Magnetic fields in the IGM/ICM

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TABLE 1 Cluster magnetic fields

Method	Strength μG	Model parameters
Synchrotron halos	0.4–1	Minimum energy, $k = \eta = 1$, $\nu_{\rm low} = 10$ MHz, $\nu_{\rm high} = 10$ GHz
Faraday rotation (embedded)	3–40	Cell size = 10 kpc
Faraday rotation (background)	1–10	Cell size = 10 kpc
Inverse Compton	0.2–1	$\alpha = -1$, $\gamma_{\rm radio} \sim 18000$, $\gamma_{\rm xray} \sim 5000$
Cold fronts	1–10	Amplification factor ~ 3
GZK	>0.3	AGN = site of origin for EeV CRs

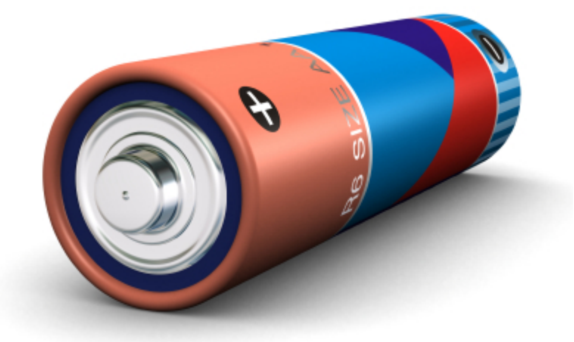
Carilli & Taylor 2002

What does the magnetic field do and where does it come from?

Origin of cluster magnetic fields

Seed field

battery



primordial

dynamo

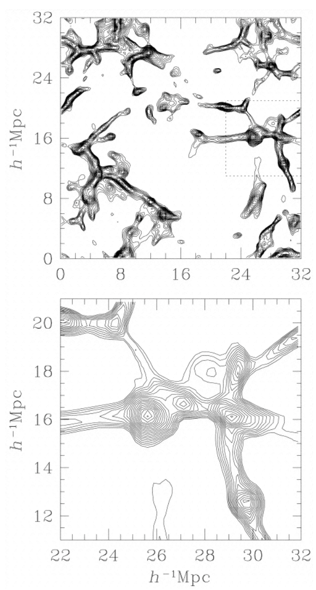
shocks

galactic winds

AGN

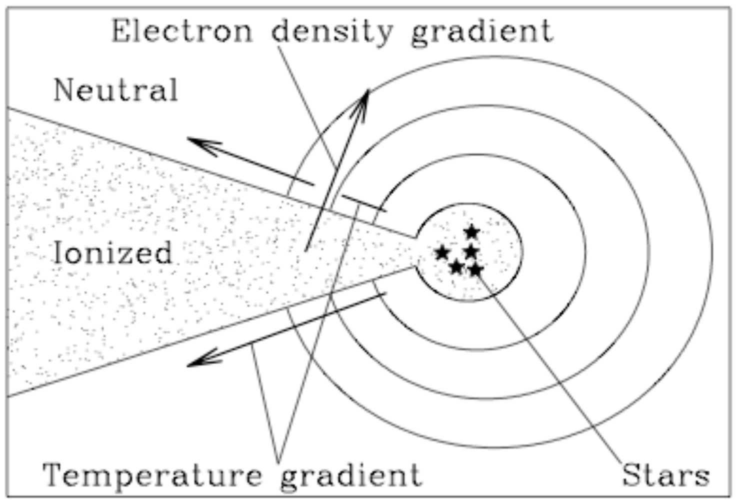
Origin of cluster magnetic fields

battery



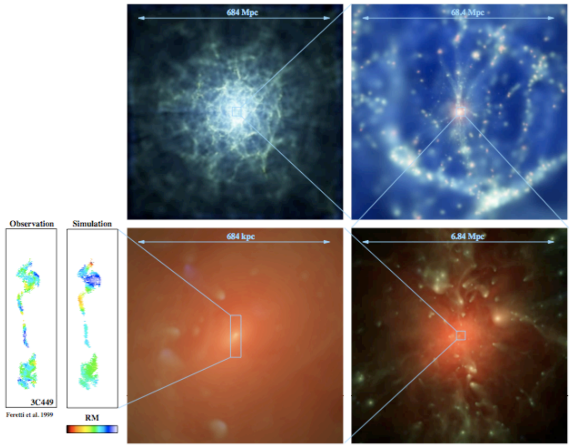
Kulsrud et al. 1994

primordial



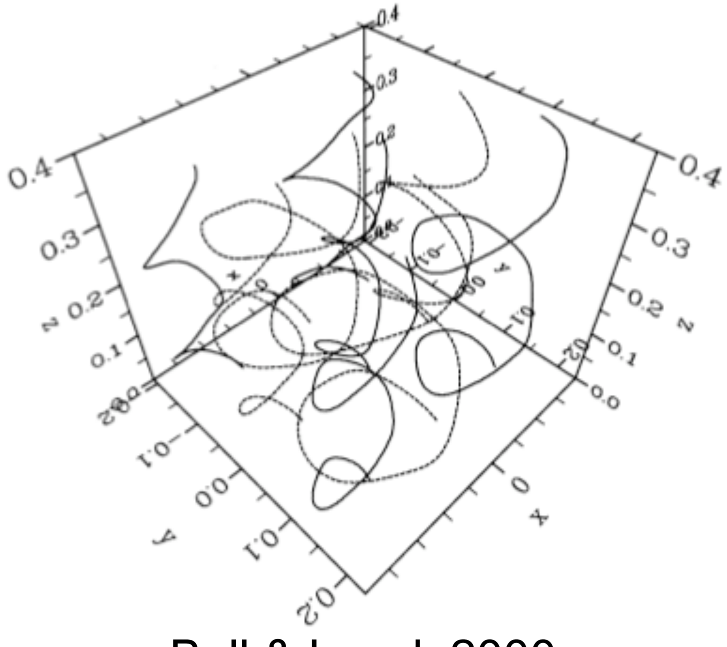
Gnedin, Ferrara & Zweibel 2000

dynamo



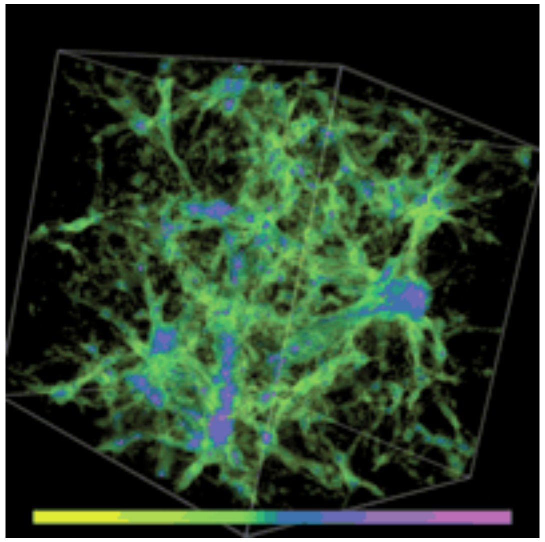
Dolag & Stasyszyn 2010

shocks + CR



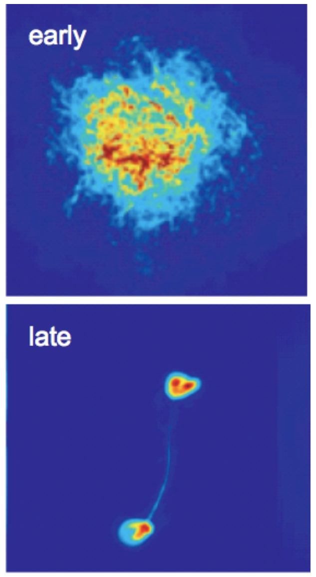
Bell & Lucek 2000

turbulence



Ryu et al. 2008

AGN



Xu et al. 2010

GLOBAL (profiles, transport)	TURBULENCE (+ dynamo, fluid instabilities, etc.)	PLASMA (micro-instabilities)
100 kpc	1–10 kpc	*a few times* ρ_i 10^4–10^6 km **(1-100 npc)**
1 Gyr	10 Myr	*a fraction of* Ω_i 10 hours

Slide from Alex Schekochihin

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100 kpc	1–10 kpc	ρ_i km npc)
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MICROPHYSICS SETS ICM VISCOSITY AND CONDUCTIVITY, AFFECTS EVERYTHING (*NOT* A SMALL CORRECTION!)

OBSERVABLE

THEORY PARADISE (but measurable in SW!)

Slide from Alex Schekochihin

Adiabatic MHD simulations of galaxy clusters

Initial uniform magnetic field with strength $B_{\rm IGM} = 10^{-4} - 10^{-5}\,\mu{\rm G}$

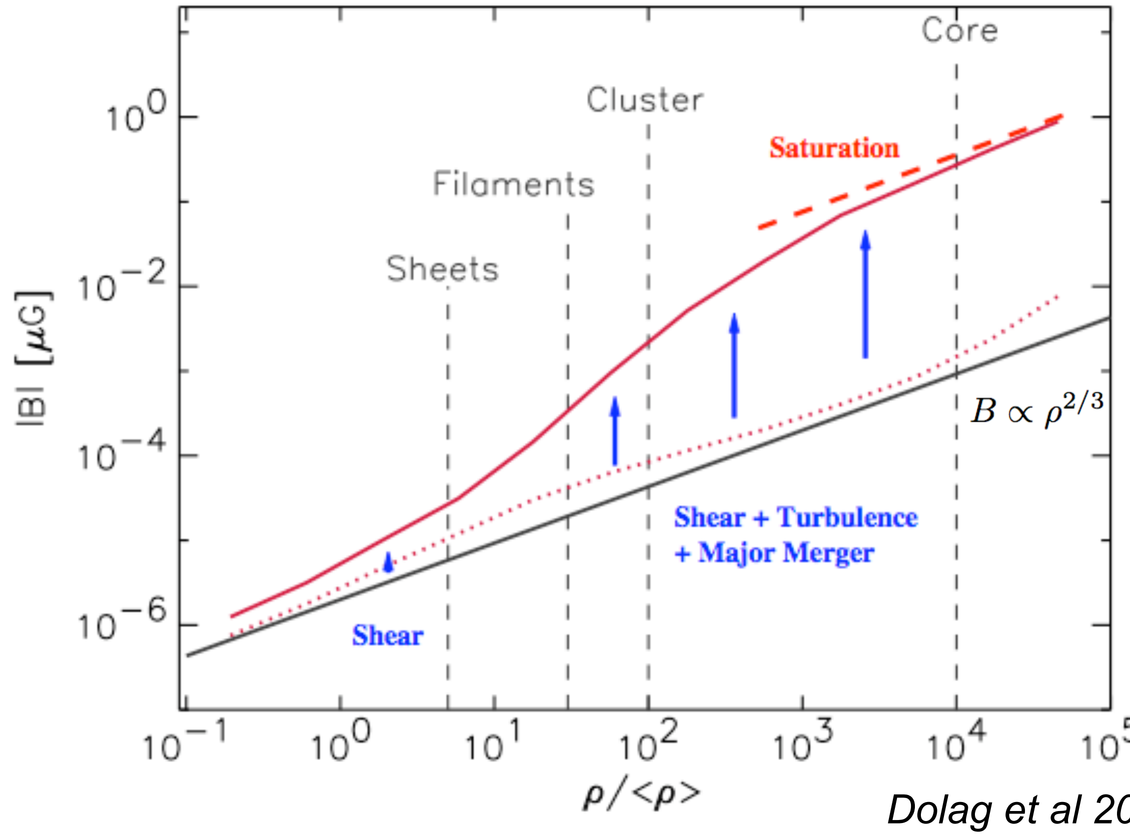
Unigrid: *Miniati et al. 2001*
SPH: Dolag et al. 2005
AMR: Brüggen et al. 2005

