Low-frequency Radio Observations of Galaxy Cluster Merger Shocks

Reinout van Weeren

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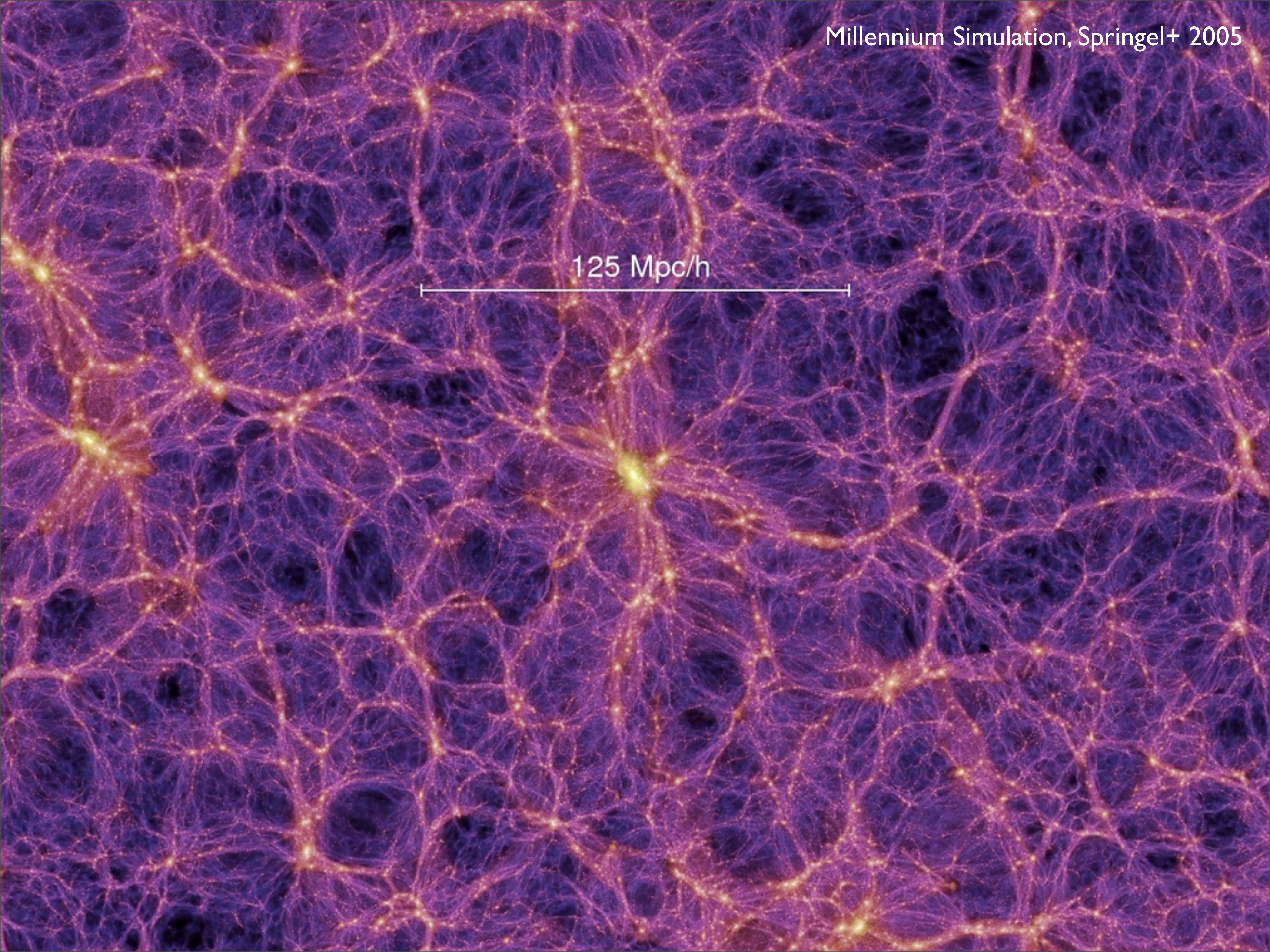
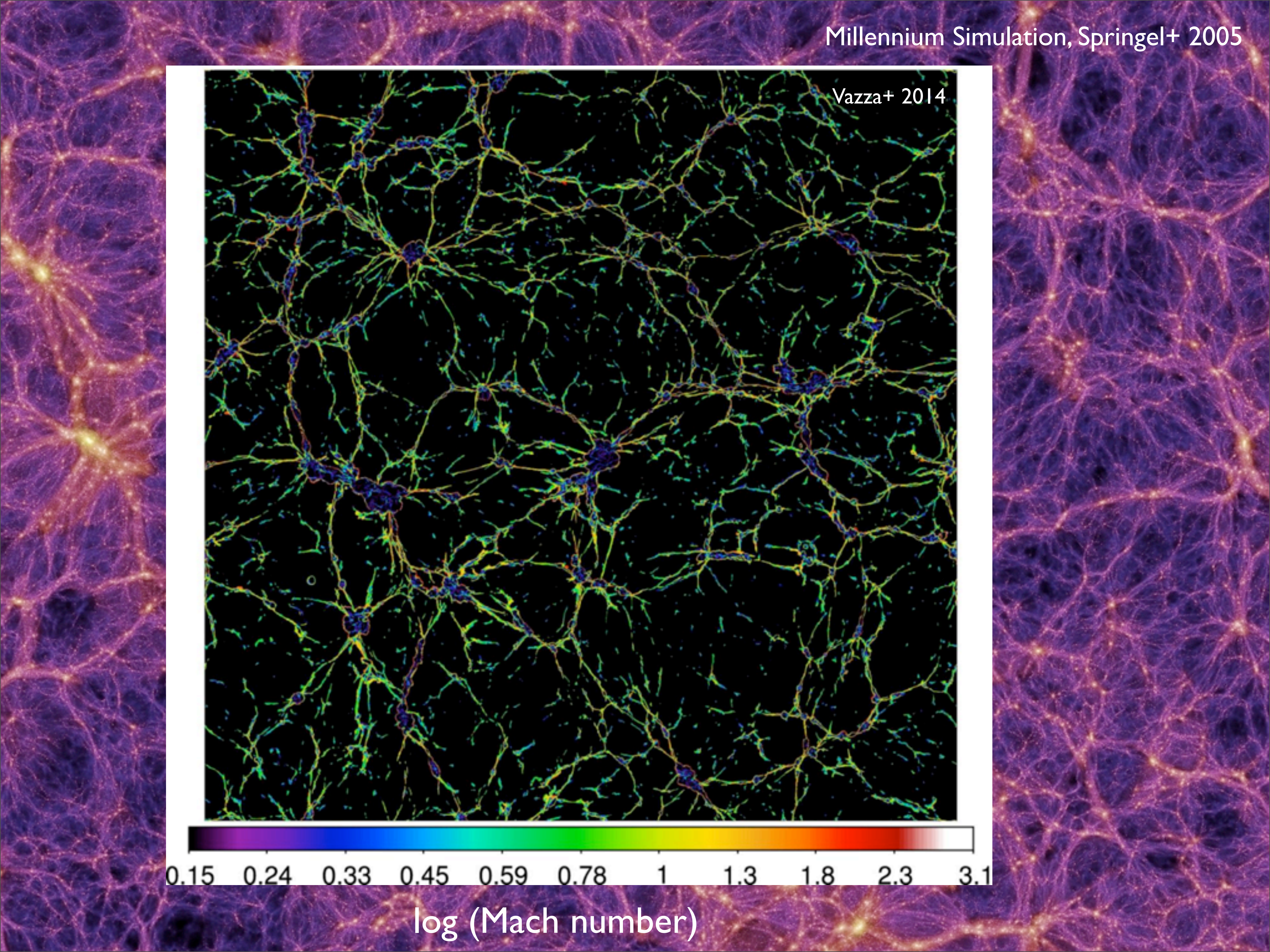
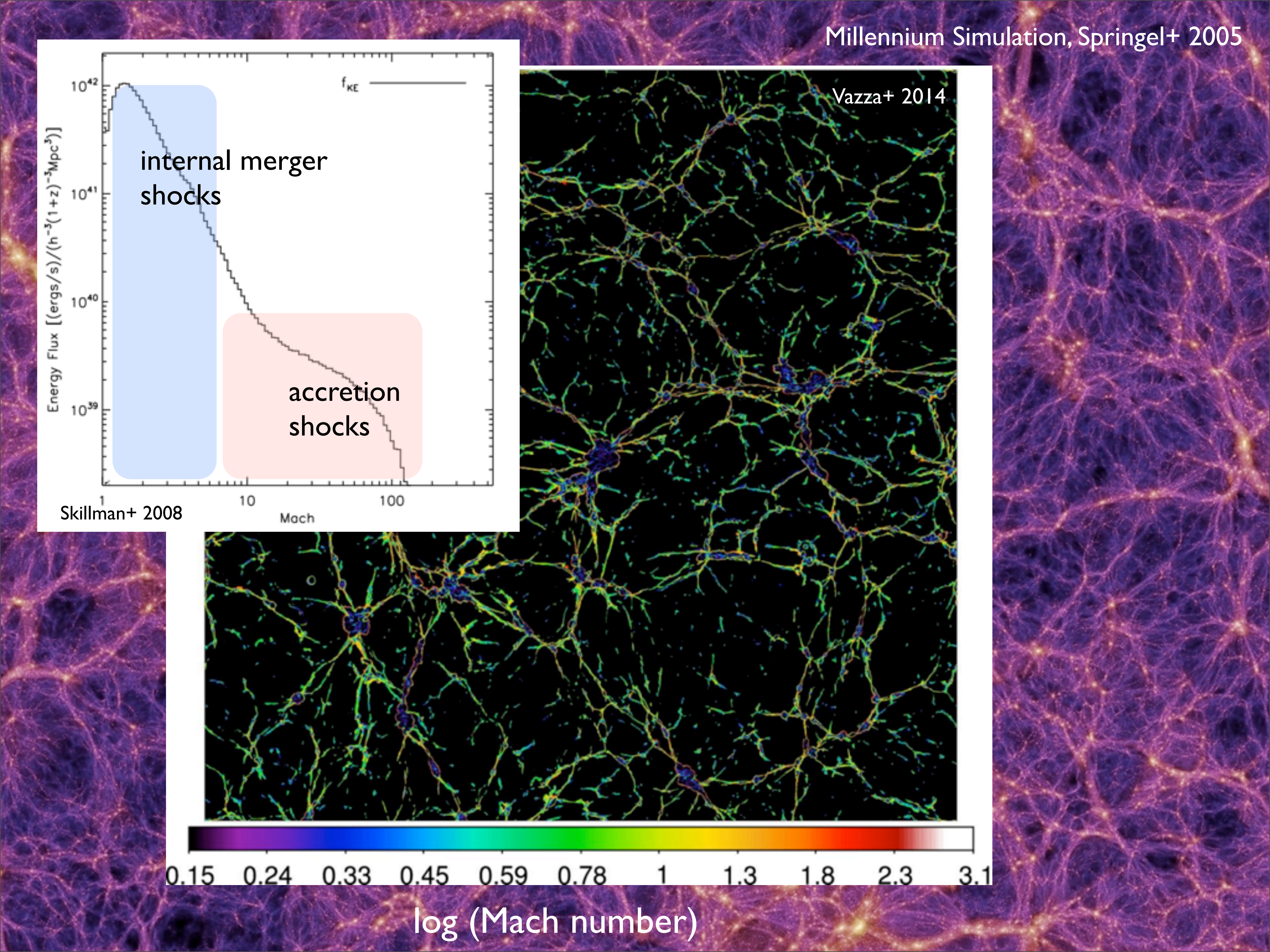
H. Intema, A. Stroe, G. Ogrean, F. Andrade-Santos W. Forman, C. Jones,
M. Brüggen, H. Röttgering, A. Bonafede, G. Brunetti, M. Hoeft

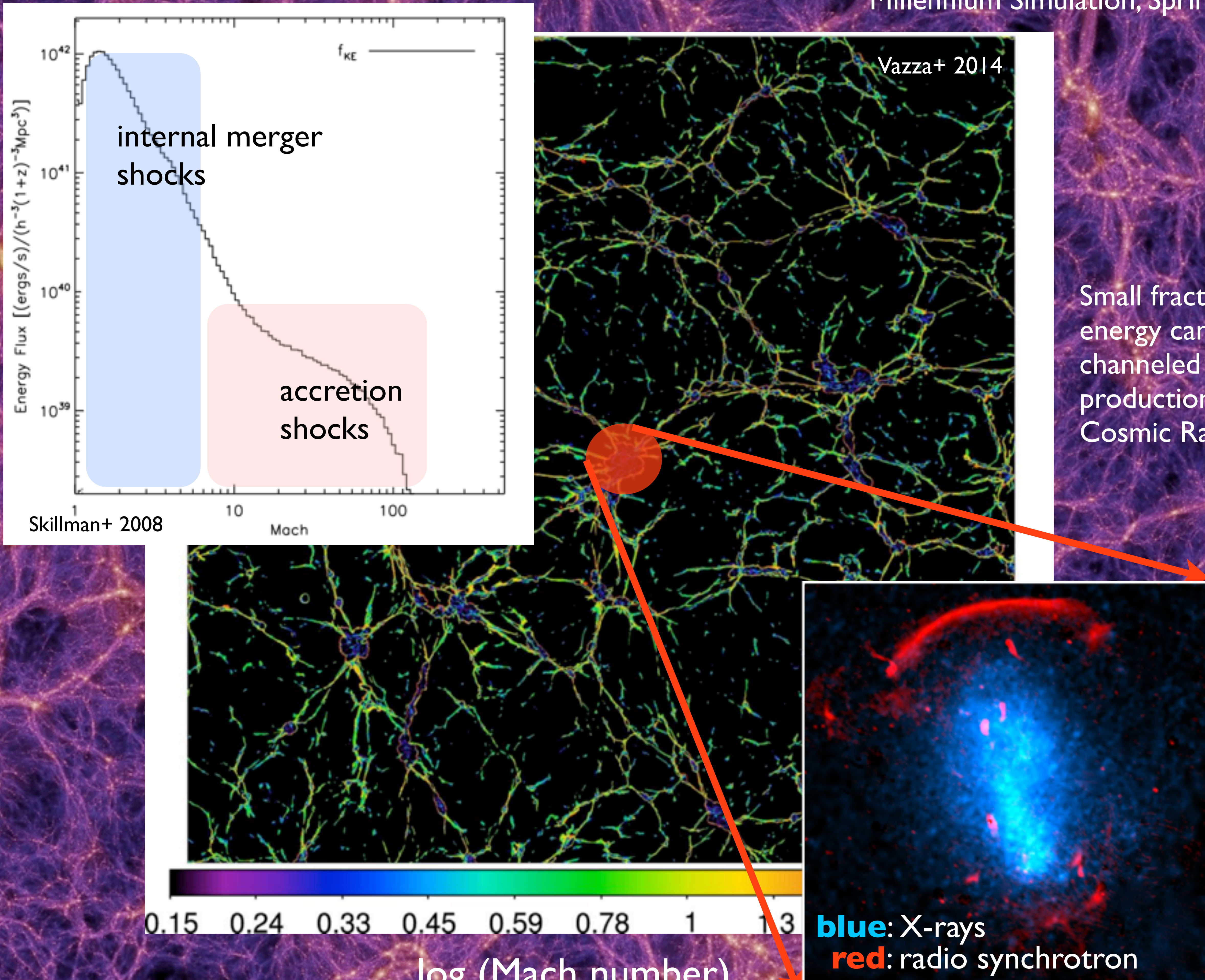

Millennium Simulation, Springel+ 2005
125 Mpc/h


Millennium Simulation, Springel+ 2005
Vazza+ 2014
0.15 0.24 0.33 0.45 0.59 0.78 1 1.3 1.8 2.3 3.1
log (Mach number)



Millennium Simulation, Springel+ 2005
Vazza+ 2014
internal merger shocks
accretion shocks
Skillman+ 2008
f_KE
Energy Flux [(ergs/s)/(h^-3(1+z)^-3Mpc^3)]
10^42
10^41
10^40
10^39
1
10
100
Mach
0.15 0.24 0.33 0.45 0.59 0.78 1 1.3 1.8 2.3 3.1
log (Mach number)

