UNIVERSITY OF CAMBRIDGE

Massive molecular gas flows and AGN feedback in galaxy clusters

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Michael McDonald (MIT), Alastair Edge (Durham), Francoise Combes (Paris),
Philippe Salomé (Paris), the SPT collaboration et al.

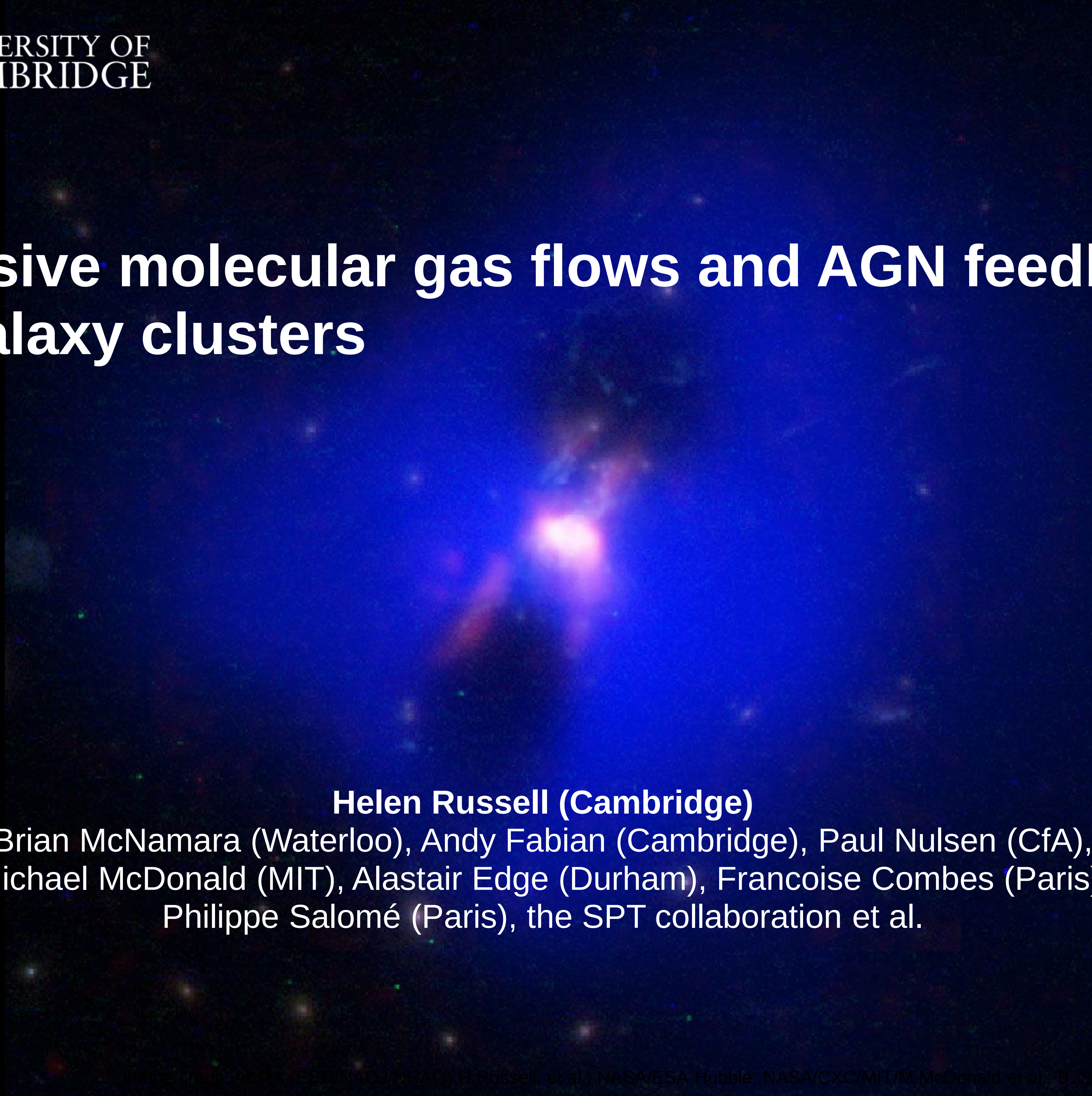
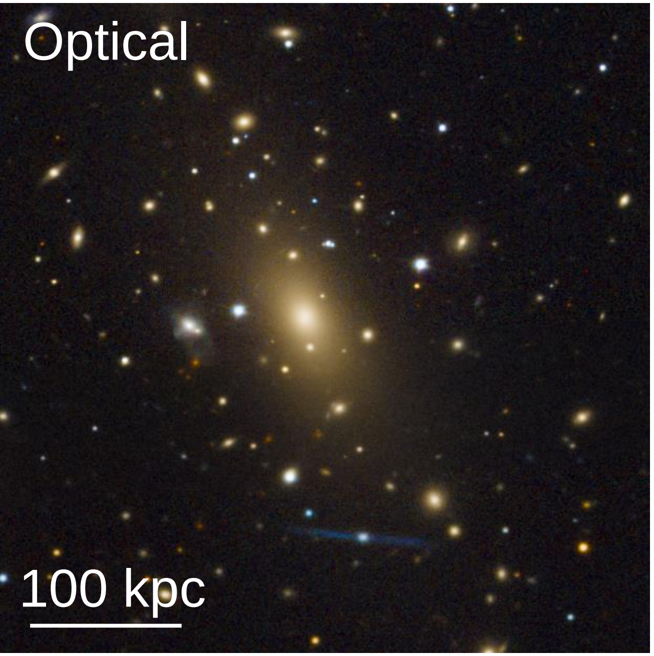


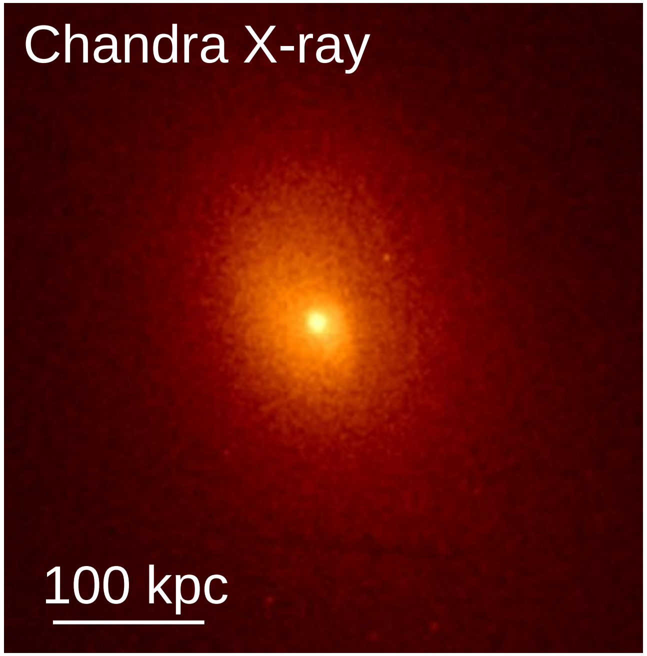
Image credit: ALMA (ESO/NAOJ/NRAO) H.Russell, et al.; NASA/ESA Hubble; NASA/CXC/MIT/M.McDonald et al.;

Outline

- Introduction
    - Radiative cooling in galaxy clusters
    - AGN feedback
- Results
    - ALMA observations of molecular gas in central cluster galaxies
    - Massive filaments drawn up around radio bubbles
    - Direct uplift of molecular clouds or cooling in situ?
    - Closely coupled feedback
    - Prospects for Lynx
- Conclusions

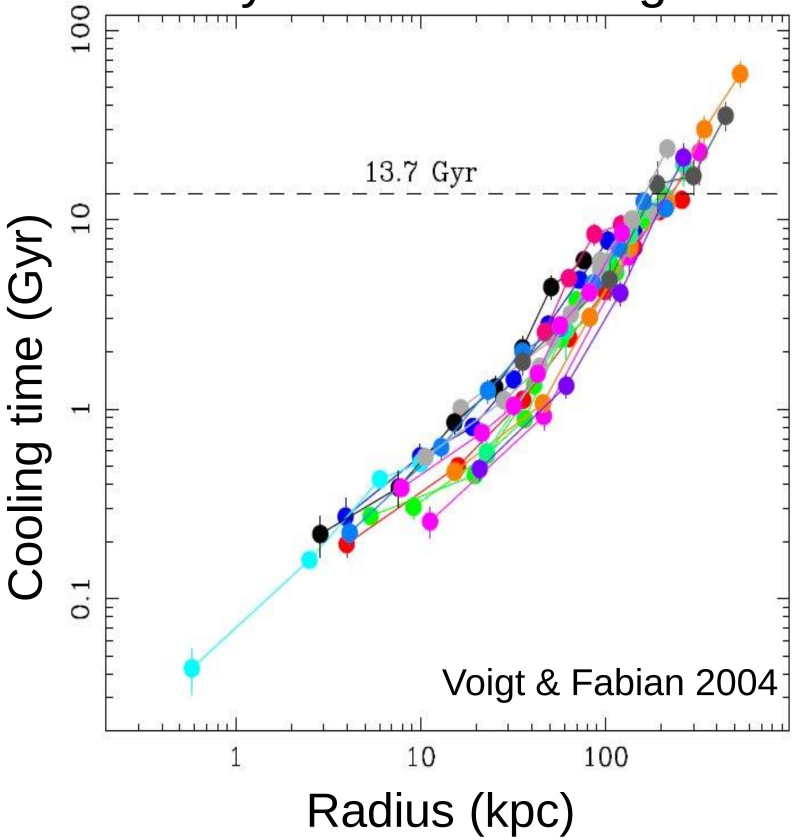
X-ray surface brightness peaks in cluster cores





