Driving hot and cold gas flows with AGN feedback in galaxy clusters

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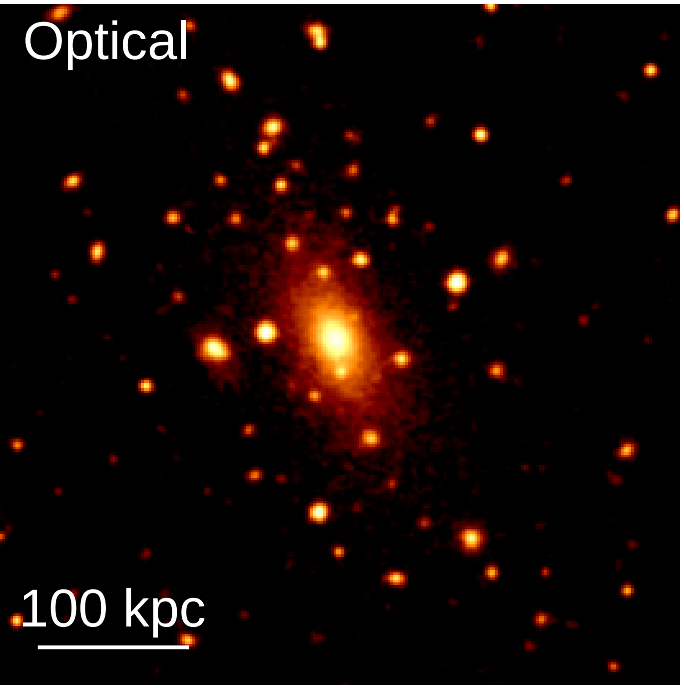
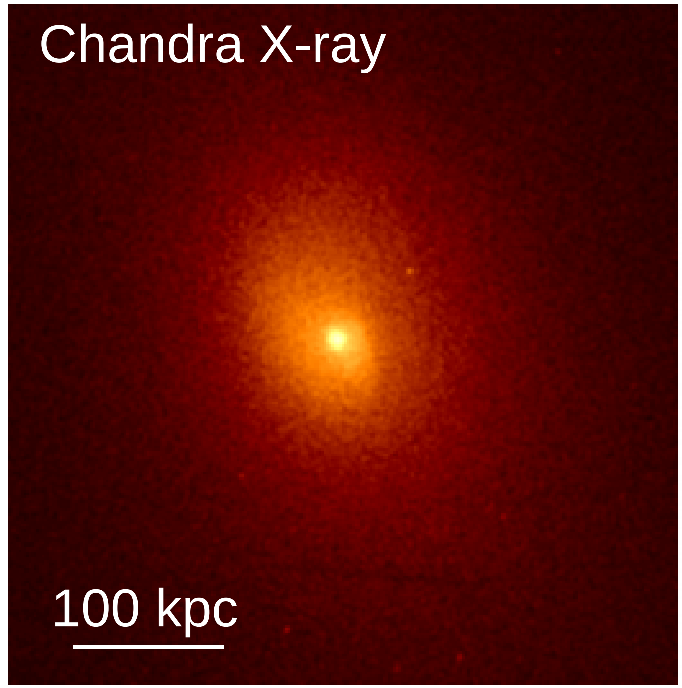
Outline

- Introduction
  - Radiative cooling in galaxy clusters
  - AGN feedback
- Results
  - ALMA observations of molecular gas in central cluster galaxies
    - A1664 and A1835
    - PKS0745
  - Extended filaments, AGN-driven gas outflows, rotating gas disks
- Conclusions

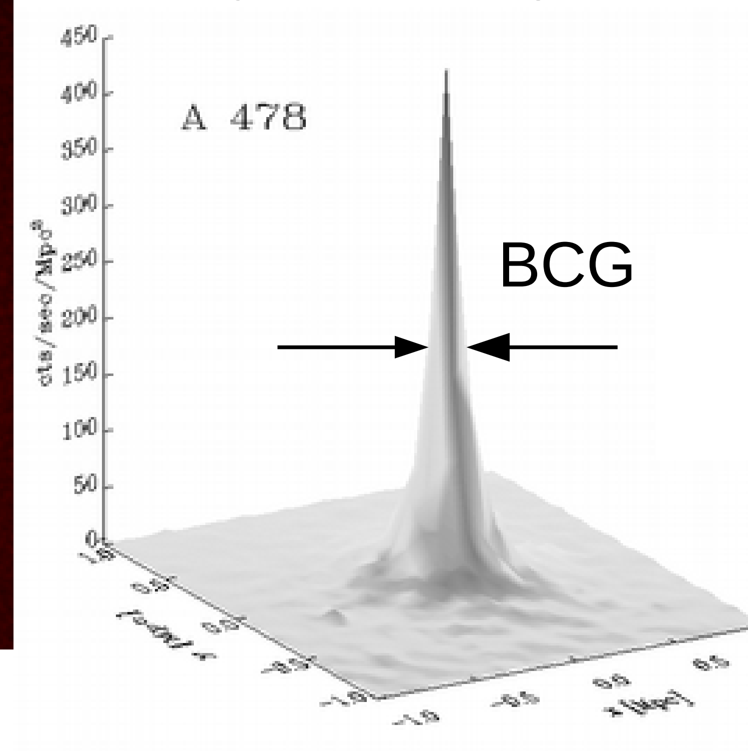
X-ray surface brightness peaks in cluster cores





