Gasflows in Galaxy Clusters

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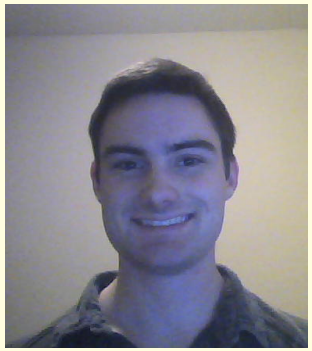
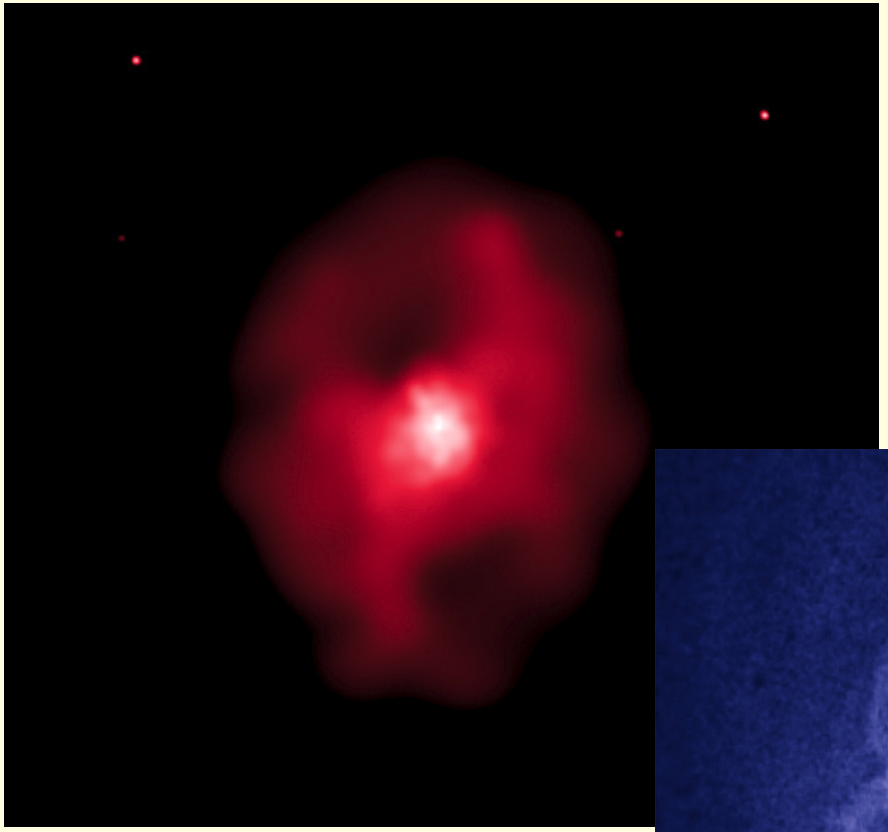