Collapse of a gas sphere with $\nabla.\mathbf{B} = 0$

Magnetic flux is conserved

$$\oiint \mathbf{B}.\mathrm{d}\mathbf{S} = 0 \quad \Rightarrow \quad B \propto \rho^{2/3}$$

Adiabatic SPH simulation



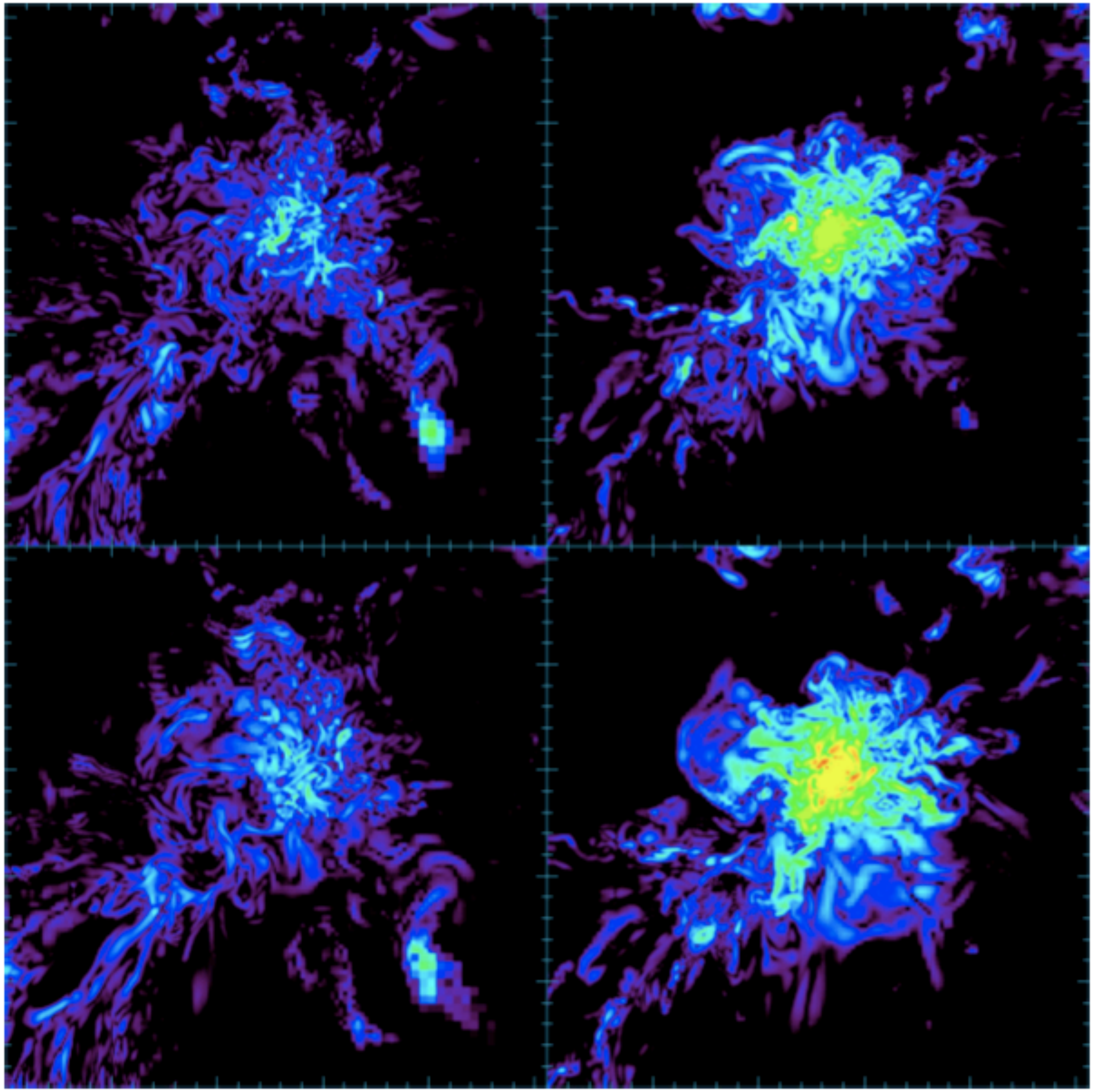
Dolag et al 2005

Magnetic field amplified by gravity and turbulence

magnetic pressure slices

no cooling
no conduction

cooling
no conduction



no cooling
conduction

cooling
conduction

8/ h Mpc

FIG. 7.— Cross sections through the cluster center showing the distribution of the logarithm of the magnetic field pressure. The minimum and maximum range of magnetic field values is the same in all panels. The arrangement of the figures is the same as in Figure 1 that shows the temperature distribution: right column is for radiative runs and bottom row is for the runs with anisotropic thermal conduction. All panels show the central region that measures $8h^{-1}$ Mpc on the side.

Ruszkowski, Brüggen, Oh, Parrish 2010

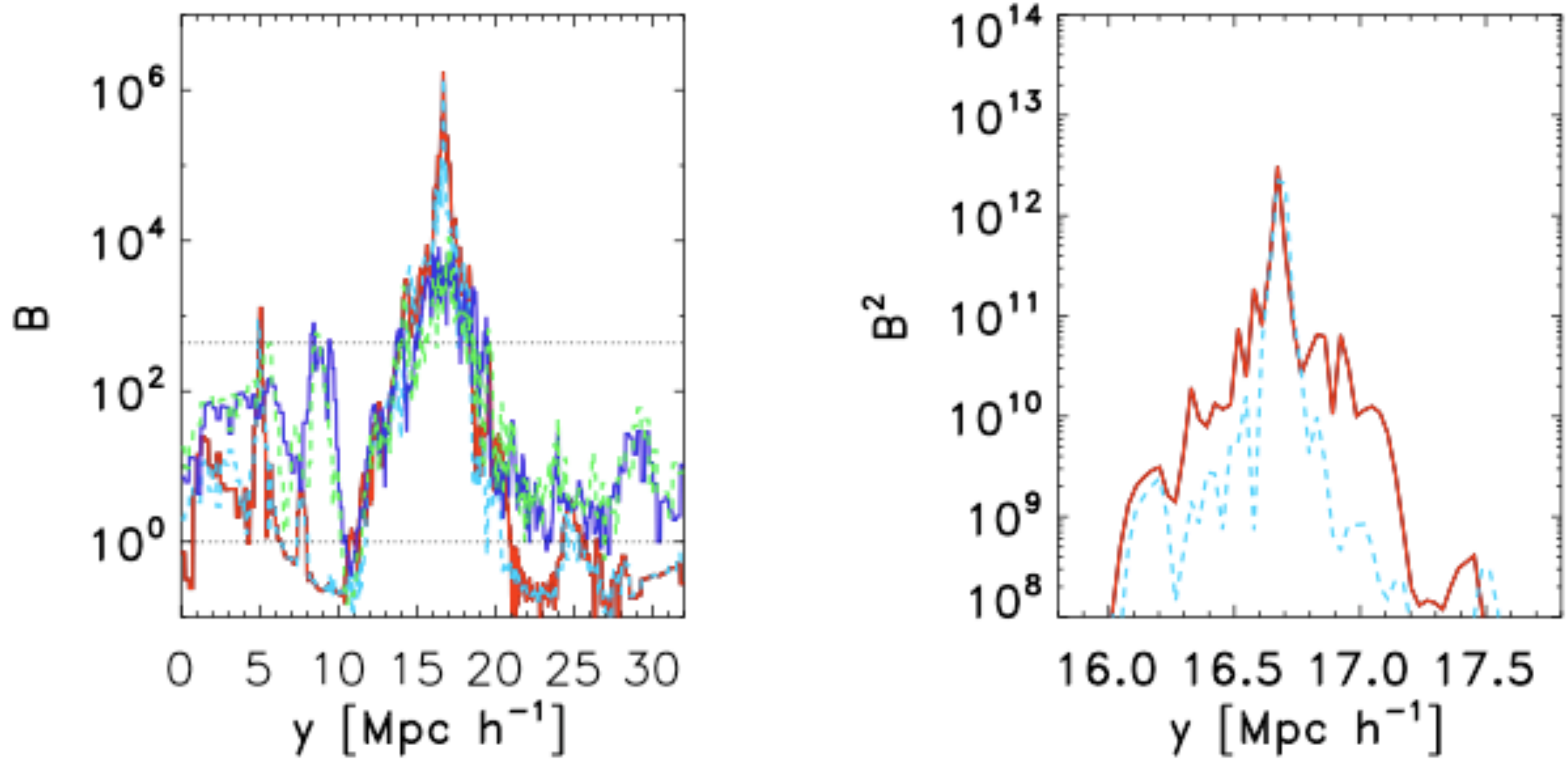


FIG. 8.— The distribution of the magnetic field along the line passing through the cluster center (left panel). The color coding of the curves is the same as in Figure 2. The top horizontal line denotes the physical field at the initial redshift ($z = 20$) and the bottom one is for the value of the field that would result from cosmological expansion down to $z = 0$ without any structure formation effects. Right panel shows the magnetic pressure along the line passing through the cluster. Here the solid red line is for the anisotropic conduction and cooling while the dashed light blue line is for the run that includes only radiative cooling.

