Broad-band observations of hotspots

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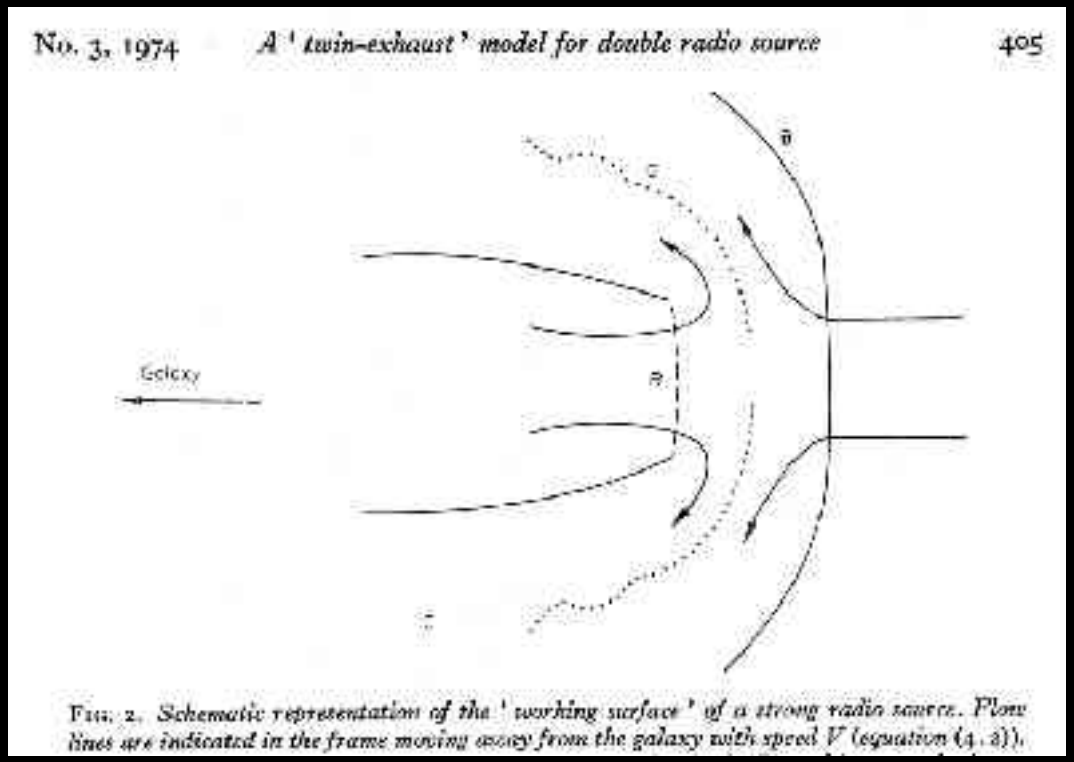
Cracow: Challenges of Relativistic Jets

With thanks to my collaborators past and present on hotspot radio & X-ray observations, particularly Ralph Kraft, Dan Harris, Diana Worrall, Mark Birkinshaw, Judith Croston

Synopsis

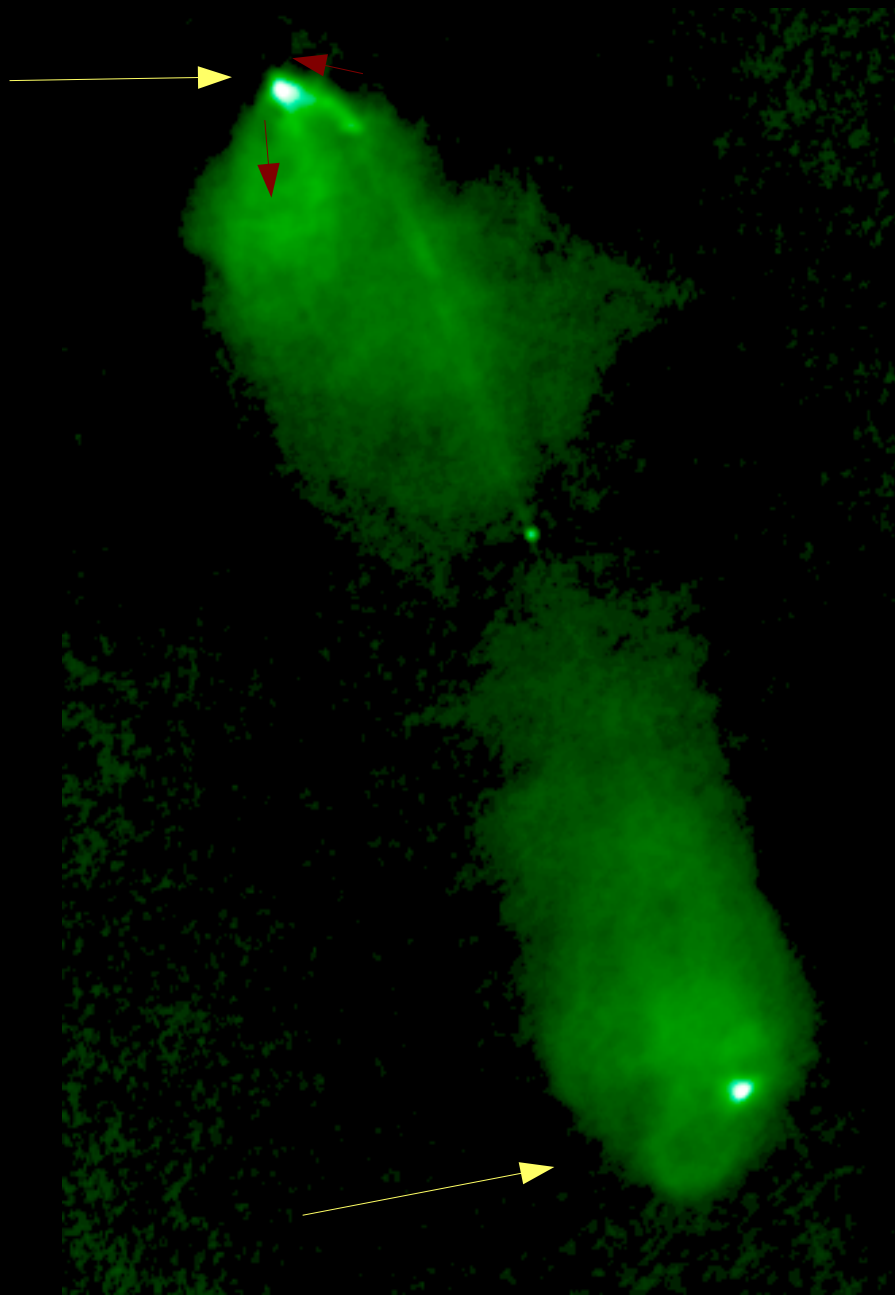
- Introduction
  - What are hotspots? The pre-Chandra landscape
- X-ray emission processes
  - synchrotron self-Compton emission
  - synchrotron emission
  - others
- Problems for one-zone X-ray synchrotron models: it's not just jets!
  - spectral breaks
  - offsets
- Where does this leave us?

Introduction



Hotspots have been identified since the 1970s as the visible manifestation of the shock at the jet termination.

(Sketch from Blandford & Rees 1974)

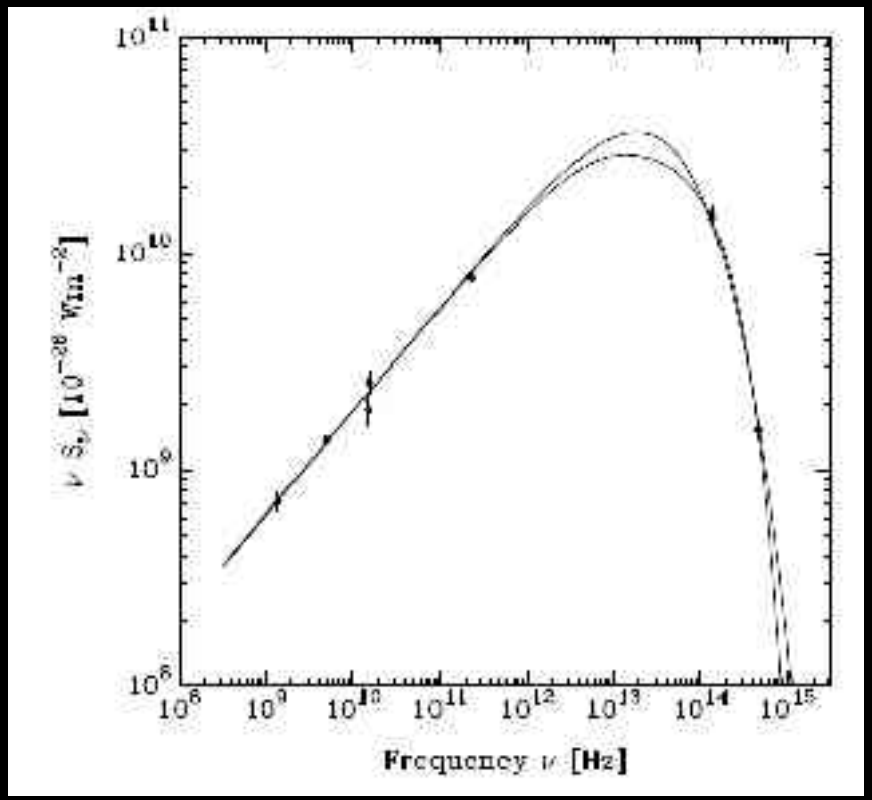


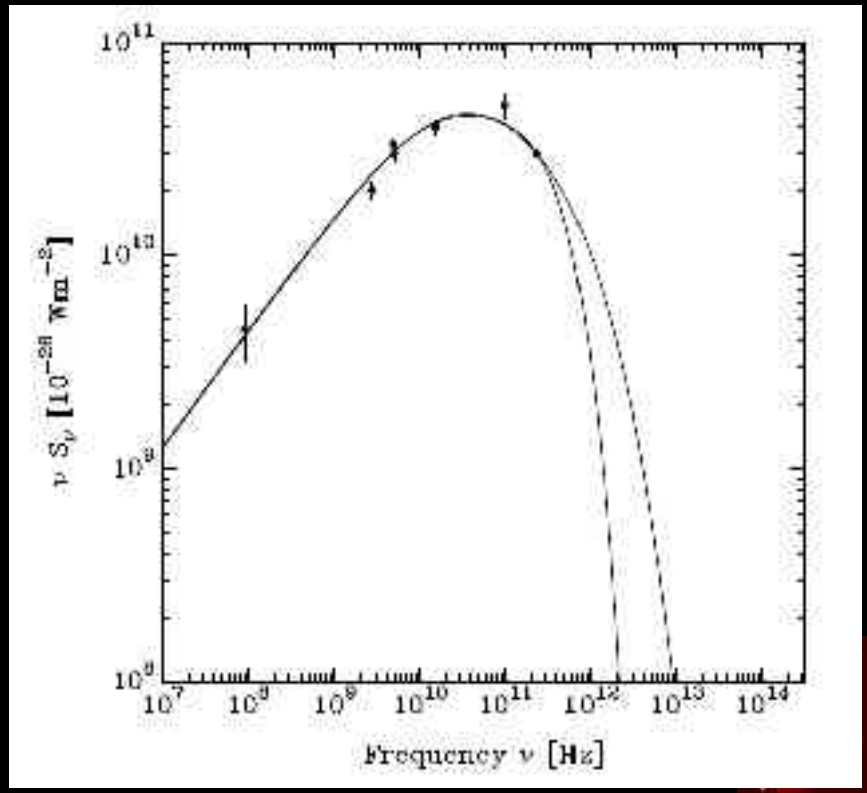
Why study hotspots?

- Looking under the lamp: bright and compact broad-band emitters, well away from nucleus => easy to study.
- But also:
  - supposed to be major (only?) sites of particle acceleration in powerful sources. (Traditionally) assumed to set parameters for lobe electron population.
  - magnetic fields are high if in equipartition (see later) so low-energy electrons are shifted into observable regime and loss timescales are short for high-energy electrons.
  - beaming is probably not dominating what we see (e.g. Kataoka talk: but see later)

Broad-band spectra and particle acceleration

- Best direct evidence for shock model: radio through optical SEDs of hotspots (e.g. Meisenheimer et al 1989) often consistent with a simple model for shock particle acceleration + loss (Heavens & Meisenheimer 1987)...



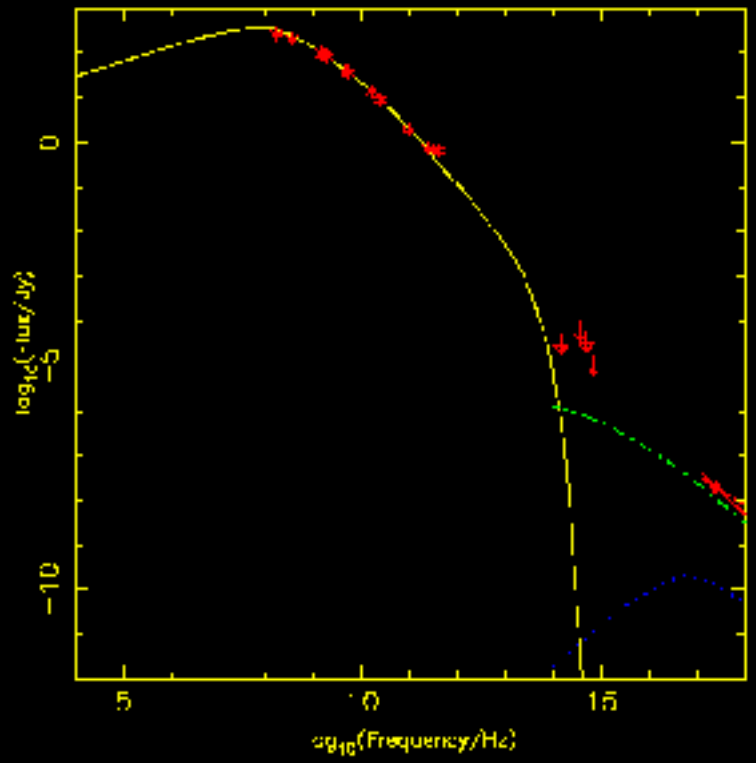


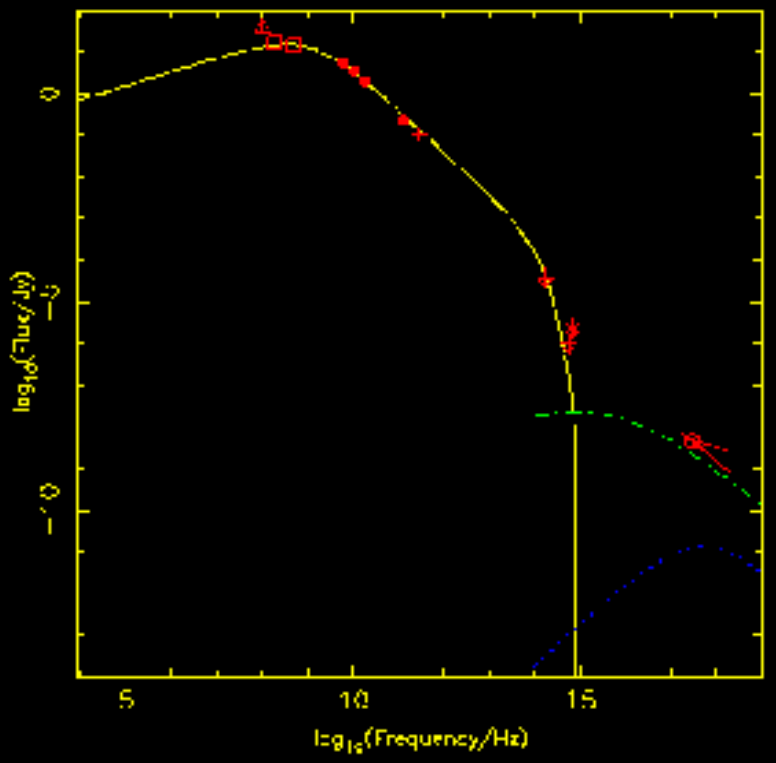
Broad-band spectra and particle acceleration

- Best direct evidence for shock model: radio through optical SEDs of hotspots (e.g. Meisenheimer et al 1989) often consistent with a simple model for shock particle acceleration + loss (Heavens & Meisenheimer 1987).
- High-frequency break and cutoff sensitive to magnetic field strength => low-luminosity hotspots more likely to have optical and X-ray synchrotron emission (Meisenheimer et al 1997, Brunetti et al 2003, Hardcastle et al 2004: see later).
- NB in these models break is an effect of spatial averaging: cutoff comes directly from acceleration region physics, i.e. loss/energy input balance.

Particle acceleration continued

- Electron energy indices usually close to, but not exactly, 2.0 ($\alpha = 0.5$).
- Low-energy 'cutoff' indicated by spectral turnover in a few sources at electron LF of $\gamma_{min} = 500 .. 1000$...





