Stimulated Feedback in Galaxies

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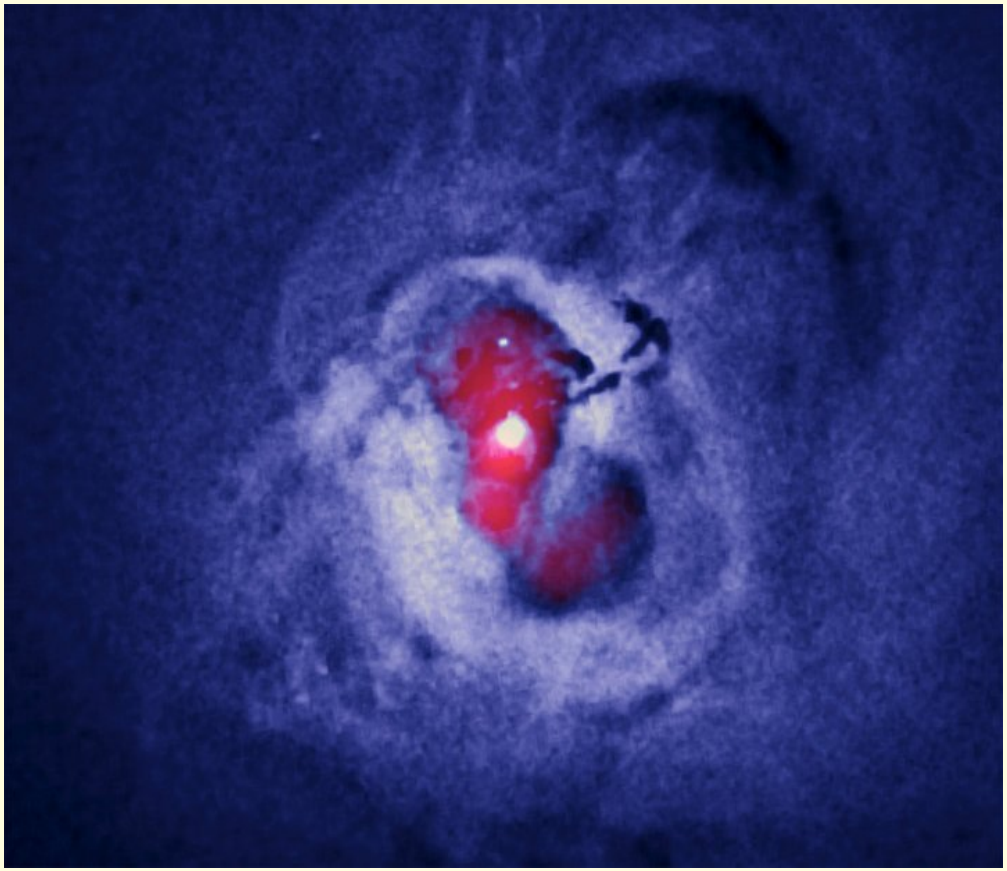
Outline:

- the t_c/t_{ff} thermal instability indicator: does it work?
- cooling time/entropy threshold
- cold & hot gas flows in clusters – important element of feedback
- *Stimulated* Feedback, uplift & circulating gas flows McN + 16, ApJ in press

Minneapolis, August 24, 2016

Cooling in central galaxies is apparently stabilized by AGN feedback

How is feedback fed?



Perseus

Fabian + 00, 2008

Renewed interest in thermal instability inspired by several influential papers:

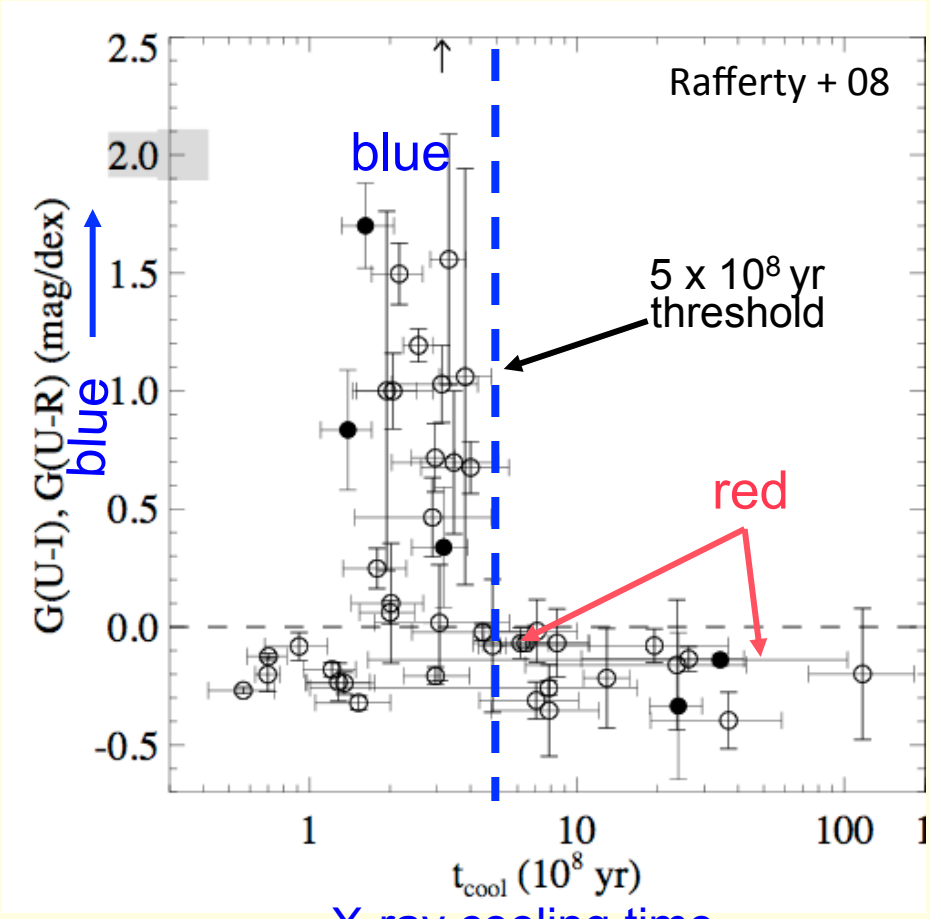
Nulsen 86
Pizzolato & Soker 06
McCourt + 2012 – marvelous paper
Sharma + 2012
Li & Bryan 2014
Li+2015
Gaspari + 2011,12,….
Voit + 2015
Voit & Donahue 2015
Prasad + 2015
Voit + 2016

What role, cooling time, free-fall time, entropy?

