The X-Ray Universe 2014

Galaxy Clusters: Trouble in the Periphery

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Main collaborators:

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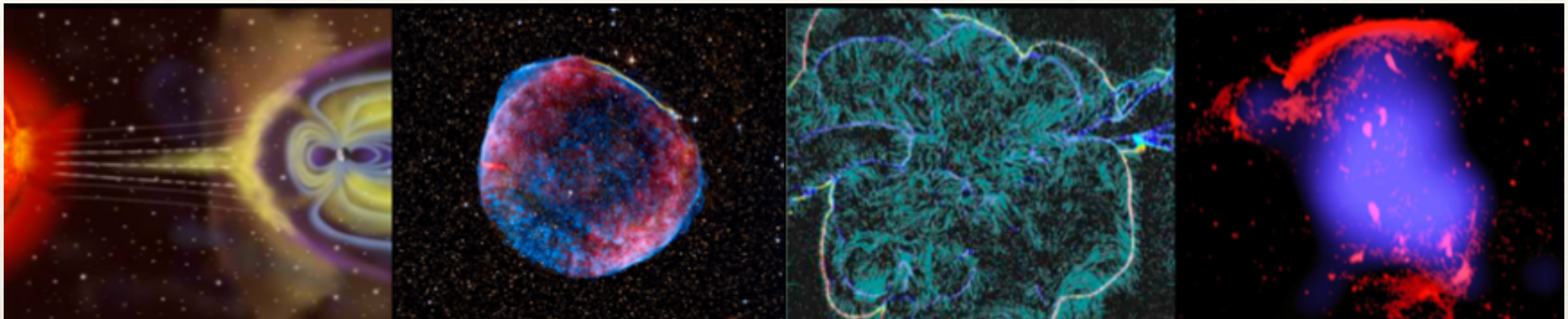
Explore the connection between shock waves and radio relics.



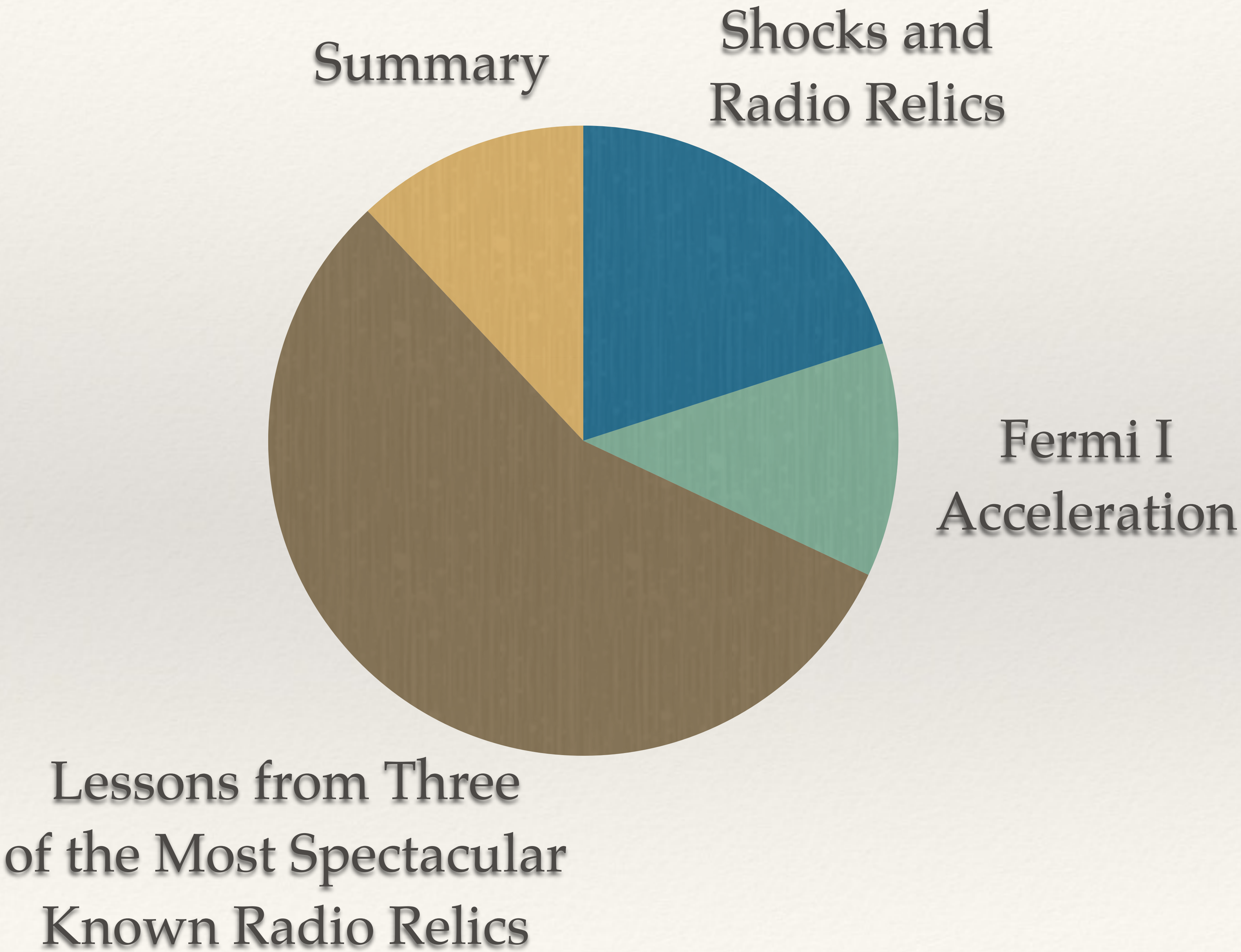
Earth's Bow Shock	Supernova Remnants	Accretion Shocks	Merger Shocks
$n_e \sim 10$ cm^{-3}	$n_e \sim 1$ cm^{-3}	$n_e \sim 10^{-5}$ cm^{-3}	$n_e \sim 10^{-4}$ cm^{-3}
$T_e \sim 10^5$ K	$T_e \sim 10^4$ K	$T_e \sim 10^4$ K	$T_e \sim 10^7$ K
$v \sim 300$ km s^{-1}	$v \sim 4000$ km s^{-1}	$v \sim 3000$ km s^{-1}	$v \sim 1500$ km s^{-1}
$B \sim 30$ μG	$B \sim 5$ μG	$B \sim 0.01$-0.1 μG	$B \sim 1$-5 μG
$\beta \sim 1$-5	$\beta \sim 1$	$\beta \sim 100$	$\beta \sim 100$
$M \sim 5$-10	$M \sim 100$	$M \sim 10$-100	$M \sim 2$-4

Why study shocks?

Shocks virialize infalling material and maintain an approximate state of hydrostatic equilibrium.

Unique chance to study particle acceleration at weak shocks in diffuse, high-beta plasma.

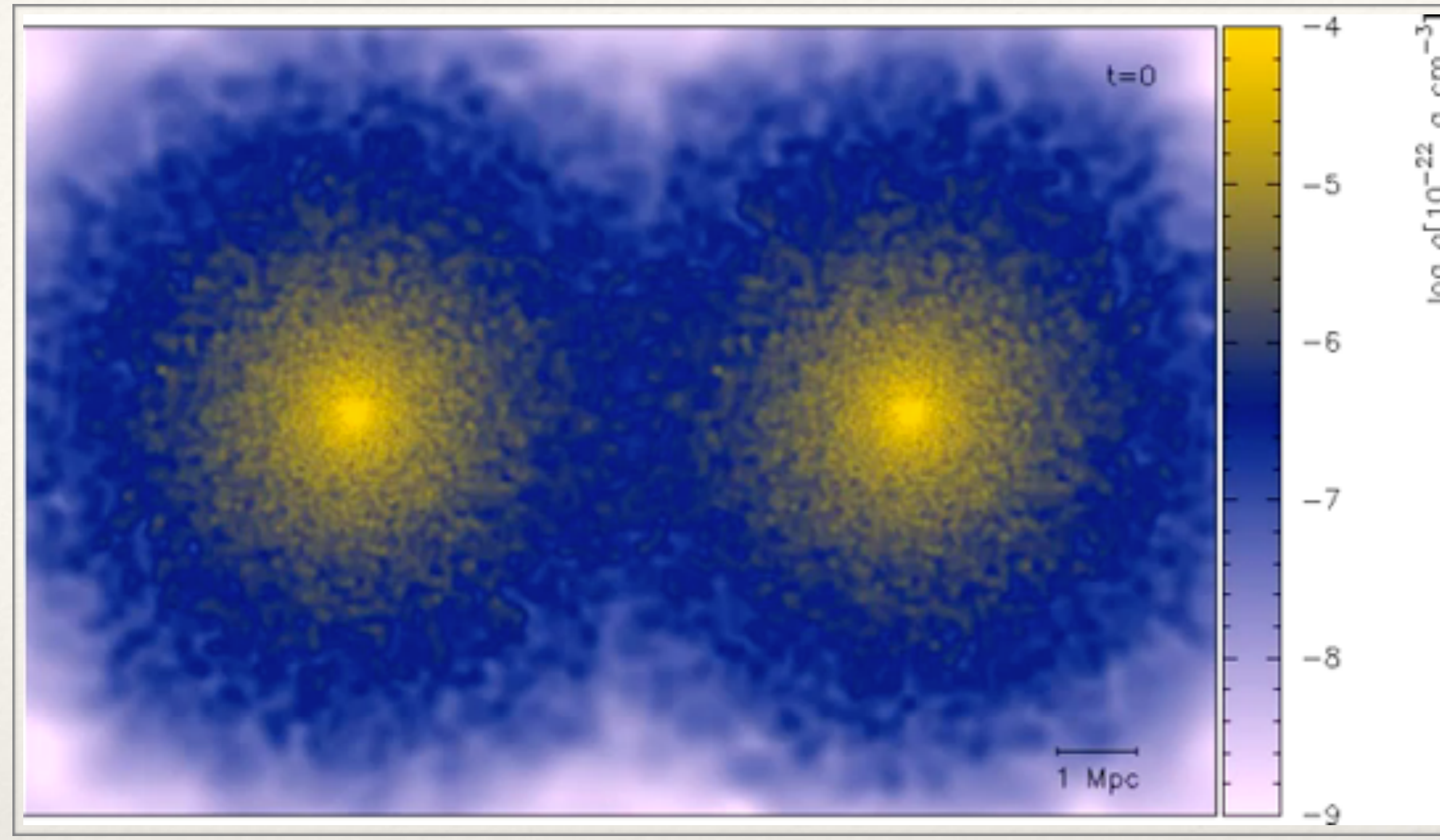
Outline of the Talk



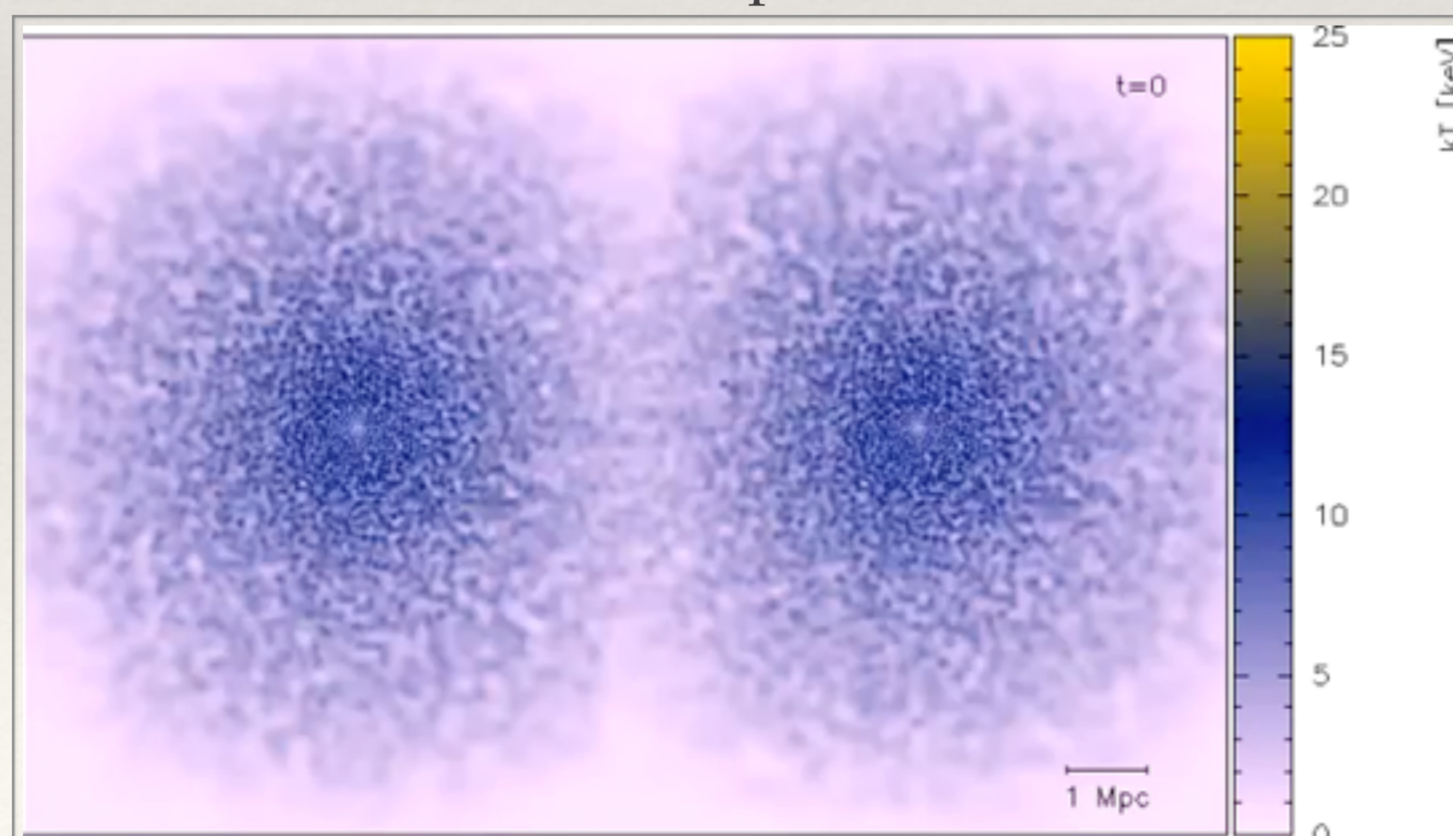
Shocks in Merging Clusters

A Head-On Galaxy Cluster Collision

ICM density



ICM temperature



Credit:

Simulation Library of Astrophysical Cluster Mergers (SLAM)

M. Chatzikos, C. Sarazin, B. O'Shea

http://www.astro.virginia.edu/research/Xray/SLAM_1_bw.pdf

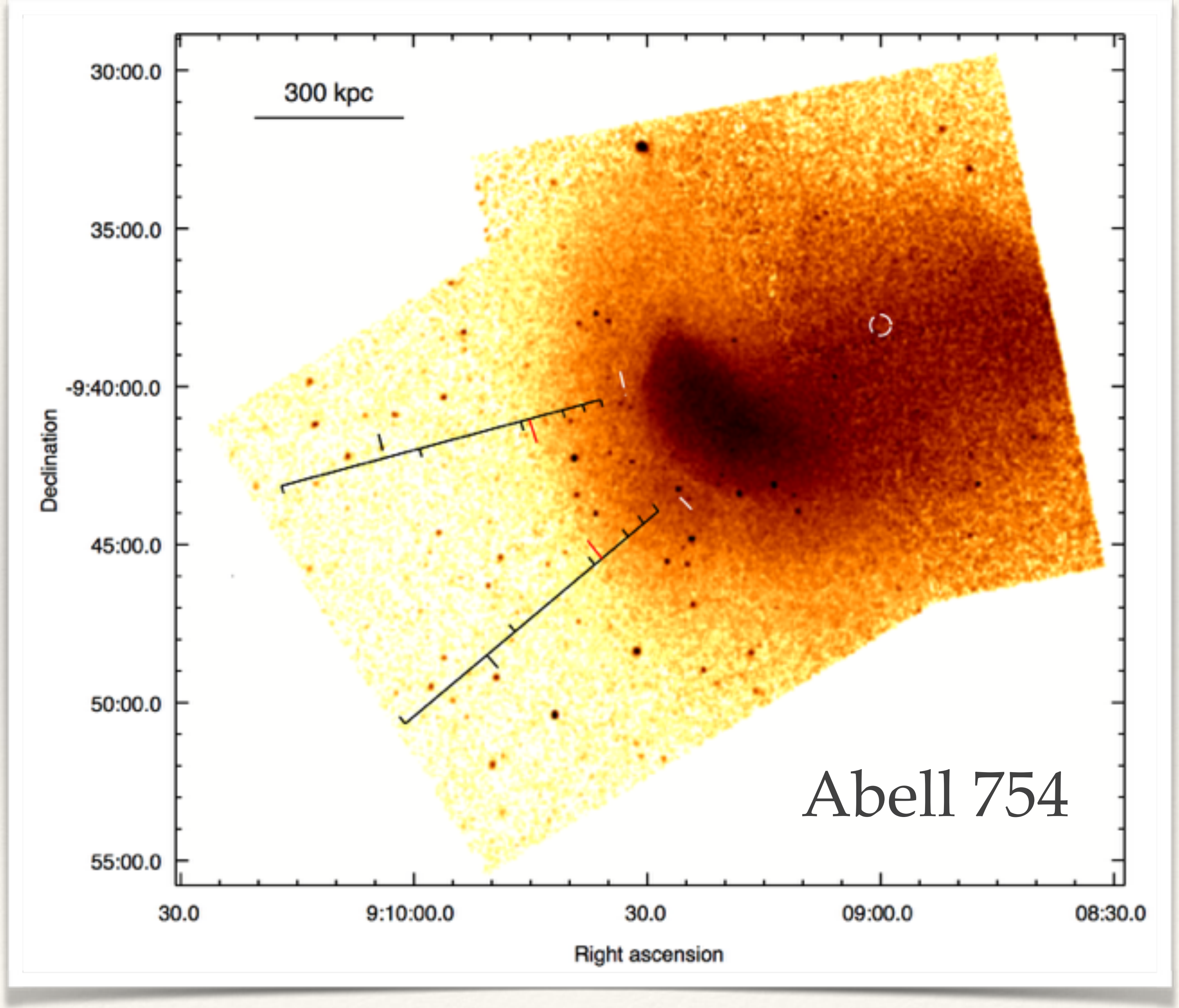
Shock Waves in the ICM

Image info:

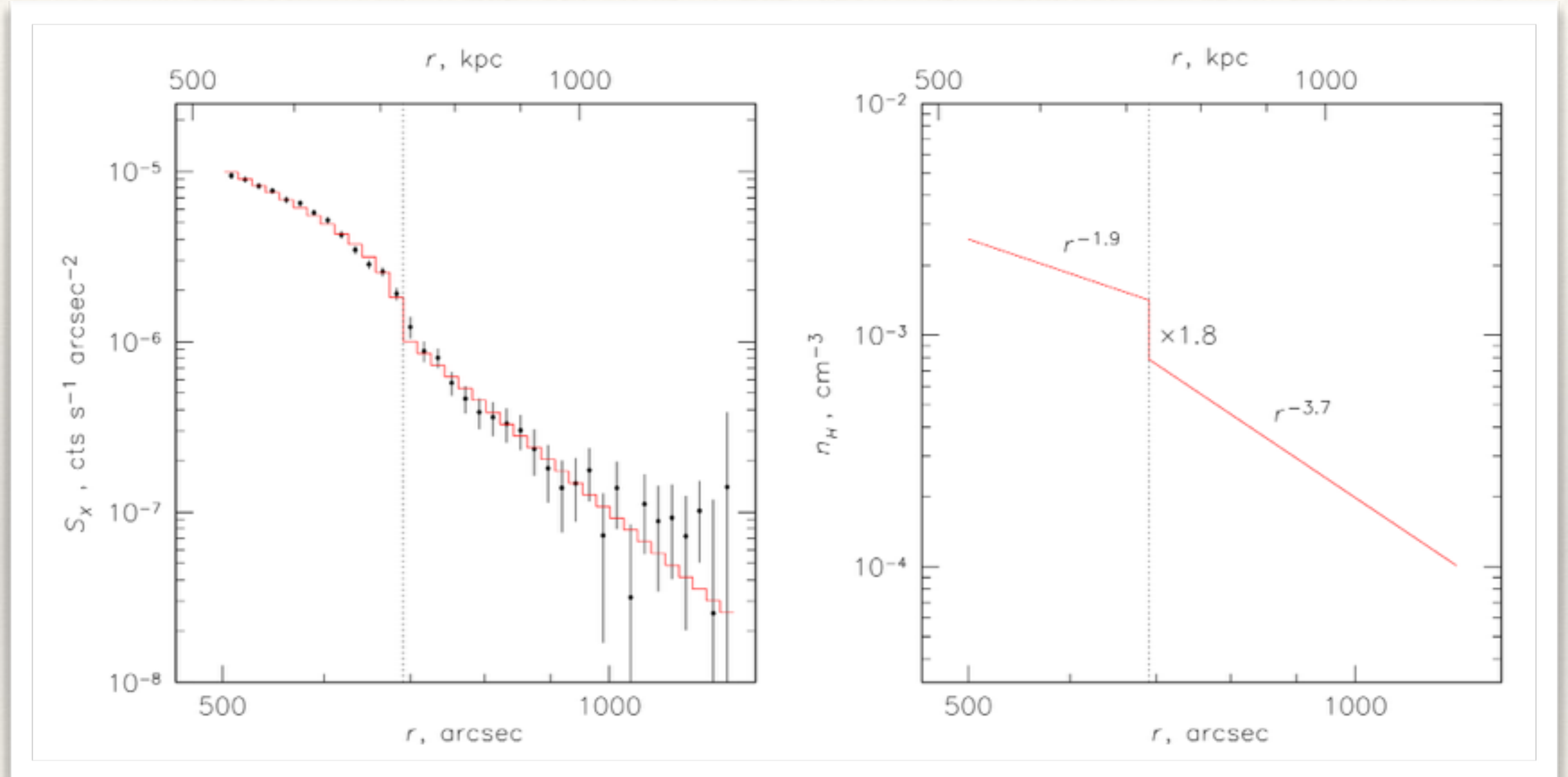
- Chandra
- 0.5 - 4 keV
- 135 ks

Credit:

Macario et al. (2011)

