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

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Where do these elements come from?
How do metals form? The quick answer...

Core-collapse supernovae

<table>
<thead>
<tr>
<th>Stage</th>
<th>Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>H burning</td>
<td>7 million years</td>
</tr>
<tr>
<td>He Burning</td>
<td>0.5 million years</td>
</tr>
<tr>
<td>C Burning</td>
<td>600 years</td>
</tr>
<tr>
<td>Ne Burning</td>
<td>1 year</td>
</tr>
<tr>
<td>O Burning</td>
<td>6 months</td>
</tr>
<tr>
<td>Si Burning</td>
<td>1 day</td>
</tr>
</tbody>
</table>
Single degenerate

Type Ia Supernovae

Double degenerate
### Sources of metals

<table>
<thead>
<tr>
<th>Intermediate mass stars (AGB) $M &lt; 8 , M_{\text{Sun}}$</th>
<th>Type Ia Supernovae</th>
<th>Core-collapse Supernovae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen &amp; Carbon</td>
<td>High-mass elements (Si, S, Fe, Ni)</td>
<td>Low-mass elements (O, Ne, Si)</td>
</tr>
<tr>
<td>Phase of intermediate mass stars</td>
<td>White dwarfs</td>
<td>Massive stars</td>
</tr>
<tr>
<td>Strong winds</td>
<td>Explosive ejection into ISM</td>
<td>Explosive ejection into ISM</td>
</tr>
</tbody>
</table>
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
Main ICM enrichment mechanisms

Galactic winds

Ram-pressure stripping

How and when were the elements distributed in the ICM?
Measuring elements with XMM-Newton

2A0335+096, Werner et al., 2006
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/](https://personal.sron.nl/~jellep/cheers/)
RGS line broadening
EPIC MOS images of all CHEERS clusters

1.6 Ms new observations (CHEERS)

Image courtesy: Ciro Pinto
Measuring metals with EPIC with high statistics

![Graph showing observed metal lines at different energies, with labels for various elements and energy levels.](image)

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
How to deal with systematic uncertainty?

- Simulations suggest that systematics turn into scatter.

- Formally systematic uncertainties cannot 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.
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

(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.