CHEERS:
Chemical enrichment of clusters measured using a large XMM sample

Jelle de Plaa

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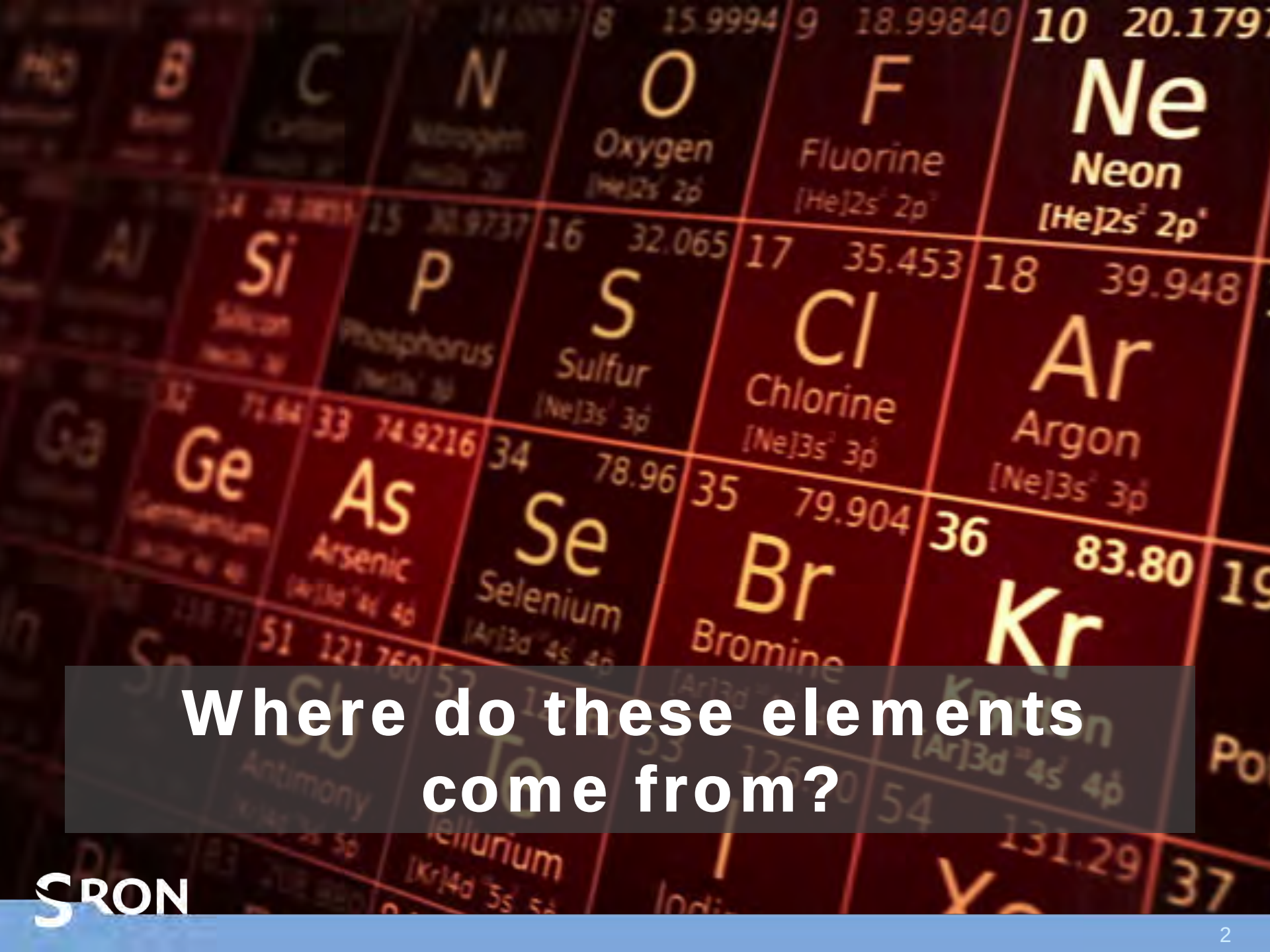
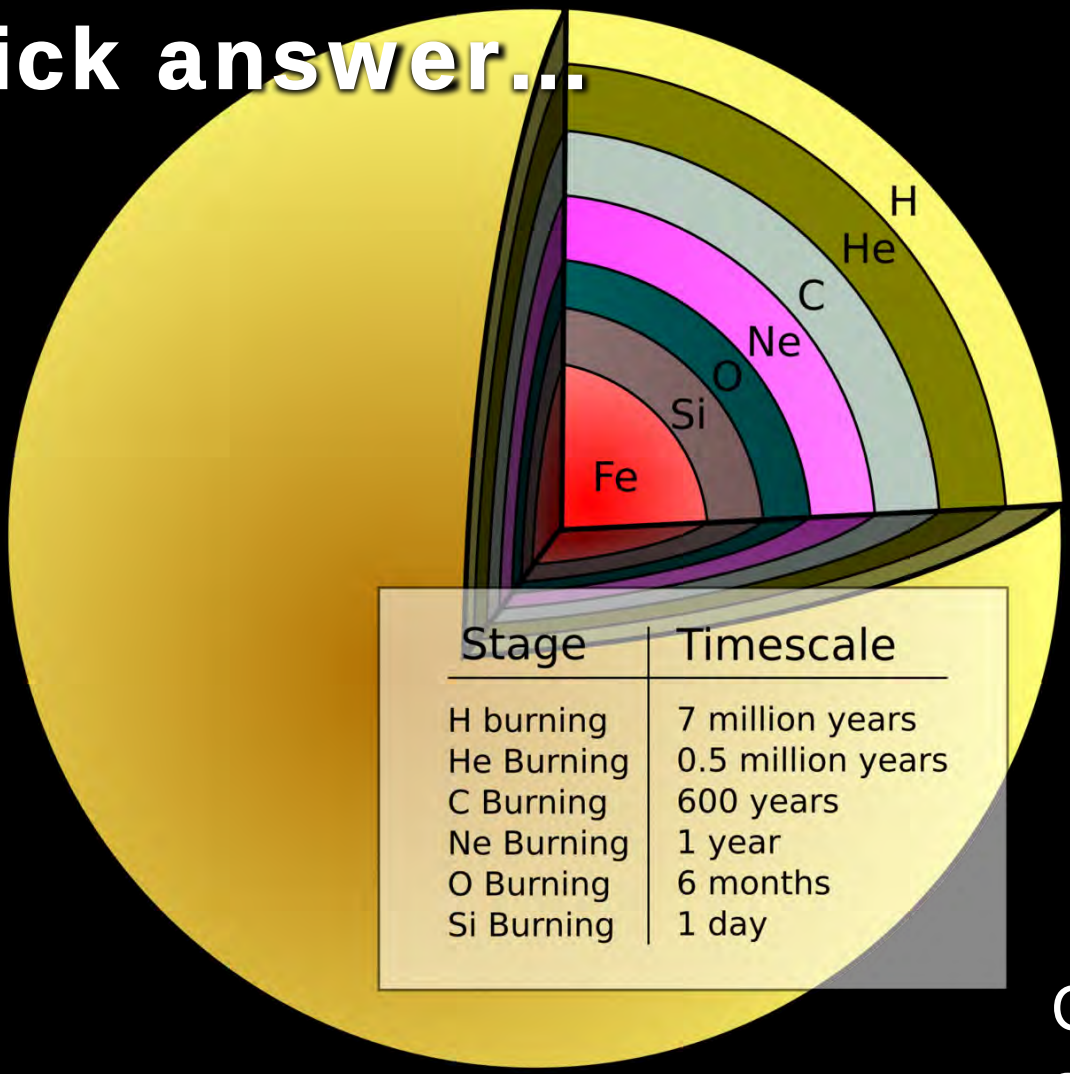
Netherlands Institute for Space Research