$t_c/t_{ff} < 10 \quad t_c/t_{ff} < 1$

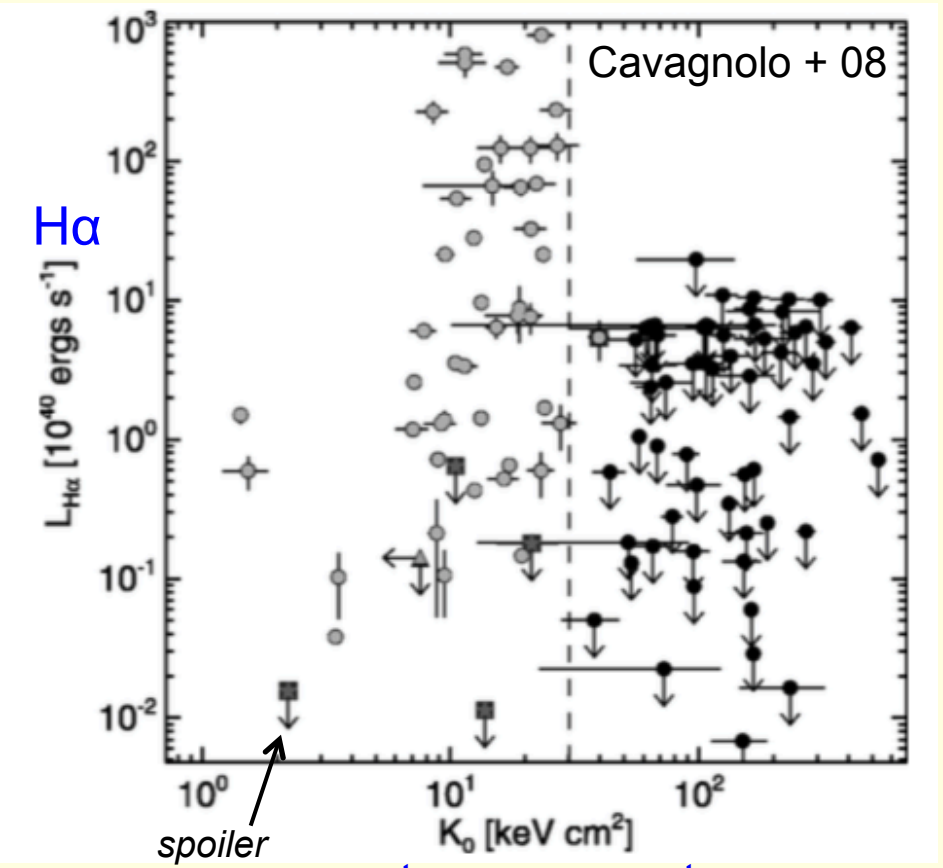
Sharp threshold for onset of thermal instability

Star formation



X-ray cooling time

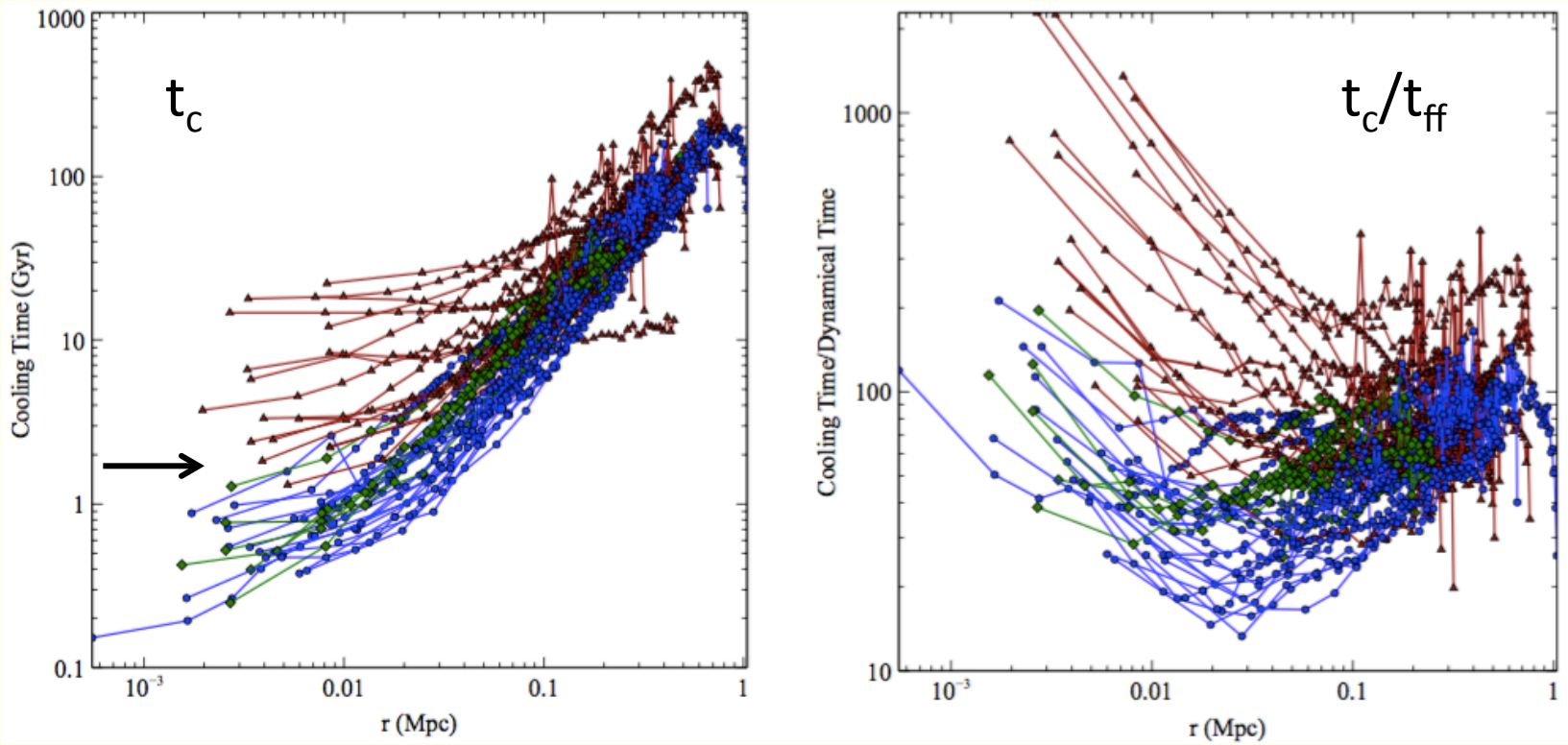
Nebular emission



entropy parameter

Cool gas & Star formation linked to cooling, X-ray atmospheres

Is t_c/t_{ff} a better probe of star formation than t_c alone?