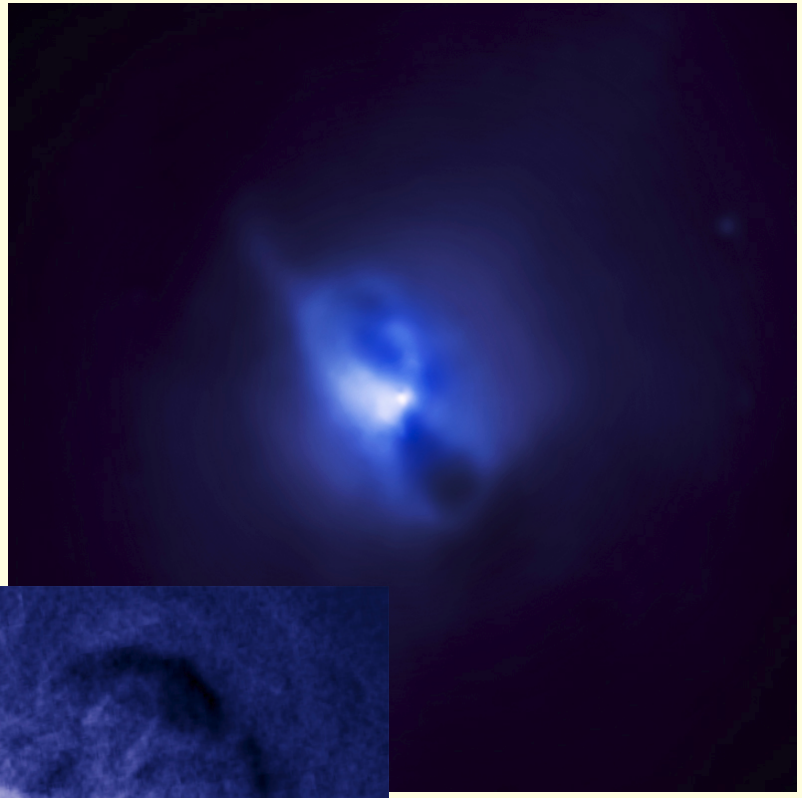
Copenhagen, August 2014

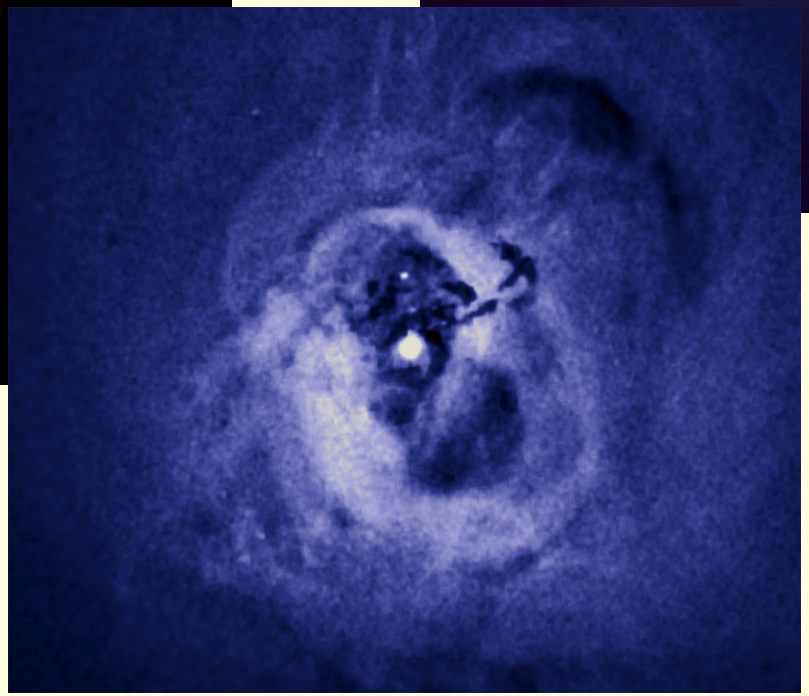
Chandra X-ray Observatory

MS0735



Hydra A

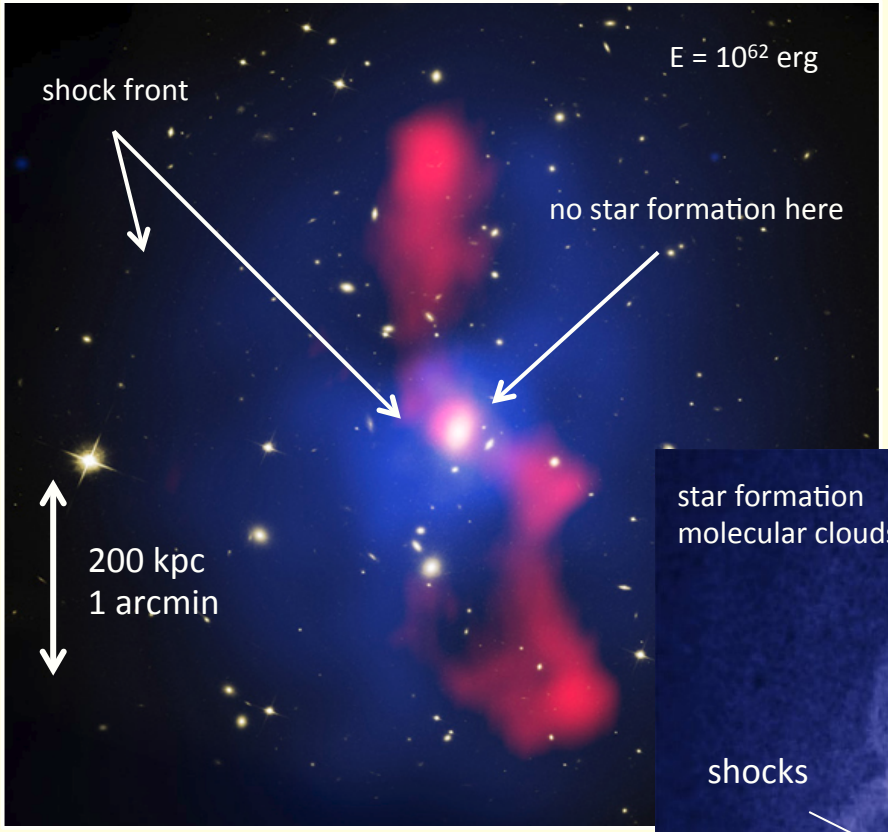




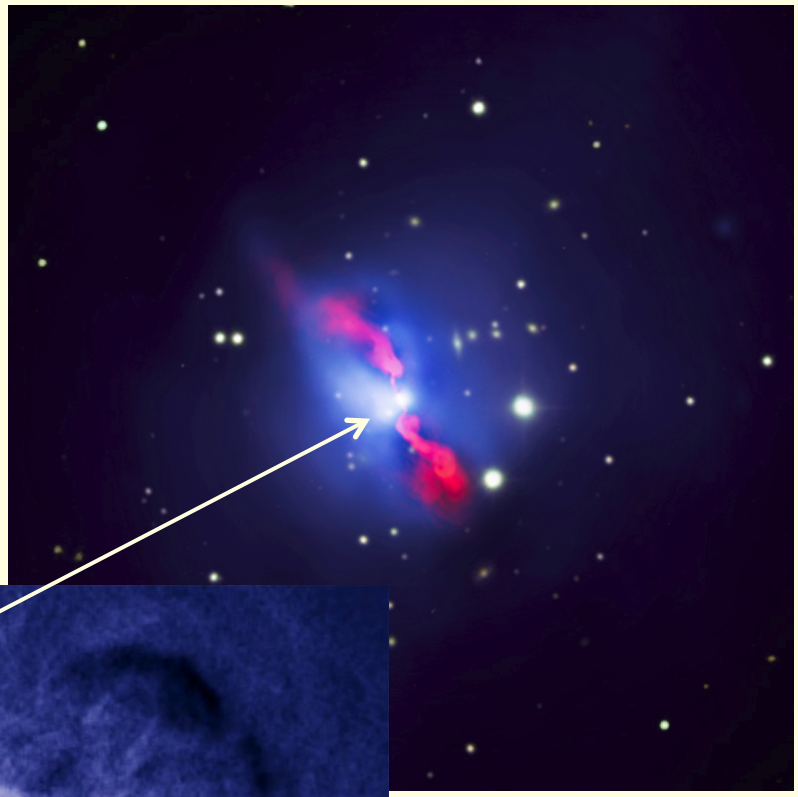
Perseus

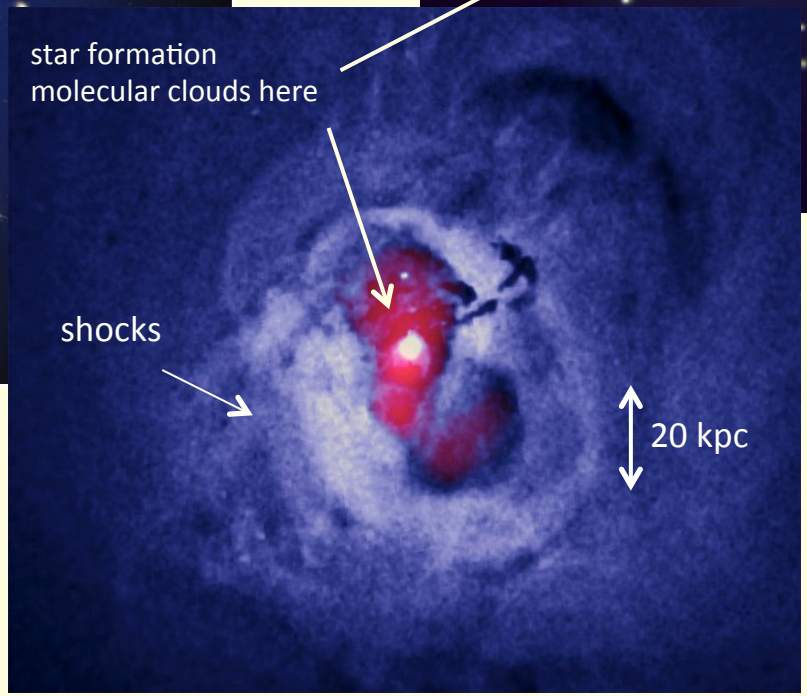
X-ray + radio = mechanical feedback

MS0735



Hydra A





Perseus

Credit: H. Russell

Molecular Gasflows in central galaxies

BCGs in cooling cores rich in molecular gas (Edge 01)

