When Galaxy Clusters Collide:

Shocking tales of structure formation

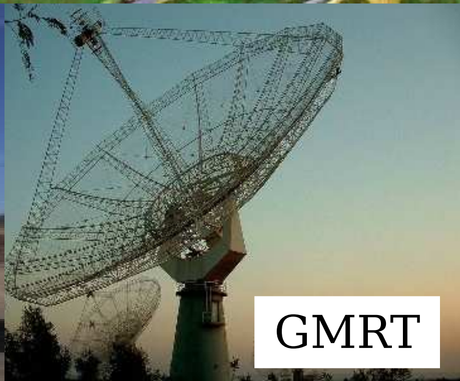
Andra Stroe
ESO Fellow
astroe@eso.org
Twitter: @Andra_Stroe
www.eso.org/~astroe

H. Röttgering, D. Sobral, J. Harwood, R. van Weeren, , M. J. Jee, W. Dawson, H. Hoekstra, C. Rumsey, H. Intema, T. Oosterloo, R. Saunders, M. Brüggen, M. Hoeft, D. Wittman, T. Shimwell, M. Hardcastle, J. Donnert, T. Jones, M. Kierdorf, R. Beck, C. Rodriguez-Gonzalvez

University of Melbourne, May 2018

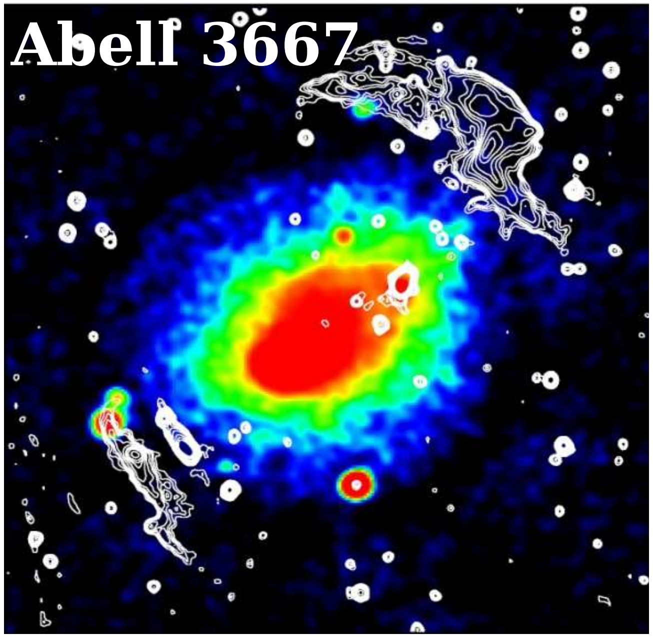
Overview

- The field of diffuse cluster emission
- Why the 'Sausage' + 'Toothbrush' clusters?
- Physics of the ICM from radio observations

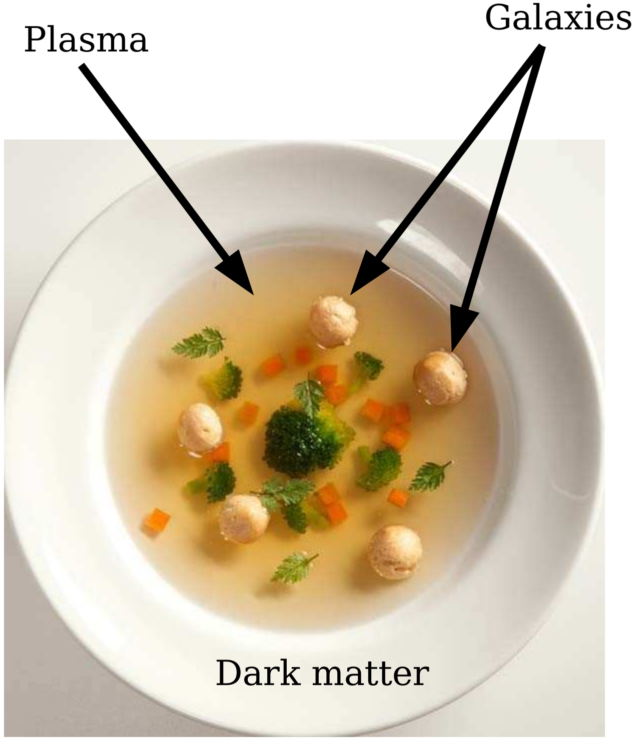


Galaxy clusters across wavelengths

- Soup of:
  - Dark matter
  - Electron gas:
    - Thermal bremsstrahlung: X-ray emission
    - Non-thermal synchrotron emission: radio emission
  - Galaxies (optical, infra-red, radio)

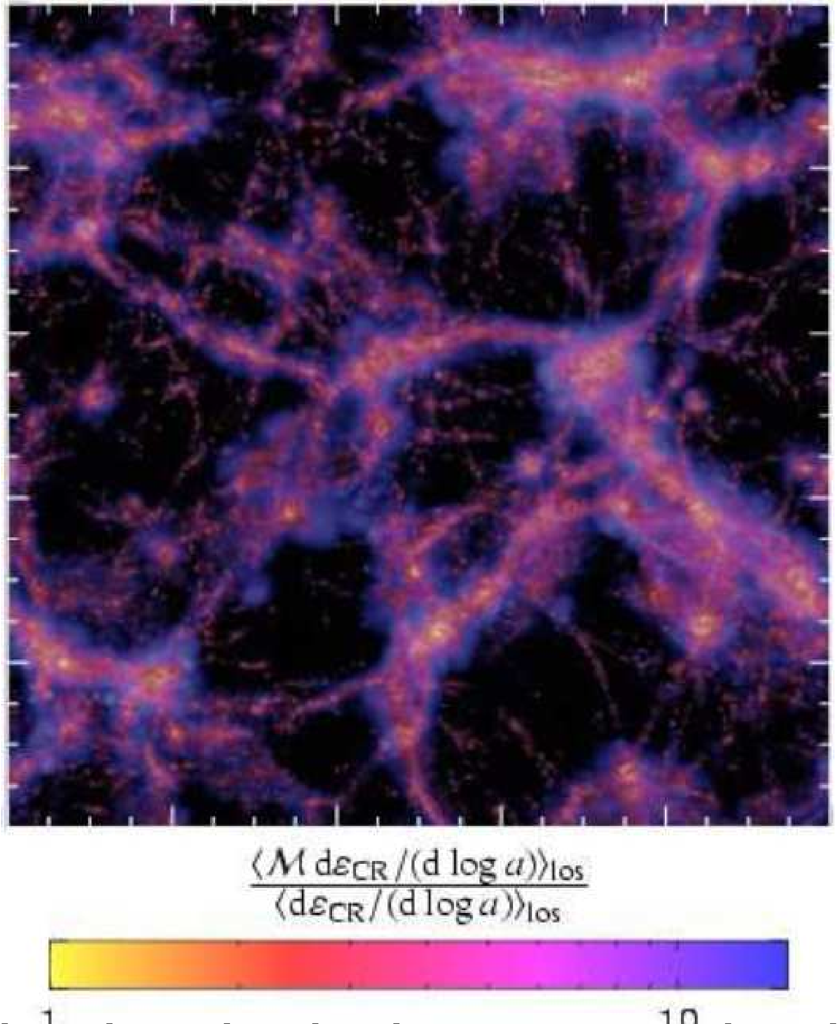


X-ray intensity in color, radio emission in white contours (Rottgering et al. 1997)



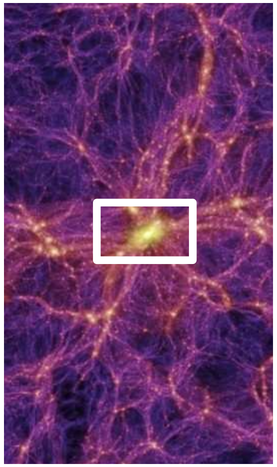
Structure formation leads to shocks and turbulence!

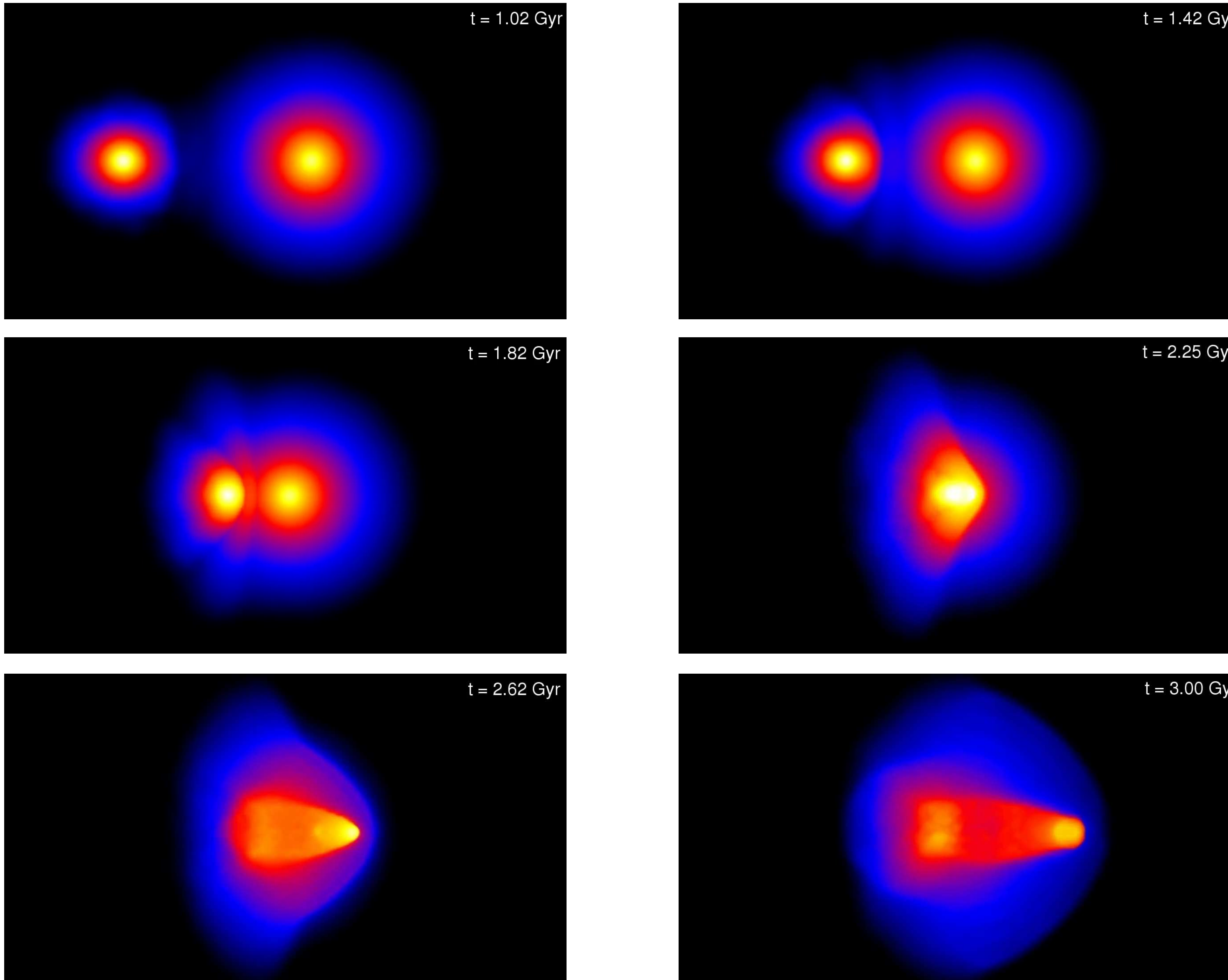
•Clusters grow through mergers
•Structure formation is a very violent process (Hoeft et al. 2004)
• Some of the energy is released in the form of shocks and turbulence
• Cosmological simulations predict M=1-10 shocks to be common in clusters and the filaments that connect them (e.g. Pfrommer et al. 2006)



Spatial Mach number distribution in a cosmological structure formation simulation (Pfrommer et al. 2006)

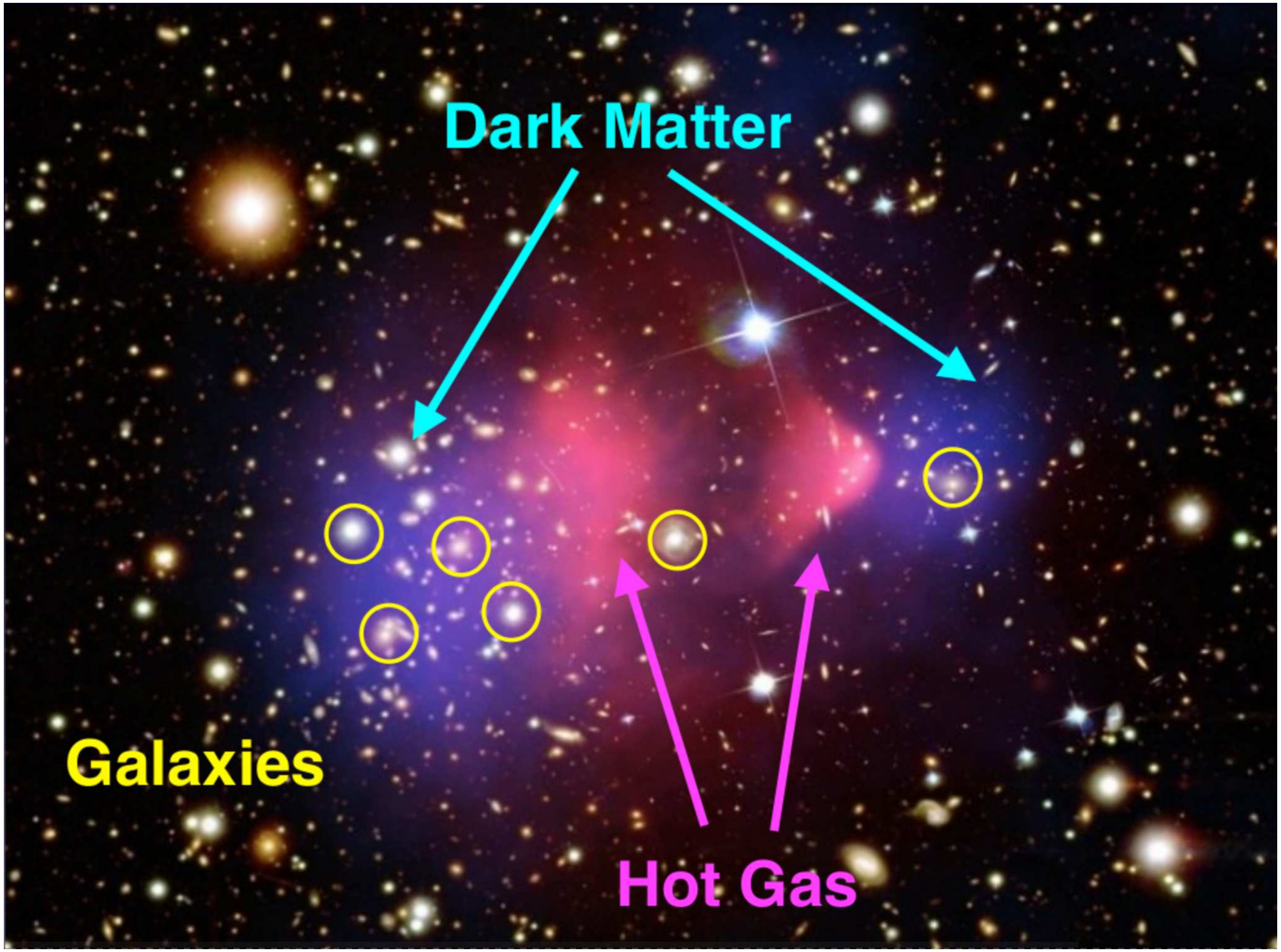
Galaxy clusters – how do they grow?