star formation + Hα

Hα only

red and dead

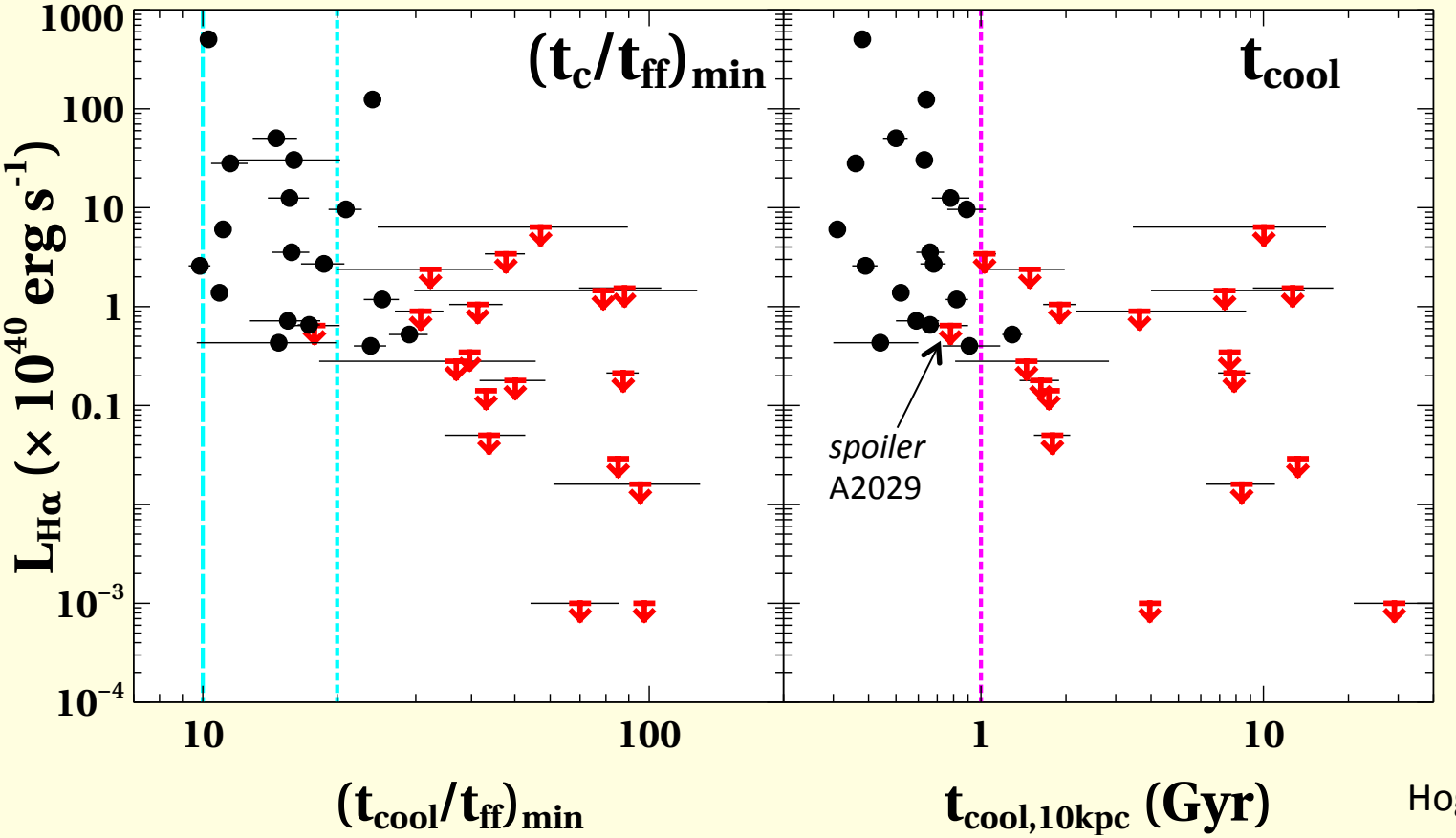
data from literature

A. Aho + 2013

t_c/t_{ff} driven by cooling time, not free-fall time

to do properly, *must* deproject and measure acceleration carefully

Comparison: t_c vs t_c/t_{ff} criteria for thermal instability



Hogan + in prep

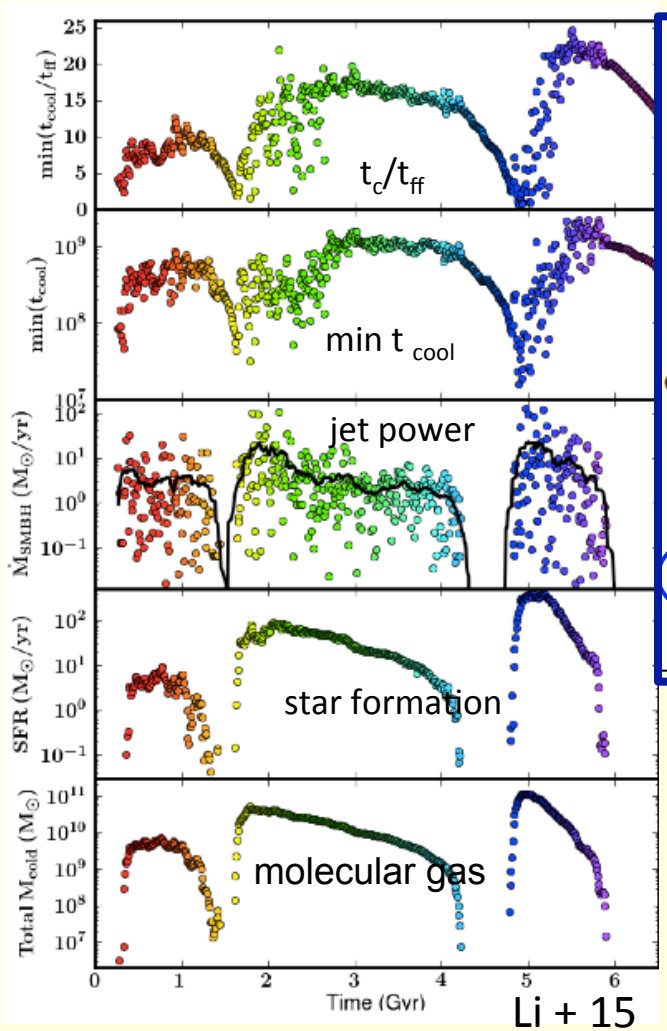
-- Cooling time threshold easily recovered

-- No connection between nebular emission and $t_c/t_{ff} < 10$

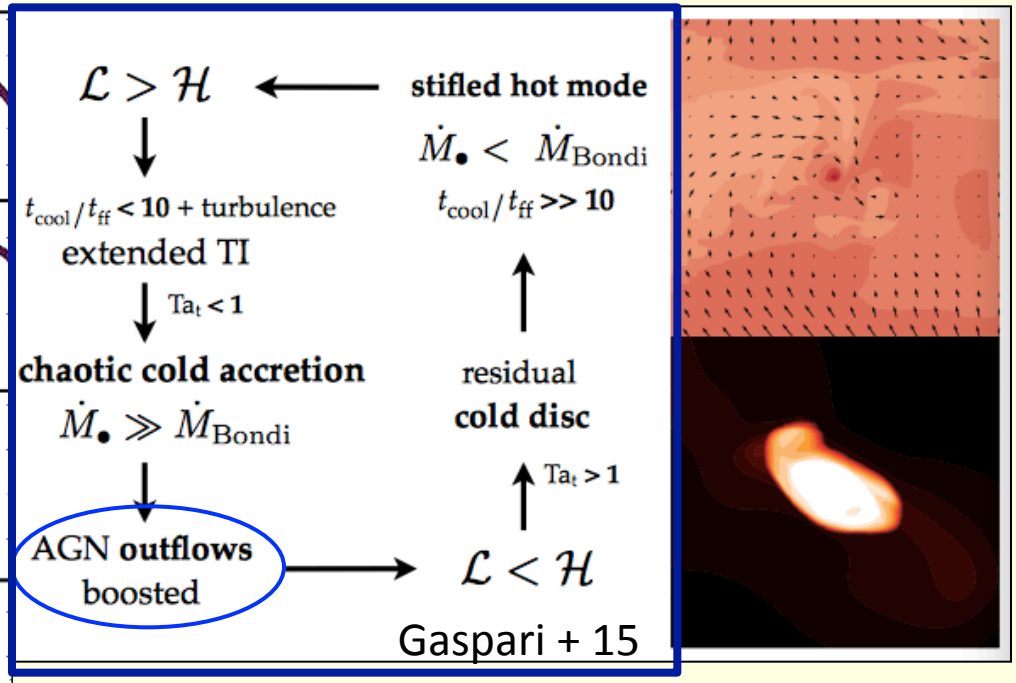
-- Adding second variable, t_{ff}, adds noise

note, t_{ff} measured from mass profiles carefully to within ~ 10 kpc show little variation

