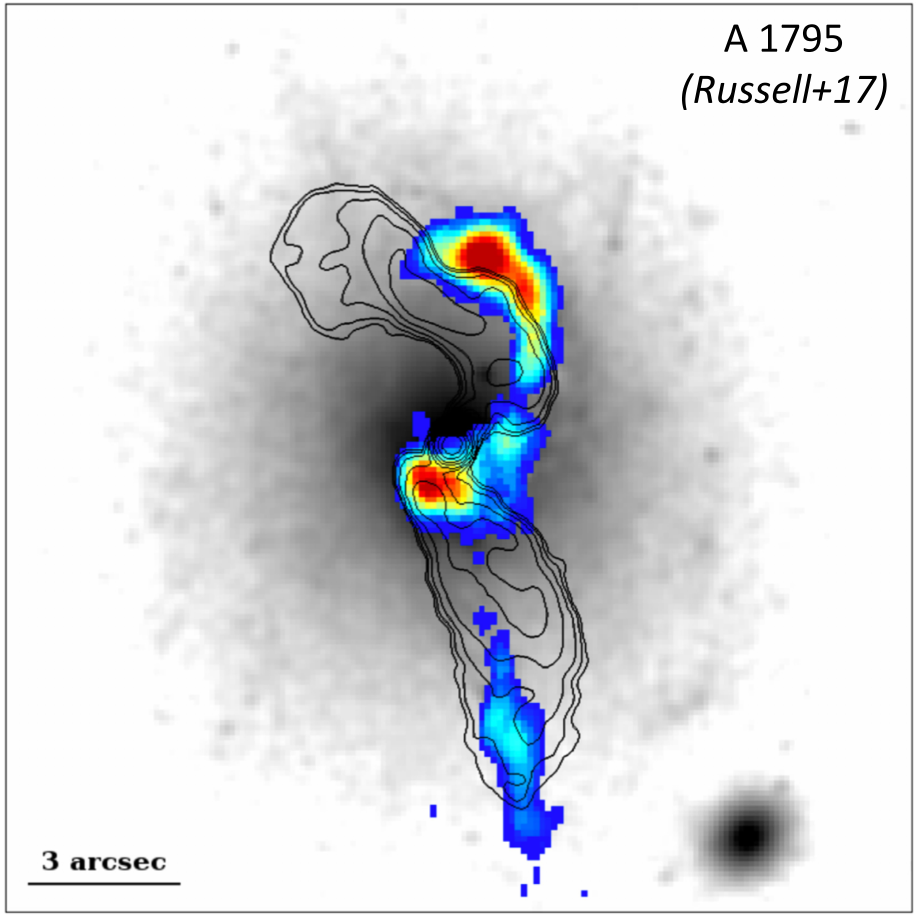
AGN feedback and molecular gas flows in clusters of galaxies: the ALMA view



Myriam Gitti

DIFA – University of Bologna

INAF – IRA Bologna

Outline of the talk

- **Introduction**
  - intra-cluster medium (ICM), cooling flow (CF) and "cooling flow problem"
- **Radio-mode AGN feedback (as solution to CF problem)**
  - AGN/ICM interaction: cavity heating and CF quenching
  - observations of X-ray cavities, radio bubbles and weak shocks
- **ALMA observations of molecular gas in central galaxies**
  - massive extended CO filaments, smooth velocity gradients
  - AGN-driven gas outflows
  - direct uplift of molecular clouds or cooling in situ?
- **Conclusions**

Clusters of galaxies and ICM

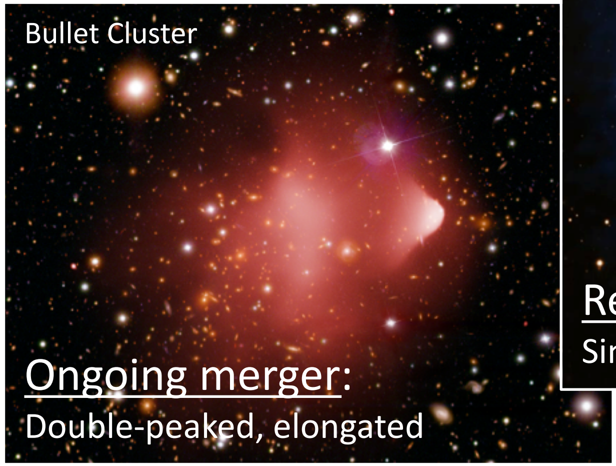
100-1000 galaxies + **thermal ICM** + DM + **non-thermal components**

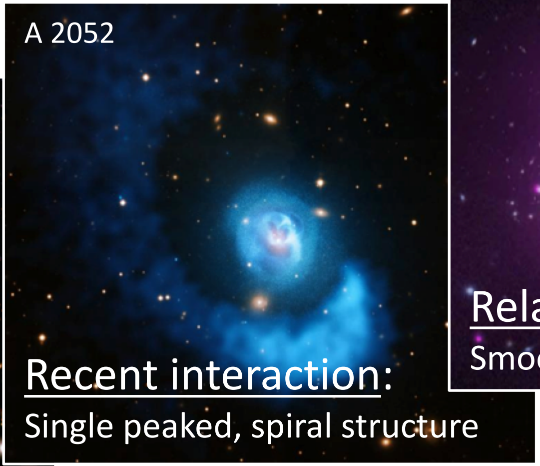
The majority of baryons are in the form of diffuse, metal-enriched, hot plasma (intra-cluster medium, **ICM**) emitting in ***X-rays*** by thermal bemsstrahlung

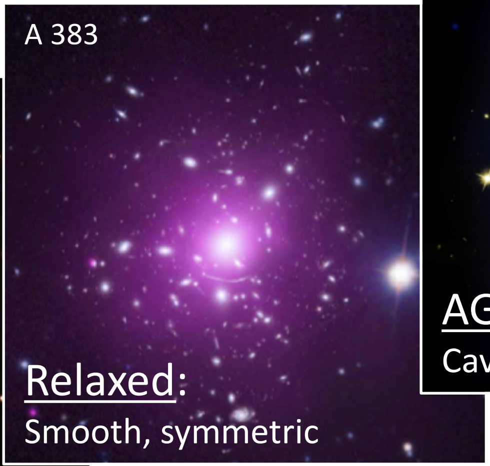
- **temperature** $T \approx 10^{7\text{-}8}$ K → $kT \approx$ few keV
- **density** $n_e \approx 10^{-4}$ - 10^{-2} cm^{-3}
- **metallicity** $Z \approx 0.3$ solar
- **luminosity** $L_X \approx 10^{43\text{-}46}$ erg s^{-1}
- **mass** $M_{gas} \approx 10^{14}$ M$_\odot$

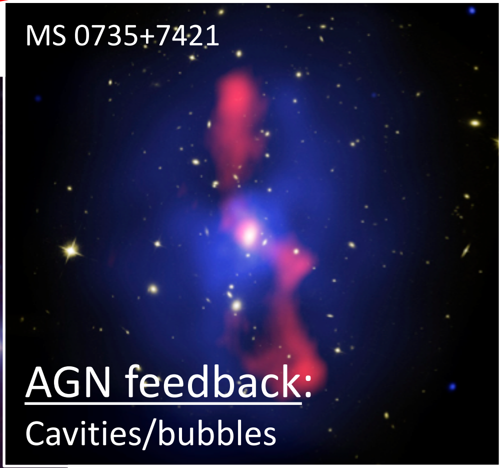
$\boxed{T\,(\mathrm{K}) = 1.16 \times 10^7\, T\,(\mathrm{keV})}$

X-ray morphology : retains imprints of major events !





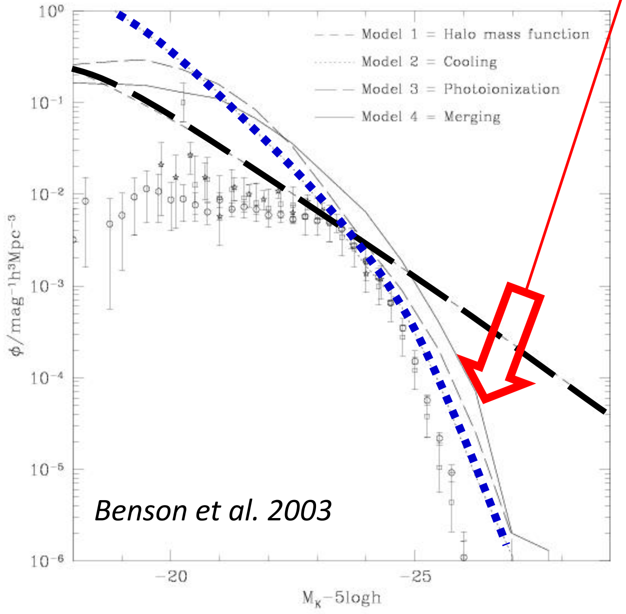




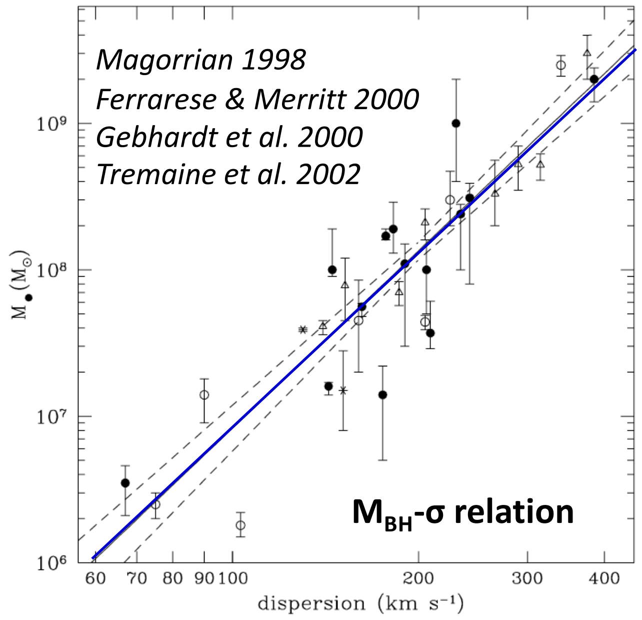
(ICM→) Baryon physics is complex

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

Models with AGN feedback reproduce the observed luminosity function of galaxies



SMBHs influence galaxy formation and evolution



X-ray observations of the ICM allow us to investigate the complex baryon physics, which is key to understand the cooling and feedback processes 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 $\approx H_0^{-1}$

Enthalpy $H = E_{\mathrm{int}} + pV = \dfrac{\gamma}{\gamma - 1} pV$

ratio of specific heats

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

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

Cooling function

!!! Note that..

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

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 $\approx H_0^{-1}$

cooling region: $r < r_{cool}$

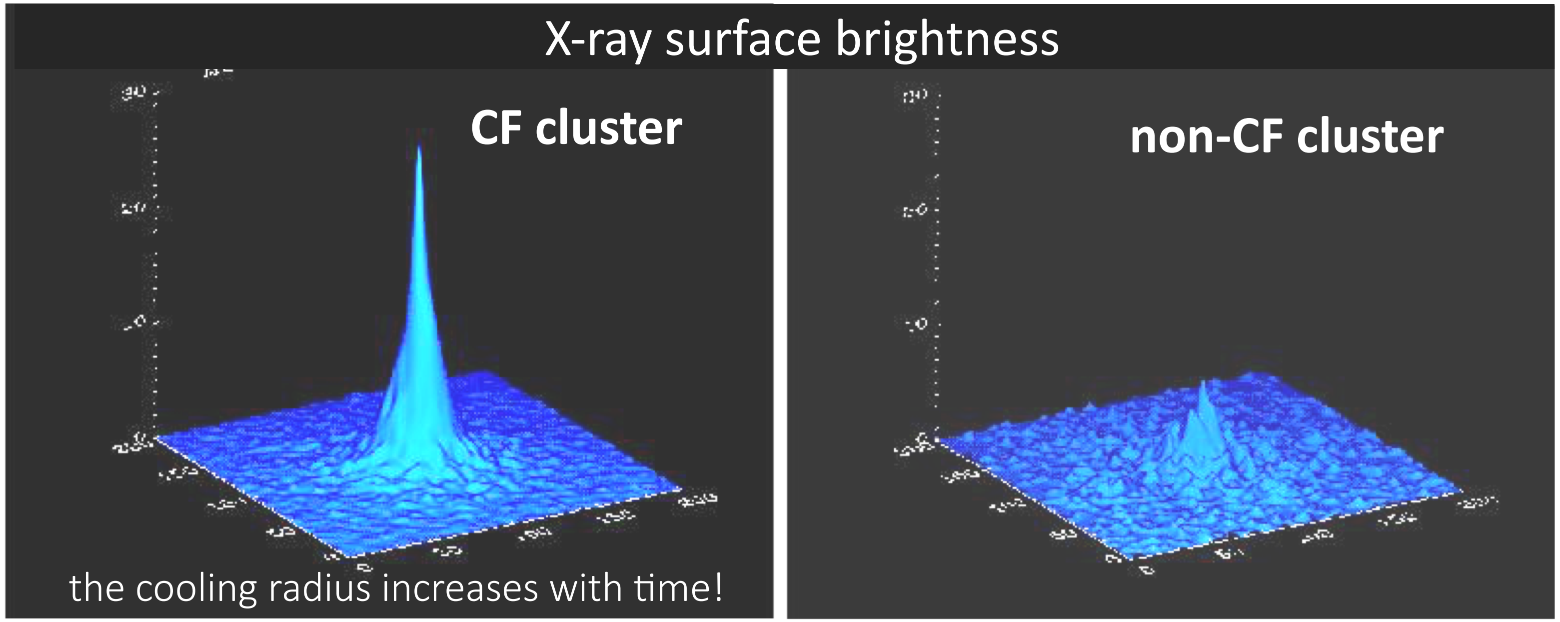
Within r_{cool}, $t_{cool} < H_0^{-1}$ $\xrightarrow[\text{hydrostatic eq.}]{}$ the cooling gas flows inward and is compressed

Compression $\Rightarrow$ **density** n_e **increases** $\Rightarrow$ **X-ray emissivity** $(\propto n_e^2)$ **increases** *(Fabian 1994)*

mass inflow rate $\dot{M}$

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

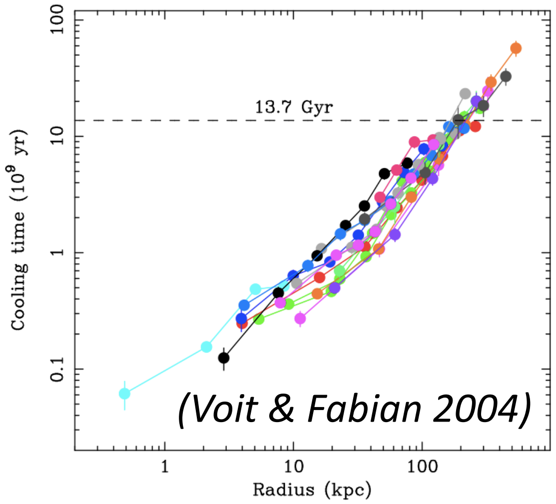
cooling luminosity



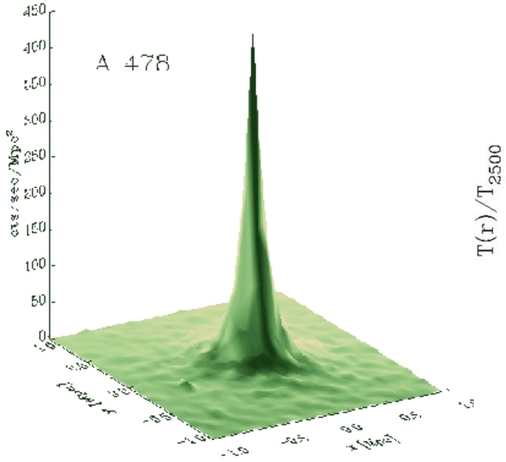
Credit: Allen + Fabian

CF – observations

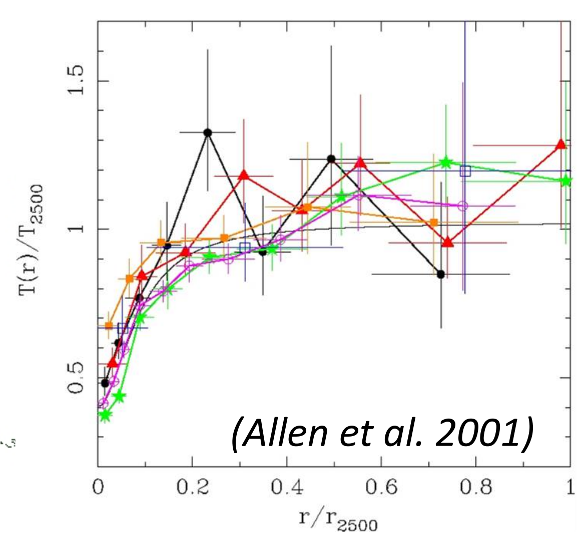
• short cooling time



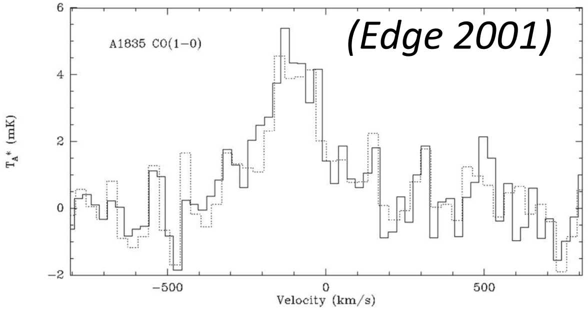
• high density



• low temperature



• **molecular gas**



BCG in cool core clusters are rich in molecular gas ($M \approx 10^9$-10^{10} $M_\odot$)

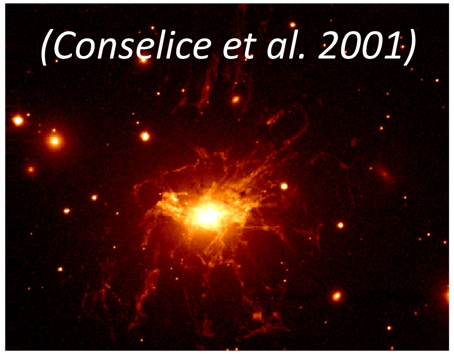
Evidence of cooling

but SFR ≪ X-ray cooling rates

□↓

classical "*mass sink*" CF problem

• Hα filaments



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

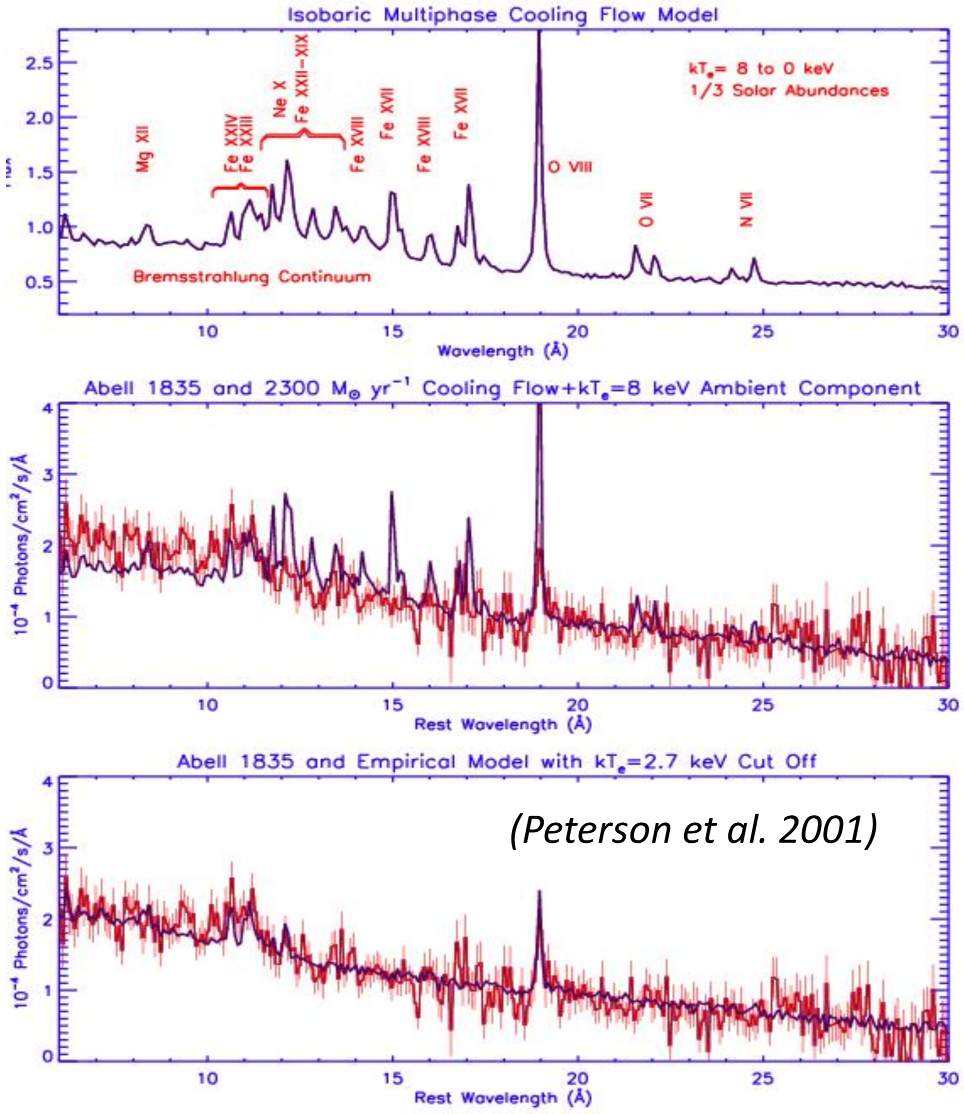
Gas drops to $T_{\rm min} \sim 0.3\ T_{\rm vir}$
Chandra spectra consistent

$$\dot{M} \lesssim (0.1 - 0.2)\ \dot{M}_{\rm X}$$

$\Rightarrow$ (soft X-ray) **CF problem:**

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

[*new nomenclature*: **COOL CORE (CC)**]



CF problem – proposed solutions

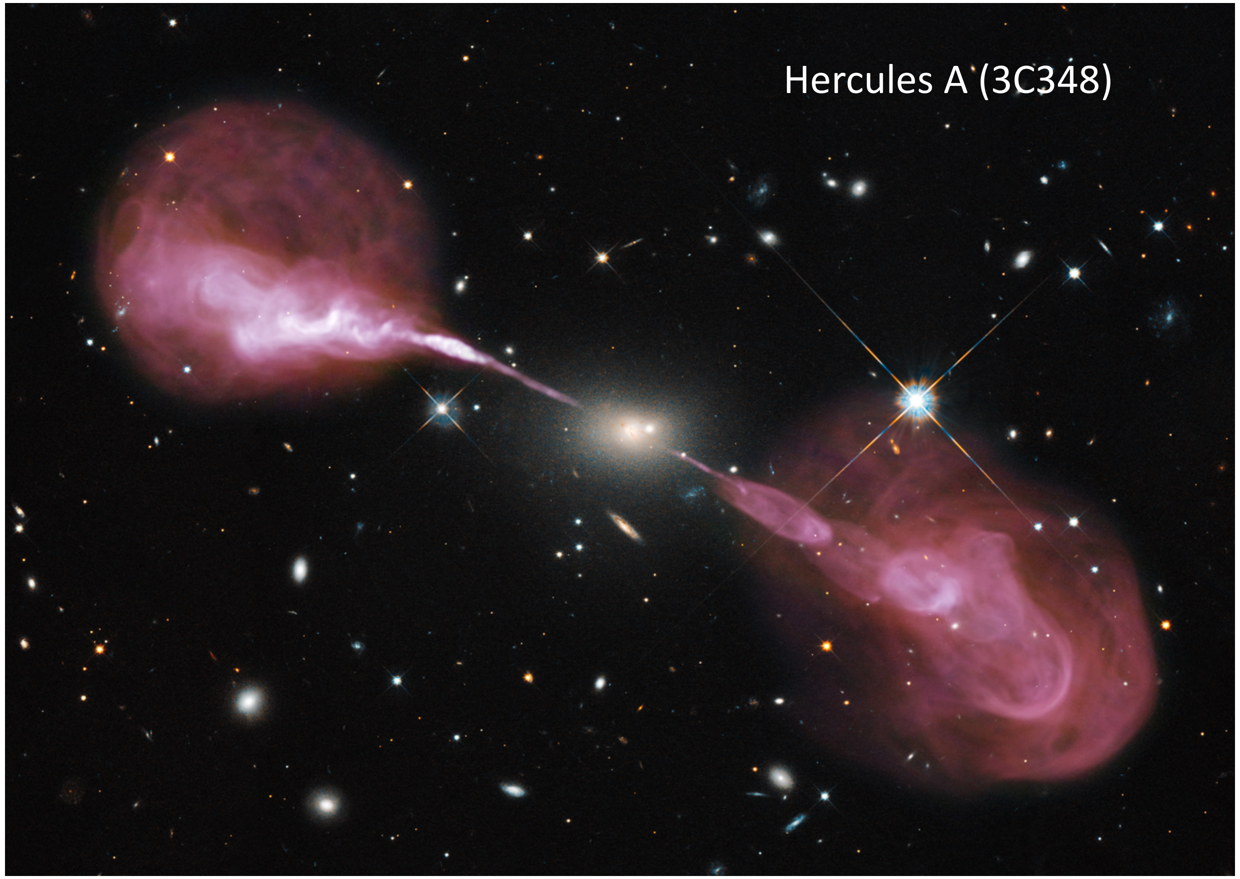
- **Signature of cooling $\leq$ 1-2 keV suppressed**
  - absorption
    (Peterson+01, Fabian+01)
  - mixing with cooler gas/dust
    (Fabian+02, Mathews&Brighenti03)
  - inhomogeneous metallicity
    (Morris&Fabian03)

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

- **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...