Lewis et al. 2003, Allen et al. 2004

X-ray surface brightness

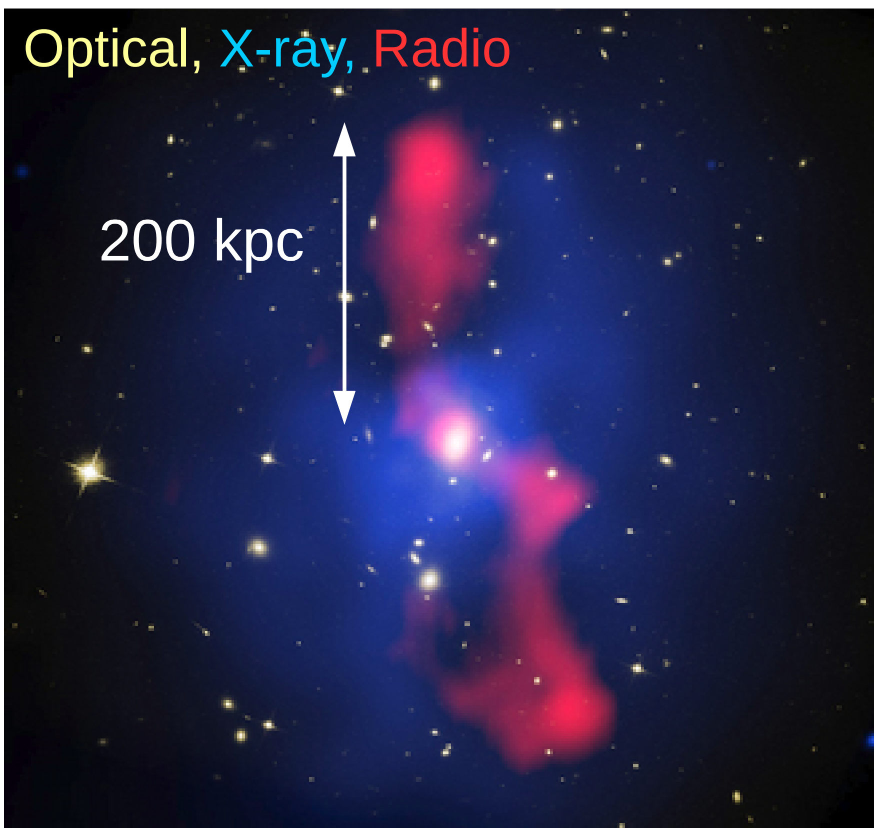


Credit: S. Allen + A. Fabian

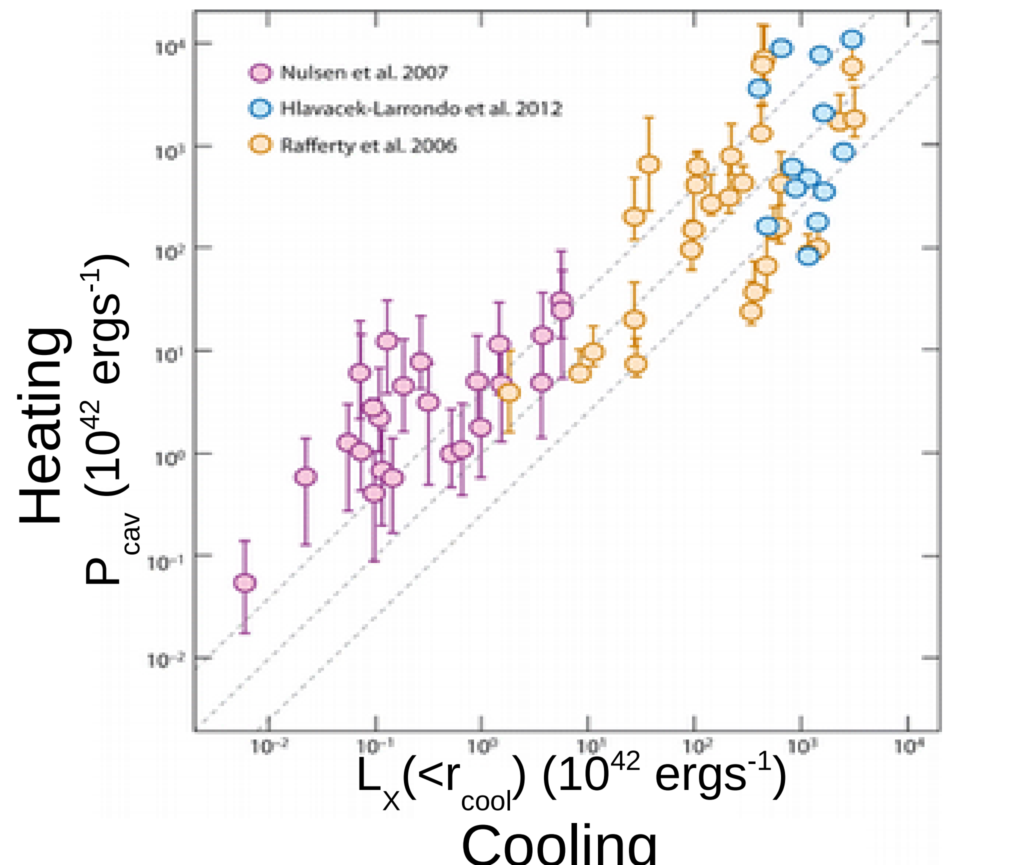
- 100 – 1000 $M_{\odot}$ per year gas cooling?

Radio jets heat cluster gas

- Searches for vast reservoir of molecular gas find less than 10% of that expected (Edge '01, Salomé + Combes '03) → residual cooling
- AGN heating replaces radiative losses → feedback loop



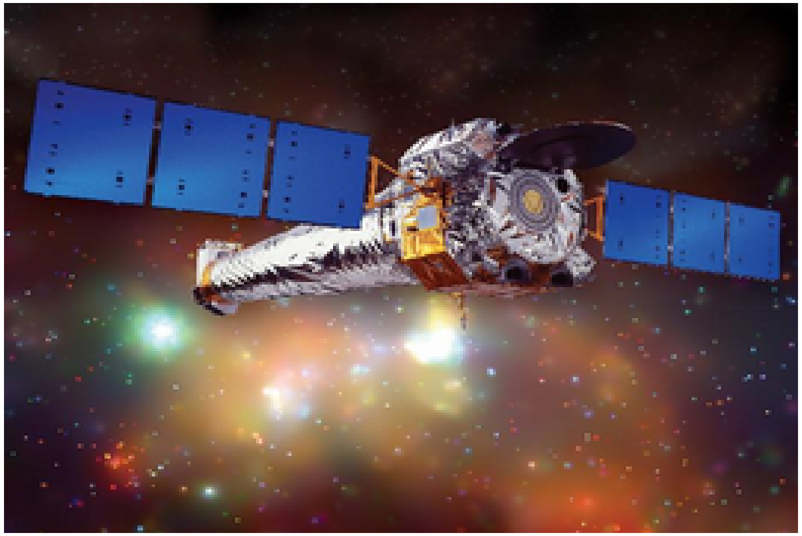
MS0735, McNamara et al. 2005



Rafferty et al. 2006; Birzan et al. 2004; Fabian 2012

What is the role of molecular gas in feedback?

BCGs in cool core clusters are rich in molecular gas
(Edge 2001, Salomé & Combes 2003)



Chandra: energy output → ALMA: fuelling?

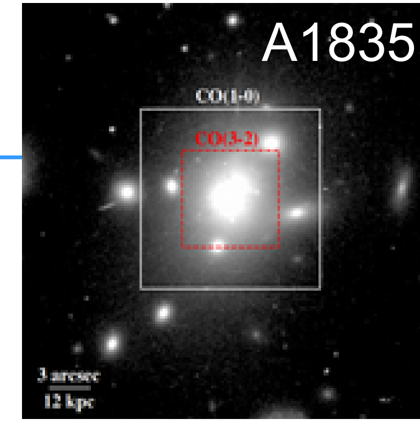
- Origin of molecular gas in BCGs?
- Is molecular gas fuelling feedback?
- Does radio-jet feedback operate on molecular clouds?

