GMRT and LOFAR observations of Massive and Distant Galaxy clusters

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LOFAR collaboration - survey Key project

Outline

- Radio emission from the Intra Cluster Medium

- The MACS sample: massive and distant galaxy clusters

- Radio observations at the GMRT

- Comparison with cosmological simulations

- LOFAR observations of the most distant and powerful radio halo

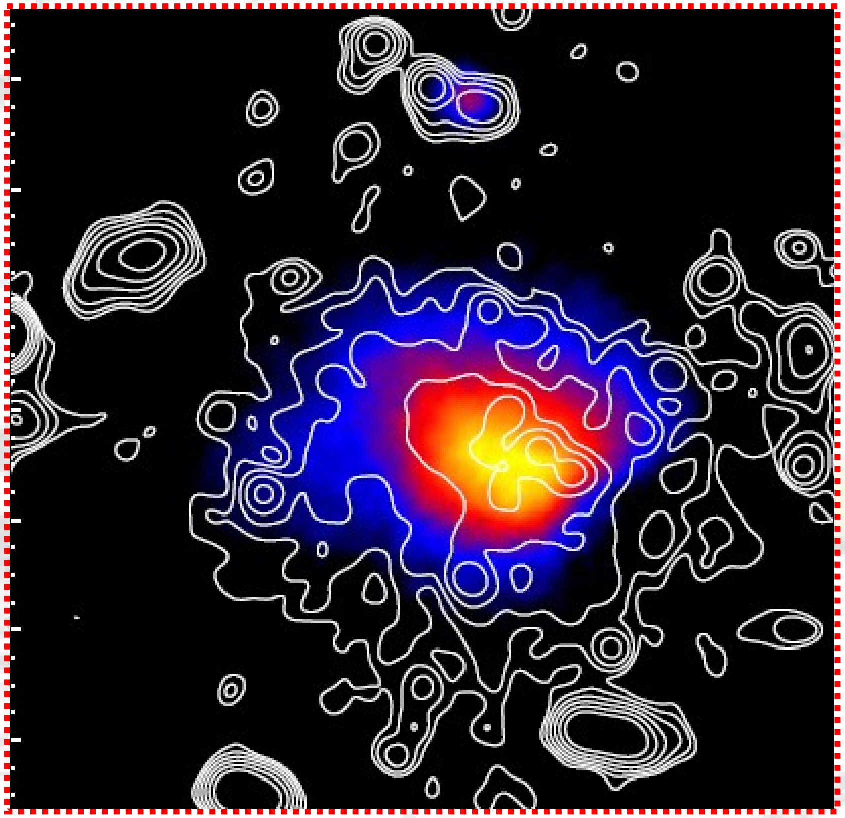
Radio halos

Synchrotron emission on Mpc scale

Low surface brightness
~ 1 μJy/arcsec² at 1.4 GHz

Usually unpolarized → depolarization

- always found in merging clusters



Feretti et al. (2001), Govoni et al. (2004)

→ particles generated or accelerated everywhere in the cluster

Radio halos: models

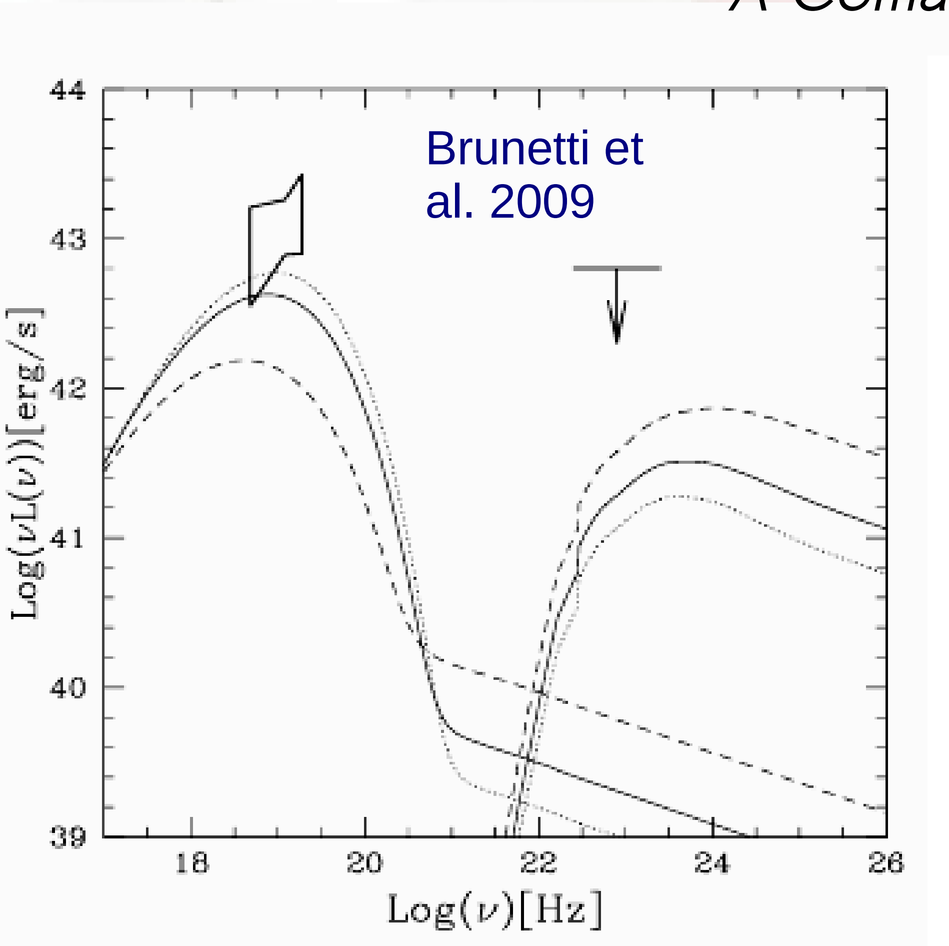
Models	process	Particle spectrum
Re-acceleration models (e.g. Brunetti et al. 2001 Petrosian 2001)	Fermi II mechanism Unefficient process	curved spectral index
Hadronic models (e.g.Dennison 1980 Keshet 2010; Ensslin et al. 2010)	Fermi I mechanism	straight spectral index

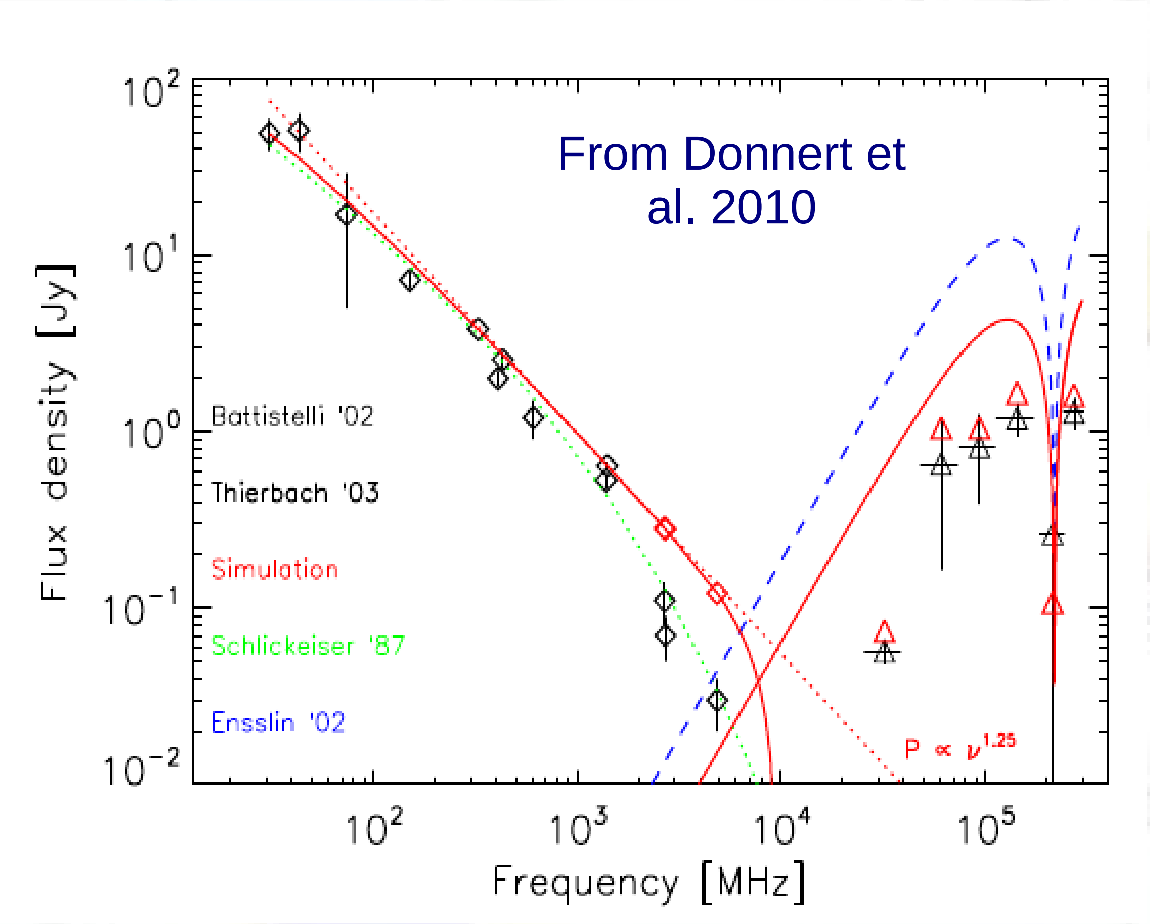
Radio halos: models

Re-acceleration models

Hadronic models

A Coma-like cluster



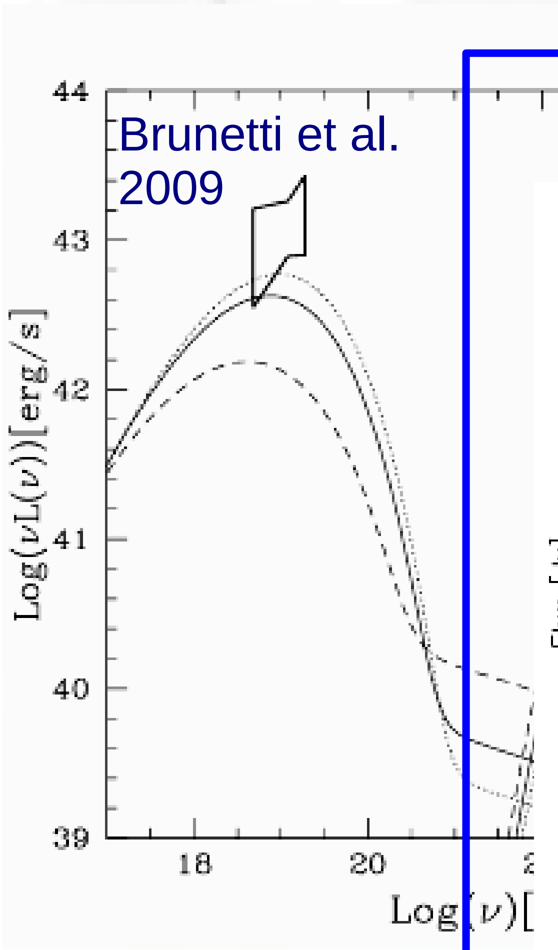


Radio halos: models

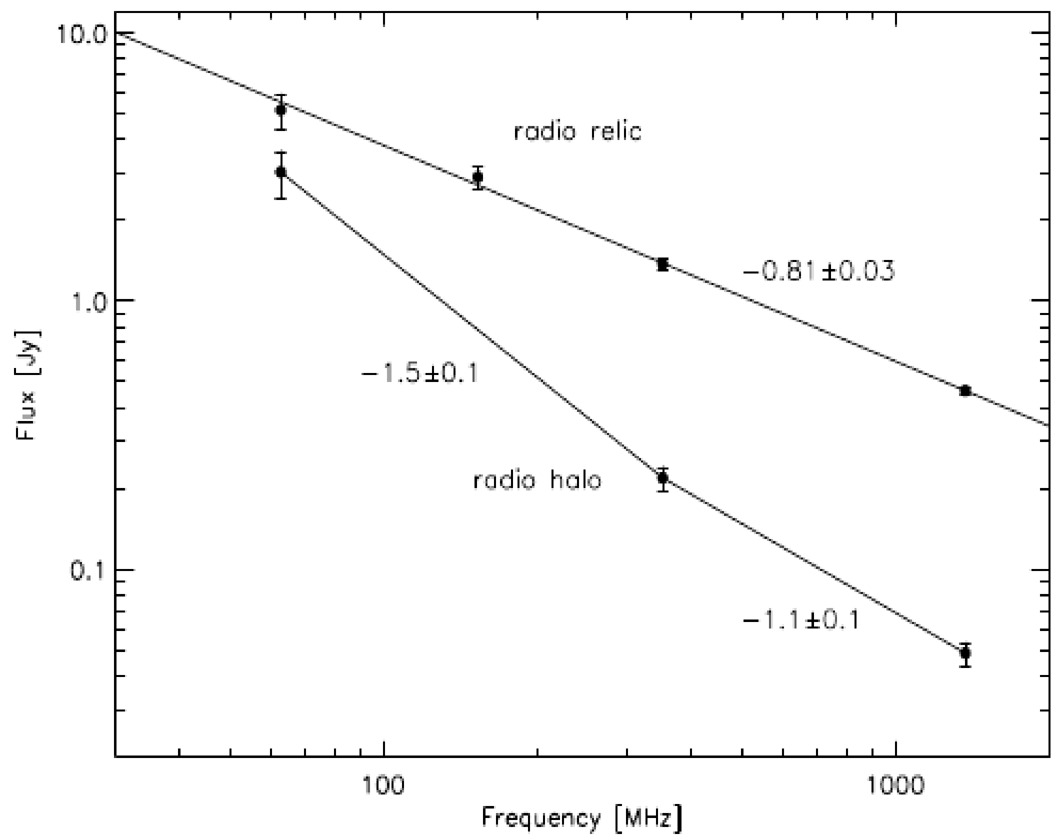
Re-acceleration models

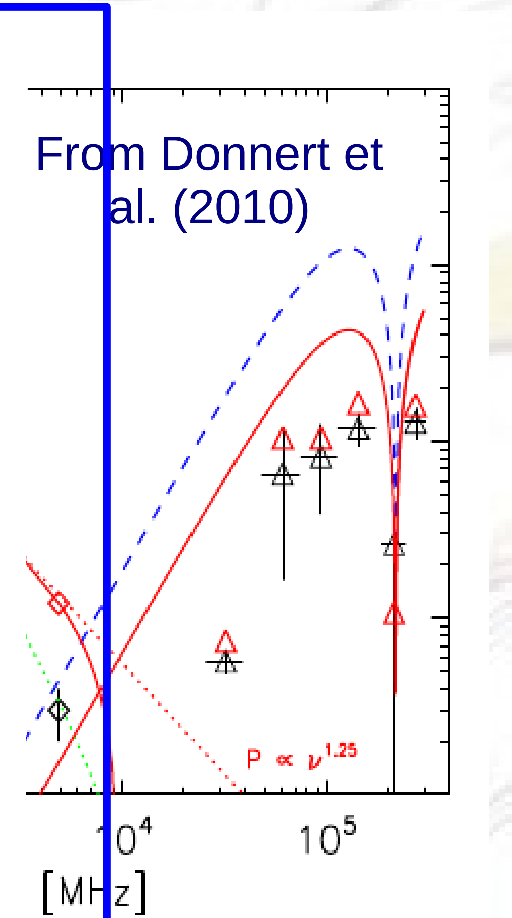
Hadronic models

A Coma-like cluster



A2256 – 1st halo observed by LOFAR
Van Weeren et al. 2012



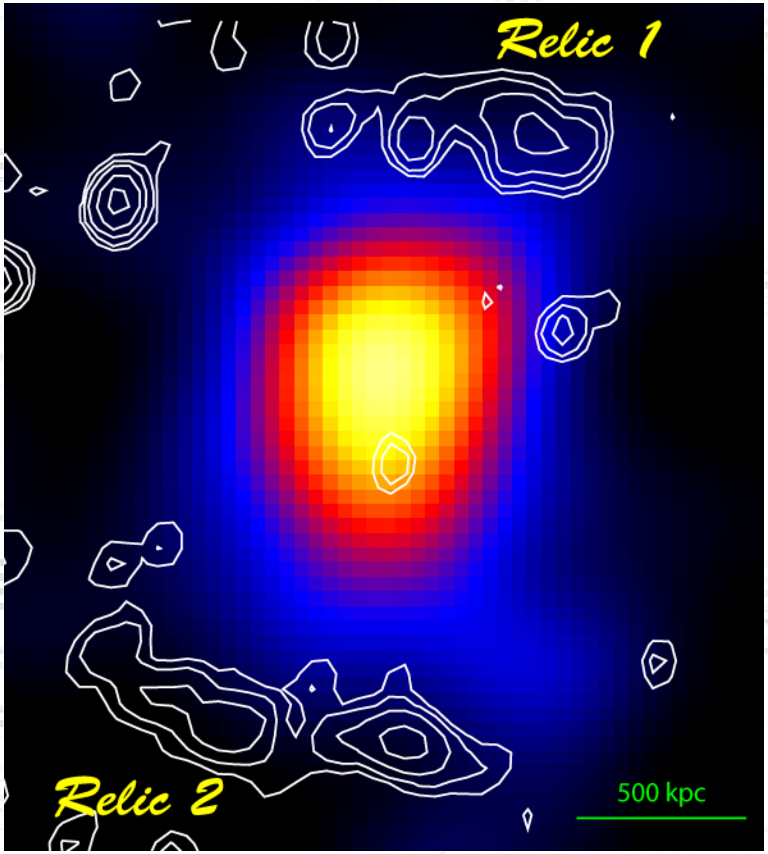


Radio relics

Synchrotron emission on Mpc scale in the cluster outskirts

Low surface brightness ~ 1 μJy/arcsec² at 1.4 GHz

Polarized ~ 20% at 1.4 GHz



Bonafede et al. (2009)

→ particles accelerated and/or magnetic field ampified. shocks?

Radio relics:

Model predictions | **Radio observable signatures**

→ DSA

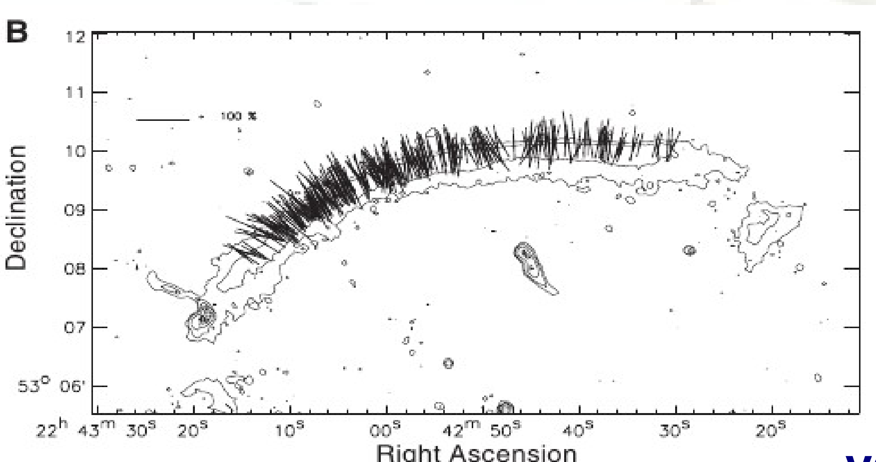
→ injection spectral index > 0.5

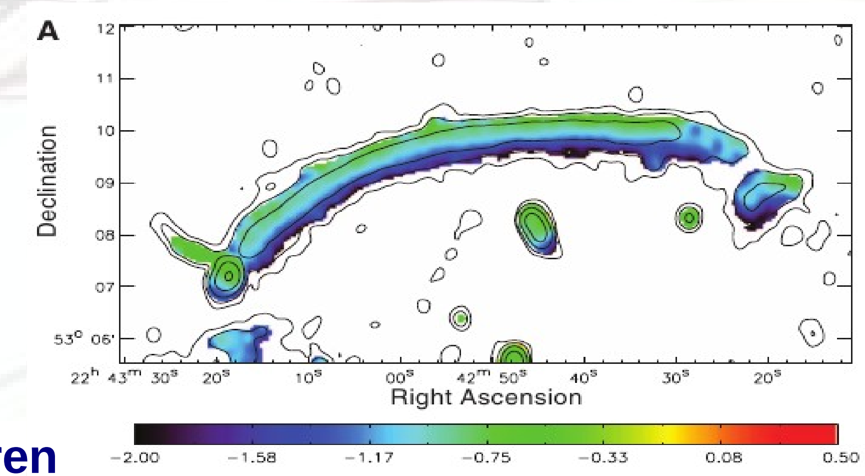
→ Magnetic field compressed by the shock

→ detectable polarization
- magnetic field aligned with shock surface

→t_acc ~ 10^5 yr
t_loss ~ 10^8 yr

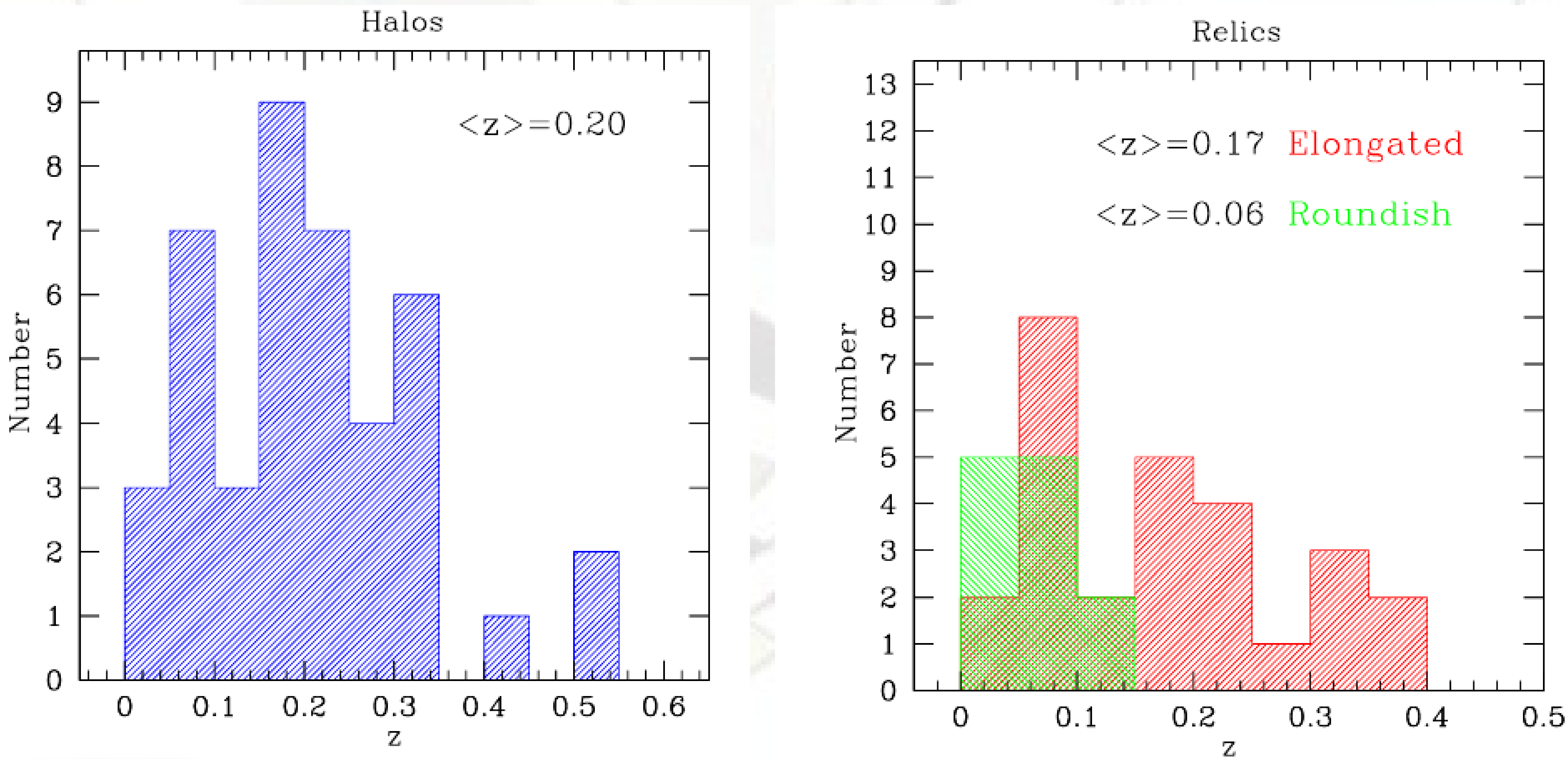
→ steady state reached, power-law spectrum
steepening of the spectral index as particle move from the acceleration site





van Weeren et al. 2010

Distribution of halos and relics



Feretti et al. 2012

Aim of the work:

Extend our knowledge of halos and relics to $z > 0.3$

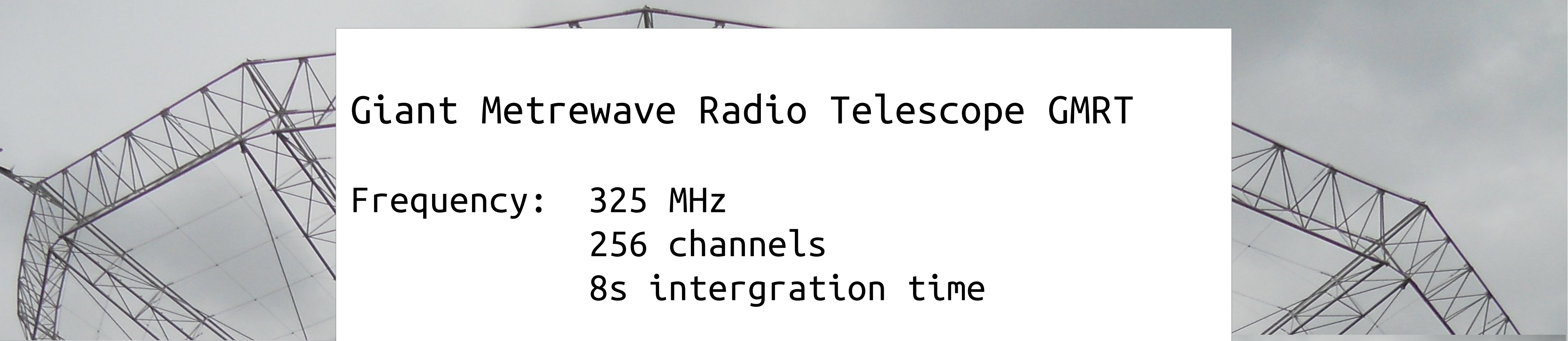
MACS catalog (Ebeling et al. 2007,2010):

- From ROSAT Bright Source Catalog (Voges et al. 99)
- $z > 0.3$
- $L_x > 2\ 10^{-12}$ erg/s/cm^2 [0.1 -2.4 keV]

128 clusters

Most promising candidates selected on the basis of
- Chandra / XMM-Newton data available
- merging signature
- hints of diffuse emssion from NVSS

Radio Observations



Giant Metrewave Radio Telescope GMRT

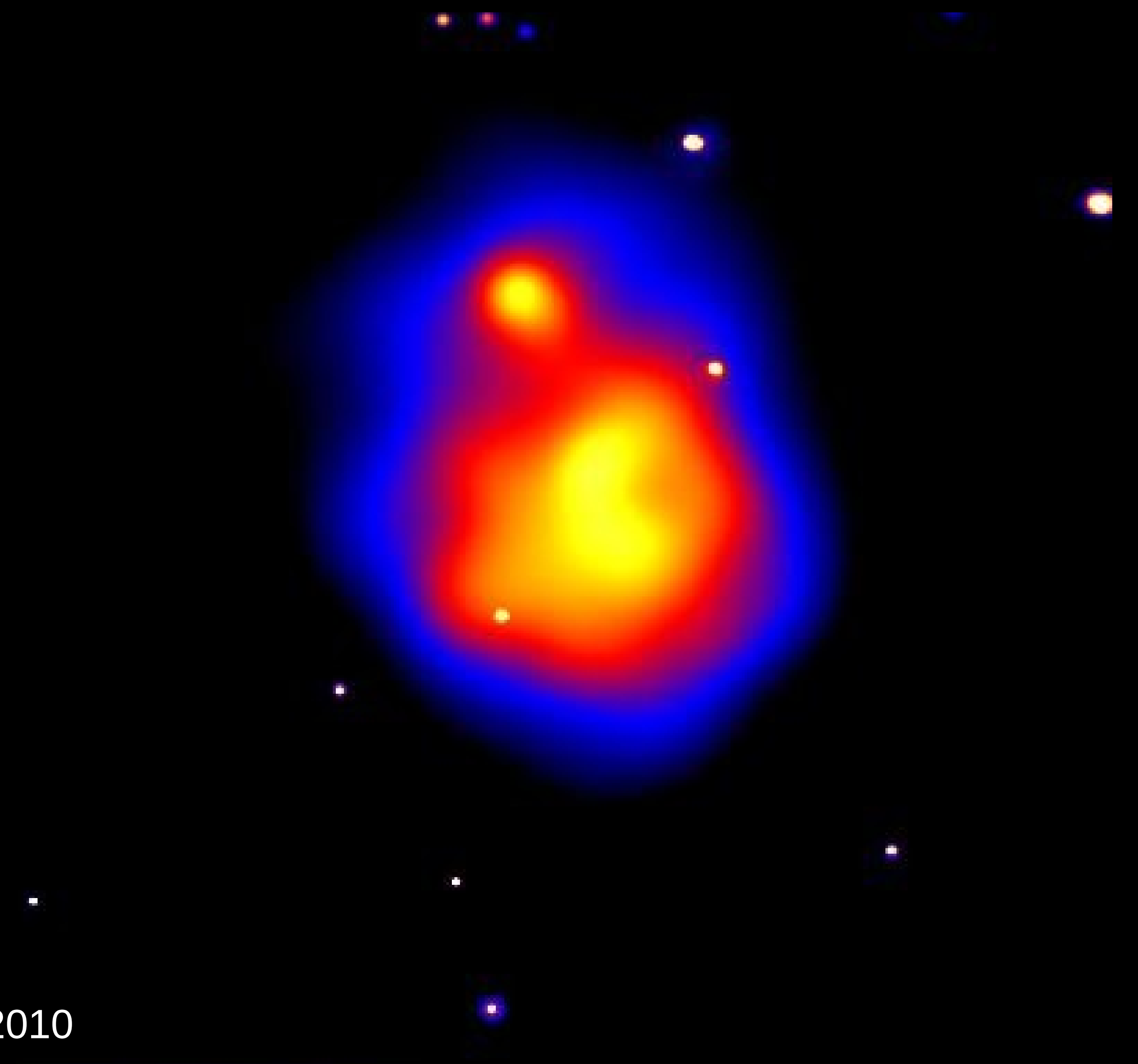
Frequency: 325 MHz
256 channels
8s intergration time

Time: 6 hours per cluster (net ~ 3.5 - 4)

MACSJ1731.6+2252

z=0.389

Lx = 2.5 10^{45} erg/s



Ebeling et al. 2010

MACSJ1731.6+2252

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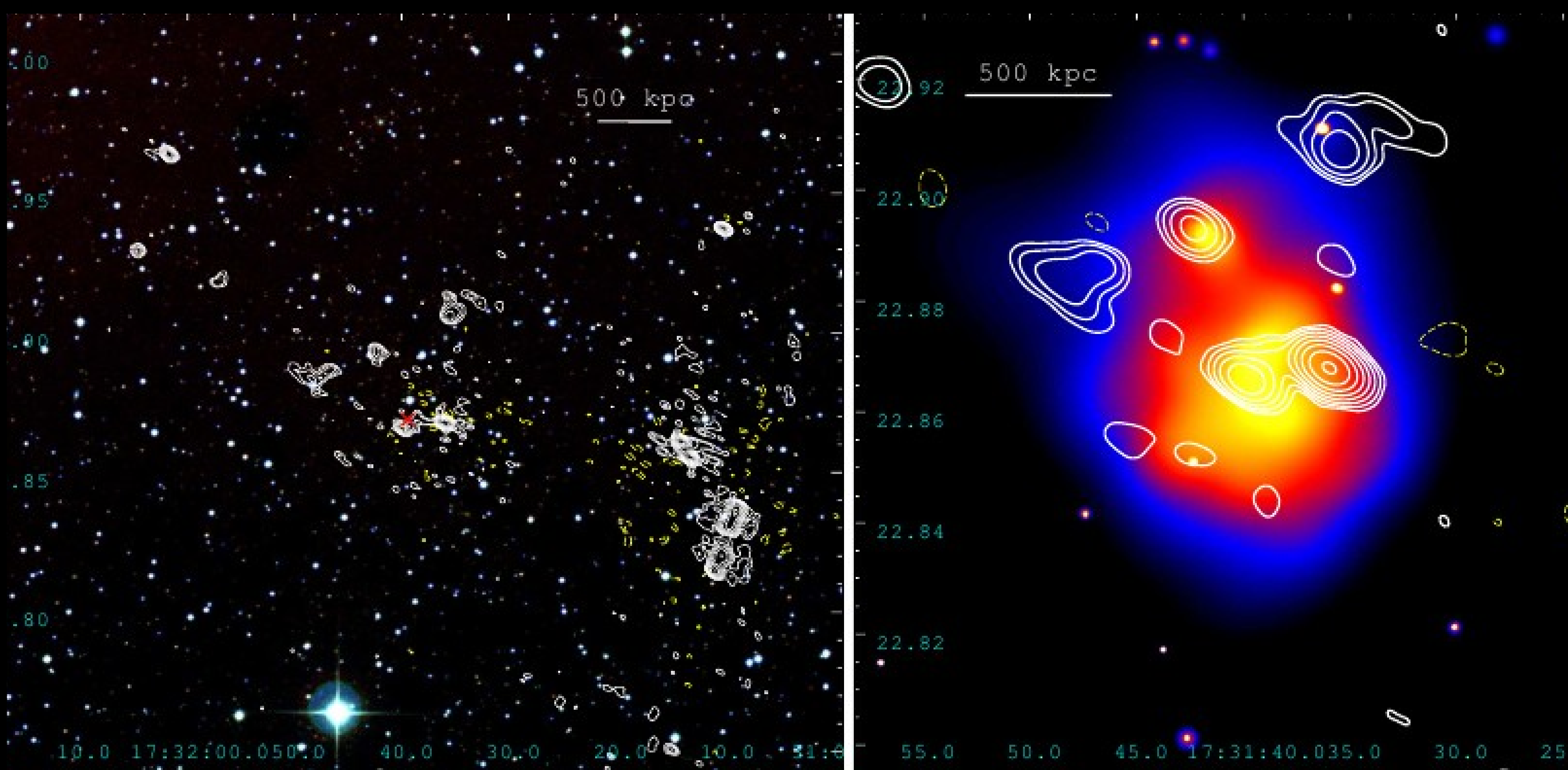
High resolution Image

Low resolution Image



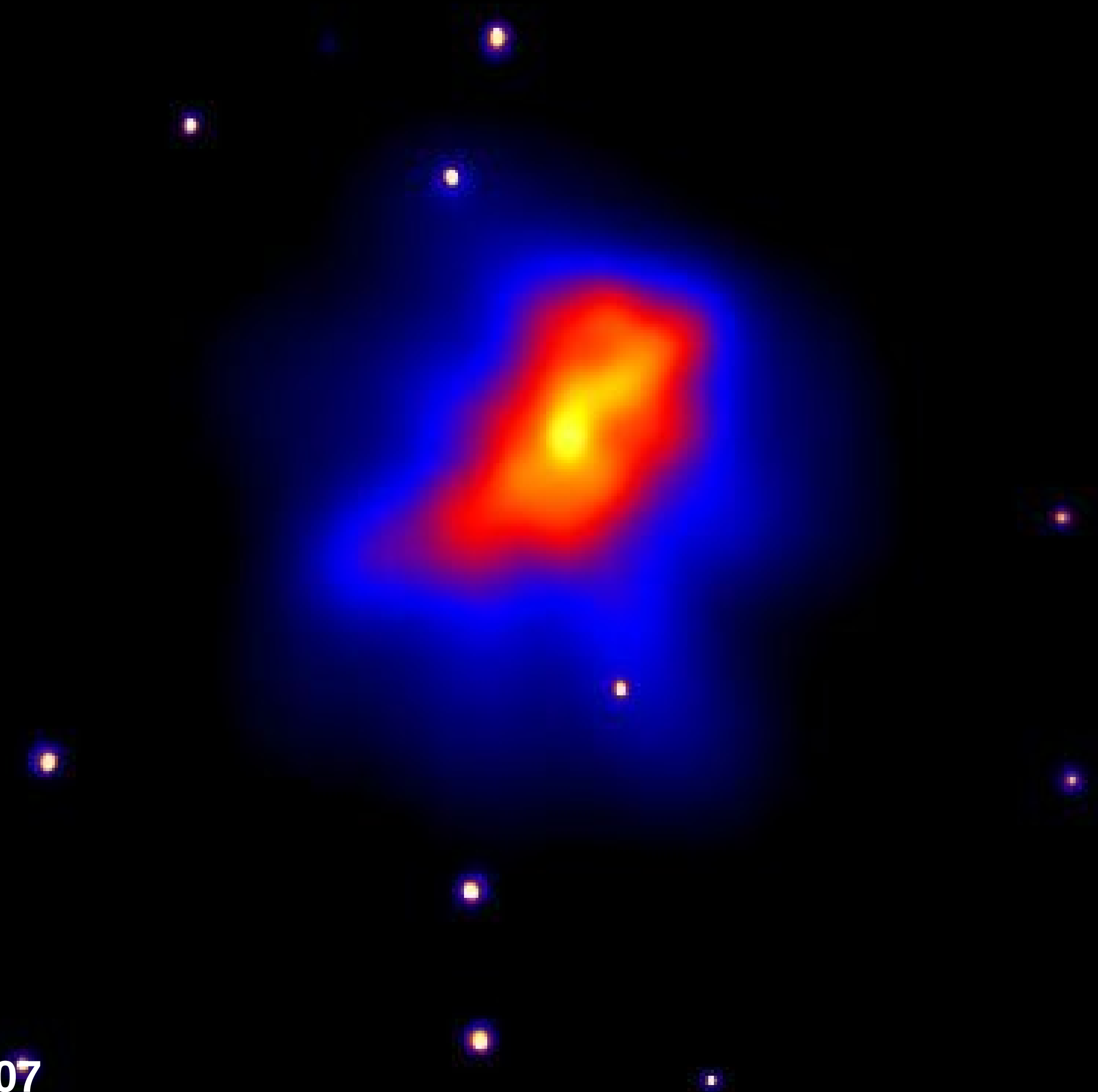
Contours: 323 MHz
rms 0.3 mJy/beam Beam ~ 10.6" x 6.6"
Colors: DSS 2

Contours: 323 MHz
rms 0.5 mJy/beam Beam ~ 26" x 17"
Colors: Chandra (Ebeling et al. 2010)

MACSJ1149.5+2223

z=0.544

Lx = 1.4 10^{45} erg/s



Ebeling et al 2007

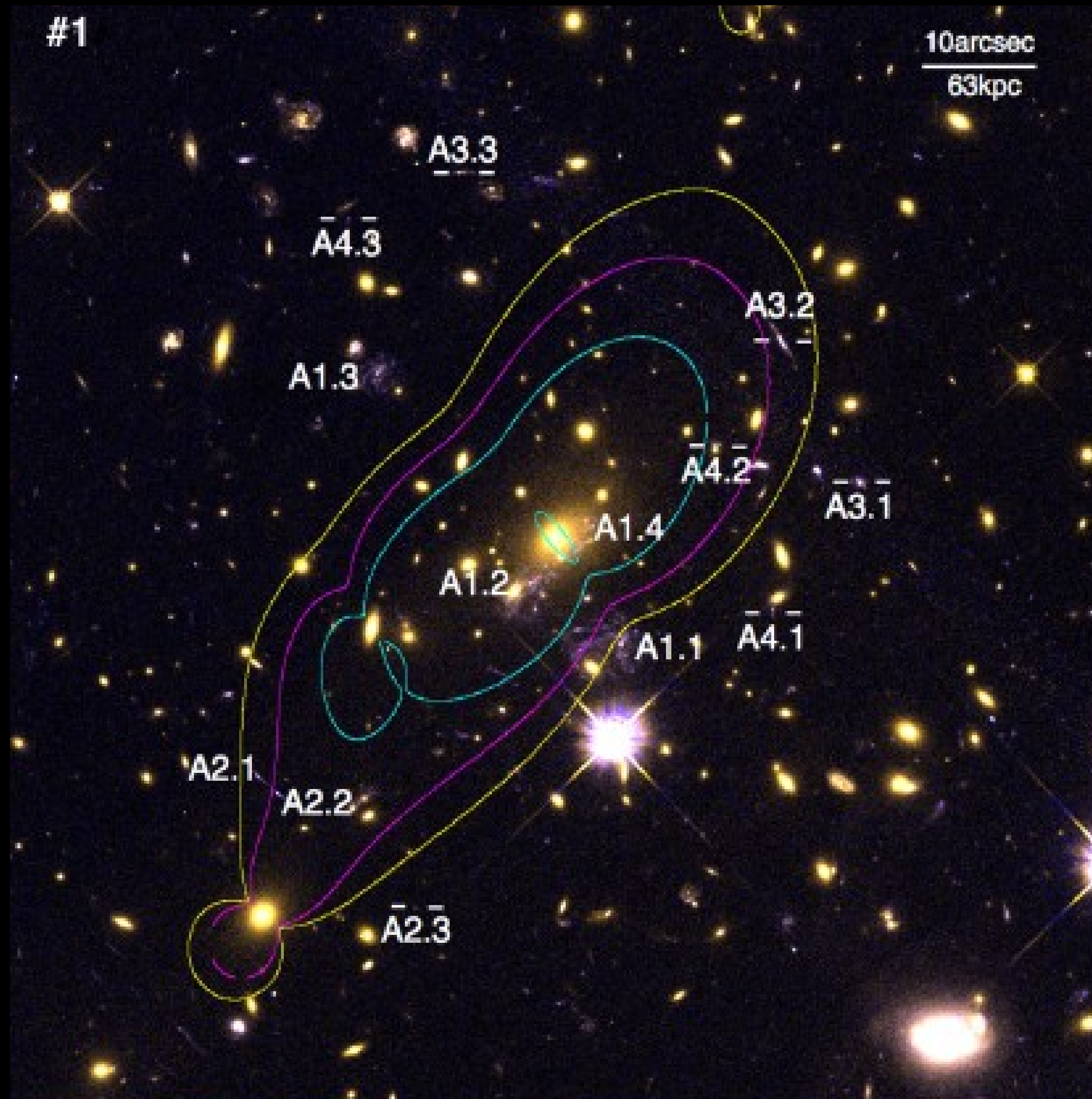
MACSJ1149.5+2223

z=0.544
Lx = 1.4 10^{45} erg/s

Lensing:
7 mutiply
images
galaxies

Main halo
M (500 kpc) ~ 7 10^14 M_sol

+ 3 sub-halos



Tangential critical curves
At z= 1.49, 1.89, 2.45

Smith et al 2009

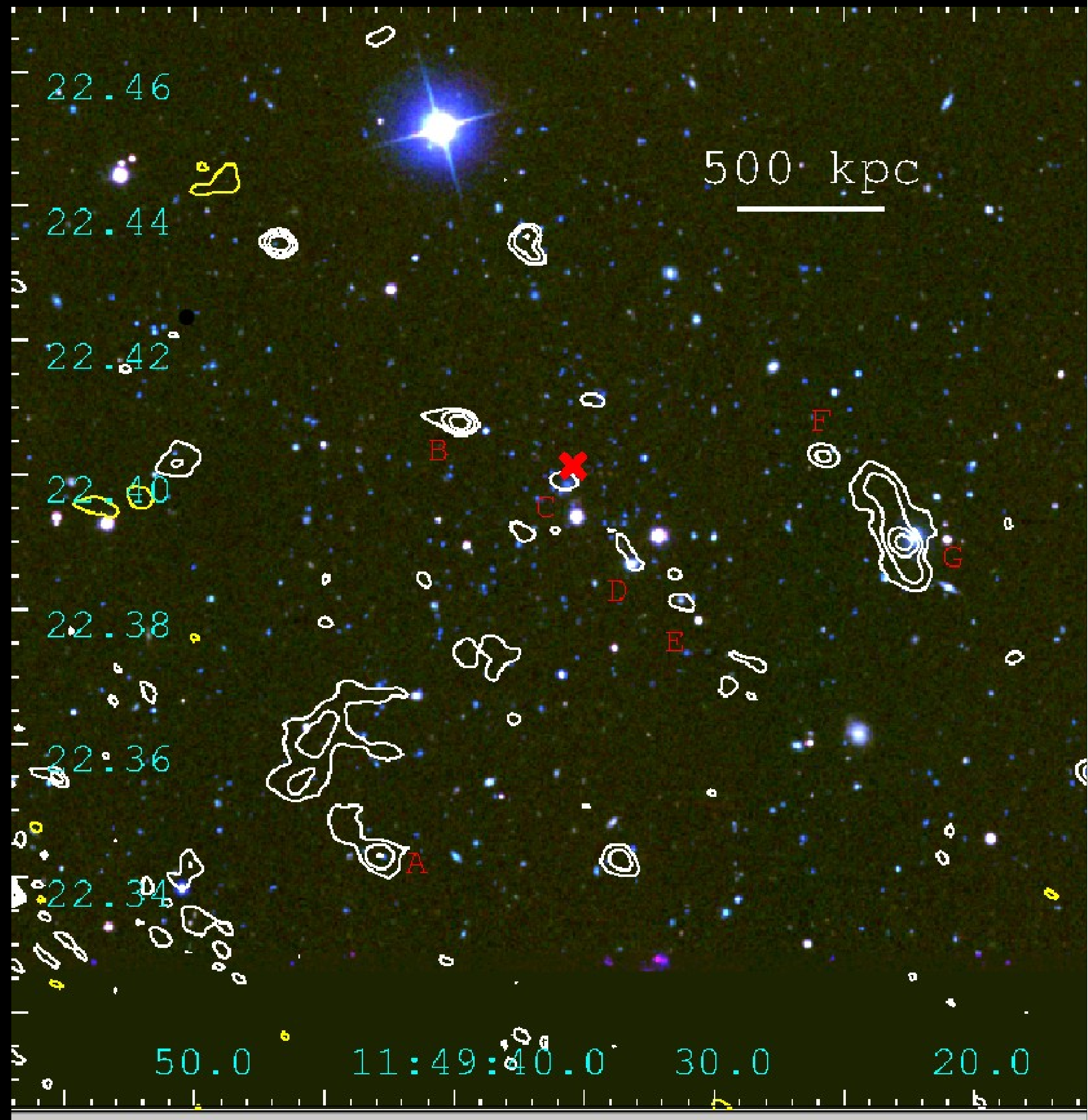
MACSJ1149.5+2223

z=0.544

Lx = 1.4 10^{45} erg/s

High resolution Image

Contours: 323 MHz
rms 0.3 mJy/beam
Beam ~ 11.5" x 7.8"
Colors: SDSS dr7



MACSJ1149.5+2223, z=0.544

Low resolution Image
(briggs Scheme
+ uvtaper)

