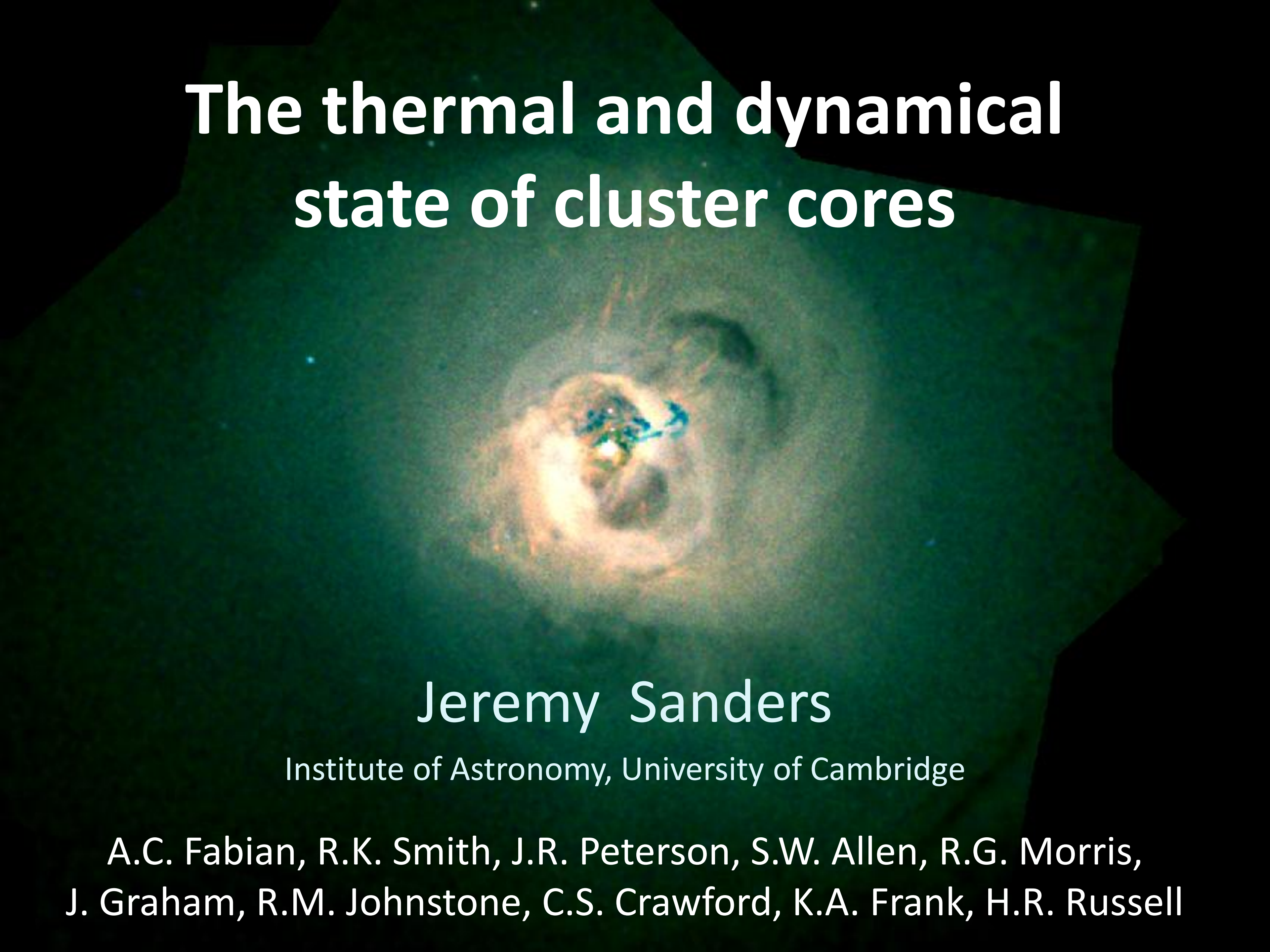


The thermal and dynamical state of cluster cores

Jeremy Sanders

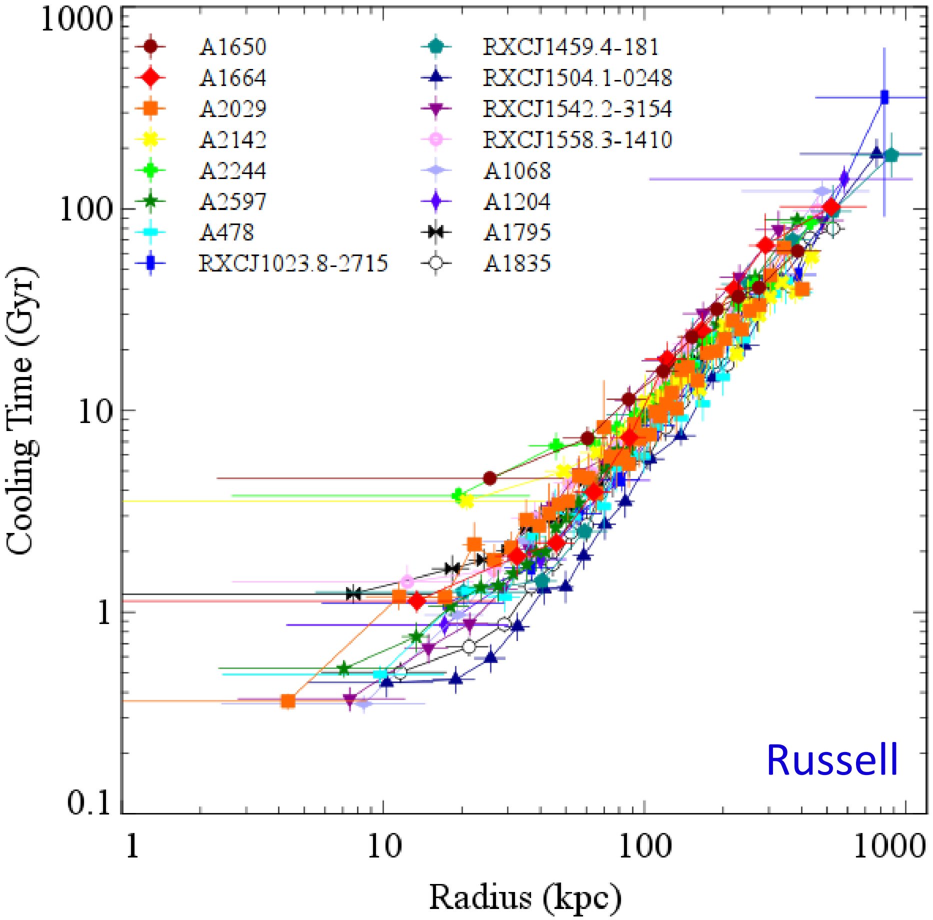
Institute of Astronomy, University of Cambridge

A.C. Fabian, R.K. Smith, J.R. Peterson, S.W. Allen, R.G. Morris,
J. Graham, R.M. Johnstone, C.S. Crawford, K.A. Frank, H.R. Russell

THERMAL STATE OF CLUSTER CORES

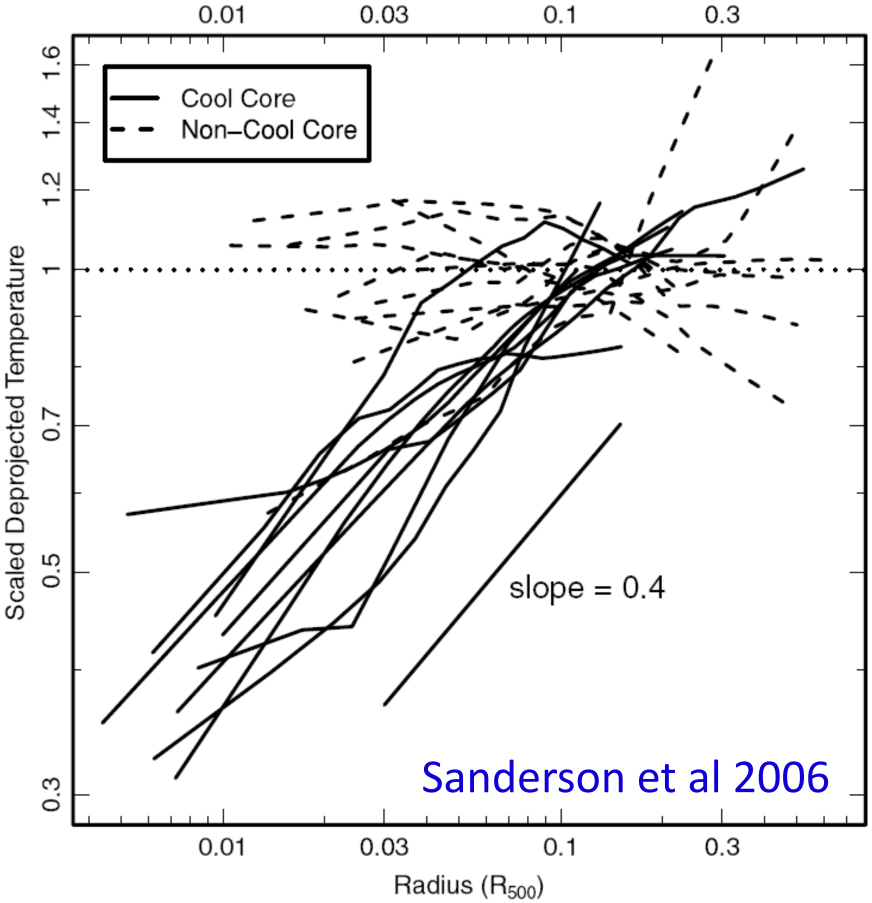
Cluster radial properties

Mean radiative cooling time



Russell

Temperature



Sanderson et al 2006

- Steeply peaked surface brightness profiles
- Mean radiative cooling times in centres < 10^9 years
- Cluster centres cooler by ~1/2 to 1/3

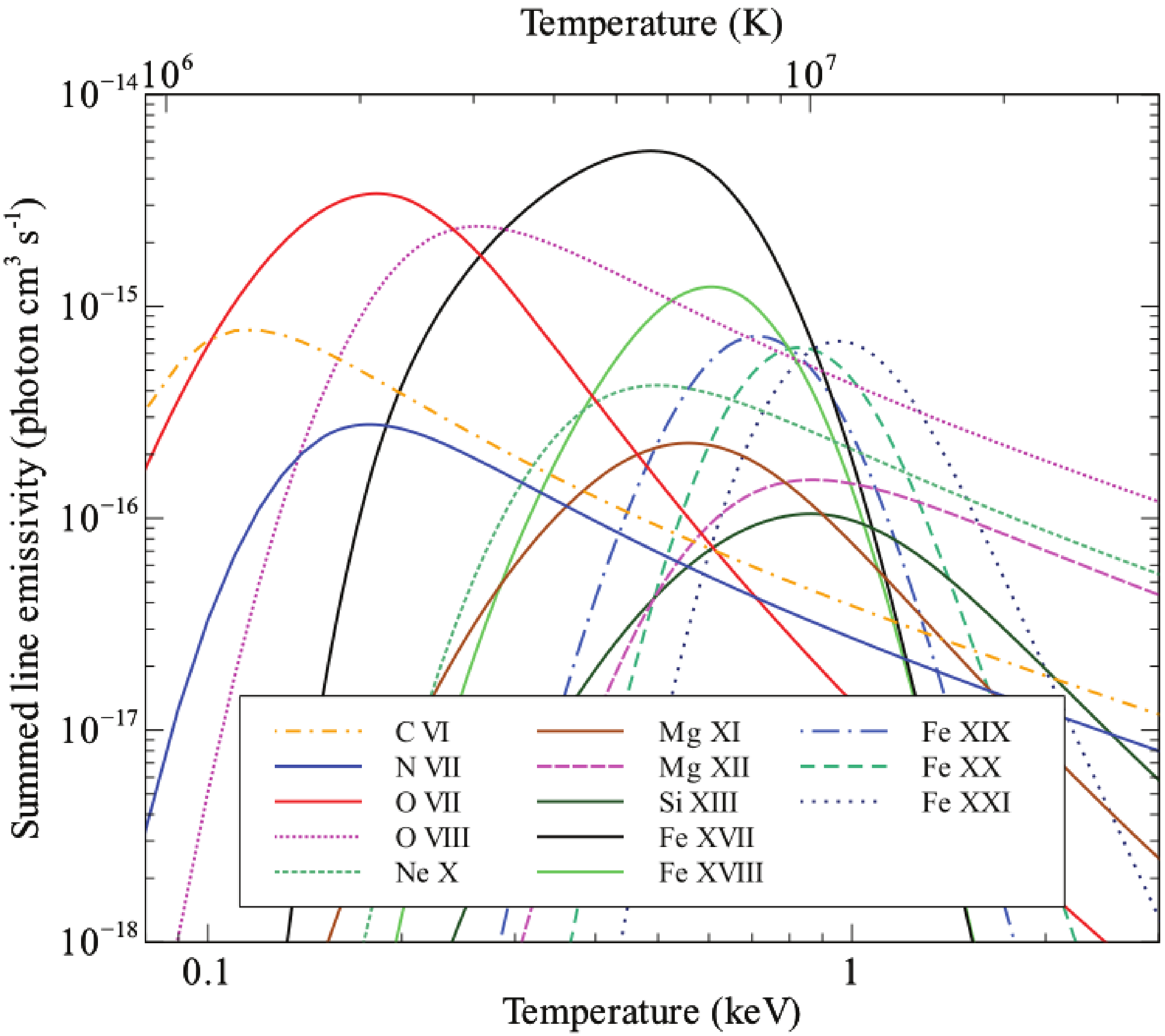
Cooling in cluster cores

- If no heating, should be a mass deposition rate

$$\dot{M} \approx \frac{2}{5} \frac{L \mu m}{kT}$$

- Luminosities imply 10-1000s $M_\odot$ yr^{-1}
- "Cooling flow" (Fabian 1994)

