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Radio Bubbles in Clusters: Relativistic Particle Content

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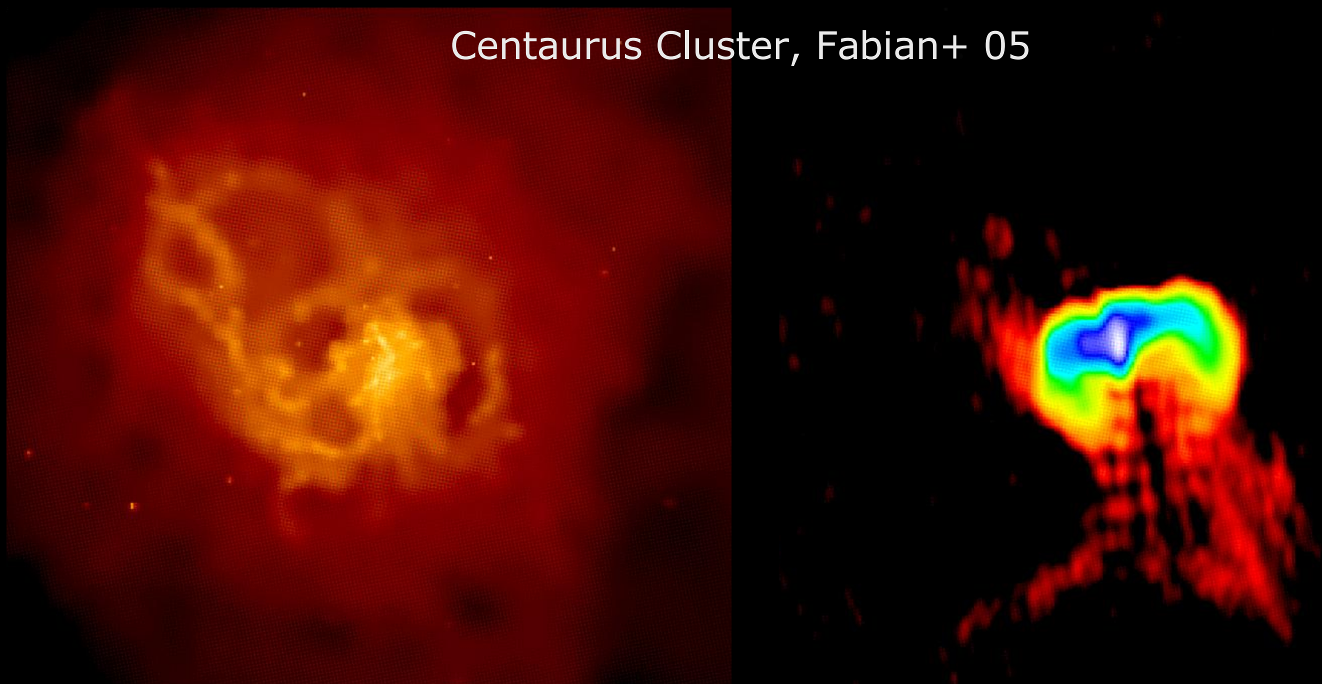
Outline

