Deep X-Ray and Optical Observations of Quasar Jets

A status report on our survey and follow-up work

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A status report on our survey and follow-up work

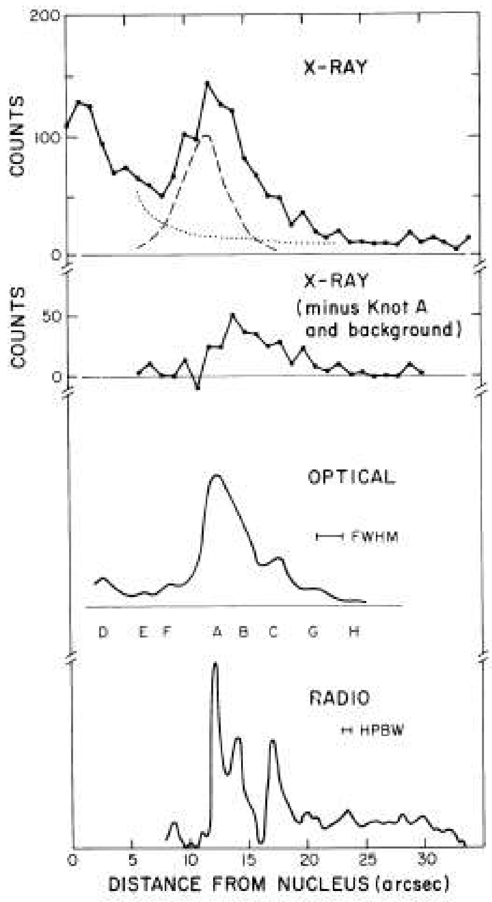
Outline:

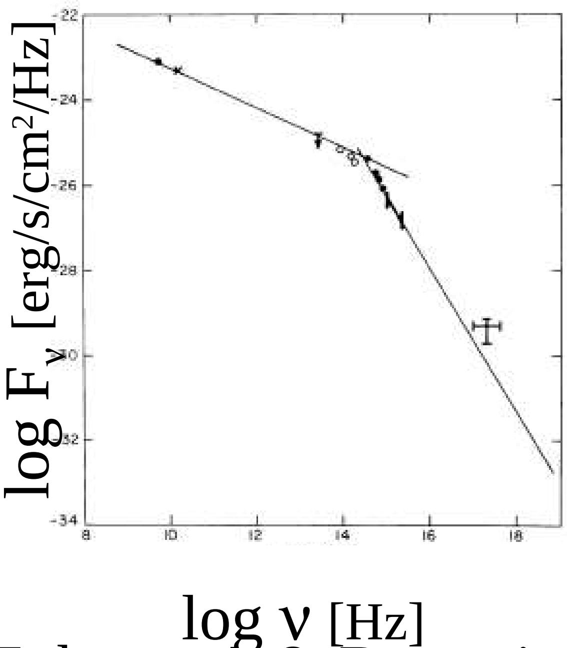
- Motivation: the case of PKS 0637-752
- Our multiwavelength survey
- Some follow-up targets:
  - PKS B1421-490
  - PKS 1055+201
  - PKS 2101-490

Early X-ray Jet Detections

- Before Chandra, few X-ray jets were known
- X-rays thought to originate as either synchrotron emission or inverse Compton scattering of radio synchrotron photons (synchrotron self-Compton, SSC)

Early X-ray Jet Detections

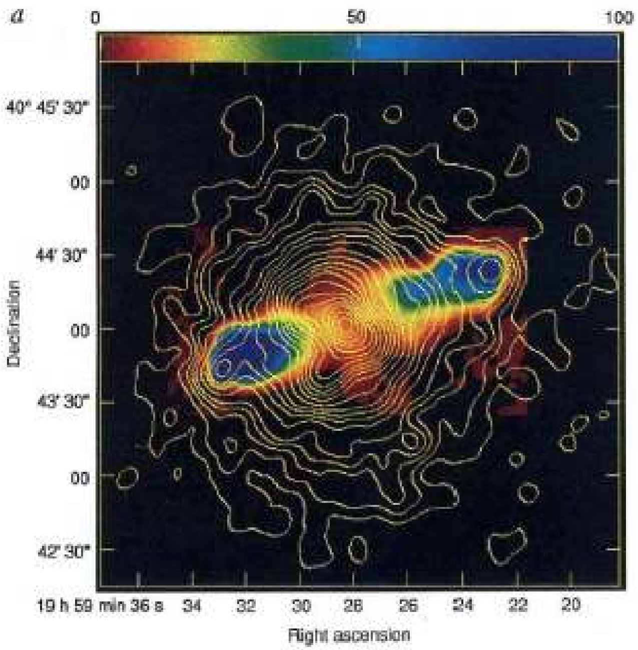




- M87: knots A & B consistent with continuation of synchrotron spectrum

  (Schreier et al 1982, ApJ 261, 42)

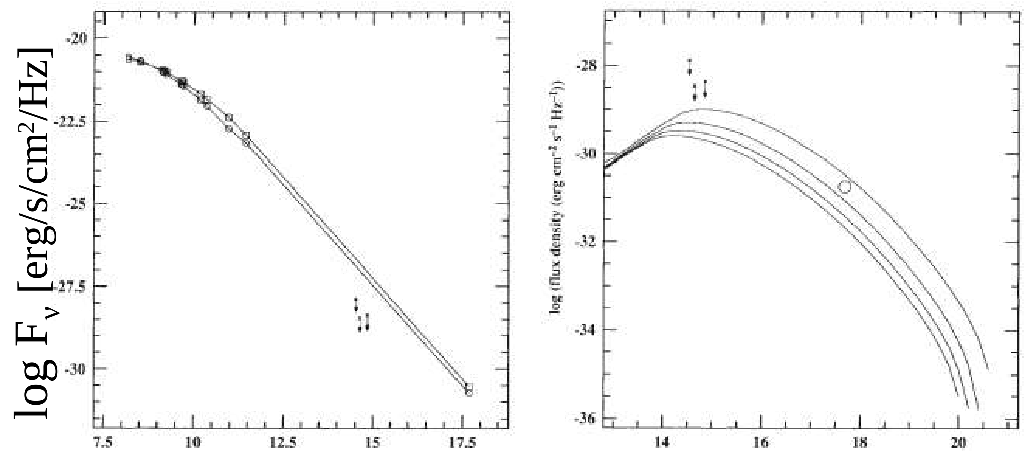
Early X-ray Jet Detections



Rosat contours over 327 MHz radio map of Cygnus A

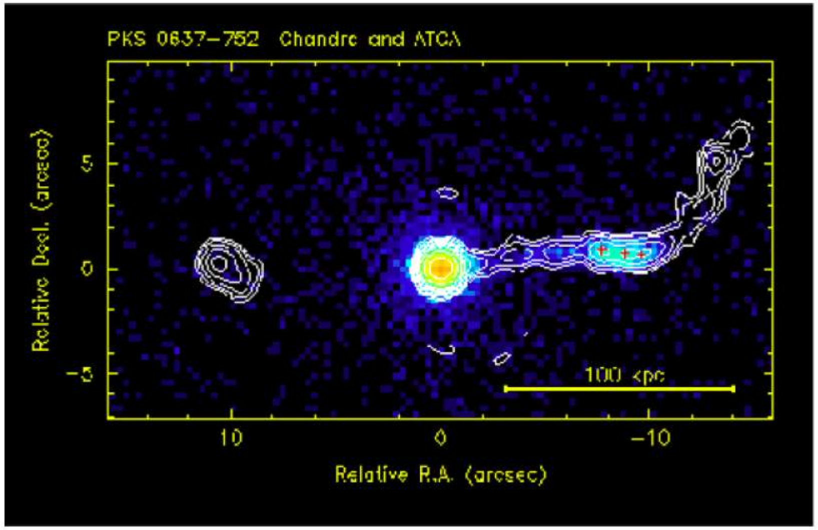
(Harris et al. 1994, Nature 367, 713)

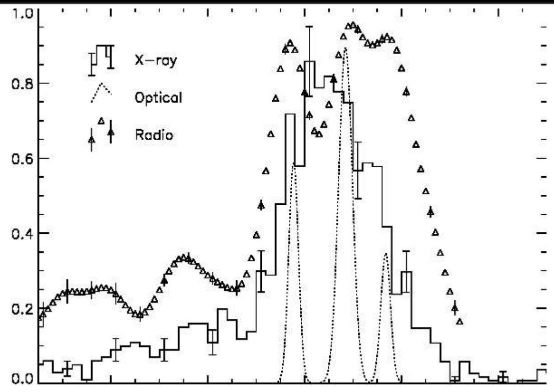
- Optical data too low for synchrotron spectrum
- SSC can describe data



SEDs of Cyg A hot spots

PKS 0637-752





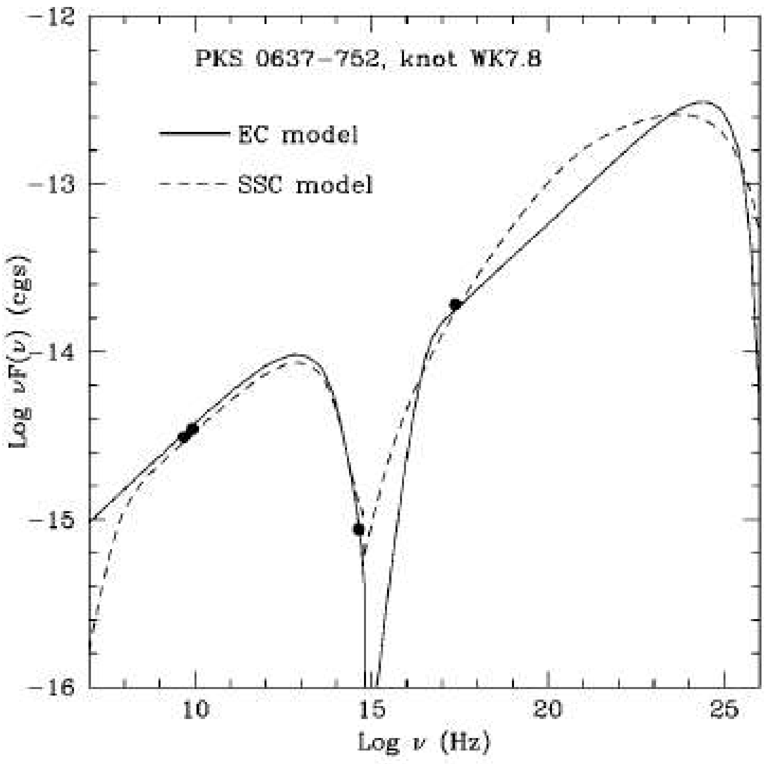
Normalized flux

Angle from core [arcsec]

- First celestial target for Chandra
- Chosen as a point source to refine focus
- X-ray jet discovered
- Optical knots found with HST

(Schwartz et al. 2000, ApJ 540, L69)

PKS 0637-752



IC-CMB model of Tavecchio et al. (2000, ApJ 544, L23)

- Optical flux too low for simple synchrotron models
- SSC model requires severely non-equipartition magnetic field and fine-tuned parameters
- Inverse Compton scattering of CMB (IC-CMB) can fit the SED, using $\Gamma \sim 10$, B ~ 15 μG, and $\gamma_{min} \sim 10$. Parameters consistent with VLBI jet in core.

Our Chandra survey

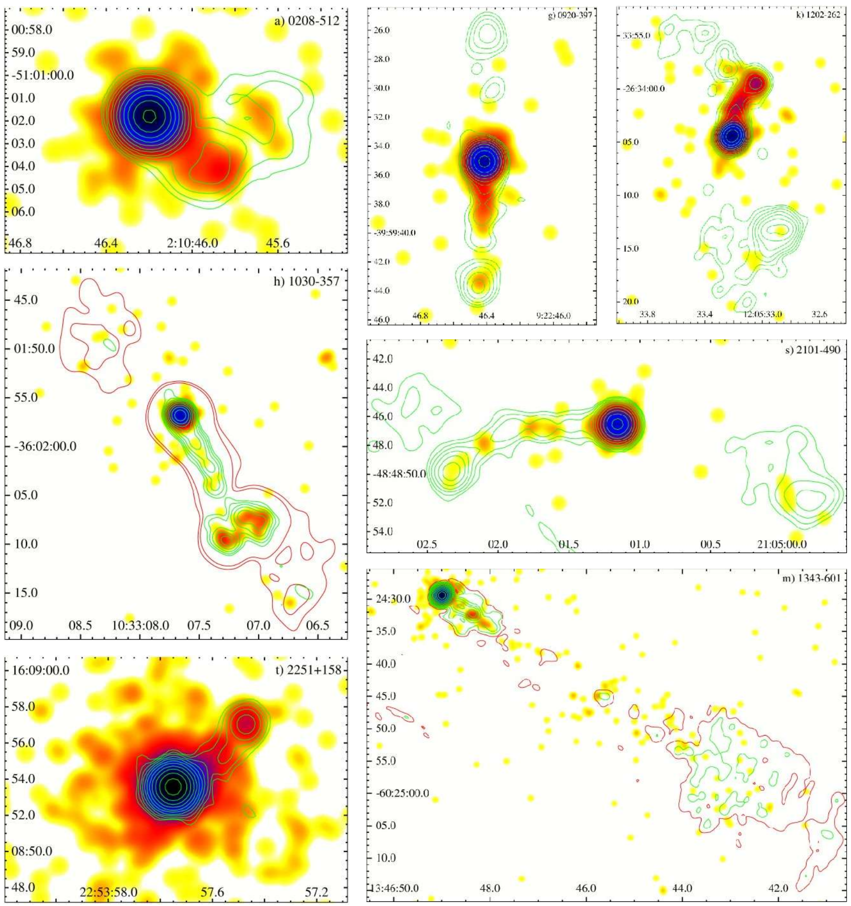
Some motivating questions:

- Is PKS 0637-752 typical of high power (FRII) quasars?
- What fraction of radio jets have strong X-ray emission?
- What processes dominate this emission?
- What are the physical conditions within the jets?

