# The fight between cooling and heating in galaxy clusters

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Ciro Pinto

H. Liu, C. Bambic, P. Kosec, J. Sanders, A. Fabian, F. Mernier, J. De Plaa, J. Kaastra, L. Gu, A. Ogorzalek, N. Werner, M. Guainazzi, I. Zhuravleva, J. Ahoranta, A. Simionescu, A. Finoguenov, C. Reynolds, H. Russell, M. McDonald, YY Zhang

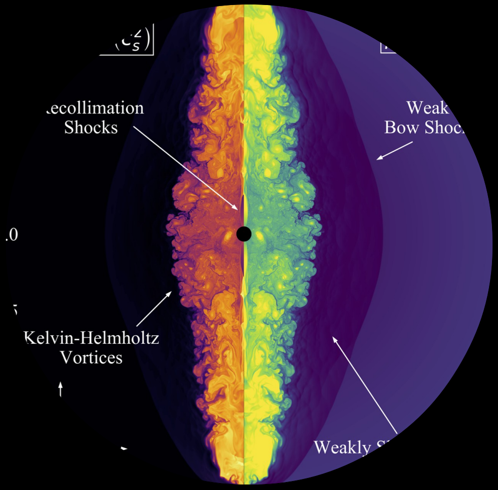
# Outline

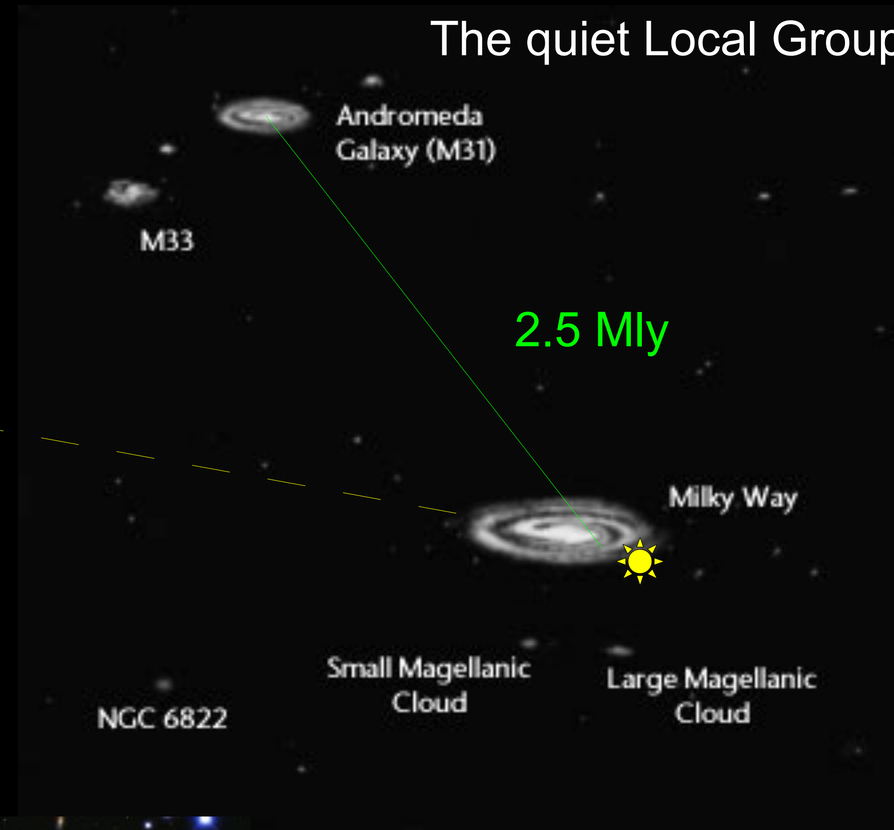
- Intra-Cluster Medium
- X-ray diagnosis
- ICM Thermal balance

  How should the ICM cool?

  What's heating the ICM?

- State-of-art
- Future missions

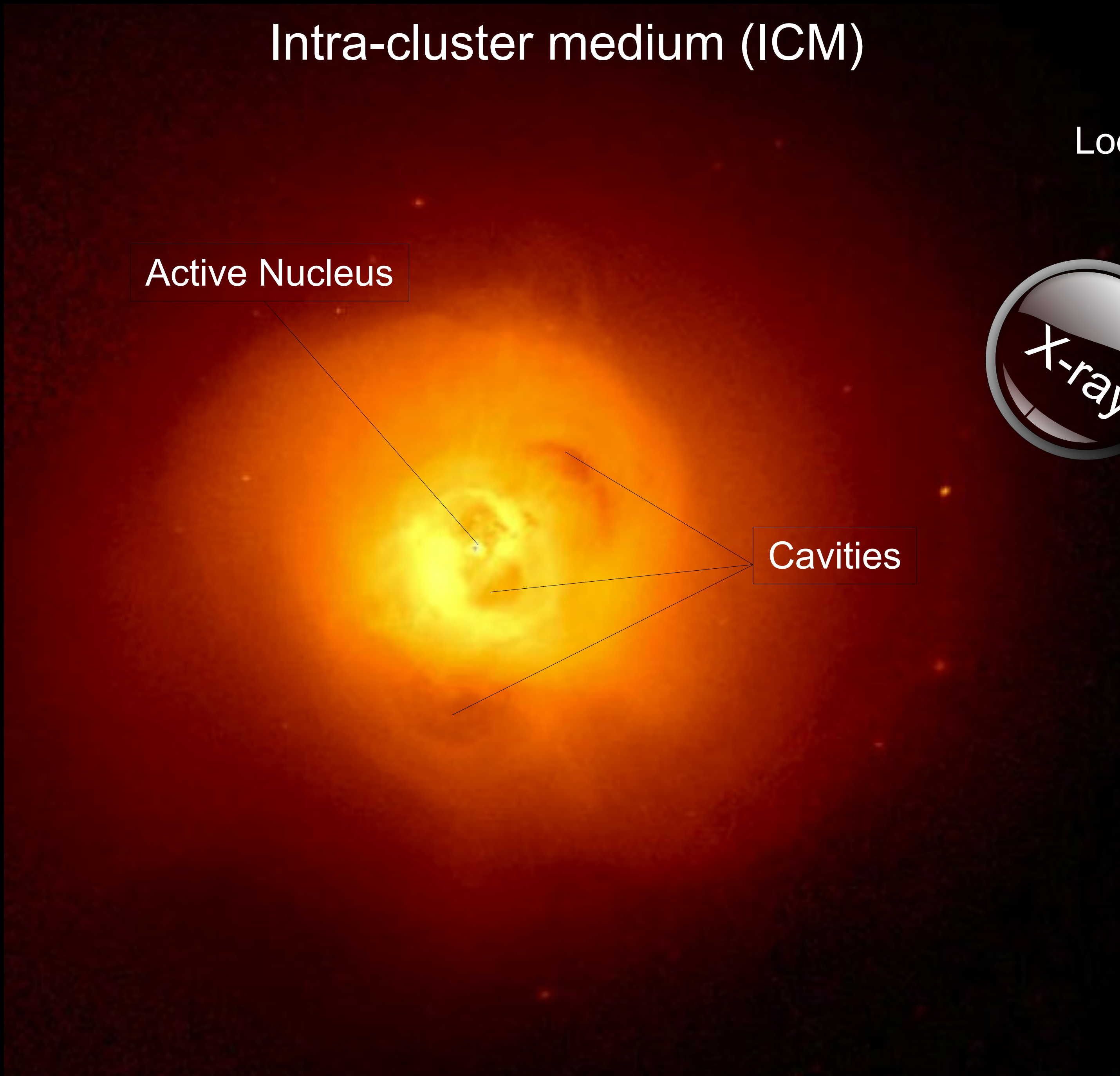



Perseus cluster

# Perseus cluster of galaxies

# Perseus cluster of galaxies



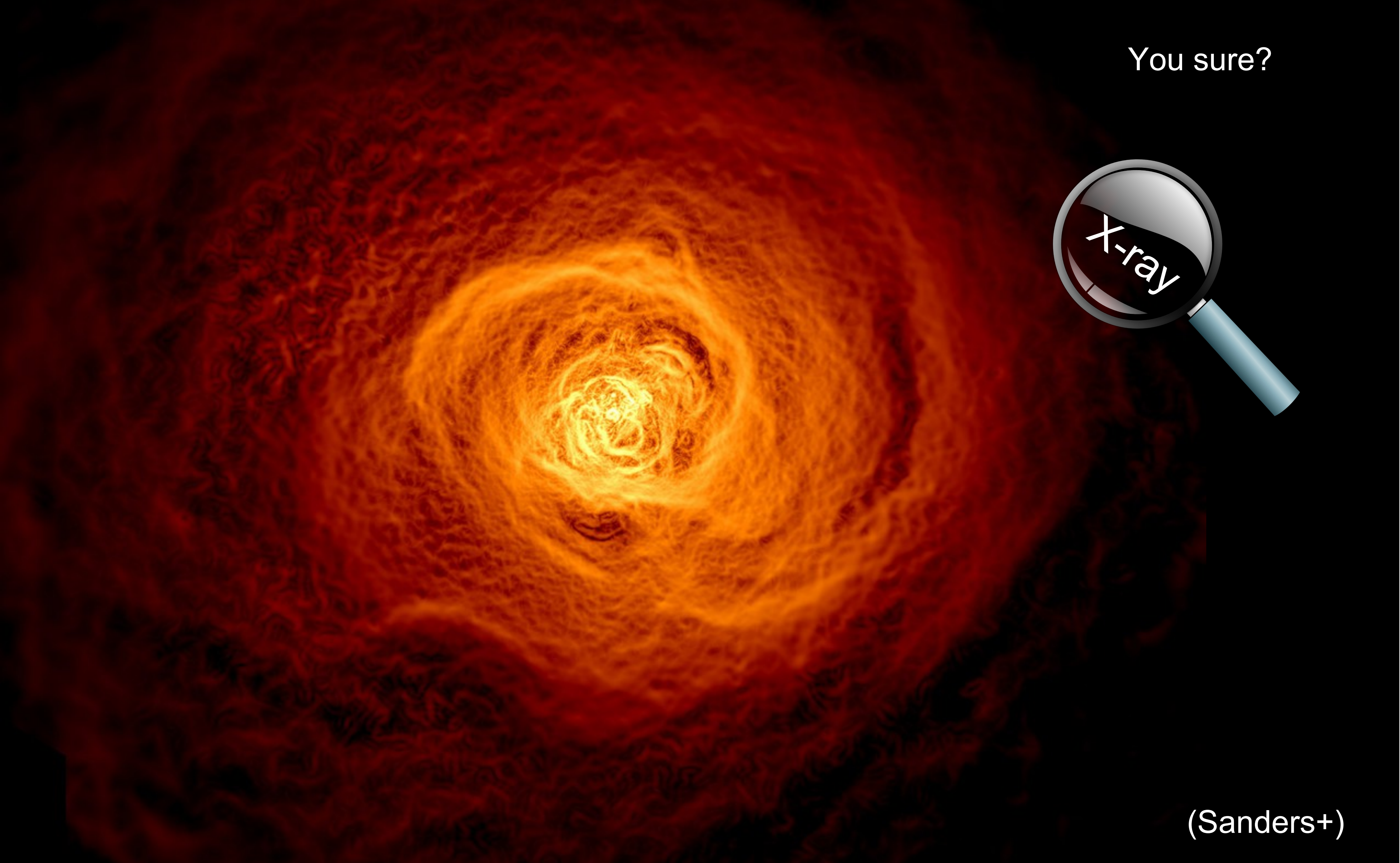


Looks quiet!

(Fabian+)

# Perseus cluster of galaxies

Intra-cluster medium (ICM)



# Clusters of galaxies

100s-1000s galaxies

~ 1 Mpc (3 x $10^{19}$ km)

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

collisional equilibrium

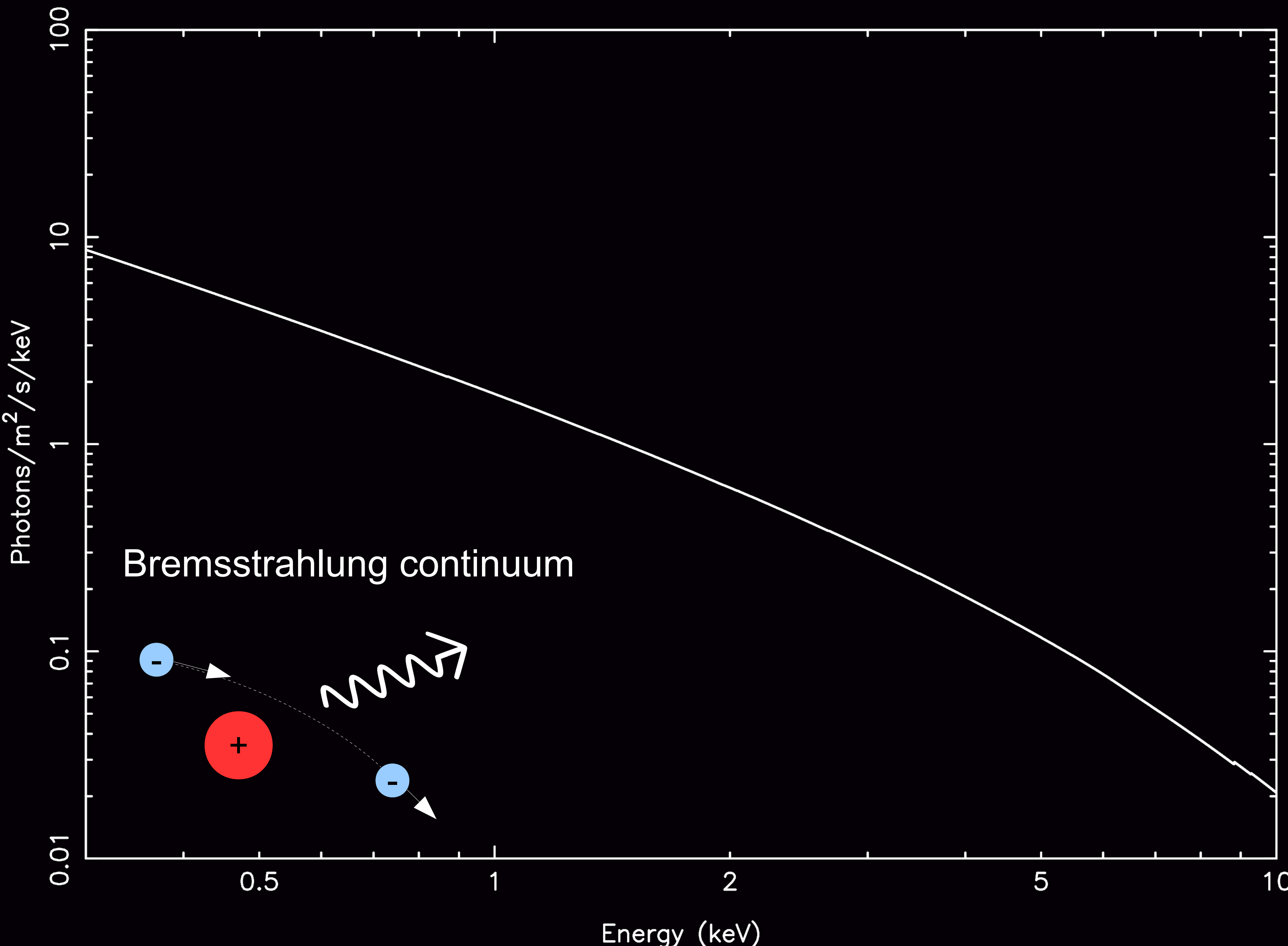
$Y = n_H n_e V$

X-ray and Optical images of the Perseus cluster

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

(Galaxies + ICM) → ICM ≈ 90 % Barionic matter

# X-ray emission (6 keV ~ 70 mln K)



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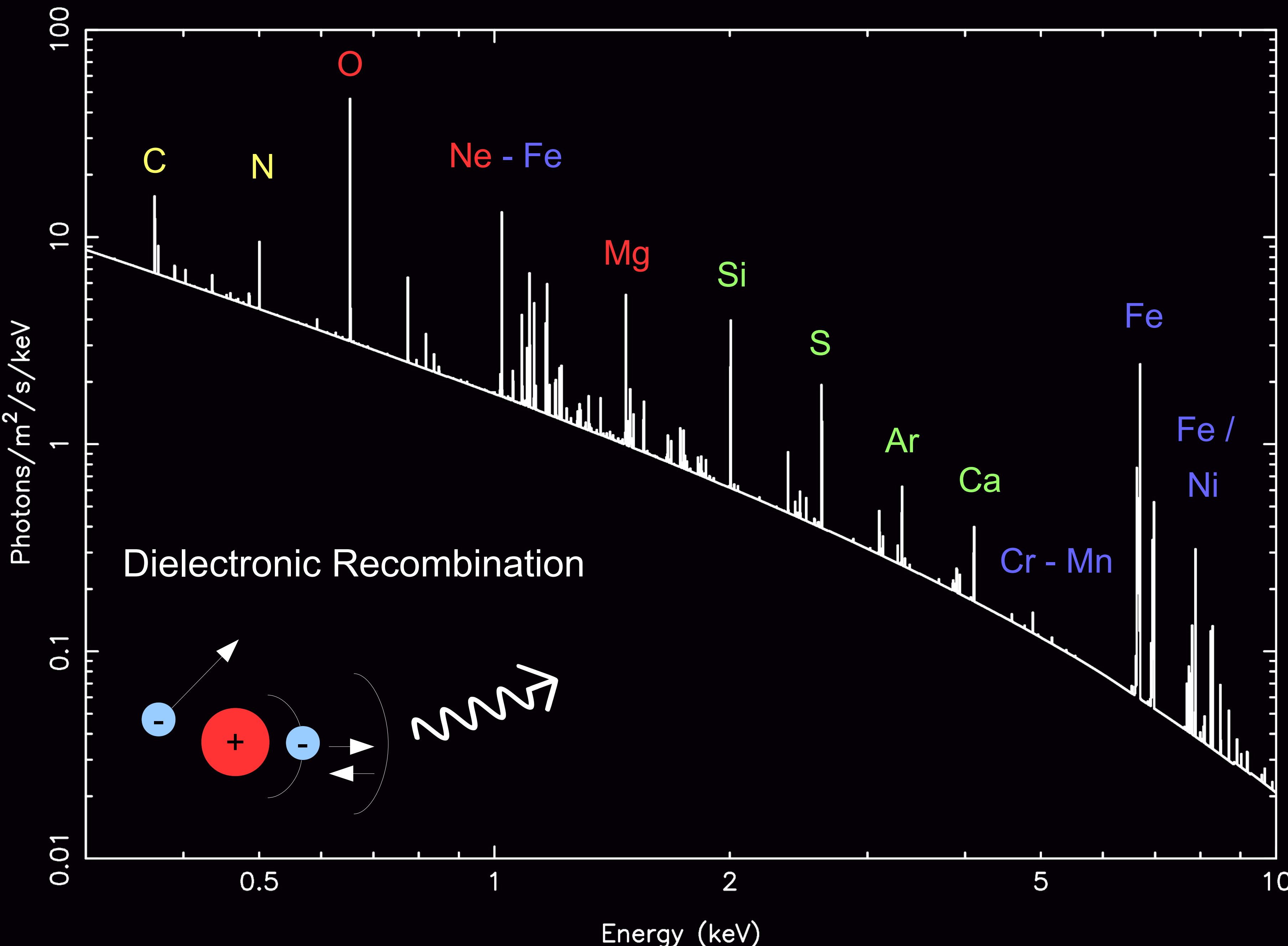
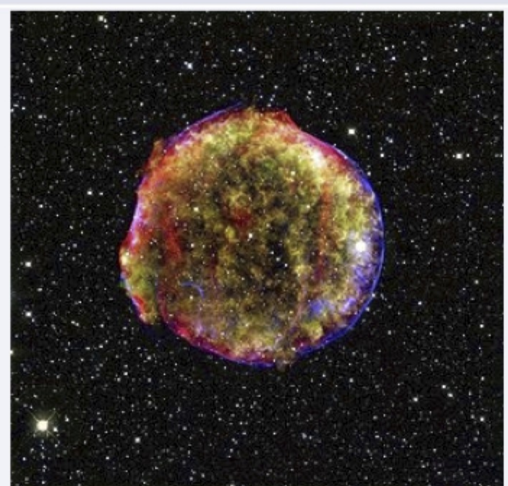
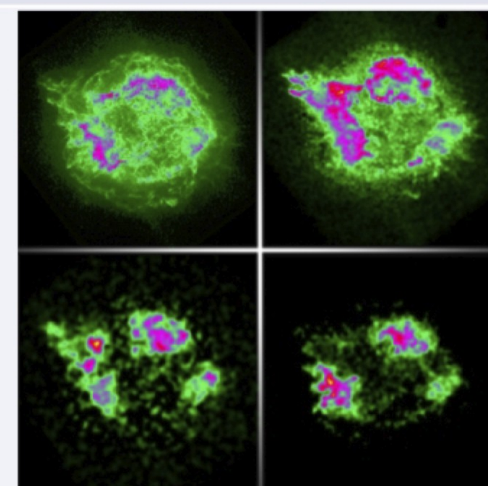
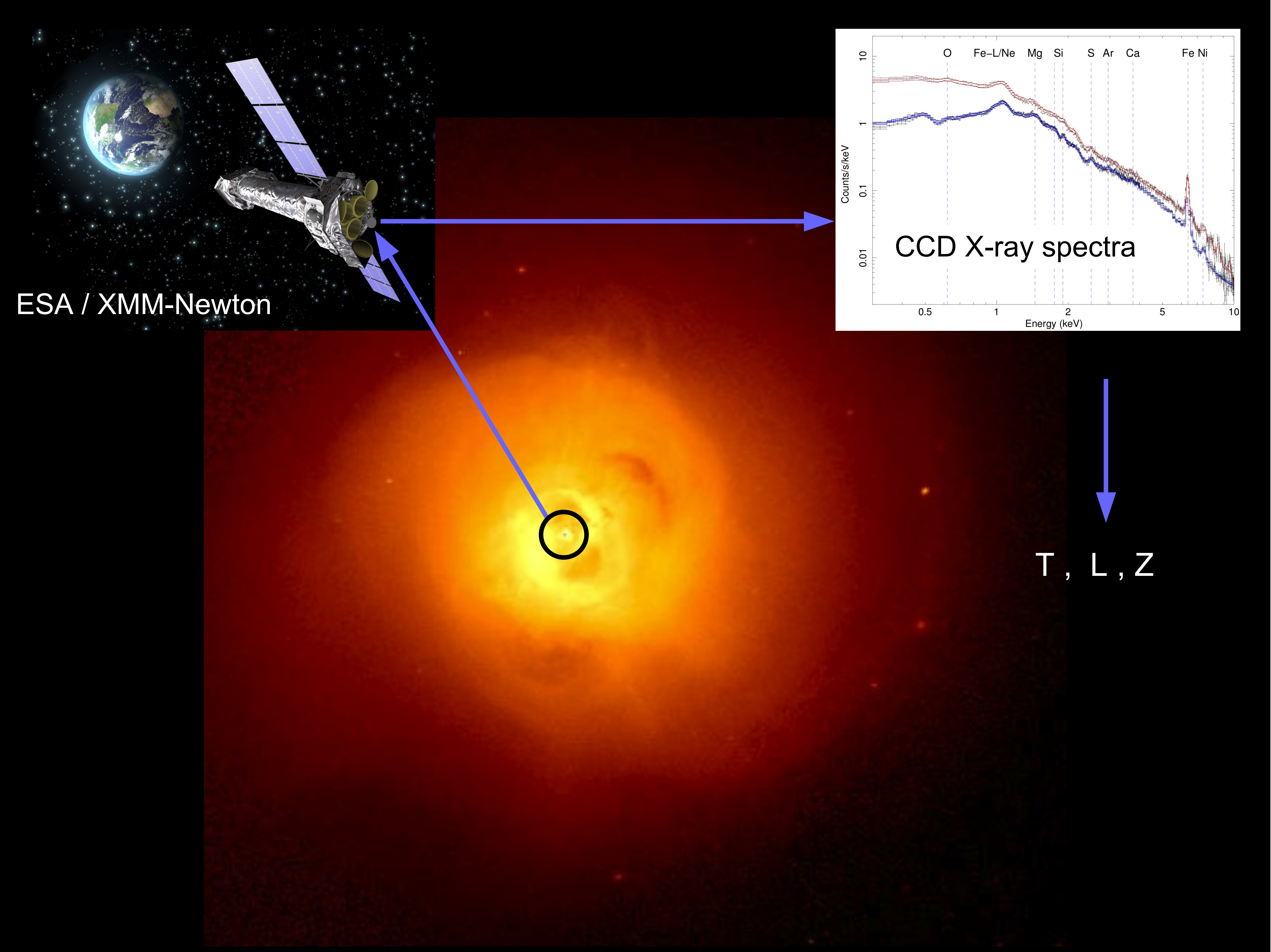
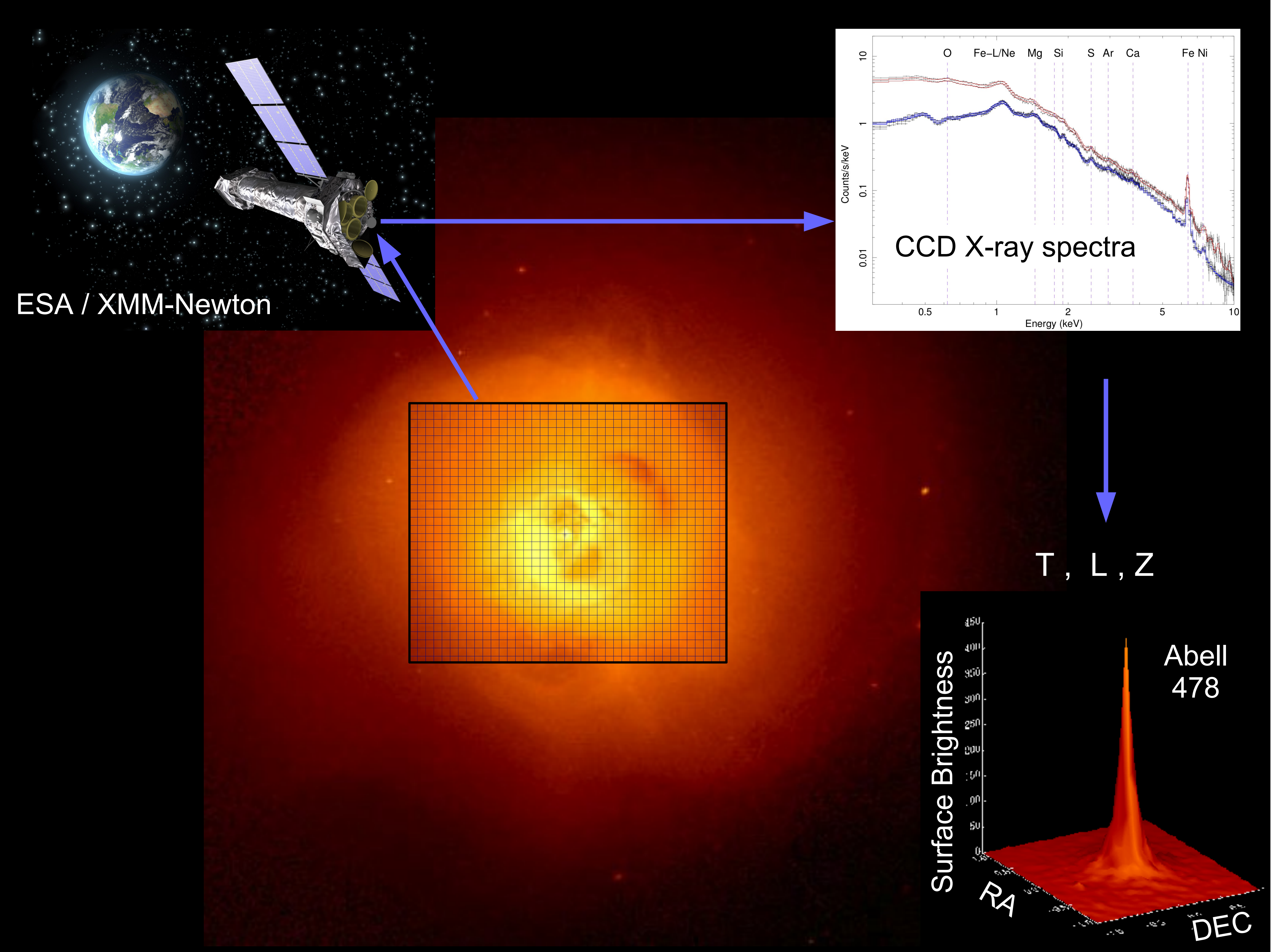


# ICM chemical enrichment

| **Intermediate mass stars (AGB) M < 8 $M_{sun}$** | **Type Ia Supernovae** | **Core-collapse Supernovae** |
|---|---|---|
| •Nitrogen & Carbon<br><br>•Strong winds | •High-mass elements (Si, S, Fe, Ni)<br><br>•Explosive ejection into ISM | •Low-mass elements (O, Ne, Si)<br><br>•Explosive ejection into ISM |
|  |  |  |

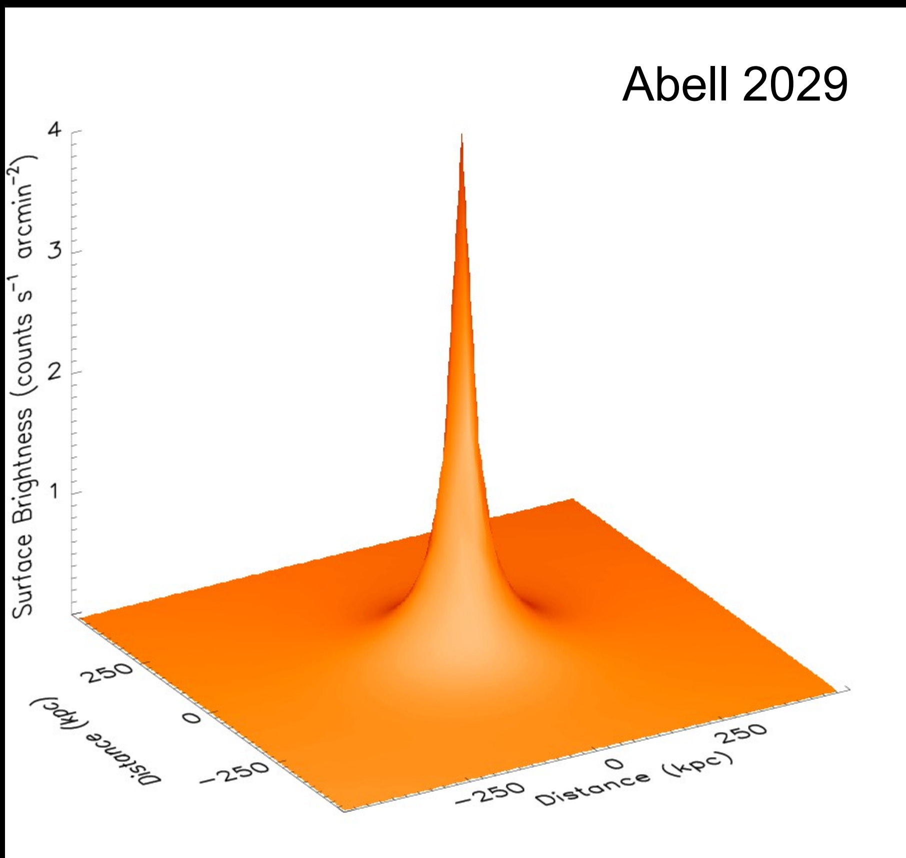
Closed boxes → Chemical history → Bonus slides

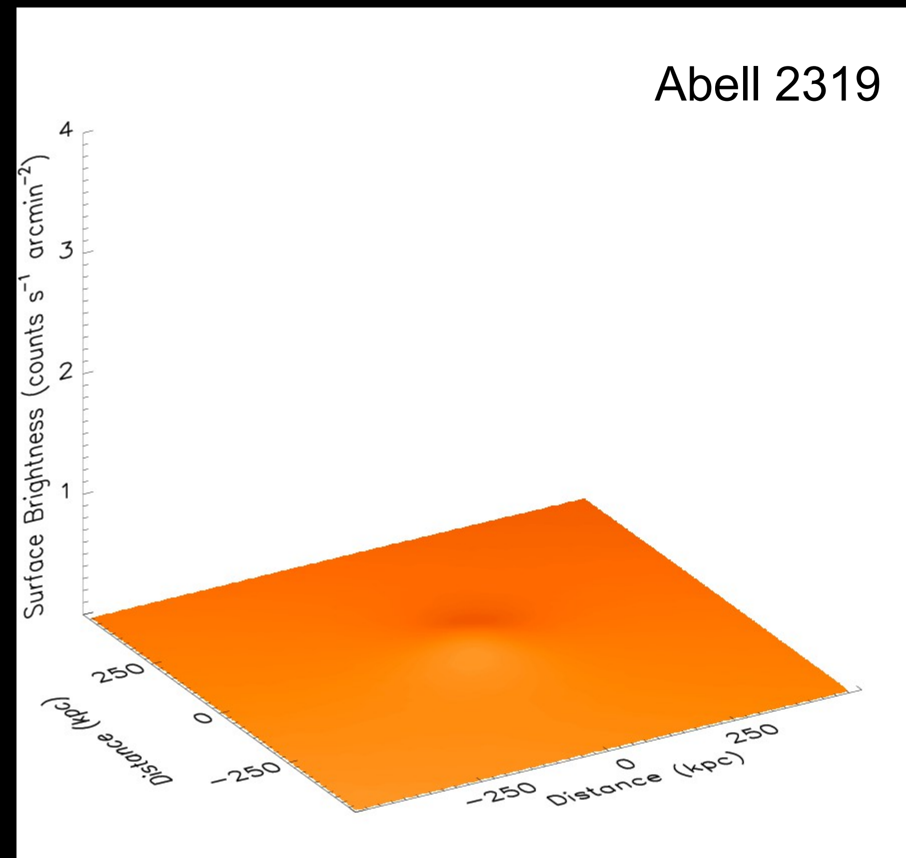

ESA / XMM-Newton
O
Fe–L/Ne
Mg
Si
S
Ar
Ca
Fe
Ni
10
1
0.1
0.01
Counts/s/keV
CCD X-ray spectra
0.5
1
2
5
10
Energy (keV)
T , L , Z



ESA / XMM-Newton
CCD X-ray spectra
O
Fe–L/Ne
Mg
Si
S
Ar
Ca
Fe Ni
Counts/s/keV
Energy (keV)
T , L , Z
Surface Brightness
RA
DEC
Abell
478