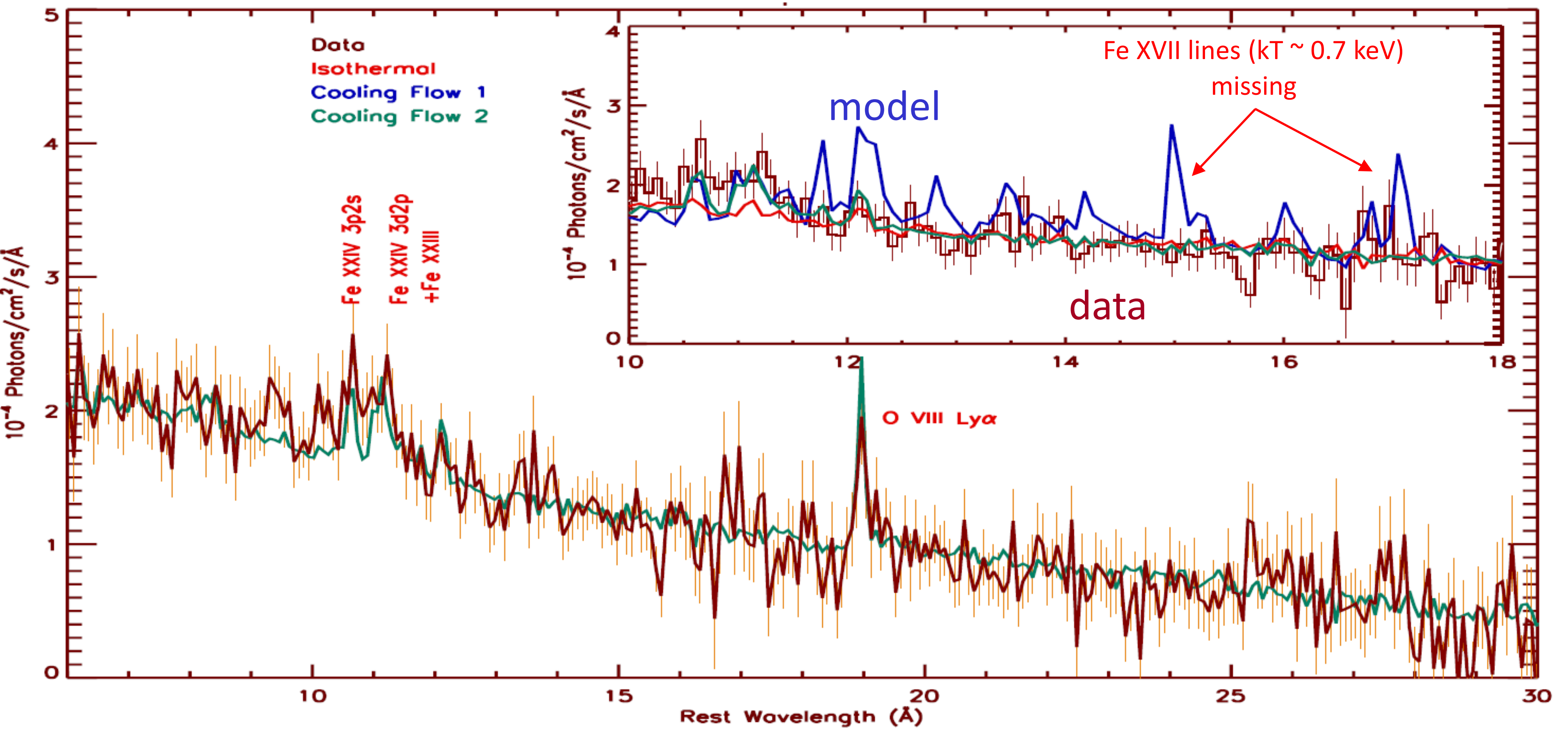
Line emissivity vs temperature



Sanders & Fabian 2011

Lack of cool X-ray emitting gas

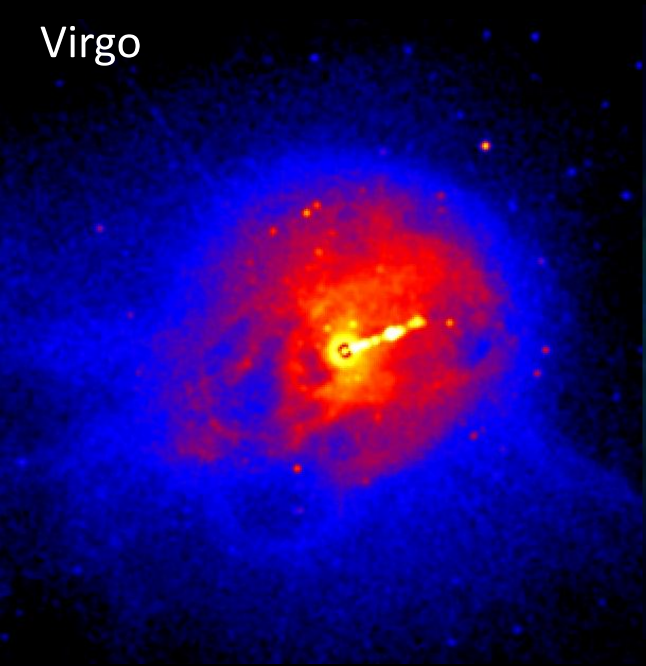
Abell 1835: Peterson et al 2001 (**60 ks** XMM-Newton RGS observation)



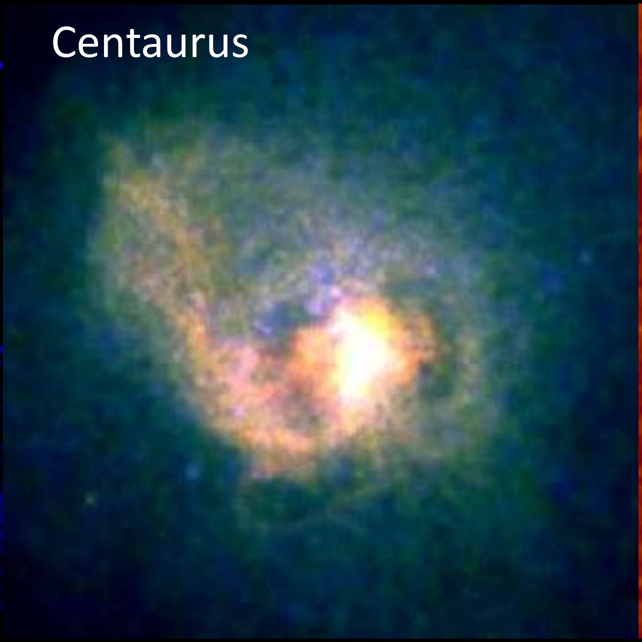
Less than 10% of cooling rates expected

Down to 1/2 or 1/3 outer temperature

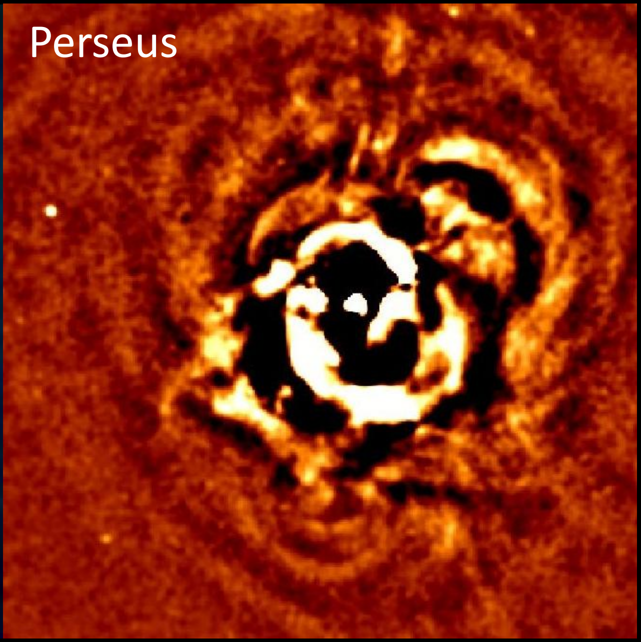
see also Peterson et al 03, Kaastra et al 01, 03, Tamura et al 01,...



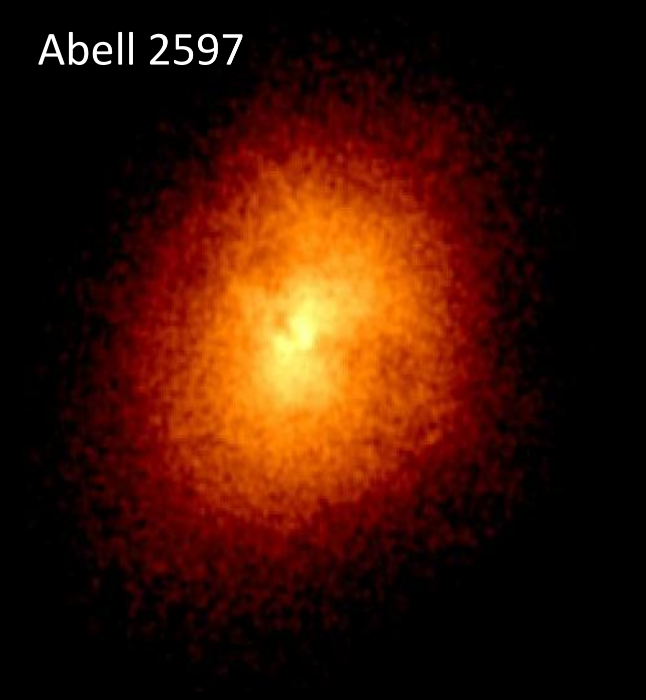
Virgo



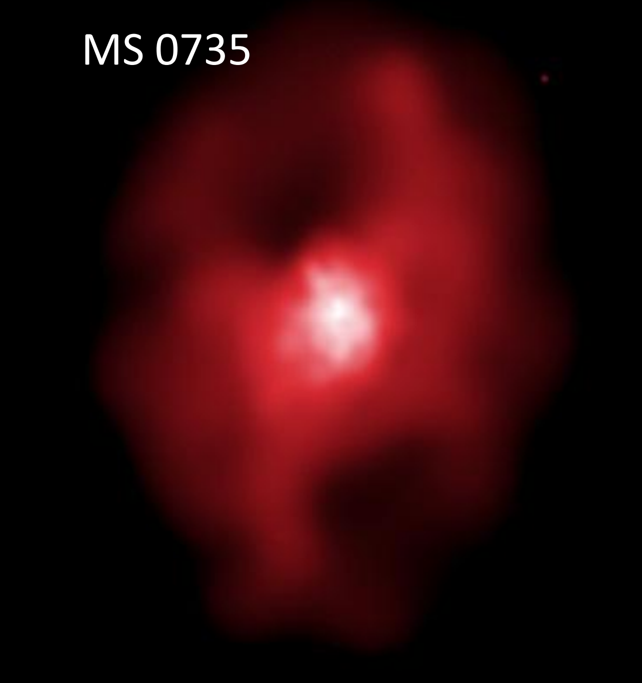
Centaurus



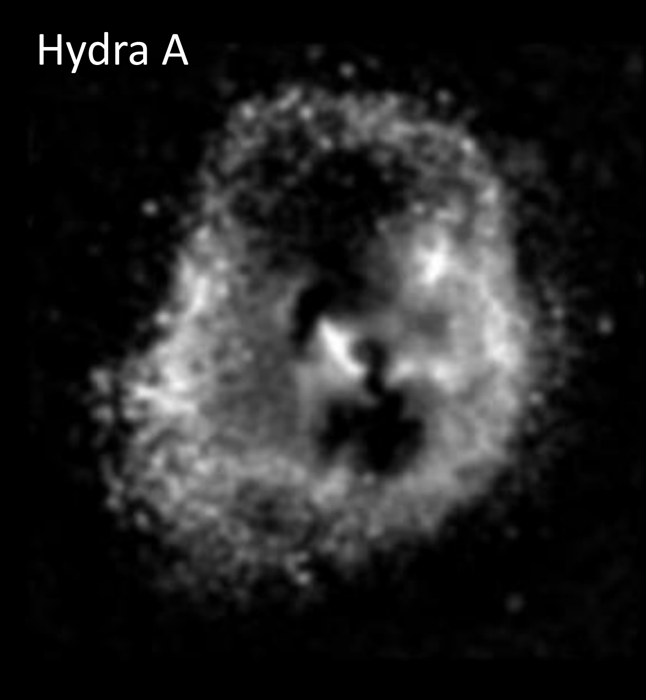
Perseus



Abell 2597



MS 0735



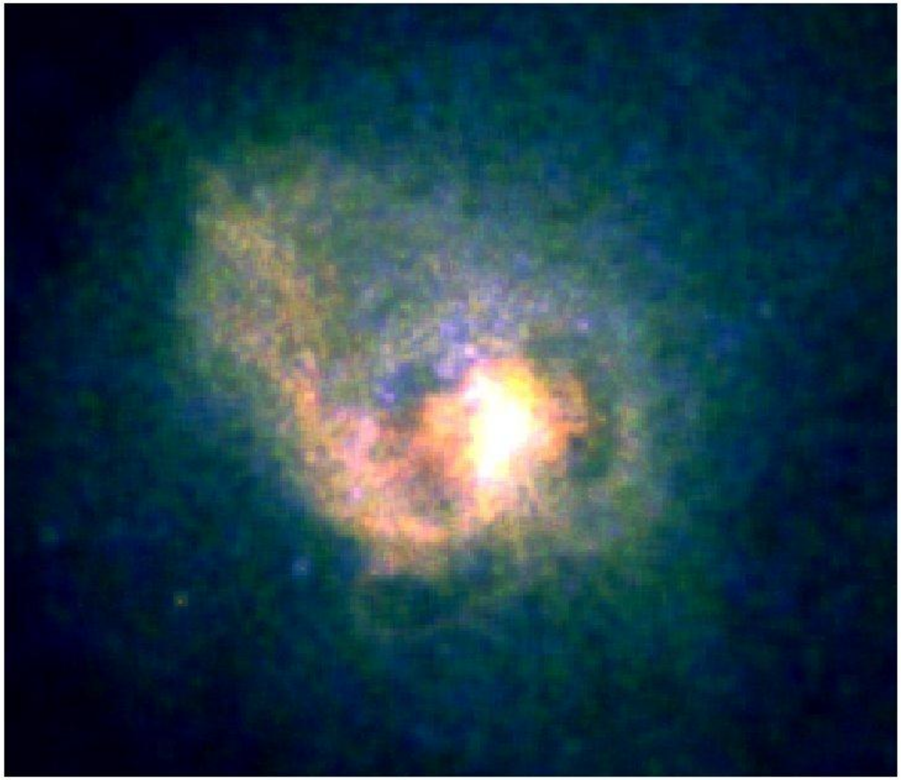
Hydra A

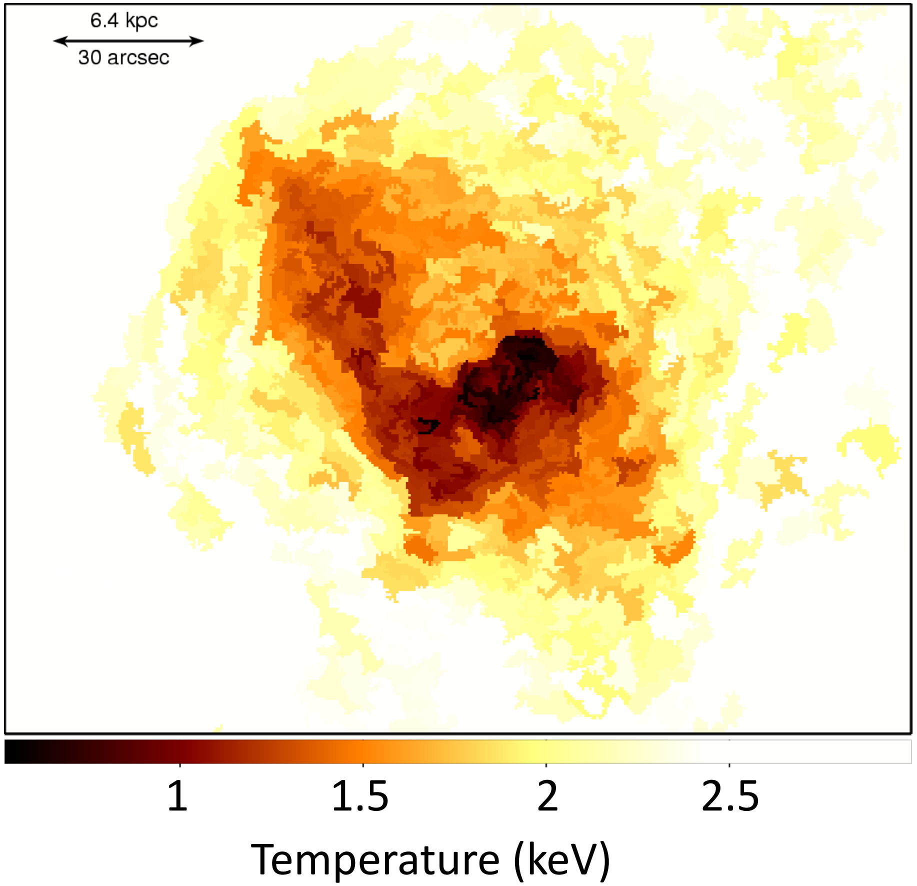
Centaurus cluster

Fabian et al 2005

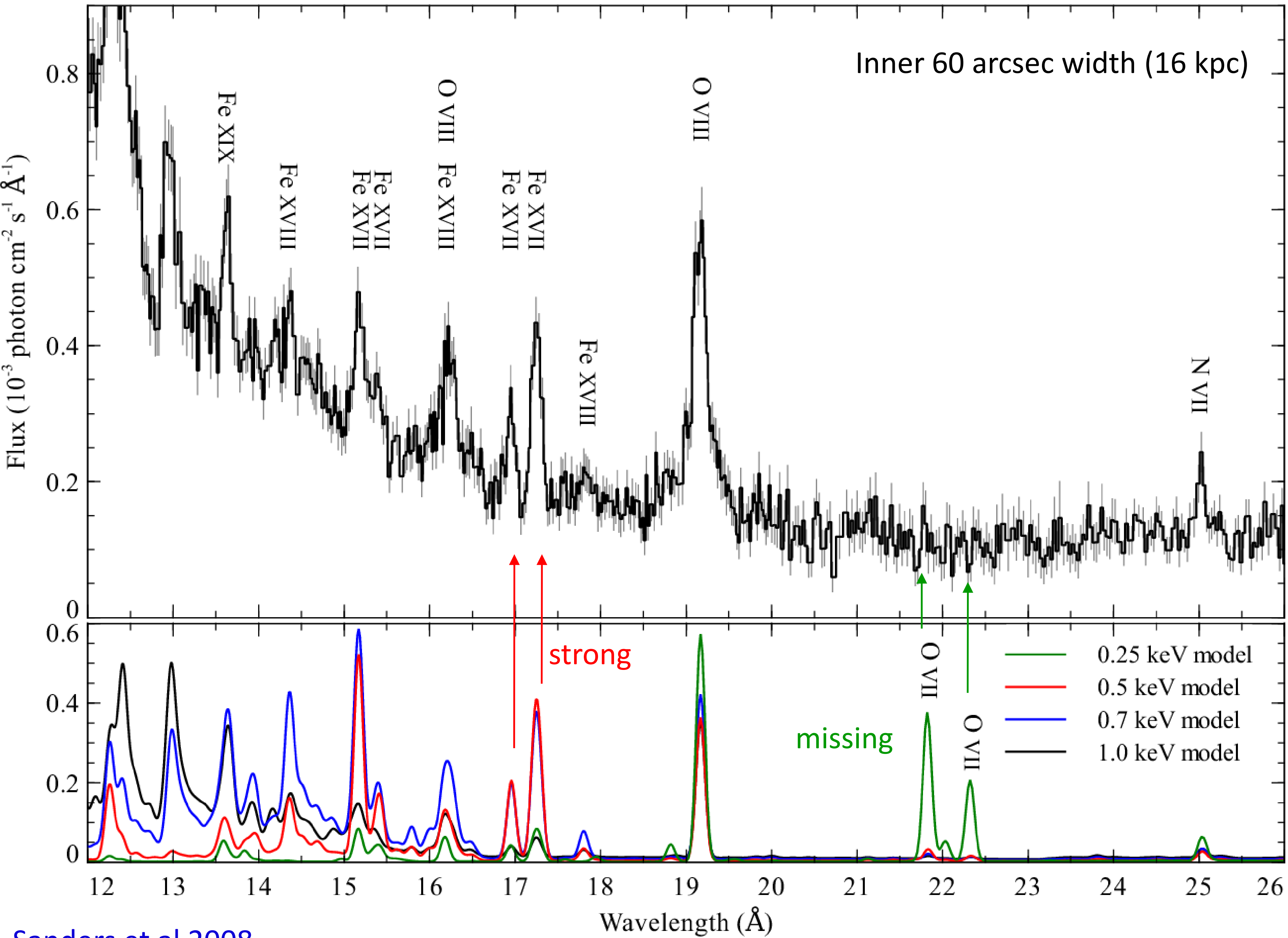
Chandra 200ks observation

Crawford et al 2005





- Centaurus: metal rich (2 solar), nearby (z=0.010) and cool core
- Ideal object for deep 160 ks XMM RGS observation



