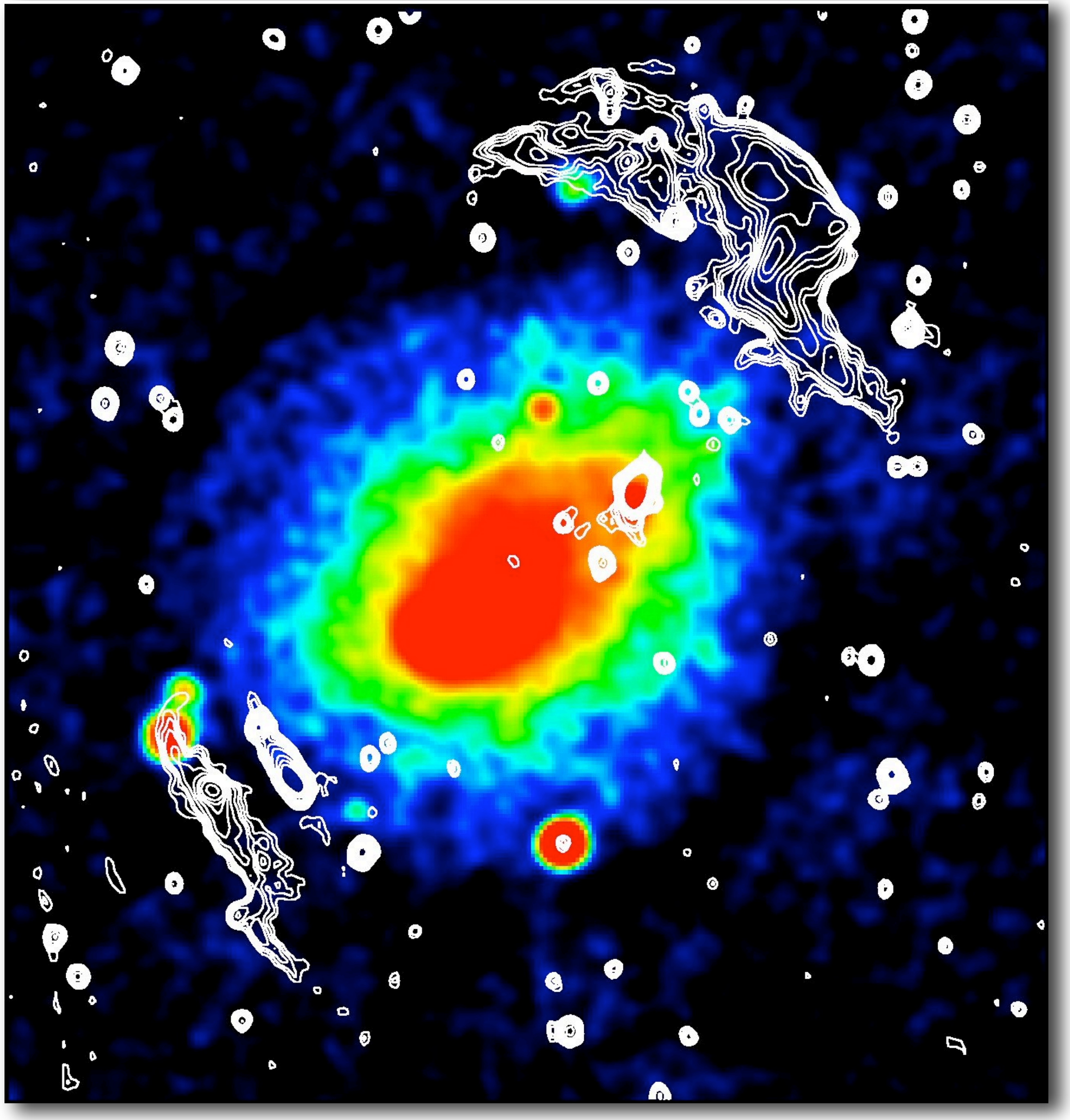
The radio signature of structure formation shocks

Matthias Hoeft

Thüringer Landessternwarte Tautenburg

The definition of 'radio relic'

- extended (about 1Mpc) diffuse emission at the periphery of galaxy clusters
- no optical counterpart
- irregular morphology



Abell 3667

Color: X-ray

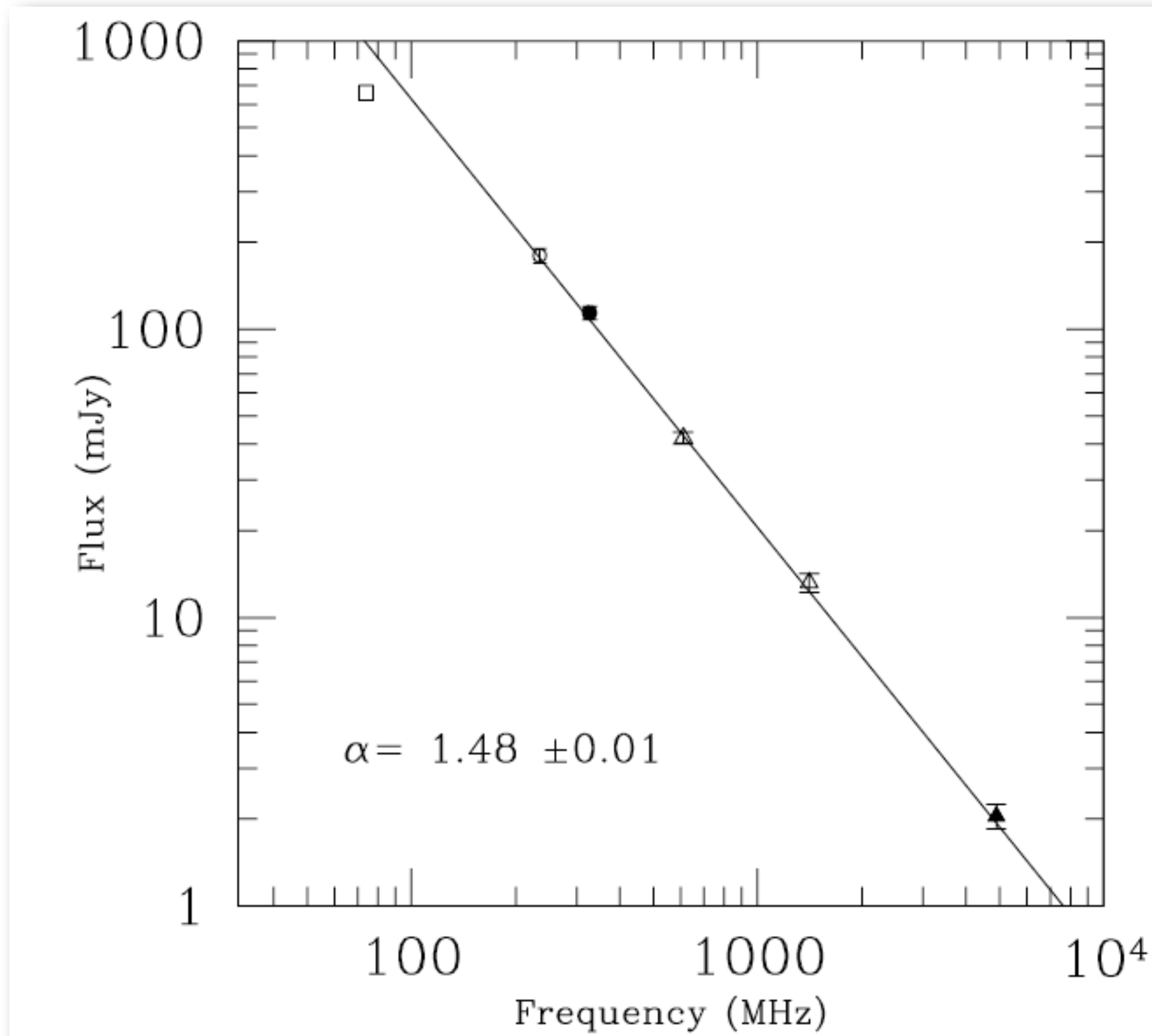
Contours: radio

[Roettgering et al. 97]

The overall radio spectrum

- perfect power-law in radio spectrum
- fits very well 'simple' DSA predictions:

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

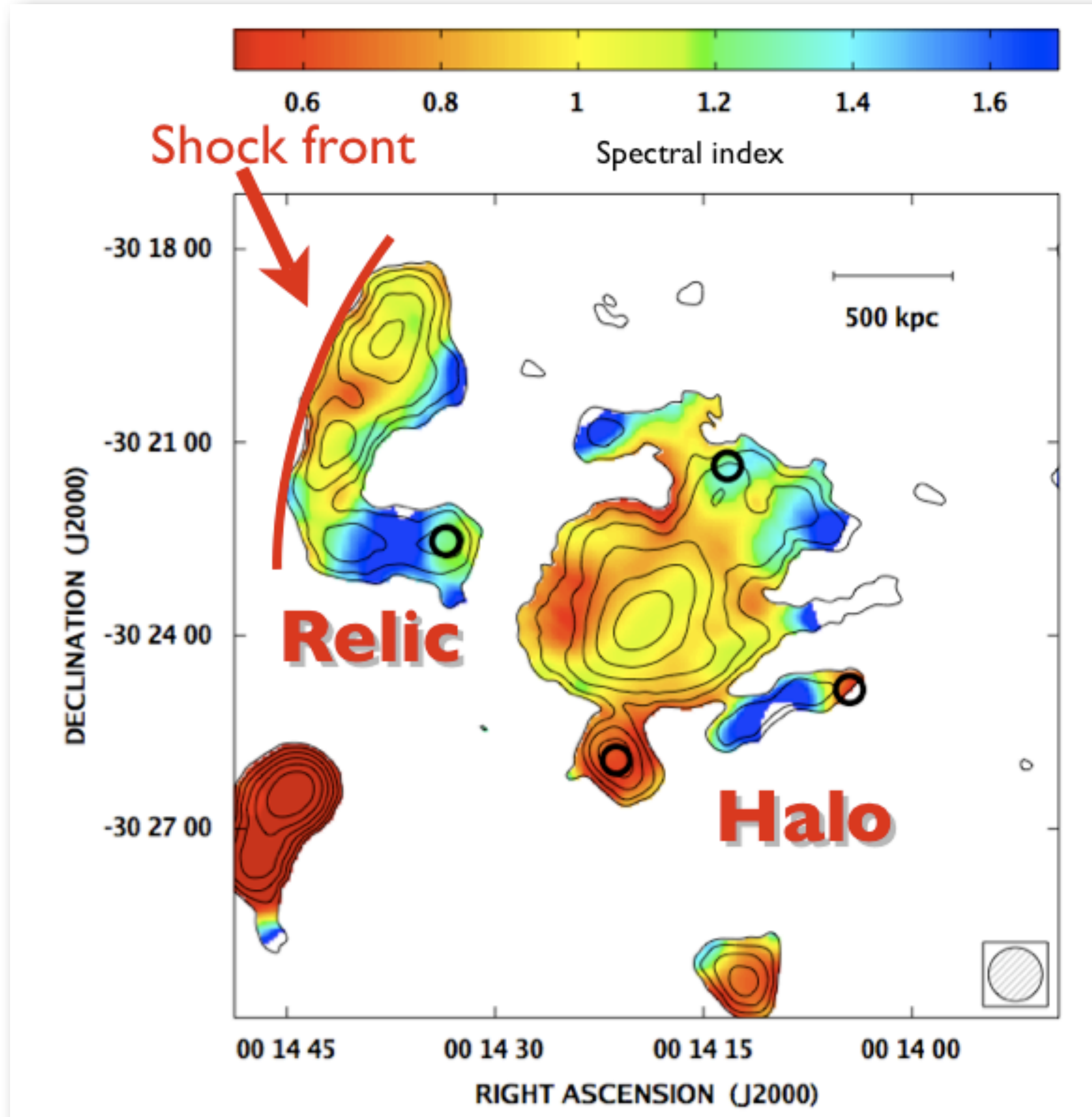


Abell 521

[Giacintucci et al. 08]

Spectral index map - aging

- systematic trend perpendicular to the long extend of the relic
- indicates motion of the shock front and aging of electrons



Abell 2744

[Orrù et al. 04]

Polarization of the diffuse emission

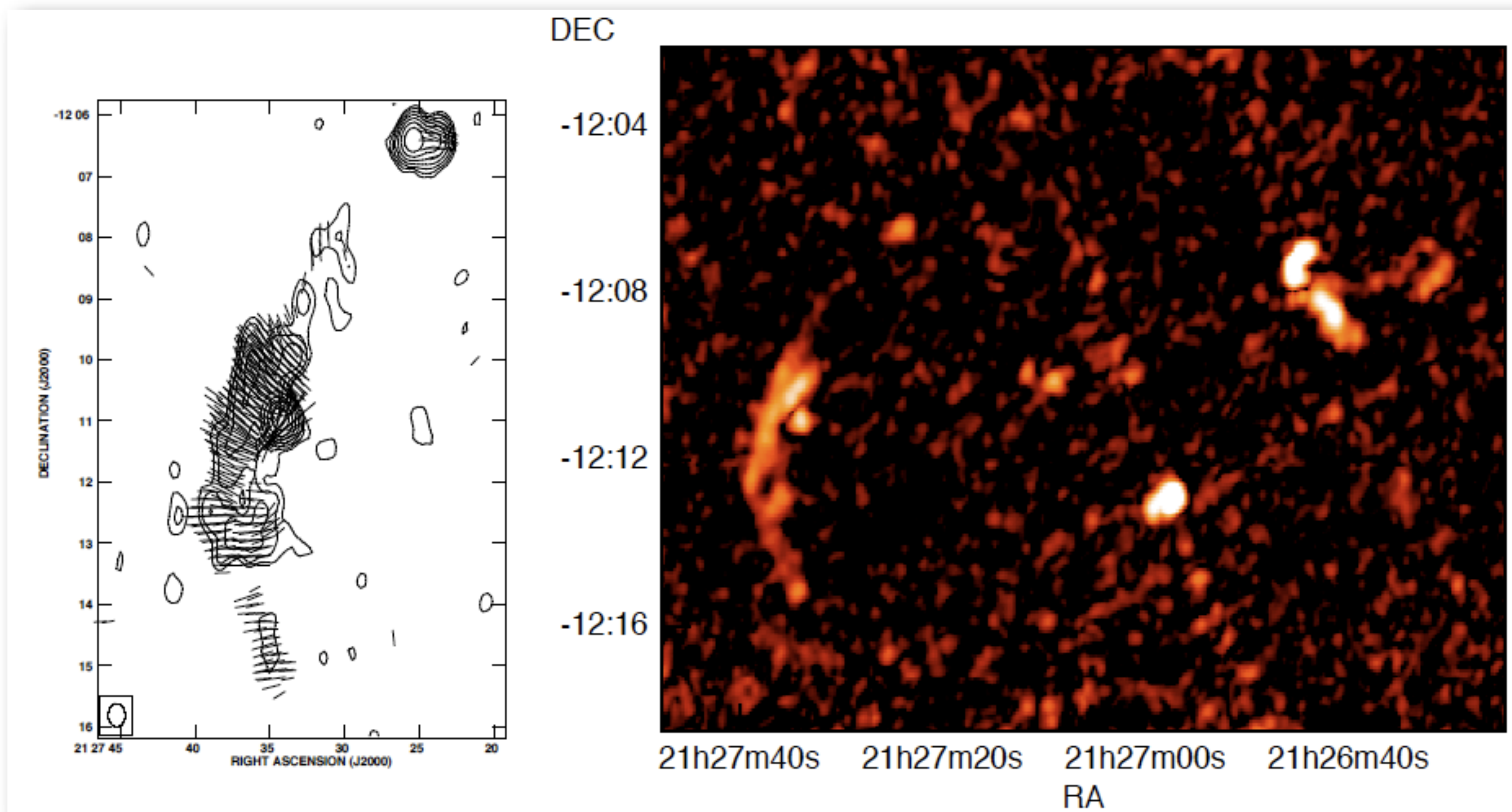
- for A2345: average polarization 22%
  maximal polarization 50%
- other example Abell 786: average polarization 53%
  [Harris et al. 93]

Abell 2345

VLA 1.4 GHz

Color: polarized emission

[Bonafede et al. 2009]