Millennium Simulation, Springel+ 2005



Small fraction of the energy can be channeled into the production of Cosmic Rays

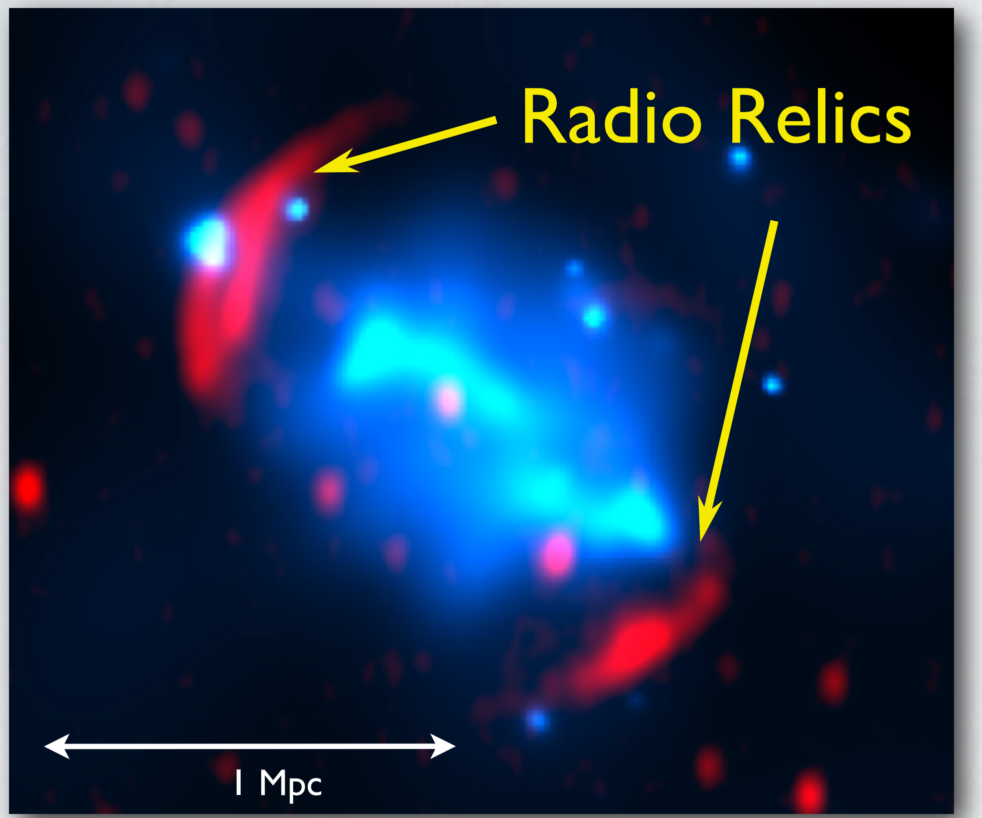
QUESTIONS

- Physics of shocks & turbulence
- Origin of Cosmic Rays (CR) and magnetic fields in the ICM
  - Particle acceleration mechanisms
  - Acceleration efficiency of shocks/turbulence
  - Magnetic field amplification
- Contribution of CRs and B-fields to the ICM pressure budget

DIFFUSE CLUSTER RADIO EMISSION

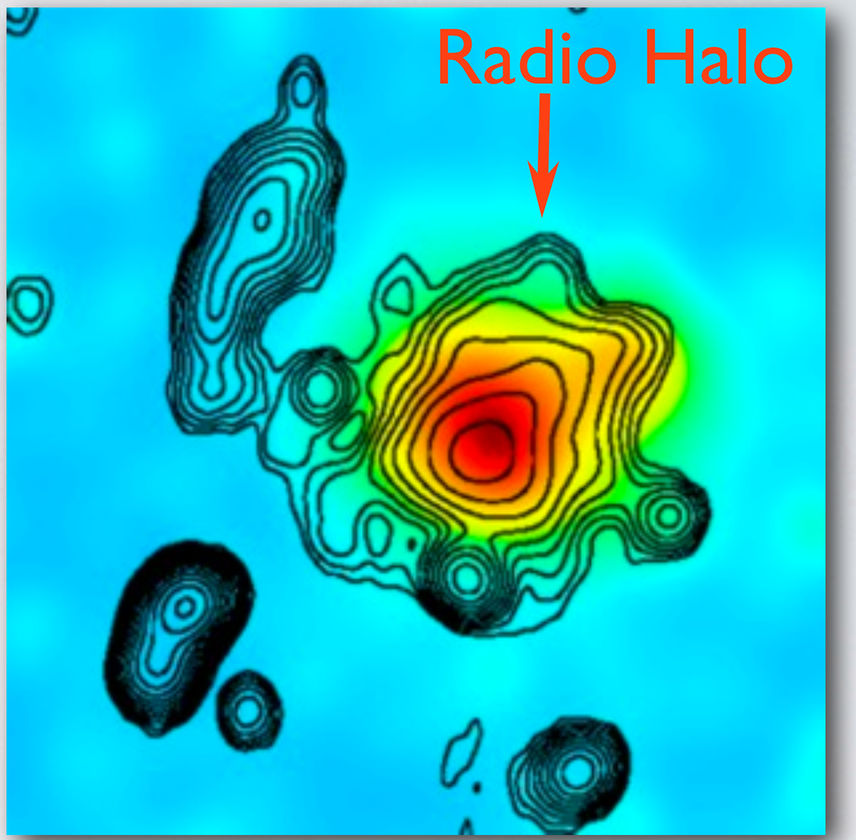
latest review paper: Brunetti & Jones 2014

Radio (WSRT) + X-rays (XMM)



MACS J1752.0+4440 (van Weeren+ 2012; Bonafede+ 2012)

X-ray image + radio contours



Abell 2744; Feretti+ 2012, Govoni+ 2001

GIANT RADIO RELICS:

- Cluster outskirts, elongated
- Radio emission traces merger shocks
- Particle acceleration mechanism :
  - diffusive shock acceleration? (Ensslin+ 1998)

GIANT RADIO HALOS:

- Smooth, centrally located
- Particle acceleration mechanism:
  - Radio emission generated via turbulent re-acceleration mechanism? (Brunetti+01, ...)
  - Radio emission from secondary electrons (products of hadronic collisions)? (Dennison 1980, ...)

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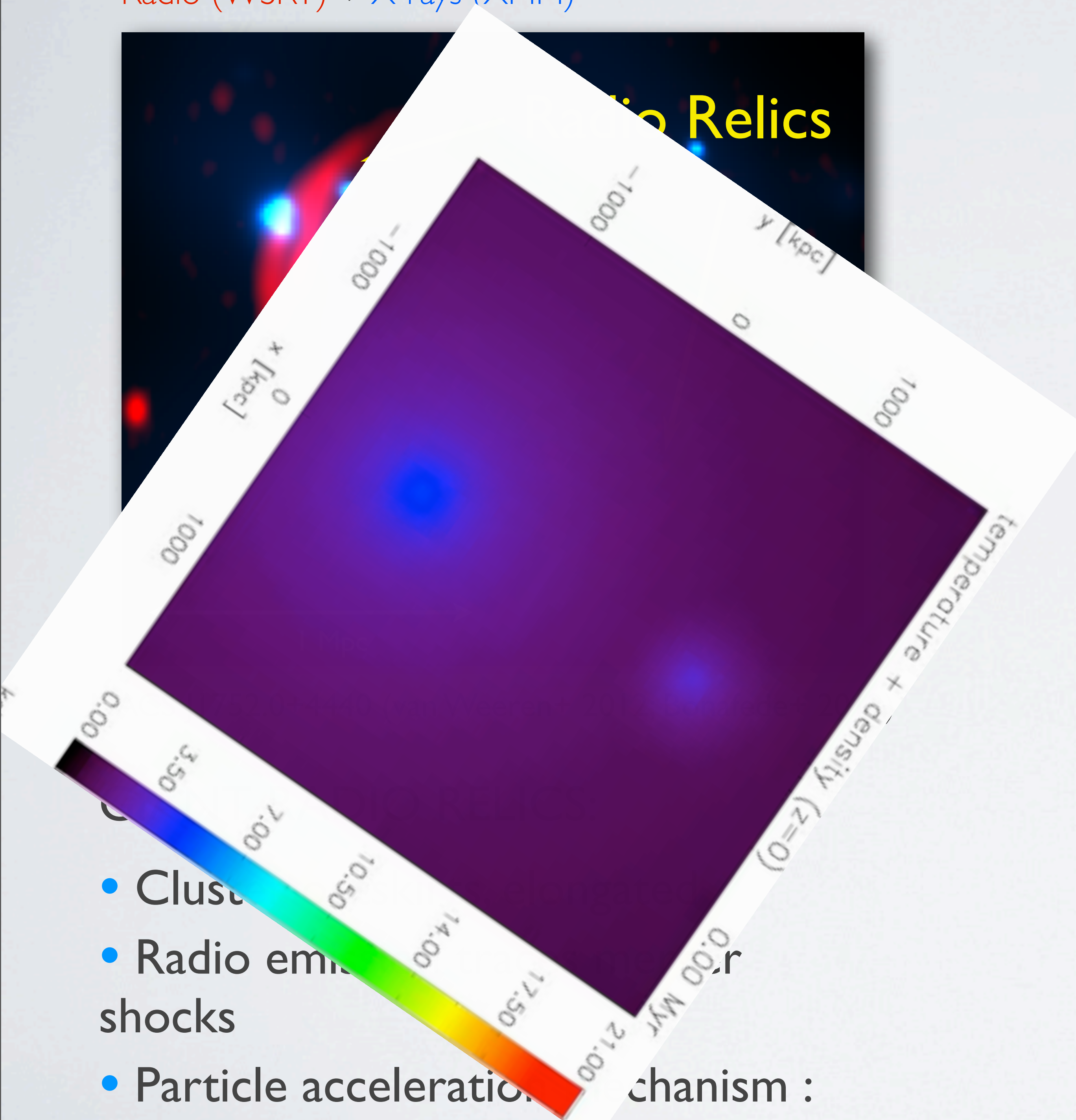

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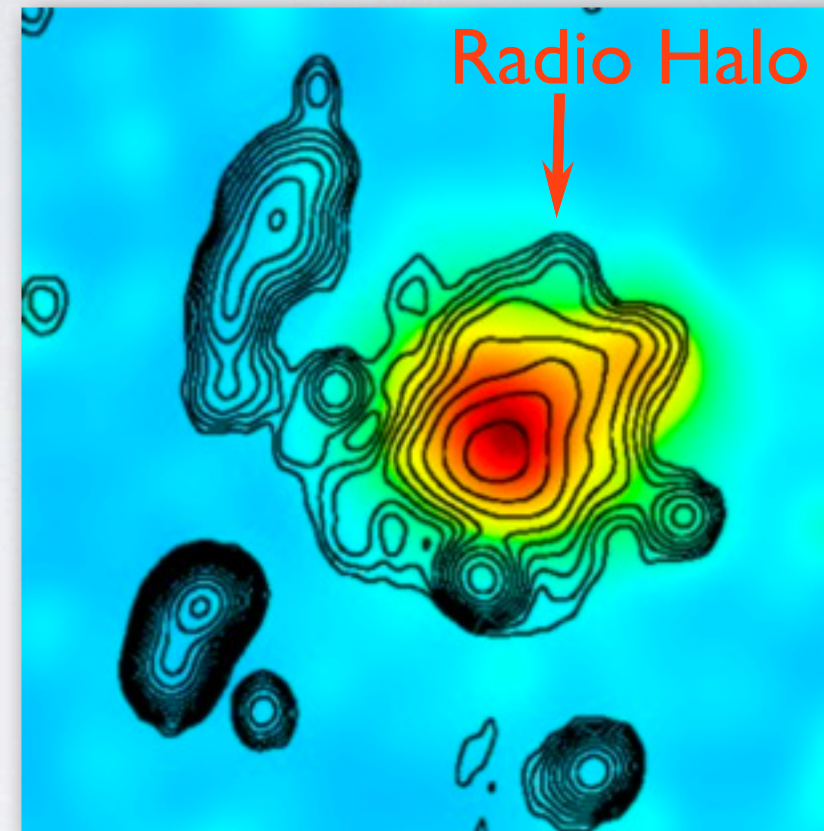

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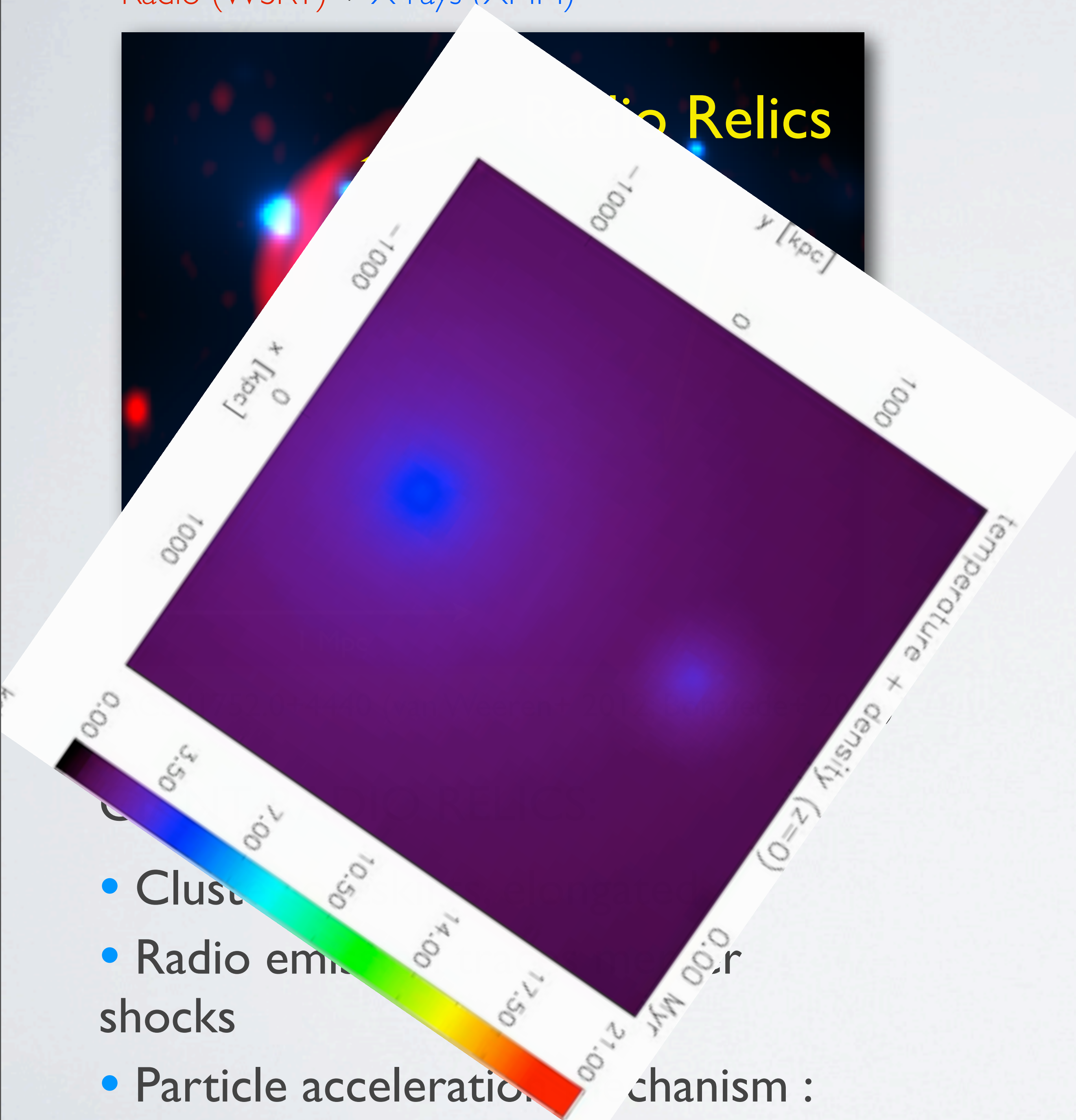

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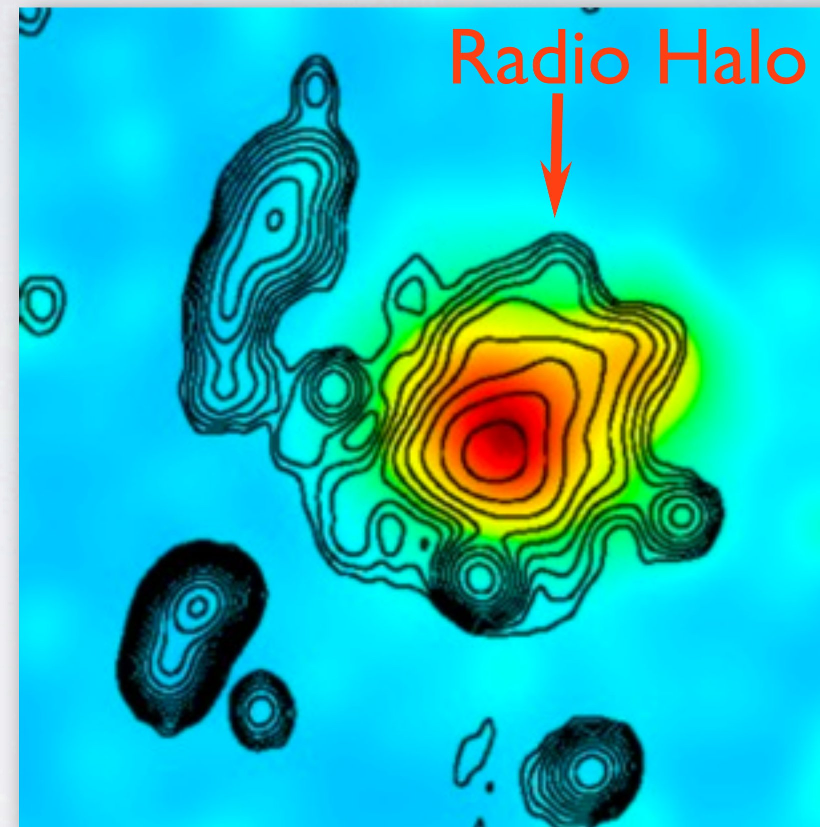

