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X-ray synchrotron radiation and particle acceleration

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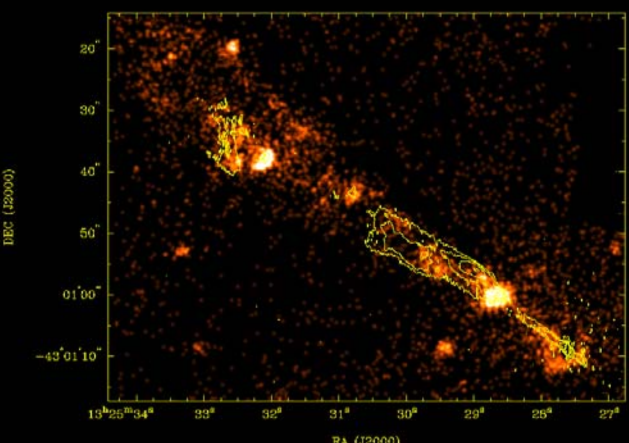
Outline

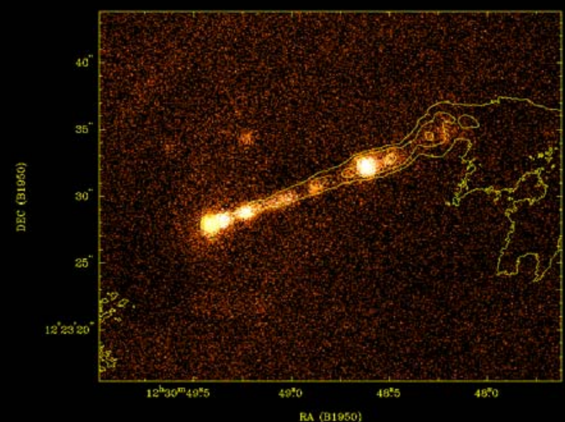
- X-ray synchrotron radiation as probe of particle acceleration
- FRI (low-power) jets
  - Problems and successes of a synchrotron model
  - Cen A and localization of particle acceleration sites: relation to dynamics
- FRII hotspots

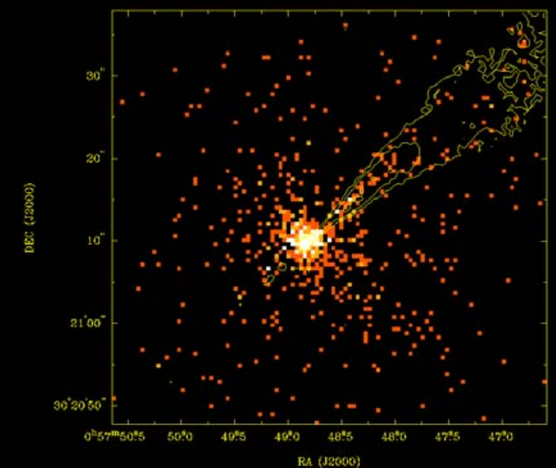
Introduction

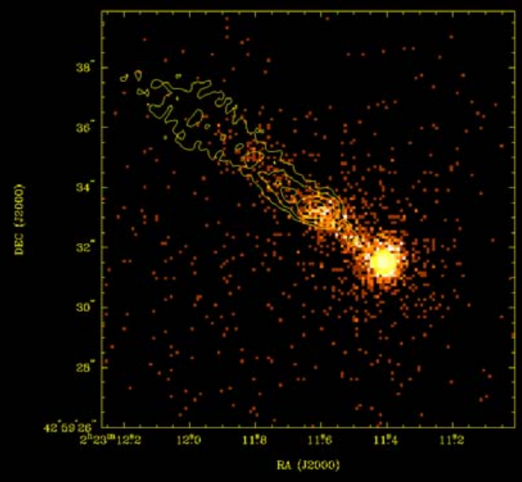
- Important to locate sites of jet dissipation, i.e. where jet bulk kinetic energy is transferred into random energy of particles
- X-ray synchrotron emission probes this uniquely well
- Loss timescale in typical magnetic and photon fields is ~ tens of years
- For $v < c$ emitting electrons can travel only a few pc from the site of energization.

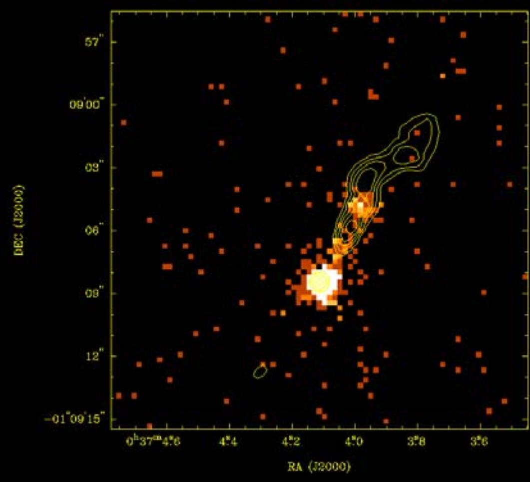
FRI X-ray jets (6/15)

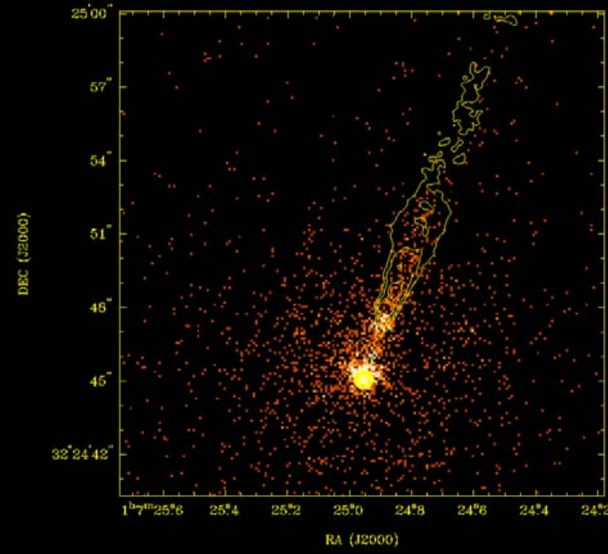






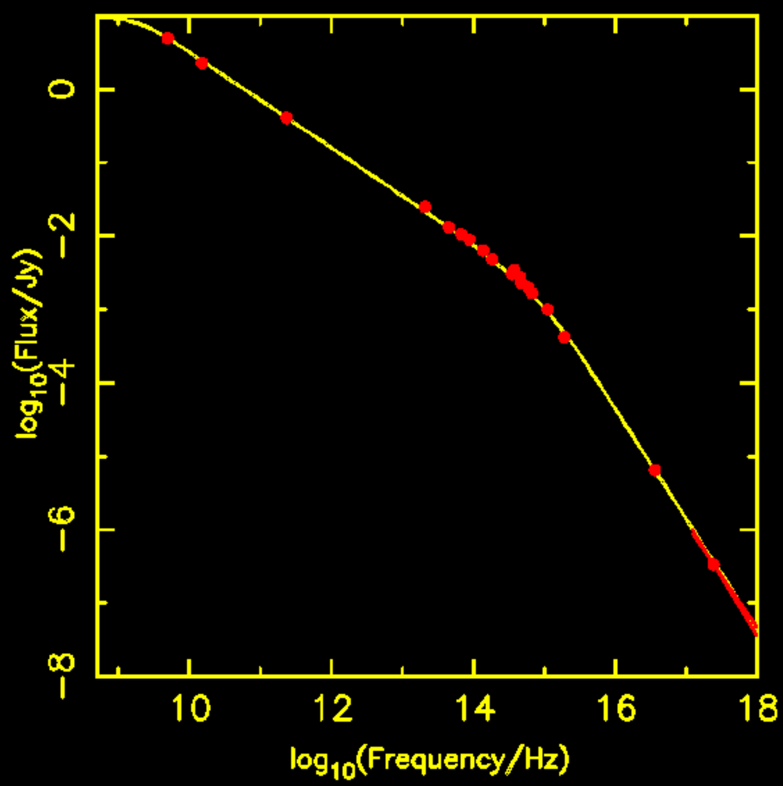






Synchrotron emission?

