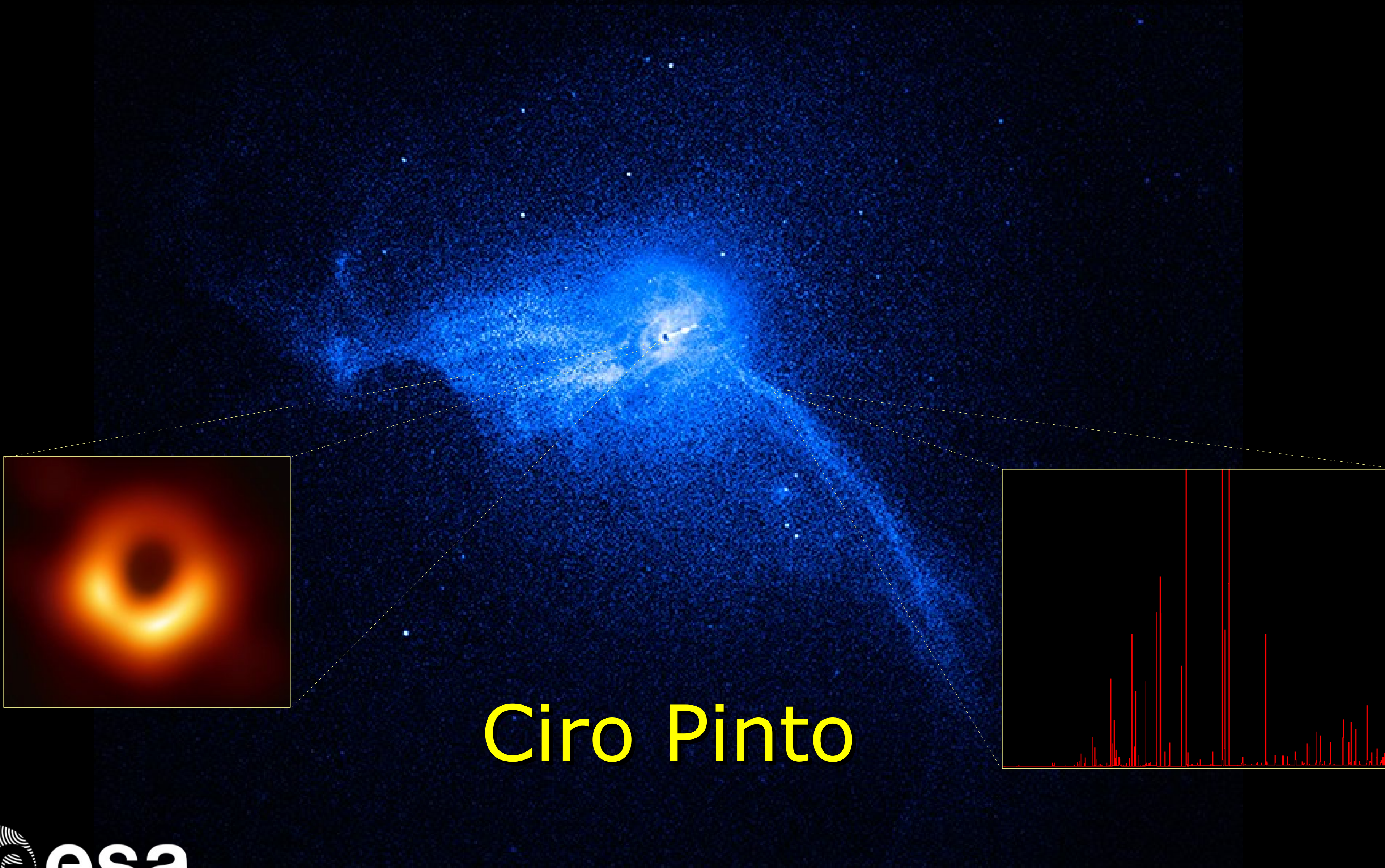
X-ray-solving AGN feedback in clusters of galaxies



Ciro Pinto

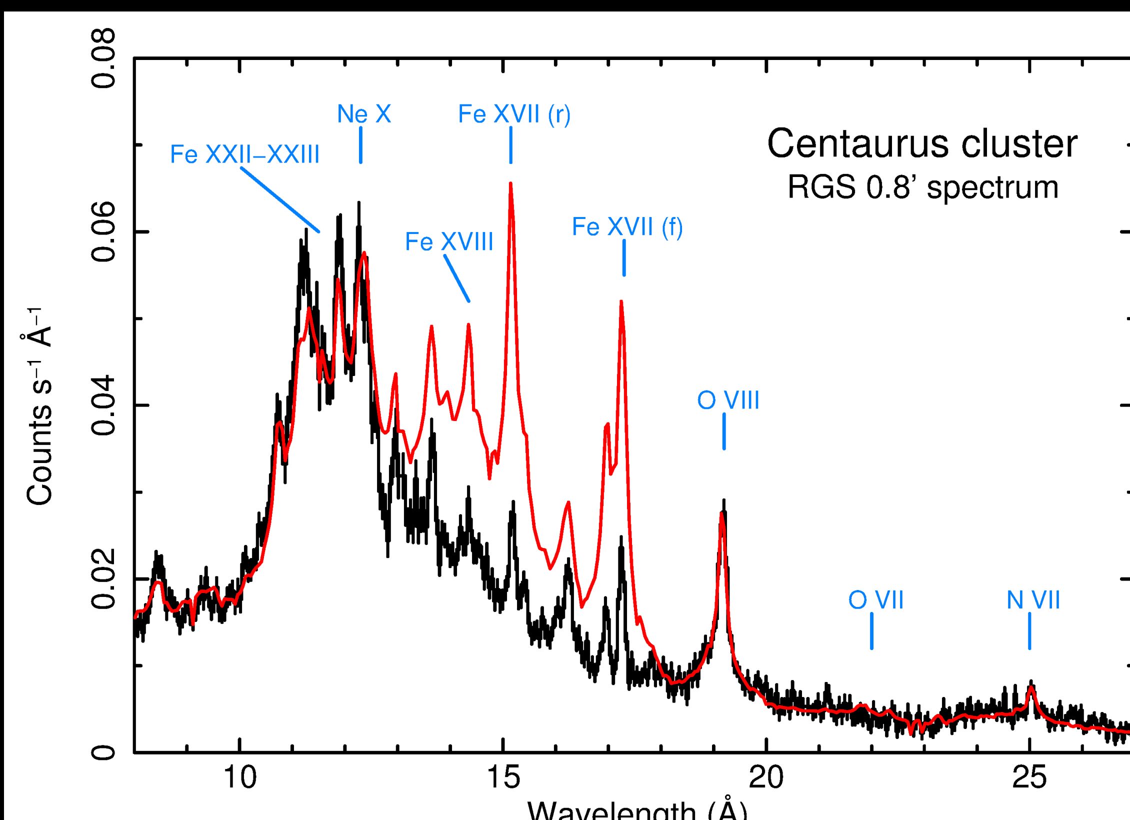
European Space Agency

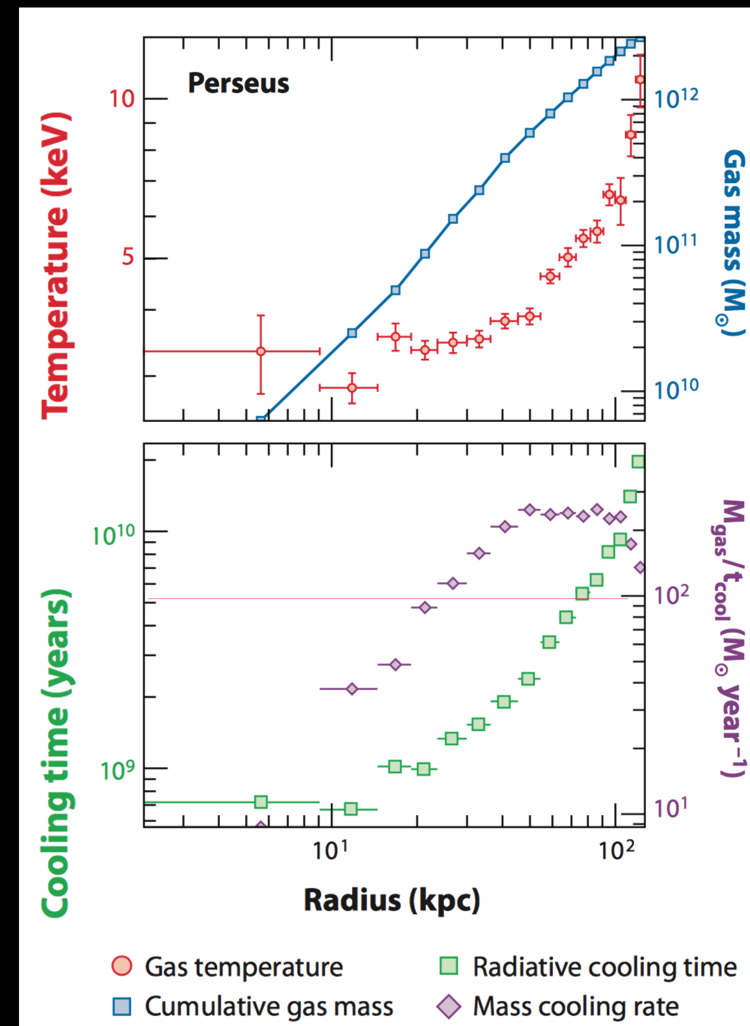
A. Fabian, J. Sanders, C. Bambic, H. Liu, C. Reynolds, H. Russell, M. McDonald, J. De Plaa,
J. Kaastra, L. Gu, J. Mao, A. Ogorzalek, N. Werner, I. Zhuravleva, J. Ahoranta, M. Guainazzi

Cooling flows in galaxy clusters

Cooling time shorter than cluster age

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





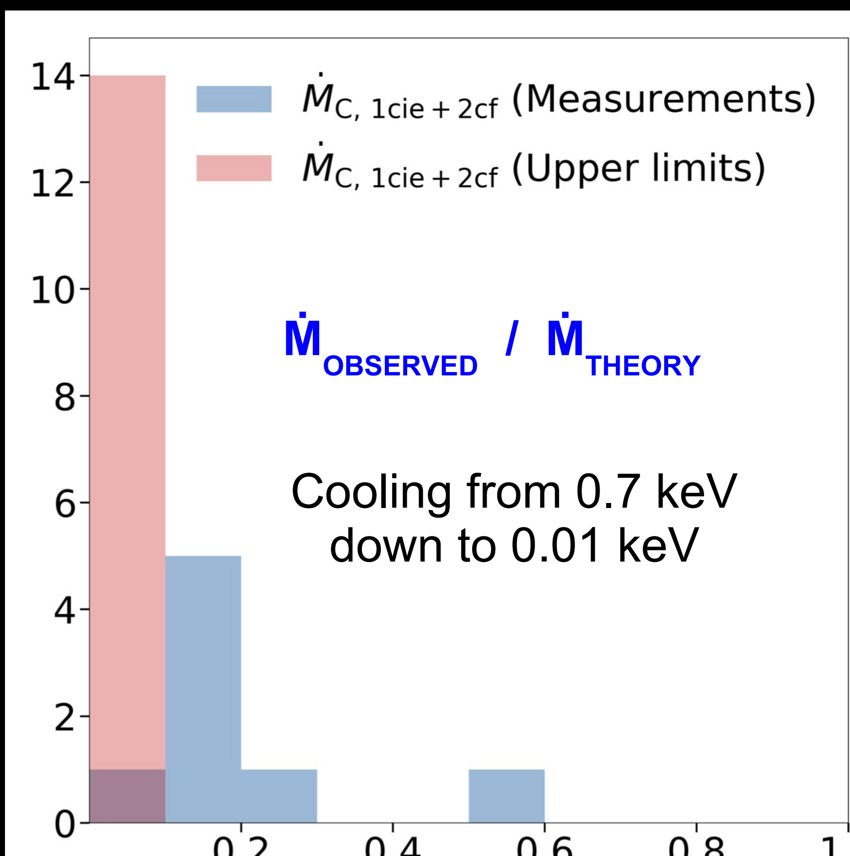
Fabian 2012 (figure by J. Sanders)

