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and Some Related Recent Radio Observations

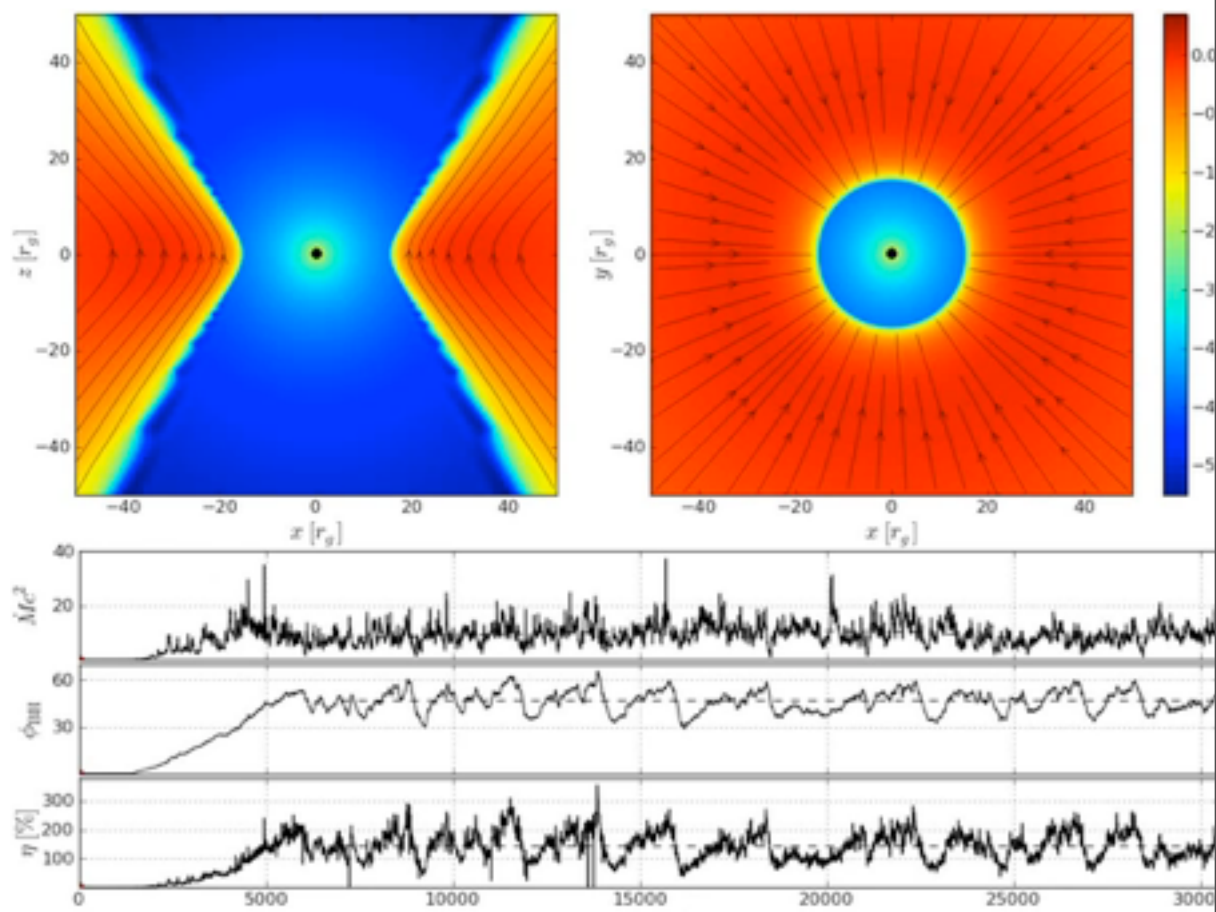
Anthony Readhead

California Institute of Technology

Extragalactic Relativistic Jets; Cause and Effect Bangalore 12-20 October 2015

There are Three Major Aspects to the Unified AGN Story

Theory & Simulations



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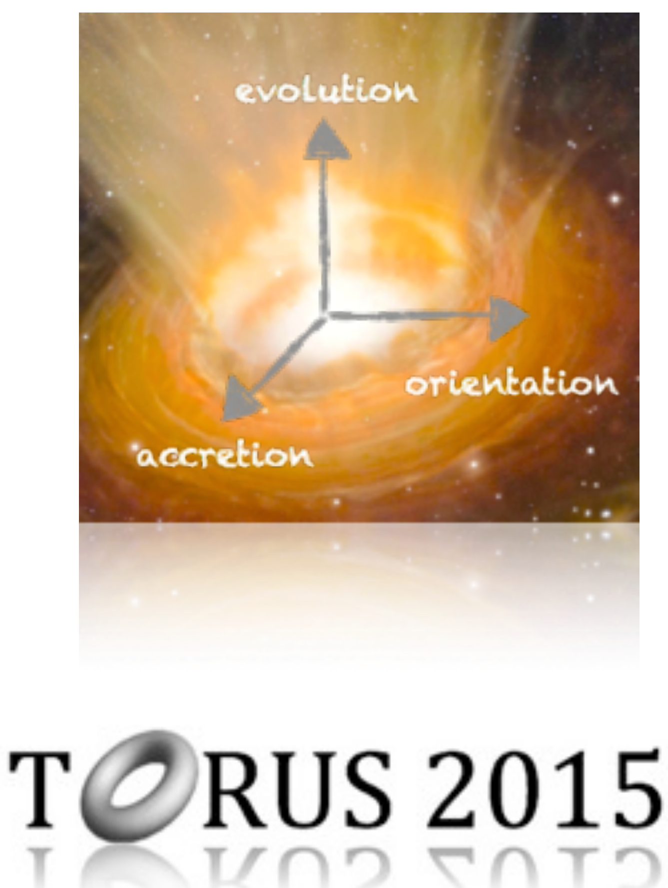

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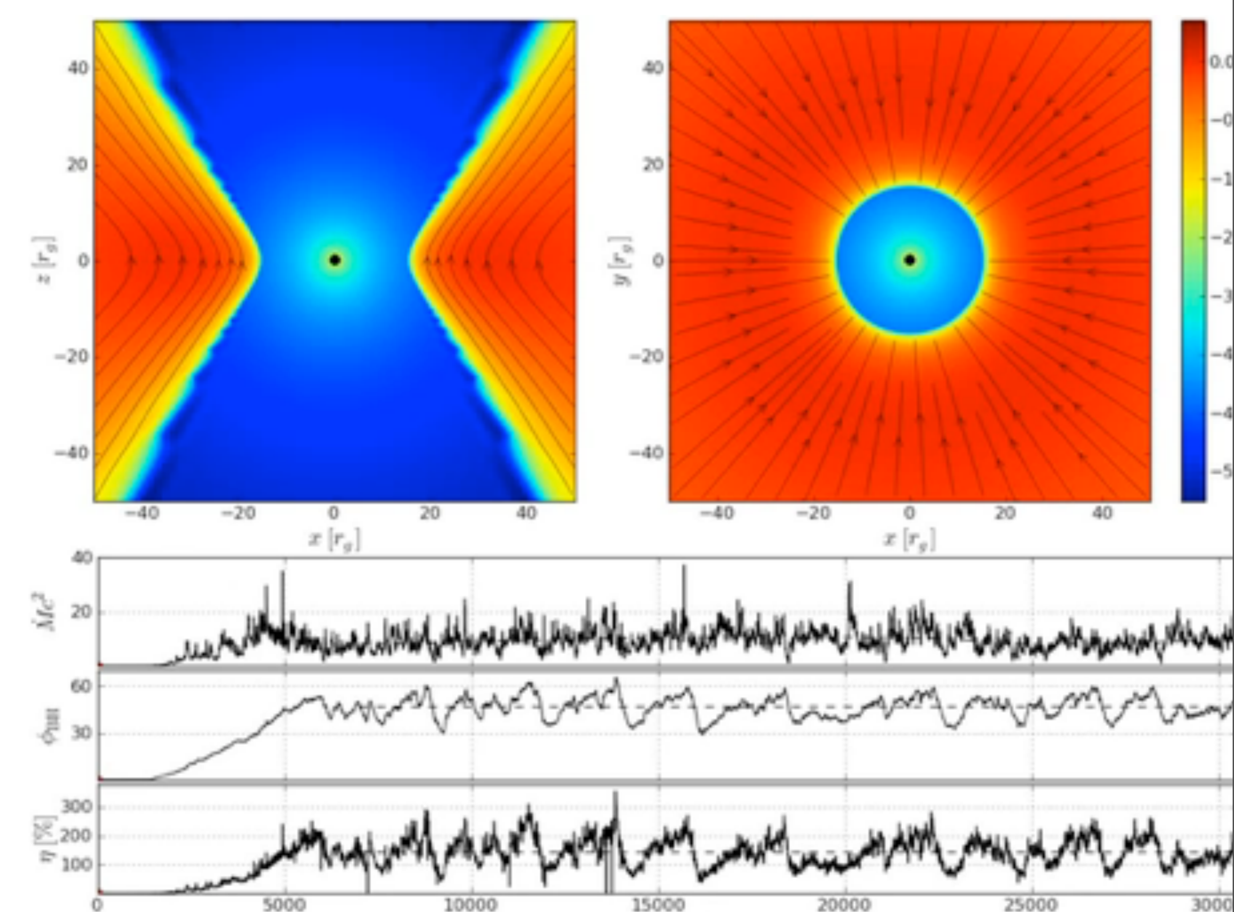

