Chemical Abundances in Clusters- Not In Longair

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

arXiv:1811.01967

Enrichment of the hot intracluster medium: observations

F. Mernieret al

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 bremmstrahlung 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

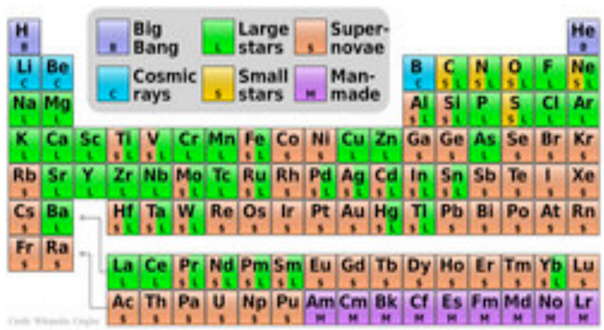
- A major area of astrophysical research is understanding when stars and galaxies formed and how the elements are produced
- With the exception of H and He (which are produced in the big bang) all the other elements (called metals in astrophysical jargon) are "cooked" in the centers of massive stars and supernova and then "ejected" by explosions or winds
- The gas in these explosions is moving very fast (1000 km/sec) and can easily 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

•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



The Cluster gas is a good place to measure abundances

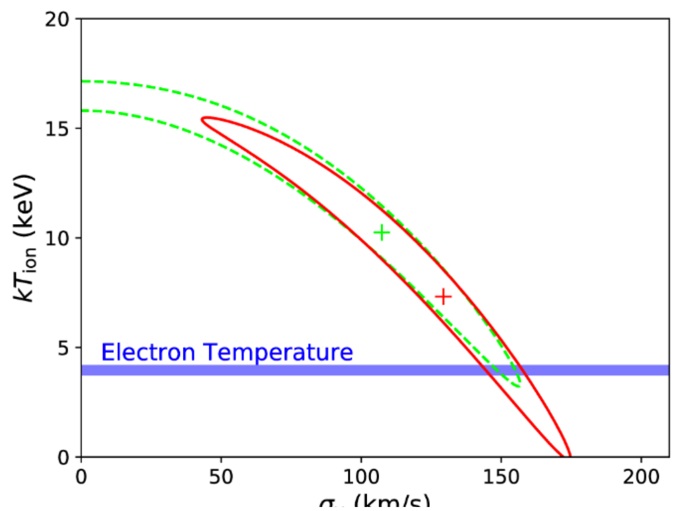
- Most of the baryons and metals are in the hot gas
- Well understood emission mechanism
- No radiative transfer difficulties
- Dust not a problem
- The deep potential well captures an integrated record of all the metals produced
- True averages
- Simple physics (H and He-like lines)
- Wide range of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

We can thus obtain a true measure of the metal formation mechanism and its evolution

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~100kpc climb up the gravitational potential well of the cluster, they are affected by a gravitational redshift of~20km s−1..



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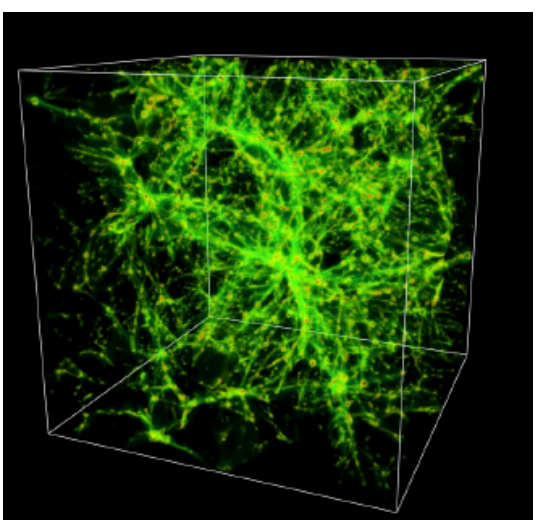
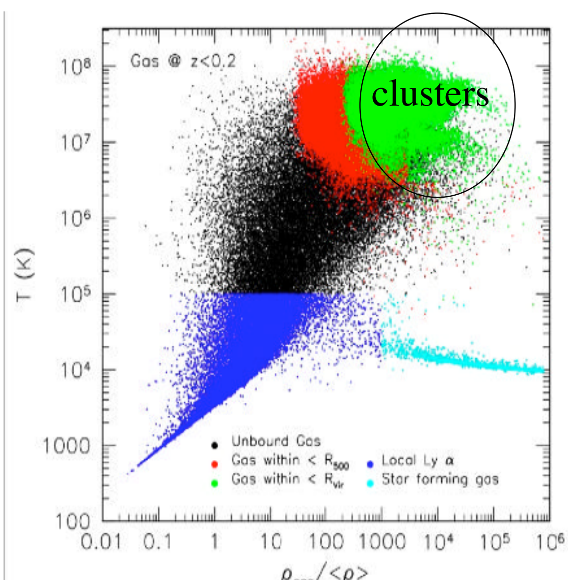
Where do the Baryons Go?

- Most of the baryons in the universe (>80%) do not live in galaxies (Fukugita and Peebles 2007) Ω_{stars} h = 0.0027 +/- 0.00027
  Ω_{total}(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

7 Origin of 'Metals'

- Metal production is dominated for (0…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

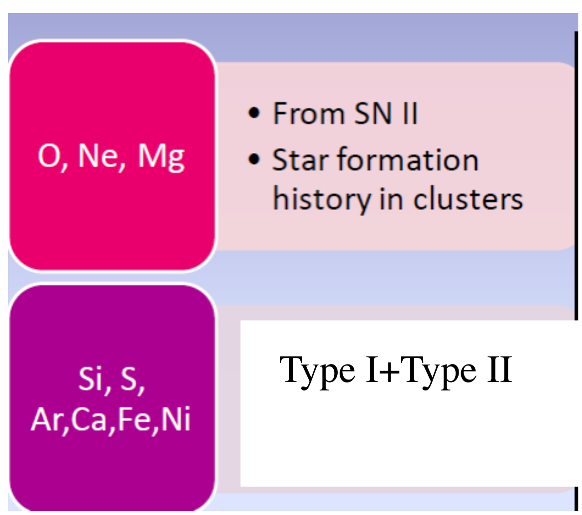
Since most of the metals are in the gas >70% of the metals generated in galaxies has to be 'lost' from galaxies (where the stars live) to the ICM

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 large percentage of elliptical and S0 galaxies)

8 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.



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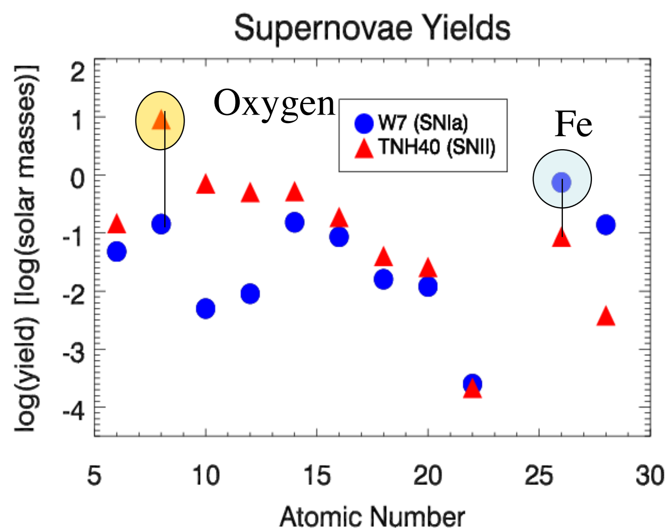
Supernova Yields

- 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



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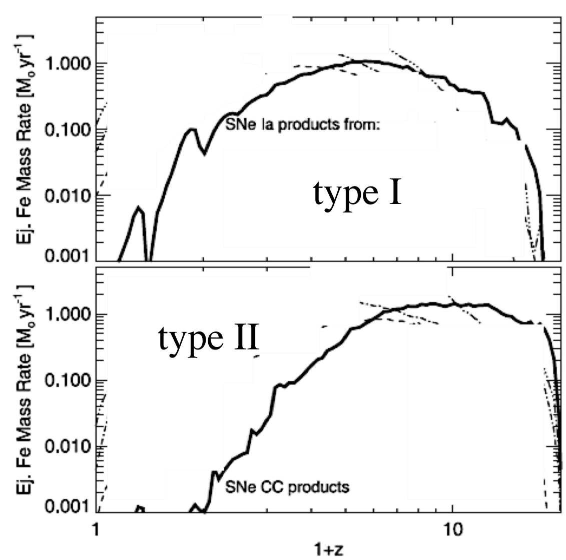
- The study of the metal enrichment of the intra-cluster medium (ICM) represents a direct means to reconstruct
  - the past history of star formation
    - the slope of the initial mass function (IMF)
    - the relative number of type I and II SN
  - the role of feedback processes
  - the metallicity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

