Unconventional Views of Jets

(some goals in next the 10-years)

C. C. Teddy Cheung

Naval Research Laboratory

Energy Transport in Radio Galaxies and Quasars
ASP Conference Series, Vol. 100, 1996
P. E. Hardee, A. H. Bridle, and J. A. Zensus (eds.)

← 1996

Overview

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Abstract. A survey of mostly recent developments in the state of our knowledge and/or understanding of energy transport towards AGN from a gas disc and out of AGN into the jets, hot spots, and lobes of radio galaxies and quasars.

1. Introduction

The big questions remain:

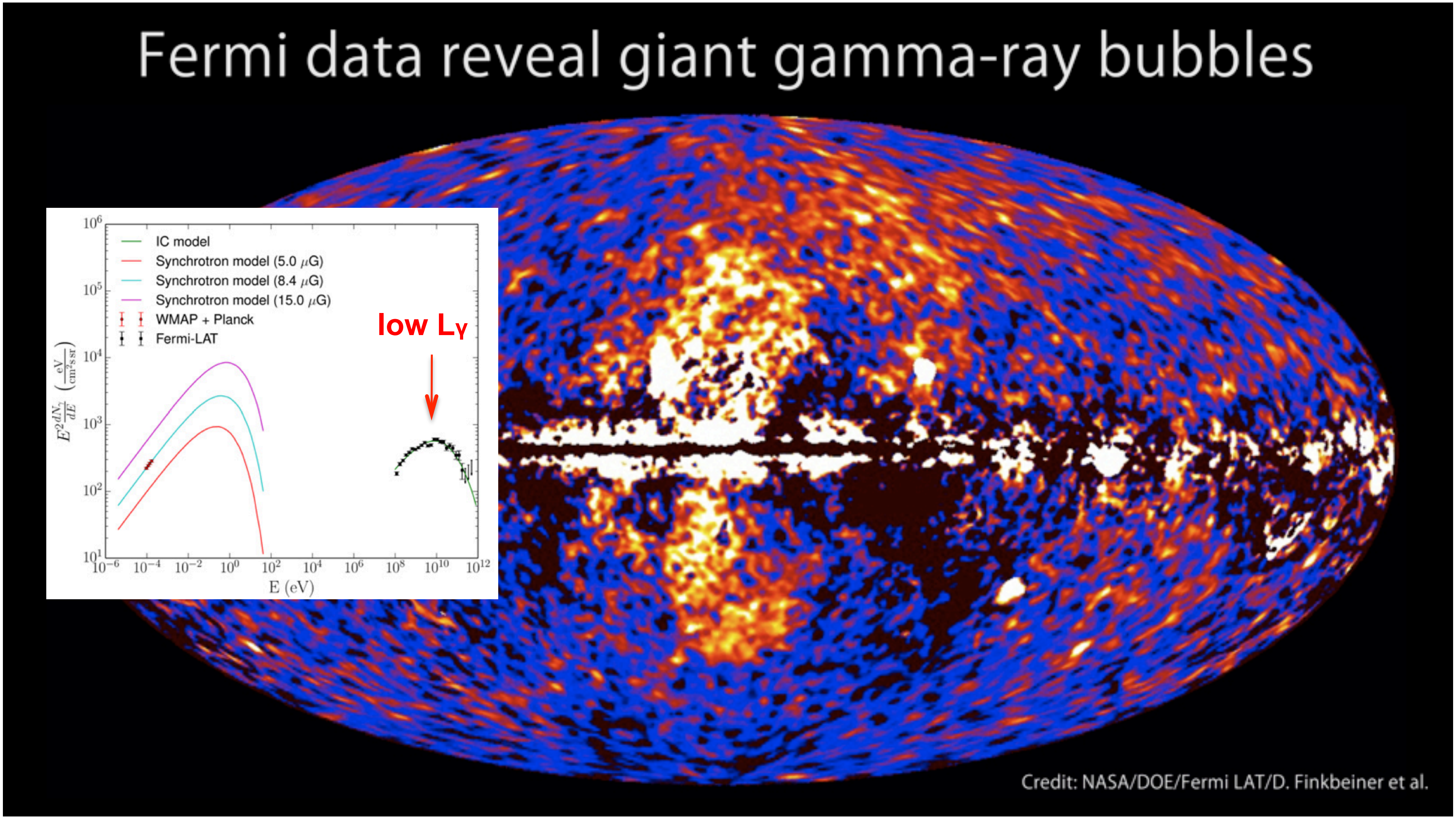
1. Do most/all galaxies have an AGN phase? ← **Clues from γ-rays and X-rays?**
2. Why do AGN produce powerful jets if and only if the host galaxy is an elliptical? **?**
3. Why the FR I—FR II boundary? **?**
4. What makes the magnetic field, and why is $|\mathbf{B}| \approx B_{\mathrm{equipartition}}$? **?**
5. Are jets p^+— e^- or e^+— e^- (or something else)? **?**
6. Do large-scale jets move at $\gamma \approx 10$, or do they slow down to $\gamma < 1.5$? ← **Two tests**

Topics

- New Light in Lobes, Episodes
  - γ-ray lobes in radio galaxies, young radio sources, spiral hosts
  - Episodic activity (nascent jets), other AGN signatures
- Counter-jets – will we see them (all)?
  - Detections and measurements of *N* x 1000's jet-counter-jets
  - Extra credit: nagging questions
- Superluminal motion for the patient
  - Direct proper motion measurements on >10's kpc scales, deprojected, on many *N* decade timescales

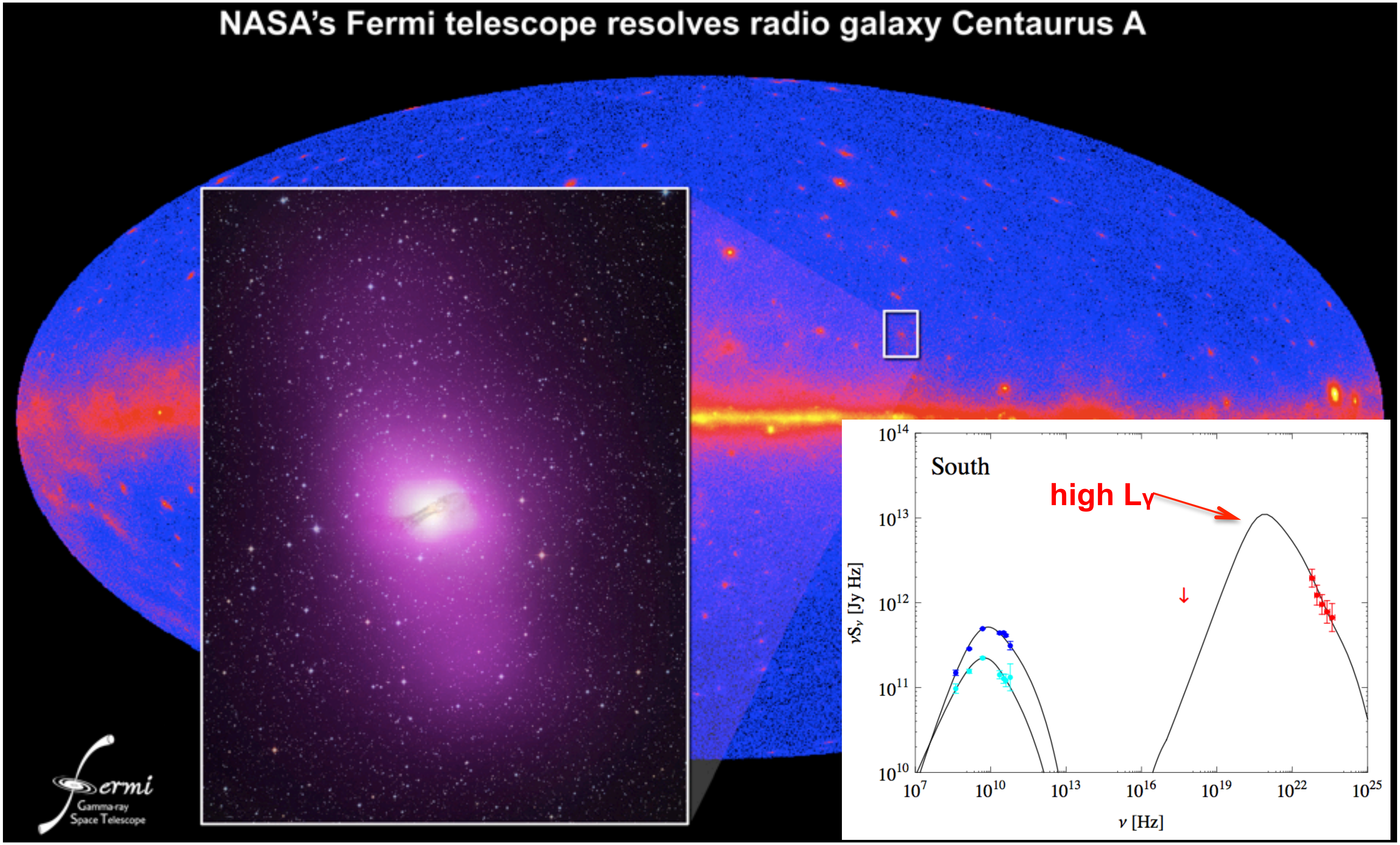
*For broader jet discussions, see, e.g. SKA meeting proceedings (Agudo et al. 2015; Kapinska et al. 2015, Laing 2015)

The Unseen Light in Lobes



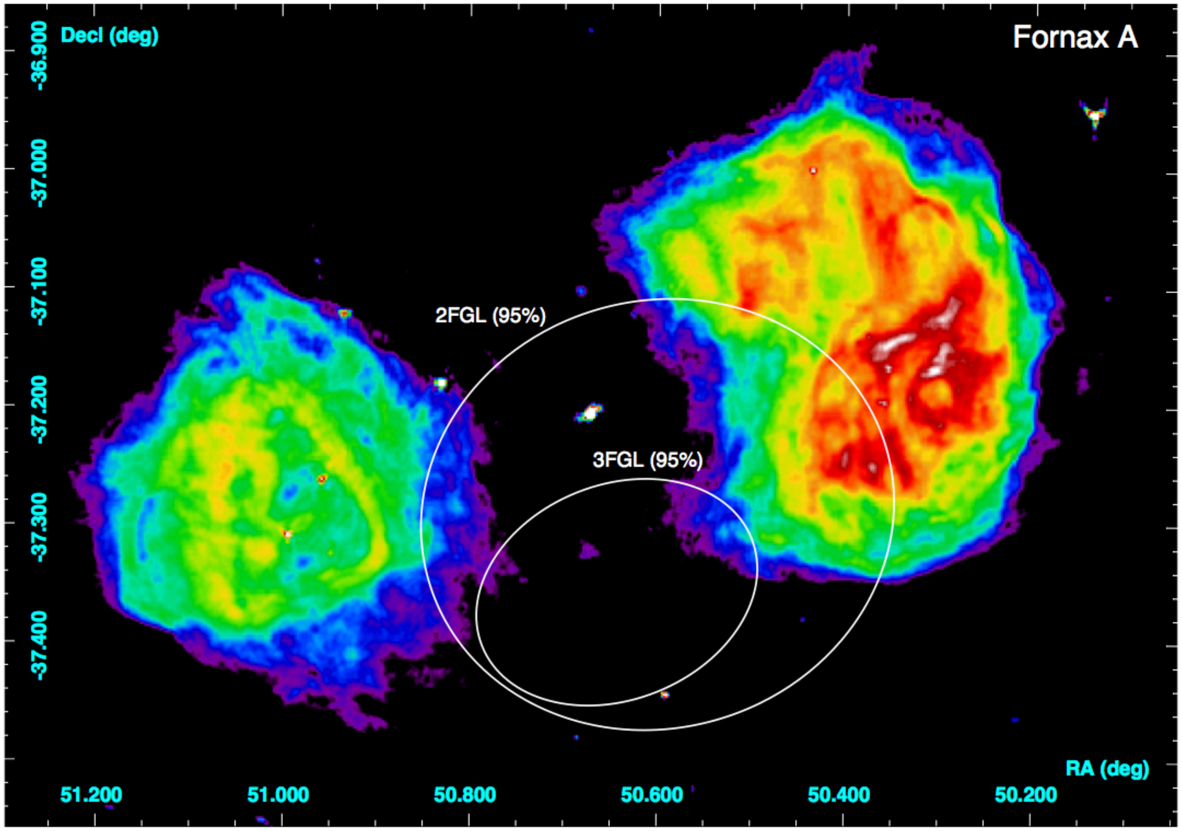
Fermi γ-ray Bubbles (Su et al. 2010, Ackermann et al. 2014)

The Unseen Light in Lobes



Cen A γ-ray lobes (Abdo et al. 2010)