Ruszkowski, Brüggen, Oh, Parrish 2010

Galaxy clusters: three evolutionary stages

Stage 1. Cluster formation, $0 \lesssim t \lesssim 4$ Gyr

- Volume-filling random flow, $v_0 \simeq 300$ km/s, $\ell_0 \simeq 150$ kpc,
- produced in the major merger event

  (e.g., wakes of merging subclusters).
- Re $\gtrsim 100 \Rightarrow$ turbulence
- Fluctuation dynamo: B amplified by a factor $A > 3000$,
- $B \simeq 2\ \mu$G, $\ell_B \simeq 20$–30 kpc (if $B_0 > 10^{-9}$ G),
- $\sigma_{RM} \cong 200$ rad/m^2

See work by Dongsu Ryu

Slide from Anvar Shukurov

Stage 2. Decay after major mergers, $4 \lesssim t \lesssim 9$ Gyr

$v_0 \propto t^{-3/5}$, $\ell_0 \propto t^{2/5}$

$\Rightarrow v_0 \simeq 150$ km/s, $\ell_0 \simeq 300$ kpc at $t = 9$ Gyr

Dynamo action, $\mathrm{A} > 2\times10^4$, $B \simeq 1\ \mu\mathrm{G}$, $\ell_B \simeq 40$ kpc

R_m, $\mathrm{Re} \propto t^{-1/5}$, $\sigma_{\mathrm{RM}} \propto t^{-2/5}$

Slide from Anvar Shukurov

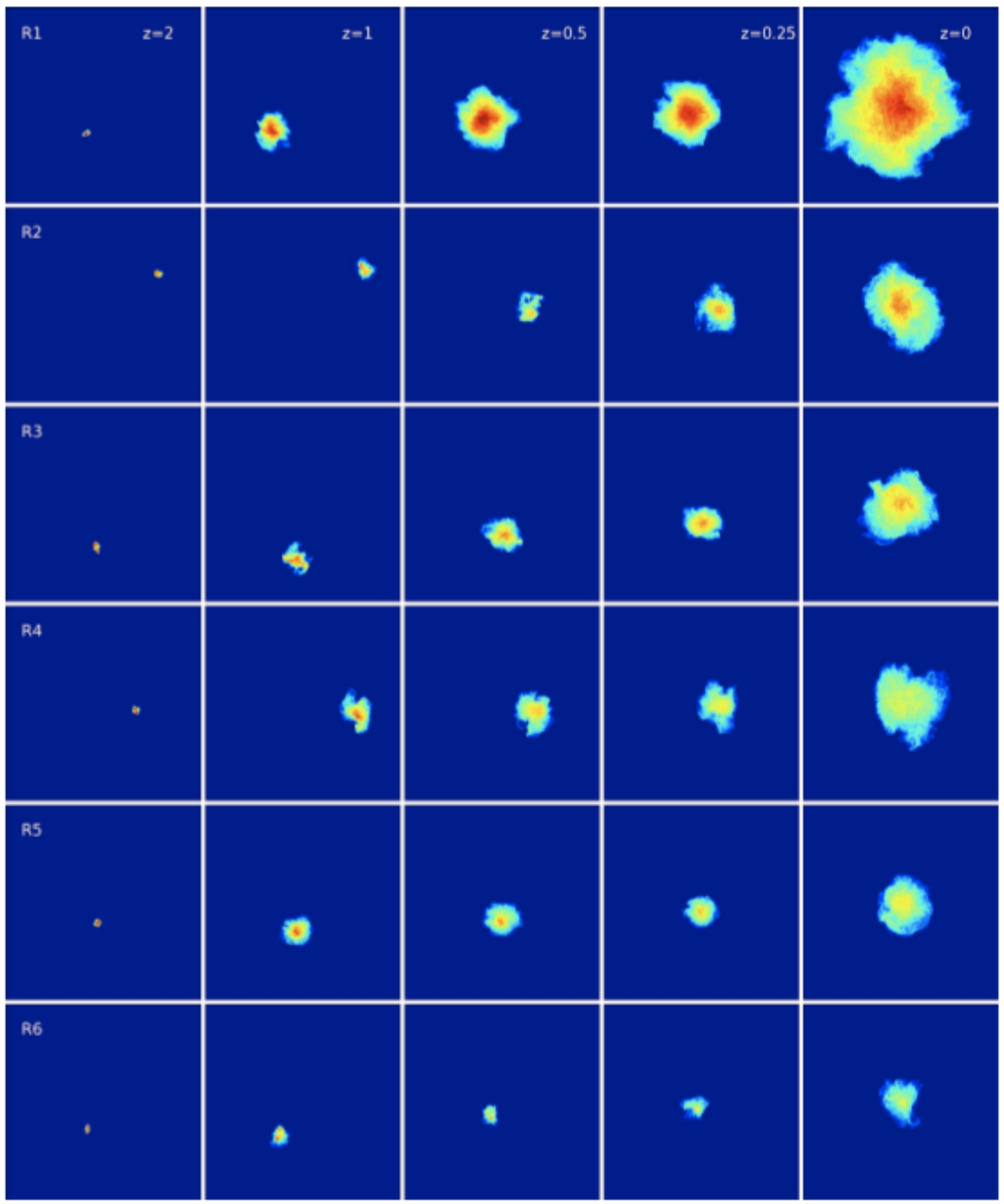
Stage 3. Mature cluster: turbulence in the wakes of galaxies and galaxy groups

- Clumps $m = 3\times10^{13}M_\odot$ falling into cluster $M = 10^{15}M_\odot$ every $\Delta t \propto m^{-1/2} \simeq 0.3$ Gyr (Lacey & Cole 1993),
- gas stripping radius $R_0 \simeq 100$ kpc,
- wake length $\dfrac{X}{R_0} = 27\left(\dfrac{\mathrm{Re}}{10^3}\right)^3$
- $v_0 \simeq 250$ km/s, $\ell_0 \simeq 200$ km/s, $B \simeq 2\ \mu$G, $\ell_B \simeq 30$ kpc
- Volume filling factor: $f_V \simeq 0.02\left(\dfrac{\mathrm{Re}}{10^3}\right)^5$
- Area covering factor: $f_S \simeq 0.2\left(\dfrac{\mathrm{Re}}{10^3}\right)^4$

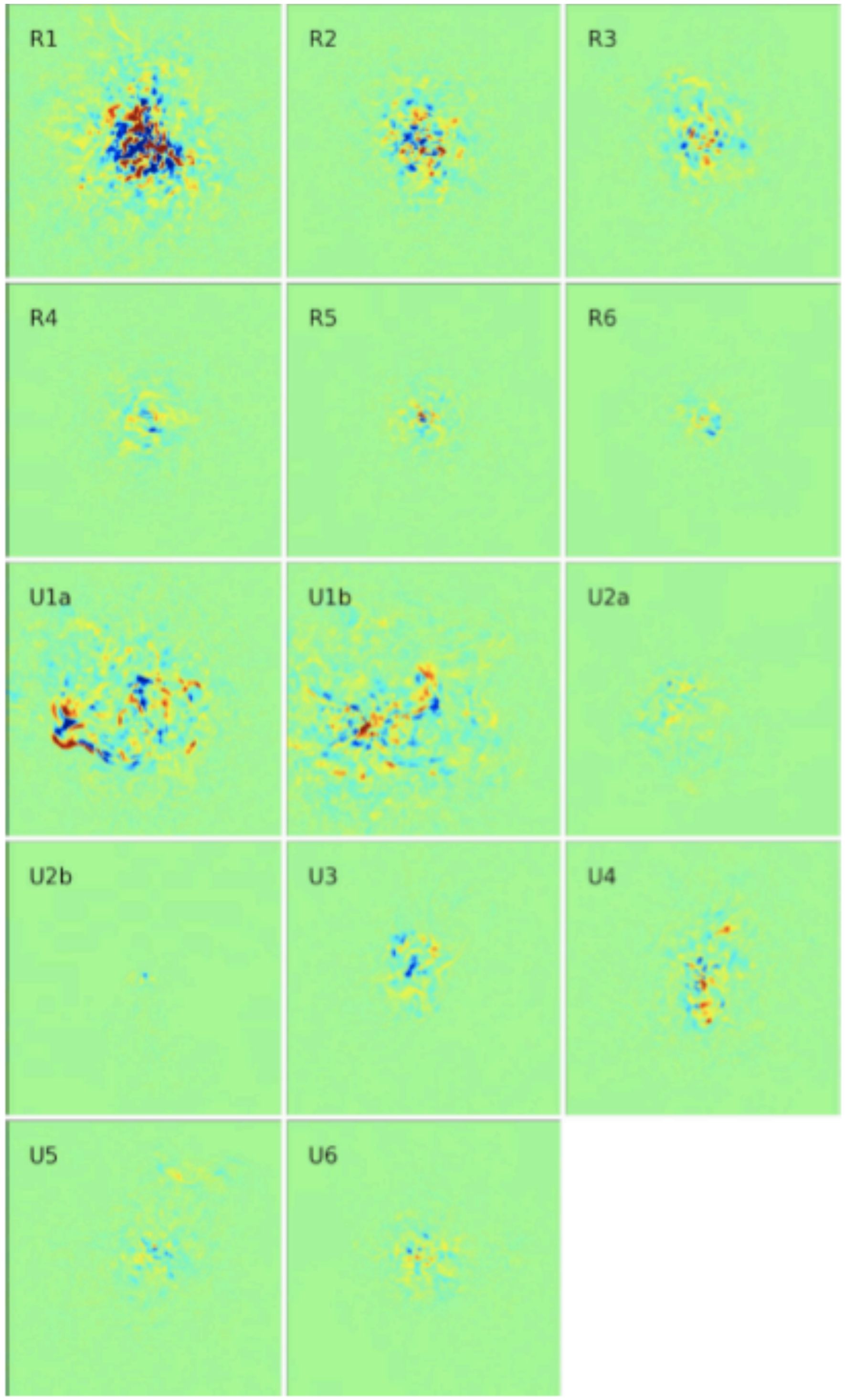
Slide from Anvar Shukurov

AGN injection in IGM

ENZO simulations: magnetic AGN @z=3



RM maps

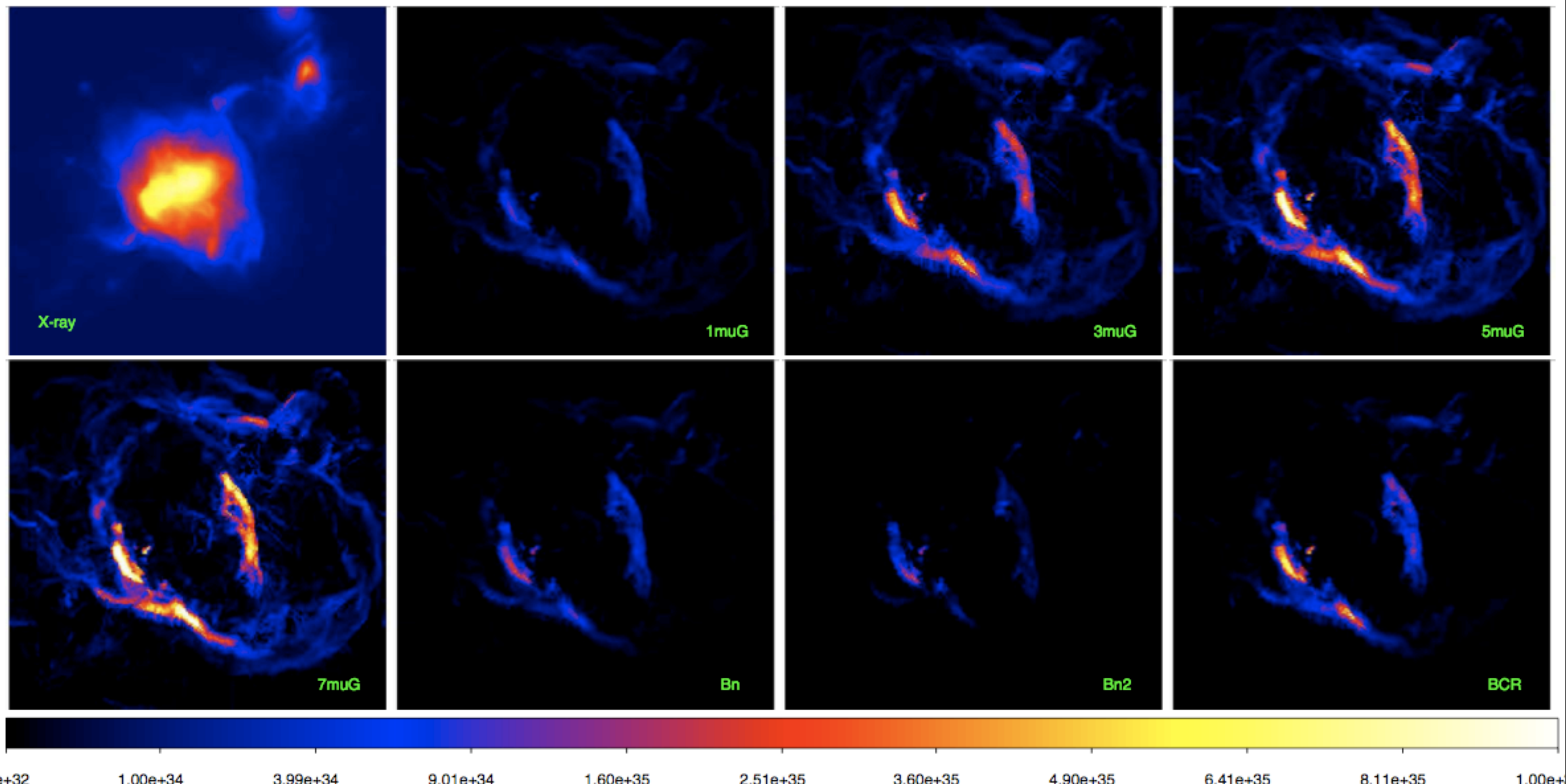


Xu et al. 2011

- magnetic field is primarily driven by small-scale dynamo
- it scales as mass of cluster squared
- magnetic fields fill cluster
- additional fields from AGN do NOT have a great impact
- B field in relaxed clusters self-similar - in non-relaxed clusters not
- RM distribution is good prove for magnetism history

