



The Properties of Radio Relics and the Connection with Radio Halos in Galaxy Cluster and their Correlation with Non-Thermal Phenomena at Multi-Frequency

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&

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Radio relics in galaxy clusters: phenomenology and physics

- Radio Relics (RRs) are faint Mpc-scale (Feretti et al., 2012) extended non-thermal radio sources located preferentially at the outskirts of Galaxy Clusters (GCs)
 - Steep synchrotron spectra ($\alpha < -1$) (Clark et al., 2014; de Gasperin et al., 2015)
 - Very low-surface brightness emission ($10^{-6} \text{ Jy arcsec}^{-2}$, de Gasperin et al., 2015)
 - Elongated or arch-like structures (Giovannini et al., 2013)
 - Strongly polarized, with linear fractional polarization at 1.4 GHz of 10-30%, reaching values up to 50% in some regions (Bonafede et al. 2010)
 - Are usually divided into two main groups:
 - Radio Gischt, where among them are double-relics with the two relics located on different sides of a cluster centre (Vazza et al. al. 2012)
 - Radio phoenixes, which are related to radio-loud Active Galactic Nuclei (AGN) (Vazza et al. al. 2012)

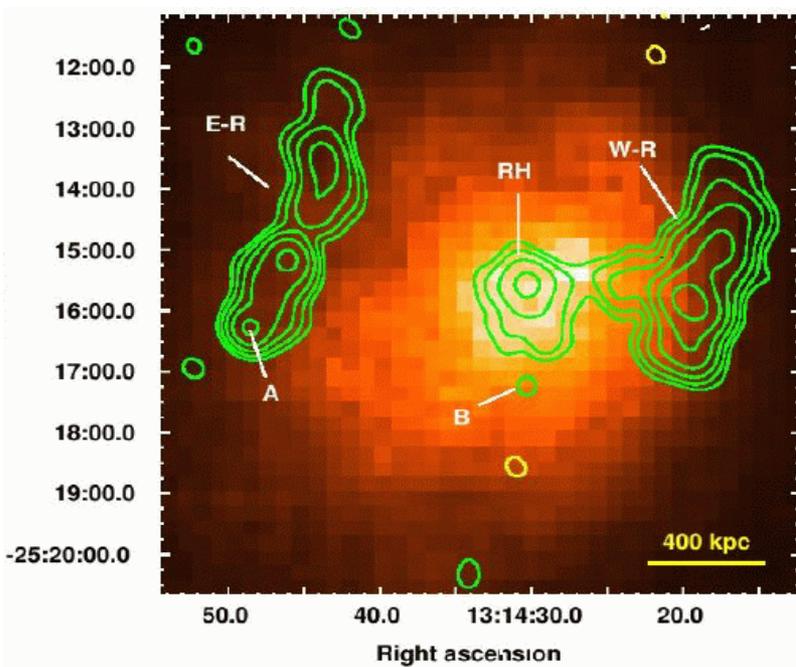


Figure: RCXJ1314.4-2515. E-R: Eastern Relic, W-R: Western Relic, RH: Radio Halo, A and B: Radio Sources. Credit: <http://www.ira.inaf.it/Research/Clusters.php>

Radio relics in galaxy clusters: origin

- ✓ Diffusive shock acceleration (DSA) or not?
 - ✓ Link between RRs: & Radio Halos (RHs), & other galaxy cluster (GC) parameters, & Radio Galaxies?
- The common explanation of RRs origin is radio emission from shock (re-)accelerated electrons (see, e.g., Keshet, 2010)
 - This mechanism shows however several inconsistencies:
 - Observations show that the position of the relic doesn't coincide with the position of the X-ray shocks in several cases (see, e.g., Shimwell et al., 2014)
 - Mach number (M) at the outer edge of the relic derived from the temperature difference is significantly lower ($M \leq 4$) than the value derived from the radio spectral index assuming a simple DSA theory (see, e.g., Itahana et al., 2015)
 - If DSA model is correct, thus we expect re-acceleration of cosmic-ray protons in GC, but high-energy observations of nearby GCs have not revealed any diffuse gamma-ray (γ -ray) emission (Vazza et al., 2015)
 - Geometry: why relics only in the periphery of clusters and not in the center?
 - Relic-halo bridges: what is the origin of the bridge? (Coma bridge exhibits a powerful Radio Galaxy at its center)

Alternative explanations

TABLE 2.1: The sample of GC with detected RRs.

Cluster Name (1)	z (2)	References (3)	Cluster Name (4)	z (5)	References (6)
A0013	0.01	1	A3667-NW	0.06	1
A0085	0.06	1	A3667-SE	0.06	1
A0115	0.20	1	A4038	0.03	1
A0133	0.06	3	ACT-CLJ0102-4915-NW	0.87	2
A0521	0.25	1	ACT-CLJ0102-4915-SE	0.87	2
A0523	0.10	3	AS753	0.01	1
A0548b-NW	0.04	1	CIZA J0649.3+1801	0.06	1
A0548b-N	0.04	1	CIZA J2242.8+5301-N	0.19	1
A0610	0.10	1	CIZA J2242.8+5301-S	0.19	1
A0725	0.09	3	CL0217+70-NW	0.07	1
A0746	0.23	1	CL0217+70-SE	0.07	1
A0754	0.05	1	CL1446+26	0.37	1
A0781	0.30	1	PSZ1 G108.18-11.53-N	0.33	6
A0786	0.12	3	PSZ1 G108.18-11.53-S	0.33	6
A1240-N	0.16	1	MACS0717+37	0.55	3
A1240-S	0.16	1	MACSJ1149.5+2223-E	0.54	2
A1300	0.31	1	MACSJ1149.5+2223-W	0.54	2
A1351	0.32	4	MACSJ1752.0+4440-NE	0.37	2
A1367	0.02	1	MACSJ1752.0+4440-SW	0.37	2
A1443	0.27	7	MaxBCG 138.9	0.32	3
A1612	0.18	1	MaxBCG J217+13	0.16	3
A1656	0.02	1	PLCK G287.0+32.9-N	0.39	1
A1664	0.13	1	PLCK G287.0+32.9-S	0.39	1
A1758	0.28	3	PSZ1G096.89+24.17-N	0.30	2
A2034	0.11	1	PSZ1G096.89+24.17-S	0.30	2
A2048	0.10	1	RXCJ1314.4-2515-E	0.25	1
A2061	0.08	1	RXCJ1314.4-2515-W	0.25	1
A2063	0.03	1	RXCJ1053.7+5452	0.07	1
A2163	0.20	1	S1081	0.22	1
A2255	0.08	1	ZwC10008.8+5215-W	0.10	1
A2256	0.06	1	ZwC10008.8+5215-E	0.10	1
A2345-W	0.18	1	ZwCL 2341.1+0000-N	0.27	2
A2345-E	0.18	1	ZwCL 2341.1+0000-S	0.27	2
A2443	0.11	1	0217+70	0.07	3
A2744	0.31	1	0809+39	*	3

TABLE 2.2: Continuation of Table 2.1.

