AGN Feedback in Nearby Clusters

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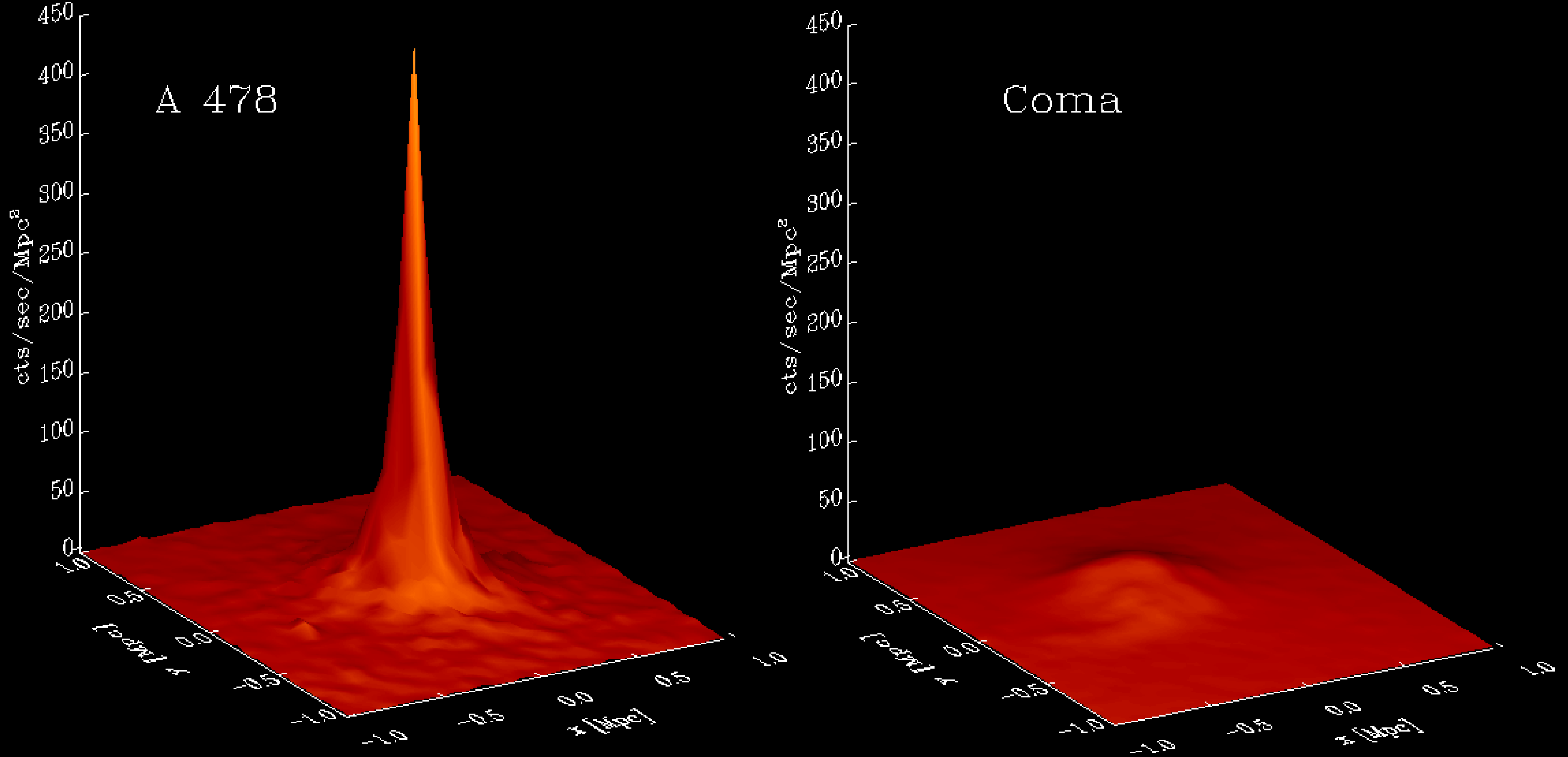
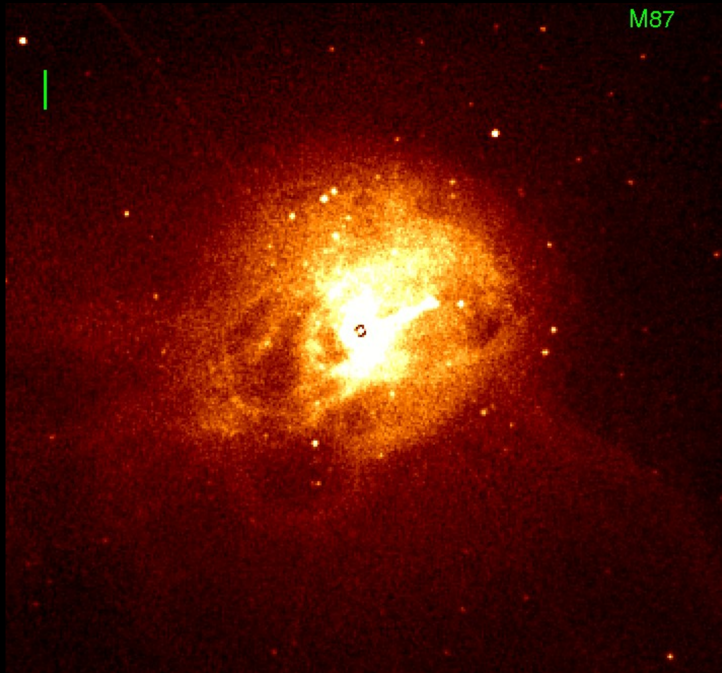
With much help from Jeremy Sanders, Gary Ferland and many others

AGN Feedback in Nearby Clusters

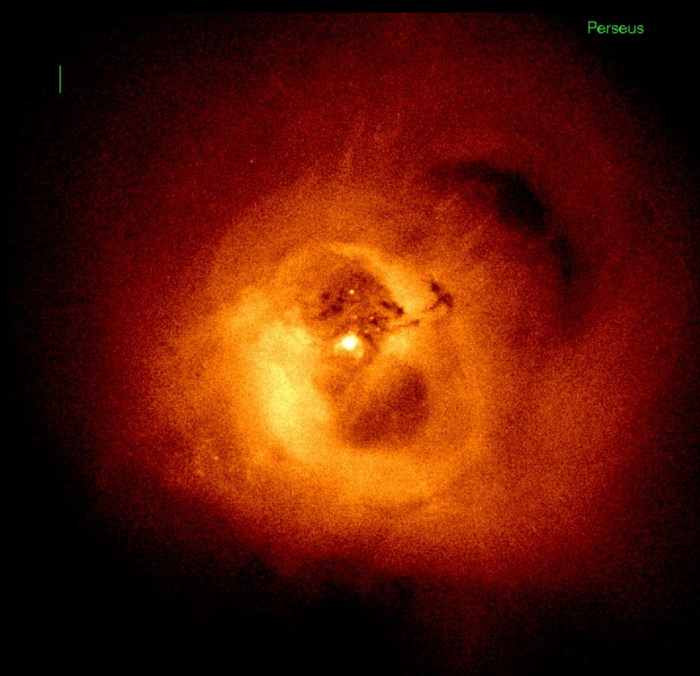
Feedback in the central galaxies of the Perseus and Centaurus

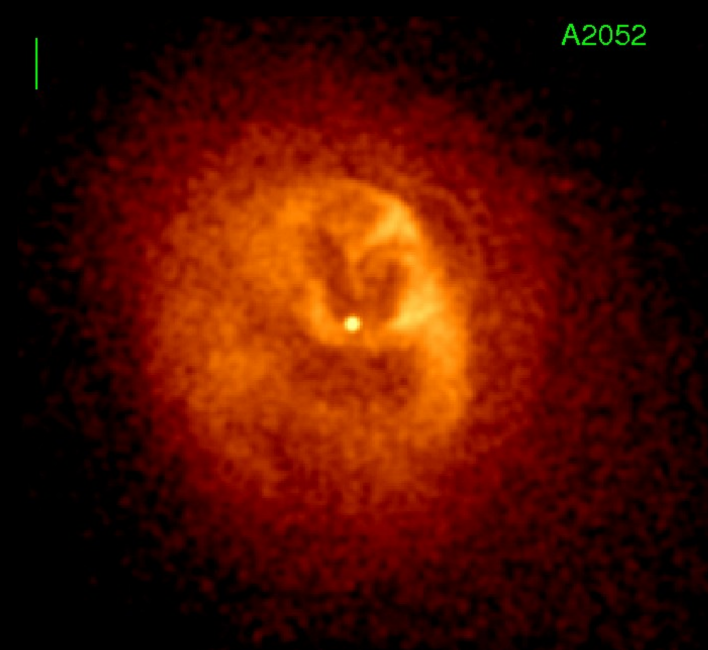
X-ray surface brightness of typical clusters of galaxies



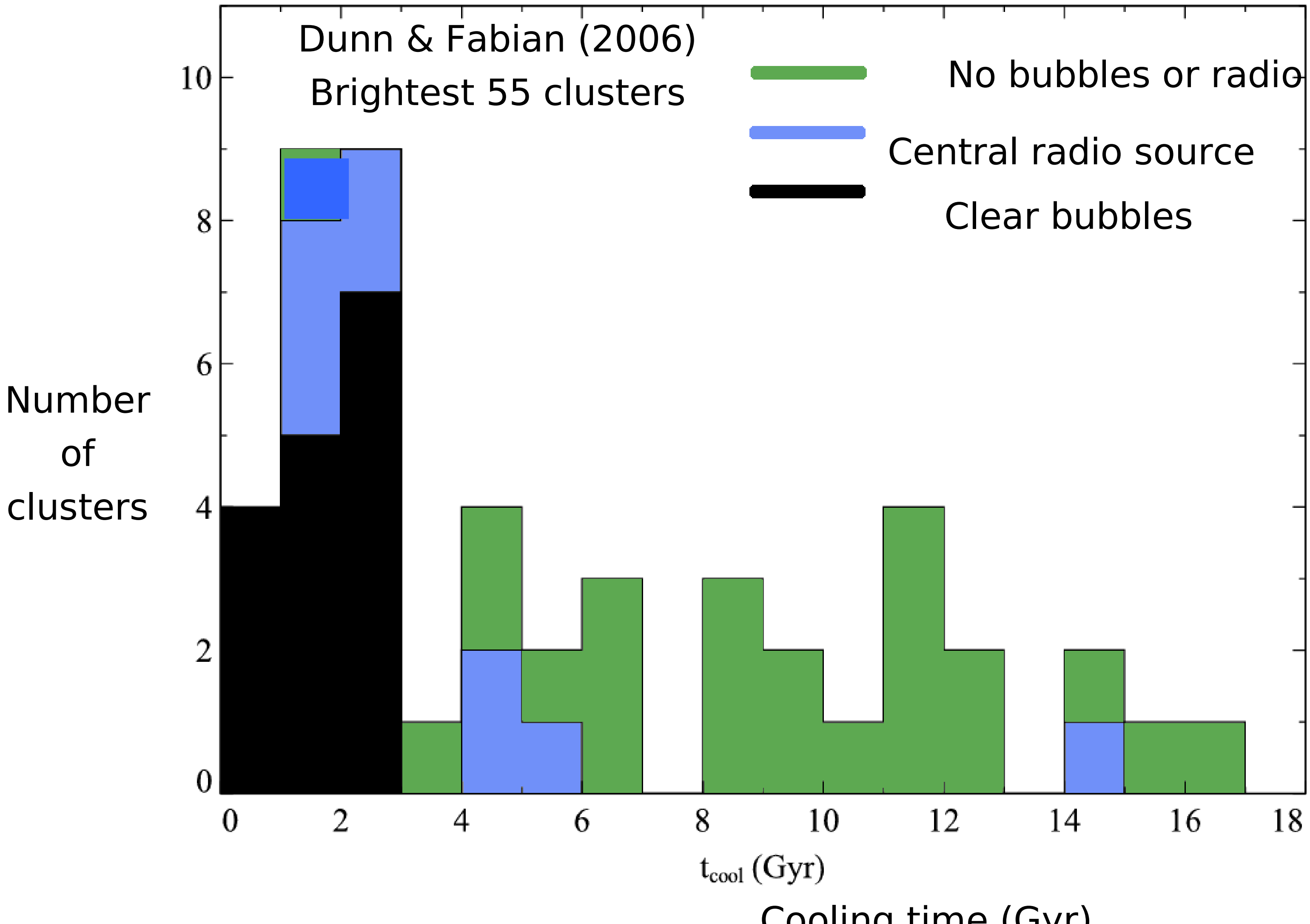

M87


Centaurus

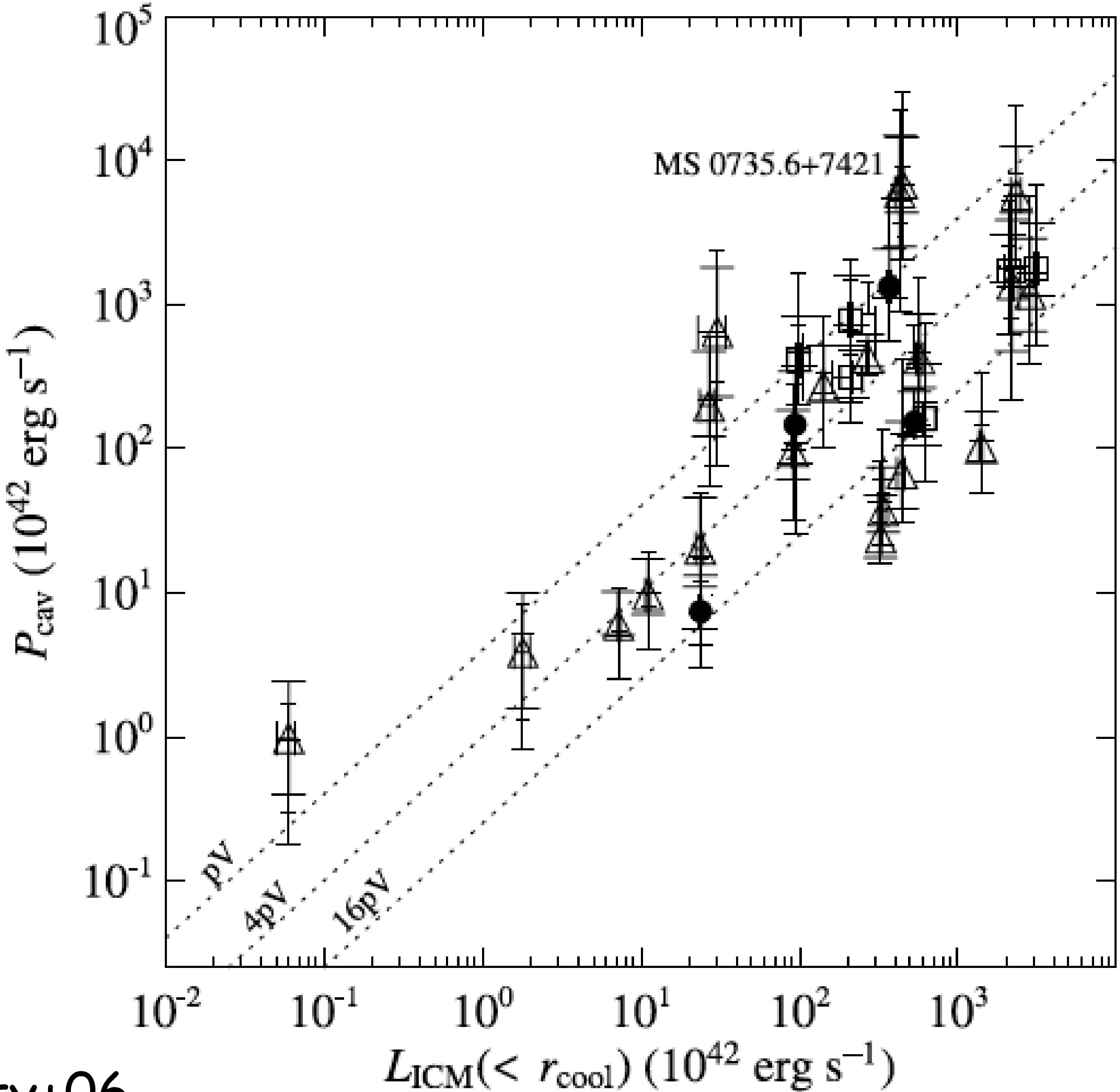

Perseus


A2052

Duty cycle is ~100%



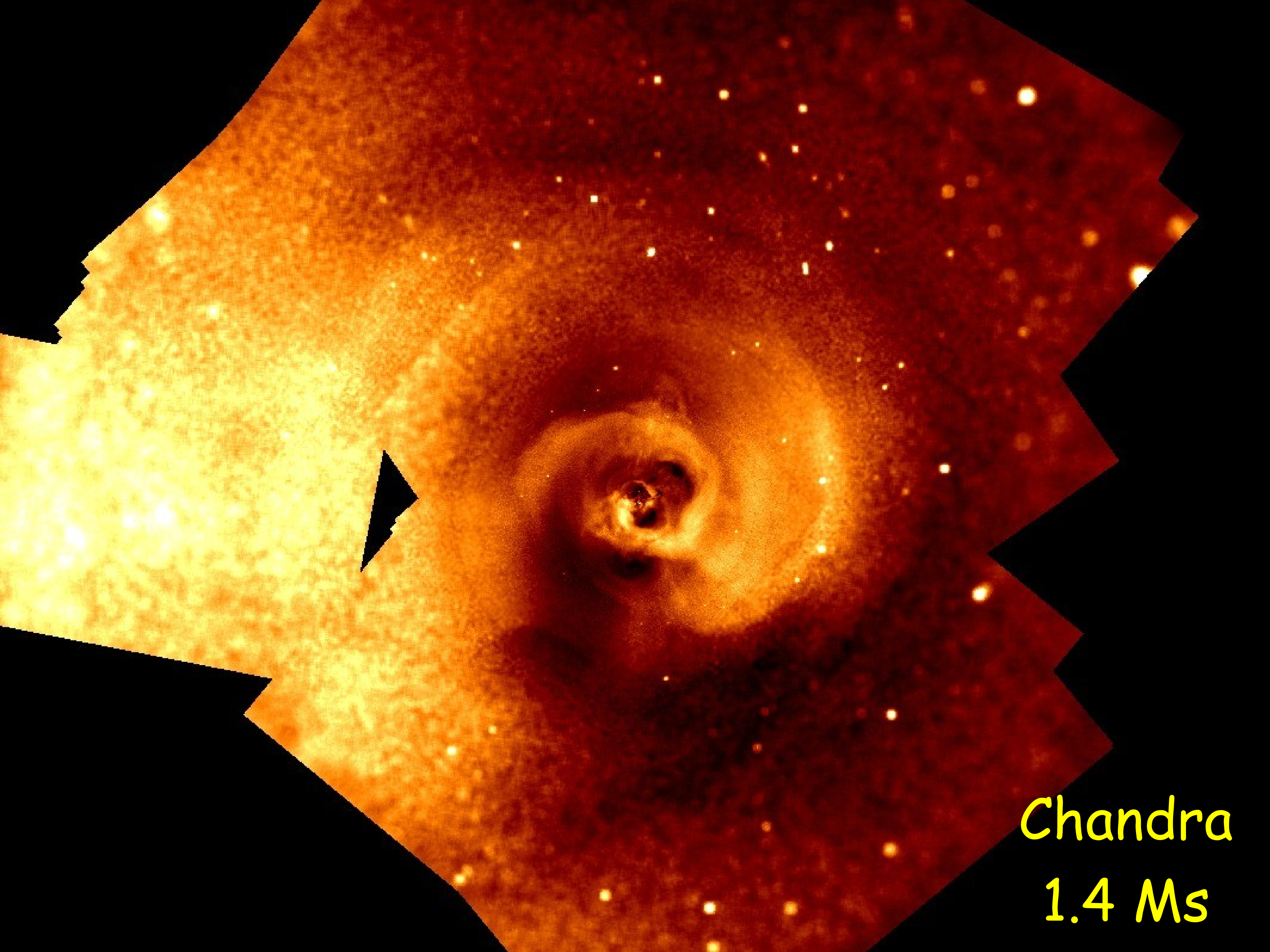
See also Birzan+04, Rafferty+06+08, Dunn+F07


MS 0735.6+7421
pV
4pV
16pV
P_{cav} (10^{42} erg s^{-1})
$L_{ICM}(< r_{cool})$ (10^{42} erg s^{-1})
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

Rafferty+06

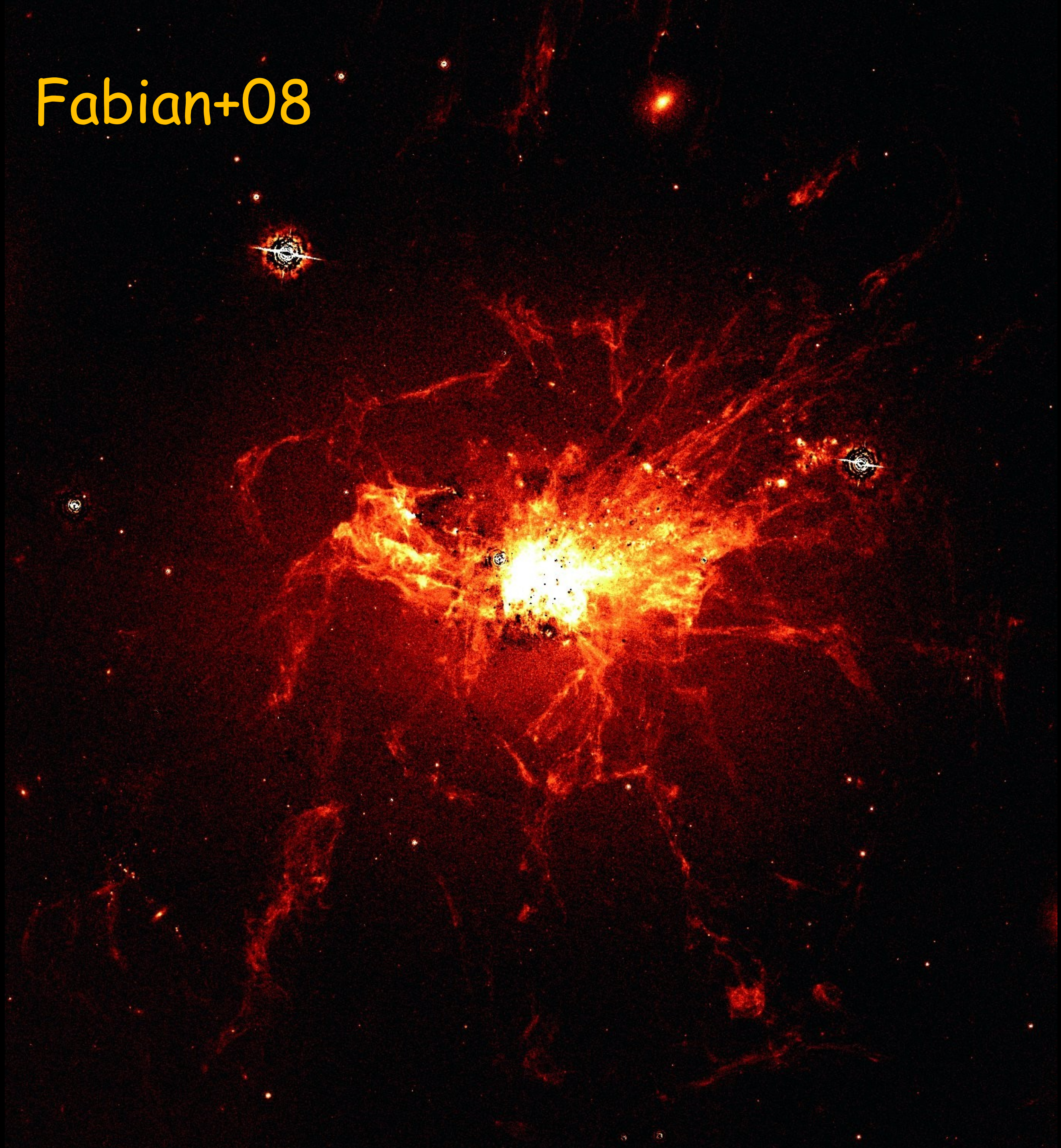
Issues

- Total Energy not an issue.
- How does energy get distributed?
- How close is the heating/cooling balance? Feedback too good?
- Observations suggest better than 10% for many Gyr in some objects.
- HOW DOES THE AGN DO THIS?
- Moreover, (how) is coolest X-ray gas (ie $T<5.10^6$K with radiative cooling time $\sim10^7$yr) prevented from cooling?

