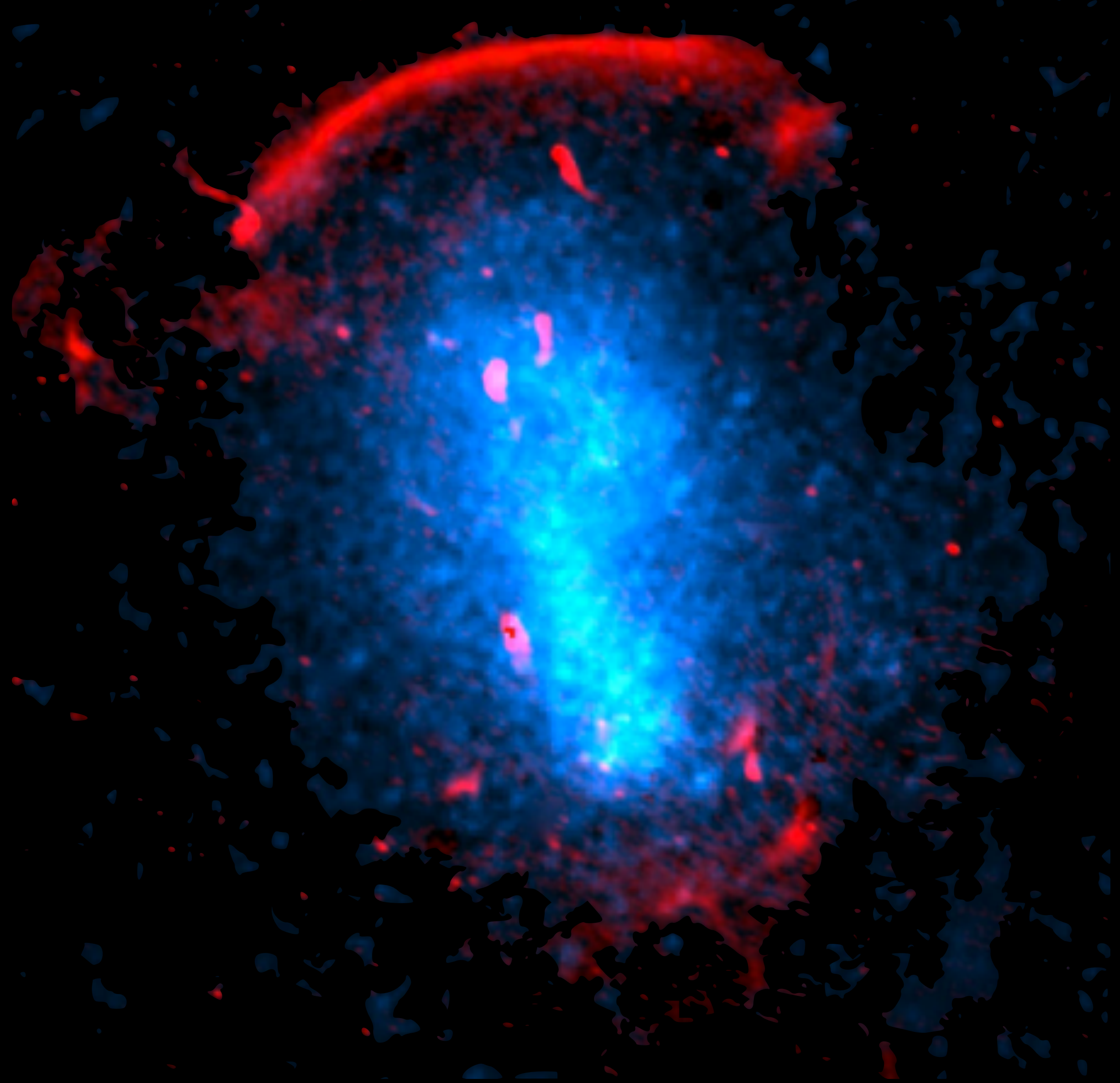
Diffuse Radio Emission in Galaxy Clusters: Observational Evidence



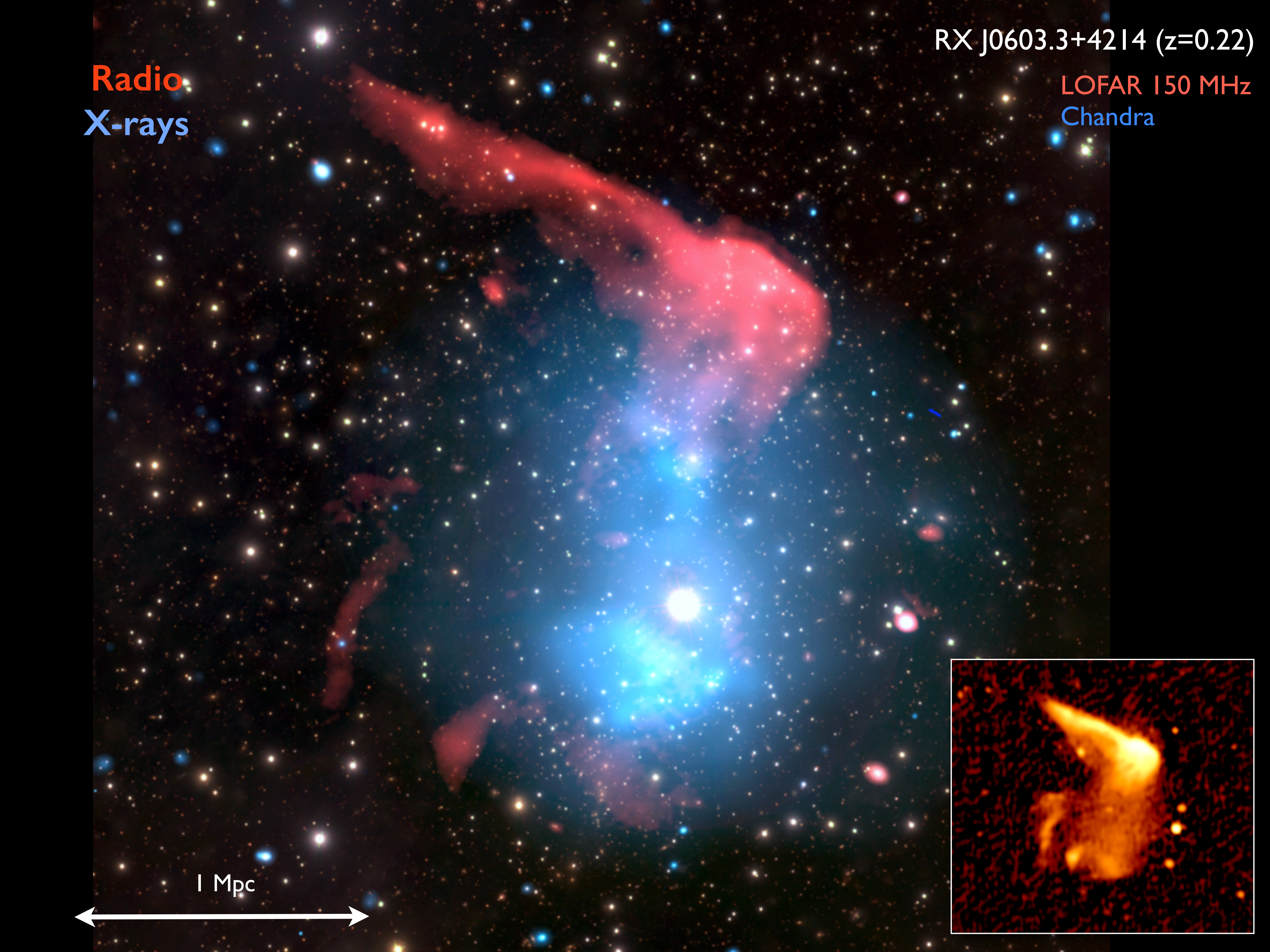
Reinout van Weeren

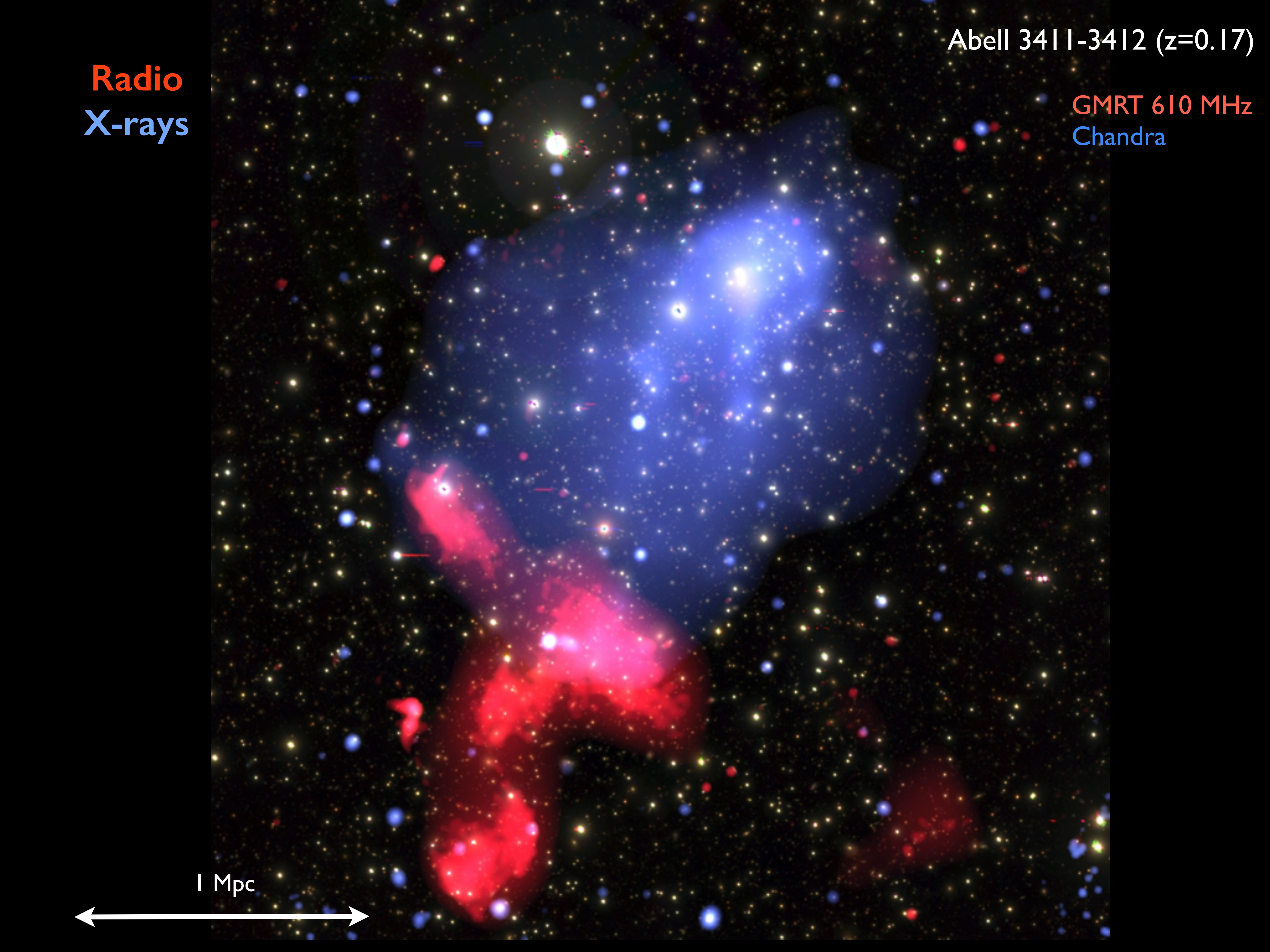
Harvard-Smithsonian Center for Astrophysics

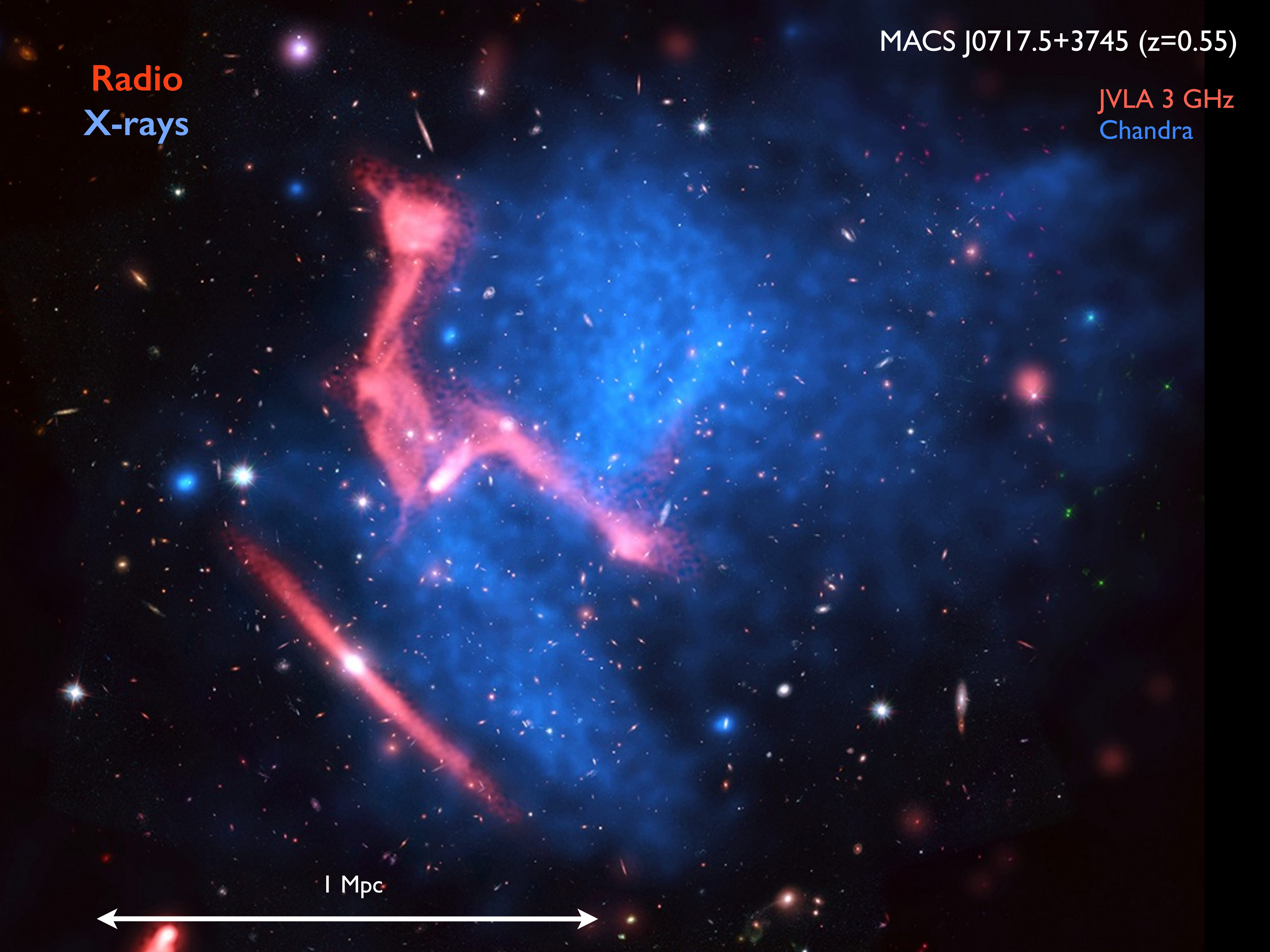
W. Forman, C. Jones, W. Dawson, H. Intema, G. Ogrean, M. Brüggen,
H. Röttgering, A. Bonafede, G. Brunetti, LOFAR Surveys KSP

OUTLINE

- Introduction
- Halos
- Relics
- Low-frequency observations
- Summary


RX J0603.3+4214 (z=0.22)
LOFAR 150 MHz
Chandra
Radio
X-rays
1 Mpc


Radio
X-rays
Abell 3411-3412 (z=0.17)
GMRT 610 MHz
Chandra
1 Mpc


Radio
X-rays
MACS J0717.5+3745 (z=0.55)
JVLA 3 GHz
Chandra
1 Mpc

- GIANT RELICS
- PHOENICES

- Elongated, filamentary
- Polarized
- Radio emission traces shocks
- Particle acceleration mechanisms :
  - Diffusive shock acceleration (Ensslin+ 1998; ....)
  - Shock re-acceleration (Markevitch+ 2005; ...)
  - Adiabatic compression (Ensslin & Gophal-Krishna 2001; ...)