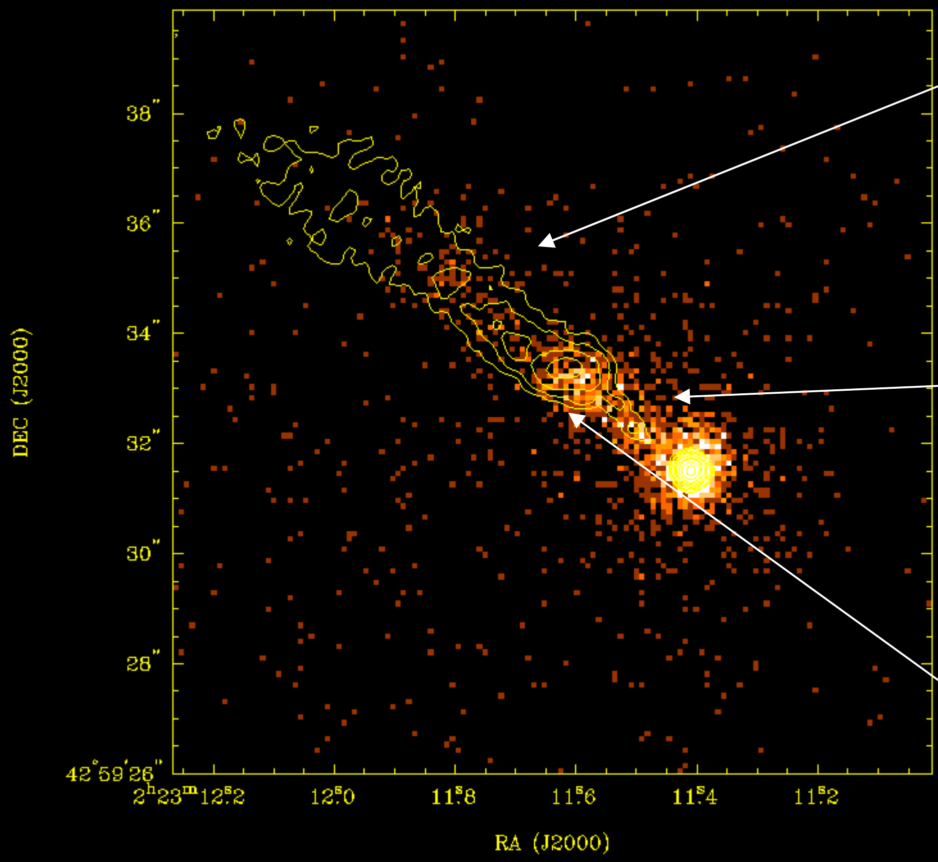
1. Radio and optical is certainly synchrotron
2. Radio / optical / X-ray join up (reasonably well)
3. Steep overall X-ray spectra
4. Inverse-Compton impossible (from 3, plus B would have to be << B_{eq}).



Association with deceleration

- X-ray and optical jets only in the inner few kpc (almost no exceptions – NGC6251?)
- 3C31 jet exactly in the place where strong dissipation should be taking place (Laing & Bridle)
- Short lifetimes imply in situ particle acceleration
- Energetics work (easily).

Problems of a synchrotron model



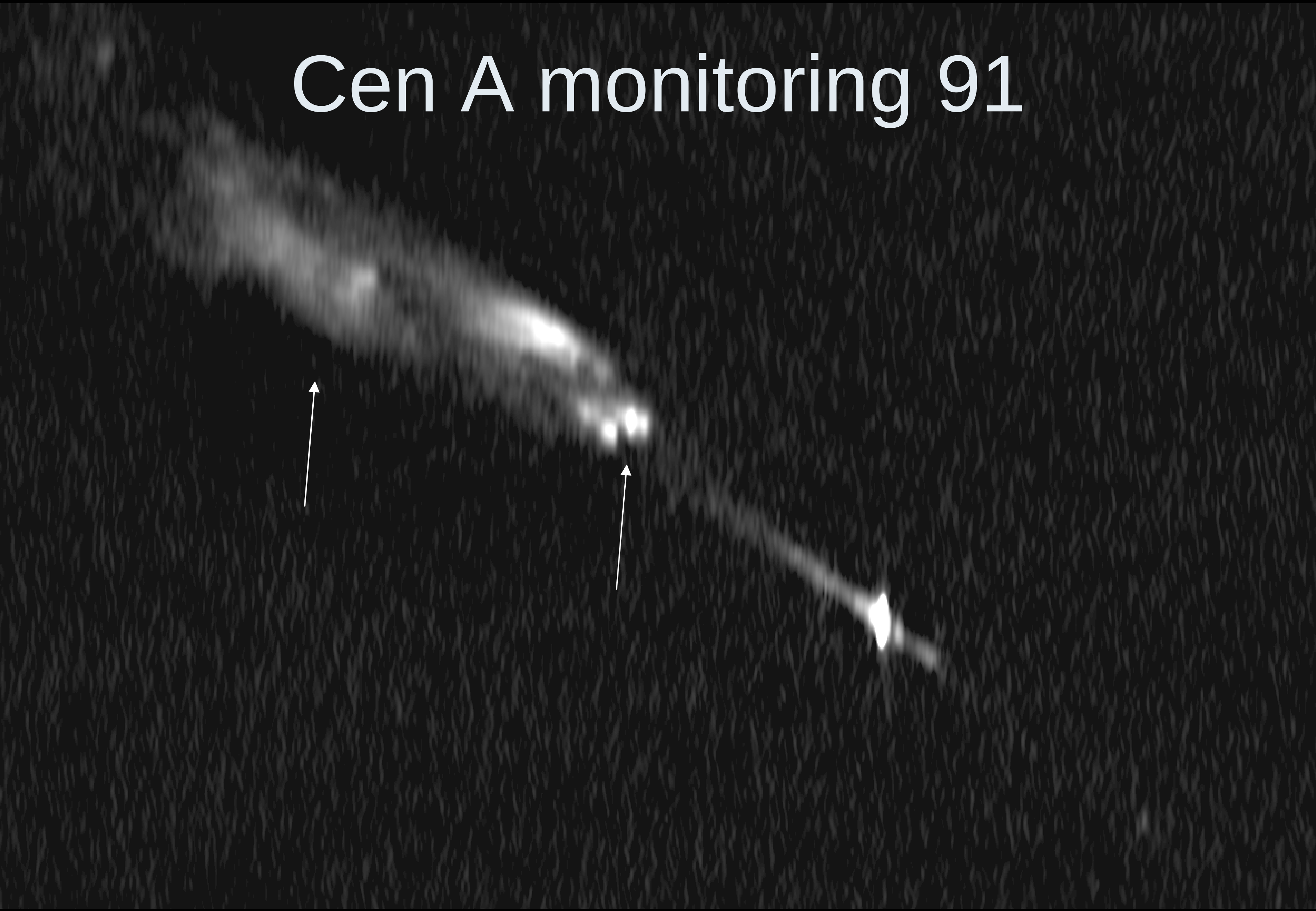
3C66B, a 'typical' z ~ 0.02 (D ~100 Mpc) jet

- Diffuse X-ray emission (acceleration mechanism?)
- Point-to-point radio/X-ray spectral differences
- Offsets in peaks
- Conventional synchrotron spectra don't fit.