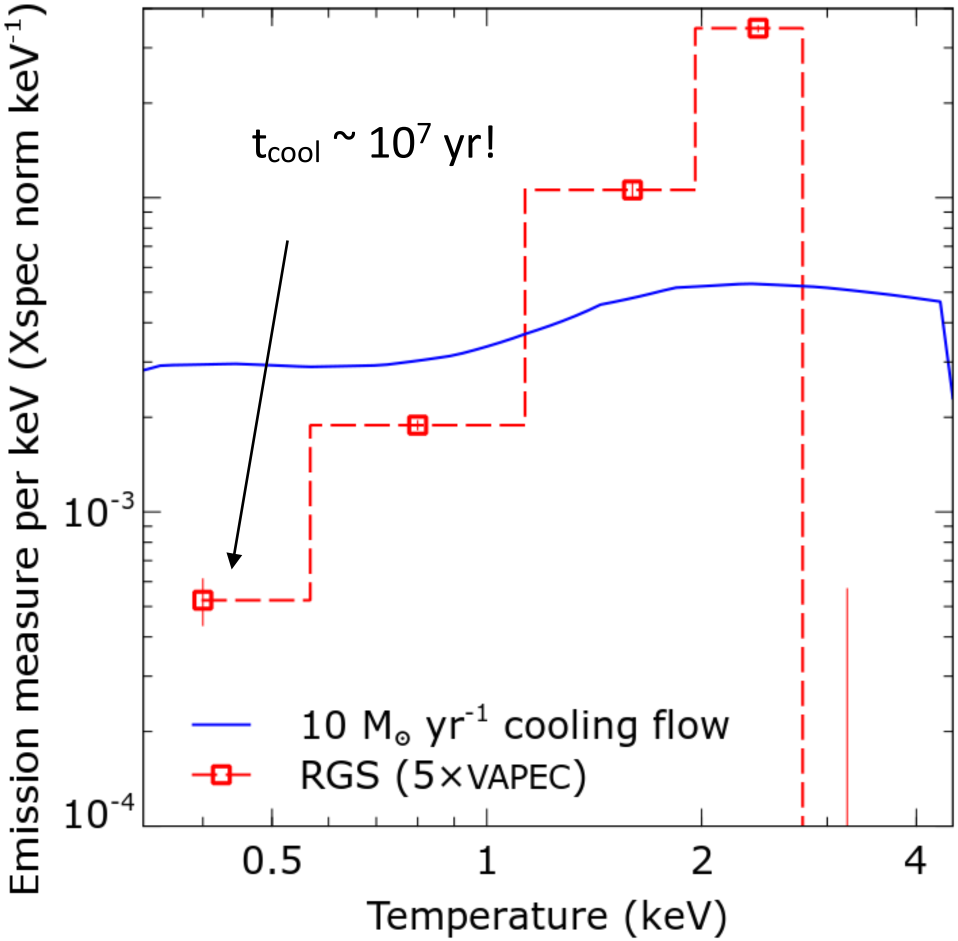
Inner 60 arcsec width (16 kpc)

strong

missing

Sanders et al 2008

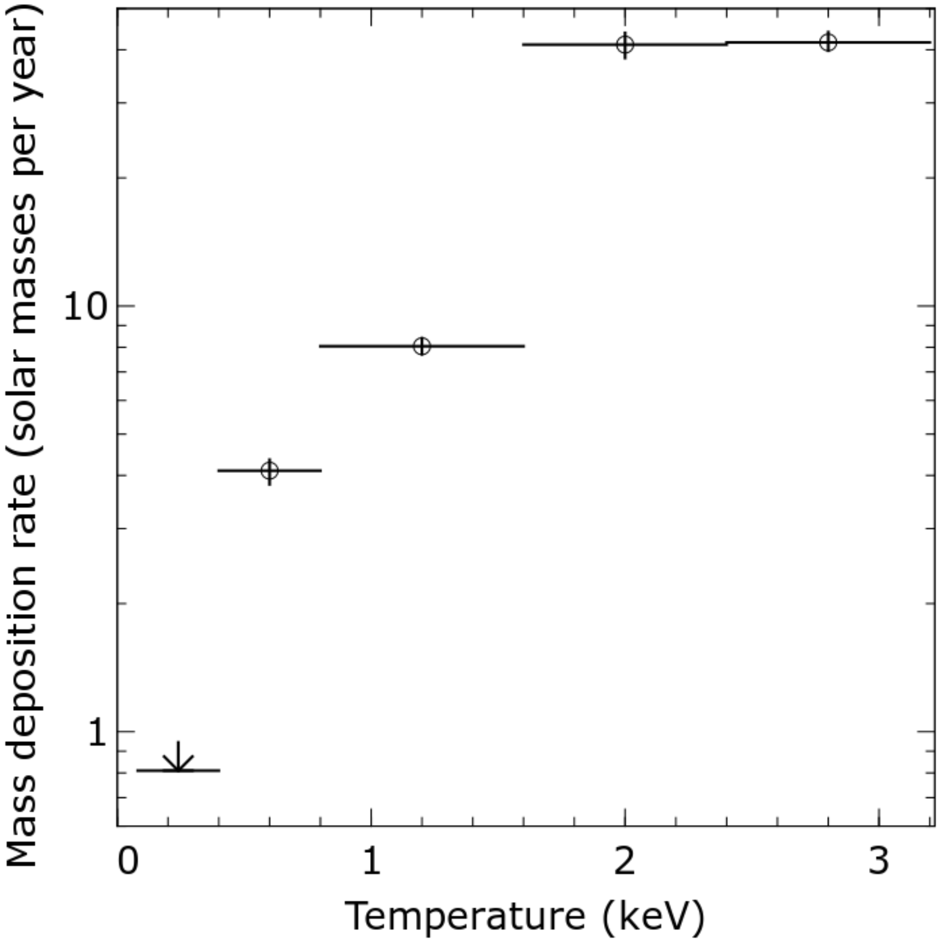
Centaurus – spectral fitting limits on gas kT



$t_{cool} \sim 10^7$ yr!

Multi temperature model

fixed temperatures but
varying emission measure



Cooling model

mass cooling rate in absence of heating

Factor of 10 in temperature

> factor of 10 in mass cool rate

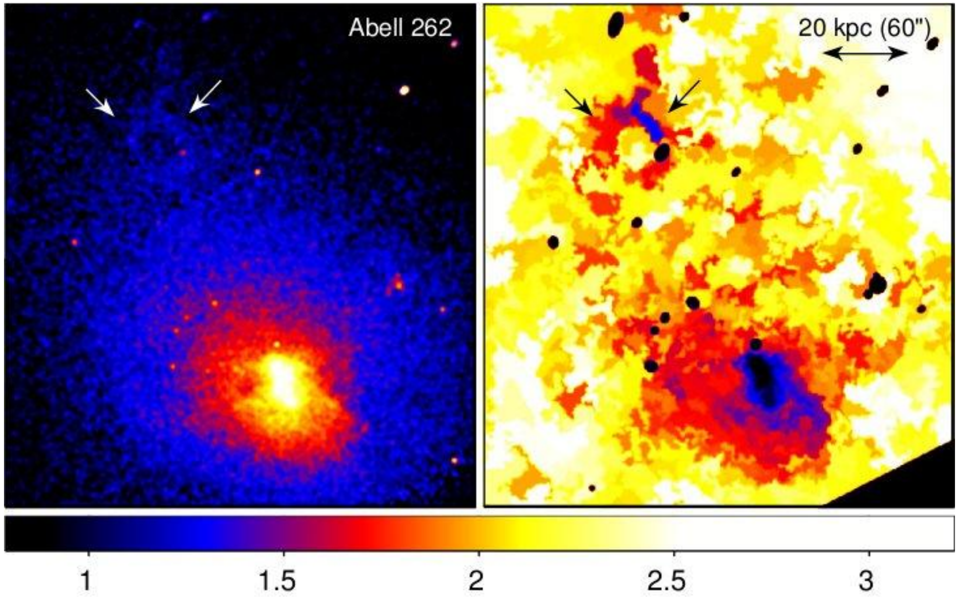
Deep observation sample

Sanders et al 2010

Cooler objects with strong emission lines:

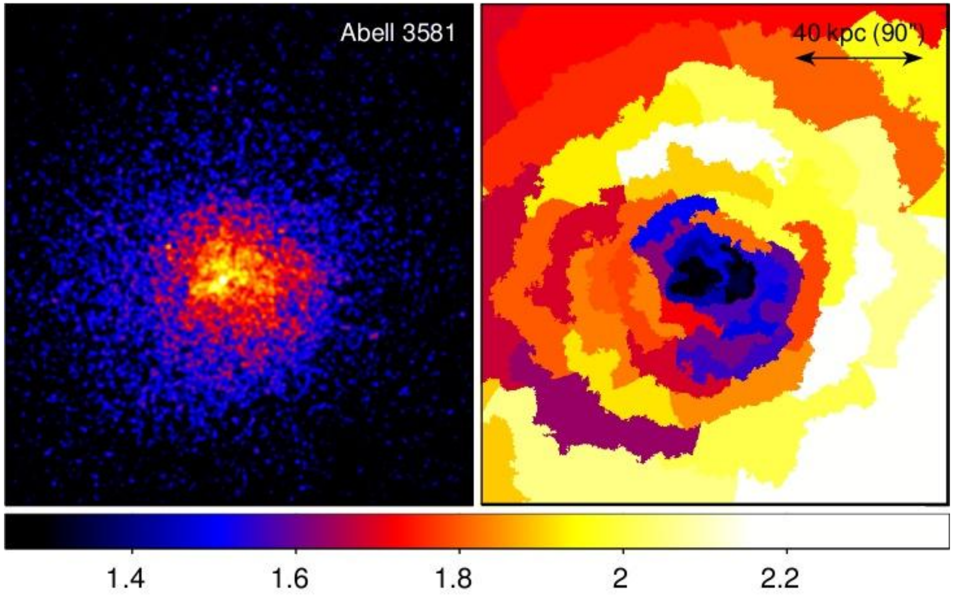
- A262, A3581 and HCG62

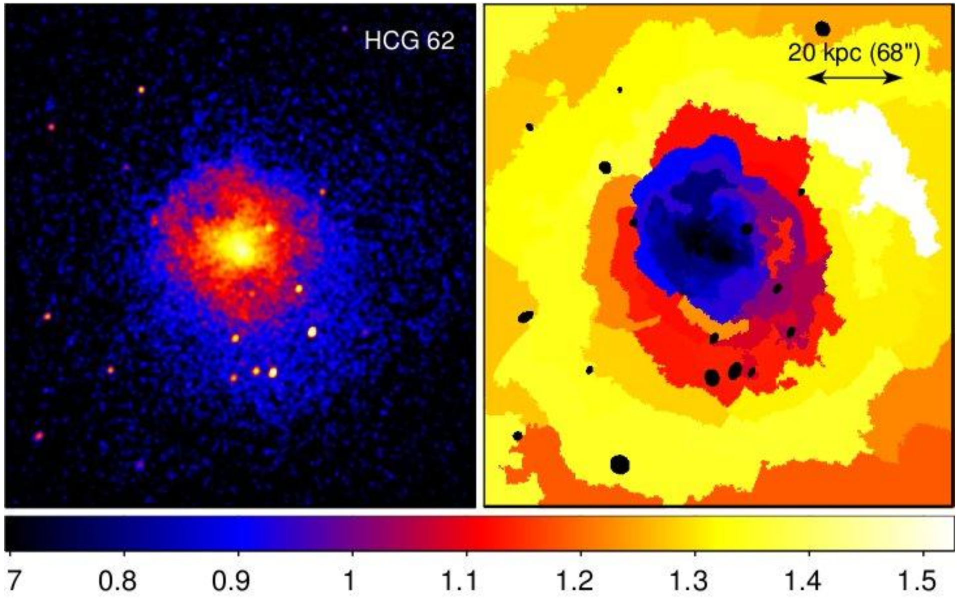
Exposure times 155 to 190 ks



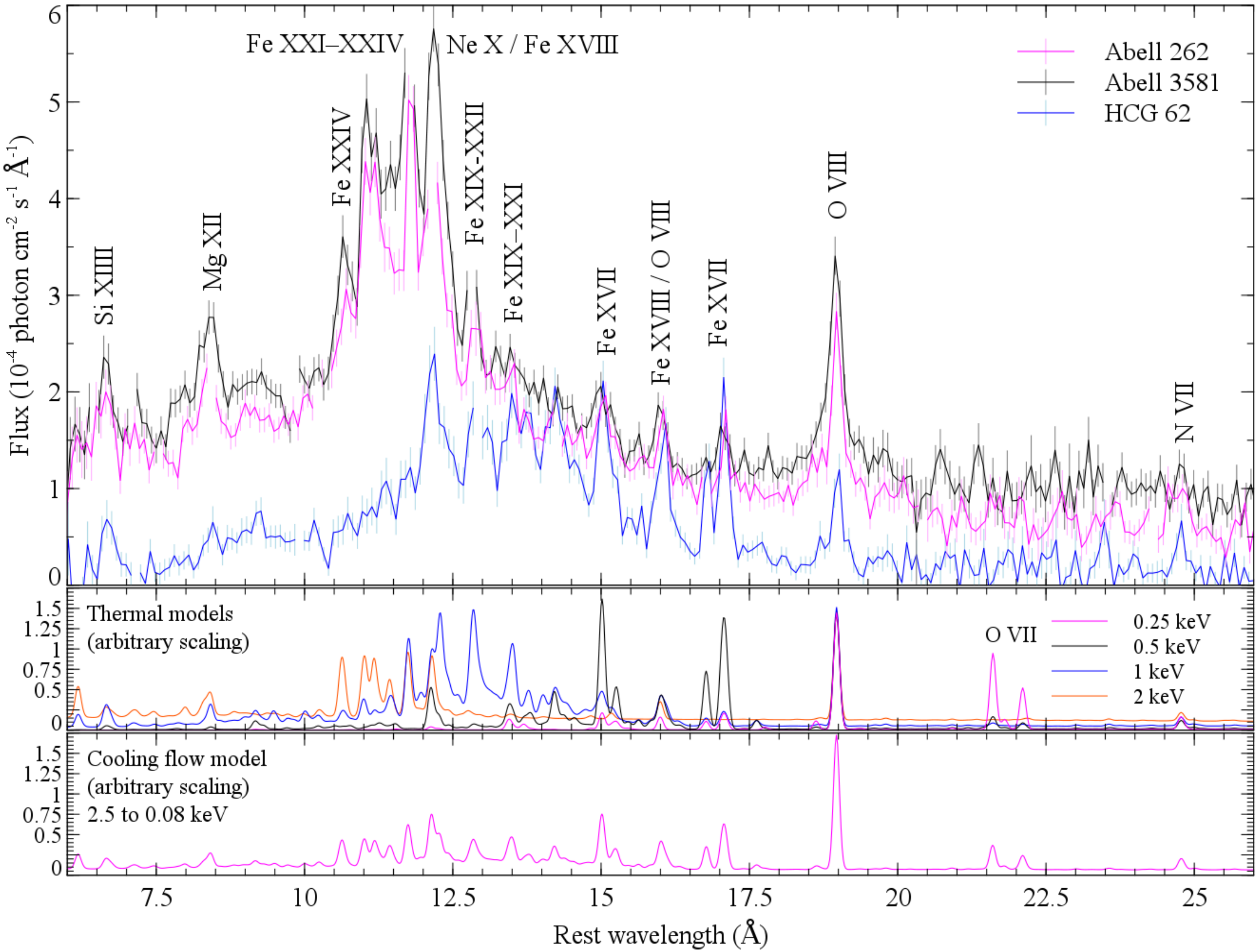
Chandra image

Chandra Temperature map



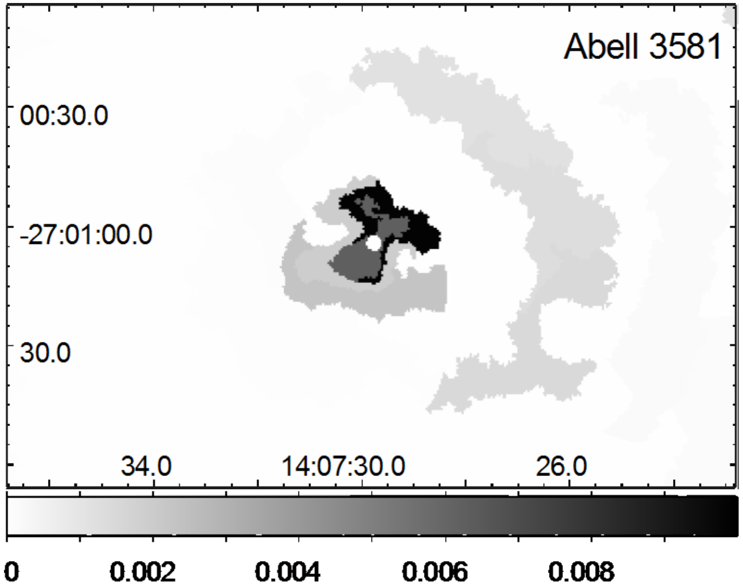


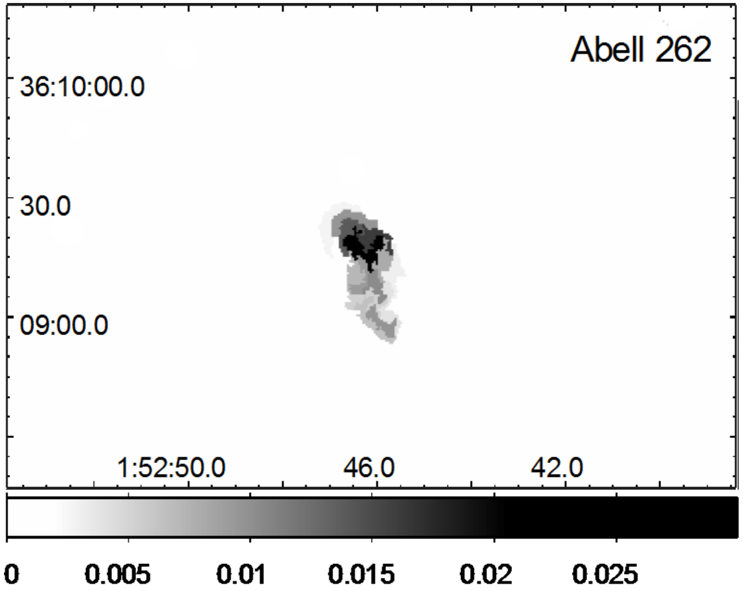
Deep sample – RGS spectra



Volume filling fraction

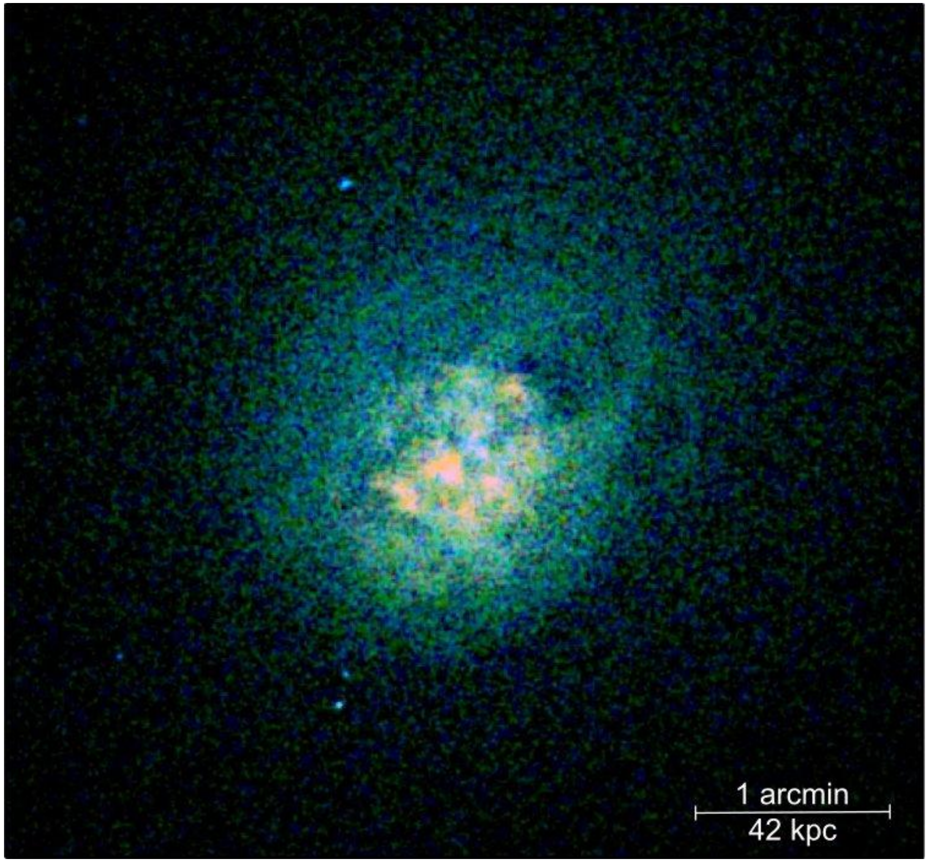
- Cool gas has low volume filling fraction: multiphase
- Blobs have half temperature of surrounds
- Emissivity 4× larger (if pressure balance)
- AGN heating cannot work in volume-averaged way
- Range in temperature larger in hotter clusters, e.g.
    - 15 in A2204 (Sanders et al 2009a)
    - 12 in Perseus (Sanders & Fabian 2007)
    - 10 in A1835 (Sanders et al 2010)
- Non radiative cooling?





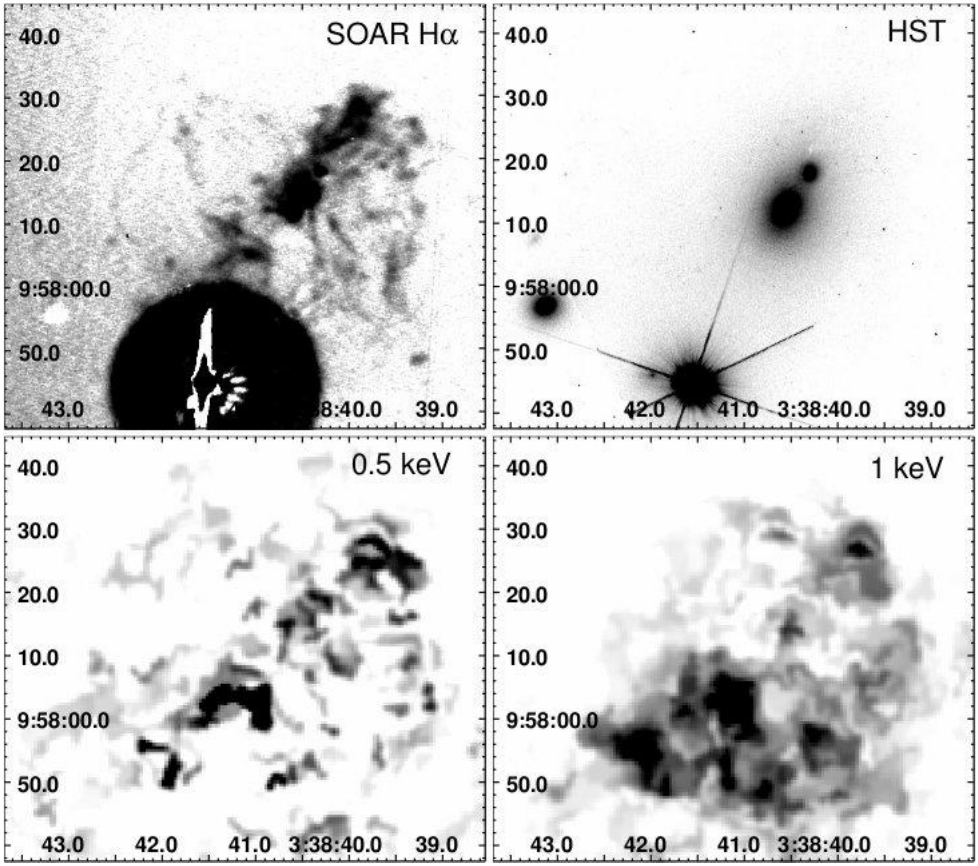
2A 0335+096: multiphase material

RGB Chandra image (94 ks)