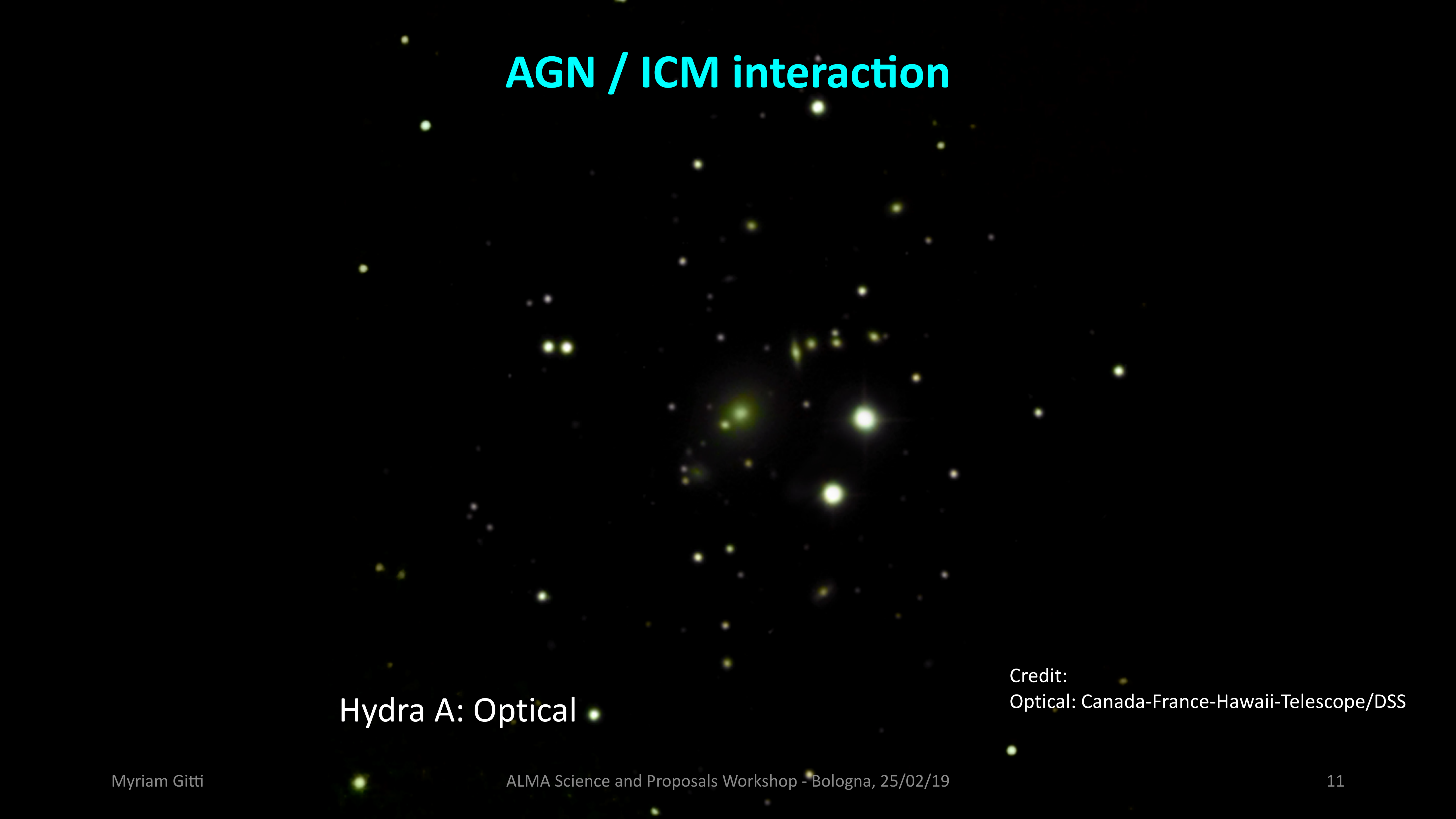
$$\dot{M} \sim 0.1\,\dot{M}_X$$

Most promising solution to CF problem:
Radio-loud AGN heat cluster gas



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



Hydra A: Optical

Credit:
Optical: Canada-France-Hawaii-Telescope/DSS

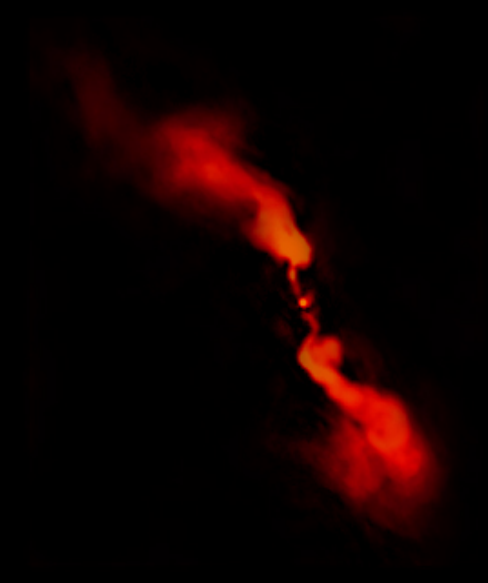
AGN / ICM interaction

Hydra A: X-ray

Credit:

X-ray: NASA/CXC/U.Waterloo/C.Kirkpatrick et al.

AGN / ICM interaction

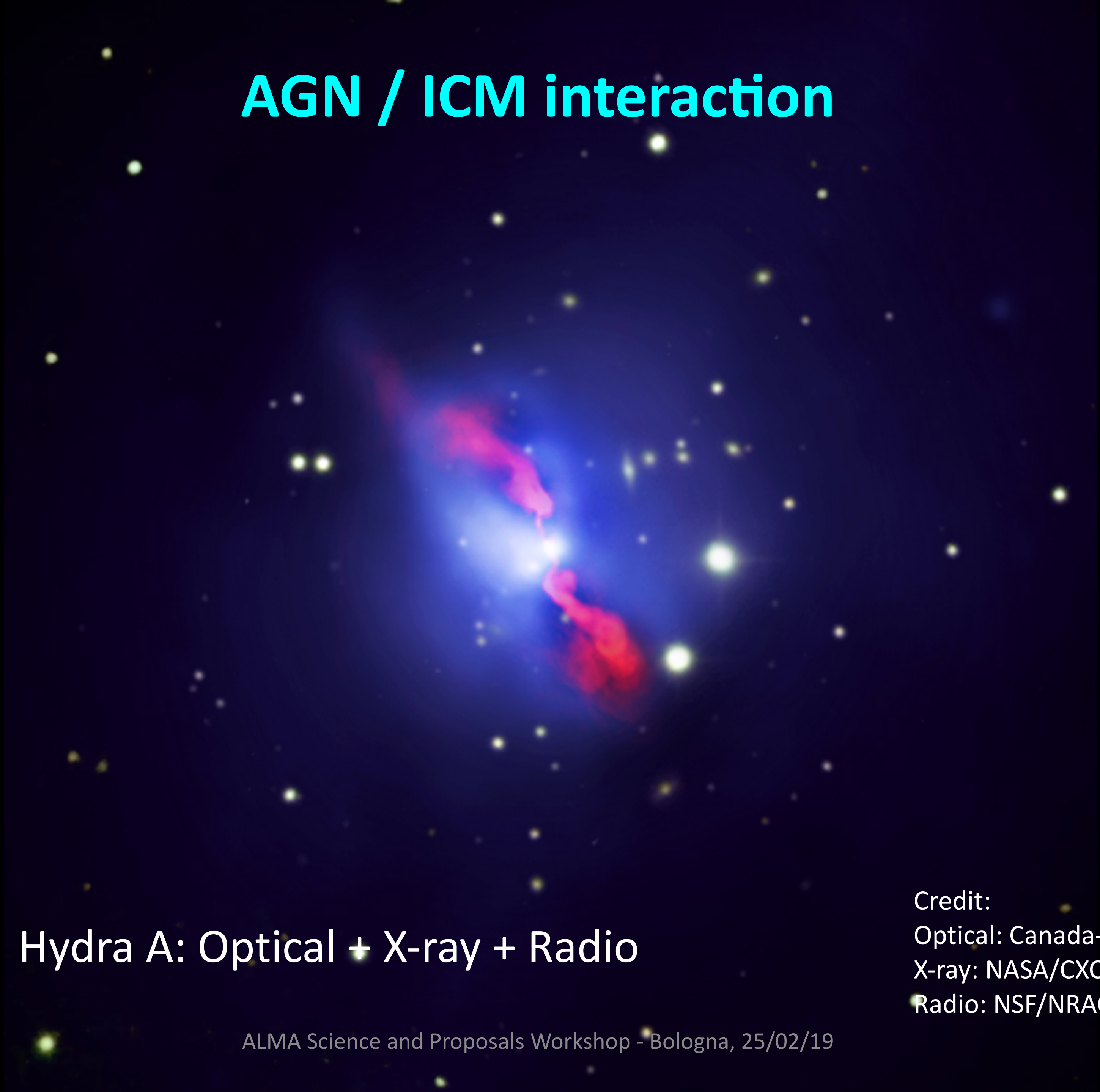


Hydra A: Radio

Credit:

Radio: NSF/NRAO/VLA

AGN / ICM interaction

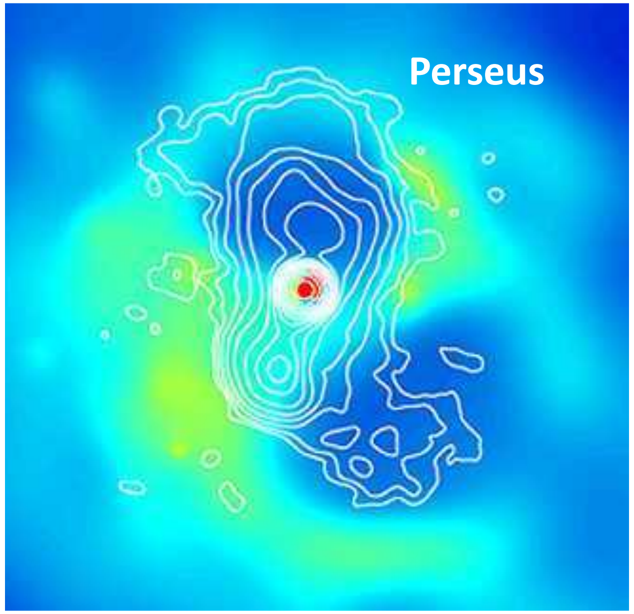


Hydra A: Optical + X-ray + Radio

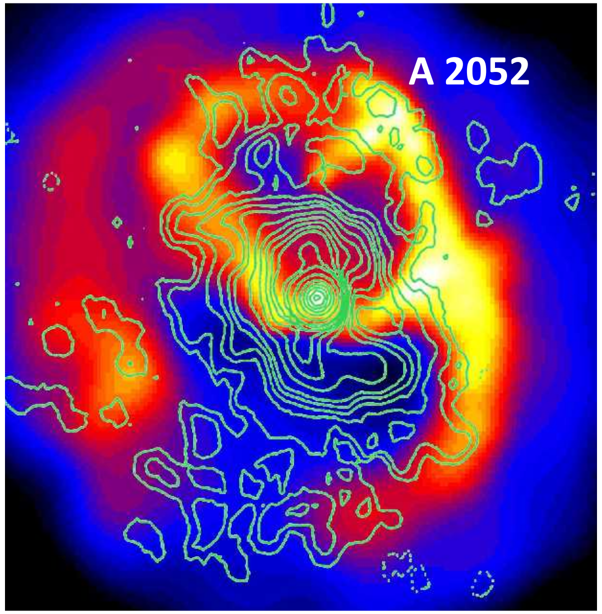
Credit:
Optical: Canada-France-Hawaii-Telescope/DSS
X-ray: NASA/CXC/U.Waterloo/C.Kirkpatrick et al.
Radio: NSF/NRAO/VLA

AGN / ICM interaction

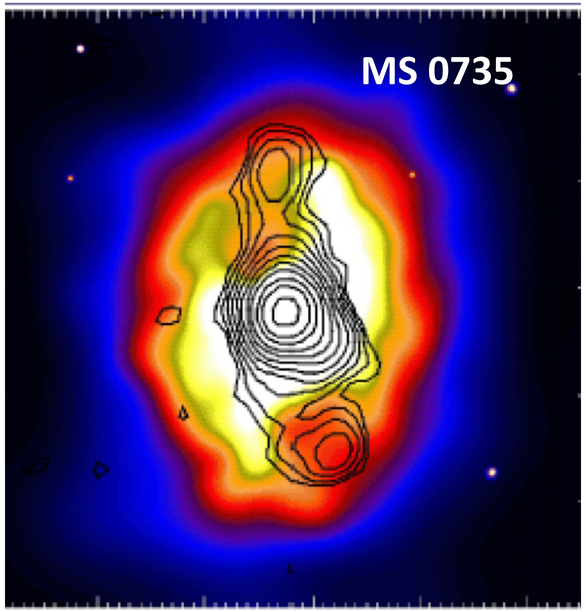
- most $(\sim 70\%)$ CF clusters contain powerful radio sources associated with BCG
- central ICM shows "holes" often coincident with radio lobes (*Chandra*)



Fabian et al. 2000



Blanton et al. 2001

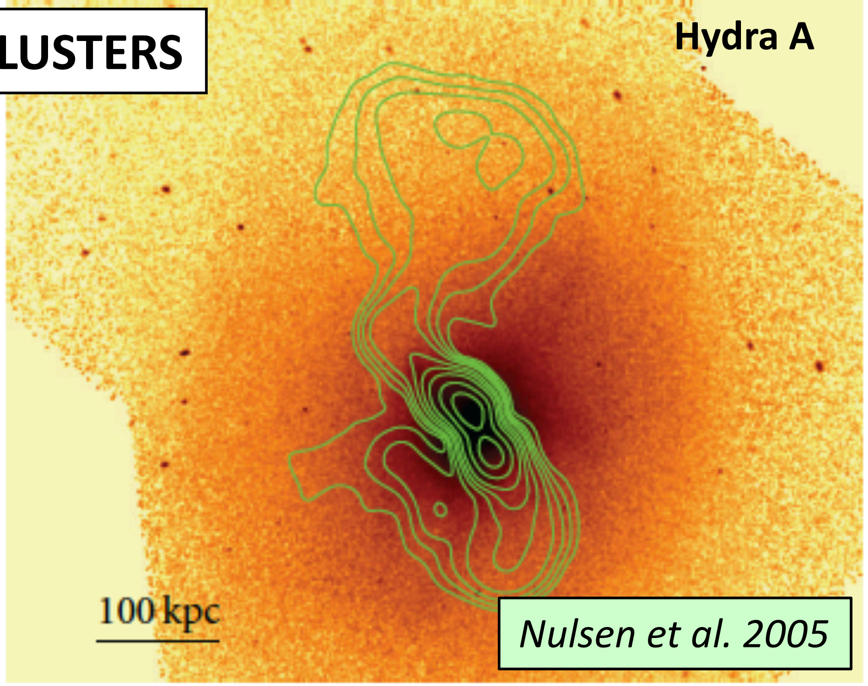


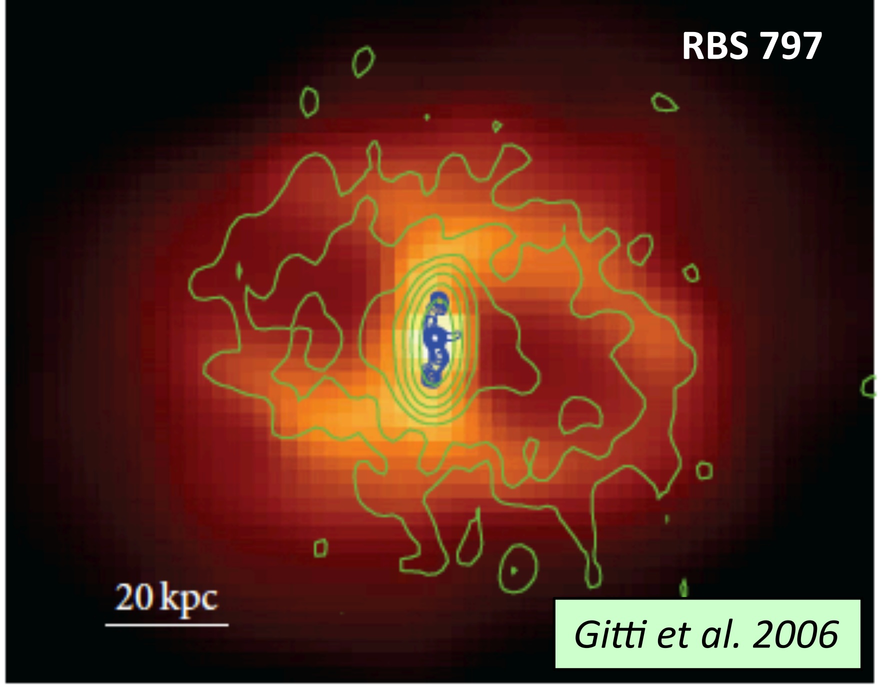
McNamara et al. 2005

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

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

GALAXY CLUSTERS

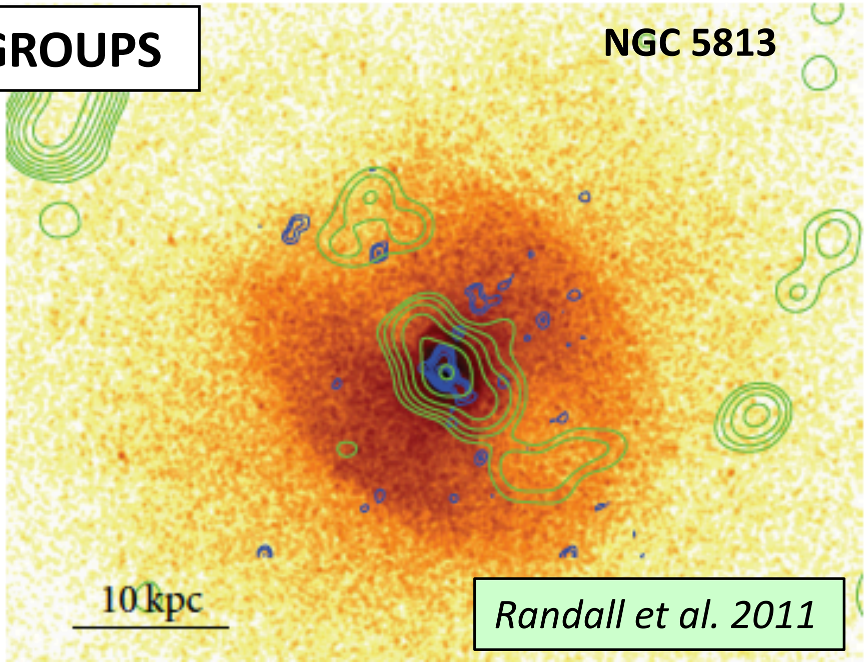


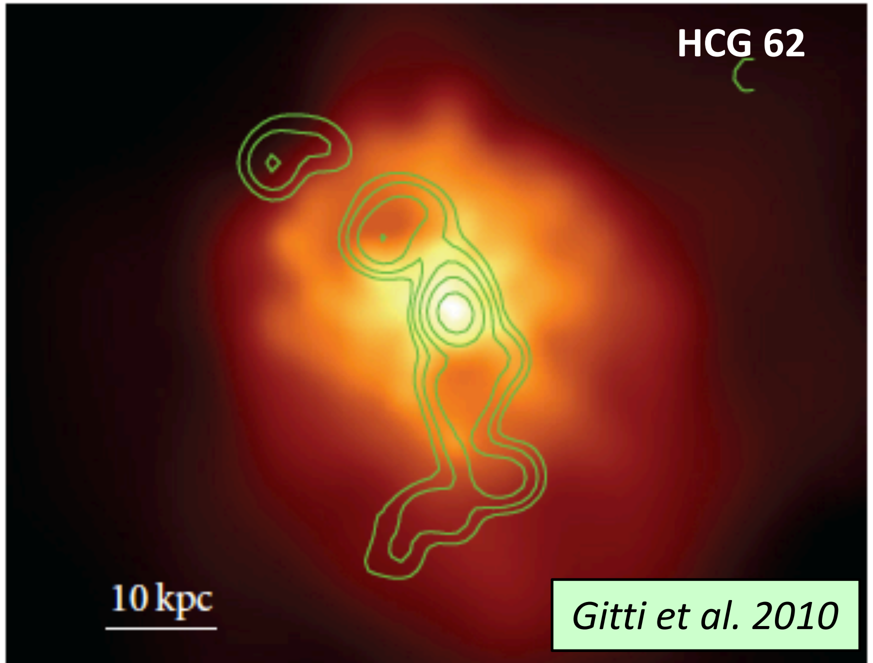


HCG 62

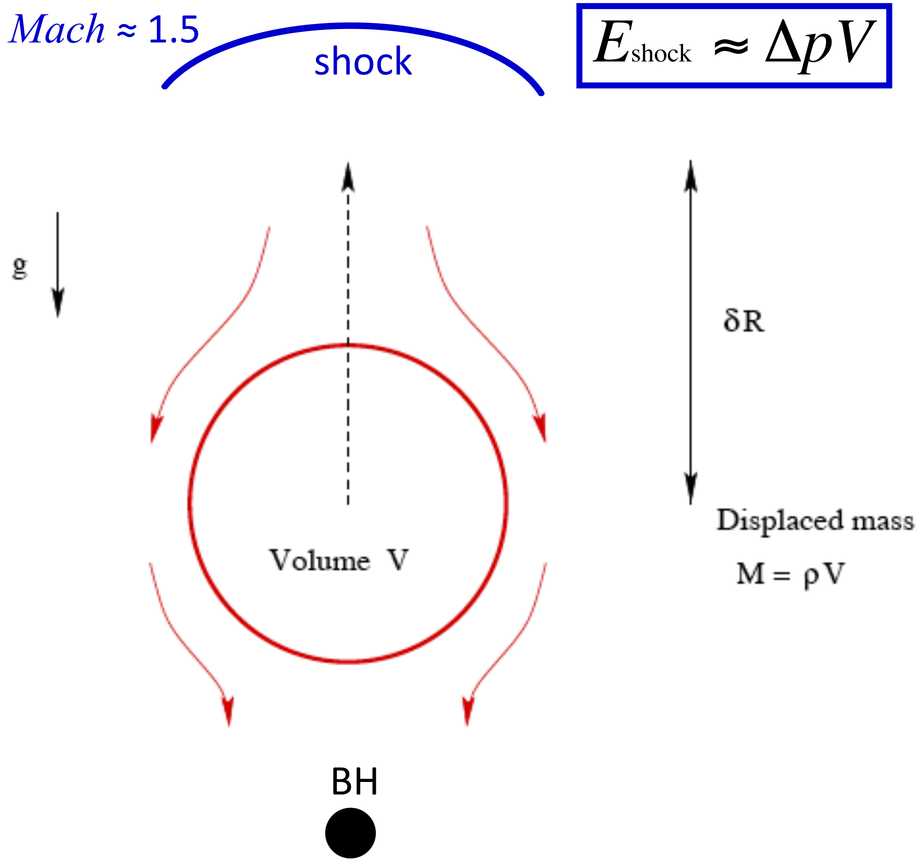
HCG 62

GALAXY GROUPS

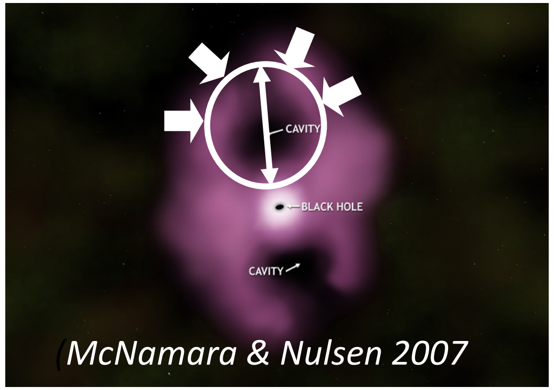




Cavity (+ shock) heating



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



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

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

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

direct measure of the *mechanical* energy

➔ total energy of AGN outburst :

$$\boxed{E_{\rm tot} = E_{\rm cav} + E_{\rm shock} = 10^{55} - 10^{62}\,{\rm erg}}$$

X-ray cavities as gauges of AGN power

$$E_{AGN} = E_{cav} + E_{shock} \geq E_{cav} \longrightarrow P_{AGN} \sim P_{cav} = \frac{E_{cav}}{t_{cav}} = \frac{4pV}{t_{cav}}$$

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

from: - sound crossing time
- buoyancy time

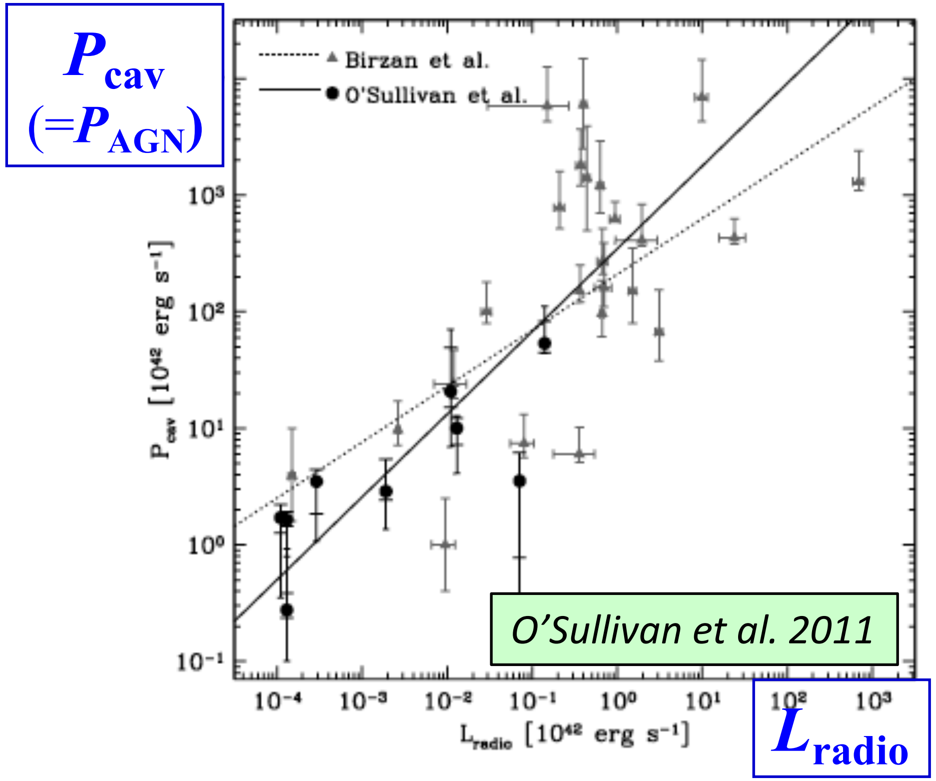
➔ P_{cav} provides the best-available gauge to the true total mechanical *(not synchroton!)* power of the AGN outburst