Machado & Lima Neto (2013)

Clusters mergers – dark matter laboratories

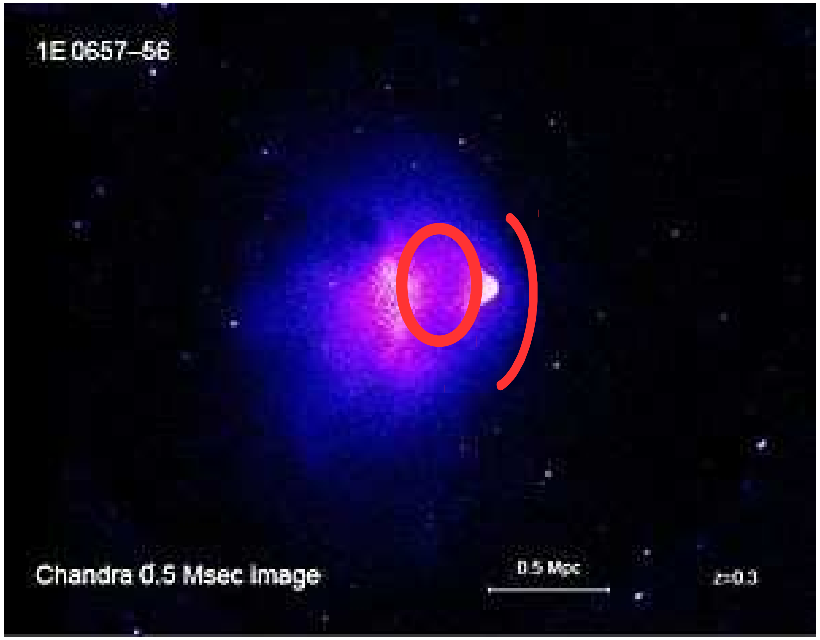


Markevitch & Clowe (from presentation by ZuHone)

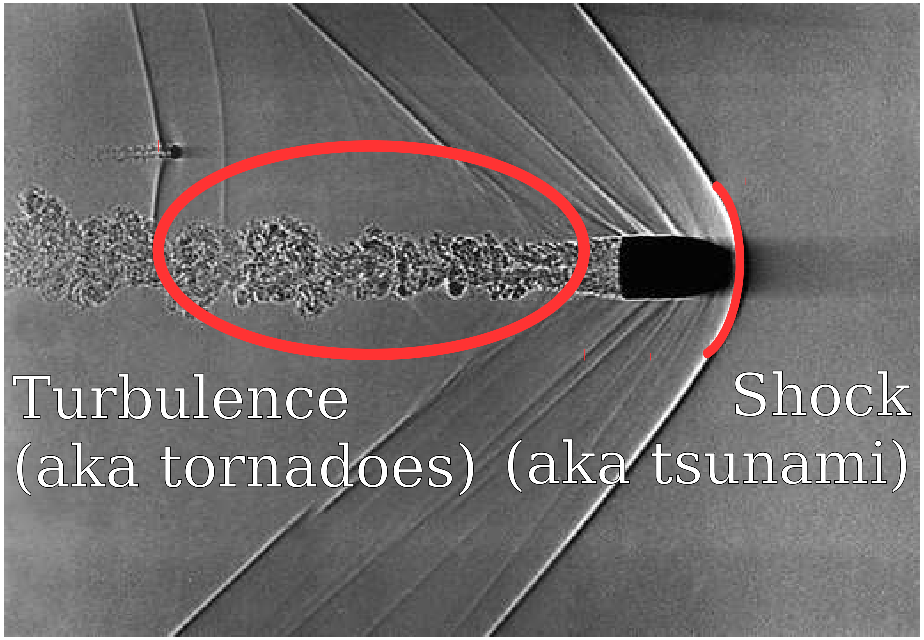
Galaxy cluster merger

- Mergers → shocks and turbulence
- Shocks: M ~ 2 – 4, but much higher speed

'Bullet' cluster

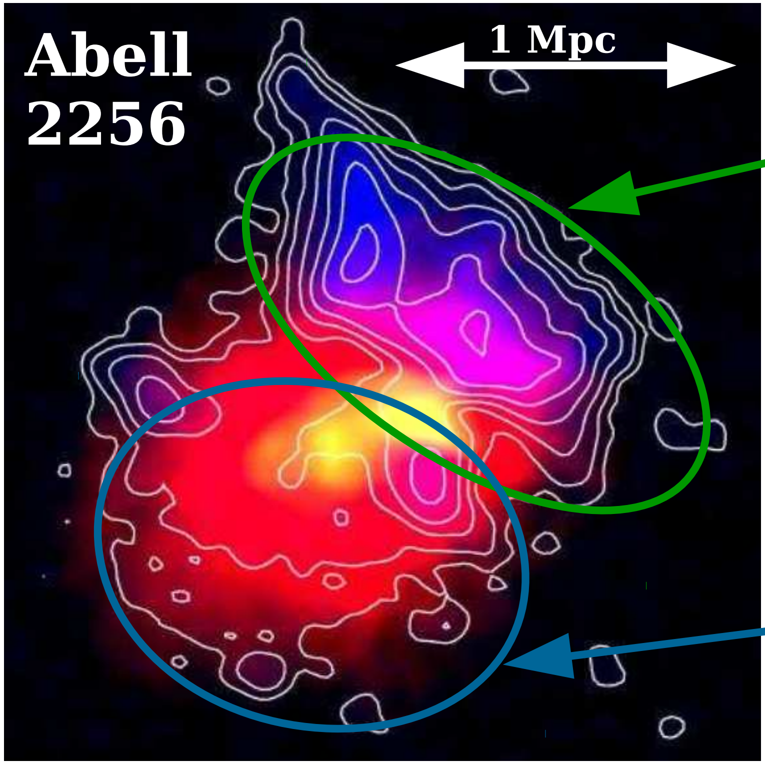


Actual bullet



Adapted from talk by J. ZuHone

Diffuse radio emission in clusters



X-ray intensity in colour, radio emission in white contours (Clarke & Ensslin 2006)

Radio relics

- Diffuse radio synchrotron emission
- Mpc-sized, extended
- Located at cluster outskirts
- No optical counterpart, strongly polarised
- Related to cluster shocks

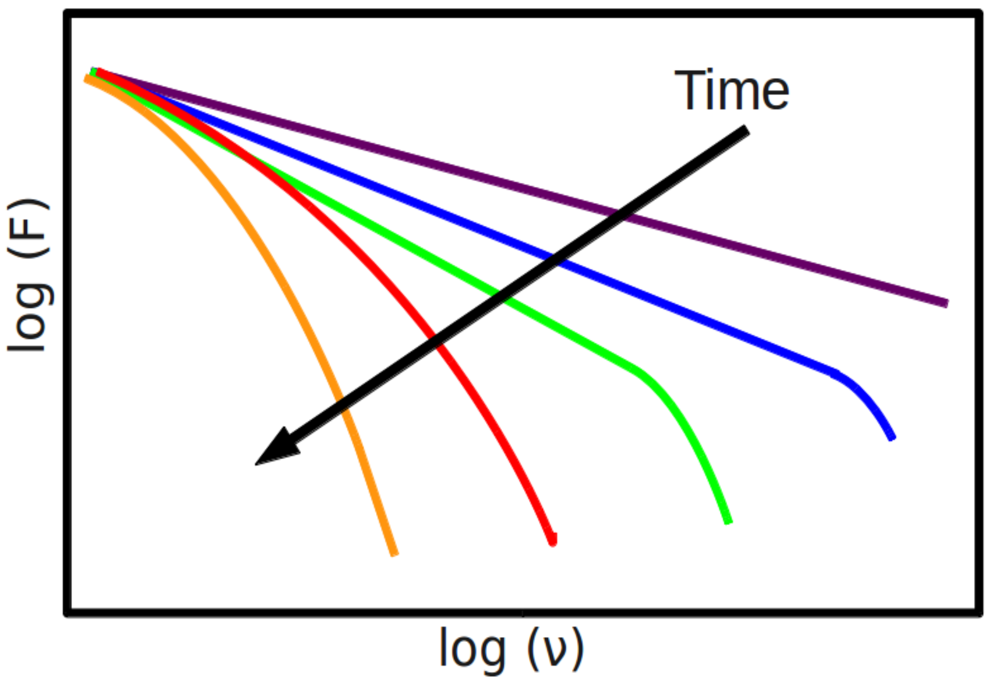
Radio haloes

- Diffuse, located at cluster centres, unpolarised
- Follow the ICM X-ray distribution
- Formed via turbulent re-acceleration of ICM electrons

Merger → shocks → radio relics → turbulence → radio halo
(Donnert et al. 2013)

Shocks+synchrotron

- Formation mechanism:
  - Two/more galaxy clusters collide
  - Shock waves travel through the ICM
  - Accelerate thermal electrons → emit synchrotron
  - Similar to supernova remnants → but very different scales
- Spectrum:
  - Initially a linear function
  - Spectral index steepening
  - Spectral curving

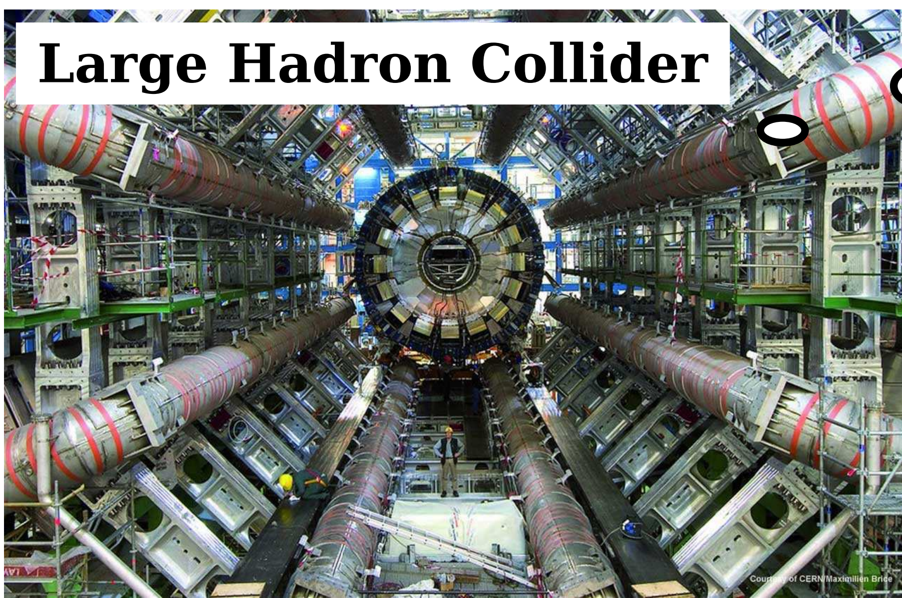


Radio (red) and X-ray (blue) emission on top of an optical image (ESO)

Why are relics+halos important?

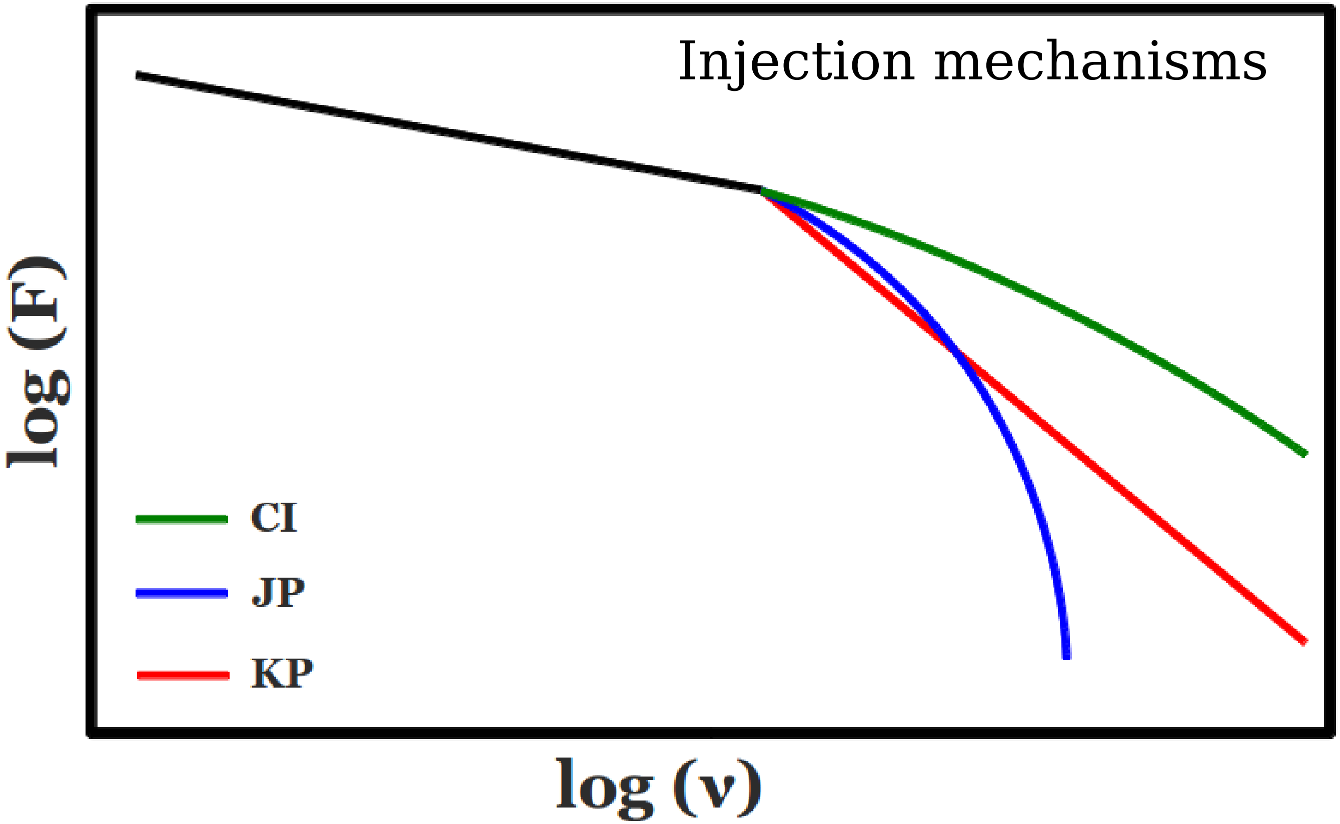
- The largest particle accelerators in the Universe!
- Complementary way to discover clusters
- Probably in all clusters
- Non-negligible non-thermal pressure (6-10%, Eckert et al. 2018)
- Probe magnetic fields + turbulence
- Shocks are ubiquitous → shock efficiency? injection spectra?
- Important to quantify for cosmology
- Basic physics applicable to other astronomical fields

The LHC is not impressed
with radio relics!
Maybe it's just jealous!



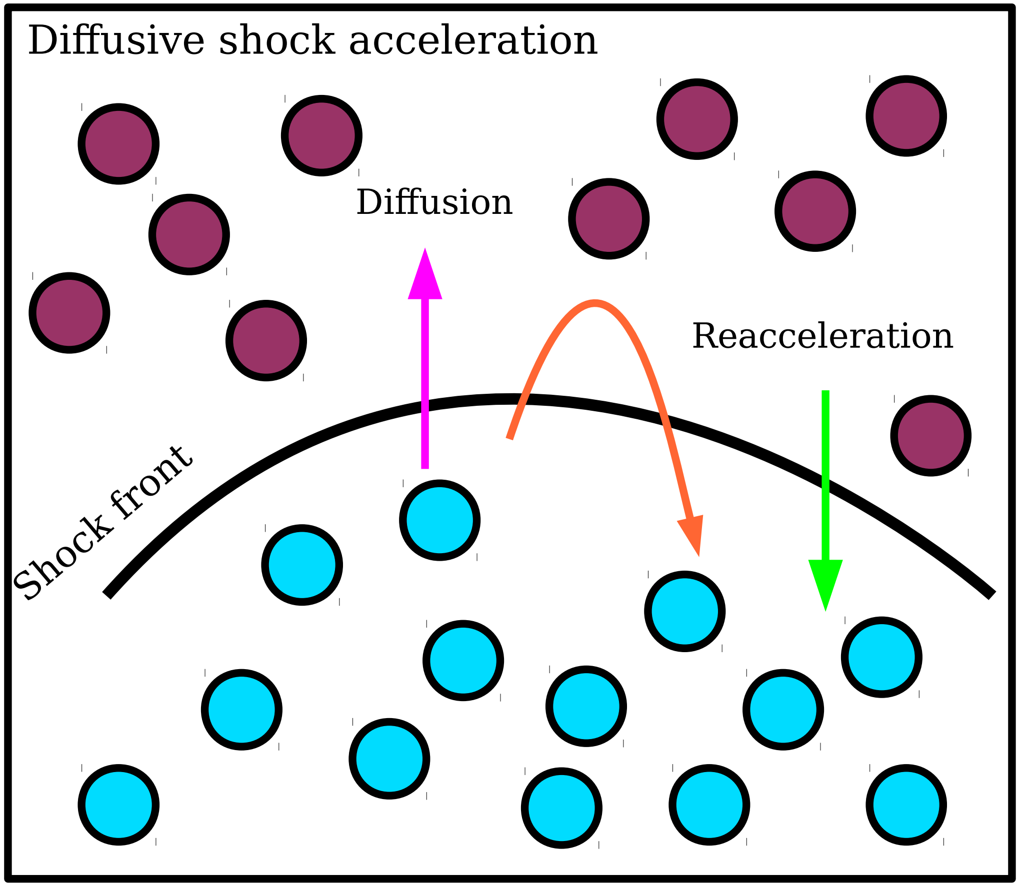
Ageing models

- Continous injection (CI, Pacholczyk 1970)
- Kardashev-Pacholczyk (KP, Kardashev 1962, Pacholczyk 1970)
- Jaffe-Perola (JP, Jaffe & Perola 1973)
- Tribble (Tribble 1993)



Acceleration

- Adiabatic compression (Ensslin & Gopal-Krishna 2001)
- Diffusive shock acceleration (Ensslin et al. 1999)
- Phoenixes vs relics: curved vs straight integrated radio spectra

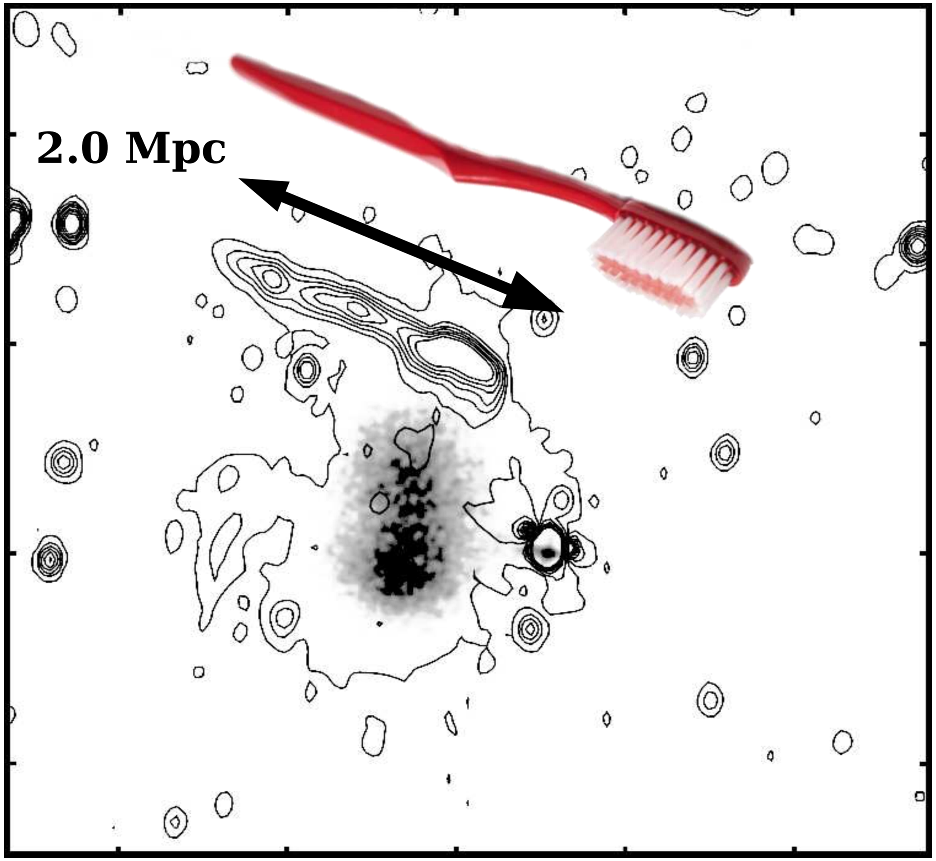


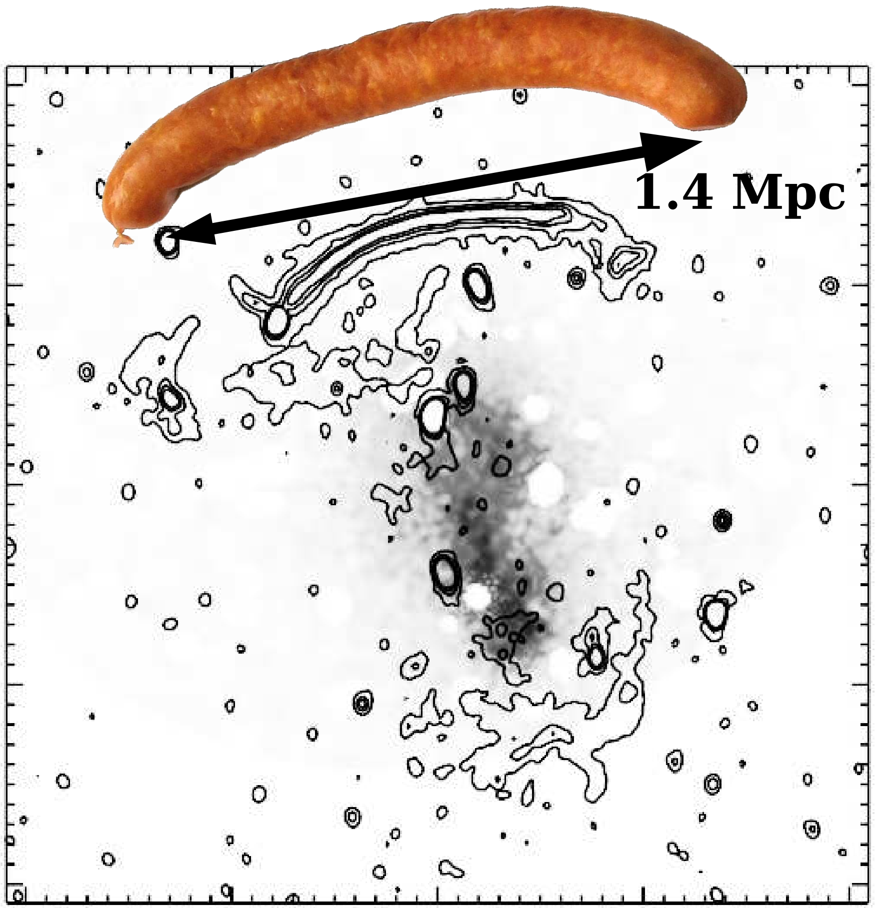
Why is it hard?