Particle acceleration continued

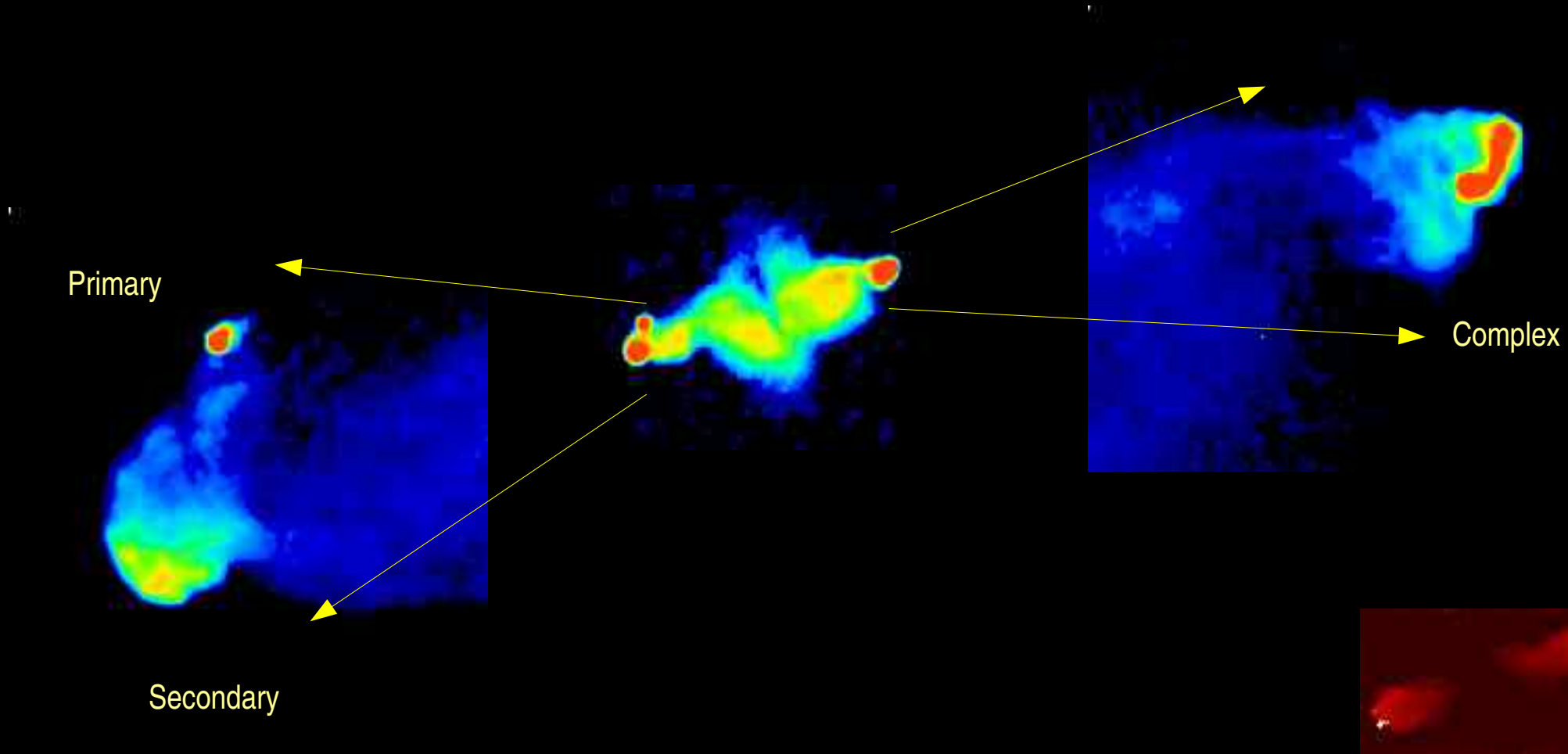
- Electron energy indices usually close to, but not exactly, 2.0 ($\alpha = 0.5$).
- Low-energy 'cutoff' indicated by spectral turnover in a few sources at electron LF of $\gamma_{min} = 500 .. 1000$. Not well constrained in general, but must be < few x 10^3 to avoid appearing at GHz frequencies. Not synch self-absorption.
- Origin of cutoff unknown: adiabatic expansion means it's likely to be more complex in observed hotspot region than a simple $N(\gamma) = 0$ for $\gamma < \gamma_{min}$ (Brunetti 2002).
- Intrinsic to jet? See earlier discussion of bulk Comptonization.

Beaming

- Recall that fluid flow speed through hotspots can be >> hotspot advance speed.
- Bulk of the emission is thought to be *post-shock* – so bulk speeds should be < c/3 for a strong perpendicular shock.
- But could be higher for oblique shocks.
- The jet may brighten and confuse the issue near termination.
- Correlation – bright hotspot on jet side in quasars (Laing 1989).
- Detailed radio spectra of source head regions => modestly relativistic post-hotspot bulk speeds (Dennett-Thorpe et al 1997).

Multiple hotspots

- Known since early 80s (e.g. Laing 1982) that many sources have more than one hotspot ('primary', 'secondary', 'hotspot complex')...

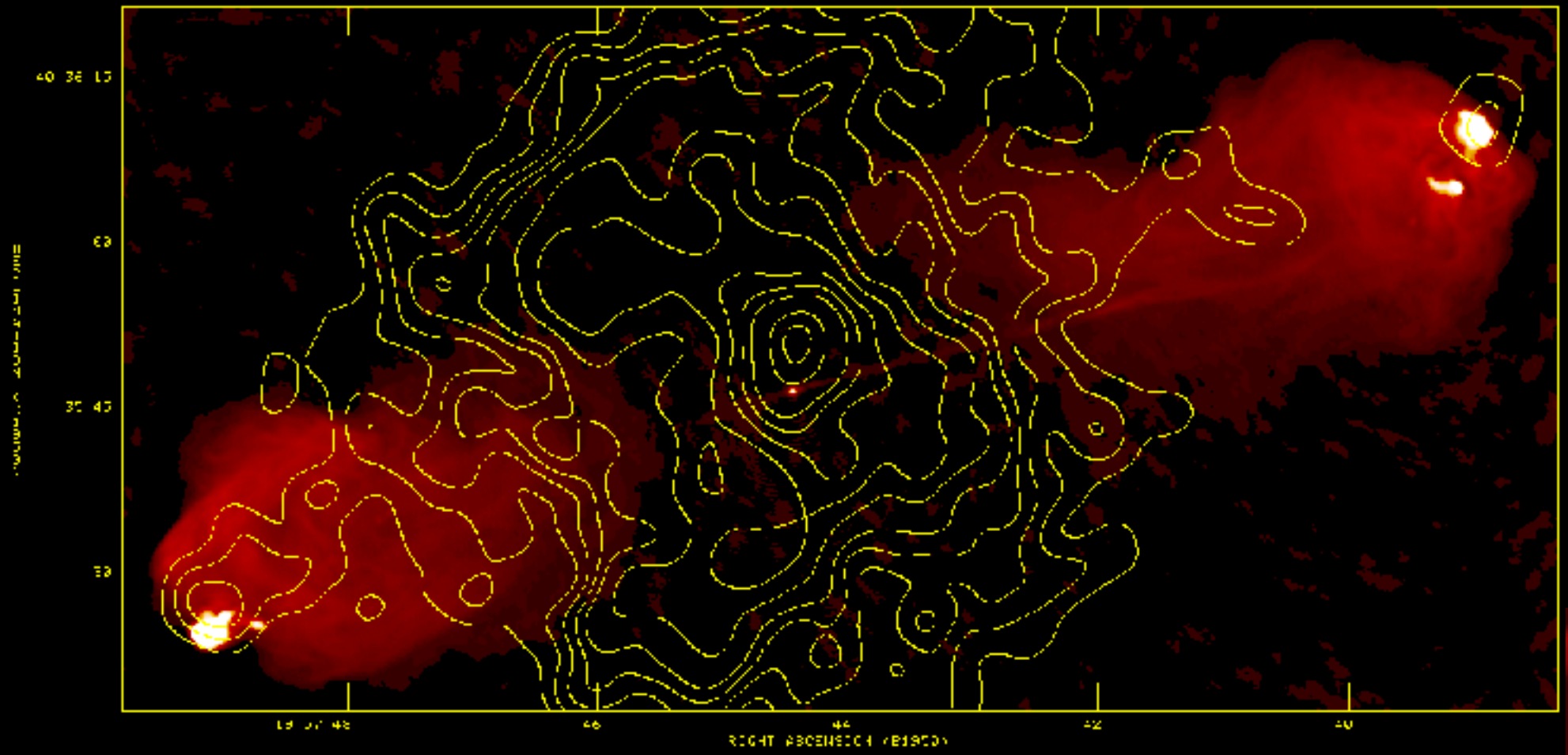


Multiple hotspots

- Known since early 80s (e.g. Laing 1982) that many sources have more than one hotspot ('primary', 'secondary', 'hotspot complex').
- Different models ('splatter-spot', 'dentist's drill' etc) – all can be produced in numerical simulations.
- Are some hotspots 'relics' disconnected from energy supply? SED work suggests ongoing particle acceleration in at least some.
- Numerical work shows strong perturbation of jet by bulk motions in source head – multiple hotspots, departure from axisymmetry and distributed particle acceleration are expected.
- Hotspots are transient features.

X-ray emission processes

- Synchrotron self-Compton emission is a required process. First seen in Cyg A...



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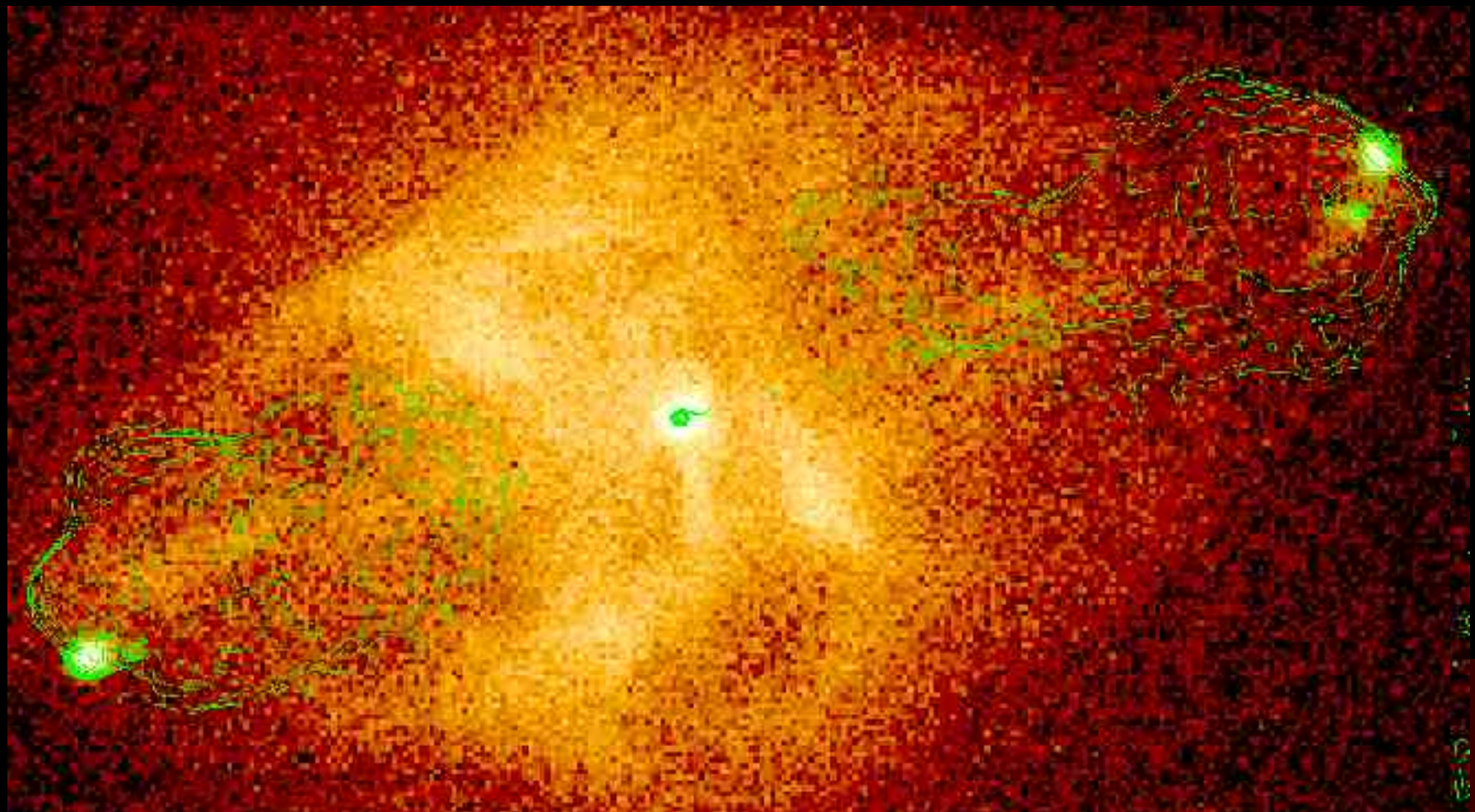
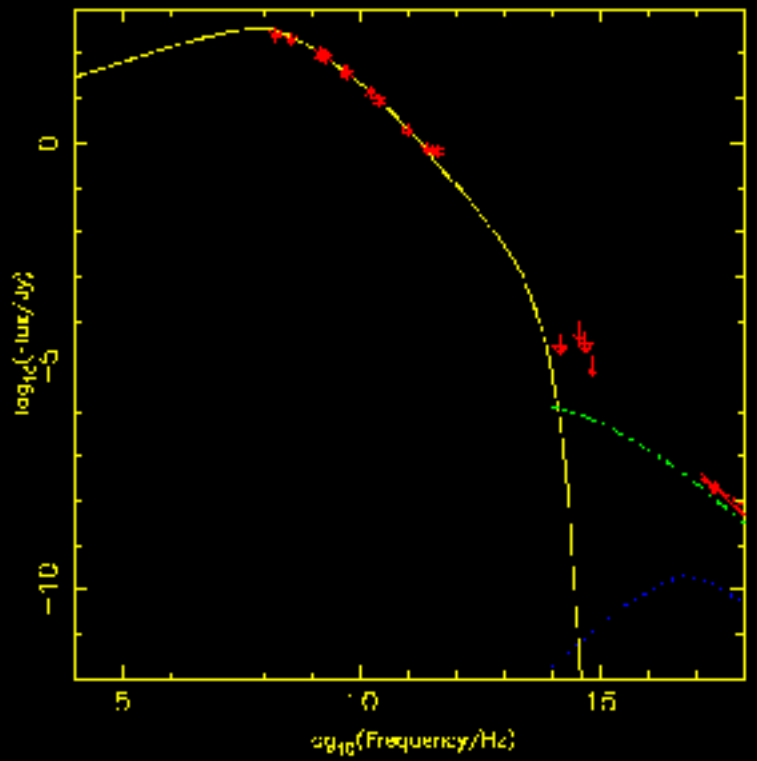


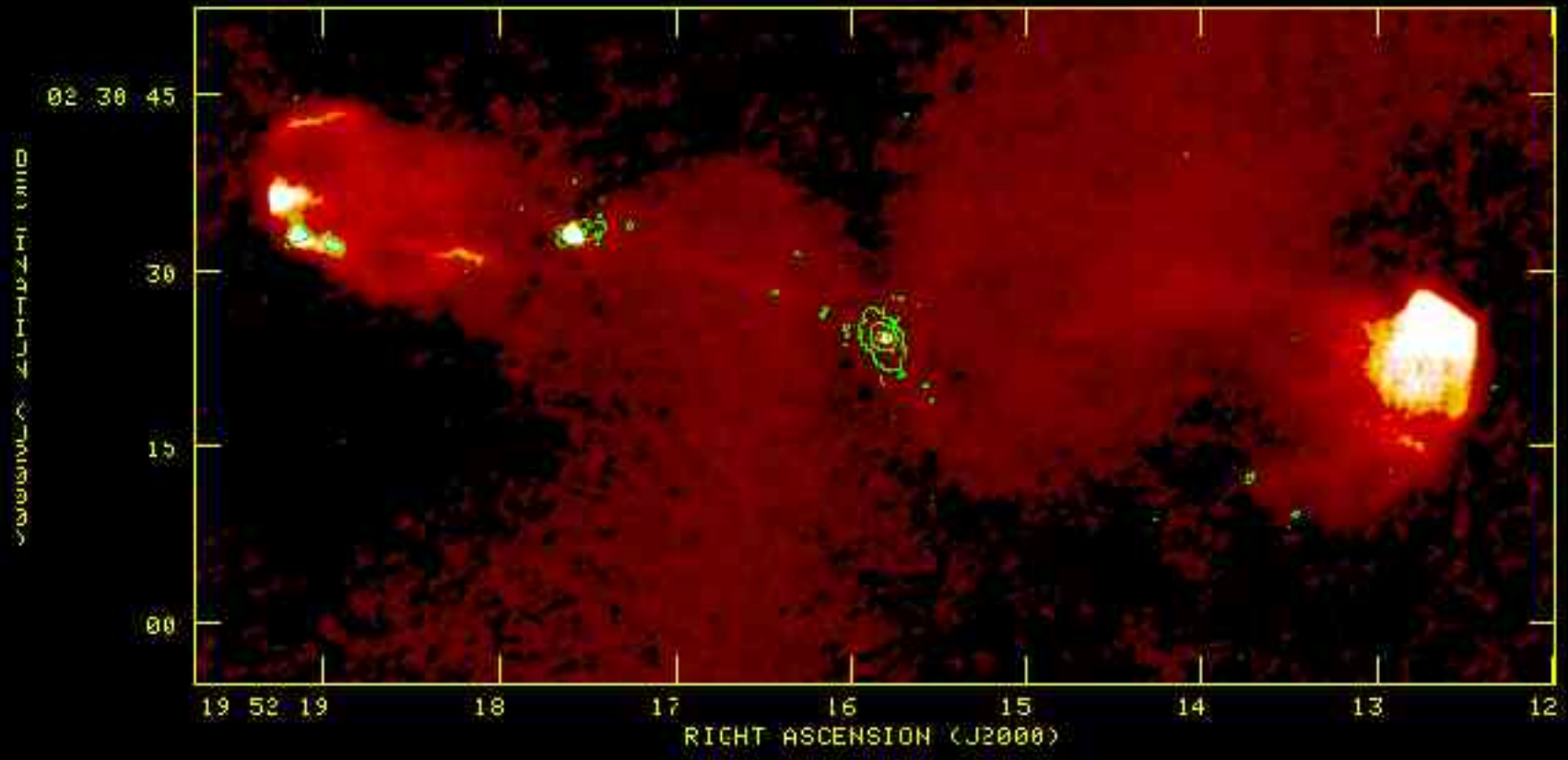
X-ray emission processes

- Synchrotron self-Compton emission is a required process. First seen in Cyg A.
- Excellent agreement between X-ray and radio structure – as expected.
- SEDs in good agreement with predictions if mag. fields close to equipartition w/o energetically dominant proton population: single synch. model not possible.



