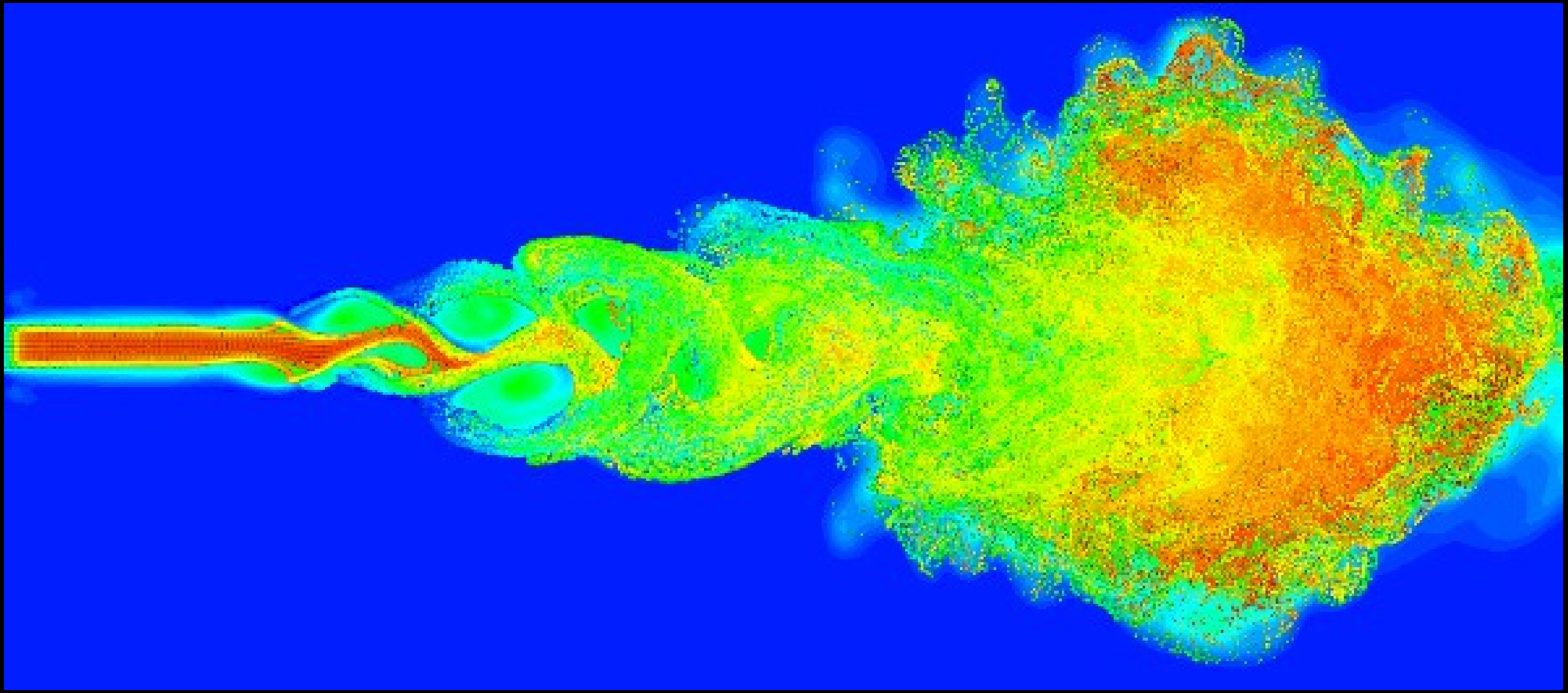
Turbulence in the intracluster medium: XMM-Newton Legacy



Ciro Pinto

Andy Fabian, Jeremy Sanders, Jelle De Plaa, N. Werner, A. Ogorzalek, I. Zhuravleva, Y-Y Zhang, L. Gu, J. Ahoranta, A. Finoguenov, R. Canning

UNIVERSITY OF CAMBRIDGE

erc European Research Council Established by the European Commission

Cambridge X-Ray Astronomy

Clusters of galaxies

100s-1000s galaxies

~ 1 Mpc

$10^{7\text{-}8}$ K intracluster medium (ICM)

collisional equilibrium
$Y = n_H n_e V = f(T)$

X-ray and Optical images of the Perseus cluster central 185 kpc (Fabian et al. 2011)

Galaxies	~ 1% mass	Optical
ICM	~ 9% mass	X-ray
Dark matter	~ 90% mass	Gravity

$\left.\begin{array}{l} \text{Galaxies} \\ \text{ICM} \end{array}\right\}$ Baryonic matter

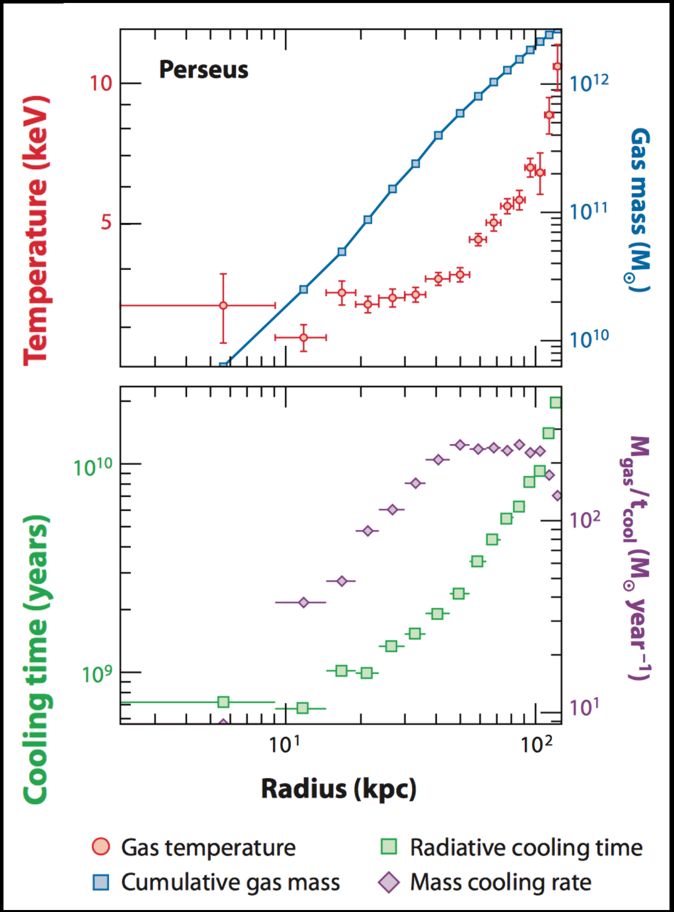
Theory predicts cooling flows

Cooling time shorter than age

→ mass deposition towards core

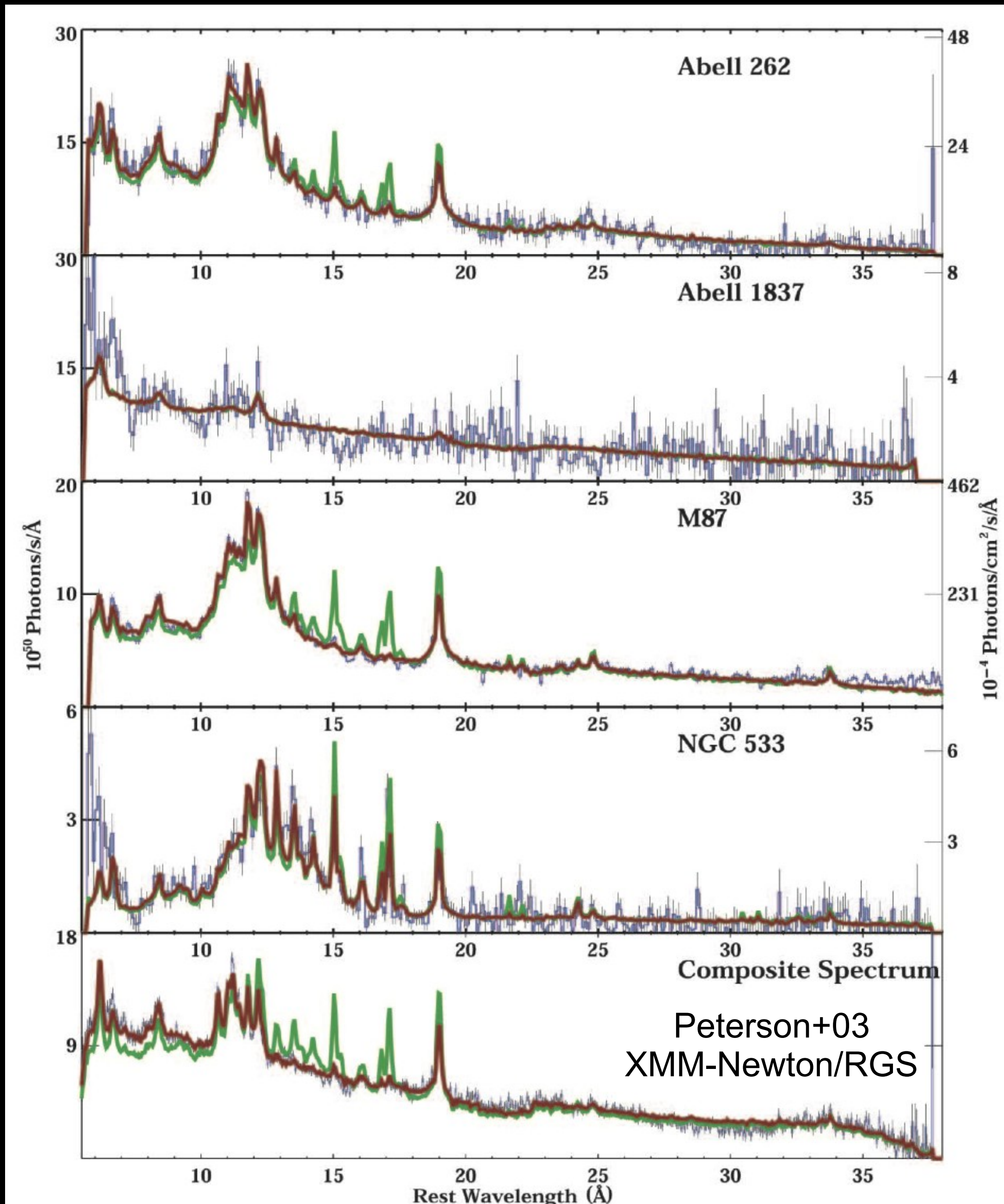
100-1000 M_{sun} yr^{-1} for clusters

0.1-1 M_{sun} yr^{-1} for galaxies



Fabian 2012 – Perseus
(figure by J. Sanders)