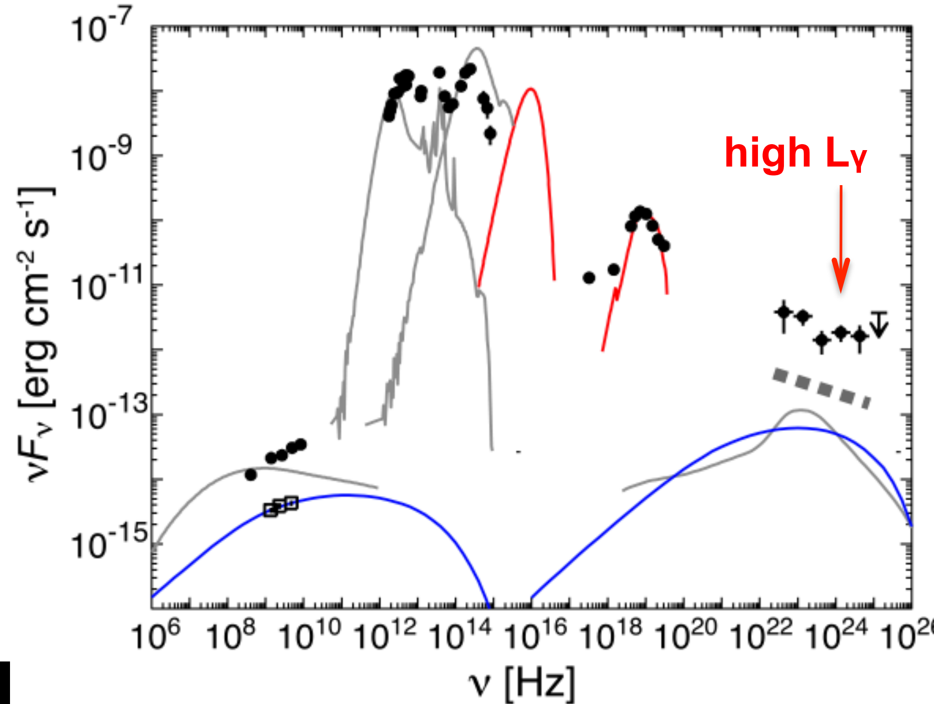
A 2nd γ-ray Radio Galaxy

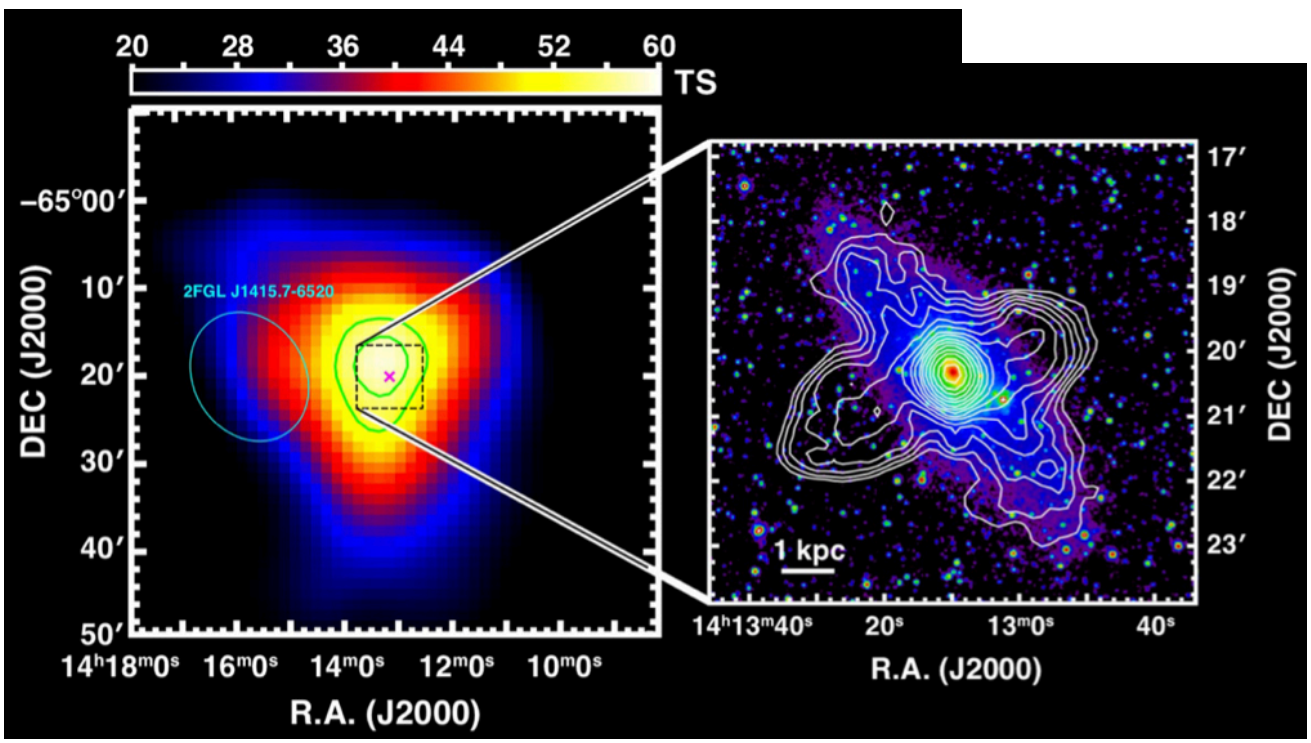


Fornax A
VLA 1.5 GHz image (Fomalont et al. 1989)
2FGL and 3FGL error ellipses
(take 2FGL flux as representative)

LAT γ-ray source is *extended, lower L_γ than radio*
See: J. Perkins et al. poster

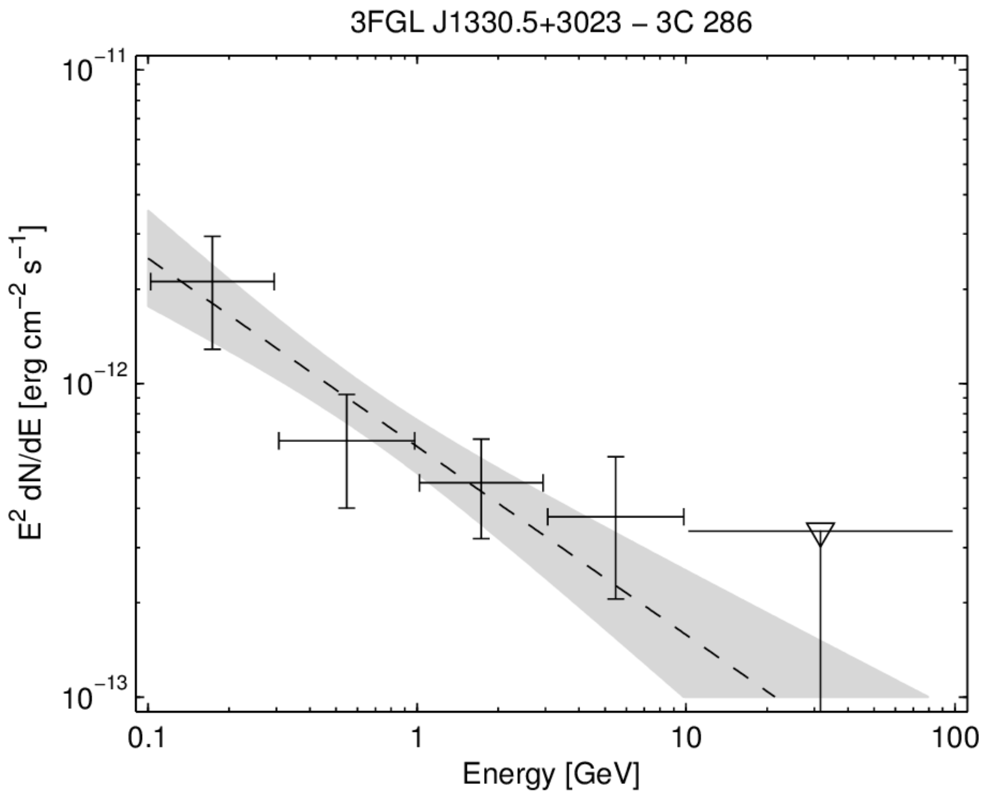
Circinus Galaxy: γ-ray Lobes?

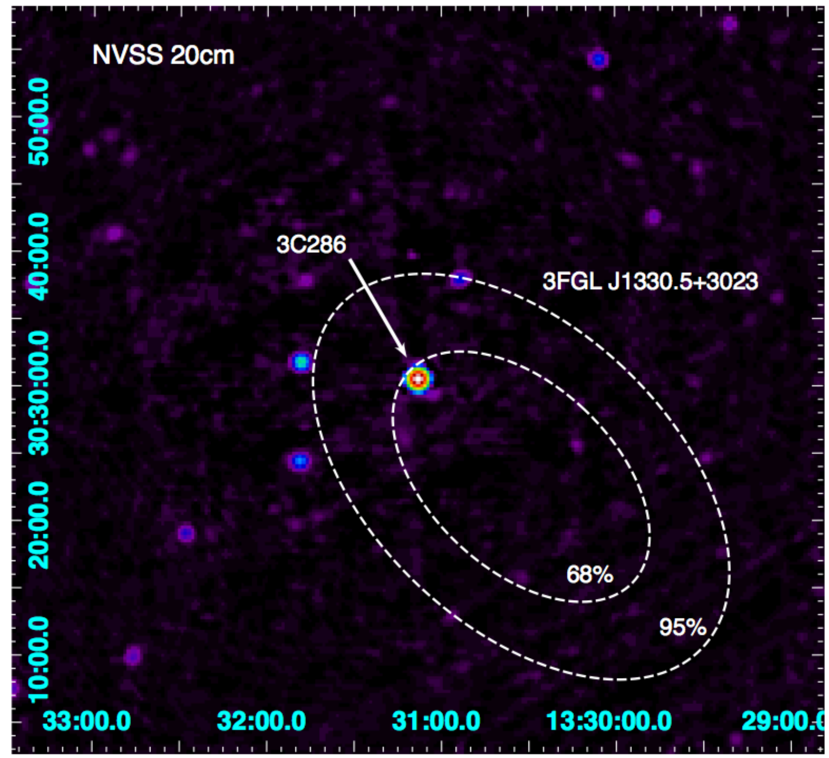




Hayashida et al. 2013

Young Radio Galaxies?

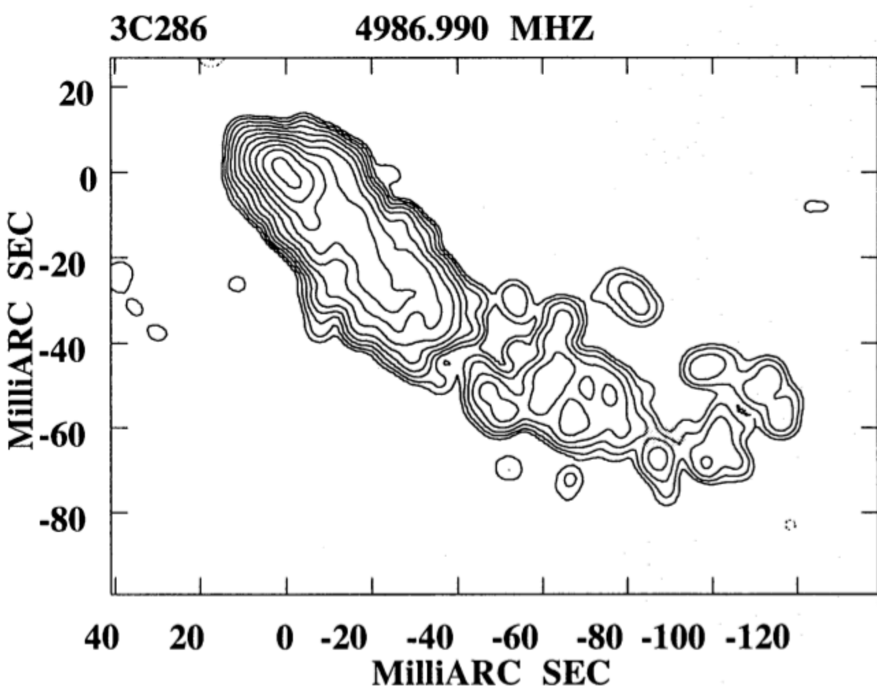




3C286 NVSS 1.4 GHz image
3FGL error ellipse overlaid

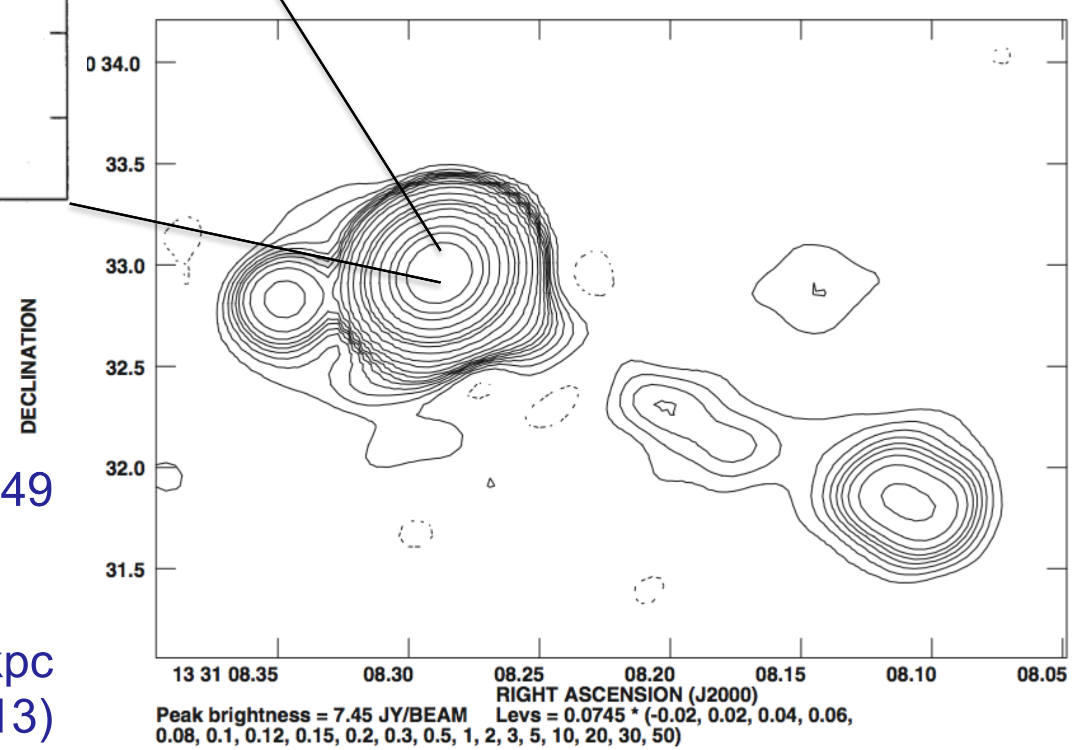
3FGL (Acero et al. 2015), 3LAC (Ackermann et al. 2015)

3C286 Radio Structure



VLBI: ~0.15" = 1.1 kpc
Jiang et al. (1996)