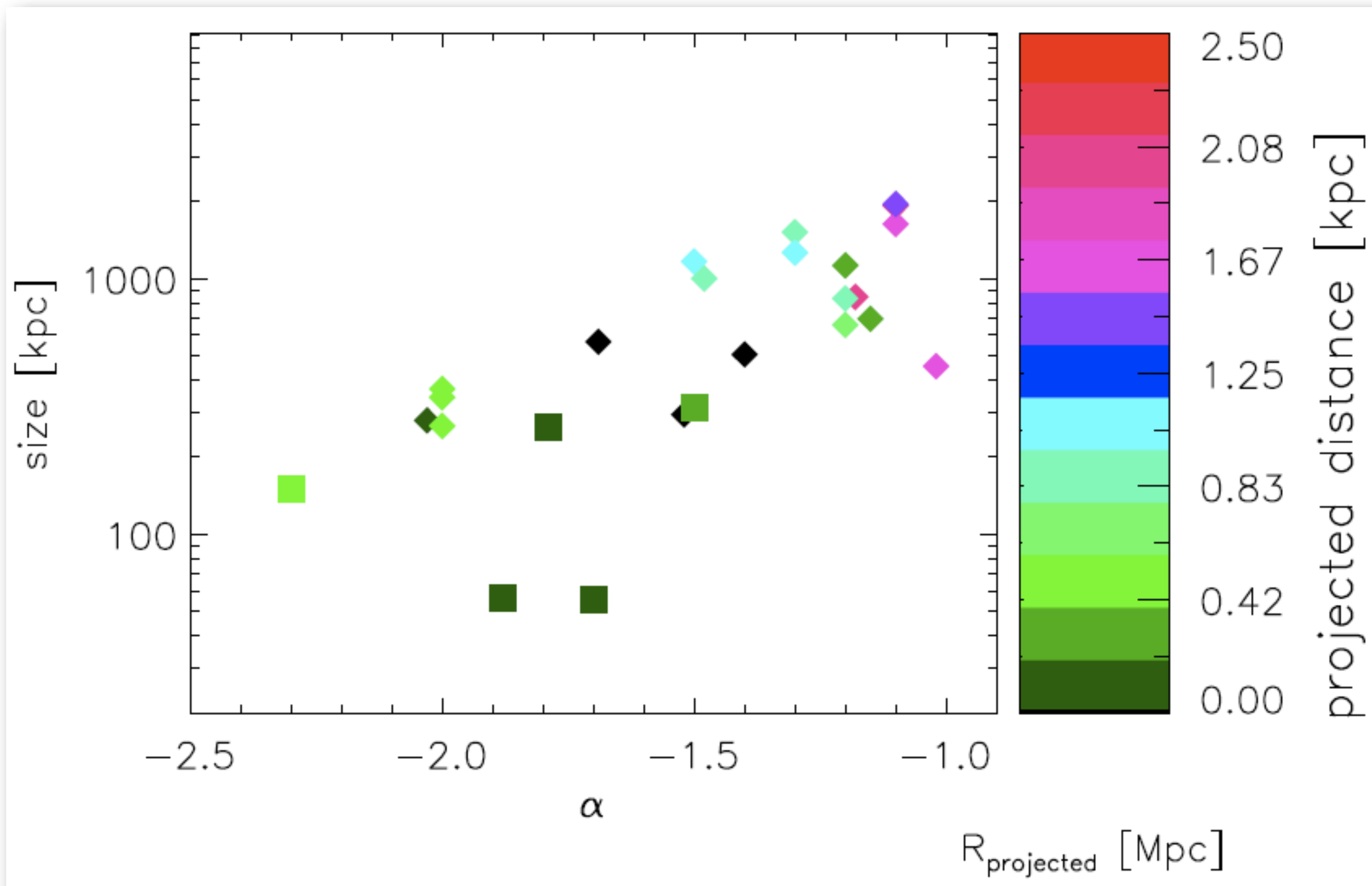


Estimates for the magnetic field strength

	Abell 3667 NW relic
Rotation measure of background sources	3-5 μG [Johnston-Hollitt 04]
Inverse Compton emission would directly measure the electron density $$\frac{F^{\rm sync}}{F^{\rm IC}} = \frac{U_{\rm B}}{U_{\rm CMB}}$$	> 1.6 μG Suzaku 10-40 keV upper limit [Nakazawa et al. 08]
Equipartition	2 μG

Statistics of radio relics

- about 25 relics are known (only!)
- size ∝ distance
- correlation between luminosity and slope



[van Weeren et al. 2009]

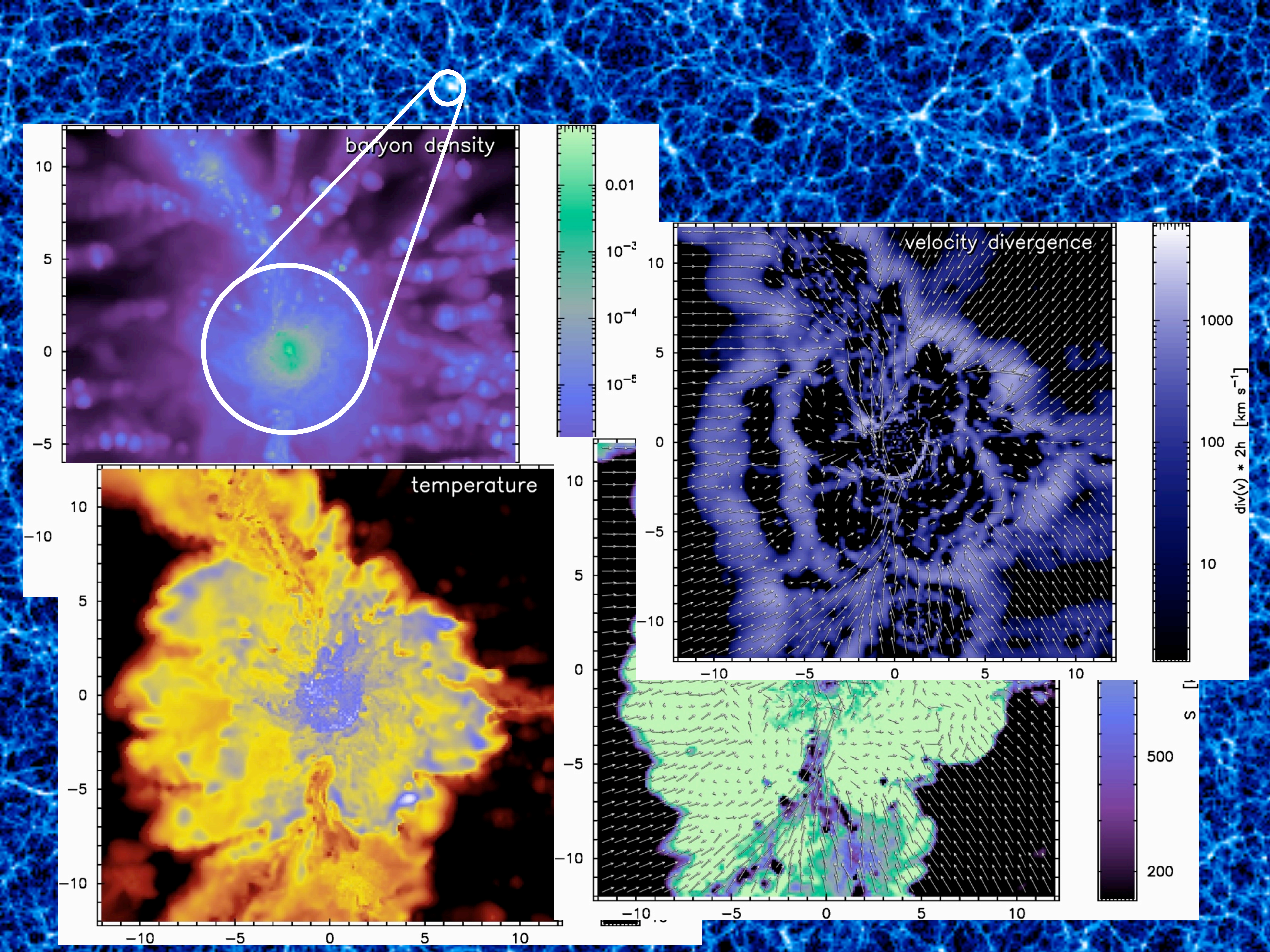
The resulting overall picture

- diffusive shock acceleration produces non-thermal electrons at the shock front with a slope close to -2 (energy)
- energetic electrons are advected downstream with the thermal plasma and cool by IC and synchrotron losses
- magnetic fields in the emission region are at least about a few μG
- main field component parallel to long axis of relics, resulting polarization is up to 60%