$\Downarrow$

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

total AGN power (P_{AGN}) vs. syn. power (L_{radio})

➢ **estimate of P_{AGN} from L_{radio}**



O'Sullivan et al. 2011

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

The relationship between AGN power and $L_{\mathbf{cool}}$

For a sample of cavity systems, calculate and compare:

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

$\boldsymbol{P}_{\mathbf{cav}}$ is a measure of the energy injected into the ICM by the AGN outburst

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

$\boldsymbol{L}_{\mathbf{cool}}$ is the luminosity that must be compensated for by heating to prevent cooling

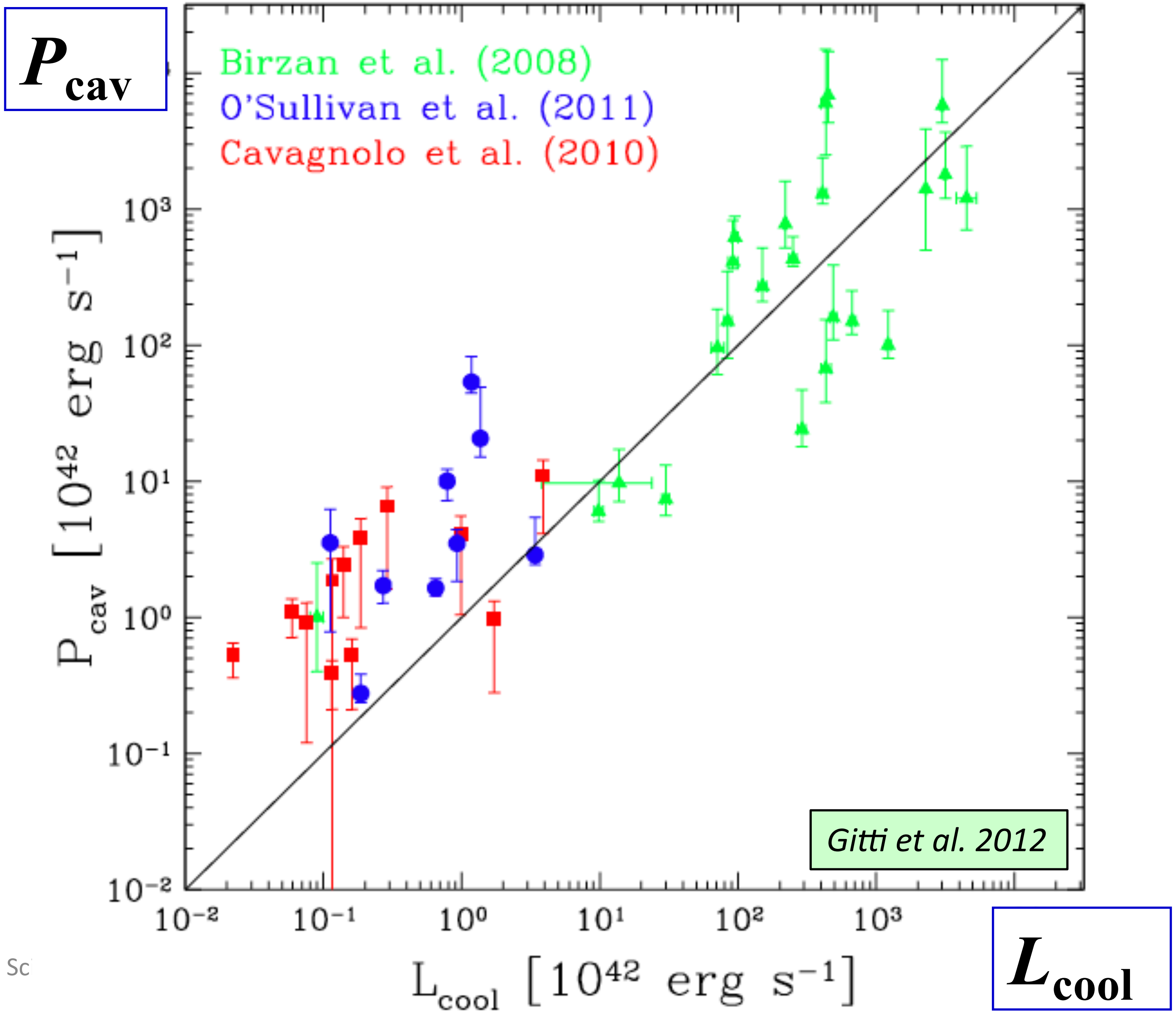
→ it is found that the cavity power scales in proportion to the cooling X-ray luminosity, although with a big scatter

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:

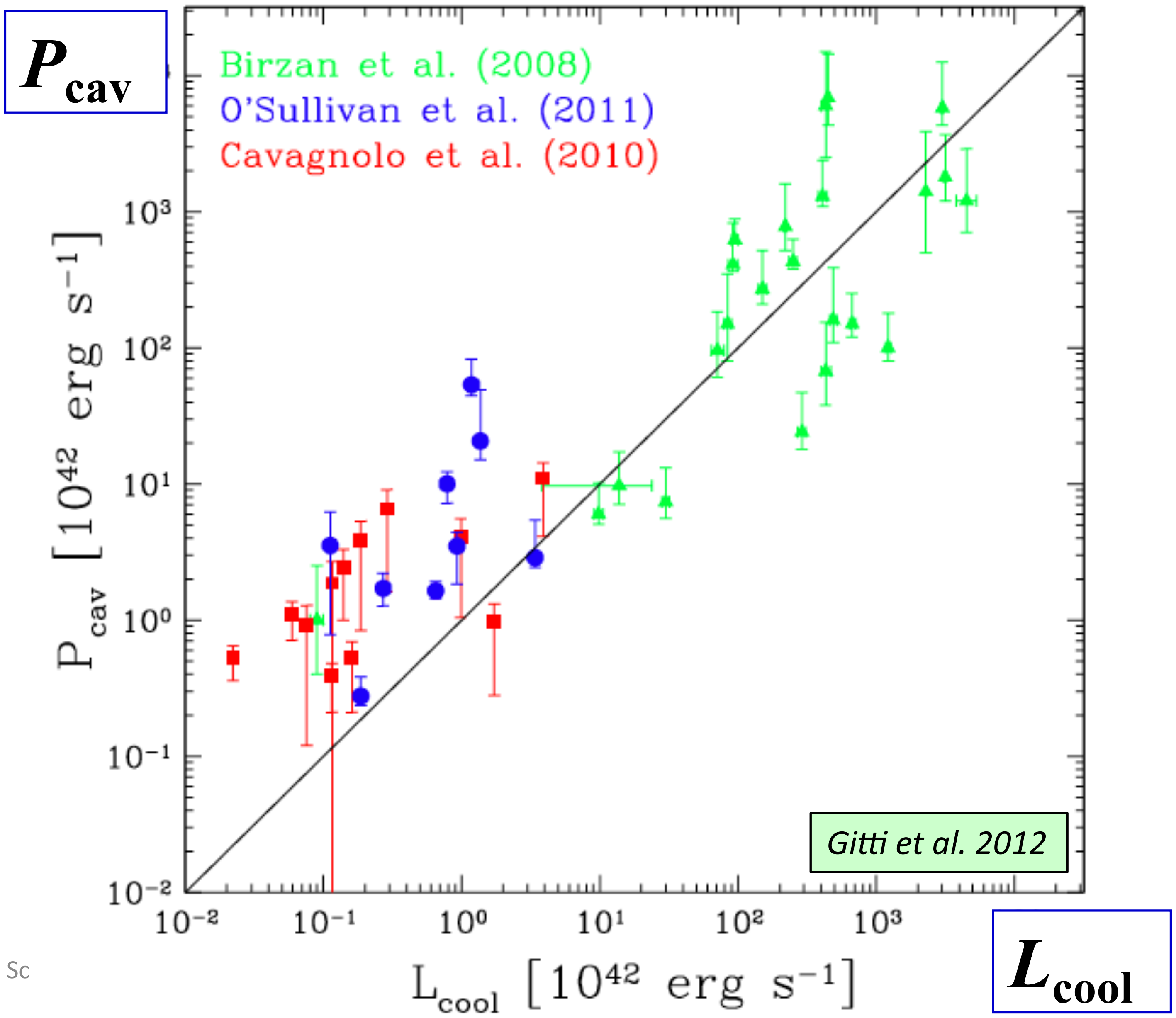
$$\begin{cases} L_{cool} = 4.1\times10^{44}\ \mathrm{erg/s} \\ P_{cav} = 6.2\times10^{44}\ \mathrm{erg/s} \end{cases}$$

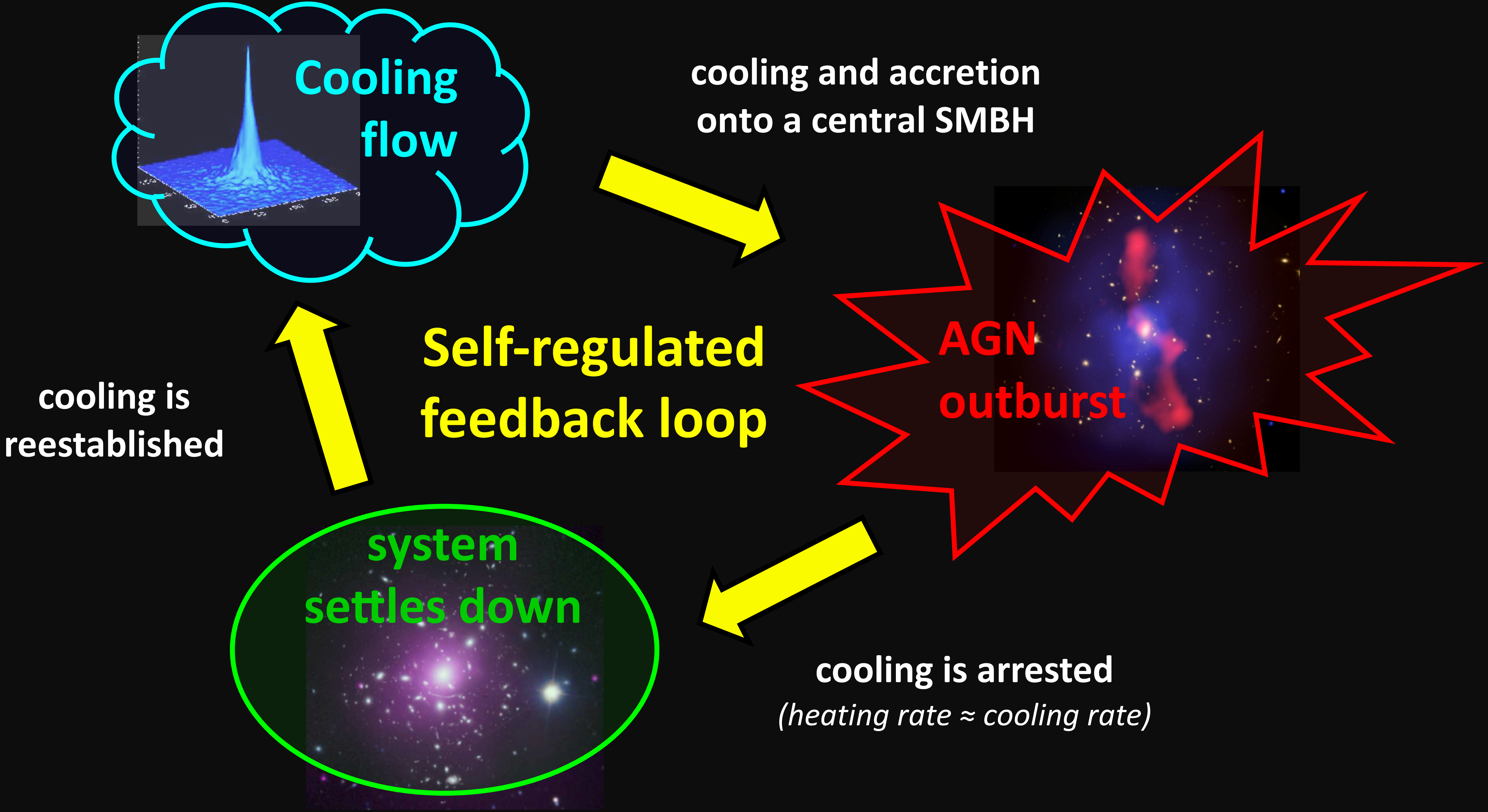
$\downarrow$ *duty-cycle ~ 70%*

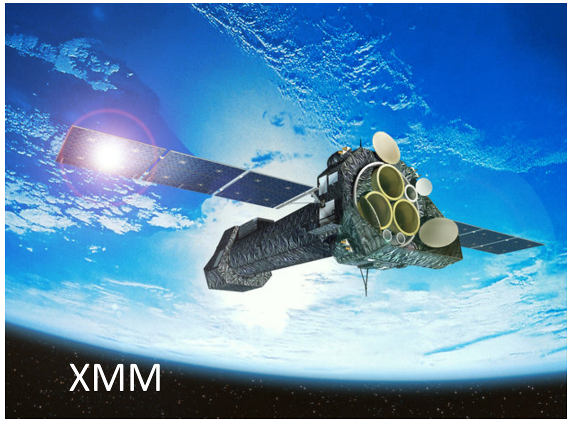
$$P_{cav,d} \approx (0.7\times6.2)\times10^{44}\ \mathrm{erg/s}$$

➔ $\mathbf{L_{cool} / P_{cav,d} \approx 1}$

Radiative losses of thermal ICM are balanced by mechanical heating from AGN *over the system lifetime*

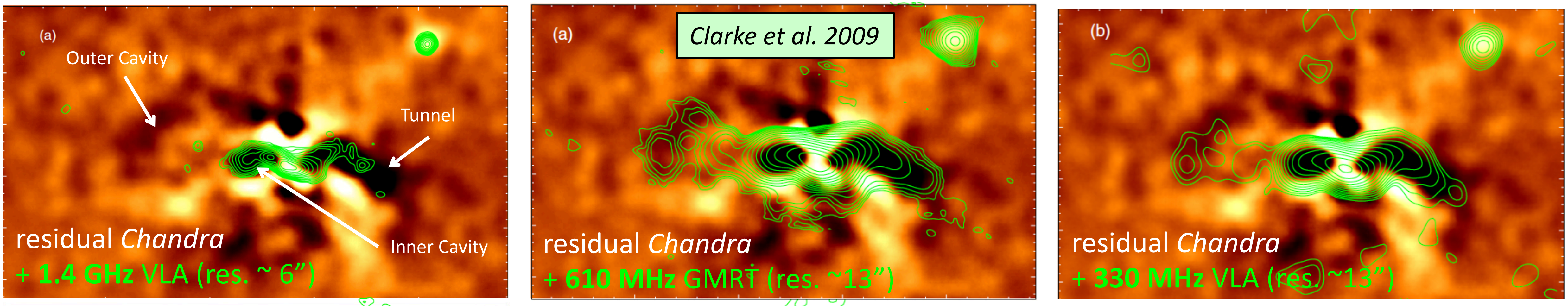



Cooling flow
cooling and accretion onto a central SMBH
AGN outburst
Self-regulated feedback loop
cooling is reestablished
system settles down
cooling is arrested
(heating rate ≈ cooling rate)



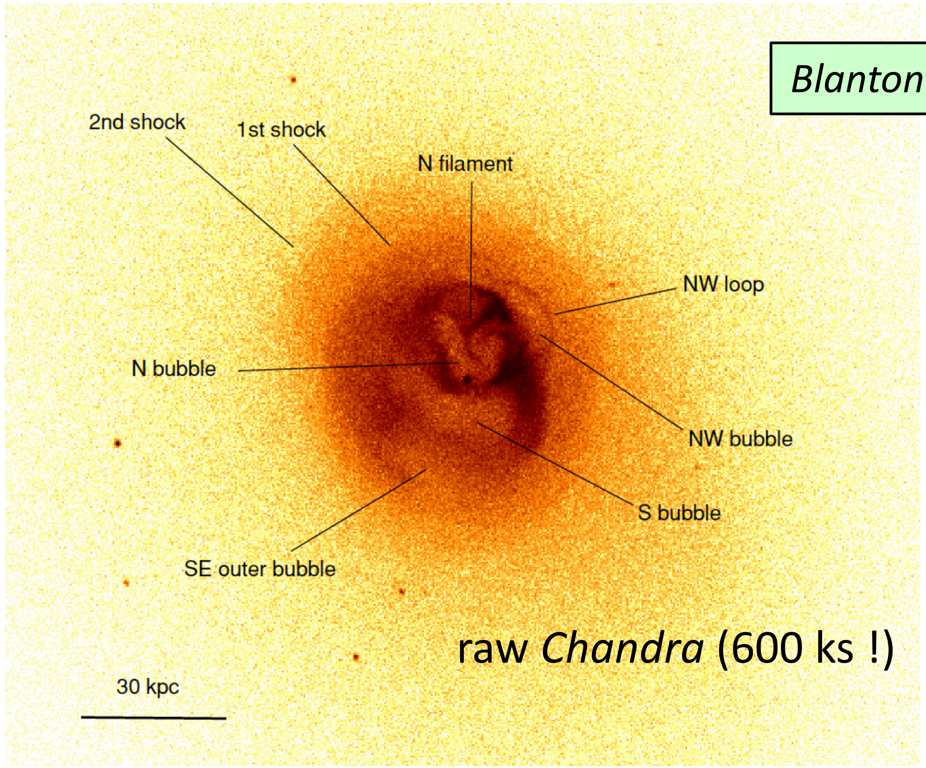
Observations of X-ray cavities and shocks: catching the radio-AGN feedback in action

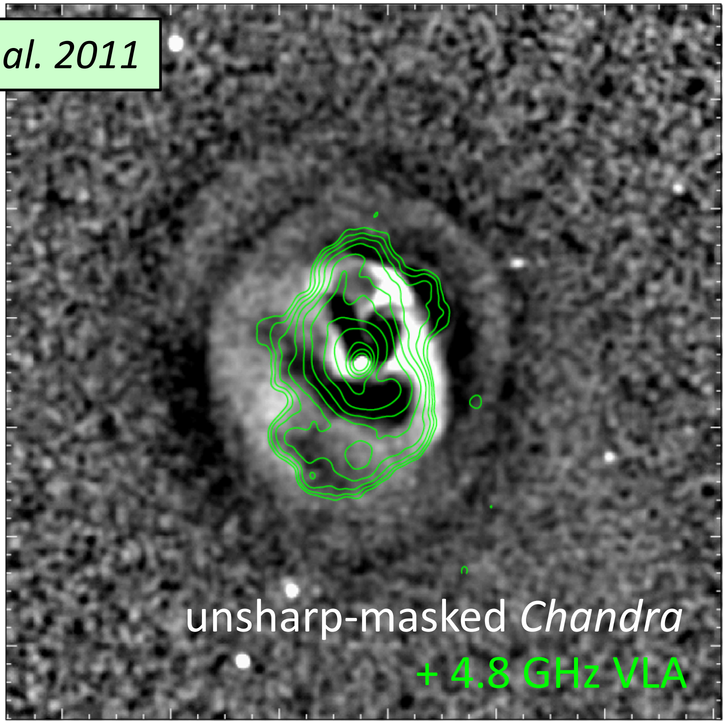
A 262: multiple generations of AGN feedback

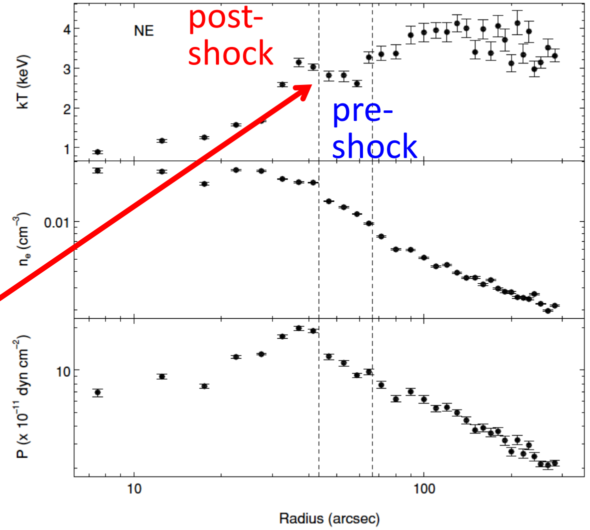


- X-ray tunnel filled with ***low-frequency*** radio emission:
  multiple radio outbursts pile up and accumulate over several AGN activity cycles with $\tau_{\rm rep} \geq 30$ Myr
- source capable of offsetting radiative cooling over several outburst episodes

A 2052: bubbles, shocks and sloshing

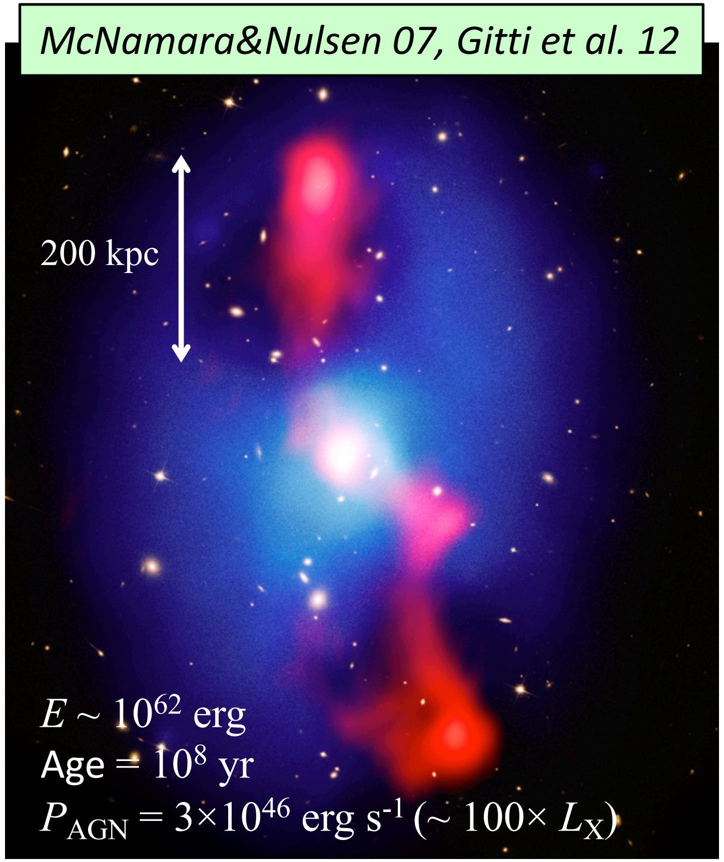




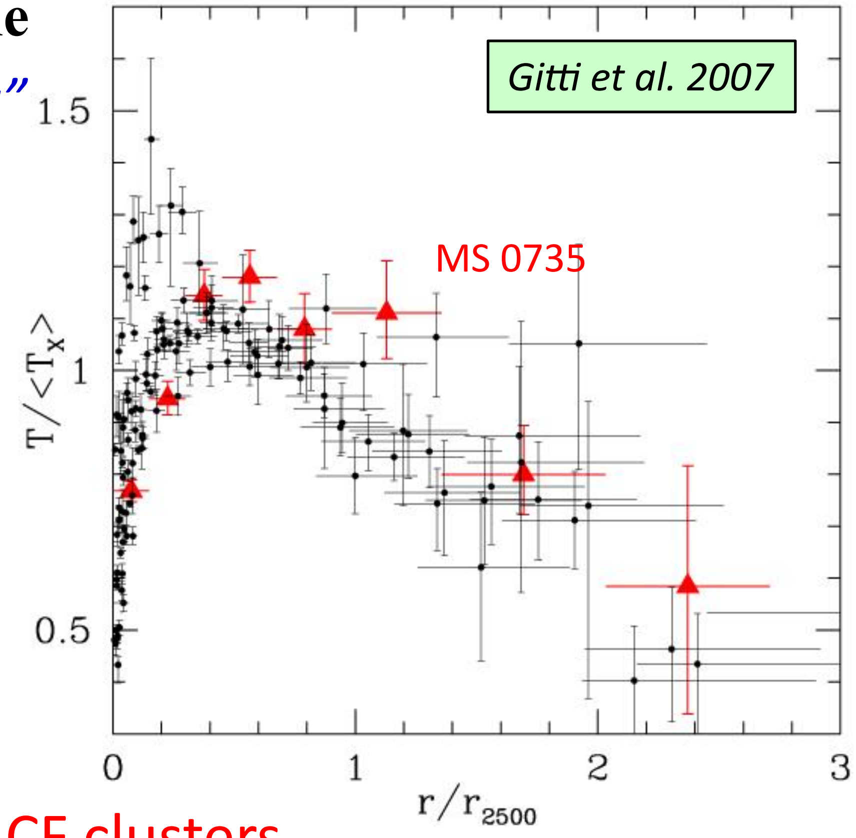


- Radio emission fills X-ray inner and outer cavities
- Cavities surrounded by X-ray bright rims, filaments
- Ripple-like features → two concentric weak shocks