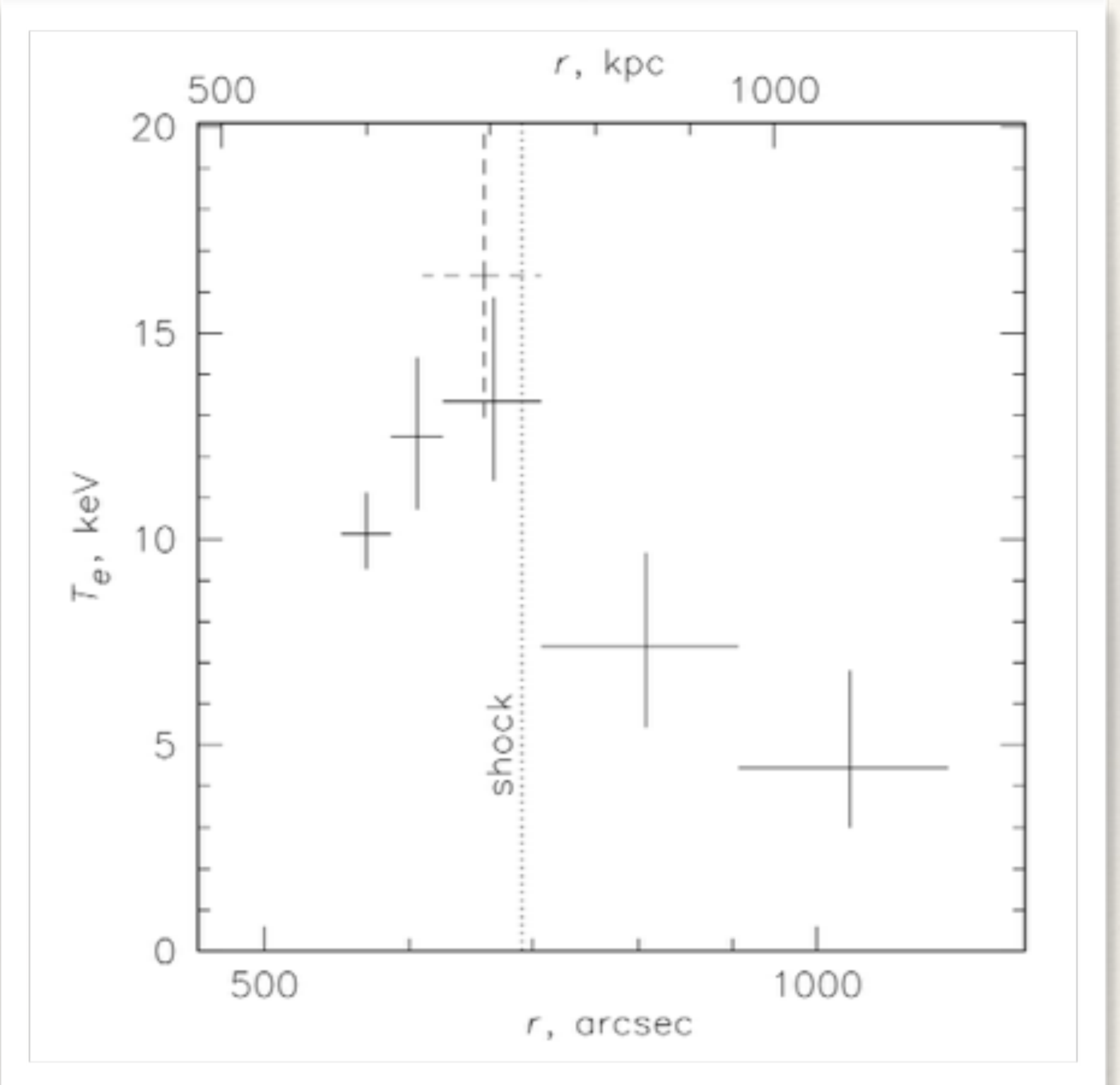


Density discontinuity



Credit: Macario et al. (2011)

Temperature discontinuity



Credit: Macario et al. (2011)

Rankine-Hugoniot conditions:

$$1/C = n_1/n_2 = 3/4M^2 + 1/4$$

$$T_2/T_1 = (5M^4 + 14M^2 - 3)/16M^2$$

Notations:

M: Mach number

C: density compression at the shock

n: number density

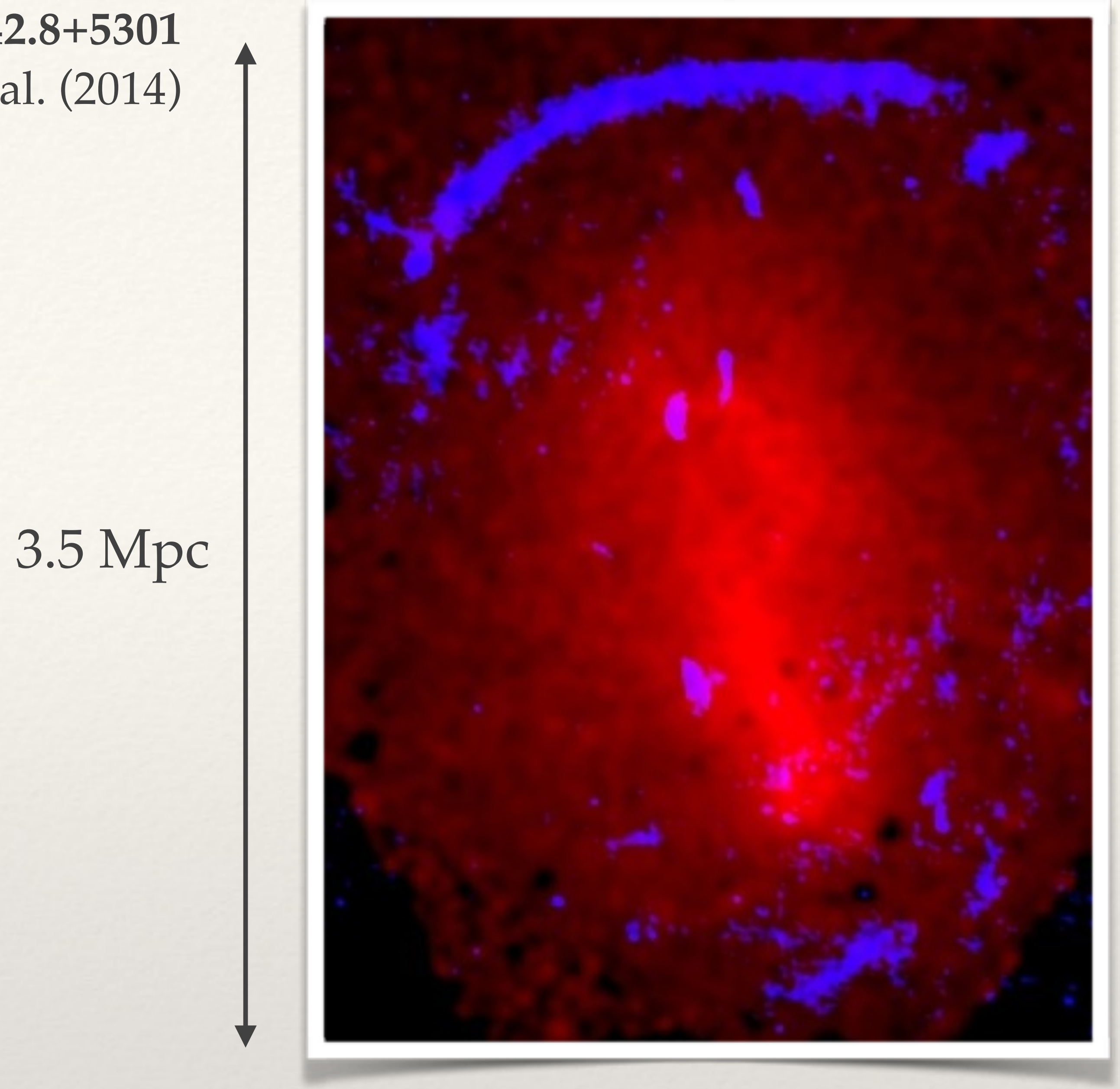
T: temperature

X-Ray Challenges

- **reminder: $\mathscr{E}_\nu \propto n^2\, T^{-1/2}\, e^{-h\nu/kT}$**
- X-ray faint cluster outskirts
- need substantial exposure times
- foreground, sky background, and instrumental background components dominate
- temperature measurements are affected by systematic errors

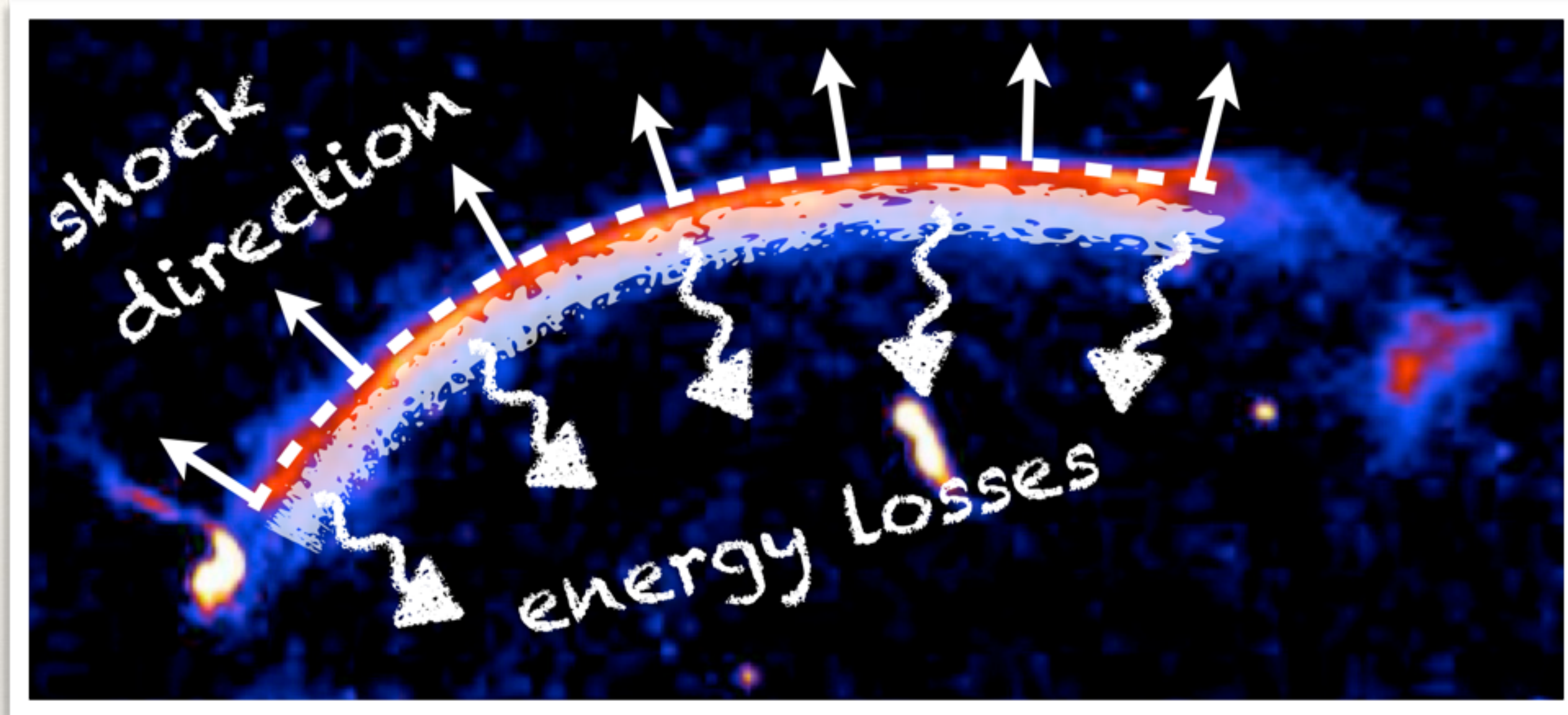
Radio Relics

CIZA J2242.8+5301
van Weeren et al. (2010), Ogrean et al. (2014)

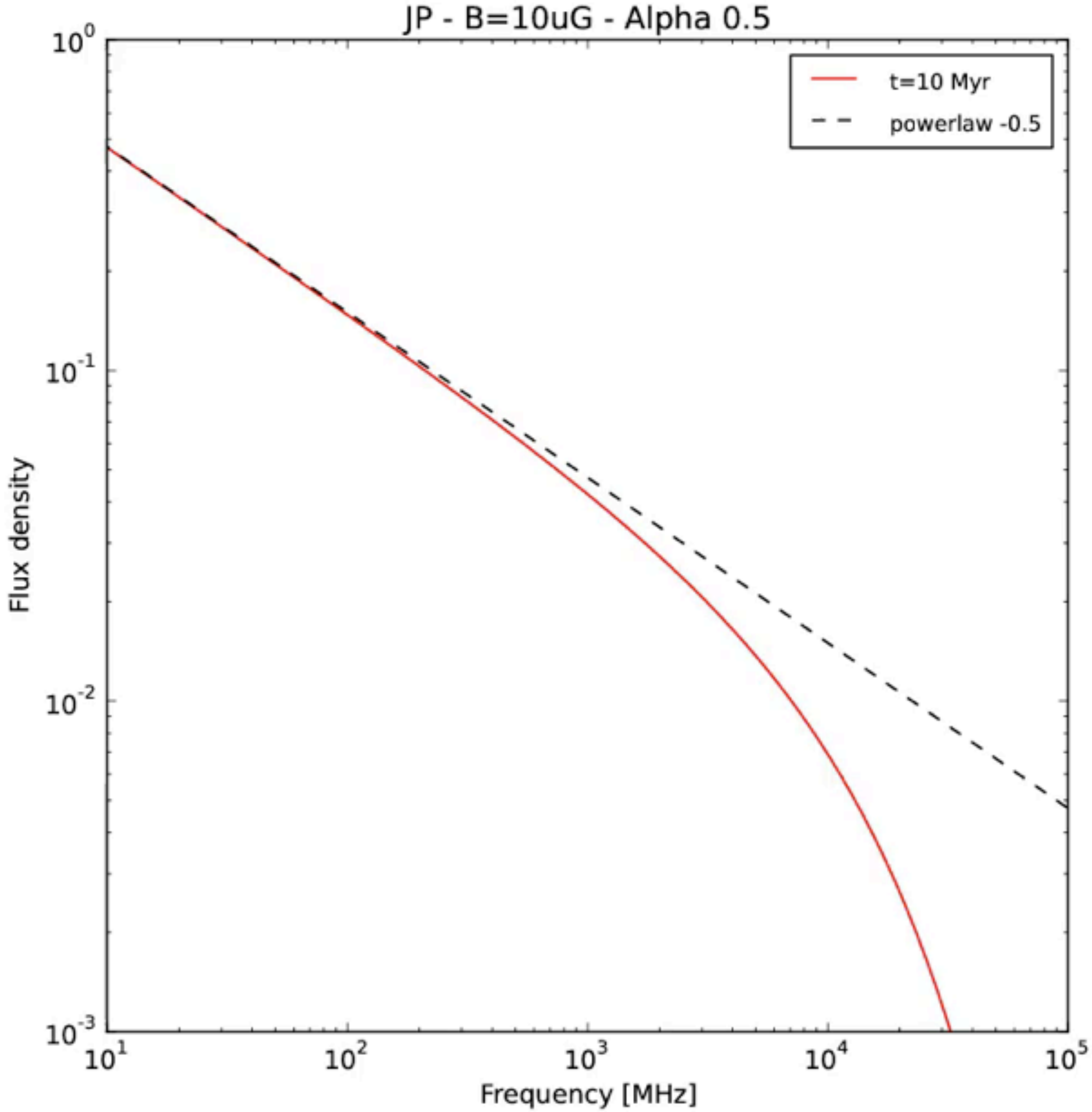


Radio Relics

- diffuse sources, linear scale ~ 1 Mpc
- believed to be created by particle acceleration at large-scale shocks triggered during mergers, possibly via diffusive shock acceleration (DSA)
- low radio brightness, $S_\nu \sim 1\ \mu\text{Jy arcsec}^{-2}$ at 1.4 GHz

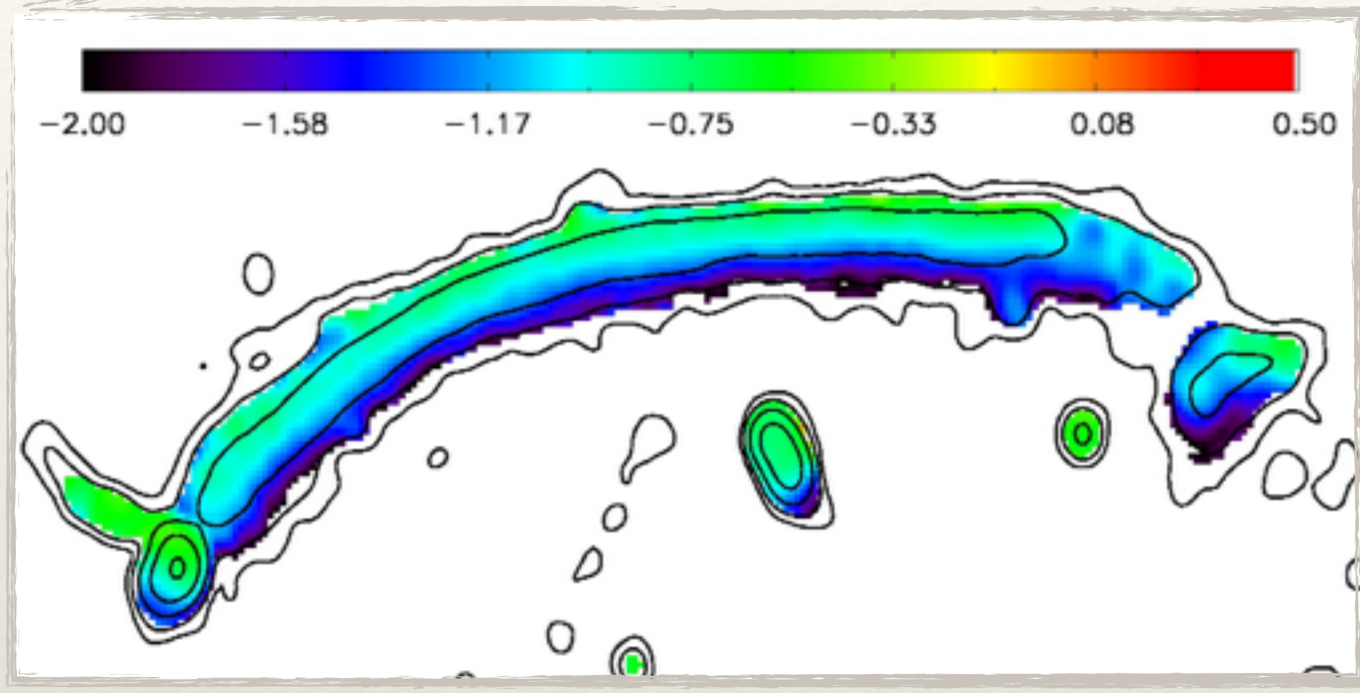


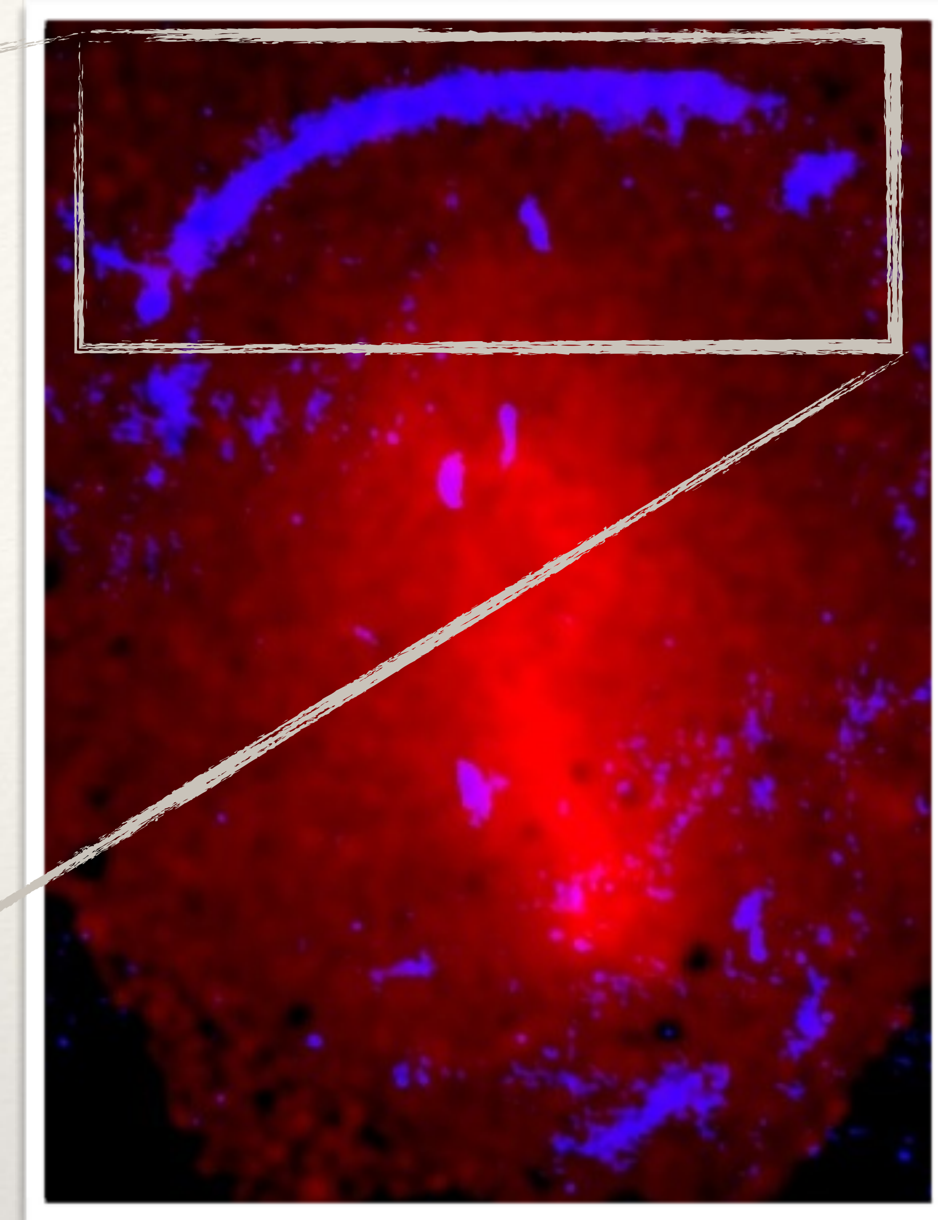
Synchrotron and inverse Compton energy losses in the downstream region of the shock.



Credit: F. de Gasperin

CIZA J2242.8+5301
van Weeren et al. (2010)





Radio Relics

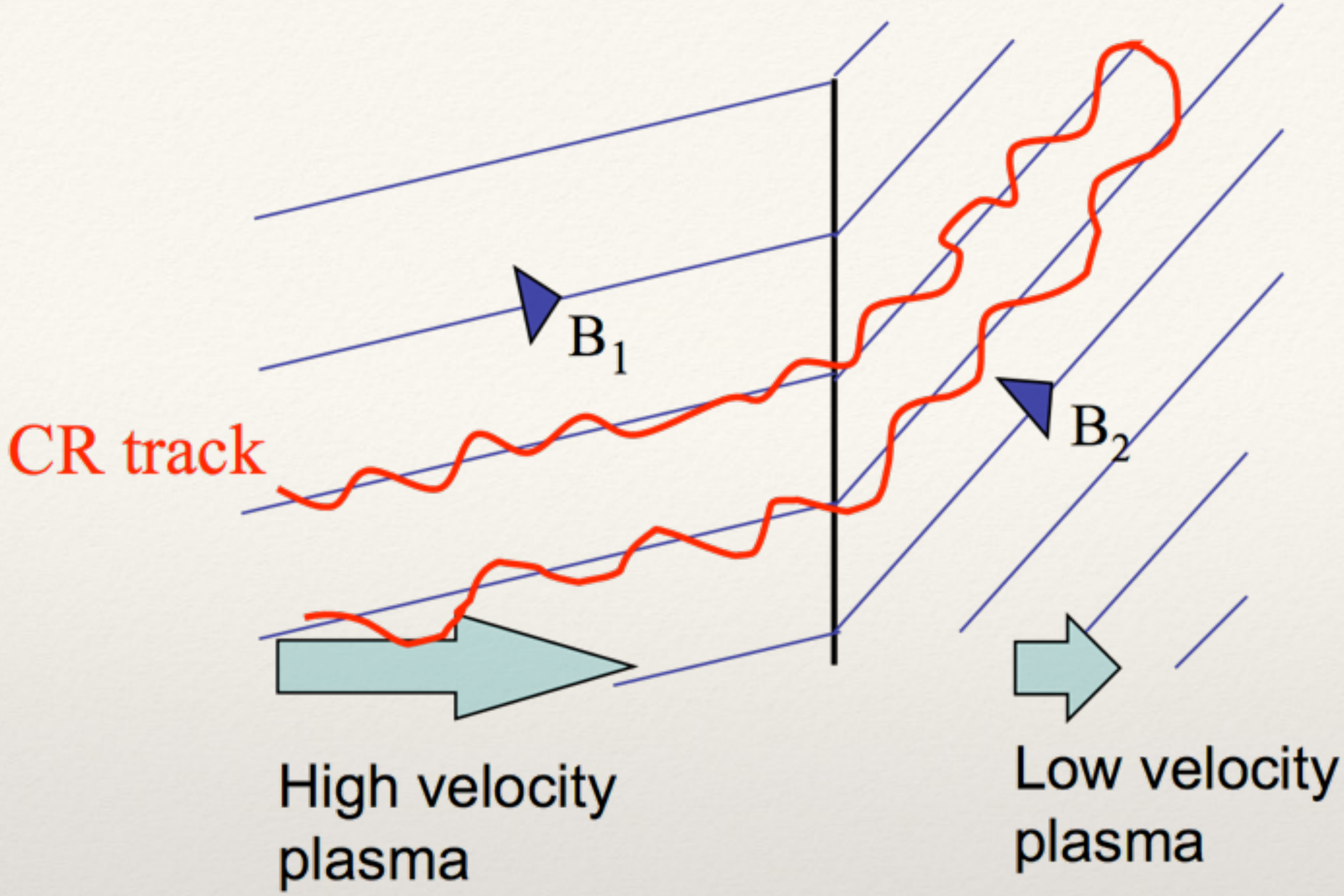
- diffuse sources, linear scale ~ 1 Mpc
- believed to be created by particle acceleration at large-scale shocks triggered during mergers, possibly via diffusive shock acceleration (DSA)
- low radio brightness, $S_\nu \sim 1\ \mu$Jy arcsec^{-2} at 1.4 GHz

- gradual spectral index steepening towards the cluster "centre"

Fermi I Acceleration
(a.k.a. Diffusive Shock Acceleration)

GOOD NEWS!