Cluster Name (1)	z (2)	References (3)	Cluster Name (4)	z (5)	References (6)
A3365-E	0.09	1	1E0657-55.8	0.29	5
A3365-W	0.09	1	1RXs 06+42	0.23	3
A3376-W	0.05	1	24P73	0.16	3
A3376-E	0.05	1			

Notes: (*) No value is available. The letters N, NE, NW, S, SE, SW, E and W denotes the direction with respect to cluster center (Vazza et al., 2012).

References: (1) Feretti et al. (2012); (2) de Gasperin et al. (2014); (3) Nuza et al. (2012); (4) Giacintucci et al. (2009); (5) Shimwell et al. (2015); (6) de Gasperin et al. (2015); and (7) Bonafede et al. (2015).

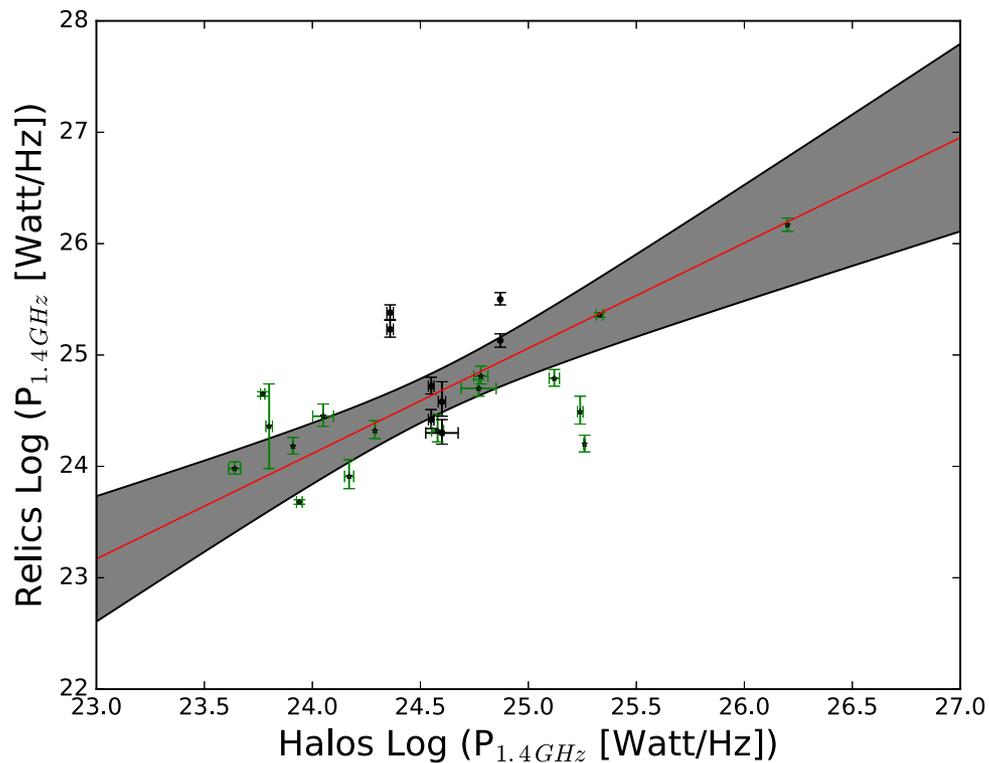
In order to better understand the present models and their limitations, and to motivate the search for a more successful astro-physical model:

- 60 GCs with detected RRs which are available in the literature
 - 77 RRs
 - 43 Single
 - 17 Double

Alternative explanations

- Correlations between RRs and:
 - RHs
 - Other GC parameters
 - ✓ Sunyave-Zel'dovich Effect (SZE), X-ray Bolometric Luminosity (L_x), and Cluster Cooling time (t_{cool})
 - ... M
 - (Active)-Galaxies in GC