- Faint & extended → difficult to detect
- Lack of suitable telescopes
- Simple cluster mergers:
    - Equal mass systems
    - Merging in the plane of the sky
    - Low impact parameter
    - At the right moment

The 'Toothbrush' and 'Sausage' clusters

- z~0.2
- X-ray luminous, disturbed morphology
- Merger in the plane of the sky → twin, outward traveling shock waves
- In the Galactic plane → radio does not care, but a nightmare for the extragalactic optical astronomer!

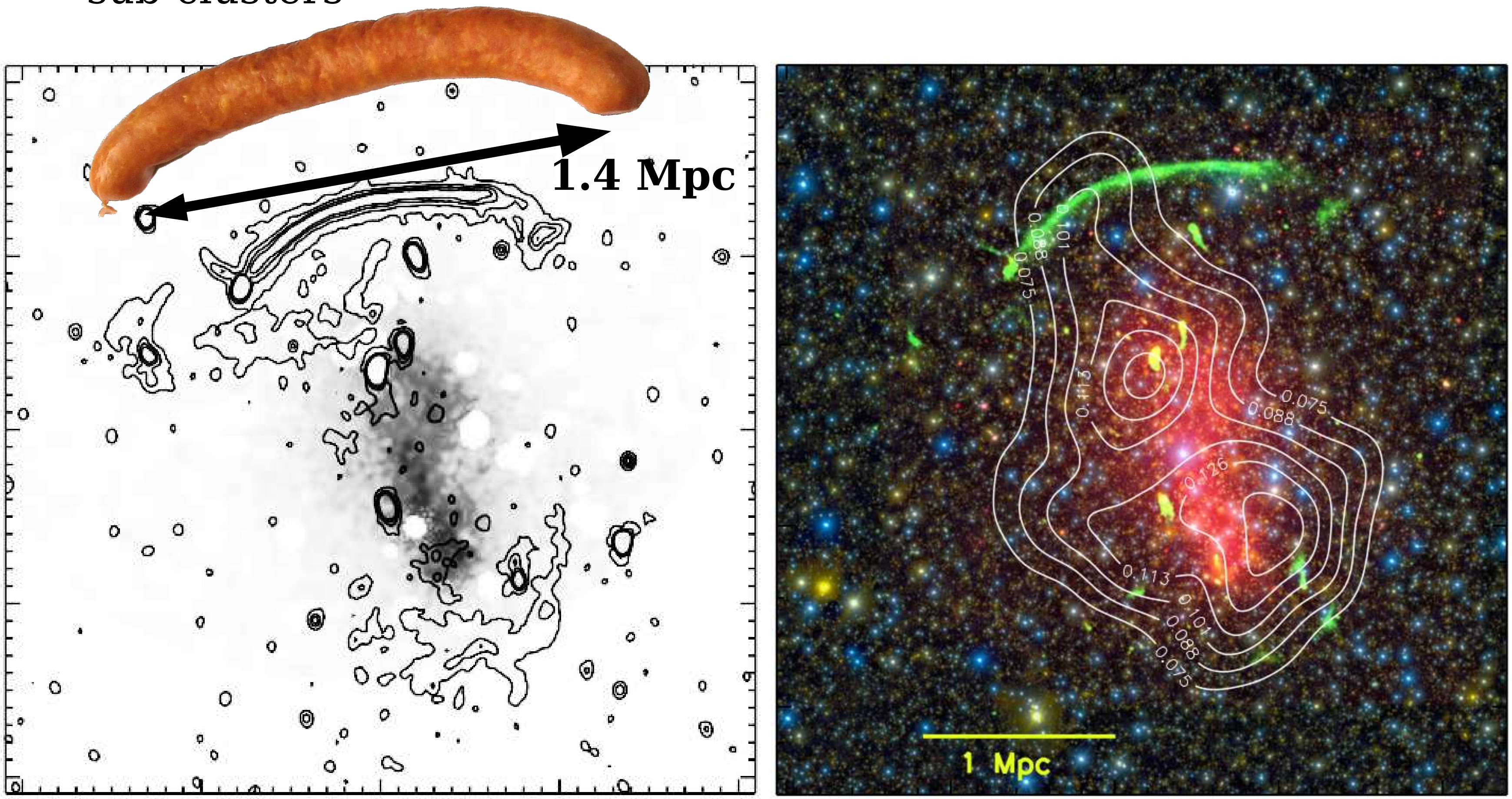




X-ray intensity, radio overlays (van Weeren et al 2010, 2012, Akamatsu & Kawahara 2013, Ogrean et al. 2013)

The 'Sausage' cluster

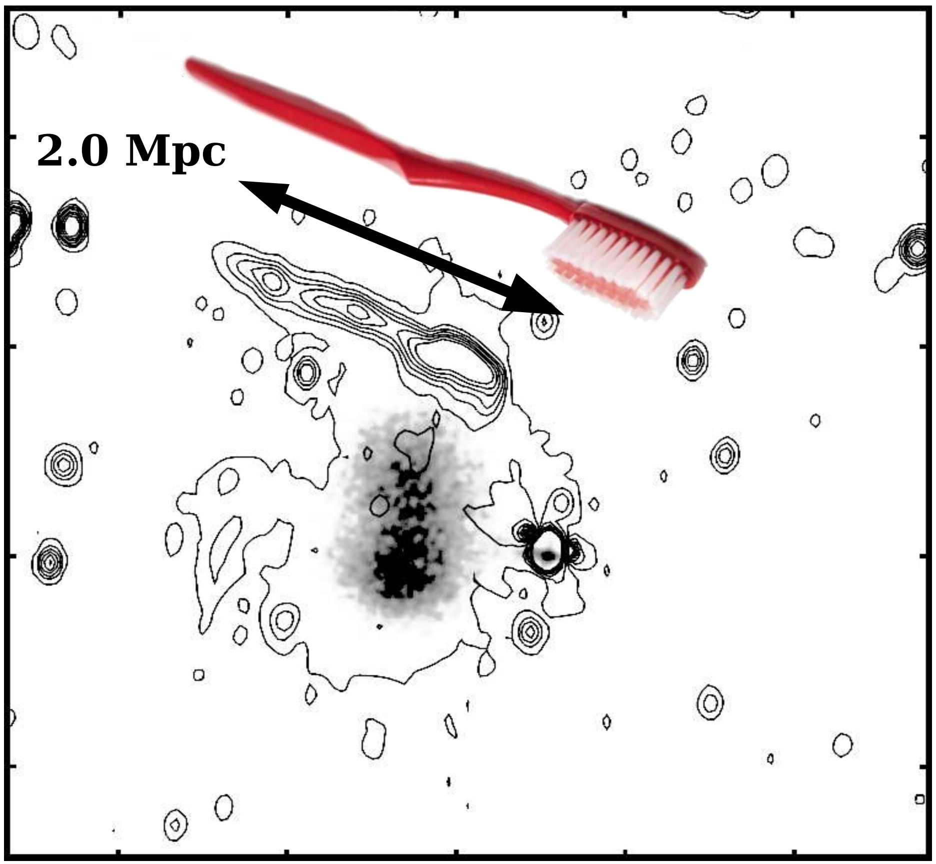
- Massive (~2·10^{15} $M_{\odot}$), weak lensing: dark matter is elongated, two sub-clusters

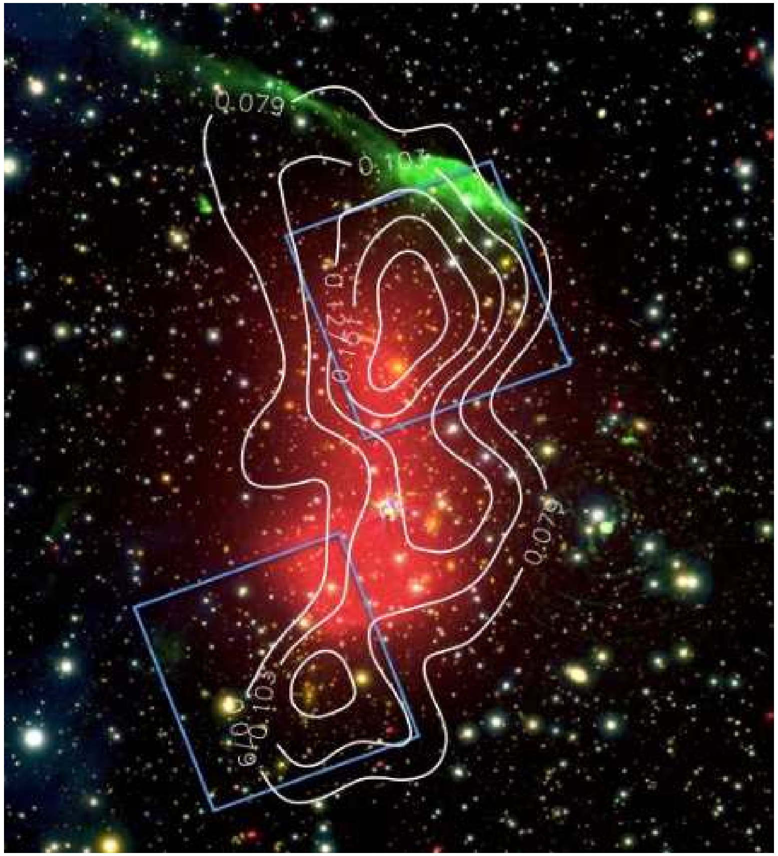


Left: X-ray intensity, radio overlays (Ogrean et al. 2013, van Weeren et al. 2010)
Right: weak lensing contours, radio in green, X-ray gas in pink on top of a two band optical composite (Jee, Stroe et al. 2014)

The 'Toothbrush' cluster

- Massive (~$1\cdot10^{15}\ M_{\odot}$), weak lensing: dark matter is elongated, two main sub-clusters (3:1)

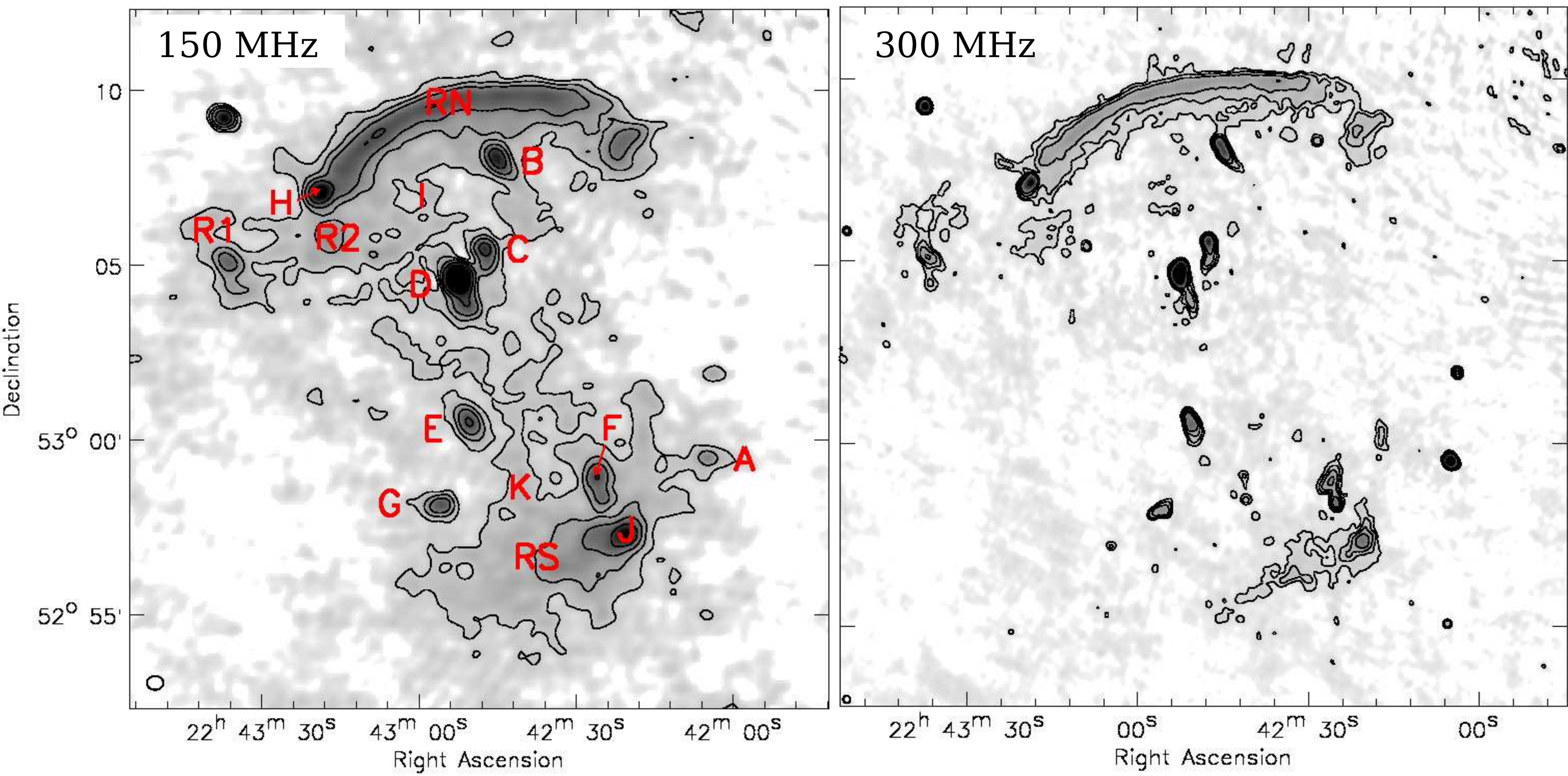




Left: X-ray intensity, radio overlays (van Weeren et al. 2012)
Right: weak lensing contours, radio in green, X-ray gas in pink on top of a two band optical composite (Jee et al. 2016)

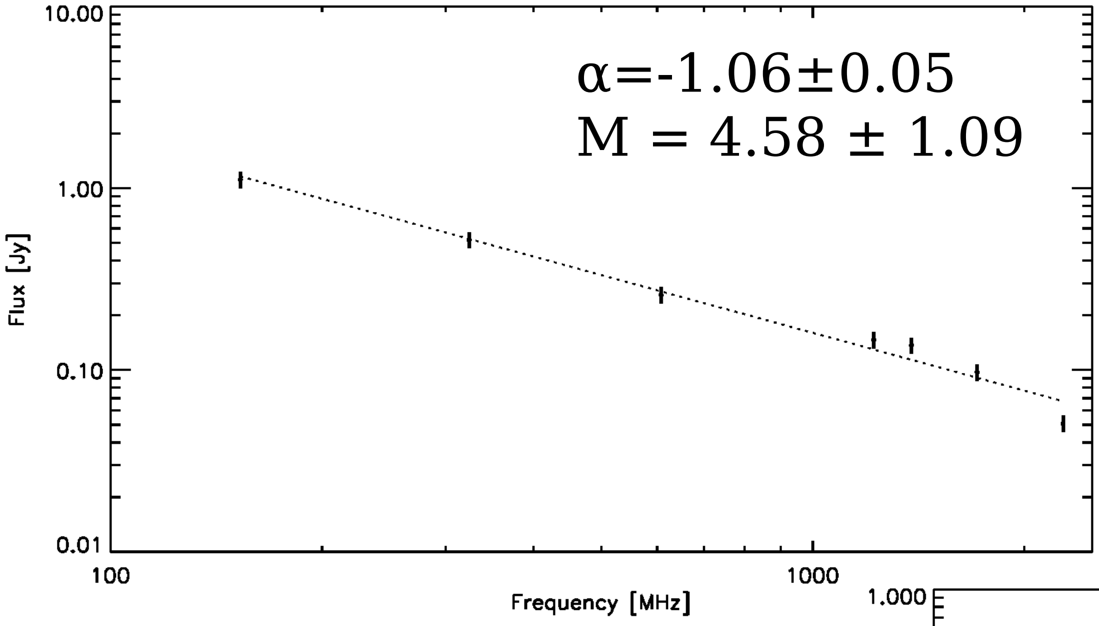
'Sausage' cluster - Pretty pictures

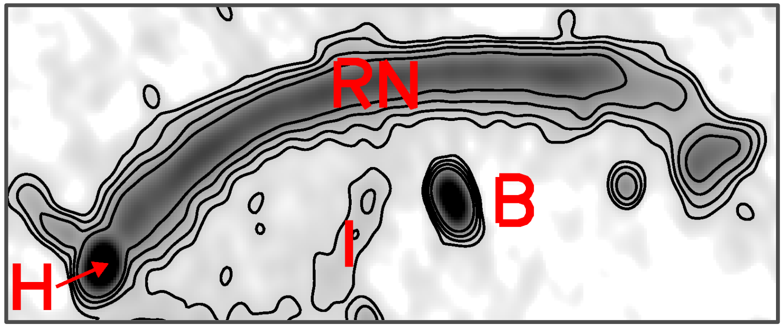
- Radio maps (GMRT) with contours drawn at [4, 6, 8, 16, 32] · σ_{RMS}
- Lower frequency = brighter emission