MS 0735: the most powerful AGN outburst



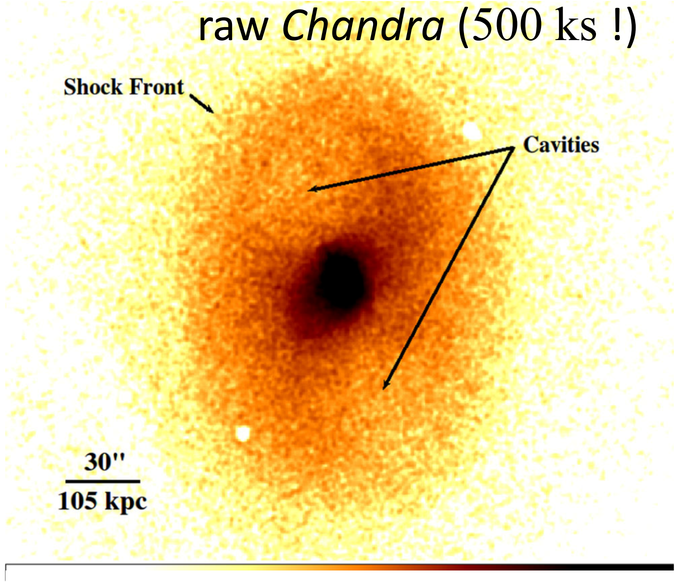
- AGN injects $\sim 10^{62}$ erg into the ICM → heating on cluster scale
- Mass within 1 Mpc is being heated at the level of **~1/4 keV/particle**
  → contribution to *"pre-heating"*
- ..but ***no marked effect on the temperature profile***

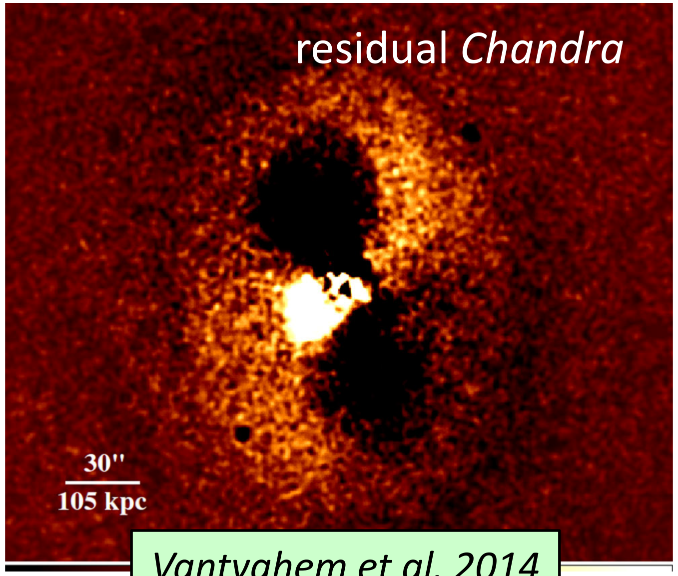


- Giant cavities are $\sim 10\%$ of cavity samples, age $\sim 10^8$ yr *(Rafferty+06)*
- Outbursts are active most of the time *(Dunn+05)*

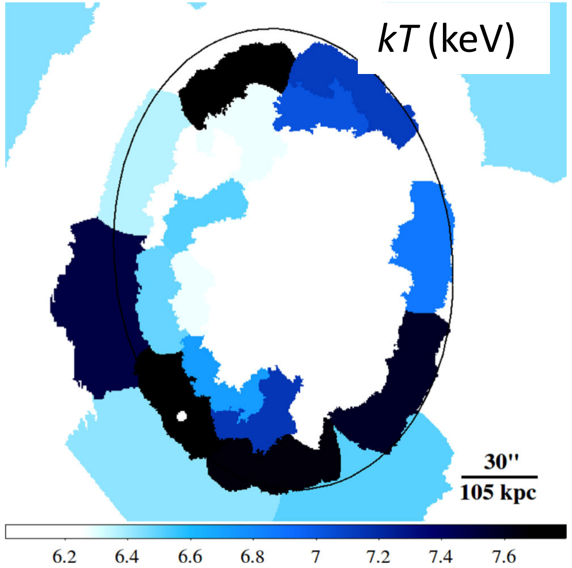
→ powerful outbursts likely occur $\sim 10\%$ of the time in *most* CF clusters

MS 0735: the most powerful AGN outburst

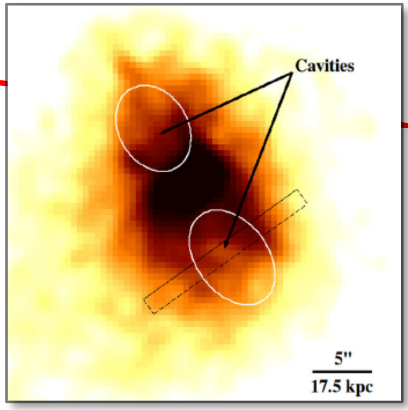


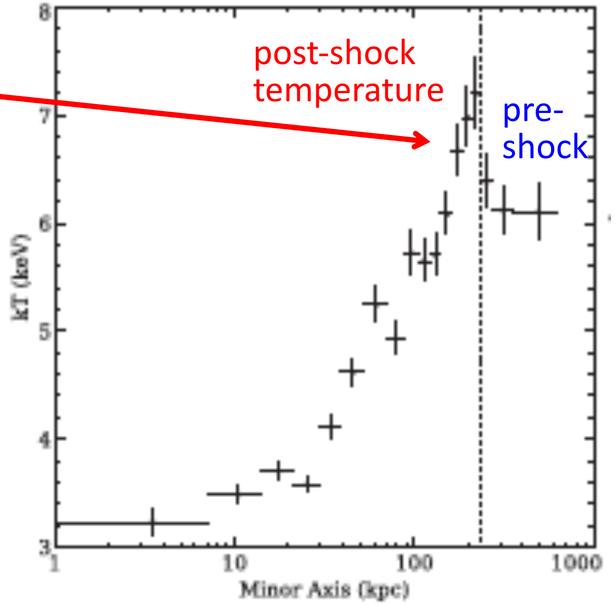


Vantyghem et al. 2014

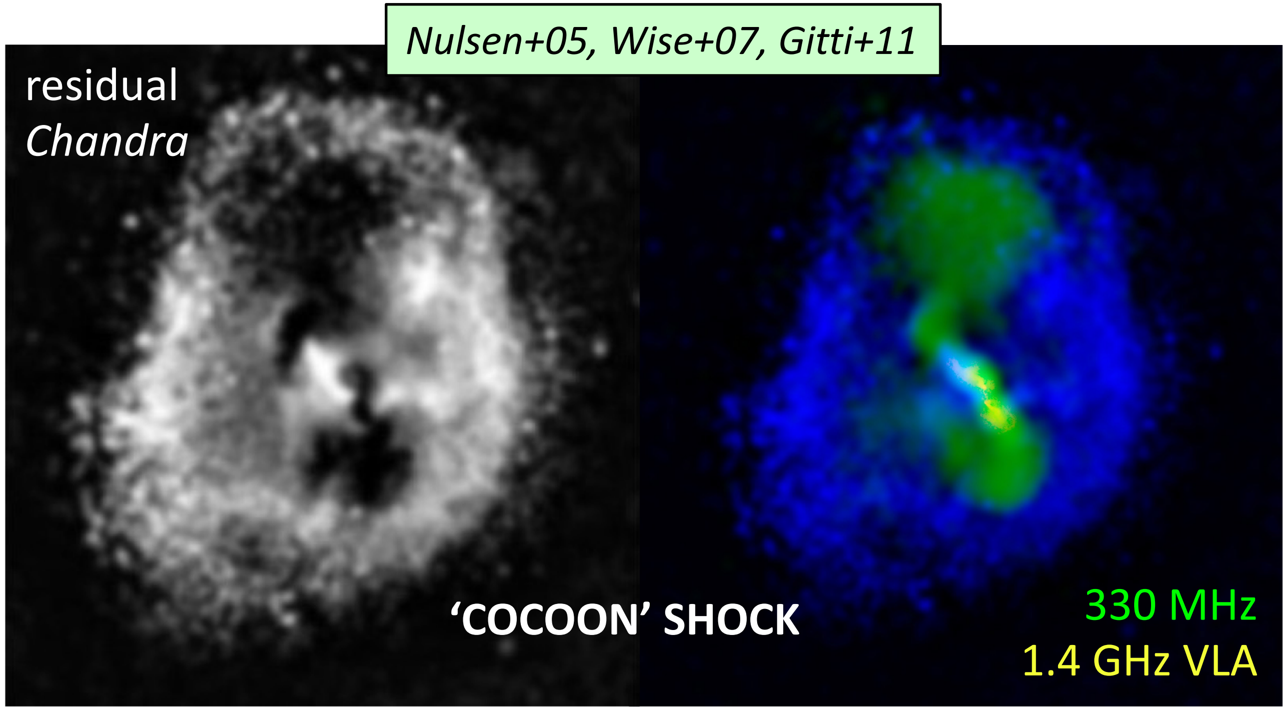


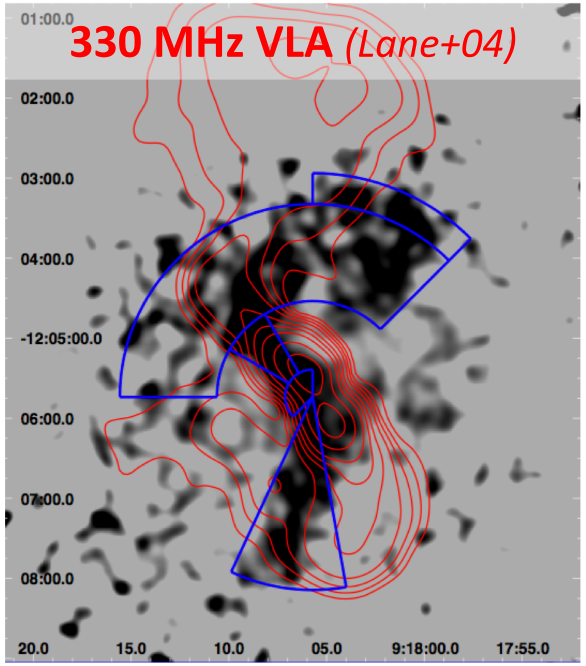
- Elliptical shock front, $Mach \sim 1.3$ (measured ~ 1 keV temperature rise)
- Second pair of younger, smaller cavities
  → AGN power has declined
- Cool gas along the radio jets → entrainment in the jets





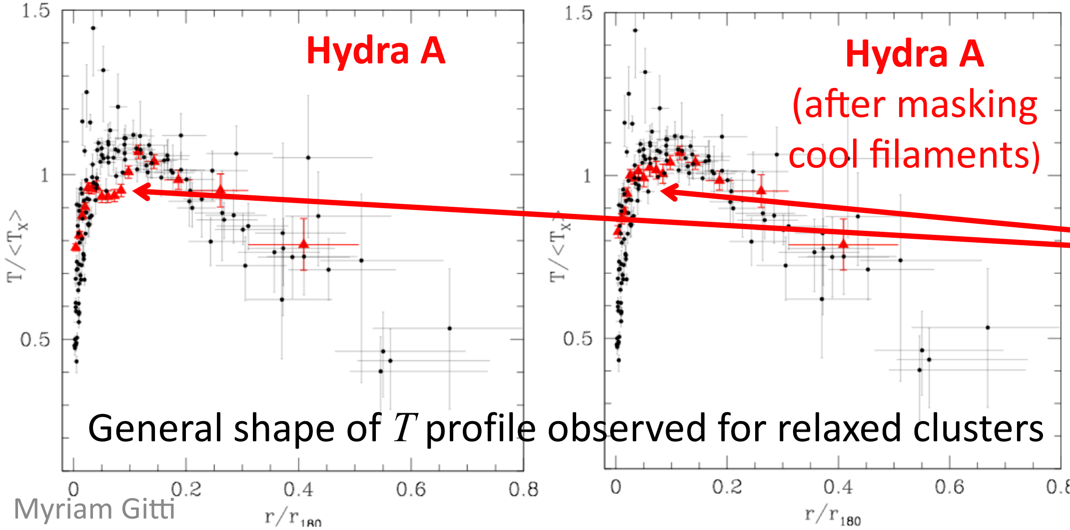
Hydra A: evidence for mechanical outflows





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

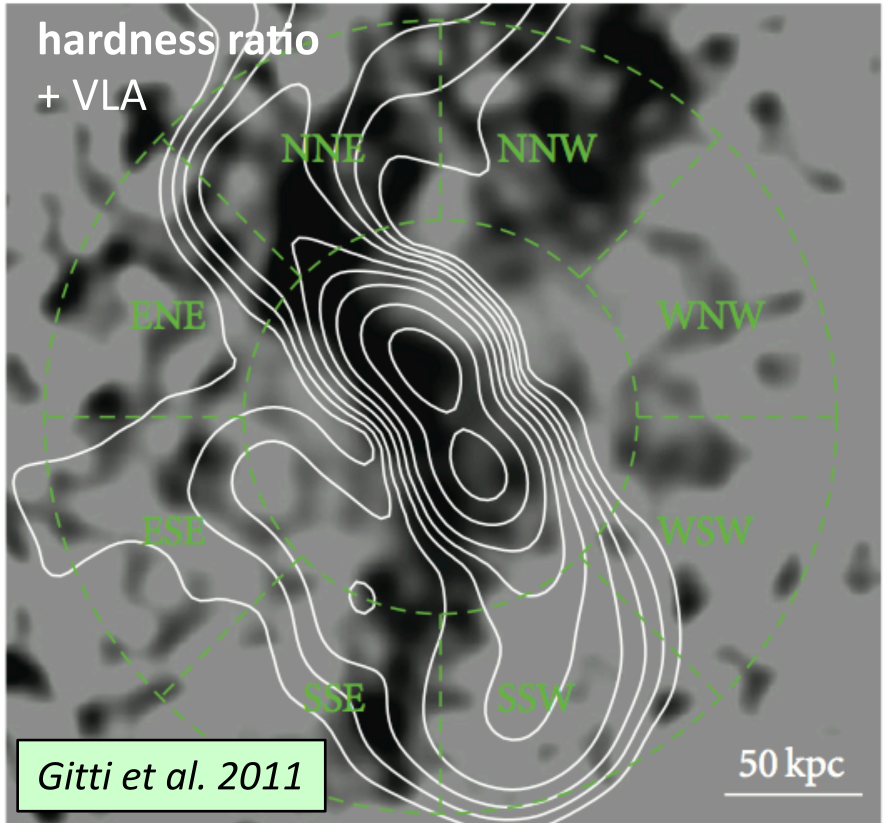
→ dark = low-T gas

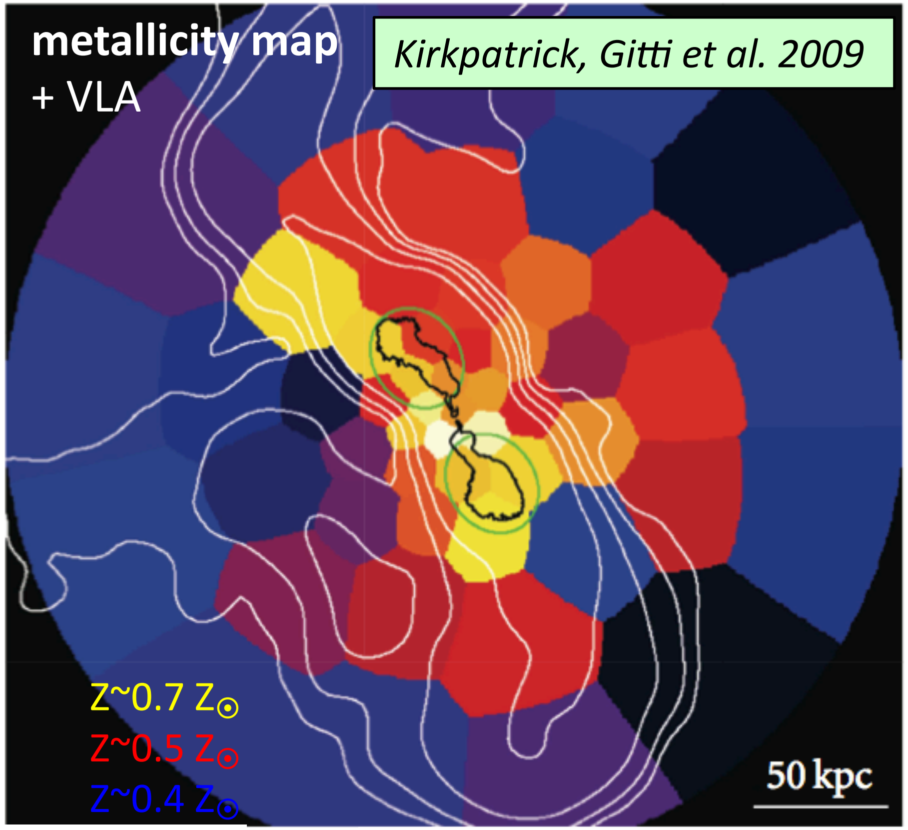


- Soft filaments along the radio jets
- T 'plateau' in the region ~70-150 kpc (removed after masking filaments)

→ the filaments contain cool gas

Hydra A: evidence for mechanical outflows





- Spectral evidence for multi-phase gas along the filaments

$$\begin{cases} kT_{\mathrm{hot}} \sim 4.0\ \mathrm{keV} \\ kT_{\mathrm{cool}} \sim 1.6\ \mathrm{keV}: \ \boldsymbol{M_{\mathrm{cool}} \approx 10^{11}\ M_\odot} \text{ lifted from the center} \end{cases}$$

→ **outflows of ≈few 100s $M_\odot$/yr in the rising lobes**

- Iron enriched outflow

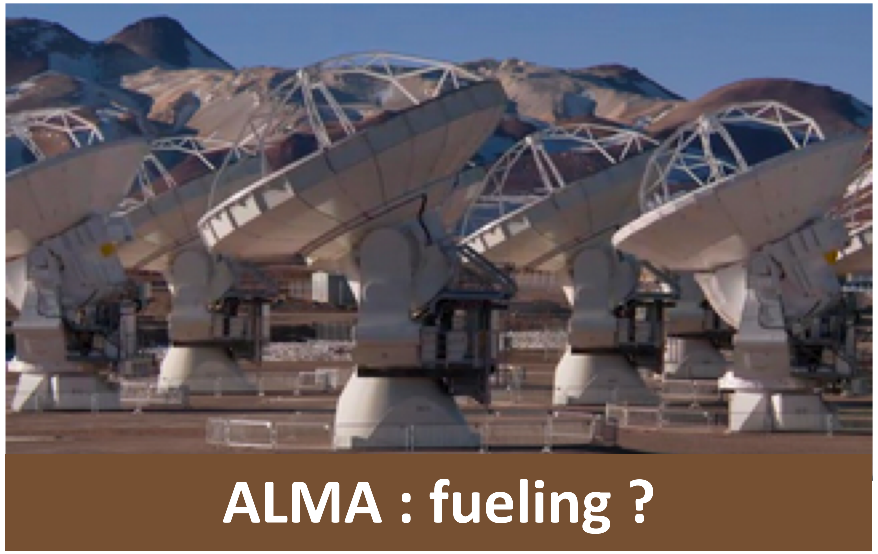
→ **AGN-Jets disperse metals throughout ICM**

$\Delta M_{\mathrm{Fe}} \approx 5 \times 10^7\ M_\odot,\ R \sim 120\ \mathrm{kpc}$

ALMA observations of molecular gas in central galaxies

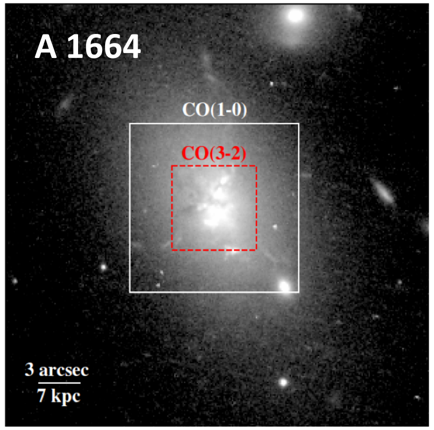
What is the role of molecular gas in feedback?

$M \approx 10^9\text{-}10^{10}\ M_\odot$ of molecular gas are prevalent in BGC at the center of cool core clusters with $t_{cool} < 10^9$ yr *(Edge 2001, Salomé & Combes 2003)*

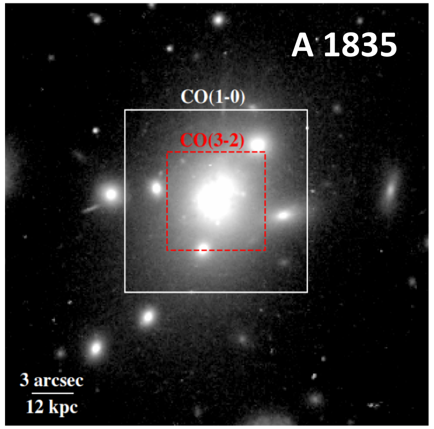


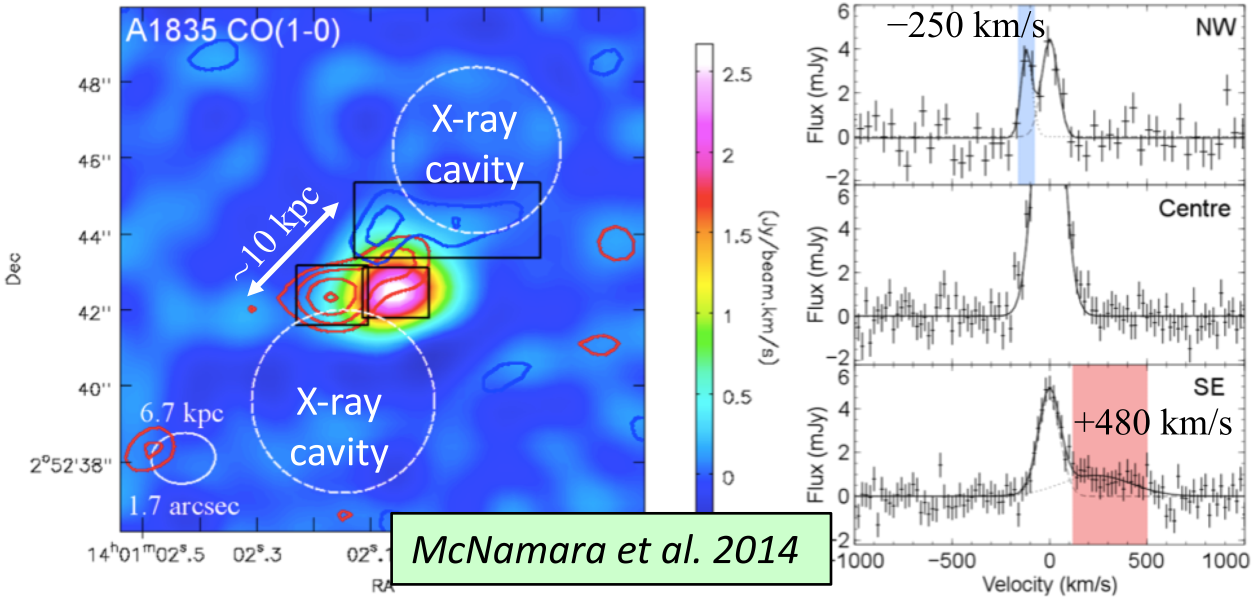
- Origin of molecular gas in BCG ?
- Is molecular gas fueling feedback?
- Does radio-mode feedback operate on molecular clouds?