Netherlands Organisation for Scientific Research (NWO)

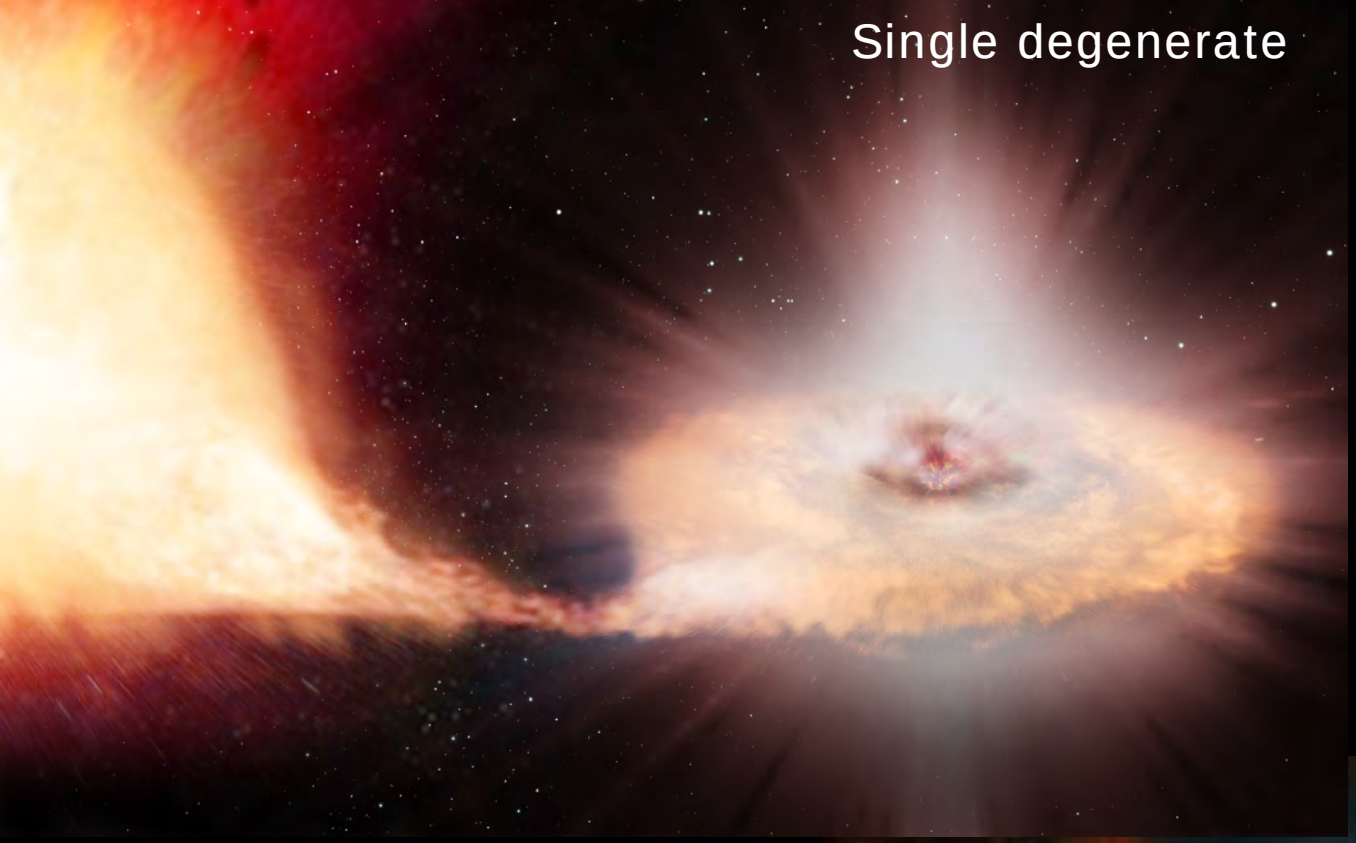

Where do these elements come from?

How do metals form?
The quick answer...



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

Core-collapse supernovae



Type Ia Supernovae

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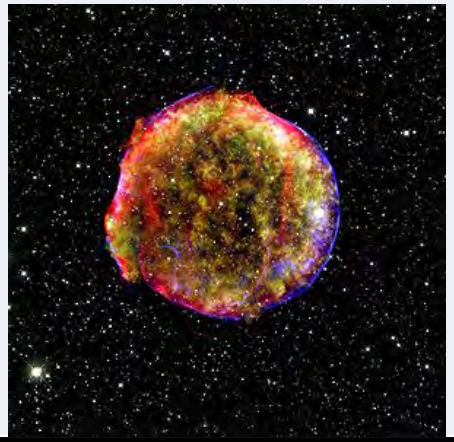
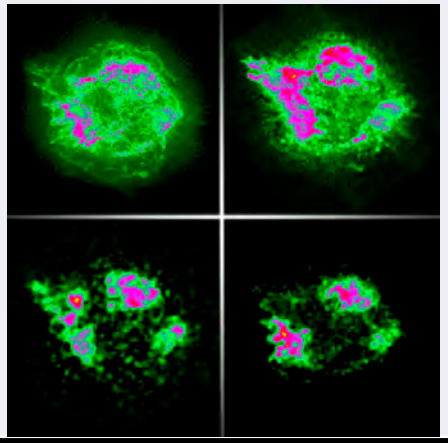
Sources of metals

Intermediate mass stars (AGB) $M < 8\ M_{sun}$	Type Ia Supernovae	Core-collapse Supernovae
Nitrogen & Carbon	High-mass elements (Si, S, Fe, Ni)	Low-mass elements (O, Ne, Si)
Phase of intermediate mass stars	White dwarfs	Massive stars
Strong winds	Explosive ejection into ISM	Explosive ejection into ISM
		

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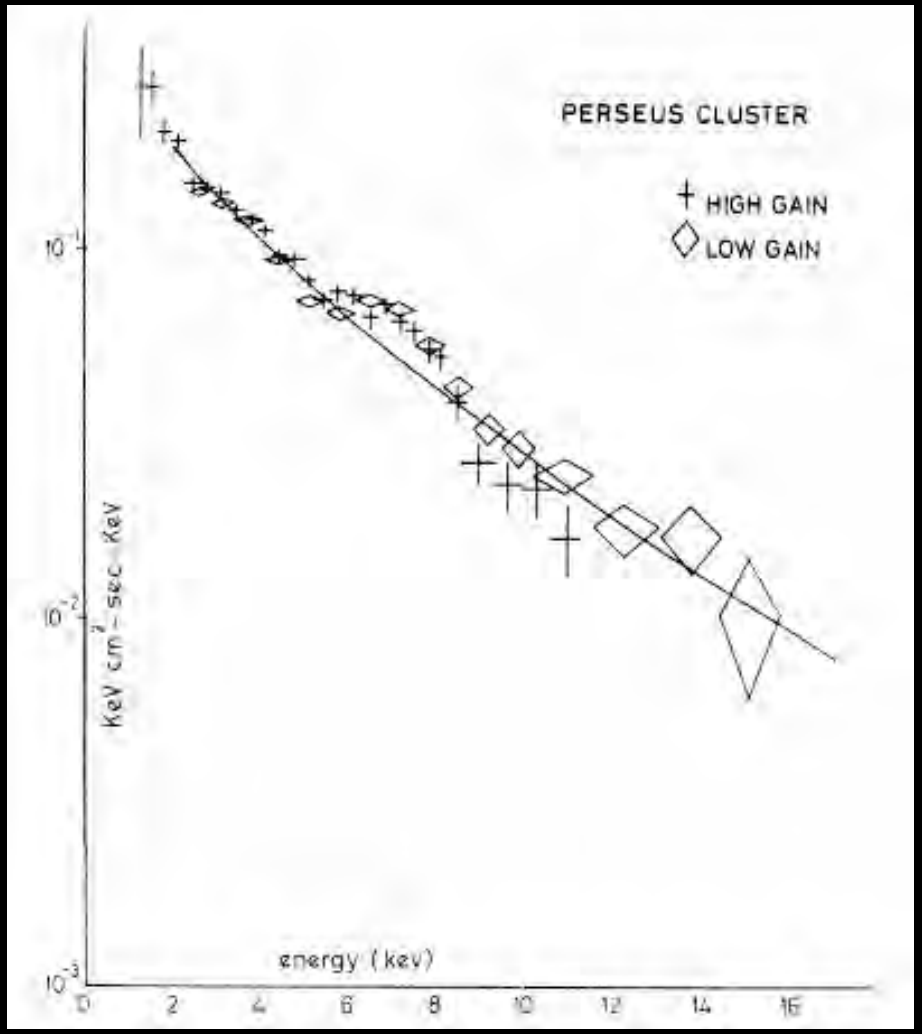
Supernova enrich at large scales!