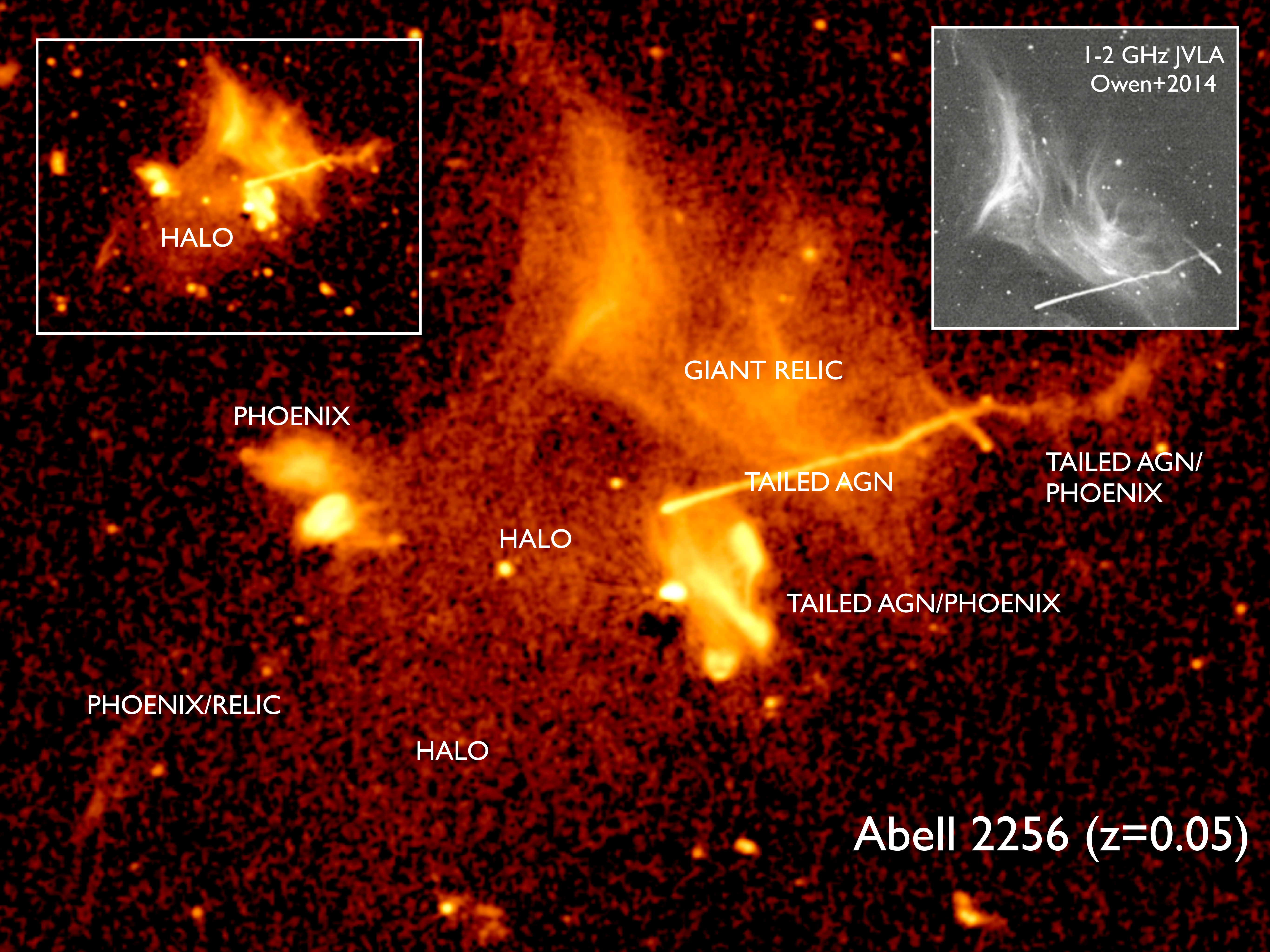
- GIANT HALOS
- MINI-HALOS

- Smooth, centrally located
- Follow ICM X-ray emission
- Unpolarized
- Particle acceleration mechanisms:
  - Turbulent re-acceleration mechanism (Brunetti+01; Petrosian 2001; ...)
  - Secondary electrons: products of hadronic collisions (Dennison 1980; Blasi & Colafranceso 1999; ...)

Review papers: Brunetti & Jones 2014; Feretti+ 2012

QUESTIONS

- Physics of shocks, turbulence, and particle acceleration in dilute plasmas
- Origin of Cosmic Rays and magnetic fields
- Diffuse Radio emission as a tracer of cluster mergers

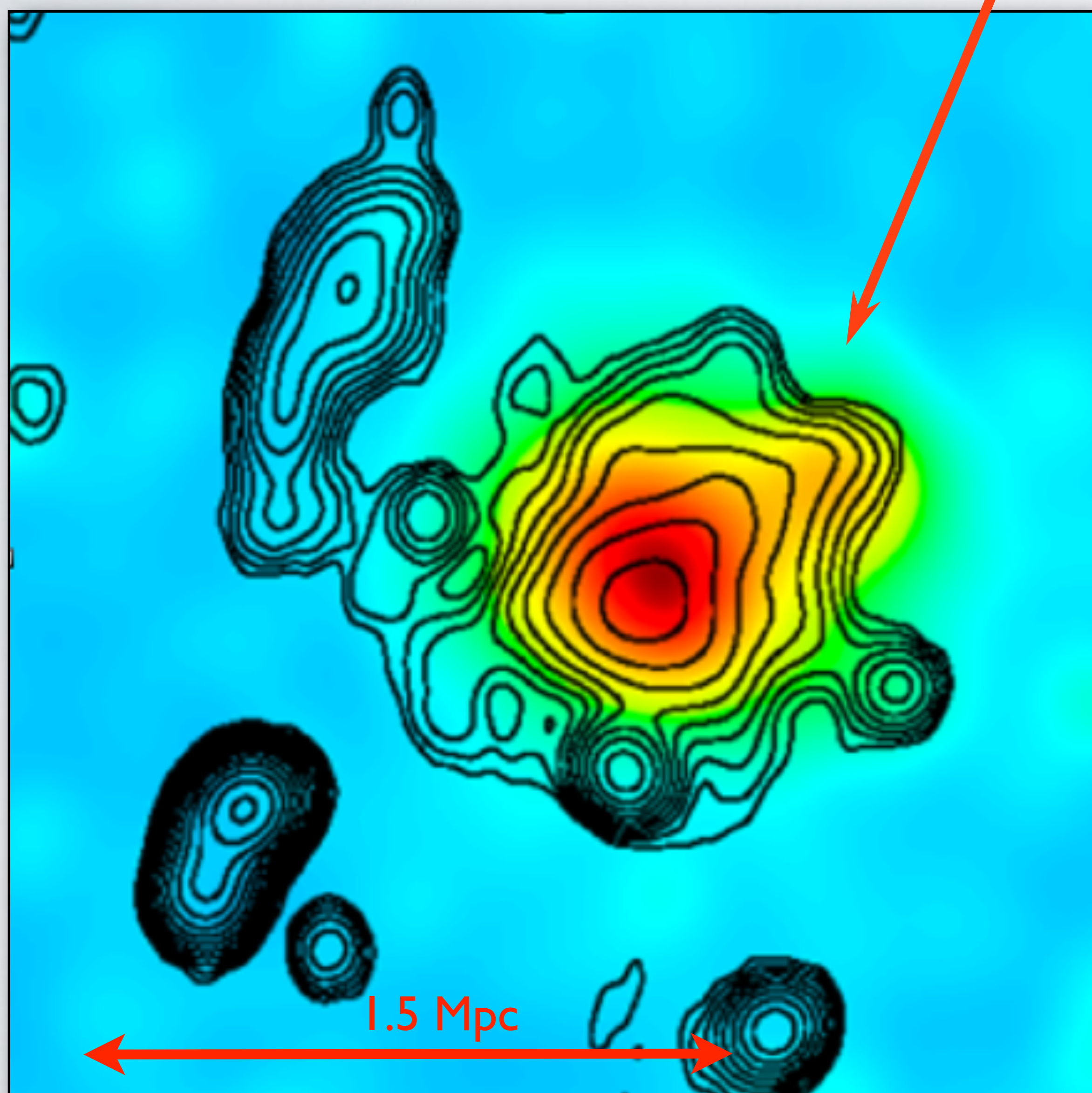

HALO
1-2 GHz JVLA
Owen+2014
GIANT RELIC
PHOENIX
TAILED AGN
TAILED AGN/
PHOENIX
HALO
TAILED AGN/PHOENIX
PHOENIX/RELIC
HALO
Abell 2256 (z=0.05)

RADIO HALOS

GIANT HALOS

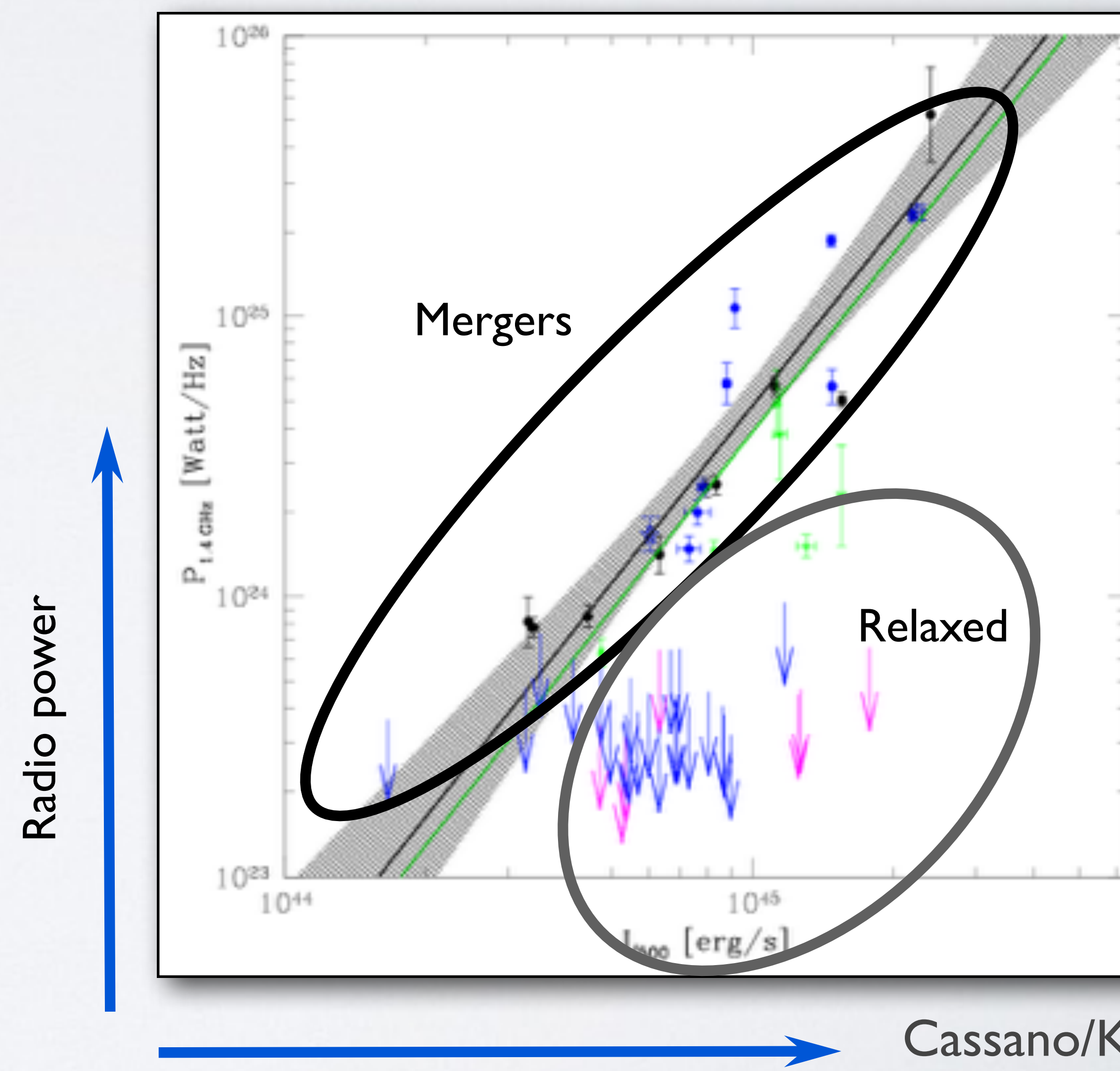
X-ray image + radio contours

Radio Halo



Abell 2744: Feretti+ 2012; Govoni+ 2001

- Mpc sizes, centrally located
- unpolarized
- found in disturbed clusters
- radio luminosity scales with cluster mass

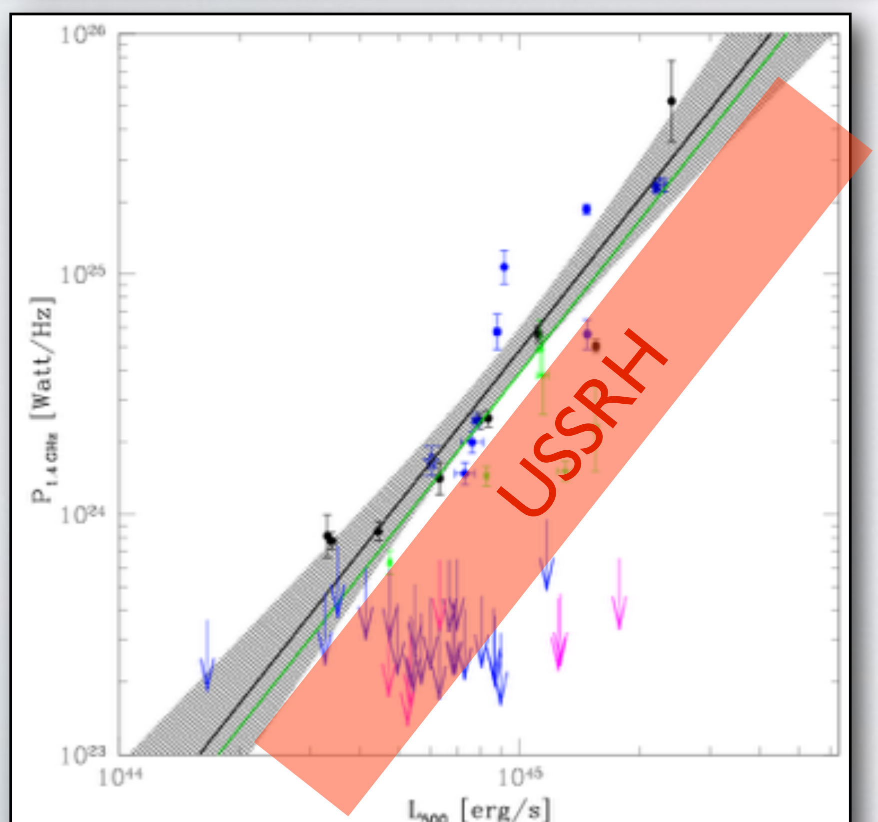


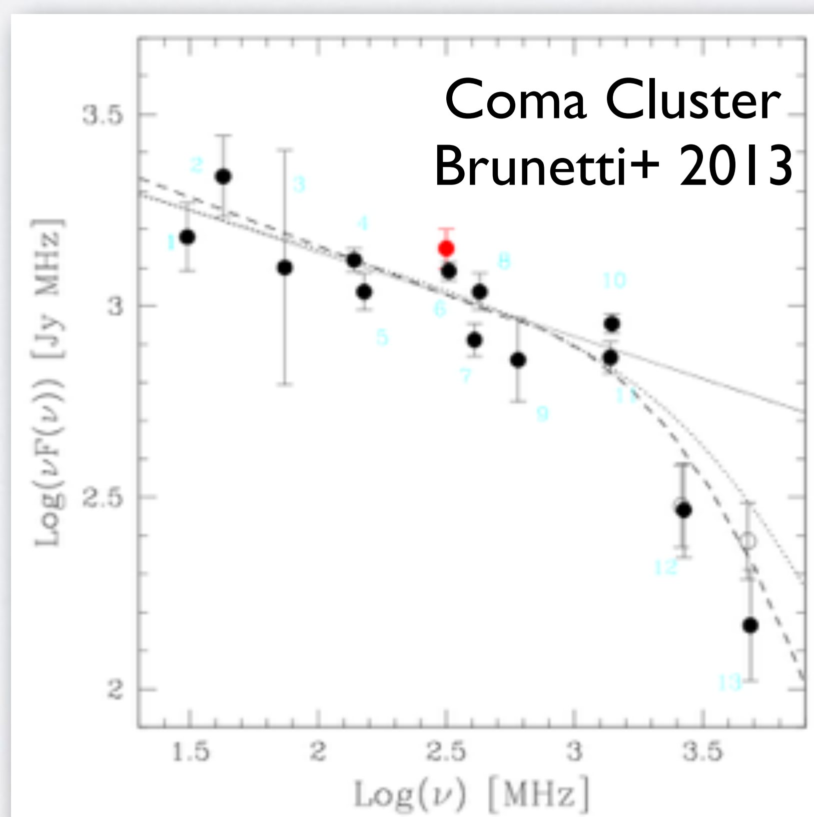
Cassano/Kale+ 2013

HALO SPECTRA

- Typical spectral index -1.1 to -1.3
- USSRH: Should occur in less energetic mergers
- USSRH: Handful discovered (Brunetti+2008; Macario+2010; Bacchi+2003; ...)