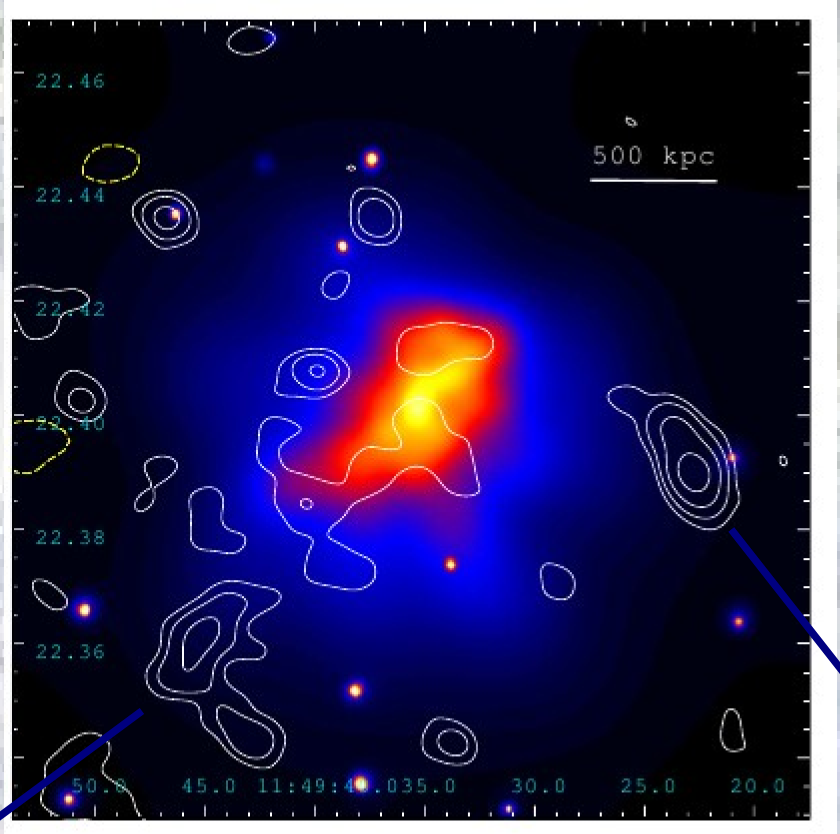
Contours: 323 MHz
rms 0.5 mJy/beam
Beam ~ 24.5” x 20”
Colors: Chandra (Ebeling et al. 2007)

MACSJ1149.5+2223, z=0.544

Double relics

- the most distant discovered so far -

- peculiar position



E- relic
LLS ~ 800 kpc
Distance ~ 1.4 Mpc
S = 23 +/- 2 mJy

W- relic
LLS ~ 800 kpc
Distance ~ 1.1 Mpc
S = 17 +/- 1 mJy

MACSJ1149.5+2223, z=0.544

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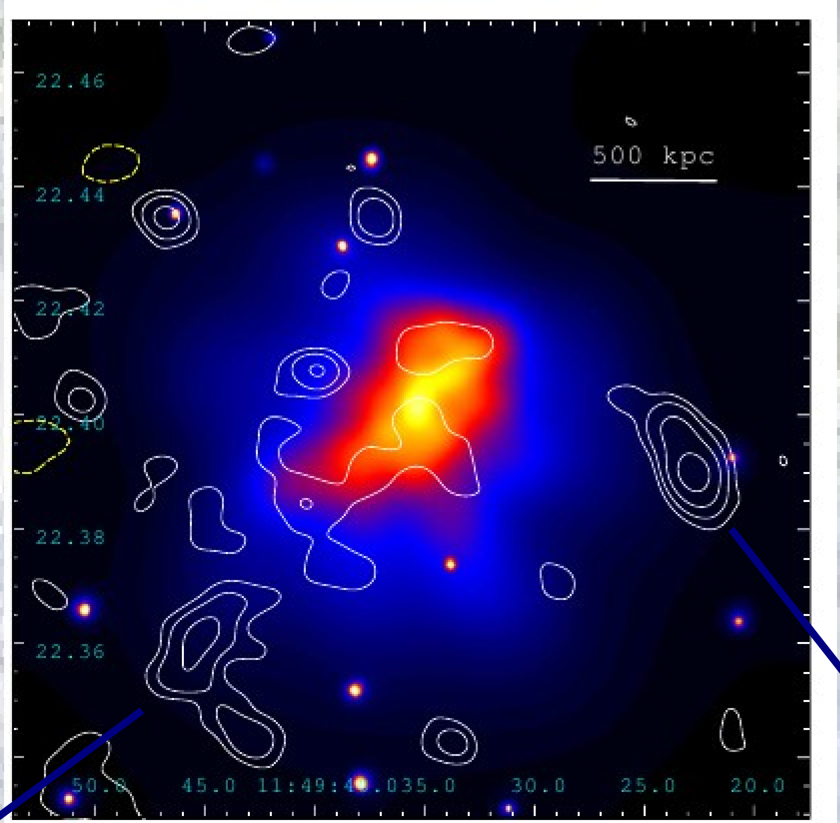

Radio halo (?)

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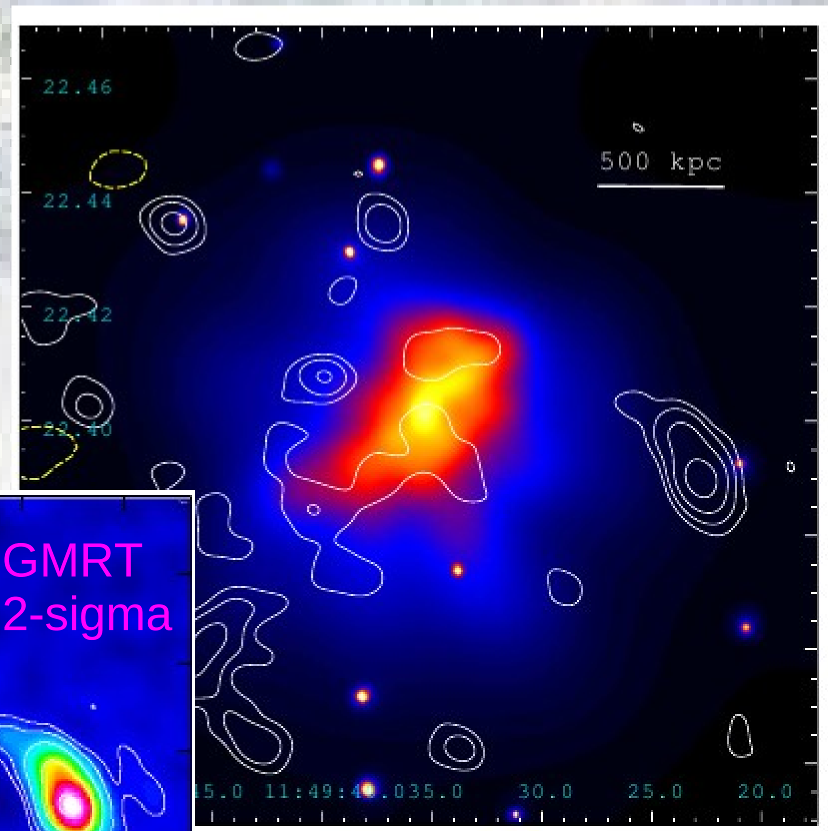
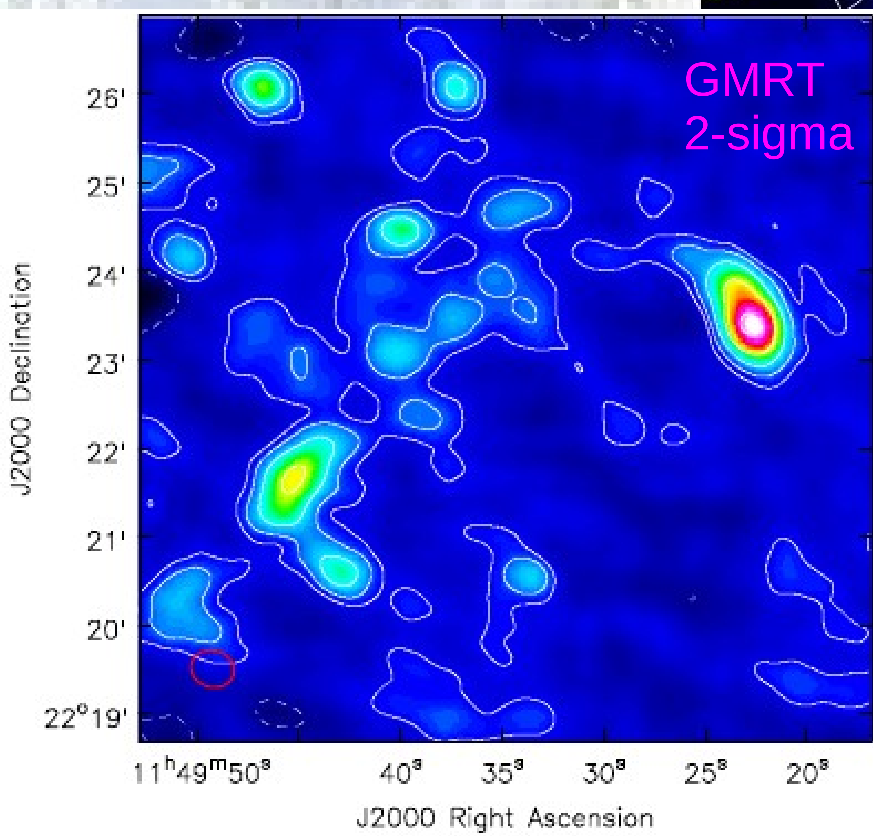
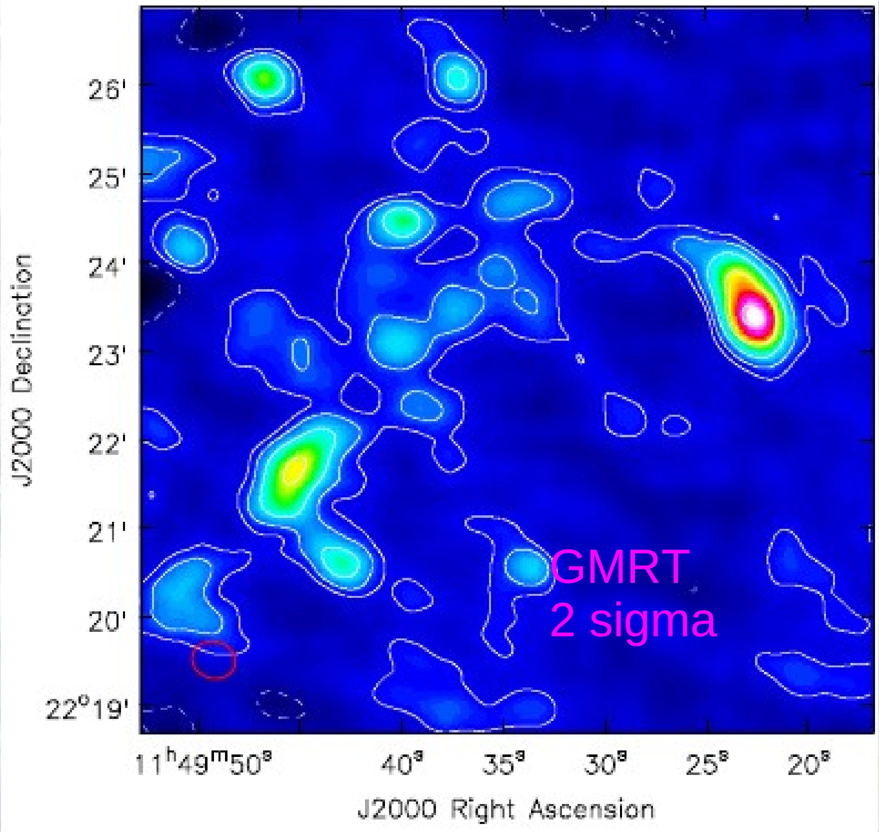


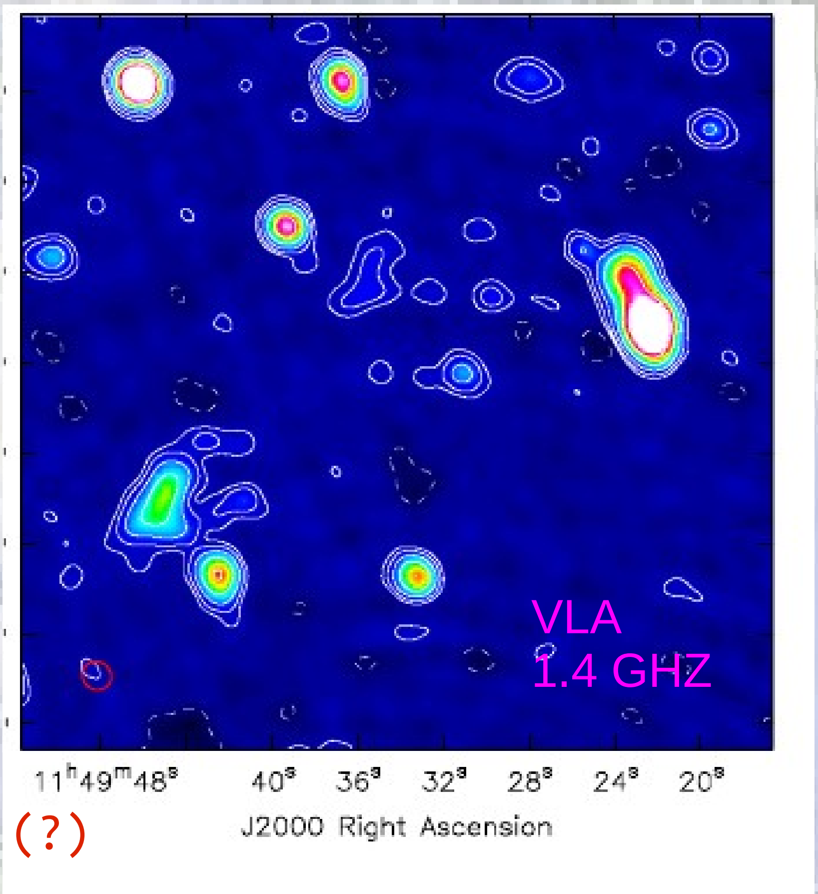
Radio halo (?)

LLS ~ 1.3 Mpc



MACSJ1149.5+2223, z=0.544





Radio halo (?)

LLS ~ 1.3 Mpc

$\alpha \sim 2$

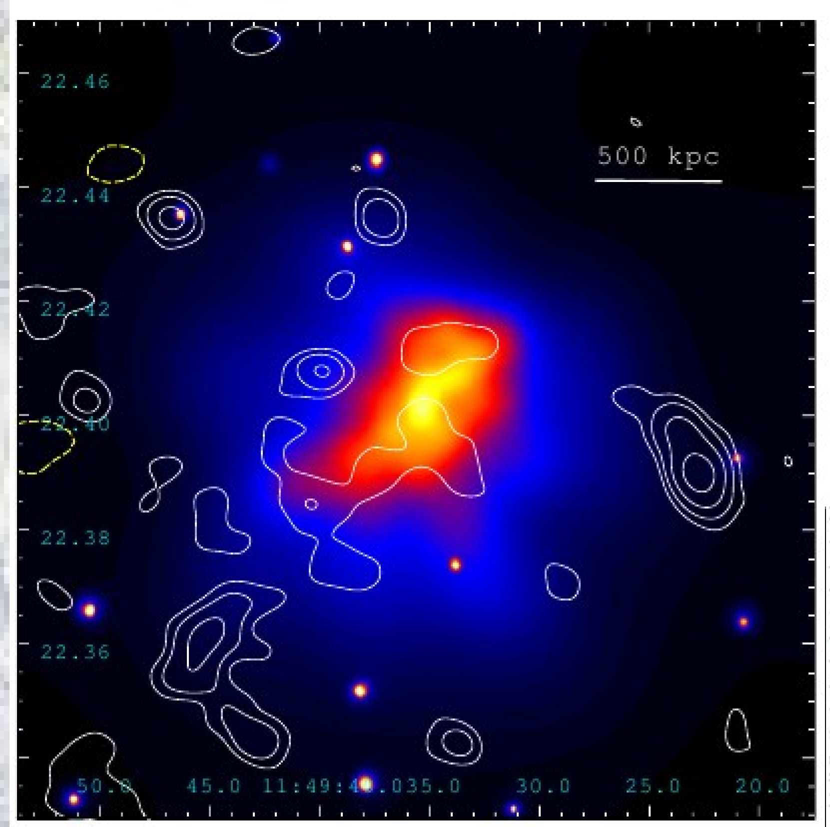
The steepest spectrum observed in halos so far

$\alpha > 1.5$ rules out hadronic models (Brunetti et al. 2008+DallaCasa et al. 2009)

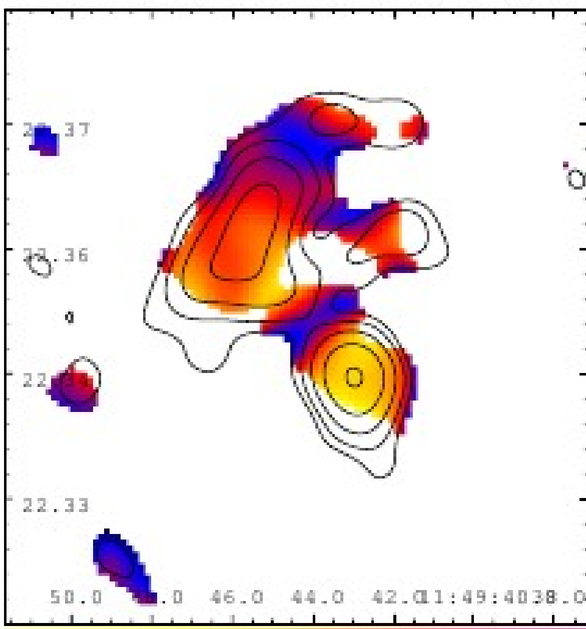
But see Ensslin et al (2010)