Diffusive shock acceleration (DSA) of thermal particles is the only acceleration process for which it is very easy to determine the shock Mach number from the radio spectral index.



- Particle scattering at the shock causes cosmic rays to recross the shock front many times before escaping the acceleration region.
- With each crossing, the energy of the cosmic ray increases by a factor:

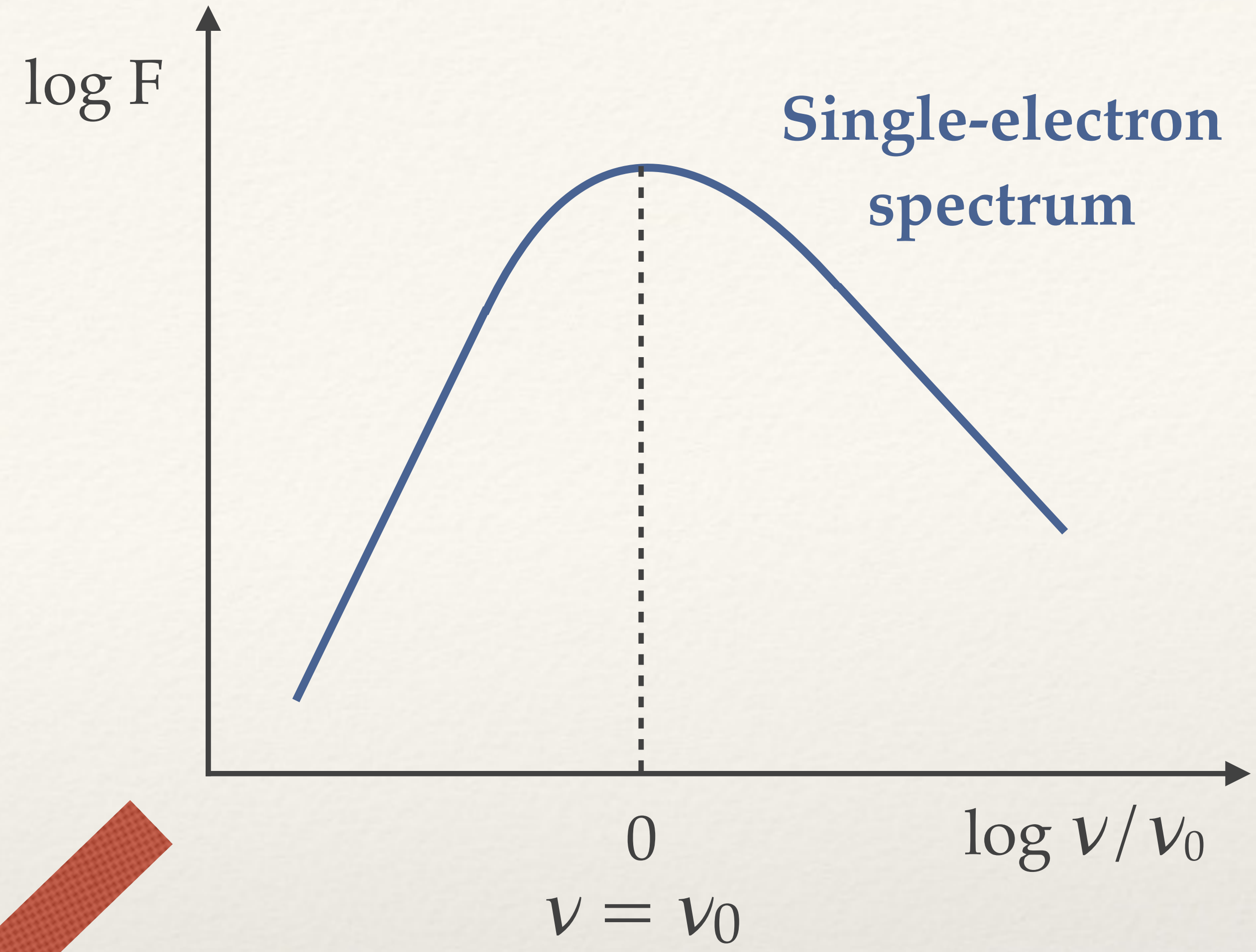
$$\beta \equiv \Delta E / E = v_s / c$$

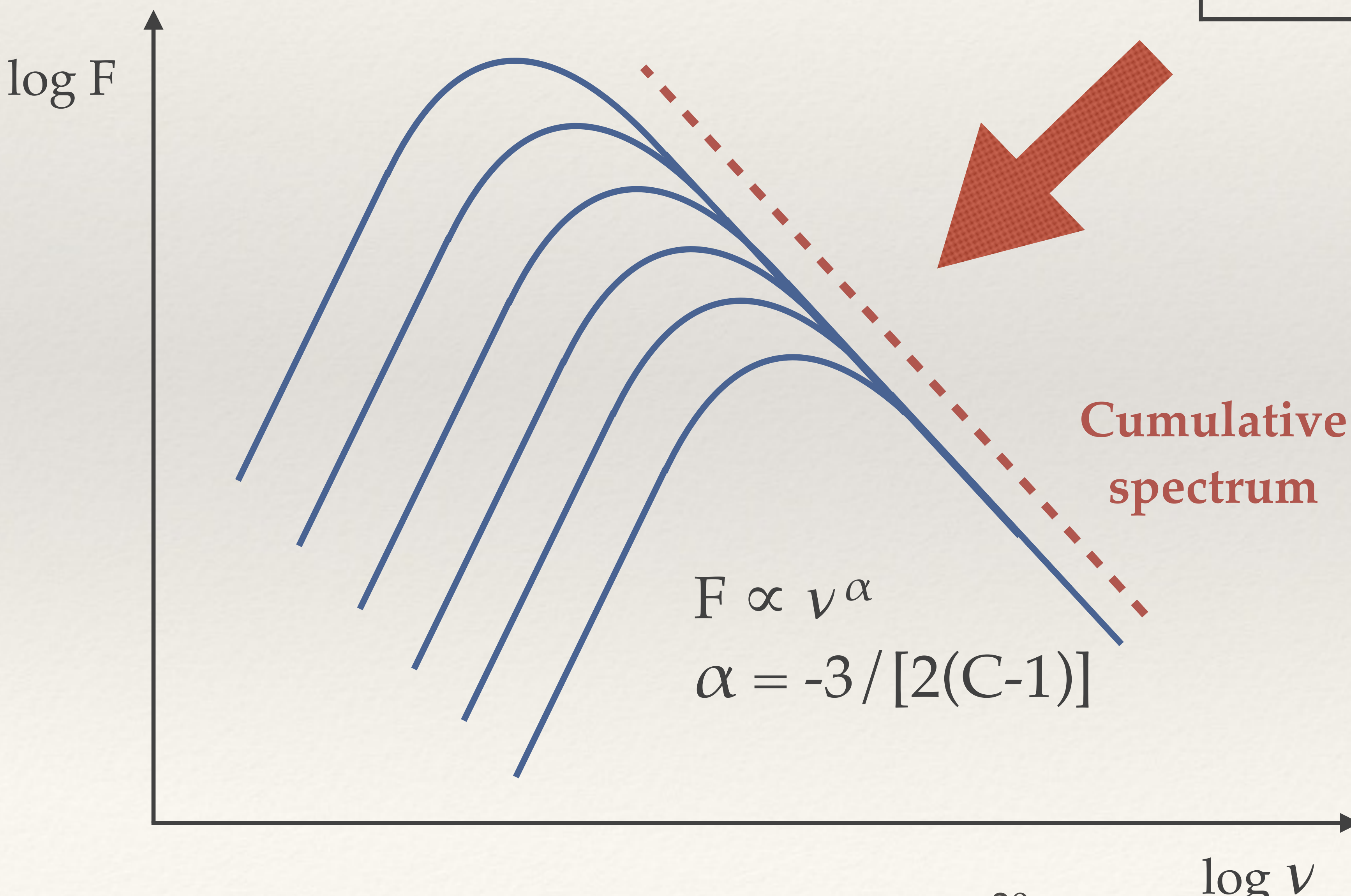
(β to the first power, hence the name "Fermi I" acceleration)

After *k* crossings, for an isotropic particle distribution:

$$dN_k/dE \propto E_k^{-s}$$

$$s = (C+2)/(C-1)$$





Notations:

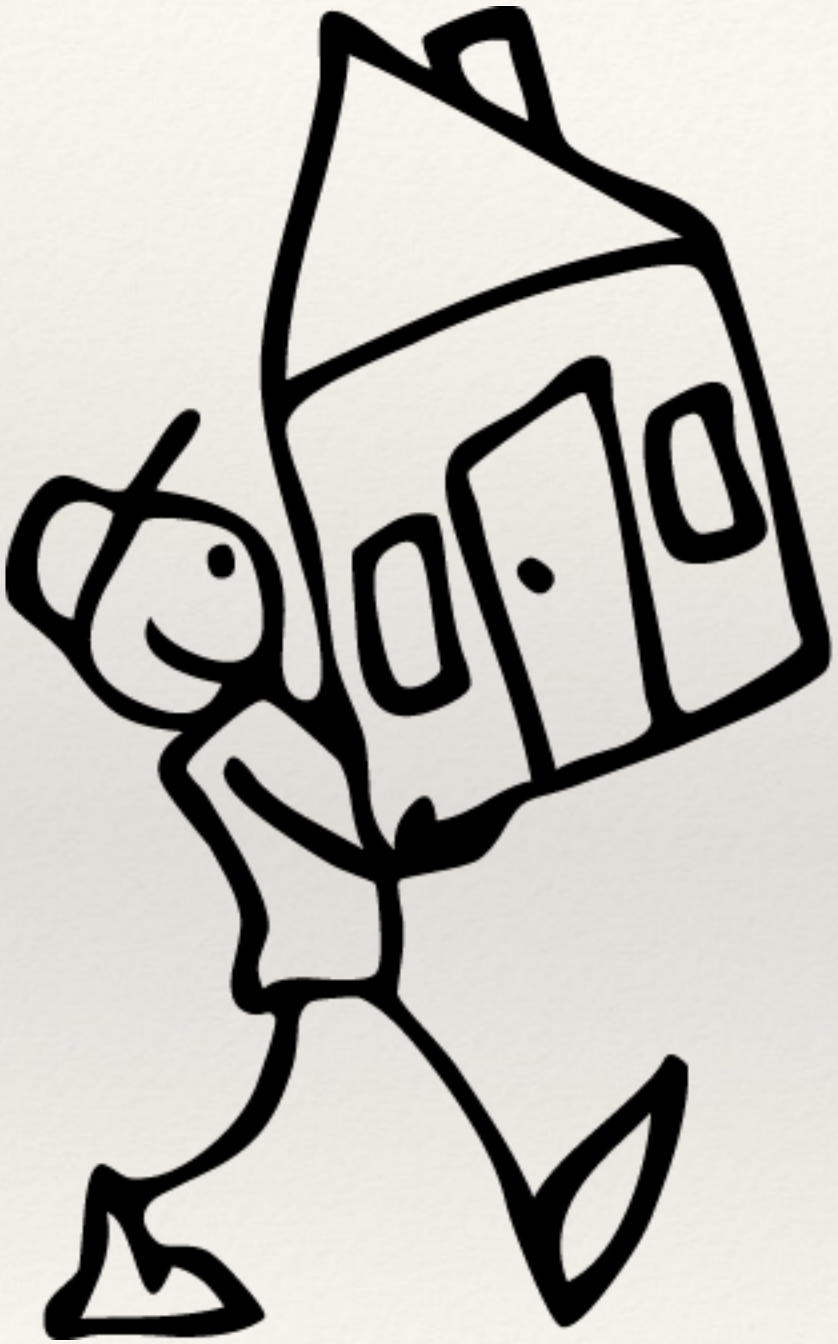
N: number of particles in the accelerating region

C: density compression at the shock

α: spectral index

s: slope of the particle distribution

Take-Home Message (so far)

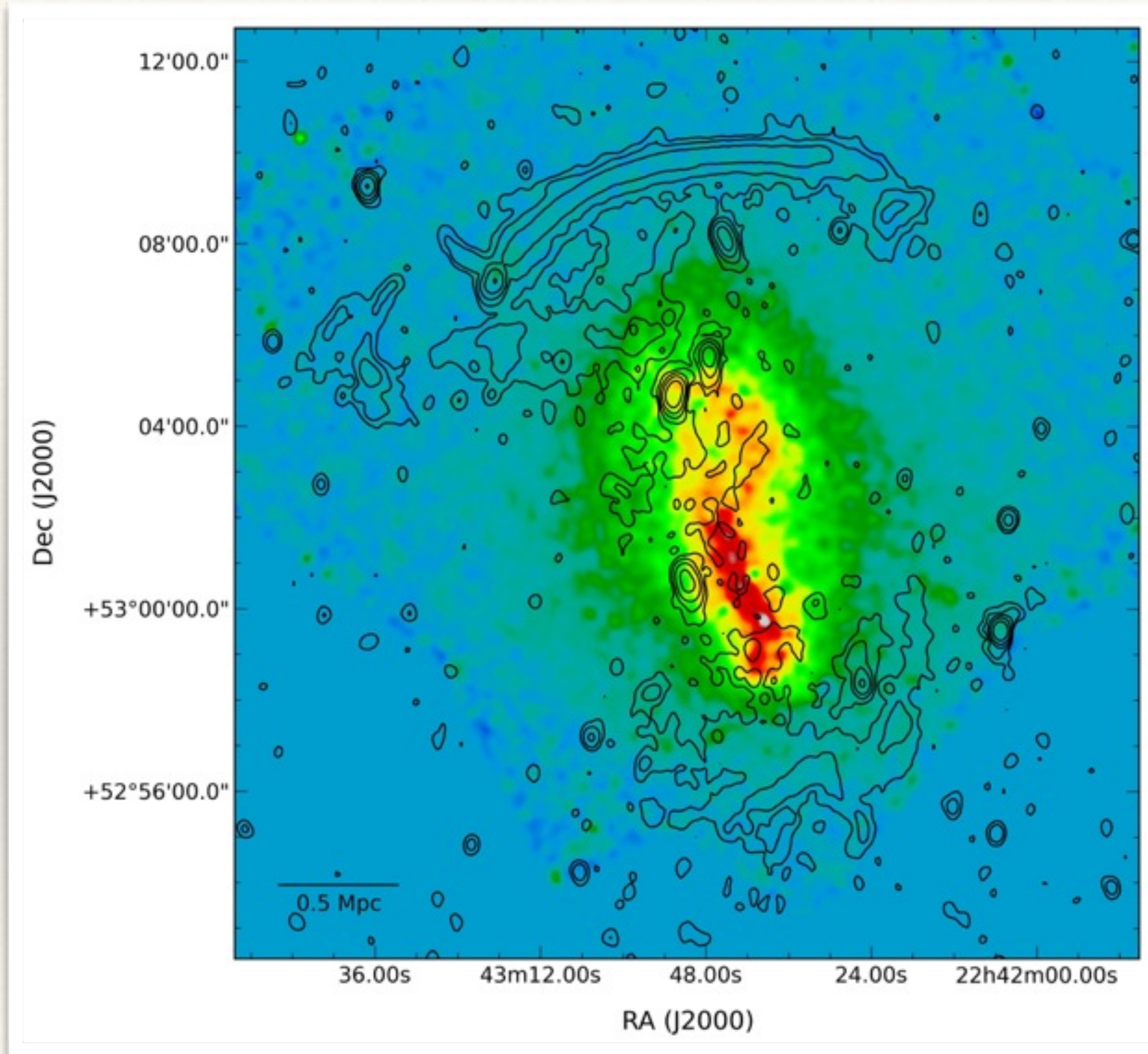


- Weak shocks in merging galaxy cluster outskirts are expected to be associated with radio relics.
- The outer edge of the relic should trace the shock front.
- The arcs spanned by the relic and by the corresponding shock front should have the same length.
- If relics are described by the standard DSA model, then the Mach number of a shock could be independently determined from X-ray and radio observations.

Puzzling Results on the Sausage, Toothbrush, and ZwCl 2341 Clusters

CIZA J2242.8+5301
a.k.a. the Sausage Cluster

Ogrean et al. (2014)

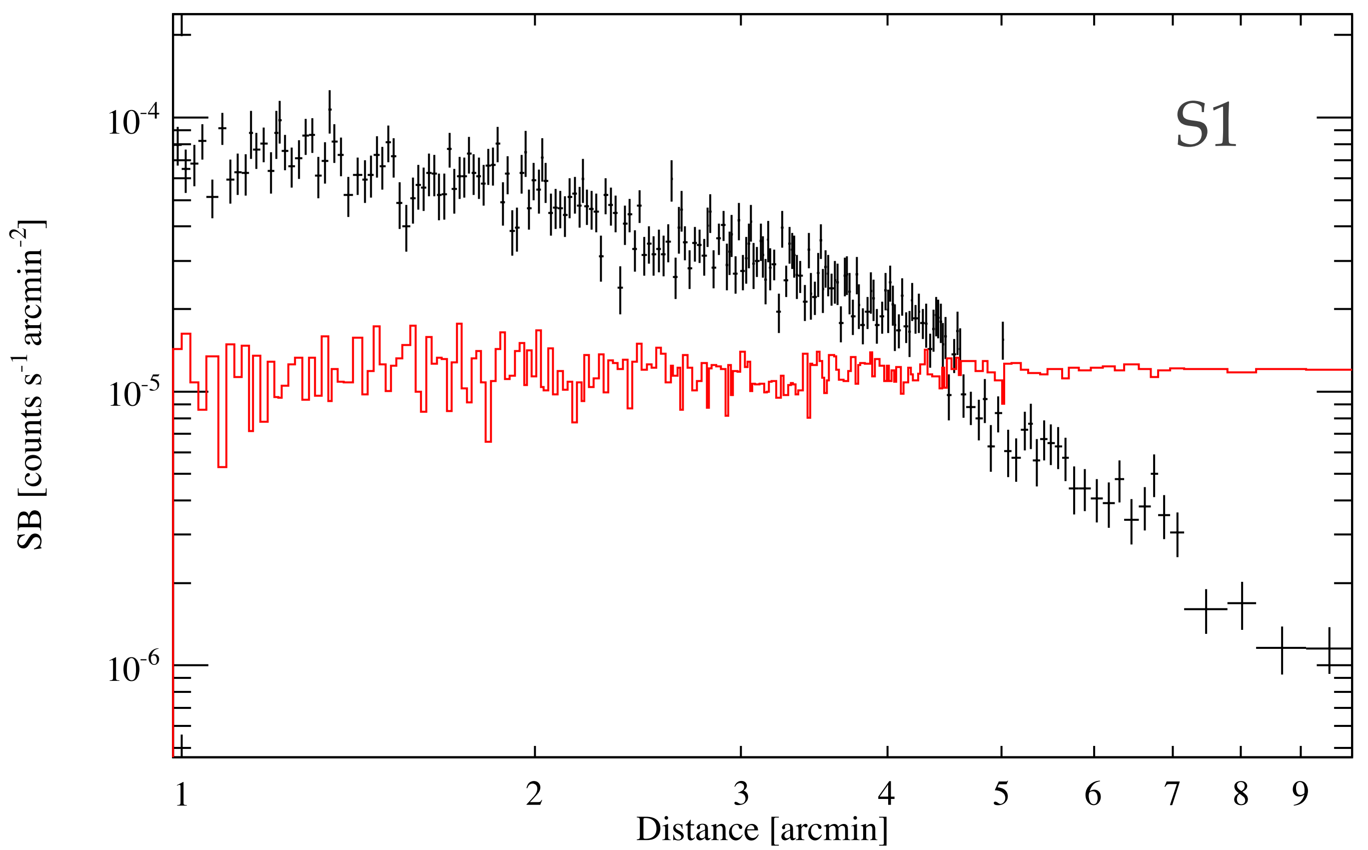


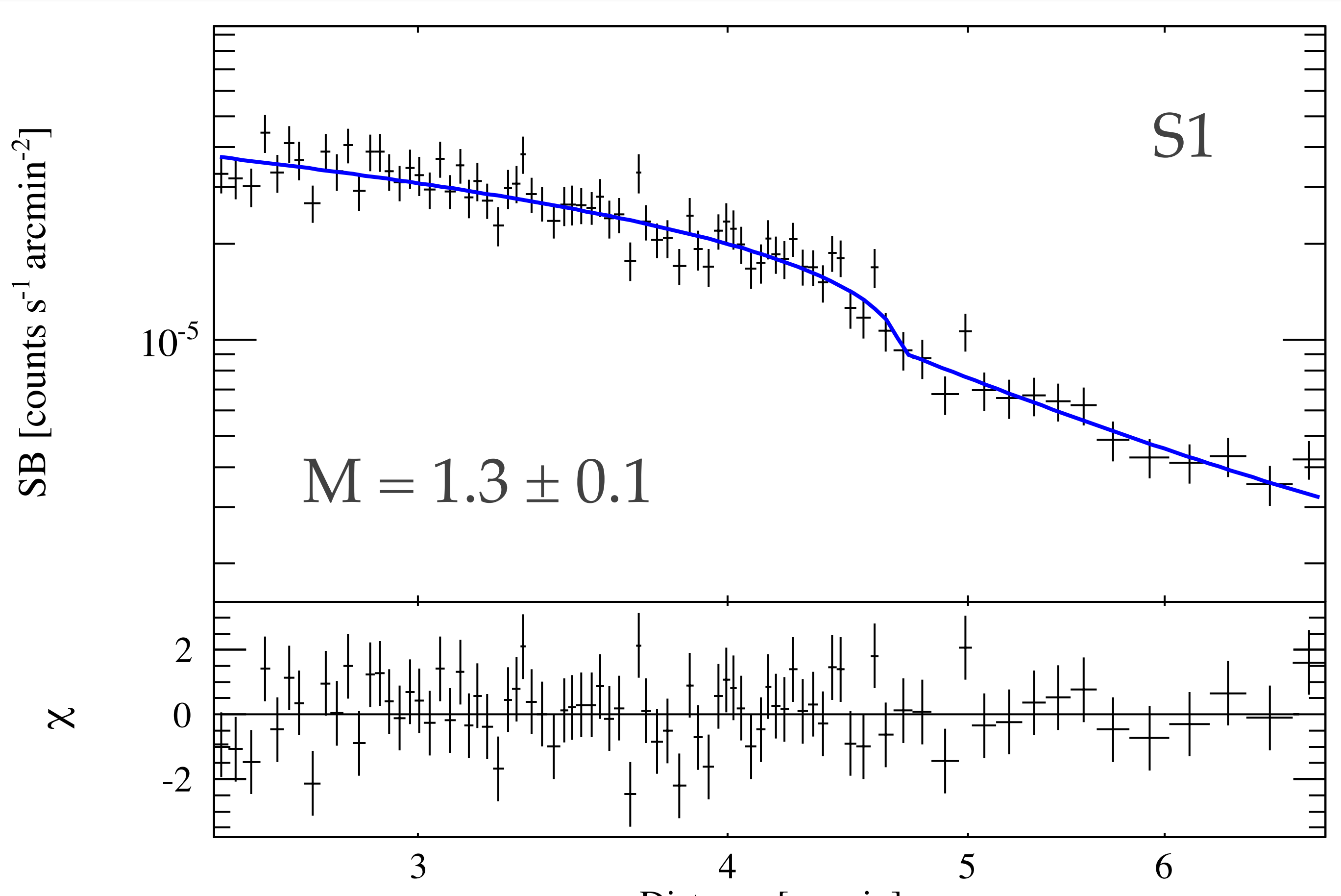
Basic info:

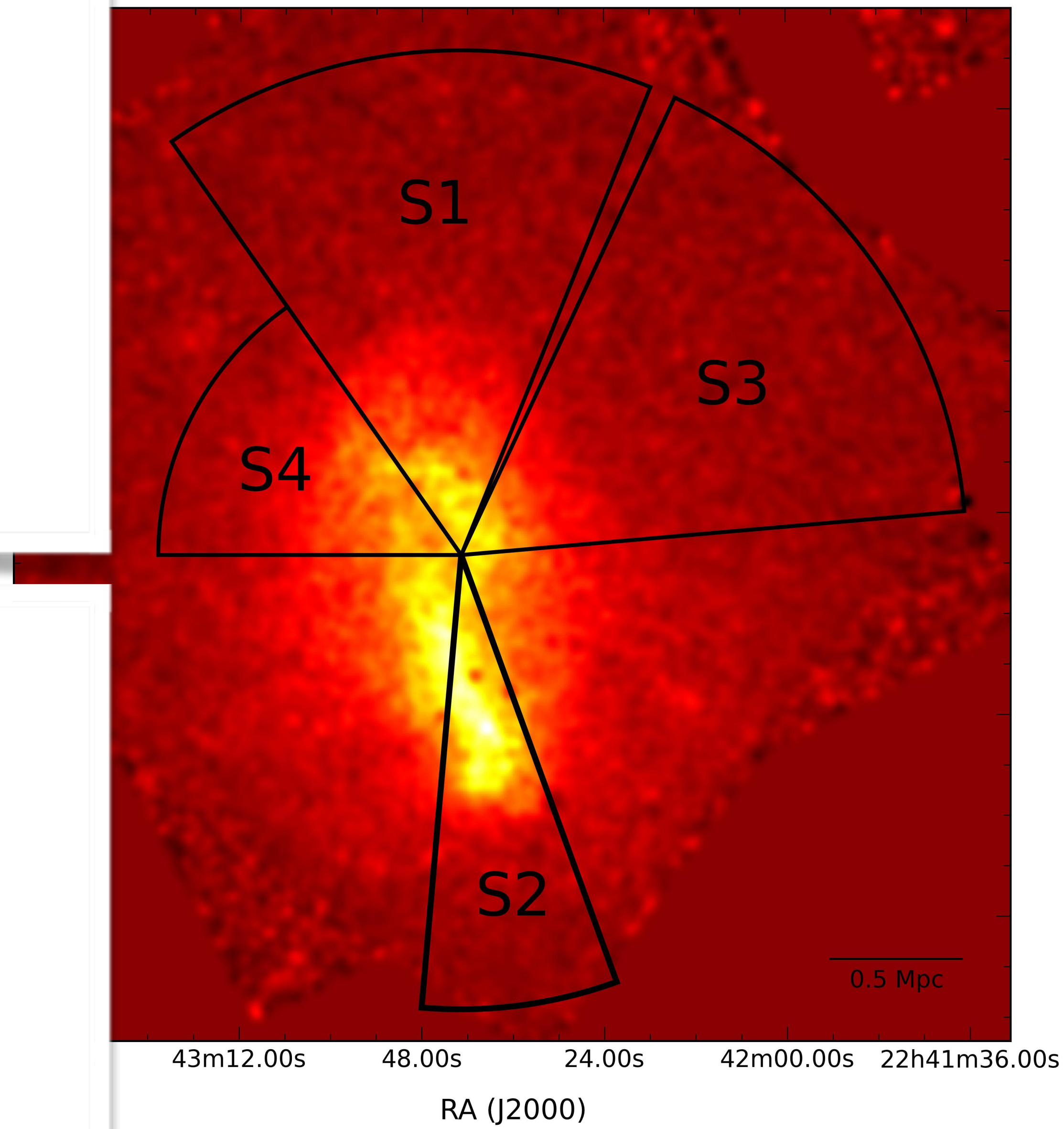
- z = 0.19
- T = 9 keV
- XMM-Newton (130 ks), Chandra (200 ks; PI: Ogrean), and Suzaku (100 ks)
- GMRT, WSRT, VLA, LOFAR

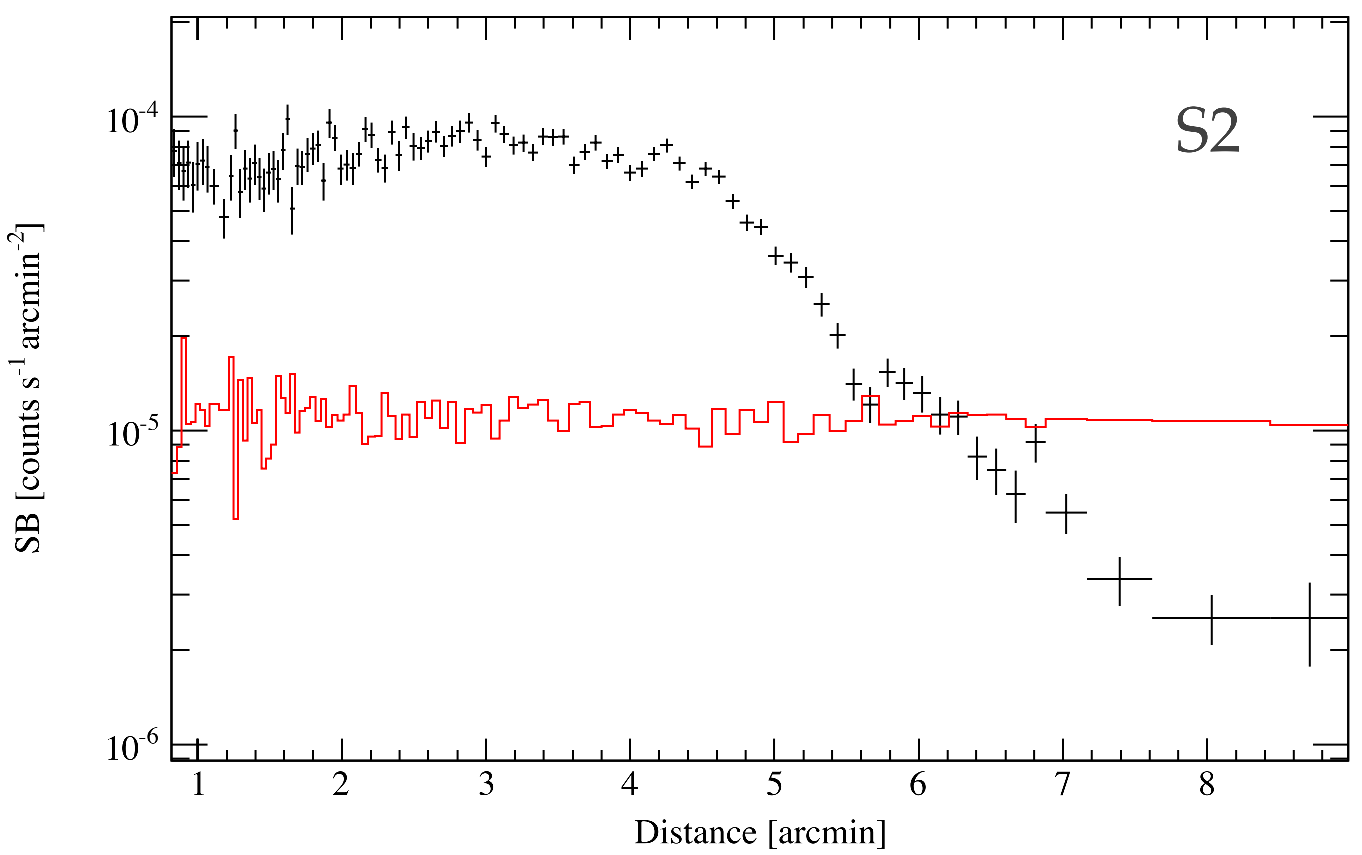
Right image:

Chandra 0.5-7 keV (color)
WSRT 1.4 GHz (contours; van Weeren et al. 2010)

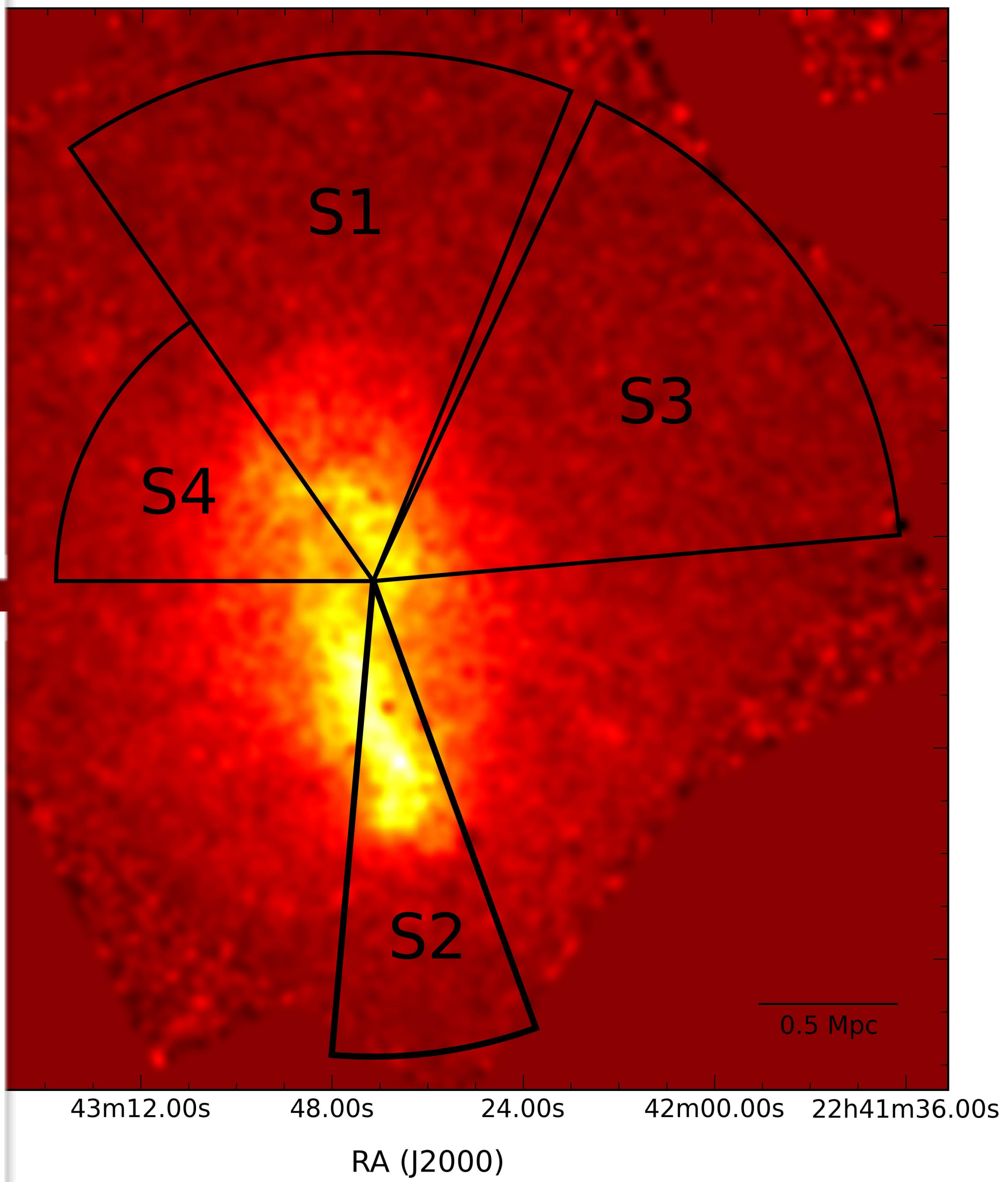

S1
10-4
10-5
10-6
SB [counts s-1 arcmin-2]
1
2
3
4
5
6
7
8
9
Distance [arcmin]


S1
10-5
SB [counts s-1 arcmin-2]
M = 1.3 ± 0.1
χ
2
0
-2
3
4
5
6
Distance [arcmin]


S1
S2
S3
S4
0.5 Mpc
43m12.00s
48.00s
24.00s
42m00.00s
22h41m36.00s
RA (J2000)



S2
SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
10^{-6}
1
2
3
4
5
6
7
8
Distance [arcmin]



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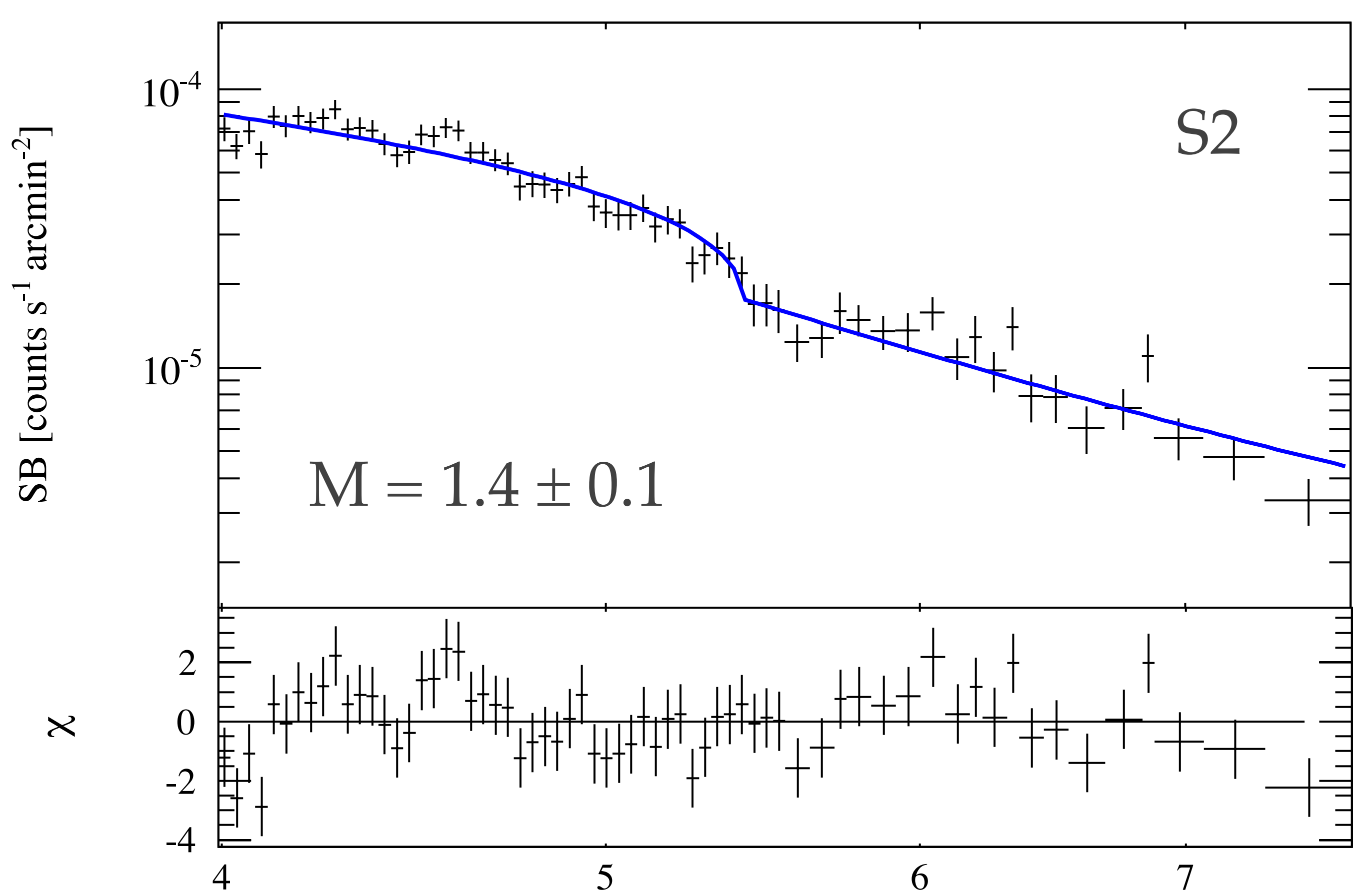
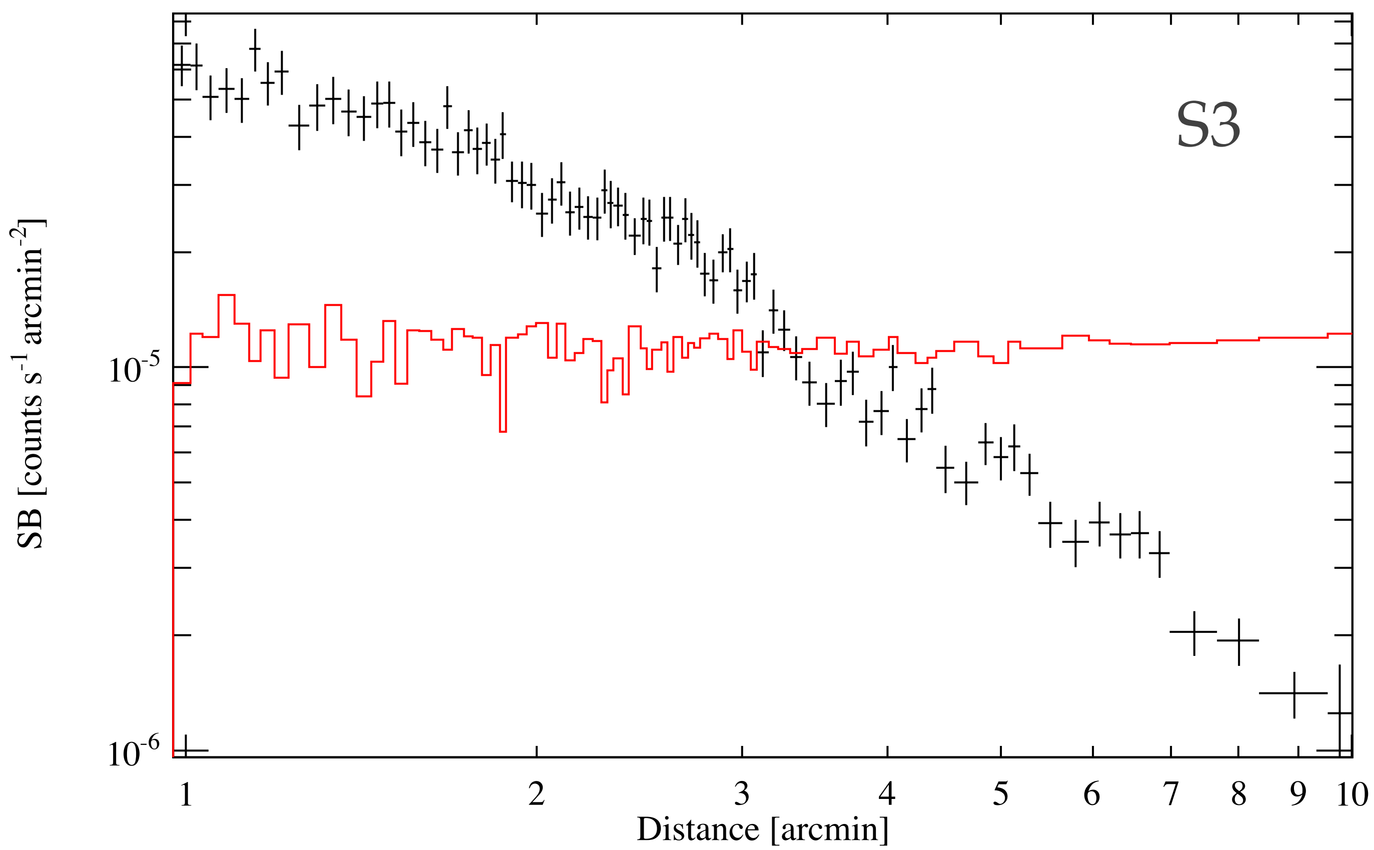
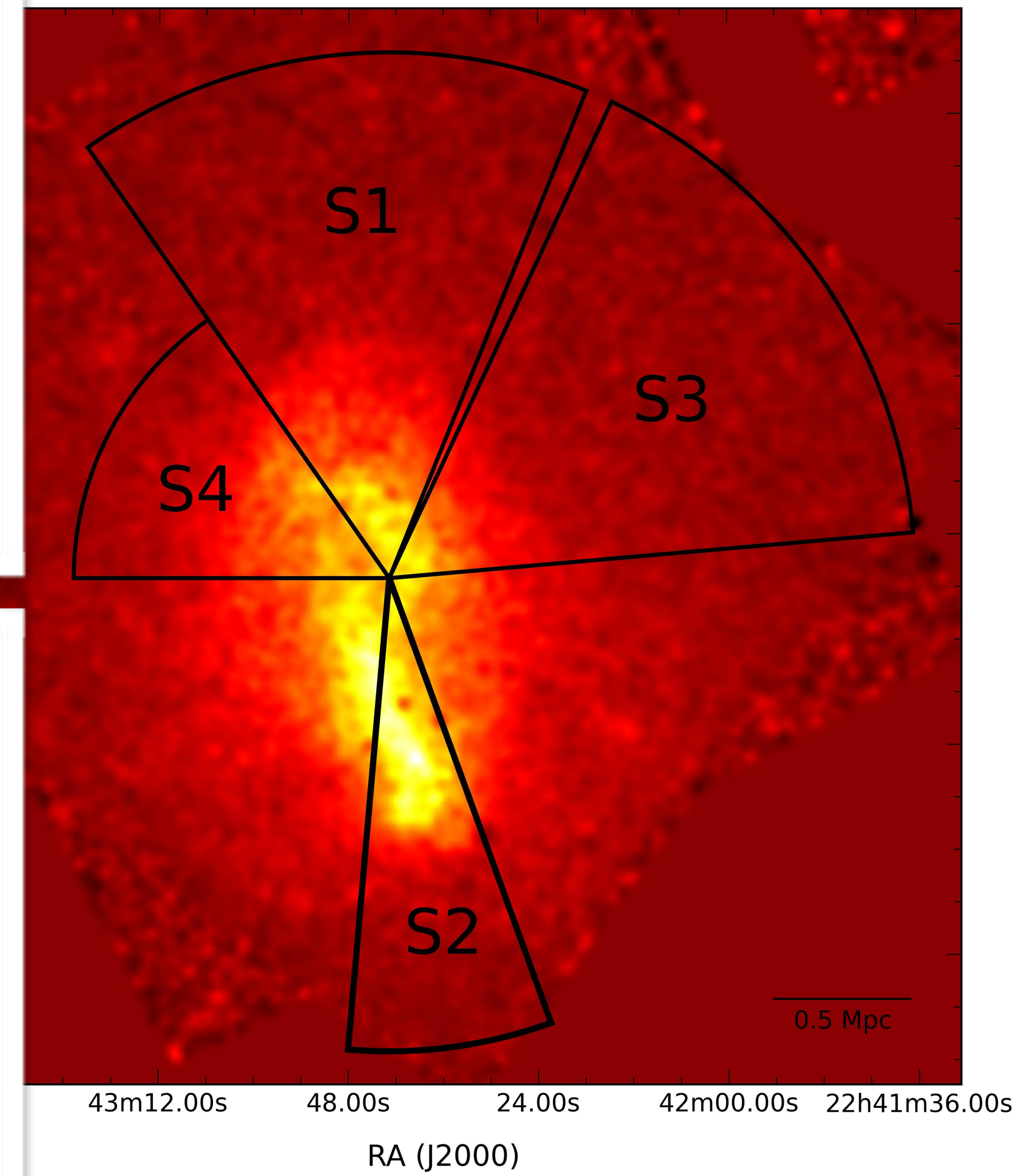