Hα

HST



0.5 keV component

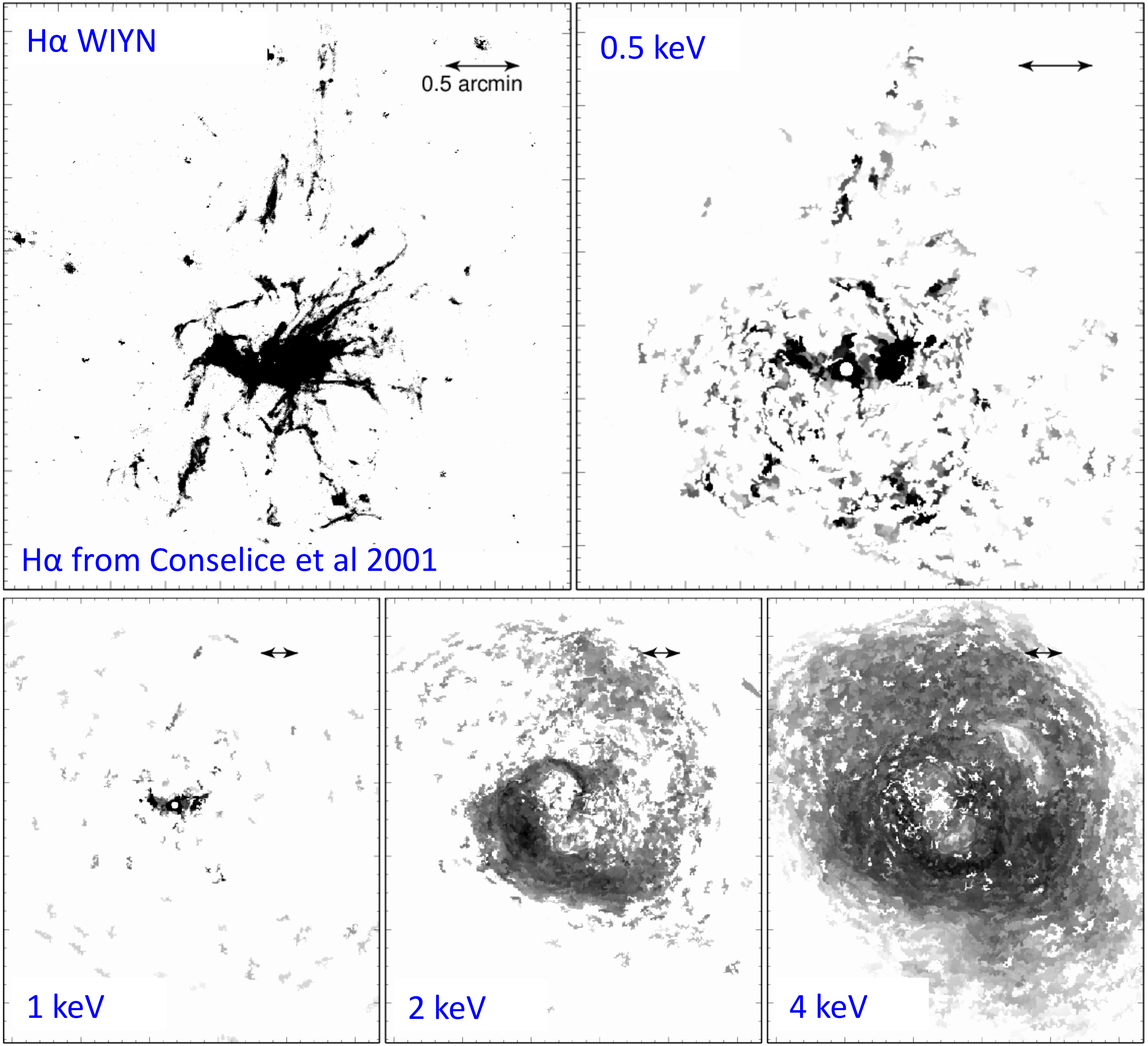
1 keV component

Sanders et al 2009a

Volume filling fraction ~0.2%

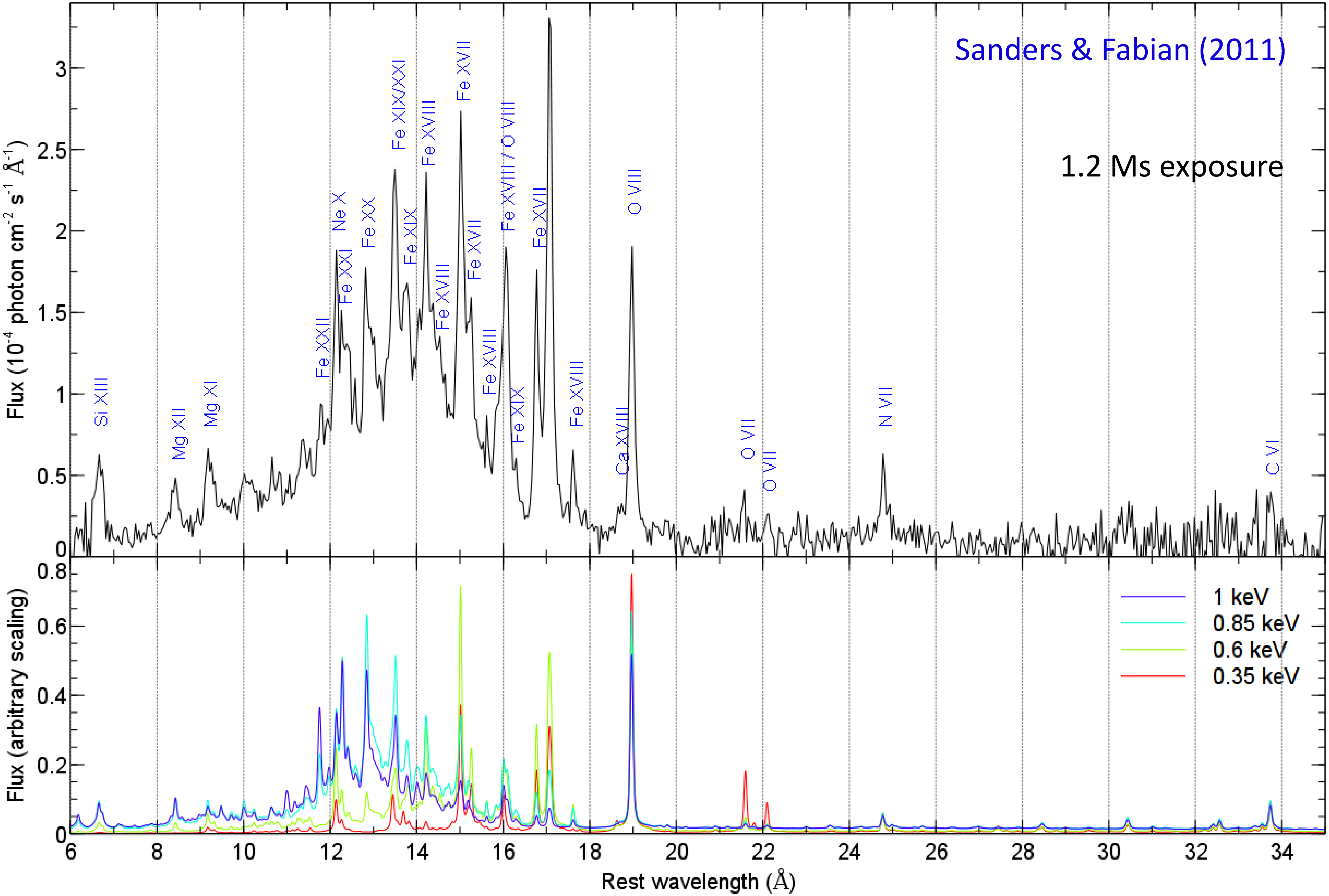
Also seen in RGS as Fe XVII

Multiphase cool gas in Perseus



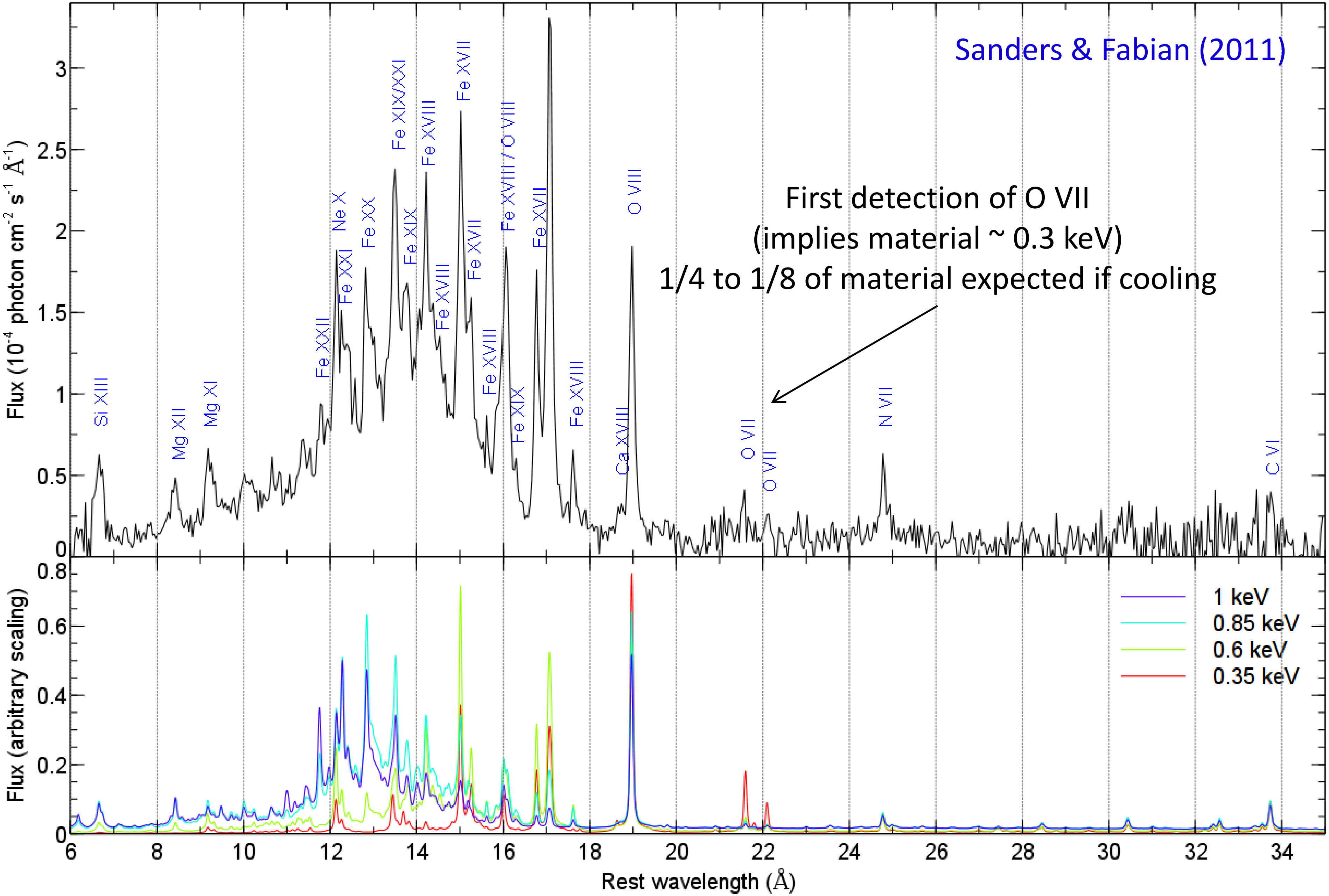
Hα from Conselice et al 2001

Stacked ≤ 1 keV temperature spectra


Sanders & Fabian (2011)

1.2 Ms exposure

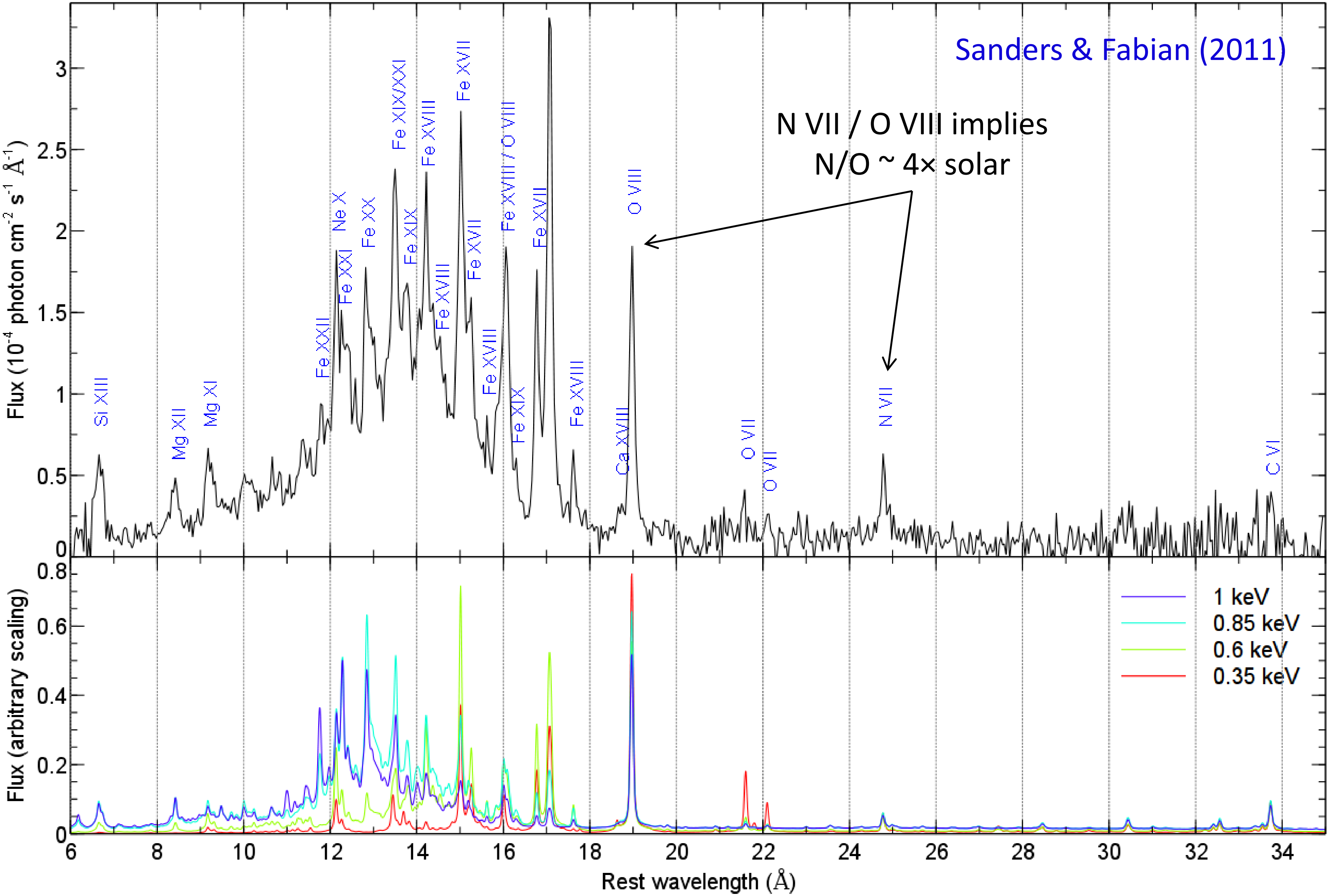
Stacked ≤ 1 keV temperature spectra



Sanders & Fabian (2011)

First detection of O VII
(implies material ~ 0.3 keV)
1/4 to 1/8 of material expected if cooling

Stacked ≤ 1 keV temperature spectra



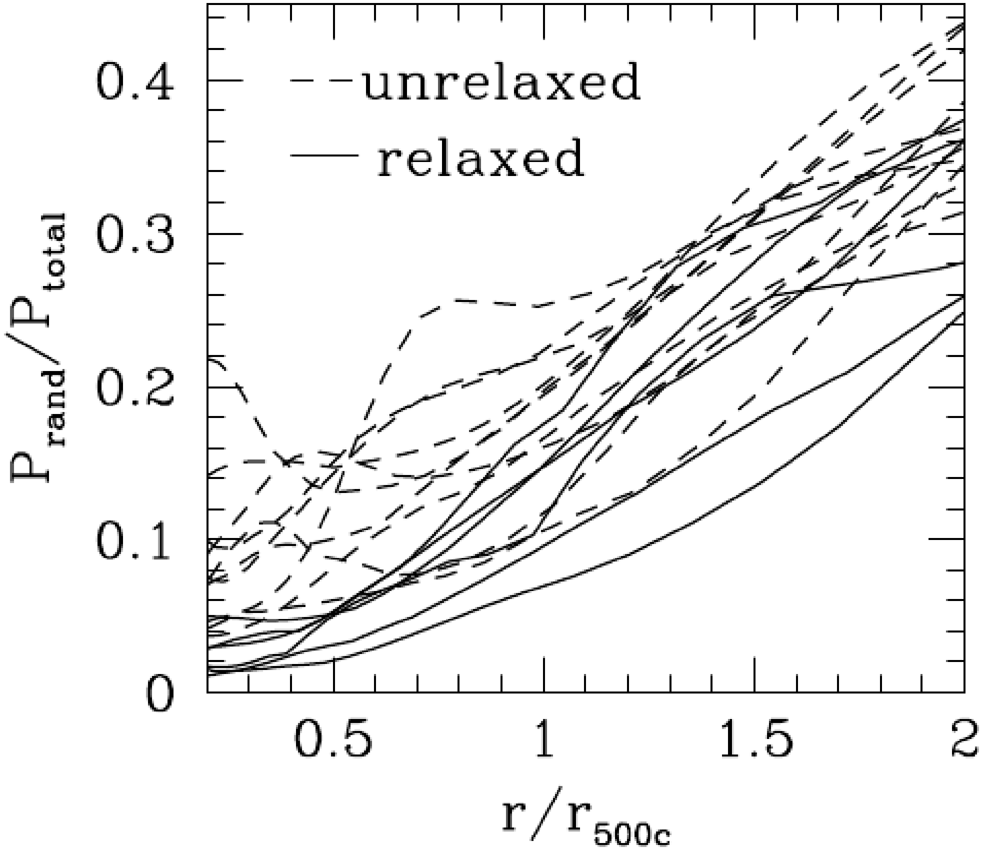
Sanders & Fabian (2011)