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How Old are the Galaxies

- 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

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

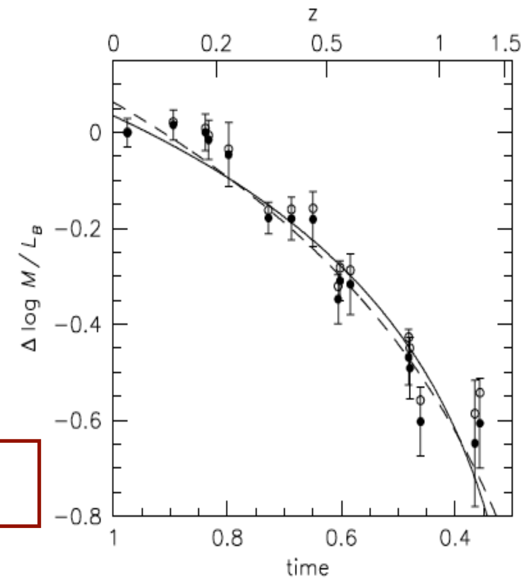

FIG. 8.— Evolution of the mean M/L_B ratio of massive cluster galaxies with time. Open symbols are the same datapoints as shown in Fig. 6. Solid symbols with errorbars are offset by $-0.05 \times z$ to account for progenitor bias (see text). The solid line shows the best fitting model for a Salpeter-like IMF, which has a formation redshift of the stars $z_* = 2.01$. The broken line shows a model with a top-heavy IMF (slope $x = 0$) and a formation redshift $z_* = 4.0$ (see § 7).

the stars in massive early-type galaxies in clusters have a mean luminosity weighted formation redshift $z_* = 2.01^{+0.22}_{-0.17}$.

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van Dokkum and van der Maerl 2007

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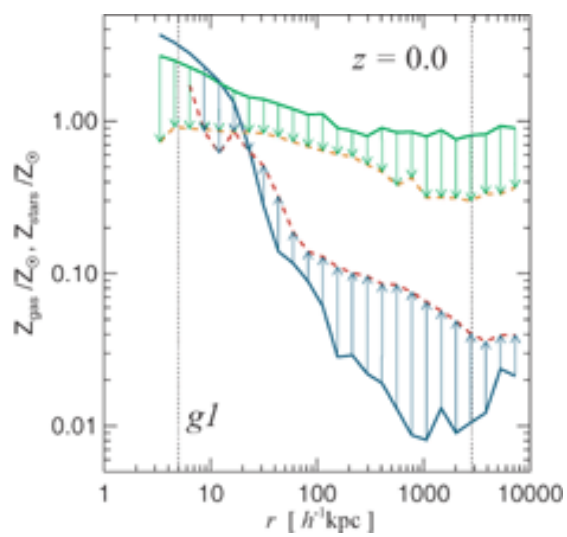
Effect of AGN Feedback on Metallicity

- 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

Metals are synthesized in stars (galaxies):

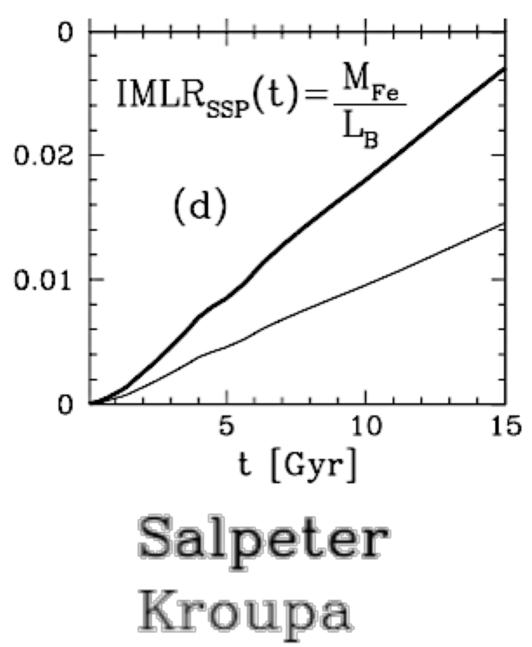
Compare the mass of metals $M_{\mathrm{metal},<R}$ (in units of $\boldsymbol{M_\odot}$) with luminosity of stars in some band to get the (element) mass to light ratio (similar to mass to light ratio)

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

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

Dependence on IMF

- Two of the most used intial mass functions are those of Kroupa and Salpeter.
- At late times (today) on can see that the 'Iron mass to light ratio' (IMLR) differs by a factor of over 2 for the same amount of Fe produced



Physics of Line and Continuum Emission

- Density 10^{-5}–10^{-1} cm^{-3} cluster outskirts to the densest regions
- 3 fundamental emission processes contribute to the radiation:
  - free–free or bremsstrahlung radiation
  - free–bound or recombination
  - bound–bound or deexcitation
  - The first two processes give rise to continuum radiation and the latter to line radiation.
- low density of the plasma ensures that all the ions excited by collisions have sufficient time for radiative deexcitation before a second deexciting collision occurs.

•contrary to laboratory plasmas, all "forbidden" transitions actually happen in the ICM plasma.

•all exciting, recombining, and bremsstrahlung causing collisions lead to the radiation of a photon, which is referred to as the thin plasma radiation limit (or "coronal limit", as similar conditions prevail in the solar corona).

•The modeling of the thermal plasma spectrum is a book keeping exercise . The collision rates are in general a function of temperature)and the outcome is directly proportional to the electron density

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.

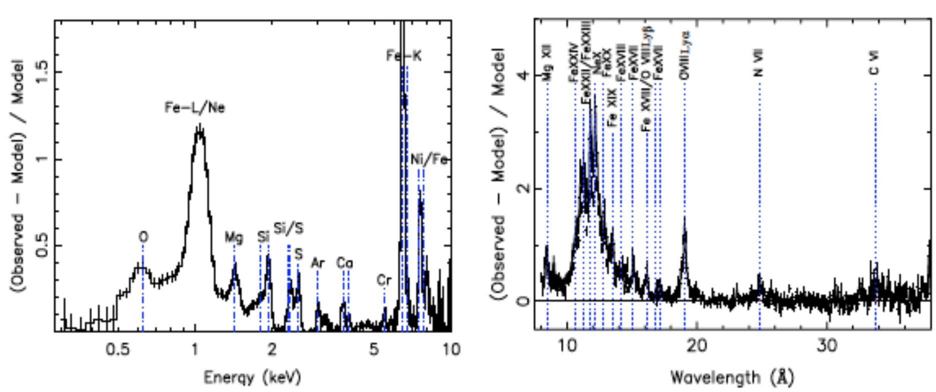
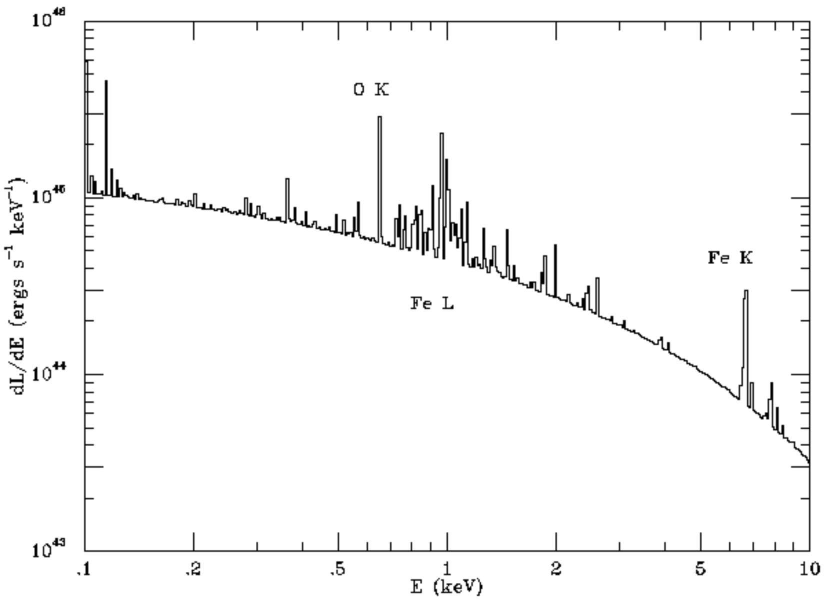


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

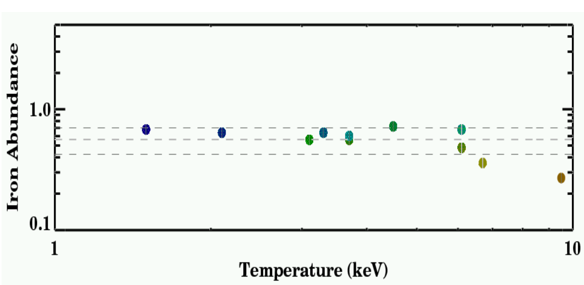
- Spectral model

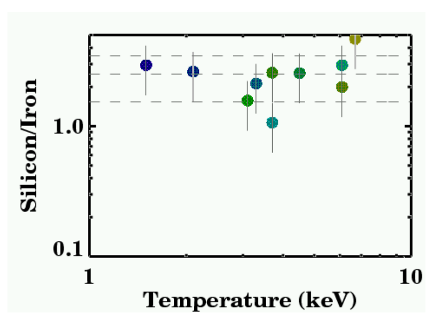


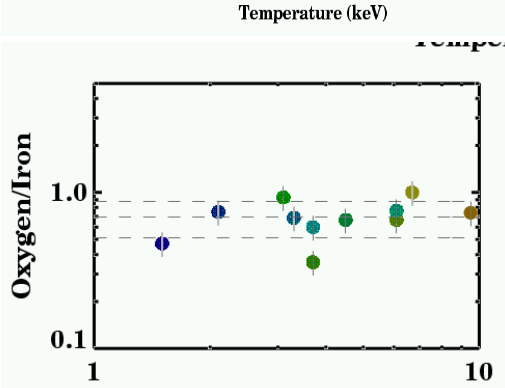
Virialized systems- Clusters, Groups and Big galaxies