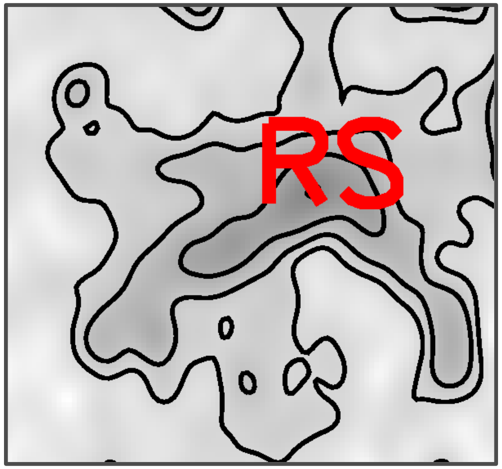


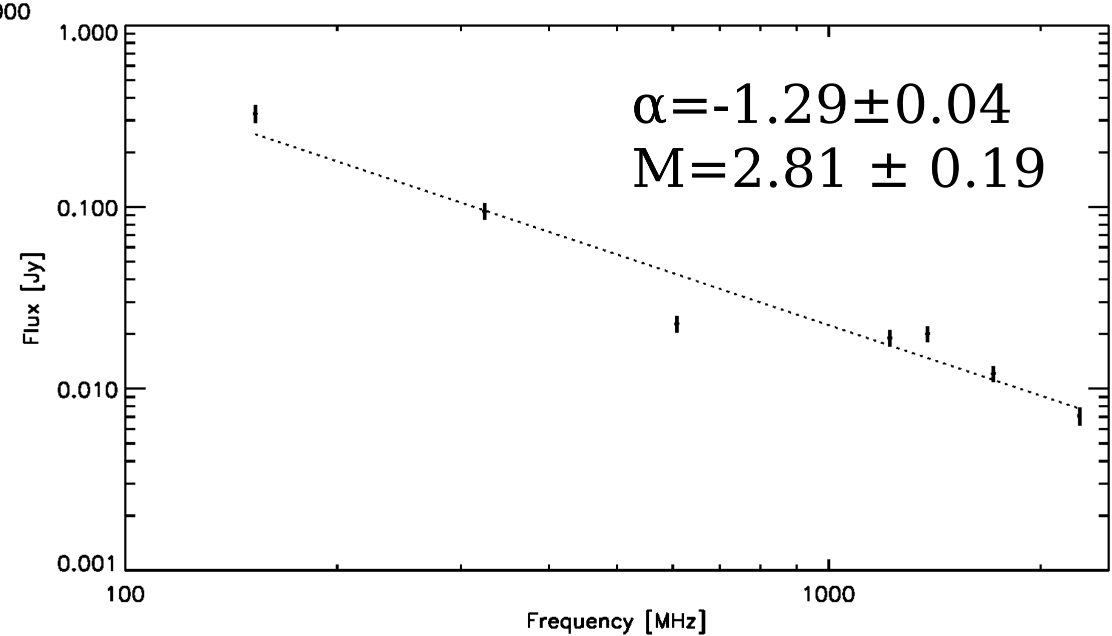
Stroe et al. (2013)

Integrated spectra – Northern & Southern relic





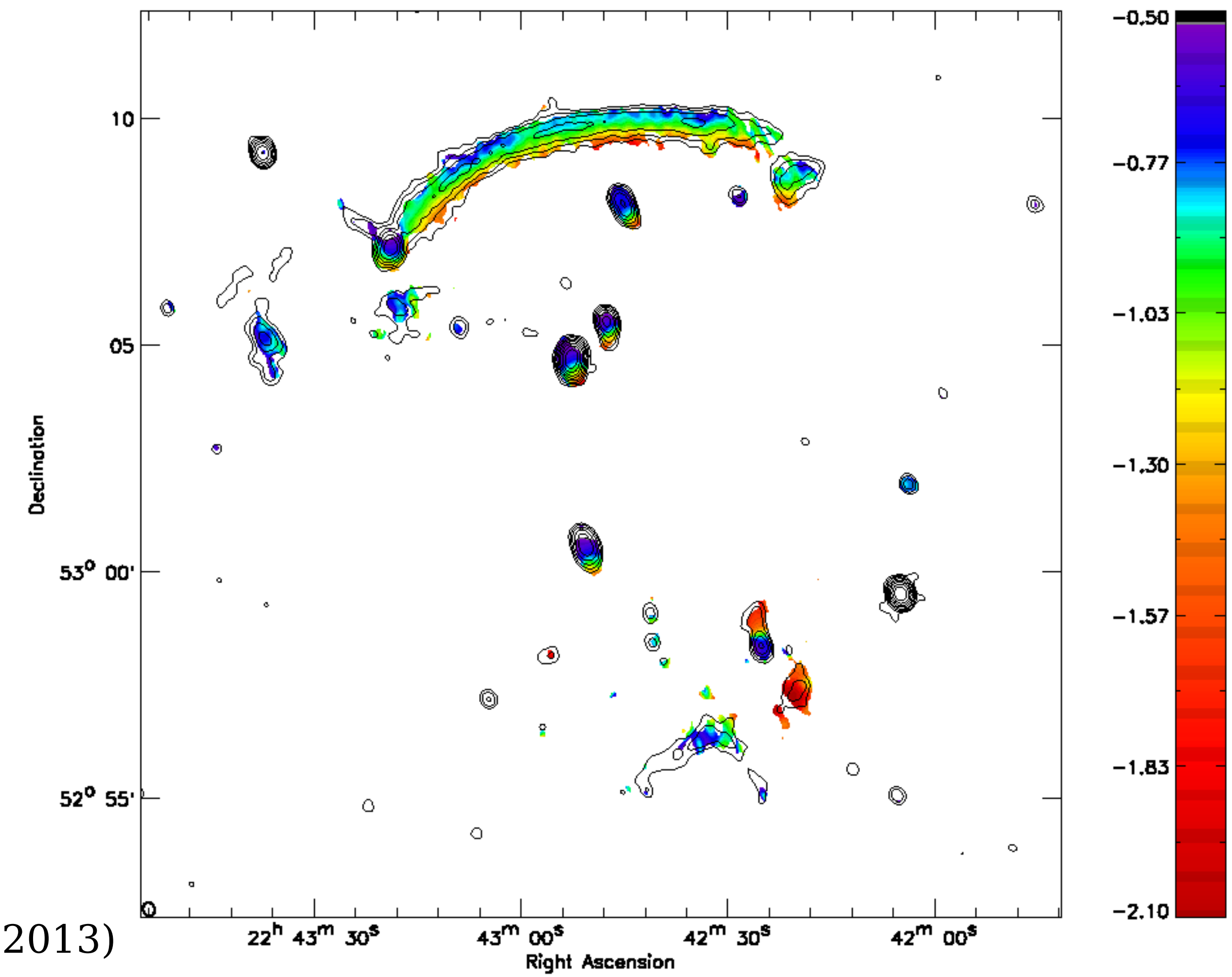




Stroe et al. (2013)

7 frequency spectral index

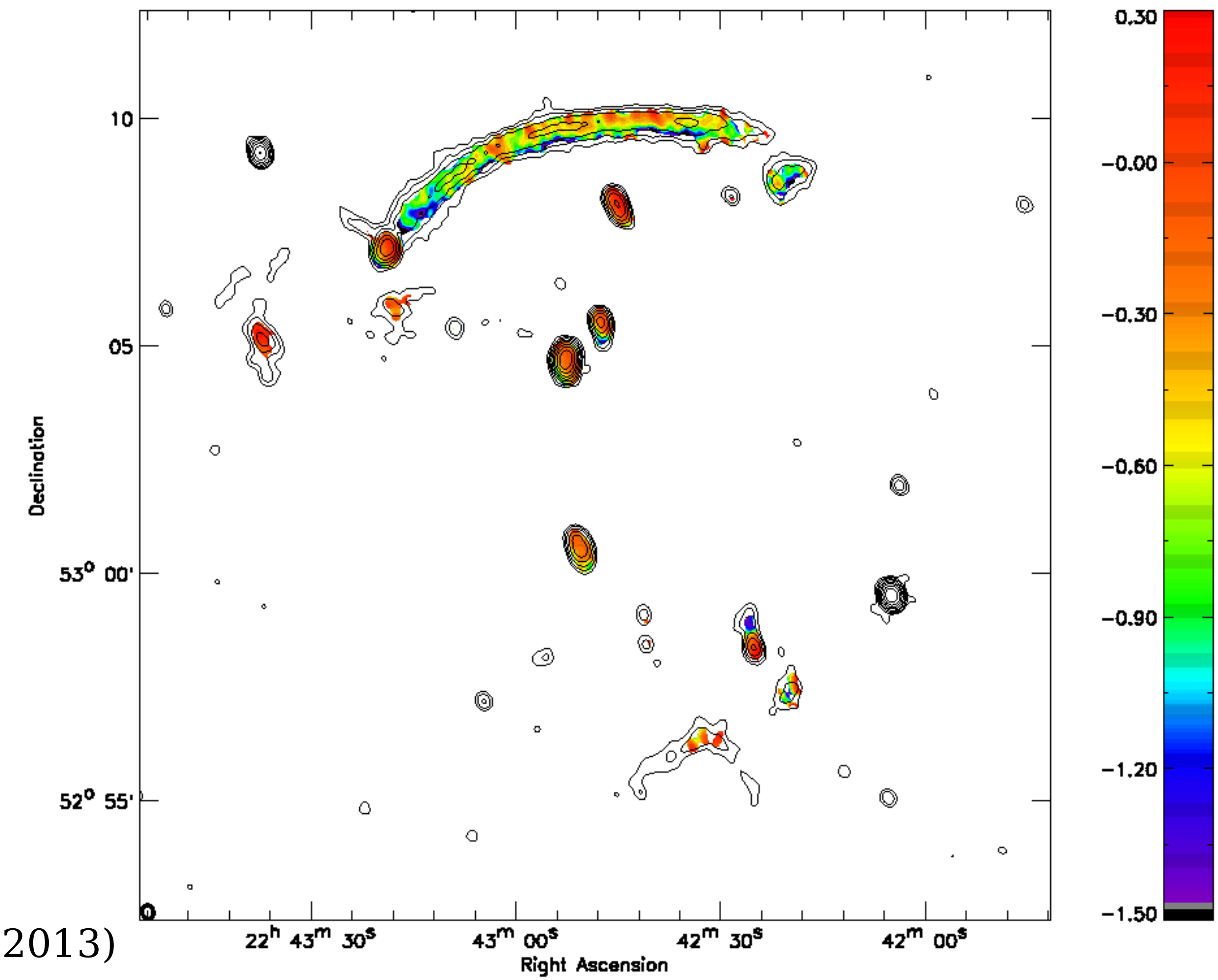
- Fit a spectrum to every pixel in our 7 radio maps (GMRT+Westerbork)
- Consistent with DSA – indicative of ageing behind a shock



Stroe et al. (2013)

7 frequency spectral curvature

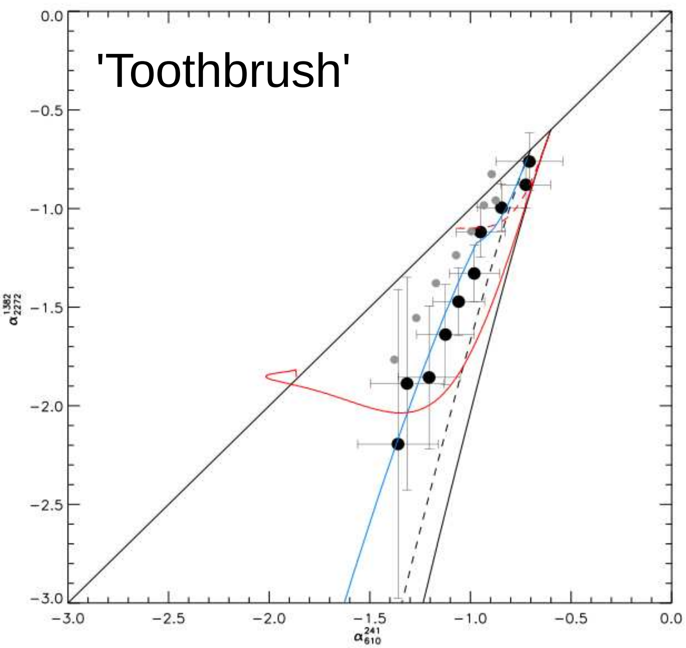
- Fit second order function to every pixel
- Predicted by DSA, but never observed



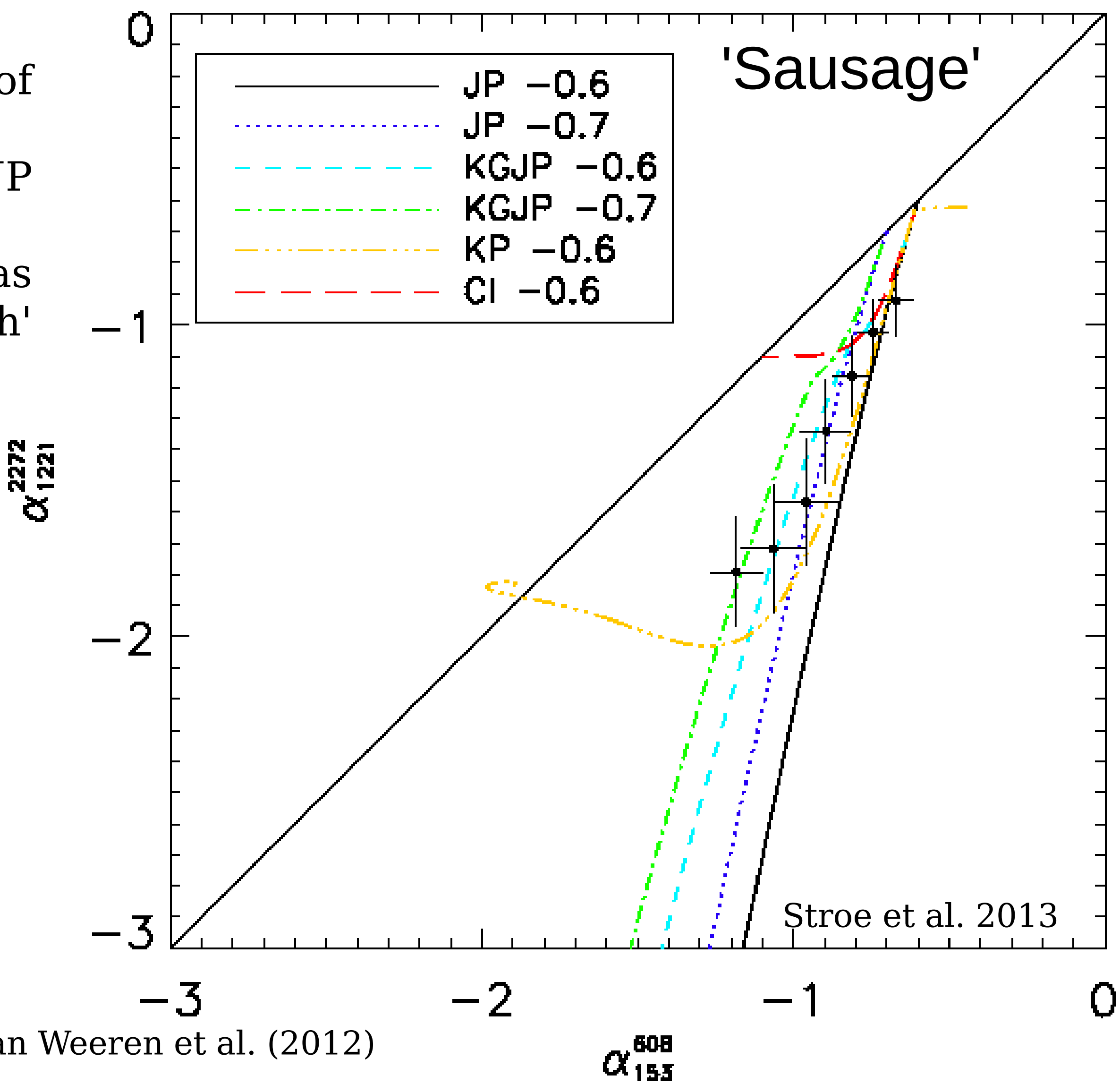
Stroe et al. (2013)

Colour-colour plot

- KGJP model fit the data best
- Multiple populations of electrons of different ages
- All populations follow a JP injection model
- Sanity check – the same was obtained for the 'Toothbrush' cluster



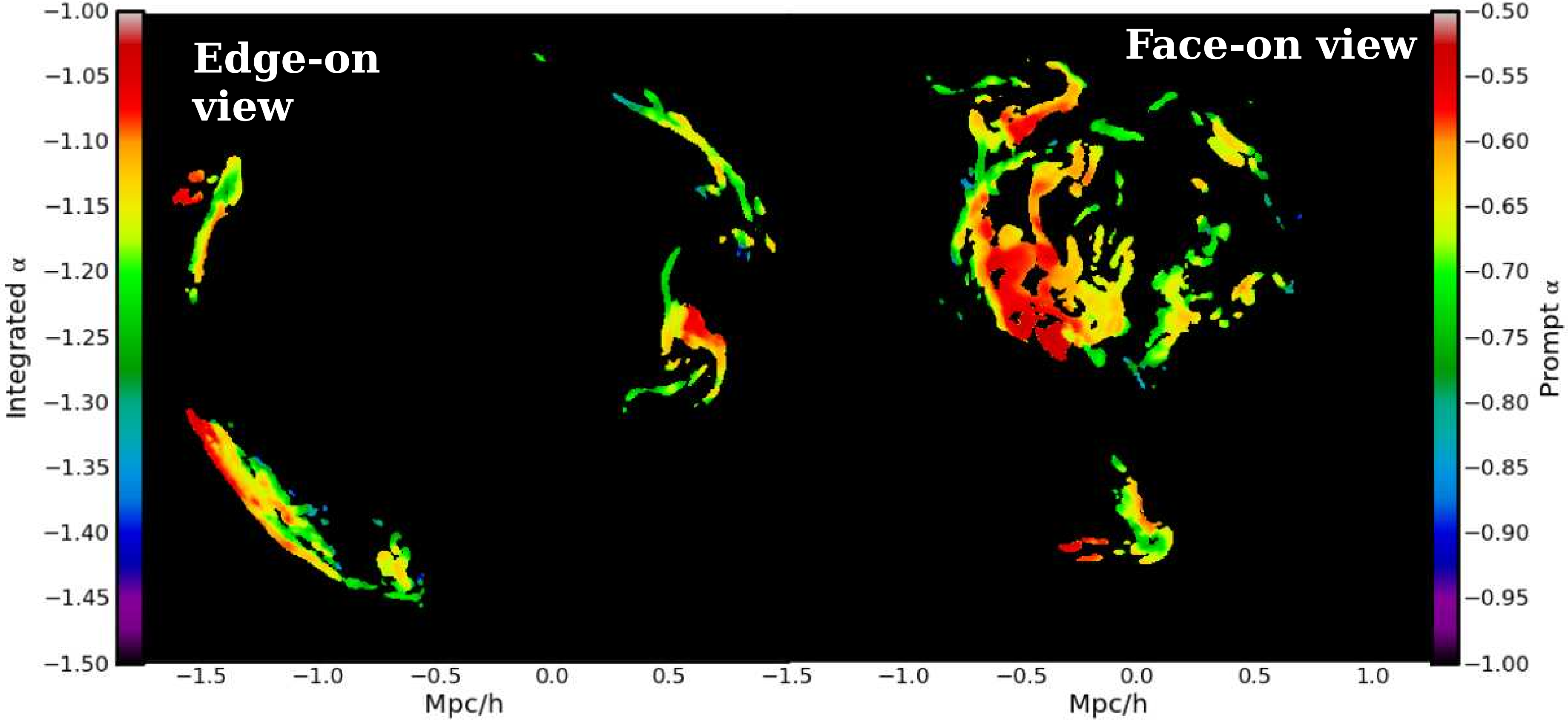
van Weeren et al. (2012)



Stroe et al. 2013

But, some disagree!

