TeV emission from radio galaxies

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Liverpool – TeV Universe meeting

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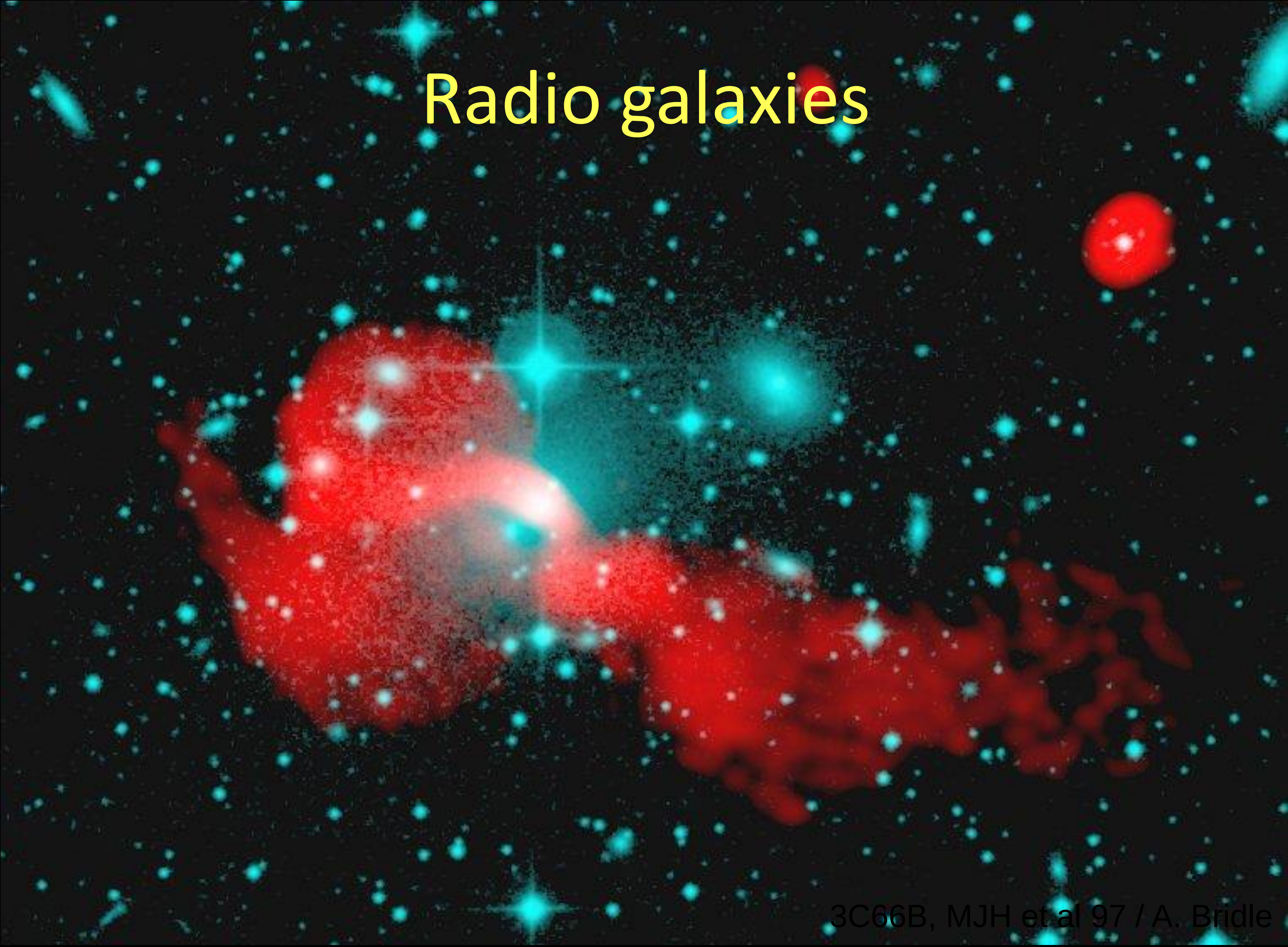
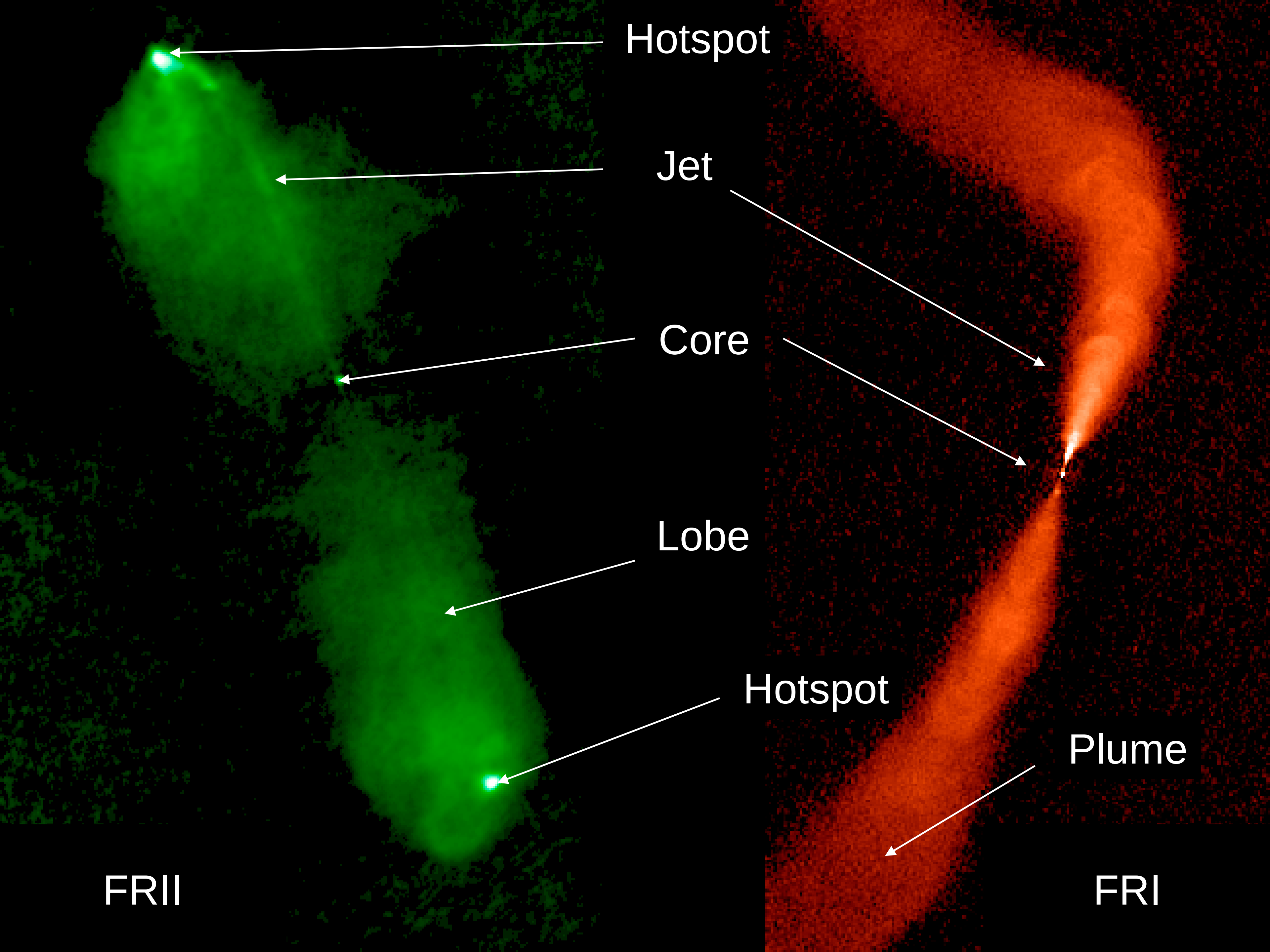
Outline

- Introduction:
  - Radio-loud AGN and their physics
  - The power of inverse-Compton
  - Where are the TeV electrons?
- Existing TeV sources
- Inverse-Compton modelling and its implications
- What can the CTA do for us?