ALMA capabilities

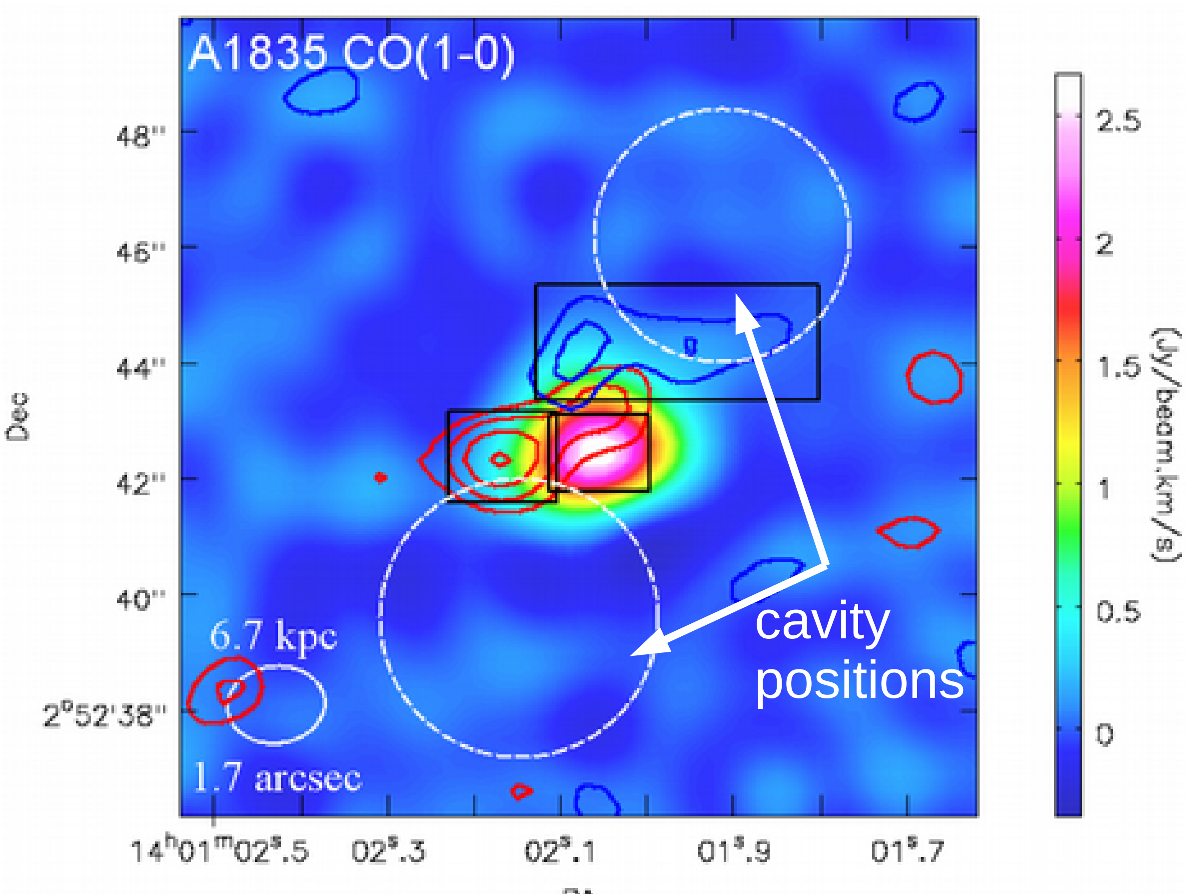
- 50 x 12m antennas in the 12m Array plus 12 x 7m and 4 x 12m antennas in the ACA
- Range of configurations with baselines up to 16km (0.013” at 300GHz)
- Receiver bands cover 84 to 950GHz in atmospheric windows
- ALMA will image CO in MW-like galaxies out to z=3 and [CII] or dust continuum in moderate starburst galaxies to epoch of reionization

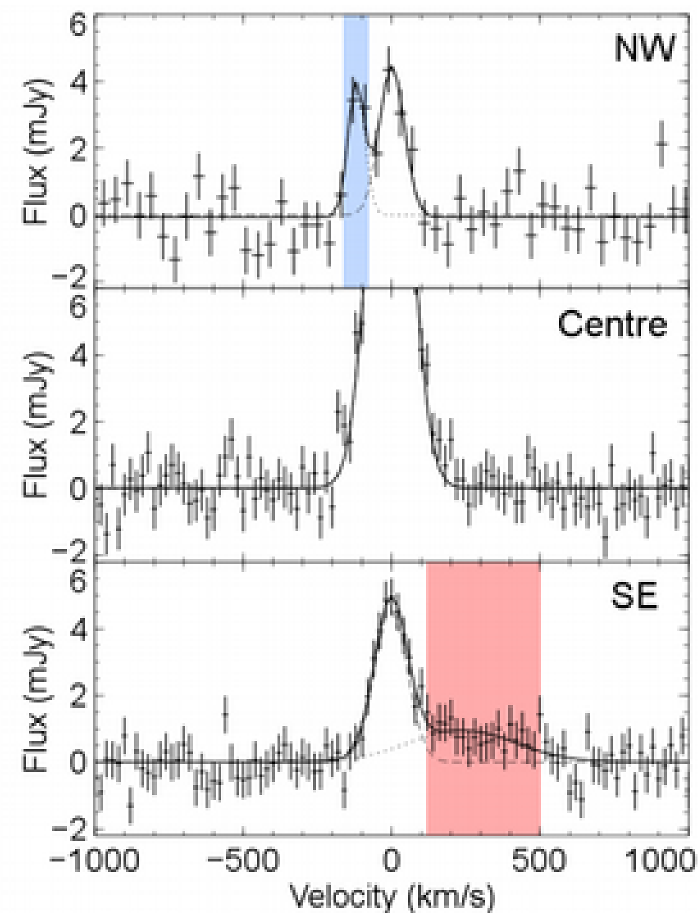
Credit: ESO

ALMA Early Science: extended filaments



- A1664 and A1835 show molecular gas filaments extending to 10kpc
- 10^{10} $M_{\odot}$ molecular flow at 200-400 km/s lies beneath X-ray cavities with P_{cav} ~ 10^{45} erg/s