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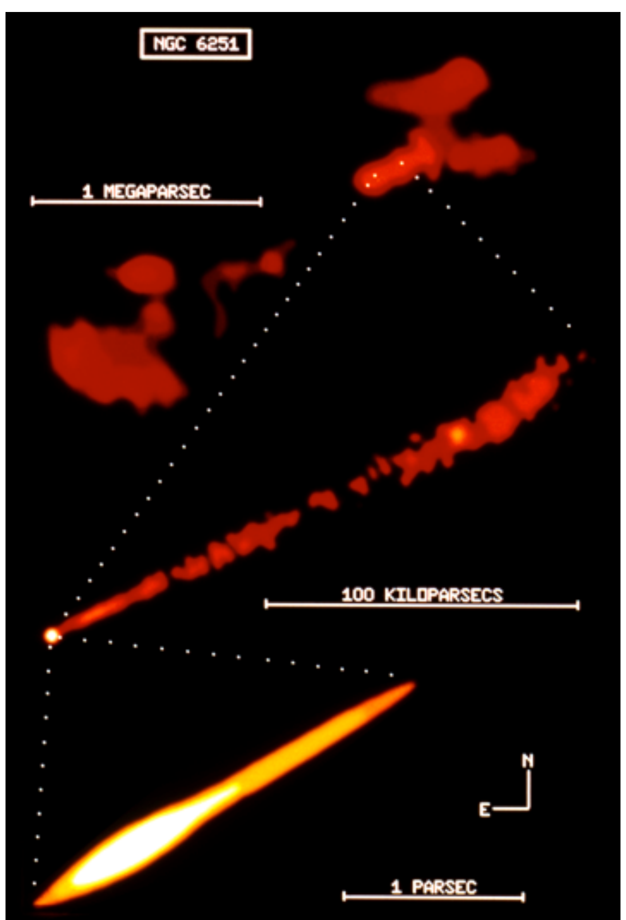

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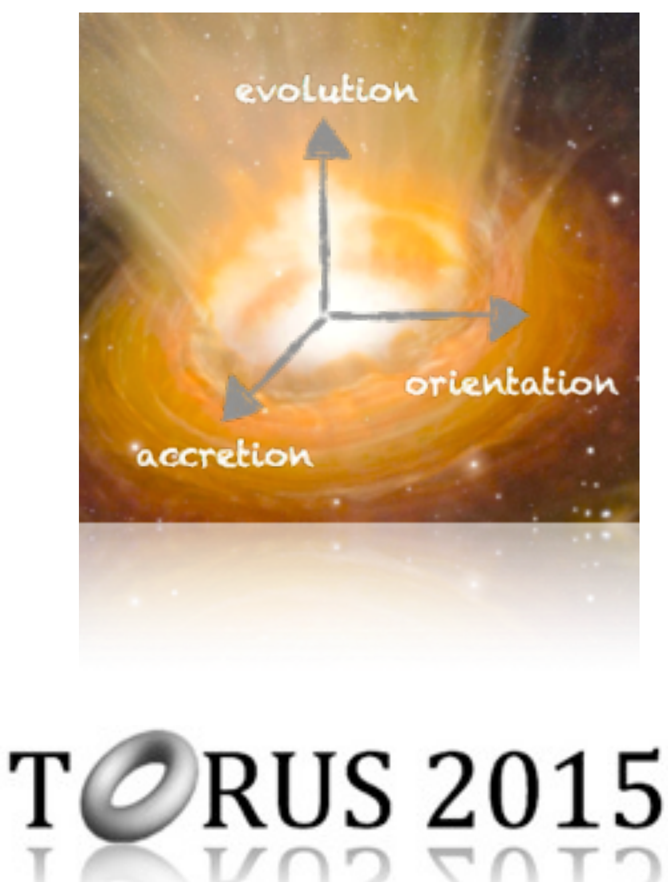

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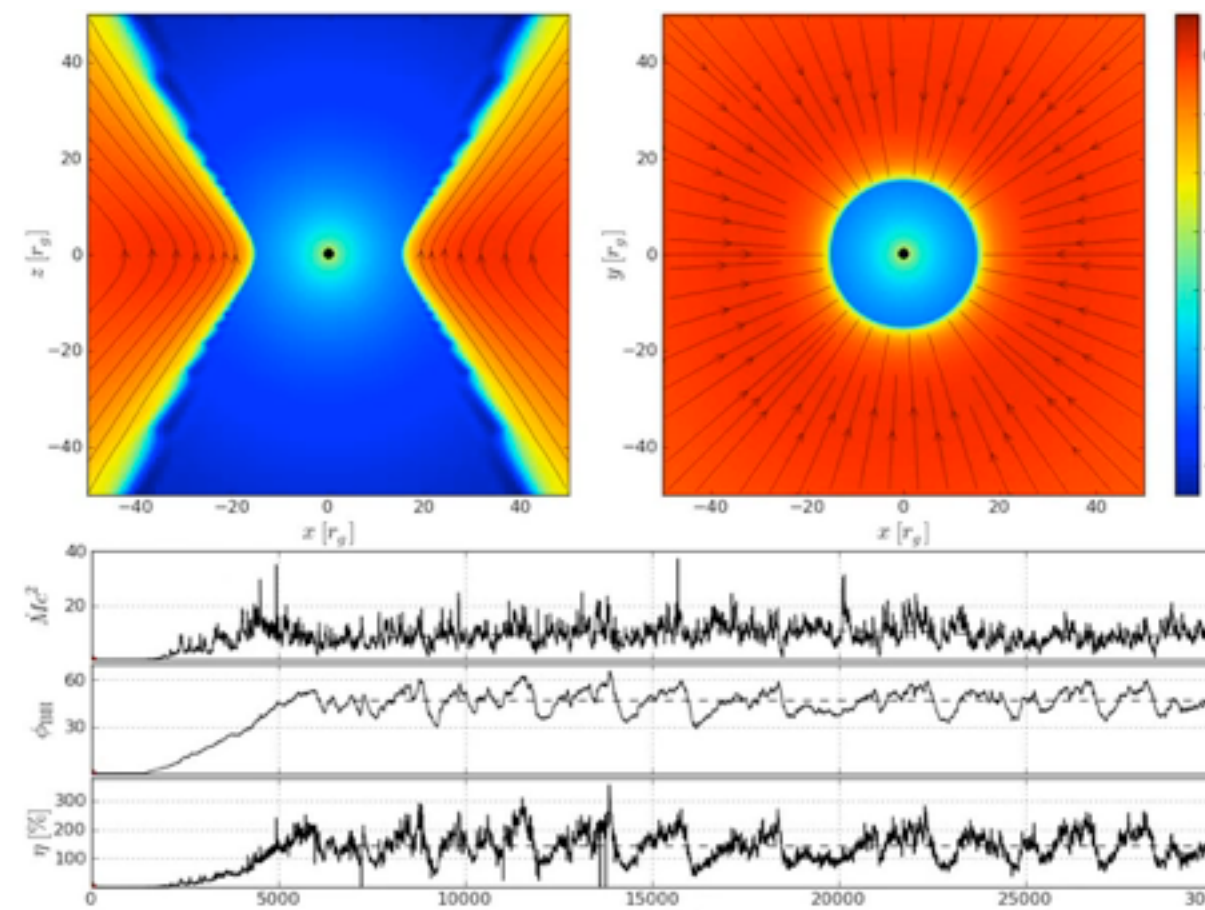