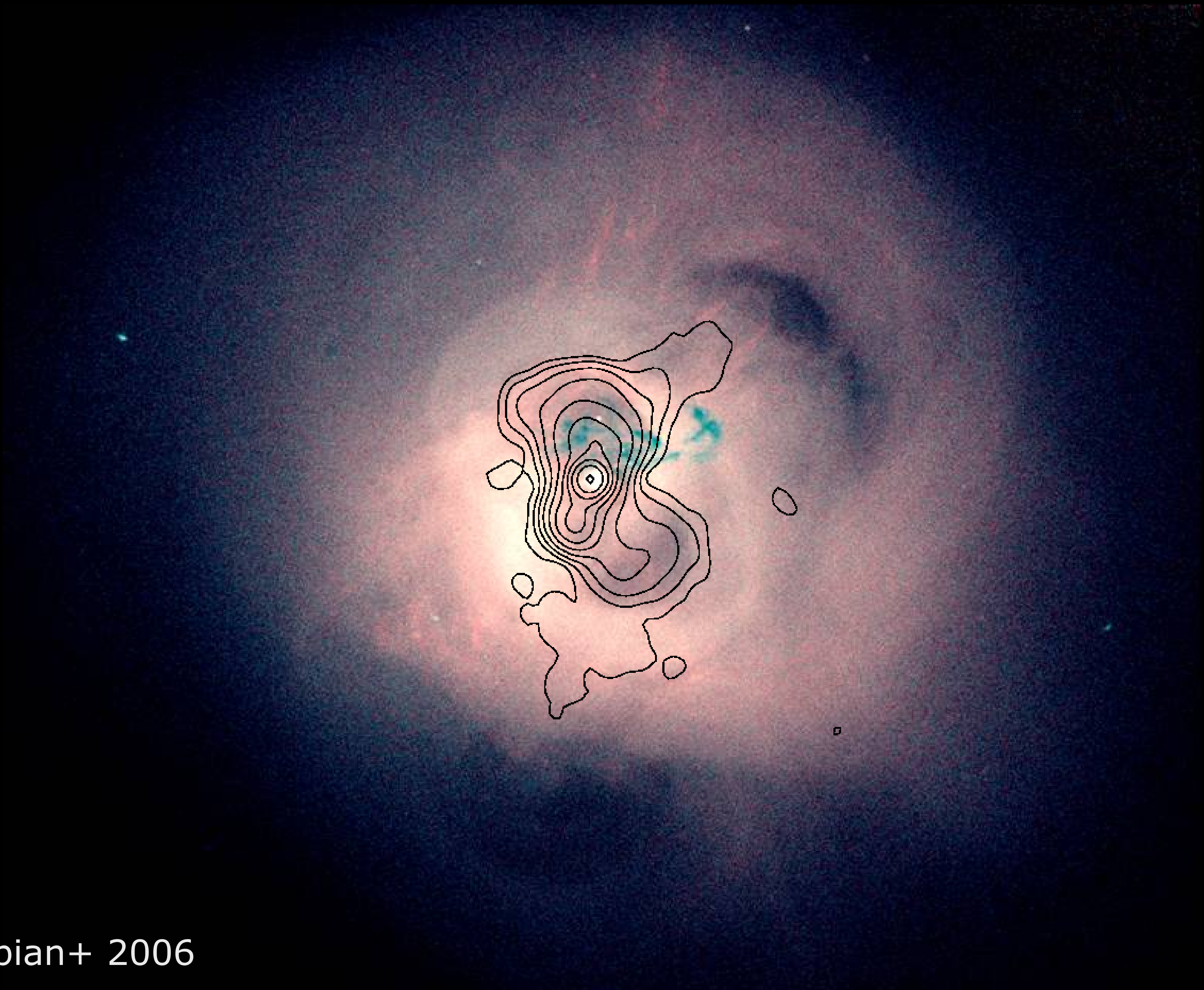
- Radio Bubbles in Clusters.
- Constraining the internal energy of the radio lobes.
- Distribution of particle energies.
- Low frequency radio spectrum/low energy electron population.
- How LOFAR will help.

Radio Sources in Clusters



Centaurus Cluster, Fabian+ 05

- *ROSAT* images of the Perseus Cluster showed cavities in the X-ray emitting ICM (Böhringer+ 93).
- More recent *Chandra* images show that many clusters have cavities which match the radio emission (e.g. A2052, Blanton+ 01; Hydra, McNamara+ 00; M87, Forman+ 05)



Fabian+ 2006

Bubble Dynamics

- The cavities are thought to act as buoyant bubbles of relativistic plasma.
- For the bubble to be created, then initially it must be overpressured compared to its surroundings.
- The expansion speed of the bubble is thought to be around the sound speed.
- Therefore a physical age for the bubble can be calculated.
- Older bubbles are expected to rise buoyantly within the cluster.