No flat spectrum radio core so these are likely "mini-lobes"… similar to…

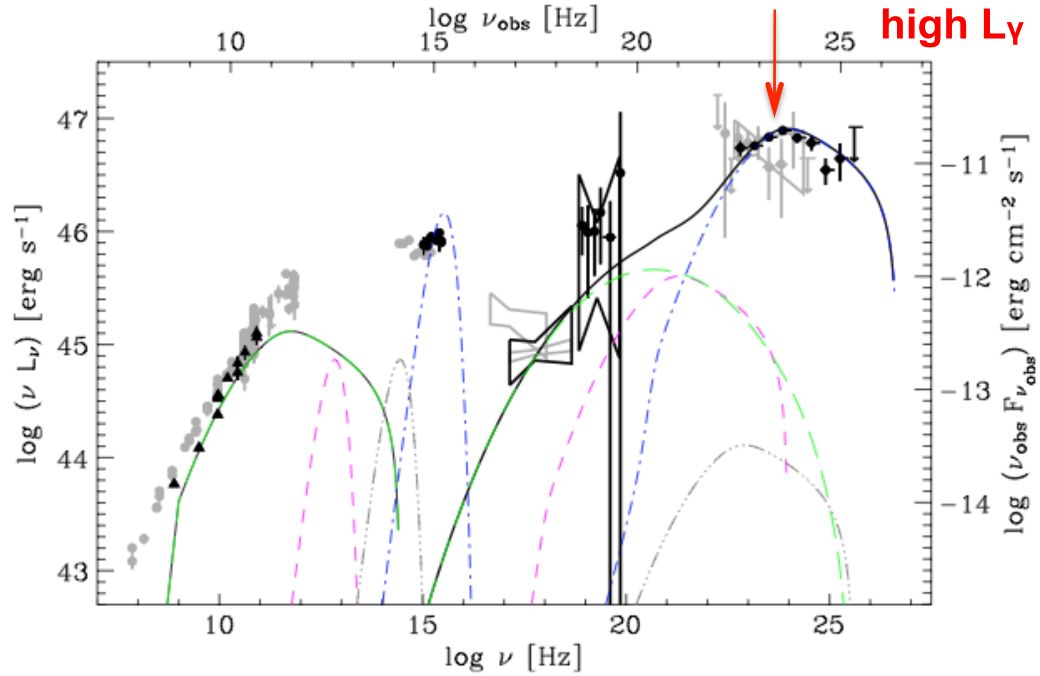


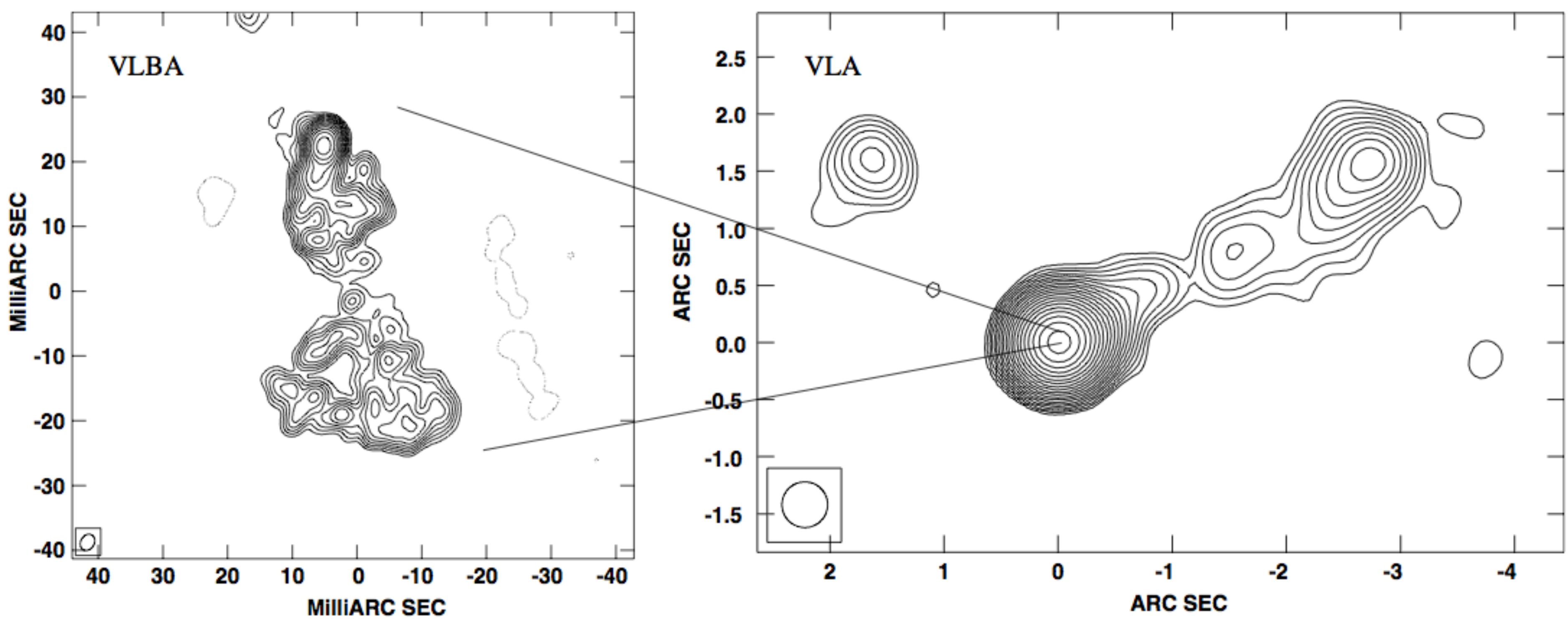
z=0.849

VLA: ~3" = 20 kpc
Perley & Butler (2013)

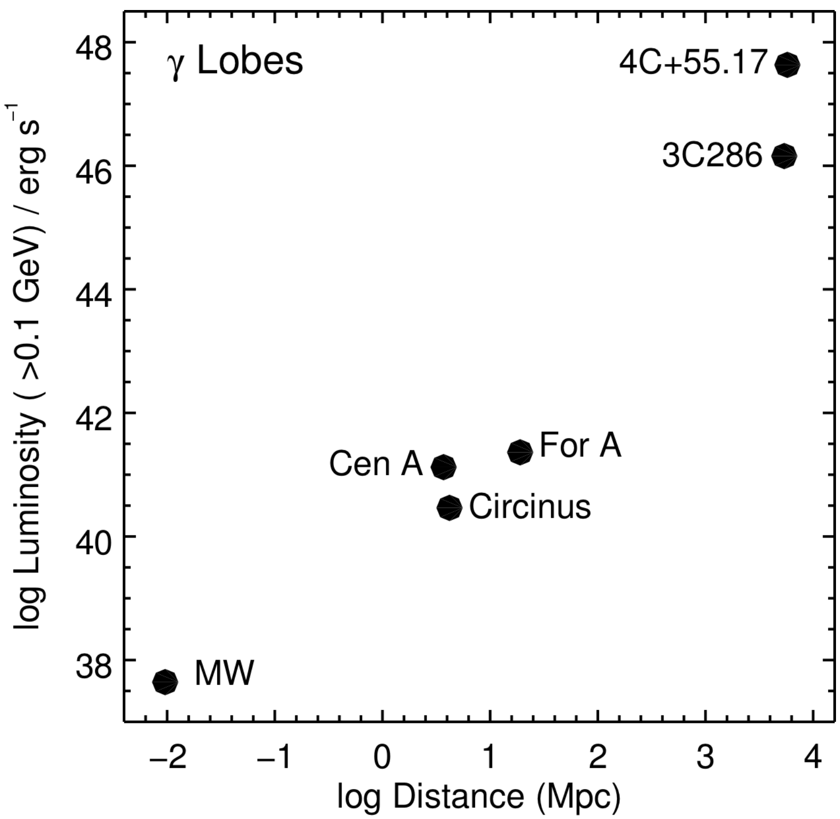
3C286 and 4C +55.17 two of a kind?

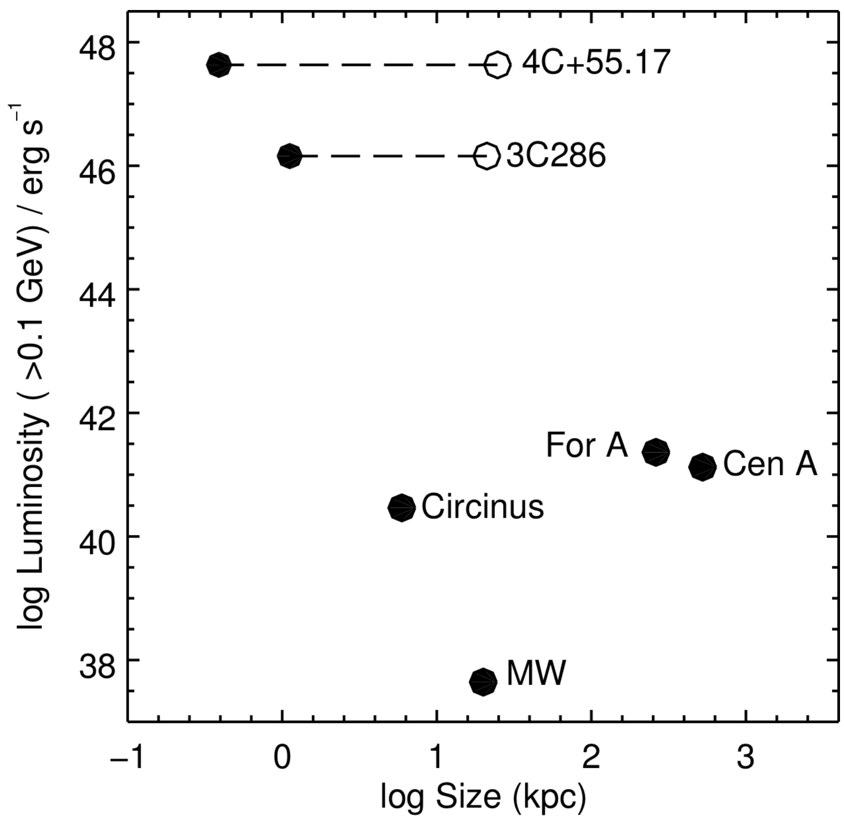
McConville et al. (2011)





γ-ray Lobes

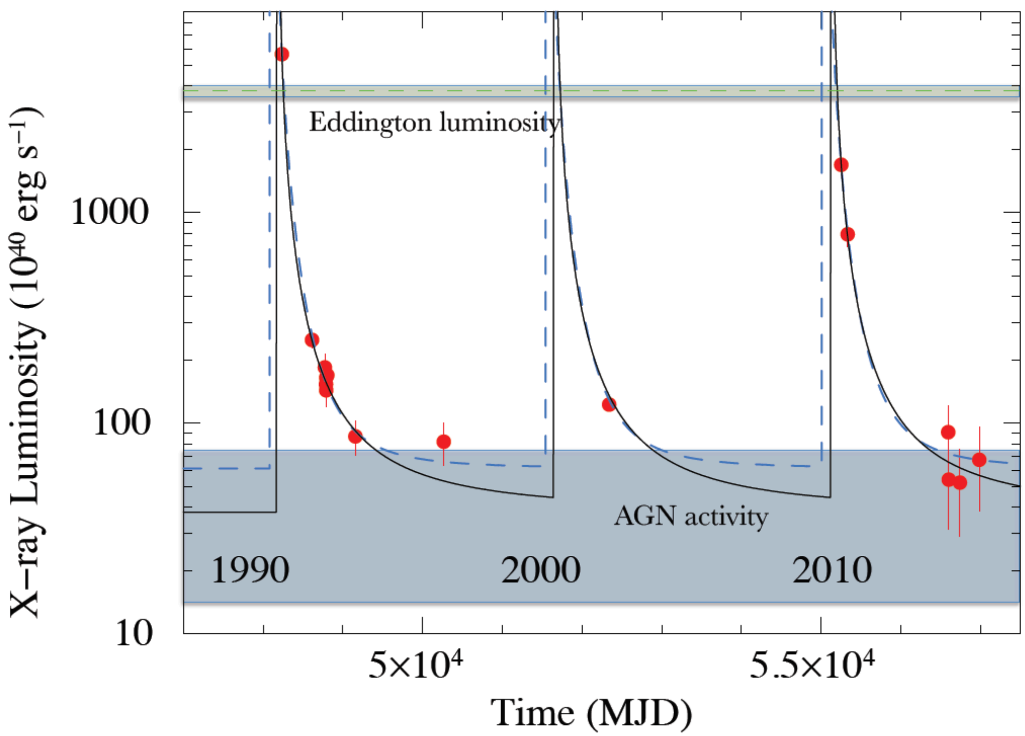




- Widely different lobe properties, different ambient radiation fields relevant at different scales, or hadronic?
- Nearby γ-rays lobes with CTA?

Inner lobes likely source of γ-rays in quasars 4C+55.17, 3C286

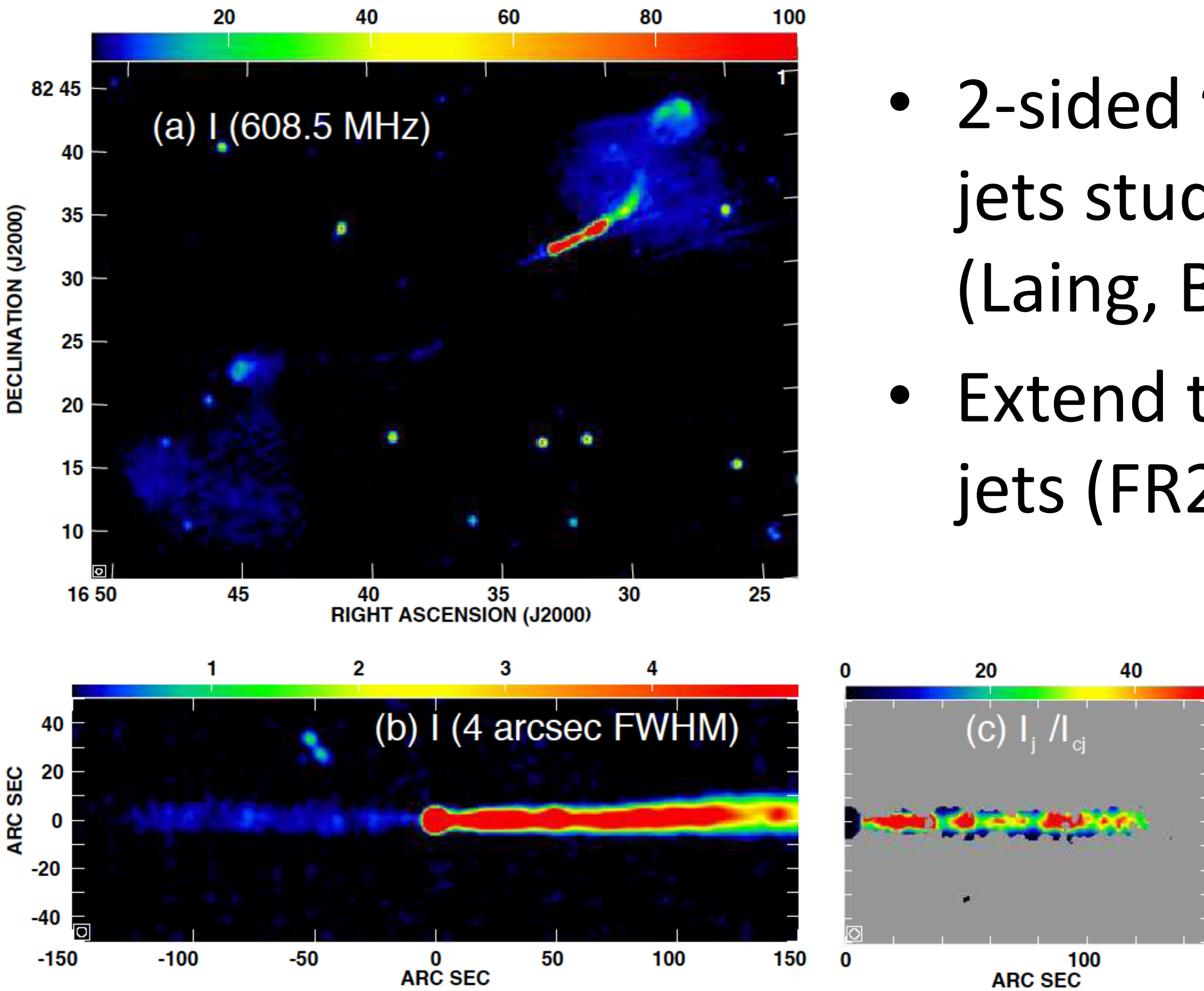
Nascent Jets?



