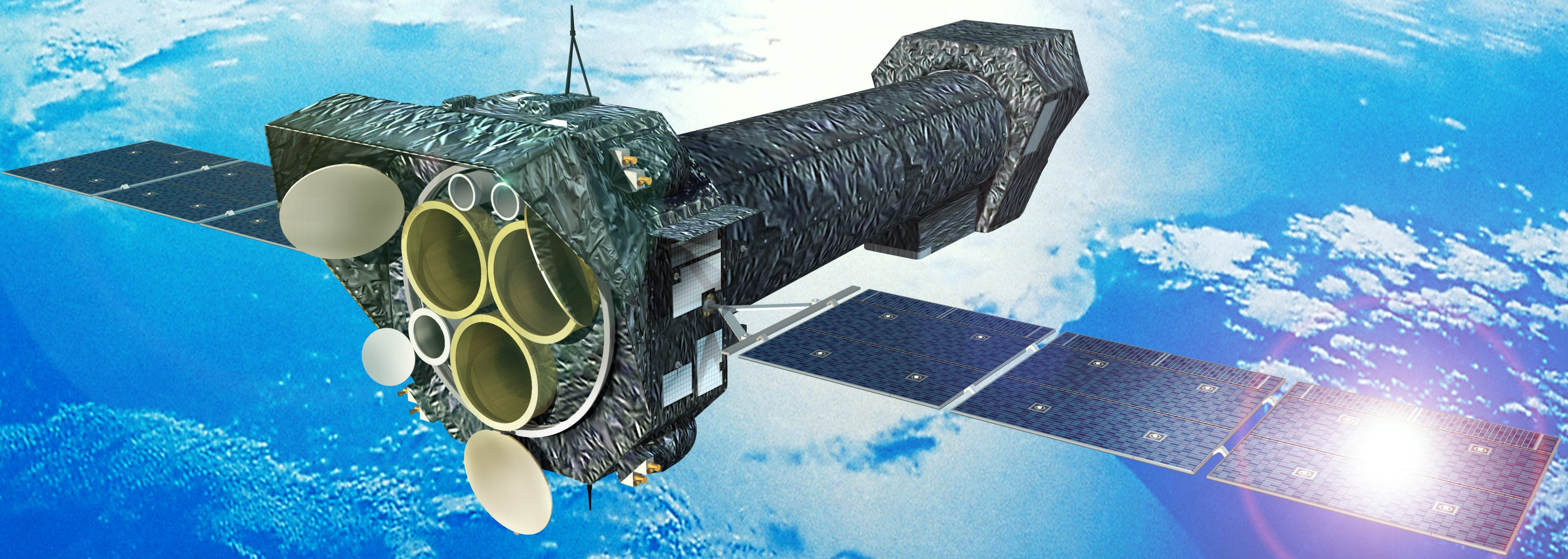
Lessons learned from 19 years of high-resolution X-ray spectroscopy of galaxy clusters with RGS



Ciro Pinto

European Space Agency

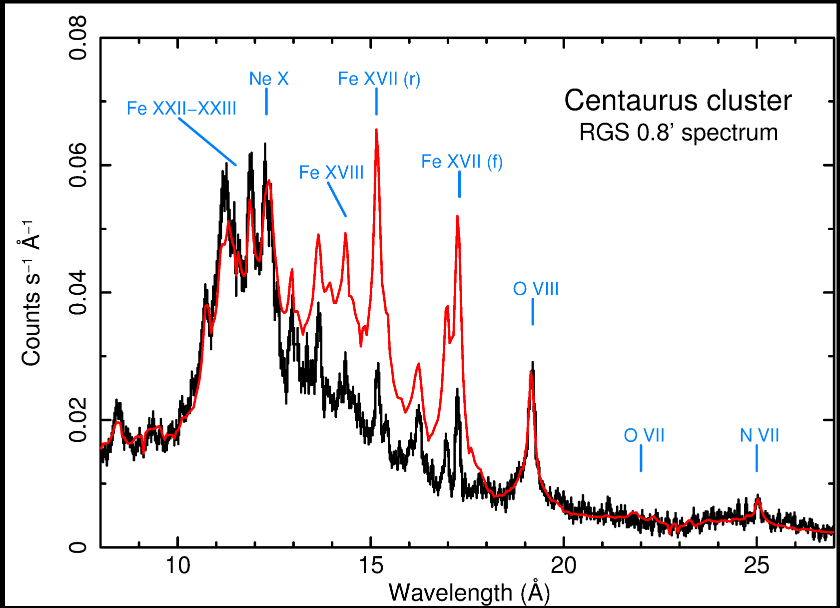
Outline

- Cooling – Heating balance

  Cooling rates

  Turbulent heating

- Chemical enrichment
- Temperature structure
- Atomic physics (RS, CX)
- WHIM & missing baryons

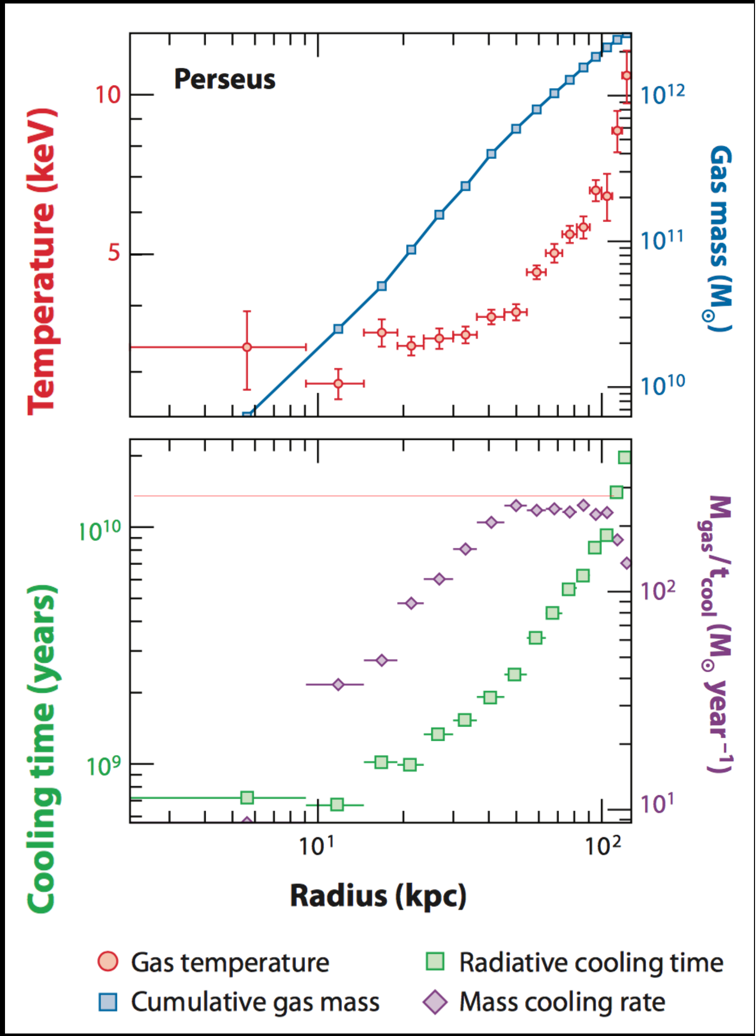


Cooling flows in clusters of galaxies

- Cooling time shorter than Universe age

  → 100-1000 M_{sun} yr^{-1} in cores of clusters

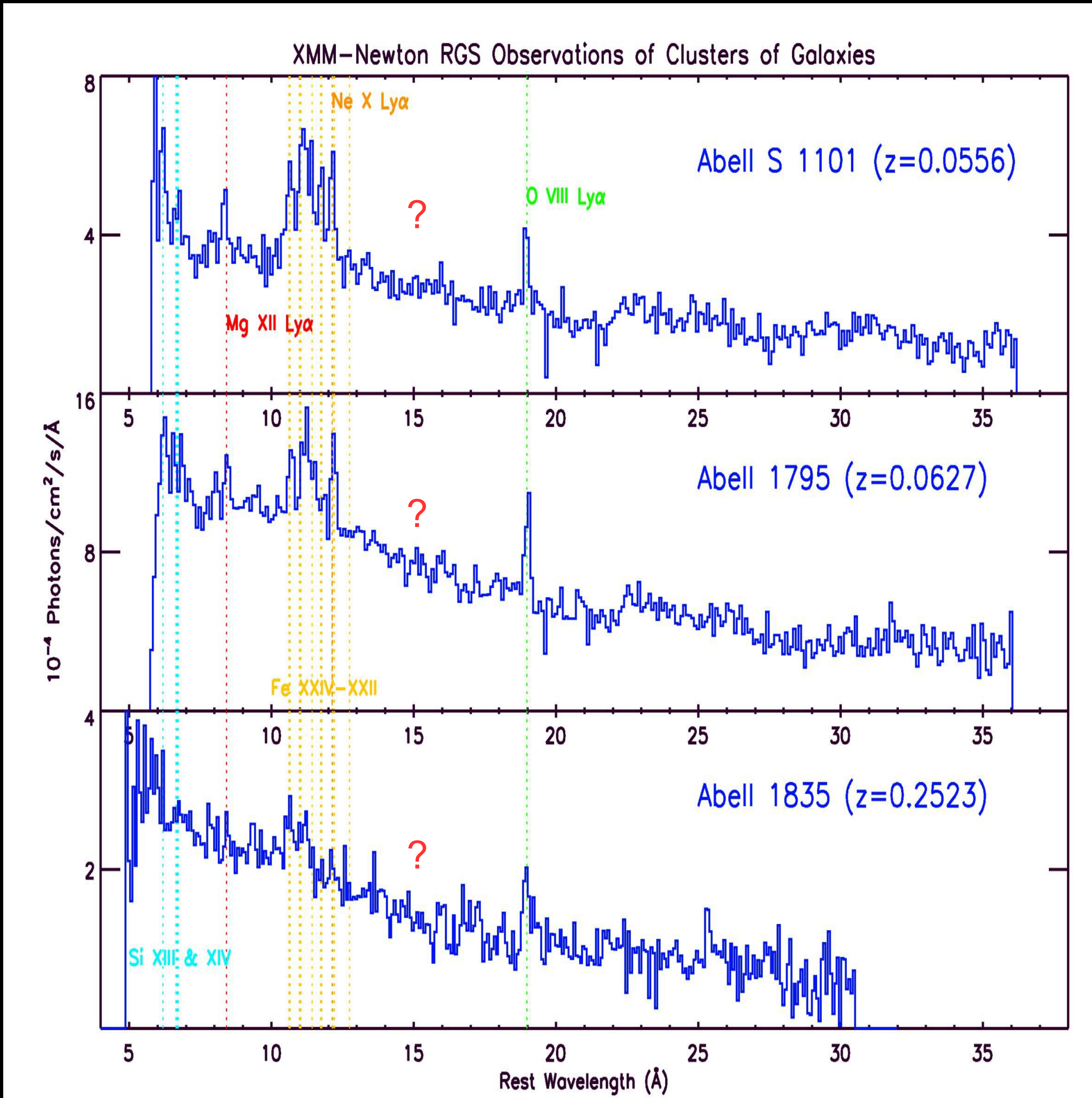
- Early (CCD) observations indicated lower cooling rates compatible with absorption (e.g. Peres+98)



