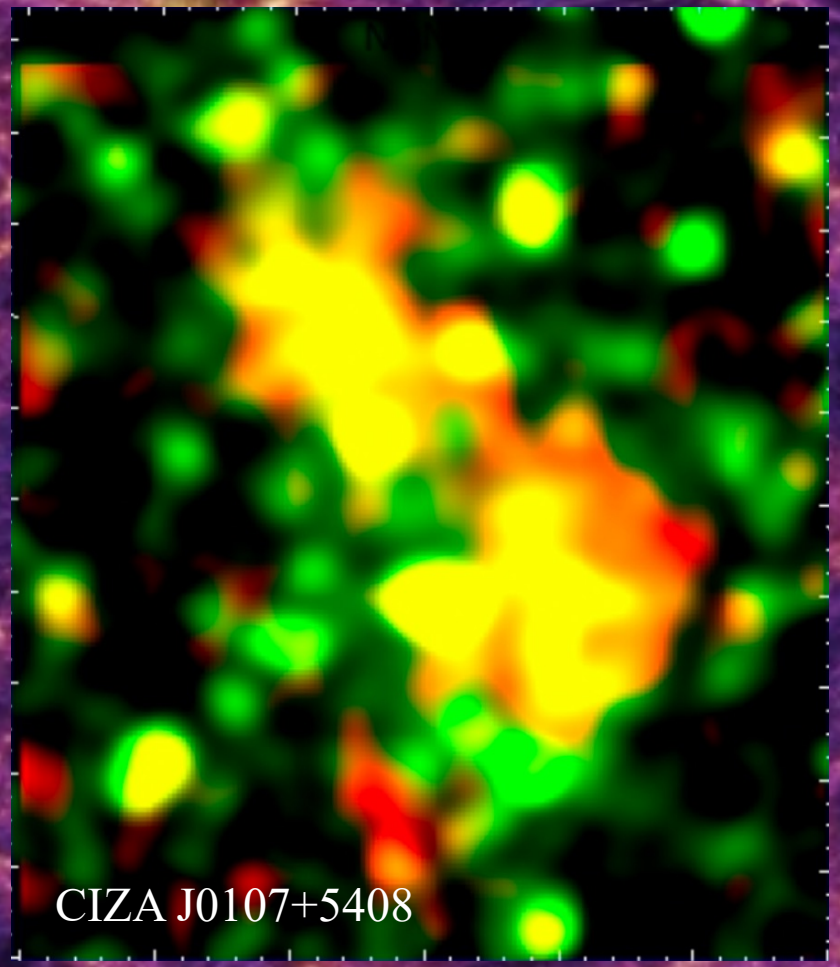
# DIFFUSE RADIO EMISSION FROM GALAXY CLUSTERS

EMMA SCHWARTZMAN – 1/29/2021

# INTRODUCTION TO GALAXY CLUSTERS

- Largest bound objects in our universe
  - Connected by elongated of filaments of galaxies
    - Composed of warm-hot intergalactic medium (WHIM)
    - WHIM has lower density + temperature, but is ~50% of universe's baryons
  - Creates larger, but unbound structures
- Contain up to several thousand galaxies each
- Mass:
  - 15% baryonic
    - Mostly in intracluster medium – hot! - emits bremsstrahlung (X-ray)
  - 80% dark matter



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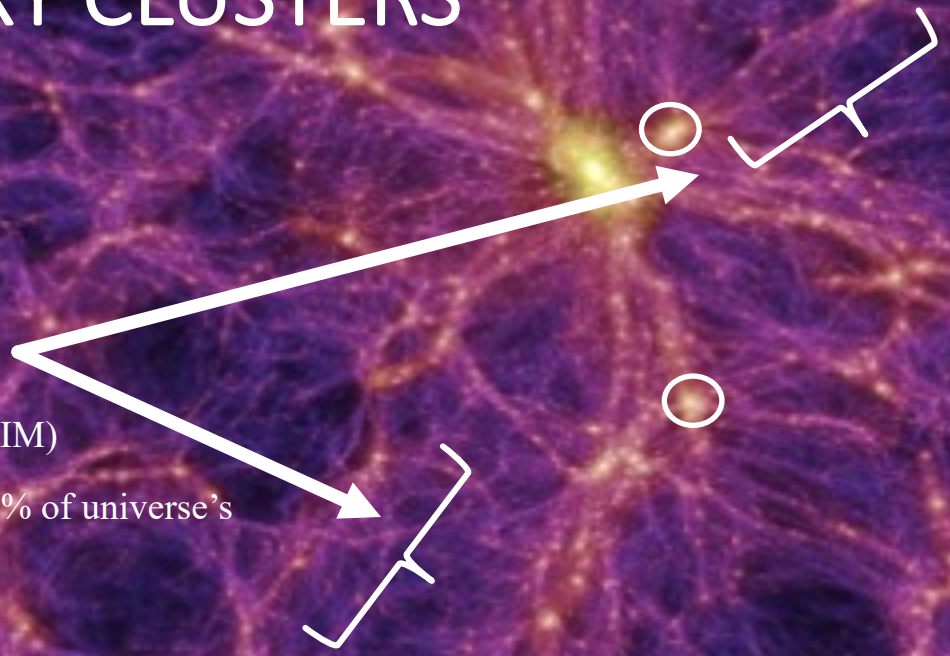

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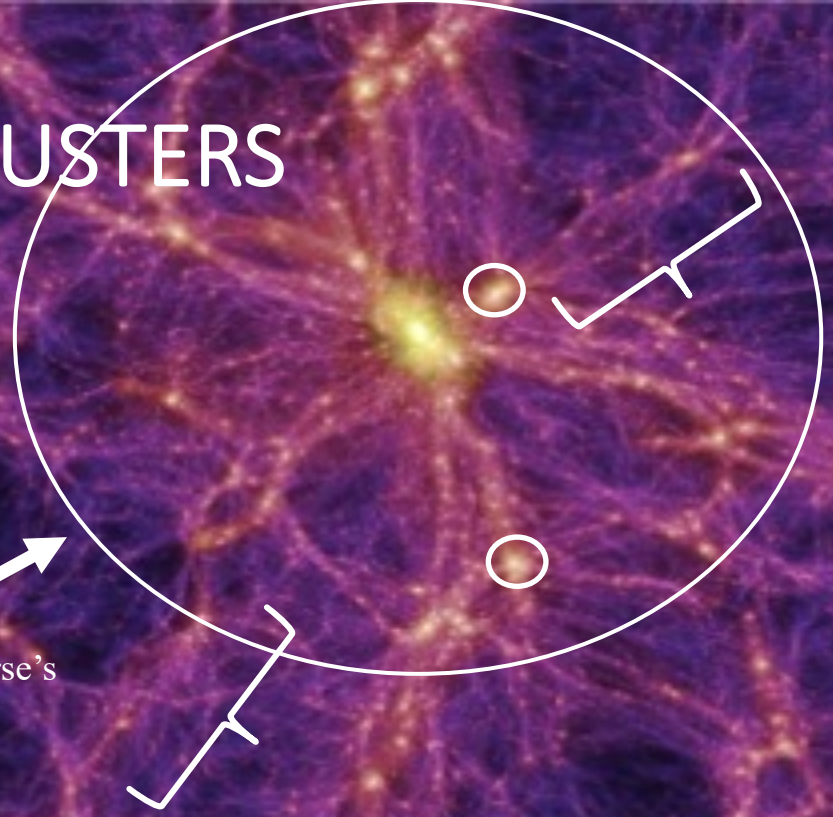

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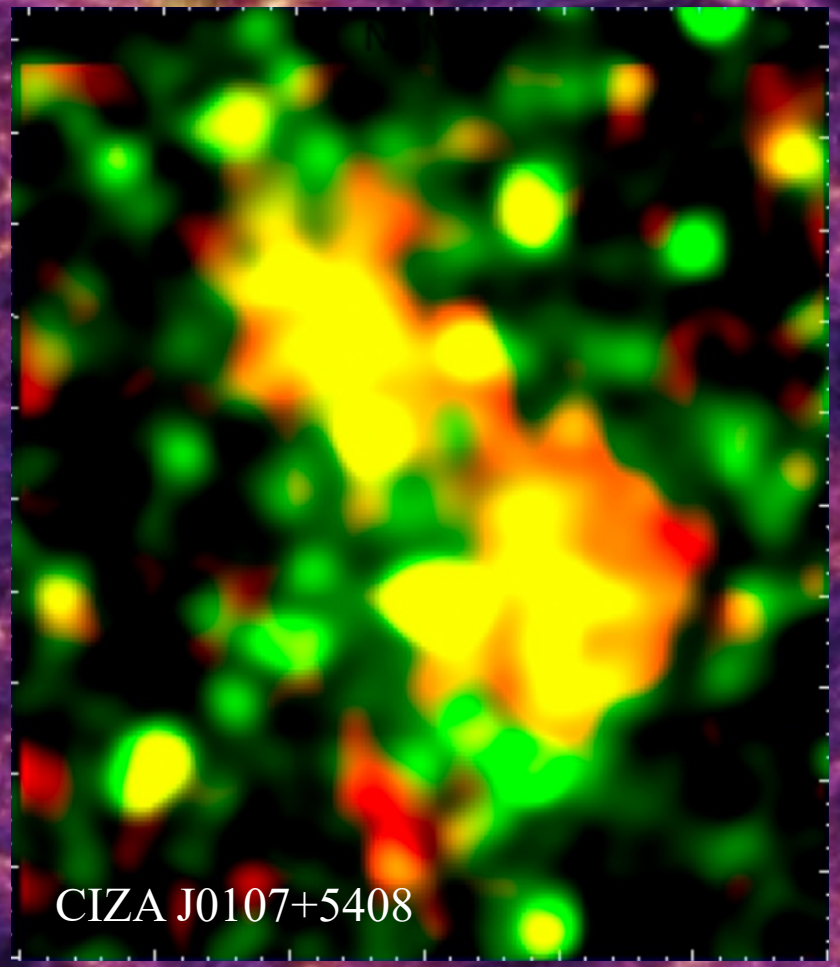
- Radio galaxies within clusters show signs of ICM interaction in their jets and halos



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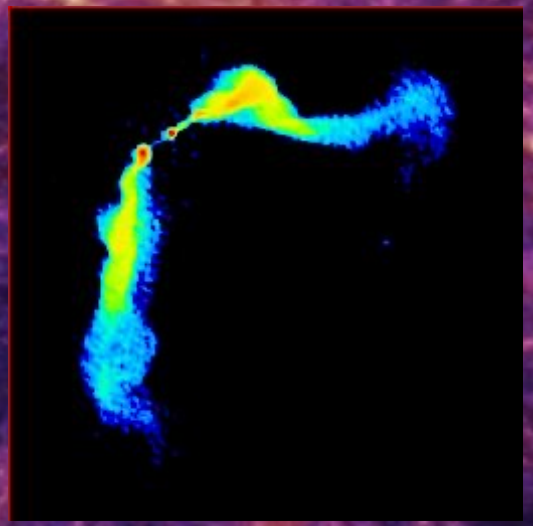

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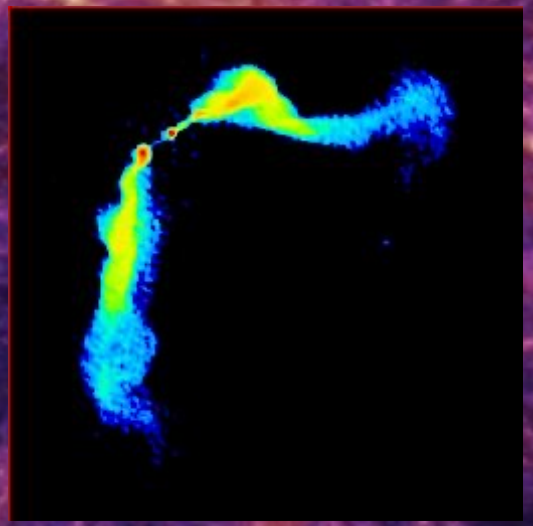

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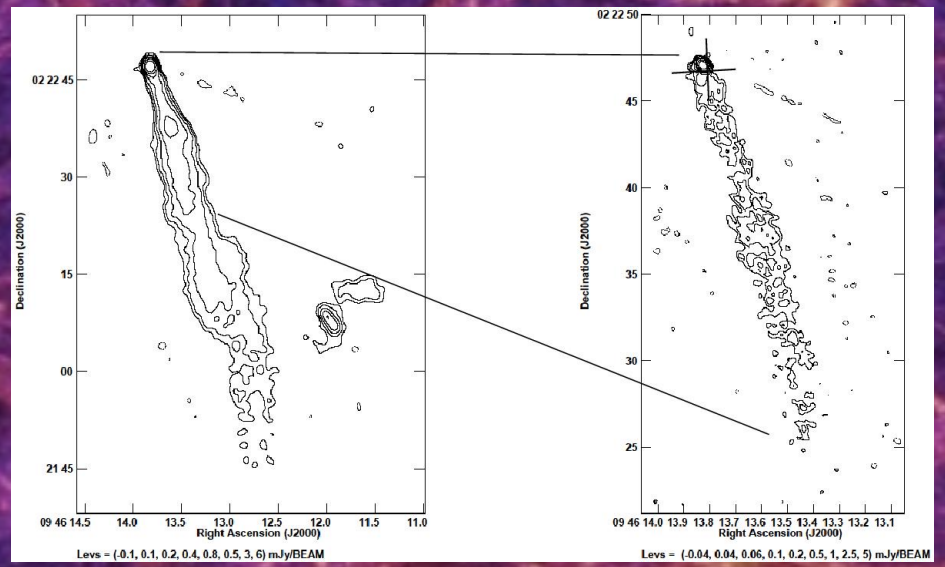

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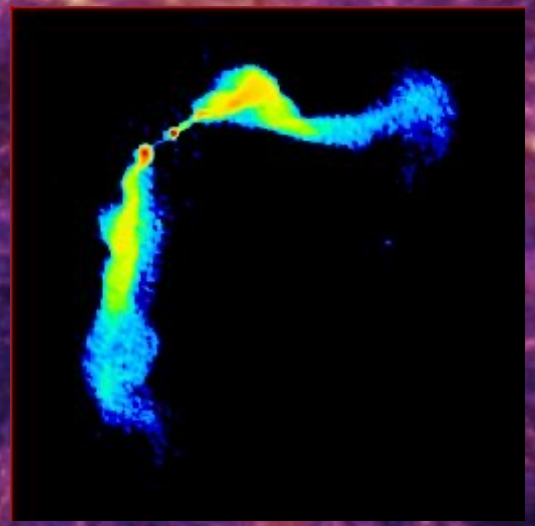

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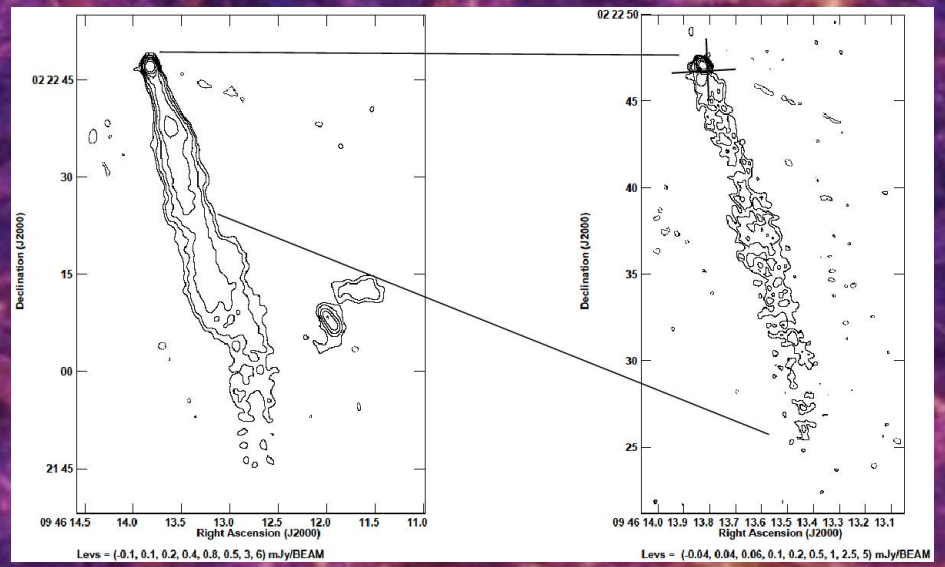
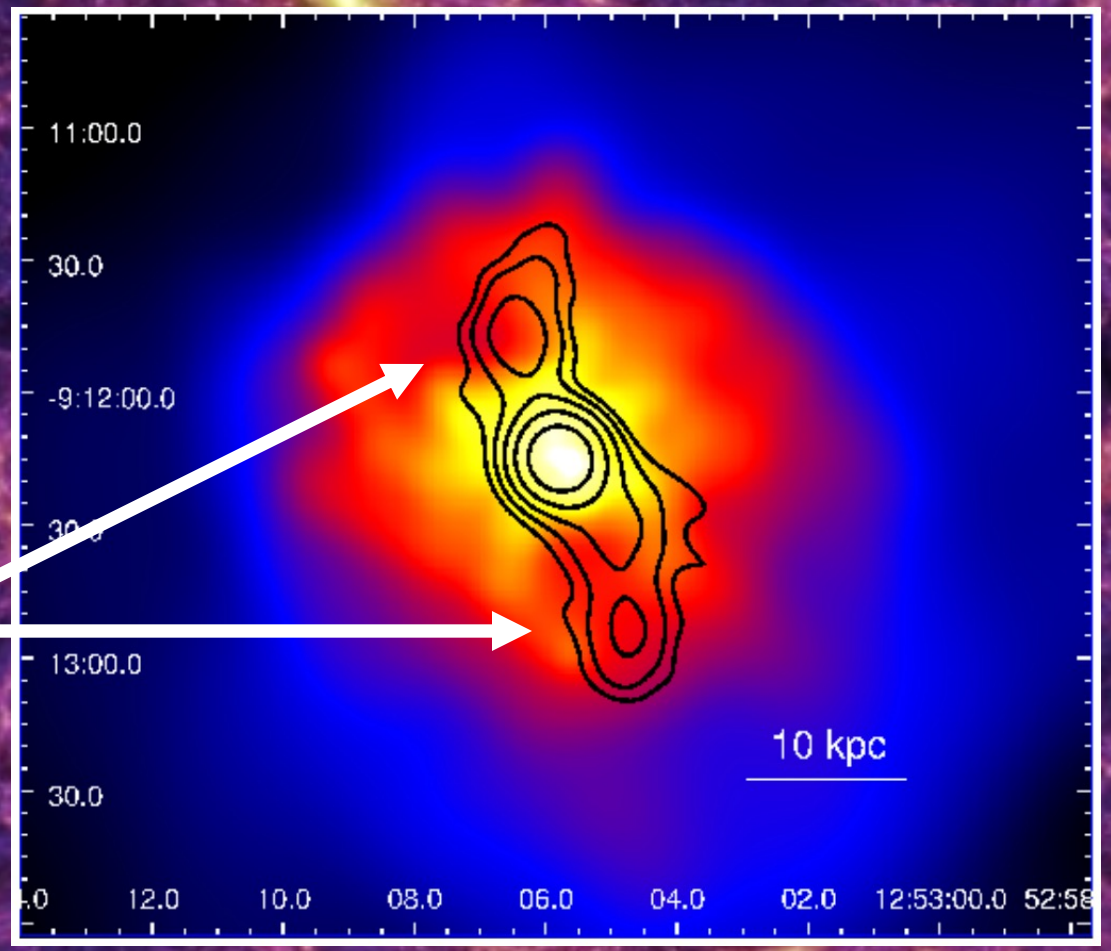