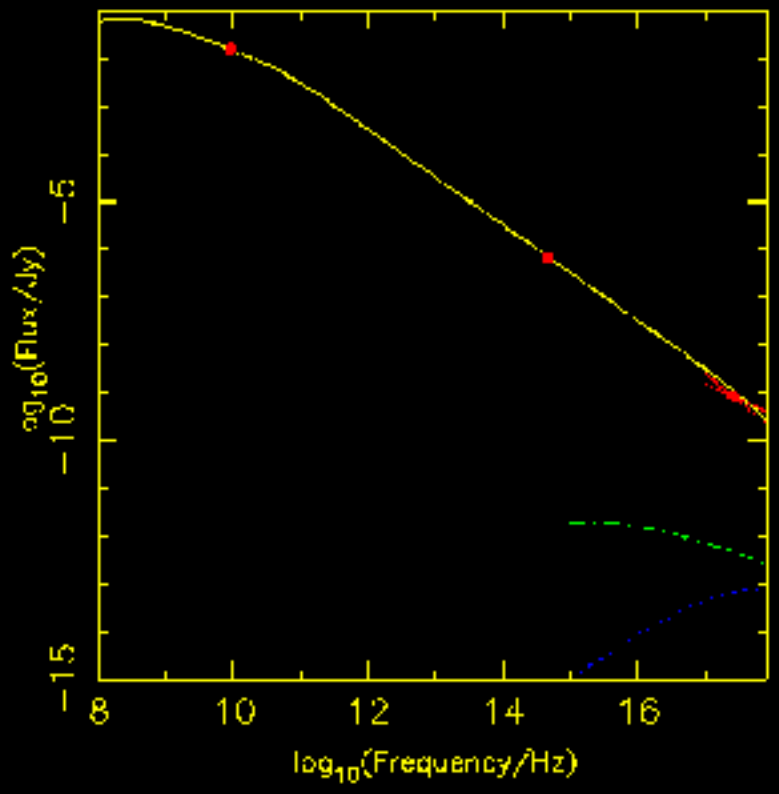
X-ray emission processes (2)

- Synchrotron emission is the obvious explanation in cases where X-ray is extension of synchrotron spectrum. X-ray then traces acceleration regions...



X-ray emission processes (2)

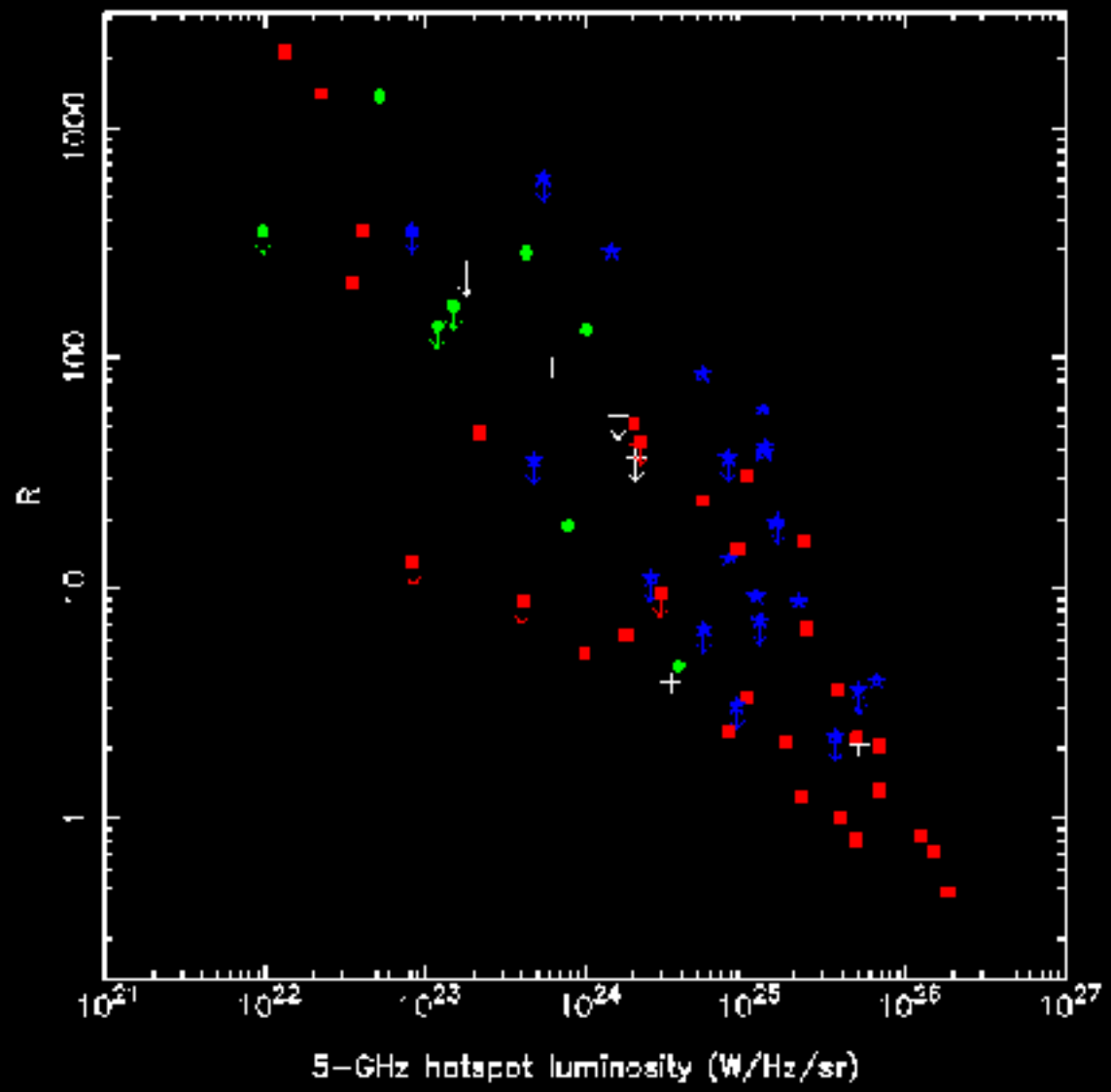
- Synchrotron emission is the obvious explanation in cases where X-ray is extension of synchrotron spectrum. X-ray then traces acceleration regions.
- SSC models predict very low flux densities.
- Particle acceleration to $\gamma > 10^7$ required.
- Spatial agreement not always good...



(Kraft et al 2005)

X-ray emission processes (3)

- Dominant X-ray emission process is luminosity-dependent...



(Hardcastle et al 2004. Colours indicate emission-line type)

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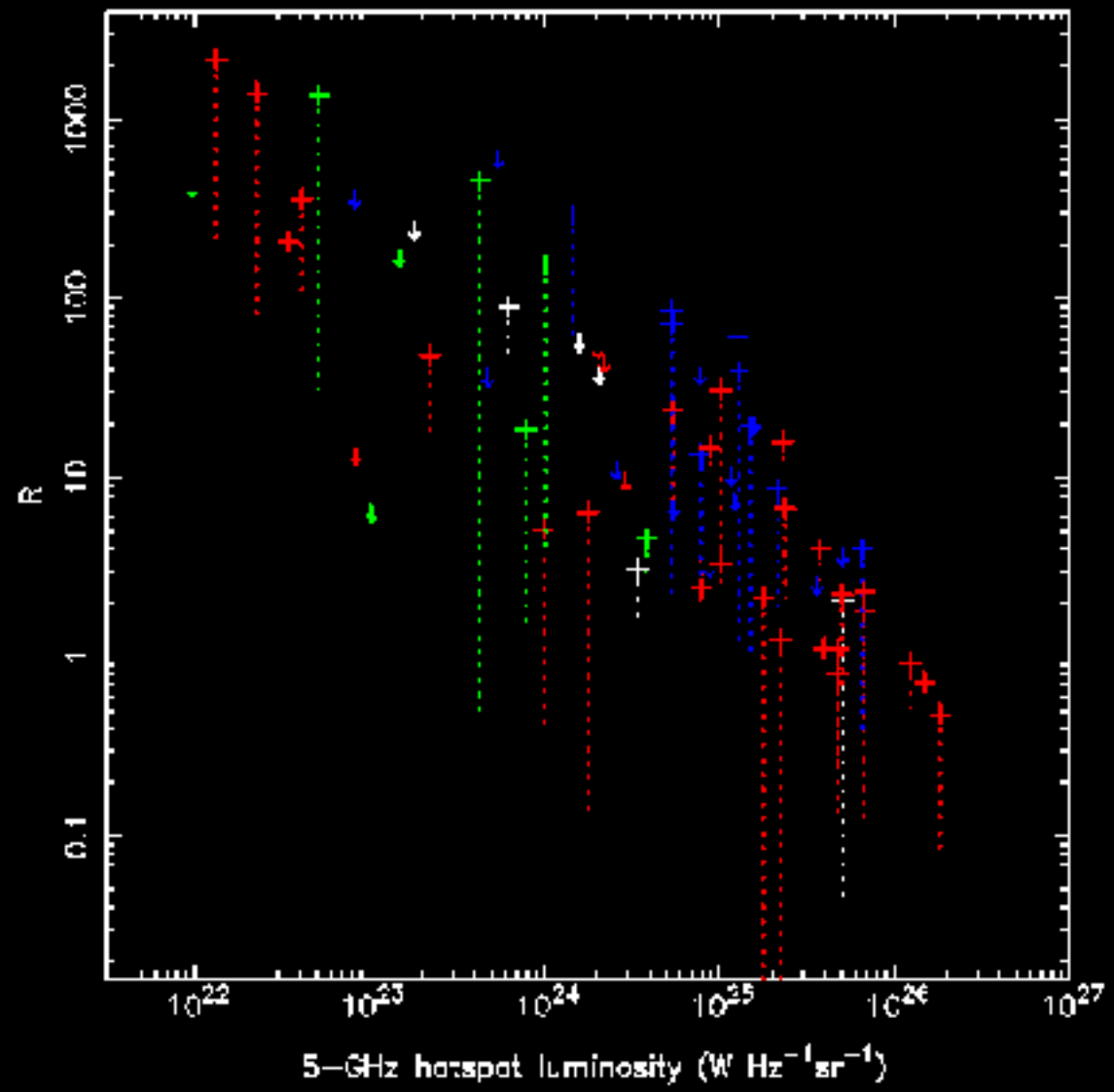


X-ray emission processes (3)

- Dominant X-ray emission process is luminosity-dependent.
- No luminous hotspot has X-ray emission a long way above the SSC prediction.
- All low-luminosity hotspots detected in the X-ray *necessarily* lie well above the SSC expectations (SSC from these would not be detectable).

Beaming?

- The first few hotspots to show excesses over SSC were all clearly on the jet side of strongly beamed objects (Pic A, 3C390.3...).
- We don't expect hotspots themselves to have high bulk LF (as is possible for jets) so IC/CMB model not likely to work.
- Georganopoulos & Kazanas (2003) pointed out that the decelerating jet sees & IC-scatters boosted radiation from the hotspot.
- Only important on jet side of sources at reasonably small angles to the line of sight, and depends on details of the velocity structure and electron density in the jet.
- *In addition* to known tendency for jet side hotspots to be brighter/more compact in beamed sources.

Is everything simple?

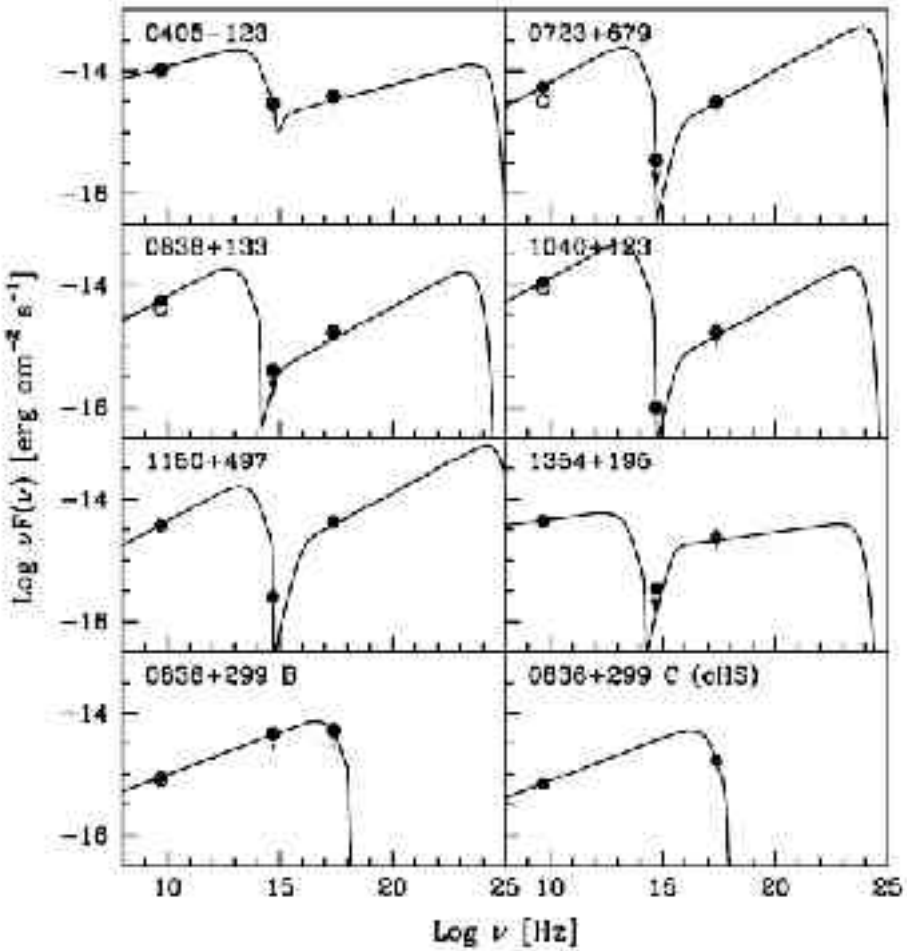
- Can we explain all hotspot X-ray emission using (a combination of) the two simplest processes: SSC with $B \sim B_{eq}$ and synchrotron with a simple, one-zone, broken power-law model as in Meisenheimer et al fits, with negligible beaming effects?
- In 2004 the available data suggested maybe the answer was 'yes'...

Is everything simple?

- Can we explain all hotspot X-ray emission using (a combination of) the two simplest processes: SSC with $B \sim B_{eq}$ and synchrotron with a simple, one-zone, broken power-law model as in Meisenheimer et al fits, with negligible beaming effects?
- In 2004 the available data suggested maybe the answer was 'yes'...
- ... now I think the answer is definitely 'no'.

Problems for single synchrotron models

- Tavecchio et al (2005) use optical constraints to show that single concave synchrotron spectra cannot explain X-ray detections of hotspots in powerful quasars...

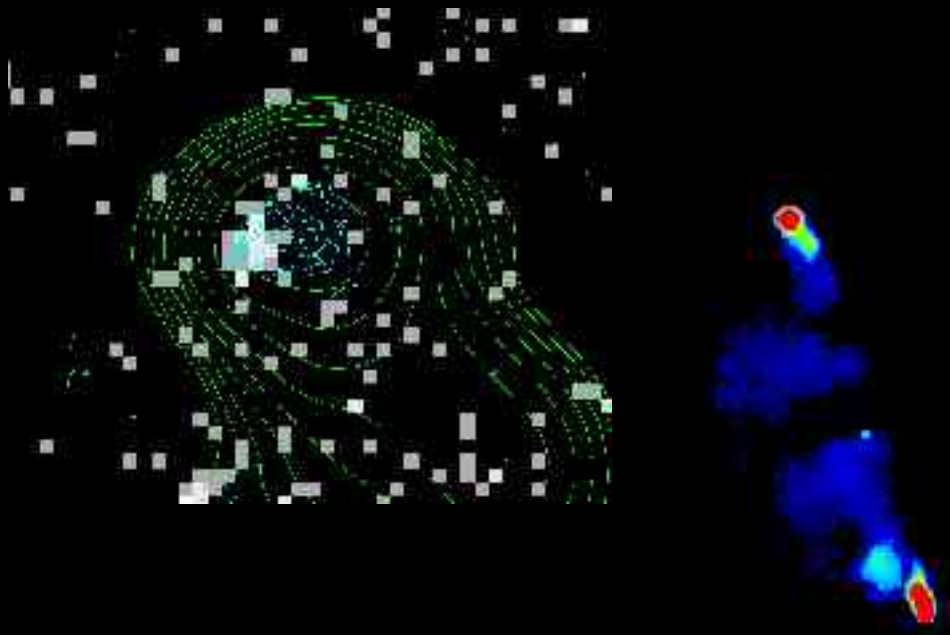


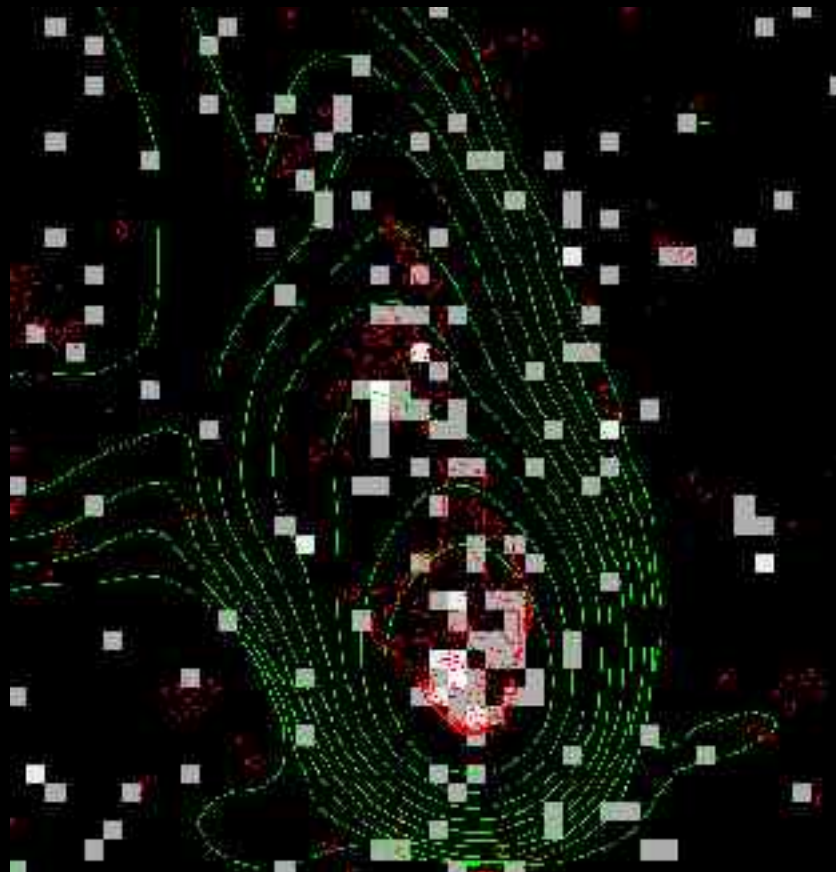
Problems for single synchrotron models

- Tavecchio et al (2005) use optical constraints to show that single concave synchrotron spectra cannot explain X-ray detections of hotspots in powerful quasars...
- ... could beaming be important here?
- Illustrates importance of optical data points (cf Jester talk, jets)

More problems: 3C33

- Beaming can definitely be ruled out for sources near the plane of the sky...