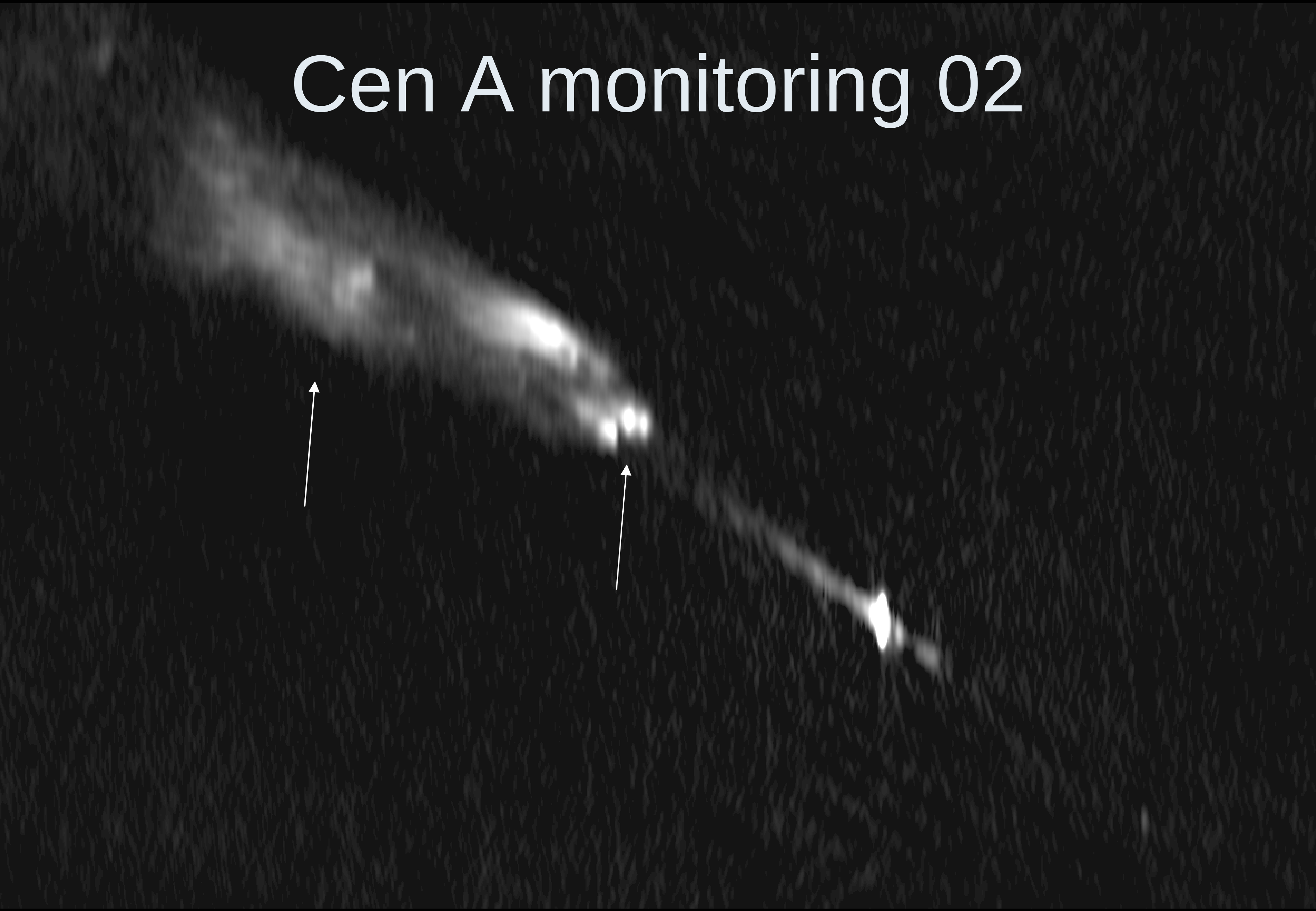
Centaurus A

- Clearly there are things going on in these sources that do not fit a simple picture
- In general distance means that we are averaging over many loss scales; there *must* be substructure we are missing
- Chandra’s resolution probes the loss scale of ~ few pc in only one source: Cen A (D = 3.4 Mpc; 1 arcsec = 17 pc).
- Observed with Chandra & VLA.