Reynolds+ 05

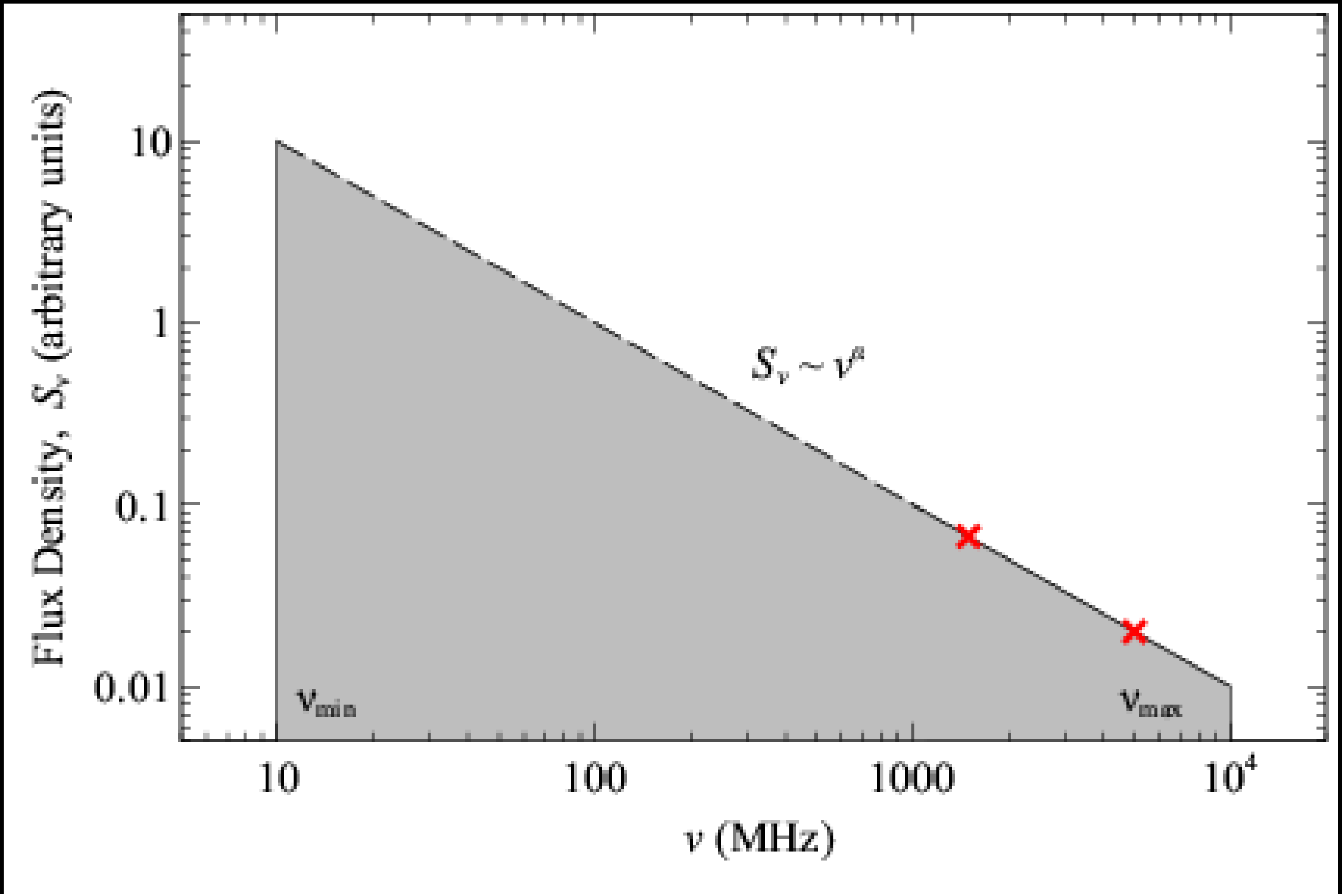
Radio Source Particle Content

- Calculating the energy content of radio lobes has been difficult as the contributions from the particles and magnetic field are linked.
  - Traditionally equipartition (~minimum energy) has been assumed (Burbidge 1959).