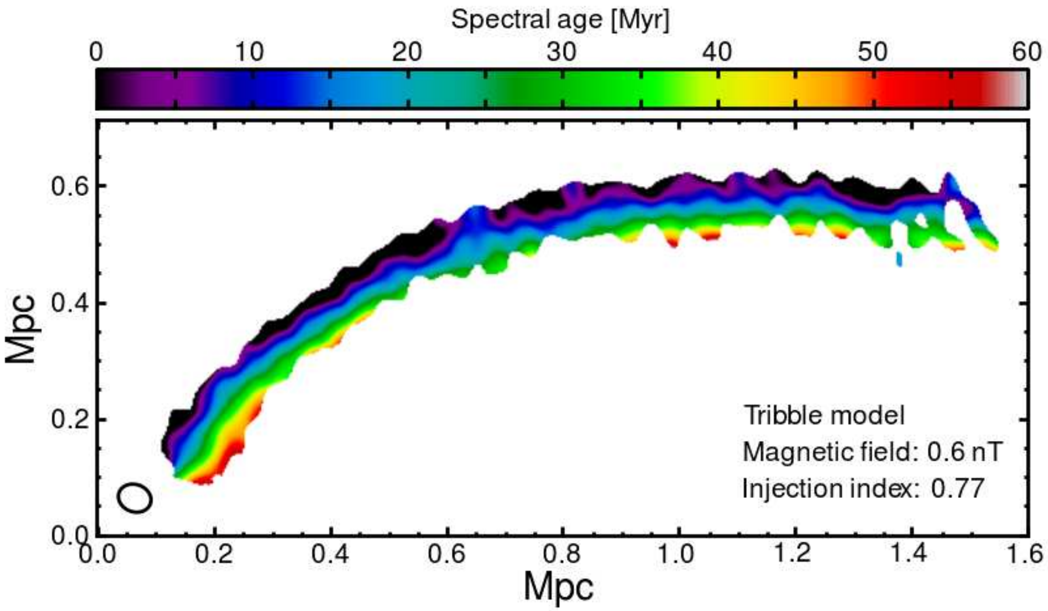
- You could see spectral index trends just be caused by projection effects



Spectral index of simulated radio relic emission at different viewing angles (Skillman et al. 2013)

Spectral modelling

- We fit ageing models pixel by pixel
- Clear trends of increasing spectral electron age from the shock front into the downstream area → shock is clearly moving northwards
- Age varies very little along the relic → maximum ICM inhomogeneities of 10% in density/temperature at 1.5 Mpc cluster-centric distance
- Shock moves at ~2500 km/s speed → cluster core passage ~800Myr ago
- Magnetic field is turbulent in the downstream area, pitch angle gets isotropised



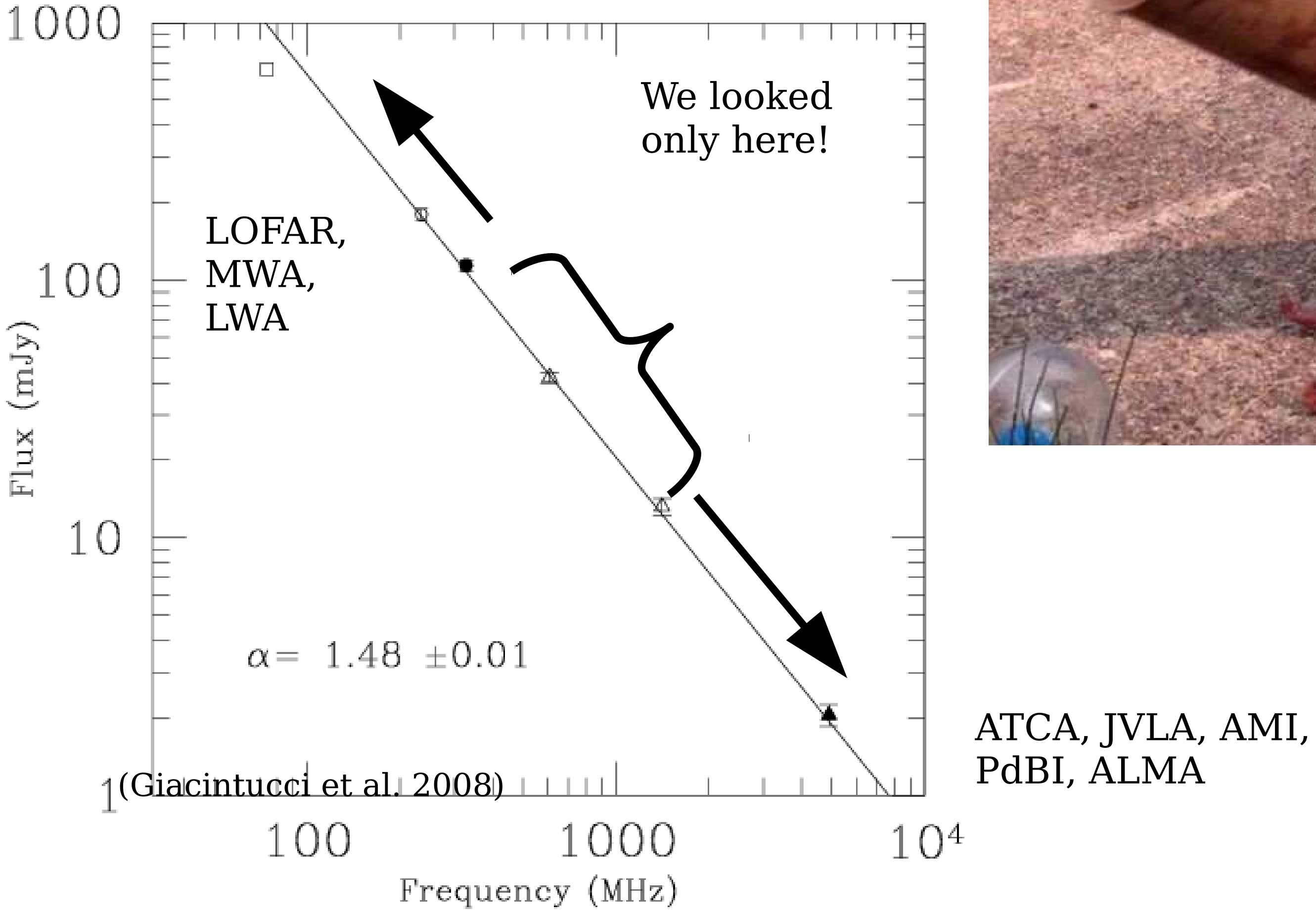
Age (time since last acceleration) of the electrons (Stroe et al. 2014c)

We now have a consistent picture!

Some violent galaxy cluster mergers lead to traveling shock waves. The shock waves accelerate thermal particles from the intra-cluster medium through the diffusive shock acceleration mechanism. The particles radiate synchrotron emission within an ordered magnetic field, with isotropisation of the pitch angle between the electrons and the B field.

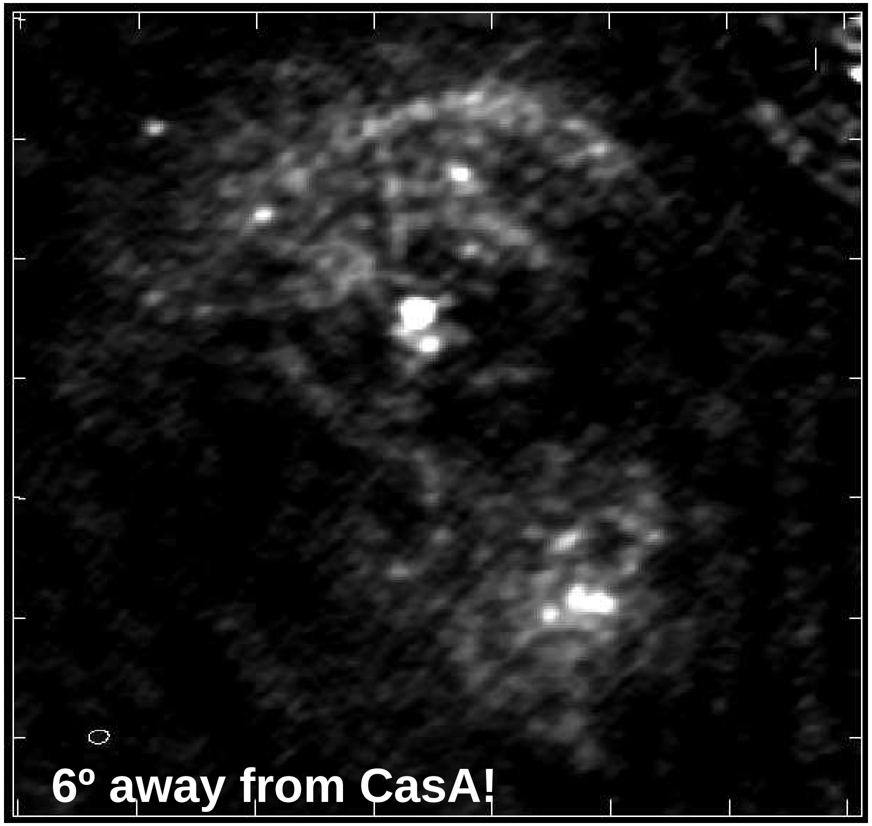
Or maybe we don't?

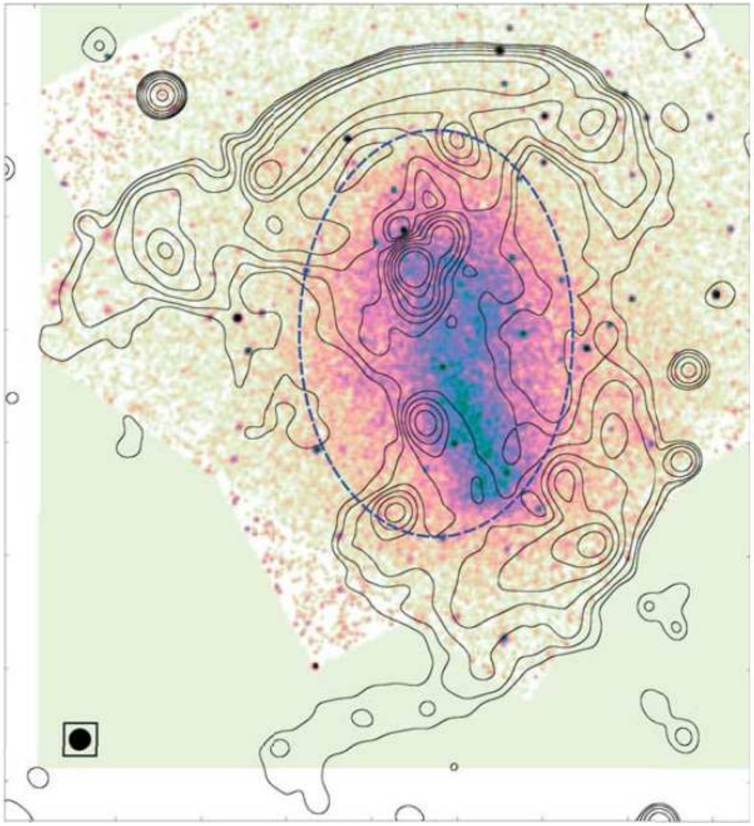
We searched a narrow frequency range!



Low frequencies!

- LOFAR commissioning data at 60 MHz (circa 2012) vs Hoang et al. (2017) at 150 MHz

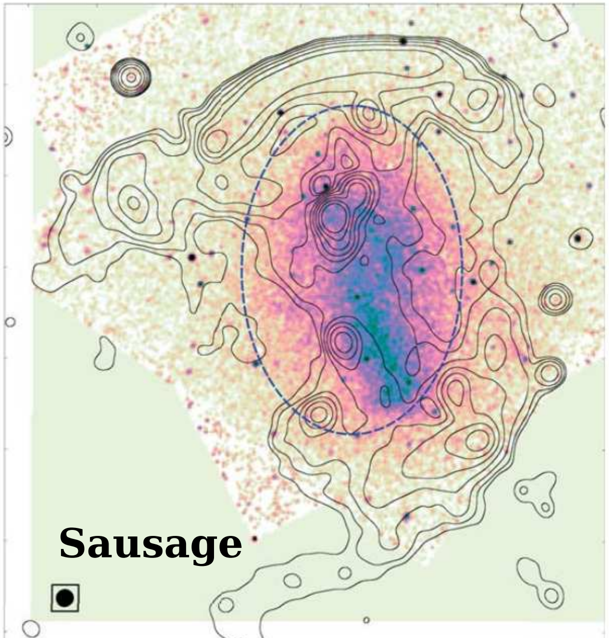




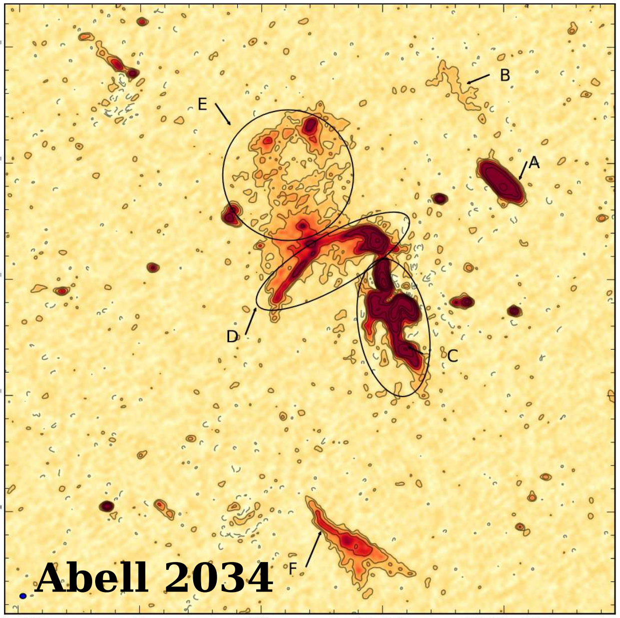
Low frequencies = potential for discovery

- Steep spectrum sources
- New types of sources

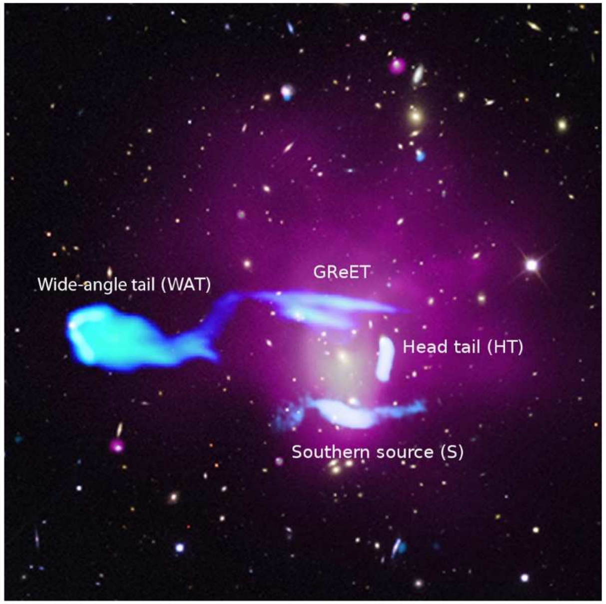
Hoang et al. (2017)



Shimwell et al. (2016)