Cen A monitoring 91

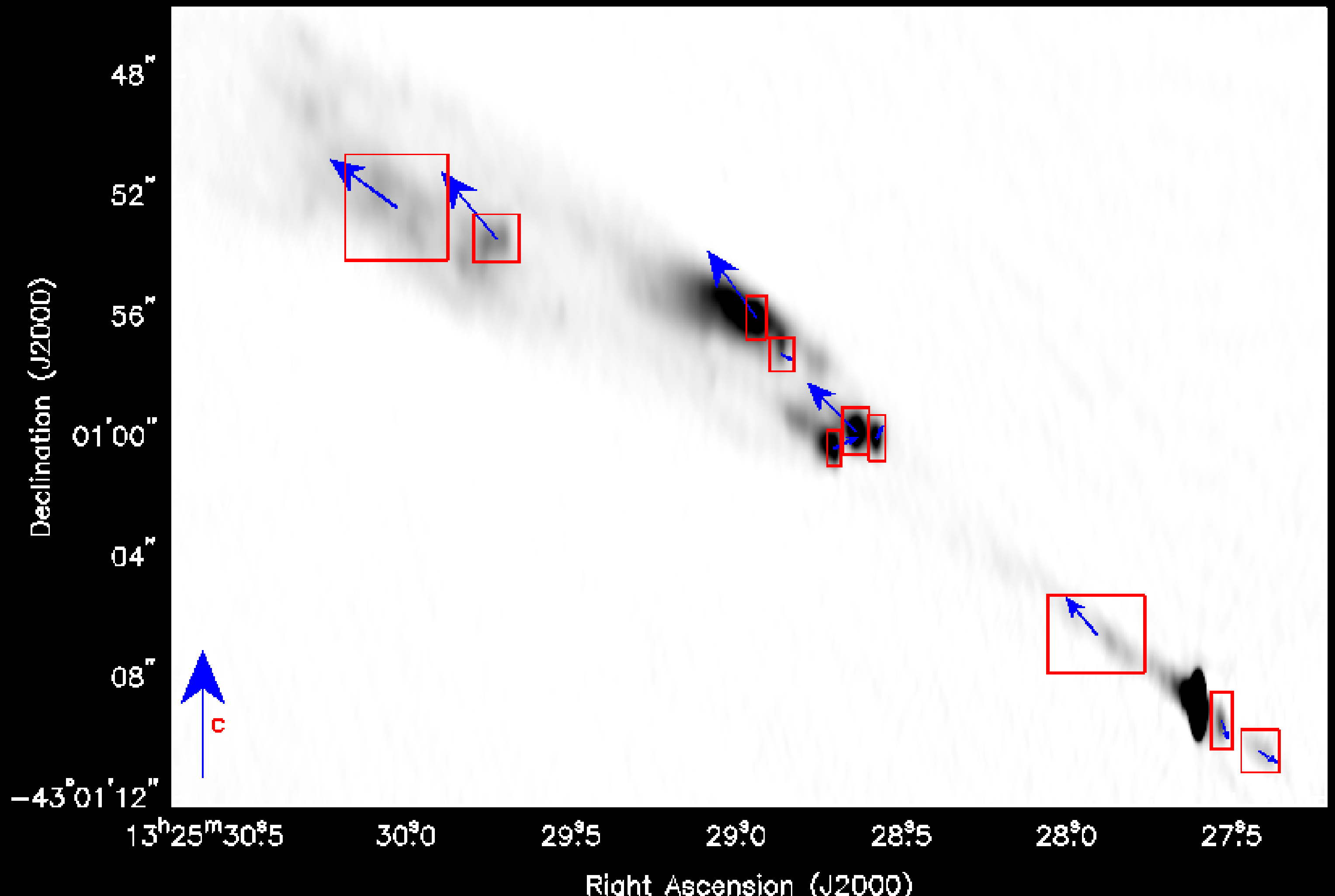


Cen A monitoring 02

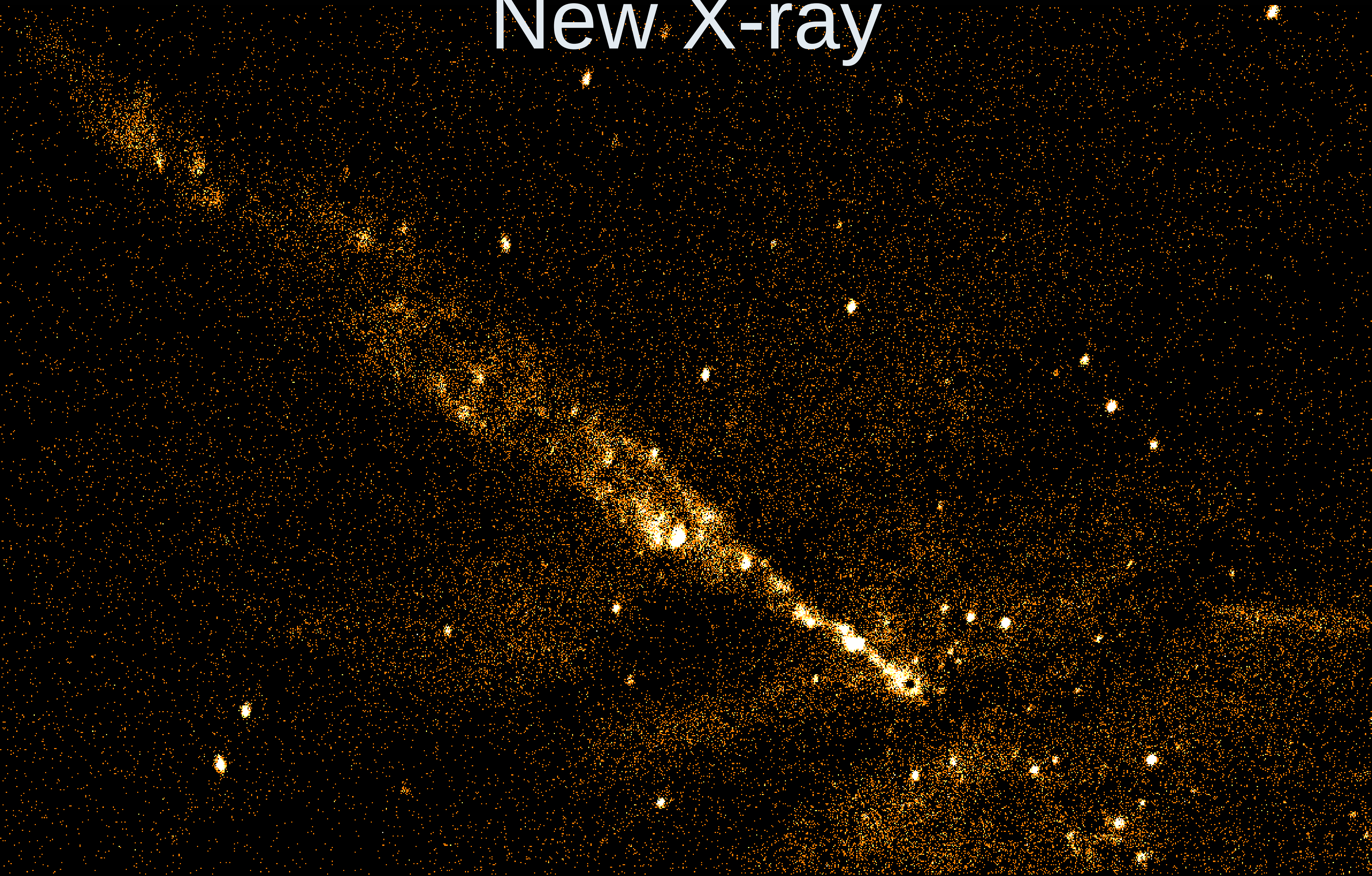


Cen A monitoring 03

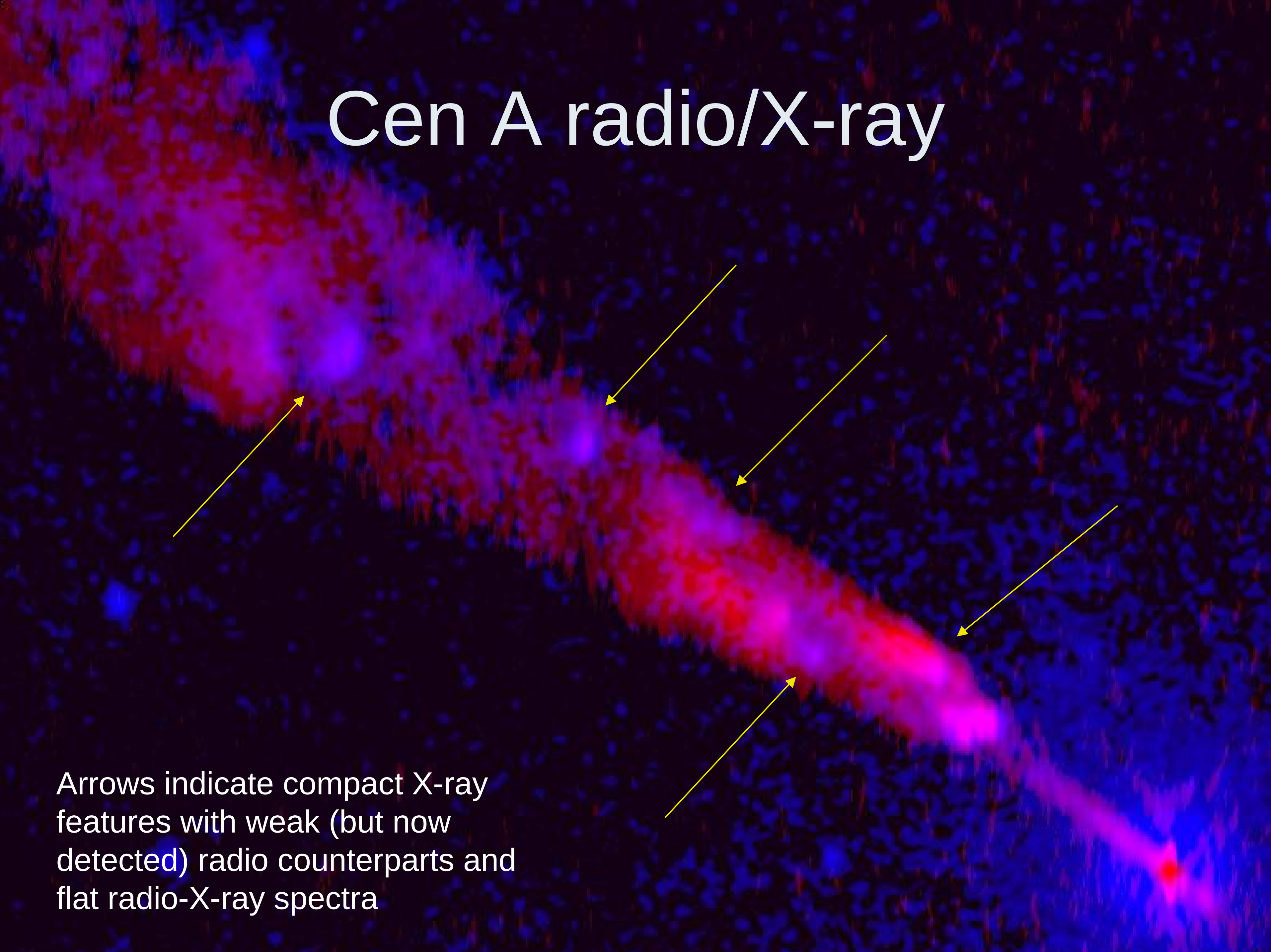
Jet proper motion



New X-ray



Cen A radio/X-ray



Arrows indicate compact X-ray features with weak (but now detected) radio counterparts and flat radio-X-ray spectra

Radio/X-ray

- Most X-ray knots now have detected, coincident radio counterparts
- Some diffuse X-ray emission not resolved into knots, and the radio/X-ray relation is complex; clear edge-brightening.
- Knots and diffuse emission spectrally distinct.
- Strong X-ray knots are all associated with *stationary* radio features.

Shocks