ROSAT detected first outburst (e.g., Komossa & Bade 1999)
New outburst(s) seen with Swift (Campana et al. 2015; Grupe et al. 2015)

- Multiple tidal disruption events (TDEs) – low rate / duty cycle, e.g. seen in IC 3559 in X-rays
- Relativistic TDEs considered thus far, extrapolated from Swift J1644 (e.g., Donnarumma & Rossi 2015) -- SKA1 radio survey `non-relativistic TDEs' (ADAF, RIAF)
- Terahertz peaked sources (TPS) / sub-millimeter ?

Counter-jets: Radio Galaxies



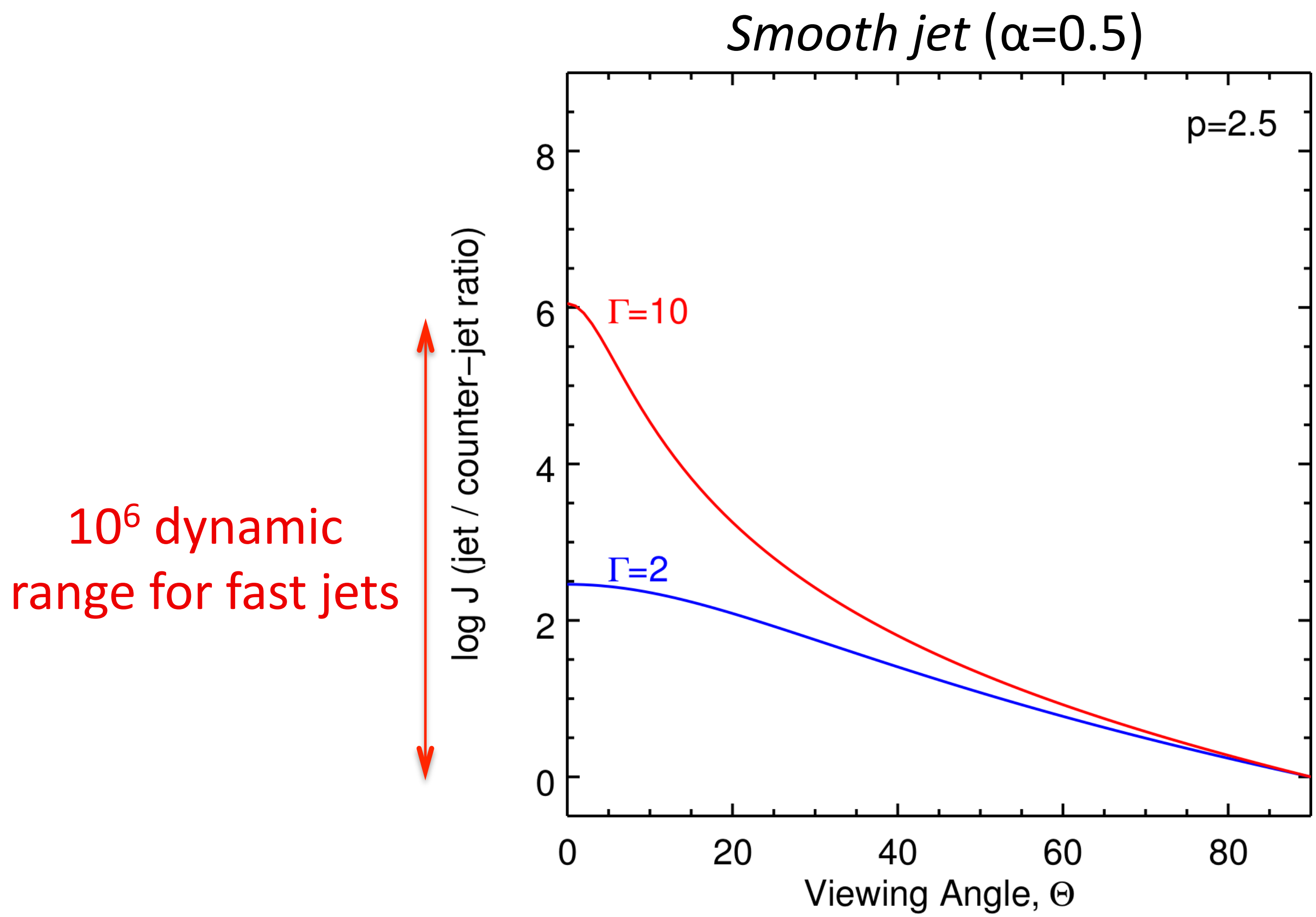
- 2-sided ~kpc-scale jets studied in FR1's (Laing, Bridle & co.)
- Extend to powerful jets (FR2's, quasars)

$$J=\left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{p}$$

NGC 6251 jet and counter-jet (Laing 2015)*

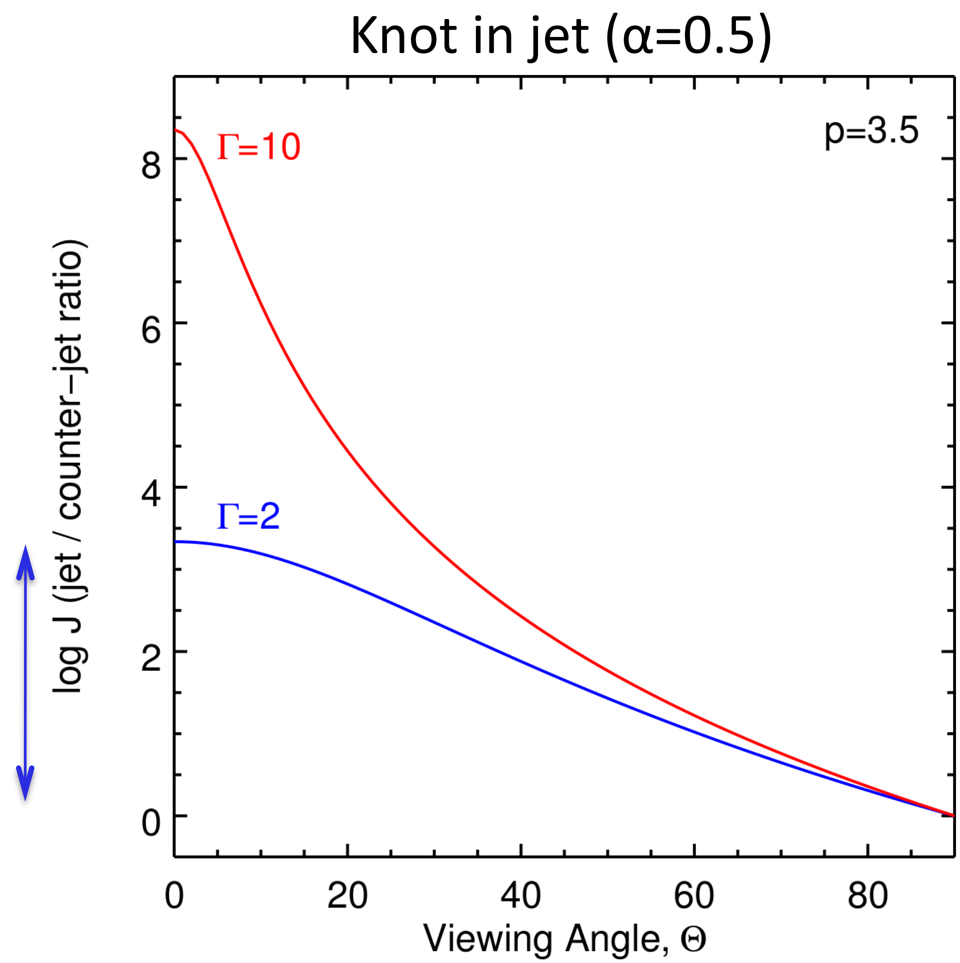
*Faraday rotation measure gradients "especially if the gradient is reversed in a counter-jet…" (Blandford 1993)

Jet to Counter-jet Flux Ratios: $J = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^p$



Jet to Counter-jet Flux Ratios: $J = \left(\frac{1+\beta \cos \theta}{1-\beta \cos \theta} \right)^p$

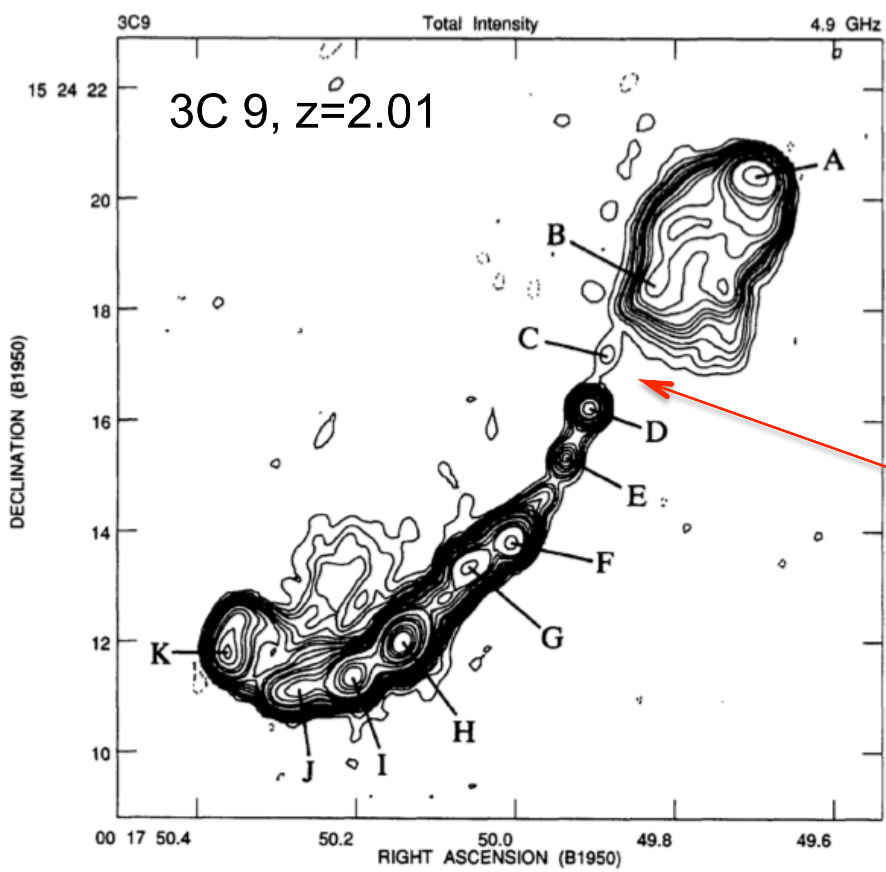
~10^3 dynamic range for slow jets



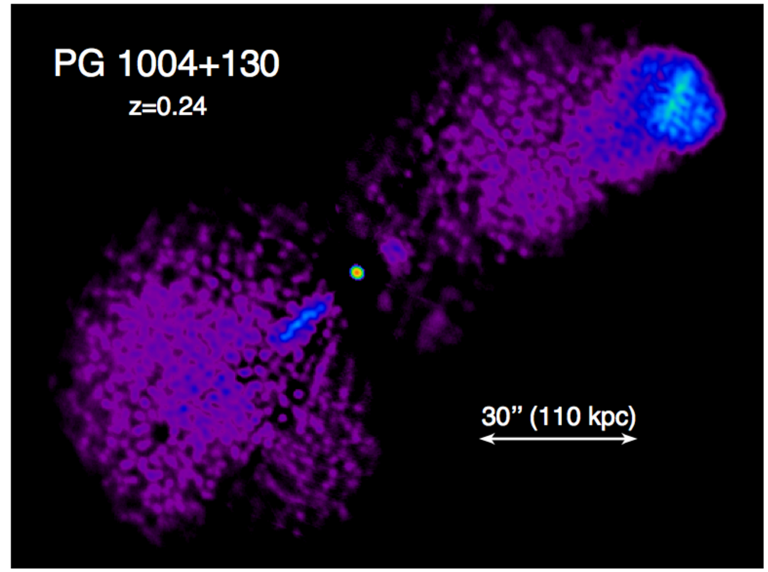
Gradual increase to J ≈ 2000 for *"slow"* jet knot (Γ =2),…

i.e., slow jets should have ~2000x fainter counter-jets – ***detectable?***

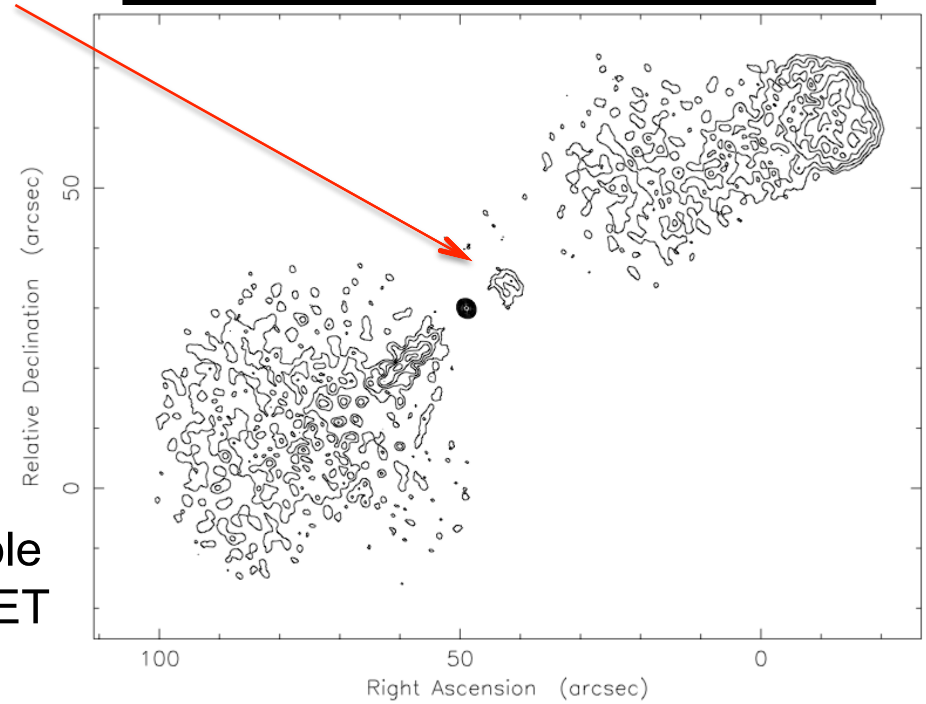
Counter-jets: in Quasars ?



Twelve 3CR quasars
(Bridle et al. 1994)



?