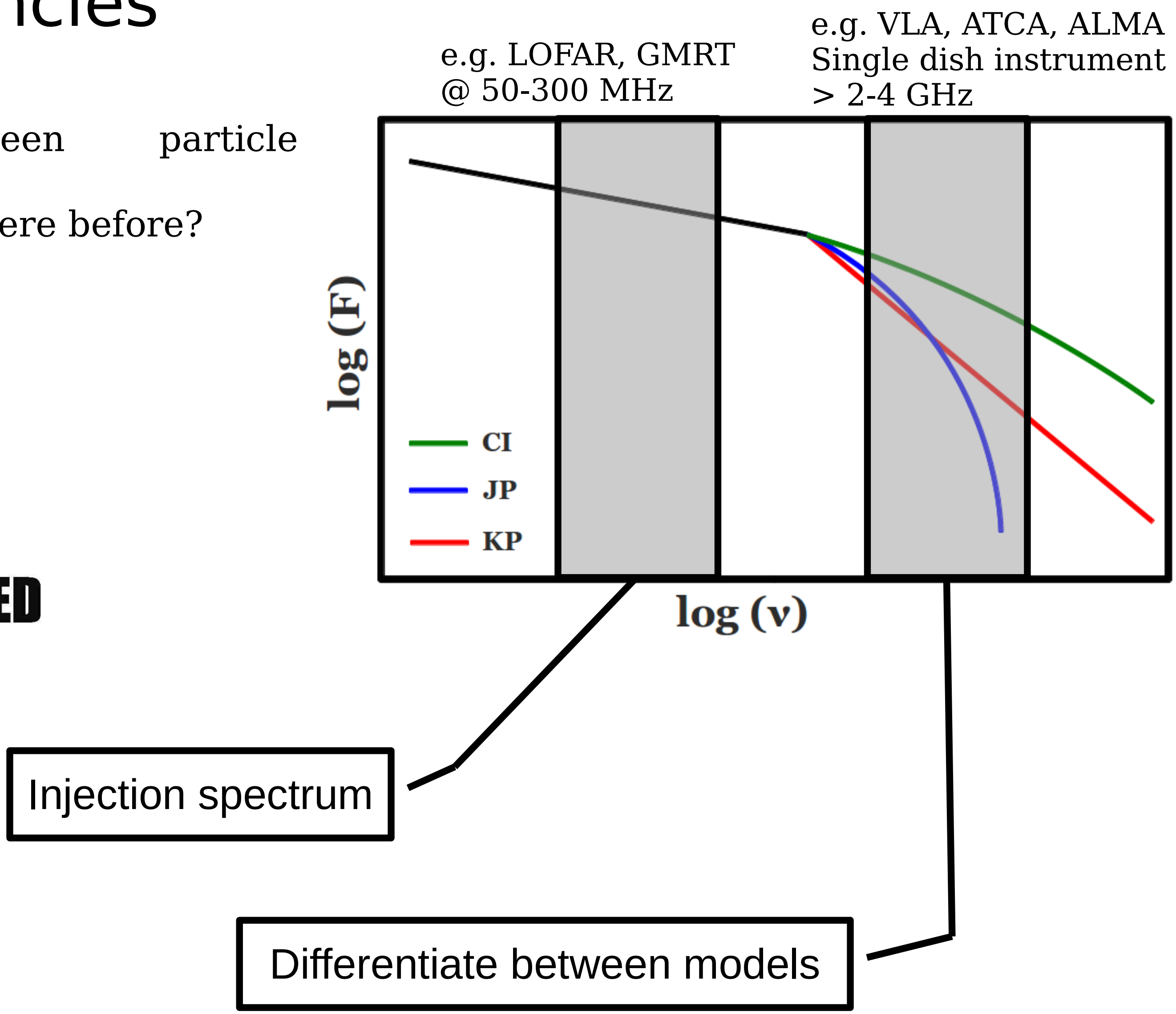
de Gasperin et al. (2017)



GReET

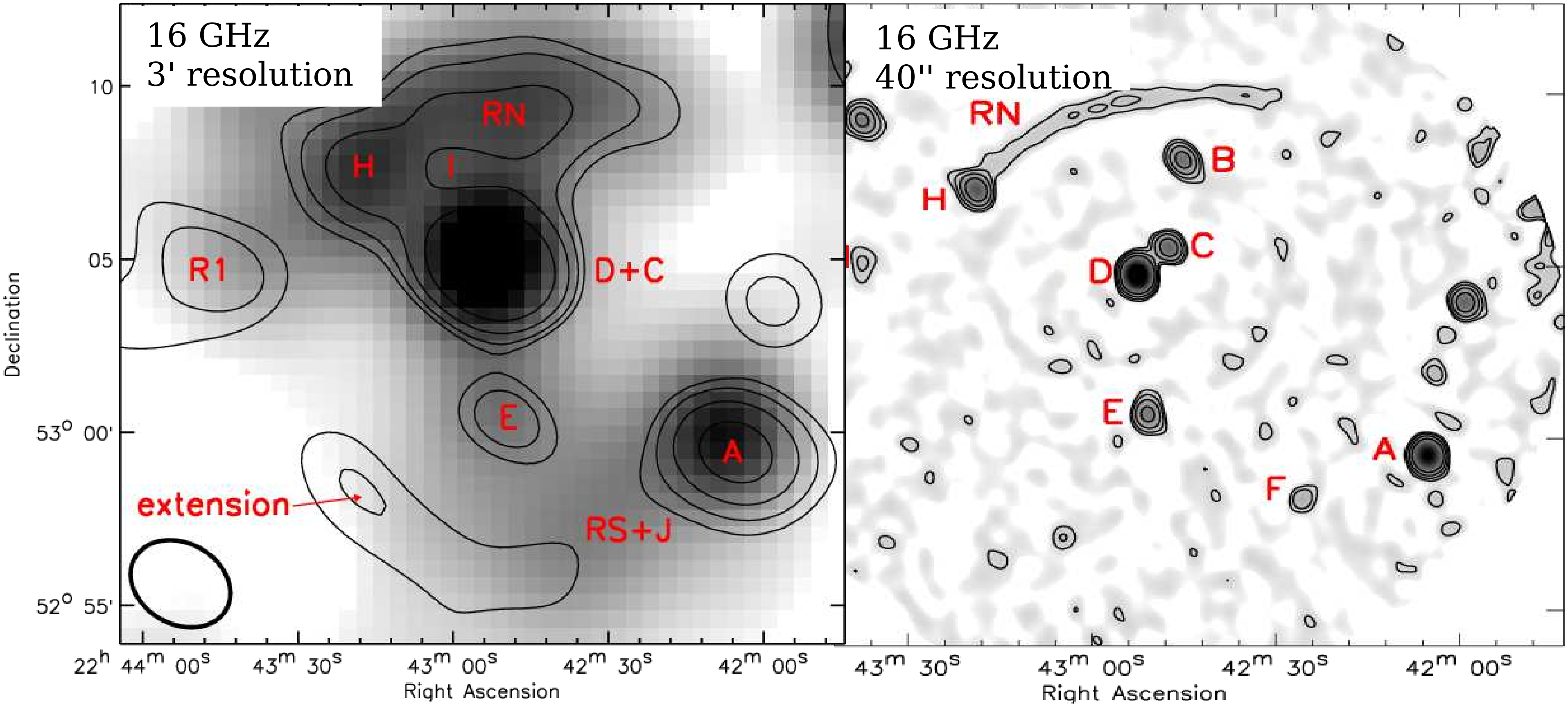
High frequencies

- Beyond 2-4 GHz
- Differentiate between particle acceleration models
- Why haven't we look here before?



16 GHz detection!

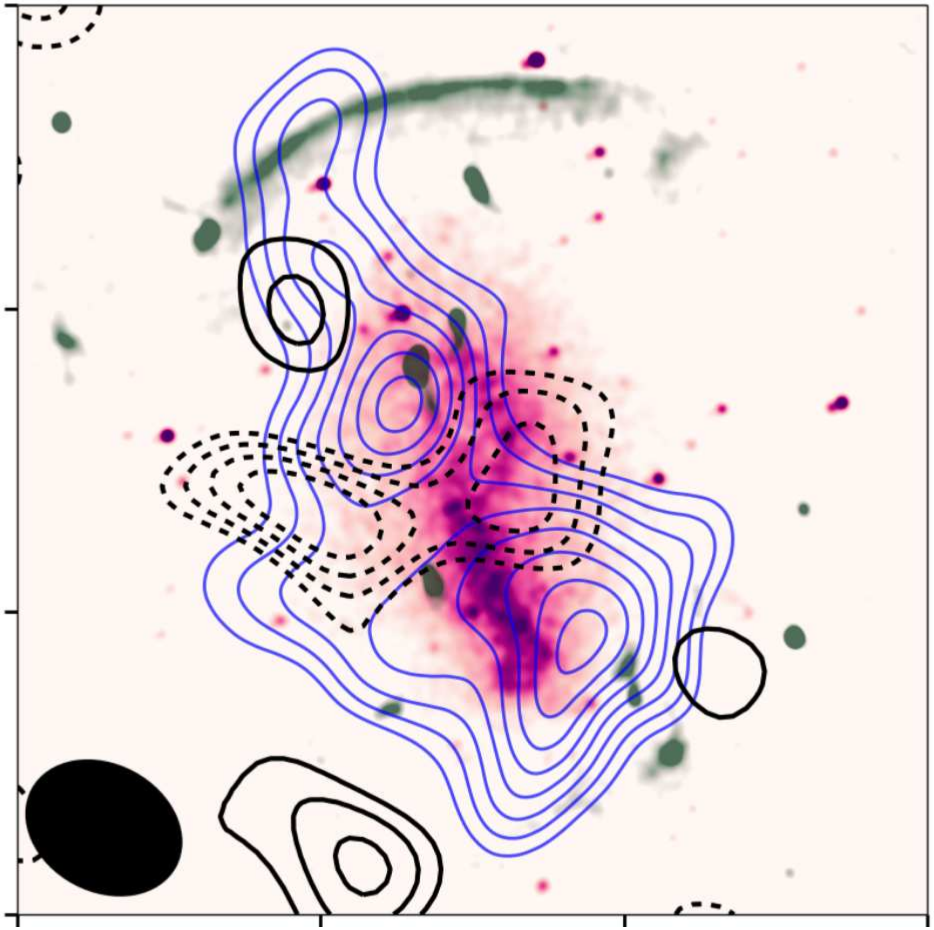
- We were looking for the Sunyaev-Zeldovich signal of the cluster
- Radio maps with contours drawn at [4, 8, 16, 32] · σ_{RMS}
- Recover northern relic at high S/N



Stroe et al. (2014b)

An aside: constraining the SZ

- SZ signal shows high pressure region
- Disc-like region of high pressure gas, formed as the progenitors merged → torus-like when the progenitor gas cores orbited past each other



Dashed contours = SZ from AMI (Rumsey et al. 2017)

Blue contours = weak lensing,

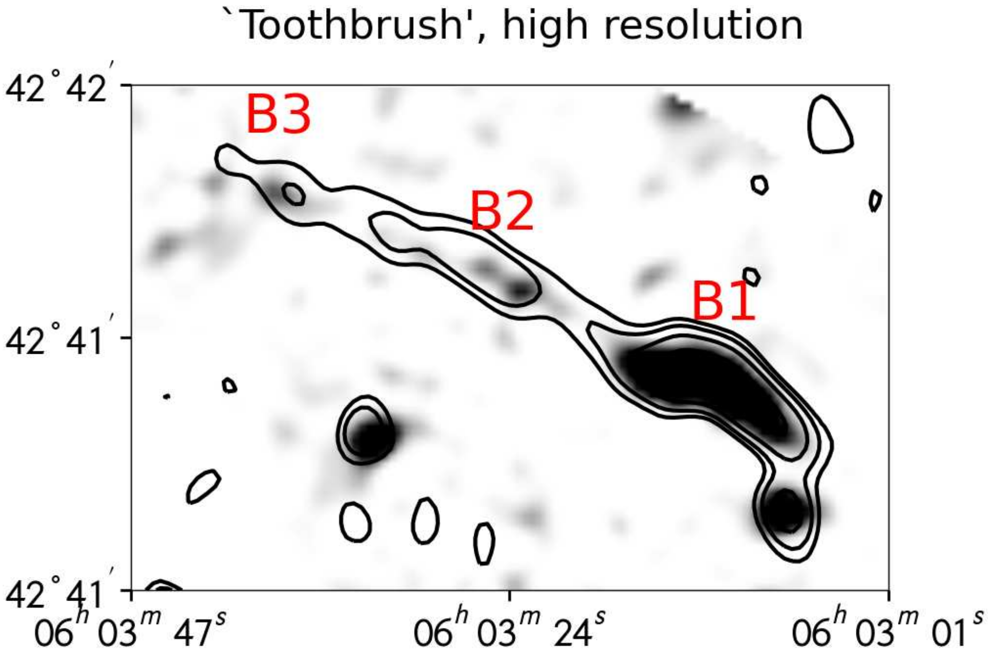
Subaru+CFHT (Jee, Stroe et al. 2015)

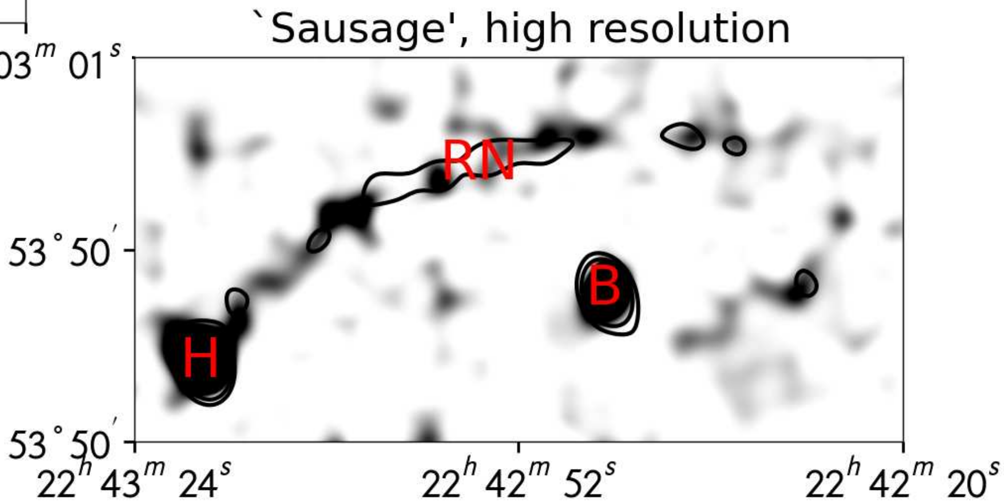
Pink = X-ray from Chandra (Ogrean et al. 2013)

Green = Radio @ 300 MHz (Stroe et al. 2013)

30 GHz detection!

- For both the 'Sausage' and the 'Toothbrush'

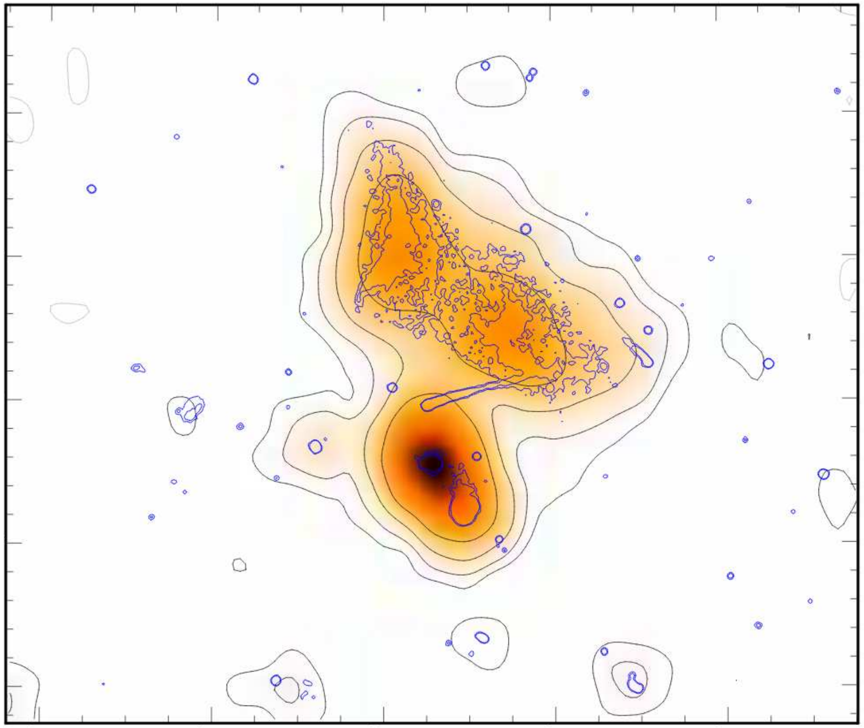




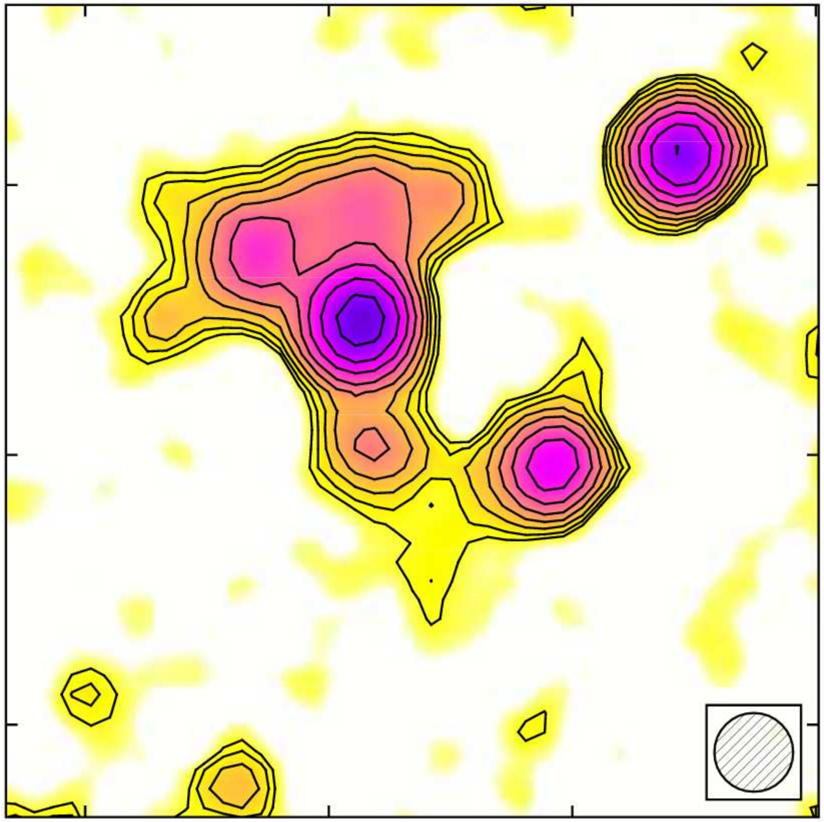
Stroe et al. (2016)

More high frequency detections!