- origin of molecular gas?
- Is molecular gas fuelling the AGN? see McN + 11
- Does radio/mechanical feedback affect molecular clouds?
- Feeding star formation

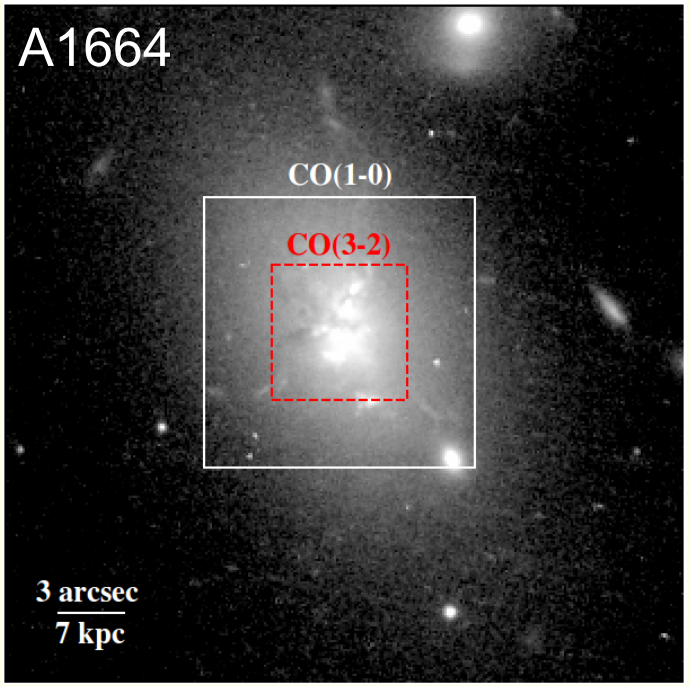
60 twelve meter dishes;
6 seven meter dishes
Baselines 150m to 16 km

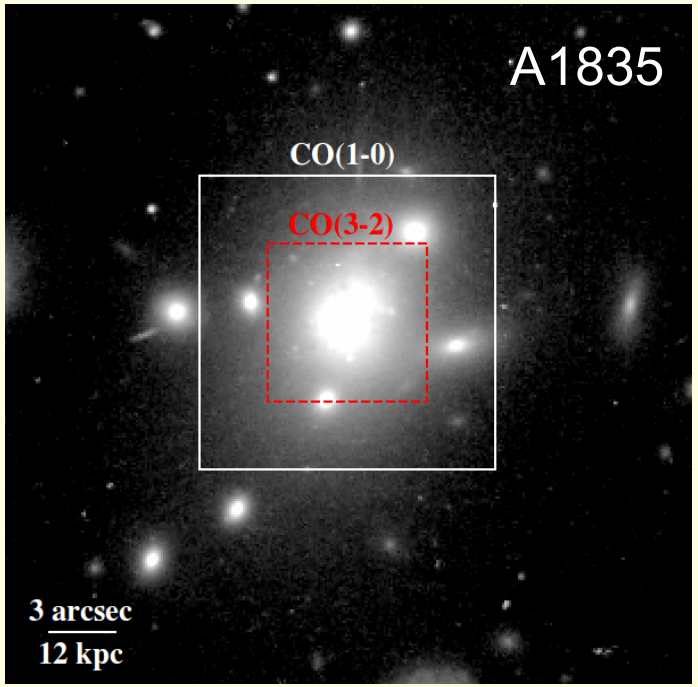
Programs in Cycles 0-2

McNamara + 14
Russell + 14
David + 14

ALMA Early Science

- Large X-ray cooling rates, SF rates 20-180 $M_{\odot}$ yr^{-1}
- Single dish CO observations: molecular gas ~10^{10} $M_{\odot}$
- Mergers unlikely – Cooling out of hot atmospheres

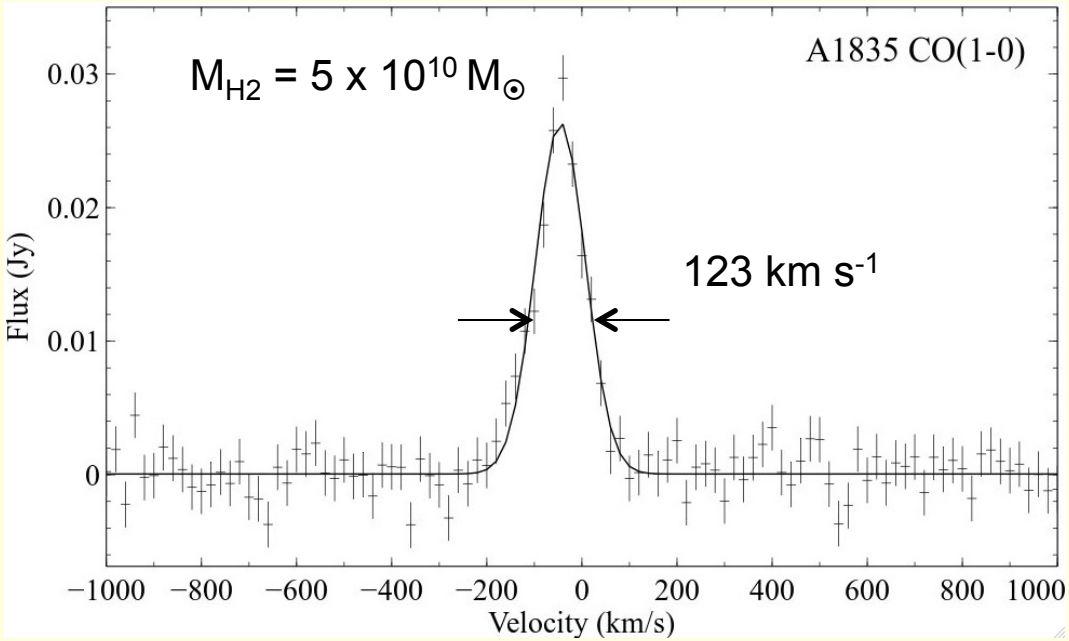




HST observations, O'Dea et al.10
Early IRAM CO observations: Edge 01, Salome & Combes 02

ALMA Spectrum: 20 dishes

exp ~ 1 hr



A1835

McN+14

FWHM = 123 km/s << stellar velocity dispersion ~ 300 km/s

Cannot be supported by dynamical pressure?