Cooling flows are missing

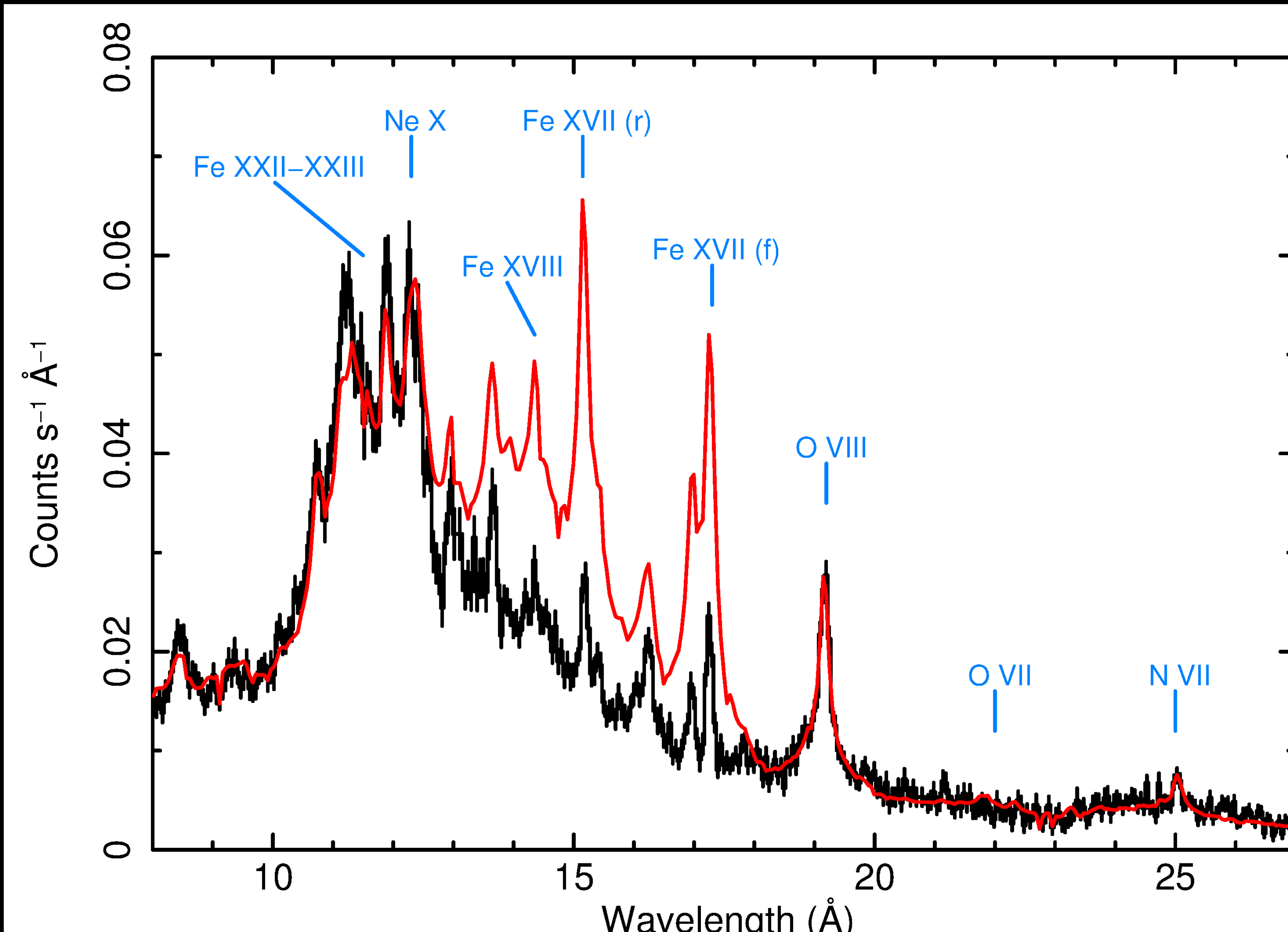


XMM/RGS grating spectra

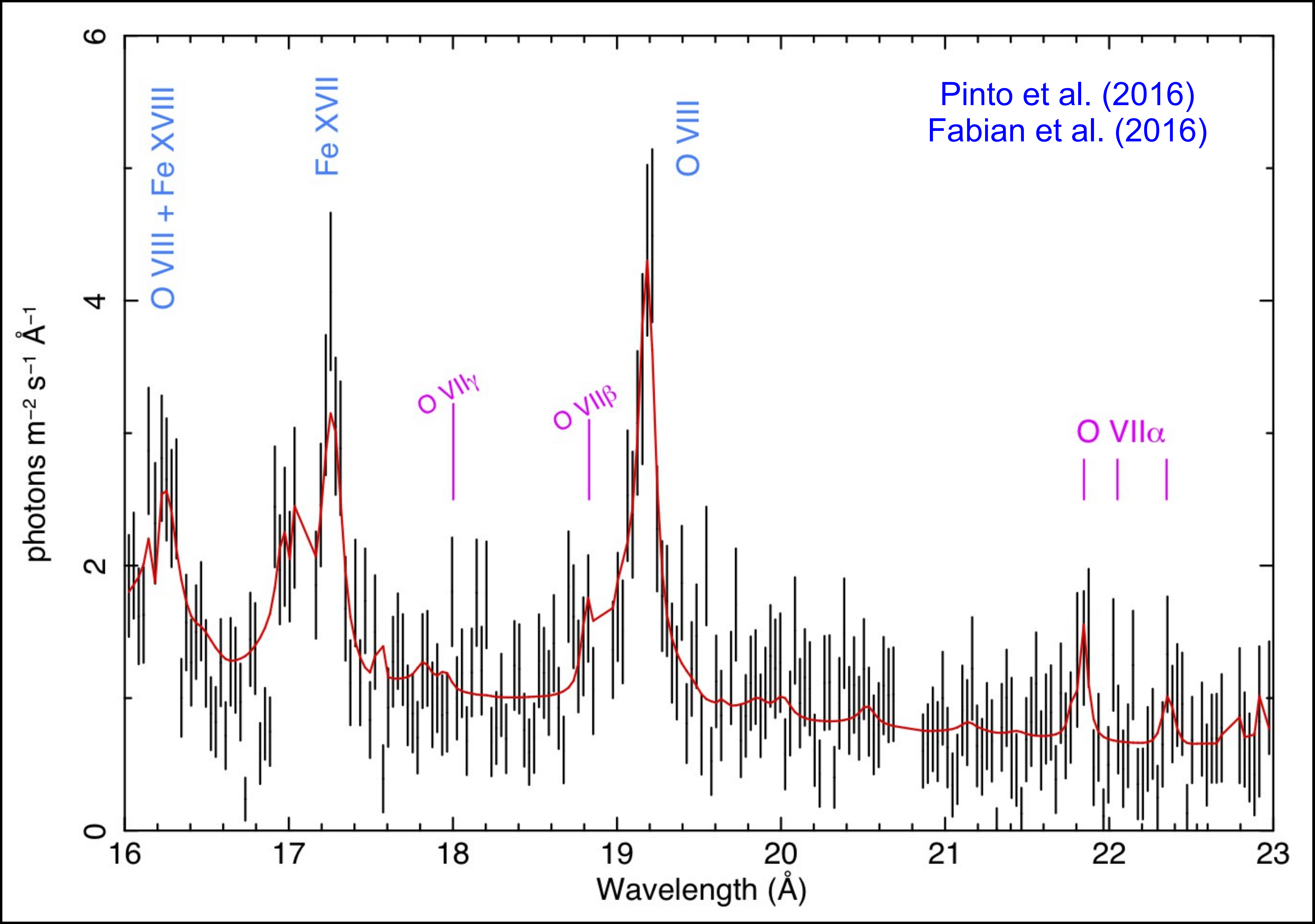
Low cooling rates
~ 10s $M_\odot$ yr^{-1}