Fabian 2012 (figure by J. Sanders)

$t_{cool} \sim T^{1/2}, n^{-1}$

RGS clusters first light



Individual lines resolved!
Ne K and Fe L separated.
First detection of O VIII

No Fe XVII-XX lines?
Much lower cooling rates!
Absorption no major role

Peterson+01,02,03
Kaastra+01,02,03
Tamura+01ab,03

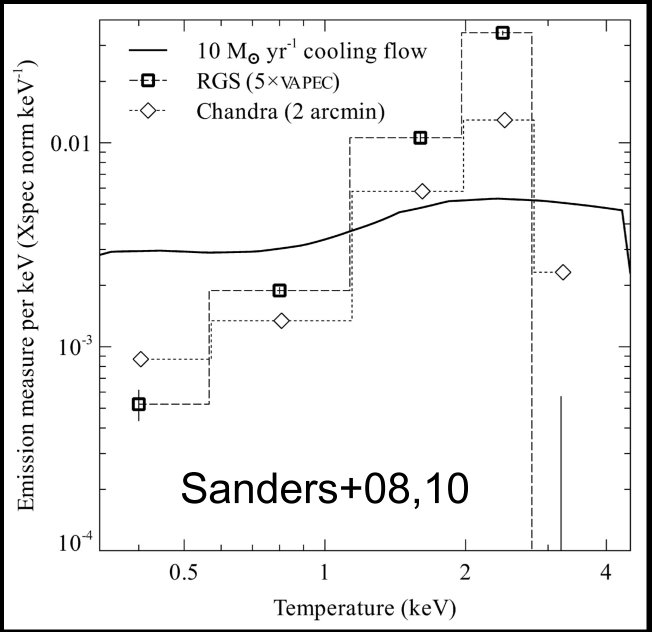
Recent development

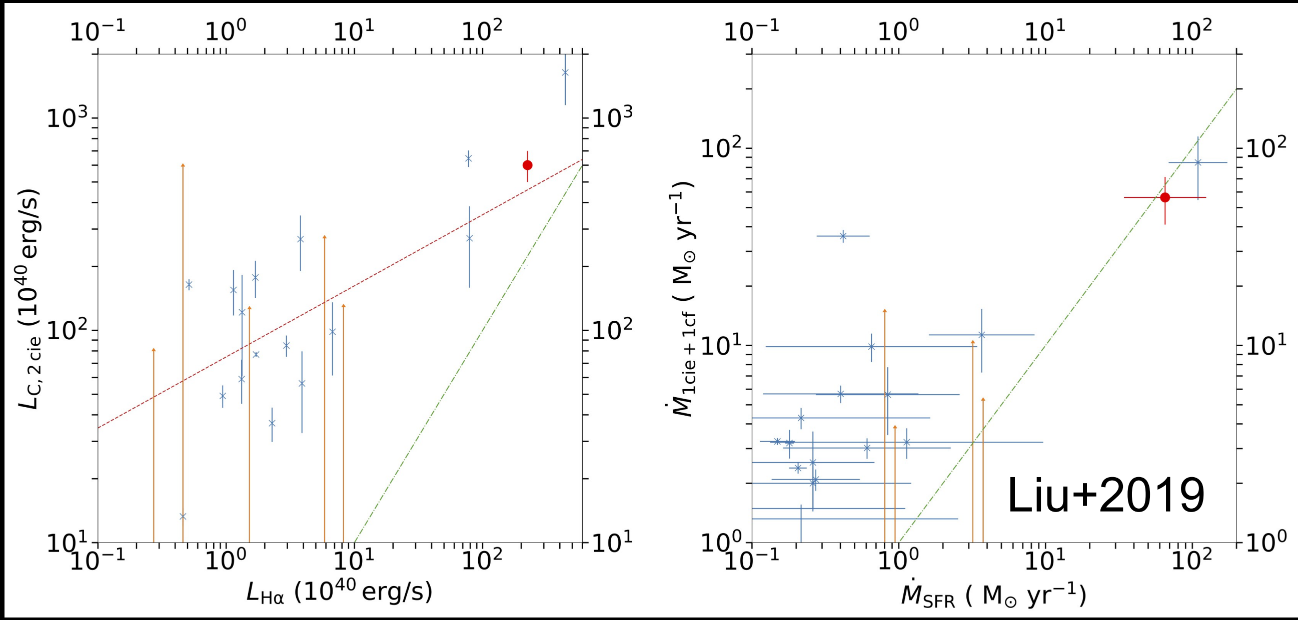
Lack of cooling below 0.5 keV is even more severe

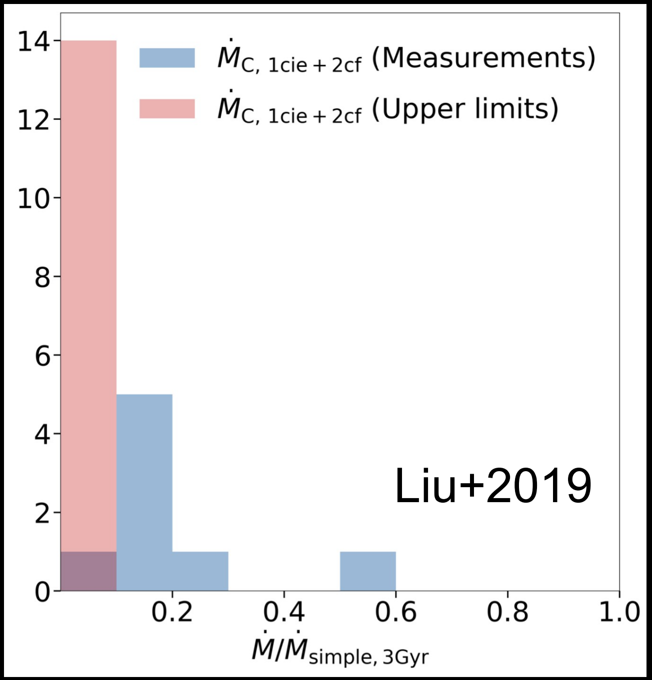
- Cool gas is 10x less than theoretical predictions

- But may be sufficient to produce Hα gas, SFR

→ *Haonan Liu's Talk!*





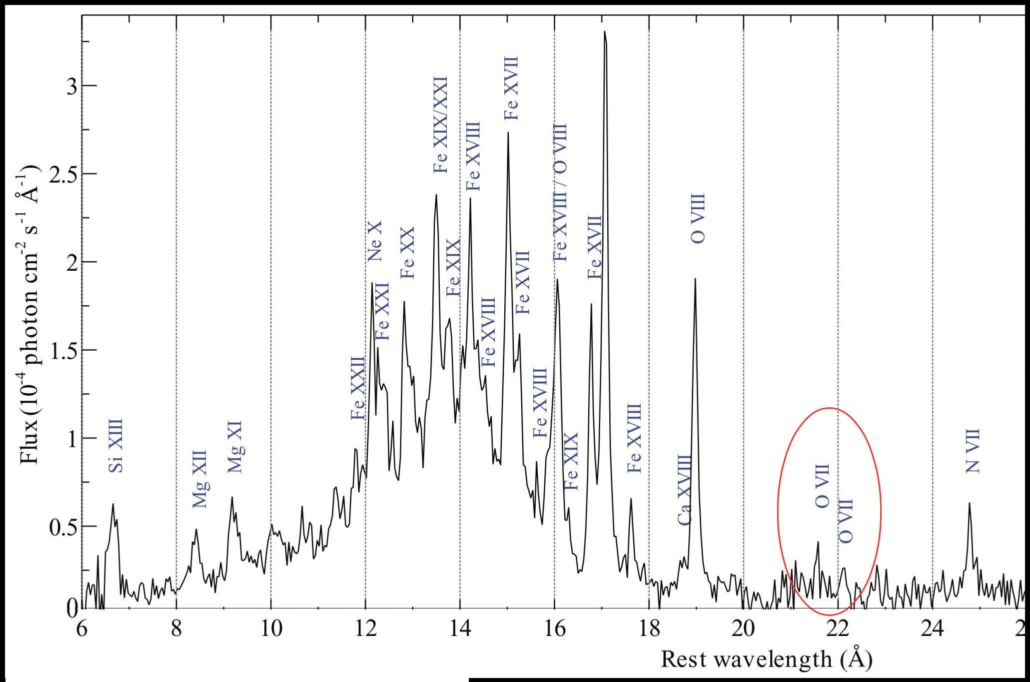


O VII in galaxy groups

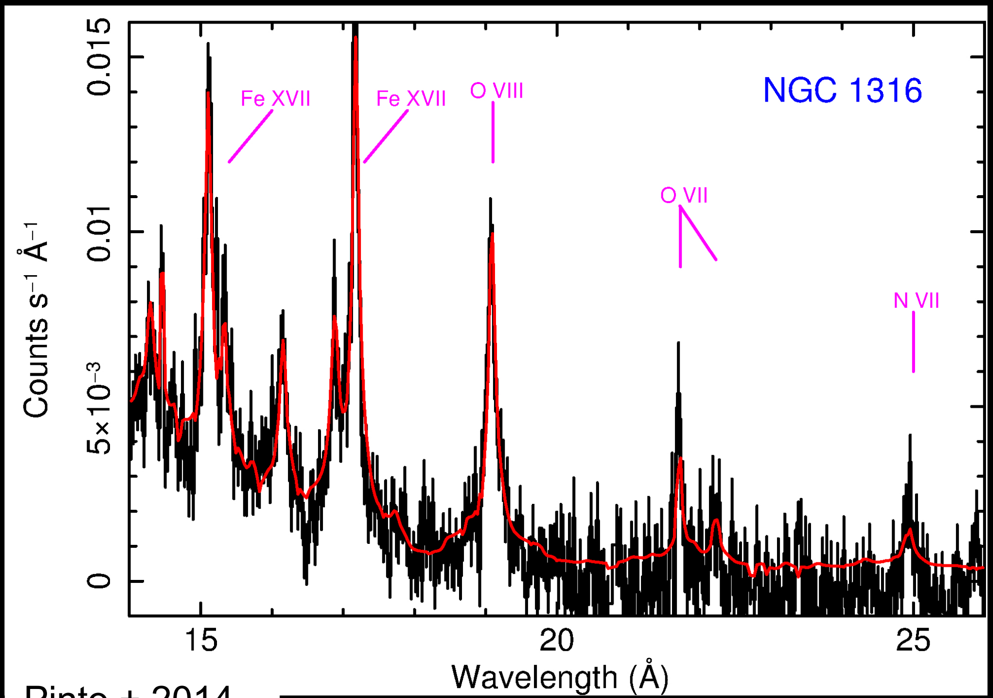
Sanders & Fabian 2011,
Pinto et al. 2014b, 2016b,

