Magnetic Fields

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Bonn, 16 April 2008

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Magnetic fields in the universe

• Earth	0.5 G (at surface)
• Jupiter	4 G
• Sun	10 G (poles) 2000 G (spots)
• White Dwarfs	10^6G
• Neutron Stars	10^{12}G
• Galaxy	5 x 10^{-6}G
• Starburst galaxies	50 x 10^{-6}G
• radio galaxies	10^{-6}G
• ICM	10^{-6}G
• IGM	10^{-7}G-10^{-9}G

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Spiral galaxies: thin rotating discs of 10^{10} stars and interstellar gas,
$\langle n \rangle \simeq 1\,\mathrm{cm}^{-3}$, $10^{3} \lesssim n \lesssim 10^{-3}\,\mathrm{cm}^{-3}$, $10 \lesssim T \lesssim 10^{6}\,\mathrm{K}$

M51

NGC 891

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The multi-phase interstellar medium (ISM) in spiral galaxies

Phase	Origin	Density $[\,\mathrm{cm}^{-3}]$	Temperature $[\,\mathrm{K}]$	Size $[\,\mathrm{pc}]$	Fractional volume, %
Molecular clouds	Gravity, thermal instability	10^3	10	10	0.1
Hydrogen clouds	Compression	20	100	100	2
Diffuse warm gas		0.1	10^4	—	60
Hot gas	Supernovae	10^{-3}	10^6	100–1000	38

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Galactic gaseous halos:

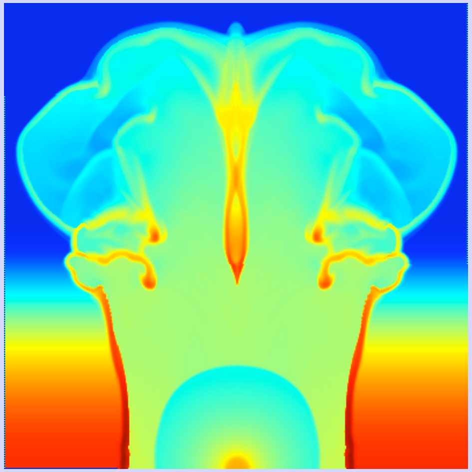
turbulent, rotating, hot, ionized, quasi-spherical gaseous envelopes of galactic discs

Multiple supernovae break through the gas layer
to fill the space above with buoyant hot gas

$$n \simeq 10^{-3}\,\mathrm{cm}^{-3},\ T \simeq 10^{6}\,\mathrm{K},\ c_{\mathrm{s}} \simeq 100\,\mathrm{km\,s}^{-1},\ L \simeq 15\,\mathrm{kpc}$$

Simulation of the superbubble breakout to the halo (M-M. MacLow)

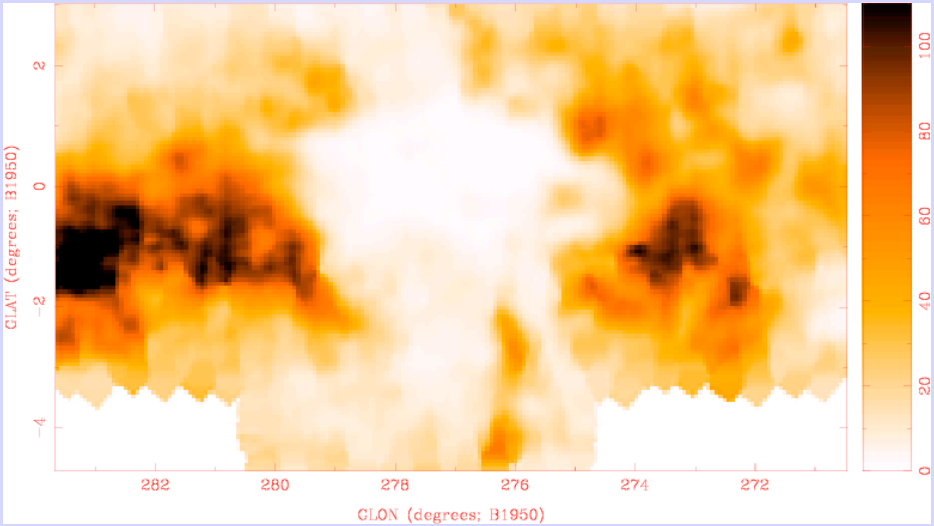
gas density in a vertical cross-section $800\,\mathrm{pc} \times 800\,\mathrm{pc}$



Neutral hydrogen supershell

distance $6.5\,\mathrm{kpc}$, diameter $600\,\mathrm{pc}$,

vertical size $1.1\,\mathrm{kpc}$ (N. M. McLure-Griffits & J. R. Dickey)



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Magnetic fields observed in spiral galaxies $(\vec{H} = \vec{B} + \vec{b}\,,\ \langle \vec{H} \rangle = \vec{B})$

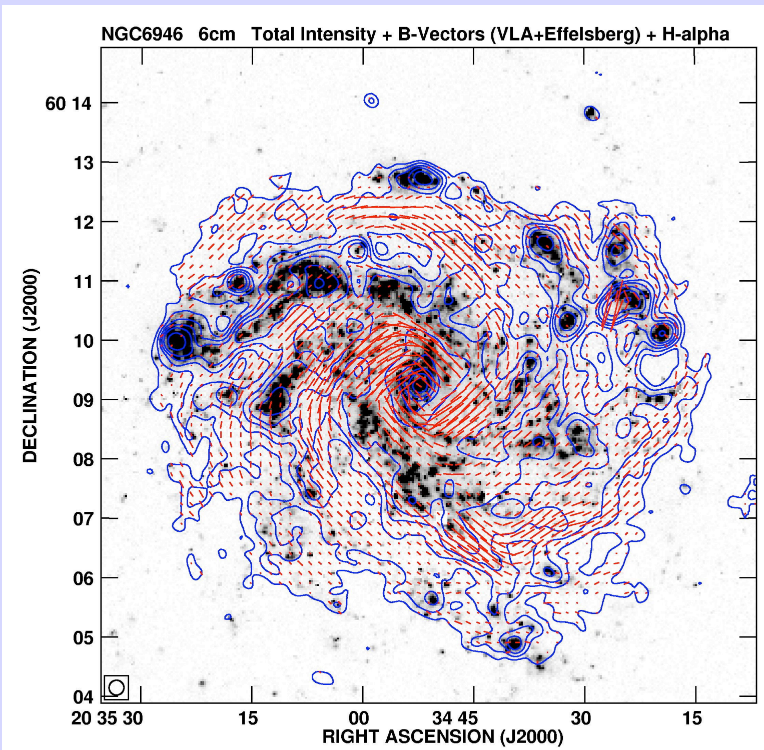
Synchrotron (radio) emission of relativistic electrons, $I \propto \int_0^L n_{\rm rel} H_\perp^2\, ds$.

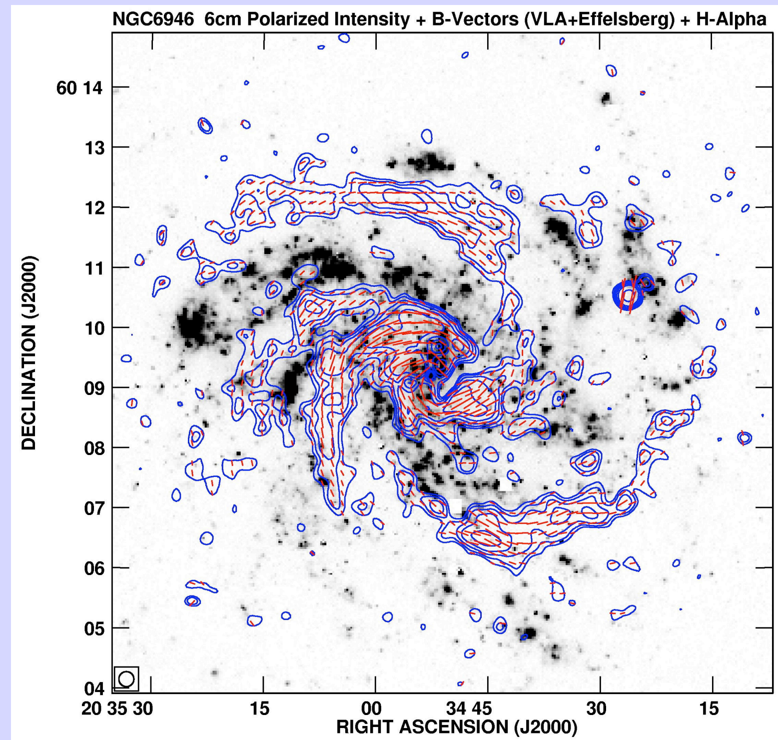
Large-scale magnetic field B:

traced by the polarized emission, $P \propto \int_0^L n_{\rm rel} B_\perp^2\, ds$,

and Faraday rotation in thermal gas, $\mathrm{RM} = K \int_0^L n_{\rm e} \vec{B} \cdot d\vec{s}$

Turbulent magnetic field b: traced by the unpolarized emission, $I - P$





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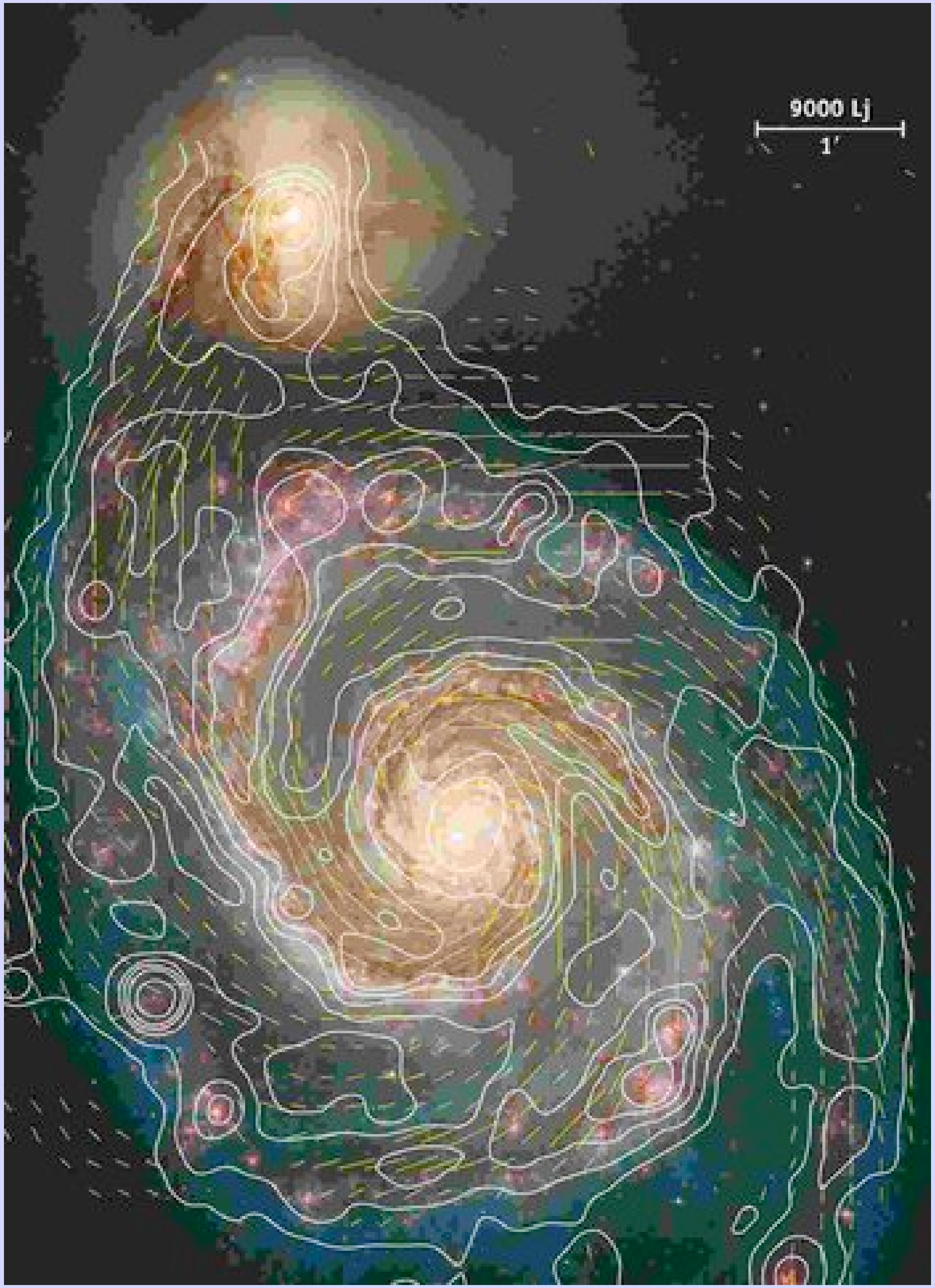
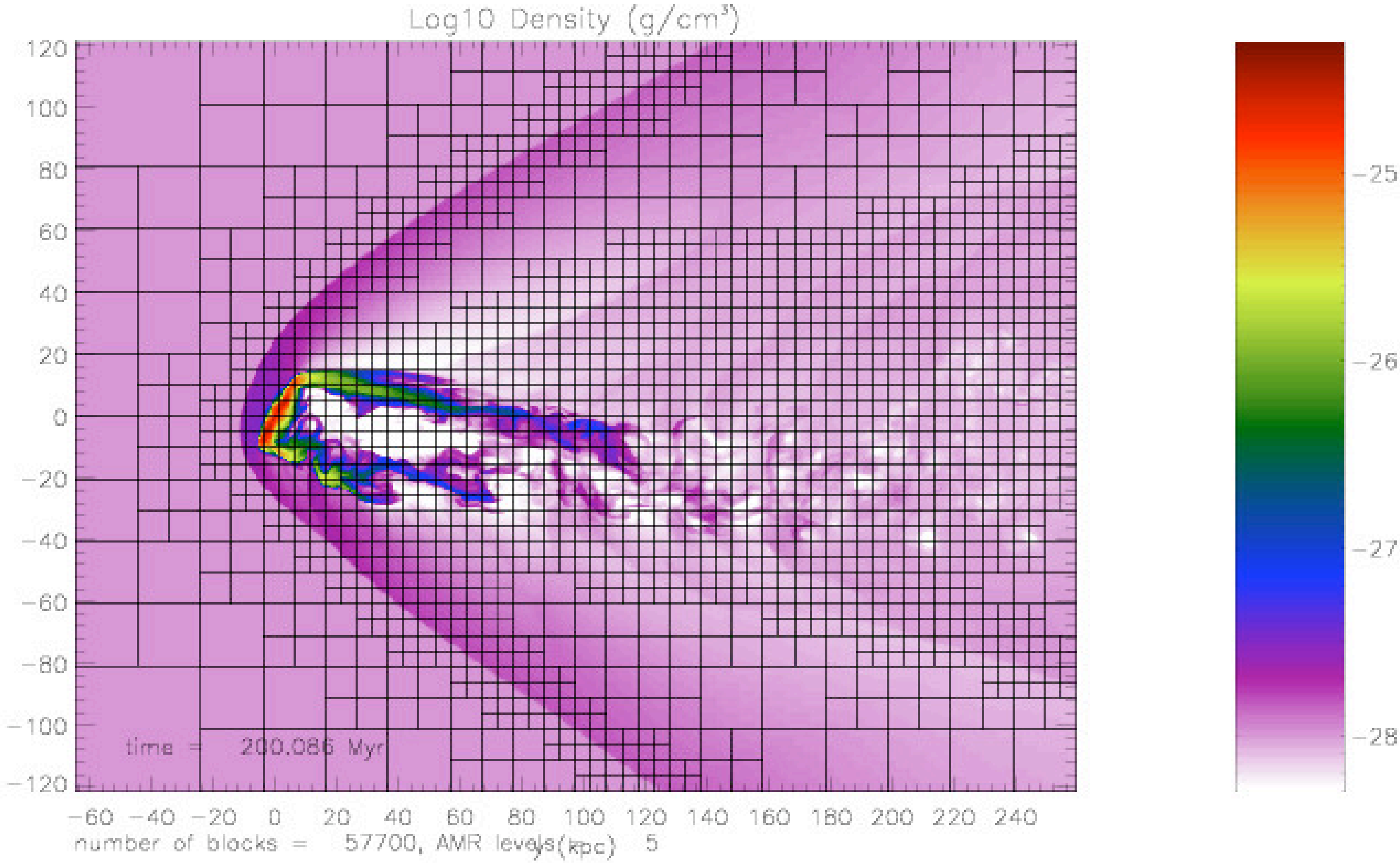
HST image of the spiral galaxy M 51 obtained, overlaid by contours of the total radio intensity and polarization vectors at 6 cm wavelength, combined from radio observations with the Effelsberg and VLA radio telescopes. The magnetic field follows well the optical spiral structure, but the regions between the spiral arms also contain strong and ordered fields.



Fletcher and Beck

Ram-pressure stripping of galaxies



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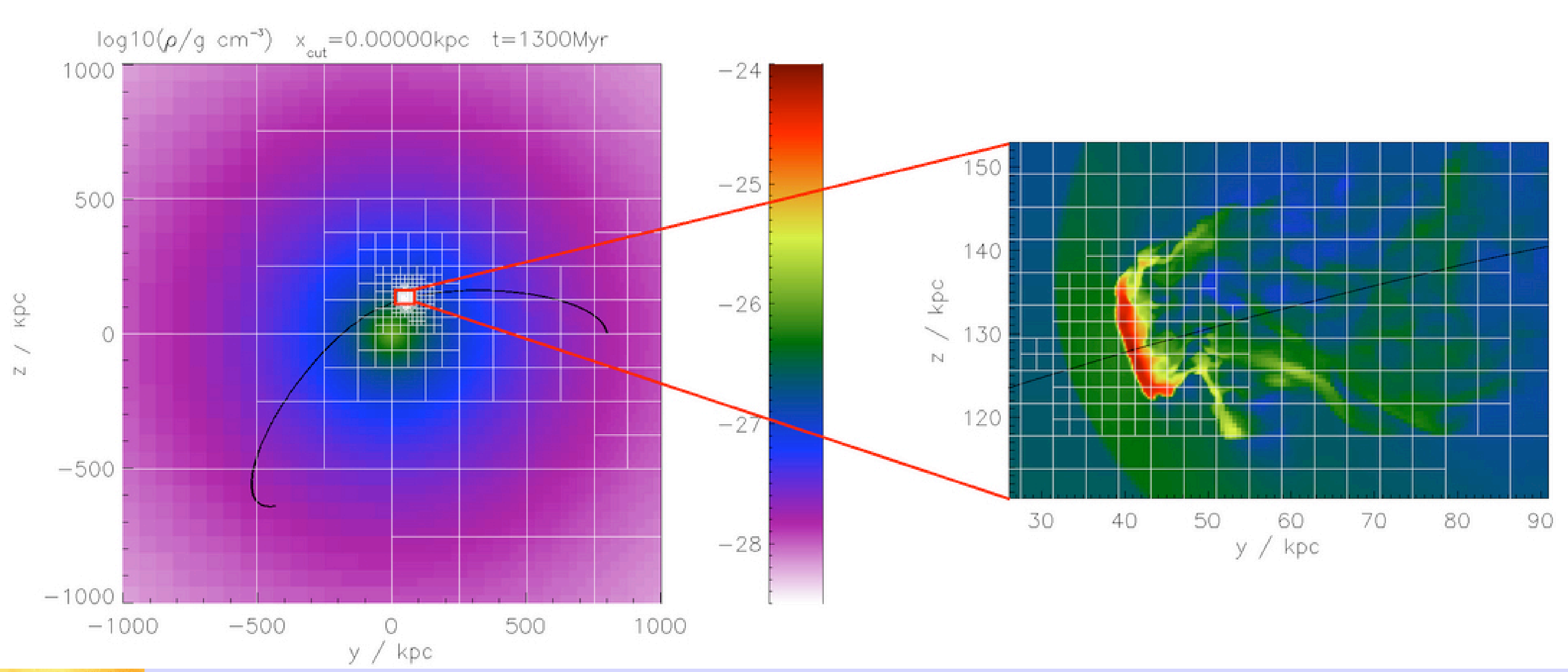
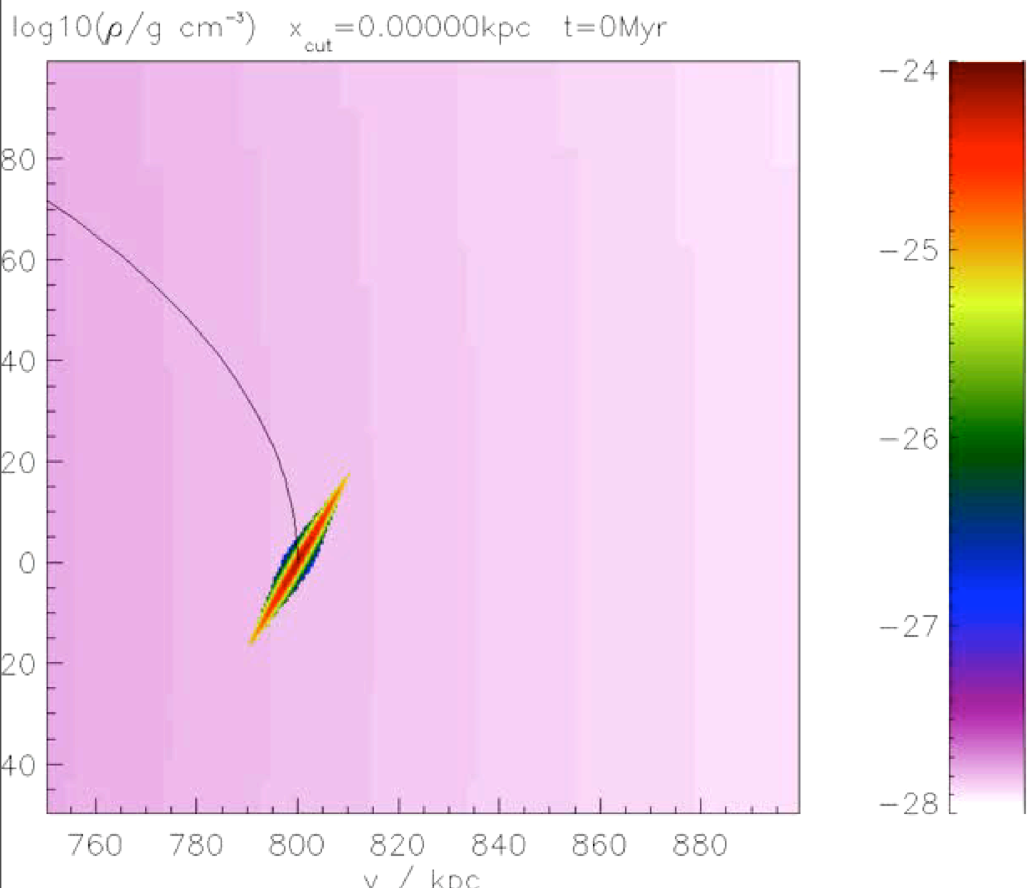
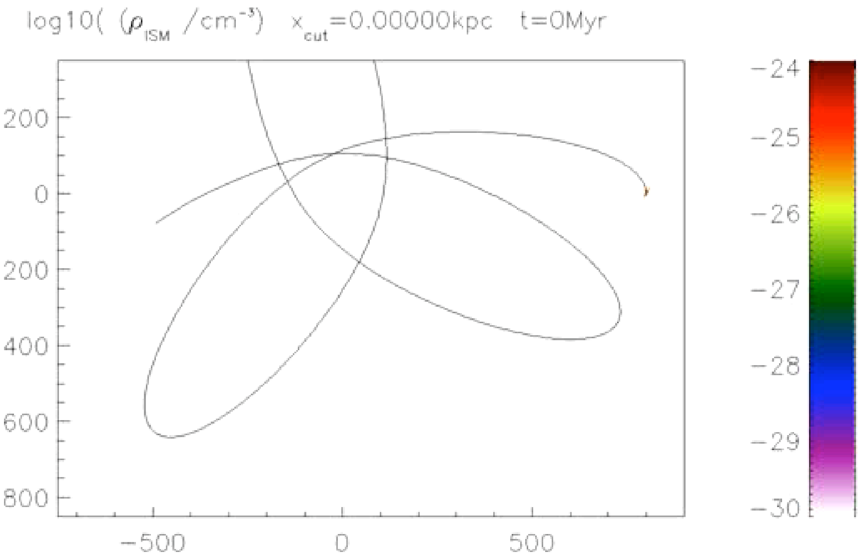
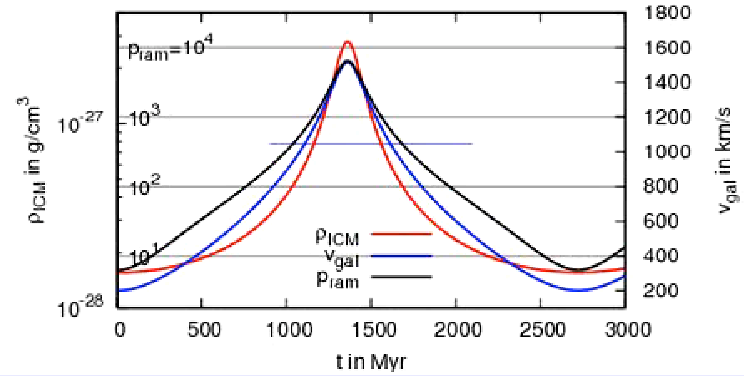