Cool (< 1 keV) gas missing
or significantly depleted

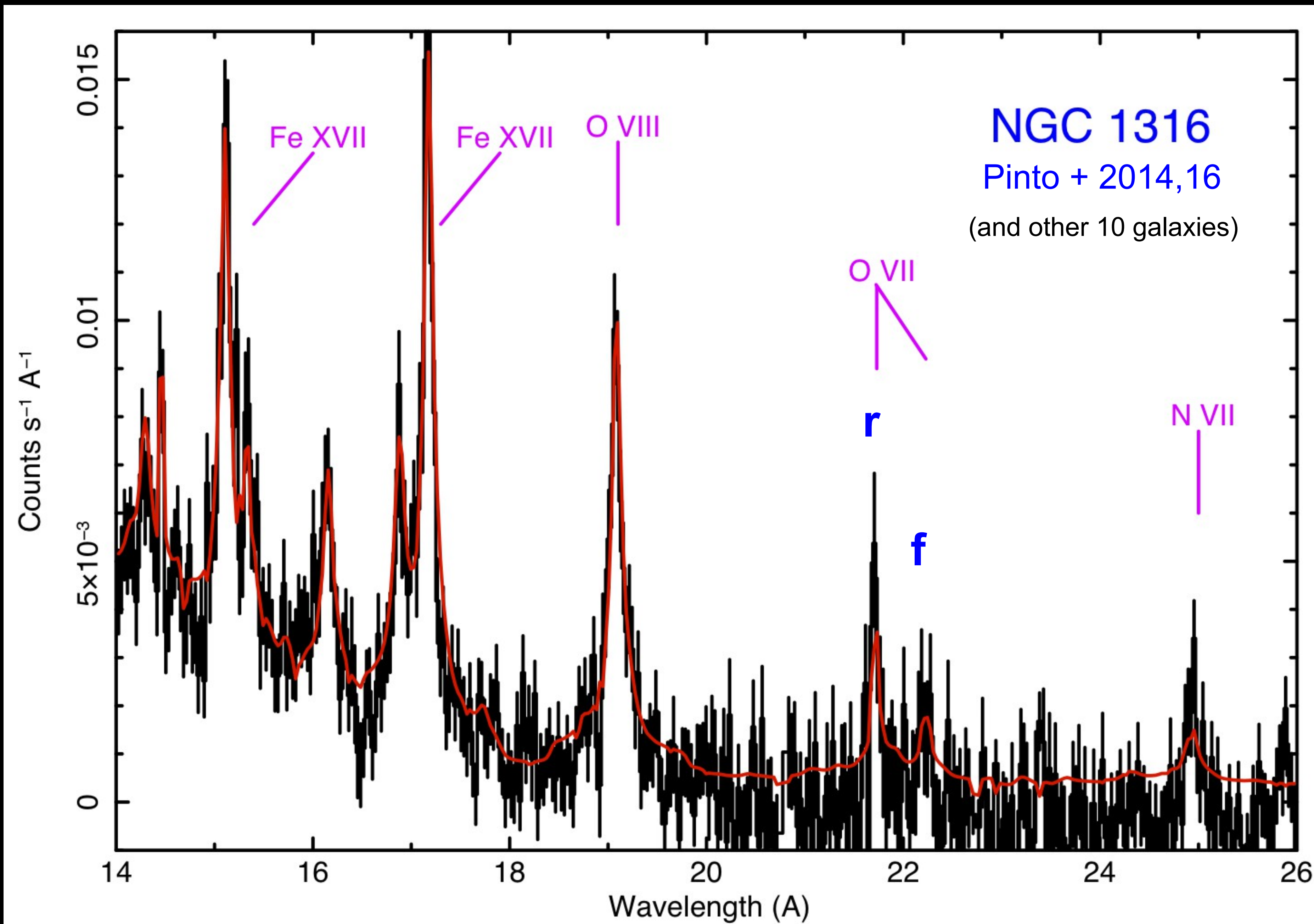
Centaurus cluster core (10 kpc)



Centaurus cluster inner core (5 kpc)



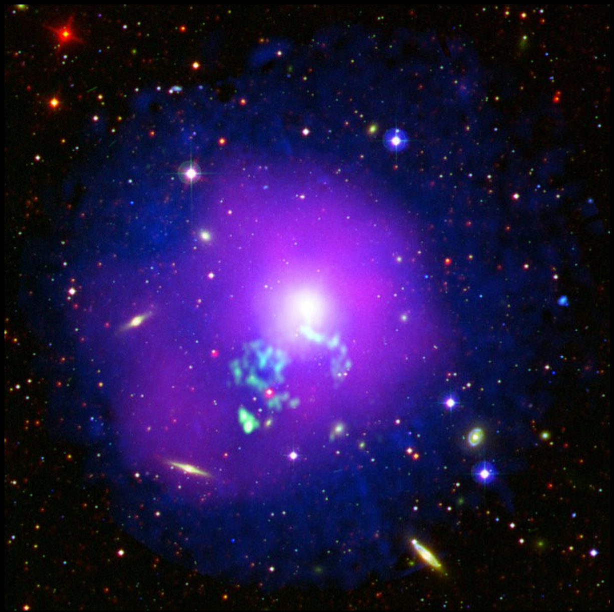
Ellipticals / groups: O VII cooling gas



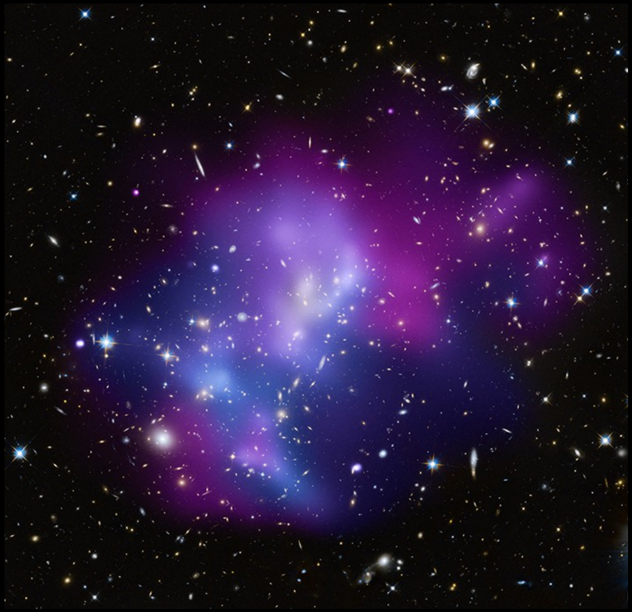
What is heating the ICM?

Galactic winds

AGN outflows

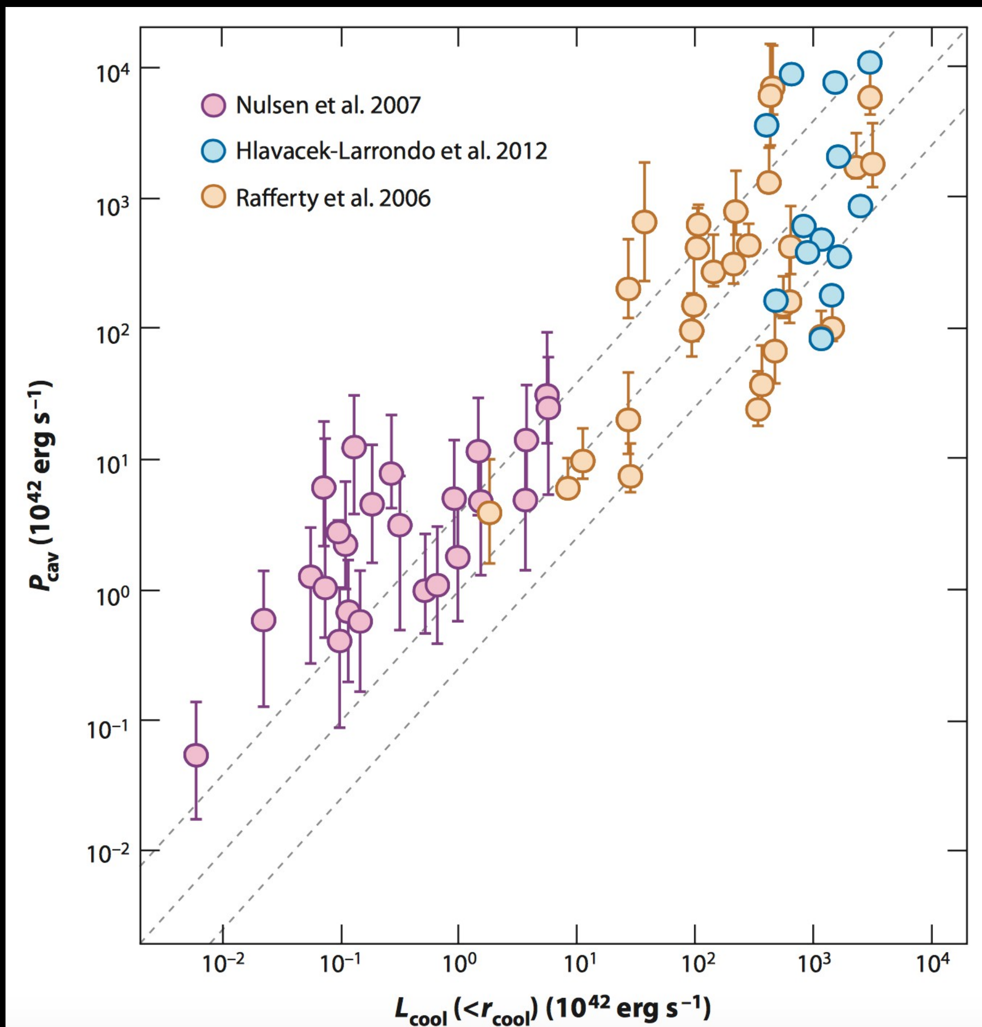


Sloshing



Mergers

AGN feedback may offset cooling



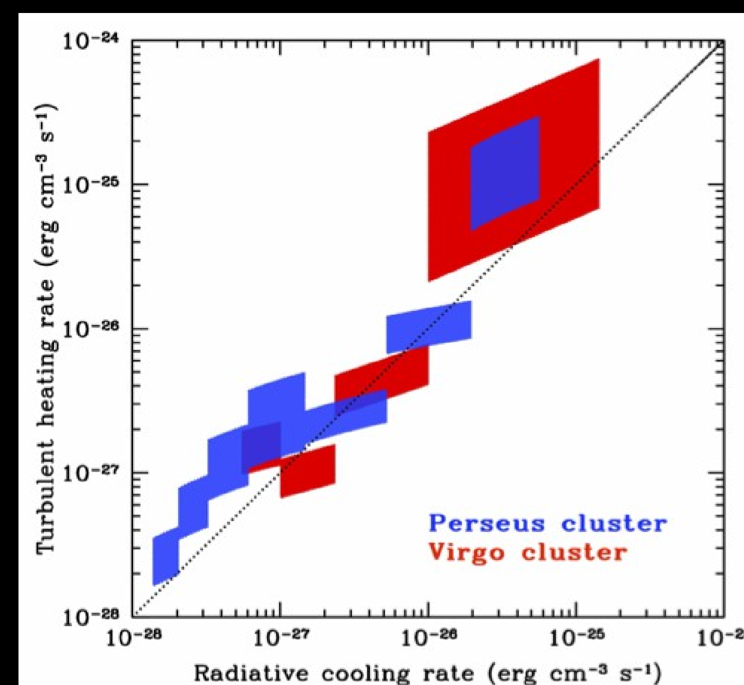
Cavity power VS ICM clusters
(figure by J. Hlavacek-Larrondo)