Kraft et al 2006, ApJ submitted

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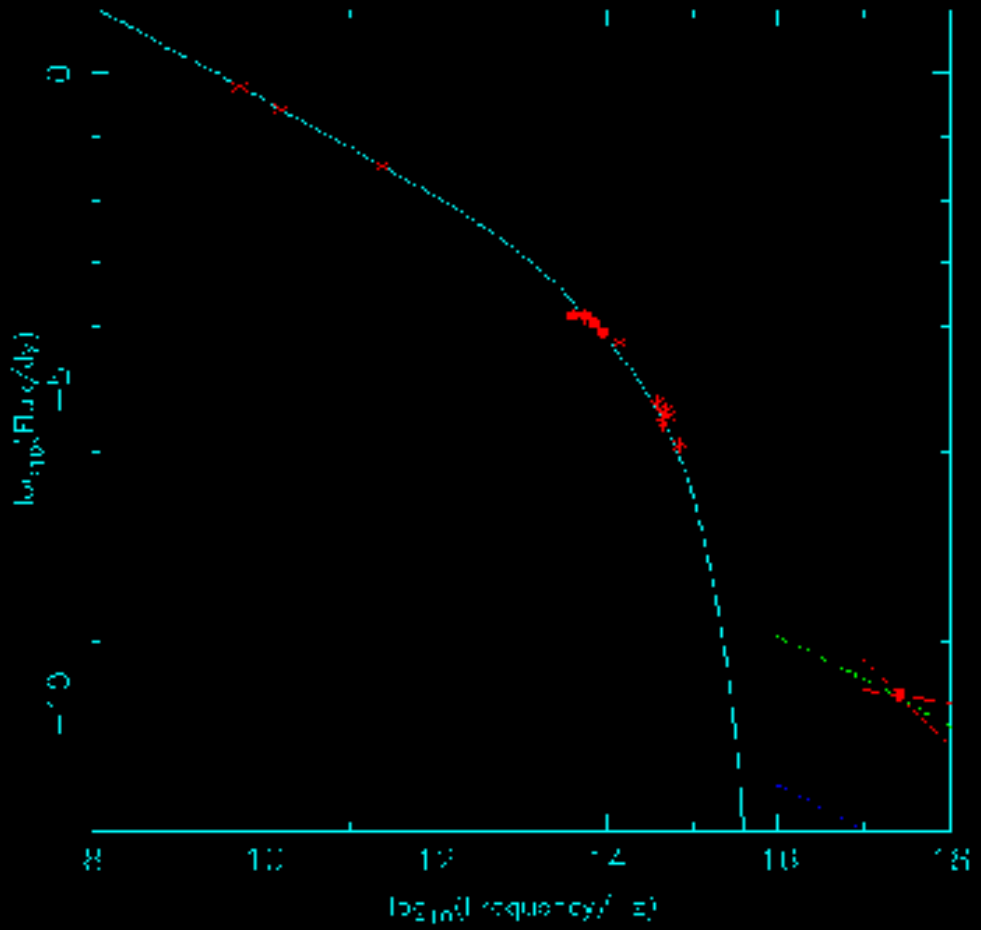

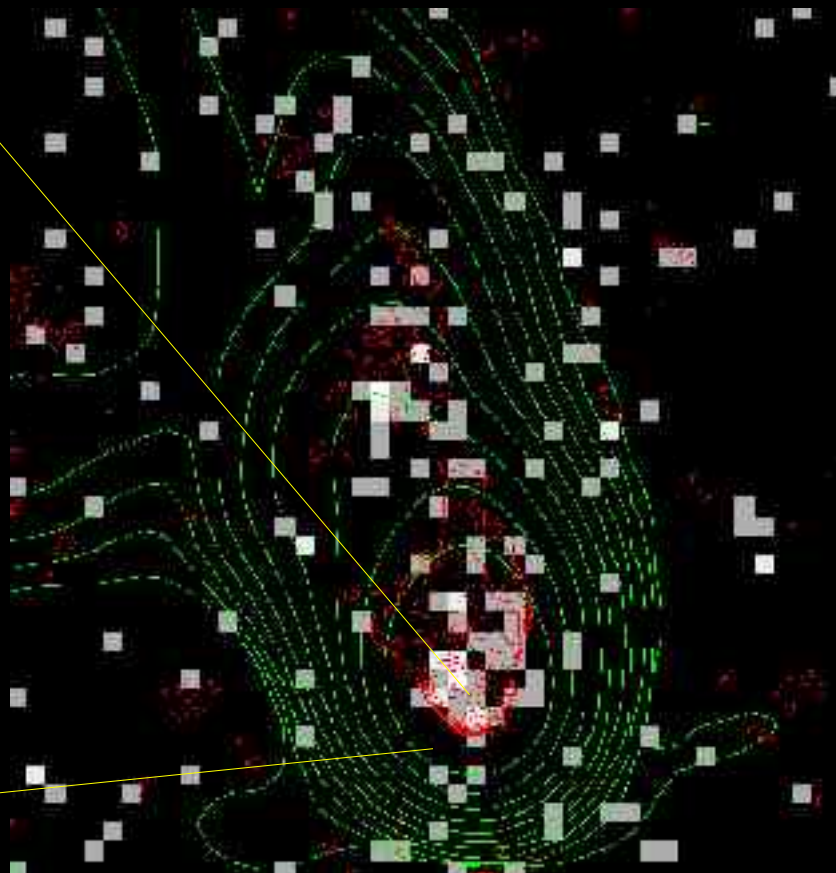

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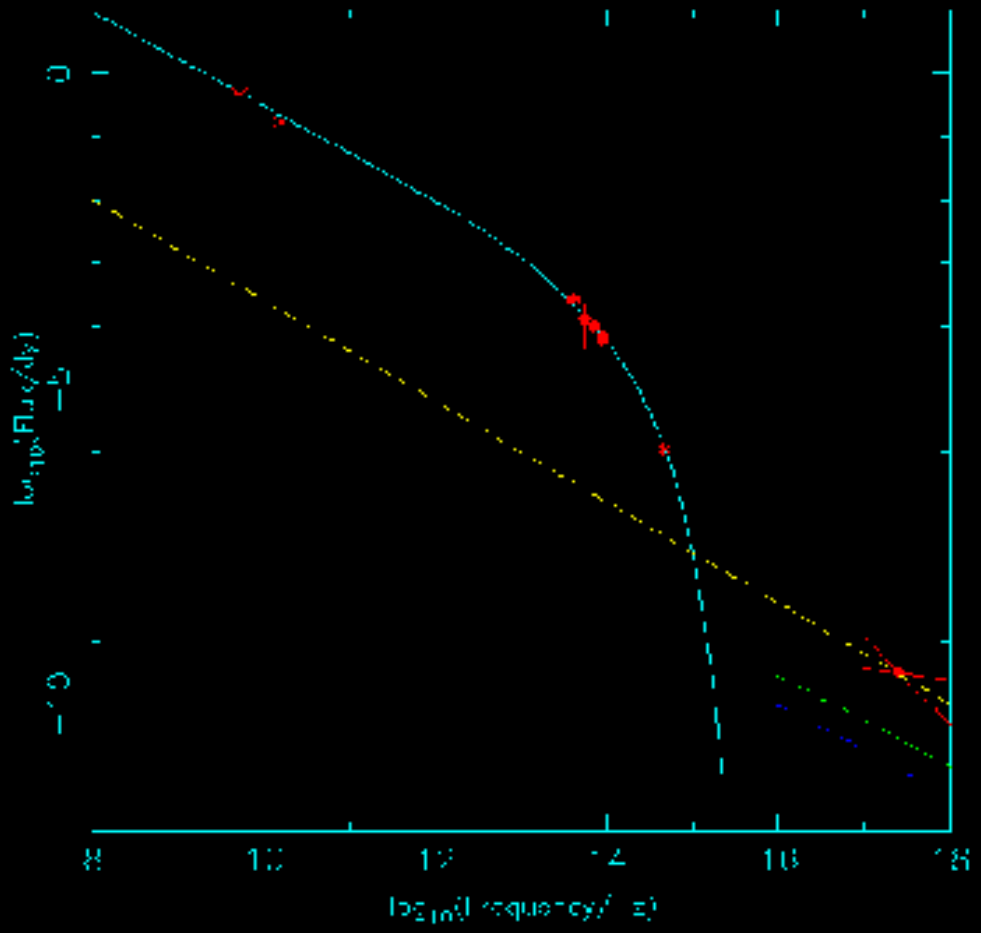

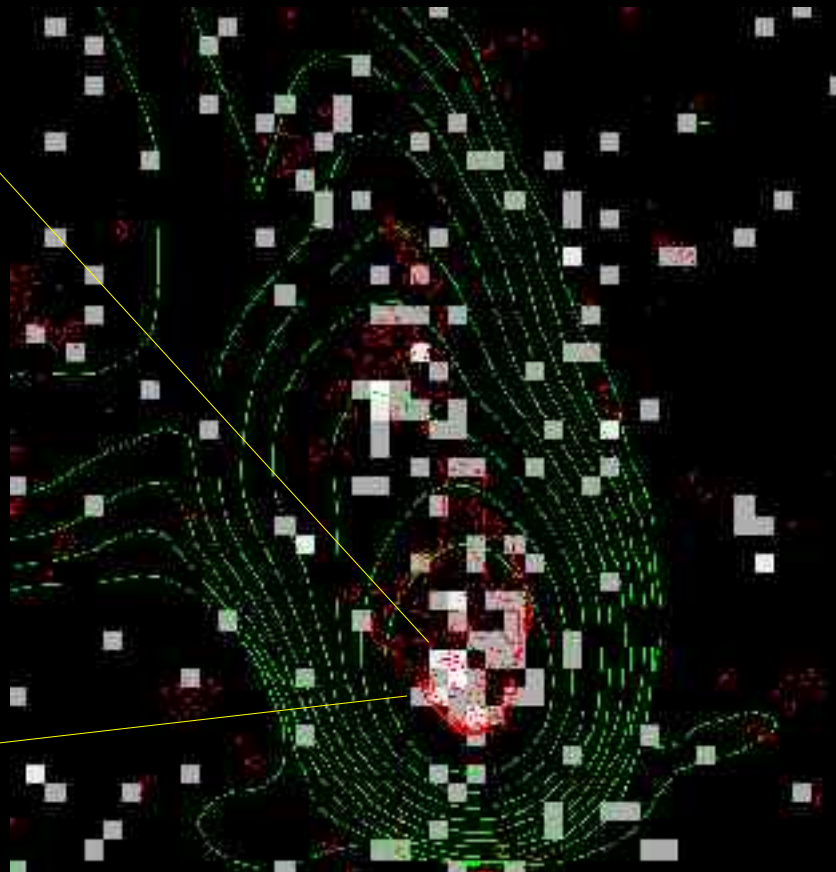

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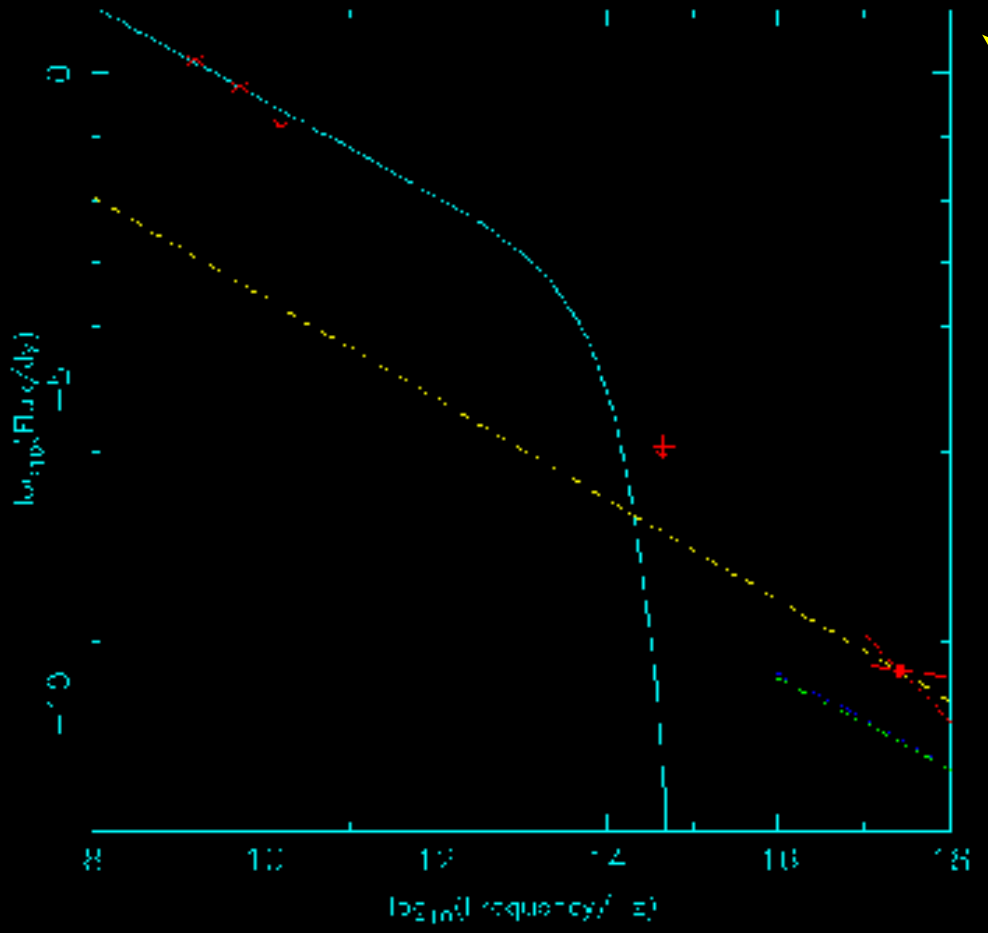