Roediger & Brüggen (2007)







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Clusters of Galaxies

- largest gravitationally bound structures
- contain 100-1000 galaxies
- contain hot (T around 10^8K), dilute (n Around $10^{-3}cm^{-3}$) Gas
- heated by accretion shocks
- most of baryonic matter is in this gas called ICM
- ICM emits thermal Bremsstrahlung in X-rays
- $L_X = 10^{43}$-10^{45} erg s^{-1}
- hierarchical structure formation: clusters form by mergers of smaller systems
- cool core clusters / non-cool core clusters
- absence of cooling flows
- Feedback

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Magnetic fields derived from inverse Compton

- If synchrotron and IC X-ray emission are produced by same population of relativistic electrons

$$L_{\mathrm{IC}} \propto u_{\mathrm{CMB}} \sim 5 \times 10^{-13}(1+z)^4 \mathrm{erg\,cm}^{-3}$$

$$L_{\mathrm{syn}} \propto u_{\mathrm{B}} = B^2/8\pi$$

$$\frac{L_{\mathrm{syn}}}{L_{\mathrm{IC}}} \propto \frac{u_{\mathrm{B}}}{u_{\mathrm{CMB}}}$$

- problems of this method:

  limitations of observations in hard X-ray

  Difficulty in distinguishing thermal and non-thermal X-rays

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Magnetic fields derived from inverse compton

- HXR non-thermal emission has been detected in coma and a2256. Other detections, e.g. in A2199 and A119 are controversial
- Magnetic field estimates yield 0.1 mu G.
- IC estimates of magnetic fields are consistently lower than faraday estimates

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Faraday Rotation Effect

- RH and LH circularly polarised waves propagate with different phase velocities within magneto-ionic material
- Polarisation angle will be rotated by amount

$$\Delta\Psi = \frac{e^3\lambda^2}{2\pi m_e^2 c^4}\int_0^L n_e(l)B_p(l)dl$$

$$\Delta\Psi = \lambda^2 \mathrm{RM}$$

- in practical units

$$\mathrm{RM}\,(\mathrm{rad/m^2}) = 812\int_0^L n_e(\mathrm{cm^{-3}})B_p(\mu\mathrm{G})dl(\mathrm{kpc})$$

- RM is + for a magnetic field directed toward the observer

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Interpretation of cluster RM

- existence of small-scale magnetic field structures produce rotation of polarisation angle and depolarisation
- Faraday rotation by tangled magnetic field
- assume it is made of uniform cells of size l_c

$$< \mathrm{RM} >= 0$$

$$\sigma_{\mathrm{RM}}^2 = 812^2 l_c \int (n_e B_p)^2 dl$$

$$n_e^2(r) = n_0 (1 + r^2/r_c^2)^{-3\beta/2}$$

$$\sigma_{\mathrm{RM}}(r_{\mathrm{perp}}) = \frac{K B n_0 r_c^{1/2} l_c^{1/2}}{(1 + r_{\mathrm{perp}}^2/r_c^2)^{(6\beta-1)/4}} \sqrt{\frac{\Gamma(3\beta - 0.5)}{\Gamma(3\beta)}}$$

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Rotation Measures

- RM from extragalactic radio sources:

  intrinsic

  Galaxy

  ICM

- RM of galactic origin 10 rad m^{-2} - 300 rad m^{-2} at low galactic magnitudes
- High-res RM studies of cyg a first showed high RM values with large gradients of arcsec scales
- Kim et al. (1991) used 106 radio sources in Coma clusters and deduced magnetic field of 10^{-6} G
- Clarke et al. (2001) find 4 - 8 muG

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Observations:

- cluster cores can host fields as high as 10 muG
- e.g. Hydra A and 3C295
- field in cool cores higher than in non-cool cores
- correlation lengths around 10 kpc
- spectral indices 1.6 – 2.0
- field in filaments around 10^{-7} G

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Question:

What produces large-scale magnetic fields in clusters and filaments?

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Possible answers:

1. Amplification of primordial seed fields by gravitational
   collapse of structures

Q: How big does the seed field have to be if this is the dominant mechanism?

Q: Where does seed field come from?

Pop III stars?
First AGN?
Shocks?
Batteries?

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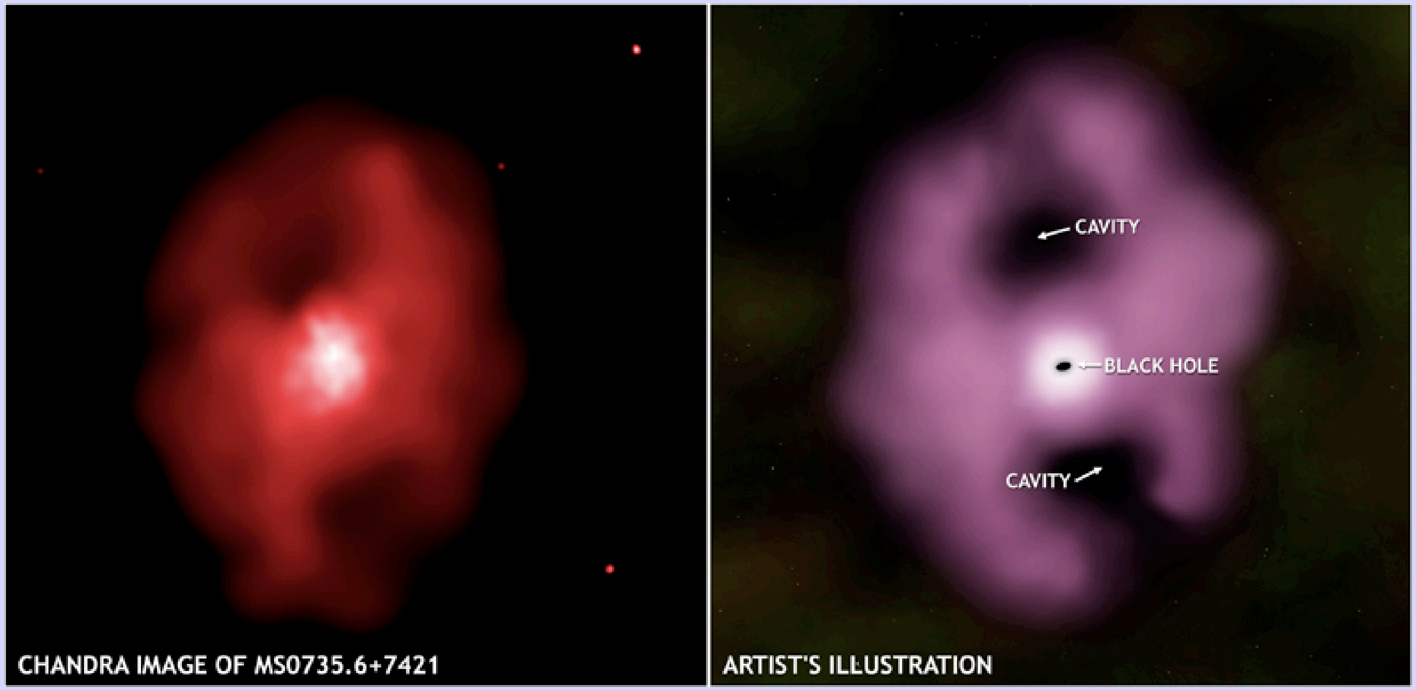
2. Injection of magnetic fields by stars and AGN etc.

Q: How does the magnetic field diffuse out into IGM?



Filaments

Magnetic field in filaments should be less polluted by outflows from AGN.

-> Better probe for gravitational amplification

Hydrodynamical models: up to half of baryonic matter should have $10^5 < T < 10^7$ K:

Warm-Hot Intergalactic Medium

WHIM difficult to observe

Can we observe diffuse synchrotron emission from filaments?

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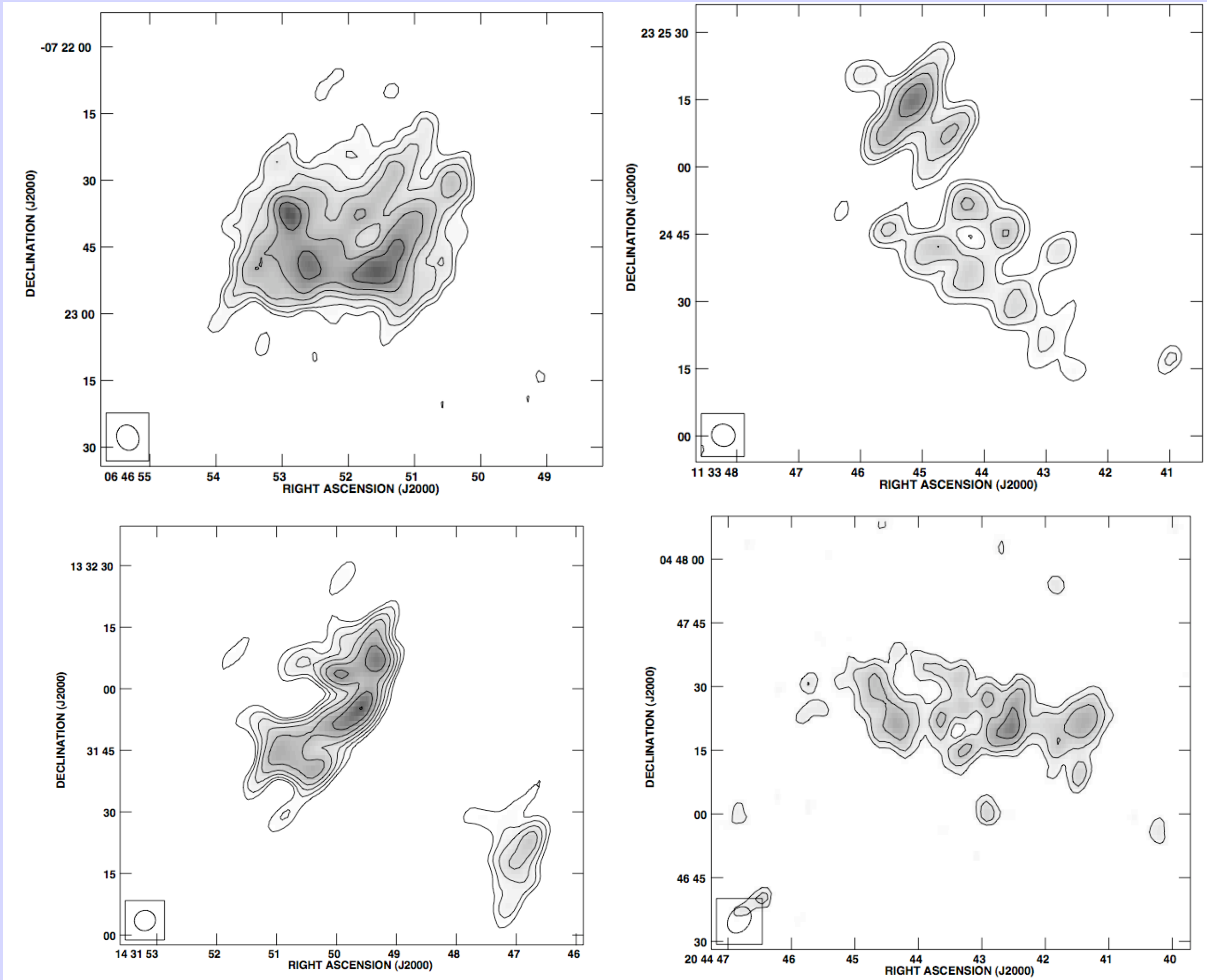

Fig. 2: Contour images at 610 MHz from the Giant Metrewave Radio Telescope (GMRT) of proposed filaments: VLSS J0646.8-0722 (*top left*), VLSS J1133.7+2324 (*top right*), VLSS J1431.8+1331 (*bottom left*), and VLSS J2044.7+0447 (*bottom right*). The Gaussian beam size (~ 6 arcsec FWHM) is shown at the bottom left corner for each image. Contour levels are drawn at $\sqrt{[1, 2, 4, 6, 8, 16, 32]} \times 1.0$ mJy beam^{-1}.

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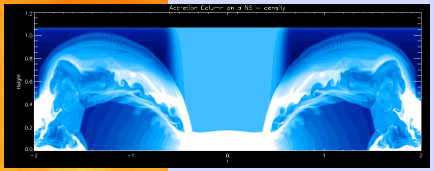
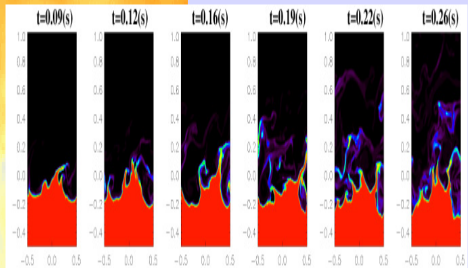
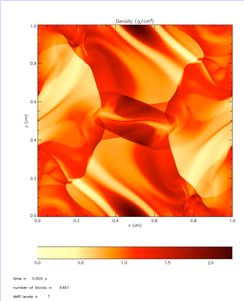
FLASH simulations...



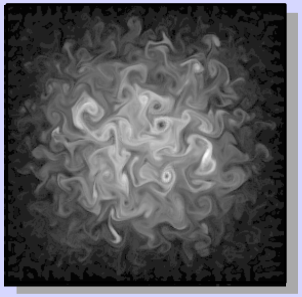
Shortly: Relativistic accretion onto NS



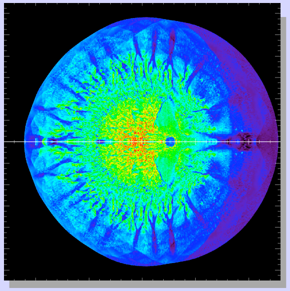
Wave breaking on white dwarfs



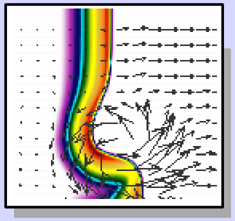
Orzag/Tang MHD vortex



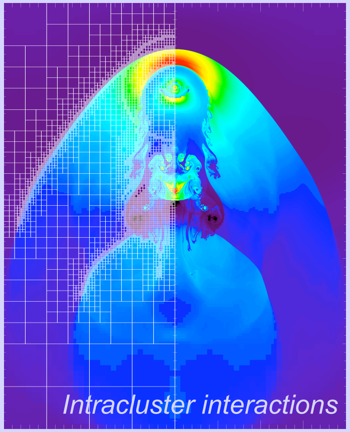
Compressed turbulence



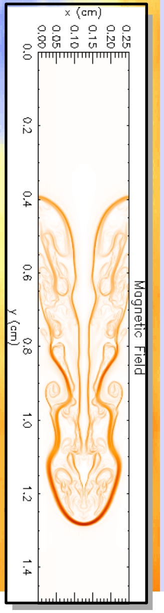
Type Ia Supernova



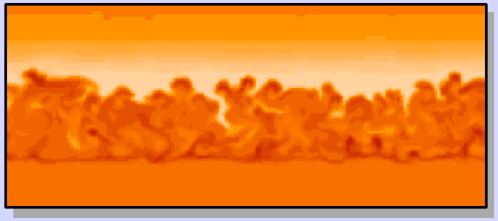
Flame-vortex interactions



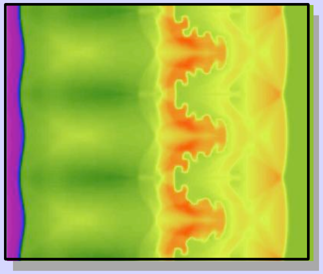
Intracluster interactions



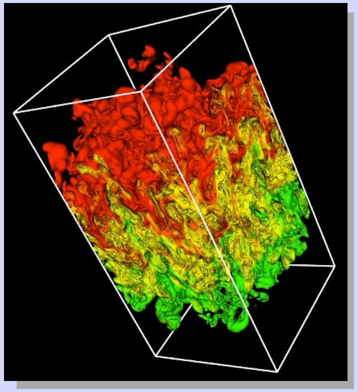
Magnetic Rayleigh-Taylor



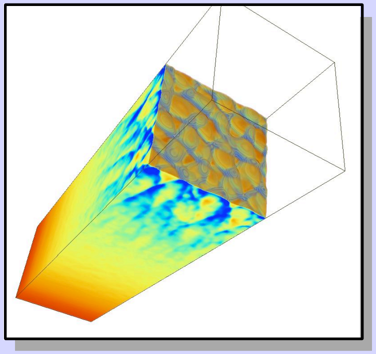
Nova outbursts on white dwarfs



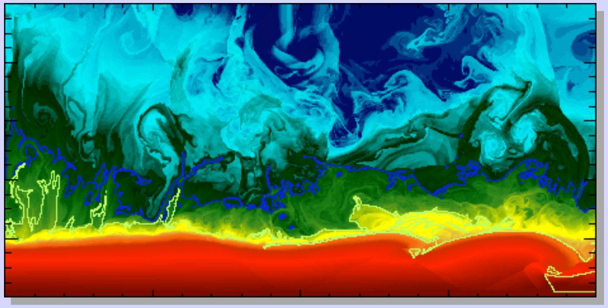
Laser-driven shock instabilities



Rayleigh-Taylor instability



Cellular detonation



Helium burning on neutron stars

Richtmyer-Meshkov instability

Some simulation specs

3D FLASH AMR simulations: 10 levels of refinement: 8192^3 effective zones

Box size =64 /h Mpc, gas + 2 million collisionless particles

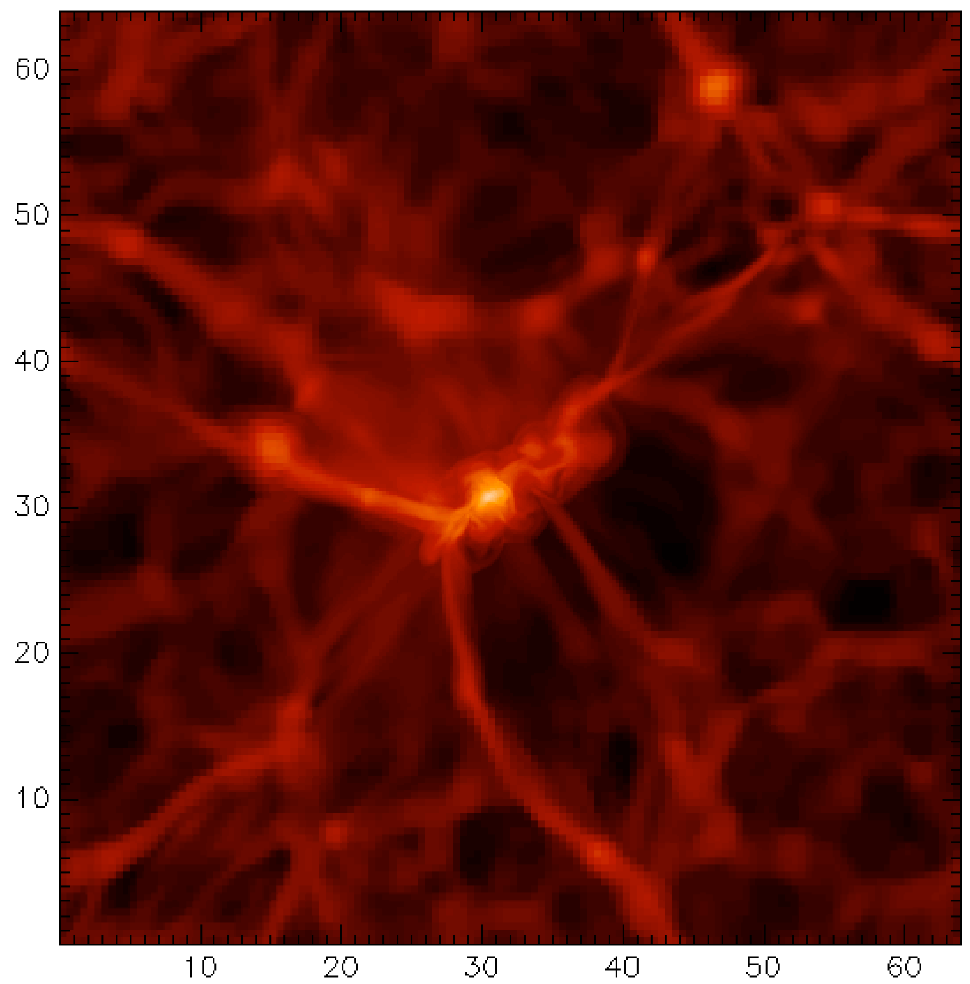
Effective resolution 7.8 /h kpc

Initial conditions: Santa Barbara cluster
(3 sigma in density smoothed over 10 Mpc at redshift z=50)

