CHEMICAL ENRICHMENT BY SUPERNOVA EXPLOSIONS IN ABELL 3112 GALAXY CLUSTER OUT TO R_{200}

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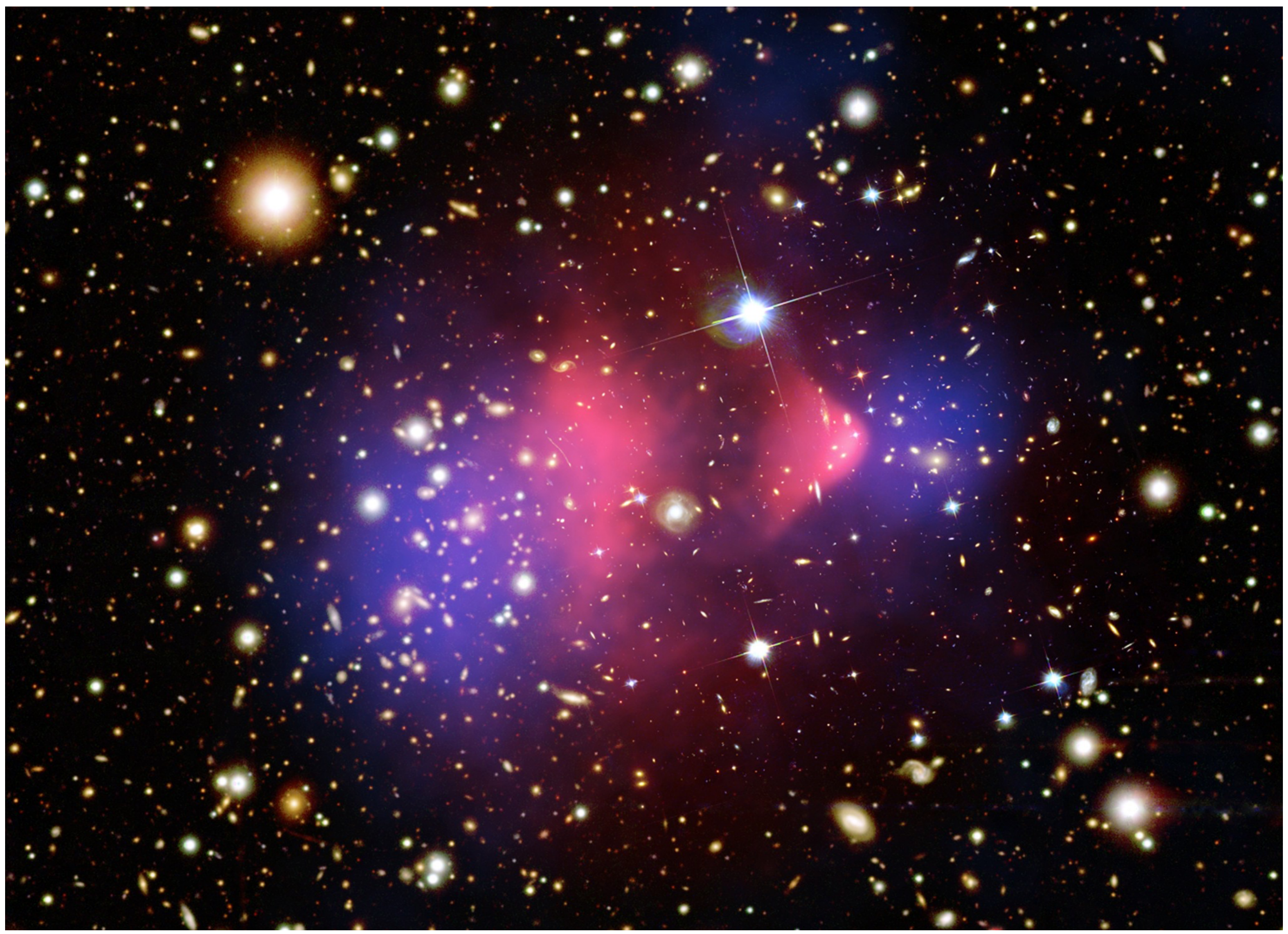
Introduction and Motivation

Galaxy Clusters

- **Clusters of galaxies are the largest concentrations of confined matter in the Universe.**



Credit: X-ray image by NASA/CXC/M.Markevitch et al.;
optical image by NASA/STScI, Magellan/U.Arizona/D.Clowe et al.;
lensing map image by NASA/STScI, ESO WFI, Magellan/U.Arizona/D.Clowe et al.

Basic Constituents:

- 84 % Dark Matter
- 13 % Hot dilute gas (ICM)
- 3 % Galaxies

Typical Properties:

- 30 -300 galaxies
- Total Mass: ~ 10^{14} – 10^{15} $M_\odot$
- Size: ~ 2 – 5 Mpc
- Temperature: ~10^7–10^8 K

Introduction and Motivation

Chemical Enrichment by Supernova Explosions

- **The types of supernova explosions (SNe) enriching the ICM can be broadly classified in two types; Type Ia (SN Ia) and core collapse (SN cc).**

Type	**SN Ia**	**SN cc**
Spectra	Si, S, Fe, Ni	O, Ne, Mg, Si
Explosion	Thermonuclear explosion (low-mass stars)	Core-collapse (massive stars)
SN Yields	W7 & W70 (I99) WDD & CDD (I99) CDDT & ODDT (M10)	10-50 $M_\odot$ 0-1.0 $Z_\odot$ (I99)

*I99: Iwamoto et al., The Astrophysical Journal Supplement Series, 125, 2, 1999.
*M10: Maeda et al., The Astrophysical Journal, 712, 1, 2010.

