# Past, present and future prospects of high resolution X-ray spectroscopy of clusters of galaxies

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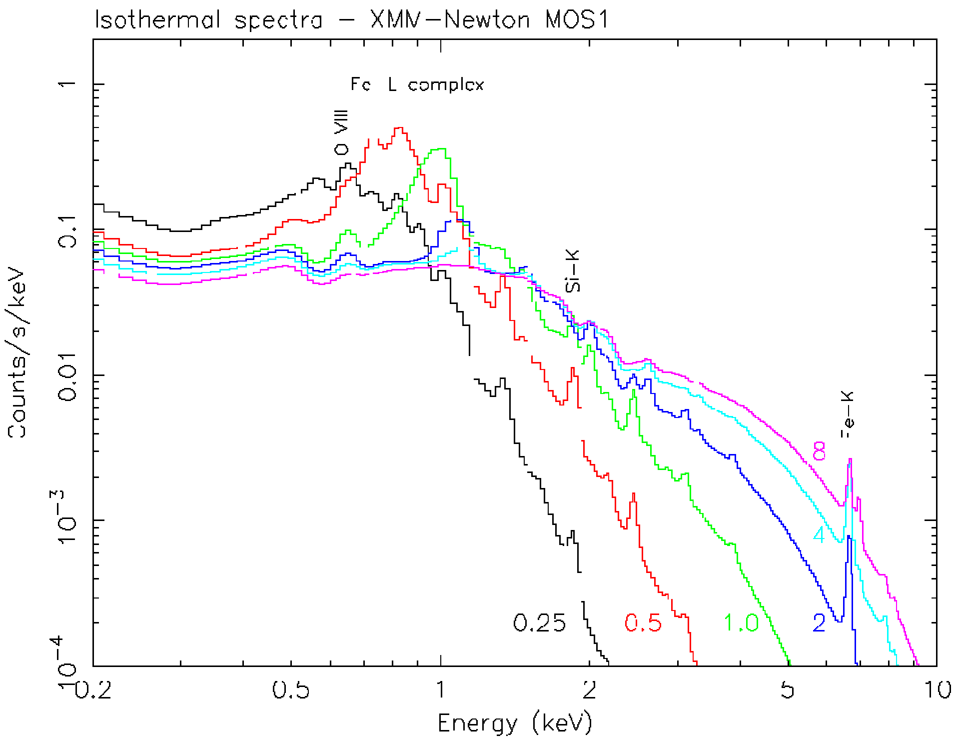
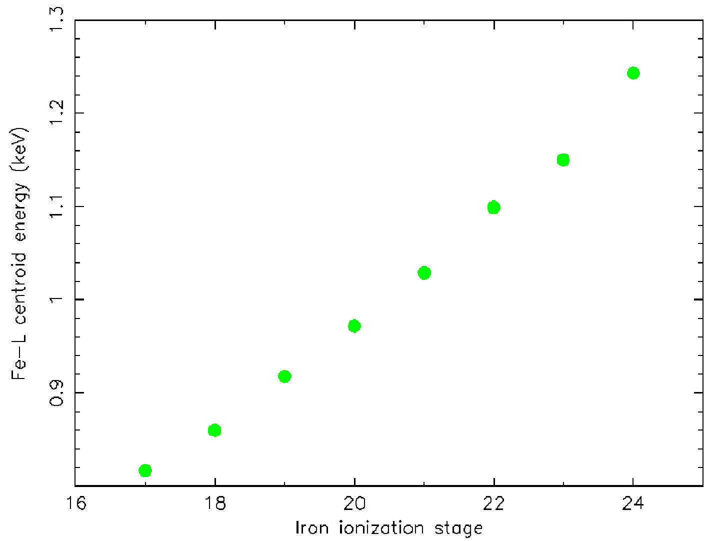
# Overview

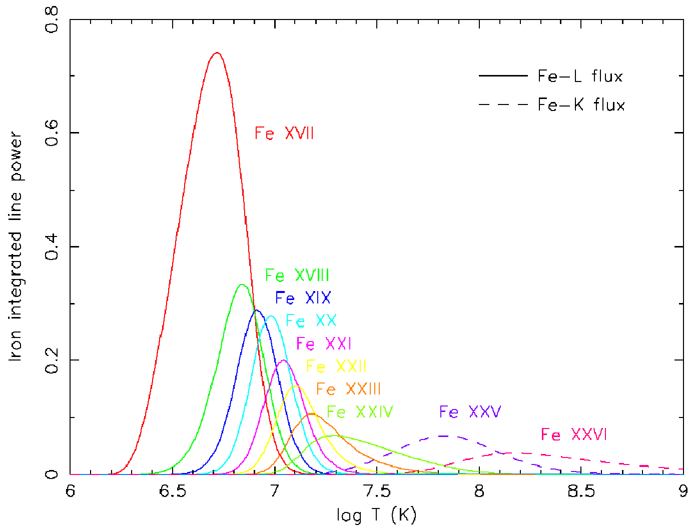
- High-resolution X-ray spectroscopy and clusters of galaxies
- Initial XMM-Newton RGS results
- Recent highlights: abundance determinations
- Future prospects

# High-resolution X-ray spectroscopy and clusters of galaxies

# “Classical” Fe-line diagnostics

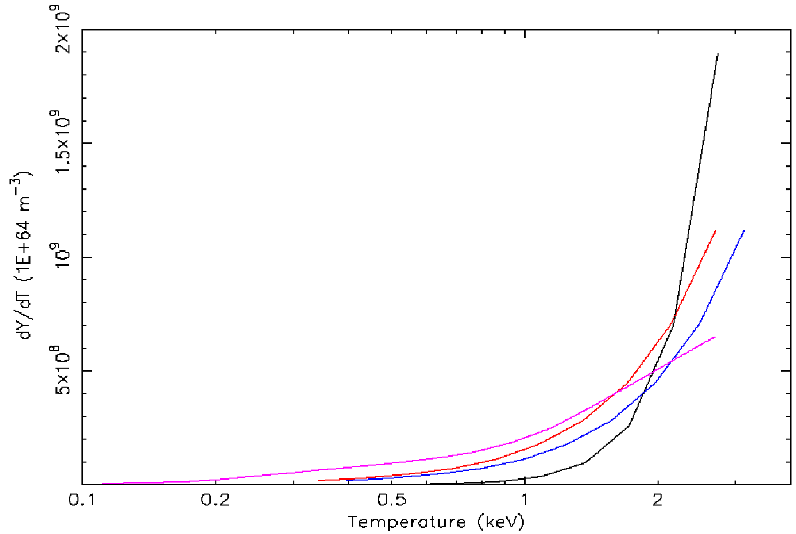


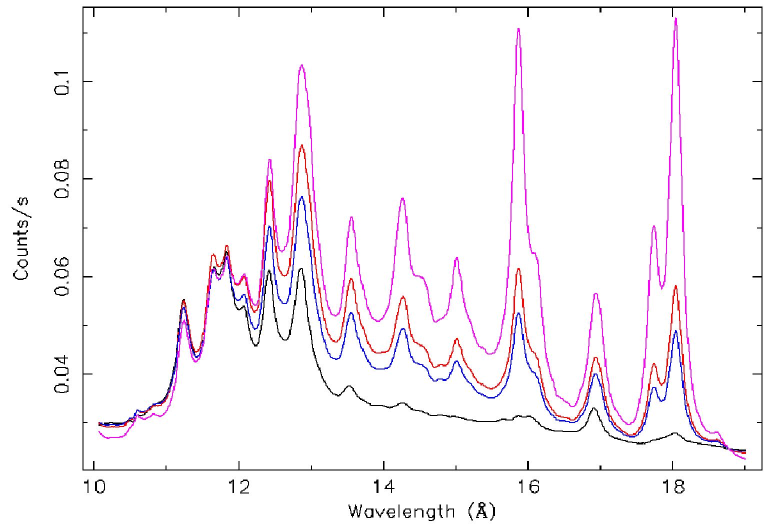



# Temperature diagnostics

- T hard to measure for E<kT from continuum
- Multi-T plasma: need lines to resolve T-structure