Rotational support in face-on *thick* disk

Forming stars at ~ 200 M_o yr^{-1}

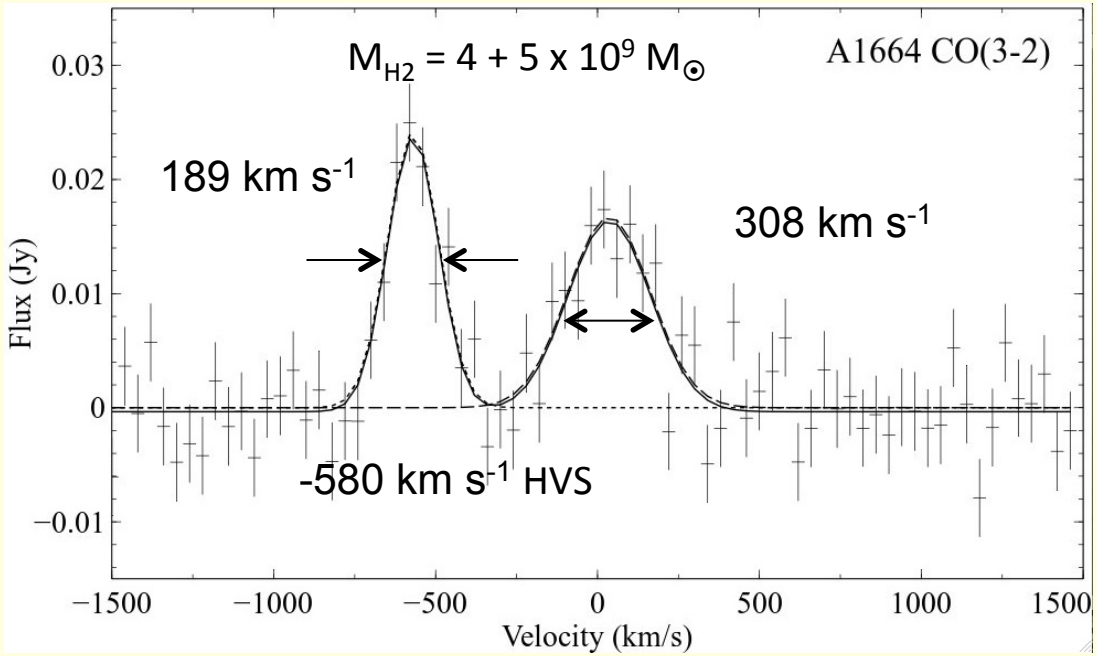
Abell 1664 BCG

Two velocity systems: possible solid-body, asymmetric disk

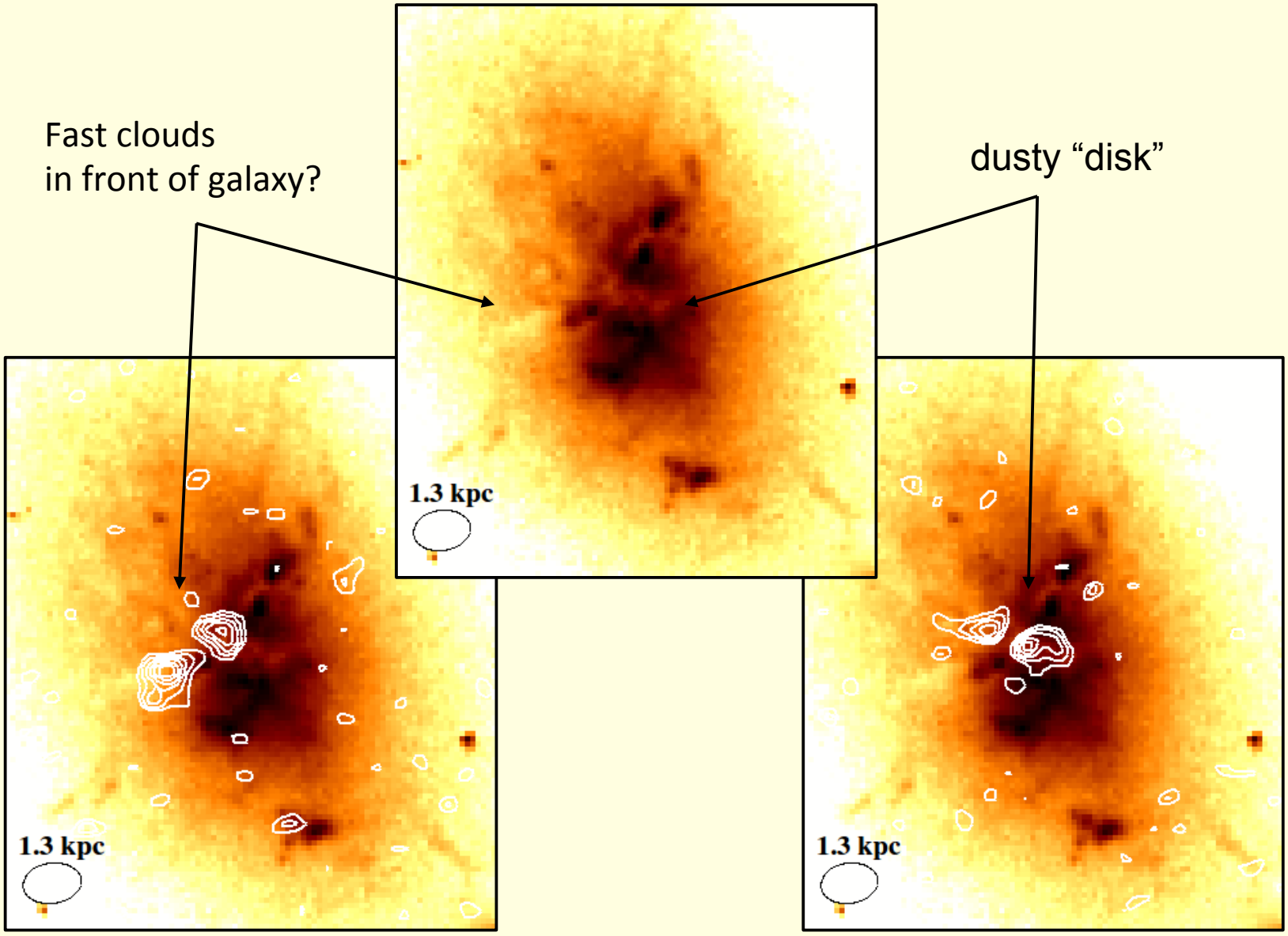
Fast clouds blueshifted at ~ 570 km/s

Inflow/outflow?