MACSJ1149.5+2223, z=0.544

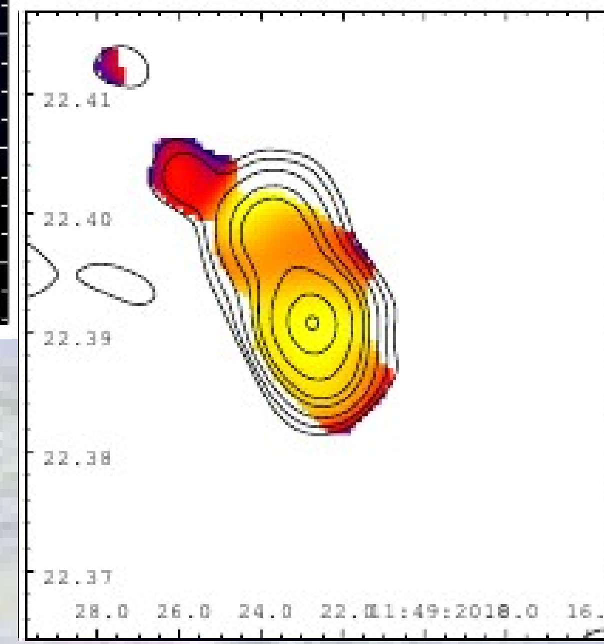
Spectral index maps

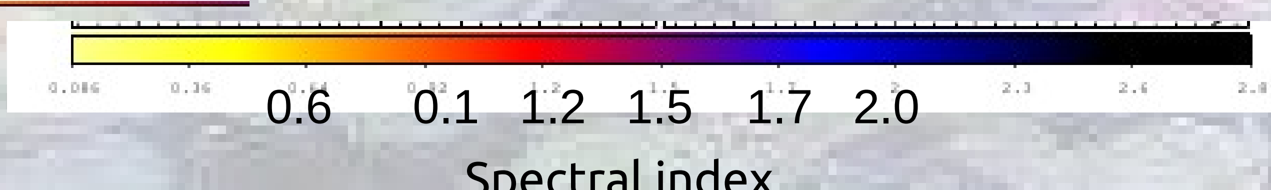


α = 1.15 ± 0.08



α = 0.75 ± 0.08

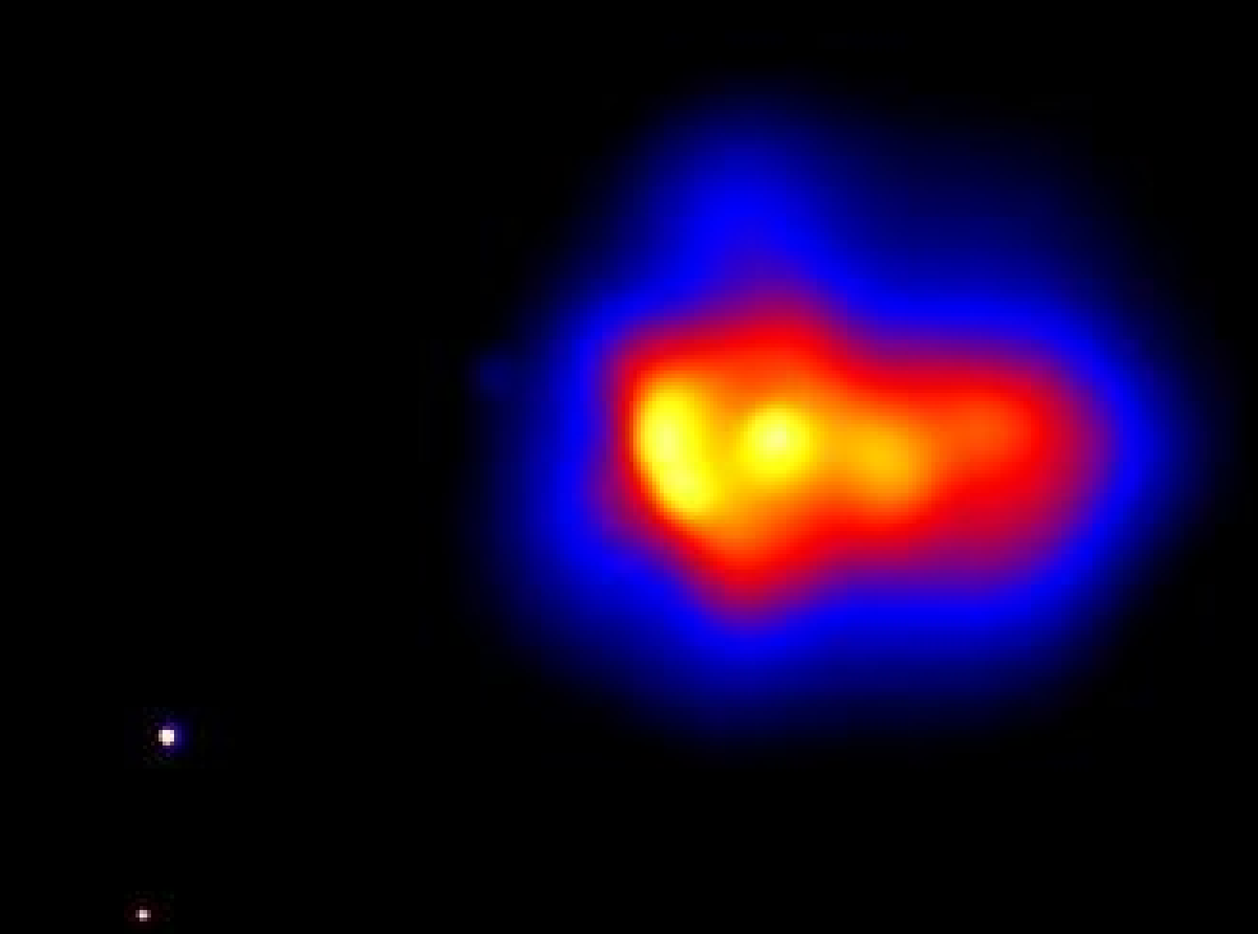




MACSJ0553.4-3342

$L_X = 1.7\ 10^{45}$ erg/s

z=0.431



Mann & Ebeling 2012

MACSJ0553.4−3342

$L_x = 1.7\ 10^{45}$ erg/s

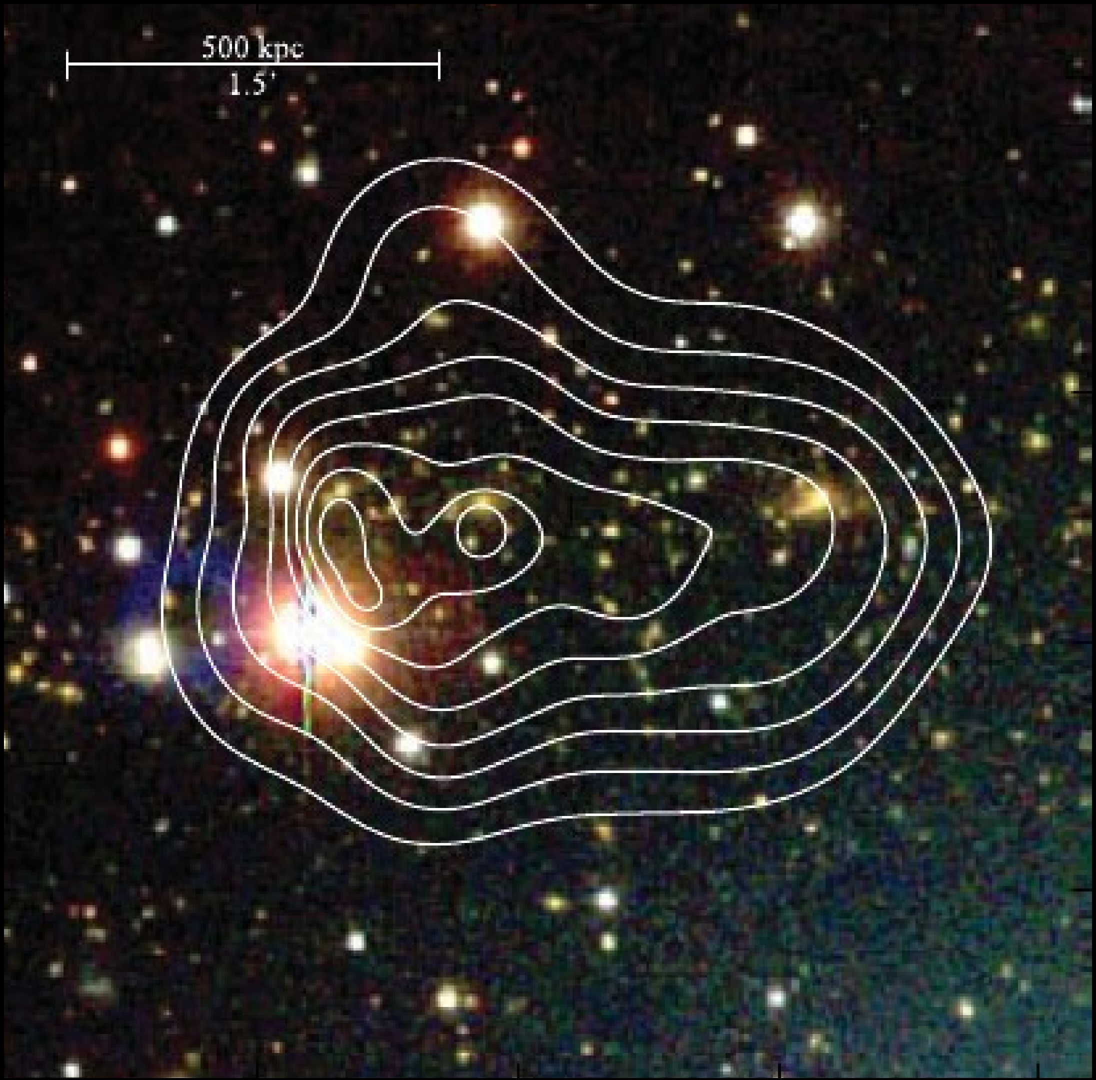
$z = 0.431$

Binary Head-On Merger

Merger in the plane of the sky

Just after the core passage
(distance between the 2 gas cores
~ 200 kpc)

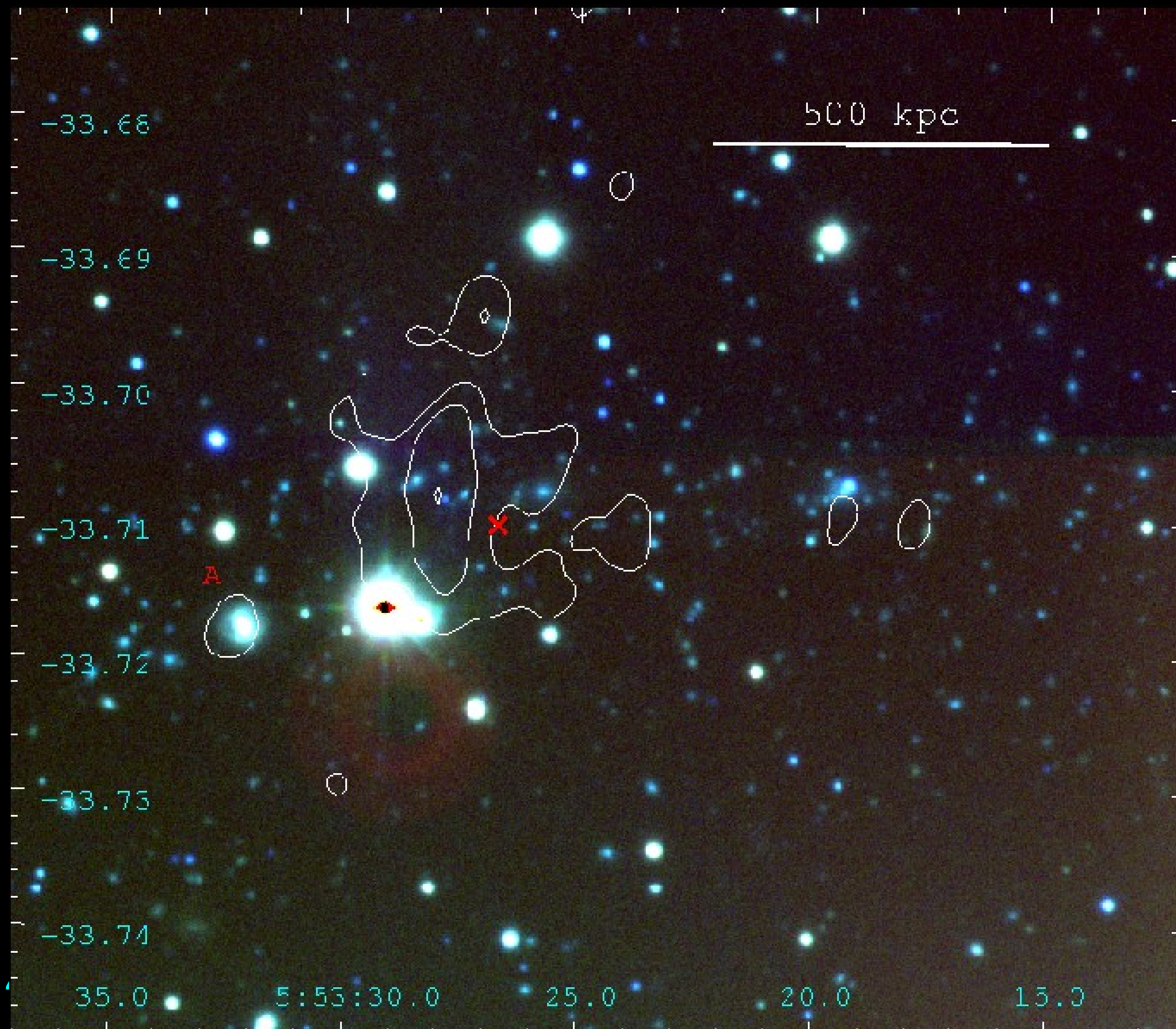
Mann & Ebeling 2012



SDSS colors + Chandra contours

MACSJ0553.4−3342, z=0.431

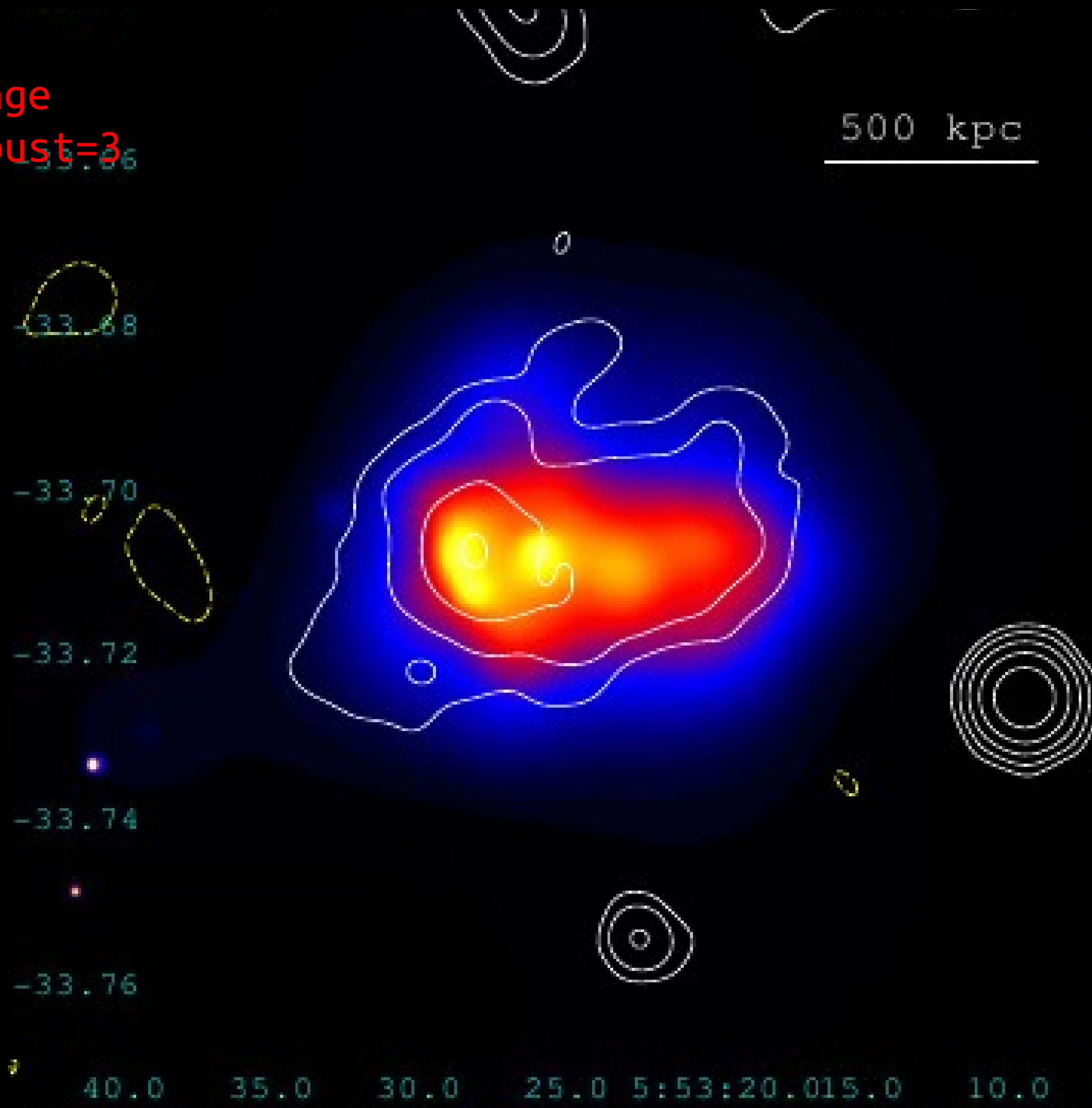
High resolution Image
(Briggs scheme, Robust=0)



Contours: 323 MHz
rms 0.15 mJy/beam Beam ~ 1
Colors: UH2m

MACSJ0553.4−3342, z=0.431

Low resolution Image
Briggs scheme, Robust=3
+ uvtaper



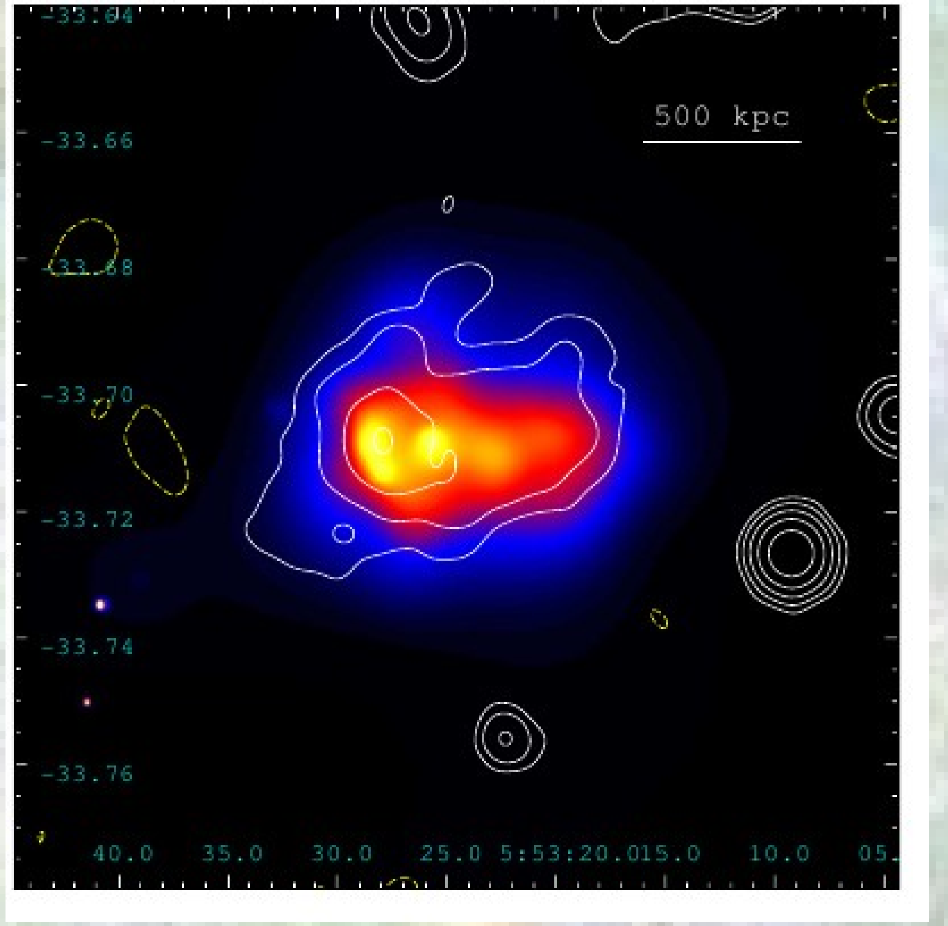
Contours: 323 MHz
rms 0.25 mJy/beam
Beam ~ 23” x 21”
Colors: Chandra (Mann & Ebeling 2012)

MACSJ0553.4−3342, z=0.431

Radio halo detected!

LLS ~ 1.3 Mpc

S = 62 +/- 5 mJy



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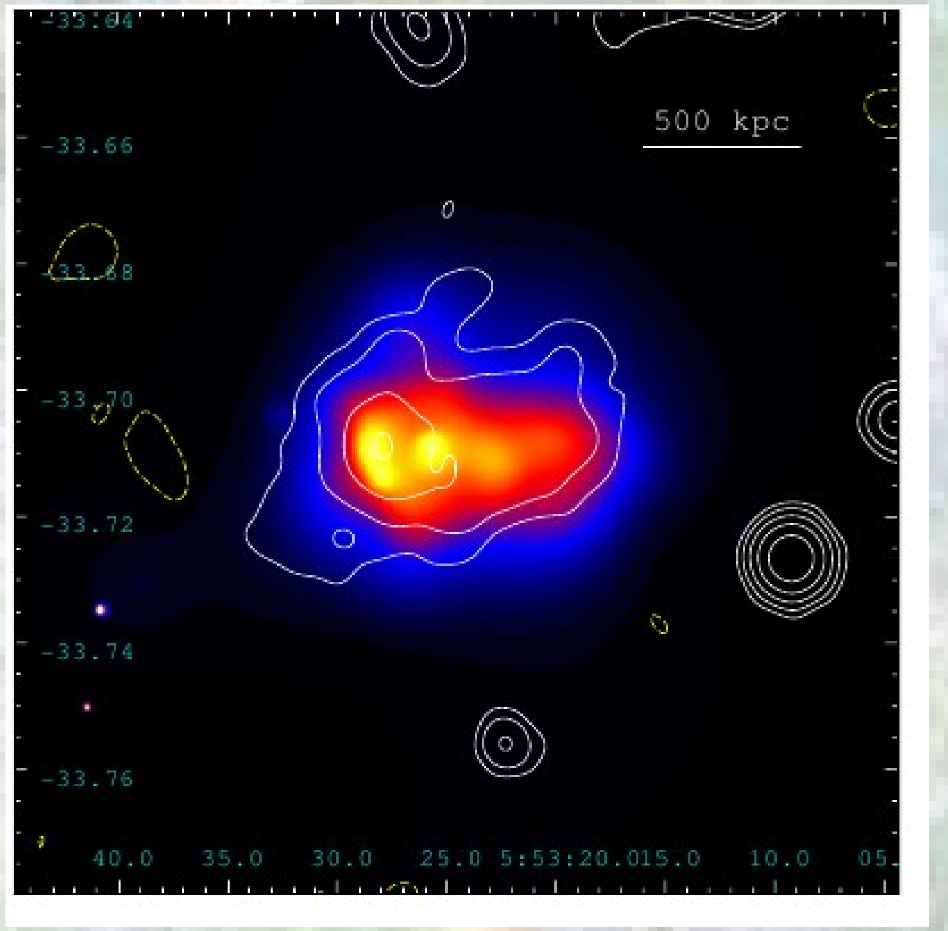

Time-scale for particle (re)acceleration

Merger in the plane of the sky
Distance between the 2 cores: 200 kpc

M ~ 10^15 M_sol

Collision ~ 0.08 Gyr ago

t_cross (= cascade time for turbuent eddies; Cassano & Brunetti 05)~ 0.5 Gyr

Turbulent re-accelartion scenarios: → Turbulence starts to develope well in time before the core passage

MACSJ0553.4−3342, z=0.431

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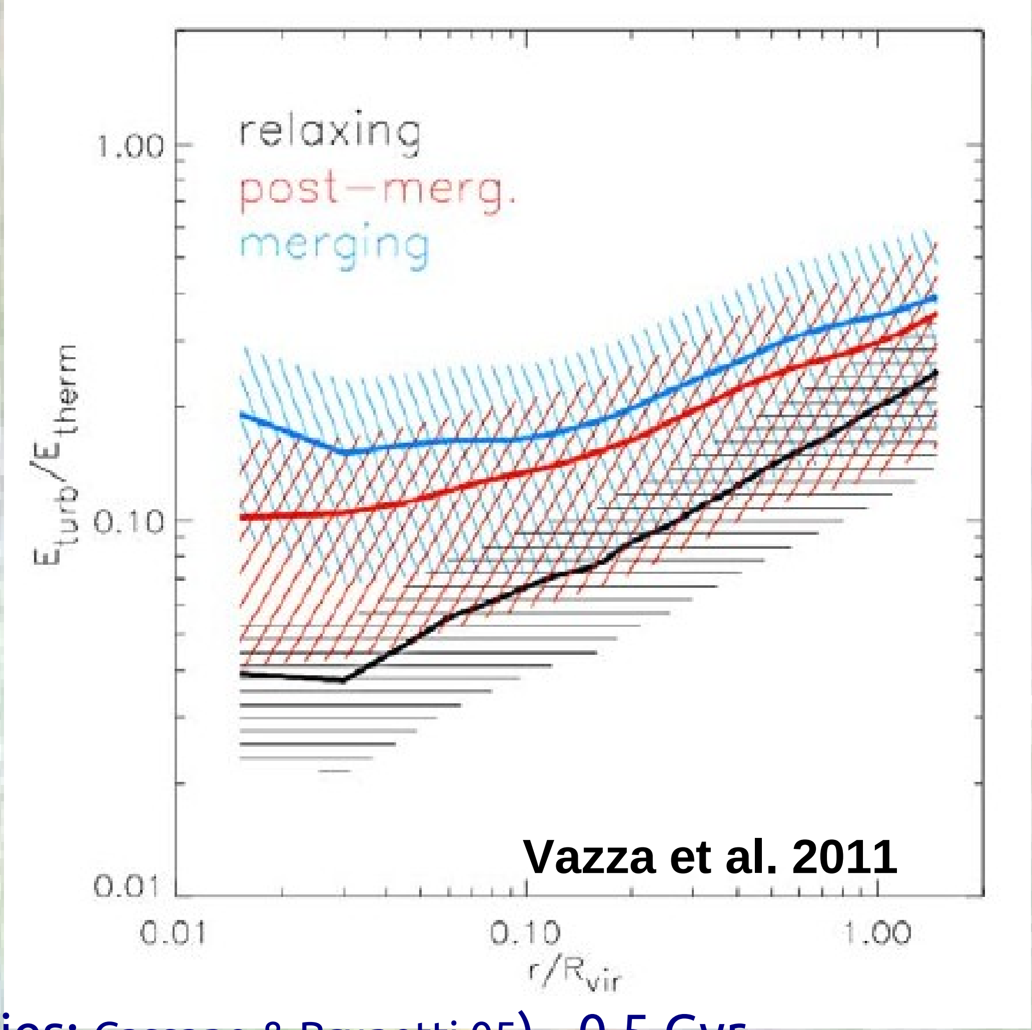
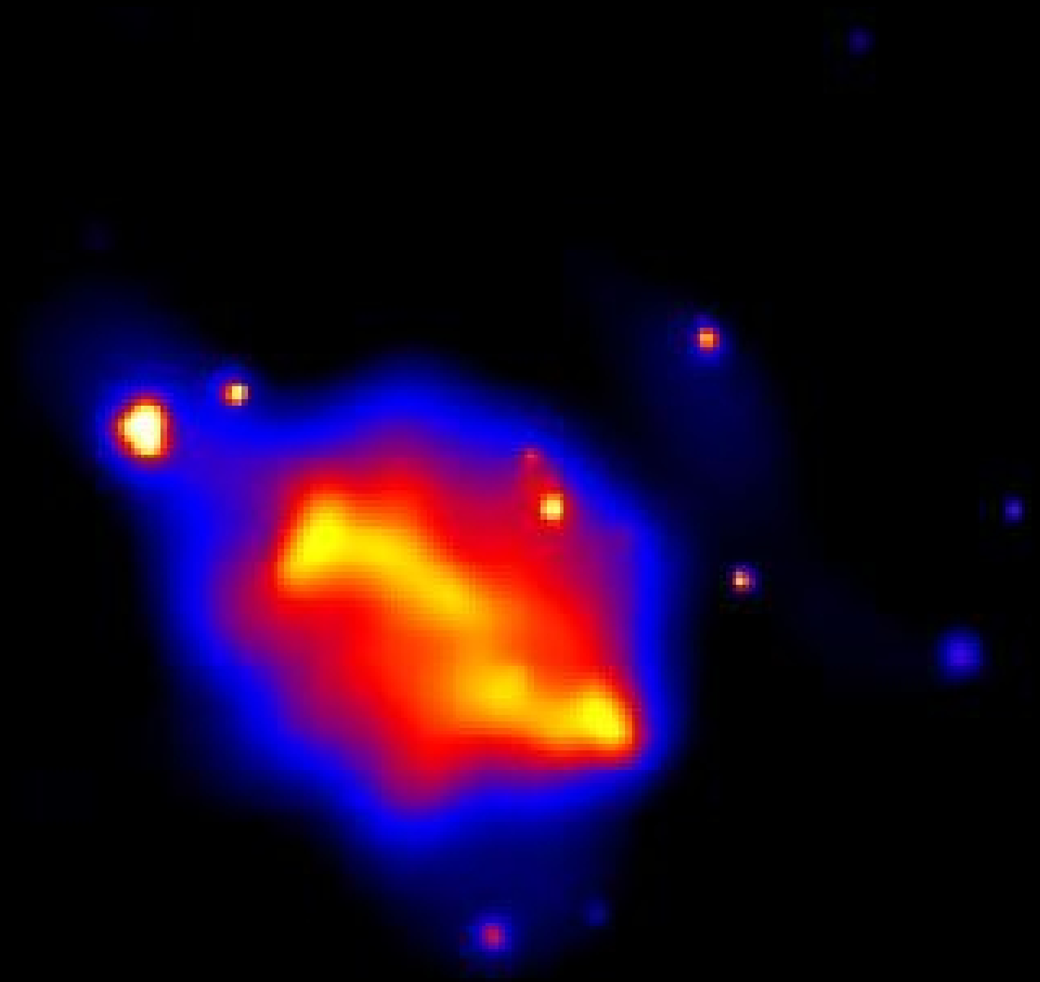