Xu et al. 2011

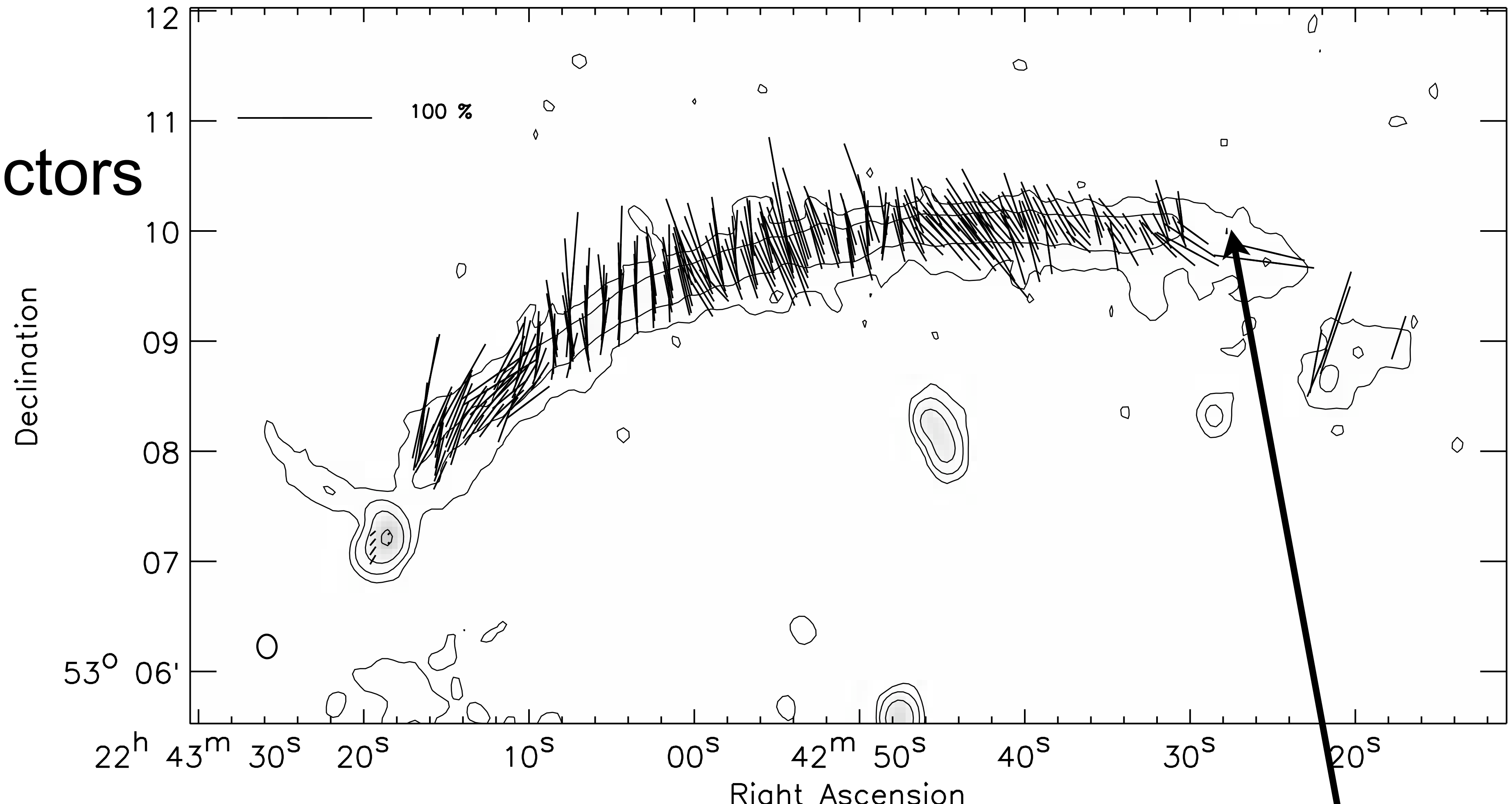
Magnetic field generation at shocks



Vazza, Brüggen, Brunetti et al. 2011

Explain this.

E-vectors



polarisation @ 2.2 GHz: 50 %

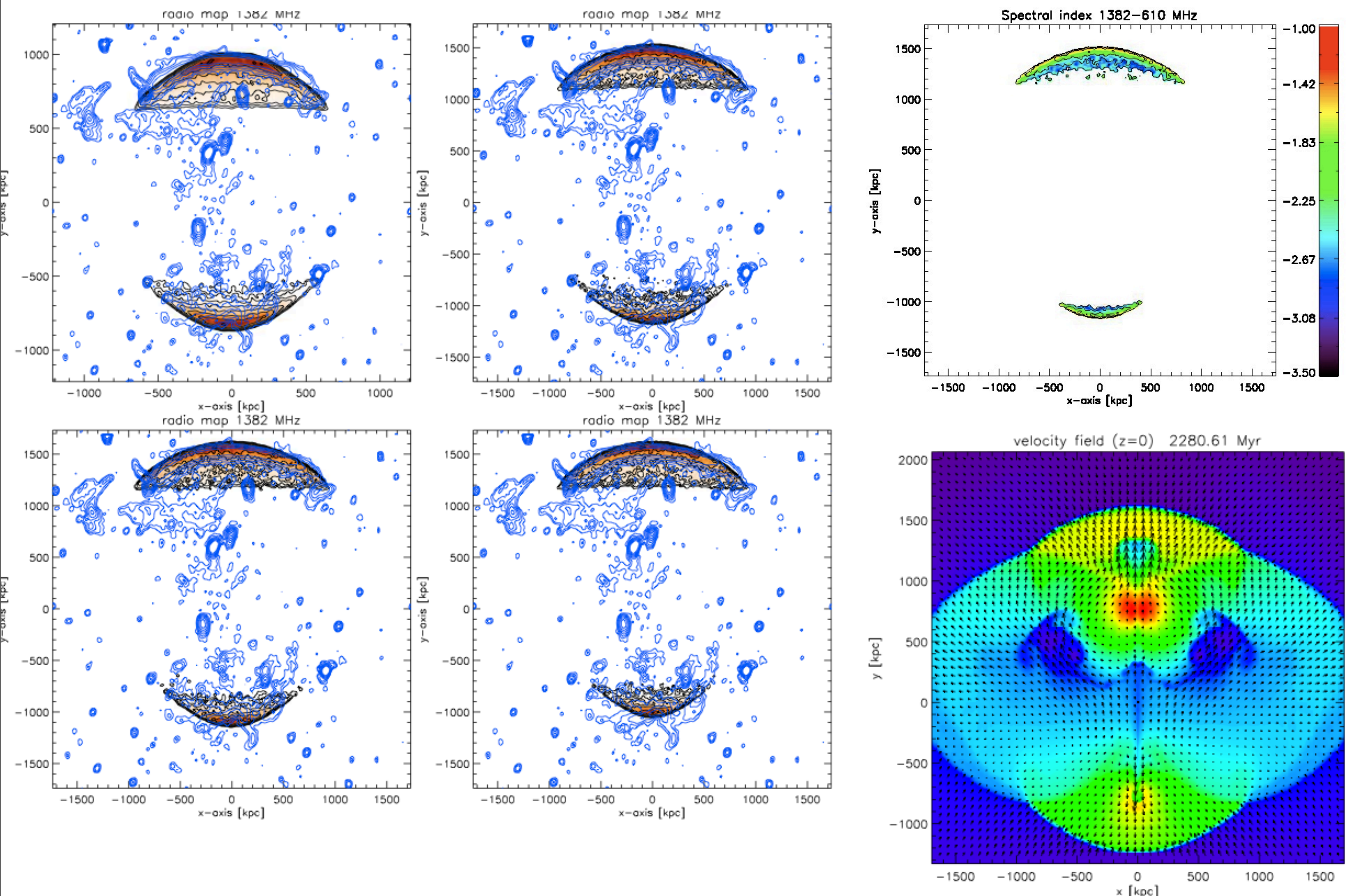
van Weeren, Röttgering & Brüggen, Hoeft 2010

Why is magnetic field parallel to the shock/relic plane?

Compression of ambient field or magnetic field generation in shock?

Why so strong?