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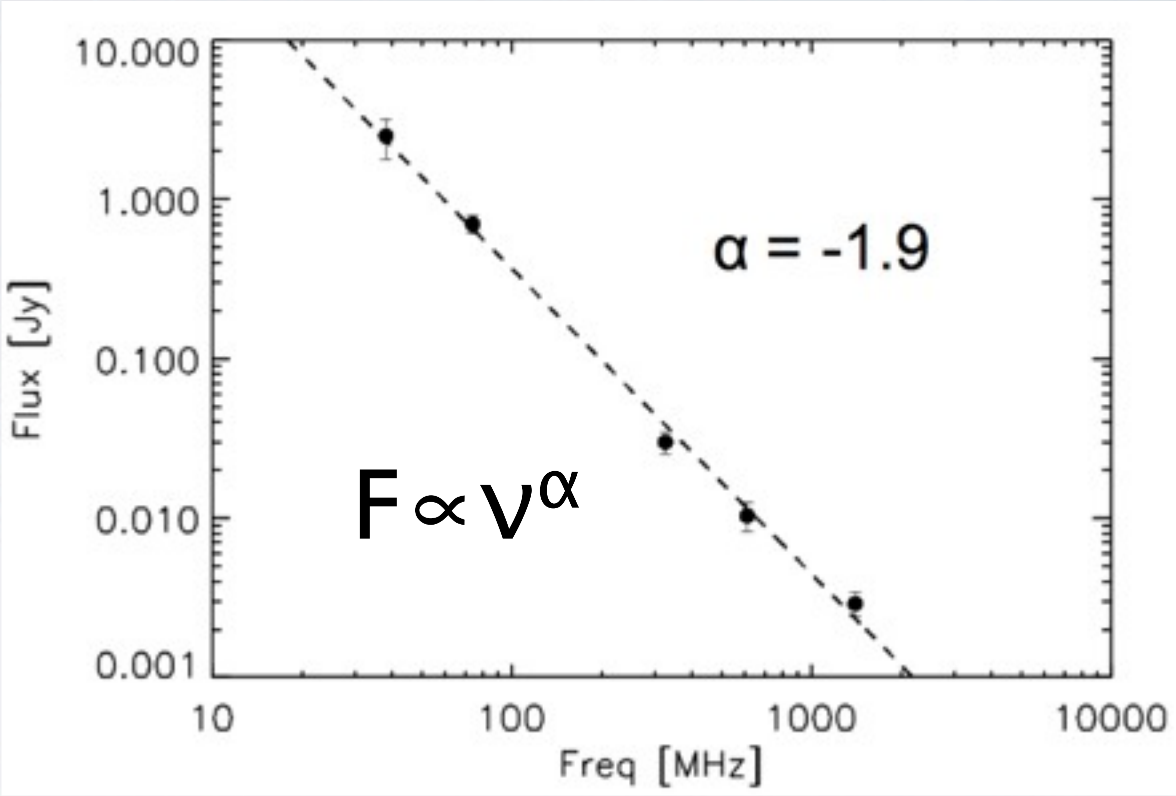
BACKGROUND: RADIO SPECTRAL INDEX

Acceleration produces power-law particle distribution

$n(E) \propto E^{-p}$, $p = 1 - 2\alpha$

"*injection spectral index*" α set by acceleration mechanism/ source physical condition



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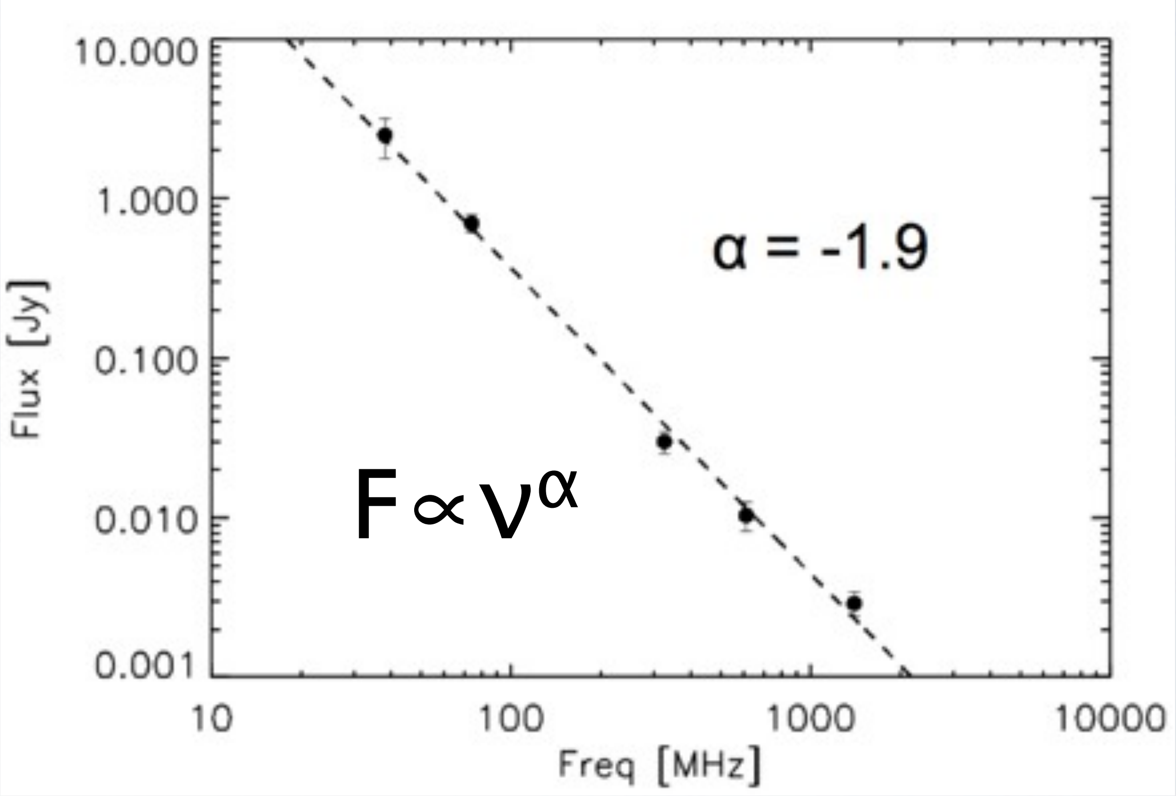
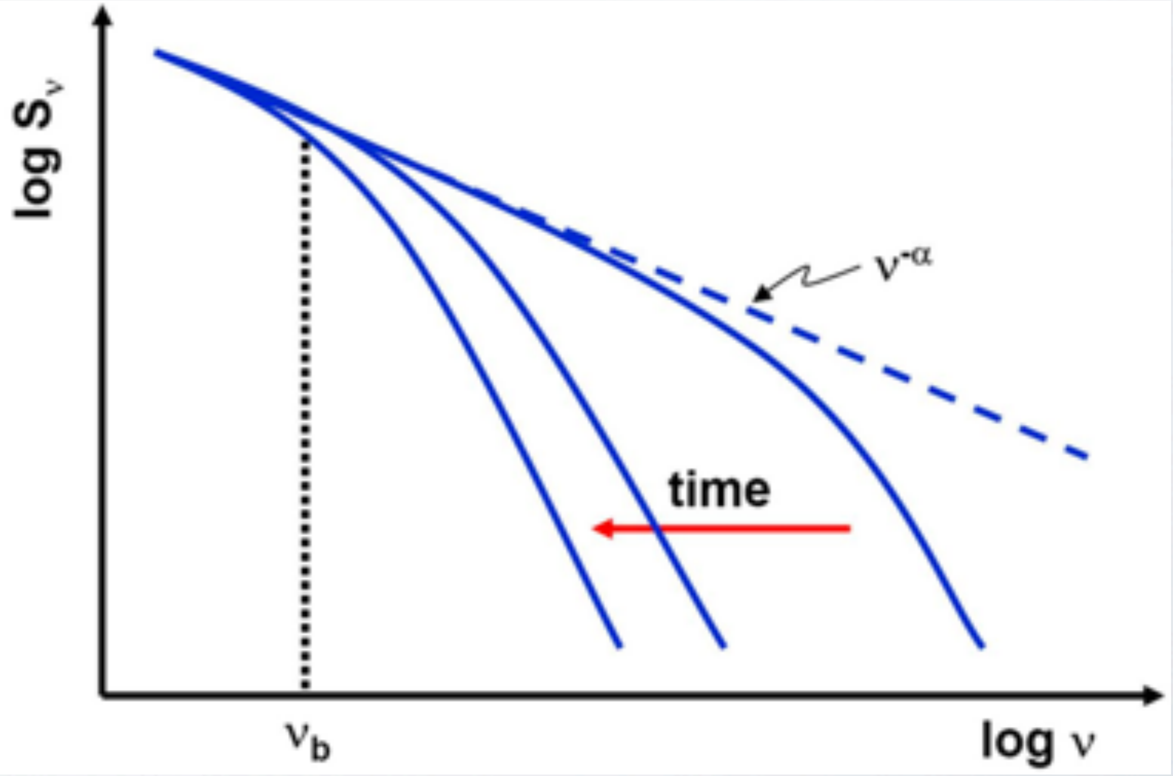


Energy losses radiating electrons:

- synchrotron losses
- Inverse Compton losses

"*Spectral ageing*"/ "*electron cooling*"

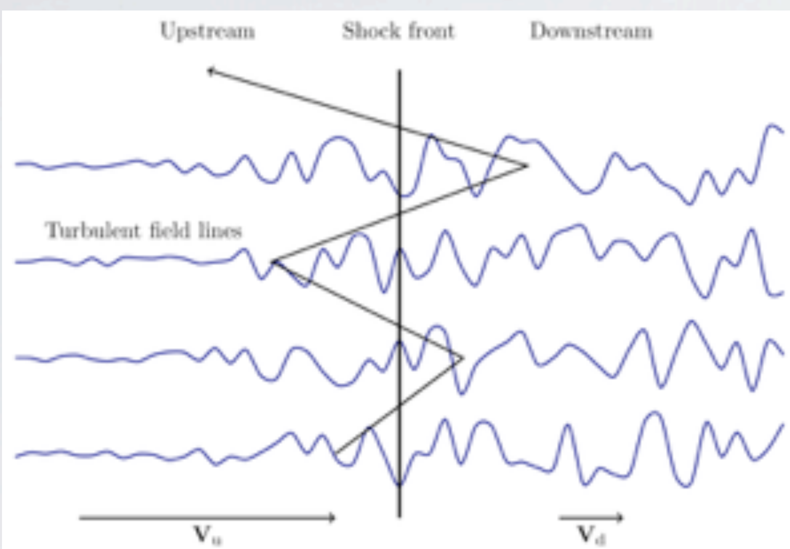
$dE/dt \propto - E^2$



→ spectrum steepens and curves with time

Origin of the radiating electrons ?

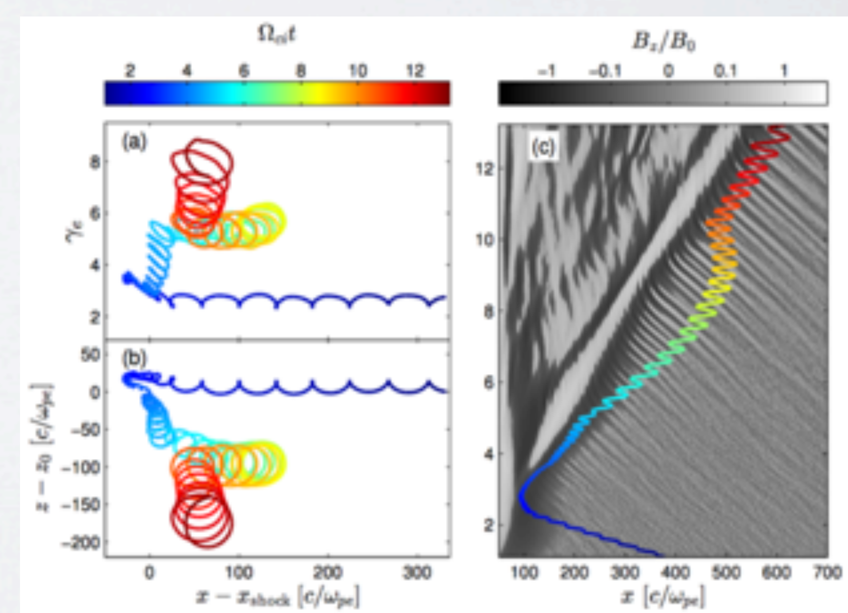
- Radiative lifetime of electrons is 10^8 yr << diffusion timescale (Jaffe 1977) → electrons are **accelerated in-situ** in the ICM
- Merger connection: giant radio relics and halos are **only** found in disturbed galaxy clusters
- ICM: Particle acceleration poorly understood in this regime



Relics: Diffusive shock acceleration (DSA) ?

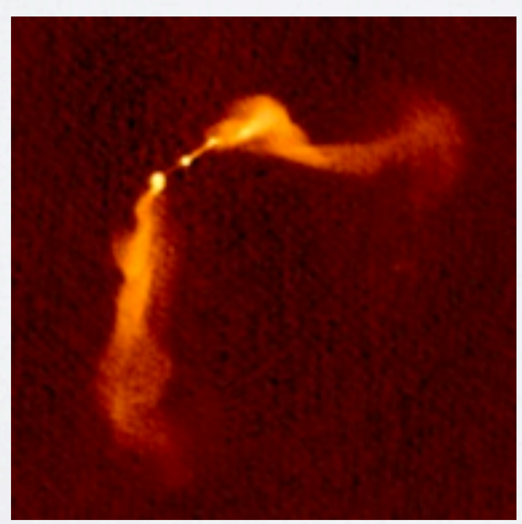
- Particles accelerated by multiple crossings of a shock front (first order Fermi process)
- Recent PIC simulations show efficient electron acceleration for low-Mach number shocks

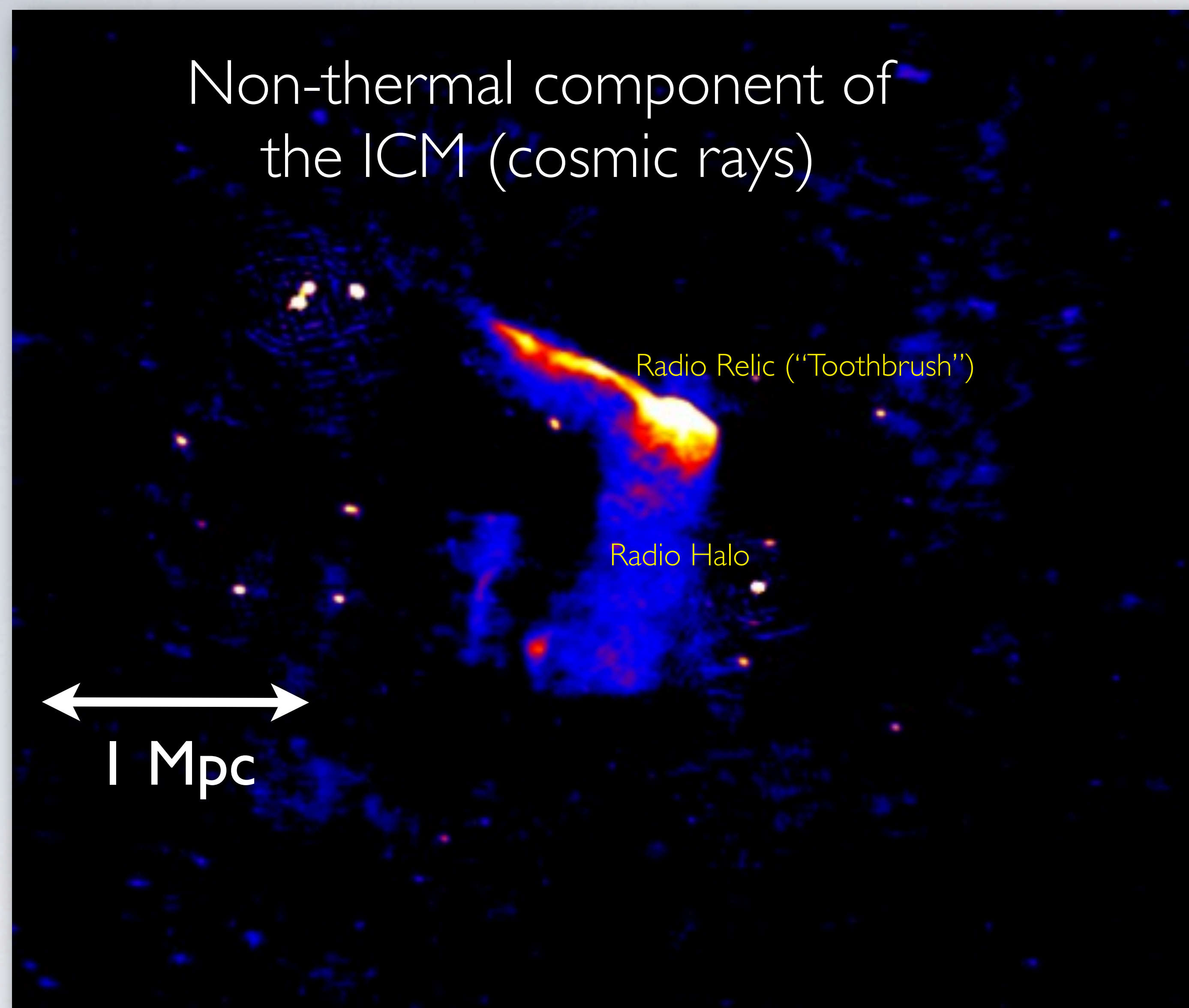
Guo+ 2014



Re-acceleration ?