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Most people who have written papers and reviews on Unified Theories of AGN over the last 30 years have ignored the fact that radio astronomy and VLBI played an Absolutely Key and Pioneering Role in the development of the story before 1980! I think this is because they just took the radio and VLBI results for granted without thinking about the implications for Unified Theories had the radio and VLBI results been different to what was found.

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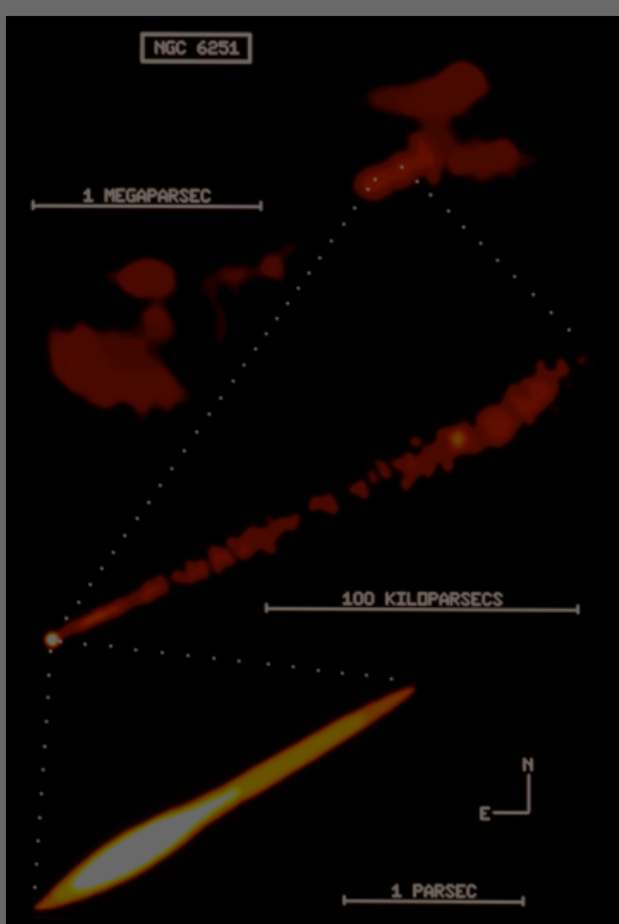

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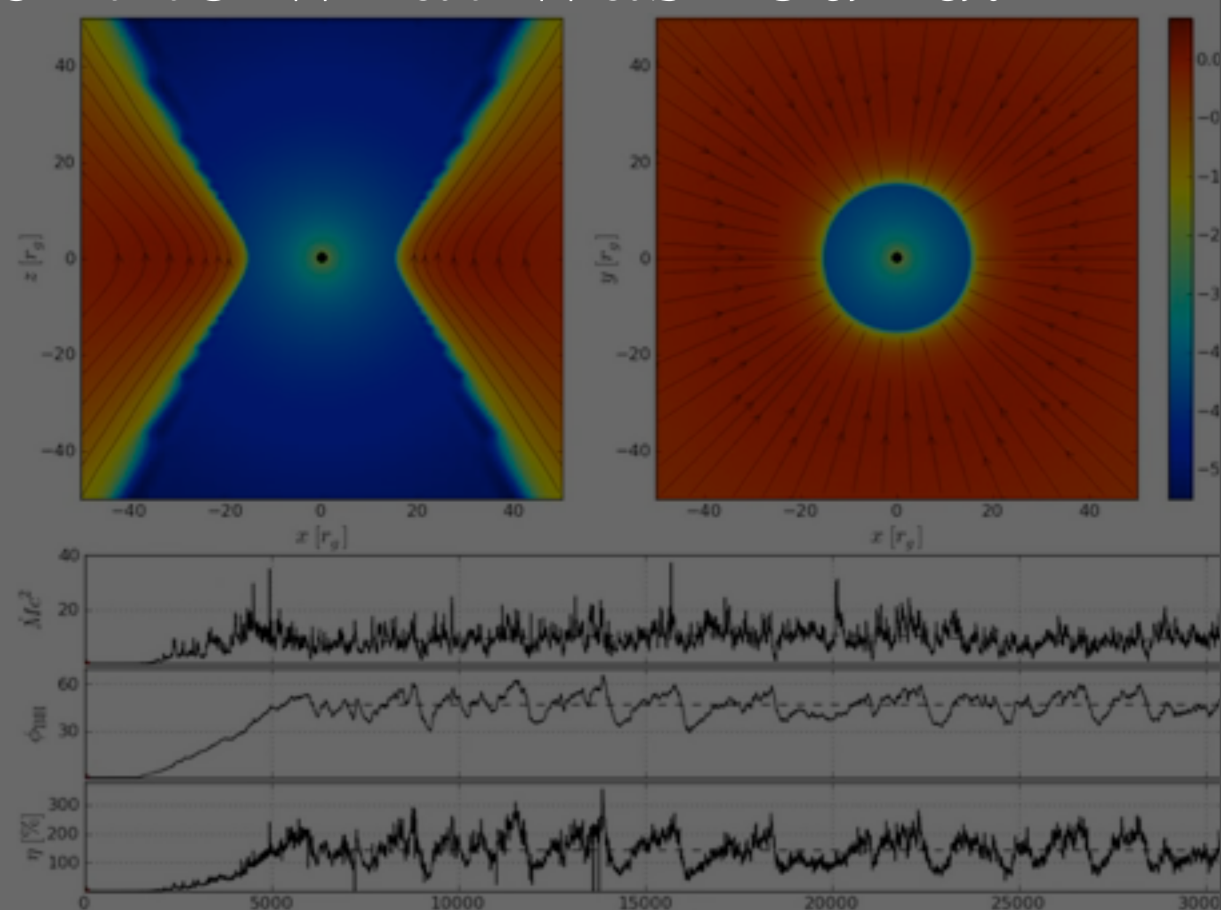

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Sir Martin Ryle and M. S. Longair

(Received 1966 December 29)