Shock fronts in a cosmological simulation

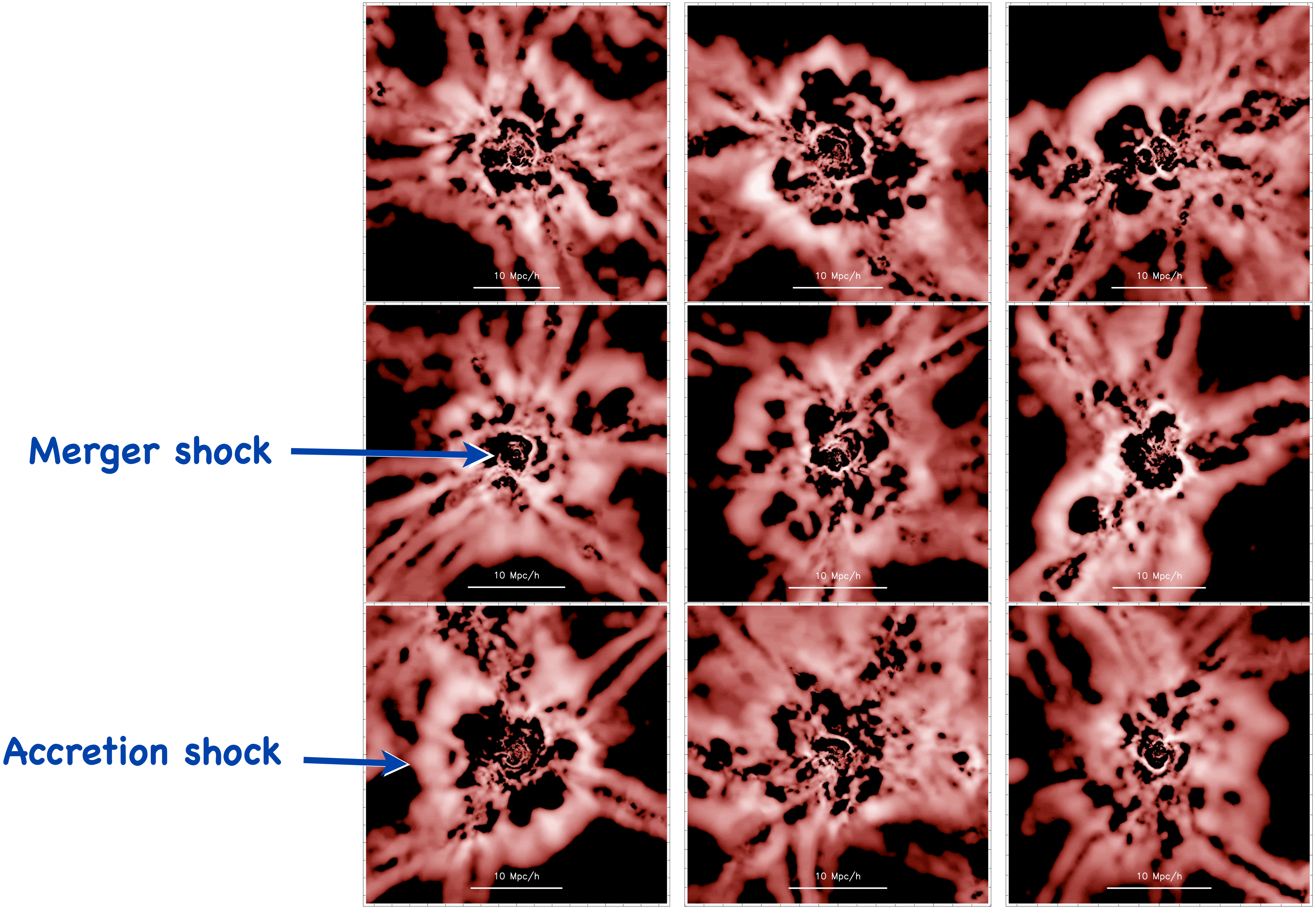
Mare Nostrum Universe:

- 500 Mpc/h
- gas and dark matter particles, 1024^3 each
- Gadget (SPH), no radiative cooling



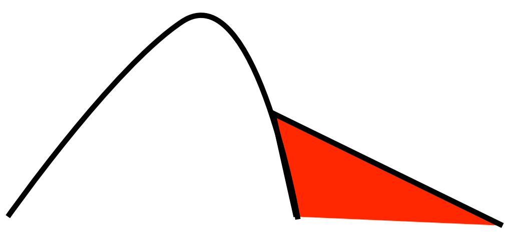
baryon density
0.01
10^{-3}
10^{-4}
10^{-5}
temperature
velocity divergence
1000
100
10
div(v) * 2h [km s^{-1}]
500
200

All clusters show shock multiple fronts!



How to compute the radio emission?

- Identify shock fronts
- Determine Mach number, downstream ρ, T, and B
- Assumption about acceleration efficiency ξ: fraction of dissipated energy into electrons supra-thermal = 5%