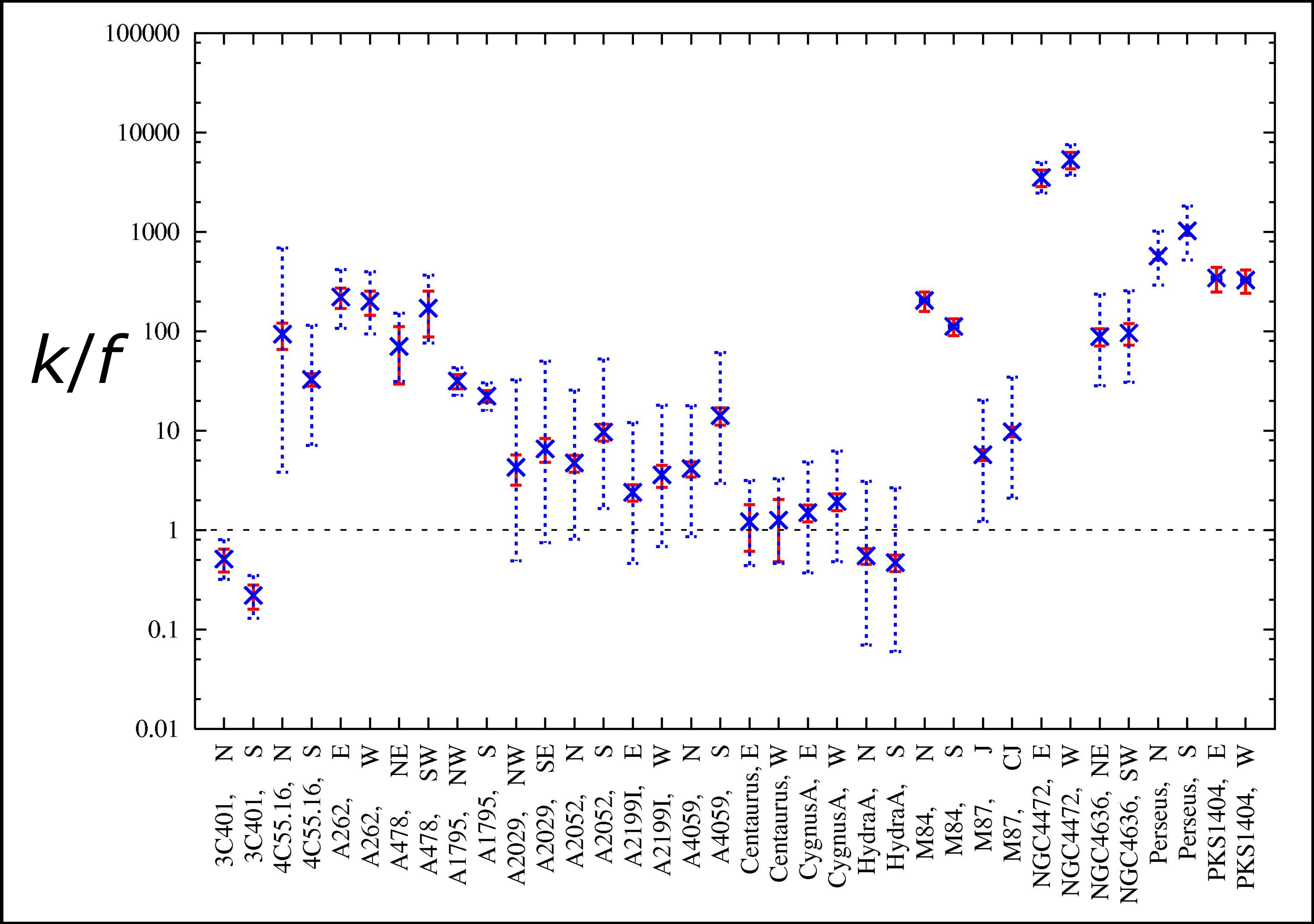
- Combining radio and X-ray observations allows the degeneracy to be lifted, by assuming that the relativistic and thermal plasmas are in pressure balance.