- Curved spectra
- Evidence for α- global ICM temperate correlation (Feretti+2004; Giovannini+2009)

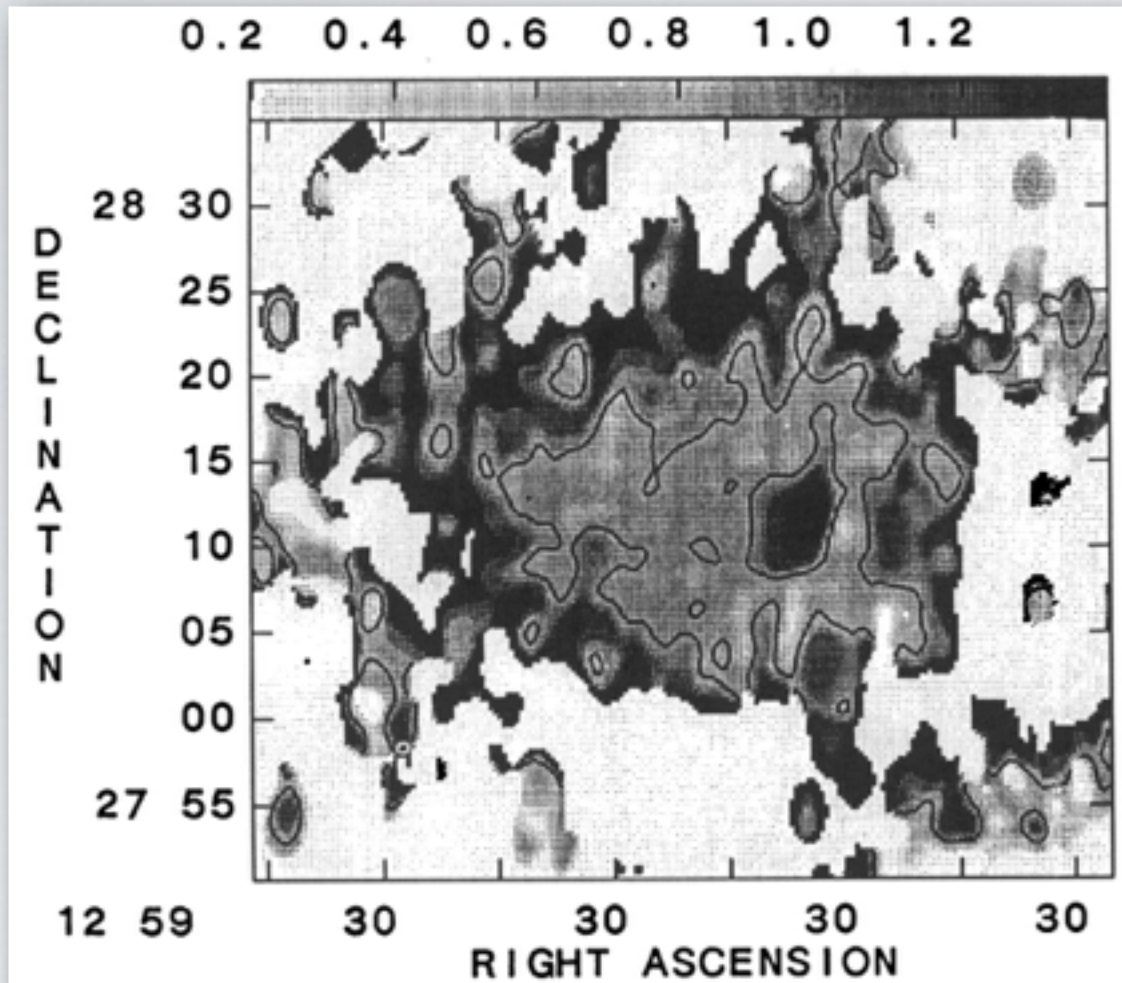




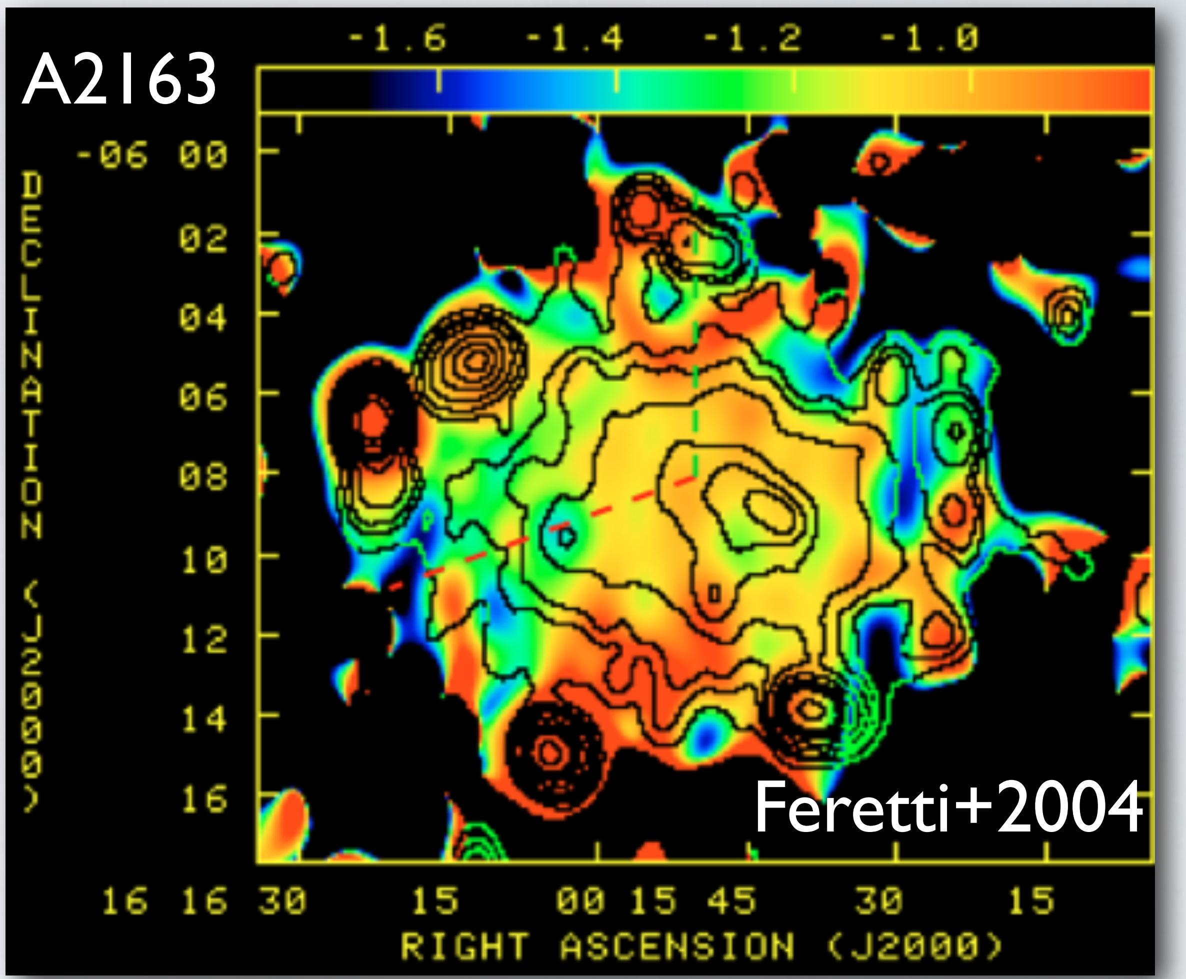
Supports turbulent re-acceleration model

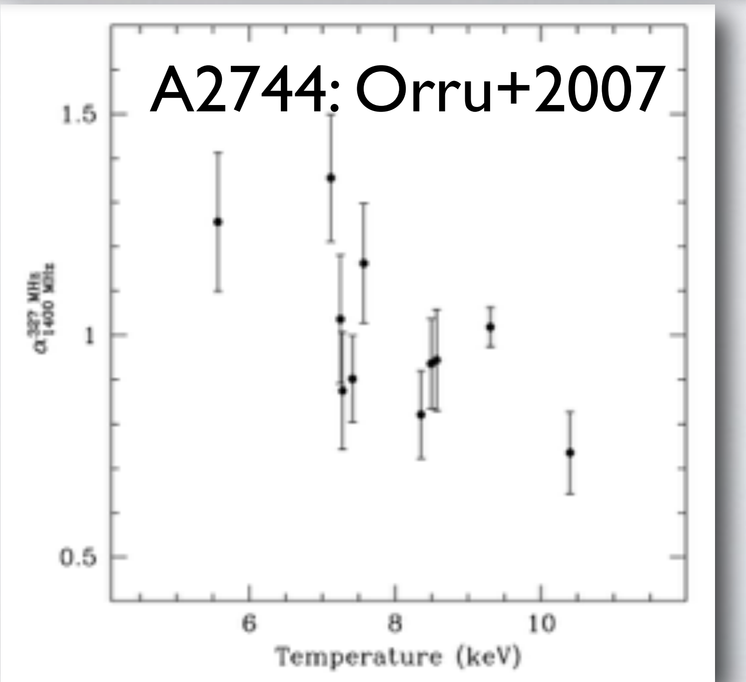
RESOLVED HALO SPECTRA (Challenging !)

Use spectral index to trace variations in ICM turbulence or B-fields ?



Coma Cluster: Giovannini+1993



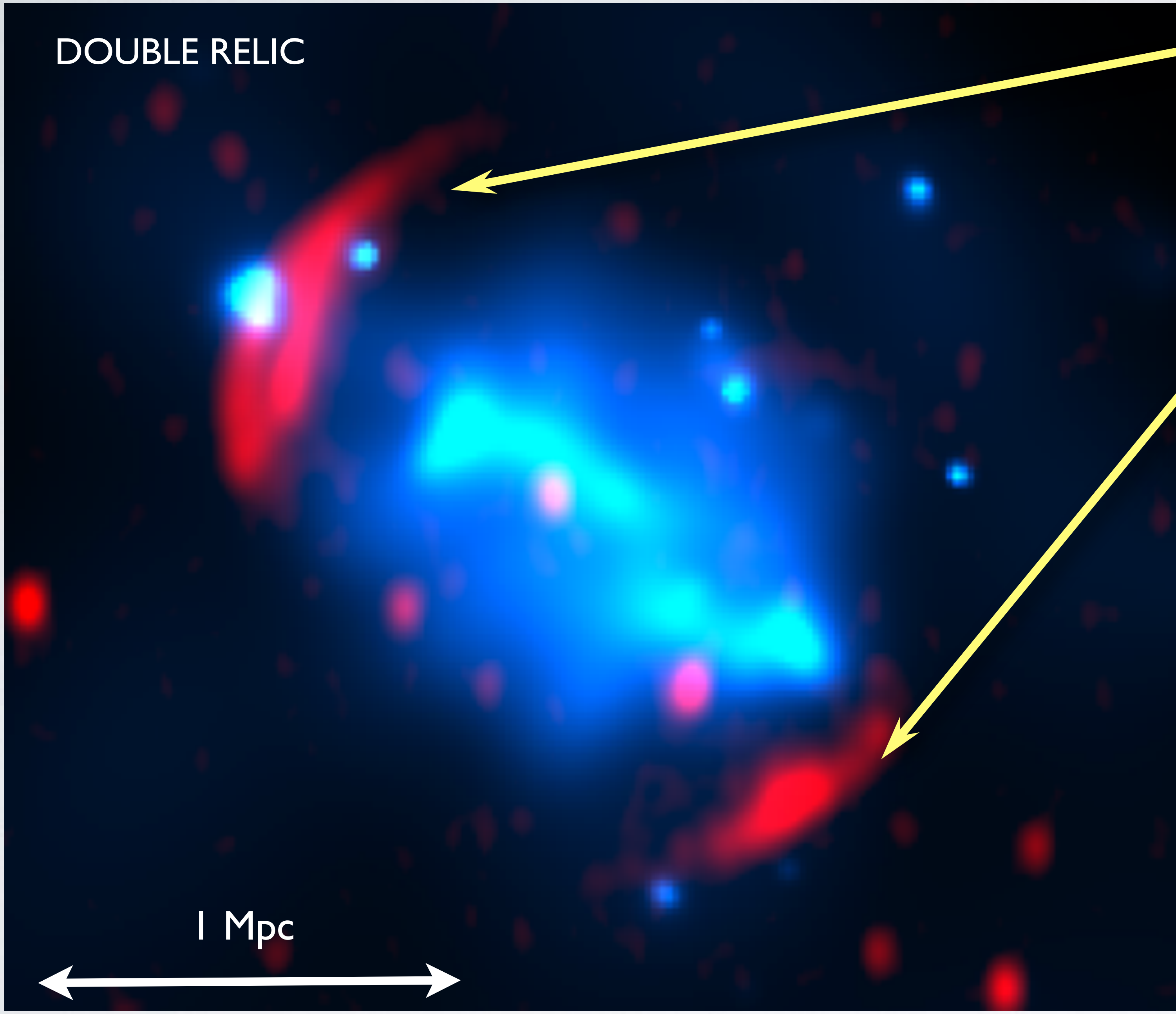


- Steepening with radial distance
- Correlation with cluster temperature distribution (Orru+2007) (but see Vacca+ 2014, Shimwell+ 2014)

RADIO RELICS

MACS J1752.0+4440

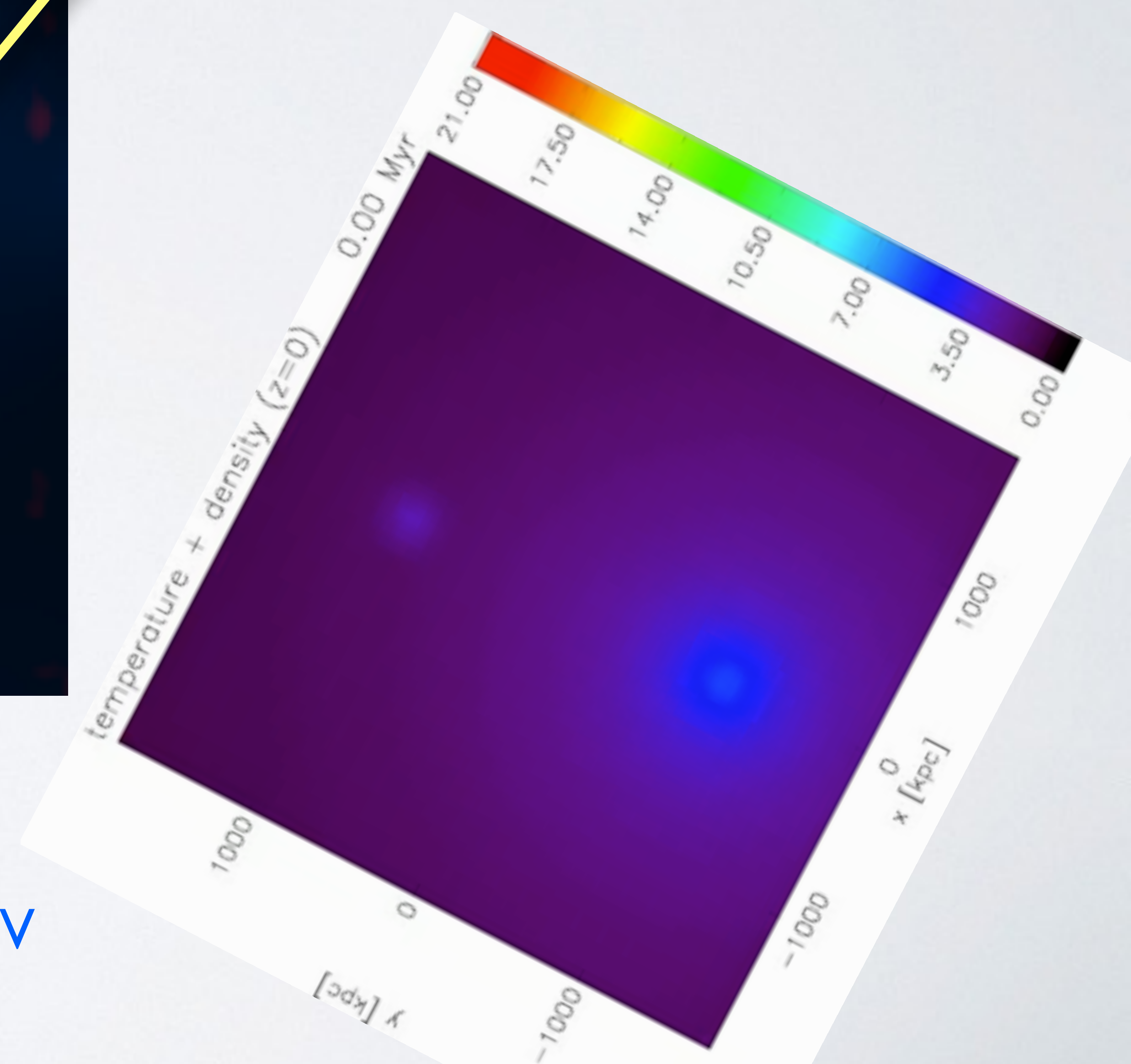
van Weeren+ 2012, Bonafede+ 2012



RADIO RELICS

(“double relic system”)

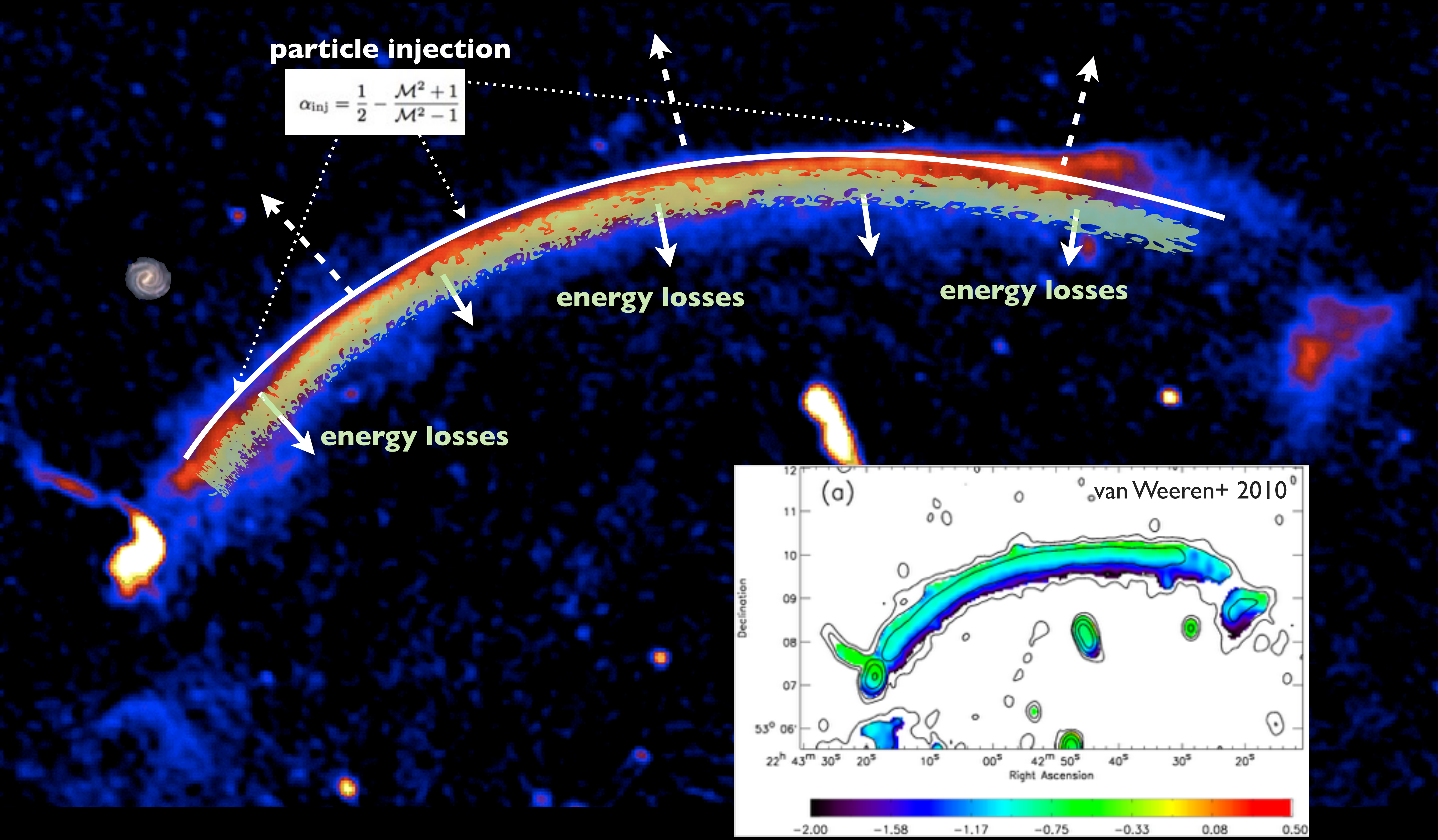
Merger or accretion shocks ?