Correlations: other GC parameters

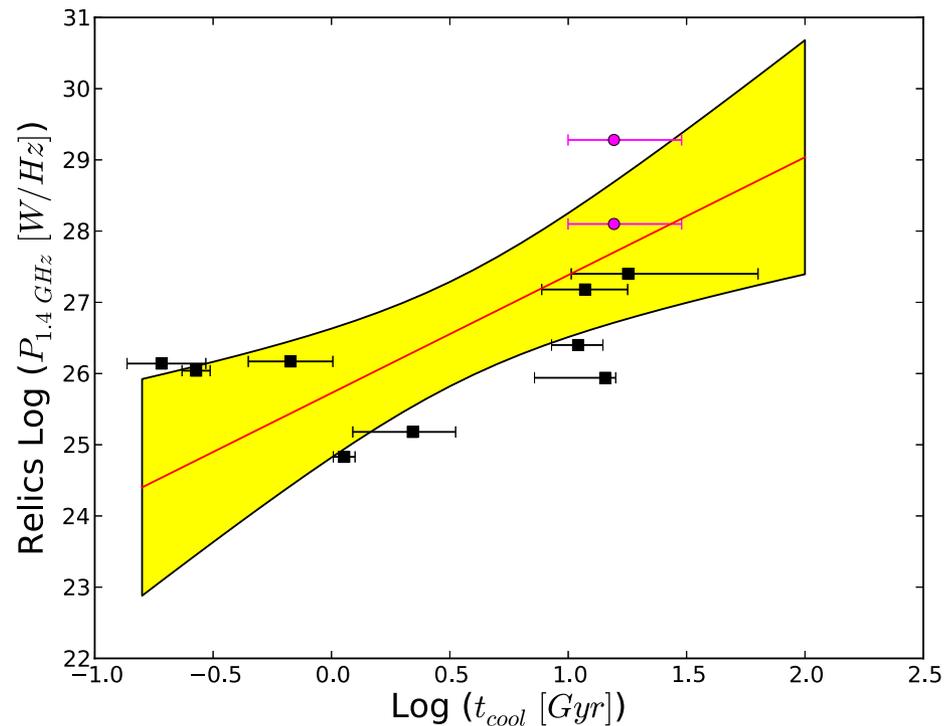


$$P_{RR} = C \cdot P_{RH}^d$$

$$d = 0.95 \pm 0.09 \quad \log_{10} C = 1.42 \pm 2.17$$

$$\rho = 0.64 \quad S\text{-rank} = 0.344$$

- Relics know about Halos
 - They scale together



$$P_{RR} = n \cdot t_{cool}^l$$

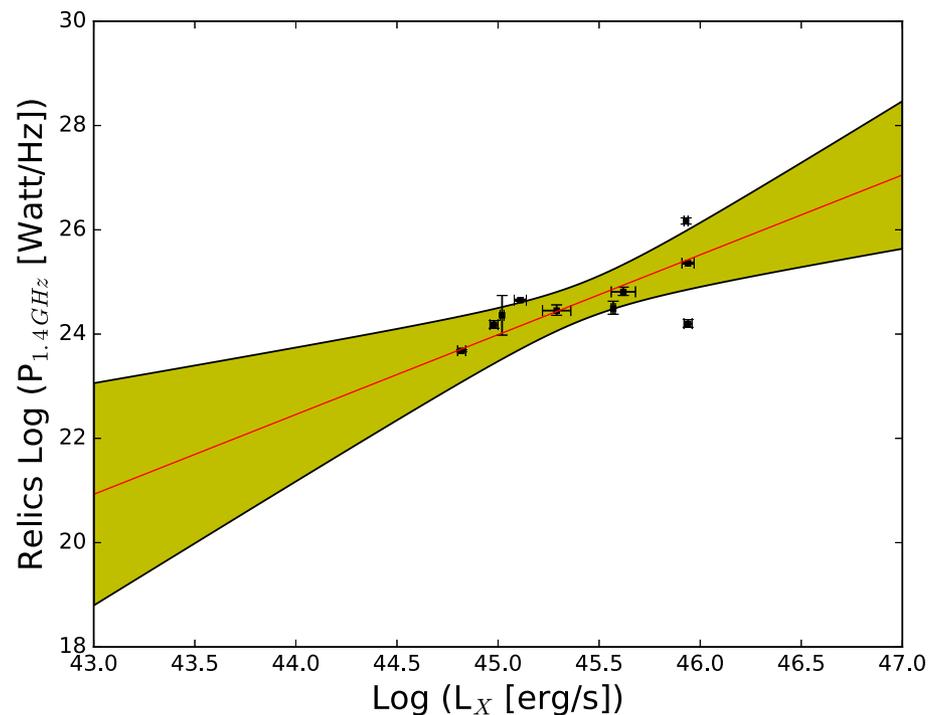
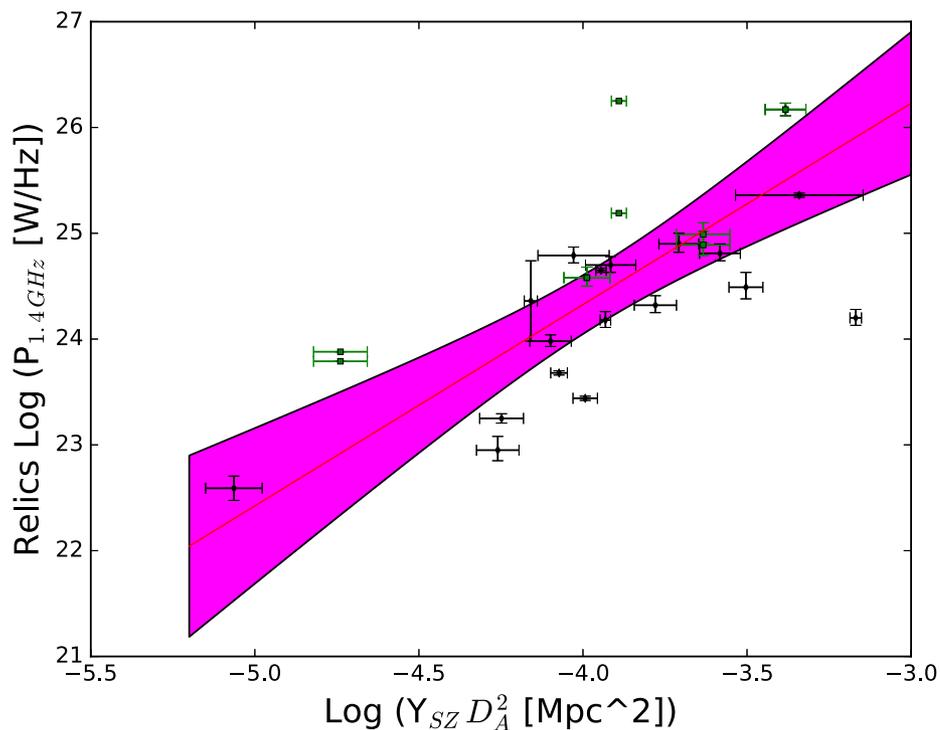
$$l = 1.656 \pm 0.444 \quad \log_{10} n = 25.726 \pm 0.426$$

$$\rho = 0.580 \quad S\text{-rank} = 0.536$$

$$t_{cool} \propto T^{1/2} n_e^{-1}$$

- Relics know about galaxy activity in the cluster center

Correlations: other GC parameters



$$P_{RR} = c \cdot (Y_{SZ} D_A^2)^m$$

$$m = 1.990 \pm 0.09 \quad \log_{10} c = 31.94 \pm 1.55$$

$$\rho = 0.653 \quad S\text{-rank} = 0.331$$

$$Y_{SZ} D_A^2 = \left(\sigma_T / m_e c^2 \right) \int P dV \quad \text{where} \quad P = n_e T$$

$$P_{RR} = B \cdot L_X^a$$

$$a = 1.53 \pm 0.35 \quad \log_{10} B = -44.92 \pm 15.92$$

$$\rho = 0.681 \quad S\text{-rank} = 0.564$$

$$L_X \propto n_e^2 T^{1/2} \quad P_{th} t_{cool}^{-1}$$

- Not very good correlation, we need to increase the statistics
- Radio relics are linked with cluster properties
- Correspondence between the thermal and non-thermal electron populations in the ICM or between the galaxy distribution and the non-thermal electron population ($V^2 \propto kT$)

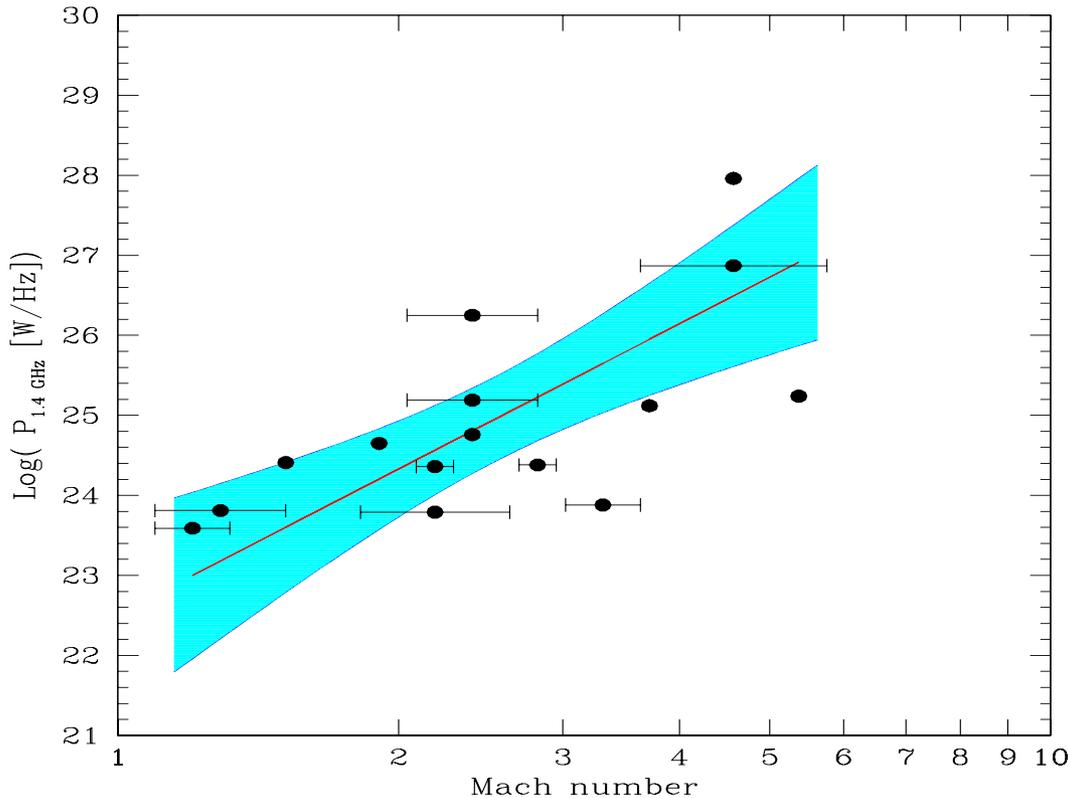
Correlation between Mach number and relic radio power