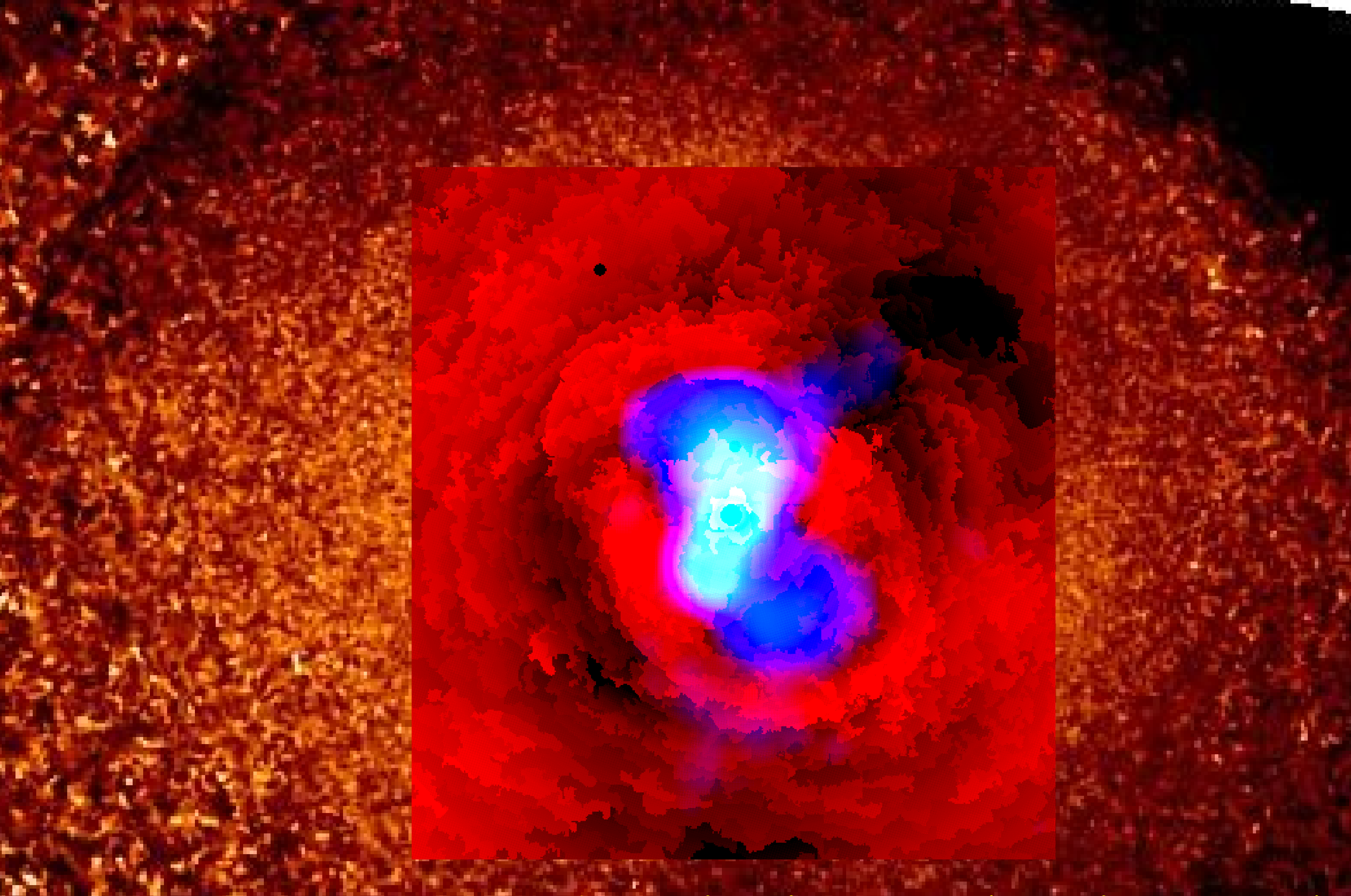

Chandra
1.4 Ms


R Jay Gabeny

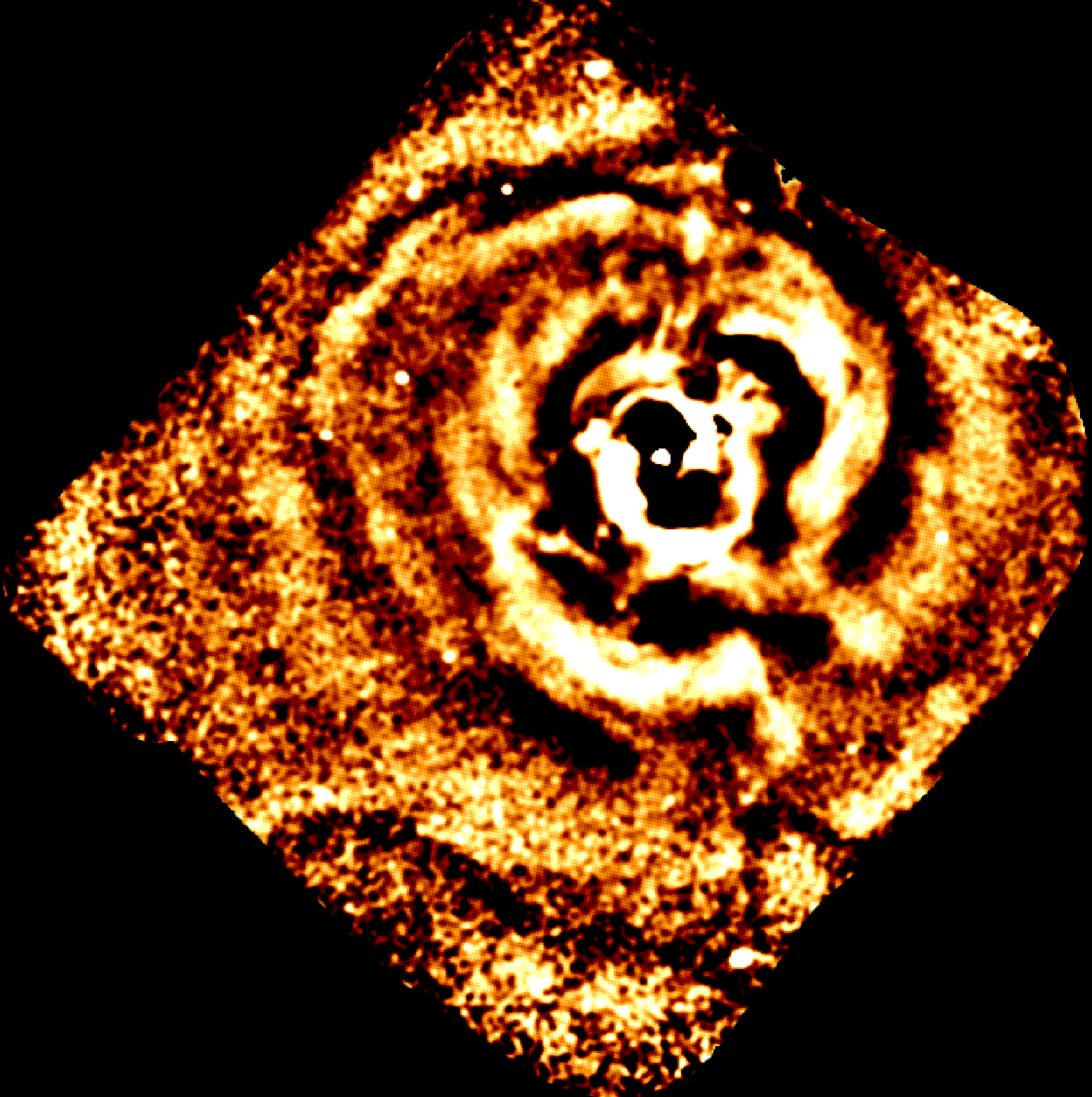
Optical Fabian+08

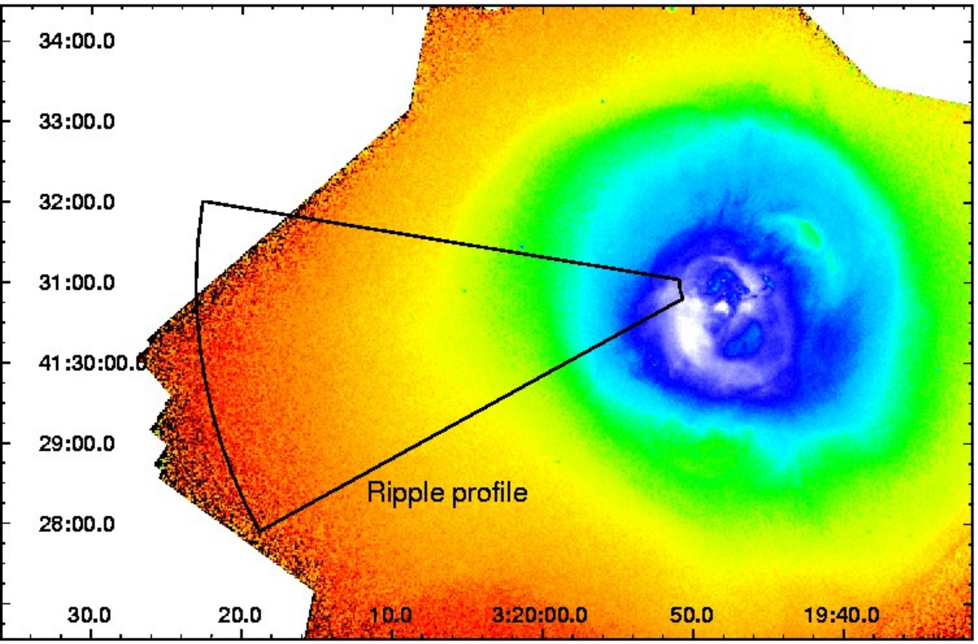


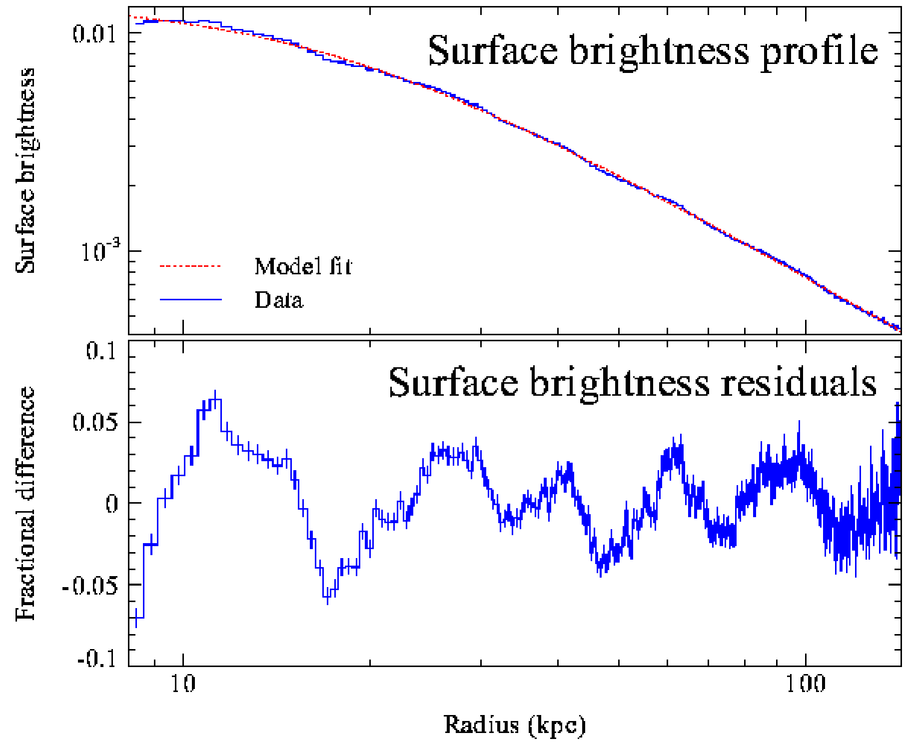

Perseus



~3.5PV measured in thick rims (Graham+08)

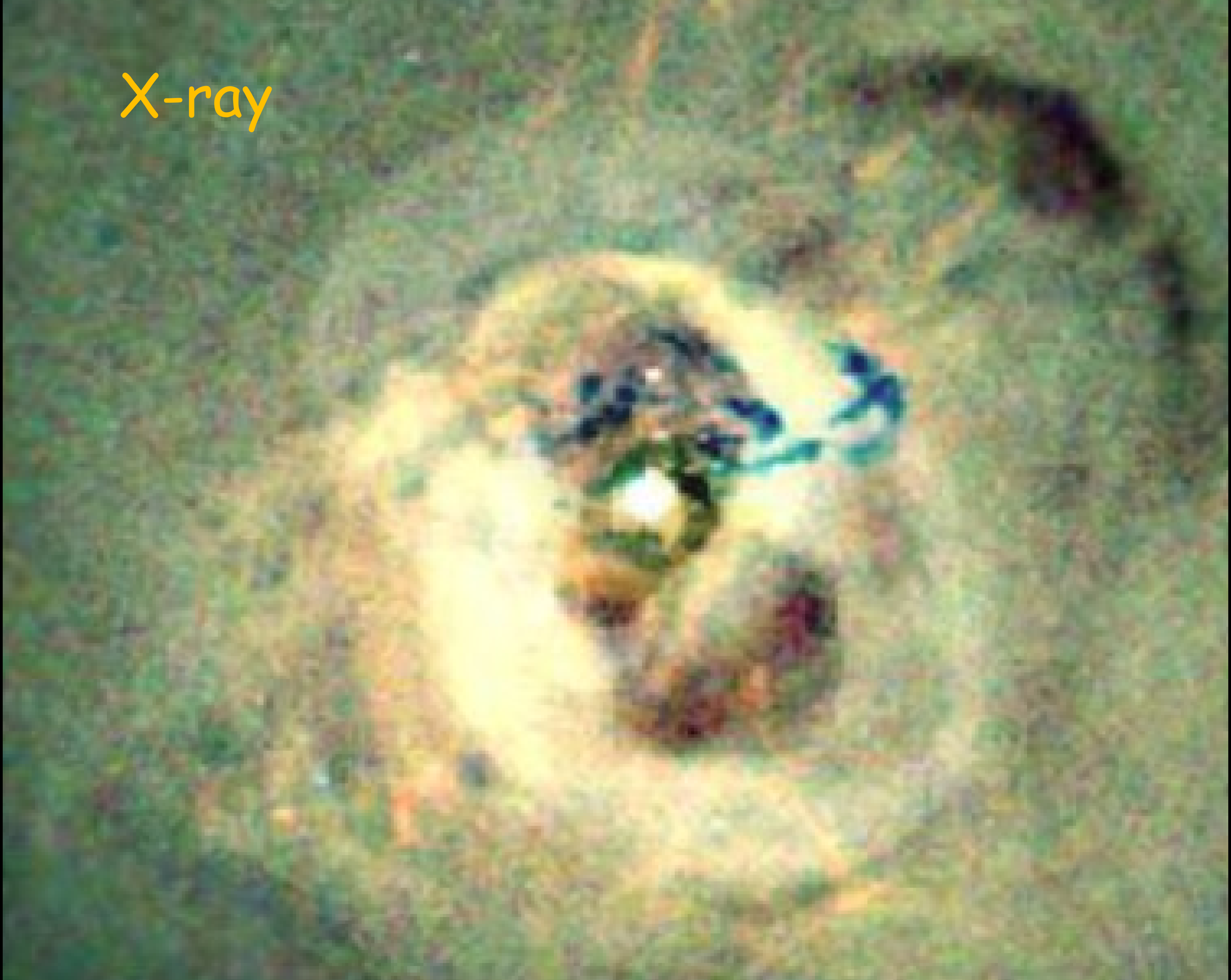


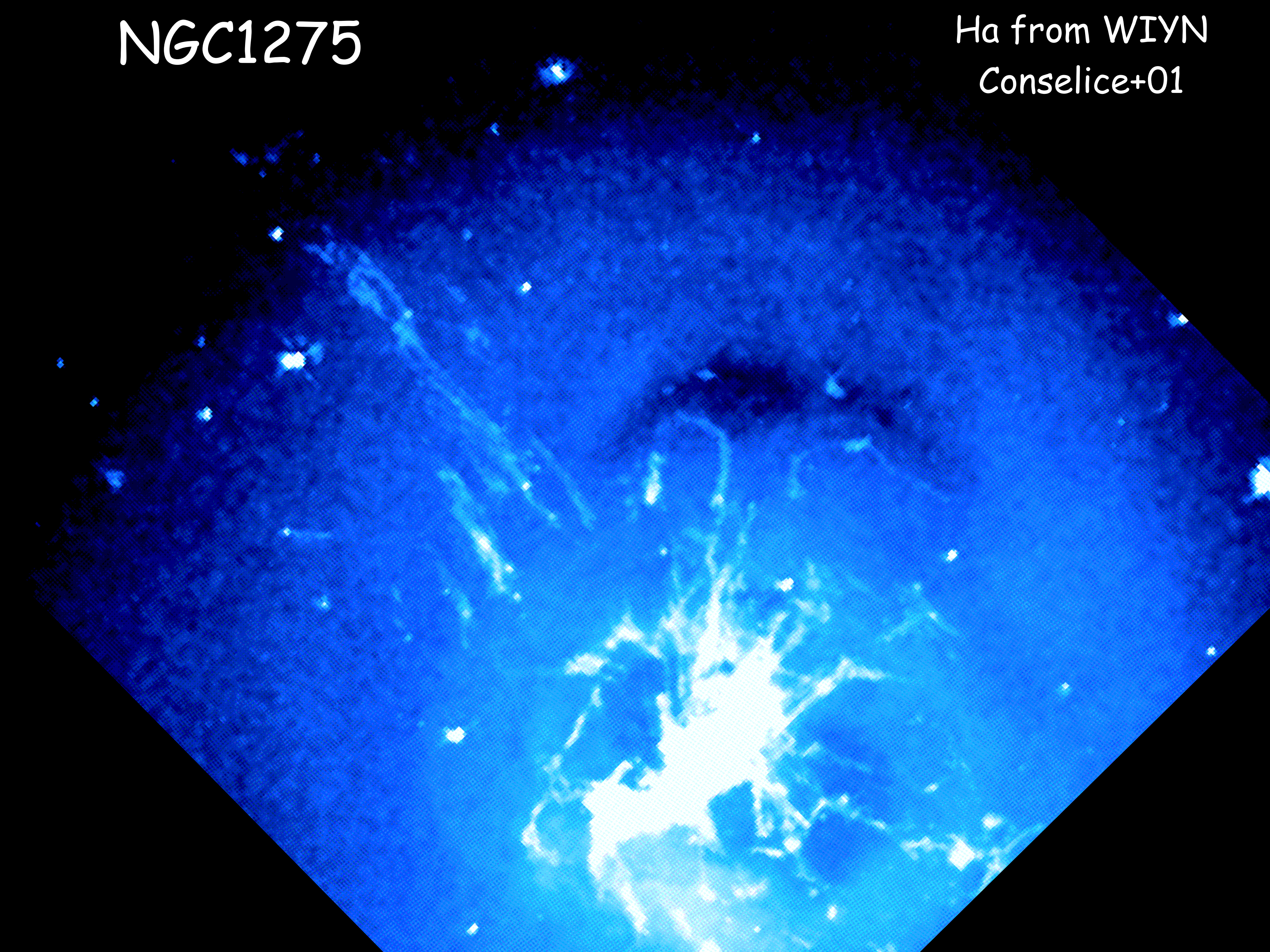


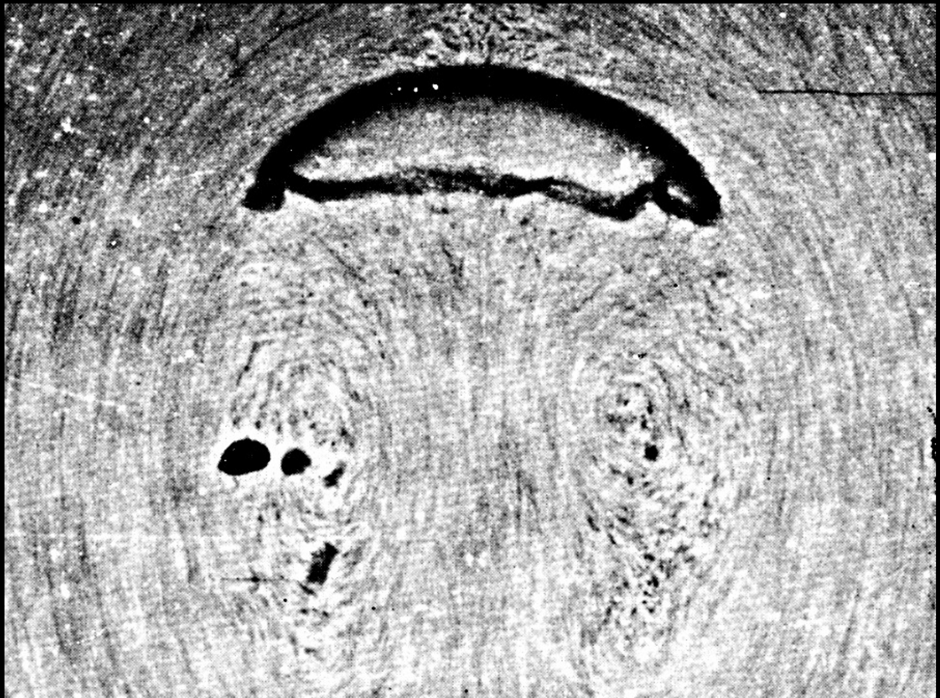


Power in ripples (sound waves) ~ X-ray luminosity within 70 kpc

Also seen in Centaurus, Virgo…

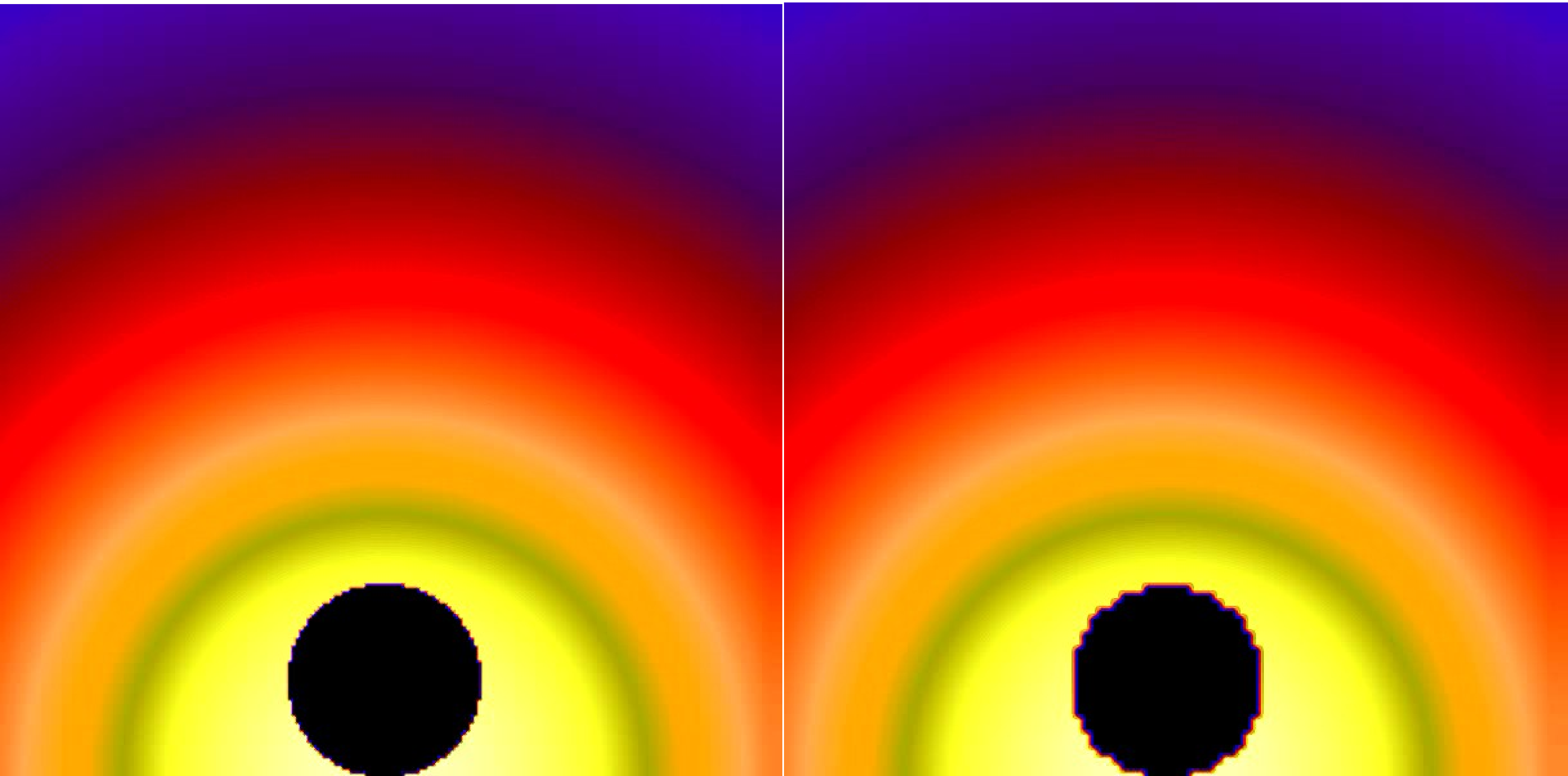

X-ray

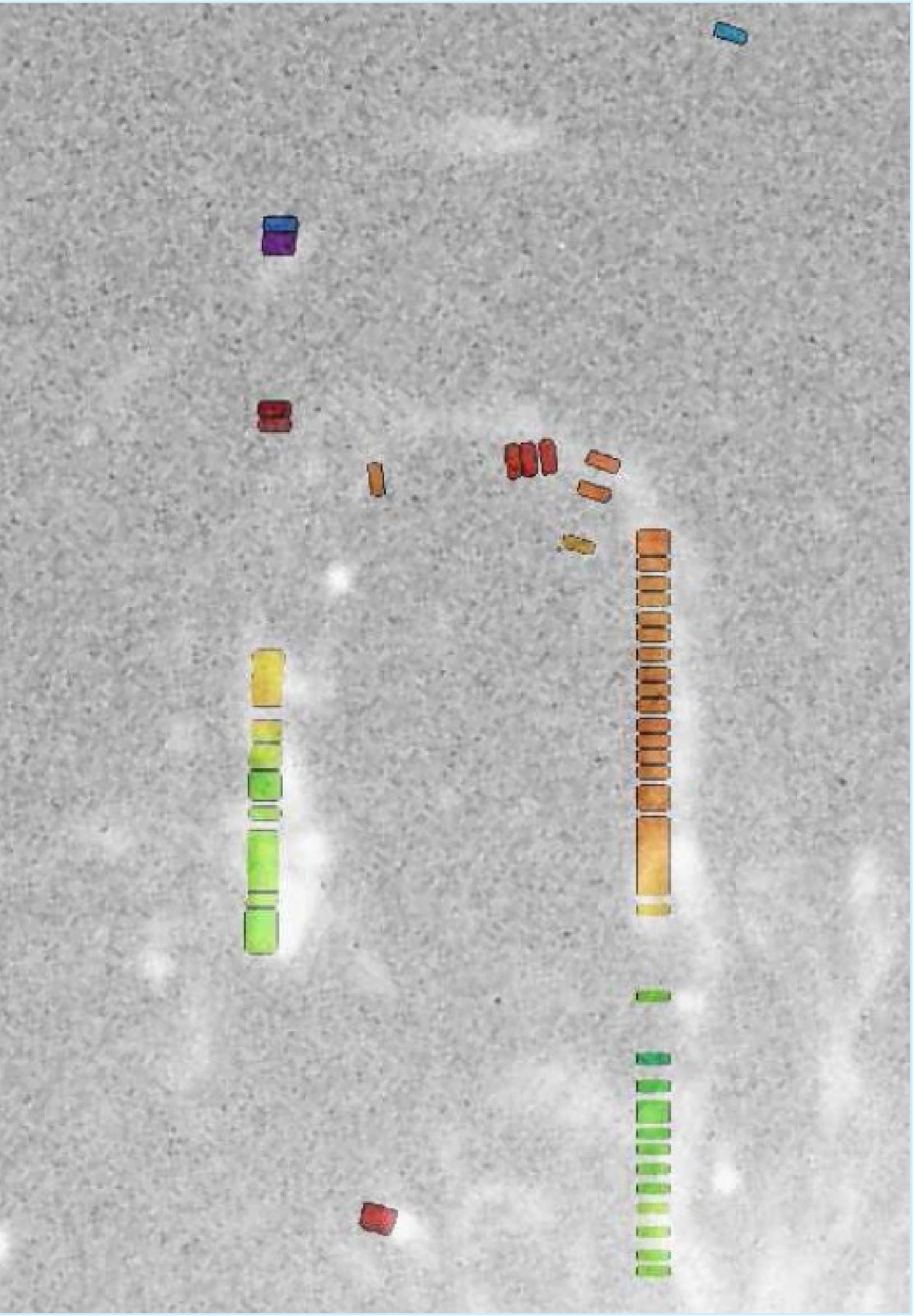

NGC1275
Ha from WIYN
Conselice+01

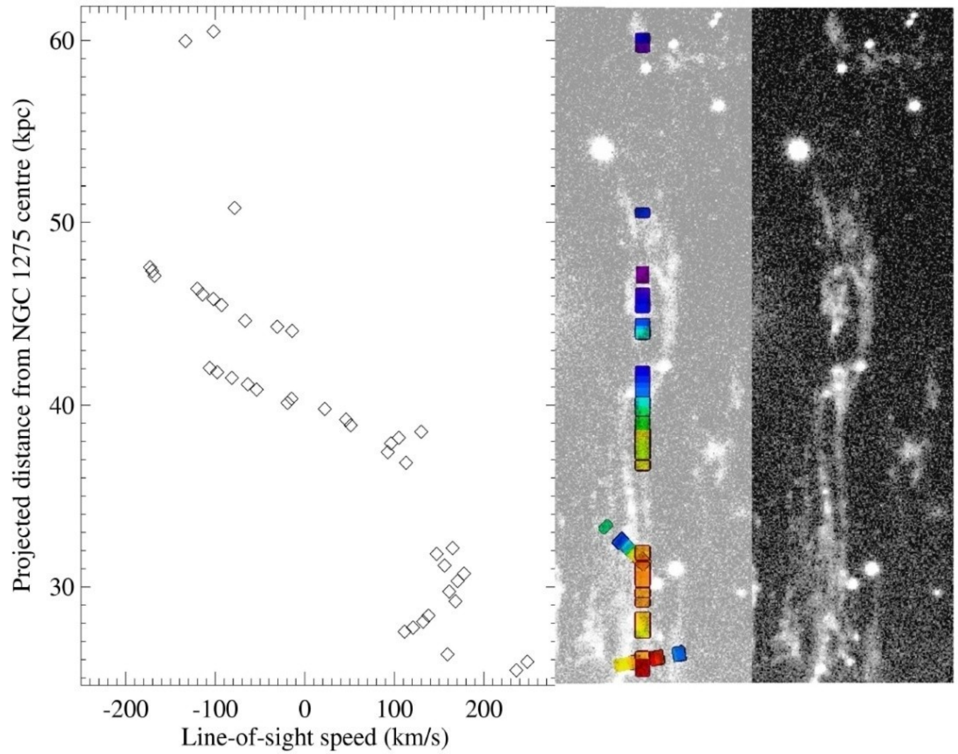
Buoyant radio lobes in a viscous intracluster medium