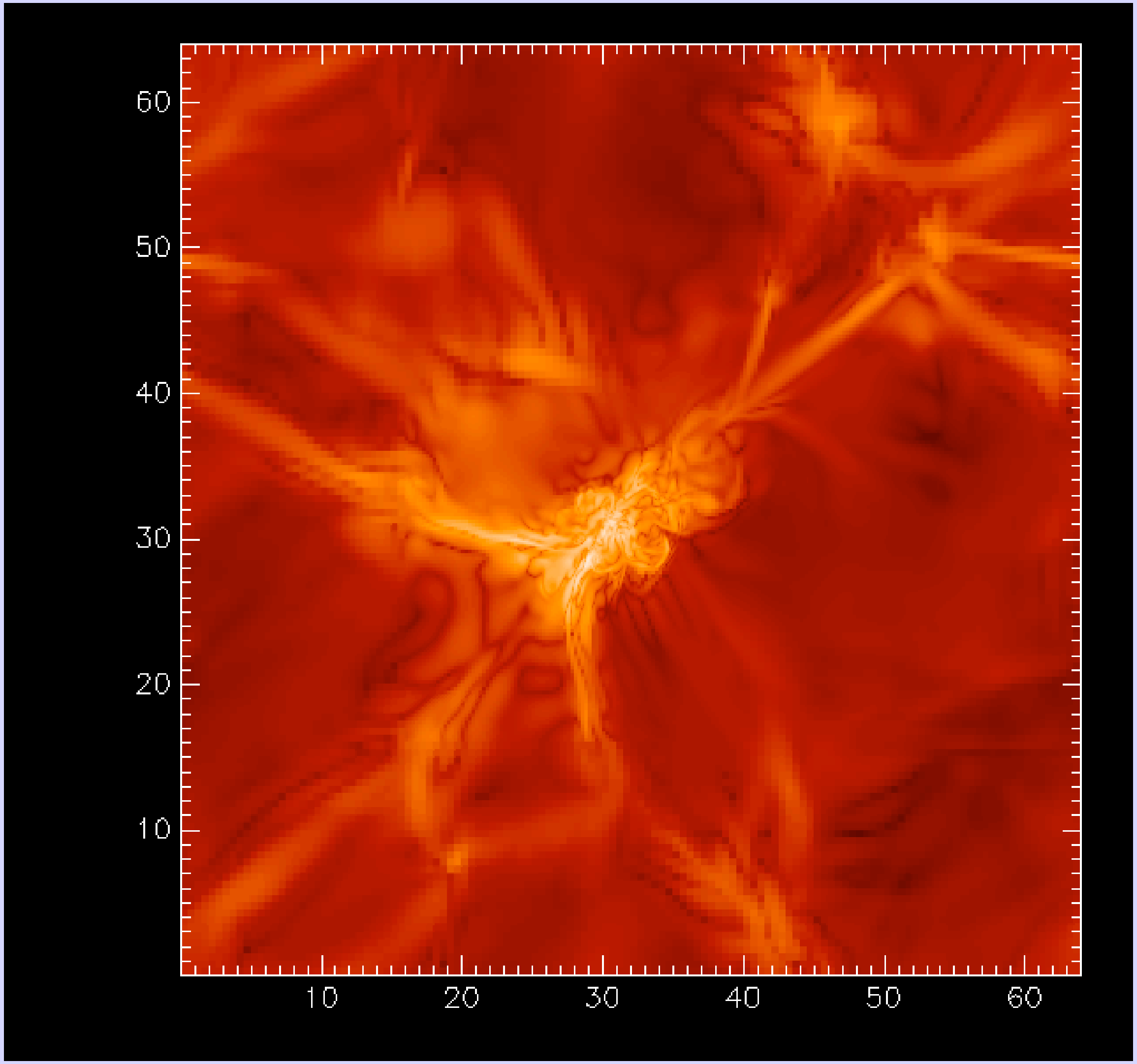
Vector field: 512 Fourier modes from random distribution

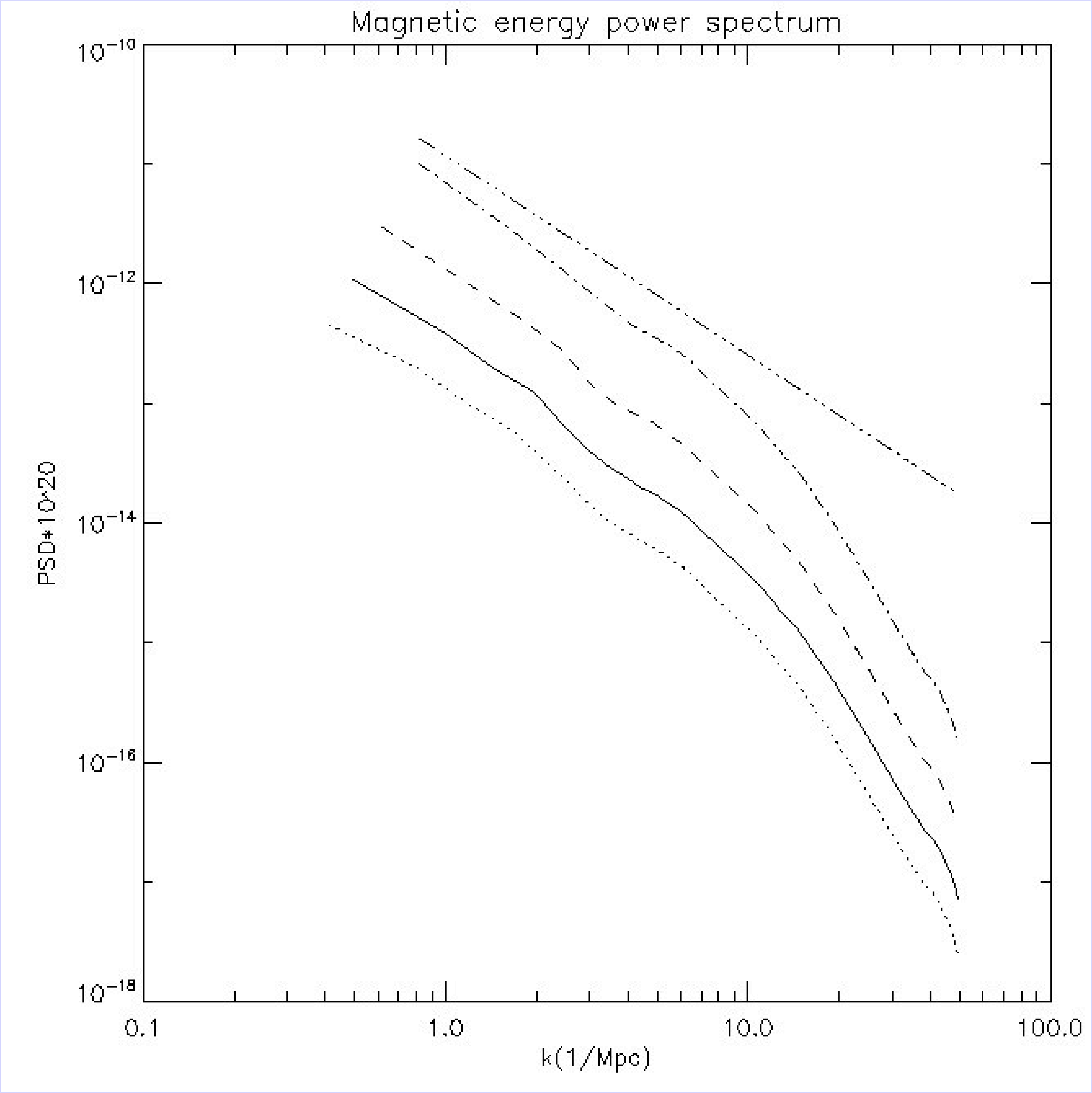
Passive magnetic field solver on staggered mesh

Log Density in slice



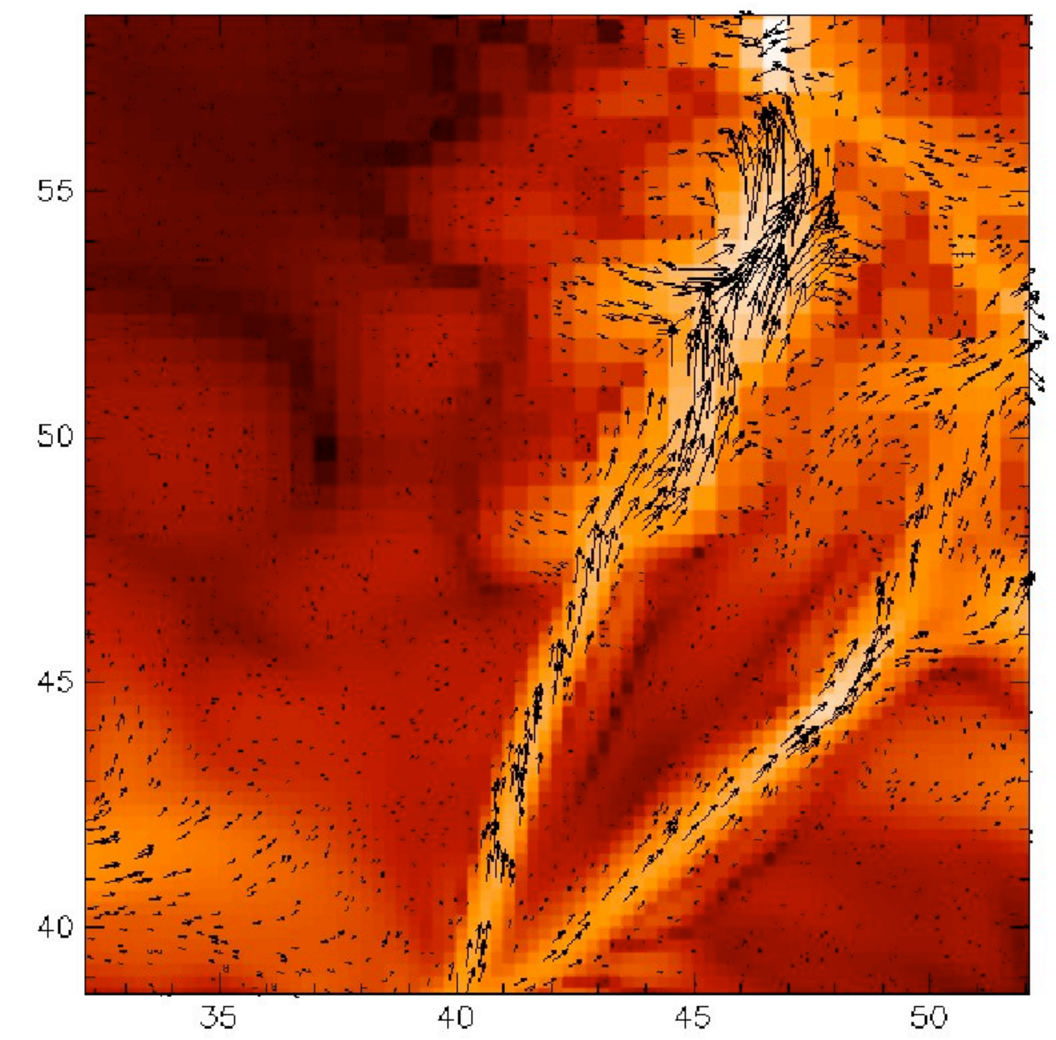
Log B^2 in slice





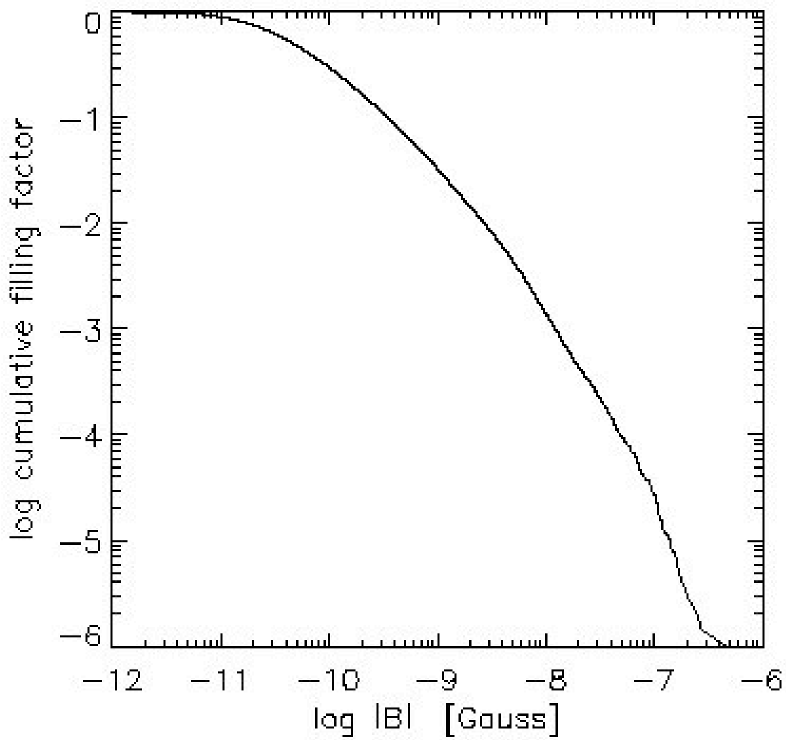
Magnetic energy power spectrum
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
PSD*10^20
0.1
1.0
10.0
100.0
k(1/Mpc)

Zoom into filament



Diffusion length much greater along filaments

Filaments are efficient traps for cosmic rays



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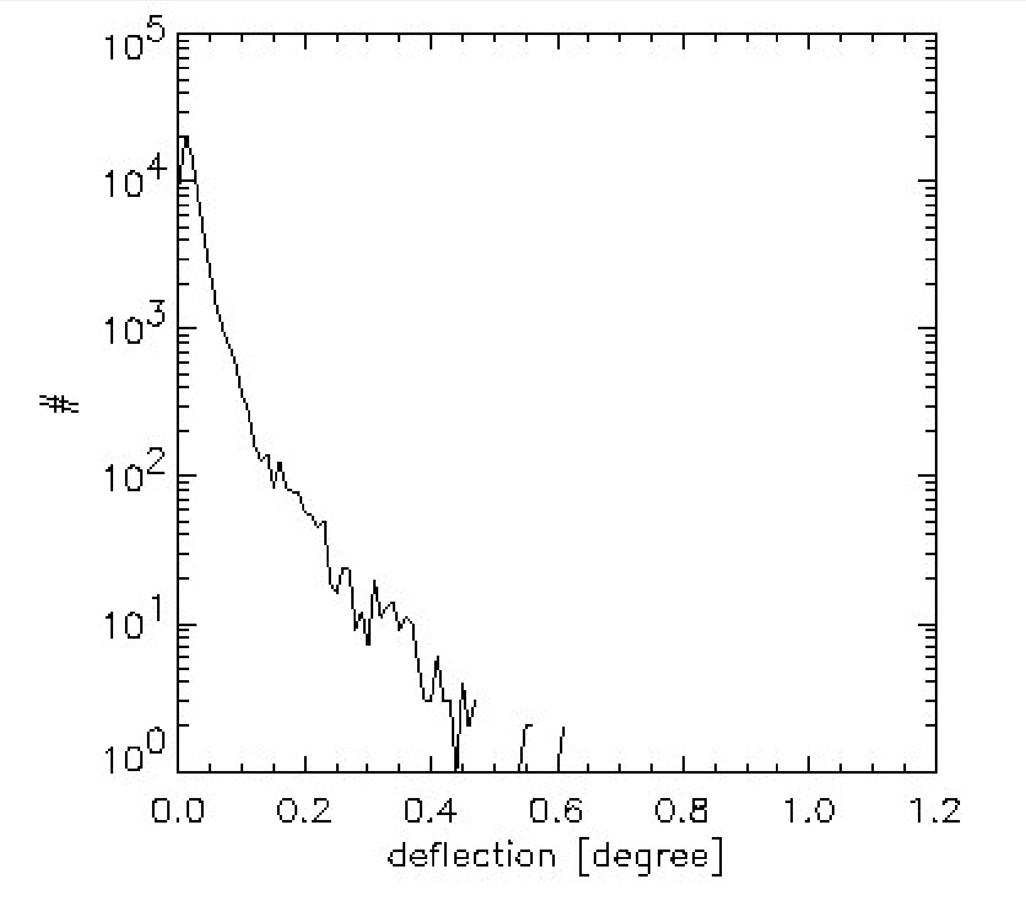
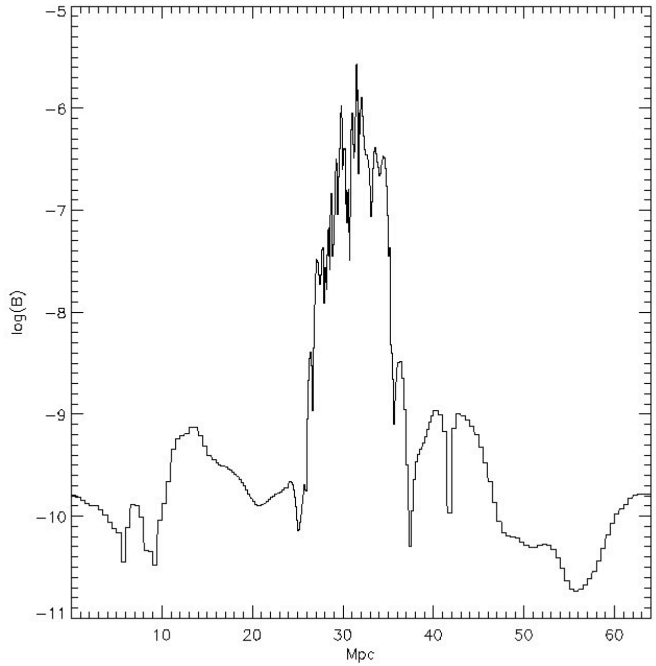
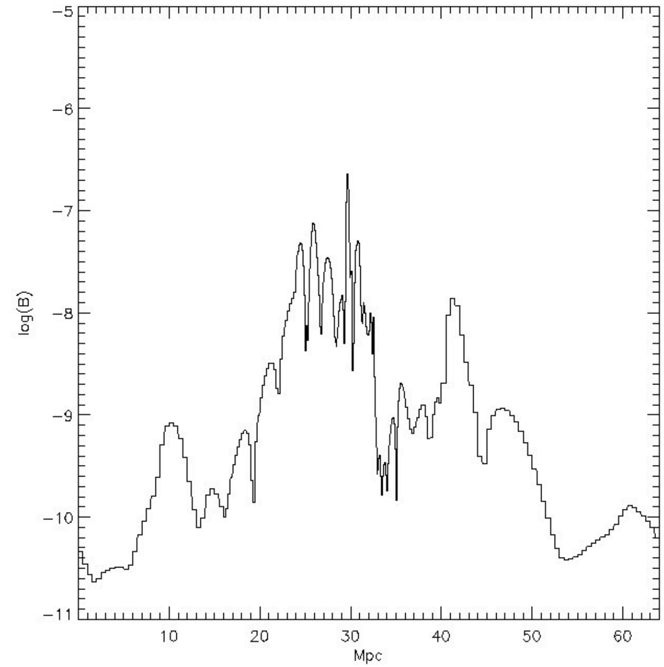
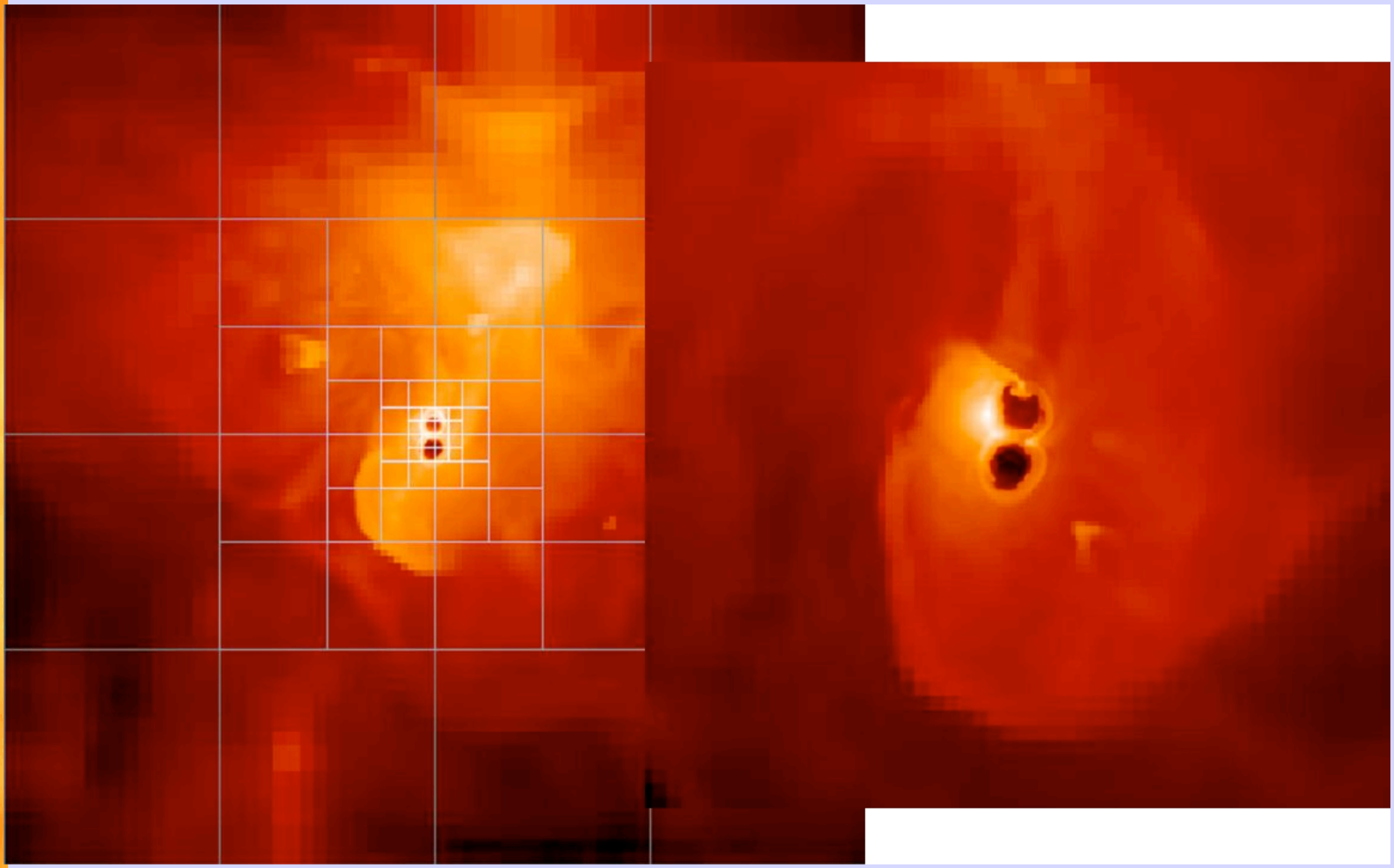


