Radio-mode AGN feedback in galaxy clusters and groups

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Outline of the talk

- **Introduction**
  - galaxy clusters and intra-cluster medium (ICM)
  - “cooling flow” (CF) and “cooling flow problem”
- **Radio-loud AGN as solution to CF problem**
  - AGN/ICM interaction
  - cavity heating and CF quenching
- **Catching the radio-AGN feedback in action**
  - observations of X-ray cavities, radio bubbles and weak shocks
  - lessons from giant cavities
- **Digression on peculiar cluster radio sources**
  - (in)direct evidence for SMBH binaries
  - radio mini-halos
- **Future and conclusions**

What are galaxy clusters made of ?

- <u>~2-5% stars:</u>

  ~90% in galaxies, ~10% diffuse

  BCG galaxy typically dominates optical light

✧ **<u>~15% hot gas:</u>**

  intracluster medium (**ICM**)

  visible in X-rays

- <u>~80% dark matter (DM):</u>

  mapped via strong & weak lensing, dynamics

The ICM is subdominant in mass, but tell us the most about the history of the cluster!

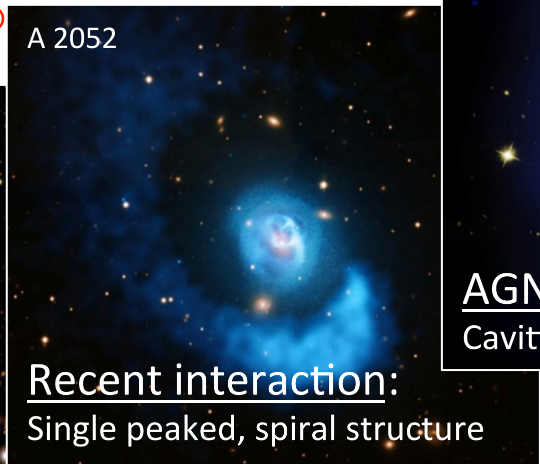
Abell 1689: A Galaxy Cluster Makes Its Mark - Chandra (X-ray) and Hubble Space Telescope
NASA/CXC/MIT/E.-H. Peng et al and NASA/STScI Release Date: Sept. 11, 2008 ASU-IPF-2903

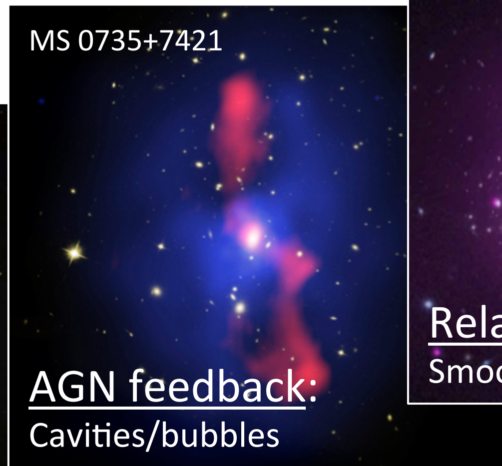
The intra-cluster medium (ICM)

The majority of baryons in clusters are in the form of diffuse, hot plasma, gravitationally heated during cluster formation

The ICM is enriched in heavy metals and emits in X-rays by thermal bemsstrahlung (+ rec. lines): $J_{br} \propto Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT}$

- **temperature kT** ~ 0.5-15 keV ($T \sim 10^{7\text{-}8}$ K)
- **density n_e** ~ 10^{-4} -10^{-2} cm^{-3}
- **metallicity Z** ~ 0.3 solar
- **luminosity L_X** ~ 10^{43}-10^{46} erg/s
- **mass M_{gas}** ~ 10^{14} $M_\odot$
- **morphology:** retains imprints of major events !

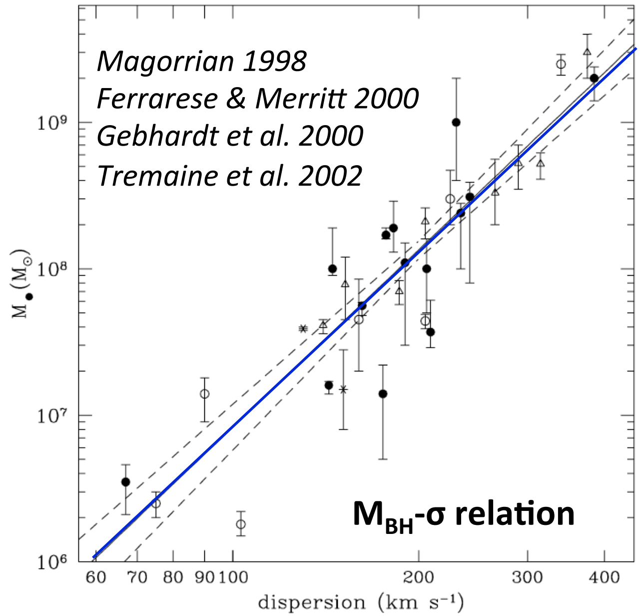




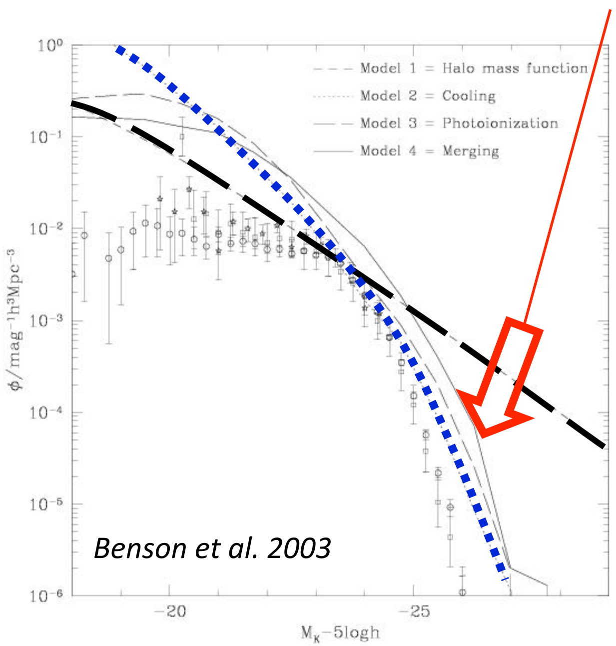
(ICM→) Baryon physics is complex

Gas dynamical models of DM halos incorporating radiative cooling and gravitational heating alone produce *too much cold gas*, *too many young stars*, and *too few hot baryons* *(Bregman 2007, Balogh et al. 2011)* → non-gravitational processes

SMBHs influence galaxy formation and evolution



Models with AGN feedback reproduce the observed luminosity function of galaxies



X-ray observations of the ICM allow us to investigate the complex baryon physics, which is key to understand the processes of cooling and feedback regulating galaxy formation

Cooling Flow (CF) – standard model

- **cooling time** t_{cool} : characteristic time of energy radiated in X-rays
- **cooling radius** r_{cool}: radius at which t_{cool}= age of the cluster ~ H_0^{-1}

enthalpy $H = E_{int} + pV = \frac{\gamma}{\gamma - 1} pV$

ratio of specific heats

$$t_{cool} = \frac{H/V}{n_e n_H \Lambda(T)} = \frac{\gamma}{\gamma - 1} \frac{kT}{\mu X_H n_e \Lambda(T)}$$

$X_H = m_H n_H / \rho$
hydrogen mass fraction

cooling function

!!! Note that..

'Cooling' = heat loss (by radiation) from the gas
→ reduction in the specific entropy $kT\, n_e^{-2/3}$
(regardless of the change in temperature !)

Cooling Flow (CF) – standard model

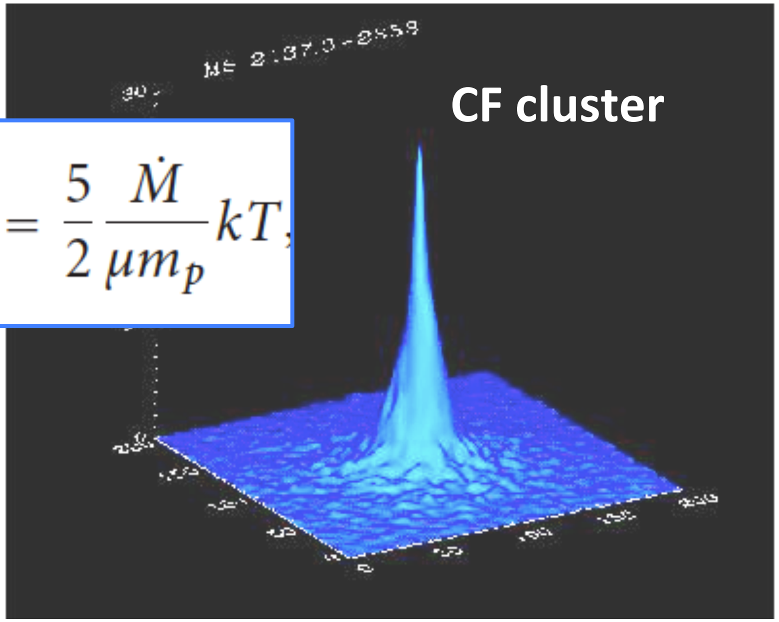
- **cooling time** t_{cool} : characteristic time of energy radiated in X-rays
- **cooling radius** r_{cool}: radius at which t_{cool}= age of the cluster ~ H_0^{-1}

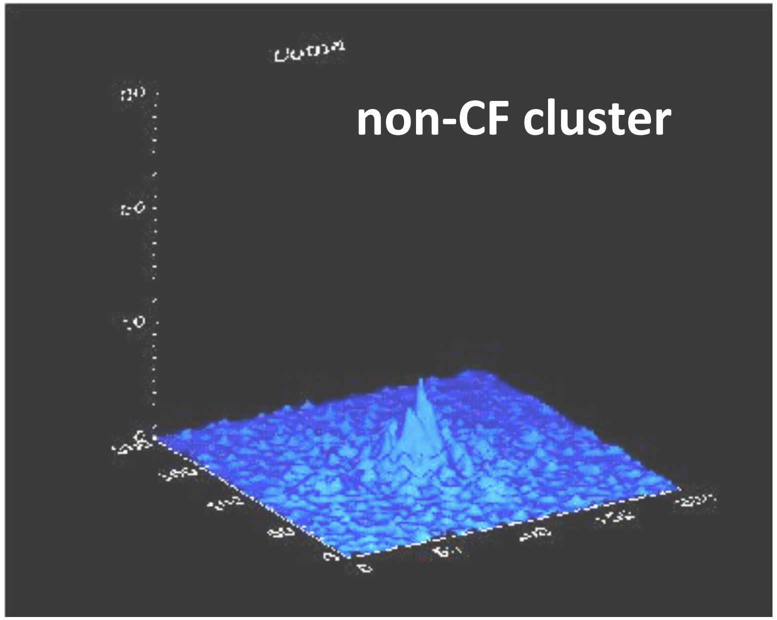
Within r_{cool} , $t_{cool} < H_0^{-1}$ → (hydrostatic eq.) the cooling gas flows inward - with a mass inflow rate $\dot{M}$ - and is compressed

Compression ⇒ density increases ⇒ X-ray emissivity $(\propto n^2\Lambda)$ increases !

(Fabian 1994)

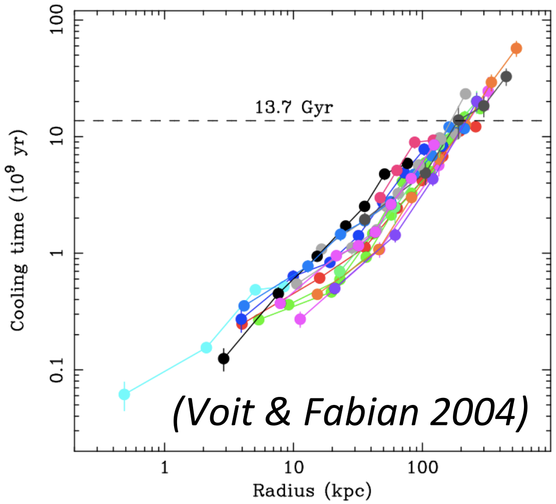
$$L_{\rm cool} = \frac{5}{2}\frac{\dot{M}}{\mu m_p}kT,$$



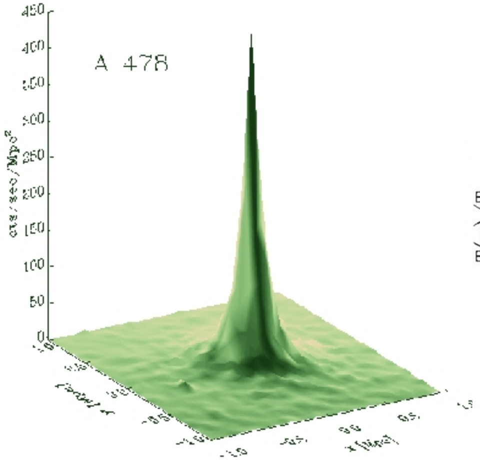


CF – observations

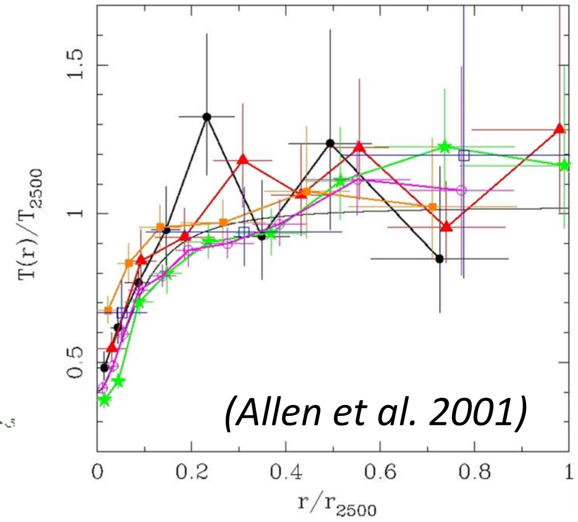
• short cooling time



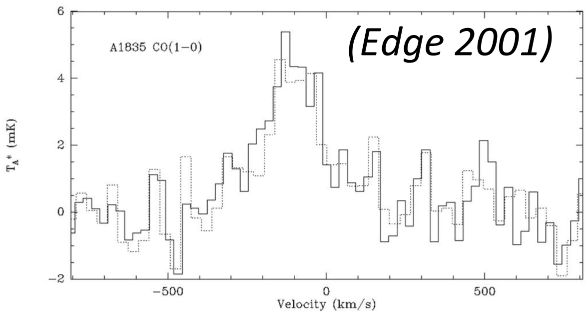
• high density



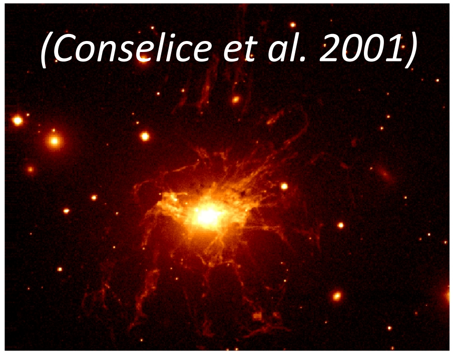
• low temperature



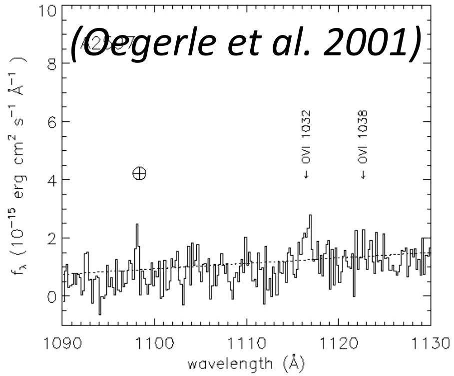
• molecular gas



• Hα filaments



• OVI



⇒ **evidence of cooling** (but star formation rates << X-ray cooling rates)

CF – observations

Lack of very cold gas !