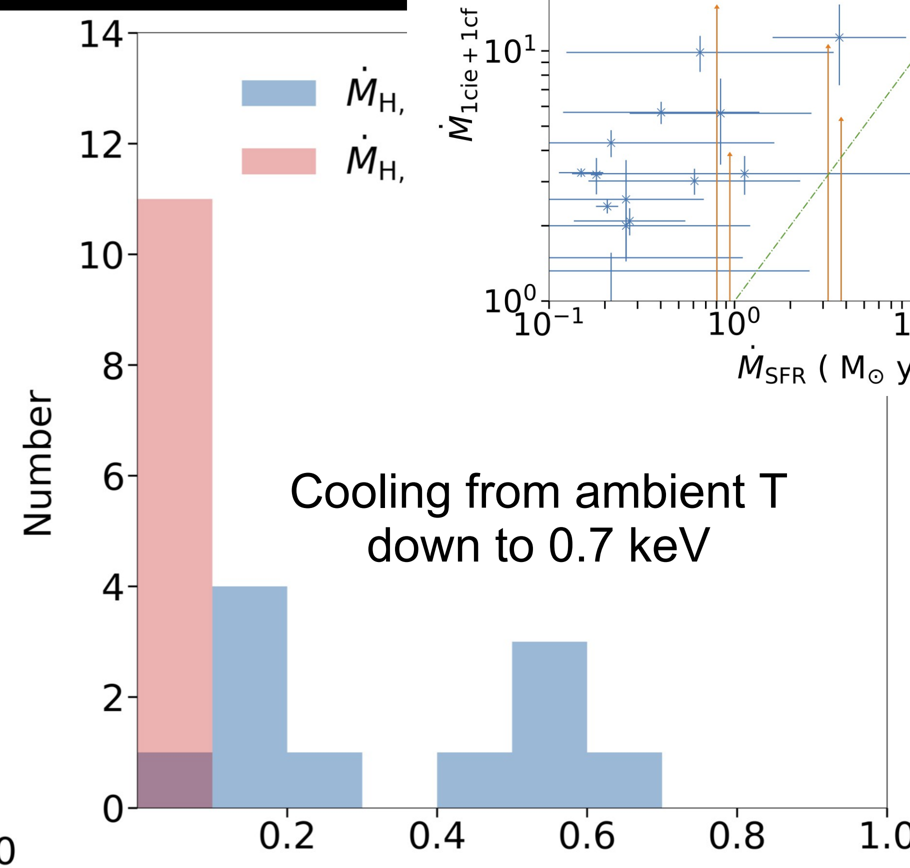
$t_{cool} \sim T^{1/2}, n^{-1}$

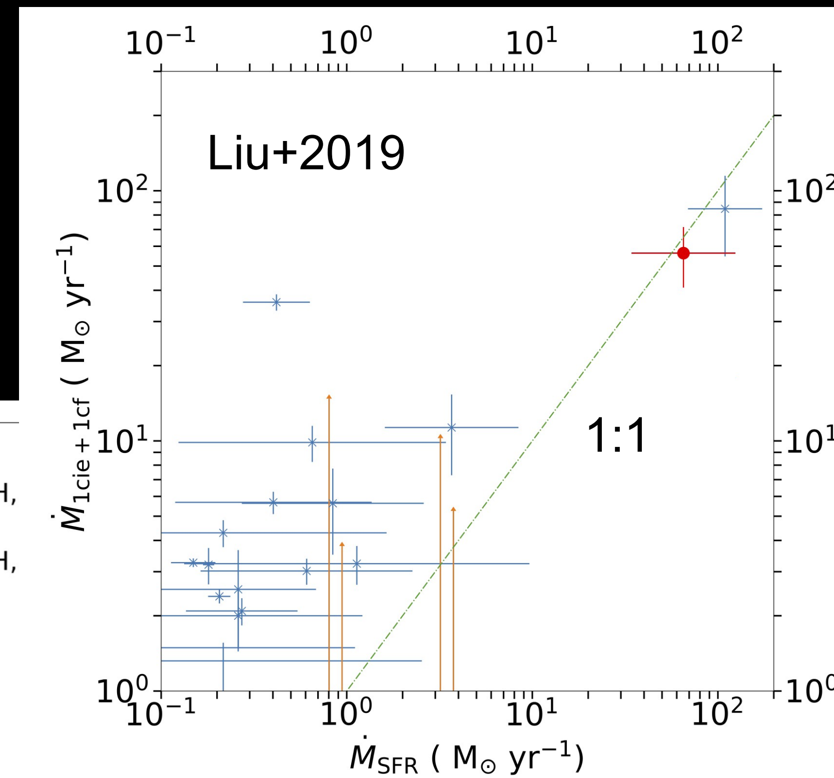
Measurements of cooling rates

Even lower cooling below 0.7 keV

But sufficient to explain the SFR

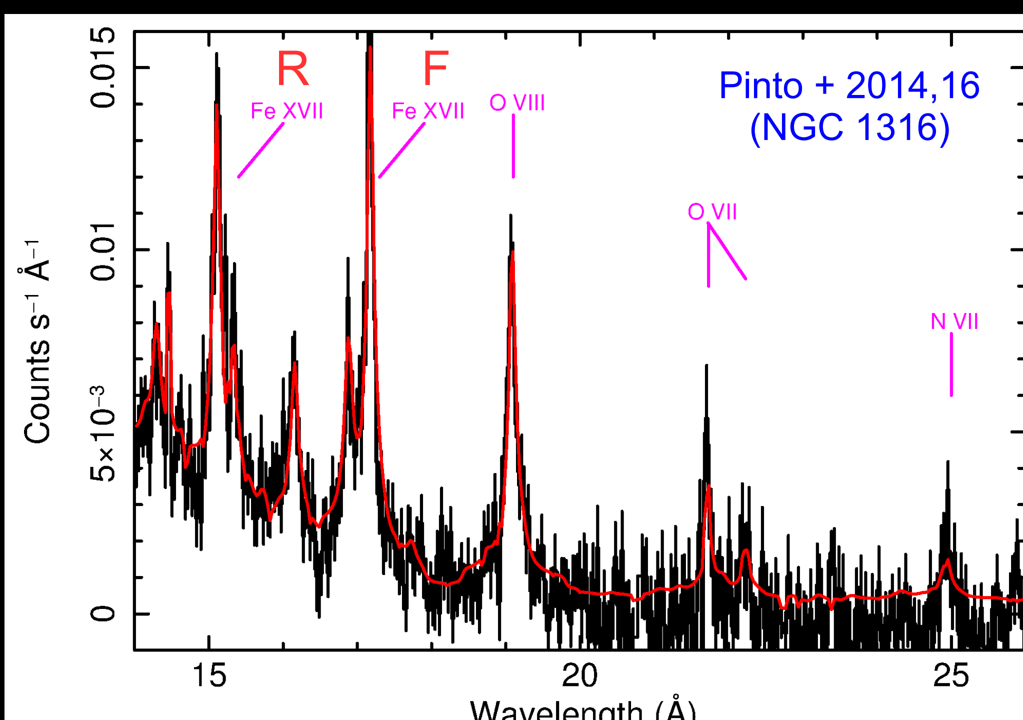


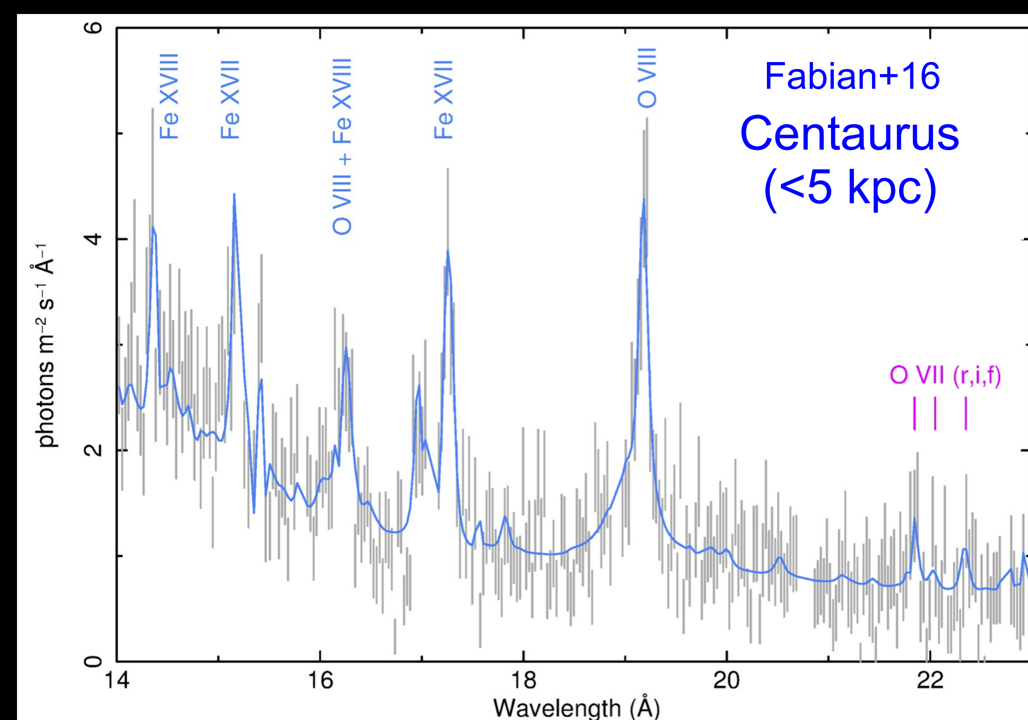




The coolest X-ray emitting gas

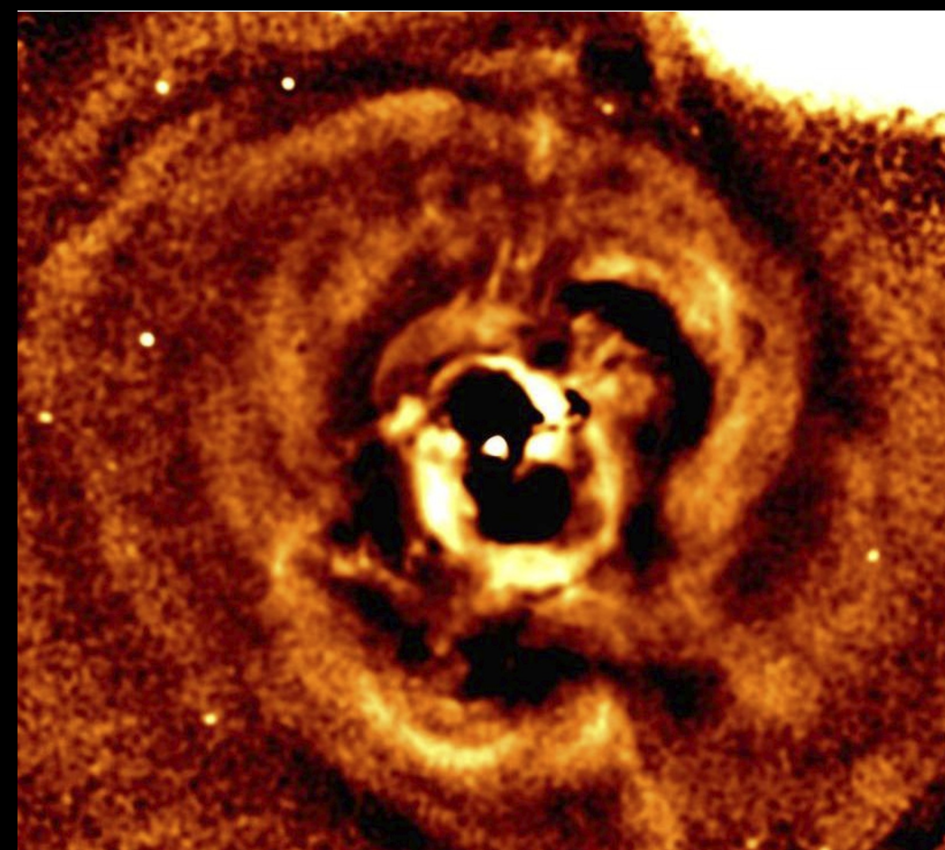
- O VII ... cooling below 2 mln K
- O VII = 4-8 times fainter than *cflow* models of galaxy gourps