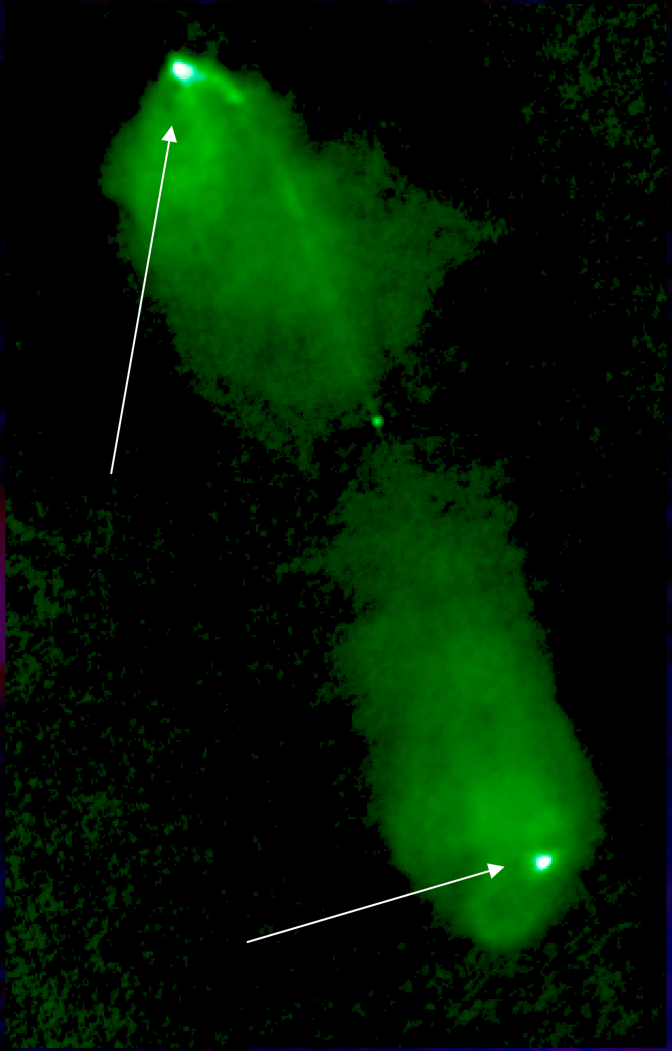
- Knot spectra imply they are not simply compressions in the flow, but privileged sites for particle acceleration
- Plausibly shocks
- Base knots can be a standing reconfinement shock, but
- Stationary knots further up the jet seem to imply that the jet fluid is running into something (most likely clumps of cold gas).

Particle acceleration

- Some may be at shocks – perhaps averaging over shocks & downstream loss regions can account for both offsets and spectral peculiarities.
- Diffuse, edge-brightened regions harder to explain in these terms – population of unresolved knots, or different process?

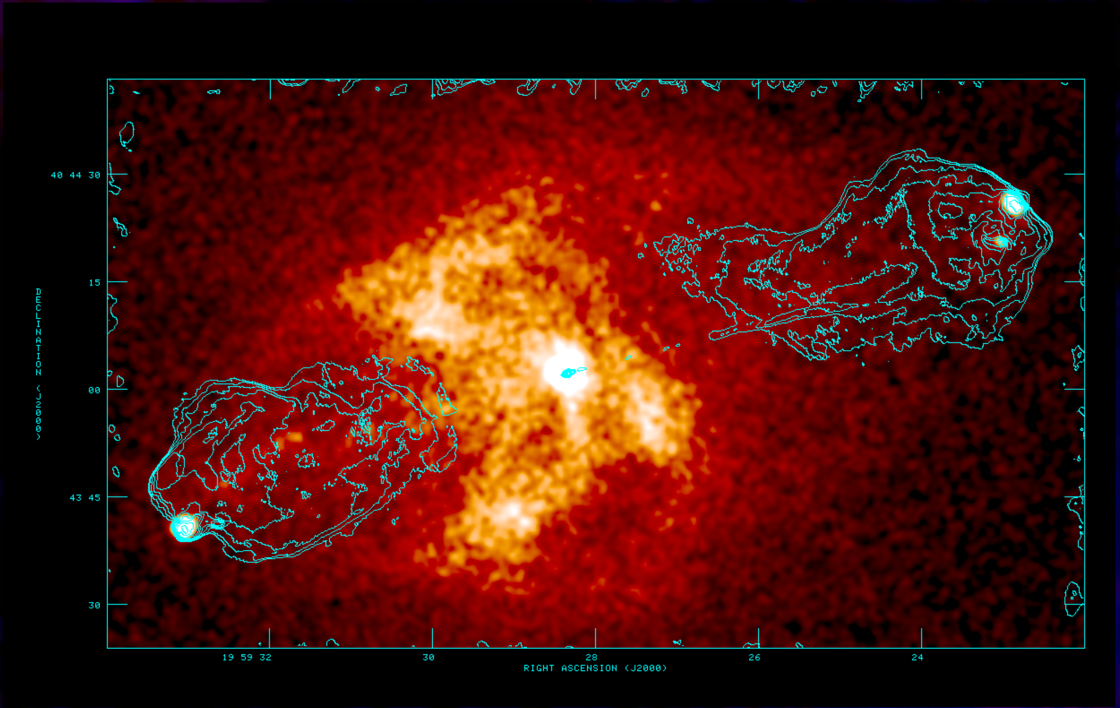
Shocks in FRIIs?