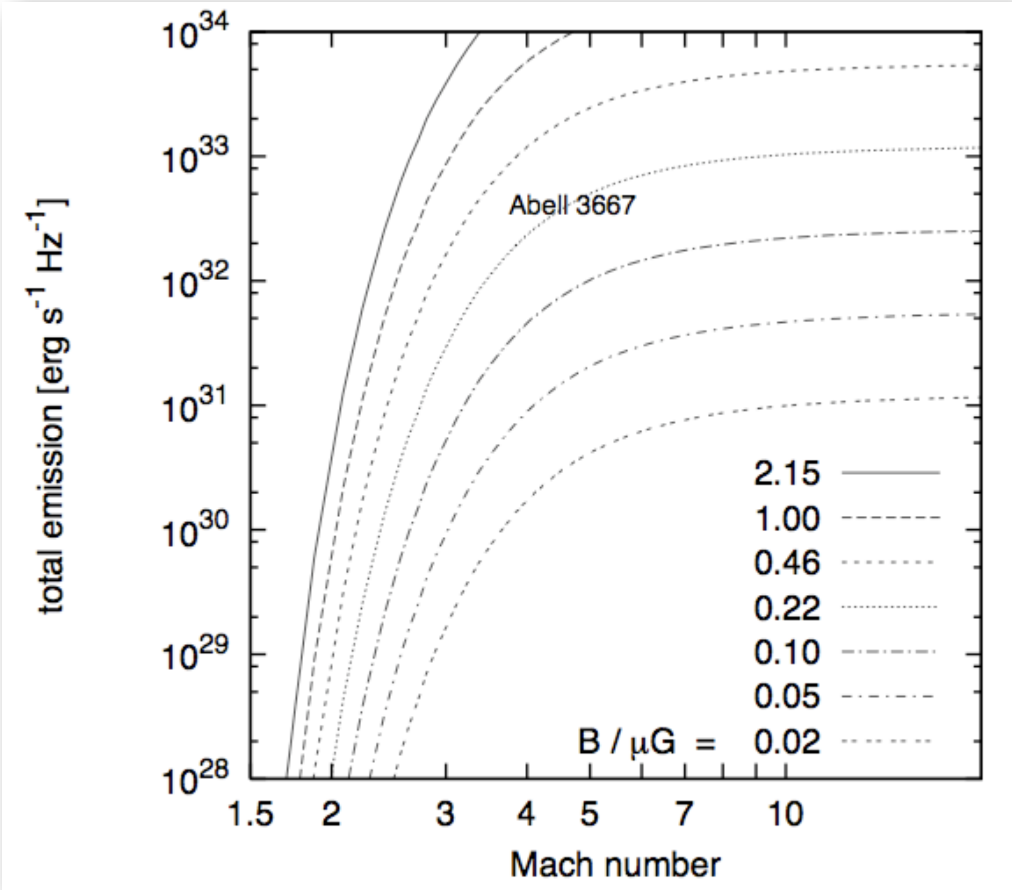


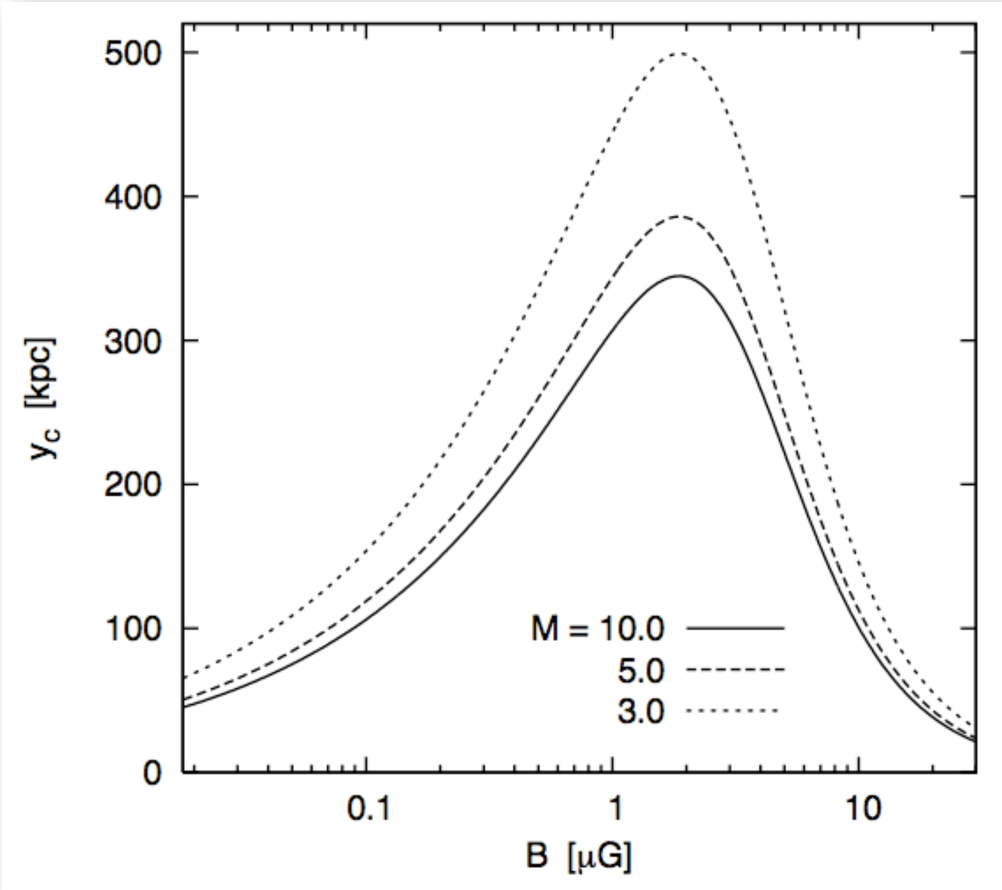
- Integrate over downstream advection and cooling

-> radio emission per shock area

$$\frac{\mathrm{d}P(\nu_{\mathrm{obs}})}{\mathrm{d}\nu} = 6.4 \times 10^{34} \frac{\mathrm{erg}}{\mathrm{s\,Hz}} \frac{A}{\mathrm{Mpc}^2} \frac{n_{\mathrm{e}}}{10^{-4}\mathrm{cm}^{-3}} \frac{\xi_{\mathrm{e}}}{0.05} \left(\frac{\nu_{\mathrm{obs}}}{1.4\,\mathrm{GHz}}\right)^{-\frac{s}{2}} \times \left(\frac{T_{\mathrm{d}}}{7\,\mathrm{keV}}\right)^{\frac{3}{2}} \frac{\left(\frac{B}{\mu\mathrm{G}}\right)^{1+\frac{s}{2}}}{\left(\frac{B_{\mathrm{CMB}}}{\mu\mathrm{G}}\right)^2 + \left(\frac{B}{\mu\mathrm{G}}\right)^2} \Psi(\mathcal{M}, T)$$

Properties of the emission model

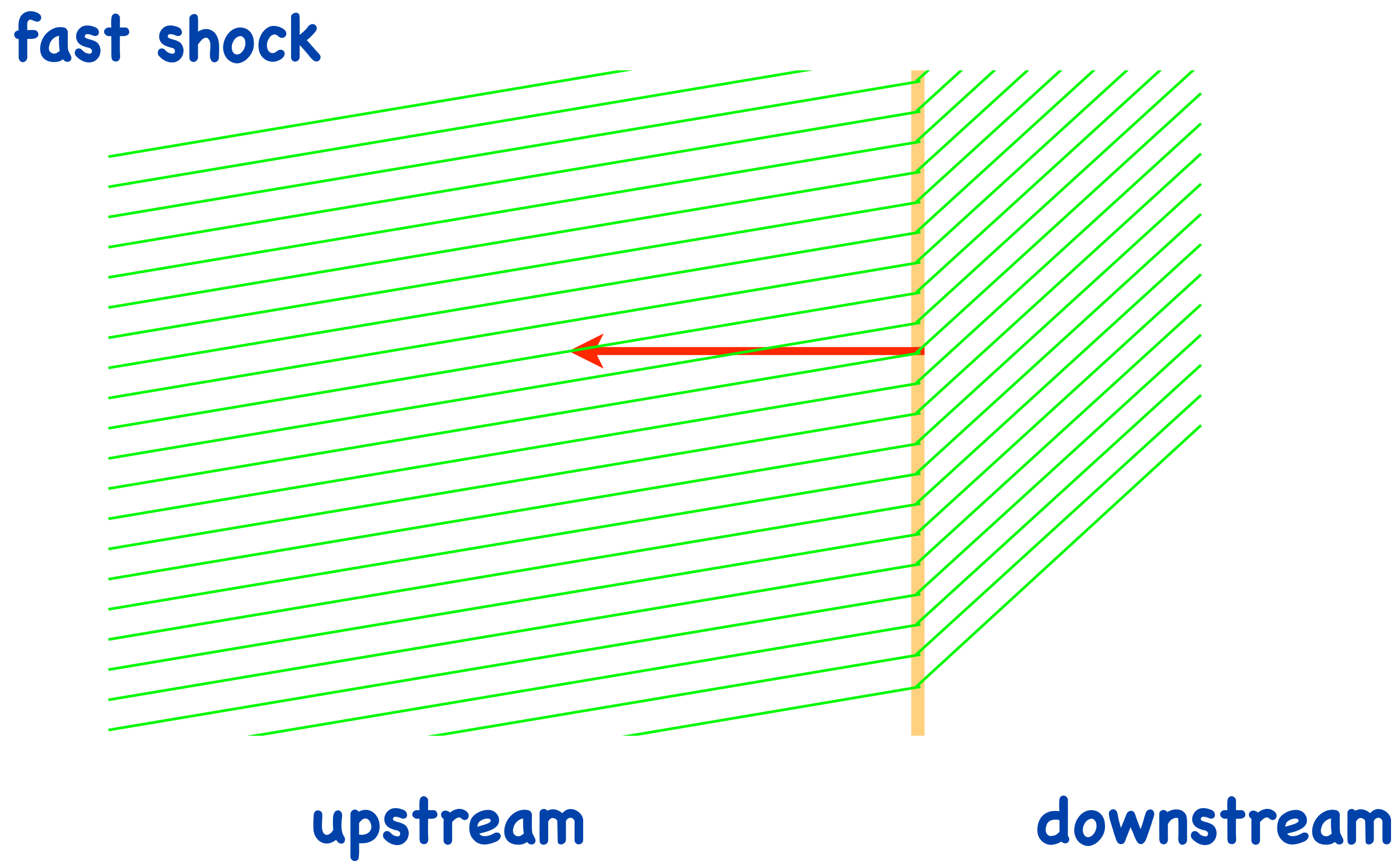




- ψ(M) rises steeply between 2-4
- acceleration efficiency of 5% overproduces radio emission, 10^{-3} seems to be more appropriate

- extension of relics 100 - 300 kpc
- magnetic fields strength of 2 μG does not fit to the width of the A3667 relic

Model for the polarization



- randomly tangled magnetic field upstream
- downstream B direction according jump conditions (fast shock)

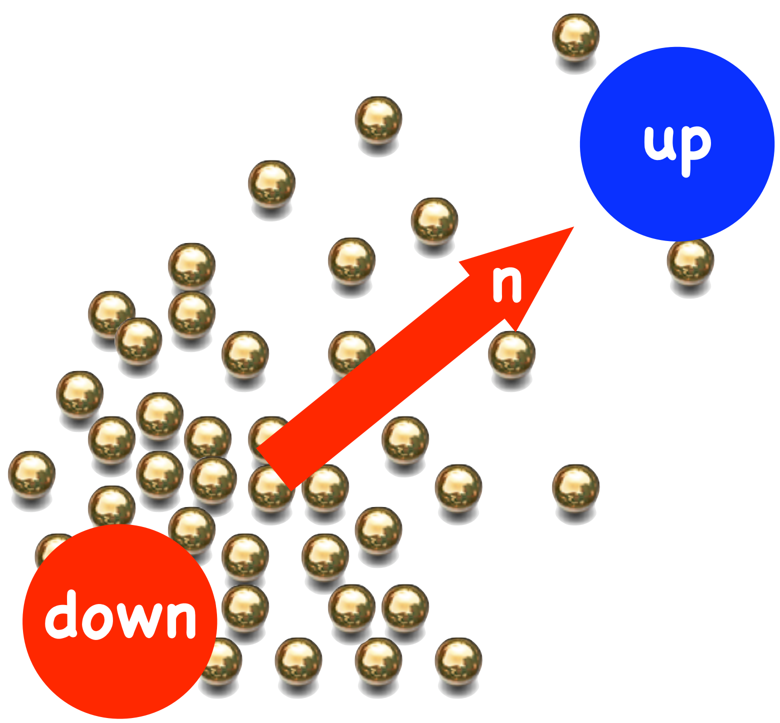
[Burn 66, Enßlin et al 98]