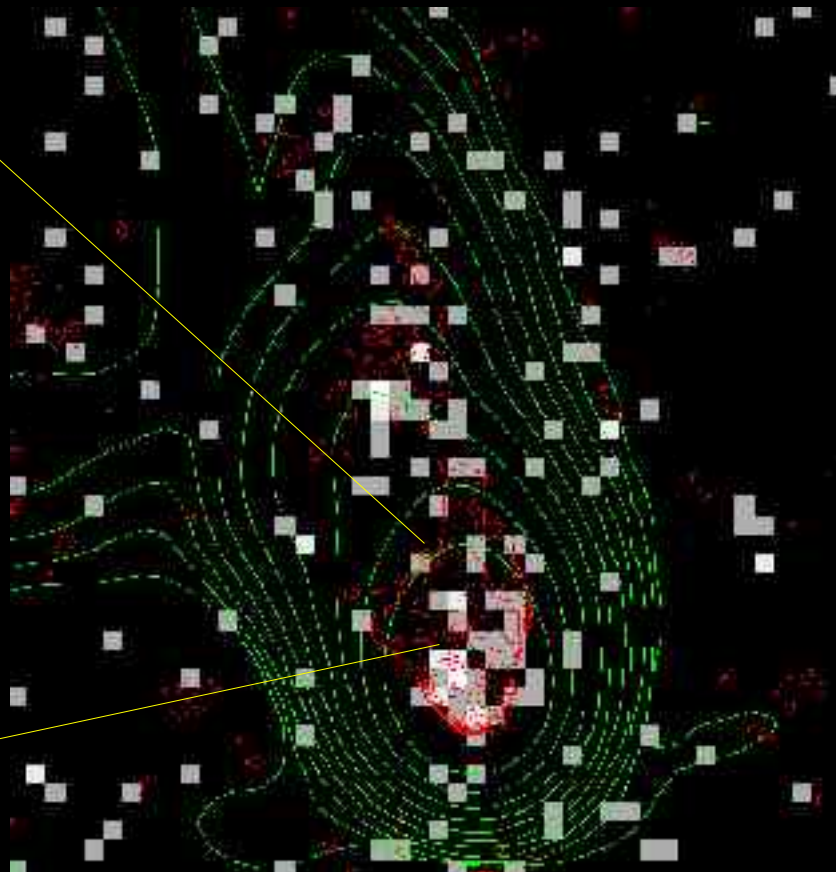

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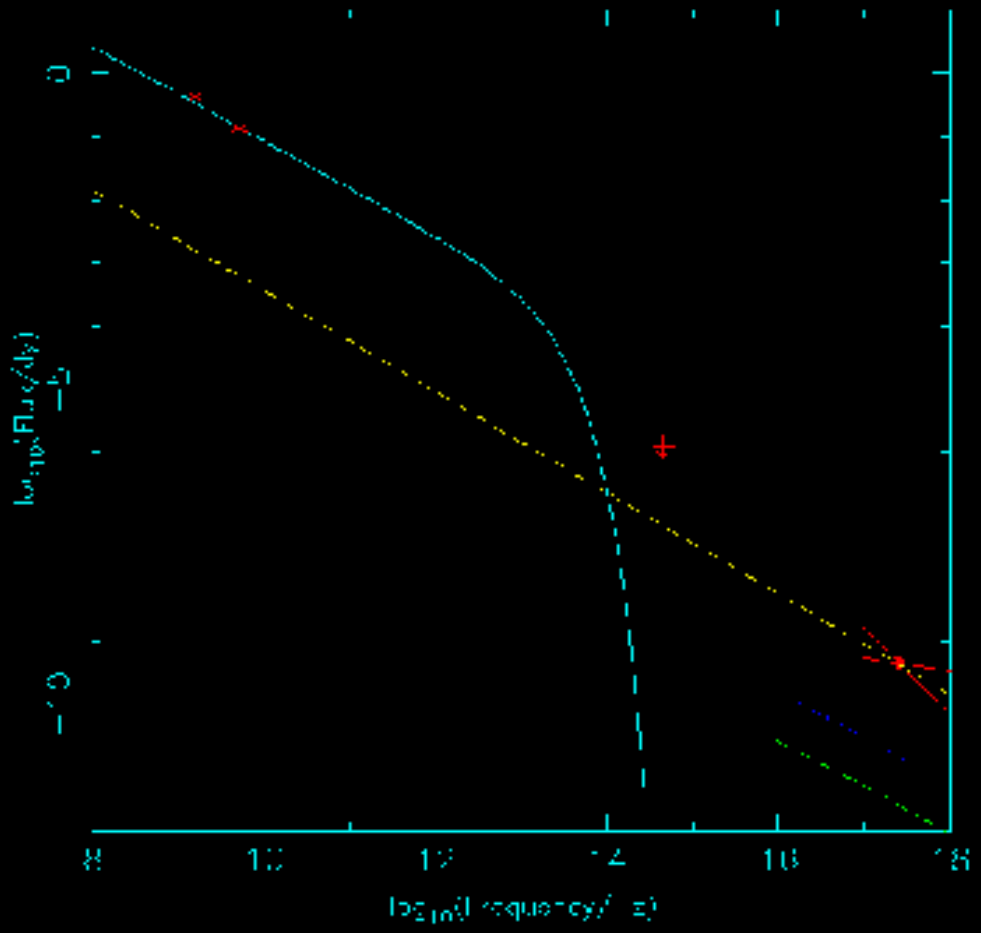
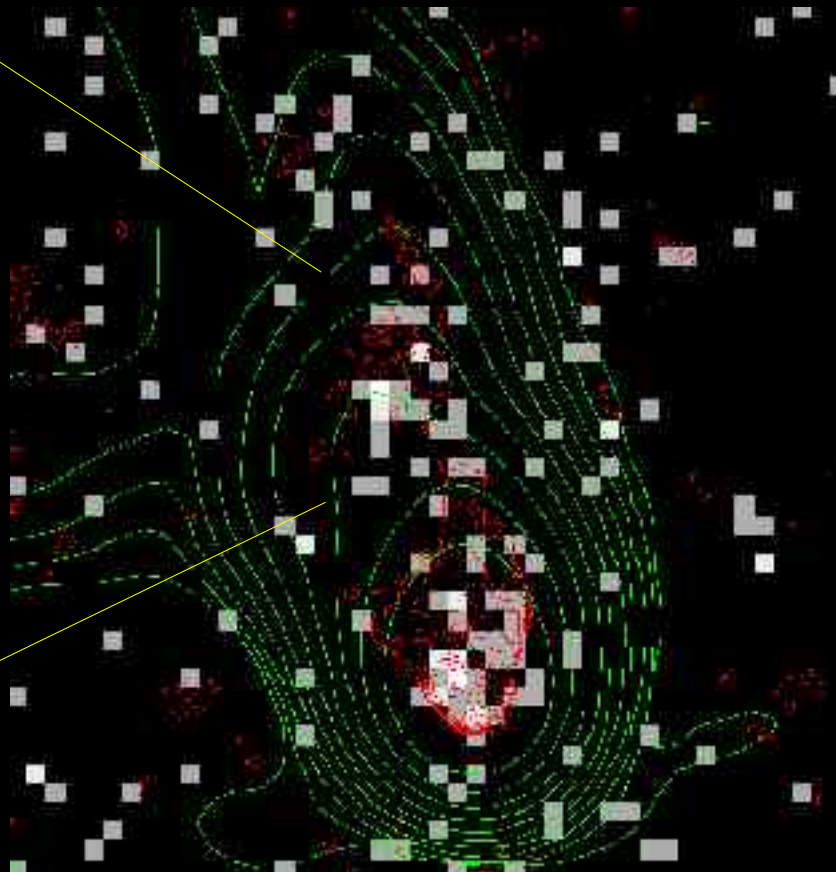
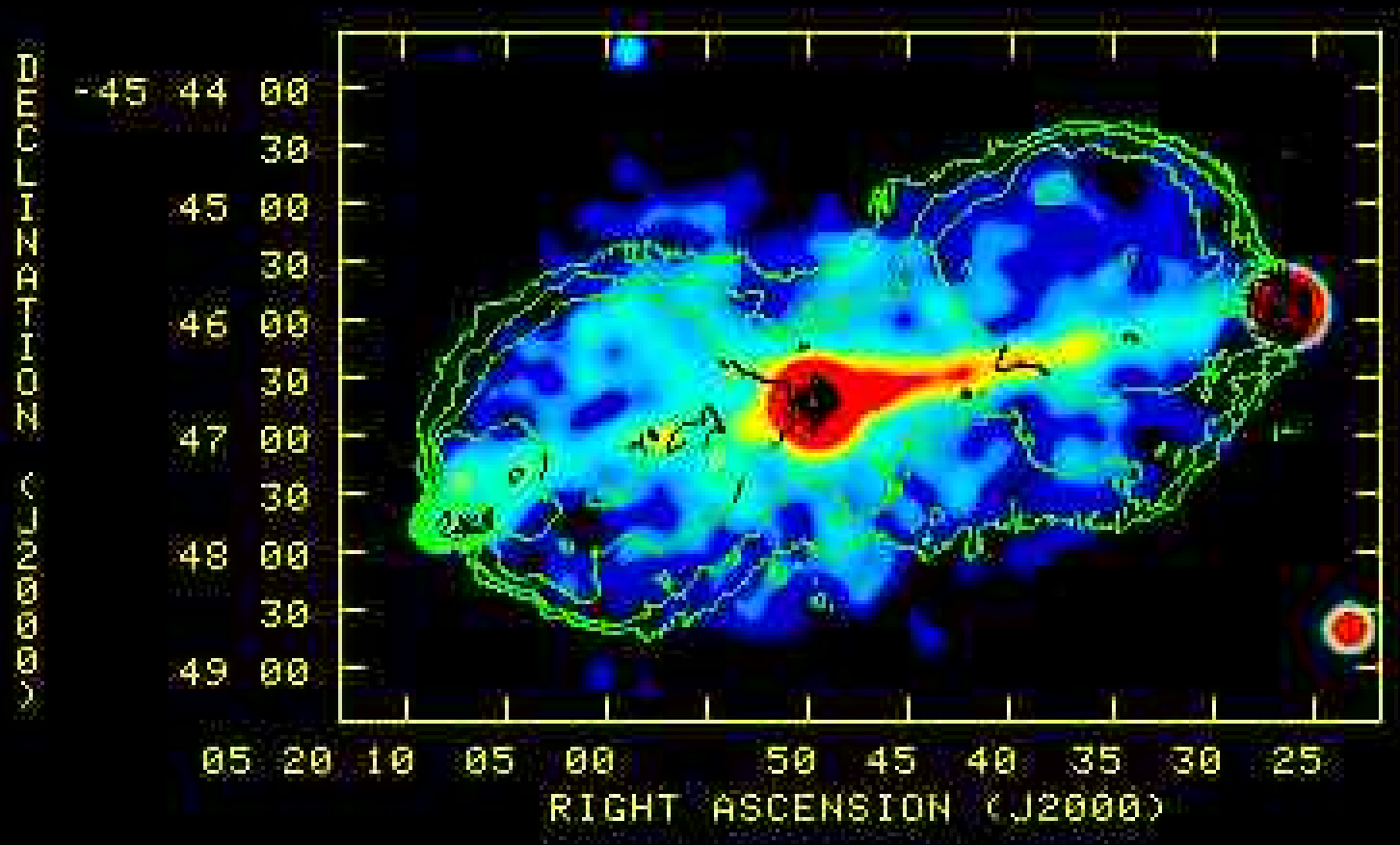




More problems: diffuse emission

- Diffuse, 10 kpc-scale X-ray emission seen around hotspots in several low-luminosity sources, though generally no optical constraints...



Pic A, H. & Croston 2005

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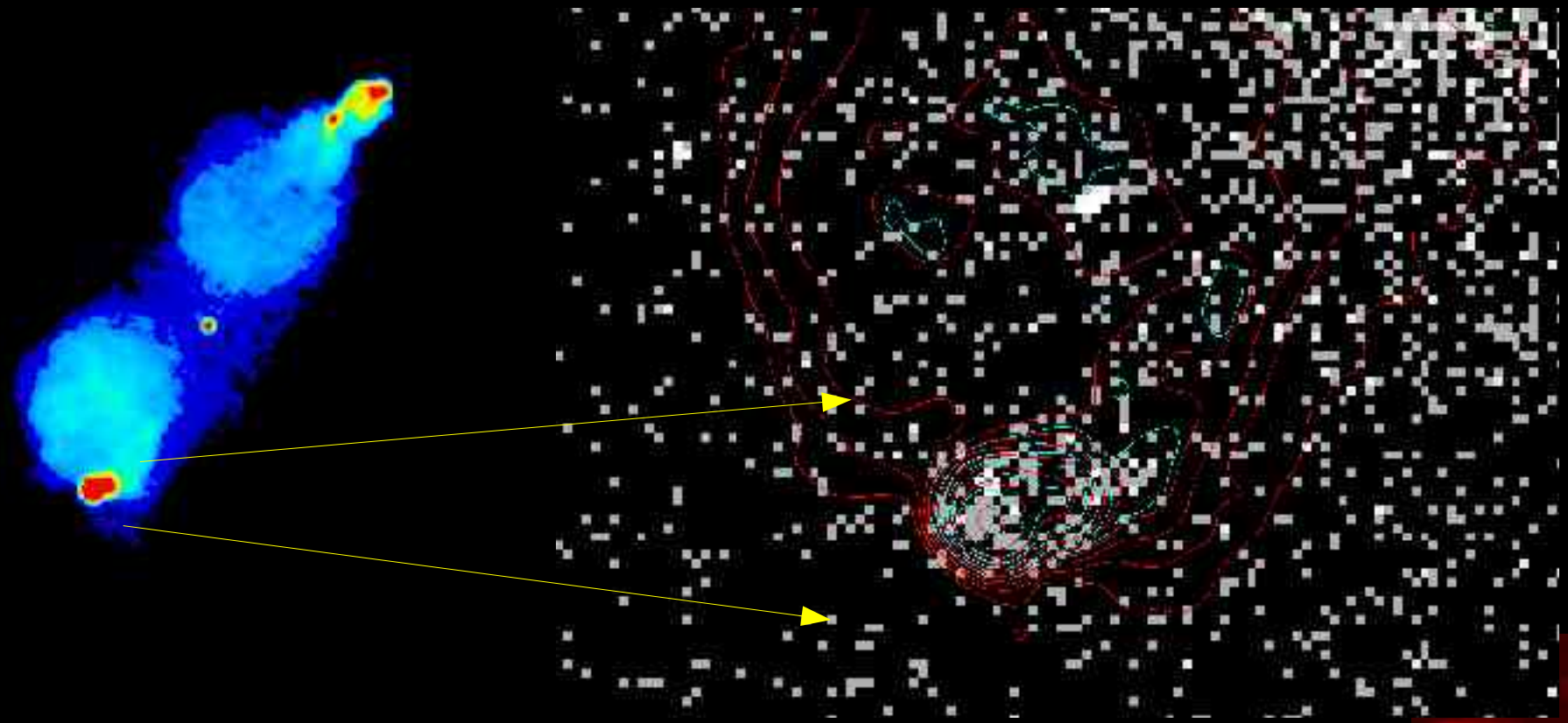


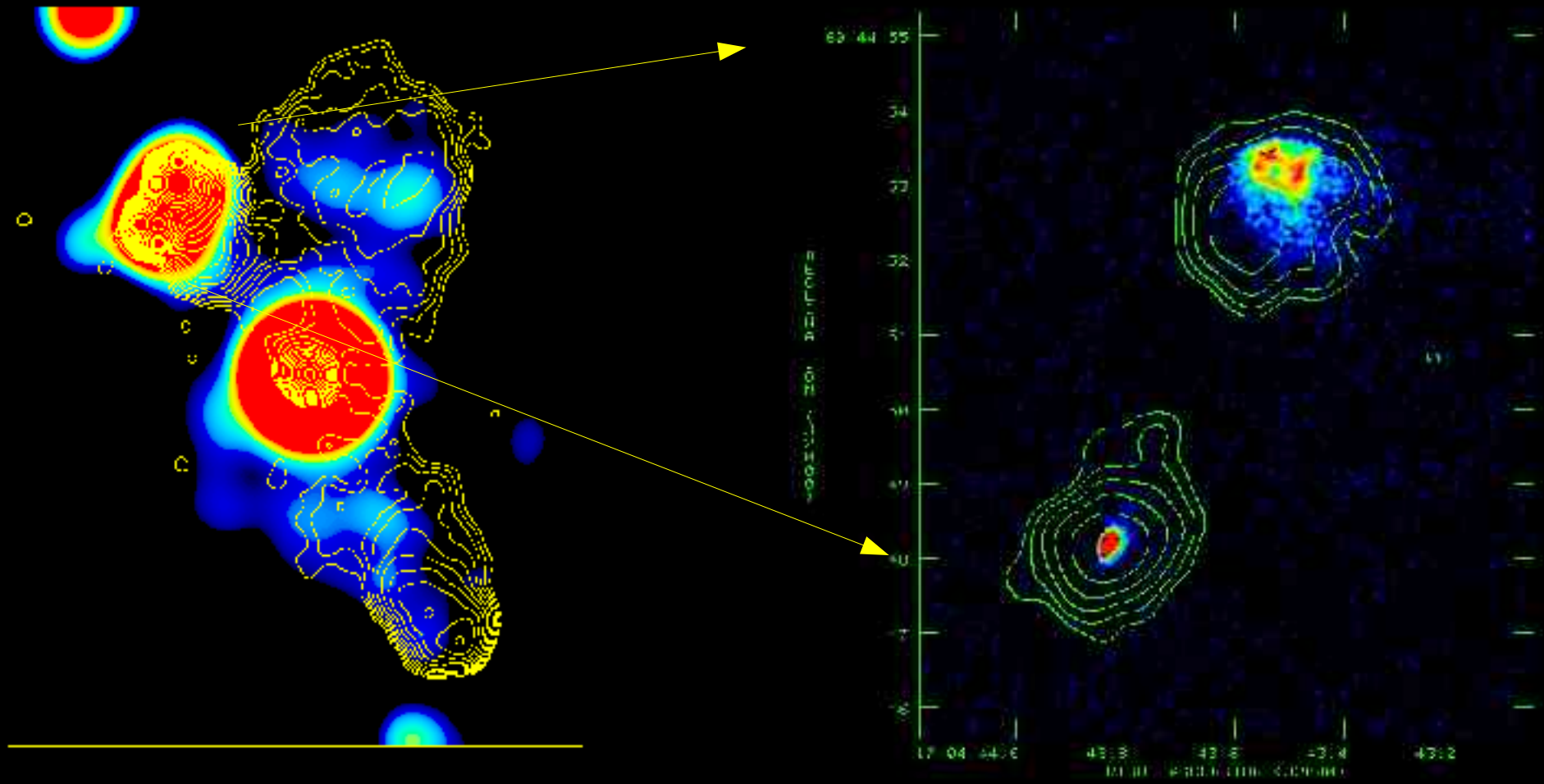
3C390.3, H. & Croston 2005

More problems: diffuse emission

- Diffuse, 10 kpc-scale emission seen around hotspots in several low-luminosity sources, though generally no optical constraints.
- This is hard to understand in a one-zone synchrotron model (too extended) and, as in 3C33, greatly exceeds IC/SSC expectations unless mag. field is << equipartition.
- Examples in 3C390.3 and Pic A on *counterjet* side of beamed sources => beaming effects would have to be in *backflow.*

More problems: offsets

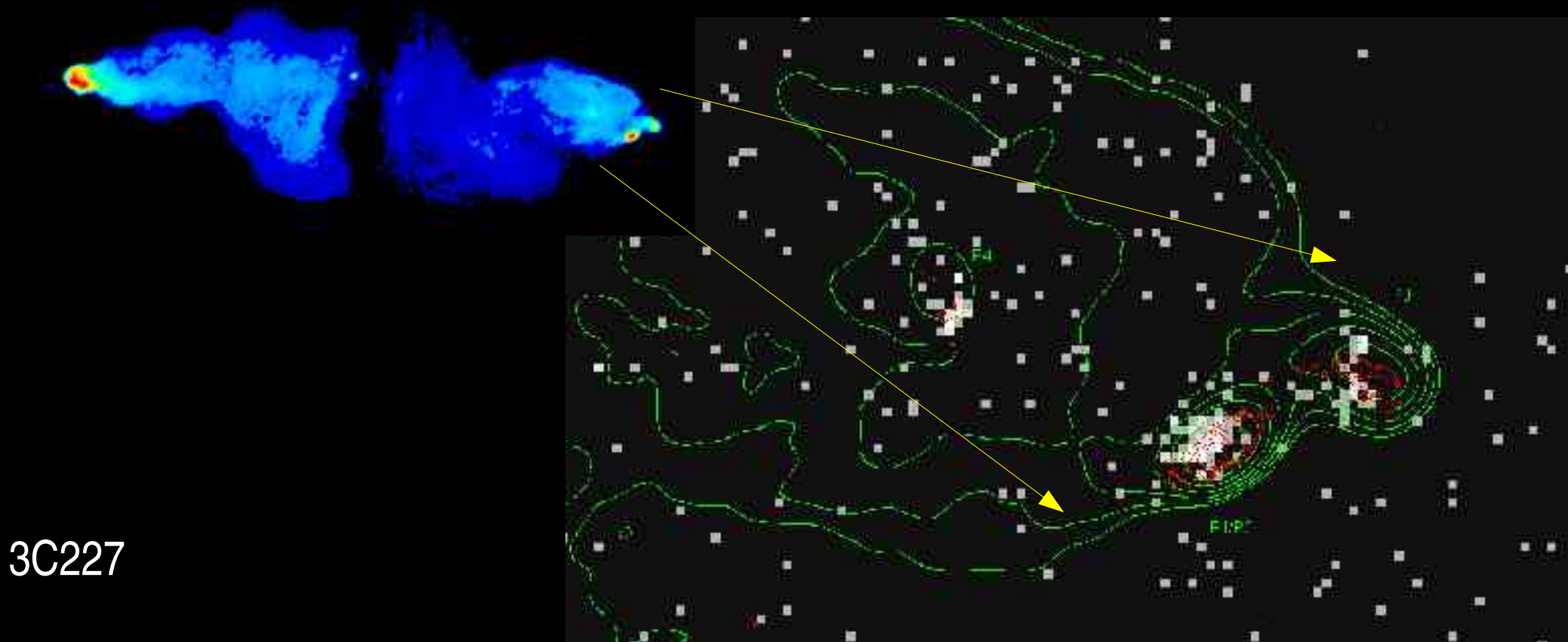
- Offsets incompatible with SSC model...