Radio (WSRT) + X-rays (XMM)

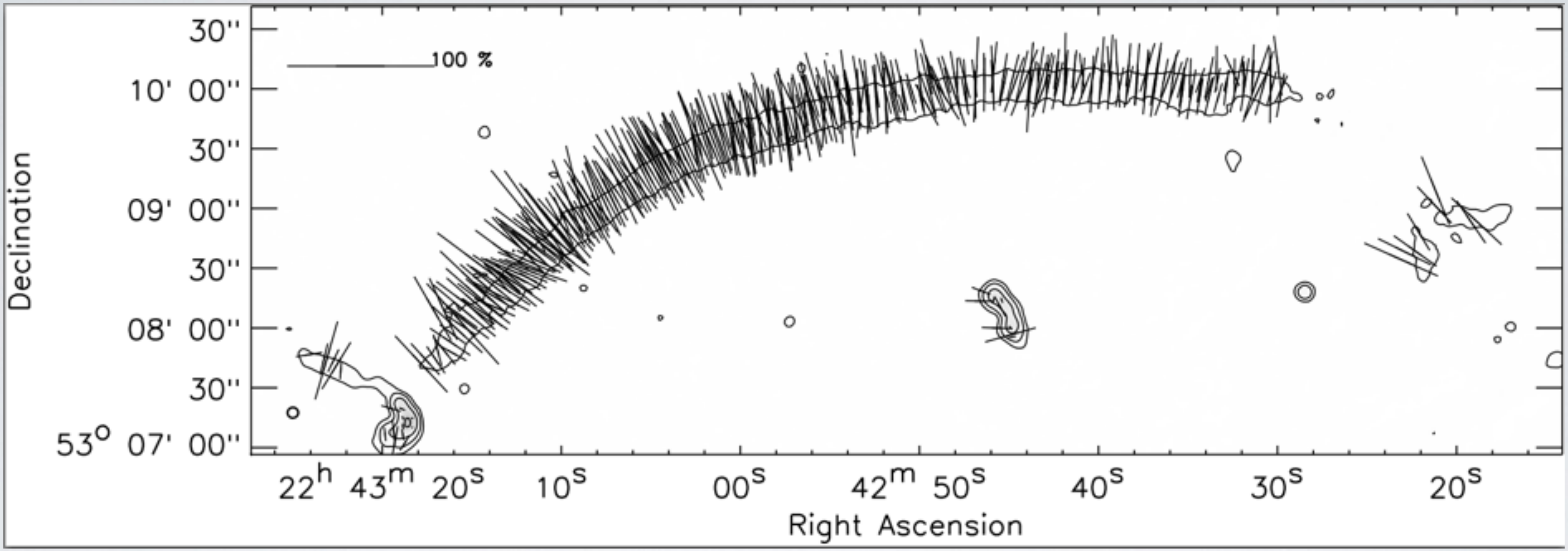
thermal Bremstrahlung ~ 10 keV

CIZA J2242.8+5301 (z=0.19)



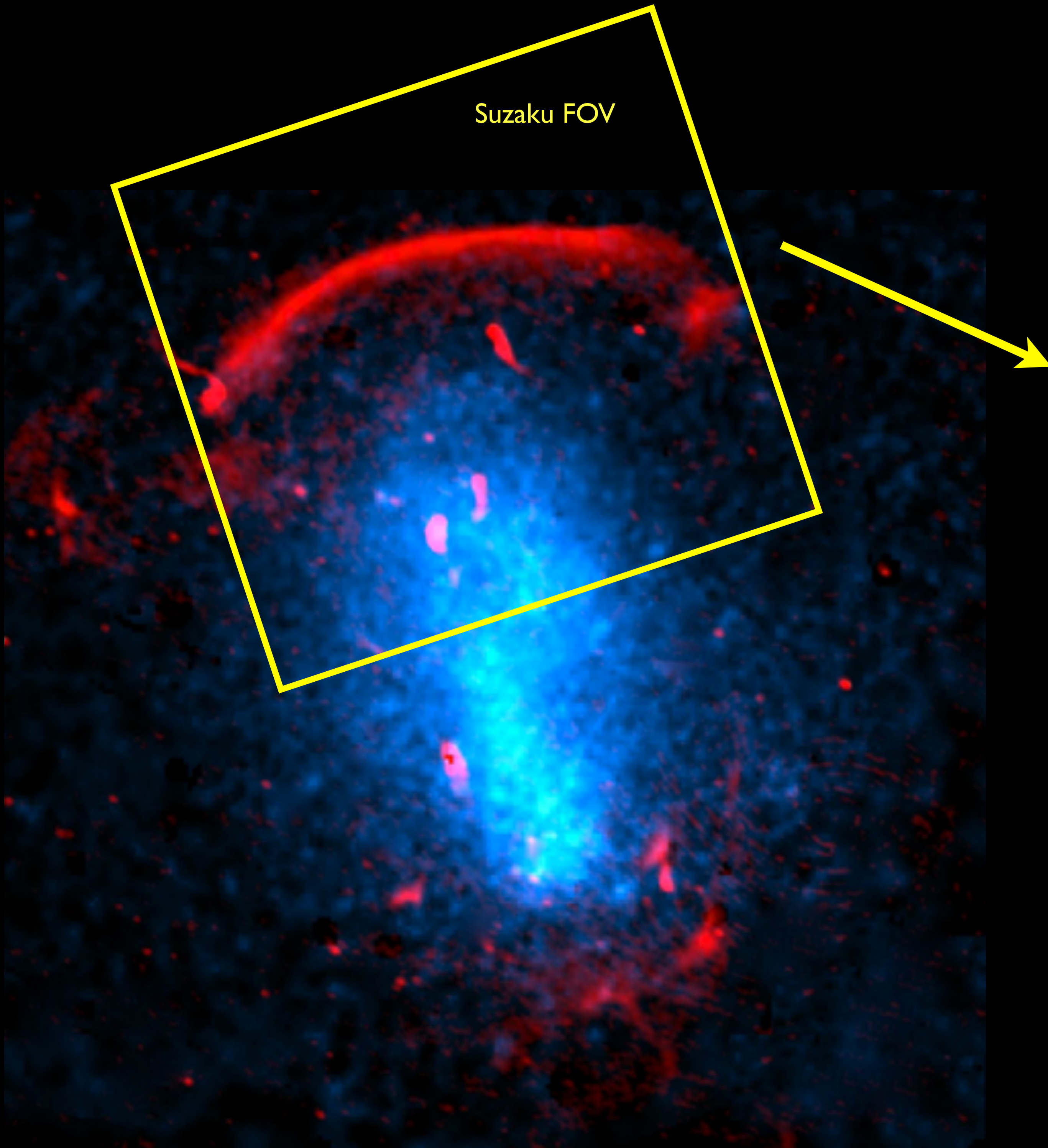
radio spectral index expected to steepen towards cluster center

POLARIZATION



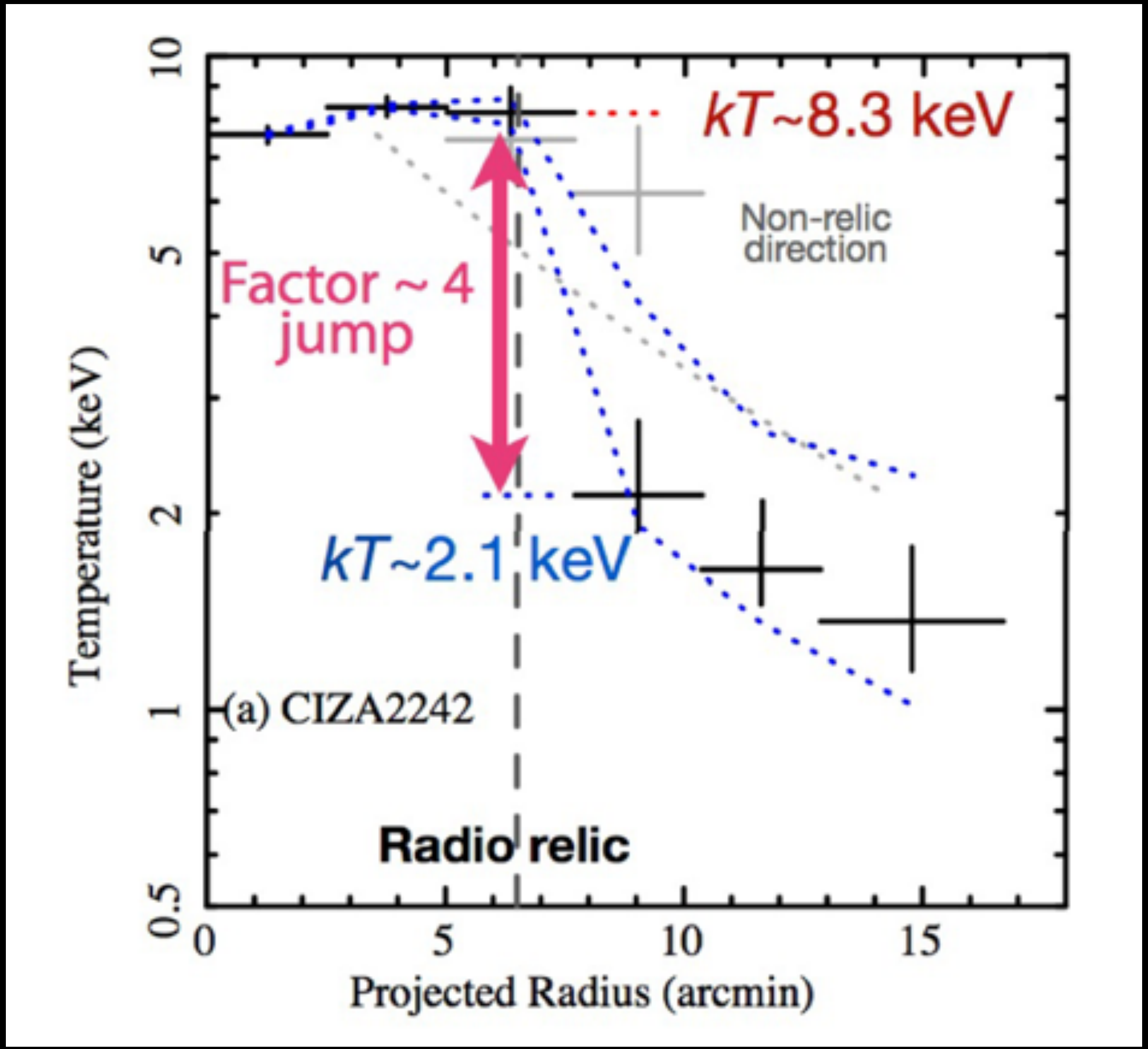
JVLA 3 GHz (E-vectors, corrected for Faraday Rotation)

- B-fields aligned with the shock plane
- Polarization fraction: 30-60%



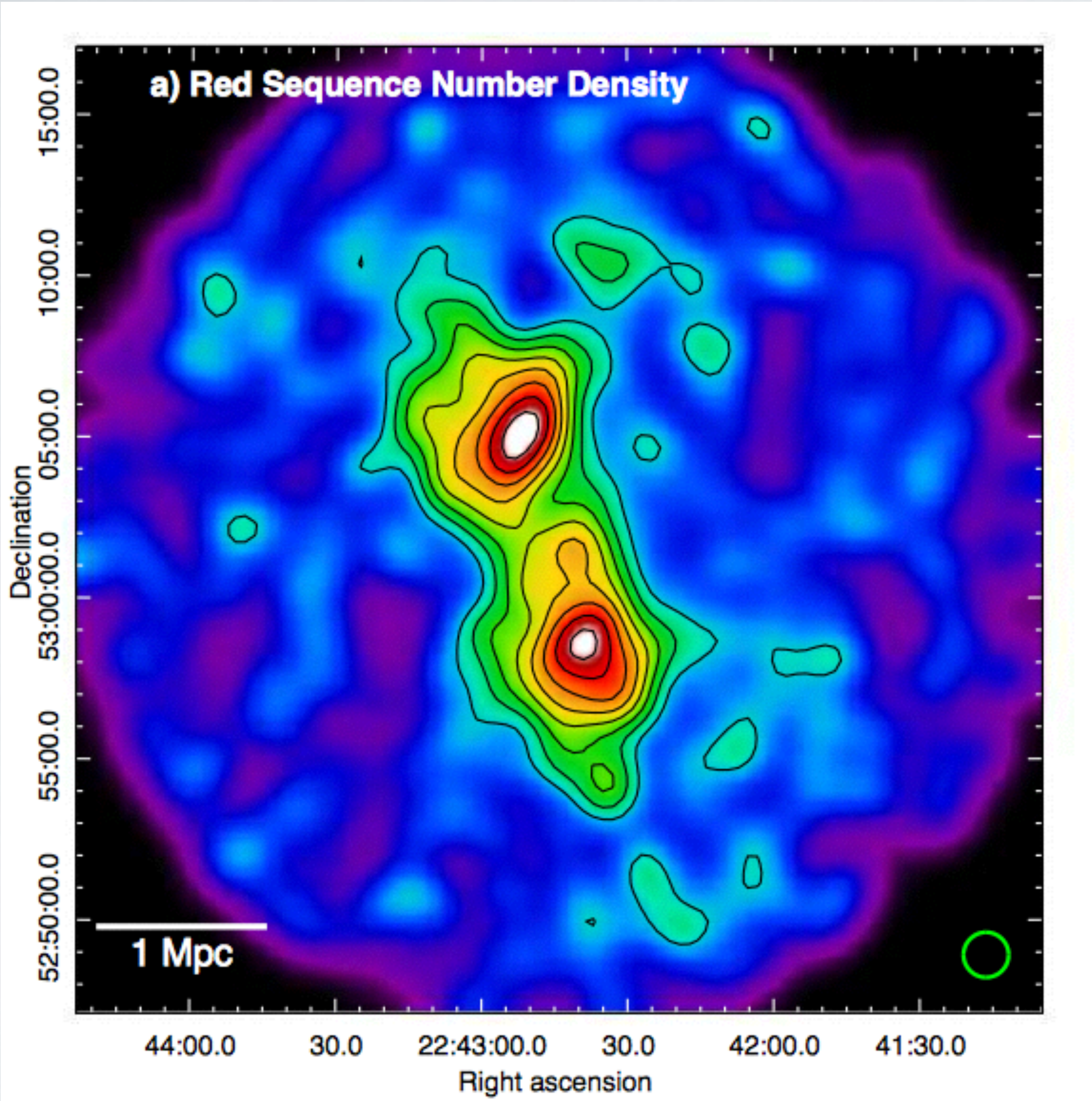
Ogrean+ 2012

X-rays (XMM) + radio (GMRT)



Akamatsu & Kawahara 2012

Derived from Subaru images



redshifts

Keck spectroscopic data

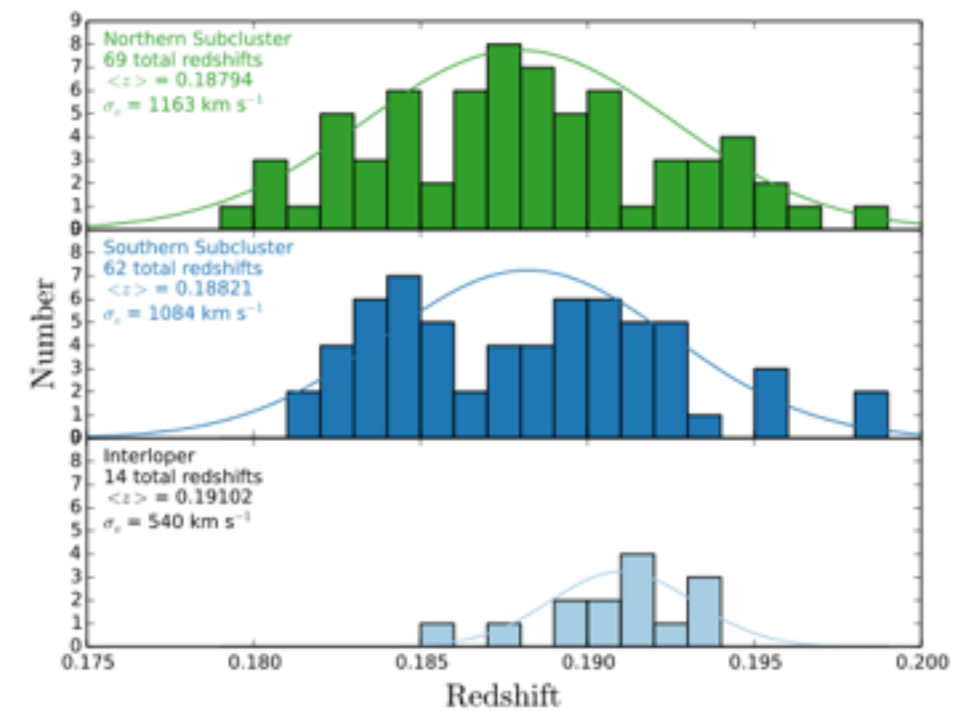


Figure 11. Redshift distributions of the northern subcluster (green), southern subcluster (dark blue), and the potential interloper (light blue). Redshift locations and velocity dispersions are listed in the upper left of each subpanel. The northern and southern subcluster histograms include spectroscopic members within a 625 kpc radius of the peak location of each subcluster (§6.1). Interloper galaxies were excluded from the southern subcluster distribution.

