.5

Summary

- X-ray cavities, shocks, etc. are direct evidence of jet-mode feedback in massive systems
  - Allow us to measure feedback power and understand its relation to radio properties
- But, these features are detectable only in bright (typically nearby) systems
  - Studies of jet-mode feedback at higher redshifts will have to rely on radio data
- LOFAR HBA is already producing results for deep fields with X-ray detected clusters at intermediate redshifts $0.3 < z < 1$ (e.g., NEP, COSMOS, XMM-LSS, Bîrzan et al. in prep.; LOFAR All Sky Survey)
- LOFAR, which observes at low frequencies with high survey efficiencies, will be an ideal instrument to detect and study LERGs at $z > 1$