N VII / O VIII implies
N/O ~ 4× solar

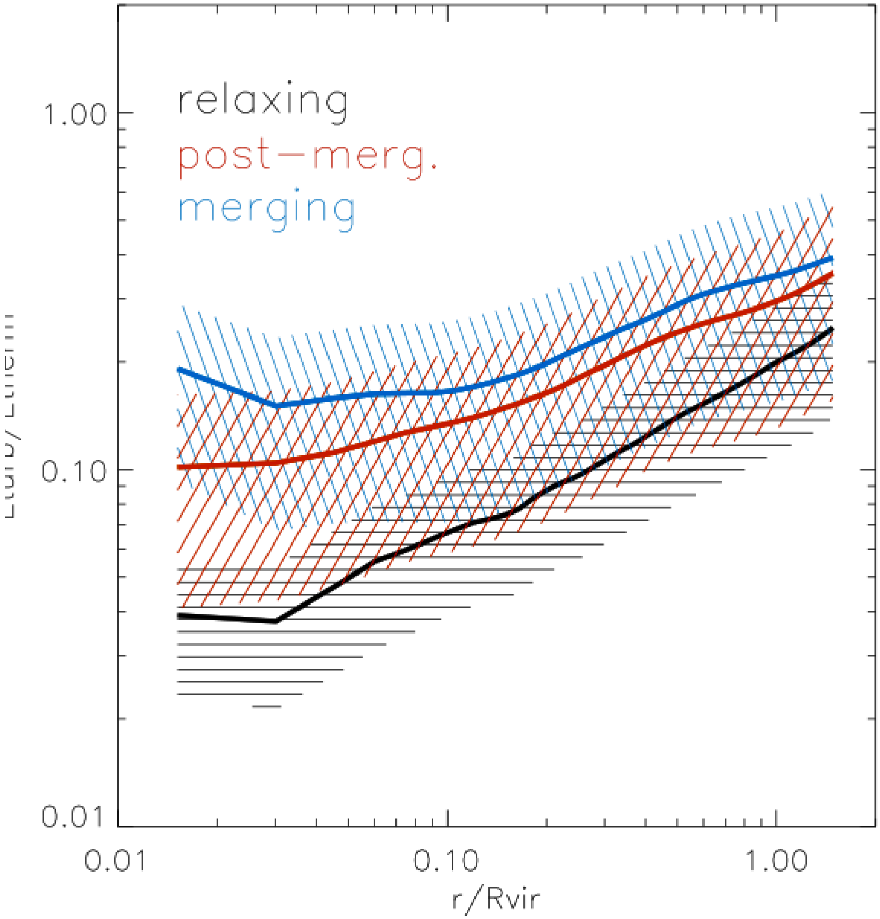
DYNAMICAL STATE OF CLUSTER CORES

Simulations of cluster-wide motions

Lau et al 2009

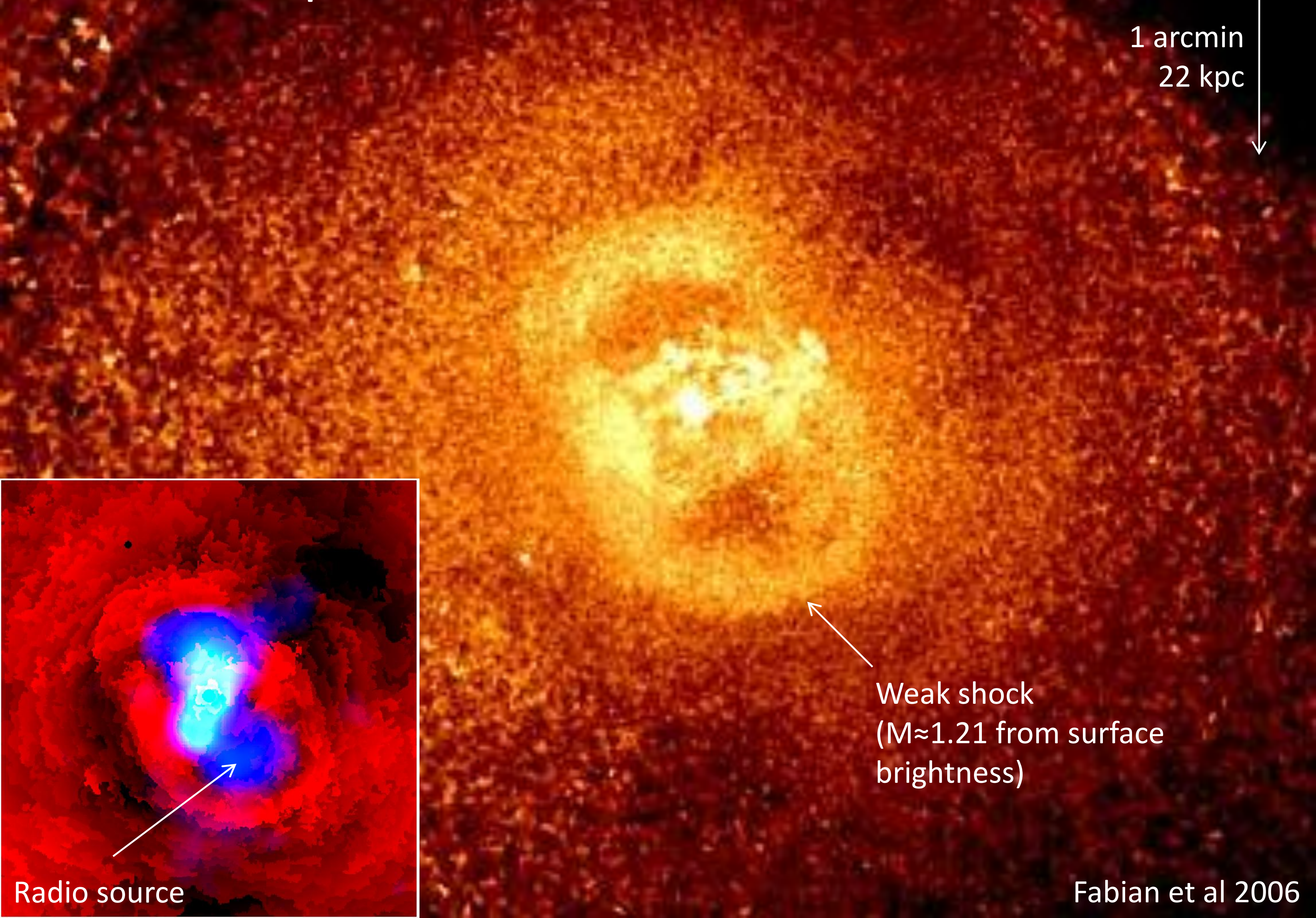


Vazza et al 2010



Cool core clusters are the most relaxed

Pressure map of the Perseus cluster



1 arcmin
22 kpc

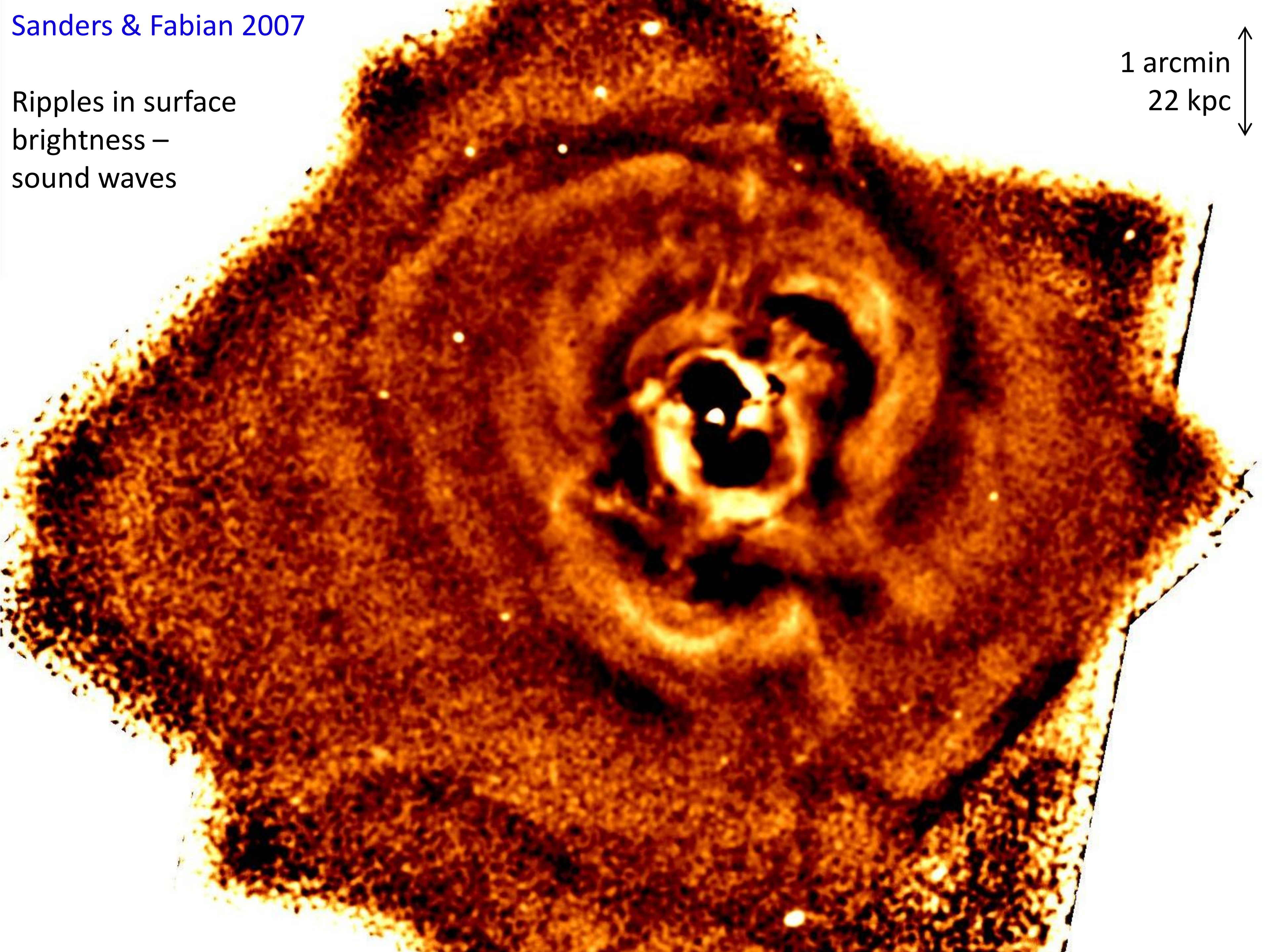
Weak shock
(M≈1.21 from surface brightness)

Radio source

Fabian et al 2006

Sanders & Fabian 2007

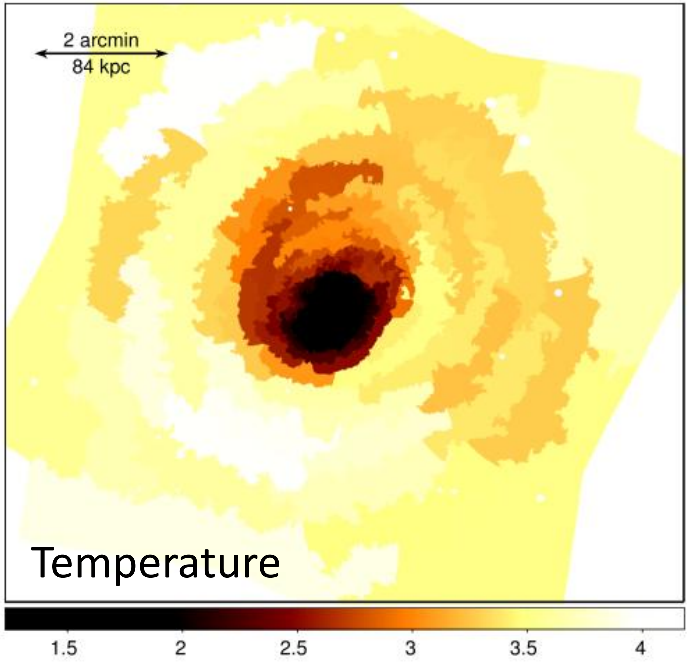
Ripples in surface brightness – sound waves

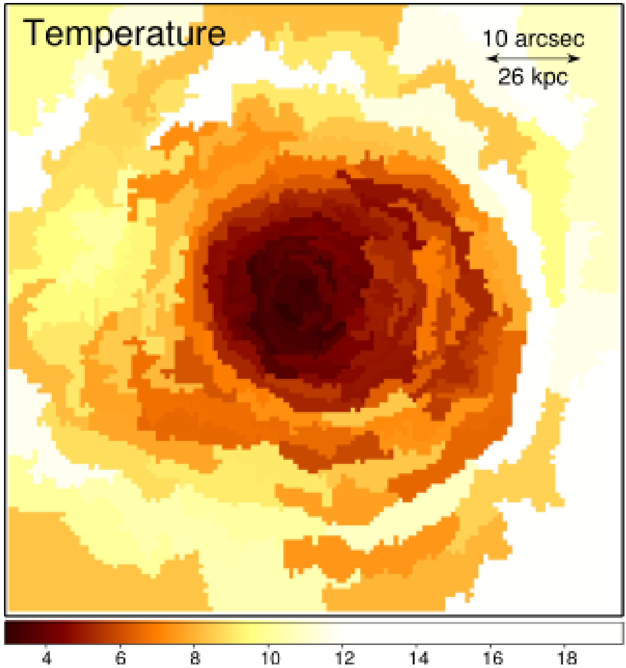


Sloshing of gas: cold fronts

Gas can slosh long time after minor merger giving a cold front. Few 100 km s^{-1} velocities.

Observations (Chandra data)

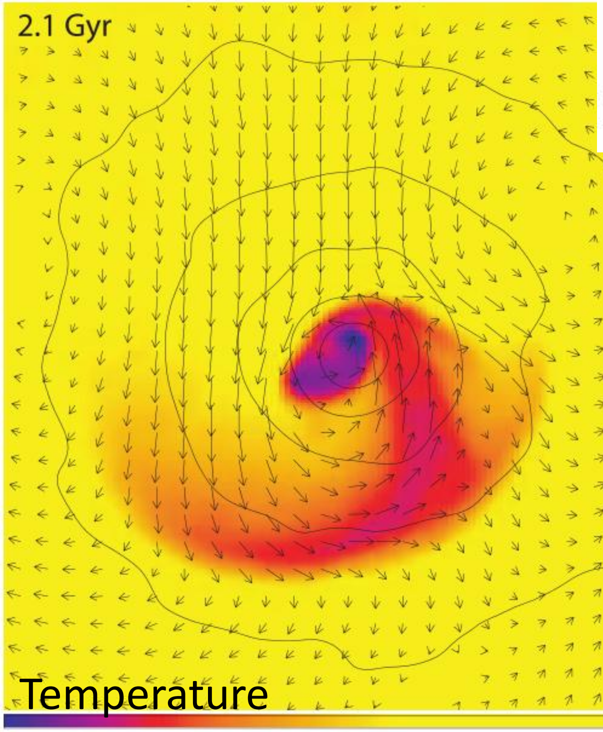




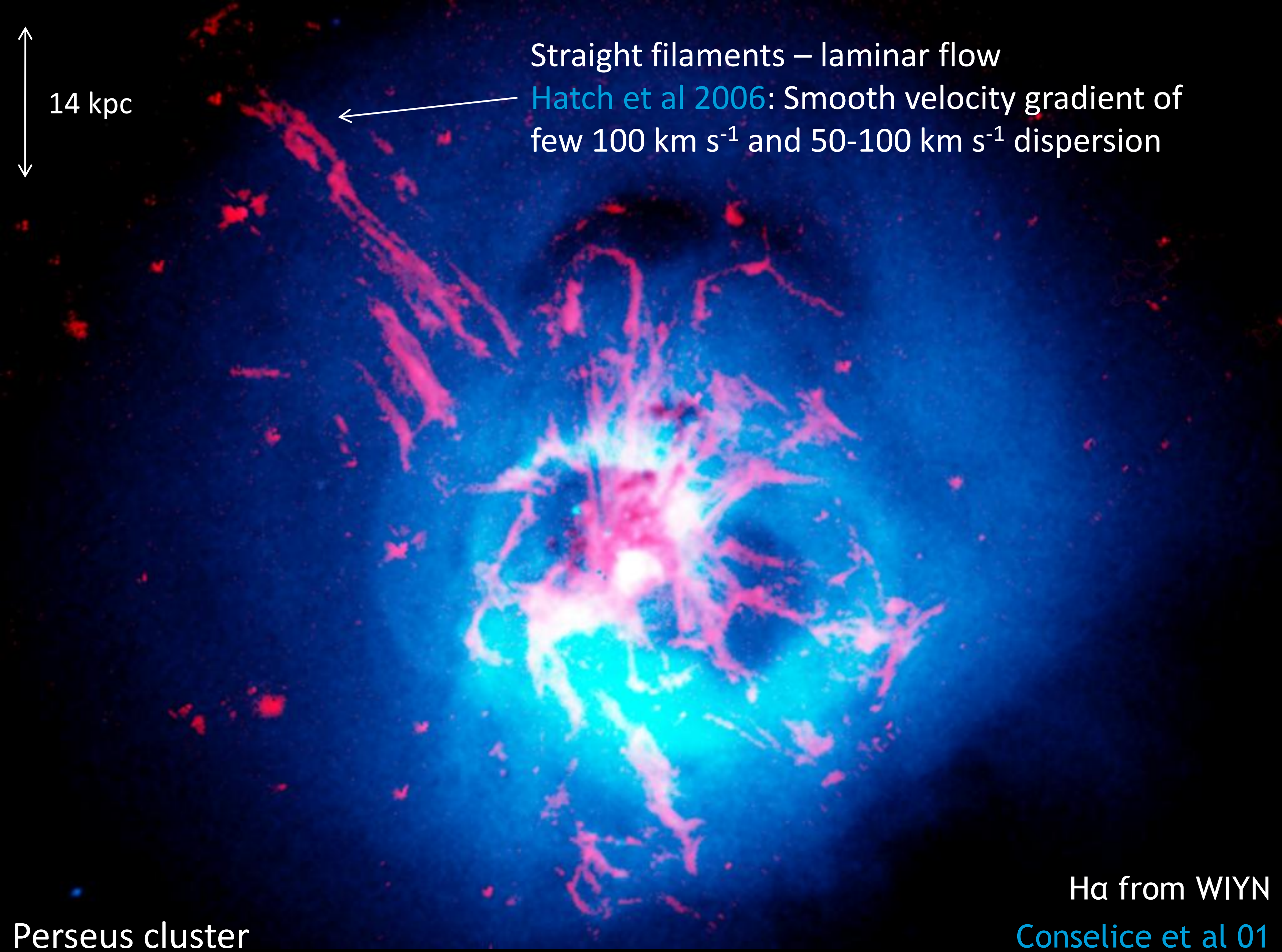
2A 0335+096: Sanders et al 2009a

A 2204: Sanders et al 2009b

Simulations



Ascasibar & Markevitch 2006



Straight filaments – laminar flow

Hatch et al 2006: Smooth velocity gradient of few 100 km s^{-1} and 50-100 km s^{-1} dispersion