Lewis et al. 2003, Allen et al. 2004

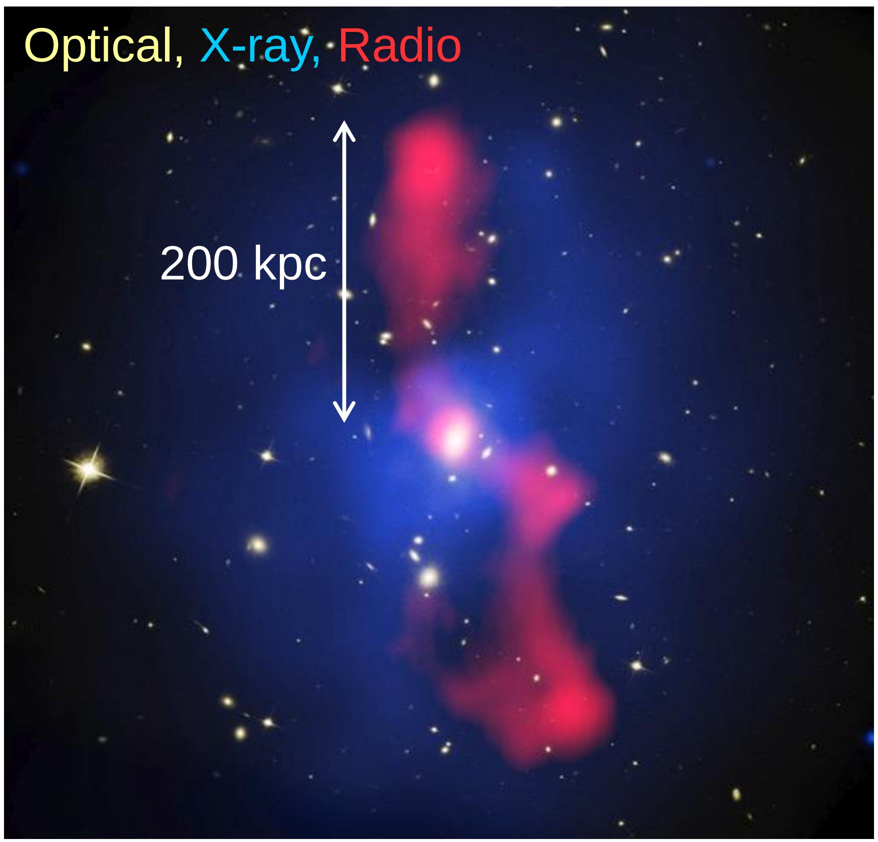
X-ray radiative cooling time



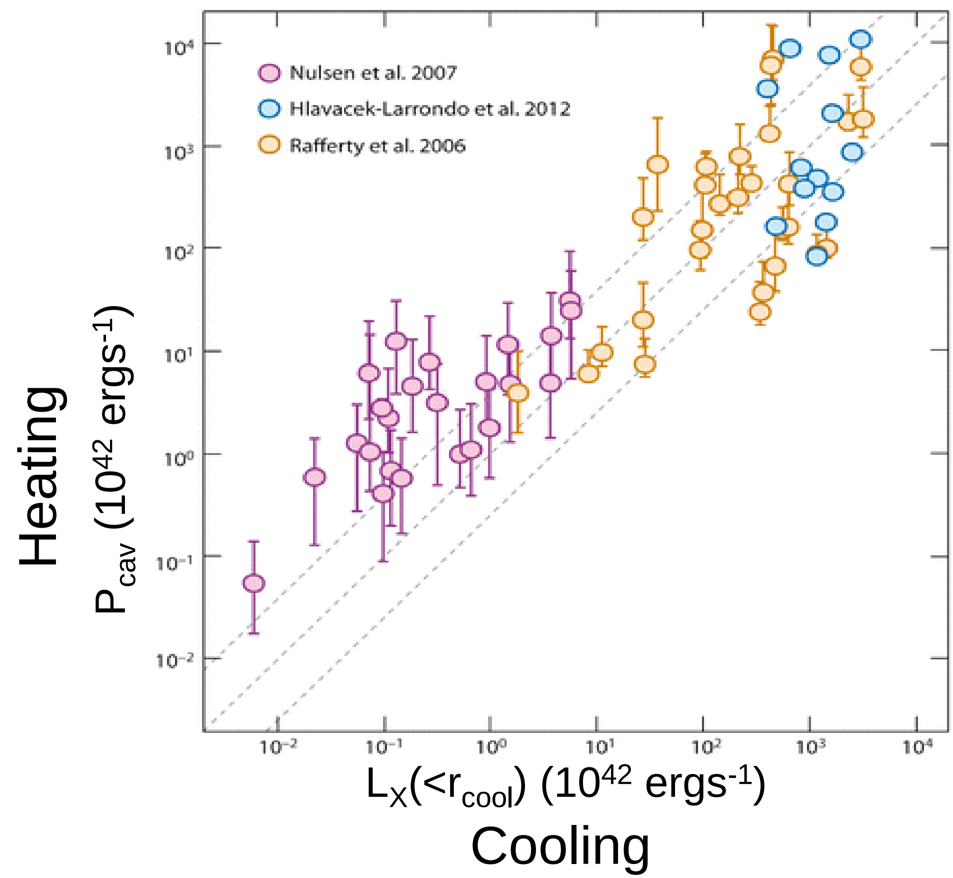
- 100 – 1000 $M_\odot$ per year gas cooling?

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
- Truncates galaxy growth, keeps ellipticals ‘red and dead’, M-σ relation



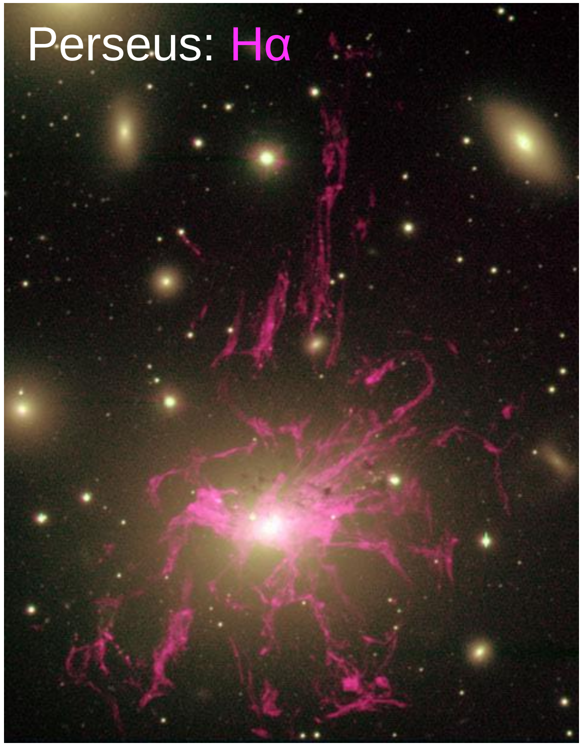
MS0735, McNamara et al. 2005



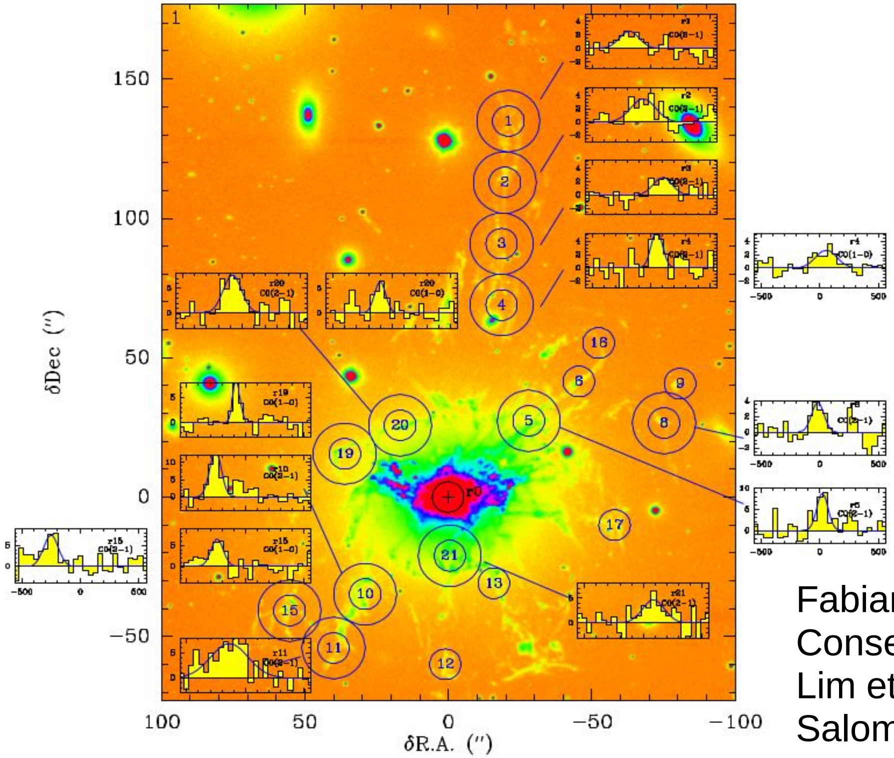
Rafferty et al. 2006; Birzan et al. 2004; Fabian 2012

What is the role of molecular gas in feedback?

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



CO detections on Hα image



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

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

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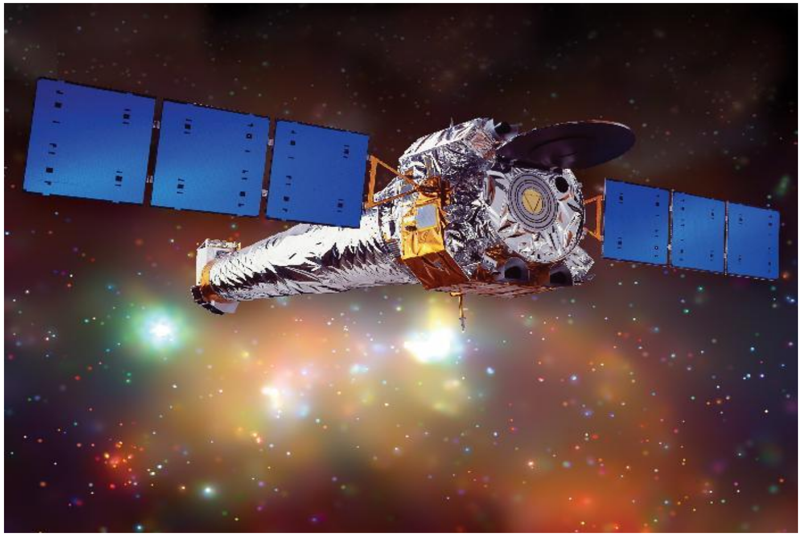


Chandra/Lynx: hot gas, energy output → ALMA: cold gas, fuelling?

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

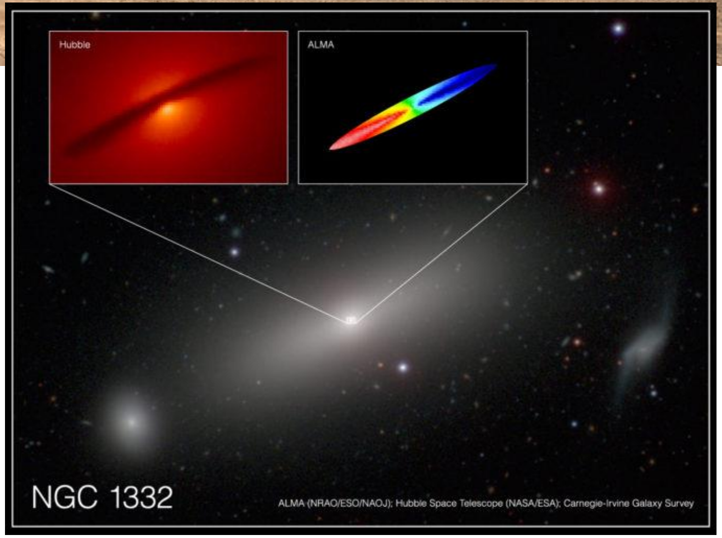
ALMA capabilities

- 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

Credit: ESO

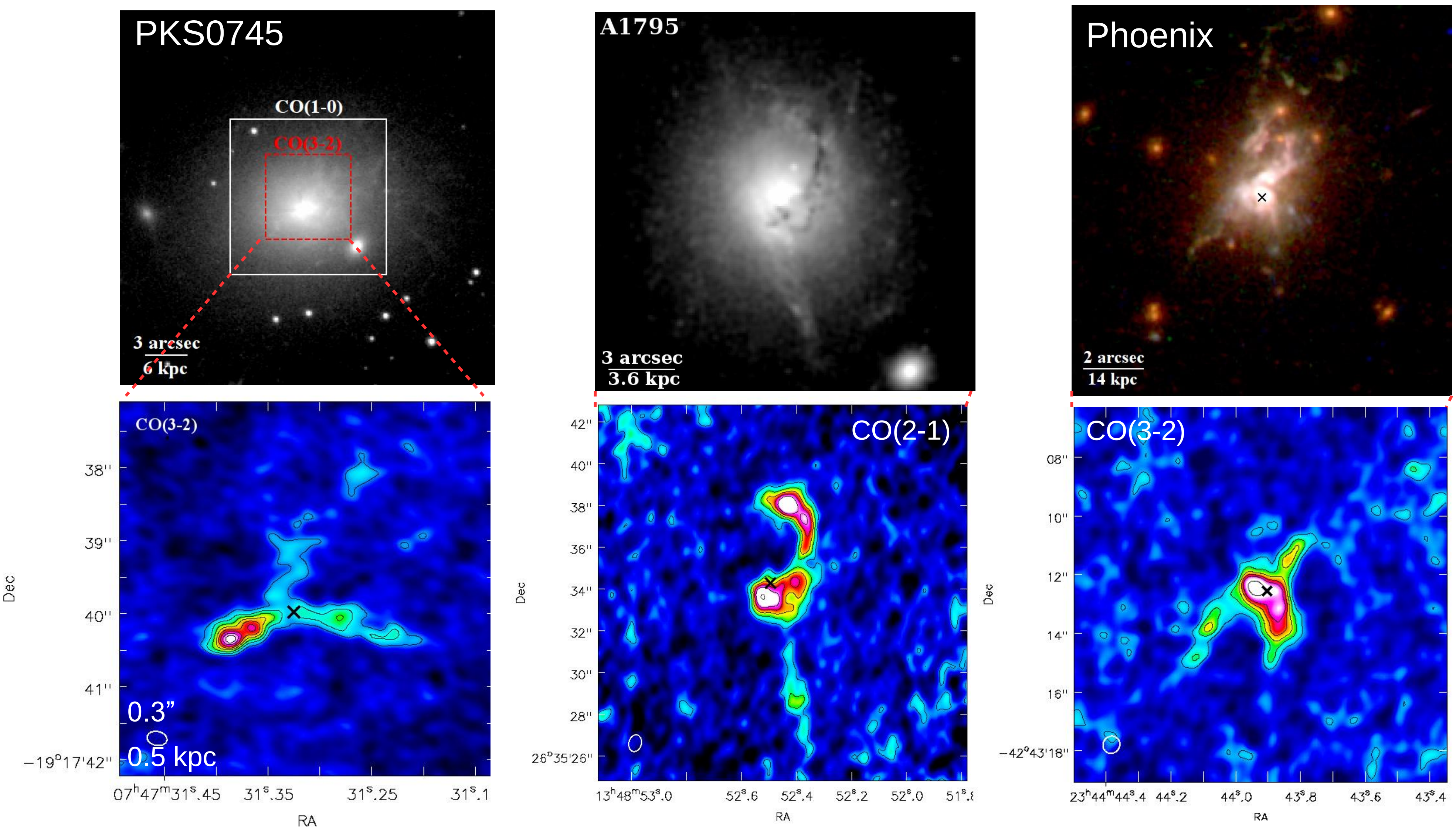
- ALMA will image CO in MW-like galaxies out to z=3 and [CII] or dust continuum in moderate starburst galaxies to epoch of reionization
- Dynamical black hole masses eg. NGC1332 $6.6 \pm 0.6 \times 10^8 M_\odot$