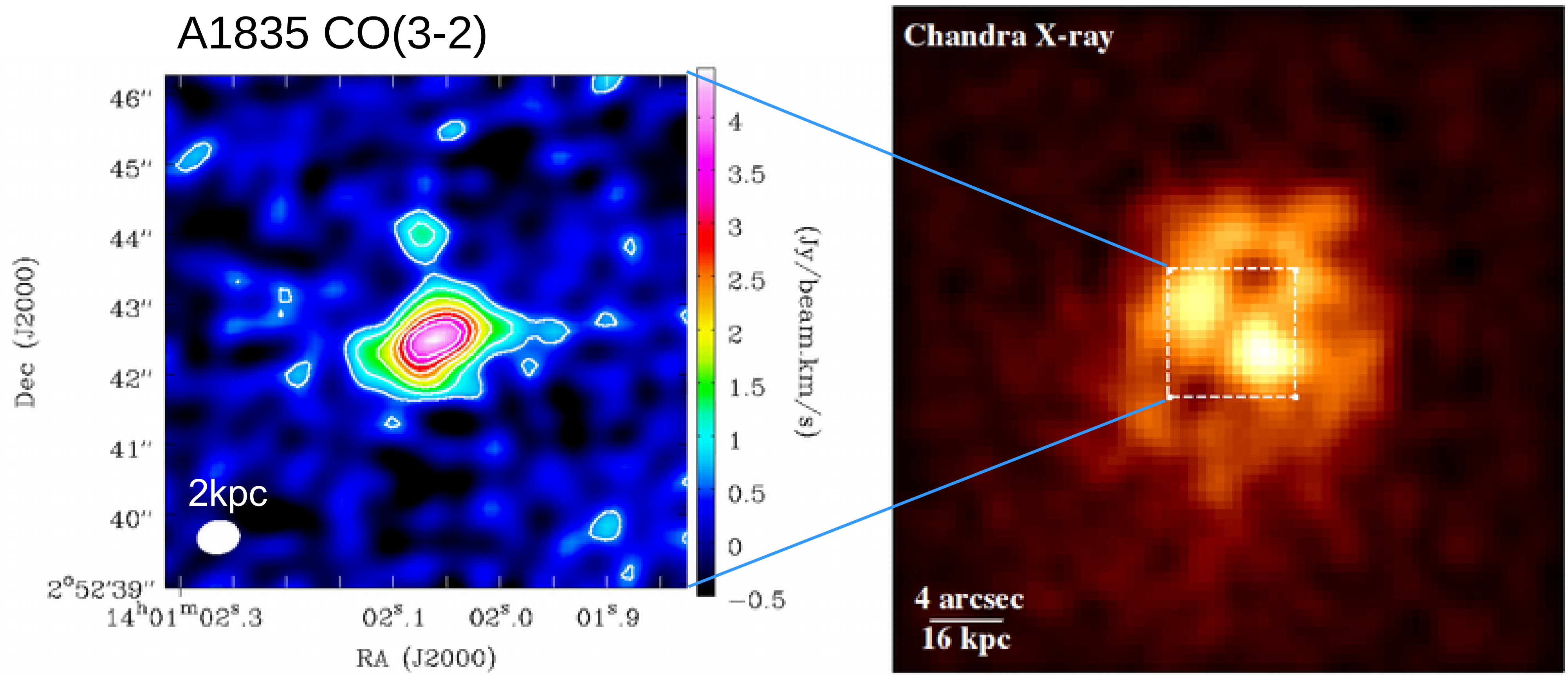


McNamara et al. 2014, Russell et al. 2014

A1835: gas flow drawn up around the X-ray cavities

- Gas filaments drawn up around radio bubble
- Interaction with cold gas in radio-mode feedback

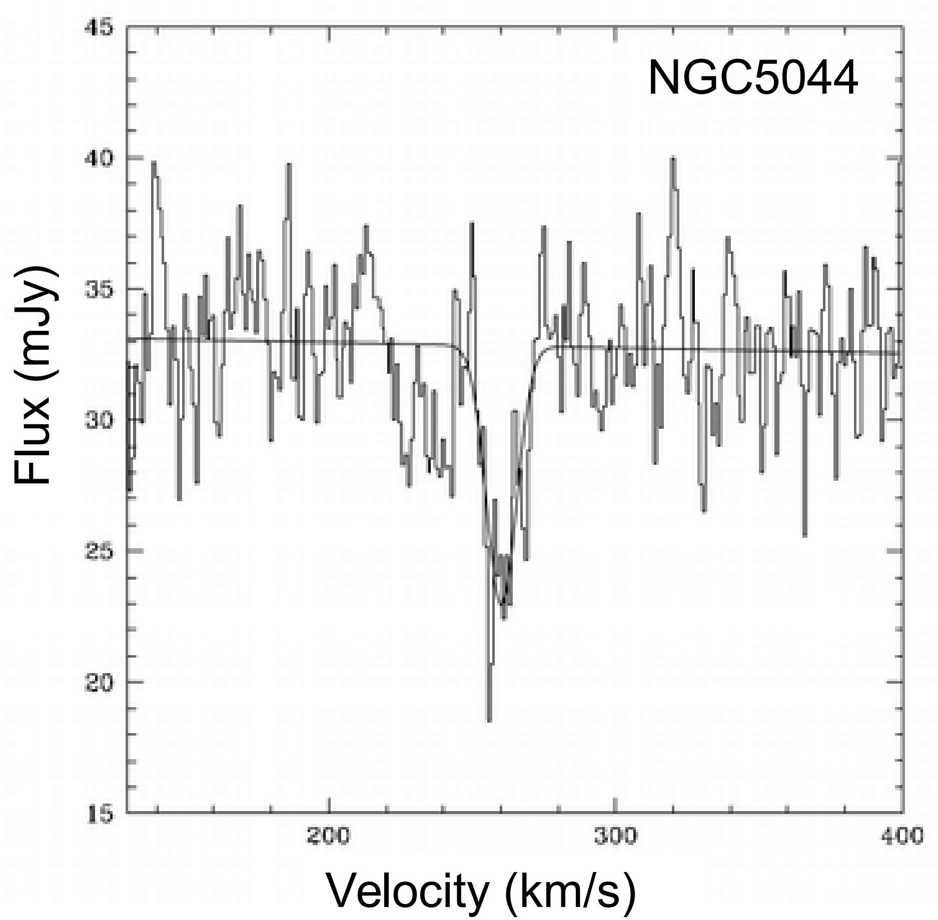
A1835 CO(3-2)