# Cool-Core VS Non Cool-core




Million & Allen 2009

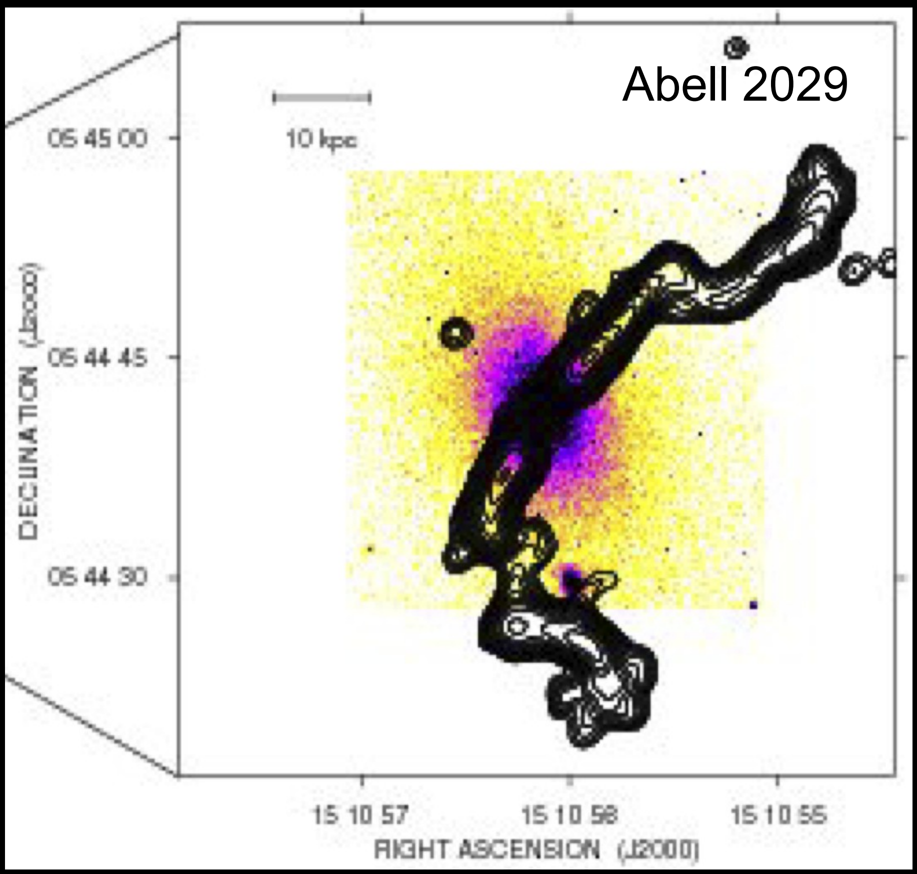
See also Molendi & Pizzolato 2001

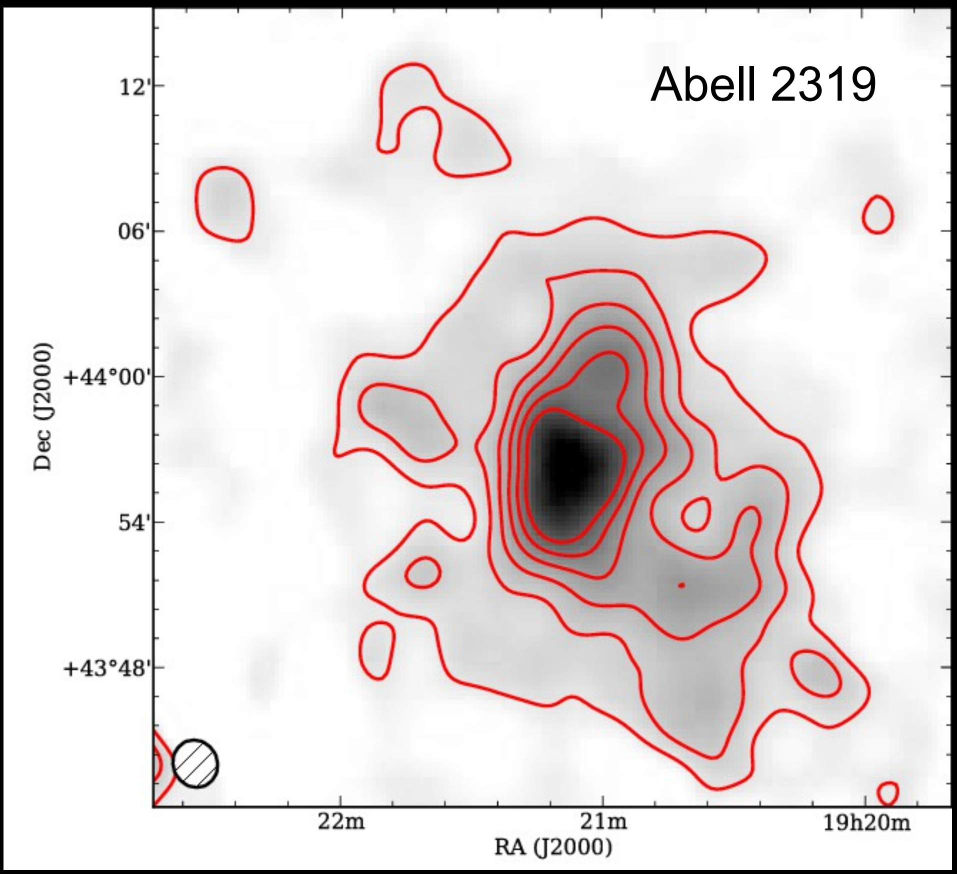
See also Ghizzardi + 2010

Higher X-ray emission & faster gas cooling

Smoother X-ray emission and less relaxed

# Cool-Core VS Non Cool-core



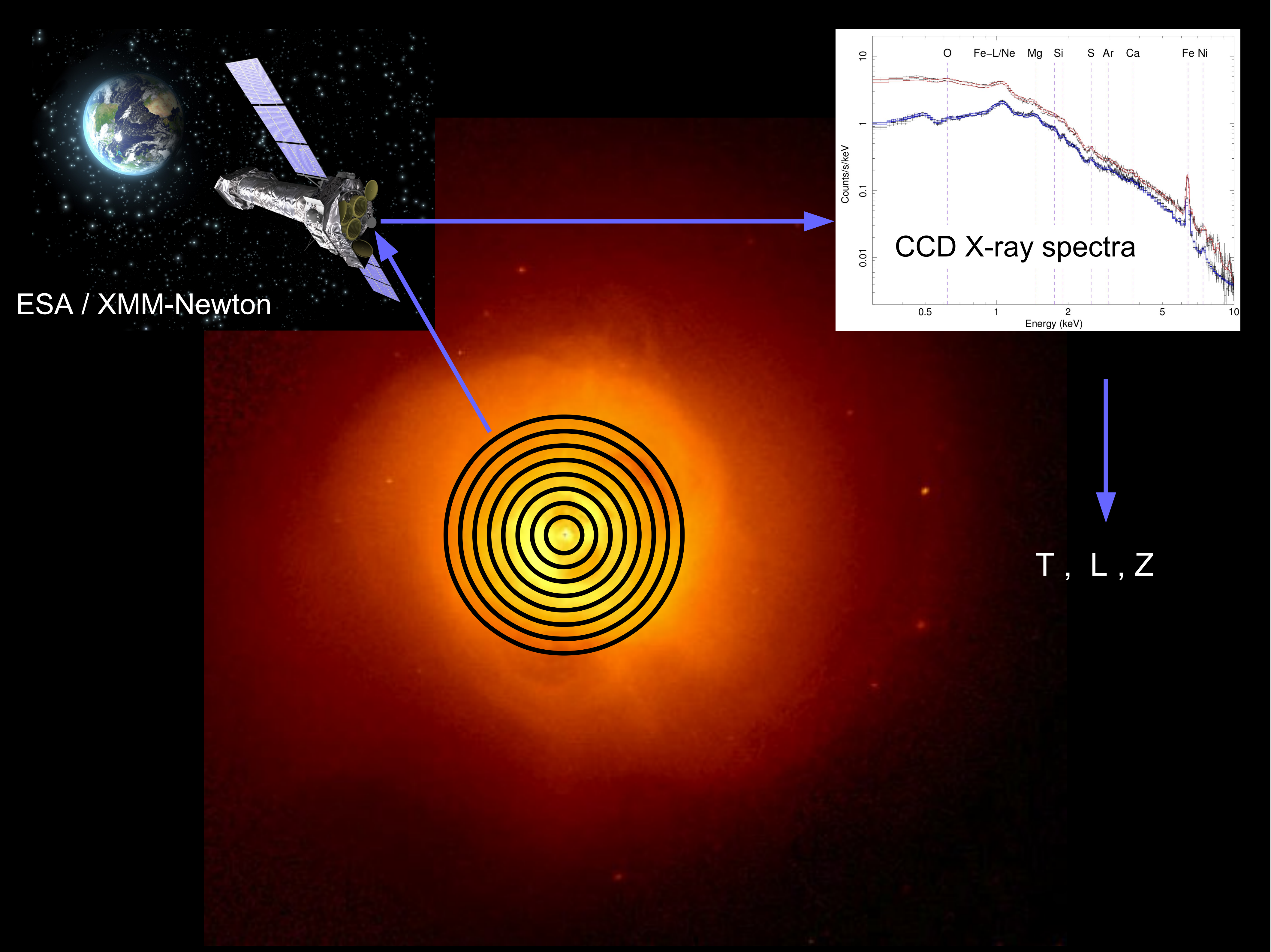

Govoni + 2009

Storm + 2014

Will relax faster than cooling (Rossetti + 2011)

Radio Jets from BCG active galactic nucleus

Strong radio halos from galactic mergers?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Counts/s/keV
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Energy (keV)
CCD X-ray spectra
T , L , Z

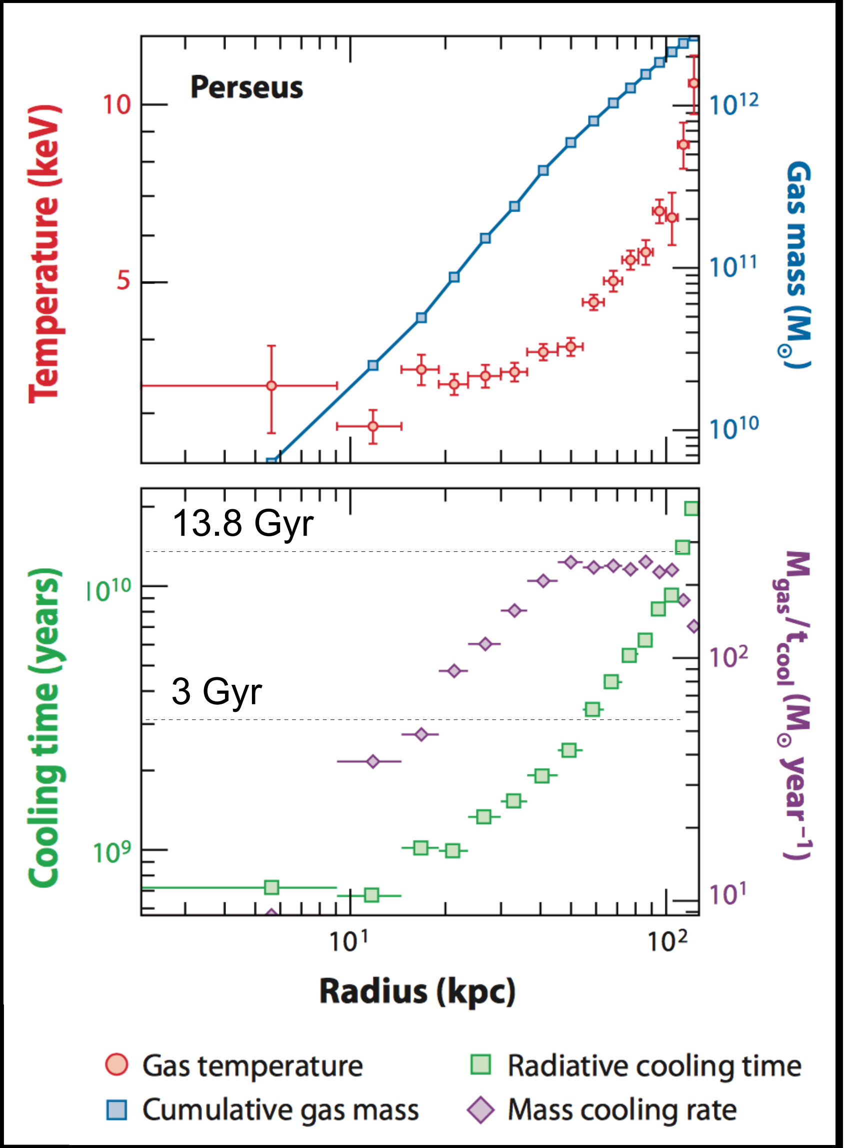
# Cooling flows in clusters of galaxies

Cooling time shorter than cluster age

→ **100s $M_{sun}$ $yr^{-1}$** in cores of clusters

in > 1/3 of galaxy clusters

(Hudson + 2010)




Fabian 2012 (figure by J. Sanders)

But noted already by Lea + 1973!
See also De Grandi & Molendi 2002

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

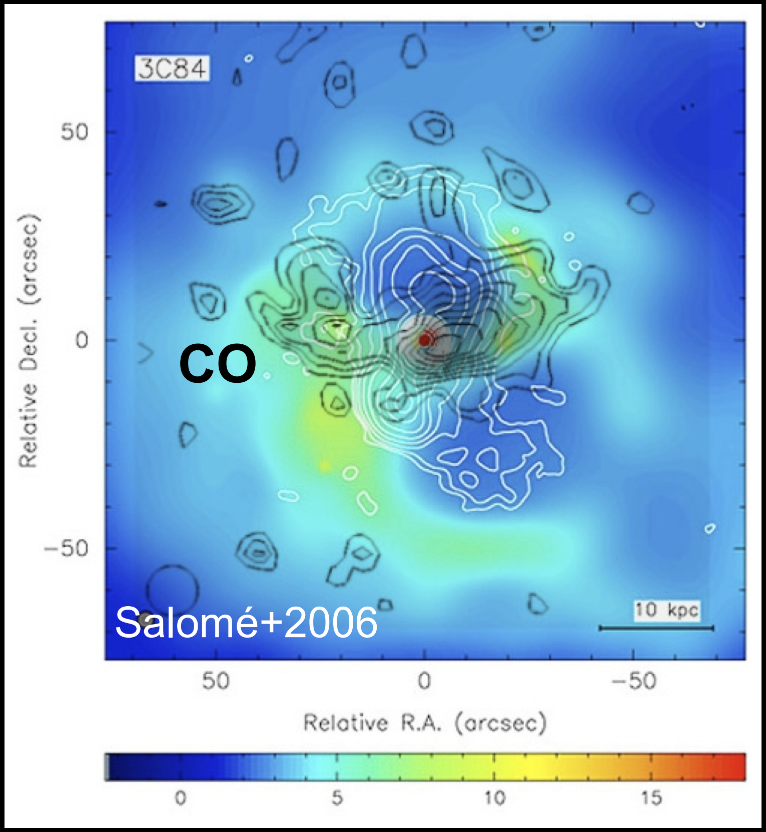
$$t_{\rm cool} = \frac{3}{2}\frac{(n_{\rm e}+n_{\rm i})kT}{n_{\rm e}n_{\rm H}\Lambda(T,Z)},$$

$$\dot{M}_{\rm classical}(<r) \simeq \frac{M_{\rm gas}(r)}{t_{\rm cool}(r)-t_{\rm cool}(0)}\,.$$

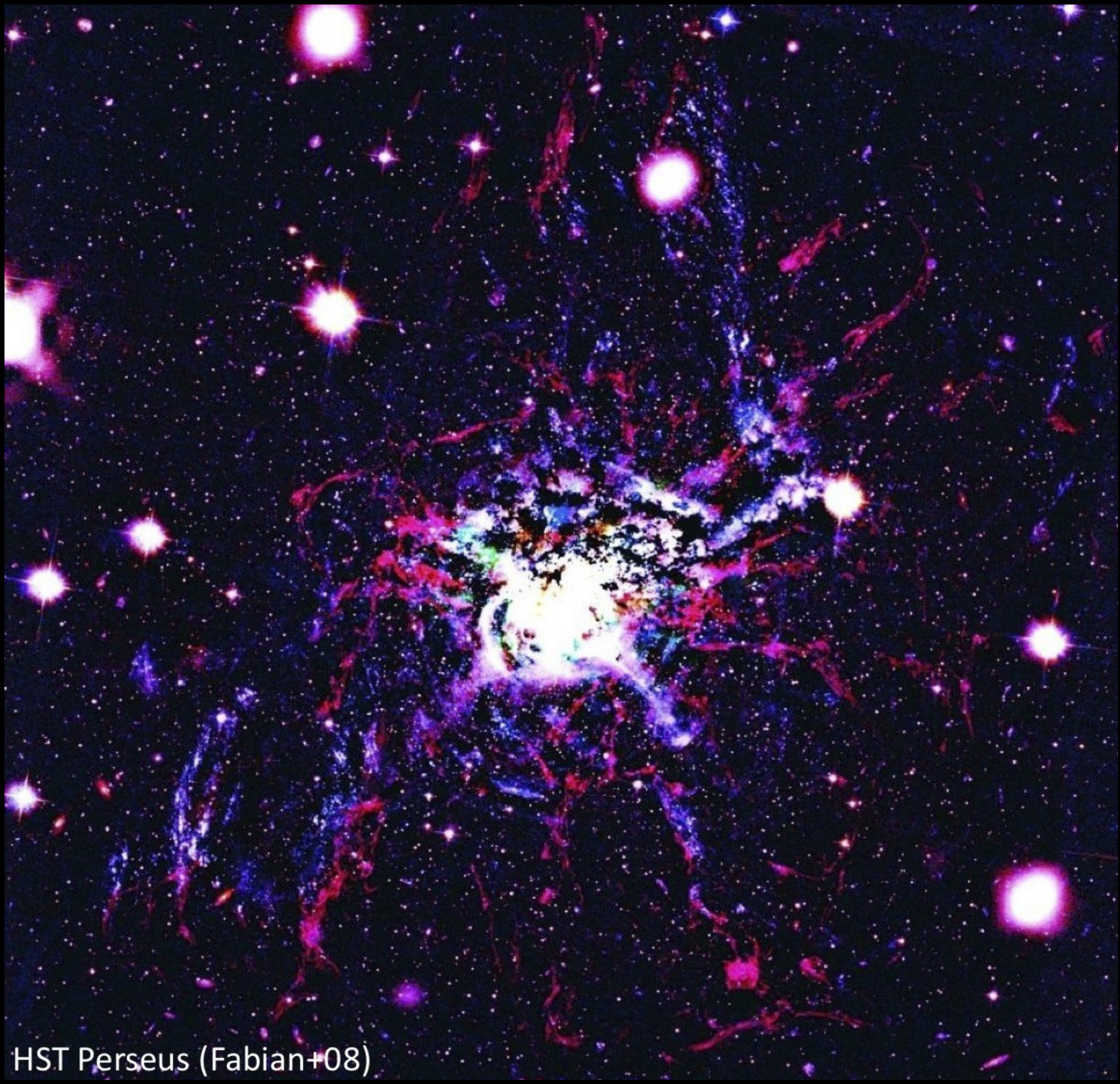
# Star Formation Rate lower than theoretical predictions

~ 20-40 $M_{sun}$ $yr^{-1}$

CO (2-1) 226.56 GHz emission



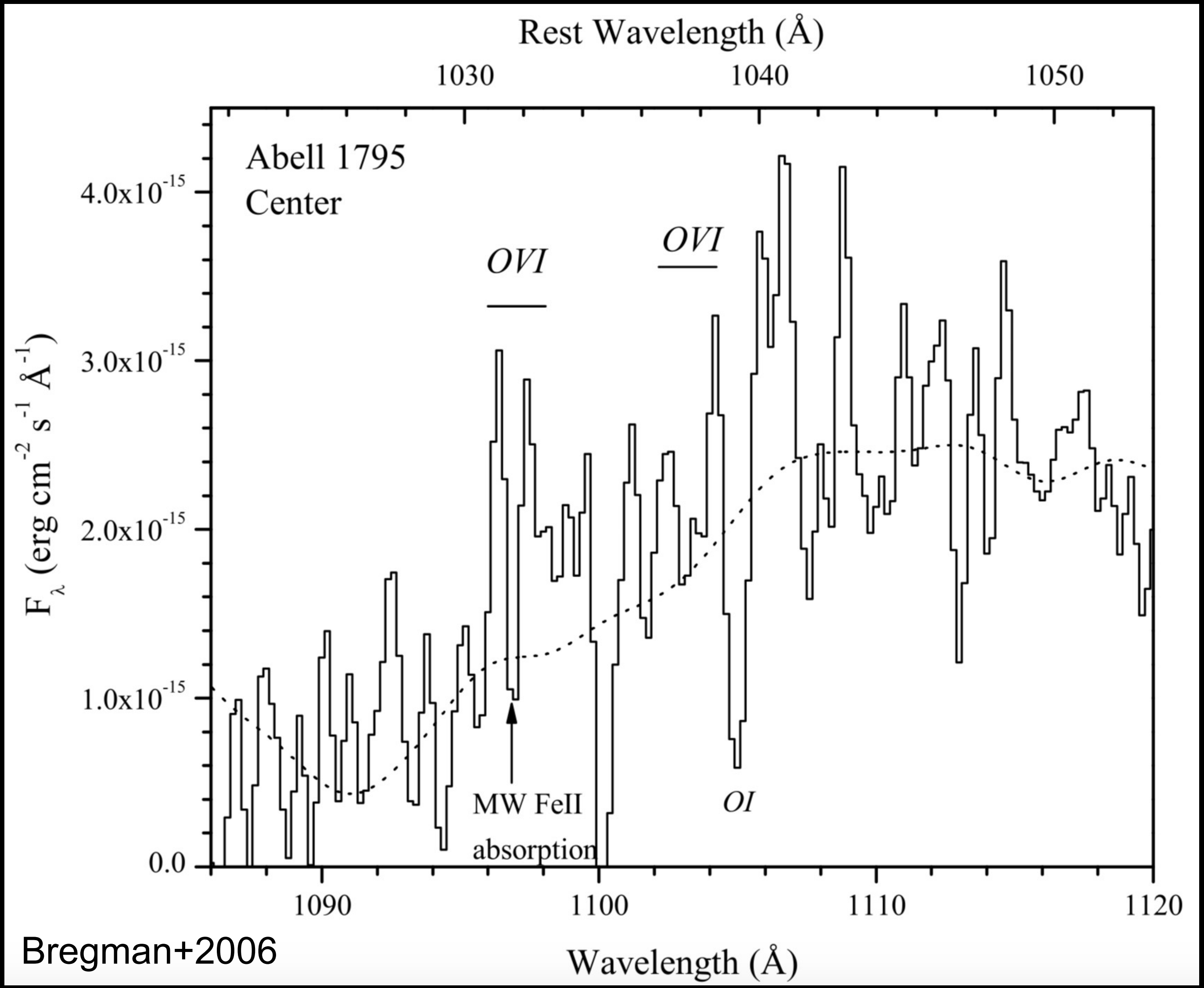

Hα emission line nebulae (~ 10000 K)



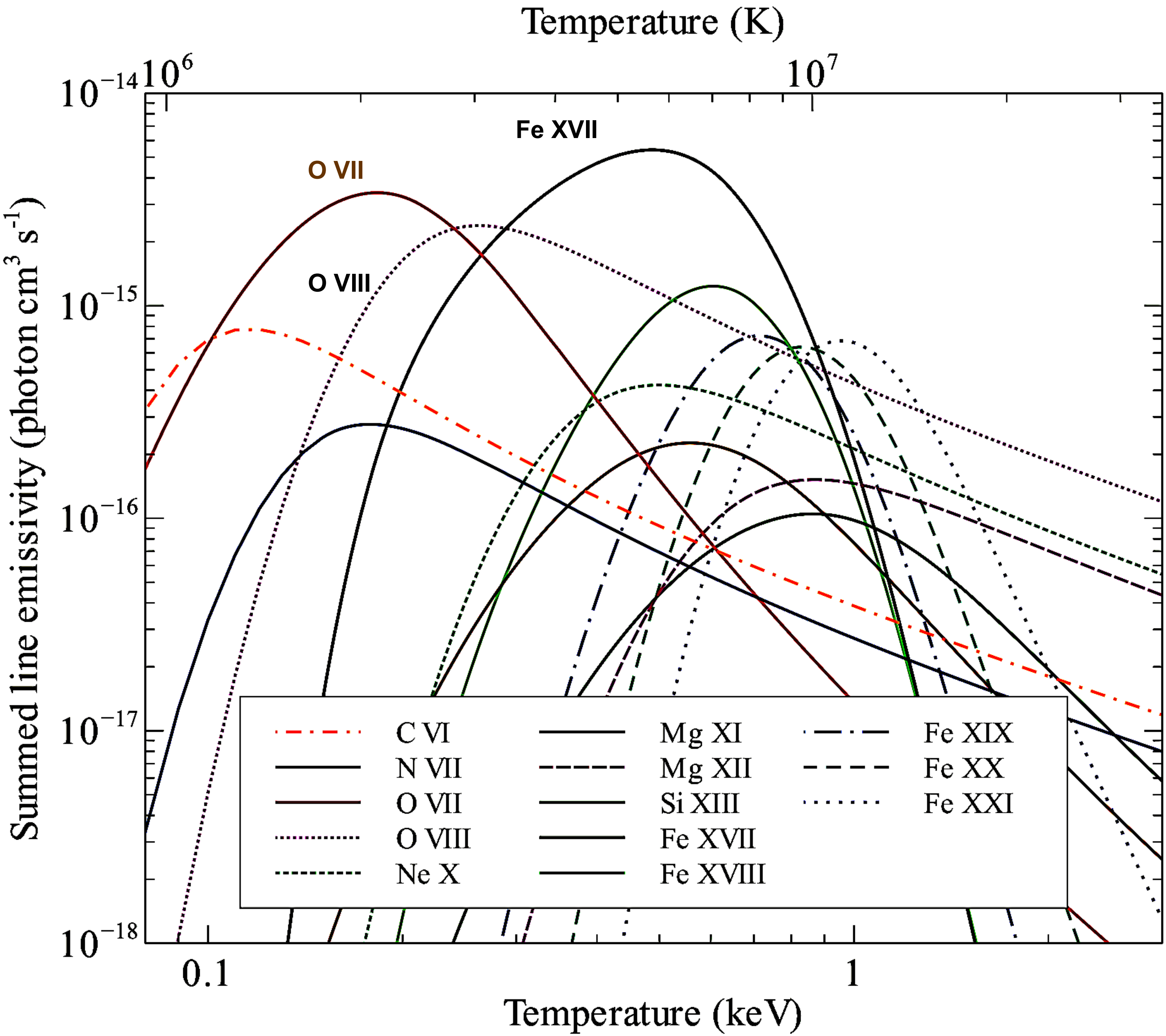
# Star Formation Rate lower than theoretical predictions

~ 20-40 $M_{sun}$ $yr^{-1}$

HST / STIS
far - UV

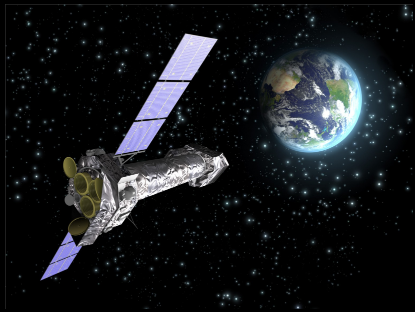


How do we search for cooling flows?

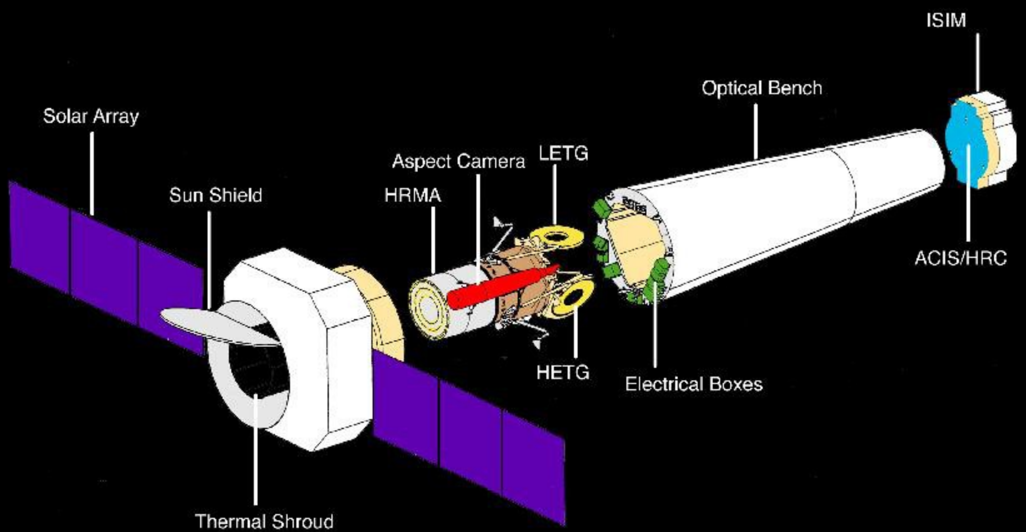

Temperature (K)
$10^6$
$10^7$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^{-18}$
Summed line emissivity (photon cm$^3$ s$^{-1}$)
Fe XVII
O VII
O VIII
C VI
N VII
O VII
O VIII
Ne X
Mg XI
Mg XII
Si XIII
Fe XVII
Fe XVIII
Fe XIX
Fe XX
Fe XXI
0.1
1
Temperature (keV)

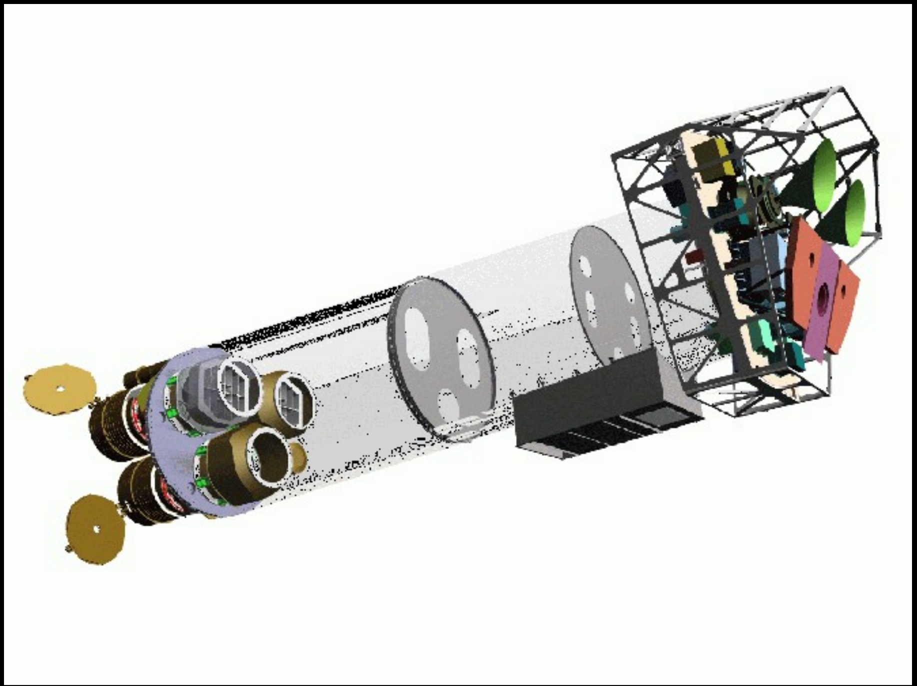
# How can we detect narrow X-ray lines from *cool* gas?