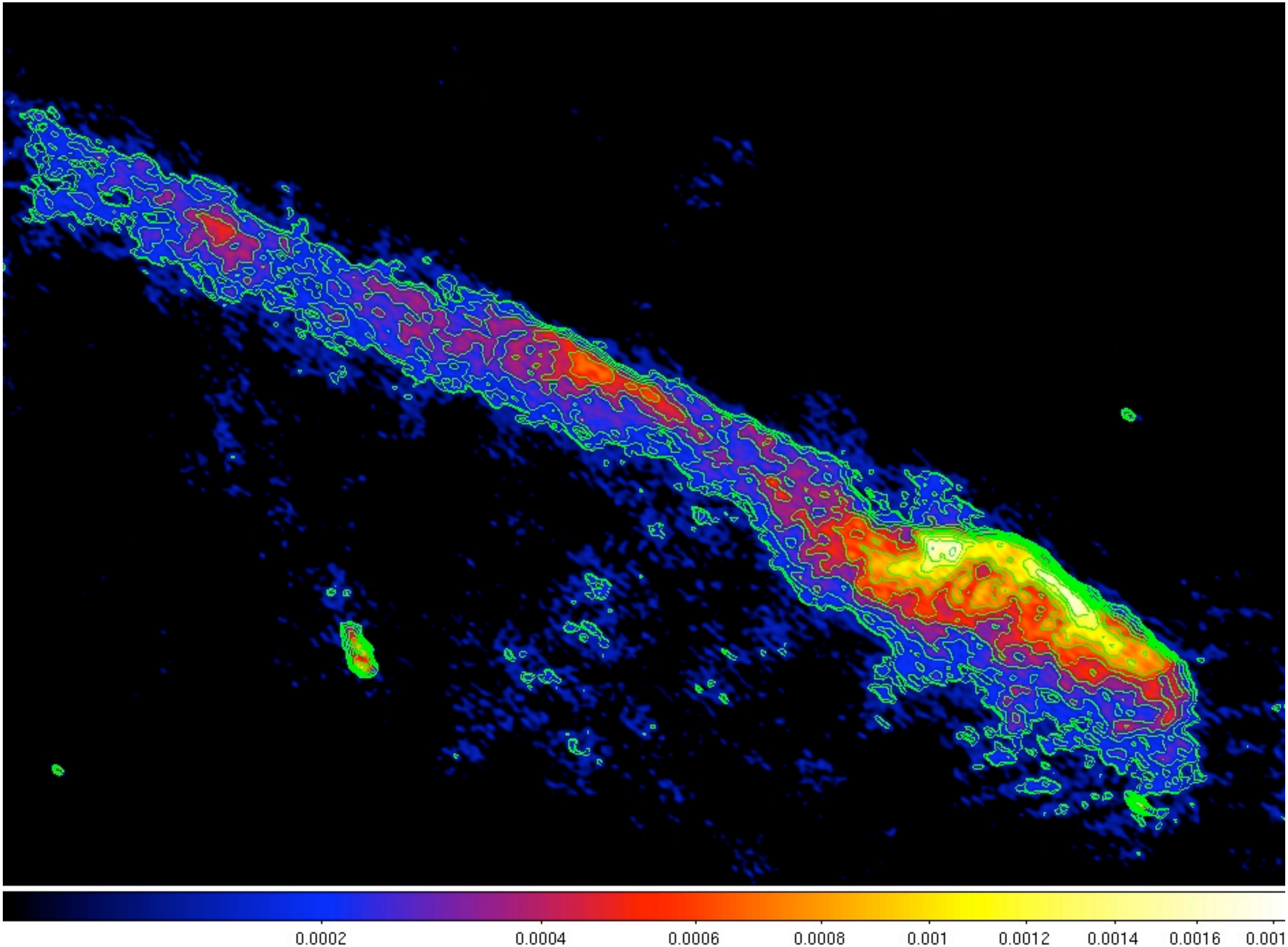
Simulations of the CIZA cluster



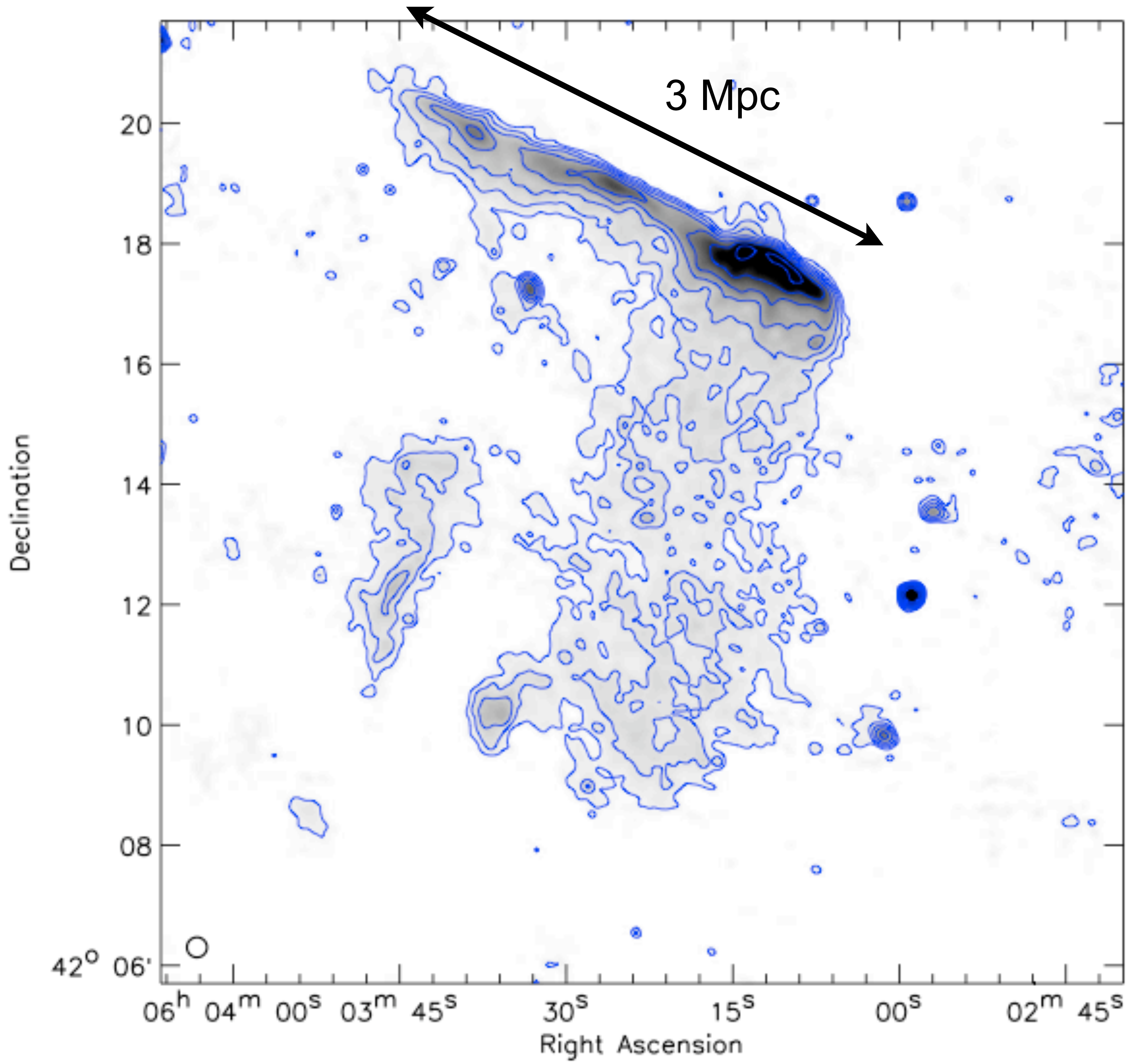
van Weeren & Brüggen (2011)

van Weeren, Röttgering, Brüggen, Hoeft in prep.