Christopher S. Reynolds,[1★] Barry McKernan,[1] Andrew C. Fabian,[2] James M. Stone[3] and John C. Vernaleo[1]





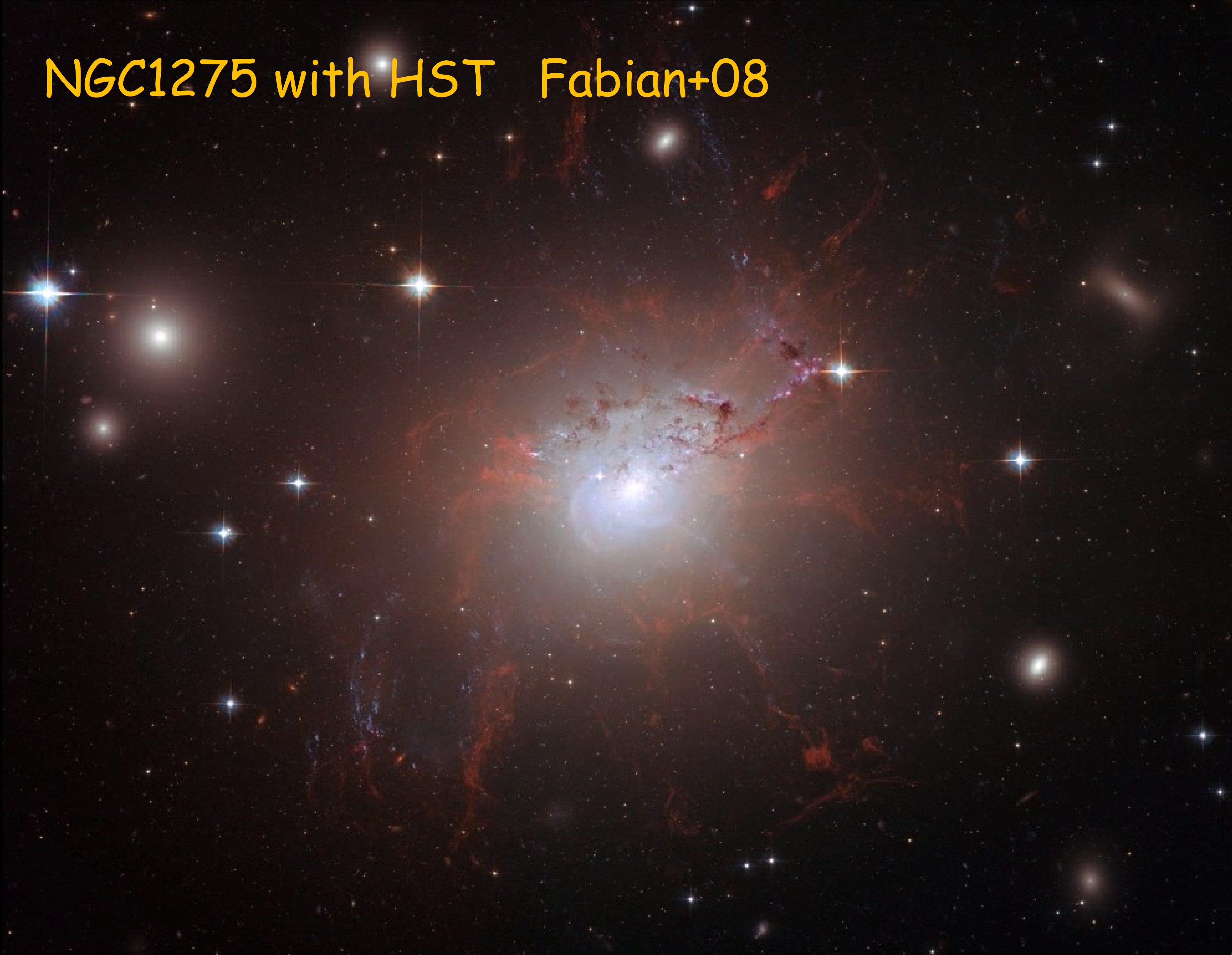
Hatch+06

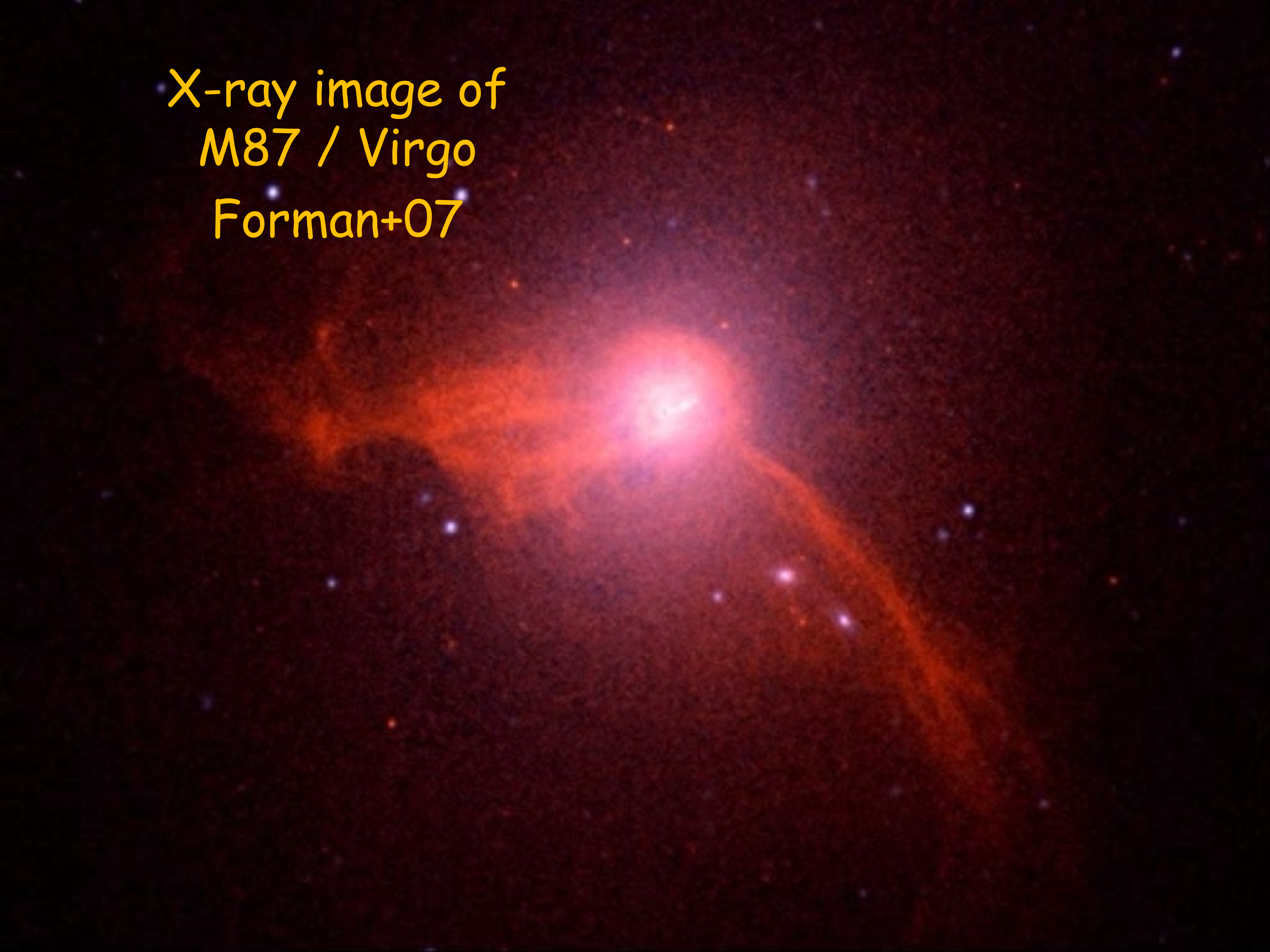


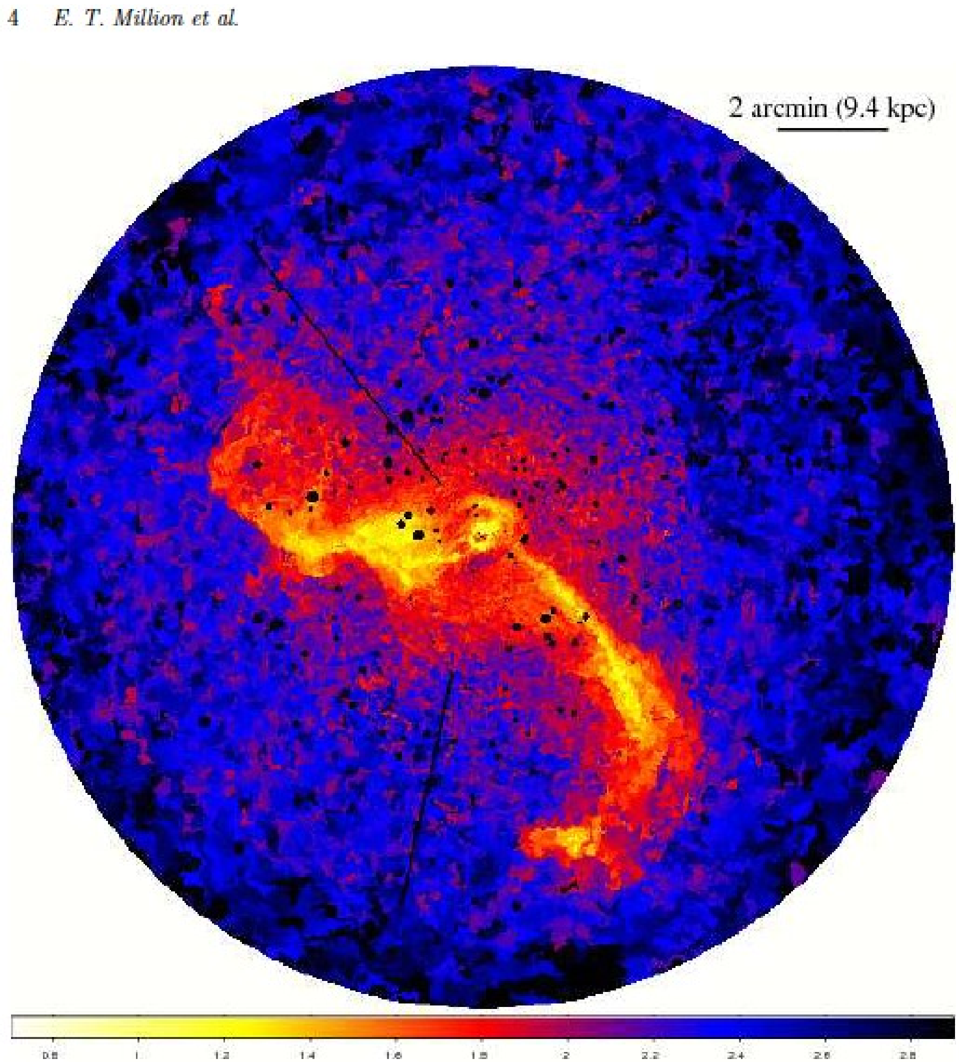
Projected distance from NGC 1275 centre (kpc)
Line-of-sight speed (km/s)
-200
-100
0
100
200
30
40
50
60


iss

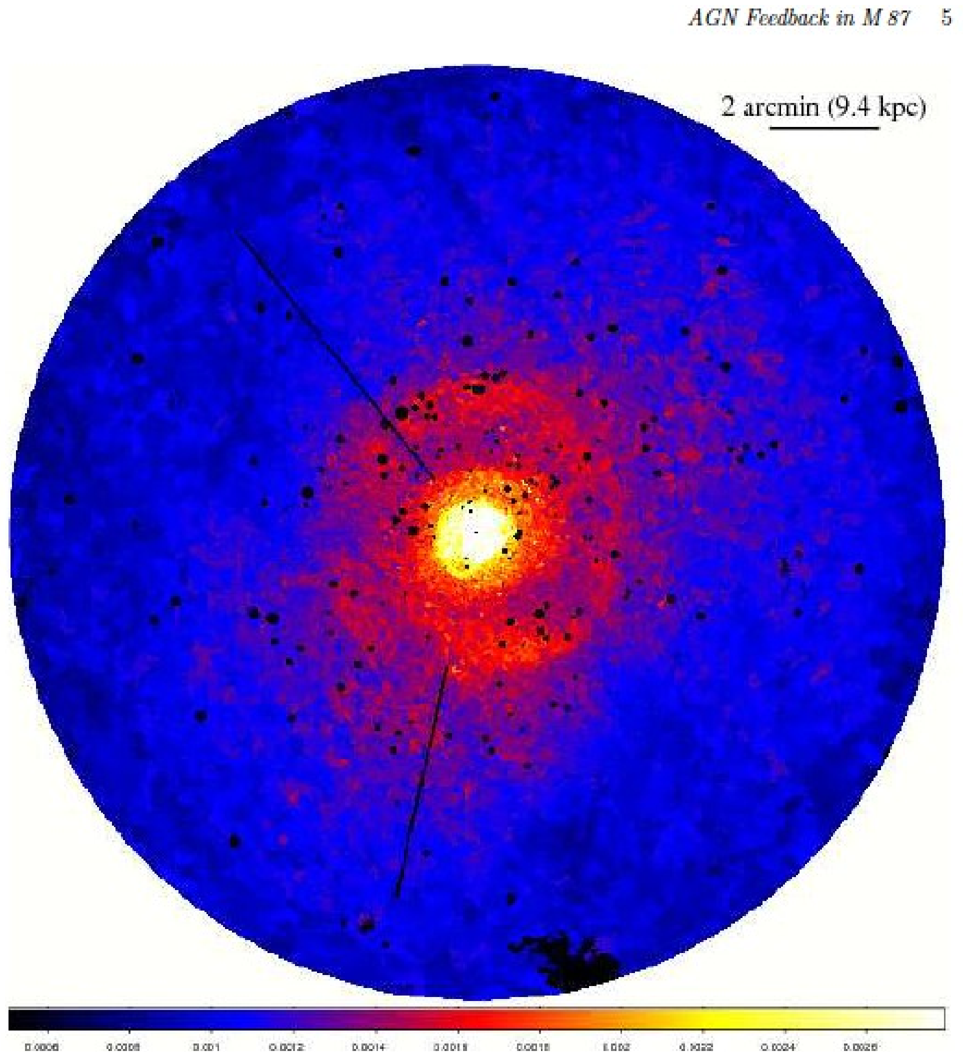
NGC1275 with HST   Fabian+08




X-ray image of
M87 / Virgo
Forman+07



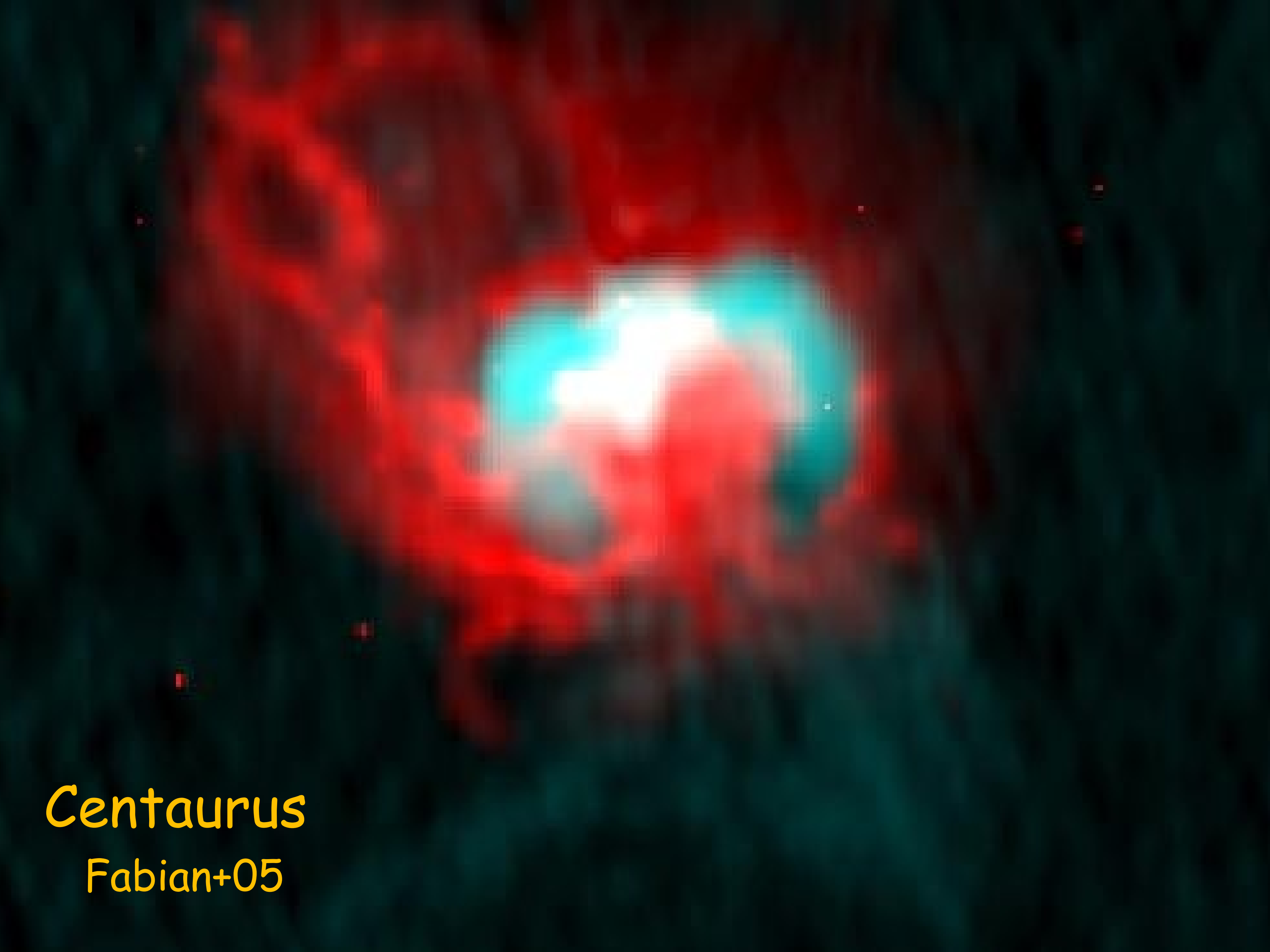
Temperature



Pressure

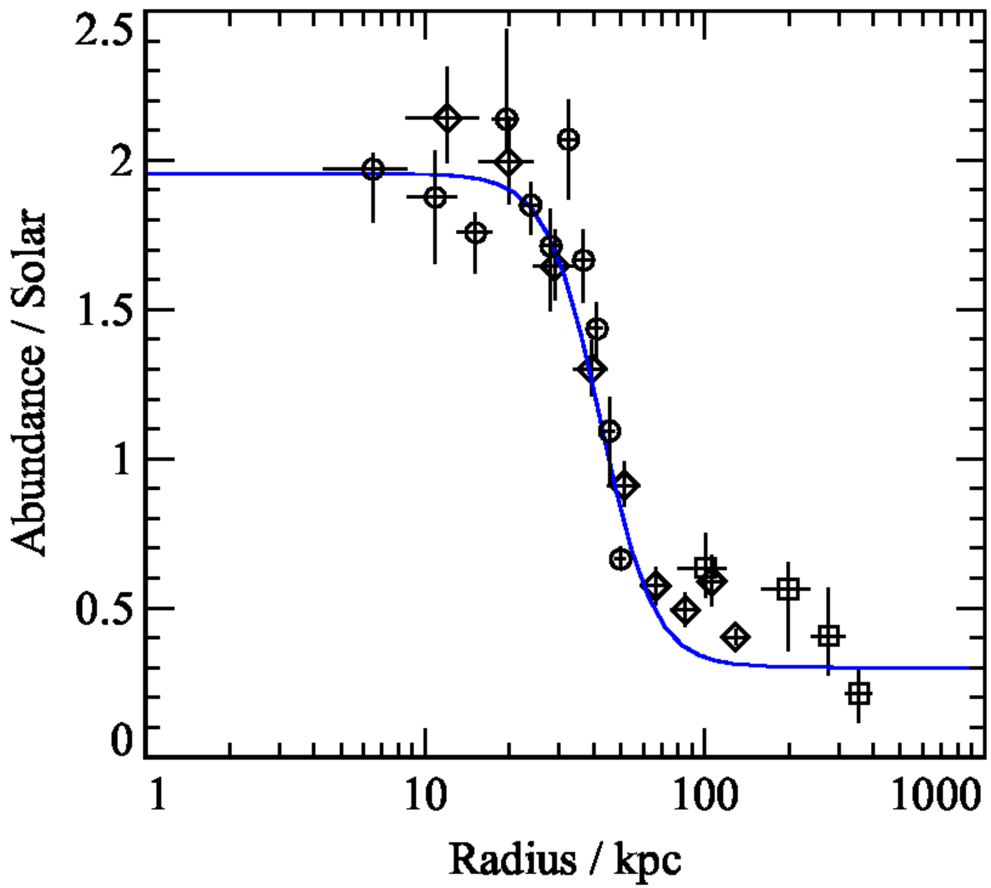

M84


Hydra A


Centaurus
Fabian+05

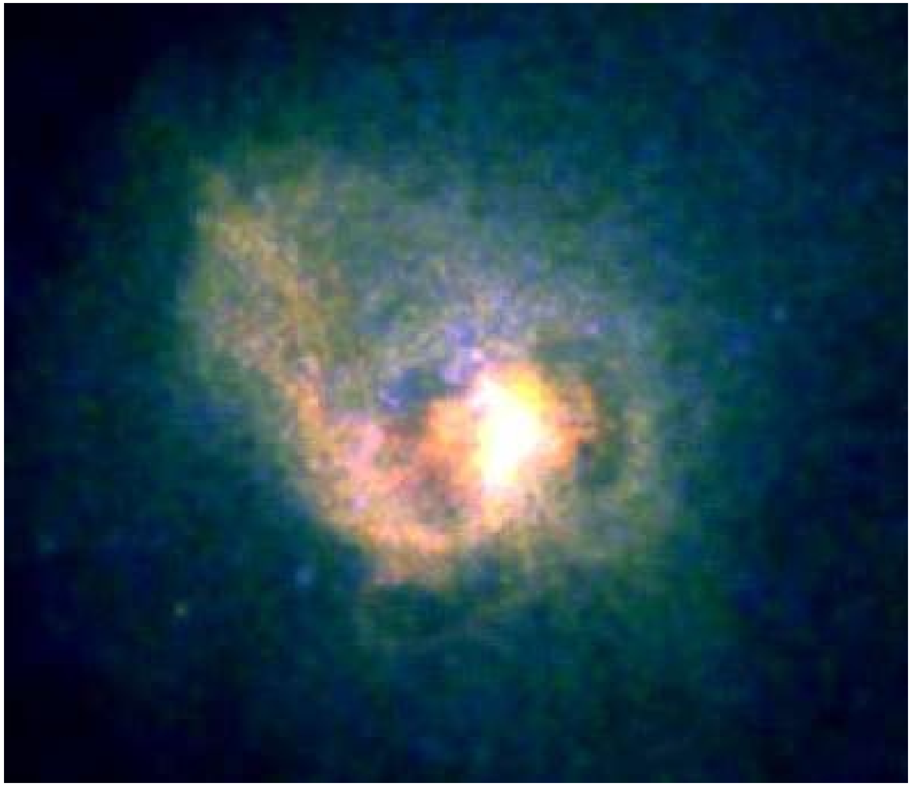
Cen cluster: Abundance profile implies little diffusion/mixing

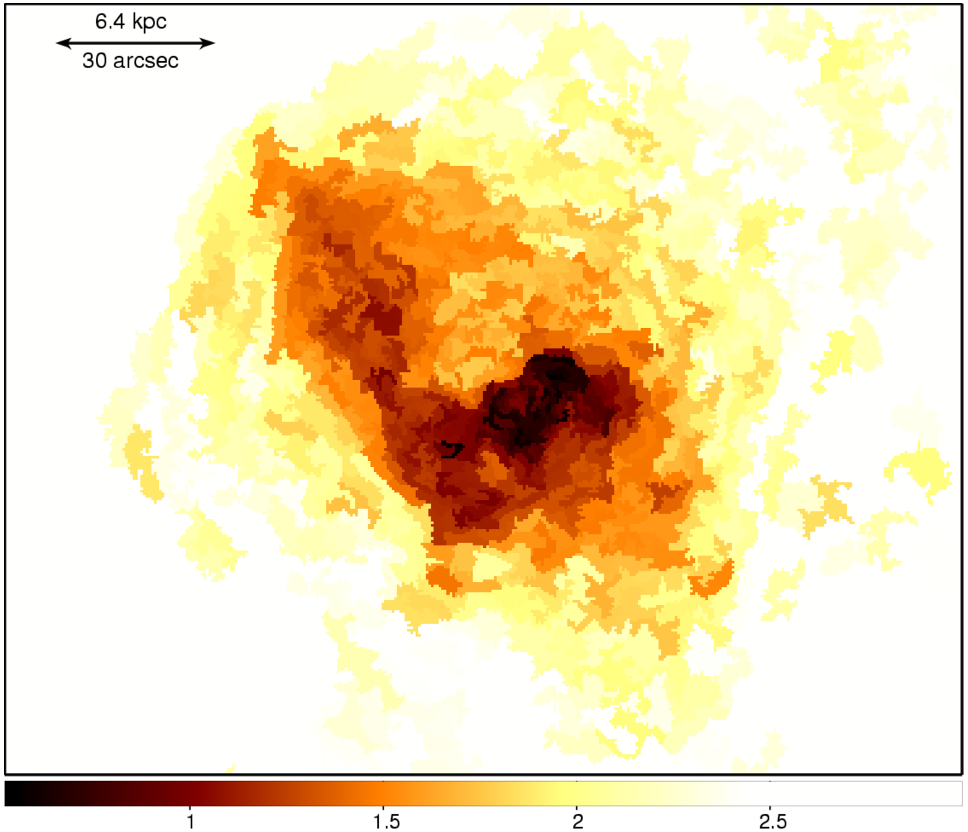
Graham+06 (following method of Rebusco+05)



