# Constraining the energy budget of radio galaxies with LOFAR

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Thanks to M. Hardcastle, E. Belsole, M. Birkinshaw, D. Harris & D. Worrall

UH

Astrophysics in the LOFAR era
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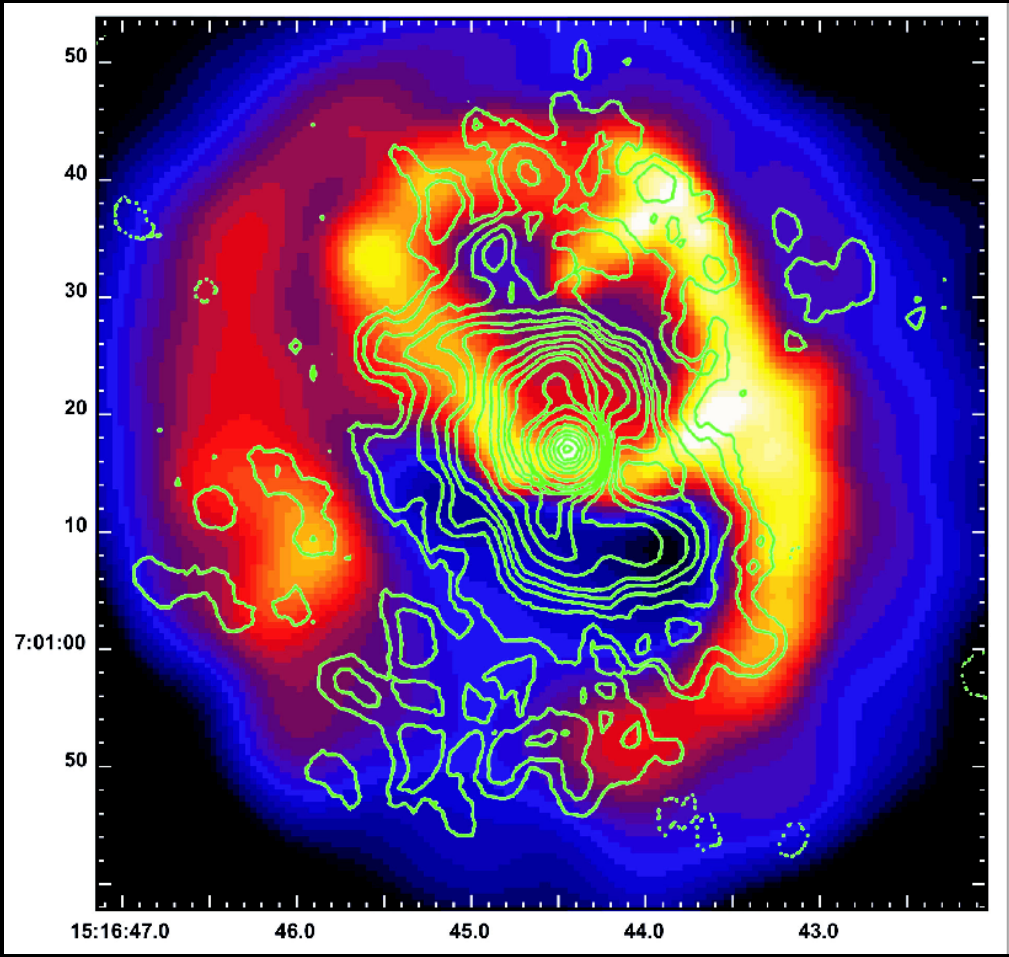
# Why is it important to constrain radio-galaxy energetics?

