

Chemical Abundances in Clusters

Why are they interesting ?

What can we learn about how and when the elements were created, what processes injected the metals into the IGM

Which stars produce the metals

What is the chemical abundance in the IGM and is it different than in galaxies

arXiv:1811.01967

Enrichment of the hot intracluster medium: observations

F. Mernieret et al

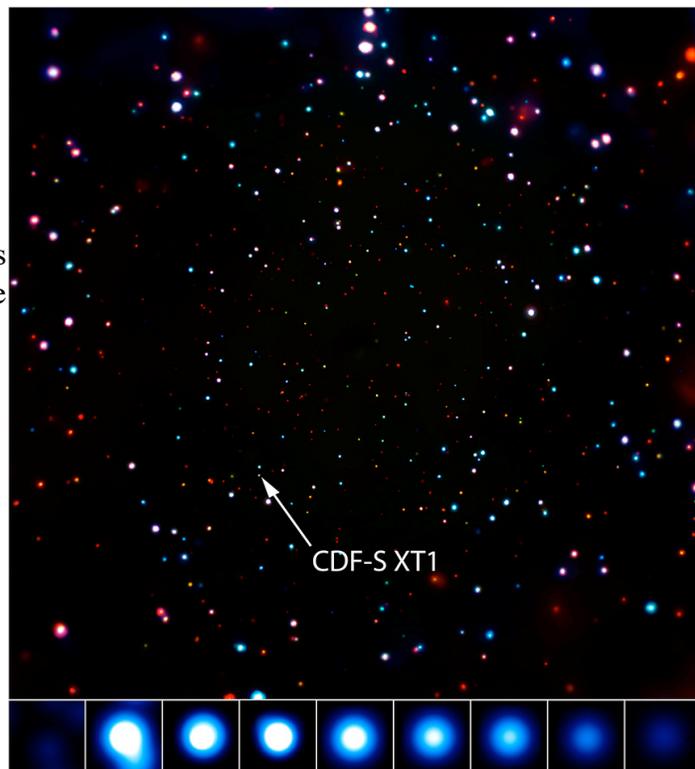
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Astronomy Picture of the Day - Today

sudden bright flash of X-rays from a previously invisible source, marked as "[CDF-S XT1](#)" It suddenly flared and stayed bright for a fraction of a day before fading.

The brightening and fading of is shown at the bottom of the image

Other X-ray sources show transient brightenings, but this source is peculiar. The way in which the source suddenly flared and faded, along with the change in the energy of the X-rays, does not seem to fit with any known type of X-ray variable. Perhaps CDF-S XT1 might be some type of exotic phenomena:



Homework 1

- Common mistakes- If you are unsure of what the problem is asking for or if the result you have obtained seems 'odd' please ask me a question. Quite a few students did come by for clarification.
- Problem 2

Some people integrated the background over 4 CCDs- Chandra images a point source to a few (2-4) Pixels

In calculating the brightness in the optical many people did not integrate the BB spectrum in the optical band and instead converted the total BB luminosity into an apparent magnitude

- Problem 4

I think the formula for the lifetime which contained $\sin \theta$ confused people and they solved for the angle. The angle is the pitch angle and one should use the average value of $\sin \theta \sim 1/2$

When doing this several people got the lifetime of the particles backward, particles that radiate at high energies have SHORTER lifetimes than those which radiate at low energies in the same magnetic field.

- The classic paper by Woltjer "B is of the order of 1 mG"
Current Science, Vol. 65, No. 2 (25 July 1993), pp. 123-130

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- Today on astro-ph Resolving the Crab pulsar wind nebula at teraelectronvolt energies-1909.09494.pdf

3

4 Chemical Abundances In Clusters

- Remember:
 - 80% of the baryons are in the gas
 - We detect line emission in the x-ray band from atomic transitions in H,He-like ions
 - Clusters are roughly big closed boxes
- Use these data to measure the chemical abundance of the gas
 - The strength of the lines depends on
 - Atomic physics
 - # of ions of a given species
 - Temperature
 - The number of protons (H atoms) depends on the strength of the bremsstrahlung continuum
 - The ratio of the number of ions to the number of protons is the abundance with respect to hydrogen
 - the gas is in 'coronal' equilibrium

Chemical Evolution of the Universe

- A major area of astrophysical research is understanding when stars and galaxies formed and how the elements are produced
- With the exception of H and He (which are produced in the big bang) all the other elements (called metals in astrophysical jargon) are "cooked" in the centers of massive stars and supernova and then "ejected" by explosions or winds
- The gas in these explosions is moving very fast (1000 km/sec) and may escape a galaxy.
- Clusters are essentially giant "boxes" which can hold onto all their material-Measurement of the amount and change of metals with time in clusters directly measures their production

Chemical Evolution of the Universe

- In the hot gas elements such as silicon and iron have only 1 or 2 electrons

These ions produce strong H, He like x-ray emission lines.

The strengths of these lines is 'simply' related to the amount of silicon or iron in

the cluster

Legend																	
Big Bang				Large stars				Supernovae									
Cosmic rays				Small stars				Man-made									
H															He		
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra																
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