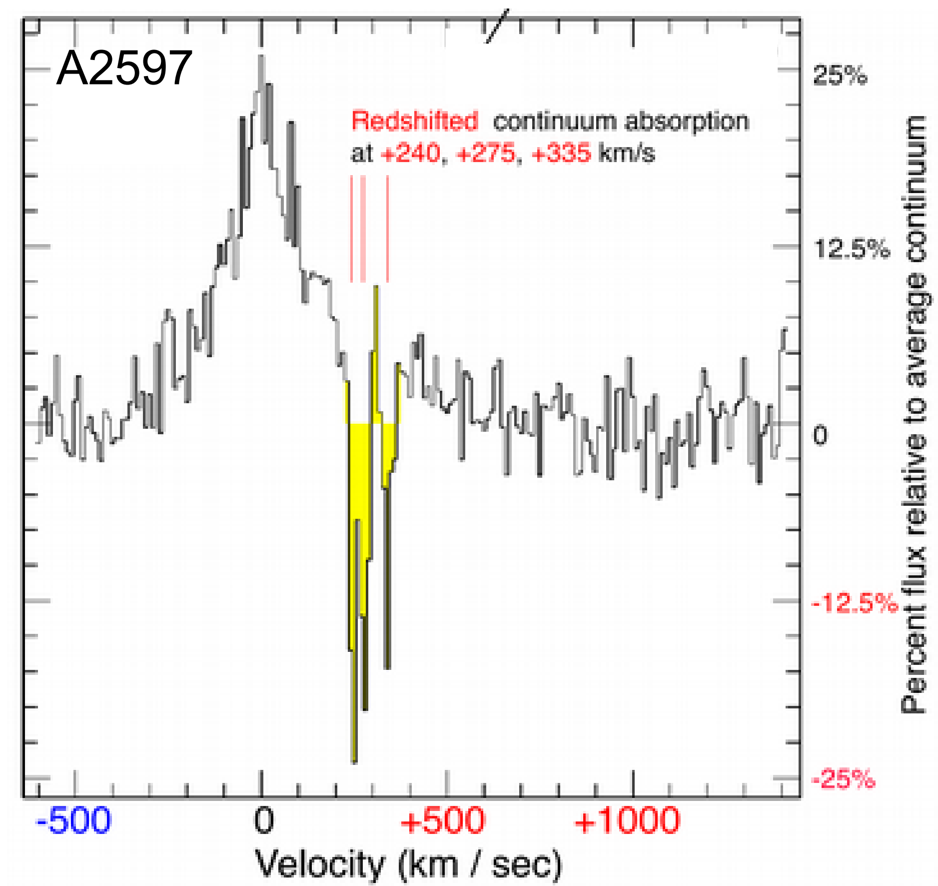
McNamara et al. 2014

NGC5044 + A2597: absorption features

- CO(2-1) absorption features with ~5km/s linewidth typical of GMC and infalling velocity 250-350 km/s.