Energy needed to create a cavity = internal (thermal) energy + work to inflate

$$H = E + pV$$

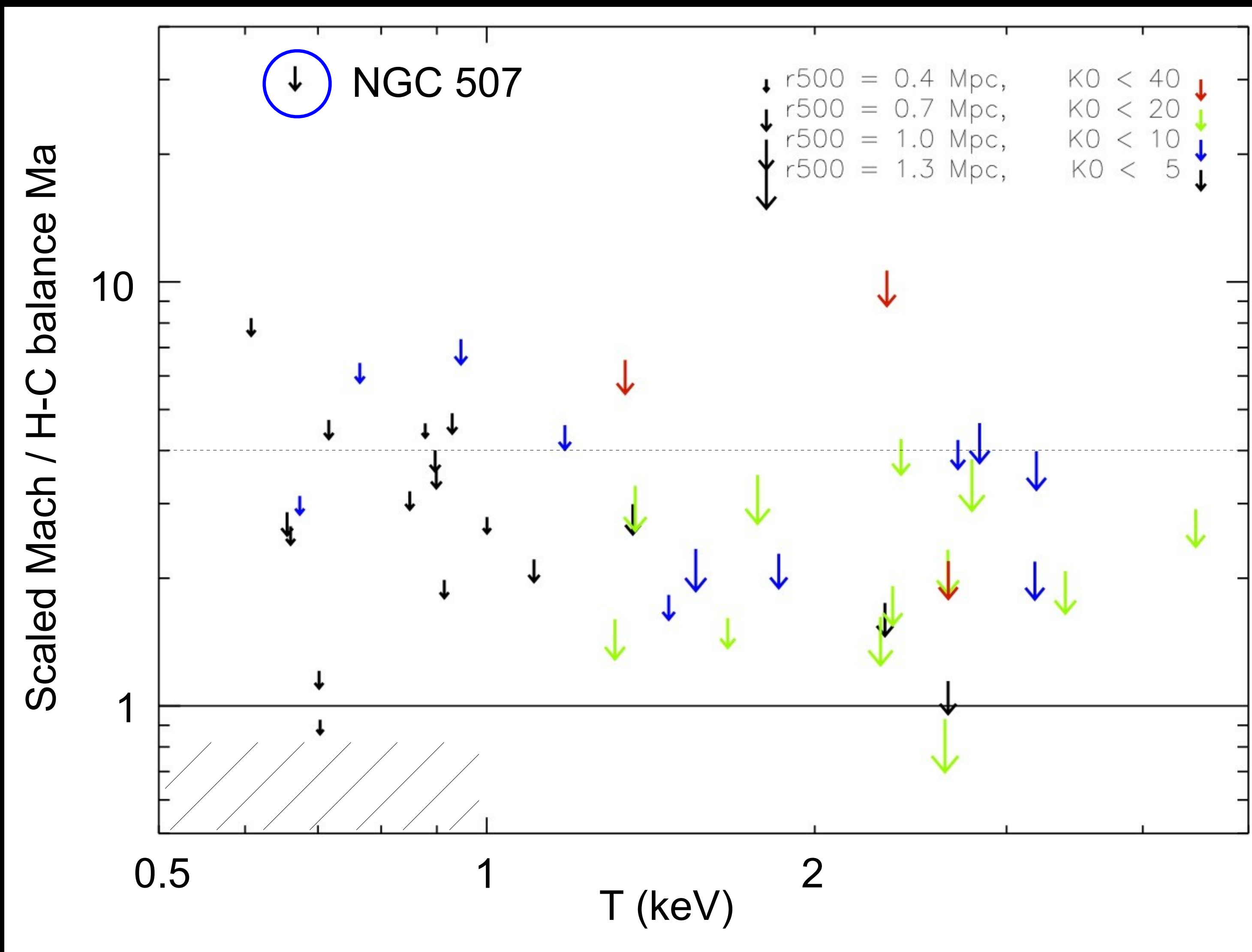
Dissipation of Turbulence

Heating VS Cooling - Zhuravleva+14



Mach numbers required to balance cooling

Through line widths and ratios in XMM/RGS spectra (CHEERS catalog, talk by J. De Plaa)



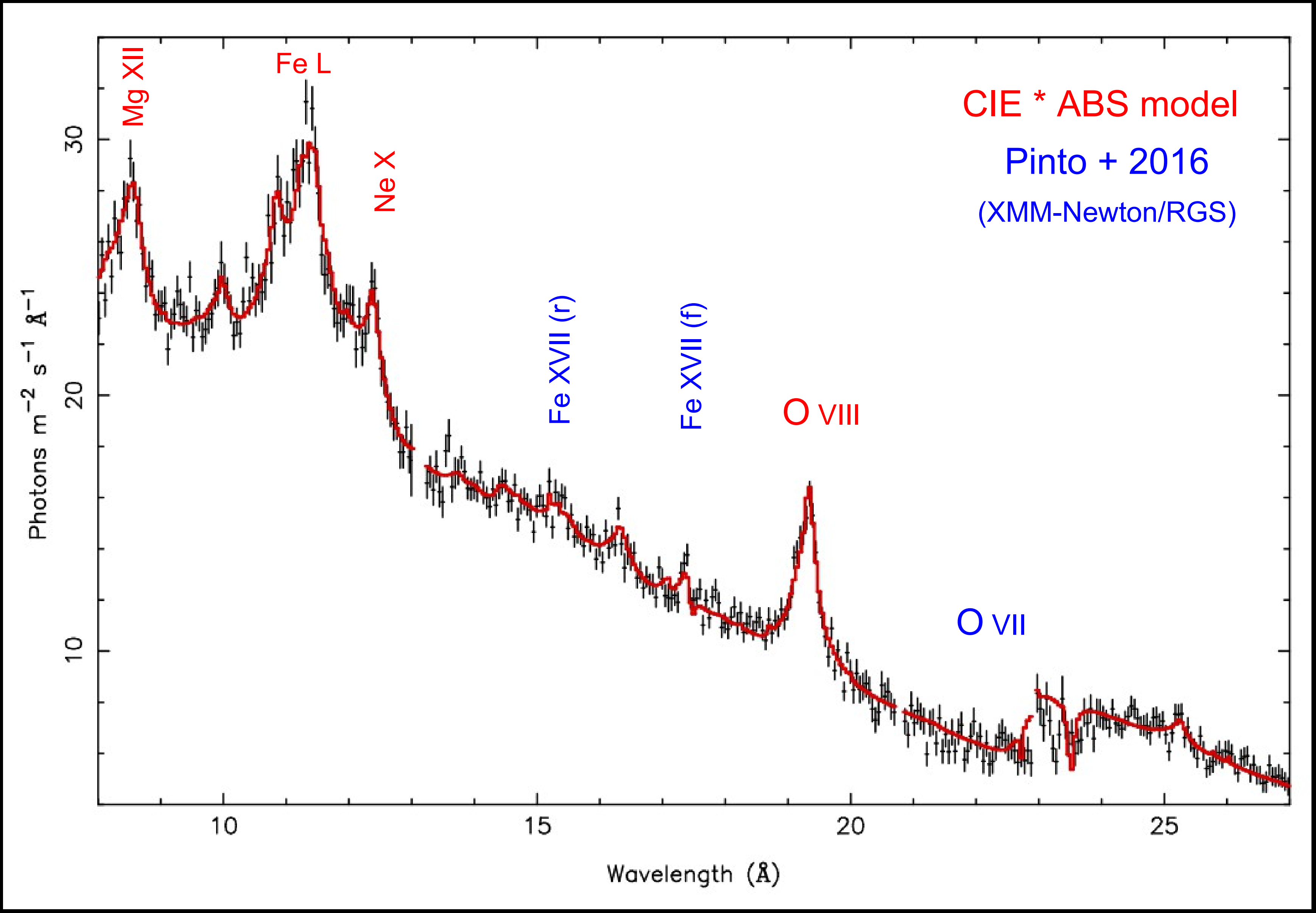
Pinto+2015
&
(Sanders+11,13)

Some lower limits:
Resonant scattering

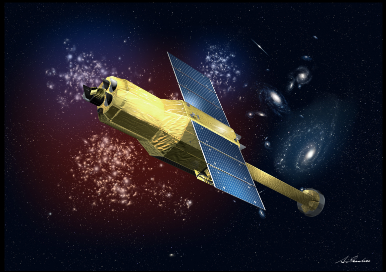
(Ogorzalek+2017)

See A. Ogorzalek's Talk!