Our multiwavelength survey

- Sample of 56 flat-spectrum radio sources selected by extended (>2”) flux at 5 GHz
  - Subsample A is flux selected: highest predicted X-ray flux assuming S_x/S_r ratio of PKS 0637-752
  - Subsample B is morphologically selected: one-sided, linear radio structure
- 5ks ACIS-S snapshots to detect strong X-ray jets
- New optical and radio observations
- Sources selected for follow-up study

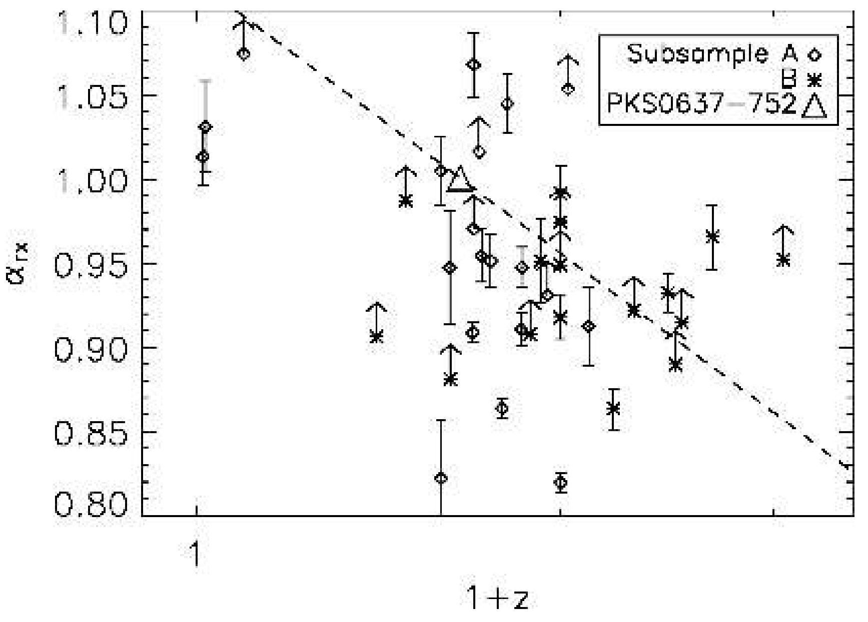
Our multiwavelength survey



(Marshall et al., 2005, ApJS 156, 13)

- Results on first 20 Chandra targets published this year
  (Marshall et al., 2005, ApJS 156, 13)
- 12/20 jet detections (9/10 A, 9/16 B)
- All X-ray jets are one-sided; varied morphologies
- IC-CMB implies B ~ 1-10 μG
  (Γ = 10 assumed)
- Insufficient data to rule out alternative models

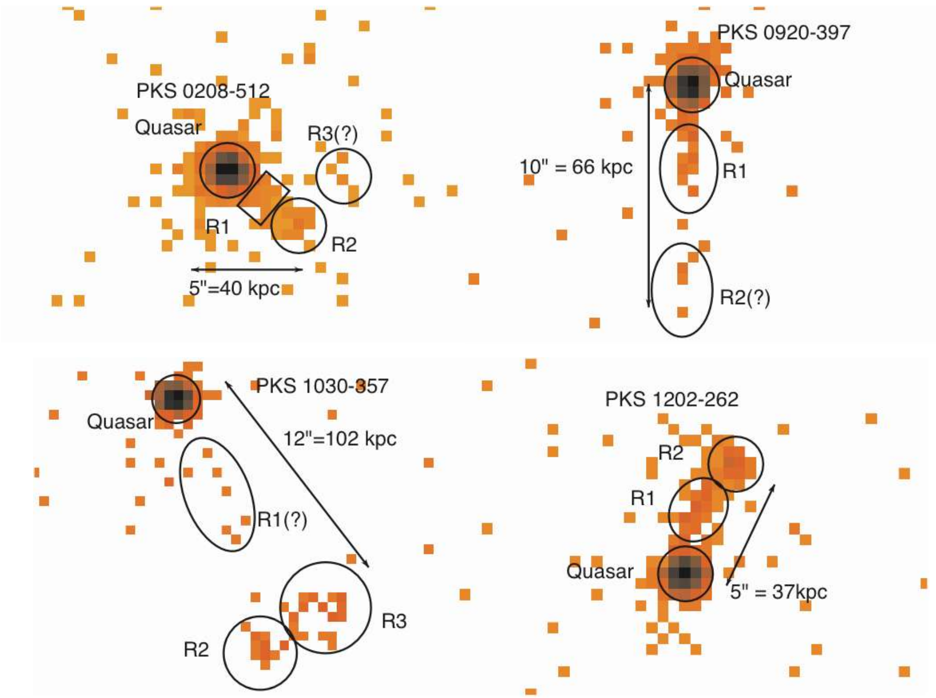
Our multiwavelength survey



Marshall et al., in prep.;
See Marshall et al. poster for more

- Now have 37 Chandra observations
- 22/37 jet detections
- Finding more unusual systems
- Trouble for IC-CMB? S_r/S_x should decrease with increasing z…

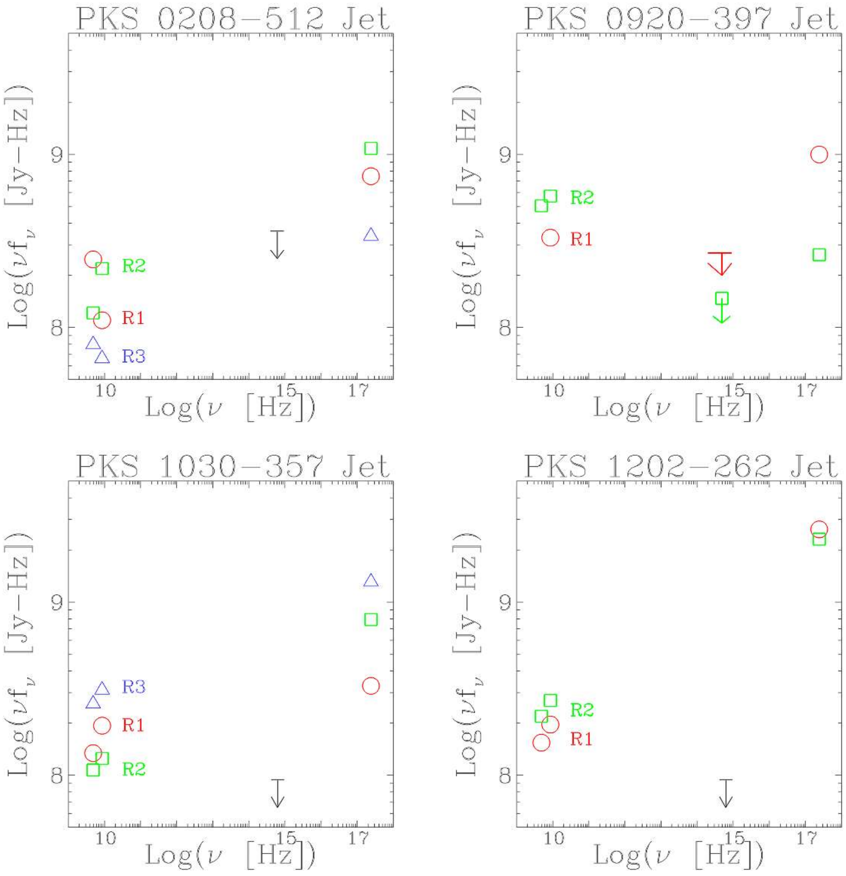
Our multiwavelength survey



- Highest S/N snapshots examined more carefully
- Distinct jet regions compared
  - Less blending of disparate regions
  - Test for evolution along jets

Schwartz et al 2005, submitted to ApJ

Our multiwavelength survey



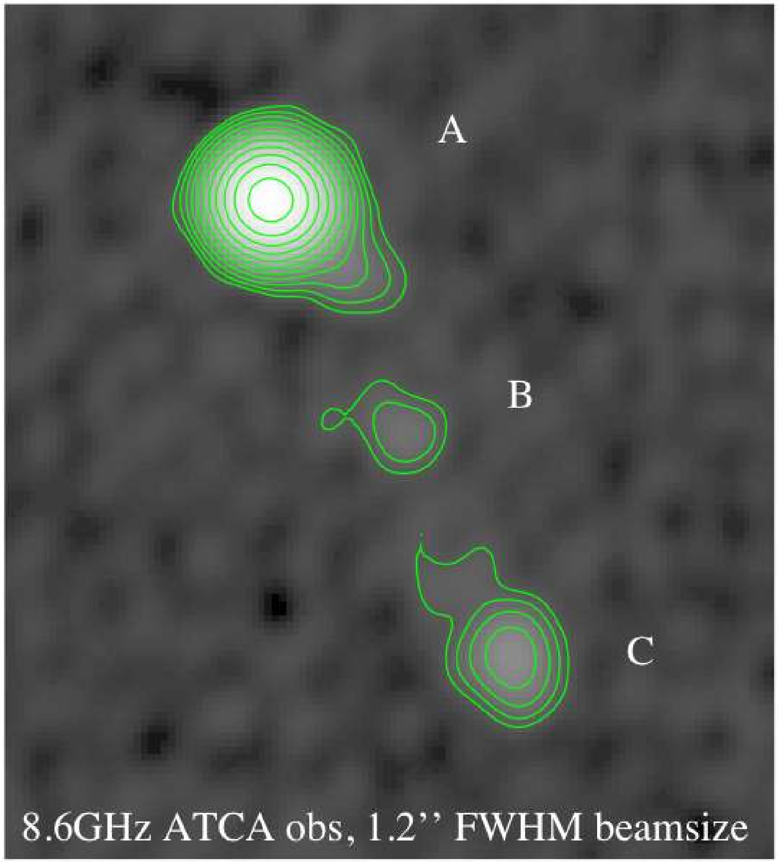
Schwartz et al 2005, submitted to ApJ

- Low optical fluxes generally rule out synchrotron X-rays from a single e^- distribution
- IC-CMB models yield B ~ 10 μG, δ ~ 5-10, θ < 10°, γ_{min} ~ 50; radiative efficiency ~ 10^4
- Some evidence of deceleration along jets

Follow-up observations

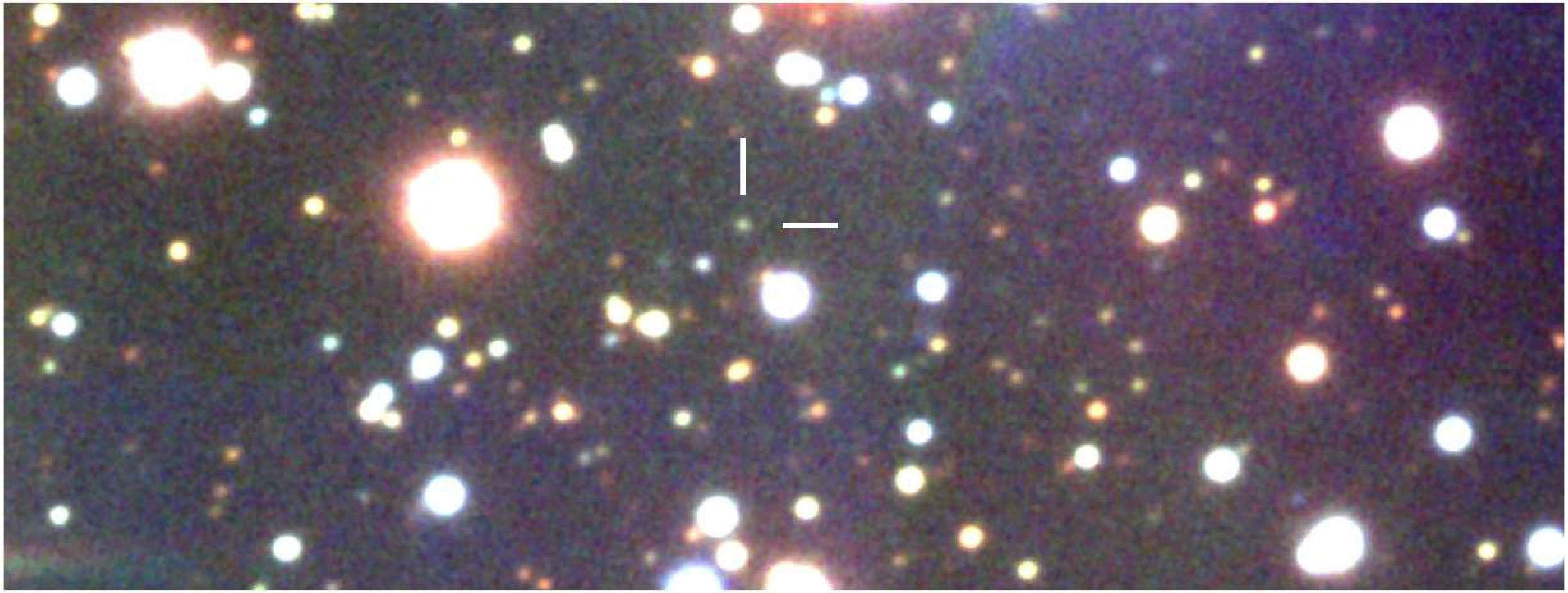
- Sources selected from our snapshot survey
- New Chandra observations ~10× deeper
- HST and ground-based optical observations
- New radio maps

Follow-up target: PKS 1421-490



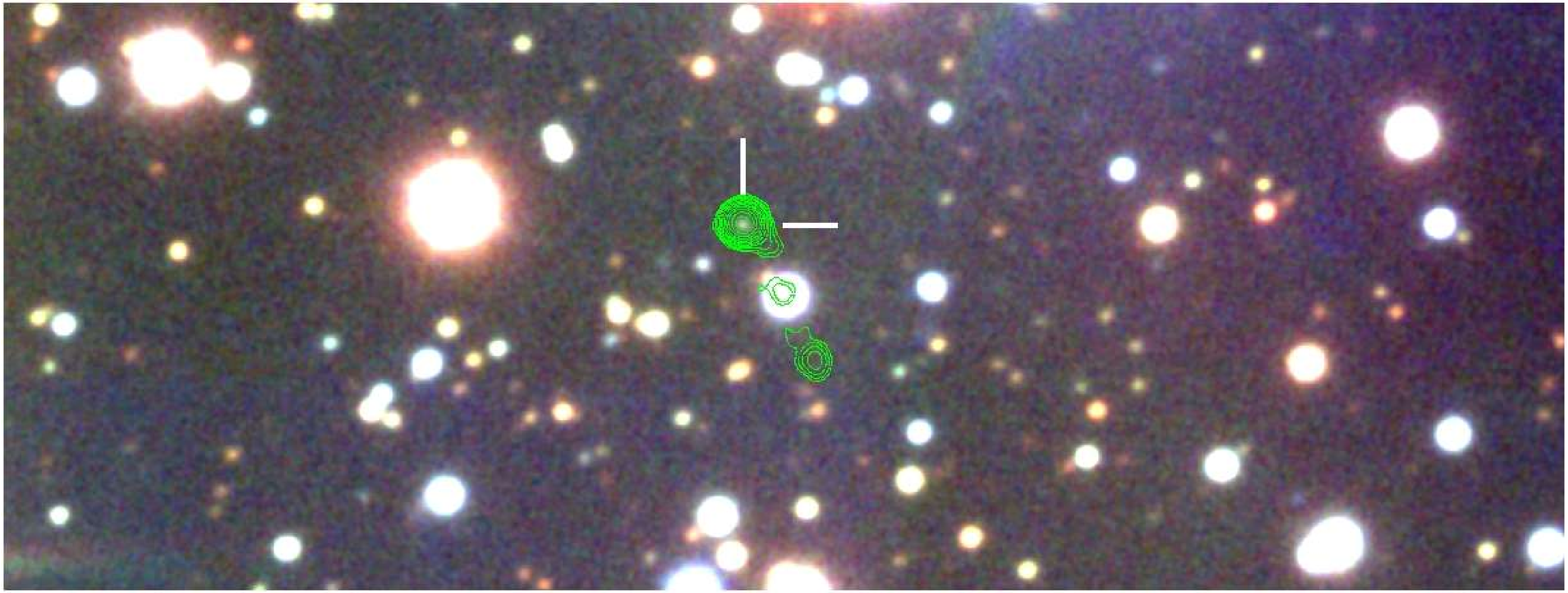
- Strong radio source
- Our only sample member without a prior identification
- Low Galactic latitude (10.9°)