Methodology

- *snapec* is a recently developed XSPEC model. This method calculates the total number of SNe explosions and measures the spatial distribution of the ratio of type Ia (SN Ia) to core collapse (SN cc) supernova explosions by directly fitting the X-ray spectra.

- Model combines *apec* with all up-to-date relative abundance scenarios (~ 124 different yields).

- Model parameters are:

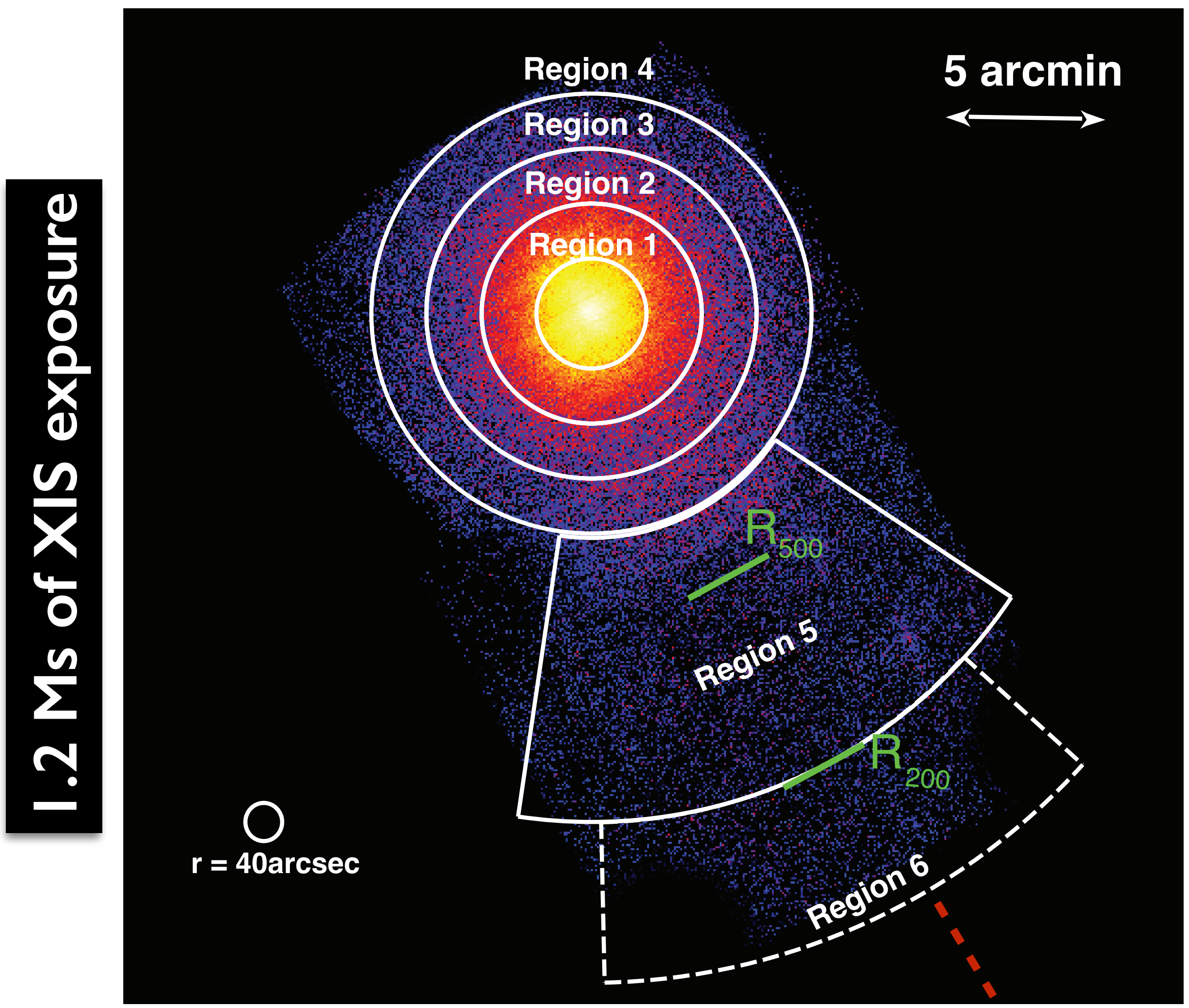
kT: Temperature
N^{SNe}: Total number of SN explosions
R: Percentage of SN Ia contribution
SNIModelIndex: Type Ia SN yields
SNIIModelIndex: Core Collapse SN yields
z: The cluster's redshift
Norm: Emission measure