ALMA Early Science: extended filaments



A 1664 and A 1835 show molecular gas filaments extending to 10 kpc from the BCG *(McNamara et al. 2014, Russell et al. 2014)*





McNamara et al. 2014

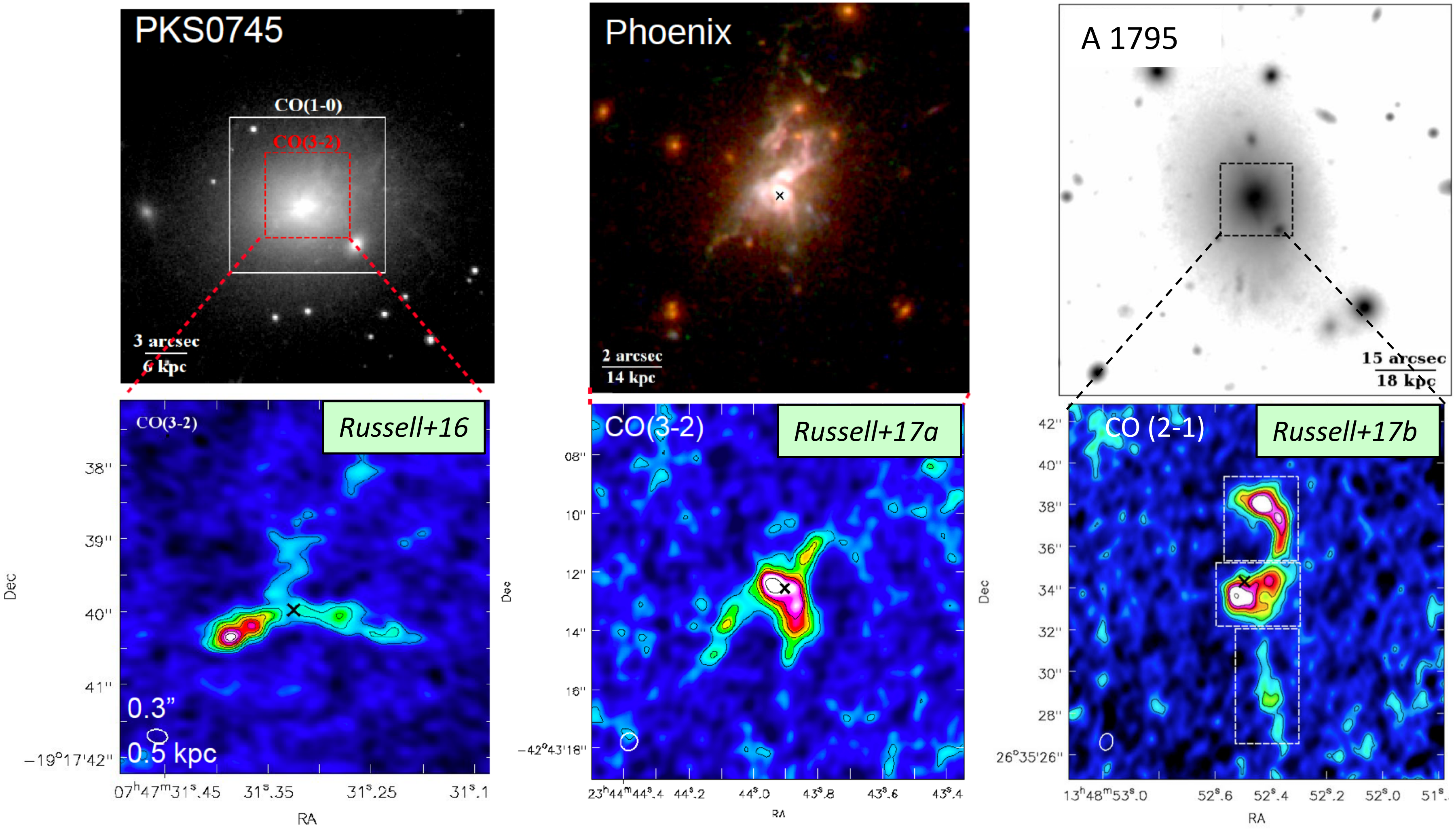
- $5 \times 10^{10}\,M_\odot$ of molecular gas within 10 kpc of the BCG
- $\mathbf{10^{10}\,M_\odot}$ molecular flow at 200-400 km/s lies beneath cavities with $P_{cav} \sim 10^{45}$ erg/s

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

Unclear if the bubbles accelerated the molecular clouds themselves (it is difficult to lift dense molecular gas out of the central disk) → molecular gas in the flow may have **cooled out of the hot plasma** in the updraft behind bubbles

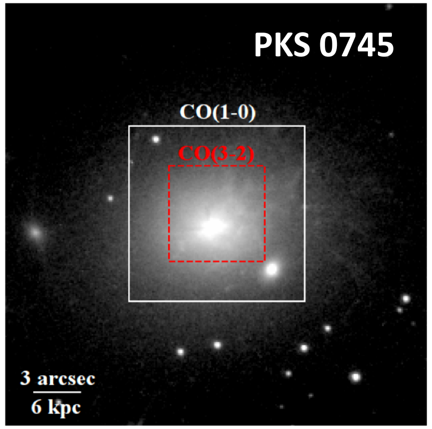
Extended filaments of molecular gas in several BCGs

Massive filaments each ~ few × 10^9-10^{10} $M_\odot$ and 3-15 kpc long



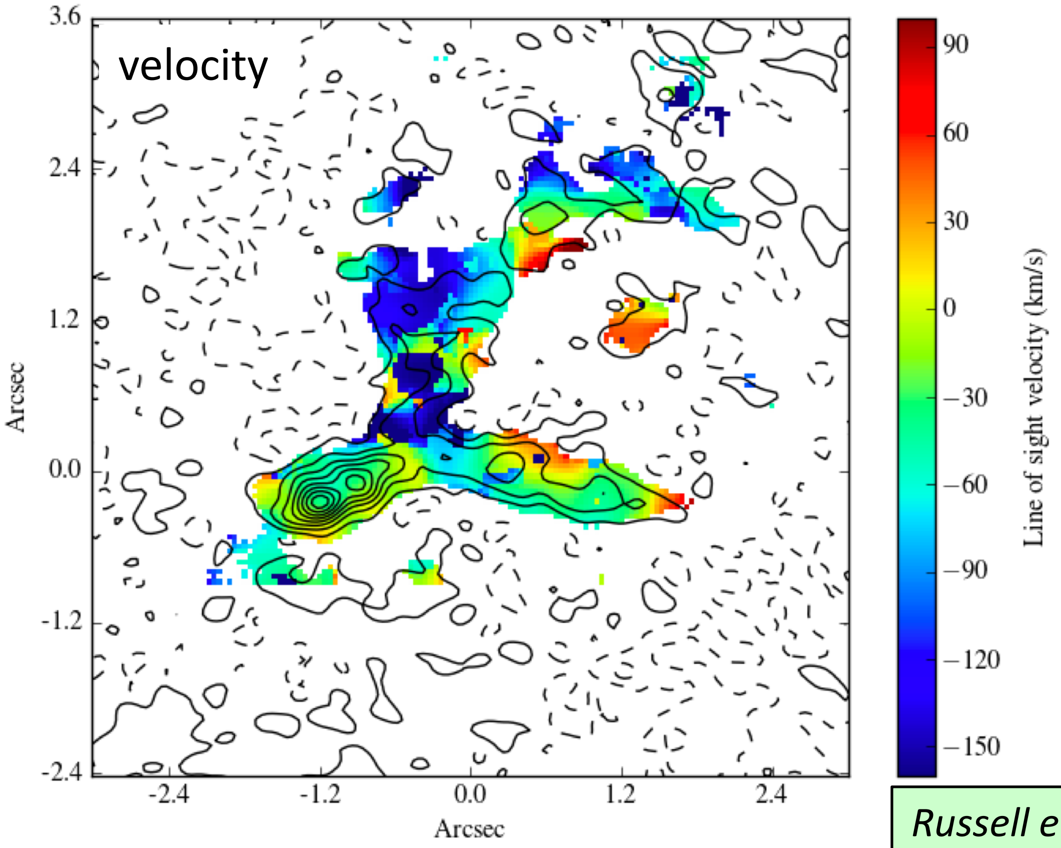
Filaments consist of many GMCs

Low velocities and low dispersions

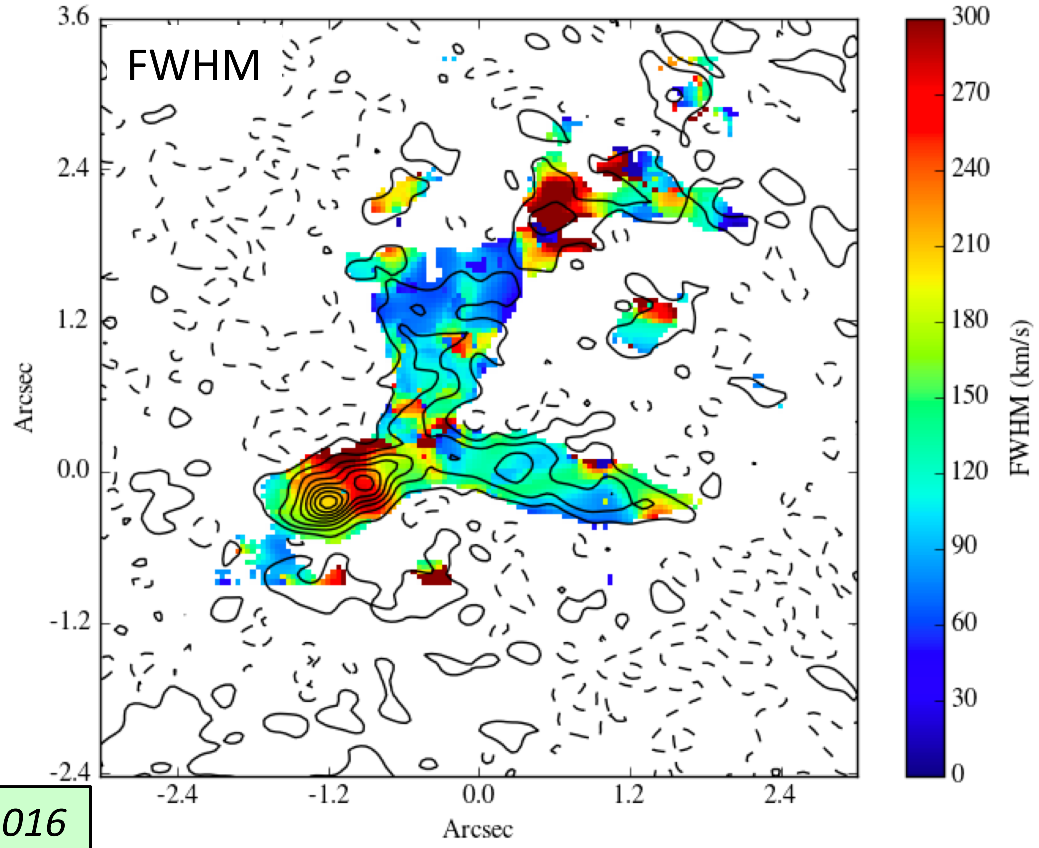


PKS 0745:

- Modest velocities ±100 km/s, narrow FWHM ~100 km/s
- Velocities too low for free fall in gravitational potential

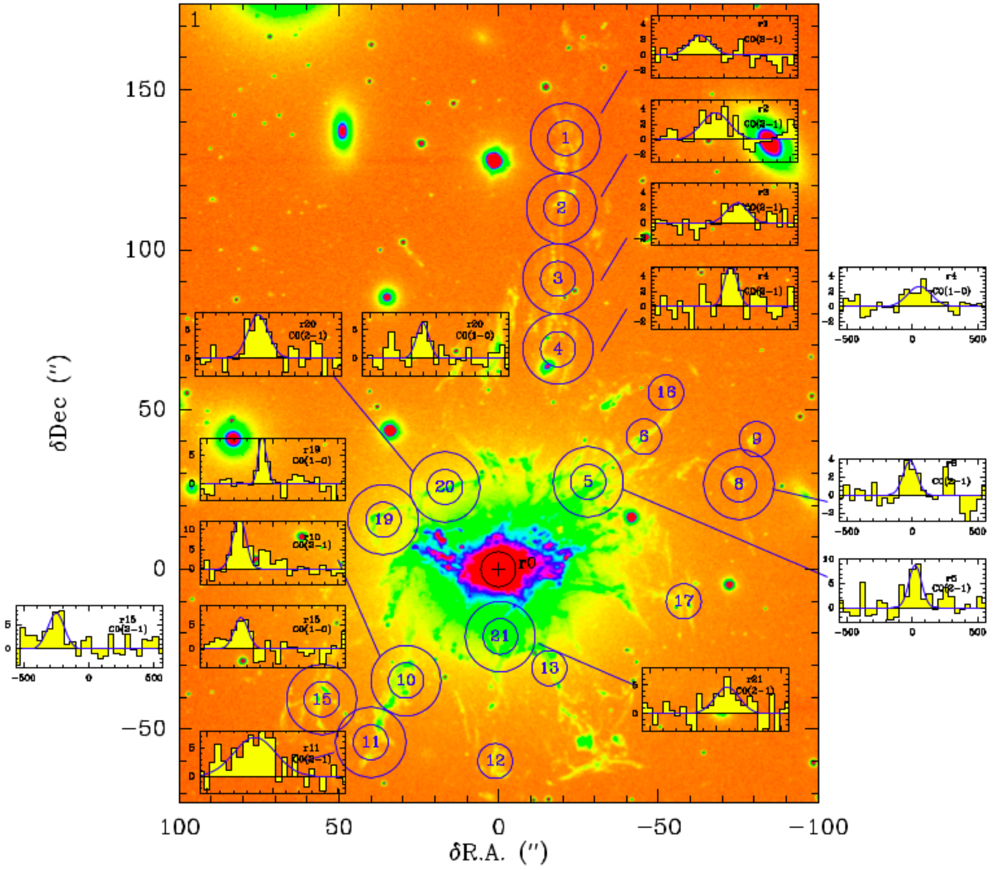


Russell et al. 2016



Molecular gas not settled in the gravitational potential

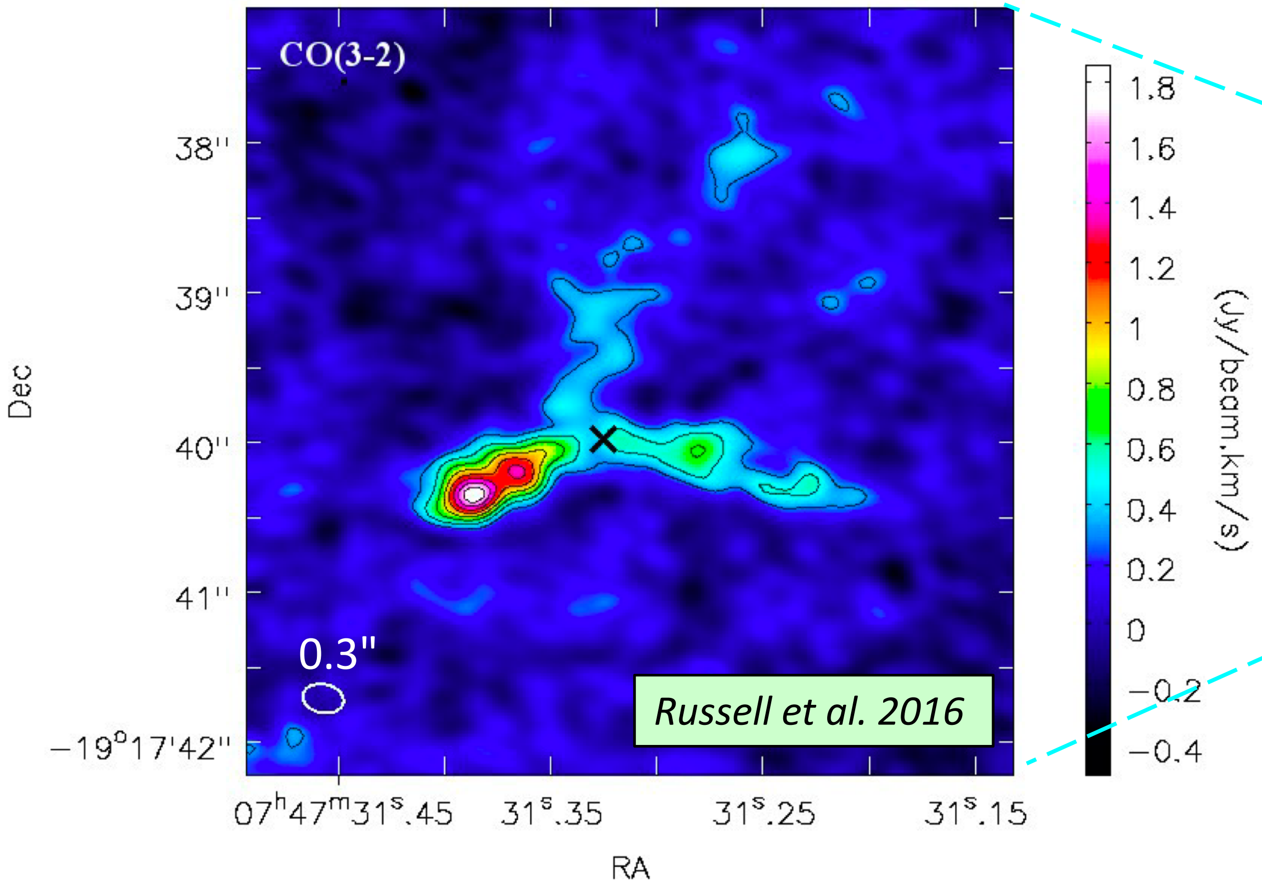
- Massive filaments, low velocities → merger origin is unlikely
- Low velocities compared to stars → filaments not supported by rotation
- Highest velocities at large radii → outflow?

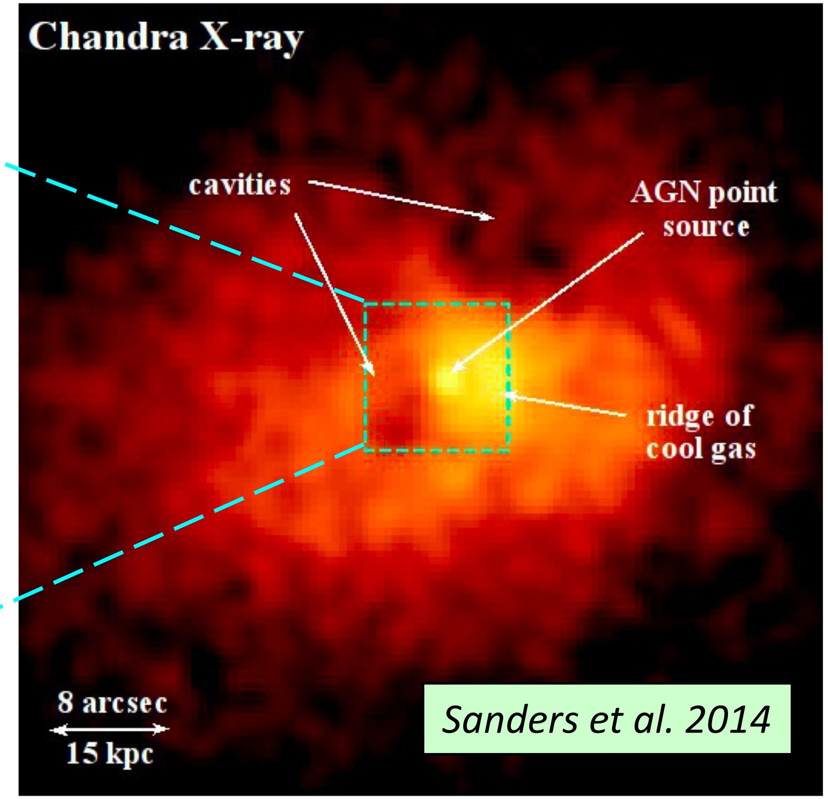


Fabian et al. 2003;
Conselice et al. 2001;
Lim et al. 2008;
Salome et al. 2011

Molecular gas filaments extend towards cavities

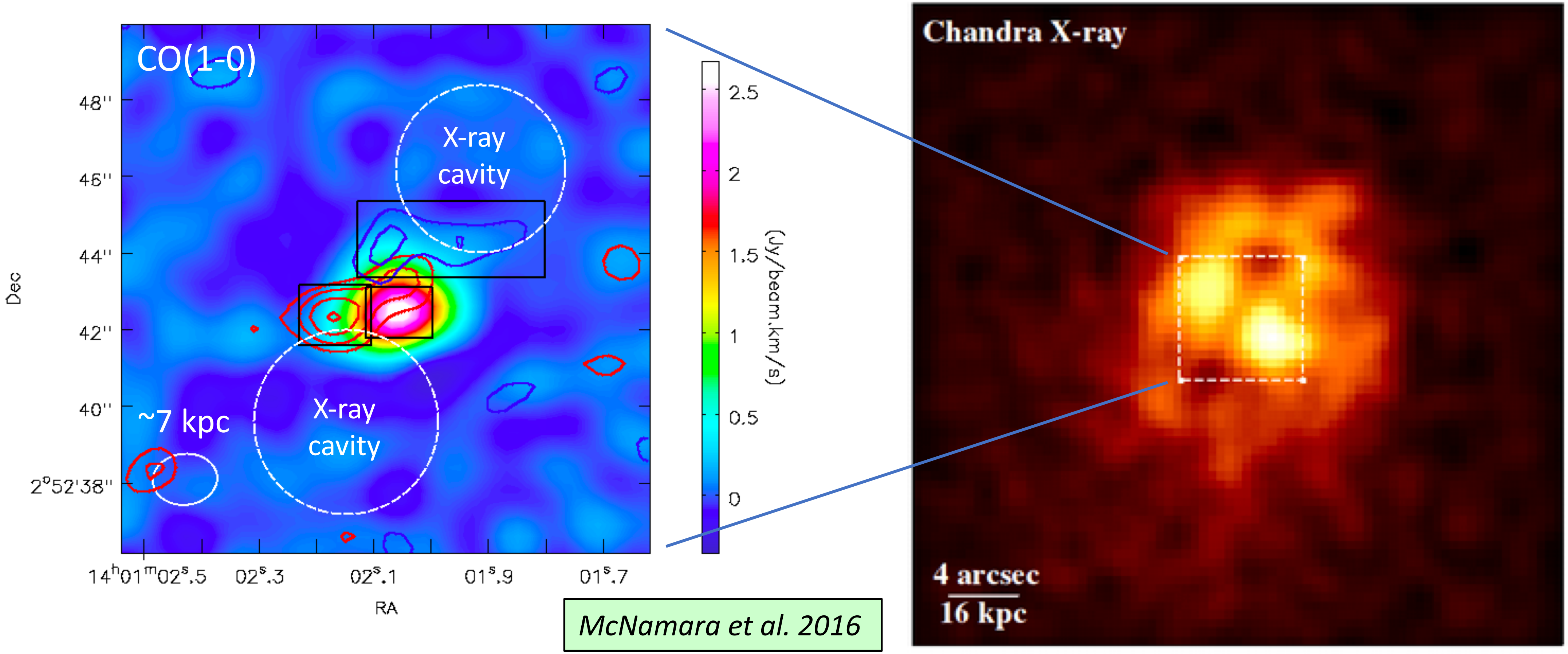
PKS 0745: massive filaments drawn up underneath X-ray cavities and radio lobes





A 1835 : gas flow drawn up around X-ray cavities

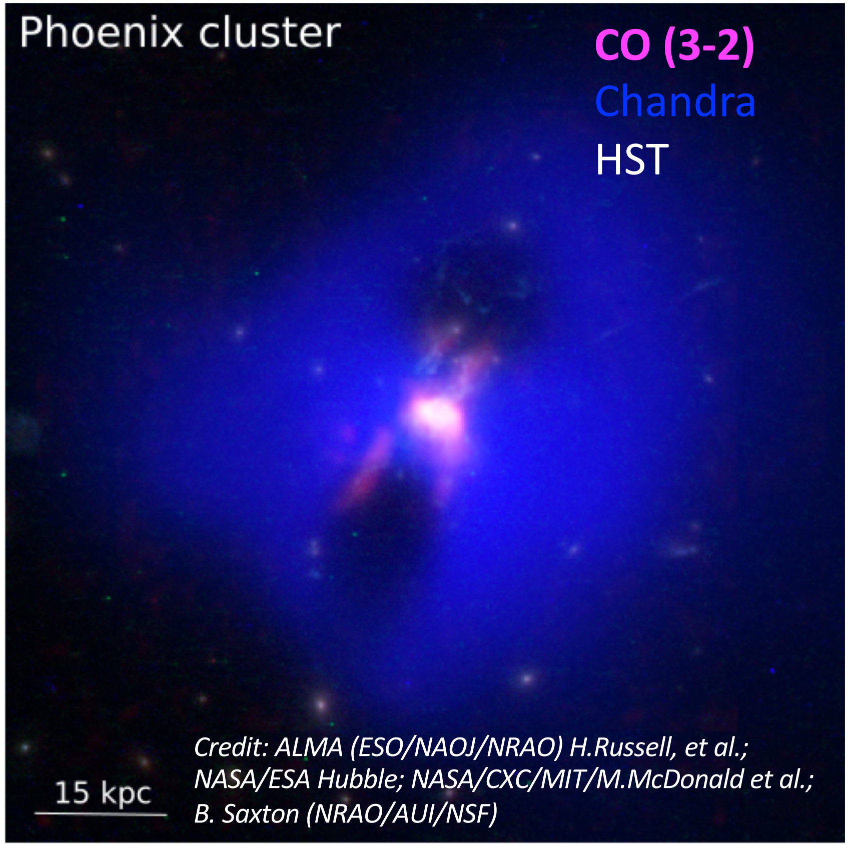
- Gas filaments likely cooled in the updraft of hot plasma behind bubbles
- Interaction with cold gas in radio-mode feedback