S2
SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
M = 1.4 ± 0.1
χ
2
0
-2
-4
4
5
6
7
Distance [arcmin]


S3
SB [counts s-1 arcmin-2]
10-5
10-6
1
2
3
4
5
6
7
8
9
10
Distance [arcmin]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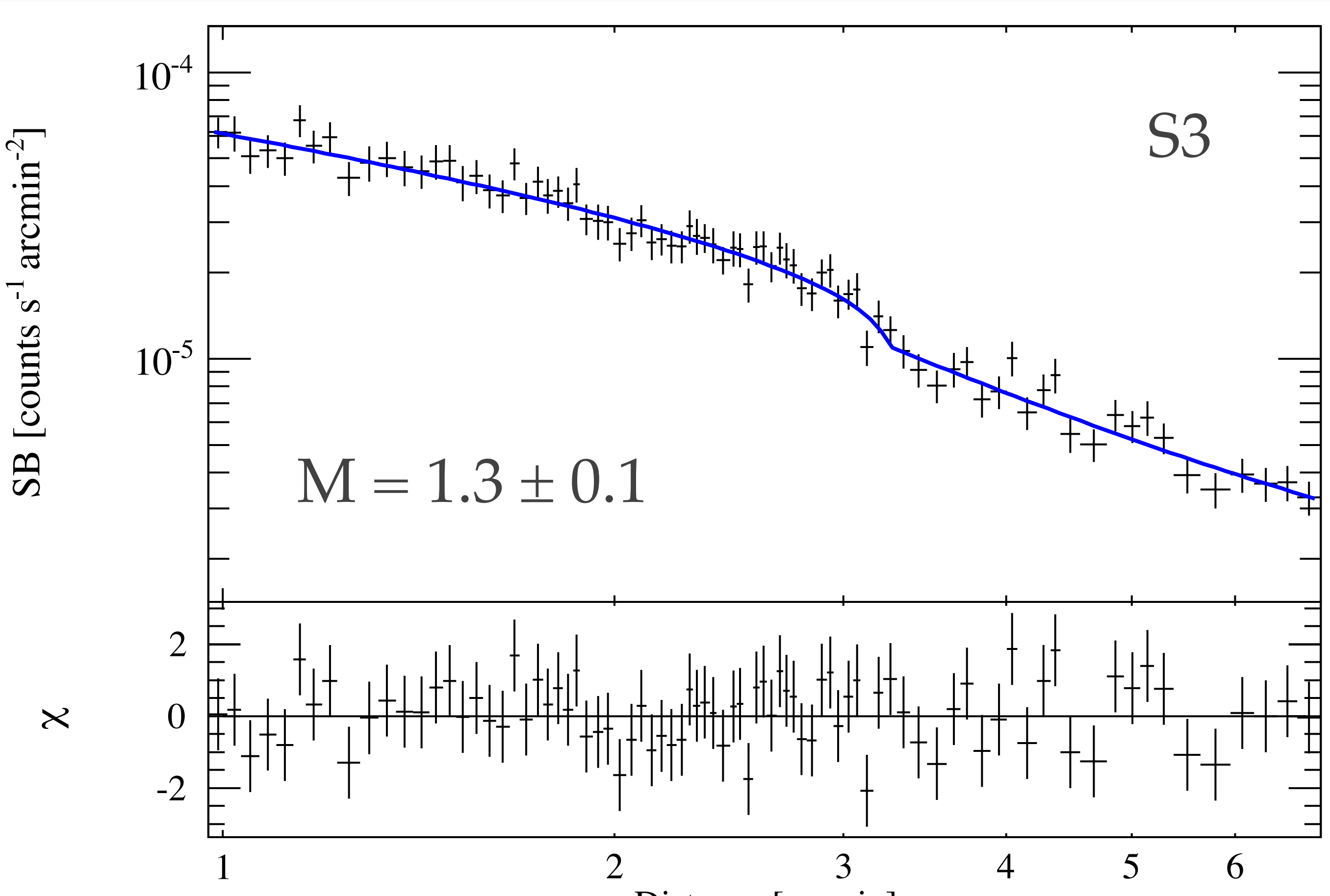
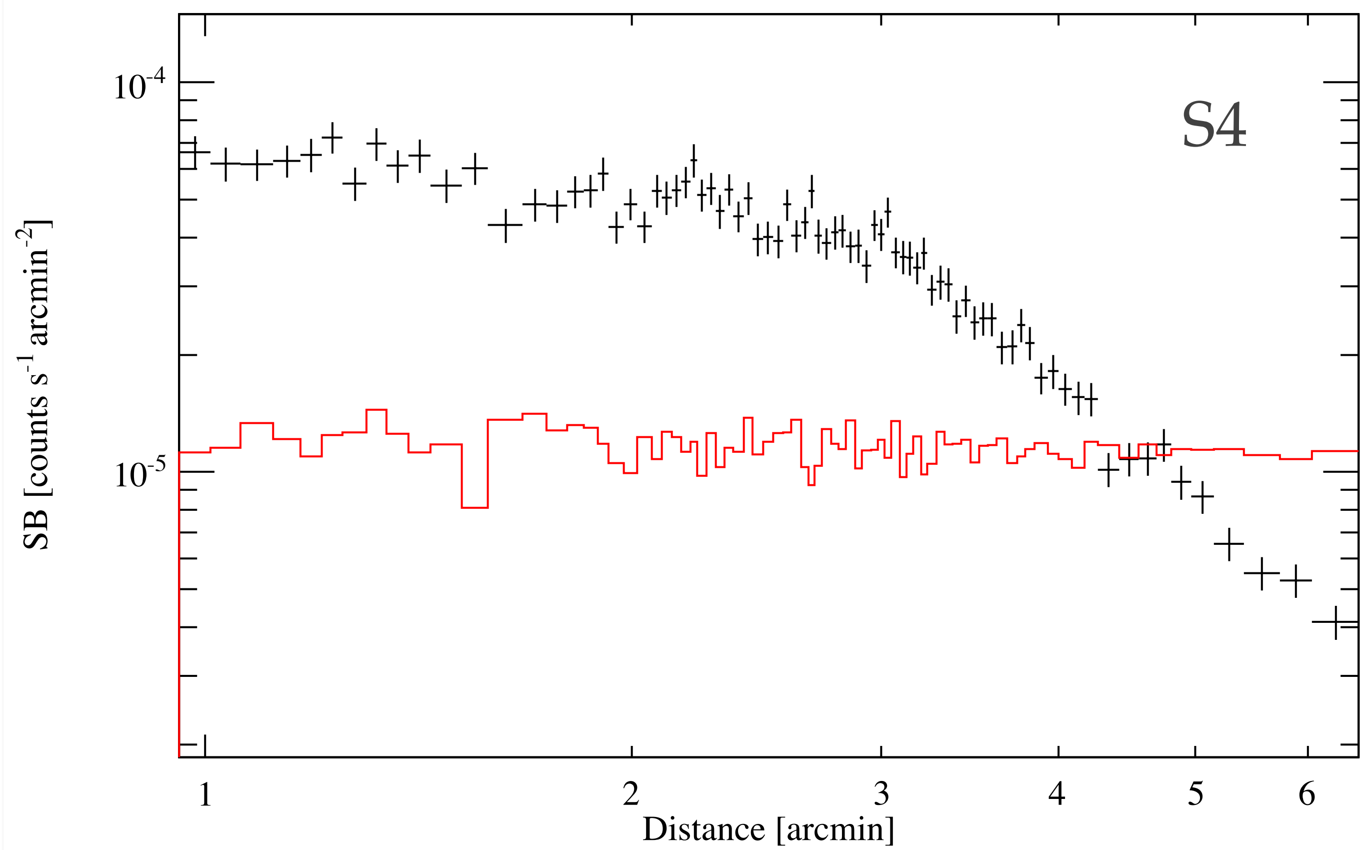
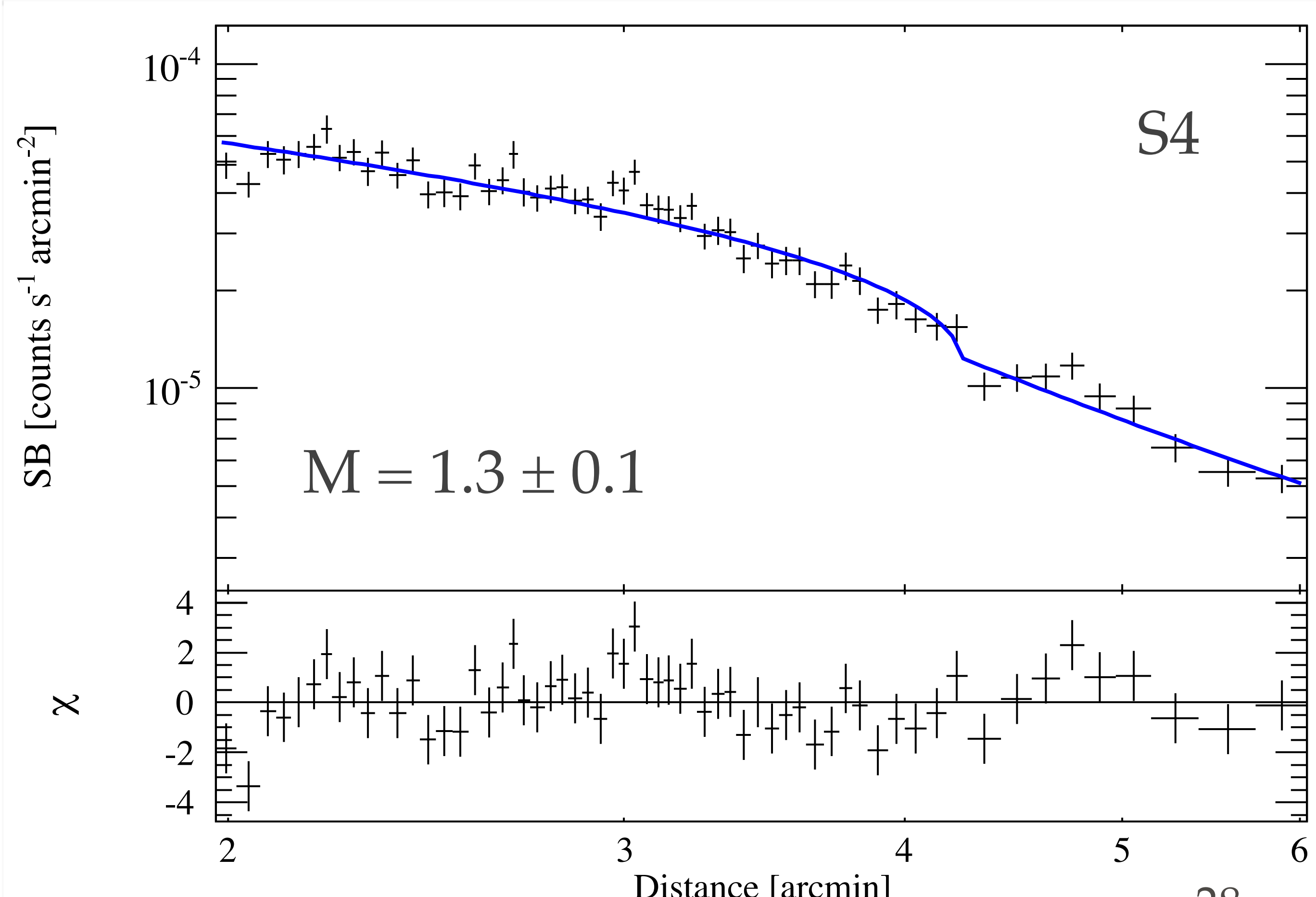
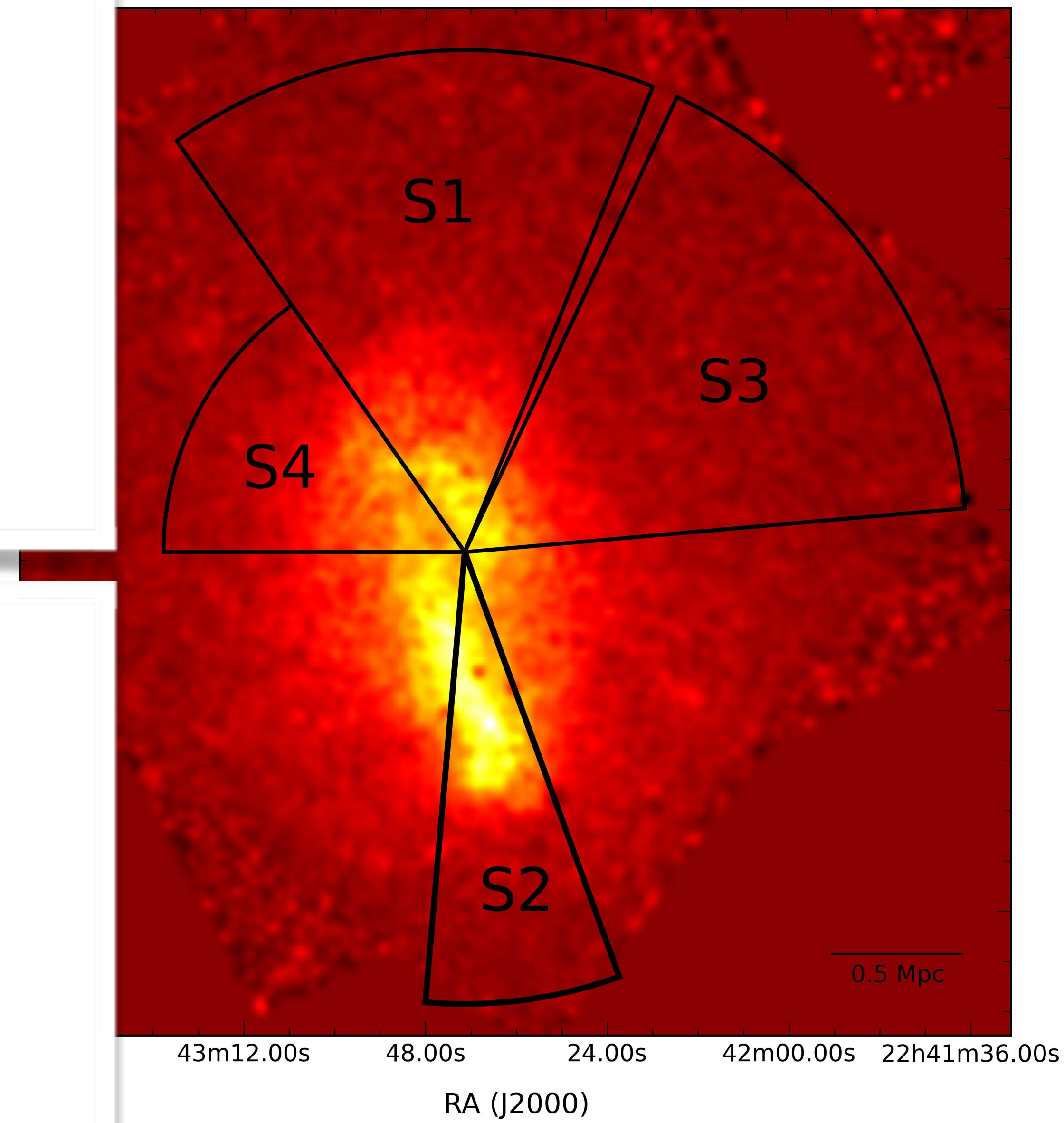

S3
SB [counts s-1 arcmin-2]
10-4
10-5
M = 1.3 ± 0.1
χ
2
0
-2
1
2
3
4
5
6
Distance [arcmin]

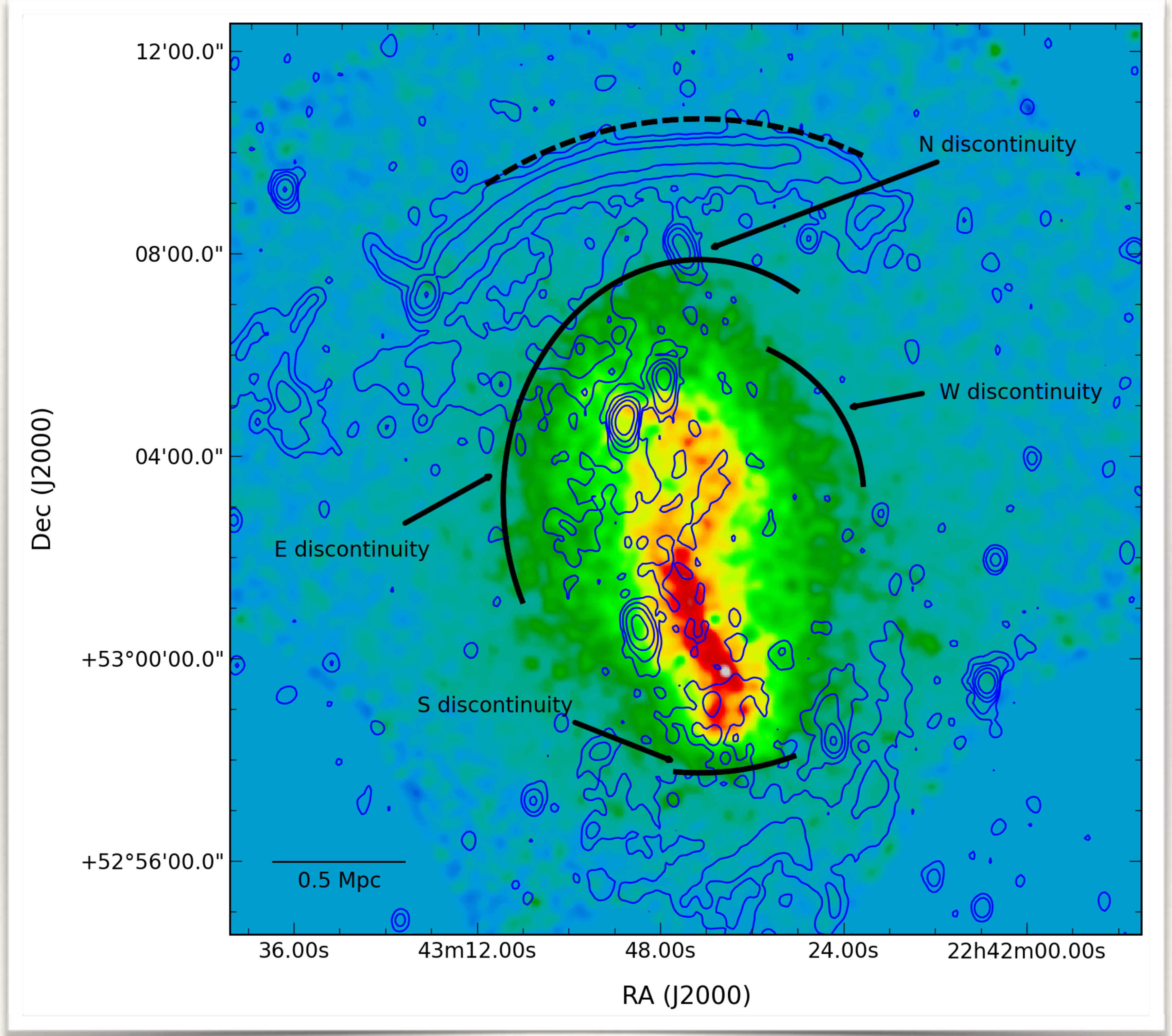

S4
SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
1
2
3
4
5
6
Distance [arcmin]

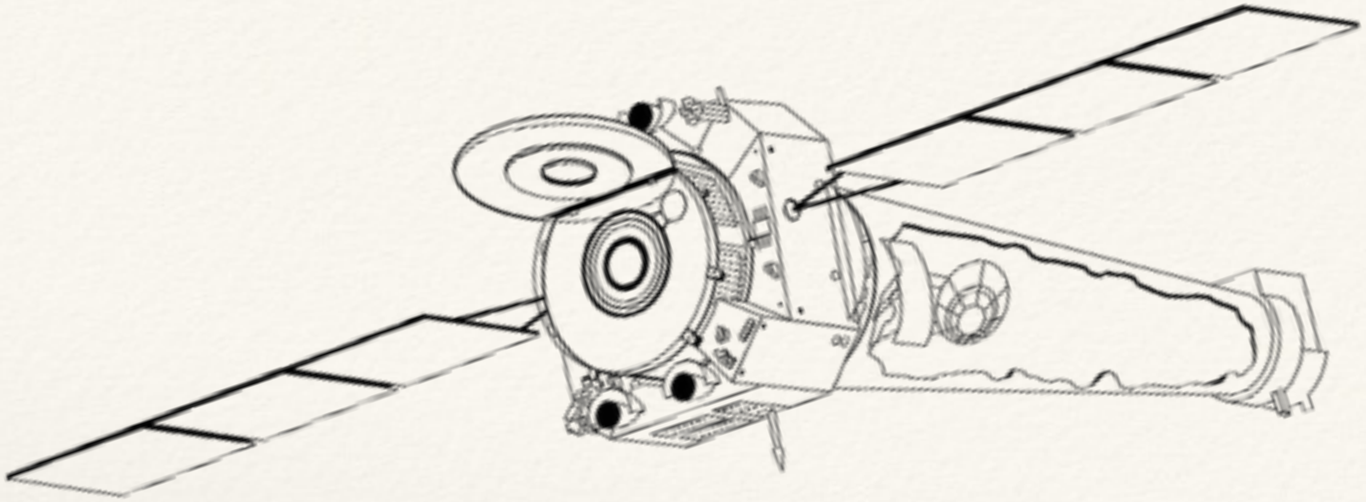

S4
SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
M = 1.3 ± 0.1
χ
4
2
0
-2
-4
2
3
4
5
6
Distance [arcmin]


S1
S2
S3
S4
0.5 Mpc
43m12.00s
48.00s
24.00s
42m00.00s
22h41m36.00s
RA (J2000)

Ogrean et al. (2014)

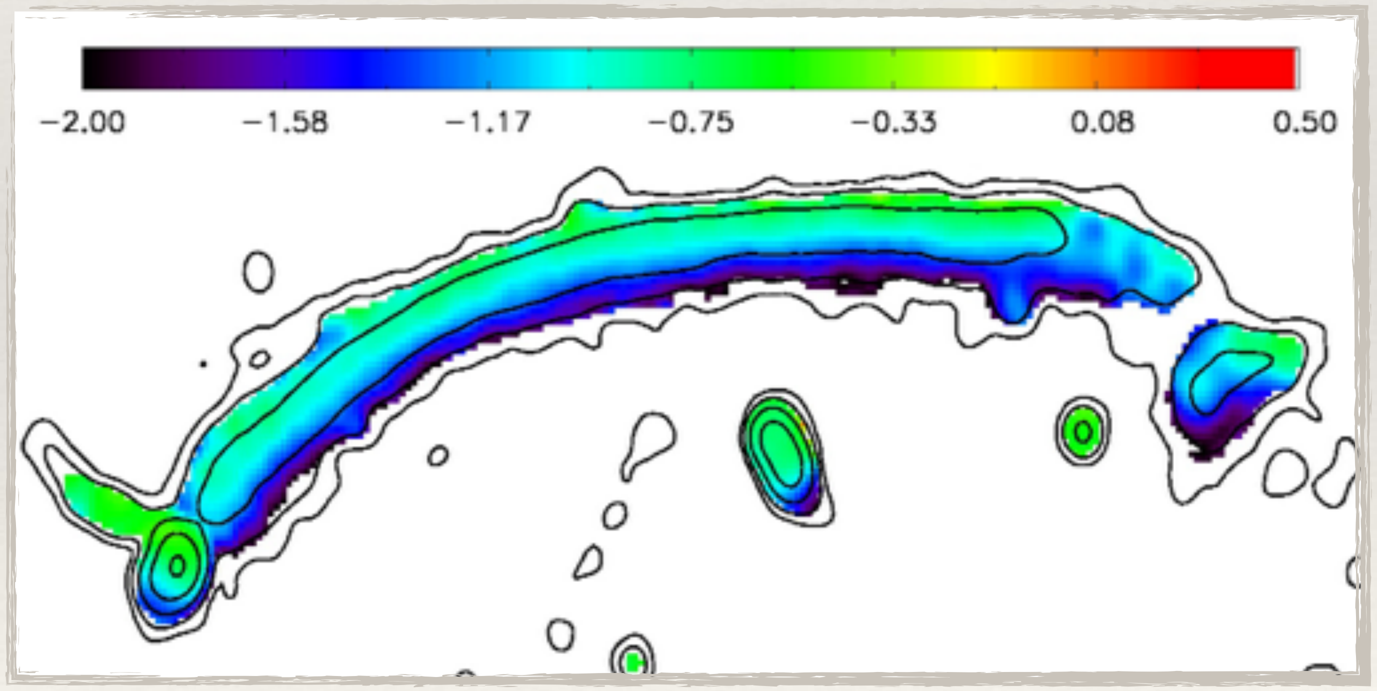
- No clear temperature jumps at the inner discontinuities.
- No clear density discontinuity detected at the N relic using the Chandra and XMM-Newton data.
- With Suzaku: M = 2.5 ± 0.5 shock at the N relic, based on the temperature discontinuity.