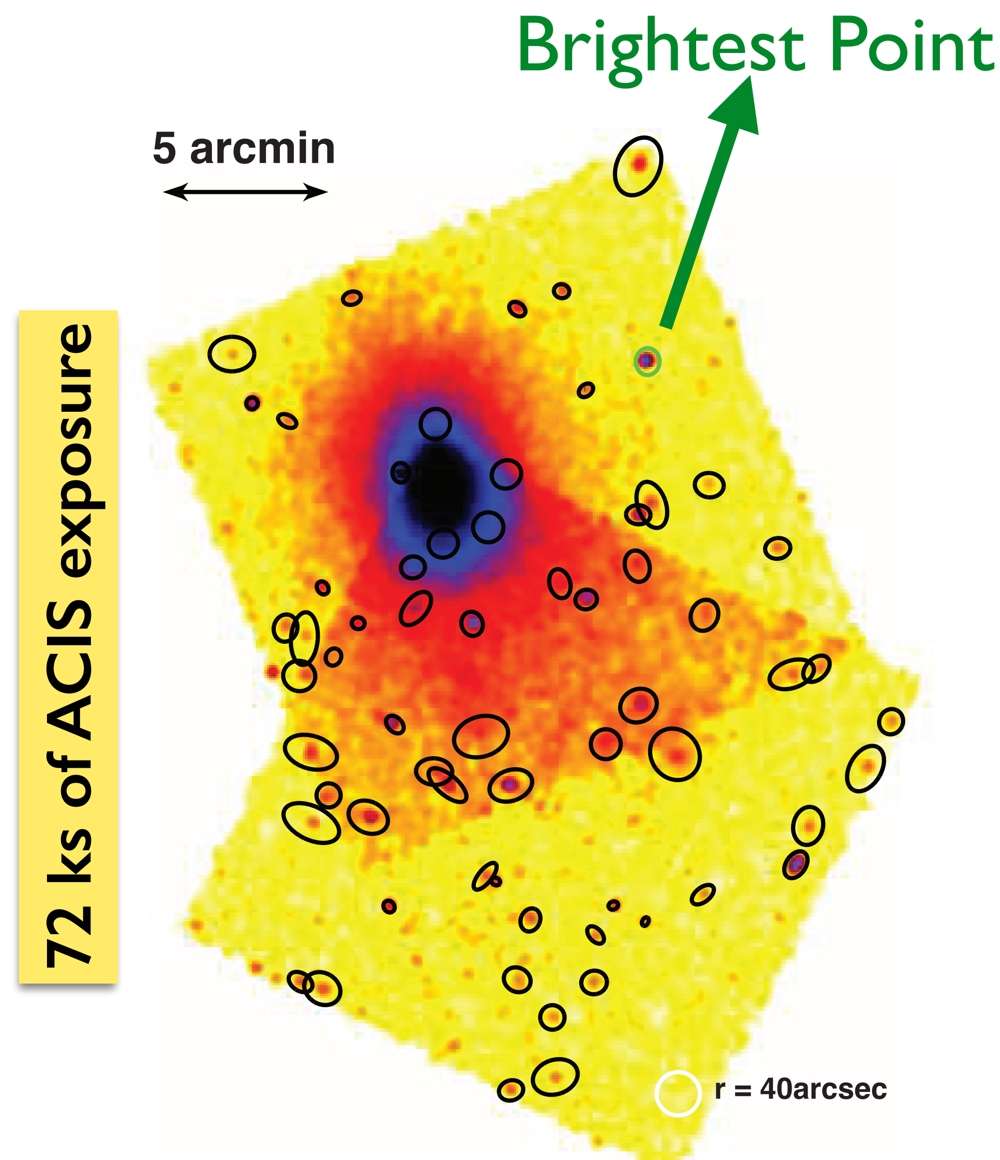
*snapec: Bulbul et al., The Astrophysical Journal, 753, 1, 2012

Analysis

Abell 3112

- **Abell 3122 is an archetypal relaxed cool core cluster at redshift 0.0752, making it ideal target for studying its chemical enrichment history.**