10^5
10^4
10^3
10^2
10^1
10^0
#
0.0
0.2
0.4
0.6
0.8
1.0
1.2
deflection [degree]


log(B)
Mpc
−5
−6
−7
−8
−9
−10
−11
10
20
30
40
50
60


log(B)
Mpc
−5
−6
−7
−8
−9
−10
−11
10
20
30
40
50
60

Fe line signature of bubbles



Conclusions

- in clusters fields are amplified by factor of 7000

between z=50 and z=0

- in filaments amplification factor is 10-300
- magnetic field is parallel to filaments
- seed field of around nG would be required at z=50
- in cluster power spectrum has index of 5/3
- 1% of volume is filled with field > 1nG

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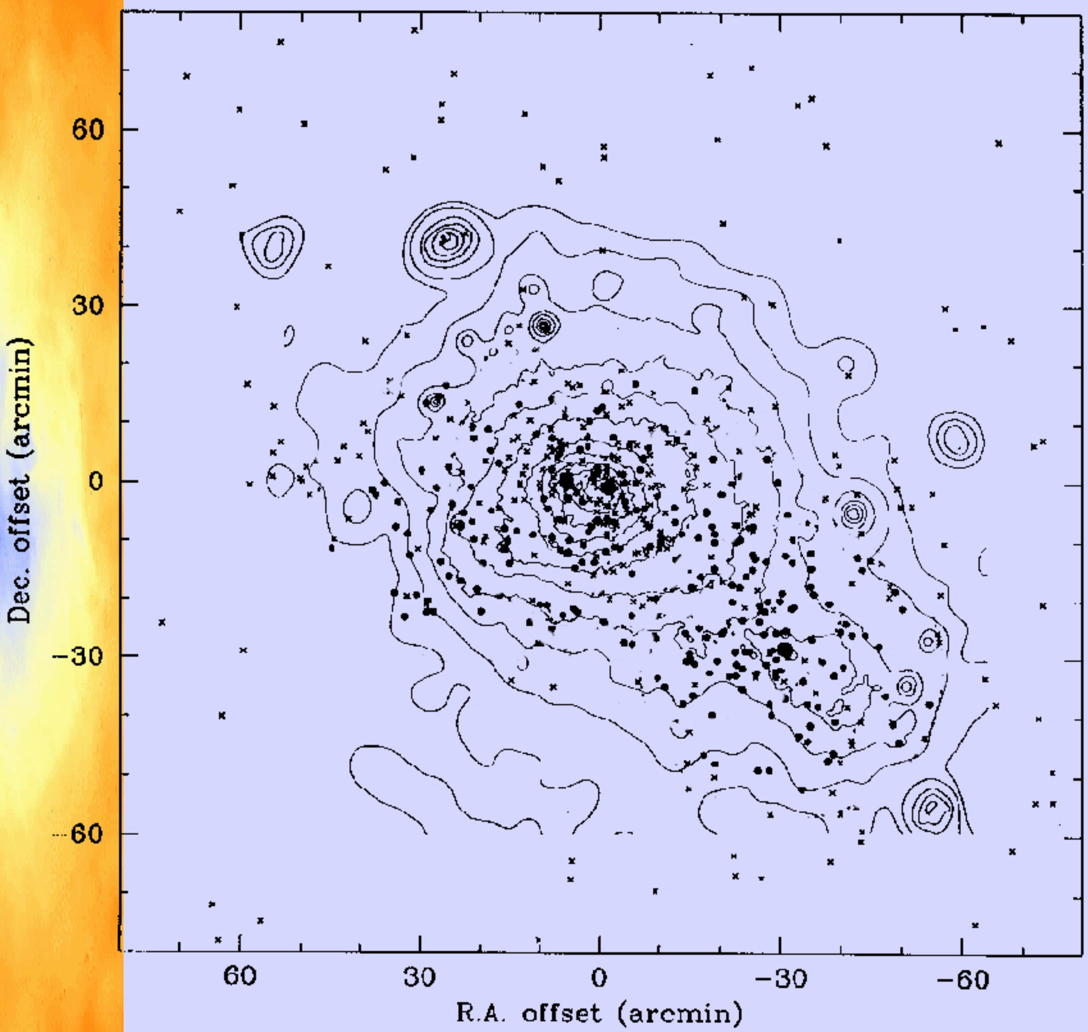
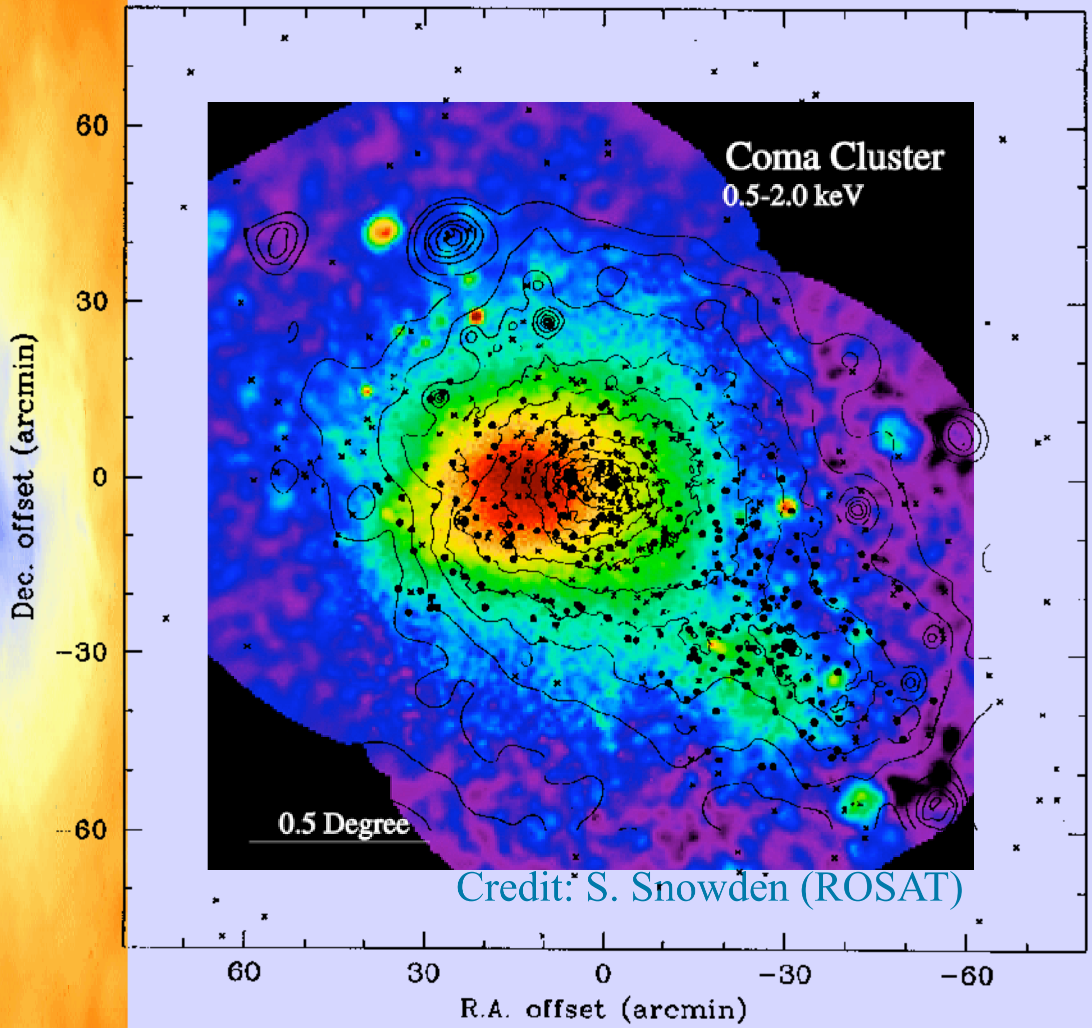
Galaxy cluster in optical, X-ray and radio



[Colless & Dunn 96]

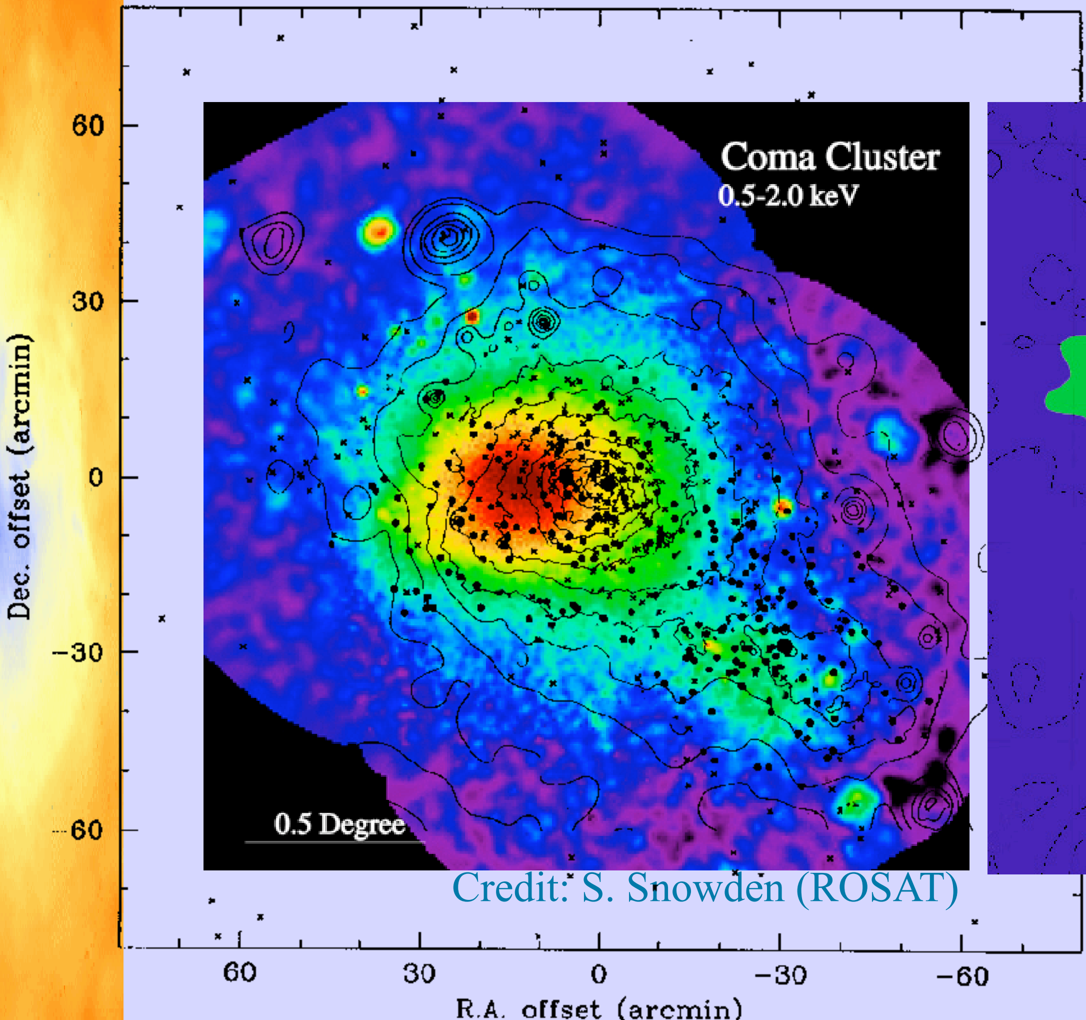
Galaxy cluster in optical, X-ray and radio



Credit: S. Snowden (ROSAT)

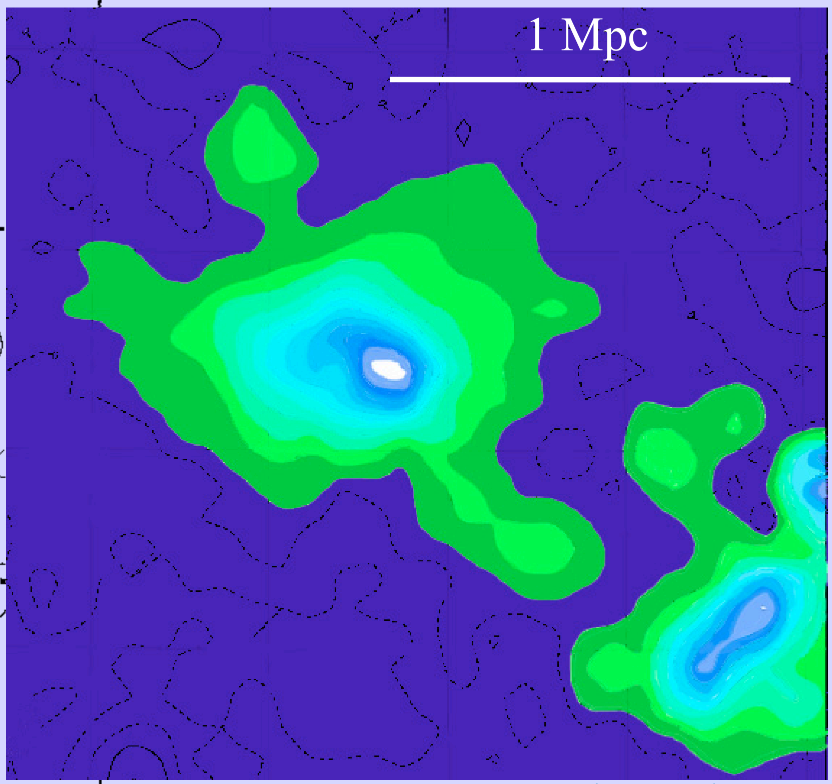
[Colless & Dunn 96]

Galaxy cluster in optical, X-ray and radio



Credit: S. Snowden (ROSAT)

[Colless & Dunn 96]



[Deiss et al. 96]

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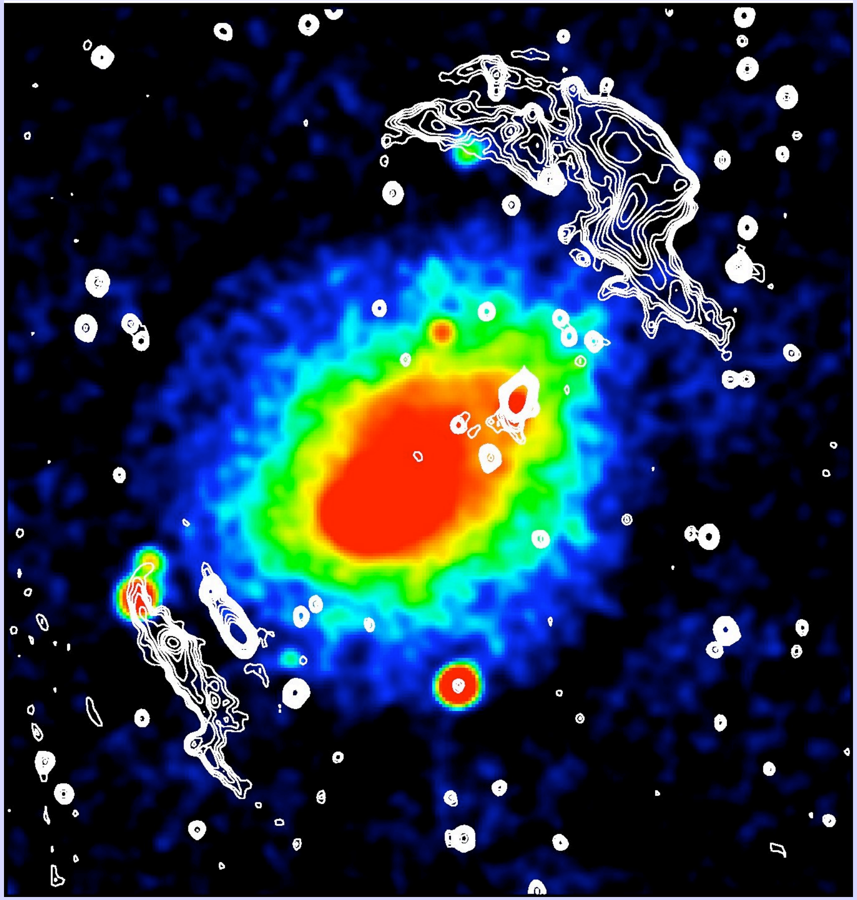
The radio zoo: double relic

Color: X-ray
Contours: Radio

Abell 3667

[Roettgering 97]



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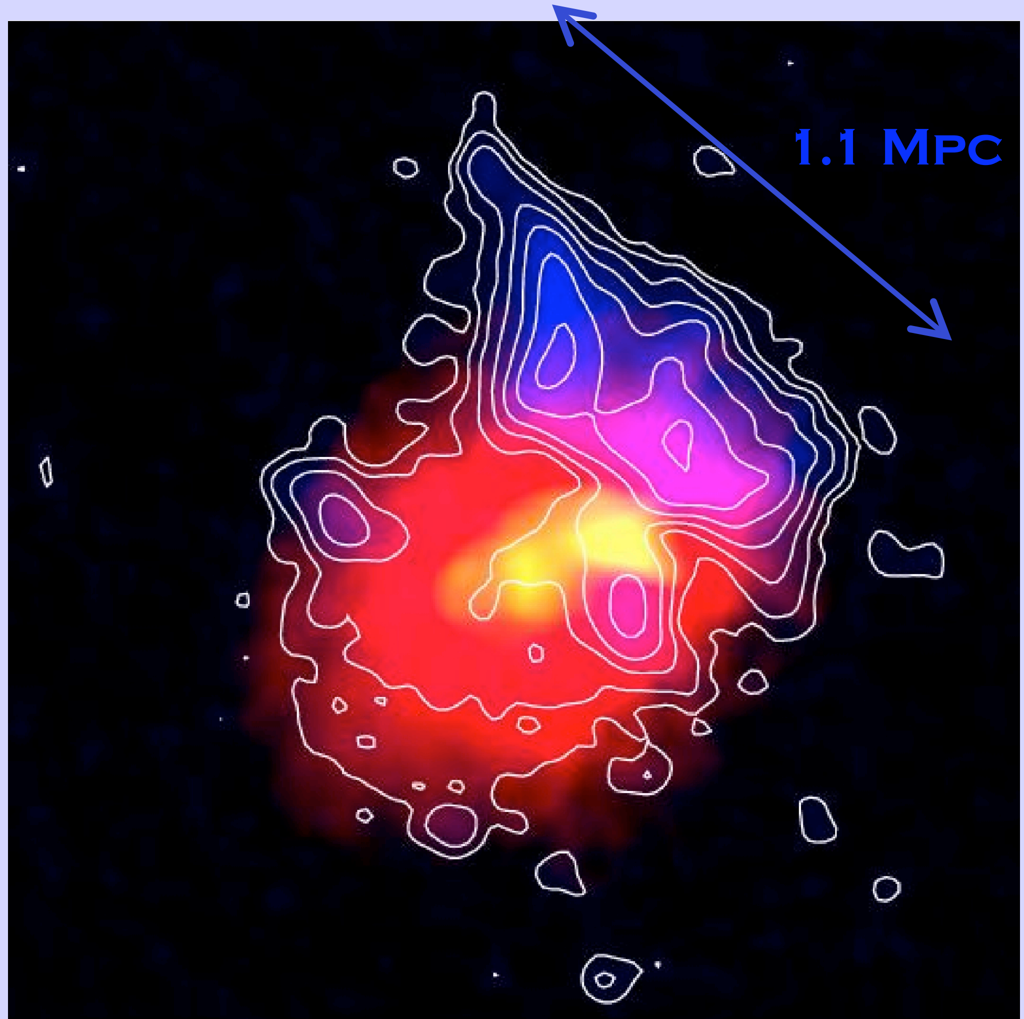
Small halo and large relic

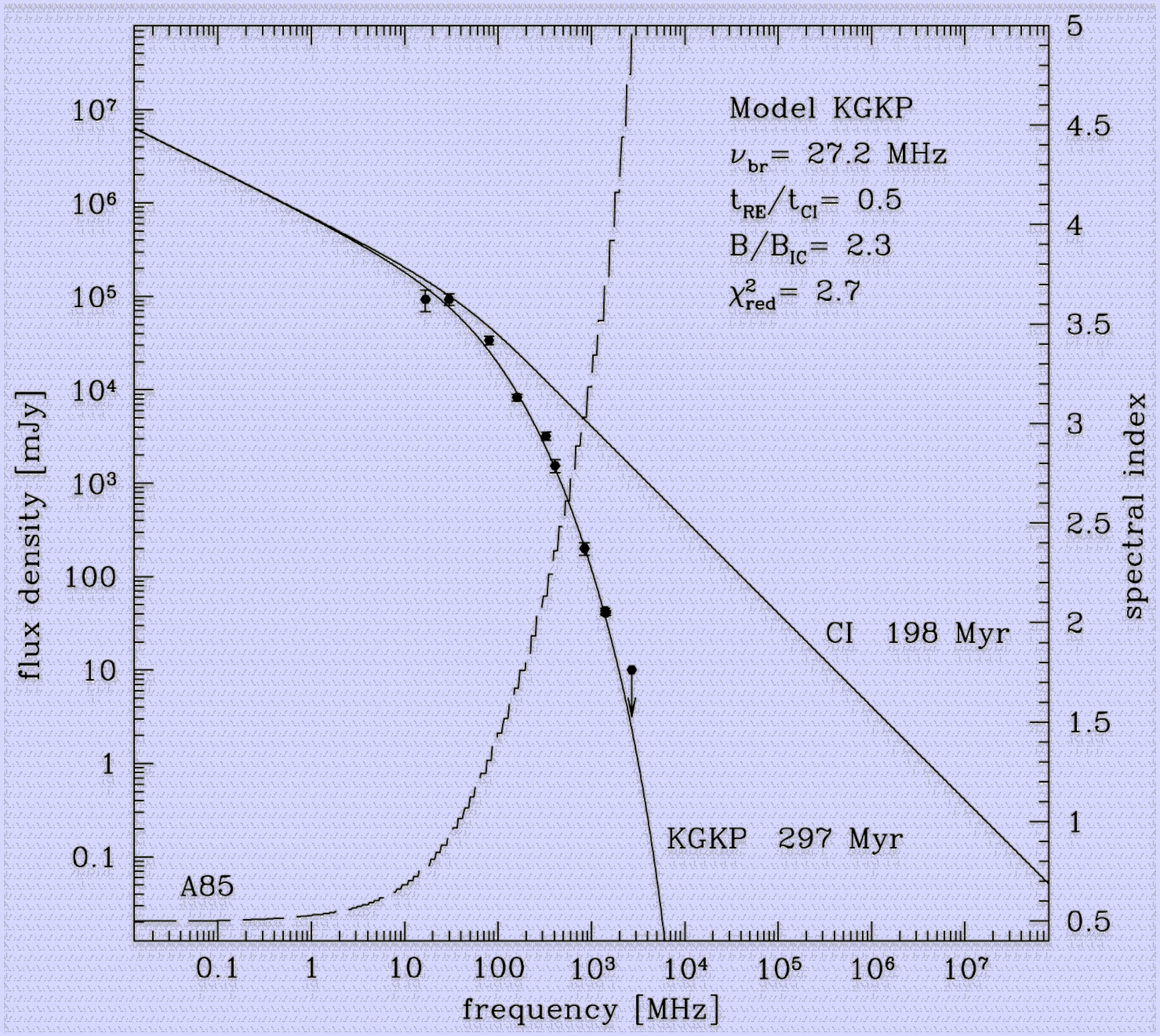


Red: X-ray
Blue: Radio

Abell 2256

[Clarke 06]

Relic spectrum



Abell 85

[Slee01]

	LLS [kpc]	D [Mpc]	Merger ?
A 85	150	0.6	subcl.
A 115	2500	1.3	boxy
A 725	440	0.3	boxy
A 786	1400	5.0	two cen.
A 1240	900	1.4	boxy
A 1664	1100	1.8	subcl.
A 2061	900	2.1	two cen.
A 2256	1450	0.7	two cen.