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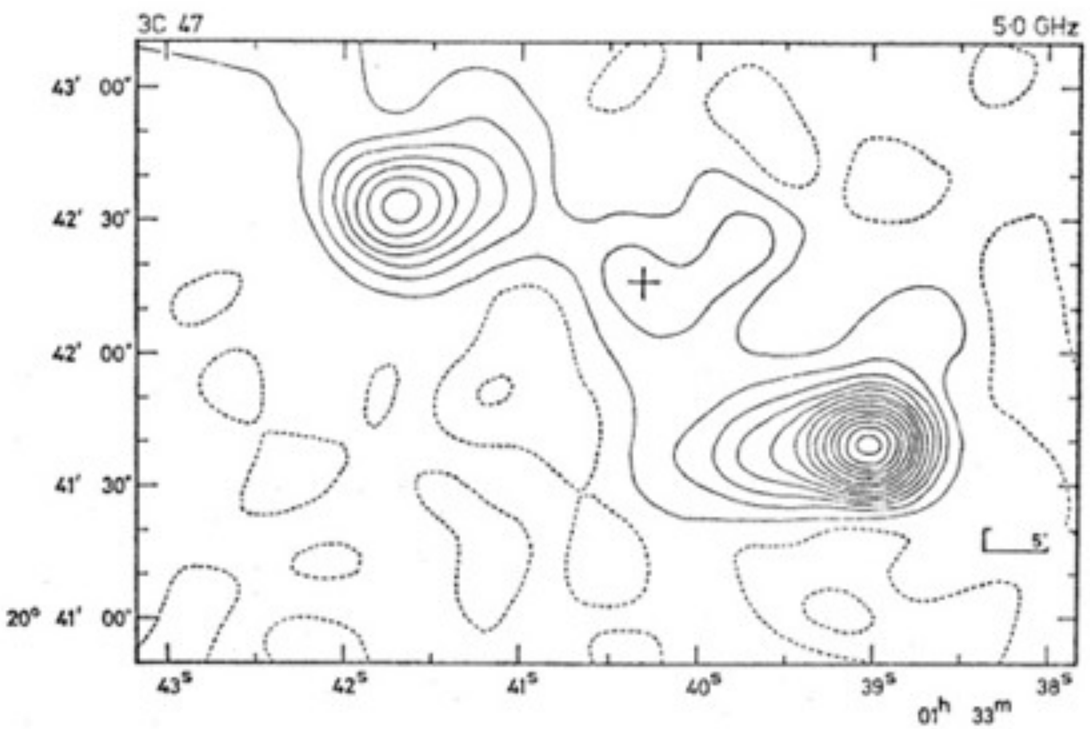

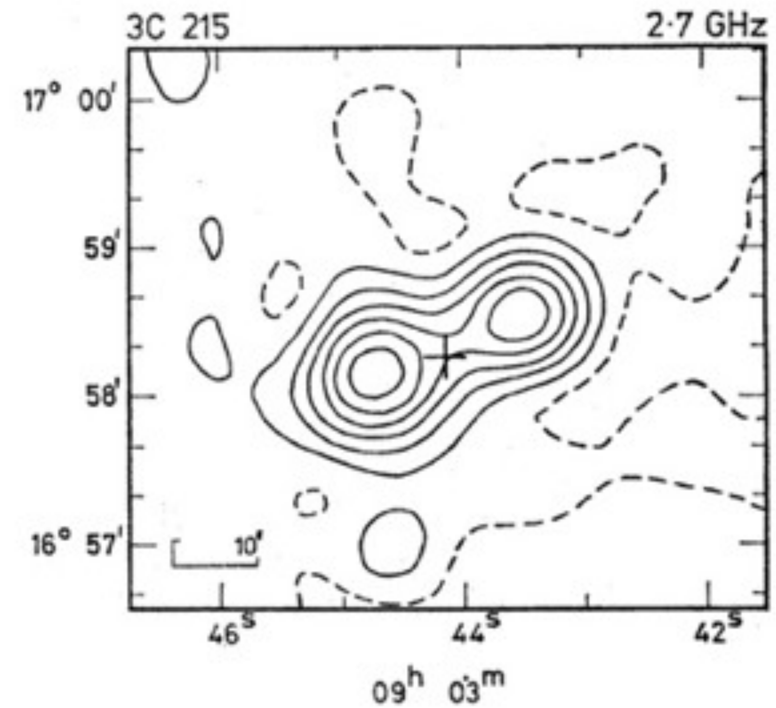

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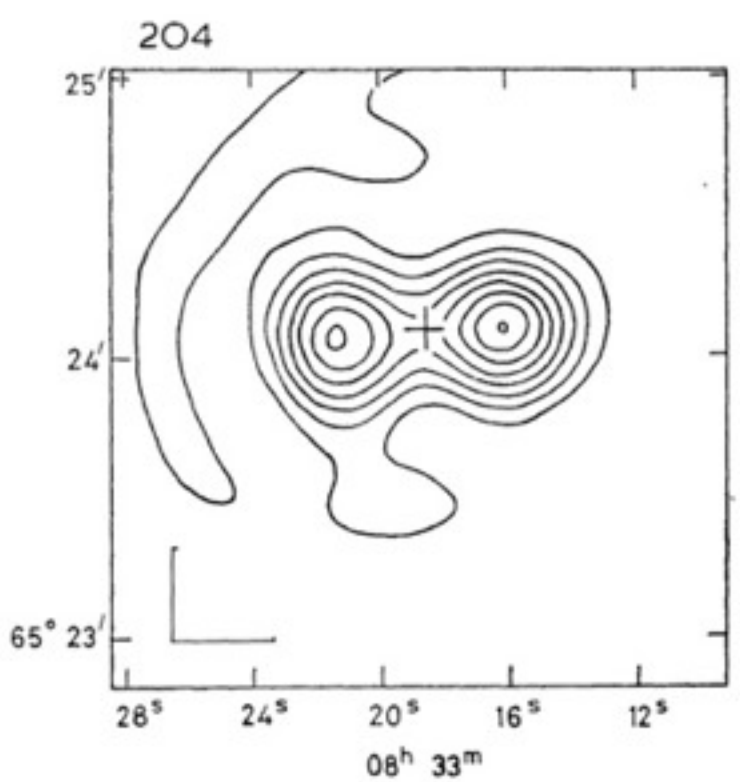