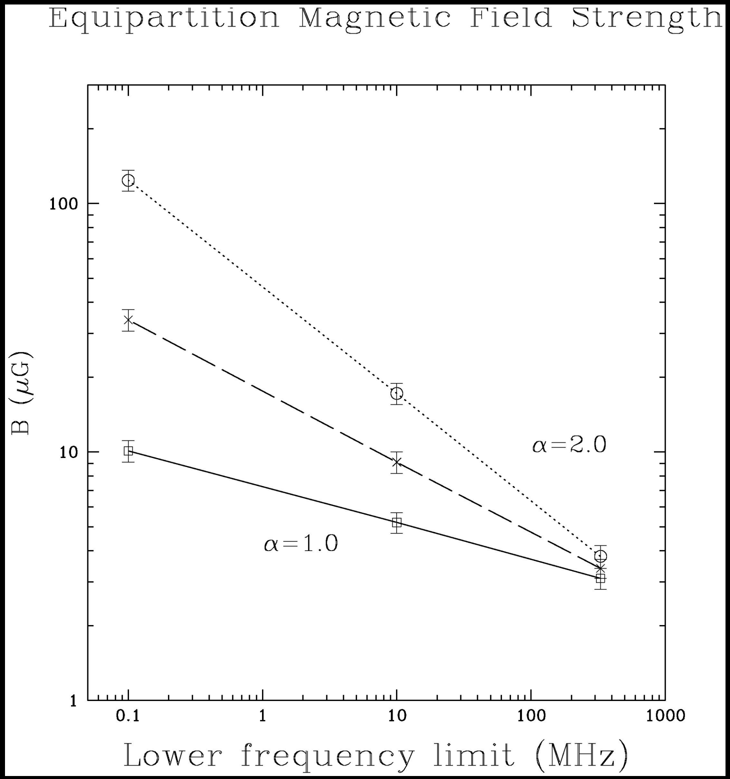
- AGN feedback appears necessary for galaxy formation.
- Radio outbursts thought to balance cooling in cluster centres
- Radio-loud AGN may play a role in explaining entropy excess in groups & clusters.

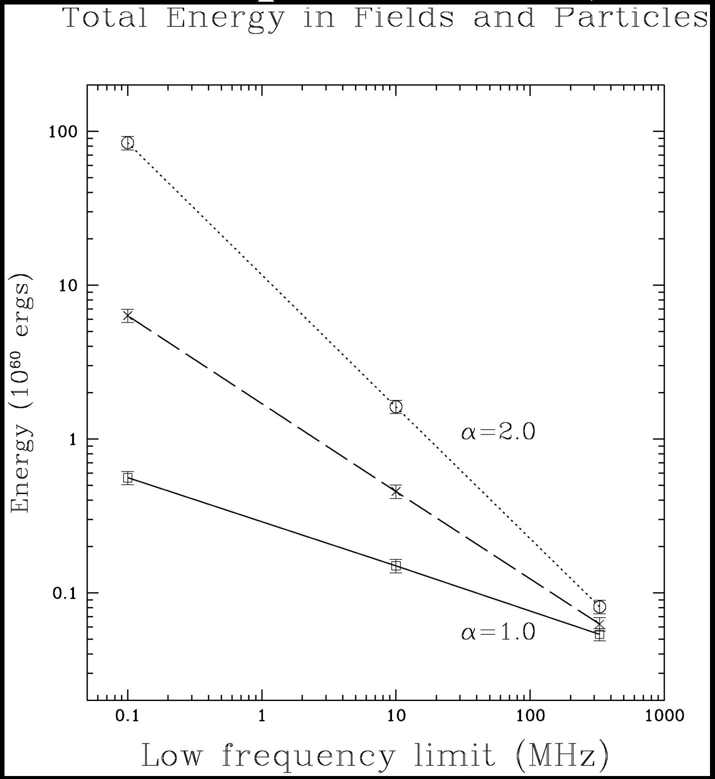



**Blanton et al. 2001**

# The low-energy electron population

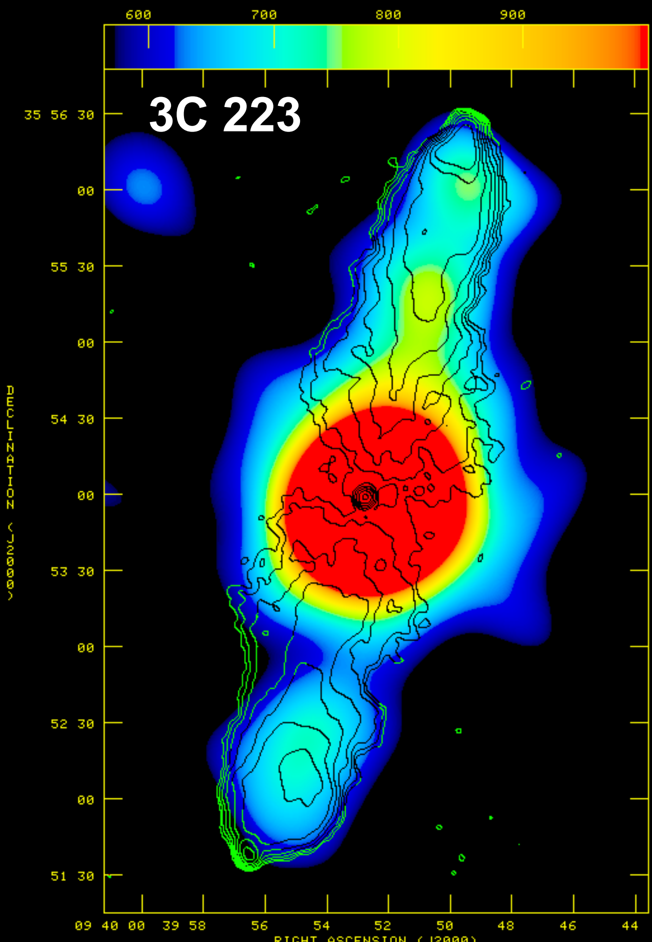
- Most of the energy density in radio galaxies and quasars is at energies below currently observable radio region.
- Radio-source properties depend strongly on assumed spectrum below ~ 300 MHz: $\alpha_{low}$ and $\gamma_{min}$.
- See discussion in Harris (2004, astro-ph/0410485)