Turbulent re-accelartion scenarios: → Turbulence starts to develope well in time before the core passage

MACSJ1752.0+4440

$L_X = 8.2\ 10^{44}$ erg/s

$z = 0.366$

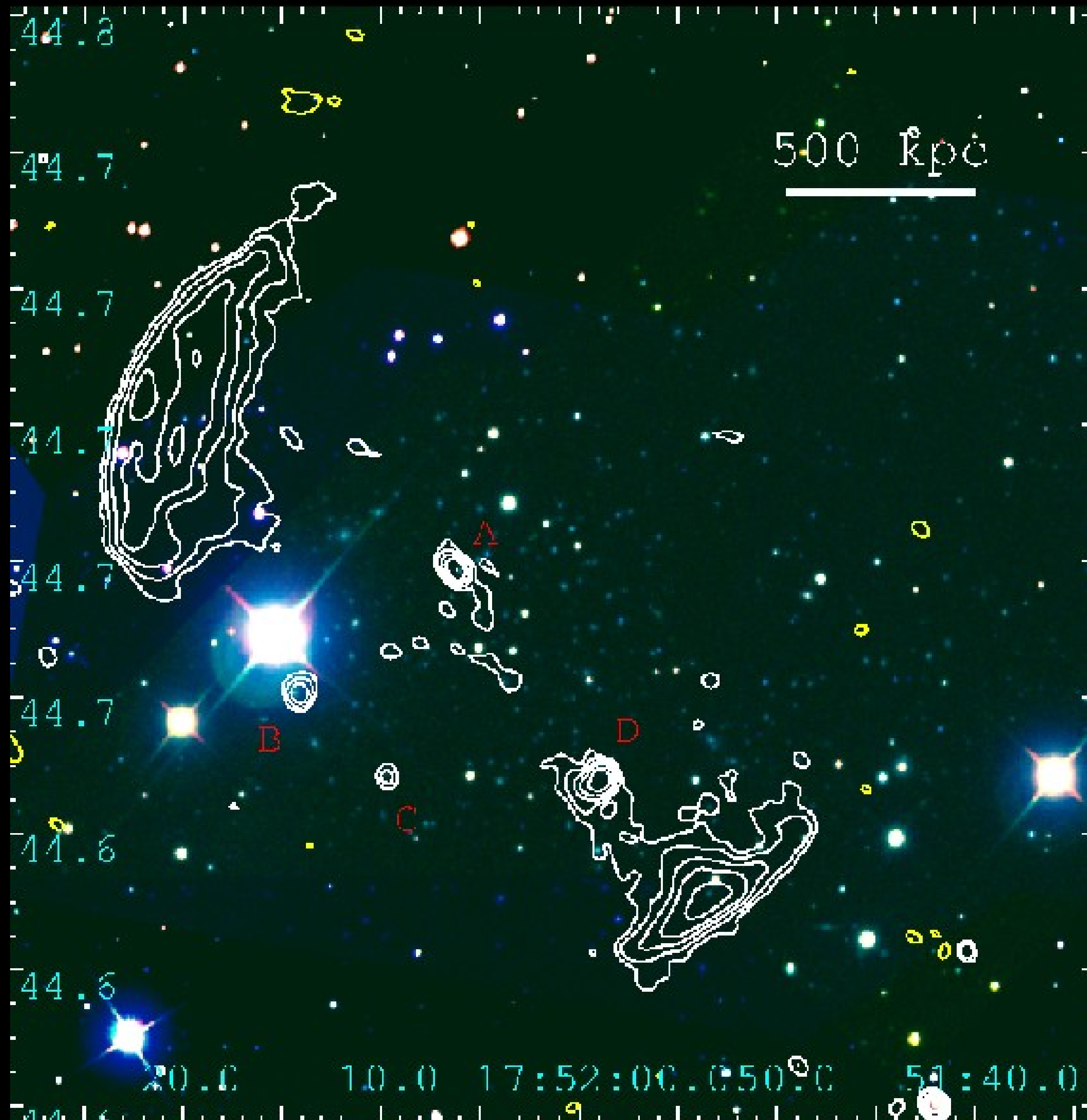


XMM-Newton image

Ebeling et al. (in prep)

MACSJ1752.0+4440, z=0.336

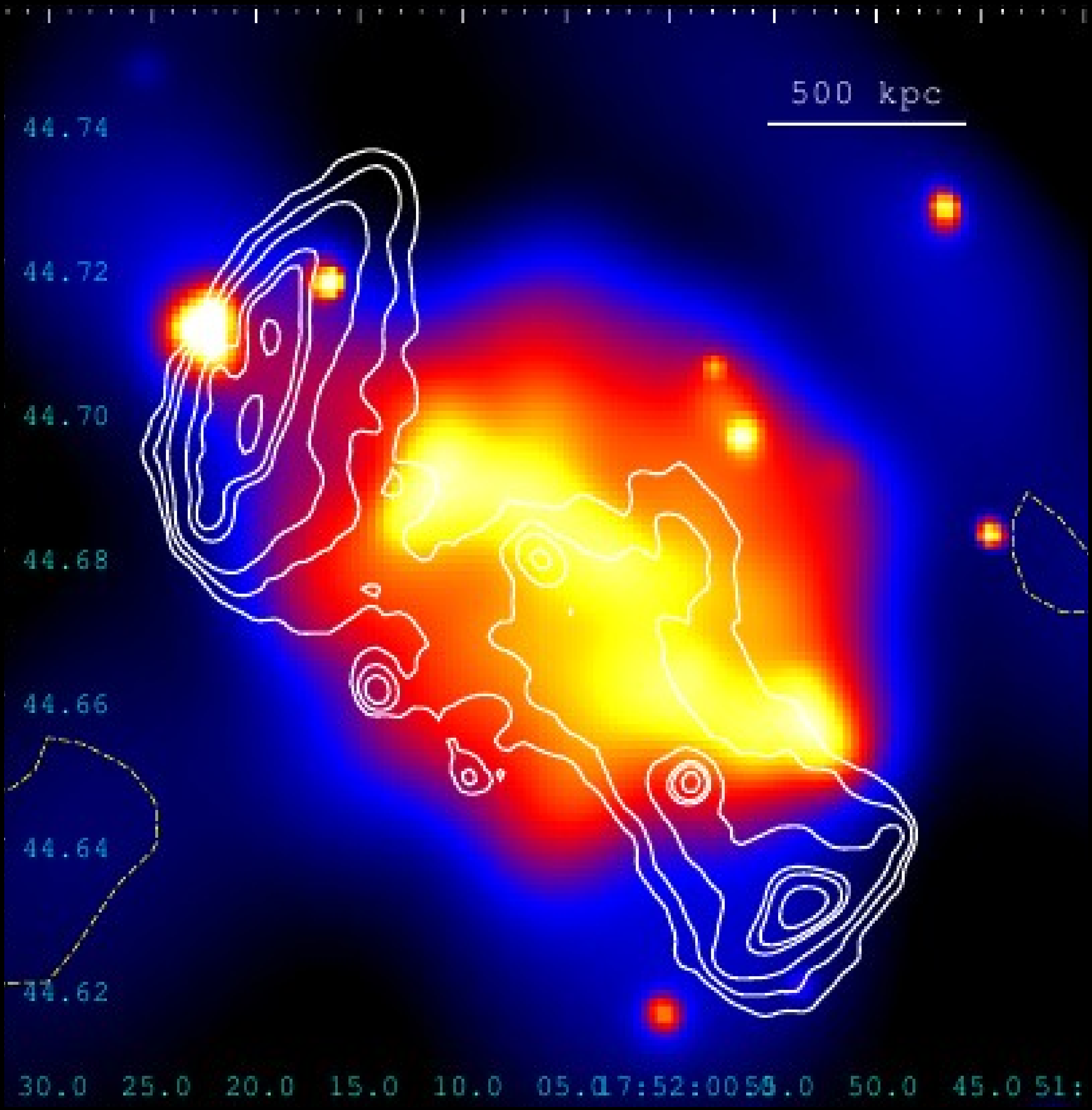
High resolution Image
(Briggs scheme, Robust=0)



Contours: 323 MHz
rms 0.2 mJy/beam
Beam ~ 9.9” x 8”
Colors: SDSS

MACSJ1752.0+4440, z=0.336

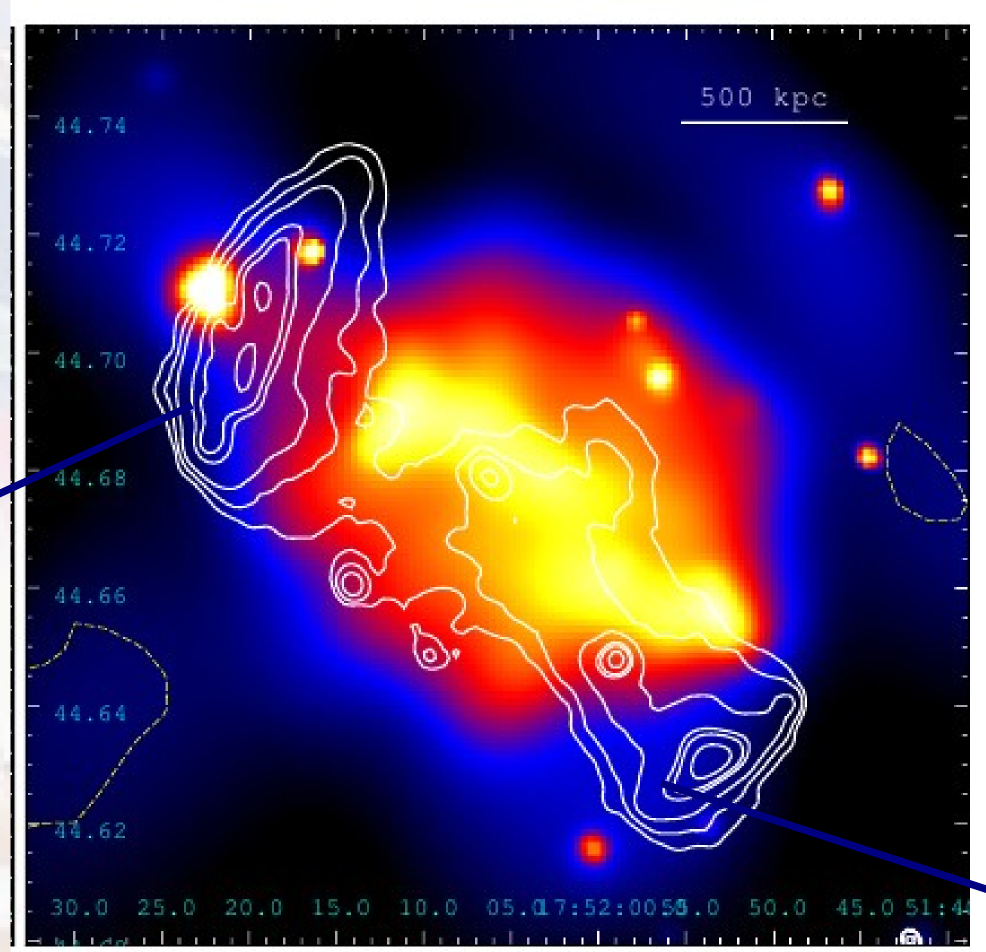
Low resolution Image
(Briggs scheme 3)



Contours: 323 MHz
rms 0.5 mJy/beam
Beam ~ 14" x 10"
Colors: XMM-Newtona (Ebeling et al. In prep)

MACSJ1752.0+4440, z=0.366

Double relics

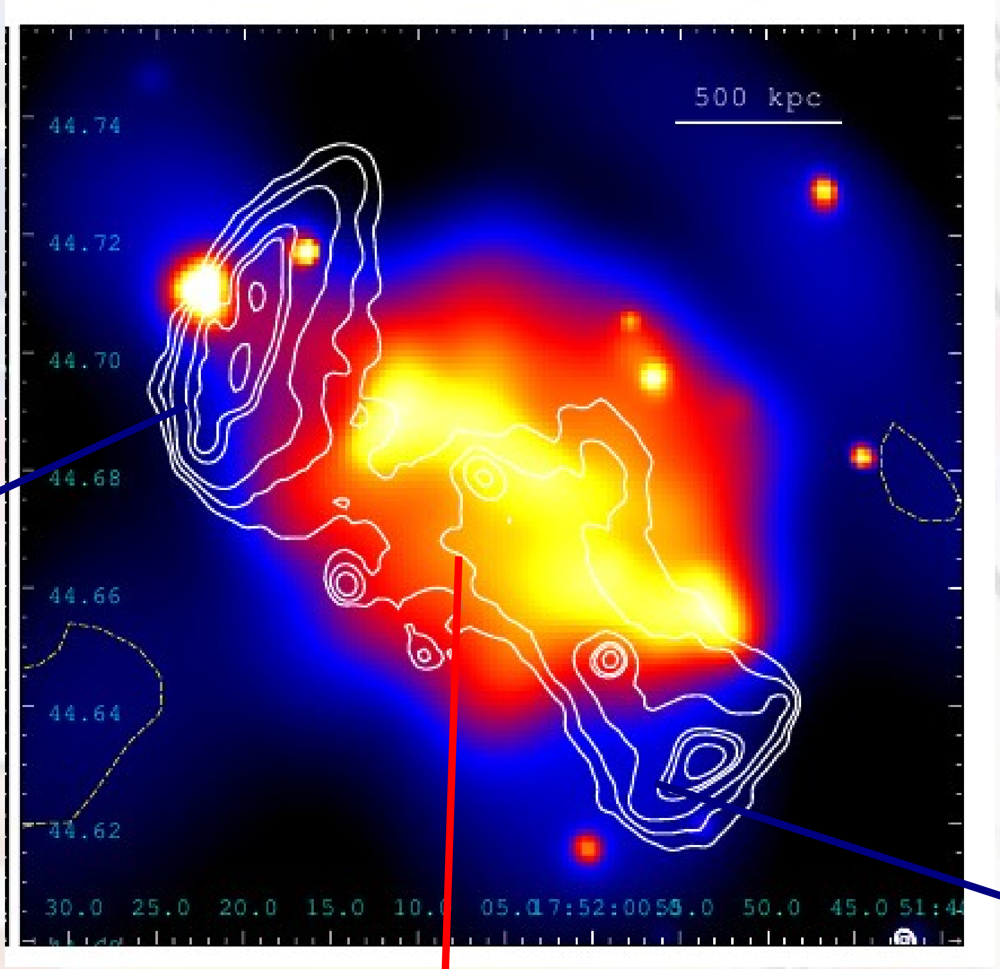


E- relic
LLS ~ 1130 kpc
Distance ~ 1.3 Mpc
S = 410 +/- 33 mJy

W- relic
LLS ~ 910 kpc
Distance ~ 0.8 Mpc
S = 166 +/- 16 mJy

MACSJ1752.0+4440, z=0.366

Double relics



Radio Halo

E- relic
LLS ~ 1130 kpc
Distance ~ 1.3 Mpc
S = 410 +/- 33 mJy

Radio halo
LLS ~ 1650 kpc

S = 164 +/- 16 mJy

W- relic
LLS ~ 910 kpc
Distance ~ 0.8 Mpc
S = 166 +/- 16 mJy

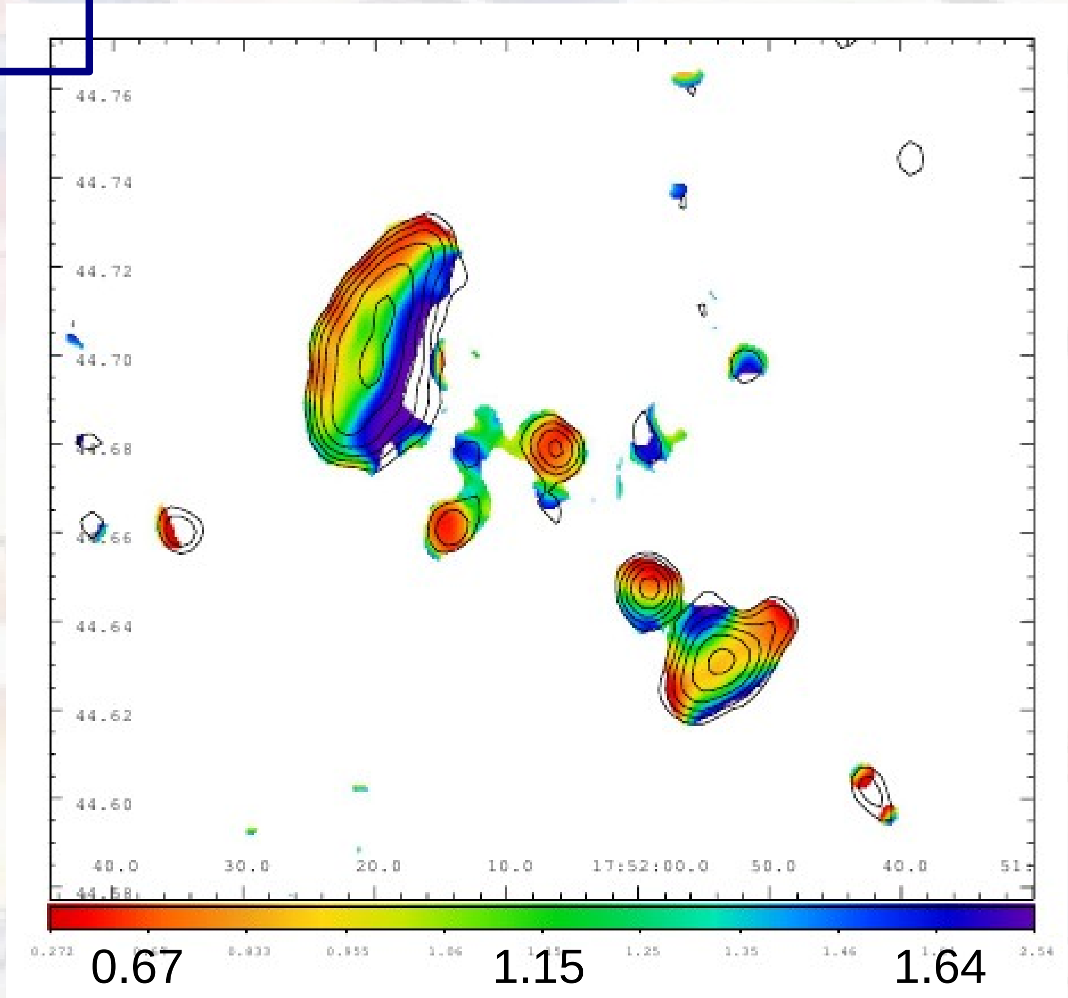
MACSJ1752.0+4440, z=0.366

GMRT + WSRT observations @ 1.7 GHz (van Weeren, Bonafede, Ebeling et al, in press)