Radio galaxies



3C66B, MJH et al 97 / A. Bridle


Hotspot
Jet
Core
Lobe
Hotspot
Plume
FRII
FRI

Radio galaxy physics

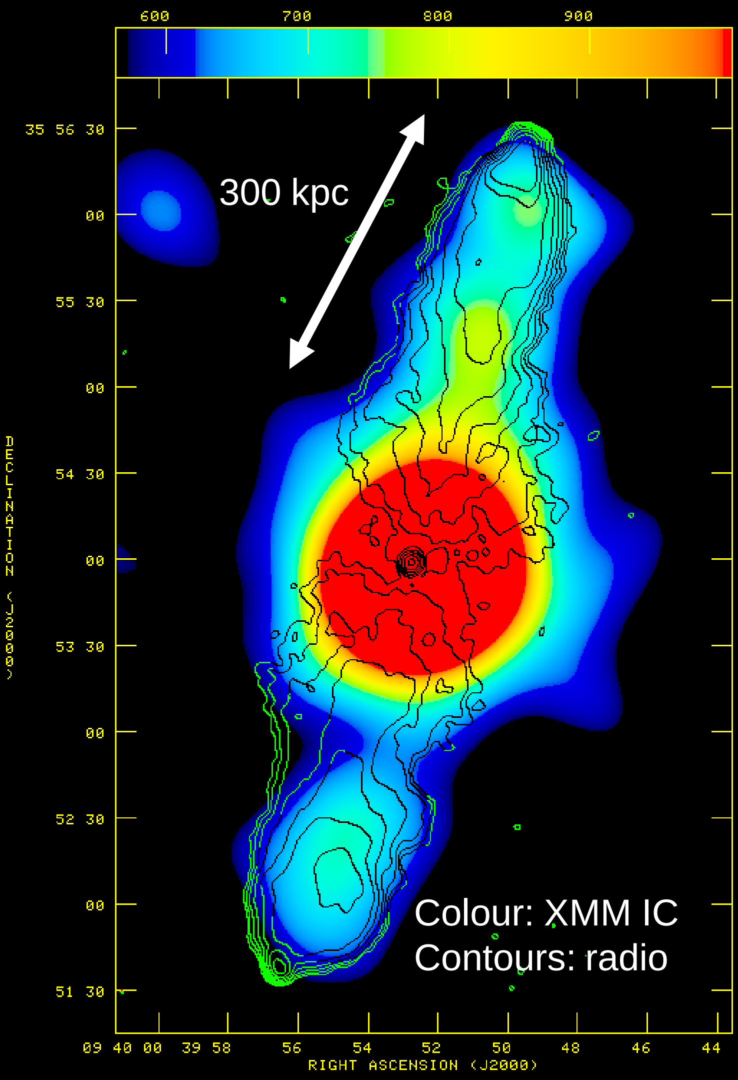
- Two key emission processes are:
  - Synchrotron radiation (relativistic electrons + magnetic fields) – peak frequency goes as $B\gamma^2$, total emissivity as $B^2\gamma^2$. For B ~ 1-10 nT, $\gamma \sim 10^3$-10^4 electrons give rise to GHz-freq radio emission
  - Synchrotron appears in all wavebands from radio through to X-ray. Higher frequencies => higher electron energies.
  - In general B not known => inferring physical conditions is hard from synchrotron alone.

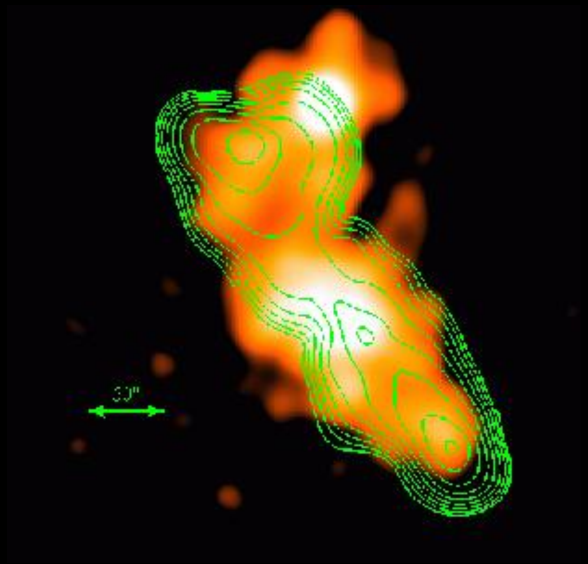
Radio galaxy physics

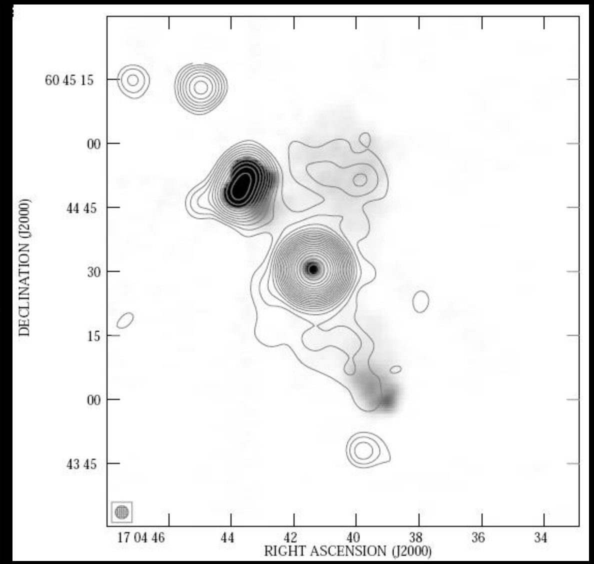
- Two key emission processes are:
  - Inverse-Compton scattering (relativistic electrons and background photon field, e.g. the CMB or the optical AGN emission). Peak frequency goes as $\nu_{photon}\gamma^2$, total emissivity as $U_{photon}\,\gamma^2$. For CMB, $\gamma \sim 10^3$ electrons scatter to ~ 1-keV X-ray photons
  - Inverse-Compton is seen in optical & X-ray and in principle up to high-energy γ-ray (no significant low-frequency photon background to scatter).
  - In general photon energy density *is* known to reasonable accuracy. With observations of both processes, B can be measured if U_{photon} is known.

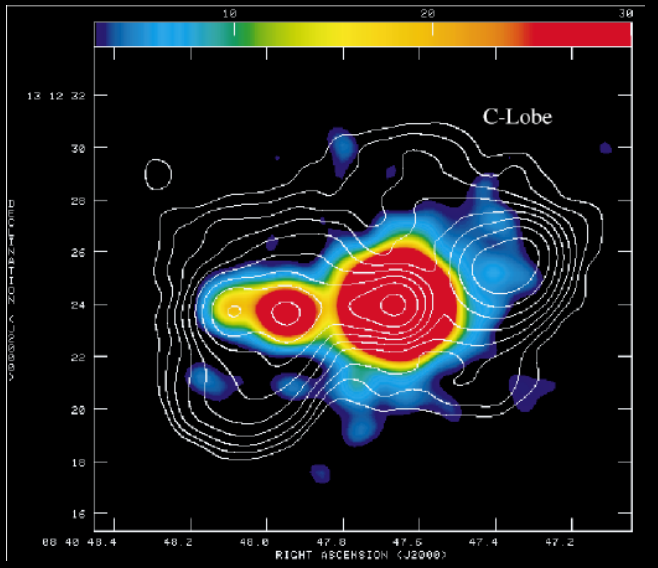
X-ray inverse Compton emission from radio lobes

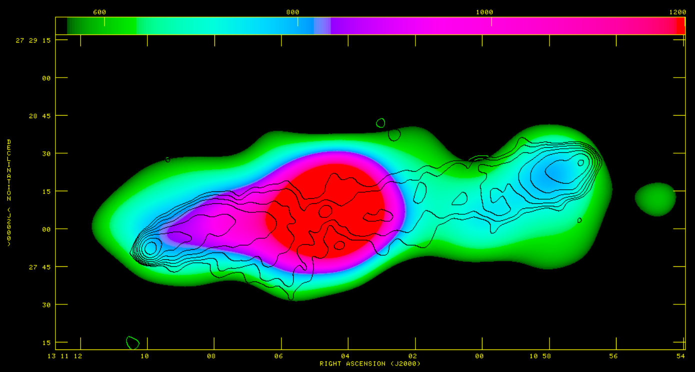
- Inverse-Compton scattering mainly of the CMB.
- Now routinely detected from FRII radio galaxies by Chandra & XMM
- Allows direct measurement of electron density, since CMB photon energy density is well known.
- X-ray IC + radio synchrotron from same electron populations provide direct measurement of B.