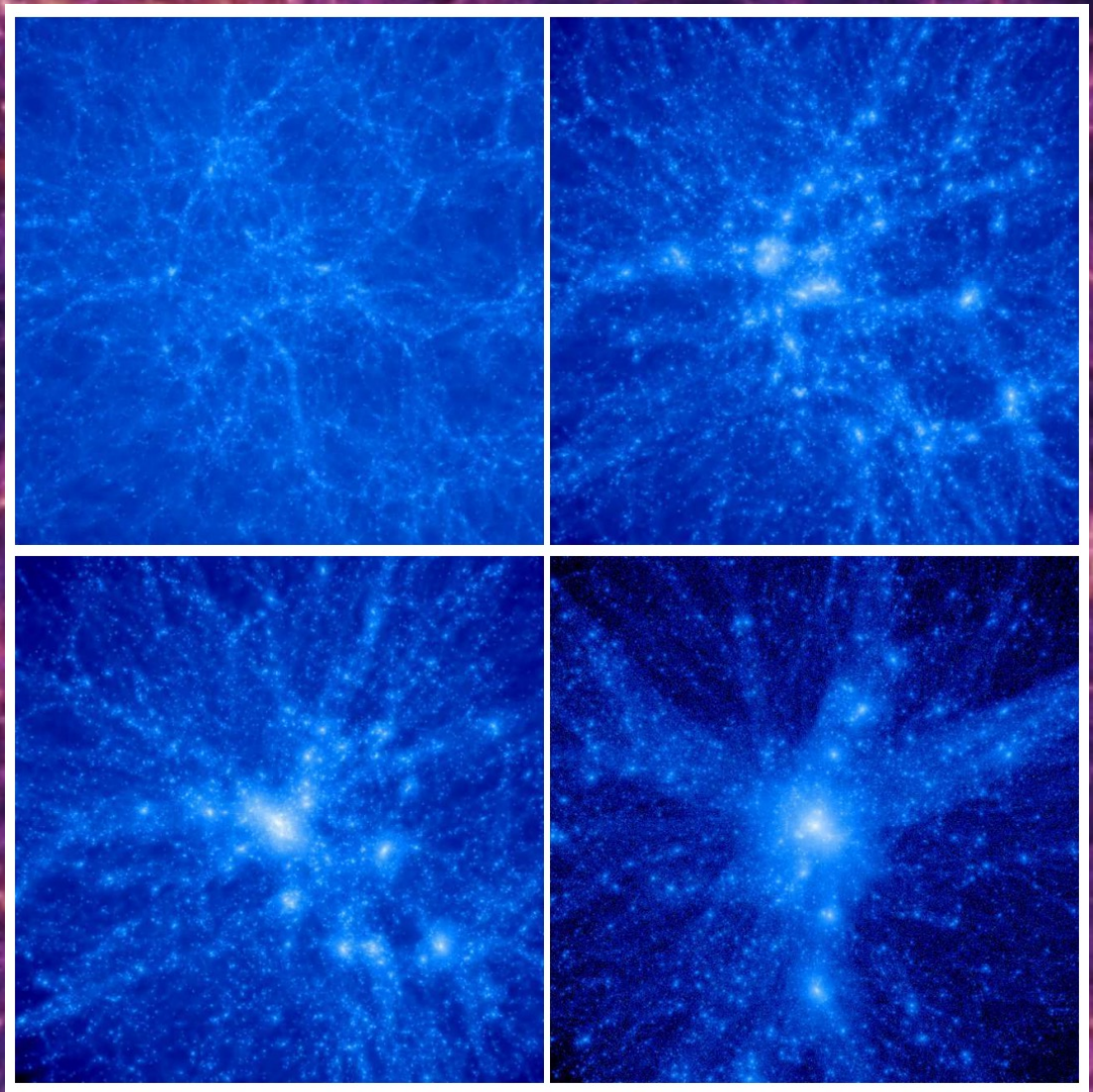
# INTRODUCTION TO GALAXY CLUSTERS

- Radio-mode Feedback
  - Central gas has radiative cooling time << Hubble time
  - No heating source, so cooling flow should develop
  - X-ray observations show temp drops = “cool-core” clusters
  - However, less cool gas than expected
  - Solution? Radio galaxies associated with Brightest Cluster Galaxies (BCGs)
  - X-ray observations show numerous cavities – coincident with BCG lobes
  - Radio plasma displaced X-ray emitting gas, bubble rises, expands, and distributes energy



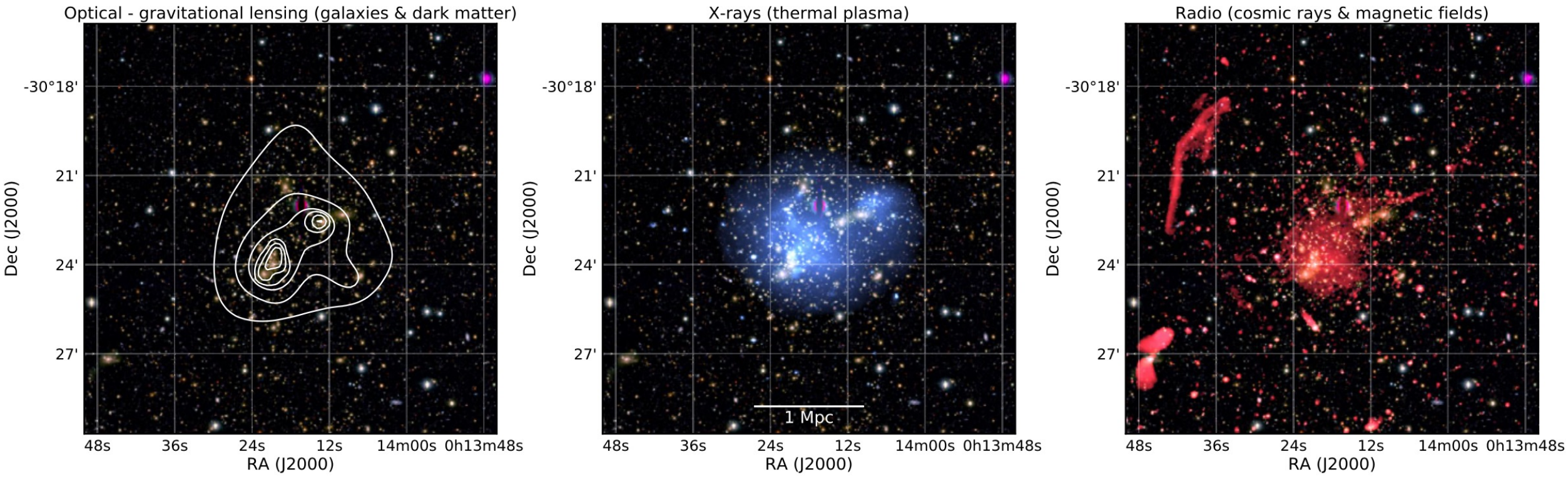
# INTRODUCTION TO GALAXY CLUSTERS

- Formation:
  - Accretion
  - Sequence of mergers of clusters and groups – HIGHLY energetic event – heat the ICM
  - Dissipated through shocks, turbulence, B field changes, etc.
  - In turn, driving particle (re)acceleration
  - Observationally, this means large field synchrotron emission
  - Turns clusters into ”laboratories”



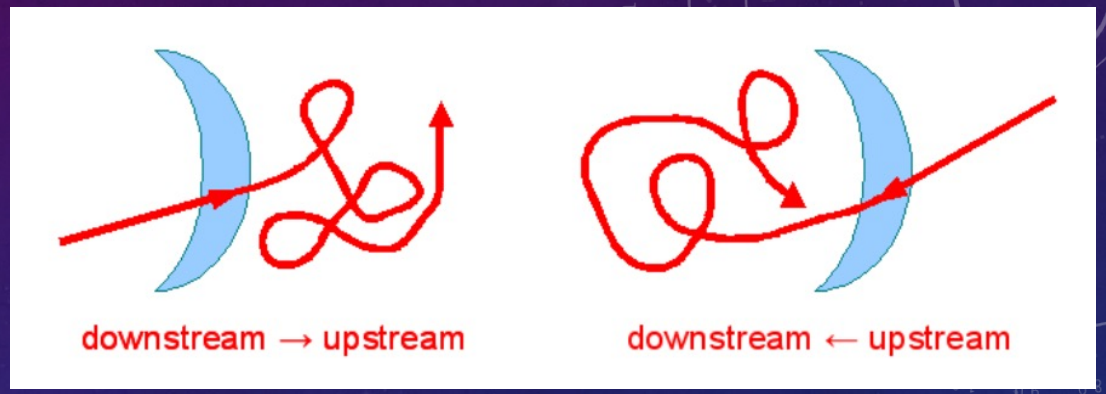
# EXTENDED SYNCHROTRON RADIO EMISSION

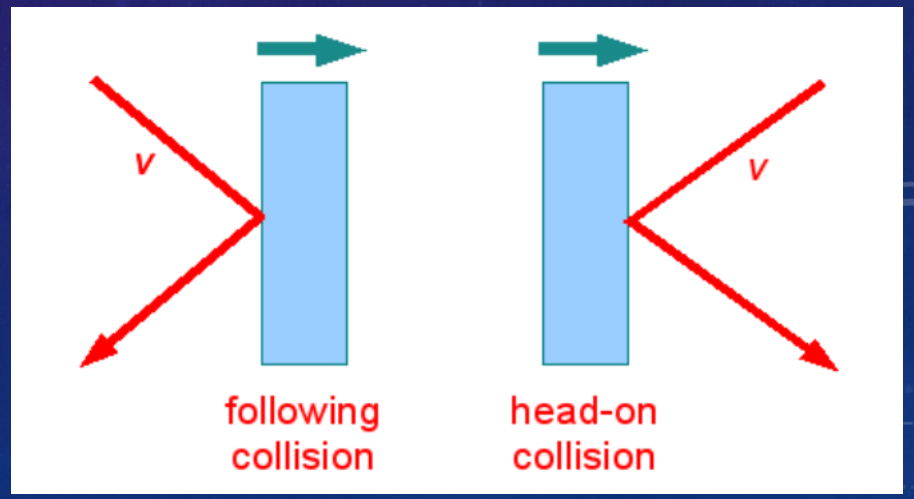
- ICM also has (non-thermal) Cosmic Ray (CR) component
  - Not directly associated with cluster radio galaxies
- GeV CR electrons emit synchrotron radiation (w/ ~μGauss ICM B field)
  - Still needs observational work, but making progress
- Extended synchrotron emission indicates large-scale ICM B field structure
  - Strength ~0.1-10μGauss
- Magnetic fields are important (!!) – but difficult to measure
  - Particle (re-)acceleration process
  - Inhibit transport processes (heat conduction, spatial mixing, CR propagation)


Optical - gravitational lensing (galaxies & dark matter)
X-rays (thermal plasma)
Radio (cosmic rays & magnetic fields)
-30°18'
21'
24'
27'
Dec (J2000)
48s
36s
24s
12s
14m00s
0h13m48s
RA (J2000)
1 Mpc

# PARTICLE ACCELERATION

- **First Order Fermi Acceleration** (Fermi-I) – in shocks
  - Also called Diffuse Shock Acceleration (DSA)
  - Particles accelerated at a shock – acceleration takes place diffusively
  - Particle cross back and forth across shock front – each crossing means additional energy
    - Particles are scattering from magnetic inhomogeneities
- **Second Order Fermi Acceleration** (Fermi-II) – in moving magnetized gas clouds
  - Stochastic (random) process – particles scatter off "magnetic mirrors"
  - Particles either gain or lose energy when scattering
    - Head-head collision = gain, head-tail collision = loss
    - Random motion = higher probability for a head-head collision (energy gain)
    - Therefore, generally there is an overall slight energy gain
  - Inefficient process



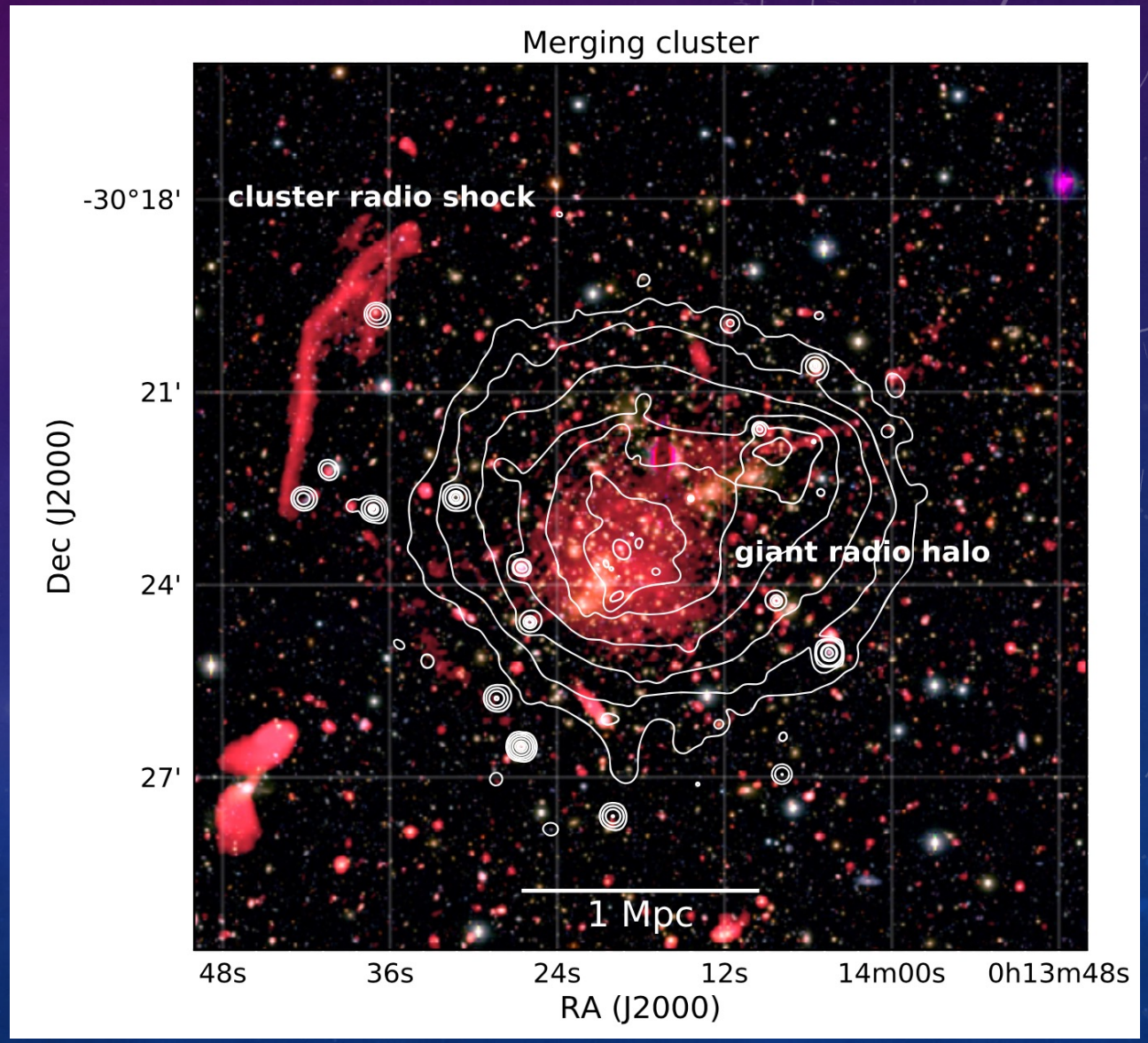



# PARTICLE ACCELERATION II

- **Adiabatic Compression**
  - Shock wave adiabatically compresses a bubble/lobe/cocoon of relativistic radio plasma from an AGN
  - CR electrons in the bubble/lobe/cocoon regain energy – boosts radio synchrotron emission
- **Secondary Models**
  - Anytime CR electrons/protons are produced as secondary particles (decay products)
    - i.e. collisions of relativistic (CR) protons and thermal ions (hadronic model) – electrons specifically
    - i.e. DSA at shocks, AGN activity, and galactic outflows – CR protons specifically
    - CR Protons have much longer lifetime compared to electrons
      - They accumulate over the lifetime of a cluster once accelerated

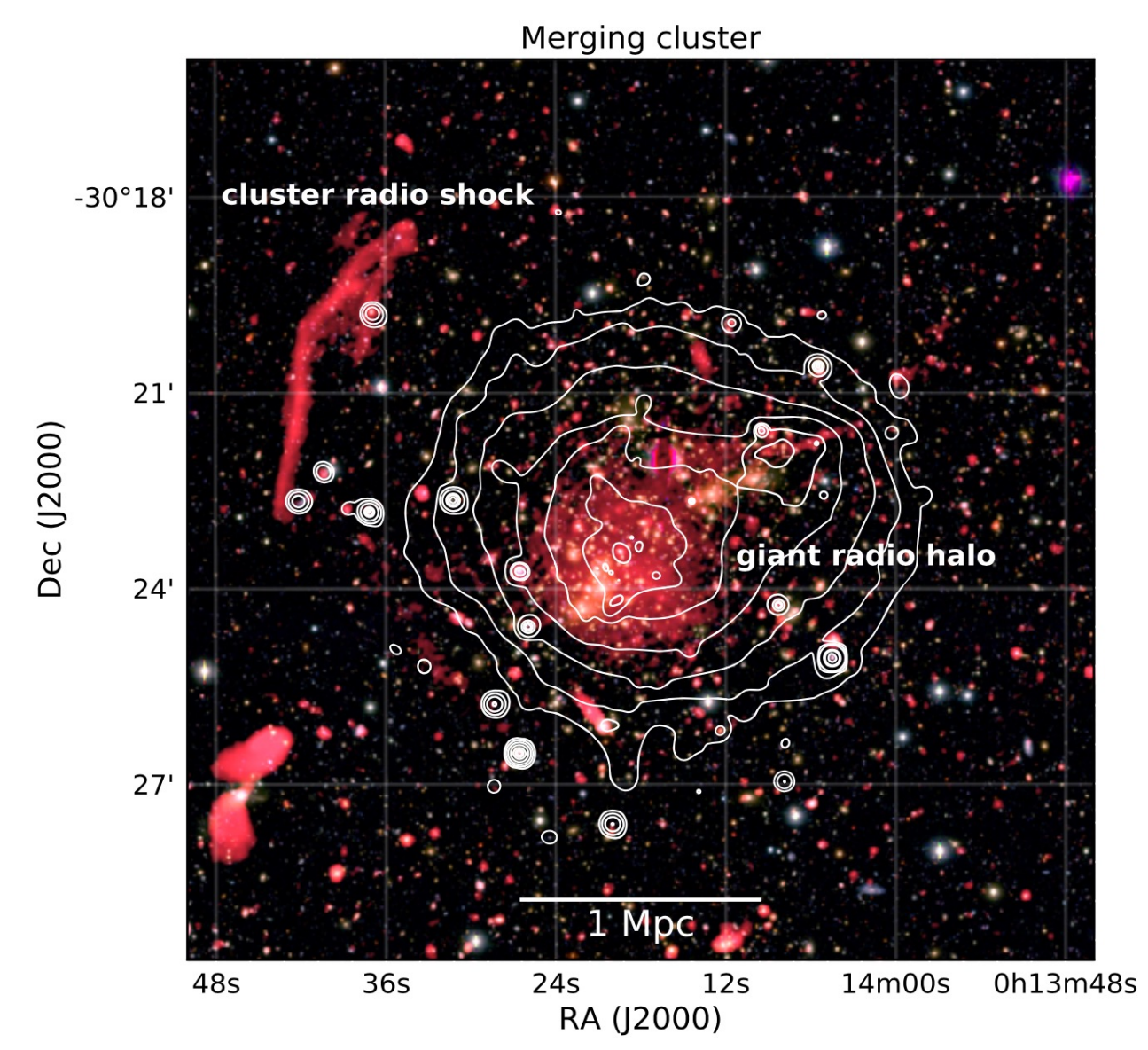
# CLUSTER RADIO SHOCKS (RADIO RELICS)