The Cluster gas is a good place to measure abundances

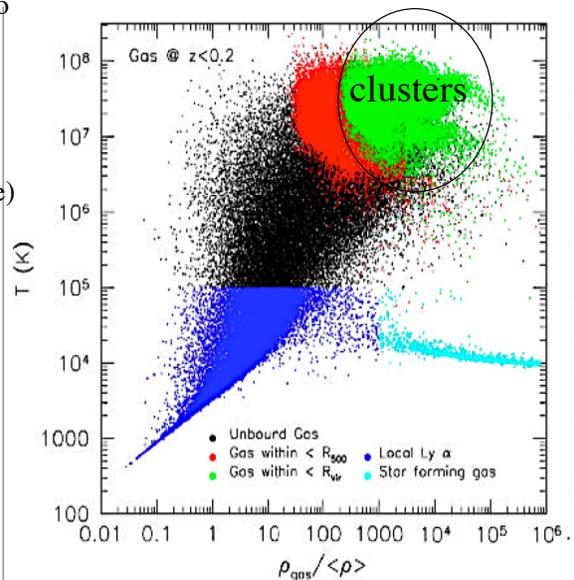
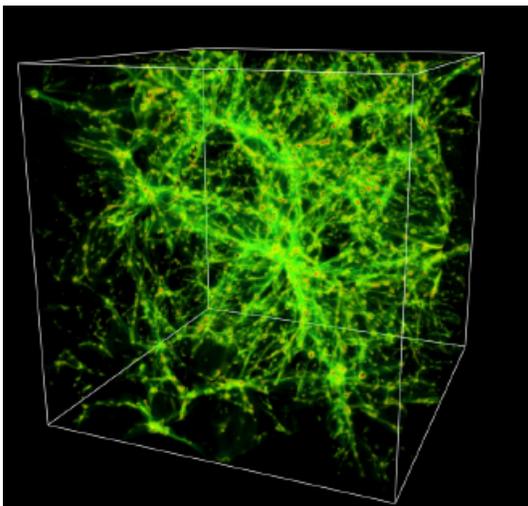
- Most of the baryons and metals are in the hot gas
 - Well understood emission mechanism
 - No radiative transfer difficulties
 - Dust not a problem
 - The deep potential well captures an integrated record of all the metals produced
 - True averages
 - Simple physics (H and He-like lines)
 - Wide range of elements
 - Direct measurement of electron temperature from continuum
 - With present data can measure Fe to $z \sim 1$ and Si to $z \sim 0.4$
- We can thus obtain a true measure of the metal formation mechanism and its evolution

7

8

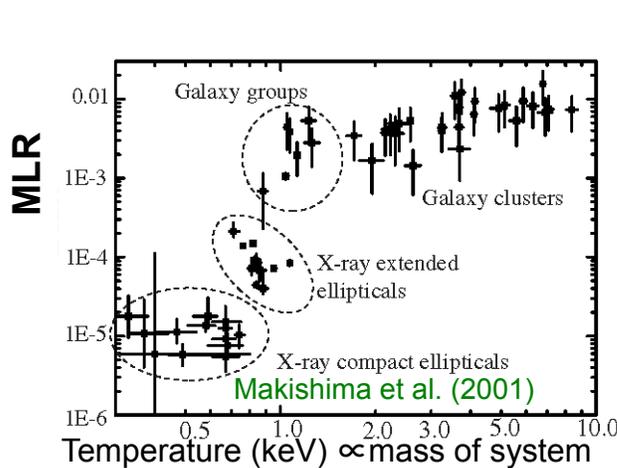
Where do the Baryons Go?

- Most of the baryons in the universe (>80%) do not live in galaxies (Fukugita and Peebles 2007) $\Omega_{\text{stars}} h = 0.0027 \pm 0.00027$
 $\Omega_{\text{total}}(\text{Baryon})h^2 = 0.0214$
- In a simulation of the formation of structure only a small fraction of the baryons (light blue) end up as stars



Numerical simulation of where the baryons live (today) Particles in red and green are in clusters- red closer to center
 Turquoise is star forming gas

Metals are synthesized in stars (galaxies):
 Compare the mass of metals $M_{\text{metal}, < R}$ (in units of M_{\odot})
 with B-band luminosity of stars- a proxy for stellar mass (today)
 (similar to mass to light ratio)



$$\text{MLR} = \frac{M_{\text{metal}, < R}}{L_{\text{B or K}, < R}} \frac{M_{\odot}}{L_{\odot}}$$

However the stars that produced the oxygen were massive stars that are no longer around

Oxygen Mass-to-Light Ratio: OMLR
 Magnesium Mass-to-Light Ratio: MMLR
 Iron Mass-to-Light Ratio: IMLR

9

10 Origin of 'Metals'

- Metal production is dominated for (O...Ni) by supernova.
- Type II (core collapse) produce most of the O and Type I produce most of the Fe.
- The fraction of other elements (e.g. Si,S) that are produced by the SN depend on the IMF and the (poorly understood) yields of the SN.
- If the observed cluster galaxies are the source of the metals and 'standard' SN rates and IMF are assumed the progenitors of the observed stars only produces 1/3 of the the observed metals

Since most of the metals are in the gas >70% of the metals generated in galaxies has to be 'lost' from galaxies (where the stars live) to the ICM

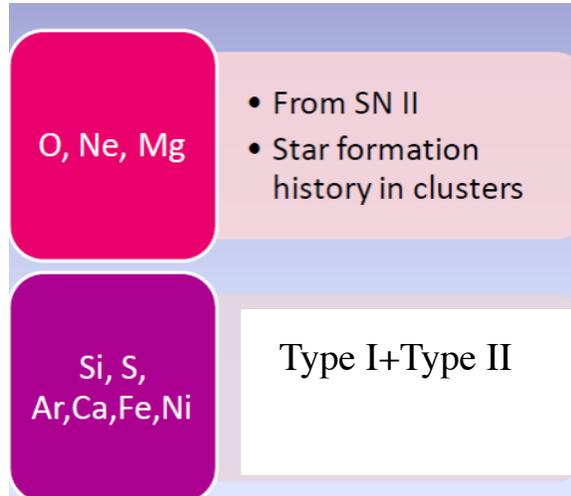
This is a direct indication that galaxies are 'open' systems

There is only little or weak evidence that the stellar populations in cluster galaxies are different from those in the field (other than the fact that clusters have a much larger percentage of elliptical and S0 galaxies)