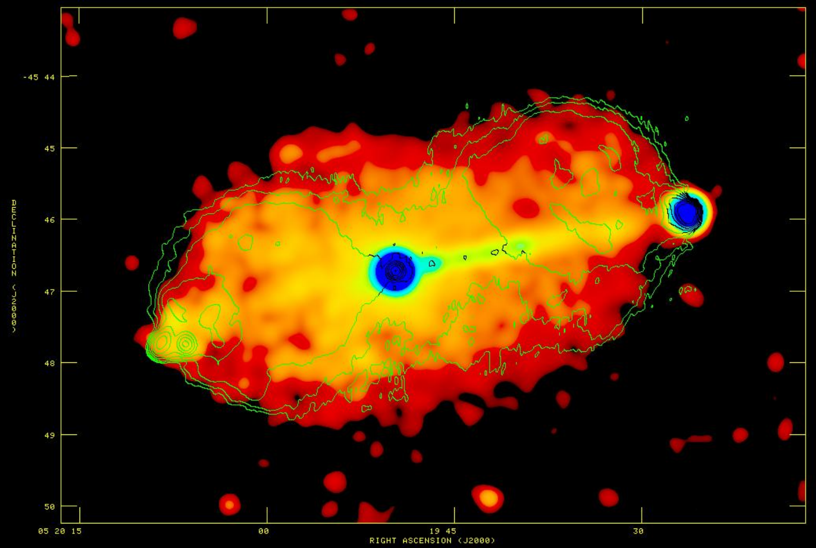


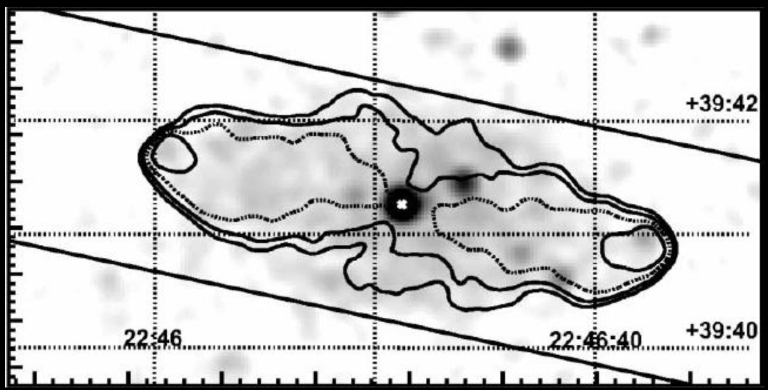






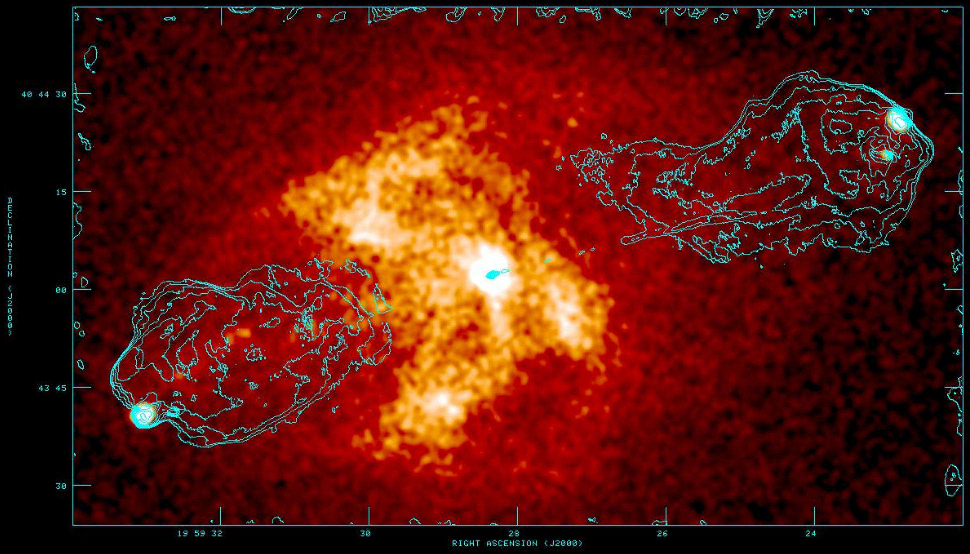






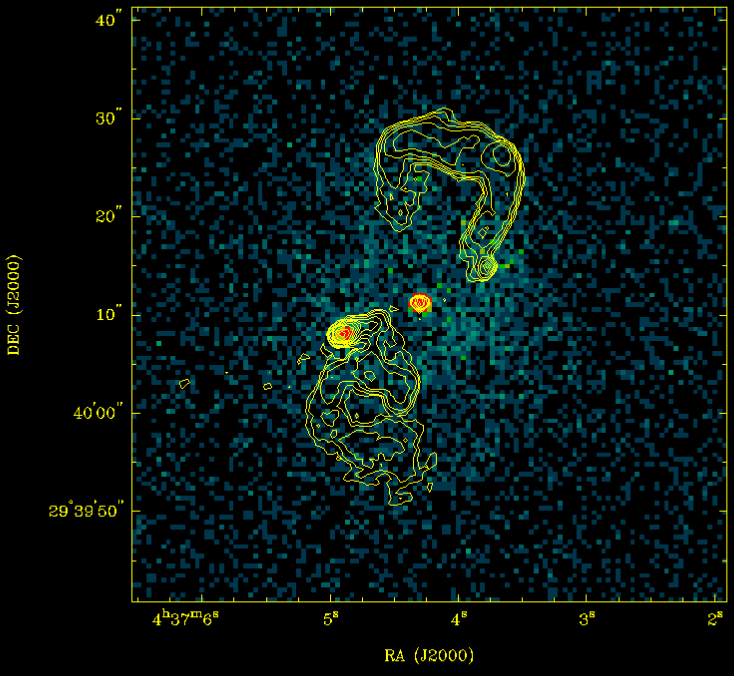
Comastri et al. 2003, Hardcastle et al. 2002, Brunetti et al. 2002, Croston et al. 2004, Isobe et al. 2002, Hardcastle et al. in prep

Inverse-Compton from hotspots



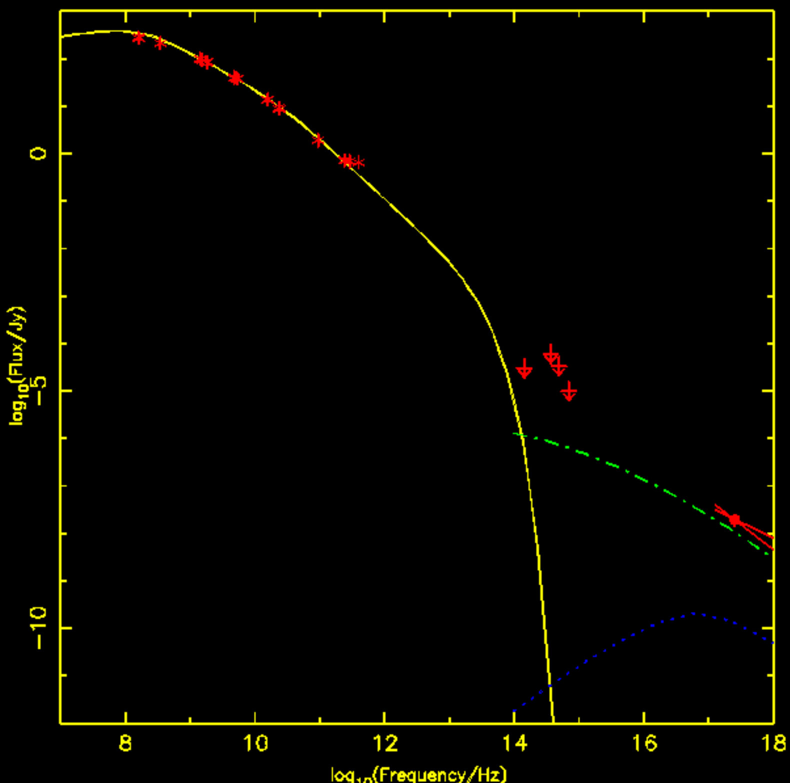
Highest synchrotron photon density => photon field is synchrotron.

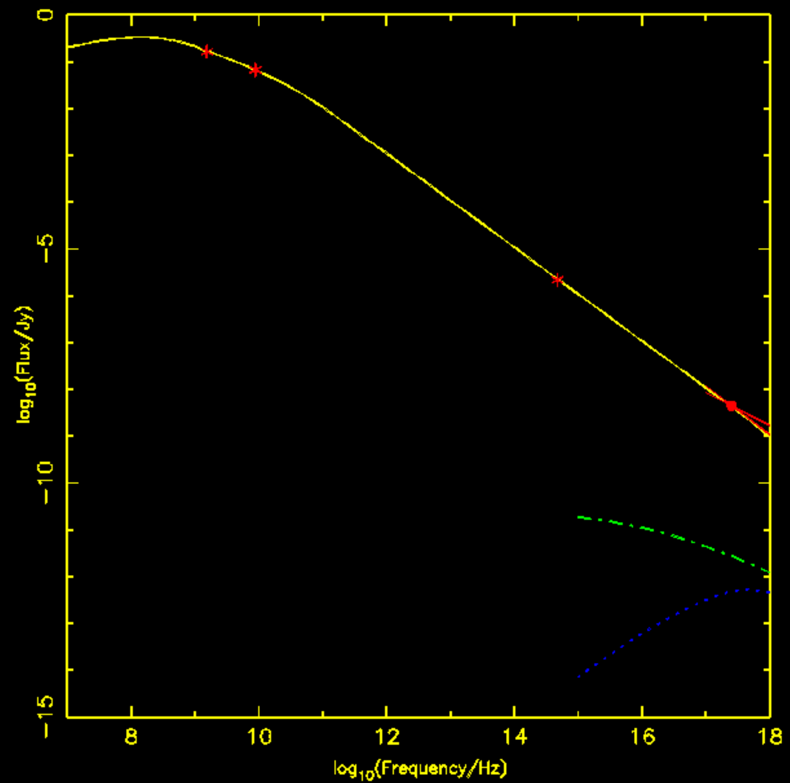
Powerful sources have magnetic fields and corresponding total energy densities close to the equipartition value.