- **Relics**
  - Extended sources with high polarization levels, trace reaccelerated particles at ICM shock waves
    - Generally, but not always, associated with DSA
  - Located in cluster periphery, can be associated with a specific shock or region
  - Observationally defined, but no optical counterparts – challenging!
  - All types of relics have AGN plasma origins and ultra-steep radio spectra
- **Radio *Gischt***
  - Large Mpc size, trace particles accelerated at shocks via DSA
- **Radio Phoenices (Phoenixes)**
  - AGN fossil plasma - compressed and revived by merger shocks
  - Display irregular filamentary morphologies, relatively small



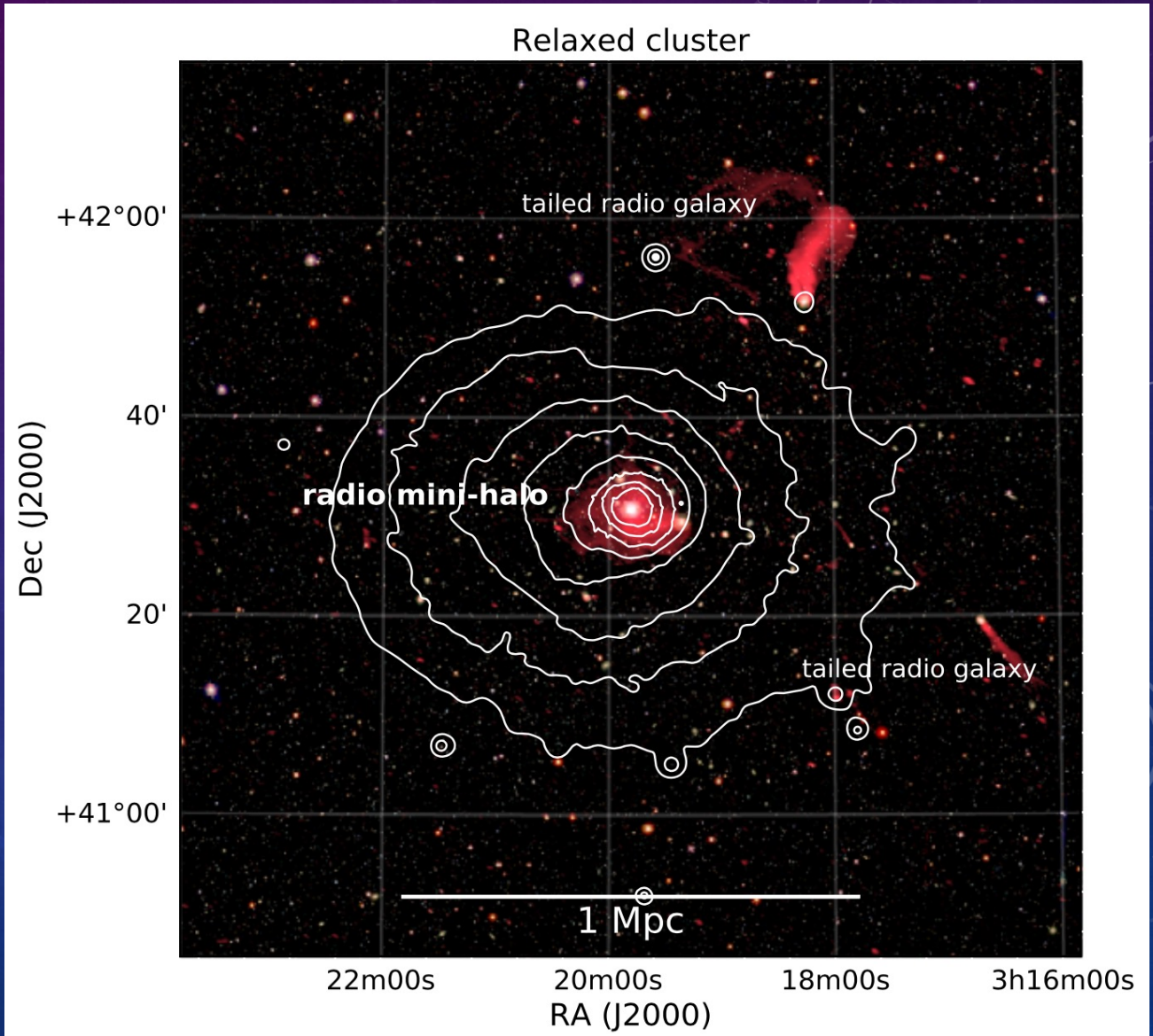
# CLUSTER RADIO SHOCKS (RADIO RELICS) + FILAMENTS

- **AGN Relics**
  - Fossil radio plasma passively evolving from an AGN (switched off)
  - Fossil plasma re-accelerated via DSA and Fermi-II
- **Gently Reenergized Tails (GReETs)**
  - Tails of radio galaxies that have been revived
  - Show unexpected spectral flattening
    - Opposite from generally seen steepening trend caused by electron energy losses
- **Radio Filaments**
  - trace large-scale filaments of cosmic web that connect clusters



# HALOS + MINI-HALOS

- **Halos**
  - Centrally located diffuse sources in merging clusters
  - No optical counterparts
  - Generally extended sources that follow baryonic ICM mass distribution
  - Sources are not localized
    - Particle production occurs throughout a significant volume of the cluster
      - Not associated with a particular shock
  - Should trace Fermi-II or secondary electrons
- **Mini-Halos**
  - Smaller sized
  - Located in relaxed cool core cluster with powerful BCG-associated radio galaxies



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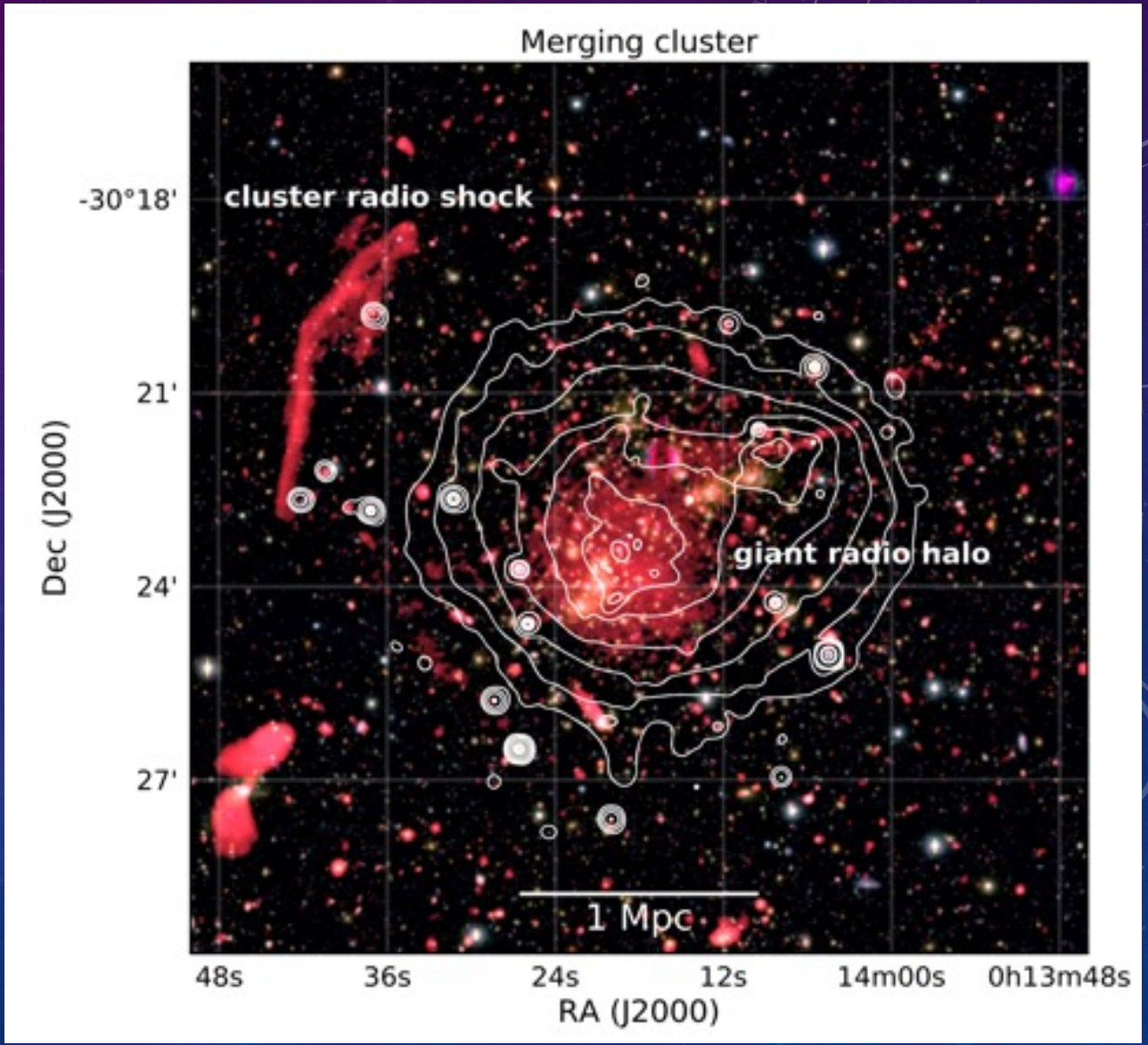
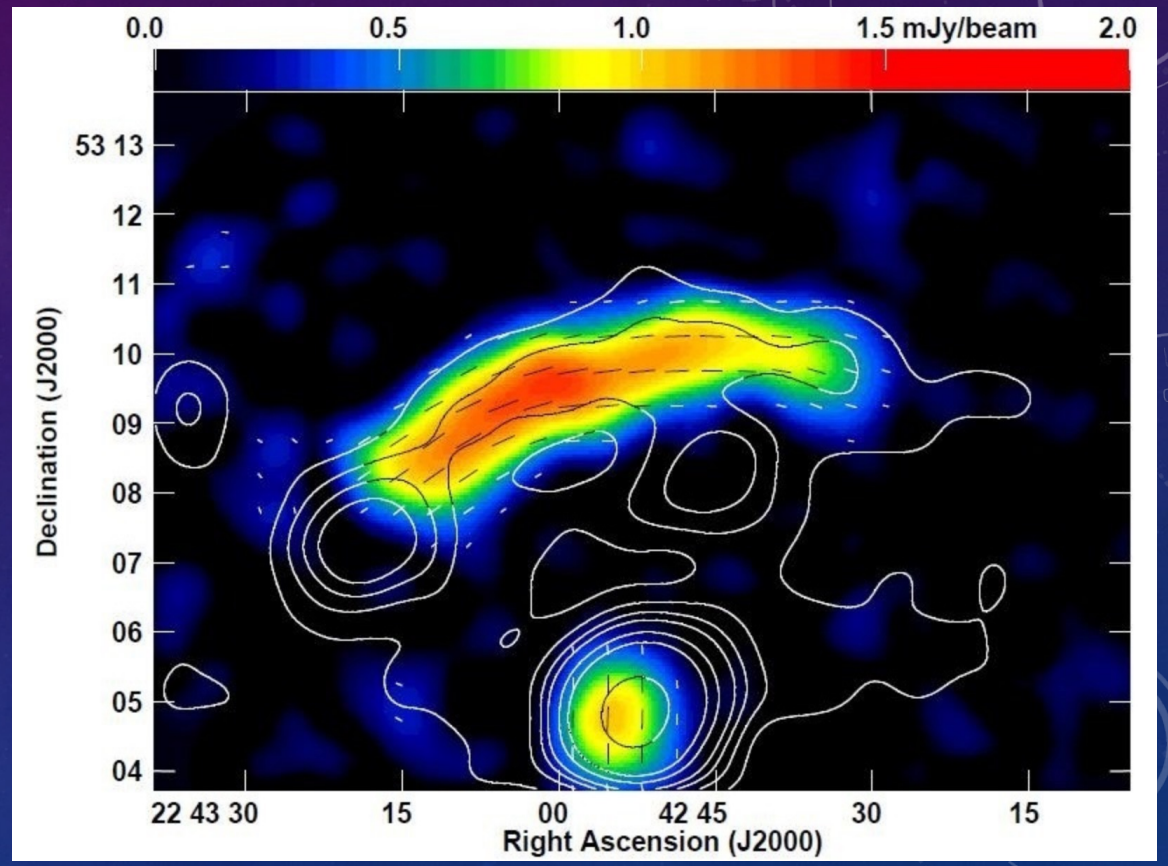


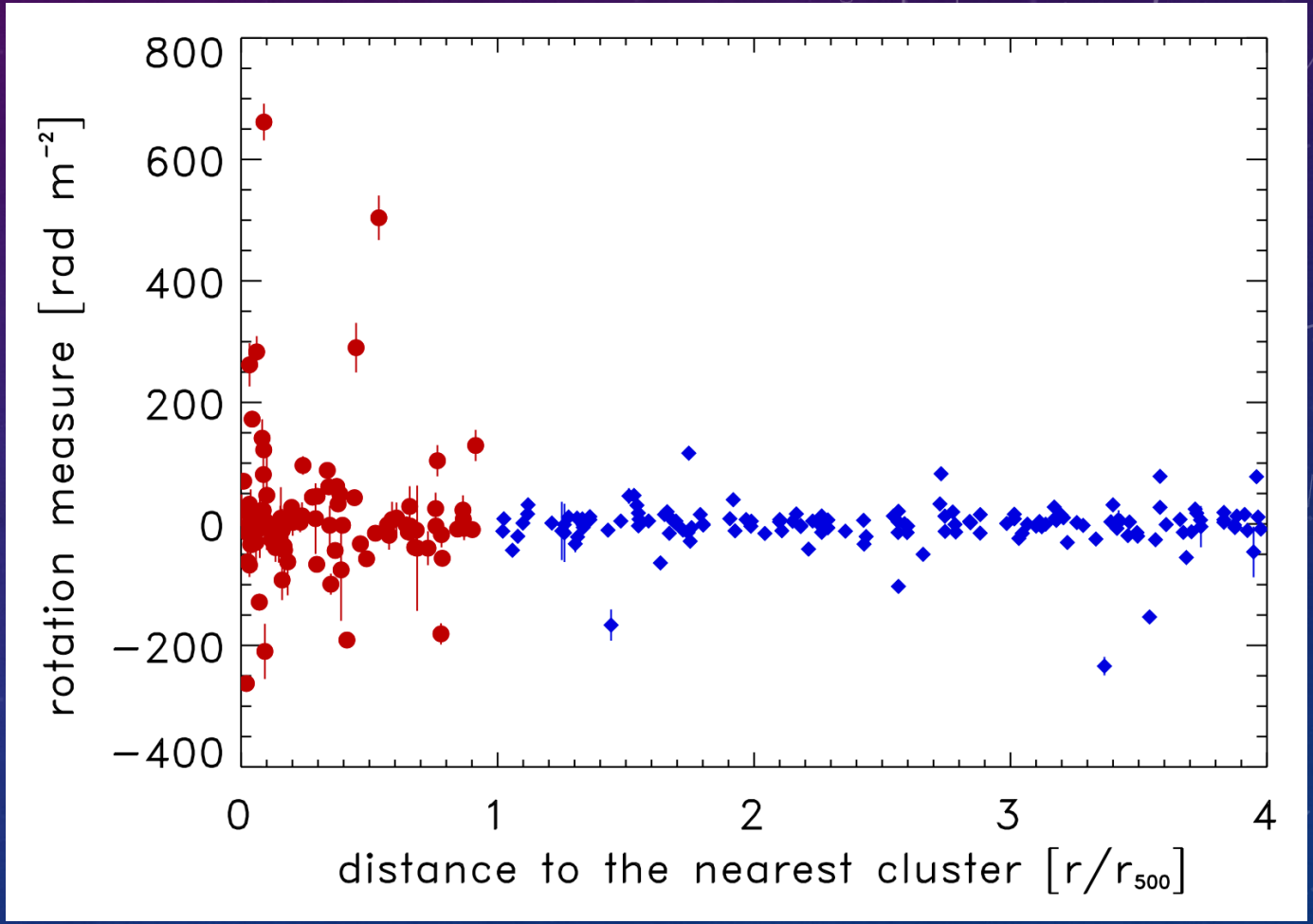
# CLUSTER MAGNETIC FIELDS

- B fields permeate galaxy clusters and IGM on Mpc scales
- B fields and B field compression play key roles in particle reacceleration and large scale structure formation
  - Impacts turbulence, cloud collapse, motion, heat/momentum transport, convection, dissipation, etc.
  - *Particularly important for* heat conduction, spatial mixing of gas, and cosmic ray propagation
- Origins? Generally unknown – best guess is amplifications of substantially weaker seed fields
- Different B field scales survive as a result of turbulent motions
- Seed Fields – origins also unknown
  - Possibly primordial – generally early in Universe (prior to recombination)
  - Possibly produced locally in later epochs – early stars and galaxies
- B fields at Cluster Radio Shocks
  - Interesting lower limits on B field strength
  - Using X-ray observations (deep) from XMM-Newton and Suzaku