Cool X-ray gas in Centaurus

200 ks Chandra observation

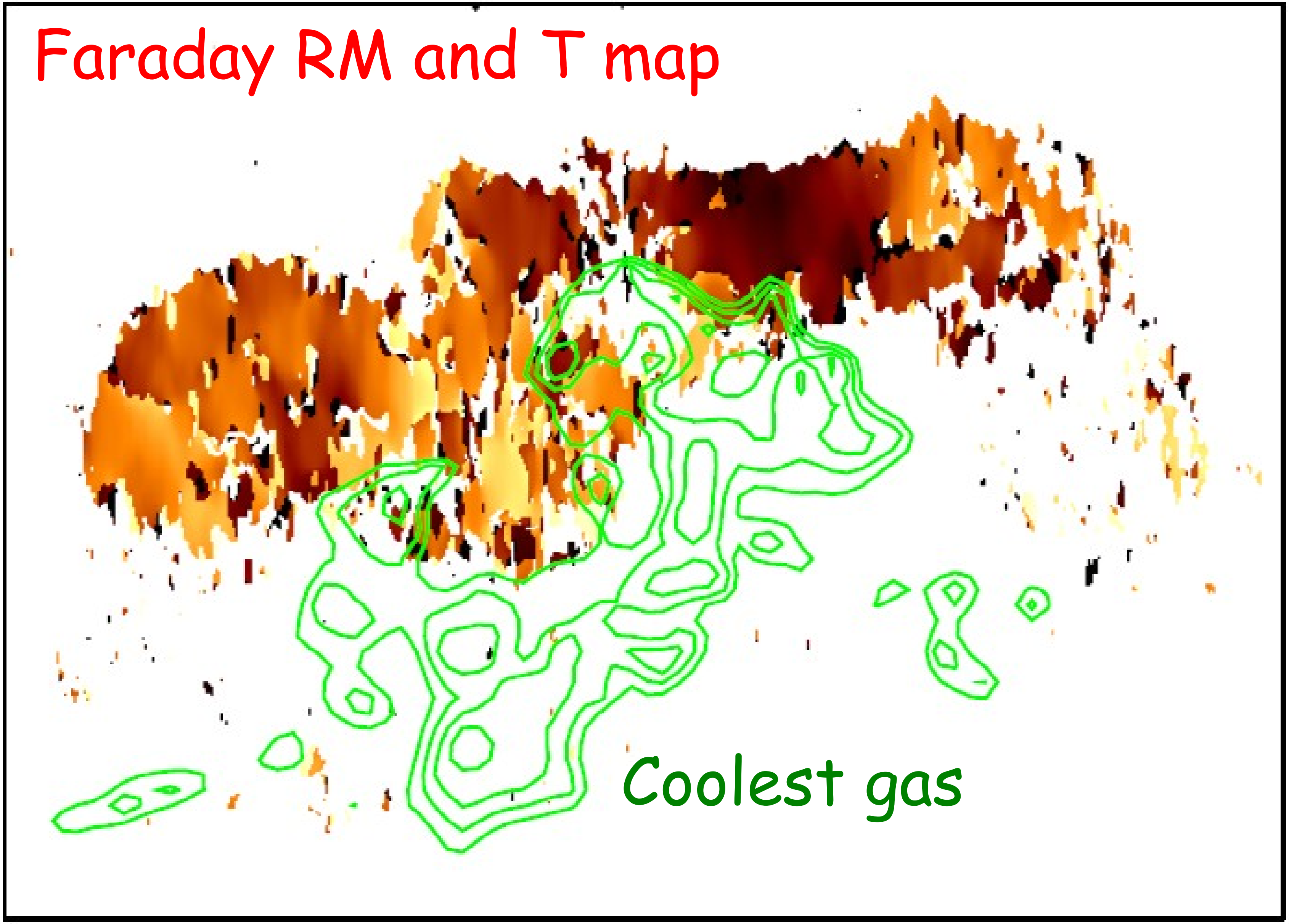




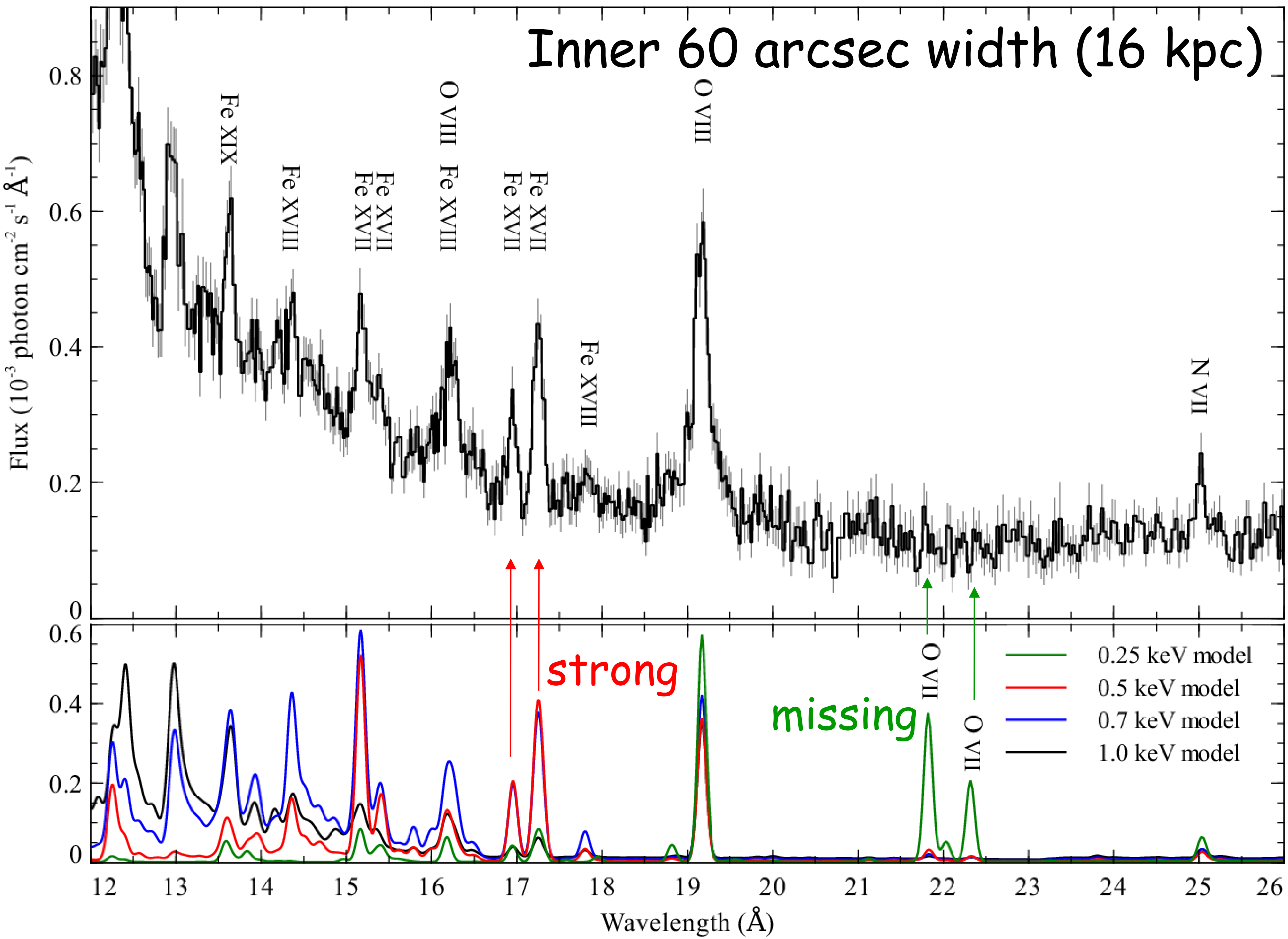
Temperature (keV)

Shows feedback (cavities) and cool gas (~0.7 keV) in CCD spectra

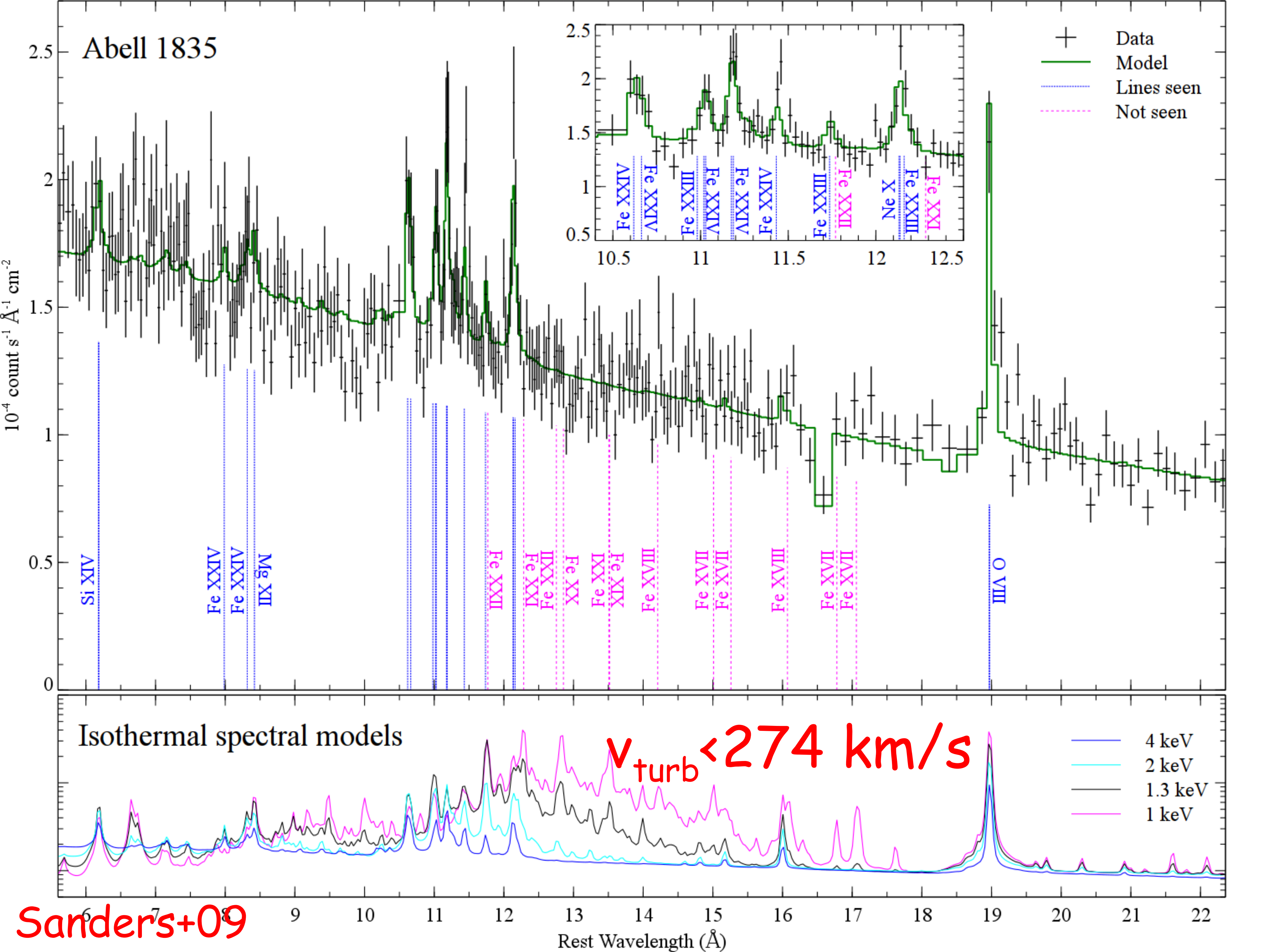
How much gas is there at low X-ray temperatures?



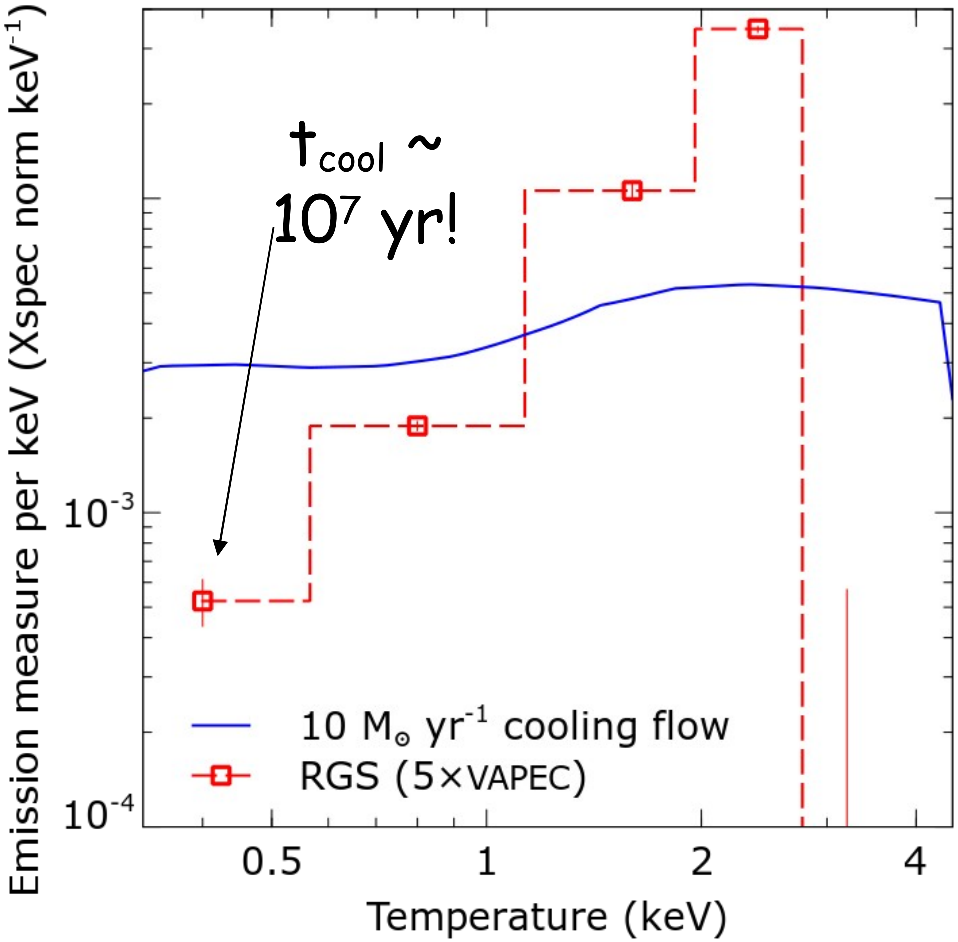
Taylor+07 B~25uG in 5e6K gas 10% thermal pressure



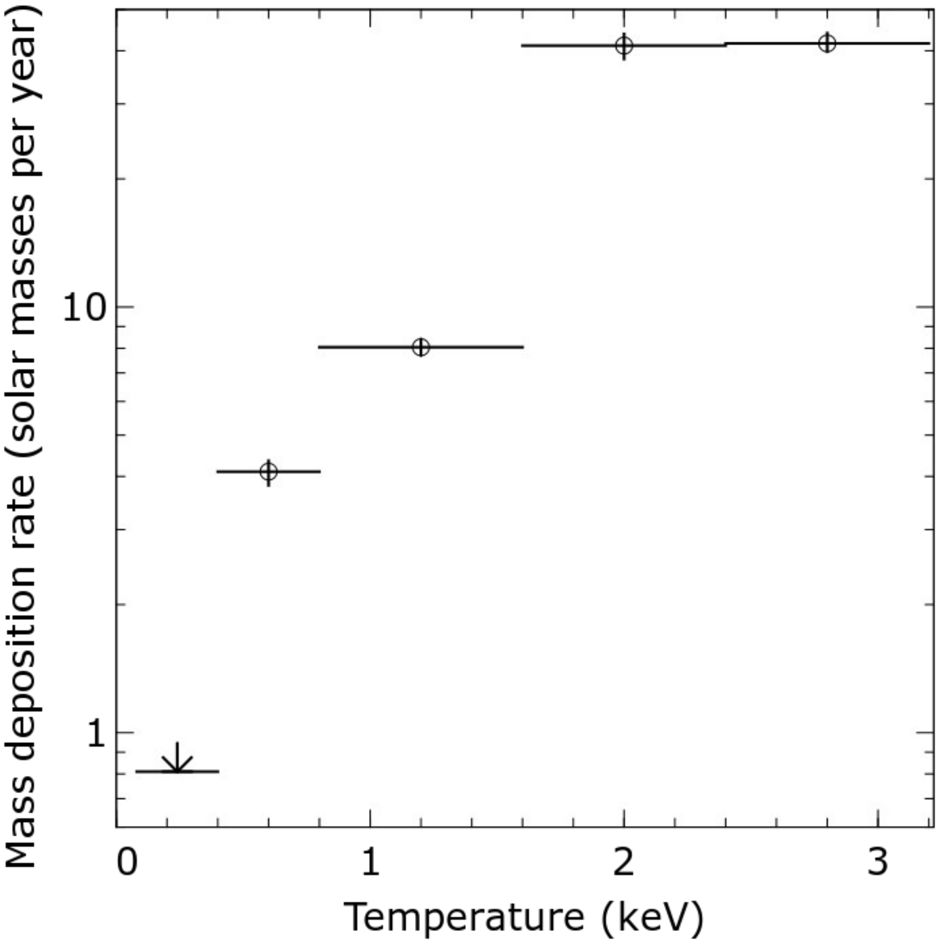
Inner 60 arcsec width (16 kpc)
Flux (10^{-3} photon cm^{-2} s^{-1} Å^{-1})
Fe XIX
Fe XVIII
Fe XVII
Fe XVII
O VIII
Fe XVIII
Fe XVII
Fe XVII
Fe XVIII
O VIII
N VII
strong
missing
O VII
O VII
0.25 keV model
0.5 keV model
0.7 keV model
1.0 keV model
Wavelength (Å)


Abell 1835
Data
Model
Lines seen
Not seen
10^{-4} count s^{-1} Å^{-1} cm^{-2}
Si XIV
Fe XXIV
Fe XXIV
Mg XII
Fe XXII
Fe XXI
Fe XXII
Fe XX
Fe XX
Fe XIX
Fe XVIII
Fe XVII
Fe XVII
Fe XVIII
Fe XVII
Fe XVII
O VIII
Fe XXIV
Fe XXIV
Fe XXIII
Fe XXIV
Fe XXIV
Fe XXIV
Fe XXIII
Fe XXII
Ne X
Fe XXIII
Fe XXI
Isothermal spectral models
v_{turb}<274 km/s
4 keV
2 keV
1.3 keV
1 keV
Rest Wavelength (Å)
Sanders+09