Chandra



XMM-Newton



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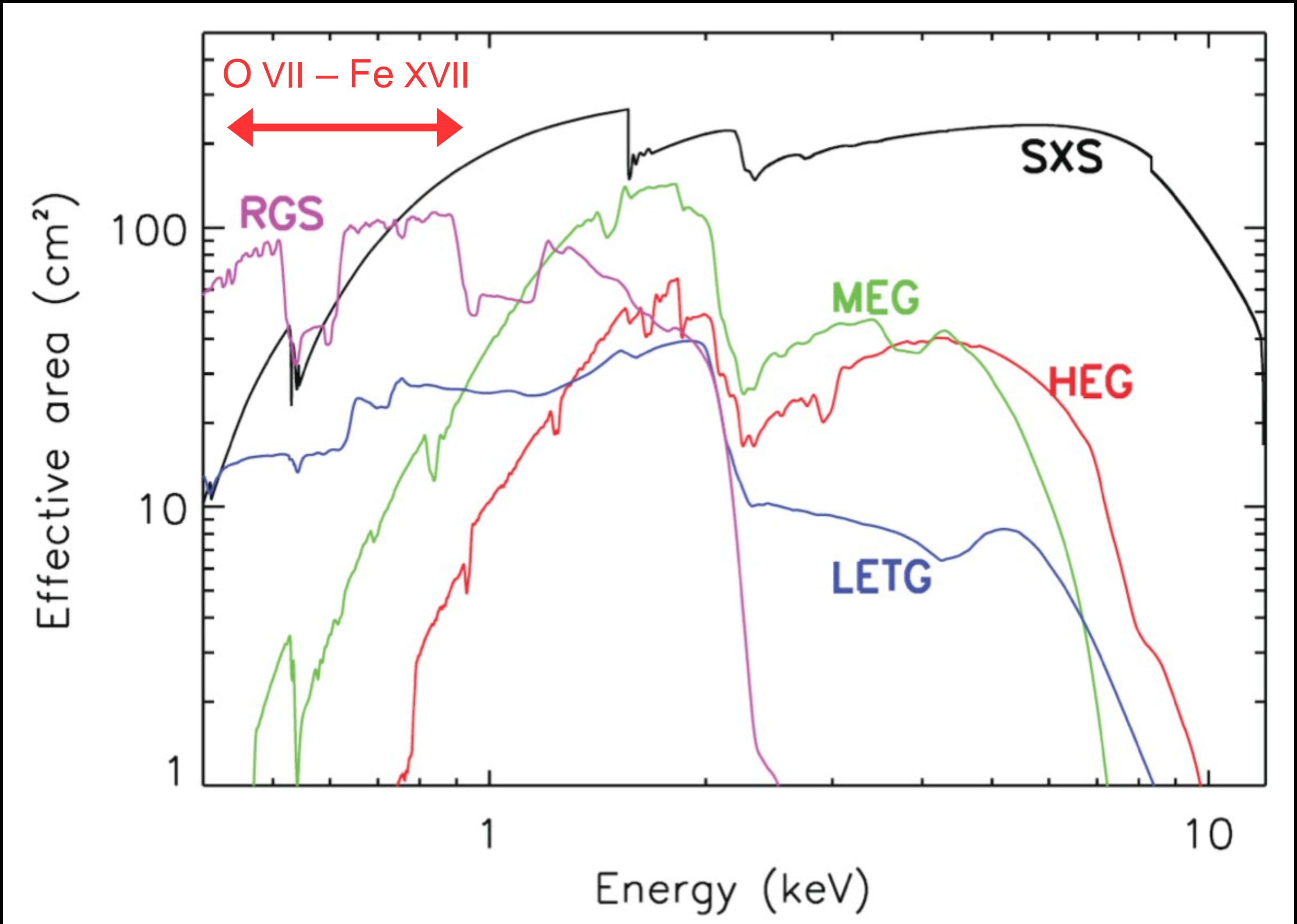
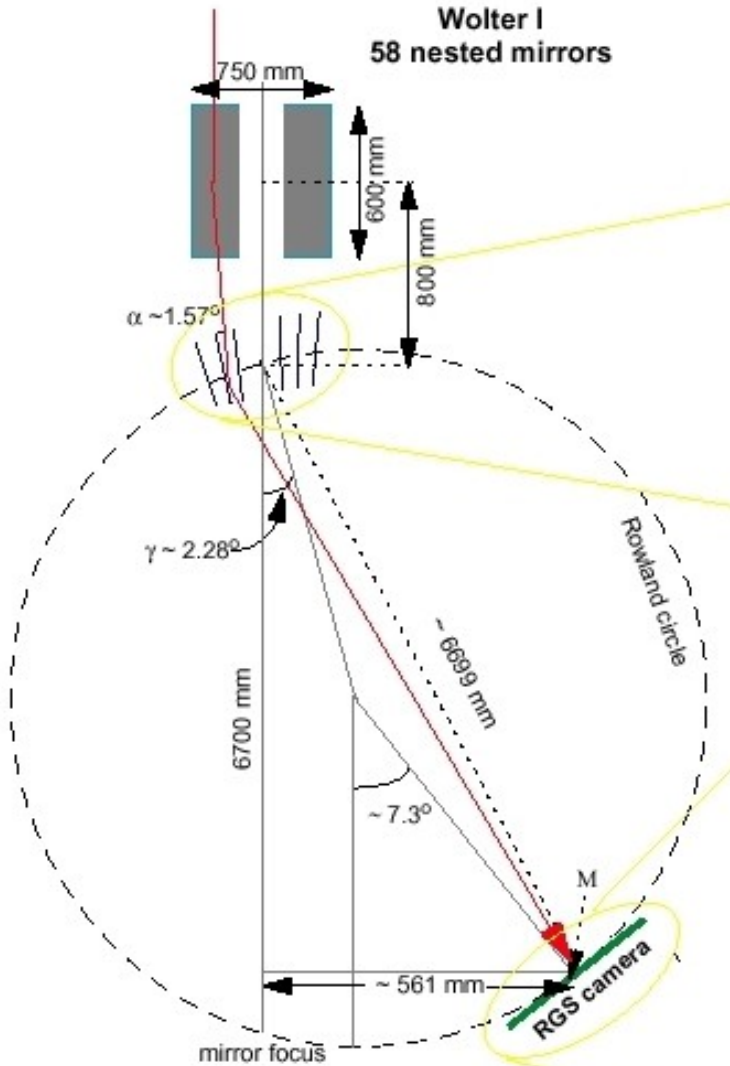


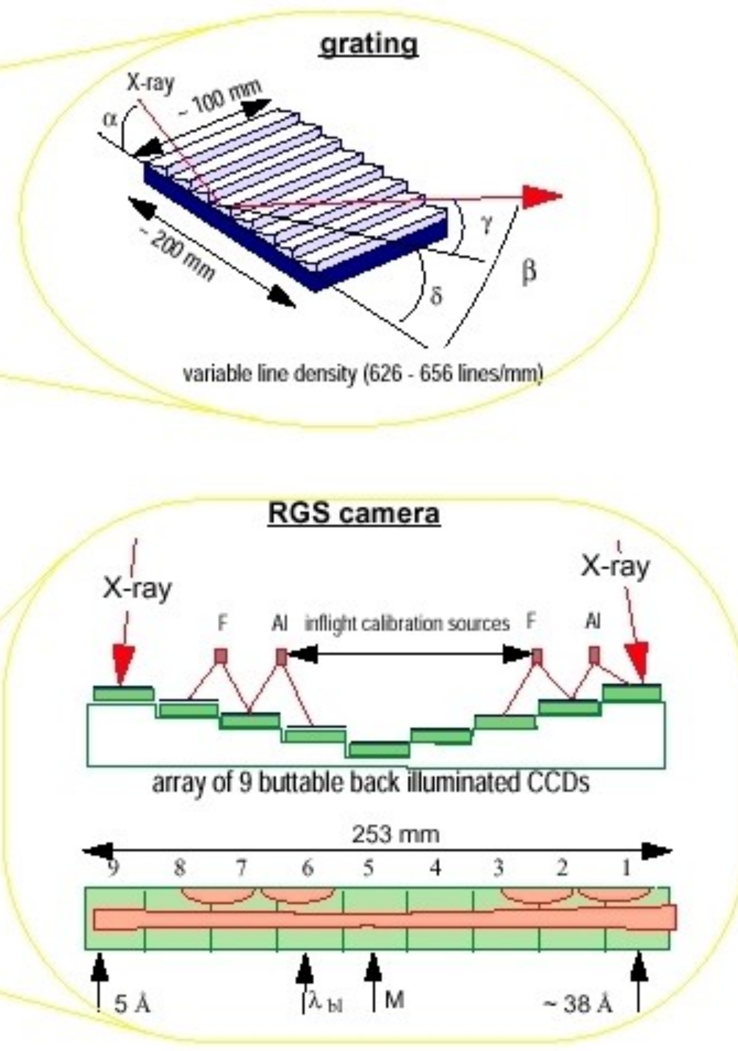
# The Reflection Grating Spectrometer (RGS) on board XMM-Newton

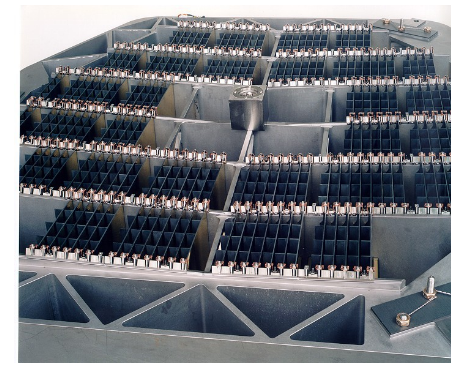
$R = E / \Delta E = 100 - 400$ 1st order

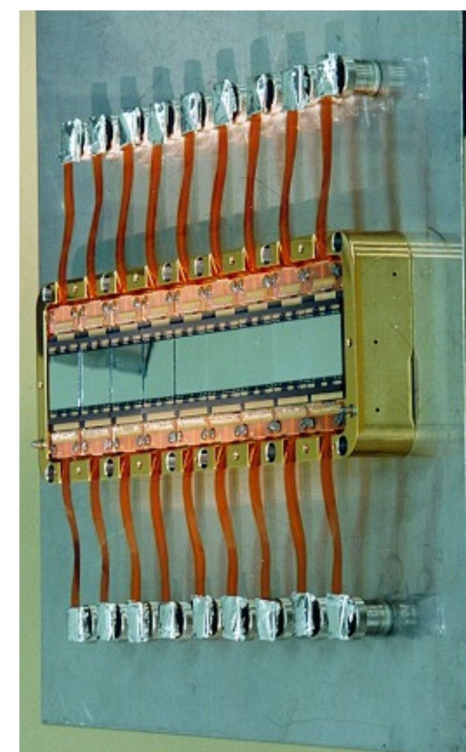
10-100x $R_{CCD}$ 0.3-1.8 keV

$> R_{Hitomi/SXS\ (5eV)}$ 0.3-1.0 keV



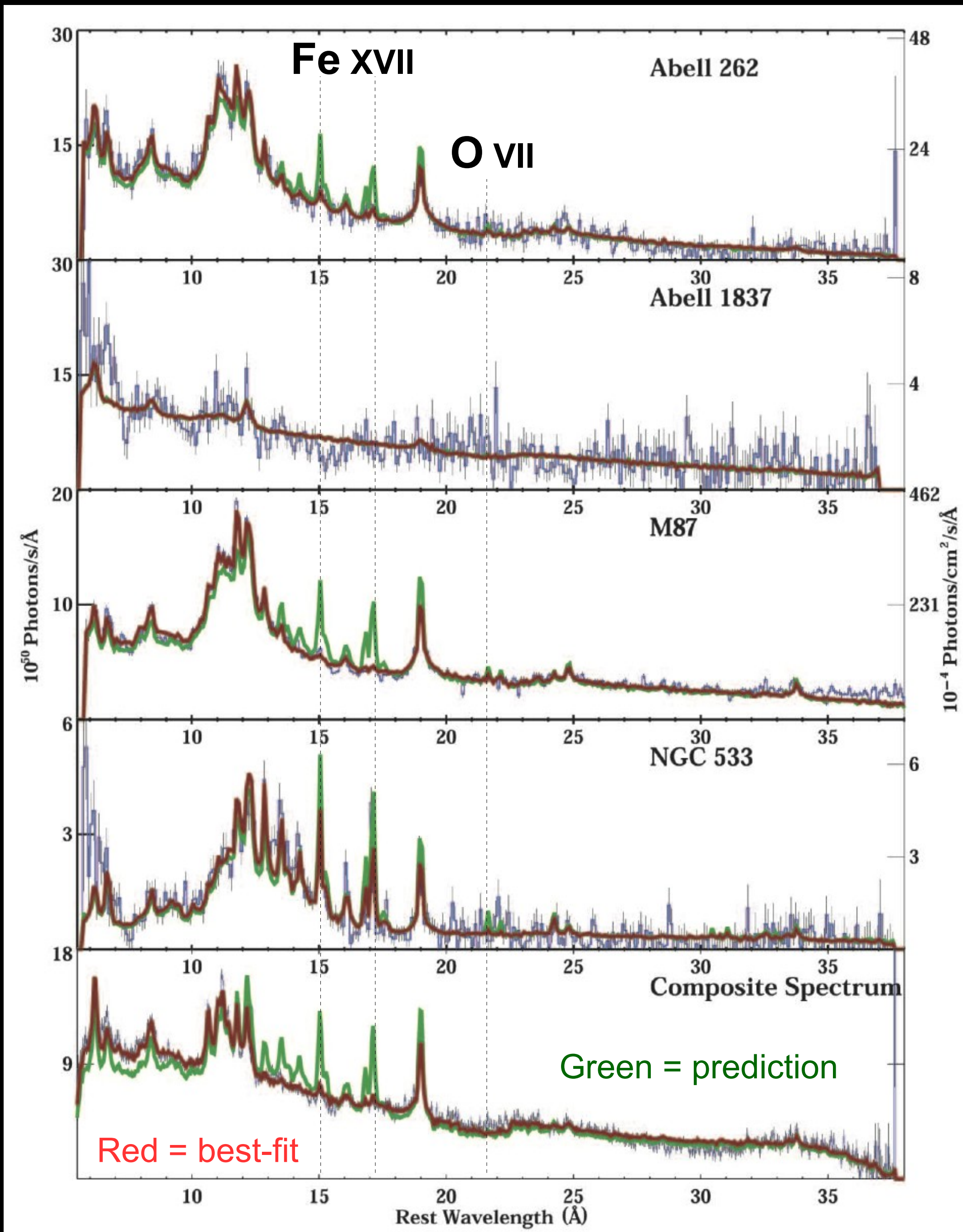





den Herder + 2001

# XMM-Newton / RGS clusters first light




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

Differential emission measure distribution for the isobaric cooling flow model:

$$dEM(T) = \frac{5}{2} \frac{\dot{M}}{\mu m_H \Lambda(T)} k \, dT$$

No O VII lines?

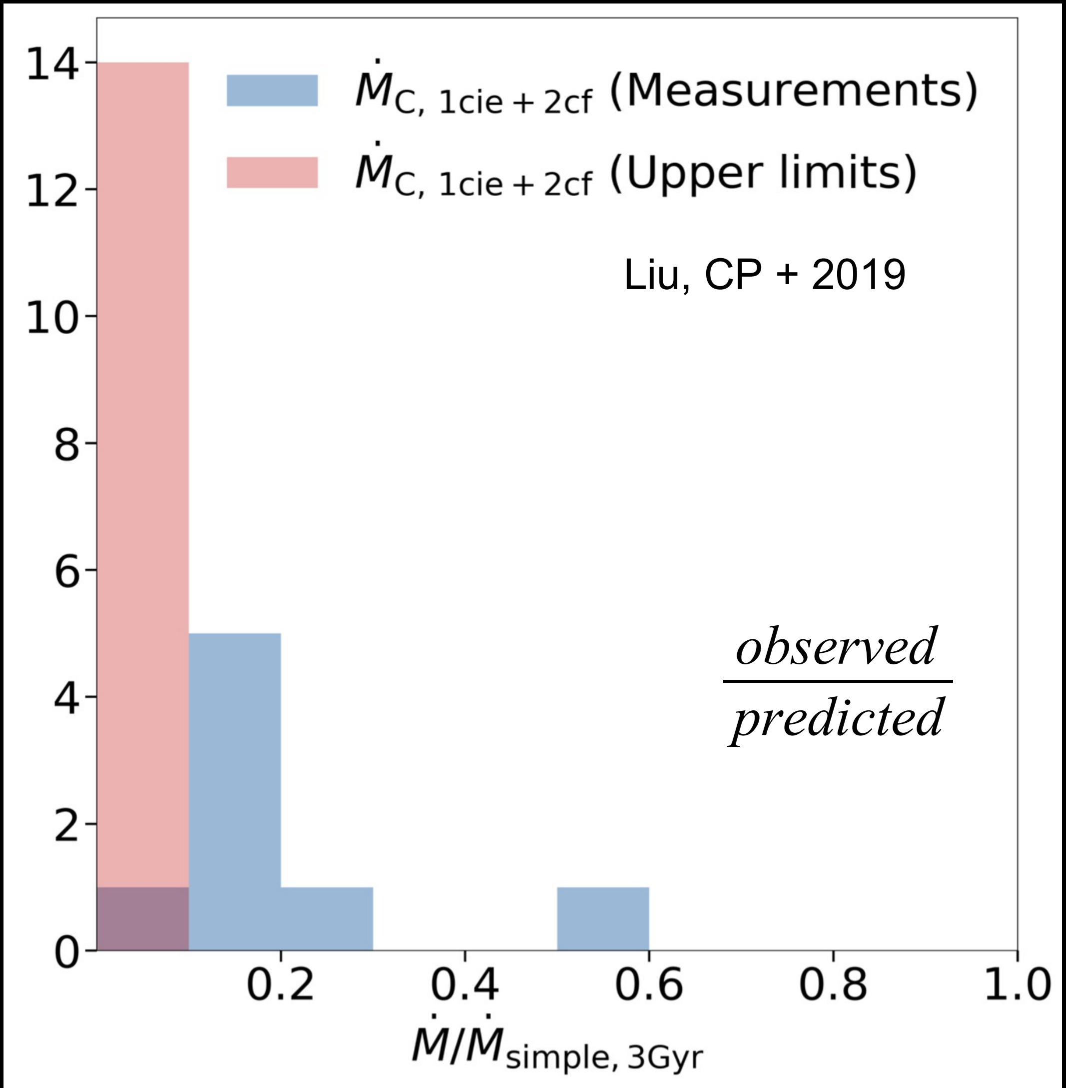
Weak Fe XVII lines

→ Much lower cooling rates!

→ Deficit of gas below 1-2 keV

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

# Cooling flows are much lower than theoretical predictions




Measured mass cooling rate:

$$\dot{M} = \frac{2}{5}\frac{\mu m_H L}{k T}$$

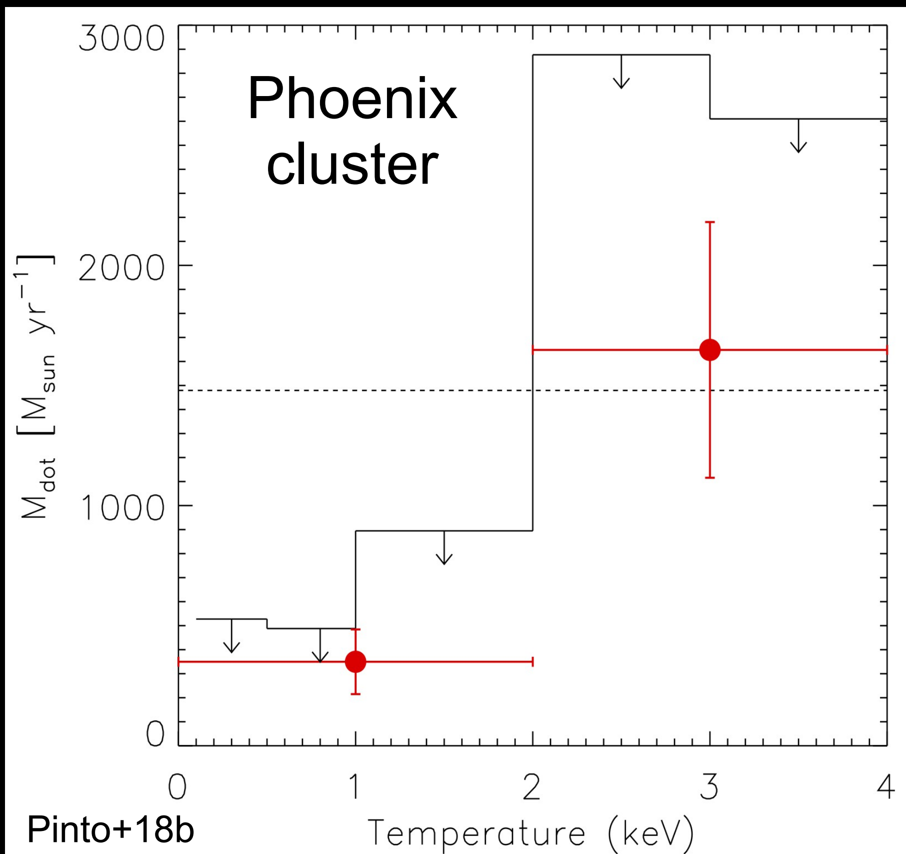
Theoretical mass cooling rate for the given amount of gas:

$$\dot{M}_{\mathrm{classical}}(<r) \simeq \frac{M_{\mathrm{gas}}(r)}{t_{\mathrm{cool}}(r) - t_{\mathrm{cool}}(0)} \cdot$$

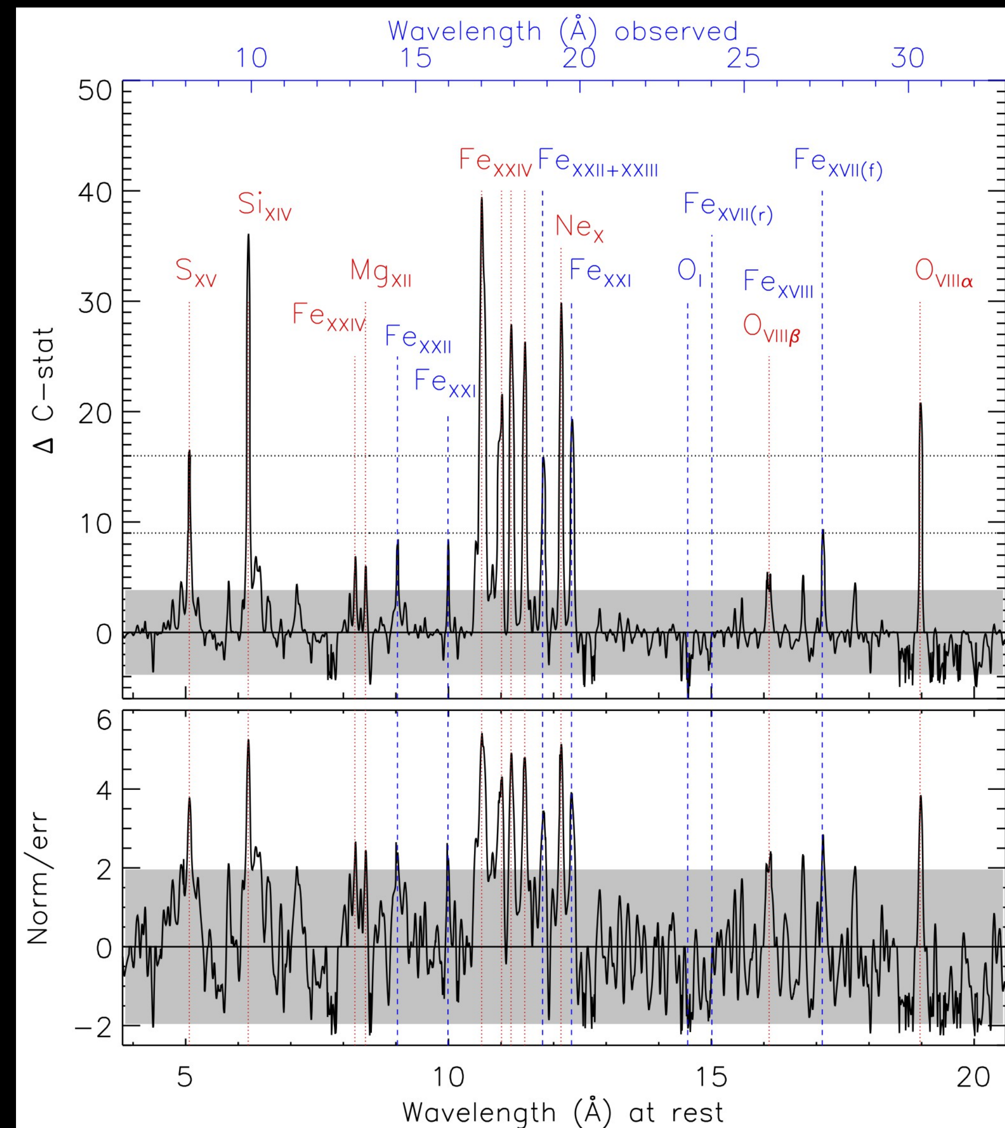
See also Hudson + 2010

# Any clusters with high cooling rates (detected)?

Cooling rates



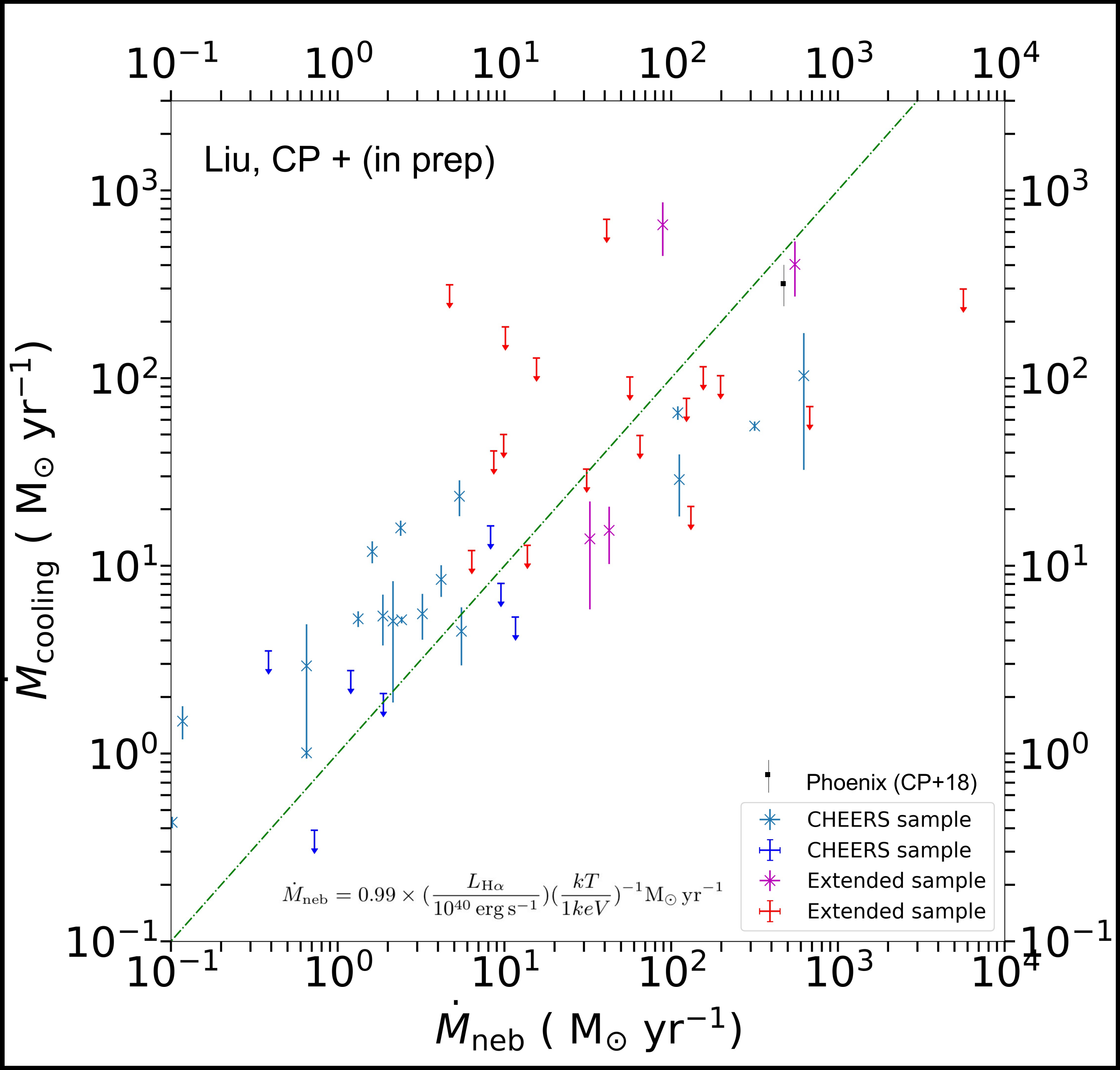

Cool gas line detection



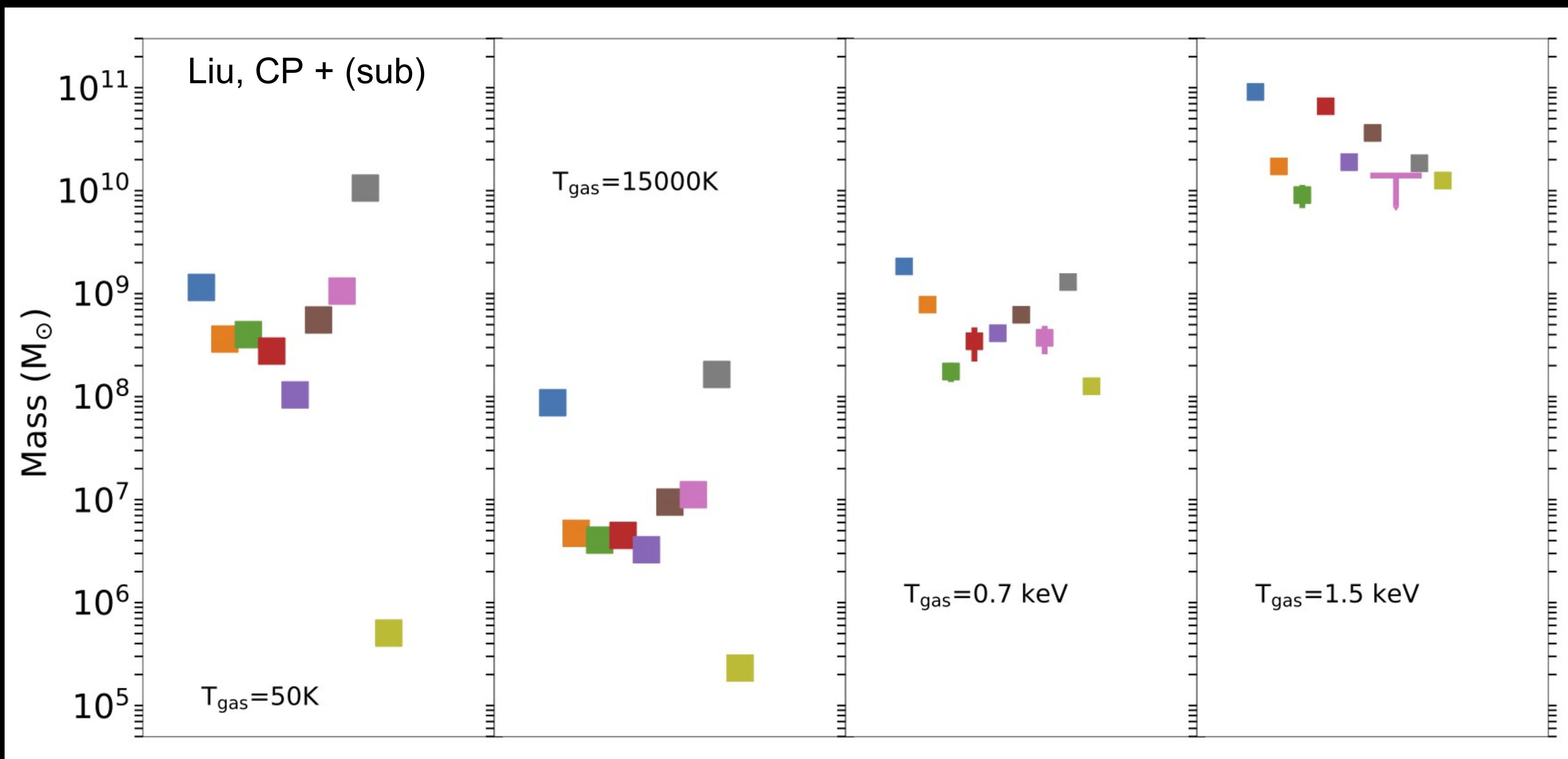

RGS cooling rate agrees with SFR rate

& CCD upper limits (<1000$M_\odot$ $yr^{-1}$, Tozzi+2015)

# But the X-ray gas may be able to produce Hα gas ...



# But the X-ray gas may be able to produce Hα gas and the molecular gas?




CO Hα Fe XVII Fe XXIII+

See also Salomé + 2011, Hamer + 2016, Russell + 2019

10 kpc region (RGS)

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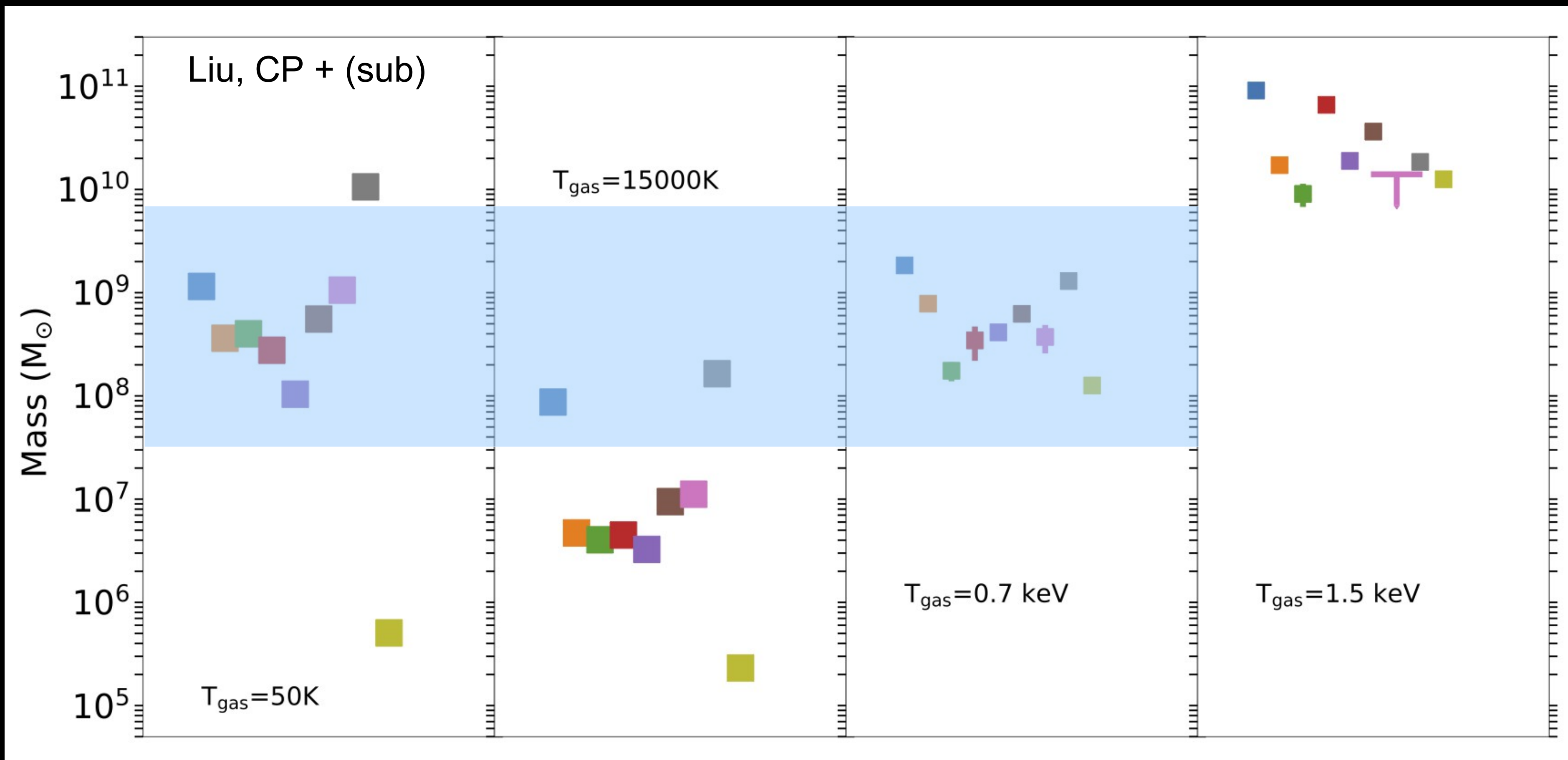