PKS 1421-490



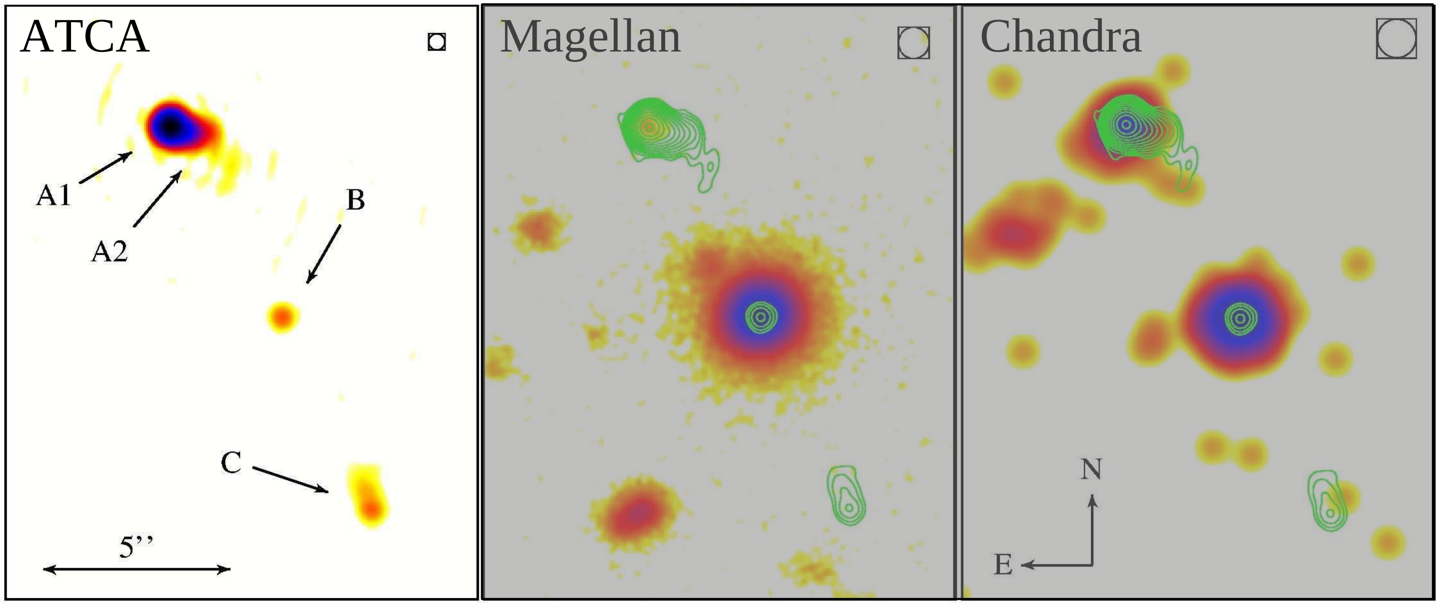
- Magellan g’-r’-i’ true-color image
- g’=24.2, i’=23.0 source at coordinates of A
- Radio source B coincides with g’=17.8, i’=17.2 object

PKS 1421-490



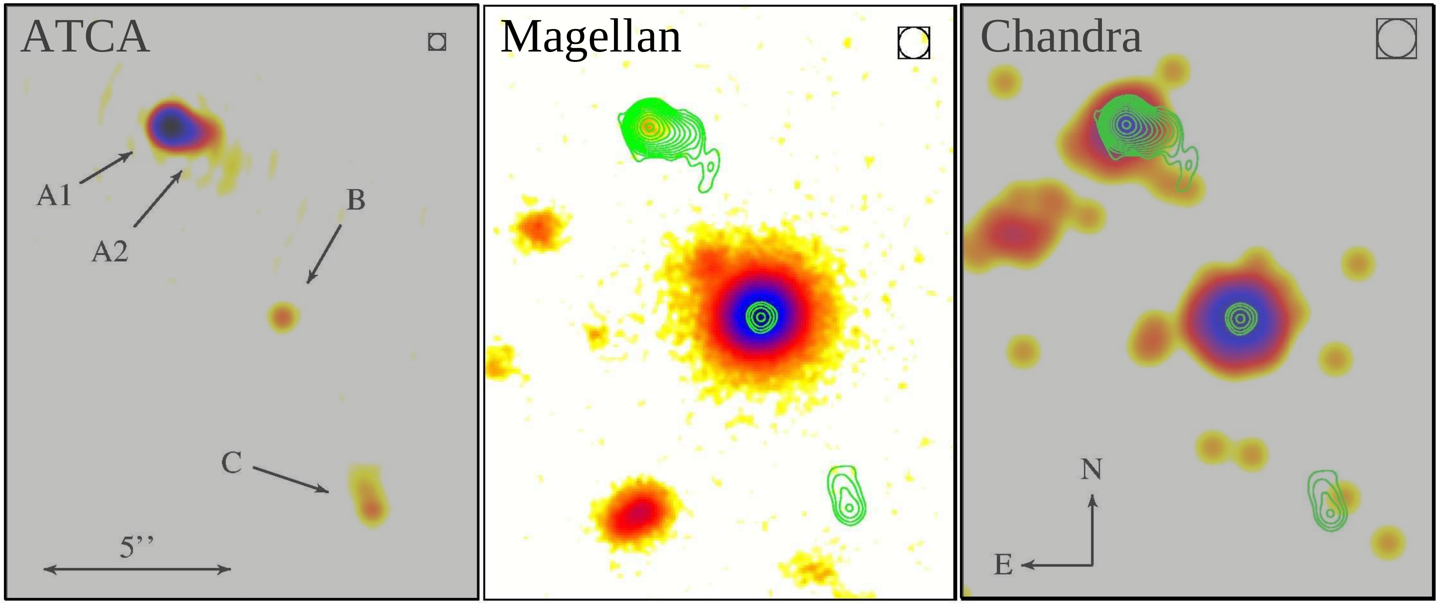
- Magellan g'-r'-i' true-color image
- g'=24.2, i'=23.0 source at coordinates of A
- Radio source B coincides with g'=17.8, i'=17.2 object

PKS 1421-490 observations



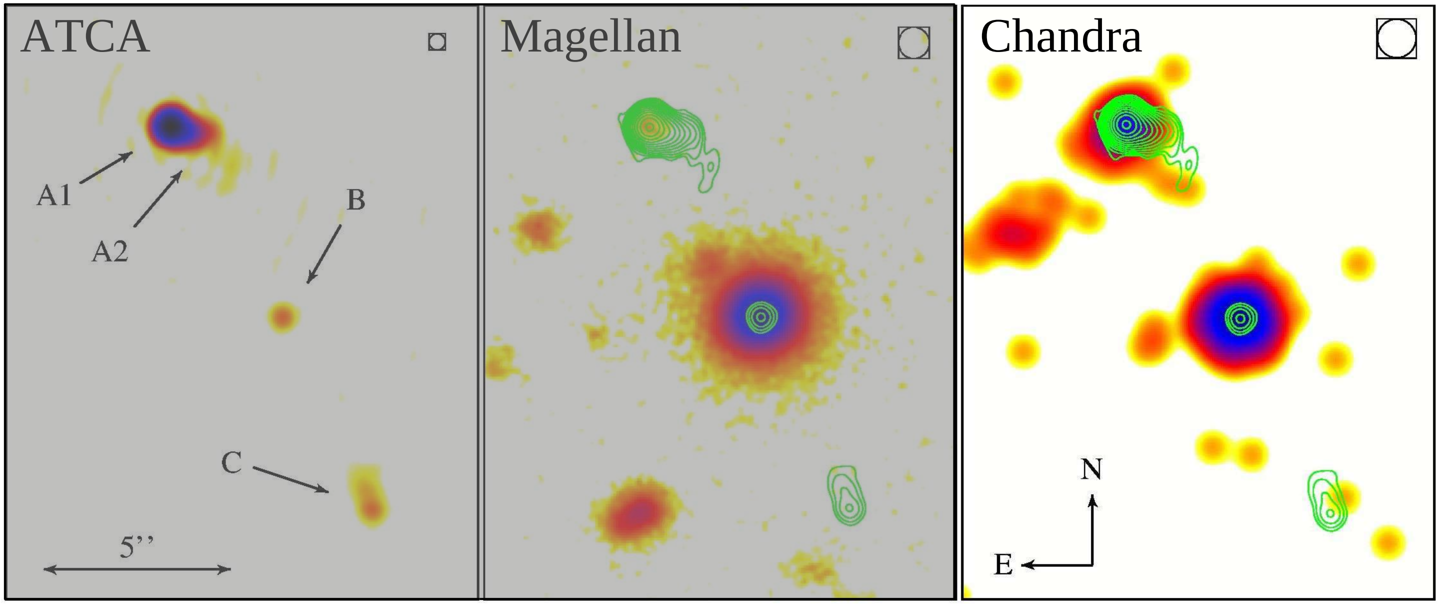
- 20 GHz radio map shows structure:
  - Strongest component is unresolved (A1) with a ~1” extension (A2)
  - Component B lies 6” SW of A; it is slightly extended
  - Component C is 12” SW of A; it is clearly extended

PKS 1421-490 observations



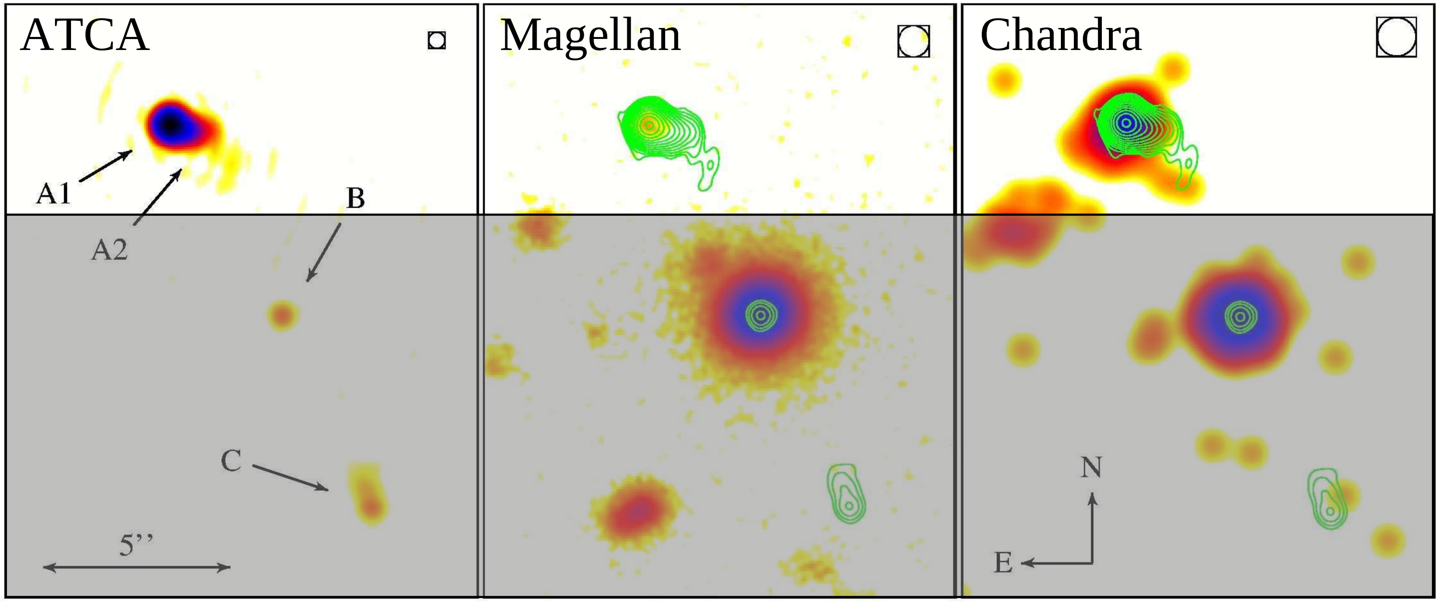
- Optical image (SDSS i' filter):
  - A (i' = 23) and B (i' = 17) are both detected; unresolved
  - B/A flux ratio is ~300
  - C is undetected

PKS 1421-490 observations



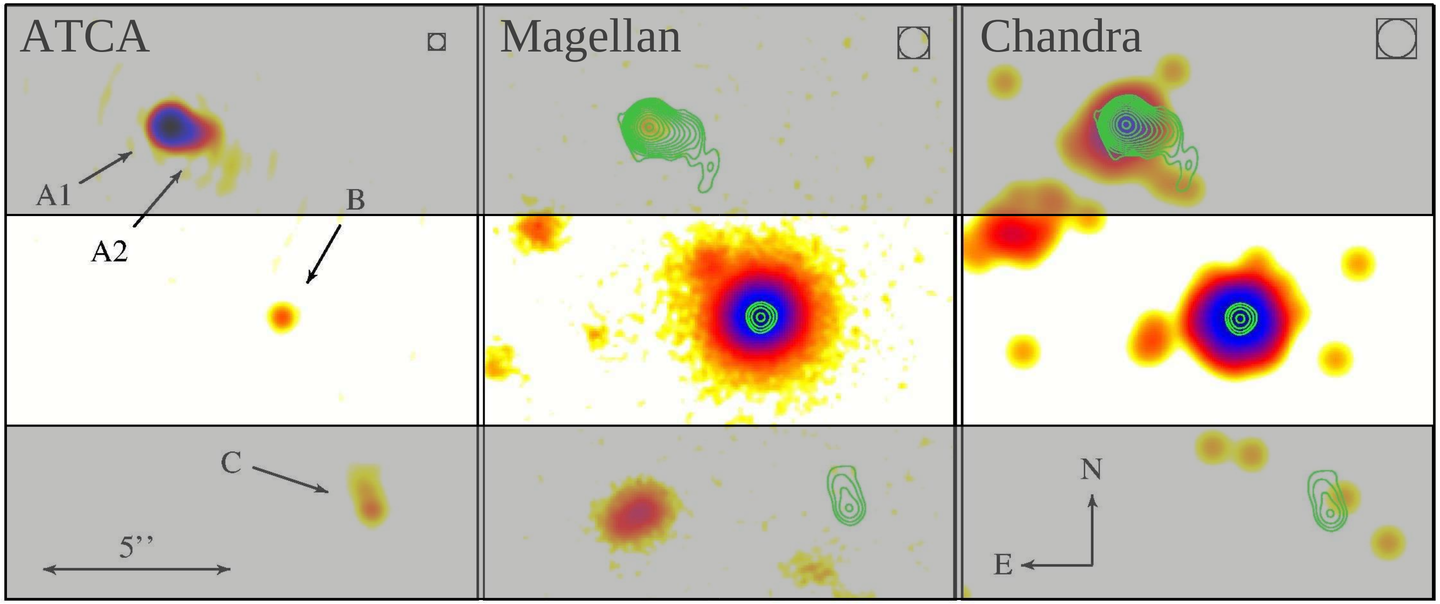
- 0.5-7.0 keV X-ray image:
  - A and B are both detected; unresolved
  - B/A flux ratio is 3.7
  - C is undetected

PKS 1421-490 components



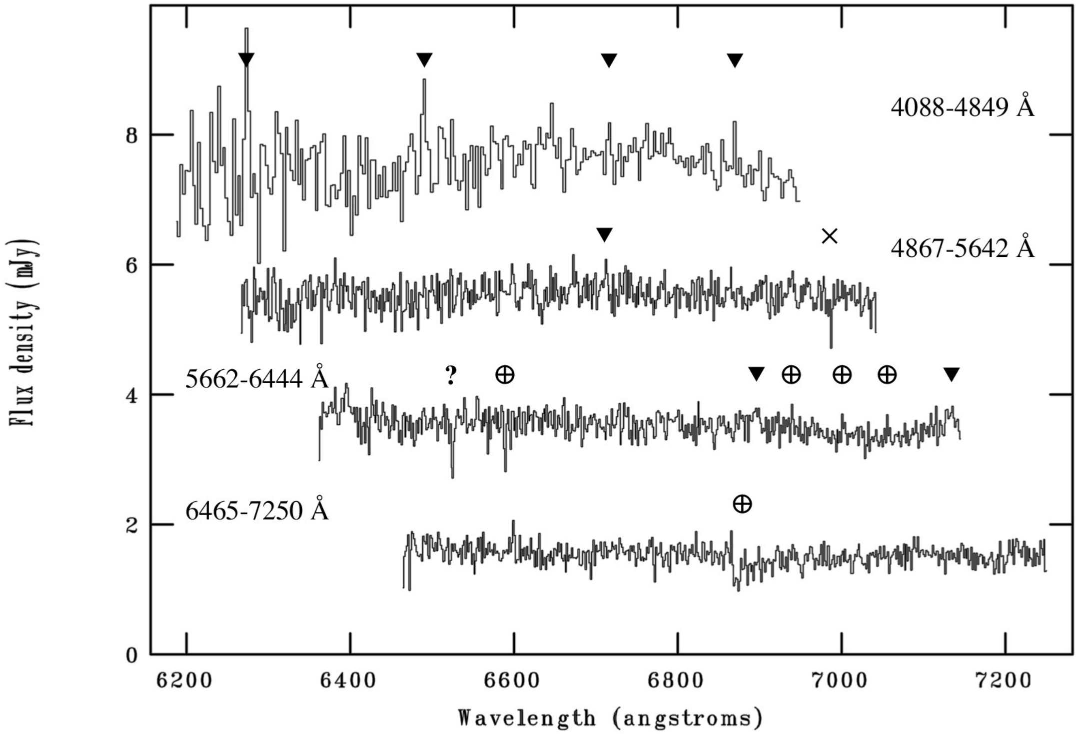
- Properties of A:
  - Flat radio spectrum: $\alpha_r = 0.448 \pm 0.005$ (where $S_\nu \propto \nu^{-\alpha}$)
  - A1 and A2 resemble a core + jet; α_r of A2 is steeper than that of A1
  - VLBI: formally unresolved (< 24 mas) at 8.425 GHz; provides 35% of overall flux (35% of blend of A1, A2, and any diffuse flux at 8.5 GHz)
  - Bluer than stars in surrounding field (g'-i' = 0.76; $\alpha_o = 1.5 \pm 0.7$)