3C351: Hardcastle et al 2002

More problems: offsets

- ... but in nearby hotspots well-resolved offsets are a challenge for single-acceleration synchrotron.



3C227

More problems: offsets

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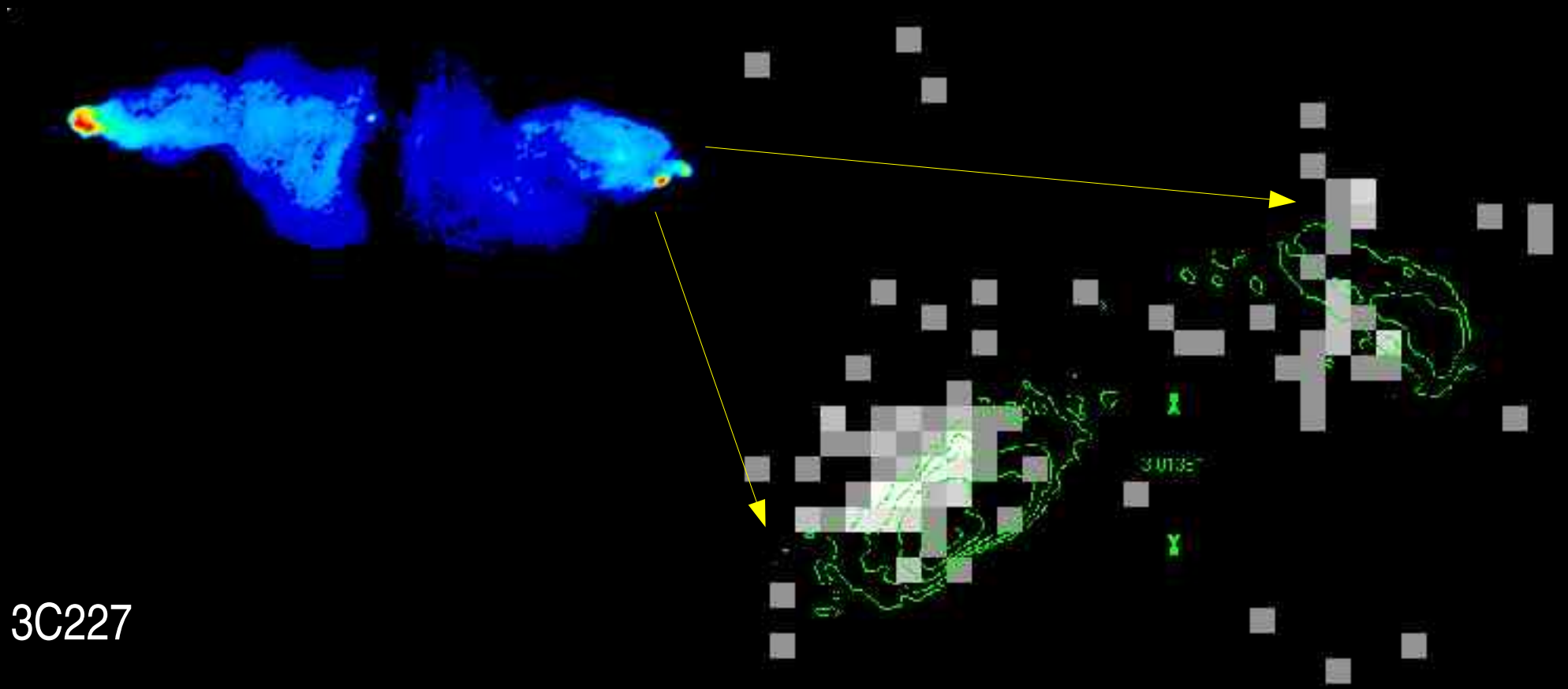

3C227

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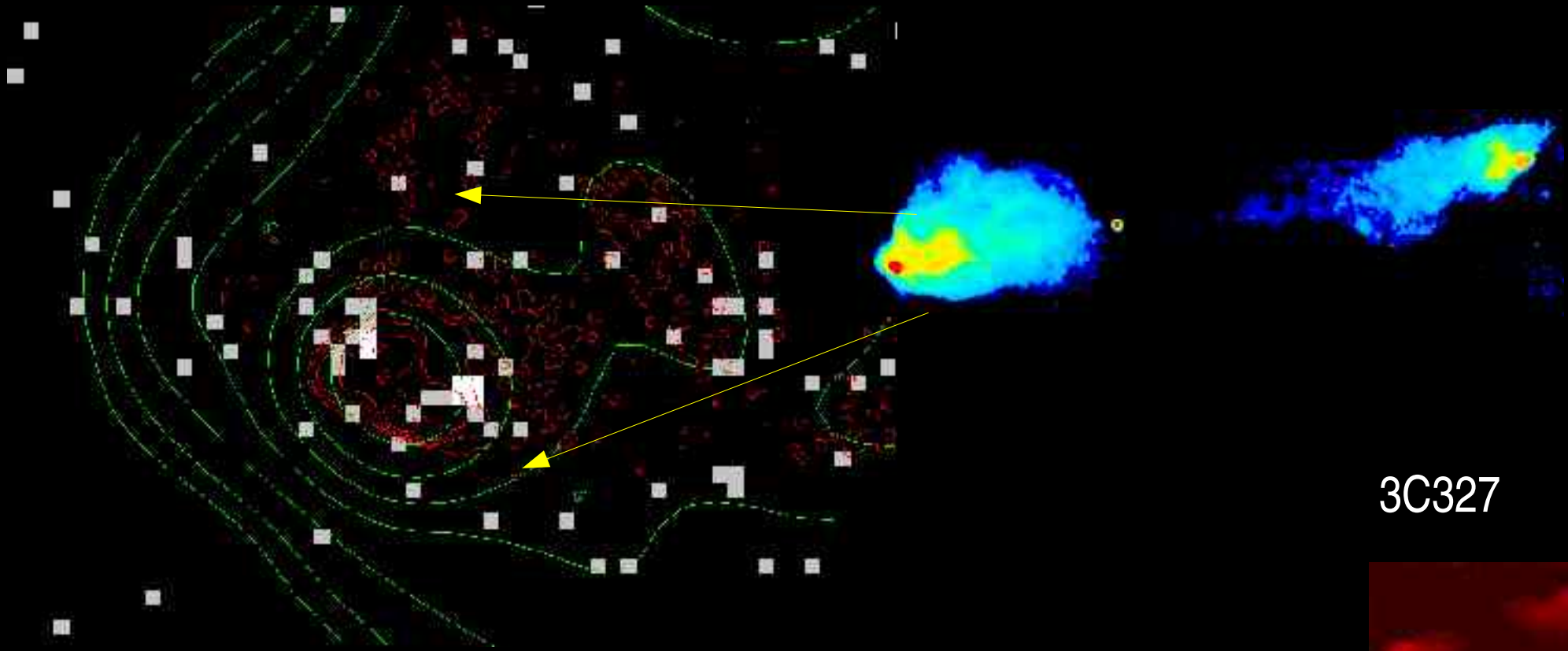
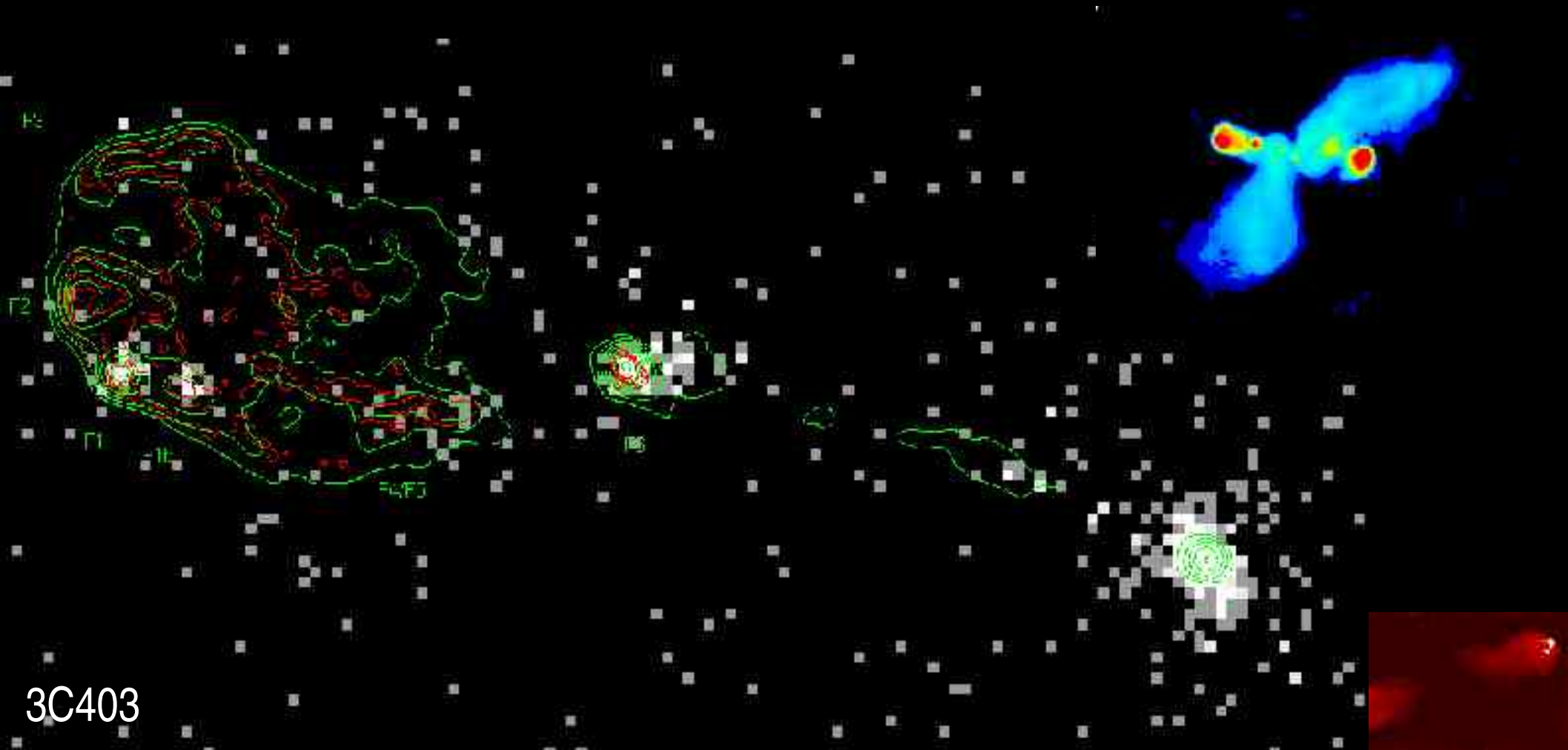


More problems: offsets

- In some cases the extension/offset is in the direction of the jet (though not all are beamed)...



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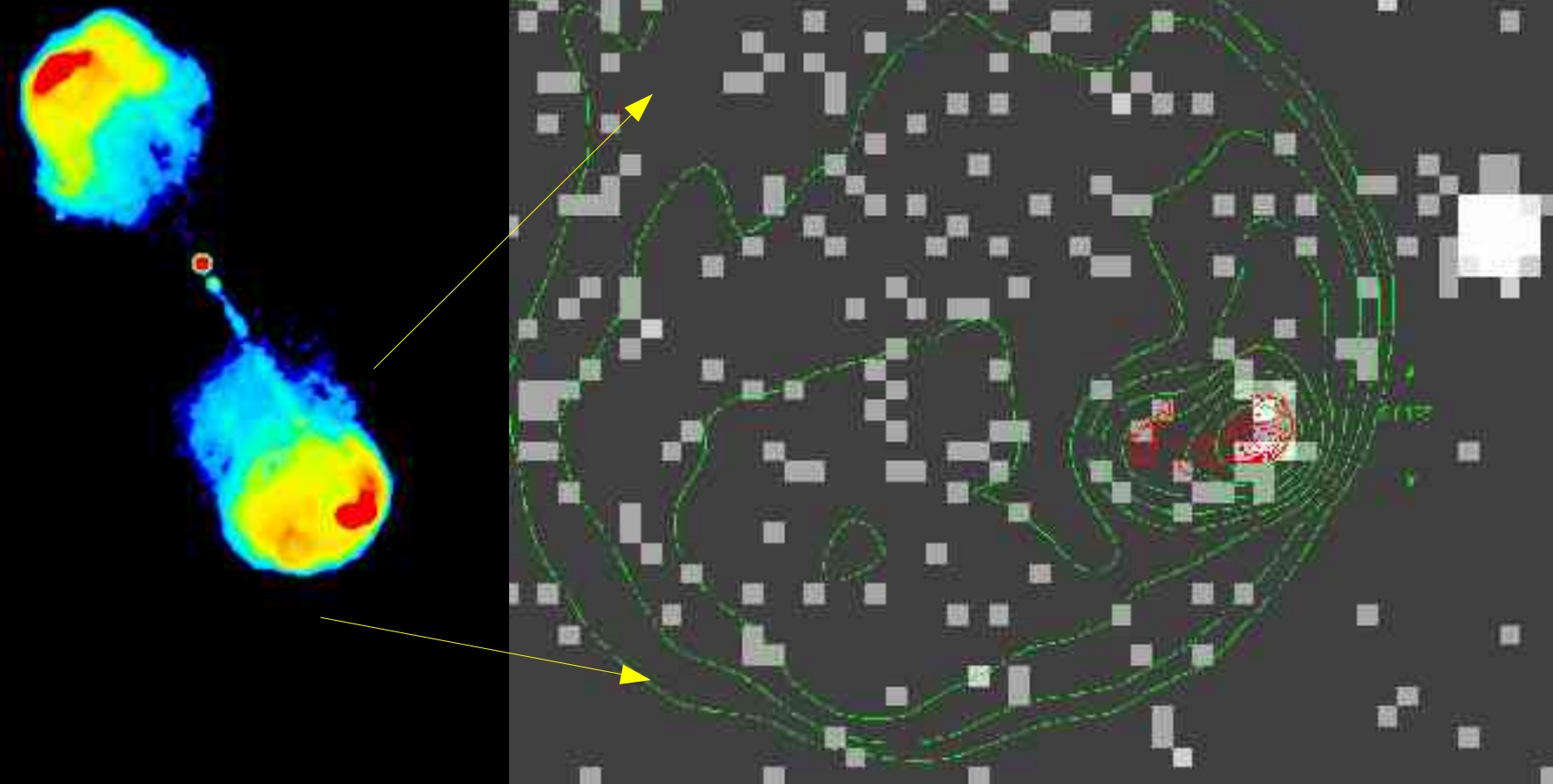

3C47

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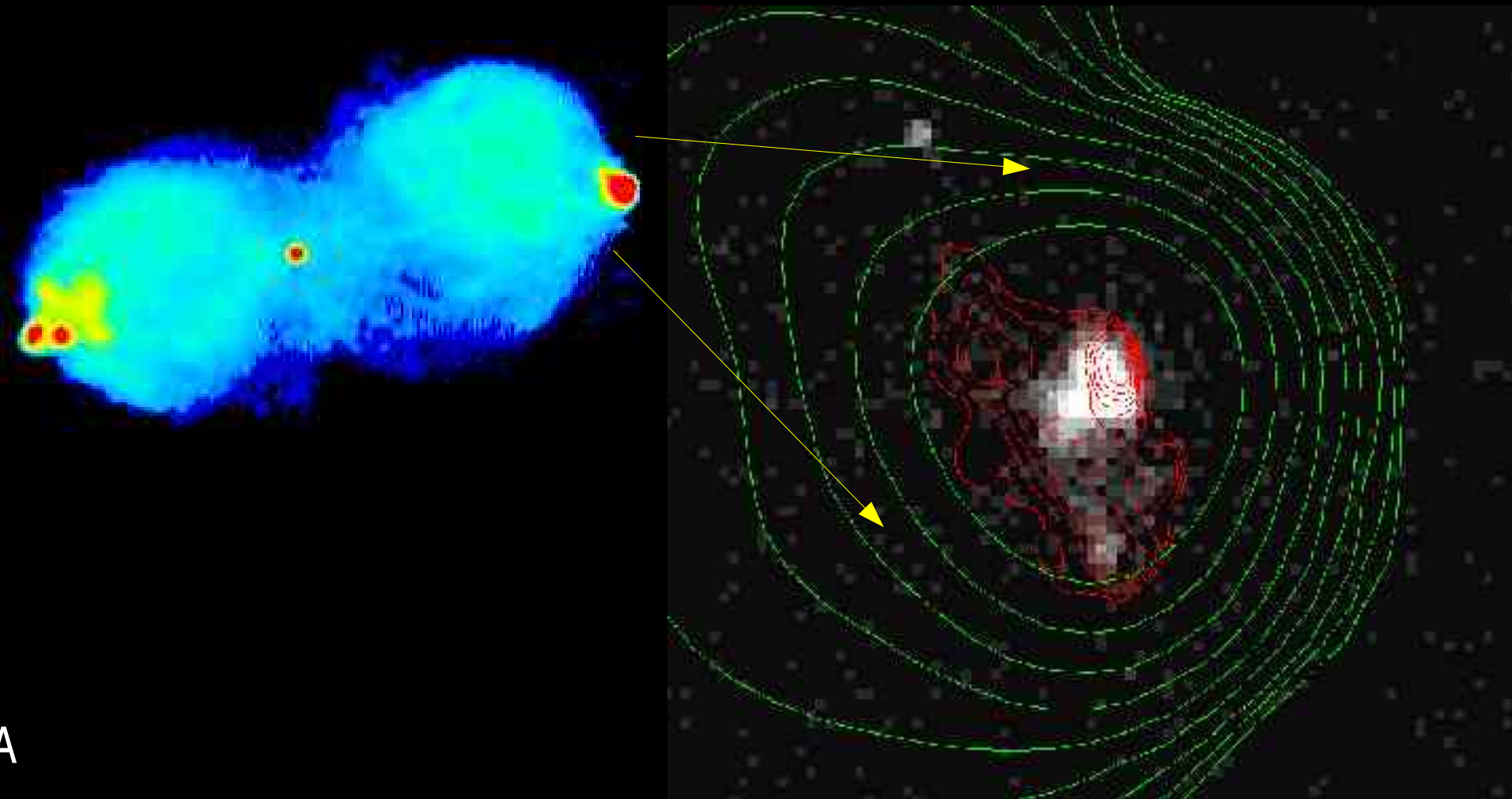