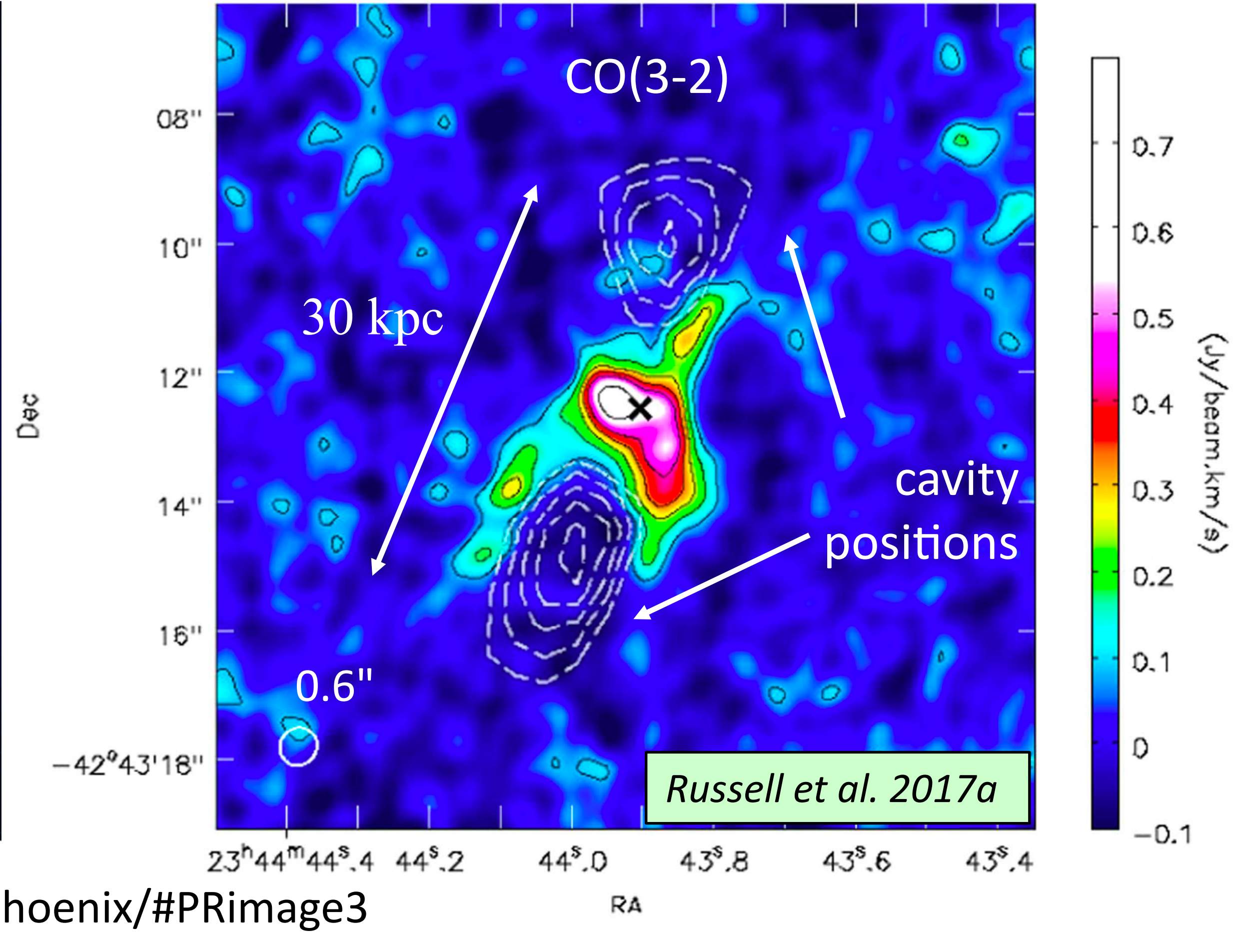


McNamara et al. 2016

Phoenix : filaments shaped by recent radio-jet activity

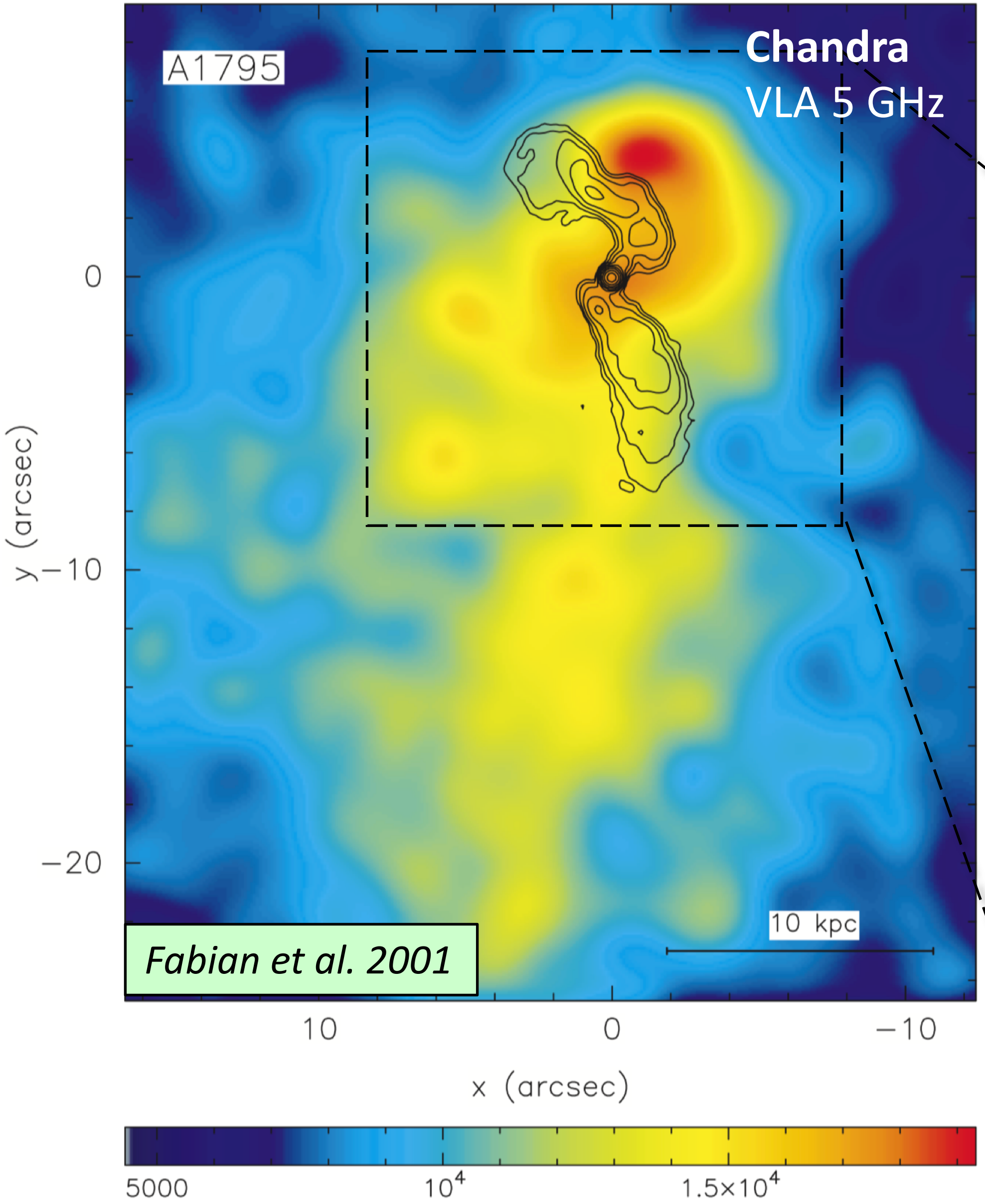
- $\approx 600\ M_\odot$/yr starburst + AGN bright in both X-ray/optical and radio
- $3 \times 10^{10}\ M_\odot$ of molecular gas with half in filaments around radio bubbles



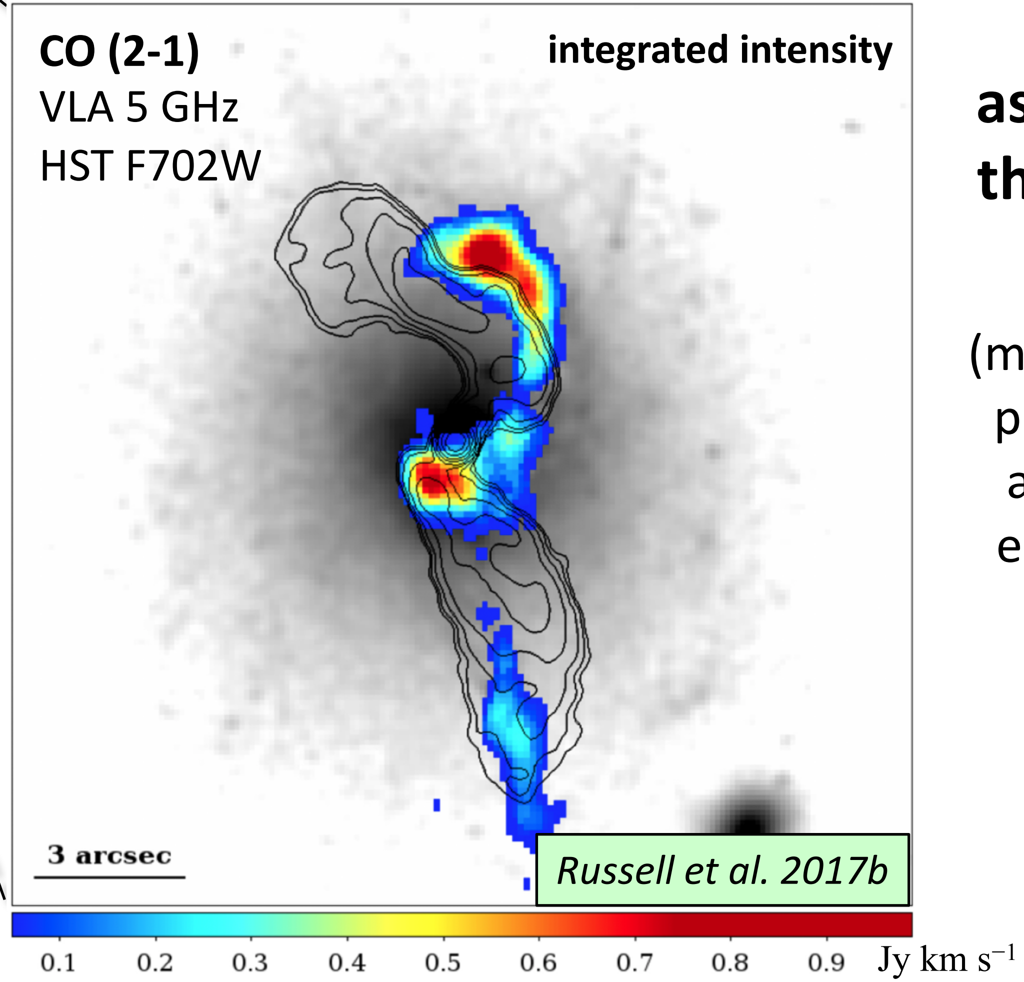


https://public.nrao.edu/news/2017-alma-phoenix/#PRimage3

A 1795 : close entrainment of molecular gas flows by radio bubbles



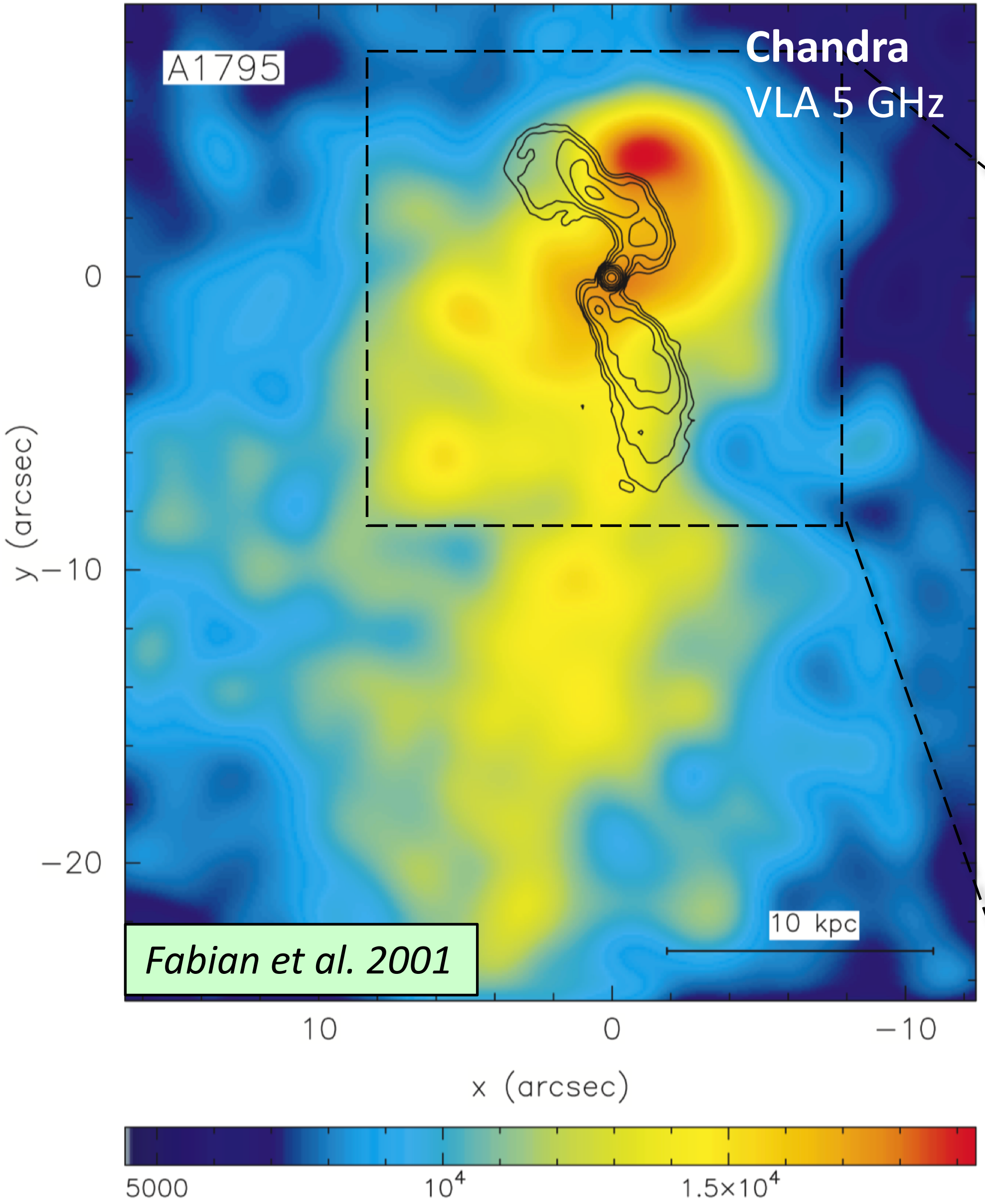
Filaments extending 5-7 kpc to the N and S from the nucleus, with total molecular gas mass $\sim 3 \times 10^9\, M_\odot$



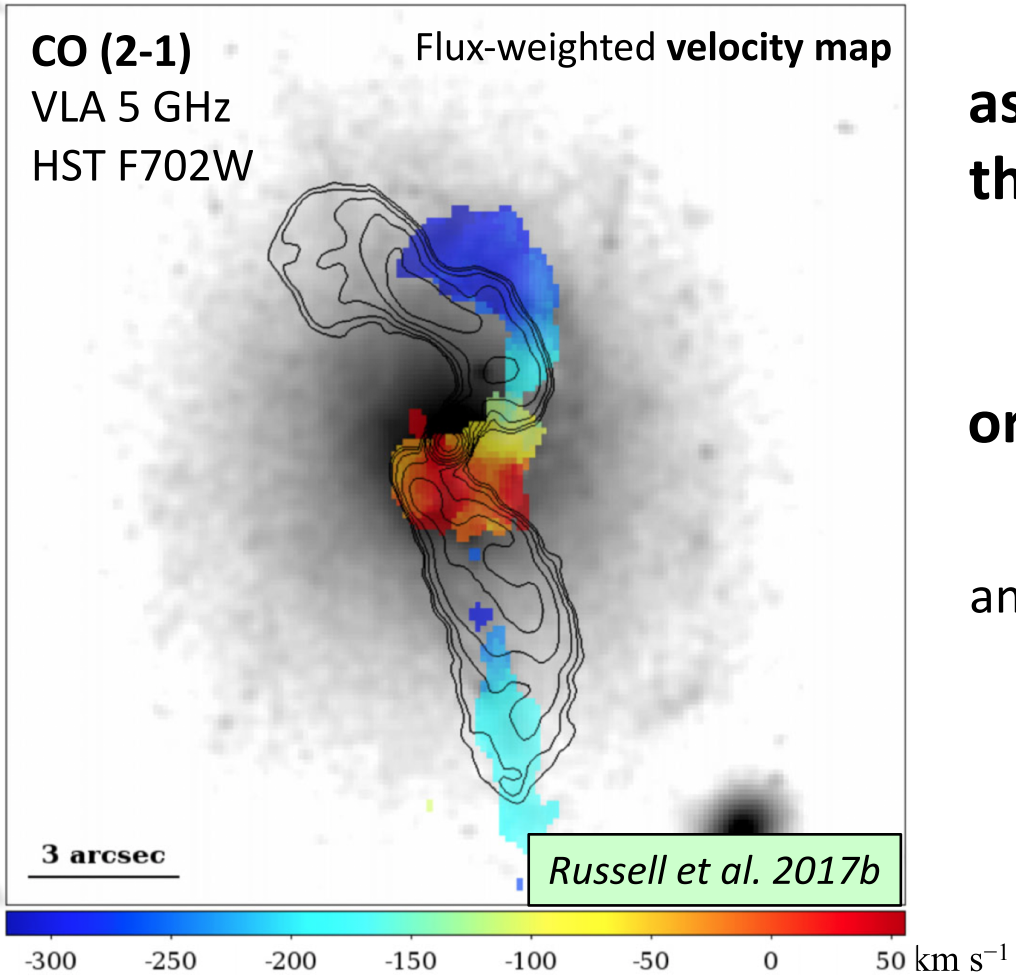
close spatial association with the edges of the radio lobes

(molecular filaments project exclusively around the outer edges of the radio bubbles)

A 1795 : close entrainment of molecular gas flows by radio bubbles



Filaments extending 5-7 kpc to the N and S from the nucleus, with total molecular gas mass $\sim 3 \times 10^9\,M_\odot$



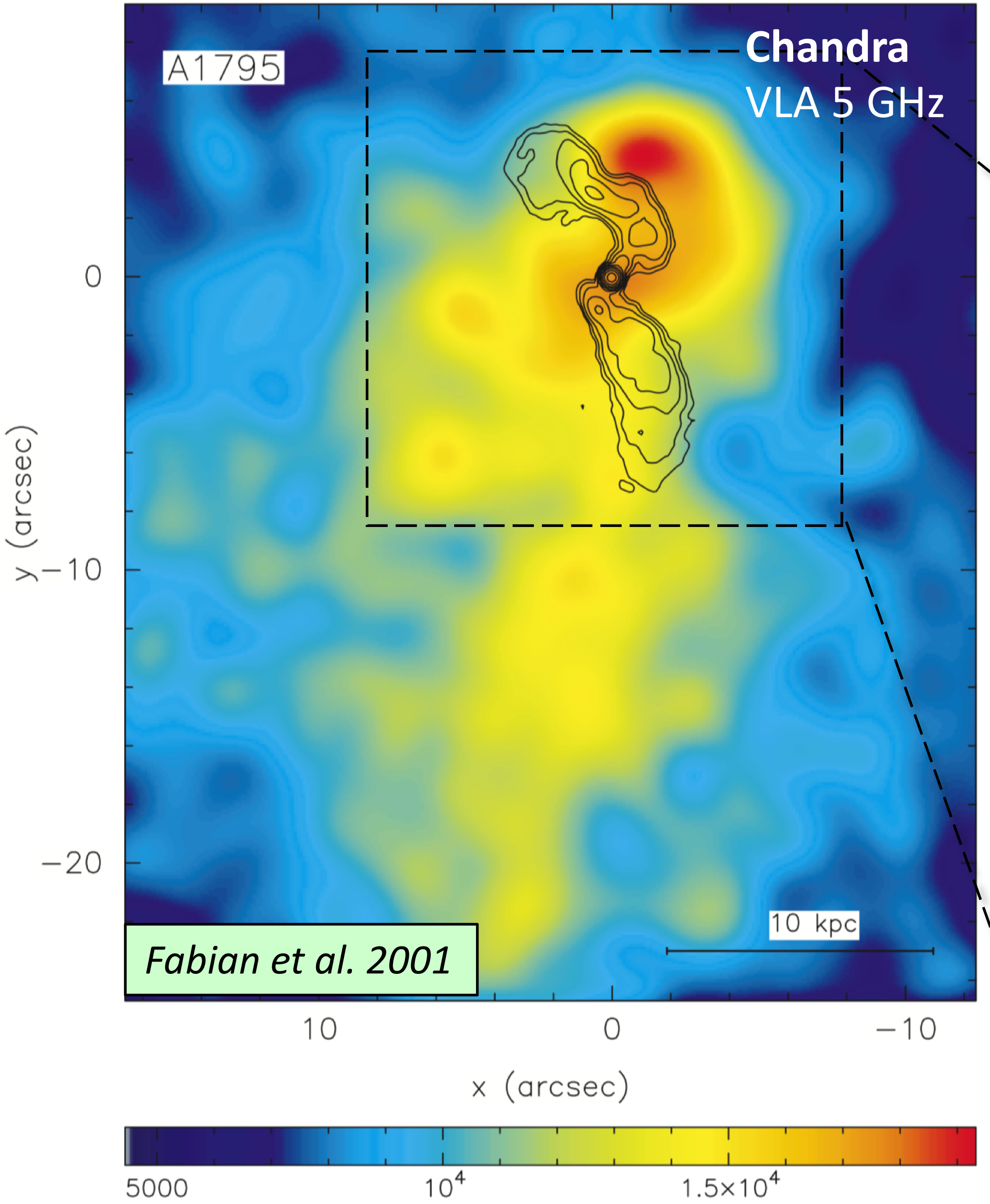
close spatial association with the edges of the radio lobes

+

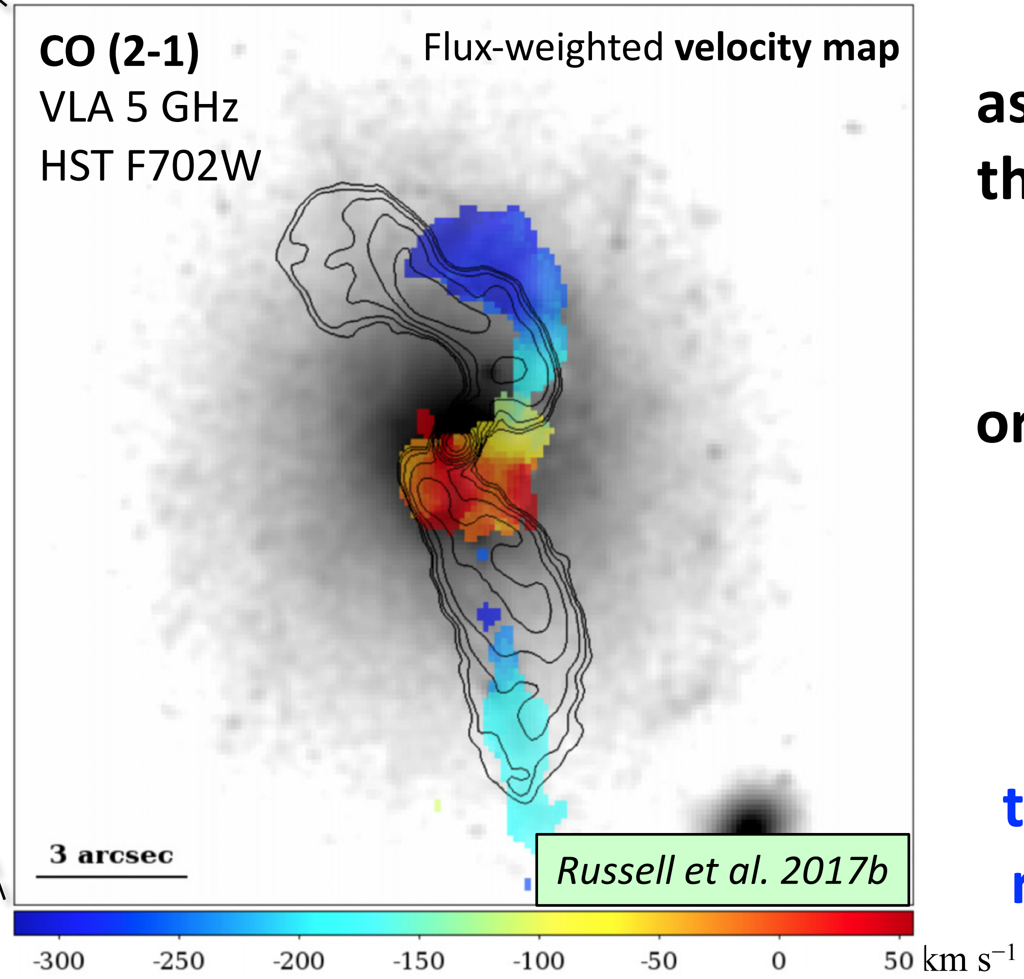
ordered velocity gradients

and narrow velocity dispersions

A 1795 : close entrainment of molecular gas flows by radio bubbles



Filaments extending 5-7 kpc to the N and S from the nucleus, with total molecular gas mass $\sim 3 \times 10^9\, M_\odot$



close spatial association with the edges of the radio lobes

+

ordered velocity gradients

↓

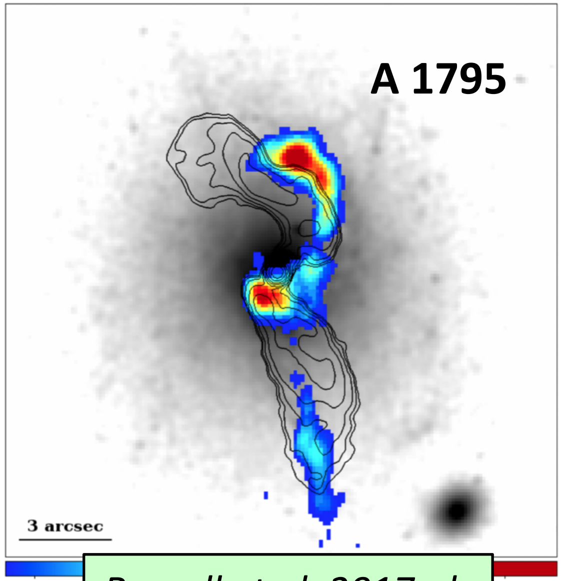
gas flows entrained by the expanding radio bubbles

Direct uplift of molecular gas or cooling *in situ* ?