The toothbrush: **1RXS J0603.3+4213**



1RXS J0603.3+4213

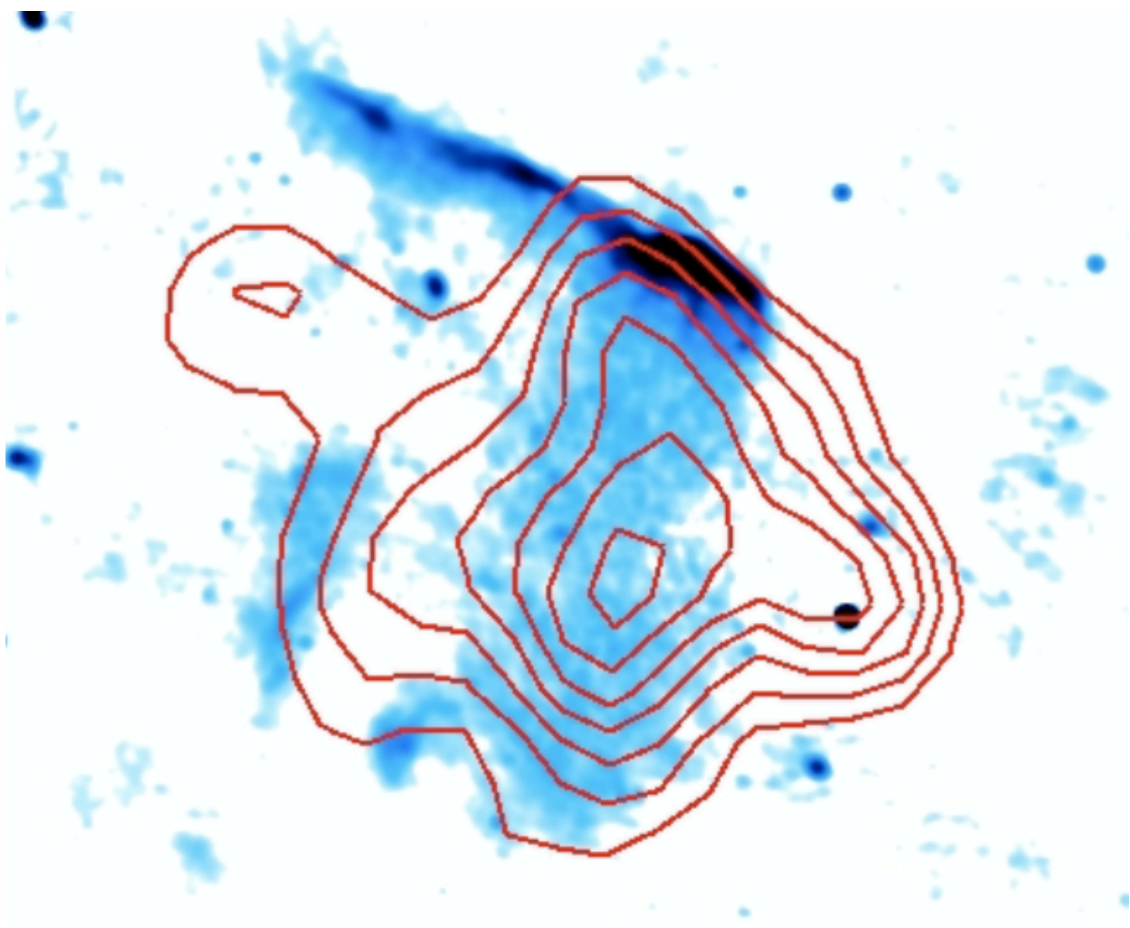


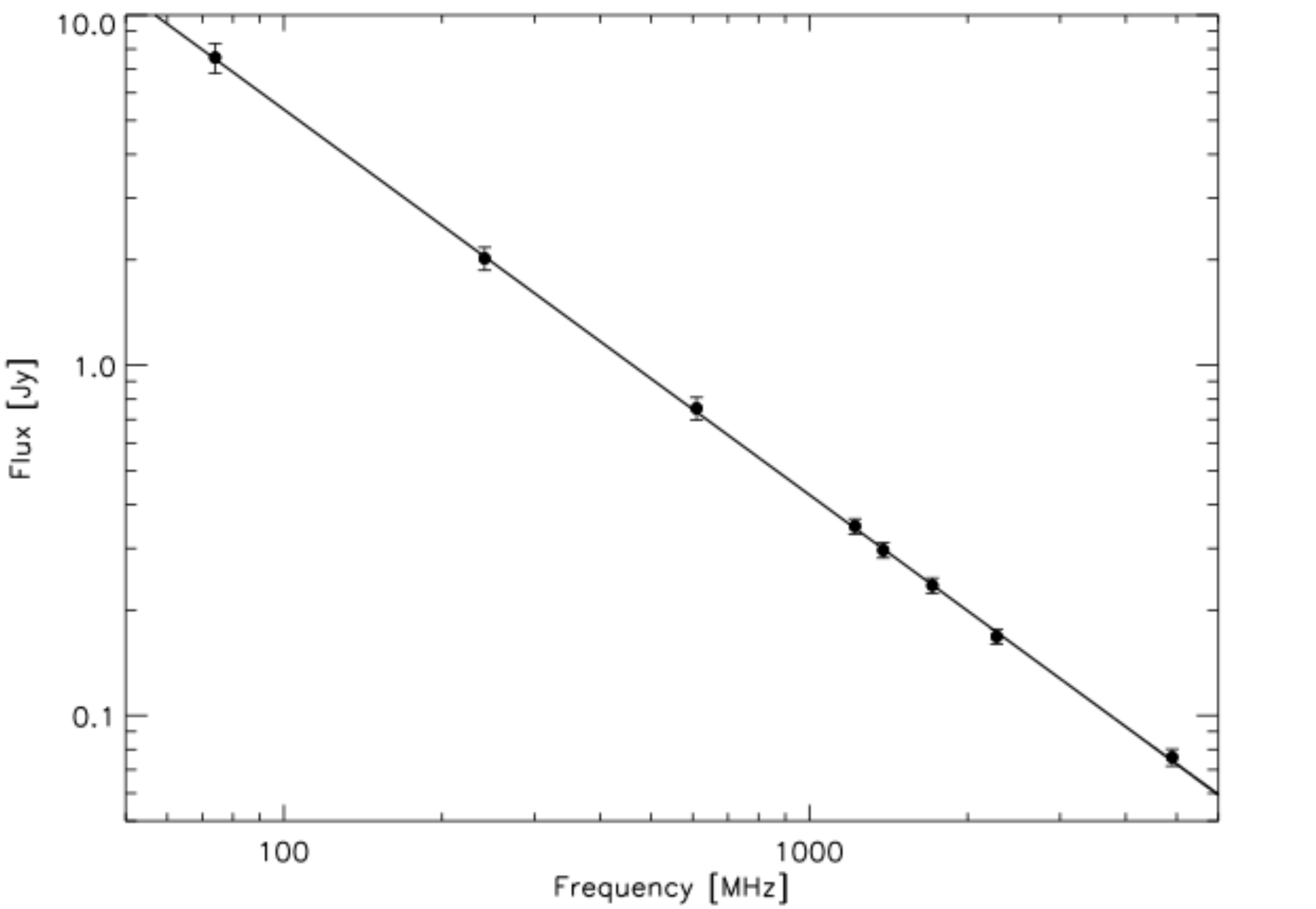
largest relic known to date

z=0.25

610 MHz GMRT map

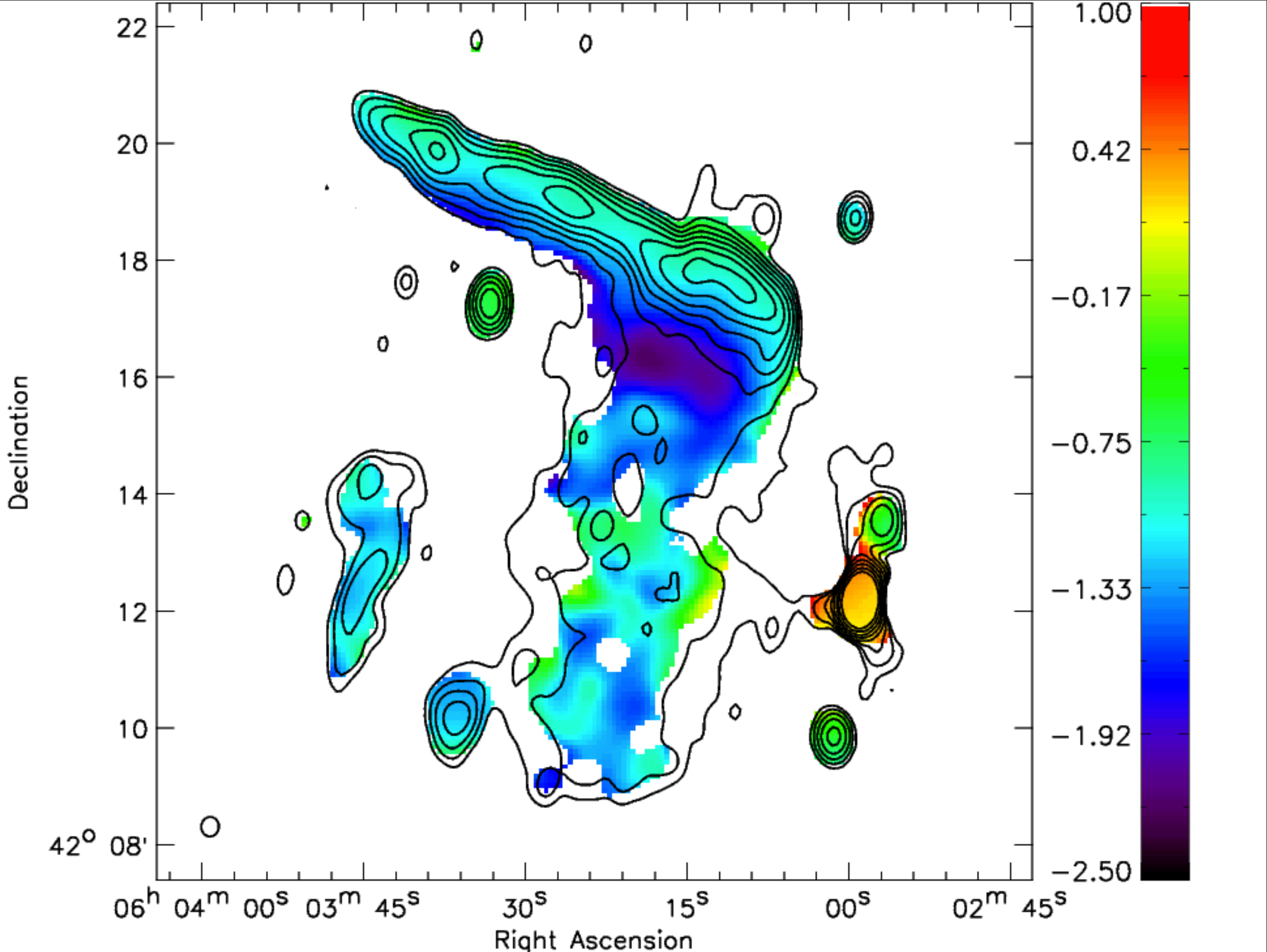
Some more puzzles



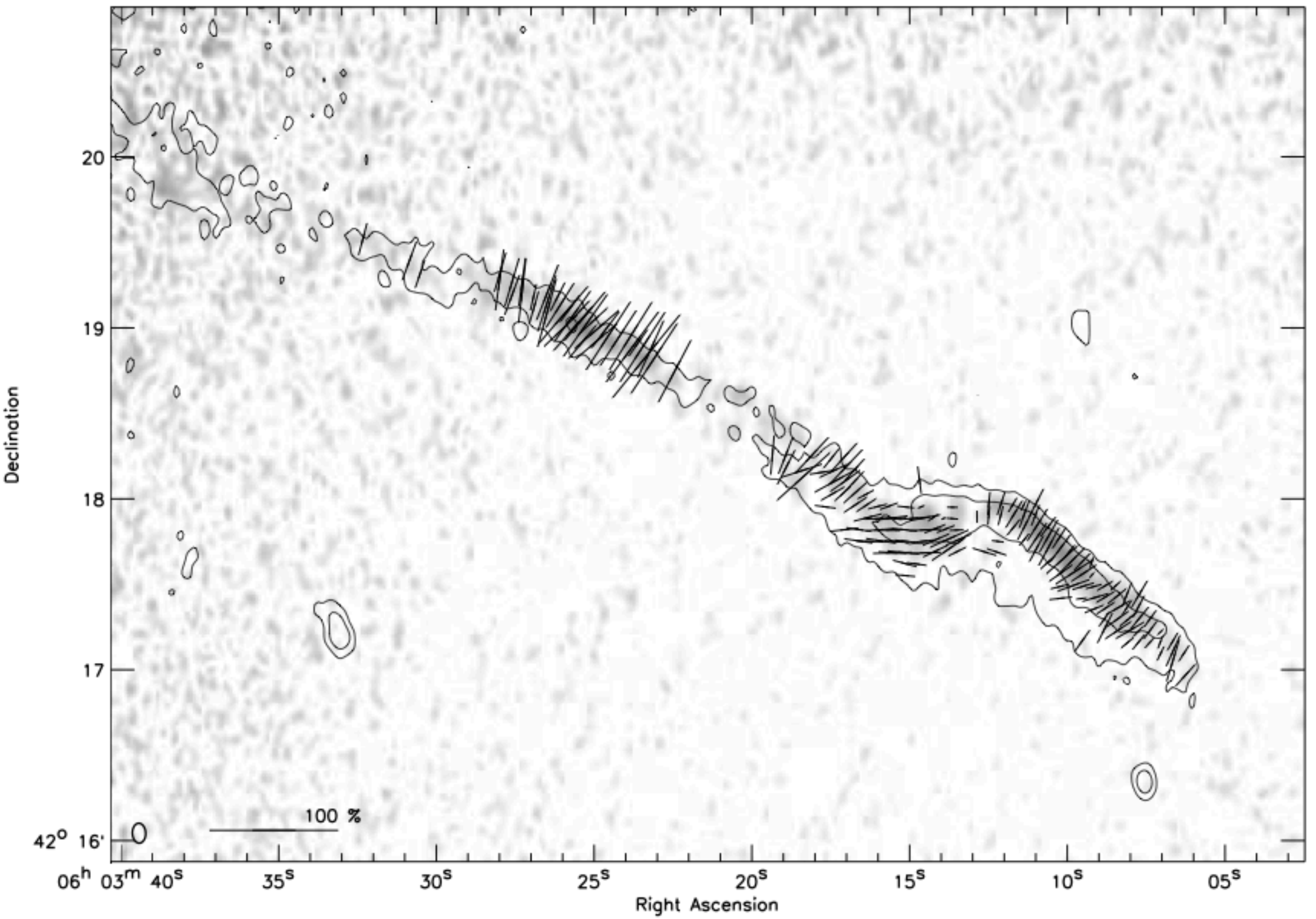


ROSAT

74 MHz - 4.9 GHz spectrum is a perfect power-law (alpha = -1.1 +/- 0.03)



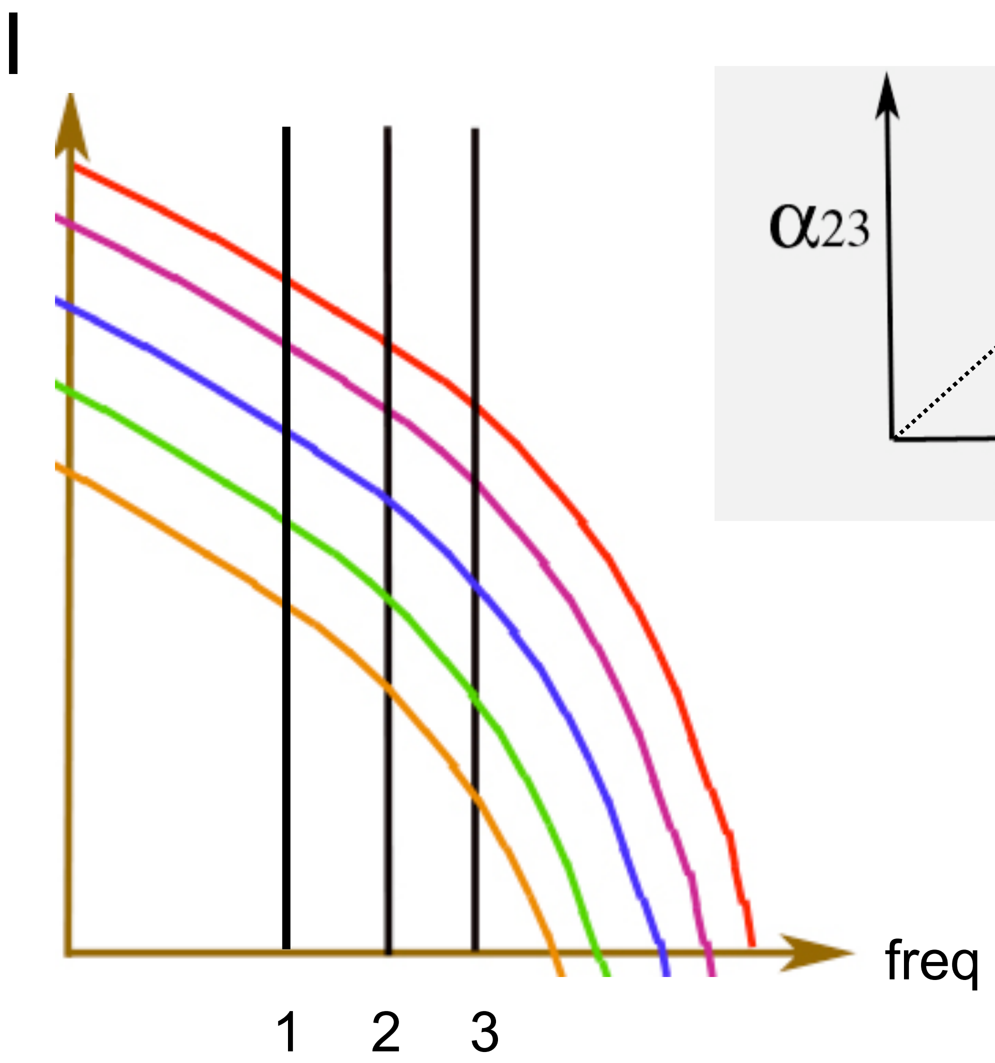
Declination
Right Ascension
22
20
18
16