Pictor A

More problems: offsets

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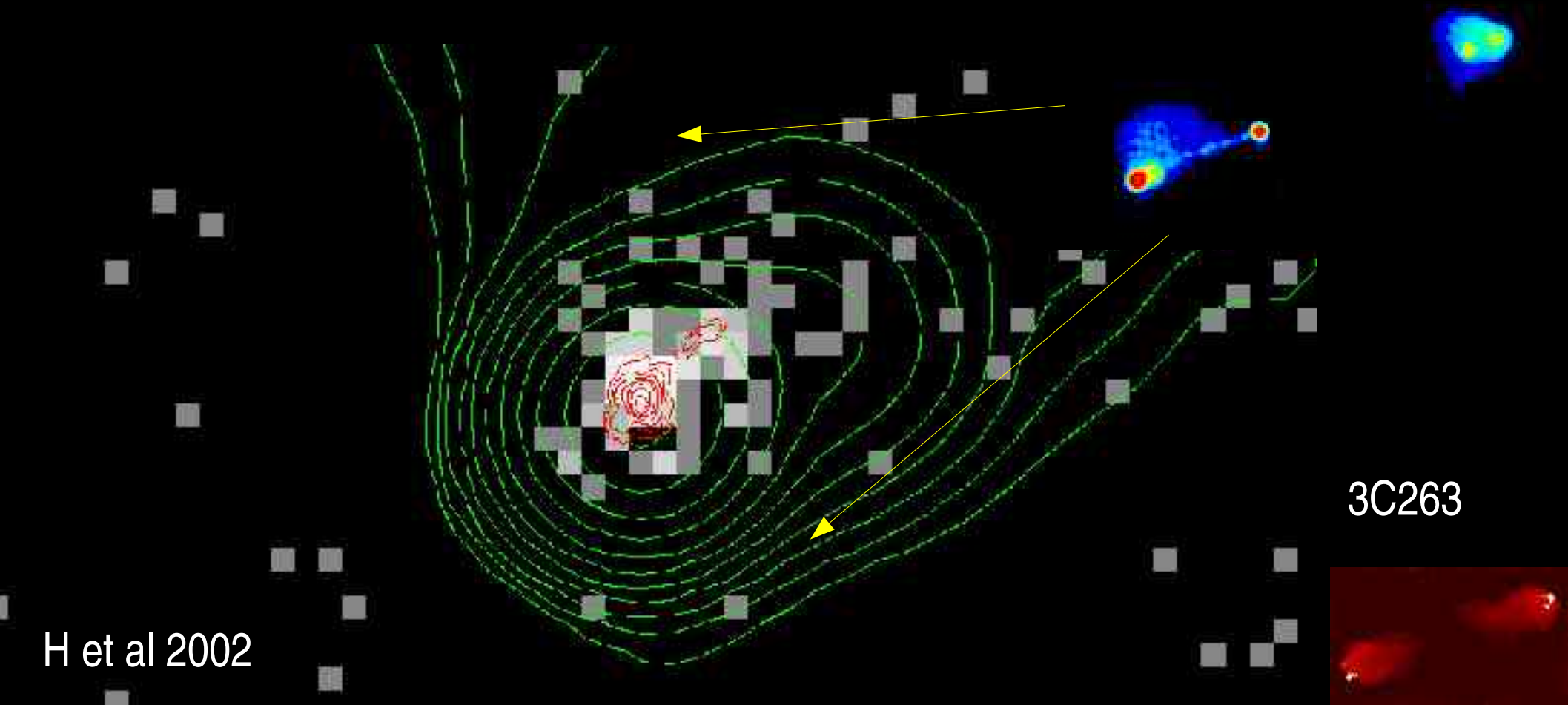
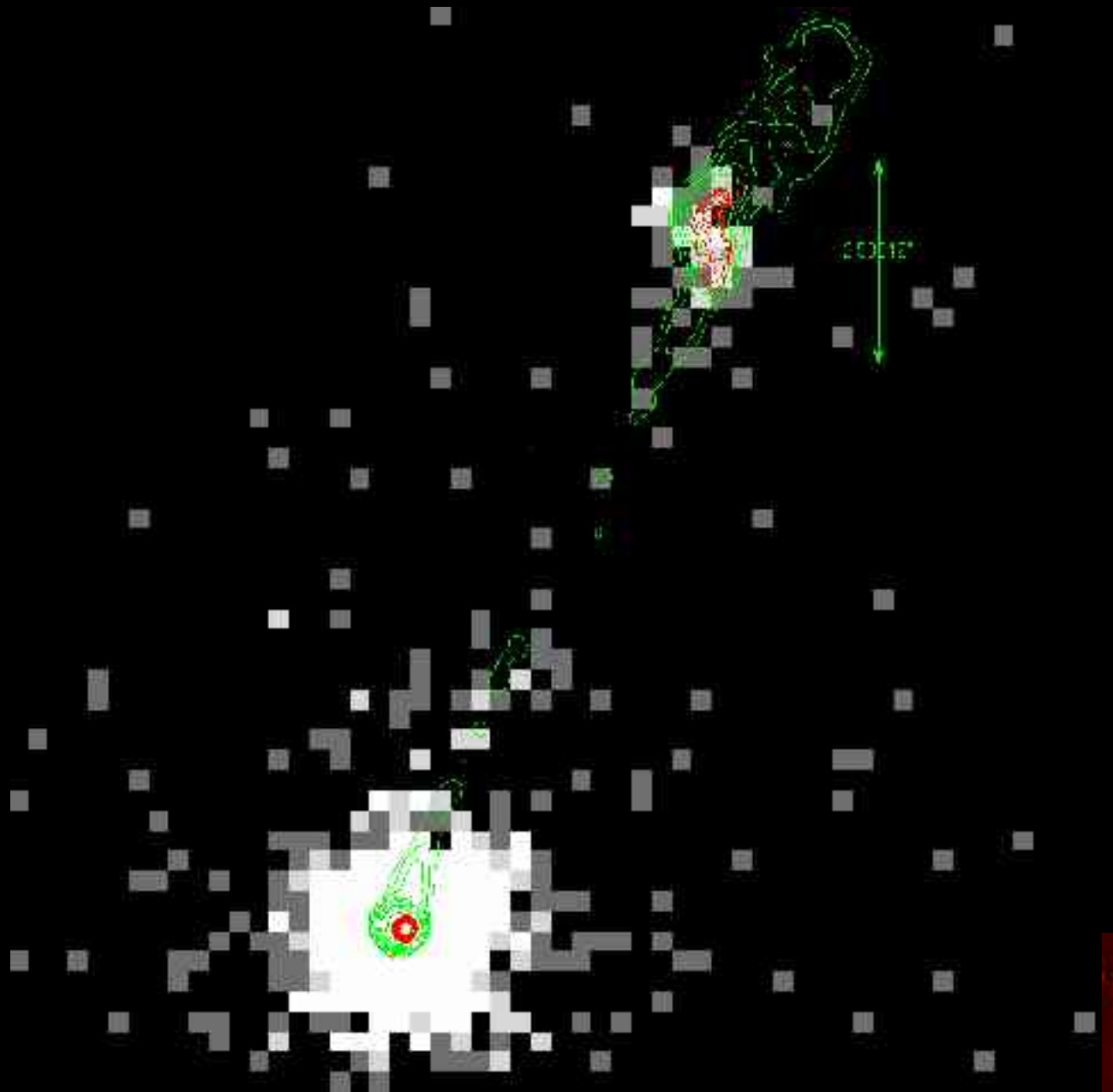


More problems: offsets

- ... but in other cases there are X-ray regions that seem to bear no relation to the jet (or other radio!)



3C275.1

More problems: offsets

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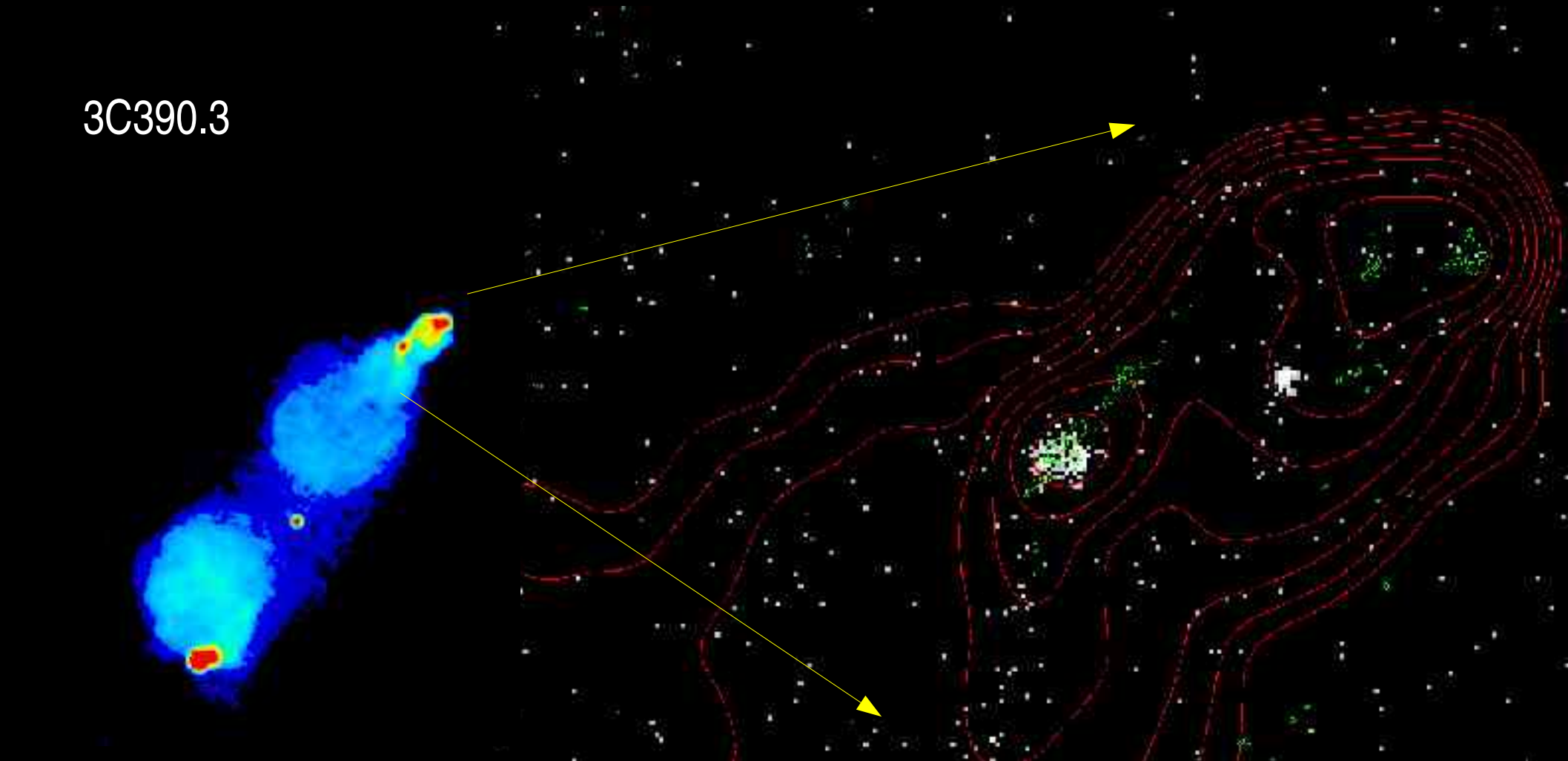

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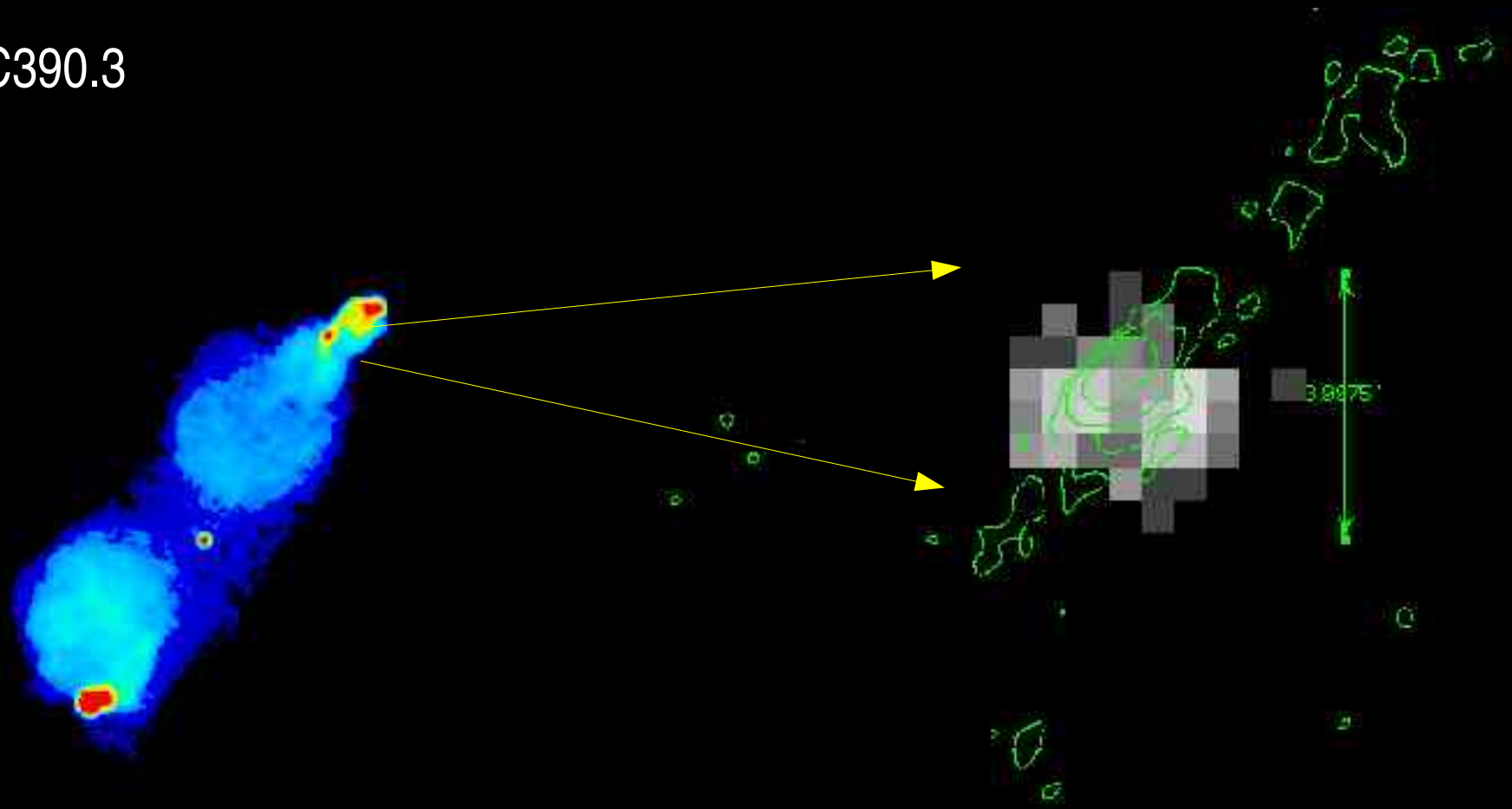
3C390.3



Problem sources: summary

- X-ray level generally >> SSC/IC expectation at equipartition
- Some have optical/IR constraints that rule out a single concave synchrotron spectrum
- Diffuse X-ray emission in some on 10-kpc scales requires a distributed acc'n mechanism if synchrotron (loss spatial scale < 10 pc).
- Some (not all) show offsets between radio & X-ray peak, or X-ray extensions w/o radio counterpart: some of these are in jet direction but many are not.
- Some have all of these features! (e.g. Pic A E+W)

Models

- SSC/IC
- Beaming
- Multi-component synchrotron

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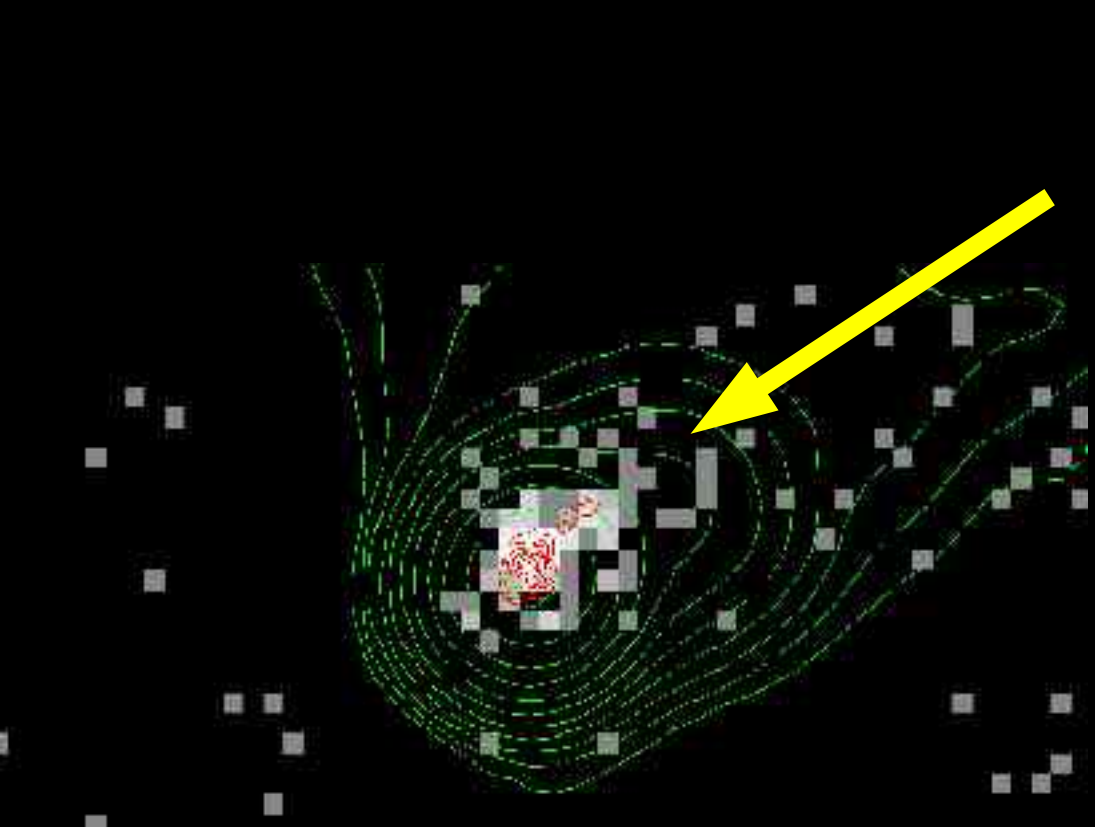
- Multi-component synchrotron