XMM/RGS failed to show the strong emission lines expected from Fe XVII as the gas cooled below 0.7 keV

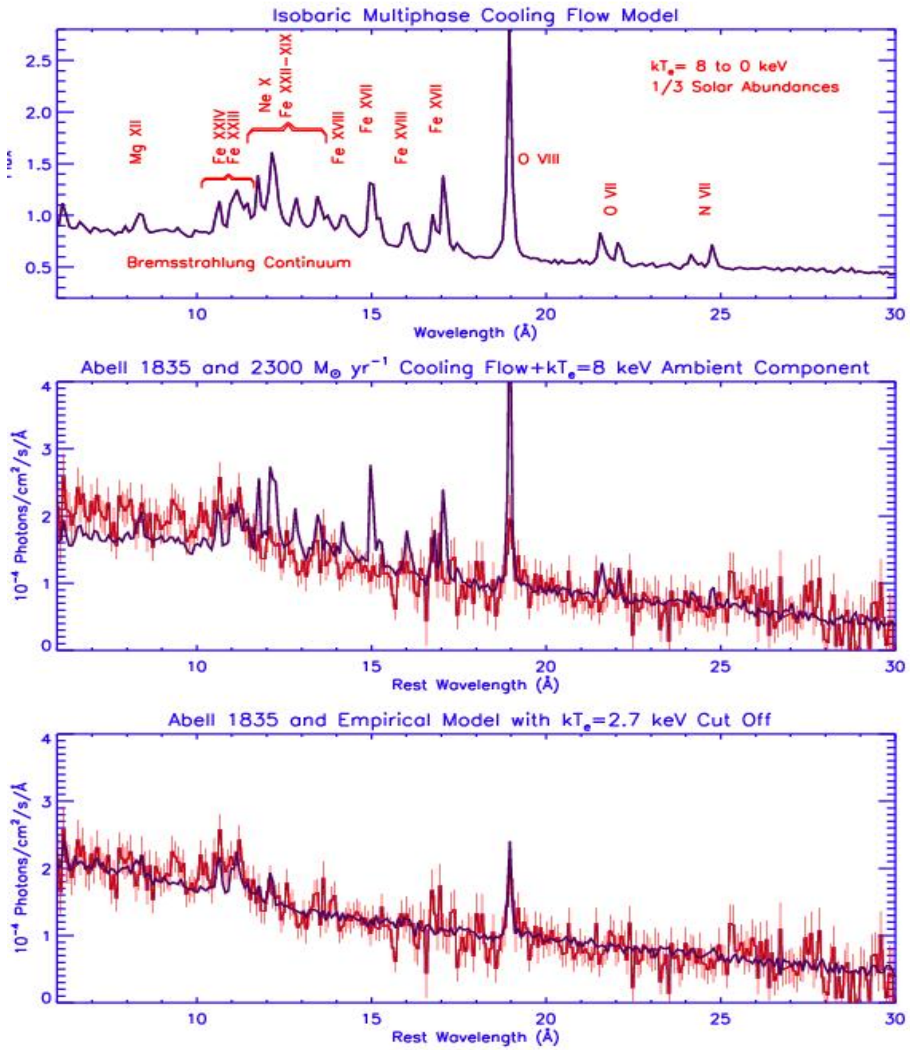
Gas drops to $T_{min} \sim 0.3\ T_{vir}$
Chandra spectra consistent

$$\dot{M}_{(<T_{min})} \sim (0.1\text{-}0.2)\ \dot{M}_X$$

⇒ CF problem:

why, and how, is the cooling of gas below T_{min} suppressed?

[new nomenclature: COOL CORE (CC)]



(Peterson et al. 2001)

CF problem – proposed solutions

- **Signature of cooling ≤ 1-2 keV suppressed**
  - absorption
    (Peterson+01, Fabian+01)
  - mixing with cooler gas/dust
    (Fabian+02, Mathews&Brighenti03)
  - inhomogeneous metallicity
    (Morris&Fabian03)

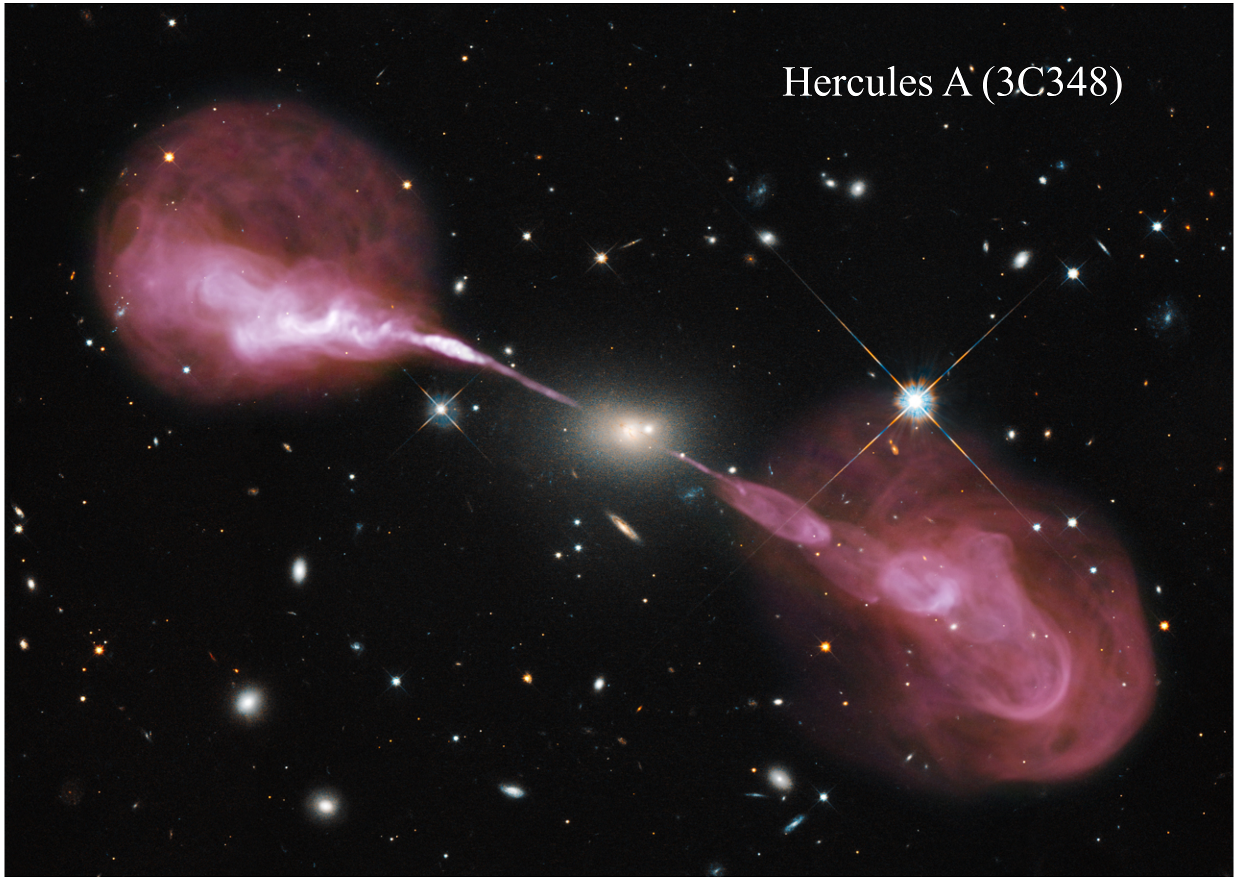
$$\dot{M} \sim \dot{M}_X$$

- **Heating balances cooling**
  - **central AGN**
    (e.g., Pedlar+90, Tabor&Binney93)
  - thermal conduction
    (e.g., Rosner&Tucker89)
  - subcluster merging
    (Markevitch+01)
  - intra-cluster SNe
    (Domainko,Gitti+04)
  - combinations/other...

$$\dot{M} \sim 0.1\,\dot{M}_X$$

Most promising solution to CF problem:

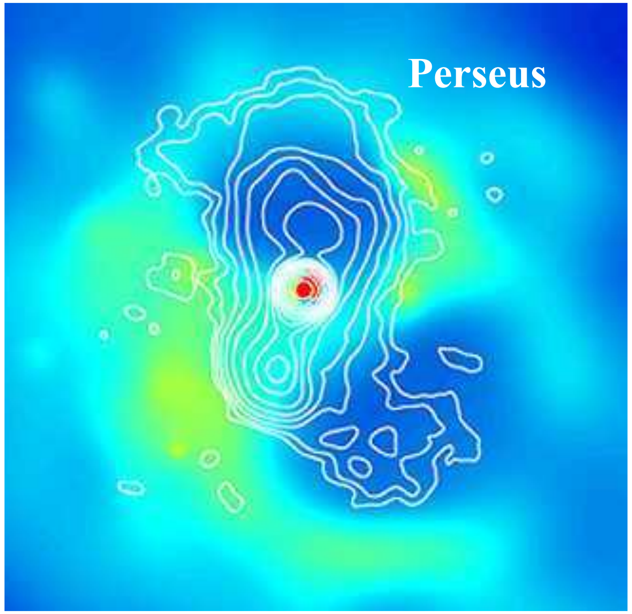
Radio-loud AGN



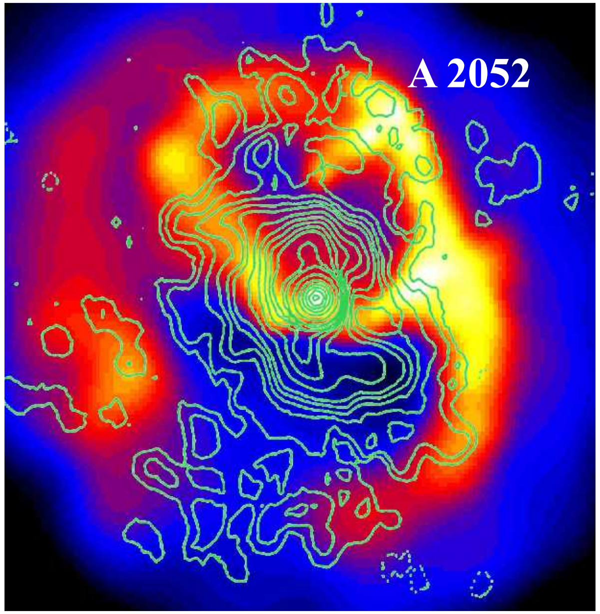
Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

AGN / ICM interaction

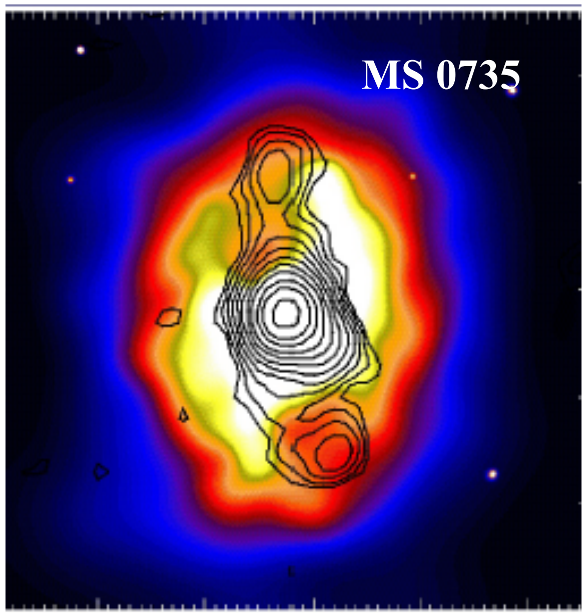
- most (~70%) CF clusters contain powerful radio sources associated with BCG
- central ICM shows "holes" often coincident with radio lobes (*Chandra*)



(Fabian et al. 2000)



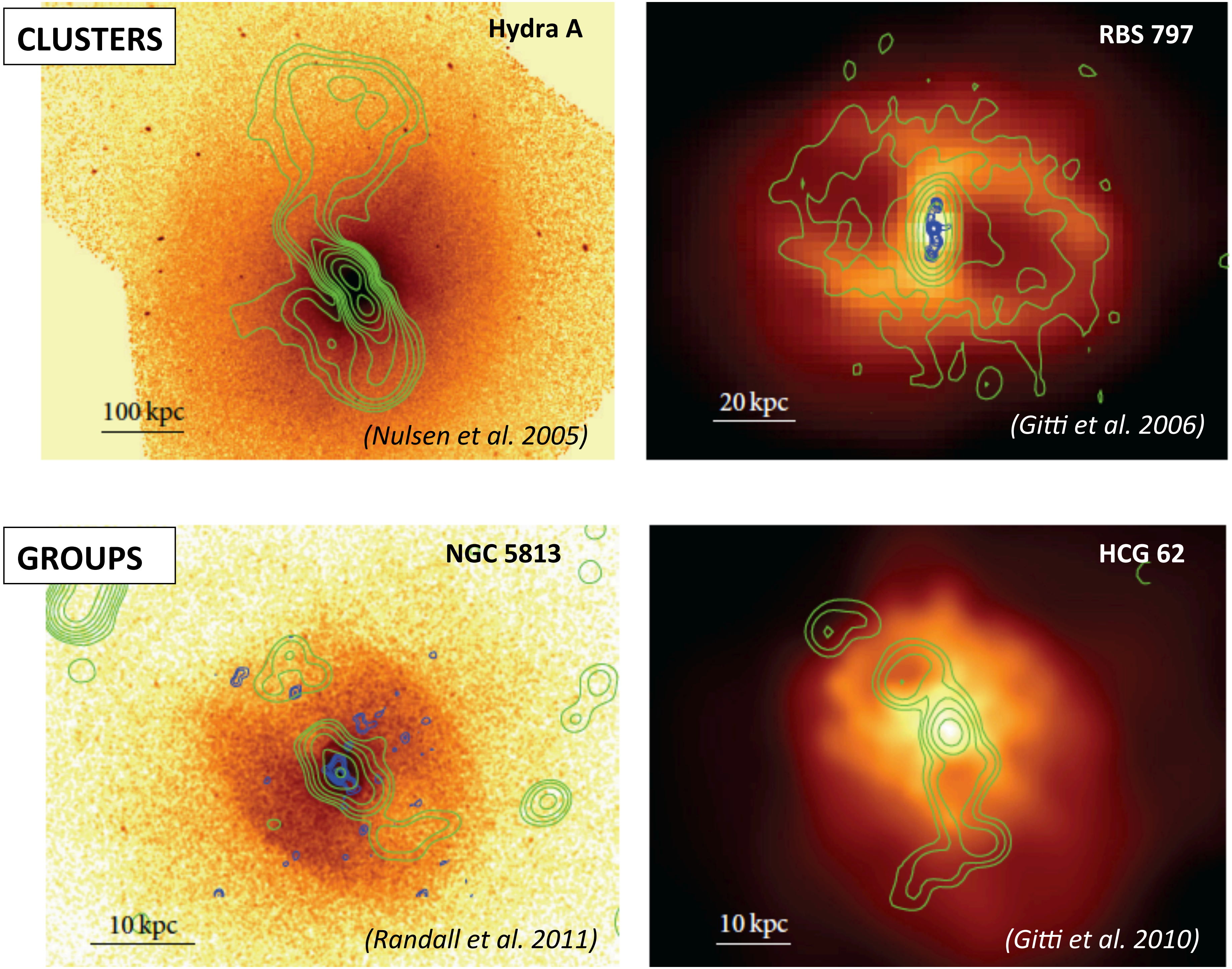
(Blanton et al. 2001)