- Discovery of O VII (X-ray gas below 2 mln K)
- O VII is 4-8 times fainter than *CFlow* predictions

→ cooling below 0.5 keV even more difficult (0.2-2 $M_\odot$ yr^{-1})



Sanders & Fabian 2011



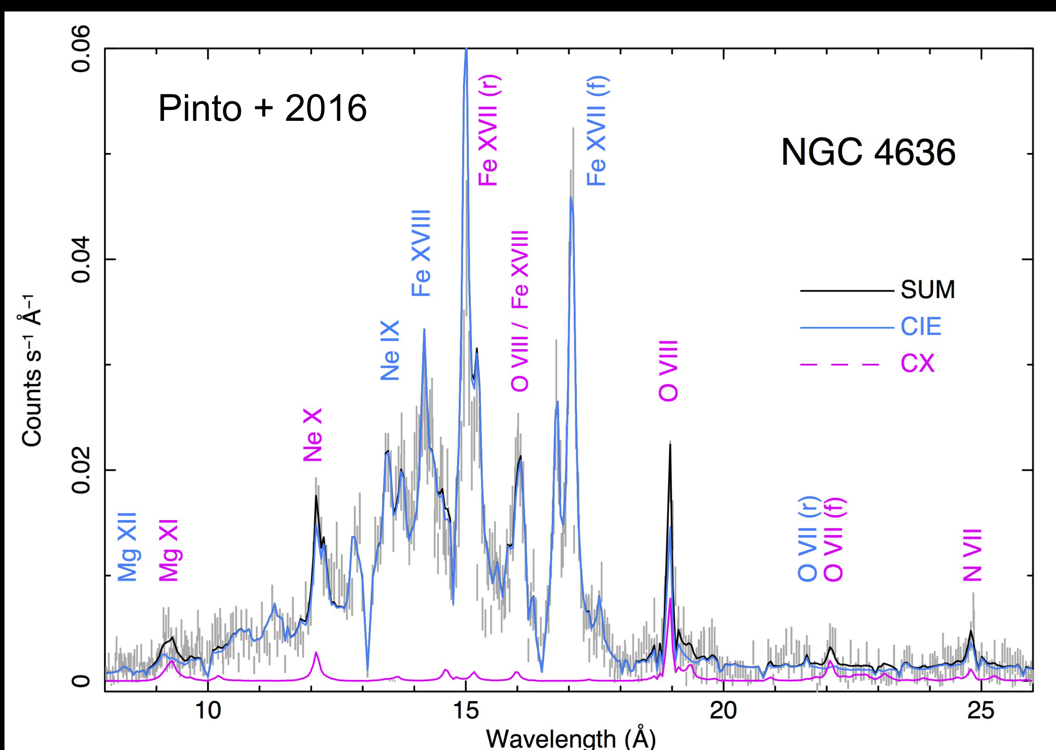
Pinto + 2014

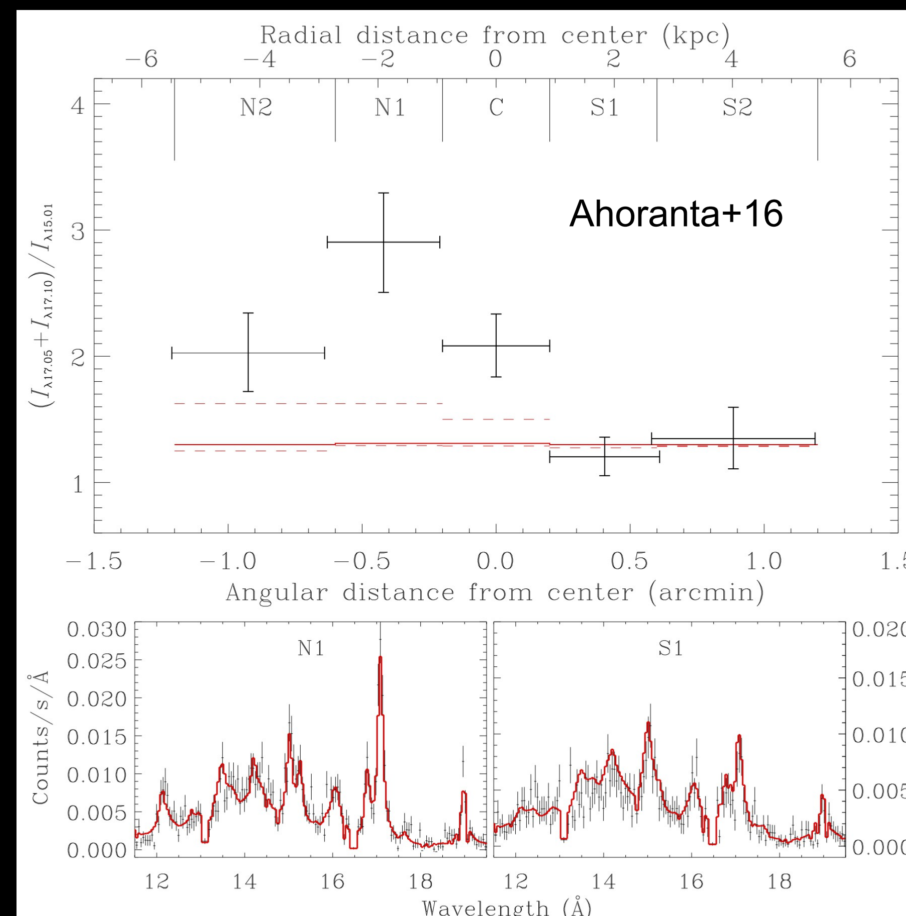
O VII in galaxy groups

- O VII detected in narrow regions, at high Fe XVII resonant scattering

Asymmetric turbulence field / sloshing?

Sanders & Fabian 2011, Pinto et al. 2014b, 2016b, Ahoranta+2016



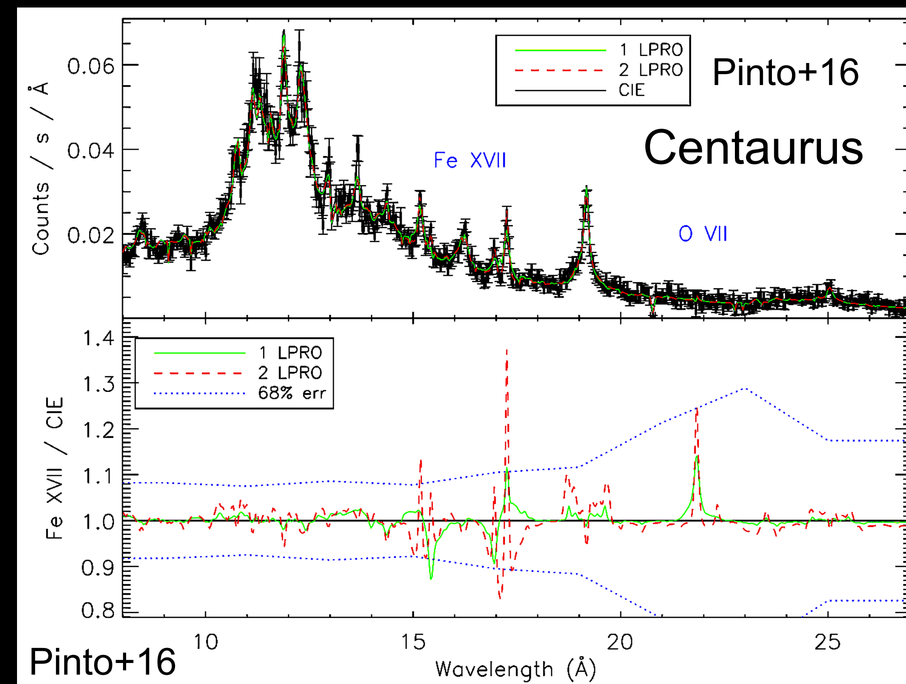


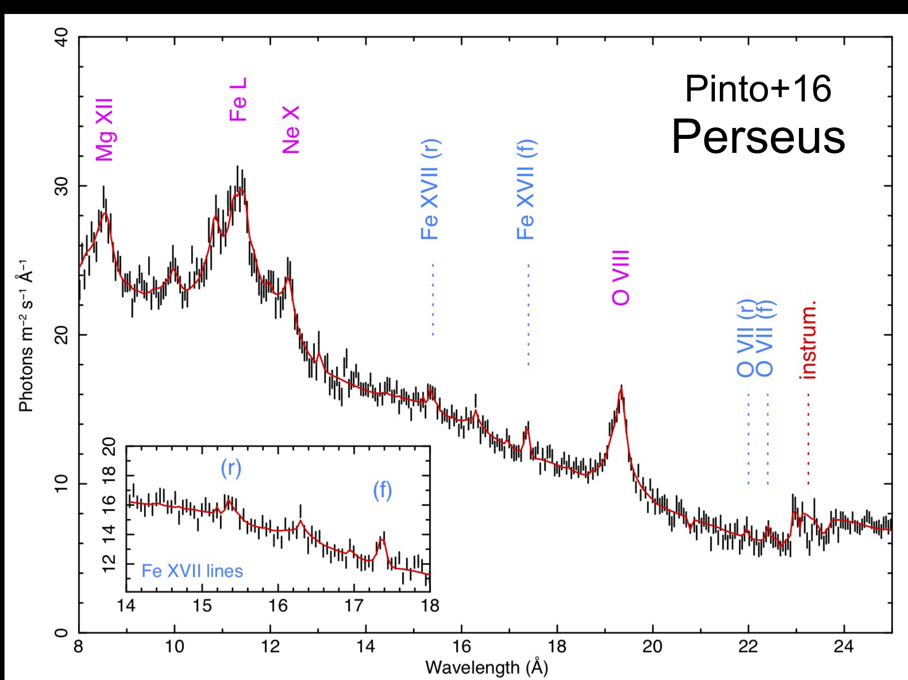
O VII in clusters?