11

Which Stars Make Which Metals

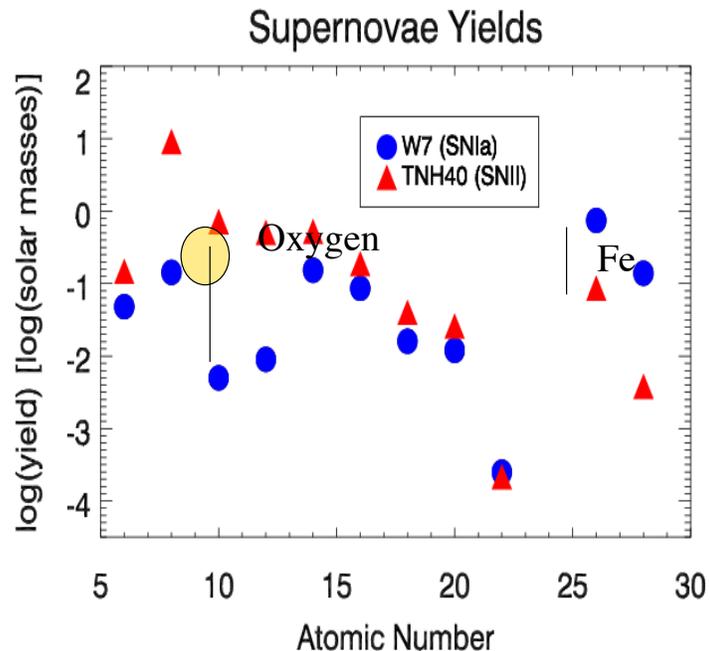
- Type II- massive stars; short lifetime, lots of light
- Type II (core collapse) produce most of the O and Type I produce most of the Fe.
- Type I - white dwarfs which explode due to accretion- old population, little optical light, long life (not well understood)
- The fraction of other elements (e.g. Si,S) that are produced by the core collapse SN depend on the IMF and the (poorly understood) yields of the SN.



12

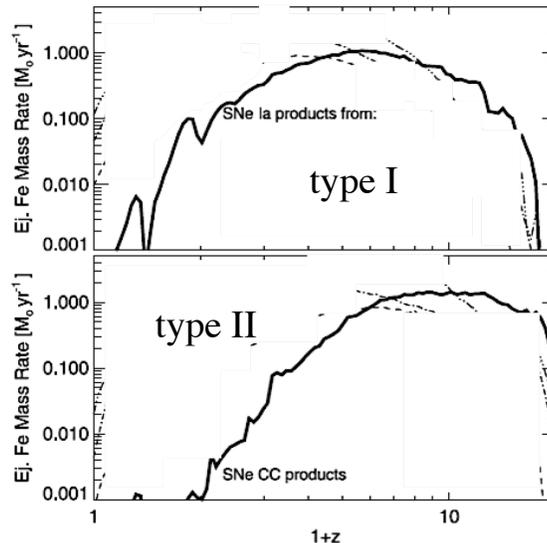
Supernova Yields

- The amount of each element depends on the type of SN, the IMF and the code used to do the prediction.
- For Saltpeter IMF and a system that holds onto all of its metals the relative yield of each element per unit mass



- The study of the metal enrichment of the intra-cluster medium (ICM) represents a direct means to reconstruct
 - the past history of star formation
 - the slope of the initial mass function (IMF)
 - the relative number of type I and II SN
 - the role of feedback processes
 - the metallicity of the gas which accretes into clusters as the universe evolves

Model of *when* Fe is produced in a galaxy formed at $z=20$ from type I and core collapse (type II) SN (massive stars)



when are the elements produced and by which types of SN

Borgani et al 2009-

How Old are the Galaxies

2006ARA&A..44..141 Renzini Stellar Population Diagnostics of Elliptical Galaxy Formation

- One of the major issues is when did clusters form and what does that mean?
- CDM simulations indicate when the mass concentrations formed- but were they populated with galaxies and gas?
- A separate issue is the age of the stellar population
 - The oldest average age for a stellar population is found in the most massive galaxies in clusters

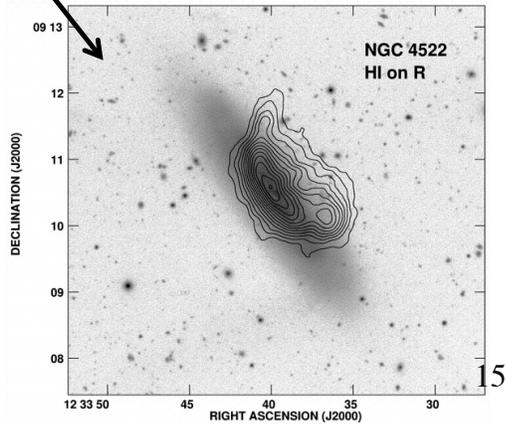
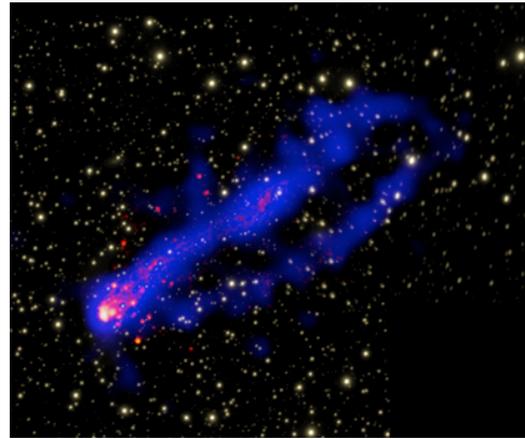
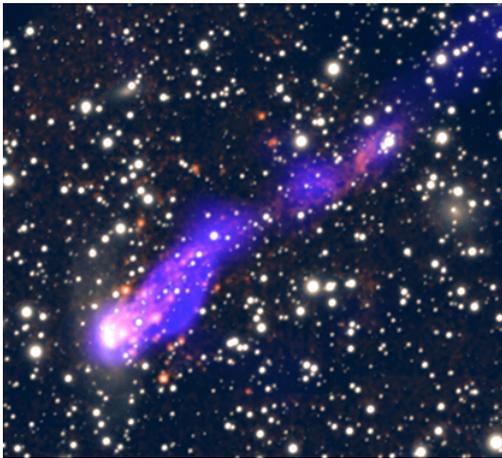
the stars in massive early-type galaxies in clusters have a mean luminosity weighted formation redshift

$$z_* = 2.01^{+0.22}_{-0.17} \quad \text{Van Dokkum and van der Maerl 2007}$$

Today on astro-ph [arXiv:1909.10434](https://arxiv.org/abs/1909.10434) The average BCG core age of the sample is 13.3 ± 2.8 Gyr, average metallicity is $[\text{Fe}/\text{H}] = 0.30 \pm 0.09$,