- Discovery of iron line emission in the Perseus cluster



Mitchell et al. (1976)

Clusters of galaxies as probes of enrichment

- Study abundance of individual SNR not easy
- Clusters of galaxies contain yields of billions of supernovae
- Gas in hydrostatic and collisional-ionization equilibrium

What are the properties of the supernovae that enriched the ICM?

Abell 85

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Main ICM enrichment mechanisms

Galactic winds

Ram-pressure stripping

How and when were the elements distributed in the ICM?

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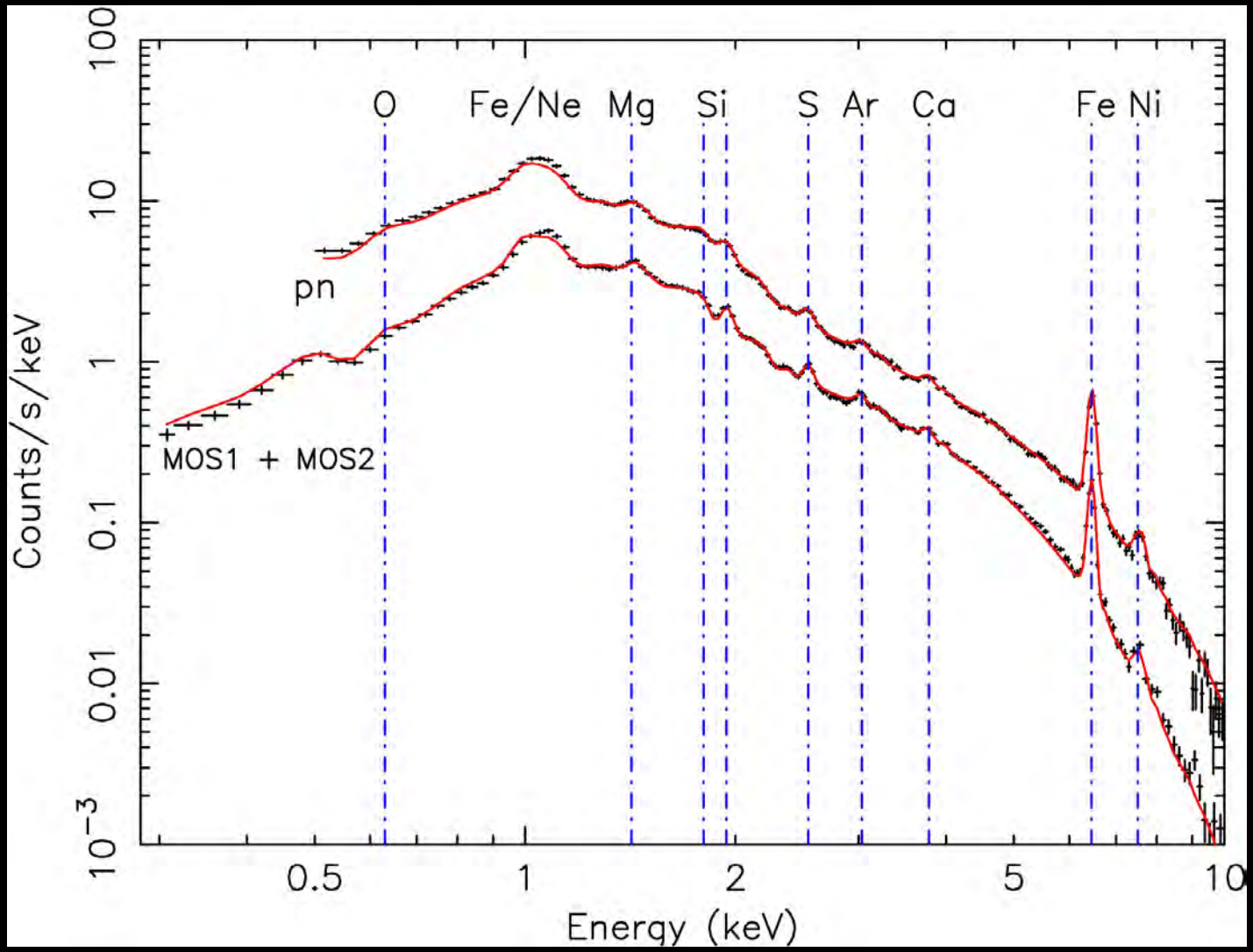
Measuring elements with XMM-Newton



2A0335+096, Werner et al., 2006

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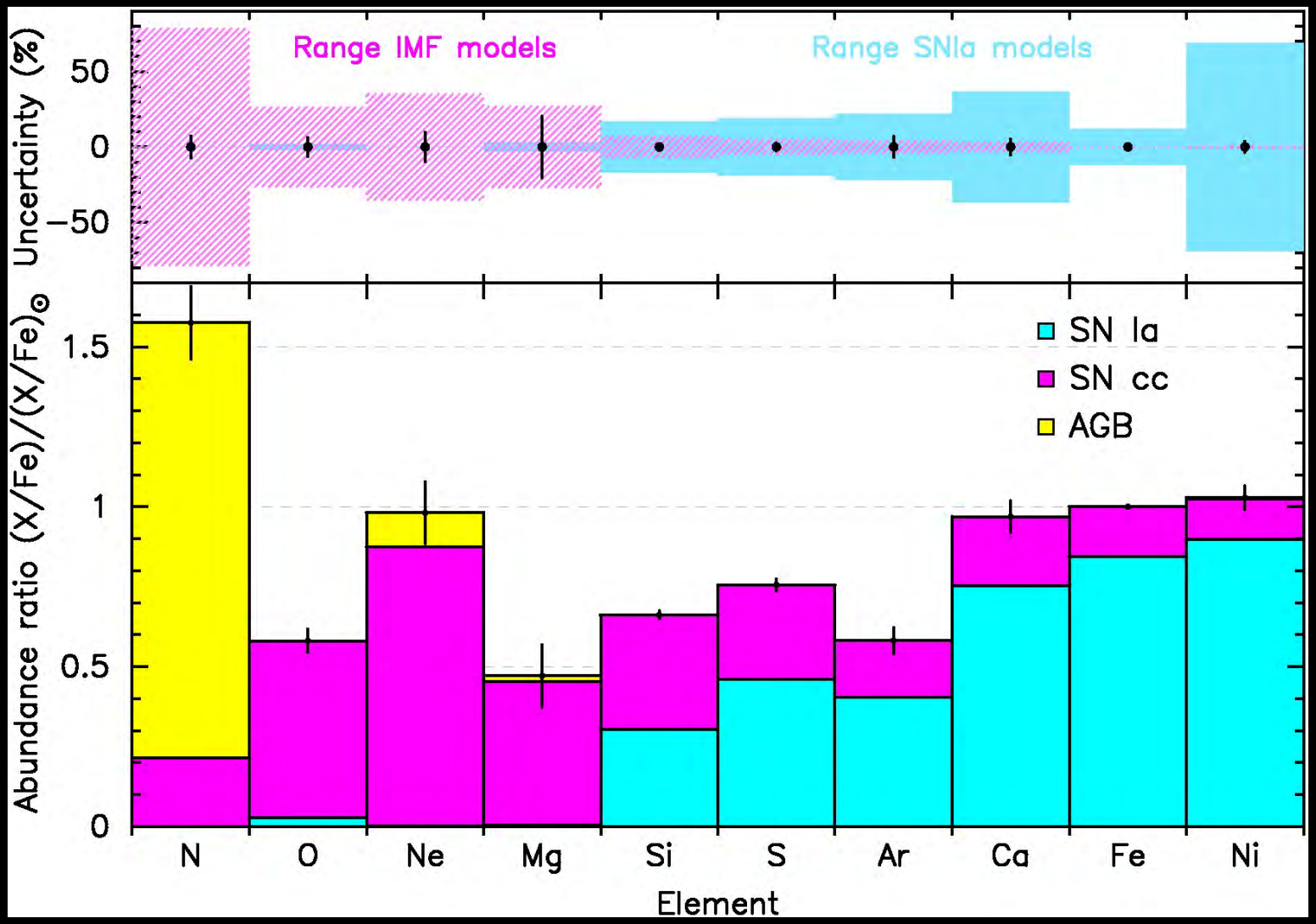
SNIa/SNCC contributions very uncertain