- Hotspots in FRIIs conventionally taken to be the sites of jet termination shocks.
- Optical emission shows that hotspots can accelerate to high energies (though mechanism not clear for extended optical regions)
- What about X-ray emission?

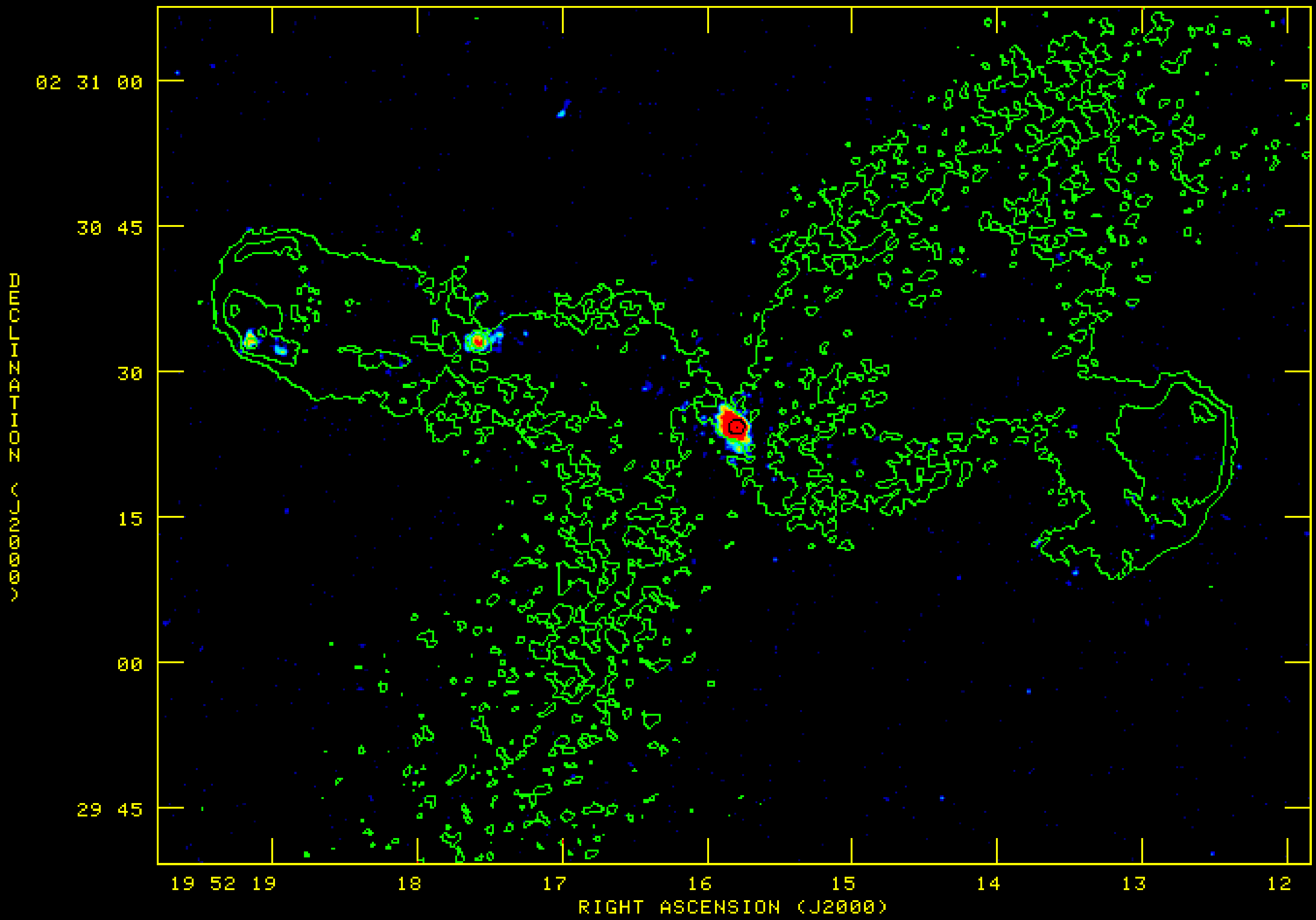


X-ray hotspots

- Early X-ray hotspot observations mostly of sources where synchrotron cuts off before optical: inverse Compton (SSC) with B close to B_{eq}.
- But we run into problems when looking at weaker hotspots with less well constrained spectra.
- Some well-known sources that don’t work with SSC models (Pic A, 3C390.3).
- Recently even more extreme sources discovered…