Perseus: Fe XVII resonant scattering

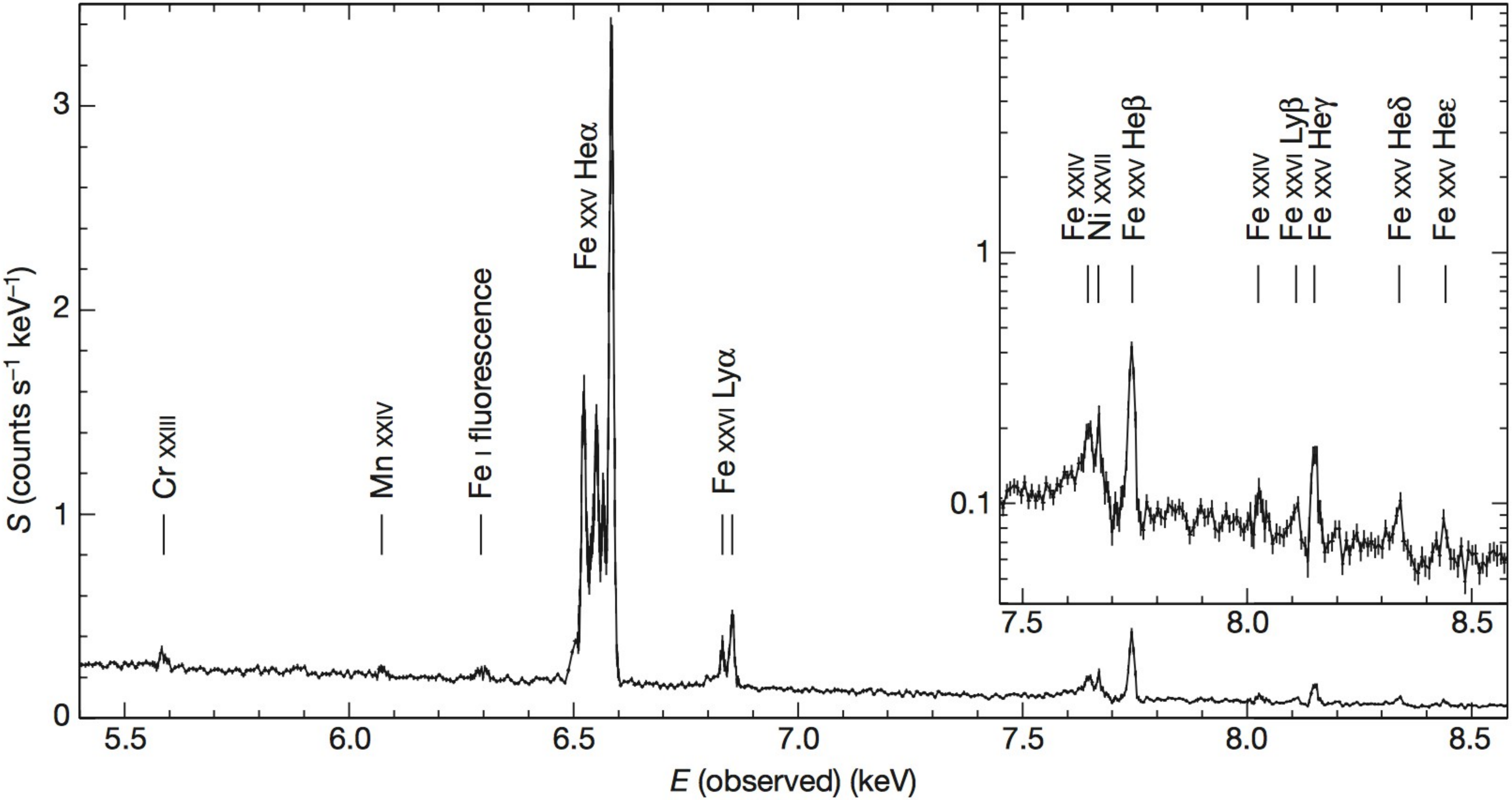


Hitomi



Velocity dispersion of 160-200 km/s, just enough to balance cooling
and sustain the population of ultrarelativistic electrons (radio synchrotron mini-halo)

Hitomi Collaboration (2016)



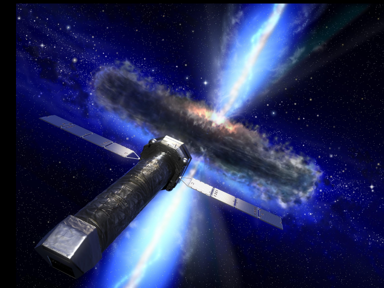
Complex solution(s)

- ➔ Which processes are producing the heat ?
  AGN (core?), mergers + sloshing (outskirts?), cosmic rays
- ➔ How exactly is the heat propagated throughout the cluster ?
  Shocks, bubbles, sound waves, ...
- ➔ How exactly is the heat released to the ICM ?
  Dissipation within bubble-debris, mixing, ...

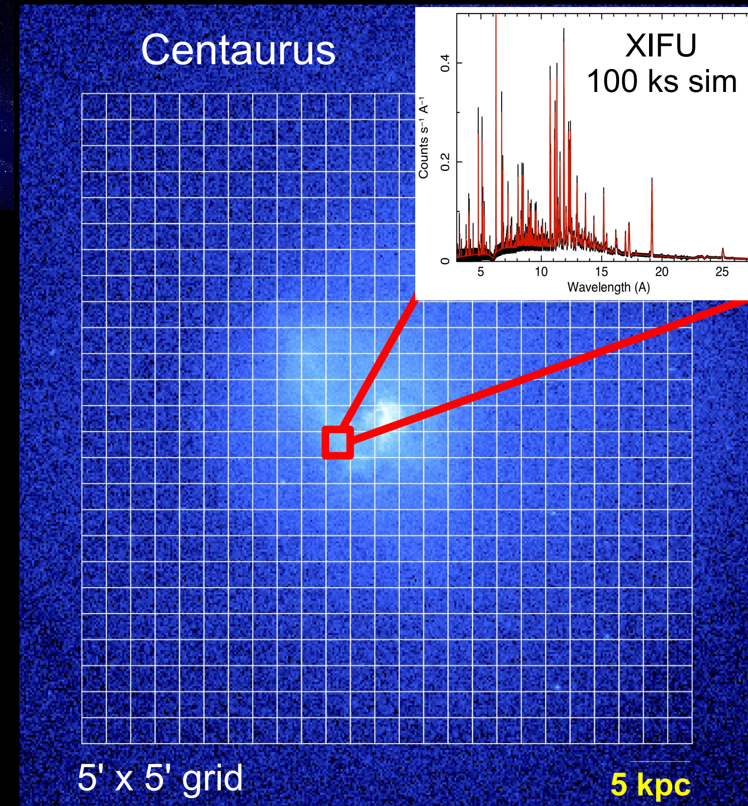
Velocity dispersion generated in situ or quickly transferred?

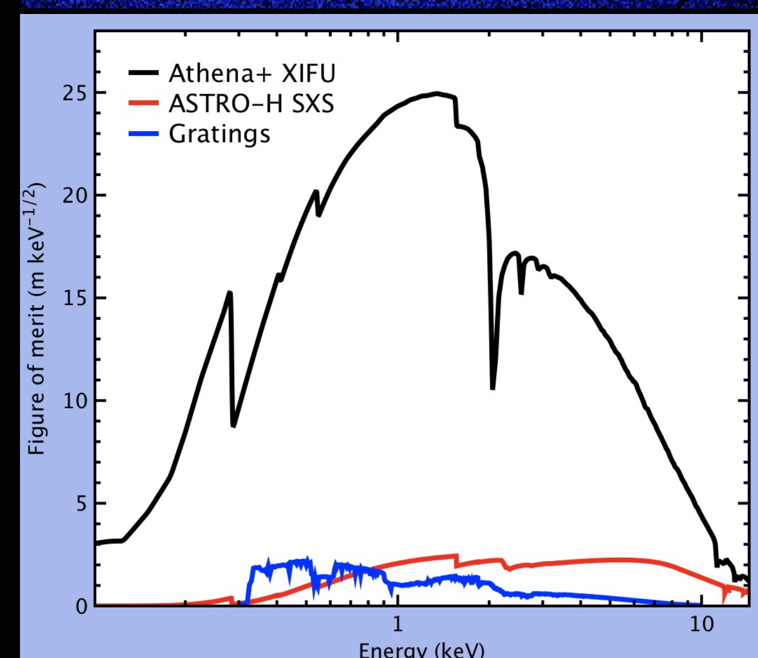
Need: observations of AGN vs merging dominated clusters

X-ray Facilities



ATHENA (2028)





XMM-Newton

1D Line broadening, shift, RS

Chandra

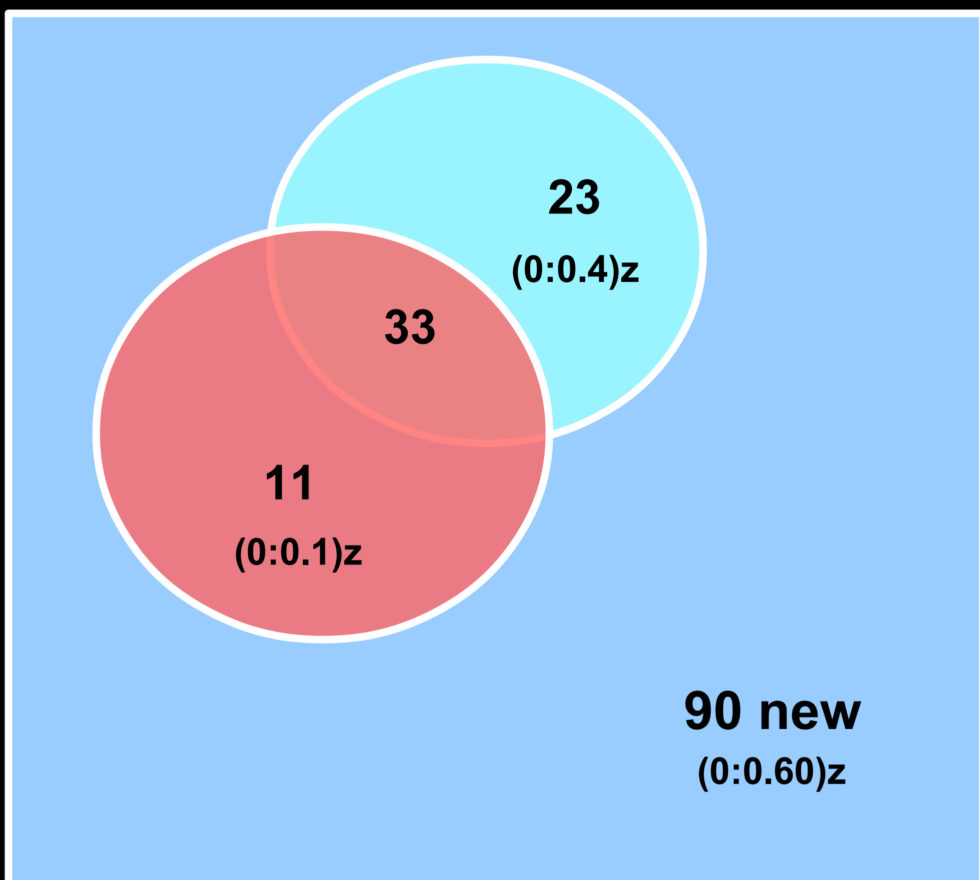
Shocks, fluctuations

XARM (2021)