Barth et al. 2016



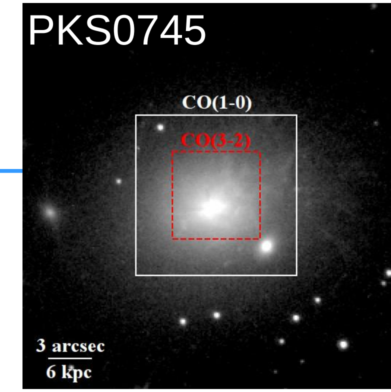
Extended filaments of molecular gas

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



Russell et al. 2016, 2017, submitted

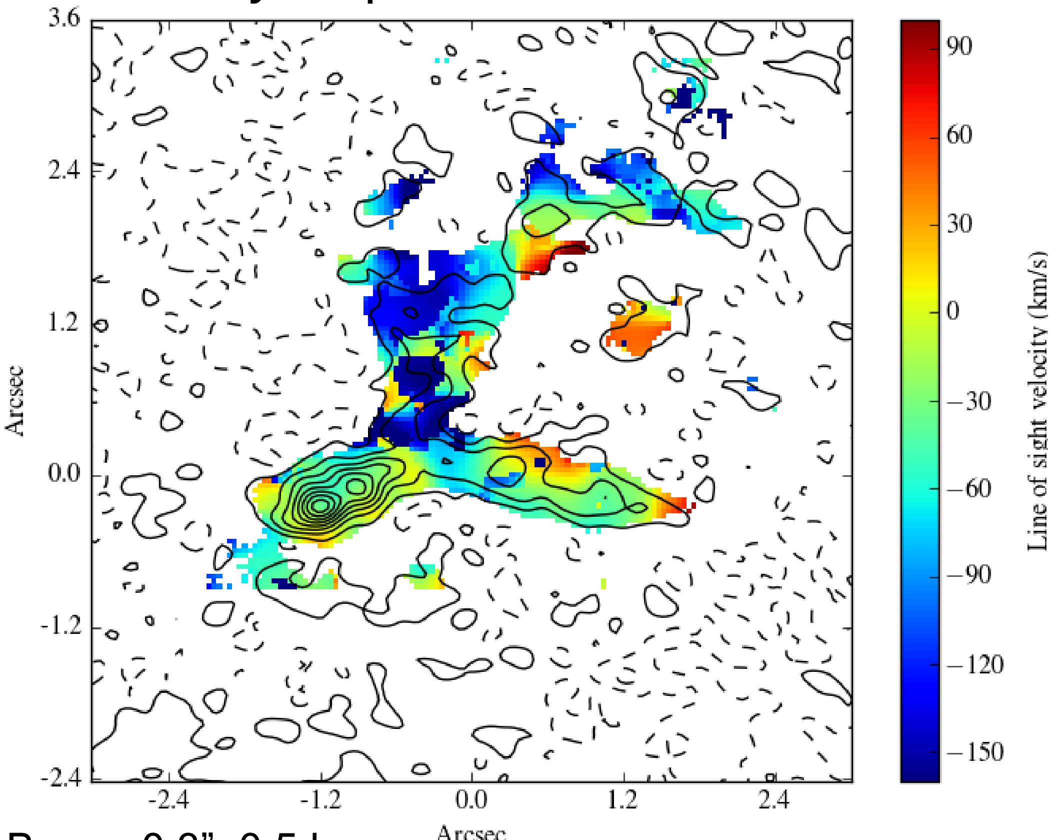
Low velocities and low dispersions



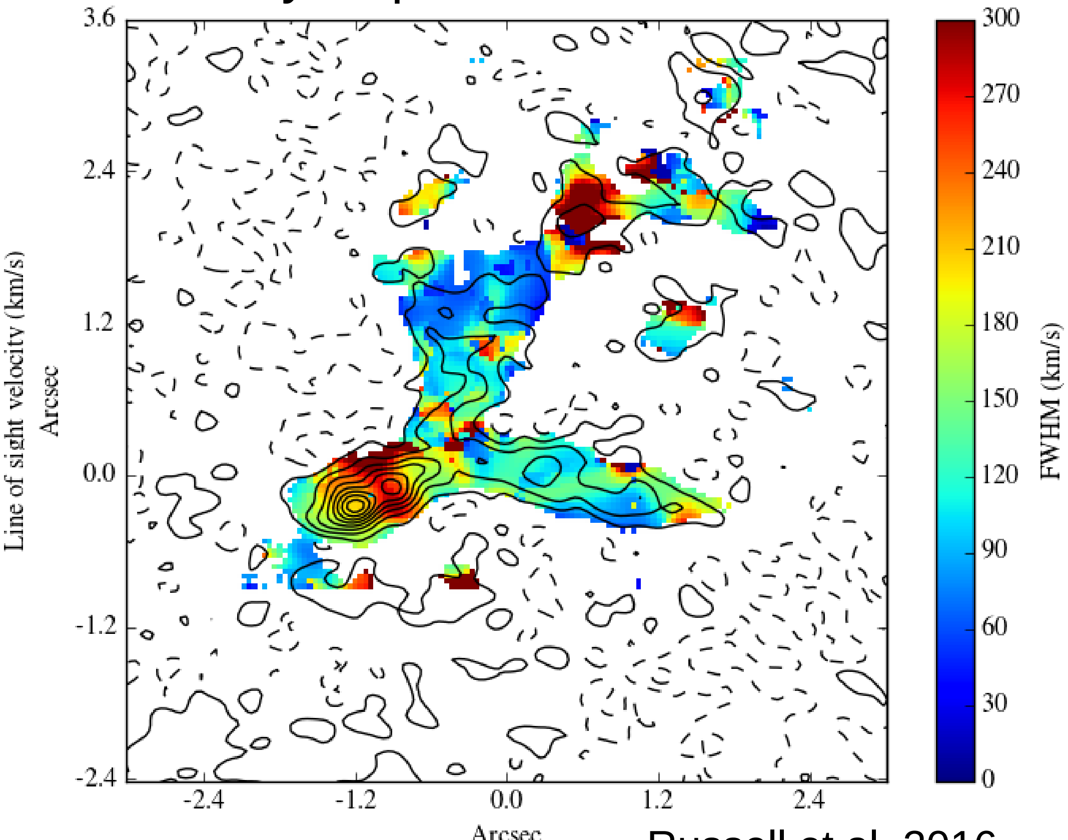
PKS0745:

- Modest velocities ±100 km/s, narrow FWHM ~100 km/s
- Gas not settled in gravitational potential
- Merger origin unlikely

Velocity map



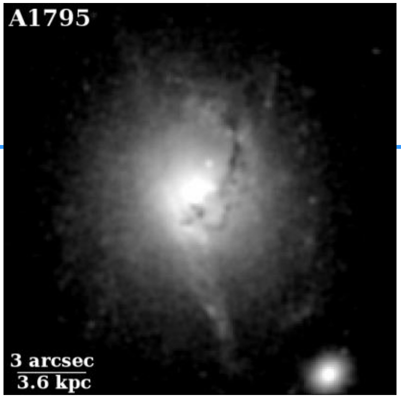
Velocity dispersion



Beam: 0.3”, 0.5 kpc

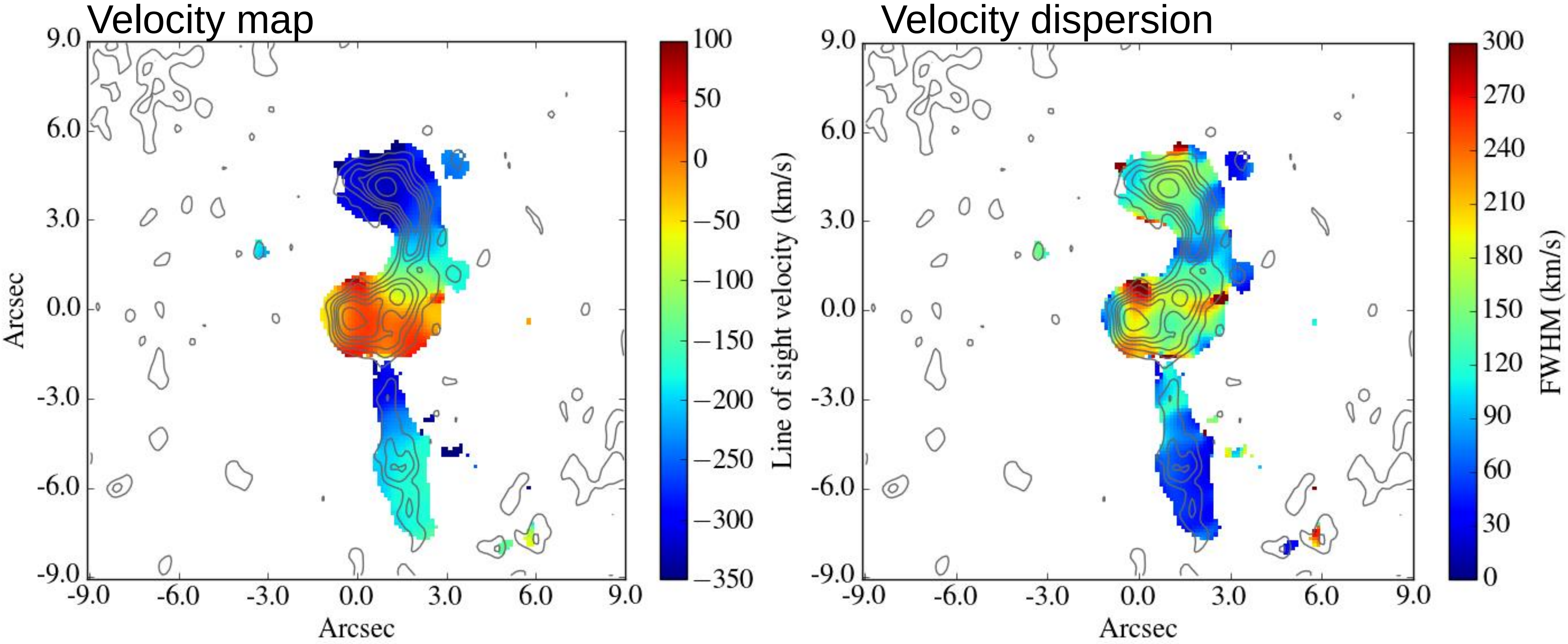
Russell et al. 2016

Smooth velocity gradients along filaments



A1795:

- Smooth gradient 0km/s to -370km/s
- Low FWHM ~100km/s

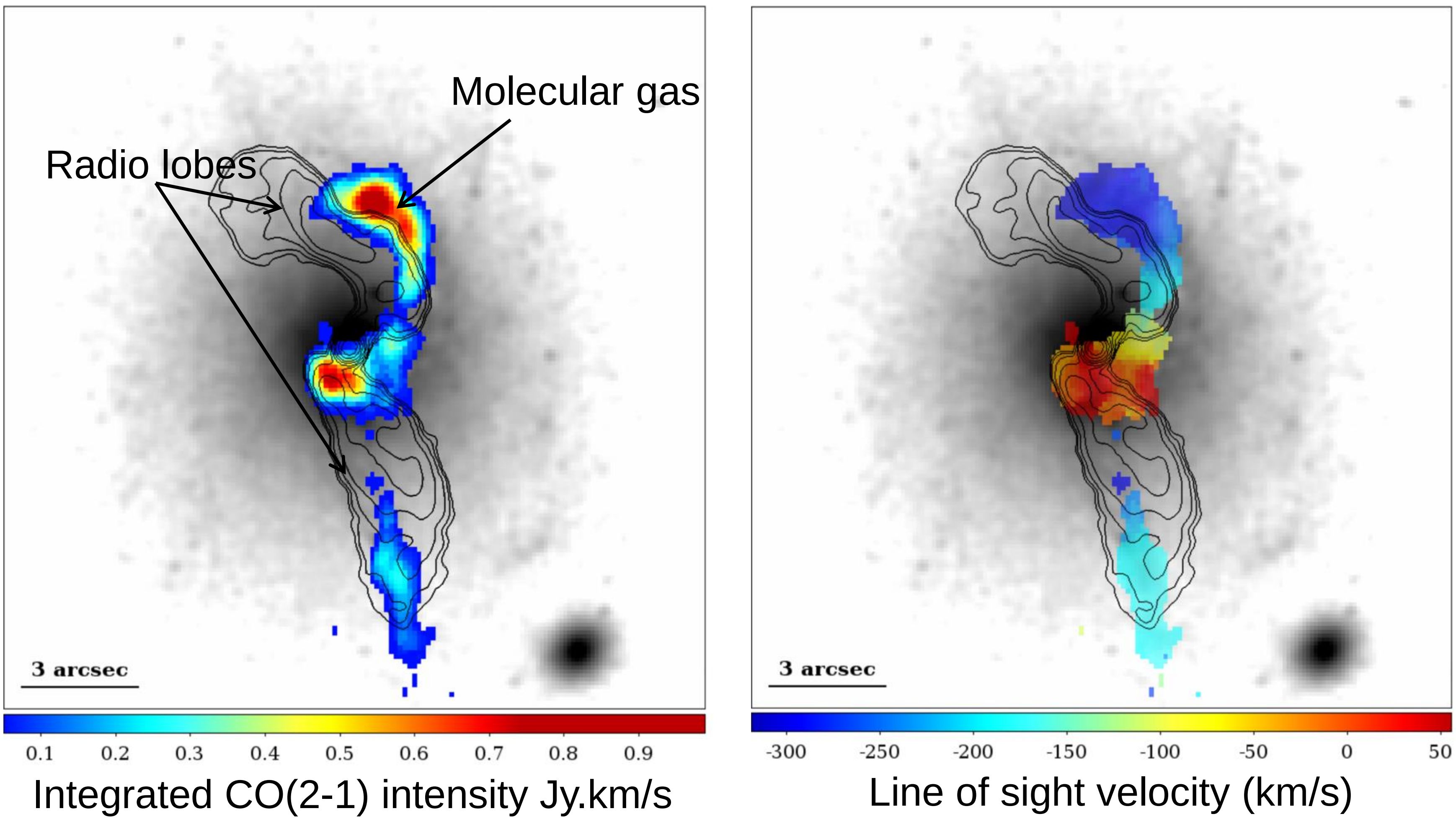


Beam size: 0.7 arcsec, 0.8 kpc

Russell et al. submitted

Molecular gas filaments encase radio bubbles

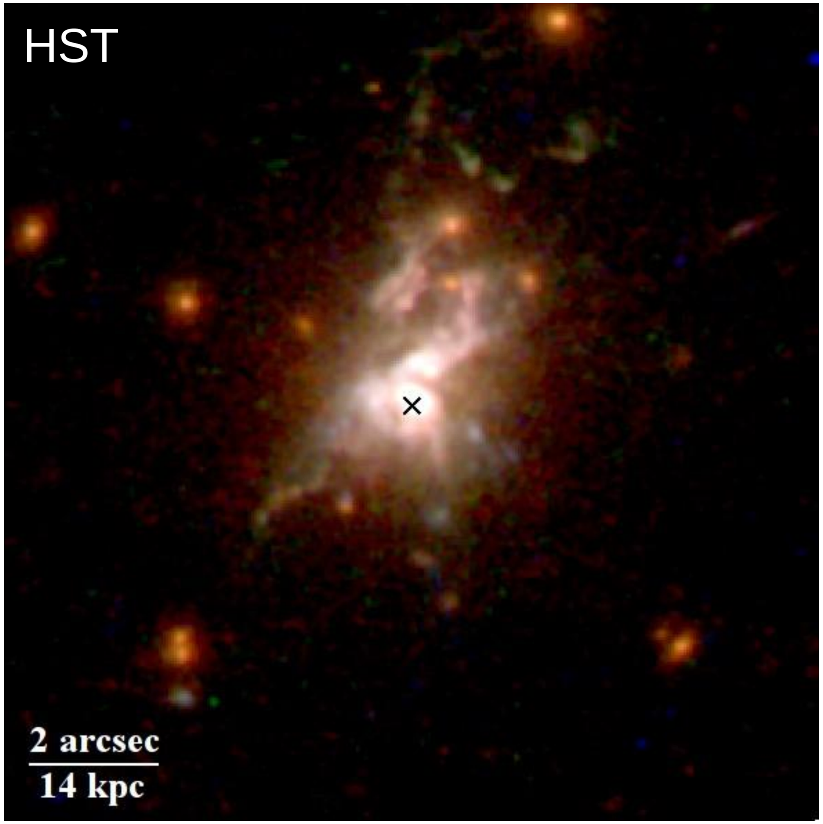
- A1795: molecular gas $2.5 \times 10^9\ M_\odot$ around N radio lobe
- Smooth velocity gradient from 0 to -370 km/s



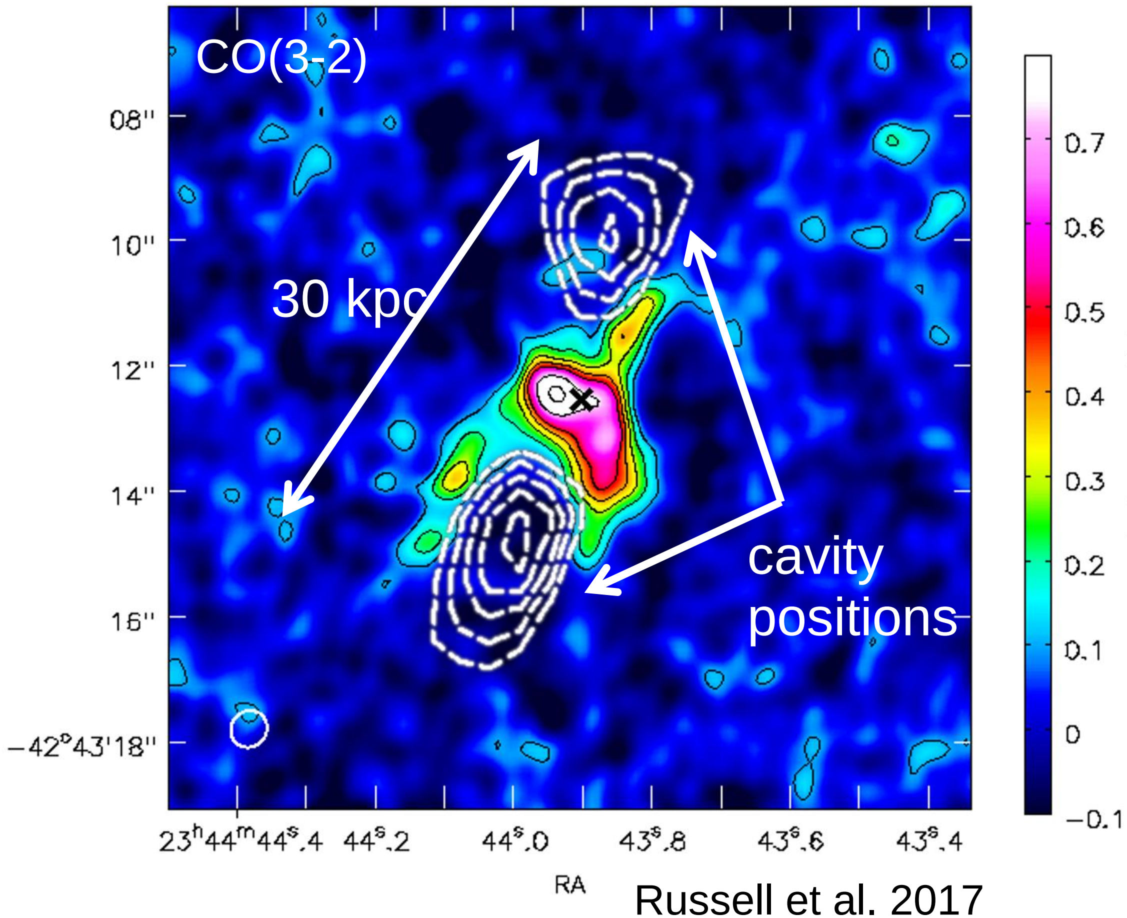
Russell et al. submitted

Molecular gas filaments encase radio bubbles

- Phoenix: filaments encase lower half of radio bubbles
- 3 x $10^{10} M_\odot$ of molecular gas total with half in filaments around radio bubbles