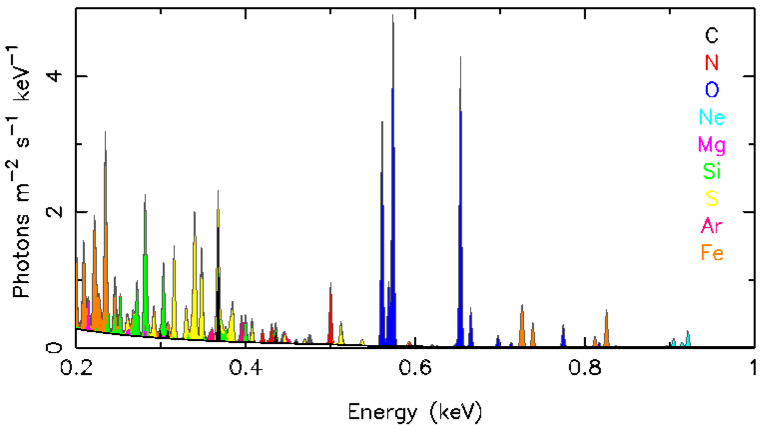


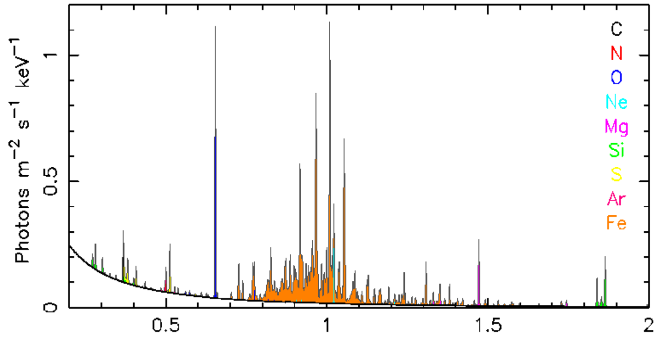

De Plaa et al. 2005

# Abundance diagnostics

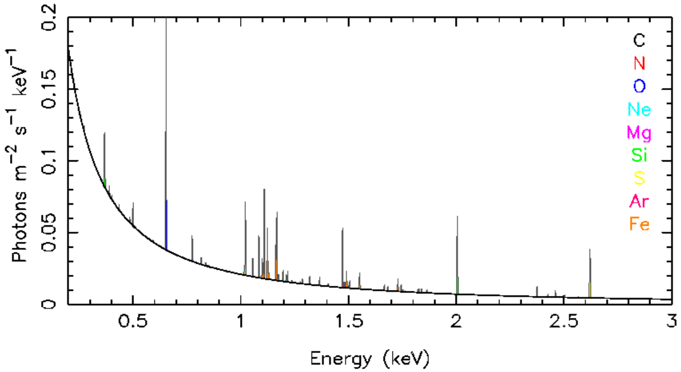
T = 0.2 keV




T = 1 keV

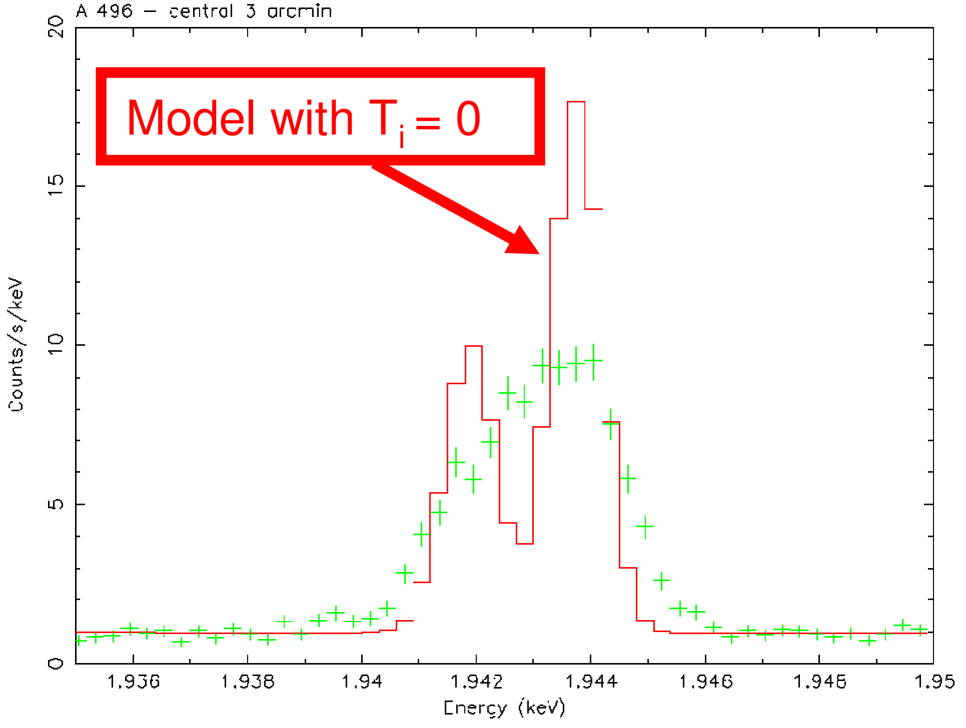



T = 5 keV



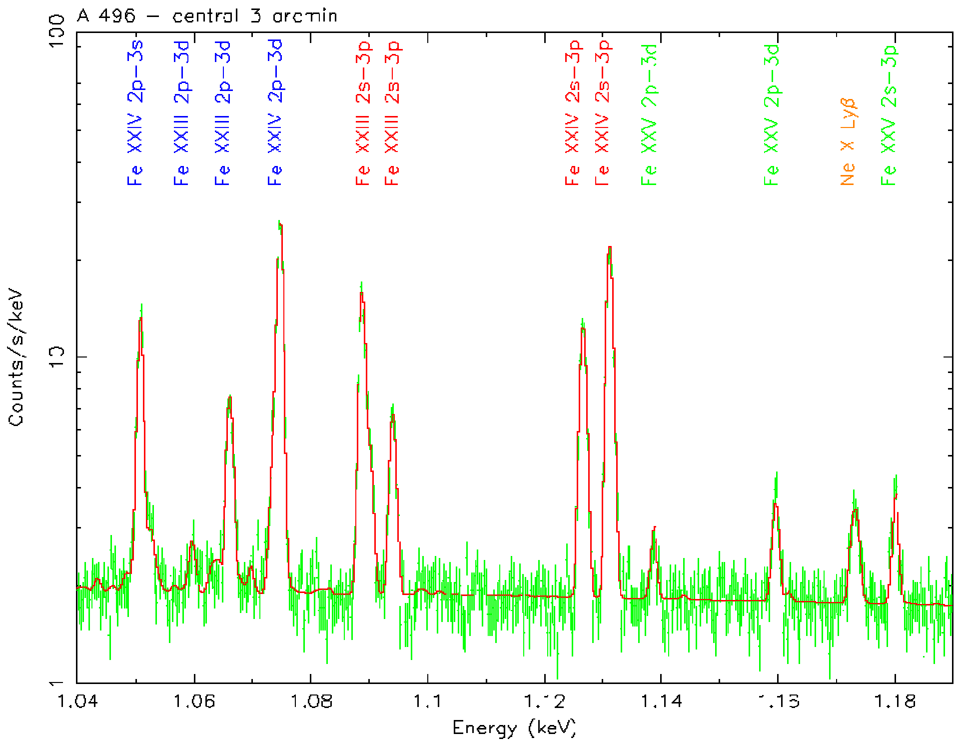
# Measuring ion temperatures

- With high resolution (~ eV) possible to measure line broadening due to finite ion temperature
- Important for shocks etc.



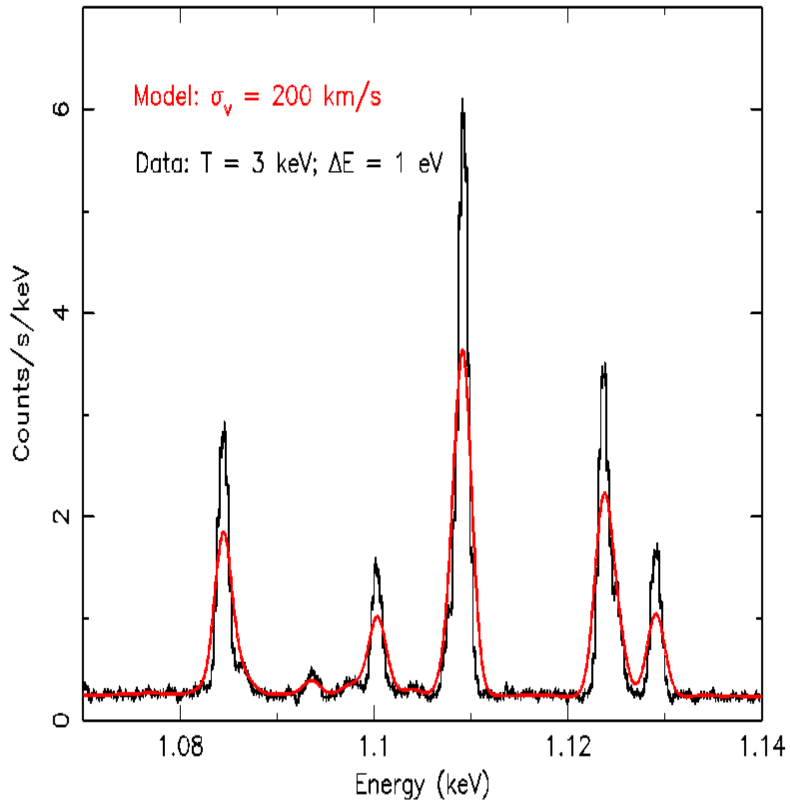
# Optical depths / turbulence

- Several Fe-L lines (red in figure) sensitive to optical depth, others (blue in figure) not
- For known distance, this gives turbulent velocity



# Measuring turbulence

- Important pressure component: turbulence
- Dynamics (Doppler shifts) important for testing e.g. merger models
- Needs high resolution (1 eV at 1 keV)

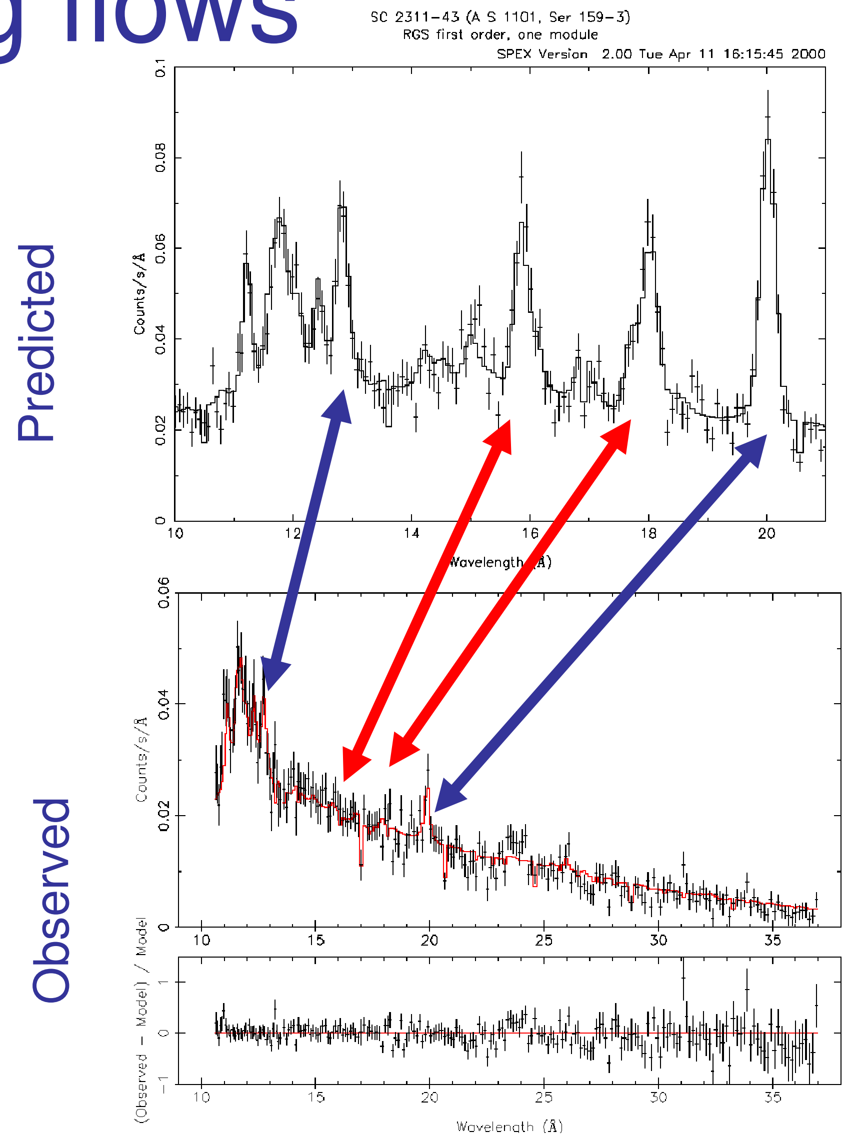


# 2. Initial XMM-Newton RGS results

- RGS optimal for point sources
- But still (unfortunately, Suzaku XRS) the best for moderately extended sources:
- $\Delta\lambda$ (Å) = 0.138 $\Delta\theta$ (arcmin)