Spectral fitting limits on gas kT

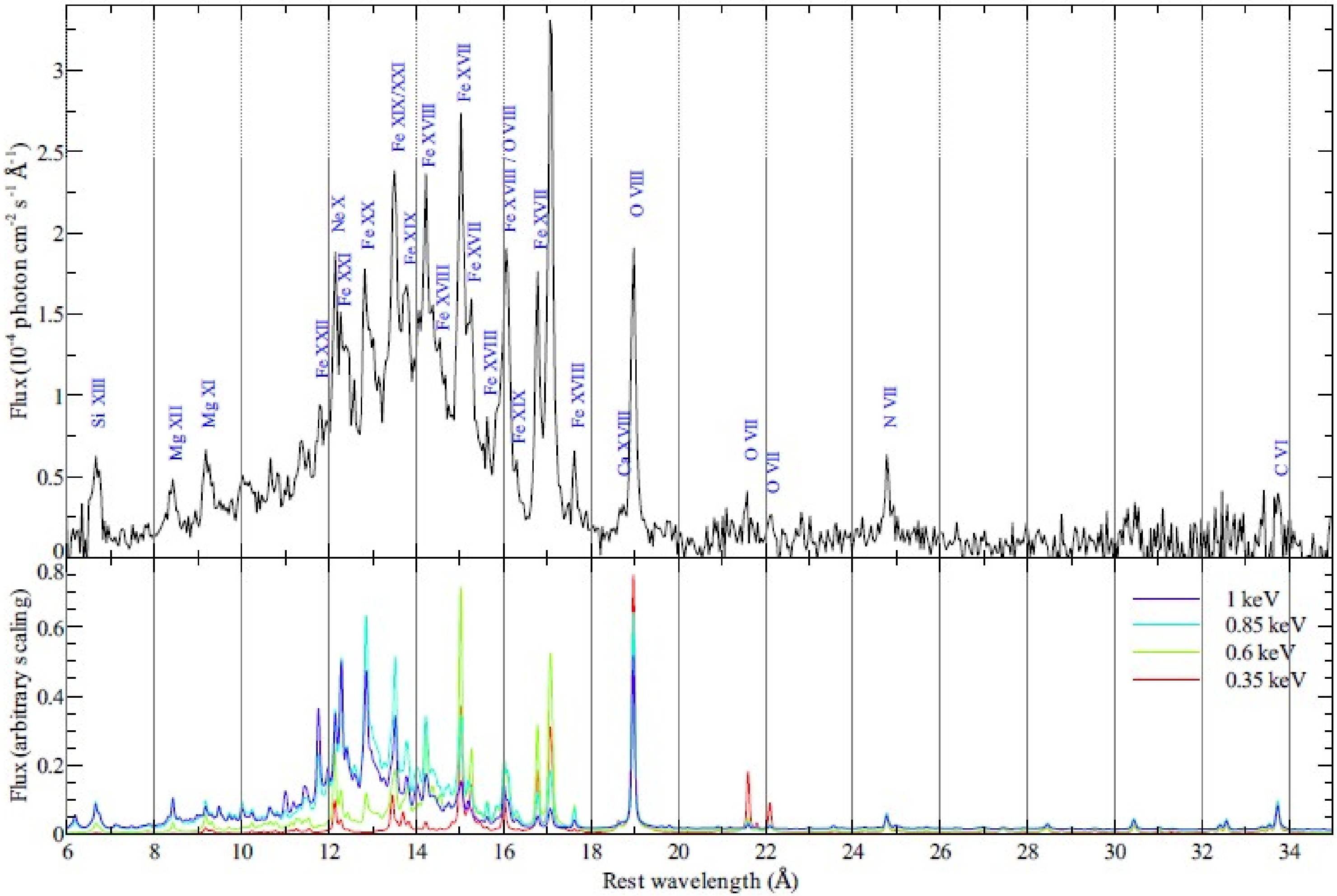


Multi temperature model



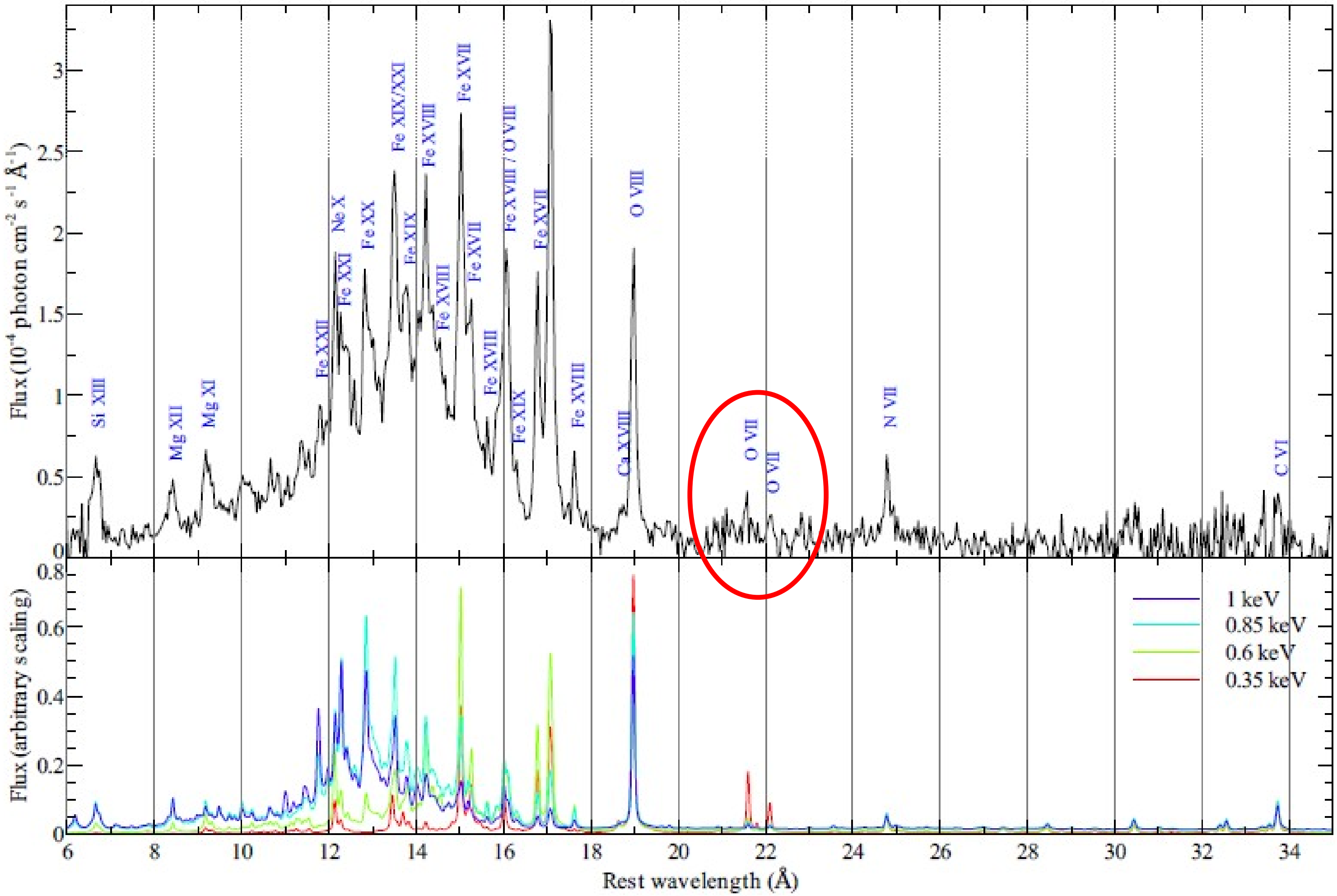
Cooling flow model

1.2Ms stack of XMM RGS spectra
Sanders+Fabian+10

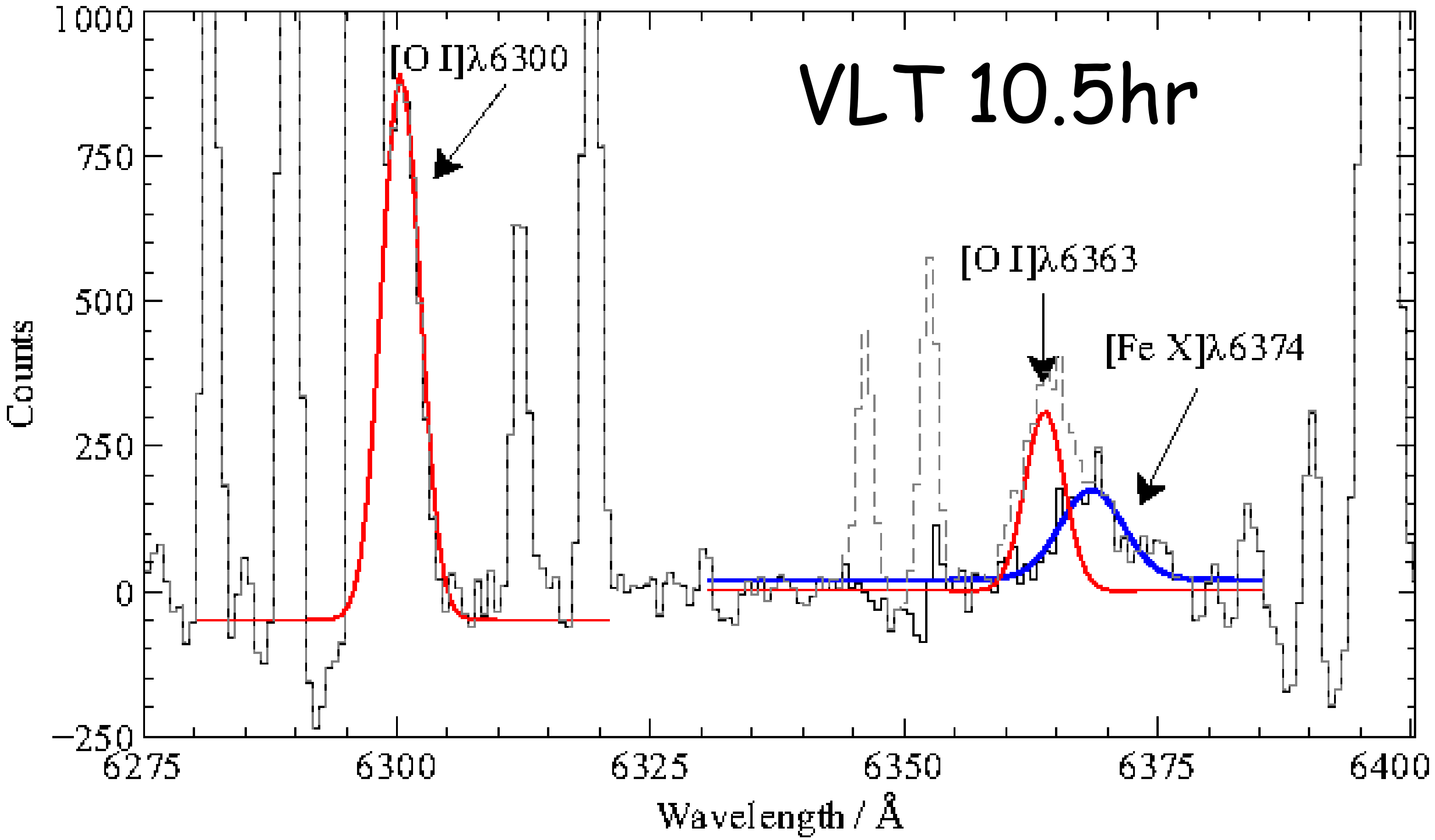


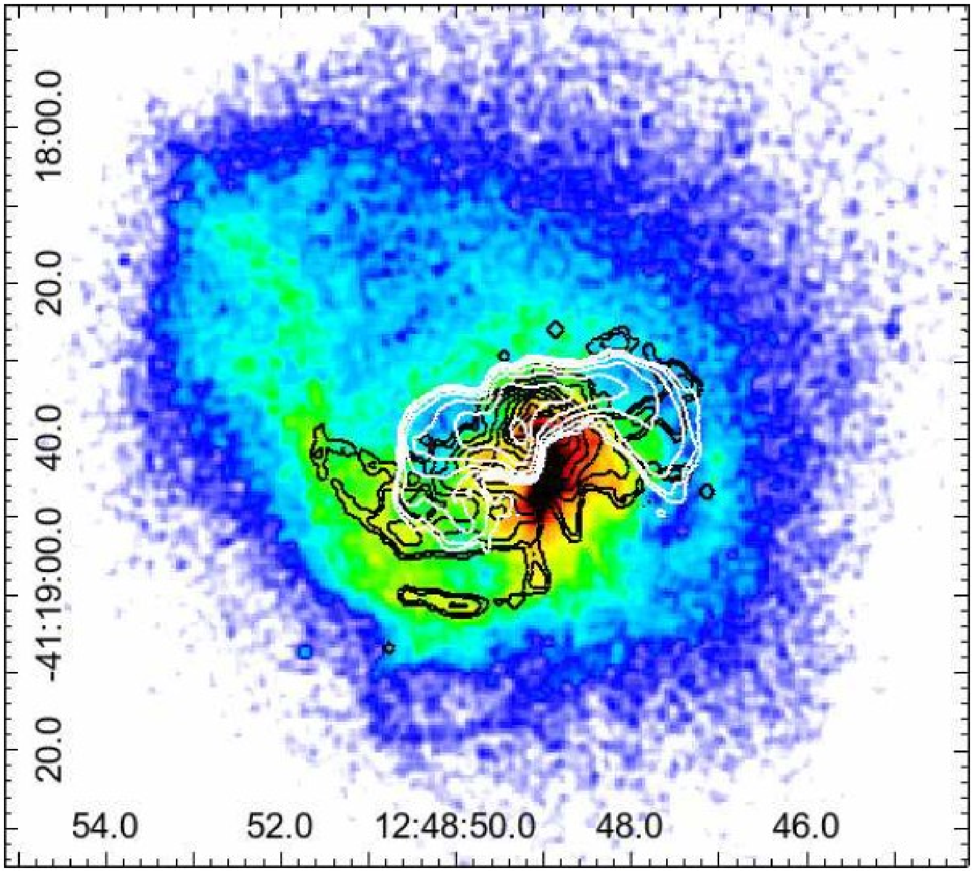
1.2Ms stack of XMM RGS spectra

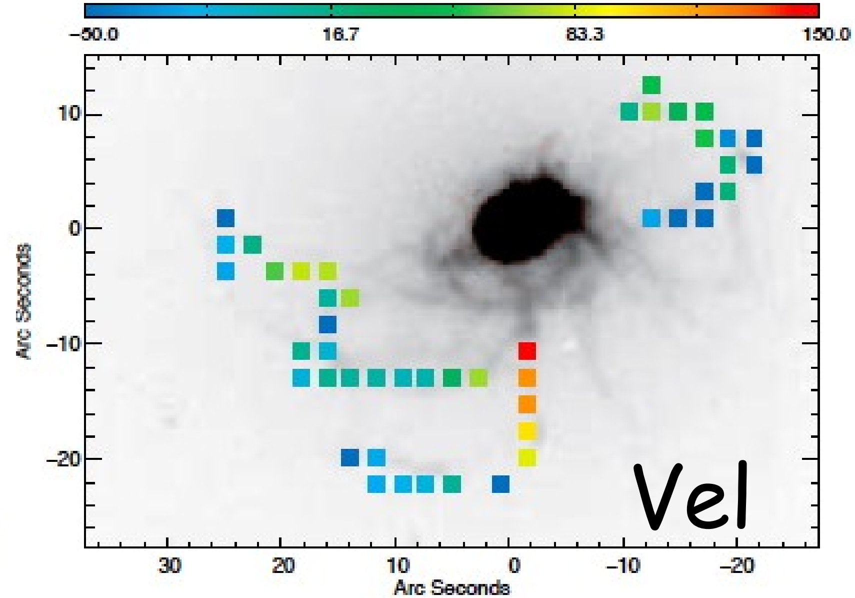
Sanders+Fabian+10

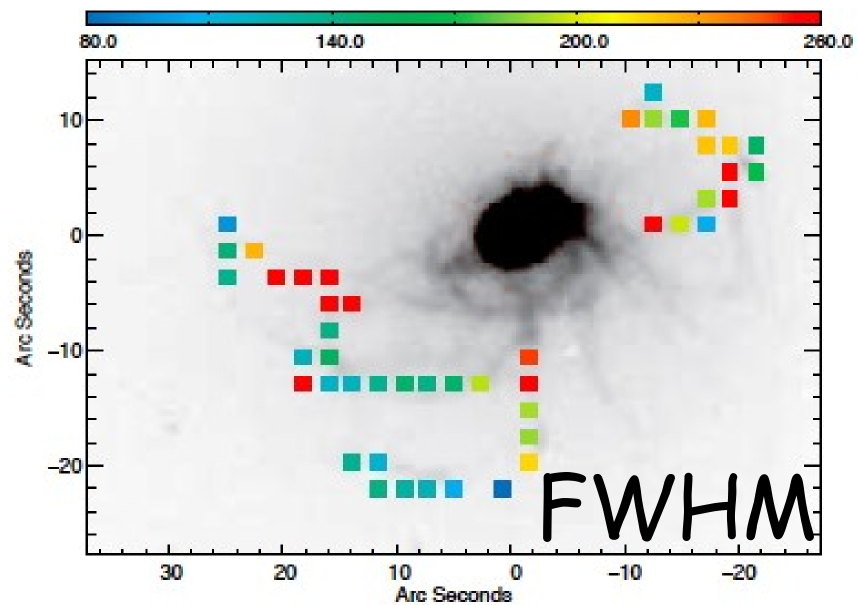


Coronal line emission [FeX] from 10^6K gas in Centaurus Canning+10




18:00.0
20.0
40.0
-41:19:00.0
20.0
54.0
52.0
12:48:50.0
48.0
46.0


-50.0
16.7
83.3
150.0
Arc Seconds
Arc Seconds
Vel


80.0
140.0
200.0
260.0
Arc Seconds
Arc Seconds
FWHM

Canning+11

Perseus SFR~20 Msunpyr   Canning+10

 +10 MACS J1931 z=0.35

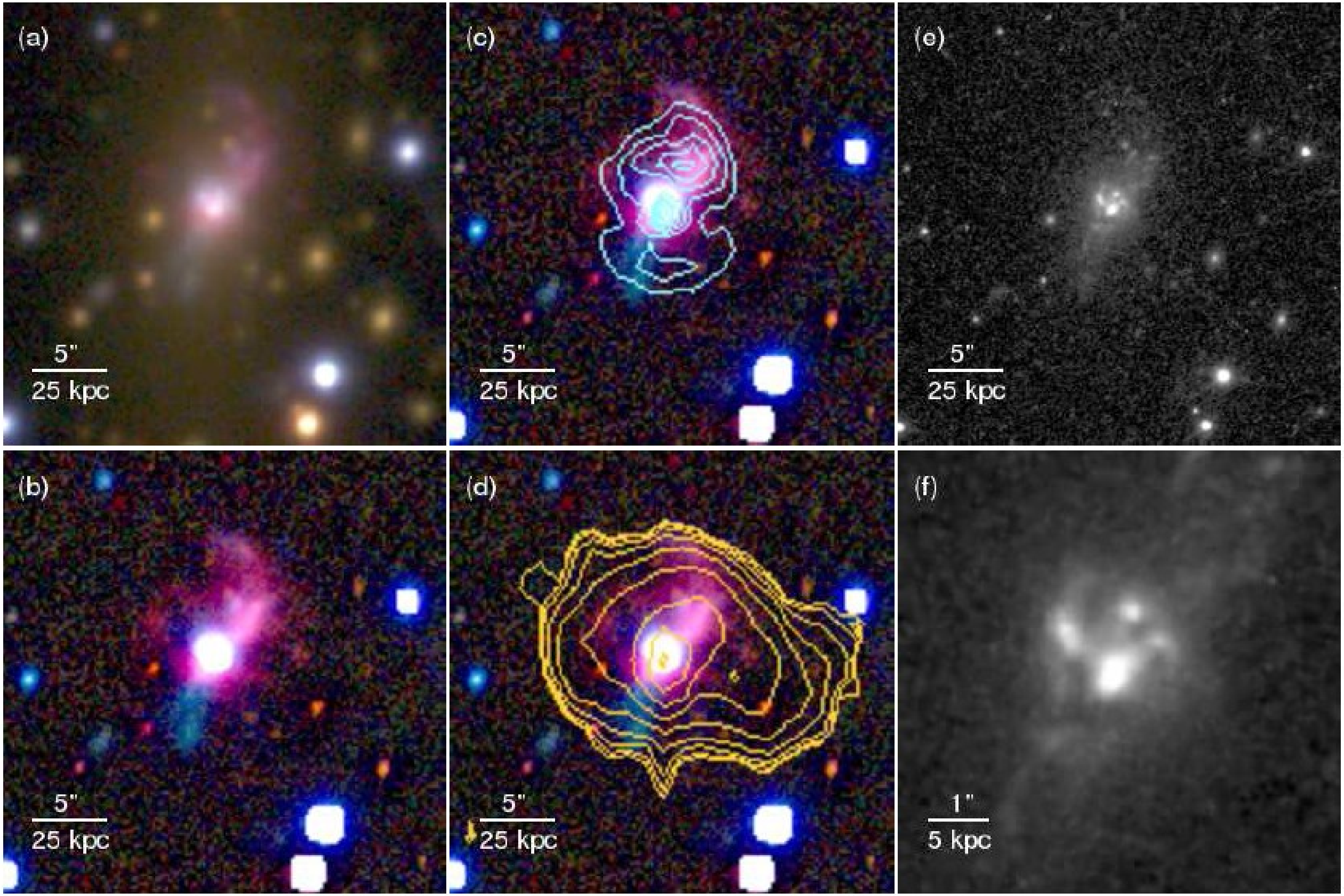


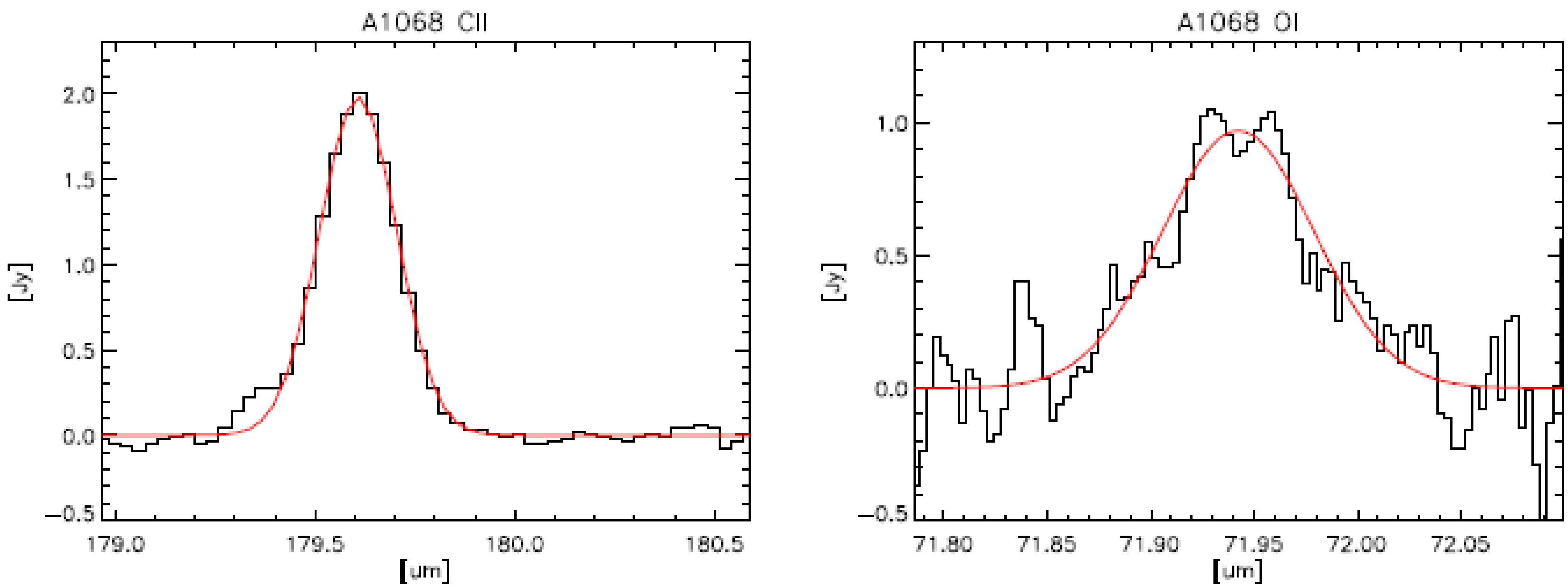
Figure 12. Optical structure of the BCG of MACS J1931.8-2634. (a): SuprimeCam *BRz* image of the central 30 arcsec × 30 arcsec. (b): For this image, the

SFR~170 Msunpyr

Letter to the Editor

Herschel observations of FIR emission lines in brightest cluster galaxies ⋆

A. C. Edge[1], J. B. R. Oonk[2], R. Mittal[3], S. W. Allen[4], S. A. Baum[3], H. Böhringer[5], J. N. Bregman[6], M. N. Bremer[7], F. Combes[8], C. S. Crawford[9], M. Donahue[10], E. Egami[11], A. C. Fabian[9], G. J. Ferland[12], S. L. Hamer[1], N. A. Hatch[13], W. Jaffe[2], R. M. Johnstone[9], B. R. McNamara[14], C. P. O'Dea[15], P. Popesso[5], A. C. Quillen[16], P. Salomé[8], C. L. Sarazin[17], G. M. Voit[10], R. J. Wilman[18], and M. W. Wise[19]

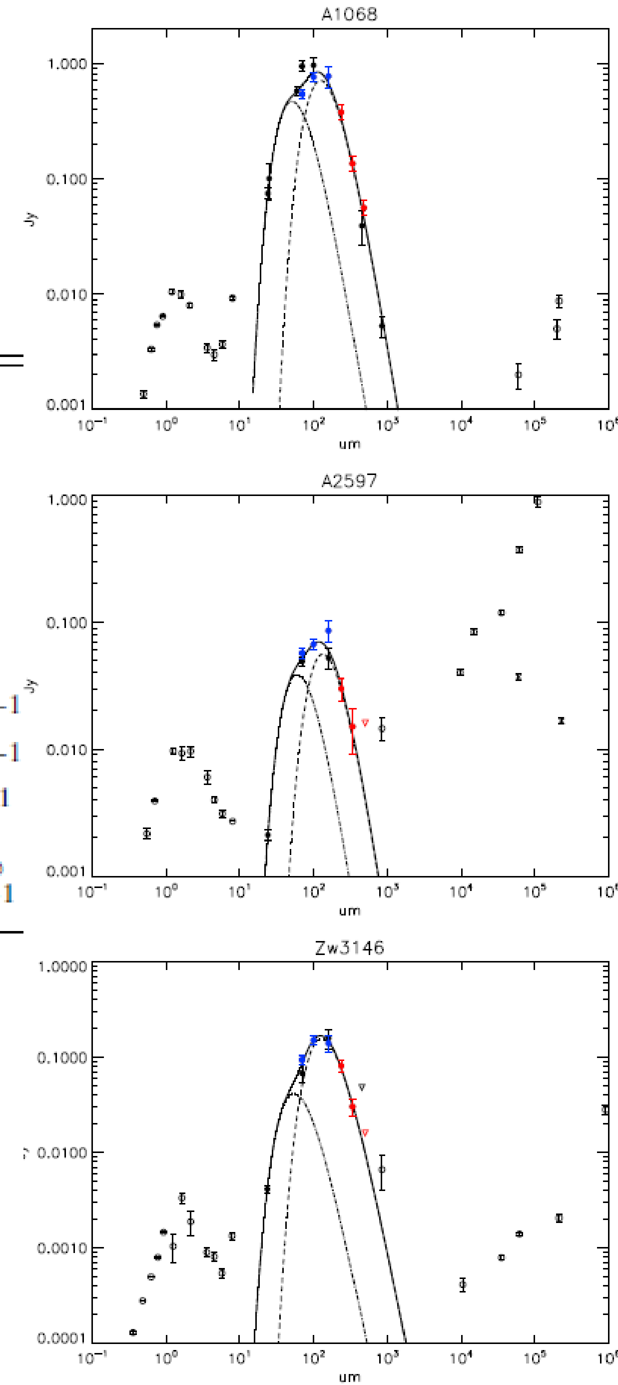


L(CII)~5x10^{42} erg/s ~6 x L(Ha)

Dust

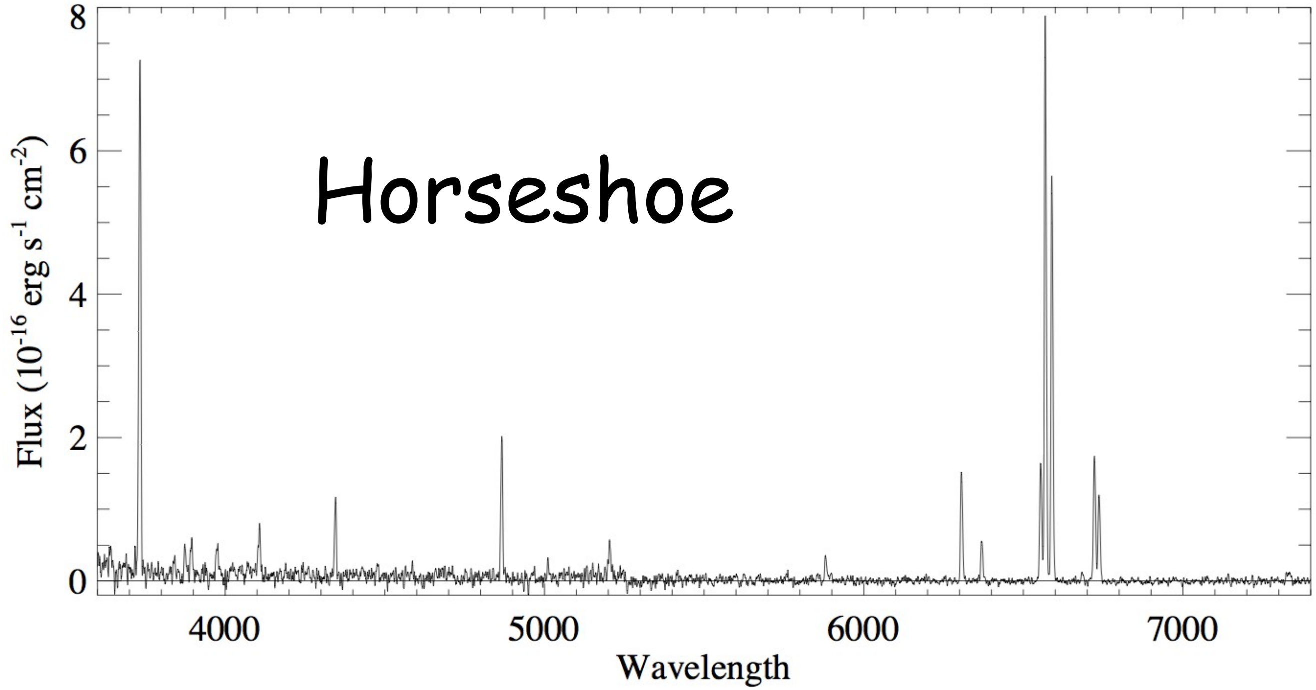
Herschel points

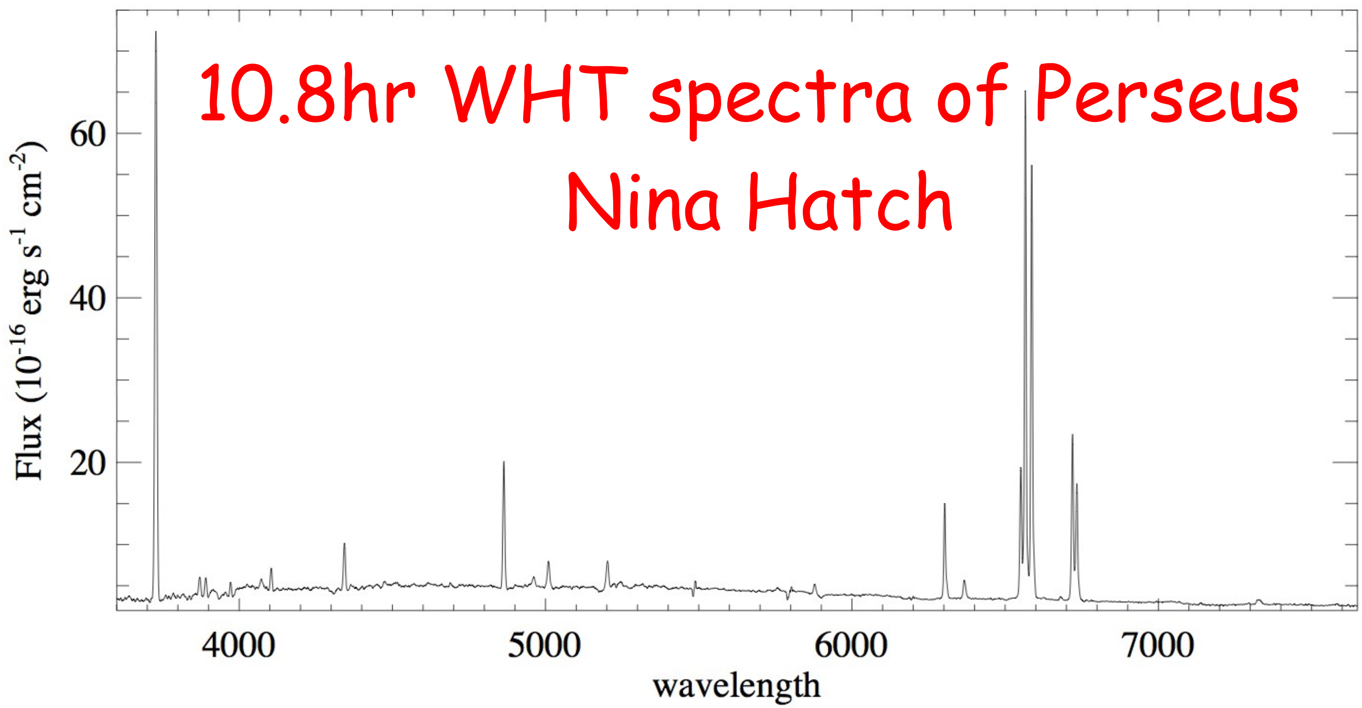
Cluster	A1068	A2597	Zw3146
Dust Temperatures	24±4K	21±6K	23±5K
	57^{+12}_{-4}K	48^{+17}_{-5}K	53^{+22}_{-6}K
Cold Dust Mass	5.1×10^{8} $M_{\odot}$	2.3×10^{7} $M_{\odot}$	5.4×10^{8} $M_{\odot}$
Warm Dust Mass	3.9×10^{6} $M_{\odot}$	2.9×10^{5} $M_{\odot}$	1.9×10^{6} $M_{\odot}$
Total FIR Luminosity	3.5×10^{11} $L_{\odot}$	8.8×10^{9} $L_{\odot}$	2.5×10^{11} $L_{\odot}$
Star Formation Rate	60±20 $M_{\odot}$ yr^{-1}	2±1 $M_{\odot}$ yr^{-1}	44±14 $M_{\odot}$ yr^{-1}
SFR *Spitzer*	188 $M_{\odot}$ yr^{-1}	4 $M_{\odot}$ yr^{-1}	70±14 $M_{\odot}$ yr^{-1}
SFR *optical/UV*	20–70 $M_{\odot}$ yr^{-1}	10–15 $M_{\odot}$ yr^{-1}	47±5 $M_{\odot}$ yr^{-1}
CO gas mass	4.1×10^{10} $M_{\odot}$	2.0×10^{9} $M_{\odot}$	7.7×10^{10} $M_{\odot}$
Hα Slit Luminosity	8×10^{41} erg s^{-1}	3×10^{41} erg s^{-1}	3×10^{42} erg s^{-1}



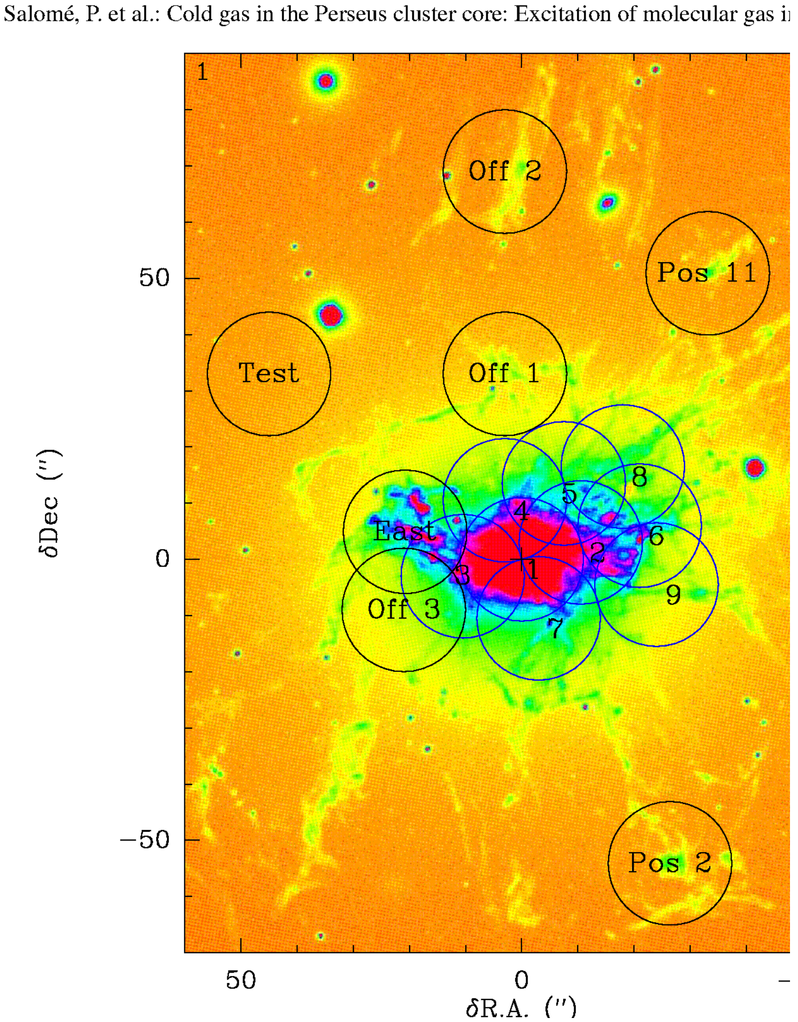
Edge+10

Spectrum of these filaments is unlike anything in Galaxy,
other than Crab
and due to energetic particles (the hot gas?) Ferland+08/9