(McNamara et al. 2005)

→ the radio "**bubbles**" displace the ICM, creating X-ray "**cavities**"

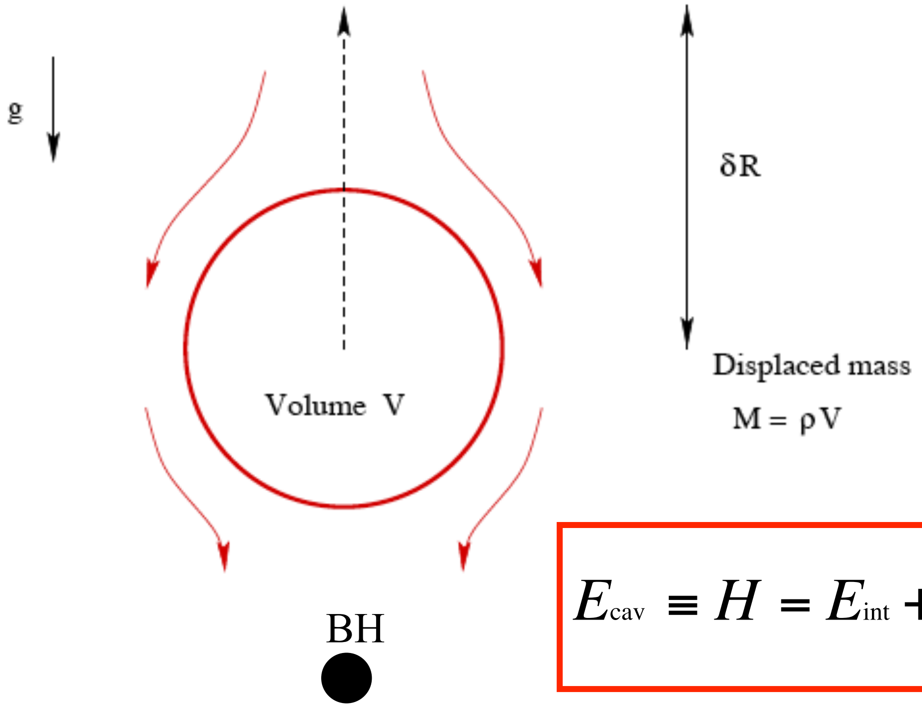
(see reviews by *McNamara & Nulsen 2007,2012*; *Gitti, Brighenti & McNamara 2012; Fabian 2012*)

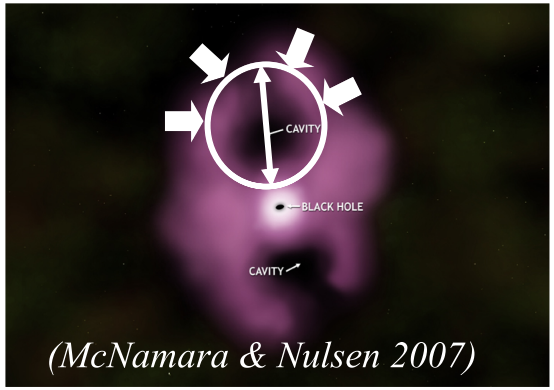


CLUSTERS
Hydra A
100 kpc
(Nulsen et al. 2005)
RBS 797
20 kpc
(Gitti et al. 2006)
GROUPS
NGC 5813
10 kpc
(Randall et al. 2011)
HCG 62
10 kpc
(Gitti et al. 2010)

Cavity (+ shock) heating

$$E_{\rm shock} \approx \Delta p V$$





(McNamara & Nulsen 2007)

the kinetic energy created in the wake of the rising cavity is equal to the enthalpy *H* lost by the cavity as it rises:

$$E_{\rm cav} \equiv H = E_{\rm int} + pV = \frac{\gamma}{\gamma - 1} pV = (2.5 - 4)\, pV$$

thermal plasma $\gamma = \frac{5}{3}$ relativistic plasma $\gamma = \frac{4}{3}$

direct measure of the *mechanical* (not synchrotron) energy

➔ total energy of AGN outburst: $E_{\rm tot} = E_{\rm cav} + E_{\rm shock} = 10^{55} - 10^{62}\,{\rm erg}$

X-ray cavities as gauges of jet power

$$E_{AGN} = E_{cav} + E_{shock} \geq E_{cav}$$

BUT shocks are very difficult to detect and are known only in a few systems..!

$$P_{AGN} \sim P_{cav} = \frac{E_{cav}}{t_{cav}} = \frac{4pV}{t_{cav}}$$

from: - sound crossing time
- buoyancy time
- refill time

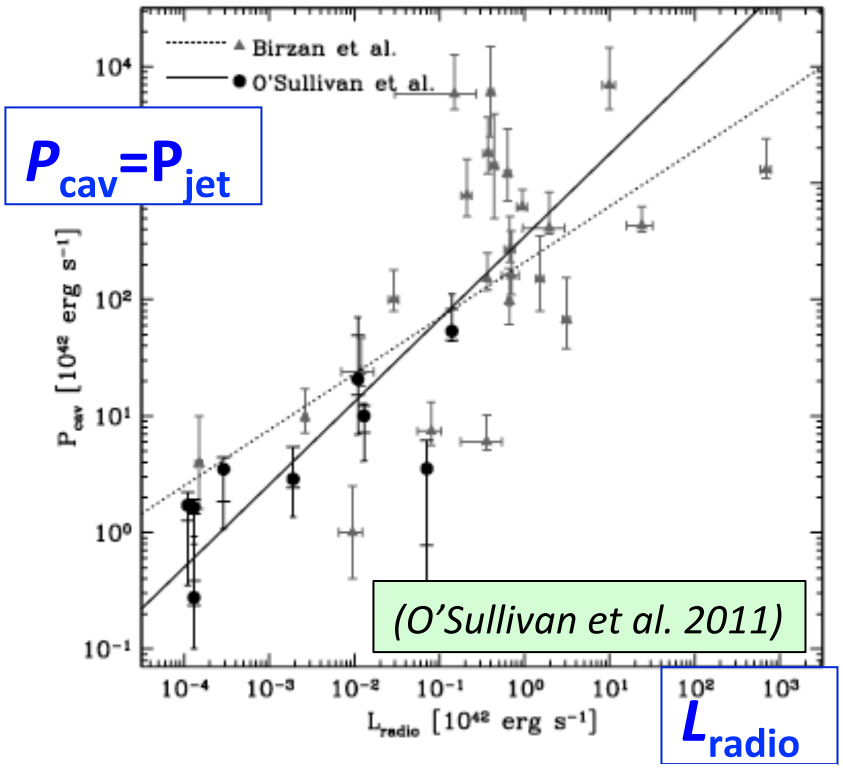
➔ P_{cav} provides the best-available gauge to the true total mechanical *(not synchroton!)* power of the AGN outburst

⇓

Radio syncrotron efficiency must be calibrated with observed cavities to derive a correlation:

total jet power (**P_{cav}**) vs. jet syn. power (**L_{radio}**)

➢ estimate of P_{AGN} from L_{radio}



$$\log P_{\rm cav} = 0.71(\pm 0.11) \log L_{\rm radio} + 2.54(\pm 0.21)$$

Study of radiosource properties ➢ radio lobe composition

$$\begin{cases} p_{radio} = p_B + p_{part} = \dfrac{E_B}{\phi V} + \dfrac{1}{3}\dfrac{E_{part}}{\phi V} = \dfrac{B^2}{8\pi} + \dfrac{1}{3}\dfrac{(1+k)E_e}{\phi V} \\ p_X \sim 2n_e kT \end{cases}$$

Standard equipartition assumptions:

- Φ =1 → lobes empty of thermal gas
- k = 1 → electron-proton jet
- k = 0 → electron-positron jet

It is typically found that $p_X \geq 10\ p_{radio}$

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Vice versa, it is possible to constrain the ratio k/Φ in the radio lobes by assuming pressure balance with the ambient gas *(Croston & Hardcastle 2014)*

→ Found large values $k/\Phi \gg 10$, interpreted as likely result of **entrainment from the surrounding atmosphere**

rather than evidence of heavy (= nonradiating relativistic proton) jets

The relationship between Jet Power and L_{cool}

For a sample of cavity systems, calculate and compare:

- $P_{AGN} \sim P_{cav} = \frac{E_{cav}}{t_{cav}} = \frac{4pV}{t_{cav}}$

P_{cav} is a measure of the energy injected into the ICM by the AGN outburst

- $L_{\rm cool} = L_X$ inside $r_{\rm cool}$

L_{cool} is the luminosity that must be compensated for by heating to prevent cooling

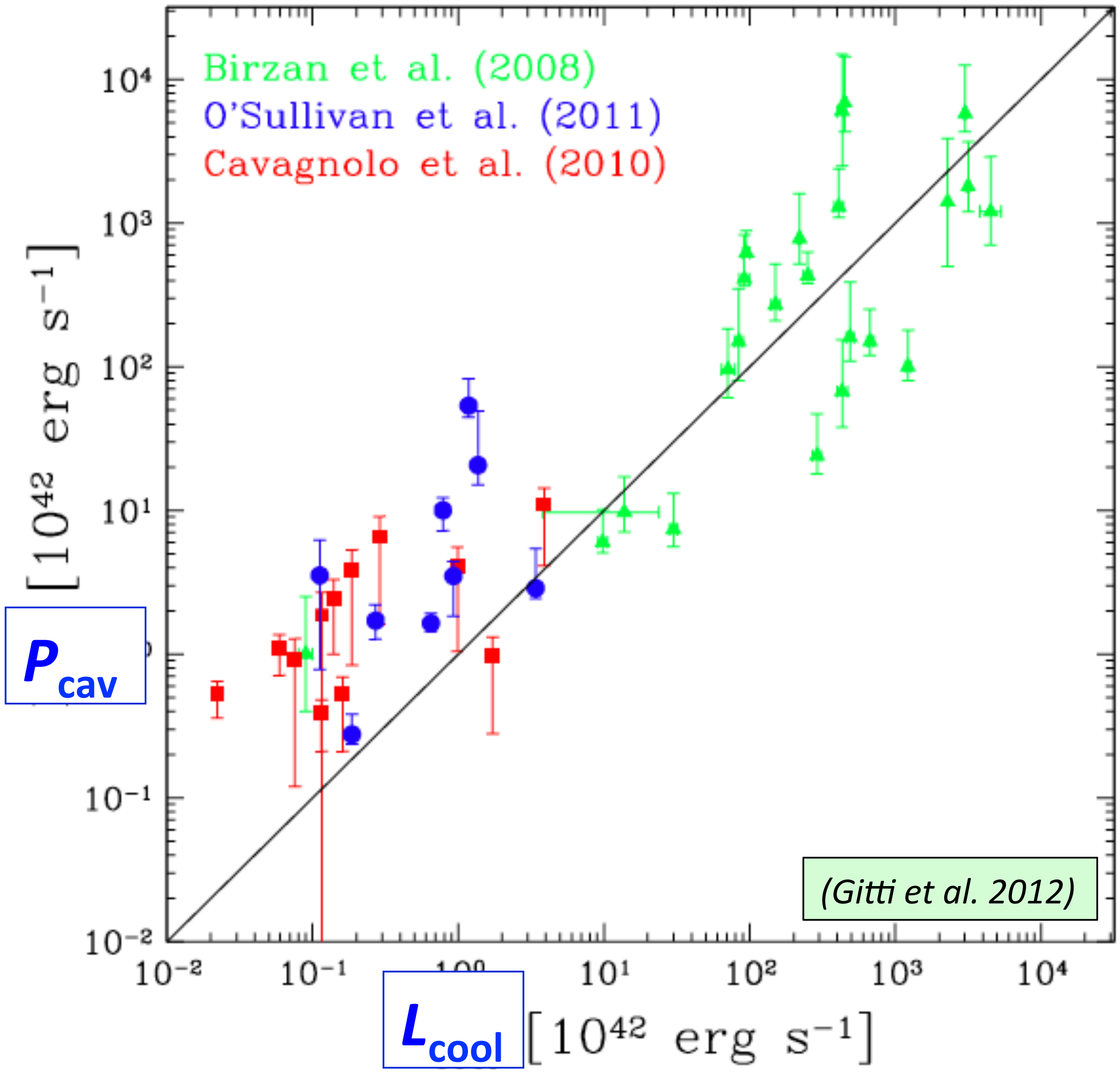
→ it is found that the cavity power scales in proportion to the cooling X-ray luminosity, although with a big scatter

Quenching cooling flows

Cavity properties

- diameter ~ 20-200 kpc
- $pV = 10^{55}$-10^{61} erg
- ages = 10^7-10^8 yr
- $P = 10^{41}$-10^{46} erg/s

trend: **feedback**



Quenching cooling flows

Sample mean values:

$L_{cool} = 4.1\times10^{44}$ erg/s

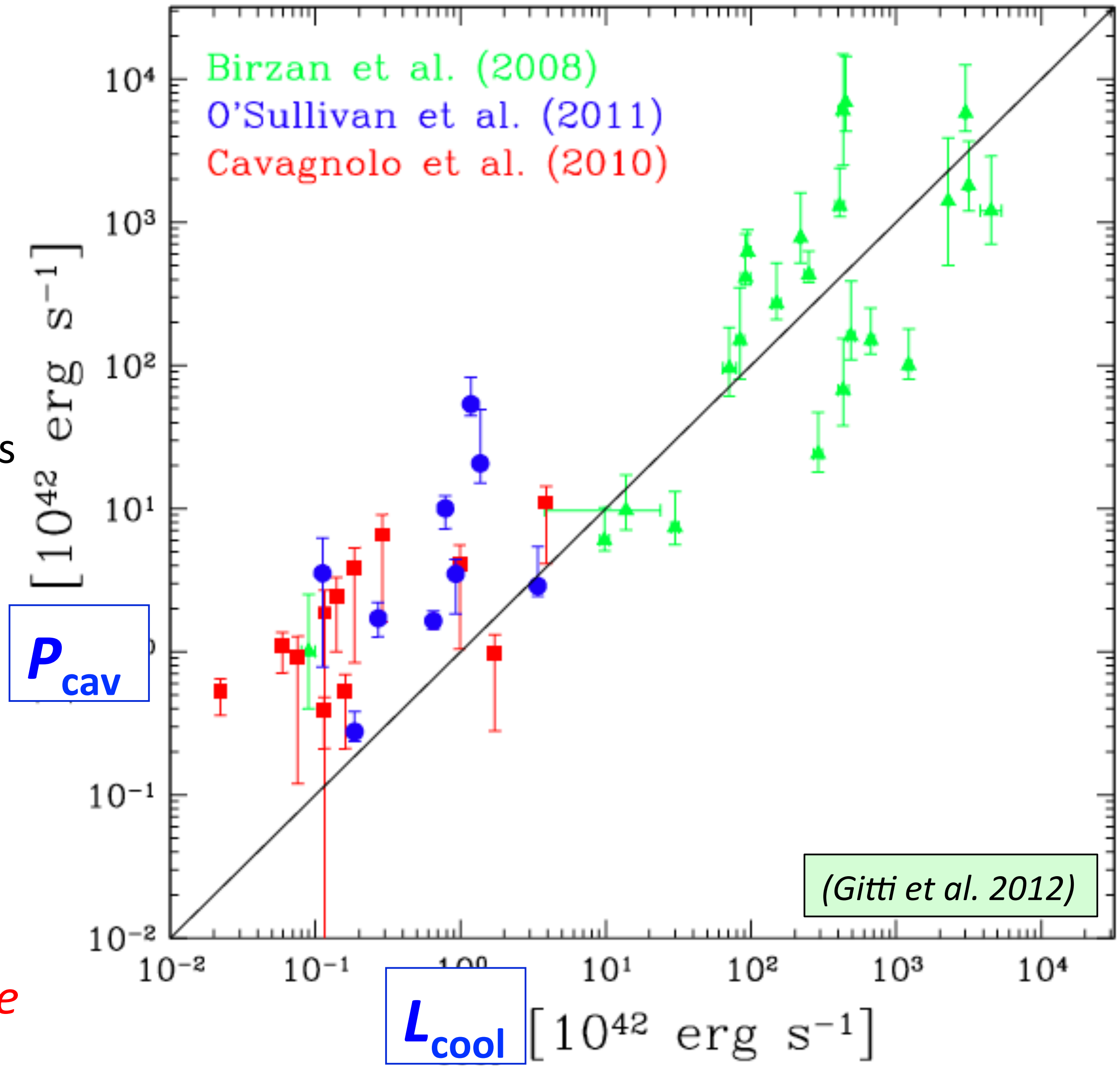
$P_{cav} = 6.2\times10^{44}$ erg/s

↓ *duty-cycle ~ 70%*

$P_{cav,d} \approx (0.7\times6.2)\times10^{44}$ erg/s

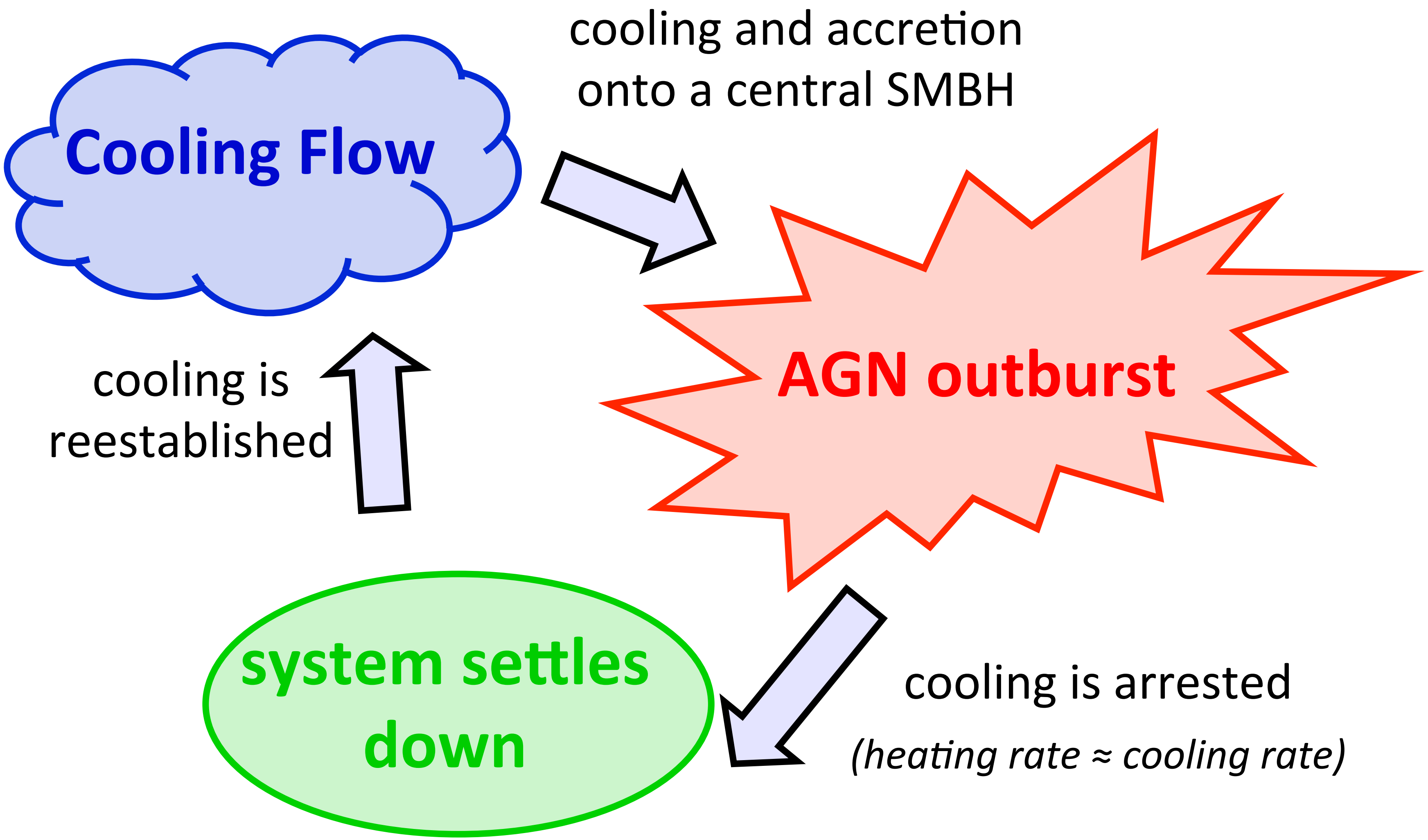
➔ $L_{cool} / P_{cav,d} \approx 1$

The radiative losses from the thermal ICM are balanced by mechanical heating from the central AGN *over the system lifetime*



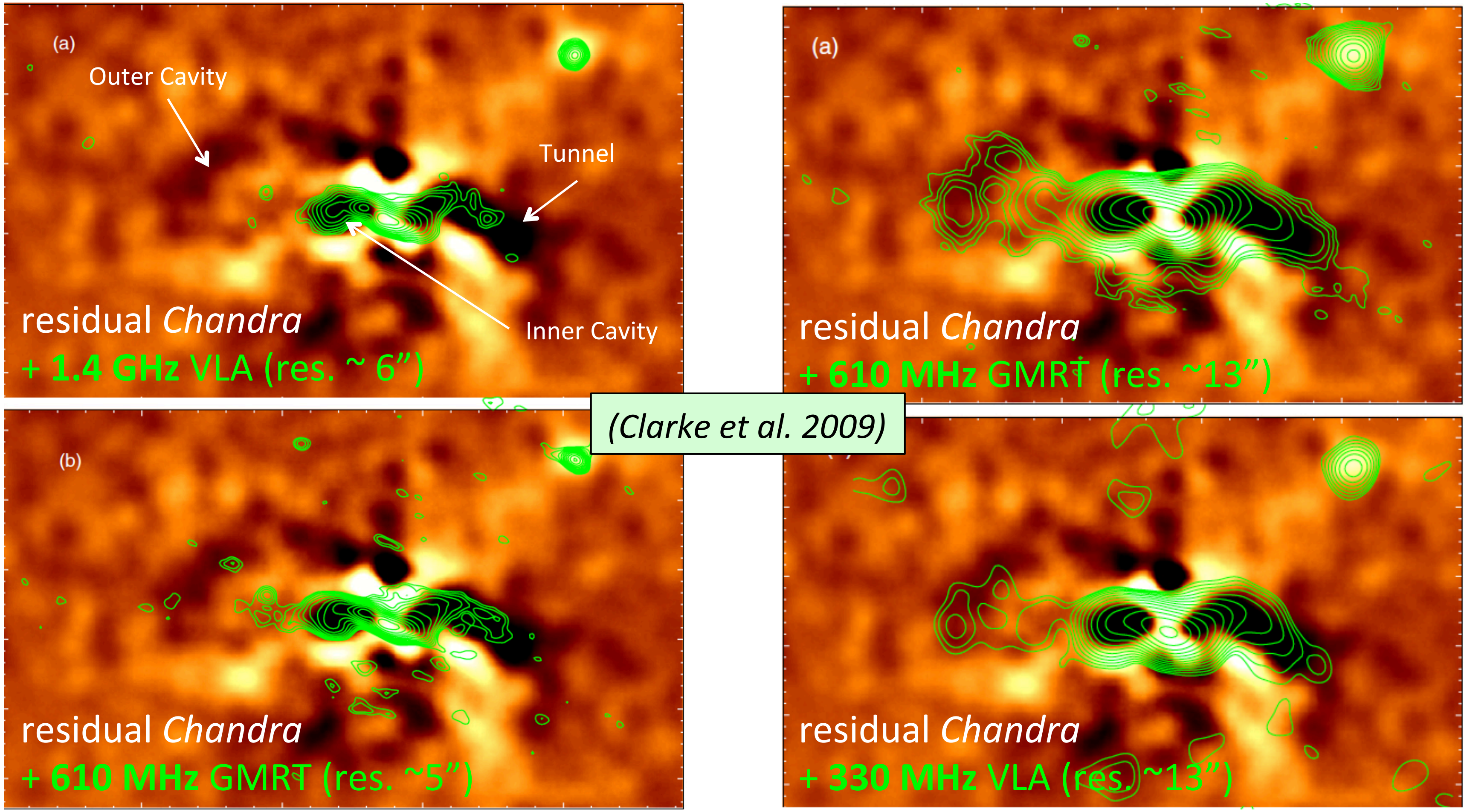
Self-regulated feedback loop

The AGN is fueled by a CF that is itself regulated by feedback from the AGN



Observations of X-ray cavities and shocks: catching the radio-AGN feedback in action

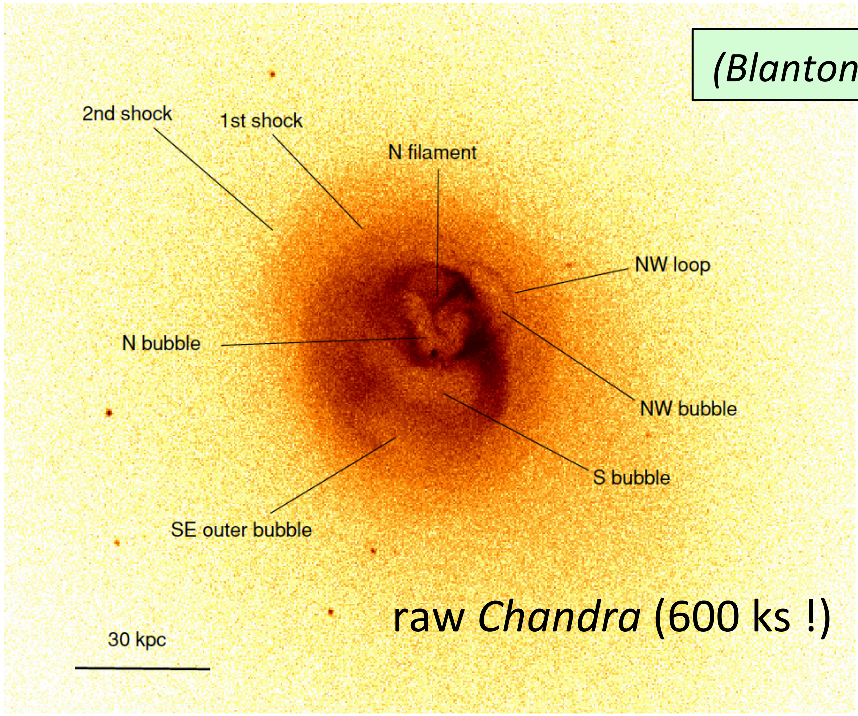
A 262: multiple generations of AGN feedback

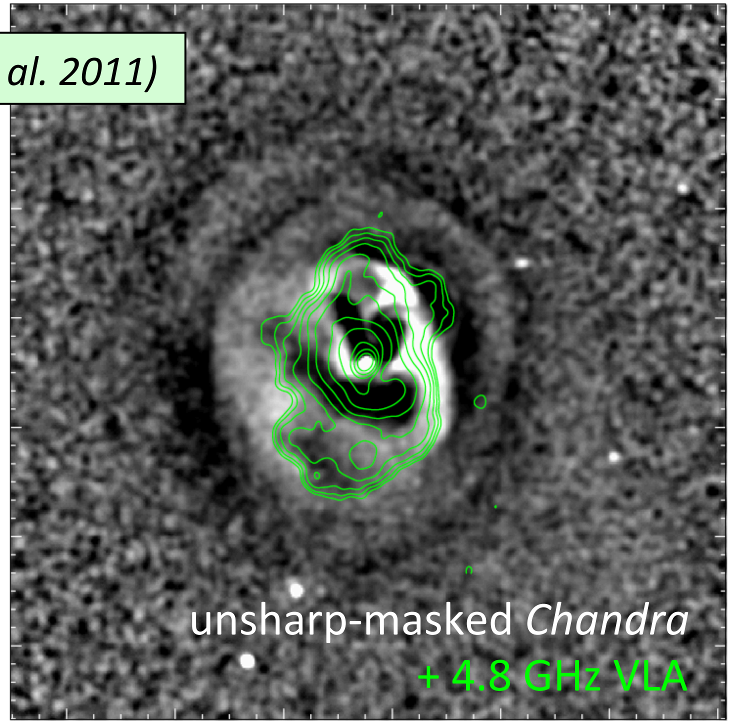


- X-ray tunnel filled with ***low-frequency*** radio emission: regions where multiple radio outbursts pile up and accumulate over several AGN activity cycles with $\tau_{rep} \geq 30$ Myr (series of overlapping buoyant lobes)
- source capable of offsetting radiative cooling over several outburst episodes