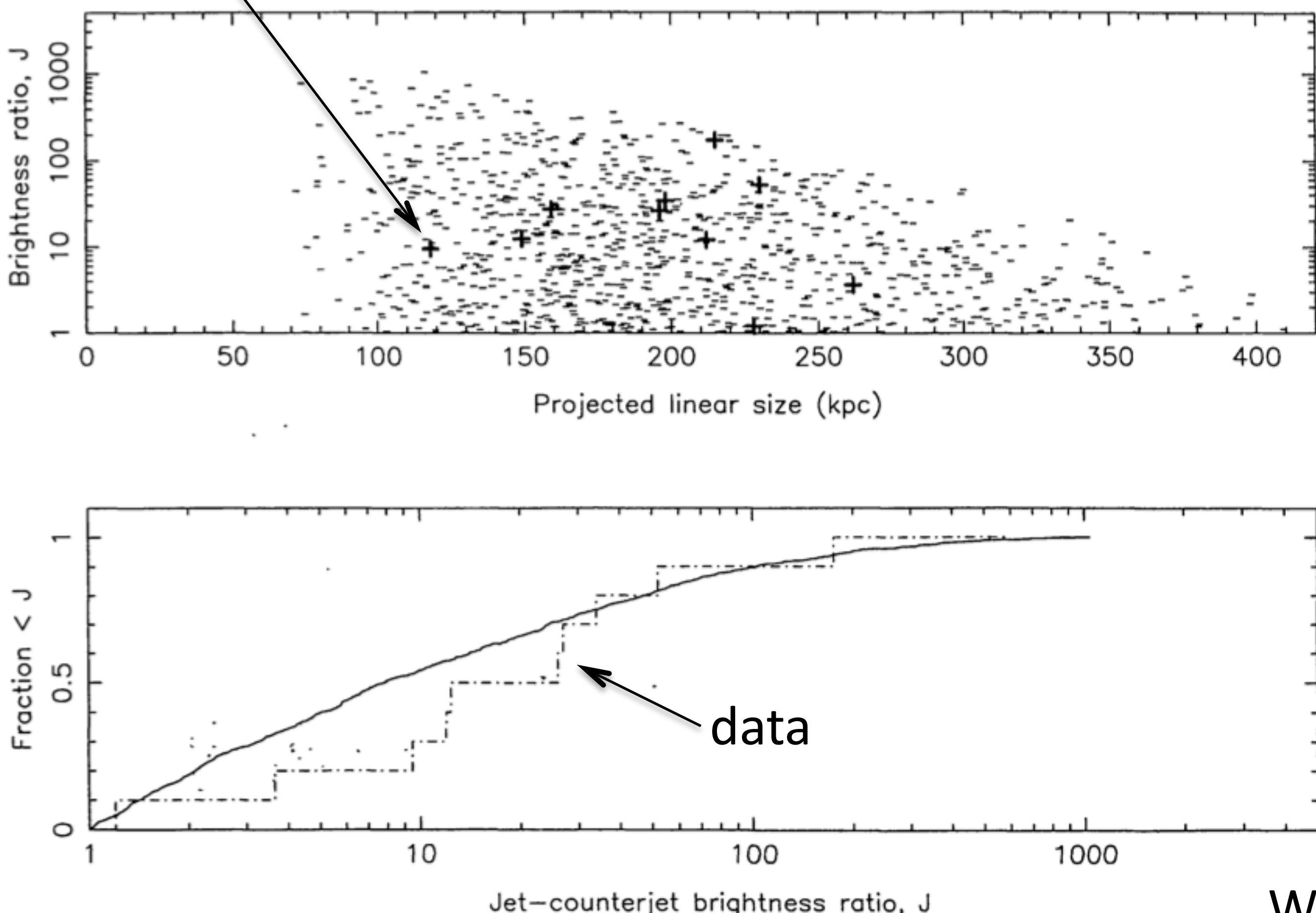


HYMOR example
Cheung, for XJET

Beaming Constraints

+ counter-jet *candidates* from Bridle et al. (1994) vs. MC simulations

assumed single speed (β=0.8), isotropic angle distribution



- $\beta \geq 0.6$, $\Theta_{max} < 75^o$
- $\beta = 0.6 - 0.7$ (**Γ = 1.25 - 1.4**) for $\Theta_{max} = 45^o - 60^o$
- Jet-to-lobe ratios constrain $\beta < 0.95$ (**Γ = 3.2**)

Wardle & Aaron (1997)

also core/jet prominences (Hardcastle et al. 1999, Mullin & Hardcastle 2001)

Problems & Obstacles

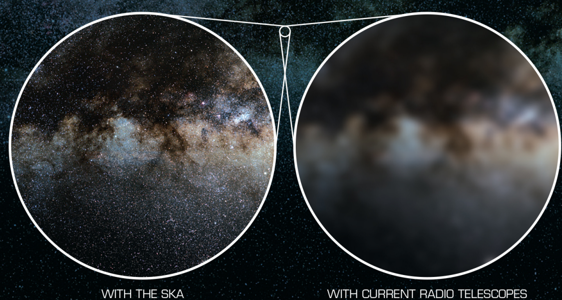
- Knots in quasar counter-jets *Candidates* – ratios may be smaller, thus (β,Γ) larger
  - Jet bending increases detectability (i.e., hard to find counter-jets with straight approaching jets)
  - Environmental (deflection) or changing angle
- Transverse velocity structures ?
- IC/CMB X-rays?

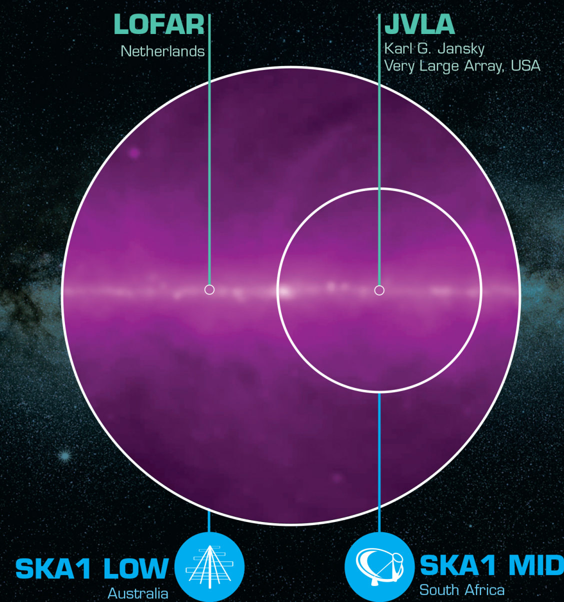
- Two Experiments …

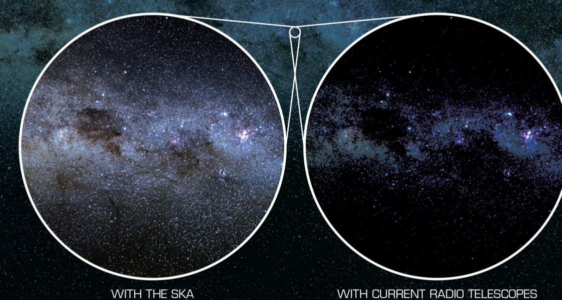
How will SKA1 be better than today's best radio telescopes?

Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.







SKA1 LOW x1.2 LOFAR NL

SKA1 MID x4 JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

SKA1 LOW x135 LOFAR NL

SKA1 MID x60 JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

SKA1 LOW x8 LOFAR NL

SKA1 MID x5 JVLA

SENSITIVITY

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array

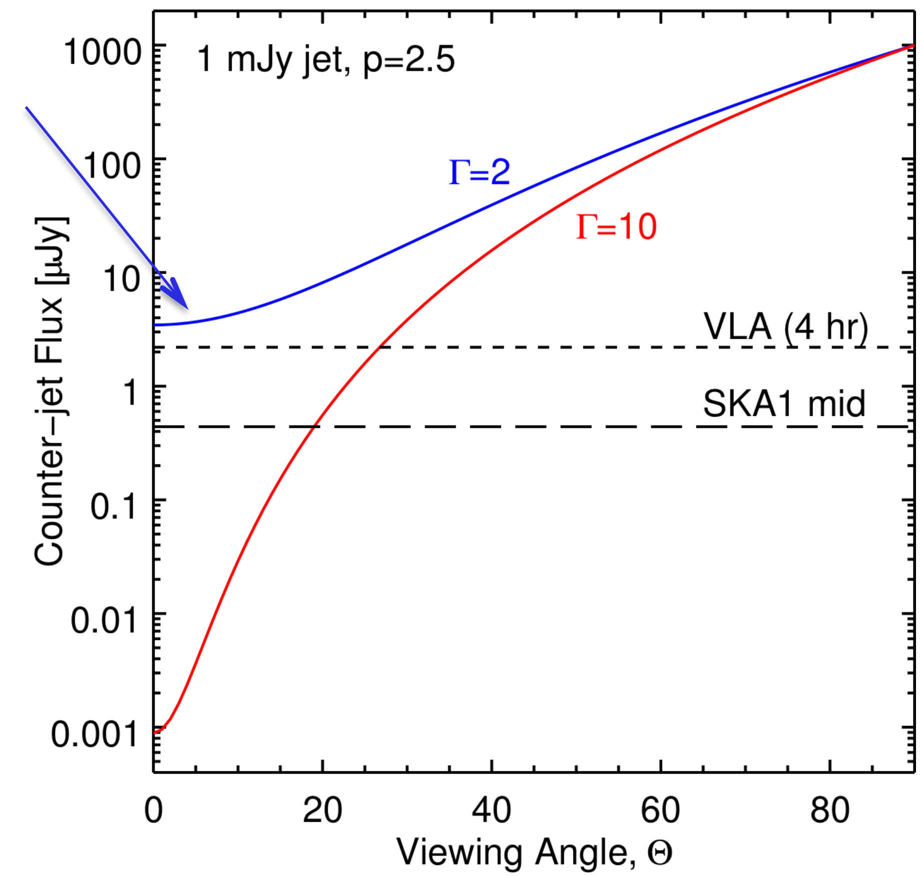
As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.

https://www.skatelescope.org/news/worlds-largest-radio-telescope-near-construction/

1. Expected Counter-jets (1 mJy jet example)

Aligned low-power counter-jets detectable with e-VLA?

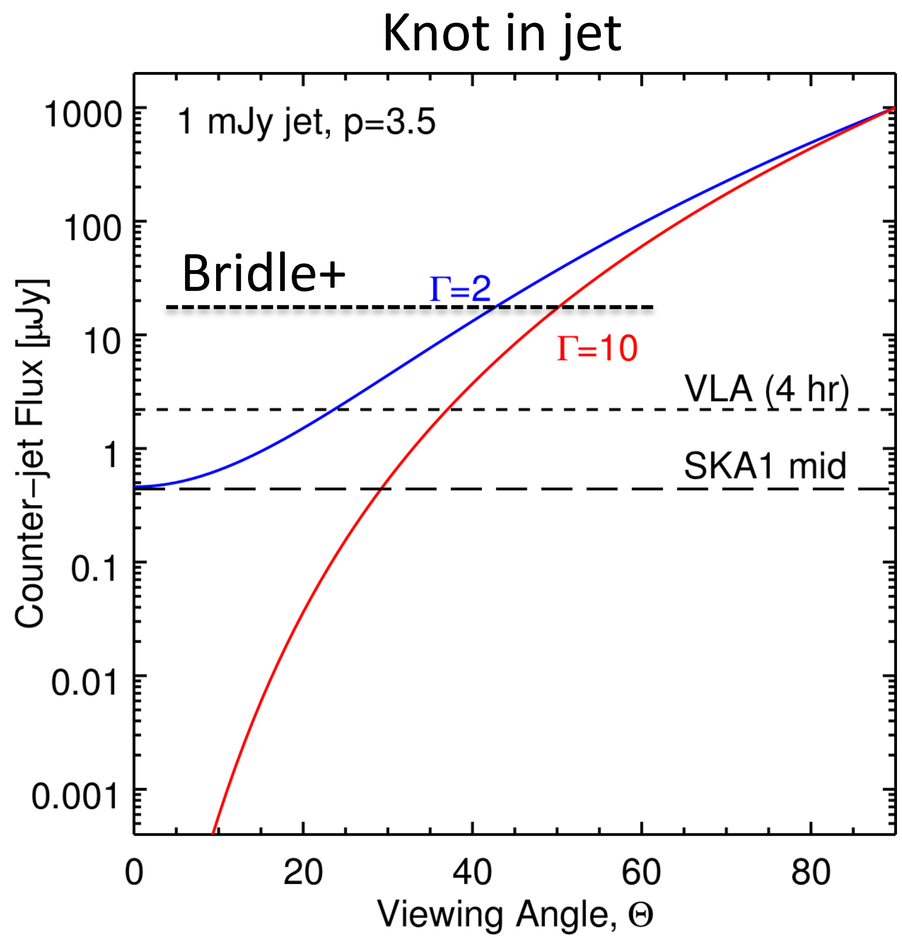
Smooth jet



Diverging predictions for slow and fast jets.

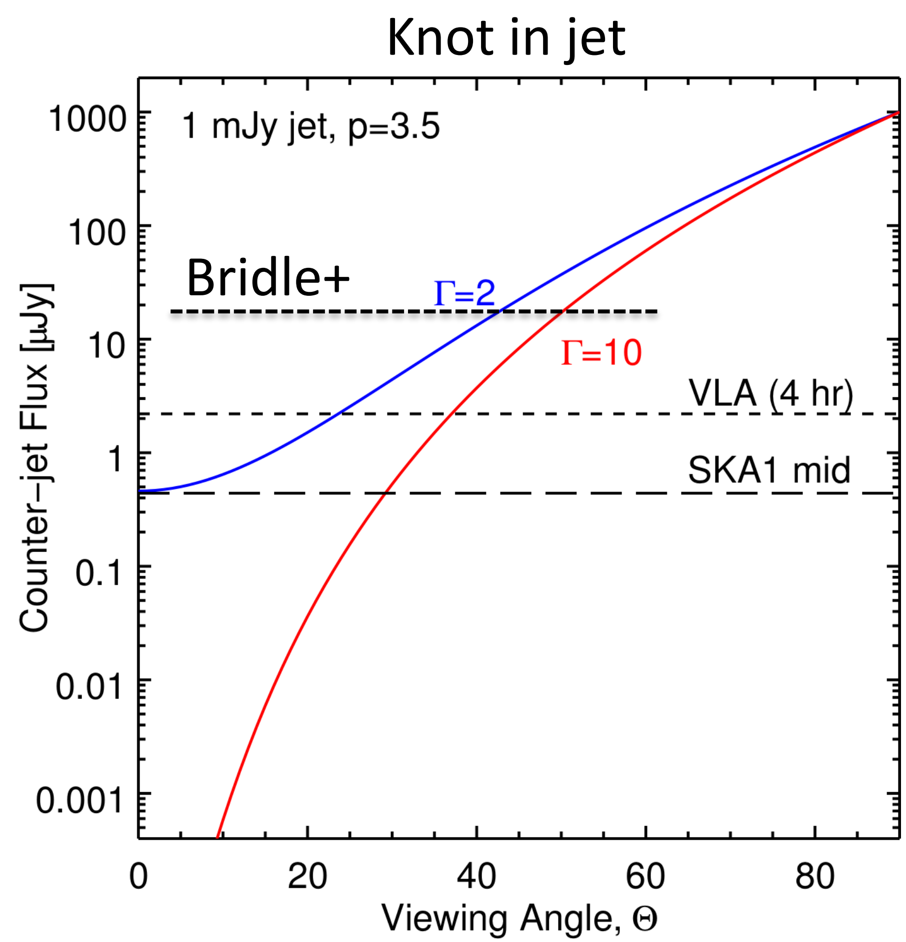
*parsec-scale absorption may affect VLBI counter-jet measurements (e.g., Jones & Wehrle 2002)

1. Expected Counter-jets (1 mJy jet example)



Diverging predictions for slow and fast jets.