- Relativistic particles accumulated over the lifetime of a cluster





GMRT radio image (325 MHz)

1RXS J0603.3+4214 (z=0.225)

Found by inspecting 1.4 GHz NVSS & 325 MHz WENSS radio survey images

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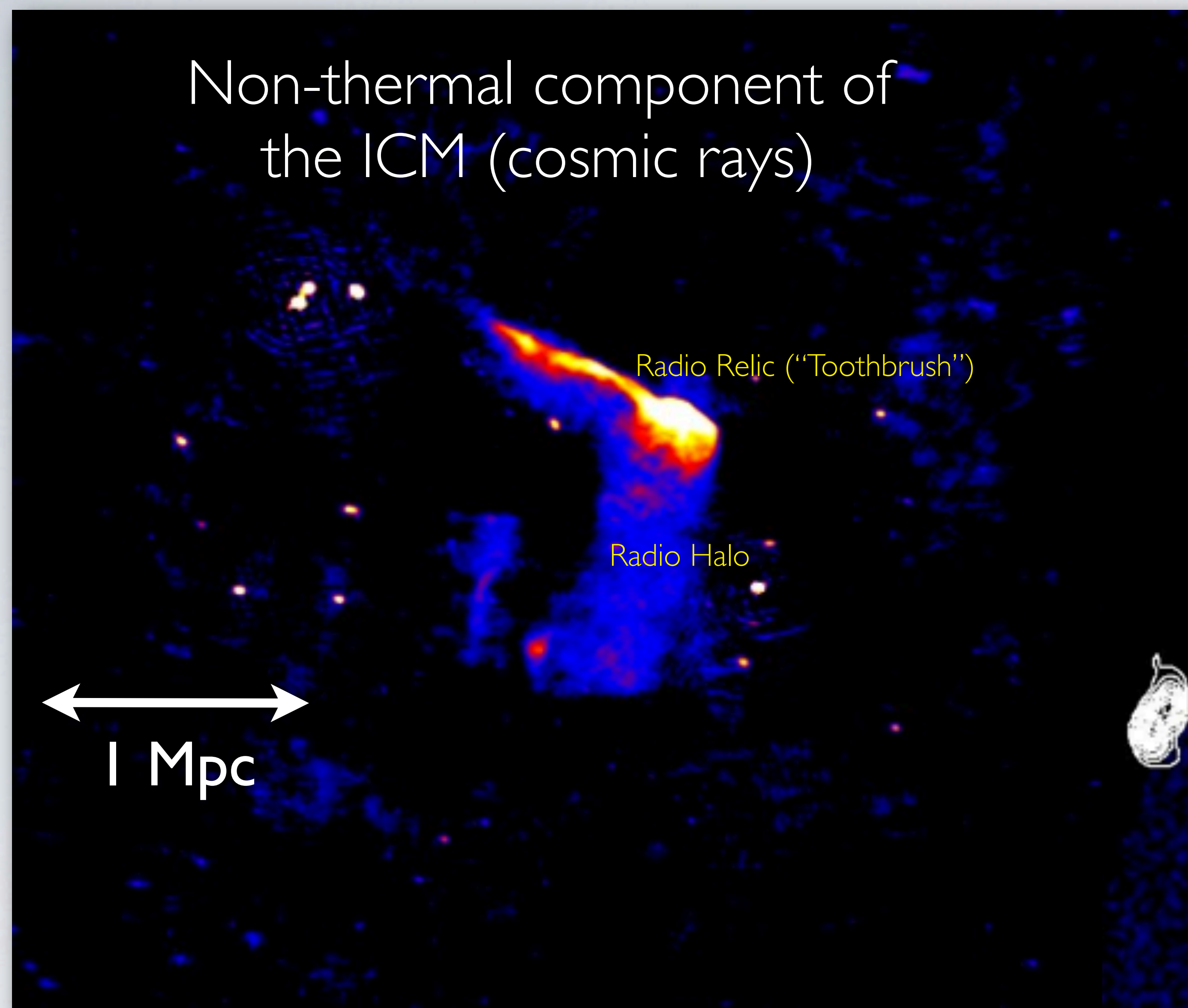

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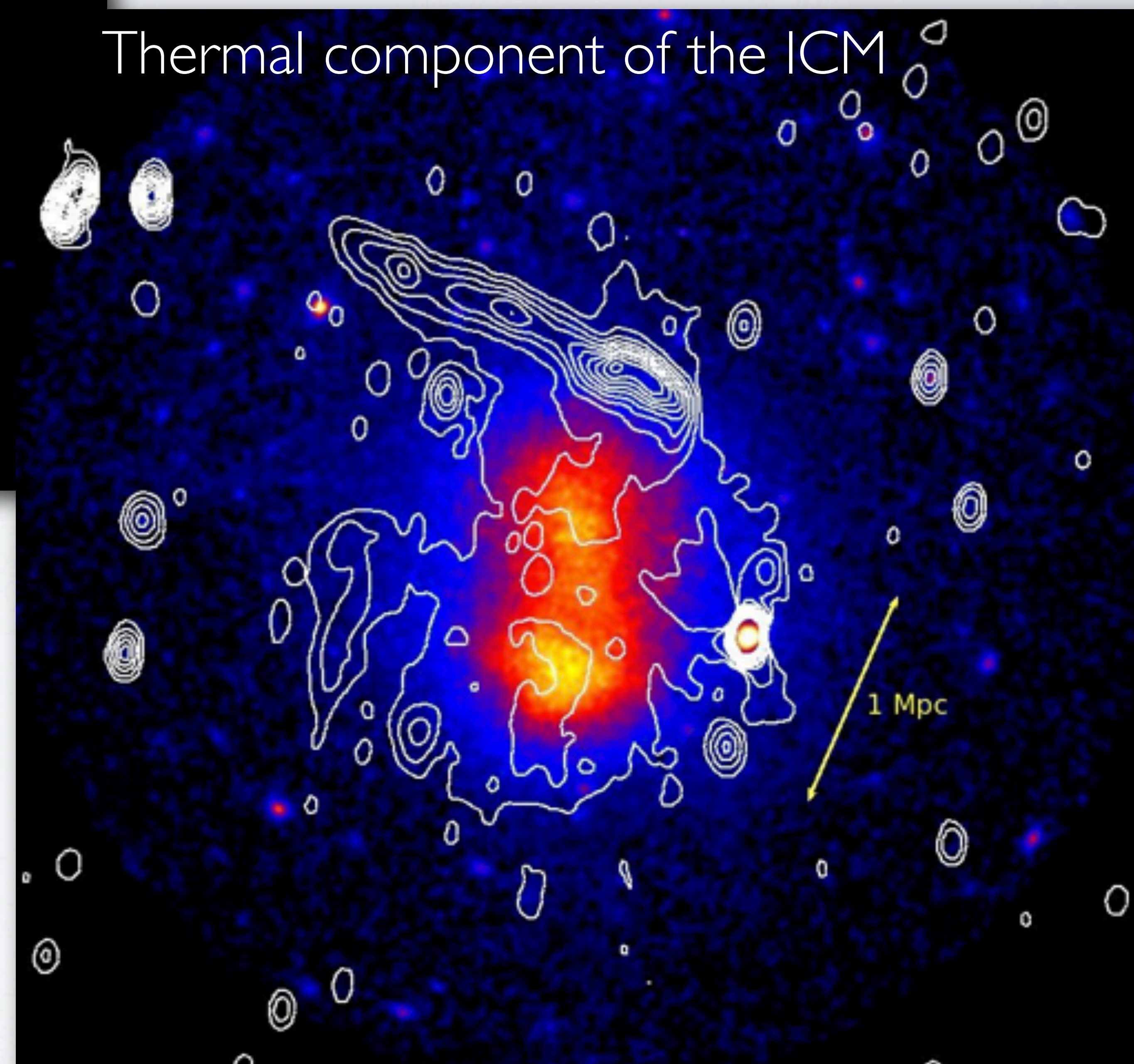
XMM X-ray image (+radio contours)



Ogrean+2013; van Weeren+2012

Follow-up XMM observations by Ogrean+2013:

- $L_X \sim 10^{45}$ erg s^{-1}, T= 7.5 keV
- main merger event in the NS direction
- evidence for shocks (M~1.5) via surface brightness jumps

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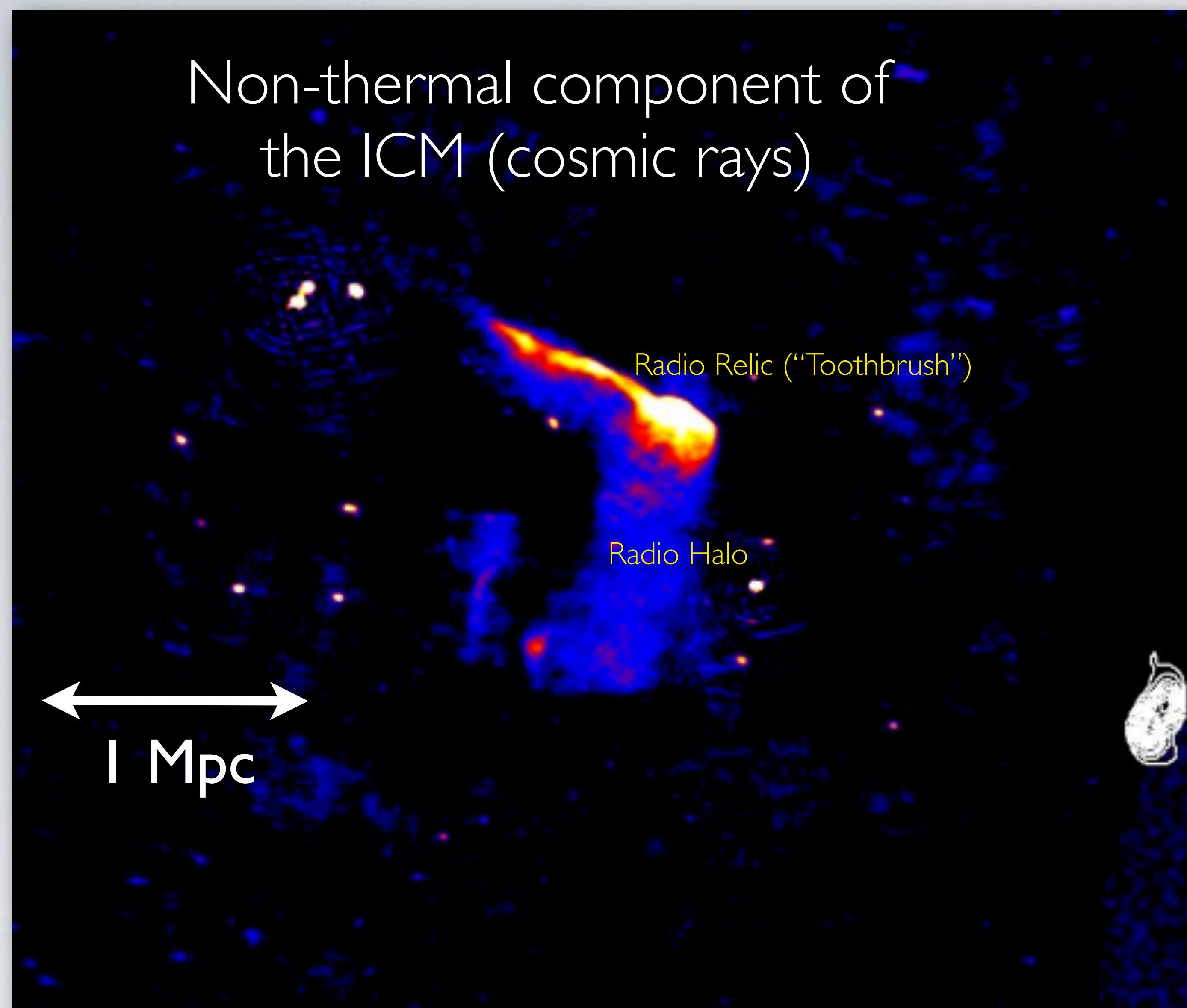

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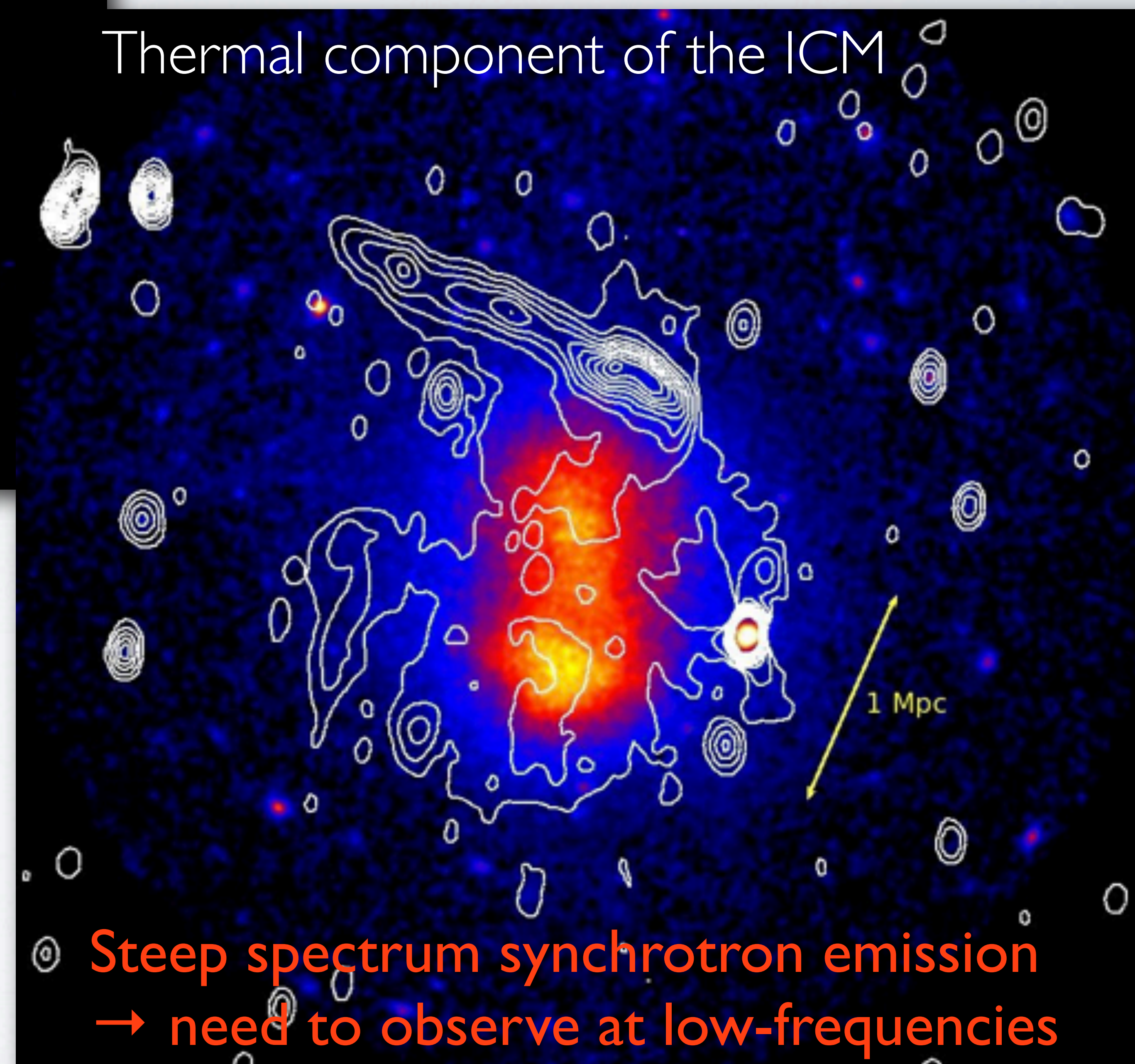