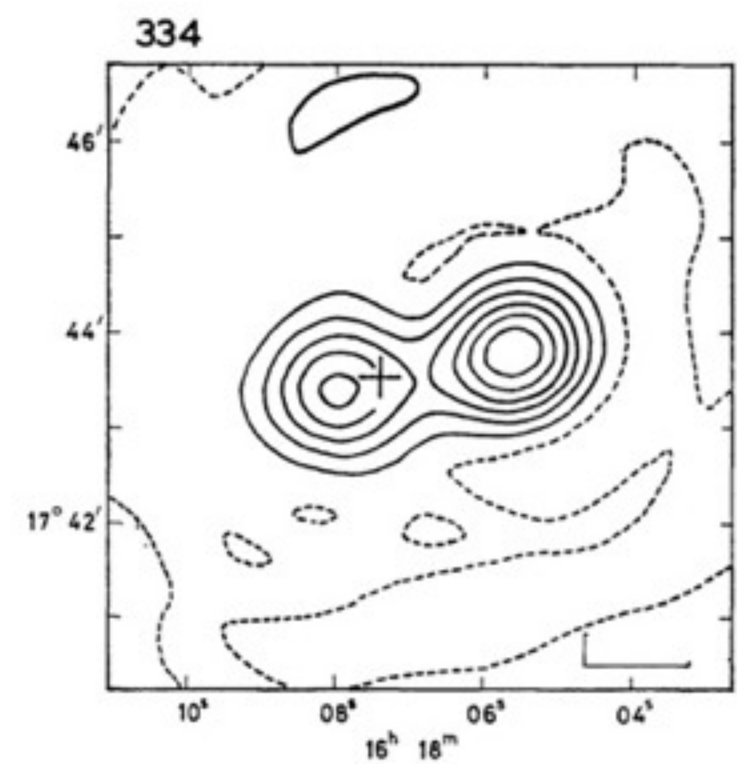

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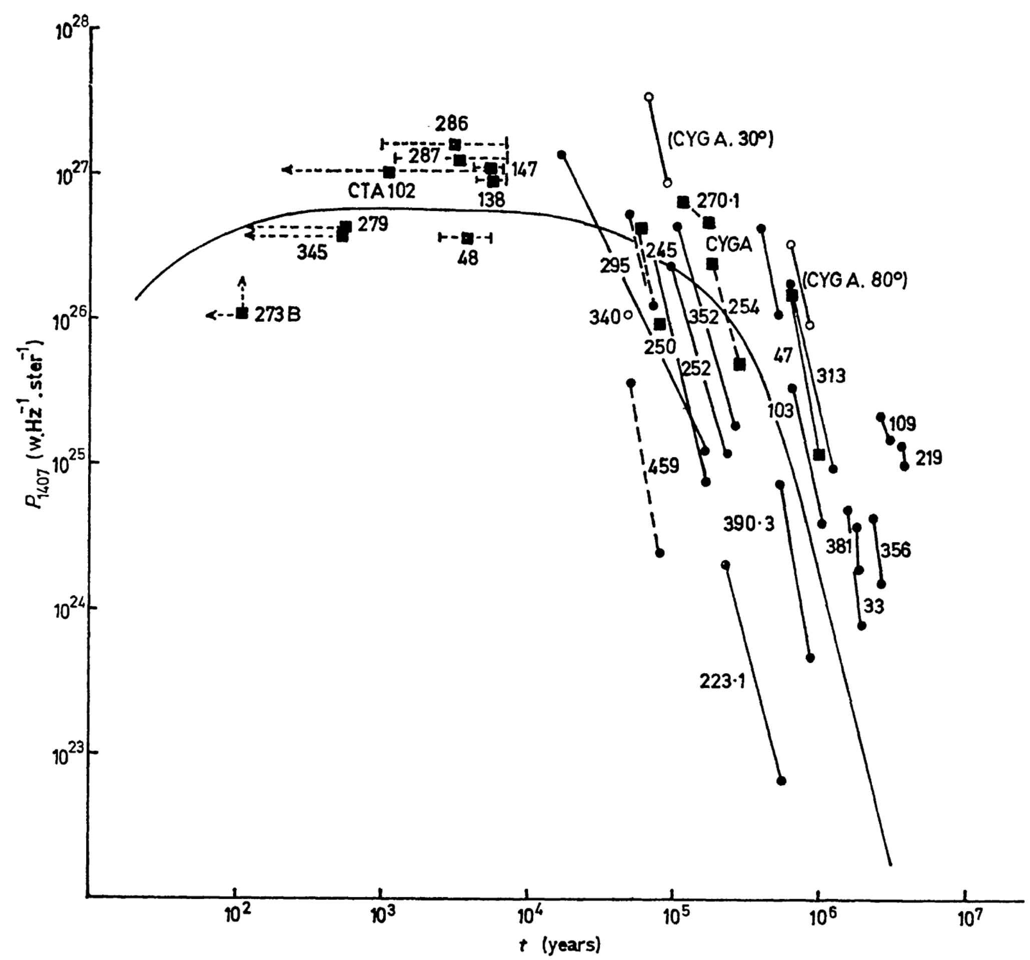

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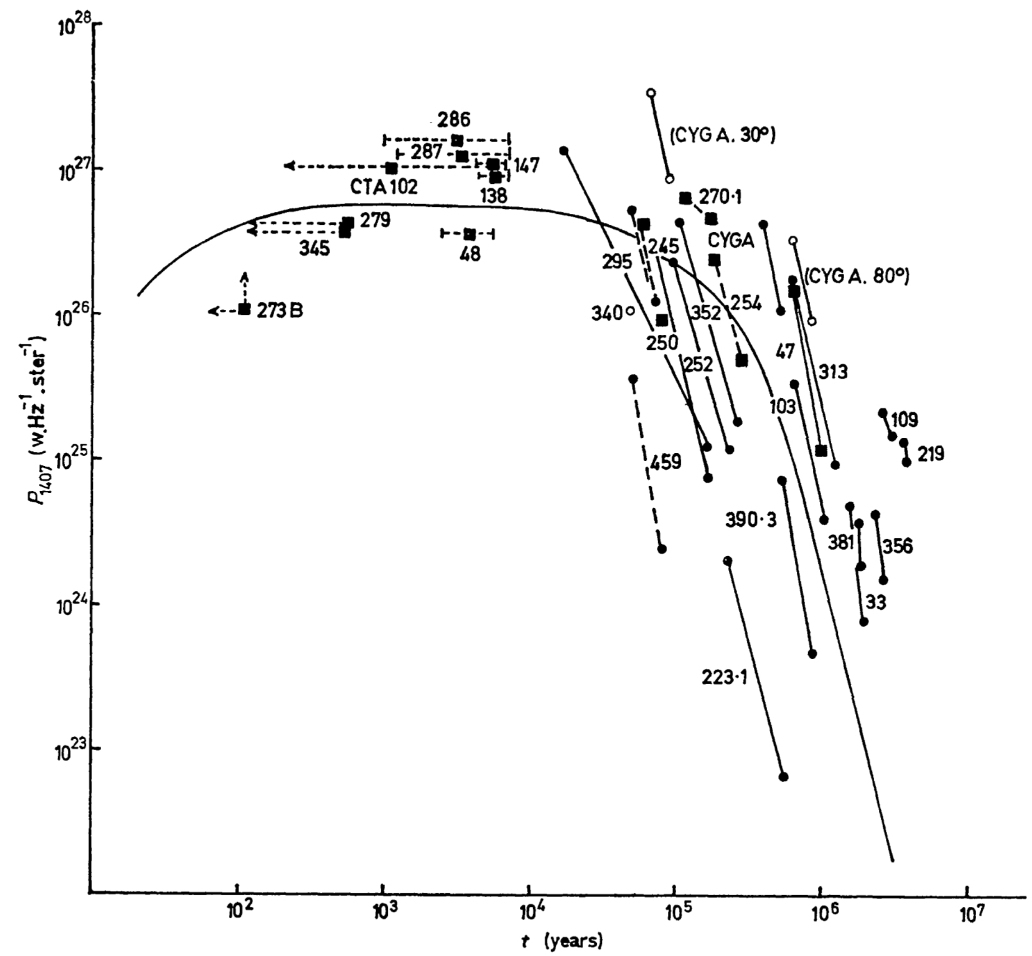
"No distinction is made between quasi-stellar sources and radio galaxies; it is indicated how both may represent different stages in one evolutionary sequence"



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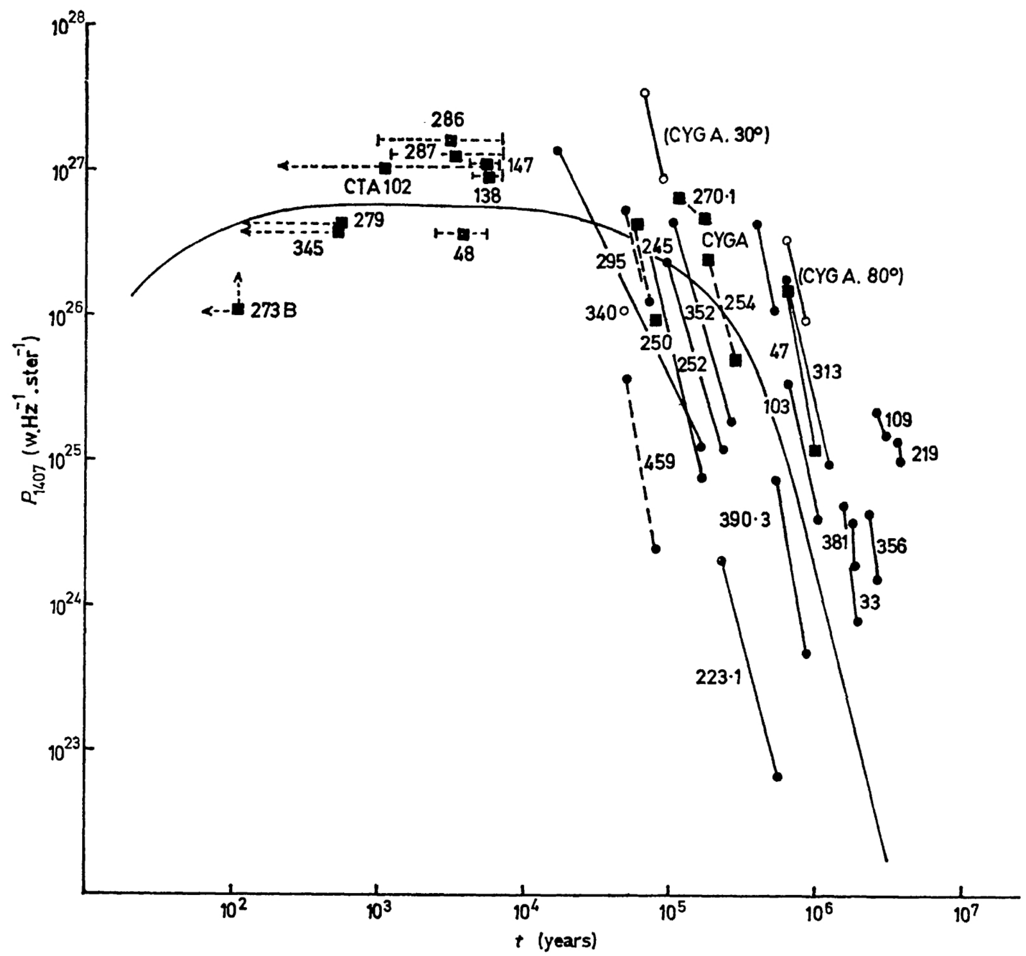