What about CHEERS?

CHEERS: CHEmical Enrichment RGS Sample

44 cluster observations with XMM-Newton (~4.5 Ms exposure, including 1.6 Ms VLP)

Main goals:

- Study chemical enrichment in cluster cores
- *Study turbulence (not this talk)*
- *Study thermodynamics of cluster core (not this talk)*

Create a 'complete' RGS legacy sample of clusters

See: https://personal.sron.nl/~jellep/cheers/

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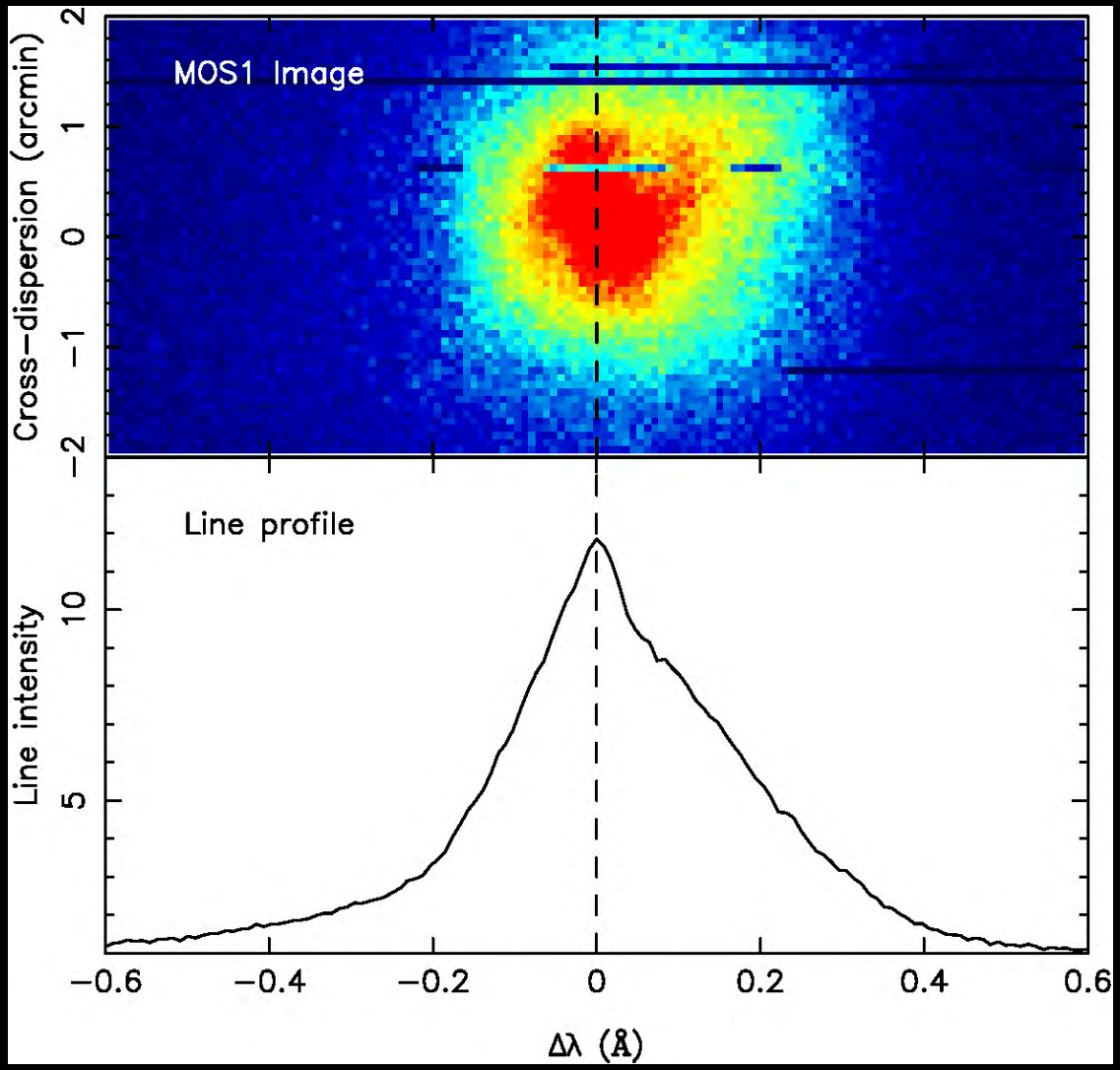
RGS line broadening