PKS 1421-490 components



- Properties of B:
  - Even flatter radio spectrum: $\alpha_r = 0.05 \pm 0.10$
  - Resolved in radio band; no VLBI data (yet)
  - Optically-dominated SED: $\alpha_{ro} = 0.20$ $\alpha_{ox} = 1.62$
  - Flat optical spectrum lacking strong lines ($\alpha_o = 0.22 \pm 0.23$; g'-i' = 0.11)

Magellan spectrum of 1421-490B



Legend:

"?" = Tentative absorption feature at 5825Å

"⊕" = telluric residuals

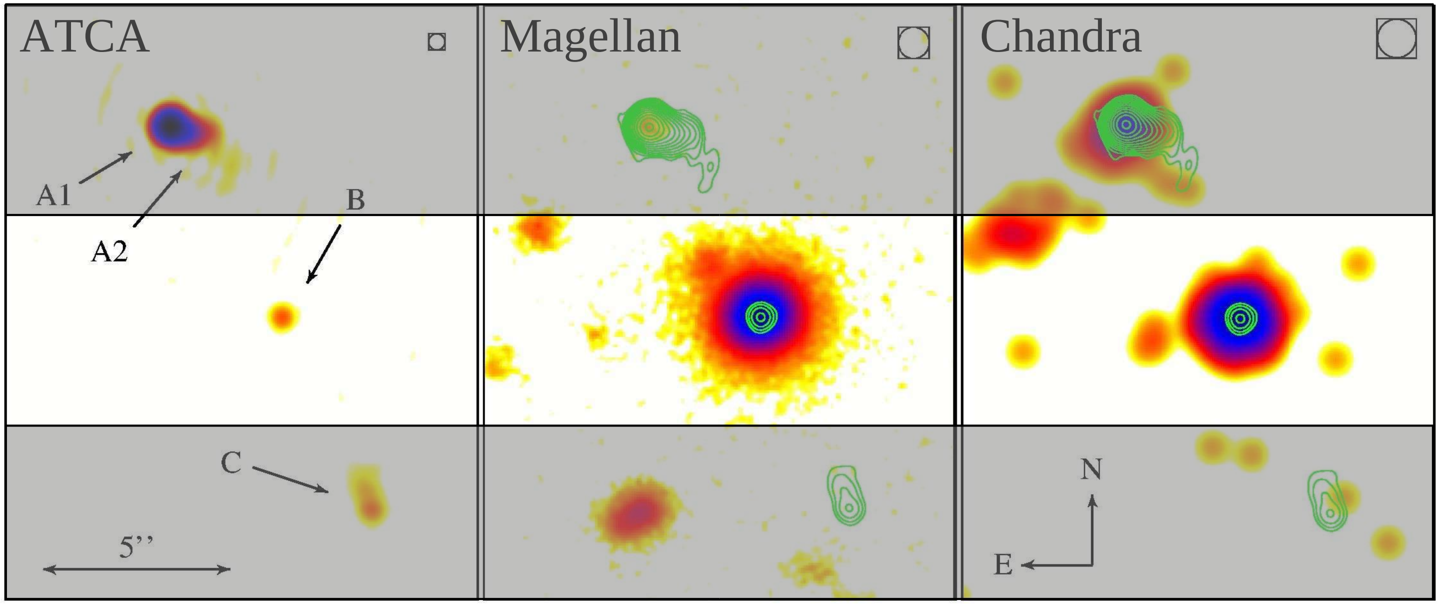
"▼" = cosmic ray residuals

"×" = a bad column

From the top down, spectra are shifted by 2100, 1400, 700, & 0 Å; 6, 4, 2, & 0 mJy

- No strong lines in optical spectrum of B (S/N ~ 8)
- The presence of a Lyman forest below $\lambda > 4370$ Å is ruled out, requiring that B have $z < 2.6$

PKS 1421-490 components



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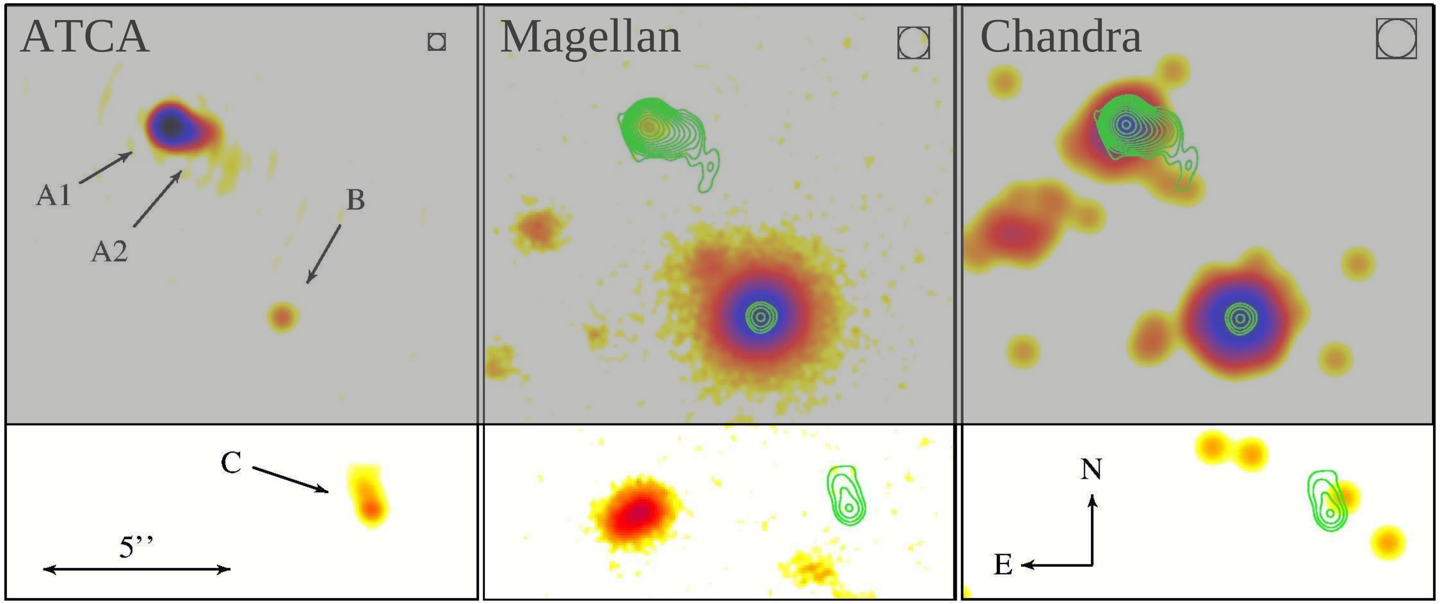
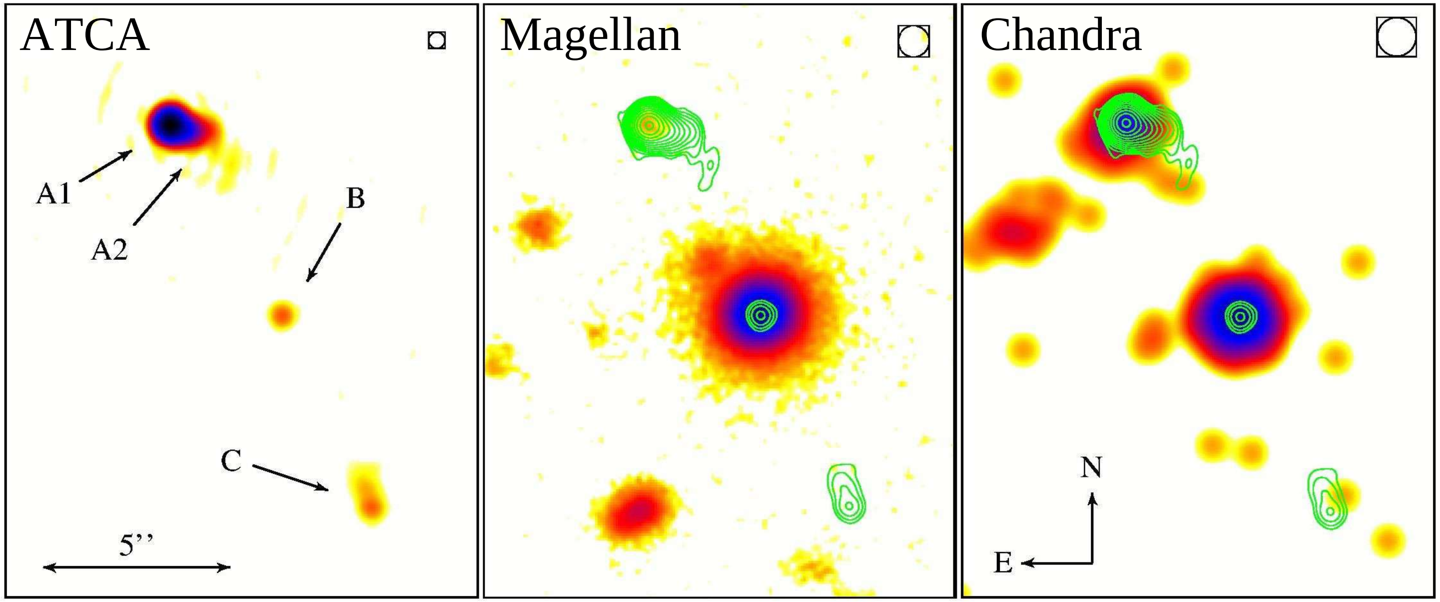
PKS 1421-490 components



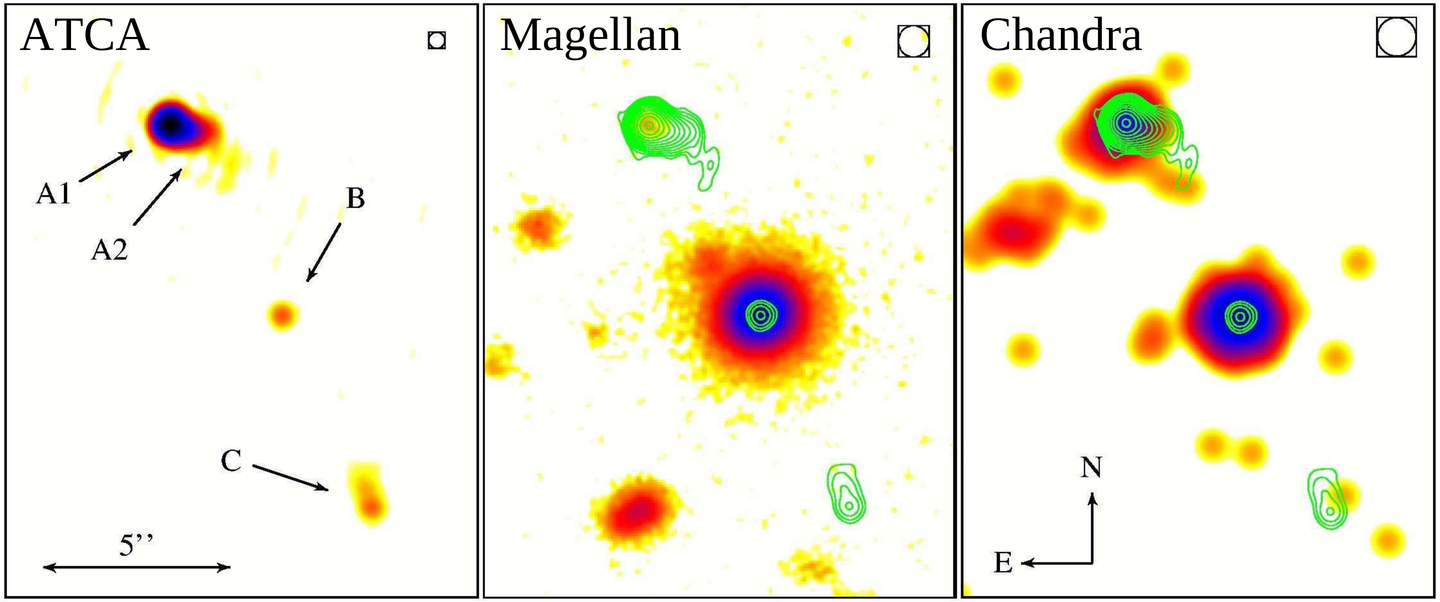
- Properties of C:
  - Steep radio spectrum: α_{xy} = 1.15 ± 0.03
  - Well-resolved radio structure
  - No optical or X-ray emission

PKS 1421-490 interpretations



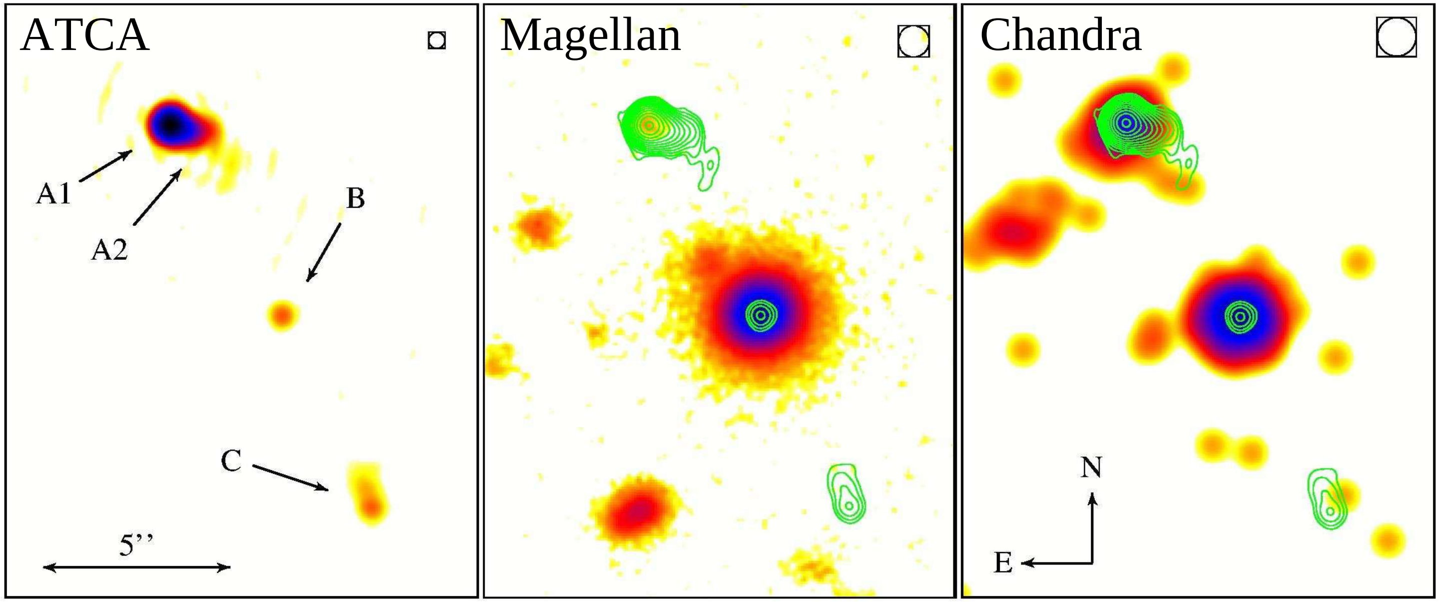
- Possibly a one-sided core-jet system:
  - core at VLBI component within A1
  - jet through A2
  - jet knot at B - a very unusual knot…
  - terminal hot spot at C