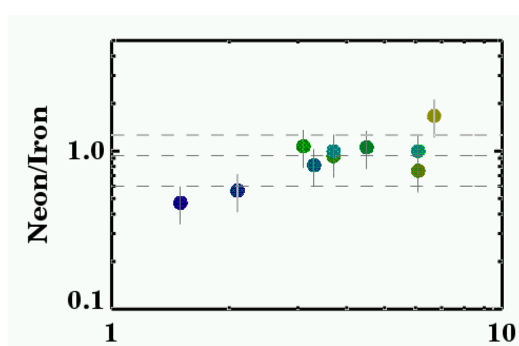
XMM Grating Results- J. Peterson et al

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









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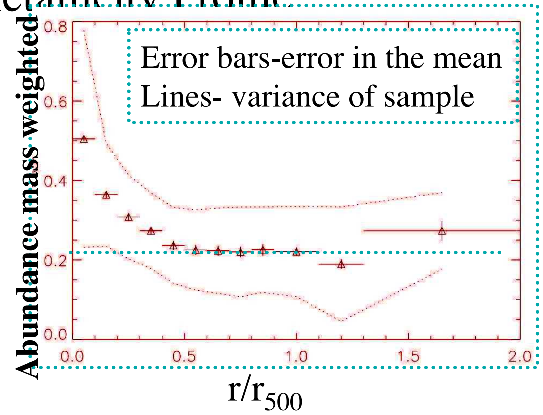
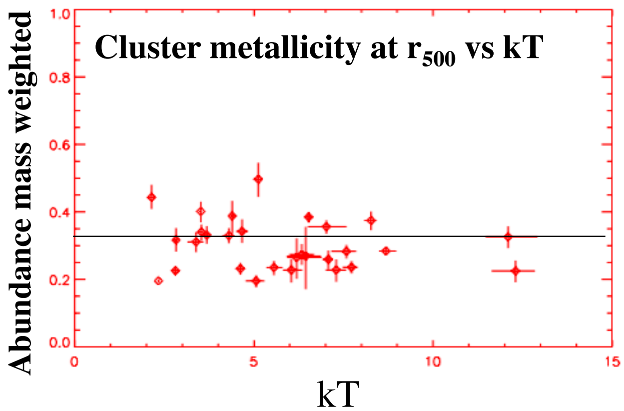
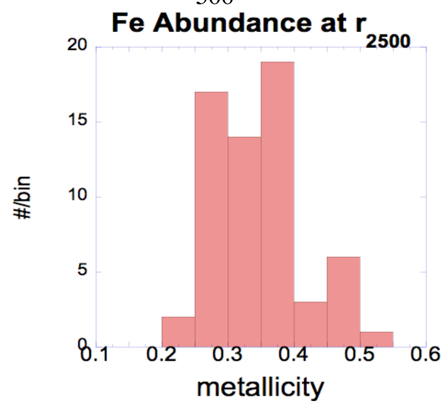
Average Cluster Metallicity Profile

- 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
- $<Fe>=0.33+/-0.08$ **but real variation** from cluster to cluster - full range is a factor of 2 at r_{500}







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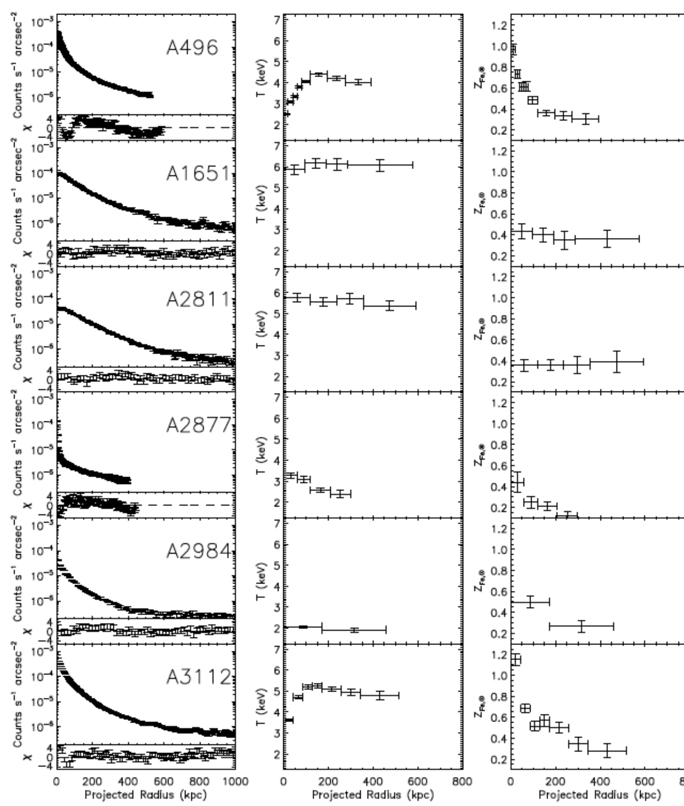
Cluster Metallicity

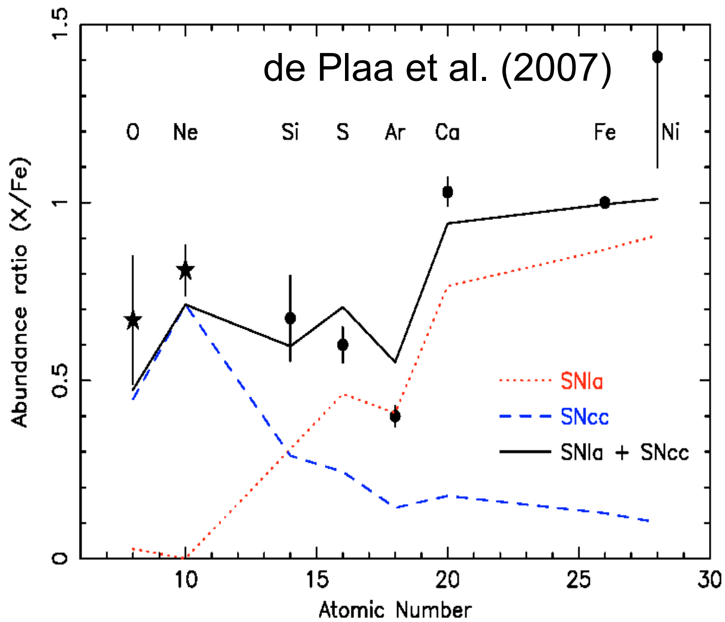
- The abundances are not uniform in the cluster but can be higher in the center- at large radius tend towars ~1/3 solar
- Most of the metals are in the outer regions (follow the baryonic mass if the abundances are constant)



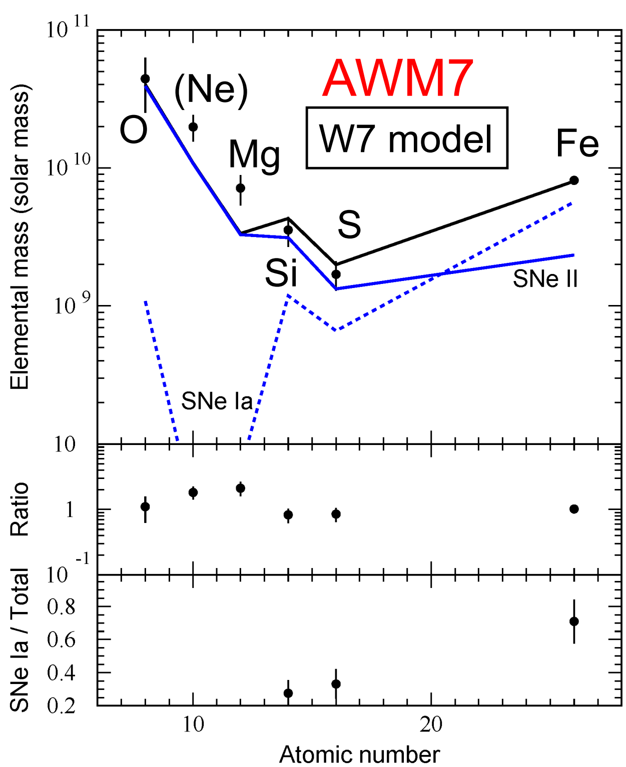
Temperature Abundance

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 (we think) 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