Dawson et al. 2014

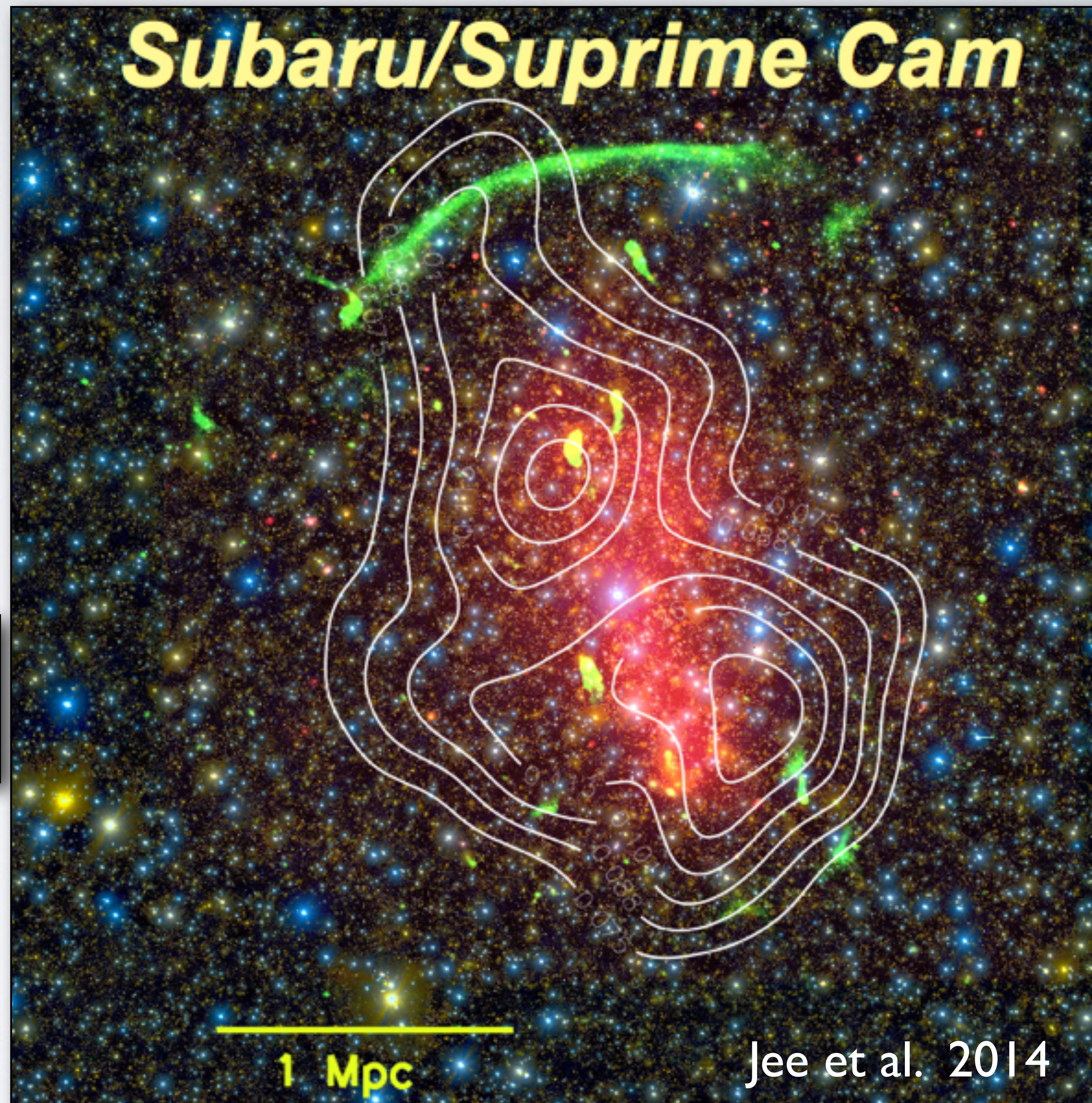
Weak lensing

CIZA J2242 merger

- ~ 1: 1 merger in the plane of the sky
- ~ 1 Gyr after core passage
- $10^{15}\,M_{1\odot}$ - $10^{15}\,M_{2\odot}$

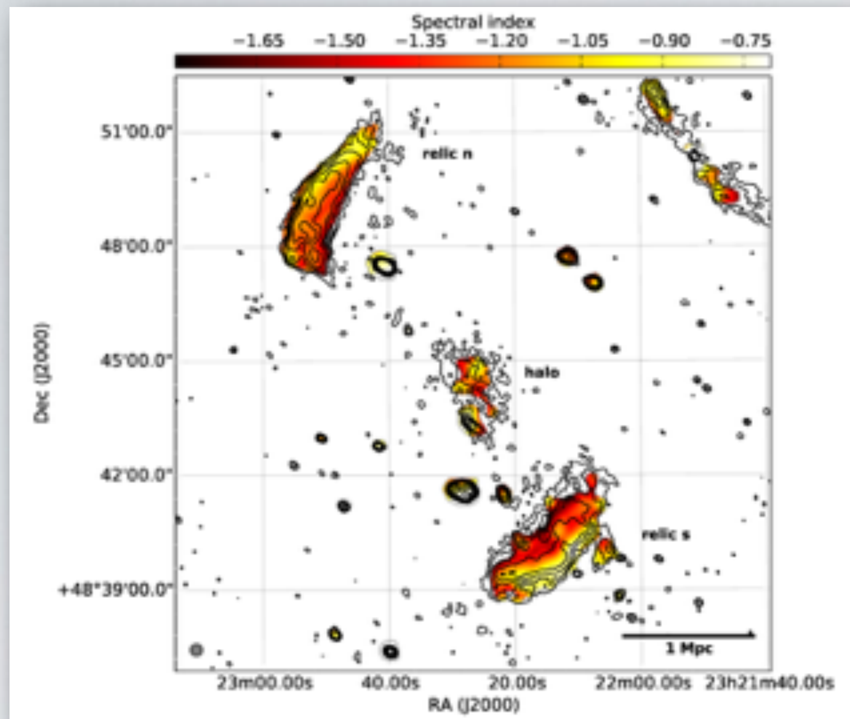
Subclusters	σ_v (km s^{-1})	c_{200c}	R_{200c} (h_{70}^{-1} Mpc)	M_{200c} ($h_{70}^{-1} 10^{14} M_\odot$)
North	967^{+113}_{-128}	$3.20^{+0.09}_{-0.08}$	$2.0^{+0.2}_{-0.2}$	$11.0^{+3.7}_{-3.2}$
South	1137^{+93}_{-101}	$3.23^{+0.08}_{-0.08}$	$1.9^{+0.1}_{-0.2}$	$9.8^{+3.8}_{-2.5}$

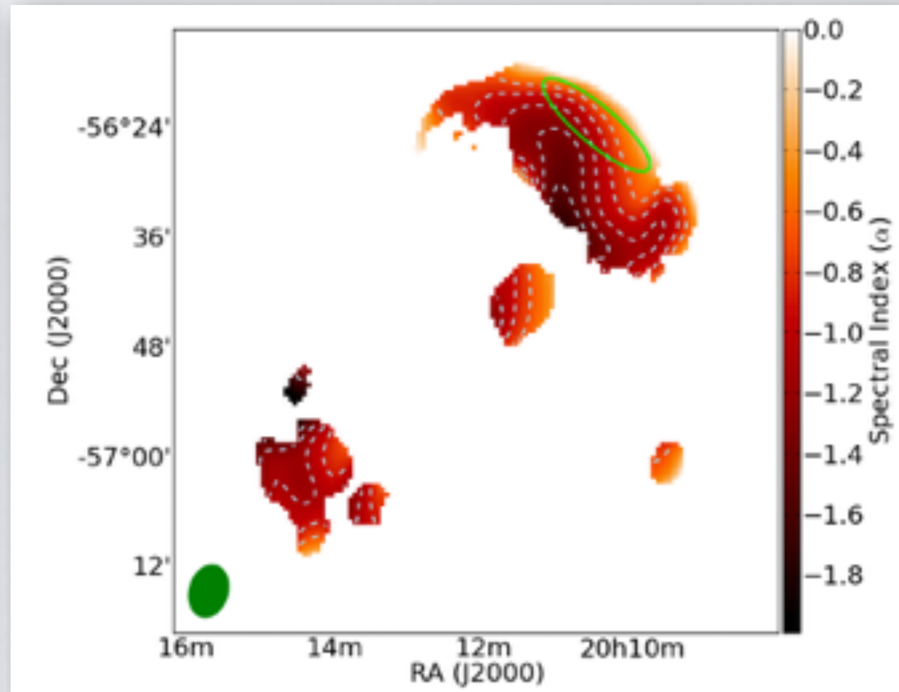
red: X-rays
green: radio
contours: mass from weak lensing