PKS 1421-490 interpretations



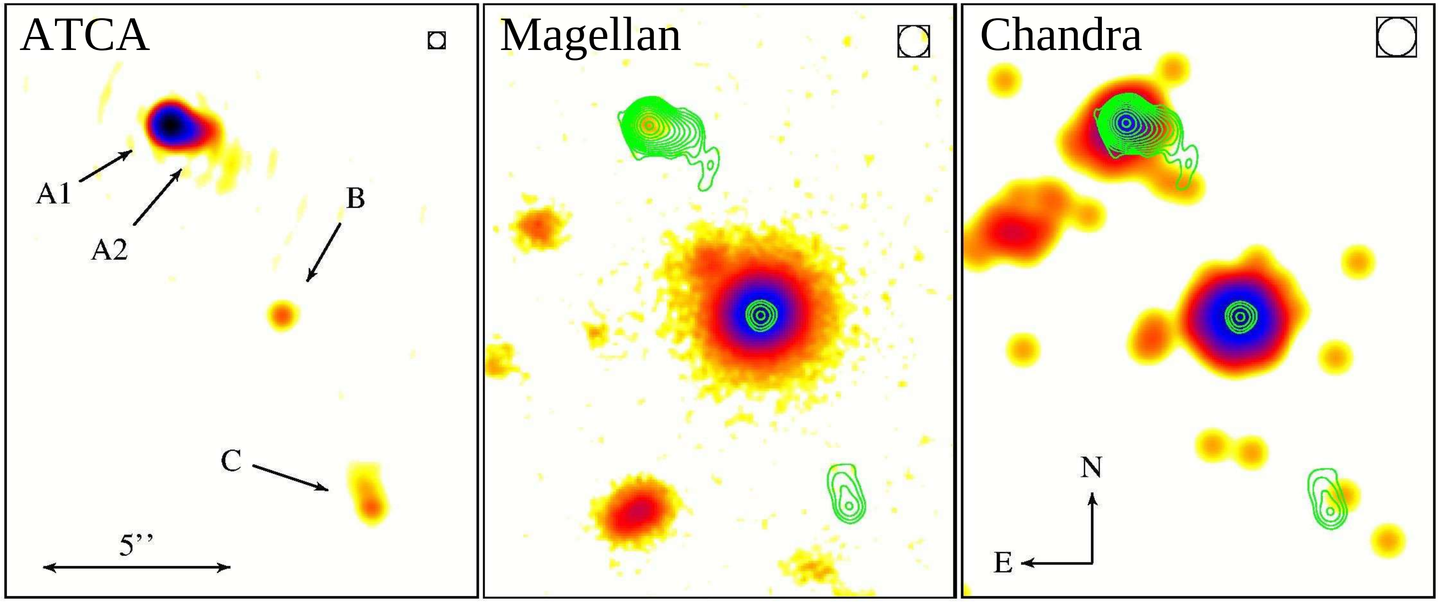
- Possibly a one-sided core-jet system:
  - Pros: VLBI hints at core-jet morphology within A1; explains flat radio spectrum at A1, steeper spectrum at A2; predicts featureless optical spectrum at B
  - Cons: knot B with optically-dominated, flat spectrum is unprecedented; optical knot-to-core ratio ~ 300 would be unique

PKS 1421-490 interpretations



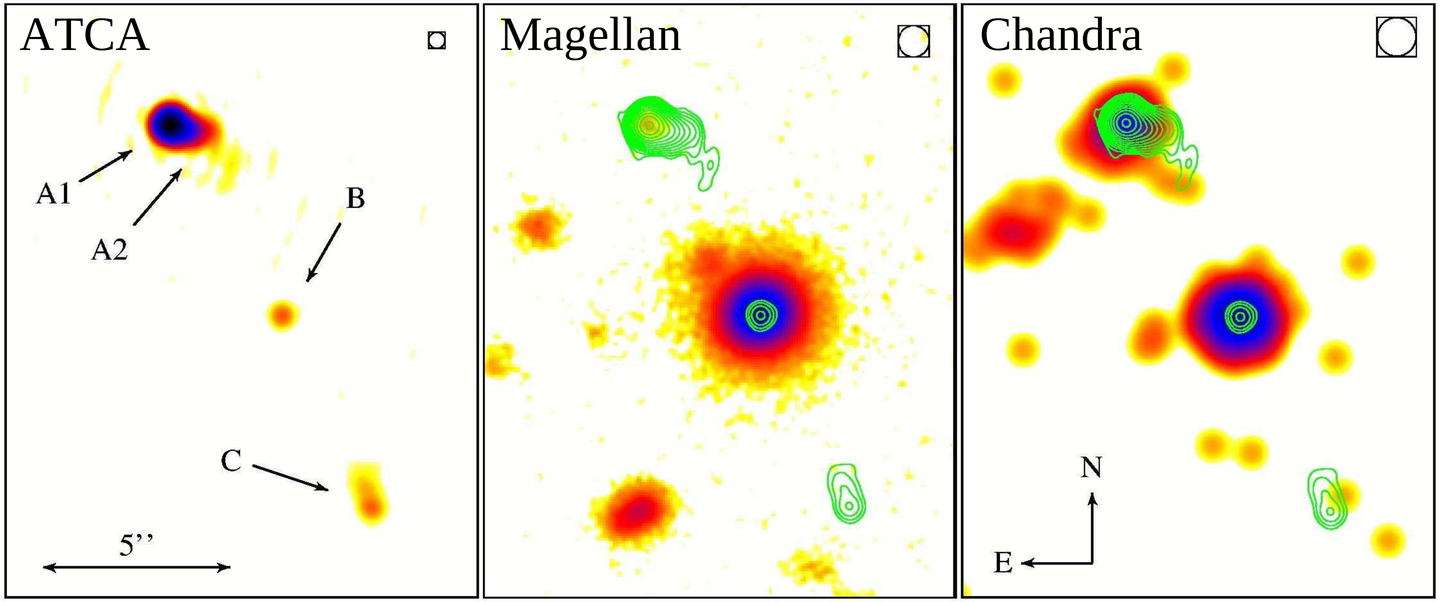
- Alternative interpretation: core at B, hotspots at A & C
  - Pros: radio spectrum, strong optical emission of B more like a core
  - Cons: trades a problem at B (knot with very flat spectrum) with multiple problems at A (flat spectrum at hot spot A; >1/3 of lobe flux in core-like VLBI component) and problem of ID of B (no evidence of host galaxy in optical spectrum; possible contradiction betw. spectrum & photometric z)

PKS 1421-490 interpretations



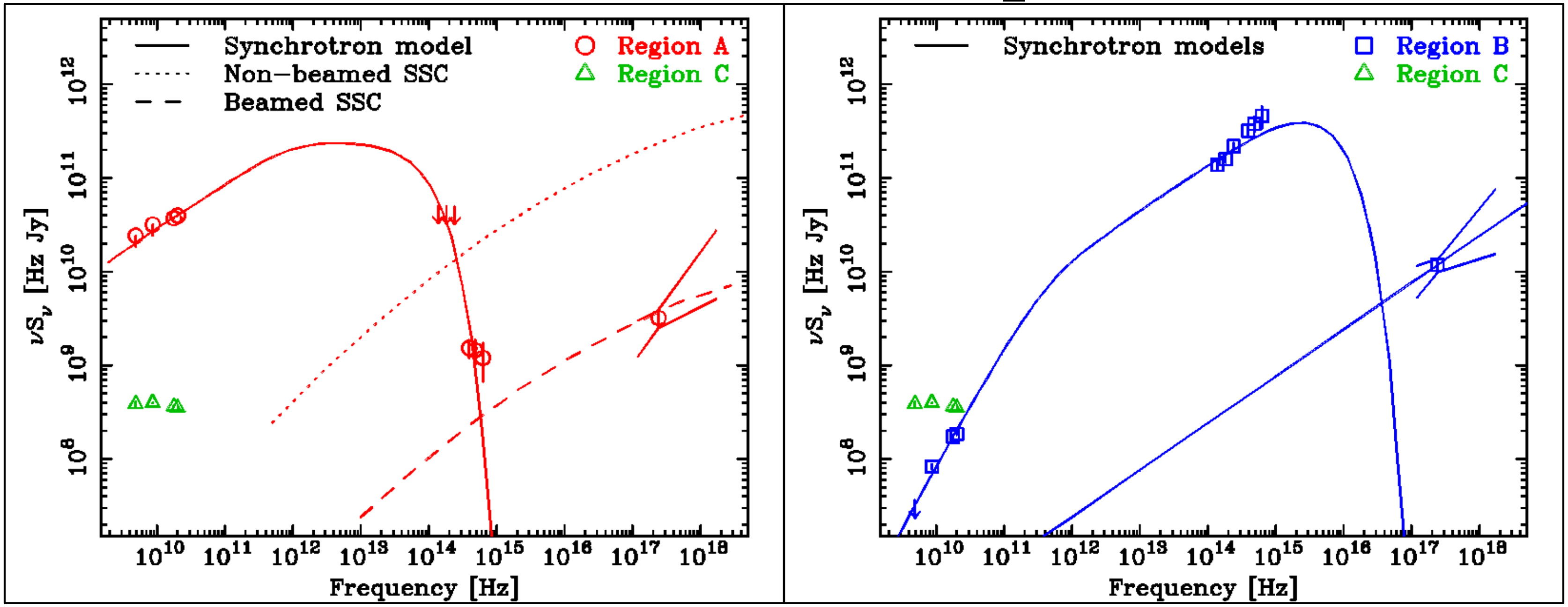
- Alternative interpretation: A & B are distinct objects
  - If B is entirely unrelated to A and C…
    - Featureless optical spectrum rules out stars, normal galaxies, most AGN
    - Not a white dwarf (wrong optical colors; proper motion < 8 mas/yr)
    - BL Lac or weak-lined quasar not ruled out, but such objects are rare and SED properties are extreme for a BL Lac

PKS 1421-490 interpretations



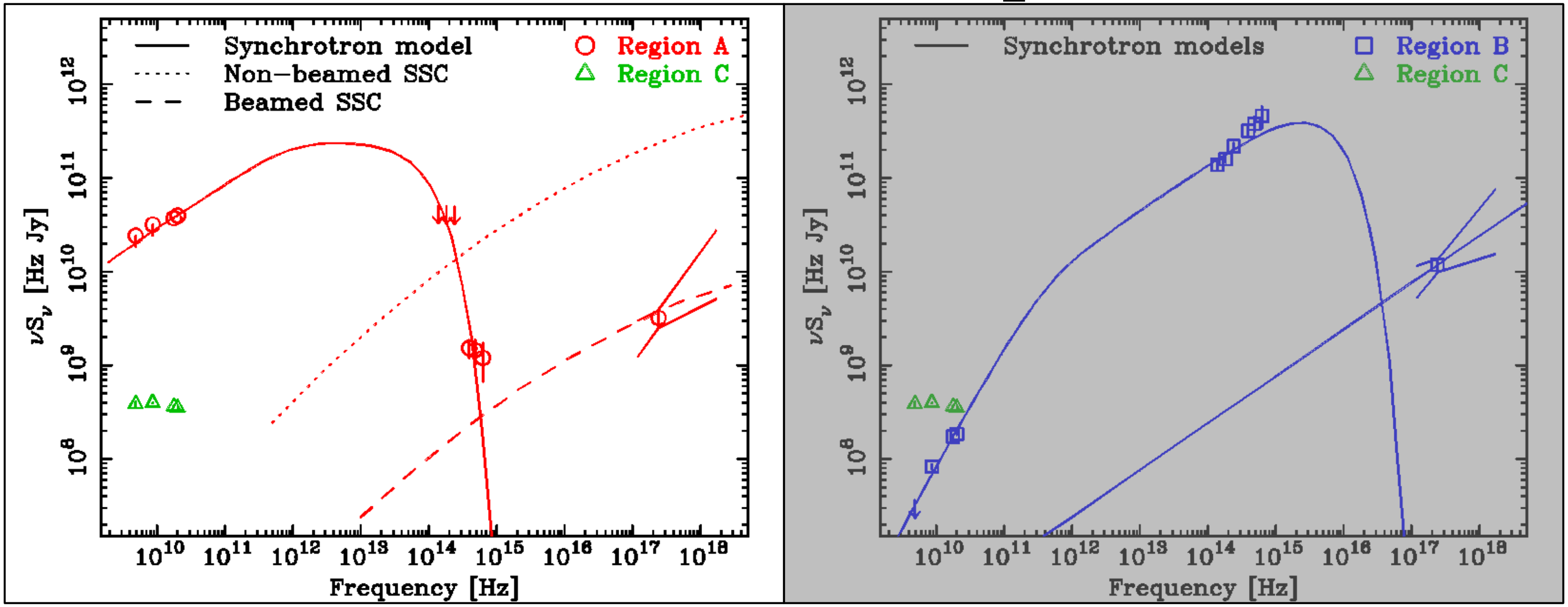
- Alternative interpretation: A & B are distinct objects
  - If B is entirely unrelated to A and C…
    - Chance proximity of $F_x > 4E\text{-}13$ erg/s/cm^2 source improbable (<0.1%); alignment with jet even less likely
  - …but B might not be entirely unrelated
    - A neighbor within a group or cluster?
    - Still must not have strong spectral features…