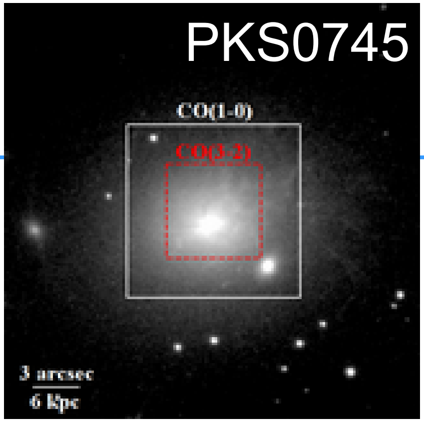


David et al. 2014

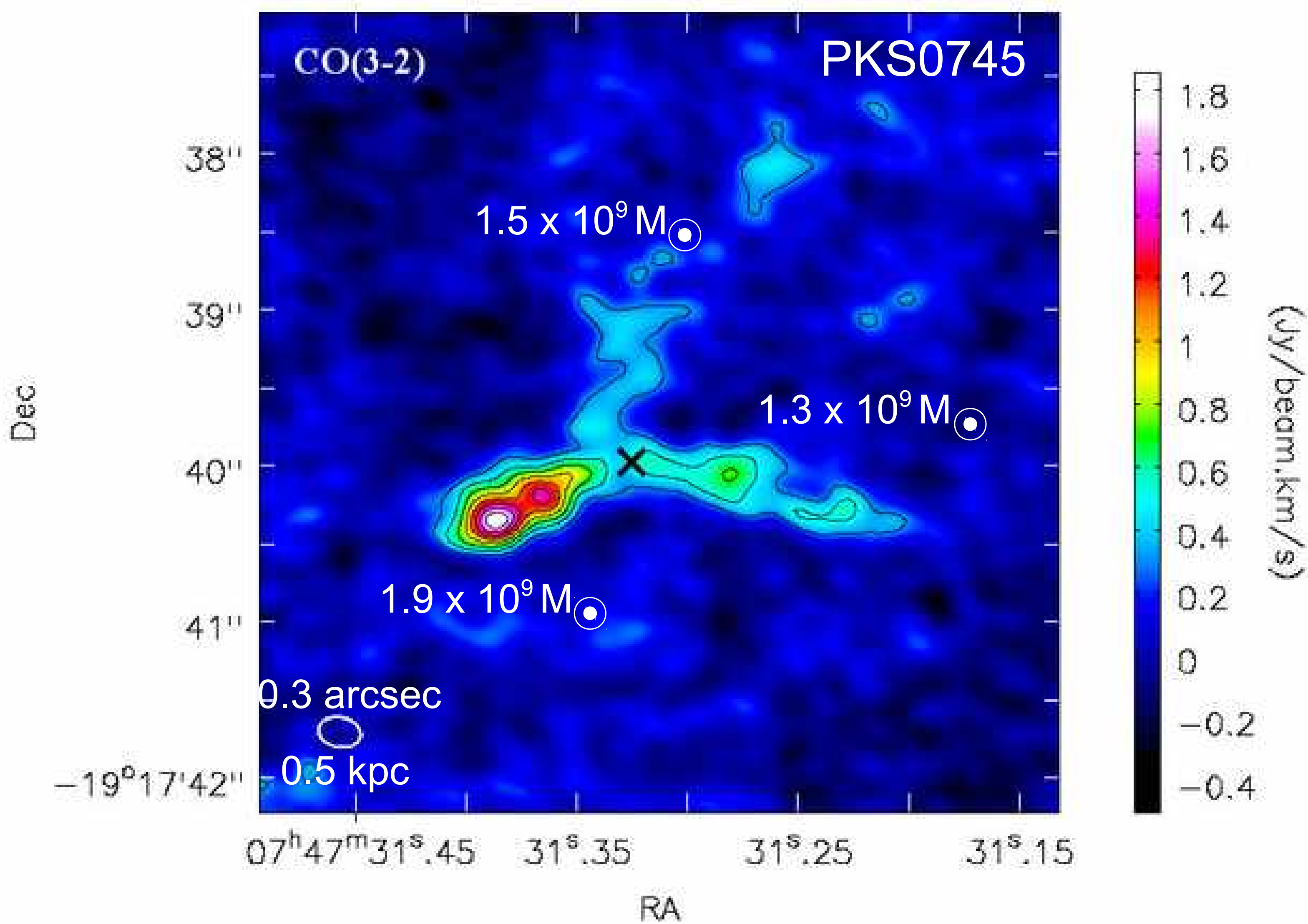


Tremblay et al. 2016

PKS0745: cold gas in extended filaments



- Molecular gas in filaments extending 3 – 5 kpc

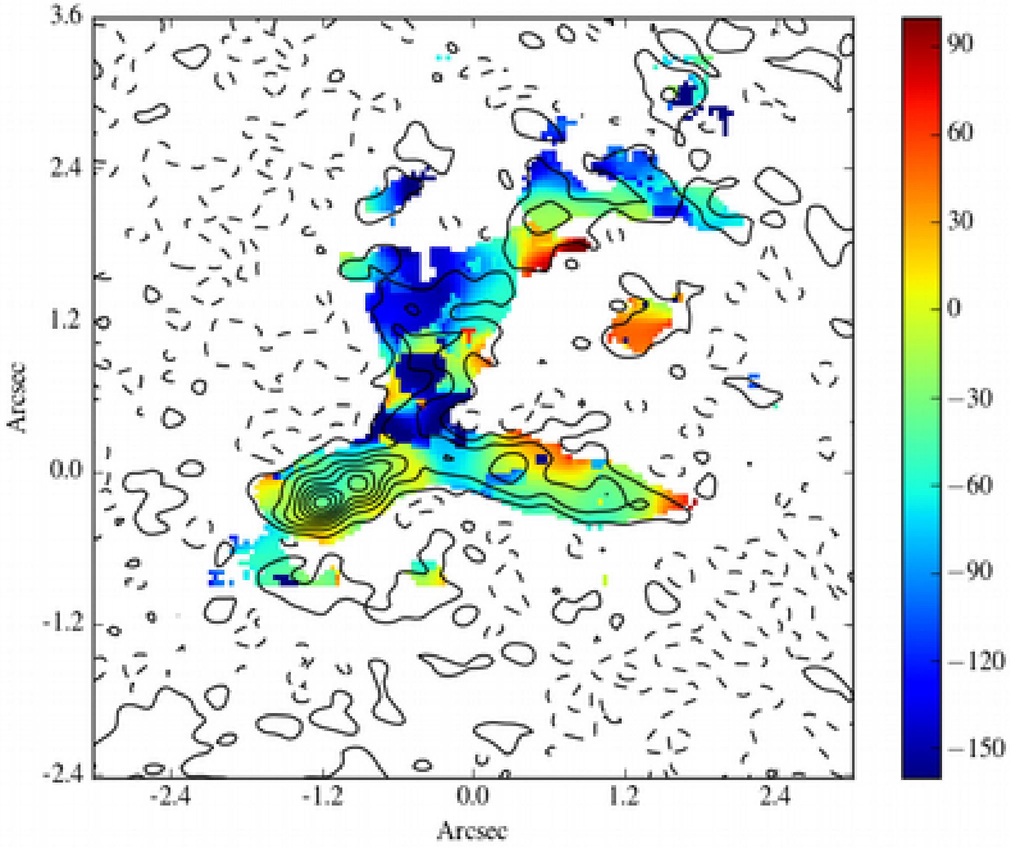


Russell et al. 2016

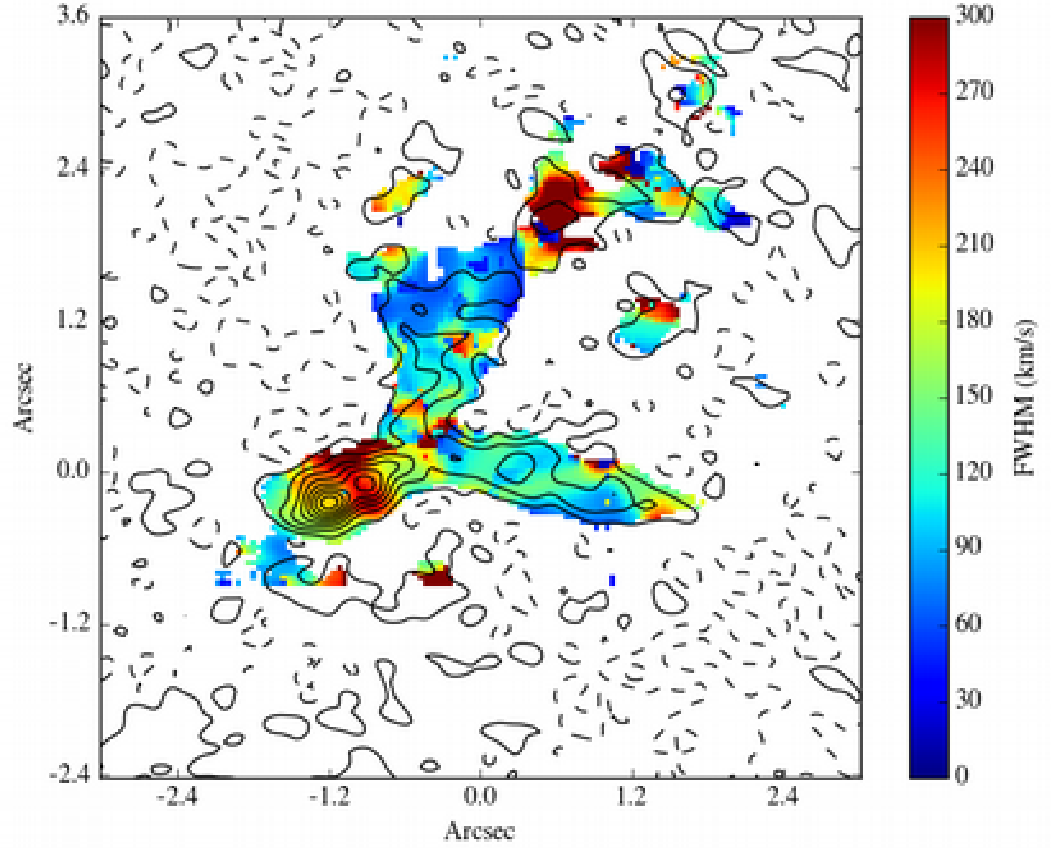
PKS0745: gas not settled in gravitational potential