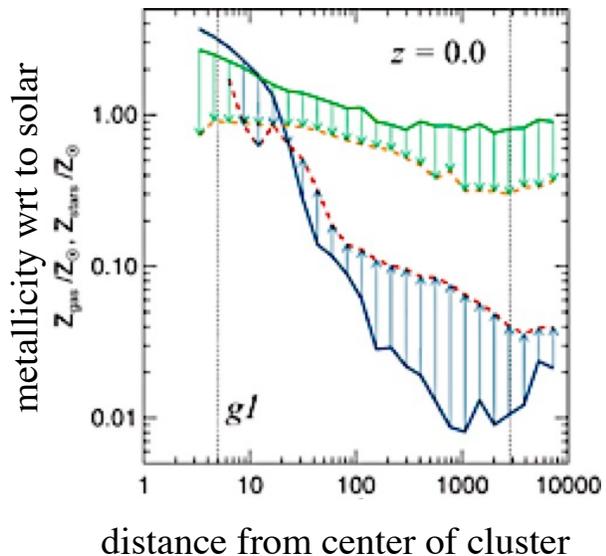
- How does the gas get out of galaxies - Ram pressure gas stripping

- ESO 130-001: in Abell 3627
- In image below zoomed into galaxy
- Image to right, H α in red, starlight in yellow
- Also see HI contours 'pushed back'



16 How Doe the Gas get out- AGN Feedback

- The AGN in the galaxy will tend to 'push' gas out of the galaxy, depositing metals and energy in the ICM
- Thus the metallicity of the galaxies and that of the ICM will be effected
- as well as the distribution of metals



Theoretical calculation of the effects of AGN feedback -Sijack et al 2007

Green solid metallicity in galaxies vs radius
dashed-same with feedback

Blue gas metallicity with and without feedback

- What did I say? - form groups and give me a quick summary of the important things we can learn about chemical evolution of the universe from studies of the hot x-ray emitting gas.



Abundances

- Clusters of galaxies deep gravitational potential wells keep all the metals produced by the stellar populations of the member galaxies within the cluster.
- The dominant fraction of these metals reside within the hot ICM.
- The chemical abundances measured in the intra-cluster plasma thus provide us with a “fossil” record of the integral yield of all the different stars (releasing metals in supernova explosions and winds) that have left their specific abundance patterns in the gas prior and during cluster evolution.

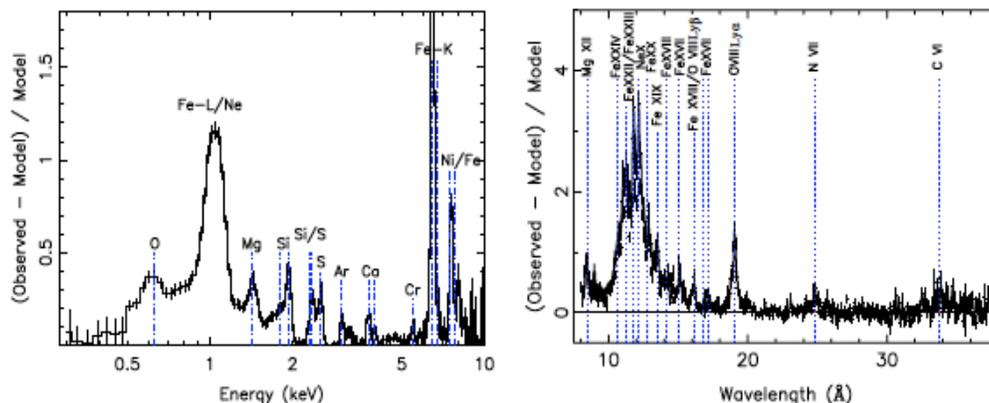
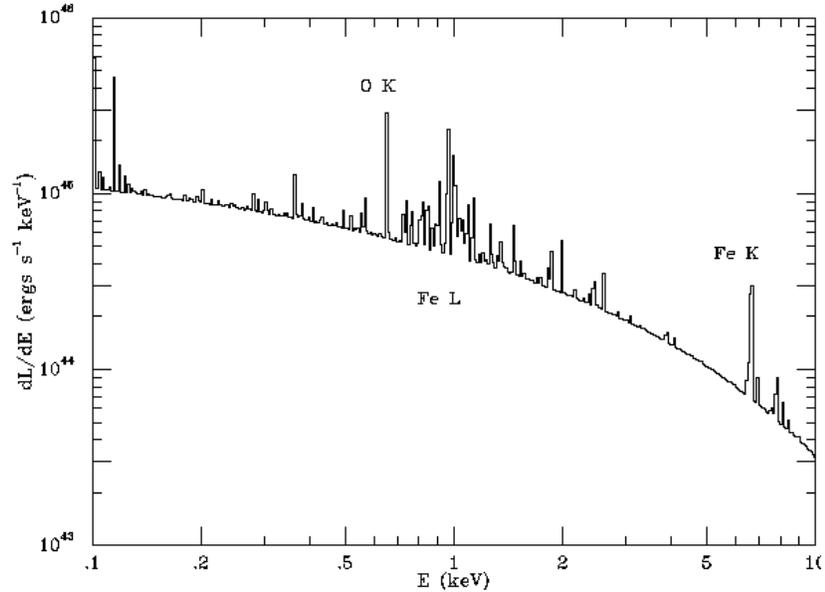


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with XMM-Newton EPIC (from [Wang et al. 2006](#)). *Right panel* Line spectrum of GM 87 as observed with XMM-Newton EPIC (from

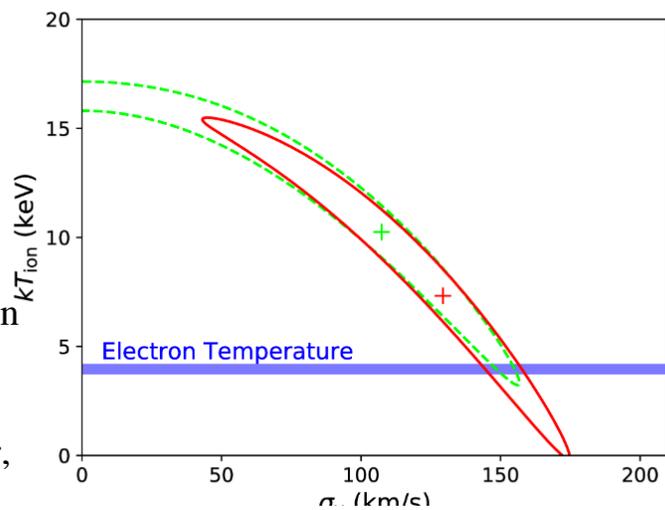
- Fit Spectral model to the data with free parameters of temperature, and abundances of each element