Spectral index map

Relic E

$\alpha = 1.21 \pm 0.06$



W relic

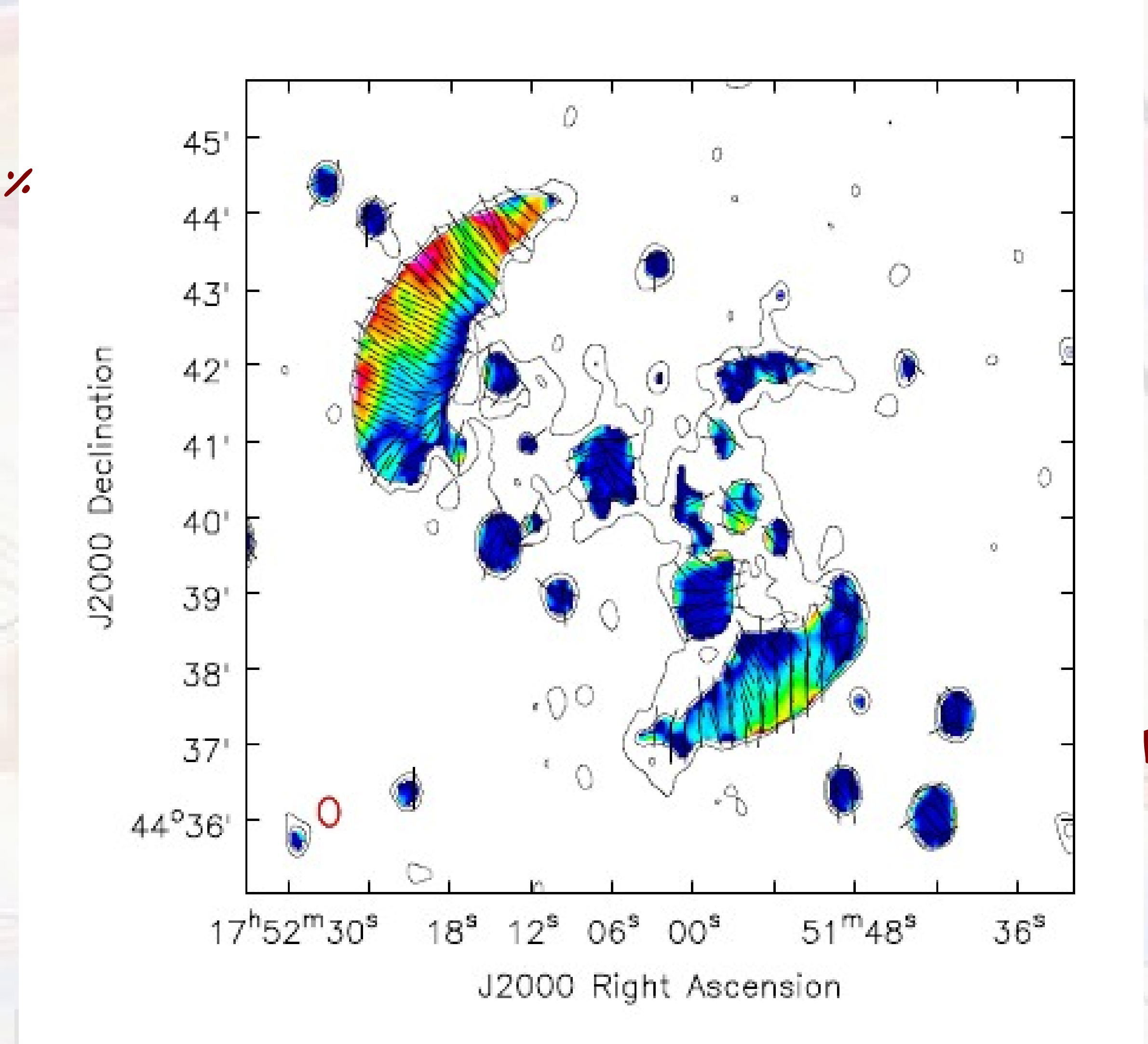
$\alpha = 1.12 \pm 0.07$

Spectral steepening toward the cluster centre → particle aging

MACSJ1752.0+4440, z=0.366

Polarization properties

F pol ~ 20 %



1.7 GHz Image from WSRT

Contours: I pol 3-sigma

Colors: Fractional polarization

F pol ~ 10 %

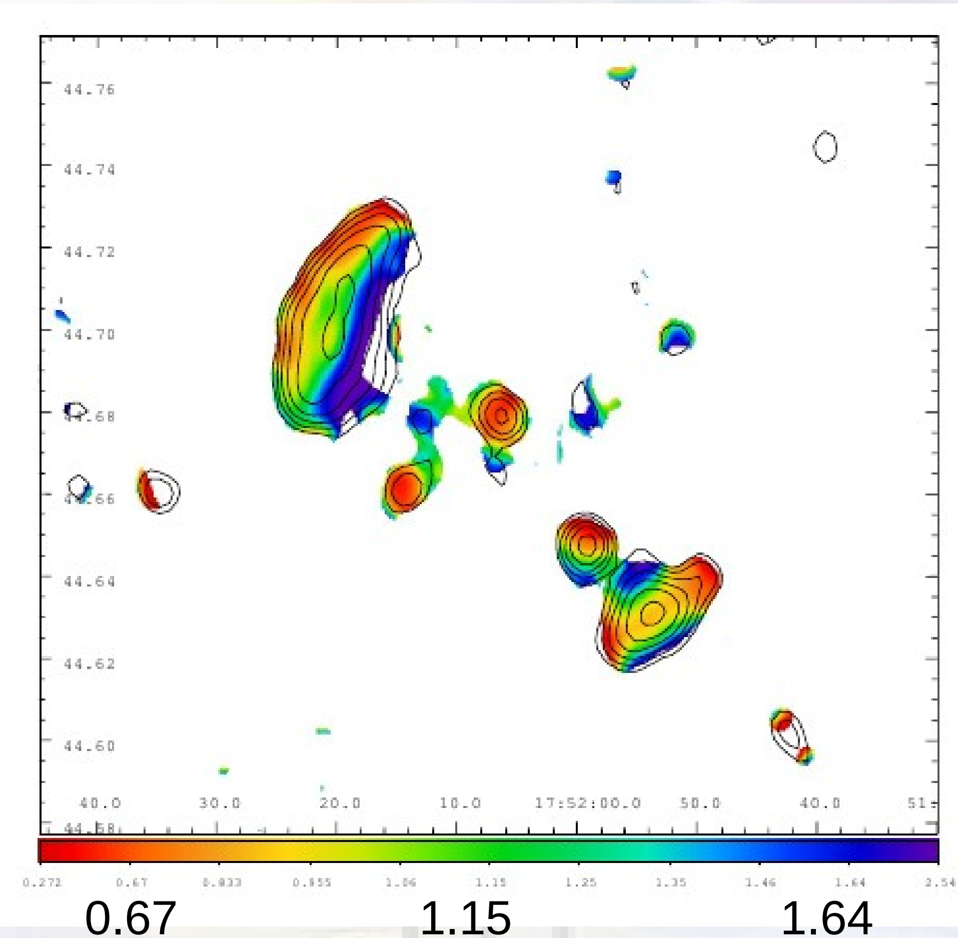
Magnetic field aligned with the relics' main axes

Mach numbers from radio spectral index

DSA regime

$$\alpha_l = -\frac{1}{2} + \frac{M^2+1}{M^2-1}$$

Blandford & Eichler 87



W relic: M ~ 3.3

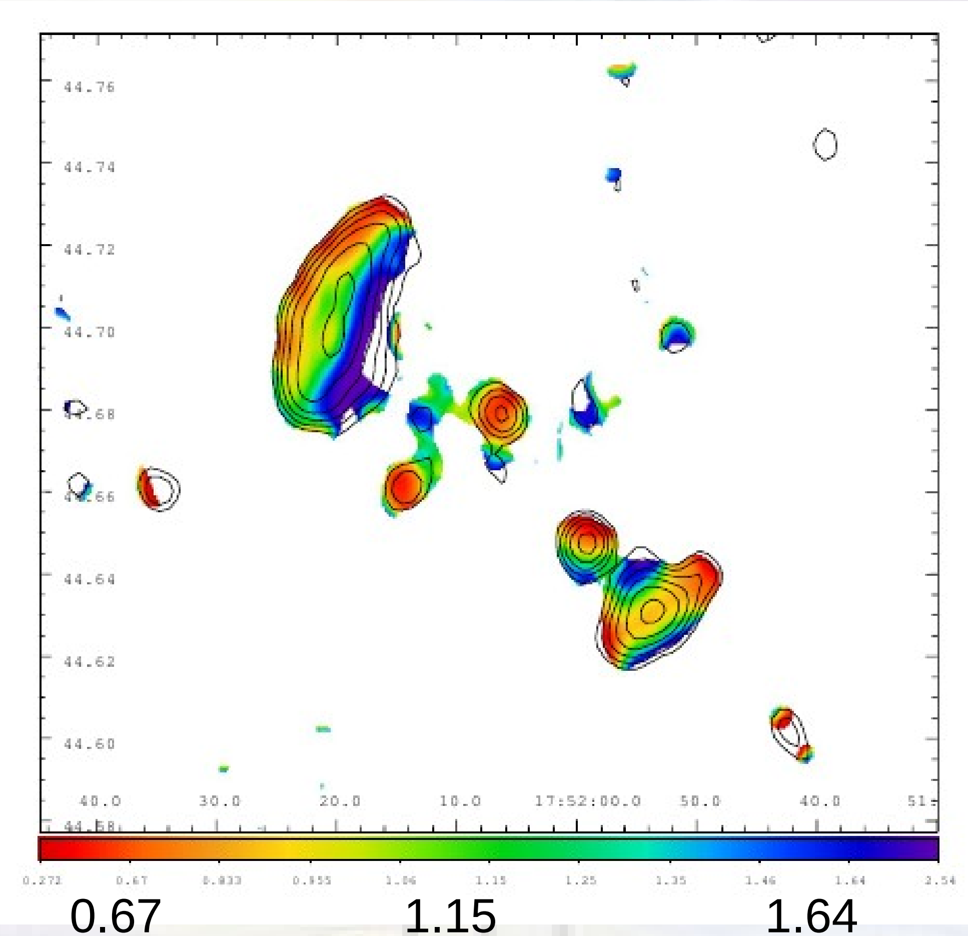
E relic: M ~ 4.6

Mach numbers from radio spectral index

DSA regime

$$\alpha_i = -\frac{1}{2} + \frac{M^2+1}{M^2-1}$$

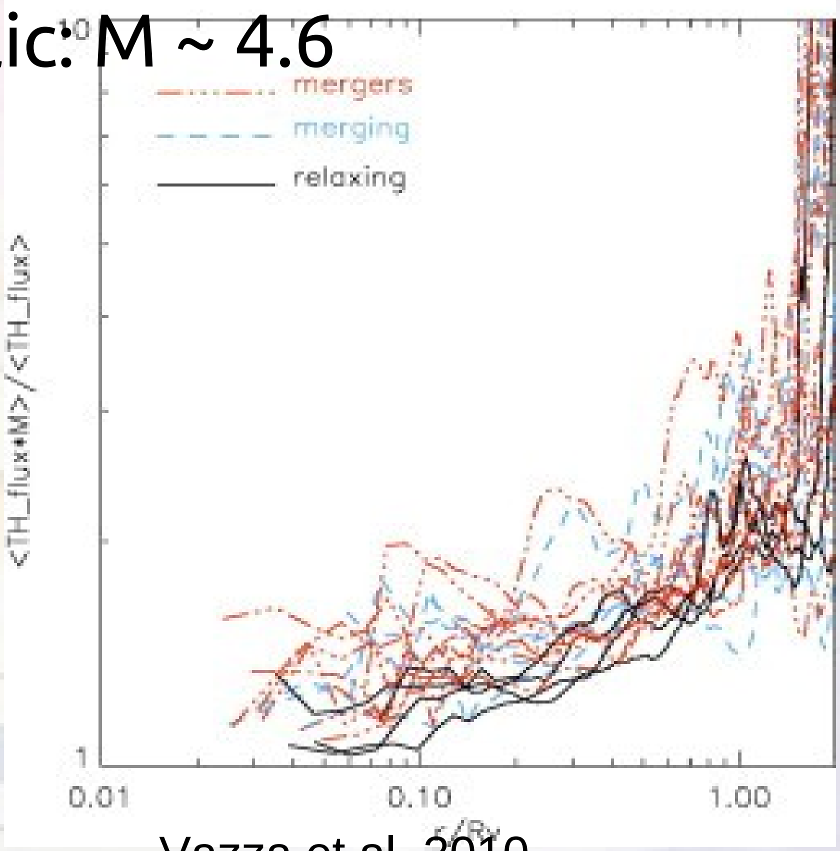
Blandford & Eichler 87



E relic: M ~ 3.3

W relic: M ~ 4.6

Rare Events!



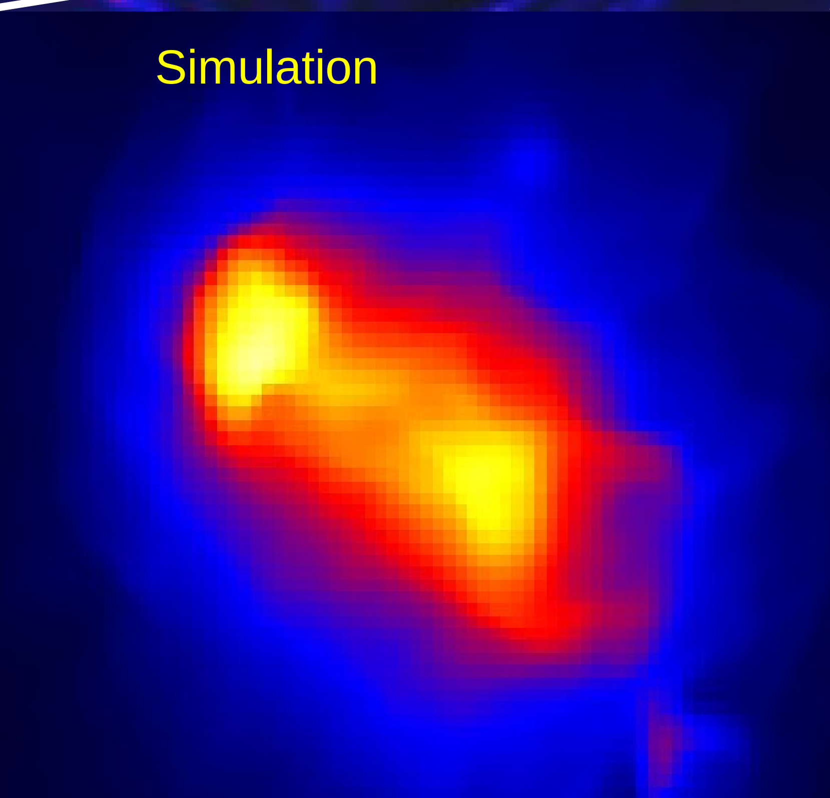
Vazza et al. 2010

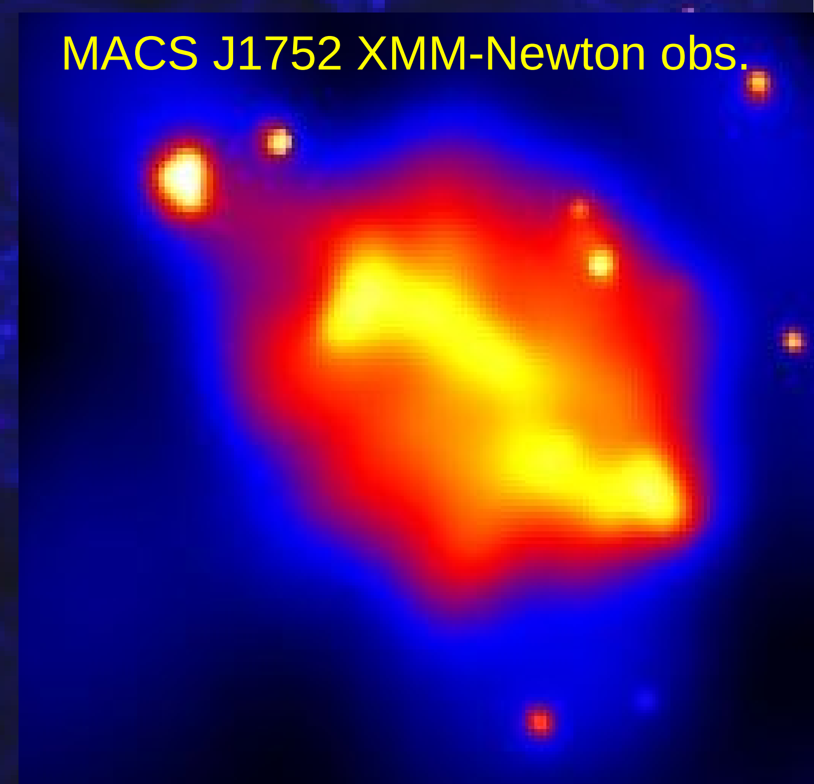
Rare Events...   but they exist:

Sample of high resolution cosmological simulations with ENZO (Vazza et al. 2010,2011)

X-ray maps from simulations

1 case of morphological similarity (shock with M ~ 5)





Sample of high resolution cosmological simulations with ENZO (Vazza et al. 2010,2011)

Measure of shock strength and turbulent motions
(recipies in Vazza et al 2009, 2012)
→ convert to radio emission

projected map of energy flux

$$\Phi_{\rm shock} = \int \rho v_{\rm s}^3 dx^2/2$$

$$\Phi_{\rm turb} = \int \rho \sigma_{\rm t}^3 dx^3/(2 \cdot l_{\rm t})$$

A fraction of the energy is converted into radio emission:

$$P_{\rm relic} \sim A_{\rm s} \Phi_{\rm shock}$$

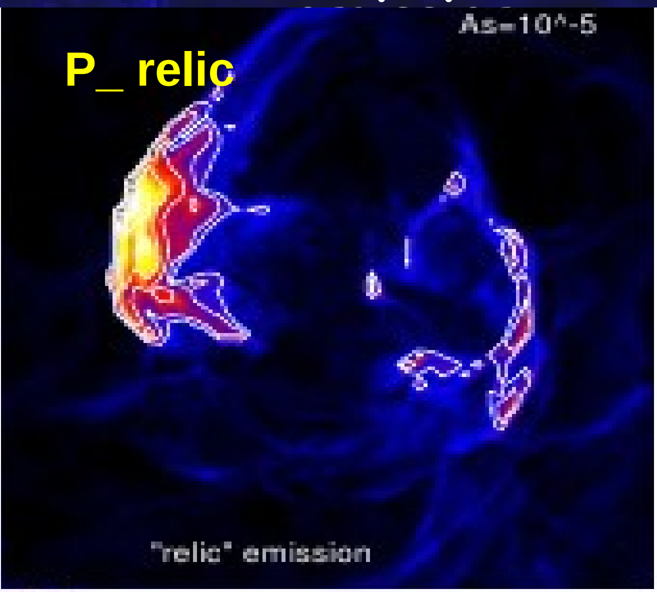
$$P_{\rm halo} \sim A_{\rm t} \Phi_{\rm turb}$$

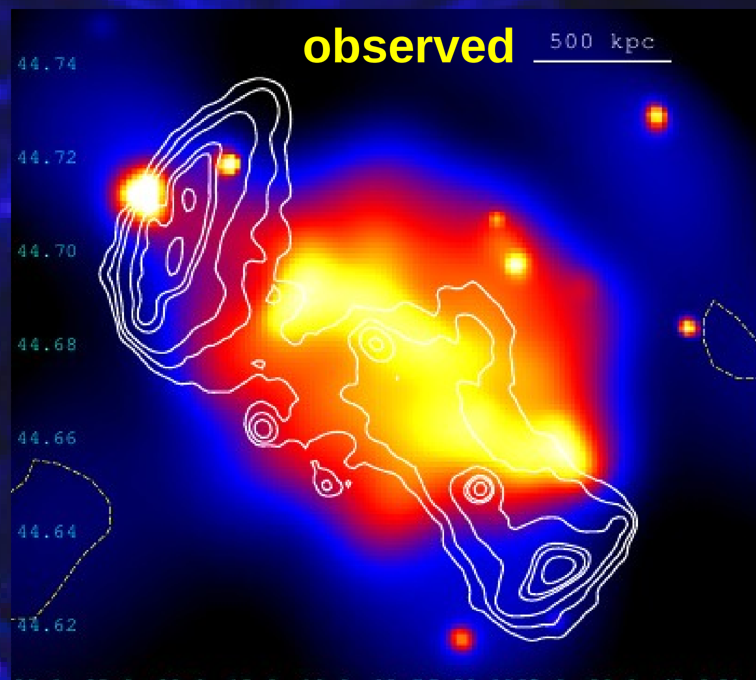
At and As tuned to reproduce the observed emission

$$P_{\mathrm{relic}} \sim A_s \Phi_{\mathrm{shock}}$$

$$P_{\mathrm{halo}} \sim A_t \Phi_{\mathrm{turb}}$$

At and As tuned to reproduce the observed





$$A_s \approx 10^{-5}$$

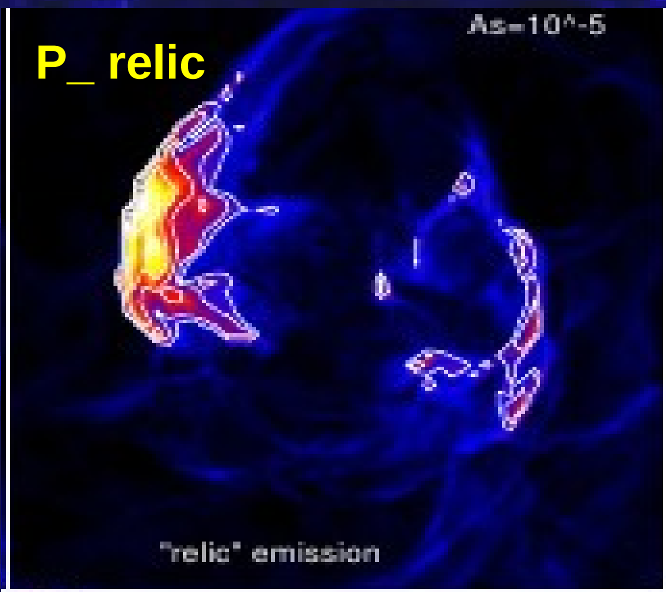
Electron to proton acceleration efficiency
(e.g. Hoeft & Brüggen 2007)