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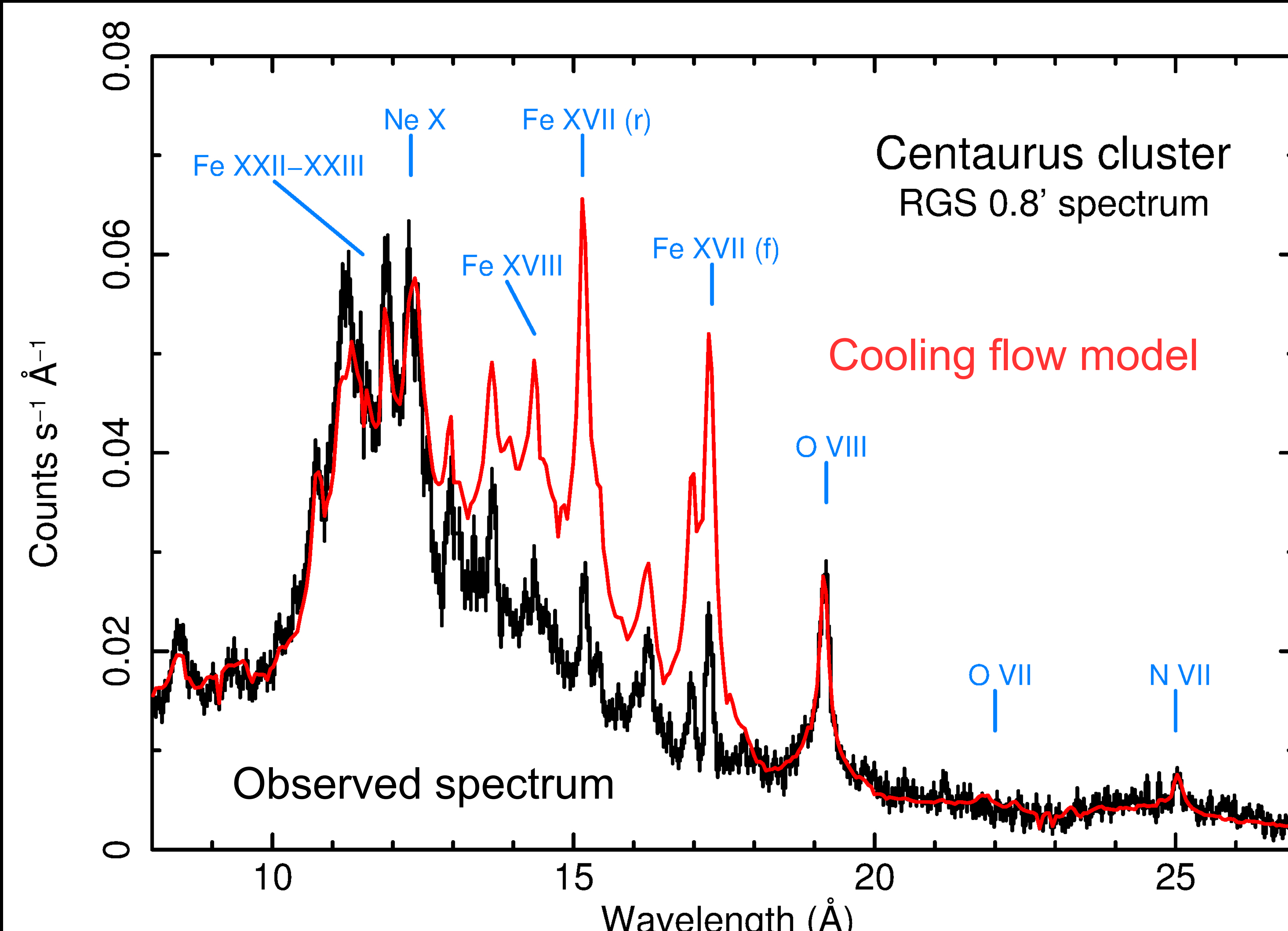
10 kpc region (RGS)

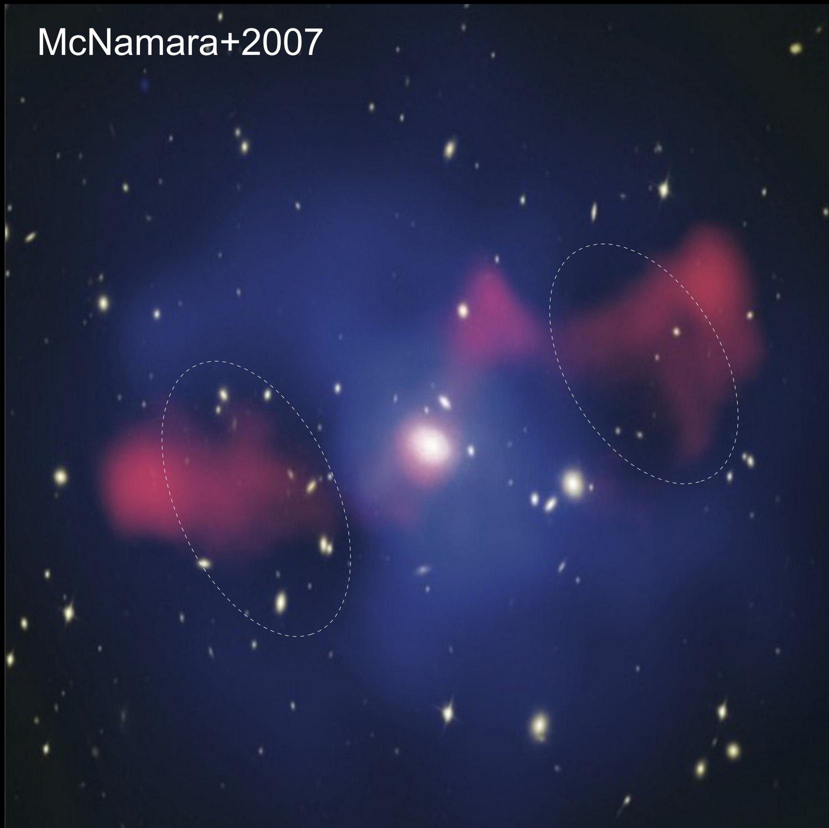

Centaurus cluster
RGS 0.8' spectrum
Cooling flow model
Observed spectrum
Fe XXII–XXIII
Ne X
Fe XVIII
Fe XVII (r)
Fe XVII (f)
O VIII
O VII
N VII
Counts s$^{-1}$ Å$^{-1}$
Wavelength (Å)
0
0.02
0.04
0.06
0.08
10
15
20
25

# What's heating the intracluster medium?

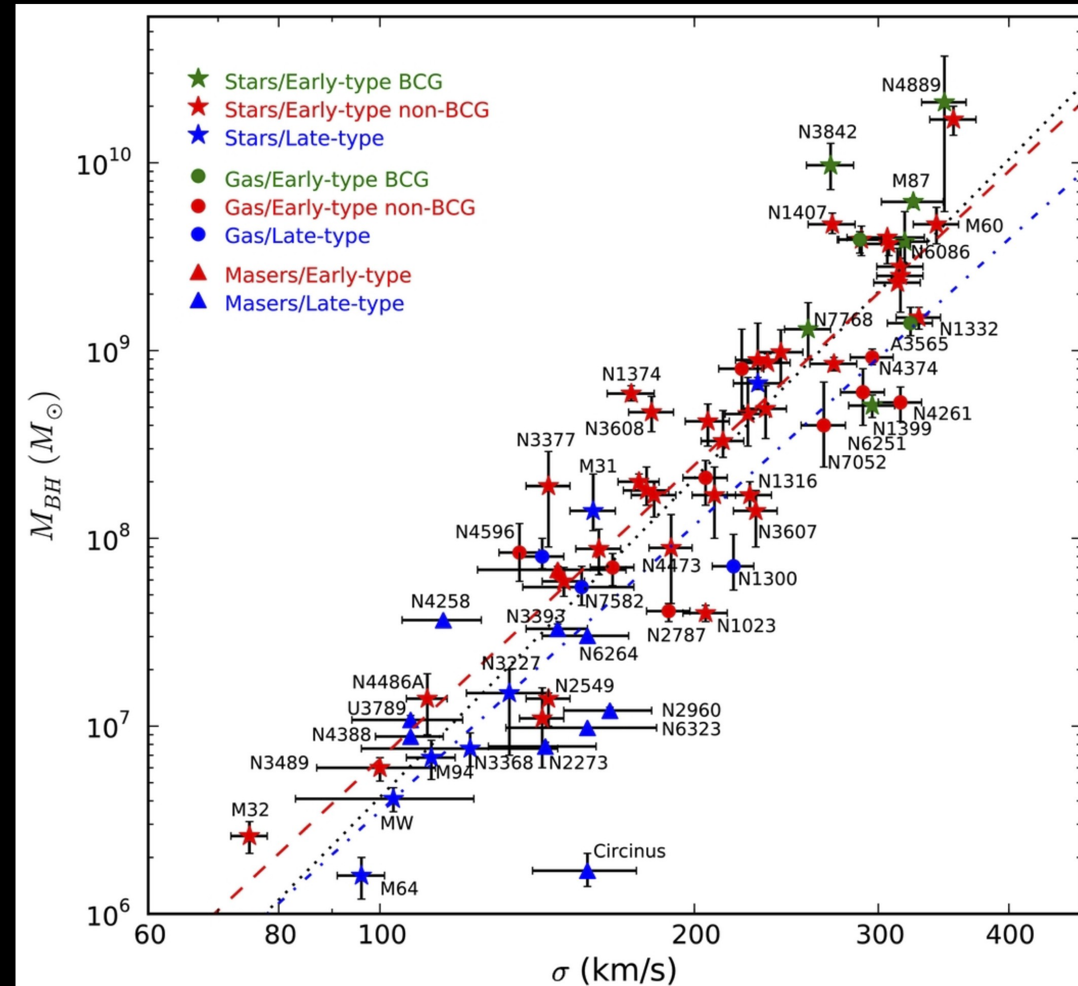
Over 5 orders of magnitude in X-ray Luminosity

Over 1+ order of magnitude in temperature,

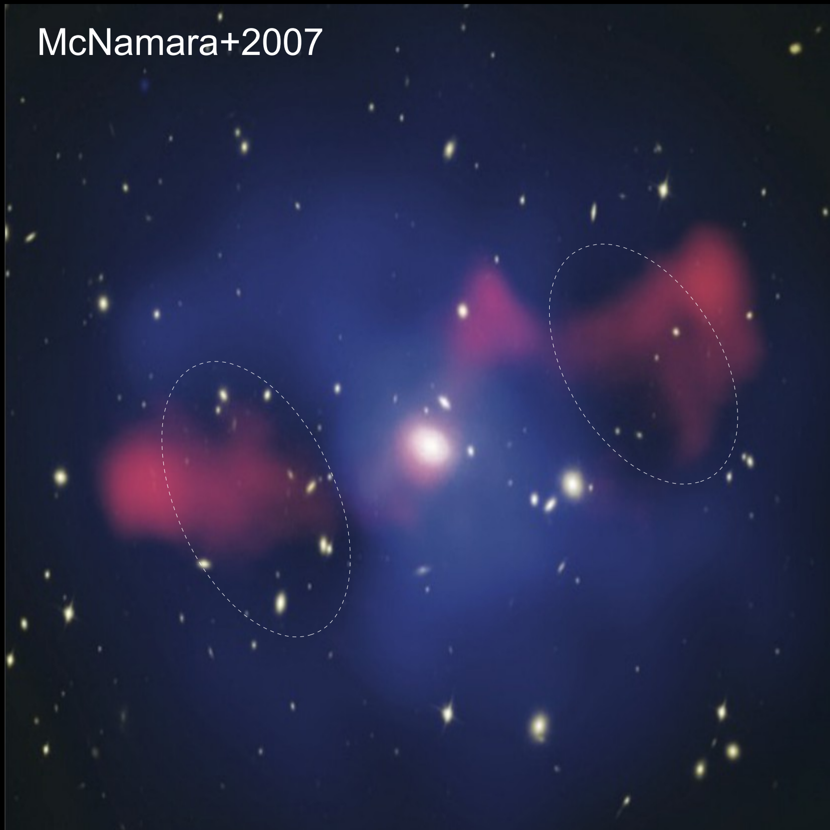
radically different masses & sizes!




Jets from the central supermassive black hole?




McConnell & Ma 2013

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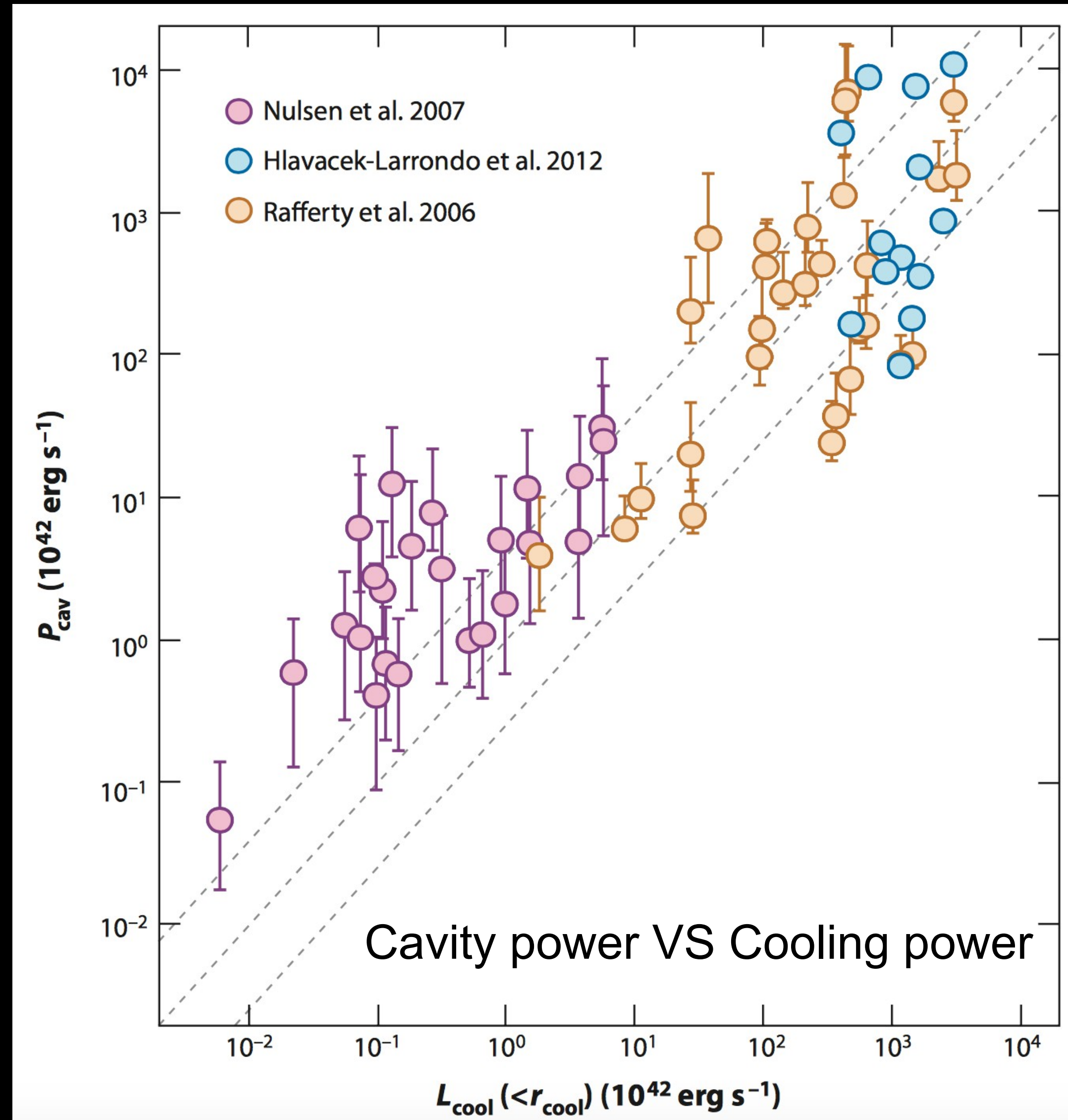
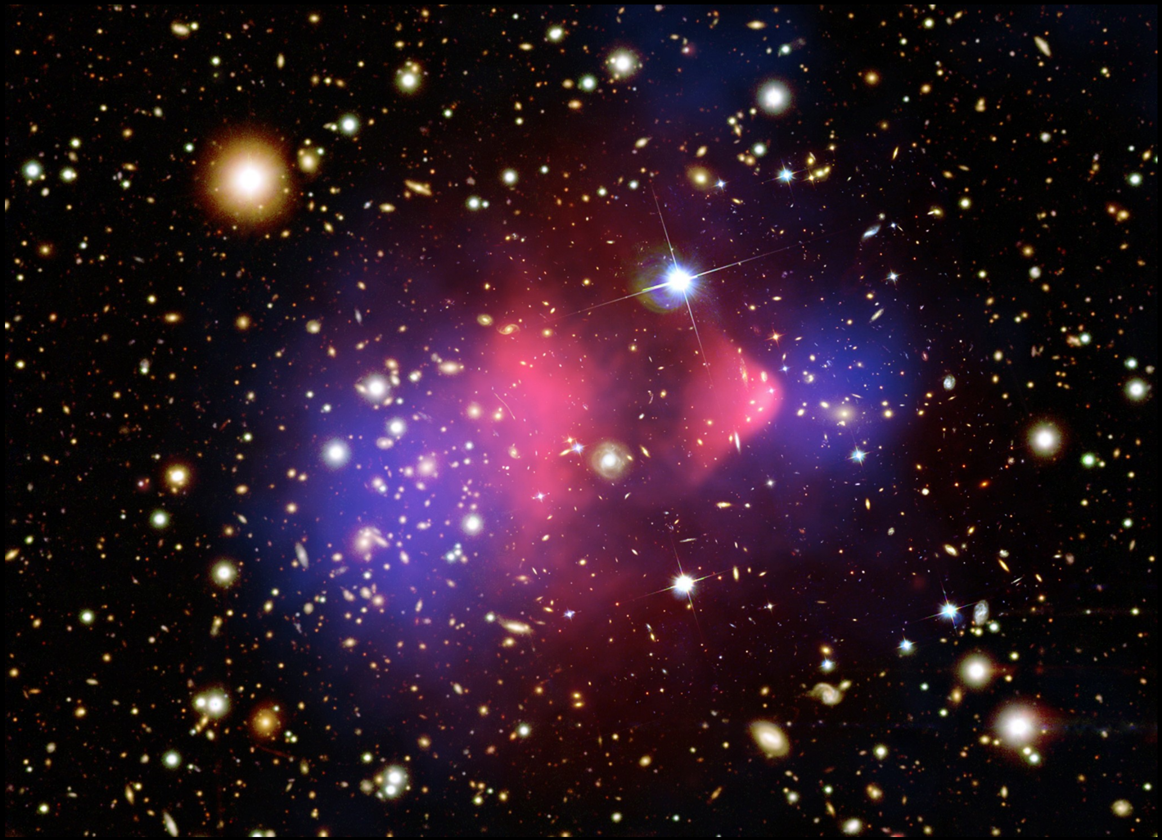


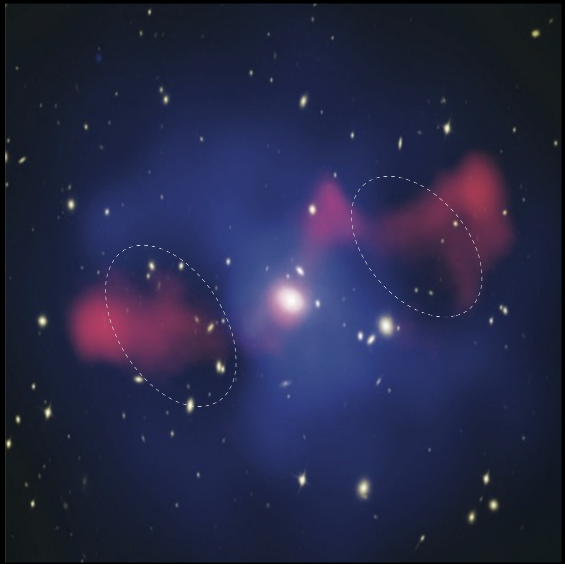

Energy needed to create a cavity = internal (thermal) energy + work to inflate

Jets from the central supermassive black hole?



Shocks from mergers among cluster member galaxies?

X-ray: NASA/CXC/CfA/M.Markevitch,
Optical & lensing map: NASA/STScI,
Magellan/U.Arizona/D.Clowe,
Lensing map: ESO WFI



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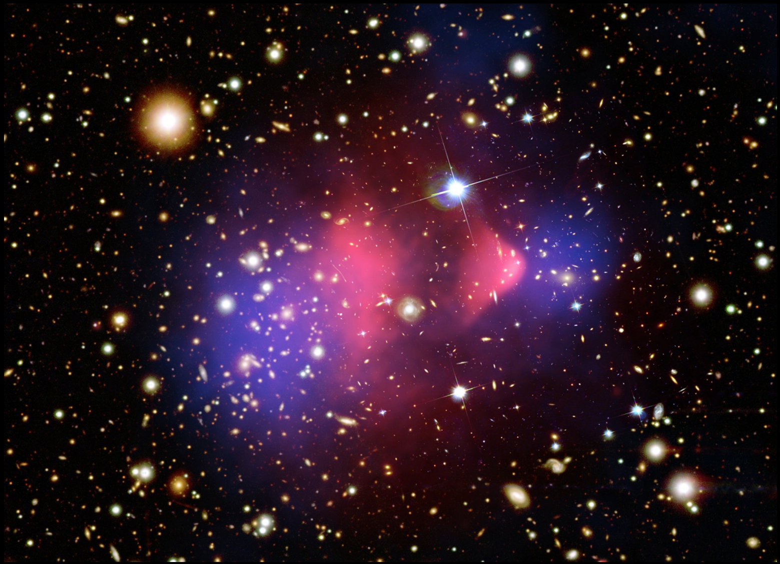

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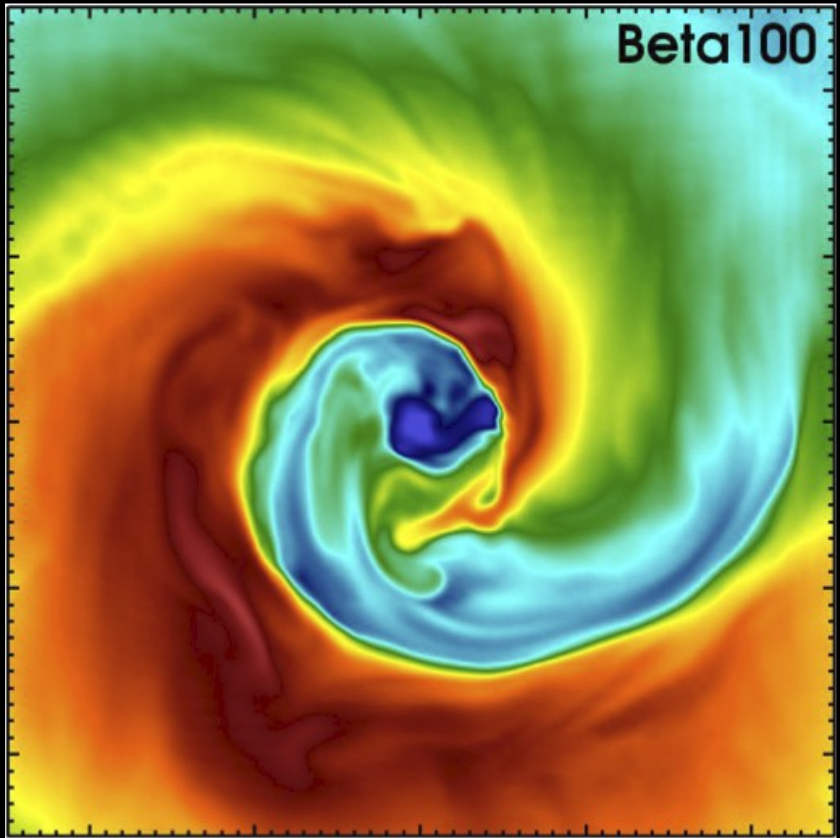


e.g. Ghizzardi + 2010, Rossetti + 2013 and Gastaldello + 2013

Sloshing of the ICM within the gravitational field perturbed by crossing galaxies?

Simulations by John ZuHone

# OK, but how is the heating released to the ICM?

- Condution? It requires a lot of fine tuning
- Shocks? In many objects no shock fronts are present
- Magnetic fields? In the center magnetic pressure > 10% ?
- Cosmic rays? Should create a pile up around 0.3 $T_{amb}$ , not observed
- Sound waves? AGN jets create sound waves but can they dissipate?
- Turbulence dissipation? But does it travel fast enough?

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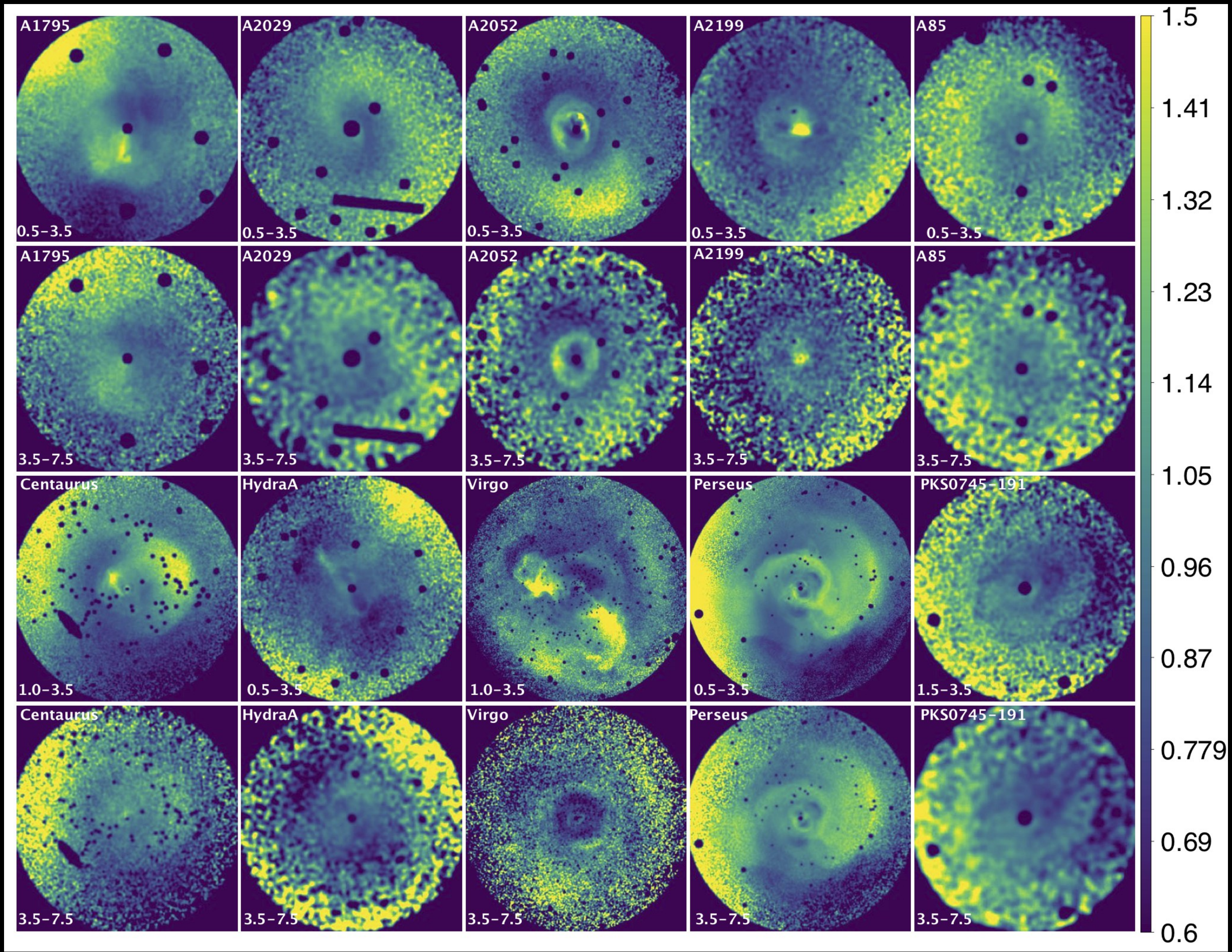
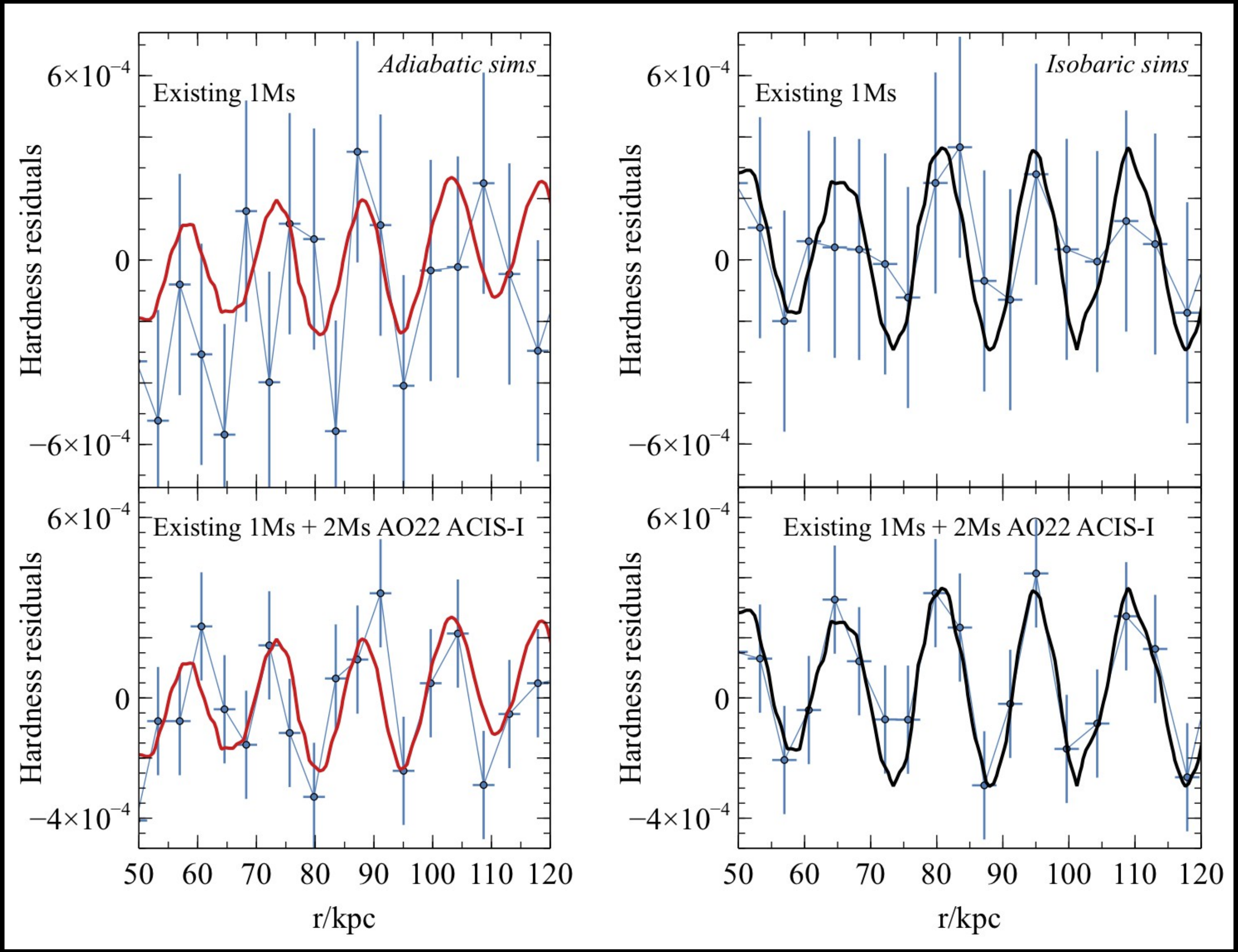
# How is the energy propagated & released?

→ ICM X-ray emission fluctuations



# Distinguishing sound wawes & turbulence

Sound waves Turbulence



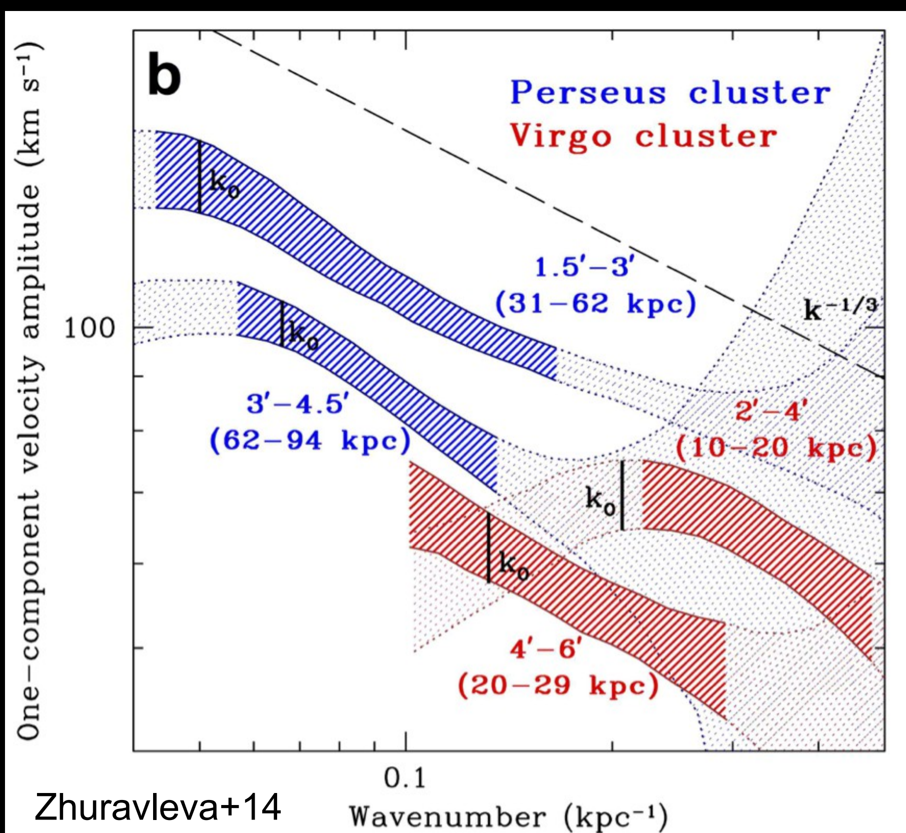

Hardness = 4–8 keV / 0.5–4 keV

Fabian + (2017)

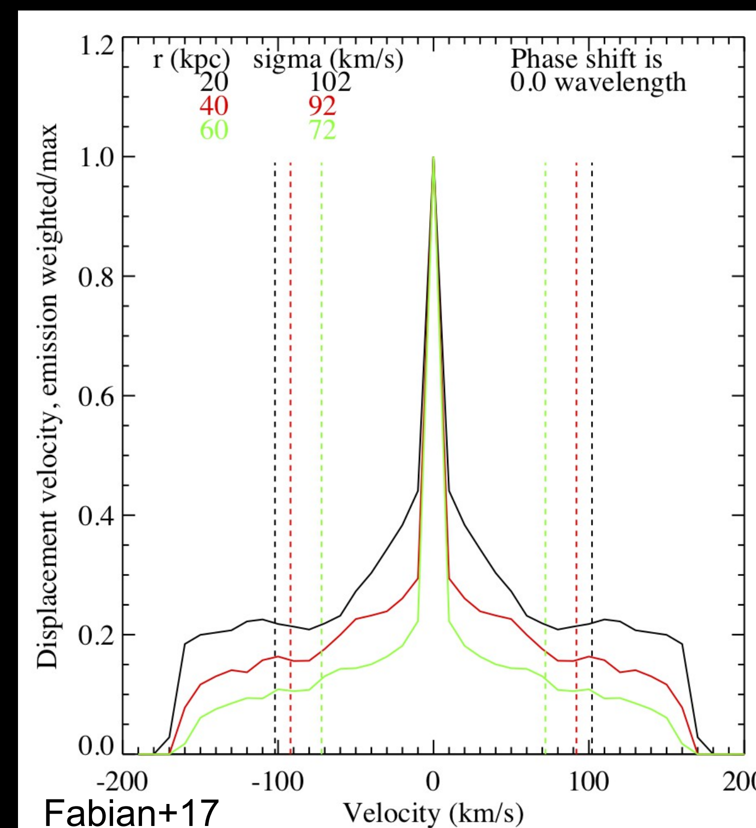
# How is the energy propagated & released?