Ion and Electron Temperatures

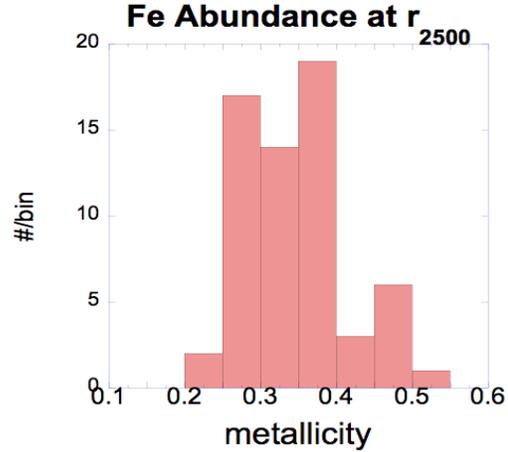
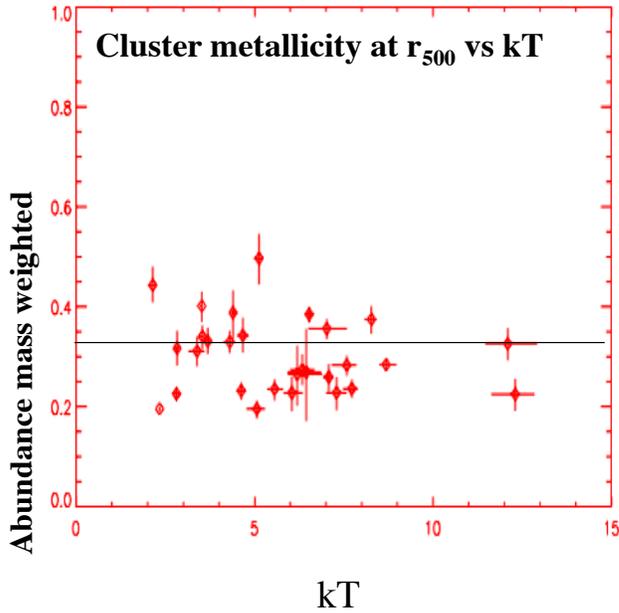
Hitomi data show that the electron and ion temperatures are the same

(if things get more precise one has to include that as the photons produced within the central $r \sim 100$ kpc climb up the gravitational potential well of the cluster, they are affected by a gravitational redshift of $\sim 20 \text{ km s}^{-1}$..



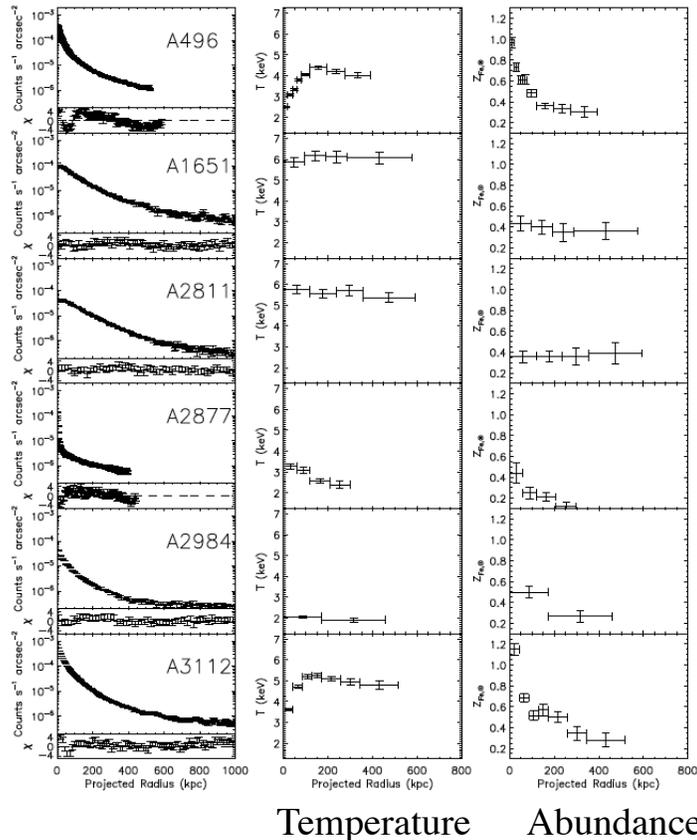
21 Average Cluster Metallicity Profile-CCD Data

- $\langle \text{Fe} \rangle = 0.33 \pm 0.08$ **but real variation** from cluster to cluster - full range is a factor of 2 at r_{500}



22 Cluster Metallicity

- The abundances are not uniform in the cluster but can be higher in the center - at large radius tend towards $\sim 1/3$ solar
- Most of the metals are in the outer regions (follow the baryonic mass if the abundances are constant)
- Due to low S/N measuring abundances at large radii is hard



Temperature Abundance

Abundance Gradients

- Small abundance gradient- all clusters consistent with $Fe/H=0.3$ at large radii – but variations in center.

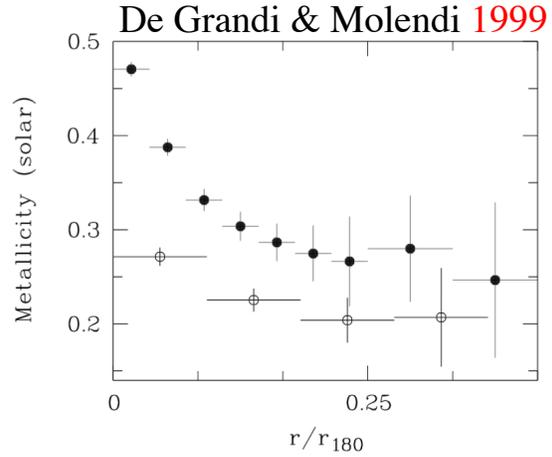
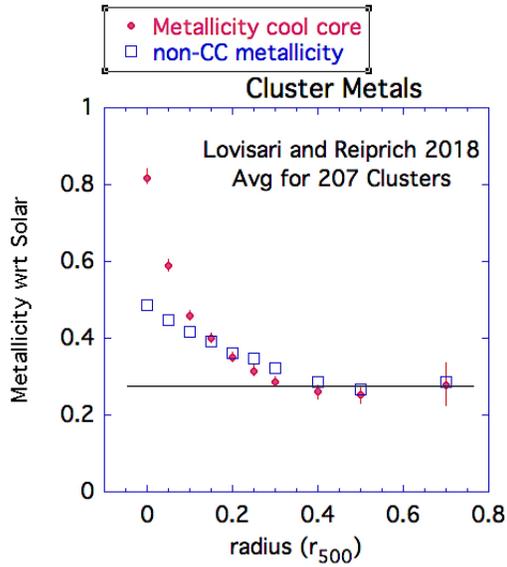