- Even fainter in clusters of galaxies





AGN feedback in clusters of galaxies

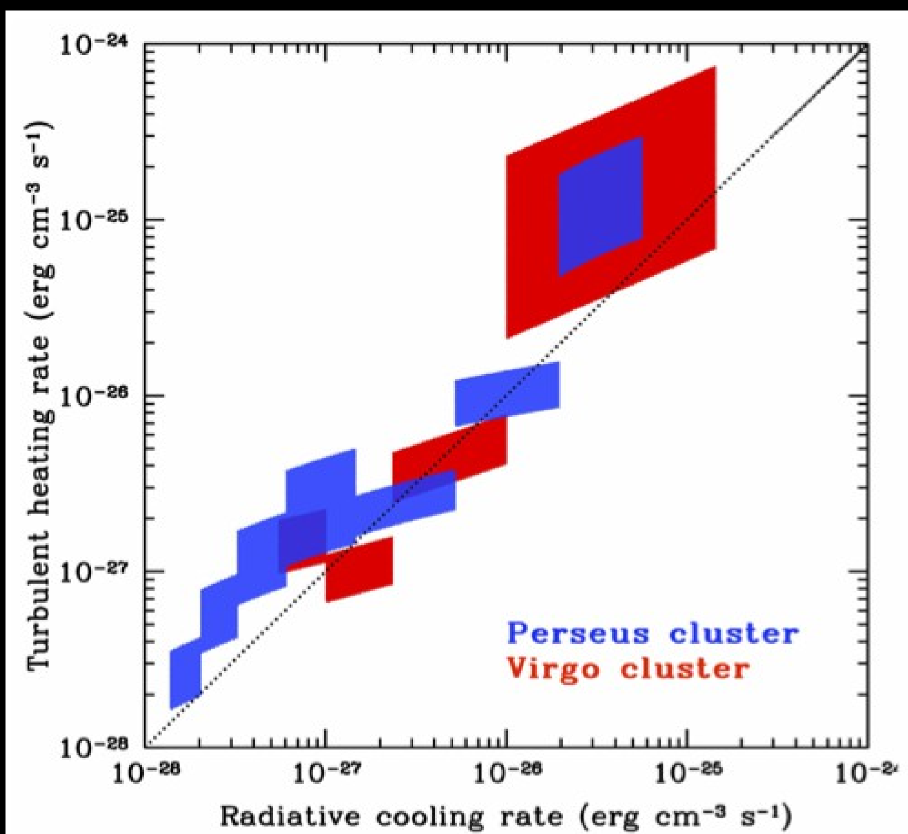
- Powerful radio jets
- Ripples, cavities, etc. in the X-ray gas



AGN feedback in clusters of galaxies

Dissipation of Turbulence?

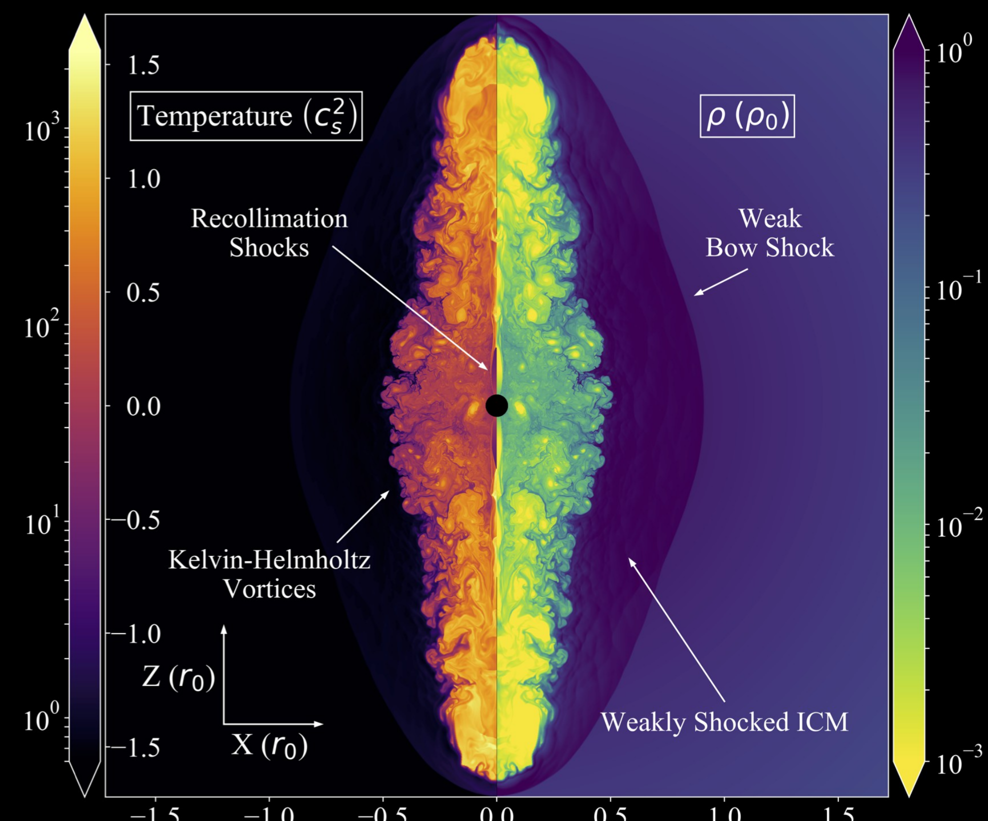
Bubbles turbulence - Zhuravleva+14



... assumes that features are turbulence

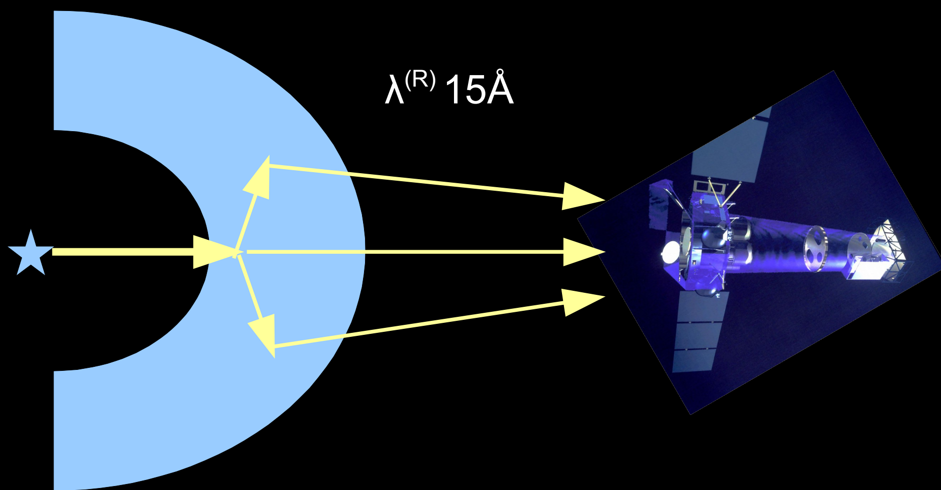
Dissipation of Sound waves?