MNRAS 471, 4747-4759 & PoS (HEASA 2016) 012

- The main problem about the origin of RRs is understanding the source of relativistic electrons that produce radio emission
- In the commonly assumed approach (see, e.g., Feretti et al. 2012) this is connected to the presence of intra-cluster shocks that are supposed to accelerate particles to high energies through DSA
- Such a scenario requires strong shocks with $M > 5$ (see, e.g., Hoeft and Bruggen, 2007)

Correlation between Mach number and relic radio power

PoS (HEASA 2016) 012



- In the strong shock limit ($M > 5$) a correlation $P_{1.4GHz} \approx \text{constant}$ is expected
- While in the weak shock limit ($M < 3$) the radio power is expected to be strongly decreasing with M
- The observed correlation for the RR subsample (Hidson et al. 2014) studied here does not support both the strong and weak shocks limits because the $P_{1.4GHz} - M$ relation does not show any change in the slope for the different values of M :

$$P_{1.4GHz} = E \cdot (M)^f$$

$$f = 6.0 \pm 1.4$$

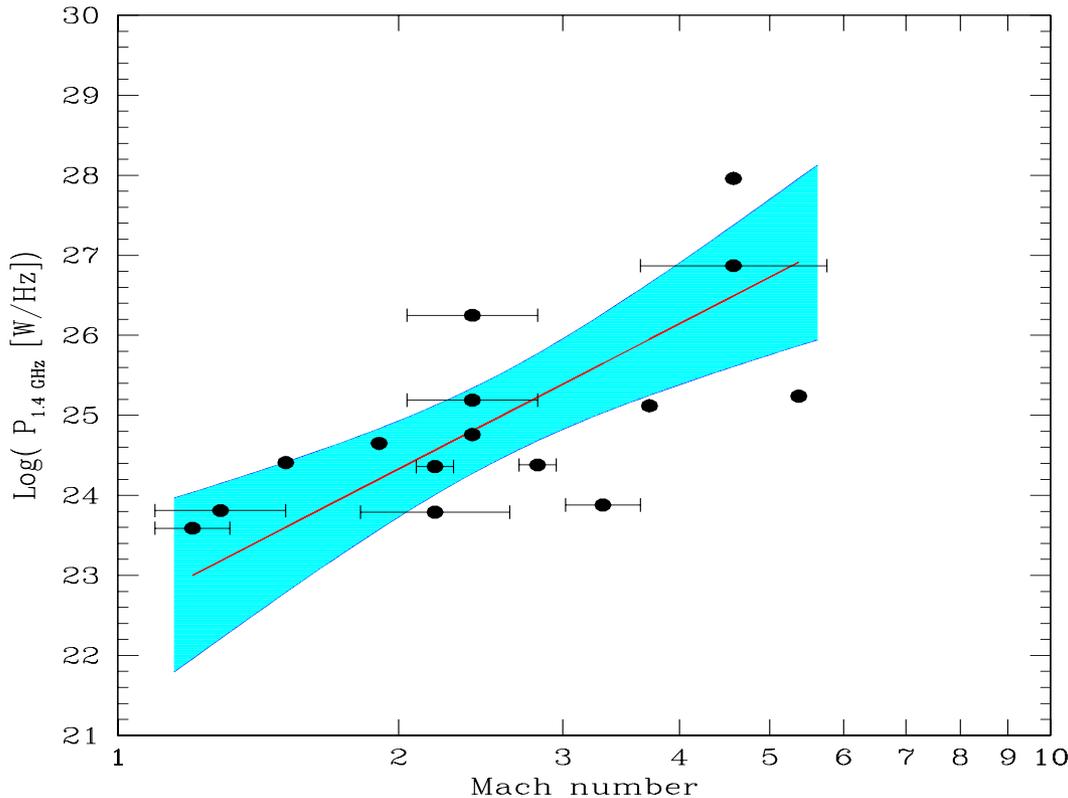
$$\log_{10} E = 22.52 \pm 0.49$$

$$\rho = 0.66$$

$$S - \text{rank} = 0.446$$

Correlation between Mach number and relic radio power

PoS (HEASA 2016) 012



- For $M < 3$ the observed slope is smaller than the theoretical one whereas for $M > 3$ the expected flattening of the relation is not observed
- A lack of a change of the slope can instead indicate adiabatic compression as an alternative scenario (Esslin & Gopal-Krishna, 2001)

$$P_{1.4\text{GHz}} = E \cdot (M)^f$$

$$f = 6.0 \pm 1.4$$

$$\log_{10} E = 22.52 \pm 0.49$$

$$\rho = 0.66$$

$$S\text{-rank} = 0.446$$

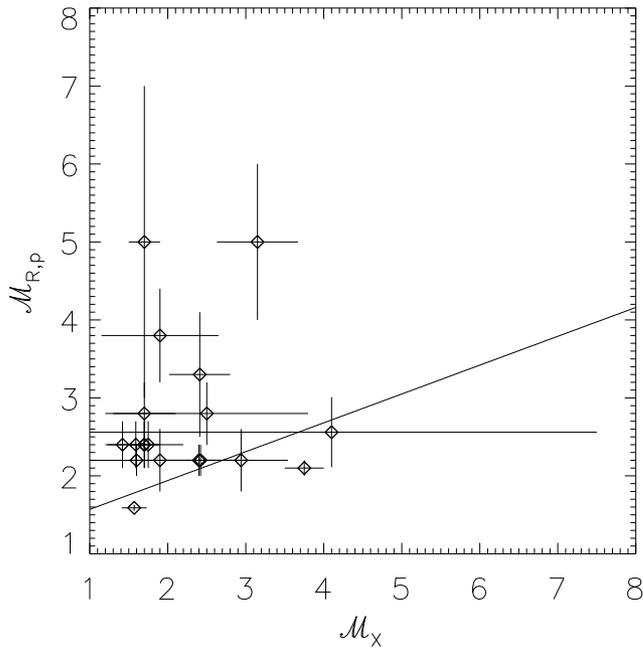
Correlation between Mach number and relic radio power