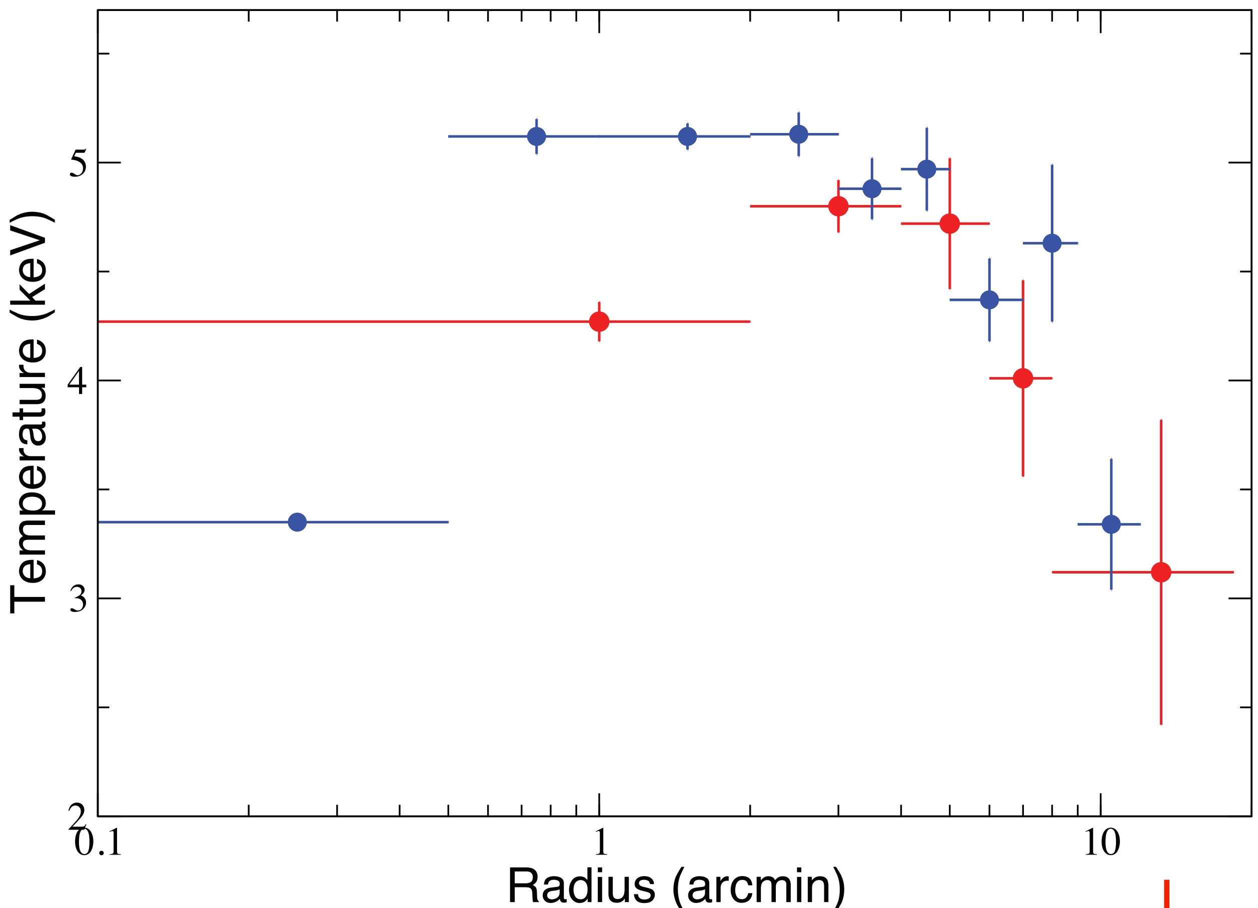
Images: 0.5 - 7.0 keV energy band

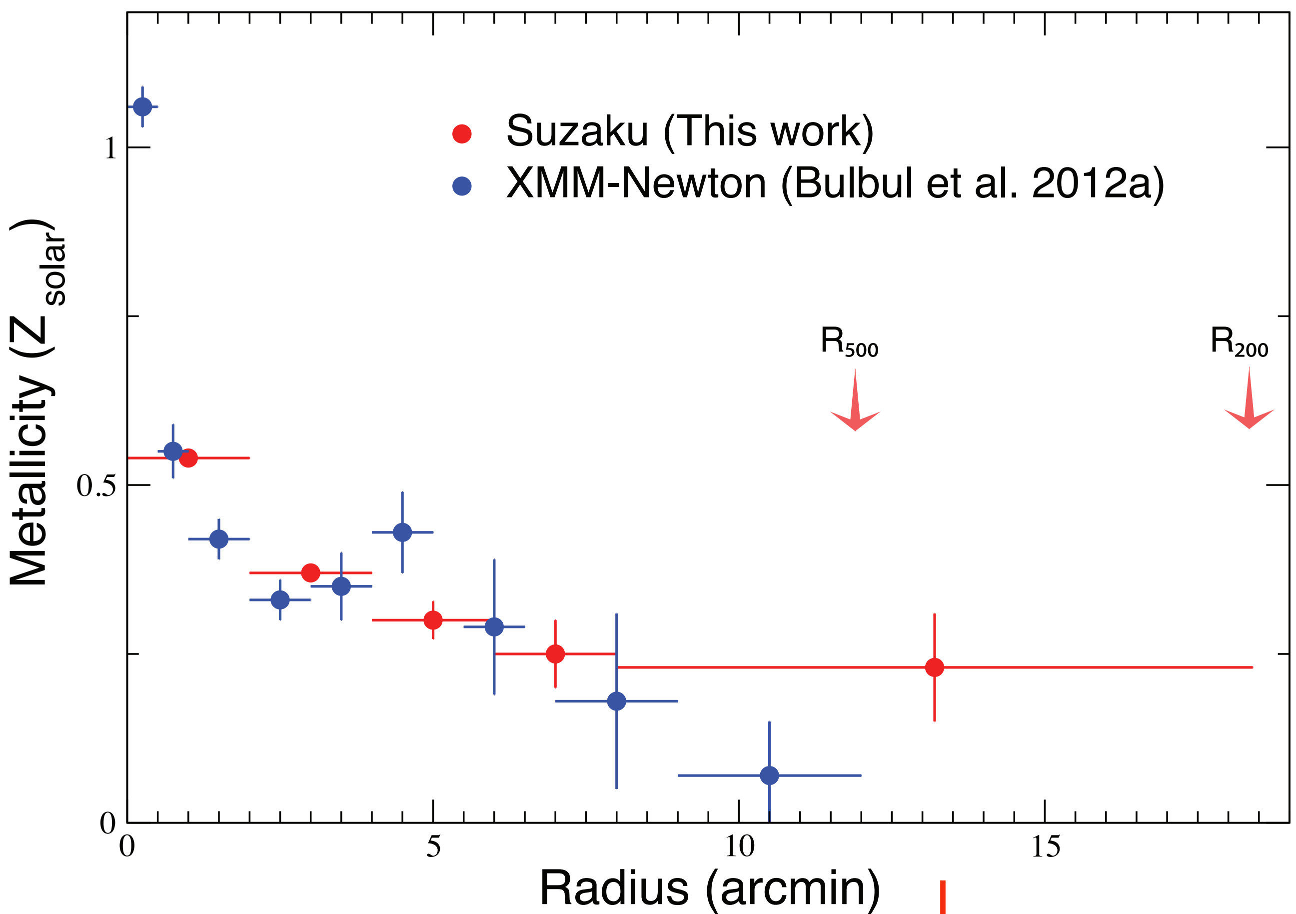
Local Background

Results

Results 1: Global Spectral Properties: 1T *apec* Model

*The best fit parameters of Suzaku observations, 1σ statistical errors together with systematics are over-plotted.