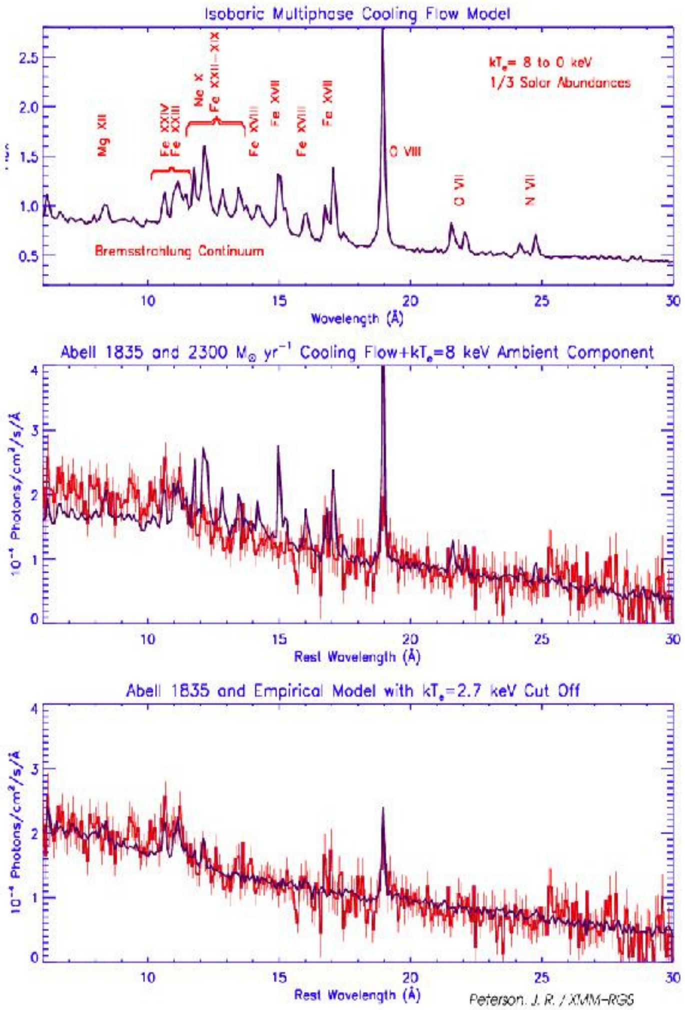
# Predictions and observations of cooling flows

- Spectrum shows predicted Fe XXIII/XXIV and O VIII from kT=2.5 keV plasma
- But almost no Fe XVII/XVIII lines!



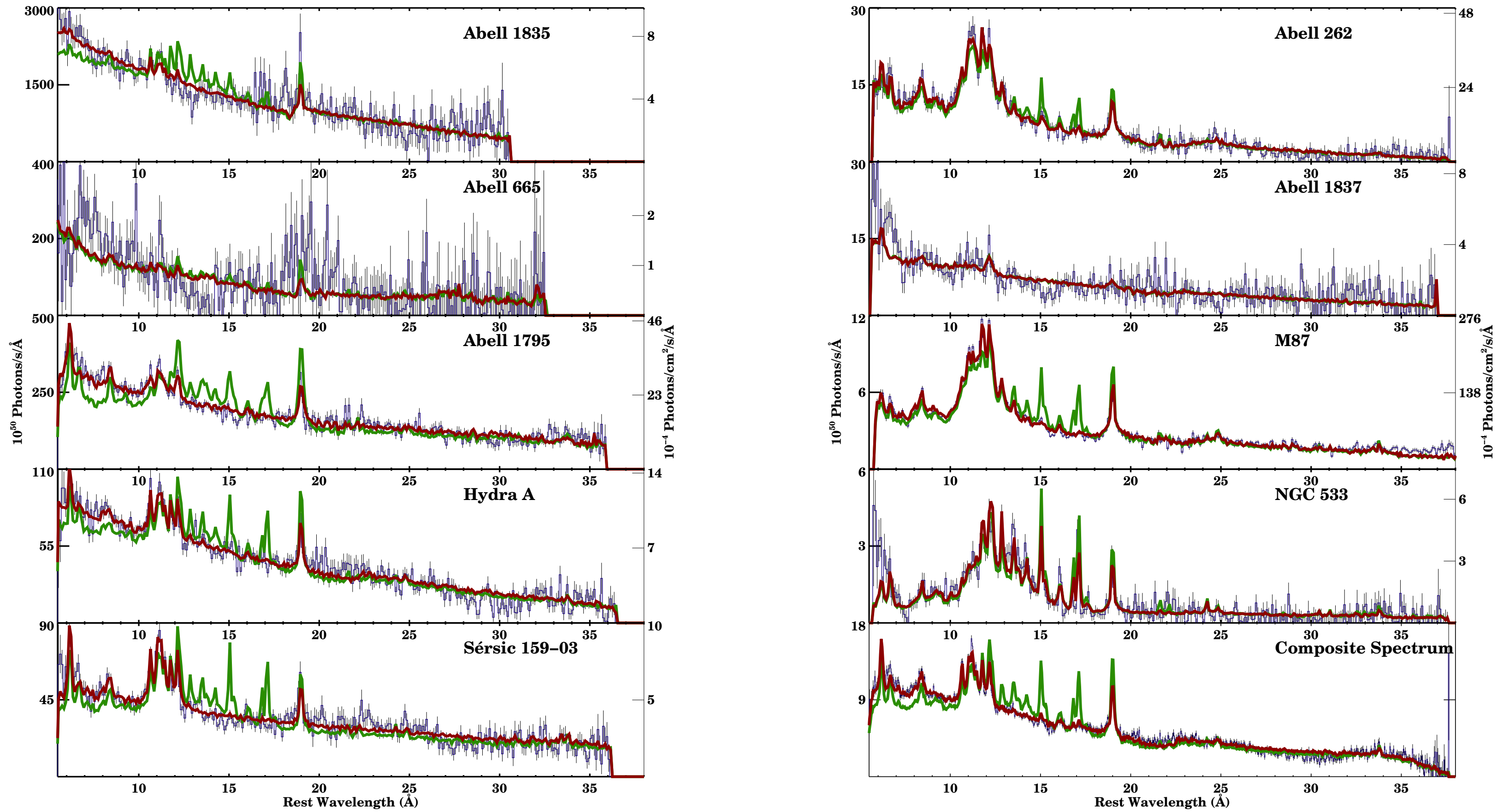
# Other cases: A 1835

(Peterson et al. 2001)



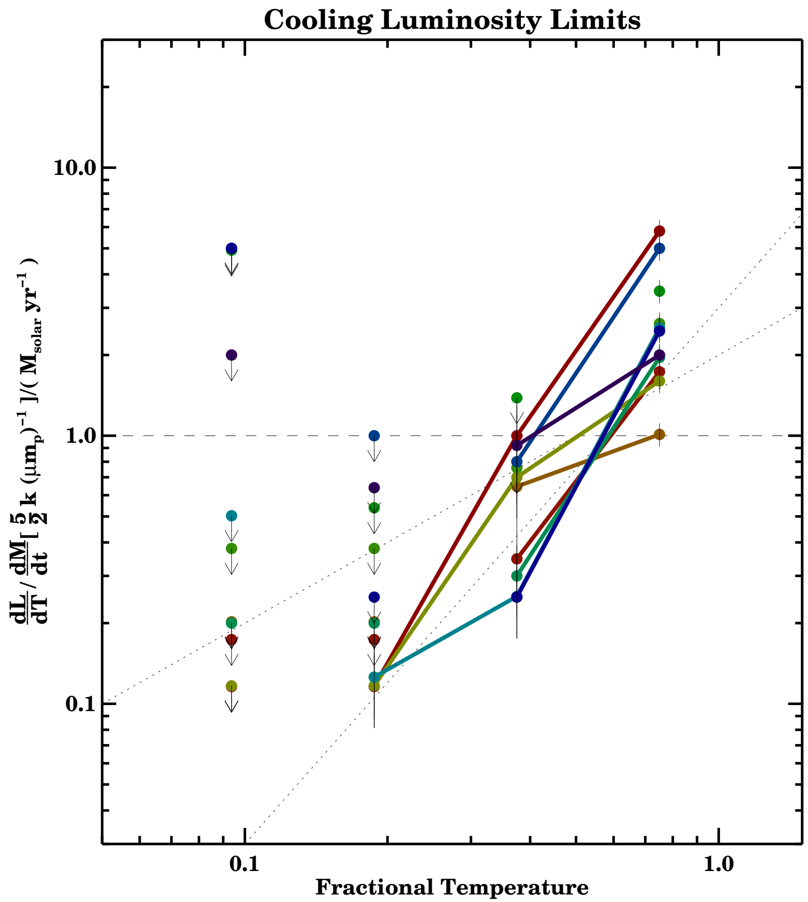
# Cooling Flow problem: universal?

(Peterson et al. 2002)



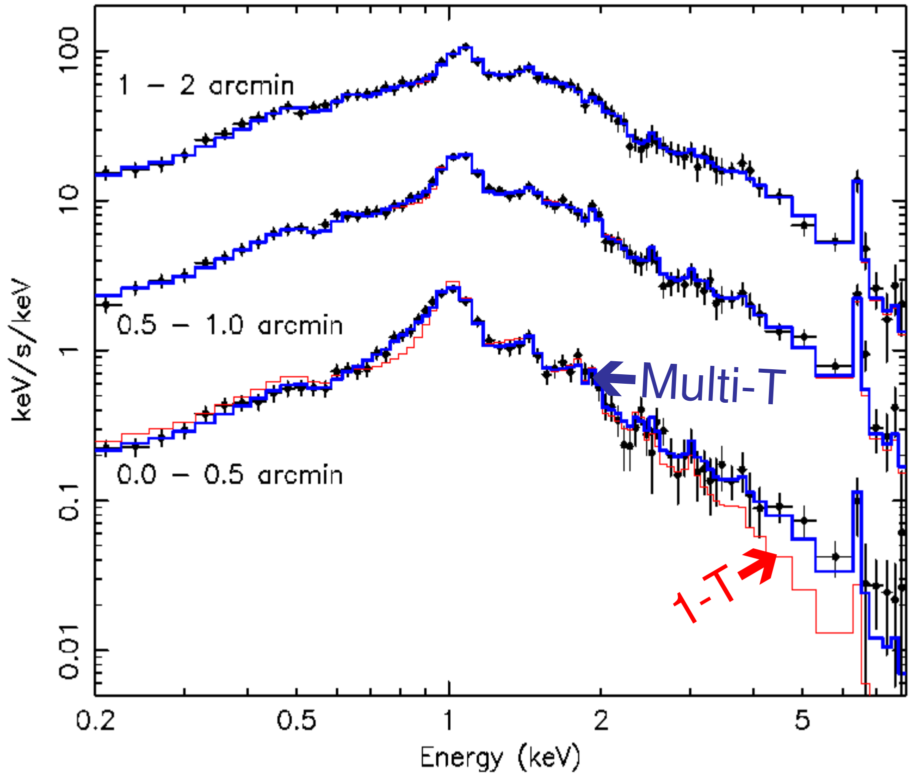
# Differential Emission Measure

- In general, too little cool gas
- Most popular models: additional heating occurs (for example AGN, heat conduction, mixing, …)