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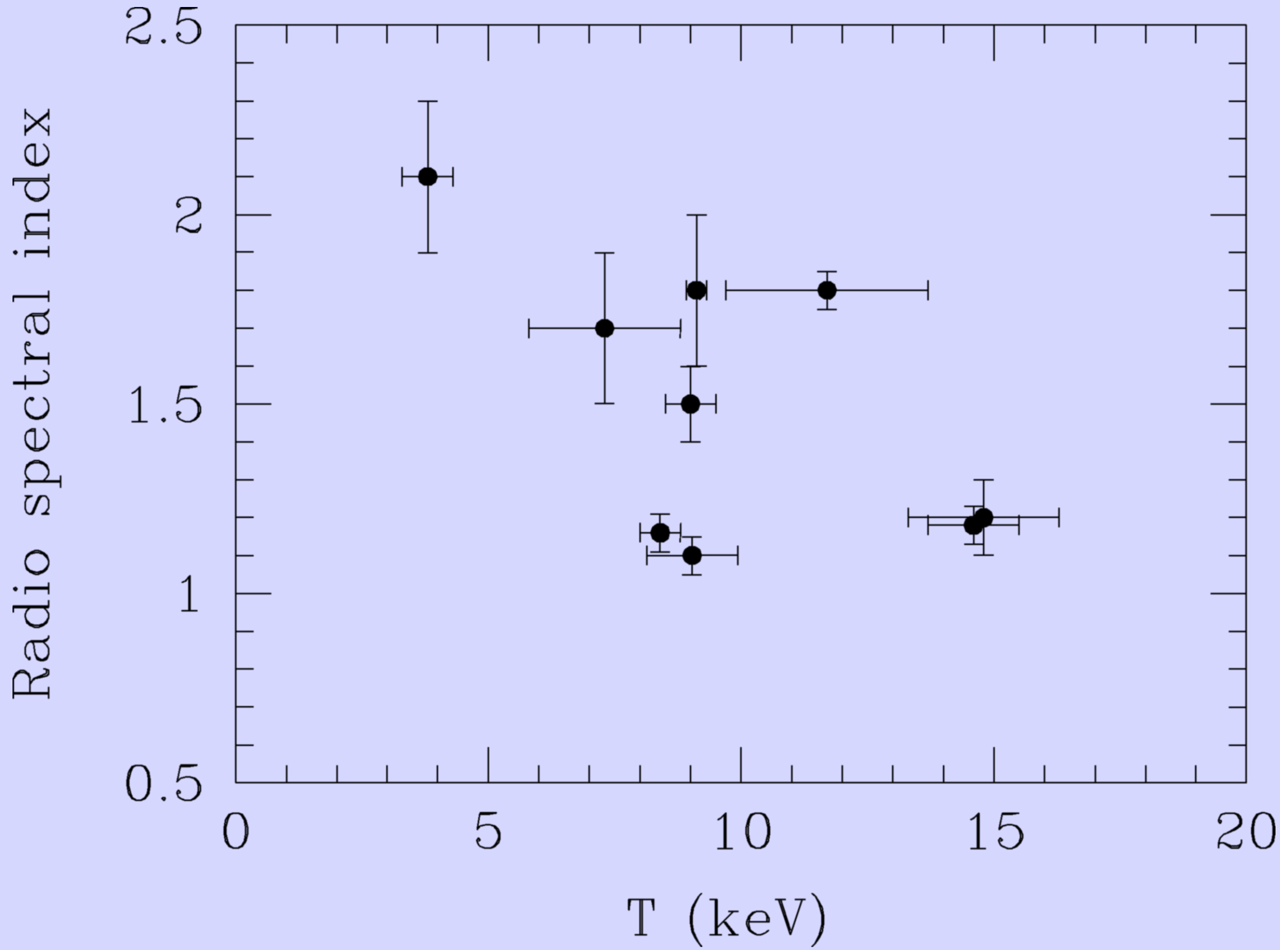
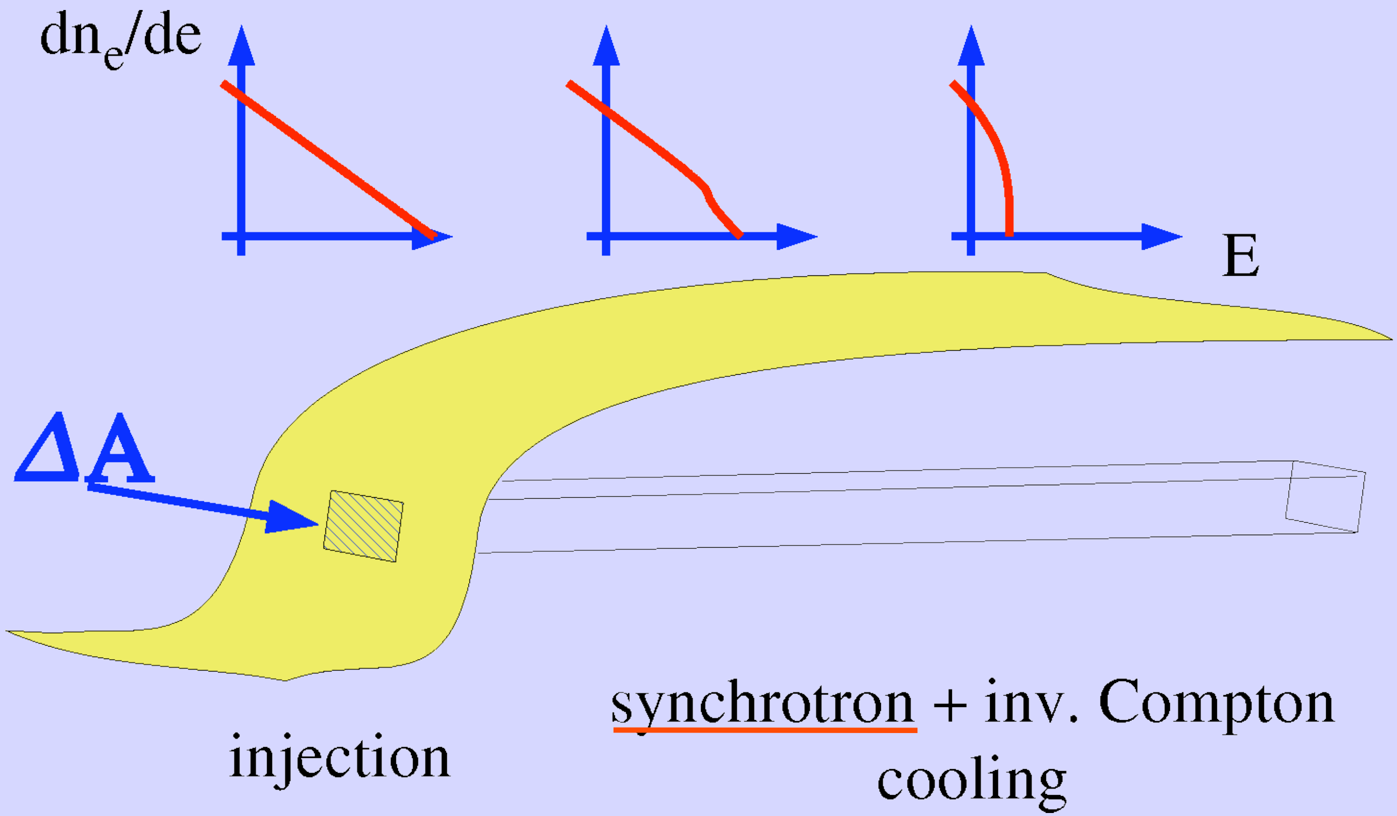
Spectral indices of radio halos

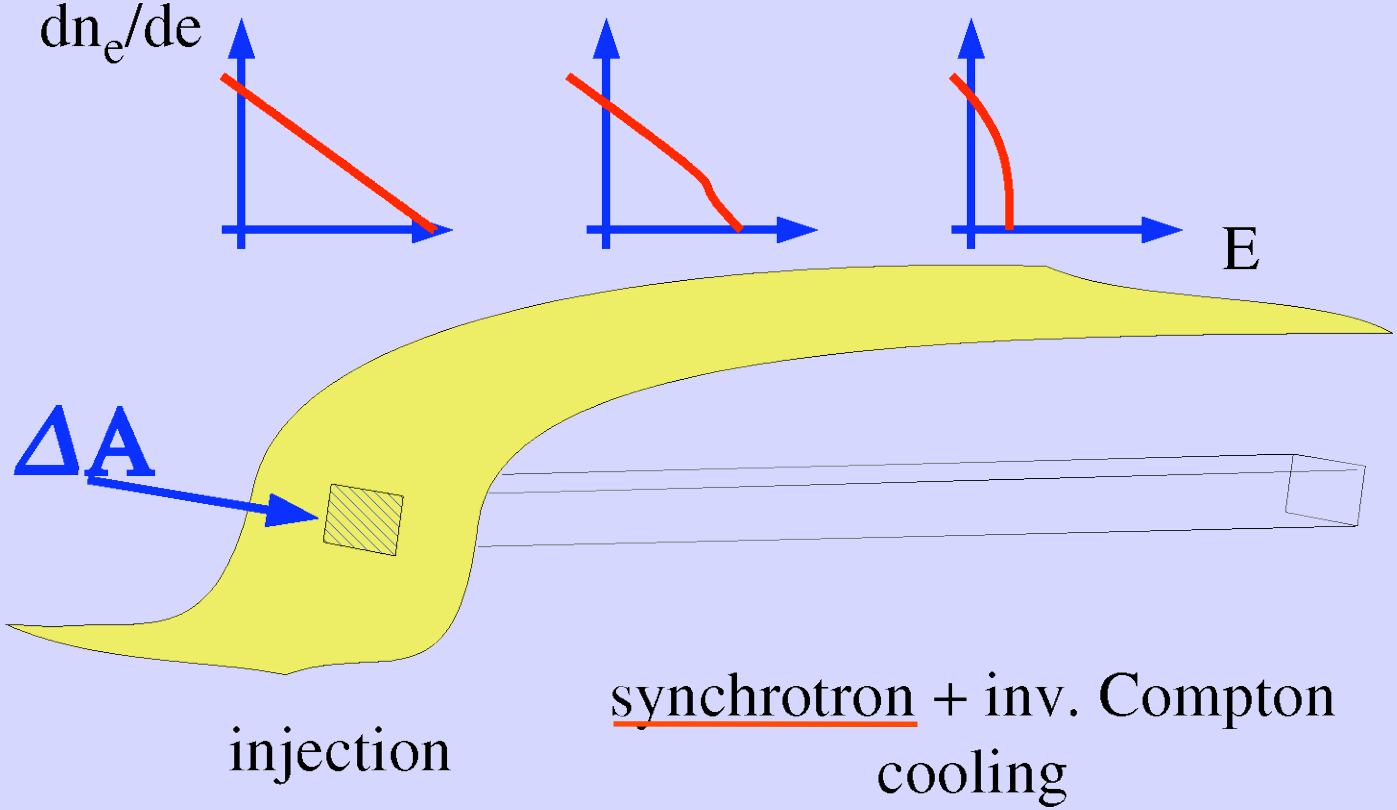


[Feretti 04]

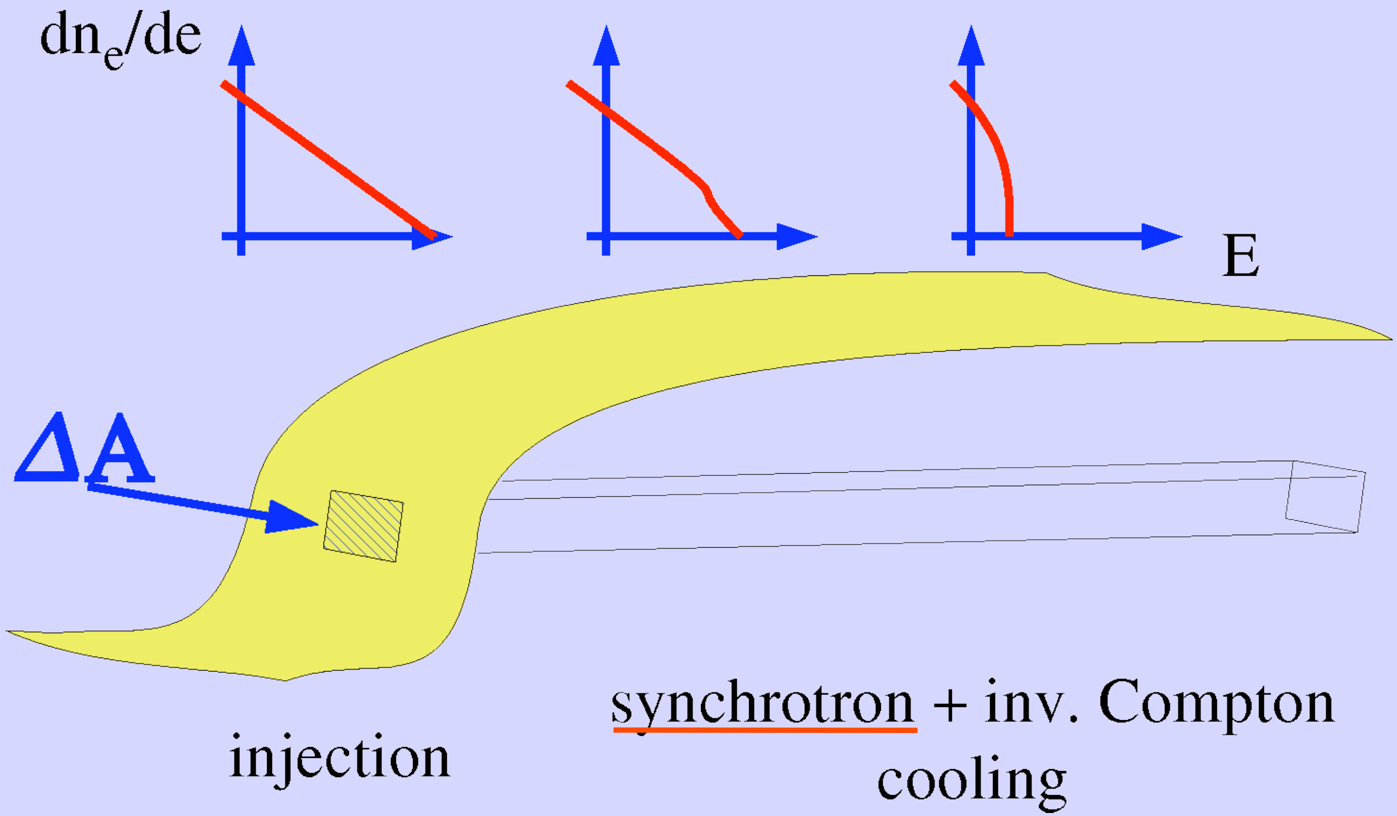


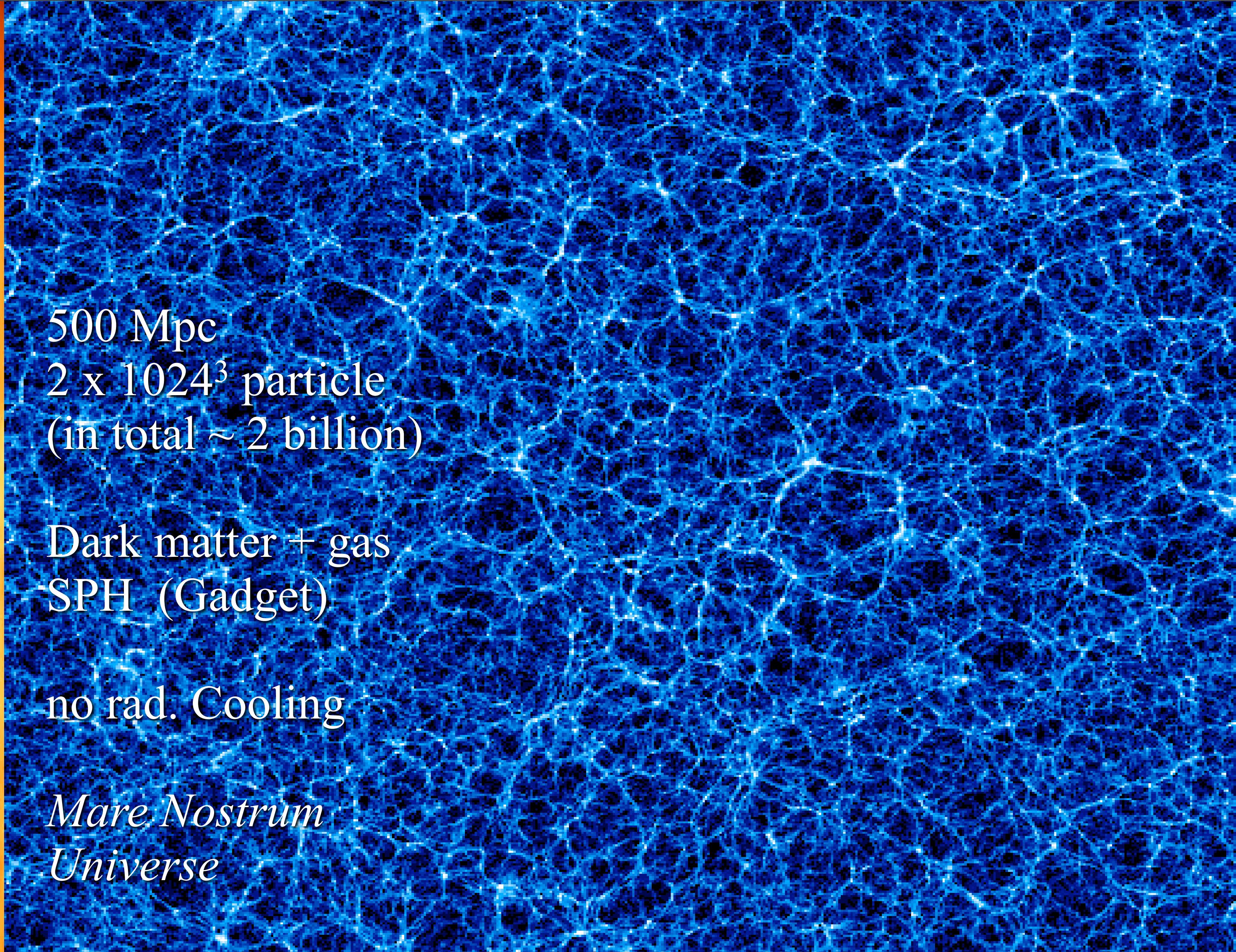
dn$_e$/de
E
ΔA
injection
synchrotron + inv. Compton
cooling

$<u_{high}> = \xi_{elec}\, u_{th,\, inj}$



$$\langle u_{high} \rangle = \xi_{elec}\, u_{th,\, inj} \qquad u_B = \xi_B\, u_{th}$$