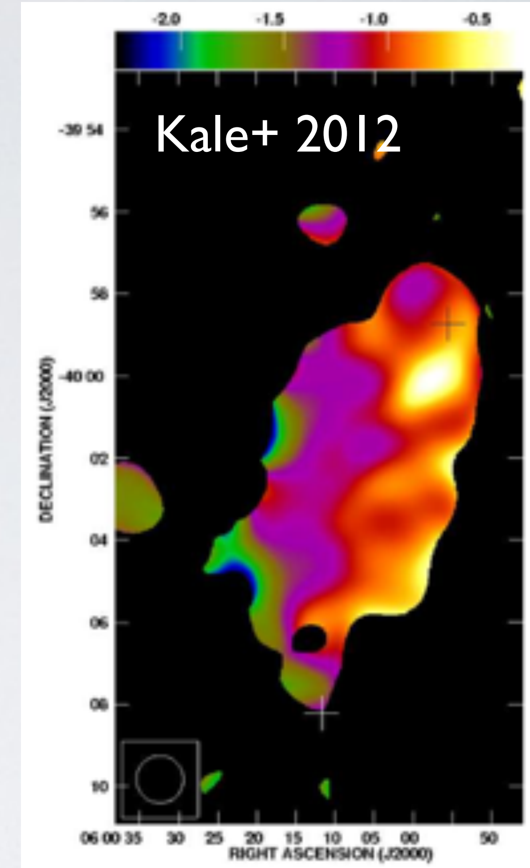
SPECTRAL GRADIENTS

de Gasperin+ 2015

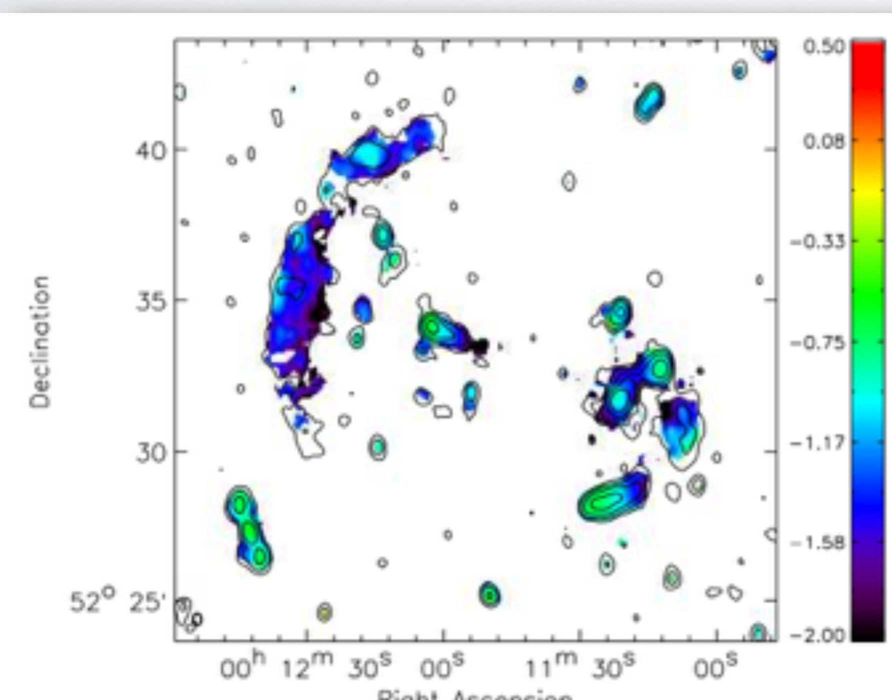




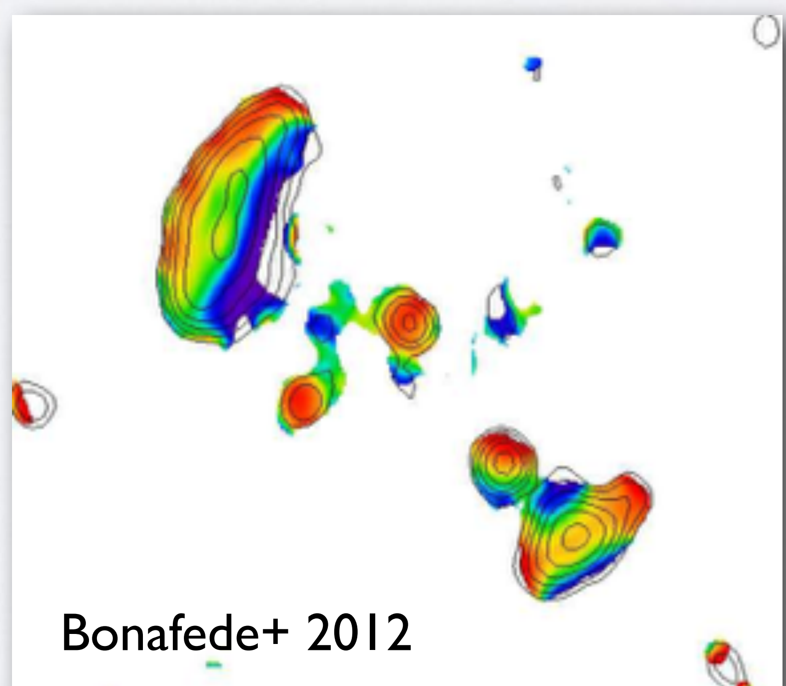
Hindson+ 2014



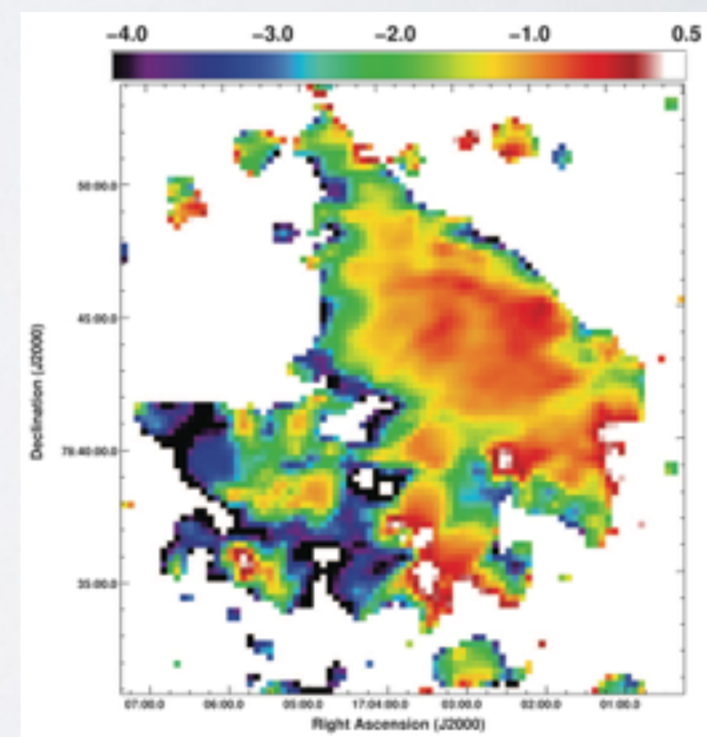
Kale+ 2012



van Weeren+ 2011



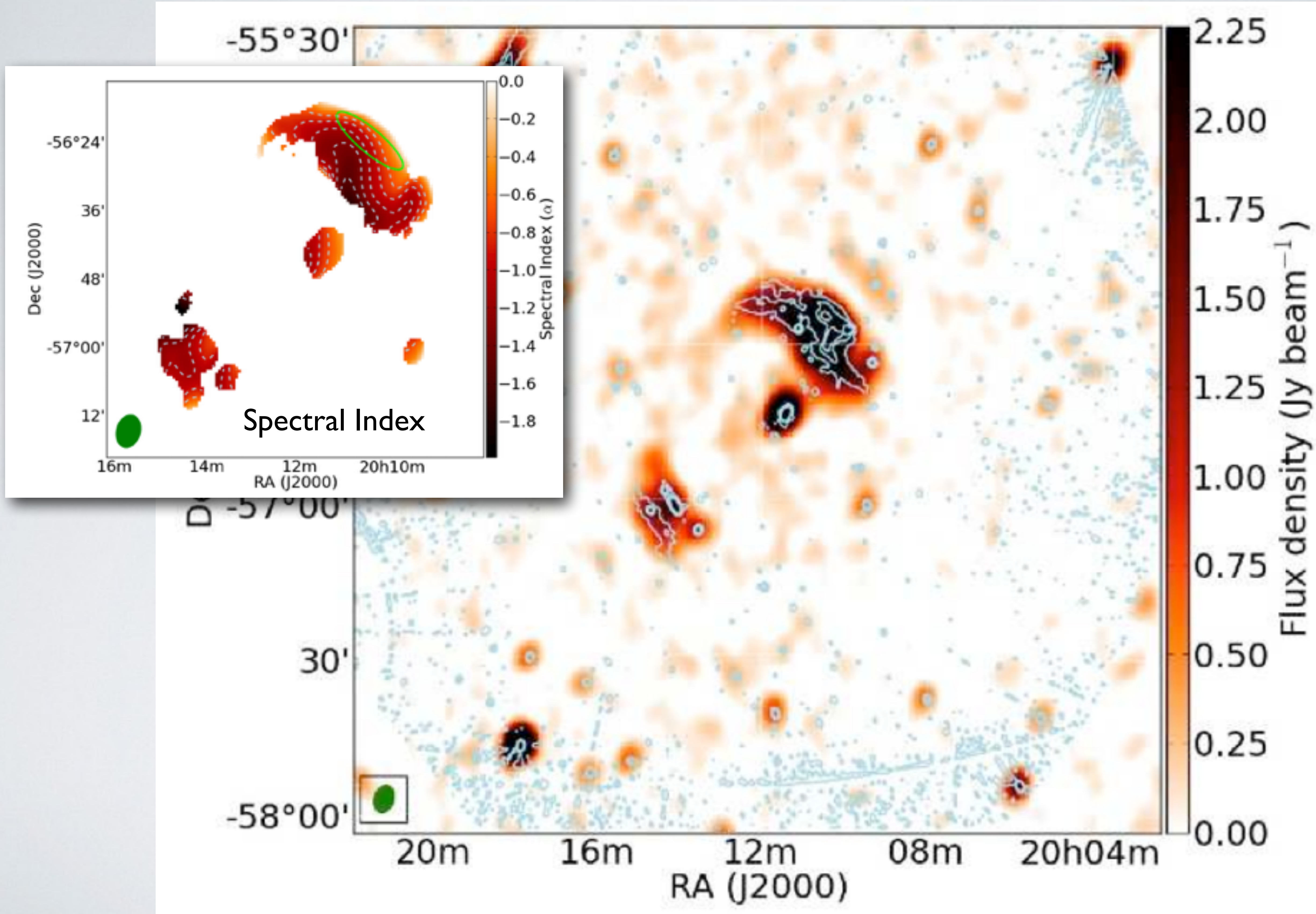
Bonafede+ 2012

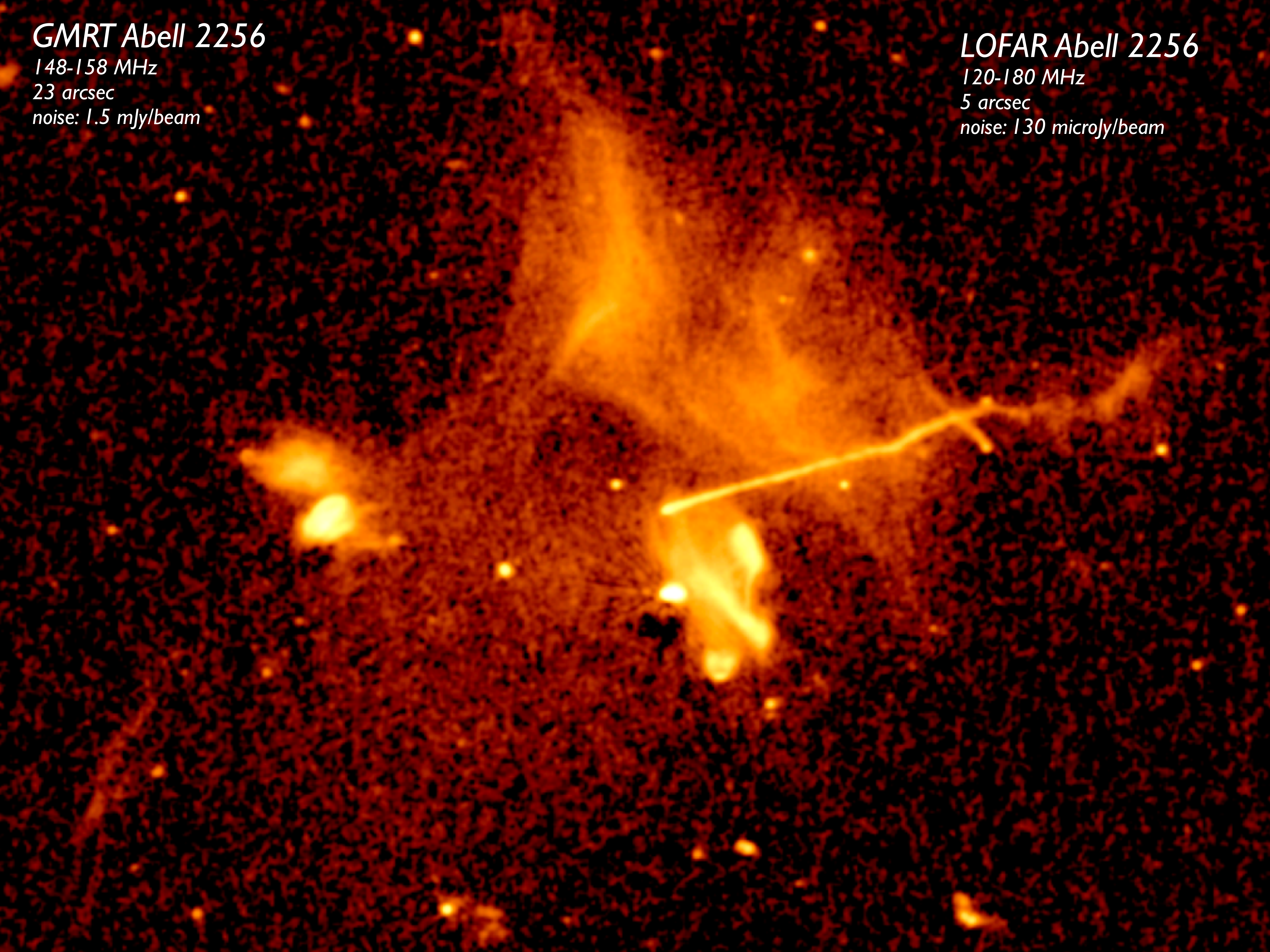


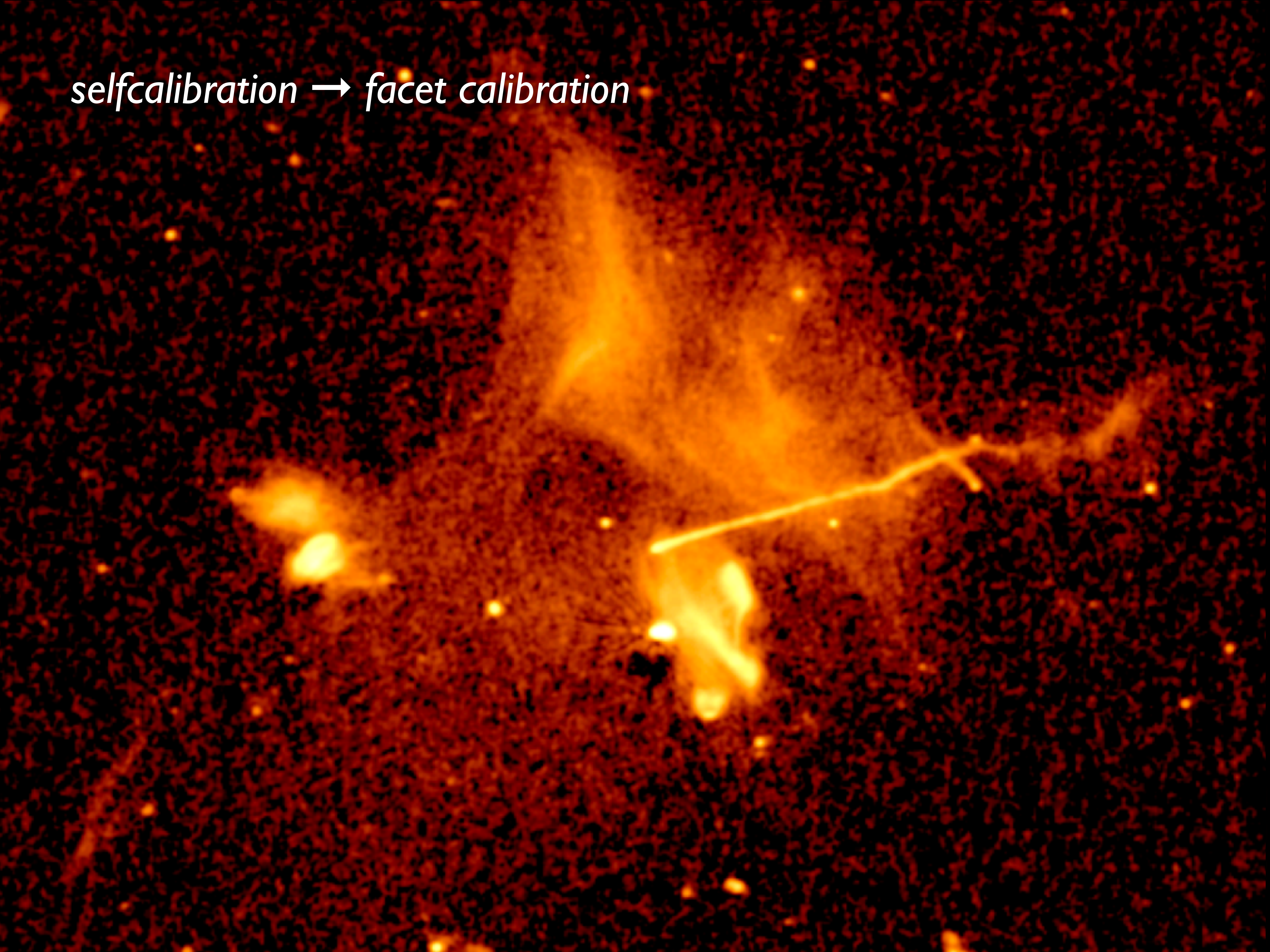
Clarke & Ensslin 2006

LOW-FREQUENCIES

A3667: Hindson+ 2014

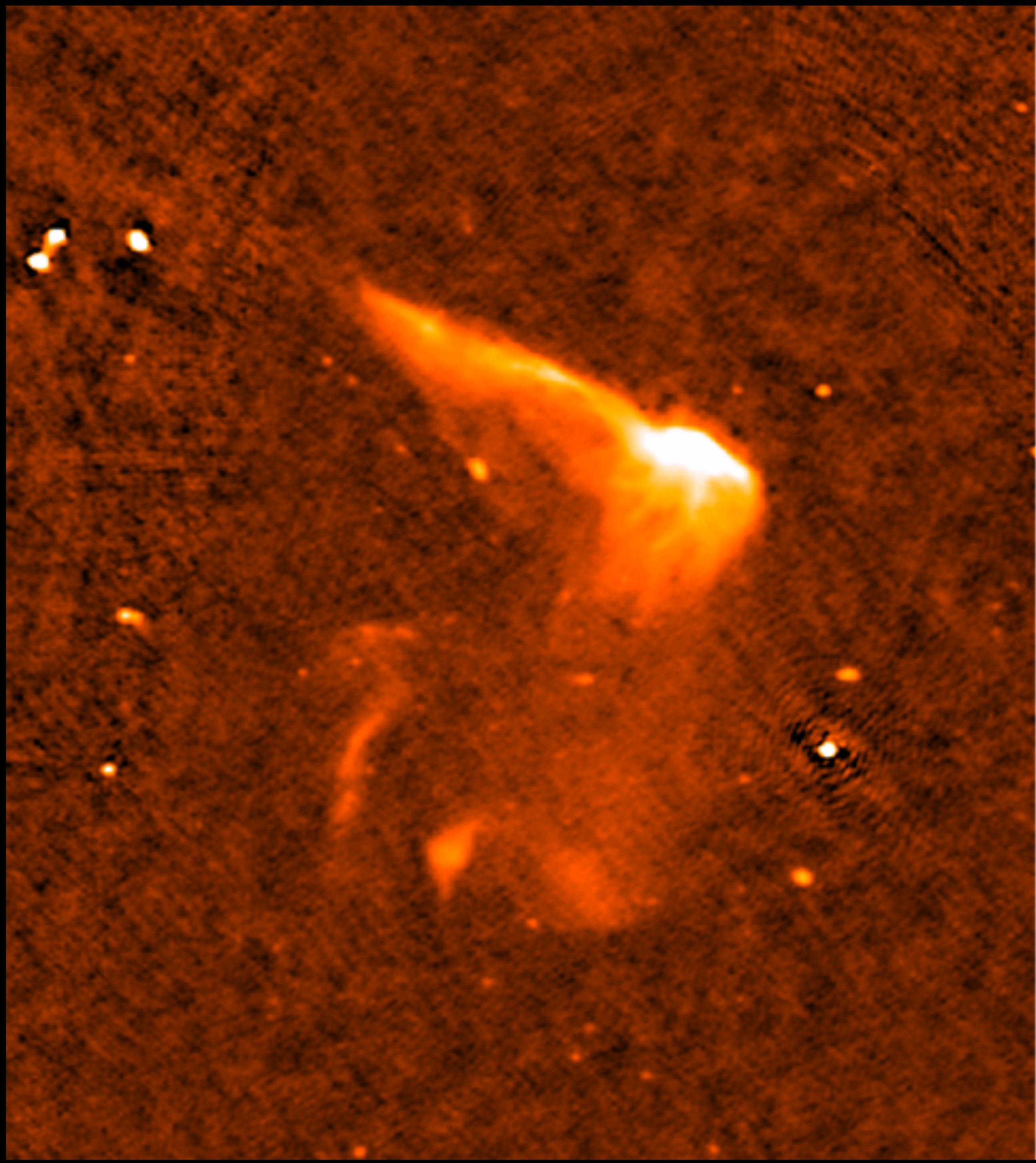



GMRT Abell 2256
148-158 MHz
23 arcsec
noise: 1.5 mJy/beam
LOFAR Abell 2256
120-180 MHz
5 arcsec
noise: 130 microJy/beam