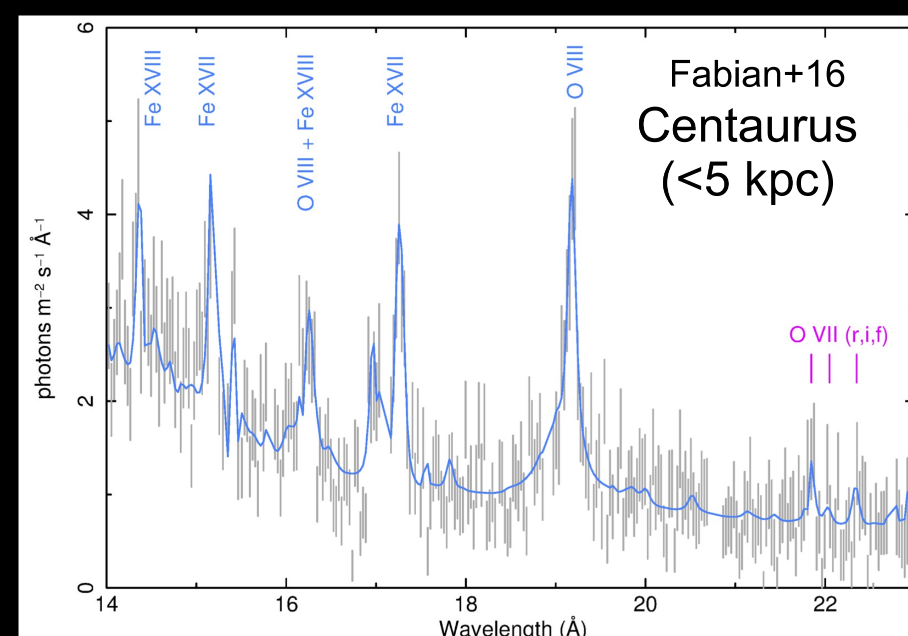
- O VII detected in narrow regions, at high Fe XVII resonant scattering

  Fe XVII (f)/(r) ~ 4 in Perseus

- Efficient cooling due to low turbulence ?

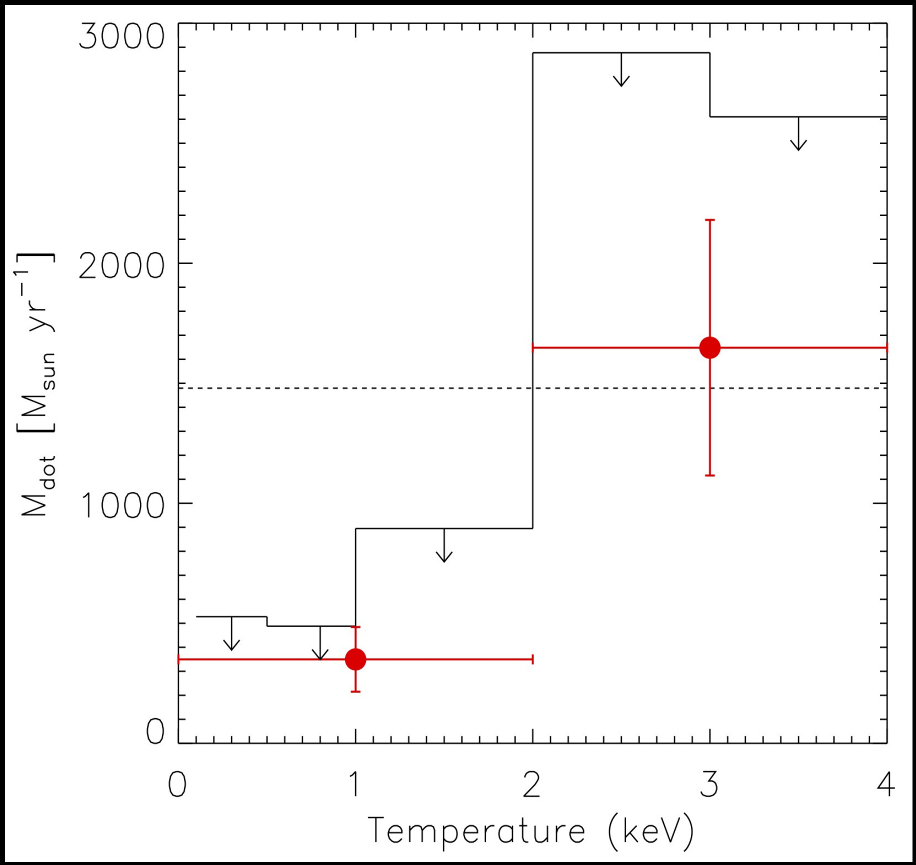




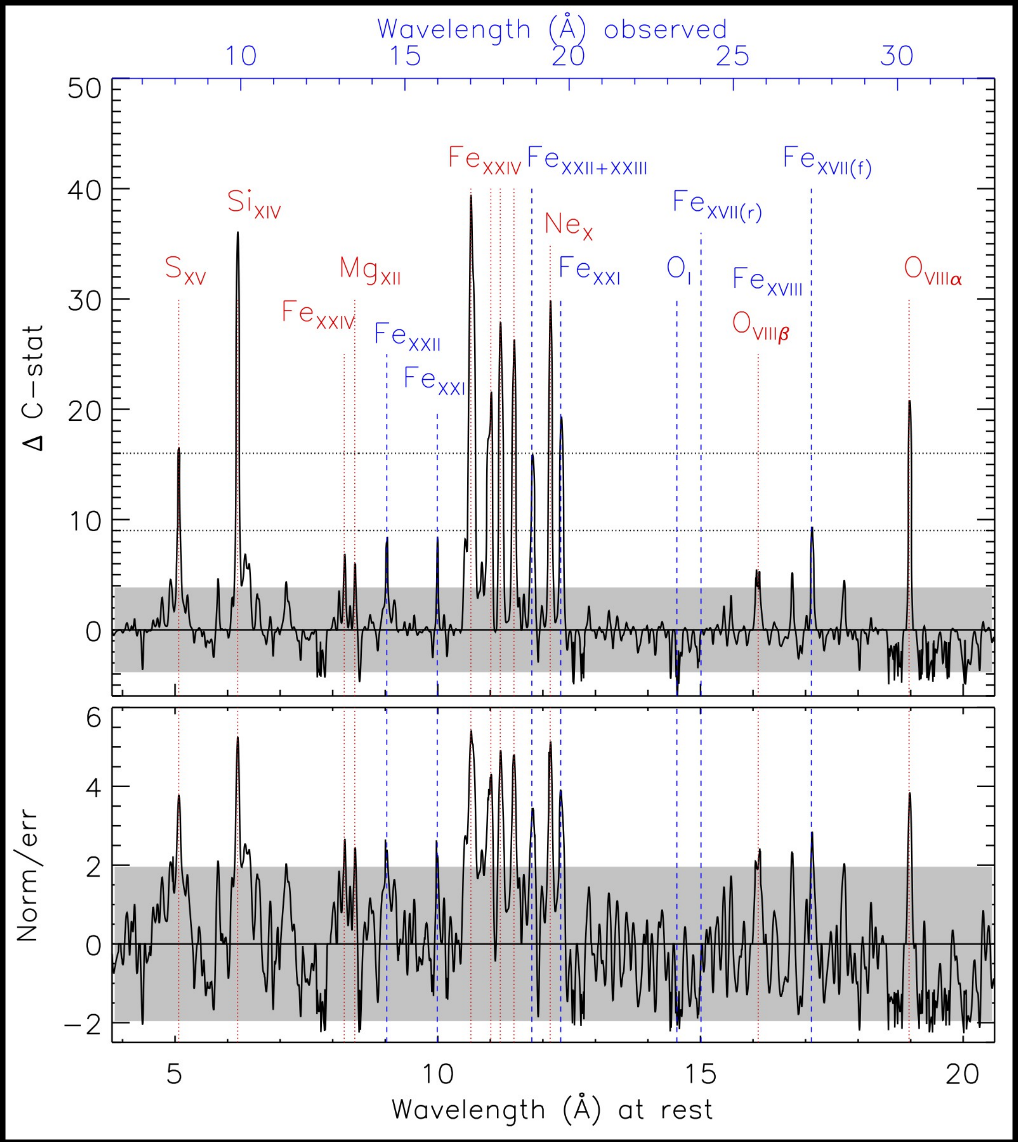


Phoenix : do AGN change mode at high redshift?

Cooling rates



Cool gas line detection



RGS cool.rate agrees with SFR rate.

& more accurate than CCD (<1000$M_{\odot}$ yr^{-1} ,

& EPIC MOS ≠ pn, Chandra, see Tozzi+15)

What's preventing high cooling rates?

Over 5 orders of magnitude in X-ray Luminosity and >1 in temperature,

in systems of radically different masses & sizes!

- Condution? It requires a lot of fine tuning (e.g. Peterson & Fabian03)
- Shocks? In many objects no shock fronts are present
- Magnetic fields? In the center magnetic pressure could be >10% ...
- Cosmic rays? Should create a pile up around 0.3 T_{amb} (Cen+03) not observed
- Sound waves? AGN jets create sound waves (Bambic & Reynolds 2019)
- Turbulence dissipation? AGN jets can produce turbulence

RGS constraints on Turbulence

1. **Line widths**

   Mostly upper limits

   (Direct, instrumental limitations)

Sanders+10-13
Bulbul+12
de Plaa+12
Pinto+15-18
Bambic+18

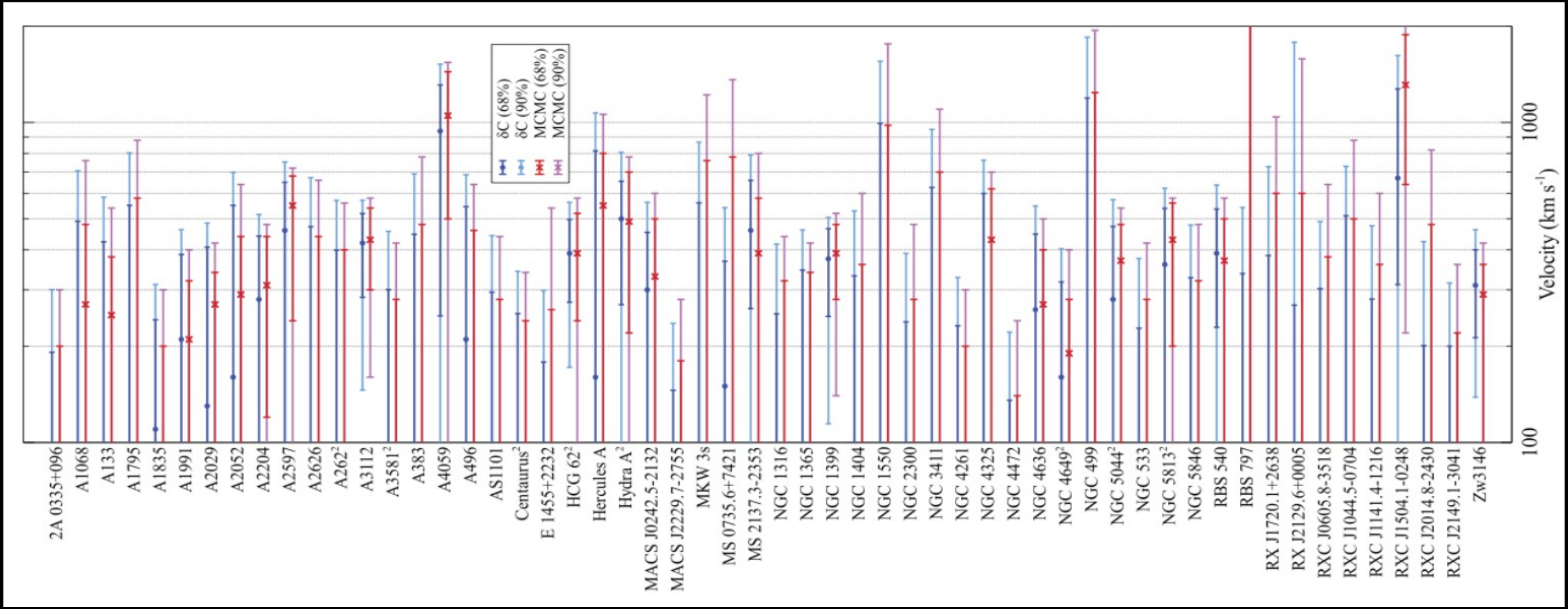
2. **Resonant scattering**

   Mostly lower limits

   (Indirect, atomic data, issues at high Mach/T)