AGN creates sw - Bambic+19

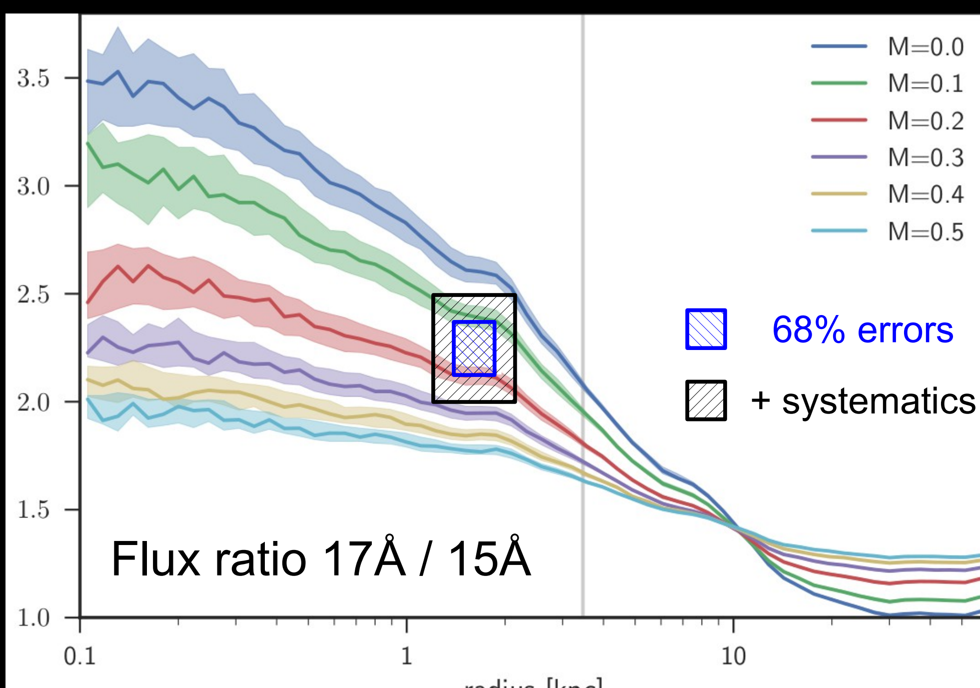


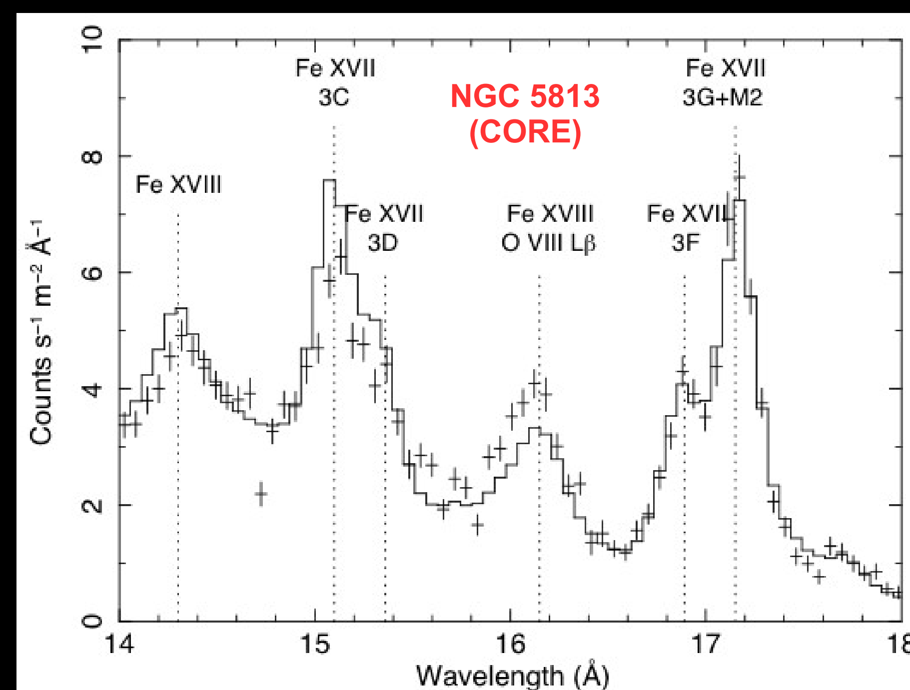
→ see talk from Chris Bambic

RGS constraints on Turbulence
Resonant scattering

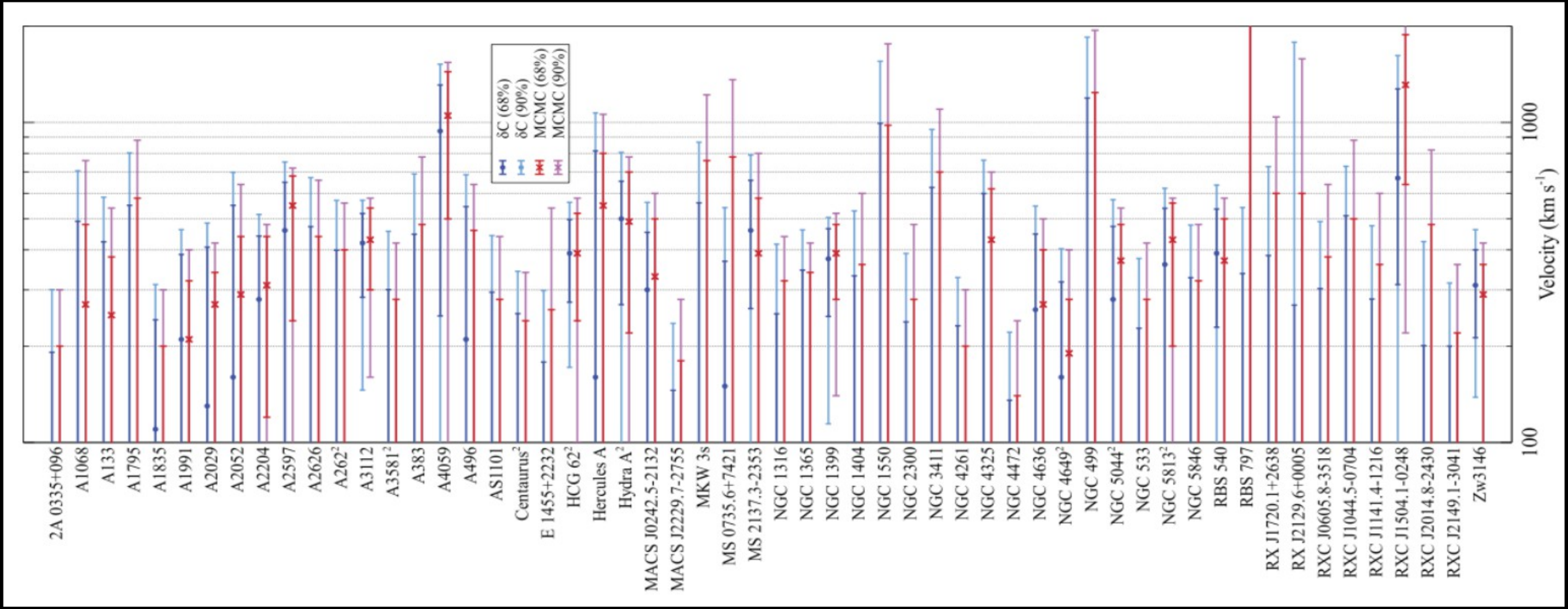


Xu+02
Werner+09
de Plaa+12
Ahoranta+16
Pinto+16b
Ogorzalek+18



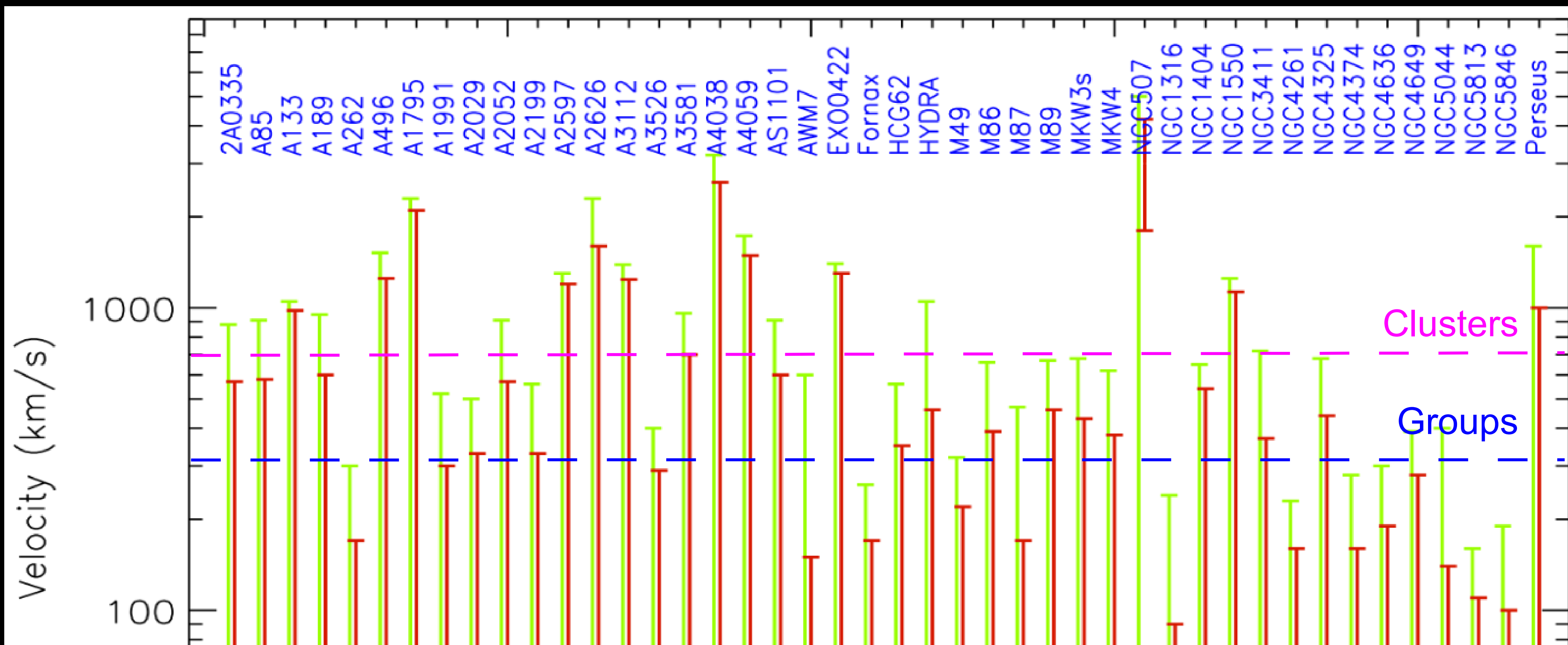


RGS constraints on Turbulence
Lines widths



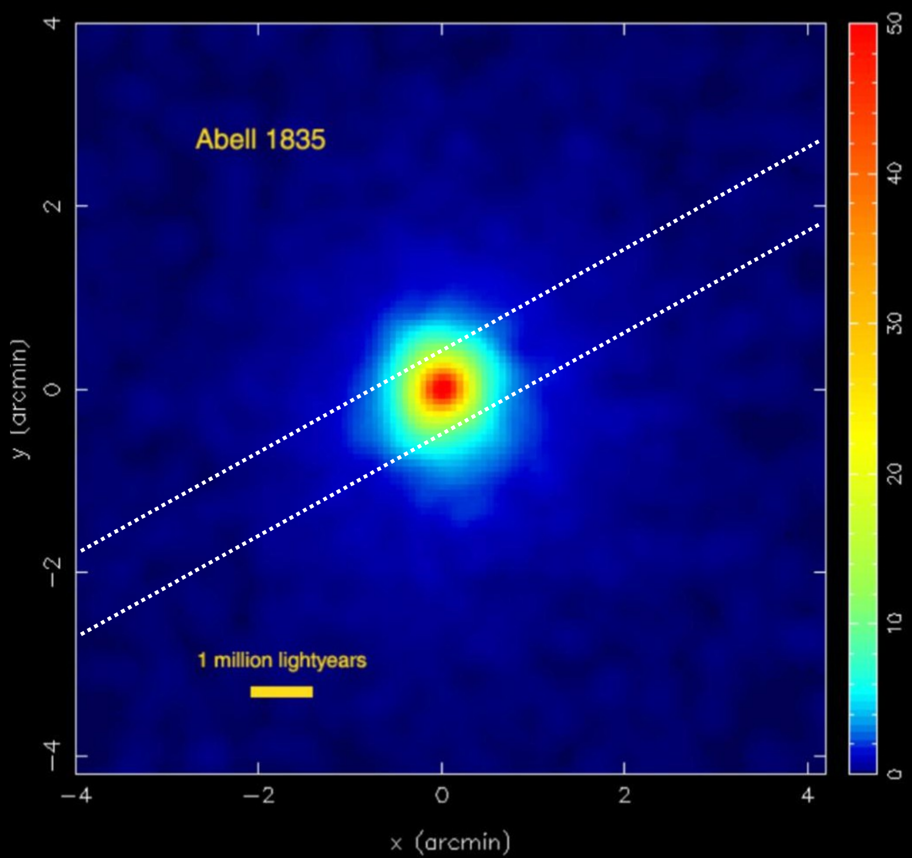
Sanders & Fabian 2013

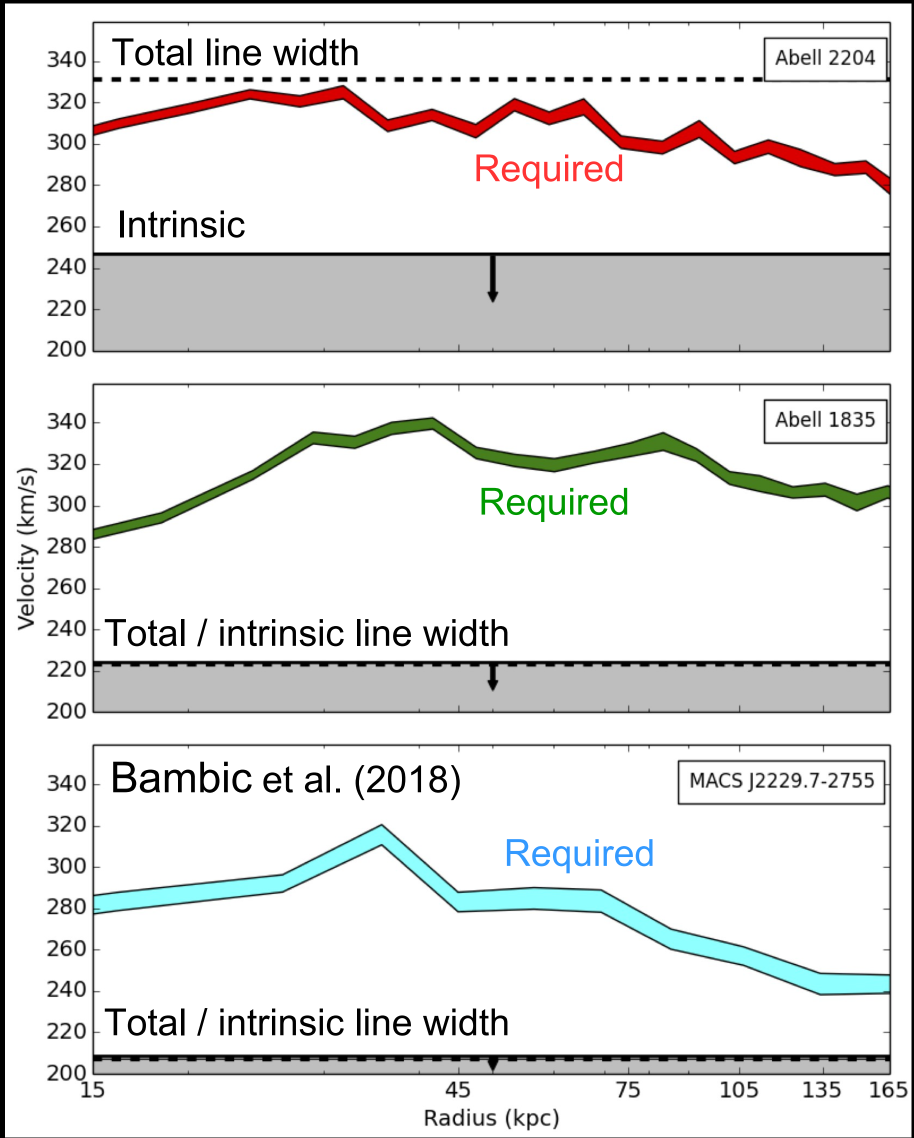