selfcalibration → facet calibration

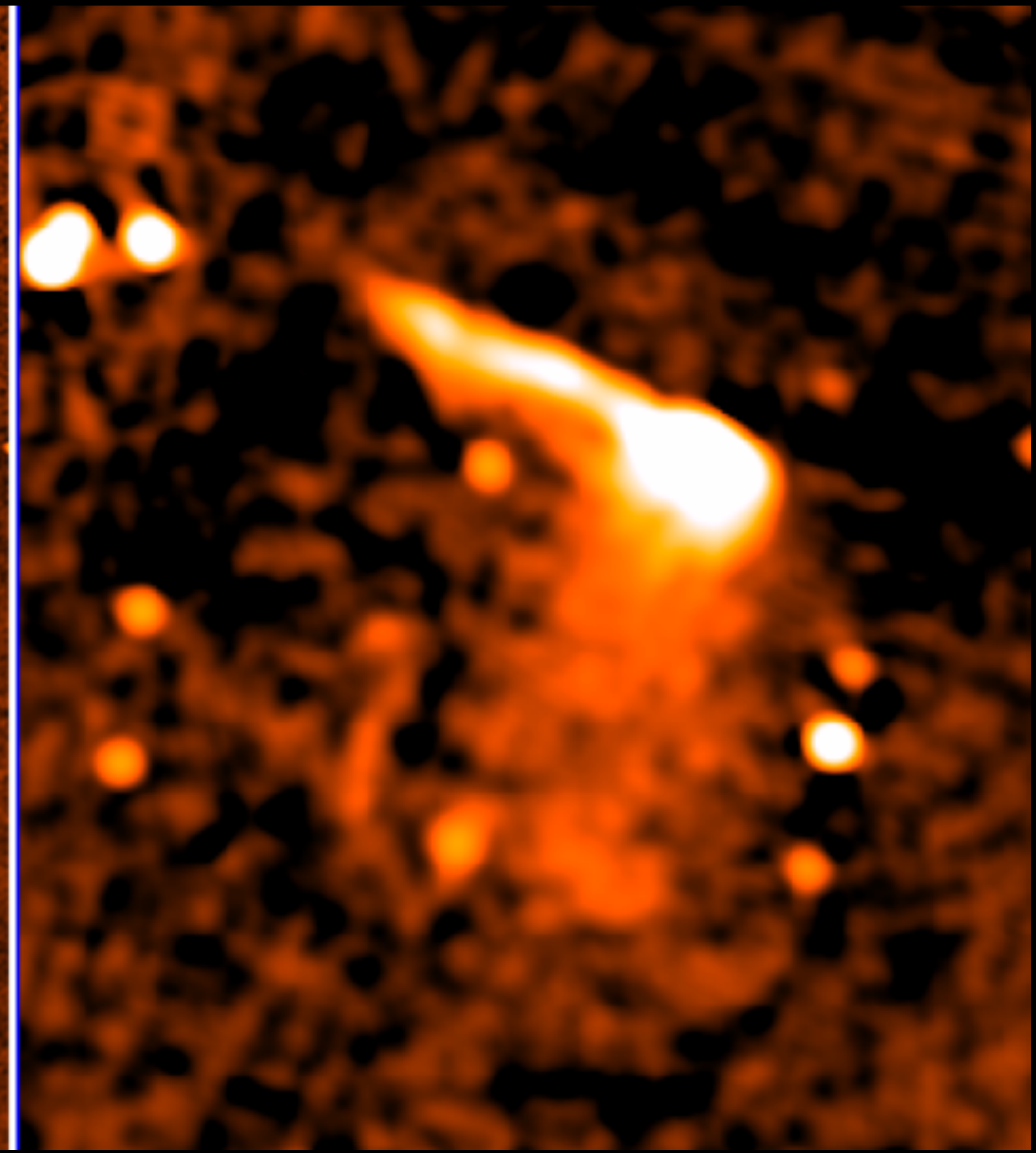
LOFAR HBA

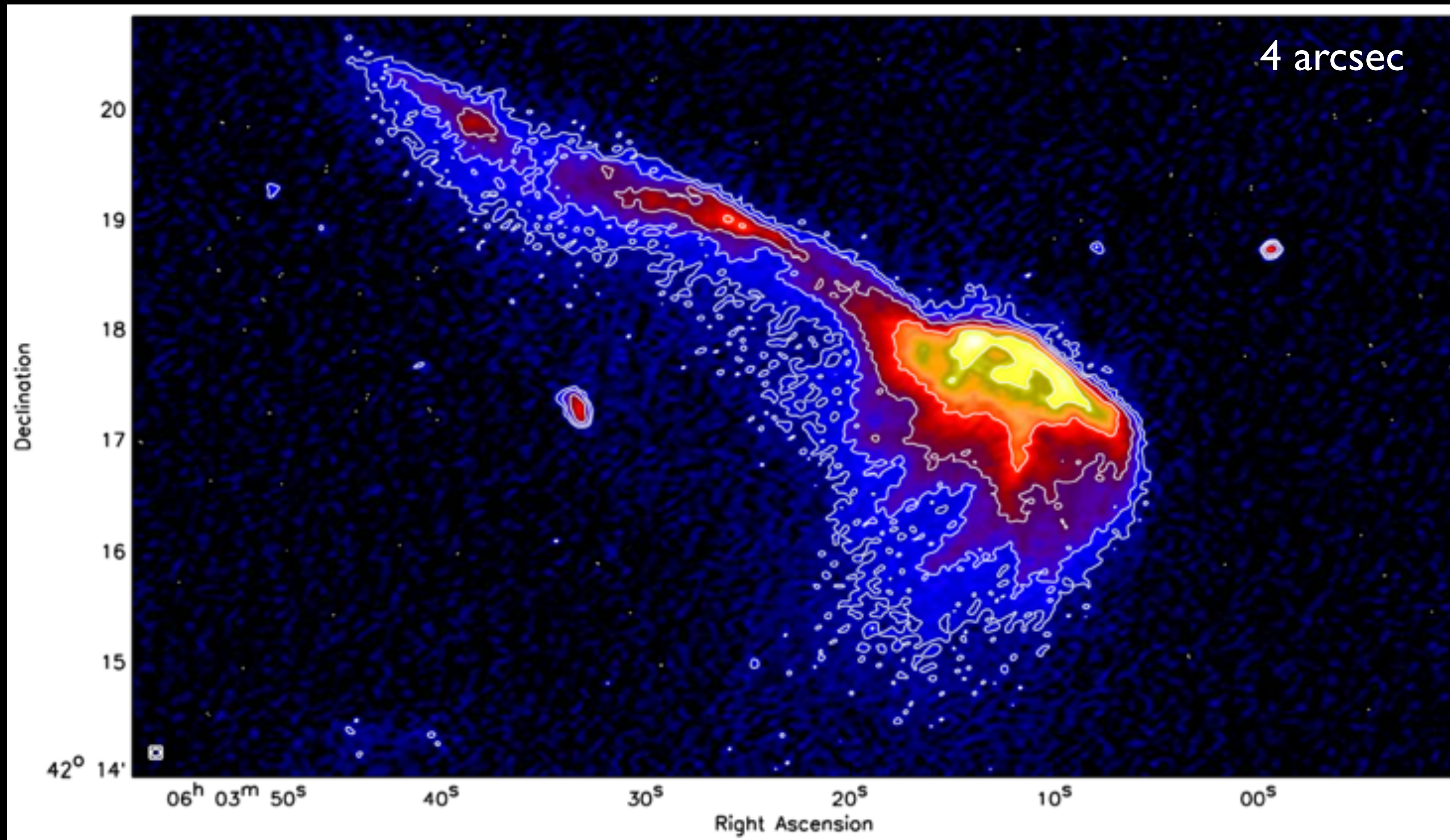
- *93 microJy/beam, 6 arcsec resolution*

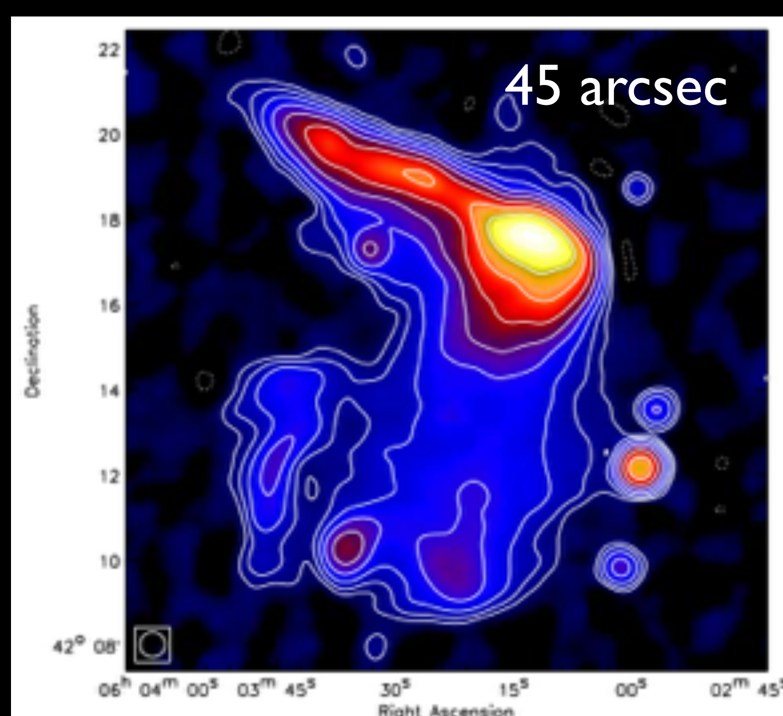


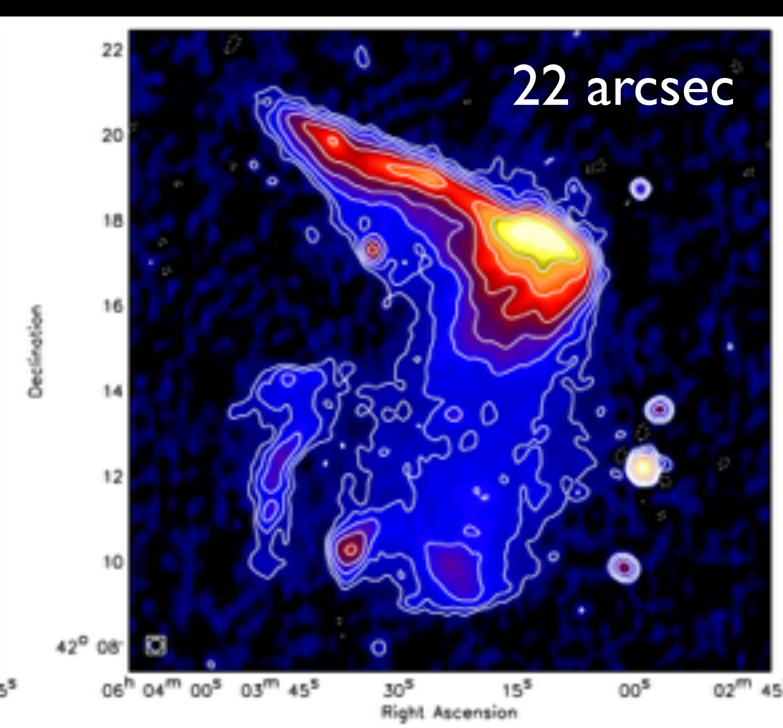
GMRT

- *1.1 mJy/beam, 22 arcsec resolution*



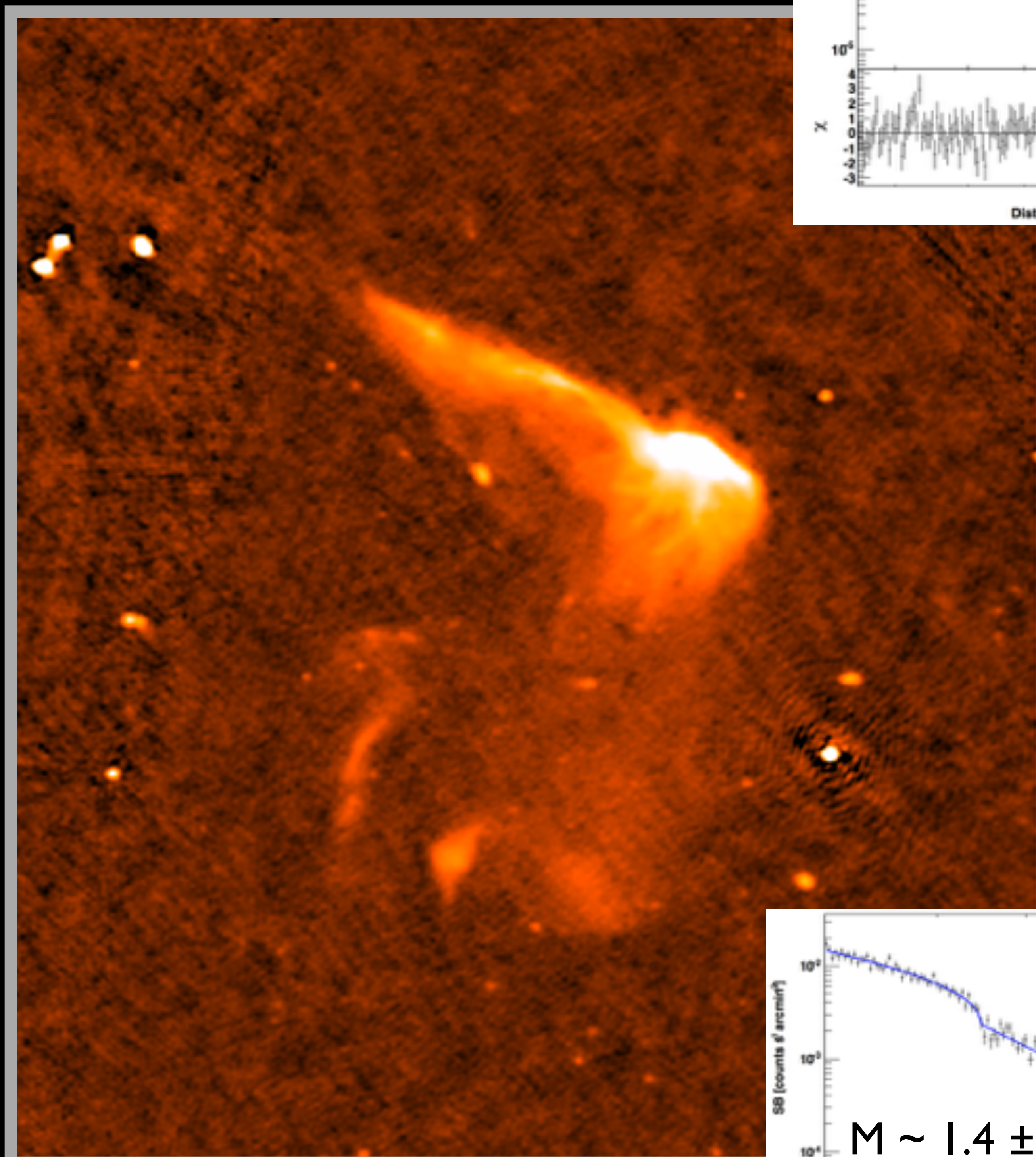

4 arcsec
Declination
20
19
18
17
16
15
42° 14'
06h 03m 50s
40s
30s
20s
10s
00s
Right Ascension

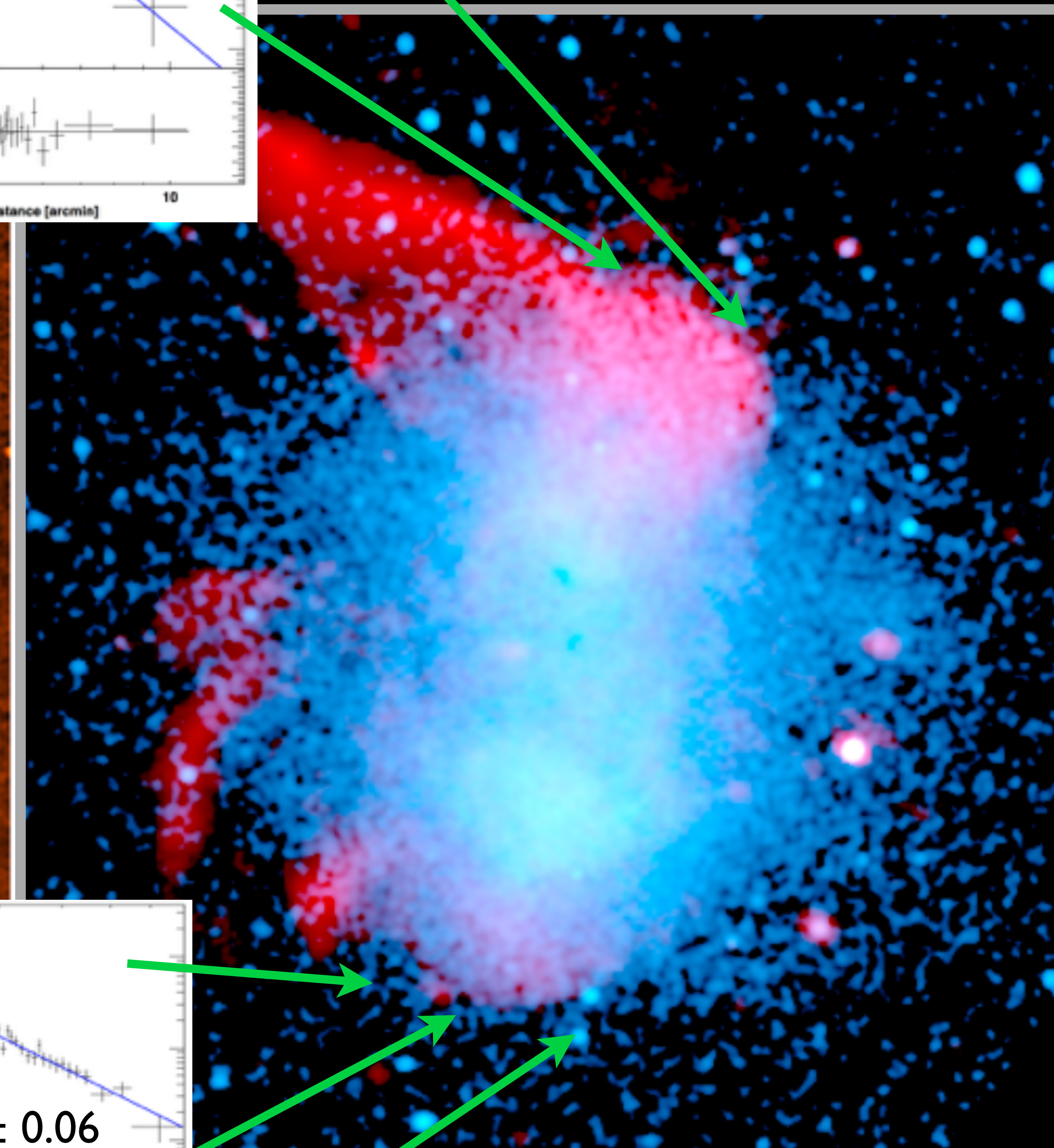

45 arcsec
Declination
22
20
18
16
14
12
10
42° 08'
06h 04m 00s
03m 45s
30s
15s
00s
02m 45s
Right Ascension

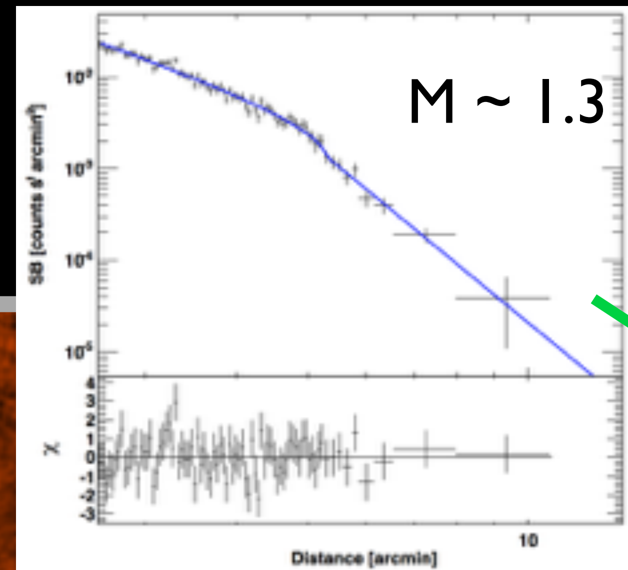

22 arcsec
Declination
22
20
18
16
14
12
10
42° 08'
06h 04m 00s
03m 45s
30s
15s
00s
02m 45s
Right Ascension