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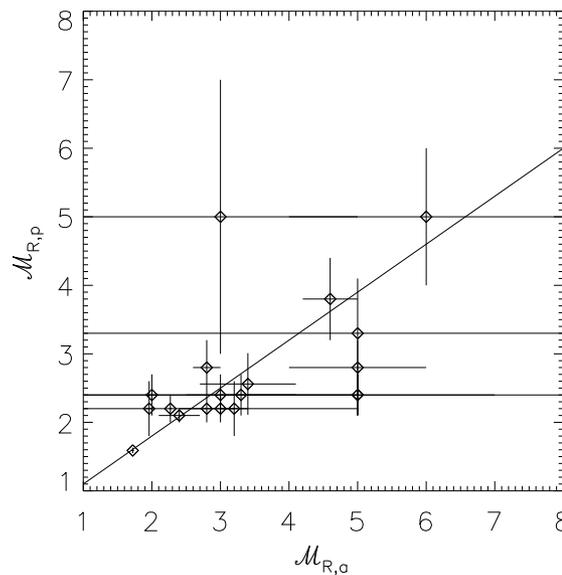
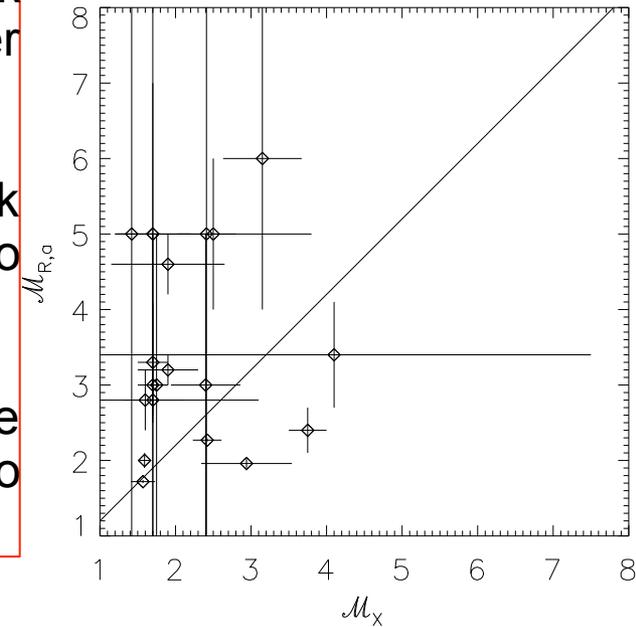
- This evidence indicates that the general shock acceleration theory is not consistent with the observed RR radio power distribution and therefore it cannot be considered as a representative model for the origin of RRs in clusters
- This argument seems to strongly contend the DSA scenario for the origin of the relativistic electron population necessary to produce RR emission

Correlation between Mach number and relic radio power

MNRAS 471, 4747-4759



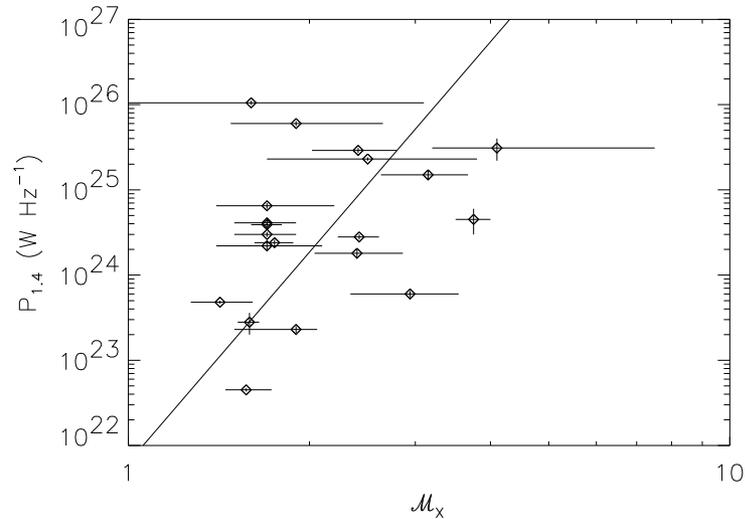
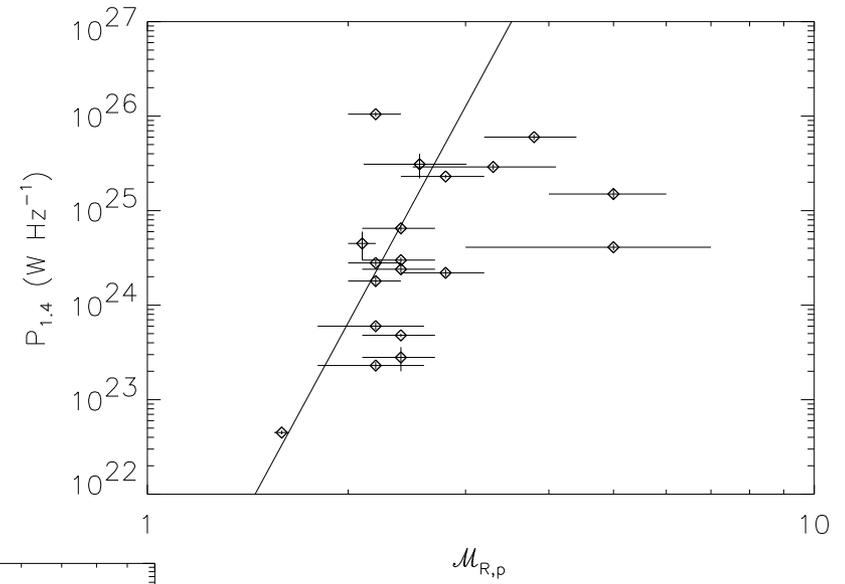
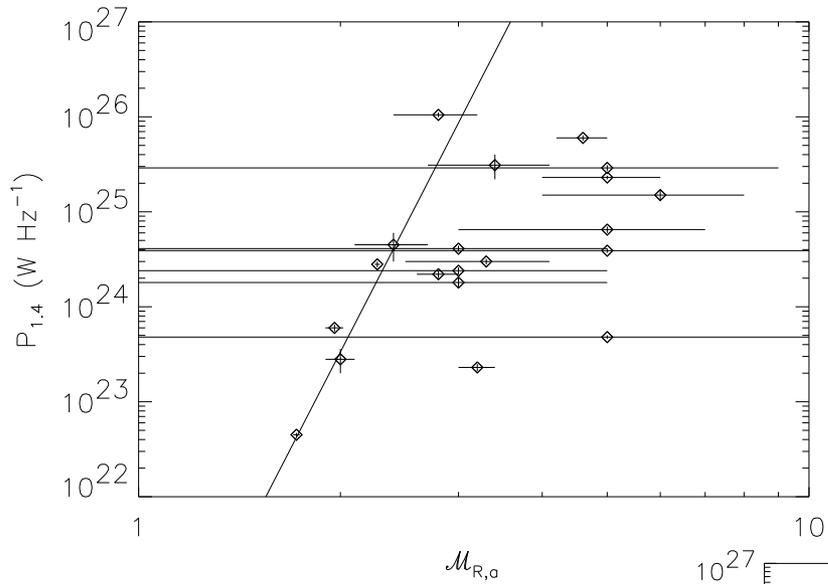
- Lack of correlation (or weak correlation) between relics power and shock
 - x-ray derived M : M_x
 - M derived from the peak values of the radio spectral index: $M_{R,p}$
 - M derived from the average values of the radio spectral index: $M_{R,a}$