Simulations: swings in jet power, cold gas, star formation correlate with t_c/t_{ff}



Li + 15



Gaspari + 15

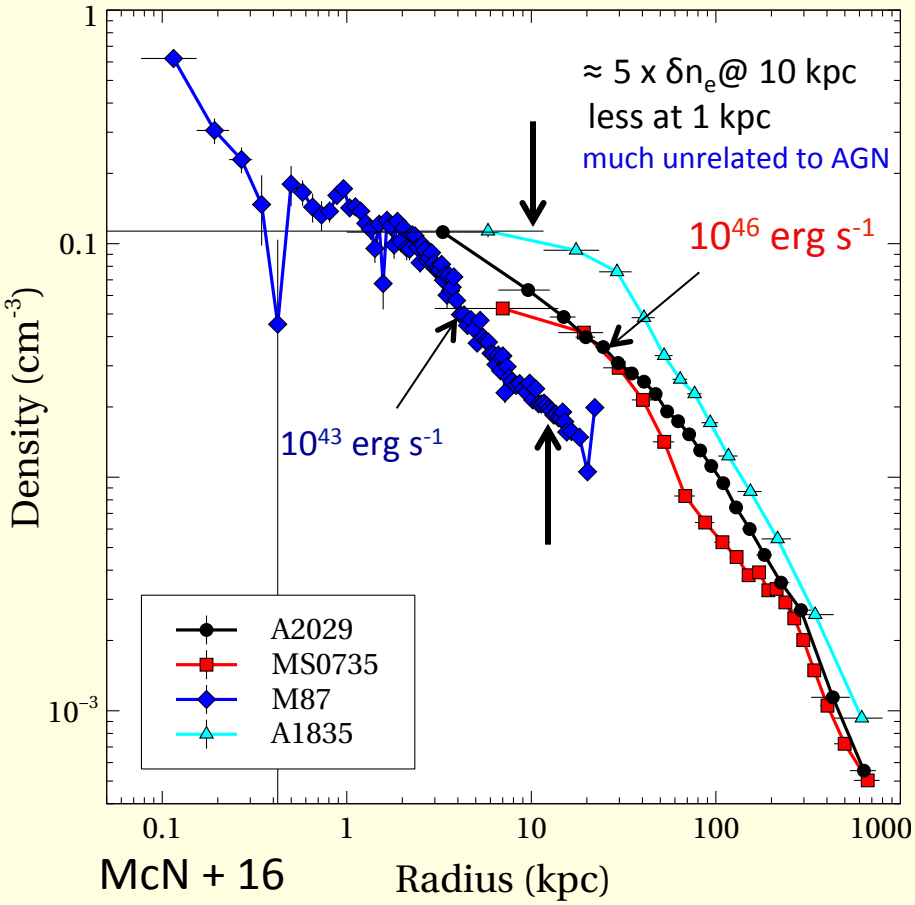
-- large swings in gas density, cooling time, t_c/t_{ff} *not observed*

- uplift *is* observed

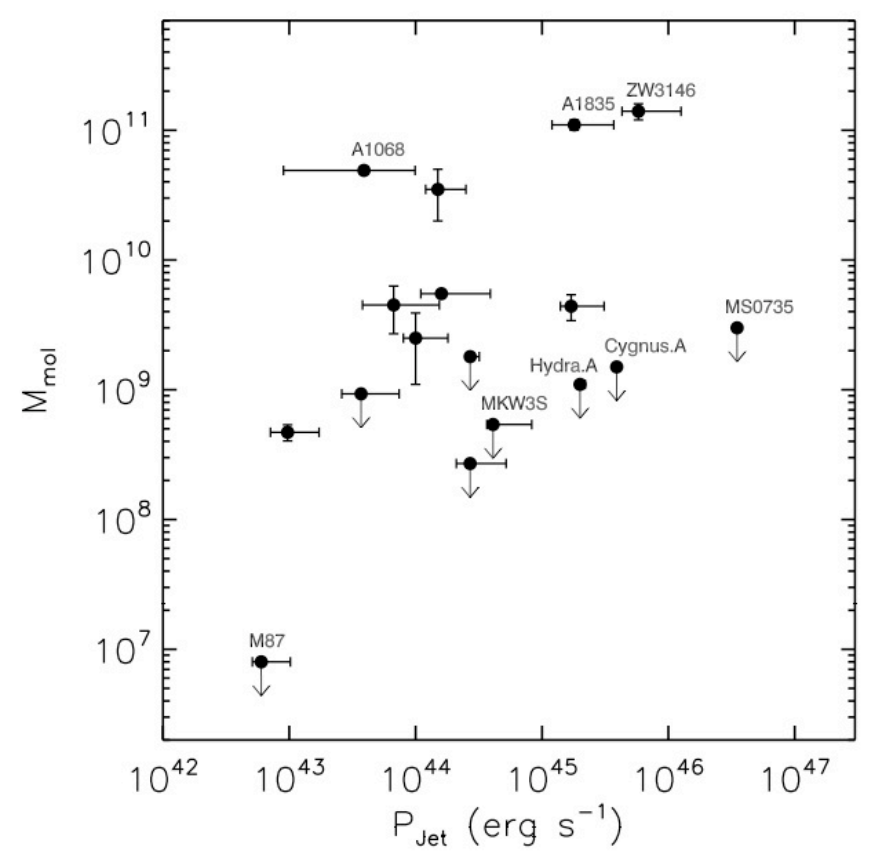
Key simulations: Uplift – Li & Bryan 14

Li et al. 2014, 2015, Gaspari et al. 2013, 2015, Prasad + 2015, McCourt + 2012, Sharma + 2012, Voit + 2015

- Density swings only factors of a few: *gentle feedback*
- Molecular gas mass and *average* AGN power uncorrelated
- Precipitation models predicts 1-2 decades of variation- not observed



McN + 16



McN + 11

no trend between t_c/t_{ff} and molecular gas mass or star formation rate
we know only that when tc < 10^9 yr, stuff happens… feedback is subtle

Conjecture: "stimulated feedback"

McN + 16, in press

Assumptions:

1) Cooling time threshold is the key observation to be understood

2) $t_c/t_{ff} \leq 1$ classical criterion for thermal instability to be satisfied

(but infall time, not free-fall time, may satisfy criterion)

to achieve 2, low entropy gas must be lifted to higher altitude – stimulated feedback

ALMA + Chandra surprises:

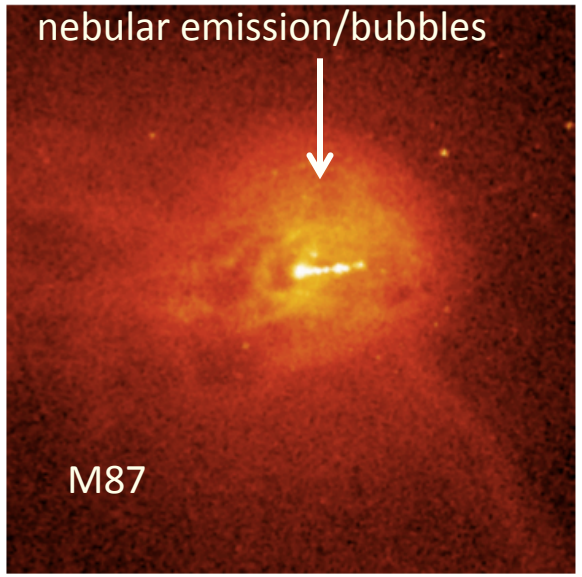
Uplift (circulation) in essentially all gas phases, molecules to plasma
slow gas (infall) velocities indicate terminal speed governs thermal instability