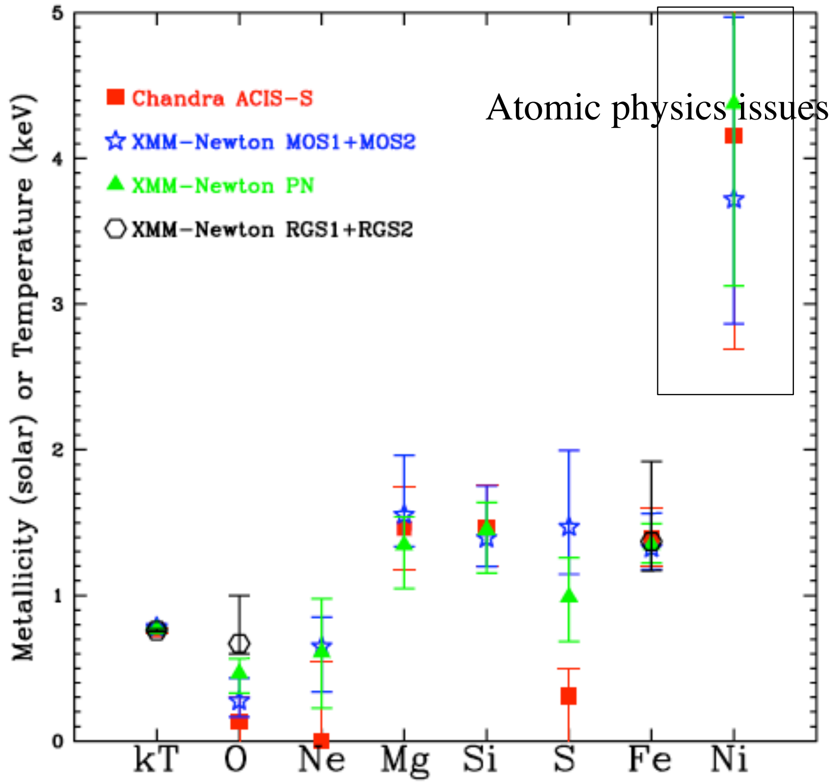
$N_{\text{SNe II}} / N_{\text{SNe Ia}} = 4.0 \pm 1.2$

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

Sato et al

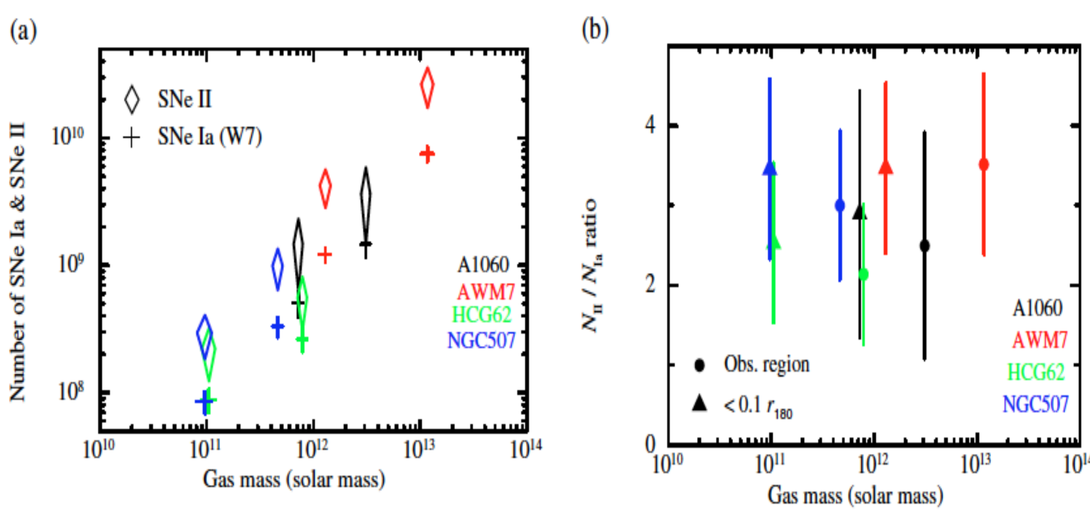
Elemental Abundances in a Group

- 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



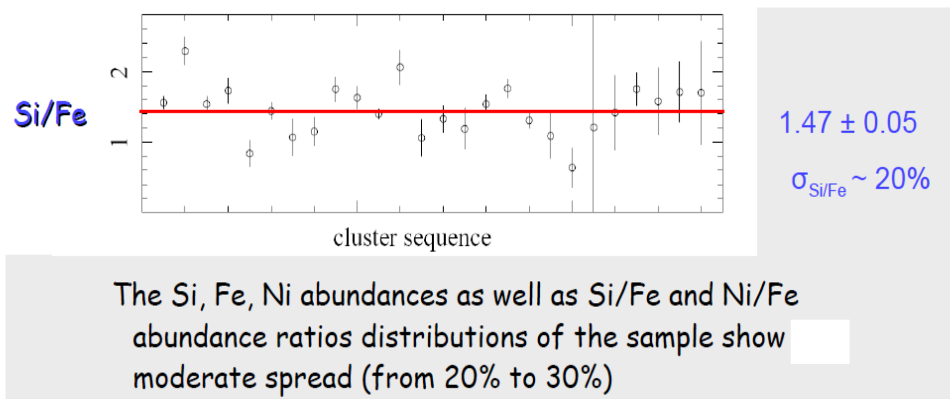
Numbers of Type I and II Supernova

- As we will discuss later 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) - (~10^9-10^{10} SN per cluster)



Metals in Clusters

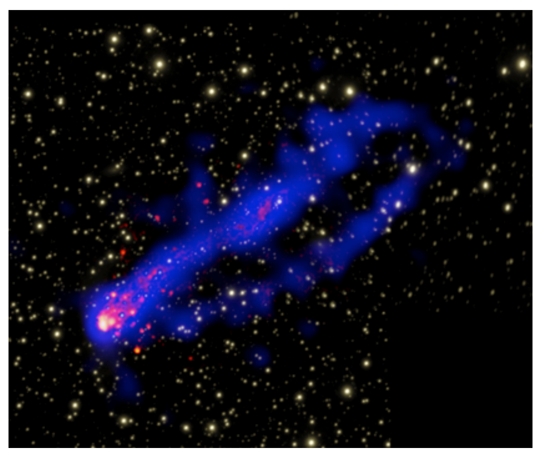
- One of the main issues in cluster physics is when and how the metals in the ICM are created
- Pattern of metallicity
- Evolution of metallicity