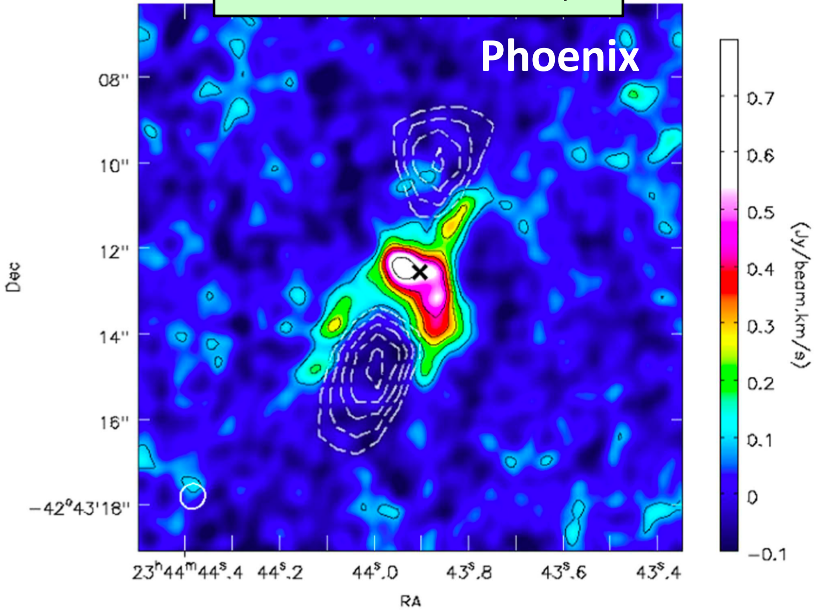
- **Molecular gas structure shaped by radio bubble expansion**

- Direct uplift of molecular gas clouds?
  - $P_{cav} \sim 10^{43\text{-}45}$ erg/s
  - High coupling efficiency required

- **Rapid cooling of uplifted thermally unstable low entropy gas?** *(McNamara et al. 2016)*
  - Molecular gas coincident with soft X-ray
  - Dust lanes

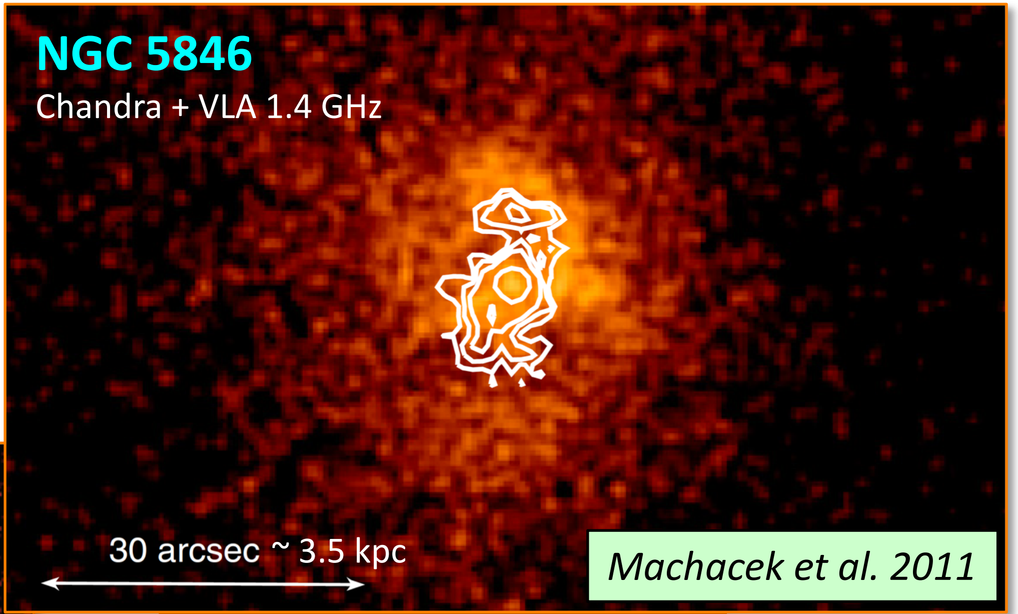


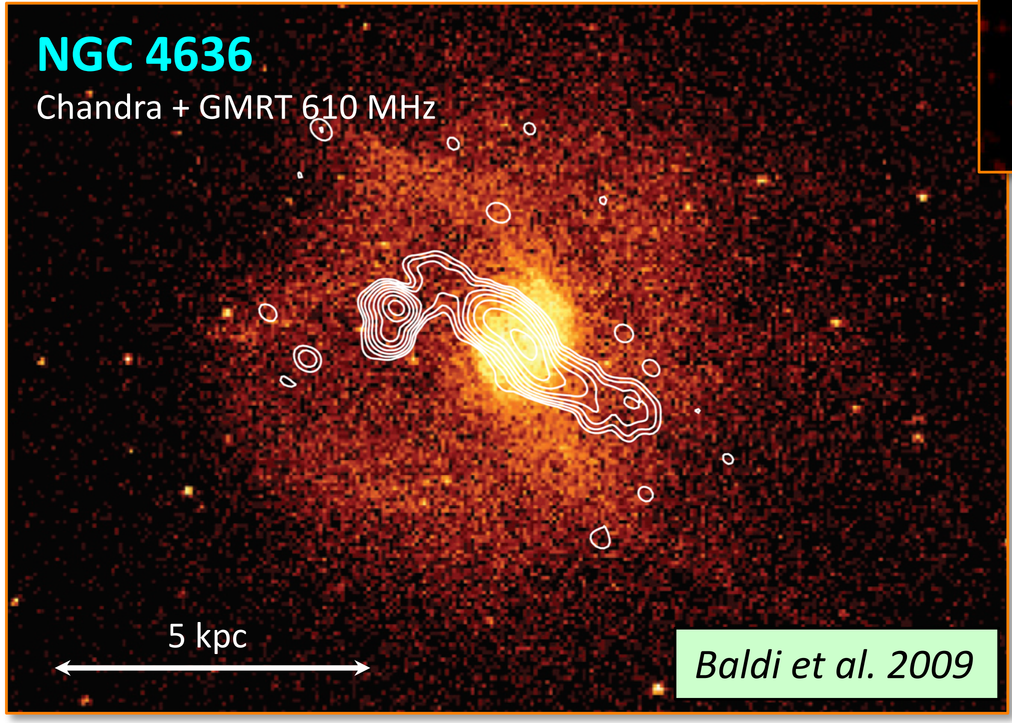
Russell et al. 2017a,b

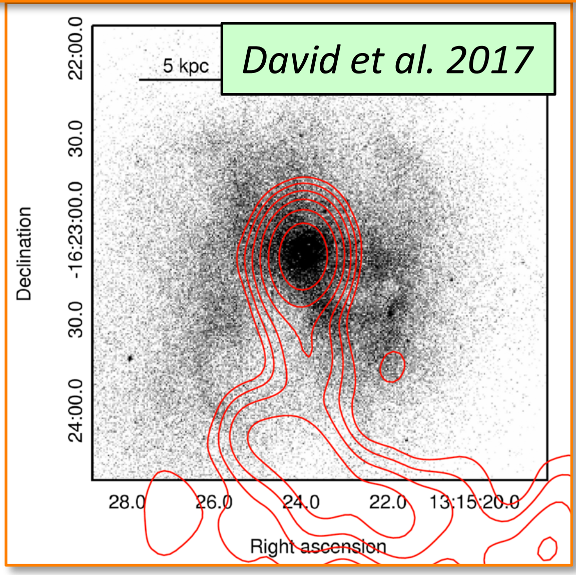


ALMA observations of group-centered Elliptical Galaxies

The selected targets are among the closest examples of AGN feedback in massive elliptical brightest-group galaxies (**BGGs**)



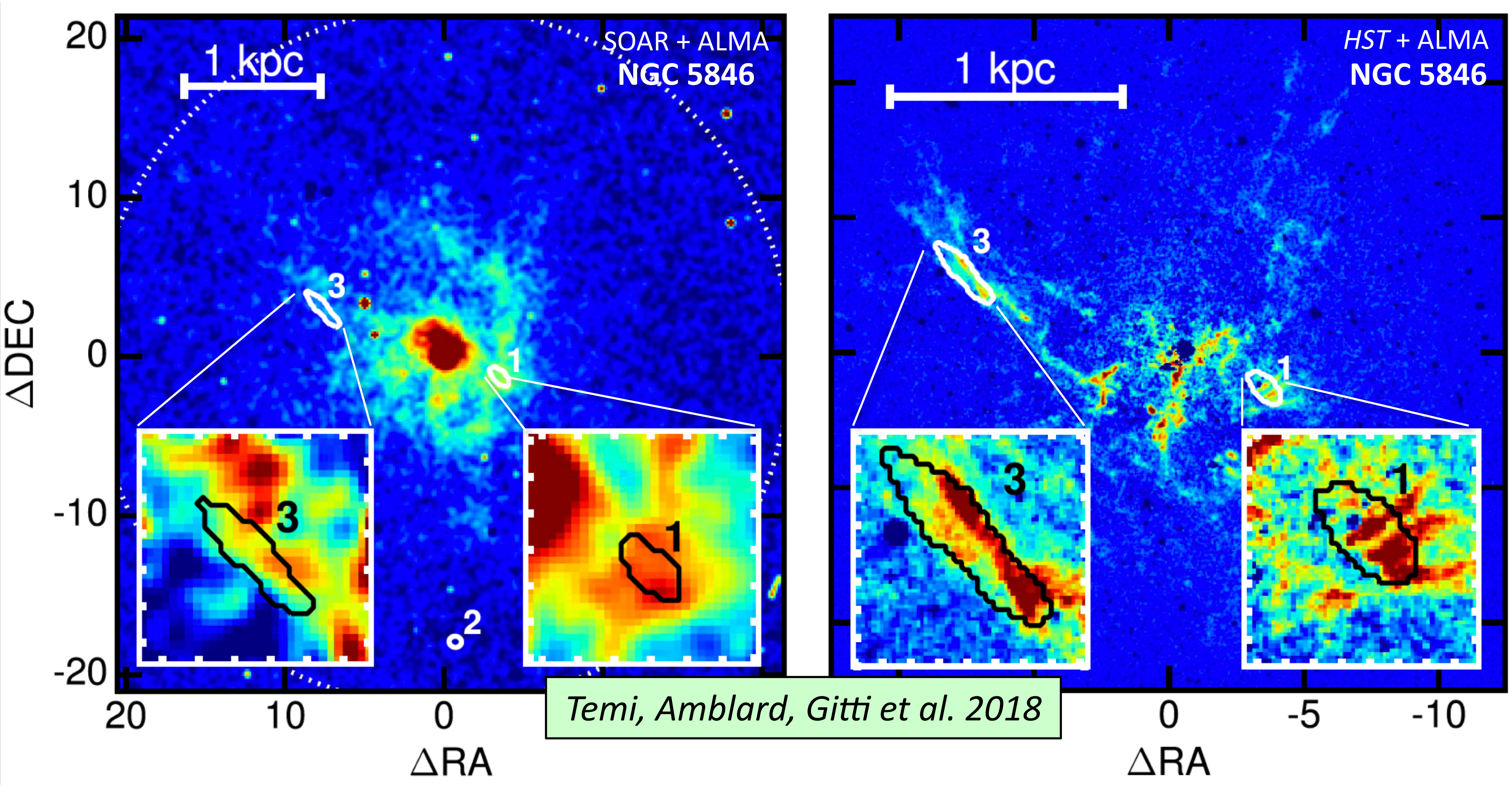




NGC 5044
Chandra + GMRT 235 MHz

ALMA observations of BGGs : CO vs. Hα and dust

Hα+[NII] + **CO contours** **Dust** extinction + **CO contours**

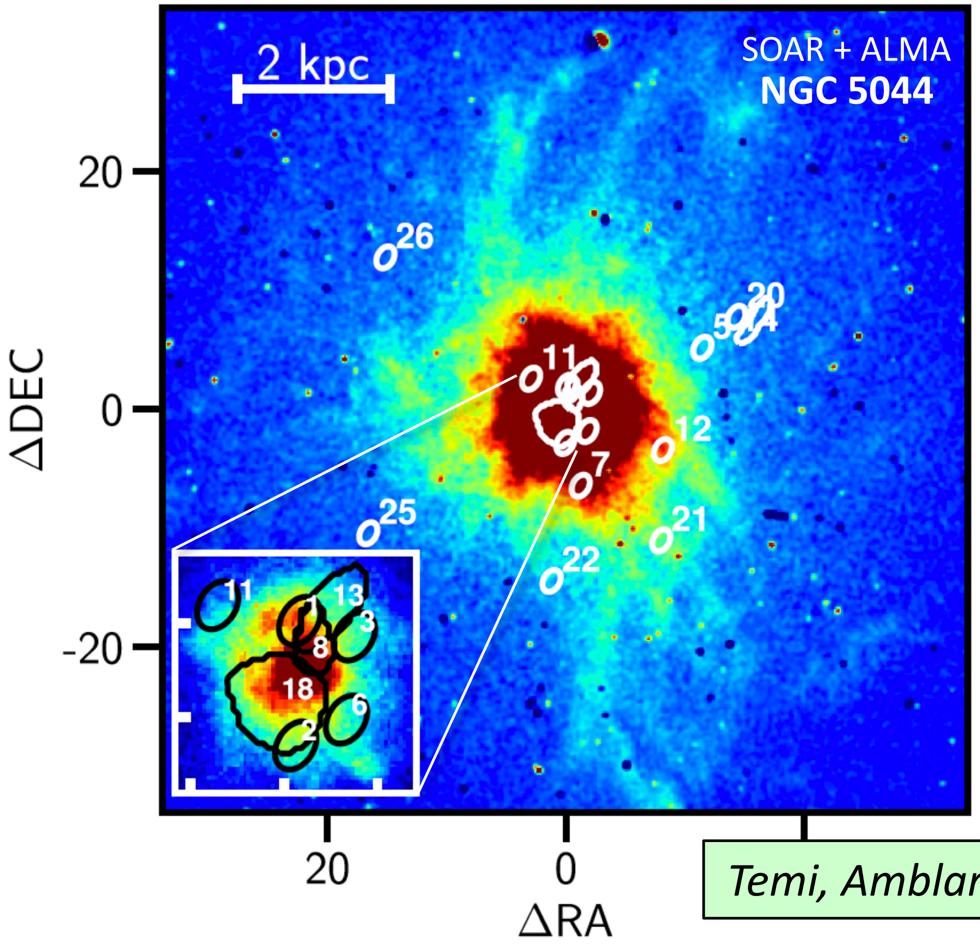


Temi, Amblard, Gitti et al. 2018

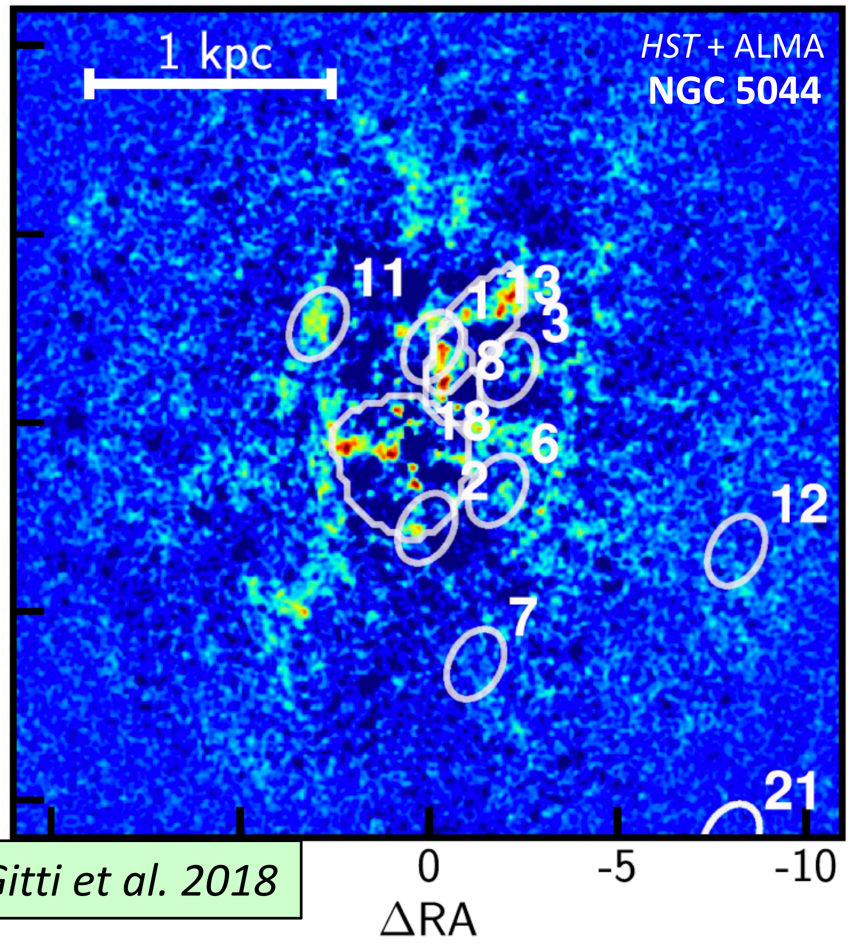
Molecular gas is a common presence in bright group-centered galaxies

ALMA observations of BGGs : CO vs. Hα and dust

Hα+[NII] + **CO contours**



Dust extinction + **CO contours**

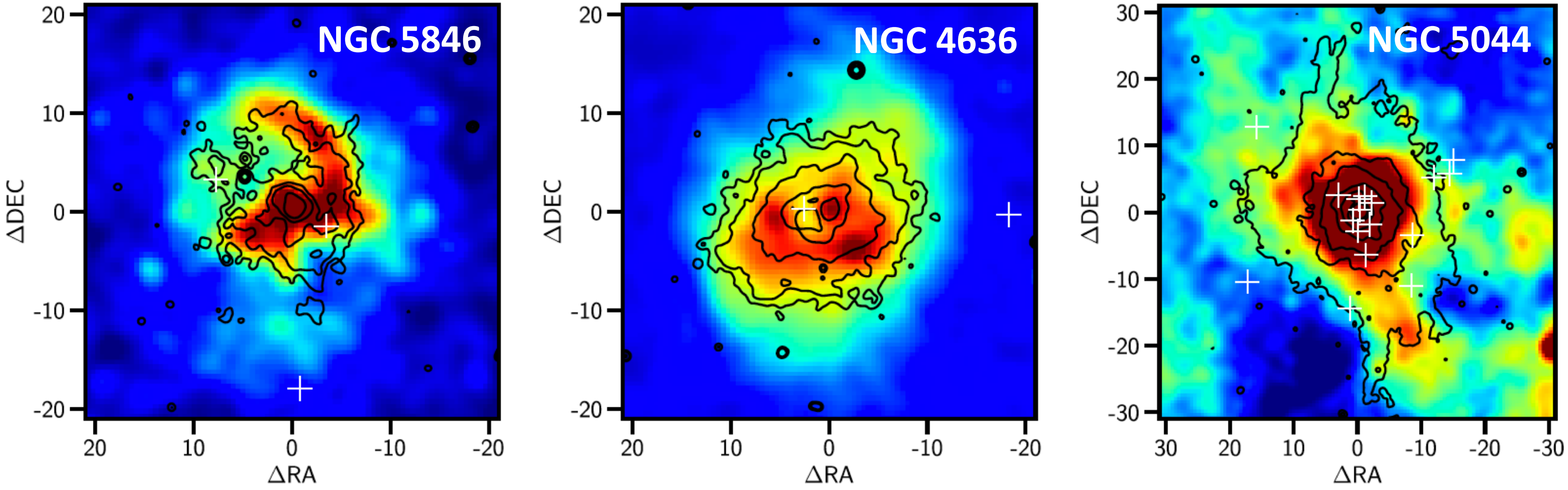


Temi, Amblard, Gitti et al. 2018

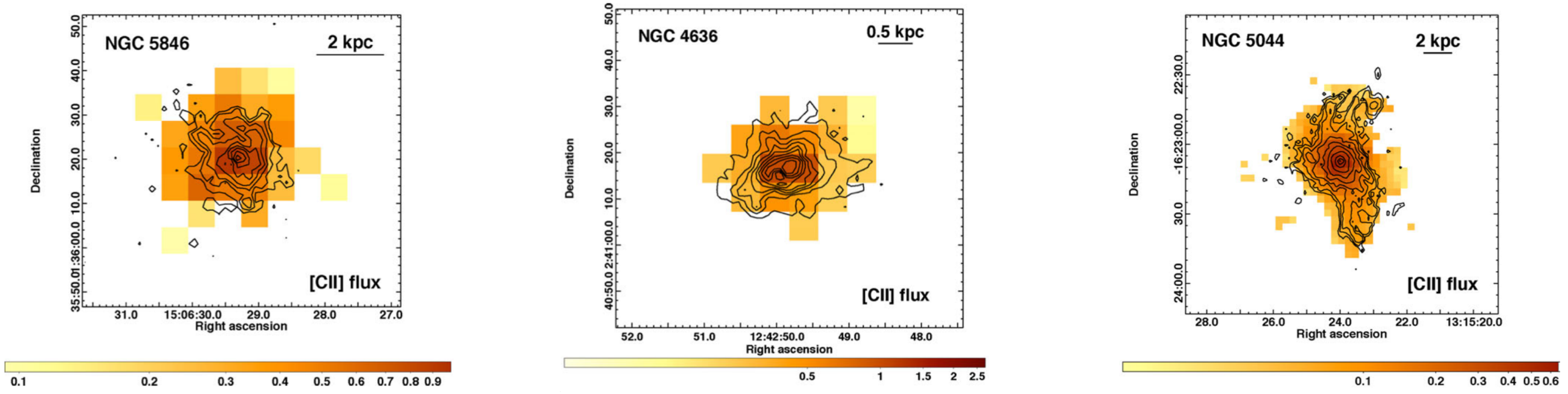
Molecular gas is a common presence in bright group-centered galaxies

Cospatiality among X-ray / Hα / [CII] / CO phases

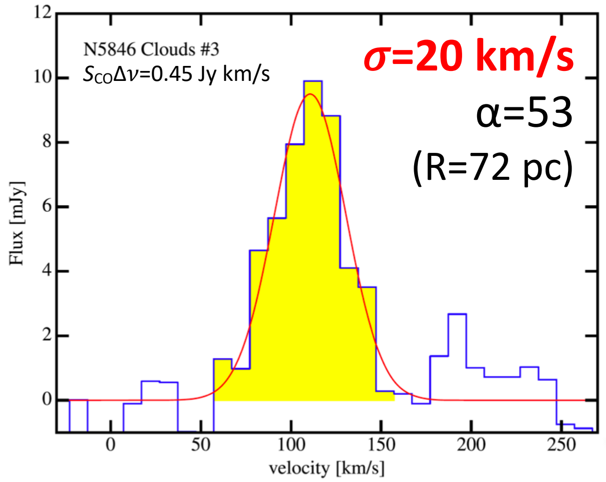
X-ray image + Hα+[NII] contours + **CO cloud positions** *(Temi et al. 2018)*