2D Line broadening, shift, RS

XMM-Newton Turbulence Legacy

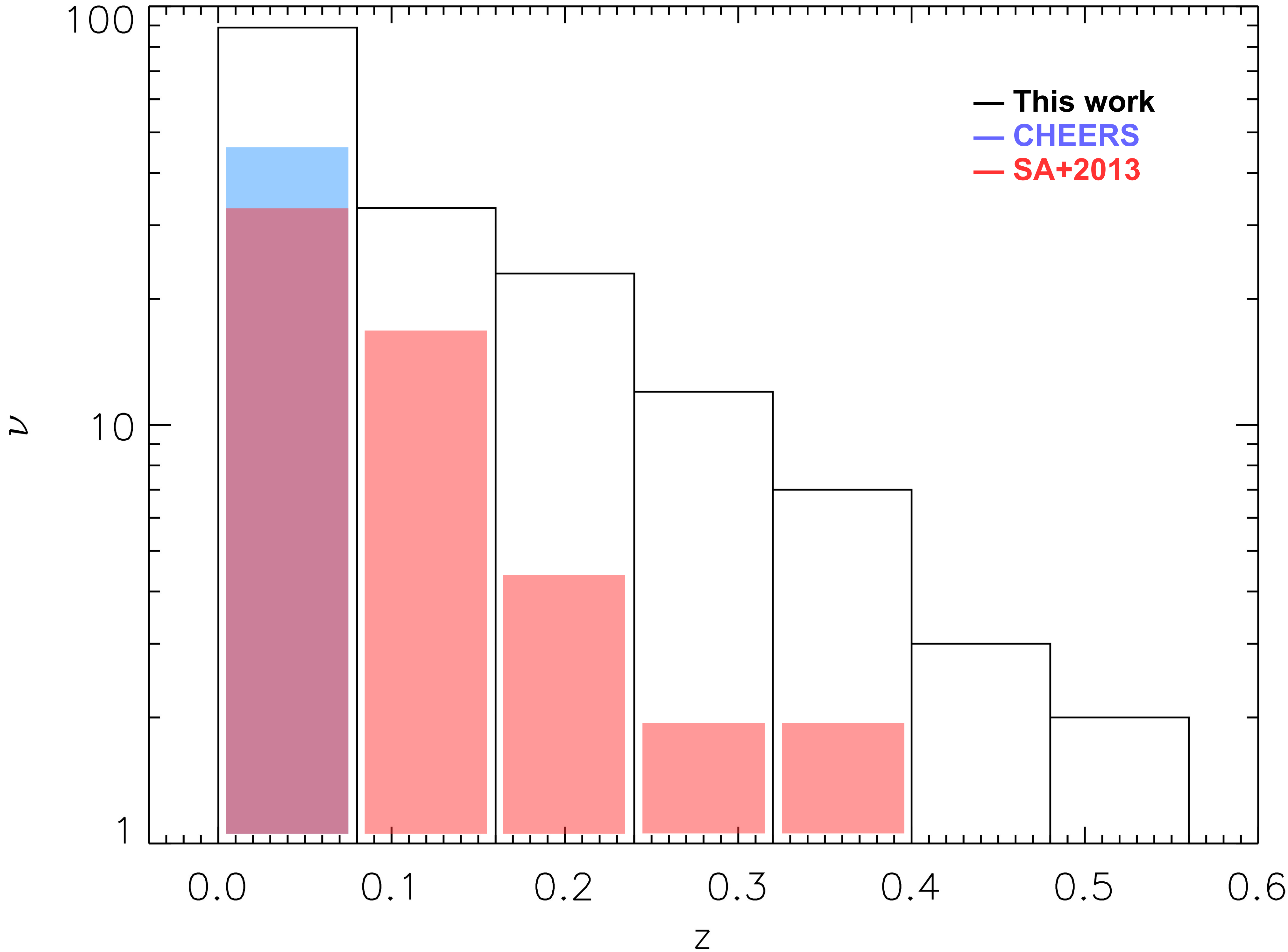
What else can we do right now?



Sanders + 2013 : 56 objects
Pinto + 2015 : 44 objects
This project : 157 objects

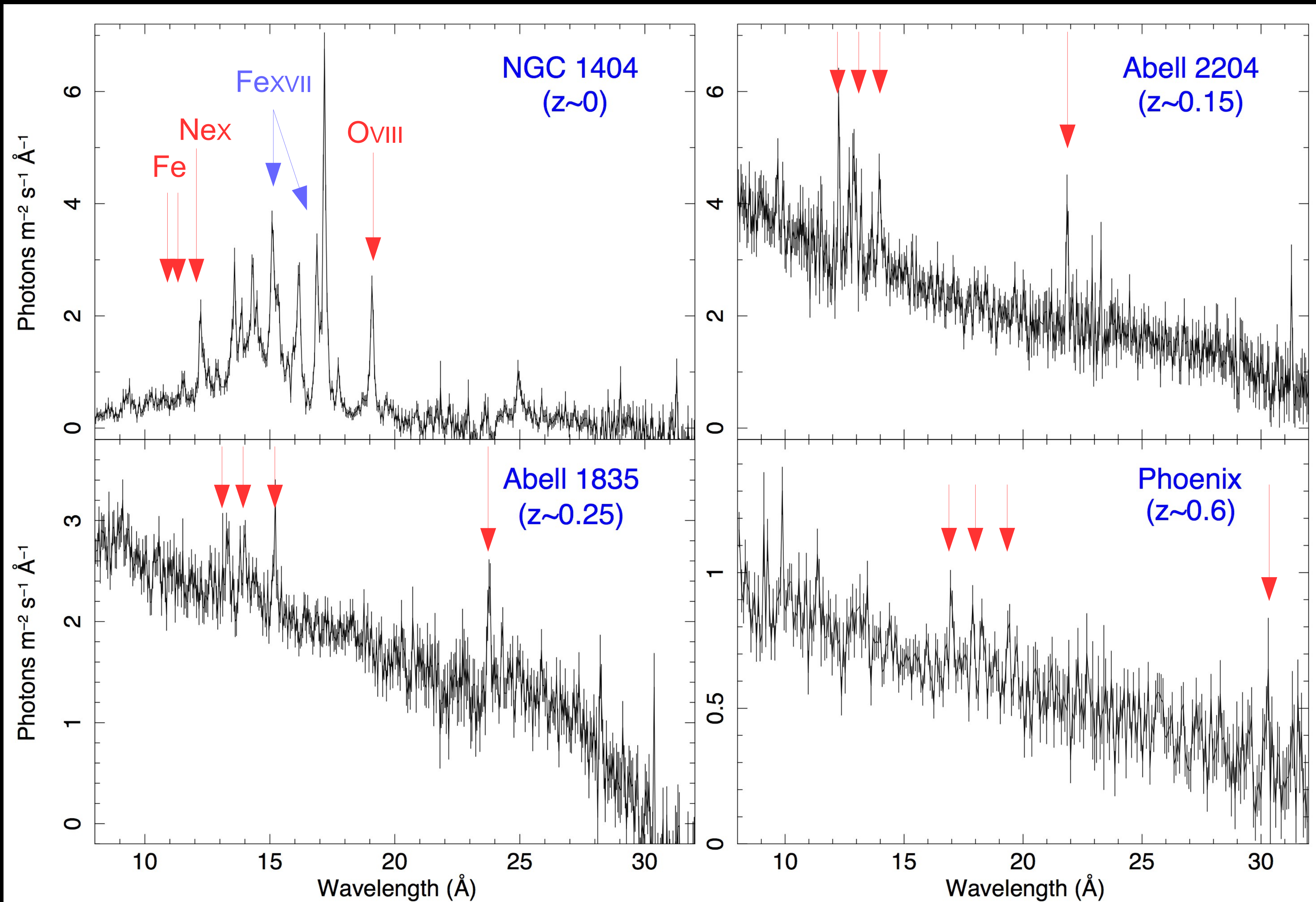
Upper-limits on velocity broadening

Resonant scattering Fe XVII, XVIII, ...



This work
CHEERS
SA+2013
100
10
1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
z
ν