Shock identification in SPH simulation

- determine pressure gradient
  -> shock normal

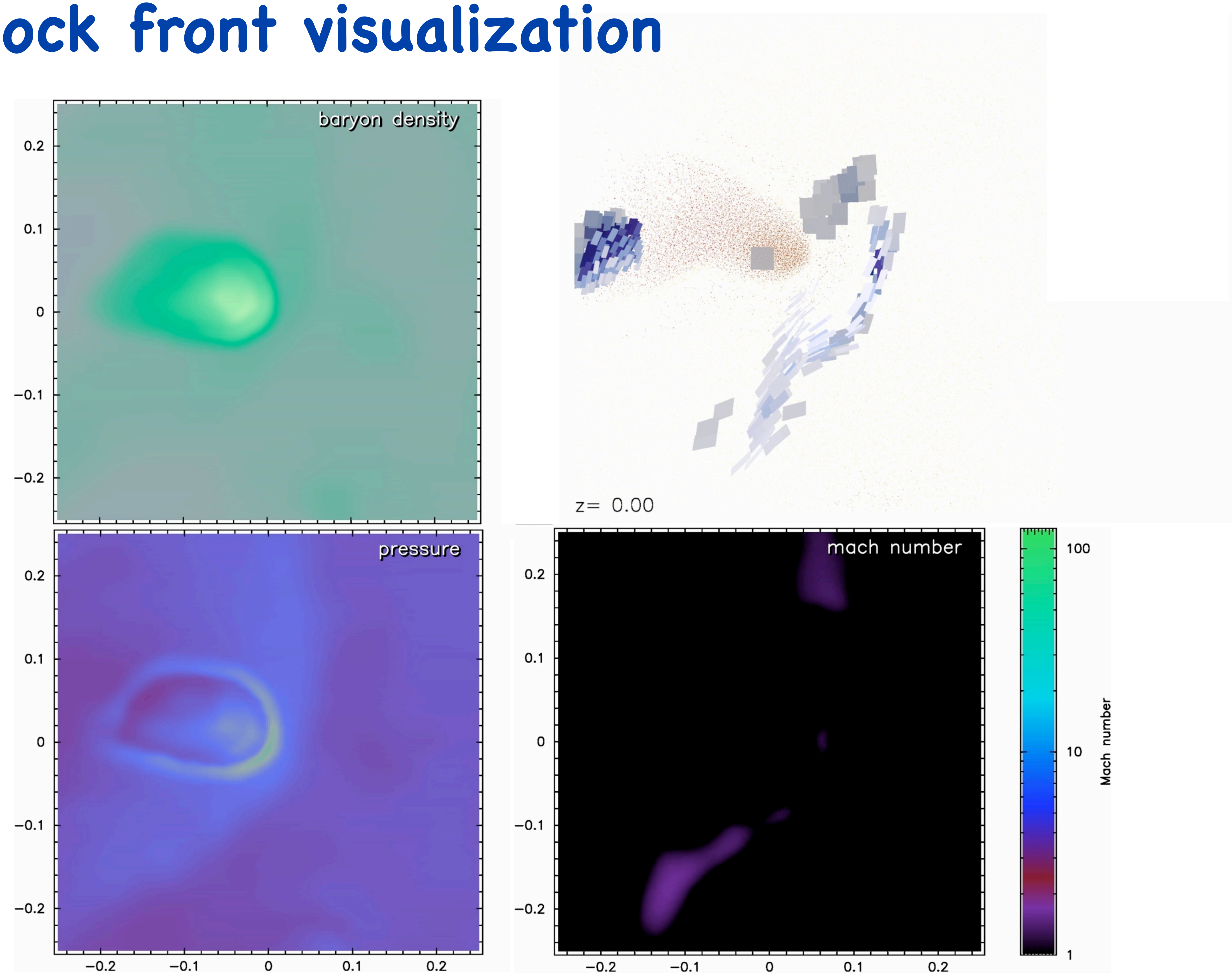
- determine velocity divergence ①,
  density and pressure jump ②,
  entropy jump ③

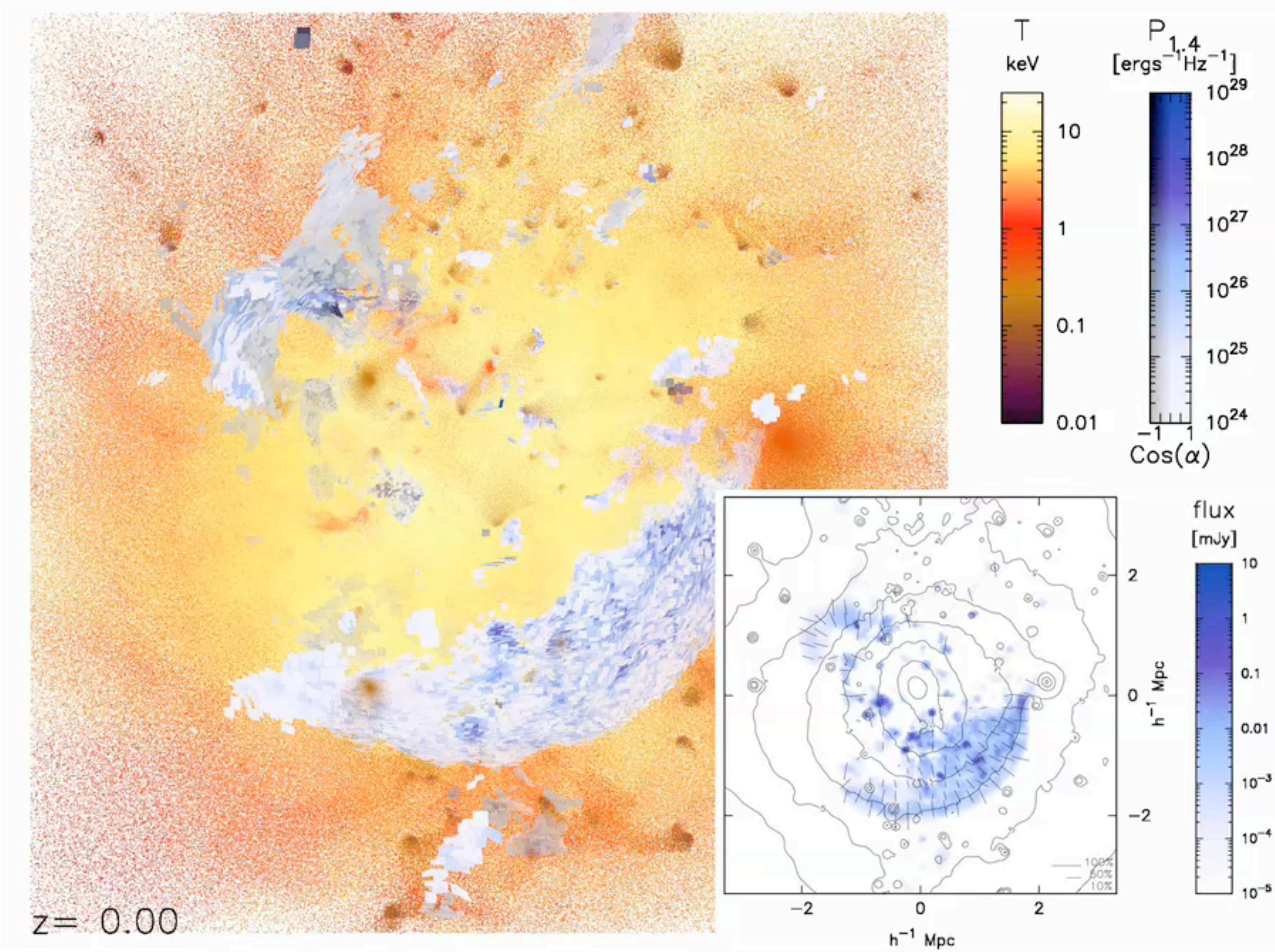
- conservative estimate for
  Mach number
  M = min(①, ②, ③)