# Multiphase gas: EPIC

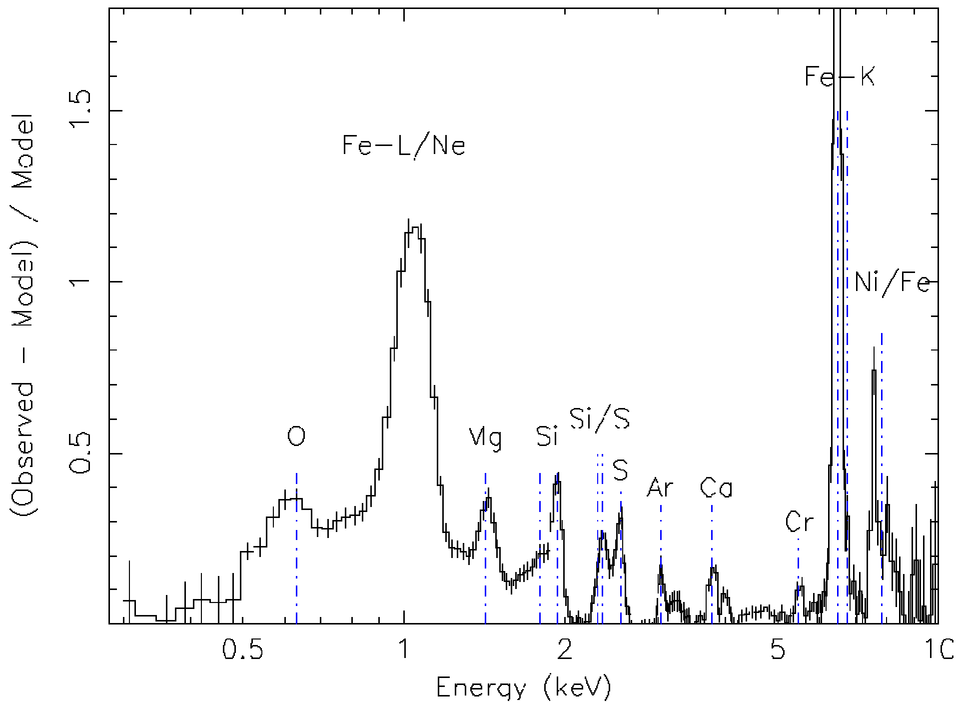
- Single T fits good first approximation
- But often $\chi^2$ enhanced in central shells:
- Example: A 2052
- Need multi-T plasma
- Needs high-res confirmation



# 3. Recent highlights: abundance determinations

# Nucleosynthesis in action: EPIC spectra …

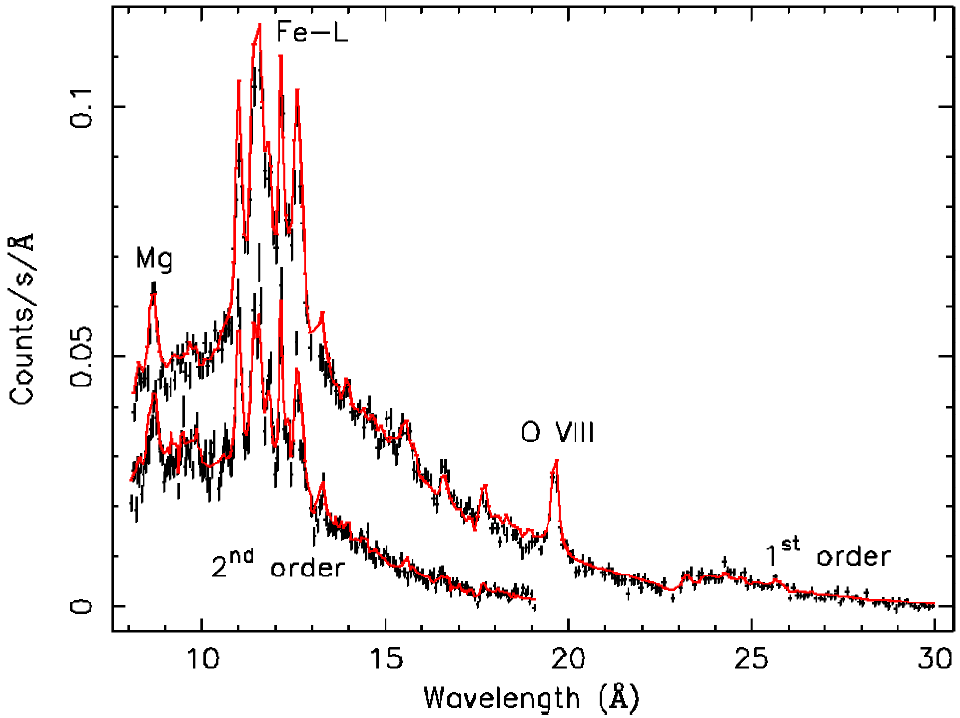
- Current best case: deep XMM-Newton observation of one of brightest clusters
- First evidence of traces of Cr
- Needs higher spectral resolution and sensitivity



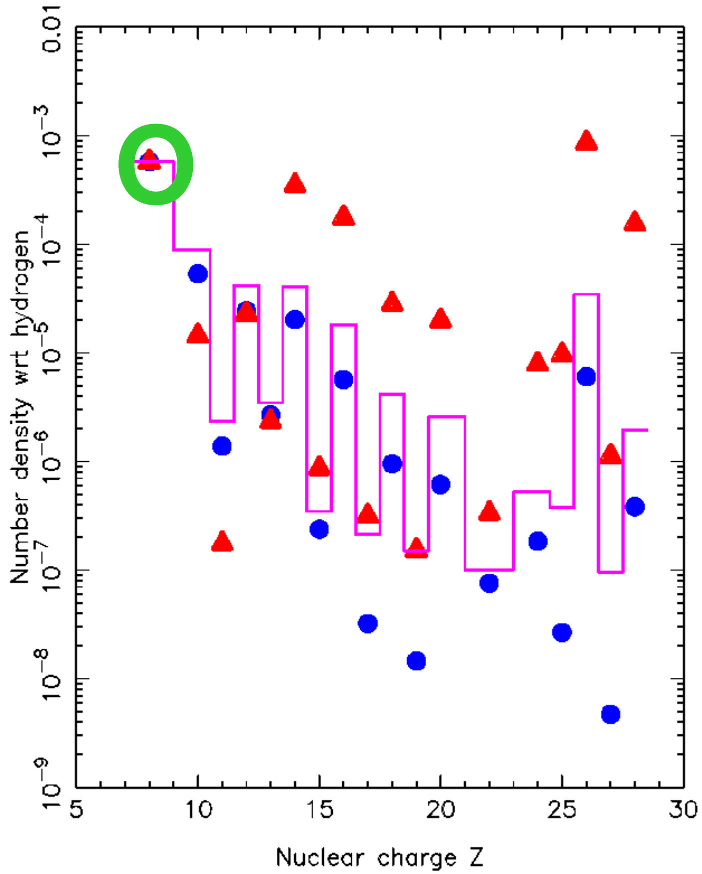

2A 0335+096,
Werner et al. 2005

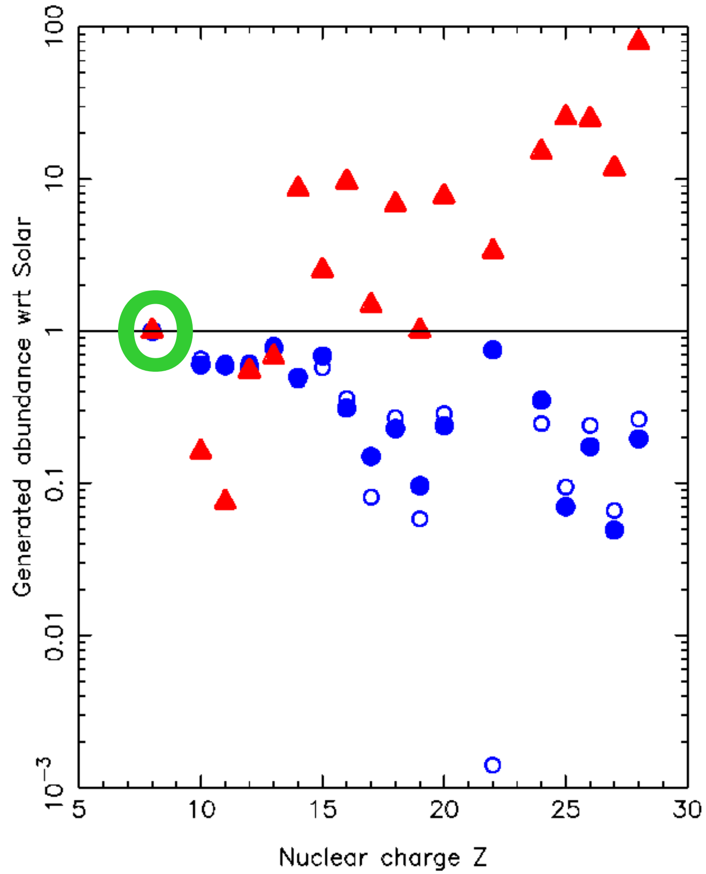
# … and of course RGS!

- Strong point of RGS: abundances of CNO
- Example: 2A 0335+096 (same data set as EPIC spectrum previous slide)

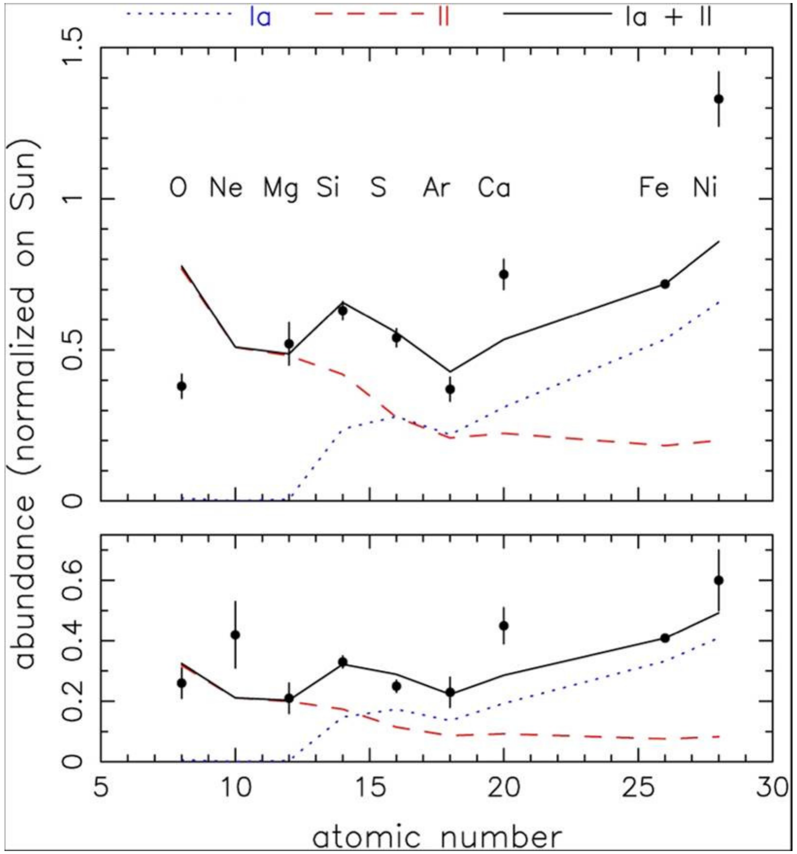


# Type Ia, Type II and Solar abundances



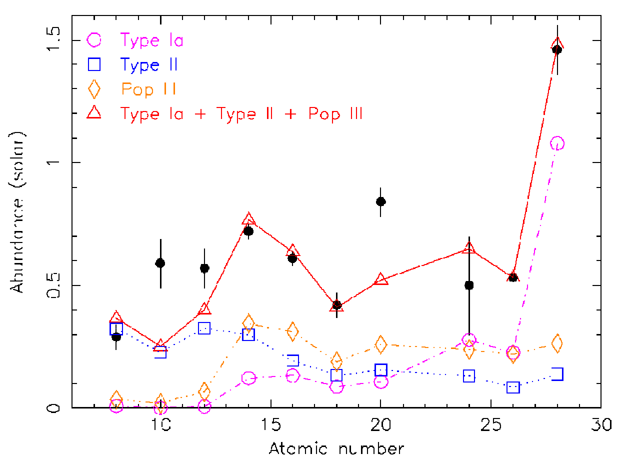



- 2A 0335+096 (top) and Sersic 159-03 (bottom)
- Light elements (O, Ne, Mg) from high mass SN (type II)
- Heavy elements (Fe, Ni) from WD collapse (type Ia)
- Ratio II/Ia is 2-3
- Few $10^9$ sn Ia per cluster