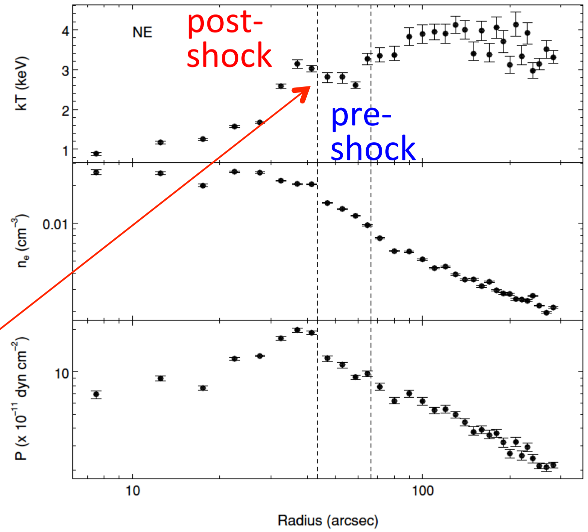
A 2052: bubbles, shocks and sloshing

(*Blanton et al. 2011*)

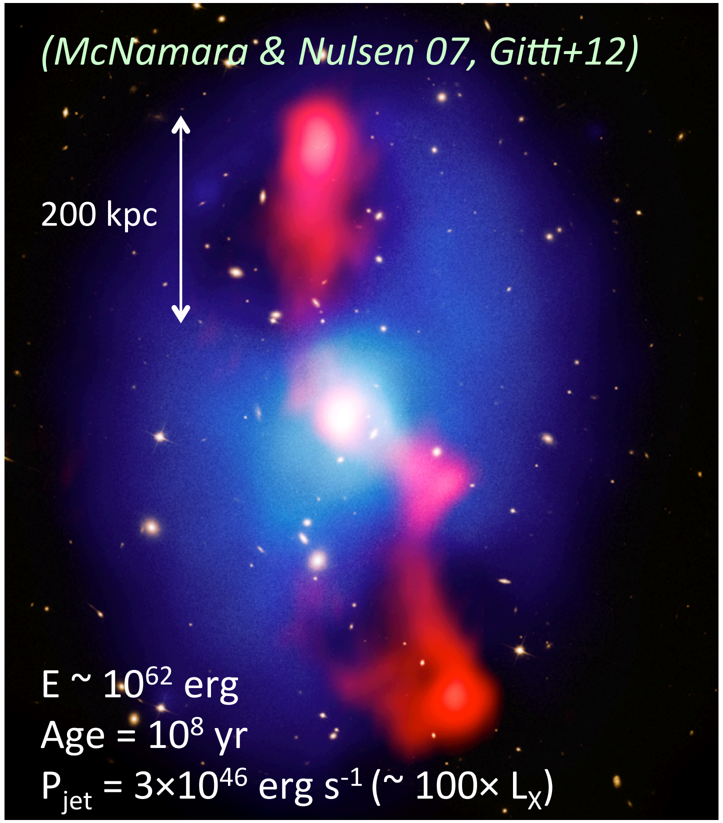




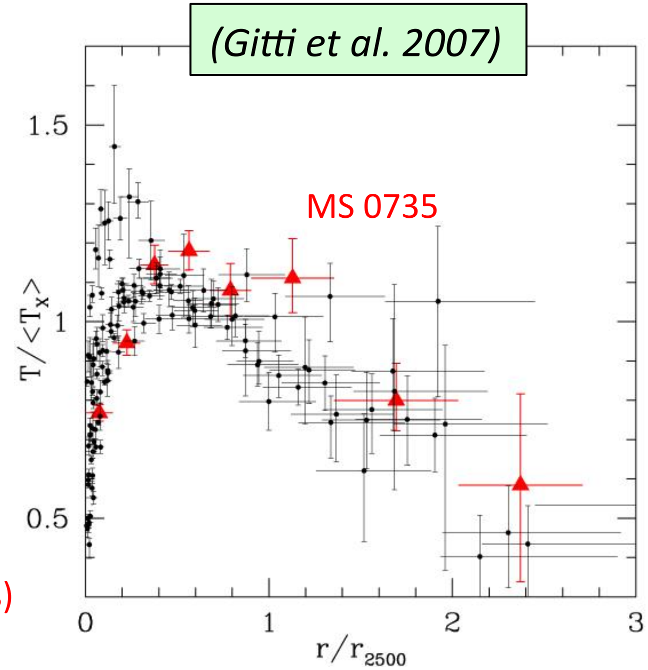
- Radio emission fills X-ray inner and outer cavities
- Cavities surrounded by X-ray bright rims, filaments
- Ripple-like features → two concentric weak shocks (temperature rise measured for the innermost one)



MS 0735: the most powerful AGN outburst



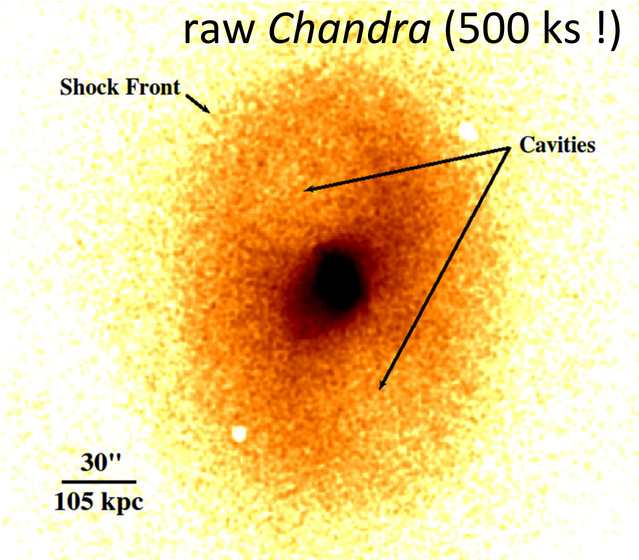
- AGN injects ~10^{62} erg into the ICM
  → heating up to cluster-wide scale
- Mass within 1 Mpc is being heated at the level of ~**1/4 keV/particle**
  → contribution to *"pre-heating"*
- ~2× more luminous than expected from observed $L \propto T^{2.6}$ cluster scaling relation
  → possible bias for flux-limited surveys
- ..but ***no marked effect on T profile***

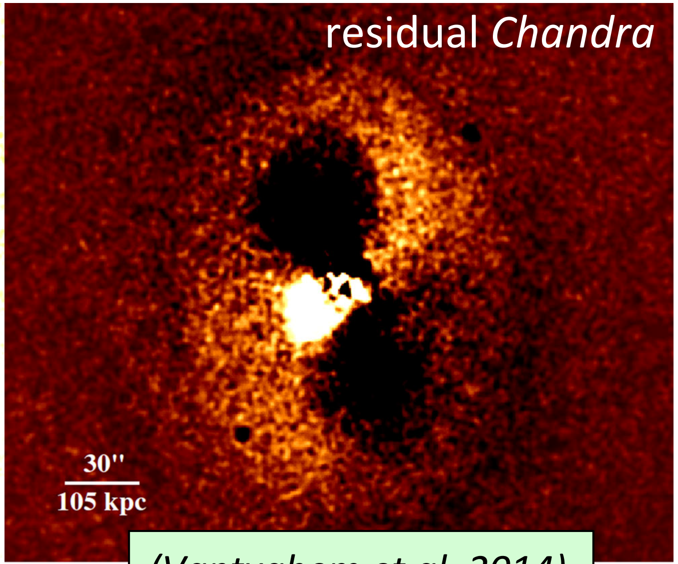


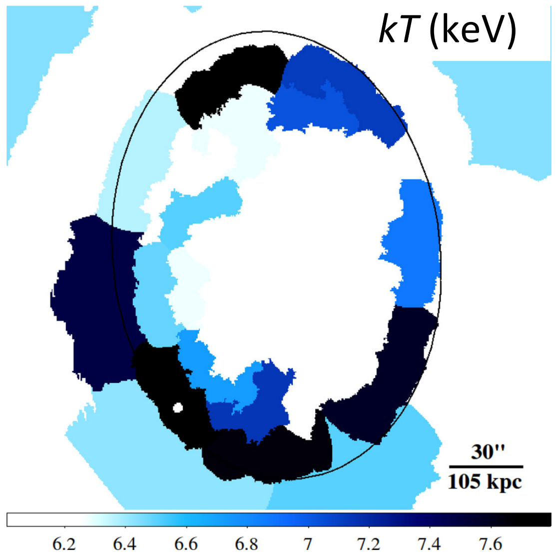
- Occurrence of giant cavities in ~10% of cavity samples, age ~ 10^8 yr *(Rafferty et al. 2006)*
- Outbursts active most of the time *(Dunn et al. 2005)*

→ powerful outbursts likely occur ~10% of the time in *most* CF clusters (rather than occurring most of the time in ~10% of clusters)

MS 0735: the most powerful AGN outburst





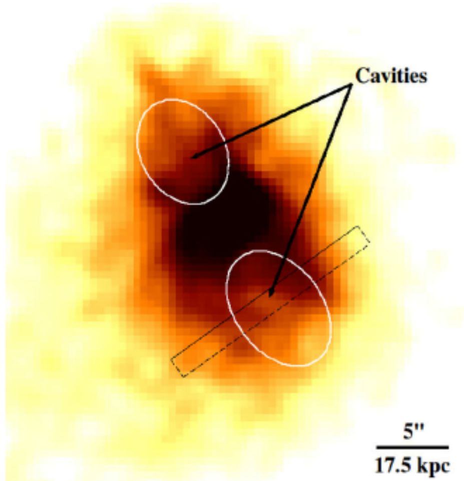


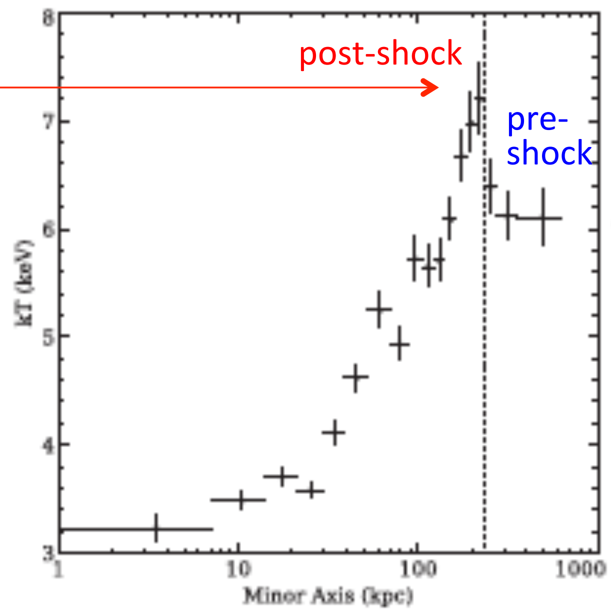
(Vantyghem et al. 2014)

- Elliptical shock front, *Mach*~1.3
  (measured ~ 1 keV temperature rise behind the shock) →

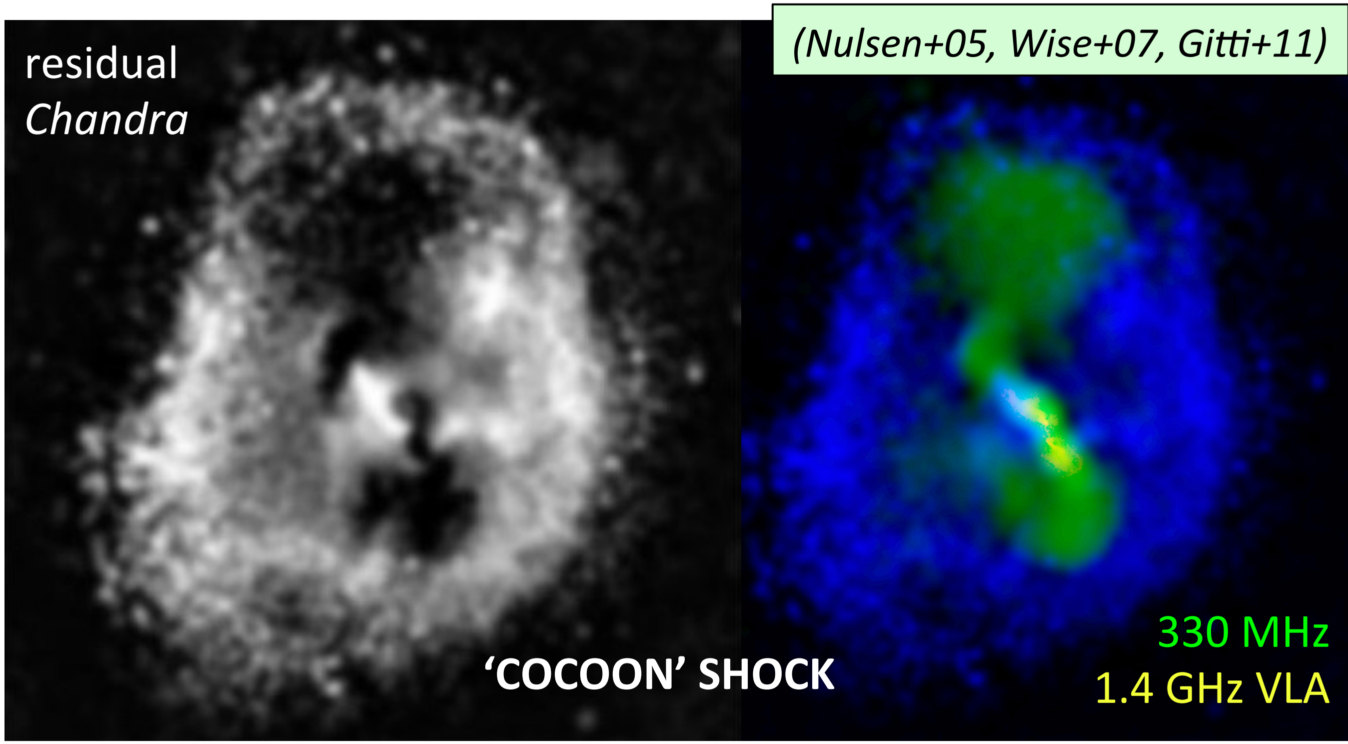
- Second pair of younger, smaller cavities along the jets
  → AGN power has declined by ~30× over the past 100 Myr