Hα from WIYN

Conselice et al 01

Perseus cluster

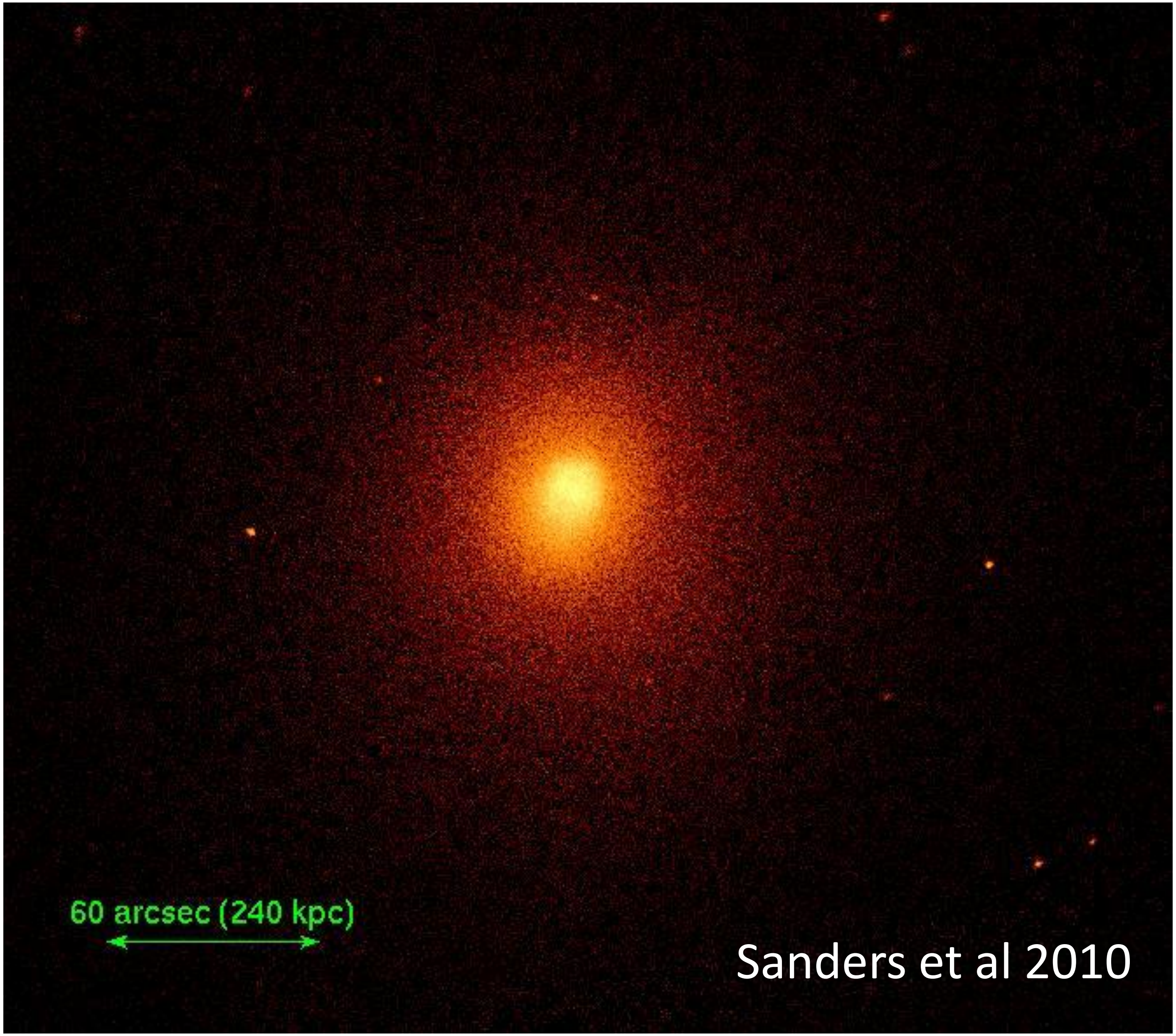
How to measure velocities

- Directly (discussing here)
- Indirectly
  - Fluctuation analysis (see Schuecker 2004, Churazov et al 2012, Sanders & Fabian 2012)
  - Resonance scattering (e.g. Churazov et al 04, Werner et al 09, de Plaa et al 12)
  - Stellar vs gas potentials (Churazov et al 08, 10)
  - Metals (e.g., Rebusco et al 05, Graham et al 06, Sanders et al 04, 07)

Directly placing limits on turbulence

- XMM RGS detects emission lines from cluster cores, ellipticals and groups
- Line width sensitive to gas motions
- Additional broadening by
  - Instrumental effects (accounted for)
  - Thermal width (accounted for)
  - Extent of source, as RGS are slitless spectrometers (broadening is 0.12/*m* Å/arcmin)

Abell 1835: a relaxed galaxy cluster

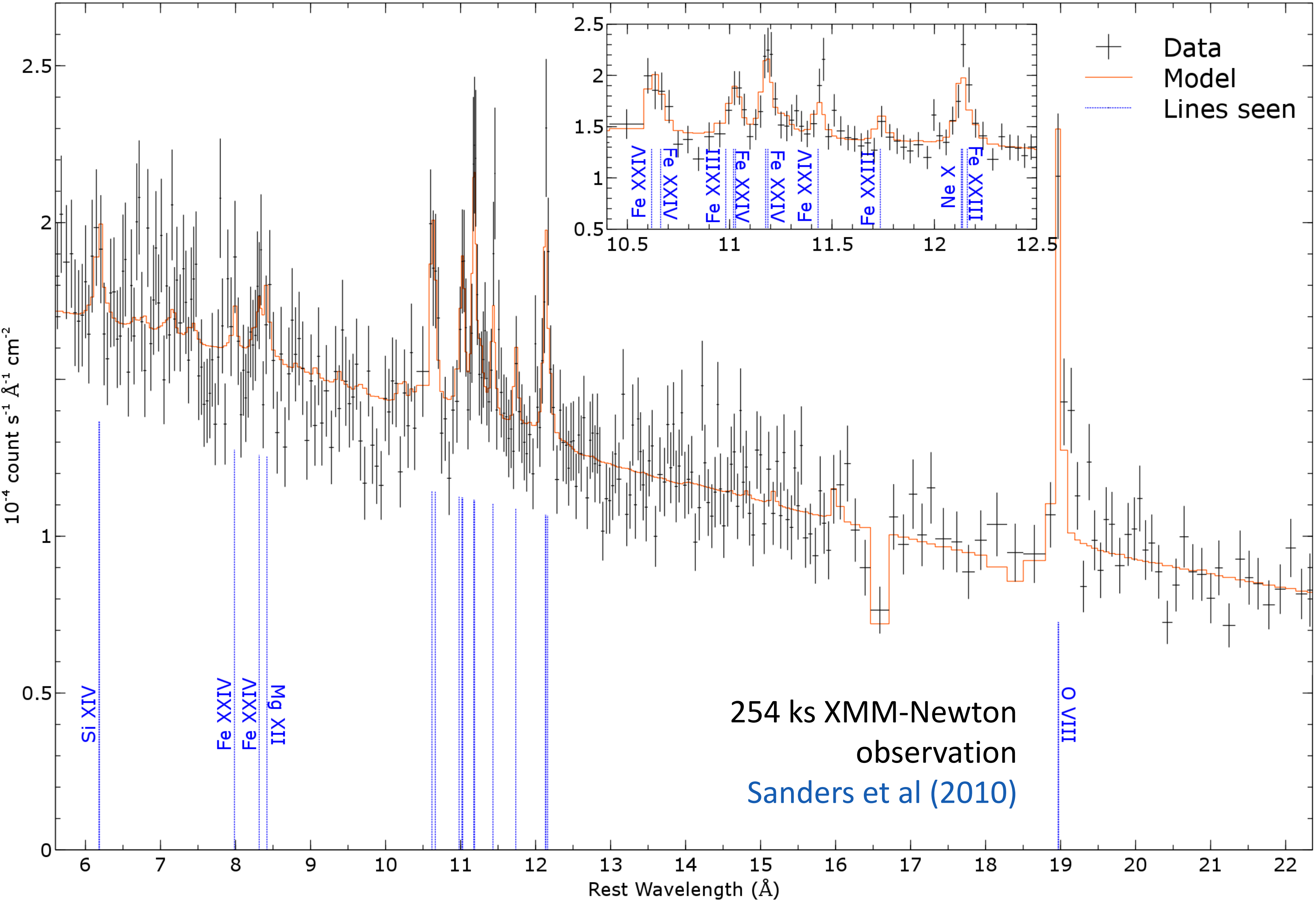


Sanders et al 2010

Abell 1835
$z = 0.2523$
$L_X \sim 2\times10^{45}$ erg s^{-1}

Relaxed, very luminous galaxy cluster

Abell 1835: measuring line widths

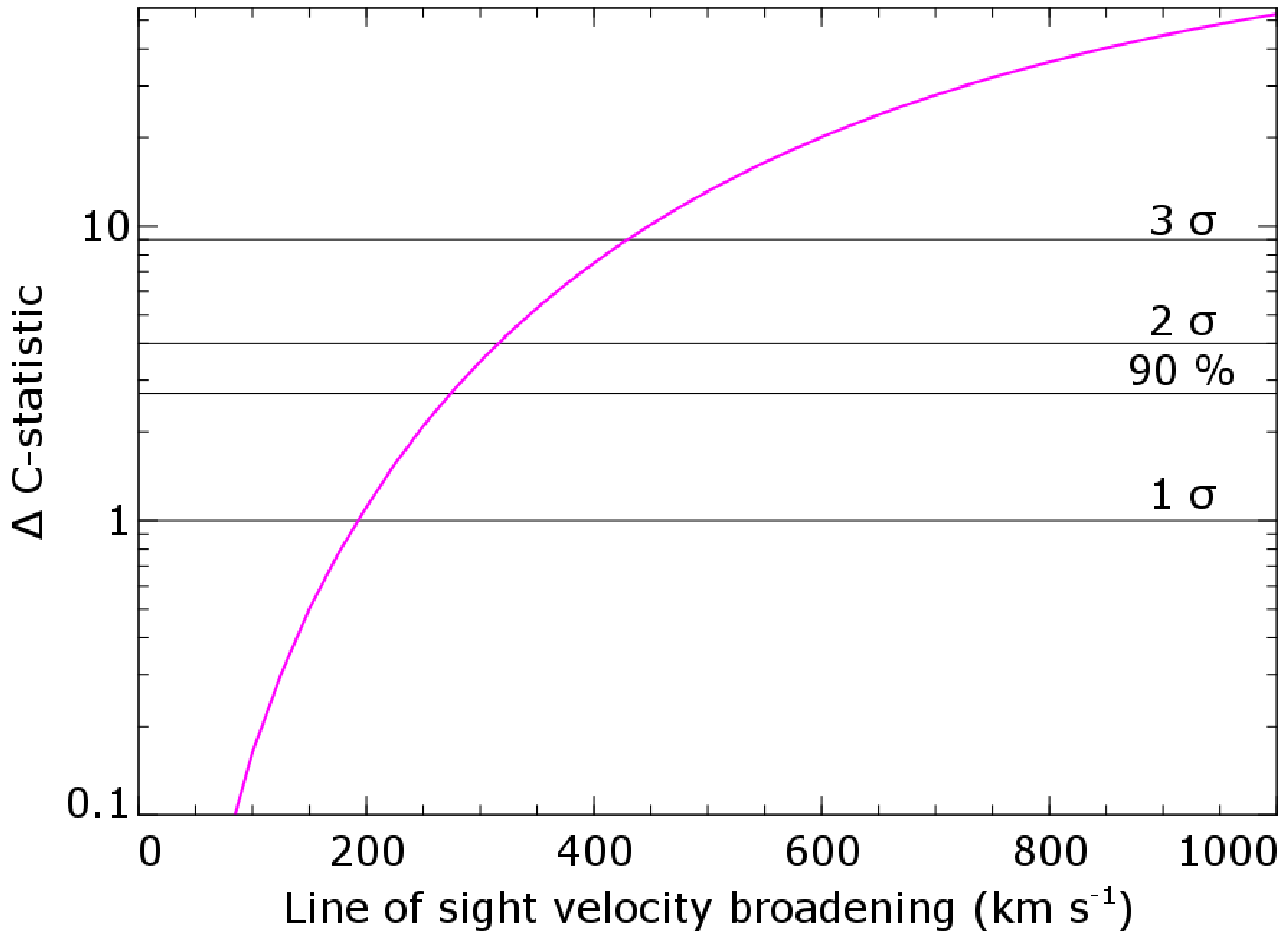


254 ks XMM-Newton observation

Sanders et al (2010)

A1835: Confidence limits on broadening

Fit spectrum and fit for additional broadening



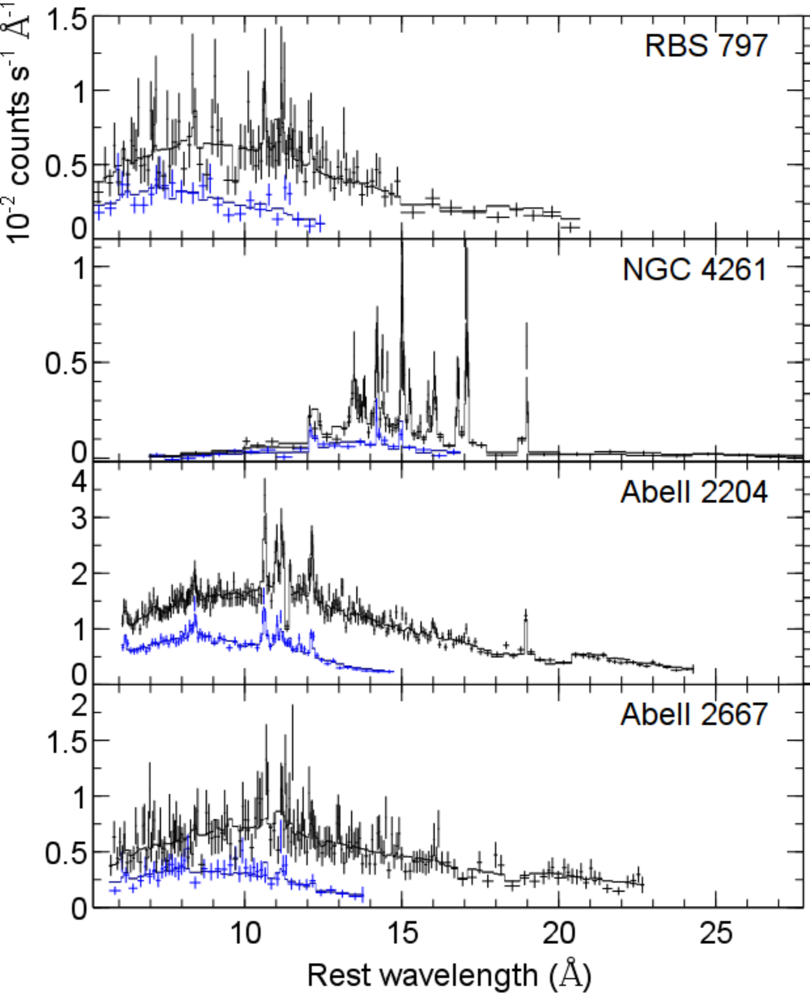
Limit is 274 km s^{-1} (90% confidence)

A1835: Estimating turbulent energy

$$\frac{E_{turb}}{E_{therm}} = \frac{\gamma}{2} M^2 = V_{los}^2 \, \frac{\mu \, m_p}{kT}$$