Correlation between Mach number and relic radio power

MNRAS 471, 4747-4759

- Lack of correlation (or weak correlation) between relics power and shock



Correlation between Mach number and relic radio power

MNRAS 471, 4747-4759

- Why relic powers are correlated with the properties of the clusters but not with M ?
- There should be two factors that contribute to form a relic:
 - one is related with the cluster as a whole (e.g., ongoing merging)
 - and a second not directly related to the shock strength
 - This second factor can be the presence of radio galaxies, jet and or lobes in the shock region

Correlations: (Active)-Galaxies in GC

- New approach motivated by:

Relic-shock connection

- Shock acceleration from thermal pool

- Mach number problem

- DSA

- Gamma-ray !!!!

- Fermi lat: upper limit

- HESS

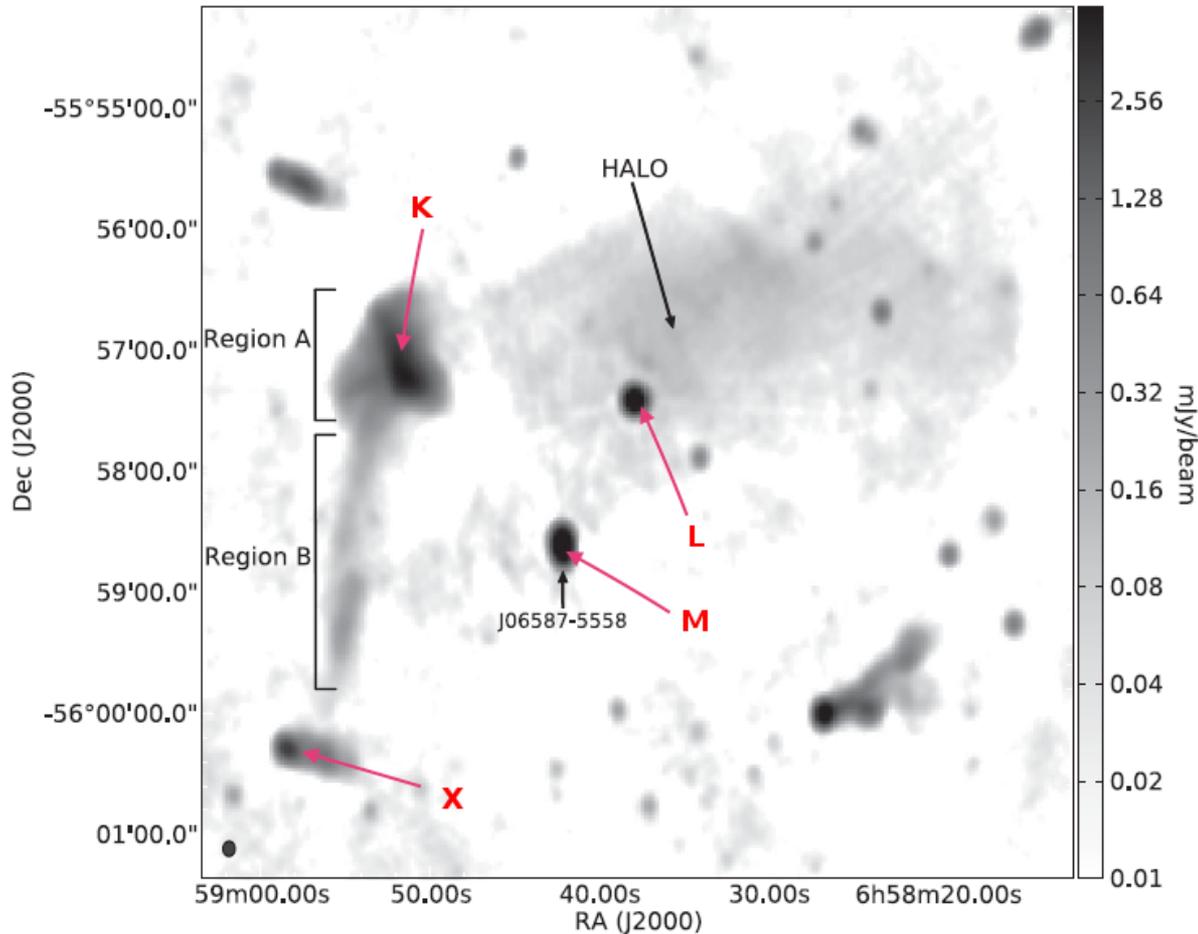
- CTA

- Shock acceleration of relativistic fossil electrons

- Past radio galaxy activities !!!!

Correlations: (Active)-Galaxies in GC

The case of Bullet Cluster: 1E0657-55.8



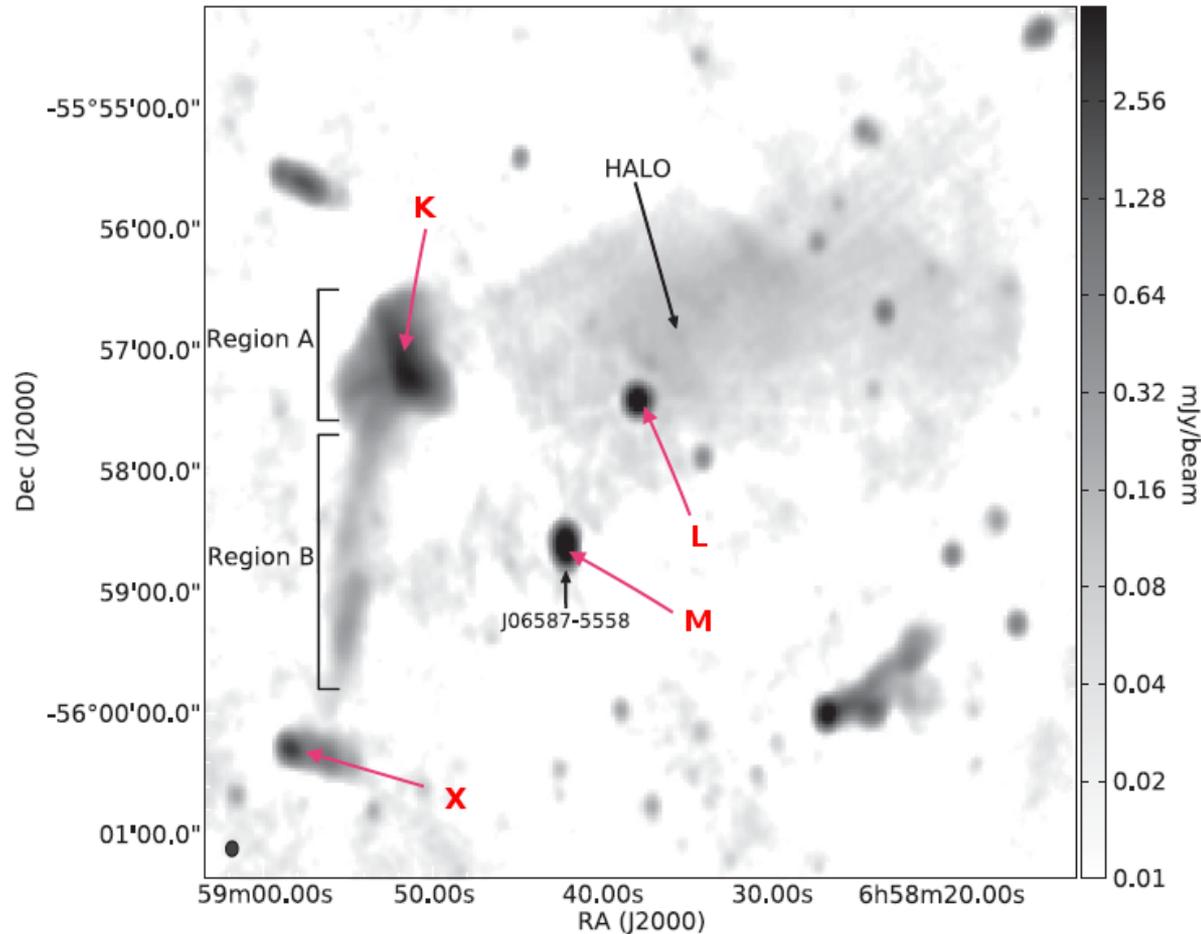
- Well-known
- Extremely hot: kT 14.7 KeV
- Massive merging cluster
- Redshift: 0.296
- X-ray: Mach number 3
- Radio: RR & RH