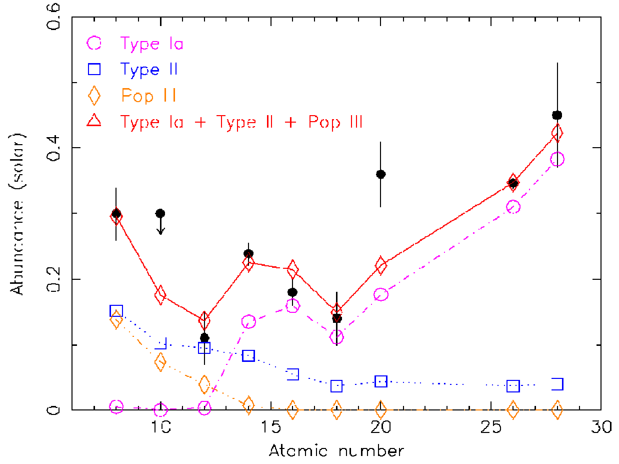


# Decomposition in SN types

- If sufficient # elements measured with high S/N, decomposition in type Ia, II and pop III stars possible




Werner et al. 2005



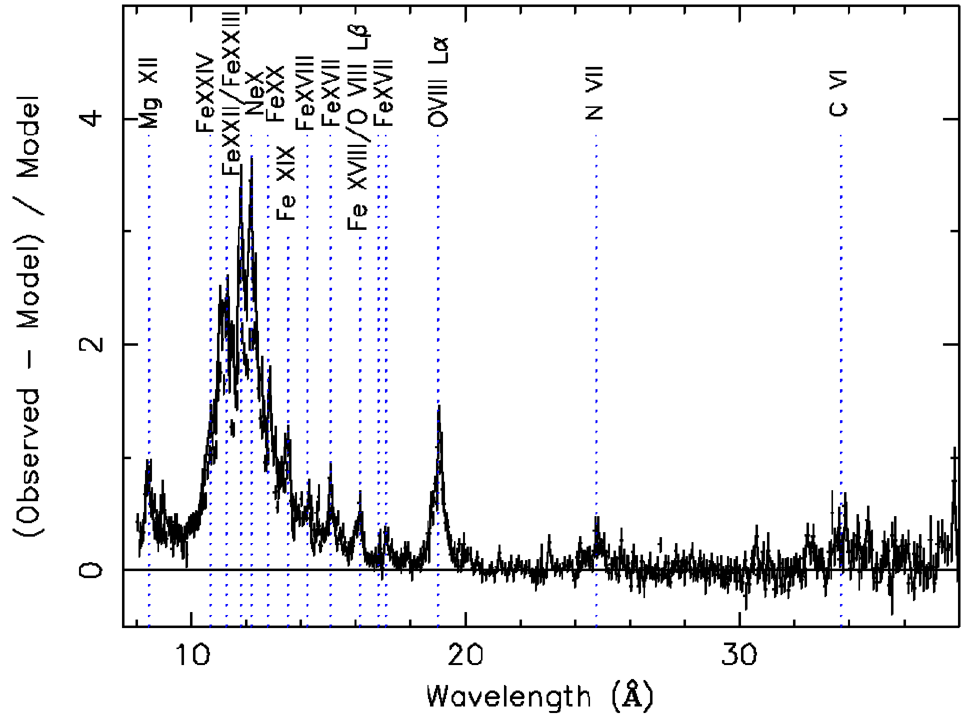

De Plaa et al. 2005

# Another case: M 87

(Werner et al. 2006)

- Total exposure time: 169 ks
- Clear lines from O, N, and C seen
- C/Fe: 1.17±0.14
- N/Fe: 1.63±0.18
- O/Fe: 0.66±0.04
- Ne/Fe: 1.31±0.09
- Mg/Fe: 1.33±0.09
- ➔ AGB stars for CN!

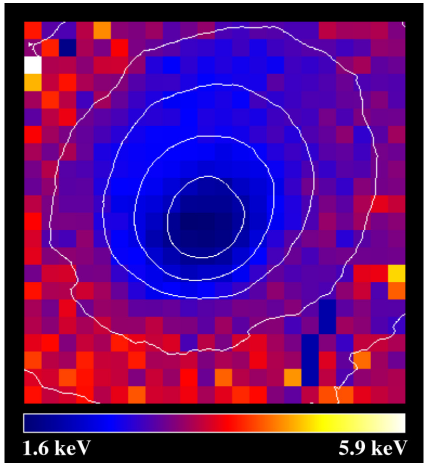
Continuum-subtracted RGS spectrum

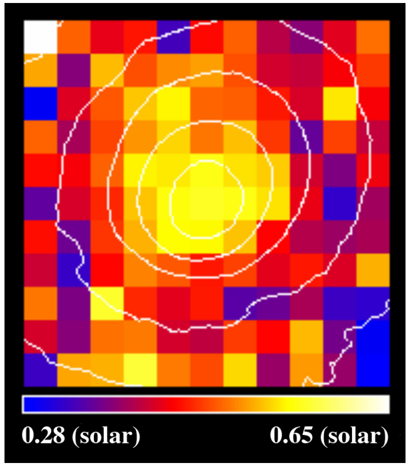


# 4. Future prospects

# What if we could resolve this…

- Plots show T-map and Fe-map in 2A0335+096 (Werner et al. 2006)
- Important to do this also for more elements: CNO, Ne, Mg, Si, etc.
- Need high spectral resolution and grasp

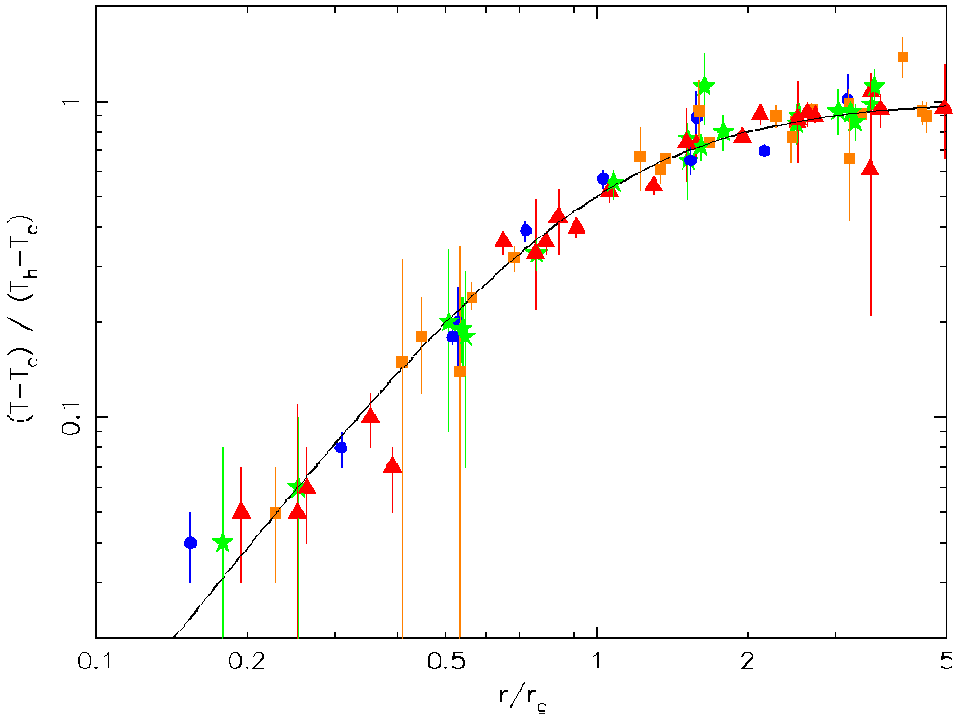


# What if we could resolve this: Temperature profiles

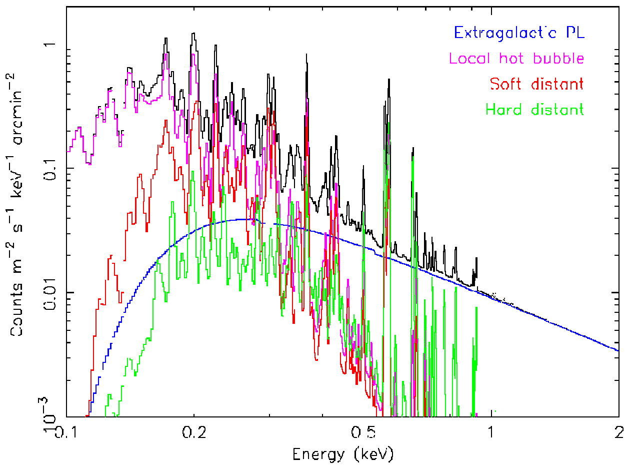
(Kaastra et al. 2004)

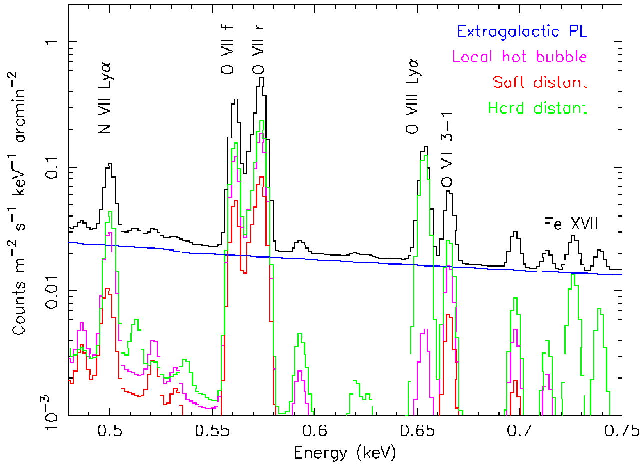
- T-profiles well resolved by EPIC
- But need to find spatially resolved temperature structure (i.e., more T components at same location)
- Only possible with new (non-grating) instrumentation