14
12
10
42° 08'
06h 04m 00s
03m 45s
30s
15s
00s
02m 45s
1.00
0.42
−0.17
−0.75
−1.33
−1.92
−2.50

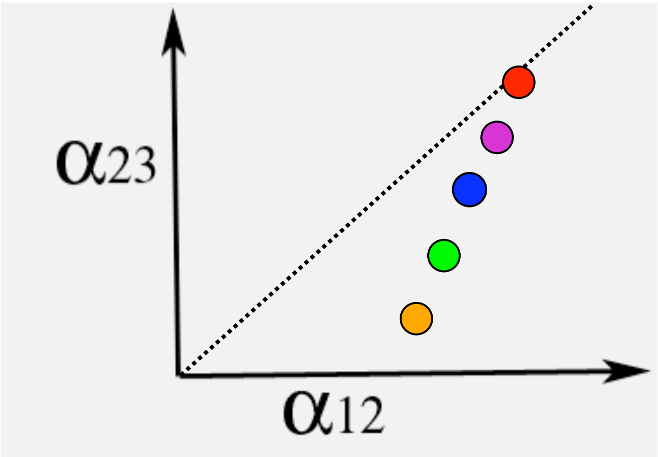


Declination
20
19
18
17
42° 16'
06h 03m 40s
35s
30s
25s
20s
15s
10s
05s
Right Ascension
100 %

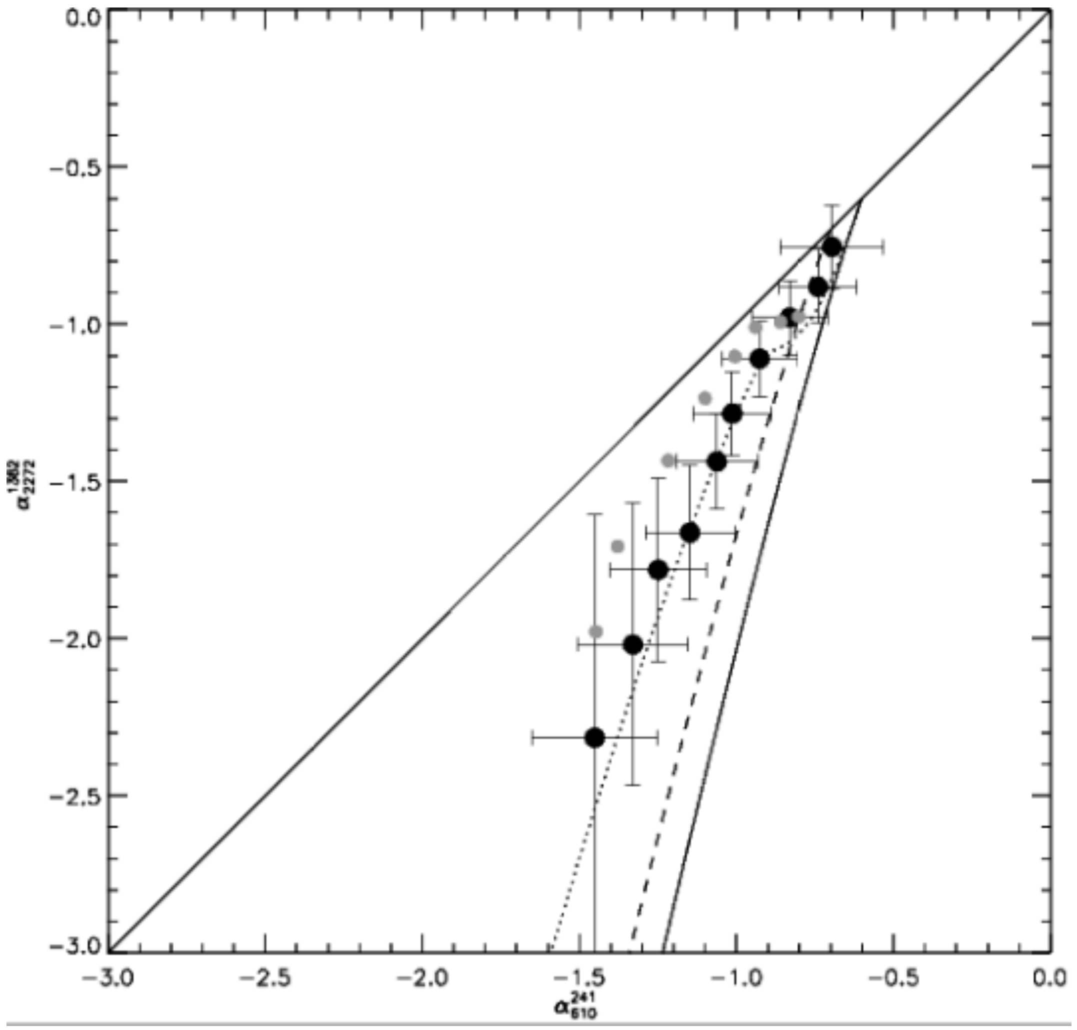
What does the relic really consist of?

- in reality things are more complicated
- not pure ageing
- mixture of populations
- PLUS extra steep spectrum component only visible at 50cm, 200cm