PKS 1421-490 interpretations



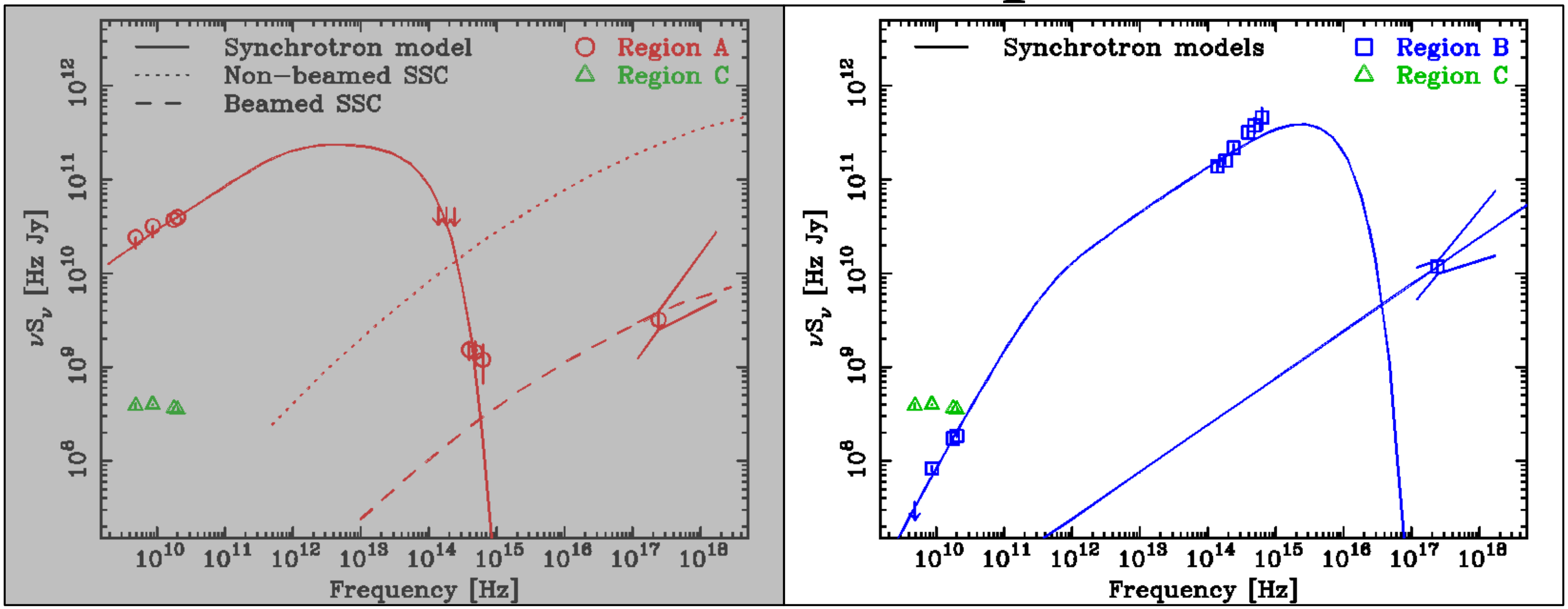
- SED of A is typical of cores
- SED of B is rather core-like, but flat optical spectrum is hard to understand
- SED of C is steeper, typical of terminal hot spots

PKS 1421-490 interpretations



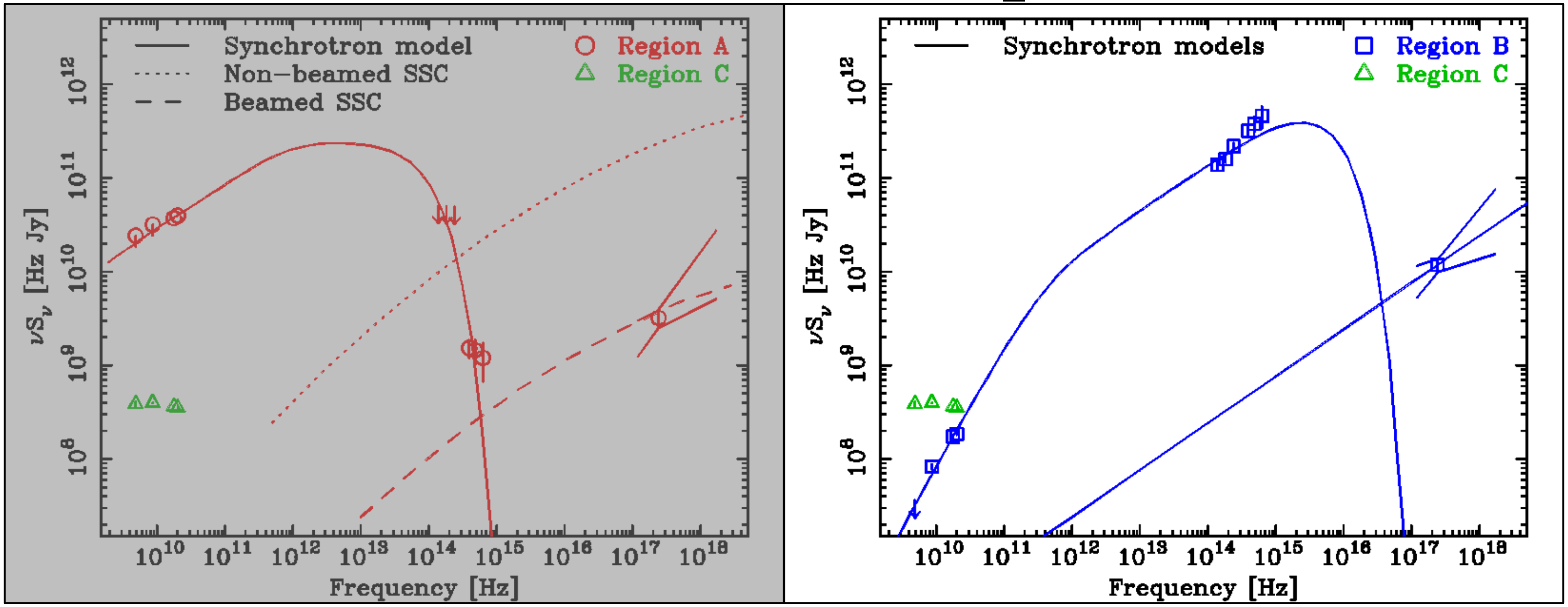
- Emission model for A: synchrotron + beamed SSC
  - Modeled as a jet with $\Gamma = 20$, $\Theta = 2.9°$, r = 0.5 mas = 4 pc. Electron distribution with p = 2.0 from $20 \leq \gamma \leq 1.6 \times 10^3$; p = 3.0 from $1.6 \times 10^3 \leq \gamma \leq 1.6 \times 10^4$.
  - B_{eq} = 13 μG

PKS 1421-490 interpretations



- B as a knot with synchrotron X-rays?
  - Requires $\gamma \geq 10^8$ electrons, but radio-optical synchrotron model (without beaming) requires B = 850 μG, $1.6 \times 10^4 \leq \gamma \leq 2 \times 10^6$
  - Narrow γ range, a second e^- population, and *in situ* acceleration?

PKS 1421-490 interpretations



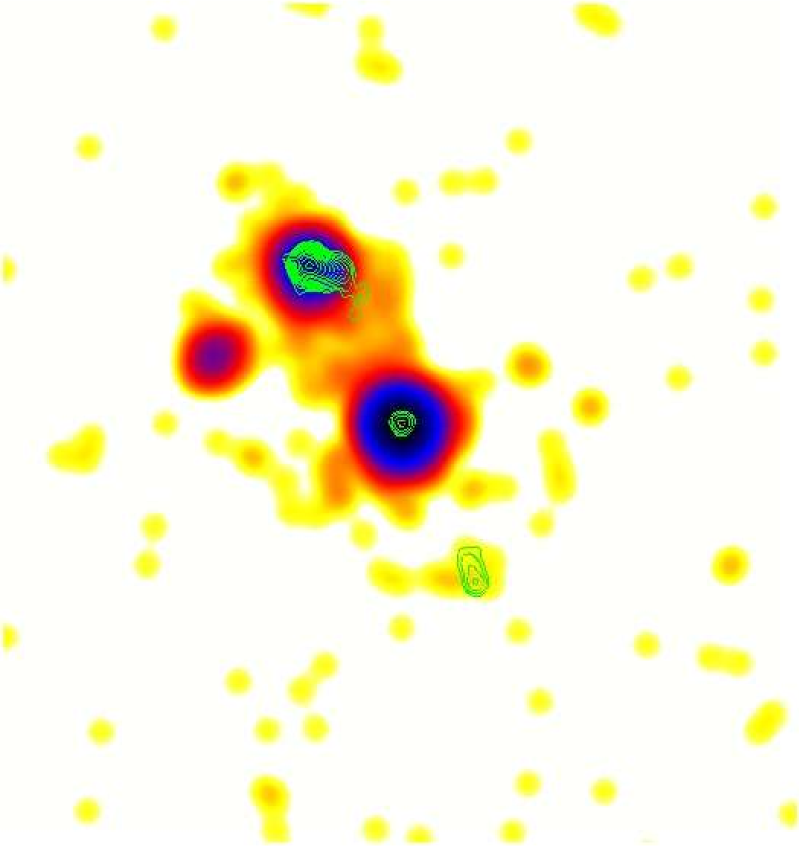
- B as a knot with inverse Compton X-rays?
  - IC-CMB requires $\Gamma > 60$; core model only has $\Gamma = 20$
  - Upstream Compton instead?
  - Both require e^- with $\gamma \leq 100$, but radio model has $\gamma_{min} \sim 10^4$
  - A second e^- population? Self-absorption in a knot??

PKS 1421-490 implications

- Core at A and jet knot at B?
  - Modelling the SED of B is a challenge
  - B likely represents an extreme of jet phenomena
- Core at B and hot spot at A?
  - B must be an unusual, extremely weak-lined AGN
  - Possibly a new type of BL Lac (some similarities to object reported by Londish et al. 2004, MNRAS 352, 903)
- A and B are both cores?
  - Chance alignment highly unlikely
  - Members of same cluster? An interacting system?

More data is needed to determine the right picture.

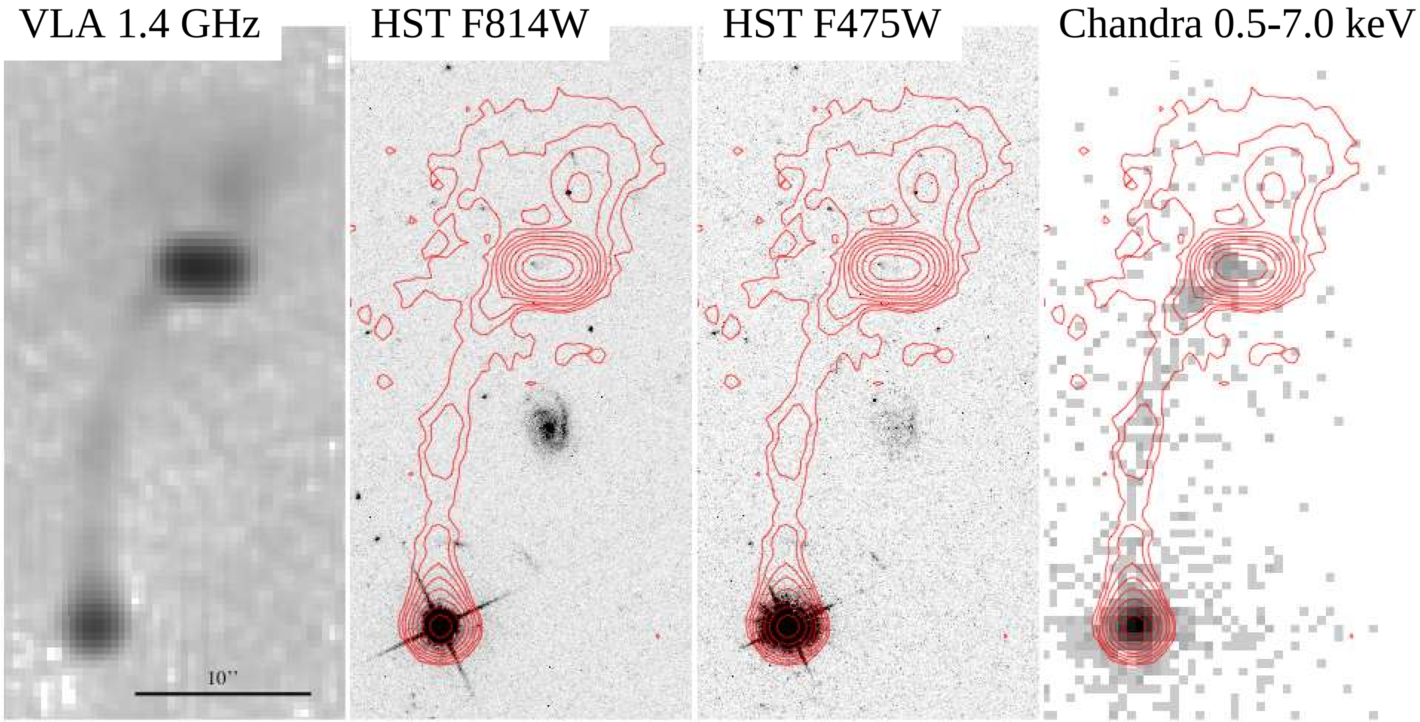
New 1421-490 data



- New Chandra 54ks exposure
- 0.5-7.0 keV image, convolved to 1.2” FWHM
- Broad bridge of X-ray emission between A & B
- No detailed analysis yet

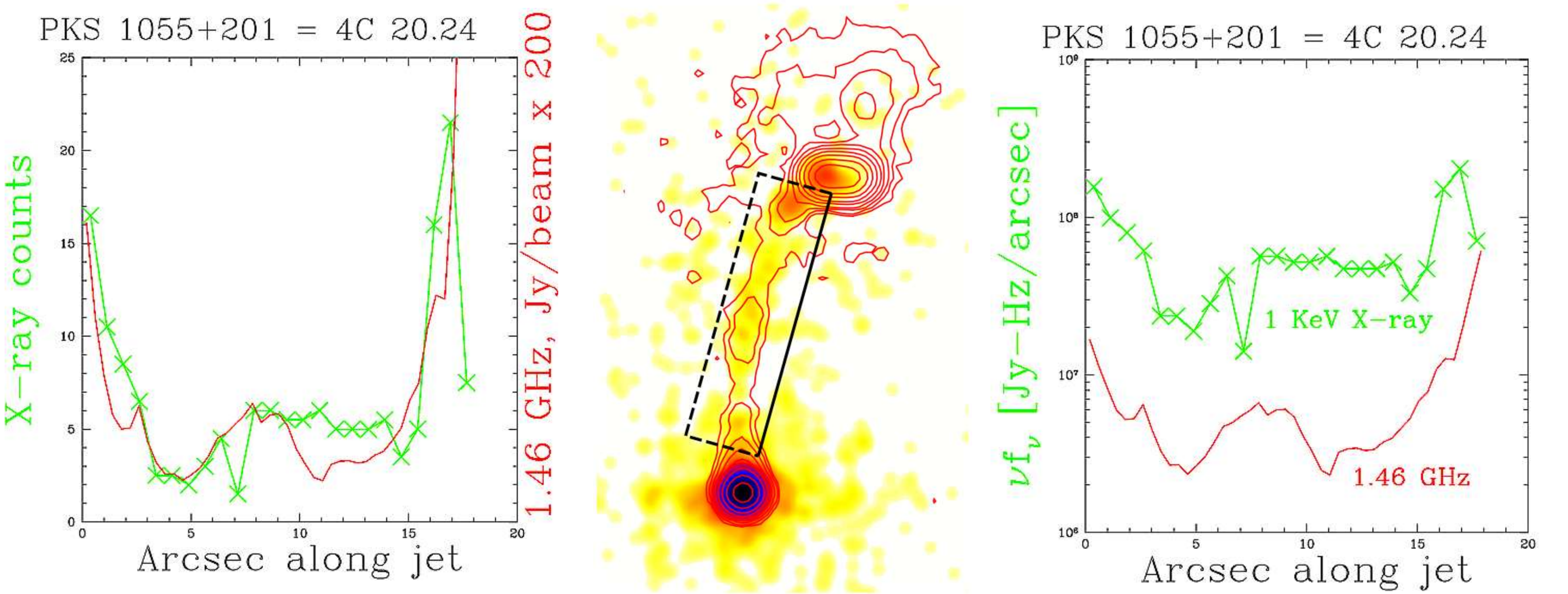
Also pending:
- VLBI map spanning from A to B
- HST imaging
- Deeper Magellan spectroscopy(?)