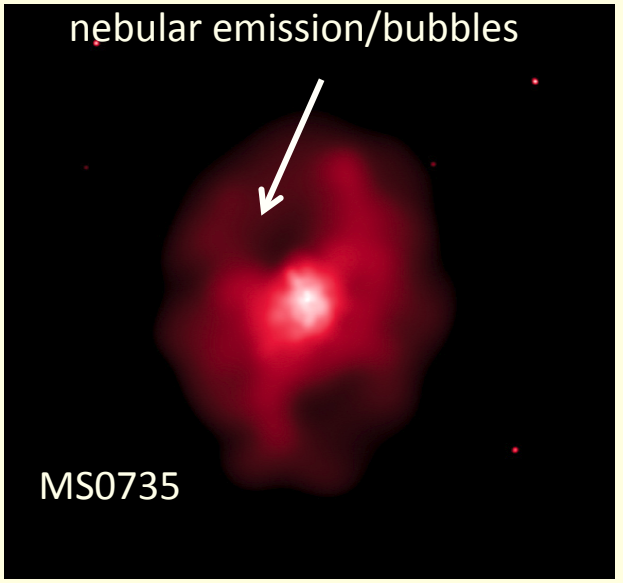
McN+16, 14, Russell+16, Kirkpatrick + 15
Simionescu +08, … others

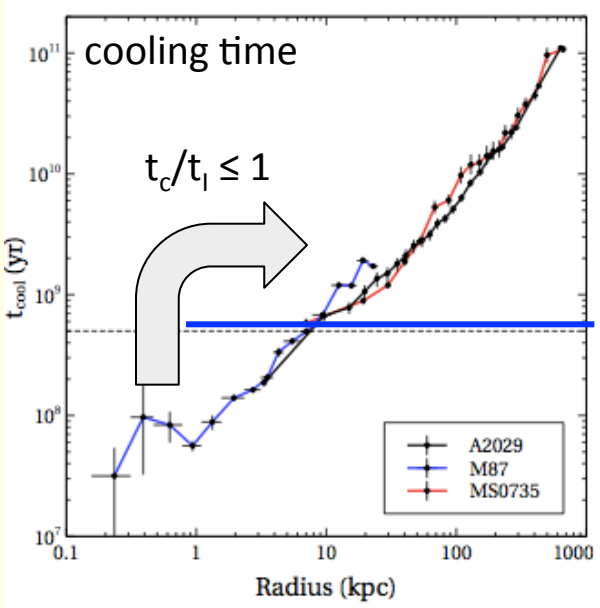
see Li & Bryan 14: uplift important in feedback simulation

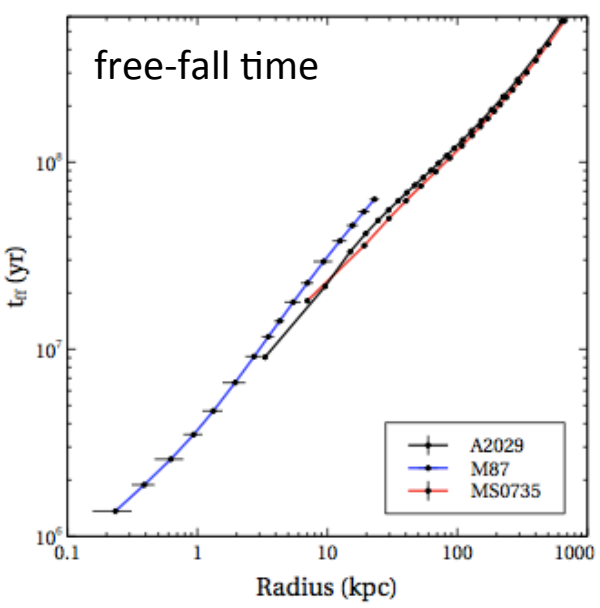
Stimulated Feedback: $t_c/t_l < 1$ requires AGN to lift gas