RGS constraints on Turbulence
Lines widths



Pinto et al. 2015

Accounting for instrumental broadening





$$L_{Cool} = L_{Turb}$$

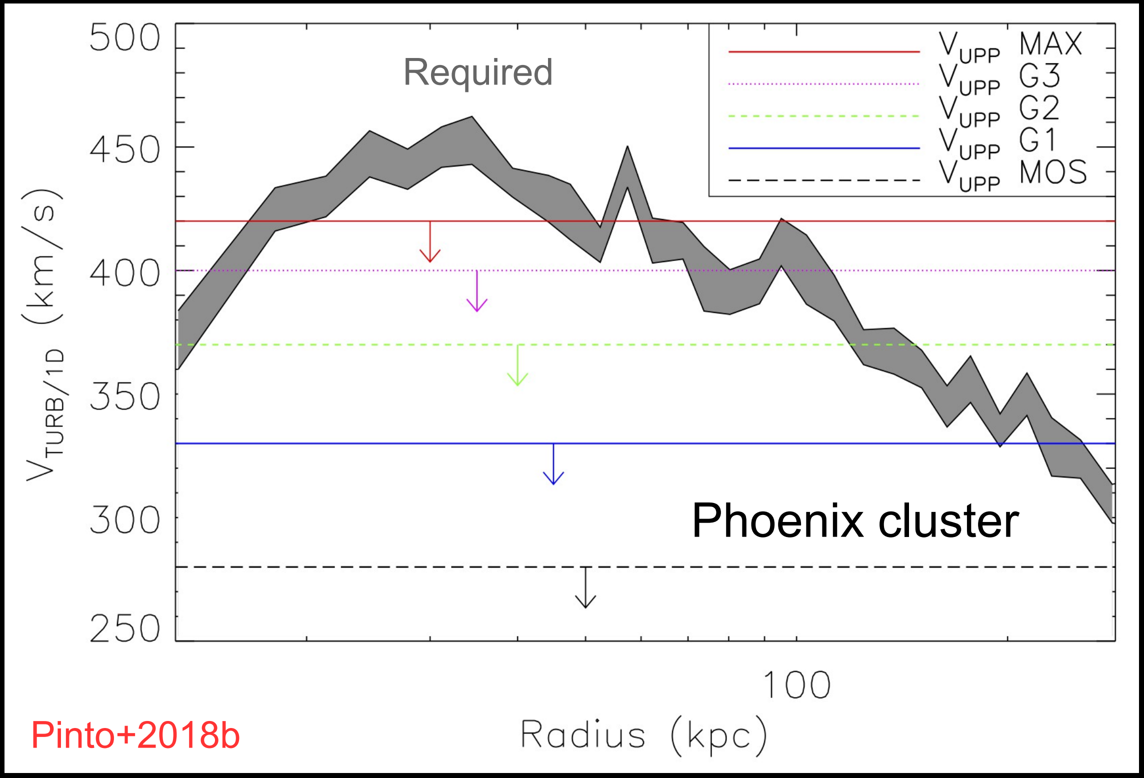
$$E_{thermal} / t_{cool} = E_{turb} / t_{turb}$$

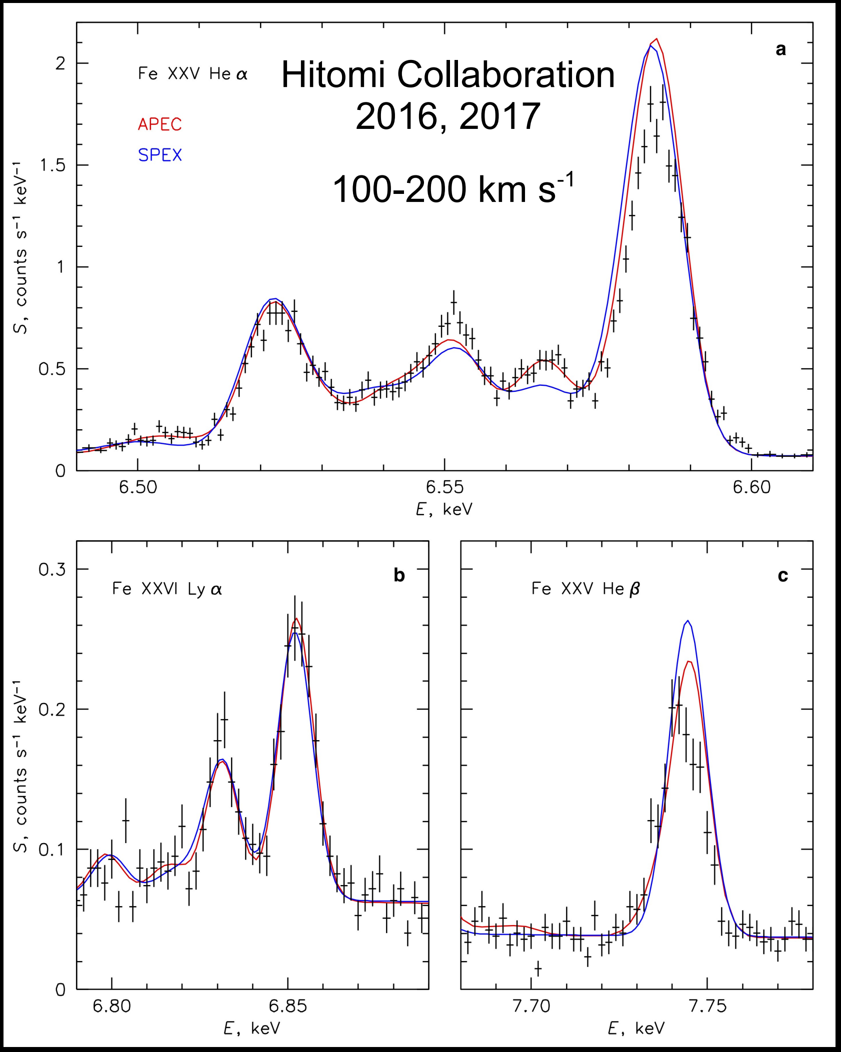
$$\sigma_{km/s} \sim (r_{kpc} T_{keV} / t_{yr})^{1/3}$$

→ *see also talk from Chris Bambic!*

XMM & Hitomi agree

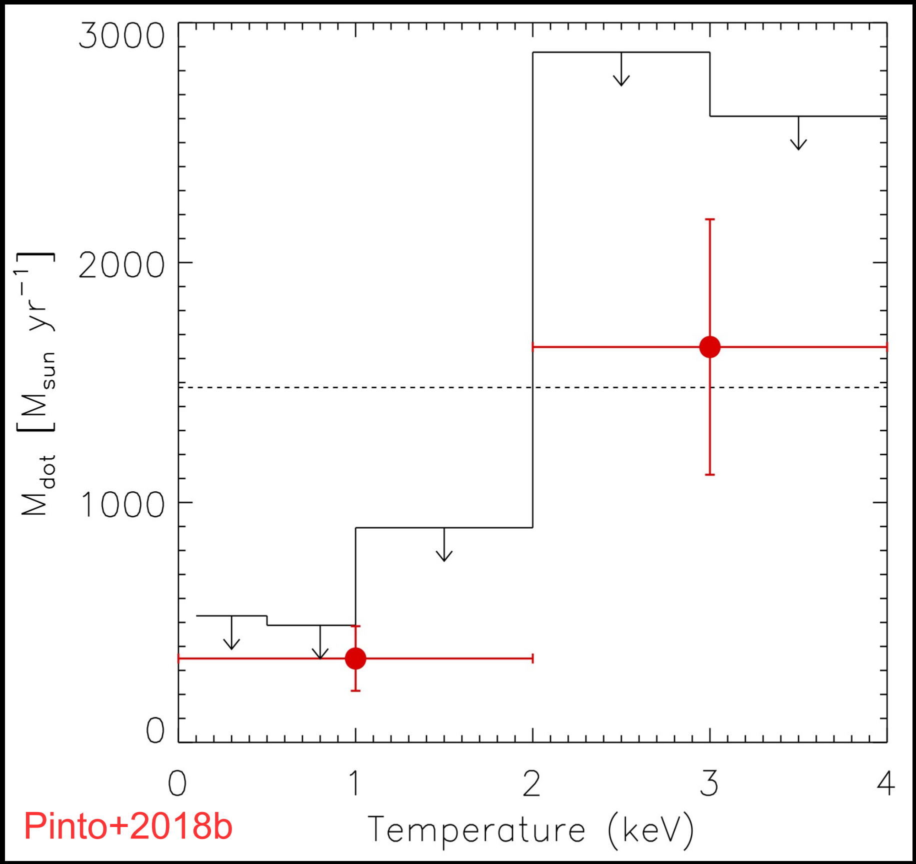
Turbulence too low to propagate heat through cluster core → additional means