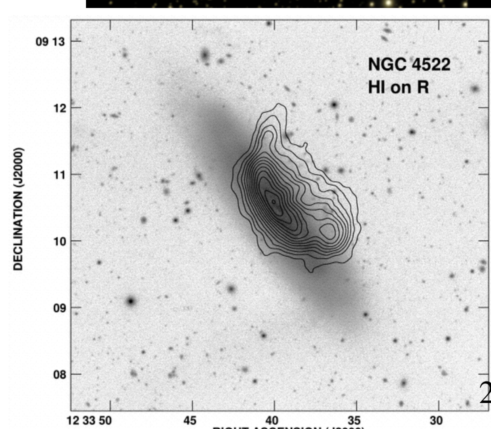


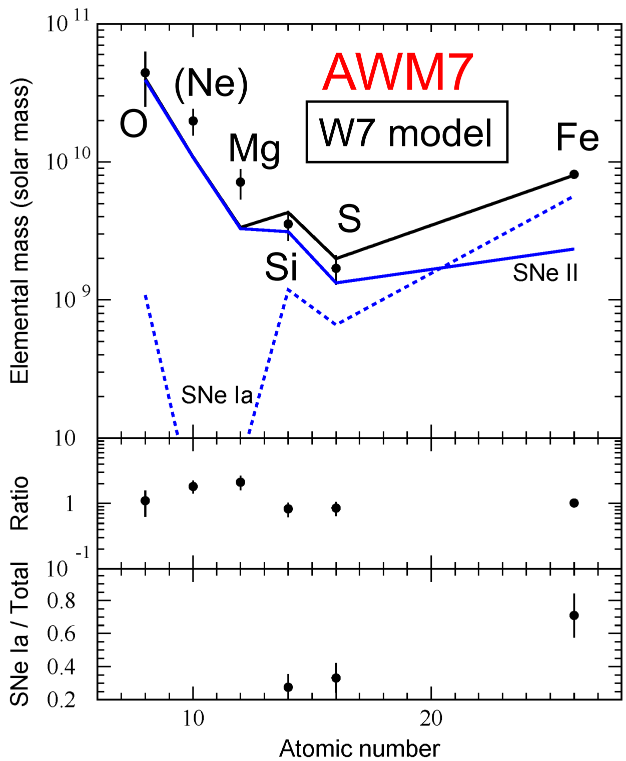
Molendi et al 2009

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

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







Ratio of the number of each type of SN

$N_{\mathrm{SNe\,II}} / N_{\mathrm{SNe\,Ia}} = 4.0 \pm 1.2$

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

Sato et al

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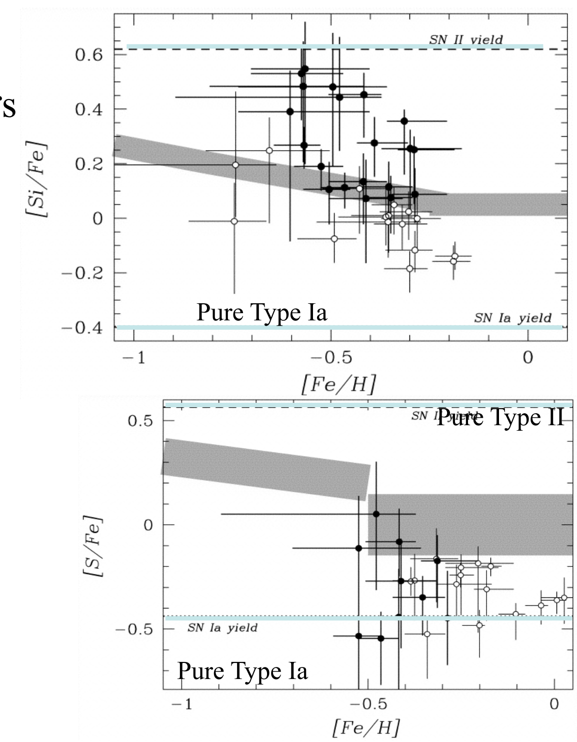
Abundance Patterns in Clusters

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

Is there a Uniform Abundance Pattern??

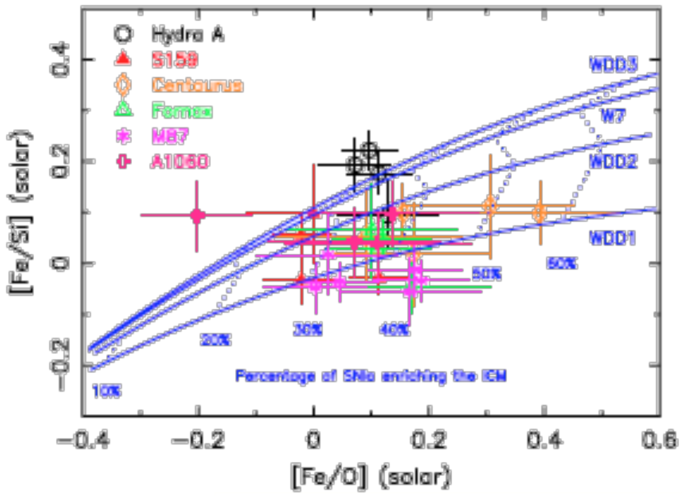
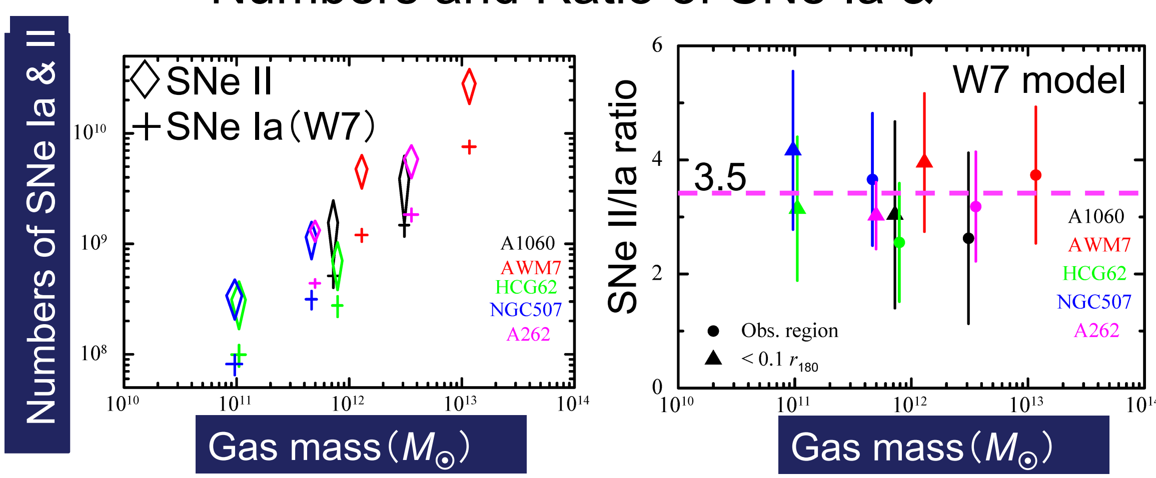


Fig. 36 Intrinsic variation of cluster abundances and their average yields. *Left panel* The observed [Fe/Si] versus [Fe/O] for different spatial regions of a sample of six clusters of galaxies. The *curves* indicate models of a mixture of SN_{CC} products assuming a Salpeter initial mass function (Tsujimoto et al. 1995) mixed with different SN Ia products (Iwamoto et al. 1999). The *dotted line* connects points of the same number contributions of SN Ia to the enrichment of the ICM. The abundance patterns in the Hydra cluster and in M 87 favor very different SN Ia models (after Simionescu et al. 2009b).

Numbers and Ratio of SNe Ia &



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

cf. Clusters (*XMM* ; de Plaa et al. 2007): ~3.5
Our Galaxy (Tsujimoto et al. 1995): ~6.7
LMC & SMC (Tsujimoto et al 1995): 3.3 – 5

HITOMI Results (Yamaguchi et al 2018, Simonescu et al arXiv:1806.00932)

See review arXiv:1811.01967 Enrichment of the hot intracluster medium: observations F. Mernier et al 2018

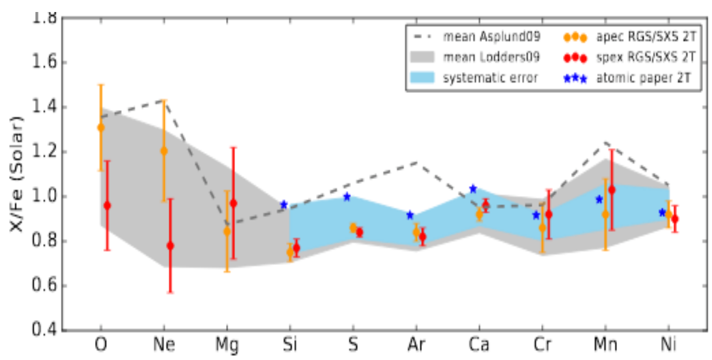
Ar/Fe, Ca/Fe, and Ni/Fe ratios are determined to 10%, Si/Fe, S/Fe, and Cr/Fe are at the 15% level, and Mn/Fe at 20% uncertainty.

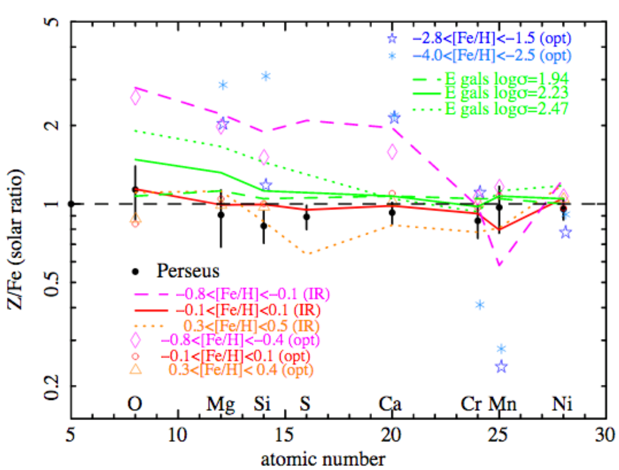
The enrichment pattern in the Perseus Cluster core and the proto-solar nebula are identical

In core of Perseus while the absolute abundance (i.e., Fe/H) decreases by about 30% with increasing radius, but no significant spatial variations in the relative abundance ratios

But this pattern is challenging to reproduce with linear combinations of existing supernova nucleosynthesis models

HITOMI Results





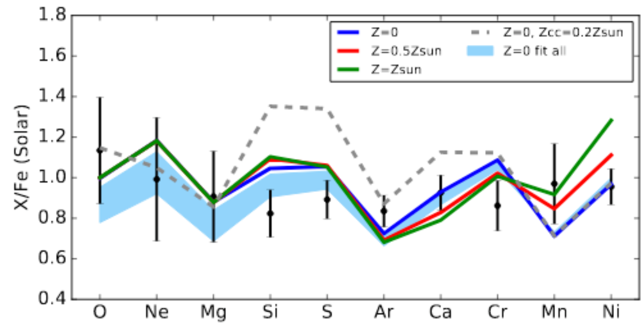
Comparison with

Stars in elliptical galaxies

Milky Way stars

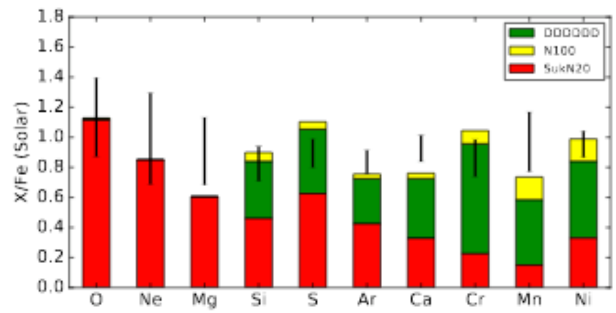
Consistent with the abundance ratios of proto-solar nebula (Lodders et al. 2009), low-mass early type galaxies (Conroy et al. 2014), typical Milky Way stars with near-solar absolute metallicity