McDonald + SPT collaboration 2012

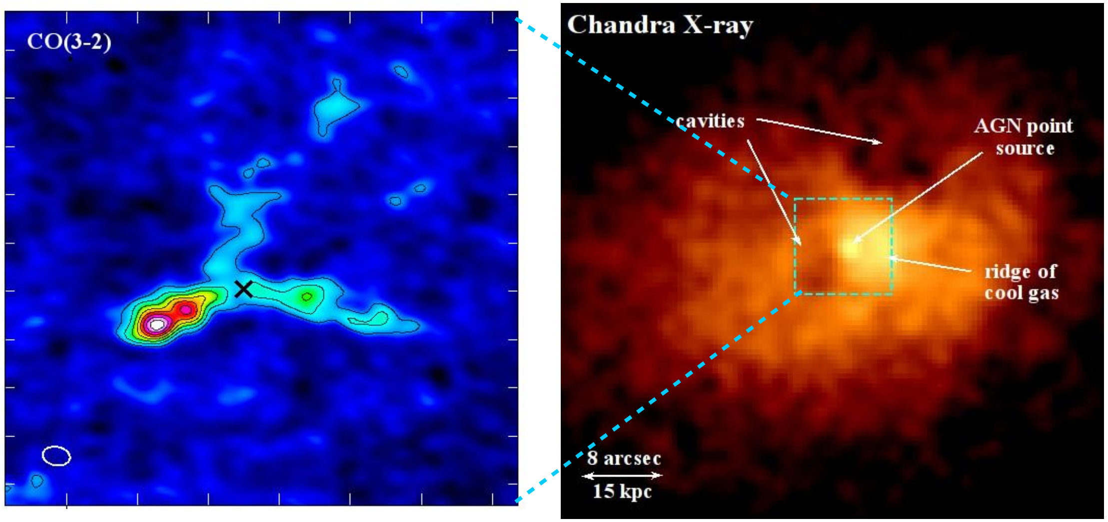


Russell et al. 2017

Molecular gas filaments extend toward radio bubbles

- PKS0745 + A1835: filaments drawn up underneath X-ray cavities and radio lobes

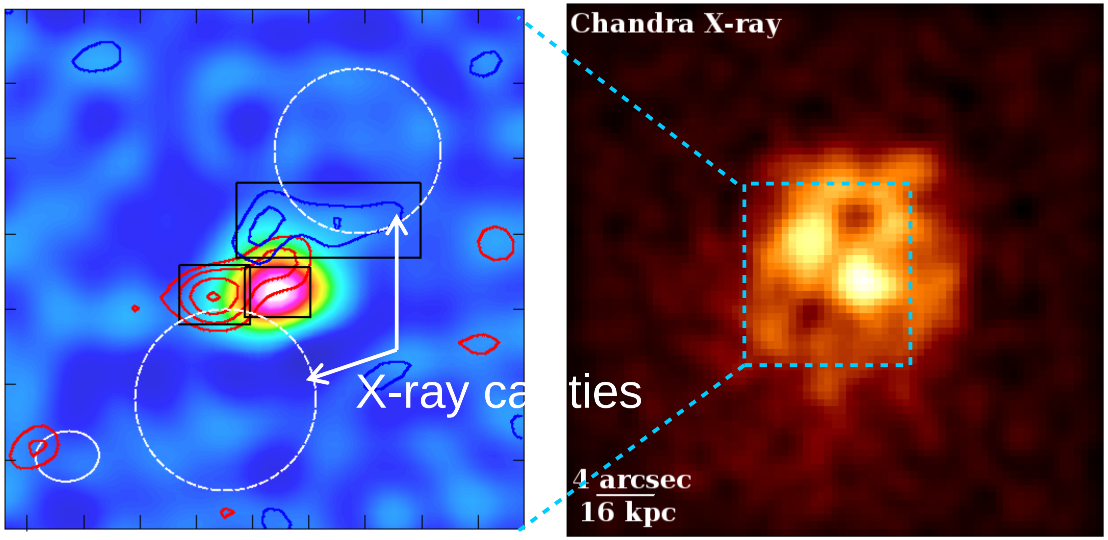
PKS0745



Russell et al. 2016

Sanders et al. 2014

A1835

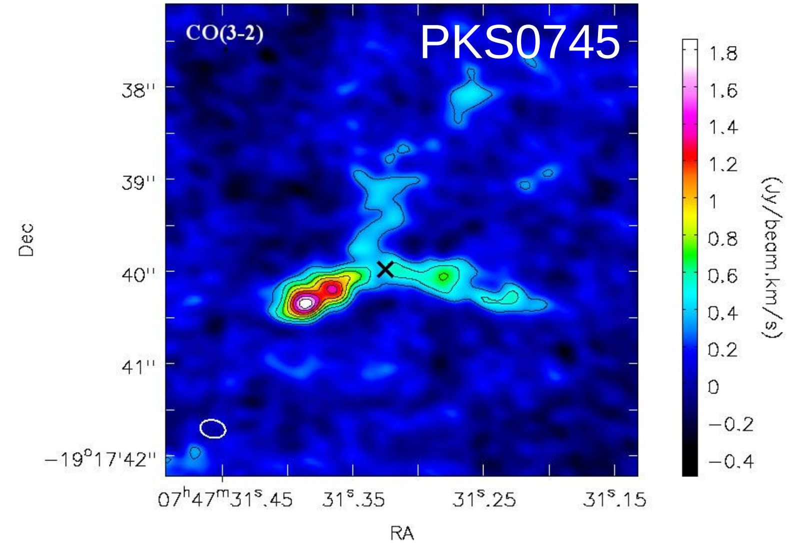


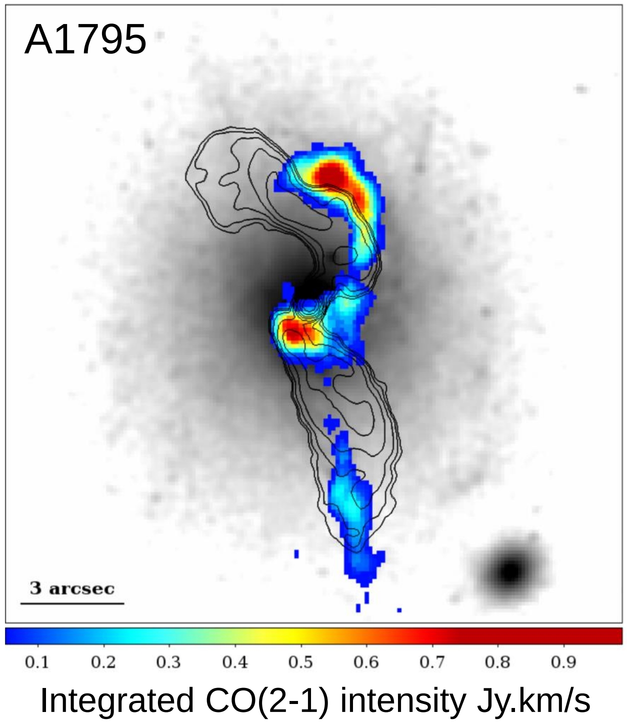
McNamara et al. 2014

Direct uplift of molecular gas clouds or cooling in situ?

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

- Rapid cooling of uplifted thermally unstable low entropy gas?
  - Molecular gas coincident with soft X-ray
  - Dust lanes





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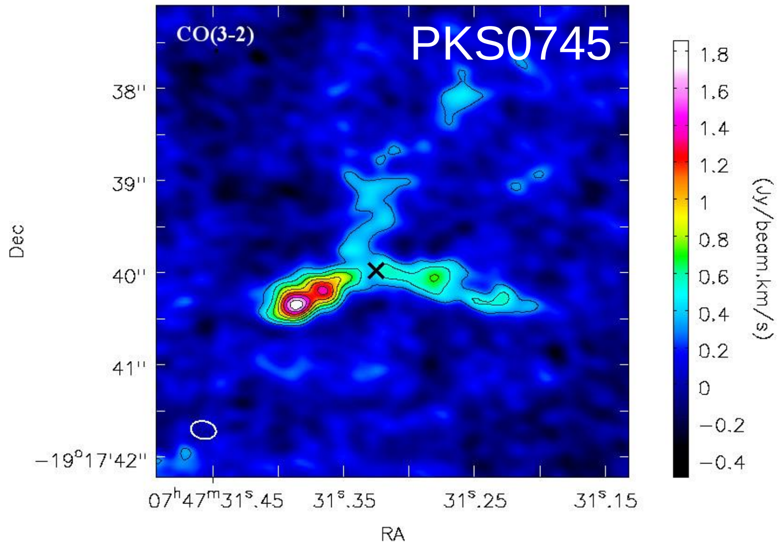
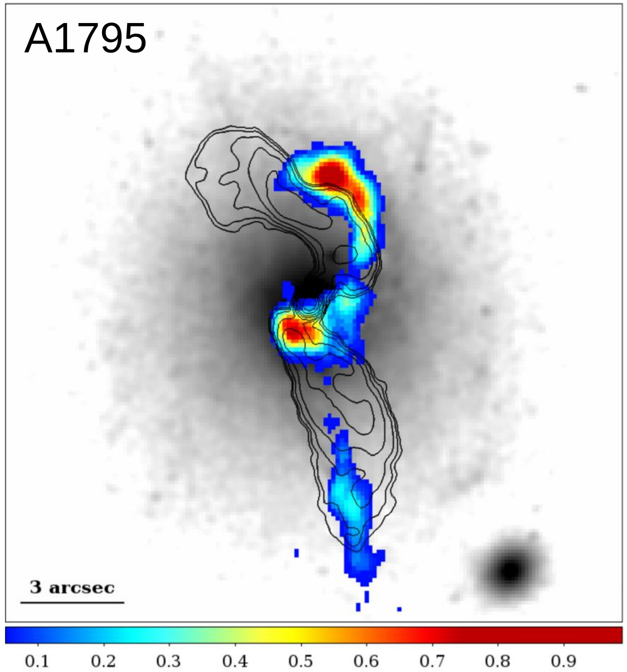


- Rapid cooling of uplifted thermally unstable low entropy gas?
  - Molecular gas coincident with soft X-ray
  - Dust lanes
  - But molecular gas mass divided by buoyancy time exceeds XMM-RGS limits
    - X_{CO} factor too large? Factor of two possible (Vantyghem et al. submitted)
    - Gas cools over multiple AGN outbursts

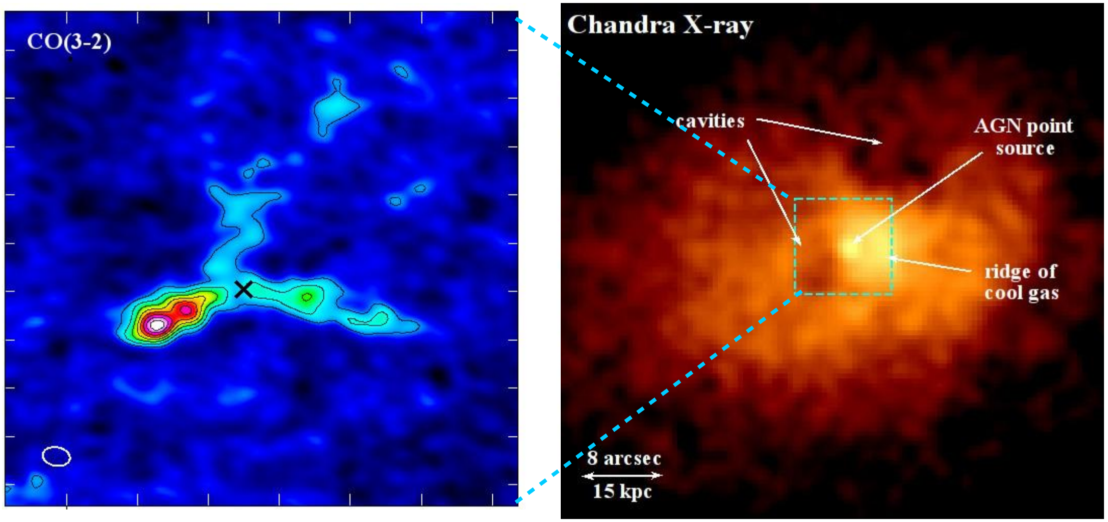


Integrated CO(2-1) intensity Jy.km/s

A closely coupled feedback loop

- Rising bubbles that heat X-ray atmospheres simultaneously promote cooling in their wakes (stimulated feedback, McNamara et al. 2016)
- Inflows fuelling subsequent AGN outbursts?

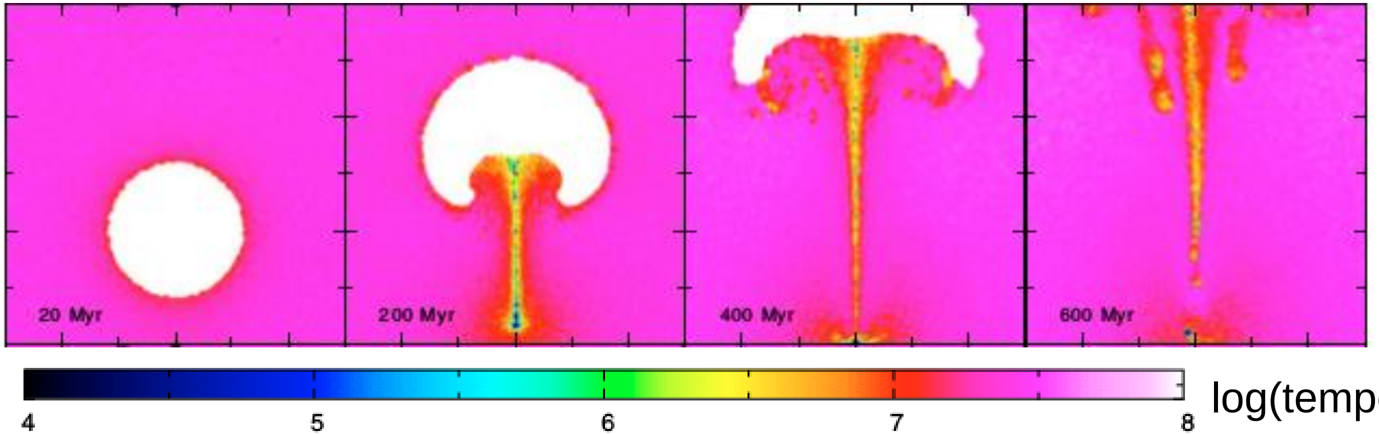
PKS0745



Russell et al. 2016

Sanders et al. 2014

Bubble simulation

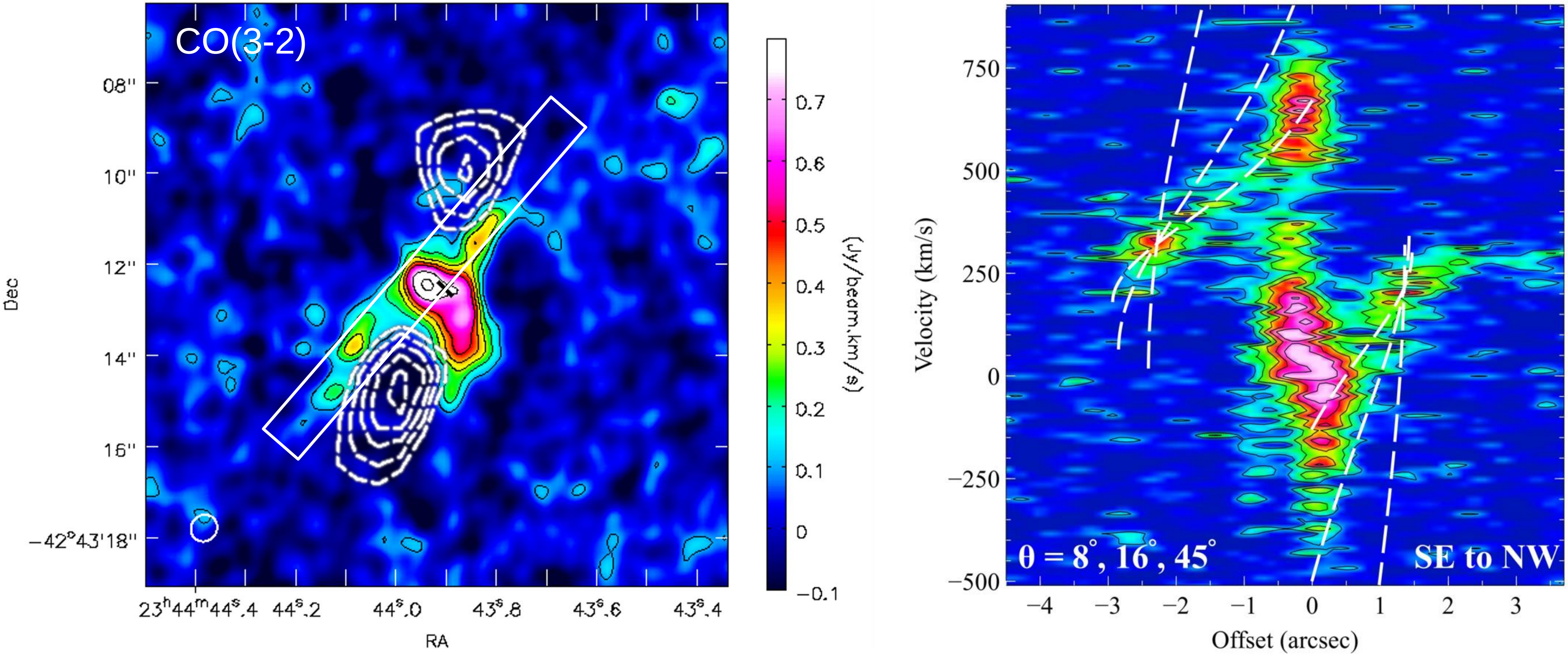


log(temperature/K)