- Modest velocities ±100 km/s
- Narrow emission lines ~100 km/s

Velocity map



Velocity dispersion

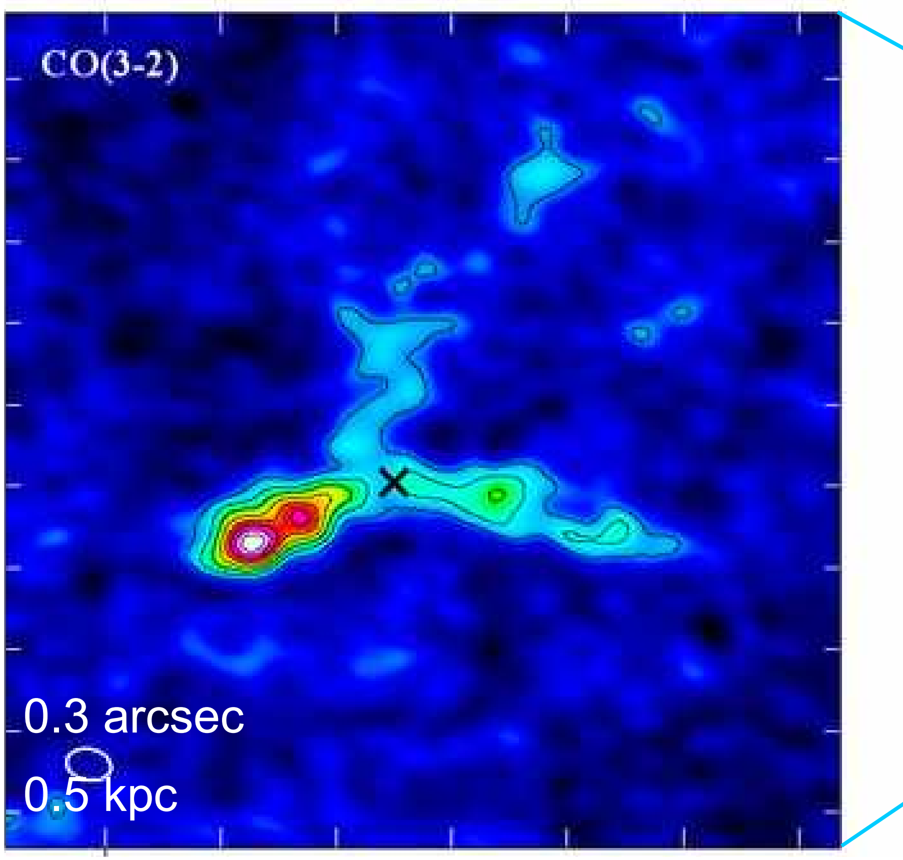


Beam size: 0.3 arcsec, 0.5 kpc

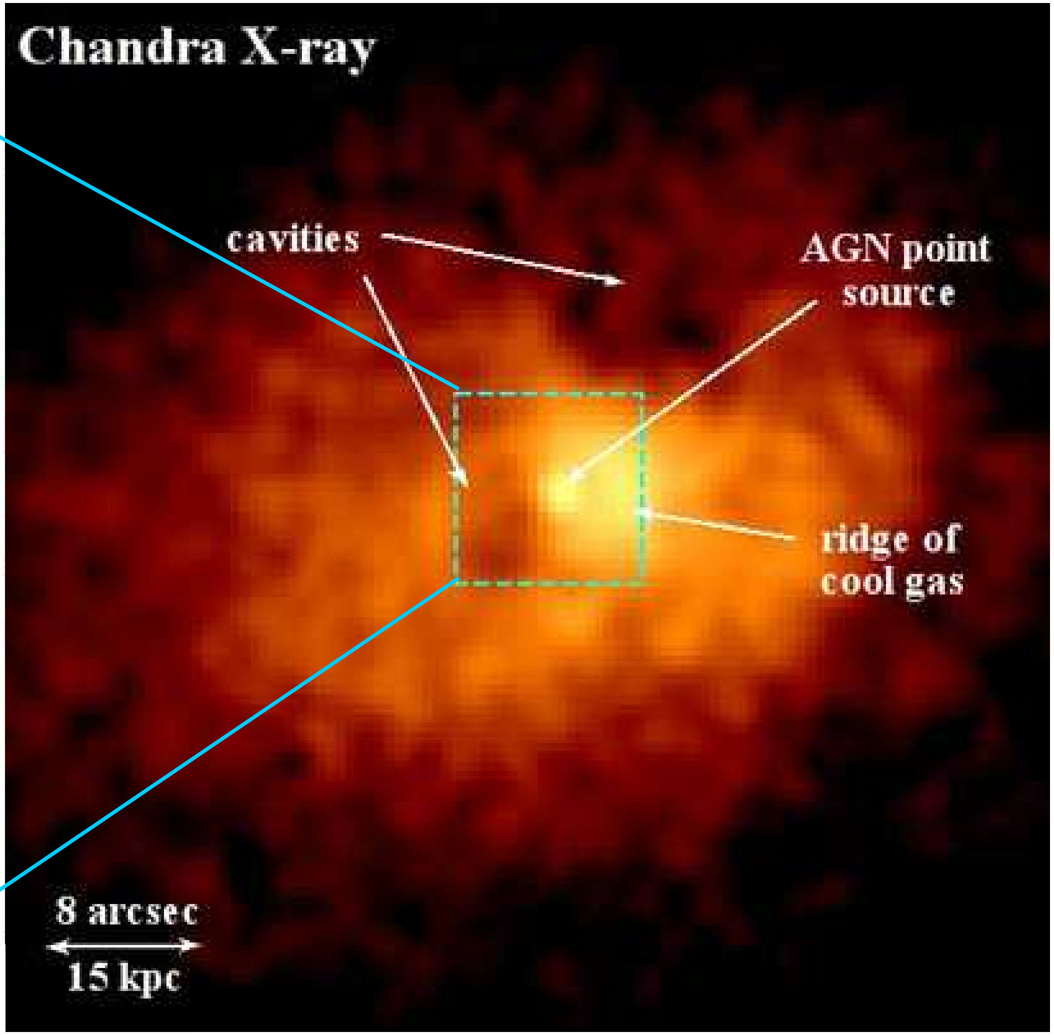
Russell et al. 2016

PKS0745: filaments extend towards cavities

- Uplift behind rising cavities?
- Implausibly high coupling efficiency
- Cooling in situ?