Horseshoe
Flux (10^{-16} erg s^{-1} cm^{-2})
0
2
4
6
8
4000
5000
6000
7000
Wavelength


10.8hr WHT spectra of Perseus
Nina Hatch
Flux (10^{-16} erg s^{-1} cm^{-2})
20
40
60
4000
5000
6000
7000
wavelength

Salome+08 CO measurements



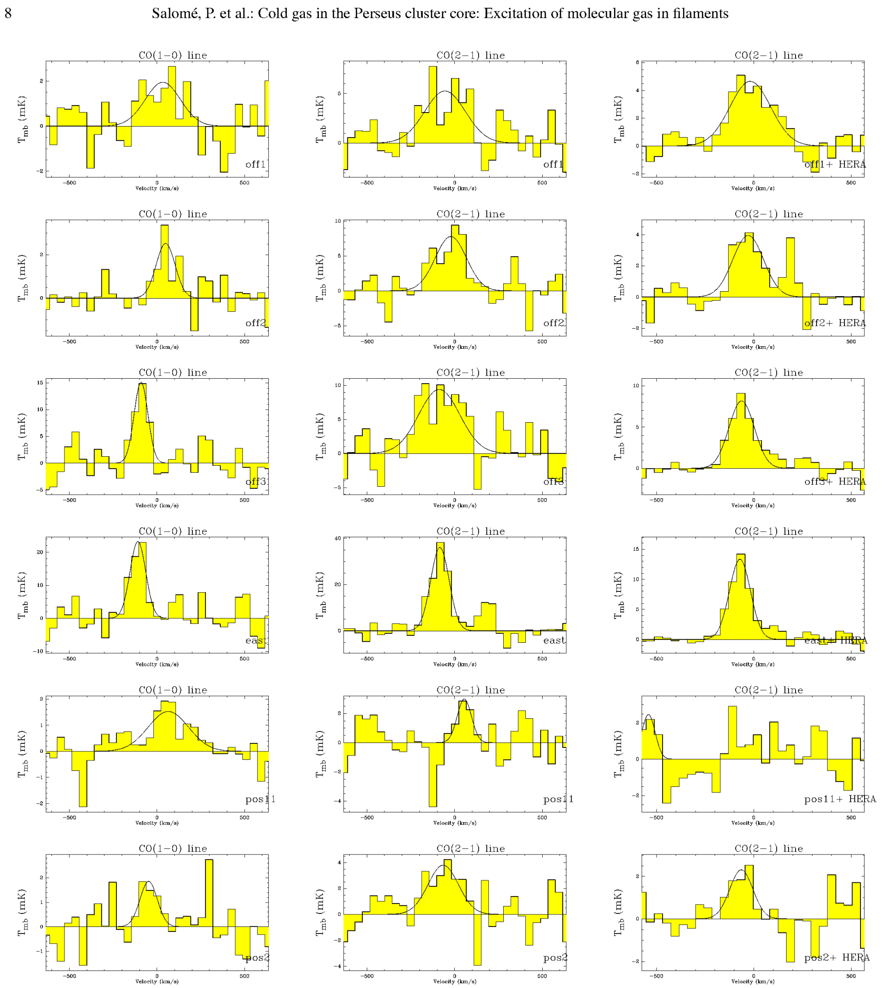
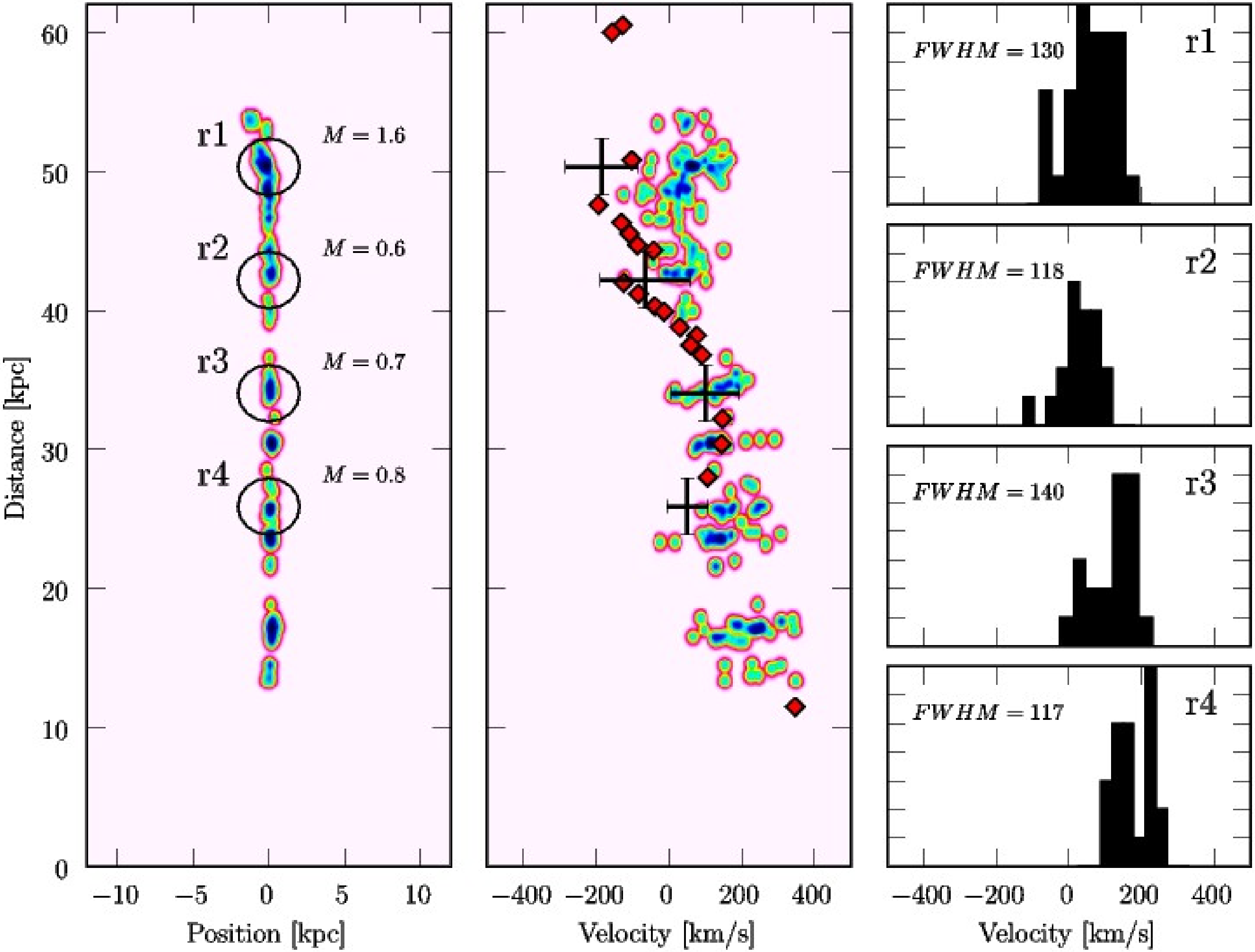


Fig. 2. CO(1–0) and CO(2–1) spectra obtained at all the positions observed as indicated at lower right in each diagram. The channel width is 42 km/s. On the left hand side are the CO(1–0) lines detected with the a100 and b100 receivers. In the middle are the results obtained for the CO(2–1) line with the A230 and B230 receivers. On the right hand side are the CO(2–1) lines computed with both A230 and B230 merged with previous HERA data and smoothed to the 3mm beam size.

Almost 10^{11} Msun of cold gas in Perseus

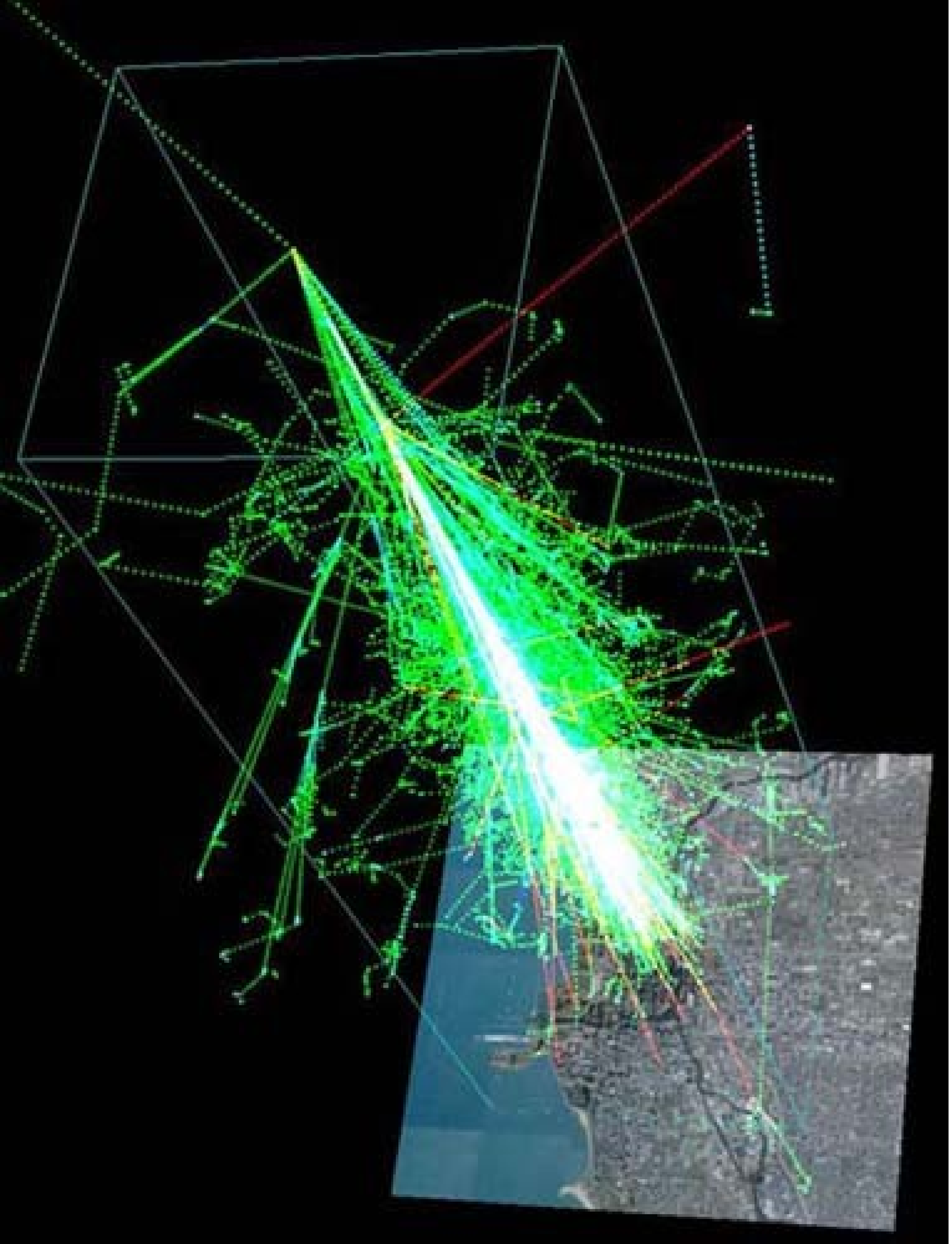


r1
r2
r3
r4
M = 1.6
M = 0.6
M = 0.7
M = 0.8
Distance [kpc]
Position [kpc]
Velocity [km/s]
Velocity [km/s]
FWHM = 130
FWHM = 118
FWHM = 140
FWHM = 117
r1
r2
r3
r4

What heats and ionises the cold gas?

Energetic particles

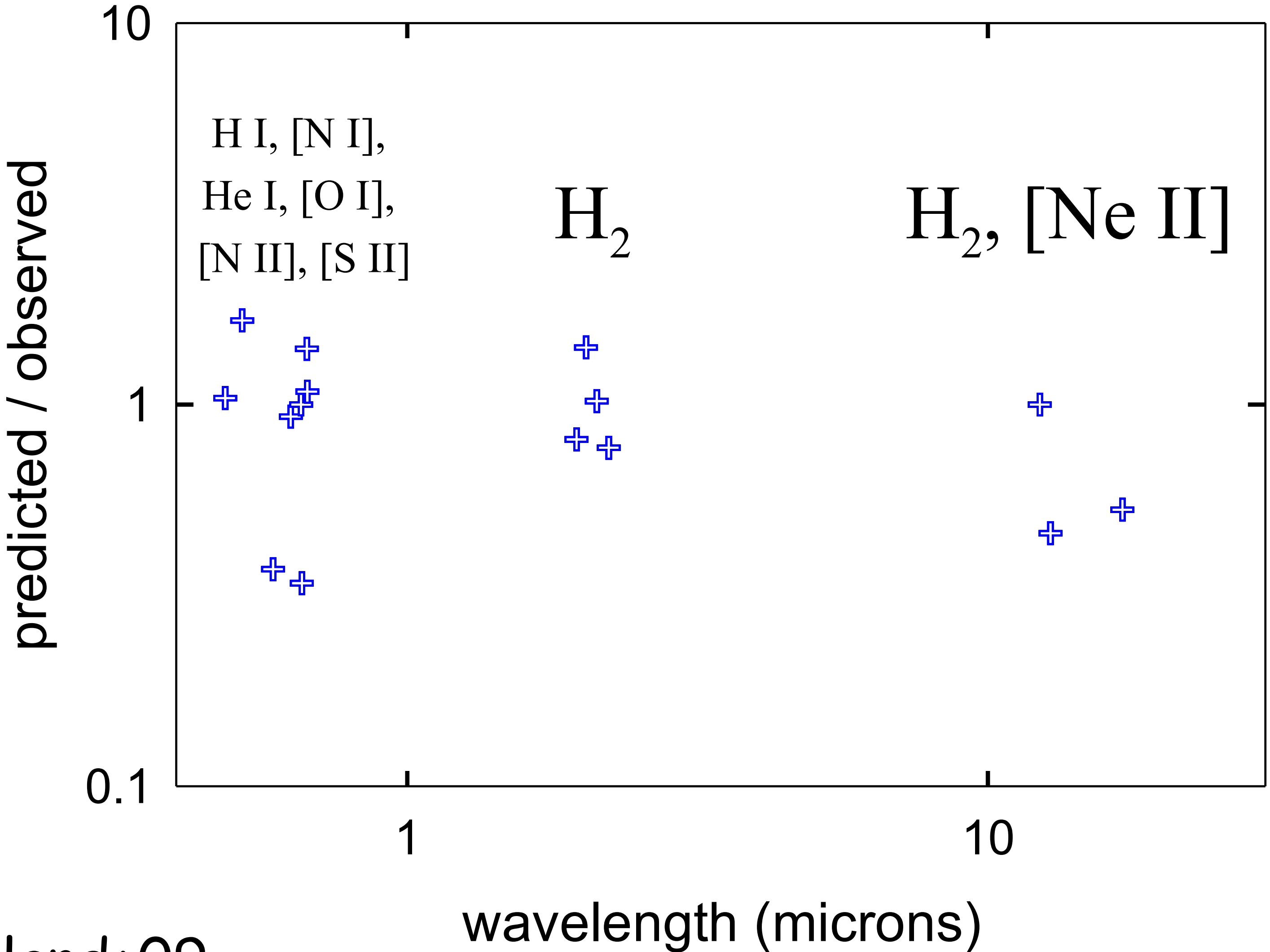
(not photons)



Ferland+08/09

- Energetic particles produce
- Ionized gas
  - Heating
- Neutral gas
  - Shower of suprathermal electrons
  - Secondary excitation and ionization
  - less heating

Observed / predicted spectrum



Ferland+09

Properties of filaments

- Densities~$10^3 cm^{-3}$ or more
- Pressure nT~$10^{6.5} cm^{-3}$K
- Magnetic Fields B~70uG
- Diameter~70pc, length many kpc
- Mass usually dominated by molecular gas

- Reconnection diffusion allows
- Hot ICM particles penetrate cold gas, providing secondary ionization
- Rate about right

  (obs flux~0.01 ergcm^{-2}s^{-1}~20% sat.cond.flux)

- Filament mass growing at

  10-100 Msun yr^{-1}

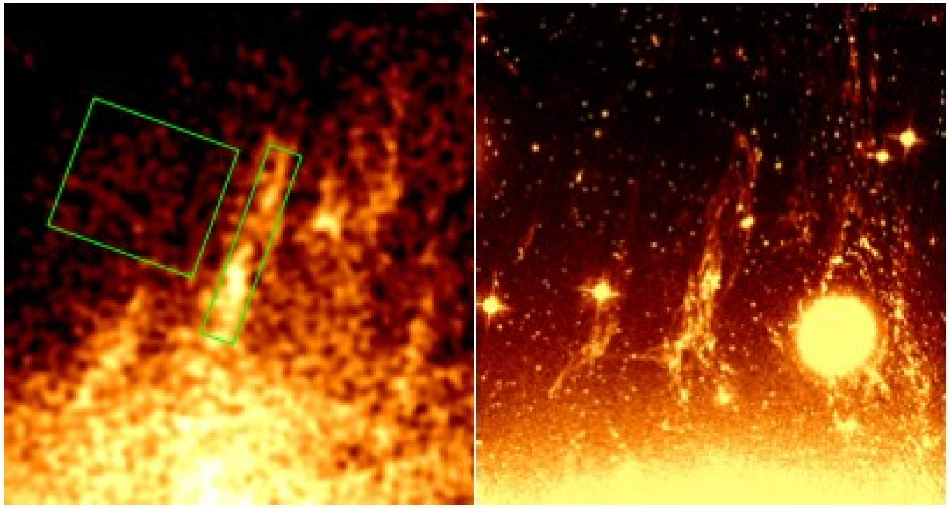
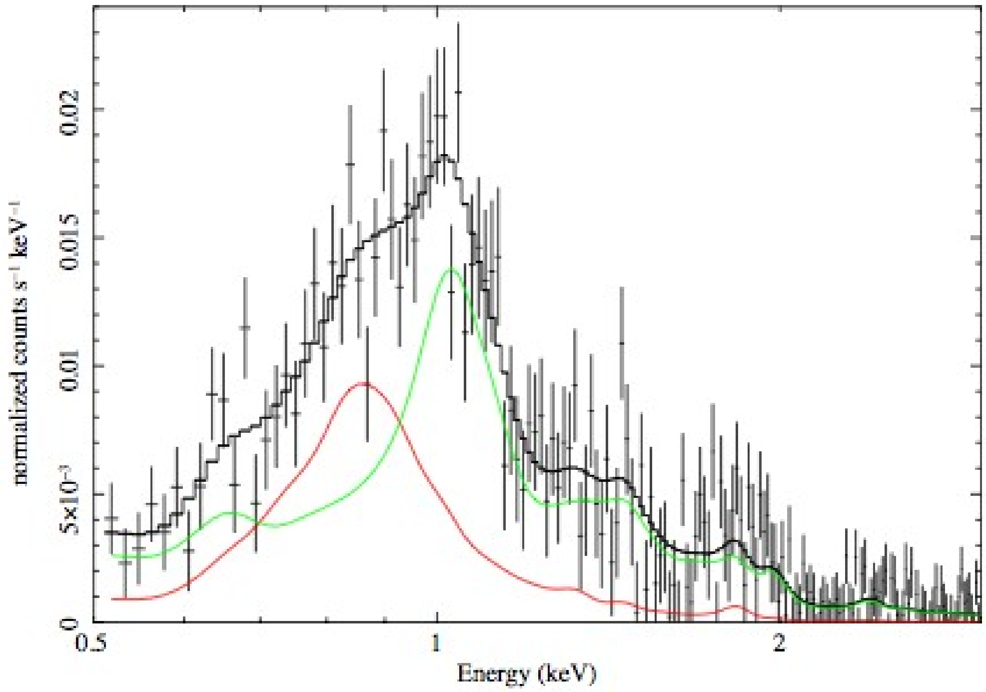


Figure 1. Chandra image of the Northern filament from which the spectrum is measured (right). The long box is 4.1 x 24.3 arcsec (1.5 x 9 kpc). The base of it is about 24.4 kpc from the nucleus of NGC 1275.

Fabian+11



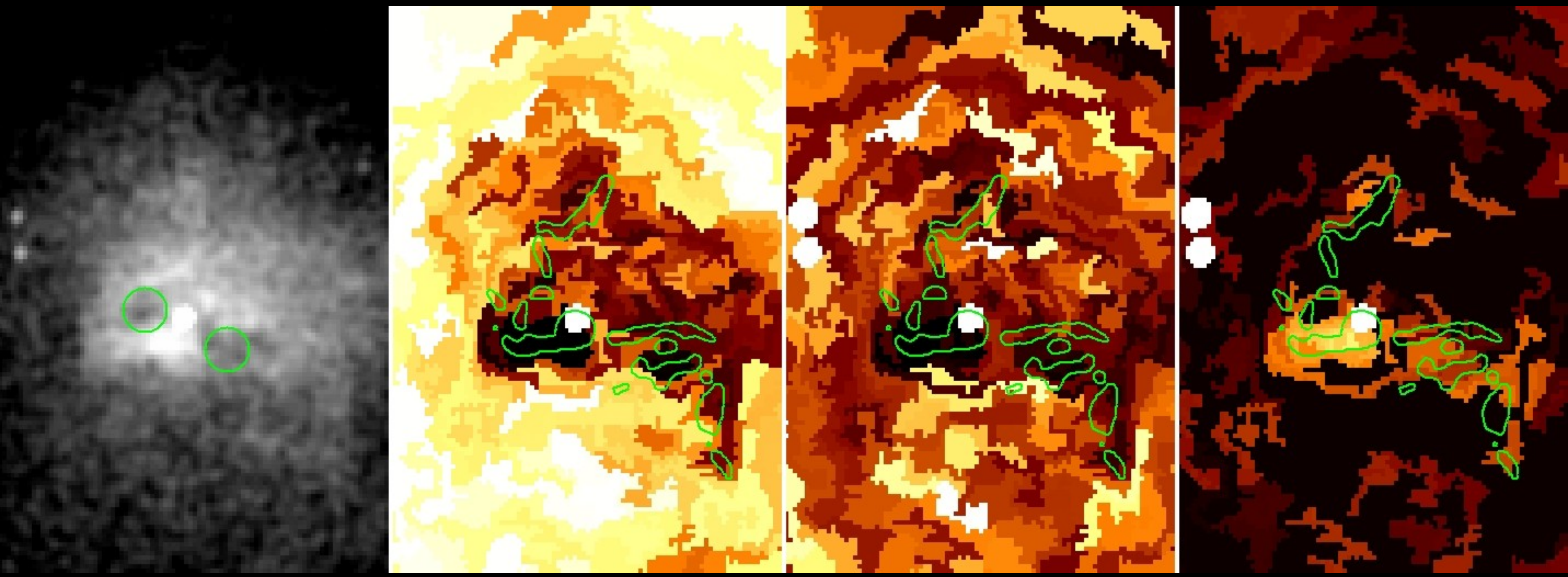
In other words

- Innermost hot gas cools radiatively through X-ray emission to ~10^7K, then plunges to <10^4K by mixing with cold filaments

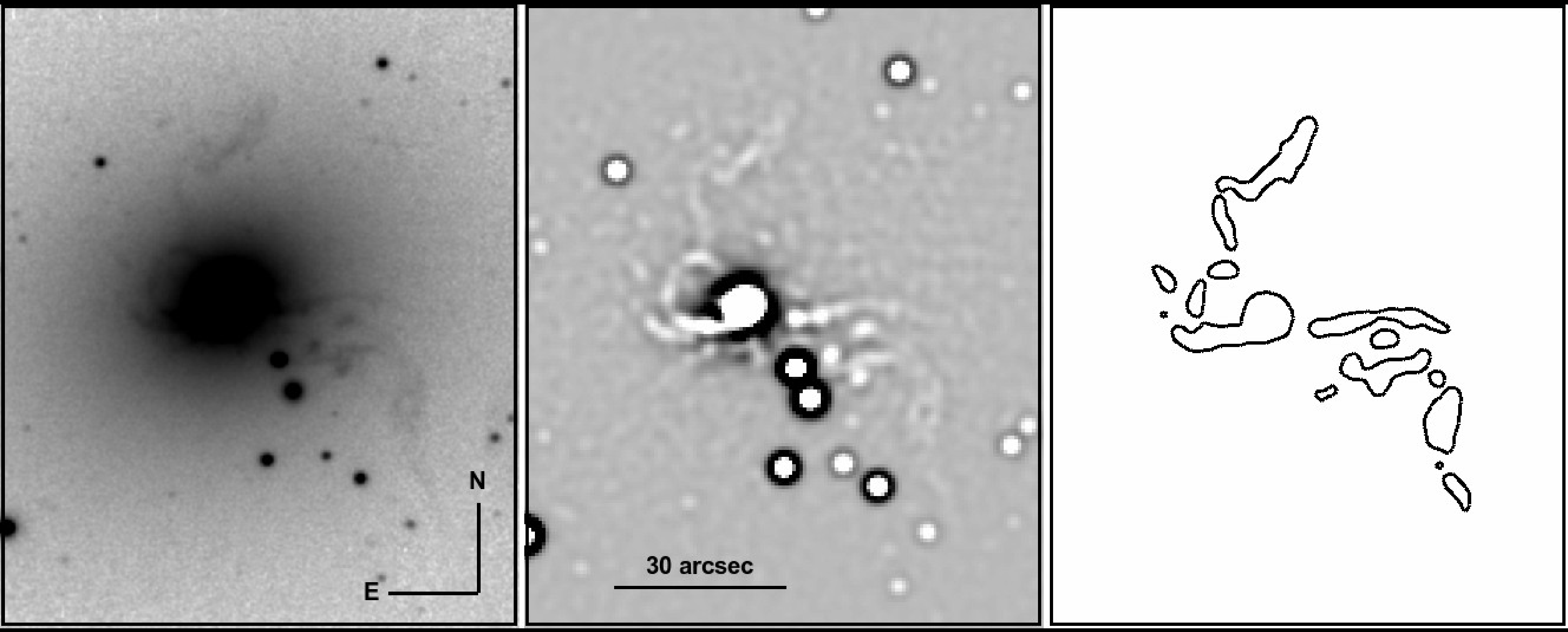
(cf Fabian+01,02, Soker04)