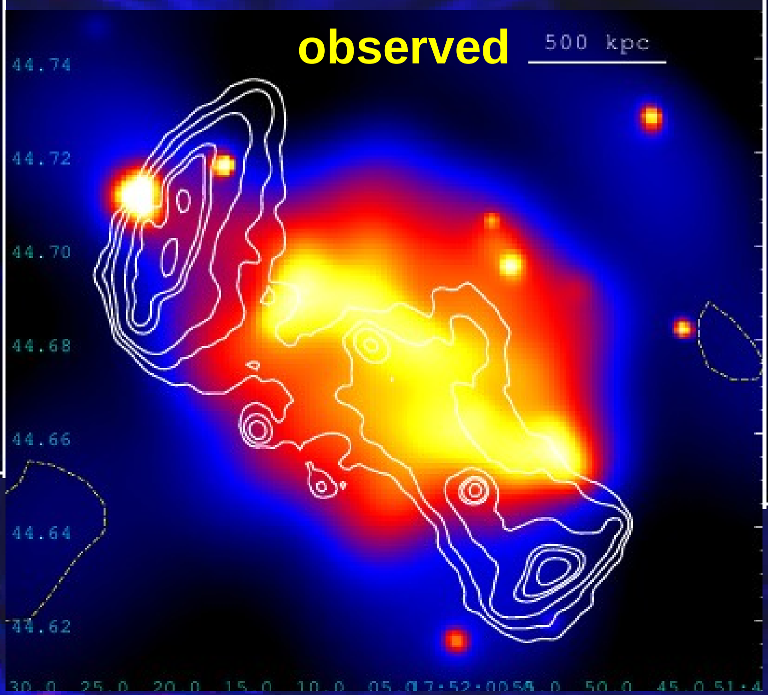
$$R_{e/p} \sim 10^{-3} - 10^{-4}$$

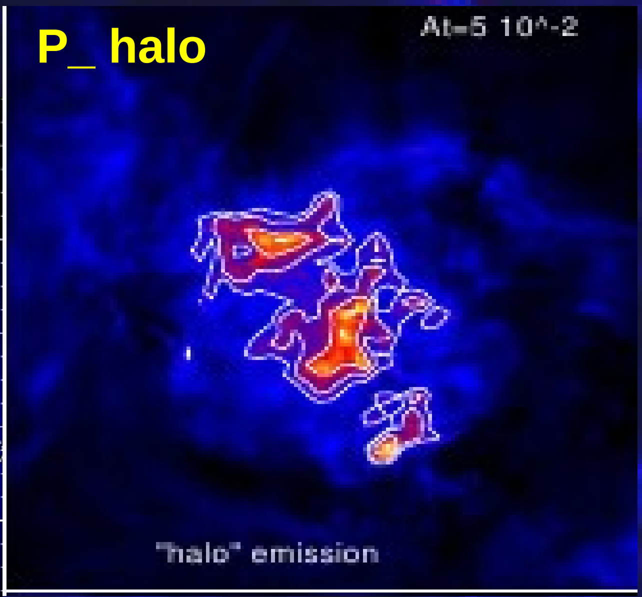
$$P_{\mathrm{relic}} \sim A_s \Phi_{\mathrm{shock}}$$

$$P_{\mathrm{halo}} \sim A_t \Phi_{\mathrm{turb}}$$

At and As tuned to reproduce the observed emission







$$A_s \approx 10^{-5}$$

$$A_t \sim 0.05$$

Electron to proton acceleration efficiency
(e.g. Hoeft & Brüggen 2007)

$$R_{e/p} \sim 10^{-3} - 10^{-4}$$

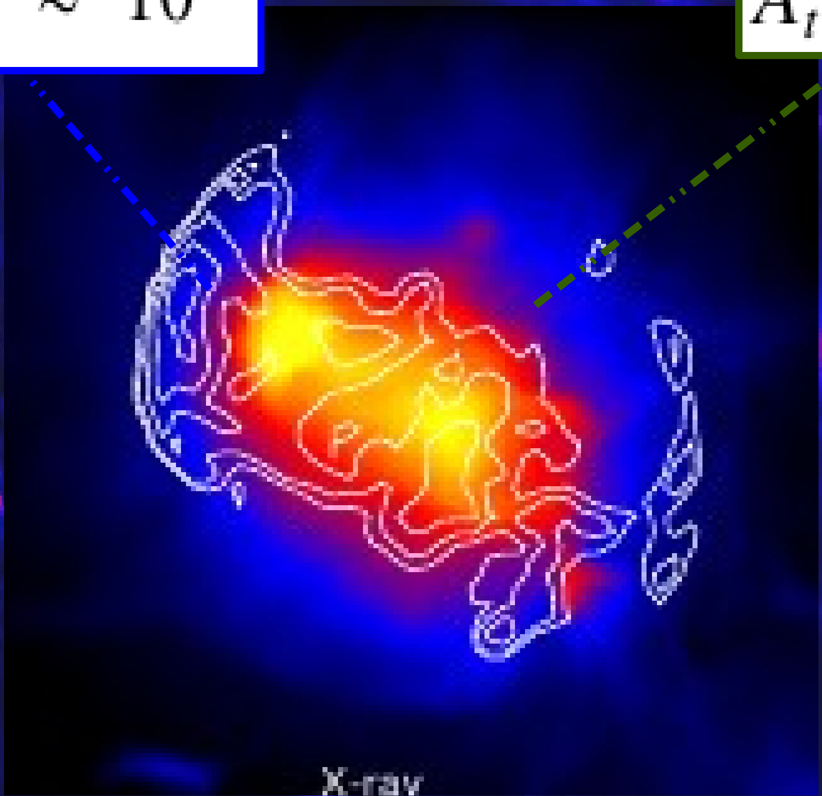
Corresponds to efficiency ~ 1e-4
(e.g. Fujita 2003; Cassano & Brunetti 2005)

$$P_{\text{relic}} \sim A_s \Phi_{\text{shock}}$$

$$A_s \approx 10^{-5}$$

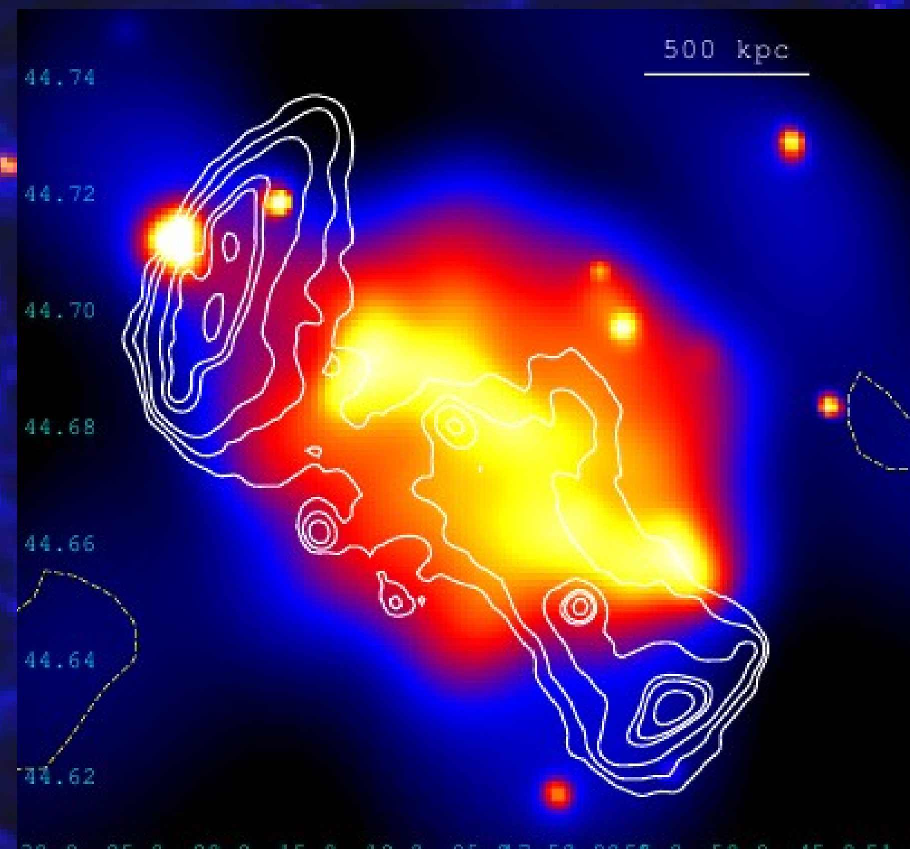
$$P_{\text{halo}} \sim A_t \Phi_{\text{turb}}$$

$$A_t \sim 0.05$$



Simulated

Observed



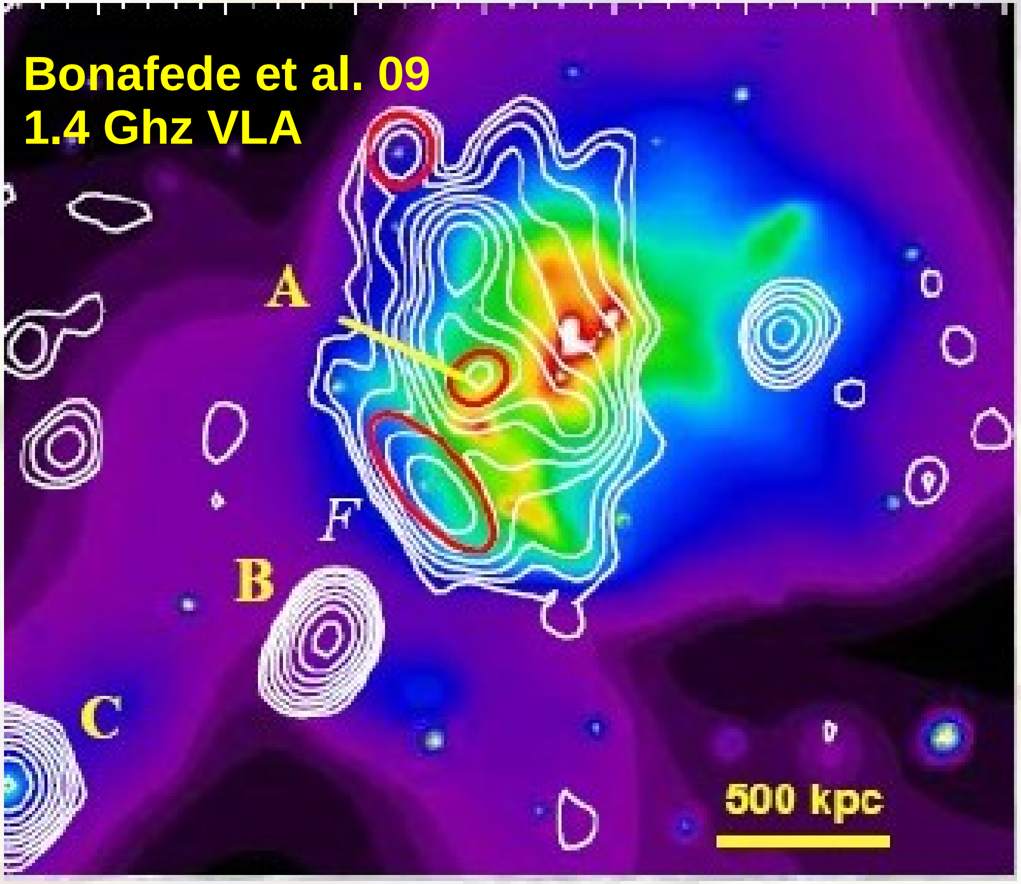
A tiny fraction of the energy injected by shocks and turbulence is required to reproduce the observed radio emission

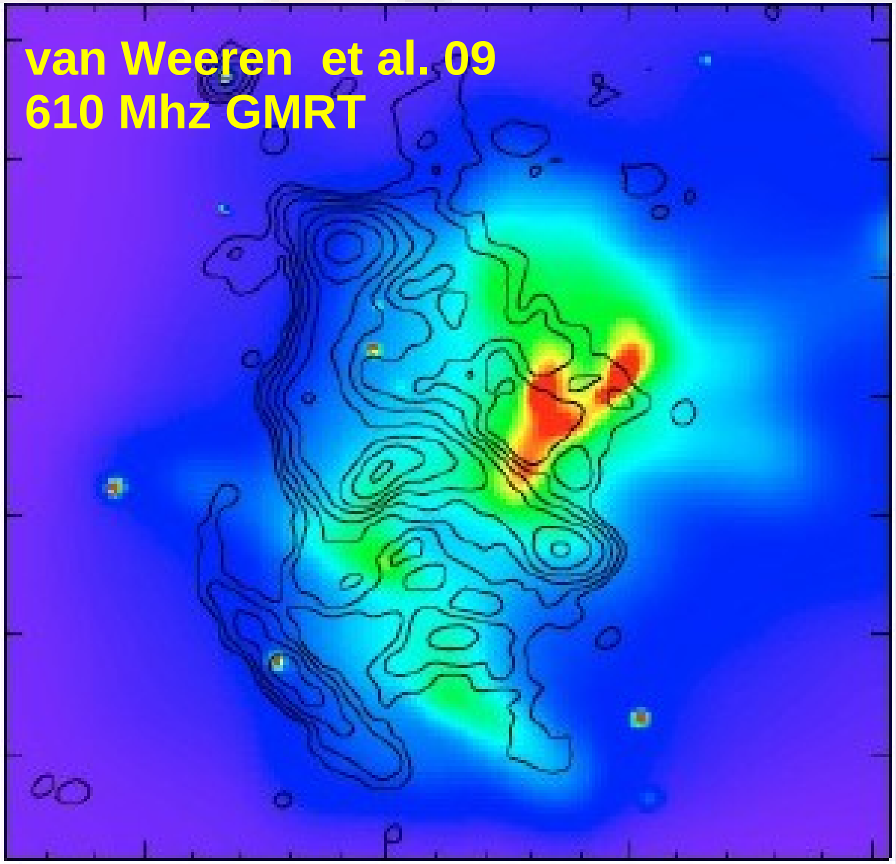
MACSJ0717+3745

z=0.55

Lx[0.1-2.4 keV]=2.74 10^45 erg/s

P [1.4 GHz] ~ 1.6 10^26 W/Hz





The most distant and powerful radio halo

LOFAR observations of MACSJ0717+3745

Observations: 1-2 April 2012
Time: 12 hours
Integration time: 2s

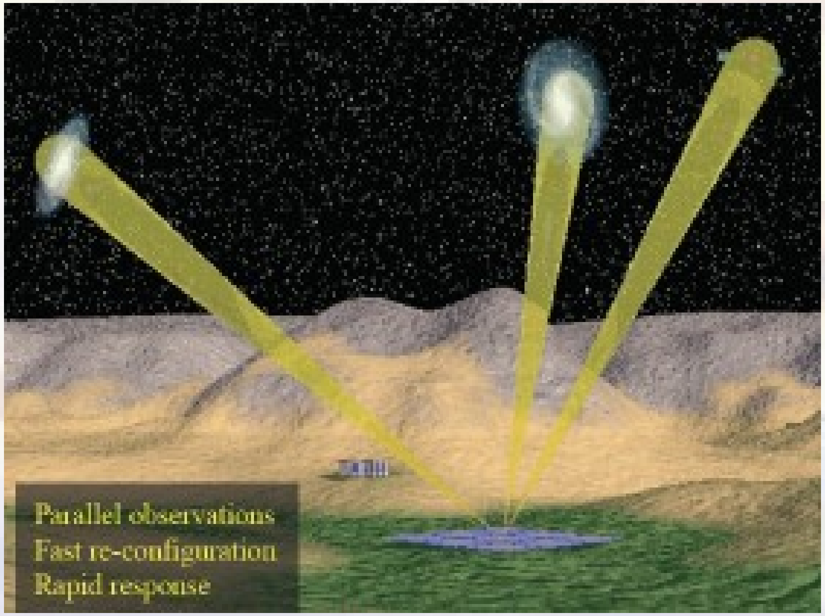
22 Core Stations
9 Remote Stations

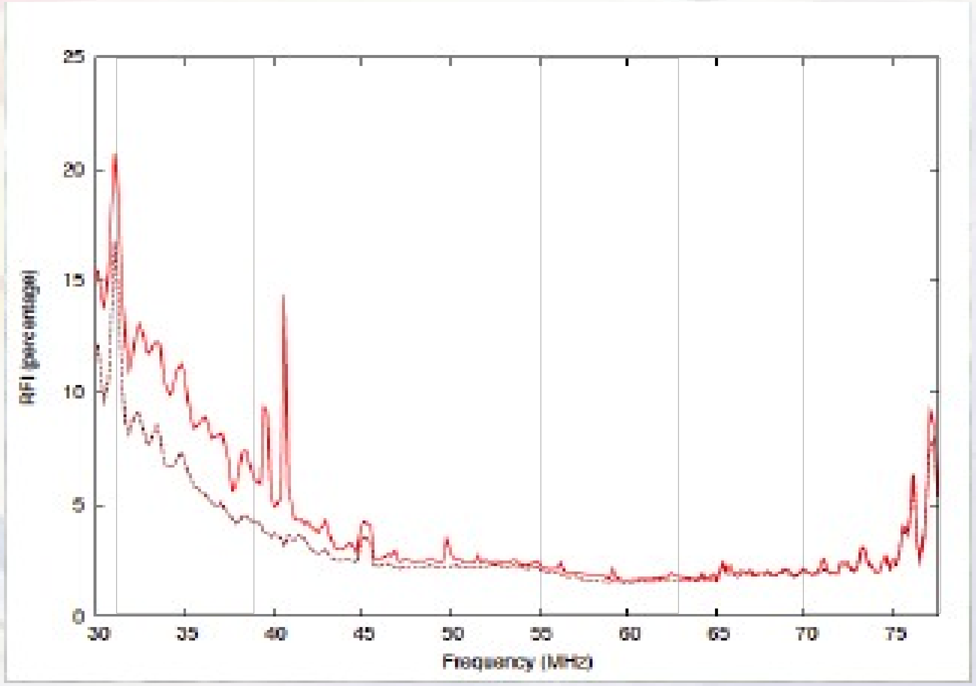
Low Band Observations

244 Sub-Bands
64 channels per Sub band

Multi-beam observation
122 SBs on the target, 122 SBs on 3C196

41 Sub-bands centerd on 34 MHZ
40 Sub-Bands centered on 58 MHz
41 Sub-Bands centered on 74 MHz





MACSJ0717+3745: calibration strategy

1)CasA demixed from the raw data

2) Calibration of 3C196 – every SB is calibrated separately

3) Amplitude Gains transfered to the target MACSJ0717+3745

4) Phase calibration of the target MACSJ0717+3745
Against a VLSS model
20 SBs within each band are combined together

No ionospheric calibration but solving for differential TEC

Pro: Robust determination of the amplitude Gains
Possibility to solve for clock-TEC- FR
Contra: half of the Band spent on the calibrator

LOFAR observations of MACSJ0717+3745

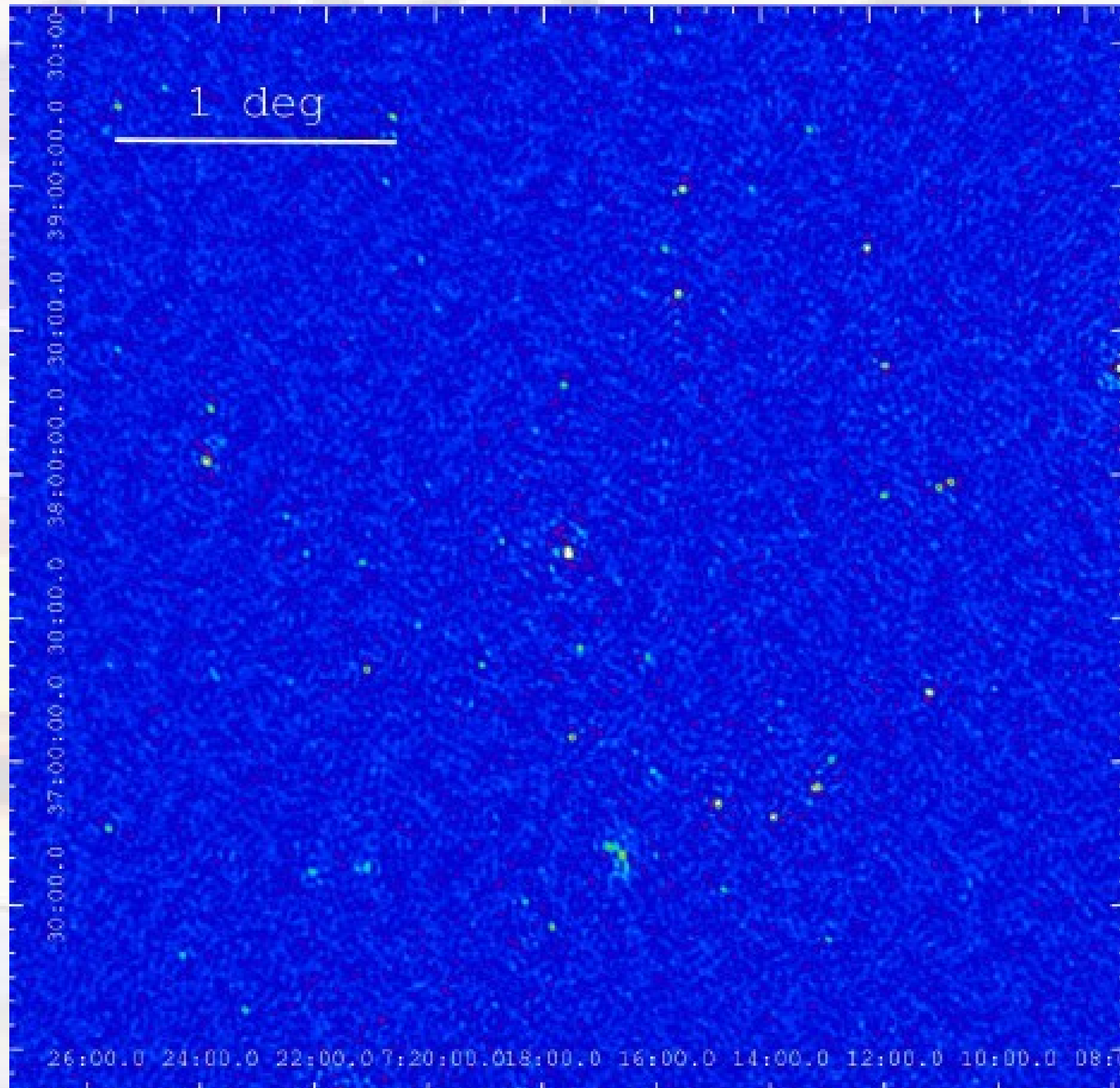
$z=0.55$

$L_{X[0.1-2.4\ keV]}=2.74\ 10^{45}$ erg/s

58 MHz image

Rms noise ~ 15 mJy/beam

Beam =43” x 32”
(robust 0 weighting scheme)