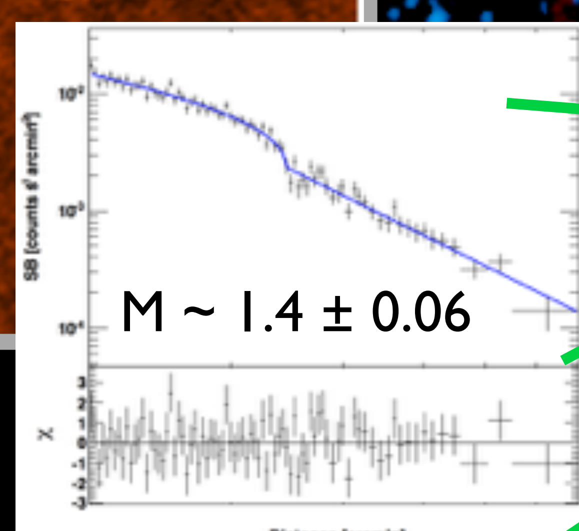
LOFAR HBA

Chandra + HBA

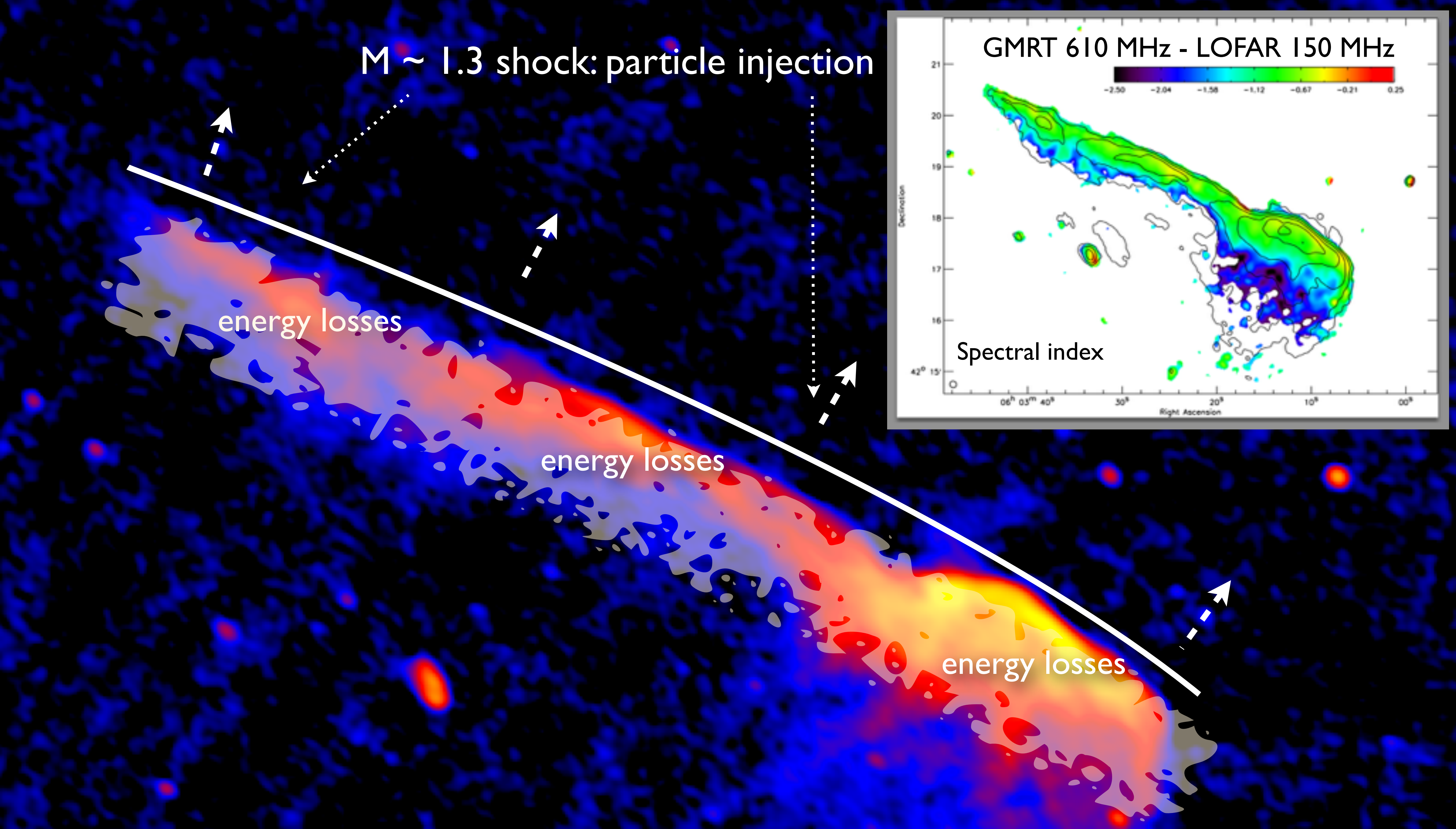








van Weeren+ (submitted)

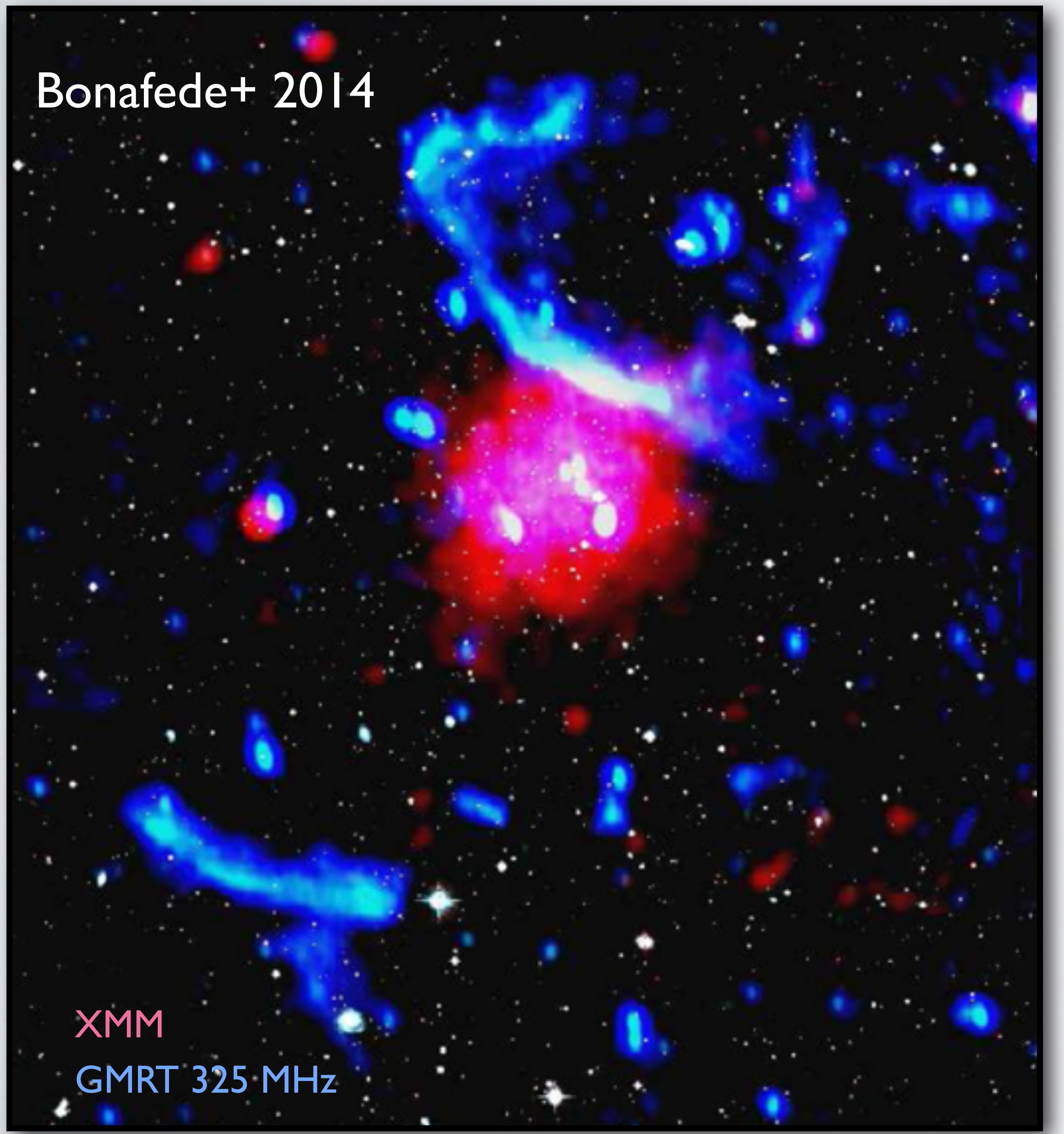


$$\alpha_{\rm inj} = \frac{1}{2} - \frac{\mathcal{M}^2 + 1}{\mathcal{M}^2 - 1}$$

Injection spectral index does not match with what is expected from the Mach number !

Radio power: unrealistic fraction of the shock energy should be converted into electrons

RE-ACCELERATION ?



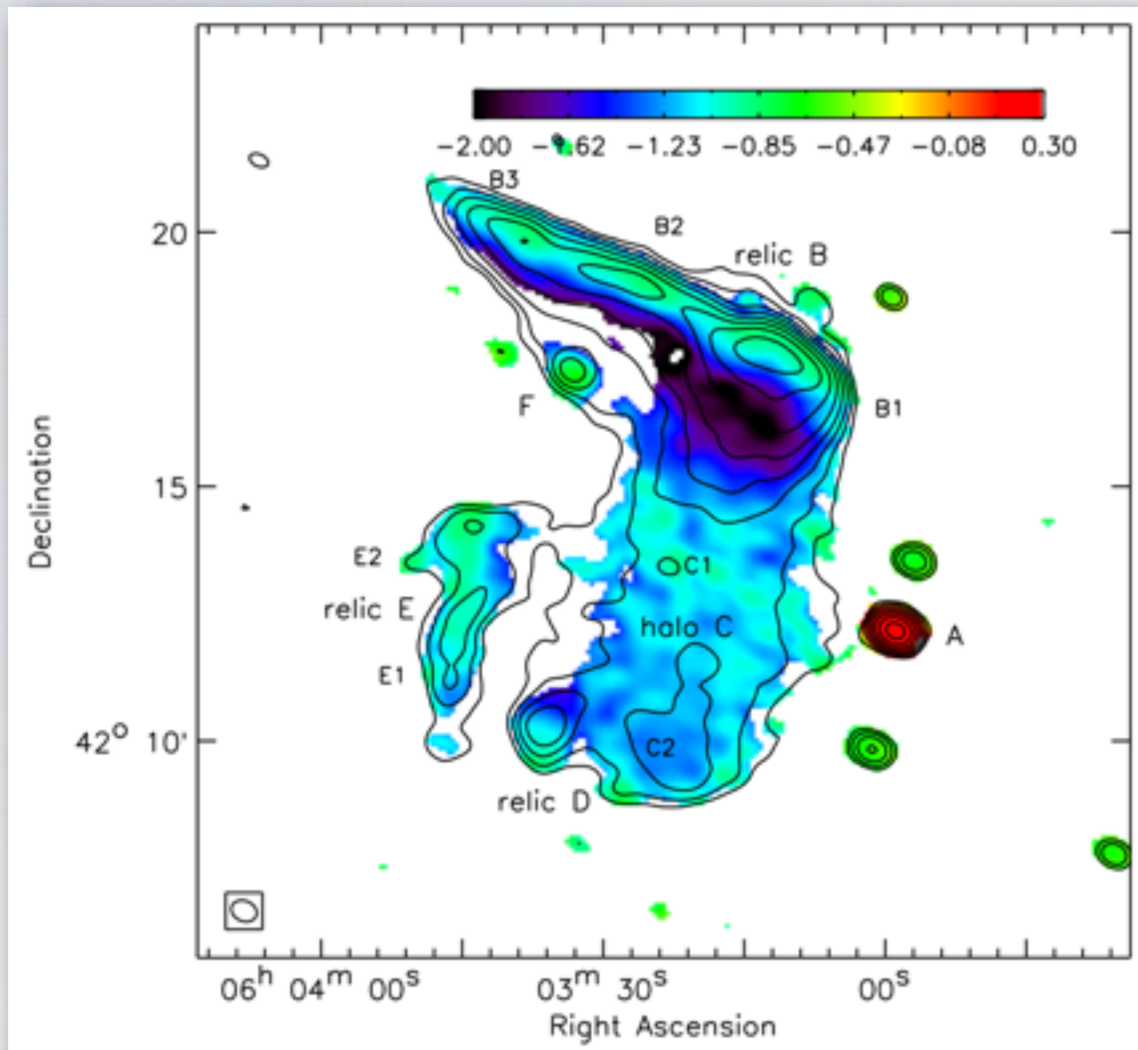
Re-acceleration

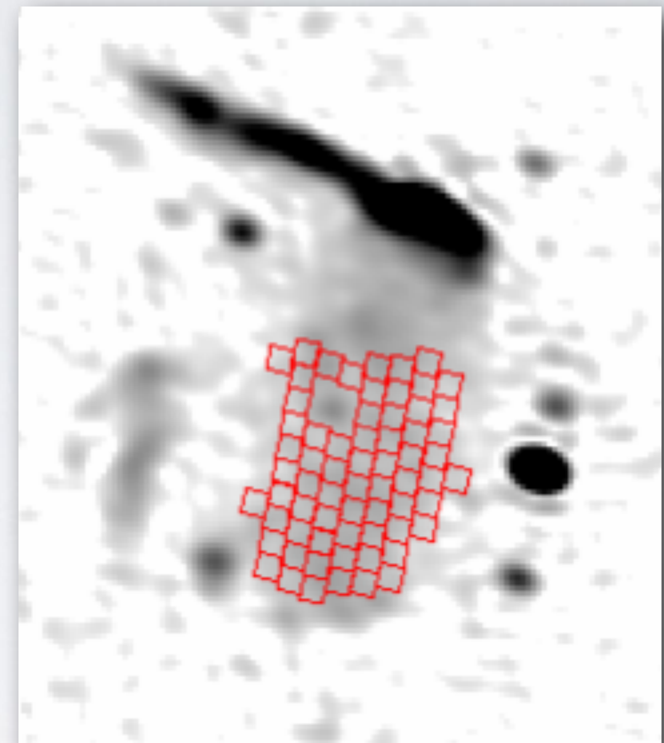
- Relativistic particles accumulated over the lifetime of a cluster
- Morphological connection between some relics and radio galaxies
- Efficient re-acceleration for low-Mach shocks
- Shocks without relics are possible (would explain A2146, Russel +2011)

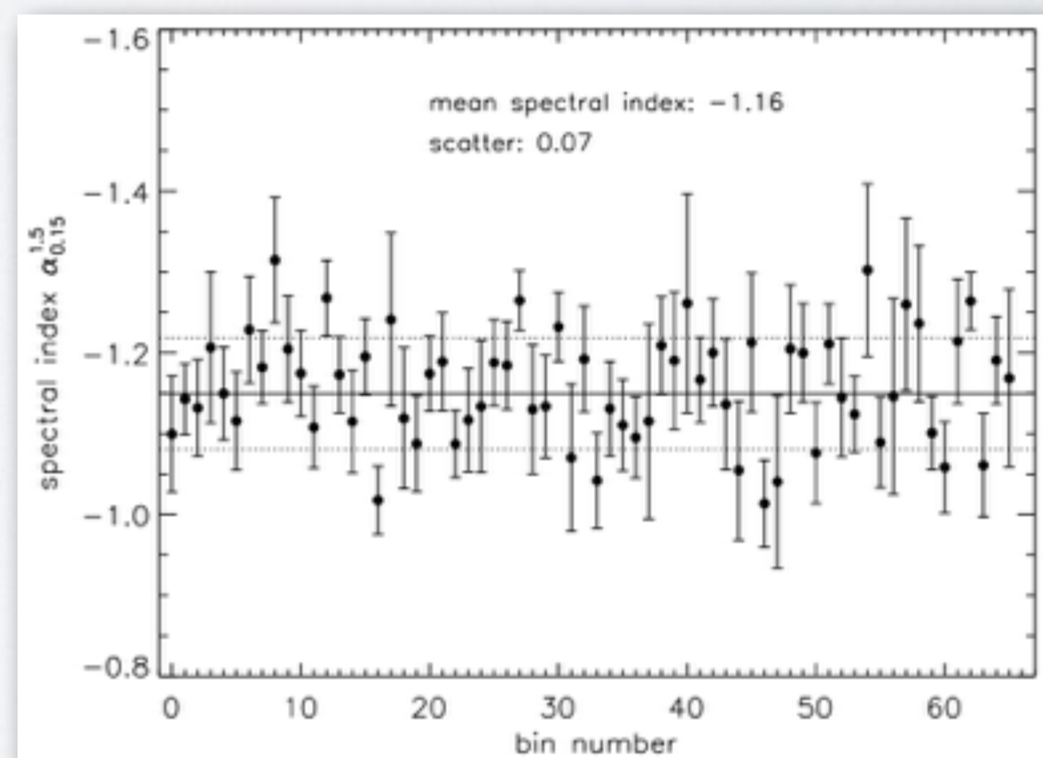
Markevitch+ 2005; Giacintucci+ 2008; Kang & Ryu 2011; Kang+2012; van Weeren+ 2015; Shimwell+ 2015;

HALO SPECTRAL VARIATIONS

Use spectral index to trace variations in ICM turbulence or B-fields ?







- Spectral index remarkably uniform
- Intrinsic variations < 0.04

SUMMARY

- Low-frequencies: enormous amount of progress recently
- Radio halo spectral indices
  - Results differ from clusters to cluster ?
  - Need more LOFAR - JVLA spectral maps
  - Need predictions from models
- Radio relics trace merger shocks
  - Spectral index gradients are quite common
  - Re-acceleration seems to be preferred for some relics ?