- Cool gas along the radio jets
  → Entrainment in the jets

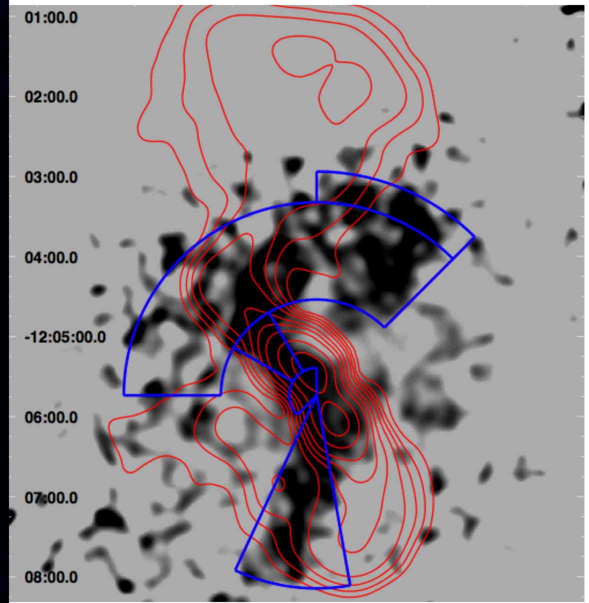




Hydra A: evidence for mechanical outflows

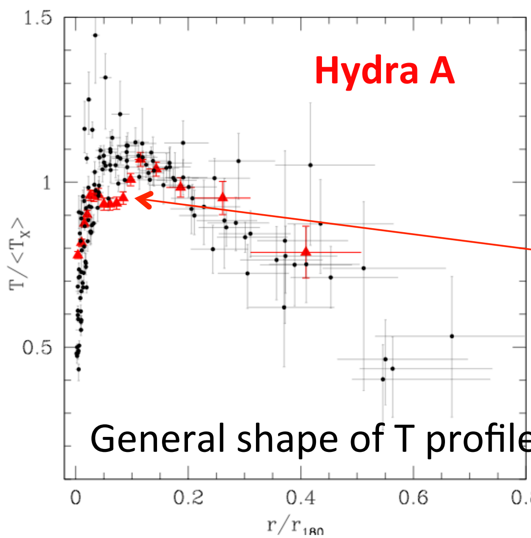


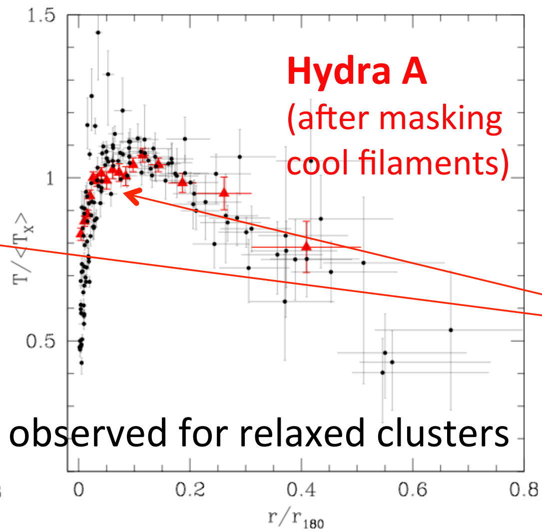
330 MHz VLA *(Lane+04)*



Chandra hardness ratio $\frac{[1.5-7.5]\mathrm{keV}}{[0.3-1.5]\mathrm{keV}}$

→ dark = low-temperature gas



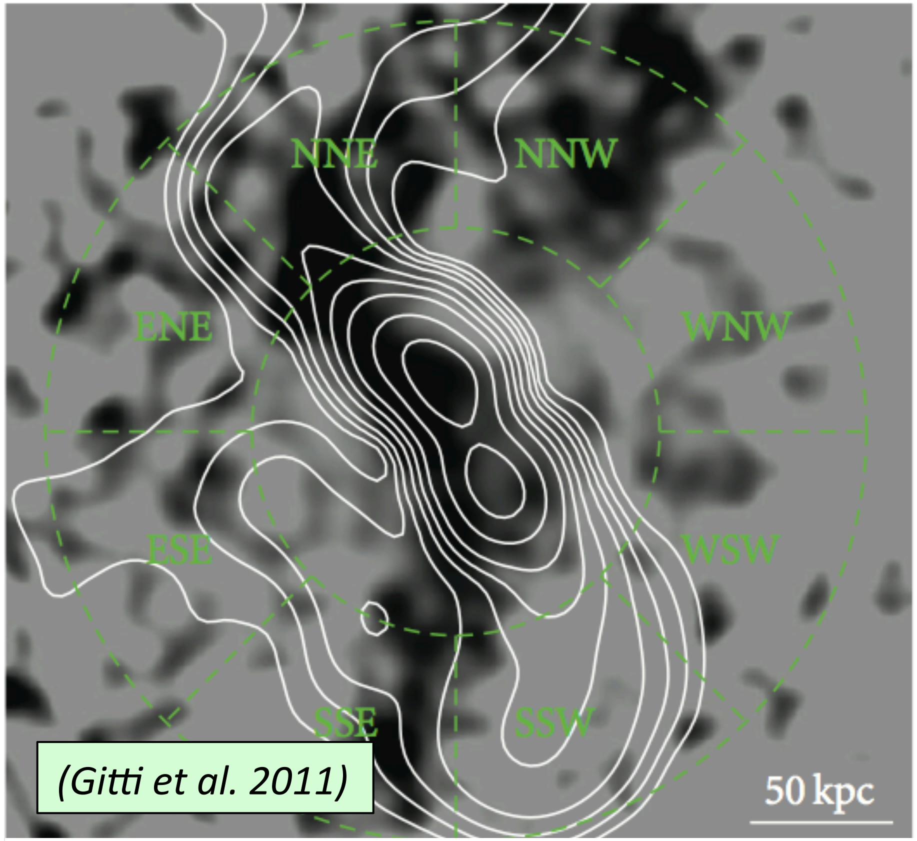


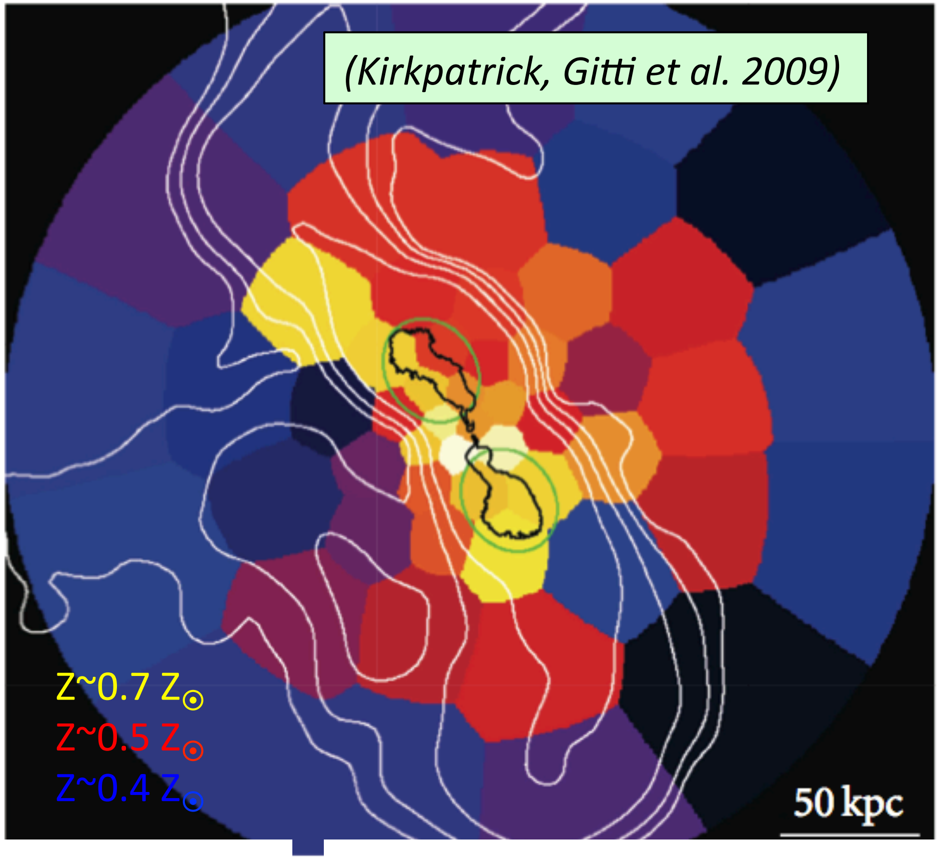
General shape of T profile observed for relaxed clusters

- Soft filaments seen in hardness ratio along the radio jets
- T 'plateau' in the region ~70-150 kpc (removed after masking filaments)

→ the filaments contain cool gas

Hydra A: evidence for mechanical outflows





- Spectral evidence for multi-phase gas along the filaments

  kT_{hot} ~ 4.0 keV
  kT_{cool} ~ 1.6 keV : $\boldsymbol{M_{cool}}$ **~ 10^{11}** $\boldsymbol{M_\odot}$ lifted from the center

  → outflows of ~few 100s $M_\odot$/yr in the rising lobes that can reduce the net inflow of cooling gas

  (energy required to lift gas ≈ work required to inflate cavities)

- Iron enriched outflow

  → AGN-Jets disperse metals throughout ICM

  ΔM_{Fe} ~5×10^7 $M_\odot$, R ~ 120 kpc

⇨ remove fuel for the SMBH

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A 10^{10} SOLAR MASS FLOW OF MOLECULAR GAS IN THE A1835 BRIGHTEST CLUSTER GALAXY

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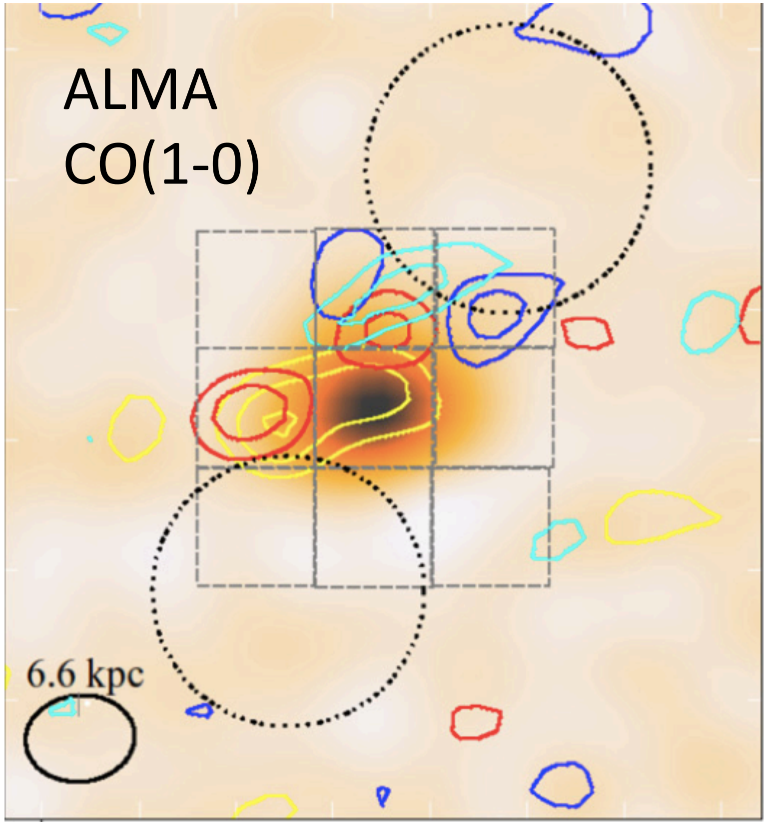


- 5×10^{10} $M_\odot$ of molecular gas within 10 kpc of the BCG

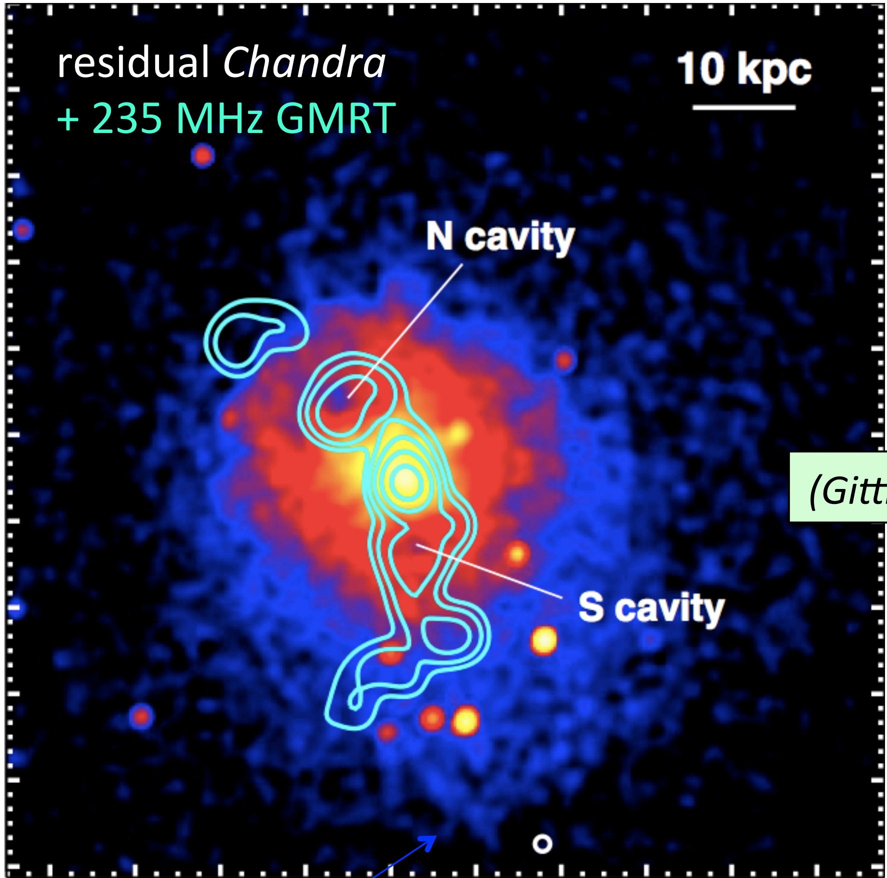
  Darkblue (−210 to −150 km s^{-1})
  Cyan (−150 to −110 km s^{-1})
  Yellow (70–270 km s^{-1})
  Red (270–470 km s^{-1})

- 10^{10} $M_\odot$ the molecular gas appears to be drawn up behind the rising bubbles

→ **molecular outflow driven by the radio AGN**

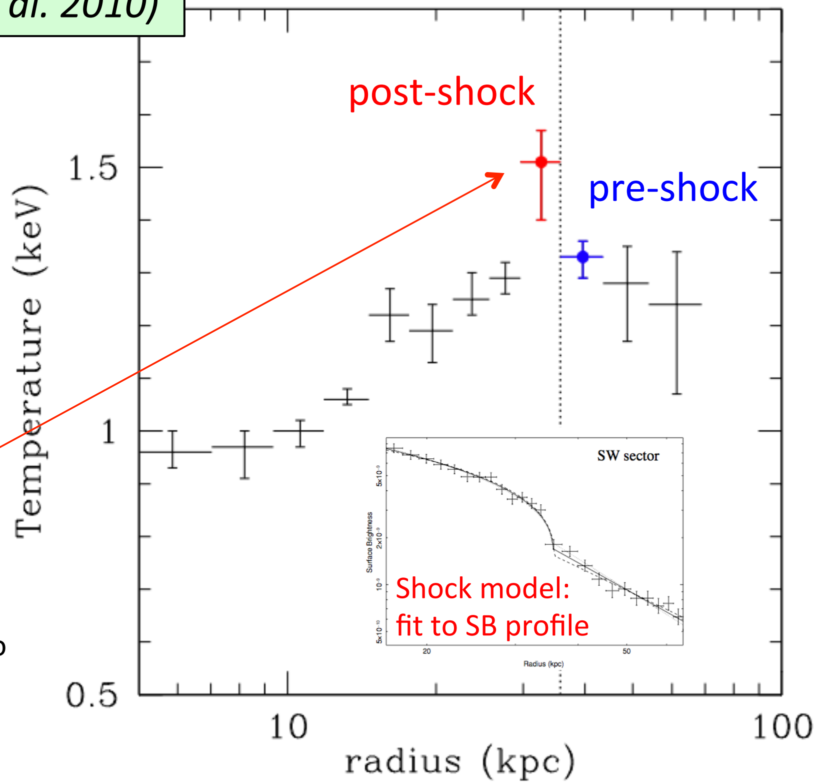
Figure 5. Left panel shows a color-scale image of CO (1–0) emission with color contours divided into separate velocity bins. The contours are integrated intensity in particular velocity ranges with $+2\sigma$, 3σ, 4σ. Dark blue (−210 to − 150 km s^{-1}), cyan (−150 to − 110 km s^{-1}), yellow (70–270 km s^{-1}), red (270–470 km s^{-1}). A two-dimensional Gaussian profile has been fitted to and subtracted from each channel in order to remove the central emission from the contour map. The right panel shows spectral extractions 1.8 × 1.8 arcsec on a side, roughly corresponding to the CO (1–0) beam size. The colors superposed on the spectra correspond to the velocity contours. This figure shows that the high-velocity molecular gas avoids the nucleus; higher speeds are observed at larger radii, indicating outflow. The black dotted circles show the locations of the X-ray bubbles. The molecular gas appears to be drawn up behind the rising bubbles.