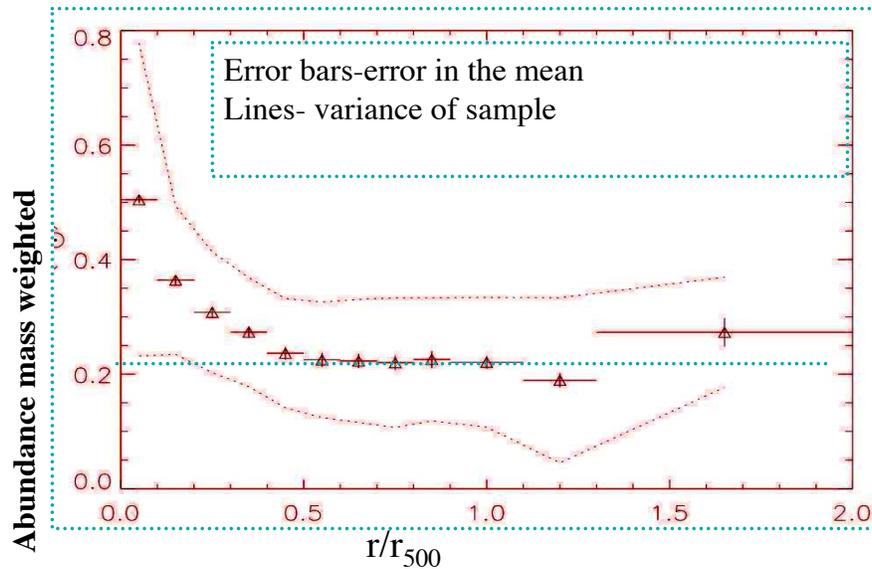
FIG. 4.—Mean metallicity profiles for the CF (filled circles) and on-CF clusters (open circles), plotted against radii in units of r_{180} .

Despite vast improvement in instrumentation from 1999 (pre-Chandra and XMM) to now result is the ~same

24

Average Cluster Metallicity Profile

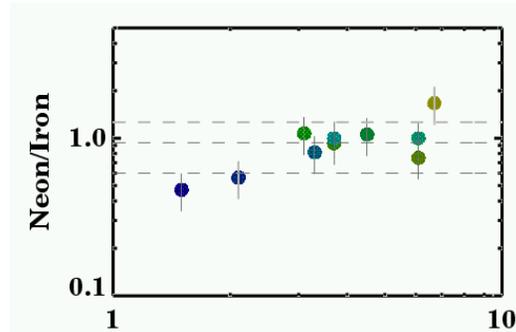
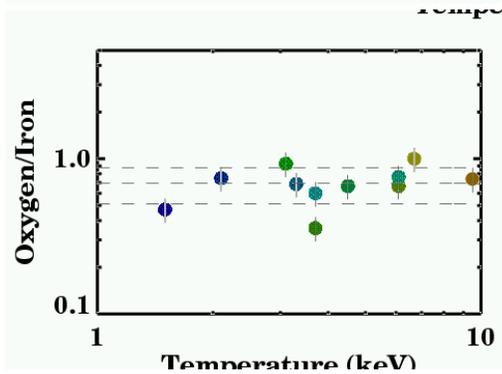
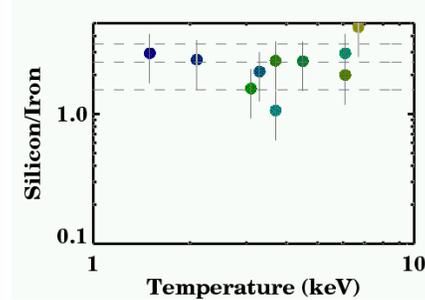
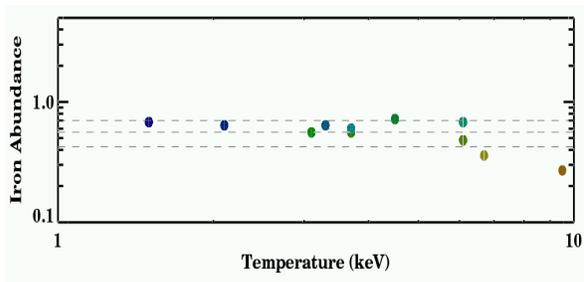
- Rises in center to ~0.5 solar
- Asymptotes at $r > 0.5r_{500}$ to 0.22 solar
 - No drop to largest radii ($1.7r_{500}$) measured



Clusters, Groups and Big galaxies

XMM Grating Results- J. Peterson et al

These data have less systematic errors than the CCD data but lower S/N

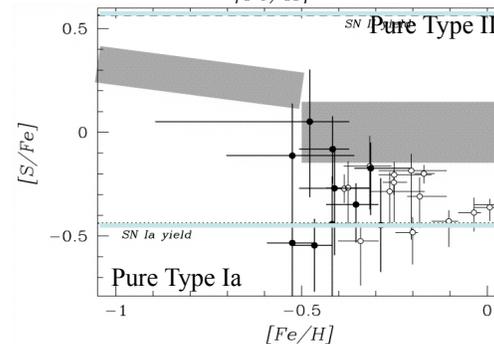
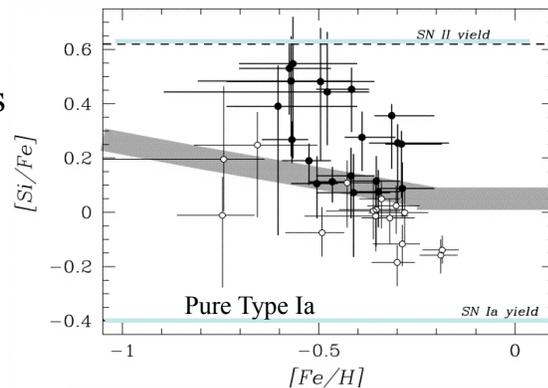