Follow-up target: PKS 1055+201



- A.k.a. 4C 20.24; $z = 1.110$
- X-rays throughout 21" ($\geq$170 kpc) north jet

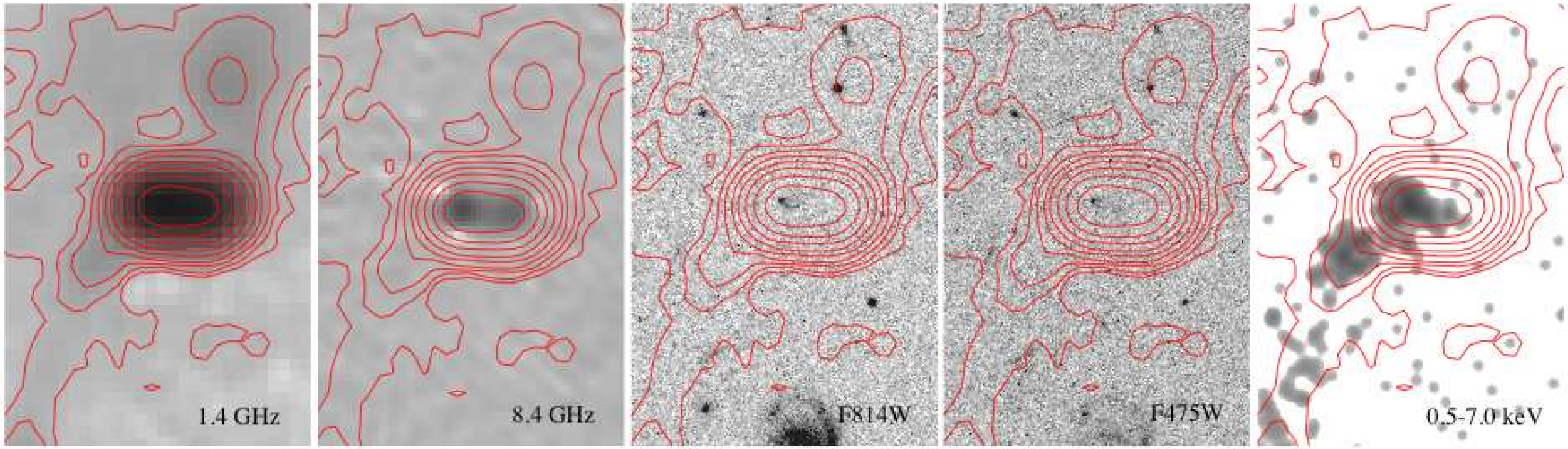
PKS 1055+201: X-ray & radio



- General agreement between radio & X-ray jets; some differences in details
  - Radio peak fades faster than X-ray after 10”: inverse Compton?
  - X-ray peaks faster than radio around 17”

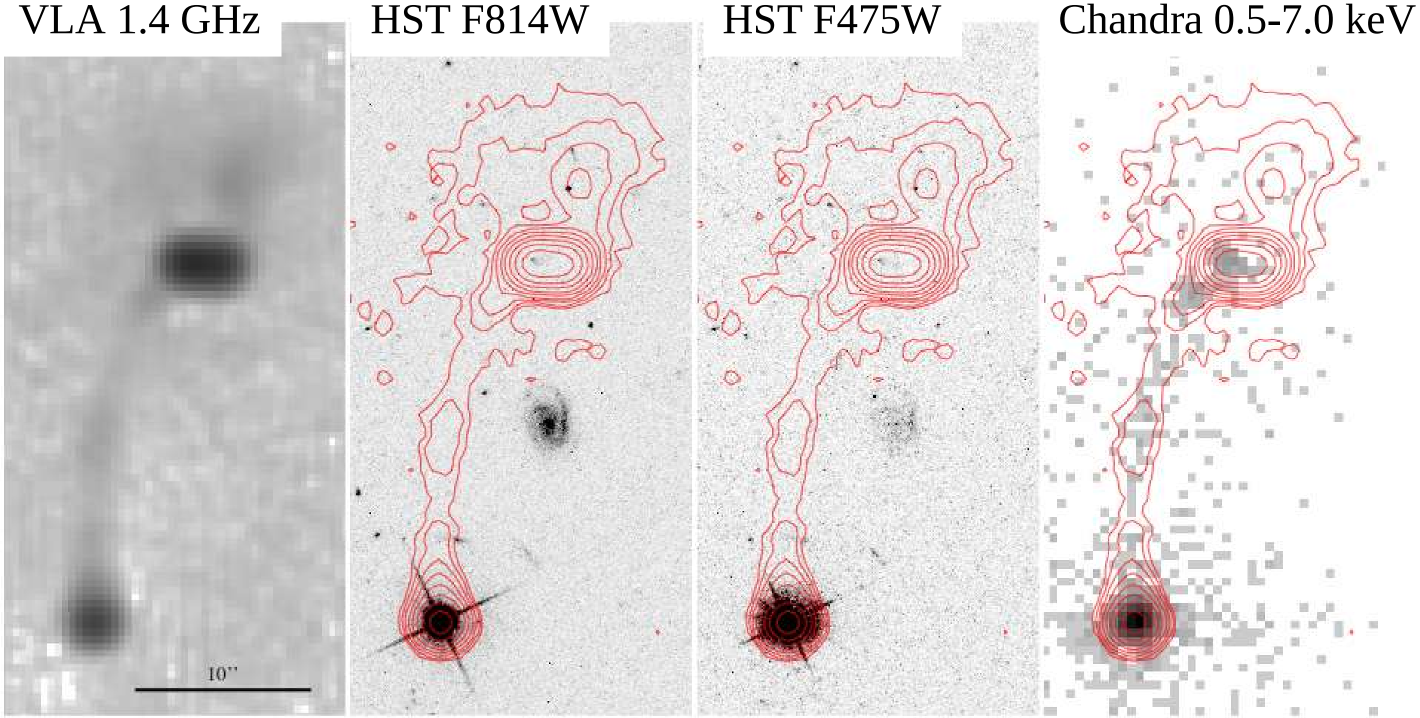
The northern knot of 1055+201

VLA 1.4 GHz | VLA 8.4 GHz | HST F814W | HST F475W | Chandra 0.5-7.0 keV



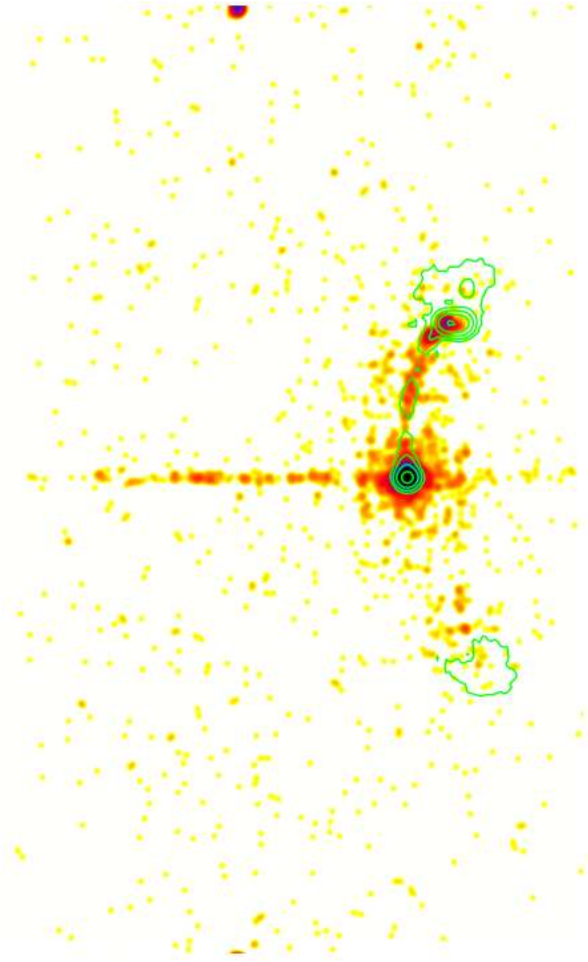
- 8.4 GHz resolves knot
- HST images reveal resolved source
- X-rays strengthen upstream of knot, peak at optical source

PKS 1055+201 jet model



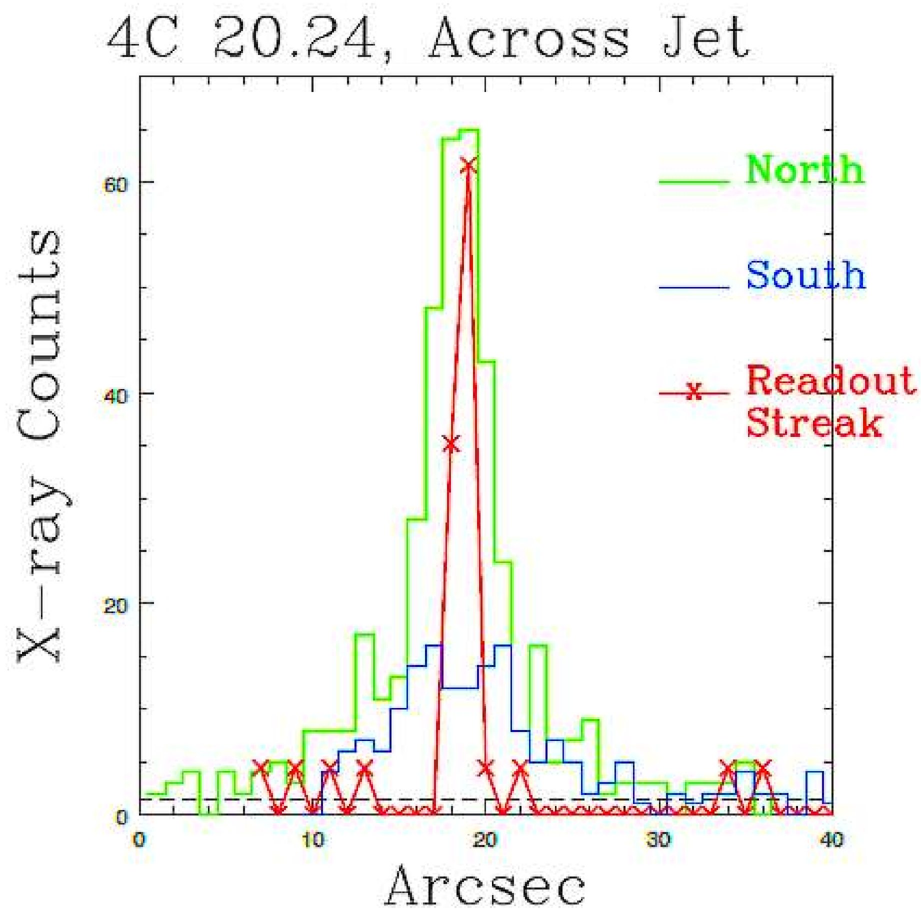
- IC-CMB model can describe integrated jet
- Model parameters: B ~ 10 μG, δ ~ 6, and θ ~ 9°

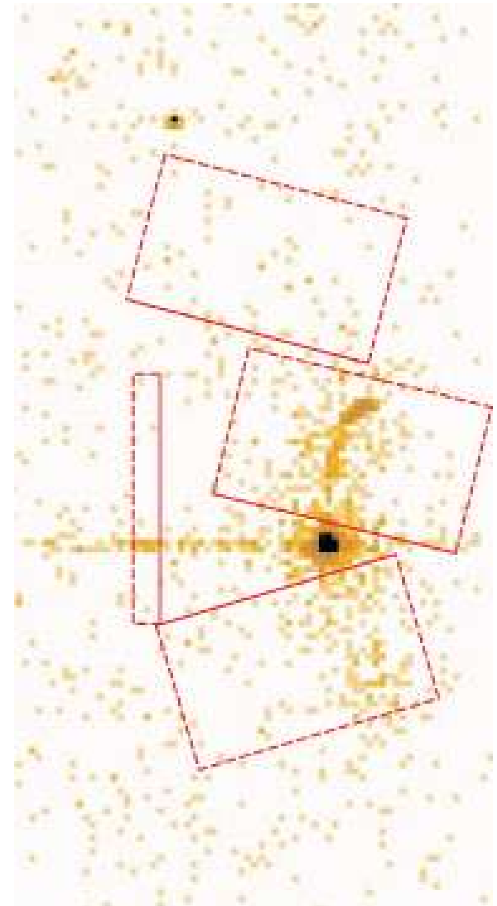
PKS 1055+201 envelope



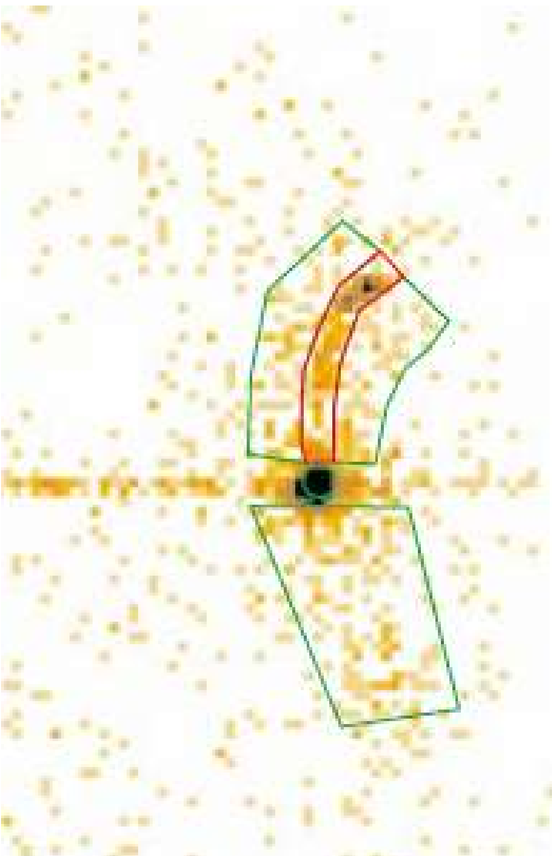
- Extended X-ray emission around north jet, stopping at lobe
- Similar emission between core and south lobe, around unseen counter-jet
- Width: ~15”; length: ~45”
- Direct evidence of the jet heating the surrounding gas