- Single dish instruments!
- Detection with SRT at 7 GHz: Sausage (Loi et al. 2017)
- Detections with Effelsberg at 5, 8 and 10 GHz: A2256 (Trasatti et al. 2015), Sausage, Toothbrush, ZwCl, A1612 (Kierdorf et al. 2017)



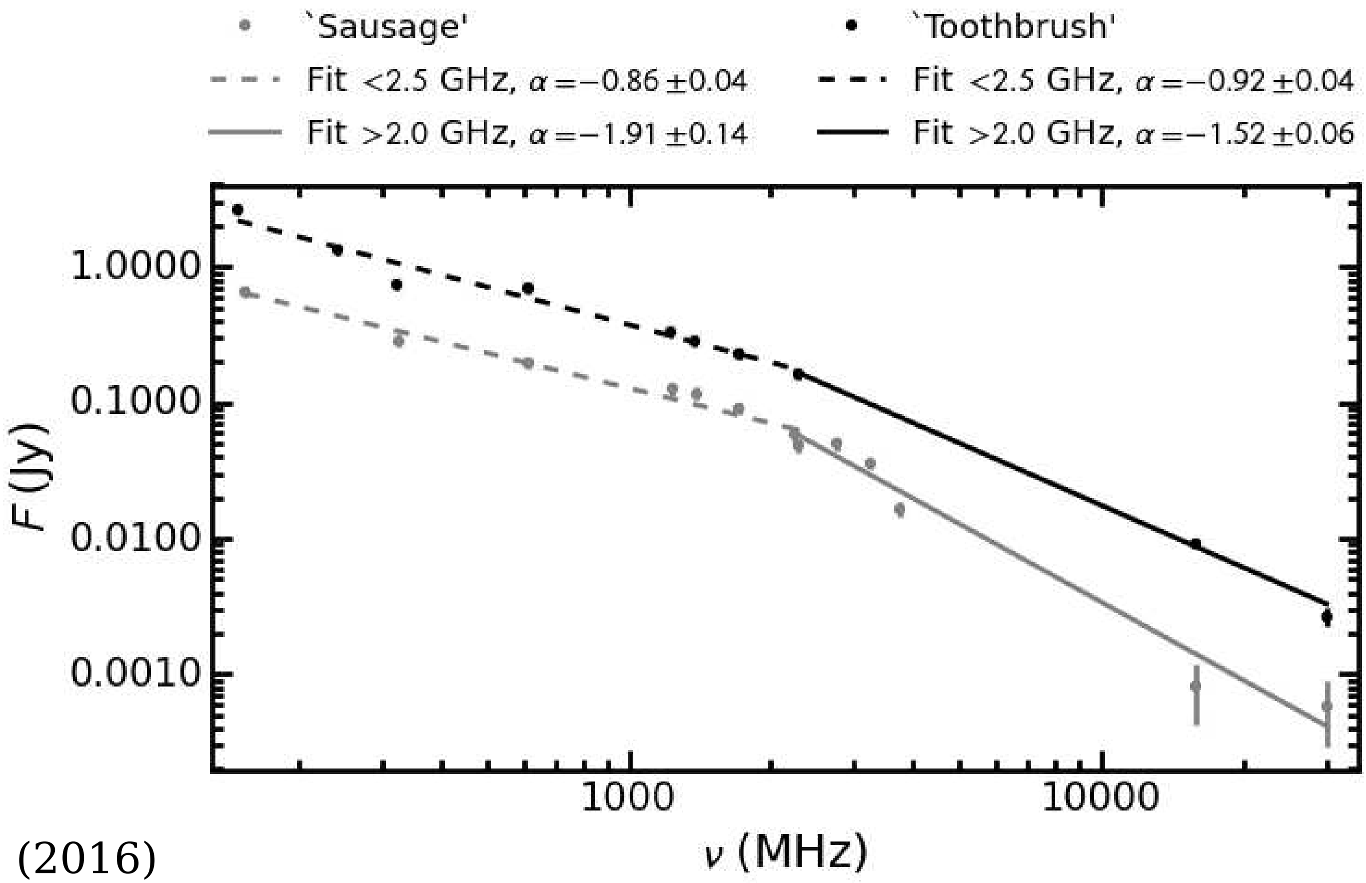
Kierdorf et al. (2017)



Loi et al. (2017)

Integrated spectra at high frequency

- All the radio, X-ray data and simulations consistent with simple DSA
- But, steepening after 2 GHz?



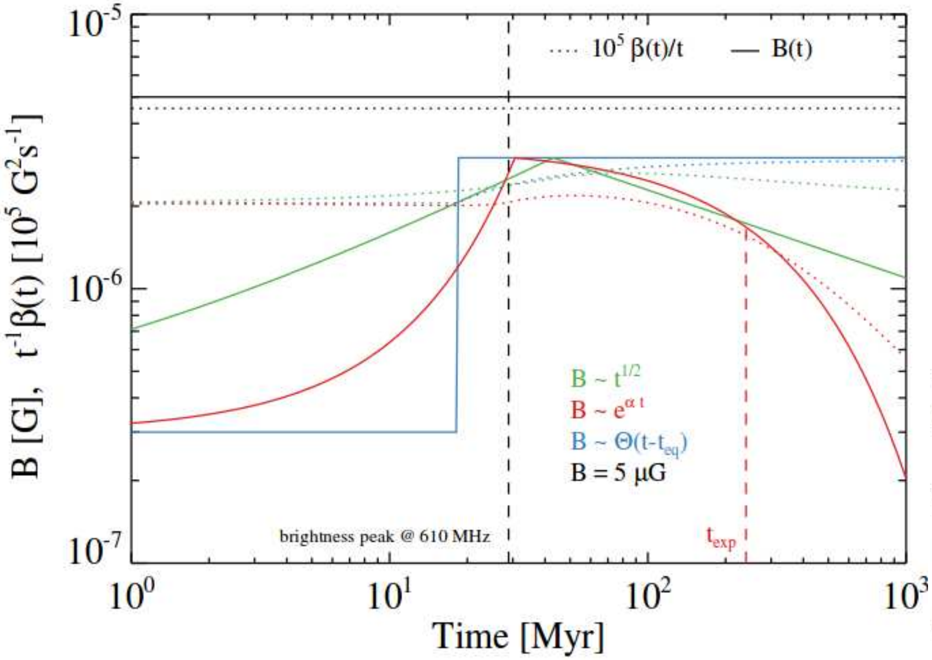
Stroe et al. (2016)

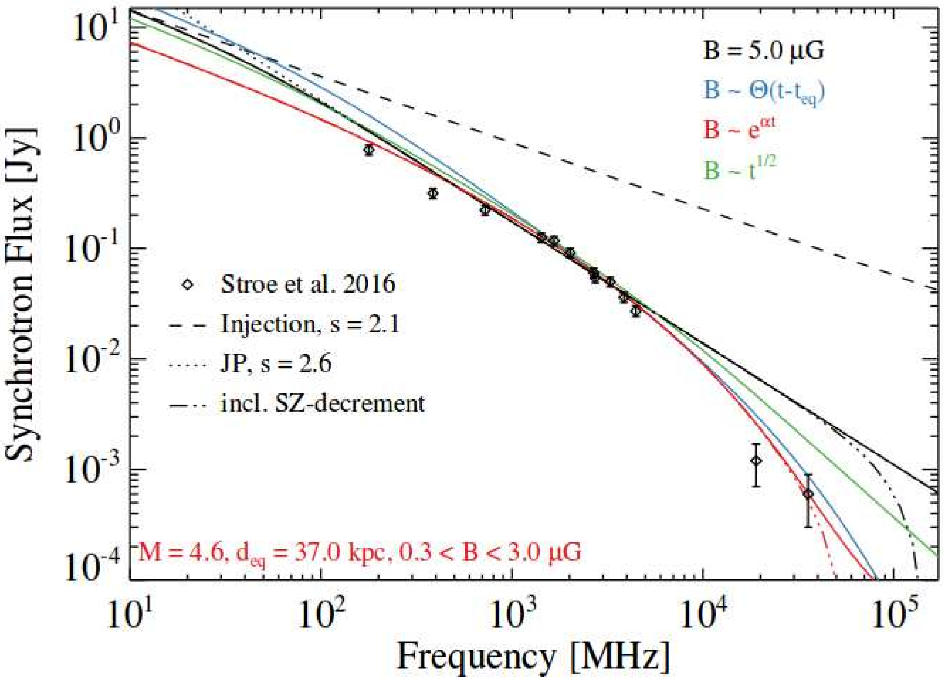
Steepening at high frequency

- Inhomogeneous medium - density, temperature gradient across the relic – **not enough**
- Sunyaev-Zeldovich - **not enough**
  - e.g. Basu et al. (2016)
- Pre-accelerated electron population – AGN activity - **possible**
  - e.g. Kang & Ryu (2016)
- Evolving magnetic field - **possible**
  - e.g. Donnert et al. (2016)

Magnetic field evolution

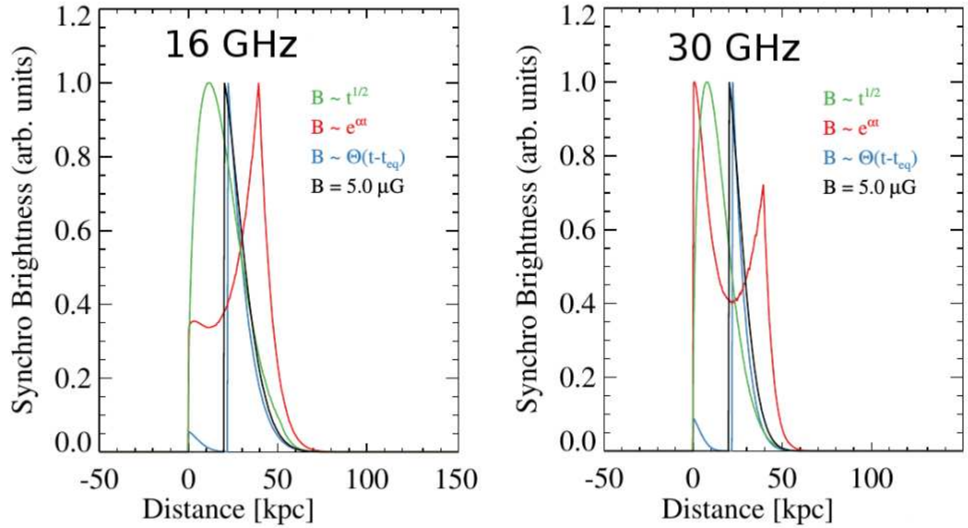
- Evolving magnetic field:
  - Behind brightness peak, magnetic field declines exponentially alongside adiabatic expansion of the gas



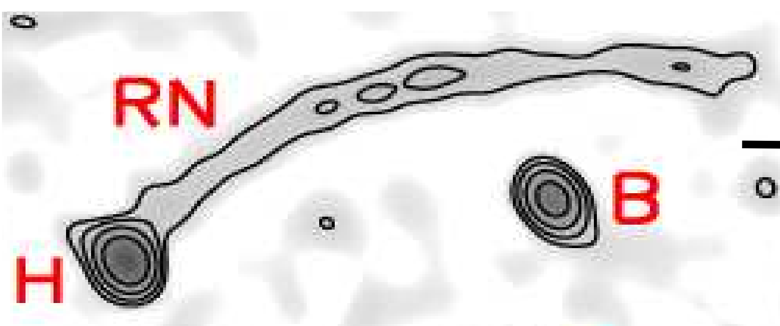


Donnert, Stroe et al. (2016)

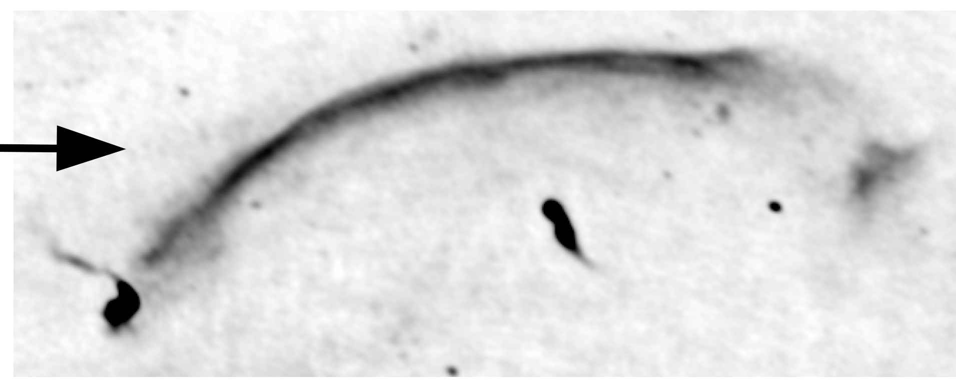
Can we constrain models?



AMI data – 40”

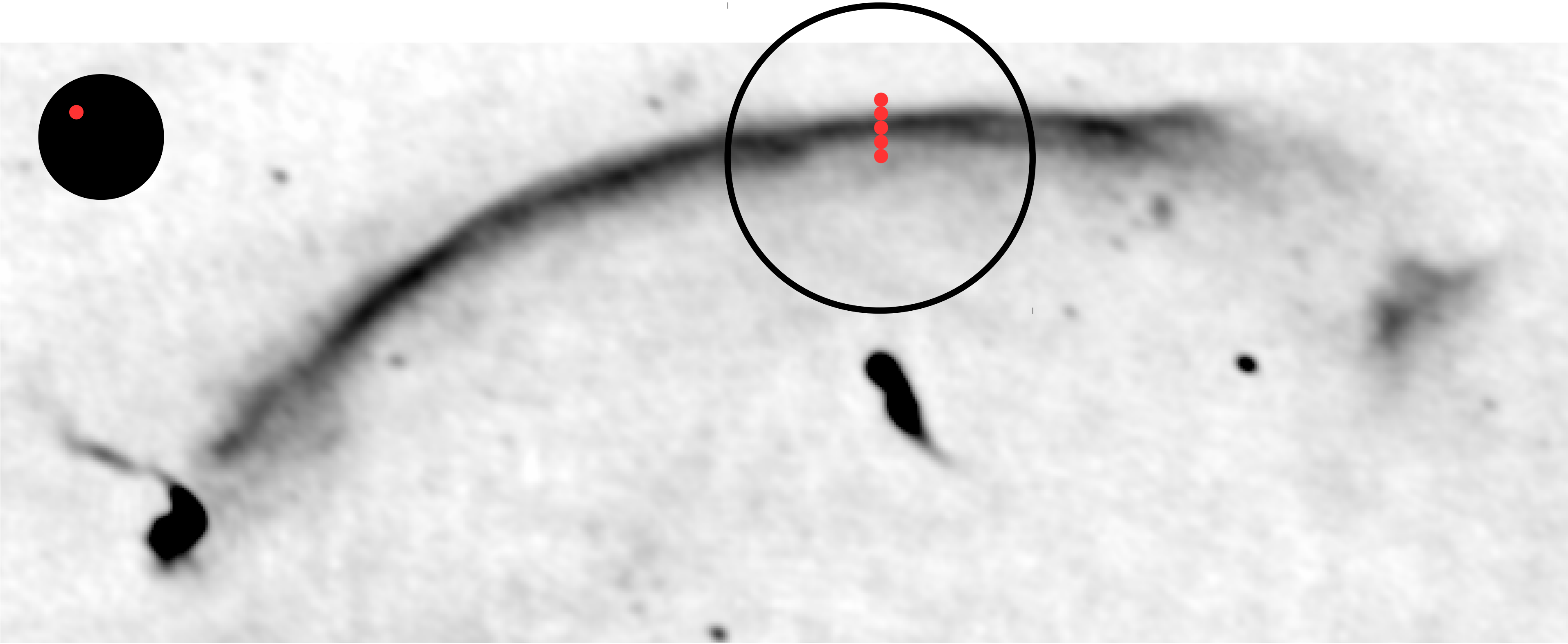


GMRT 610 MHz-like resolution

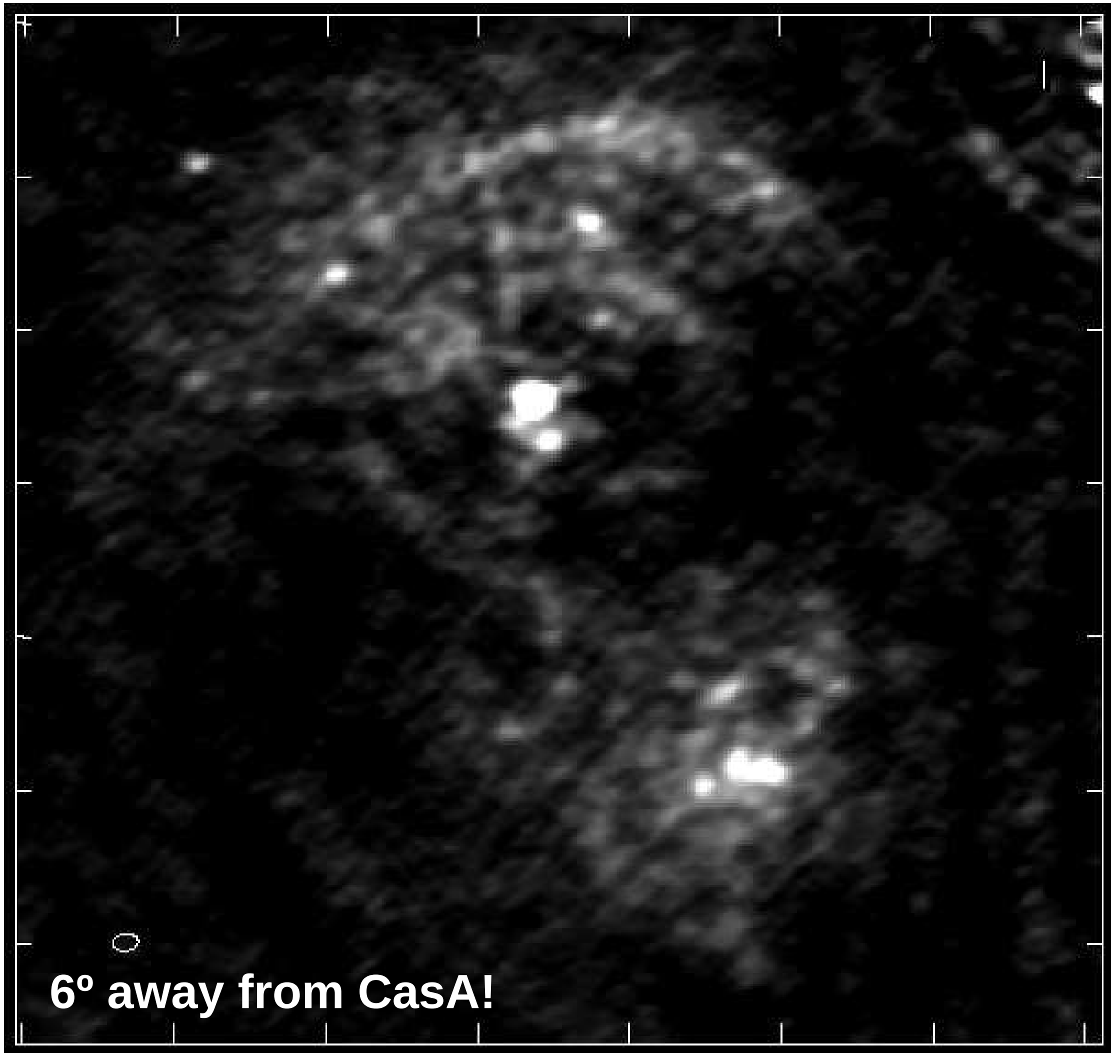


VLA observations!