26

Abundance Patterns in Clusters

In principle one could determine the pattern of type I and type II SN responsible for creating the elements- however the Si and S ratios disagree with simple models (also O/Fe values)

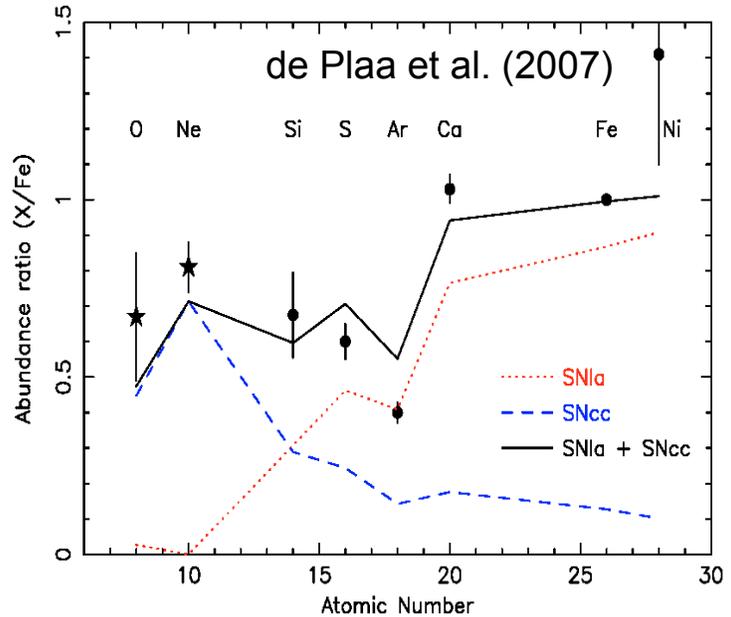
However more modern models (both atomic physics and SN) and better calibration have changed this conclusion



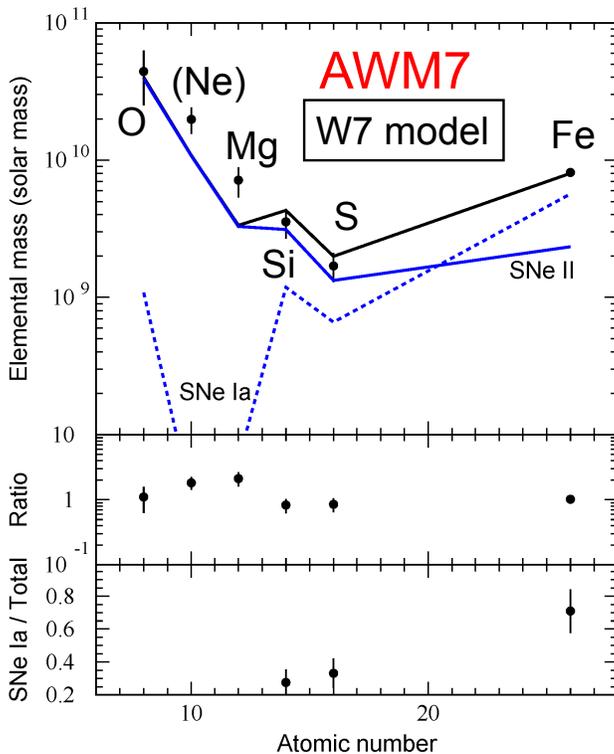
Si/Fe and S/Fe sorted by Fe abundance
Finoguenov et al -shaded band is MW stars

Relative Abundance of Different Elements

- The relative abundance of different elements is related to the processes that produce them
- Fe and Ni are mostly made in type I supernova (the explosion of a white dwarf)*
- Oxygen and Neon are made mostly in a type II SN- the explosion of a massive star
- The relative and absolute number of SN is related to the distribution of the masses of the stars and other interesting things



*we will discuss the creation of elements in SN later in the class when we discuss supernova and SN remnants



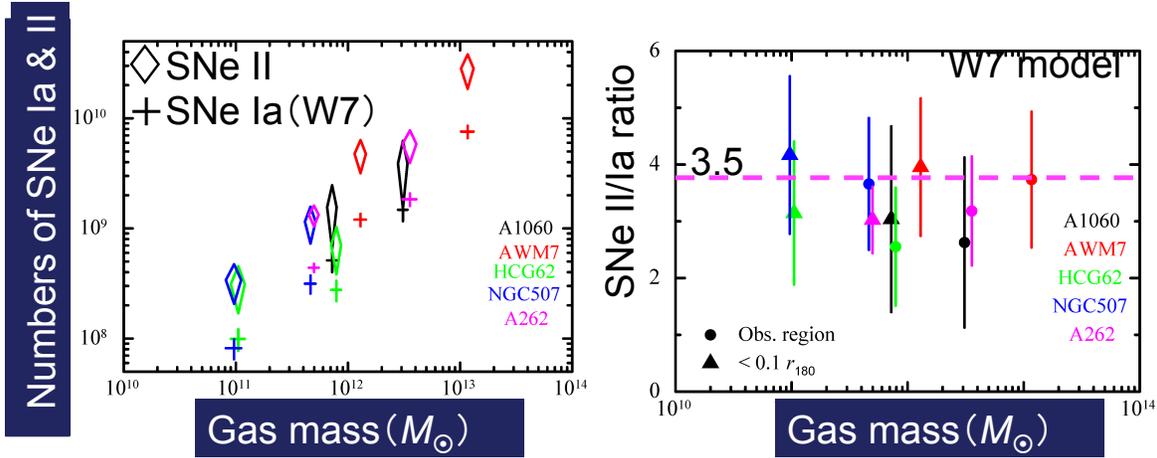
Ratio of the number of each type of SN

$$\frac{N_{\text{SNe II}}}{N_{\text{SNe Ia}}} = 4.0 \pm 1.2$$

➤ ~75% of Fe,
~40% of Si and S
from SNe Ia

Sato et al

Numbers and Ratio of SNe Ia & SNI



- Numbers of SNe Ia & SNe II/Ia Ratio: ~ 3.5 (W7 and WDD2), ~ 2.5 (WDD1)