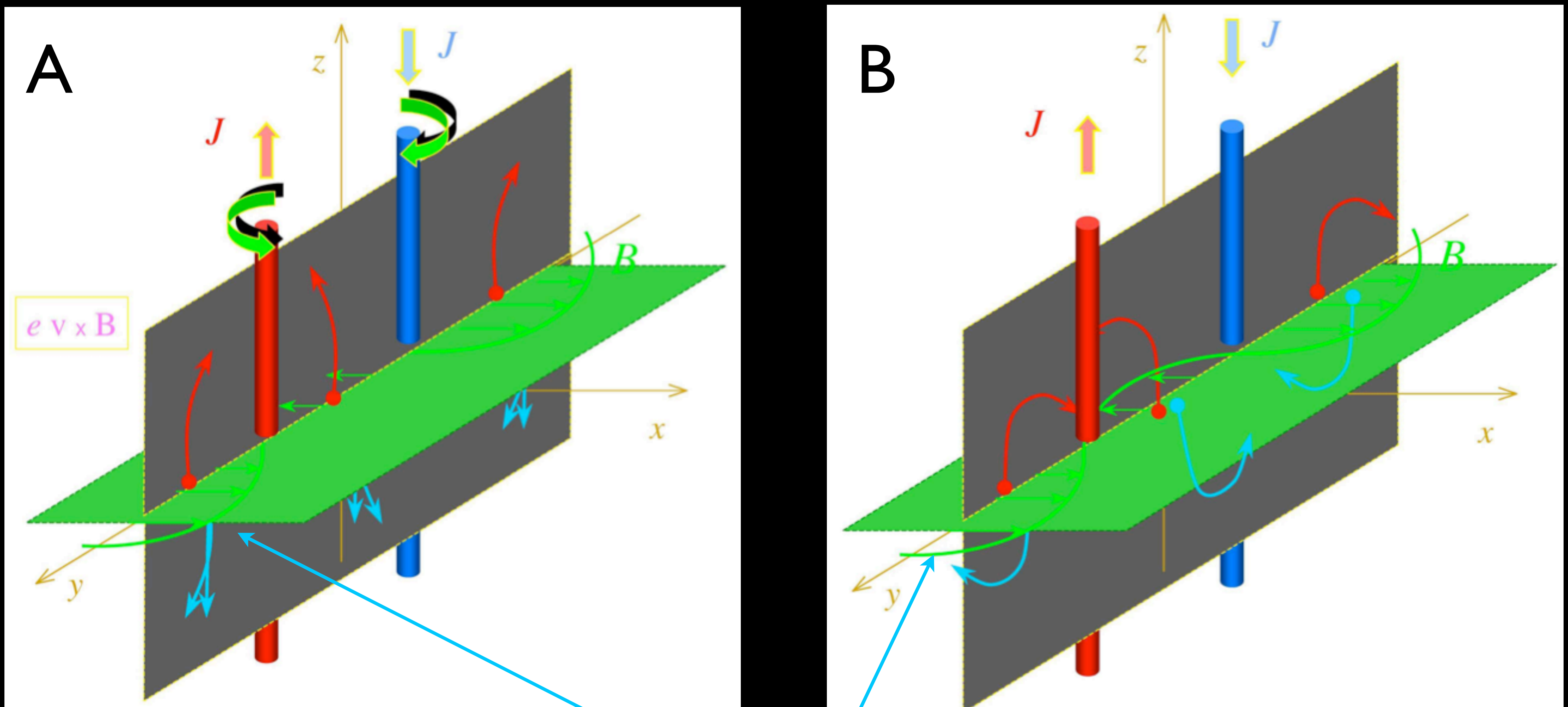


work in progress



mix of spectral ages

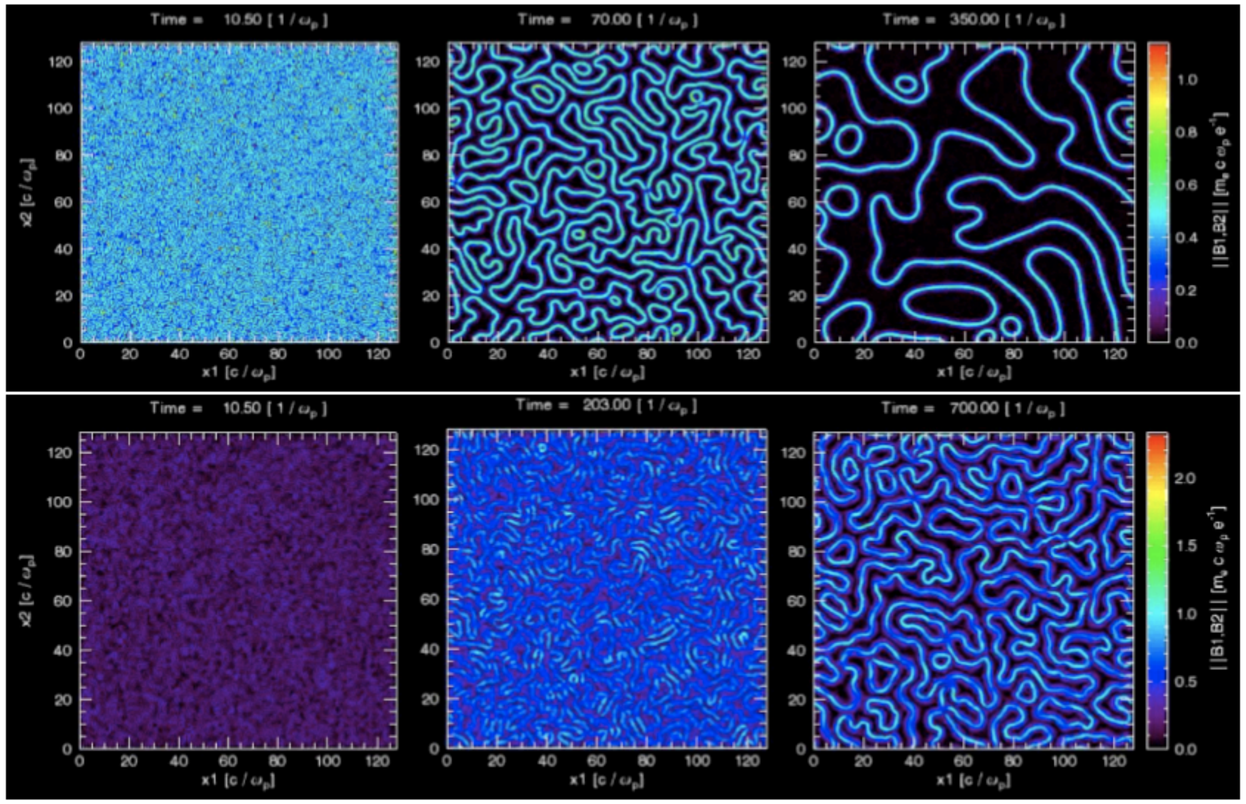
Weibel



$$\vec{B} = B_x \cos(ky)\hat{x}$$

Medvedev et al. JKAS, 37, 533 (2004)

- Weibel instability can produce magnetic fields in cosmological shocks
- The correlation length in the shock plane is very small $\lambda_B \sim 2\pi c/\omega_p \sim 10^{10} n_{\mathrm{IGM},-4}^{-1/2}\,\mathrm{cm}$
- The magnetic field generation works very fast $\tau_B \sim (c/v_{sh})\omega_p^{-1} \sim 2\times 10^2 v_{\mathrm{sh},7}^{-1} n_{\mathrm{IGM},-4}^{-1/2}\,\mathrm{s}$
- Even small M number shocks can produce magnetic fields
- magnetic fields remain sub-equipartition



Medvedev et al. 2004

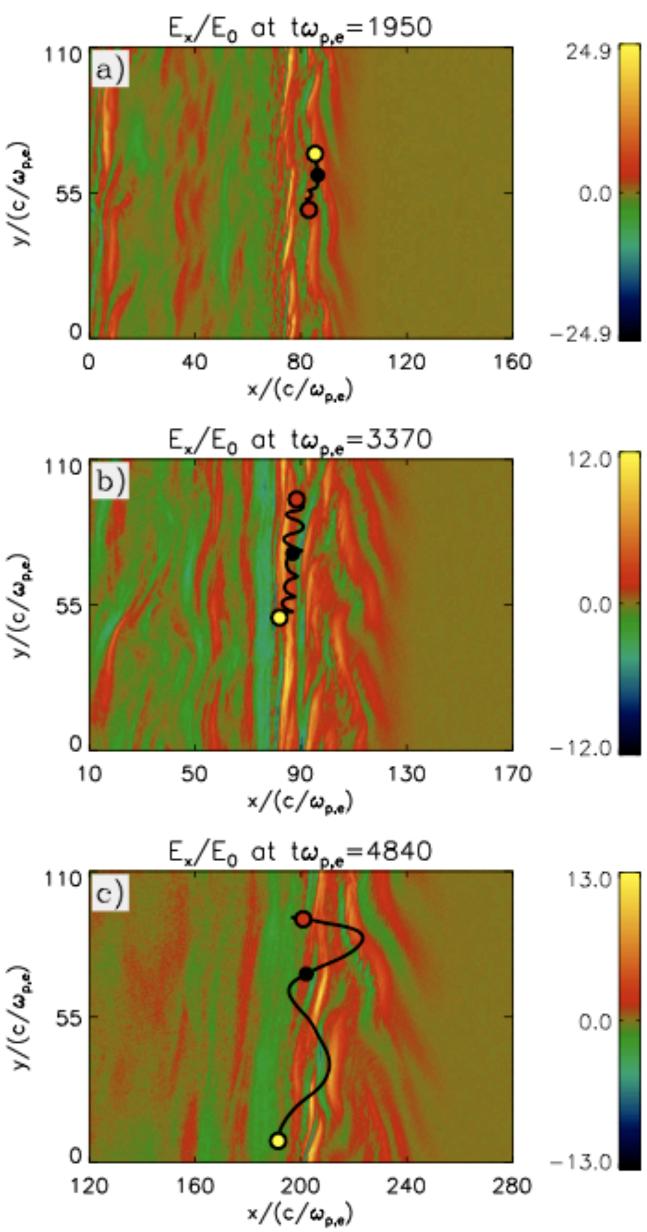
Other mechanisms:

Magnetic bootstrap (Blandford & Funk)
Cosmic rays (Miniati & Bell)

The properties of the magnetic field are important for particle acceleration?

The injection problem

PIC: Electrons accelerated by Whistler waves



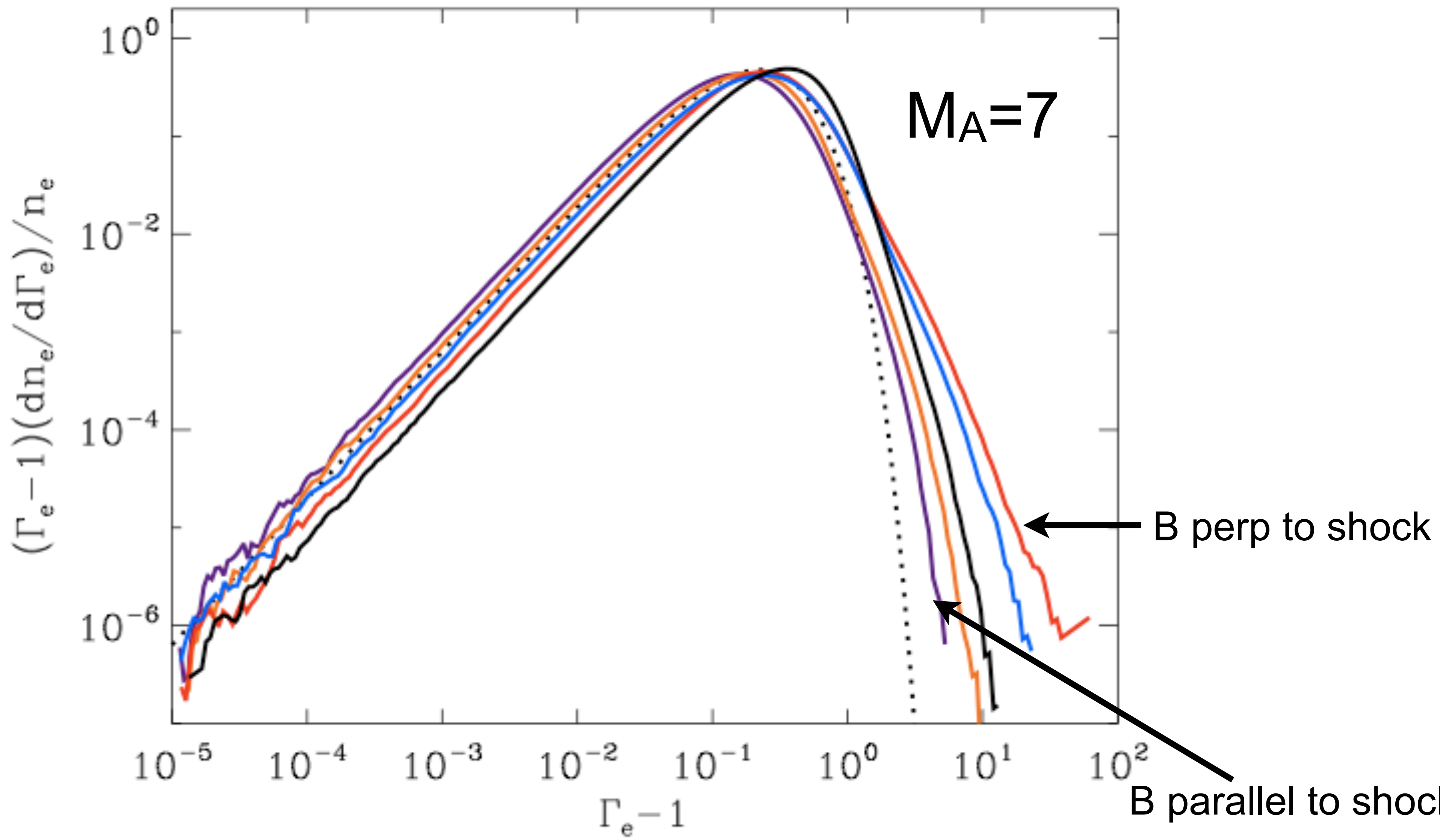


FIG. 7.— The downstream spectrum of the electrons at $t\omega_{p,e} = 10000$ ($t\omega_{c,i} = 10$) is plotted for simulations like run 2D-3 ($M_A = 7$, $v_{sh} = 0.14c$, $\theta_{Bn} = 75°$, and $m_i/m_e = 400$), but using different angle θ_{Bn}. The purple, orange, red, blue, and black lines represent the cases θ_{Bn} = 90 (run 2D-1), 80 (run 2D-2), 70 (run 2D-4), 60 (run 2D-5), and 45 (run 2D-6). For comparison a Maxwellian distribution is shown in black dashed line.

Riquelme & Spitkovski 2010

Take-home messages

- Clusters host microGauss fields that are driven by fluctuation dynamo

- Low-Mach number shocks in clusters have strong, coherent magnetic fields and are efficient at accelerating particles: challenge for theory

- Radio relics are unique probes for microphysics of shock acceleration and magnetic field generation

- LOFAR will revolutionise this field by enlarging the sample from 30 relics to 100s.