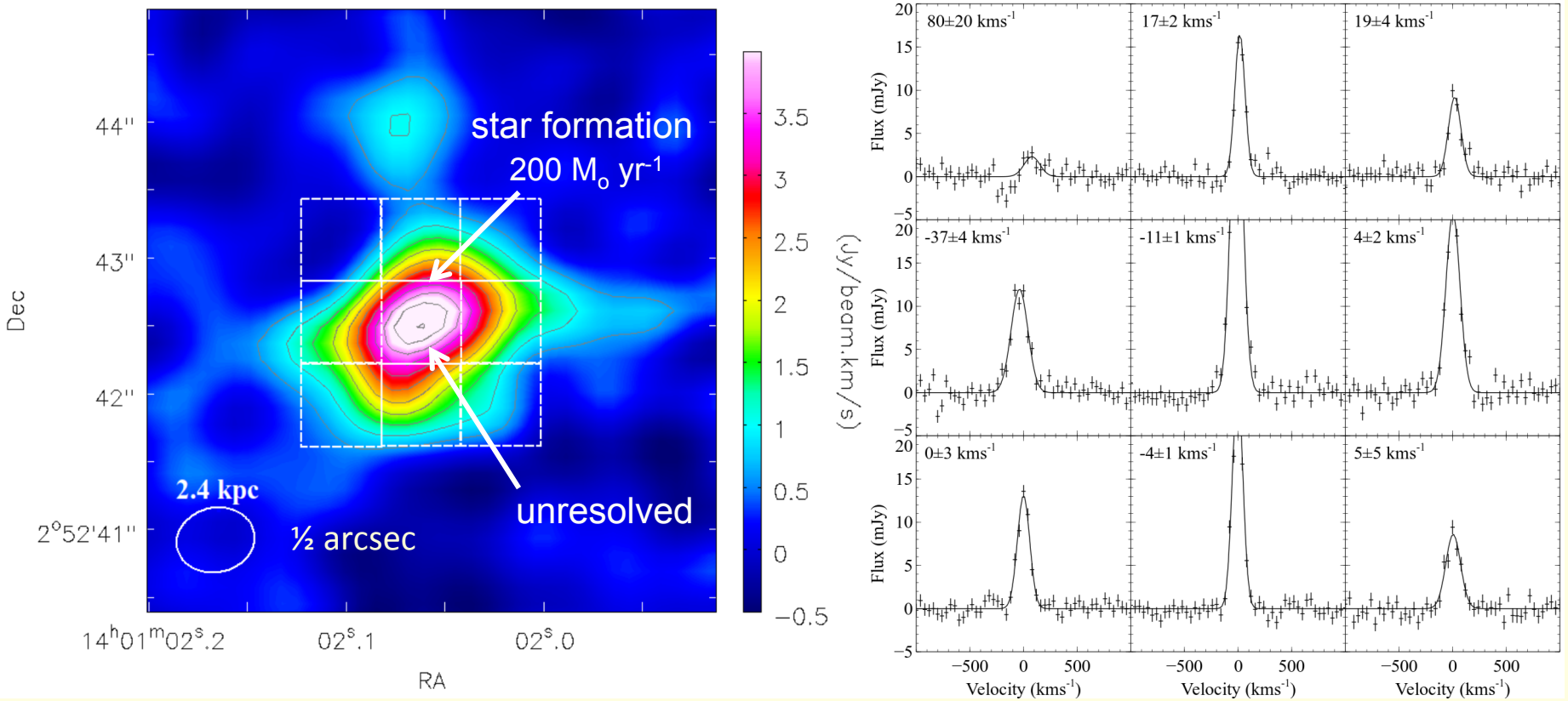
exp ~ 1 hr



A1664 CO(3-2): -580 km/s flow of gas



CO (3-2) spatially resolved spectra



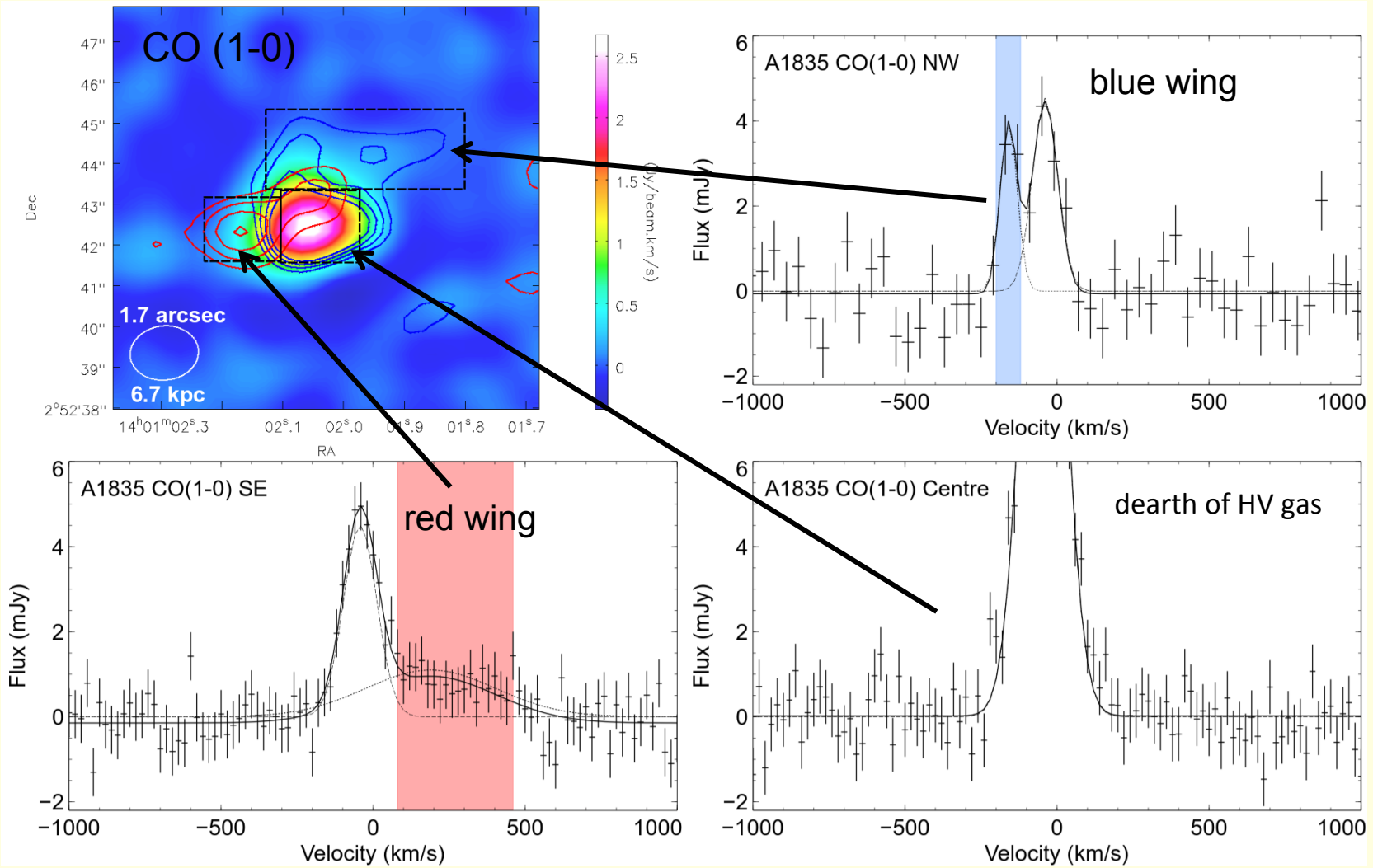
Ensemble FWHM = 130 km s^{-1} : may be supported by rotation