Summary

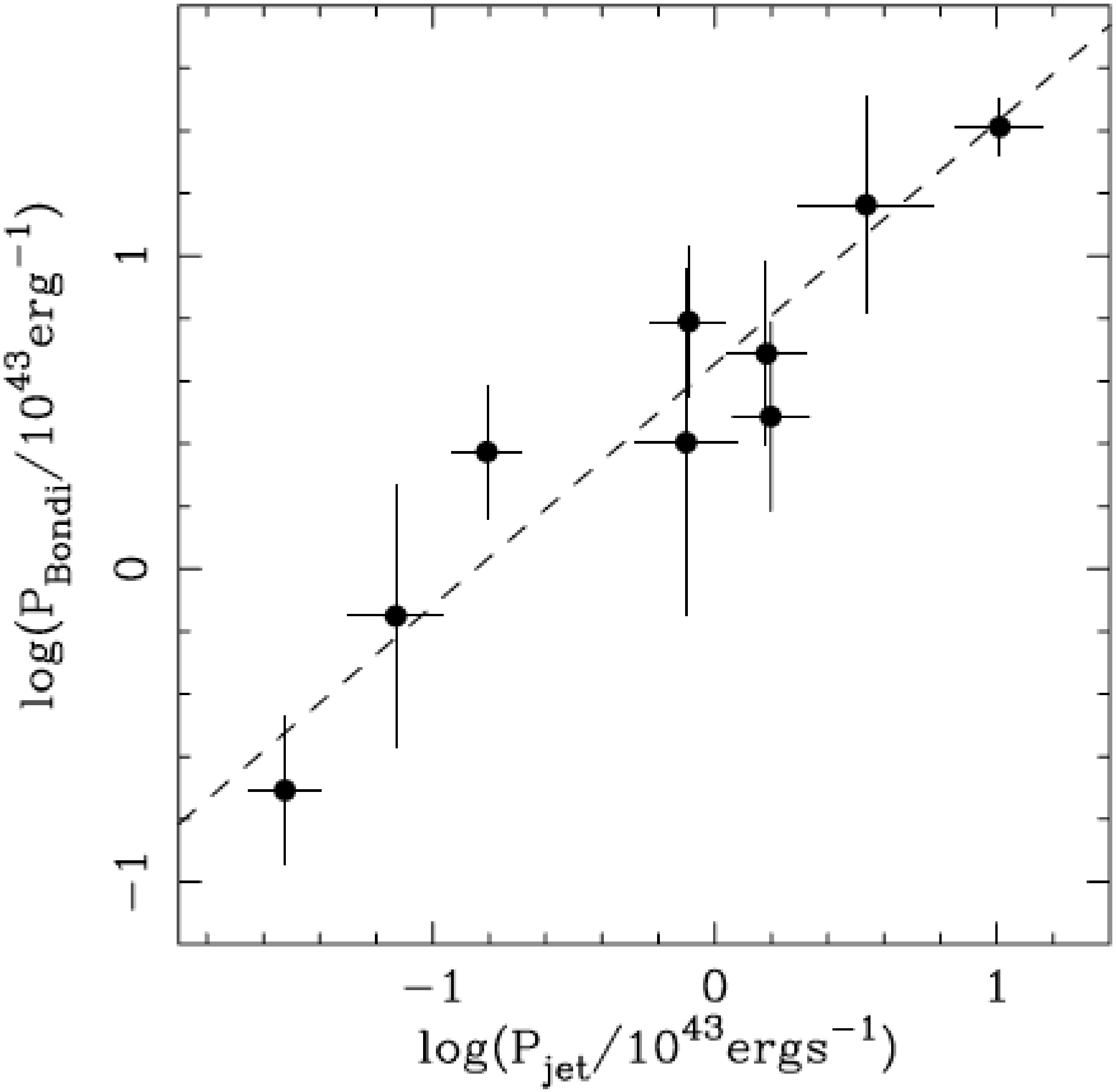
- Kinetic mode feedback operates in most massive galaxies, those with hot atmospheres, maintaining stellar mass. Parts of feedback loop observed (bubbles, sound waves, warm, cool and cold gas)
- Inner parts of hot atmosphere cooling radiatively and by mixing into cold gas



Canning, Sun+11



N
E
30 arcsec



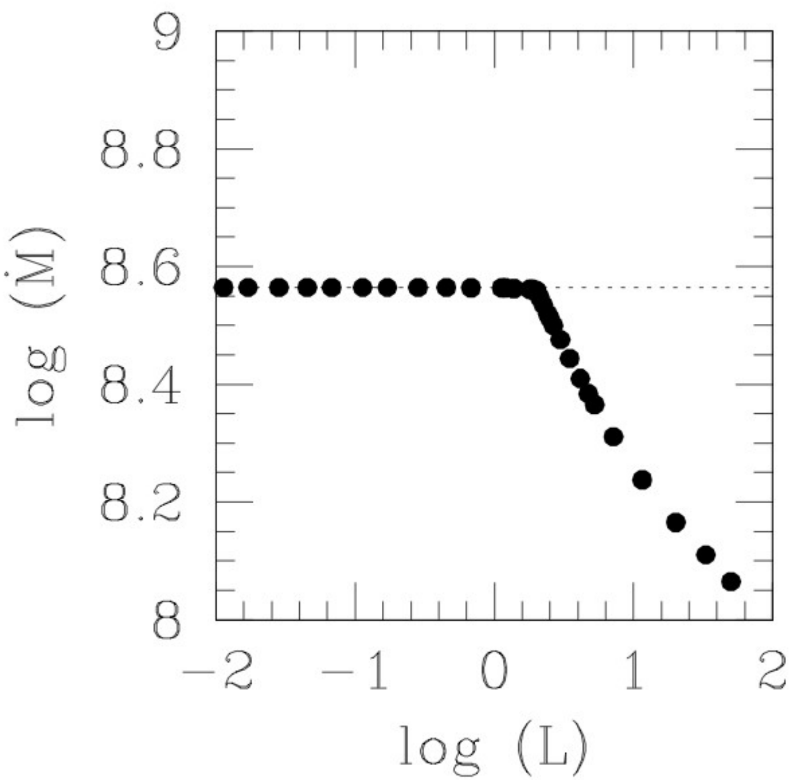
Allen+06 Implies Jet Power is 2% Bondi rate

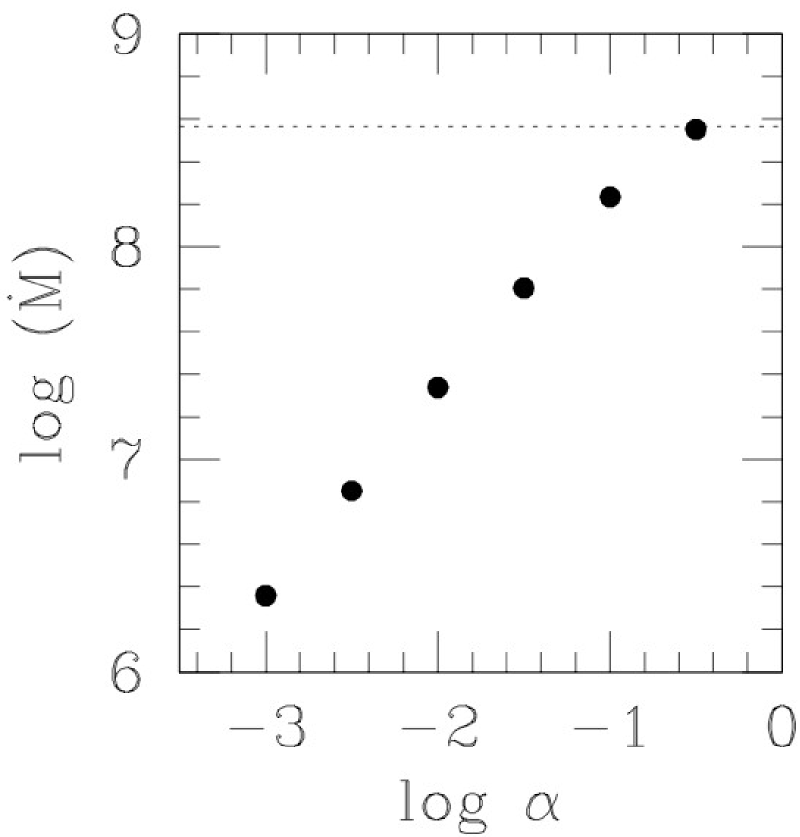
Bondi flow from a rotating hot atmosphere

(Feeding the central black hole with a giant ADAF)

Narayan & Fabian 2011

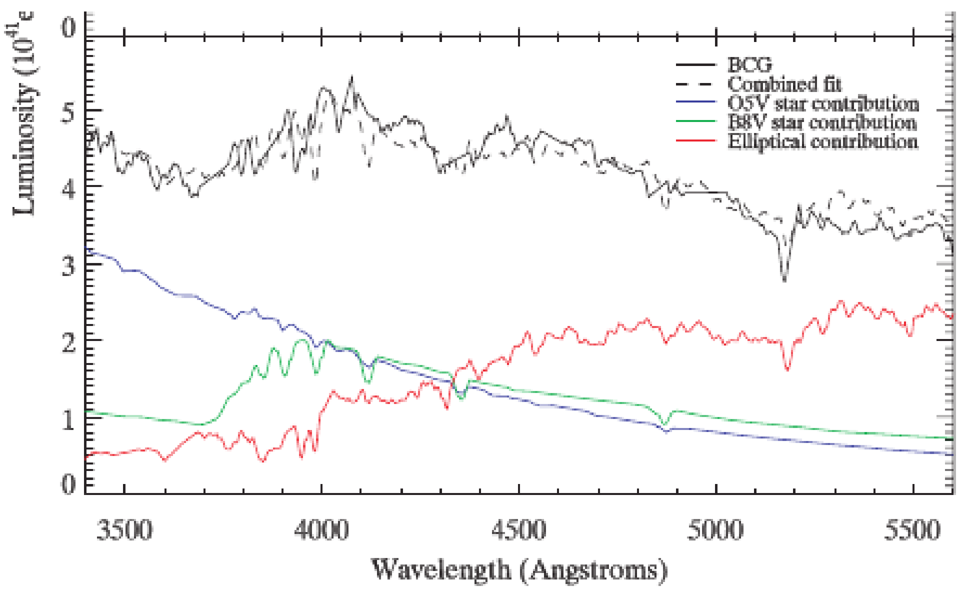
$$\mathcal{L} \equiv \frac{\ell_{\rm out}}{\ell_{\rm ms}} = \frac{\Omega_{\rm out} r_{\rm B}^2}{\ell_{\rm ms}} = 0.136\,\Omega_{\rm out}\left(\frac{c}{c_{\rm out}}\right)^4$$

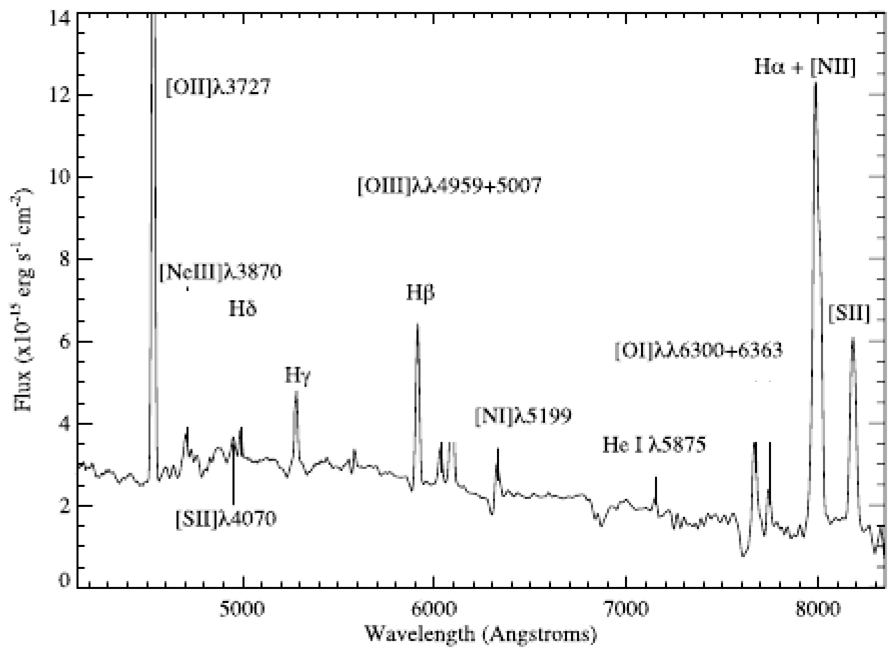


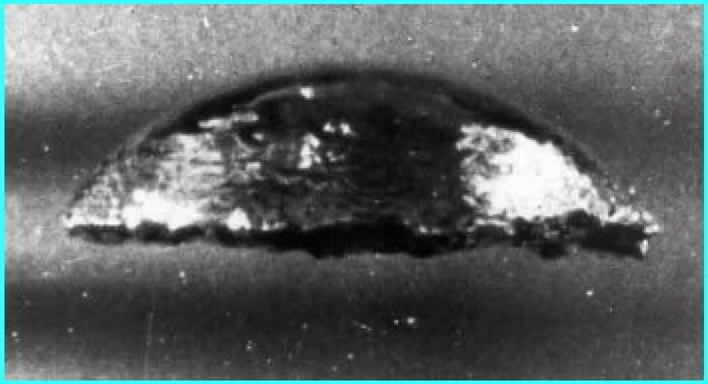


RXCJ1504 Ogrean+10 z=0.2

SFR~140 Msunpyr







Photograph of a spherical cap bubble rising in water (from Davenport, Bradshaw, and Richardson 1967).

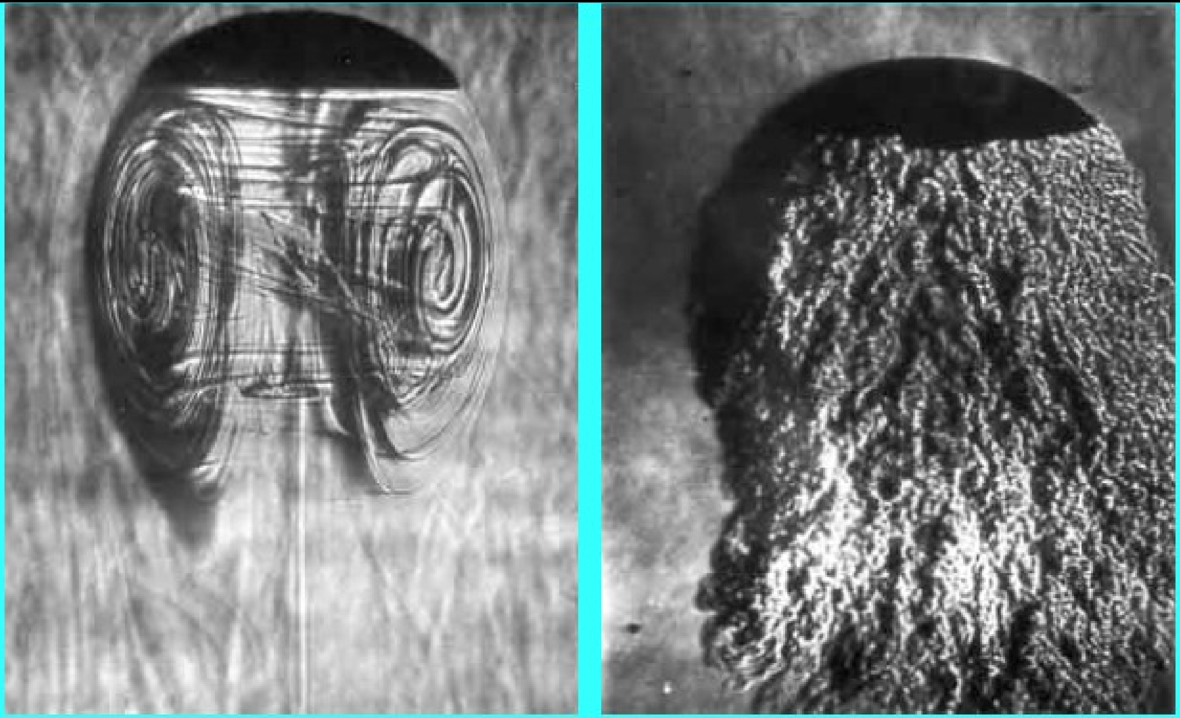
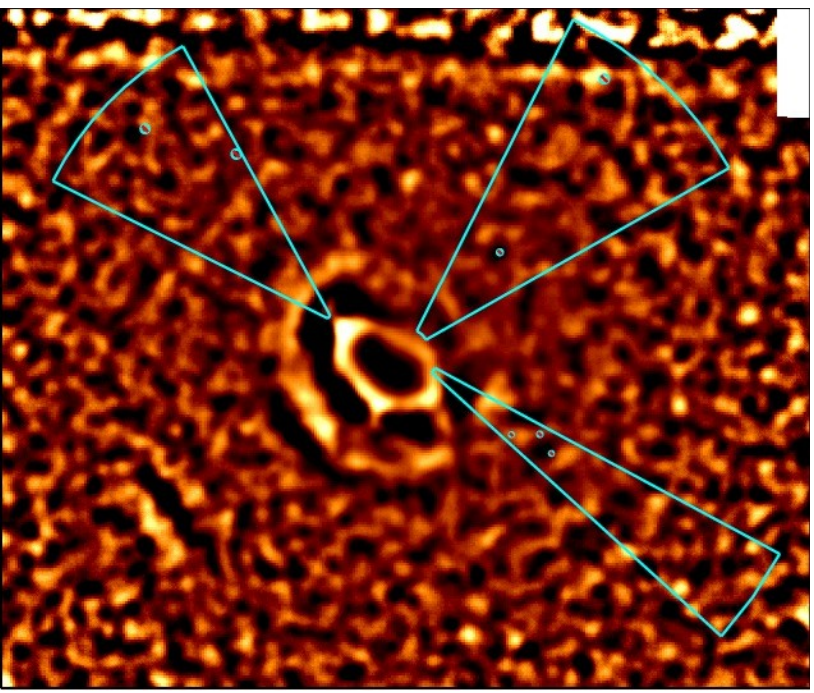


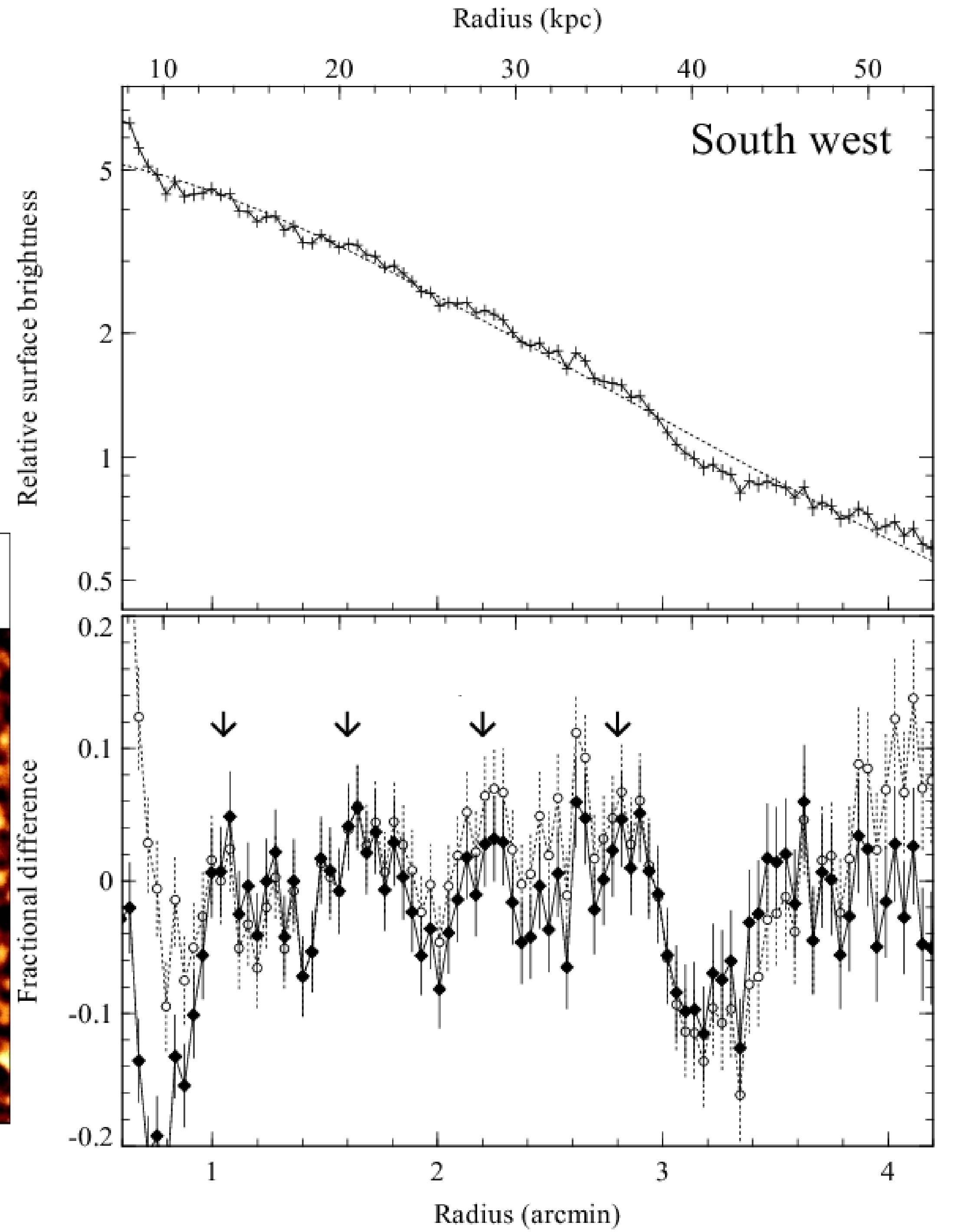
Figure 5.13 Flow visualizations of spherical-cap bubbles. On the left is a bubble with a laminar wake at Re≈180 (from Wegener and Parlange 1973) and, on the right, a bubble with a turbulent wake at Re≈17000 (from Wegener, Sundell and Parlange 1971, reproduced with permission of the authors).