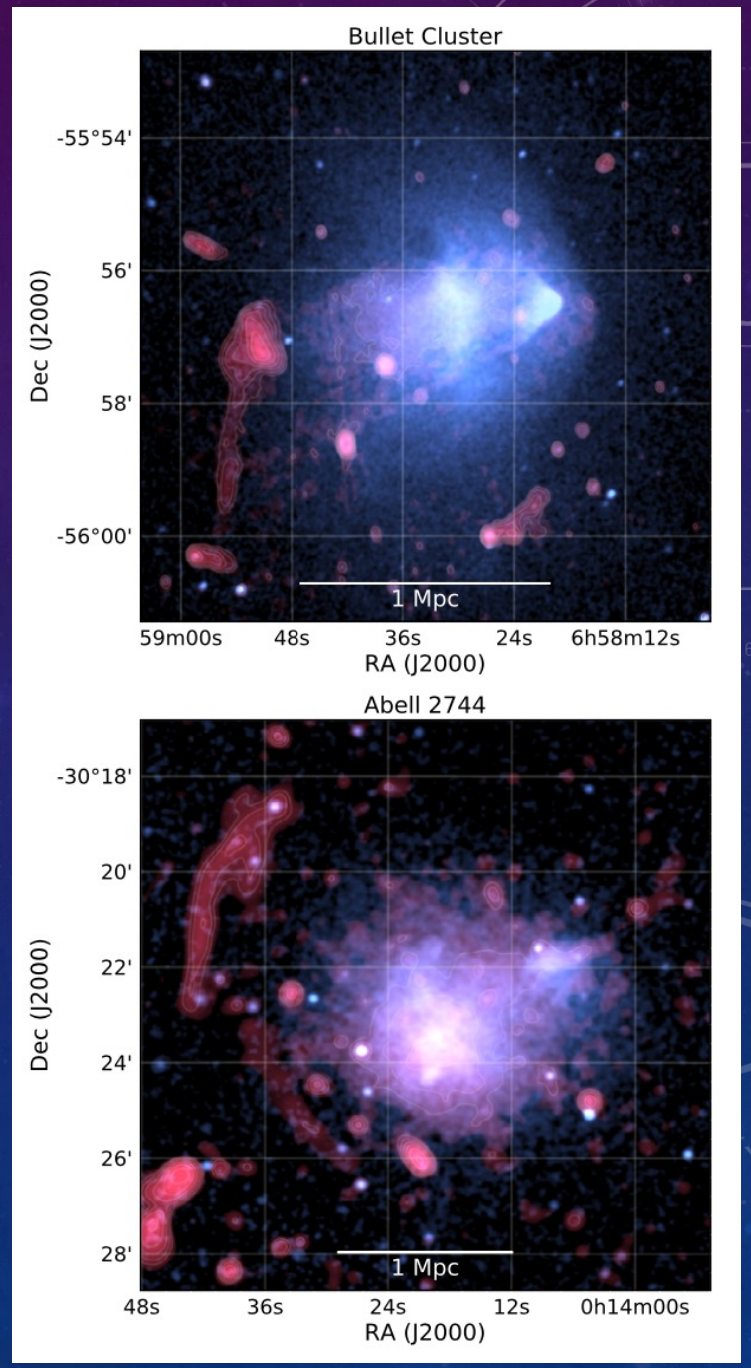
# CLUSTER MAGNETIC FIELDS

- B fields are difficult to measure
  - Most methods require numerous and pervasive assumptions
  - Most promising method – analysis of Faraday rotation of radio galaxies located inside the behind cluster
    - Rotation Measure found using Faraday depth, RM constrains strength and structure of B field
    - Tested on ~ 30 objects:
      - Cool Core Clusters: ~10 μGauss
      - Merging Clusters: ~few μGauss
      - No clear correlation for radial trend of B field, or between mean central field and cluster temperature
      - Obtains good information, but field structure understanding is poor



# RADIO HALOS – GIANTS

- **Giant Radio Halos**
  - Diffuse, extended (1-2 Mpc), brightness follows ICM (smooth and regular morphology)
  - Found primarily in massive, dynamically disturbed clusters – merger clusters
    - Merging clusters host radio halos – radio power increases with luminosity
    - Relaxed clusters don't tend to have halos – upper limits are located below the expected correlation
    - Merging events generating radio halos are characterized by larger mass ratios
  - Spectral properties reveal their origins – but reliable flux densities of extended low S/N sources are not easy to get
  - A cluster's X-ray morphology can be used as an indicator of dynamical state
  - Polarization:
    - Generally observationally unpolarized
    - Limited angular resolution (currently) causes beam depolarization
      - Significant impact when beam size becomes larger than angular scale of coherent B field rotations
      - Meaning… we think they exist but they are difficult to observe

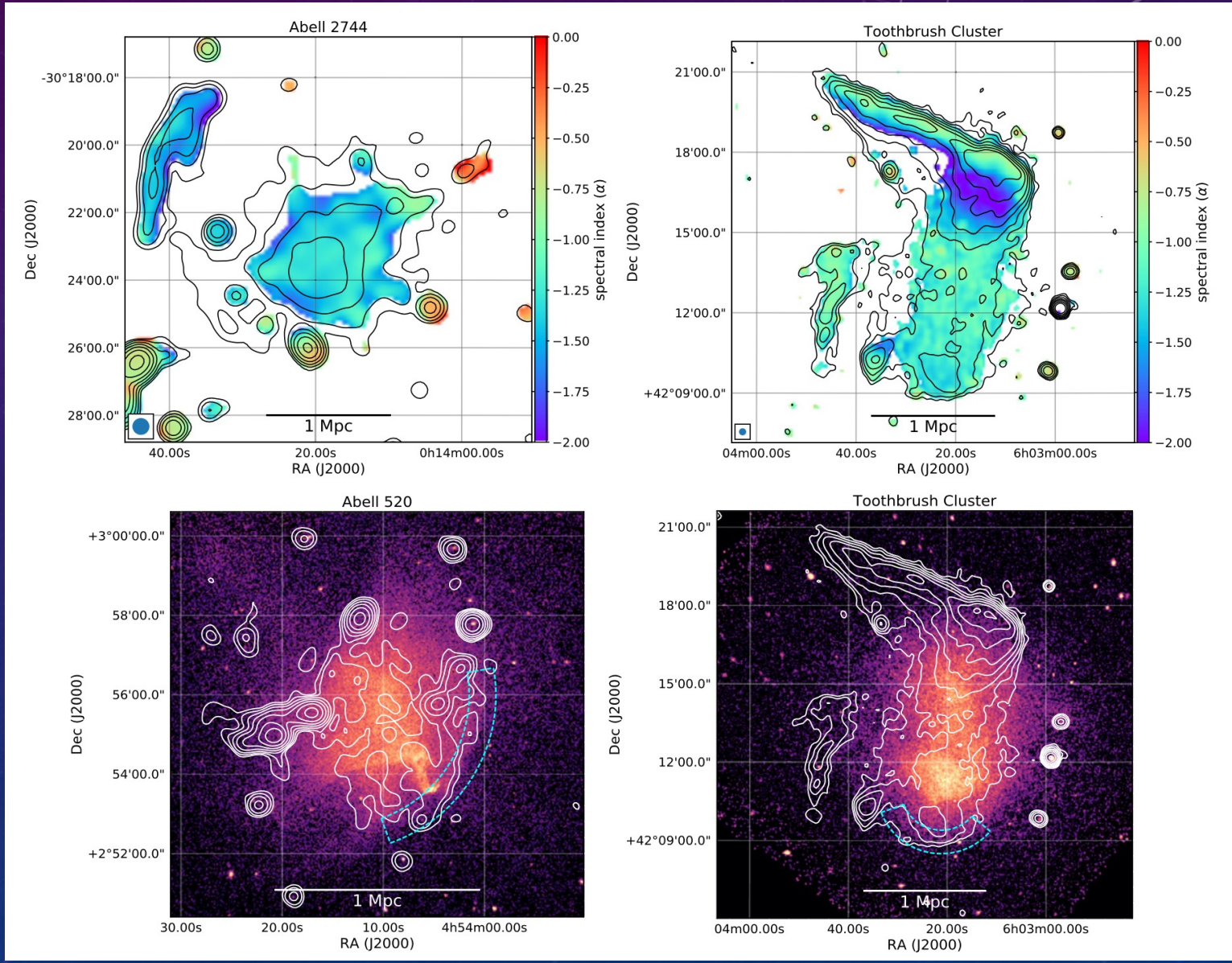


# RADIO HALOS – GIANT ORIGINS

- **Origins – Two Models**
  - **Hadronic Model**
    - Radio emitting electrons produced in hadronic interaction between CR and ICM (protons)
      - Gamma Ray observations of Coma Cluster determined that radio halos *cannot be of hadronic origin*
        - Gamma Rays in cluster come from neutral pion decays from proton-proton interactions
        - Put a direct limit on CR content – can test hadronic nature, can test contribution of secondary electrons
      - Coma cluster is important – high mass, close, right radio-halo
        - Fermi-LAT observations eliminate hadronic origin
          - Observations don't match predications – exact B field values, CR to thermal energy
  - **Turbulent Reacceleration Model**
    - A population of seed electrons is reaccelerated during powerful ICM turbulence
    - Consequence of cluster merger events
    - *Thought to be main mechanism…* so what about seed electrons?
      - Possibly secondar electrons from proton-proton interactions, or previously accelerated electrons at cluster merger and accretion shocks, or **related to galaxy outflows and AGN activity**
        - Evident thanks to low-frequency observations of gently re-energized tails (GReET)

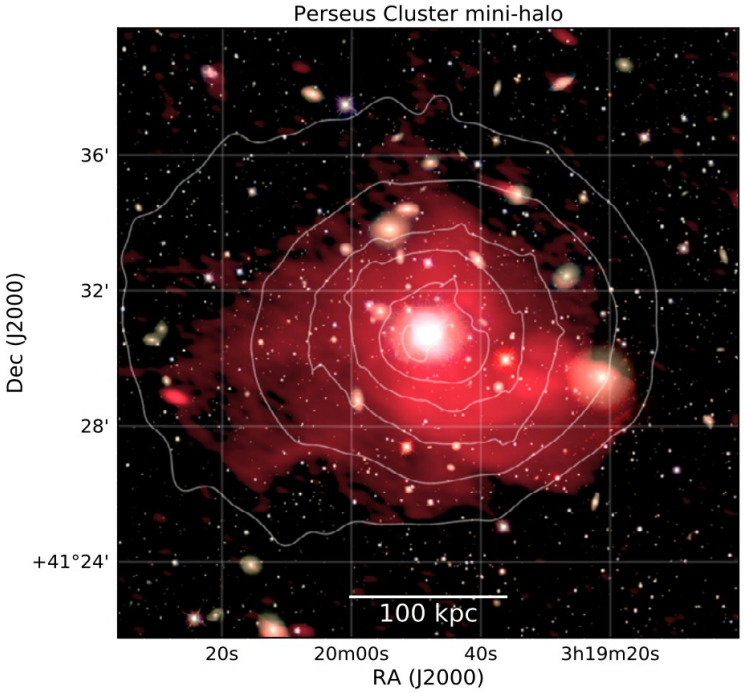
# RADIO HALOS – SHOCK EDGES

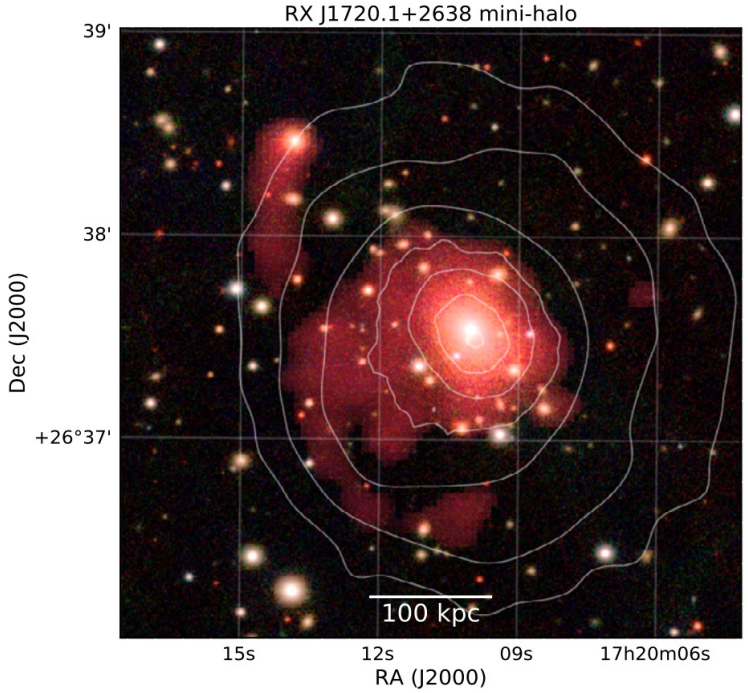
- **Shock Edges**
  - Halo emission bounded by cluster shock fronts
  - "Sharp edges" – nature is unclear
  - Some emission (this is the halo) near these shocks is actually compressed CR electrons (halo-shock edges)
  - Some emission is cluster radio shocks where electrons are reaccelerated
  - Full understanding will come with high-resolution spectral and polarimetric observations

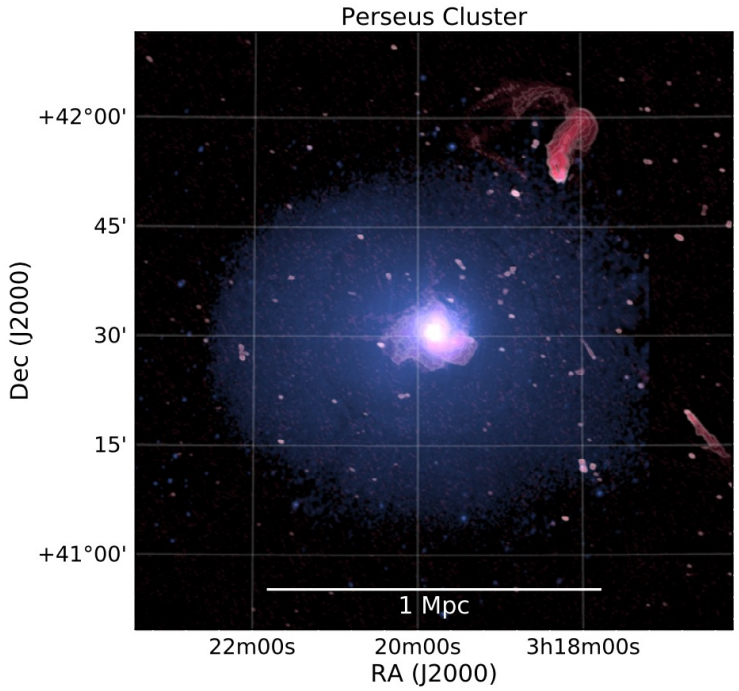


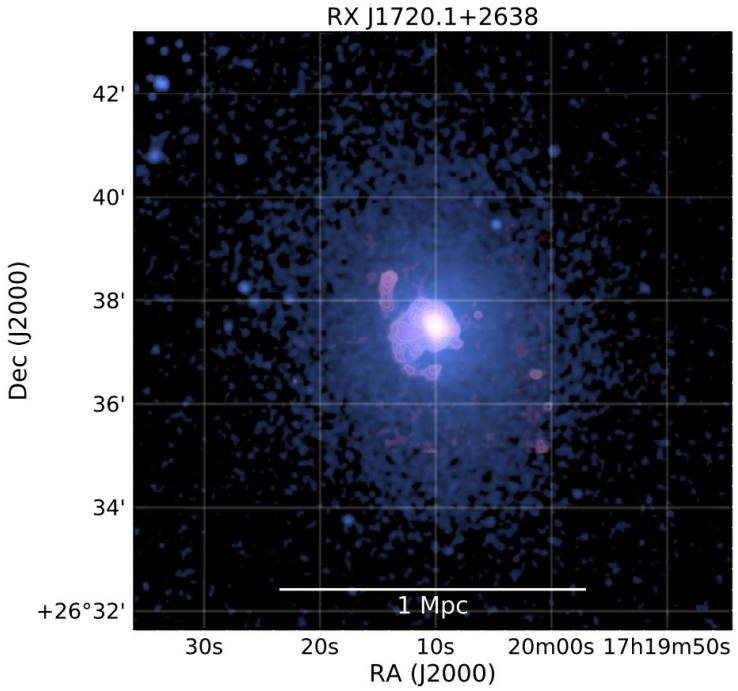
# RADIO HALOS – MINI + ORIGINS

- **Mini Radio Halos**
  - Found in relaxed, cool core clusters with central, radio loud BCG and surrounding radio emission – often confined by the cold fronts of cool core clusters
  - Comparable to the sizes of central cluster cooling regions (100-500 kpc)
  - Require in-situ acceleration – radio emission does not directly originate from central AGN
  - Generally have high synchrotron volume emissivities than giant radio halos, but similar spectral indices
  - Observations are tricky – trying to separate AGN lobes and mini-halos is observationally difficults
  - asdf
- **Origins of Mini Radio Halos**
  - Similar to origin theories for giant radio halos
  - Trace turbulence in the cluster cores generated by gas sloshing
    - Central AGN is likely candidate for the source of the fossil electrons that are reaccelerated
  - Possible scenario where turbulence induced by gas sloshing motions reaccelerates particles
- **Unification**
  - Possibly that mini-halos and giant halos in cluster are physically related


Perseus Cluster mini-halo
36'
32'
28'
+41°24'
Dec (J2000)
100 kpc
20s
20m00s
40s
3h19m20s
RA (J2000)


RX J1720.1+2638 mini-halo
39'
38'
+26°37'
Dec (J2000)
100 kpc
15s
12s
09s
17h20m06s
RA (J2000)


Perseus Cluster
+42°00'
45'
30'
15'
+41°00'
Dec (J2000)
1 Mpc
22m00s
20m00s
3h18m00s
RA (J2000)

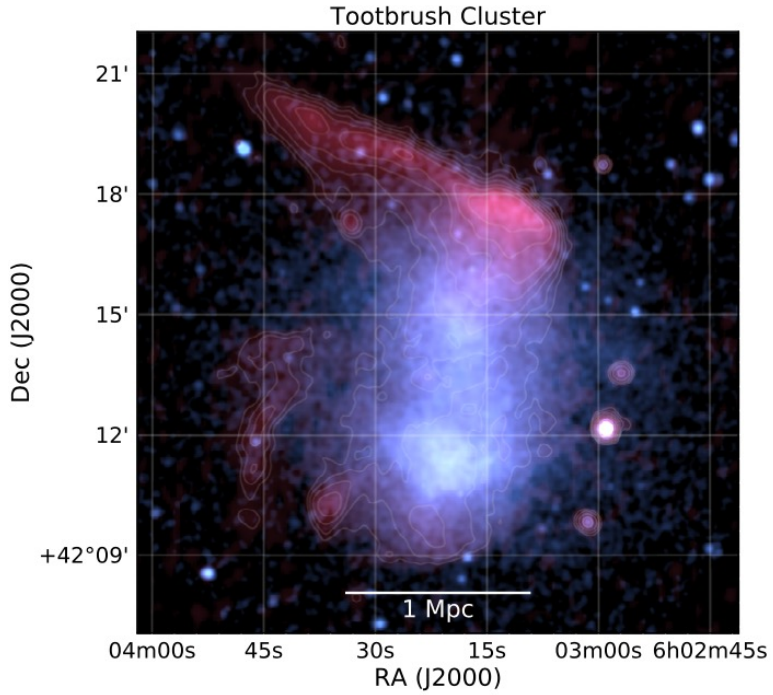

RX J1720.1+2638
42'
40'
38'
36'
34'
+26°32'
Dec (J2000)
1 Mpc
30s
20s
10s
20m00s
17h19m50s
RA (J2000)