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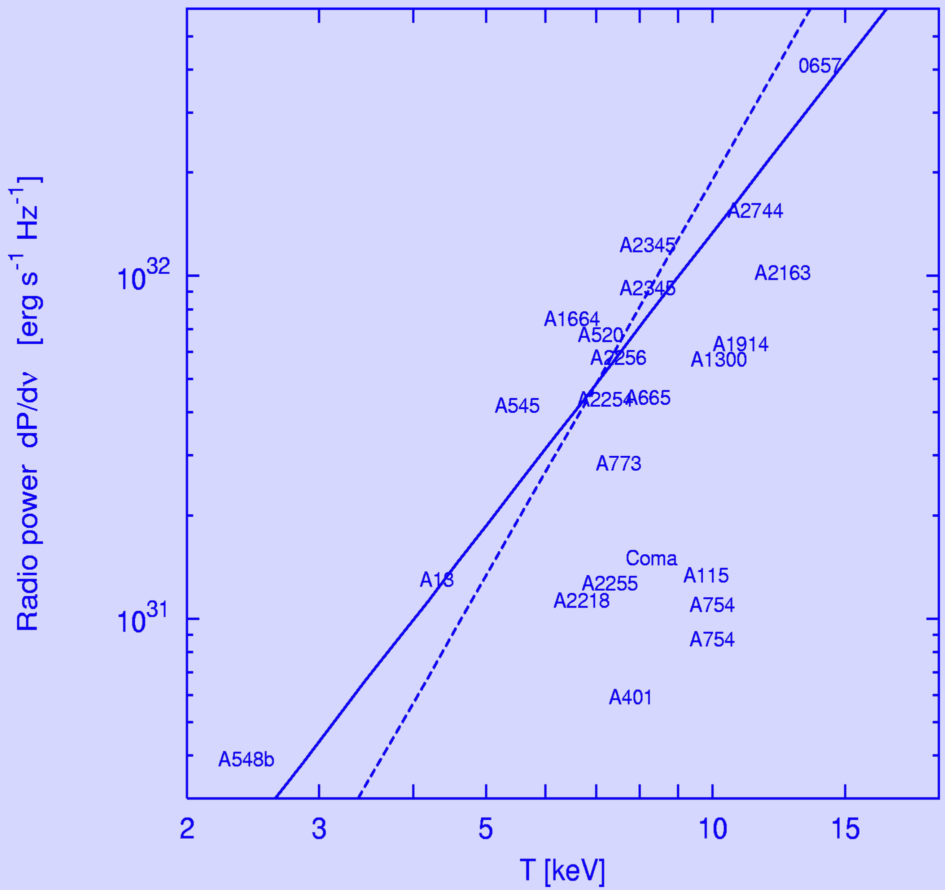
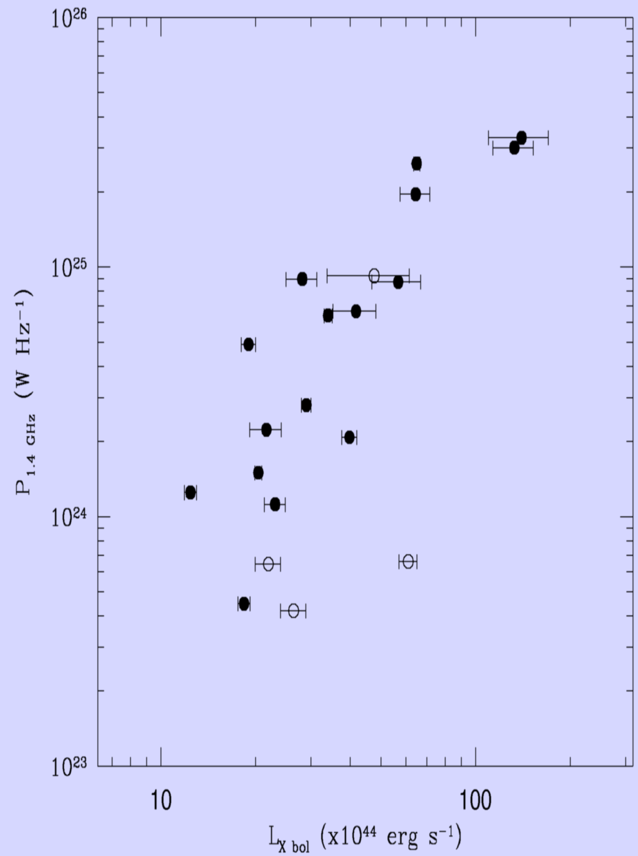
Radio power versus cluster temperature

- *if* massive clusters have a diffuse radio object, it is rather luminous

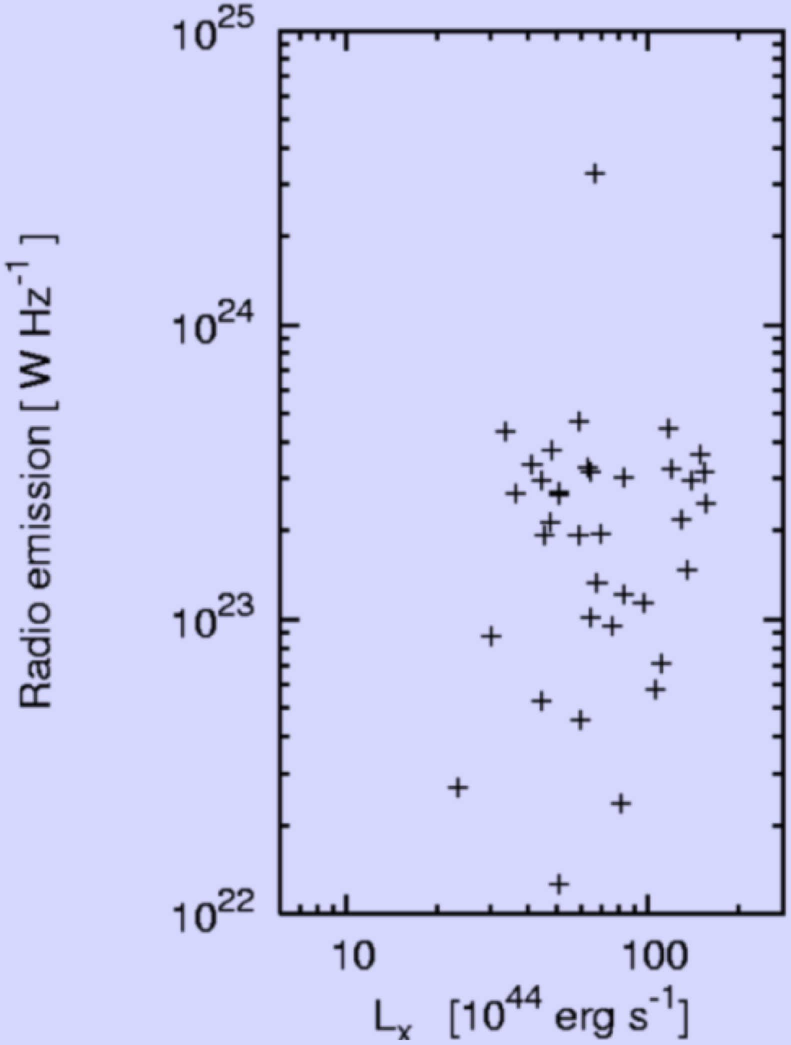
- the radio power -temperature relation is steep, index ~ 3.5

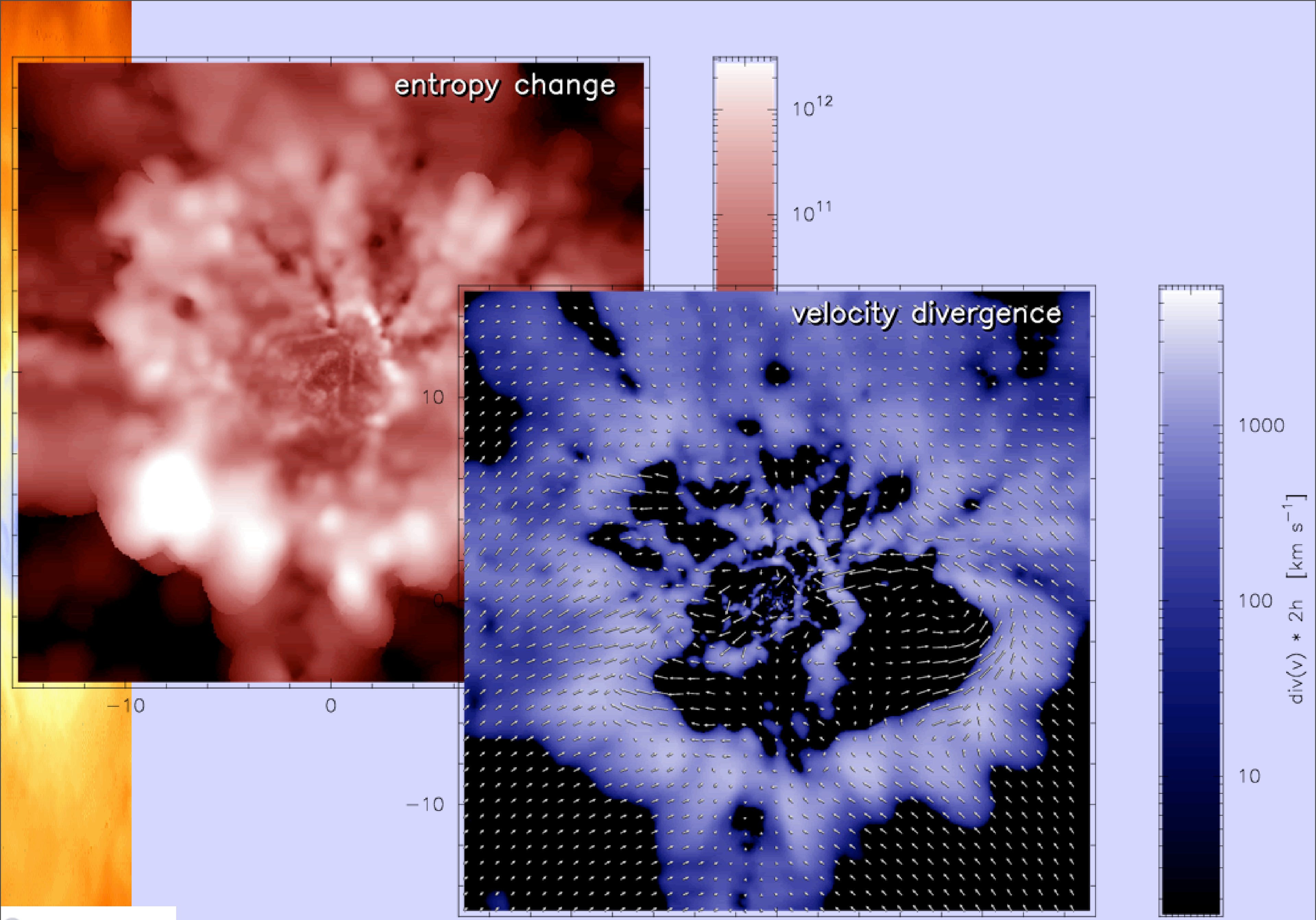


Total radio emission



[Feretti 03]





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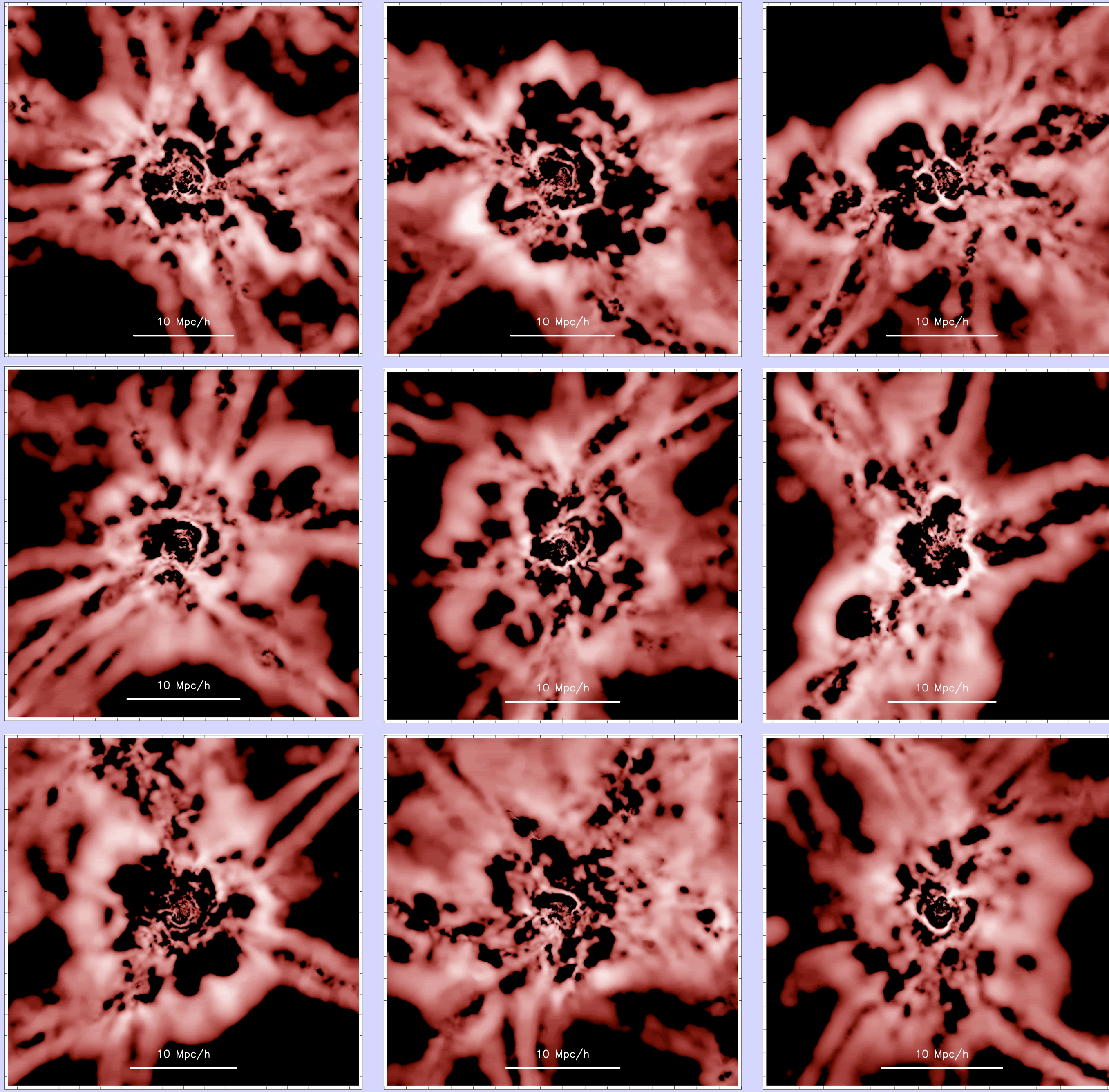

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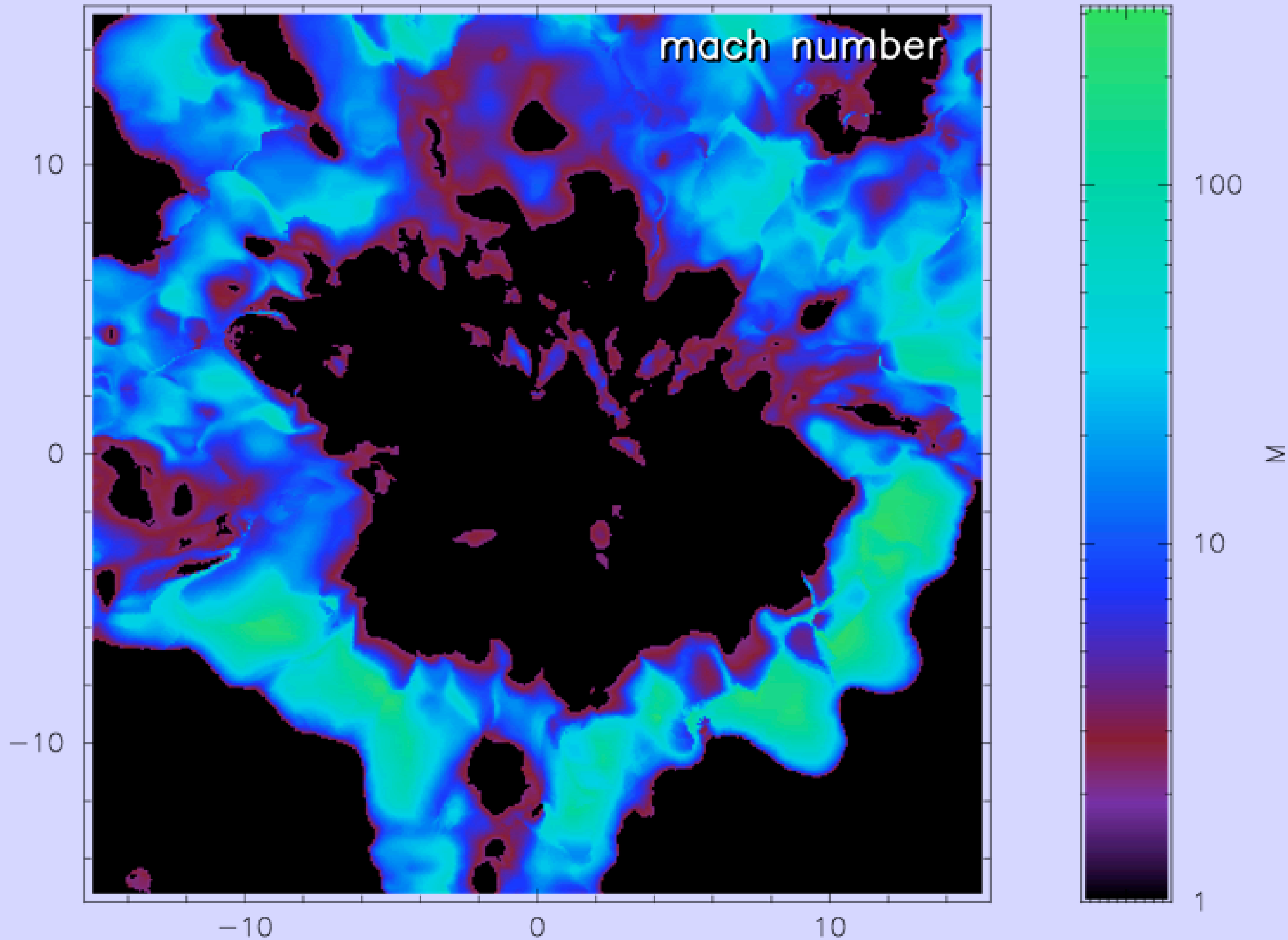
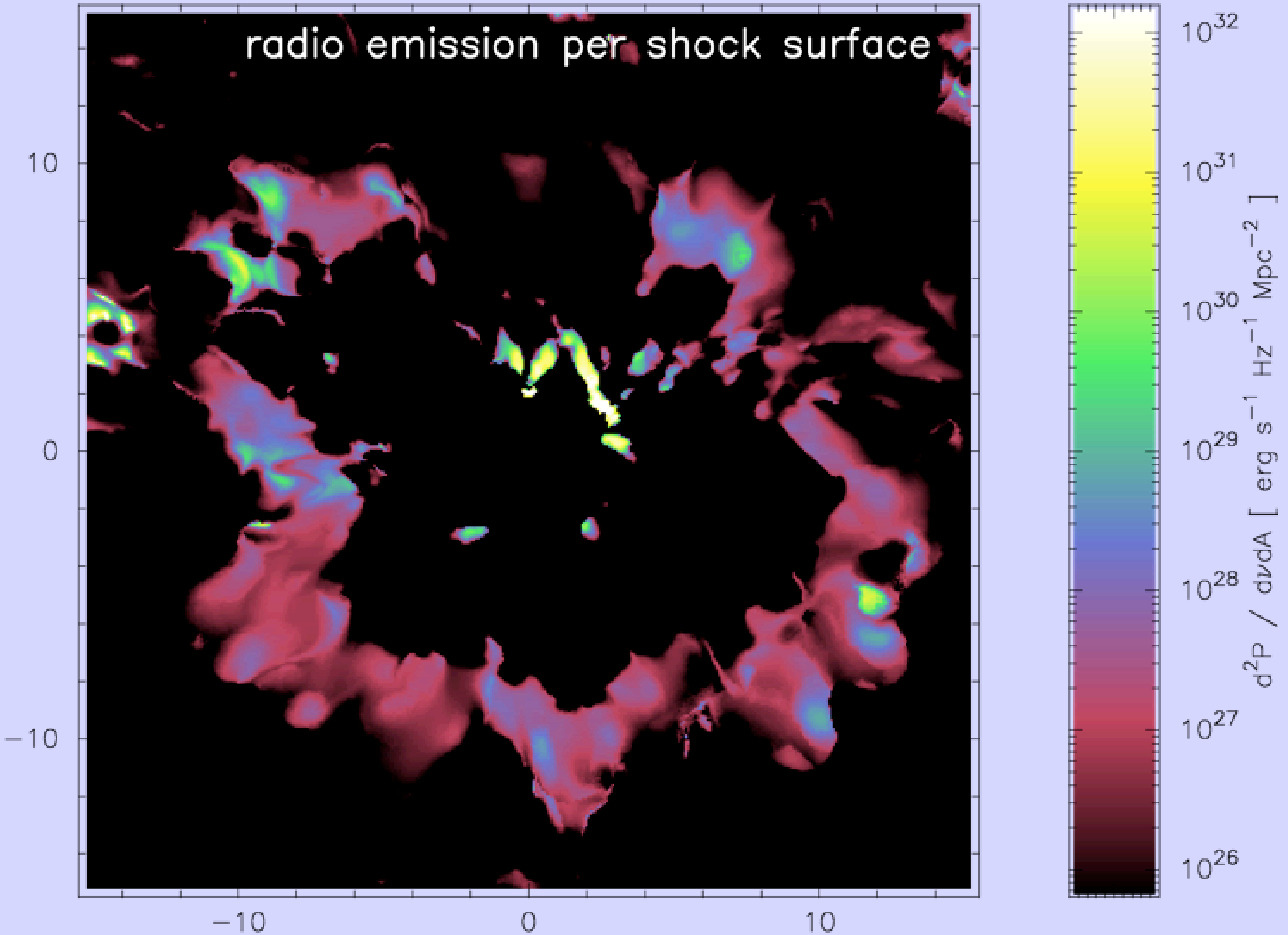