- 90% confidence upper limit of 13% of thermal energy in turbulence

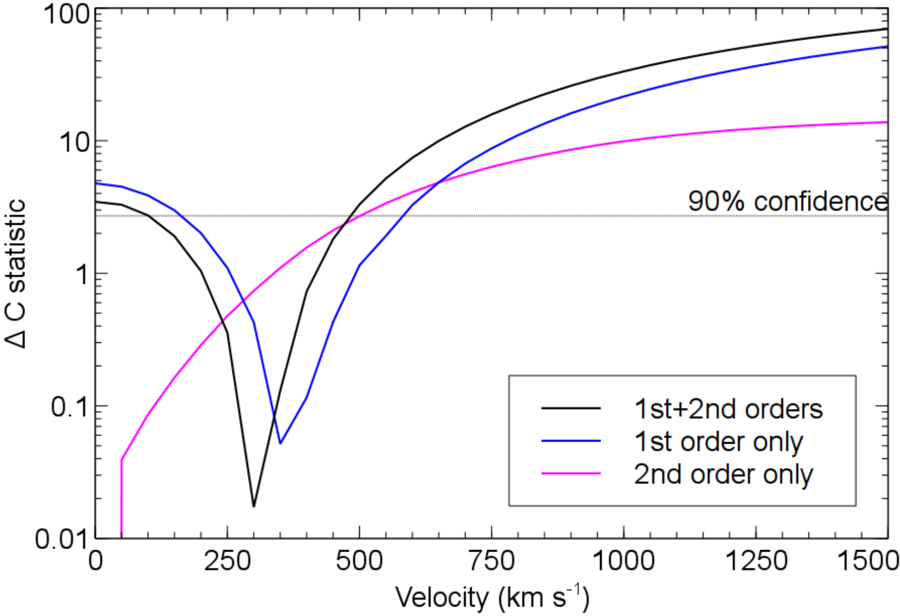
Narrow lines in large sample



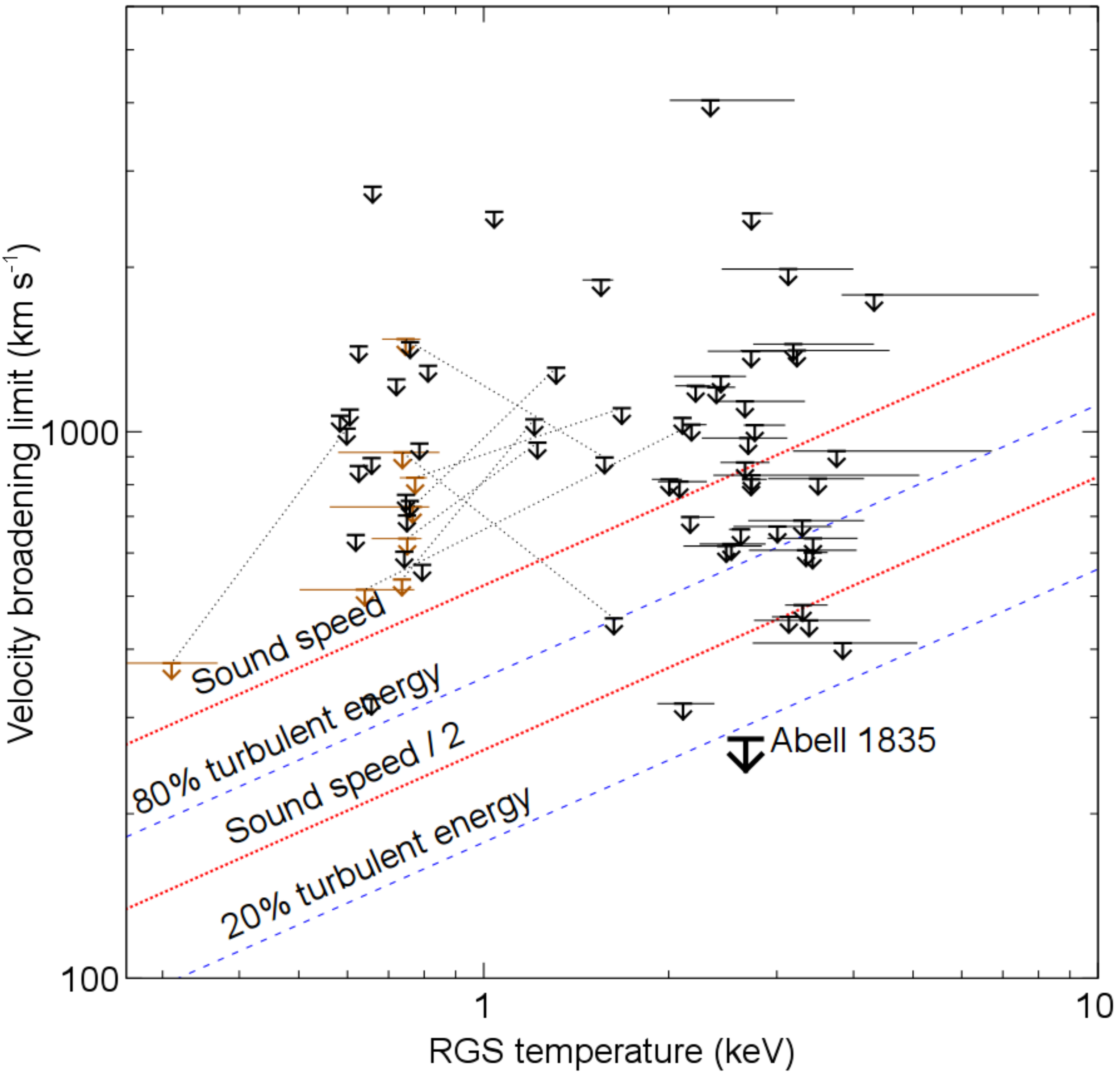
Sample of 62 bright line objects in XMM archive

Sanders et al 2011

Zw 3146
210 ks



Limit as a function of temperature



Sample is not complete, but

Seven objects with limits of less than 500 km s^{-1}

RBS797, Zw3146, NGC4261, A1991, A2204, RXCJ2149, A2667

Half of 62 targets have limits < 700 kms^{-1}

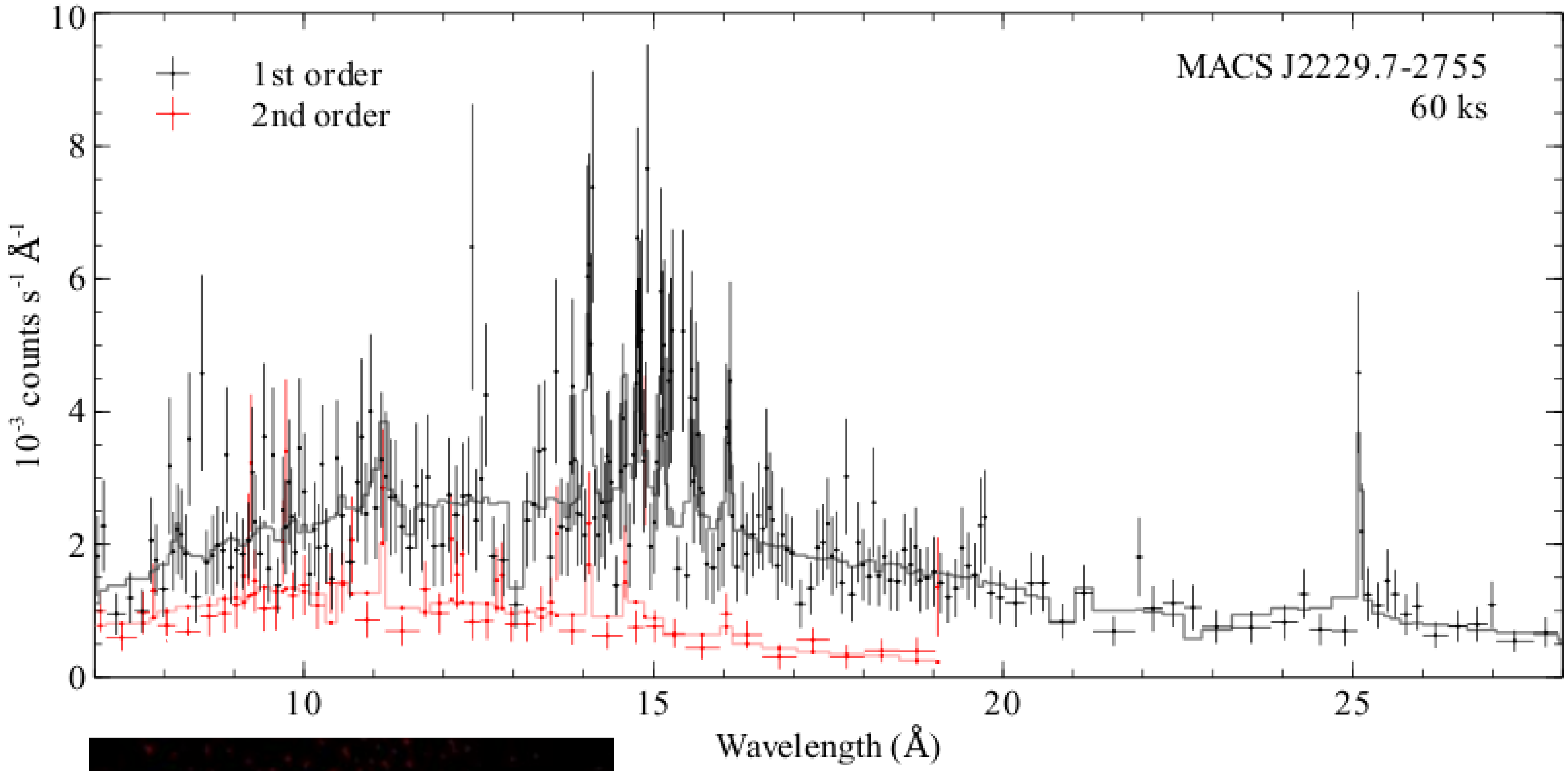
Improving on these results

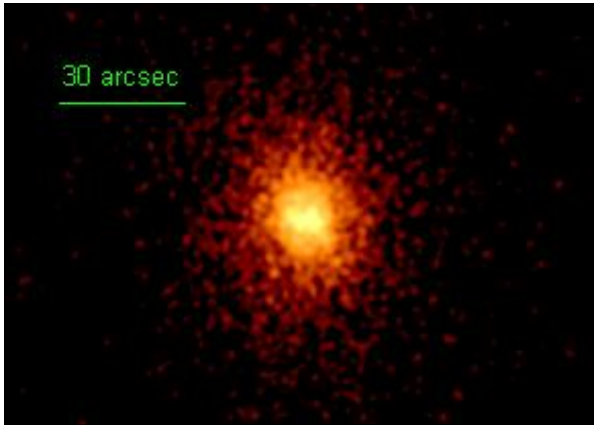
- Target sources with small spatial extents to obtain the best limits

and / or

- Model the broadening caused by extent of sources and account for it

Compact sources





MACS J2229.7, $z = 0.324$,

$L_X \sim 10^{45}$ erg s^{-1}

Broadening < 230 km s^{-1}

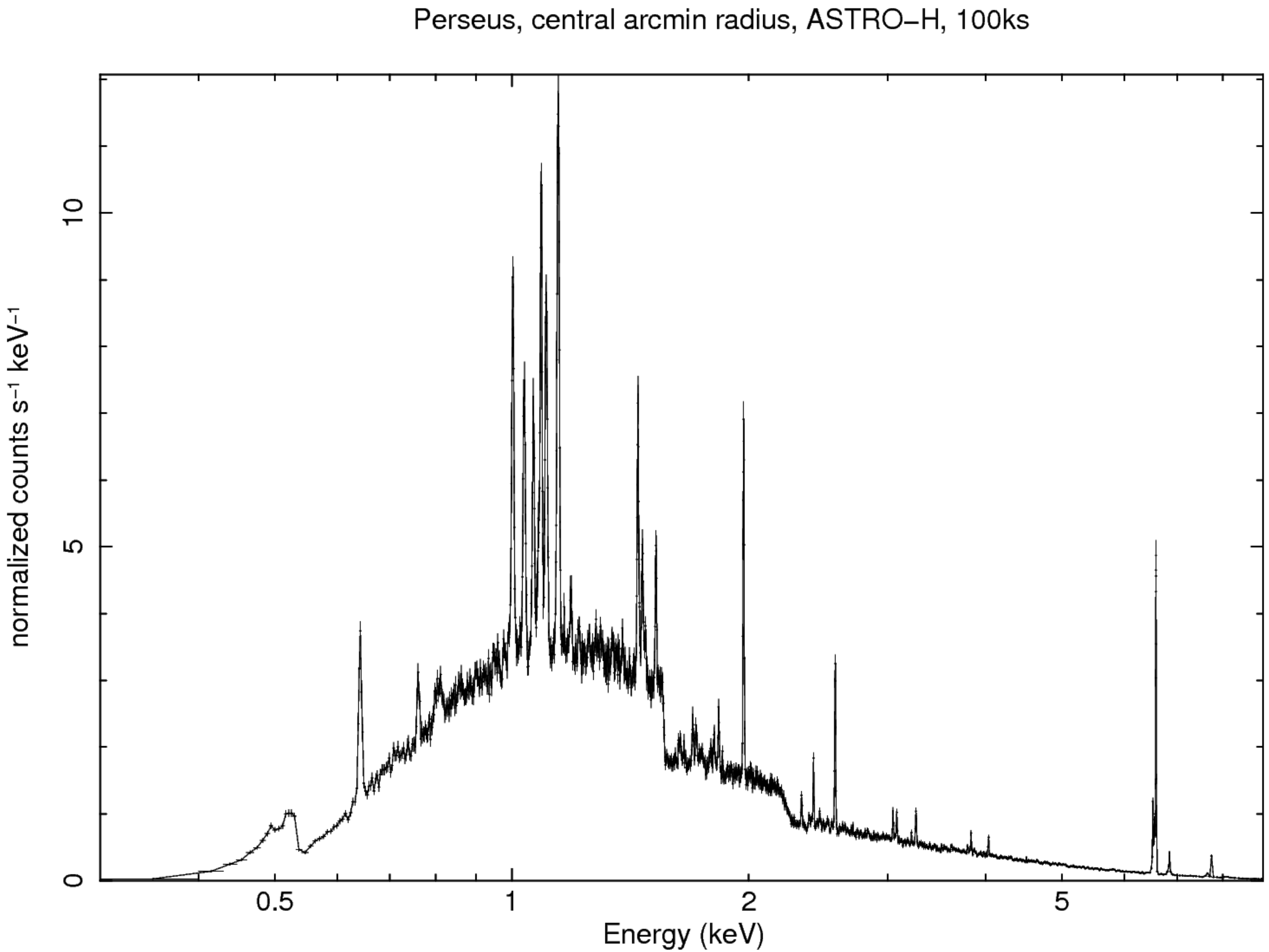
Accounting for source extent

- In Sanders et al 2011, compared simulated widths with real widths
- Trying simpler technique: Fe-L emission line images convolved with response
- V*ery important to remove continuum first*!
- Preliminary results promising: several clusters < 300 km s^{-1}
- **Despite ~10^{45} erg/s flowing in these massive objects from central AGN, very low velocities**

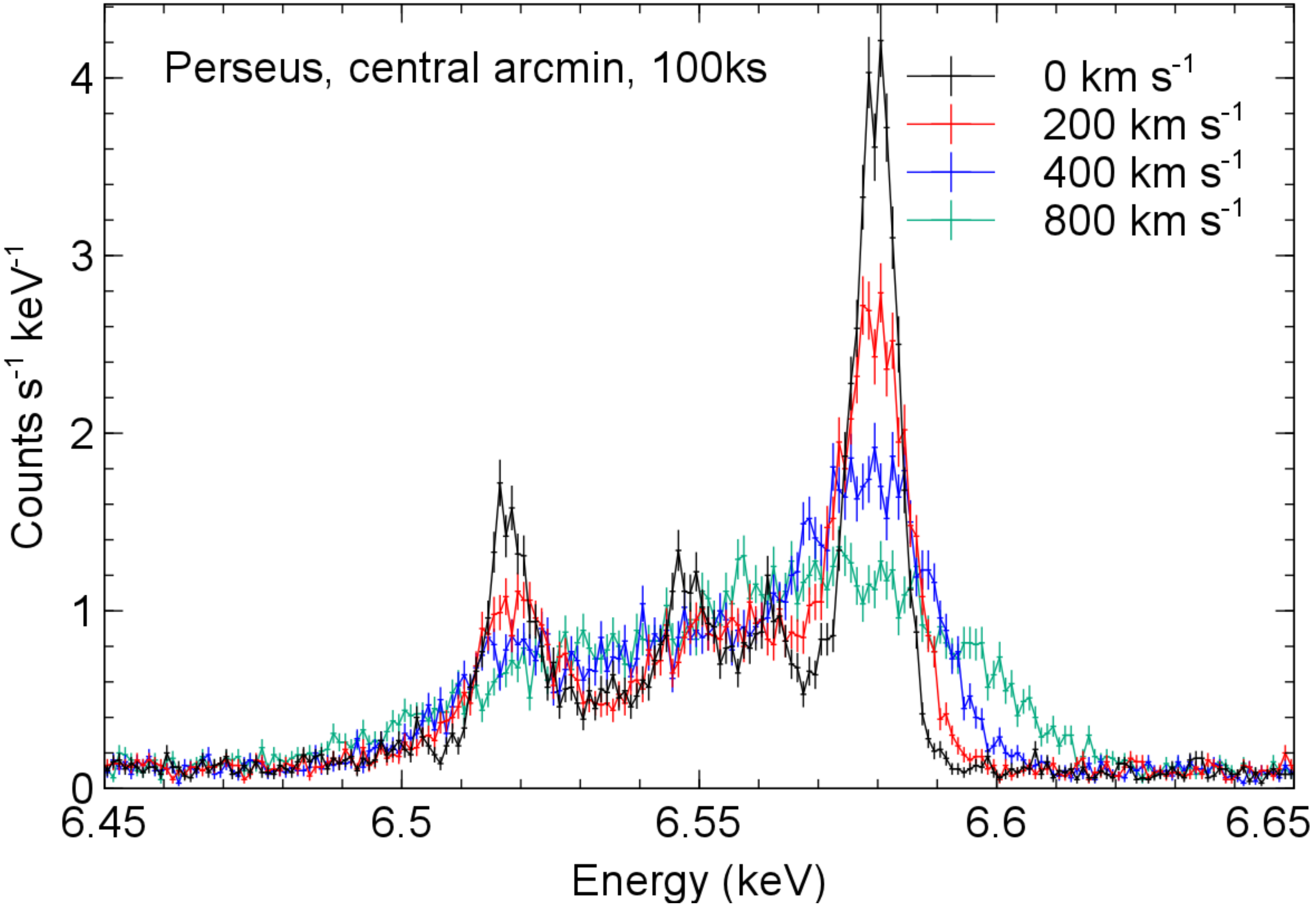
Conclusions

- Complex multiphase temperature structure in cores of cooling flow clusters
  - Temperatures range can be factor of ~10
  - Also Correlation between cool X-ray material, atomic, molecular material and stars.
  - Non radiative cooling?
- Limit turbulence on 62 targets
  - 7 targets with < 500 km s^{-1}
  - Several targets < 300-400 km s^{-1}
  - Half of targets < 700 km s^{-1}
  - Little evidence for any large velocities, despite strong feedback
  - Biased sample, however!

Future – ASTRO-H, launch 2014



ASTRO-H: detail around Fe-K in Perseus



Astro-H will measure:

- Line width
- Line position
- Line shape

as a function of position

7 eV spectral resolution (5 eV achieved on ground)