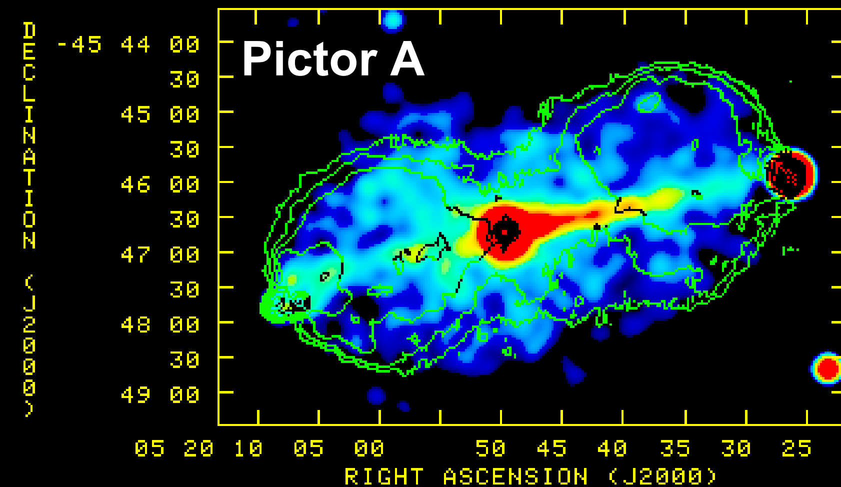


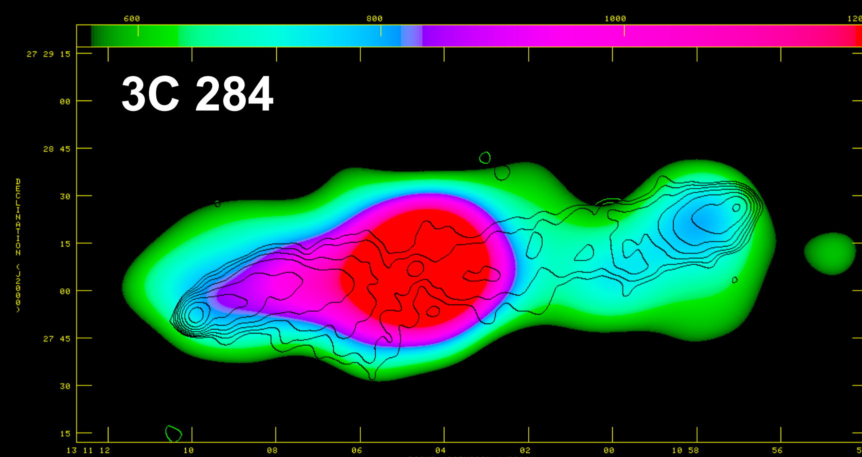




Figures from Harris (2004)