# X-ray background: need for high spectral resolution

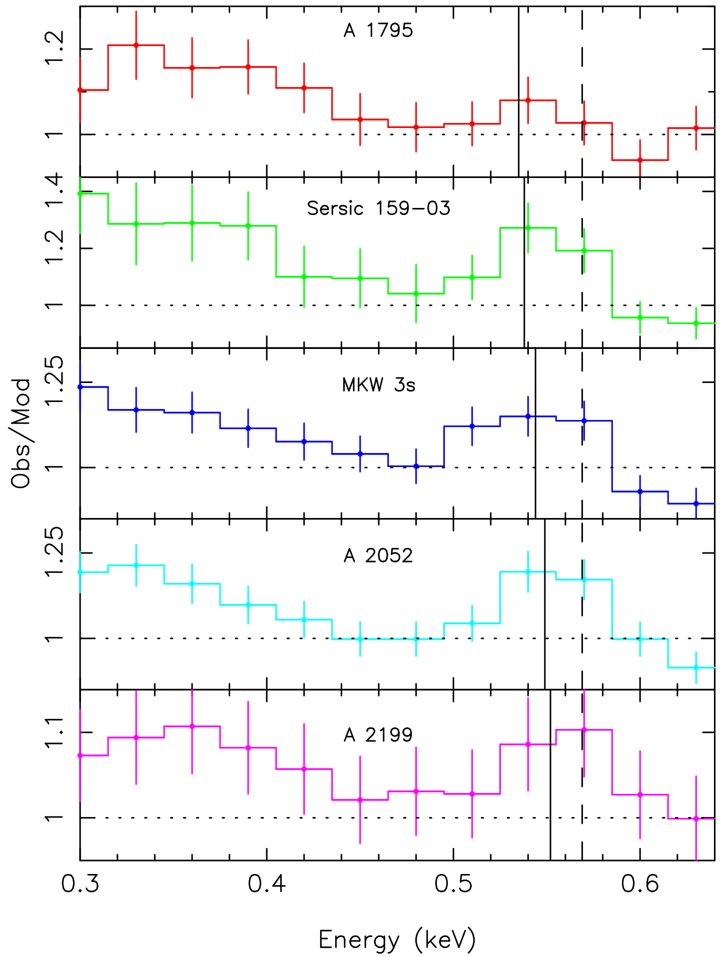
- X-ray background rich in structure
- Affects all observations of dim sources (in particular extended sources)
- Need to understand it
- Useful for study of diffuse Galactic abundances



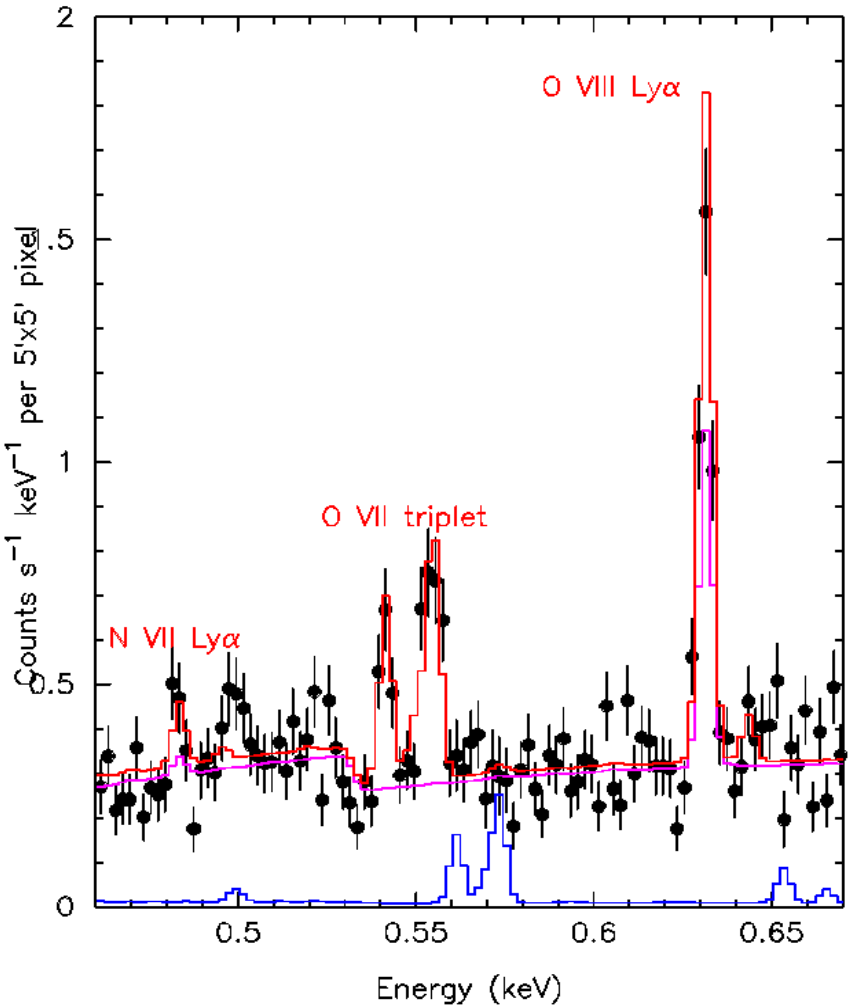
# Example: weak features in cluster outskirts: XMM-Newton O VII detection

- O VII lines are characteristic for 0.2 keV plasma
- Evidence for O VII emission in 5/21 clusters
- Emission has redshift of cluster
- But all unresolved…

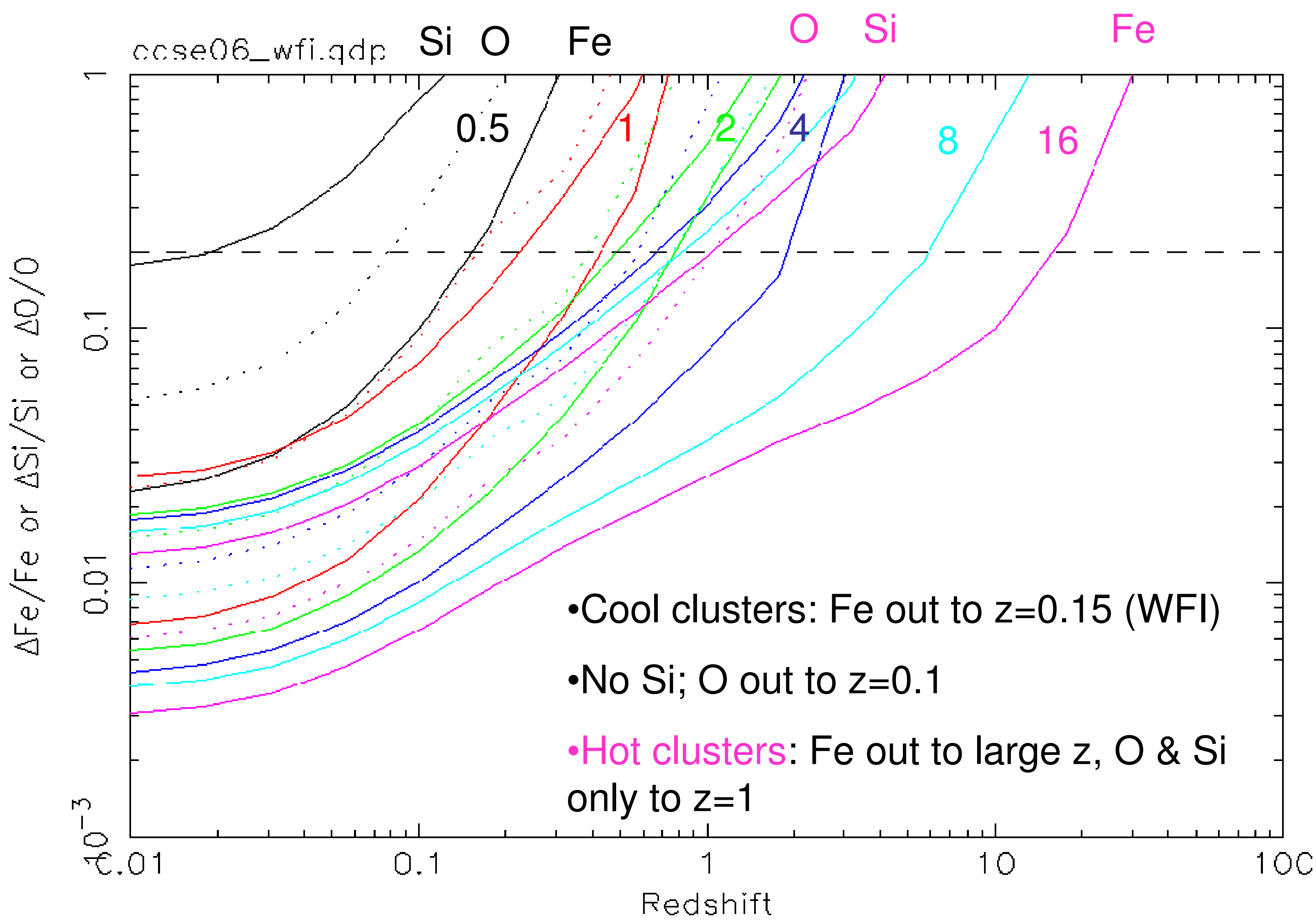


# Resolving diffuse O VII

- Example: MBE
- 4 eV resolution
- 6x6 pixels TES detector, 1ºx1º FOV
- Simulation: A 2052 at 5 arcmin off-axis