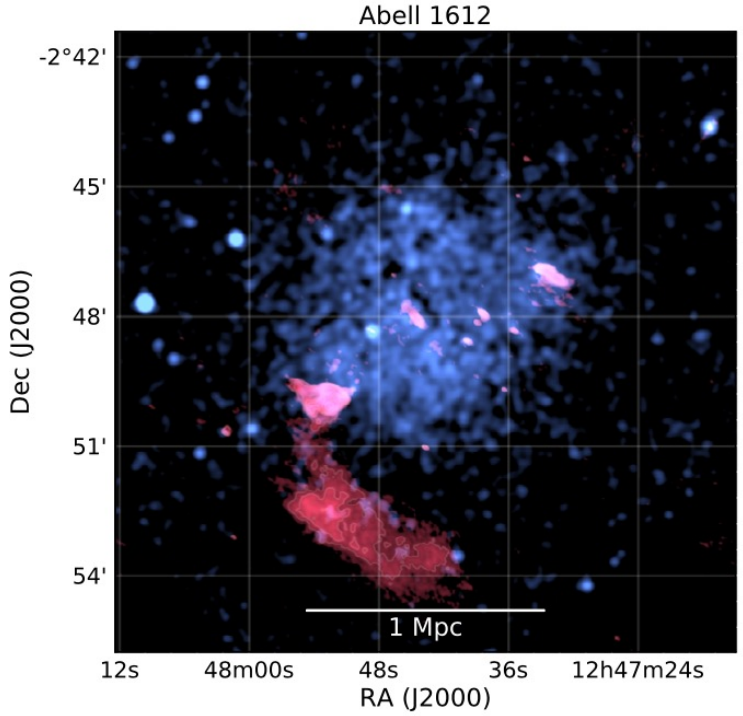
# RADIO HALOS – GAMMA-RAY STUDIES

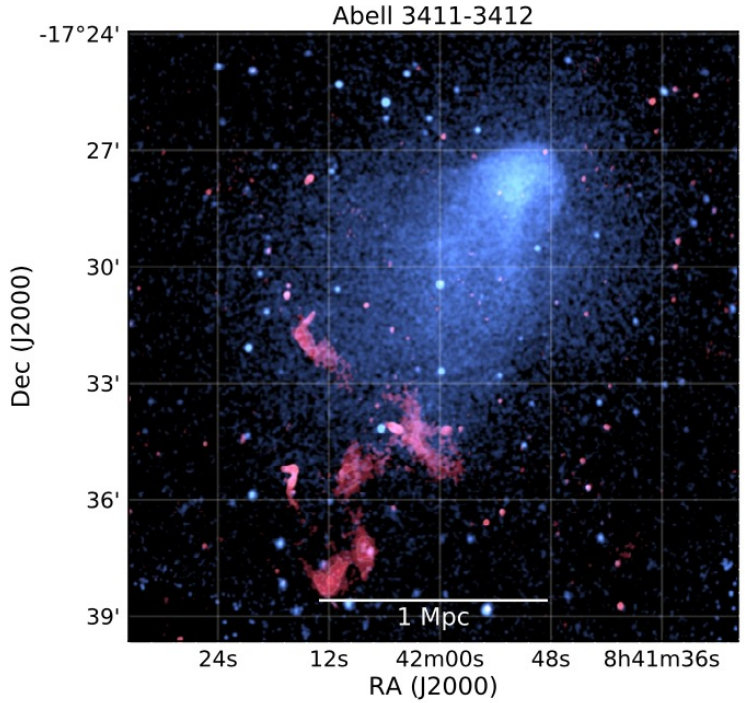
- **Gamma-Ray Studies**
  - Eventually test the hadronic interpretation of mini-halos
  - Limit the CR-proton spectral and spatial distribution
  - Test the role of AGNs
    - Proton confinement in AGN bubbles
    - How protons are transported from the central AGNs to cluster peripheries

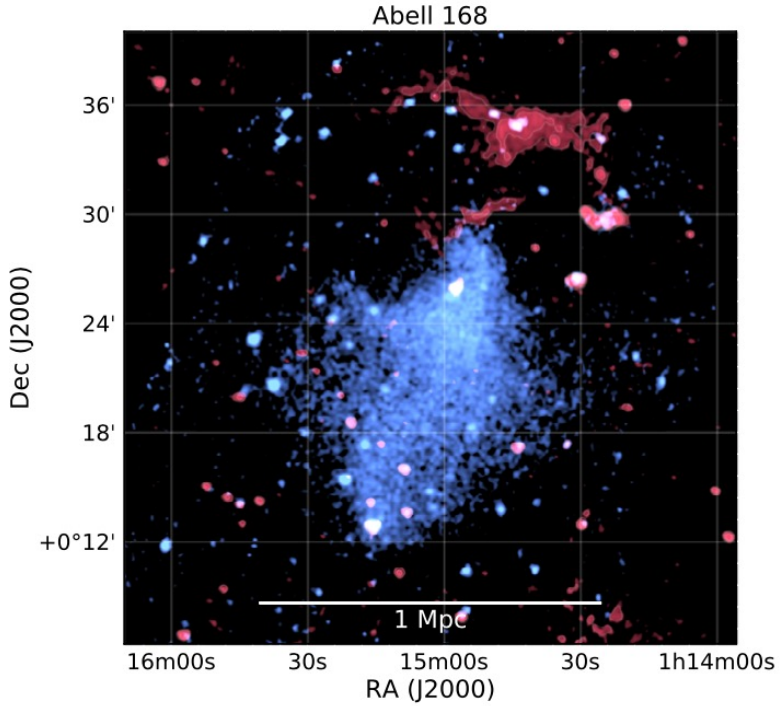
# CLUSTER RADIO SHOCKS – CLUSTER RELICS + FOSSILS

- Broadly divide diffuse cluster sources into **cluster radio shocks** and **revived fossil plasma**
- Distinction requires detection of shocks via Sunyaev-Zeldovich or X-ray measurements, plus radio spectra
- Another classification system uses Gischt and Phoenix(es) (Phoenices)
  - Evidence that Gischt trace shock waves – call them cluster radio shocks
- Radio shocks and fossil sources are detected in cluster covering a wide range of masses
  - Compare to radio halos found exclusively in massive systems
- Phoenices and other revived AGN fossil sources (GReET) are characterized by steep radio spectra, and presence of high frequency spectral breaks
  - There exist hybrid (intermediate) sources as well


Tootbrush Cluster
21'
18'
15'
12'
+42°09'
Dec (J2000)
1 Mpc
04m00s
45s
30s
15s
03m00s
6h02m45s
RA (J2000)

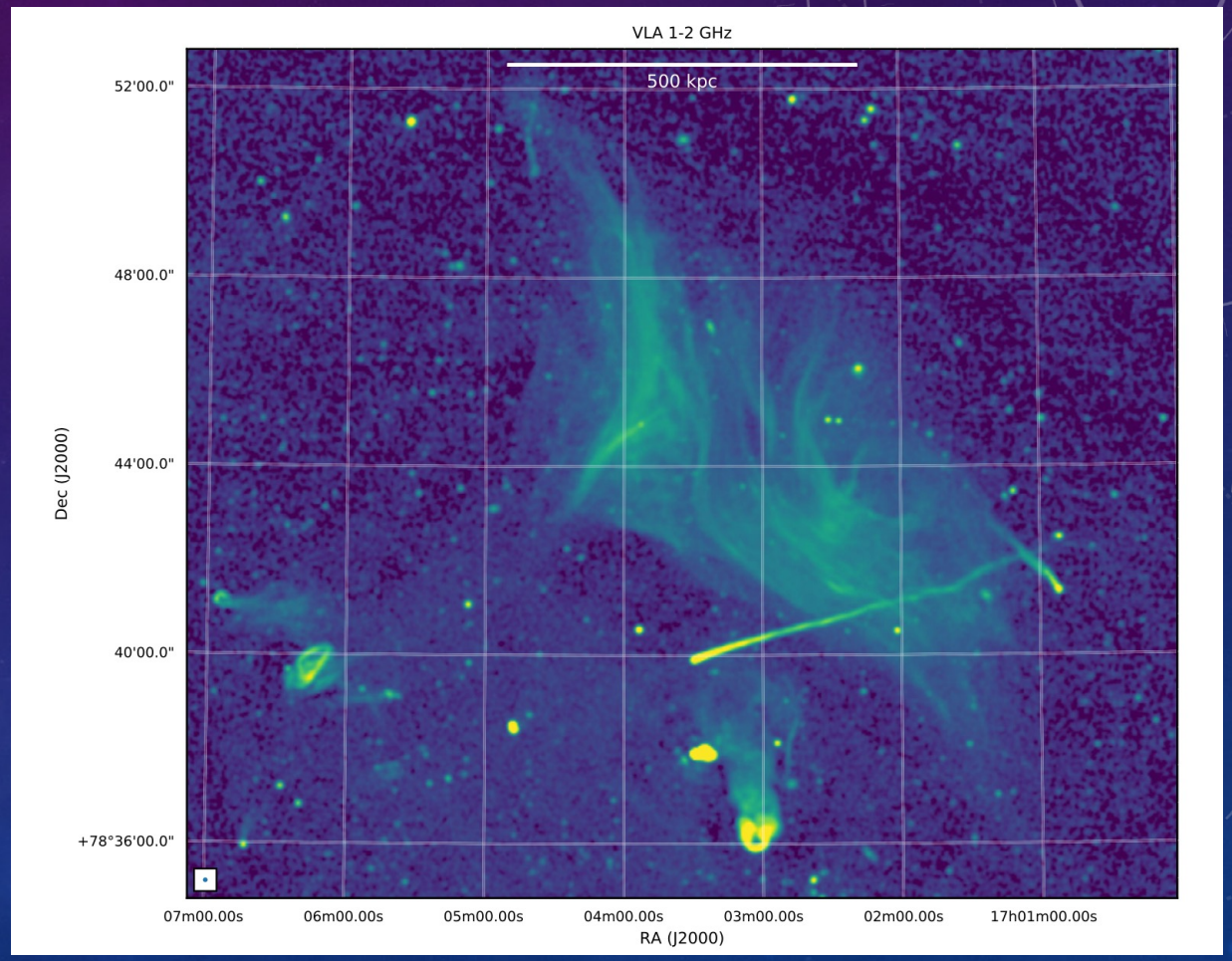

Abell 1612
-2°42'
45'
48'
51'
54'
Dec (J2000)
1 Mpc
12s
48m00s
48s
36s
12h47m24s
RA (J2000)


Abell 3411-3412
-17°24'
27'
30'
33'
36'
39'
Dec (J2000)
1 Mpc
24s
12s
42m00s
48s
8h41m36s
RA (J2000)

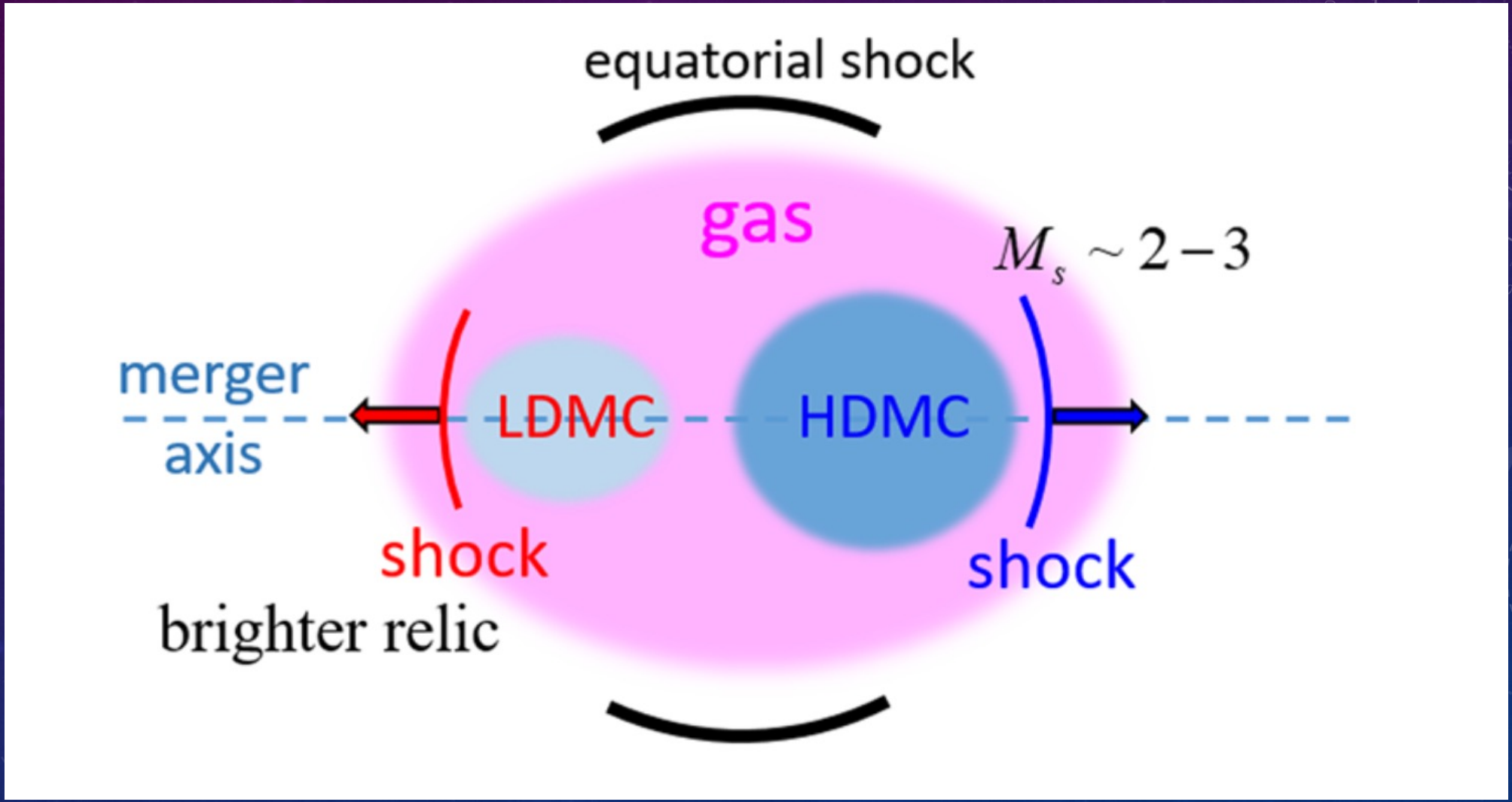

Abell 168
36'
30'
24'
18'
+0°12'
Dec (J2000)
1 Mpc
16m00s
30s
15m00s
30s
1h14m00s
RA (J2000)