EPIC MOS images of all CHEERS clusters

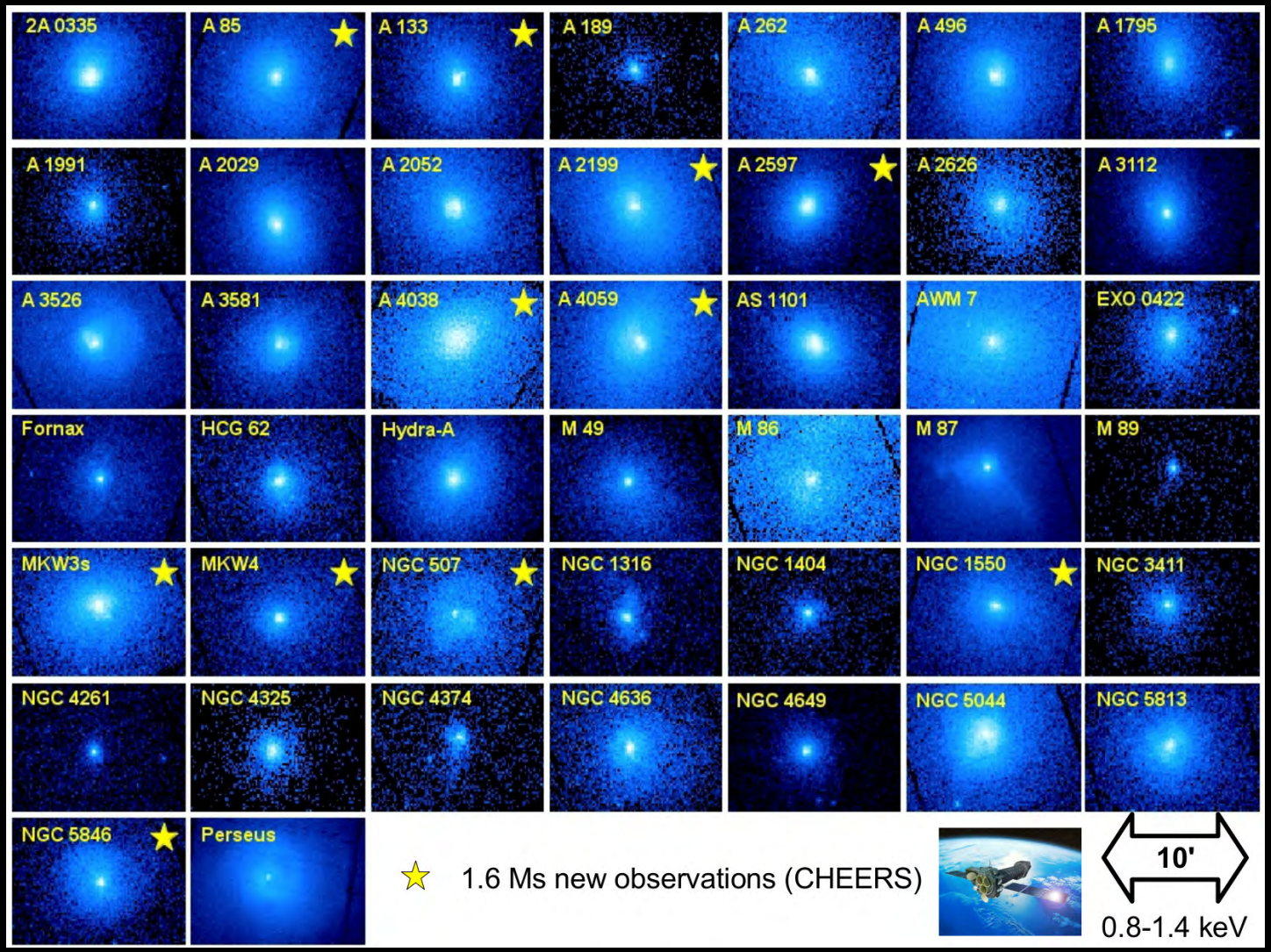
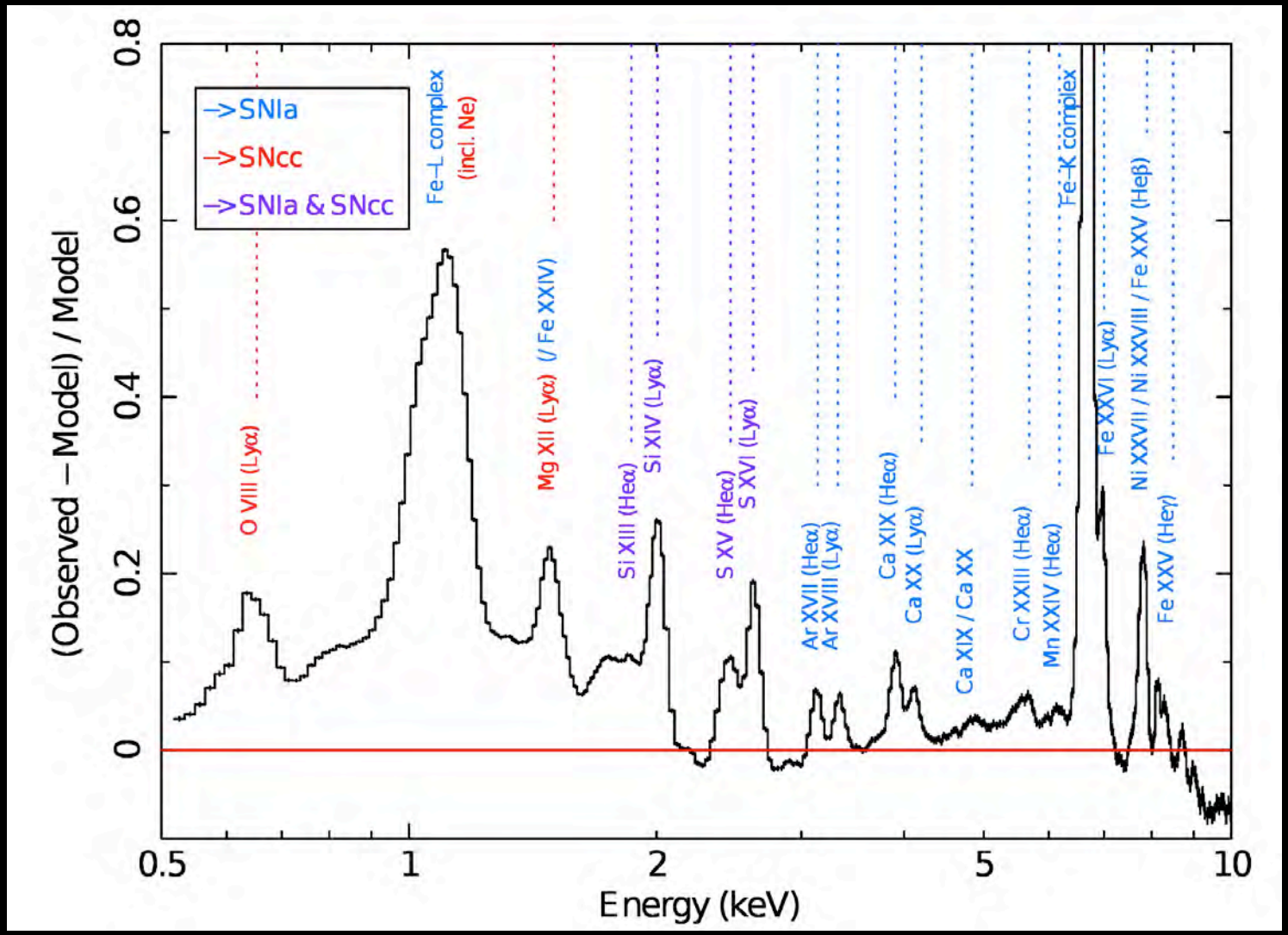