The First Time Measurements in literature

*Ezer et al., The Astrophysical Journal, 836, 1, 2017

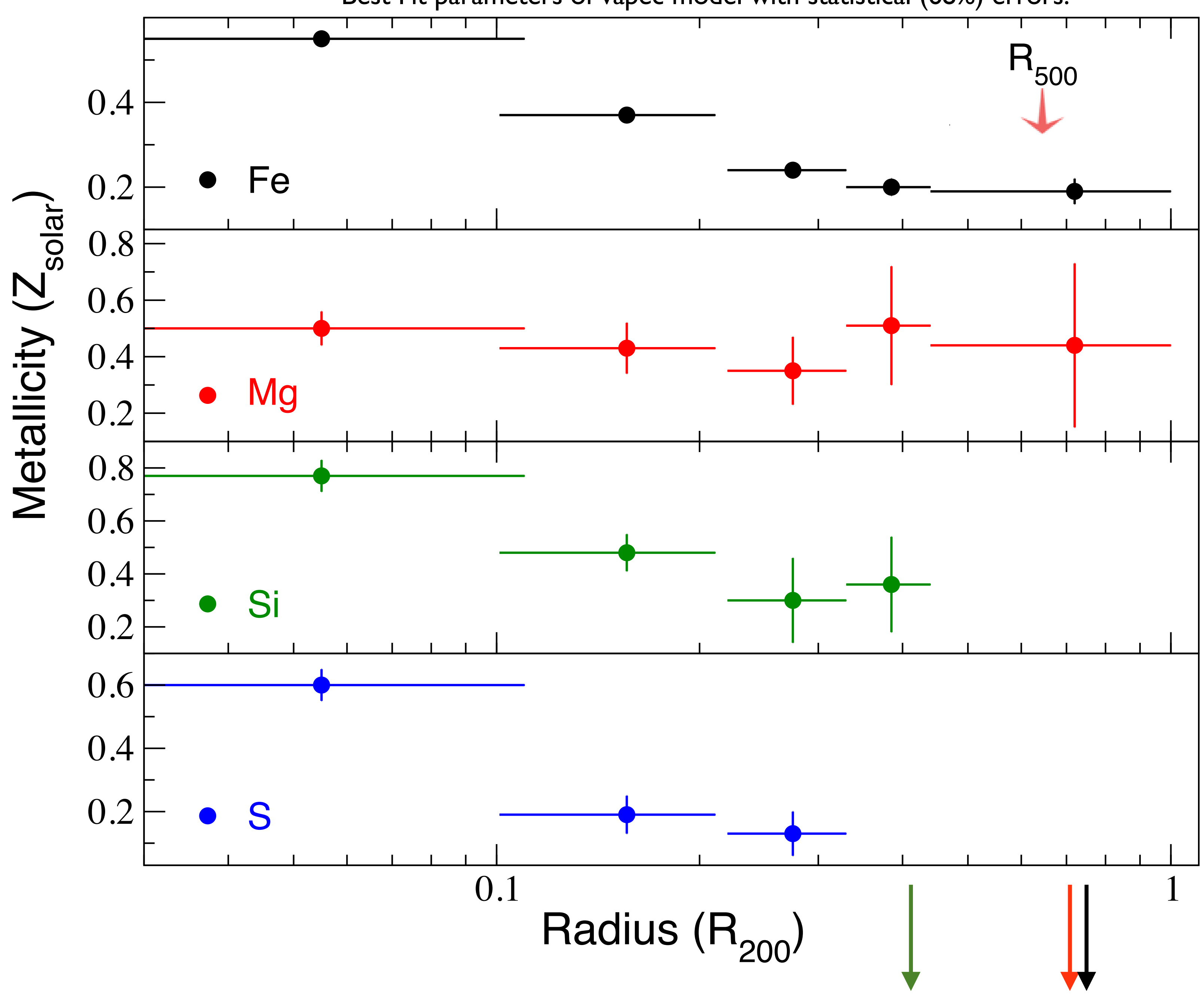
Results

Results 2: Global Spectral Properties: 1T *Vapec* Model

- **We further investigate the radial abundance distributions of individual α-elements, such as silicon (Si), sulfur (S), iron (Fe), and magnesium (Mg) out to R_{200}.**

- **The Fe, Si, S, and Mg elemental abundances are allowed to vary independently while other elemental abundances are fixed to the measured Fe abundance at the outskirts, $0.25Z_{\odot}$.**

*Best Fit parameters of vapec model with statistical (68%) errors.