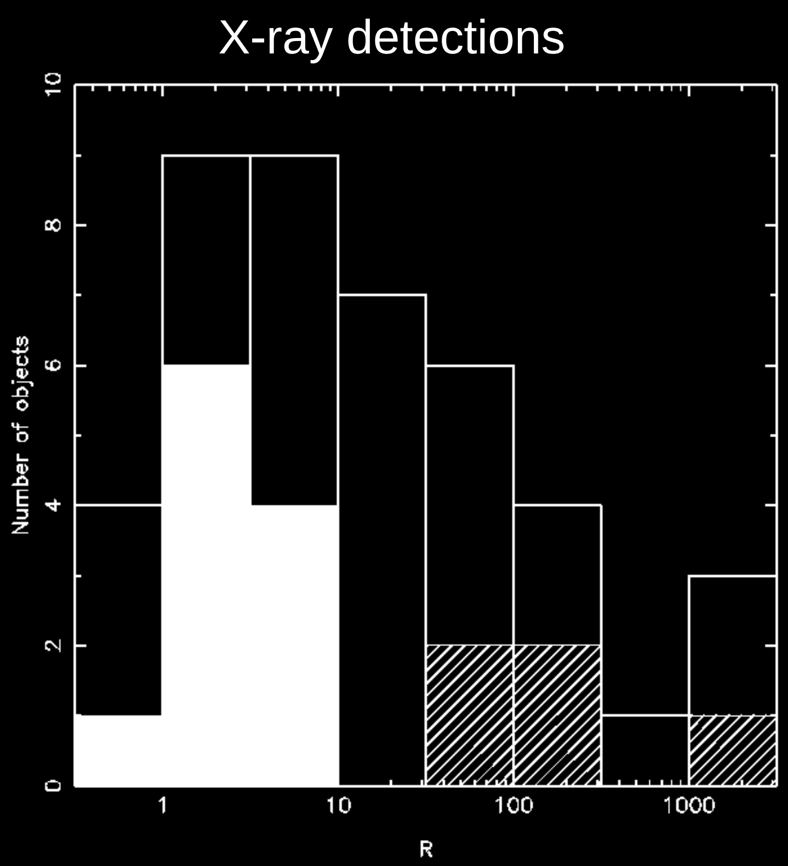


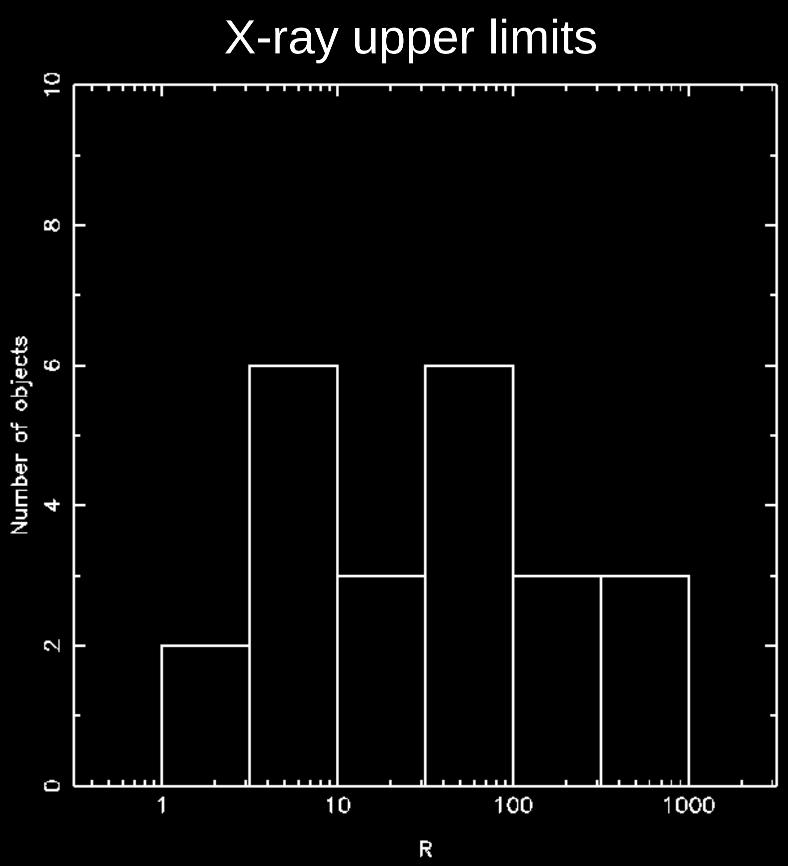
Extreme X-ray hotspots



Either we are wrong about inverse-Compton emission or we have synchrotron emission as well/instead in some sources.