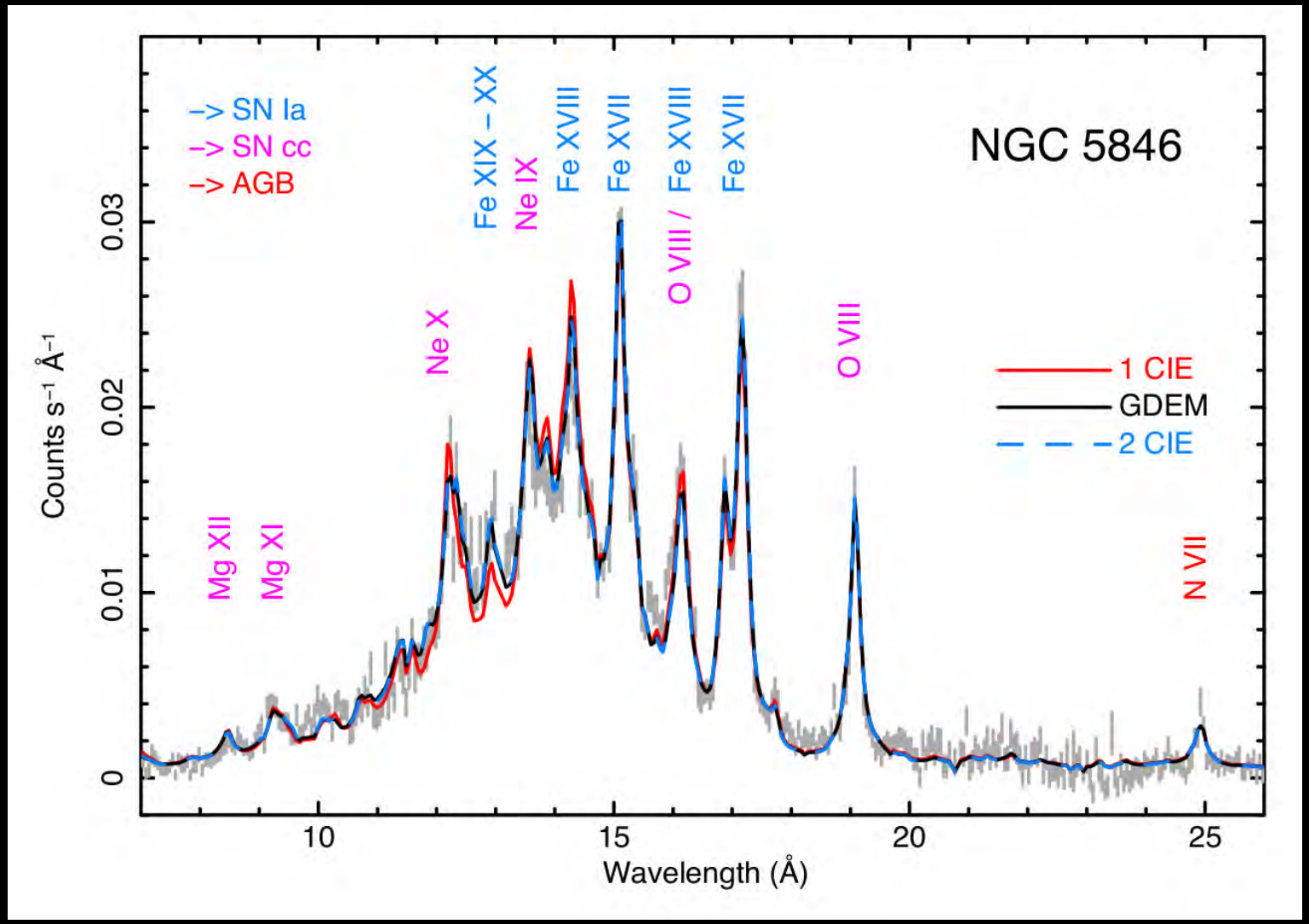
Image courtesy: Ciro Pinto

Measuring metals with EPIC with high statistics



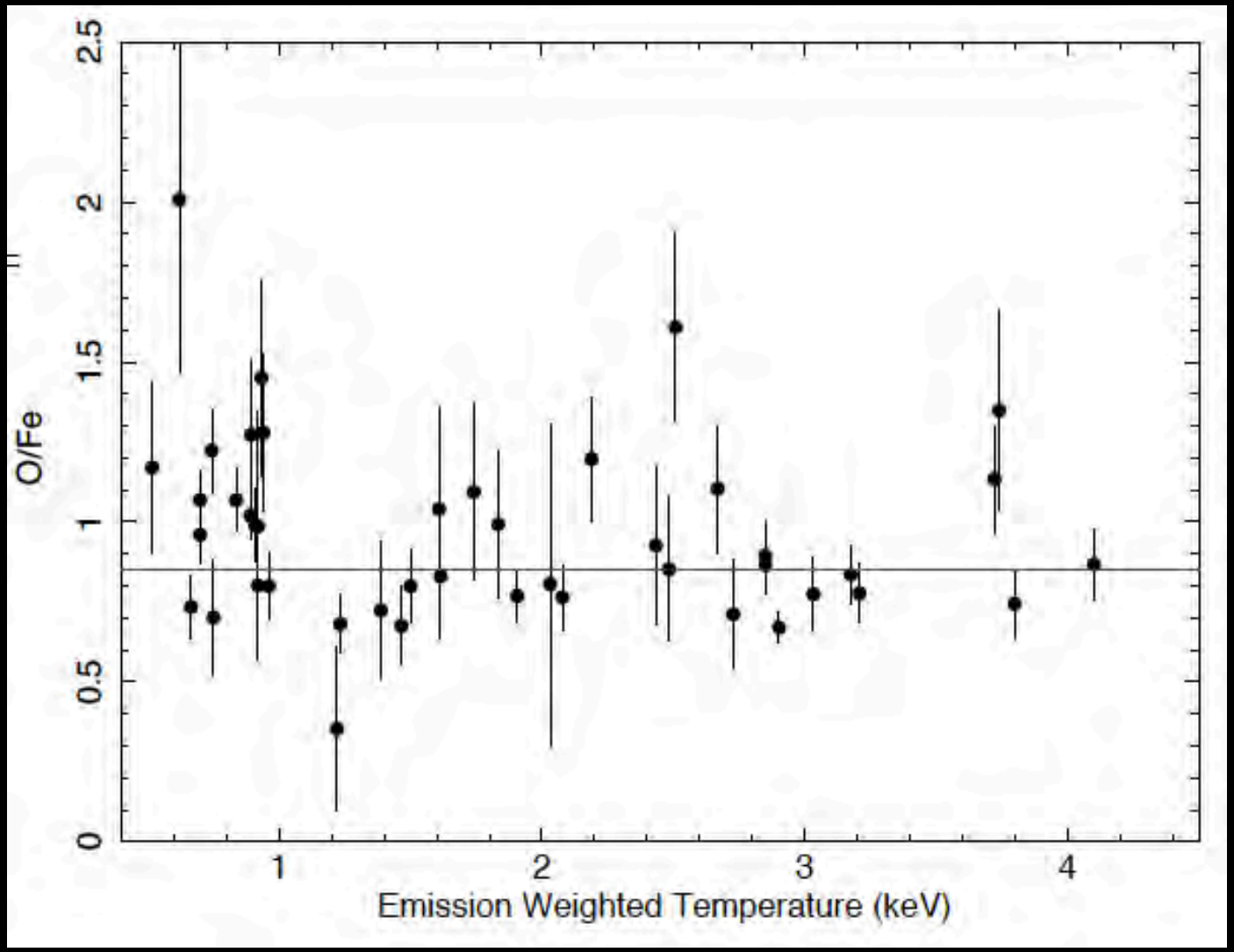
Mernier et al., 2016a

Measuring metals with RGS