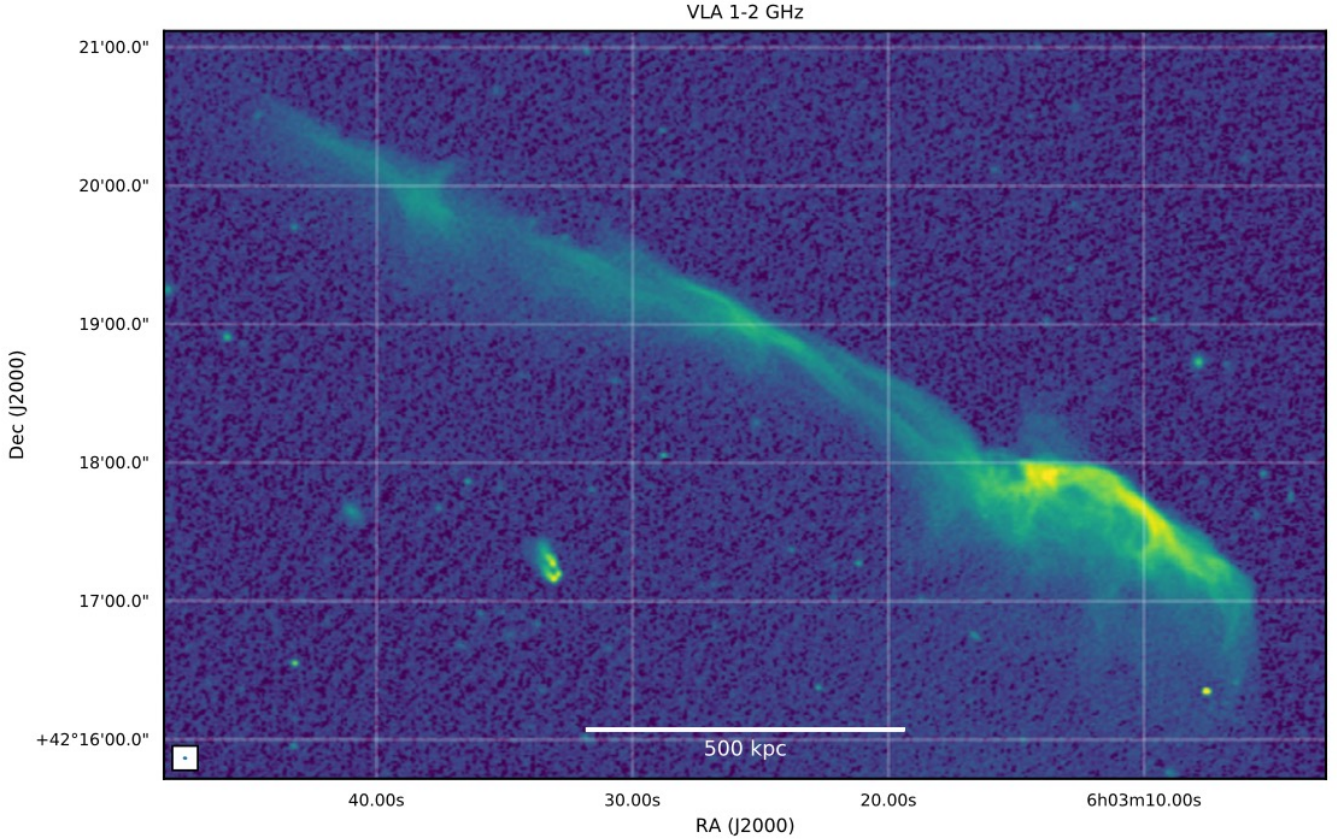
# CLUSTER RADIO SHOCKS – CLUSTER RELICS

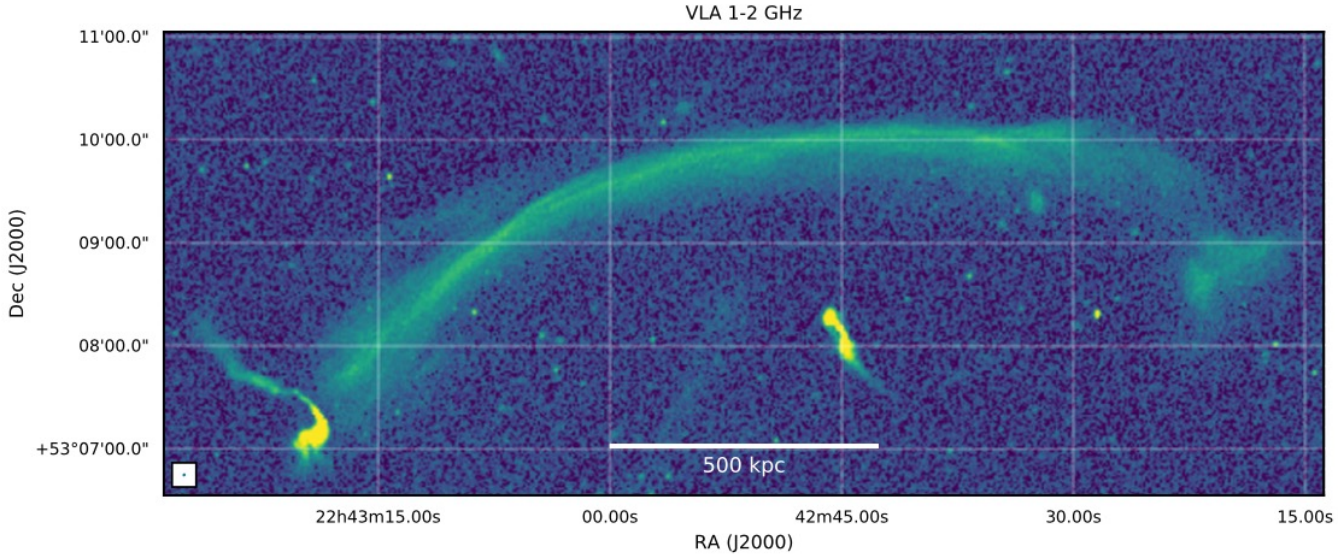
- **Relics (Cluster Radio Shocks)**
  - Mostly found in outskirts of galaxy clusters, typically elongated, and *strongly* polarized – less common than radio or mini halos
    - Shape is expected for sources that trace shock waves in cluster outskirts/seen edge on
    - Those found in cluster outskirts show asymmetric transverse brightness profiles
    - Sharp edge on side away from cluster center, and on the side of center, emission fades more gradually
    - Have significant amount of filamentary substructures
      - Not entirely understood – possible they trace B field changes, possible they reflect complex shape of shocks.
  - Merger axes of radio shock hosting cluster generally in or near plane of sky – axis is important! (unlike radio/mini-halos)
  - In some, emission from cluster radio shocks is attached to or overlaps with radio halo emission (nature is unclear)



# CLUSTER RADIO SHOCKS – CLUSTER RELICS

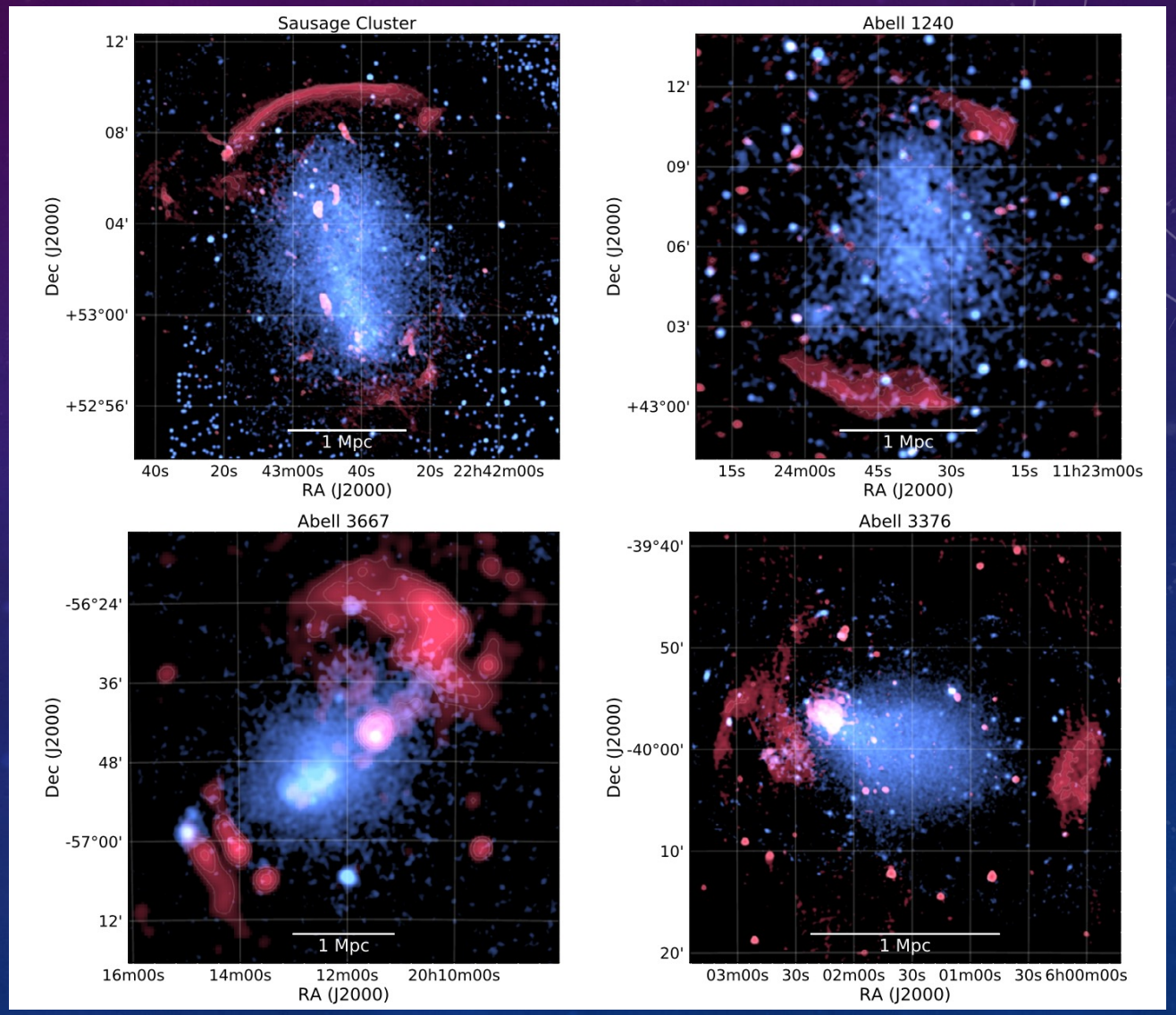



VLA 1-2 GHz
21'00.0"
20'00.0"
19'00.0"
18'00.0"
17'00.0"
+42°16'00.0"
Dec (J2000)
500 kpc
40.00s
30.00s
20.00s
6h03m10.00s
RA (J2000)


VLA 1-2 GHz
11'00.0"
10'00.0"
09'00.0"
08'00.0"
+53°07'00.0"
Dec (J2000)
500 kpc
22h43m15.00s
00.00s
42m45.00s
30.00s
15.00s
RA (J2000)

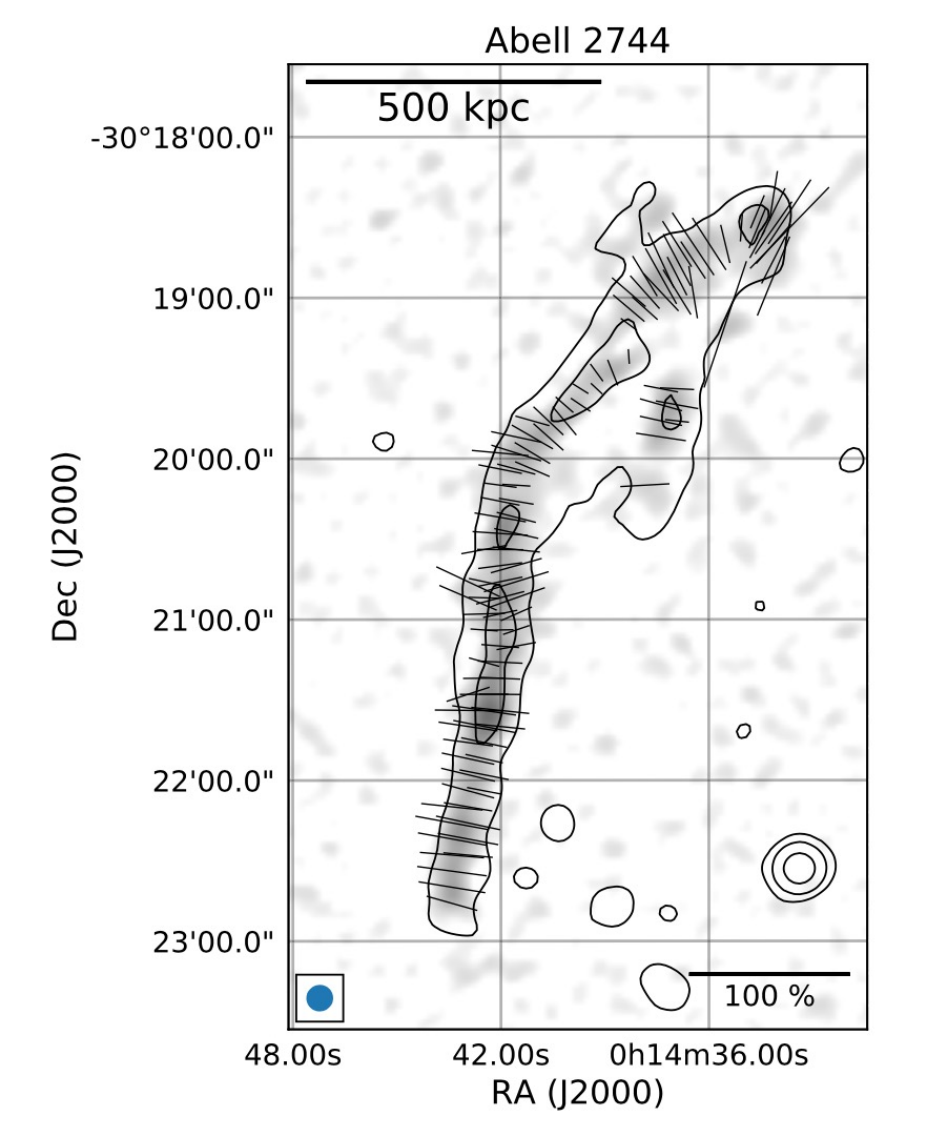
# CLUSTER RADIO SHOCKS – DOUBLES

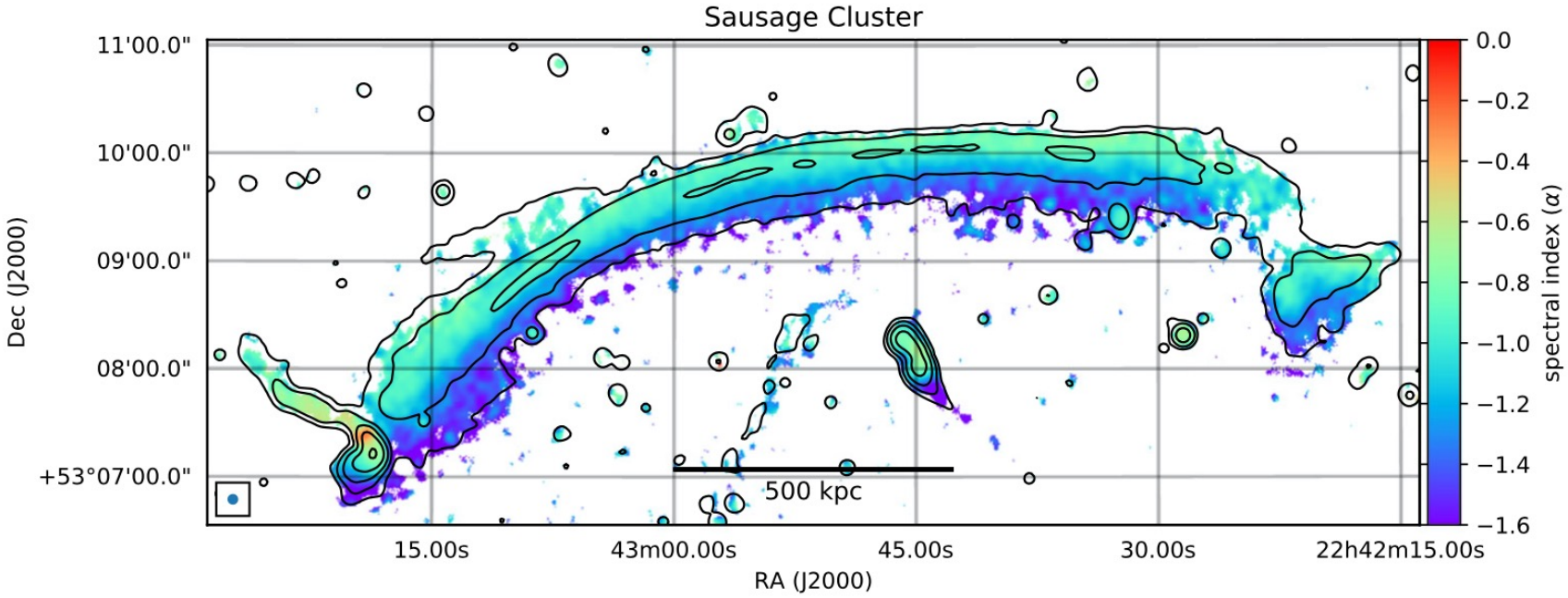
- **Cluster Double Radio Shocks**
  - Particularly interesting – two large elongate convex radio shocks found diametrically with respect to cluster center
  - Oriented perpendicularly with respect to elongated ICM distribution (merger axis)
  - Could have resulted from particles accelerated at shocks from a binary merger