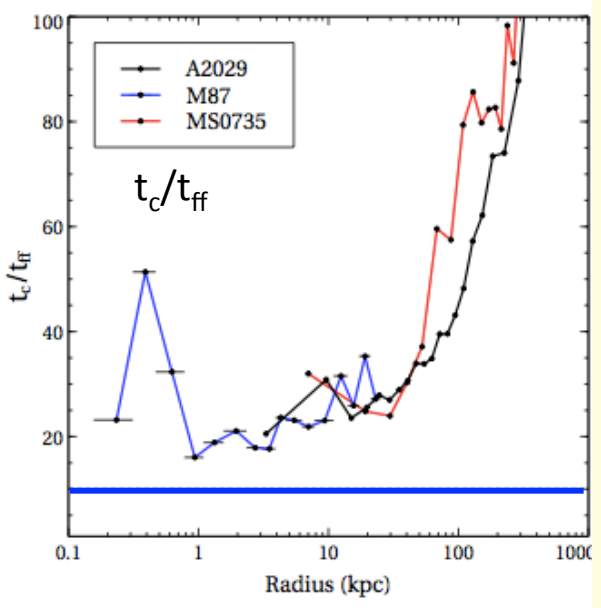
McN + 16





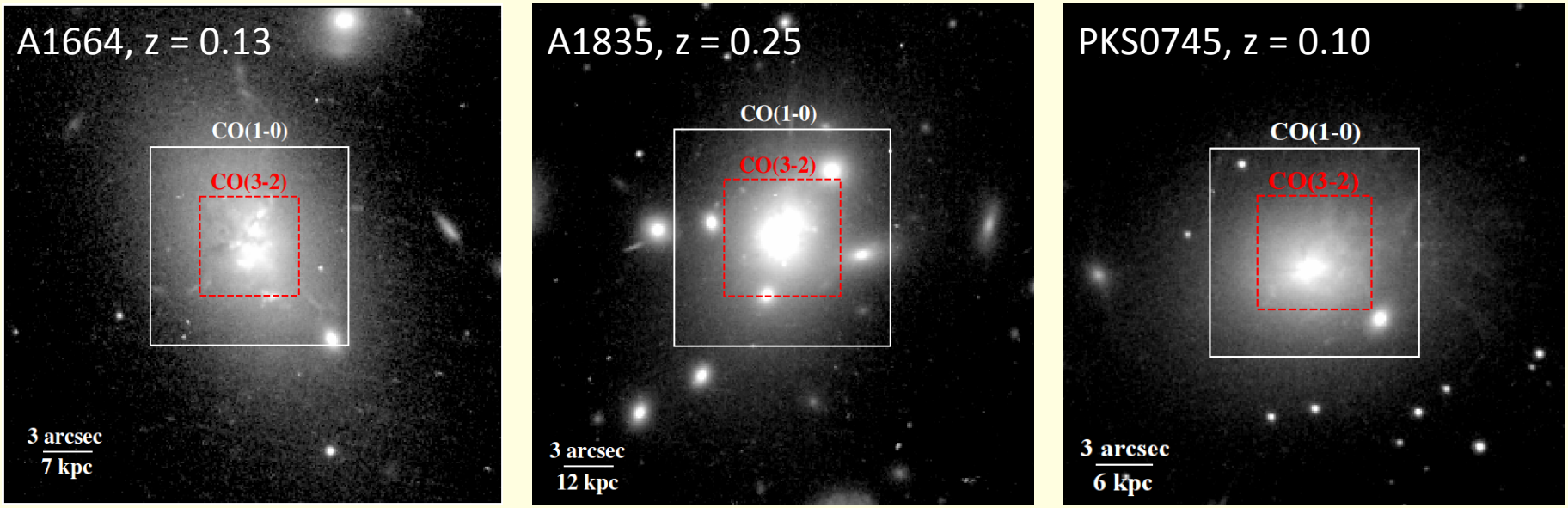






ALMA (Early) Science observations of ~15+ central galaxies

- radiative cooling times < 0.5 Gyr
- single dish observations: molecular gas > 10^9 $M_\odot$
- Mergers unlikely – gas cooling from X-ray atmosphere

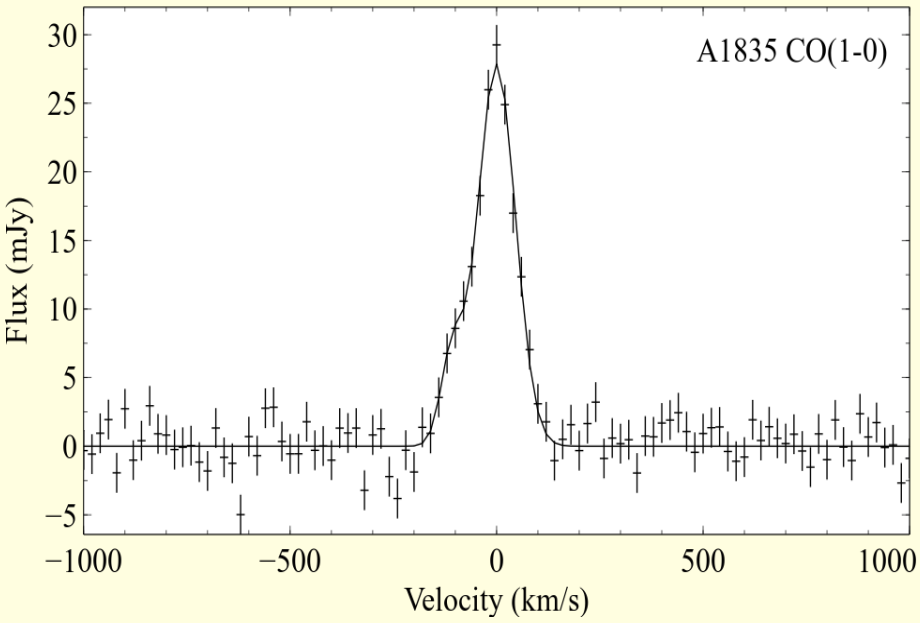


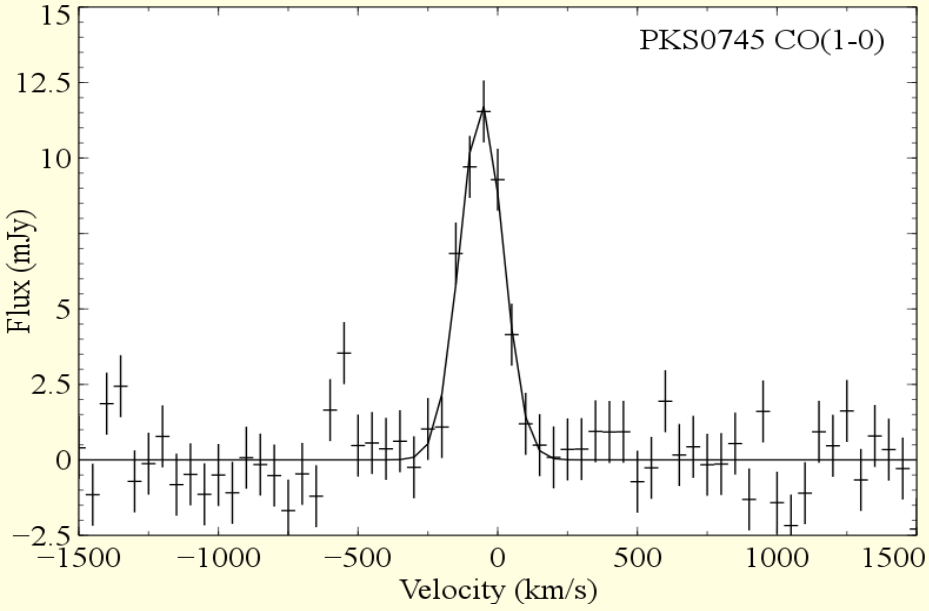
HST data: O'Dea et al. 2010

ALMA Cycles 0-4: McNamara+ '14, Russell+ '14, 16a, b, David+ '14, Tremblay + 16, Vantyghem + 16

ALMA CO (1-0) spectra: narrow lines

- Narrow molecular emission lines
  - << stellar velocity dispersion ~300 km/s
  - Gas not settled in gravitational well
  - little evidence for disks





A1835: $M(H_2) = 5 \times 10^{10}\ M_\odot$
fwhm = 120 km/s

PKS0745: $M(H_2) = 5 \times 10^{9}\ M_\odot$
fwhm = 180 km/s

PKS0745: molecular gas in 3-5 kpc filaments, narrow velocity widths

how have filaments survived?

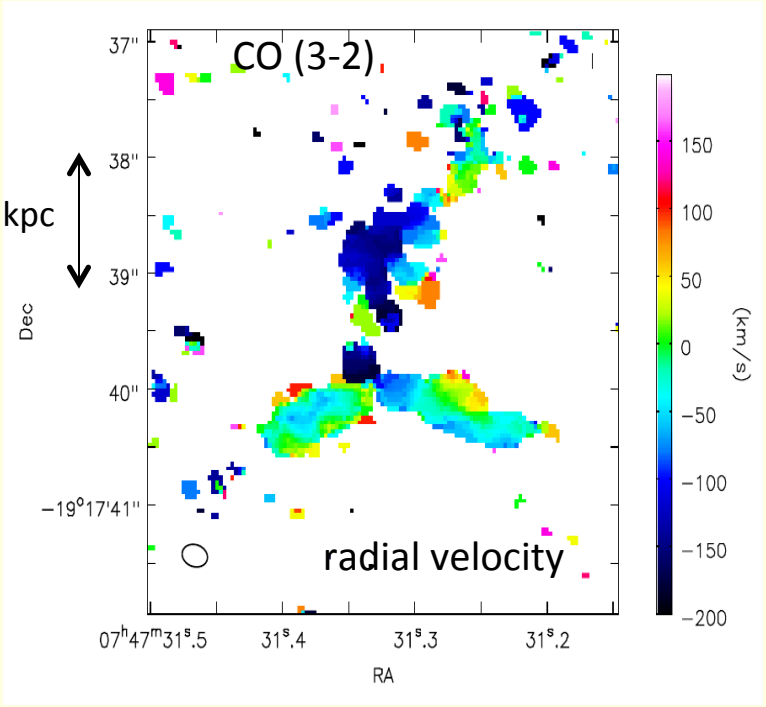
- Modest radial velocities 100 km s^{-1}
- Narrow CO emission lines ~30-50 km s^{-1}
- No disk!
- Low turbulence in hot atmosphere