- **RR**: regions **A** (high brightness) & B
 - Maybe due to a large, pre-existing population of relativistic electrons (Shimwell et al., 2015)
- Many discrete sources in the GC
 - **RR**: L, M, **X** and **K**

Figure: 1E0657-55.8. Credit: Shimwell et al. (2015)

Correlations: (Active)-Galaxies in GC

The case of Bullet Cluster: 1E0657-55.8



- **L**
 - Possible Dark Matter sub-halo in the cluster (Marchegiani et al., 2015)
- **M**
 - It is not clear if the source is physically associated to the cluster (Liang et al., 2001)
 - it can be a gravitational lensed image of a high-redshift radio galaxy or relic (Johansson et al. 2012)
- **X & K**
 - Analyzed their Spectral Energy Distribution (SED)

Figure: 1E0657-55.8. Credit: Shimwell et al. (2015)

Correlations: (Active)-Galaxies in GC

Source K

Completely dominated by non-thermal emission but without any evidence of associated host galaxy

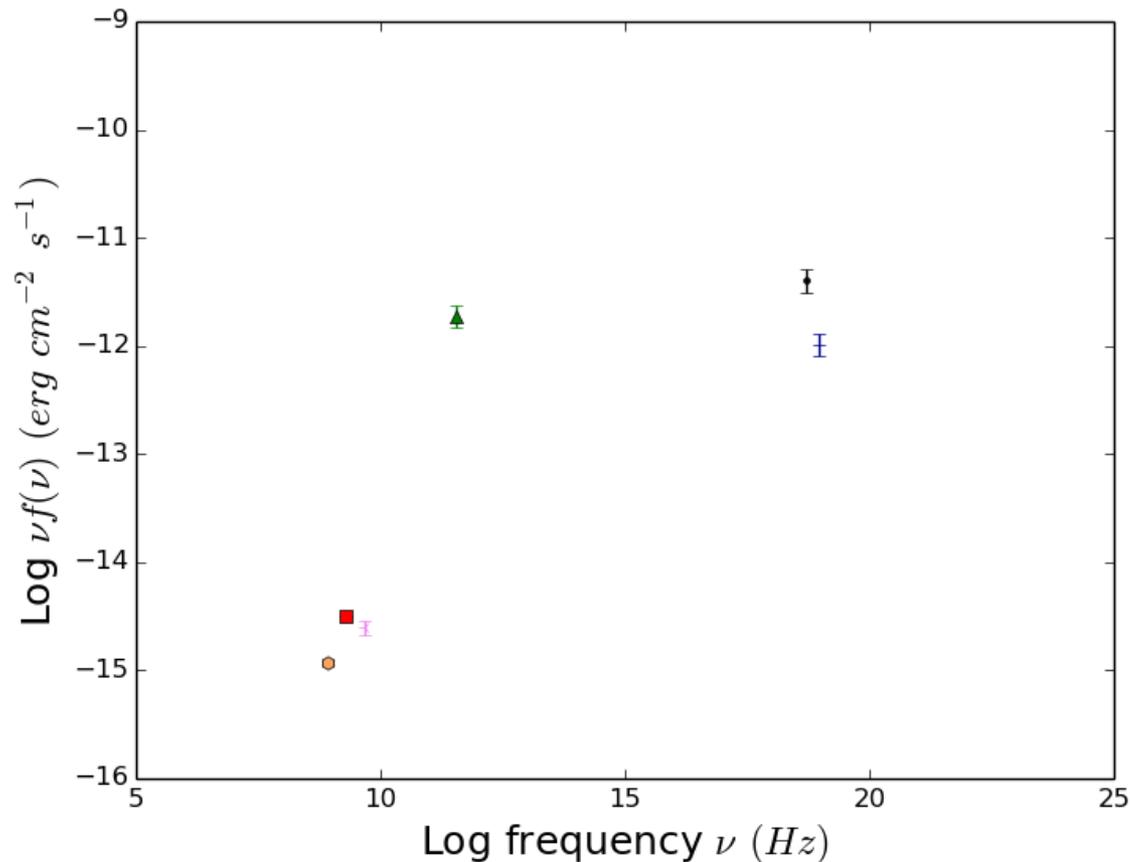


Figure: SED of source K. Data extracted from the SED Builder of ASDC Sky Explorer.

Correlations: (Active)-Galaxies in GC

Source X

Two sources spatially correlated on the ATCA radio map

- SUMSS radio source at $2.7''$ with $S = 17.7 \text{ mJy}$ and optical ($0.3''$) counterpart in the USNOB1.0 catalogue with an $R_{mag} = 16.77$

- Galaxy (around $30''$) coincident with an XMM source to the south

- Associated to an optical source with $R_{mag} = 18.39$ and XMM X-ray source in the TWOXMMIDDR3 catalogue with $S = 0.0042 \text{ cts/s}$ in the $0.2 - 12 \text{ KeV}$ band

Correlations: (Active)-Galaxies in GC

- SED show non-thermal emission with a typical galaxy host thermal spectrum
- The source **X** is the core of the emission and **K** is the terminal radio lobe: supported by spectral index map
- Redshift !!!