[CII] flux + Hα+[NII] contours *(Werner et al. 2014)*



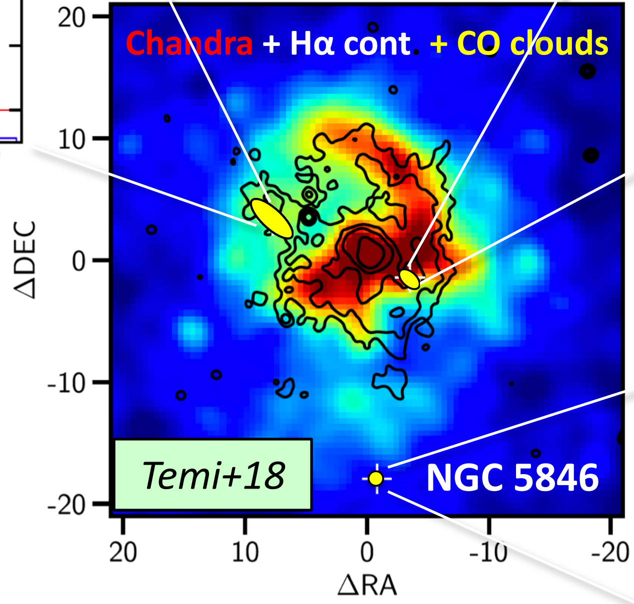
Molecular mass and kinematics in BGG

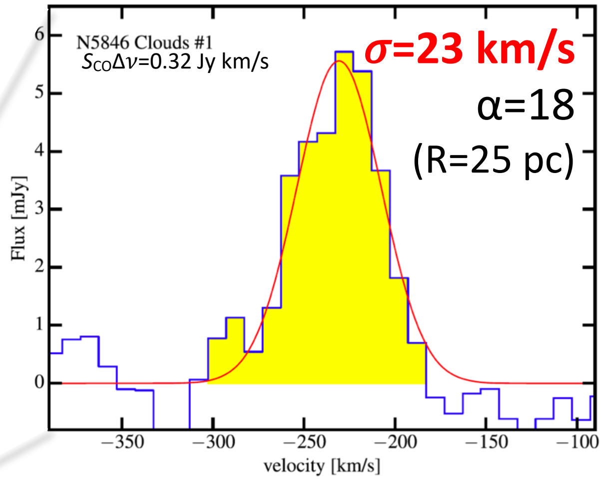


M_{mol} = 8.9×10^5 M$_\odot$

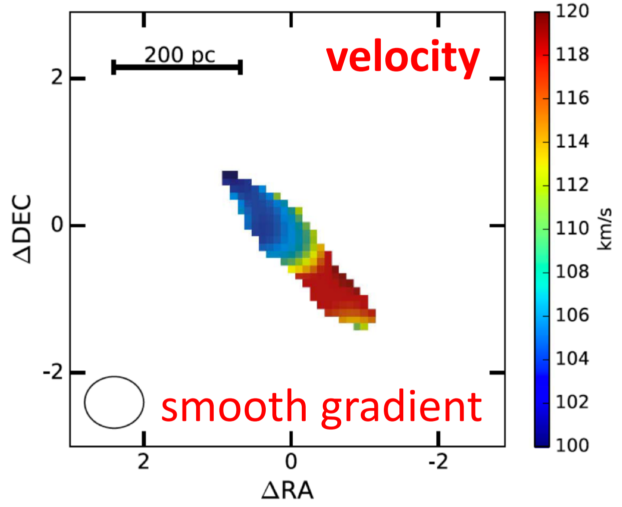
Virial parameter ≫ 1

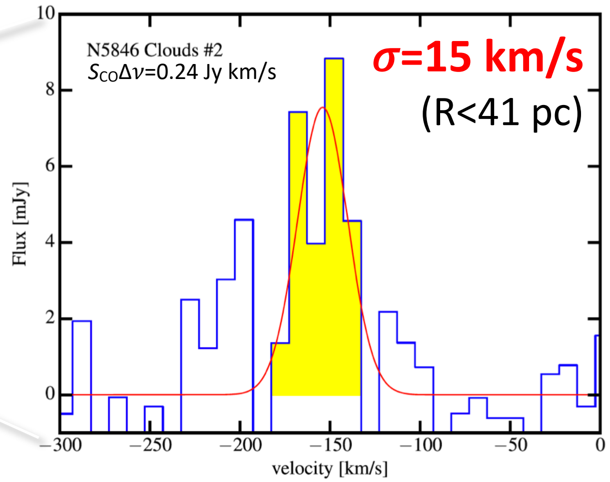
$$\alpha = \frac{5\sigma^2 R}{GM}$$





M_{mol} = 6.4×10^5 M$_\odot$



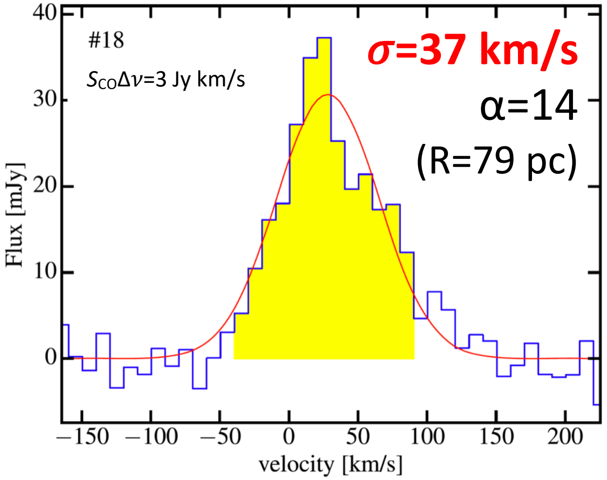


M_{mol} = 4.8×10^5 M$_\odot$

CO line widths few times broader than Galactic GMCs, with total mass

$M_{mol} \sim$ 0.3-60 × 10^6 M$_\odot$

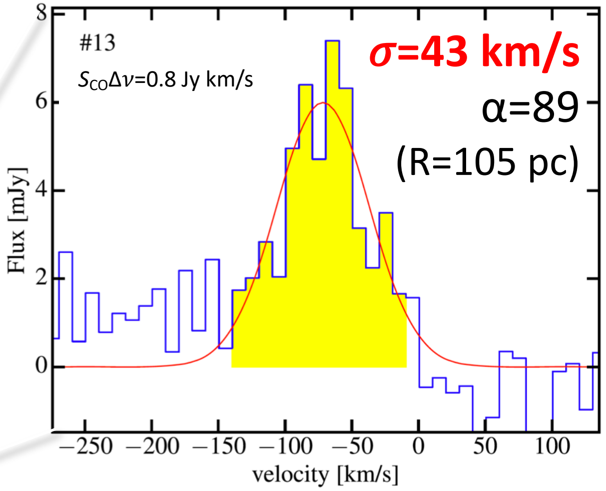
Molecular mass and kinematics in BGG



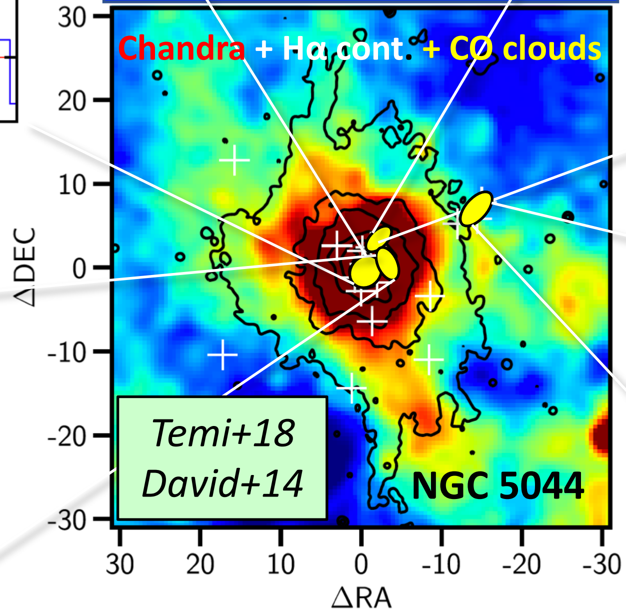
M_{mol} = 94×10^5 M$_\odot$

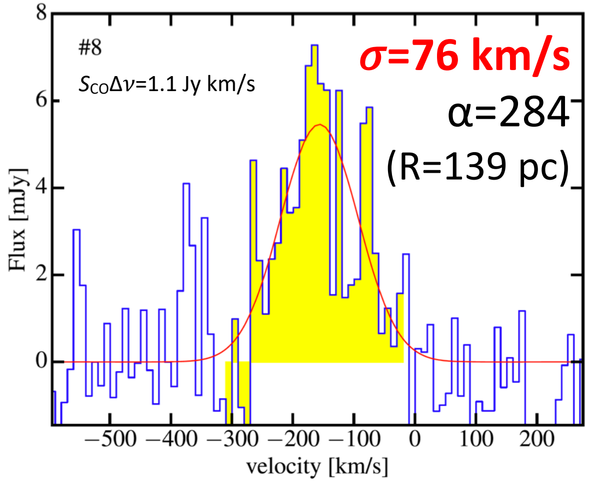
Virial parameter ≫ 1

$$\alpha = \frac{5\sigma^2 R}{GM}$$

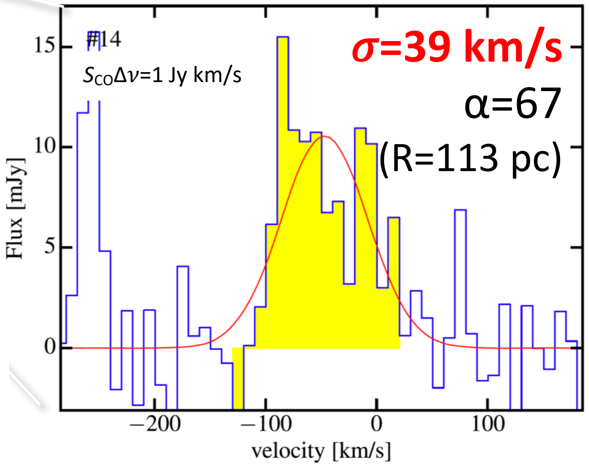


M_{mol} = 26×10^5 M$_\odot$





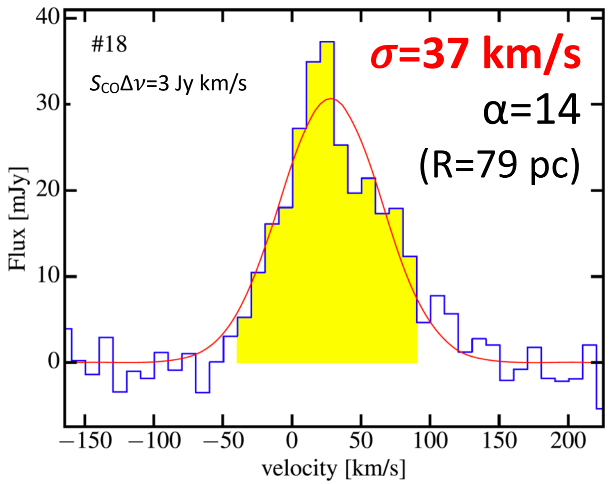
M_{mol} = 34×10^5 M$_\odot$



M_{mol} = 31×10^5 M$_\odot$

Evidence of **unbound GMAs** drifting in turbulent field, or gas flowing out from cloud surface due to heating by local hot IGM

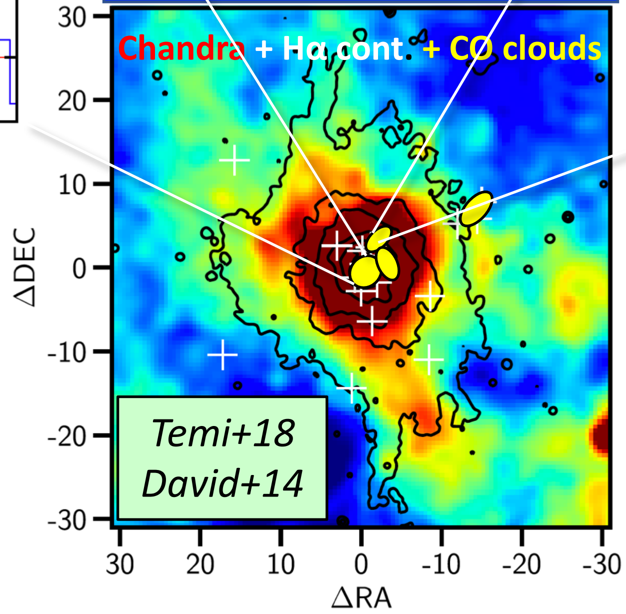
Molecular mass and kinematics in BGG

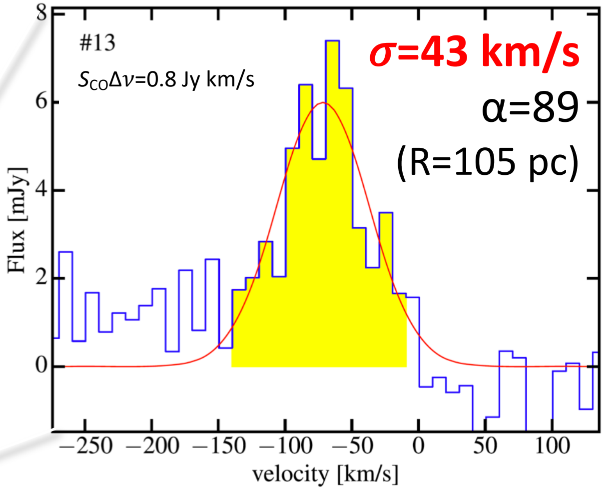


$M_{mol} = 94\times10^5\ M_\odot$

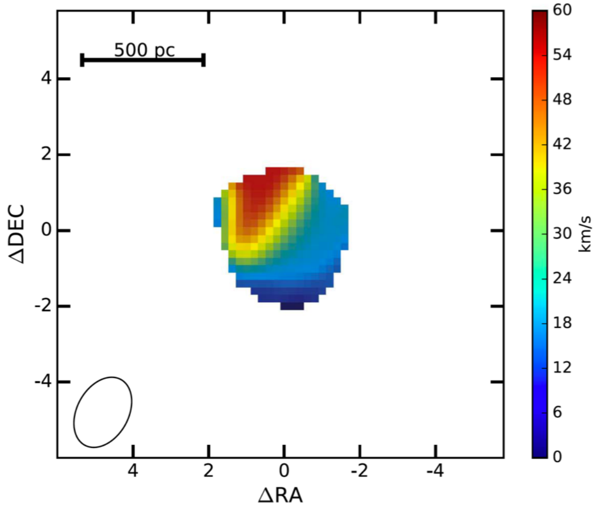
Virial parameter ≫ 1

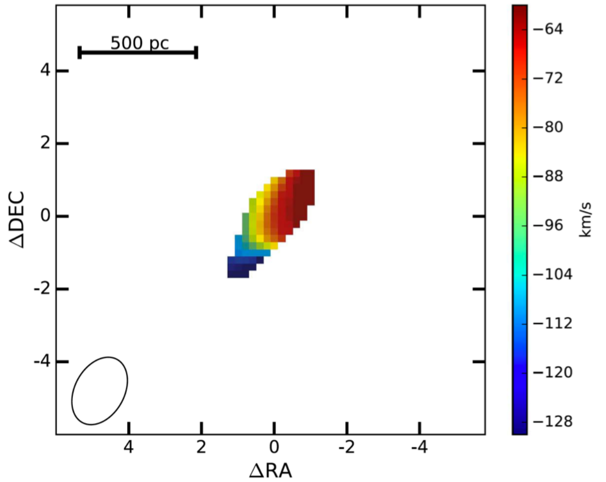
$$\alpha = \frac{5\sigma^2 R}{GM}$$





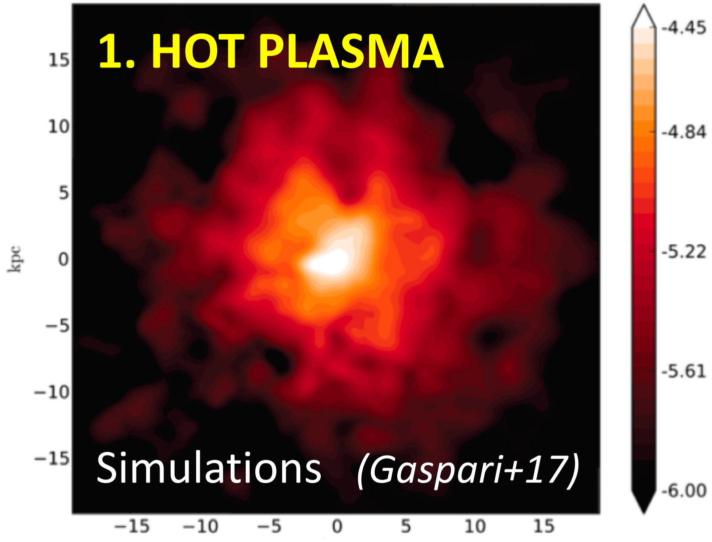
$M_{mol} = 26\times10^5\ M_\odot$



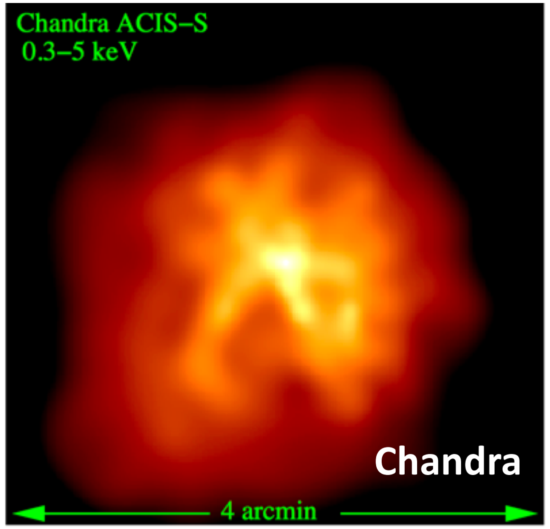


Spatially resolved clouds show
smooth velocity gradients
→ possible rotation or stretching

Multiphase Chaotic Cold Accretion (CCA)



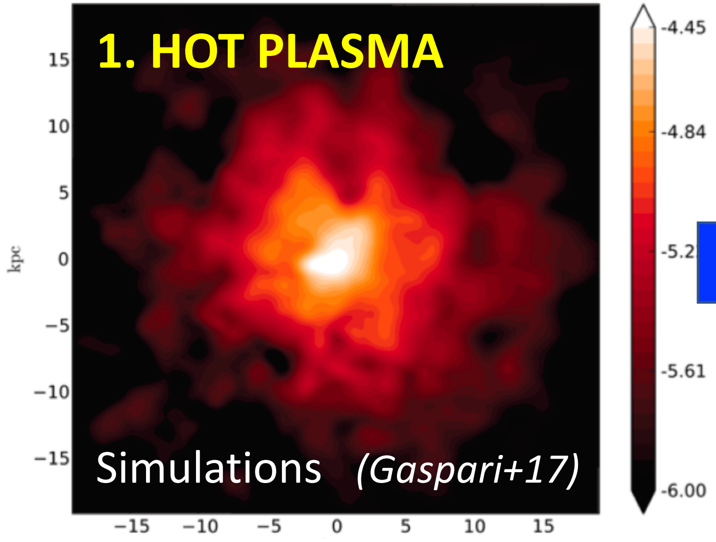
Observations *(Buote+04)*

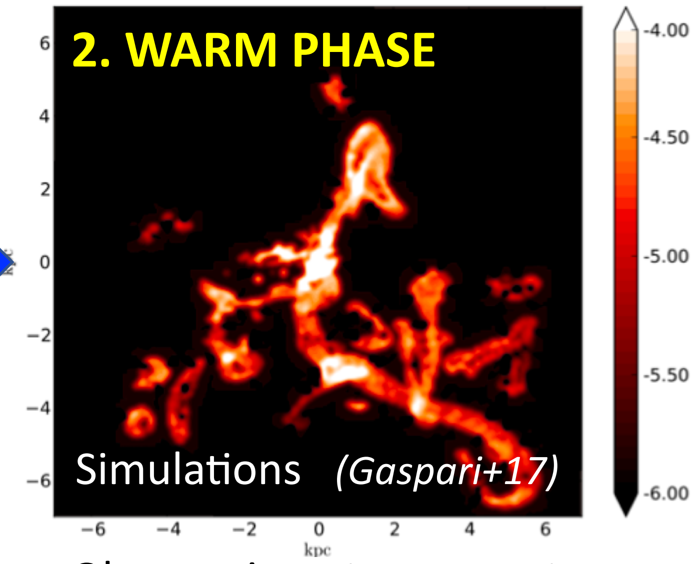


weak subsonic turbulence is enough to trigger CCA

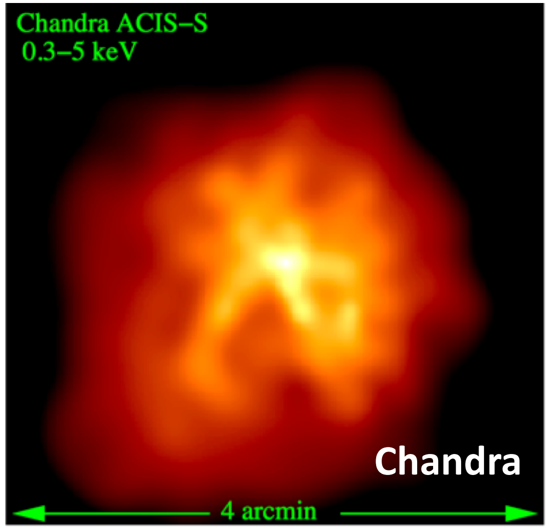
→ thermal instability

Multiphase Chaotic Cold Accretion (CCA)





Observations *(Buote+04)*

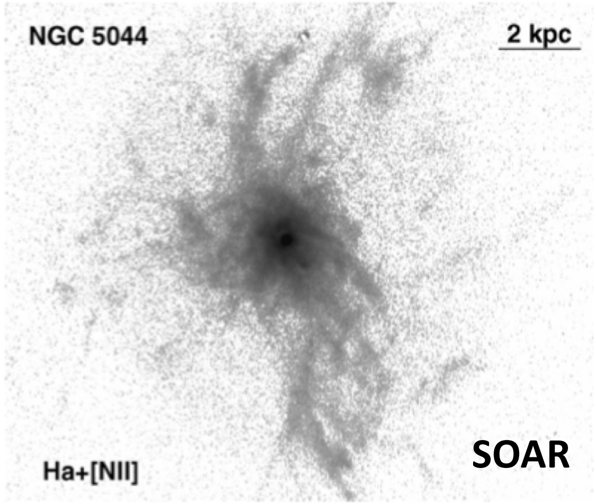


weak subsonic turbulence is enough to trigger CCA

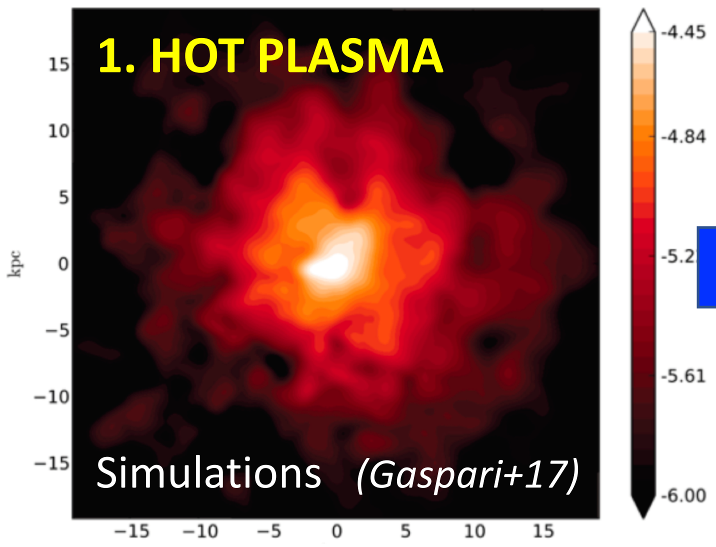
→ thermal instability

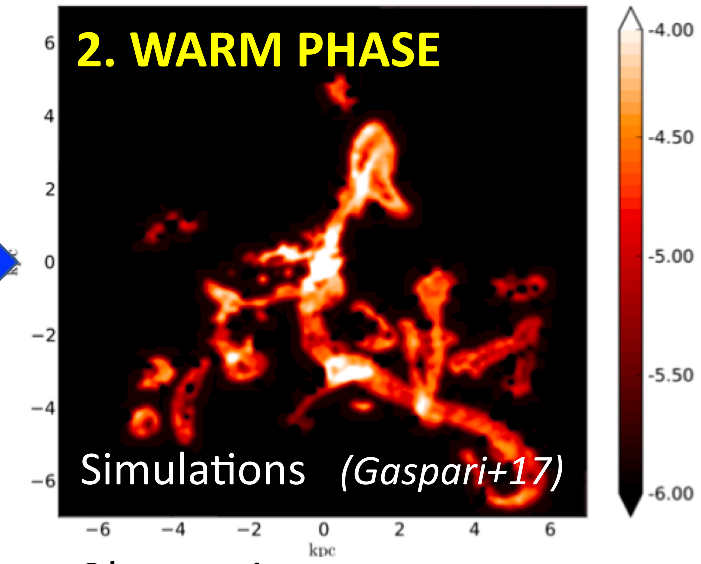
→ **multiphase condensation**

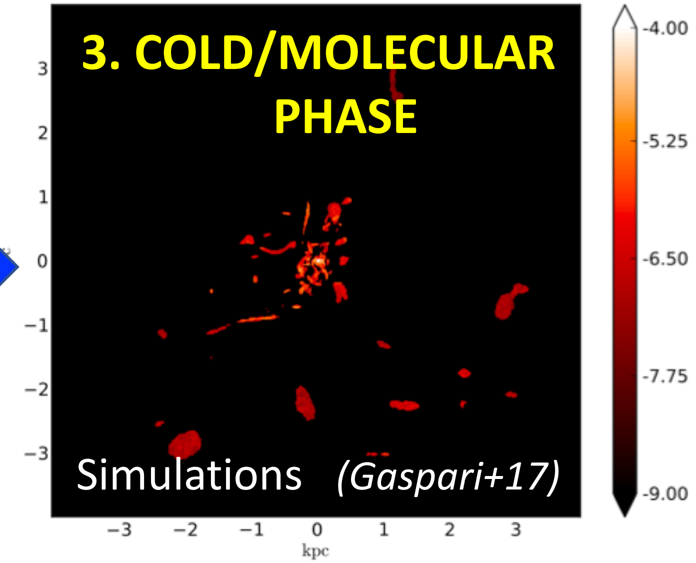
Observations *(Werner+14)*



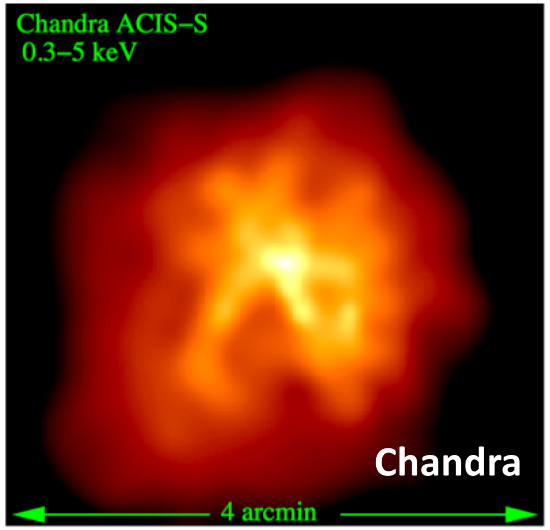
Multiphase Chaotic Cold Accretion (CCA)







Observations *(Buote+04)*

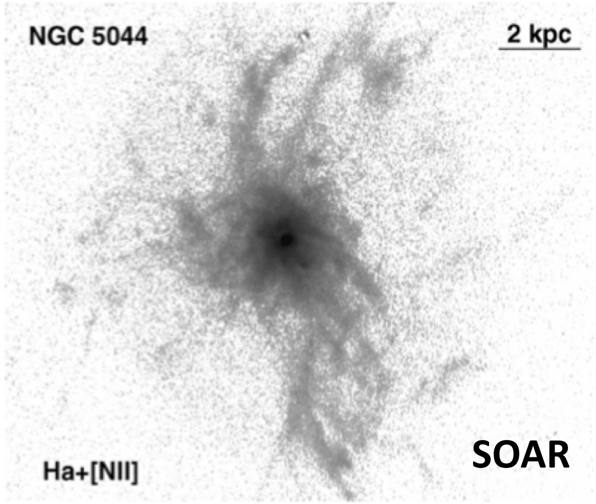


weak subsonic turbulence is enough to trigger CCA

→ thermal instability

→ **multiphase condensation**

Observations *(Werner+14)*

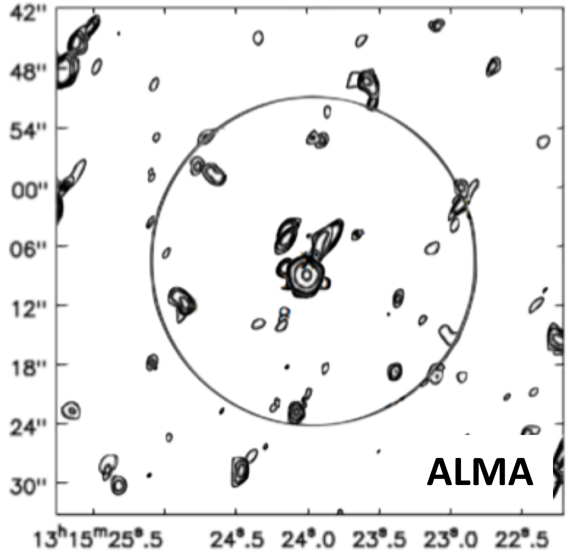


GMAs, $r \lesssim 70$ pc

cospatial with warm phase and soft X-ray plasma

dynamically supported → turbulent pressure

Observations *(David+14, Temi+18)*



Conclusions

- The main evidence 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 radio bubbles while carving X-ray cavities**, heat the ICM and induce a circulation of gas and metals on scales of ≈ 100s kpc
- ALMA: molecular gas structures shaped by radio bubble expansion
  - Massive 10^9-10^{10} $M_\odot$ filaments drawn up around and beneath radio bubbles
- Narrow molecular emission lines
  - extended filaments, ordered velocity structure, unbound GMAs
- Molecular gas likely cooled from hot gas - multiphase condensation