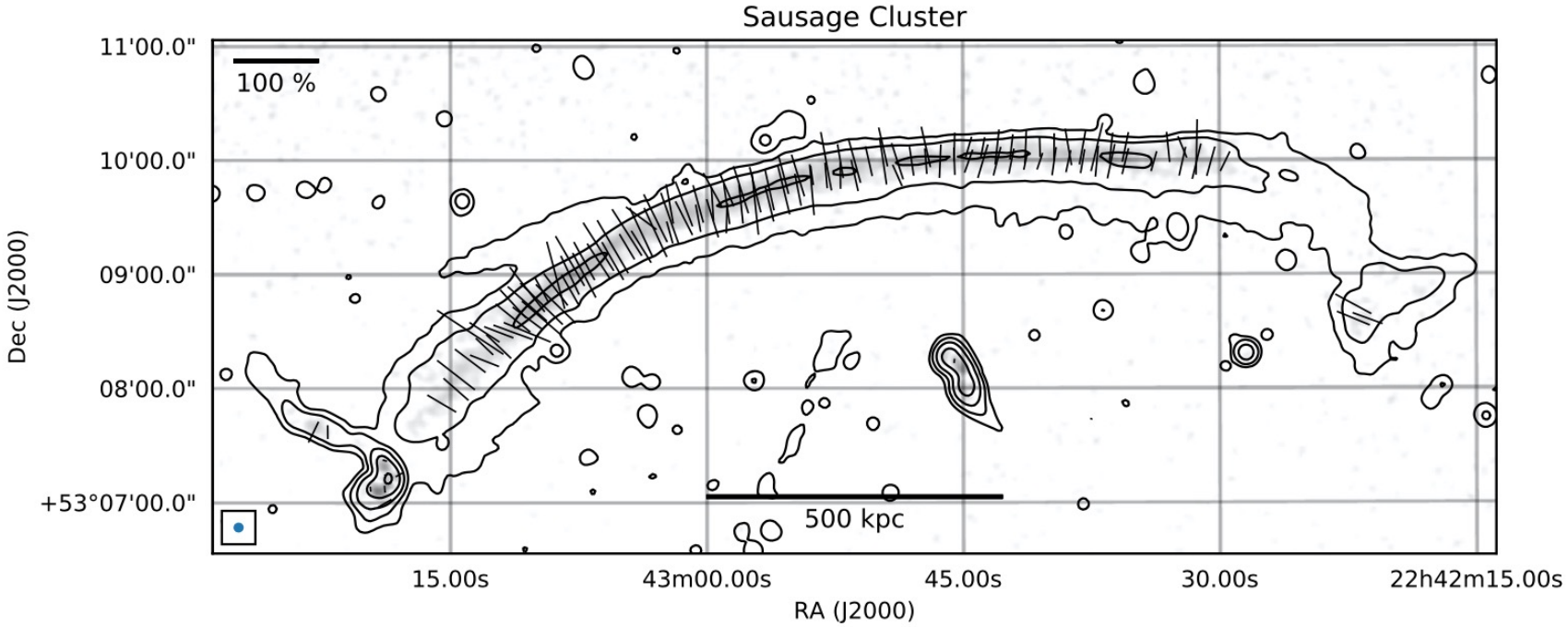


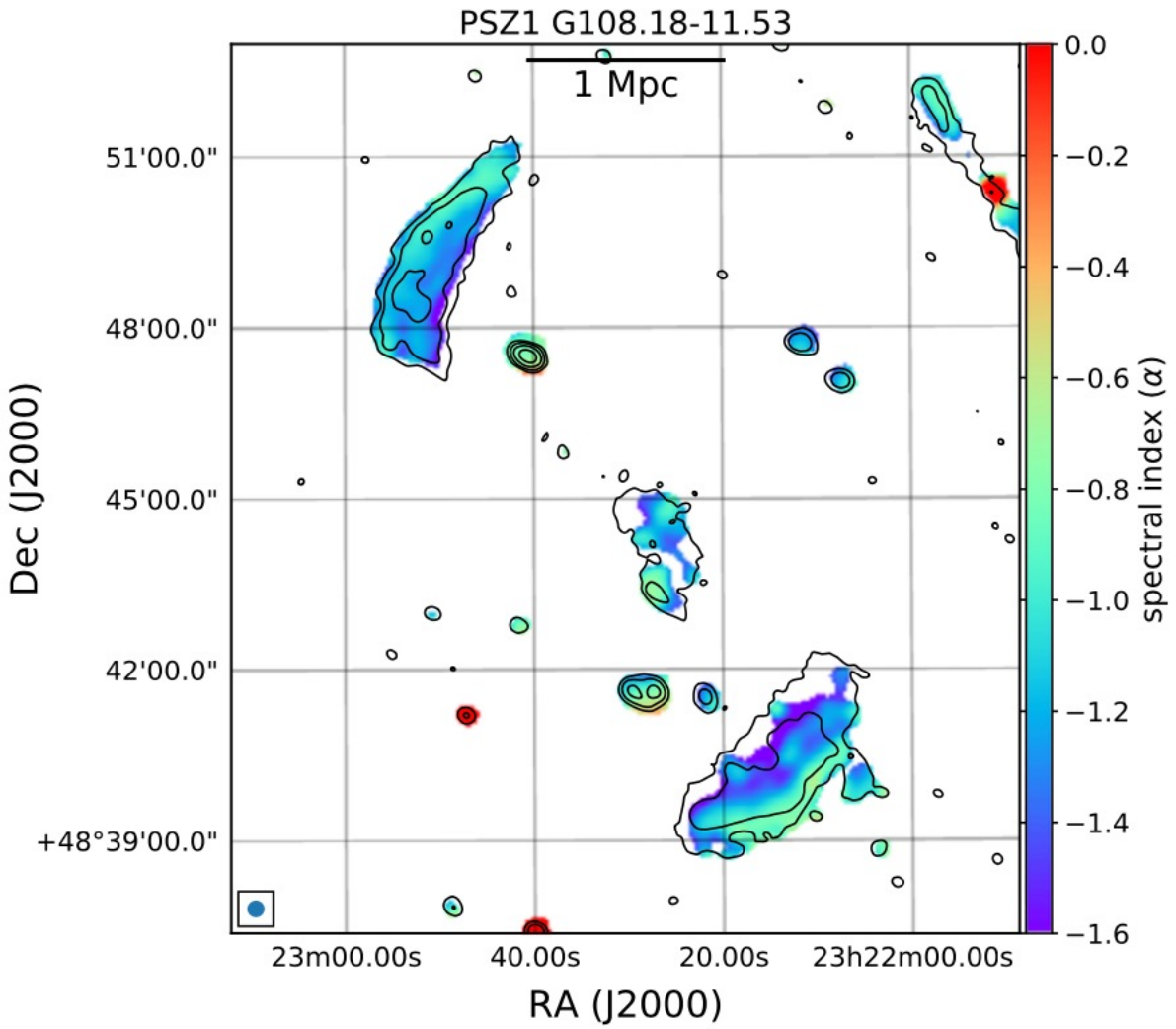
# CLUSTER RADIO SHOCKS – SPECTRA AND POLARIZATION

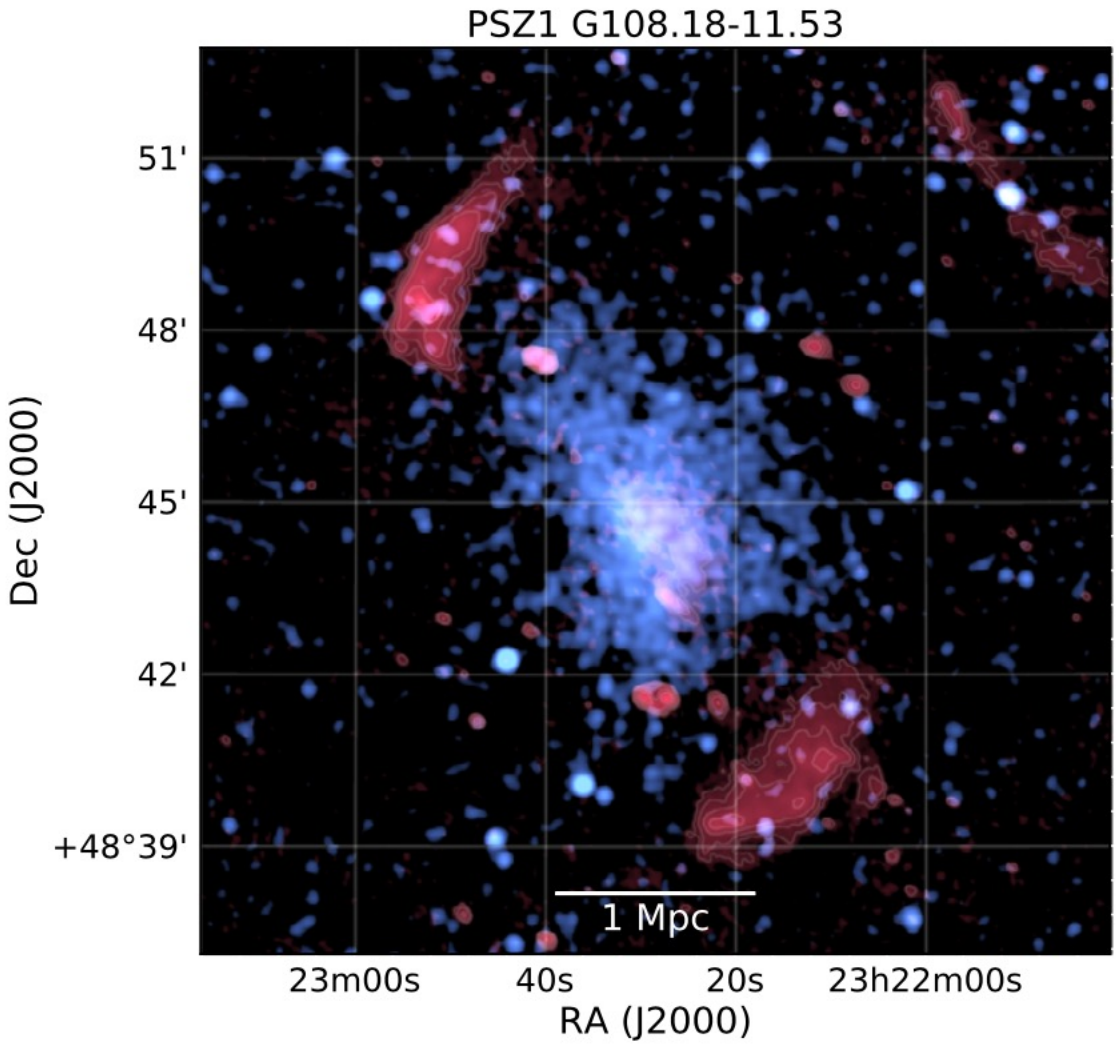
- **Cluster Radio Shocks**
  - Often shock a clear spectral index gradient across width
  - Region with flattest spectral index is on side away from cluster center
  - Toward center, spectral index steepens
    - Thought to be caused by synchrotron and IC losses in shock downstream region
- **Cluster Radio Shocks – Polarization**
  - Thought to be among the most polarized sources in the sky
  - Very elongated radio shocks usually show highest polarization fraction
  - Considered to trace particles accelerated at shocks
- **Cluster Radio Shocks – Radio vs. X-Ray**
  - Considered to trace particles accelerated at shocks
    - Shocks generated by cluster merger activity, accretion flows, etc.
  - Shock waves should coexist at locations of radio shocks – intensity of shock structure can be extrapolated from X-ray data




Sausage Cluster
11'00.0"
10'00.0"
09'00.0"
08'00.0"
+53°07'00.0"
Dec (J2000)
15.00s
43m00.00s
45.00s
30.00s
22h42m15.00s
RA (J2000)
500 kpc
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
spectral index (α)

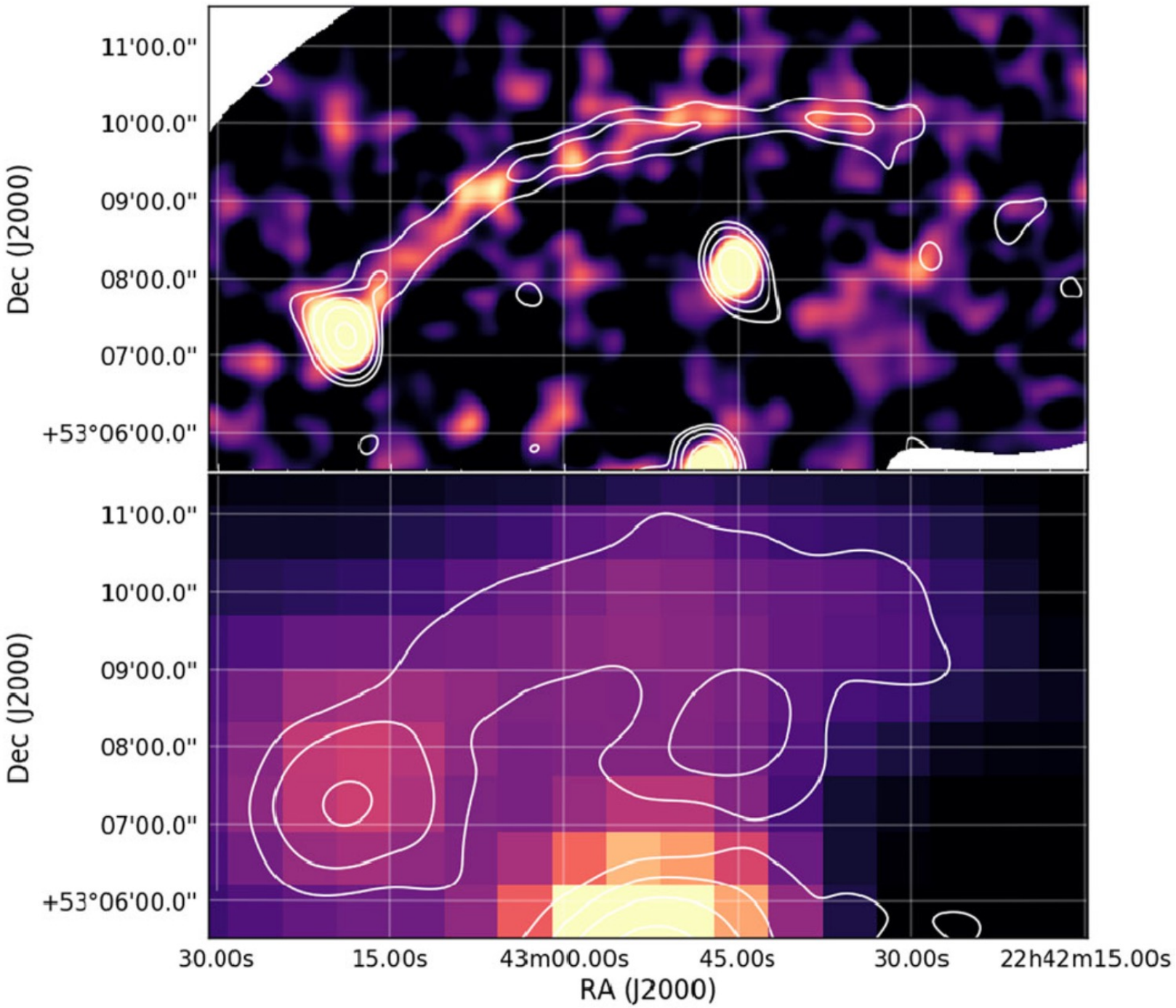

Sausage Cluster
11'00.0"
10'00.0"
09'00.0"
08'00.0"
+53°07'00.0"
Dec (J2000)
100 %
500 kpc
15.00s
43m00.00s
45.00s
30.00s
22h42m15.00s
RA (J2000)


PSZ1 G108.18-11.53
1 Mpc
51'00.0"
48'00.0"
45'00.0"
42'00.0"
+48°39'00.0"
Dec (J2000)
23m00.00s
40.00s
20.00s
23h22m00.00s
RA (J2000)
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
spectral index (α)


PSZ1 G108.18-11.53
51'
48'
45'
42'
+48°39'
Dec (J2000)
1 Mpc
23m00s
40s
20s
23h22m00s
RA (J2000)

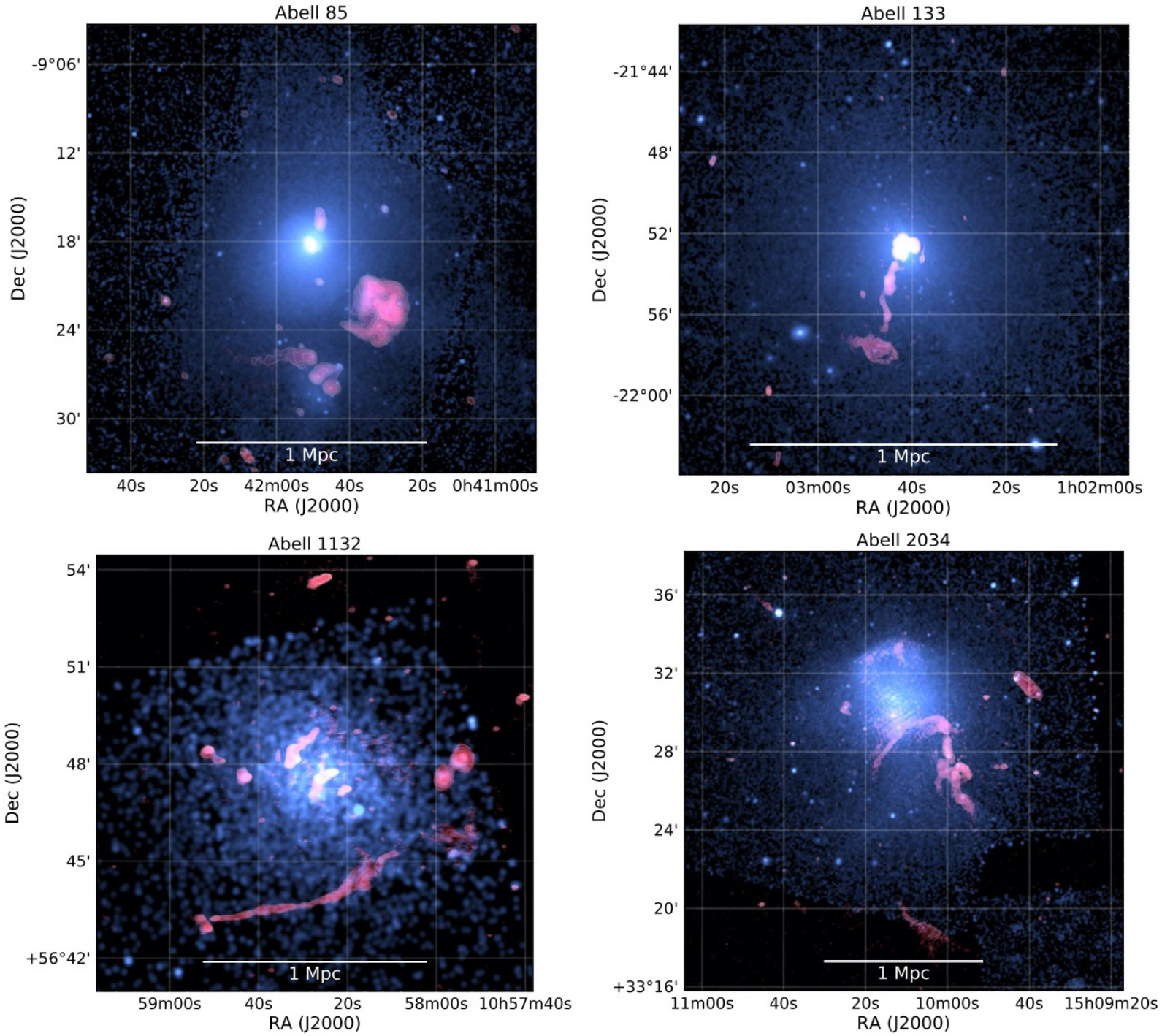
# CLUSTER RADIO SHOCKS – SZ, GR, + HF

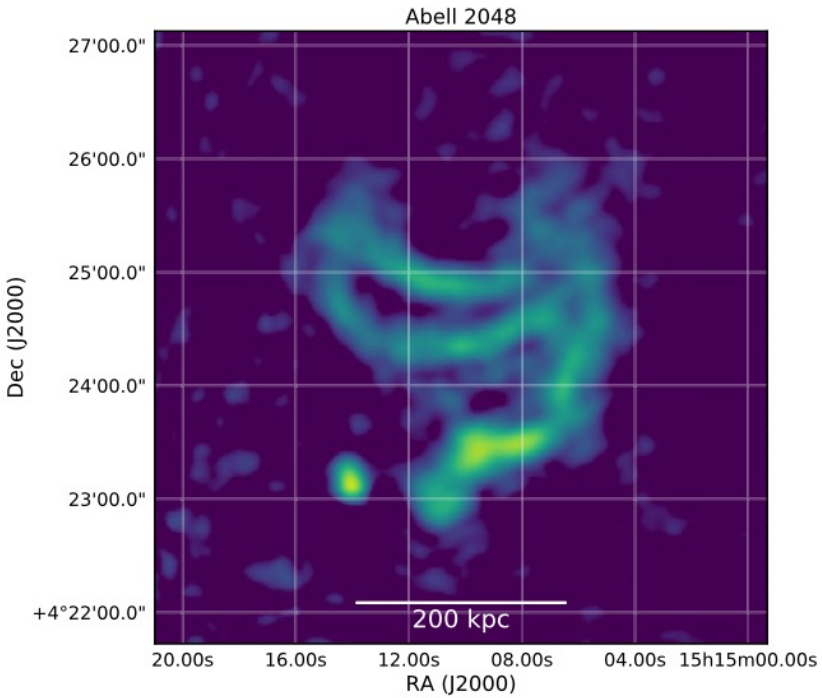
- **Sunyaev-Zeldovich Observations**
  - Thermal ICM electrons in galaxy clusters interact with CMB photons through inverse Compton scattering - S-Z effect
  - Provides complimentary way of studying the ICM
    - Particularly powerful at high redshift (redshift independent)
  - Efforts focused on measuring SZ effect at high spatial resolution
    - Aim of detecting small scale features in ICM (current studies)
      - E.g. – shocks in merging clusters!
  - SZ bulk observations have been very successful at selecting large samples of both relaxed and merging clusters ($z \sim 1.5$)
- **Gamma-Rays from Cluster Radio Shocks**
  - We know shocks should probably accelerate protons… CR protons should collide with thermal ICM and produce gamma-rays visible from hadronic interactions
  - However, expected gamma-ray emission for DSA shock acceleration at radio shocks is in tension with gamma-ray upper limits for some clusters… relative acceleration efficiency of electrons and protons is at odds with predictions from DSA (Fermi-I)
  - Possible explanation? B field at radio shocks is predominantly perpendicular to the shock normal
    - Observations indicate acceleration efficiency of protons is strongly suppressed at such shocks
    - This could reduce the tension with the low gamma-ray upper limits
- **High-Frequency Studies**
  - Radio shocks classical observed at relatively low frequencies (steep spectra)
  - Higher frequency studies pose challenges:
    - Radio shocks have steep-spectra, making them very faint at high frequencies
    - Radio interferometers typically have small fields of view at high frequencies and thus have difficult detecting extended diffuse sources
  - Current push to study radio shocks about 5 GHz barrier – current facilities and new instruments