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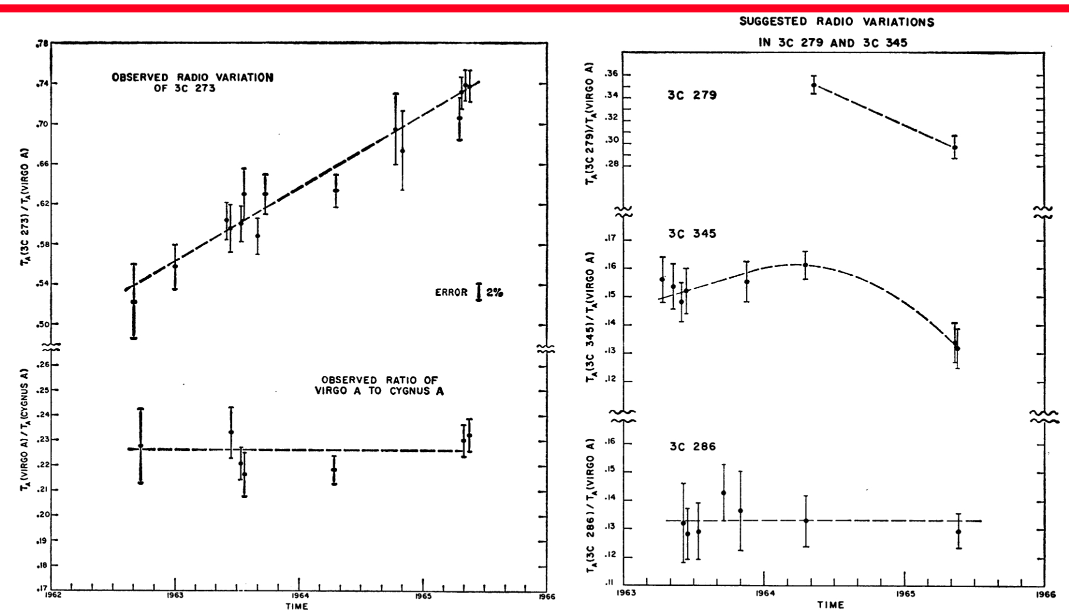
I might have concluded that the distinction of making the first step towards a unified theory of AGN went to Ryle & Longair, but in fact I think that belongs most properly to Rees for the following reasons:



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Dent 1965, Science, 148, 1458
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The Key Step: Superluminal Motion

→ APPEARANCE OF RELATIVISTICALLY EXPANDING RADIO SOURCES
Rees1966, Nature, 211, 468

1. Explained rapid variability in PEGRS
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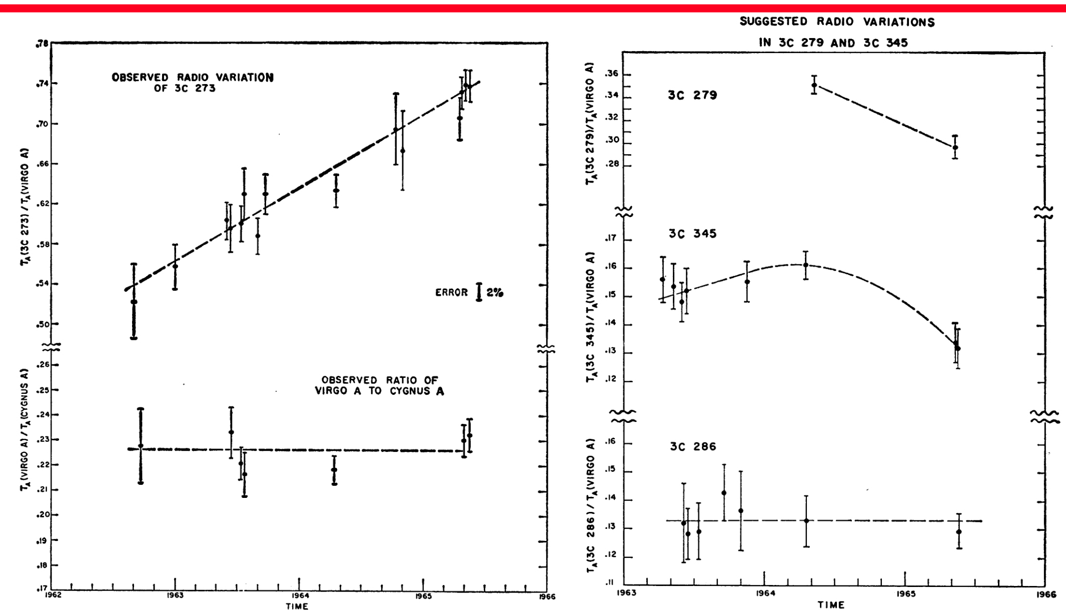

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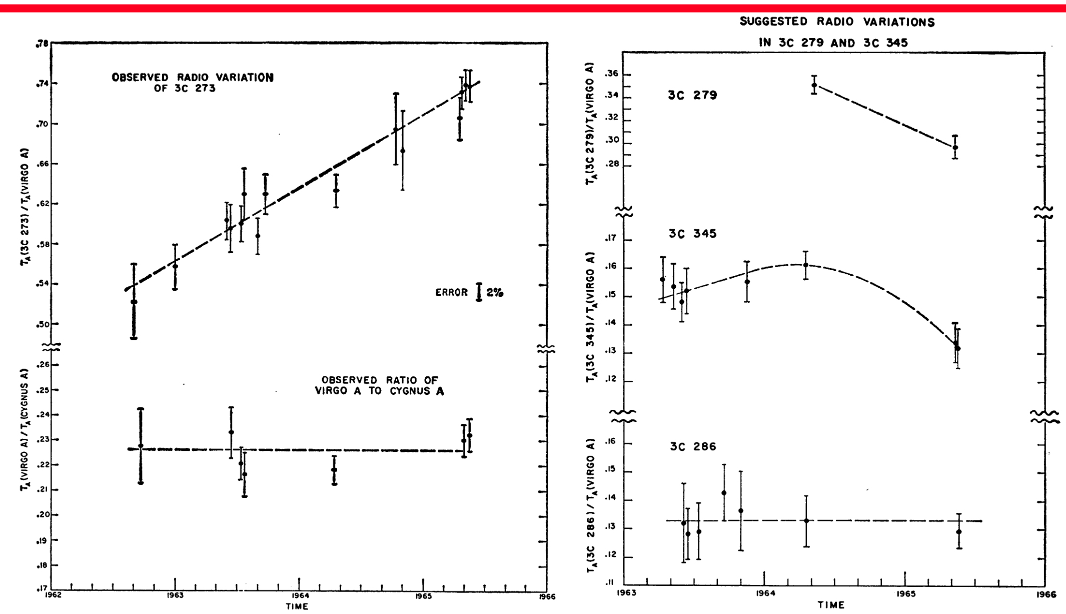