Bubbling
long lived

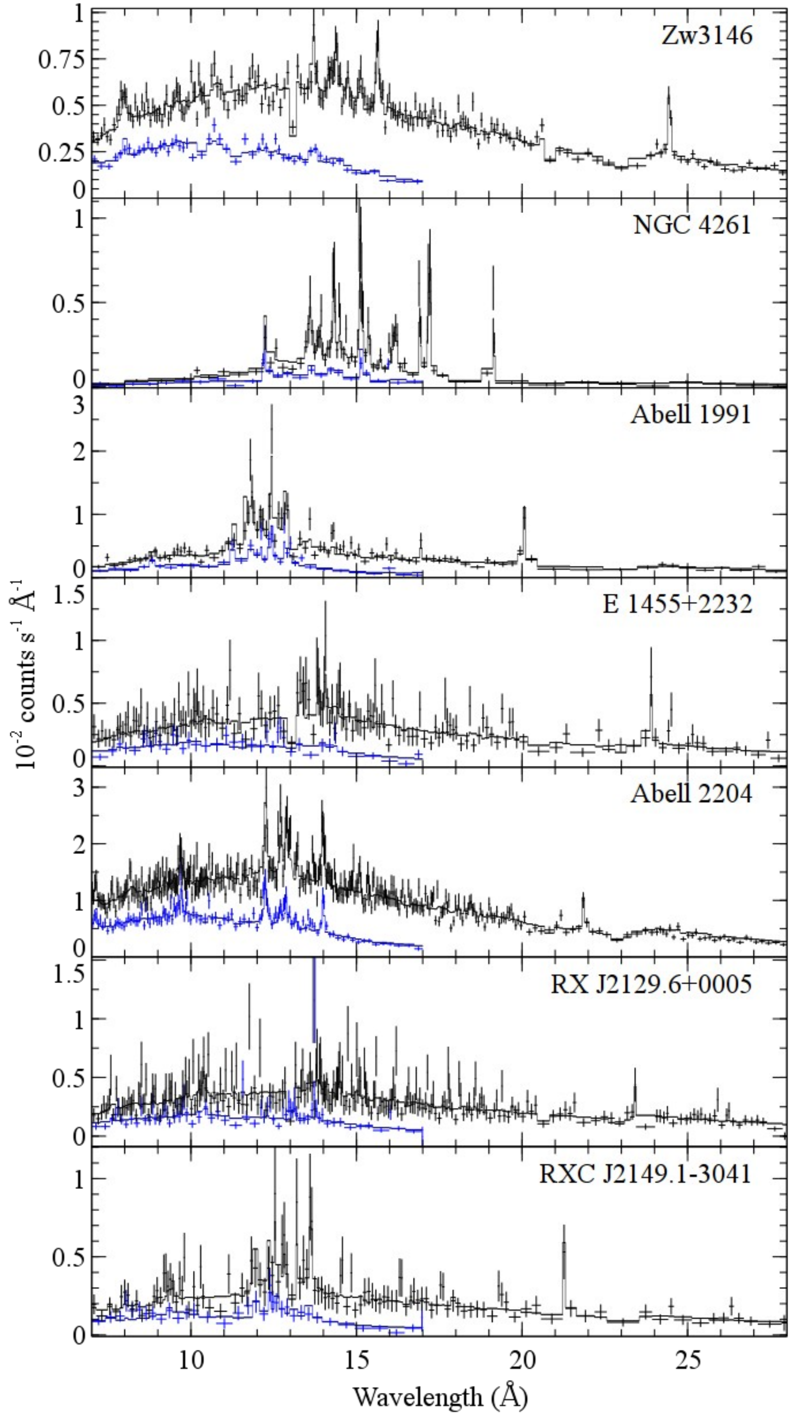
Ripples in Centaurus Cluster

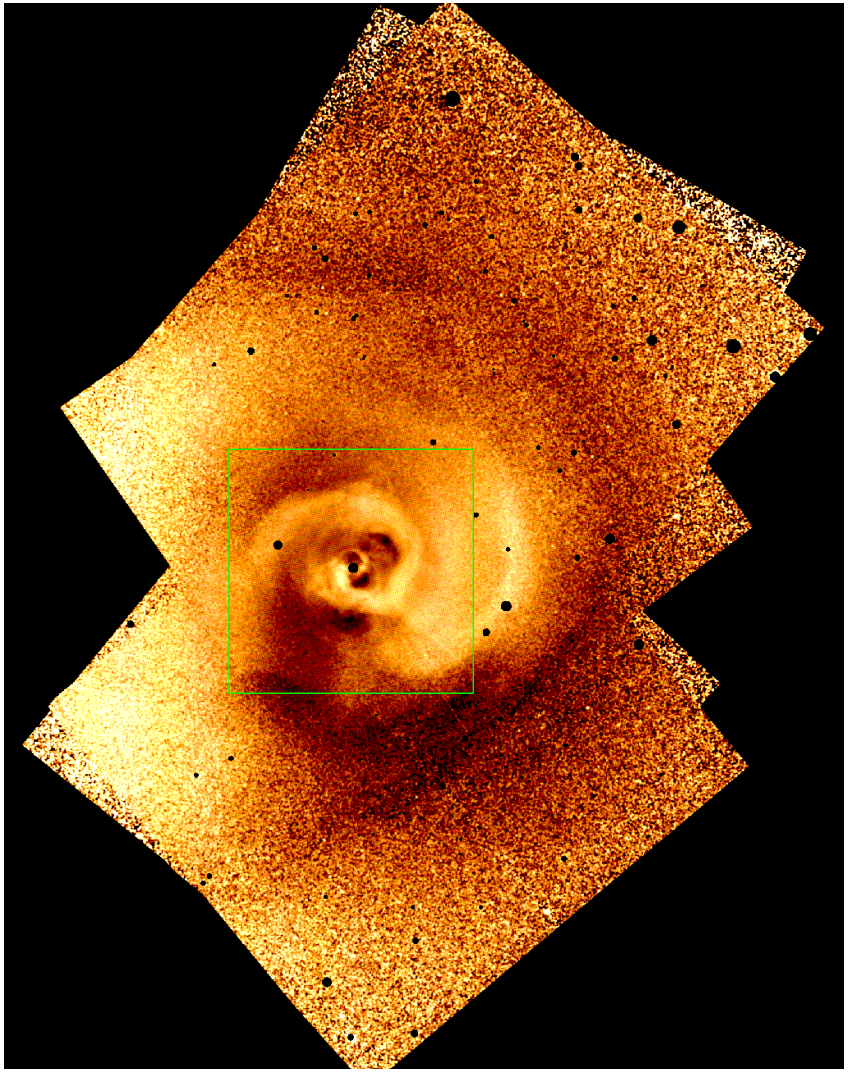
Sanders+Fabian 08

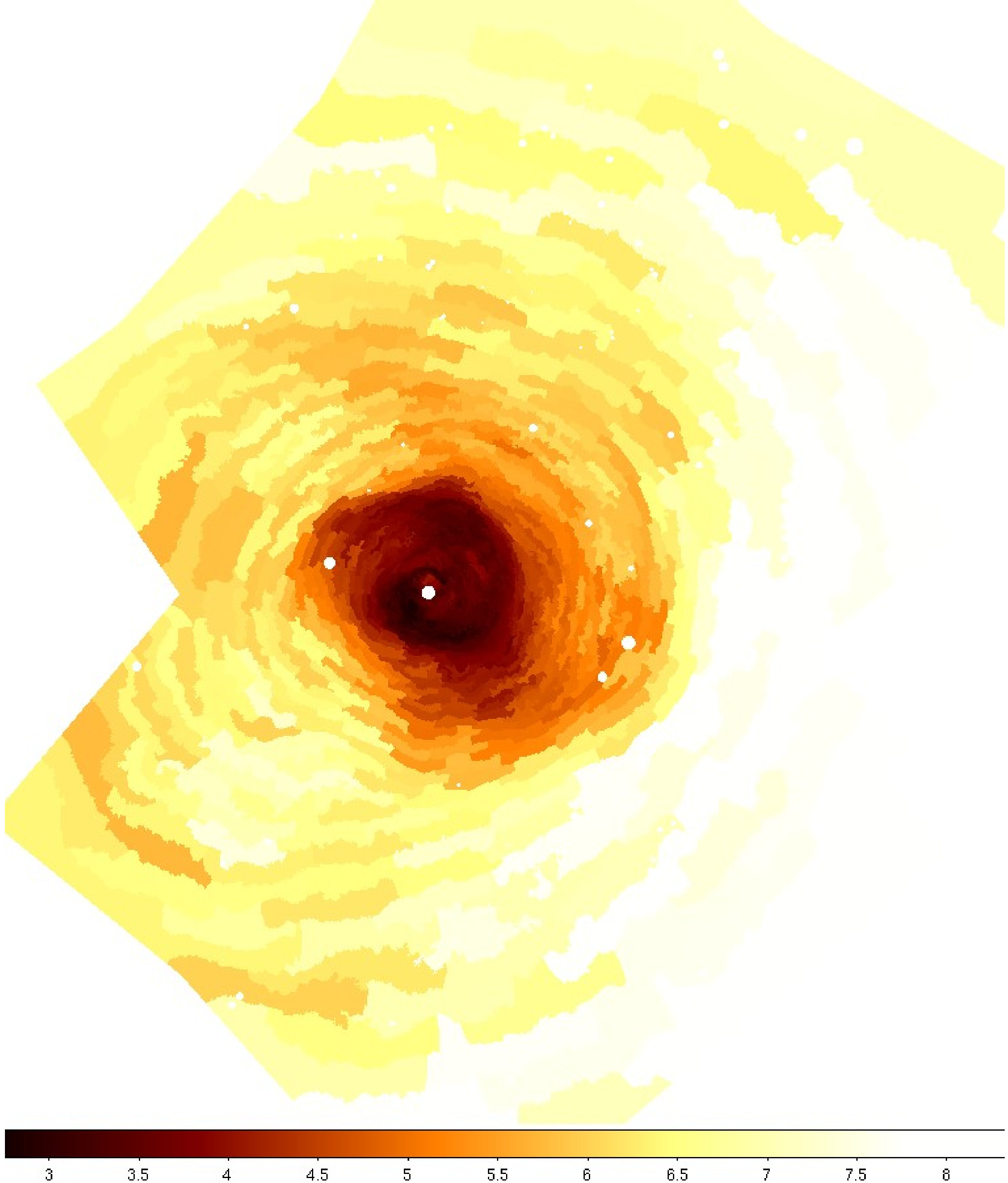


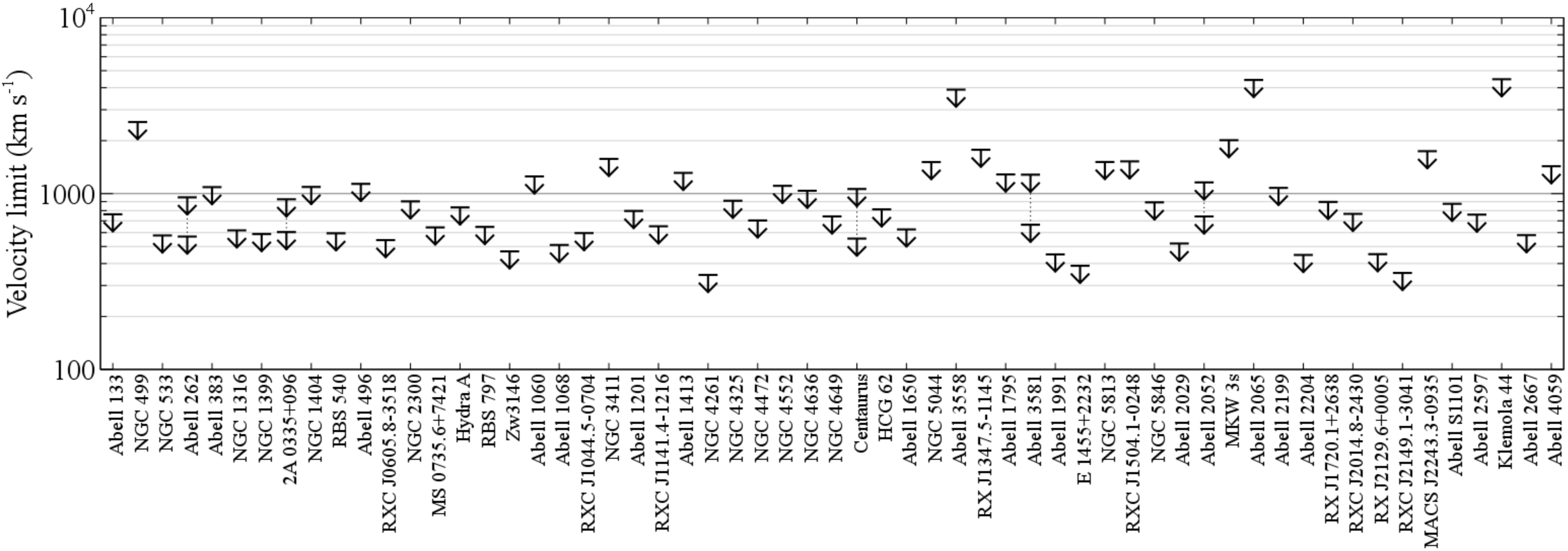


Sanders, Fabian, Smith 10 in prep



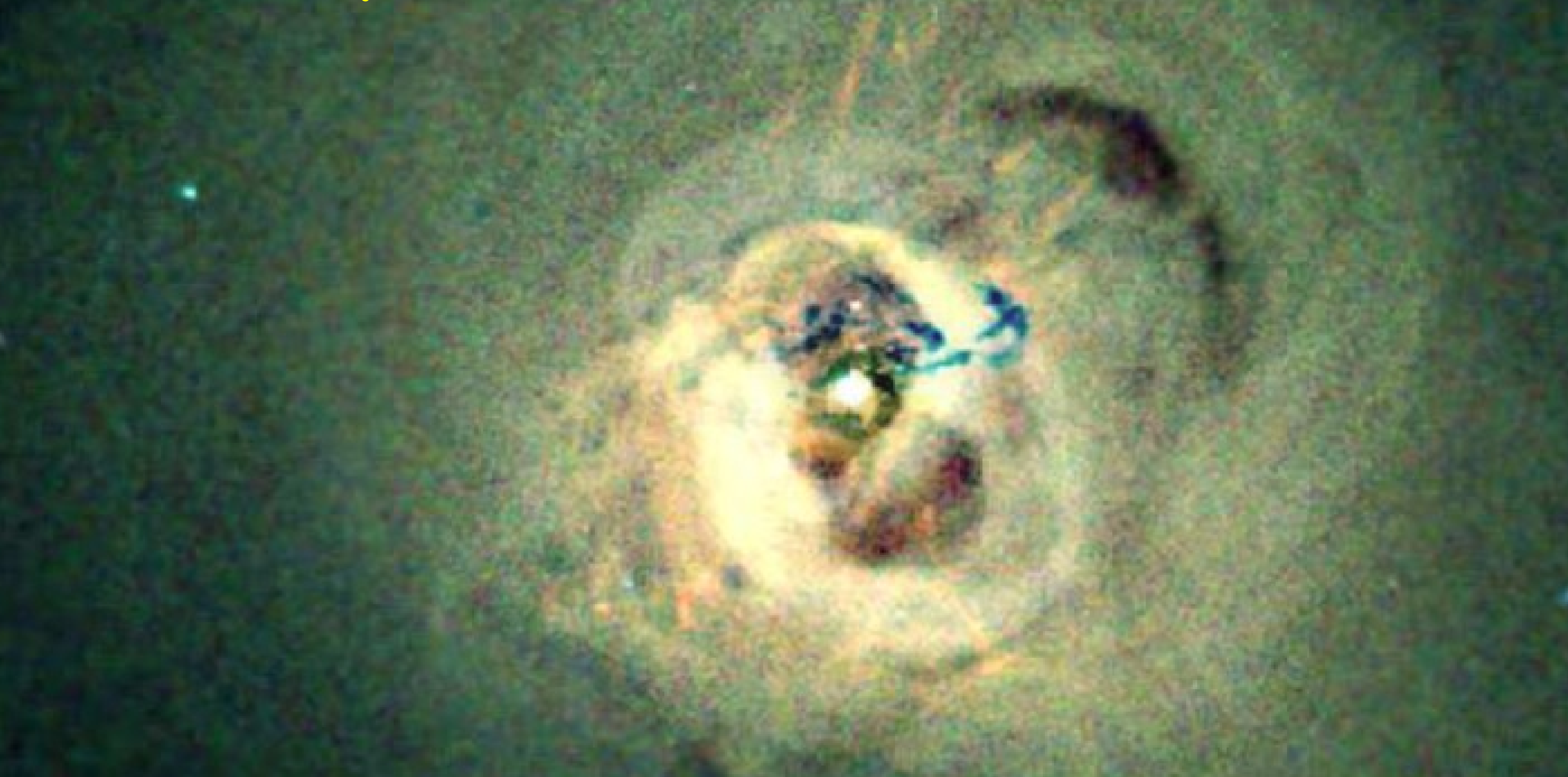



3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8



Velocity limit (km s^{-1})
10^4
1000
100
Abell 133
NGC 499
NGC 533
Abell 262
Abell 383
NGC 1316
NGC 1399
2A 0335+096
NGC 1404
RBS 540
Abell 496
RXC J0605.8-3518
NGC 2300
MS 0735.6+7421
Hydra A
RBS 797
Zw3146
Abell 1060
Abell 1068
RXC J1044.5-0704
NGC 3411
Abell 1201
RXC J1141.4-1216
Abell 1413
NGC 4261
NGC 4325
NGC 4472
NGC 4552
NGC 4636
NGC 4649
Centaurus
HCG 62
Abell 1650
NGC 5044
Abell 3558
RX J1347.5-1145
Abell 1795
Abell 3581
Abell 1991
E 1455+2232
NGC 5813
RXC J1504.1-0248
NGC 5846
Abell 2029
Abell 2052
MKW 3s
Abell 2065
Abell 2199
Abell 2204
RX J1720.1+2638
RXC J2014.8-2430
RX J2129.6+0005
RXC J2149.1-3041
MACS J2243.3-0935
Abell S1101
Abell 2597
Klemola 44
Abell 2667
Abell 4059

The Physics of Cool Cluster Cores



Andy Fabian
Institute of Astronomy, Cambridge, UK

Thermal content of bubbles?

Sanders&Fabian07

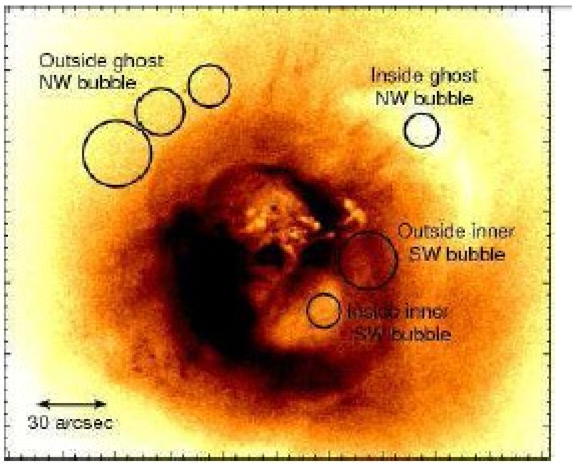


Figure 25. Regions used for examining the spectra inside and outside of the bubbles.

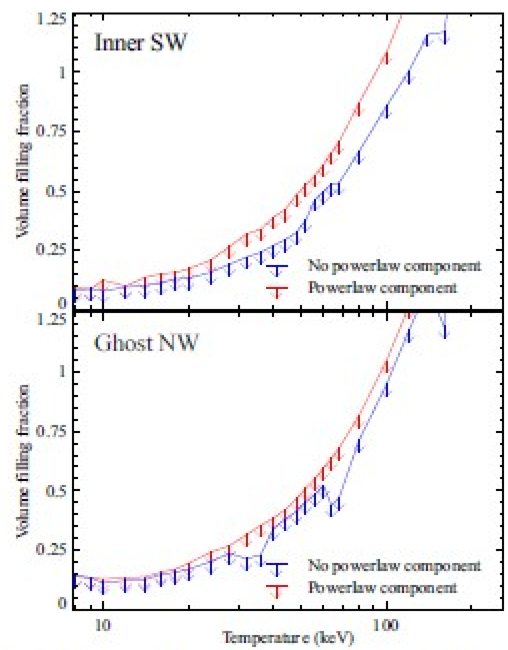


Figure 27. 2σ upper limits to the volume filling fraction of the bubbles. Models including a $\Gamma = 2$ powerlaw component are indicated.

For volume filling factor >50% kT>50 keV

Stability of bubbles

J. Fluid Mech. (1987), *vol.* 184, *pp.* 399–422 399
Printed in Great Britain

The stability of a large gas bubble rising through liquid†

By G. K. BATCHELOR
Department of Applied Mathematics & Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, UK

Mon. Not. R. Astron. Soc. **359,** 493–503 (2005) doi:10.1111/j.1365-2966.2005.08

The stability of buoyant bubbles in the atmospheres of galaxy clusters

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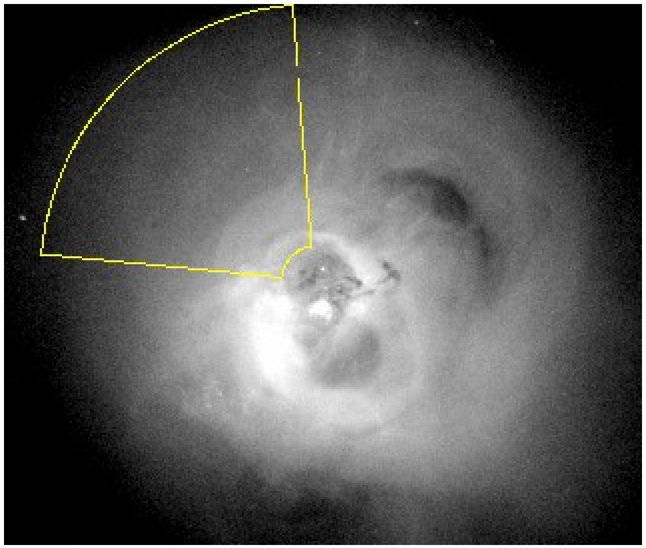
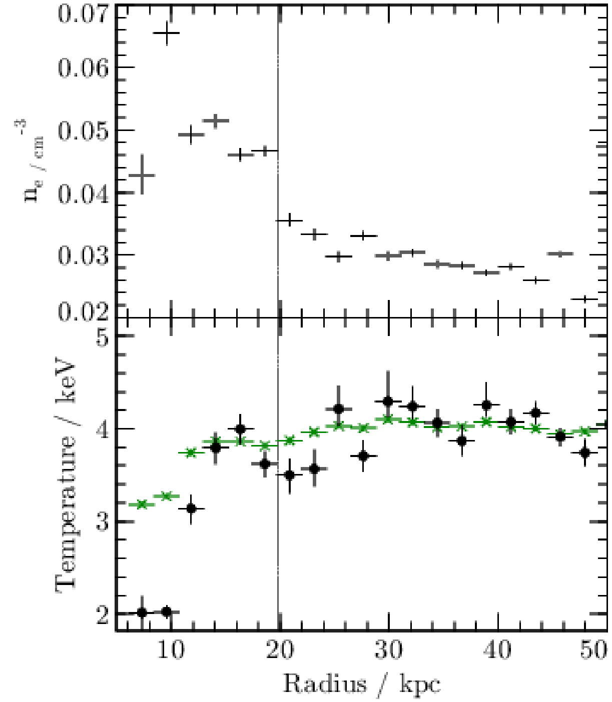
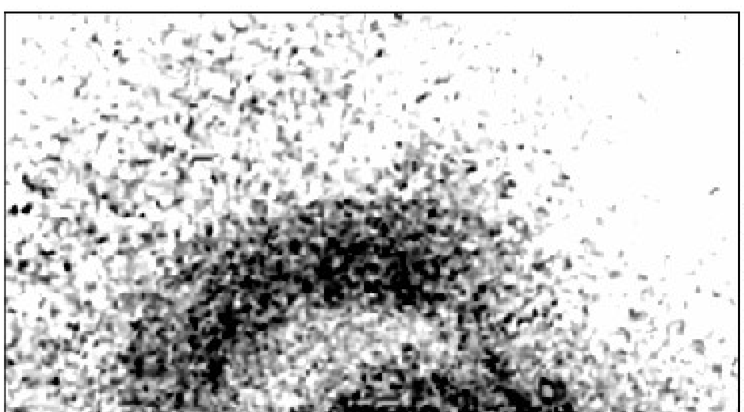
[1] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ*
[2] *School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ*

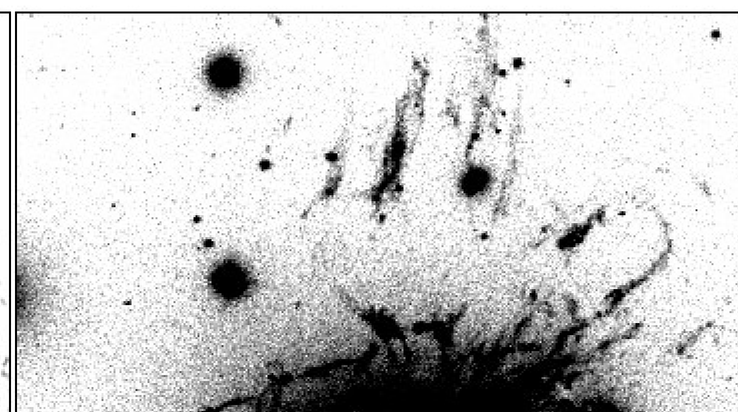
Dynamics, viscosity and magnetic draping help to stabilise bubbles and make them long-lived

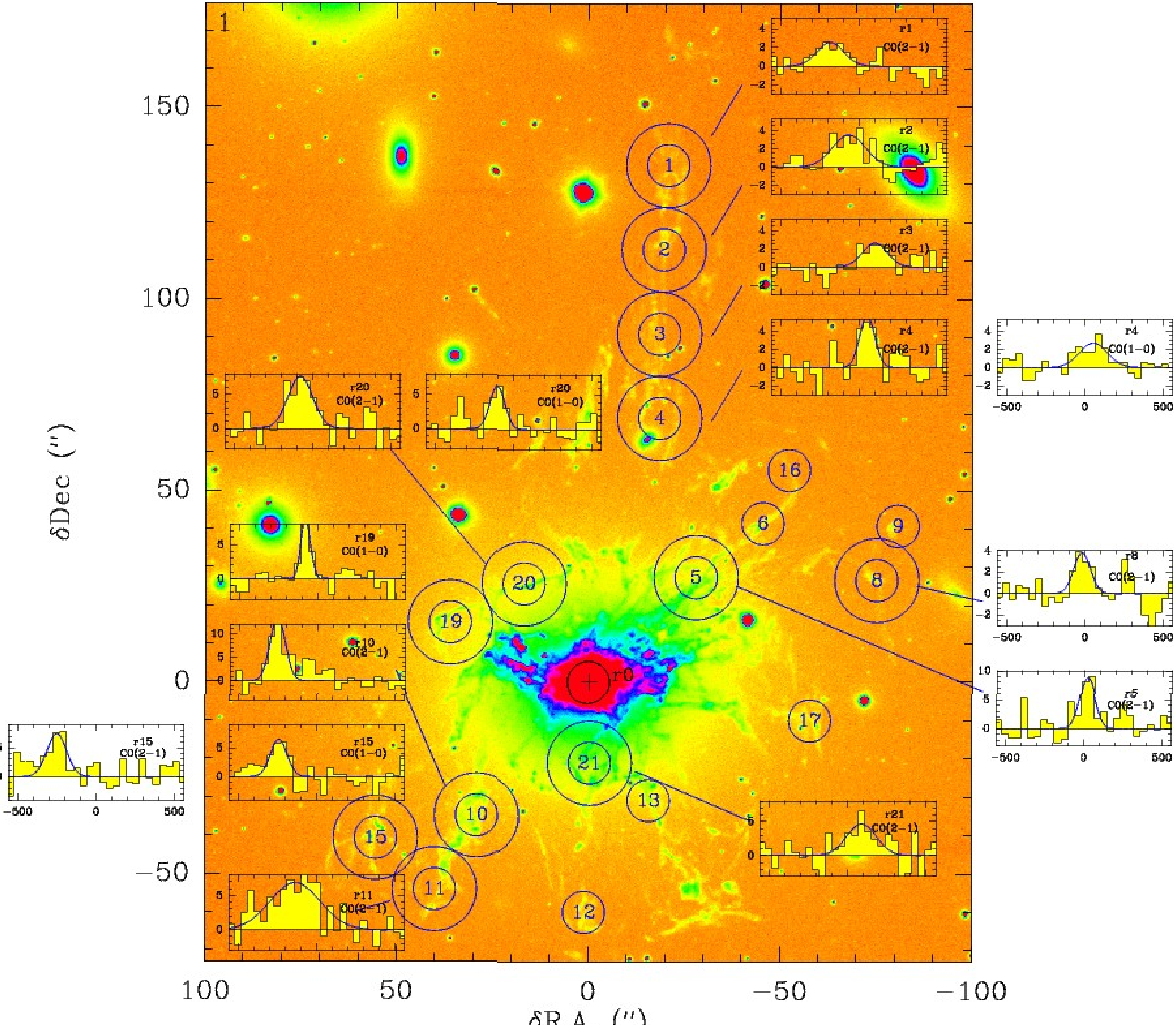
The weak shock

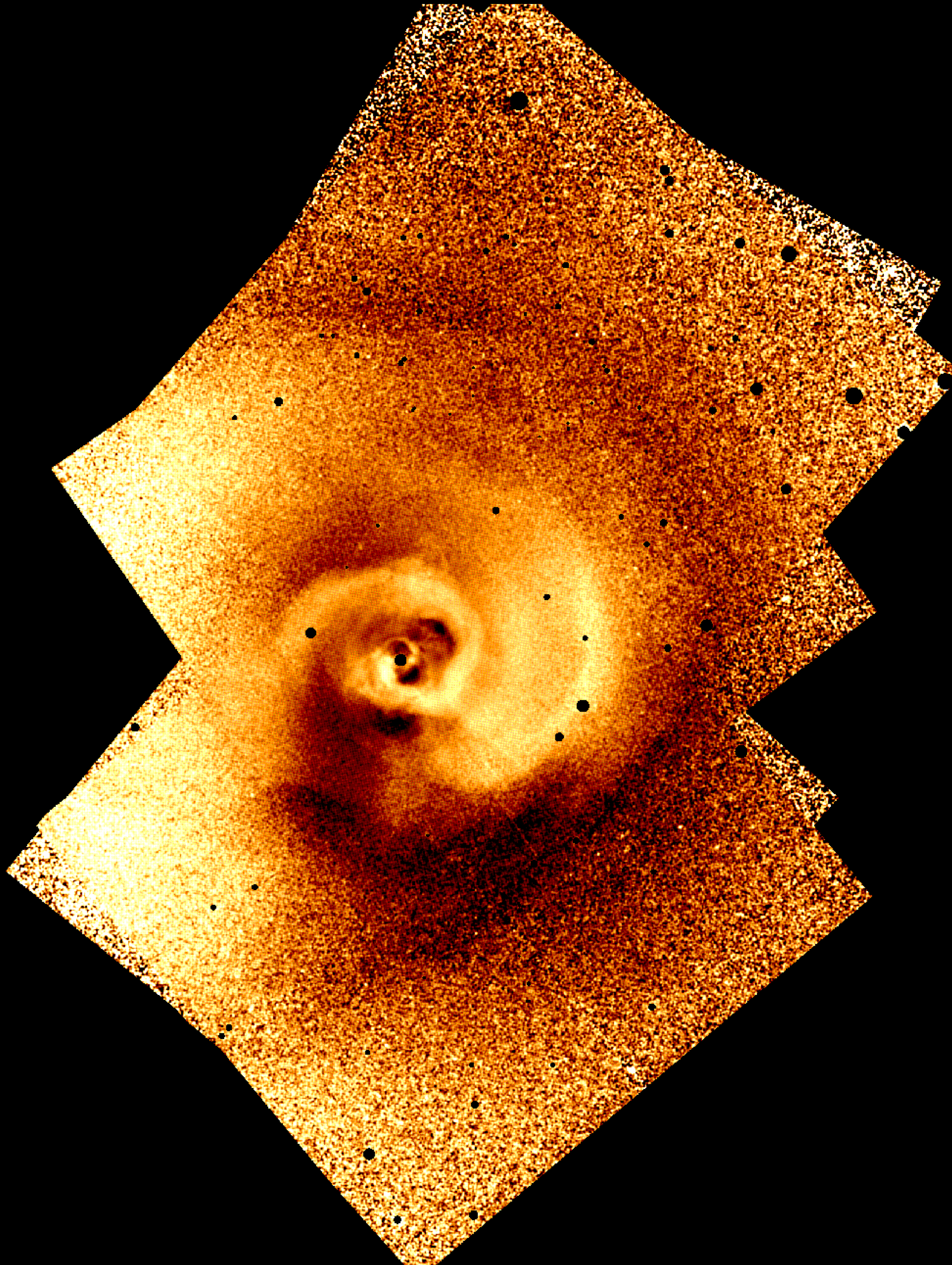









δDec (″)
δR.A. (″)
r0
r1 CO(2−1)
r2 CO(2−1)
r3 CO(2−1)
r4 CO(2−1)
r4 CO(1−0)
r8 CO(2−1)
r5 CO(2−1)
r20 CO(2−1)
r20 CO(1−0)
r19 CO(1−0)
r19 CO(2−1)
r15 CO(2−1)
r15 CO(1−0)
r11 CO(2−1)
r21 CO(2−1)



Optical