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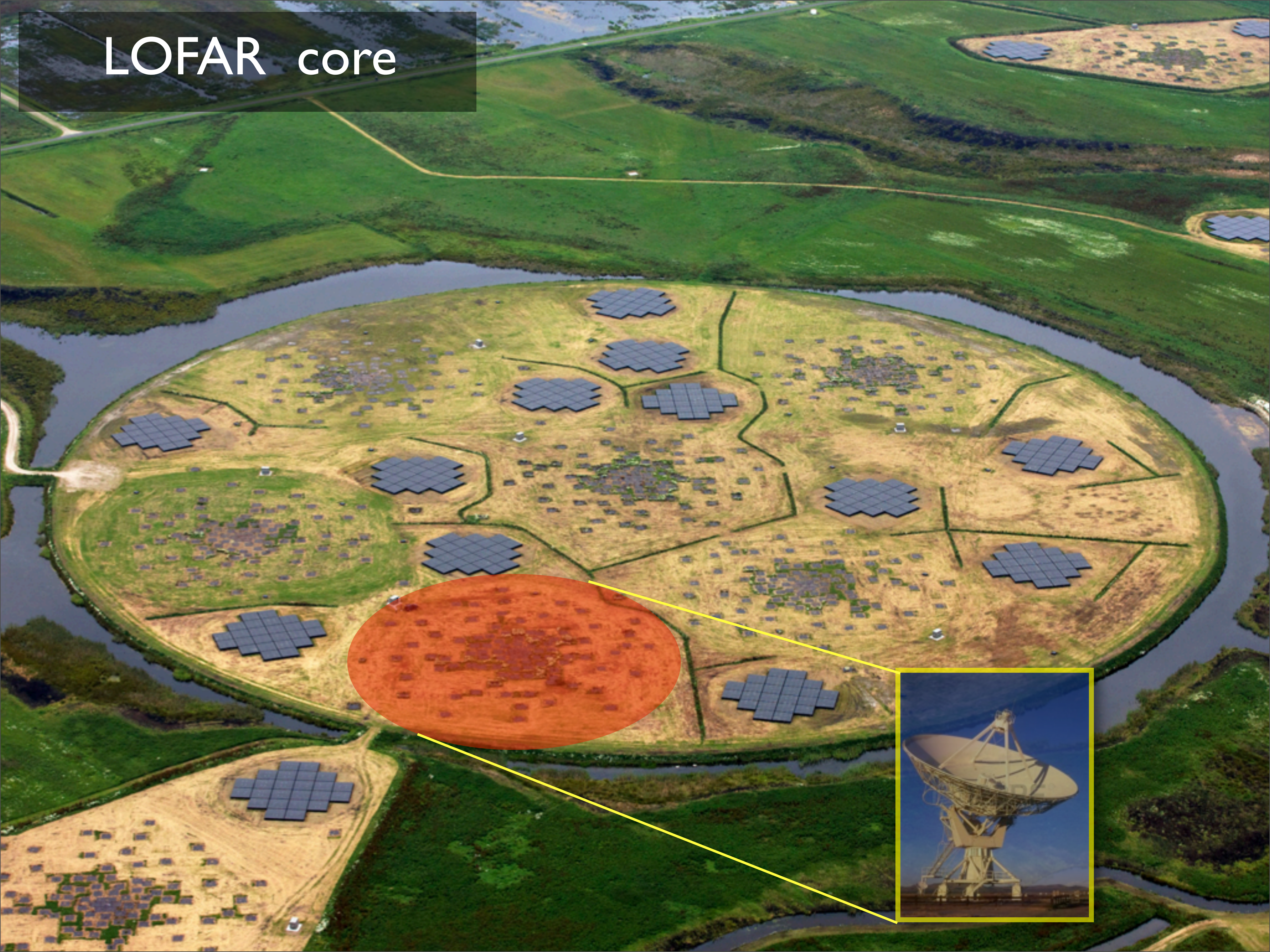
LOFAR

- New radio telescope operating at 10-250 MHz
- About 50 antenna stations
  - 40 stations in the Netherlands
  - stations in Germany, UK, Sweden, France, Poland
- Large range of baselines (100 m - 1,000 km)
- Phased-array technology (multi-beaming)


LOFAR core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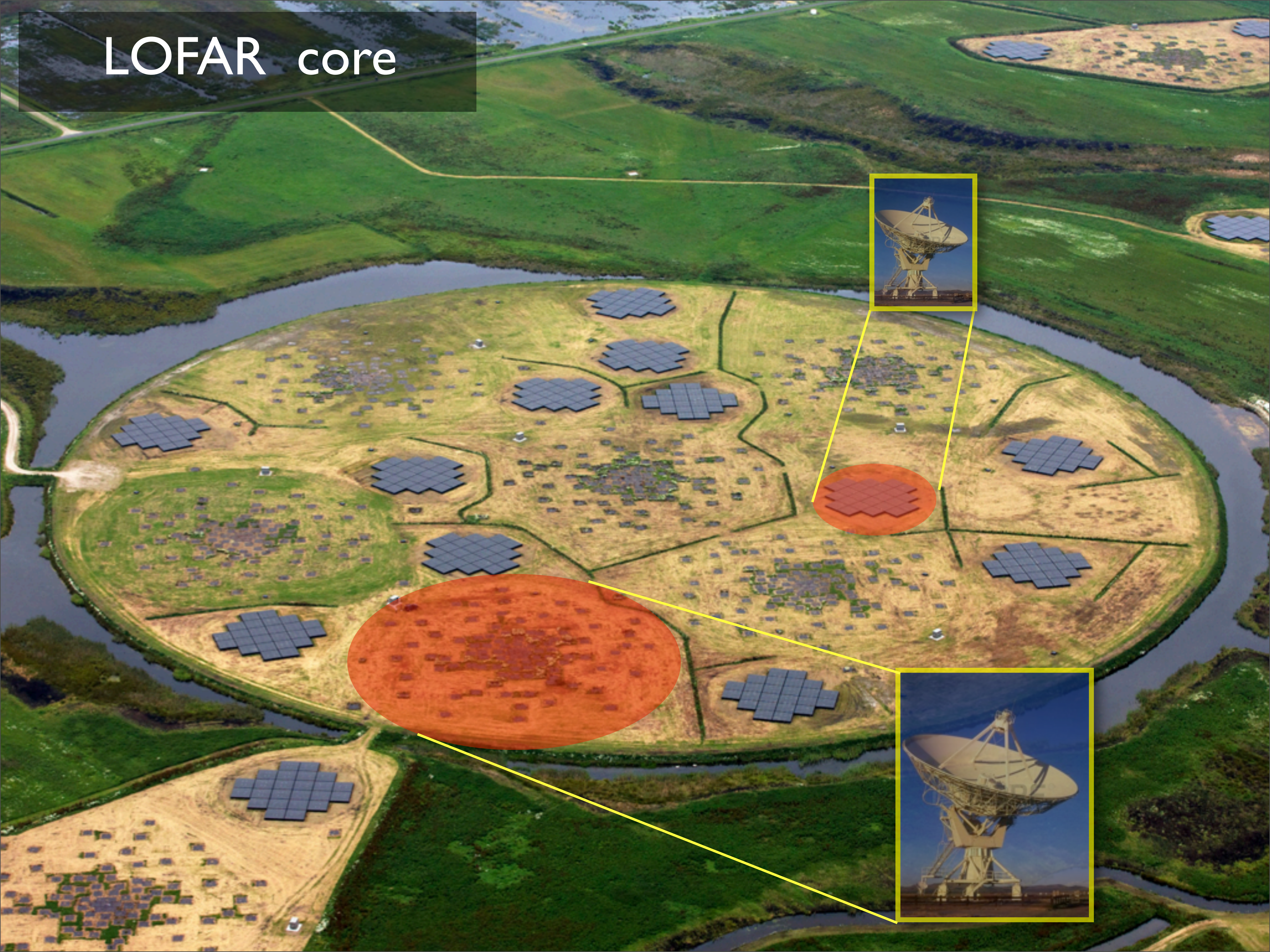
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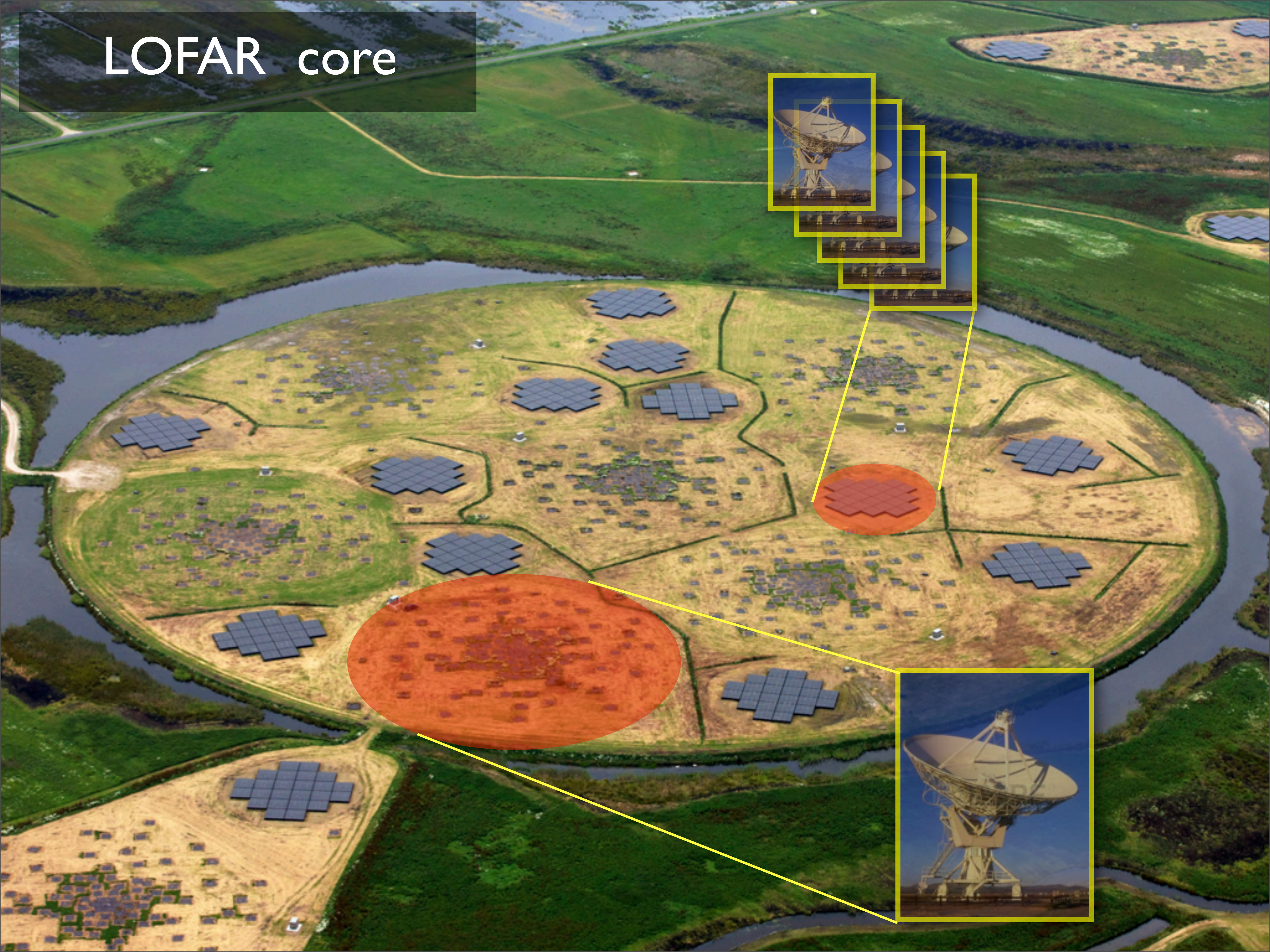
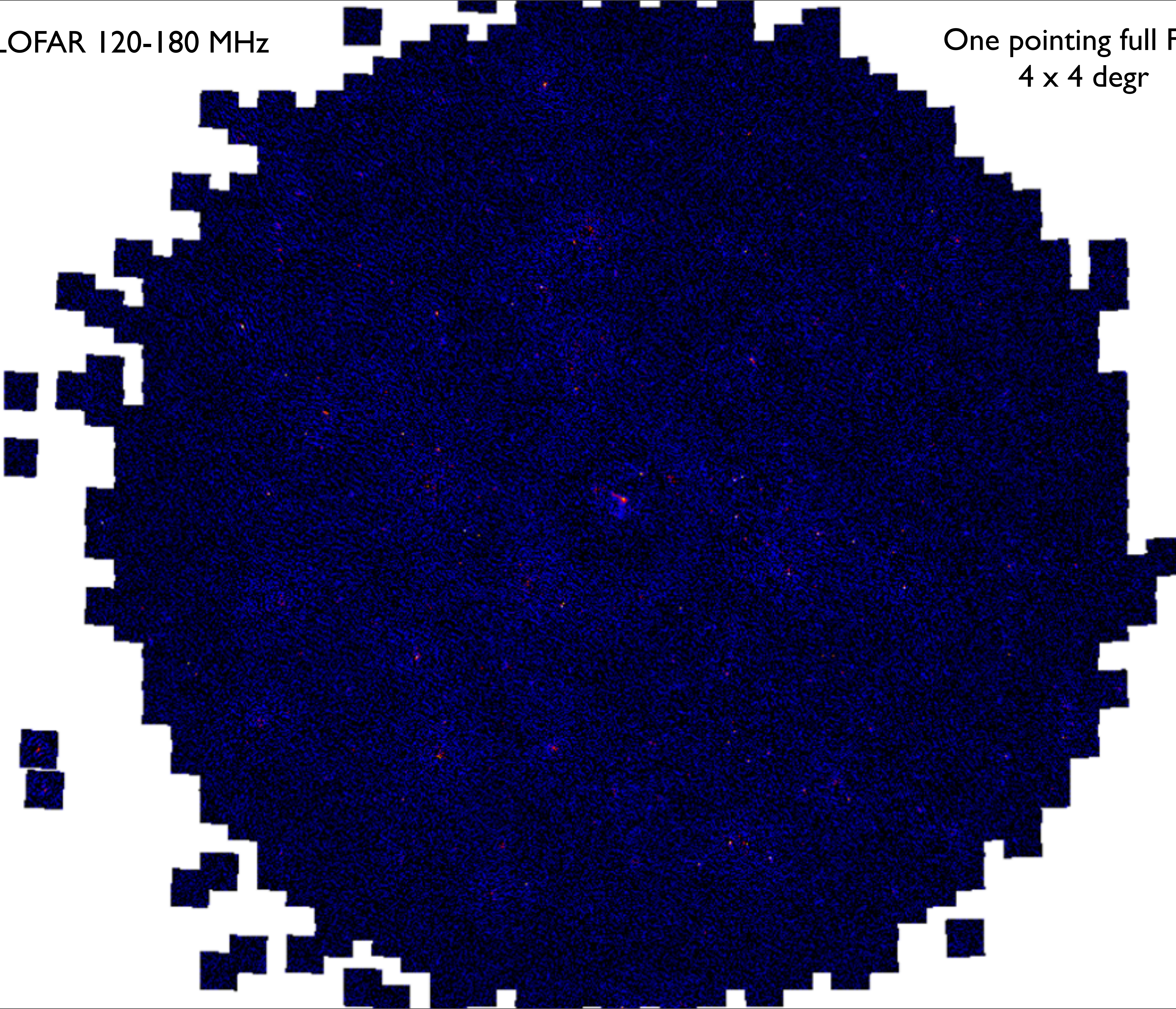
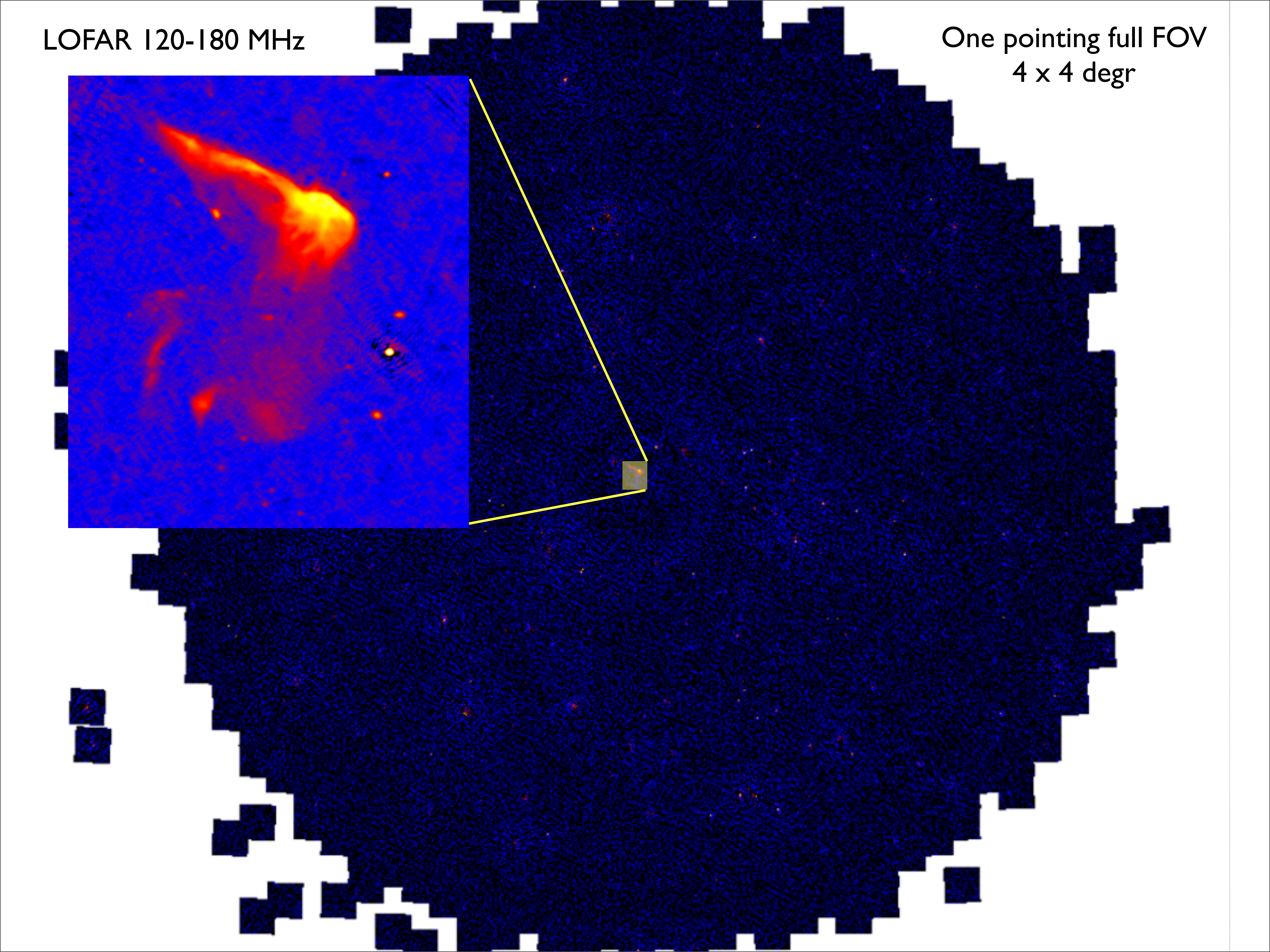