→ ICM X-ray emission fluctuations

Dissipation of Turbulence?

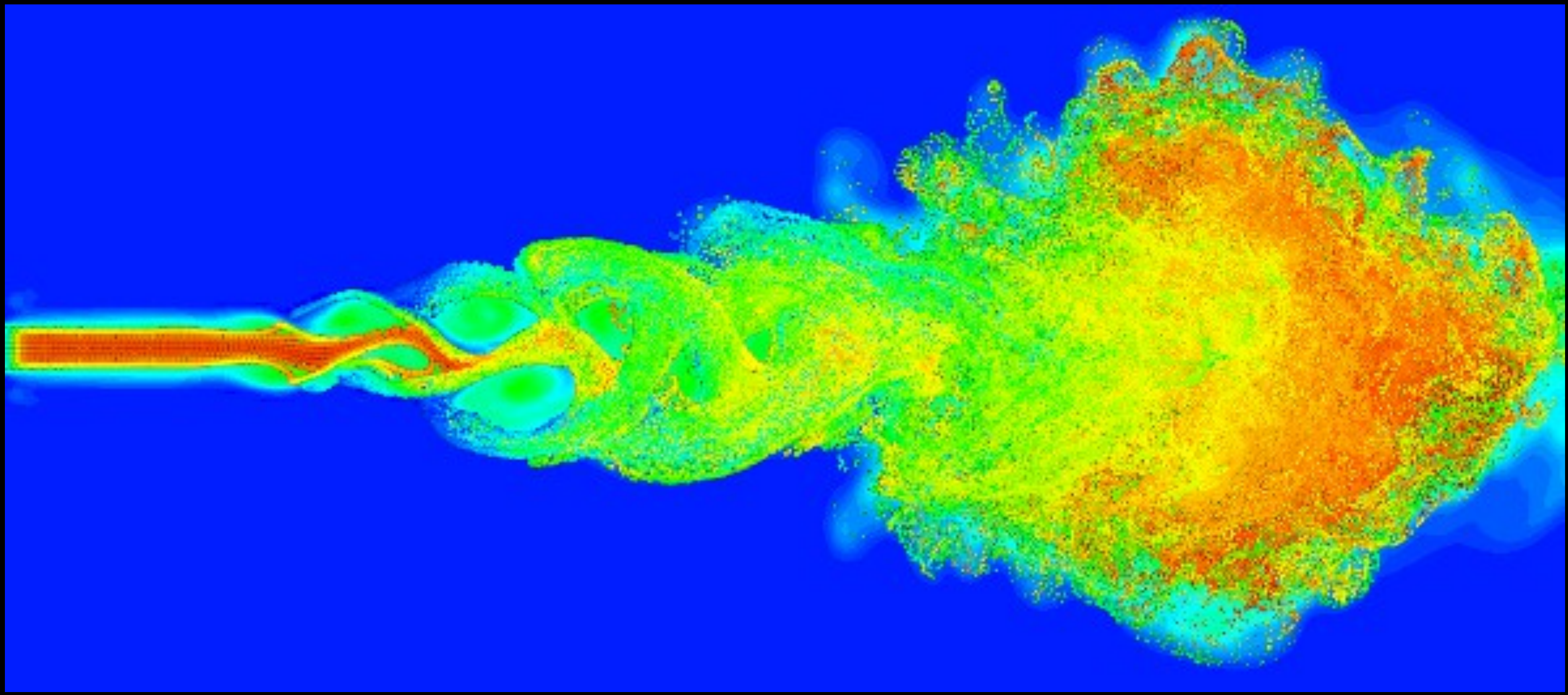


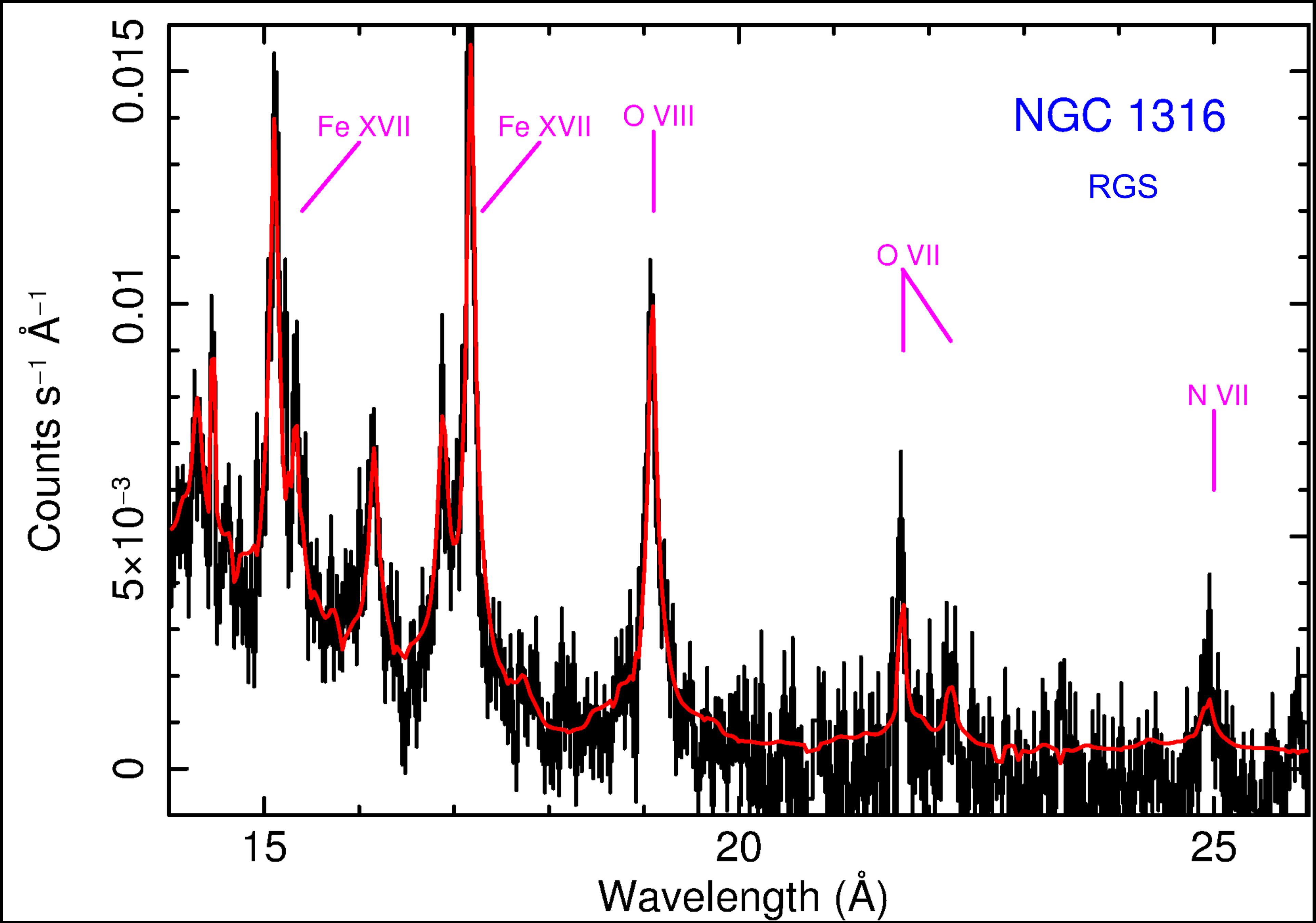

Dissipation of Sound waves?




Both predict velocity dispersion ~ 150-250 km/s

# How do we measure the ICM velocity dispersion?



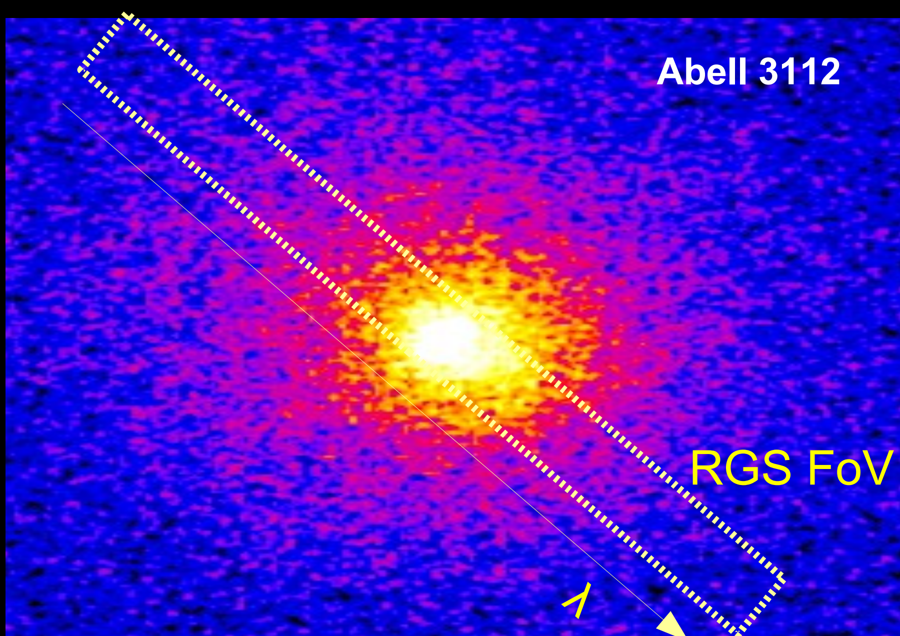


NGC 1316
RGS
Fe XVII
Fe XVII
O VIII
O VII
N VII
Counts s$^{-1}$ Å$^{-1}$
0
5×10$^{-3}$
0.01
0.015
15
20
25
Wavelength (Å)

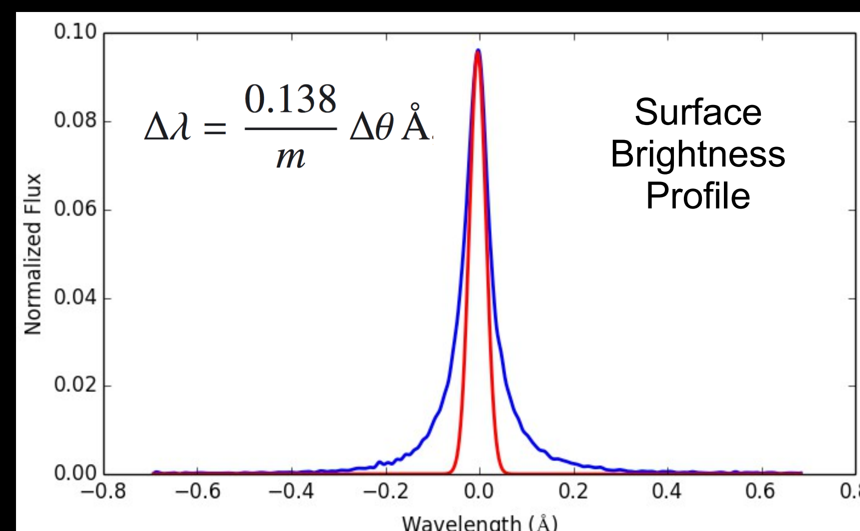

Pinto + 2014

# Accounting for instrumental broadening

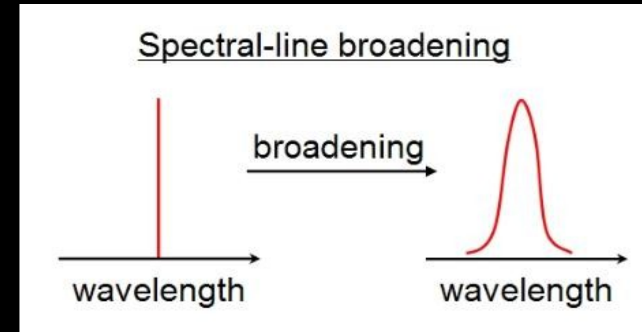
Surface Brightness profile → line-spatial-broadening

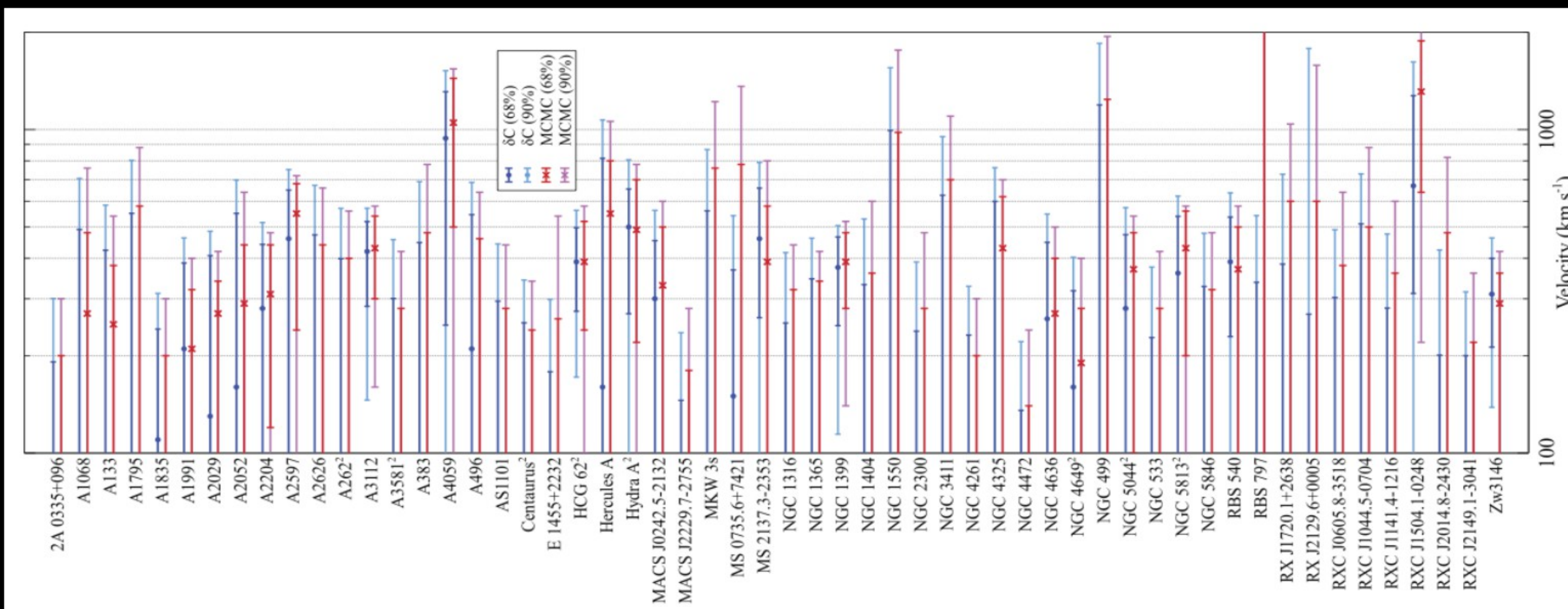



Chandra or XMM CCD image



# Line widths




Sanders & Fabian 2013

Pinto et al. 2015

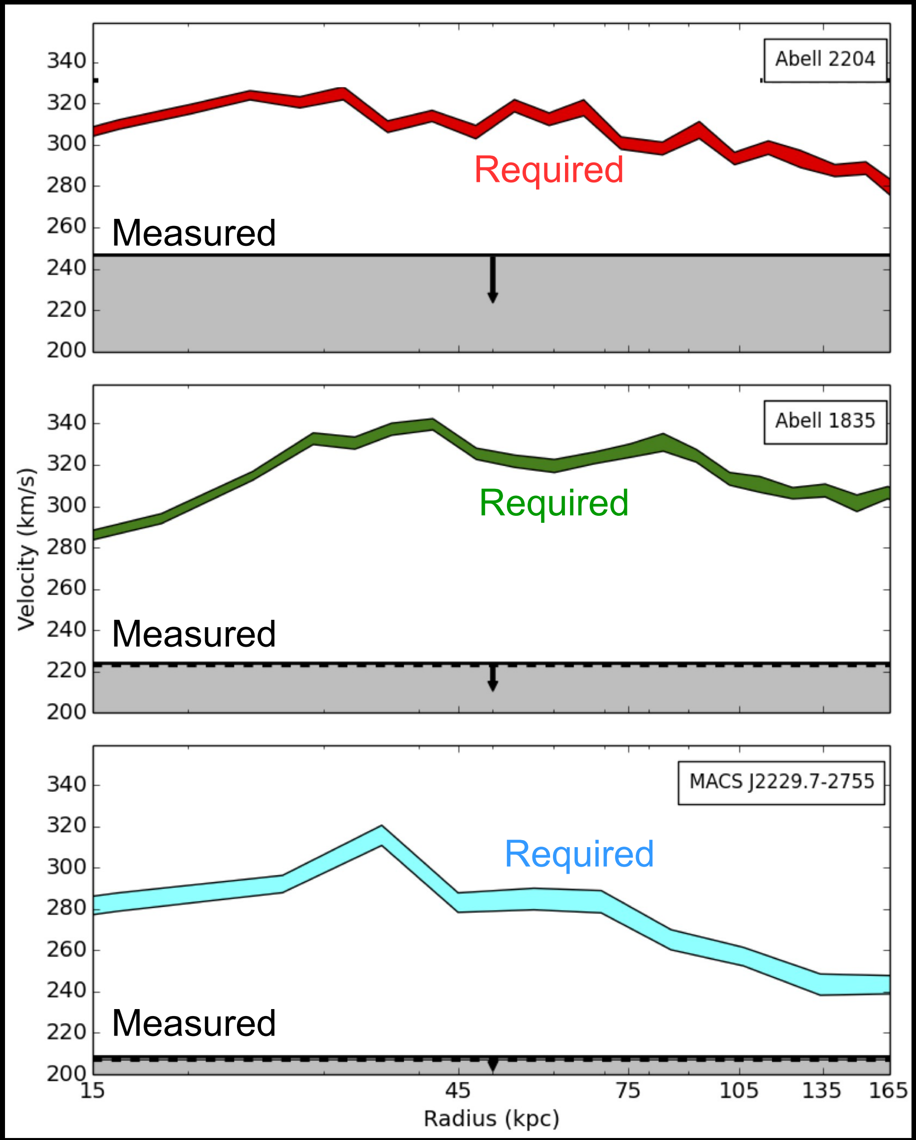
Total width (no subtraction of instrumental broadening)

# Heating Transfer Problem

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

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

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



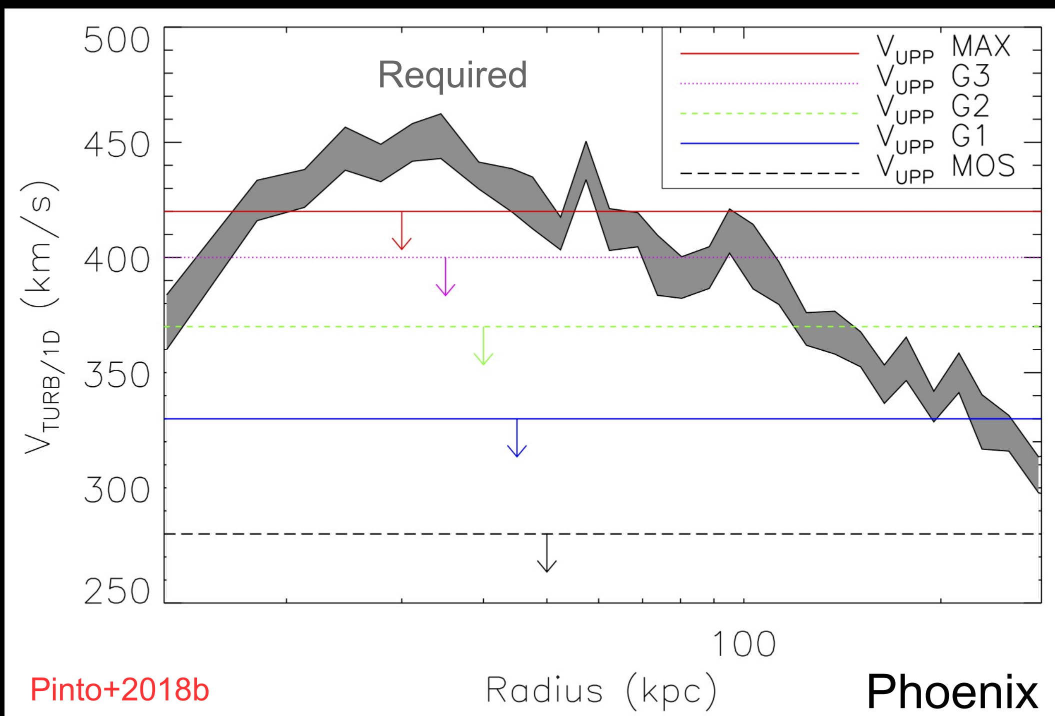

Is turbulence high enough to replenish heat throughout the cool core?

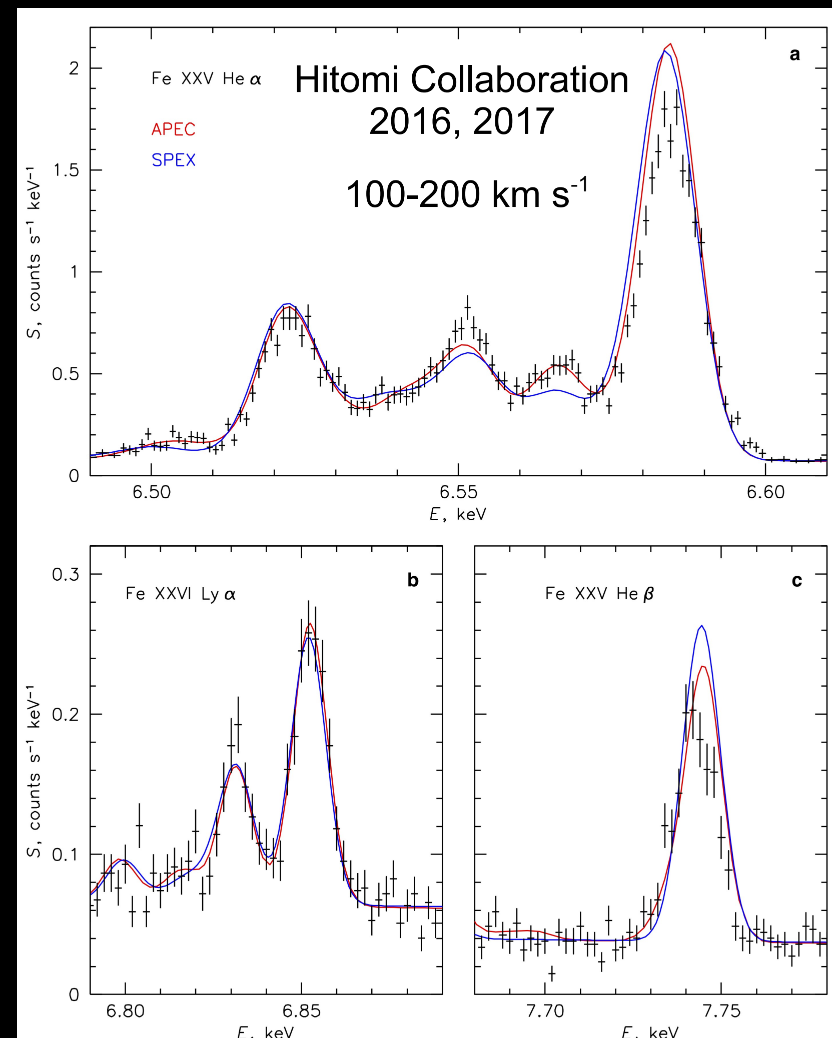
CP + 2015, Bambic, CP + 2018

Intrisic width (subtraction of instrumental broadening)

# Heating Transfer Problem

## The lines are too narrow!

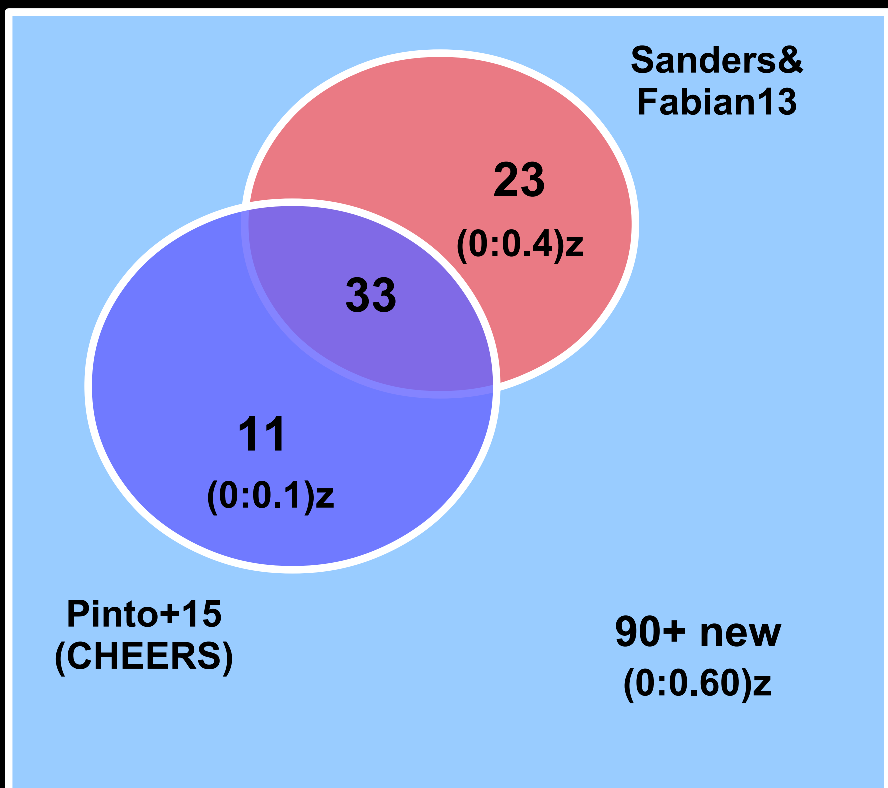


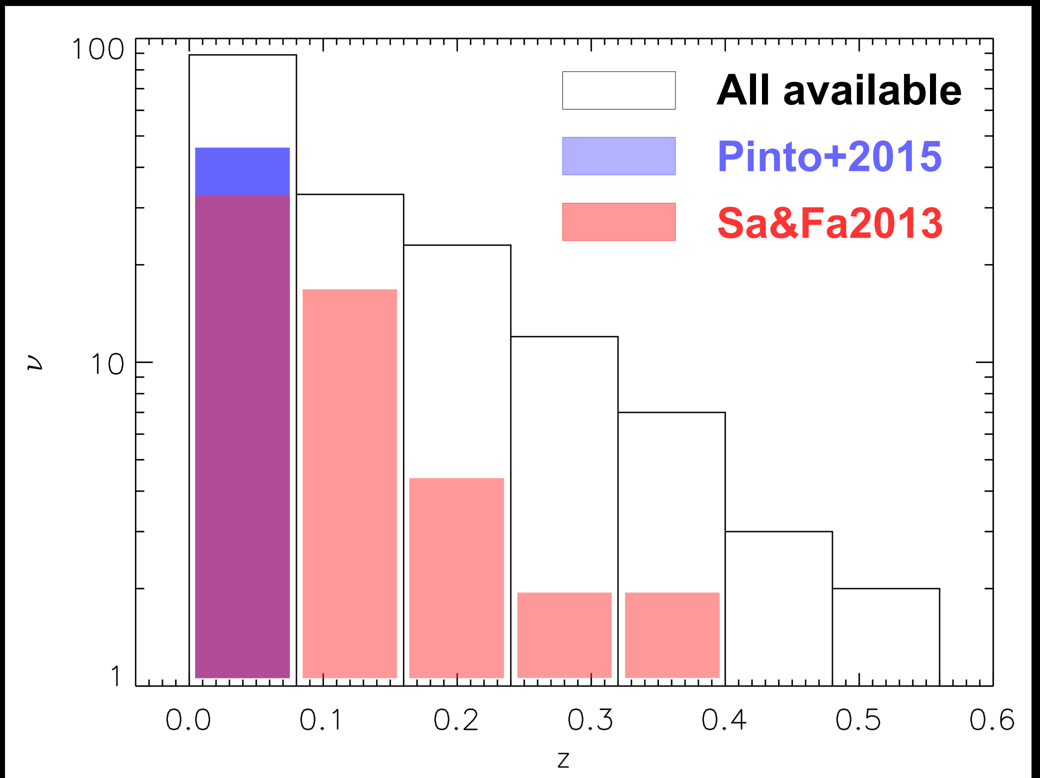




Is turbulence high enough to replenish heat throughout the cool core? NO

Intrisic width (subtraction of instrumental broadening)

# XMM-Newton/RGS Legacy Catalog



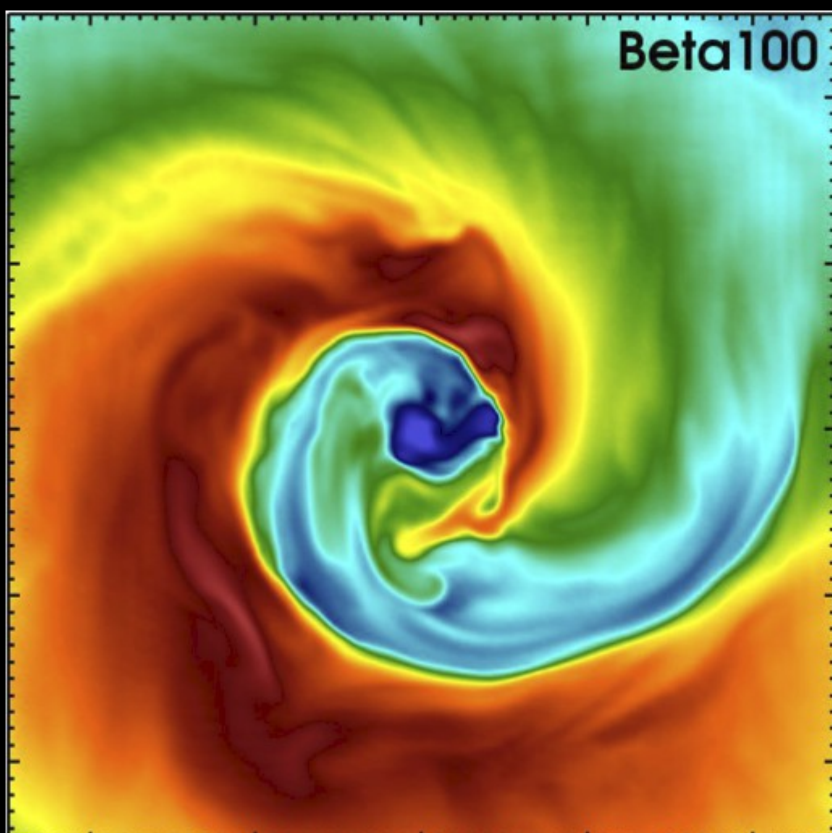




More to come by comparing local (z < 0.1) and distant (z ~ 0.1-0.6) clusters

# Other sources of heating : galactic interactions

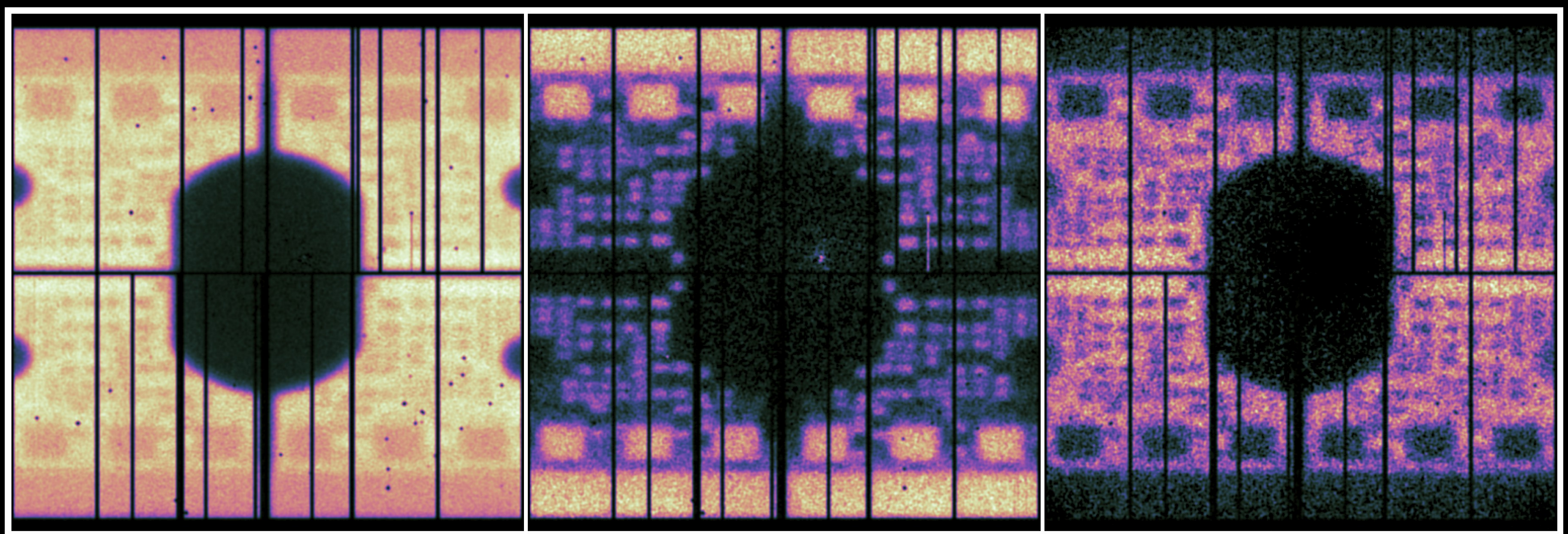
Gratings do not have a slit

CCDs cannot resolve bulk motions < 500 km $s^{-1}$



# Not all evils come to harm you!

From the Italian: "*Non tutti i mali vengono per nuocere*"