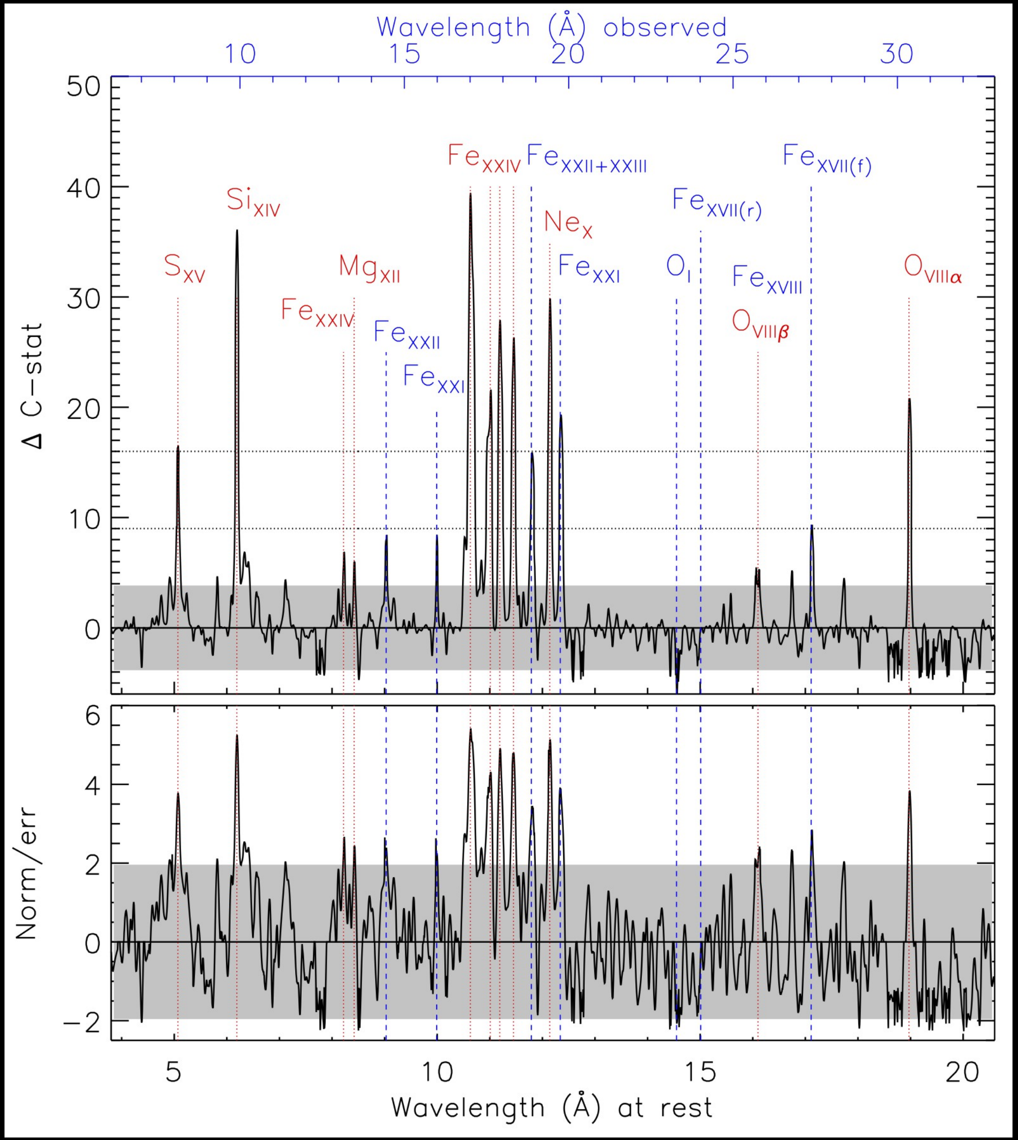


Phoenix : a different behavior at high redshifts?

Cooling rates



Cool gas line detection

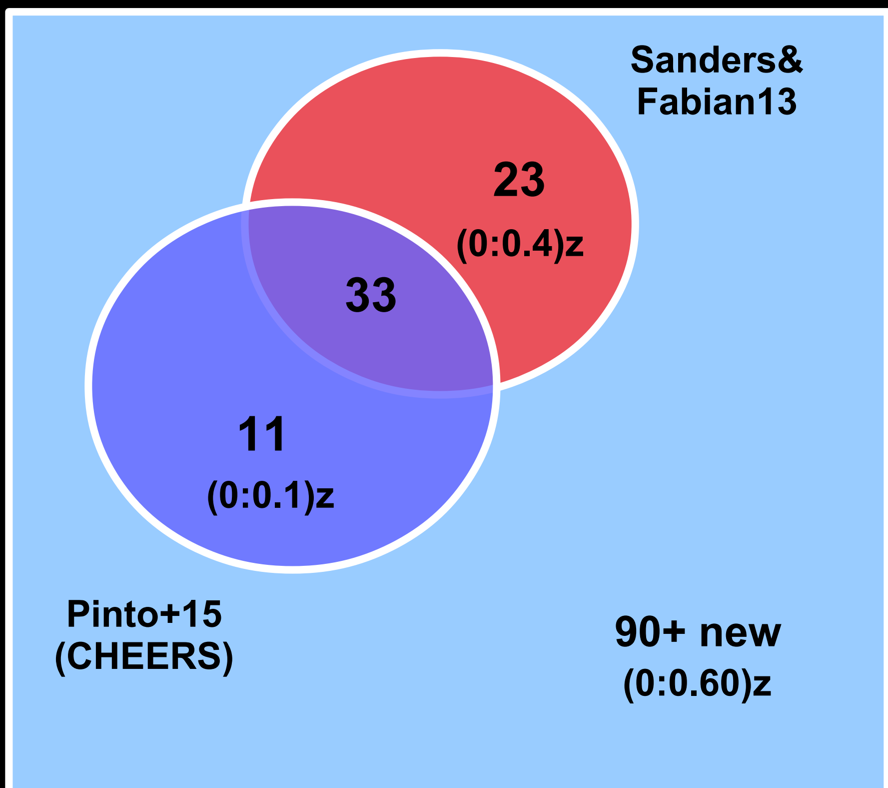


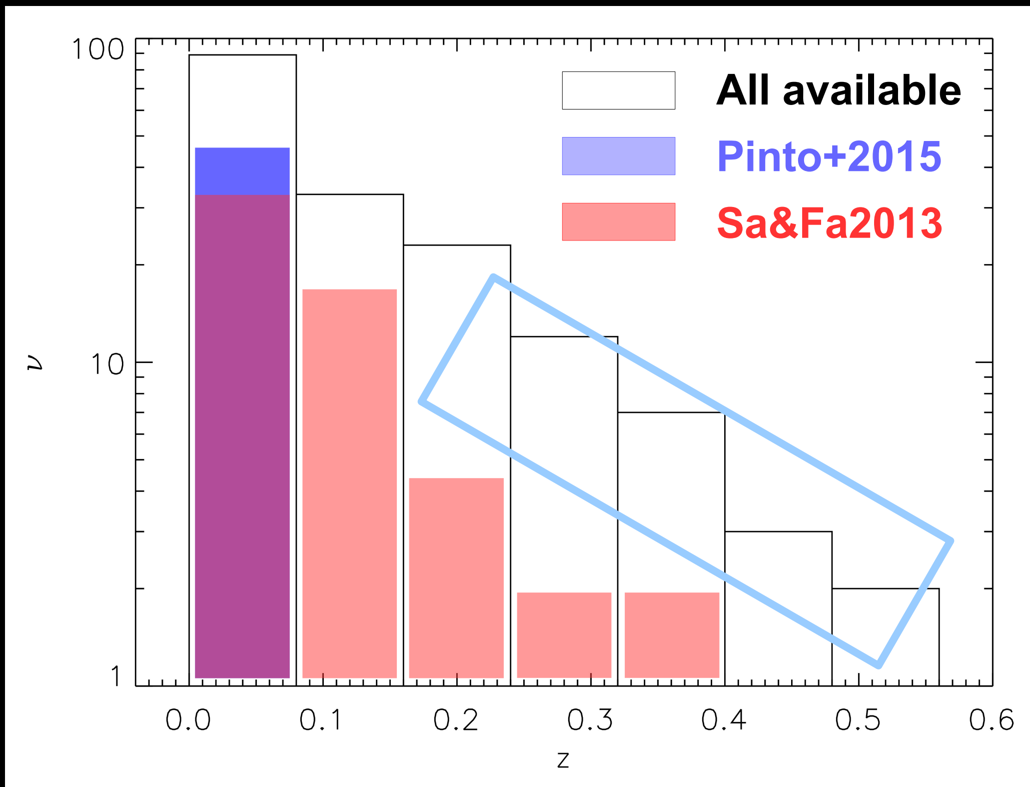
High cooling and star formation rates!

AGN Feedback "young" or other "mode" ?