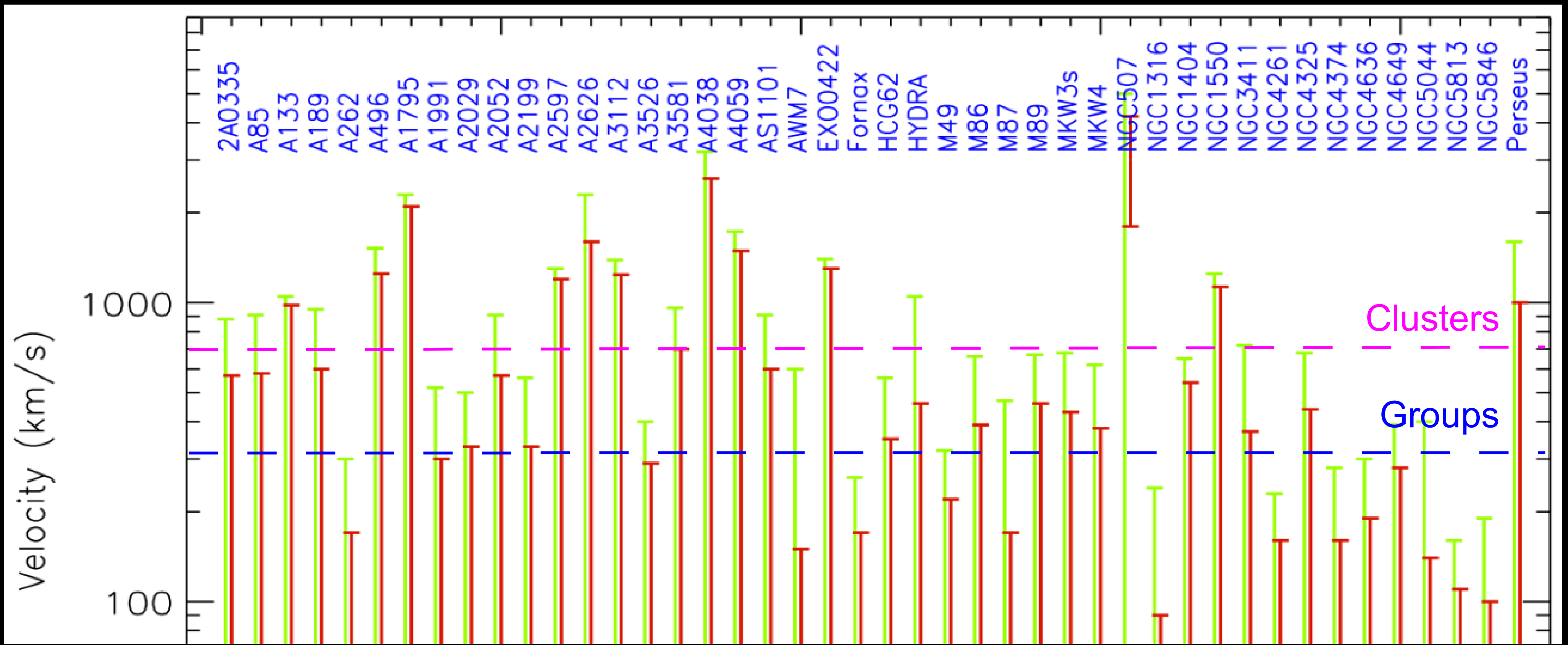
Werner+09
de Plaa+12
Ahoranta+16
Ogorzalek+17

Line widths



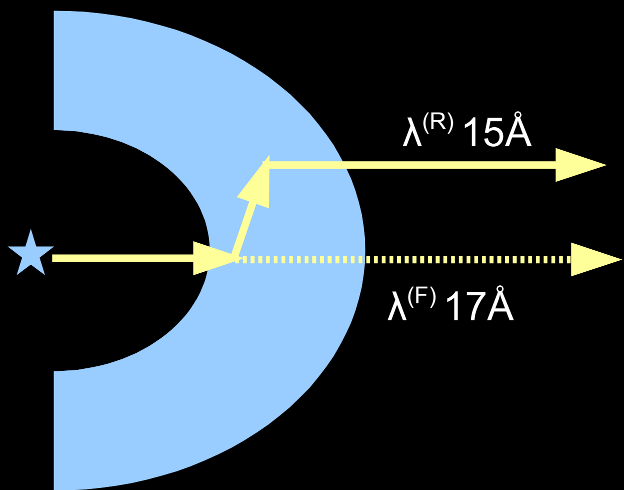
Sanders & Fabian 2013

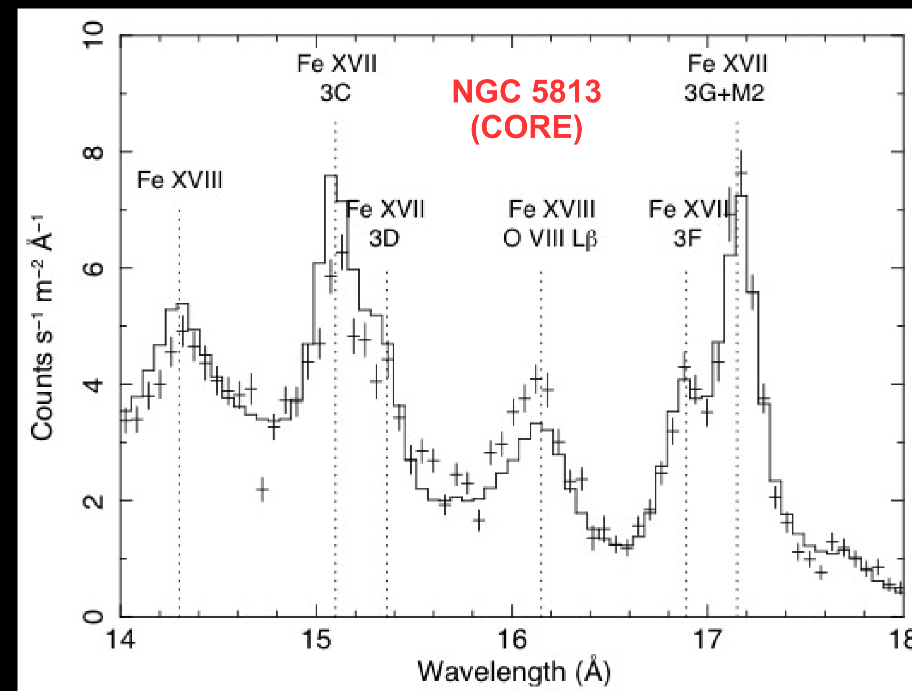
Line widths



Pinto et al. 2015

Resonant scattering

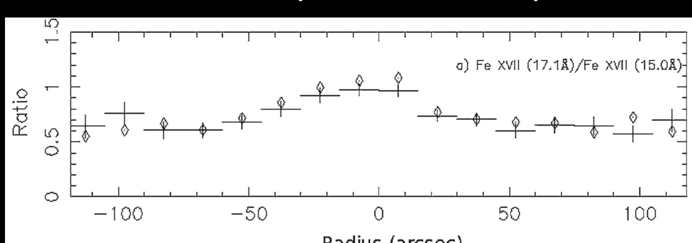




Werner+09
de Plaa+12
Ahoranta+16
Ogorzalek+18

~ 100-500 km s^{-1}

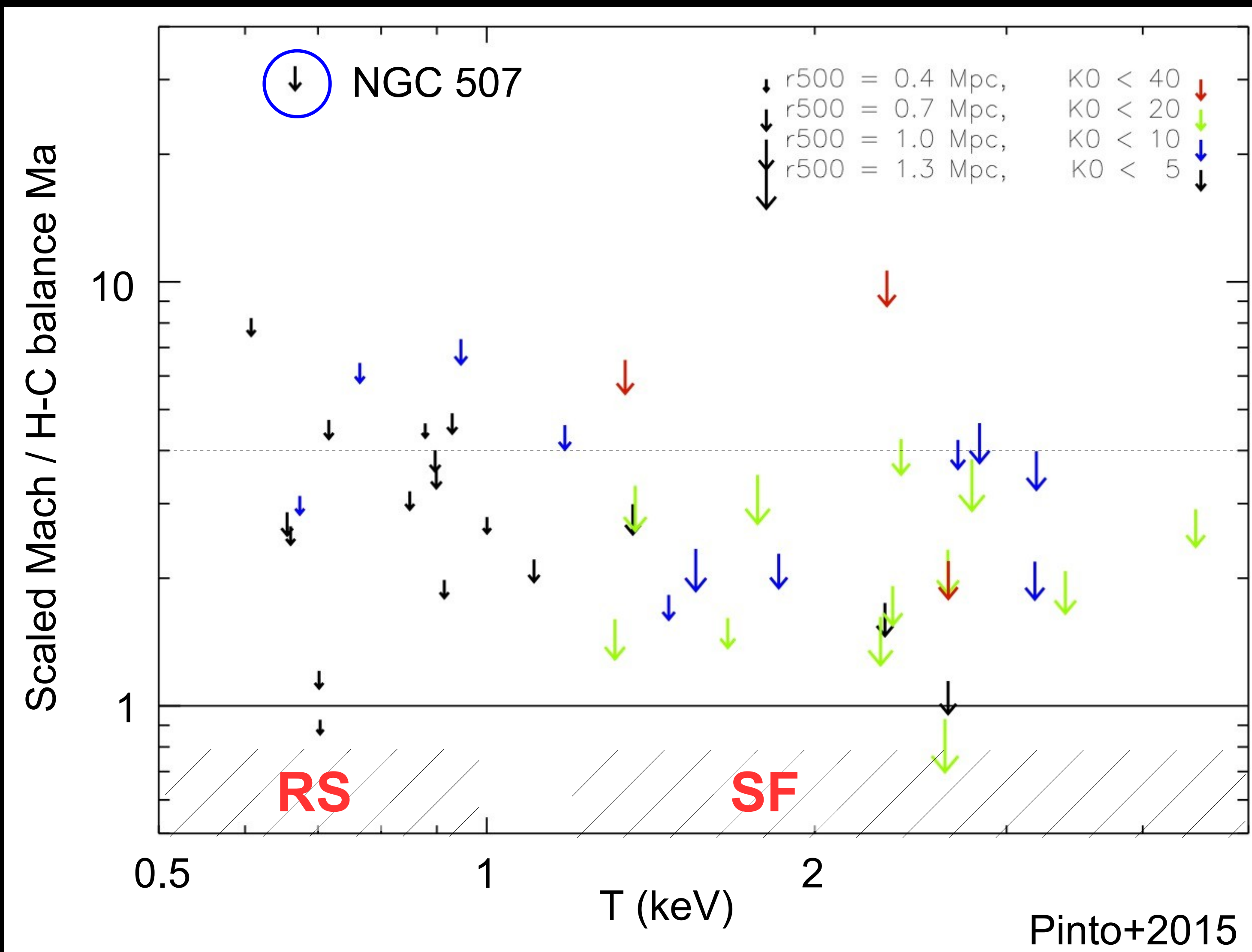
XU+02 (NGC 4636)