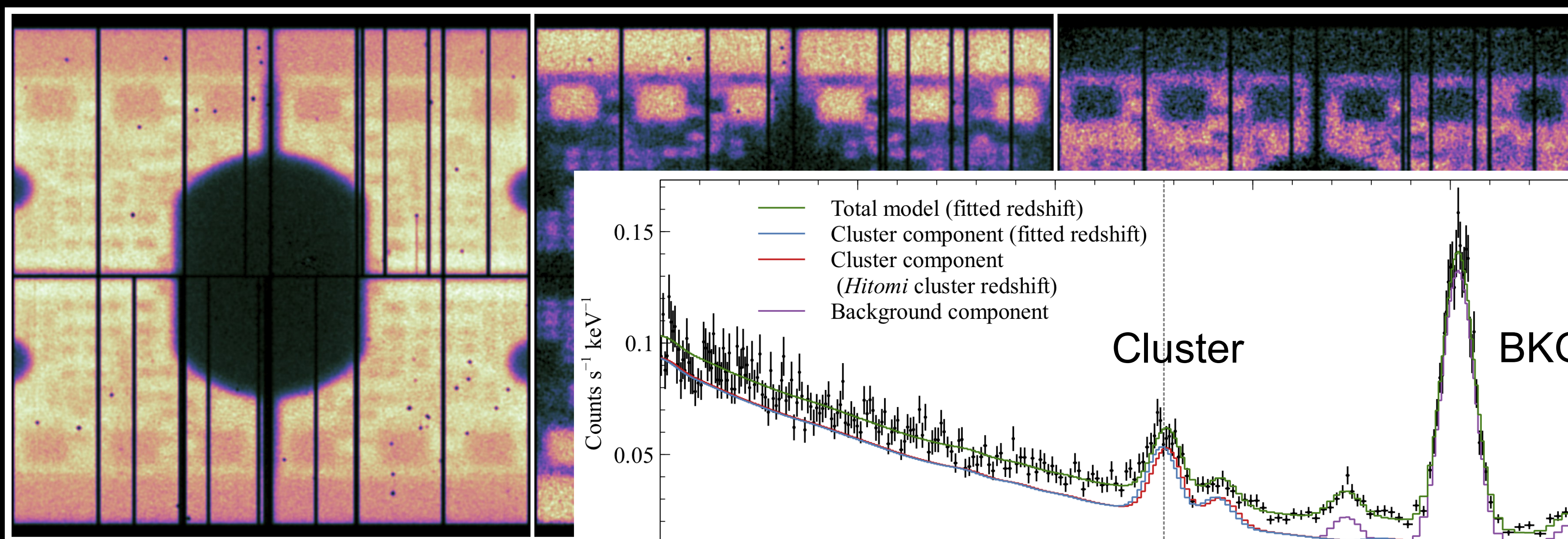
Cu-Kα (7.805 to 8.285 keV) Ni-Kα (7.280 to 7.680 keV) Cu-Kβ & Zn-Kα (8.455 to 9.075 keV)

Sanders+2020

32.6 Ms of Full Frame and 19.7 Ms of Extended FF calibration data in EPIC-pn (CCD)

# Not all evils come to harm you!

Improved accuracy of the energy scale: 550 km $s^{-1}$ → 150 km $s^{-1}$



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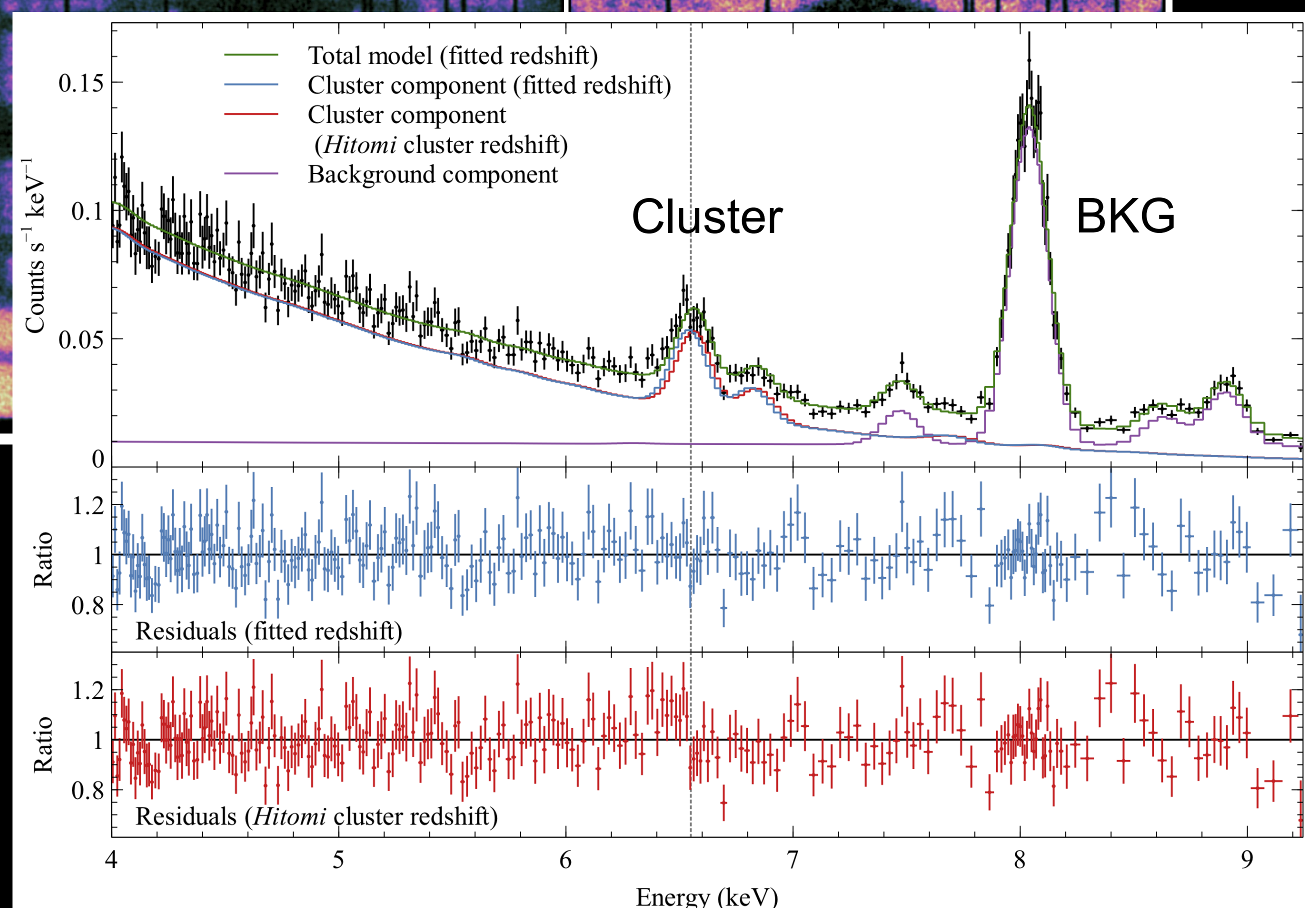

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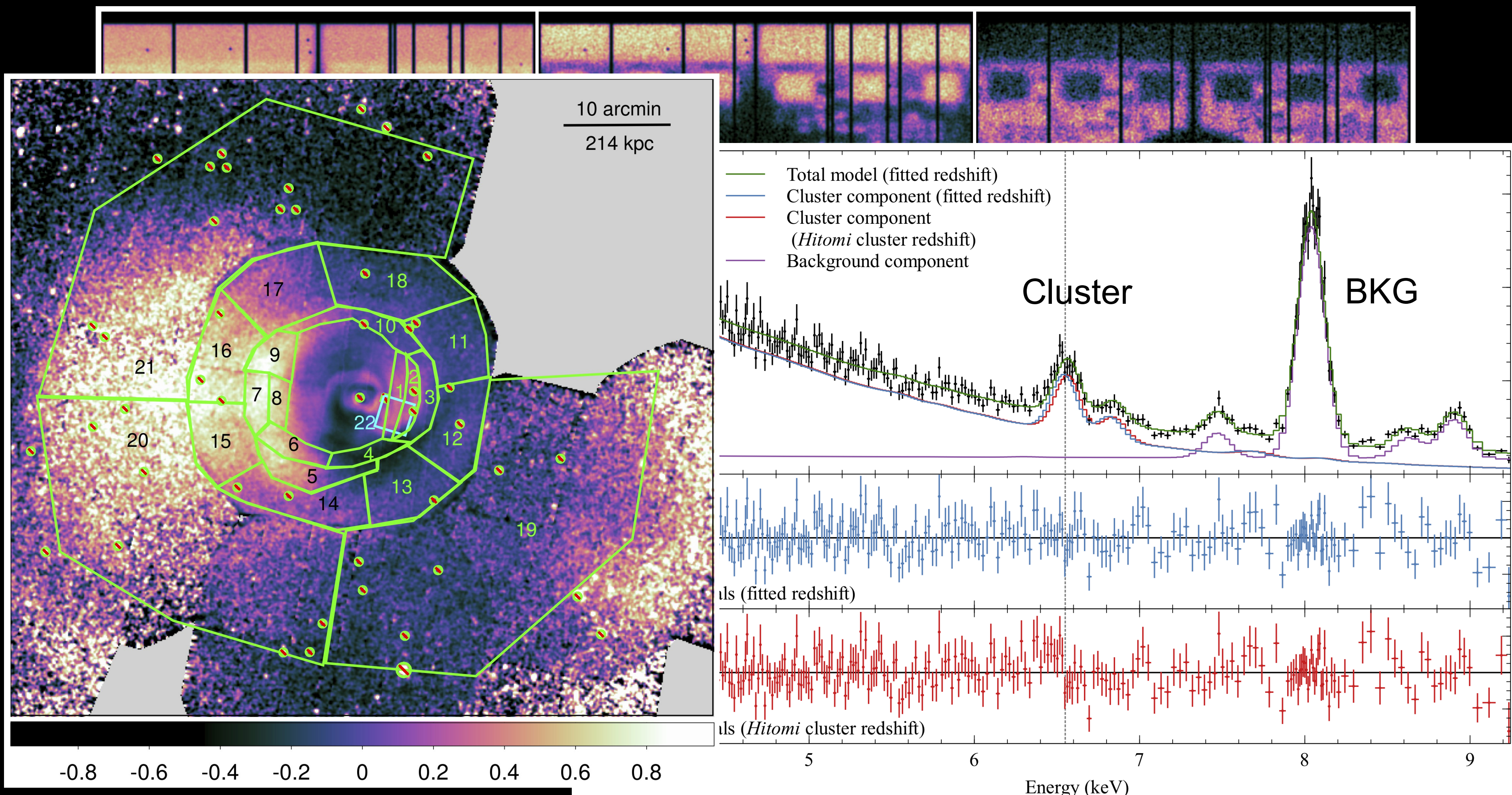
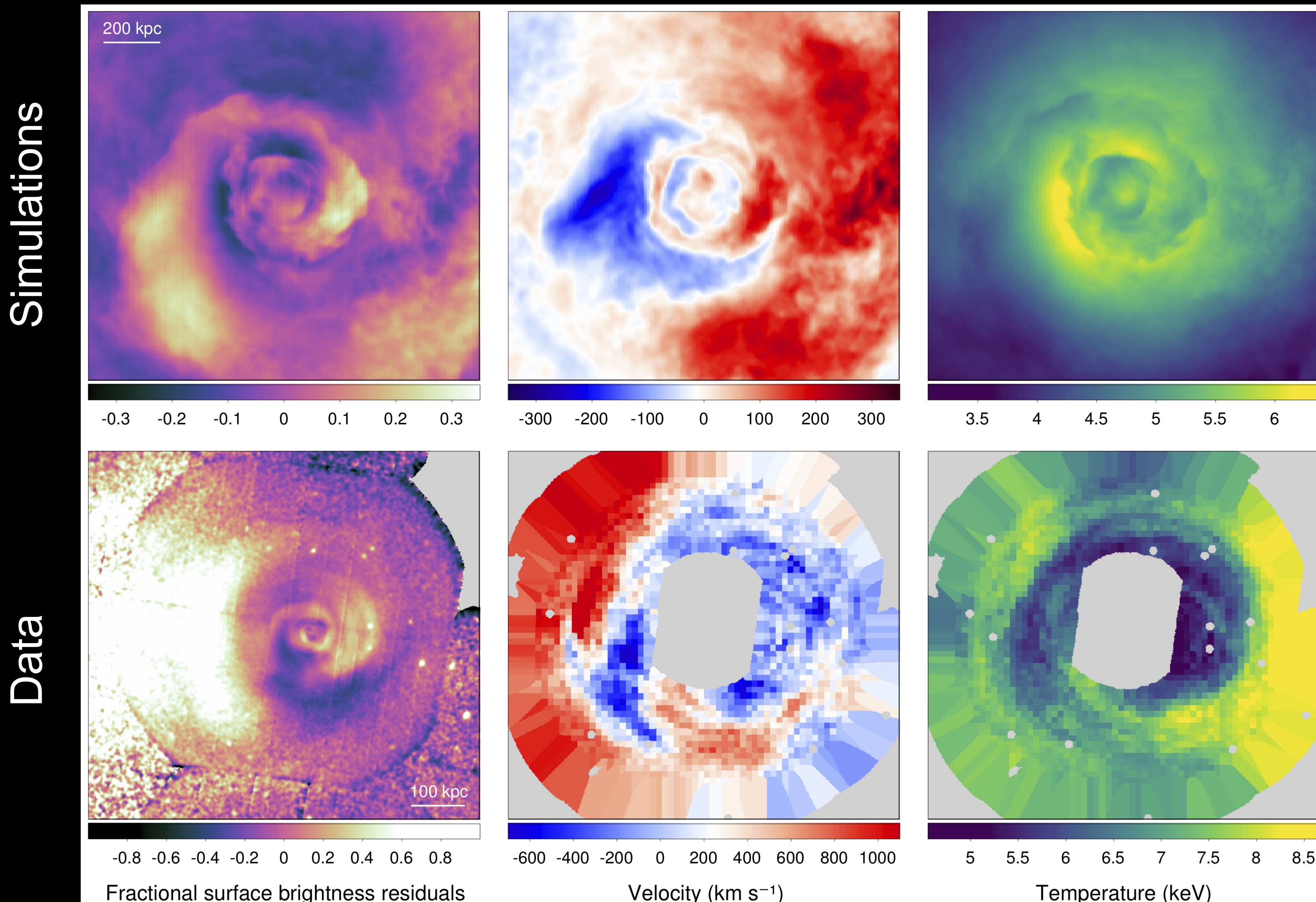
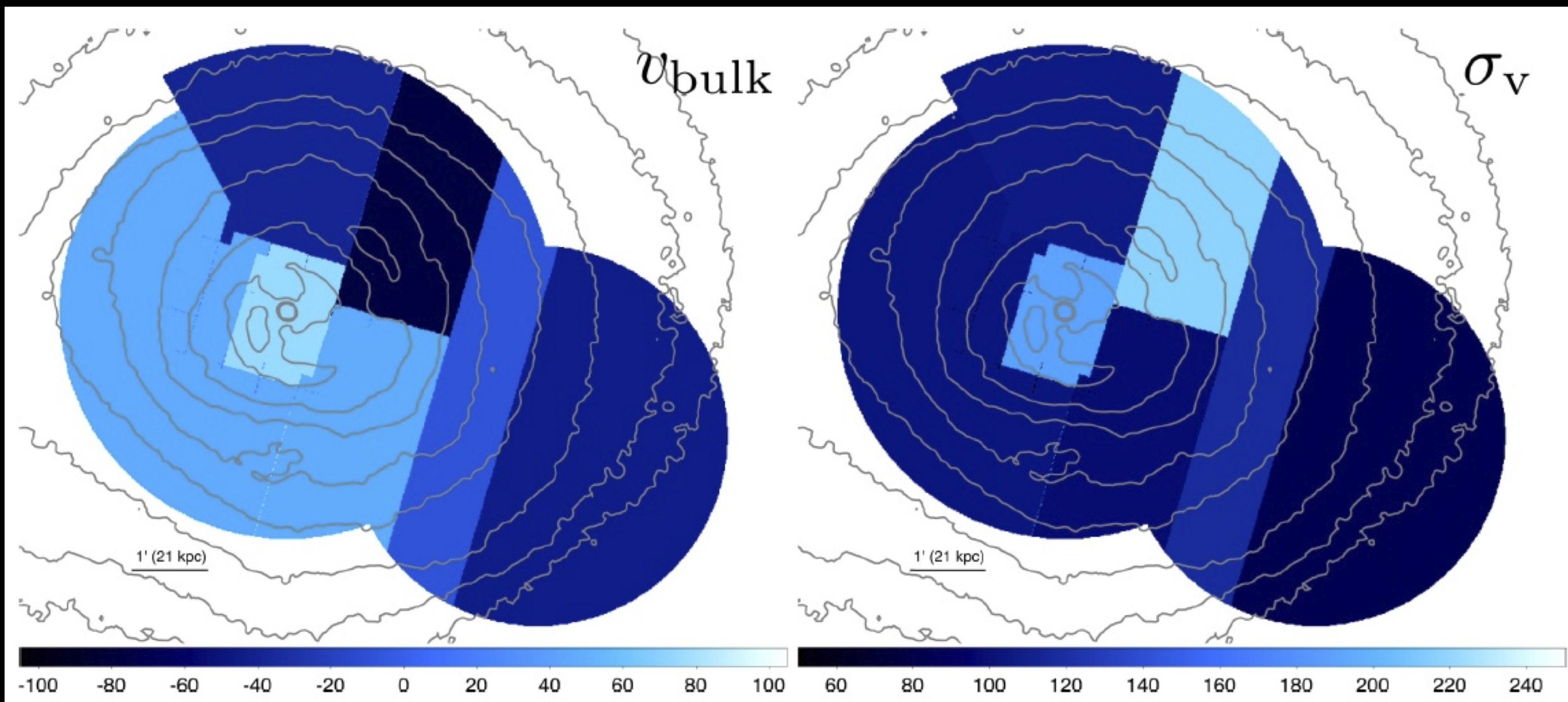


# And yet it moves! Actually, sloshes!



# And yet it moves! Actually, sloshes!

Hitomi observation of the Perseus cluster – 240 ks (and GV closed)

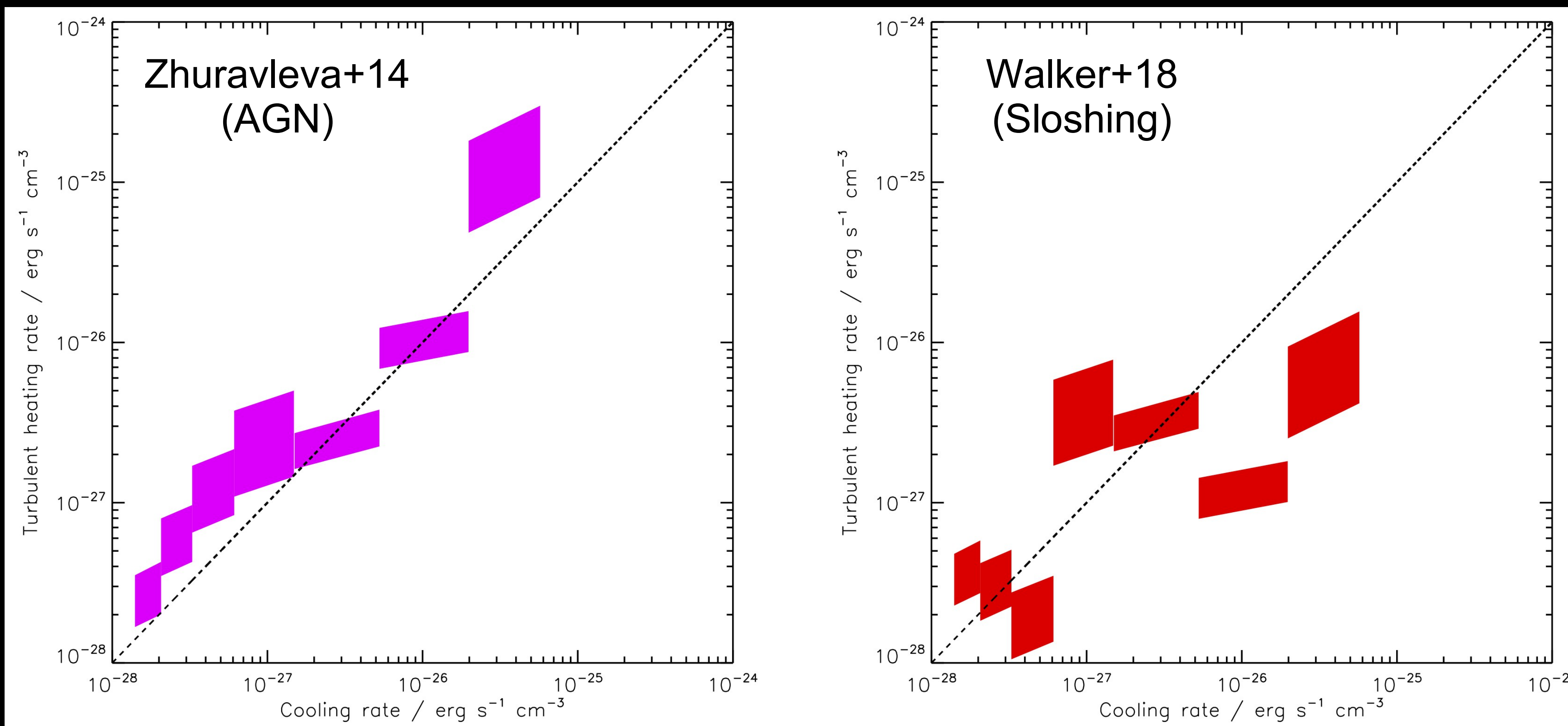



Important note for Cosmology: low turbulent pressure (~4%)

→ Corrections to hydrostatic equilibrium small

→ X-ray cluster mass function is a reliable cosmological probe (see also Bartalucci+2018)

# Sloshing may be relevant beyond 60 kpc




R > 60 kpc

thermal-to-magnetic pressure ratio of β = 200

# To cut the long story short

*The Intra-Cluster Medium is not cooling as it should*

- Viable solutions: AGN (sloshing) heats it < (>) 60 kpc
- Current issues: spatial resolution, indirect methods
- We need to minimise instrumental broadening
- We need resolve velocity & cooling structures
- Up to (at least) $z \sim 2$, now with RGS $z_{max} \sim 0.6$

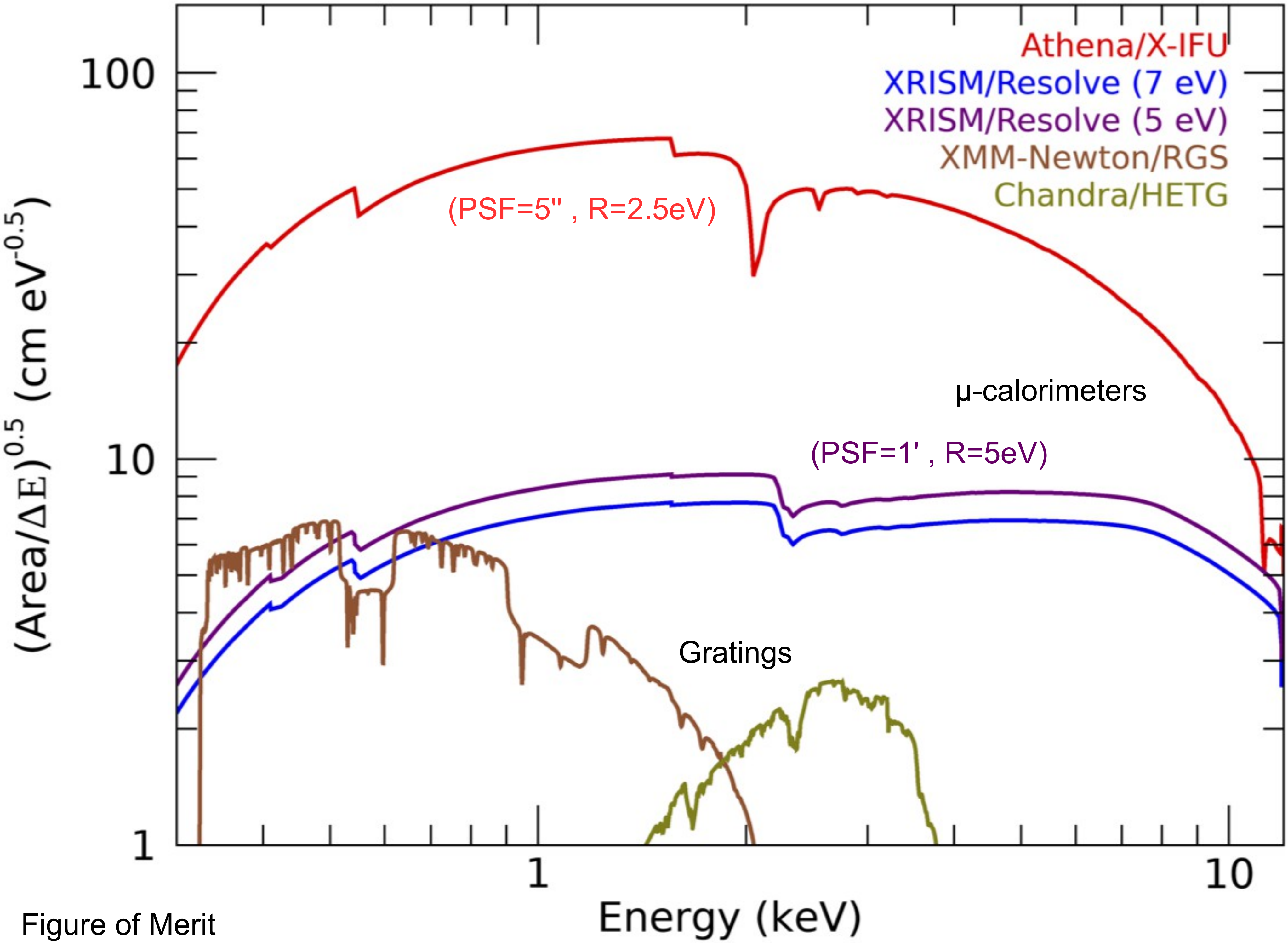
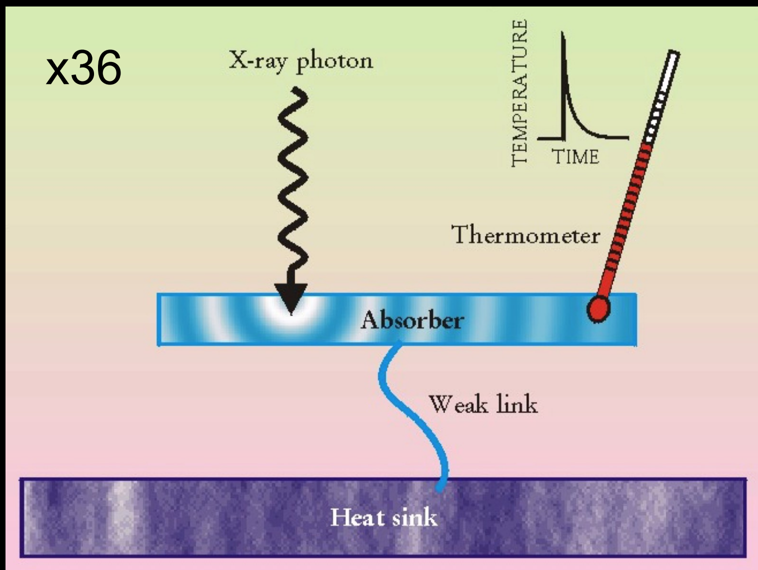



Figure of Merit

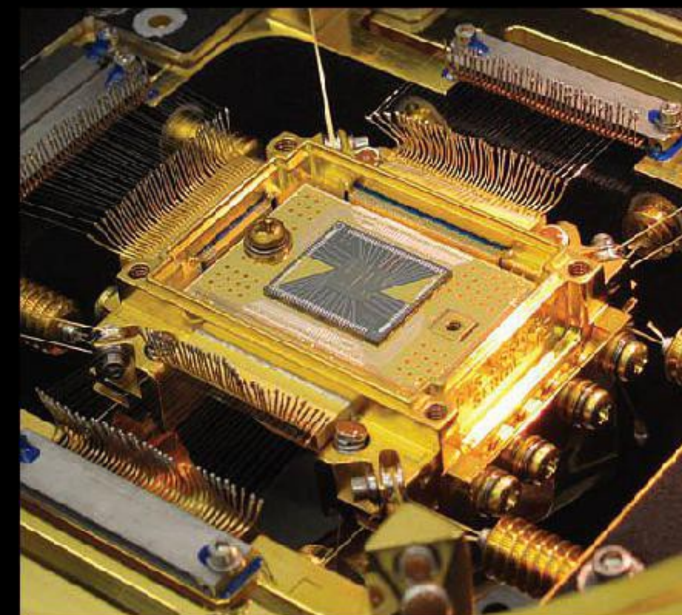
# X-ray μ-calorimeters

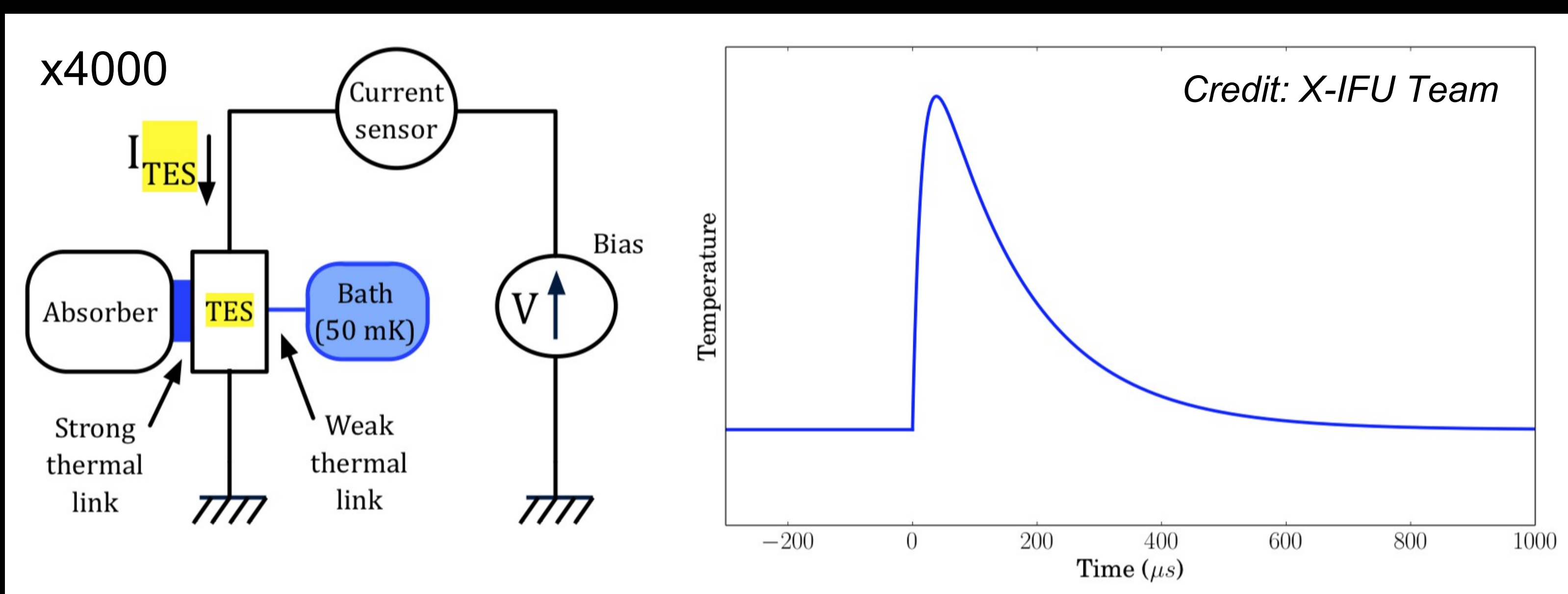



Hitomi
(2016)

*Credit: Hitomi Team*

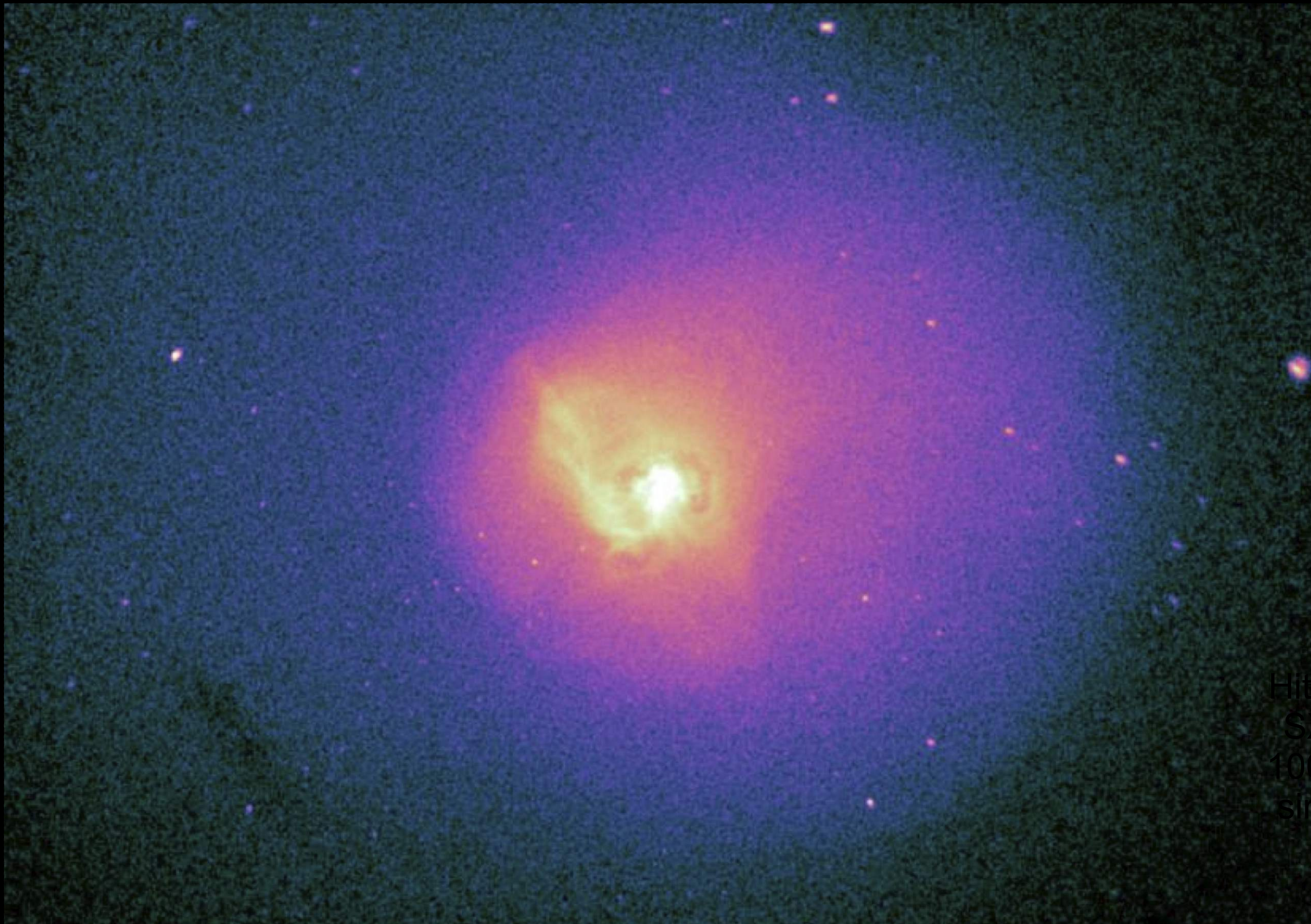
XRISM
(2022+)