Revaz et al. 2008

Phoenix cluster: ordered gas flow to centre

- Smooth velocity gradients and low FWHM in filaments
- Velocity gradient across nucleus with much higher FWHM
- Velocities too low for free fall in gravitational potential

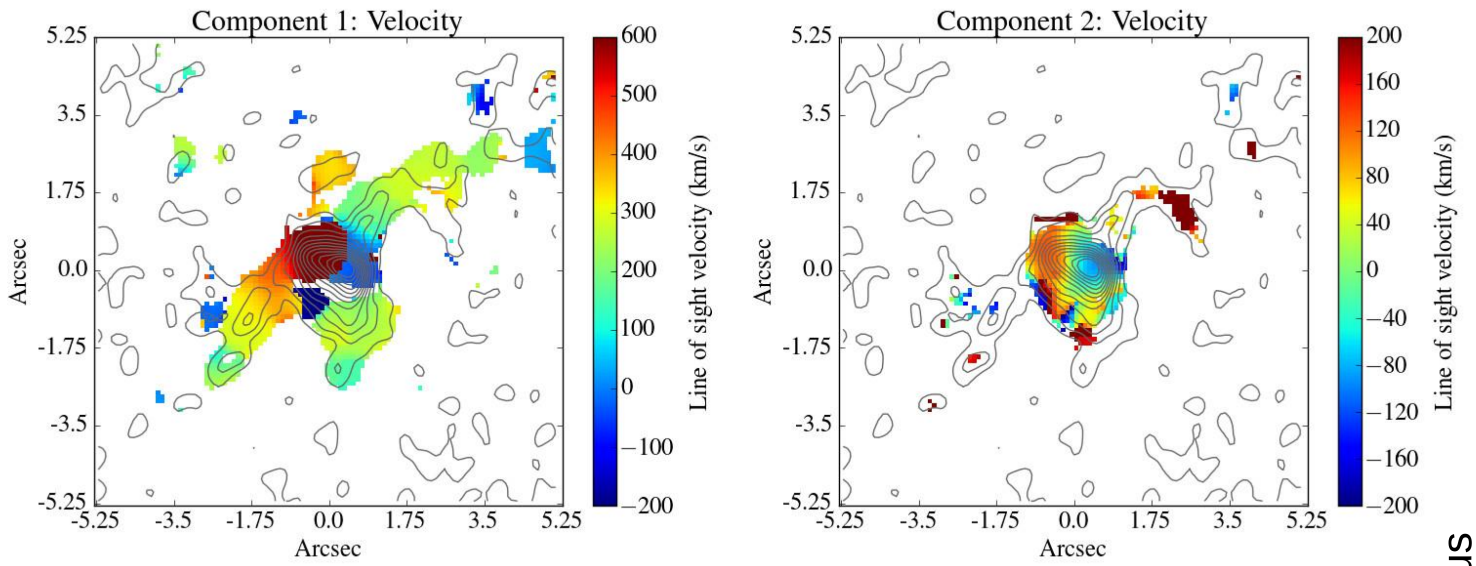


Russell et al. 2017

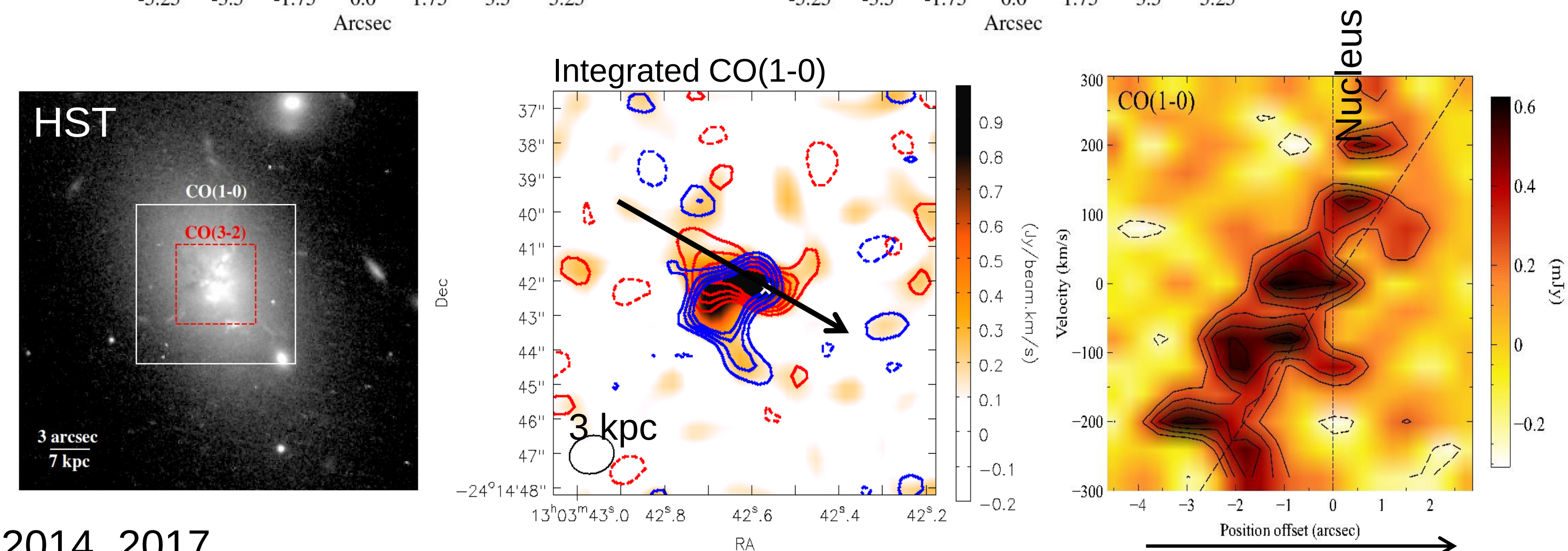
Molecular gas disks on few kpc scales

- Additional velocity component close to the BCG systemic velocity with smooth gradient across the nucleus