HITOMI Results
Comparison with models



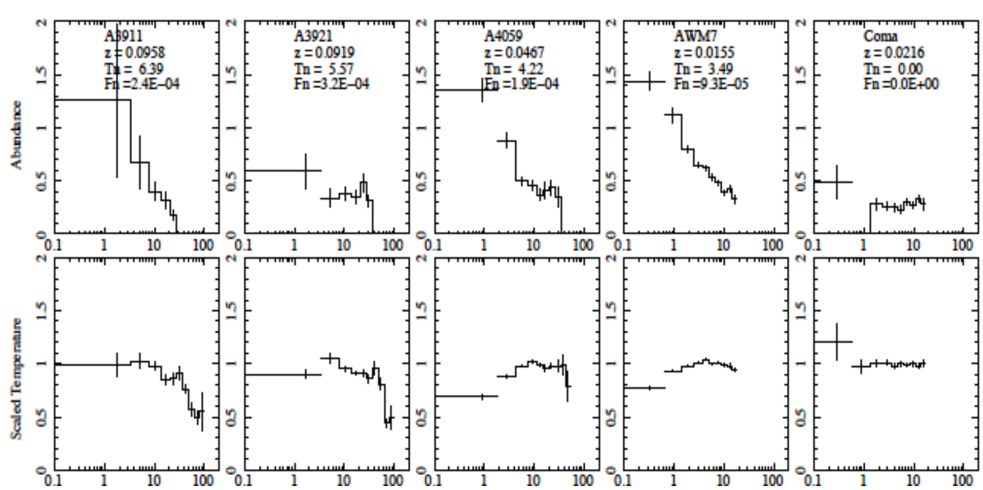
Type I and II supernova- the contribution from Type II always represents more than 50% of the total Si, S, Ar, Ca and some of Fe and Ni

Red= type II
Green/yellow- two types of Ia's



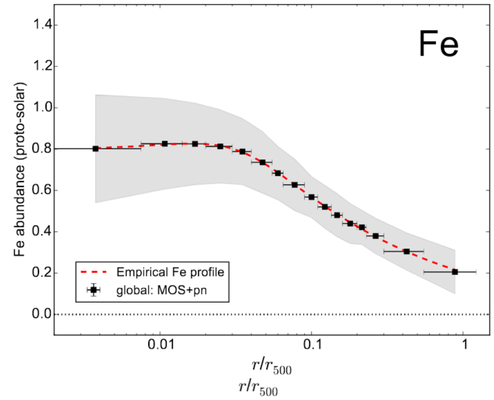
Abundance Profiles

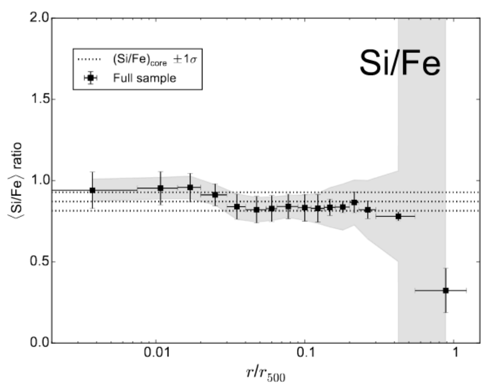
- X-ray CCD data can derive reasonable abundance profiles for the most abundant elements (O, Si, Fe)

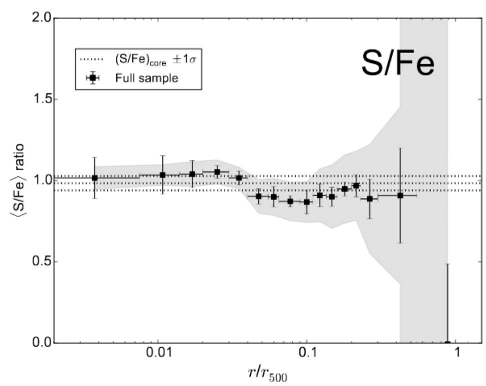


R/R$_{500}$

35 Average Metallicity-Cool Core Clusters







36 Importance of Atomic Physics

- Grey is the proto-solar nebulae (with errors)
- The different colors represent analysis of the same sample but with different atomic physics and the Hitomi results

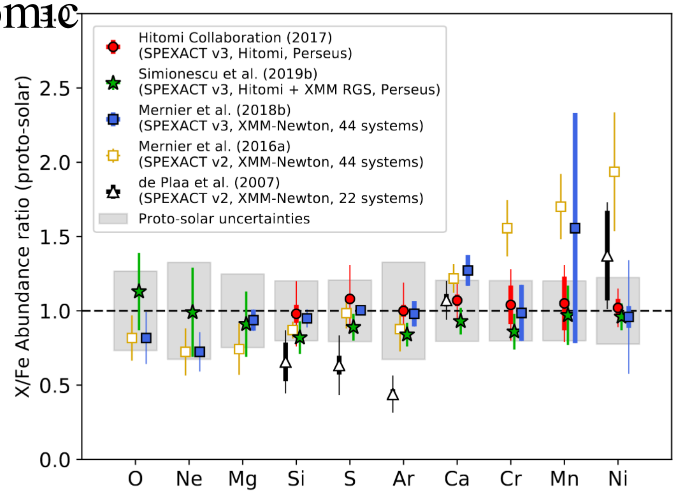


Fig. 6 Abundance ratios measured in the ICM compiled from the recent literature. All the ratios have been rescaled to the proto-solar values of Lodders et al. (2009). For comparison, uncertainties on the proto-solar values are shown by the grey filled rectangles.

it is also remarkable that these updated measurements of the ICM is significantly greater than the current accuracy we have of the chemical composition of our own Solar System

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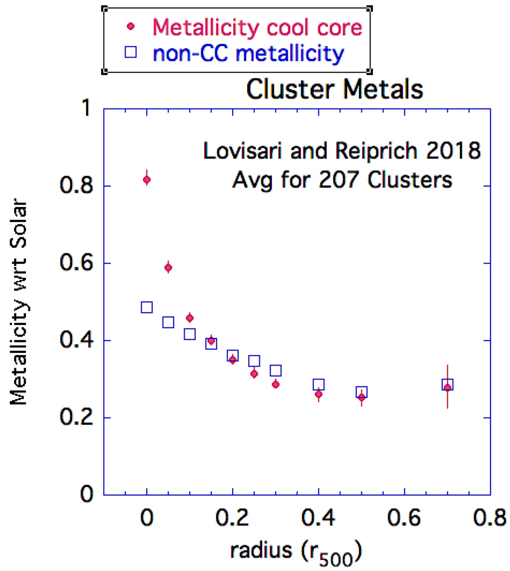
Abundance Gradients

- Little if any abundance gradient- all clusters consistent with Fe/H=0.35 at large radii – but variations in center.



De Grandi & Molendi 1999

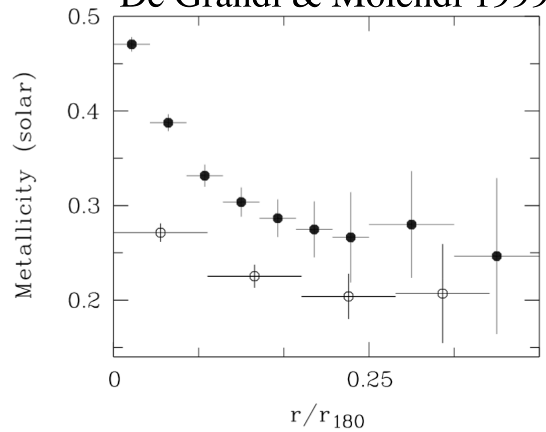


FIG. 4.—Mean metallicity profiles for the CF (*filled circles*) and on-CF clusters (*open circles*), plotted against radii in units of r_{180}.

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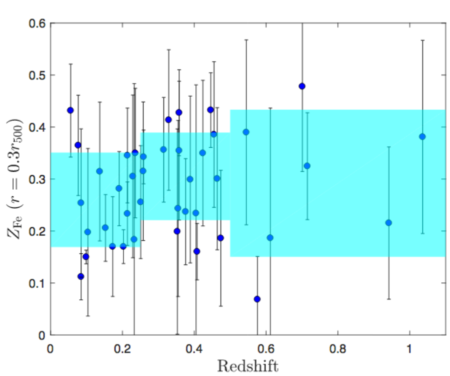
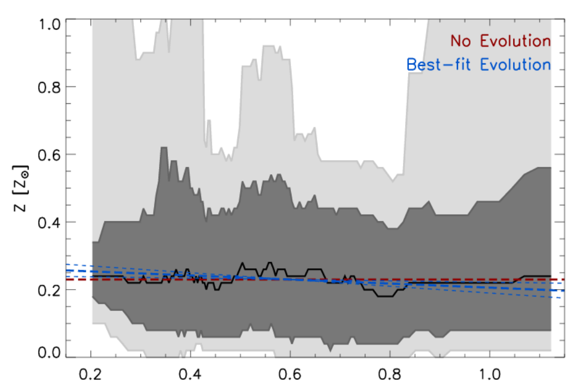
Metallicity Evolution

- Metals are created at high z: McDonald et a 2016 at
- > 60% of the intracluster metals in present-day clusters were created more than ~8 Gyr ago.