- Using Minimum energy arguments, the radio sources are usually underpressured (eg Morganti+ 88, Worrall+ 95, Hardcastle & Worrall 2000).

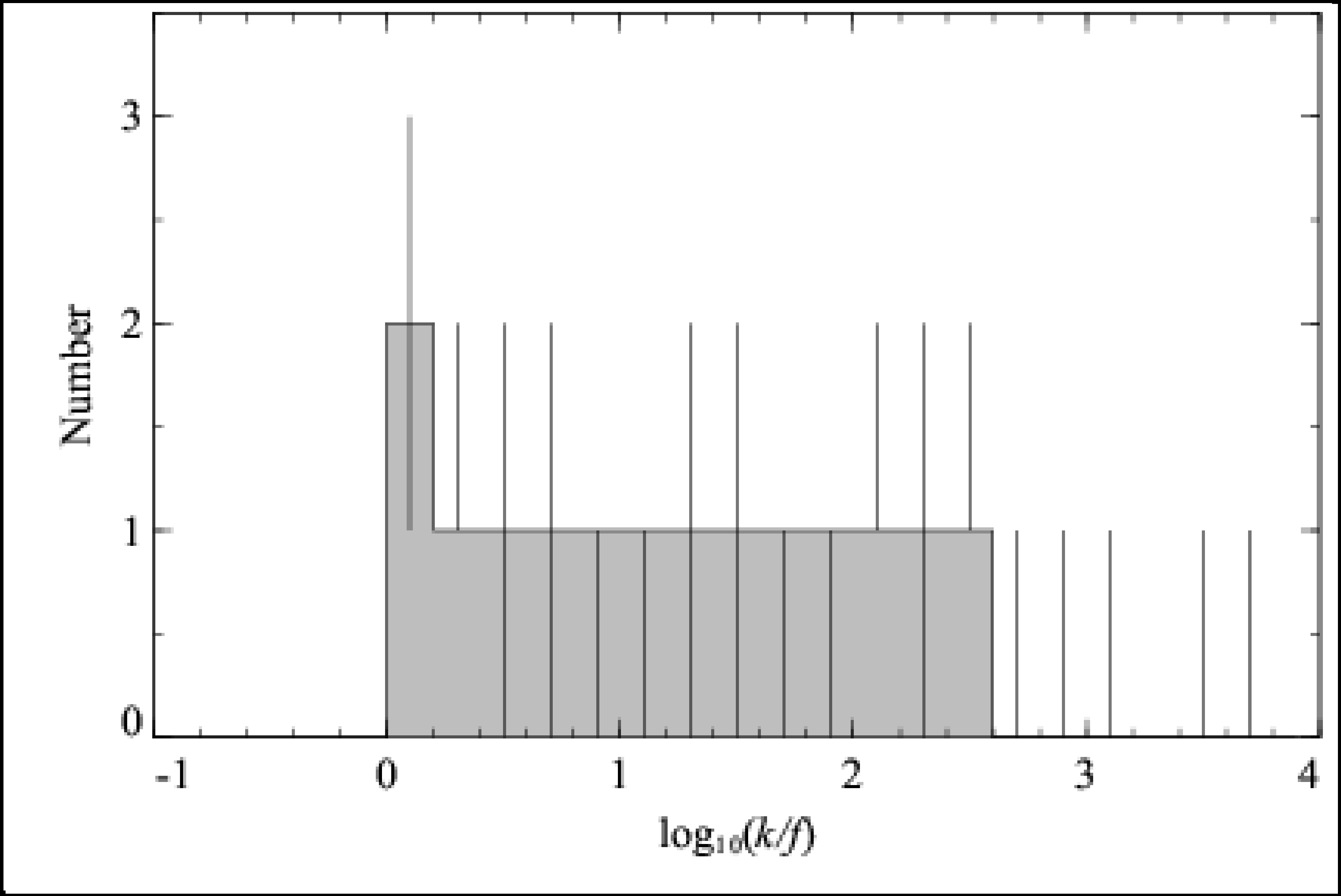
- Total energy within the lobe is: $\boldsymbol{E}_{\mathrm{tot}}=k\boldsymbol{E}_{\mathrm{e}}+f\boldsymbol{E}_{\mathrm{B}}$