- If this source belong to this cluster maybe the Compression of B-field by the shock along the jet and lobes of this radio galaxy is giving the original electron population creating RR

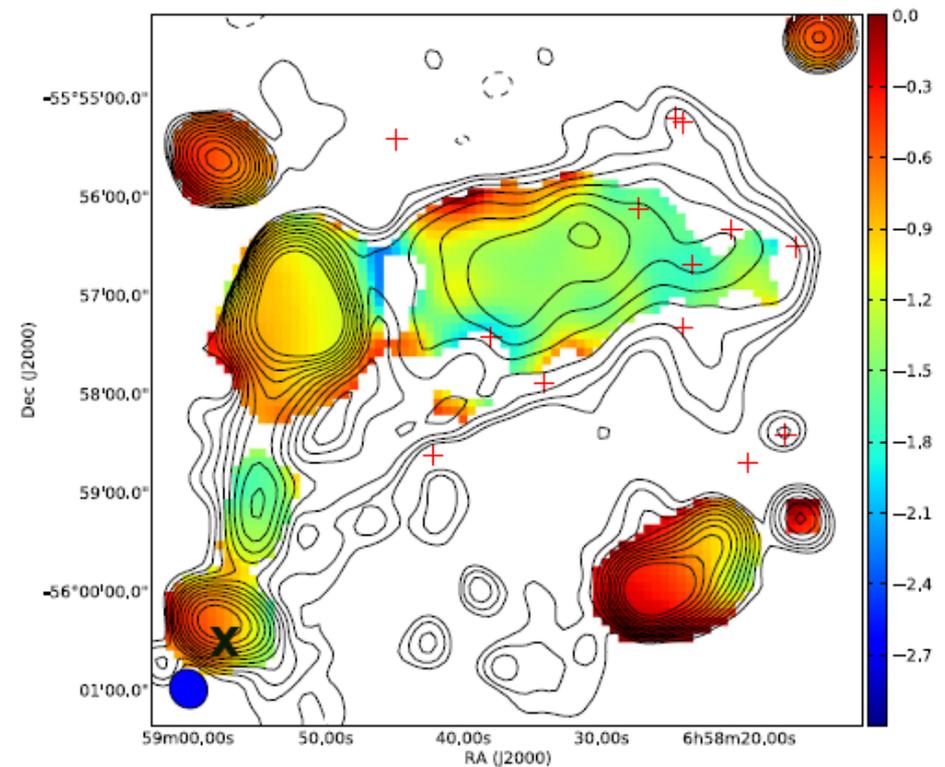
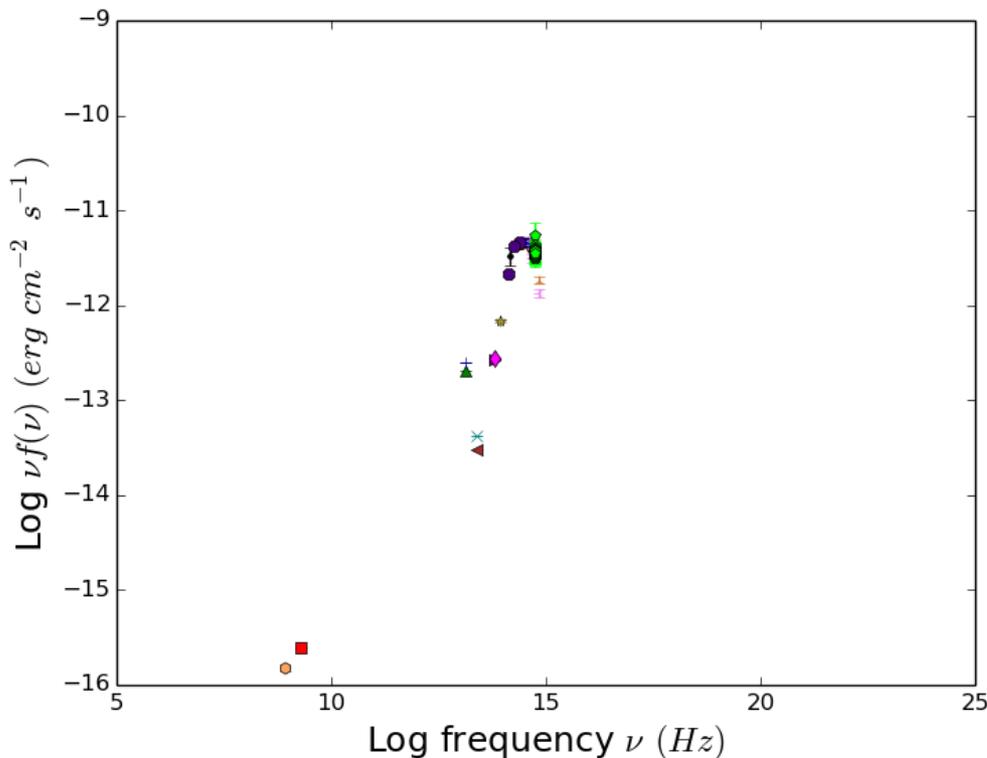


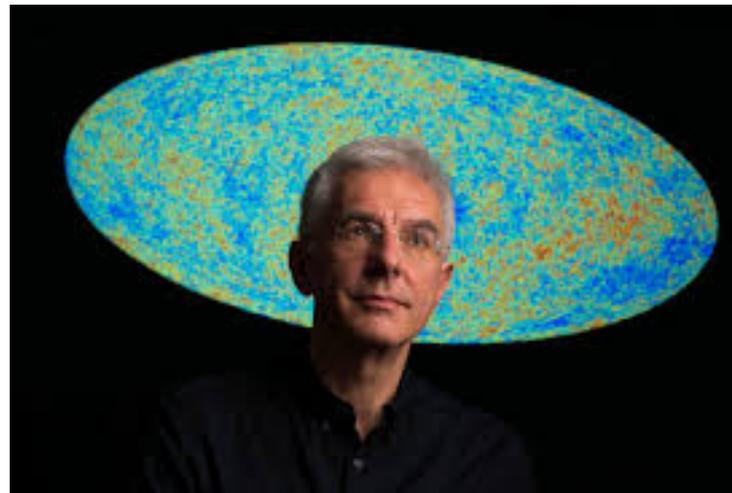
Figure: Source X. Left: SED (Data extracted from the SED Builder of ASDC Sky Explorer). Right: Spectral index image (Shimwell et al., 2015)

Summary and Future Outline

- Relics are associated mainly to various forms of galaxy non-thermal activity:
Compression of B-field by the shock
 - Arch-like: AGN jets
 - Double: RG lobes
 - Intermediate: galaxy feedback radio-mode
- Need a systematic study of relics over a large homogeneous sample
 - MIGHTEE survey (MeerKAT)
 - SKA survey (spectro-polarimetry, B-field from FR, ...)
 - KAT-7: preliminary studies
- Radio analysis will be at the center of the full multi-frequency study of non-thermal processes in clusters (MeerKAT, SKA, ALMA, MILLIMETRON, ASTRO-H, Fermi-LAT, CTA)
- MeerKAT and SKA-1
 - High Sensitivity: power more than 10X that we get now
 - More details of radio relics



- NRF, SARAO, SKA, Wits Astro Group and the Universidade Eduardo Mondlane



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