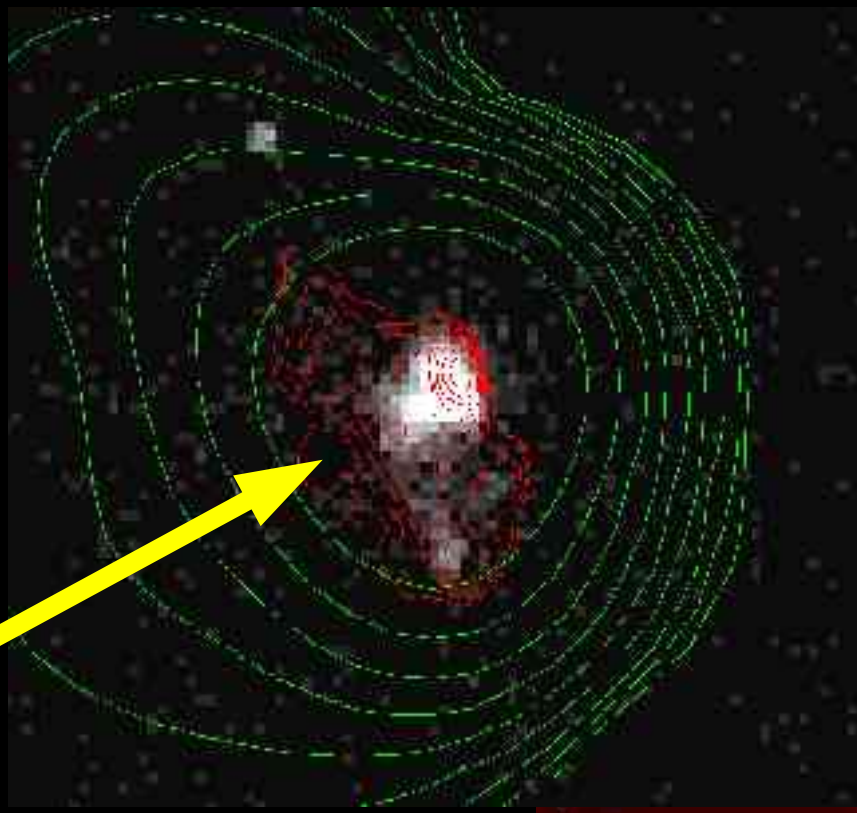
Models

- SSC/IC ✗
  - requires large, position-dependent departures from equipartition: fundamentally can't cope with large offsets.
- Beaming ✓?
  - a la Georganopoulos & Kazanas: with suitable electron distributions may explain some extensions in jet direction in some sources, but not all offsets/diffuse emission
- Multi-component synchrotron ✓?
  - can explain diffuse emission, some offsets/extensions, non-concave SED: but ad hoc?

Beaming

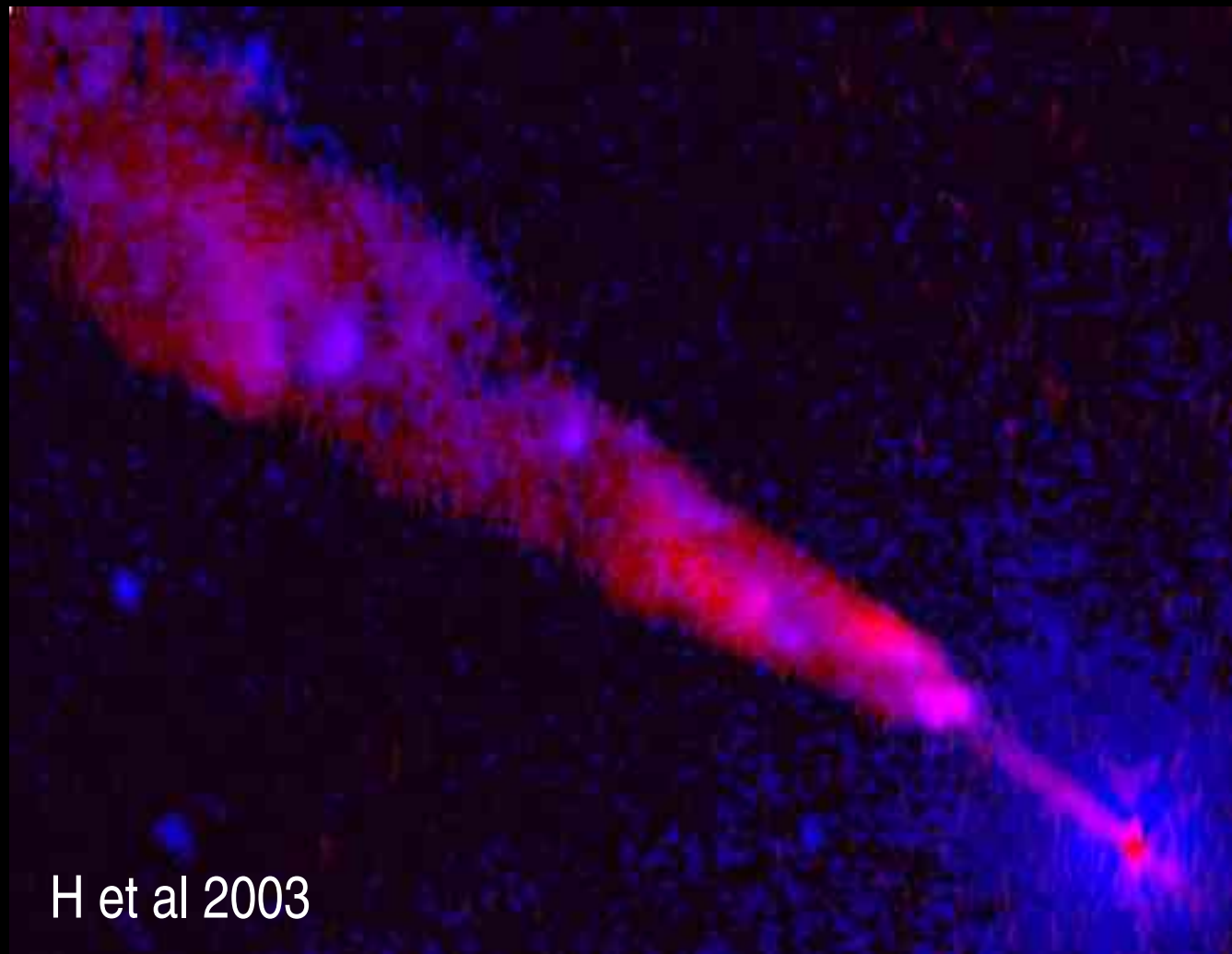
- Now desirable to carry out detailed calculations to see if the Georganopoulos & Kazanas mechanism can explain jet-directed X-ray emission in BLRG/quasars like Pic A or 3C263.





Multi-component synchrotron with spatially distributed acceleration

- Some arguments in support of investigating this further:
  - It's observed in jets in low-power radio sources.



H et al 2003

Multi-component synchrotron with spatially distributed acceleration

- Some arguments in support of investigating this further:
  - It's observed in jets in low-power radio sources.
  - It's required to explain the extended *optical* emission in hotspots like 3C33 S and Pic A W.

> 'The extraordinary spectra and the absence of any indication of synchrotron ageing in these hot spots led us to the speculation that there exists a second "jet-like" acceleration process which is responsible for the synchrotron spectra of both optical jets and optically extended radio hot spots. [...] Although its physics is completely unknown at present, we feel that a better understanding of particle acceleration and synchrotron spectra of extended radio sources in general will be impossible unless we have an idea how this new process works.'
>
> — Meisenheimer et al 1997

Multi-component synchrotron with spatially distributed acceleration

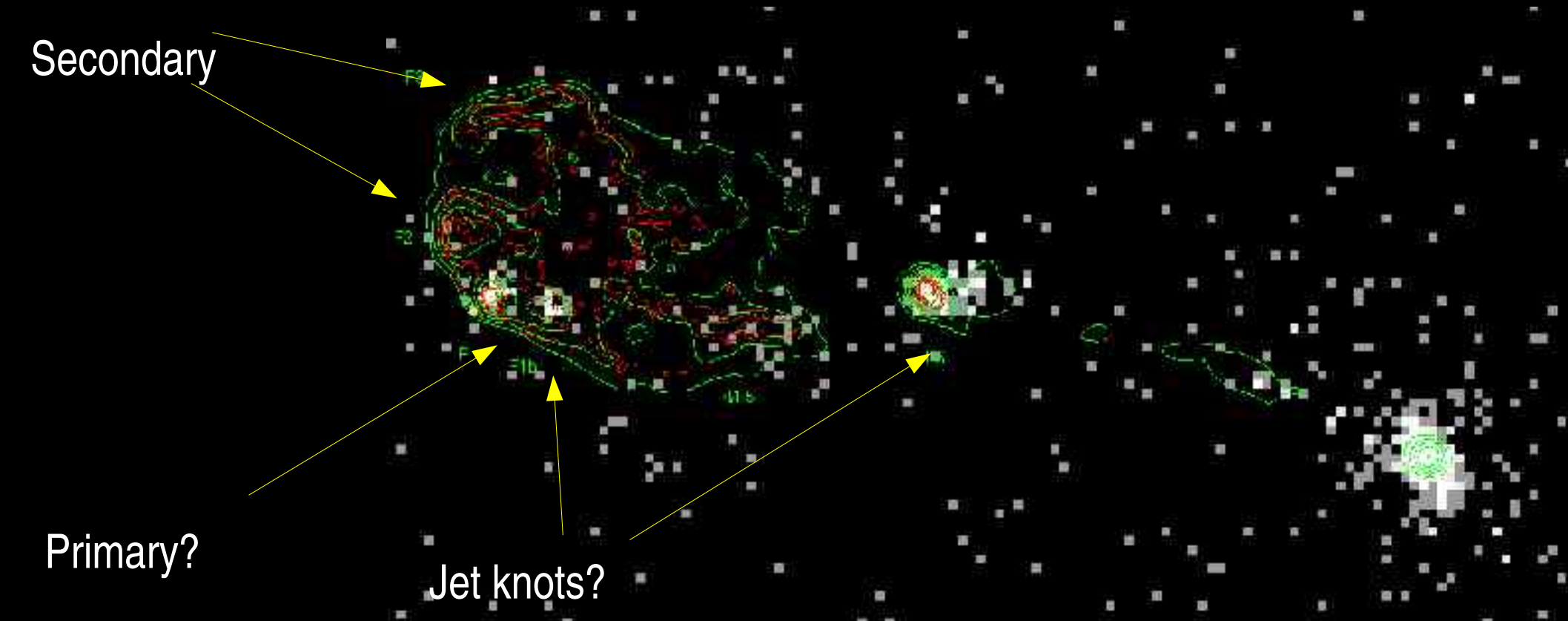
- Some arguments in support of investigating this further:
  - It's observed in jets in low-power radio sources.
  - It's required to explain the extended *optical* emission in hotspots like 3C33 S and Pic A W.
  - It may give us insight into the disputed emission mechanism for the X-ray jets in powerful quasars: note the required second spectral component in sources like 3C273 (Jester et al 2006).
- More optical data are now the priority.

Multiple hotspots (time permitting)

- We already know from success of H&M model in many secondary hotspots (Cyg A, 3C123) that they are probably now, or have recently been, sites of particle acceleration.
- Adiabatic expansion rapidly quenches hotspots, thus 'dentist's drill' generally requires us to be seeing the source at a special time, particularly if secondary has much higher energy content than primary (e.g. Valtaoja 1984; Hardcastle & Looney 2001).
- So most likely that many secondary hotspots, esp. bright ones, have continued energy supply.

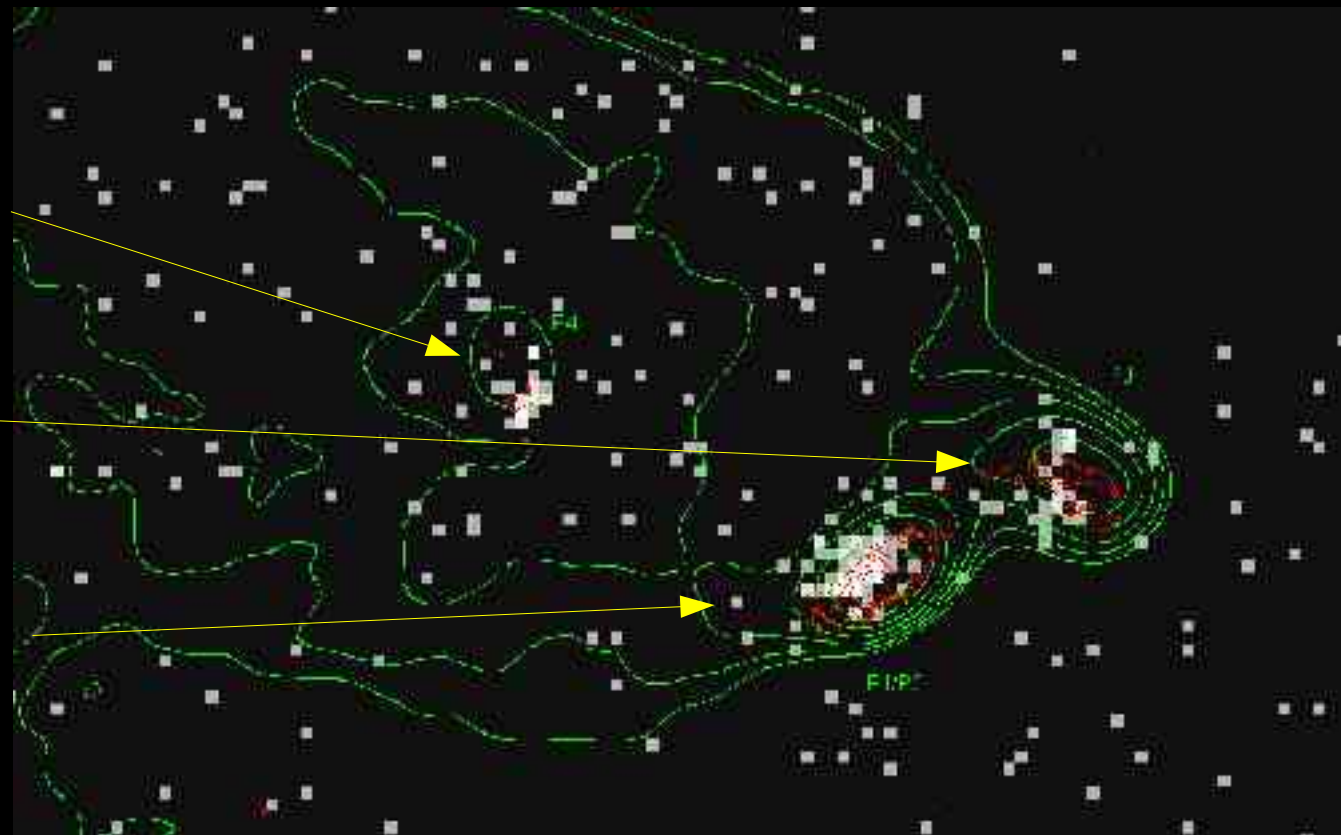
Multiple hotspots

- X-ray synchrotron emission gives us a test. Mixed results: some secondary hotspots clearly have much less X-ray emission than primary...



Multiple hotspots

- X-ray synchrotron emission gives us a test. Mixed results: some secondary hotspots clearly have much less X-ray emission than primary, others show clear X-ray detections...



Multiple hotspots

- X-ray synchrotron emission gives us a test. Mixed results: some secondary hotspots clearly have much less X-ray emission than primary, others show clear X-ray detections.
- What is different about the hotspots with & without X-ray detections? Must be telling us about acceleration process.
- Here multi-frequency radio and deep optical/IR studies will allow us both to understand hotspots better and to test the X-ray synchrotron model.

Summary

- We know that a simple shock model, with a single region of acceleration, explains broad-band (radio-optical) spectra of many sources (e.g. Meisenheimer et al 1997) although we don't understand origin of low-energy cutoff or parameters that fix injection index.
- For luminous hotspots an SSC explanation of the X-ray emission works well and implies magnetic fields close to the equipartition values.

Summary

- But X-ray (and optical) observations show radio/X-ray offsets, diffuse emission, jet-related extensions, and SEDs inconsistent with single synchrotron models or with SSC/IC at equipartition.
- Some, but certainly not all of these observations could be explained if the jet X-ray emissivity goes up close to hotspot (as in G&K model).

Summary

- Other observations almost certainly require a distributed high-energy particle acceleration mechanism existing in and around some hotspots/hotspot complexes.
- Clean case: no beaming and no likelihood of two-fluid model being necessary.
- This could be the same mechanism as operates in the diffuse regions of low-power jets, and it may also be important in more powerful systems: whatever it is, we need to understand it!