Hotspot spectra

Some hotspots are consistent with SSC in X-ray, others plausibly synchrotron

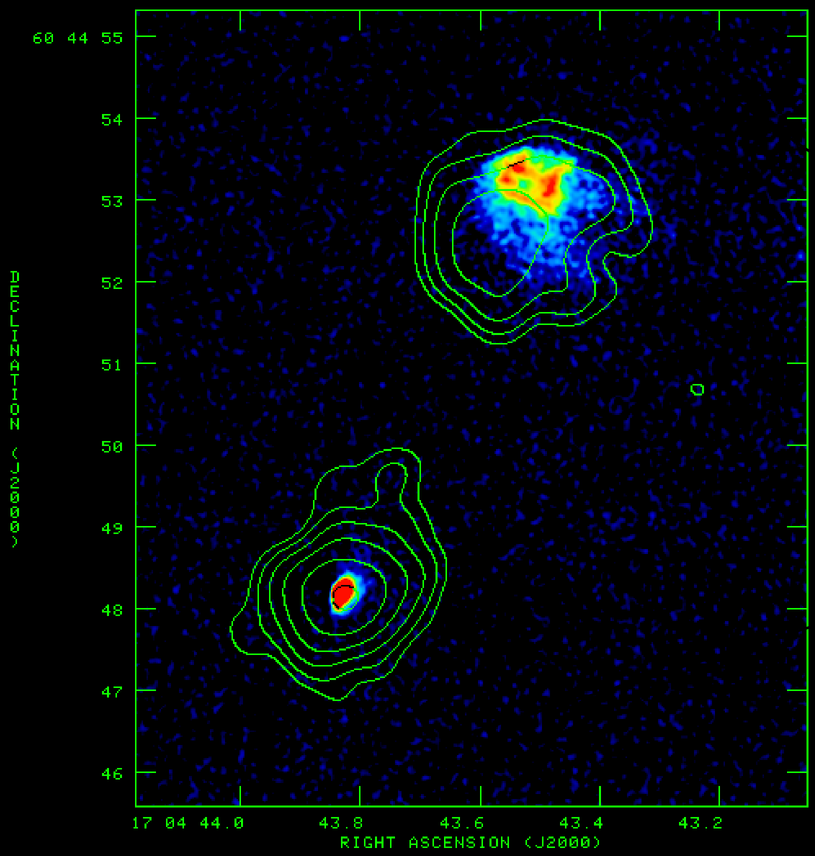


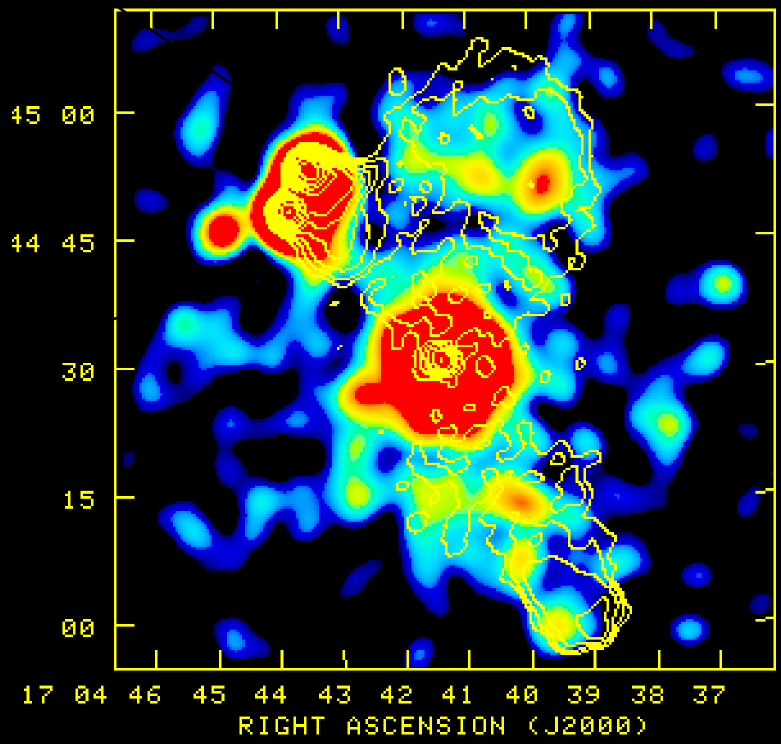


Left: Cyg A hotspot A.

Right: 3C390.3 N hotspot

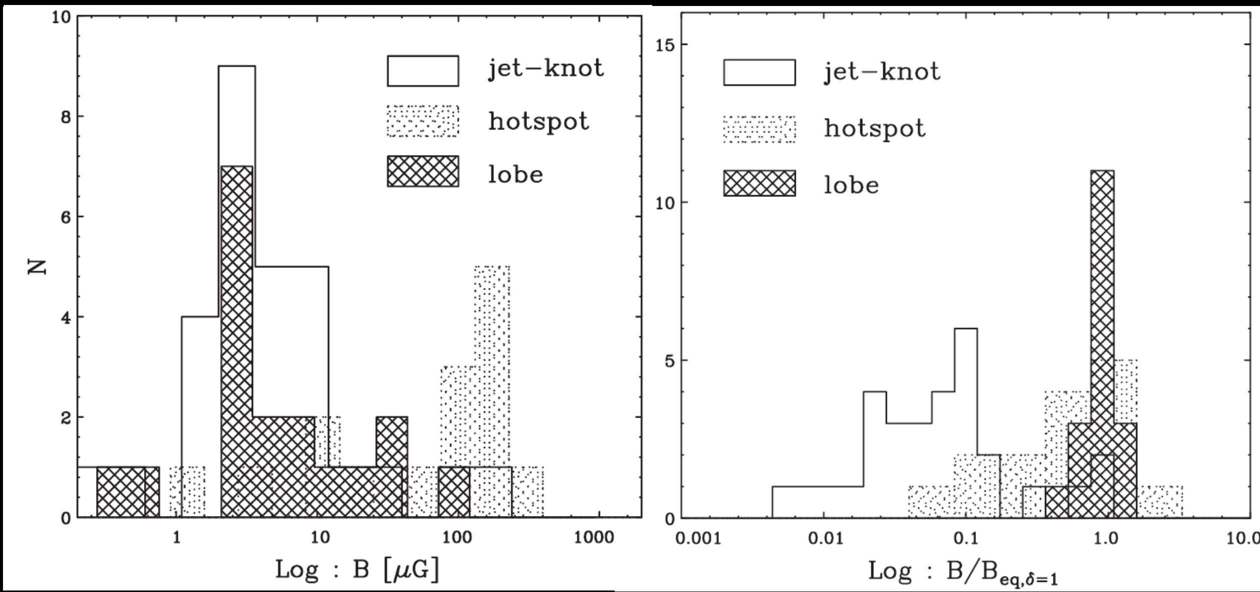
Complicated hotspots





Offsets between radio and X-ray may be a sign of multiple X-ray emission processes

Population statistics with X-ray IC

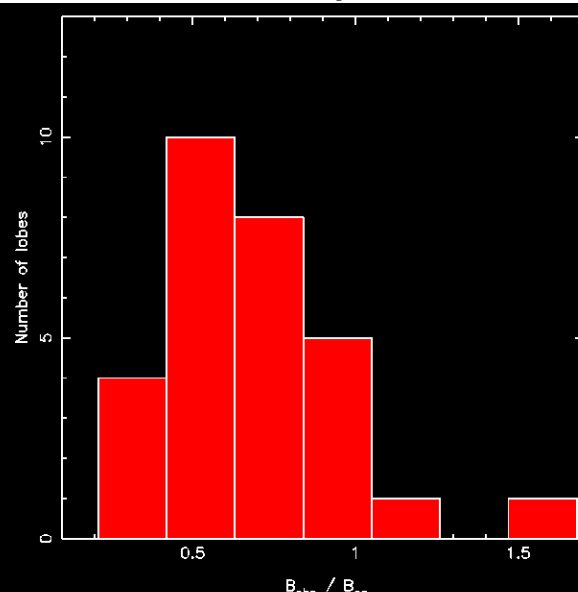


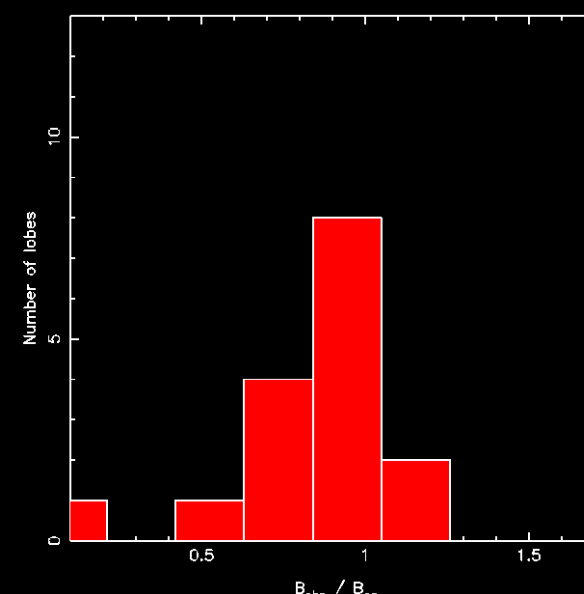
Kataoka & Stawarz 2005 ApJ 622 797:

B fields in a sample of detected jets, hotspots and lobes, including 18 lobes with redshifts ~0.006 – 2

Croston et al. 2005 ApJ 626 733:

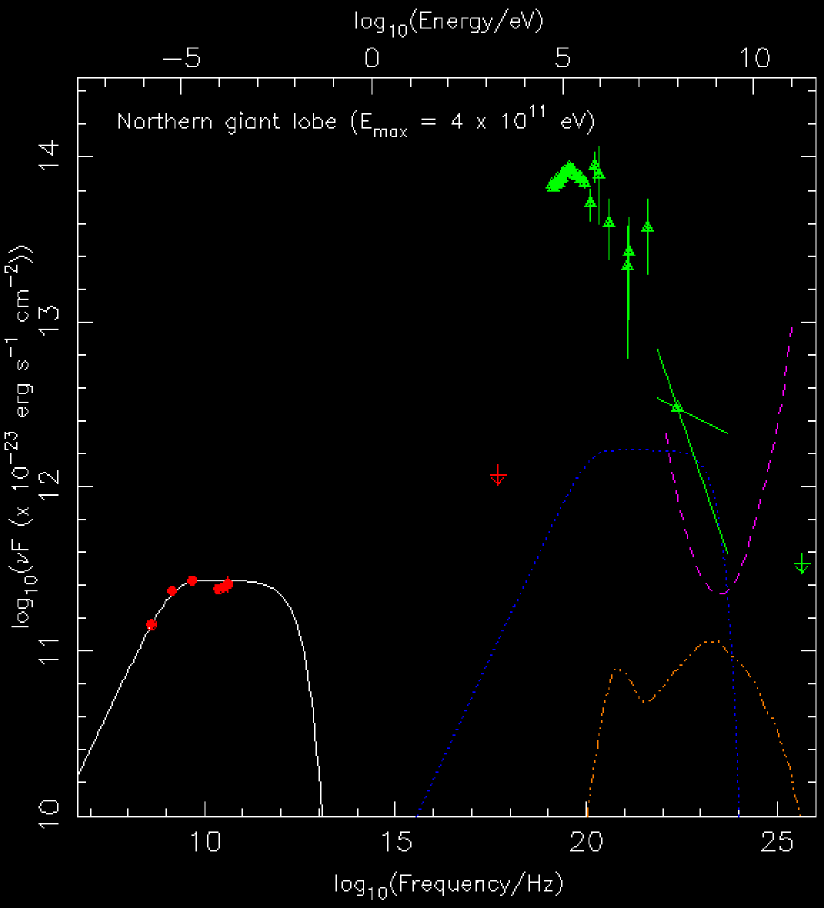
B fields in sample of 33 FRII radio-loud AGN from 3C catalogue, redshifts from ~0.05 – 2





Inverse-Compton beyond the X-ray

- Some cases where existing gamma-ray data provide best constraint – e.g., giant lobes of Cen A
- Fermi detection predicted for some electron energy spectrum models, can't comment on results (but paper submitted to *Science*, should be out soon).



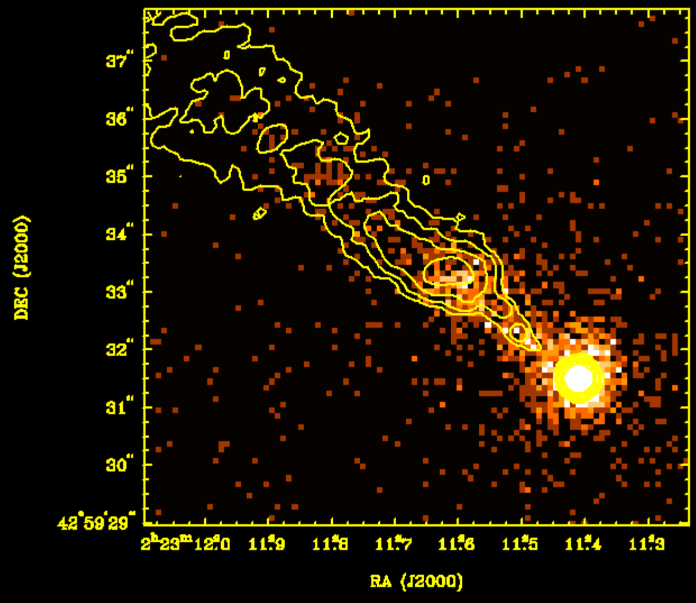
TeV inverse-Compton

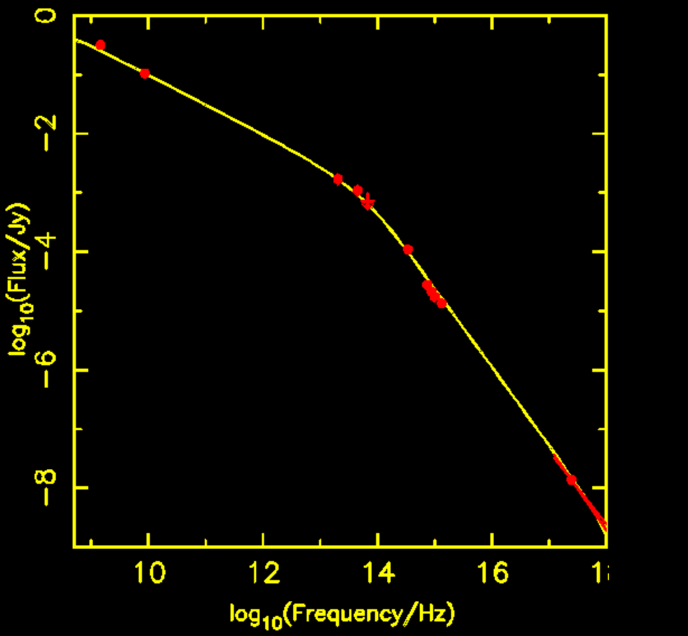
- Should be detectable (in principle) from sources containing >TeV electrons (as possibly in some SNR)
- For high B-fields (compact, kpc-scale regions of the source) these will be X-ray synchrotron sources – so X-ray is no use for measuring B.
- Can make use of relatively good sensitivity and resolution of γ-ray telescopes at highest energies.
- Probably not contaminated by p-p gammas since proton density is low or zero in these regions.