From X-ray: M = 2.5 ± 0.5

van Weeren et al. (2010)

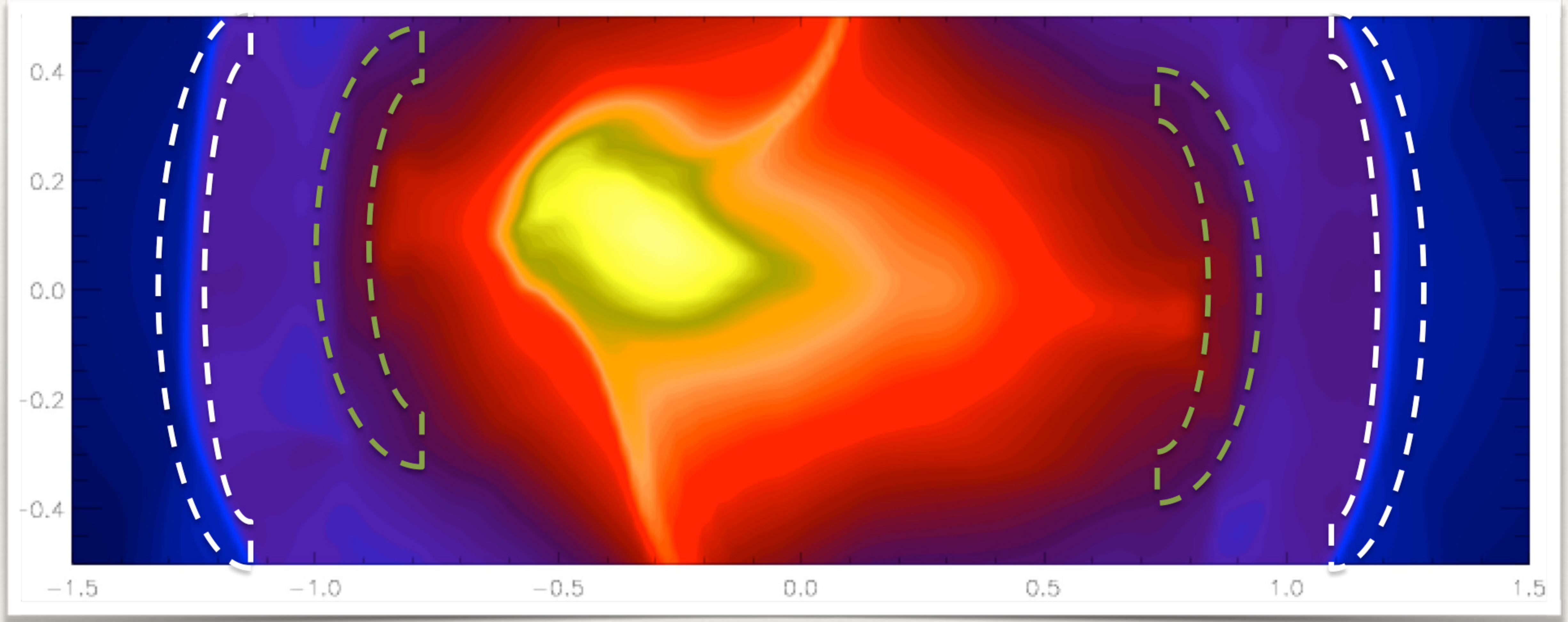


From radio: M = 4.6 ± 1.1
(α = -0.6 ± 0.05)

CIZA J2242.8+5301
Discussion

Nature of the Inner Discontinuities

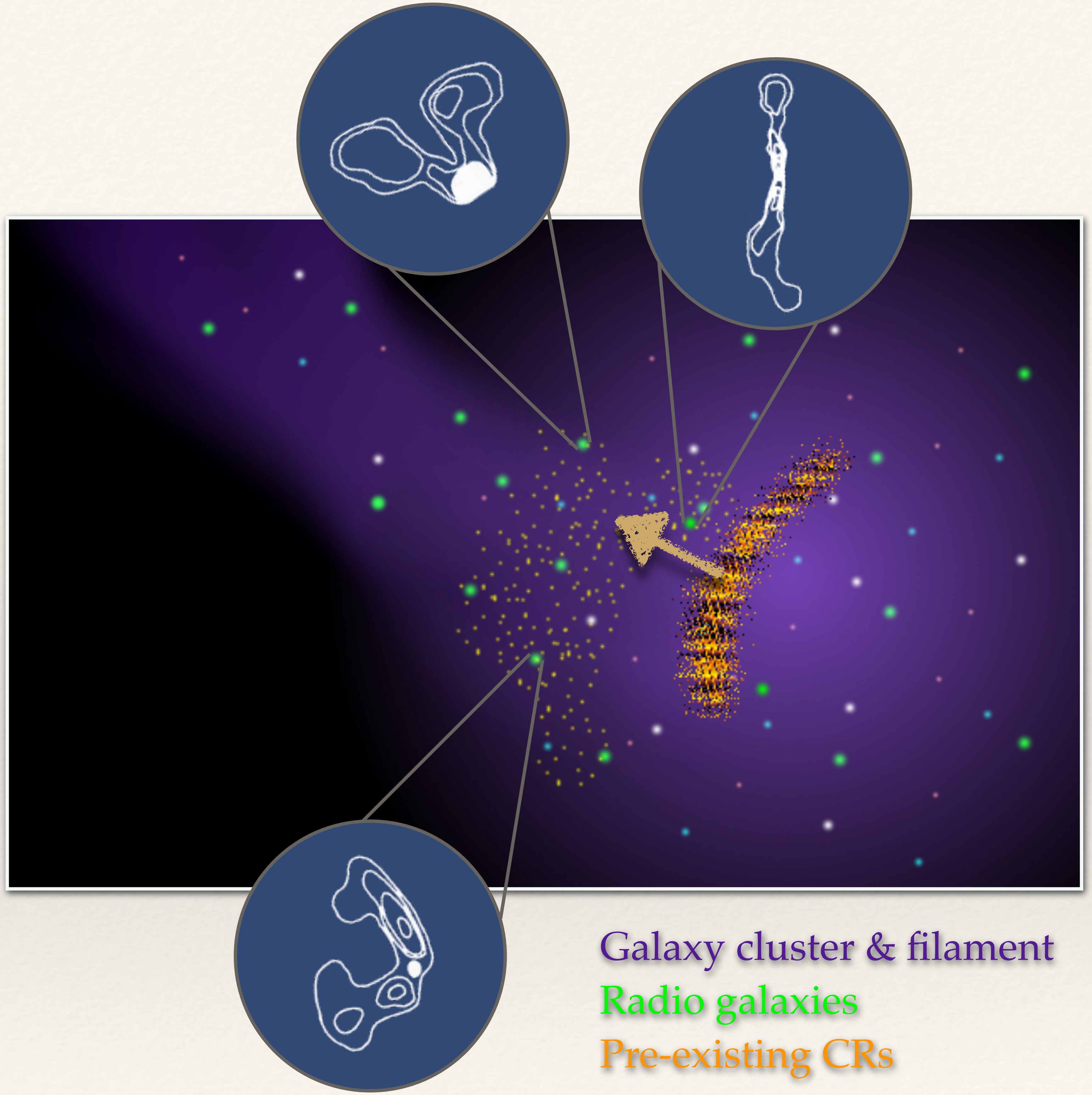
Ogrean et al. (2014)



After core passage, the DM cores undergo violent relaxation as the total gravitational potential varies rapidly. The DM cores quickly expand (timescale equal to the timescale on which the gravitational potential changes), causing an additional, inner pair of shocks.

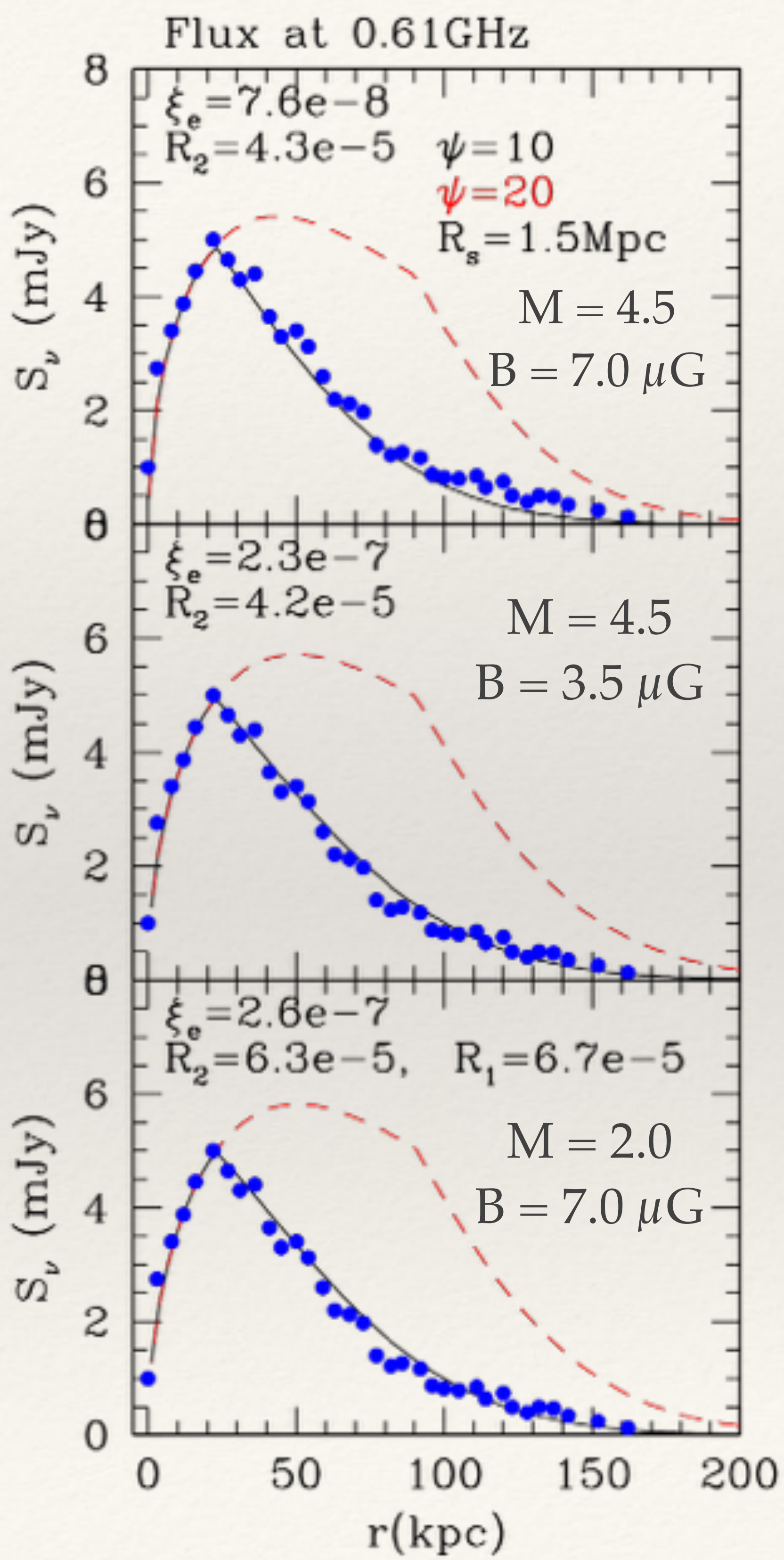
The particle acceleration efficiency of the shock is too low to accelerate thermal particles to the energies required for observable synchrotron emission.

For the same acceleration efficiency, pre-existing CRs (AGN, previous shocks, etc.) can more easily reach the required high energies.



Mach Number Discrepancy?

- The X-ray-measured and radio-predicted Mach numbers at the N relic are only marginally consistent.
- Hints that the radio Mach number is overestimated (or the X-ray Mach number is underestimated).
- The N radio relic can be modelled either with a shock of Mach number 4.6 and no pre-existing CRs, or with a shock of Mach number 2 if pre-existing CRs are present near the shock (Kang et al. 2012).



ξ_e: CRe⁻ number fraction

R_2: CR-to-gas pressure ratio

Mach Number Discrepancy?

- The N radio relic can be modelled either with a shock of Mach number 4.6 and no pre-existing CRs, or with a shock of Mach number 2 if pre-existing CRs are present near the shock (Kang et al. 2012).

Alternative explanations:

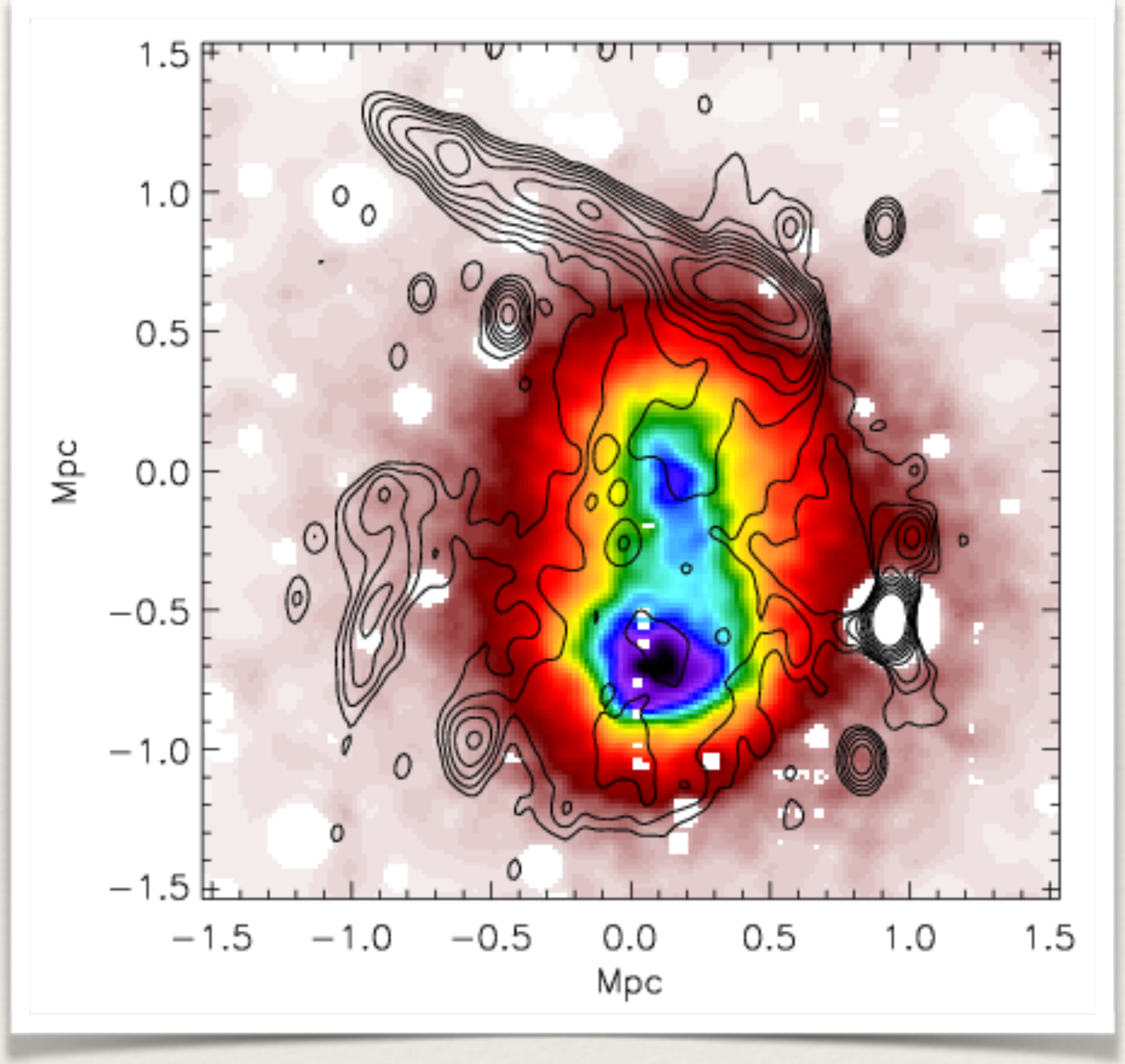
  - complex Mach number distribution across the shock front (Skillman et al. 2013)
  - oblique shock

1RXS J0603.3+4214
a.k.a. the Toothbrush Cluster

Basic info:

- z = 0.23
- T = 8 keV
- XMM-Newton (80 ks), Chandra (250 ks), and Suzaku (200 ks)
- GMRT, WSRT

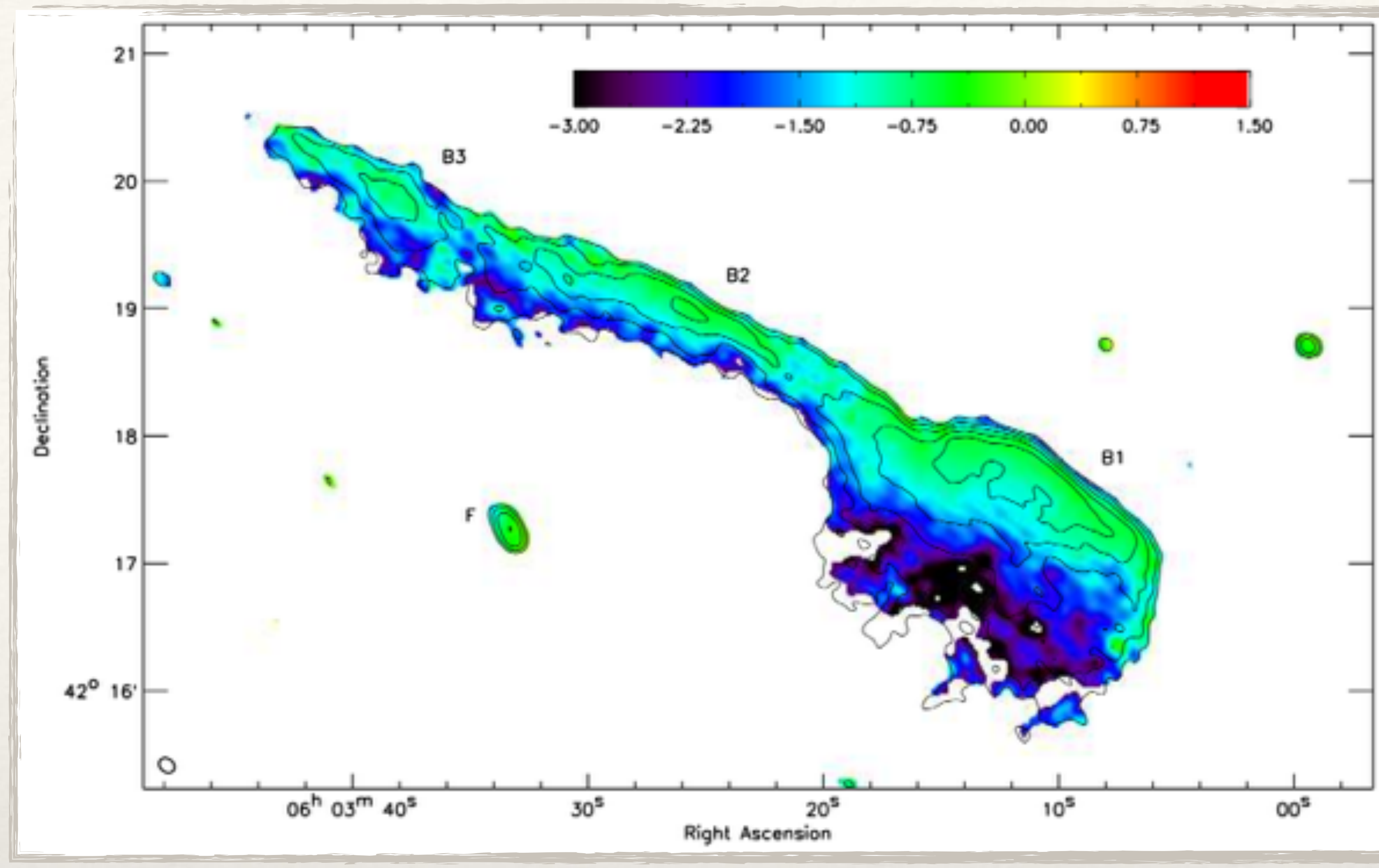
Ogrean et al. (2013)



Right image:

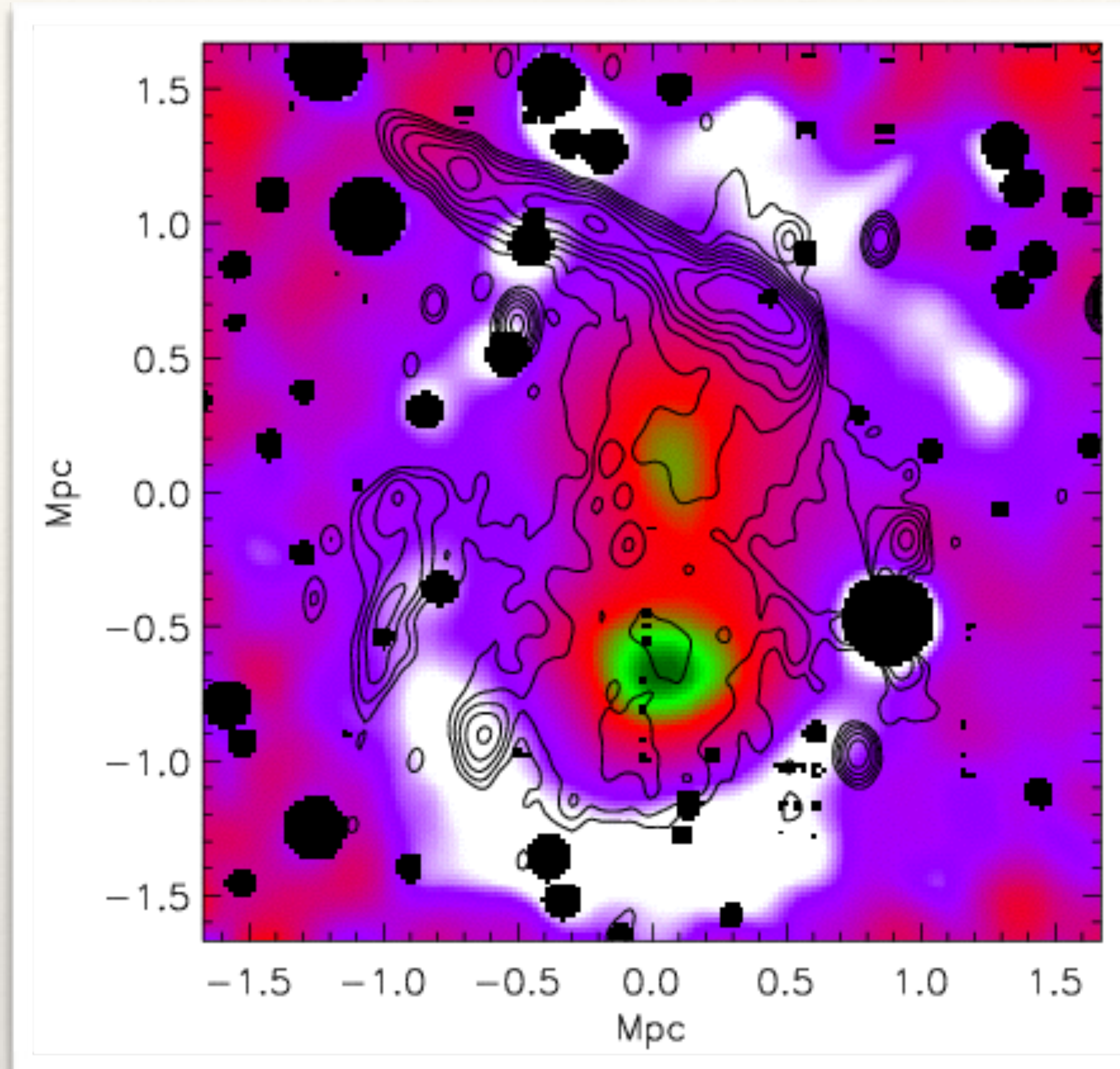
XMM-Newton 0.5-4 keV (color)
WSRT 1.4 GHz (contours; van Weeren et al. 2012)

van Weeren et al. (2012)



From radio: M = 3.3 … 4.6
(α = -0.7 … -0.6)

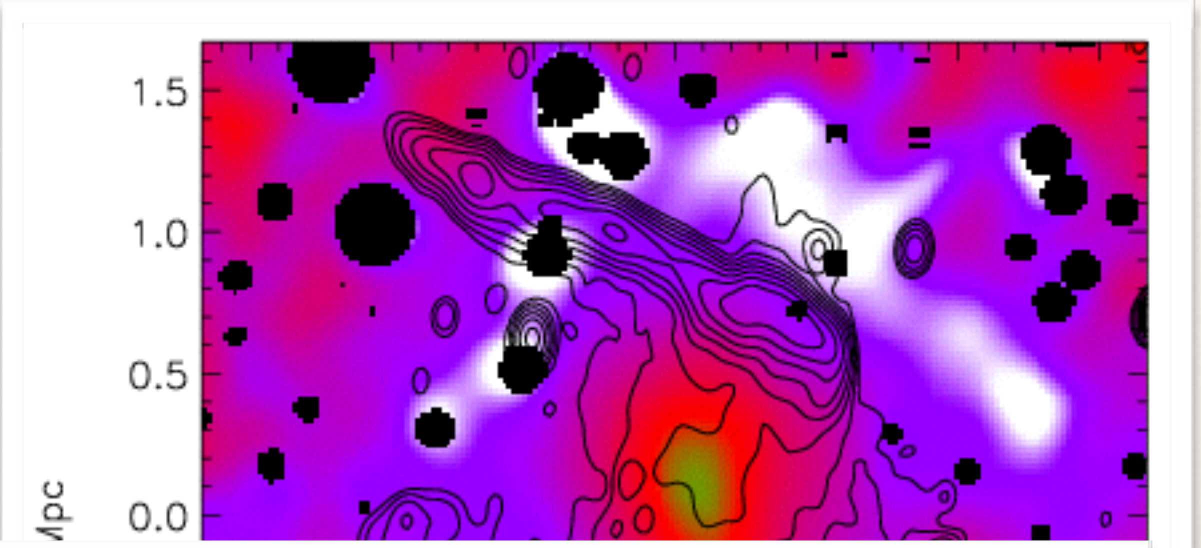
Ogrean et al. (2013)

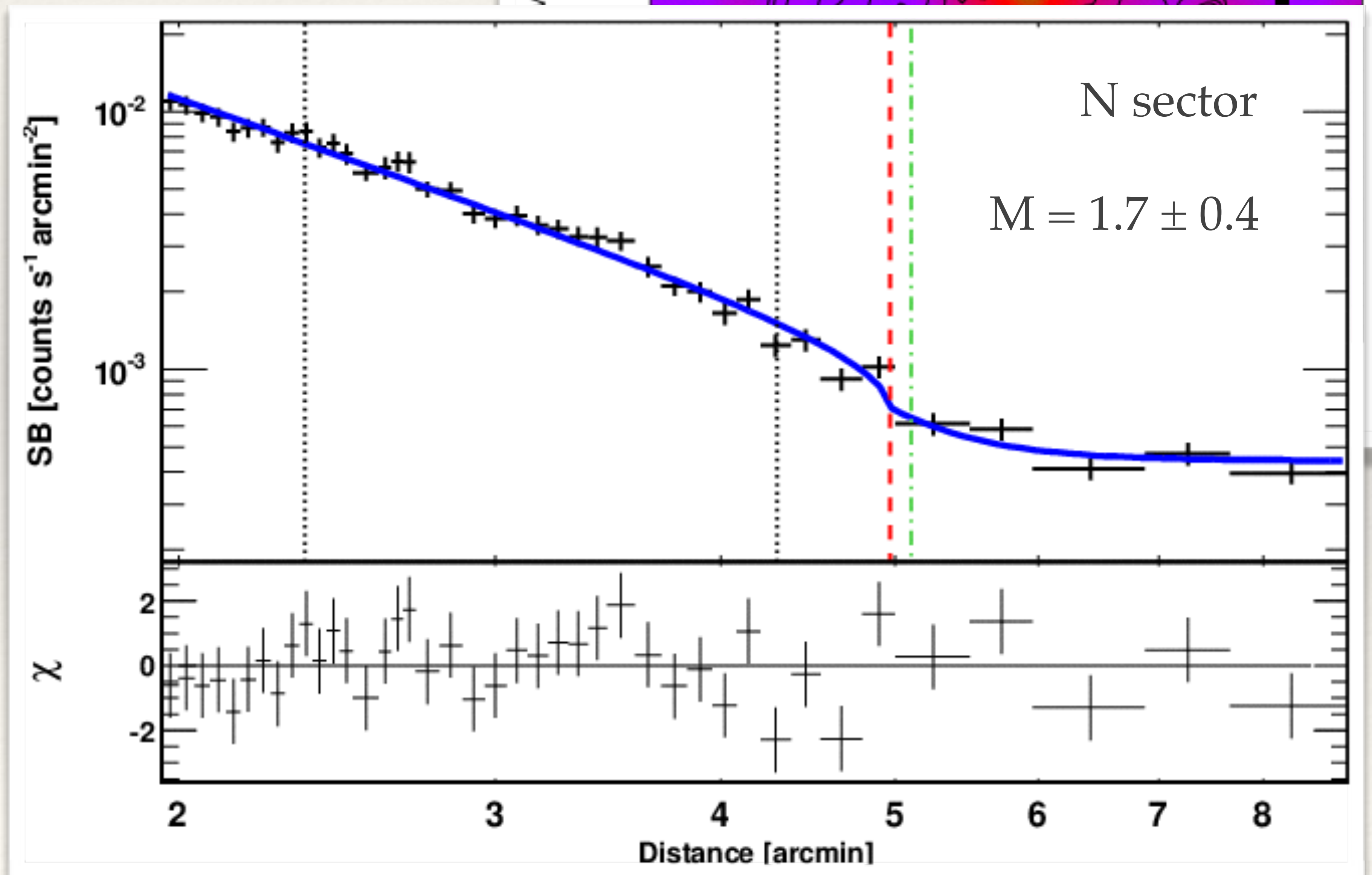


Unsharp-masked image:

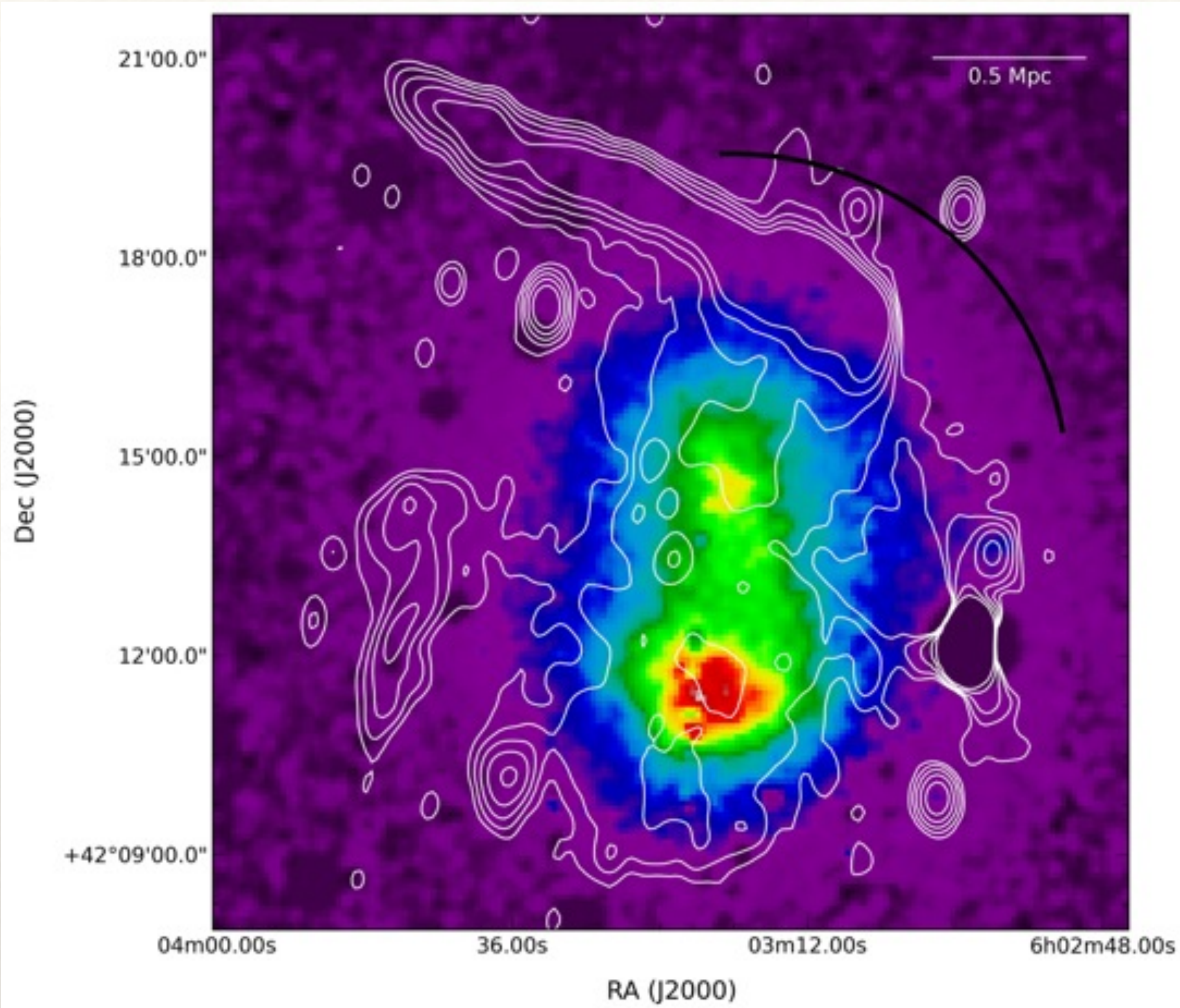
$$I = (\sigma_{0.5} - \sigma_{1.5})/(\sigma_{0.5} + \sigma_{1.5})$$

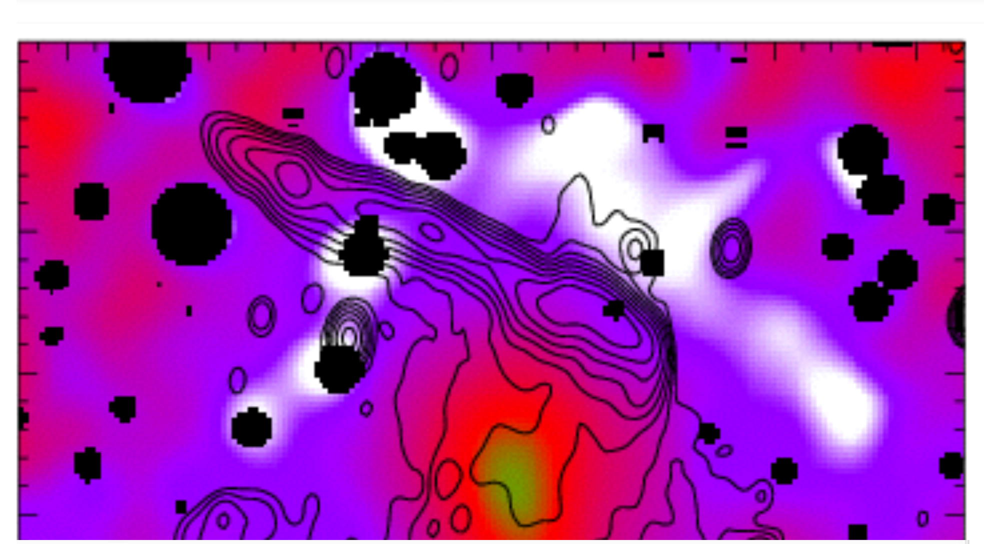
Ogrean et al. (2013)

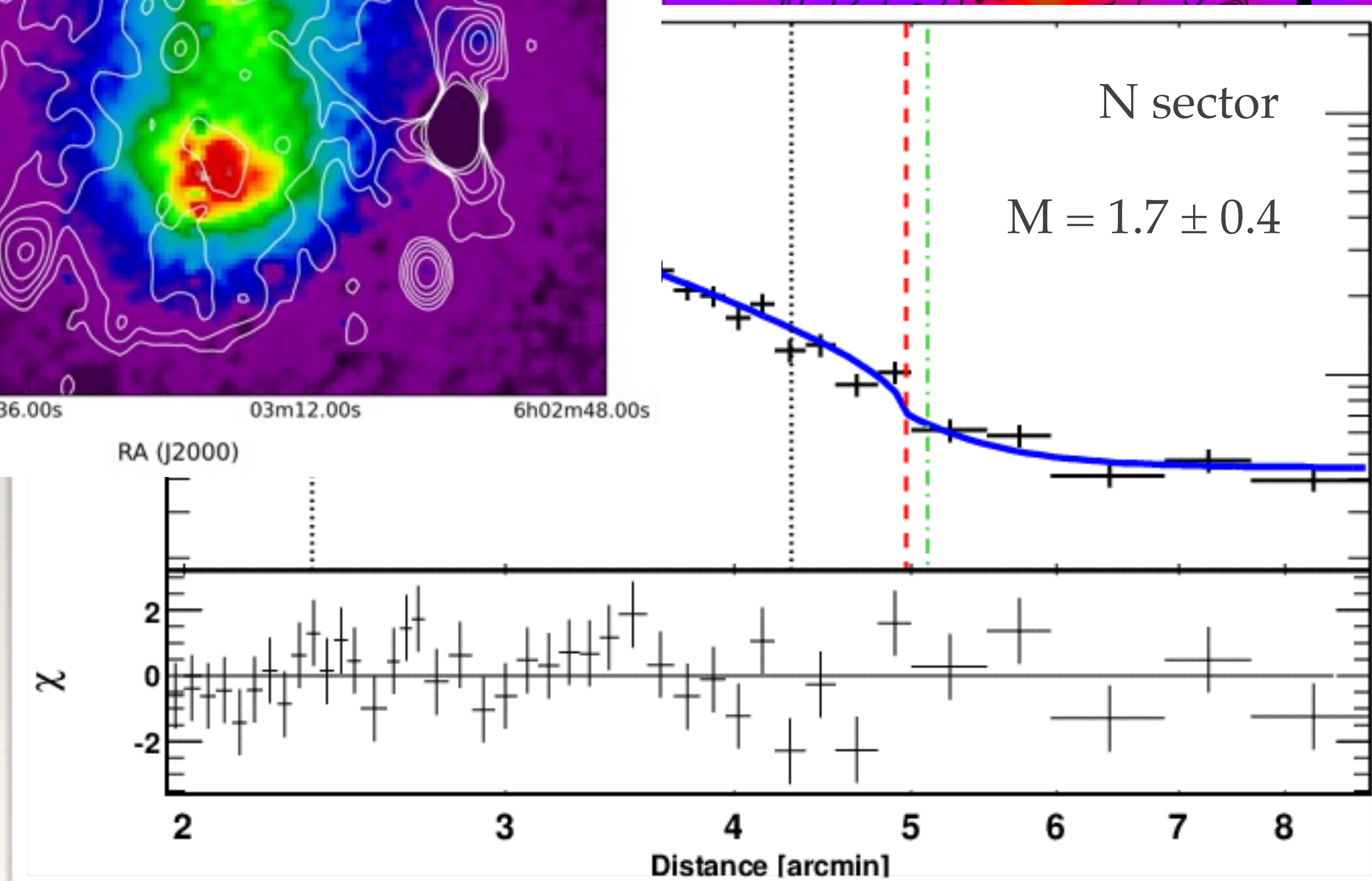




Ogrean et al. (2013)







N sector

$M = 1.7 \pm 0.4$

1RXS J0603.3+4214
Discussion

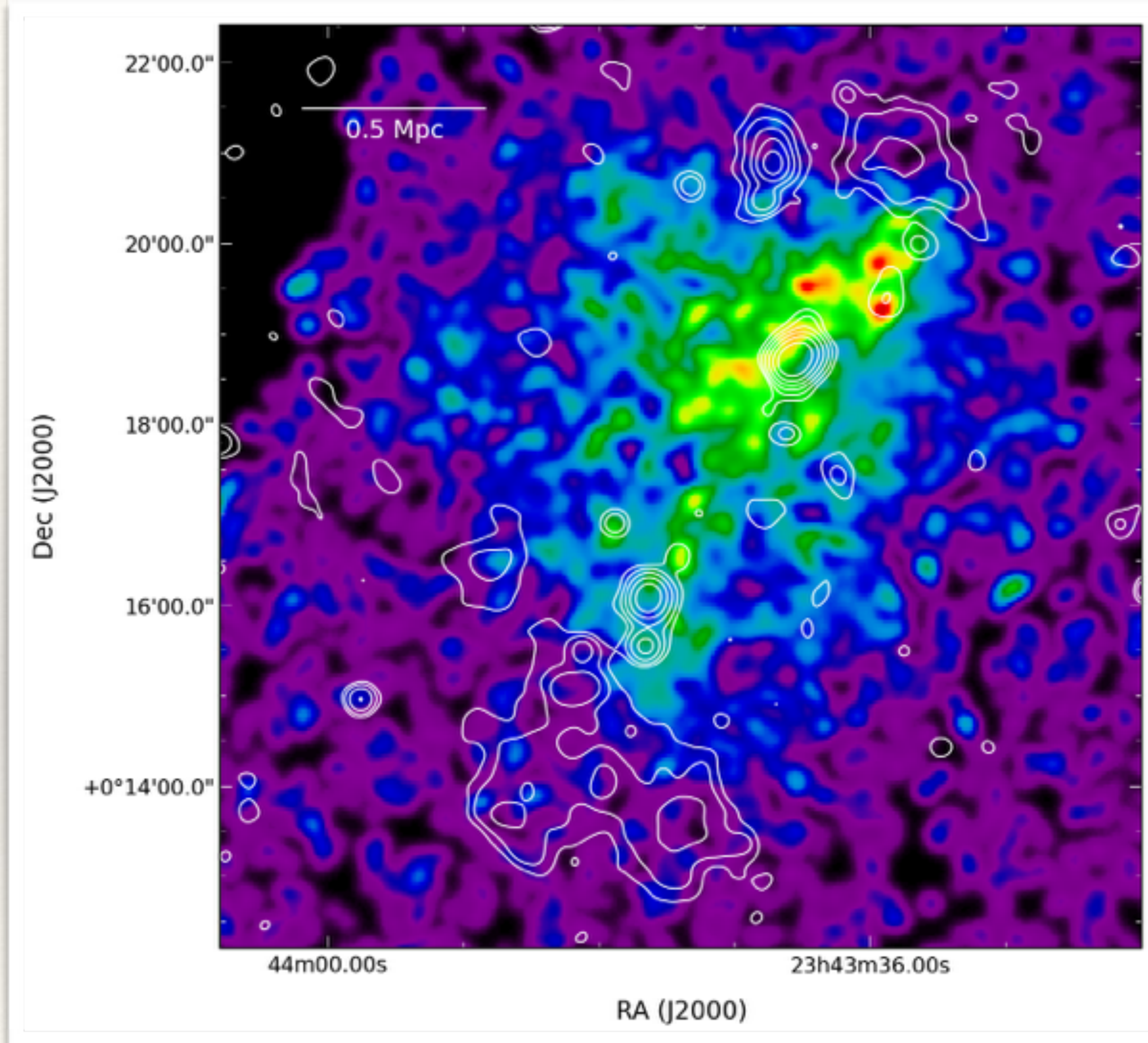
Spatial Offset Between Shock & Relic

Possible explanations:

- pre-existing CR electrons
- changes in the magnetic field between the positions of the shock and the relic
- complex Mach number distribution across the shock surface, coupled with projection effects
- two density discontinuities near the relic?