8 *A. Liu et al.*





Aantz et al 2017, McDonald et al 2016

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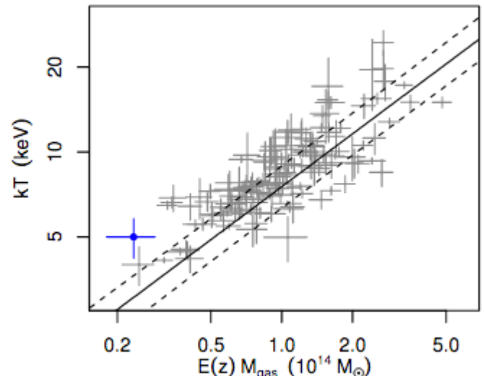
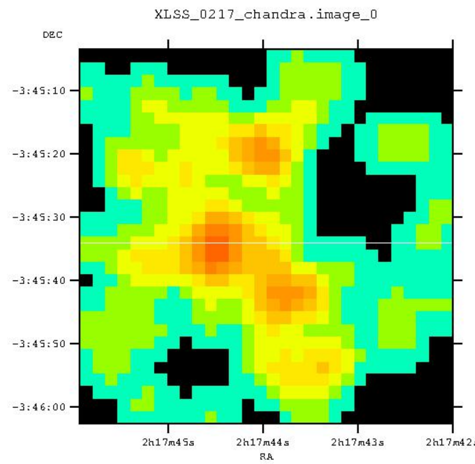
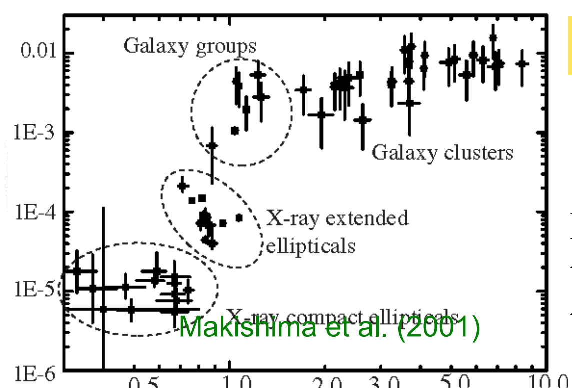
Way Back in Time

- X-ray and Sunyaev-Zel'dovich properties of the redshift 2.0 galaxy cluster XLSSC 122 (Mantz et al 2018)
- kT = 5.0 ± 0.7 keV;
- metallicity of $Z/Z_\odot = 0.33_{-0.17}^{+0.19}$, consistent with lower-redshift clusters;
- x-ray redshift of $z = 1.99^{+0.07}_{-0.06}$
- evolution of the intracluster medium in the most massive, well-developed clusters is remarkably simple, even out to the highest redshifts.





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



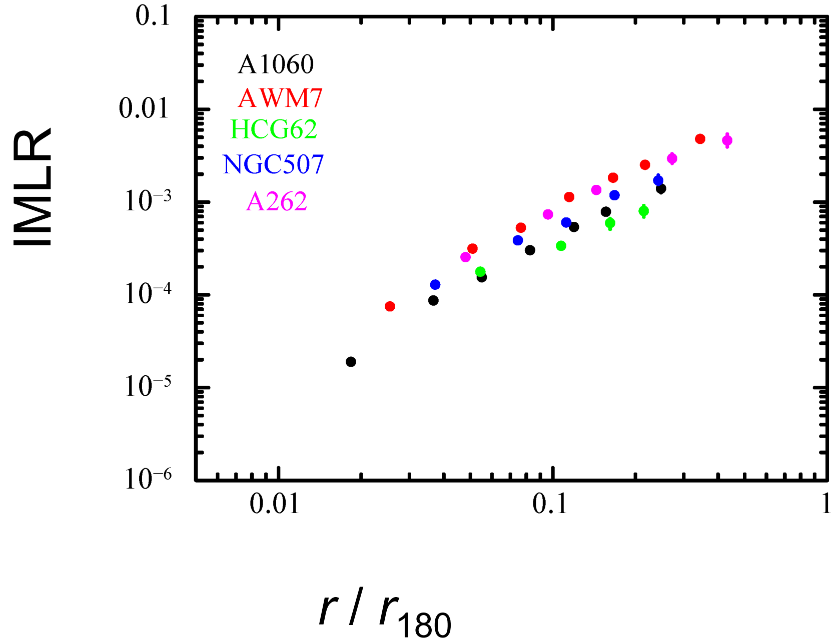
Temperature (keV) ∝ mass of system

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

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

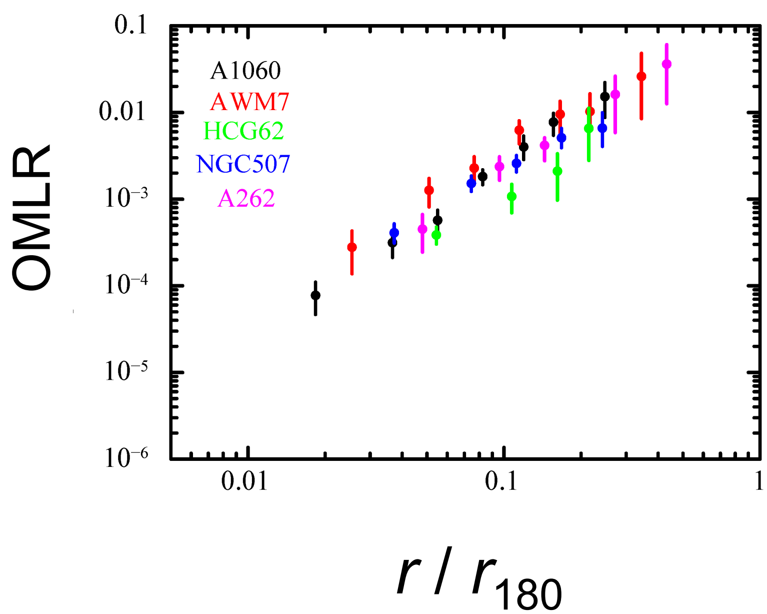
Oxygen Mass-to-Light Ratio: OMLR
Magnesium Mass-to-Light Ratio: MMLR
Iron Mass-to-Light Ratio: IMLR

Iron Mass to Light Ratio



K-band for optical light

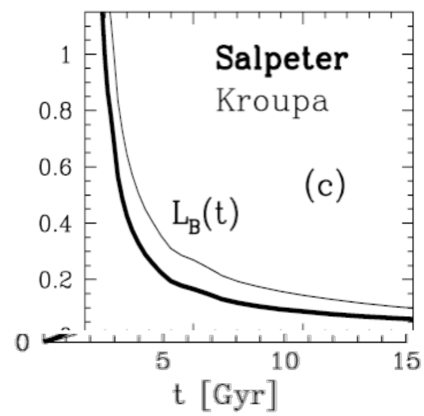
Metal enrichment process in the ICM
- shows factor of several variation



43 How Much Metals Should be Produced ?

- The present day mass in stars (inferred from their light, age and IMF) should tell us
  - how many type I and II supernova have occurred
  - and thus the total mass of metals produced over all time e.g,
- for any given IMF, one can compute the corresponding rates of SNe II and SNe Ia and the rate of production of iron $M(Fe_{tot}(t))$—or of any other element.
- For the same IMF, the corresponding SSP (simple stellar population) derived from stellar isochrones gives the luminosity evolution $L_B(t)$
- Salpeter IMF can reproduce the observed iron enrichment if ~80% of the iron synthesized is shed into the ICM!

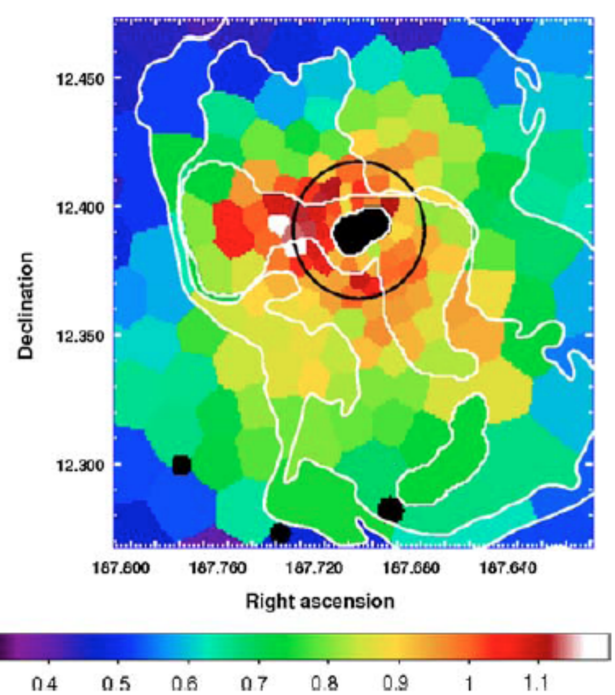
PORTINARI ET AL.