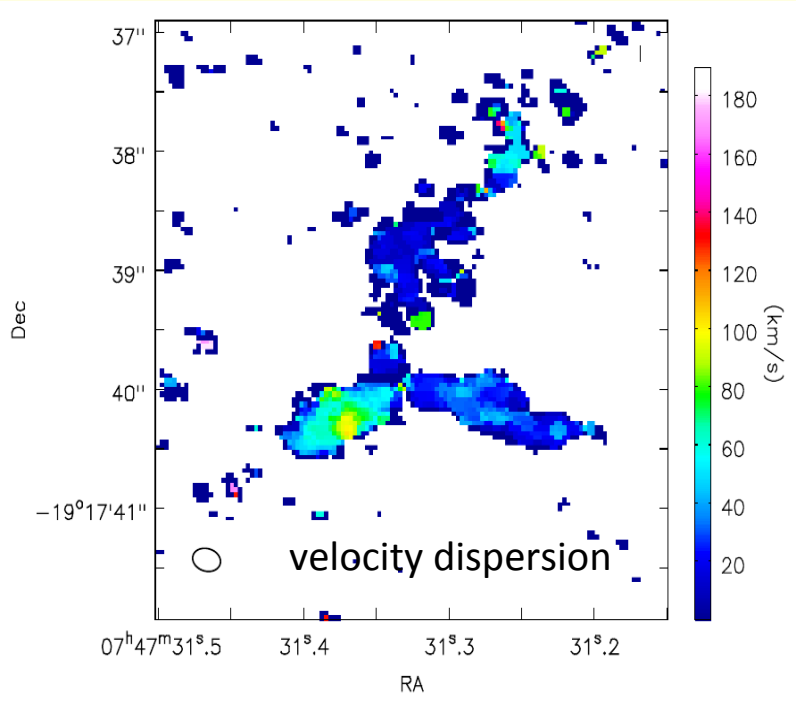
condensed rapidly: $t_c/t_{ff} << 1$

$t_{destruction} < t_{ff}$

pinned to the ICM?
transient condensations?

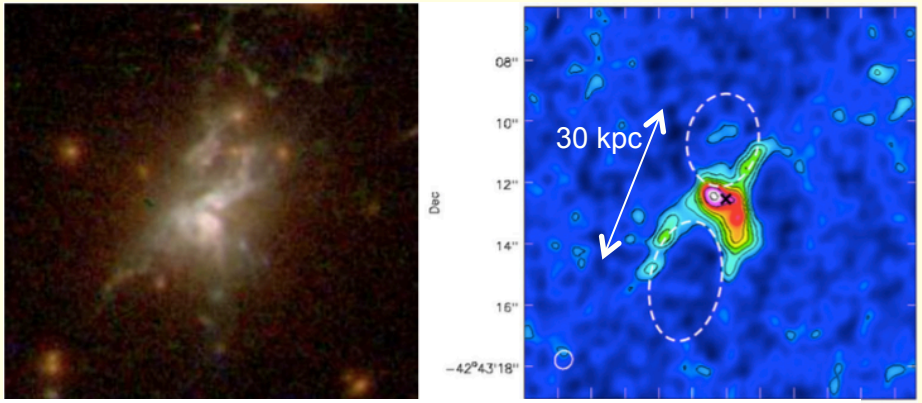
Russell + 15





beam: 0.3 arcsec, 0.5 kpc

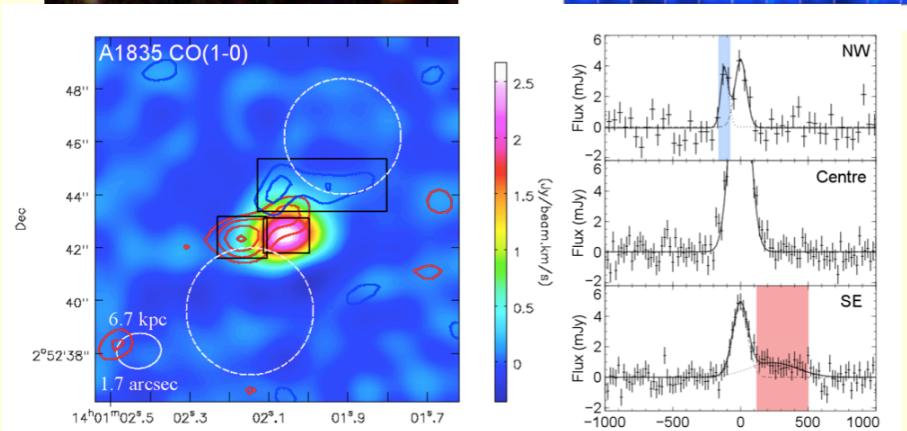
ALMA: uplifted molecular gas and hot gas cooling, circulating