HCG 62: first cavity detection in a galaxy group



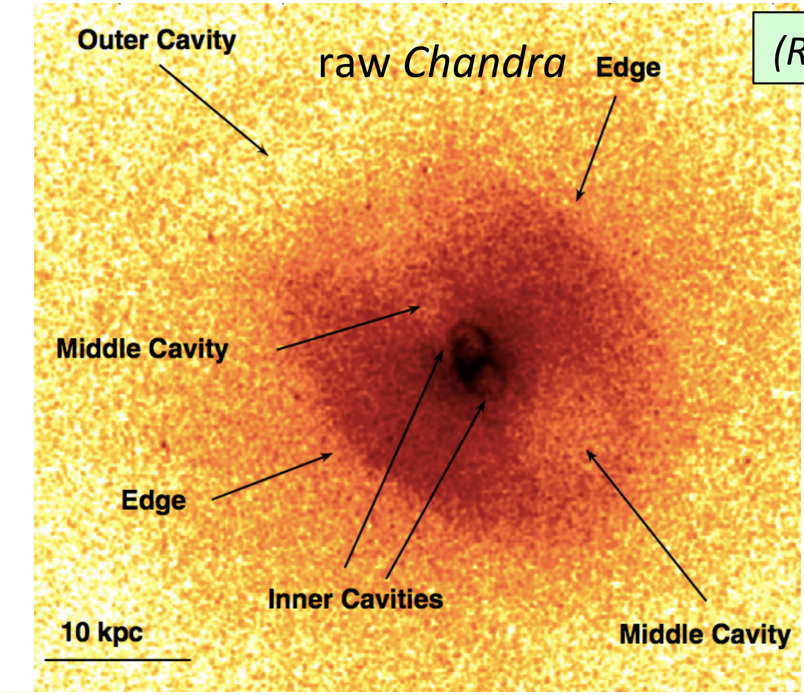
- Minimal radio emission at 1.4 GHz (*'ghost'*)
- Extended low-frequency (≤ 610 MHz) radio emission filling the X-ray cavities
- Low radiative synchrotron efficiency ~ 10^{-4}

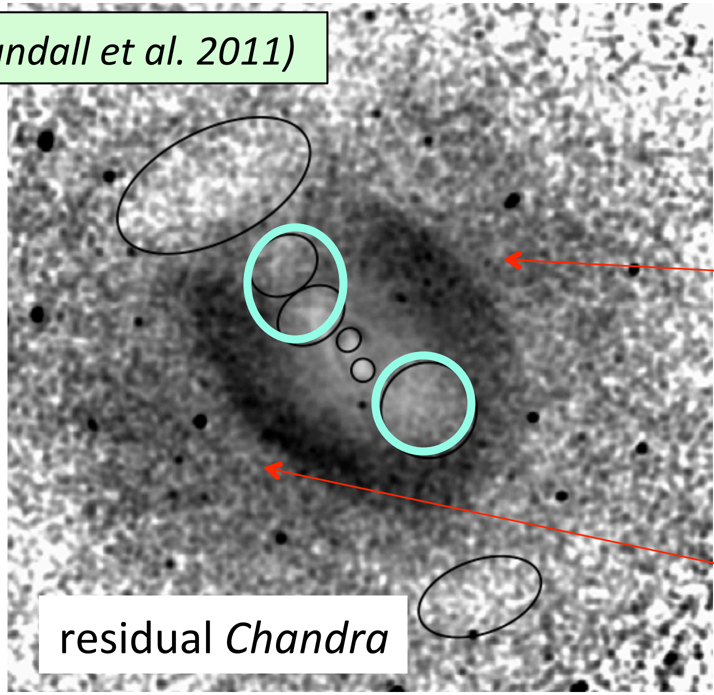
(Gitti et al. 2010)

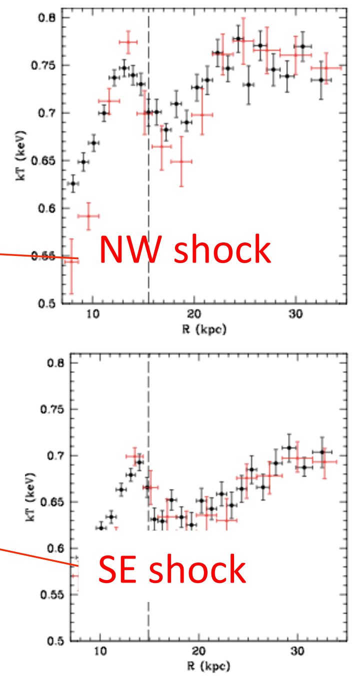


- Shock front, *Mach*~1.5 (measured ~15% T jump across the front)
- Pressure balance in the cavities: $p_X \sim 10\, p_{radio}$ → (hadronic jets or) entrainment

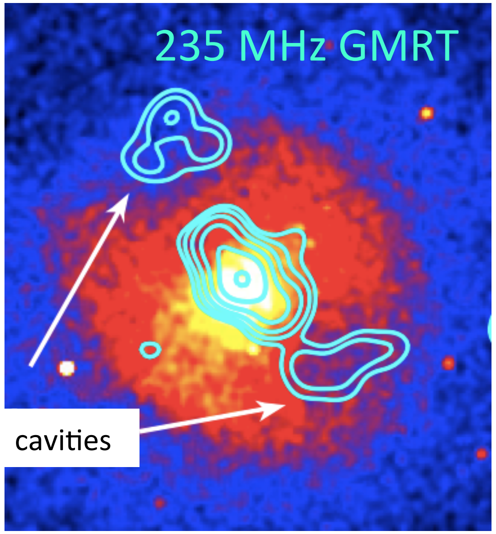
NGC 5813: shock heating in galaxy groups







- Clear signatures from *three* distinctive AGN outbursts
  - three pairs of collinear cavities
  - two shocks with *Mach*~1.6 (measured T jump)
- Outburst interval ~ 10^7 yr, with varying average jet power
- Shock heating: $(T\ \Delta S)/E = \Delta \ln(P/\rho^{\gamma})$, sufficient alone to offset radiative cooling of the gas close to the central AGN (≤10 kpc)
  → regulate feedback between the ICM and the central SMBH

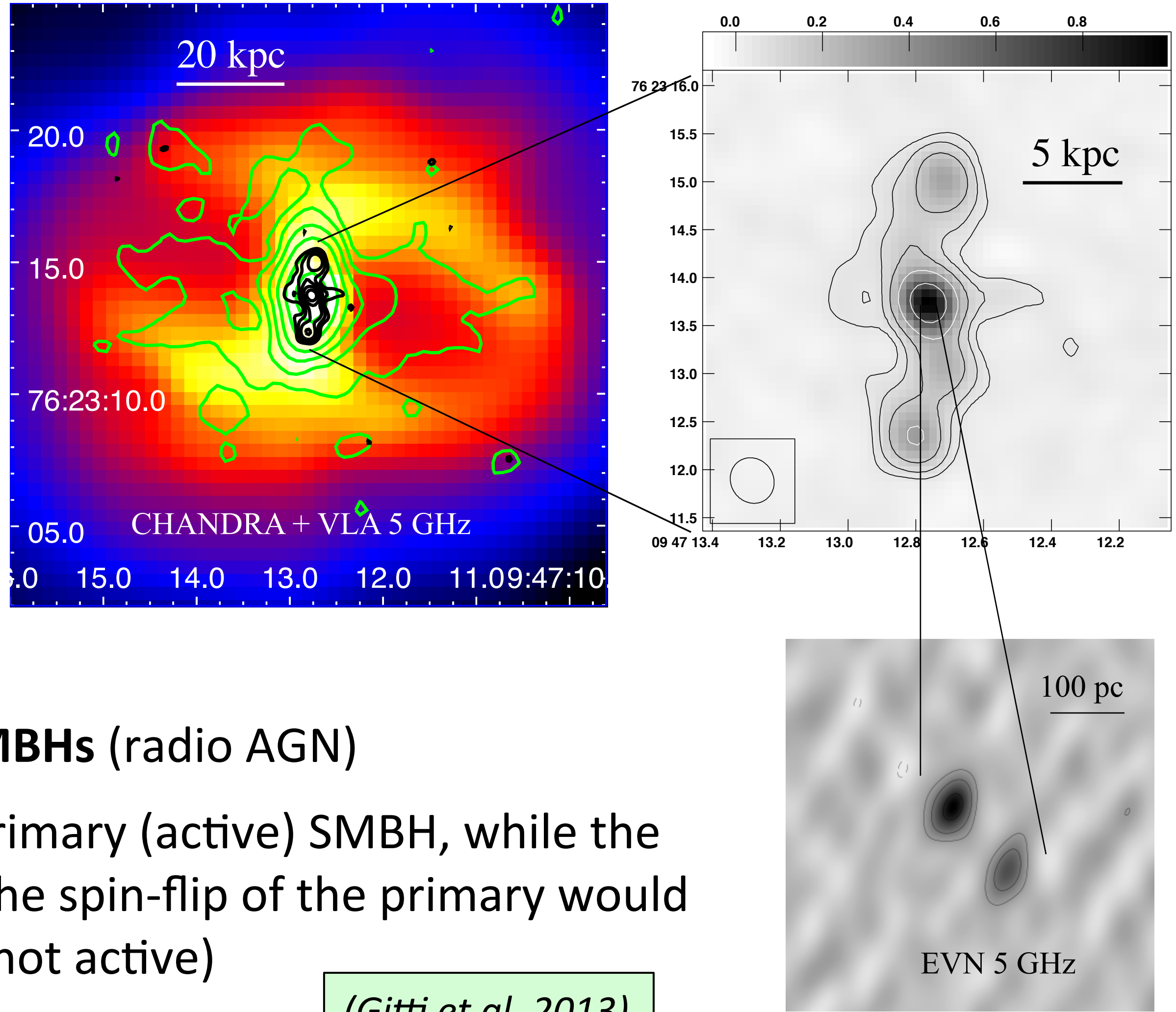


Peculiar examples of jet/ICM interaction: (in)direct evidence for SMBH binaries?

RBS 797

VLA jet-lobe misalignment + evidence for *two pairs* of jets at kpc-scale

Two VLBI compact radio components separated by only ~77 pc



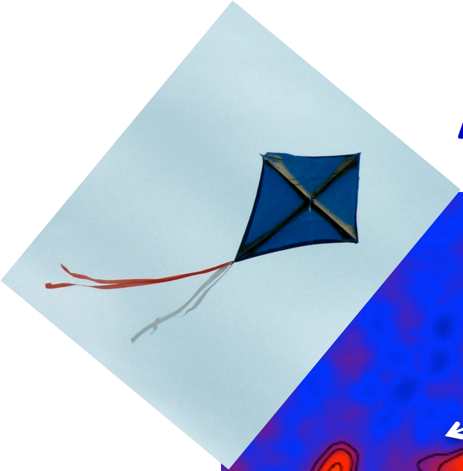
Possible scenarios:

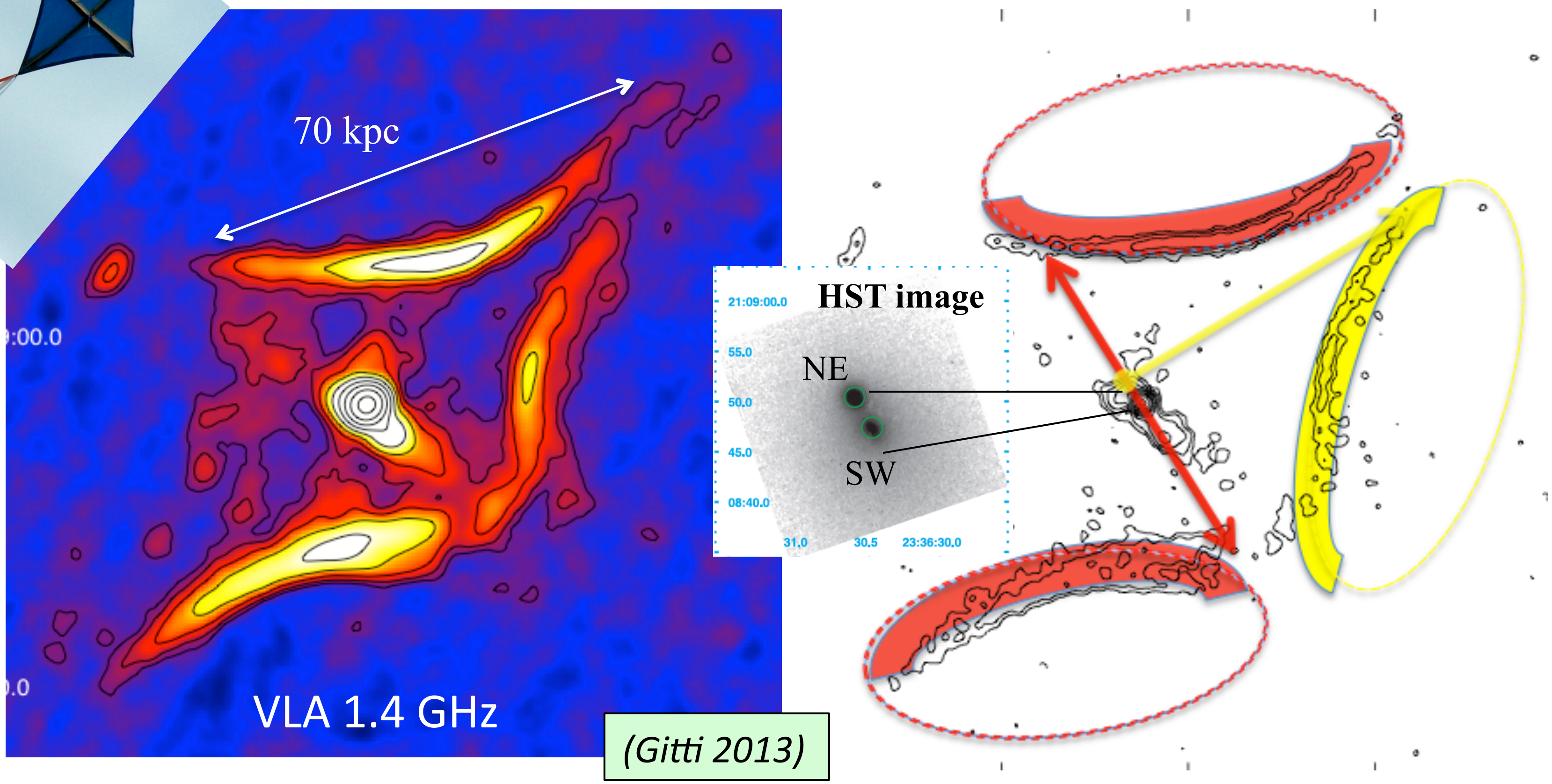
(1) Nuclei of **two active SMBHs** (radio AGN)