LOFAR core

LOFAR 120-180 MHz

One pointing full FOV
4 x 4 degr




LOFAR 120-180 MHz
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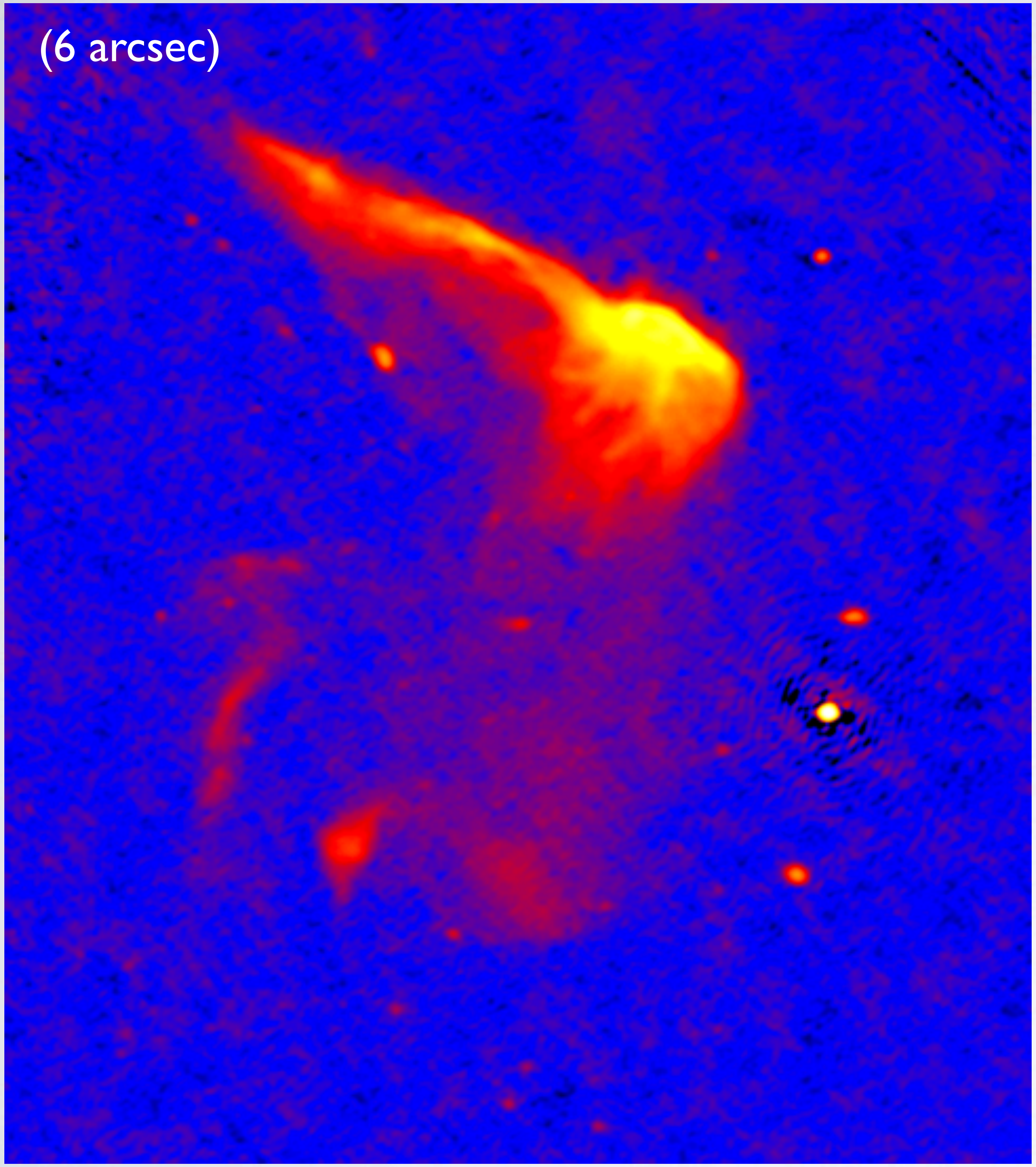
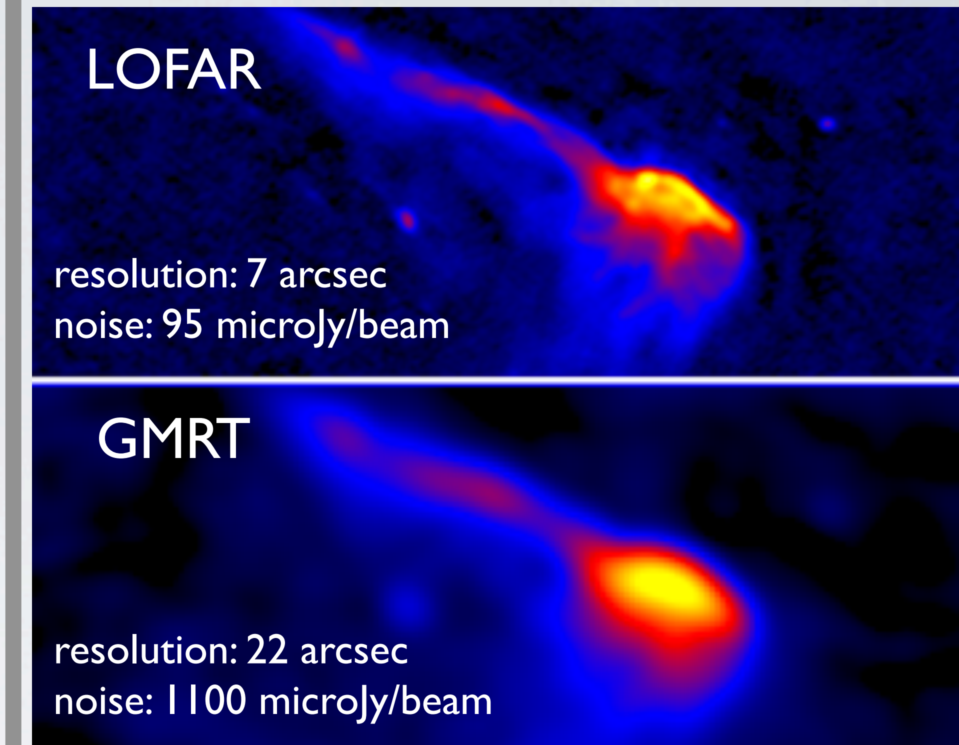
LOFAR results

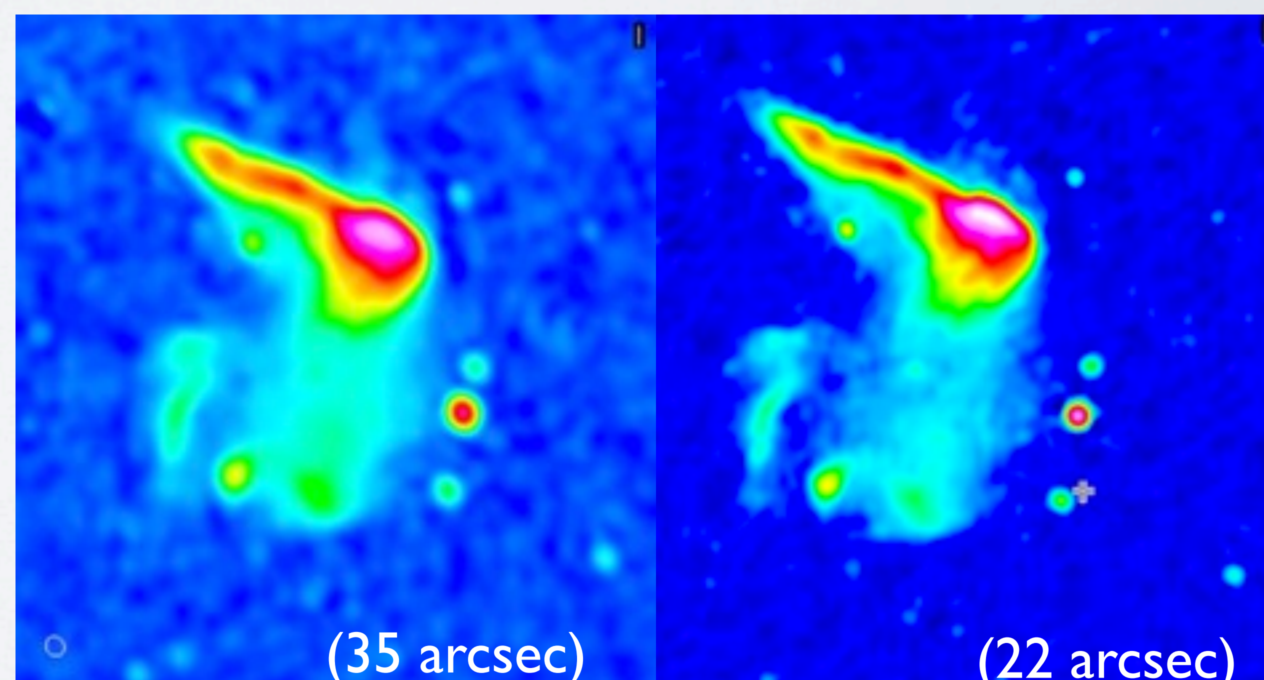


120-180 MHz, 95 microJy/beam rms noise

LOFAR vs GMRT



emphasize large-scale emission with weighting



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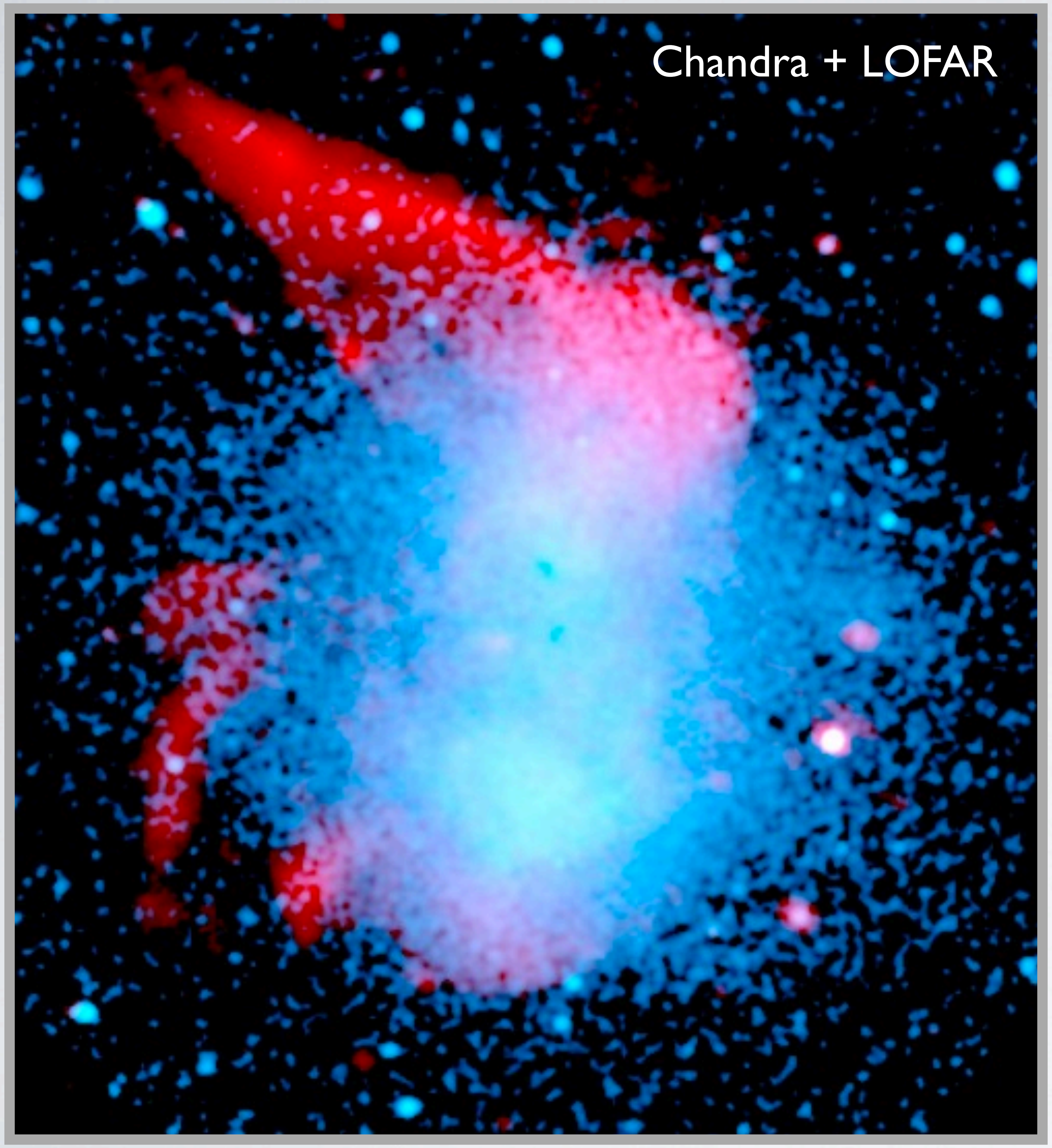