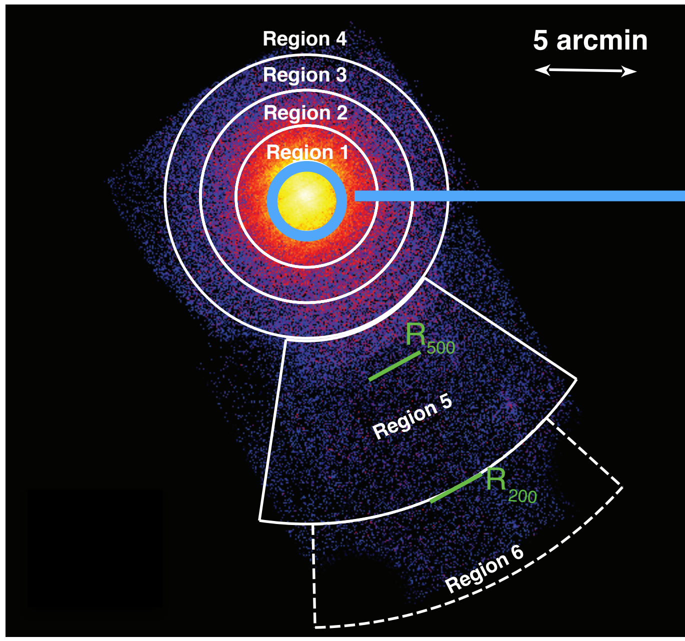


The First Time Measurements in literature

*Ezer et al., The Astrophysical Journal, 836, 1, 2017

Results

Results 3: Chemical Enrichment History: *SNapec* Model



- **To investigate chemical enrichment history out to R_{200} of Abell 3112, we fit the innermost spectra (Region 1) with 1T snapec model for various SN yields.**

Table1: Best Fit parameters of snapec model for the innermost (0' - 2') region.

SN Ia Model	N_{SNe} (x10^9)	R (N^{Ia}/N^{cc})	C-stat (dof)
W7	3.61 ± 0.16	0.10 ± 0.01	1112.4 (840)
W70	3.59 ± 0.25	0.10 ± 0.02	1108.9
WDD	3.24 ± 0.10	0.12 ± 0.02	1108.1
CDD	3.18 ± 0.15	0.12 ± 0.01	1108.8
CDDT	3.08 ± 0.28	0.41 ± 0.09	1173.3
ODDT	3.06 ± 0.21	0.18 ± 0.03	1112.3

We find that 1D delayed detonation WDD model for SN Ia is the best describing the Suzaku data of the immediate core region.

The 2D delayed detonation symmetric CDDT model can at best achieve fits that are less significant than other models, suggesting they are not a dominant process enriching the ICM.

Results

Results 3: Chemical Enrichment History: *SNapec* Model

- **To determine the distribution of SN fraction out to R_{200} rather than individual testing, we use WDD model which gives the best fit for the highest signal-to-noise region.**

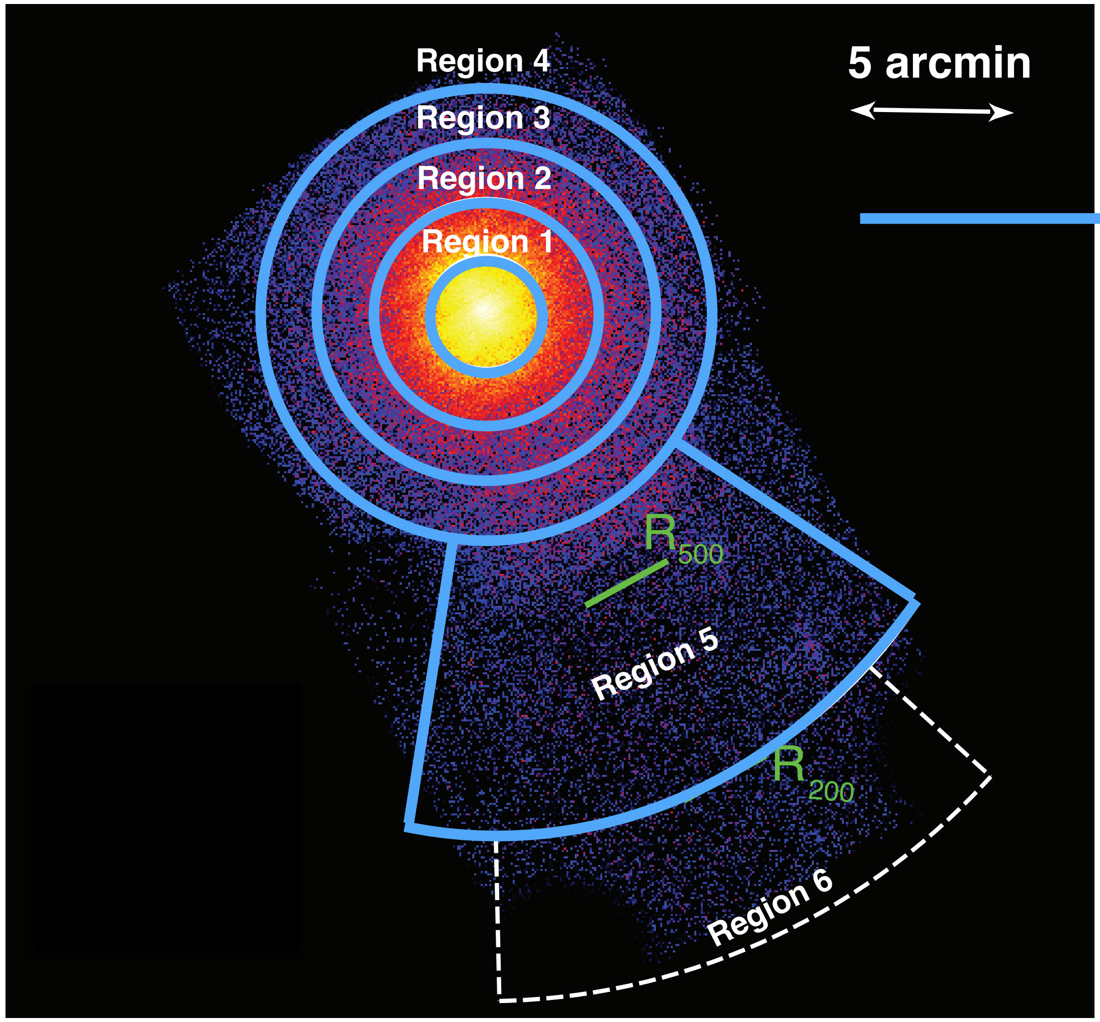


Table 2*: Best Fit parameters of snapec model parameters with 1σ statistical and systematic uncertainties are added in quadratures.