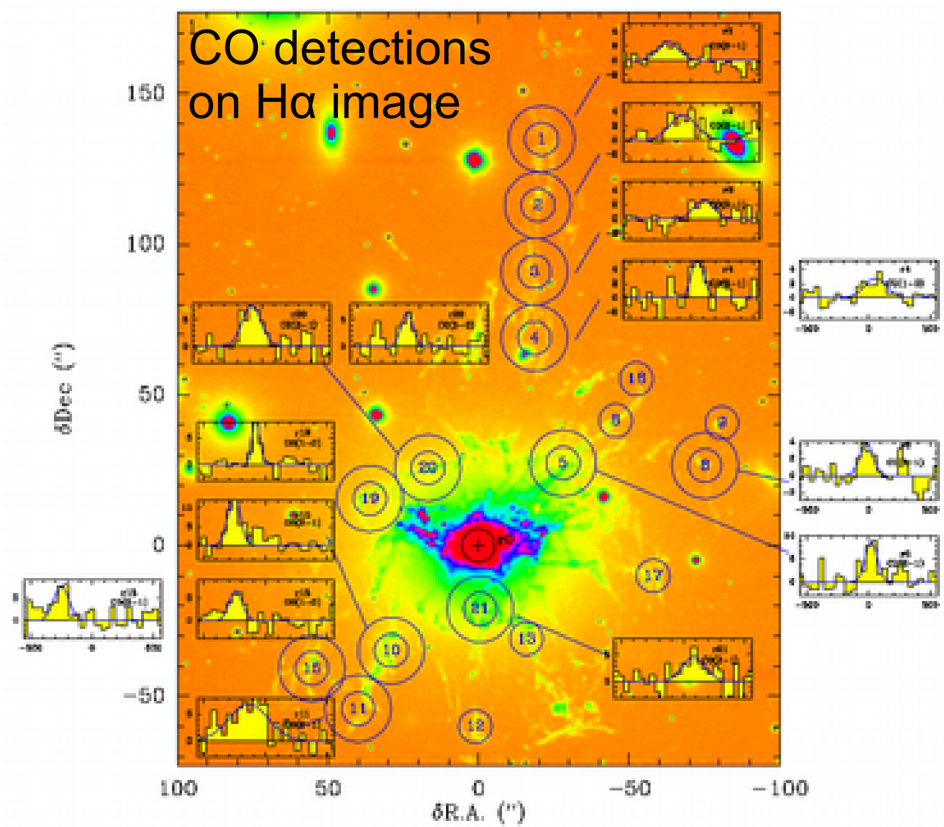
Russell et al. 2016

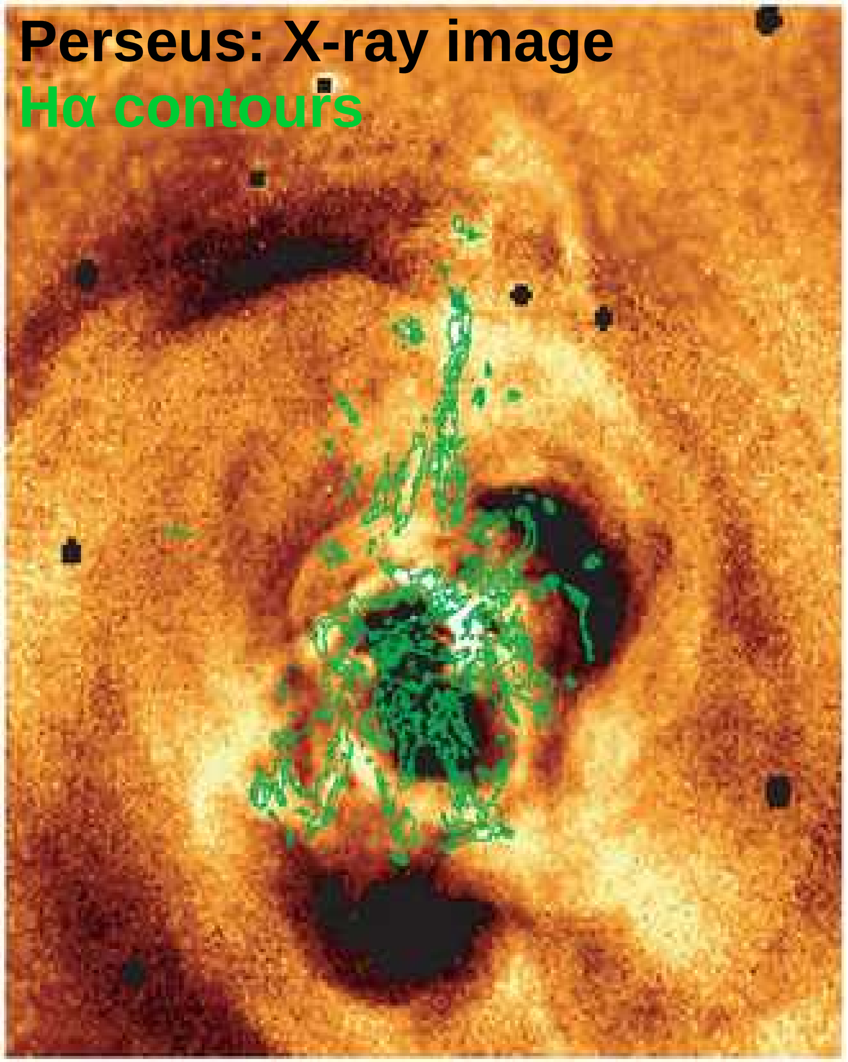


Sanders et al. 2014

Direct uplift or cooling in situ?

- Molecular gas structure clearly shaped by radio bubble expansion
- Direct uplift of molecular gas?
- Thermal instabilities in uplifted low entropy gas?



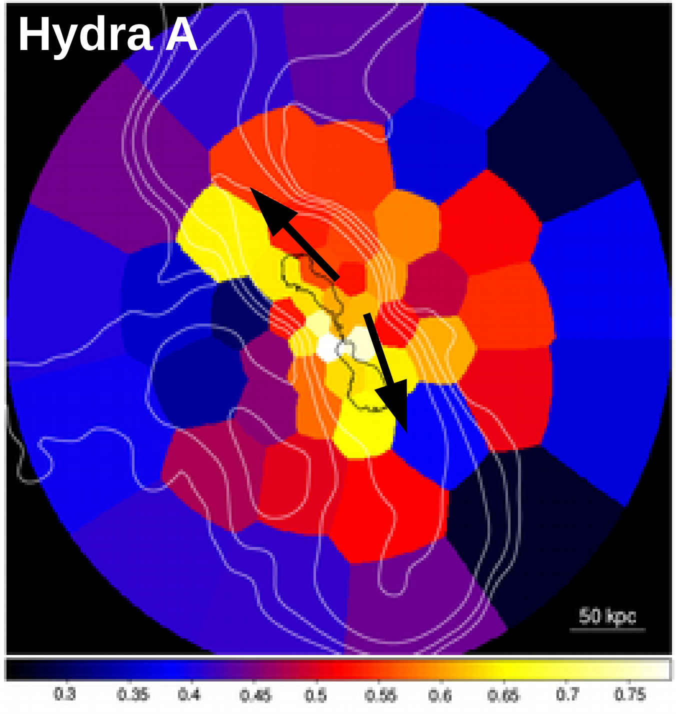


Fabian et al. 2003, 2011; Hatch et al. 2006; Salome et al. 2011

The next decade with Chandra

- Detection of cavities, soft X-ray filaments, complex structure
- Power output of AGN for studies of outflows
- Gas cooling rates and buoyancy timescales
- Metal-rich hot gas outflows in clusters
- Depletion of hot cluster gas, constraints on non-thermal pressure etc

Randall et al. 2015



Metallicity map with radio contours

Simionescu et al. 2008, Kirkpatrick et al. 2009

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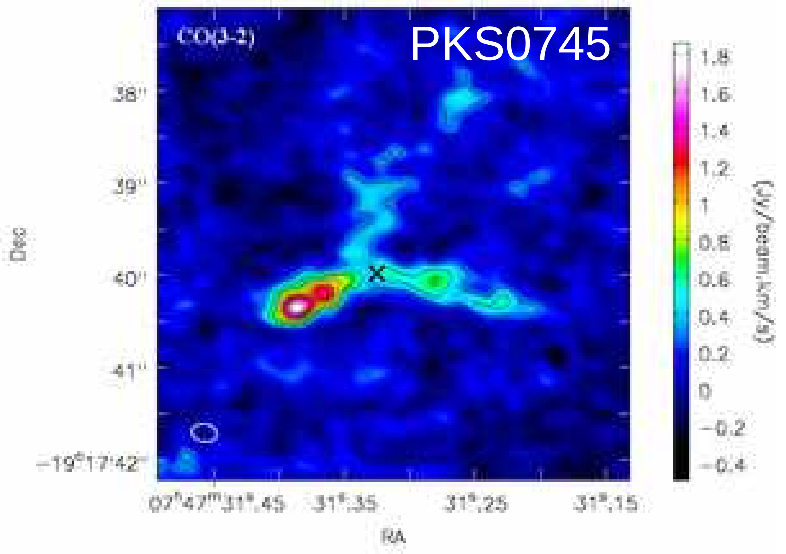
- Depletion of hot cluster gas, constraints on non-thermal pressure etc
- Deeper observations of key targets, return of XVPs, joint programs with ALMA
- Cold gas structure and dynamics from ALMA - fuel for star formation and black hole activity, dynamical black hole masses etc.

Conclusions

- Interactions between radio bubbles and cold molecular gas
  - Massive 10^9-$10^{10}M_\odot$ filaments drawn up around and beneath radio bubbles
- Molecular emission lines are narrow
  - Extended filaments, ordered velocity structure
  - Gas not settled in gravitational potential
  - Circulation flow



- Radio bubbles supply large-scale heating to stabilise cluster atmospheres and lift gas in their wakes