SPH particles

Shock front visualization



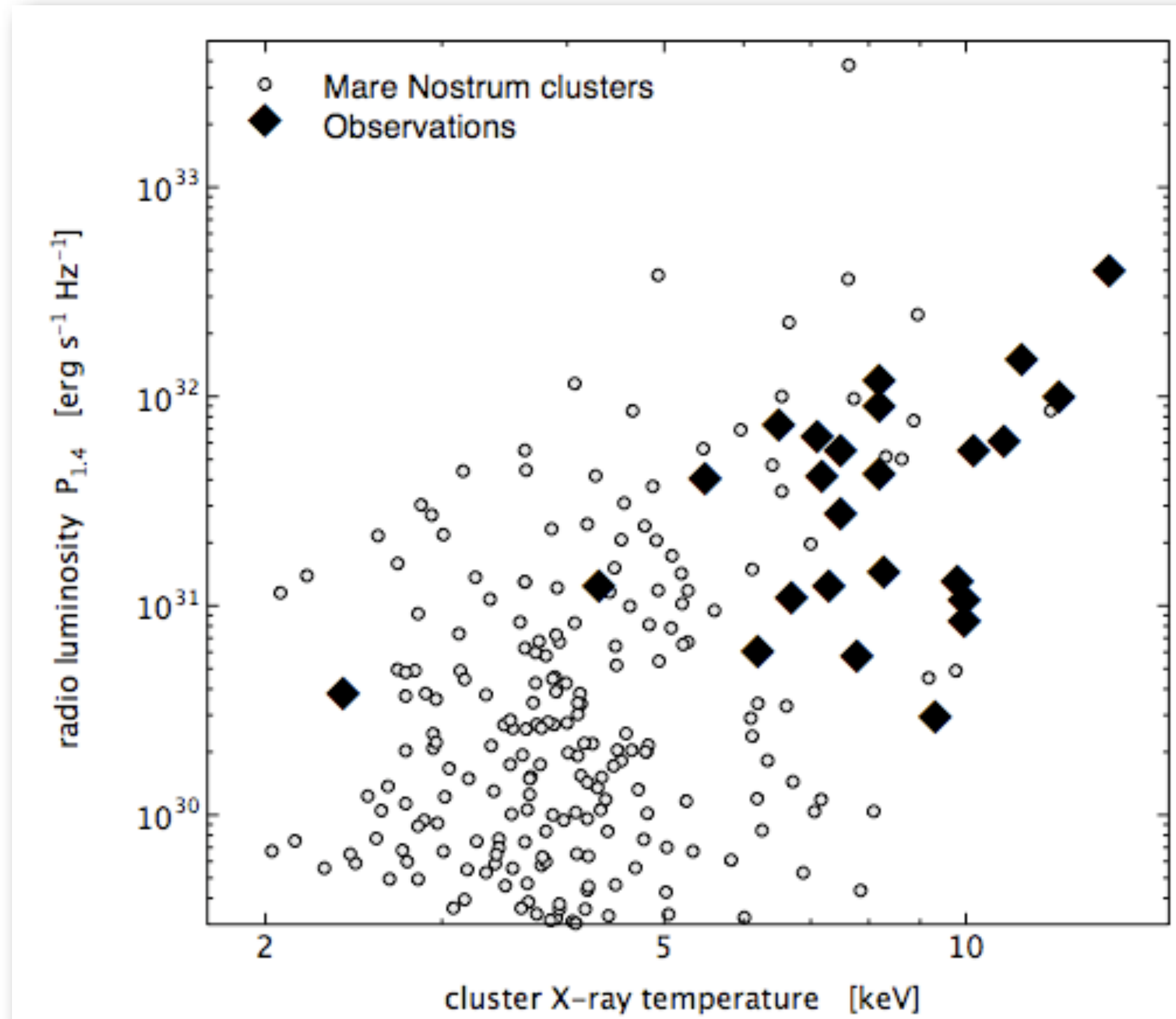

T
keV
10
1
0.1
0.01
P1.4
[ergs⁻¹Hz⁻¹]
10^29
10^28
10^27
10^26
10^25
10^24
−1
1
Cos(α)
flux
[mJy]
10
1
0.1
0.01
10^-3
10^-4
10^-5
2
0
−2
h^-1 Mpc
−2
0
2
h^-1 Mpc
z= 0.00

X-ray — radio correlation

or: 'populate' shock fronts with radio emission

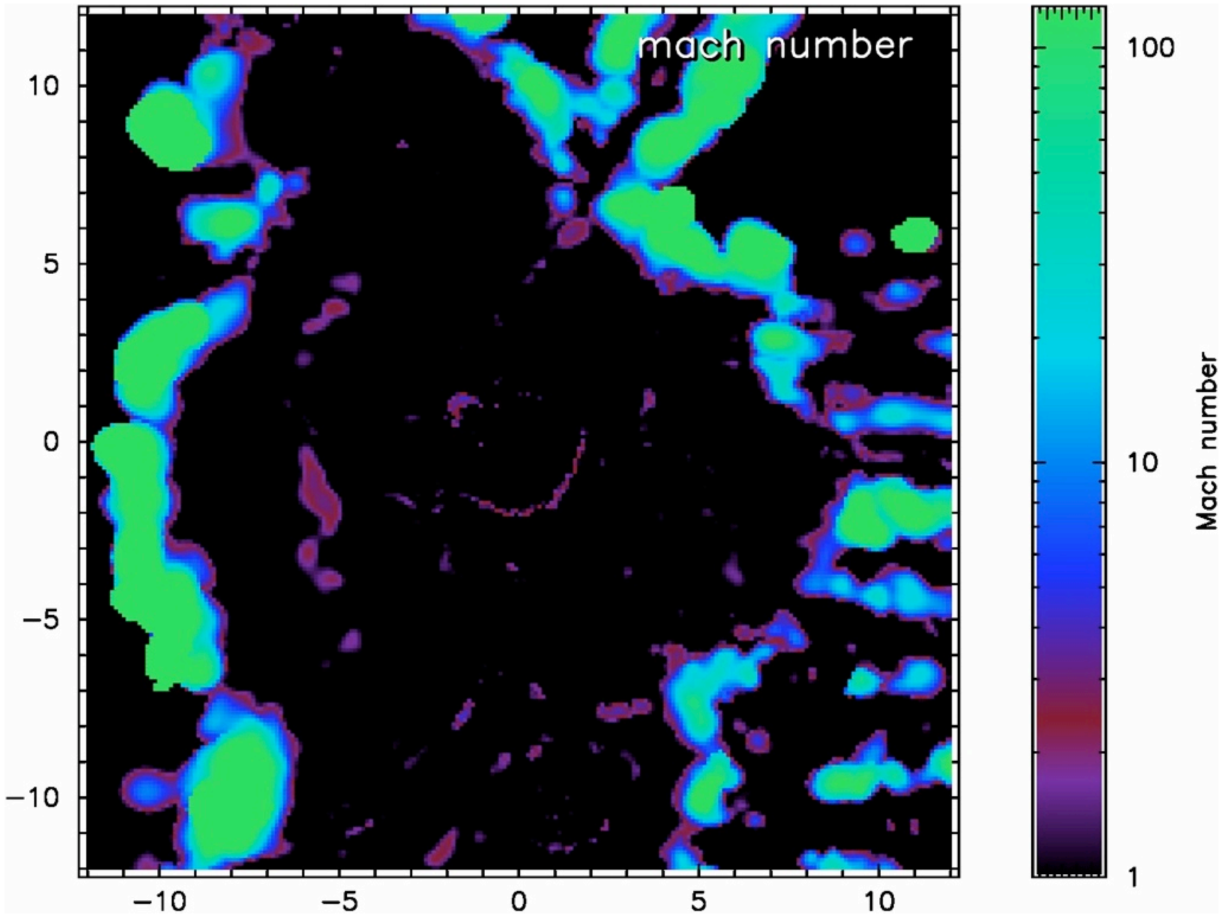
Asumptions:

- $B \propto n^{2/3}$,
  alternative: B self-generated by shocks?
- acceleration efficiency of 10^{-3},
  alternative: Mach number depended efficiency?