Some examples

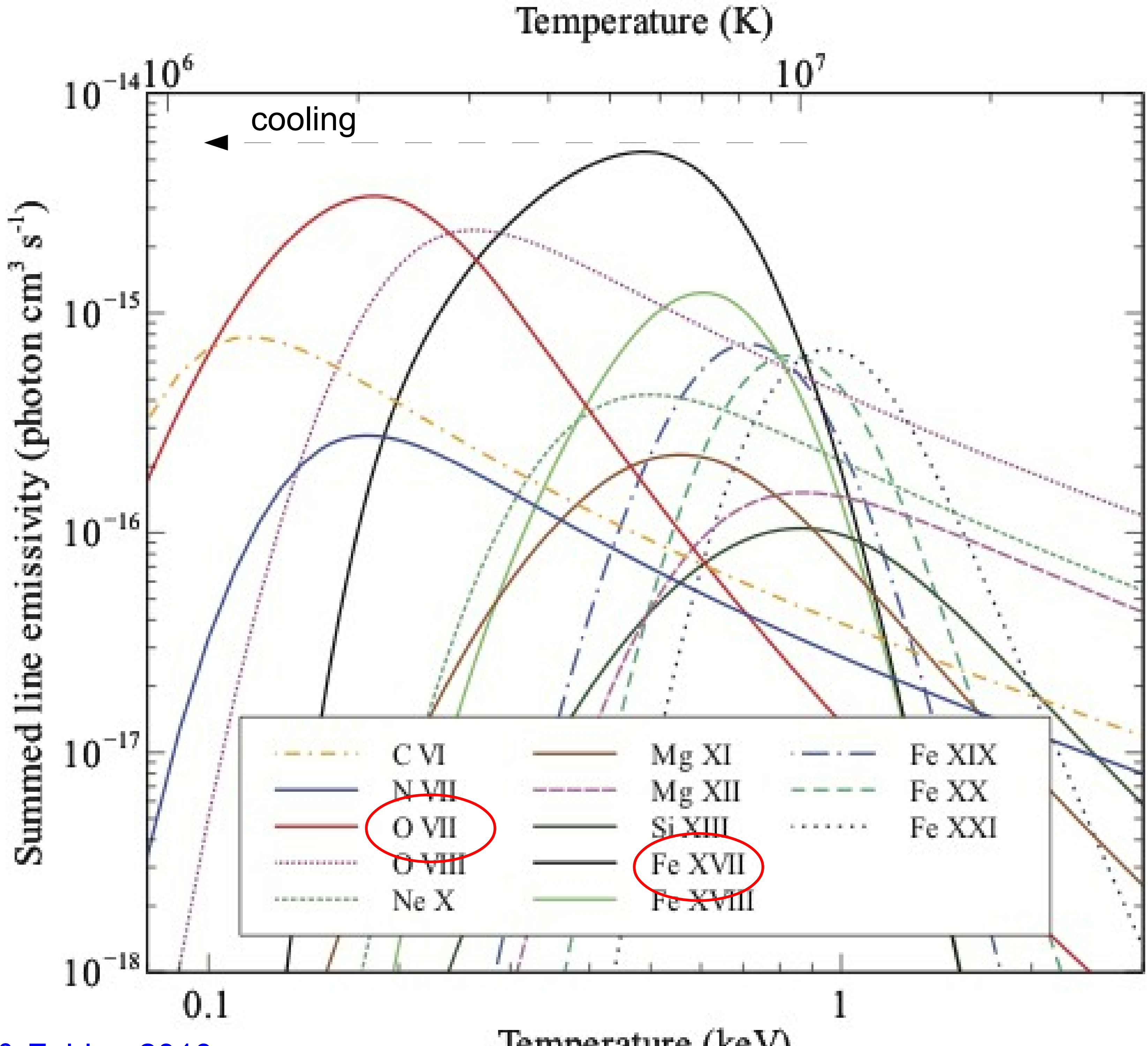


Take away message

- ICM is *cooling* down below 1 keV
- But cooling is highly suppressesed
- AGN is likely dominating in the core, but ...
- ... too few comparisons data-vs-models
- ... not clean comparisons (AGN-vs-merger clusters)
- ... conflicting results from simulations

Thanks, questions?

Bonus



Sanders & Fabian 2010

How to measure turbulence?

1. Line widths
   Upper limits in most cases
   (instrumental limits – statistics)

   Sanders+13
   Pinto+15

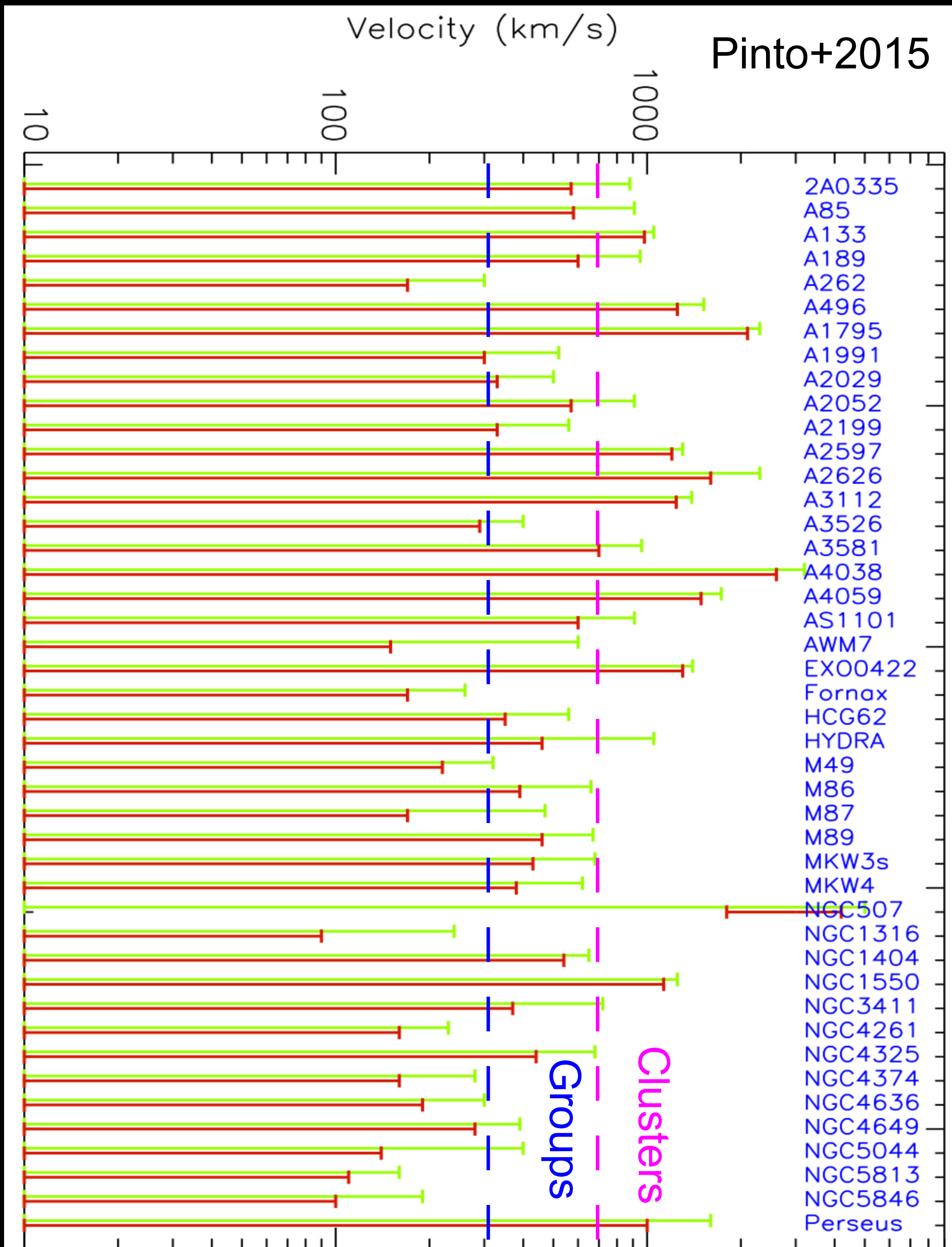
2. Resonant scattering
   Accurate lower limits
   (atomic data – high Mach numbers issues)

   Sanders+08
   Werner+09
   de Plaa+12

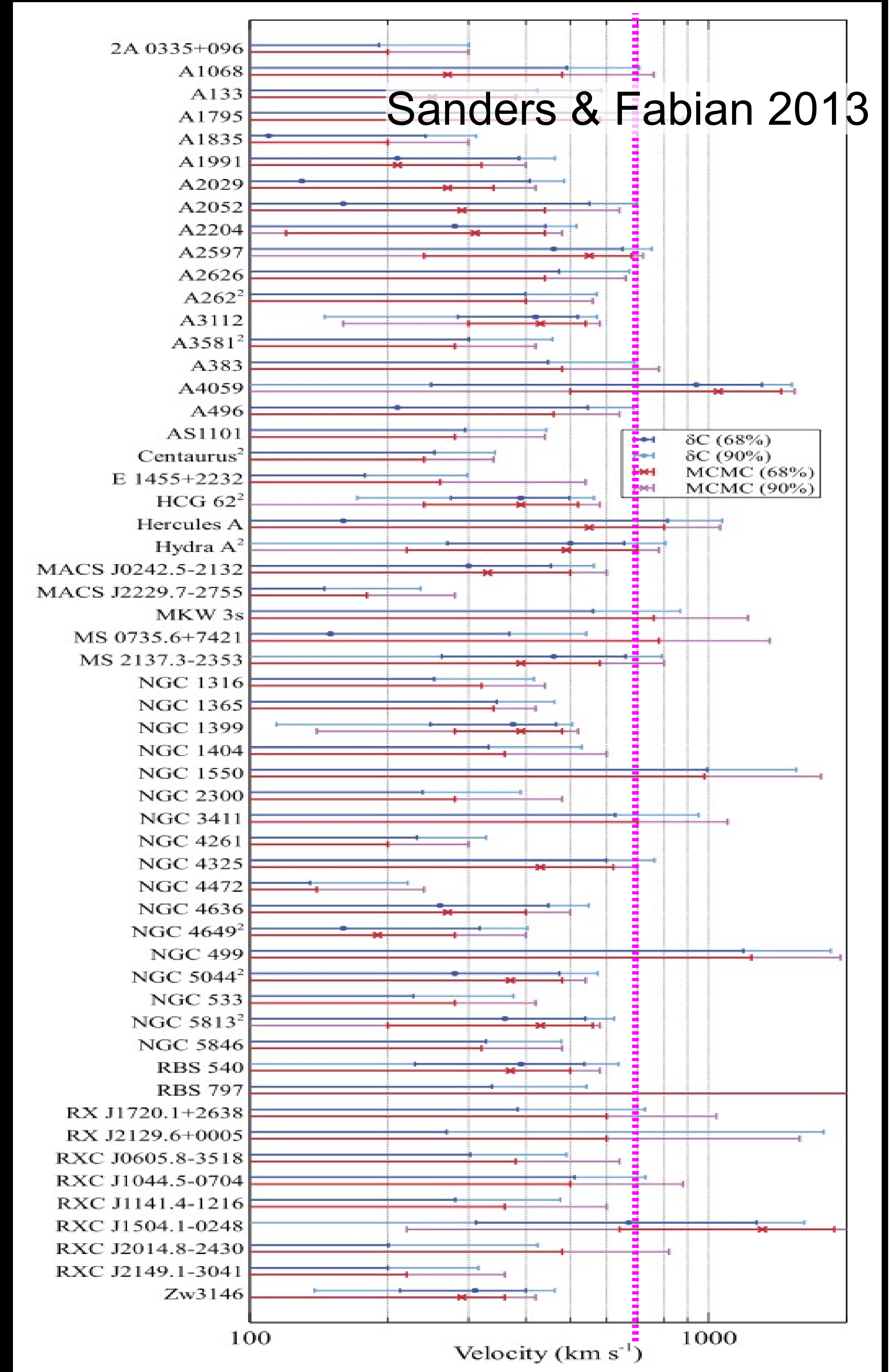
3. Surface brightness fluctuations
   (Substructures, theoretical models, stat.)