# X-ray IC emission from radio lobes



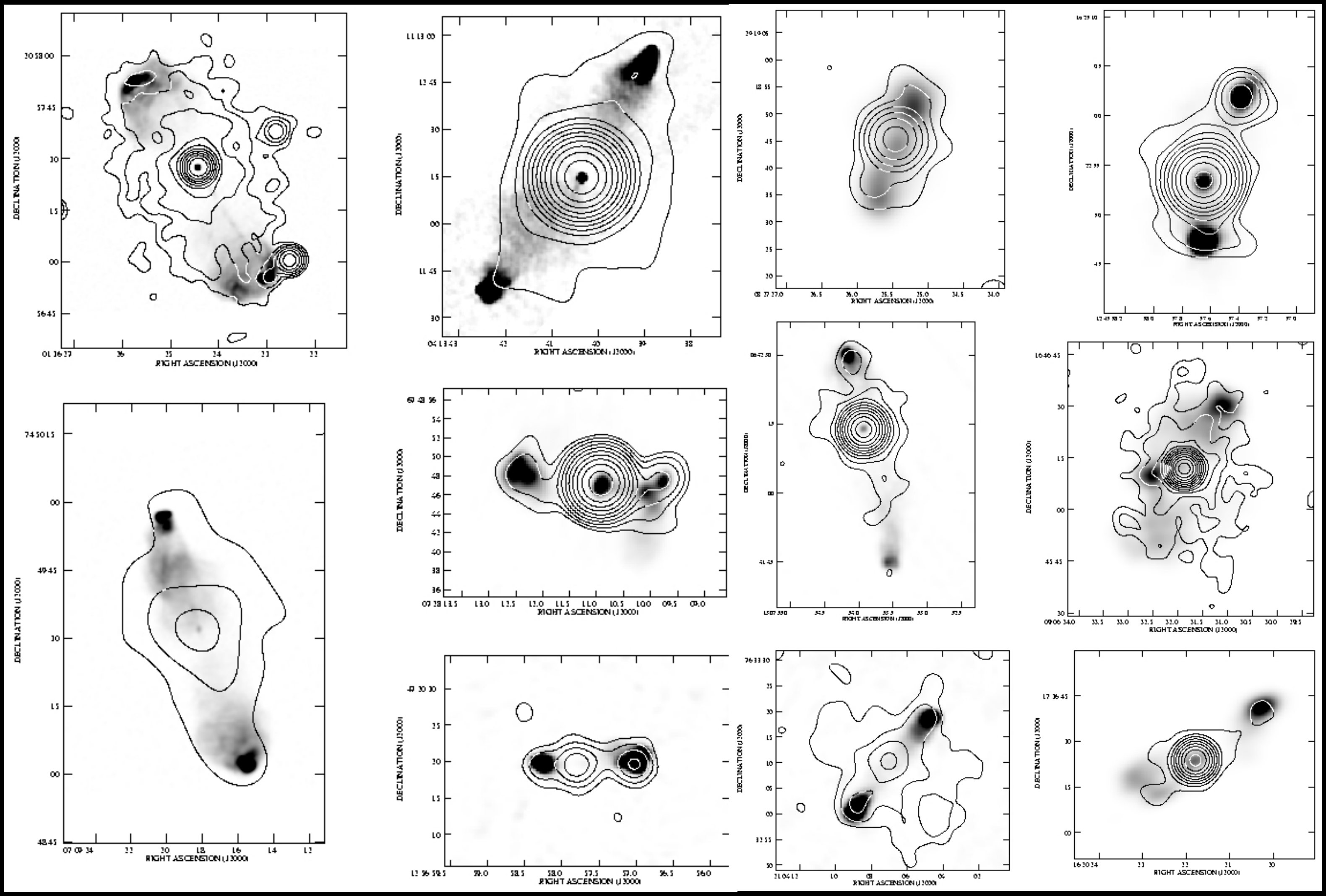




Croston et al. 2005, Hardcastle & Croston 2005

- X-ray IC emission gives probe of low-energy electrons & direct measurement of electron density.
- Can then calculate *B* using radio synchrotron emission.
- Incident photon populations are CMB ($\nu \sim 10^{11}$ Hz) and nuclear IR/optical ($\nu \sim 10^{14}$ Hz) emission (e.g. Brunetti 1997).
- $\nu_{out} \sim \gamma^2 \nu_{in}$ =>
  - To scatter CMB to X-ray, need $\gamma \sim 1000$
  - To scatter nuclear IR/optical to X-ray, need $\gamma \sim 30$ - 100
- With current instruments we have to extrapolate down to these energies from the observable radio region.