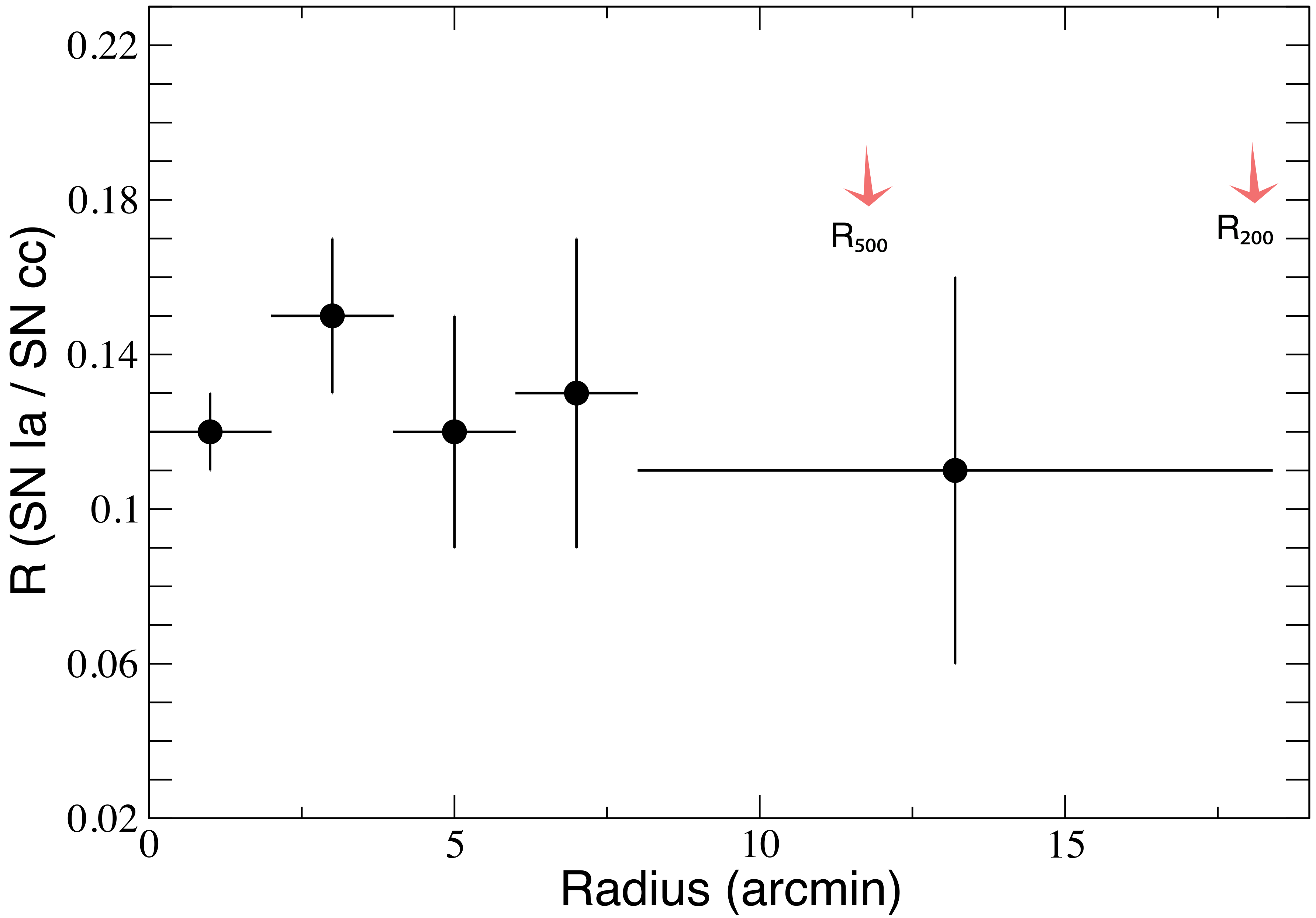
SN Models	Regions (arcmin)	N_{SNe} ($\times 10^9$)	R	C-stat (dof)
SN Ia: WDD (I99) SN cc: 10-50 M⊙, 0-1 Z⊙ (I99)	0' - 2'	3.24 ± 0.10	0.12 ± 0.02	1108.1 (840)
	2' - 4'	1.96 ± 0.36	0.16 ± 0.02	1079.9 (842)
	4' - 6'	1.48 ± 0.13	0.12 ± 0.04	1008.9 (850)
	6' - 8'	1.22 ± 0.12	0.13 ± 0.05	337.3 (259)
	8' - 18'	0.87 ± 0.17	0.11 ± 0.06	244.2 (151)

*Ezer et al., The Astrophysical Journal, 836, 1, 2017

Results

Results 3: Chemical Enrichment History: *SNapec* Model

The ratio of SN Ia to SN cc is fairly UNIFORM from the core to the outskirts.