mach number
10
0
−10
−10
0
10
100
10
1
M



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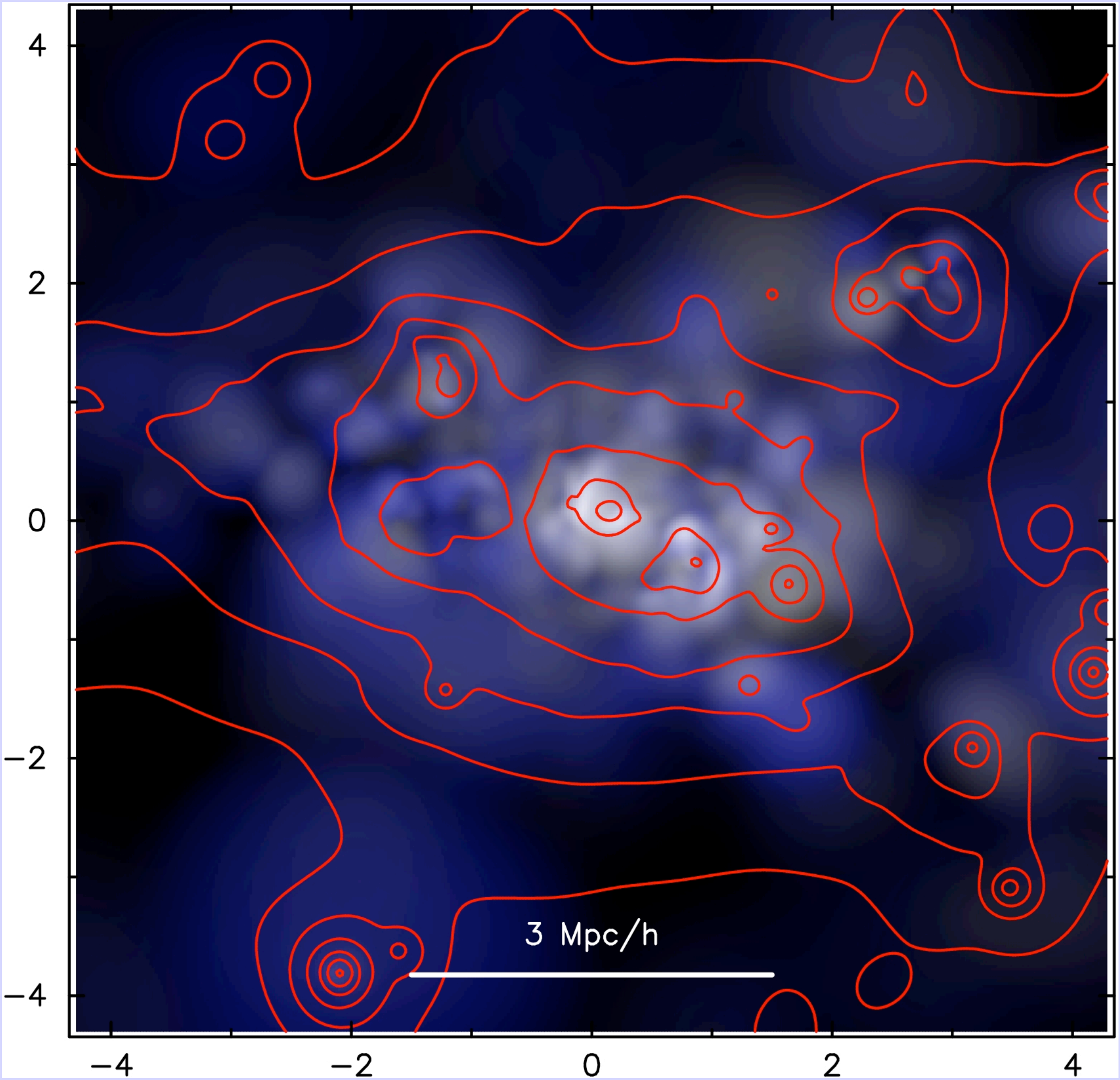
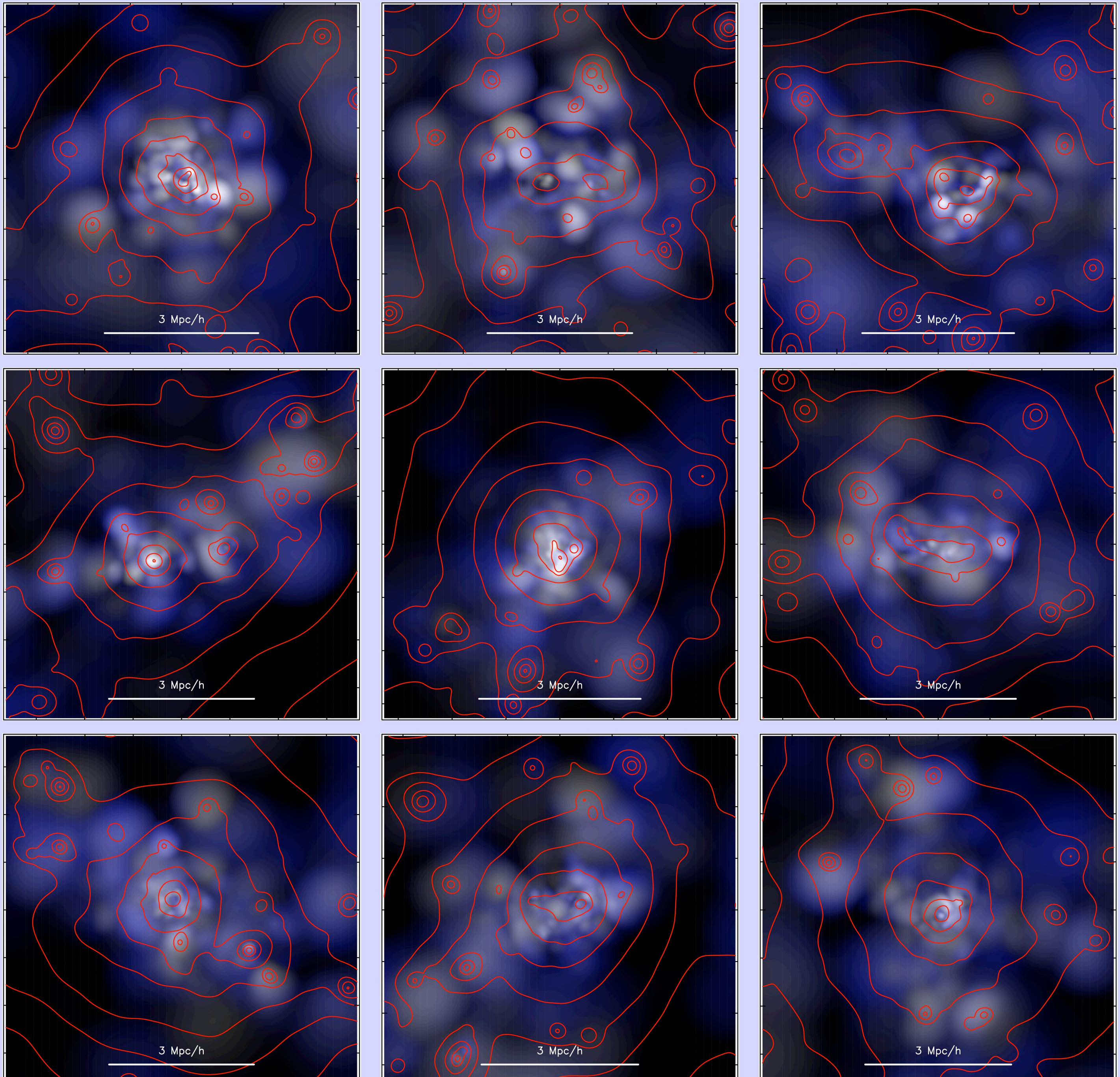


4
2
0
−2
−4
3 Mpc/h
−4
−2
0
2
4



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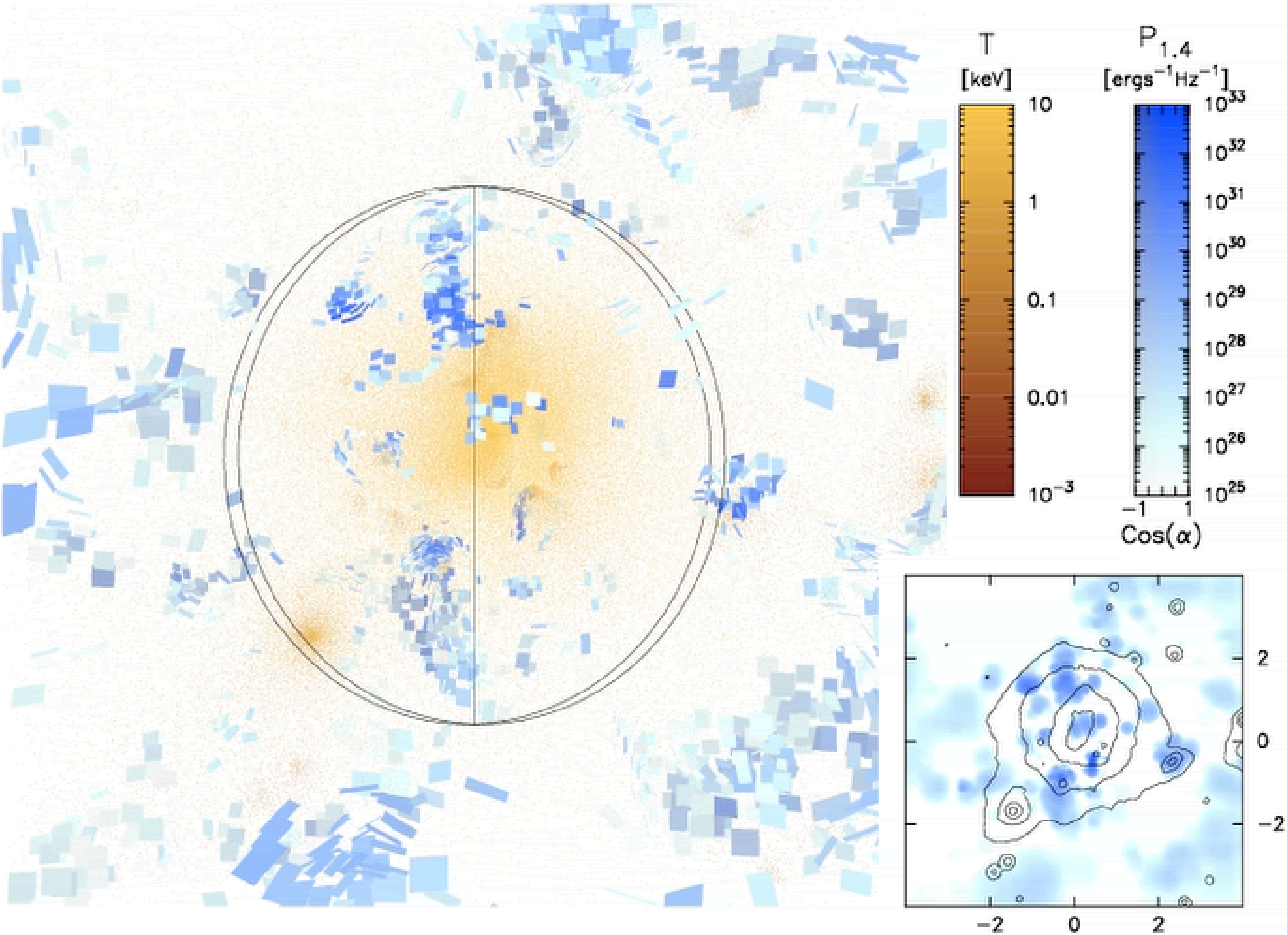

T
[keV]
10
1
0.1
0.01
10^−3
P1.4
[erg s^−1 Hz^−1]
10^33
10^32
10^31
10^30
10^29
10^28
10^27
10^26
10^25
−1
1
Cos(α)
2
0
−2
−2
0
2

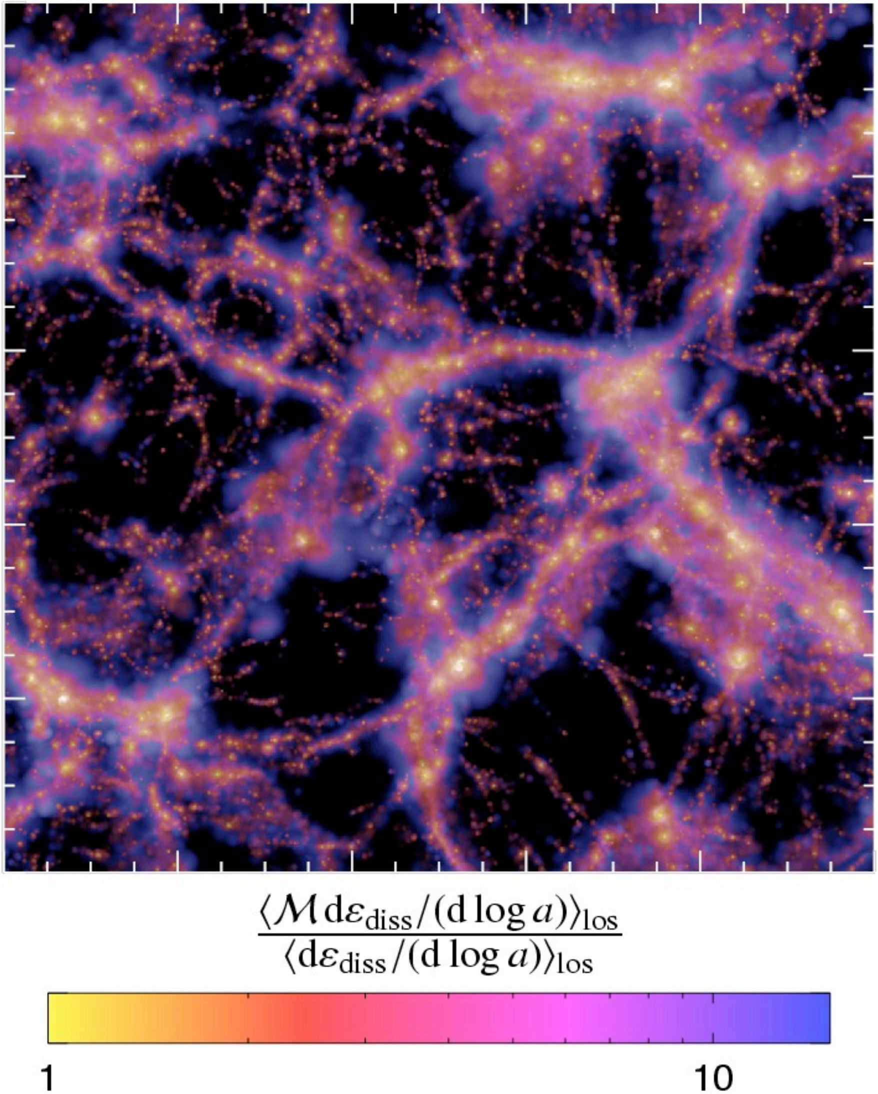
radio emission from cosmic shock waves

Enßlin et al. ’98

Miniati, Jones, Kang, Ryu ’01

Keshet, Waxman, Loeb ’04

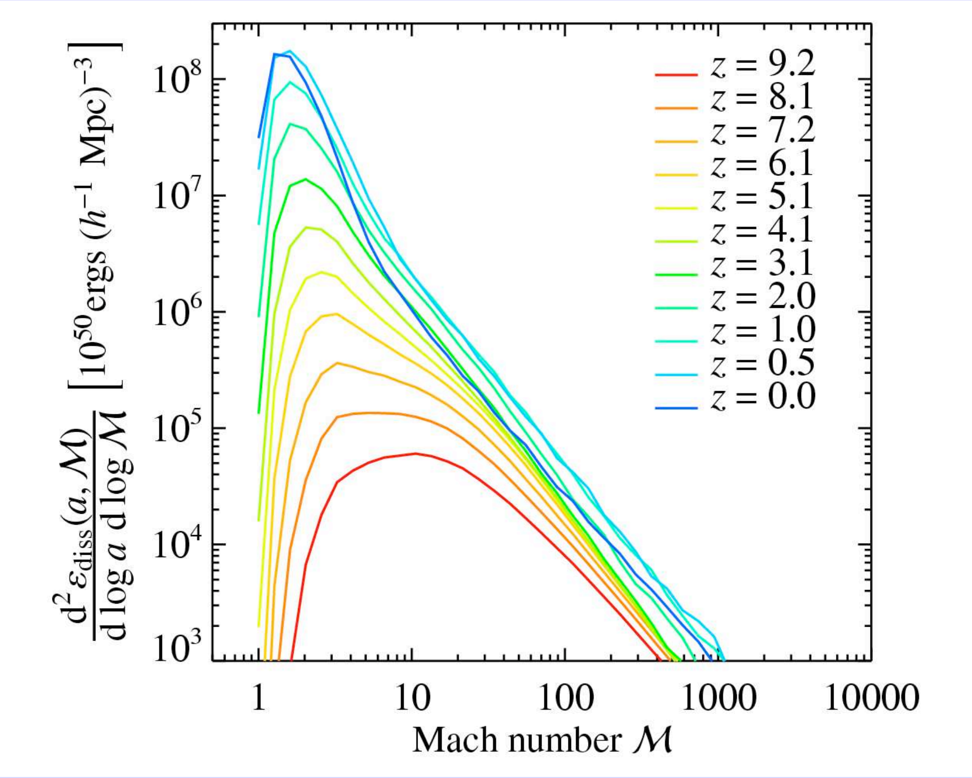
...



Pfrommer, Springel, Enßlin, Jubelgas (2006)

Cosmological Mach number statistics

- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
- more energy is dissipated at later times
- mean Mach number decreases with time



Pfrommer et al.

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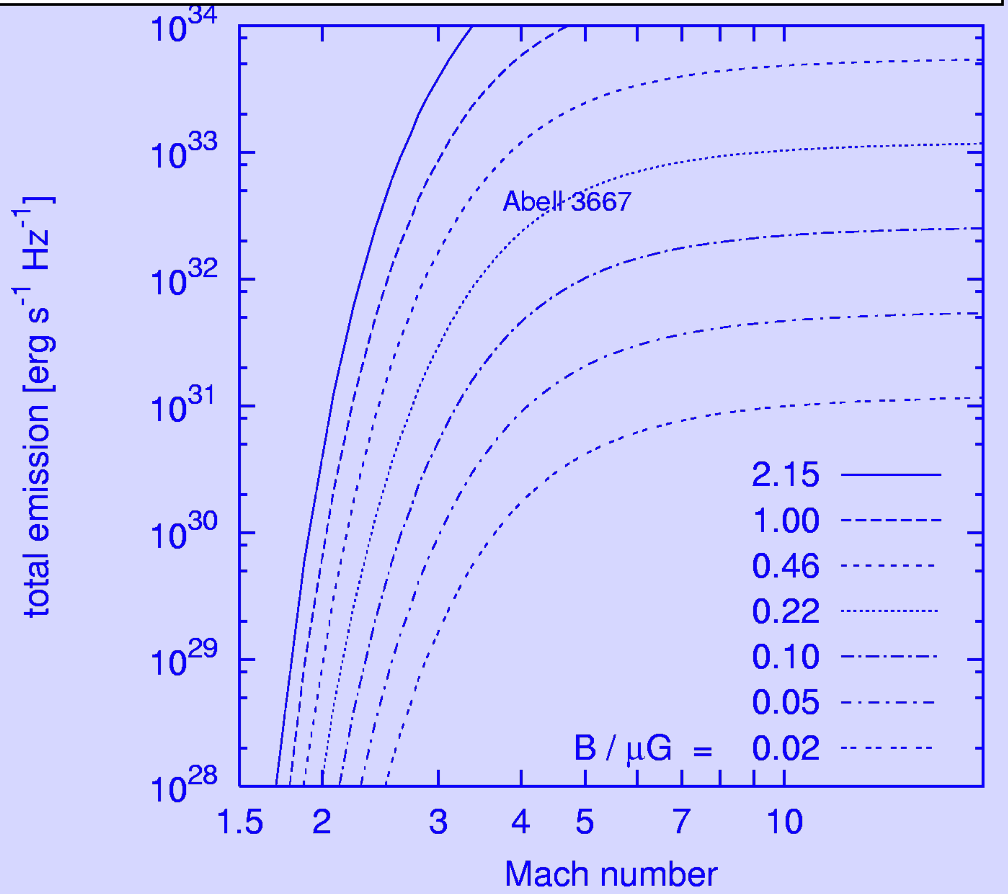
Radio power and magnetic field

- for a known Mach number we can infer the magnetic field strength

- for A3667 B ~ 0.2 μG



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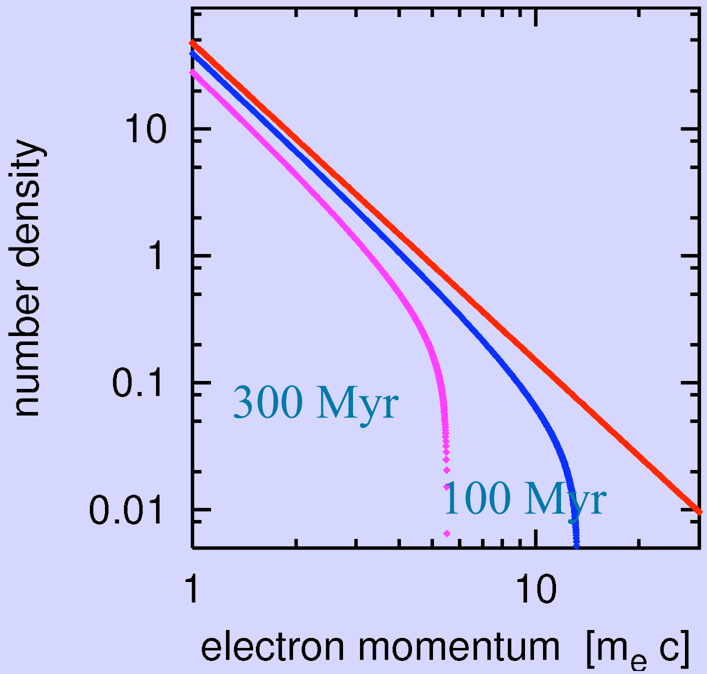
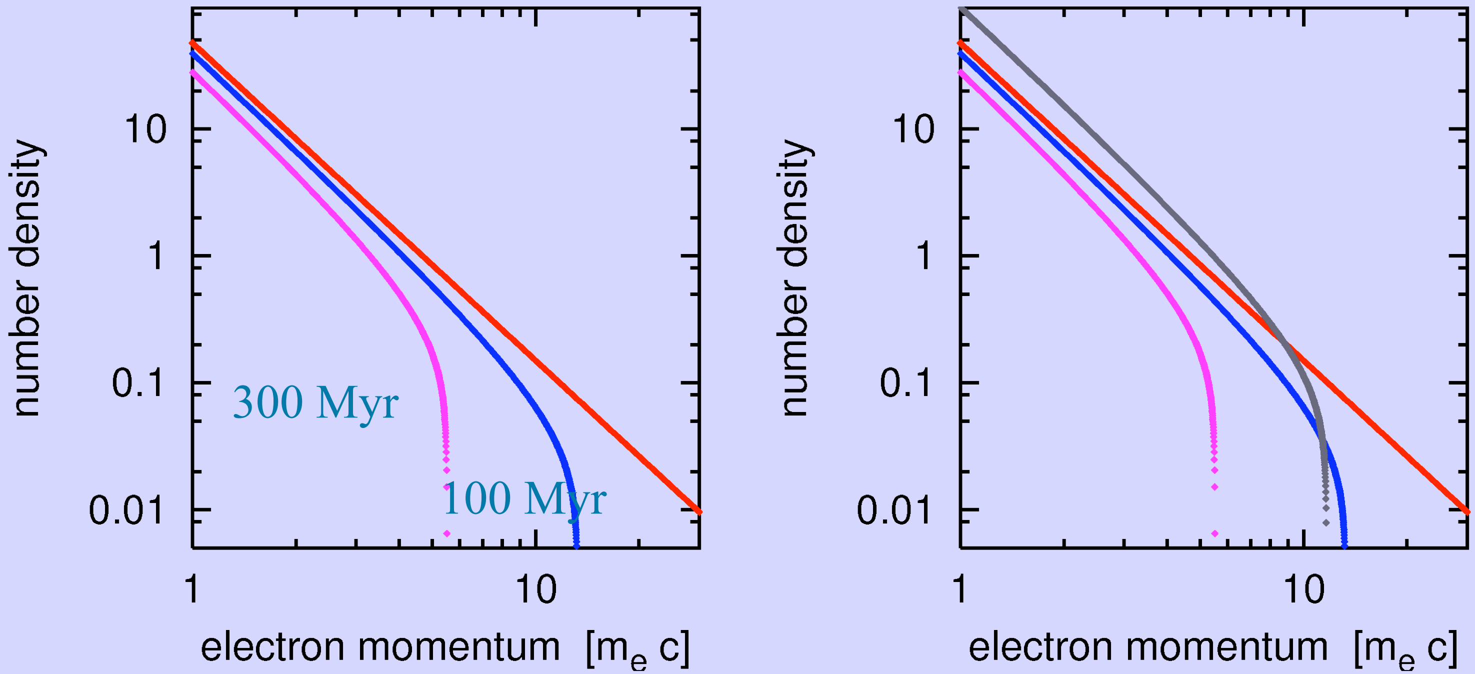
e^- momentum spectrum

$$dp = -\frac{4}{3}\sigma_T \left\{u_B + u_{\mathrm{CMB}}\right\} - \frac{1}{3}\frac{1}{V}dV$$