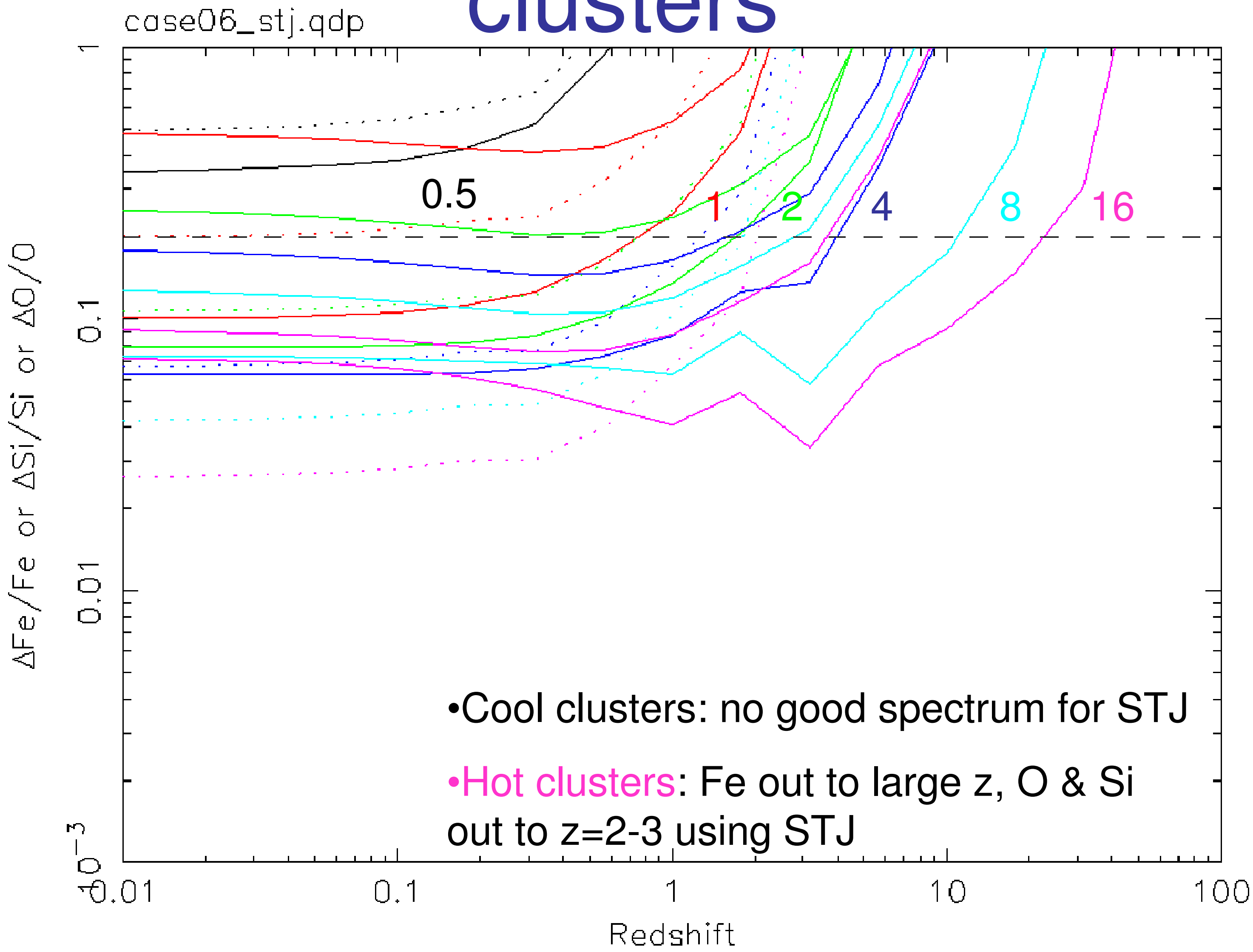


# XEUS: Abundances of Fe, Si, O in clusters




- Cool clusters: Fe out to z=0.15 (WFI)
- No Si; O out to z=0.1
- Hot clusters: Fe out to large z, O & Si only to z=1

# XEUS: Abundances of Fe, Si, O in clusters

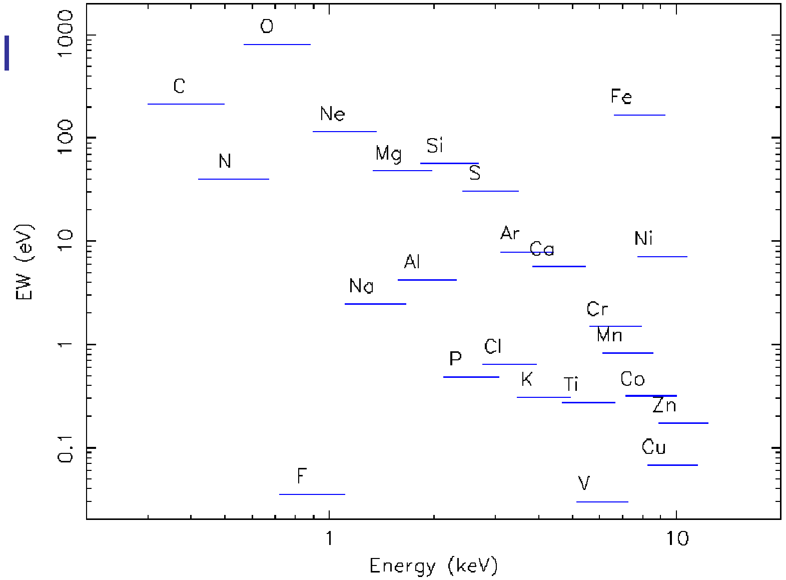


# More chemistry: rare elements

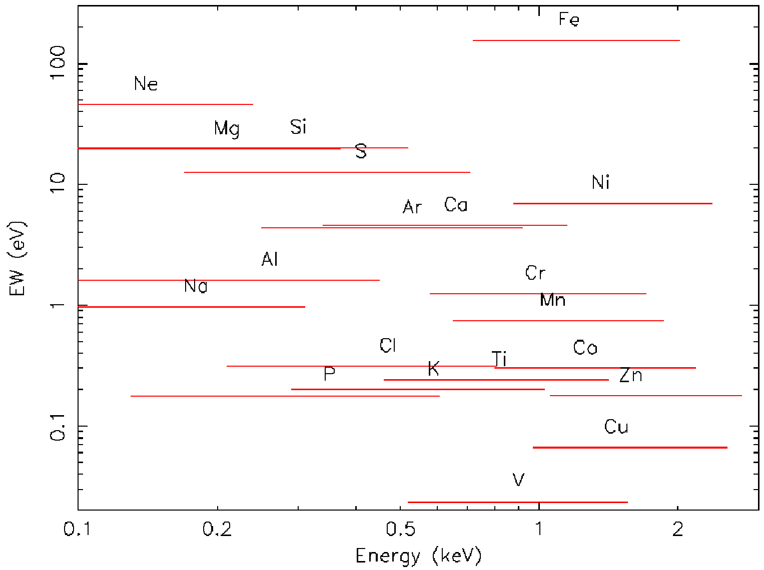
- Plots: maximum EW (as function of T) of lines for CIE plasma; solar abundances
- Lines with low EW need good:

1. Eff. area calibration
2. plasma diagnostics
3. atomic physics
4. bright sources

K-shell

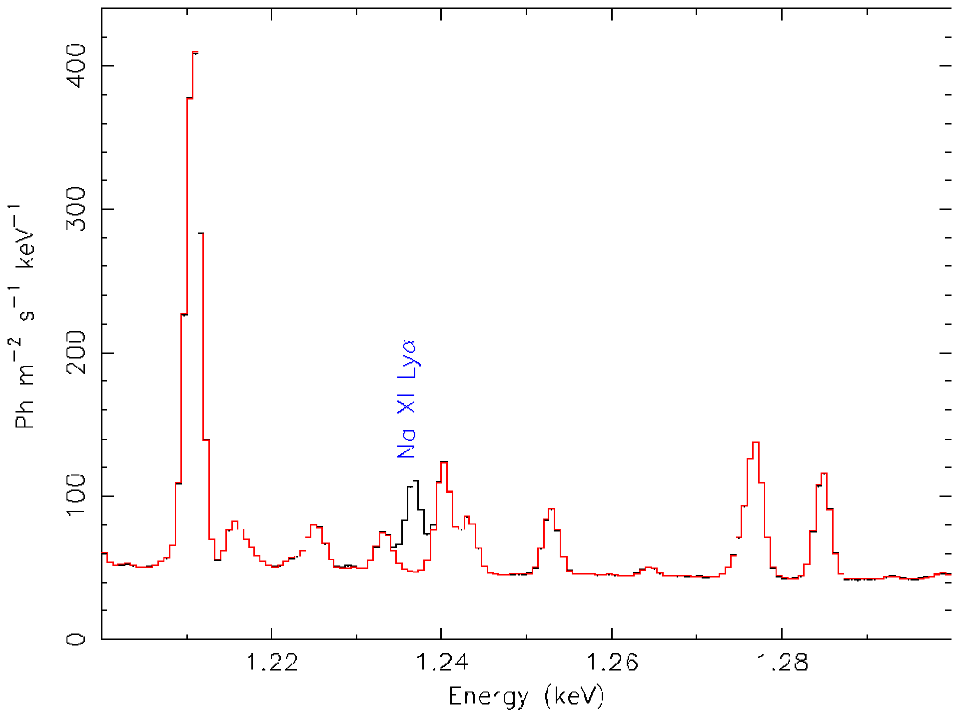



L-shell



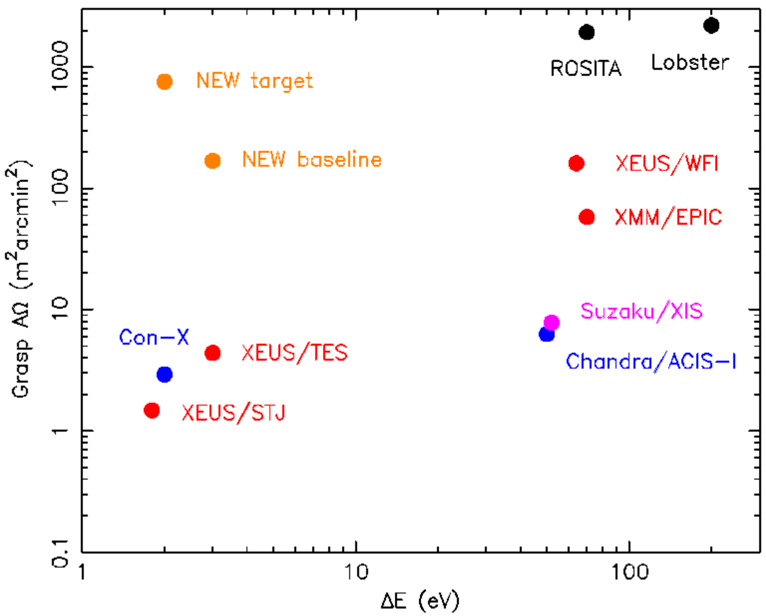
# Example: Na in coronal spectrum

- Needs to find weak lines in crowded spectral area
- High spectral resolution not only required for sensitivity but also for de-blending