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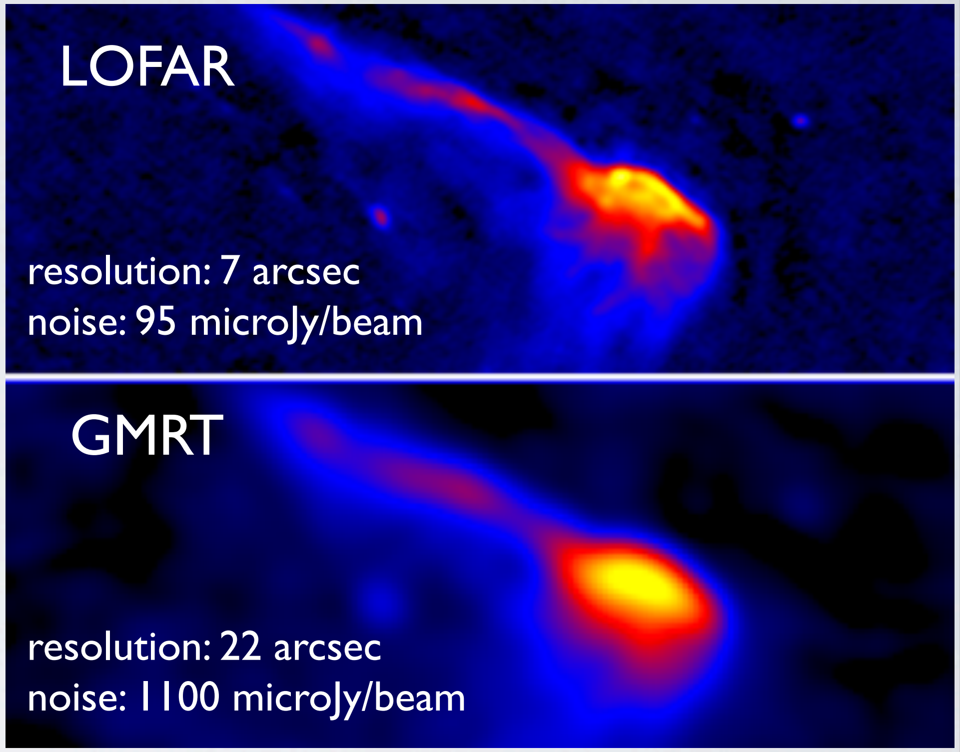

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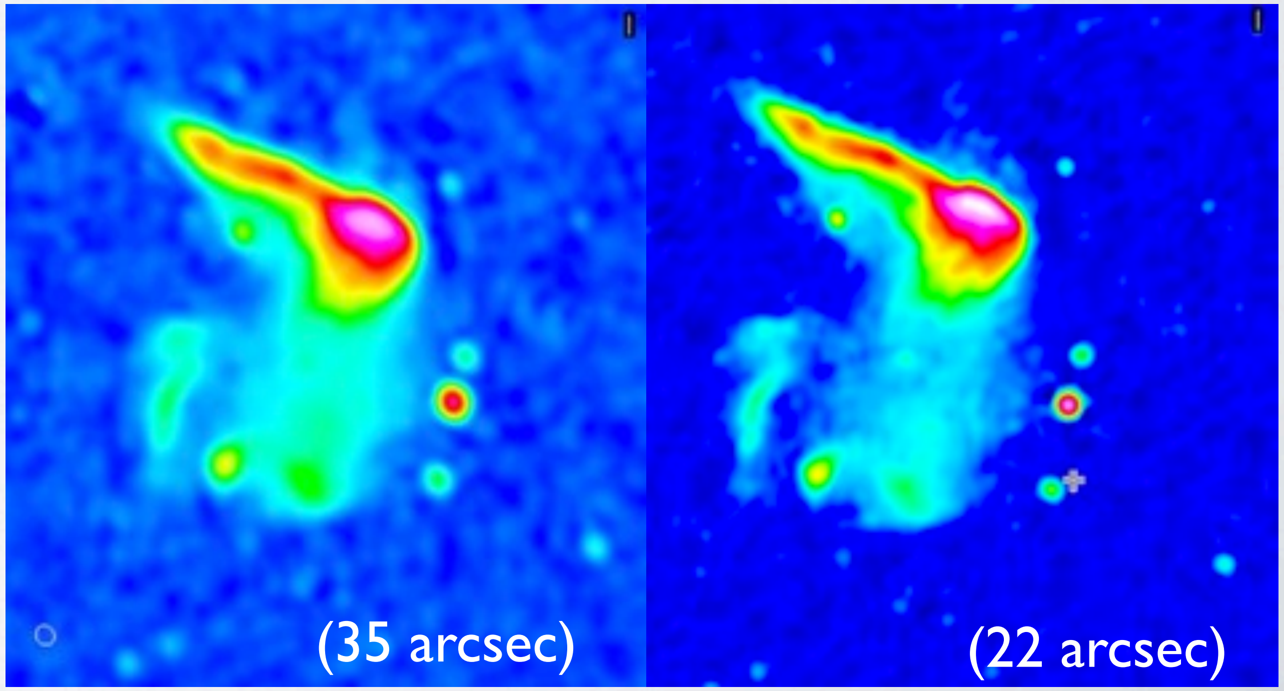
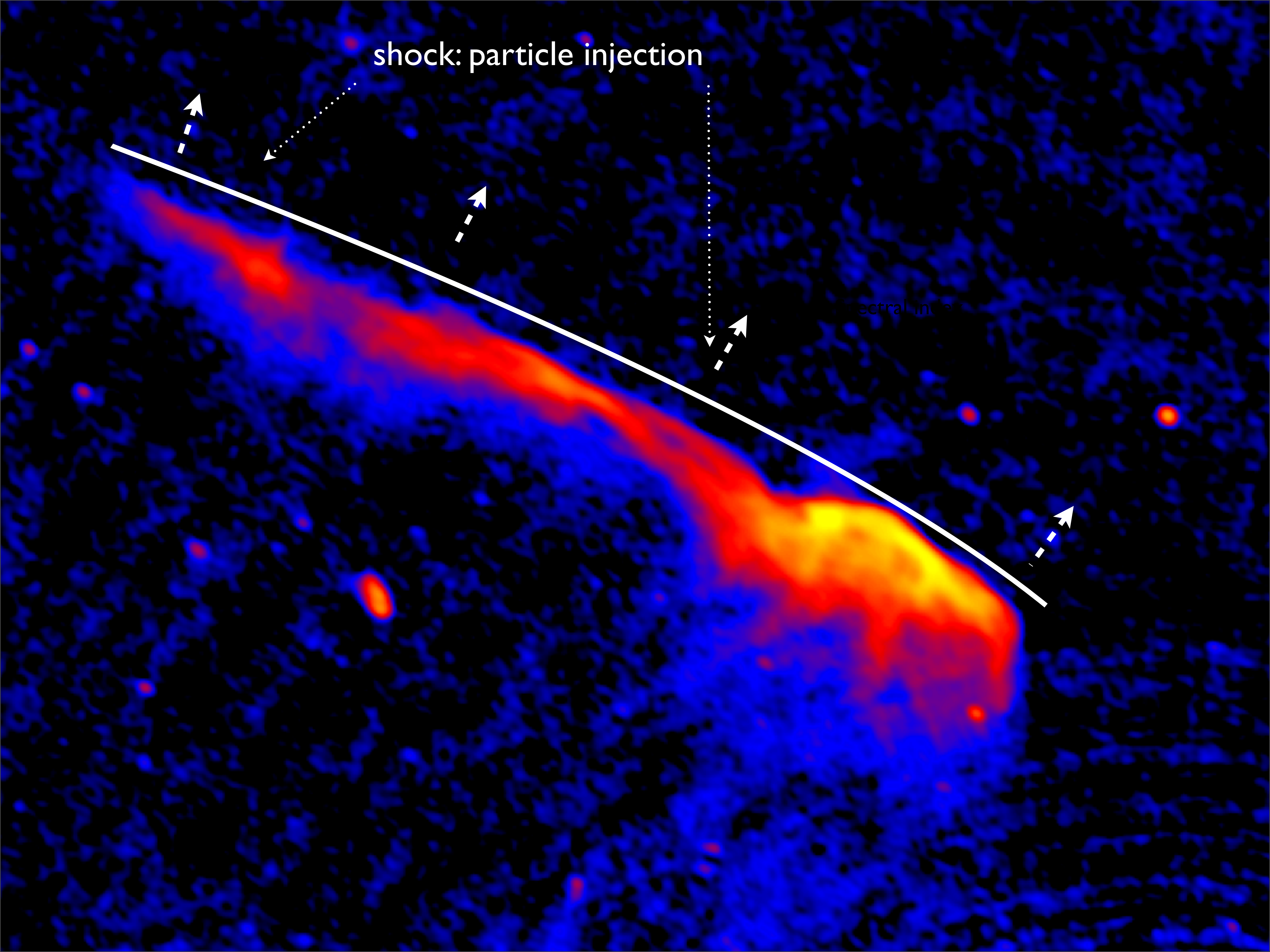
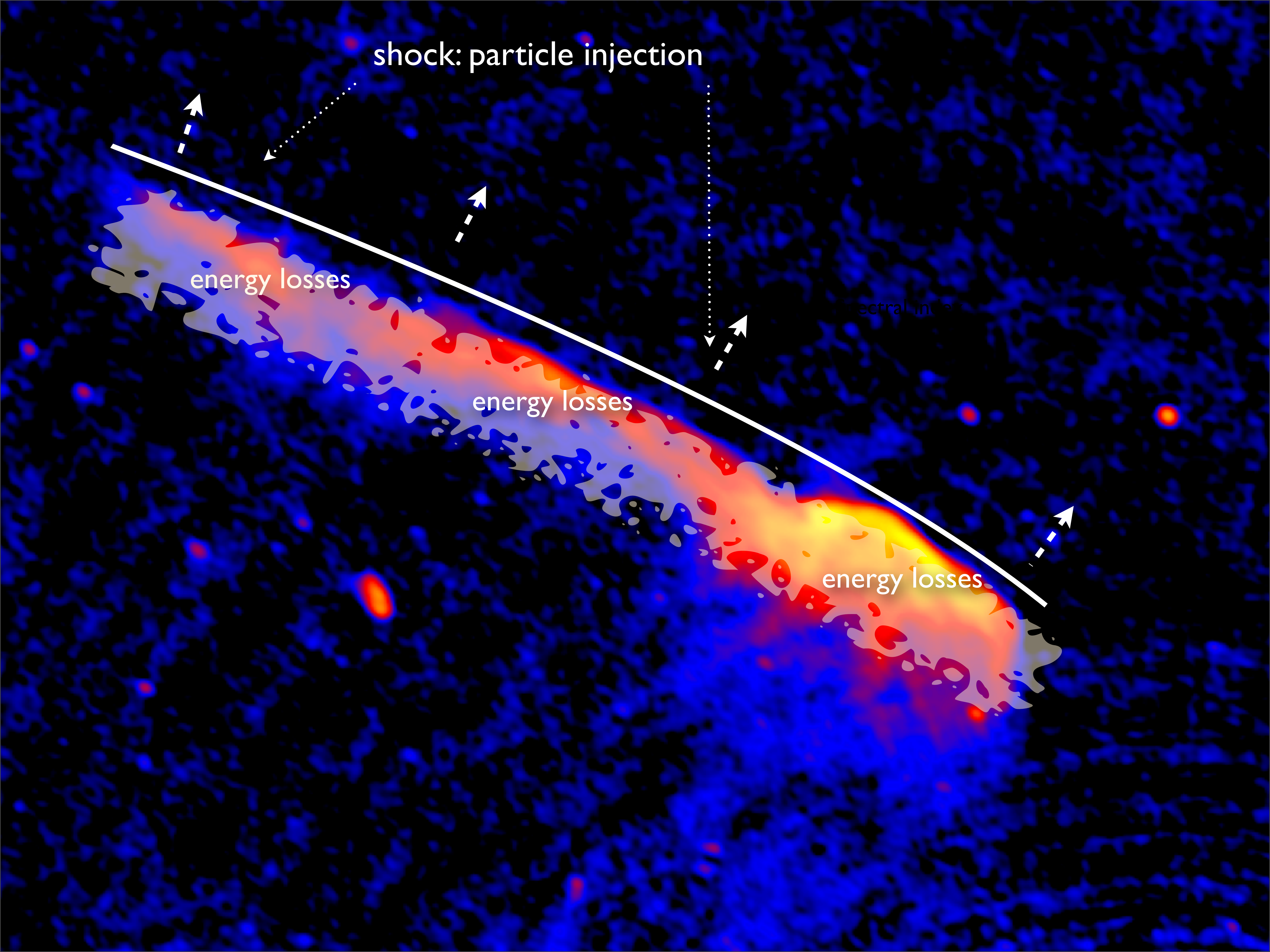
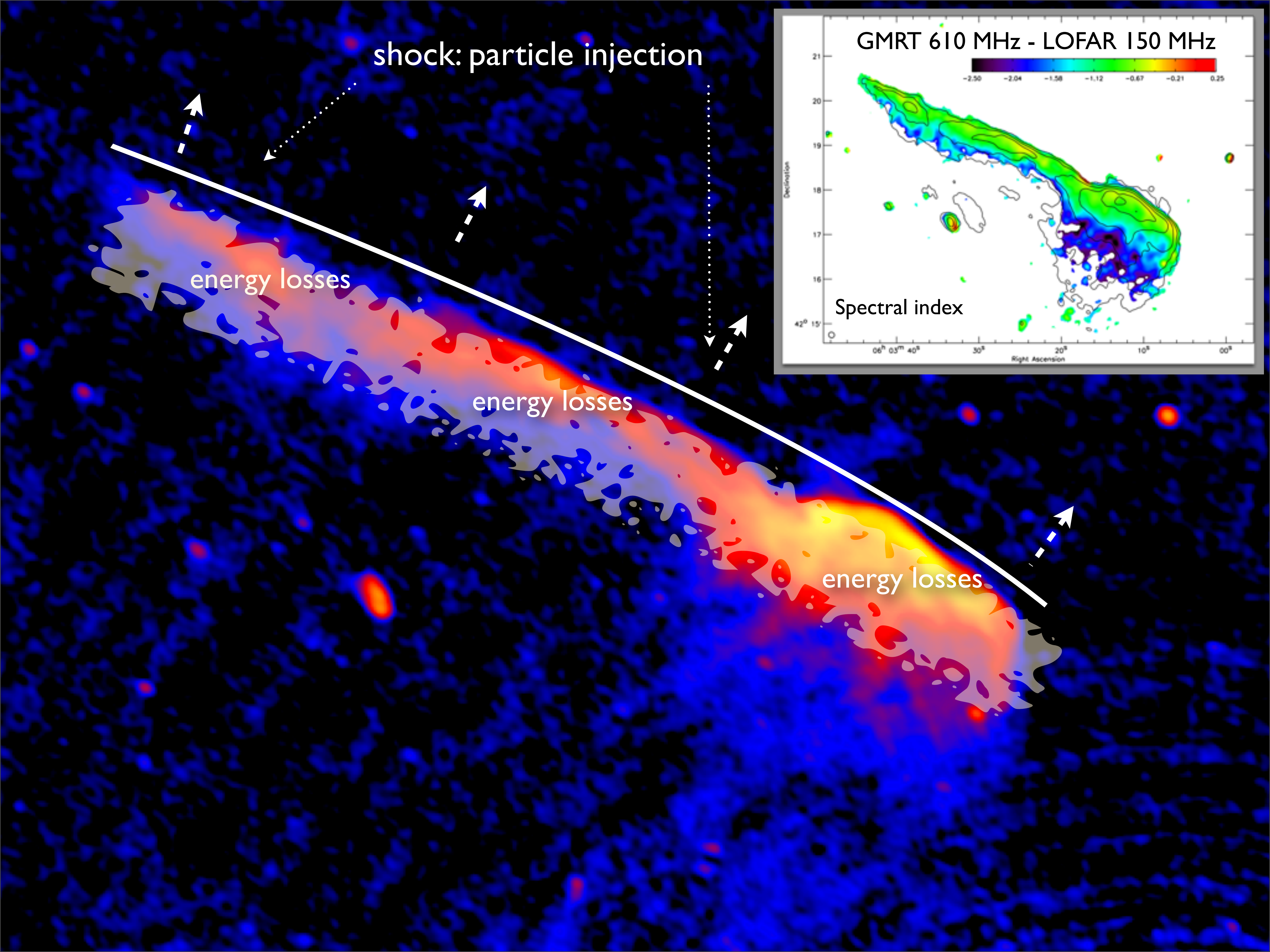