   Sanders+12
   Zhuravleva+14
   Walker+15

Line widths



Pinto+2015
Velocity (km/s)
10
100
1000
2A0335
A85
A133
A189
A262
A496
A1795
A1991
A2029
A2052
A2199
A2597
A2626
A3112
A3526
A3581
A4038
A4059
AS1101
AWM7
EXO0422
Fornax
HCG62
HYDRA
M49
M86
M87
M89
MKW3s
MKW4
NGC507
NGC1316
NGC1404
NGC1550
NGC3411
NGC4261
NGC4325
NGC4374
NGC4636
NGC4649
NGC5044
NGC5813
NGC5846
Perseus
Groups
Clusters



Sanders & Fabian 2013
2A 0335+096
A1068
A133
A1795
A1835
A1991
A2029
A2052
A2204
A2597
A2626
A262[2]
A3112
A3581[2]
A383
A4059
A496
AS1101
Centaurus[2]
E 1455+2232
HCG 62[2]
Hercules A
Hydra A[2]
MACS J0242.5-2132
MACS J2229.7-2755
MKW 3s
MS 0735.6+7421
MS 2137.3-2353
NGC 1316
NGC 1365
NGC 1399
NGC 1404
NGC 1550
NGC 2300
NGC 3411
NGC 4261
NGC 4325
NGC 4472
NGC 4636
NGC 4649[2]
NGC 499
NGC 5044[2]
NGC 533
NGC 5813[2]
NGC 5846
RBS 540
RBS 797
RX J1720.1+2638
RX J2129.6+0005
RXC J0605.8-3518
RXC J1044.5-0704
RXC J1141.4-1216
RXC J1504.1-0248
RXC J2014.8-2430
RXC J2149.1-3041
Zw3146
δC (68%)
δC (90%)
MCMC (68%)
MCMC (90%)
100
1000
Velocity (km s⁻¹)

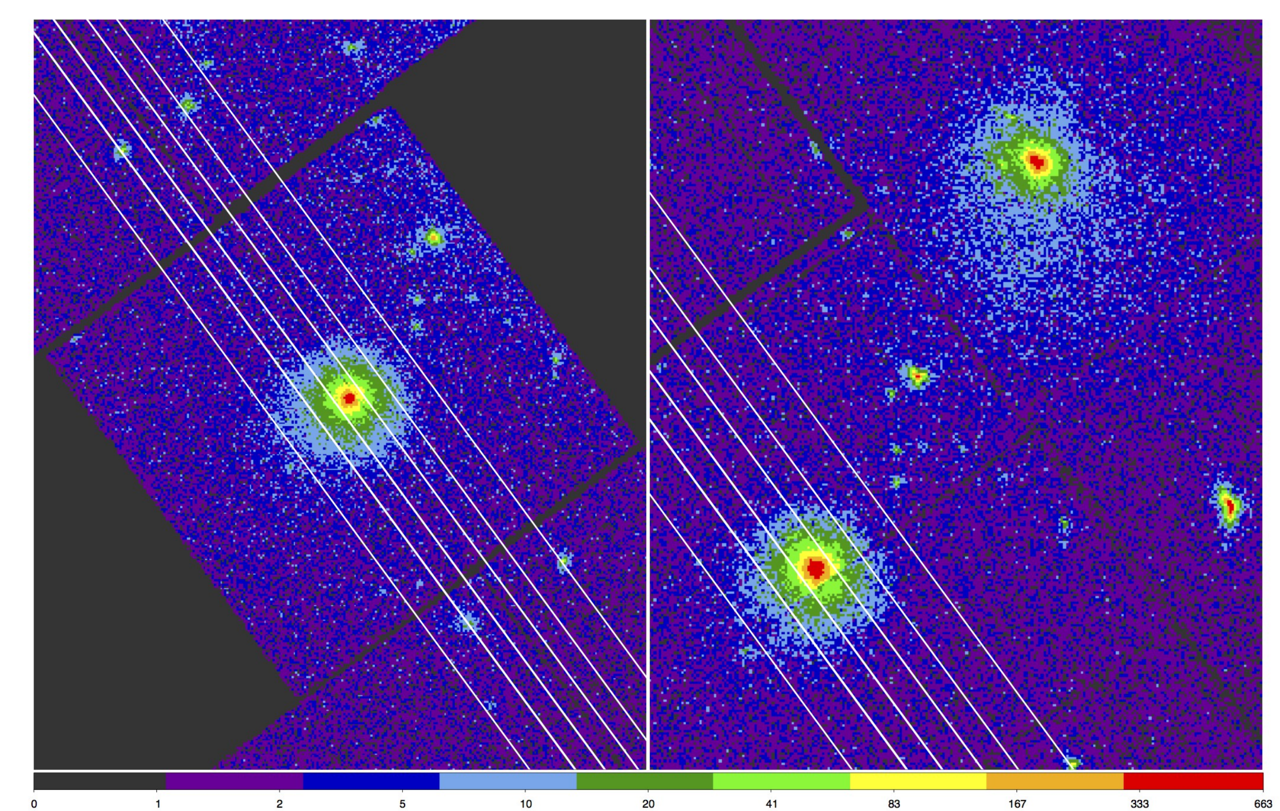
Equations

$c_s = \sqrt{(\gamma\, kT / \mu\, m_p)}$ Sound speed

$\varepsilon_{turb} / \varepsilon_{therm} = (V^2_{los} / kT)\, \mu\, m_p$ % of energy in turbulence:

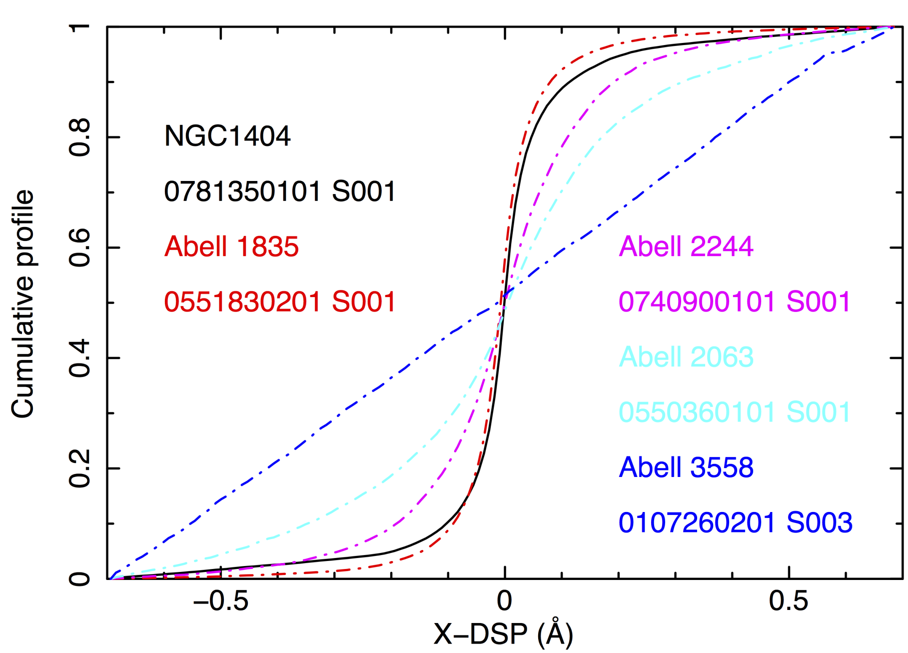
$$Ma_{REQ} \approx 0.15 \left(\frac{n_e}{10^{-2}\,\mathrm{cm^{-3}}}\right)^{1/3} \left(\frac{c_s}{10^3\,\mathrm{km\,s^{-1}}}\right)^{-1} \left(\frac{l}{10\,\mathrm{kpc}}\right)^{1/3}$$

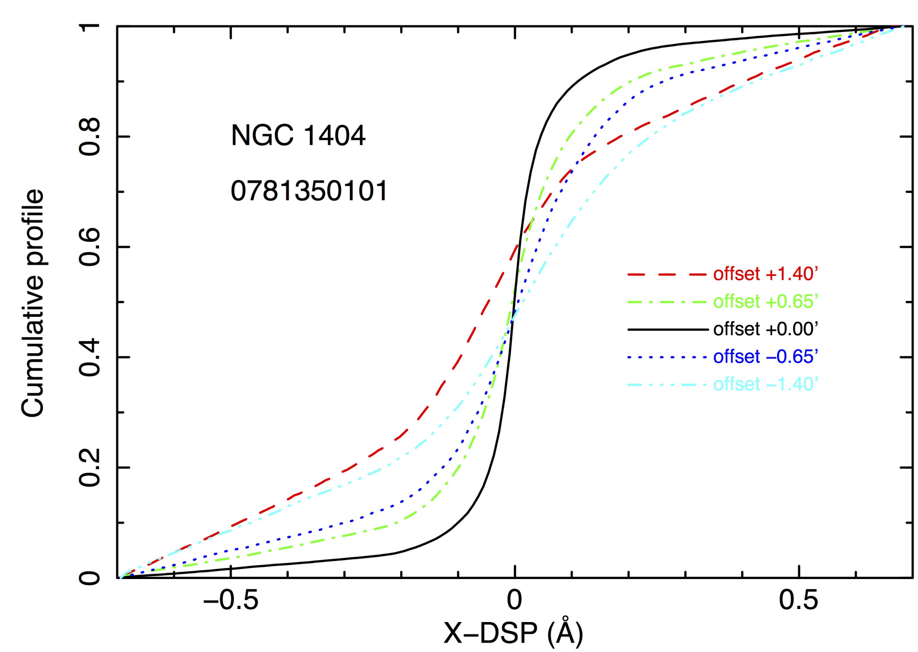
Mach number require to balance cooling



Bonus

NGC1404 vs Fornax





NGC 4636: CX or scattering?