1. Expected Counter-jets (1 mJy jet example)

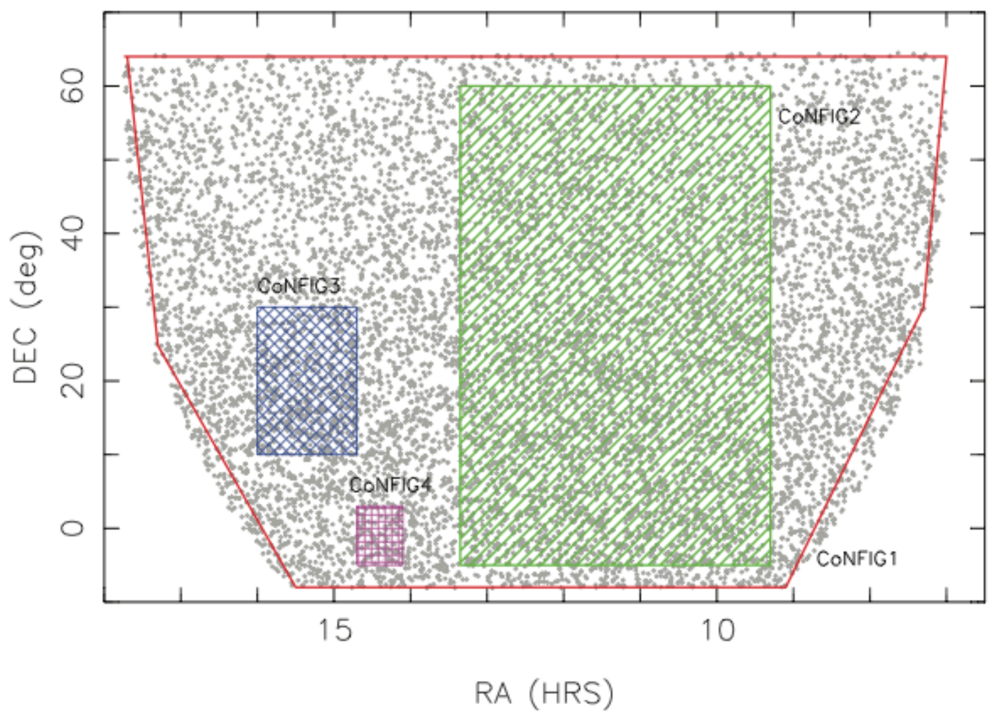


Diverging predictions for slow and fast jets.

A. Detectable counter-jets at **ALL** angles if kpc-scale jets are *slow* (Γ =2)

B. Counter-jets *very* difficult to detect at Θ < 20-30^{o} if jets are fast.

Some Naive Considerations for SKA1 MID



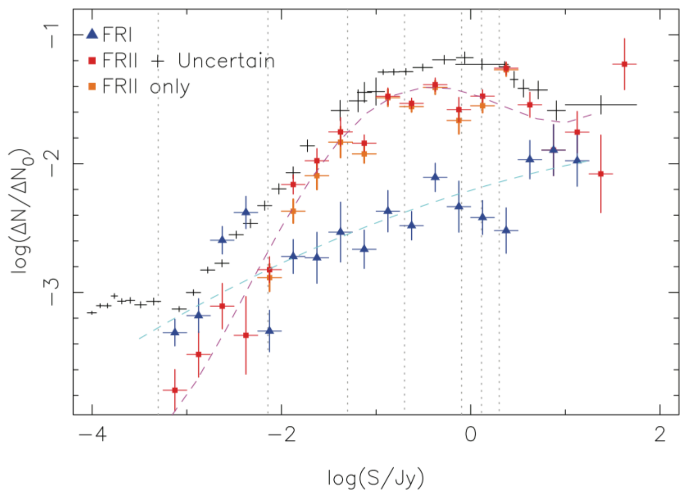
CoNFIG sample (Gendre et al. 2010)

1.4 GHz flux limits = 1.3, 0.8, 0.2, 0.05 Jy with decreasing sky coverage

- Image to 0.5 μJy limit everything >50 mJy
- Piggyback on imaging surveys of pre-determined fields
- <u>Goal</u>: N x 1000 sources, from some combination

Intrinsically symmetric jets, or environmental factors?

Extra Credit: nature vs. nurture

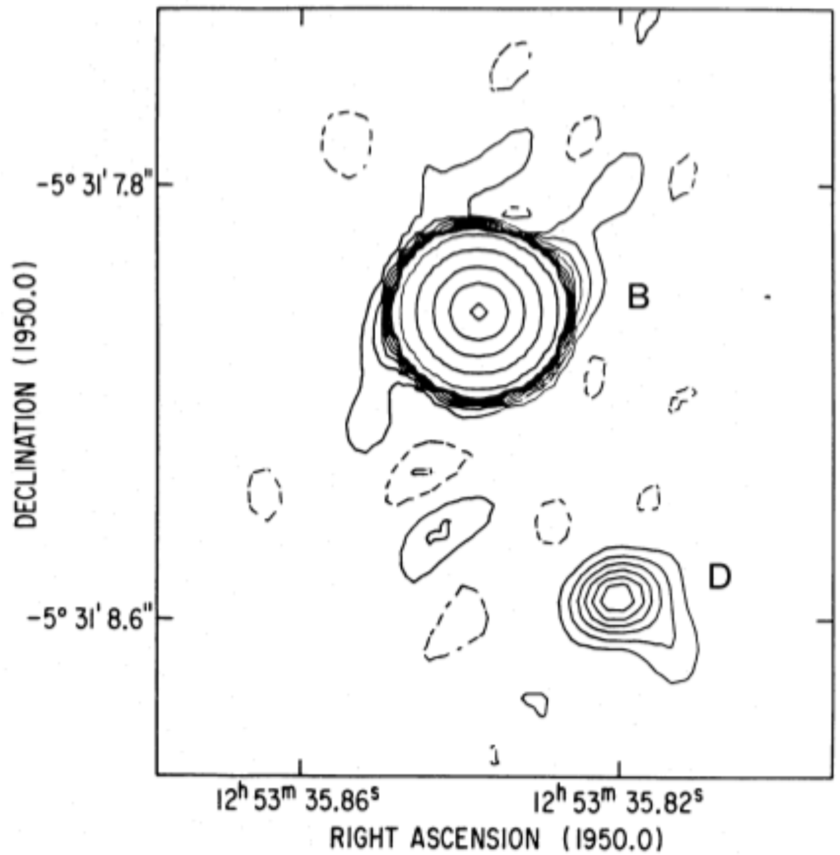


(Gendre et al. 2010)

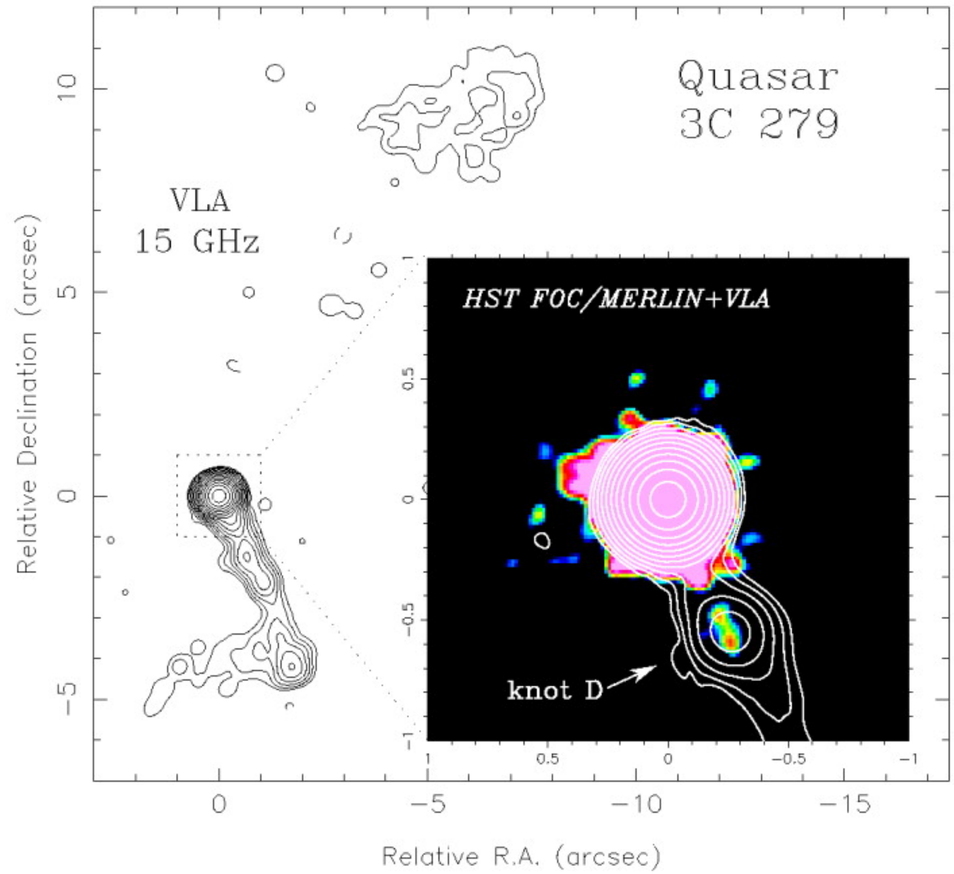
- Is there a optical host luminosity dependence of FR1/FR2 division (Owen 1993, Ledlow & Owen 1996, Bicknell 1995, Ghisellini & Celotti 2001)? See Lin et al. (2010), Gendre et al. (2013)
- How prevalent are spiral-hosted FR2 radio galaxies? (Bagchi et al. 2014, Mao et al. 2015; see Morganti et al. 2011)
- Are jets detected always on the 'FR1' side in Hybrid-morphology radio galaxies (HYMORs; Gopal-Krishna & Wiita 2000, Gawronski et al. 2006, Ceglowski et al. 2015)
  - Is there a Laing-Garrington effect in HYMORS?
- Statistics of episodic radio sources like double-doubles, X-shaped

2. Superluminal Motion for the Patient

3C279 knot D at 0.6” = 3.8 kpc, projected (**10’s kpc deprojected**)



VLA 2cm, 0.11” beam, **1982 Feb**
de Pater & Perley (1983)

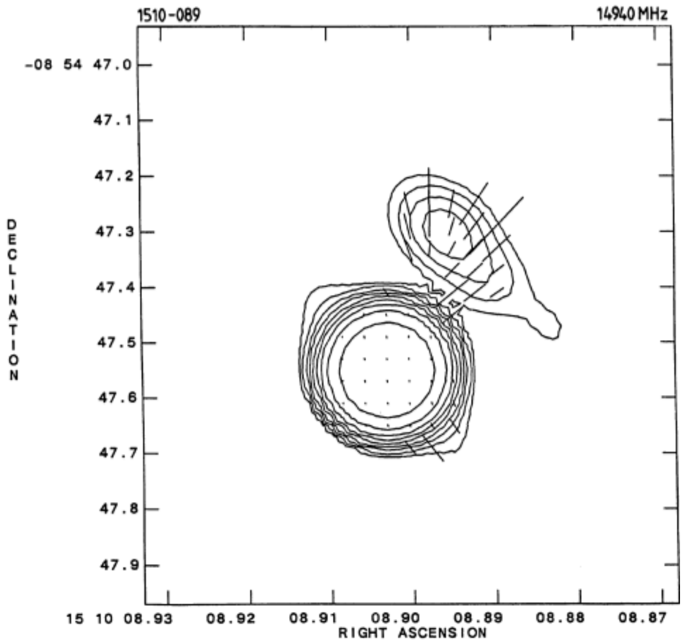


VLA 2cm, 0.40” beam
Cheung (2002)

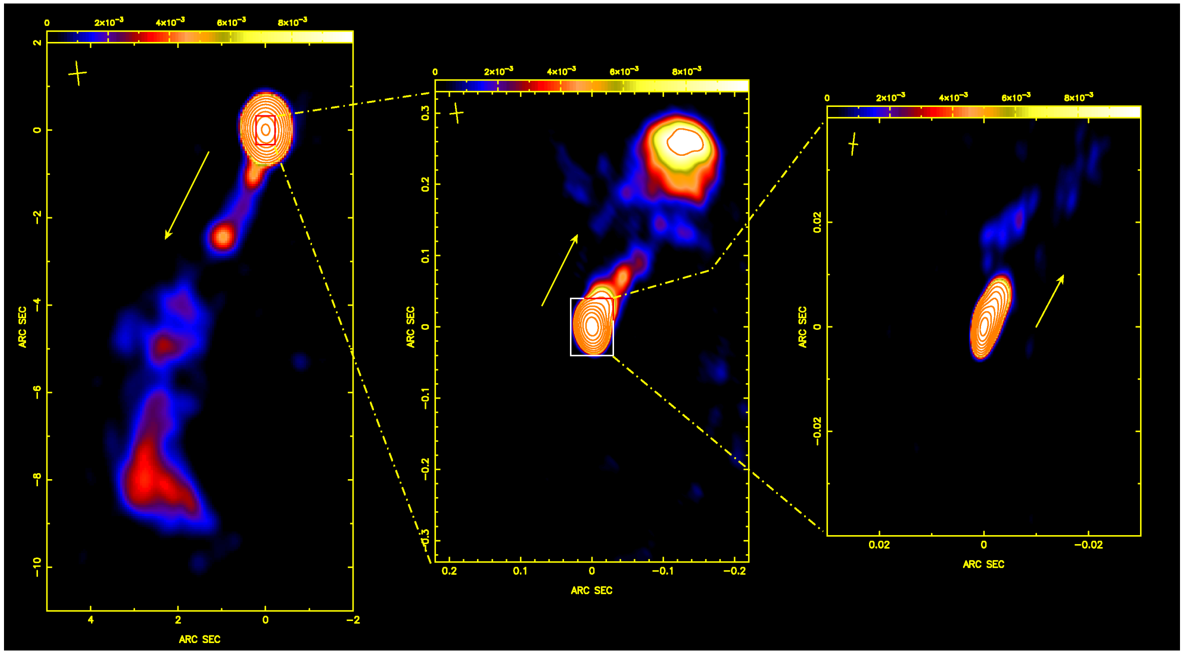
*Optical knots on these scales detected with HST can also be considered