- Spectrum of radio emission is assumed to be as shown.
  - Gives estimate on $\boldsymbol{E}_e$
- Compare synchrotron cooling time of electrons to the age of the bubble to estimate the magnetic field.


k/f
100000
10000
1000
100
10
1
0.1
0.01
3C401, N
3C401, S
4C55.16, N
4C55.16, S
A262, E
A262, W
A478, NE
A478, SW
A1795, NW
A1795, S
A2029, NW
A2029, SE
A2052, N
A2052, S
A2199I, E
A2199I, W
A4059, N
A4059, S
Centaurus, E
Centaurus, W
CygnusA, E
CygnusA, W
HydraA, N
HydraA, S
M84, N
M84, S
M87, J
M87, CJ
NGC4472, E
NGC4472, W
NGC4636, NE
NGC4636, SW
Perseus, N
Perseus, S
PKS1404, E
PKS1404, W

RJHD+ (2005)



RJHD+ 2005

Interpretation

- There is a large spread in *k/f* but no clear shape for the underlying distribution.

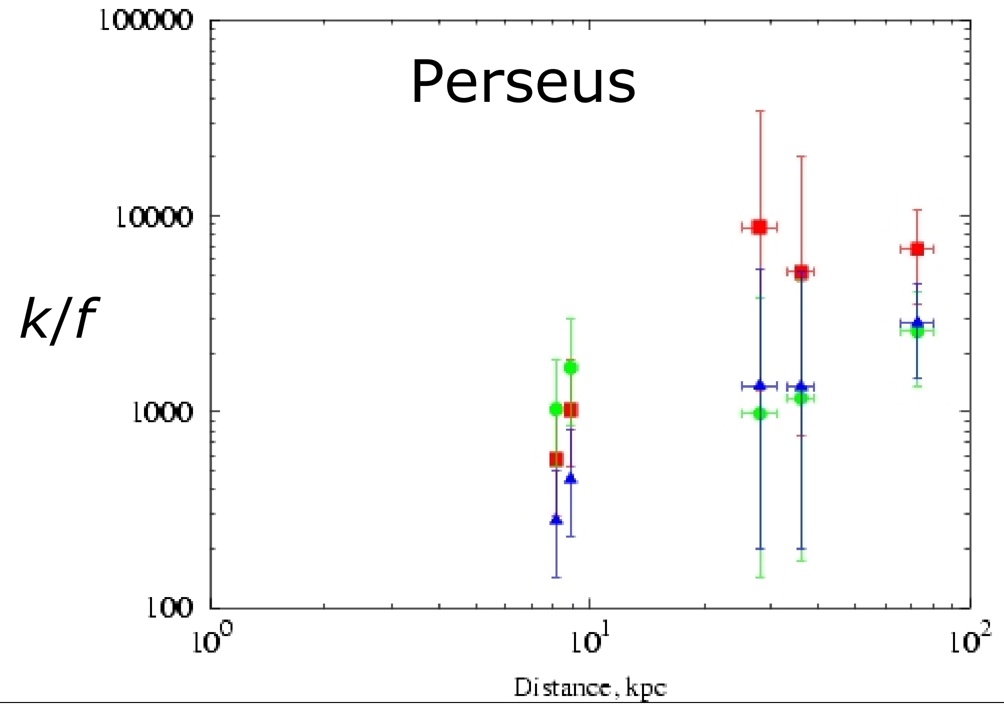
- This may be the result of a significant population of non-relativistic particles present in some of the bubbles.
  - The jets may intrinsically contain protons when they form.
  - There may be entrainment of material surrounding the black hole.