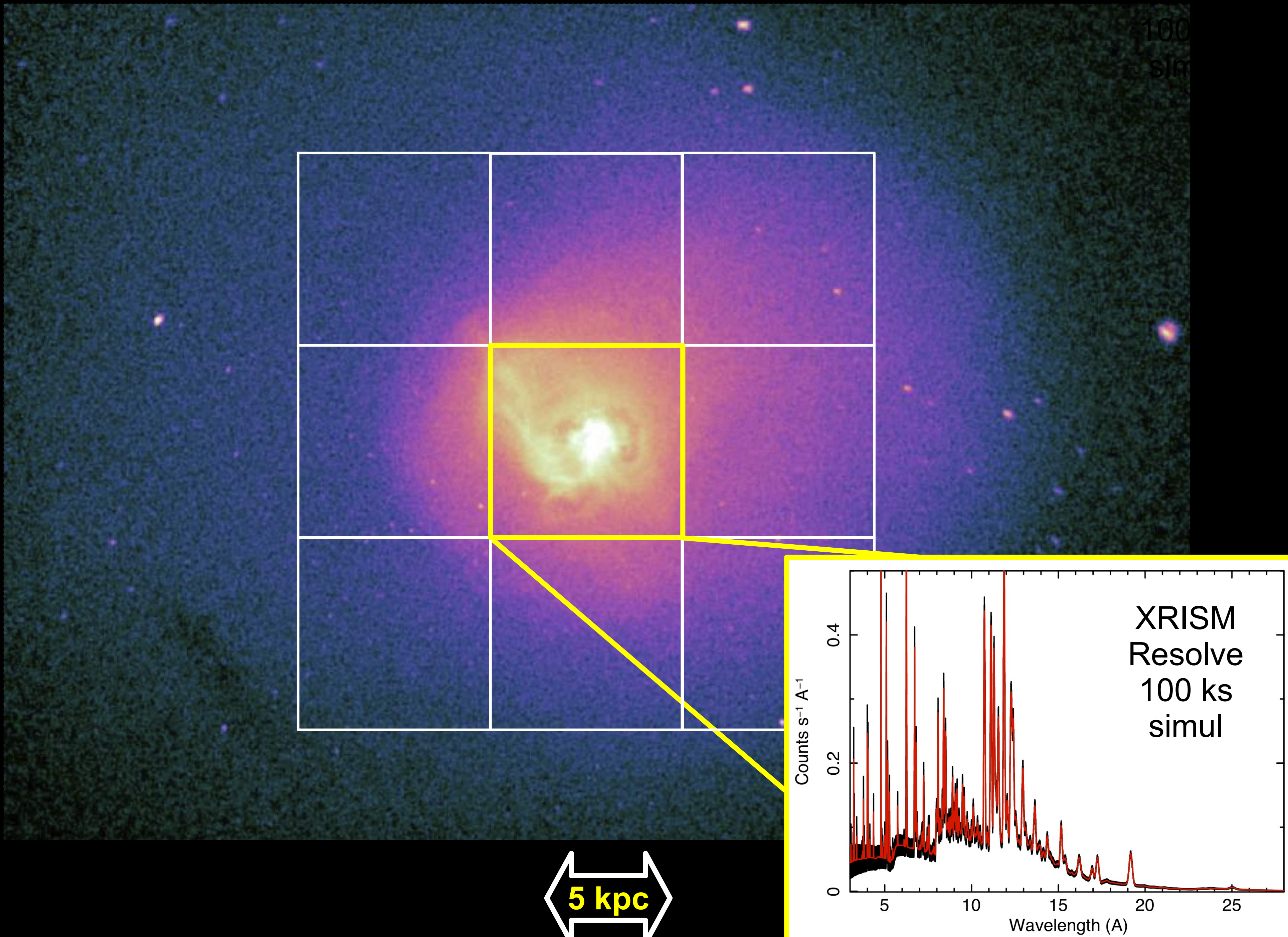

ATHENA
(2031+)

# Nearby clusters : Centaurus

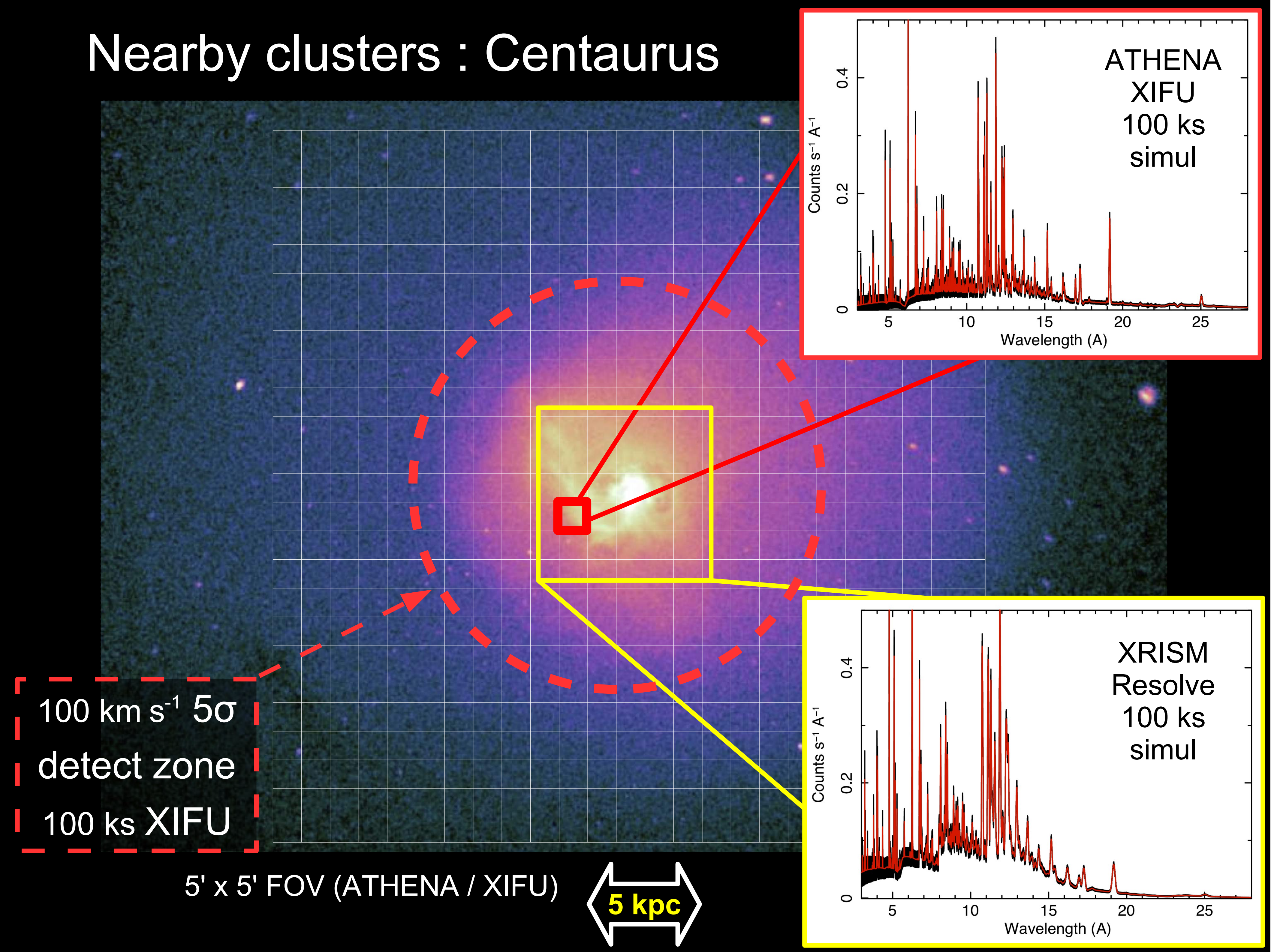


5 kpc

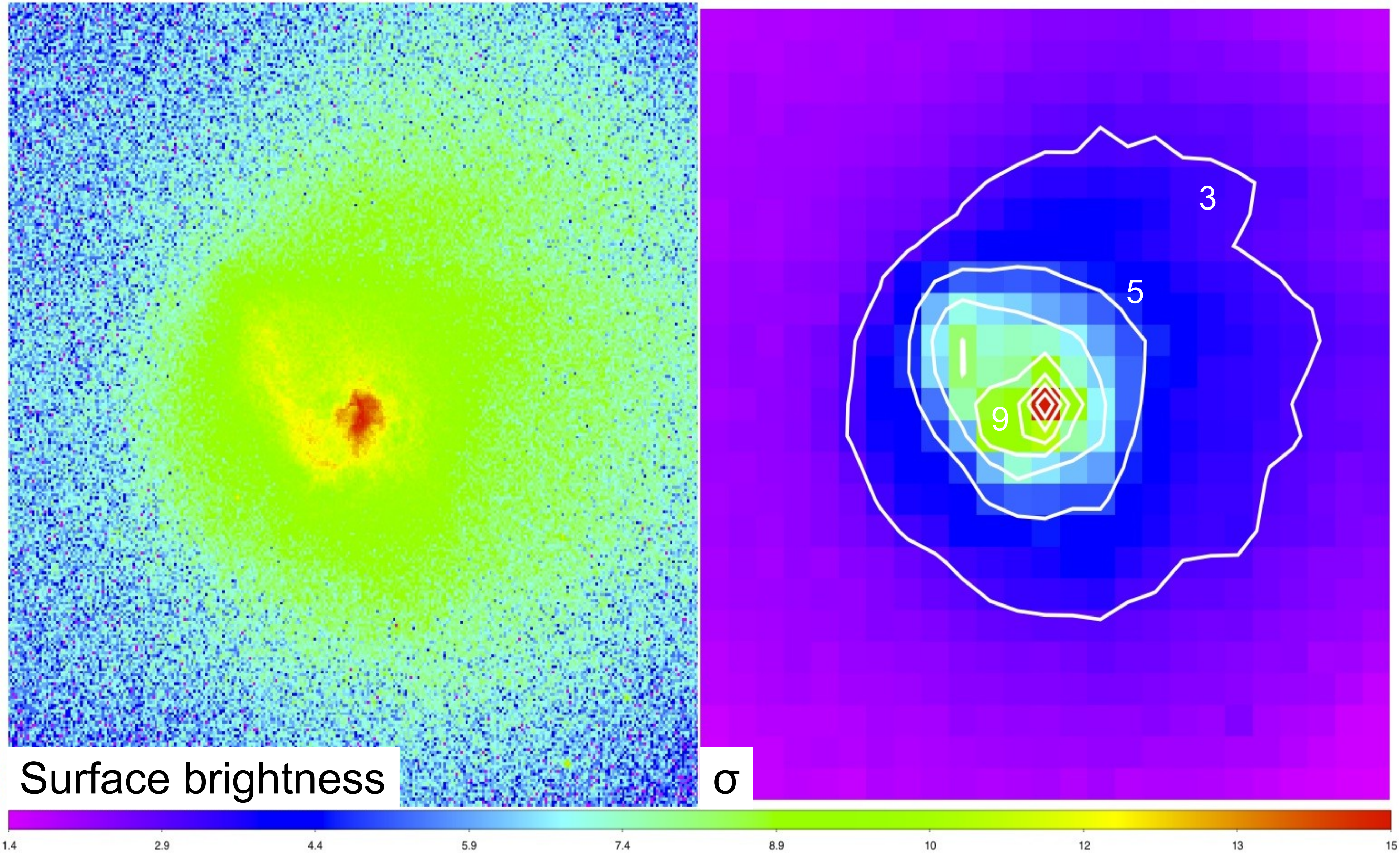
# Nearby clusters : Centaurus



# Nearby clusters : Centaurus

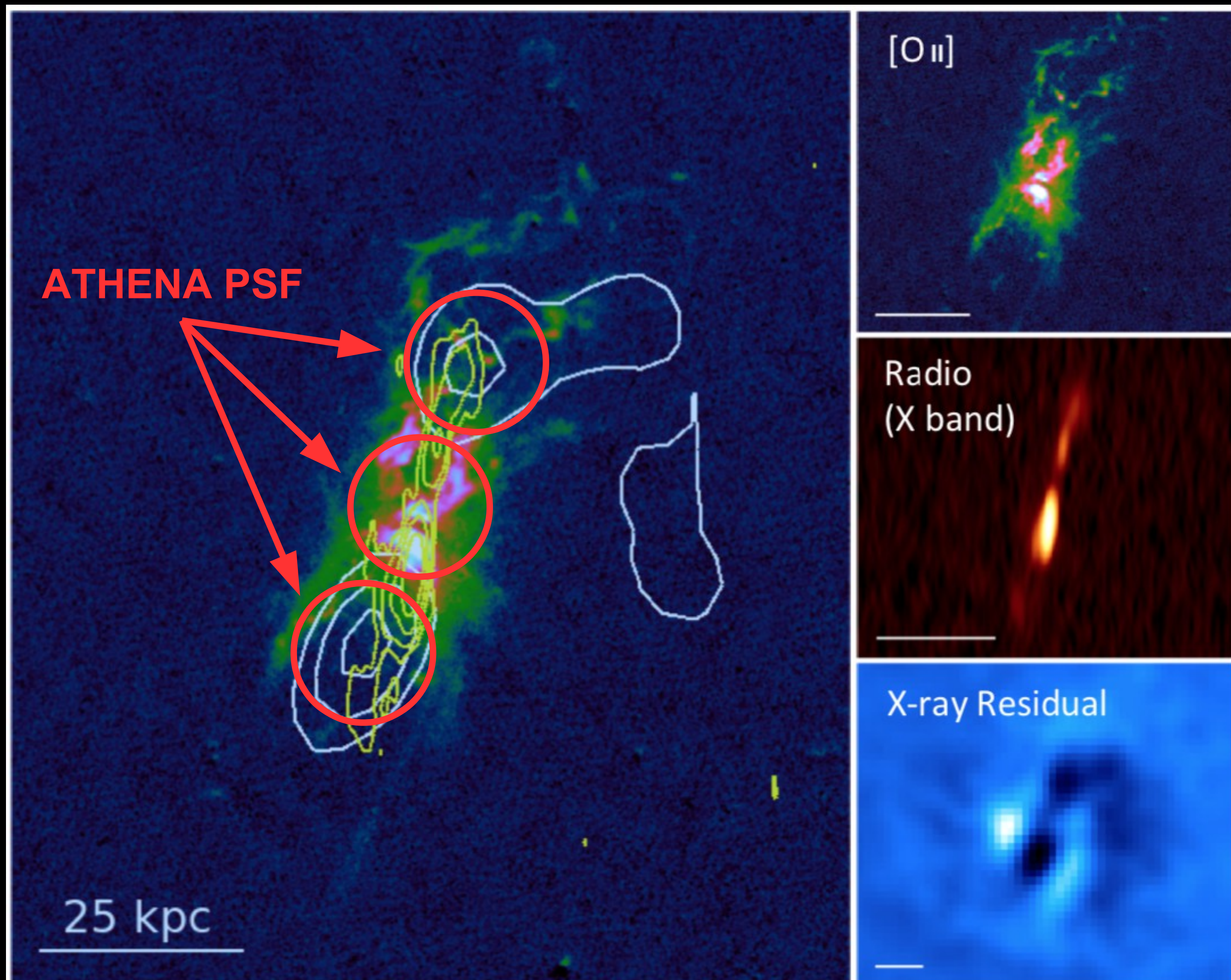


# Centaurus cluster (100 ks ATHENA / X-IFU)
## Velocity broadening detection



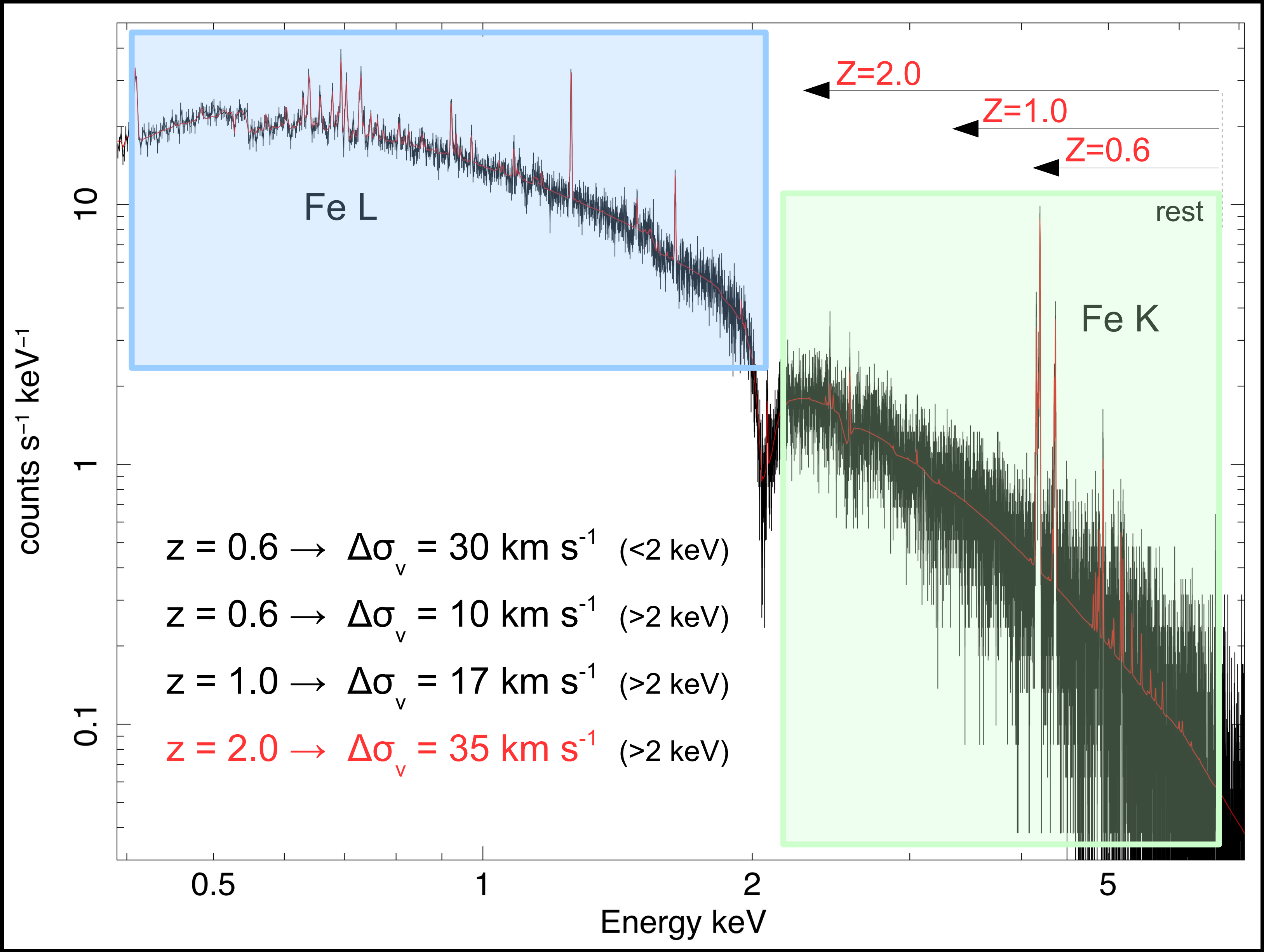
# Distant clusters : Phoenix

Figure by M. McDonald



# Phoenix cluster

(z=0.6, 14 ks XIFU sim, $\sigma_v$ = 300 km $s^{-1}$)




→ see also Bonus slide on ESA Voyage 2050

# … in the future

To understand cooling-heating balance in the ICM:

- Current instruments have been used close to their limits
- XRISM will measure bulk velocities in nearby clusters
- ATHENA will measure & resolve velocity fields in nearby clusters and measured bulk properties up to z > 2

# … in the future

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- Current instruments have been used close to their limits
- XRISM will measure bulk velocities in nearby clusters
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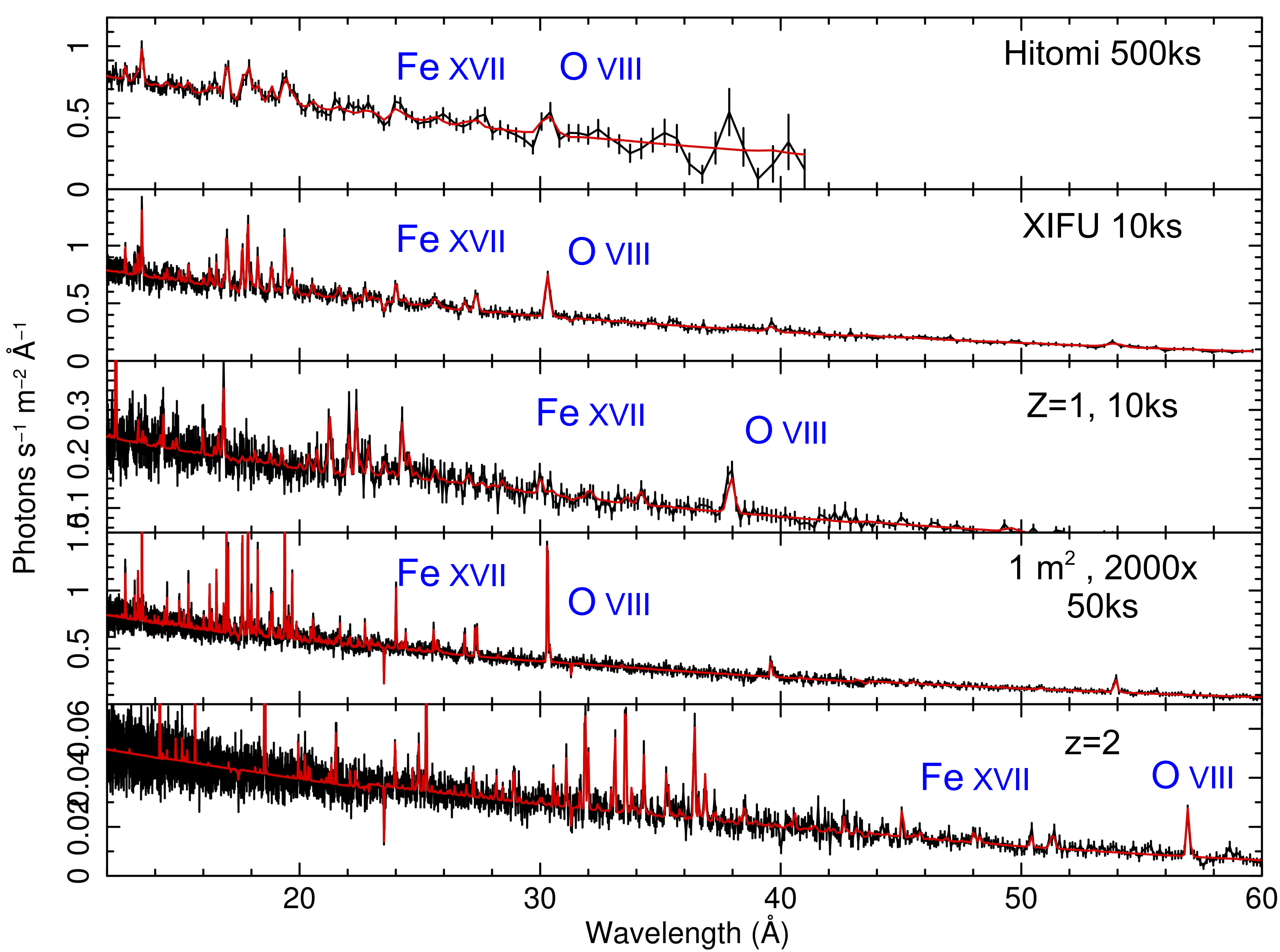
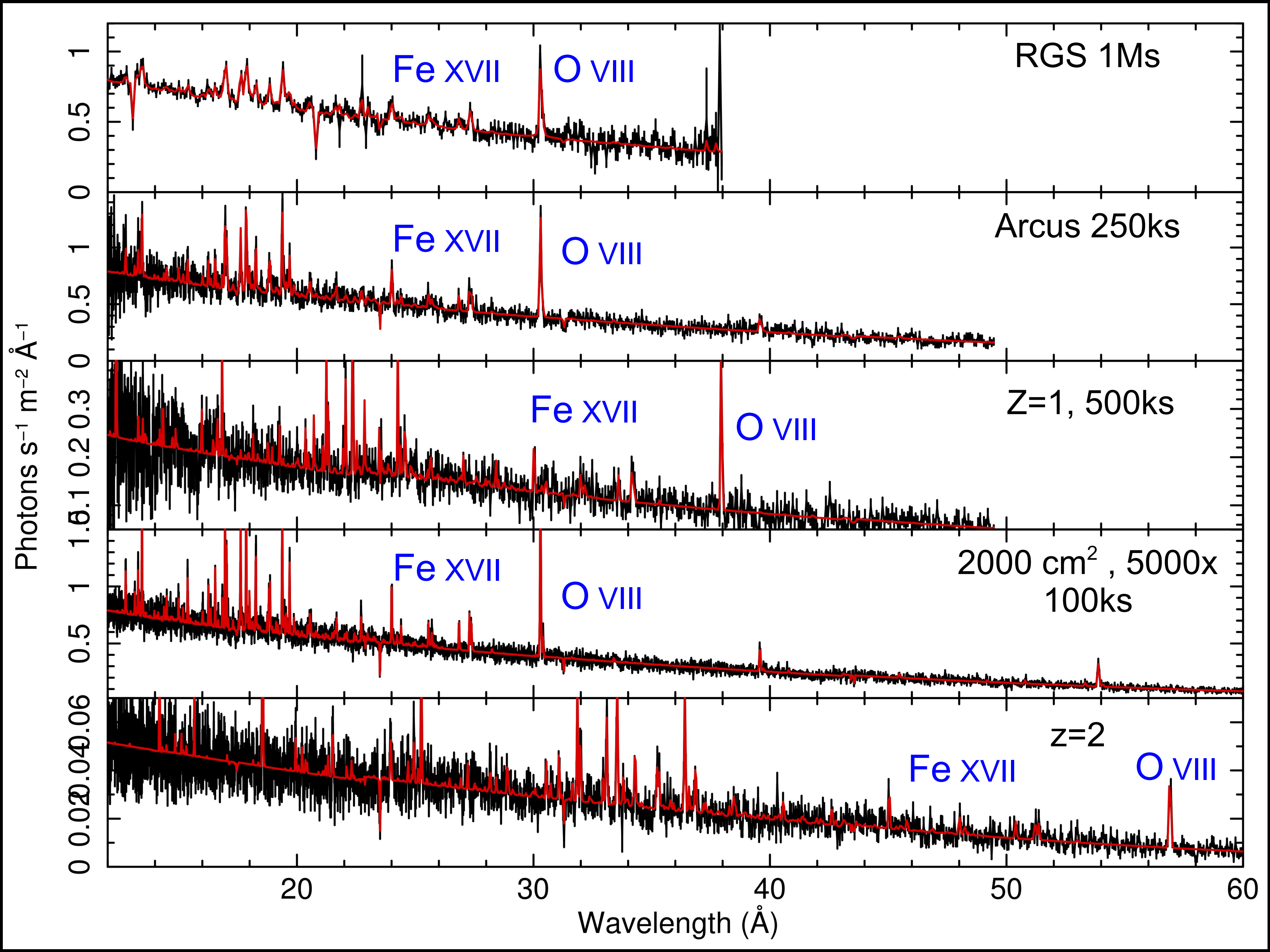
*Thanks a lot for the attention!*

# Bonus slides

# Towards ESA Voyage 2050 : Calorimeters



# Towards ESA Voyage 2050 : Gratings

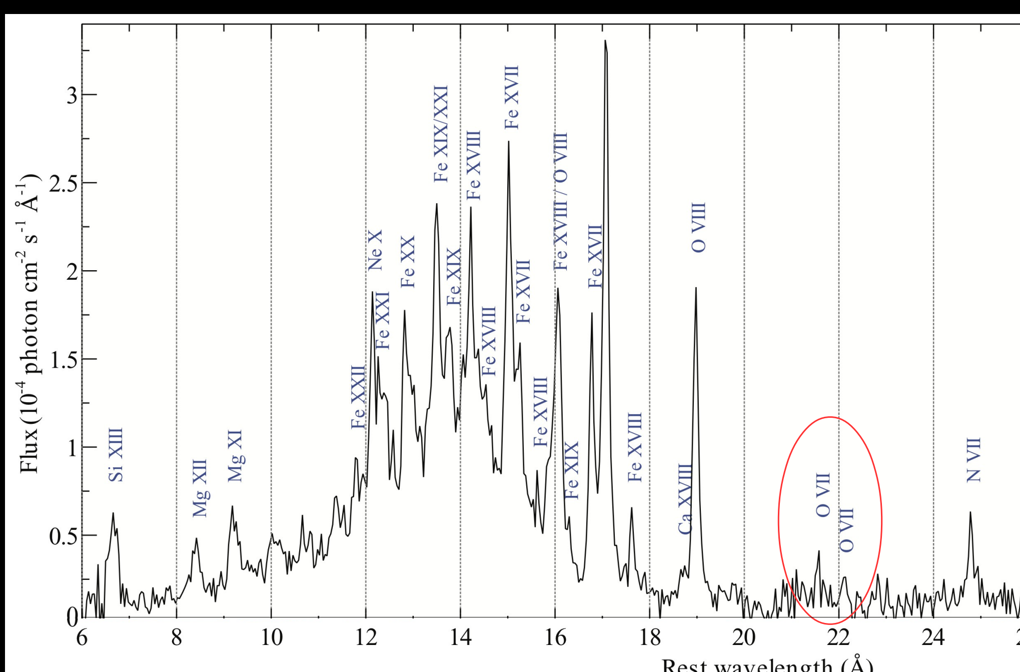


# O VII in galaxy groups

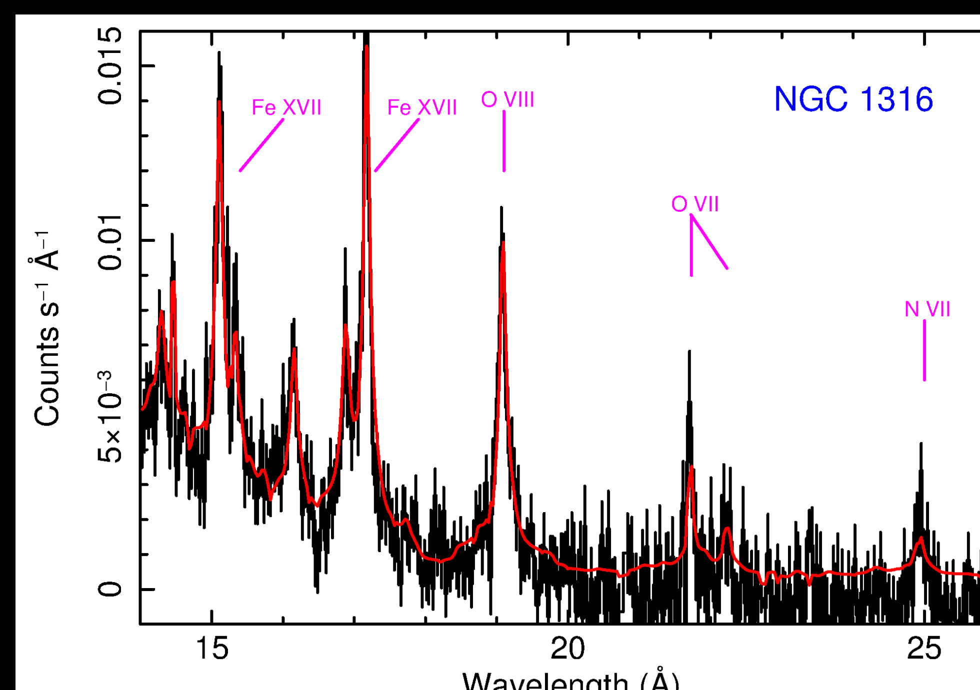
Sanders & Fabian 2011,
Pinto et al. 2014b, 2016b,

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

→ cooling below 0.5 keV even more difficult (0.1-1 $M_\odot$ $yr^{-1}$)




Sanders & Fabian 2011



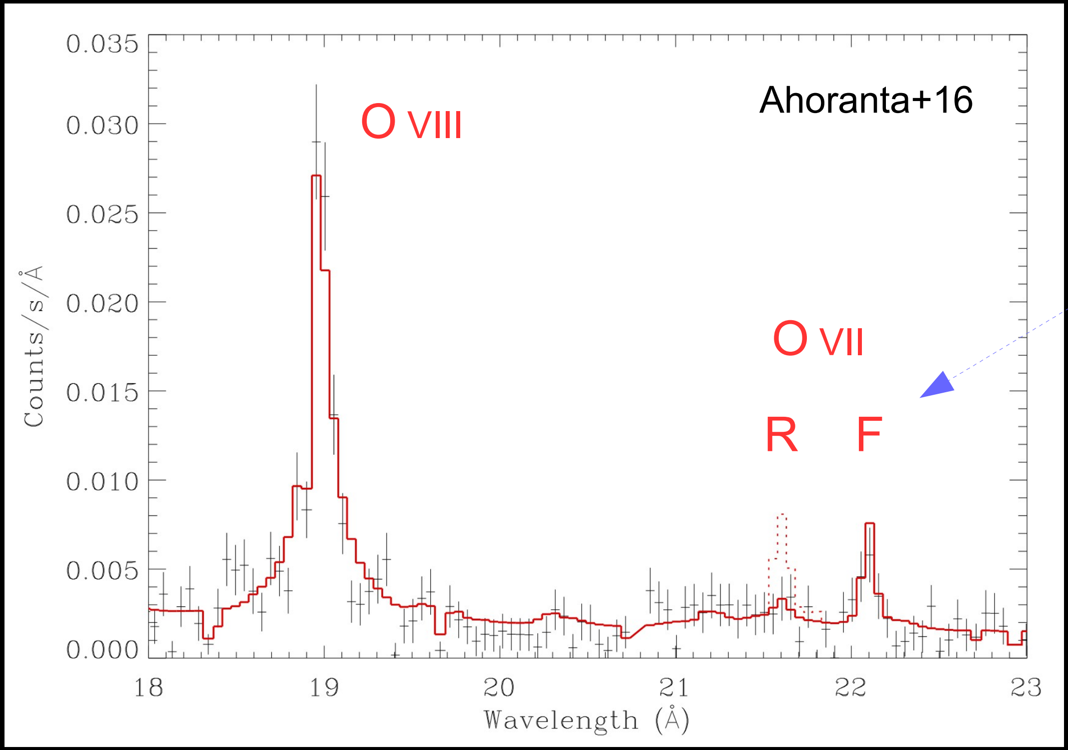

Pinto + 2014

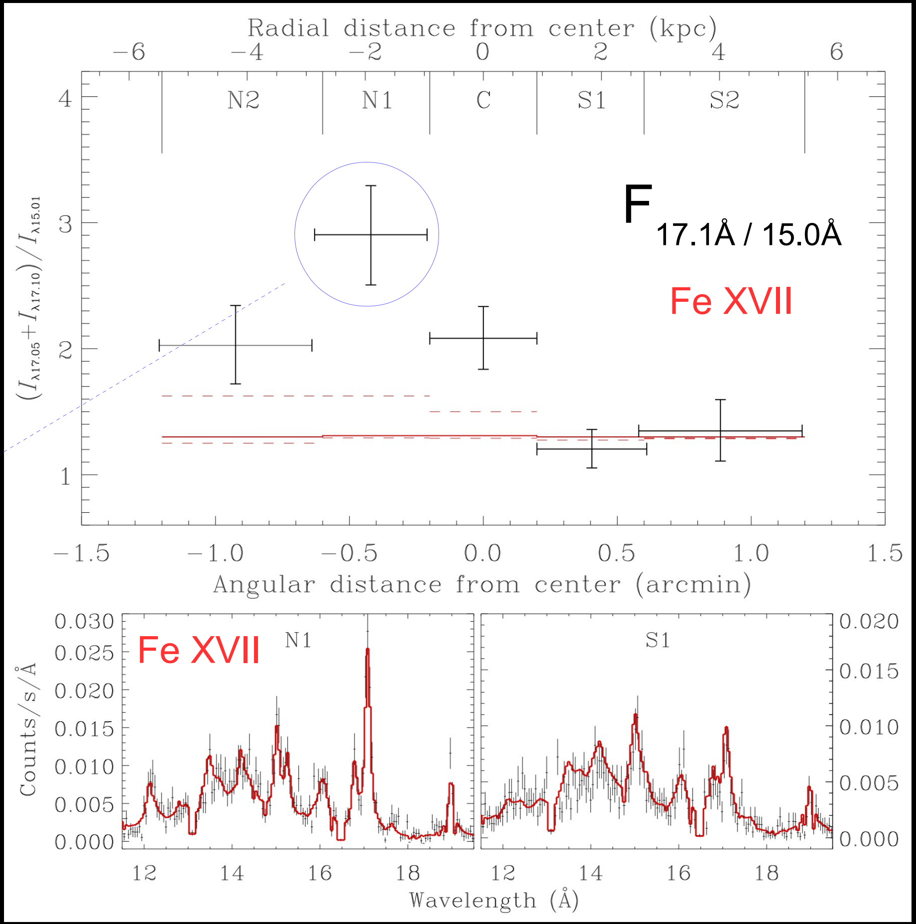
# O VII in galaxy groups

- O VII resonant scattering
- Fe XVII resonant scattering

→ low turbulence?