Phoenix



A1664

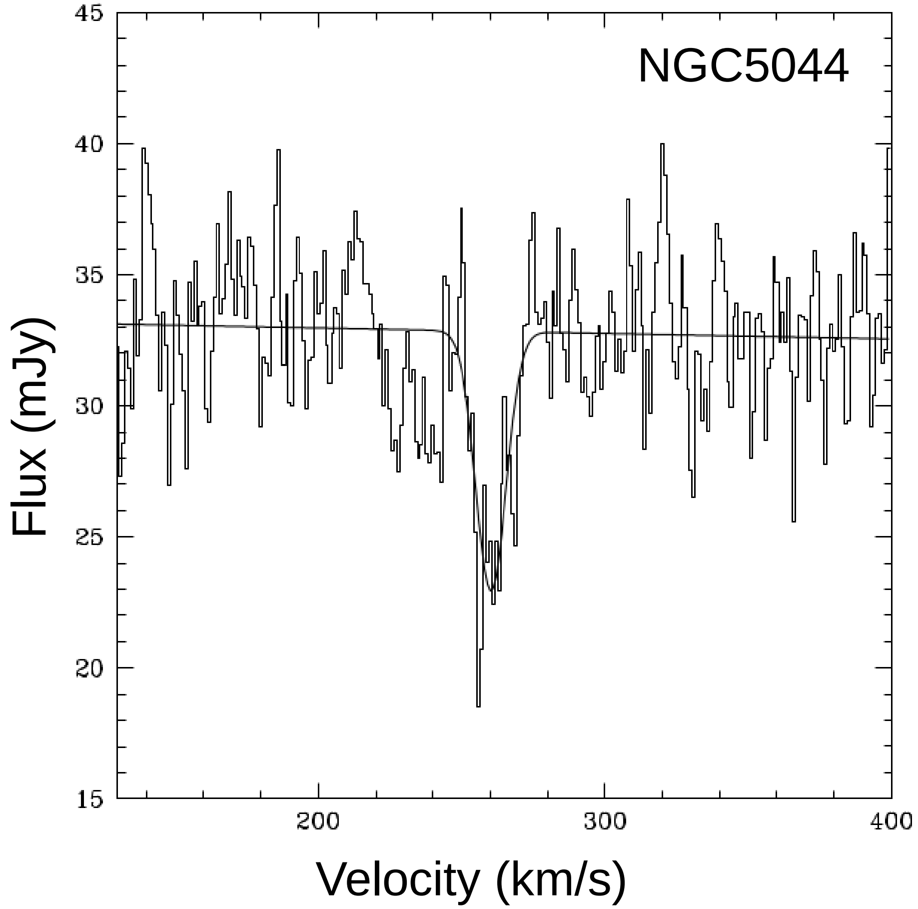


Russell et al. 2014, 2017

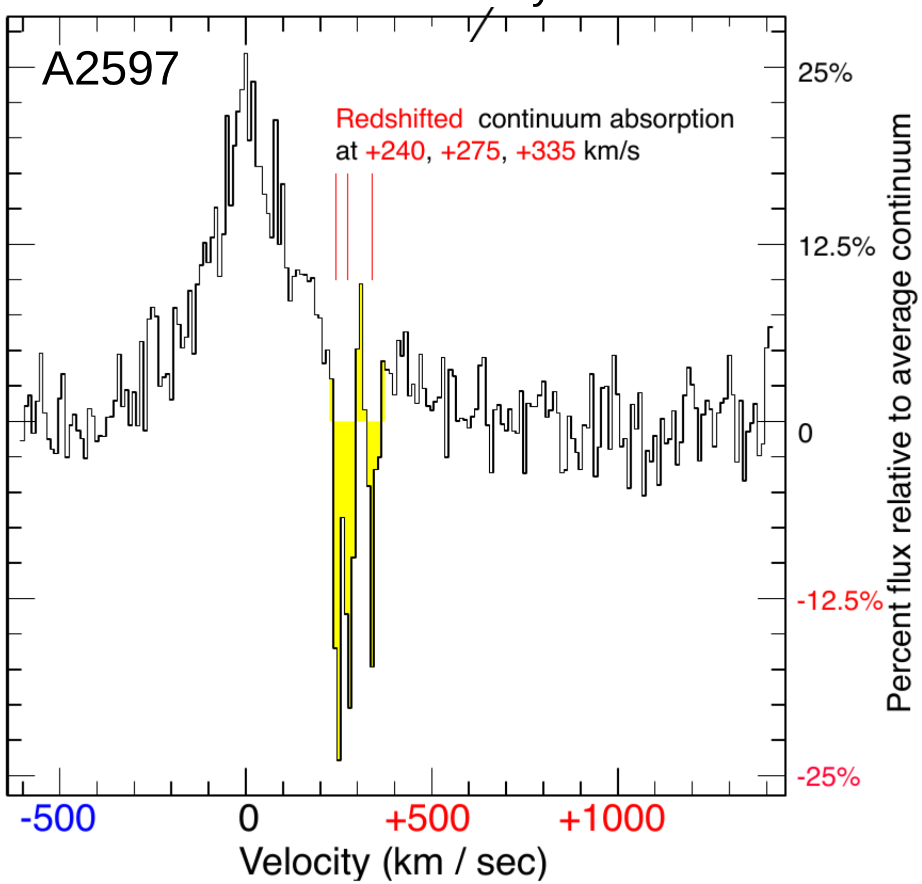
NGC5044 + A2597: absorption features

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

David et al. 2014

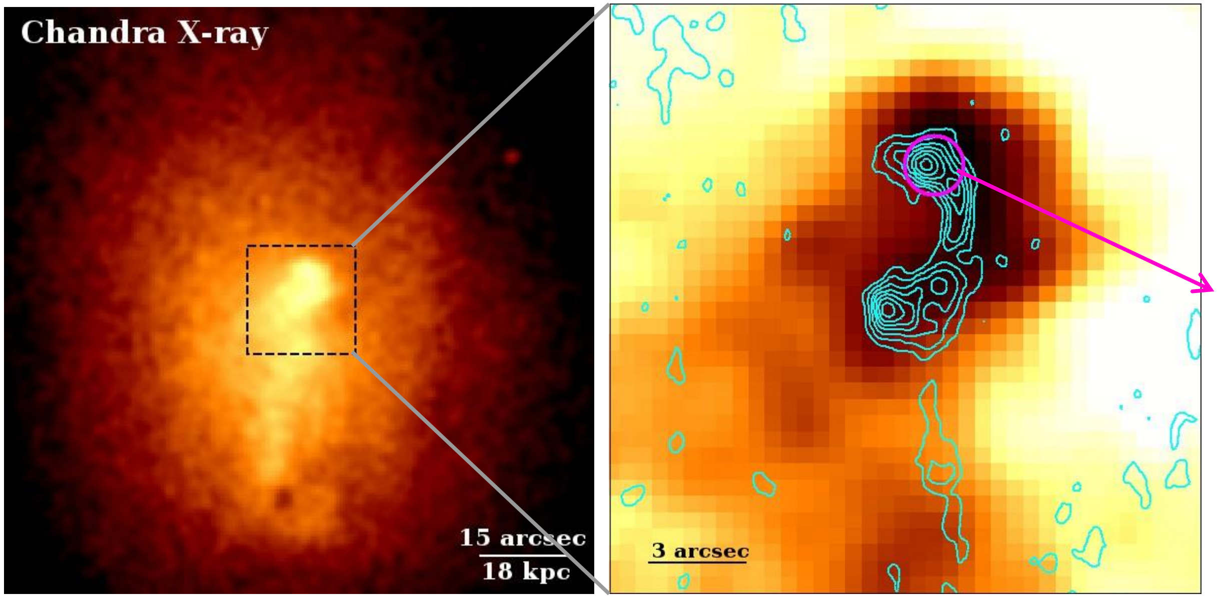


Tremblay et al. 2016



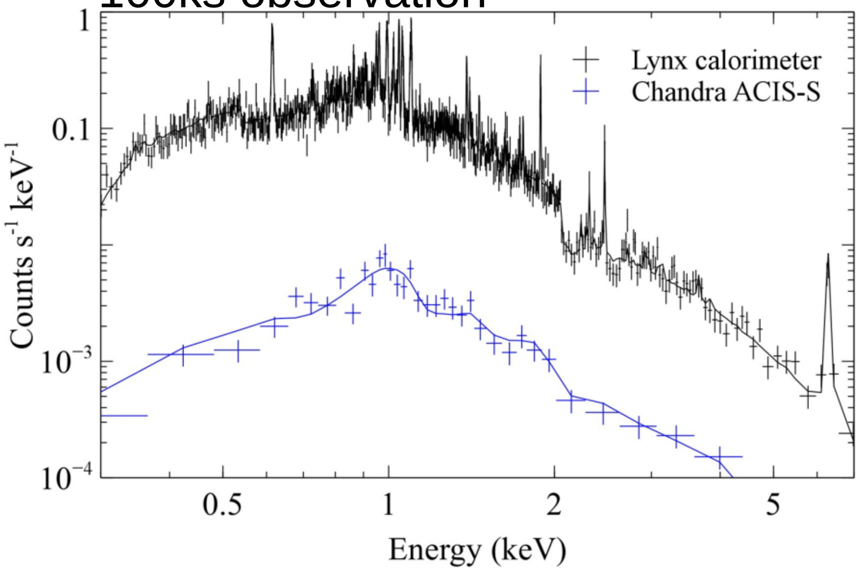
Lynx science

- Hitomi results for Perseus: X-ray velocity gradient matches that along Hα/CO filaments
- Dissipation and distribution of jet energy over large scales
- Regulation of gas cooling and AGN fuelling
- Detection of cavities, soft X-ray filaments, complex structure
- Jet power, gas velocities, X-ray cooling rates



Abell 1795

100ks observation



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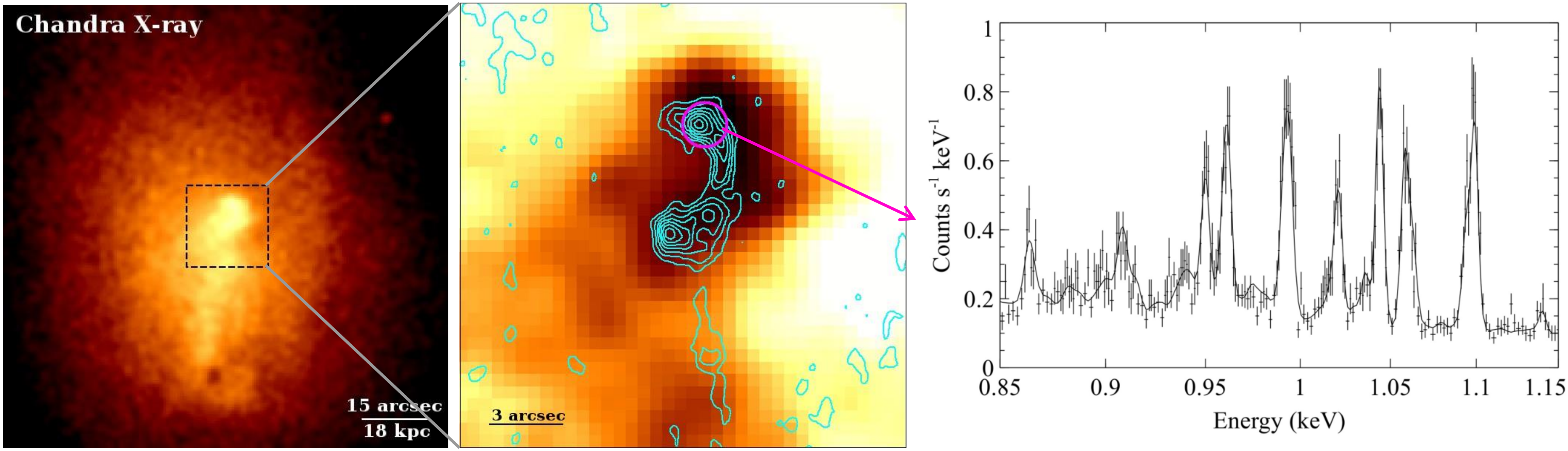
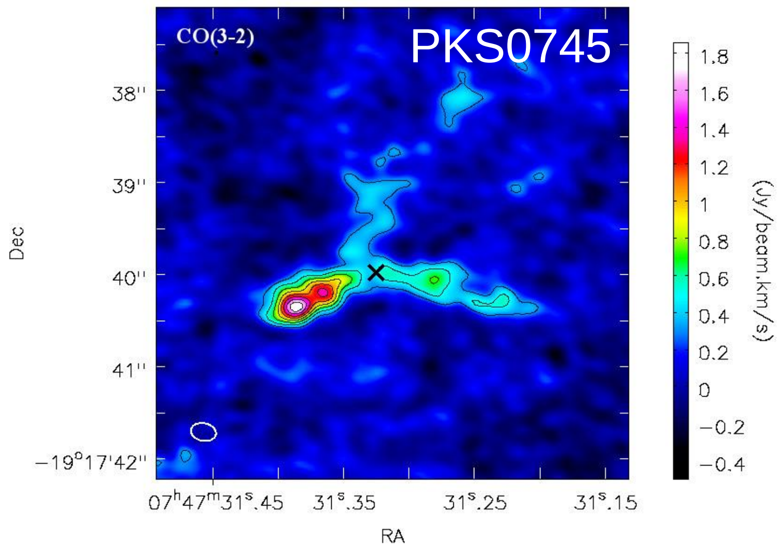
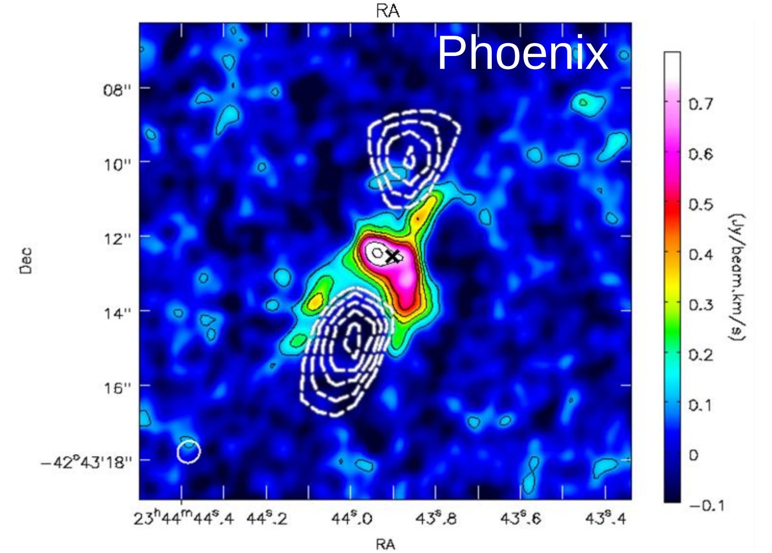


Abell 1795

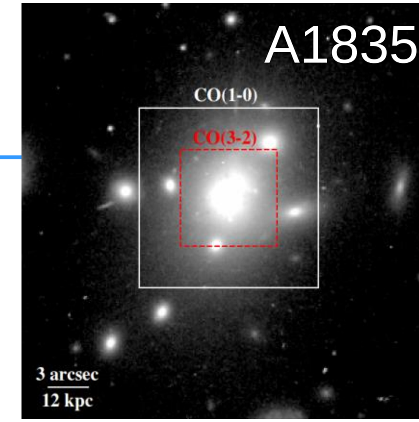
Conclusions

- Molecular gas structure shaped by radio bubble expansion
  - 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
  - Long-lived feedback loop