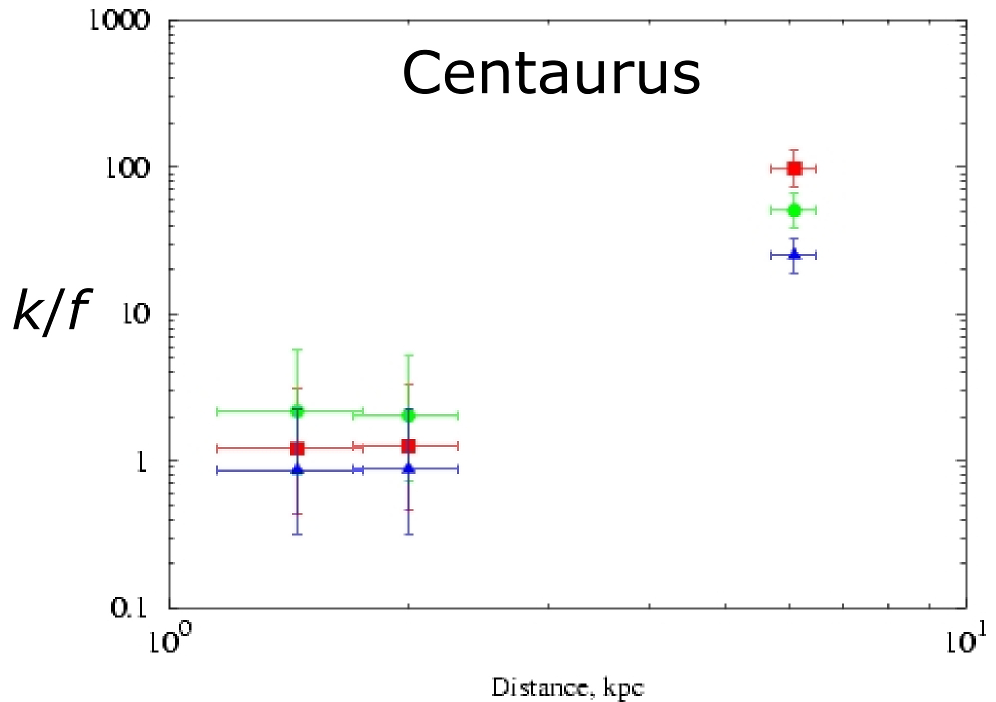
- May also arise from relativistic particles outside of the assumed spectrum – spectral aging, adiabatic expansion effects etc.

- *f* is not thought to vary very much.
  - Schmidt+ (2002) rule out the presence of <11keV gas throughout the Perseus bubbles.