2. Superluminal Motion for the Patient

PKS 1510-089 knot at 0.3” = 1.5 kpc, projected (**10’s kpc deprojected**)



VLA 2cm, 0.10” beam
1985 March
O’Dea et al. (1988)

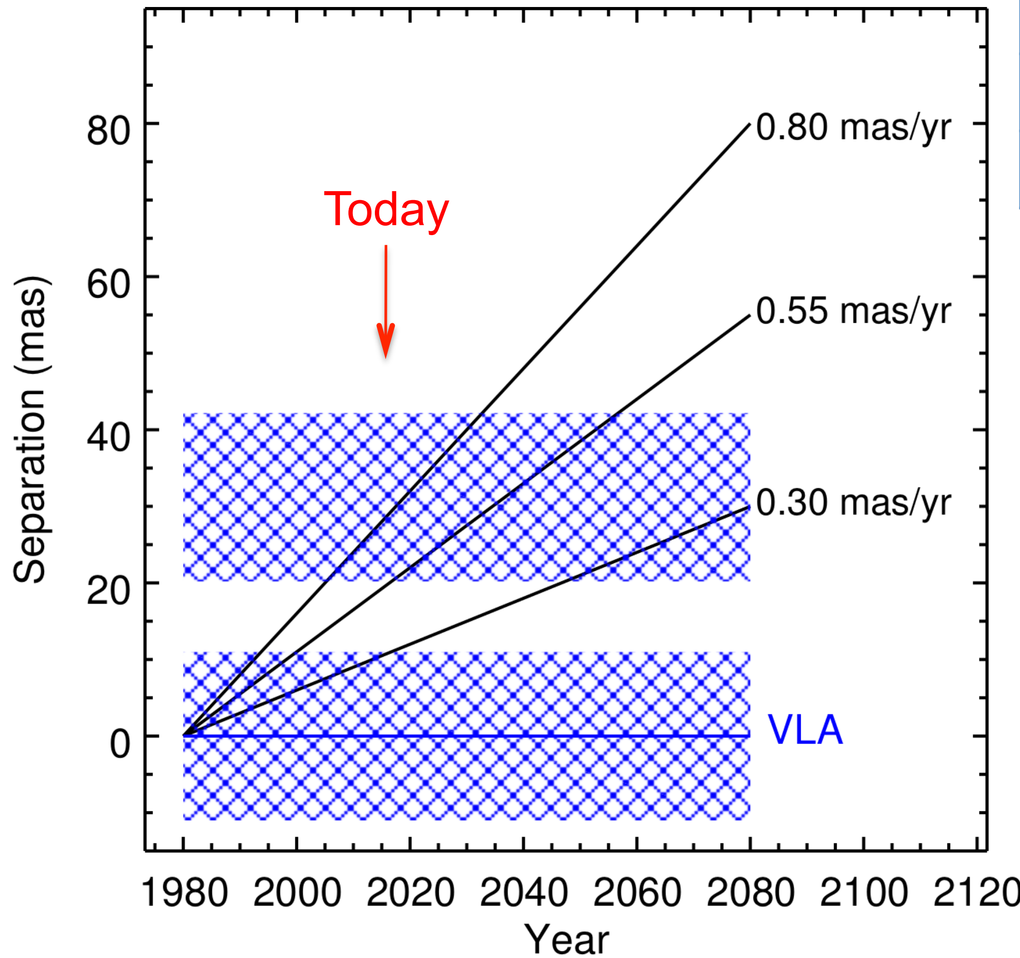


VLA 5 GHz, VLBA 1.7 and 5 GHz
Homan et al. (2002)

*VLBI 20-30c apparent velocities imply small viewing angles with deprojected sizes ~1-1.5 Mpc

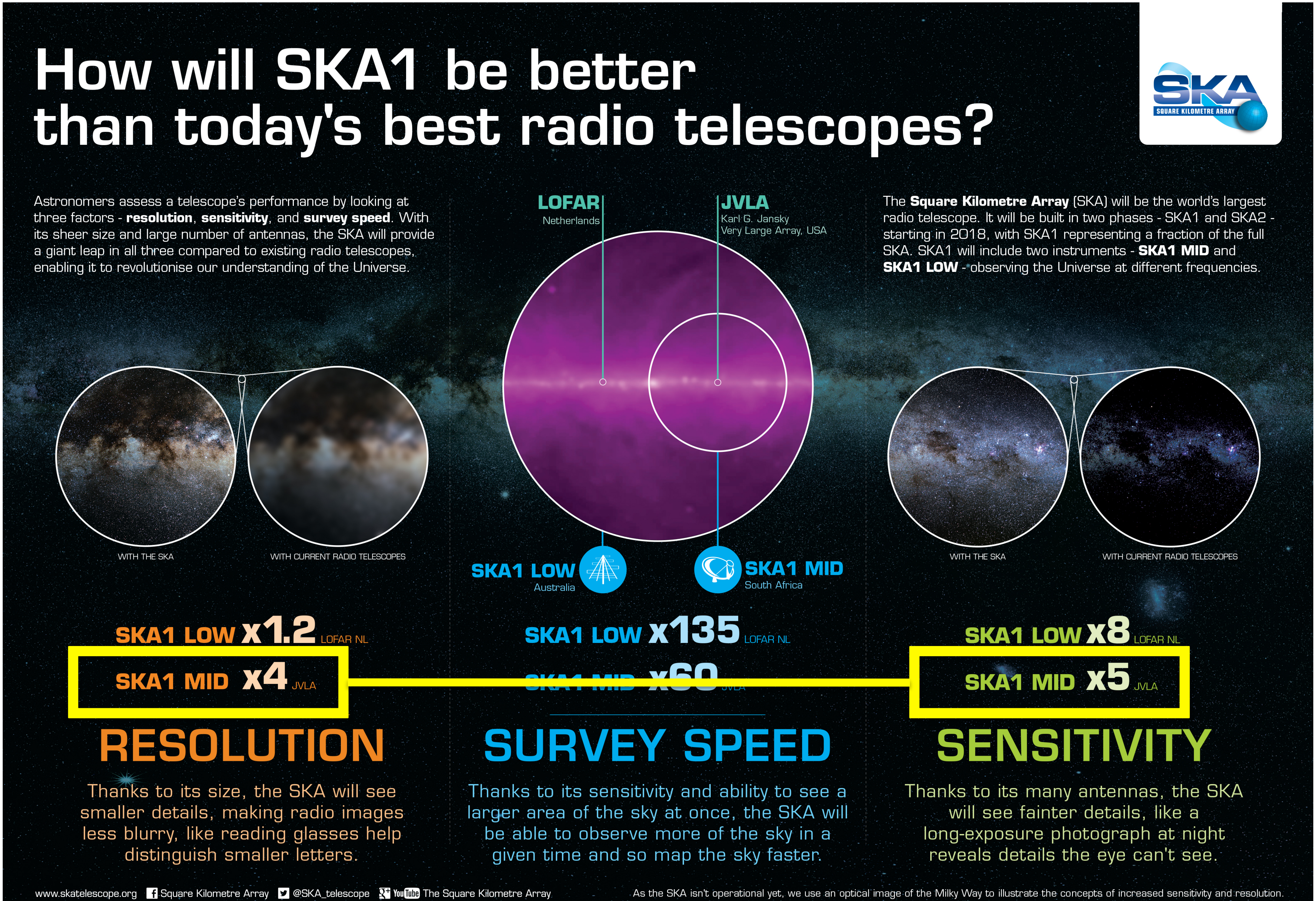
2. Apparent Motions on Kiloparsec-scales?

2-σ proper motion detections
(separation error = 1/5th 0.11" beam)



Source	Deprojected	μ (β = 10)
3C279	44 kpc , Θ = 5°	**0.32** mas/yr
PKS 1510-08	17 kpc , Θ = 5°	**0.45** mas/yr

- VLBI, β_{max} = 20.6, 28.0, respectively (MOJAVE; Lister et al. 2009)
- Superluminal motions already measured on >1 kpc-scales, deprojected for closest aligned blazars, Θ < 2° (see e.g. Homan et al. 2003)



https://www.skatelescope.org/news/worlds-largest-radio-telescope-near-construction/

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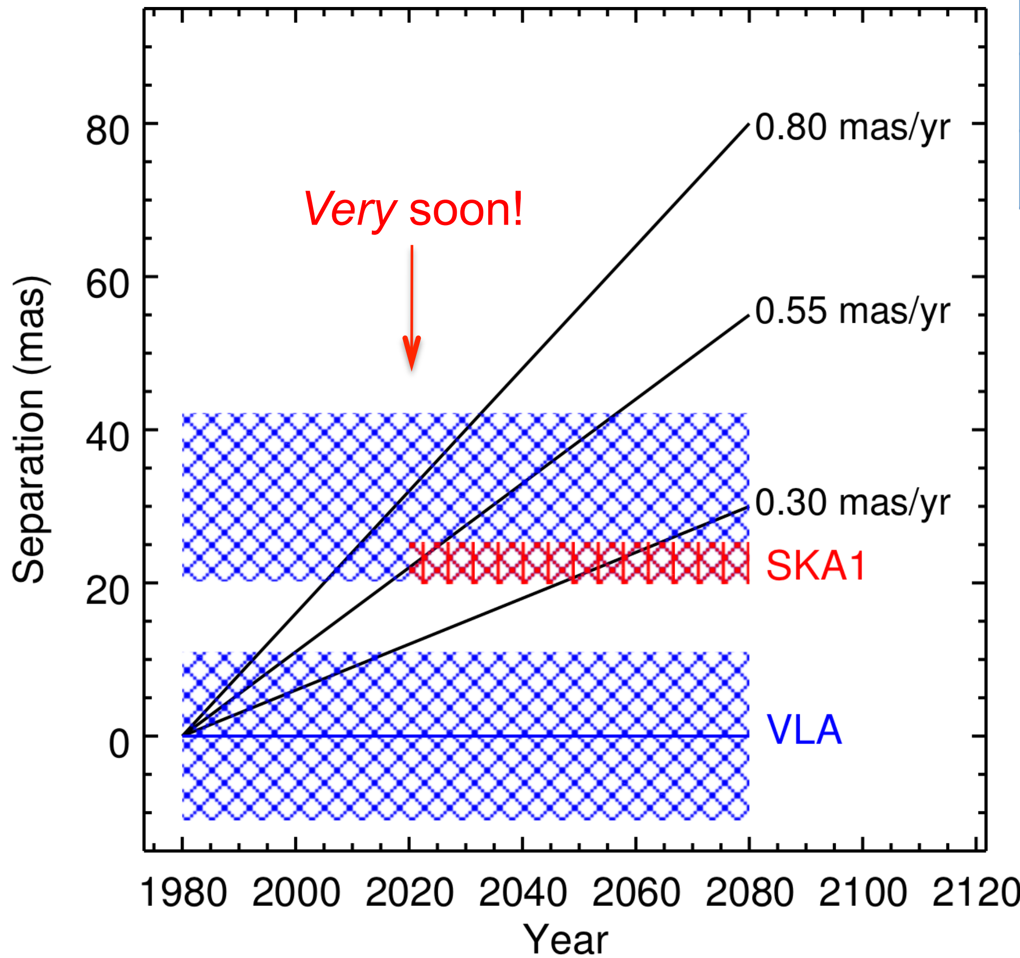