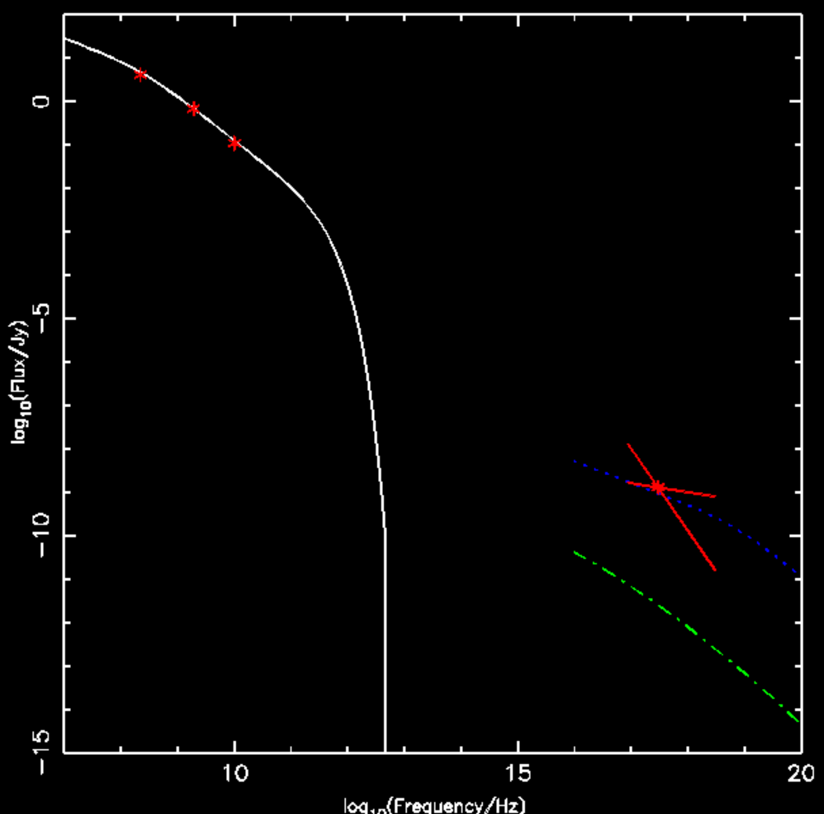
# A Chandra/XMM survey of radio-source electron content



**Croston et al. 2005, ApJ, 626, 733**

# X-ray/radio analysis

- 33 sources, 11 new detections, X-ray detection in at least one lobe in 70% of sources.
- Electron population modelled using radio spectrum:
  - 1.4 GHz maps with regions matched to X-ray extraction regions
  - 3C flux densities at 178 MHz
- Low-energy assumptions:
  - $\delta = 2$ (prediction from shock acceleration)
  - $\gamma_{min} = 10$
- Determine predicted X-ray IC/CMB emission at 1 keV for $B = B_{eq}$ for comparison with $S_{obs}$.



# Results

- Consistent with IC/CMB with $B = (0.3 - 1.3)\ B_{eq}$
- For our assumptions about low-energy electrons, typically predicted $S_{nuclear} << S_{cmb}$ .

- Peak in $B$ distribution at $B \sim 0.7\ B_{eq}$
- > 75% of sources at equipartition or slightly electron dominated
- Magnetic domination must occur rarely, if at all.
- Good agreement with equipartition argues against energetically dominant relativistic electron population.
- **Total internal energy in FRII radio sources is typically within a factor of 2 of minimum energy.**

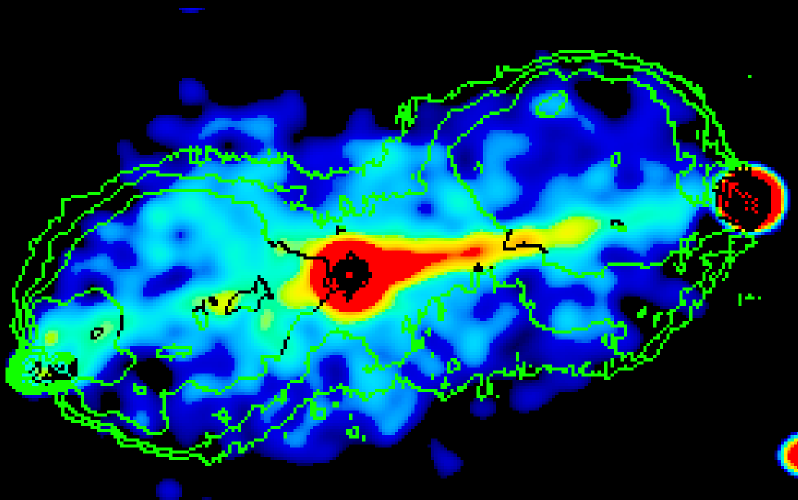
# Assumptions about low-energy electrons