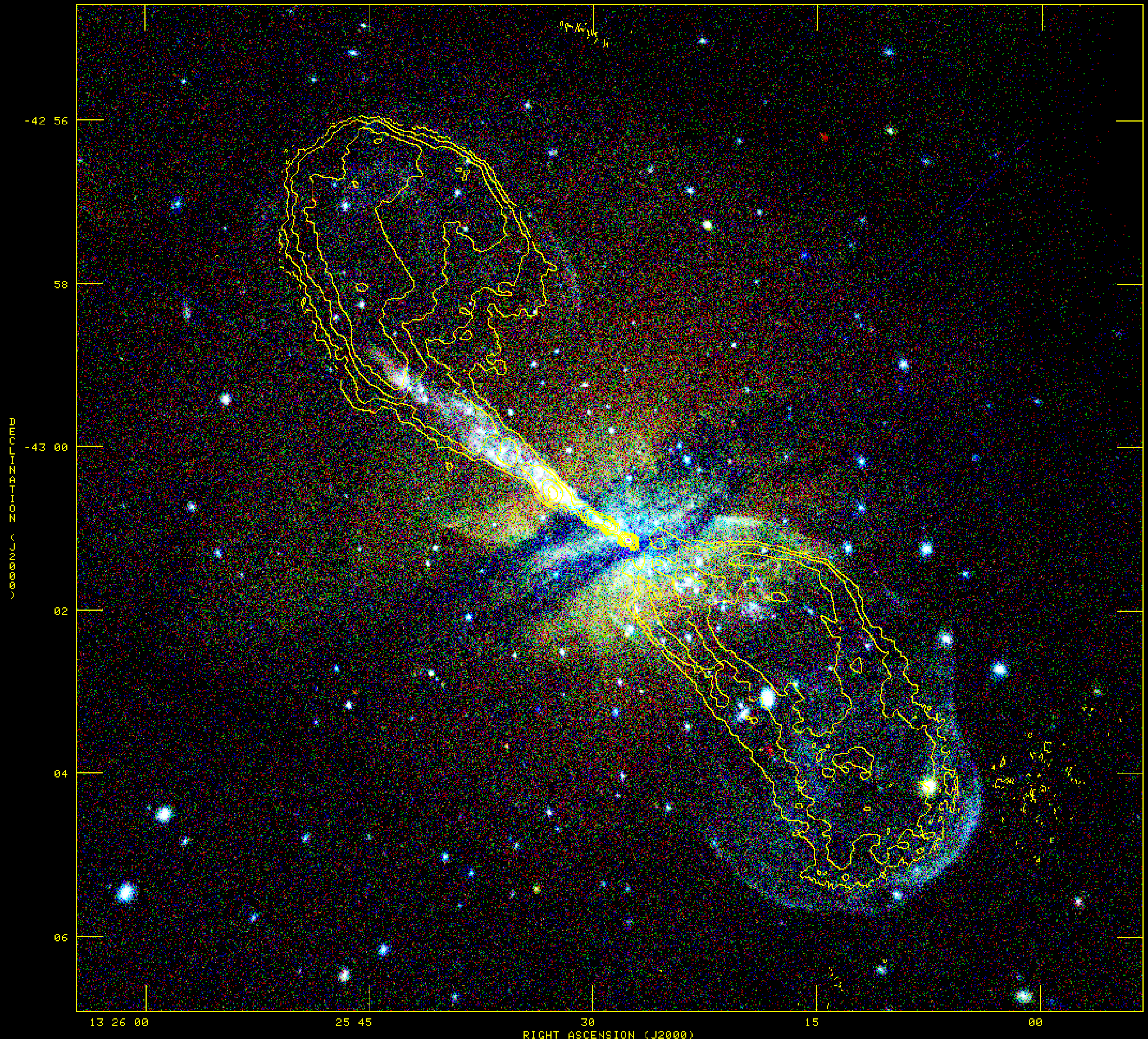
Where are the TeV electrons?

1) Sub-pc jets of all classes of object?
2) FRII hotspots – as discussed above
3) Jets of FRI radio galaxies, and
4) Shocks around the large-scale lobes

In the last two cases nearby objects give us exquisitely detailed pictures of the electron distribution...







-42 56
58
-43 00
02
04
06
DECLINATION (J2000)
13 26 00
25 45
30
15
00
RIGHT ASCENSION (J2000)

Existing TeV sources

Many blazars, plus a total of 2.5 radio galaxies:

- M87: long-standing detection; recent timing analysis shows at least some TeV associated with inner jet (Acciari+ 09)

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B s

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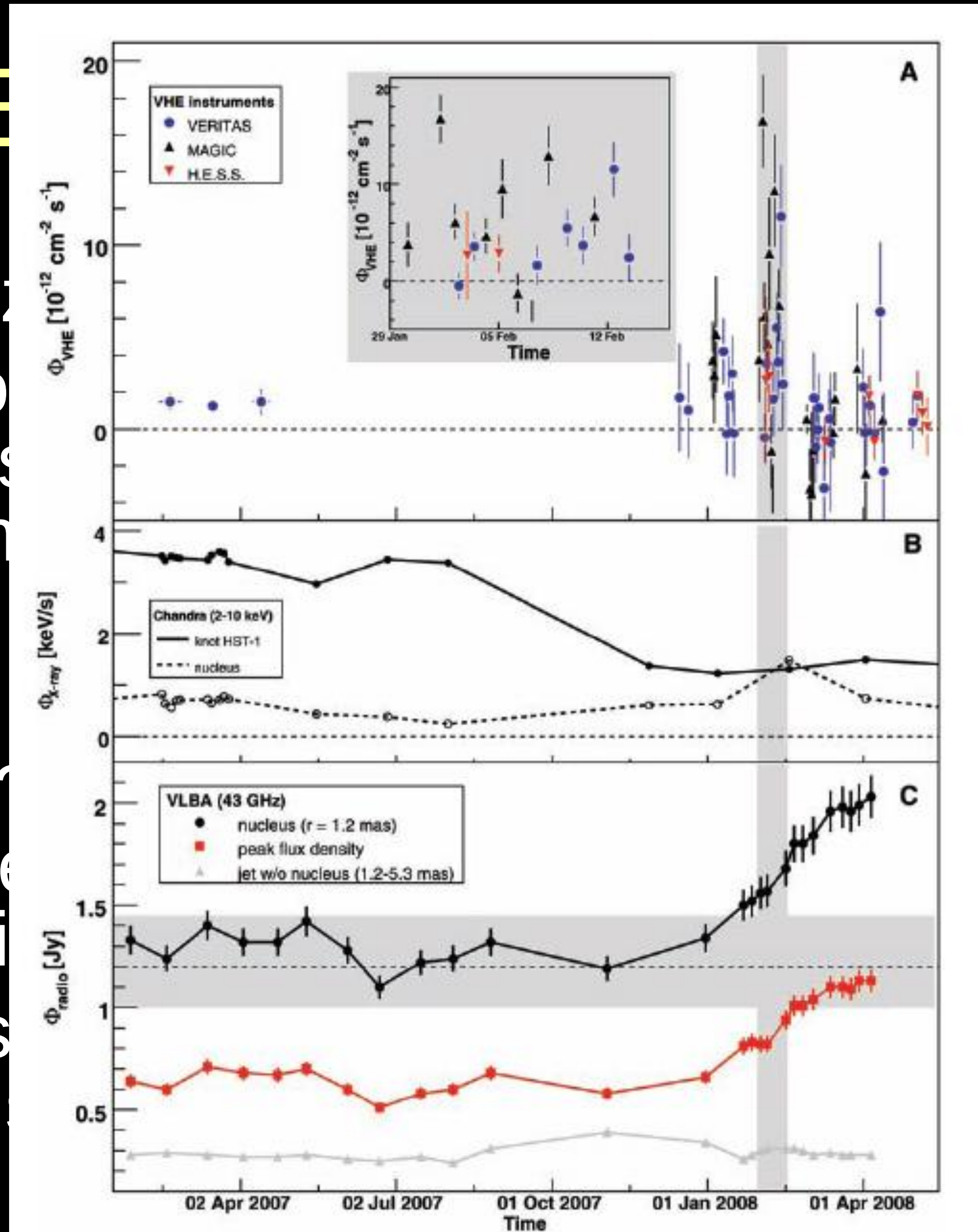
- 3C66B A, but a possible Ghiselli

All 3 RGs electrons on kpc



Existing TeV sources

Many blazars, plus a total of 2.5 radio galaxies:

- M87: long-standing detection; recent timing analysis shows at least some TeV associated with inner jet (Acciari+ 09)
- Cen A: recent HESS detection (Aharonian+ 09)
- 3C66B? Confused with blazar 3C66A, but a possible detection (e.g. Tavecchio + Ghisellini 09)

All 3 RGs have bright X-ray jets (TeV electrons on kpc scales).