LOFAR observations of MACSJ0717+3745

$z=0.55$

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58 MHz image

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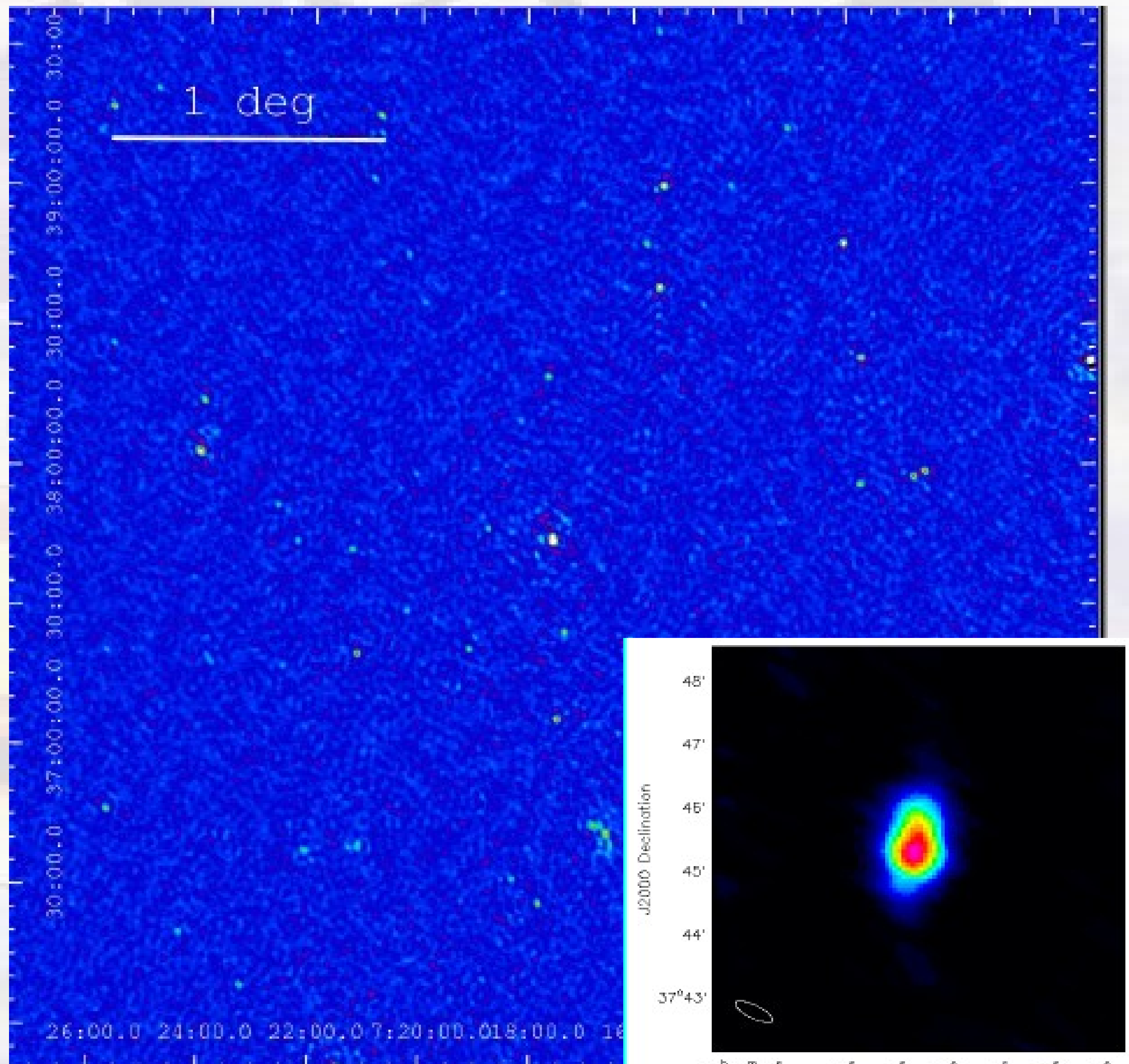
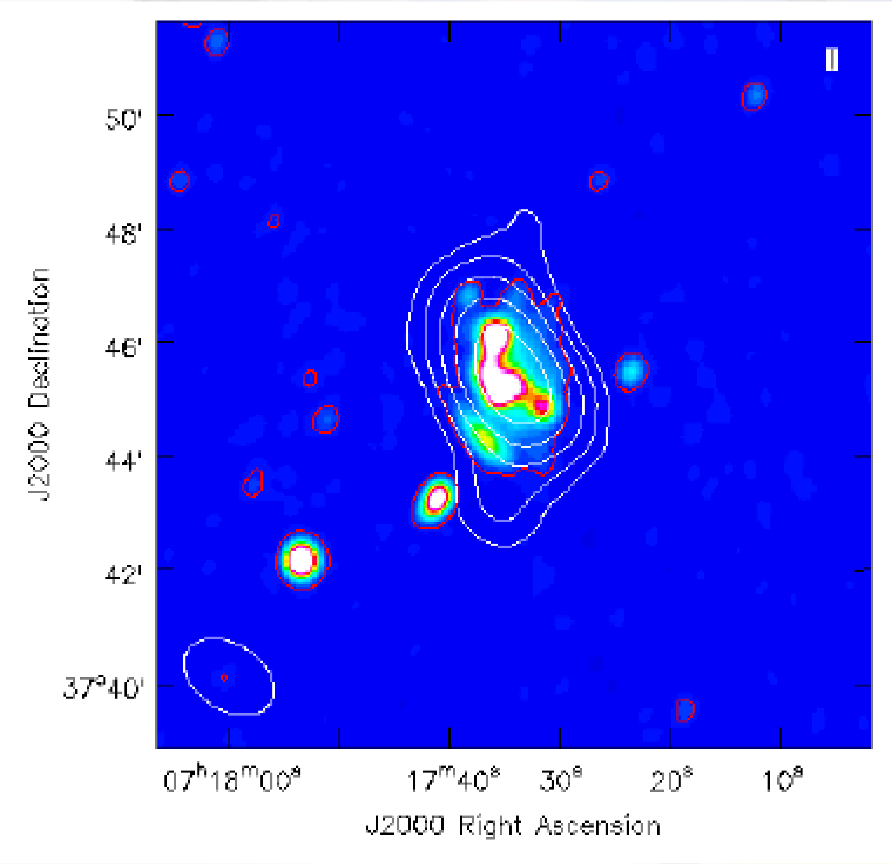


Robust = -0.2
HPBW =12” x 38”
Rms noise 12 mJy/beam

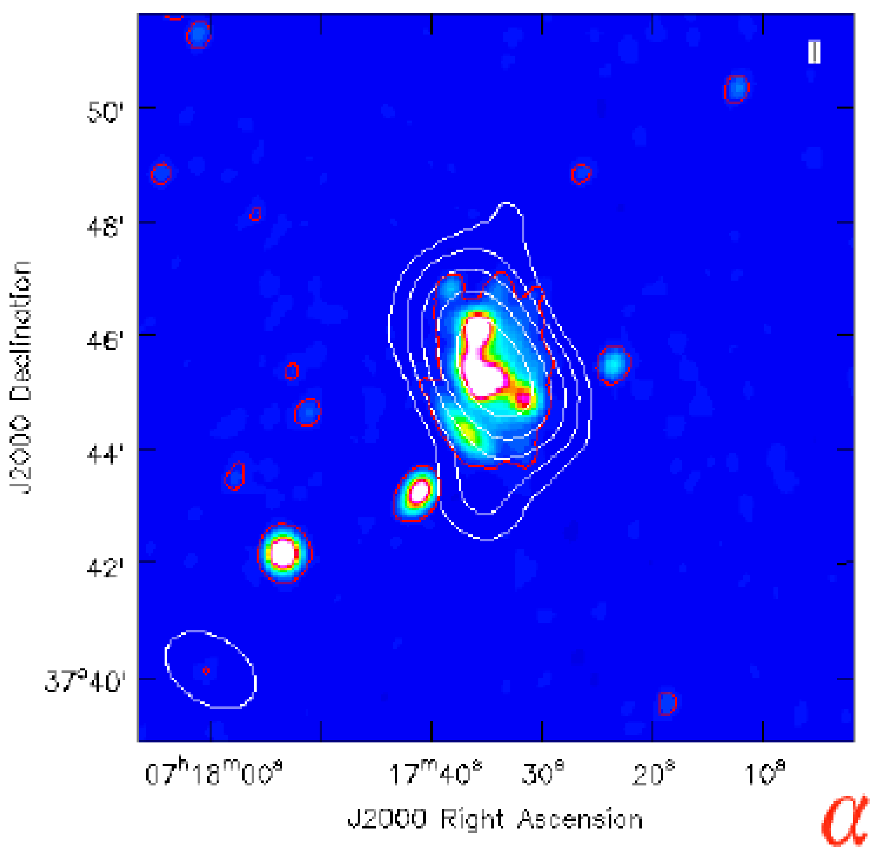
MACSJ0717 – preliminary results



- colors: VLA 1.4 GHz
White contour: LOFAR 34 MHZ

Additional extended emission detected at 34 Mhz

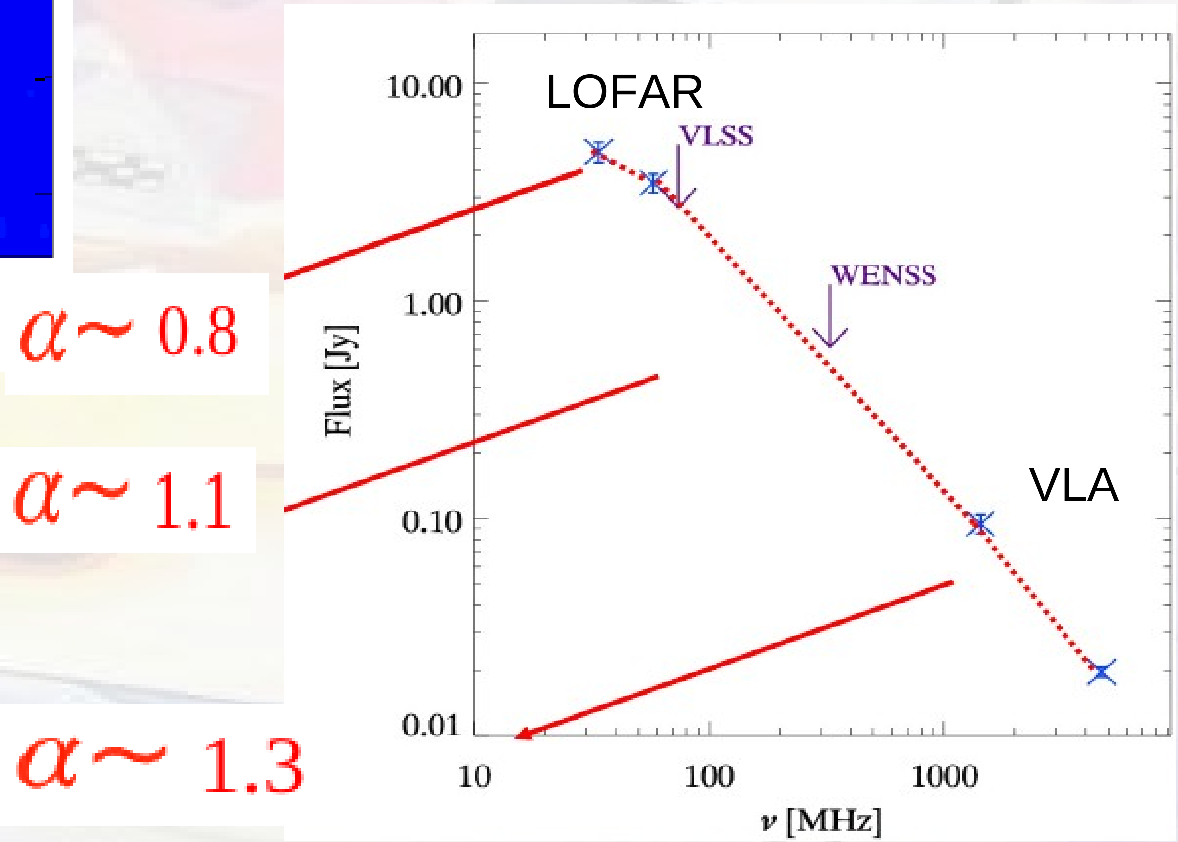
Spectral index - preliminary



- colors: VLA 1.4 GHz
White contour: LOFAR 34 MHZ

Additional extended emission detected at 34 MHz

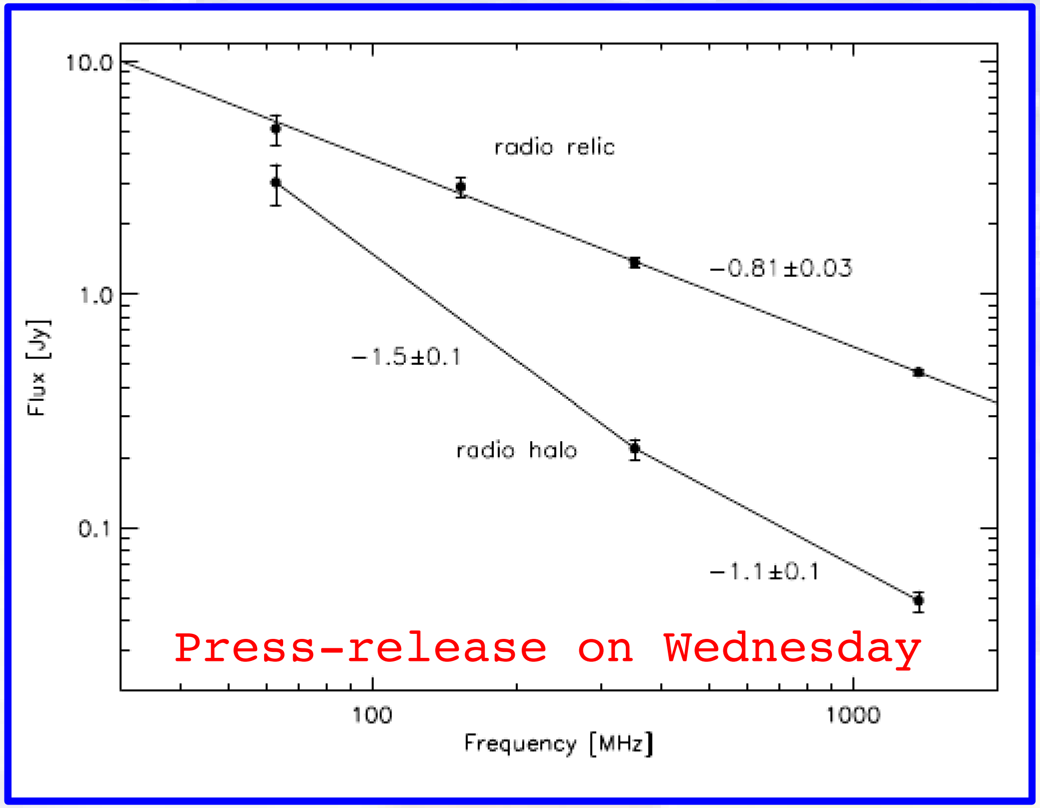
Spectral index of the whole emission:



Radio halos observed by LOFAR so far

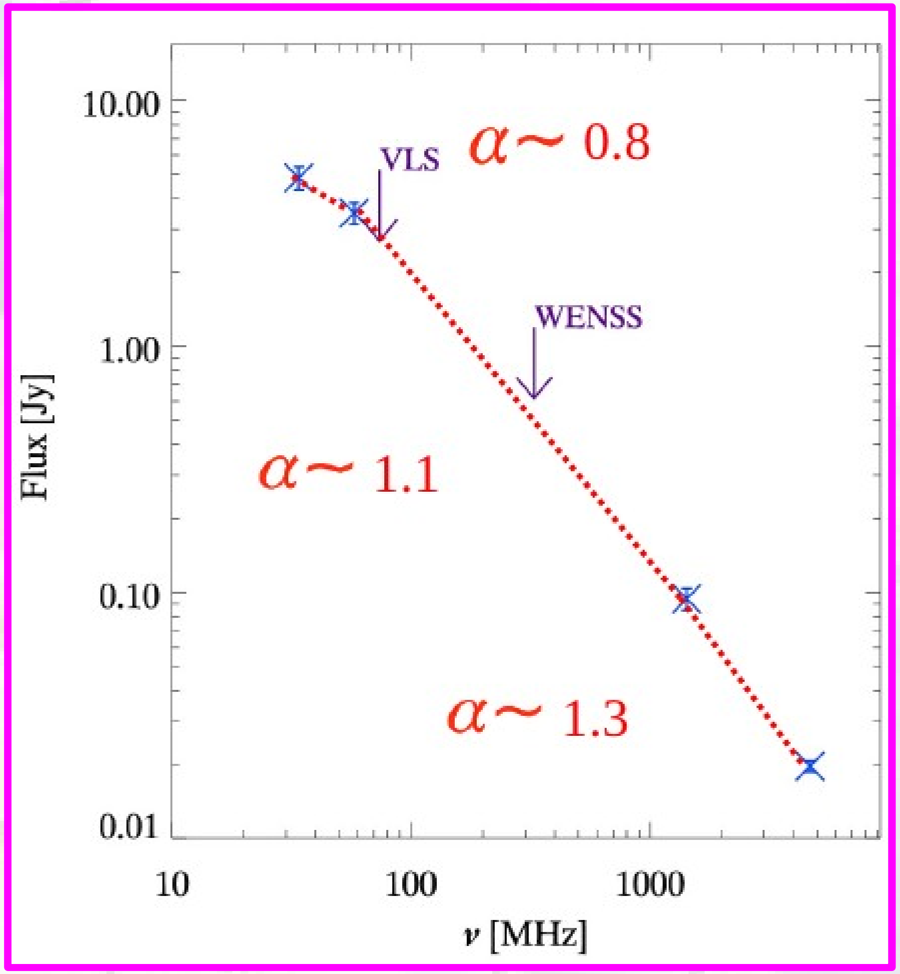
Abell 2256

Van Weeren et al. 2012, in press



MACSJ0717+3745

Bonafede et al, in prep.



Spectral index of the whole emission:

MACSJ0717+3745: Plans to improve the calibration

Ionosphere:Clock + TEC + Faraday Rotation

From XX, YY to RR LL

RR+LL phase → affected by clock and TEC
(~ ν and $1/\nu$)

RR-LL phase → affected by Faraday Rotation
(~ ν^{-2})

1) Fit clock and TEC and FR for a strong calibrator –
!! Needs a lot of BW on a calibrator!!

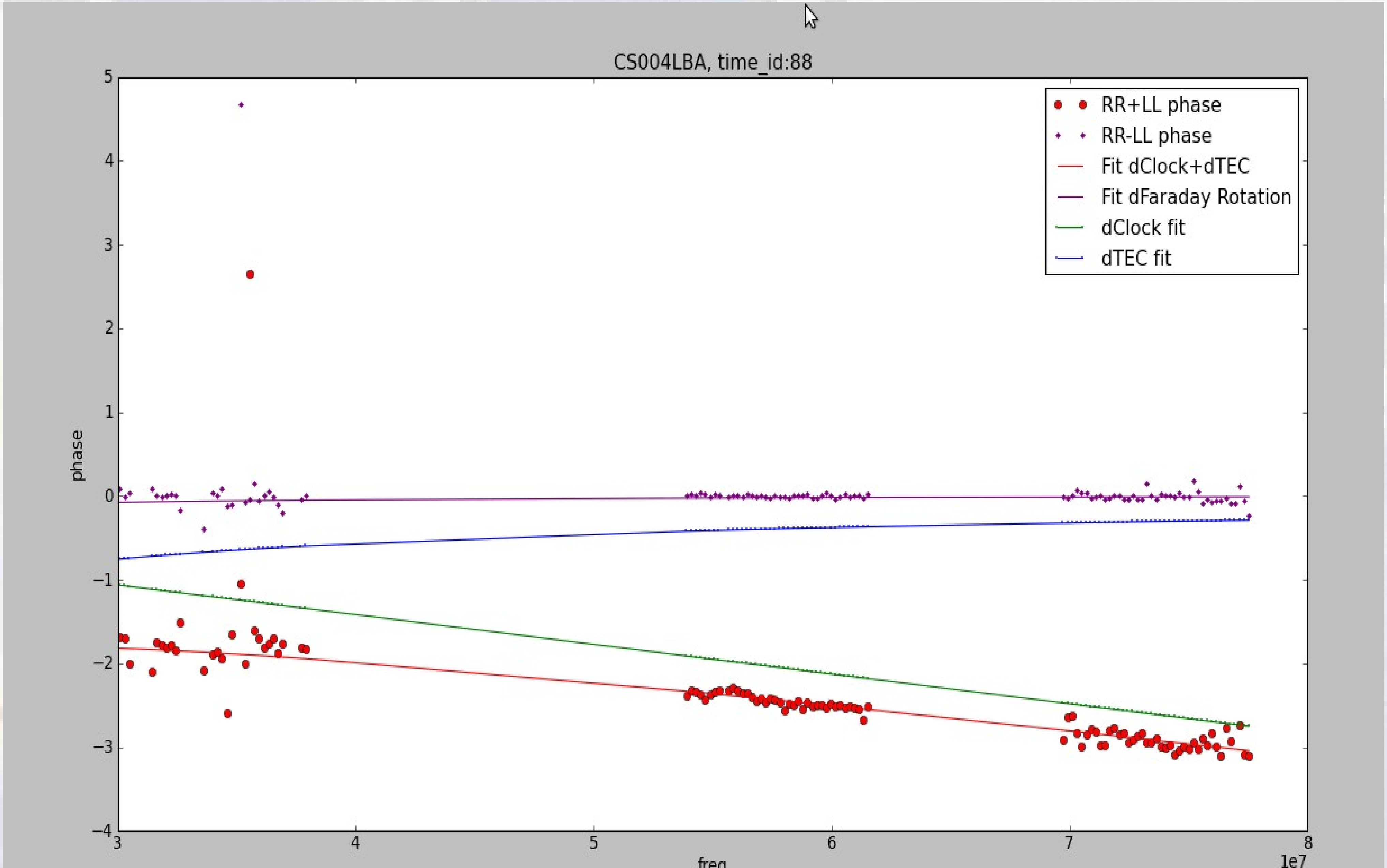
2) Correct for clock on your target

3) Solve for FR and TEC on your target

Python script by R. van Weeren and B vd Tol to fit clock, TEC and FR

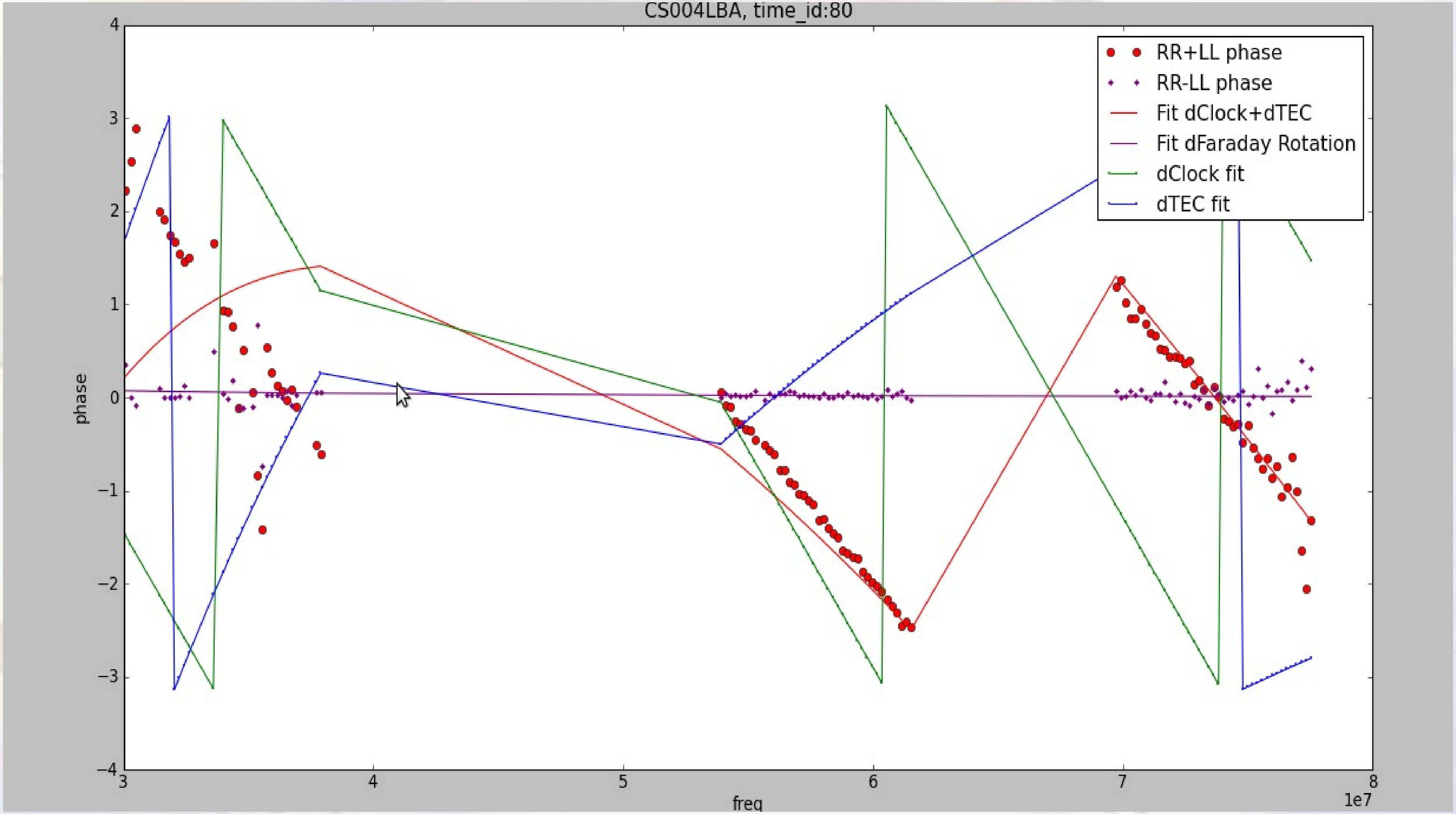
MACSJ0717+3745: clock and TEC separation

CS- CS baseline



MACSJ0717+3745: clock and TEC separation

RS- CS baseline   PHASE UNWRAPPING NEEDED
(work in progress with R. van Weeren and Bas van der Tol



Thanks!