Thick ~ face-on disk?

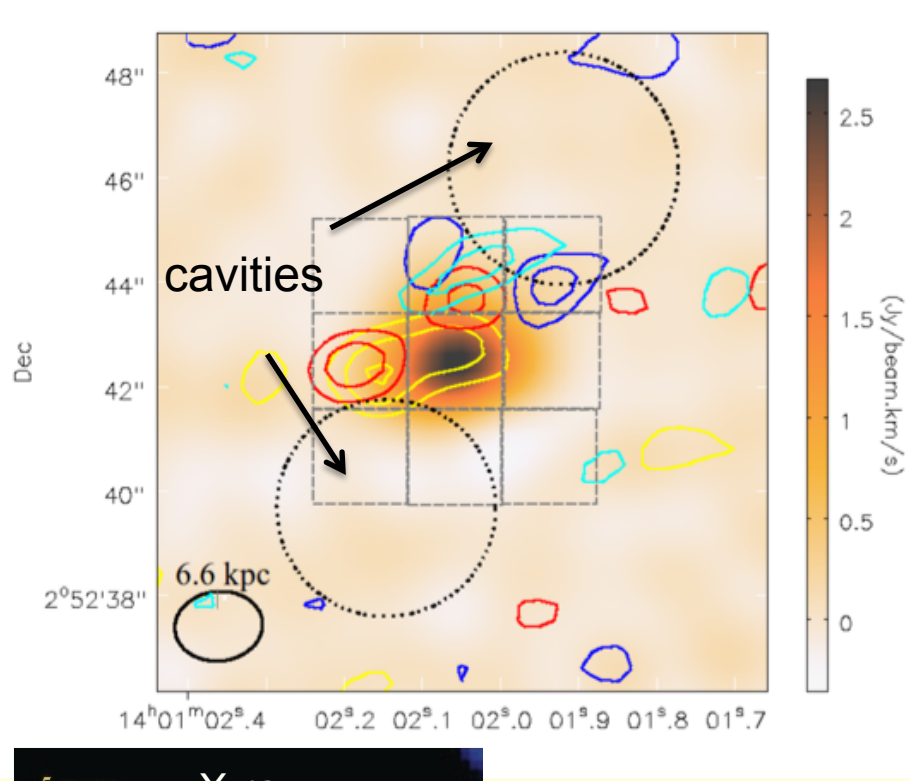
Puffed up by supernovae in star-forming disk?

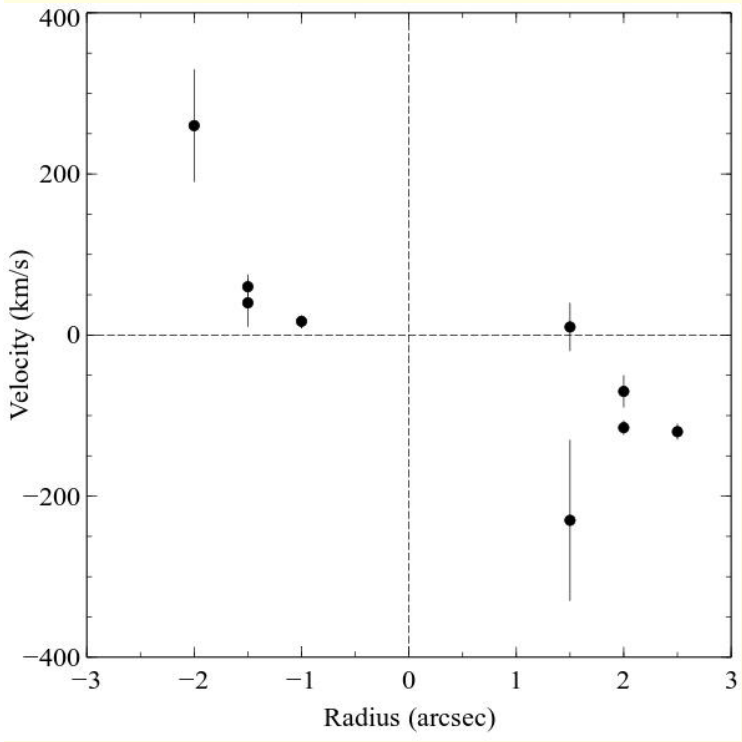
Abell 1835: molecular (out)flow

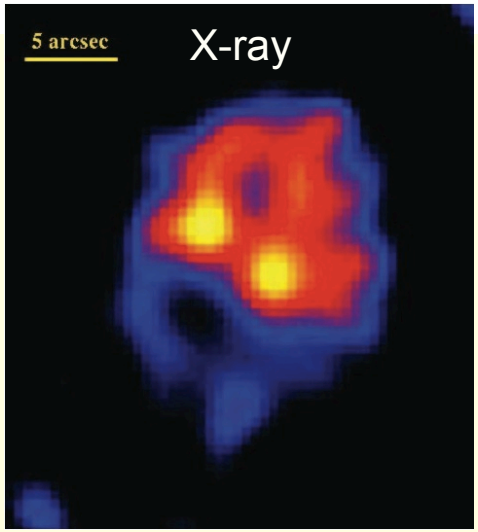
- 200 - 480 km s^{-1} molecular flow - $M_{flow} \sim 10^{10} M_{\odot}$ - r = 5 -10 kpc
- Directed toward the cavities - $E_k \sim 10^{58}$ erg < 1% of jet energy



Abell 1835: 10^{10} M_o fast clouds at 10 kpc: in/out flow?