Phoenix

$M_{H2} = 2.7 \times 10^{10} M_\odot$

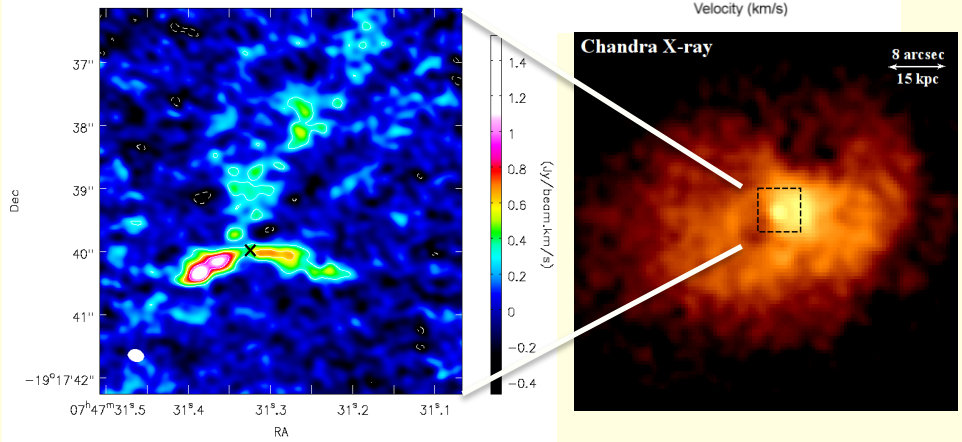
Russell + 16



Abell 1835

$M_{H2} = 5 \times 10^{10} M_\odot$

McN + 14

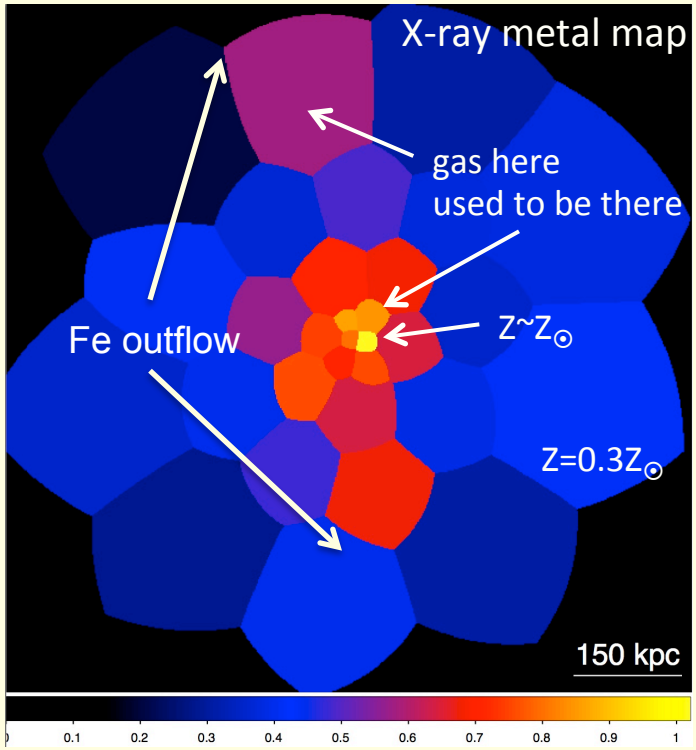


PKS 0745-191

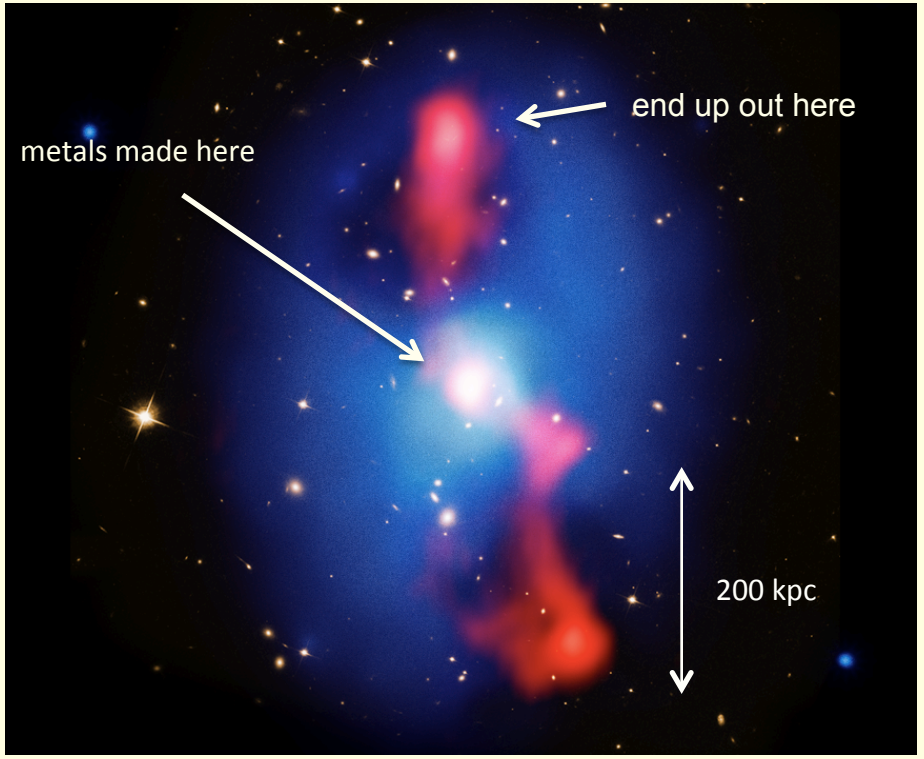
$M_{H2} = 5 \times 10^{9} M_\odot$

Russell + 16

Uplifted Hot Gas



R_{Fe}~300 kpc



McN+09, 12
Vantyghem + 14

X-ray, VLA, HST

Powerful thrust:

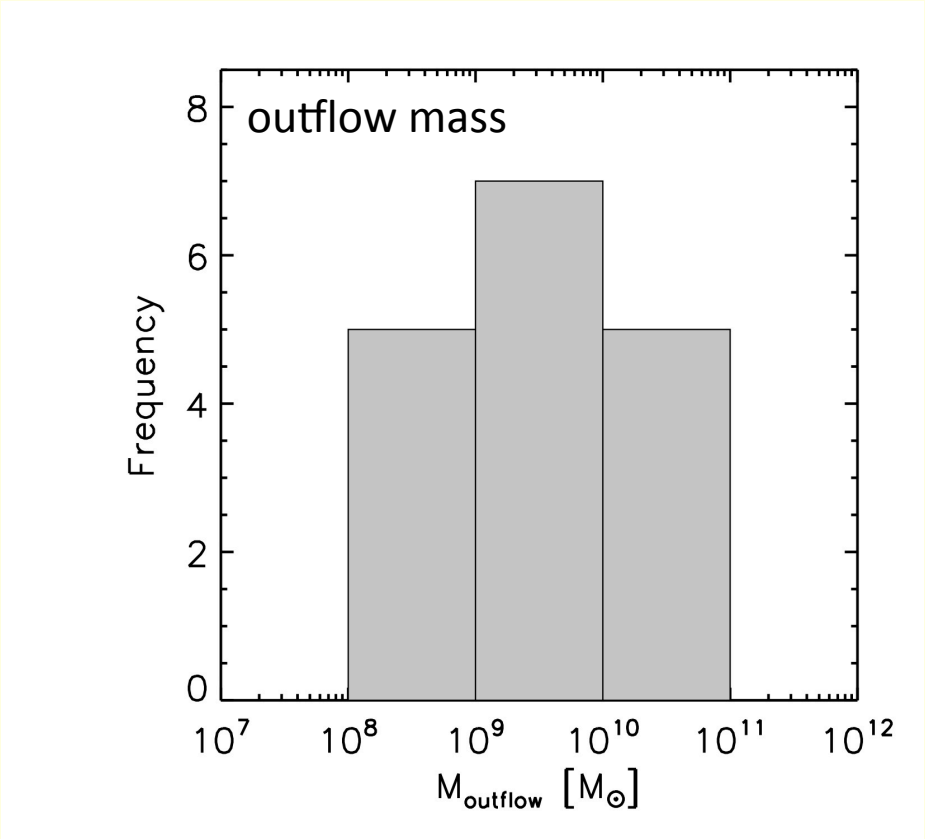
P_{jet}~ 3×10^{46} erg s^{-1}

E_{jet} ~ 10^{62} erg

Lifted/displaced mass ~ 10^{10} $M_\odot$ ~100 $M_\odot yr^{-1}$

See also Simionescu + 08, Kirkpatrick 09,11,14

Hot outflows promote cooling & star formation?



- Outflow rates several to a few hundred solar masses per year
- A few to a few tens of % of the cooling gas is re-circulated
- Outflow mass <u>consistent with molecular gas masses</u>

Kirkpatrick & McNamara 15

Summary

Uplift ubiquitous, important

Precipitation models, $t_c/t_{ff} < 10$ inconsistent with observation

$t_c/t_{ff} < 1$ achieved by lifting low entropy gas to higher altitudes
stimulated feedback

Low molecular cloud velocities observed in many systems
pinned to hot gas? (c.f., Hitomi Perseus result)

TI criterion: $t_c/t_l \leq 1$,
infall time bounded by free-fall and terminal speeds

Stimulated feedback conjecture – must be tested
must recover cooling time thresholds