(2) Core-jet structure of primary (active) SMBH, while the secondary SMBH causing the spin-flip of the primary would remain undetected (likely not active)

(Gitti et al. 2013)

A 2626: the "Kite" radio source





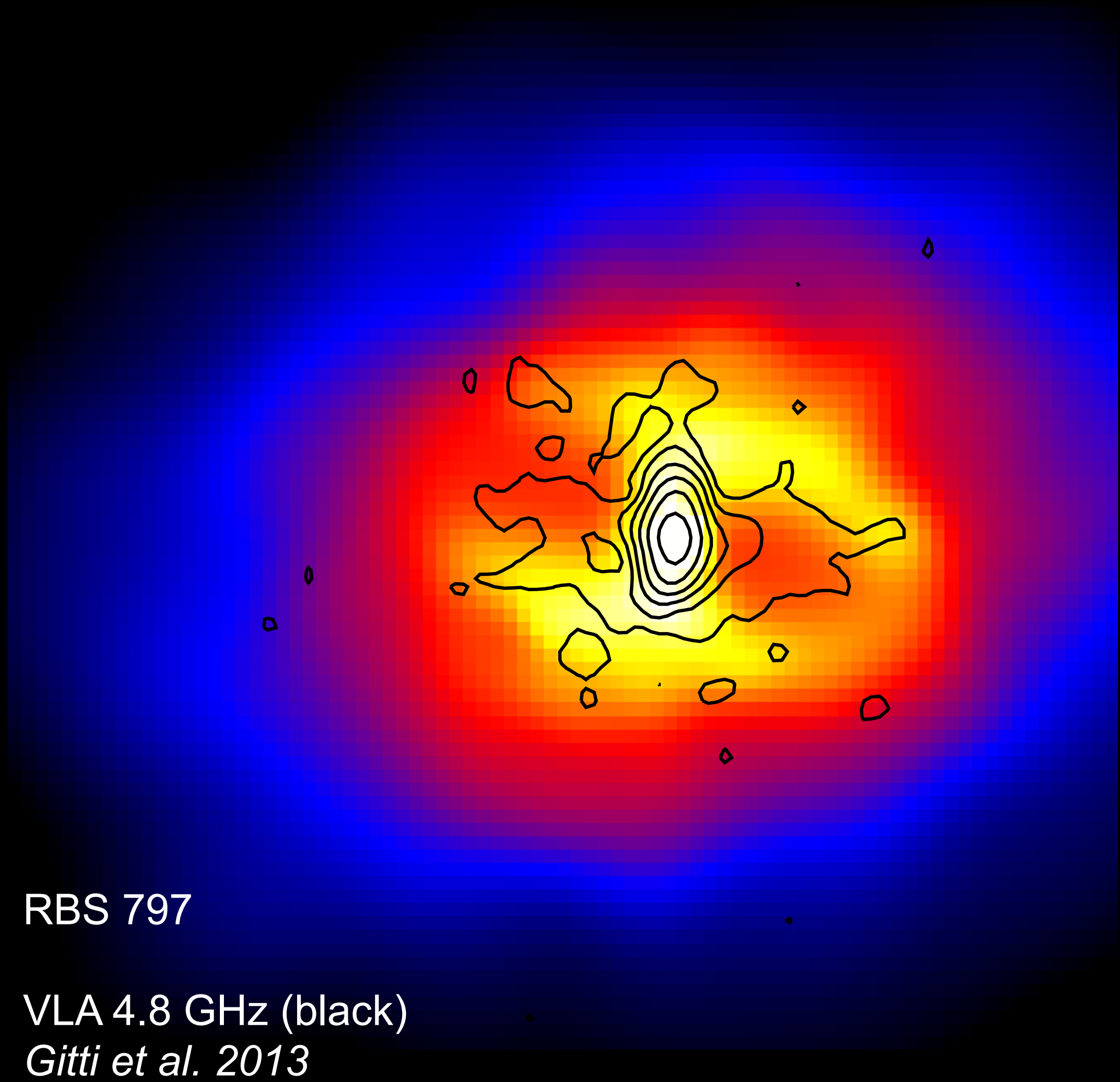
(Gitti 2013)

"Kite"-like radio source unlike typical jet-lobe structure in cool core clusters (no X-ray cavities), with *three symmetric radio arcs.* Possible scenarios:

(1) Radio emission powered by **two pairs of precessing jets**, one pair for each nucleus of the dumbbell cD (separation ~4 kpc), stopped at a "working surface"

(2) Relic sources accelerated by cluster shocks (but no polarization)

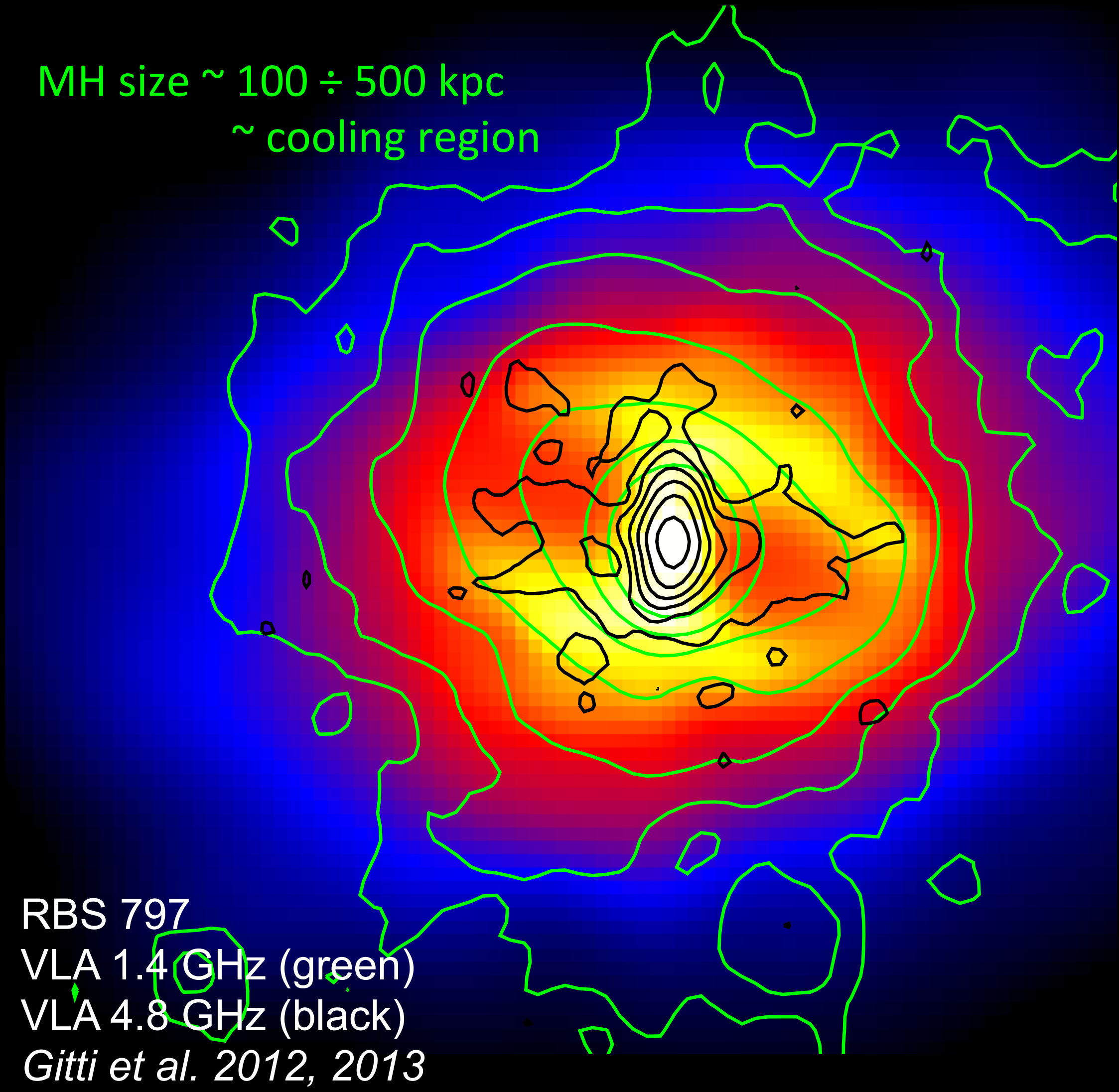
Non-thermal emission from CF clusters: (not only) radio-loud BCGs



- **<u>Radio-loud BCG</u>**: “bubbles” filling the X-ray cavities

→ *thermal and non-thermal components <u>spatially separated</u>*

Non-thermal emission from CF clusters: radio-loud BCGs + diffuse mini-halos



- **Radio-loud BCG**: "bubbles" filling the X-ray cavities

  → *thermal and non-thermal components spatially separated*

- **Radio mini-halo (MH)** :

  diffuse, faint, amorphous (roundish) radio emission surrounding the radio-loud BCG in a number of CF clusters not directly powered by central AGN but truly generated from ICM

  → *thermal plasma and relativistic electrons are mixed*

The future: the SKA view of CC clusters

PROCEEDINGS OF SCIENCE

The SKA view of cool-core clusters: evolution of radio mini-halos and AGN feedback

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Radio observations of galaxy clusters provide a wealth of information on the physics of the intra-cluster medium (ICM). In about 70% of the population of relaxed, cool-core galaxy clusters, the brightest cluster galaxy (BCG) is radio loud, showing non-thermal radio jets interacting with the surrounding thermal ICM. In recent years such interactions have been unambiguously shown thanks to spectacular images where the lobe radio emission is observed to fill the cavities in the X-ray-emitting ICM. This phenomenon is widespread and is critical to understand the physics of the inner regions of galaxy clusters and the properties of the central BCG. In a number of cases, the radio-loud BCGs are surrounded by radio mini-halos, diffuse radio emission on scales comparable to that of the cooling region. Mini-halos are not directly connected with radio bubbles but the emission is on larger scales and is truly generated from the ICM. Large mini-halo samples are necessary to establish their origin and connection with the clusters thermal properties and dynamics, also in the light of future X-ray characterization of the cluster cores as it is expected by ATHENA-XIFU. We show that All-Sky reference survey at Band 2 with SKA1 at confusion limit (rms $\sim$2 μJy per beam) has the potential to detect up to $\sim$ 700 mini-halos at redshift $z <$ 0.6, whereas Deep Tier reference surveys at Band 1/2 with SKA1 at sub-arcsec resolution (rms $\sim 0.2\mu$Jy per beam) will allow a complete census of the radio-loud BCGs at any redshift down to a 1.4 GHz power of 10^{22} W Hz^{-1}. We further anticipate that the full SKA might detect up to $\sim$ 2000 new mini-halos at redshift $z < 0.6$ and characterize the radio-mode AGN feedback in every cluster and group up to redshift $z \sim 1.7$ (the highest-z where virialized clusters are currently detected) and even beyond, thus providing a complete picture of the feedback phenomenon and its role in shaping the large scale structure of the Universe.

Advancing Astrophysics with the Square Kilometre Array
June 8-13, 2014
Giardini Naxos, Sicily, Italy

*Speaker.

◆ **<u>SKA1:</u>**

- complete census of radio-loud BCGs at any z down to $P_{1.4} \sim 10^{22}$ W Hz^{-1}
- detect radio bubbles in clusters at any z
- detect up to ~700 new MHs at z<0.6

◆ **<u>full SKA:</u>**

- characterize radio-mode AGN feedback in every cluster and group up to $z \sim 1.7$
- detect up to ~2000 new MHs at z <0.6

➢ SKA will open an unprecedented window on the exploration of the AGN feedback phenomenon and its role in shaping the large scale structure of the Universe

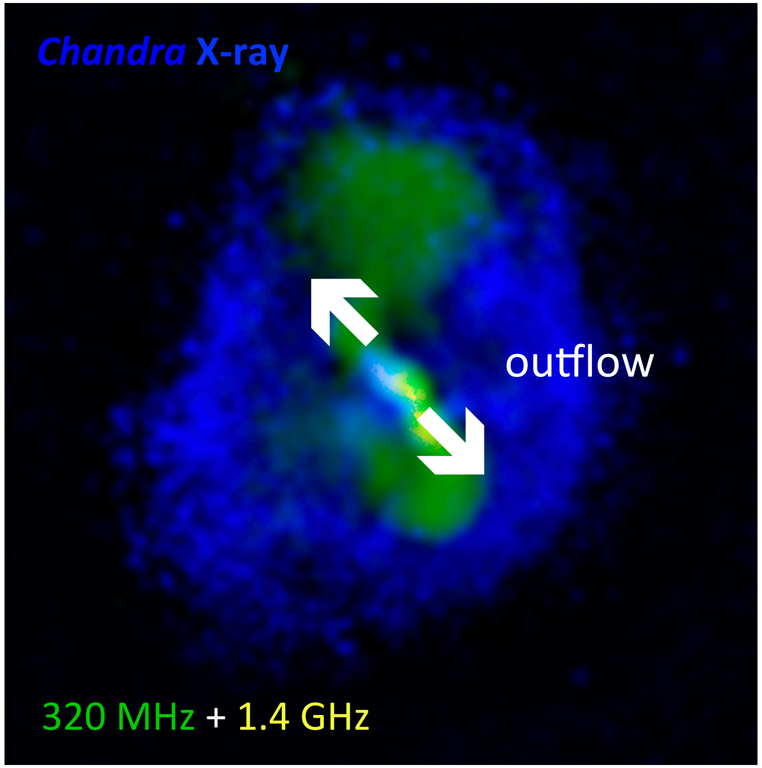
(Gitti et al. 2015, in "Advancing Astrophysics with the Square Kilometer Array")

Conclusions

- The main evidence of the action of radio-mode AGN feedback is in cool-core clusters and groups

- Radio-mode AGN feedback manifests as collimated, massive subrelativistic bipolar outflows emerging from the BCG core, that inflate large radio bubbles while carving X-ray cavities and driving weak shocks, heat the ICM and induce a circulation of gas and metals on scales of several 100s kpc

  (..but many details still unclear..)



- SKA (in synergy with ATHENA) will trace and characterize the radio-mode AGN feedback activity in any cluster up to z~1.7


Thank you
Myriam Gitti
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