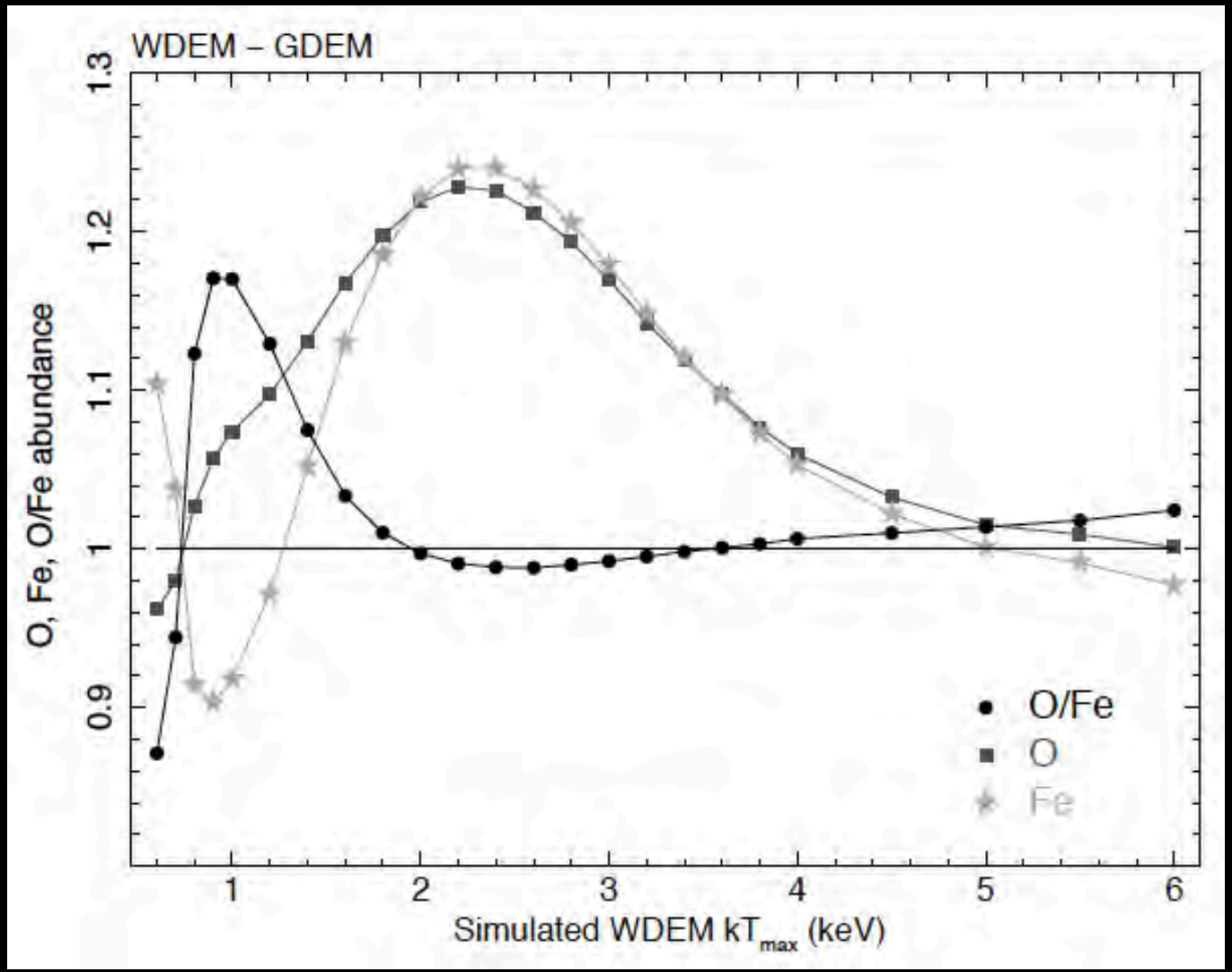
Pinto et al., 2015

Scatter in the abundance ratios: O/Fe (RGS)



RGS, de Plaa et al. 2017, submitted

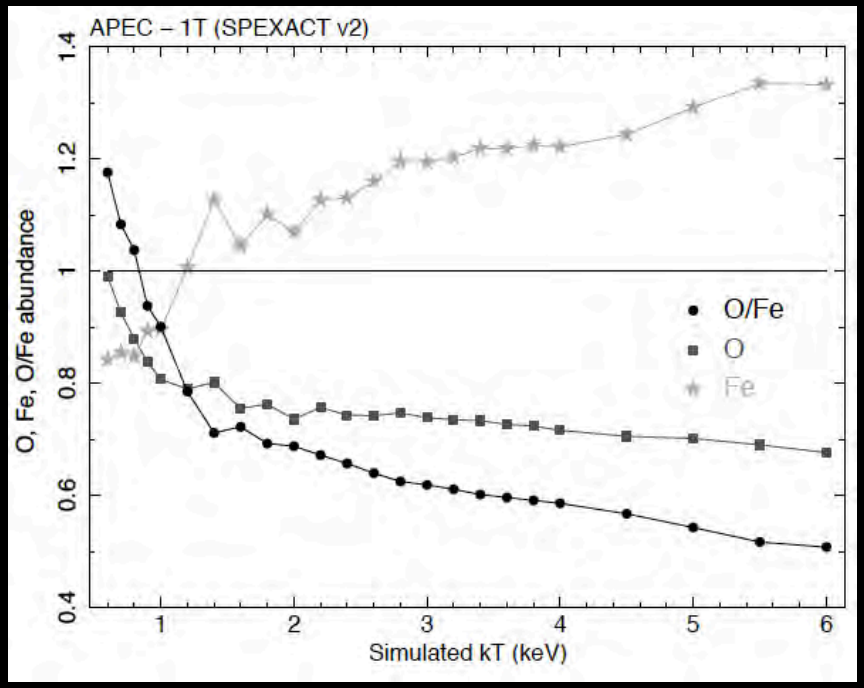
Systematics: Multi-temperature structure (RGS)