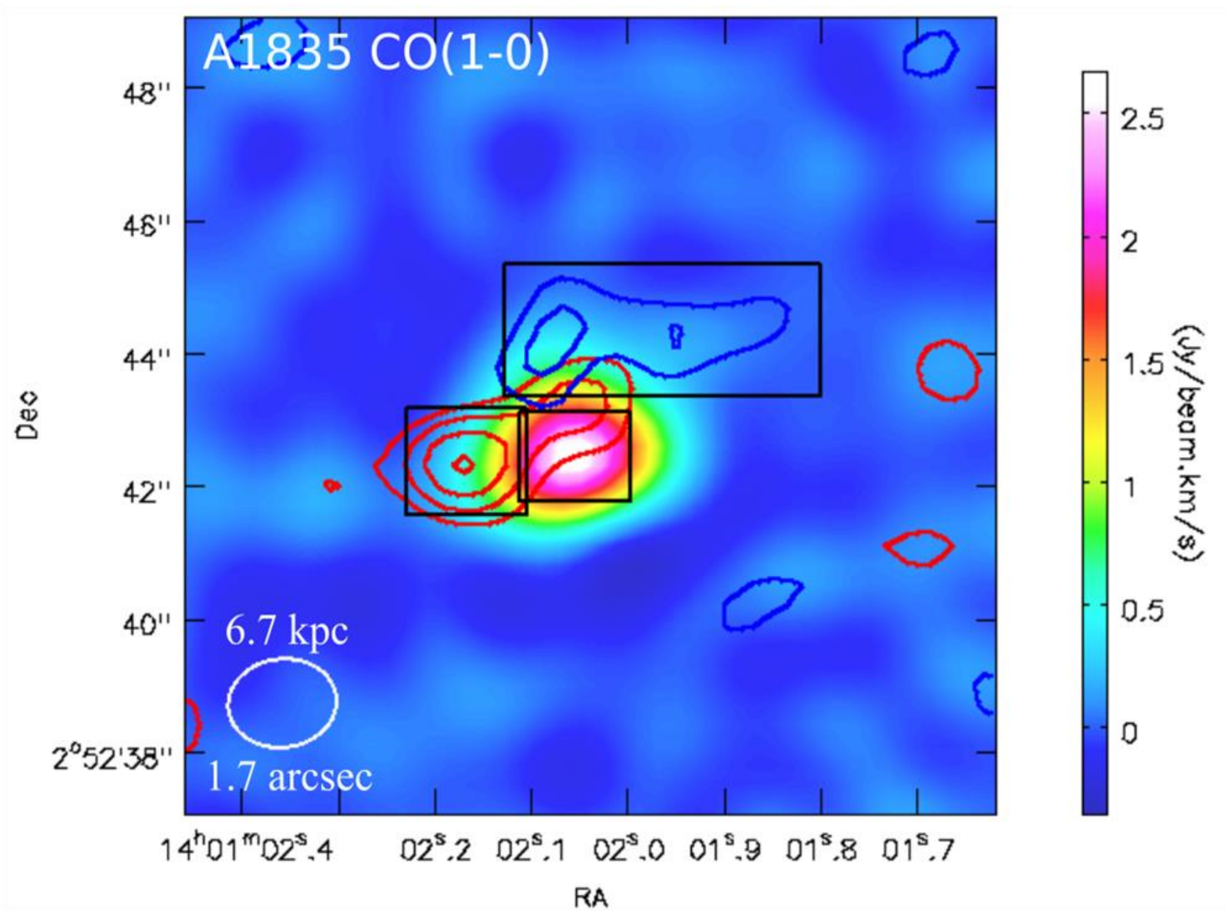


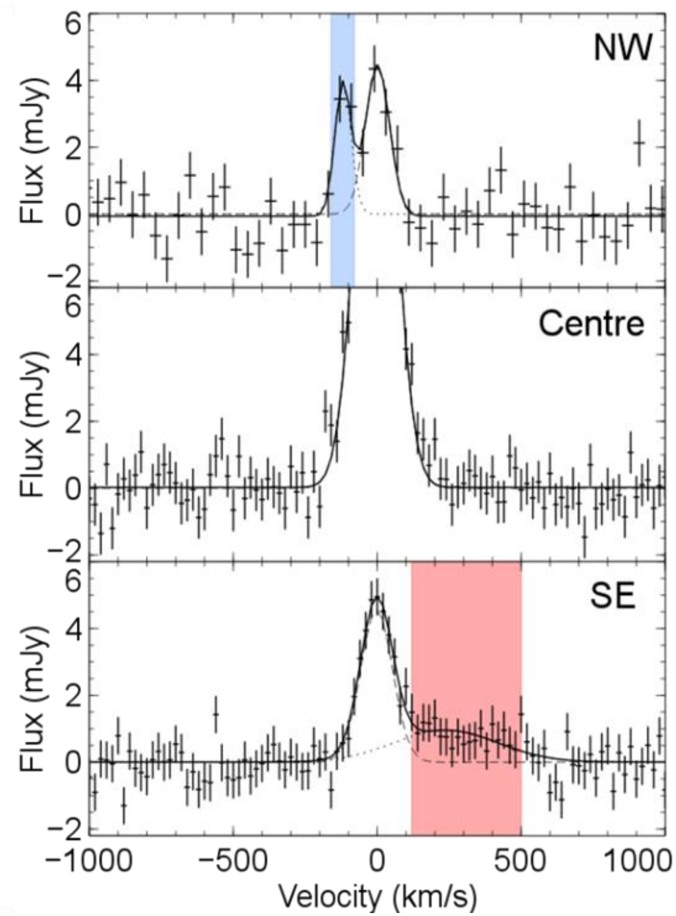
Highest velocities at largest radii



A1835:

- $10^{10}\,M_\odot$ molecular flow at 200-400 km/s extending to 10kpc



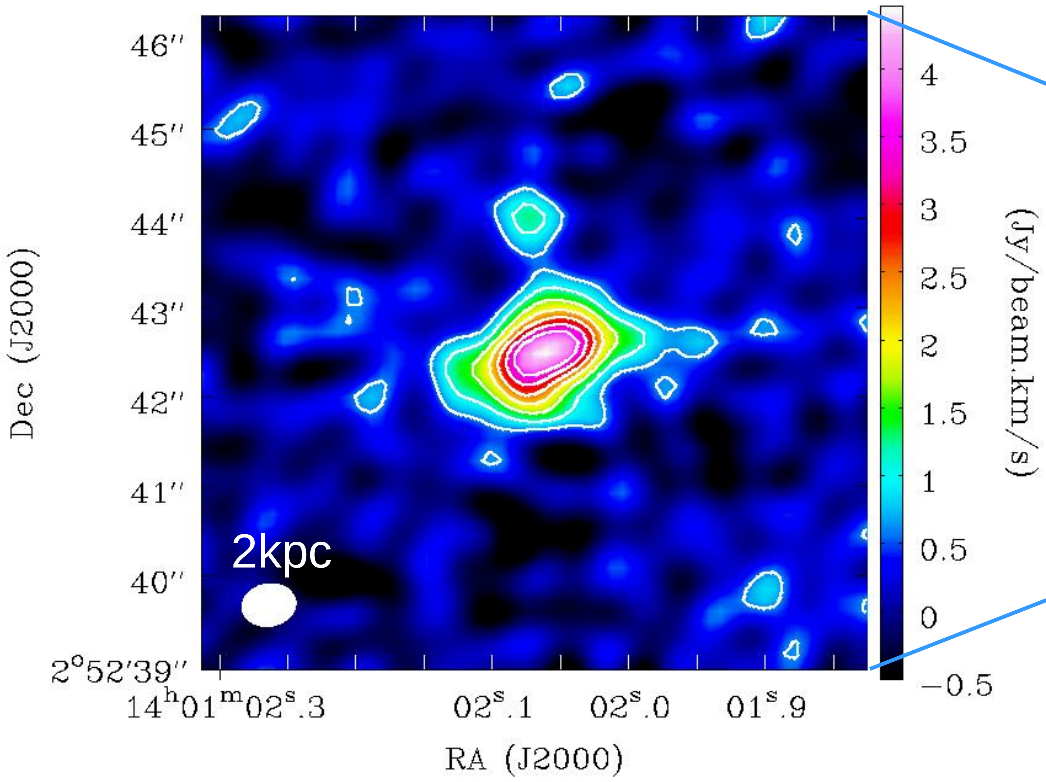


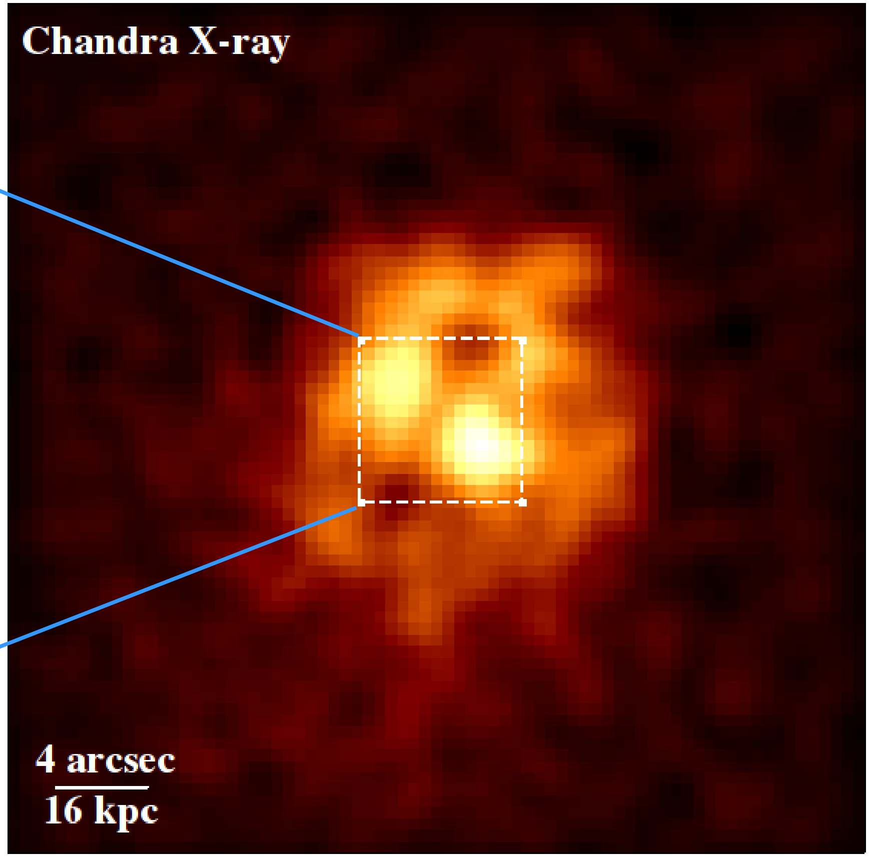
McNamara et al. 2014

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)

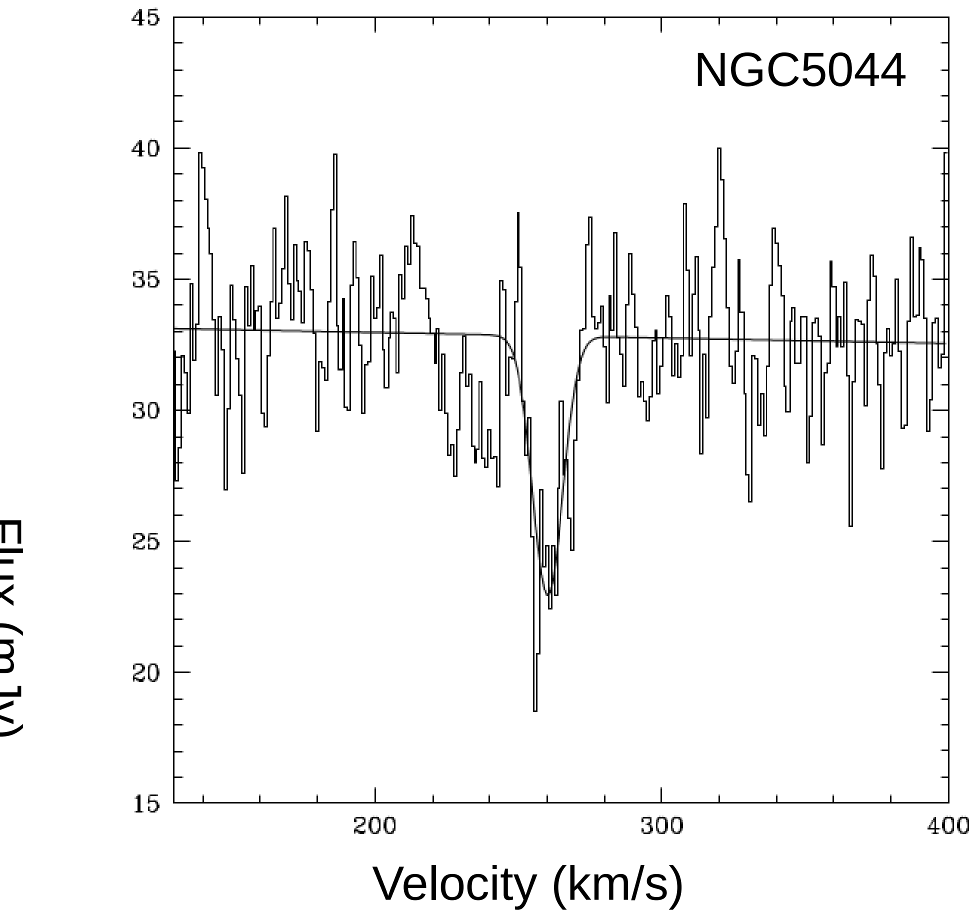




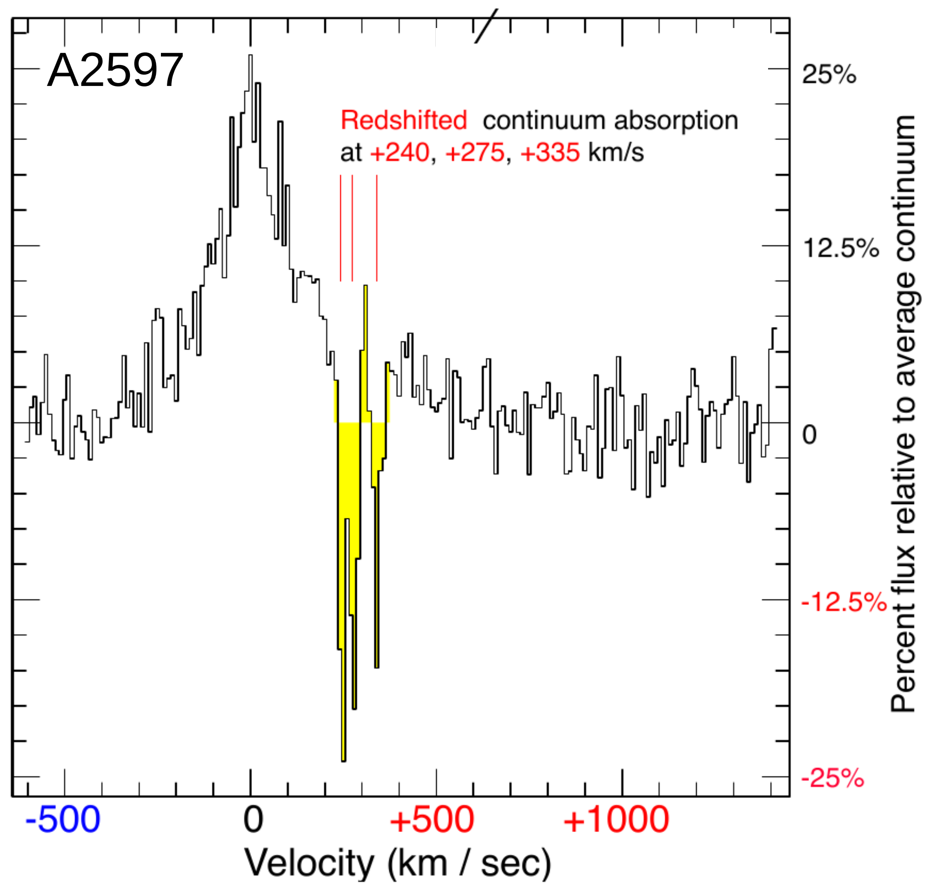
McNamara et al. 2014

Filaments consist of many GMCs

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



David et al. 2014



Tremblay et al. 2016