Outflow rate 200 M_o yr^{-1} comparable to SFR

McN+14

UV flux & SN explosions unable to power outflow

Low velocities, absence of high velocity gas at center consistent with outflow, gun barrel acceleration

How do rising cavities couple to molecular gas?

Are cold and hot outflows related?

hot outflows: Kirkpatrick+ 09,11,14, Simionescu & Werner

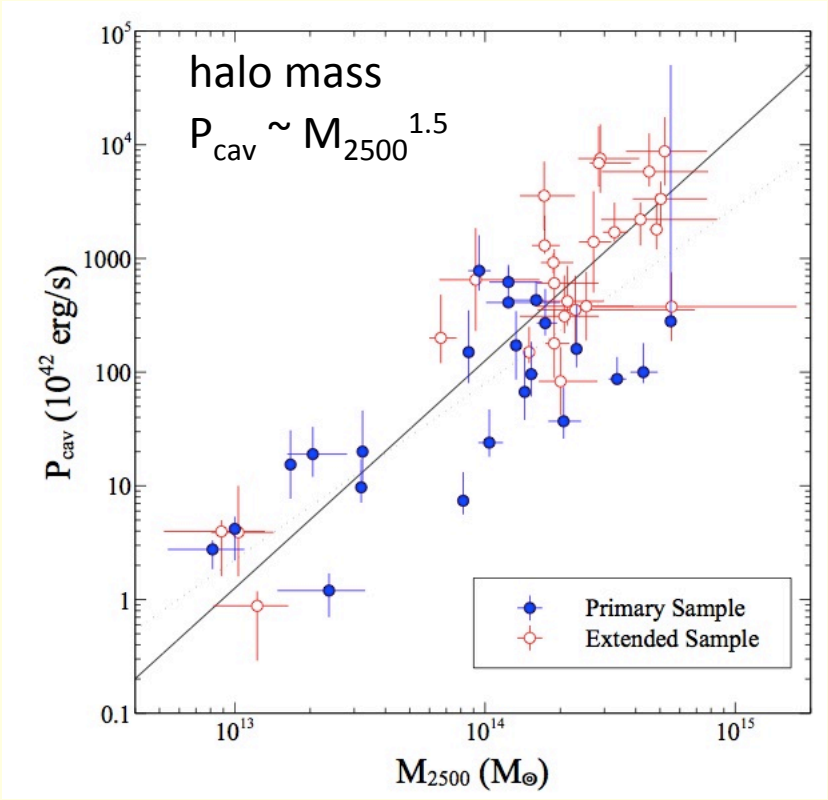
Radio/mechanical-mode feedback scaling with mass

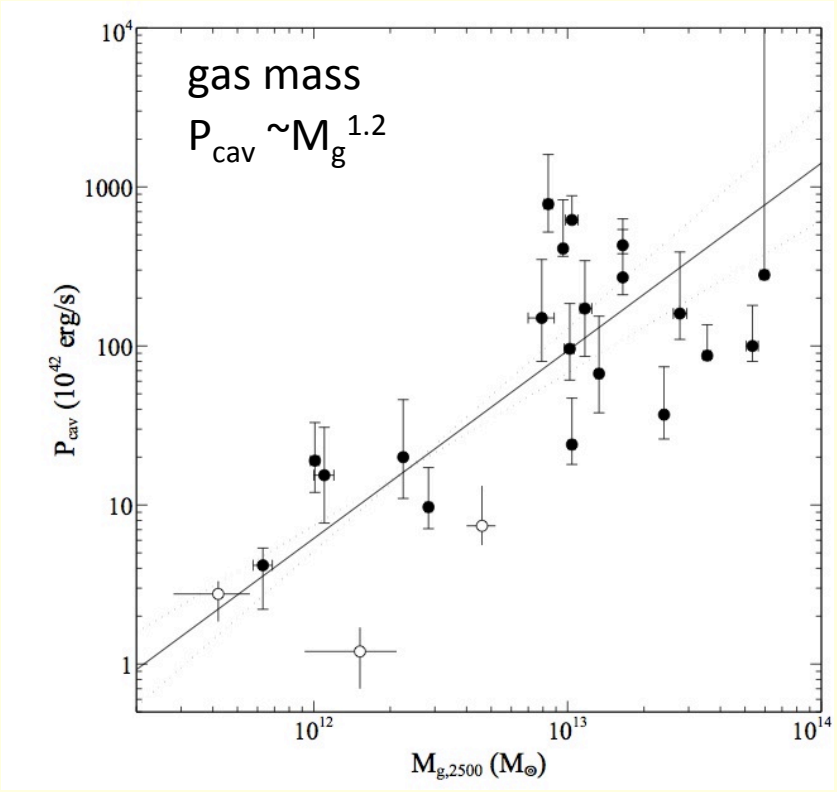
Robert Main

H. Russell, P. Nulsen..

New Stuff…..