Models for RG TeV emission

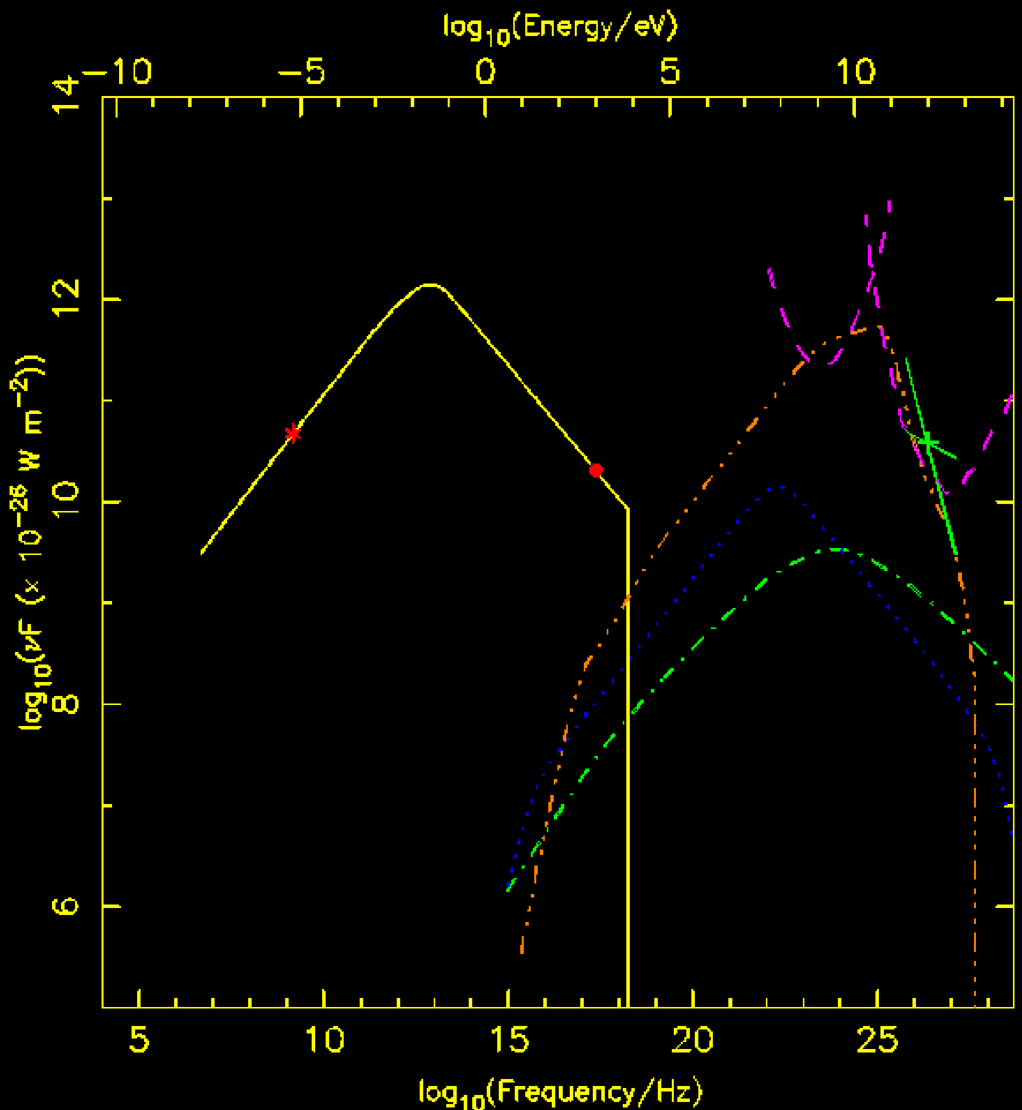
Three general classes of IC models:

1) From close to accretion flow – e.g. Rieger + Aharonian 09 for Cen A.
2) From pc-scale jet – e.g. Ghisellini+ 05. Requires assumptions about electron distributions that are not directly testable, but consistent with variability observations in M87 & with many detections of blazars; probably true at some level.
3) From kpc-scale structures (e.g. Stawarz+ 03) – constrained by, and constraining of, reasonably well-understood physics.

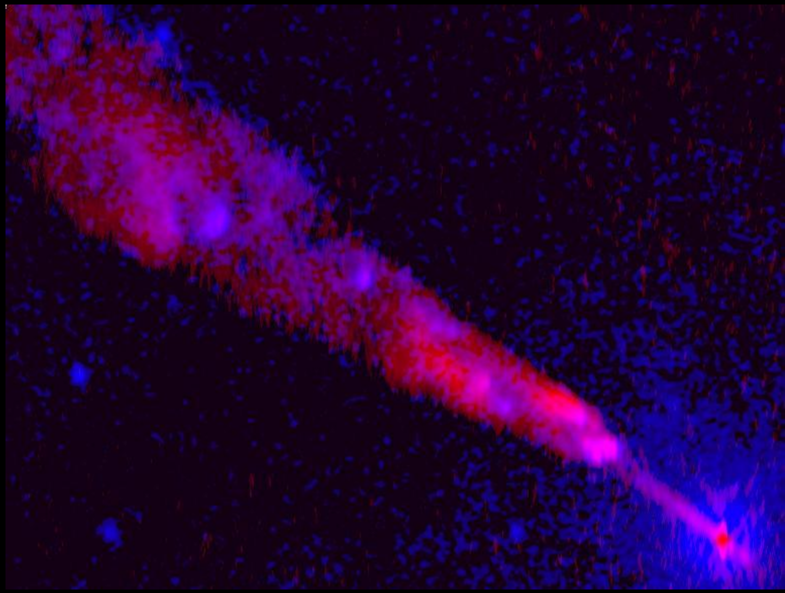
Extended IC modelling

- Electron energy distribution constrained via synchrotron observations
- Various photon fields must be considered:
  - Synchrotron photons (SSC)
  - CMB
  - Extragalactic background light (EBL)
  - Starlight (inside host galaxy)
  - Hidden quasar/blazar
- Crucial to take Klein-Nishina effects and anisotropy of photon fields, IC emissivity into account. Work in progress...

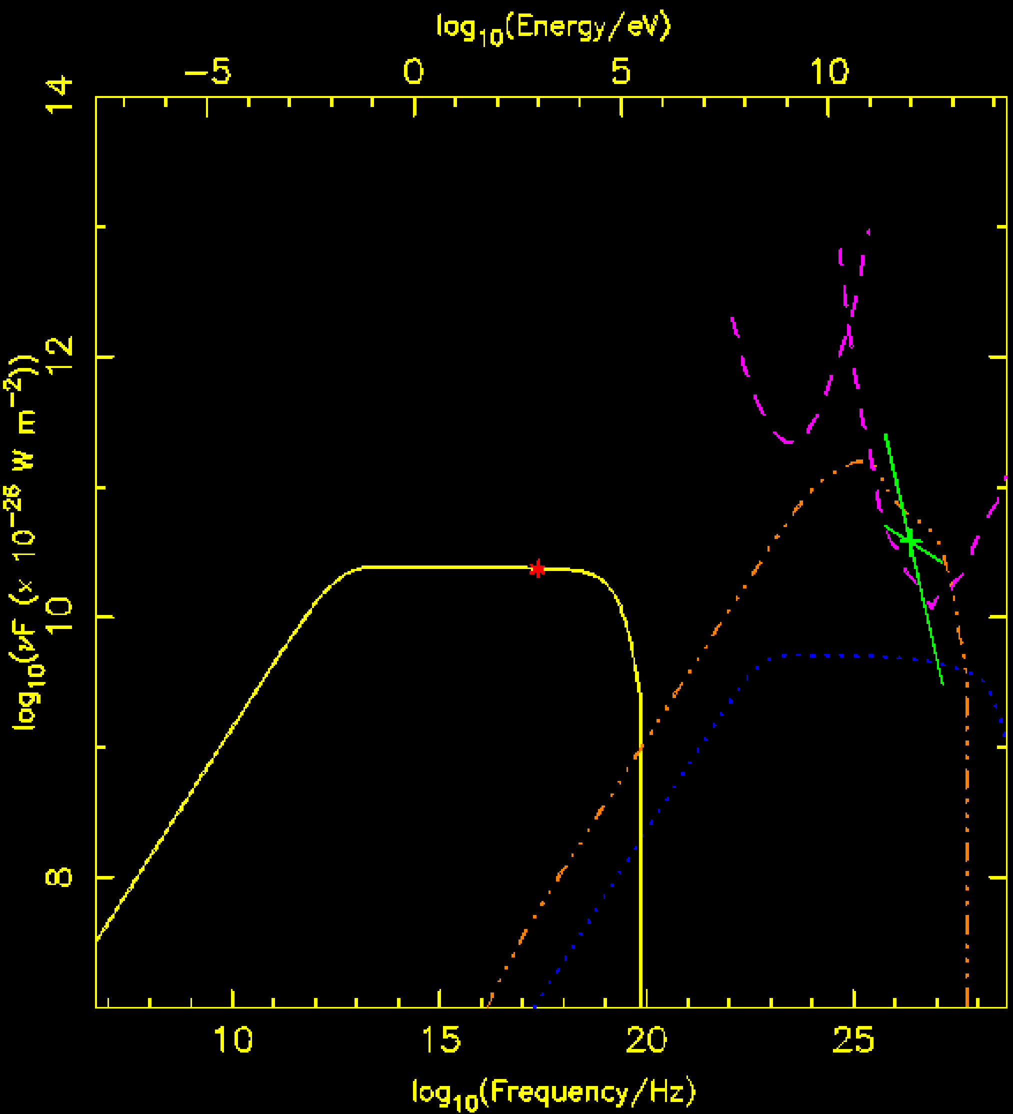
Cen A jet



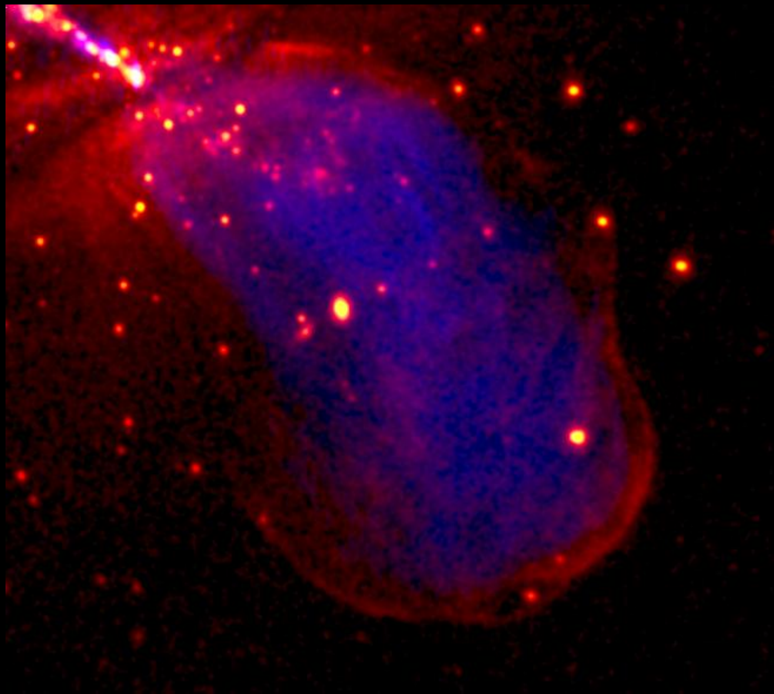
One-zone model of X-ray jet. Starlight dominates. Klein-Nishina corrections crucial. Beaming has significant effect.