Pinto et al. 2014b, 2016b, Ahoranta+2016

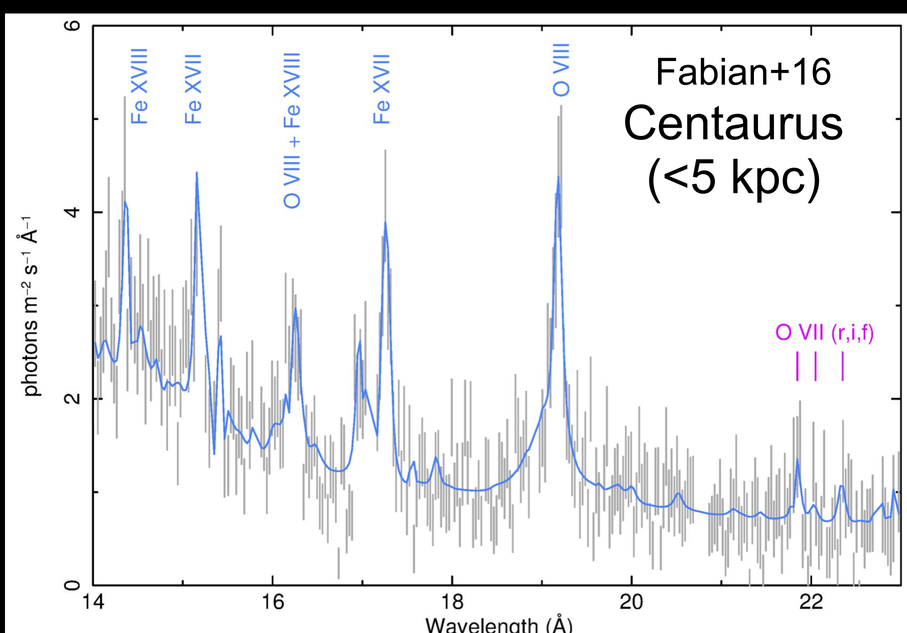


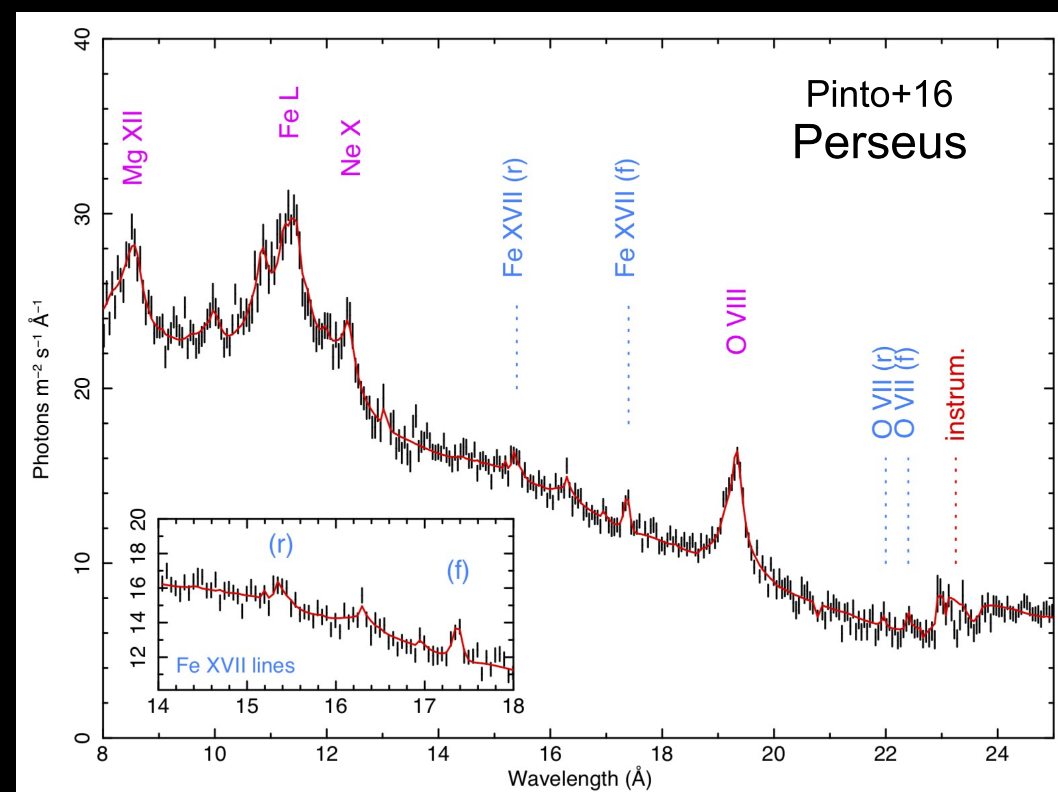



# O VII in clusters?

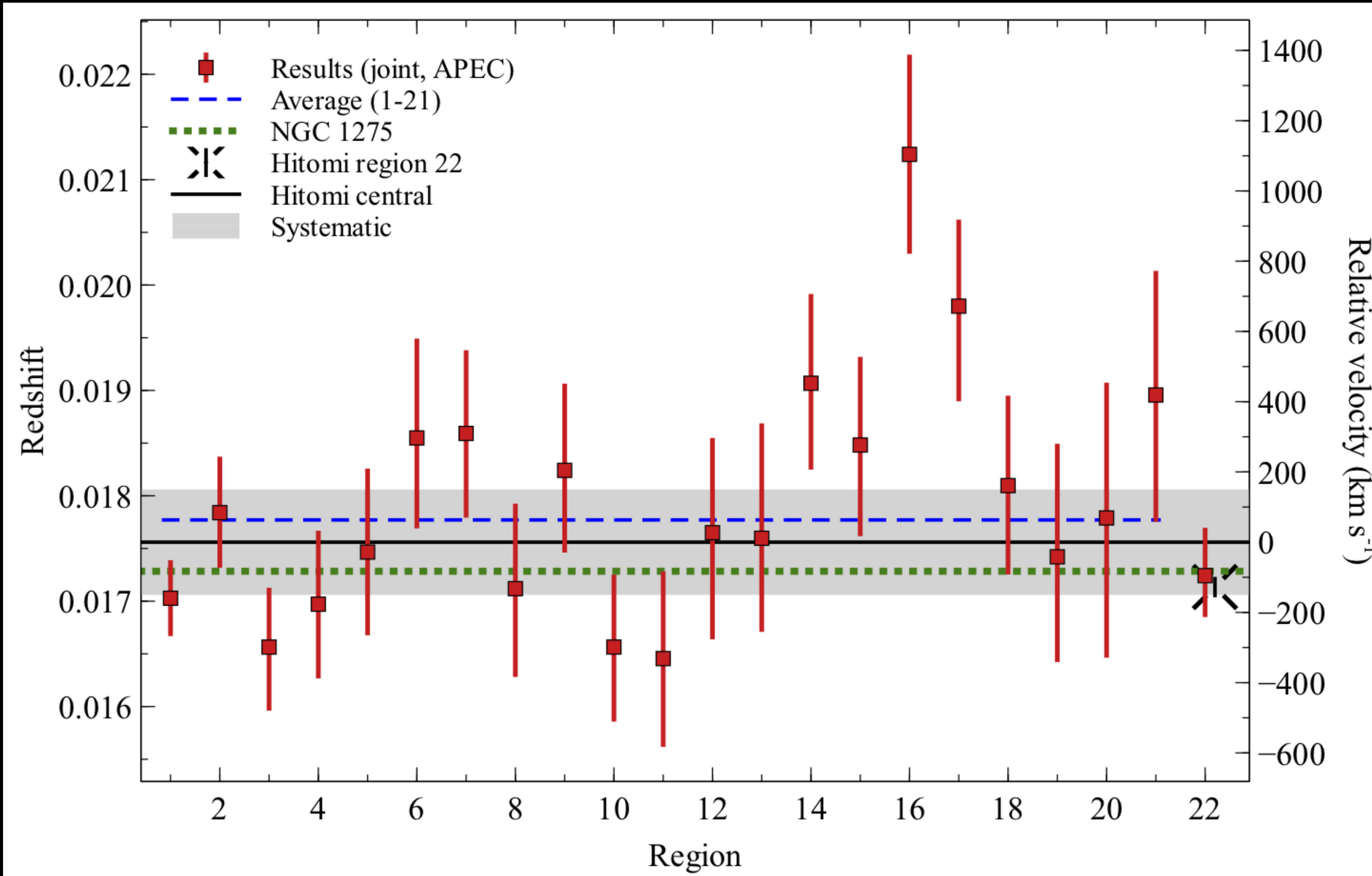
- O VII resonant scattering
- Fe XVII resonant scattering

→ low turbulence?



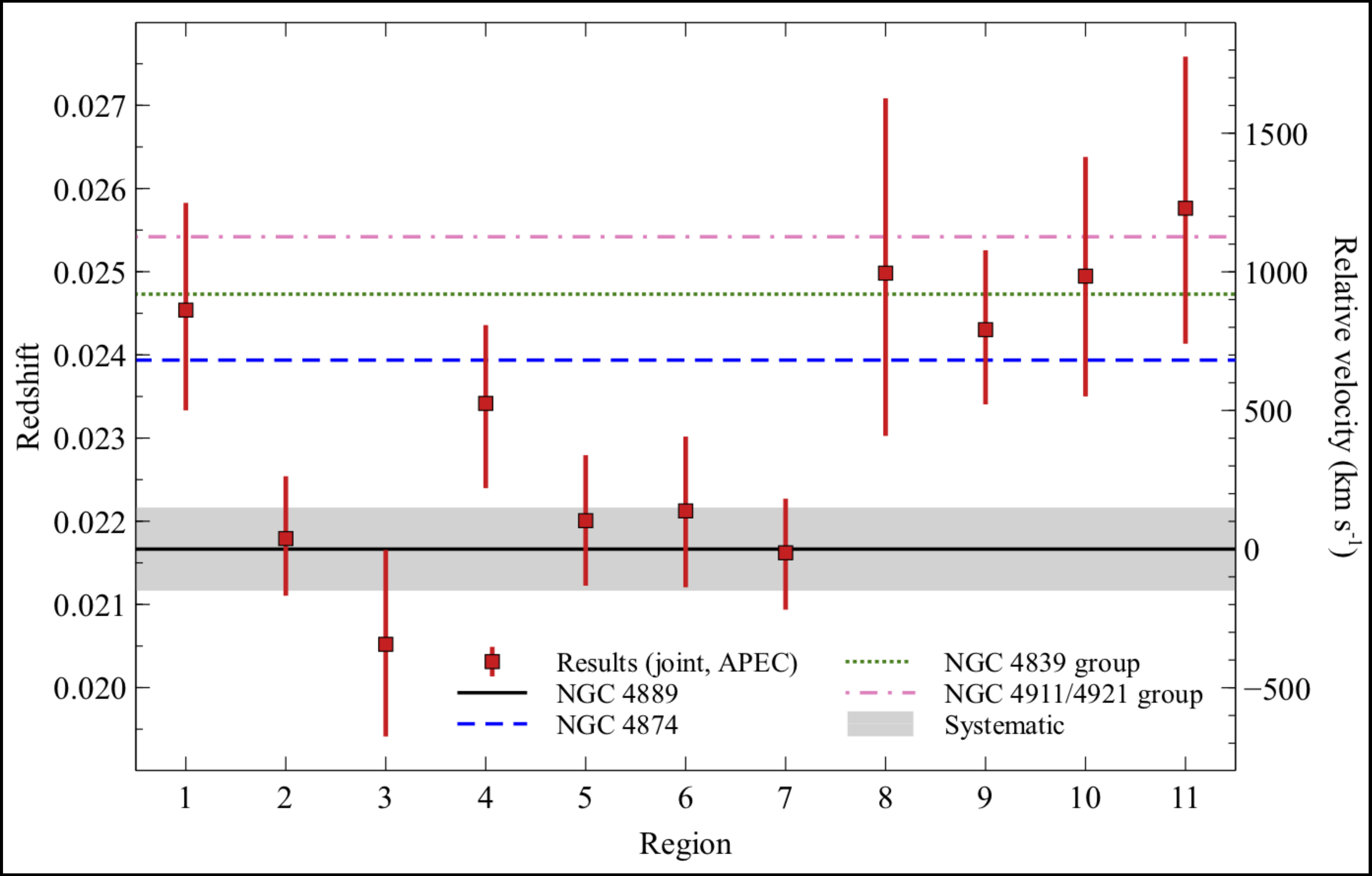



# XMM-EPIC vs Hitomi sloshing in Perseus



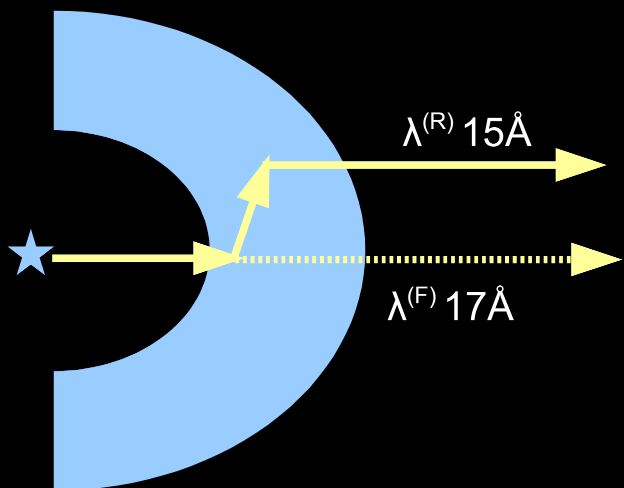

Sanders + 2020

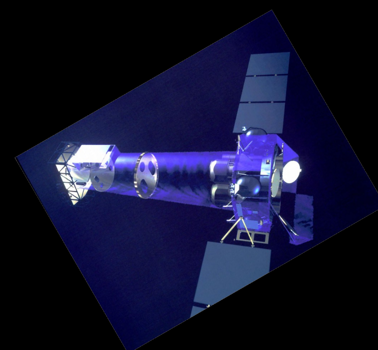
# XMM-EPIC vs Hitomi sloshing in Coma

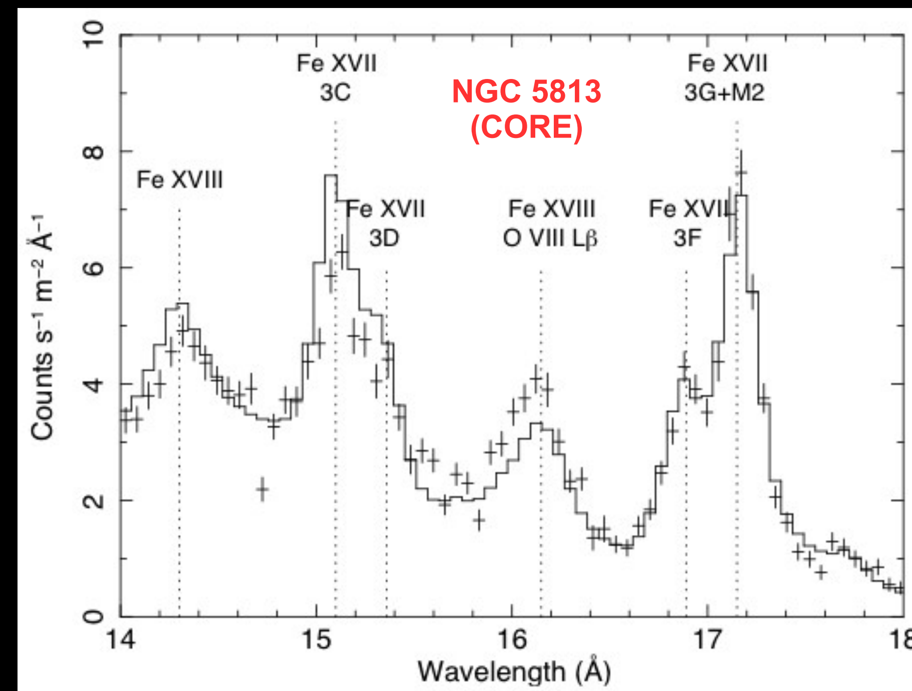


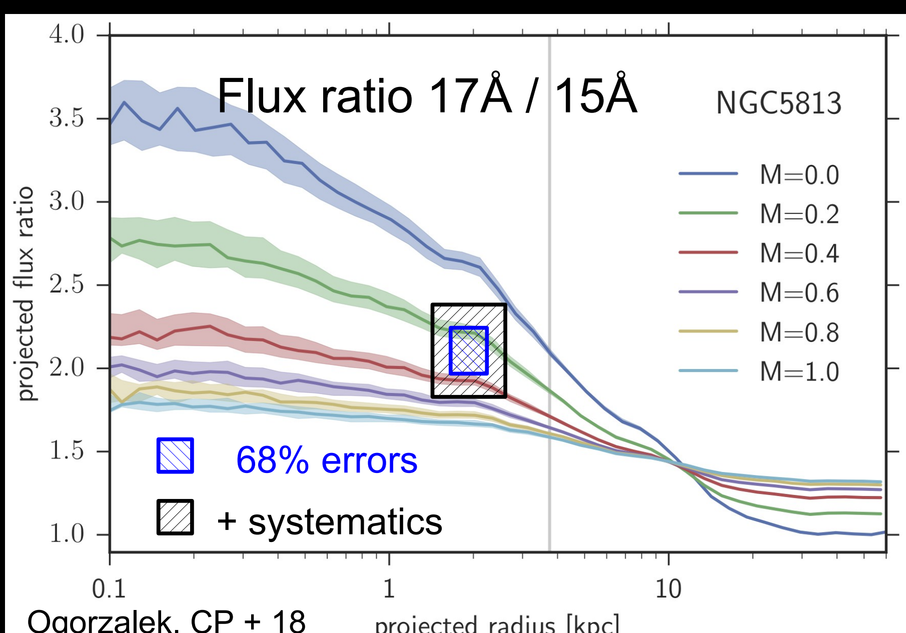

Sanders + 2020

# Resonant scattering





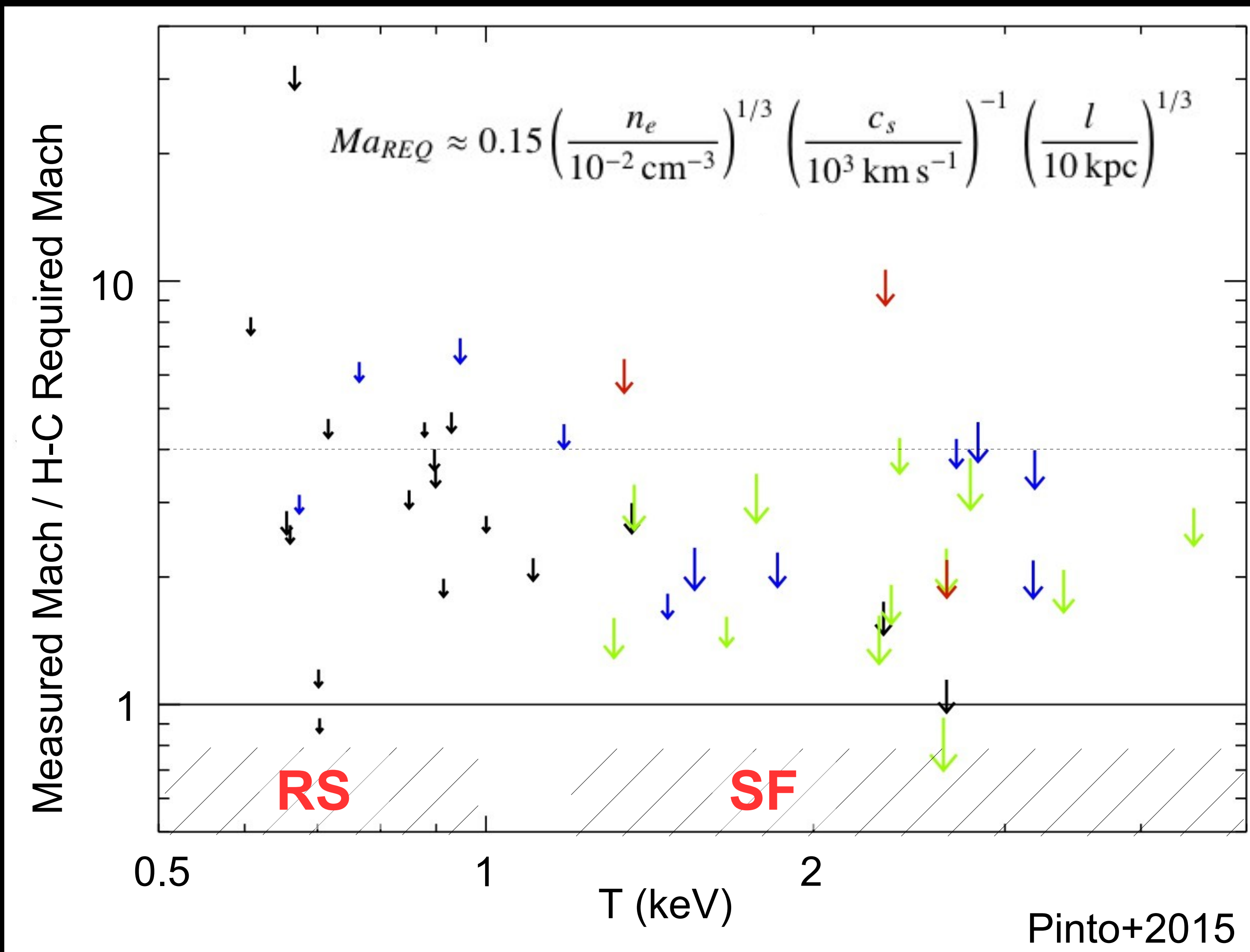

Werner+09
de Plaa+12
Ahoranta+16
Ogorzalek+18

~ 100-300 km $s^{-1}$

LOW Turbulent pressure 5 %

(agree with simulations of relaxed clusters)

# 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)

# 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

$L_{cool} = L_{turb}$

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

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

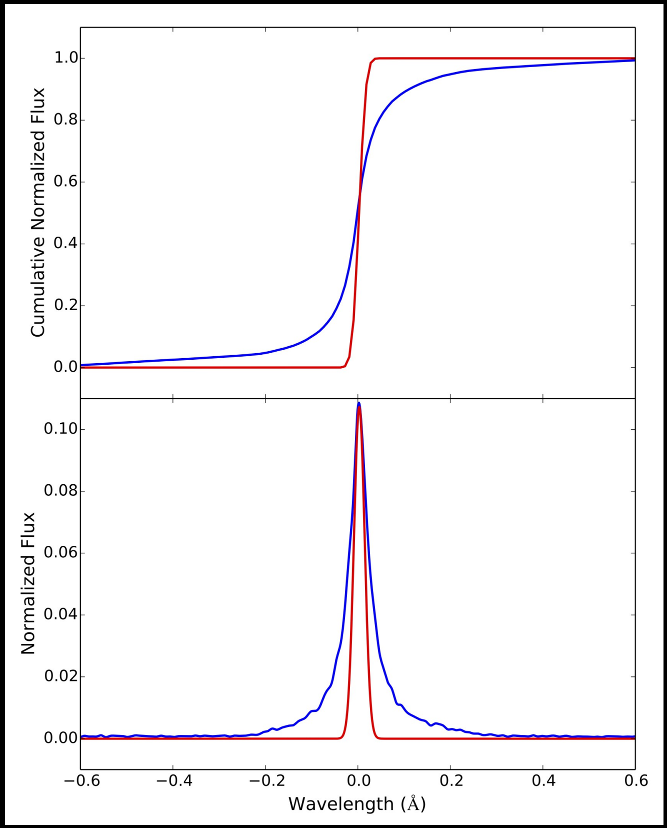
$E_{turb} = 3/2\ M_{gas}\ \sigma_{turb}^{\ 2}$

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

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

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

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



# 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)

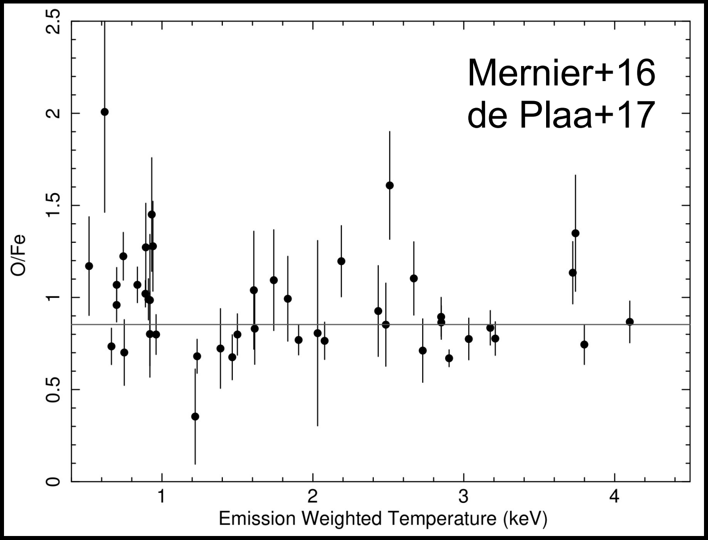
→ SN Ia / (SN Ia + SN cc) ~ 25-45% (solar environment ~15-25%)

- α / Fe uniformly distributed

(from ellipticals to massive clusters)

→ Most metals formed around z~2 ?

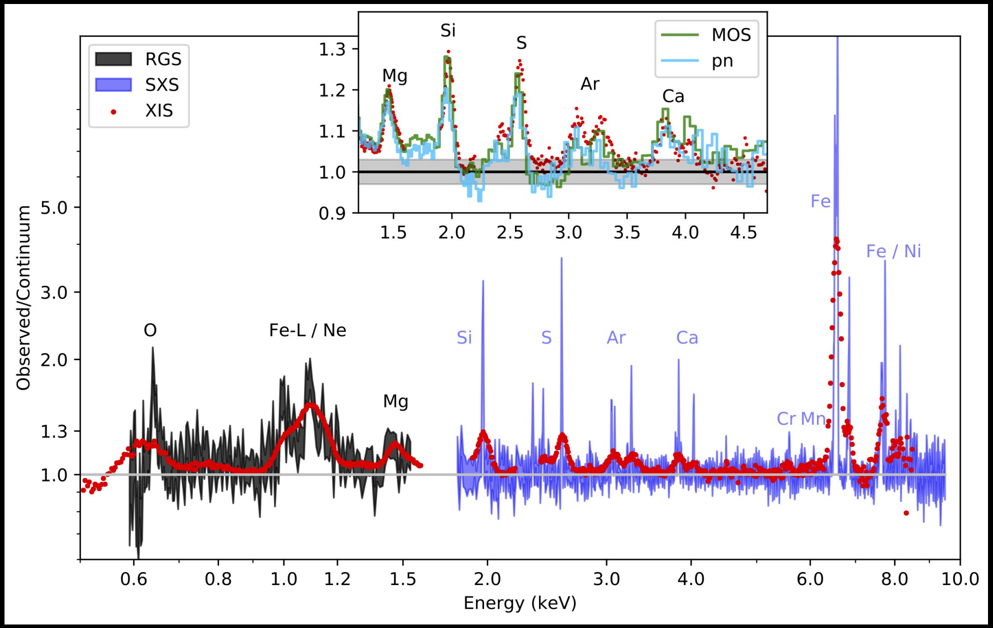
BCG SNIa small ? Sloshing ?

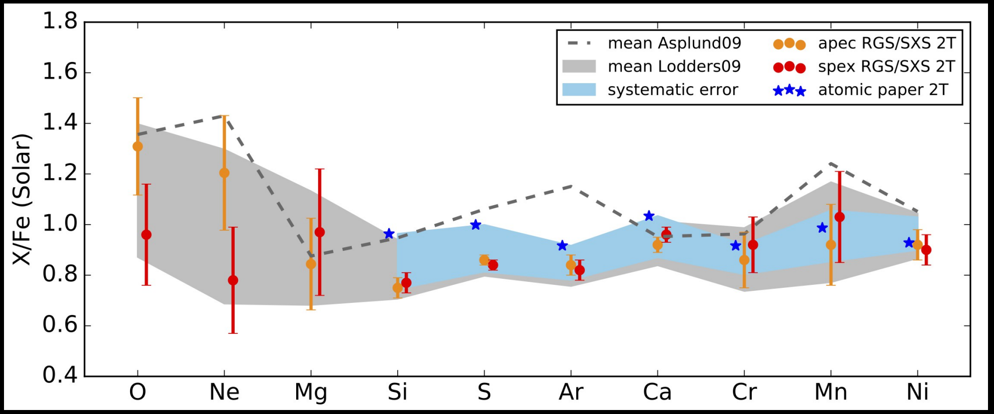


# Synergies with other facilities

XMM/RGS + Hitomi/SXS simultaneous fits

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




Simionescu+2019

Challenges any linear combination of SN yields

Including neutrino physics in the SN cc yields may help ...

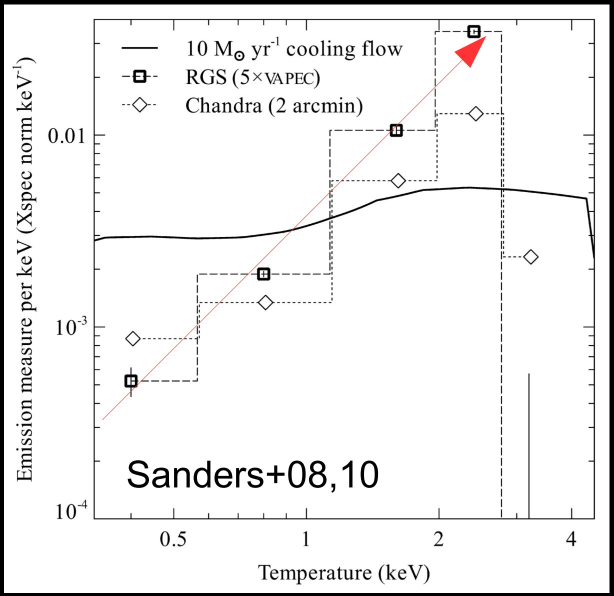
# ICM complex structure

- Multi-phase structure

Powerlaw EM temperature distribution

Fe XVII reveal 0.7-0.8 keV phase

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

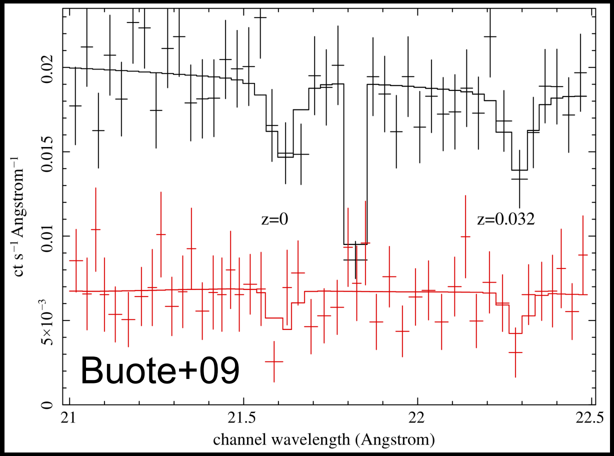



- WHIM (via quasars behind clusters)

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, ...)



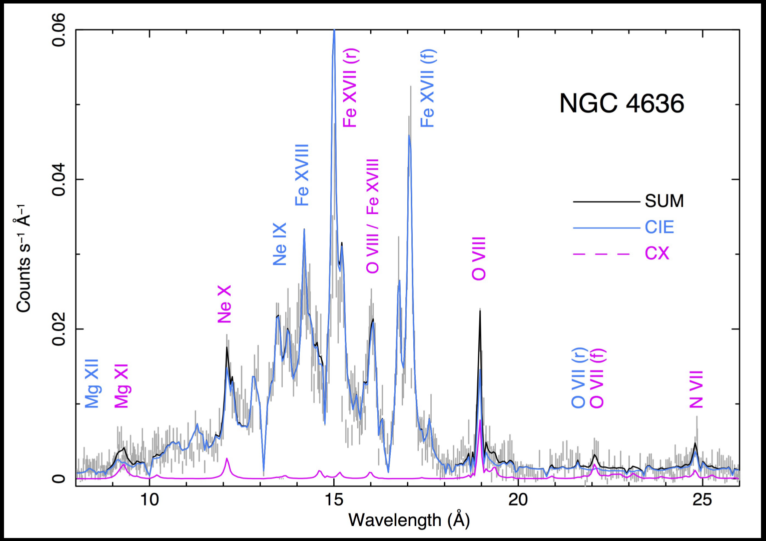

Caution: low stat, calib, bad pixels, ISM contamination

# 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 ...