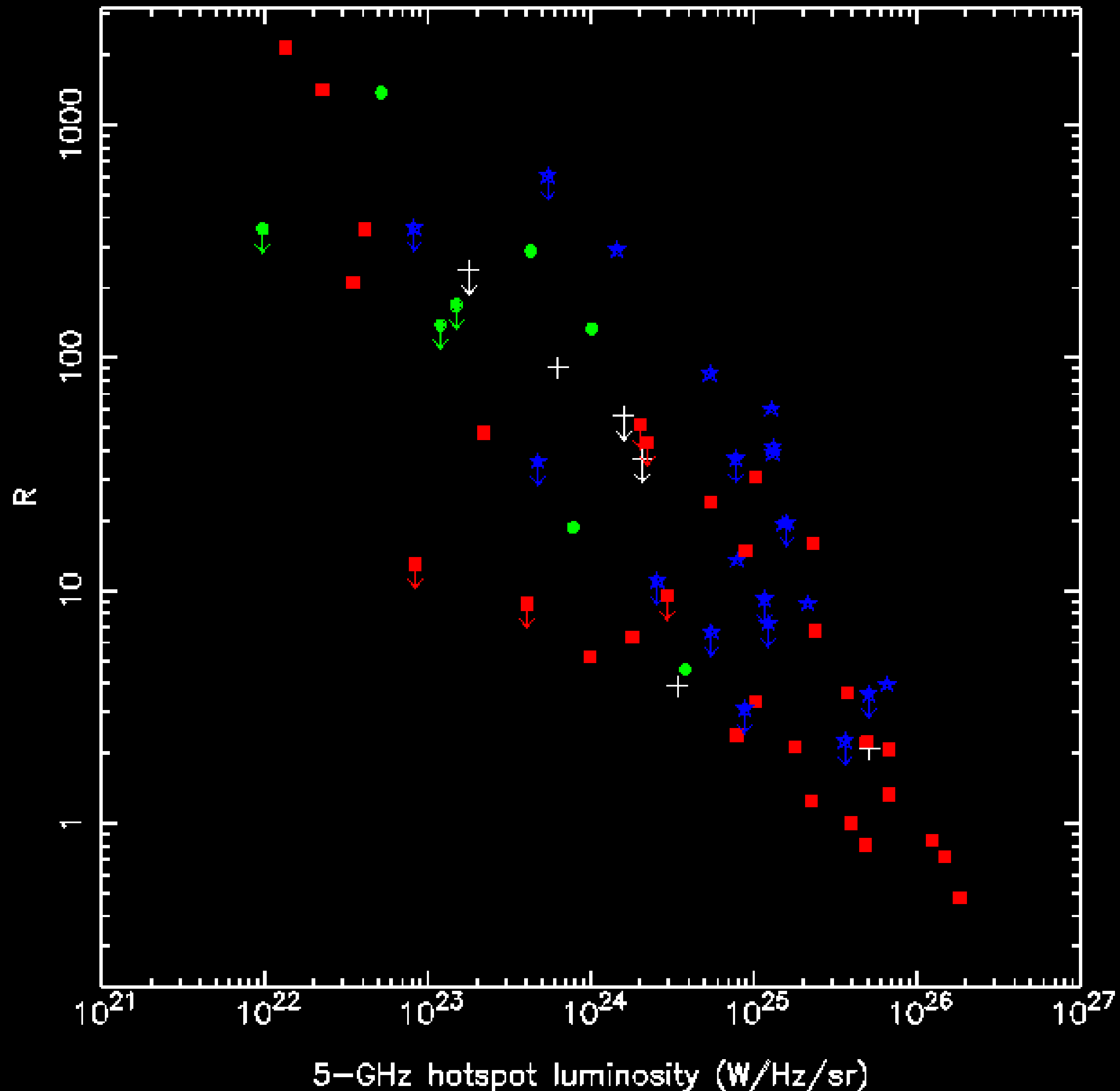
3C sources with hotspots



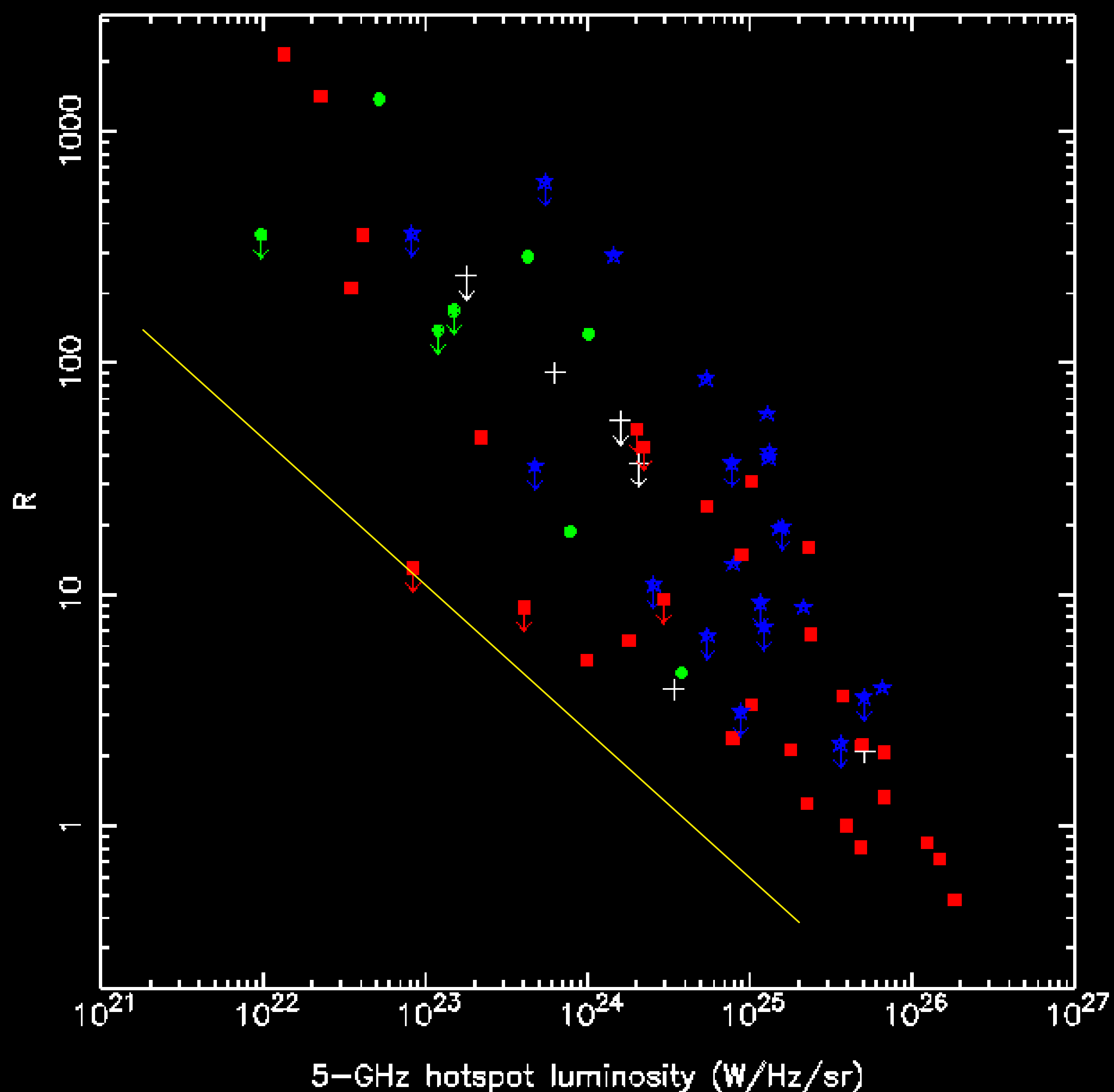


- Search for 3C FRII sources in Chandra archive
- Examine ratio R of observation to IC prediction

R and hotspot power

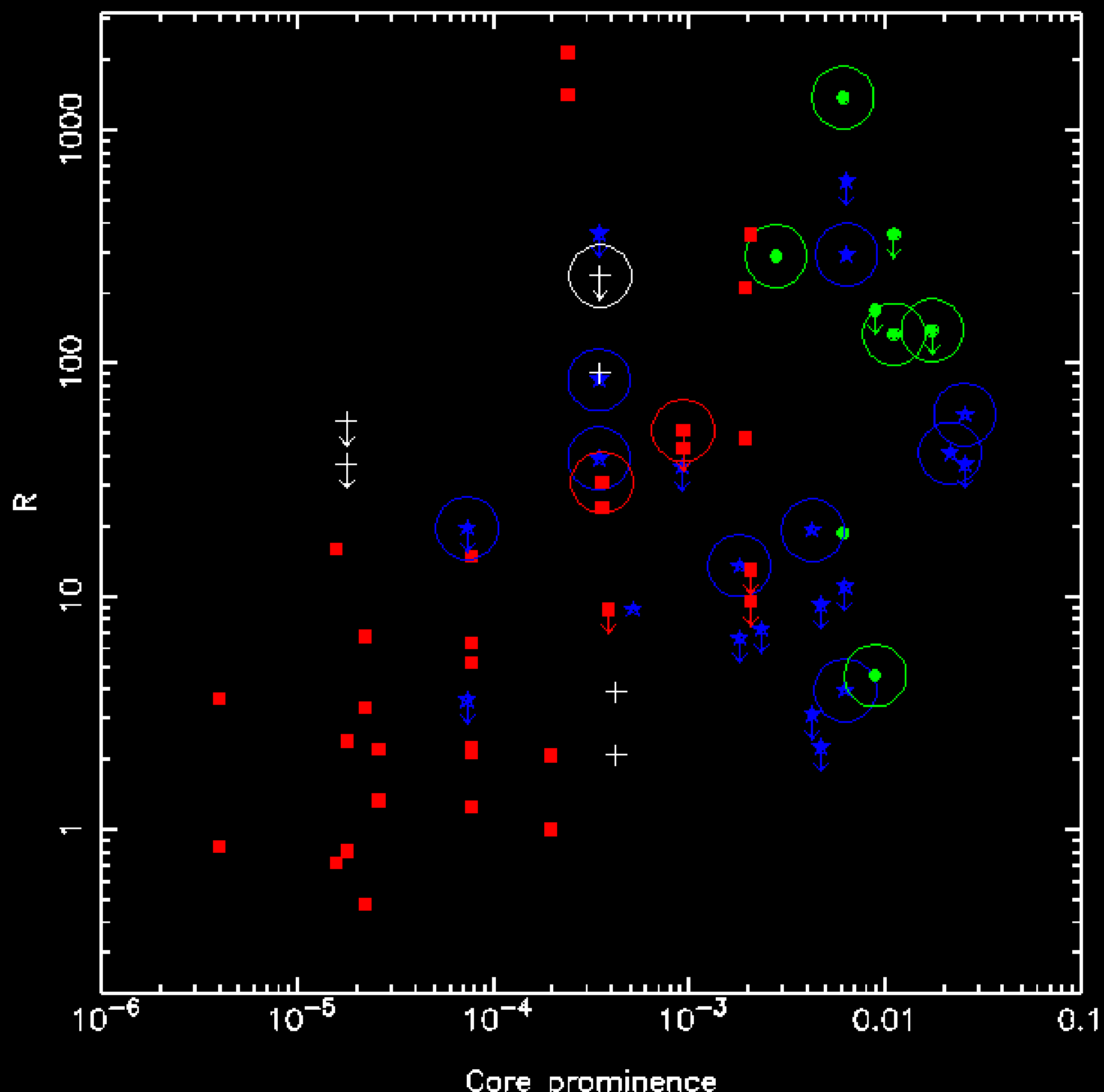


R and hotspot power



Not as good a correlation as it looks!

R and beaming



Crosses – LERG

Boxes – NLRG

Circles – BLRG

Stars – Quasars

Large circles show hotspots that jets enter

Hotspot conclusions

- Many low-power hotspots have much more X-ray emission than would be expected on SSC model.
- Dominant influence appears to be radio power. Explicable in terms of synchrotron model – greatly increased high-energy losses. Hard to explain on IC model.
- Effect of beaming is secondary, but probably still there. Again explicable in synchrotron model.

Summary

- In low-power jets X-ray synchrotron probes particle acceleration associated with bulk jet deceleration.
- In Cen A at least some of the particle acceleration is localized and can be related to small-scale jet dynamics.
- In FRII hotspots synchrotron X-ray may be the best way to understand the bright X-ray emission seen in many hotspots; acceleration mechanism is far from clear as yet.