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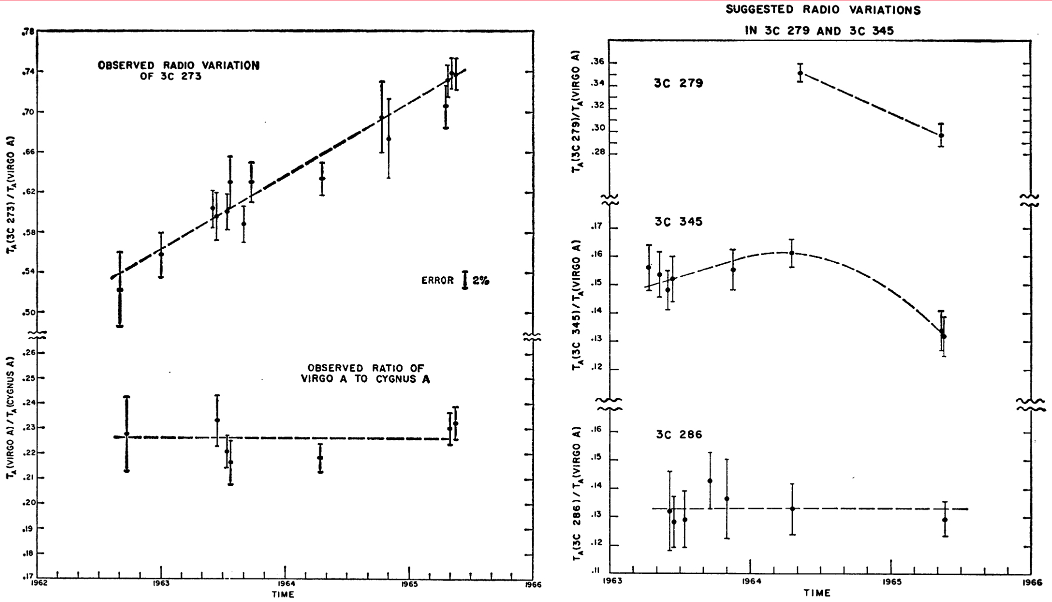

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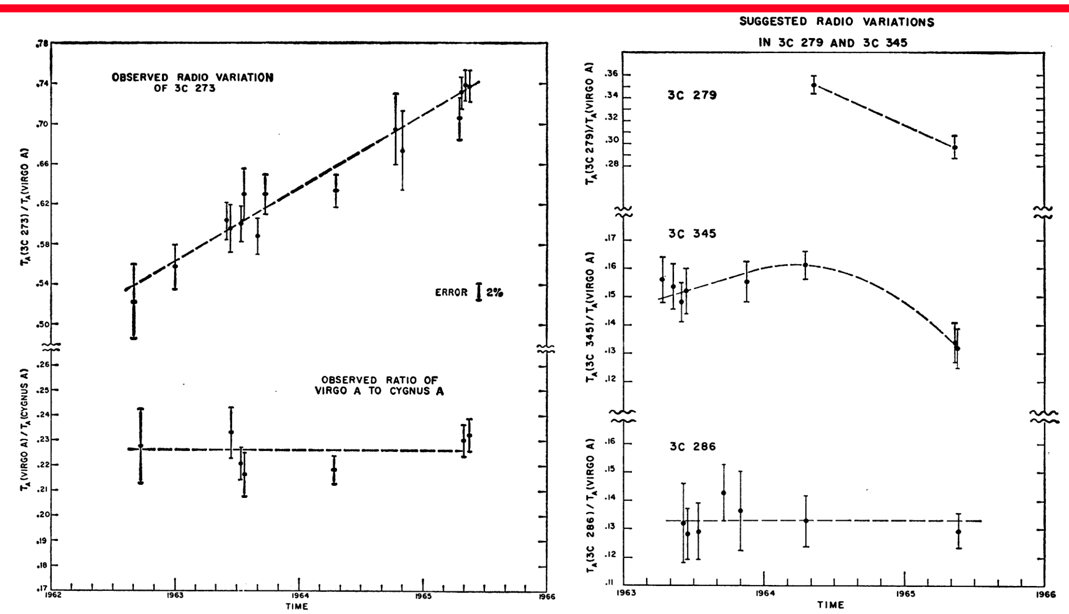

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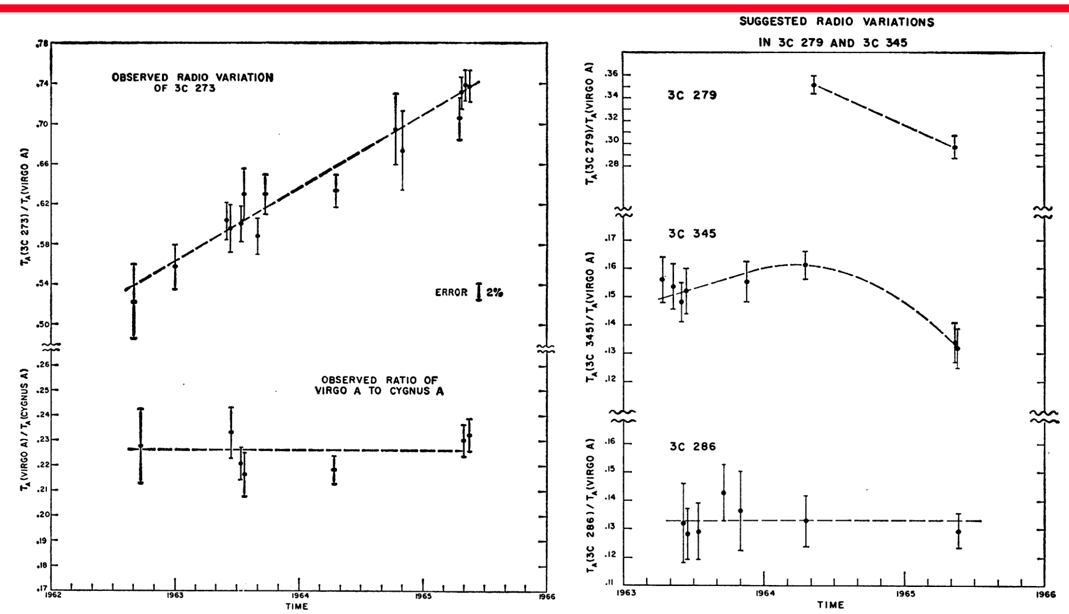

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ELECTROMAGNETIC EXTRACTION OF ENERGY FROM KERR BLACK HOLES	Blandford & Znajek 19777, MNRAS, 179, 433
RELATIVISTIC JETS AS COMPACT RADIO SOURCES	Blandford & Konigl 1979 ApJ, 232, 34
HYDROMAGNETIC FLOWS FROM ACCRETION DISKS AND THE PRODUCTION OF RADIO JETS	Blandford & Payne 1982 MNRAS, 199, 883

What about Key Observational Steps in AGN Unification in the 70s?