Turbulent pressure 5 % (agree with simulations of relaxed clusters, e.g. Lau+09, Vazza+11)

RS affects abundance measurements (10-20%)

Mach numbers required to balance cooling (*locally*)



Upper limits:

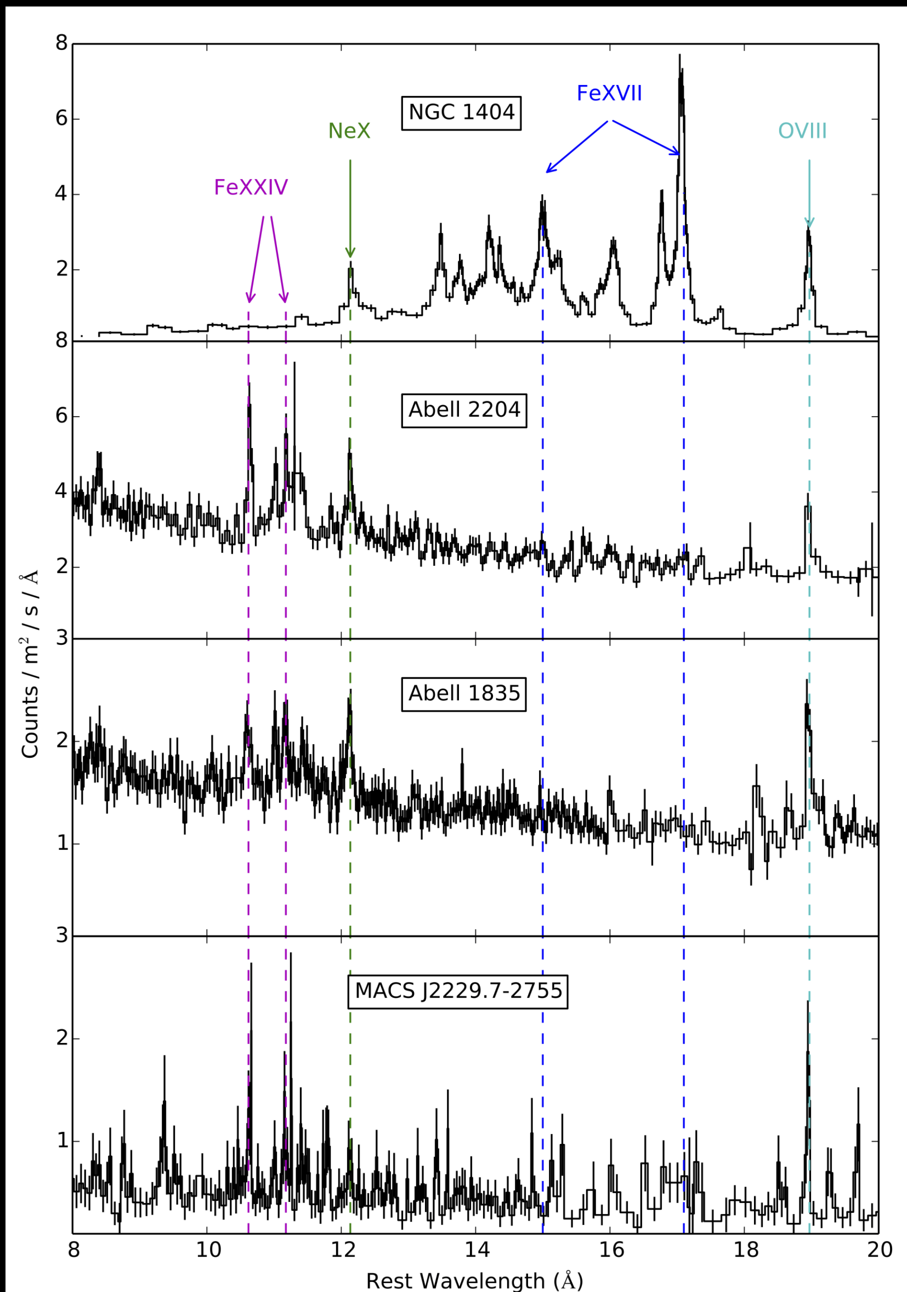
Line widths
(Pinto+15)

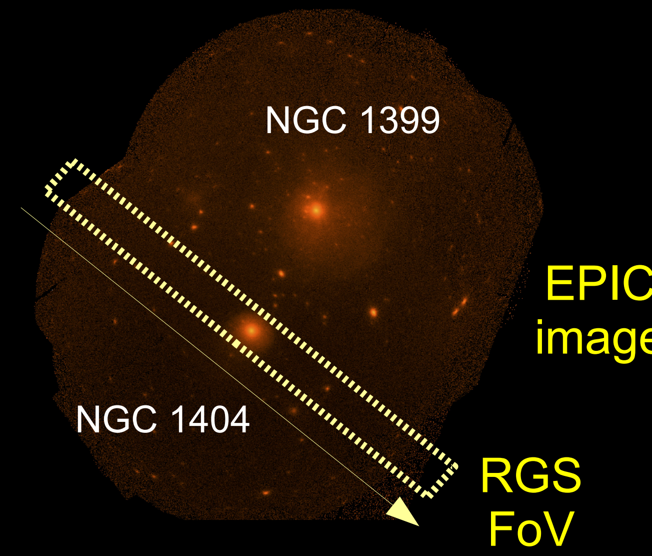
Lower limits:

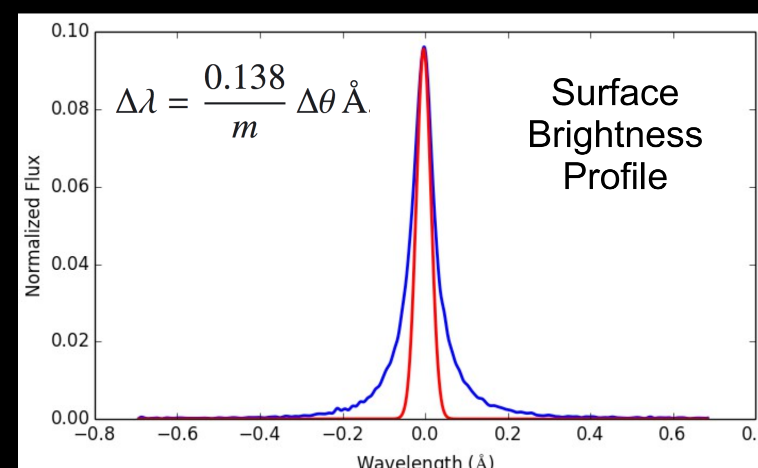
Resonant scattering
(Werner+09
de Plaa+12
Ogorzalek+18)

Surface brightness
fluctuations
(Zhu+14,Eckert+17)

Accounting for instrumental broadening







Gaussian fit of line core width

Bambic et al. (2018)

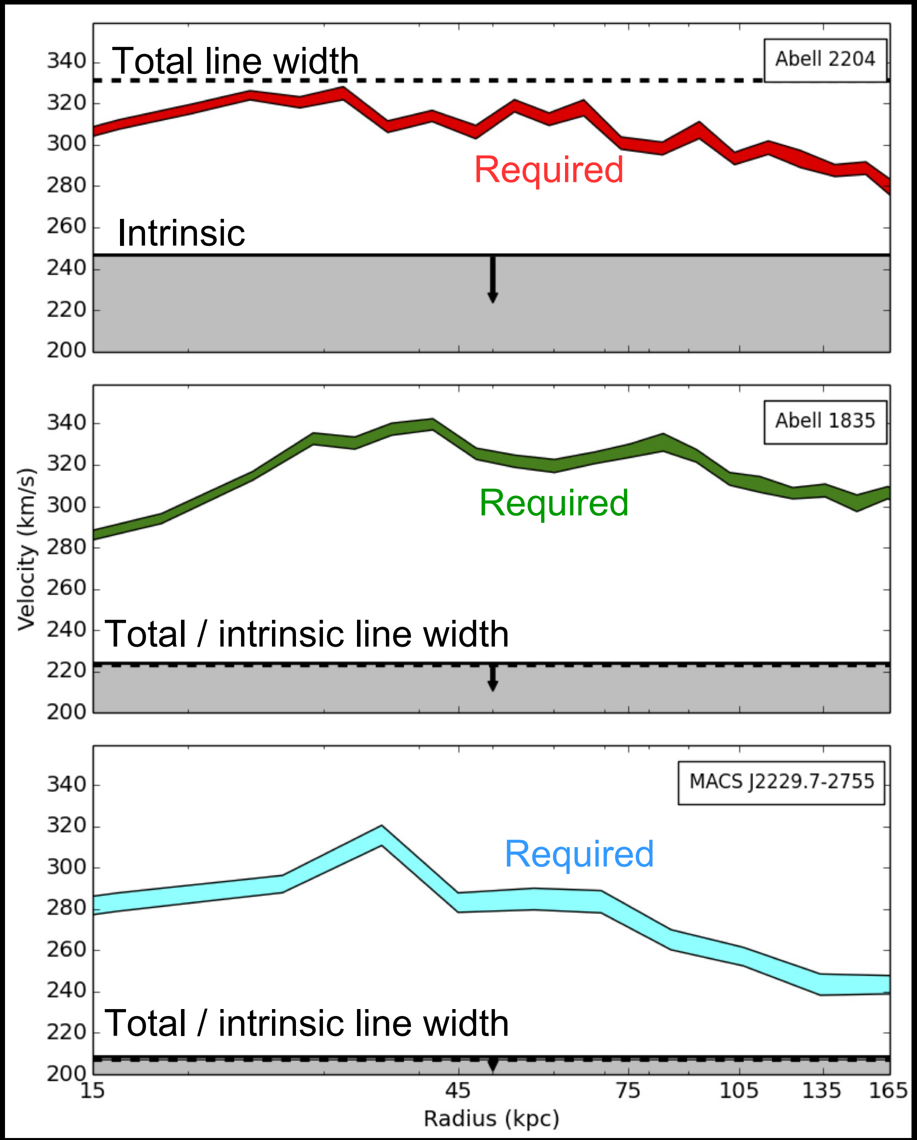
Heating Transfer Problem

Is turbulence high enough to propagate throughout the cool core?