Clusters (XMM ; de Plaa et al. 2007): ~ 3.5

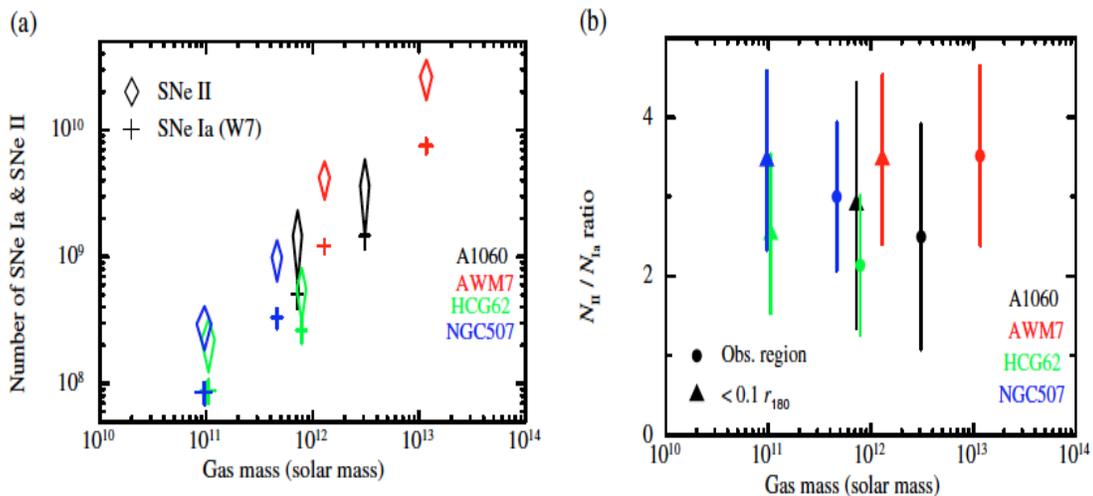
Our Galaxy (Tsujiimoto et al. 1995): ~ 6.7

LMC & SMC (Tsujiimoto et al. 1995): 3.3 – 5

29

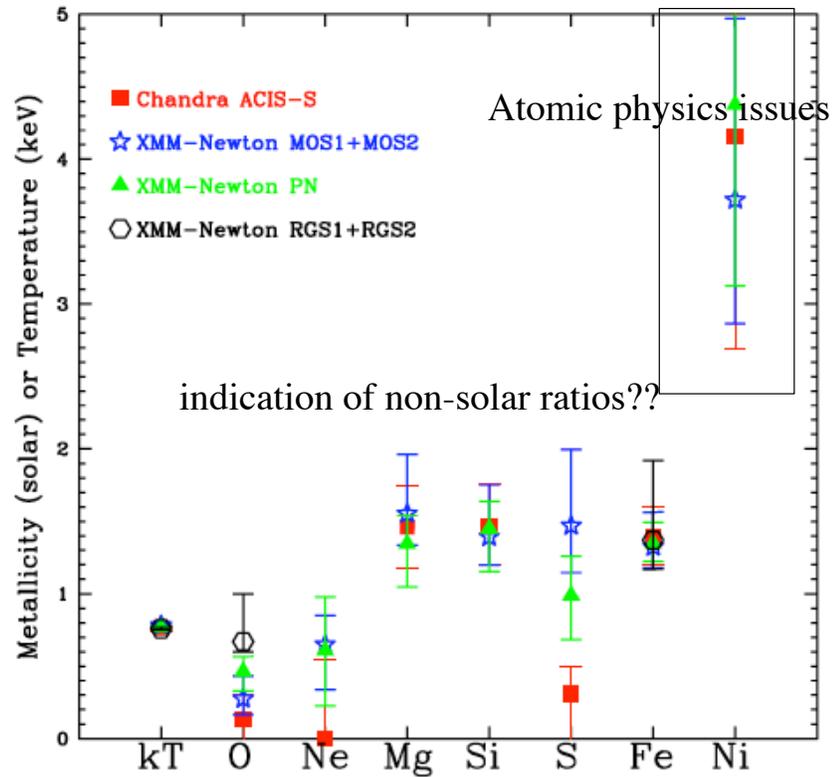
Numbers of Type I and II Supernova

- the two types of SN produce a very different mix of heavy elements
- This allows a decomposition into their relative numbers and absolute numbers (Sato et al. 2008) - ($\sim 10^9$ - 10^{10} SN per cluster)- this is related to the fraction of massive stars that exploded as SNI



Elemental Abundances in a Group

- Li et al compared the elemental abundances with respect to solar for Oxygen thru Ni for the gas in the center of NGC4636 a nearby low mass group

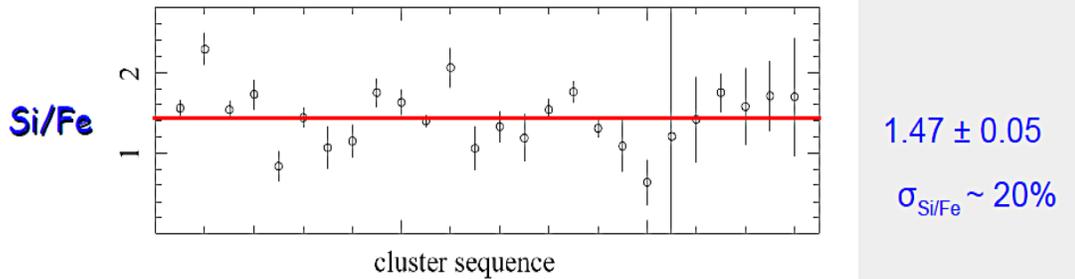


Is the process that produces the elements the same everywhere?

Clusters have a very different formation process than MW
 subject of intensive investigation (Choi et al [2019ApJ...872..136C](#))

Metals in Clusters

- One of the main issues in cluster physics is when and how the metals in the ICM are created
- Pattern of metallicity
- Evolution of metallicity
- It seems as if different clusters have slightly different patterns and so different histories



The Si, Fe, Ni abundances as well as Si/Fe and Ni/Fe abundance ratios distributions of the sample show moderate spread (from 20% to 30%)

Molendi et al 2009³³