Evolution of *k/f*

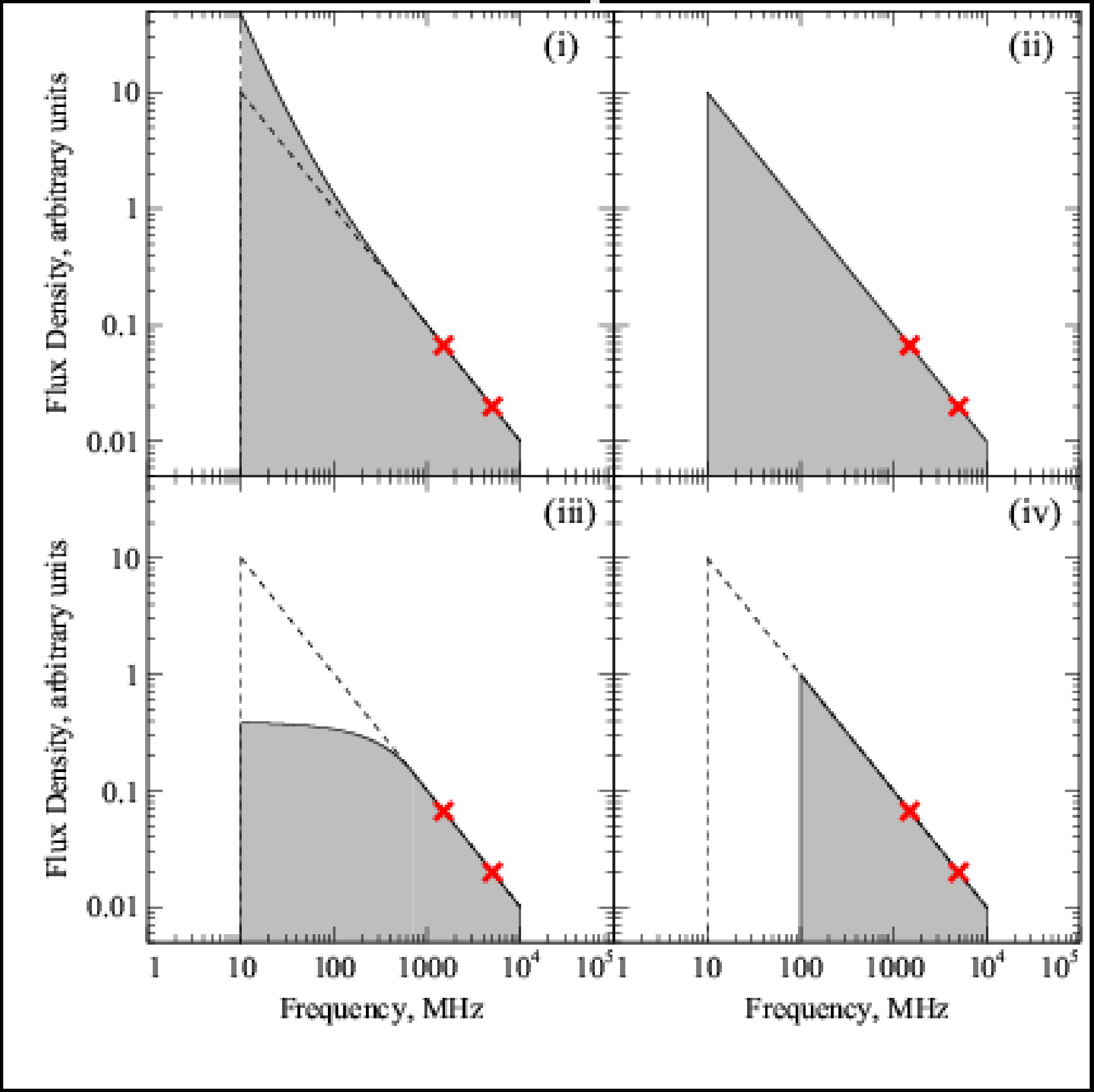
- Perseus & Centaurus have clear young and ghost bubbles.
- There is a trend for *k/f* to increase as the bubbles age.
- This is likely to be the result of the aging of the synchrotron plasma.





Low Energy Electron Spectrum

- Have so far assumed a simplistic model for the spectrum
- Most of the uncertainties in the *k/f* values arise from uncertainties in α.
- Improving the model of the low energy spectrum is important.



How LOFAR will help.

- The low frequency sensitivity and resolution will help in accurately characterising the radio spectrum over a wide band.

- Any spectral break will aid in accurately determining the age of the radio plasma within the bubble.
  - This may further constrain the age of the bubble itself and hence influence estimates on the energy injection rate of the AGN.
  - Mainly for older “ghost” bubbles.

- Low frequency observations may increase the number of clusters which have old and young / detached and attached bubbles which will allow the investigation into the evolution of *k/f* as the bubbles evolve.

Results

- The magnetic field estimates show that none of the radio lobes has simple equipartition between the relativistic particles and the magnetic field.
- There is a large range in *k/f* but there are not enough objects in the current sample to determine the shape of the underlying population.
- Entrainment of material is likely to play a part in causing this range, an effect which is stochastic and highly dependent on the environment surrounding the black hole.
- The exact form of the low-energy electron population is important in improving these results.

Summary

- Particle energy density of the radio lobes is currently uncertain.
- Combining X-ray and radio observations allow estimates to be calculated without resorting to equipartition arguments.
- LOFAR will help in characterising the low energy electron spectrum for these radio sources.
  - Allow clear determination of the spectral break in older bubbles, and hence the plasma age.
  - Determine the shape of the low frequency spectrum, allowing the model for the particle energy within the lobes to be refined.