Assuming : $L_{Cool} = L_{Turb}$

$$E_{thermal} / t_{cool} = E_{turb} / t_{turb}$$

$$\sigma_{km/s} = 5.39 \times 10^4 \, (r_{kpc} \, T_{keV} / t_{yr})^{1/3}$$

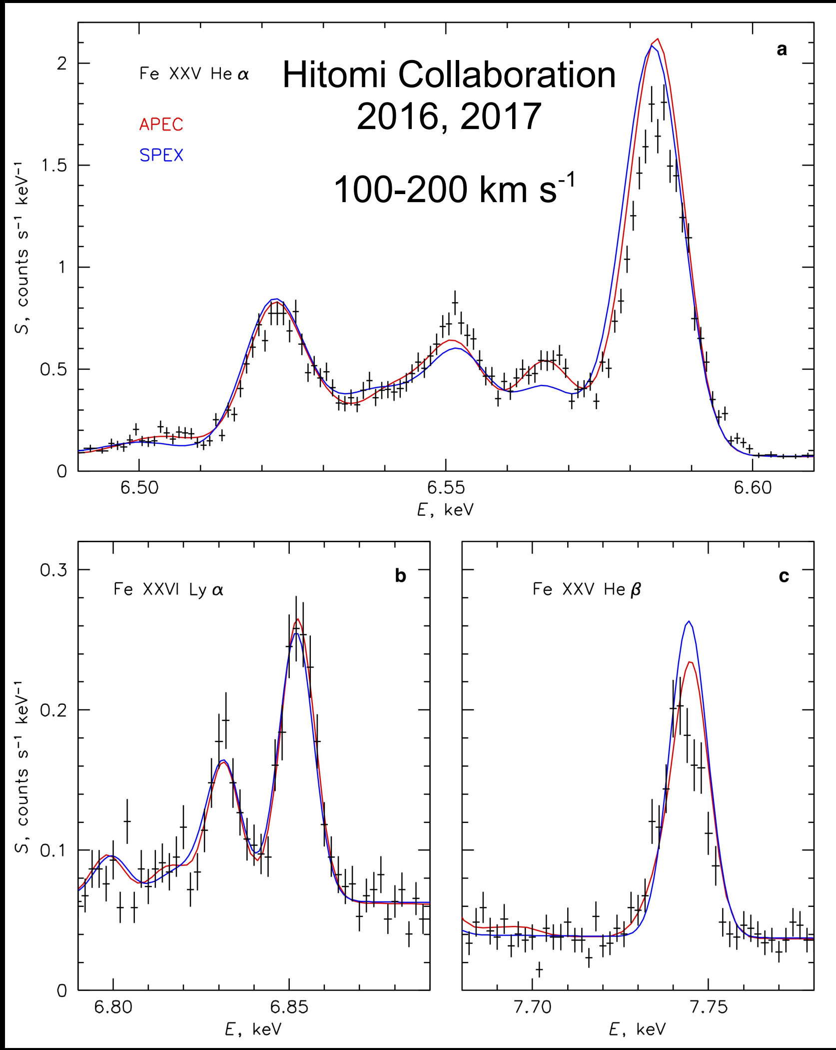


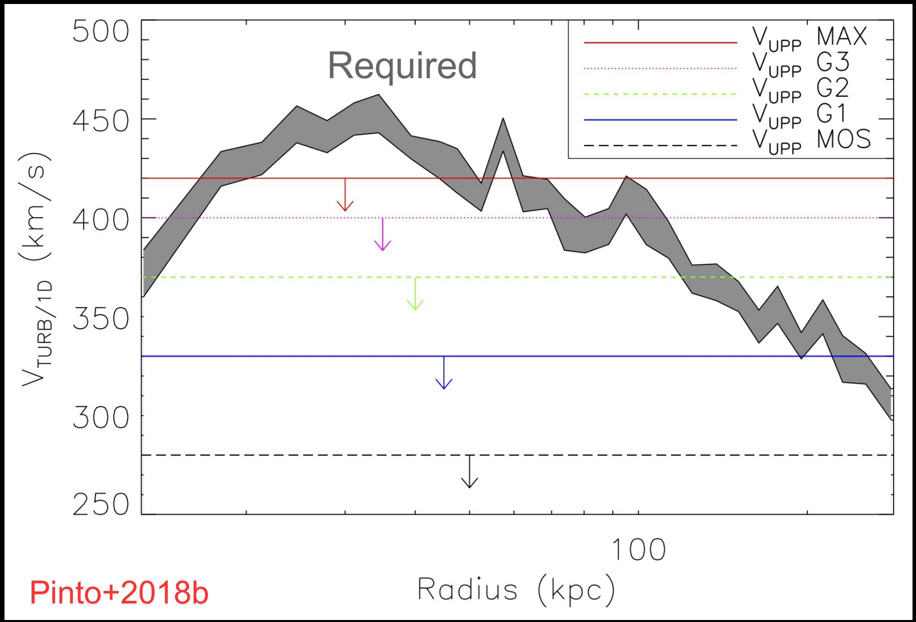
Bambic et al. (2018)

Major achievements

- Cooling rates are much lower than theory / CCDs
- But X-ray gas seems enough to power Hα, SFR
- Turbulence may be too low to propagate heat over the cluster core → additional means?

(confirmed by *Hitomi* Perseus observations)





Chemical enrichment history

- Accurate abundances

N / Fe* , O / Fe , Ne / Fe < 1

e.g., Tamura03, Buote+03, DePlaa04, Werner+06, Grange+11, Simionescu+09, Bulbul+12, Mernier+16, (*) in ellipticals Mao+19 N / Fe > 1(AGB)

→ SN Ia / (SN Ia + SN cc) ~ 25-45%

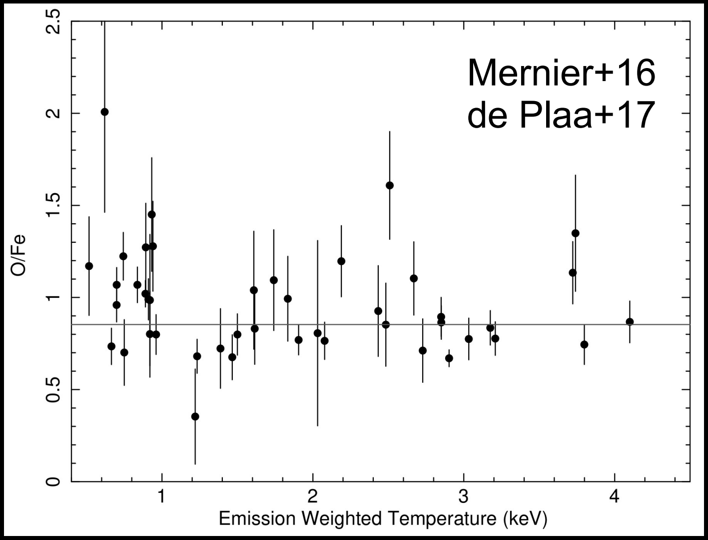
(proto-solar environment ~15-25%)

- α / Fe uniformly distributed

(from ellipticals to clusters)

→ Most metals formed around z~2 ?

(BCG SNIa small , Metal uplift , Sloshing)



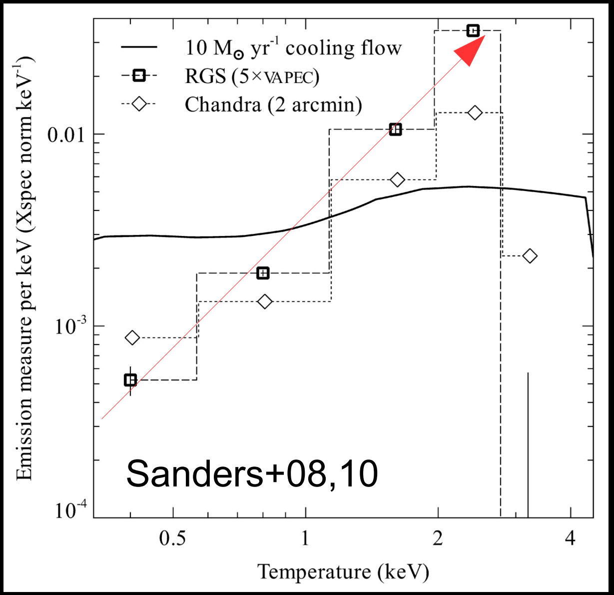
ICM complex structure

- Multi-phase structure

  Powerlaw EM temperature distribution

  Fe XVII reveal 0.7-0.8 keV phase

  (e.g. DePlaa04 , Werner+06 , Sanders+08)

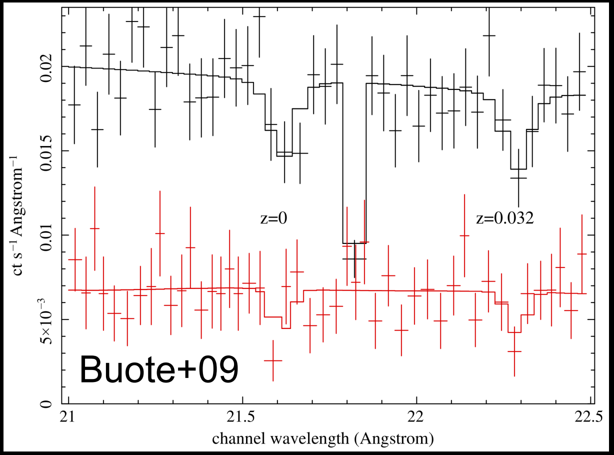


- WHIM (via quasars behind clusters)

  O VII-VIII , Ne IX fluxes ~ as expected

  Common significance ≤ 3σ

  (e.g. Virgo Fujimoto+04, Coma Takei+07, Sculptor Wall Buote+09, Ren+14, Nicastro+18, Bonamente+19, Nevalainen+19, ...)