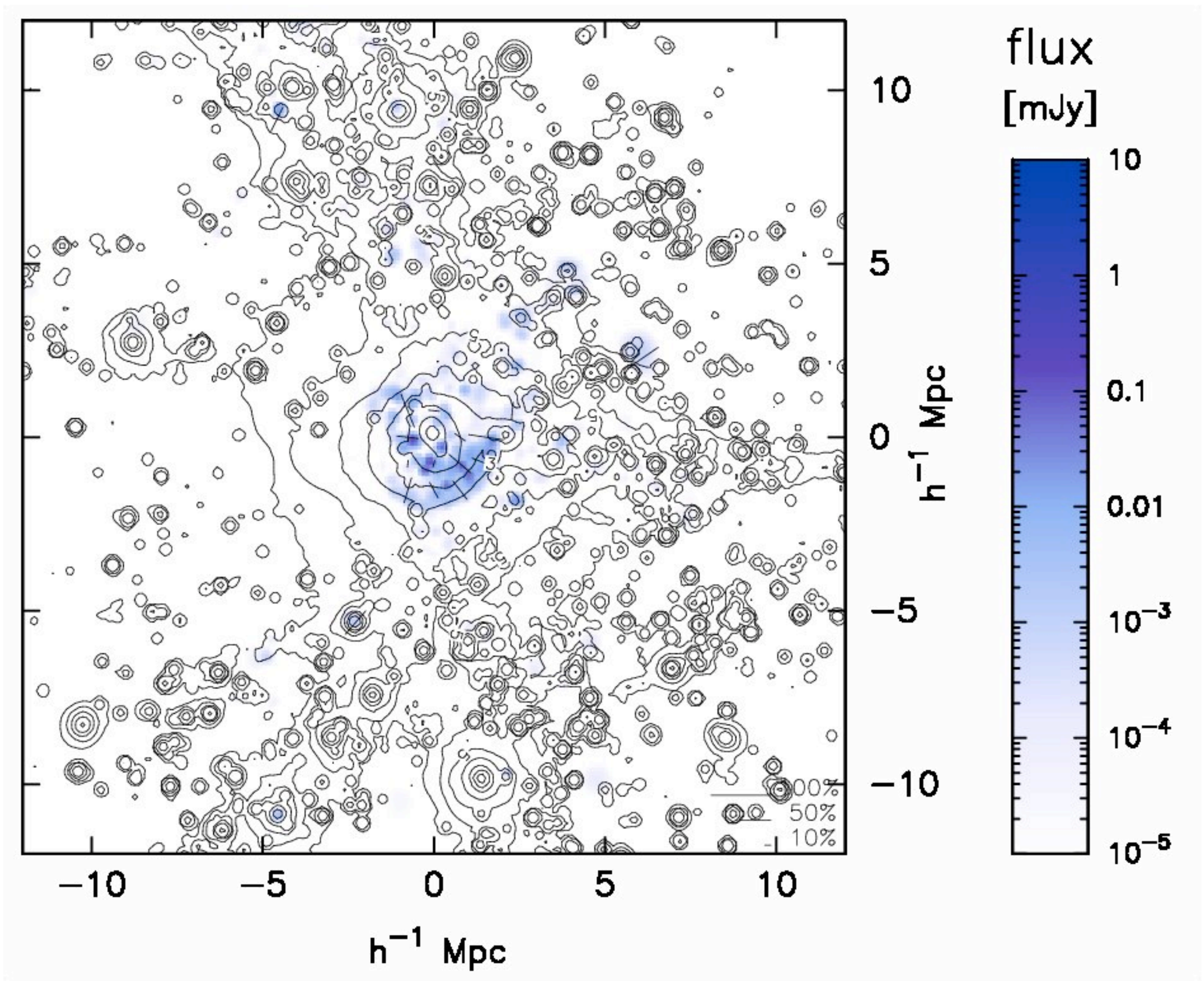


Radio emission from accretion shocks?

Mach number (slice)



X-ray and radio lumin (project.)

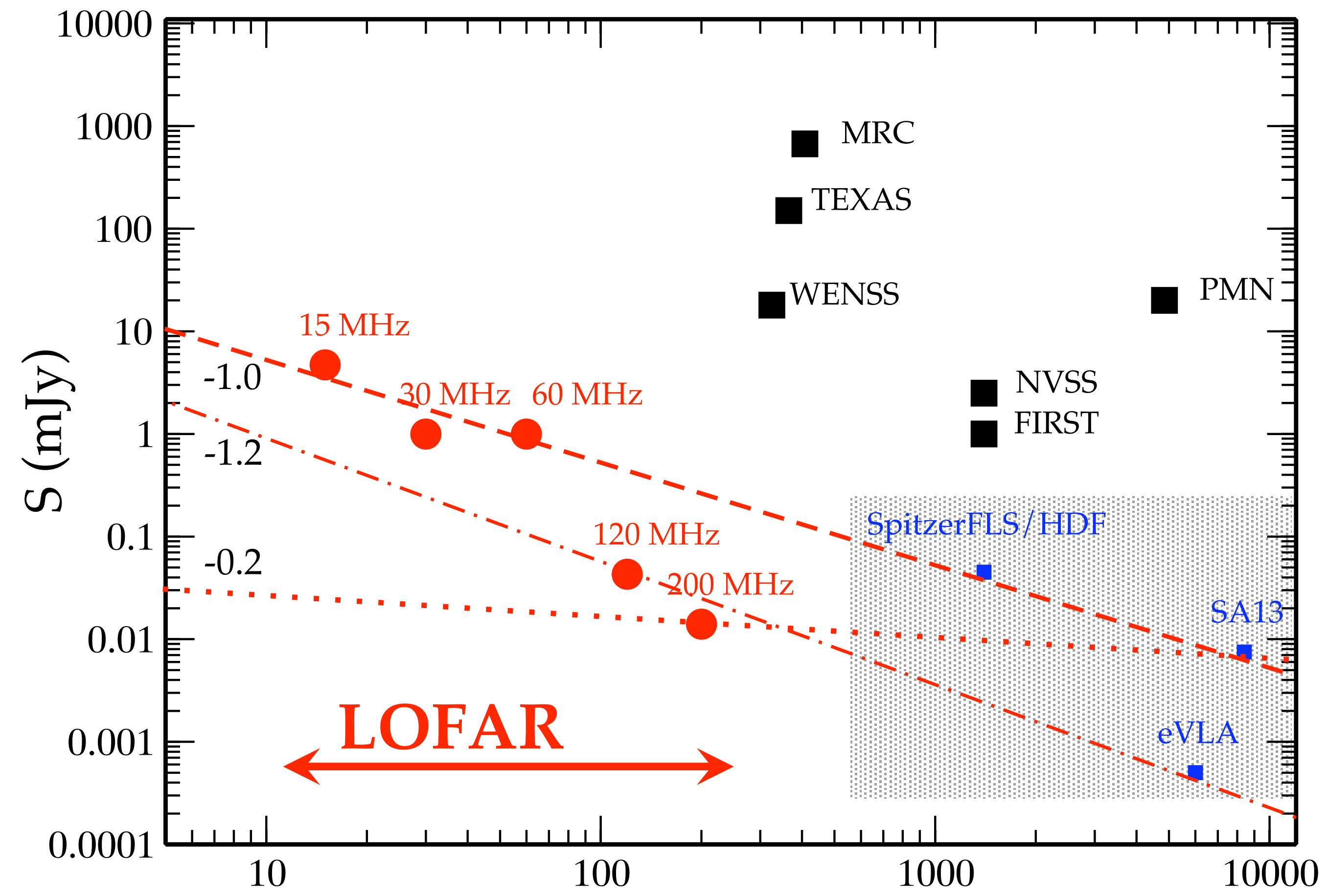


- high efficiency of high Mach number shocks and self-generated B-field may boost radio emission of accretion shocks


LOFAR
30 - 80
& 120 - 240 MHz
aperture
synthesis array
core, remote and
international stations
Nordsee
Ostsee
Atlantik
© Spektrum der Wissenschaft
Emde-Grafik

Sensitivity and resolution of Lofar

Freq. (MHz)	λ (m)	Resolution L = 80 km (arcsec)
15	20.0	41.3
30	10.0	20.6
45	6.67	13.8
60	5.00	10.3
75	4.00	8.25
120	2.50	5.16
150	2.00	4.13
180	1.67	3.44
210	1.43	2.95
240	1.25	2.58



[Roettgering 06]

Conclusion, or: open questions

- We have a roadmap to simulate the shock abundance in a cosmological volume
- LOFAR has the potential to observe hundreds of radio relics
- This will (hopefully) provide an expression for $L_{radio}(M,n,T,..)$
- hence, next time there will be more input to discuss
  - the downstream magnetic field (origin, structure, ...)
  - efficiency of electron acceleration