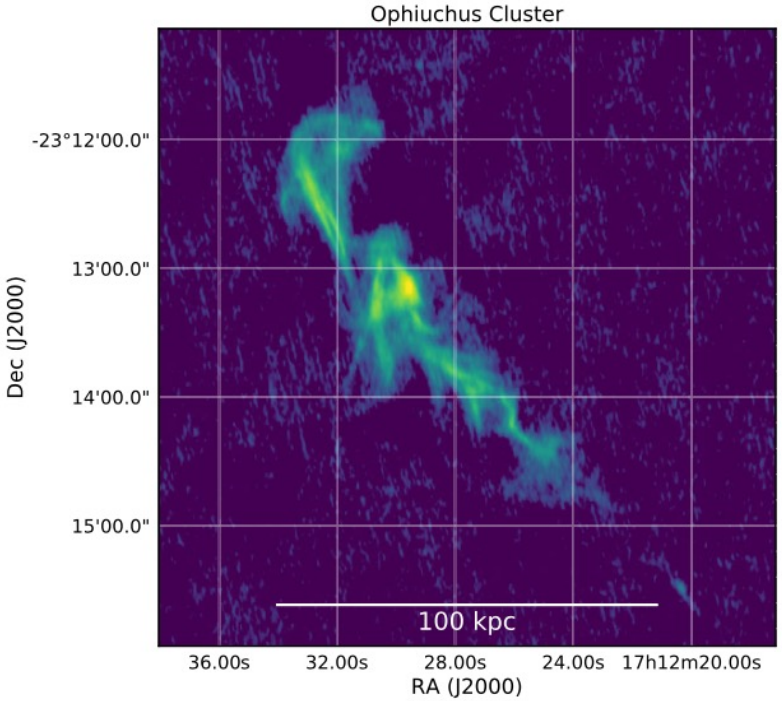

11'00.0"
10'00.0"
09'00.0"
08'00.0"
07'00.0"
+53°06'00.0"
Dec (J2000)
11'00.0"
10'00.0"
09'00.0"
08'00.0"
07'00.0"
+53°06'00.0"
Dec (J2000)
30.00s
15.00s
43m00.00s
45.00s
30.00s
22h42m15.00s
RA (J2000)

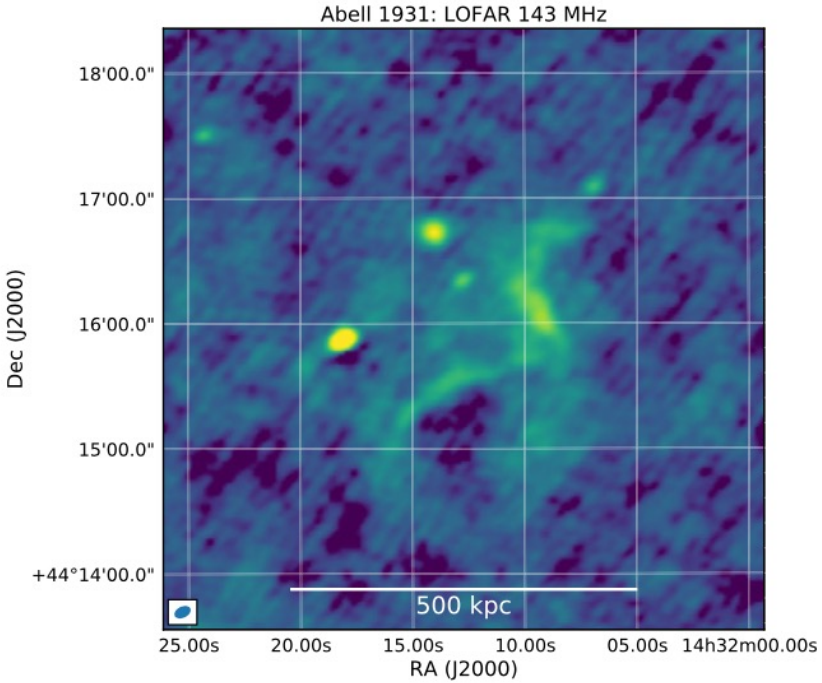
# CLUSTER RADIO SHOCKS – GR(E)ET AND FOSSILS

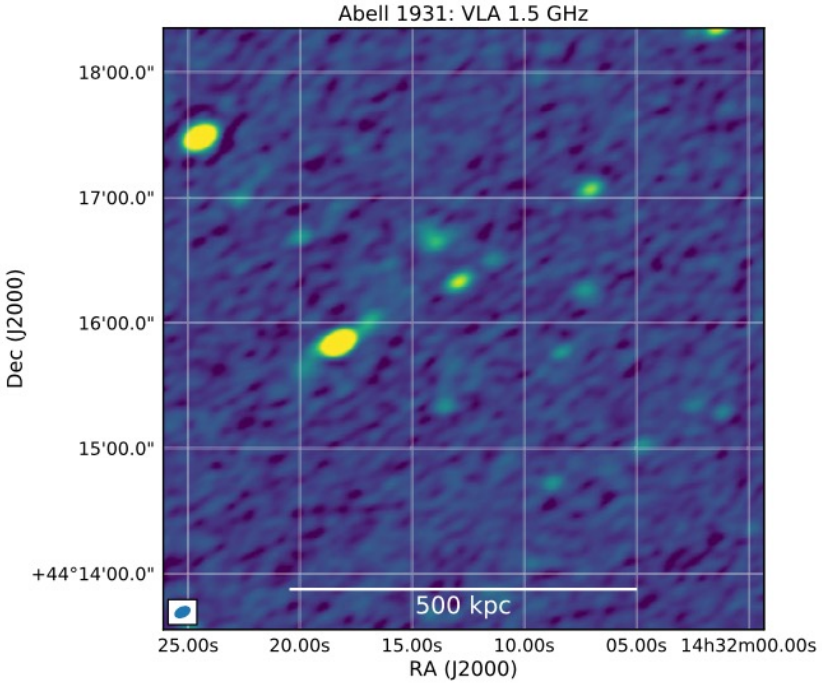
- **Mildly relativistic AGN fossil plasma – important since old populations of relativistic electrons are invoked as seed particles for the formation of radio halos and cluster radio shocks**
- **Radio Phoenices and Revived Fossil Plasma**
  - Phoenices trace old radio plasma from past episodes of AGN activity
    - Shock compresses plasma, causing increase in momentum of relativistic electrons
    - B field strength can produce a source w/ steep, curved radio spectrum
  - Phoenices often have complex morphologies – merger events not required for their formation
- **Reacceleration and Fossil Plasma**
  - DSA shock models for CRe acceleration show efficiency is low when electrons accelerated directly from thermal pool – hard to reconcile with observed brightness + radio spectrum of some cluster radio shocks (high acceleration efficiency)
  - In great majority of cases, presence of a source of CR electrons near the radio shock is missing, forcing the question: are pre-energized CRe necessary to power all radio shocks?
  - Current and future proposals are to better understand this connection
- **GReET (Gently Reenergized Tails)**
  - Inferred as possible new mechanism to energize old radio plasma
  - A WAT source fades into two fairly thin filaments – with these, emission starts to brighten, synchrotron spectrum flattens
  - GENTLE process of reenergization – barely balances radiative losses of cosmic rays
  - Could be a seed population of energetic particles (if GReET process is common)

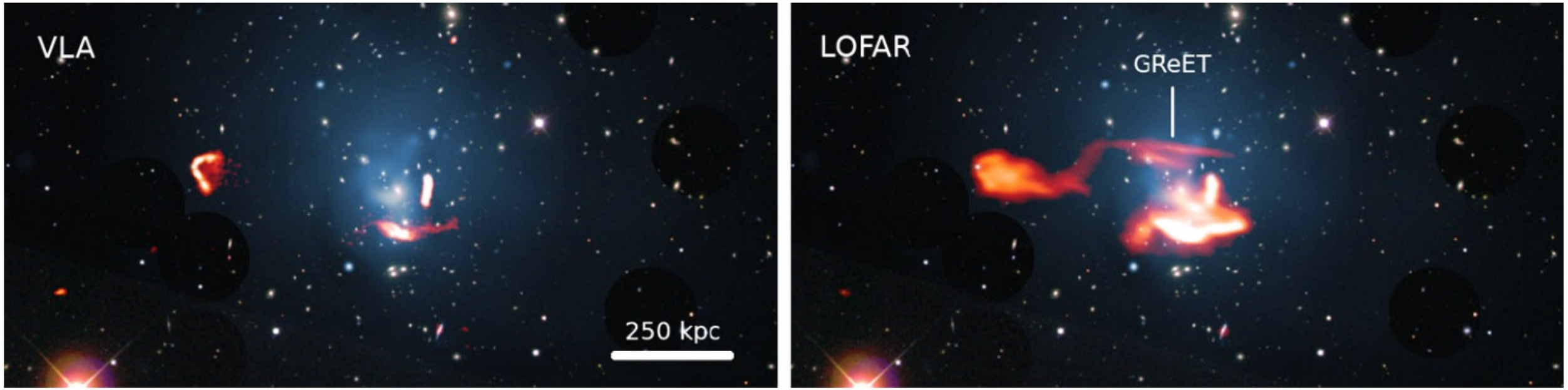

Abell 85
-9°06'
12'
18'
24'
30'
Dec (J2000)
1 Mpc
40s
20s
42m00s
40s
20s
0h41m00s
RA (J2000)
Abell 133
-21°44'
48'
52'
56'
-22°00'
Dec (J2000)
1 Mpc
20s
03m00s
40s
20s
1h02m00s
RA (J2000)
Abell 1132
54'
51'
48'
45'
+56°42'
Dec (J2000)
1 Mpc
59m00s
40s
20s
58m00s
10h57m40s
RA (J2000)
Abell 2034
36'
32'
28'
24'
20'
+33°16'
Dec (J2000)
1 Mpc
11m00s
40s
20s
10m00s
40s
15h09m20s
RA (J2000)


Abell 2048
27'00.0"
26'00.0"
25'00.0"
24'00.0"
23'00.0"
+4°22'00.0"
Dec (J2000)
200 kpc
20.00s
16.00s
12.00s
08.00s
04.00s
15h15m00.00s
RA (J2000)


Ophiuchus Cluster
-23°12'00.0"
13'00.0"
14'00.0"
15'00.0"
Dec (J2000)
100 kpc
36.00s
32.00s
28.00s
24.00s
17h12m20.00s
RA (J2000)

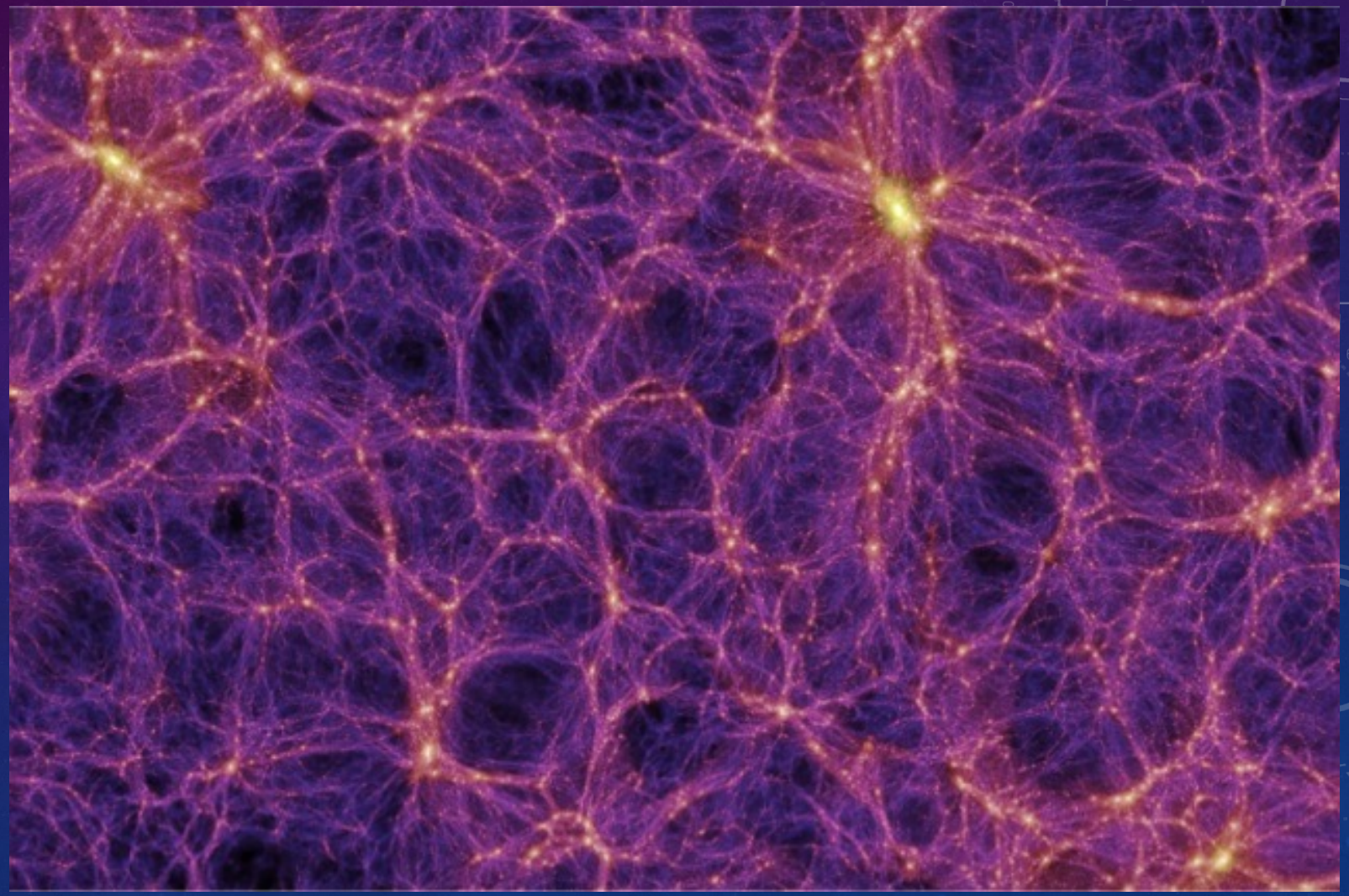

Abell 1931: LOFAR 143 MHz
18'00.0"
17'00.0"
16'00.0"
15'00.0"
+44°14'00.0"
Dec (J2000)
500 kpc
25.00s
20.00s
15.00s
10.00s
05.00s
14h32m00.00s
RA (J2000)

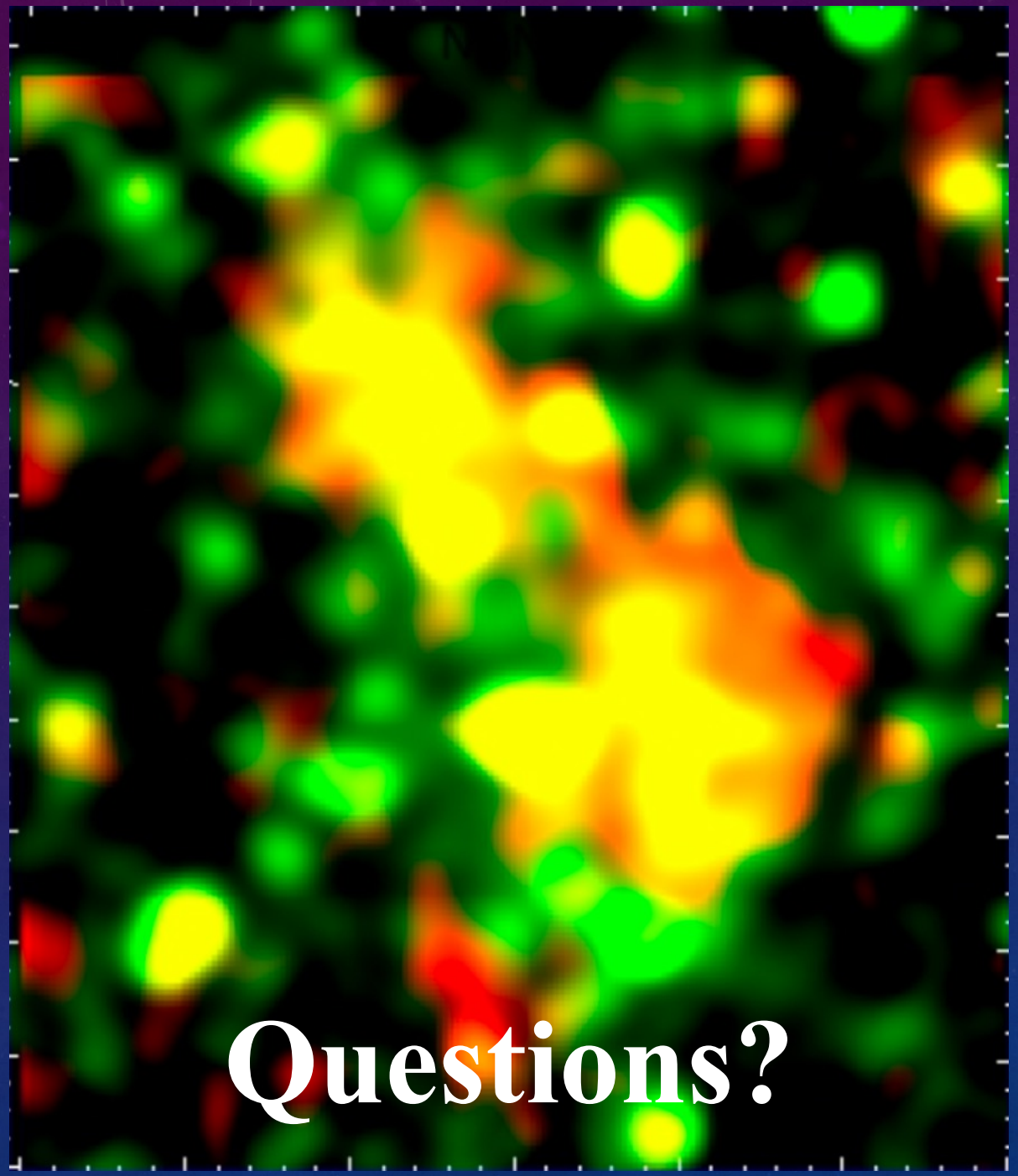

Abell 1931: VLA 1.5 GHz
18'00.0"
17'00.0"
16'00.0"
15'00.0"
+44°14'00.0"
Dec (J2000)
500 kpc
25.00s
20.00s
15.00s
10.00s
05.00s
14h32m00.00s
RA (J2000)


VLA
250 kpc
LOFAR
GReET

# DIFFUSE RADIO EMISSION OUTSIDE CLUSTERS

- Elongated filaments of galaxies span and regions between clusters
- Compared to intracluster medium, IGM has low density and cooler temperature
- Filaments are surrounded by strong accretion shocks
  - Where plasma is first shock heated
- Studying any of this is notoriously difficult due to last of sensitive observational tools





# Questions?