XMM-Newton/RGS Legacy Catalog

More can be done with RGS, particularly at high redshifts

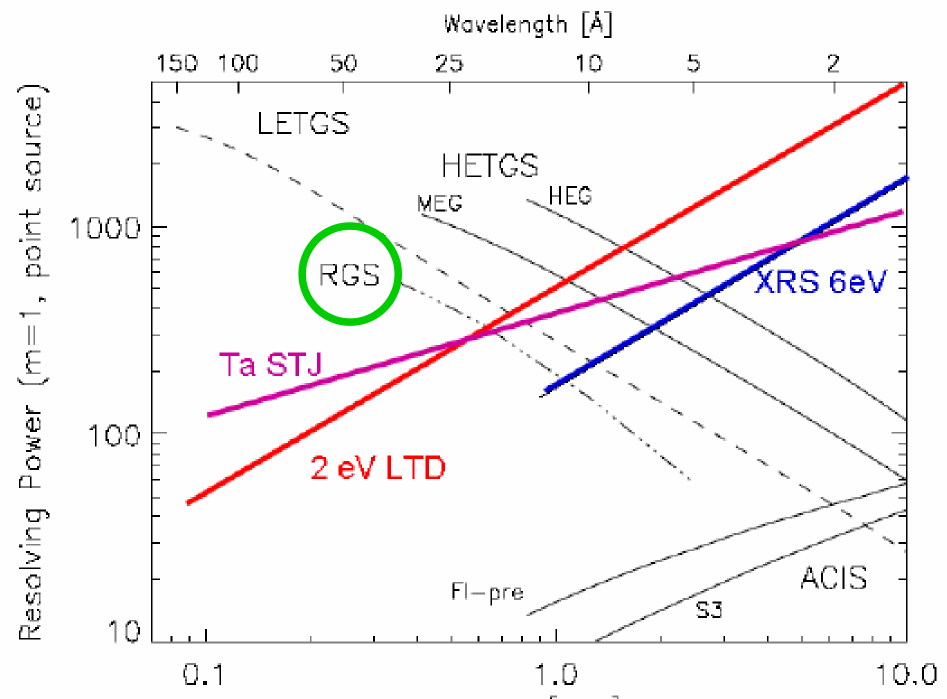




... and some more (CIELO – J. Mao et al. 2019)

Ideal future high-resolution detector(s)

- Ideally a combination of gratings + micro-calorimeters → XMM + XRISM
- Spatial resolution and spectral resolution → ATHENA + ...
- Need for state-of-art atomic databases (theory + lab)



Resolving power

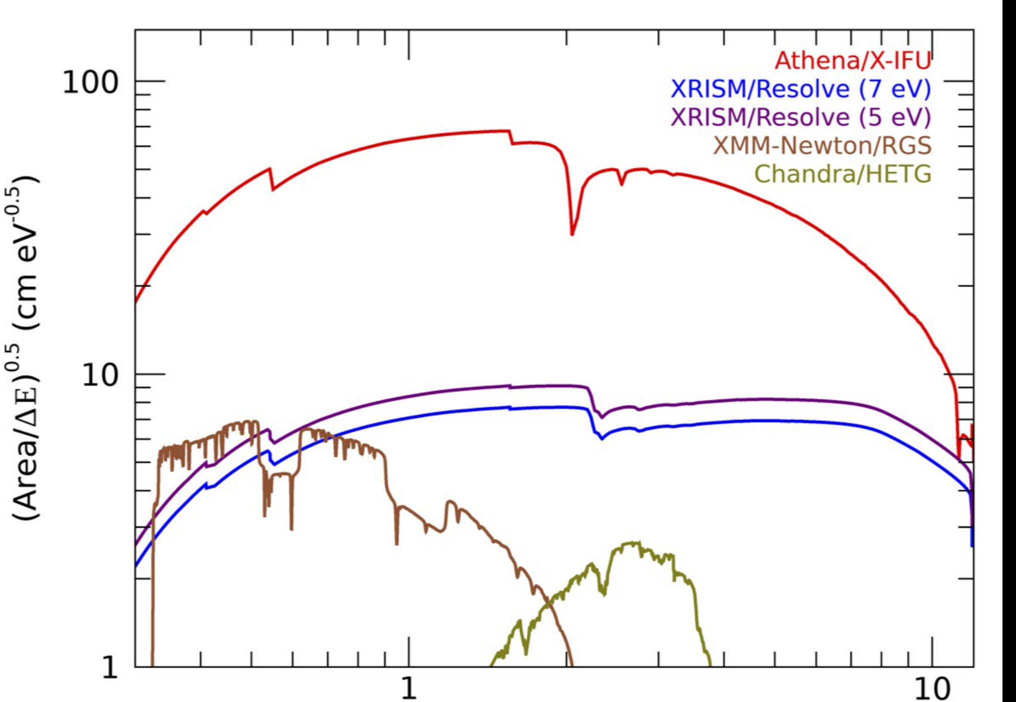
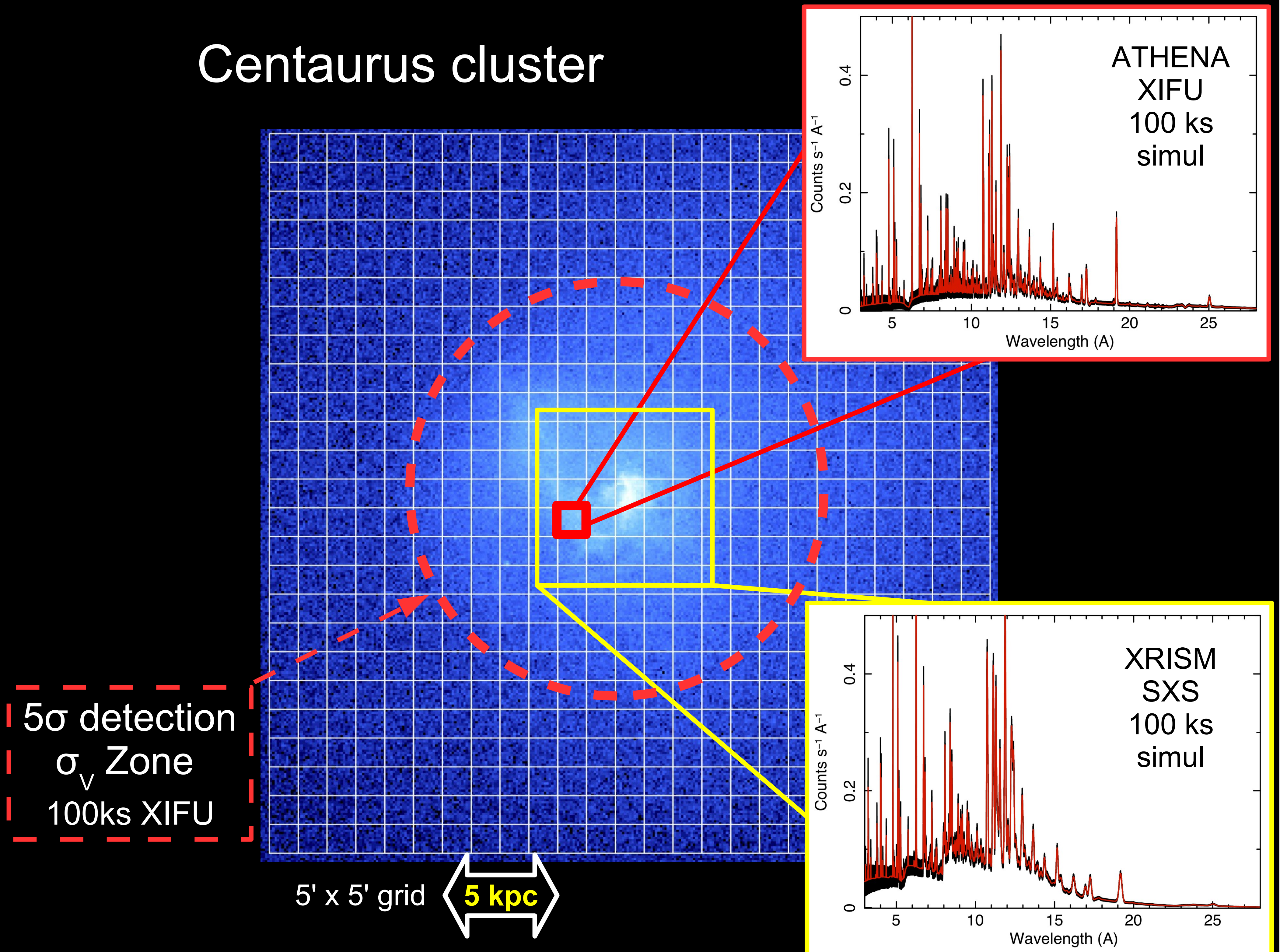