Cen A lobe shock



Magnetic field on assumption of a lepton-dominated pressure matched to the known pressure in the lobe (Croston+ 09).



Extended IC modelling

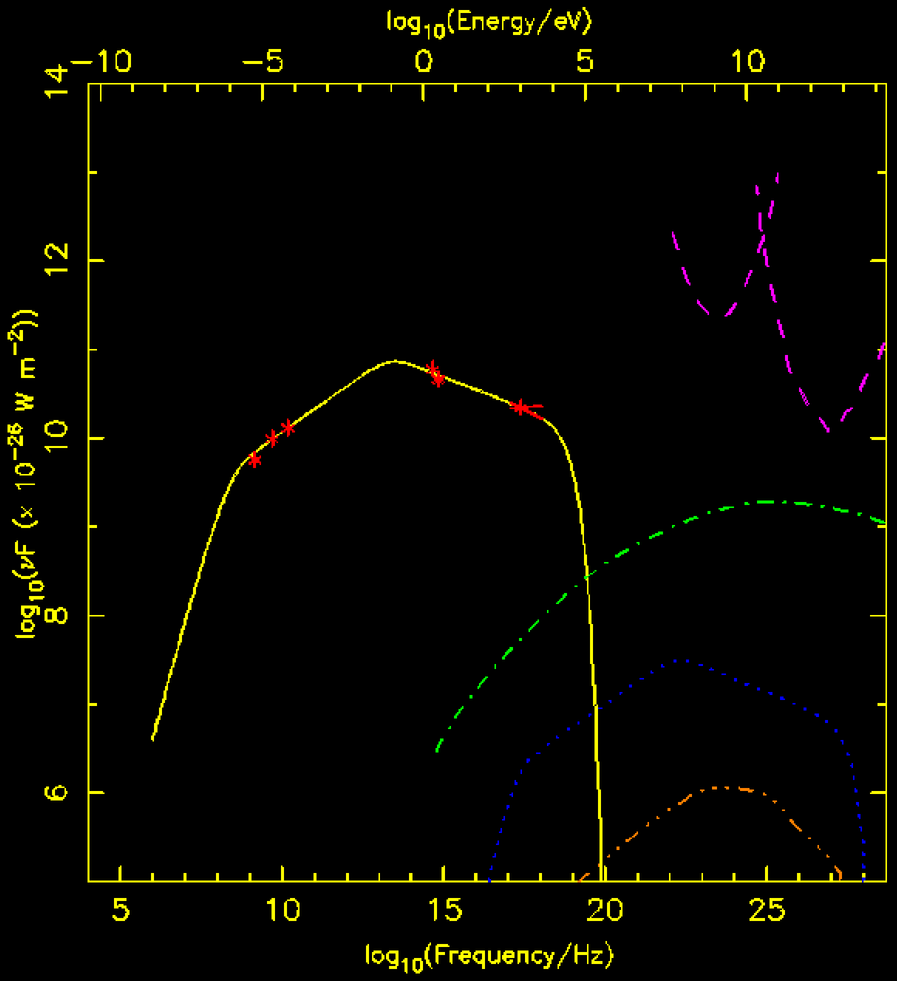
- Work still needed on spatially resolved modelling codes, but
- At the moment it appears that HESS detections of Cen A are already constraining – limits set on B-field strength.
- Could also consider non-varying component of M87 TeV flux?

What can the CTA do for us?

- Improved sensitivity
  – But we are going to struggle to detect new non-nuclear IC sources, see next slides
- Improved spatial resolution
  – Helps us separate nuclear and off-nuclear components, important for emission mechanism constraints.

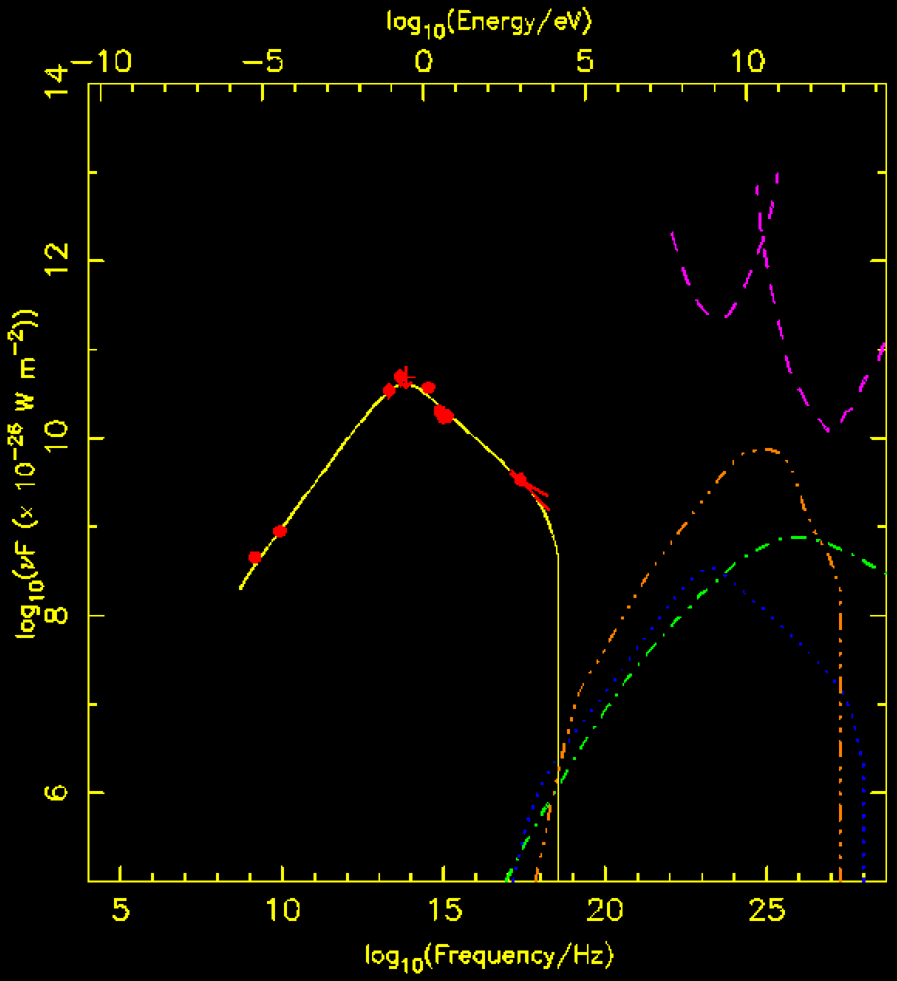
Pictor A

- Brightest nearby X-ray synchrotron hotspot.
- Not readily detectable in SSC for fields close to equipartition.
- (Consistent with Zhang+ 09 – they assume B << B_{eq}.)
- Tough to detect hotspots even with CTA, but still an interesting experiment...



3C66B

- Representative nearby (D = 100 Mpc) FRI radio galaxy – not M87 or Cen A!
- Better luck here thanks to starlight – but still only marginally detectable in this one-zone model.
- (Electron distribution gives IC peak in between CTA and Fermi sensitivity maxima.)
- MAGIC detection, if real, is probably not jet IC?



CTA resolution

- Peak resolution ~ couple of arcmin
- Capable of resolving nearby FRII sources – if any are detectable ($B \ll B_{eq}$)
- Marginally resolves Cen A jet and inner lobes! – if jet is not detected strong constraints are placed on B-field strength in jet.

Summary

- TeV studies of (lobe-dominated) radio-loud AGN provide us with the opportunity to extend successful use of inverse-Compton diagnostics to systems in which X-ray studies are not possible. TeV IC is mandatory for X-ray synchrotron sources.
- Detailed inverse-Compton studies taking into account all the physics have not yet been done, but existing constraints are already interesting for a few famous objects.
- CTA sensitivity and resolution will improve things, though there will still be a lot that we can't see!