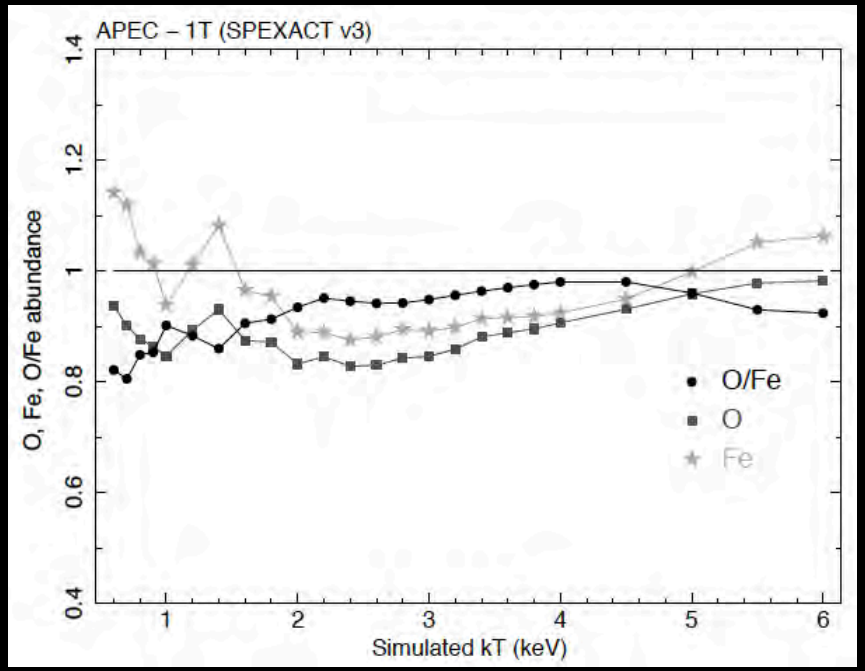
RGS, de Plaa et al. 2017, submitted

Systematics: The importance of atomic data

APEC vs SPEX v2

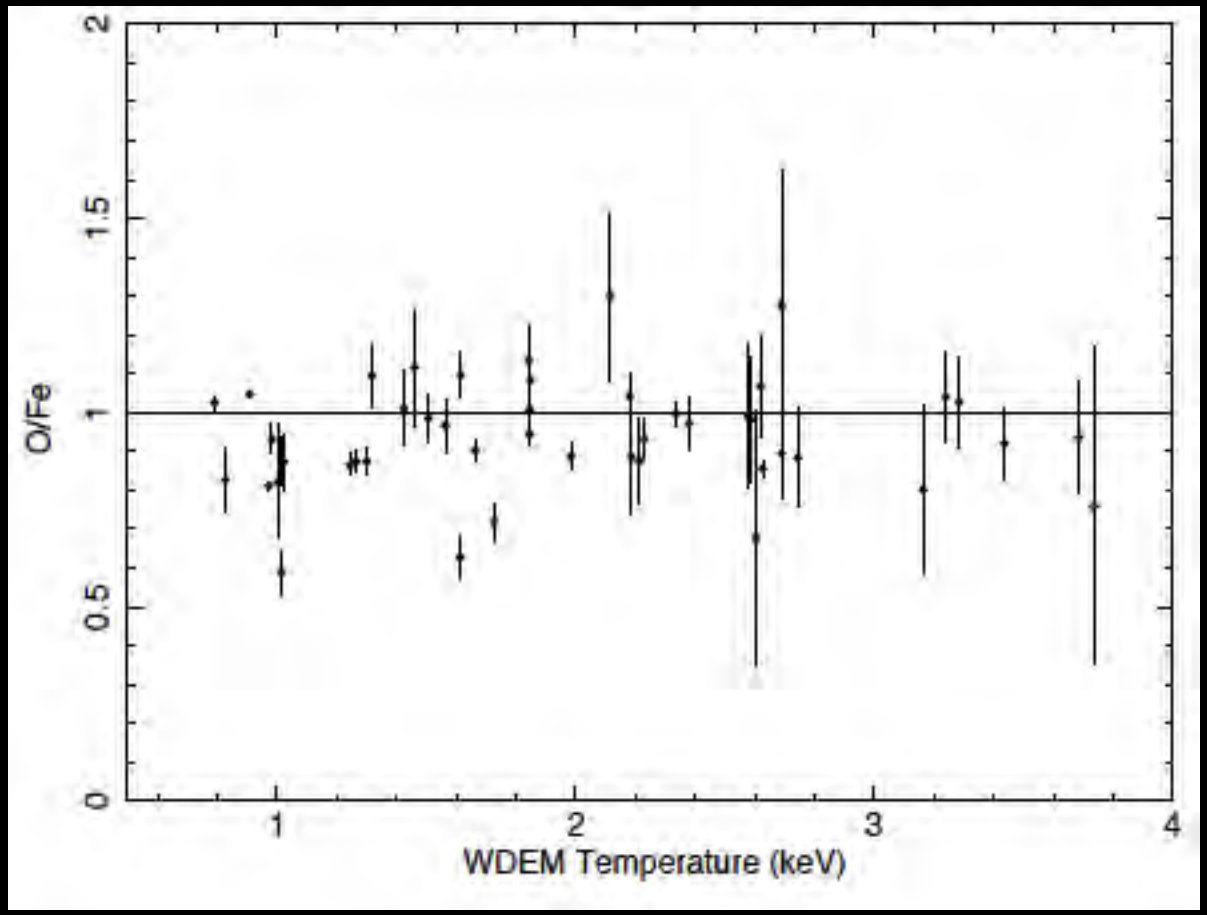


APEC vs SPEX v3



RGS, de Plaa et al. 2017, submitted

Systematics: Effect on simulated data > scatter



RGS, de Plaa et al. 2017, submitted

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How to deal with systematic uncertainty?

- Simulations suggest that systematics turn into scatter
- Formally systematic uncertainties can **not** be added in quadrature to statistical errors, but sometimes we have to…
- Conservative estimate is 20-30%, but lower than 40% for O/Fe (RGS)
- Difficult with current data to separate intrinsic from systematic scatter
- For combined data, the weighted average is shown with an error bar reflecting the scatter between clusters.

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Best abundances compared to SN models

This figure will be published in the final
version of Mernier et al. (2017b) with the title:

"Origin of central abundances in the hot intra-cluster medium III. The impact of spectral model improvements on the abundance ratios"

Reference details can be found here once the paper has been accepted and published:

https://personal.sron.nl/~jellep/cheers/papers.html

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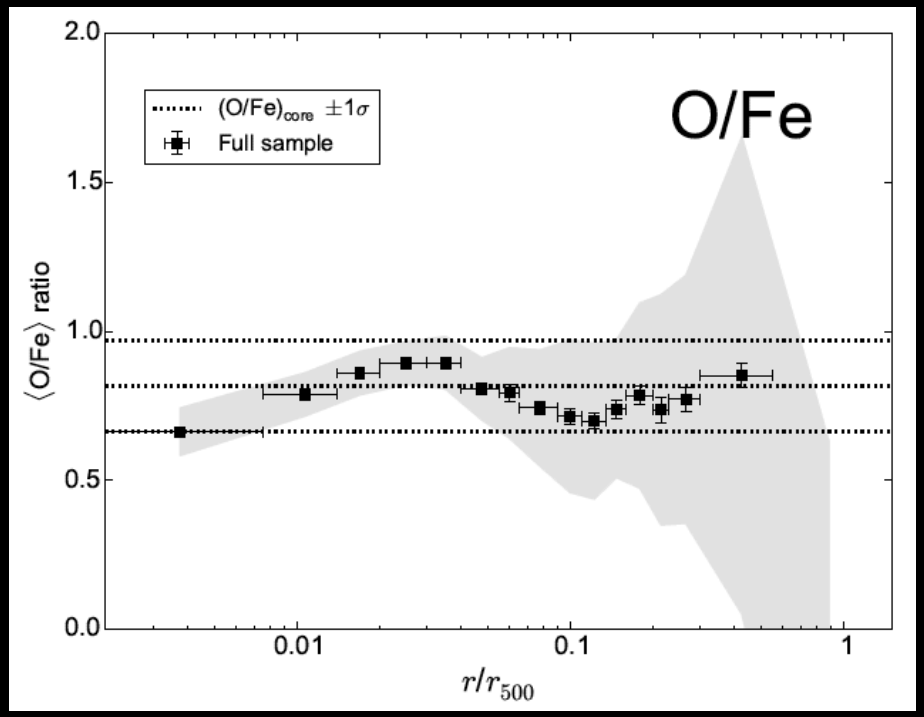
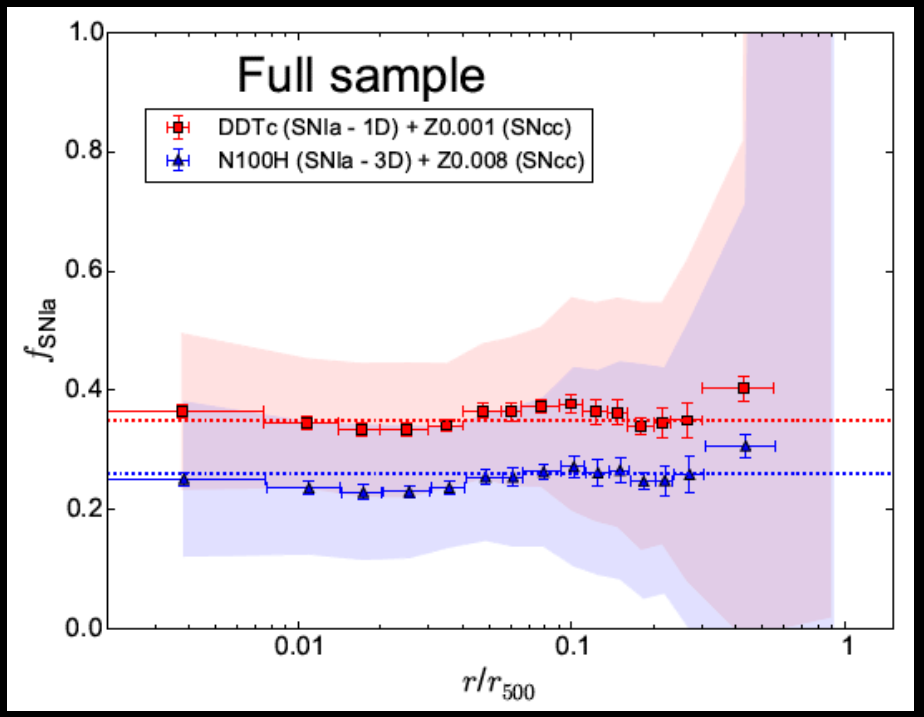
(Mernier et al., 2017b, submitted)

EPIC radial O/Fe and SN ratio profile





Mernier et al., 2017a, arXiv/1703.01183

How was the ICM enriched?

- This and other observations suggest early enrichment of ICM (z~2-3), consistent with, e.g., Simionescu et al. (2015)
- Metals were well mixed into pre-ICM by galactic winds during star-burst period
- Formation of ICM around z~2 stopped star formation, remaining SN activity and ram-pressure stripping is there but contributes little to ICM enrichment
- Few supernova models fit the data well (older 1D models fit better than new 3D models)

Summary

- Excellent XMM-Newton dataset with 4.5 Ms effective exposure
- Systematic effects are dominating!
- Atomic codes are main limiting factor for accuracy
- Also effect of multi-T structure, effective area calibration, etc.
- Systematic effects cause scatter on sample abundance results

- O/Fe ratio consistent with being constant with radius
- => SNIa/SNcc ratio constant with radius!

- Abundances accurate enough relative to other measurements, so good enough to constrain supernova models.

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