Change in light of galaxy as a function of time

44 Non-Uniform Distribution of Metals

- Fe Abundance in M87- all is not so simple !
- In addition to radial gradients in some clusters there is true spatial variation
- Presumably this is due to the effects of mergers and the relics thereof



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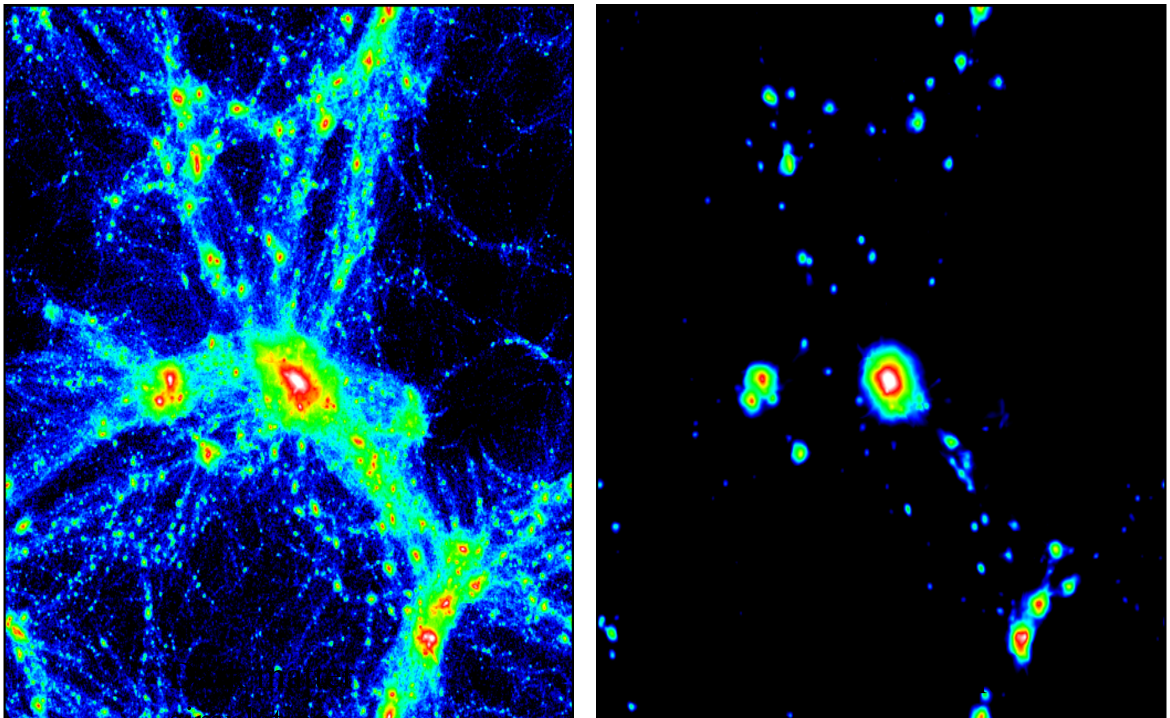
Comparison of dark matter and x-ray cluster and group distribution

Every bound system visible in the numerical simulation is detected in the x-ray band - bright regions are massive clusters, dimmer regions groups,



simulation simulation

Summary of Some of the Important Equations

Sound Crossing Time

- Sound speed

$$c_s^2 = \gamma \frac{P}{\rho} = \frac{5}{3}\frac{P}{\rho}$$

$$c_s \approx 1500 \left(\frac{T}{10^8\,\mathrm{K}} \right)^{1/2} \mathrm{km/s}$$

- Sound crossing time

$$t_s \approx 6.6 \times 10^8 \left(\frac{T}{10^8\,\mathrm{K}} \right)^{-1/2} \left(\frac{D}{\mathrm{Mpc}} \right) \mathrm{yr}$$

Less than age → unless something happens (merger, AGN, …),

gas should be nearly hydrostatic

Cluster Potentials

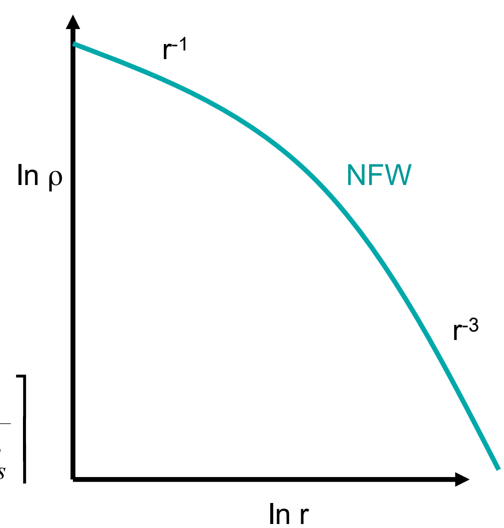
NFW (Navarro, Frenk, & White 1997)

$$\rho_{dm}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

$$c \equiv r_{vir} / r_s \approx 5 \text{ for clusters,}$$

$$r_{vir} \approx 2\,\mathrm{Mpc}, \;\; r_s \approx 400\,\mathrm{kpc}$$

$$M(r) = 4\pi \rho_s r_s^3 \left[\ln(1 + \frac{r}{r_s}) - \frac{r}{r + r_s} \right]$$



Hydrostatic Equilibrium

$$\nabla P = -\rho \nabla \phi$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\phi}{dr} = -\frac{GM(r)}{r^2} \quad \text{spherical}$$

If we wish to use the positions and velocities of the galaxies because they have 'orbits' they cannot be treated as a fluid and one has to use a different equation.

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1 - \frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1 - \frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

•Dynamical data: use the collisionless Boltzman eq (conceptionally identical to the use of gas temperature to measure mass, but stars have orbits while gas is isotropic)

the r, θ and ϕ components of the velocity dispersion σ , the logarithmic derivative of the stellar density ν, and the circular velocity V

Hydrostatic Equilibrium

•density and potential are related by Poisson's equation

$\nabla^2\phi = 4\pi\rho G$

•and combining this with the equation of hydrostatic equil

•$\nabla \cdot (1/\rho \nabla P) = -\nabla^2\phi = -4\pi G\rho$

assuming spherically symmetric system

$1/r^2\, d/dr\, (r^2/\rho\, dP/dr) = -4\pi\rho G\rho$ which can be expressed as

$GM(r) = kT_g(r)/\mu G m_p)\mathbf{r}\, (d\ln T/dr + d\ln\rho_g/dr)$

$$M(r) = -3.71 \times 10^{13}\, M_\odot\, T(r)\, r\left(\frac{d\log\rho_g}{d\log r} + \frac{d\log T}{d\log r}\right),$$

where T is in units of keV and r is in units of Mpc (

Mean Free Path for Collisions/ Energy

- Mean-free-path λ_e ~ 20 kpc < 1% of cluster size

$$\lambda_p \approx \lambda_e = \frac{3^{3/2}(kT)^2}{8\sqrt{\pi}\, n_e e^4 \ln\Lambda}$$

$$\approx 23\left(\frac{T}{10^8\,\mathrm{K}}\right)^2\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}\mathrm{kpc}$$

At T>3x10^7 K the major form of energy emission is thermal bremmstrahlung continuum

ε~ 3x10^{-27} T $^{1/2}$ n^2 ergs/cm^3/sec- how long does it take a parcel of gas to lose its energy?

τ~nkT/ε ~8.5x10 ^{10}yrs(n/10^{-3})$^{-1}$ T$_8$ $^{1/2}$

At lower temperatures line emission is important

Beta Model

(Cavaliere & Fusco-Femiano 1976)

Assume King Model DM potential
Alternatively, assume galaxies follow King Model, and have isotropic, constant velocity dispersion

$$\sigma_{gal}^2 \frac{d\ln\rho_{gal}}{dr} = -\frac{d\phi}{dr} = \left(\frac{kT}{\mu m_p}\right)\frac{d\ln\rho}{dr}$$

$$\rho_{gal}(r) = \frac{\rho_{gal,0}}{\left[1+\left(\frac{r}{r_c}\right)^2\right]^{3/2}}$$

Beta Model (cont.)

$$\rho(r) = \frac{\rho_0}{\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{3\beta/2}}$$

$$\beta \equiv \frac{\mu m_p \sigma_{gal}^2}{kT}$$ but treat as fitting parameter

$$I_X(r) \propto \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta+1/2}$$

Beta Model (cont.)

Fit outer parts of clusters

$\beta \approx 2/3$

$\rho \alpha r^{-2}$

$I_X \alpha r^{-3}$