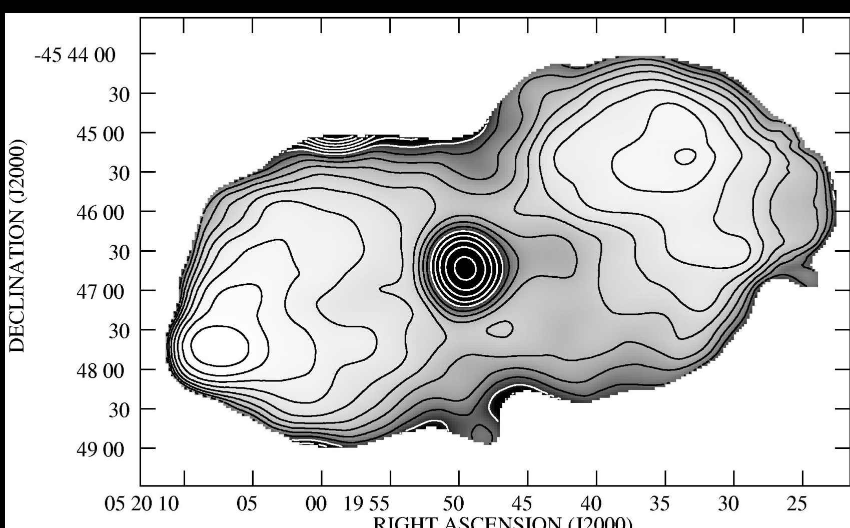
- Cut-off frequency, $\gamma_{min} = 10$
  - In hotspots, $\gamma_{min} \sim 100 - 1000$ required (e.g. Carilli et al. 1991)
  - Adiabatic expansion => lower energy electrons in lobes
- Spectral index, $\alpha_{low} = 0.5$ (flattening)
  - Shock acceleration models predict $\delta = 2 - 2.3$ (corresponding to $\alpha = 0.5 - 0.7$)
  - Also supported by hotspot observations (Carilli et al. 1991, Meisenheimer et al. 1997)

# How assumptions about low-energy electrons affect the results

- For $\alpha_{low} = \alpha_{obs}$:
  - R values increase by a factor of ~ 2
  - increase in $U_{tot}$ of up to factor of 20
  - But prediction for IC/nuclear becomes significant => *B* and $U_{tot}$ uncertain
- For $\gamma_{min} = 1000$ (instead of 10):
  - R values unchanged
  - IC/nuclear contribution decreases
  - Conclusions not affected
- For $\alpha_{low} >> \alpha_{obs}$:
  - all bets are off!

# Spatially resolved X-ray IC






- X-ray/radio ratio 3x higher close to nucleus compared to lobe centre.
- X-ray/radio ratio higher at edges of lobes.
- Radio spectrum steeper in inner regions

- IC/nuclear?
  - requires nuclear luminosity > $10^{40}$ W
  - expect counterjet side to have ~7 times more nuclear emission, but jet-side lobe has higher X/radio ratio
- Variations in B?
  - requires modest changes of factor ~ 1.5 in $B/B_{eq}$.
  - explains relatively uniform X-ray IC surface brightness
  - correlation between high X/radio ratio & steep radio spectrum requires larger variation in *B*
- Variations in electron spectrum?
  - With single $\alpha$ and *B* along line-of-sight, can only obtain factor < 2 variation in X/radio ratio.
  - More detailed source model may help.
- <u>Conclusion:</u> variations in both *B* and the low-energy electron spectrum are required.

# Summary

- First X-ray IC survey of FRII population detects >70% of sources.
- For *reasonable* assumptions about the low energy electron population:
  - $B = (0.3 – 1.3)\ B_{eq}$
  - $U_{tot}$ typically within a factor of 2 of $U_{min}$
  - No energetically dominant proton population
- Detailed studies of individual sources (Isobe et al. 2002, Hardcastle & Croston 2005) imply spatial variations in both electron spectrum and B within lobes.
- 10 – 200 MHz observations essential to confirm these results: LOFAR will remove main uncertainties in constraining group/cluster energy input from FRIIs.
- LOFAR will also enable detailed spatial studies of electron and field distribution in radio lobes by probing same electron population as X-ray IC.