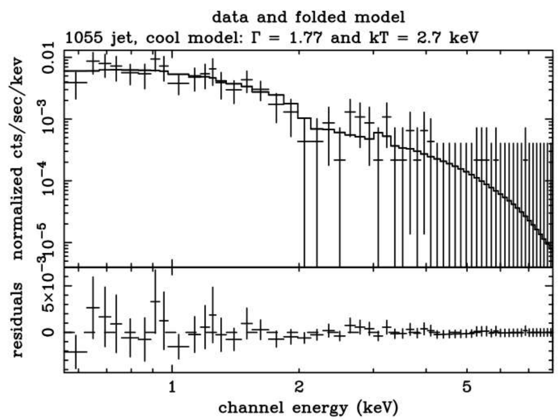
PKS 1055+201 envelope

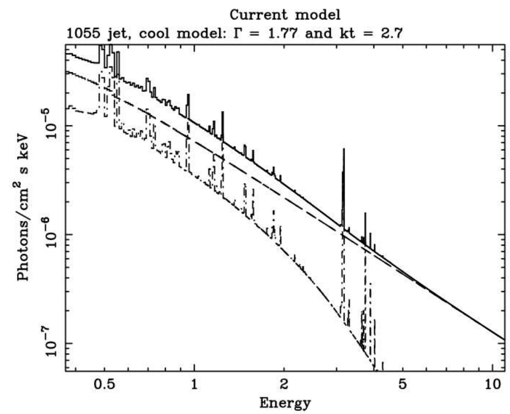




Jet X-ray spectrum



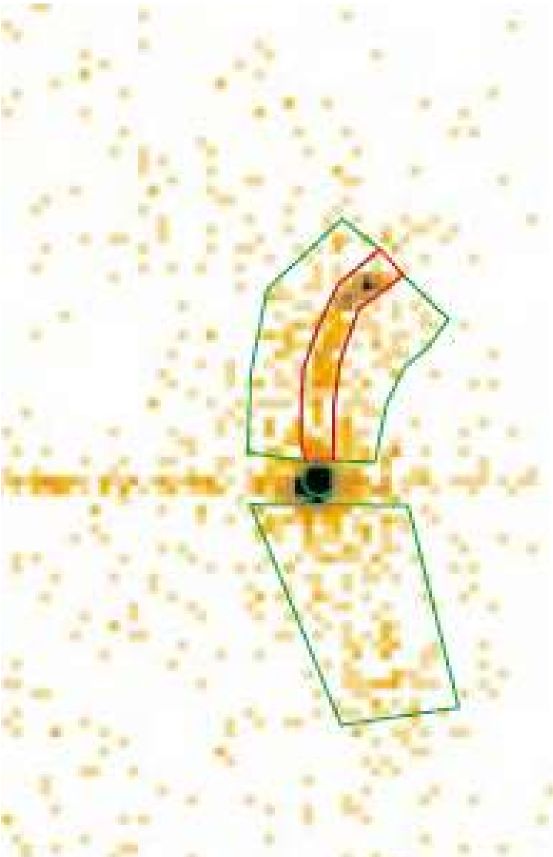


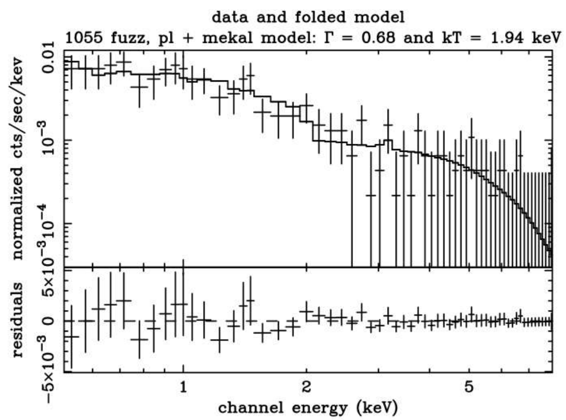


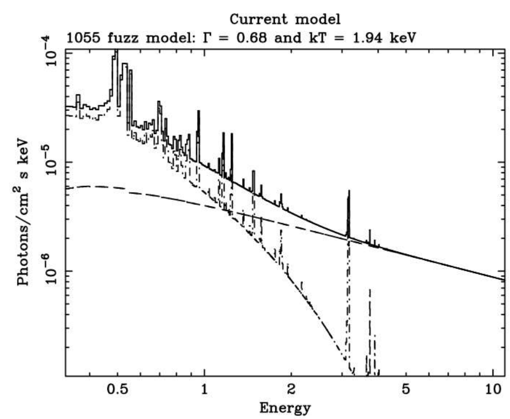
Best-fitting model includes a power law with $\Gamma = 1.8$ and a thermal component with kT = 2.7 keV.

(244 counts)

Envelope X-ray spectrum



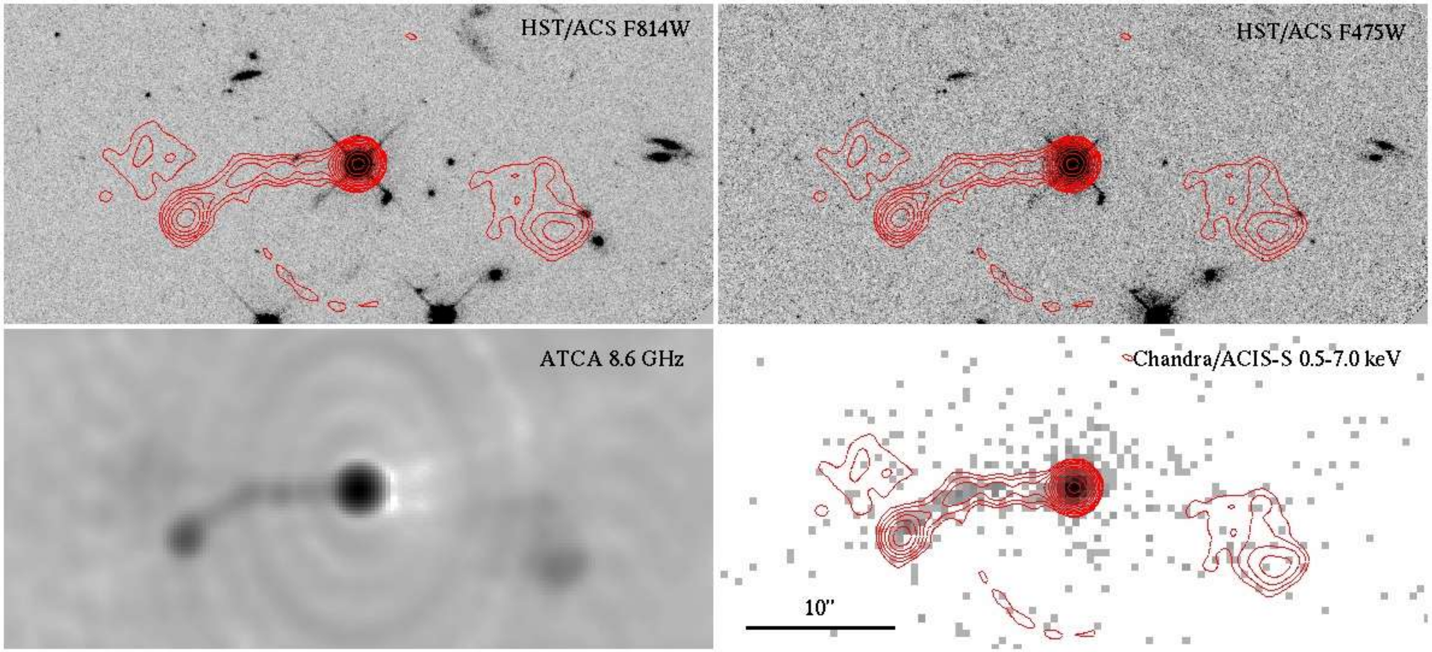




Best-fitting model includes a power law with $\Gamma = 0.7$ and a thermal component with kT = 1.9 keV.

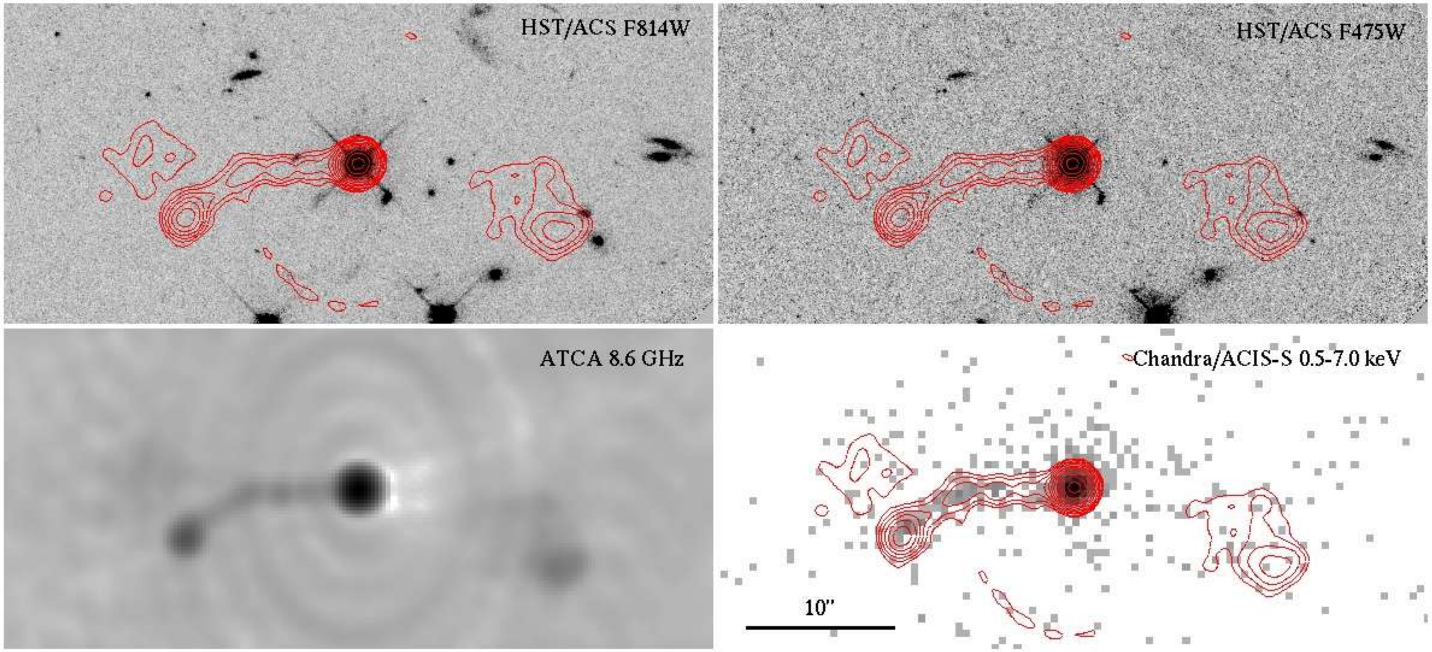
(310 counts)

Follow up target: PKS 2101-490



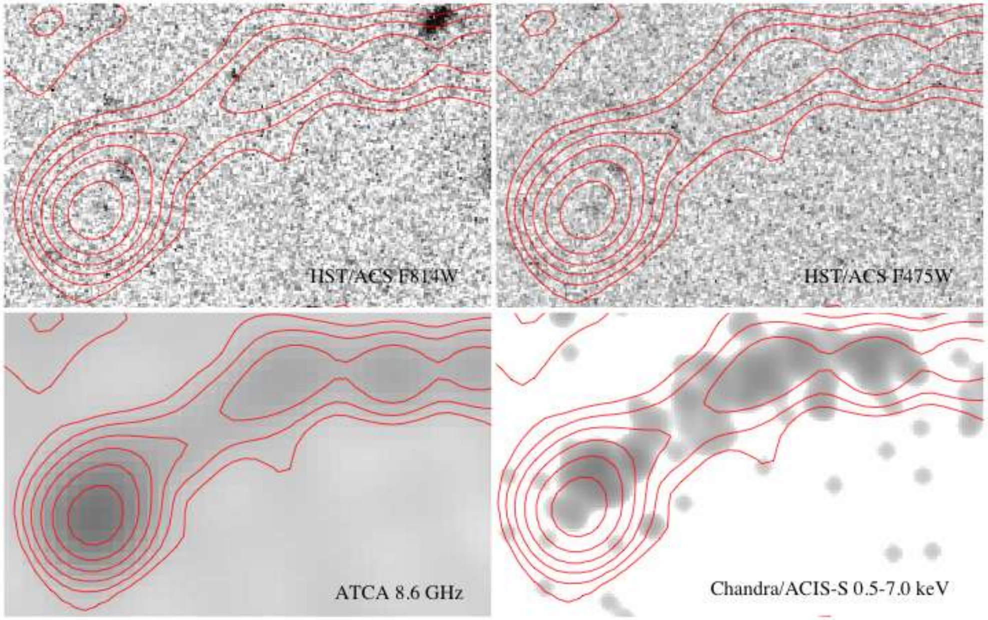
- Quasar at z=1.04 (Gelbord & Marshall, in prep)
- New Chandra and HST observations

Follow up target: PKS 2101-490



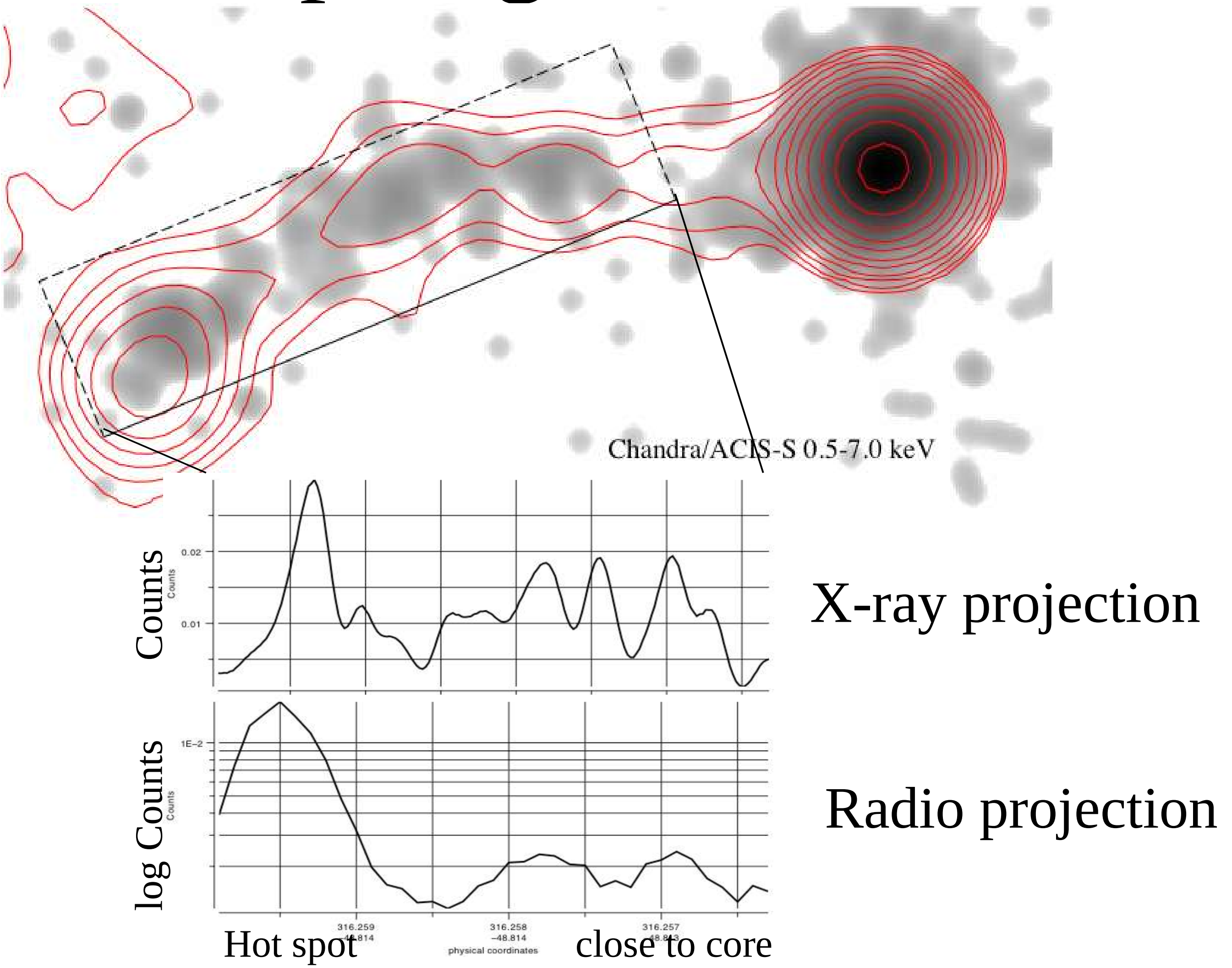
- Similarities with PKS 1055+201:
  - Diffuse X-ray flux around unseen counter-jet
  - HST detection at terminal hot spot

Follow up target: PKS 2101-490



- Similarities with PKS 1055+201:
  - Diffuse flux around unseen counter-jet
  - HST detection at (leading edge of) terminal hot spot

Follow up target: PKS 2101-490



Summary (so far…)

- PKS 1421-490…
  - Knot B pushes the boundaries of known jet phenomena
    - a second e- population with *in situ* acceleration?
    - knot emission from compact, self-absorbed clumps?
  - If not a knot, then…
    - …B is a new type of BL Lac
    - …region A pushes the limits of known hot spot phenomena
    - …possibly an interacting system with two nuclei
- PKS 1055+201 & PKS 2101-490
  - Direct evidence of the interaction between the jet and its surroundings?
  - X-ray and optical peak lead radio at terminal hot spot
  - Inverse Compton along the jet?

See http://space.mit.edu/home/jonathan/jets for updates, preprints, images, etc.