	X	Ku	K
Frequency	8-12 GHz	12-18 GHz	18-26.5 GHz
Resolution	7” 21 kpc	4.6” 14 kpc	3.1” 9 kpc
FOV	145”	97”	66”

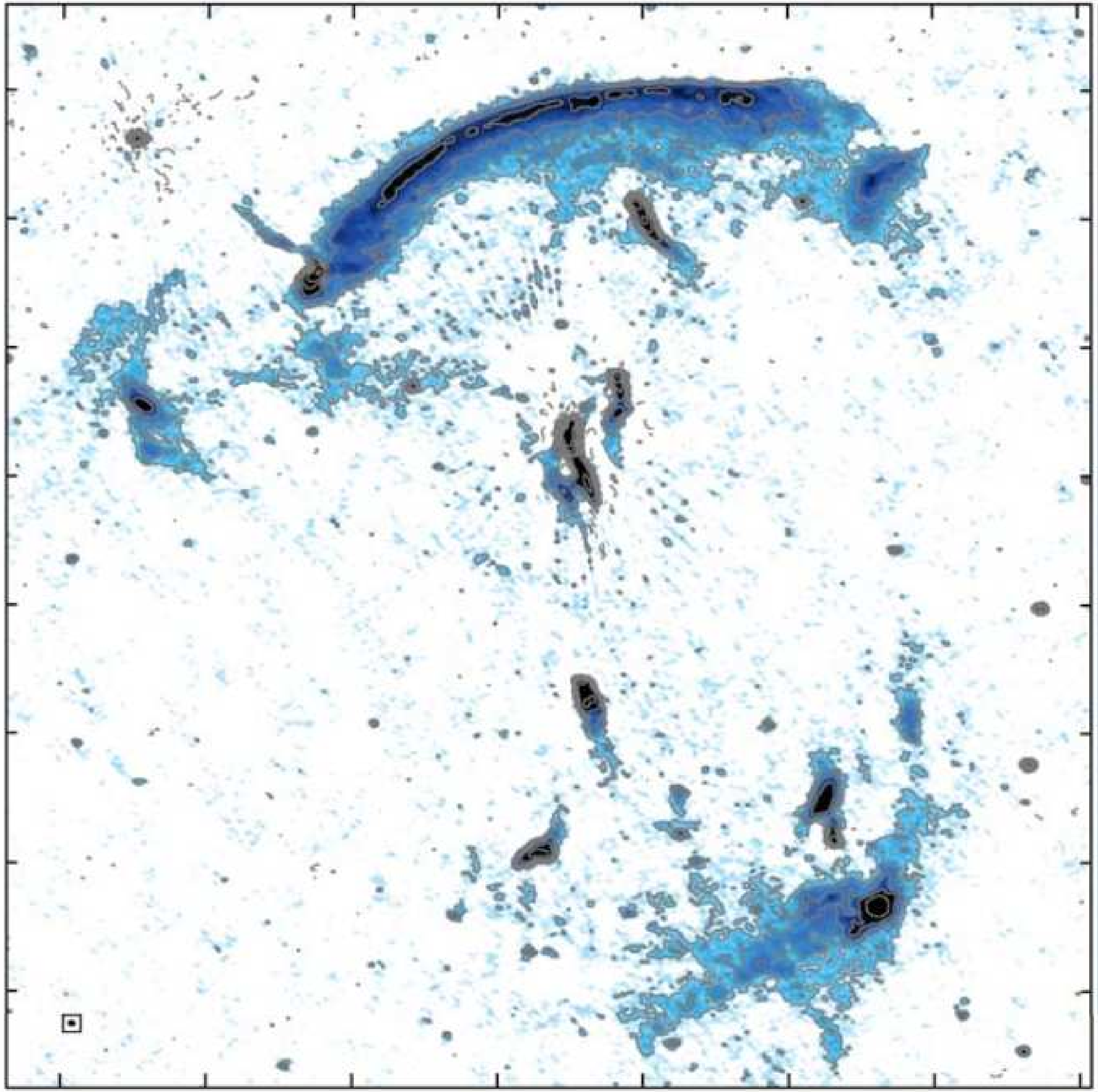


LOFAR image at 60 MHz



(Stroe et al. in prep)

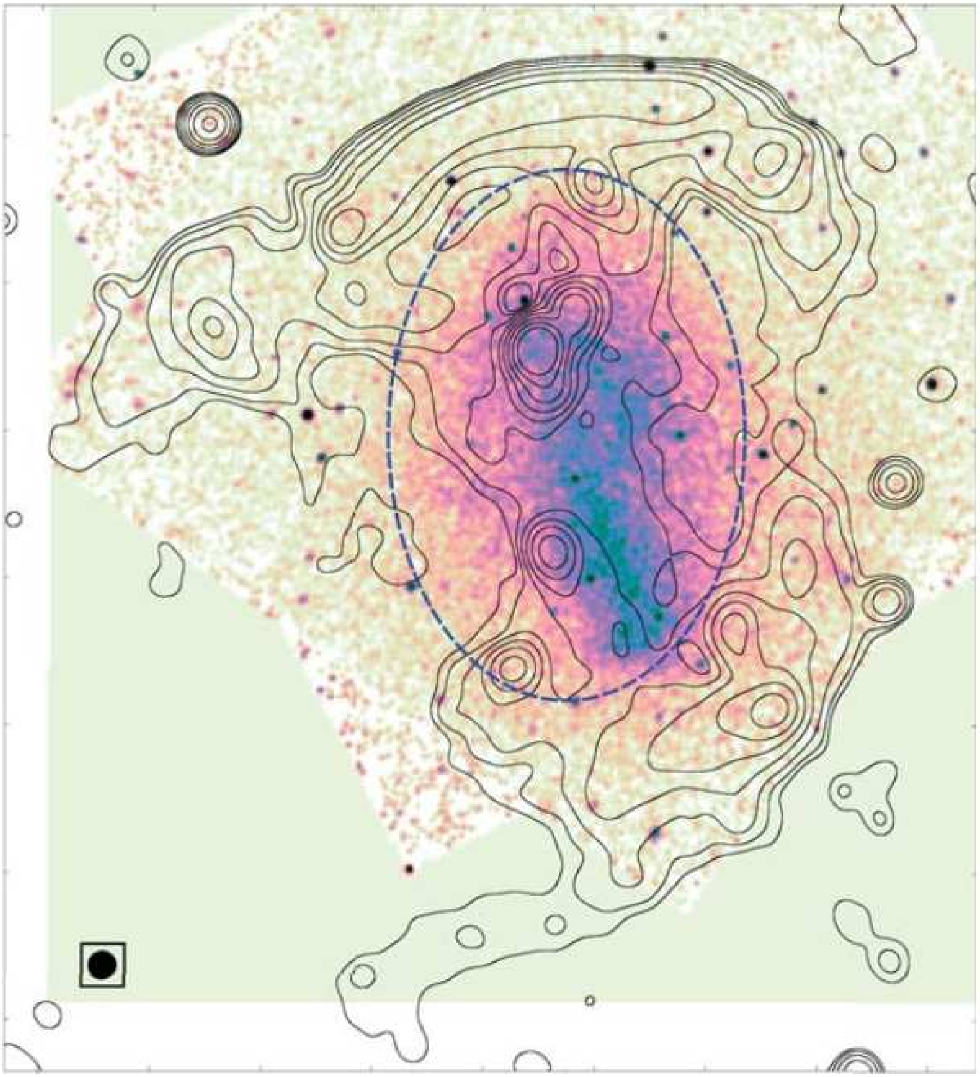
LOFAR image at 150 MHz



(Hoang, Shimwell, Stroe et al. 2017)

- 140 μJy/beam noise
- 10 times better than GMRT
- 7'' x 5'' resolution
- 4 times better than GMRT
- Comparable to 610 MHz GMRT

LOFAR image at 150 MHz – low resolution

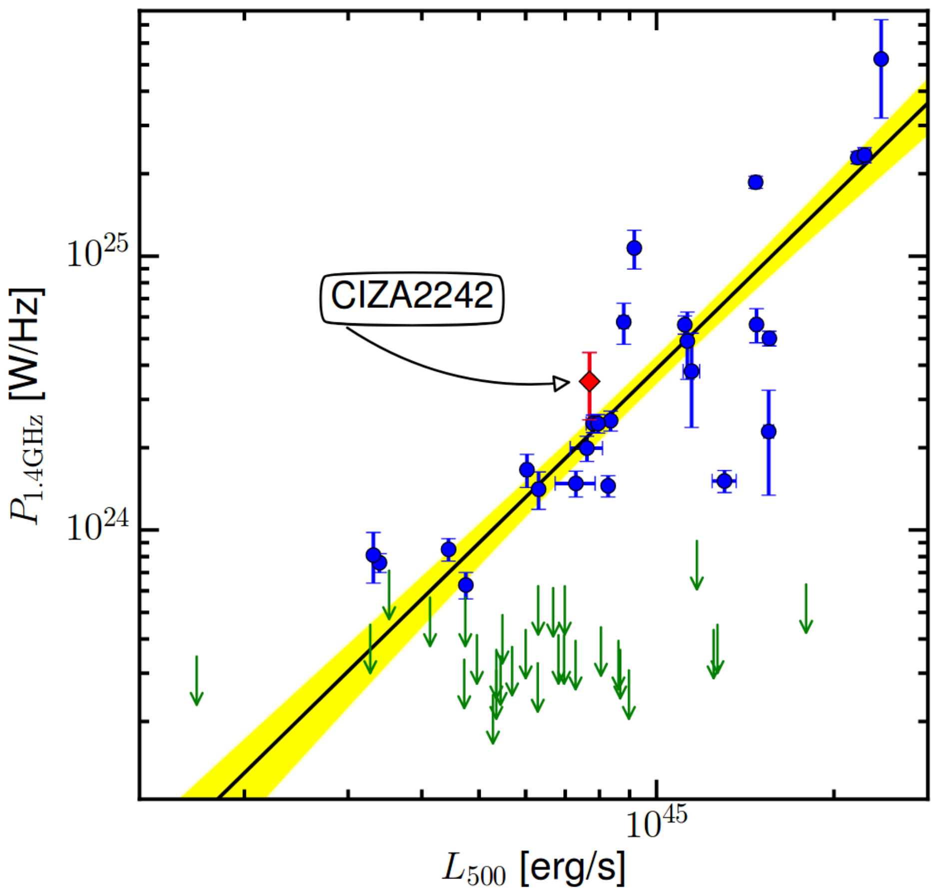


(Hoang, Shimwell, Stroe et al. 2017)

- Faint cluster wide halo!
- Not detected at other frequencies
- Steep spectrum? NO! Flat, but very faint!

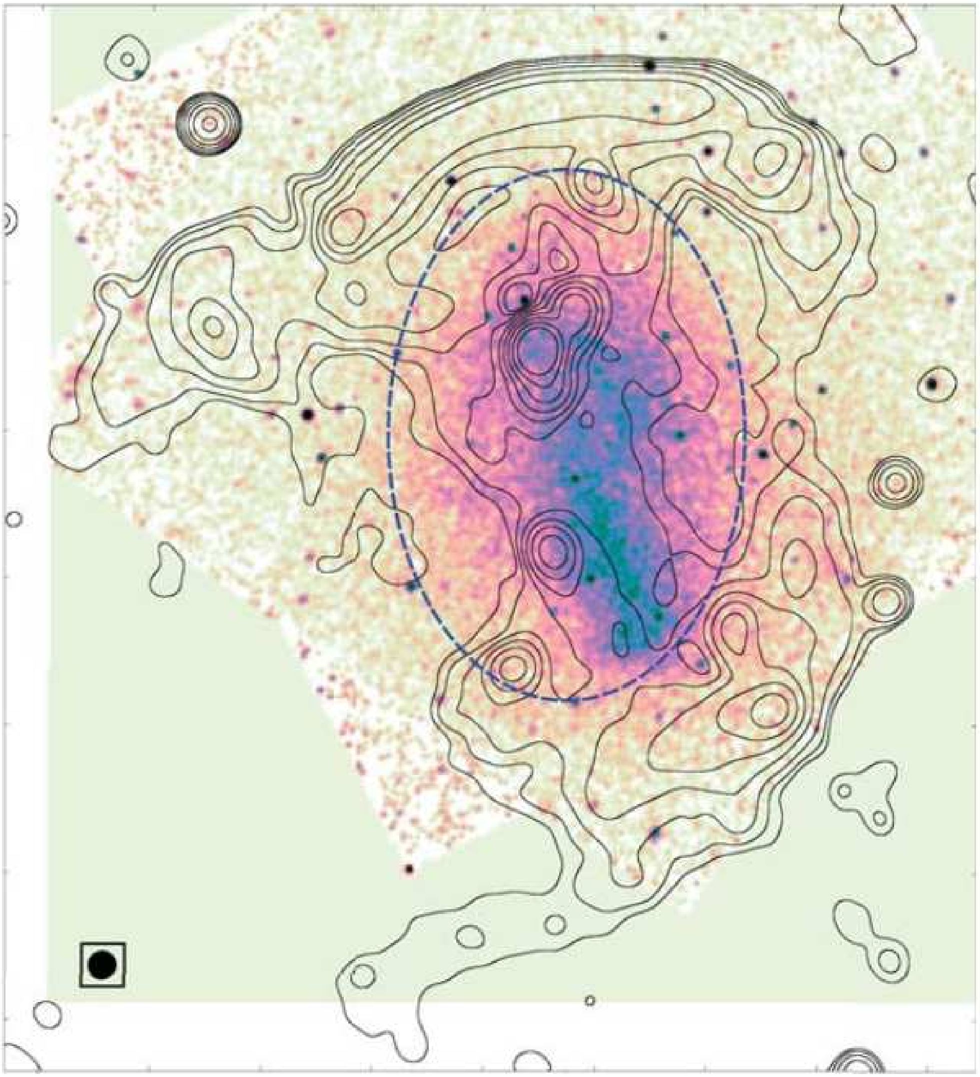
Halo power

- Halo power correlates with X-ray luminosity and cluster mass
- Sausage halo is relatively faint and very steep spectrum:



(Hoang, Shimwell, Stroe et al. 2017)

Sausage halo



(Hoang, Shimwell, Stroe et al. 2017)

- Young cluster (<1 Gyr after core passage)
- Radio halo still in the brightening phase

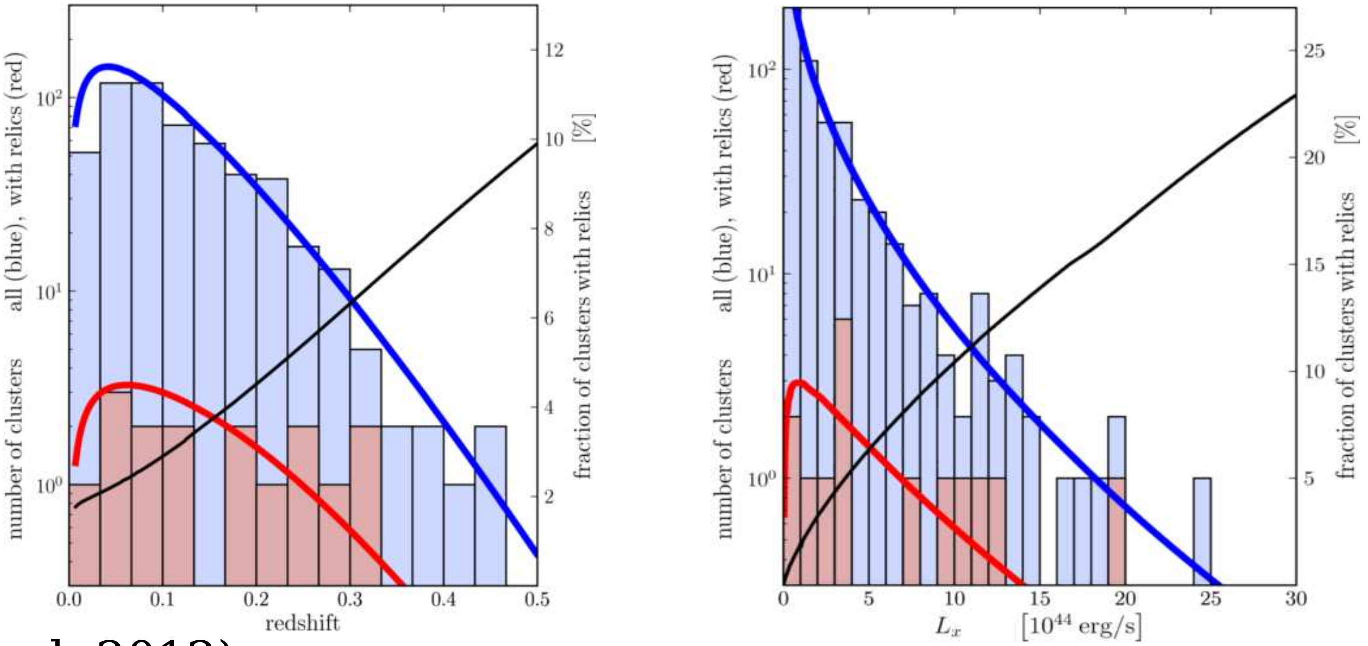
Next steps for radio relics and halos?

- **Low** and **high frequency** data:
    - Injection spectrum of electrons
    - Ageing mechanism
    - SKA, LOFAR, ALMA
- More **realistic models**
- Detailed studies on **larger samples**:
    - Cosmic evolution of relics and halos

CartoonStock.com

Next steps for radio relics and halos?

- **Low** and **high frequency** data:
    - Injection spectrum of electrons
    - Ageing mechanism
    - SKA, LOFAR, ALMA
- More **realistic models**
- Detailed studies on **larger samples**:
    - Cosmic evolution of relics and halos



(Nuza et al. 2012)

Take away message

Cluster shocks and turbulence dramatically influence the evolution of the ICM

Take away message

Cluster shocks and turbulence dramatically influence the evolution of the ICM