shock: particle injection


shock: particle injection
energy losses
energy losses
energy losses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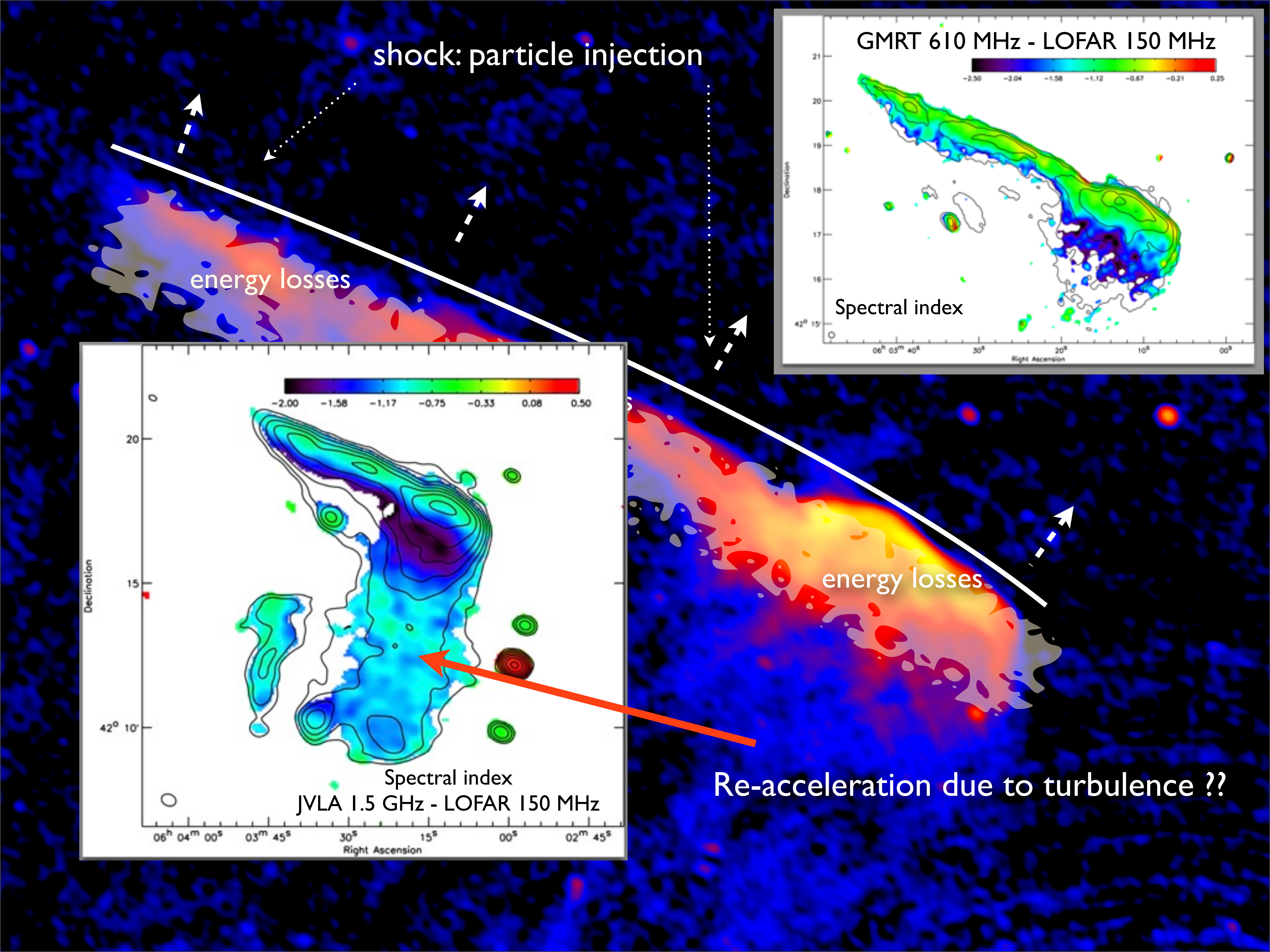
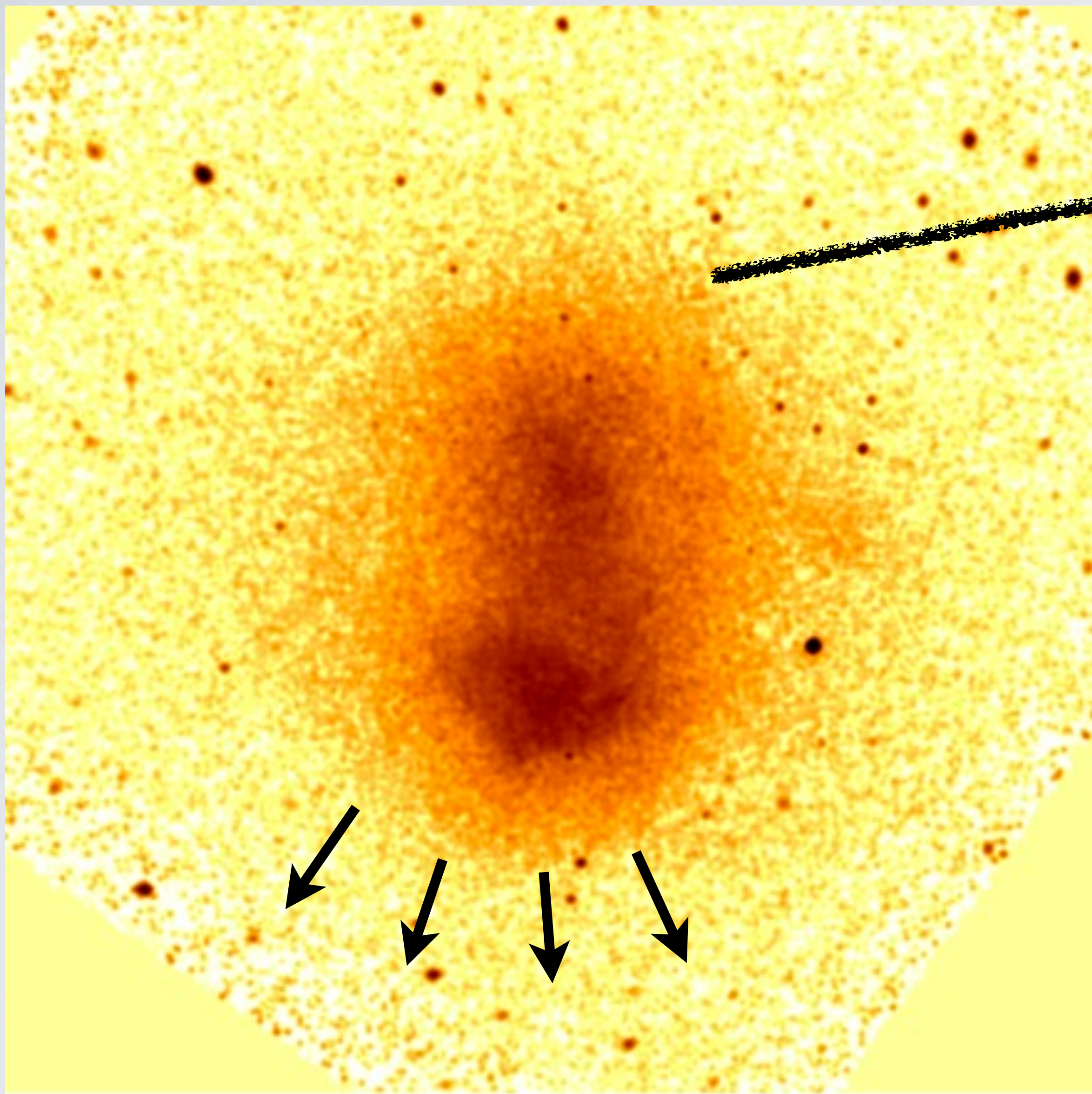
GMRT 610 MHz - LOFAR 150 MHz
Spectral index
Declination
Right Ascension

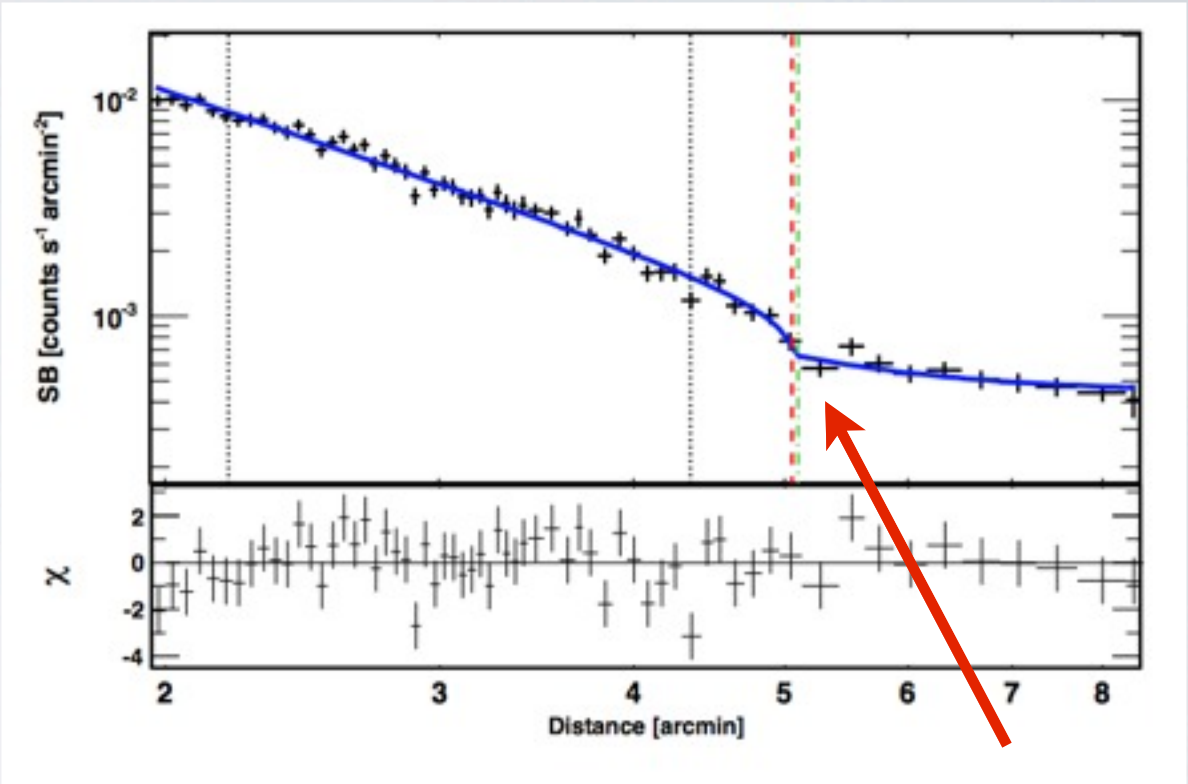

shock: particle injection
energy losses
energy losses
GMRT 610 MHz - LOFAR 150 MHz
Spectral index
Spectral index
JVLA 1.5 GHz - LOFAR 150 MHz
Declination
Right Ascension
Re-acceleration due to turbulence ??

Puzzles



Chandra 0.5-2.0 keV

Ogrean+ 2013



best fit shock position

- North: Mismatch between relic emission and shock location
- South: Shock but no bright radio relic

Puzzles

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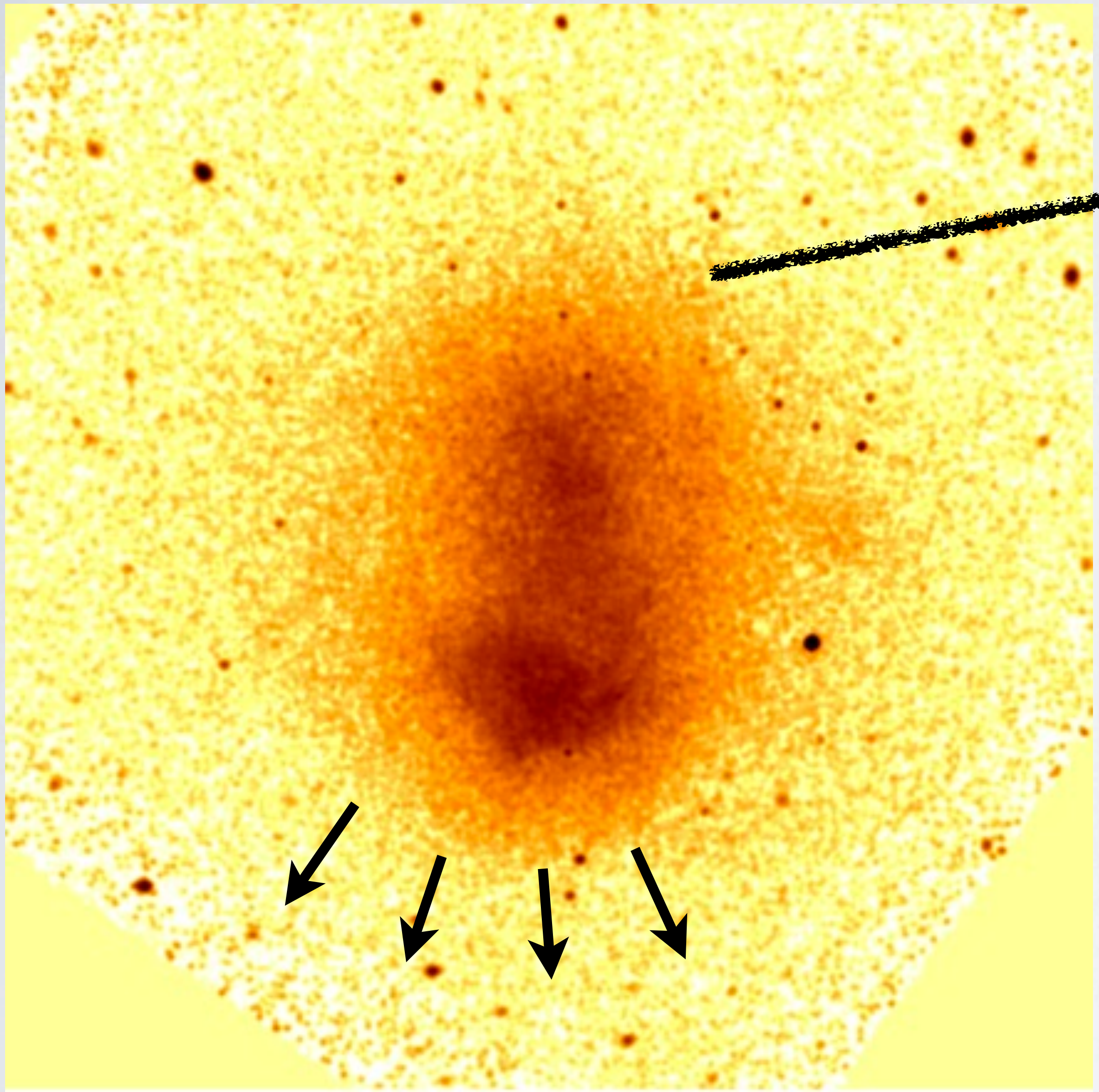

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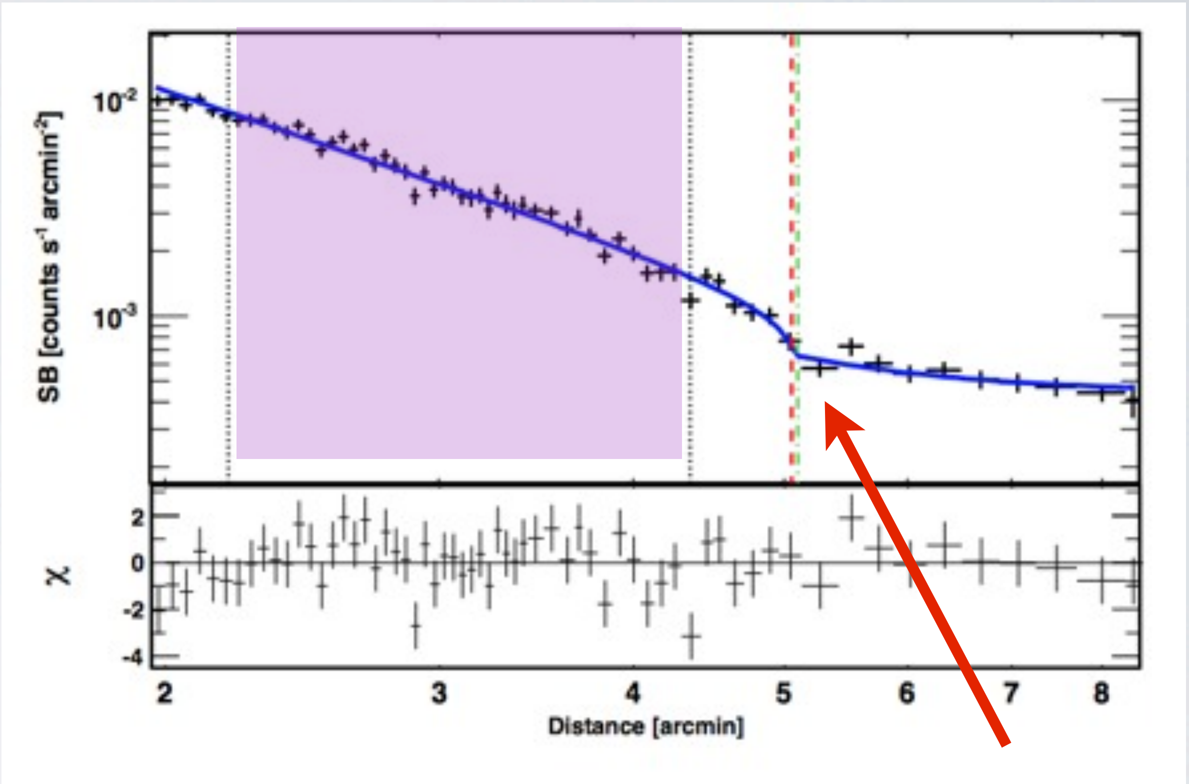

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SUMMARY

- First ultra-deep LOFAR cluster image
- Radio halos: CR electrons from shocks re-accelerated by merger induced turbulence ?
- Puzzle: Shock without clear radio relic ?
- Puzzle: Mismatch between relic and shock location ?