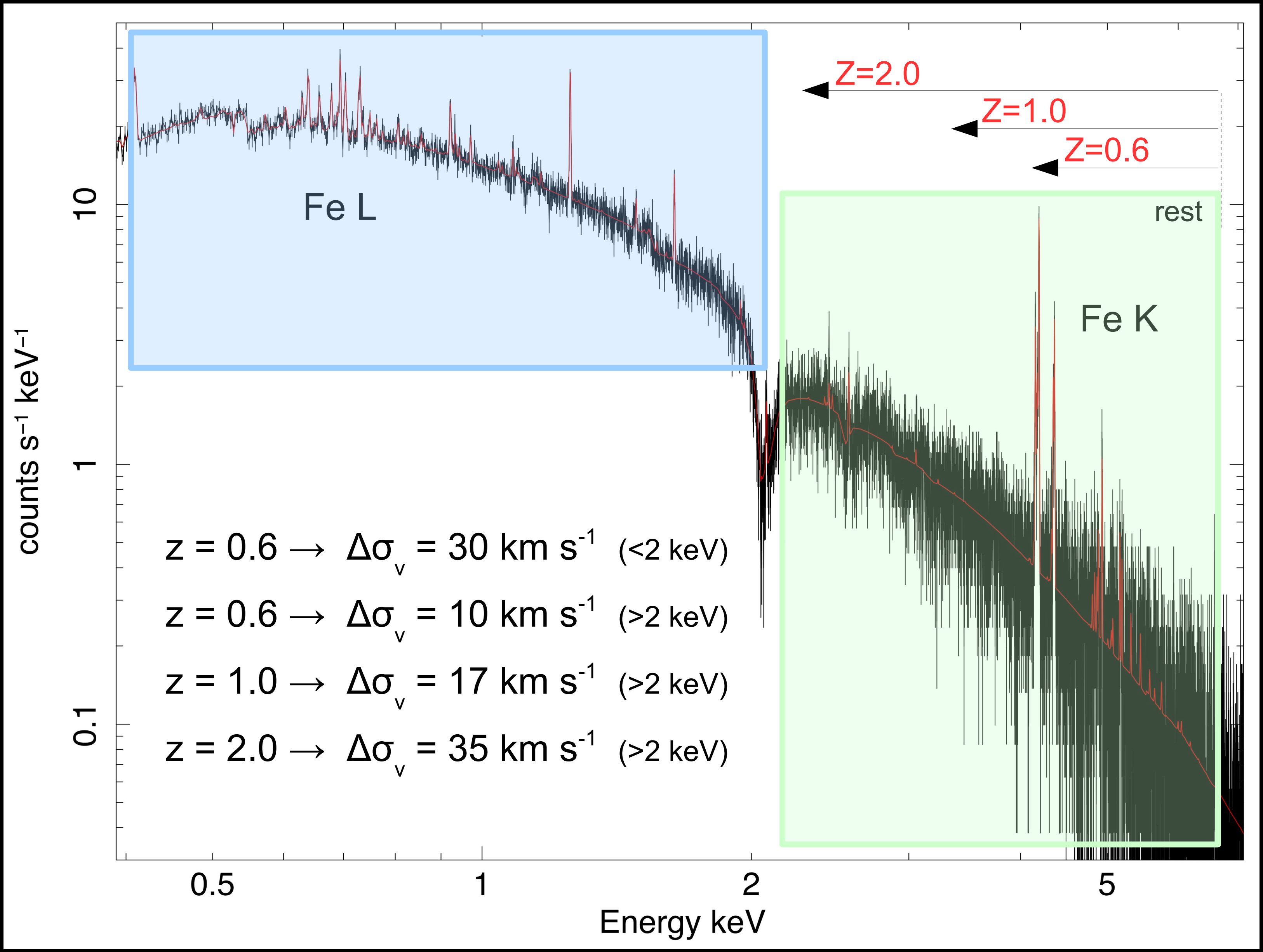
Figure of Merit



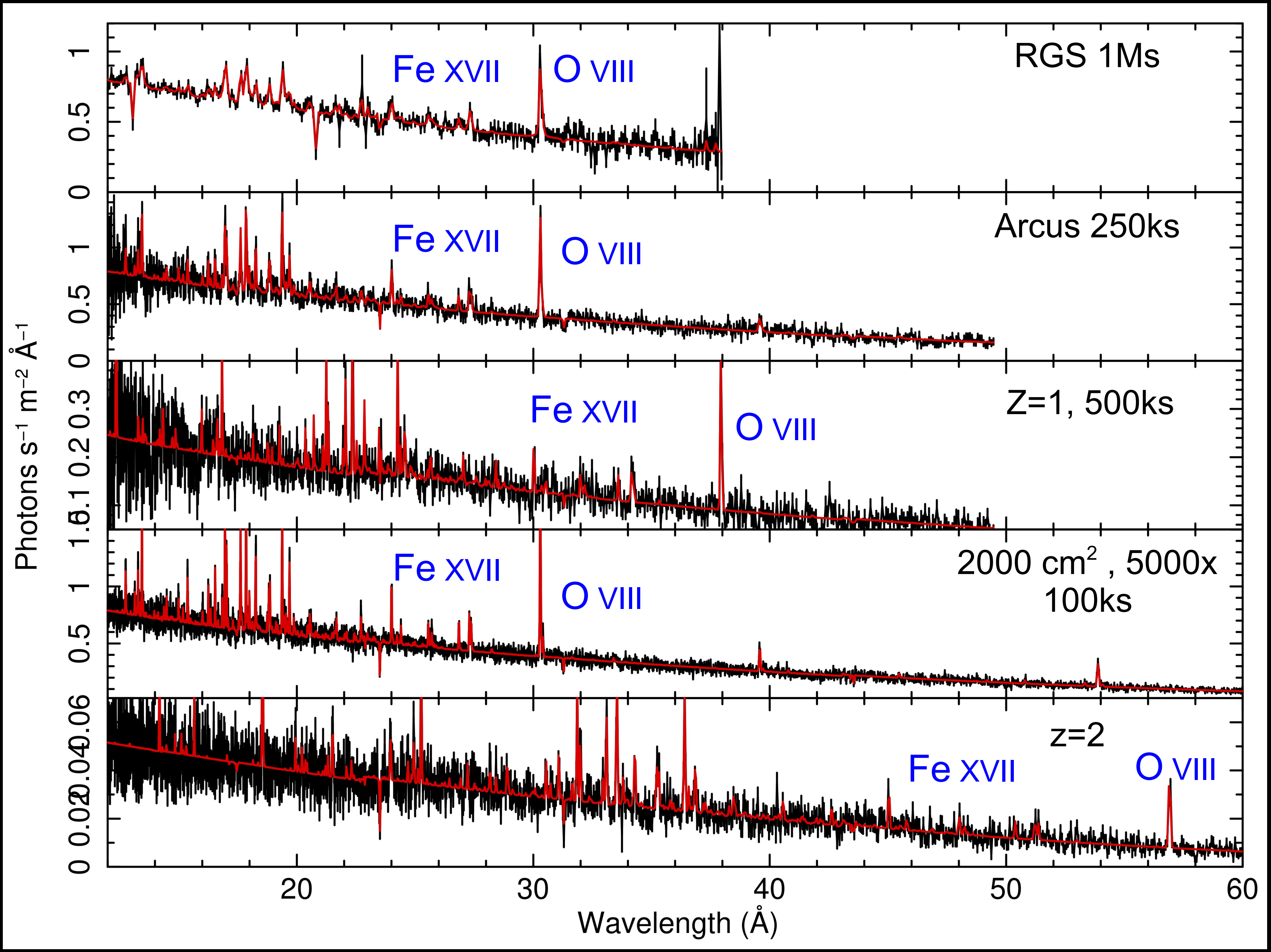
Centaurus cluster
ATHENA
XIFU
100 ks
simul
Counts s⁻¹ A⁻¹
Wavelength (A)
XRISM
SXS
100 ks
simul
Counts s⁻¹ A⁻¹
Wavelength (A)
5σ detection
σV Zone
100ks XIFU
5' x 5' grid
5 kpc

Phoenix cluster

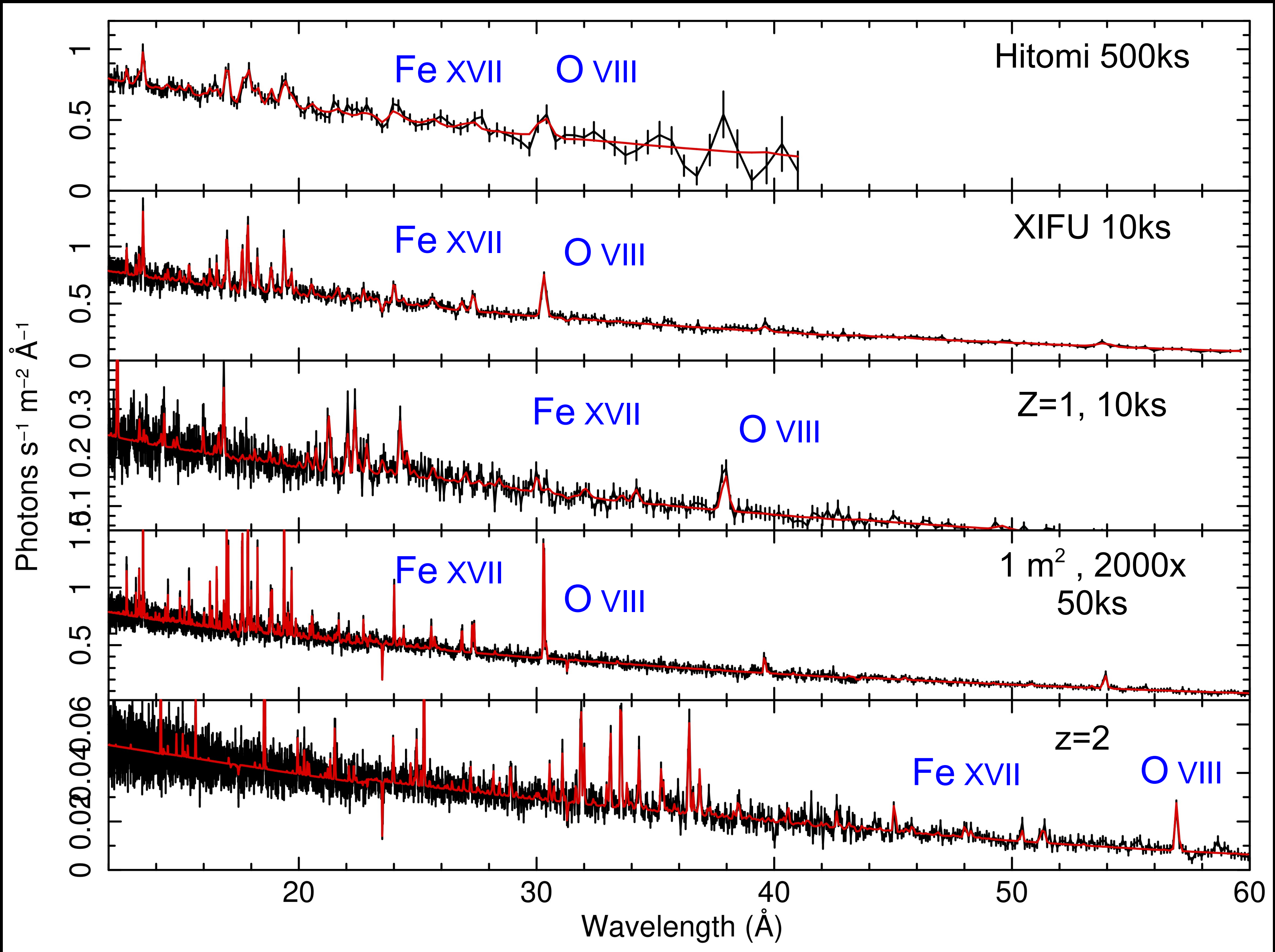
(z=0.6, 10 ks XIFU sim, σ_v = 300 km s^{-1})



Towards ESA Voyage 2050 : Gratings



Towards ESA Voyage 2050 : Calorimeters



High-resolution X-ray spectroscopy a key to understand galaxy clusters

- Accurate measurements of cooling rates
- Constraints on AGN turbulence heating
- Bright future for astrophysics of galaxy clusters
- But accurate atomic databases are required
- Prepare the road to 2050

Bonus slides

Mach Number Required for Cooling – Heating Balance

$c_s = \sqrt{(\gamma kT / \mu m_p)}$ 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 required to balance cooling

$$\sigma_{\mathrm{km/s}} = 5.39 \times 10^4 \left(\frac{r_{\mathrm{kpc}}\,\mathrm{T}_{\mathrm{keV}}}{t_{\mathrm{yr}}}\right)^{1/3}$$

Turbulence required to balance cooling

Mach Number Required for Cooling – Heating Balance

$L_{cool} = L_{turb}$

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

$\sigma_{turb} = r / t_{turb}$

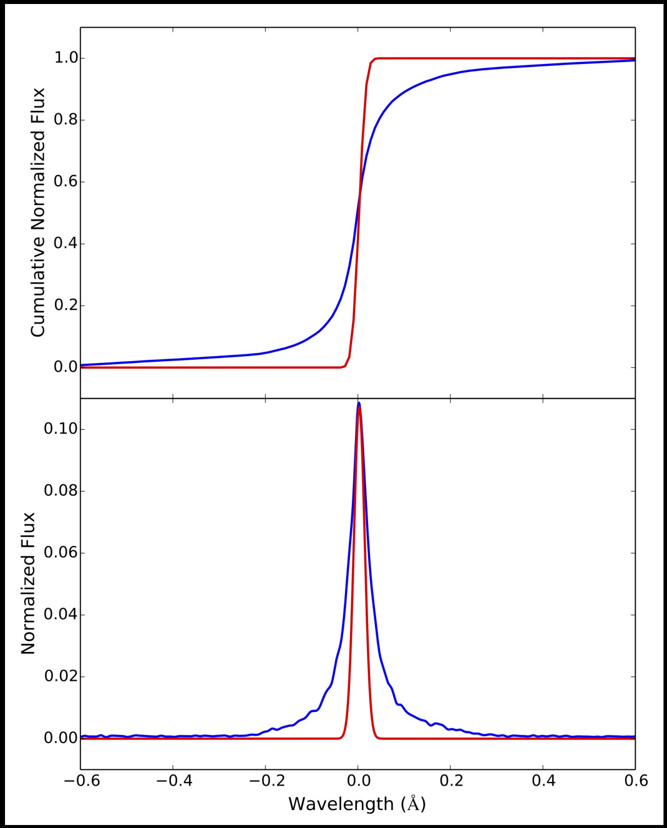
$E_{turb} = 3/2\ M_{gas}\ \sigma_{turb}^{2}$

$E_{ther} = 3/2\ N\ k_B T = 3/2\ M_{gas} / (\mu\ m_p)\ k_B T$

$\rightarrow t_{turb} = \mu\ m_p\ \sigma_{turb}^{2}\ t_{cool} / (k_B T)$

$\rightarrow \sigma_{turb}^{3} = r\ k_B T / (\mu\ m_p\ t_{cool})$

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



Centaurus cluster (100 ks XIFU)

Stat. uncertainty on velocity widths