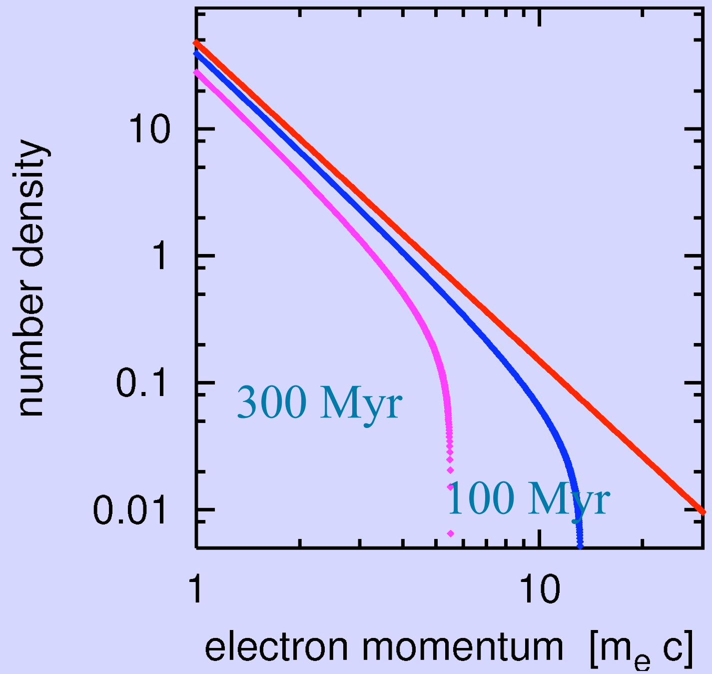
e^- momentum spectrum

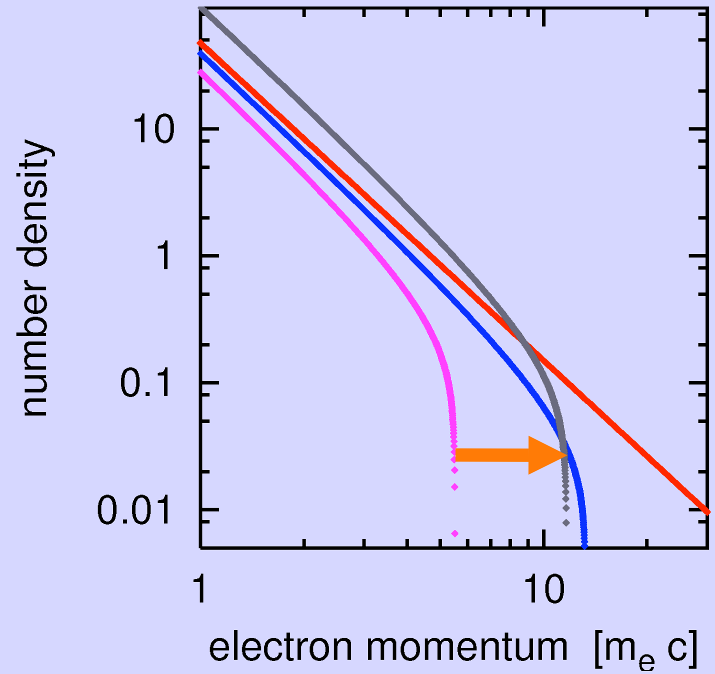
$$dp = -\frac{4}{3}\sigma_T \left\{u_B + u_{\text{CMB}}\right\} - \frac{1}{3}\frac{1}{V}dV$$



e^- momentum spectrum

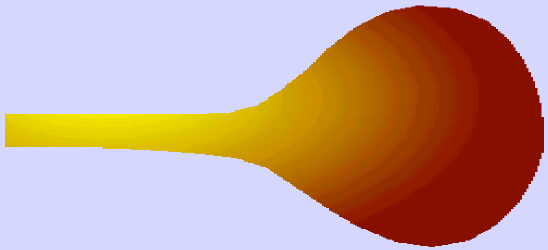
$$dp = -\frac{4}{3}\sigma_T \{u_B + u_{\mathrm{CMB}}\} - \frac{1}{3}\frac{1}{V}dV$$





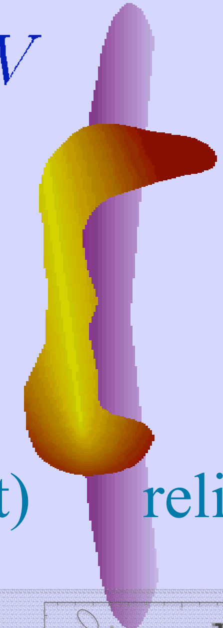
Reviving fossil radio plasma

$$dp = -\frac{4}{3}\sigma_T\left\{u_B + u_{\rm CMB}\right\} - \frac{1}{3}\frac{1}{V}dV$$

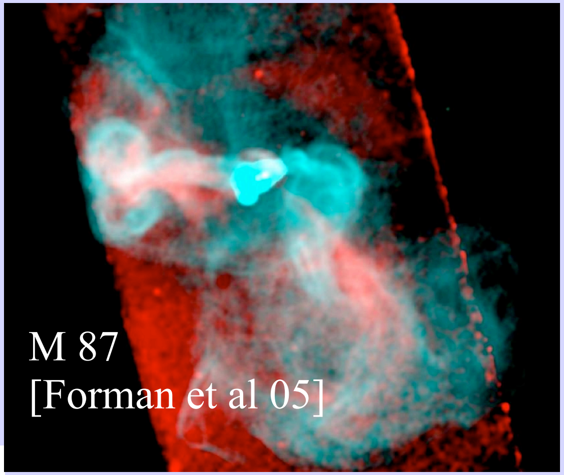


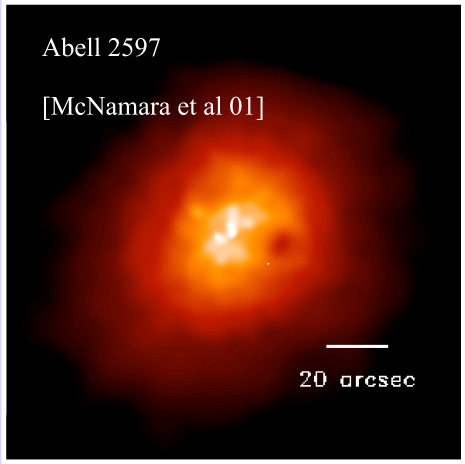
AGN

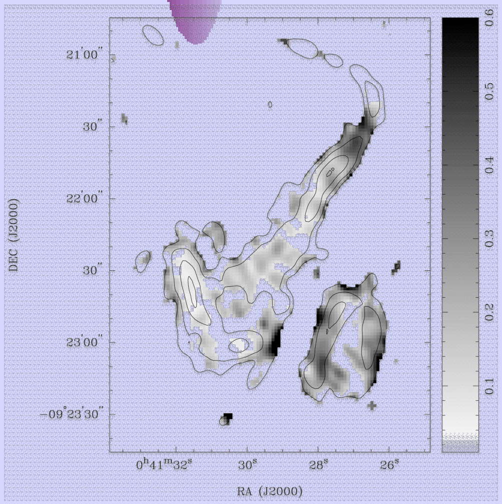
fossil radio plasma (ghost)



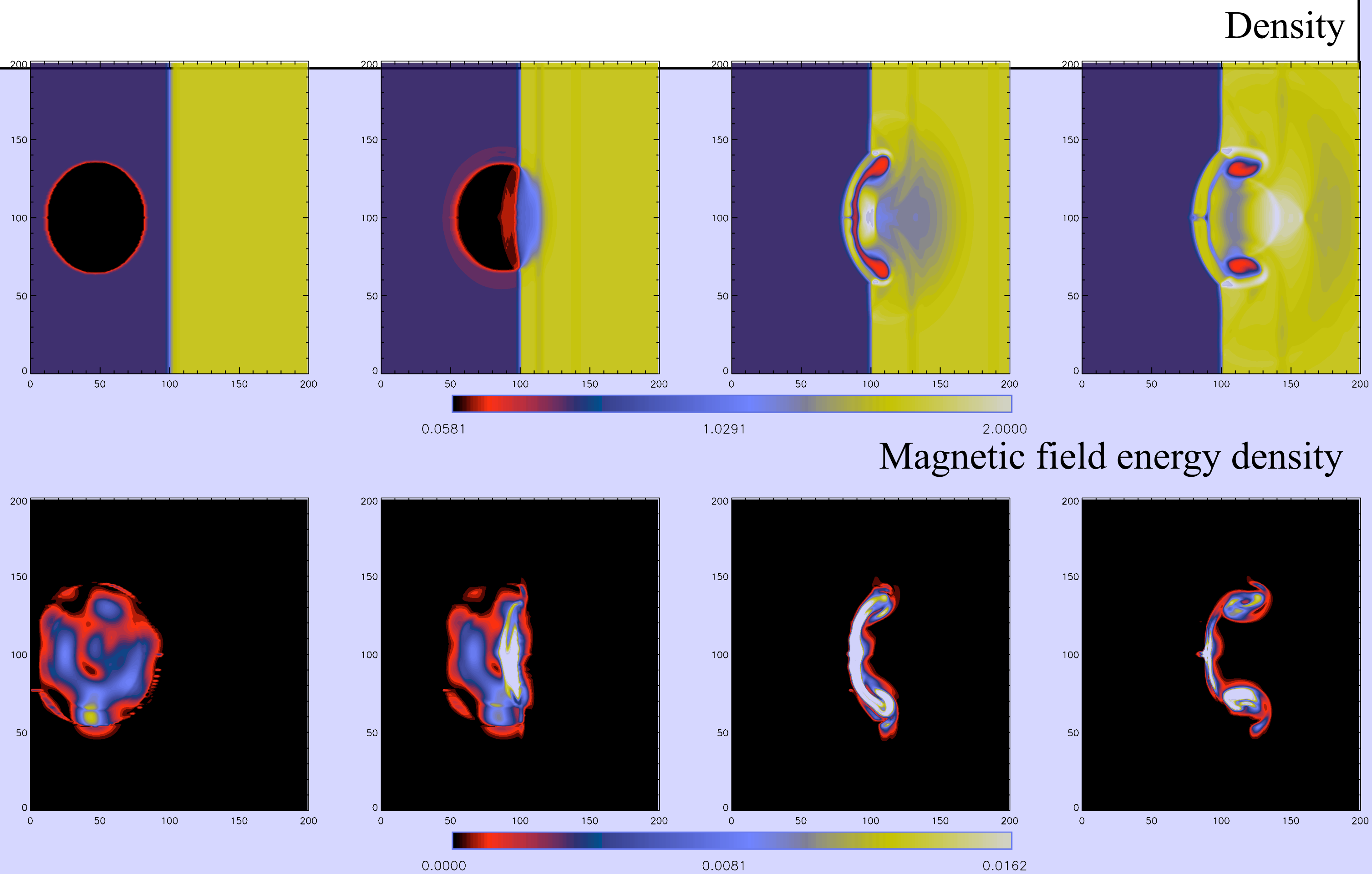
relic





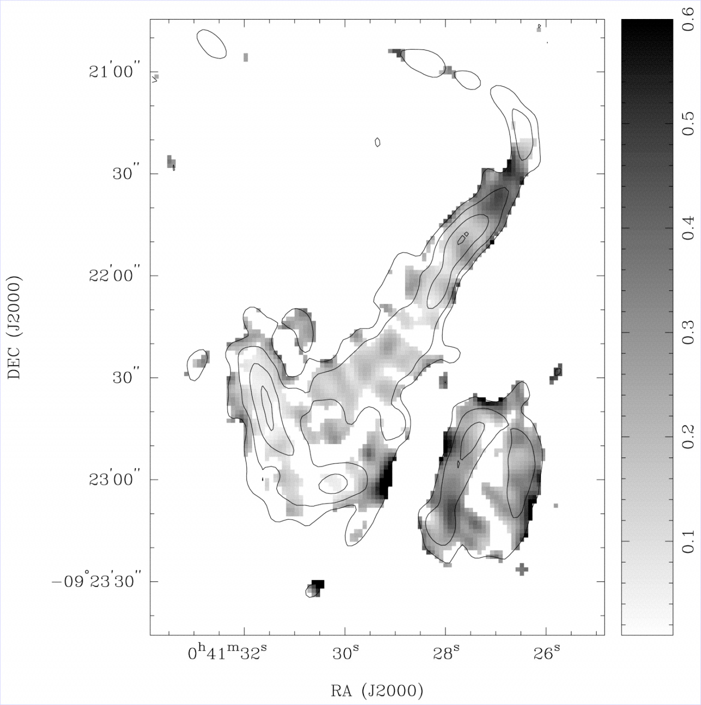


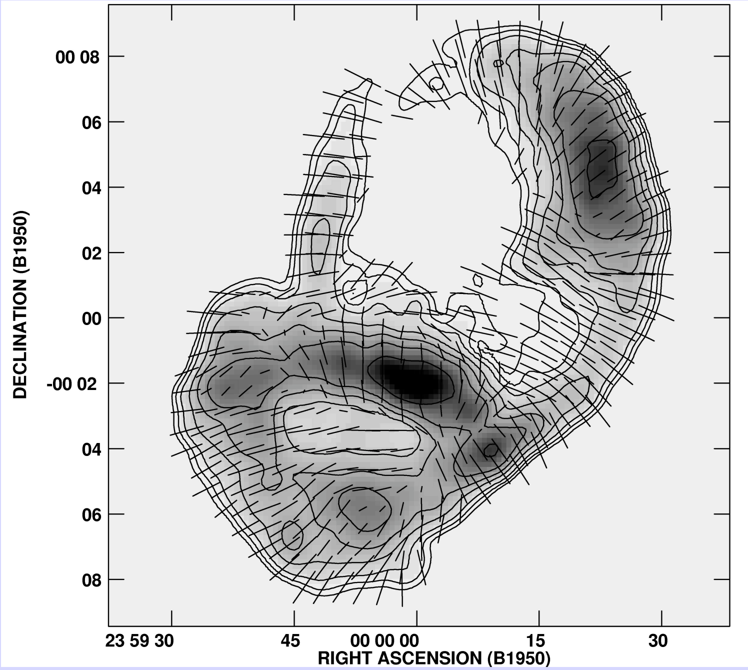
Bubble in shock front



[Enßlin&Brüggen01]

It works ...





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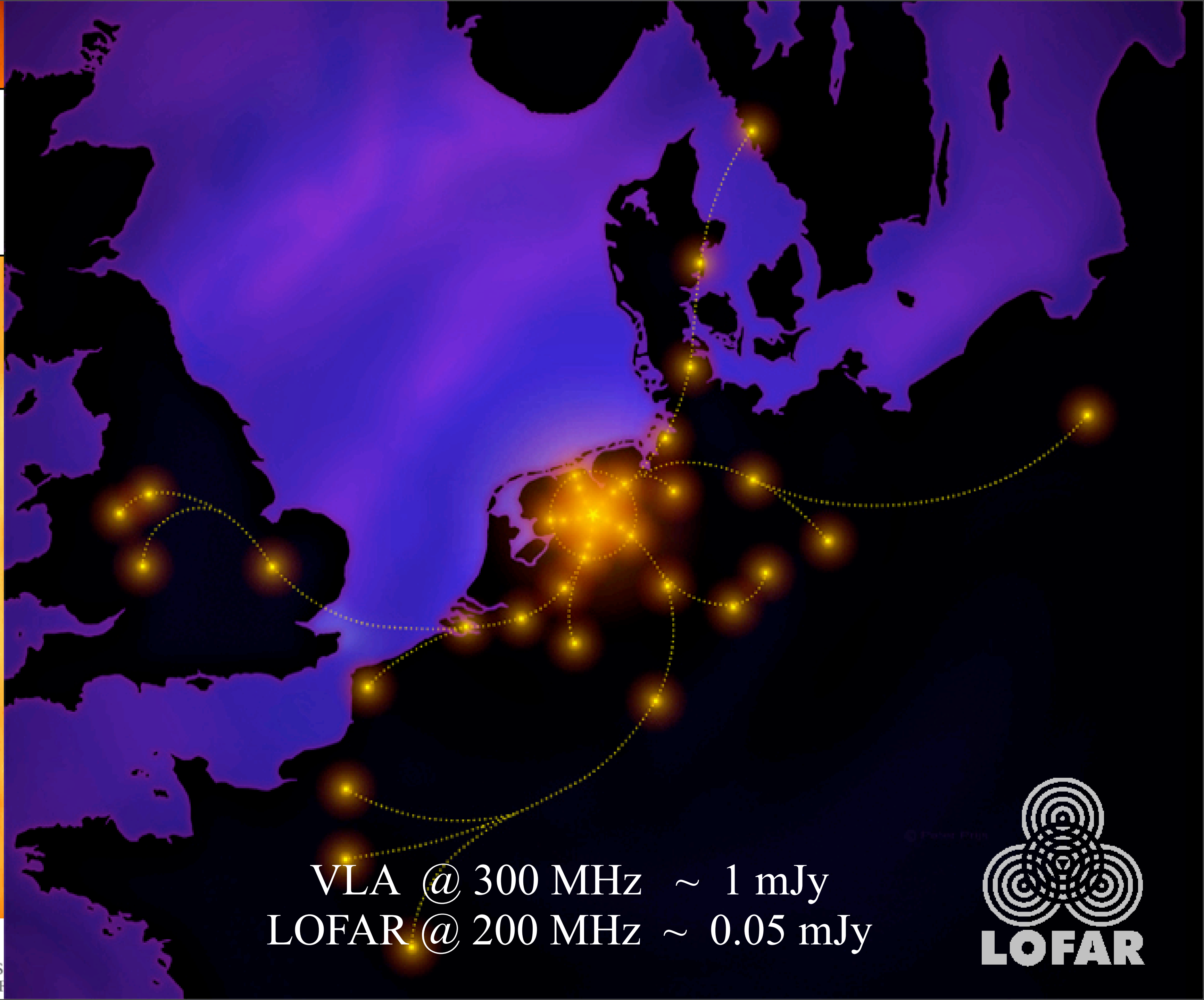
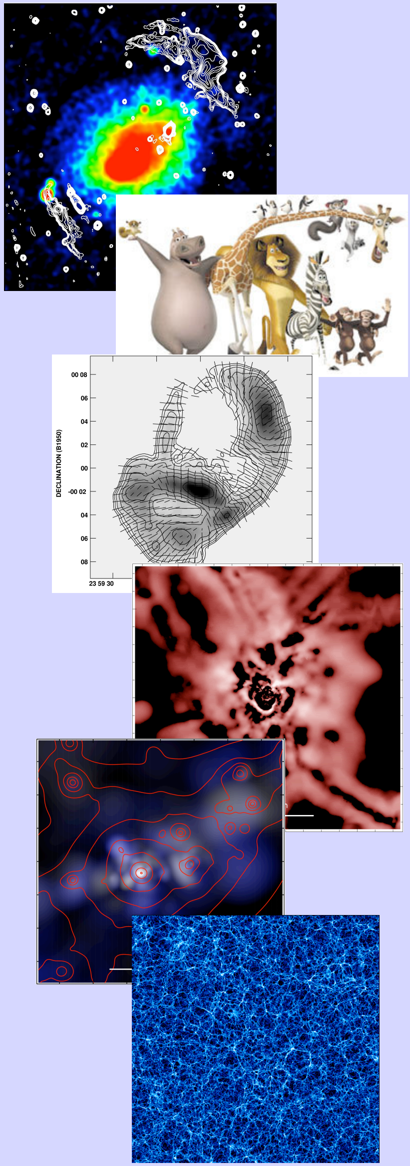


VLA @ 300 MHz ~ 1 mJy
LOFAR @ 200 MHz ~ 0.05 mJy

LOFAR

Relics Summary



A variety of diffuse radio objects has been observed

Radio galaxies and intergalactic shock waves are sources for high-energy particles in the universe

LOFAR should find > 100 relics at low frequencies

Clusters of galaxies show in general multiple strong accretion shocks

Detecting their radio emission gives unique insights into baryonic structure formation and plasma physical processes

Jacobs University