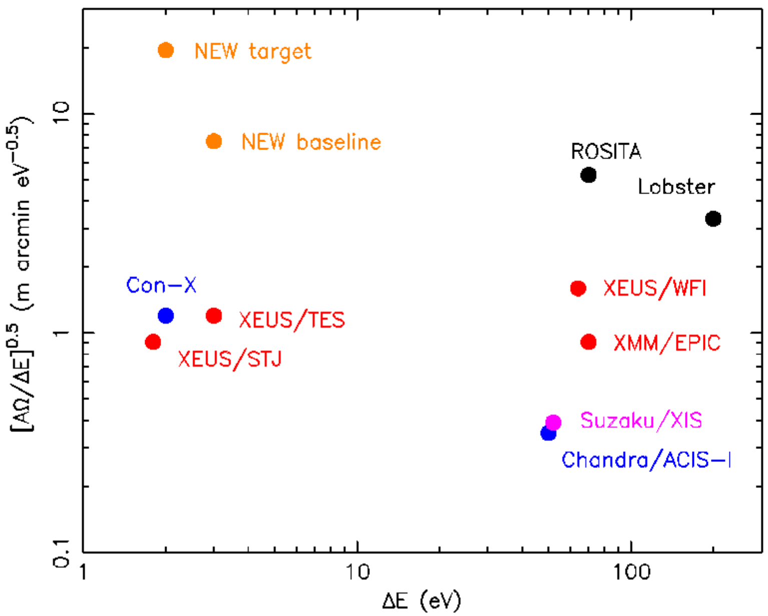


# Grasp versus spectral resolution

## Continuum

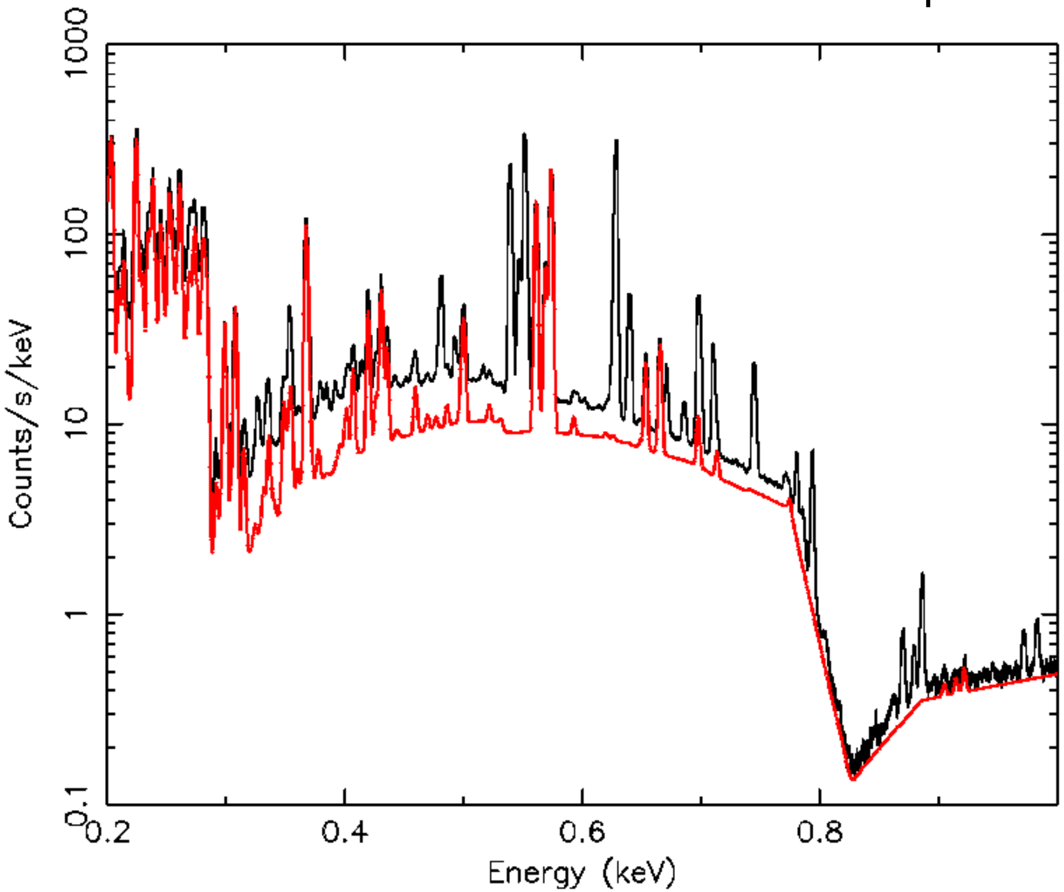



## Weak lines



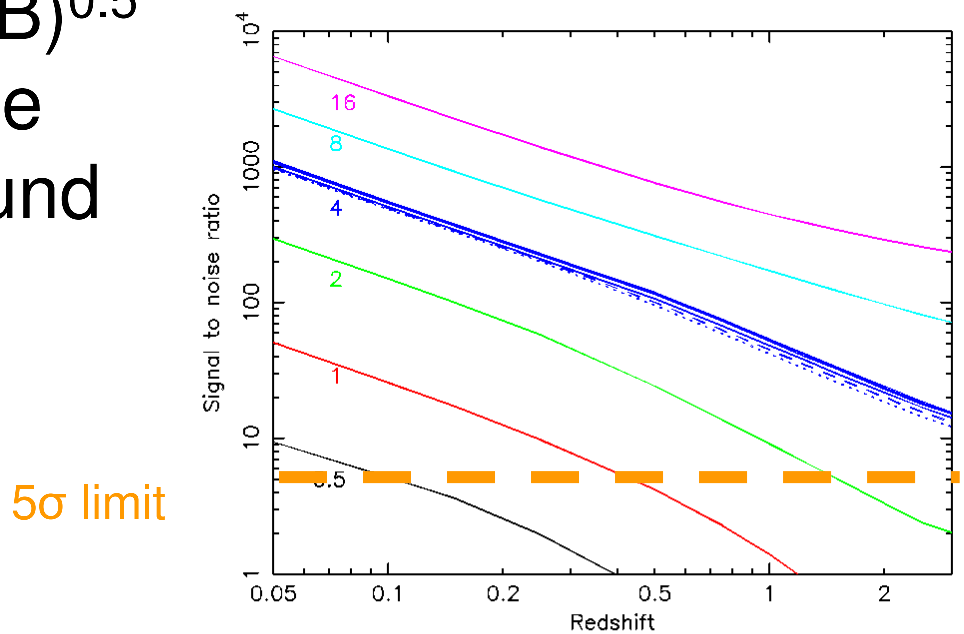
# NEW: expected spectra

WHIM spectrum near cluster



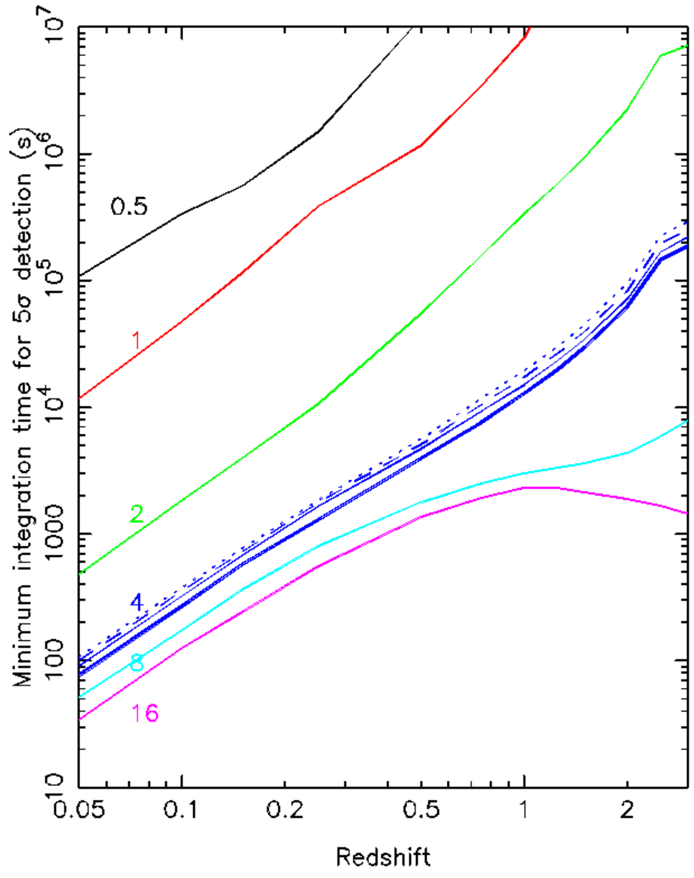
# NEW: Signal to noise ratio in cluster detections

- Broad-band S/N for radius where $S/(S+B)^{0.5}$ maximum (S=source counts, B=background counts)



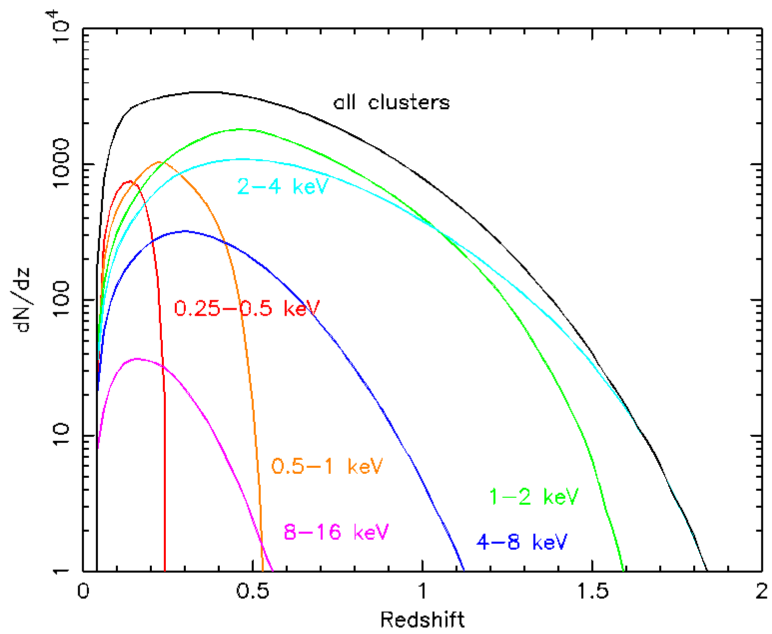
# Minimum integration time

- Hot clusters are seen wherever they are
- For high T clusters at very high z better visible!
- For cool clusters, longer exposure times really help: $10^6$ s exposure is great!



# Redshift distribution

- For low T, cut-off due to S/N: simply too low luminosity
- For high T, strong evolution effects
- Above ~2 keV, we see all clusters at any redshift
- Sample dominated by 1-4 keV clusters



# How many clusters do we see?

| | 7ºx7º<br>$10^6$ s | 7º x7º<br>All clusters | 70º x70º<br>$10^4$ s |
|---|---|---|---|
| 0.25-0.5 keV | 89 | 6776 | 0 |
| 0.5 -1 | 255 | 4584 | 129 |
| 1-2 | 1105 | 2330 | 2348 |
| 2-4 | 799 | 801 | 24032 |
| 4-8 | 143 | 143 | 14312 |
| 8-16 | 10 | 10 | 991 |
| TOTAL | 2400 | 14644 | 41813 |

# And of course:

- With the high spectral resolution foreseen for NEW (or XEUS, Con-X, etc…) we will have for bright clusters:
- Spatially resolved, high quality spectra containing in each pixel information on:
- T-structure, abundances, turbulence, velocity fields, ion temperature, etc.

# Conclusions

- High-resolution X-ray spectroscopy offers best opportunity to study detailed cluster physics
- The RGS of XMM-Newton opened this field with its break-through in cooling flow studies
- RGS (and EPIC of course) continue to provide high quality results; but we need to go to deeper exposures
- Excellent (technical) prospects for cluster research with new missions: now the funding!