*Ezer et al., The Astrophysical Journal, 836, 1, 2017

Conclusions

- Deep Suzaku (1.2 Ms of total XIS exposure) and Chandra (72ks) observations of Abell 3112.
- Global spectral features with single and multi temperature structure: temperature peaks around ~ 4.8 keV and declines to 3.37 keV in the virial radius.
- The metallicity of the ICM: $0.22 \pm 0.08\ Z_\odot$ (near the virial radius) consistent with Virgo & Perseus. Uniform Fe profile at radius > $0.2R_{200}$.
- Snapec (XSPEC model) for calculation of SN Ia to SN cc ratio.
- Our results favor 1D W7, CDD, and WDD SN Ia models. (A 2D delayed detonation SN Ia model CDDT produces less significant fits compared to priors, overestimate the observational Si abundance).
- The fractional distribution of the SN Ia (I99 WDD) to SN cc between 0.12–0.16. (In agreement with the observed fraction in our Galaxy!)
- The distribution of the SN Ia fraction is fairly UNIFORM out to R_{200} indicating:
  - Metal enrichment at an early epoch (z~2–3)
  - Mixing originating from an intense period of star formation activity
  - Metals are well-mixed into the ICM

BACKUP

Suzaku Observations:

- Deep (~1.2 Ms) *Suzaku* Observations

Position	ObsID	Total Exposure Time (ks)	Clean Exposure Time (ks)	Observation Date
On-axis	803054010	67.5/67.5/67.5	54.9/54.9/54.9	2008
On-axis	808068010	119.1/119.1/119.1	113.5/113.5/113.5	2013
On-axis	808068020	65.4/65.4/65.4	54.4/54.4/54.4	2013
Offset	809116010	107.9/107.9/107.9	87.3/87.3/87.3	2014
Offset	809116020	97.9/97.9/97.9	80.4/80.4/80.4	2014

- Total exposure time is ~ 1.37 Ms and after restrict filtering we have ~1.17 Ms

Chandra Observations and Data Reduction:

- *Chandra* Observations

Position	ObsID	Total Exposure Time (ks)	Clean Exposure Time (ks)	Observation Date
On-axis	13135	42.8	42.2	2011
Offset	6972	30.2	29.7	2006

- Total exposure time is ~ 73 ks and after filtering we have ~71.9 ks

- CIAO: *lc_clean* and *wavdetect* routines to detect the point sources.

The Background and Systematic Uncertainties

- We include various background components:
  - Non X-Ray Background (NXB)
  - Cosmic X-Ray Background (CXB)
  - Soft X-Ray Background (LHB, GH, HF)

➡ We used cluster emission free region (r> 18') together with ROSAT All Sky Survey data (RASS) to determine the background parameters.

- We include various systematic uncertainties related to:
  - Cosmic X-Ray Background (CXB)
  - Soft X-Ray and Particle (Non X-Ray) Background
  - Point Spread Function (PSF) and Scattered Light

Background Results:

We optimize the background parameters by simultaneously fitting the ROSAT All Sky Survey data (RASS) with the local background. (C-stat (dof) = 507.3 (341))

Component	kT (fixed)	Normalization	Flux (0.5-2.0 keV)
	(keV)	10^{-8} cm^{-5}	10^{-16} ergs s^{-1} cm^{-2}
GH	0.3	$0.8^{+0.7}_{-0.6}$	$0.14^{+0.09}_{-0.09}$
HF	0.75	$1.2^{+0.3}_{-0.3}$	$0.34^{+0.07}_{-0.07}$
LHB	0.1	$68.4^{+6.2}_{-6.4}$	$1.29^{+0.12}_{-0.11}$

- **CXB Norm=1.41+/- 0.14 × 10^{-7} photons keV^{-1} cm^{-2} s^{-1} arcmin^{-2}**
- **We fixed all these background parameters for further analysis.**

Systematic Uncertainties: Cosmic X-Ray Background (CXB)

- **We found our Suzaku observations' point source detection limit as**

$$S_{excl} = 6.7 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$$

in the 2.0 − 10.0 keV energy band.

- **The 1σ estimation from the CXB level:**

$${\sigma_B}^2 = \frac{1}{\Omega}\int_0^{S_{excl}} \left(\frac{dN}{dS}\right) \times S^2 \, dS$$

→

$$N(>S) = N_0\left[\frac{(2\times 10^{-15})^{\alpha}}{S^{\alpha} + S_0^{\alpha-\beta} S^{\beta}}\right]$$

→ The model for the population of the sources

	Region 1	Region 2	Region 3	Region 4	Region 5
CXB Fluctuations 10^{-12} ergs cm^{-2} s^{-1} deg^{-2}	10.10	5.78	4.48	3.78	2.12

Systematic Uncertainties: PSF and Scattered Light

- To estimate the magnitude of the uncertainty related to *Suzaku* mirror PSF (~ 2′), we use the ray-tracing simulator *xissim* to simulate a point source in our *Suzaku* field-of-view (FOV).

	Region 1	Region 2	Region 3	Region 4	Region 5
Region 1	68.5	15.6	3.47	1.33	0.33
Region 2	14.3	65.6	16.4	2.25	0.38
Region 3	0.24	17.7	64.5	13.7	0.82
Region 4	0.26	1.52	15.2	66.8	6.81
Region 5	0.09	0.27	0.79	7.06	89.2

Results 4: Gas Mass Fraction

- Our results at R_{500} are comparable to the values of the cosmic baryon fraction from 9-year WMAP results.

Our work $f_{gas} = 0.21 \; {+0.16}/{-0.11}$

WMAP $f_B = \frac{\Omega_B}{\Omega_M} = 0.166 \pm 0.0065$

- More data is needed to give an accurate result.

- A detailed analysis (including mass of the galaxies) is required to well better constrain to cosmic baryon fraction of the Universe.