ZwCl 2341.1+0000

Ogrean et al., submitted



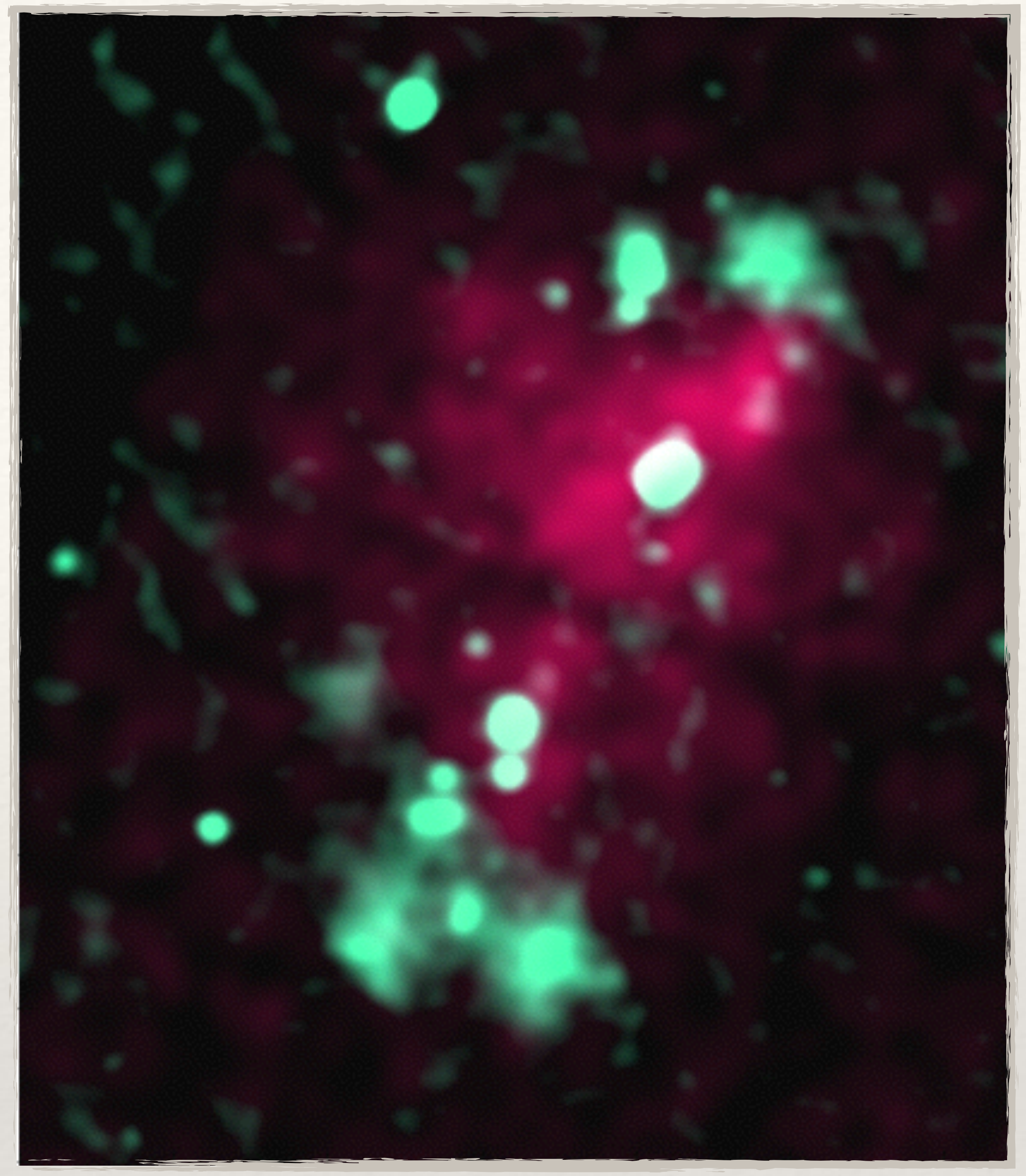
Basic info:

- z = 0.27
- T = 5 keV
- XMM-Newton (50 ks), Chandra (30 ks), Suzaku (50 ks)
- GMRT, VLA

Right image:

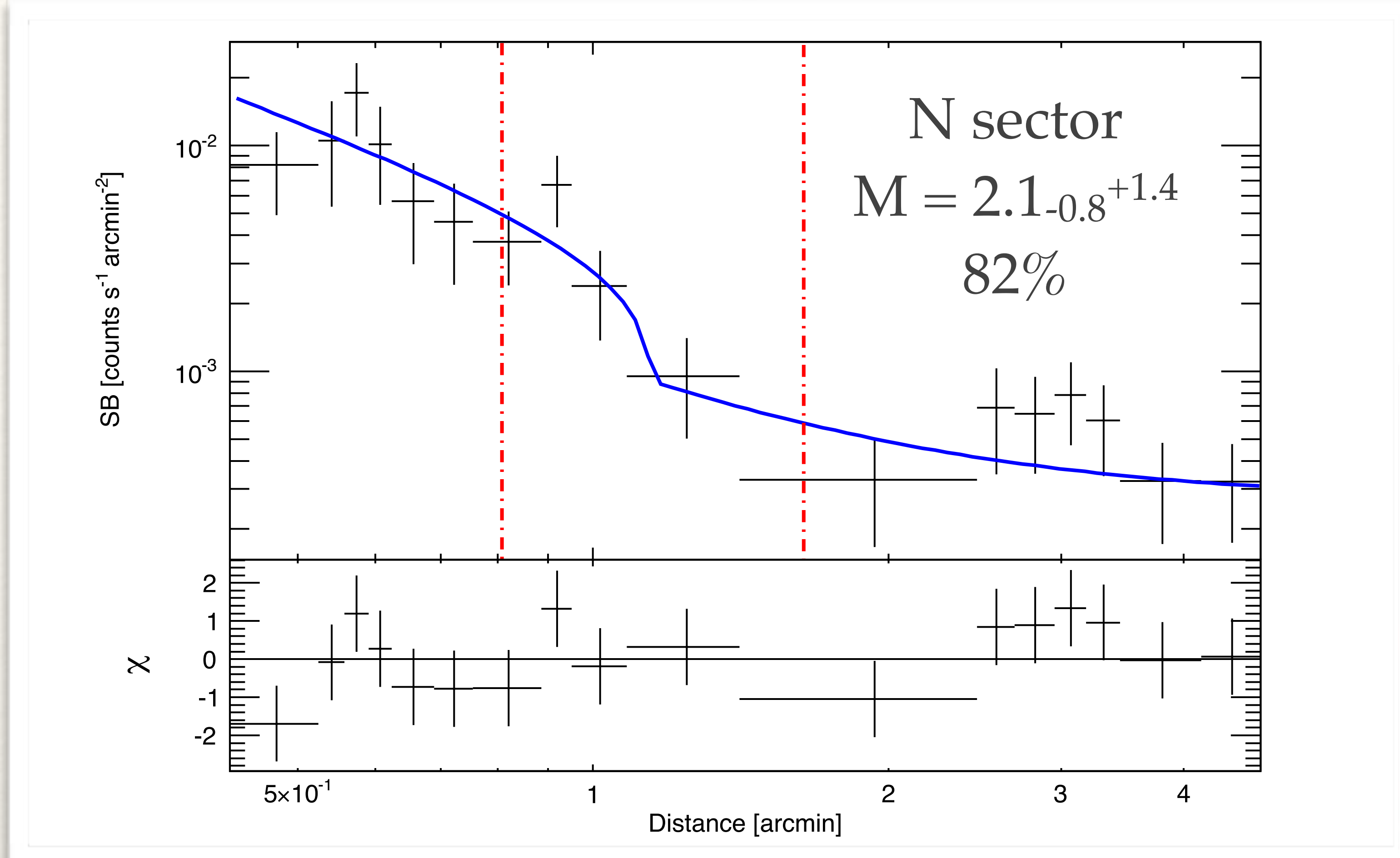
Chandra 0.5-3 keV (color)
GMRT 610 MHz (contours; van Weeren et al. 2009)

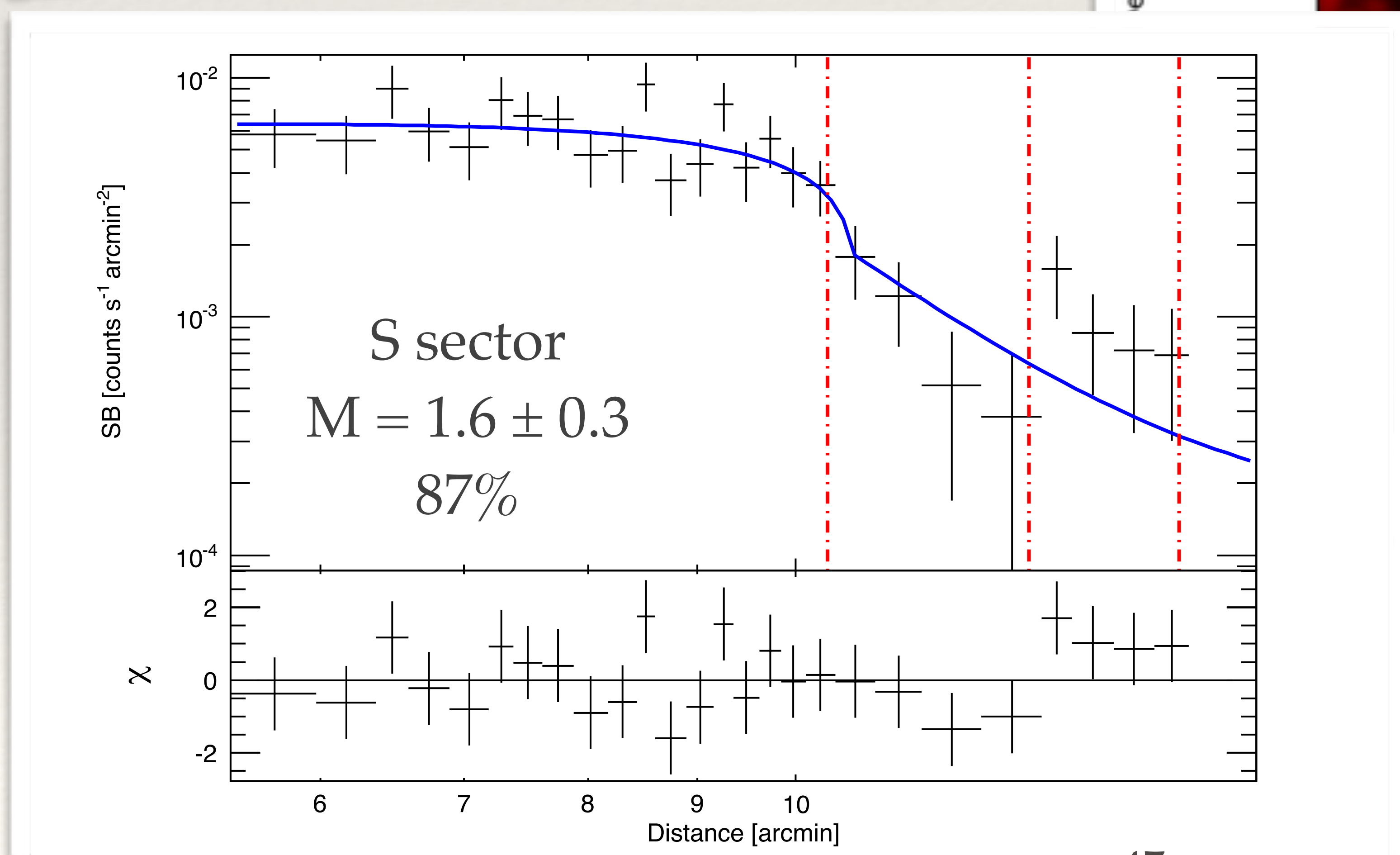
- The double-relic system with the flattest spectral indices.
- For $\alpha \geq -1$, M —> ∞.
- Interesting DSA testbed, as the radio spectra appear to be “too flat”.

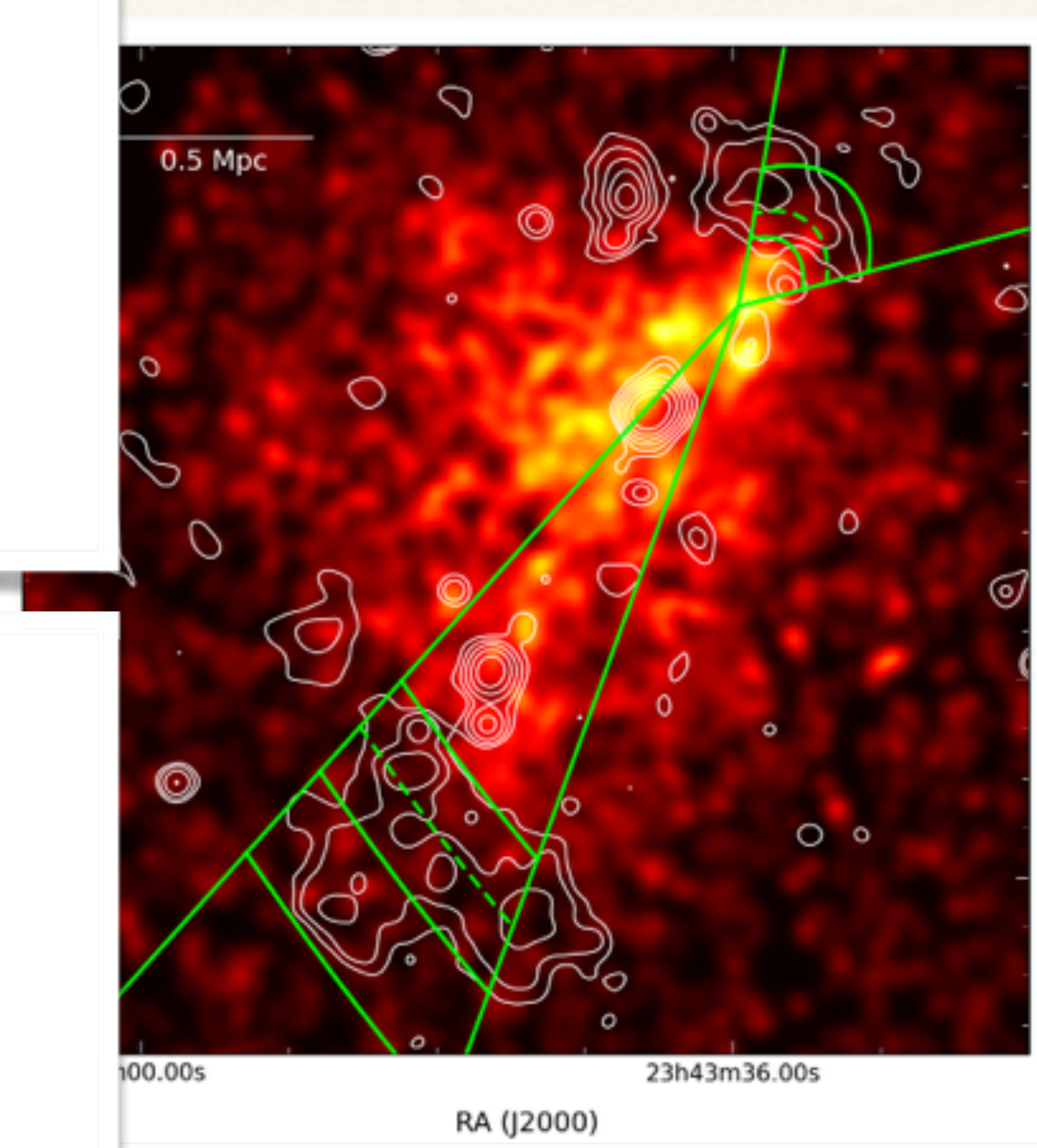


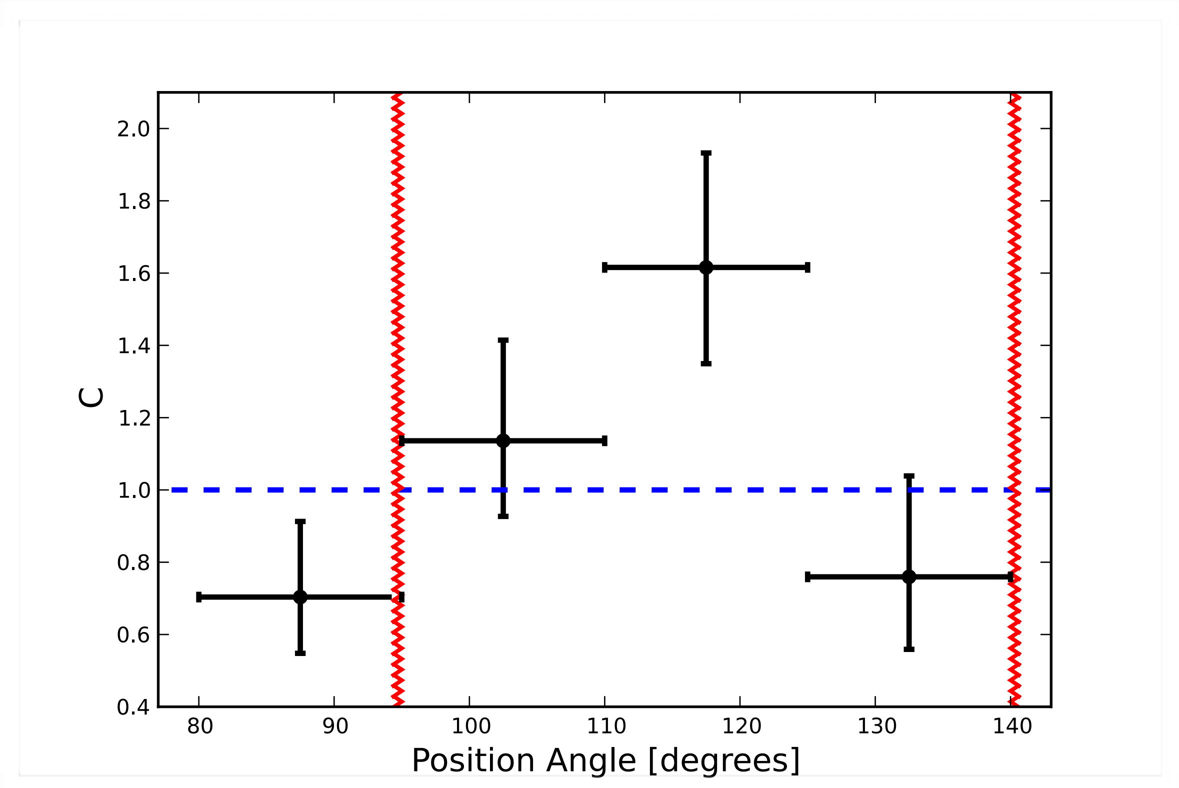
From radio: $\alpha_N = -0.5 \pm 0.2$

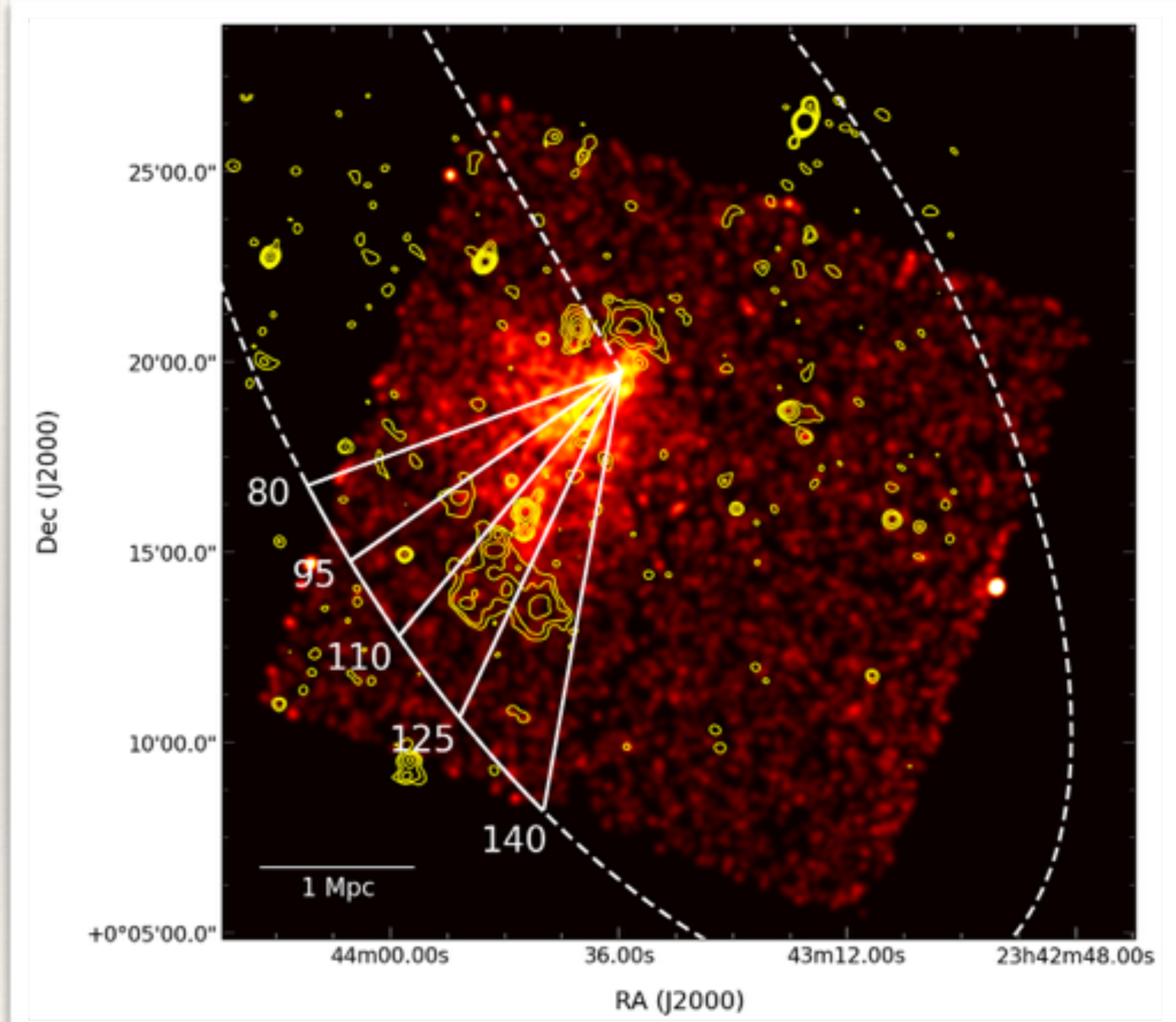
$\alpha_S = -0.8 \pm 0.2$


N sector
M = 2.1-0.8+1.4
82%
SB [counts s-1 arcmin-2]
χ
Distance [arcmin]


S sector
M = 1.6 ± 0.3
87%
SB [counts s-1 arcmin-2]
χ
Distance [arcmin]


0.5 Mpc
00.00s
23h43m36.00s
RA (J2000)





- Confidence levels: 85% for the NE tip, 94% for the SW tip (for a shock of constant Mach number across its length).
- About 2/3 of the relic's length do not appear to be traced by a shock front!

ZwCl 2341.1+0000
Discussion

Missing Shock Across Part of the Relic

ZwCl 2341 is the only known relic cluster in which the length of the arc spanned by the relic is larger than that of the arc spanned by the shock!

Possible explanations:

- convex shock shape;
- Mach number variations across the relic;
- shorter line of sight through the tips of the relic.

Summary

DIFFUSIVE SHOCK ACCELERATION

Predictions	Observations
Weak shocks in merging galaxy cluster outskirts are associated with relics.	In some clusters, there is no radio emission at merger shocks (A2146, Russell et al. 2011; CIZA J2242.8+5301, Ogrean et al. 2014).
The outer edges of radio relics trace shock fronts.	Shock fronts are sometimes spatially offset from the relics, or do not trace the relics' full length (1RXS J0603.3+4214, Ogrean et al. 2013; ZwCl 2341.1+0000, Ogrean et al. 2014).
The Mach number of a merger shock can be independently determined from radio and X-ray observations.	Discrepancies between radio predictions and X-ray measurements are common (CIZA J2242.8+5301, Akamatsu et al. 2013, Ogrean et al. 2014; 1RXS J0603.3+4214, Ogrean et al. 2013; ZwCl 2341.1+0000, Ogrean et al. 2014).

Thank you!