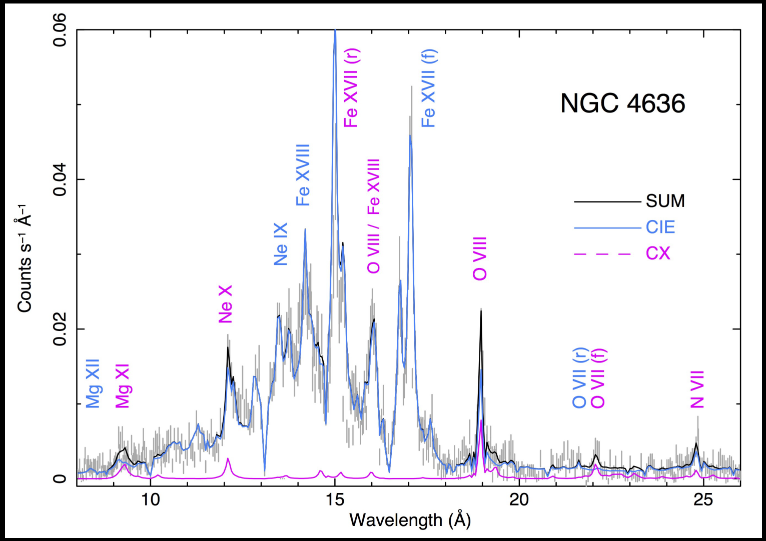
Caution: low stat, calib, bad pixels, ISM contamination

Atomic physics & biases

- Charge exchange (e.g. Pinto+2016, Gu+2018)

  Agrees with Hitomi's 3.45 keV excess

  Affects (5-20%) oxygen abundance



- State-of-art atomic database (e.g. Gu+2019)

  Fe-L new calculations (FAC, SPEX, AtomDB, ...)

  → Δ(O/Fe) = +16% Δ(Fe/H) = –12%

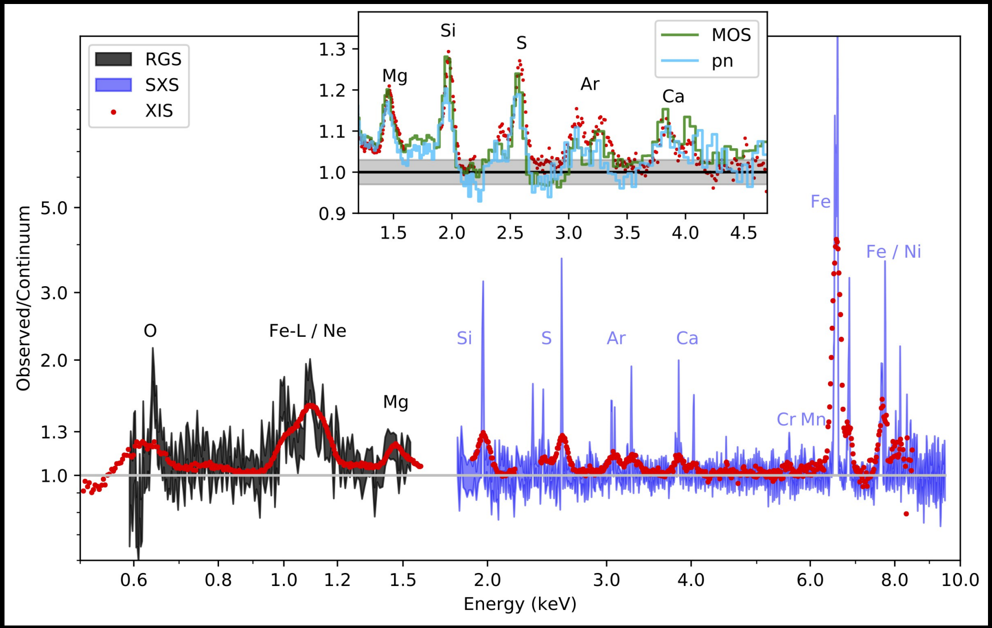
- Biases correction: (e.g. dePlaa+2017, CHEERS)

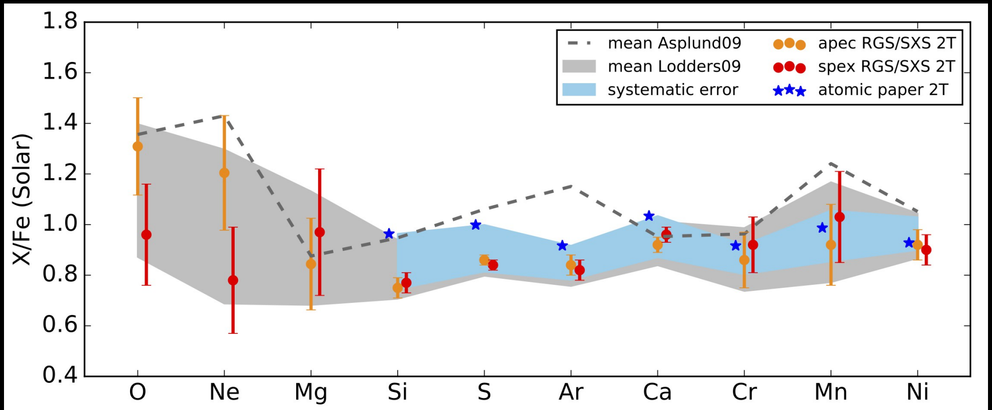
  Uncertainties in N_H , line broadening , multi-T, continuum , line emissivities , CX ...

Synergies with other facilities

XMM/RGS + Hitomi/SXS simultaneous fits

Remarkably accurate abundances, even more accurate than our own Sun!





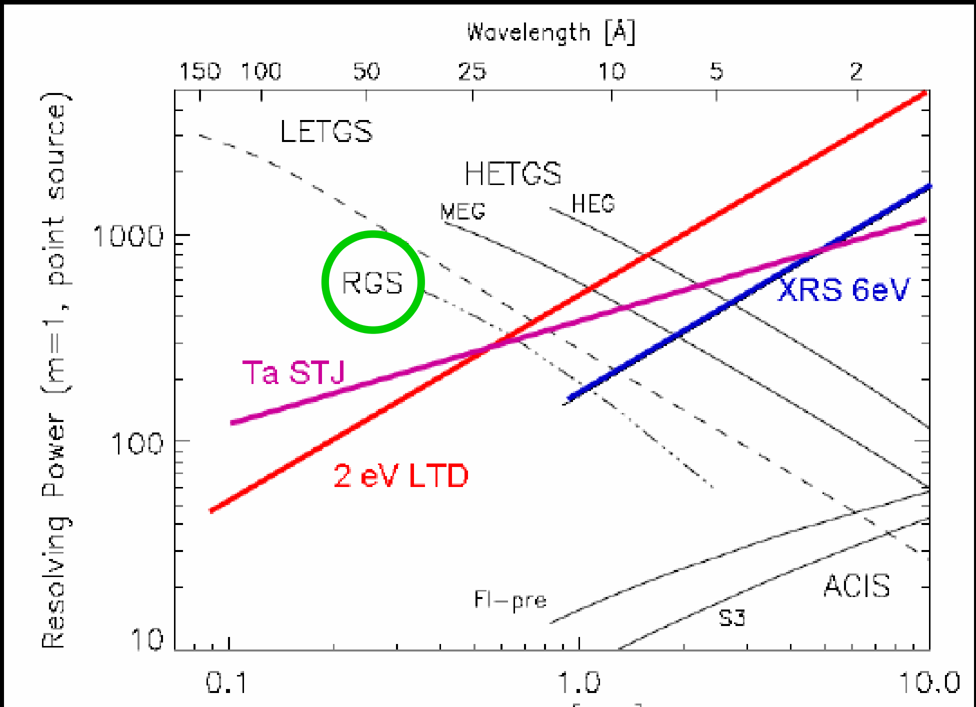
Simionescu+2019

They challenge any linear combination of SN yields

Including neutrino physics in the SN cc yields may help the yields modeling!

Ideal future high-res detector(s)?

- Ideally a combination of gratings + micro-calorimeters (XMM + XRISM)
- The boost in effective area will enable high-Z studies (XMM / Arcus + ATHENA)
- Need for state-of-art atomic databases (theory + lab)



Resolving power

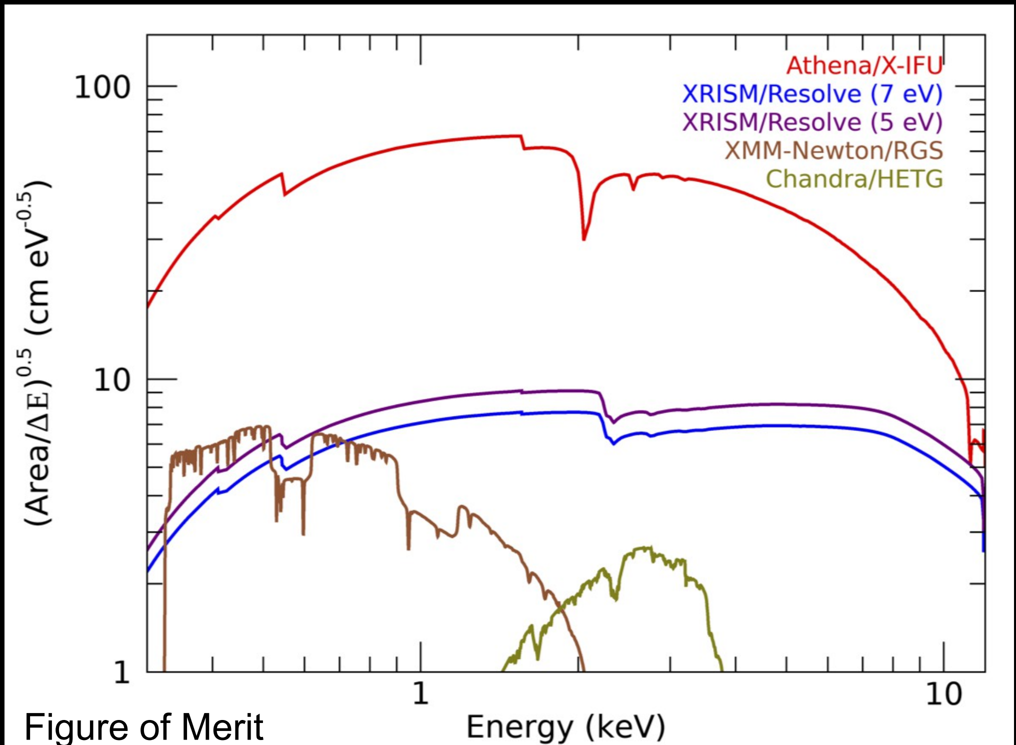


Figure of Merit

Take away message:
Lessons learned after 19 years with RGS

- Cooling rates in cool-core clusters? Use RGS.
- Turbulence directly? Use RGS .... and X-ray Micro-Calorimeters (*)
- SN & AGB yields? Use RGS .... ideally combine with CCD / M-C
- Multiphase structure? Use RGS .... ideally combine with CCD / M-C
- Resonant scattering & charge exchange? Use RGS .... and M-C
- WHIM absorption studies? Use RGS .... but with a lot of caution.