Jet Power correlated with Gas & Halo Mass



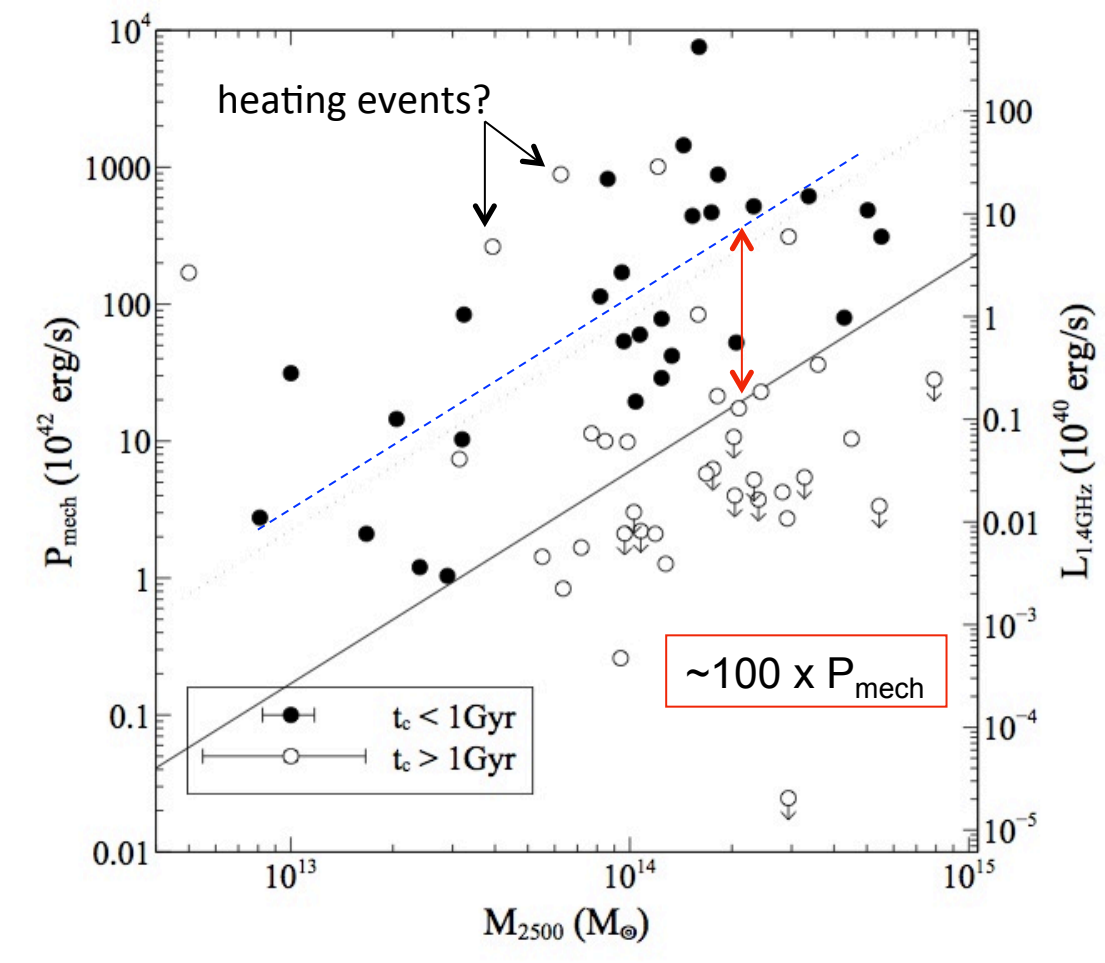


HIFLUGCS primary sample
Rafferty + 06 extended sample

Scaling is consistent with M-σ relation (Ferrarese & Merritt 00)
Beyond cooling region, clusters obey standard L,T,M relations

Radio-mode feedback controlled by at least two factors:

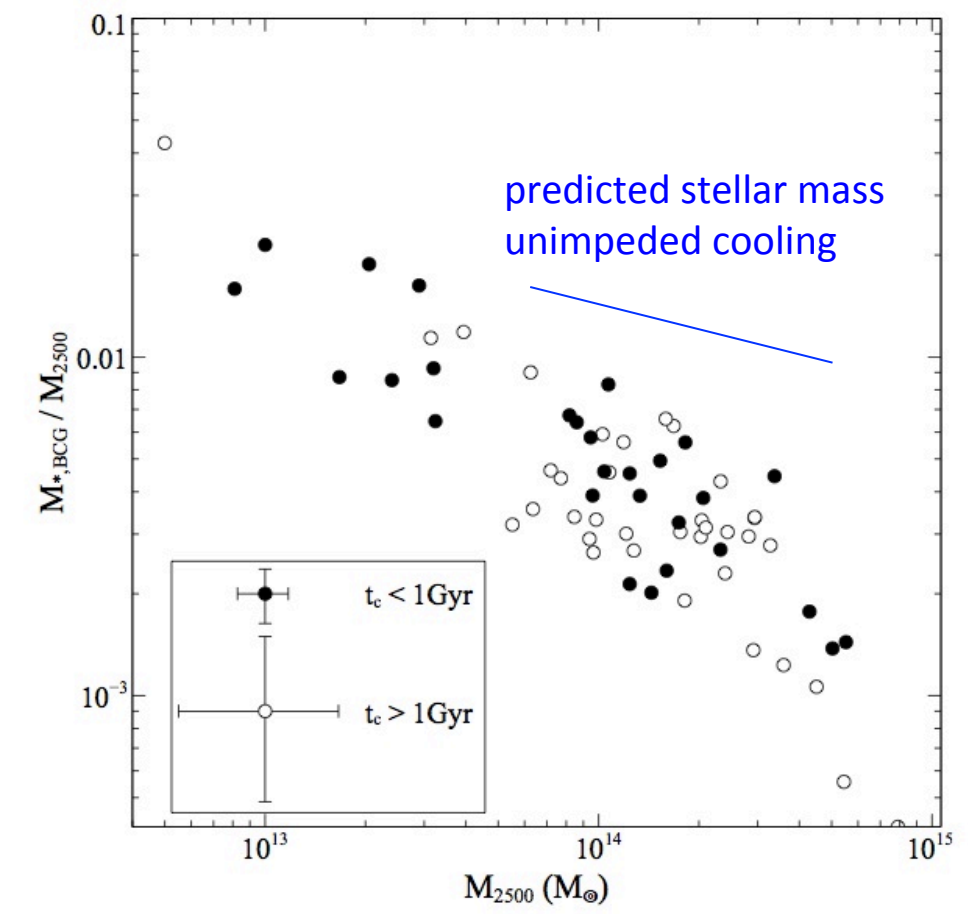
1) central cooling time -- cooling time/entropy threshold Rafferty/Cavagnolo 08
2) halo/gas/stellar mass



Main + in prep

- t_c < 1 Gyr: P_{jet} ~100 x more powerful; P_{jet} ~ M_{2500} : offset cooling
- t_c > 1 Gyr: P_{jet} weakly correlated with M_{2500}
- Continual heating (Evrard & Henry 91) significant, cf. Ma + 11, Ma + 13

Heating agent remarkably efficient at stabilizing cooling
… increasingly so at higher halo masses



Main + in prep

BCG stellar masses form single sequence in cooling time & mass

Summary

- Molecular gas settling into thick and/or asymmetric disks
  ordered motion but not always (NGC 5044)
- Star formation *not* exclusively found in molecular disks
- moderate speed (100-600 km s^{-1}) molecular gas: inflow/outflow
- Speeds too low to be merger debris– consistent with cooling atmosphere
- Are molecular flows related to hot outflows? Rates are comparable
  but bubbles would have difficulty lifting the gas (N5044 David + 14)

  Outflow: Jets lift warm, unstable gas that cools in the bubble's wake?
  -McN+14, Li & Bryan 14
- New work on mass scaling relations: heating is efficient, scales with mass

Summary

- Molecular gas settling into thick, asymmetric disks/ordered motion
- Star formation *not* exclusively found in molecular disks
- Moderate speed (100-600 km s^{-1}) molecular gas: inflow/outflow
- Early indications radio mode feedback drives molecular outflow
- Related to hot flows?
- May be a factor maintaining “red and dead” ellipticals
- Future: understanding fueling, jet formation, feedback over time
  role of molecular gas in feedback loop.

See McNamara + 14, Russell + 14 ApJ