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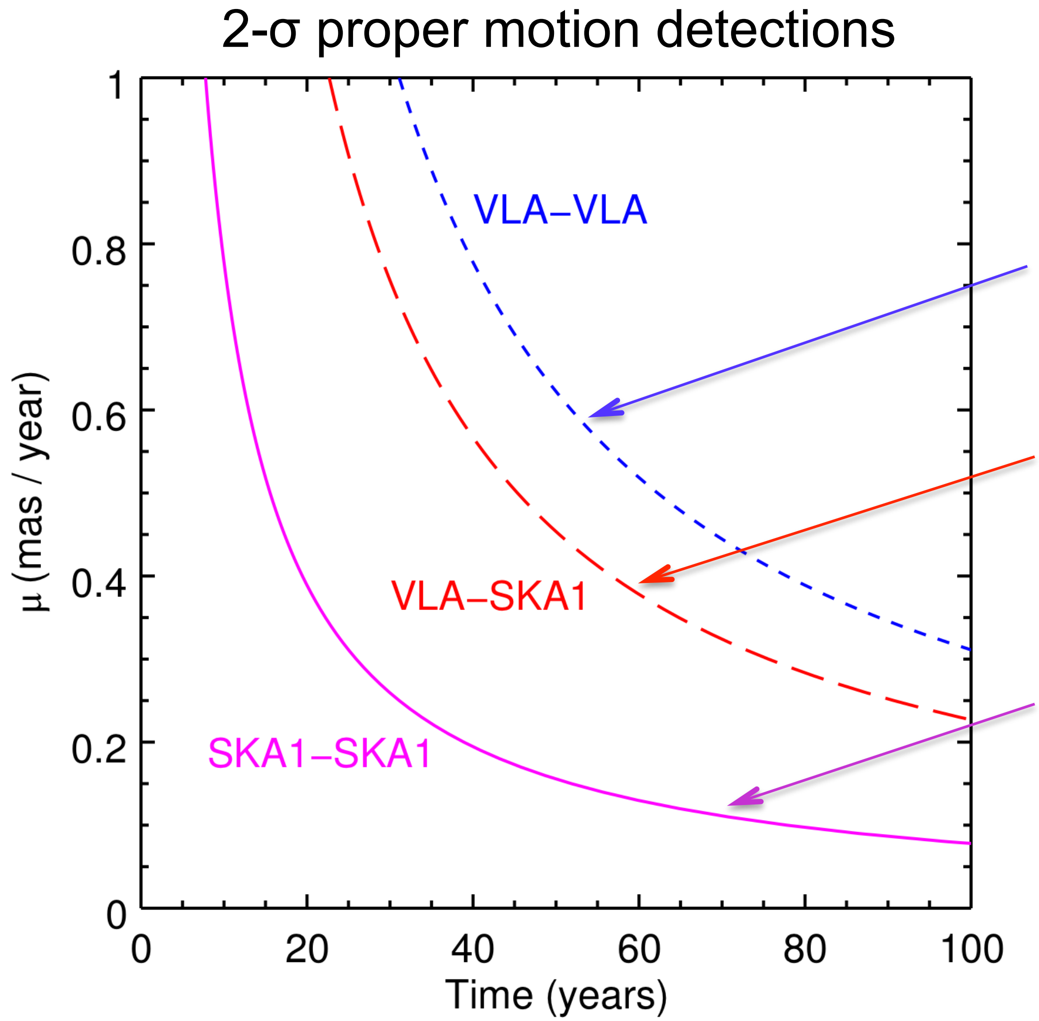
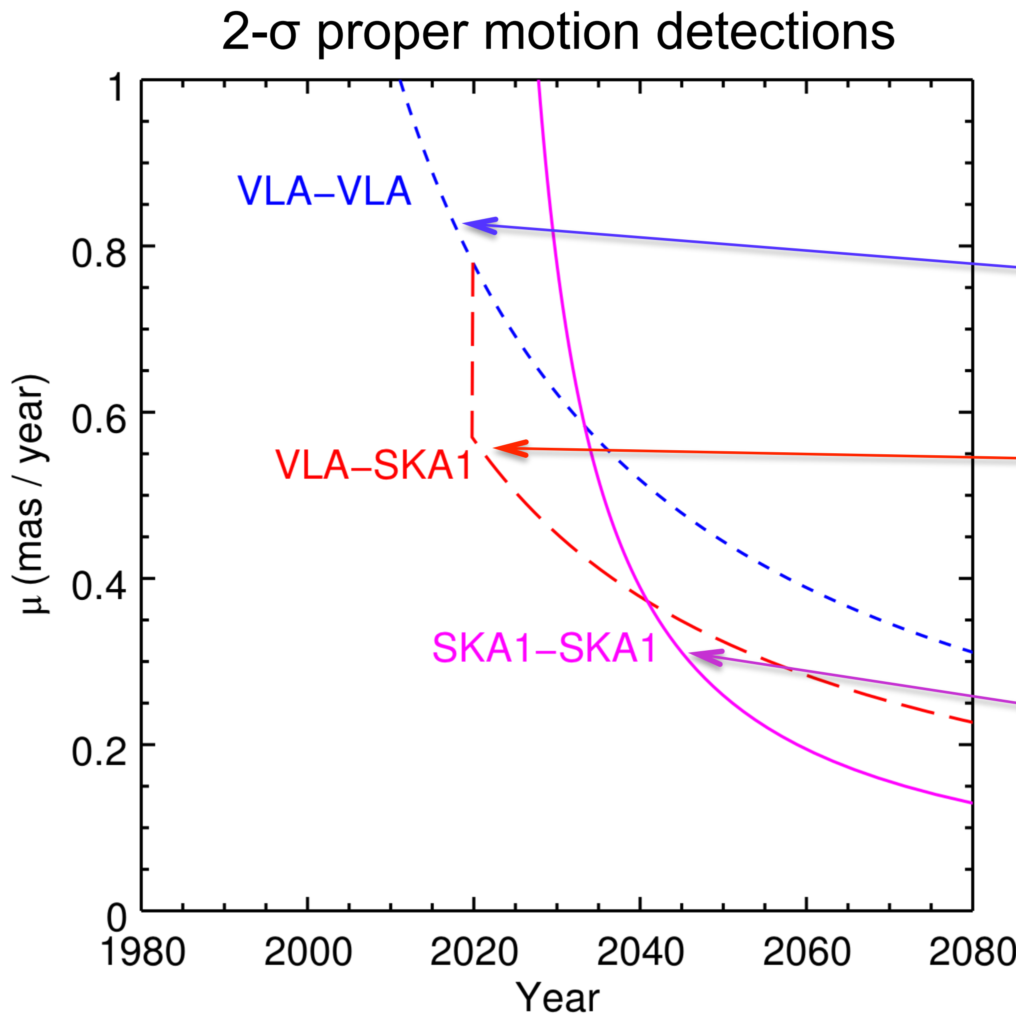
→ SKA1 immediately improves sensitivity to proper motions

2. Apparent Motions on Kiloparsec-scales?



- VLA currently sensitive to proper motions, $\mu \sim 0.8$ mas / yr
- Adding SKA1 immediately improves sensitivity to $\mu < 0.55$ mas/yr
- SKA1 alone sensitive to interesting range, $\mu \sim 0.3$ mas/yr after 25 years

2. Apparent Motions on Kiloparsec-scales?



- VLA currently sensitive to proper motions, μ ~ 0.8 mas / yr
- Adding SKA1 immediately improves sensitivity to μ < 0.55 mas/yr
- SKA1 alone sensitive to interesting range, μ ~ 0.3 mas/yr after 25 years

The time is ripe to select targets in anticipation for SKA1

← 1996 : 2015 : 2025 →

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Overview

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Abstract. A survey of mostly recent developments in the state of our knowledge and/or understanding of energy transport towards AGN from a gas disc and out of AGN into the jets, hot spots, and lobes of radio galaxies and quasars.

1. Introduction

The big questions remain:

1. Do most/all galaxies have an AGN phase?
2. Why do AGN produce powerful jets if and only if the host galaxy is an elliptical?
3. Why the FR I—FR II boundary?
4. What makes the magnetic field, and why is $|\mathbf{B}| \approx B_{\text{equipartition}}$?
5. Are jets $p^+ — e^-$ or $e^+ — e^-$ (or something else)?
6. Do large-scale jets move at $\gamma \approx 10$, or do they slow down to $\gamma < 1.5$?

- A multi-spectral view of AGN phases/episodes, young and old, in all galaxy types
- Within reach: how relativistic are jets on >10's kpc-scales via direct measurements, or limits, on jet/counter-jets and proper motions. Bearing on particles, field, energy transport.

Homework – due April 24, 2025

1. Informed by γ-ray detections of lobes at all scales in widely varying systems, (re-)evaluate commonly adopted high-energy emission mechanisms
2. Establish rate of AGN activity in otherwise inactive galaxies (X-rays, UV/optical, and radio)
3. What hidden signatures of AGN at unexplored wavelength regimes?
4. Find radio counter-jets in well-aligned low-power jets with e-VLA
5. Prepare large (N =1000+), low-frequency selected sample for SKA1 :
   1. detect jets and counter-jets, down to 0.5 μJy, derive ratios
   2. constrain characteristic jet speed (maximum, and range)
   3. Determine possible environmental factors
6. Determine the conditions where Owen-Ledlow dependence holds
7. Establish statistics of FR1 and FR2's in spiral hosts
8. Establish statistics of HYMORs
   1. Are jets always on the FR1 side?
   2. Do VLBI jets always point in the FR1 side? Or also in FR2 side?
   3. Laing-Garrington depolarization measurements of lobes
9. Establish statistics of episodic radio sources
10. Identify sample of best-aligned blazars to measure superluminal motions on >10 kpc-scales
    1. Use archival VLA data, obtain new e-VLA data now to establish intermediate time baselines
    2. Look back to MRTLI (Multi-Telescope Radio Linked Interferometer) = MERLIN data
    3. Look at HST data obtained
11. Measure, or constrain, on >10 kpc-scales, proper motions of <= 0.25-0.30 mas/yr

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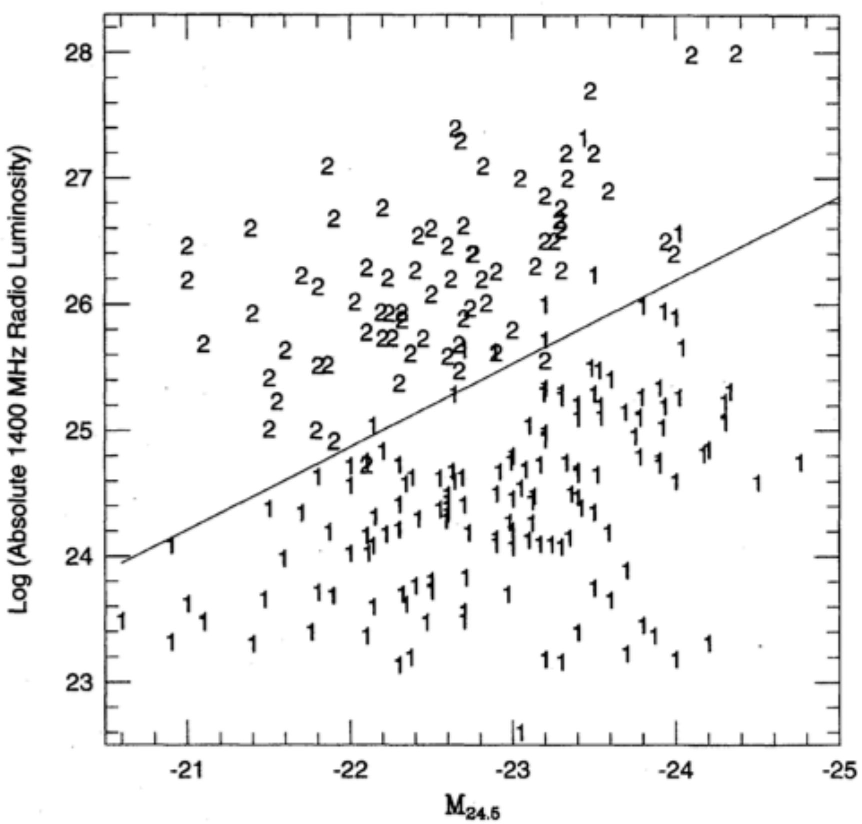
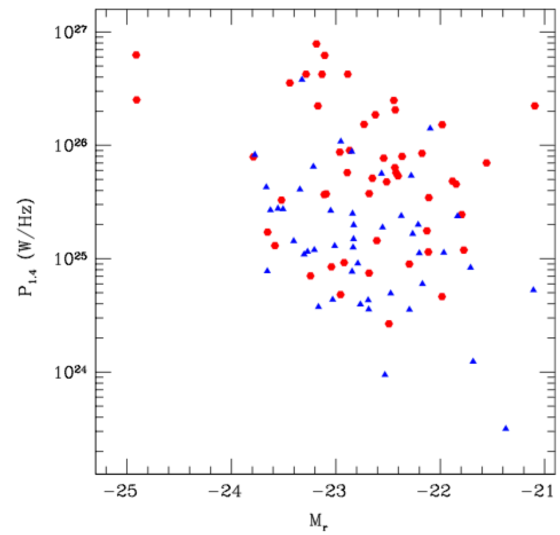
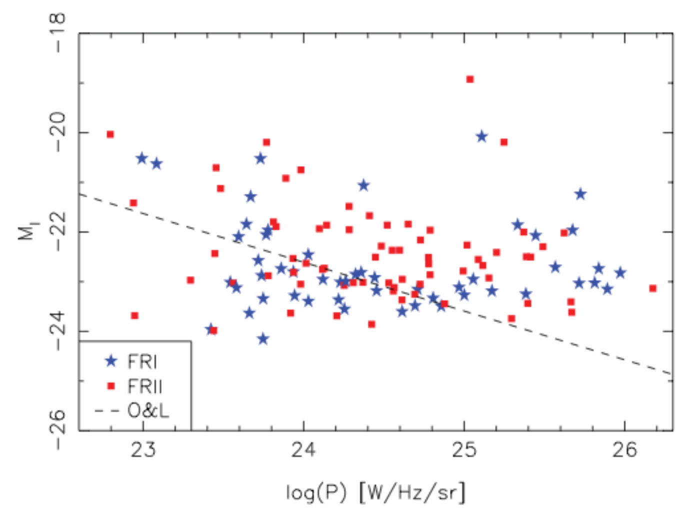
Supplement A. Owen-Ledlow Diagram



Ledlow & Owen (1996)

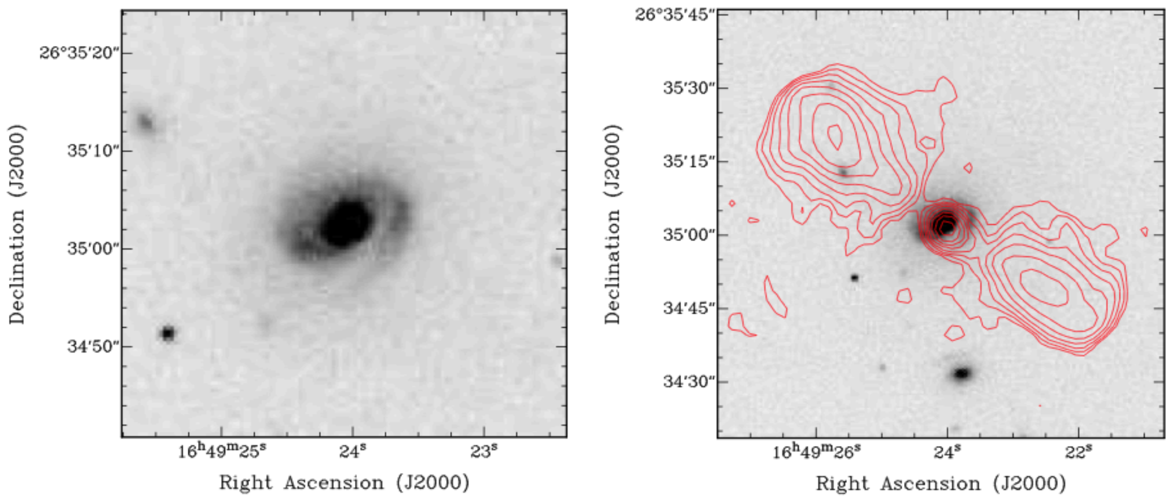


Lin et al. (2010)

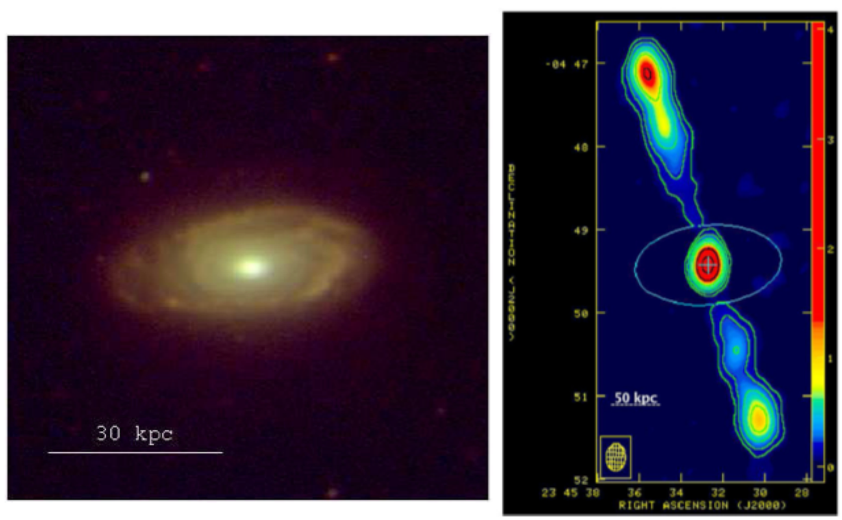


Gendre et al. (2013)

Supplement B. Spiral-hosted FR2s



J1649+2635 (Mao et al. 2015)



J2345-0449 (Bagchi et al. 2014)