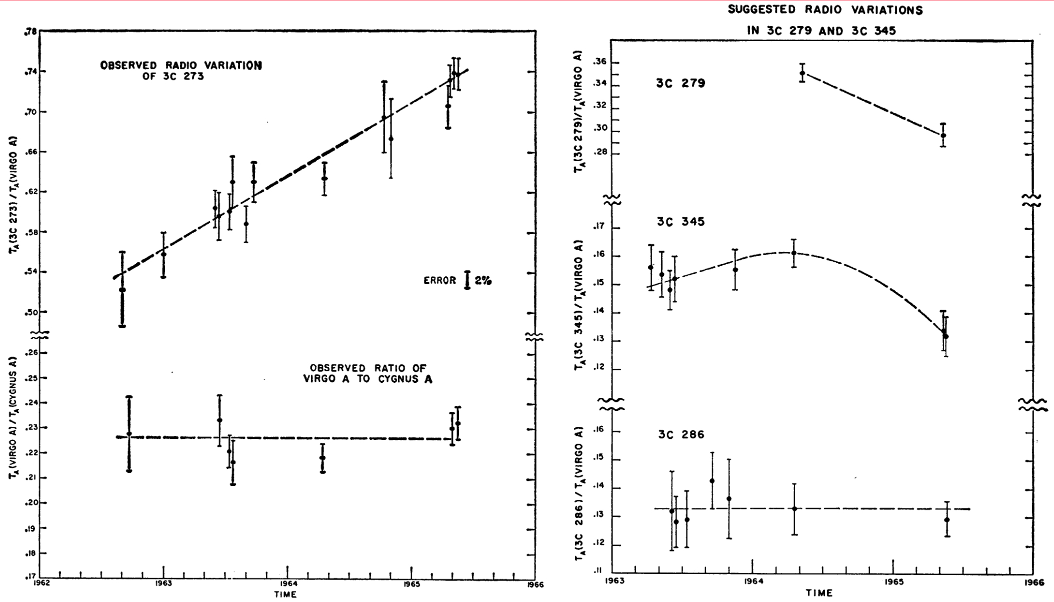


Fig. 1 (left). The ratio of the corrected antenna temperature, T_A, at 8000 Mc/sec of the quasi-stellar source 3C 273 to that of Virgo A, showing the observed 40-percent increase in the radio emission over a nearly three-year period. The measured ratio of Virgo A to Cygnus A shows no variation over the same period. Fig. 2 (right). Evidence for possible variations in the radio emissions of the quasi-stellar sources 3C 279 and 3C 345 at 8000 Mc/sec, and for a lack of variation in the quasi-stellar source 3C 286. Like 3C 273, which shows variations, both 3C 279 and 3C 345 have flat radio spectra at 8000 Mc/sec.

Dent 1965, Science, 148, 1458

Lack of synchrotron self-absorption as shown by their spectra g... emitting region... associated w...

The Key Step: Superluminal Motion

APPEARANCE OF RELATIVISTICALLY EXPANDING RADIO SOURCES
Rees1966, Nature, 211, 468

The first unification paper

STUDIES IN RADIO SOURCE STRUCTURE
Rees 1967, MNRAS, 135, 345

So while this is indeed the 30th anniversary of the Torus, it is the 49th anniversary of Unification Theories of Active Galaxies!

Gubbay, Legg, Robertson, Moffet, Ekers, Seidel 1969
Nature 224, 1094
Moffet, Gubbay, Robertson & Legg (IAU S, 44)
(conference was in 1970 - proceedings 2 years later)
Cohen et al. 1971, ApJ, 170, 207
..., 173, 225

Further...

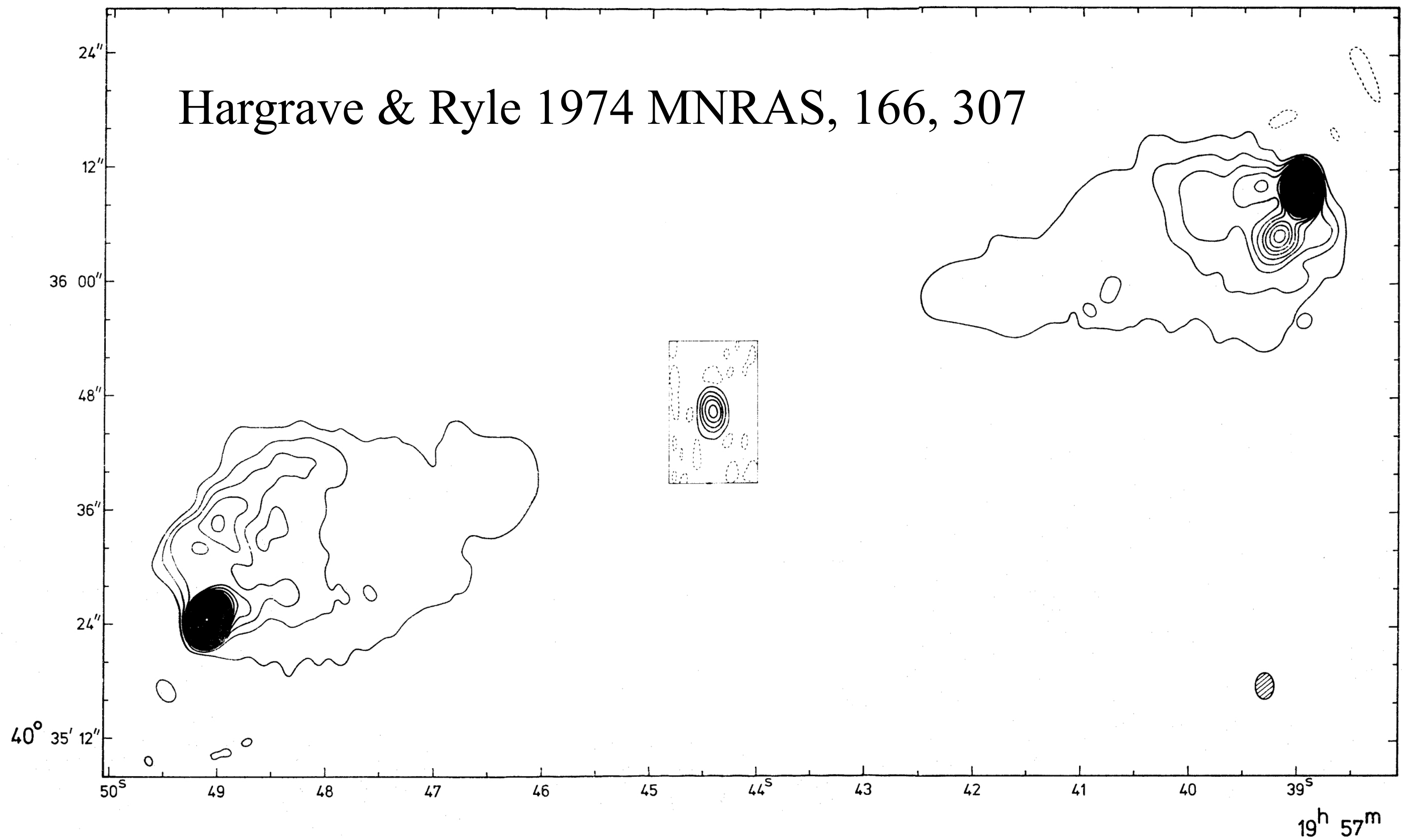
GAl... 1969 Nature, 223, 690

A TWI... ...s 1974 MNRAS, 169, 395

ELECTROMA... ...ek 19777, MNRAS, 179, 433

RI... ...onigl 1979 ApJ, 232, 34

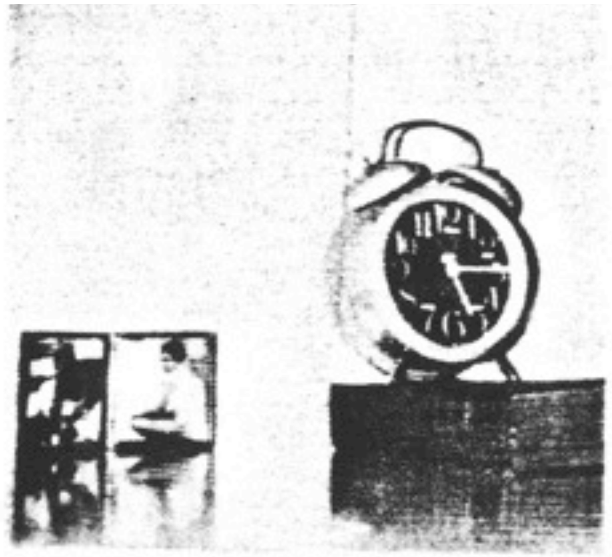
HYDROM... ...e 1982 MNRAS, 199, 883



What about Key Observational Steps in AGN Unification in the 70s?

Hewish: In aperture synthesis the image is the Fourier Transform of the complex visibility function measured by an interferometer

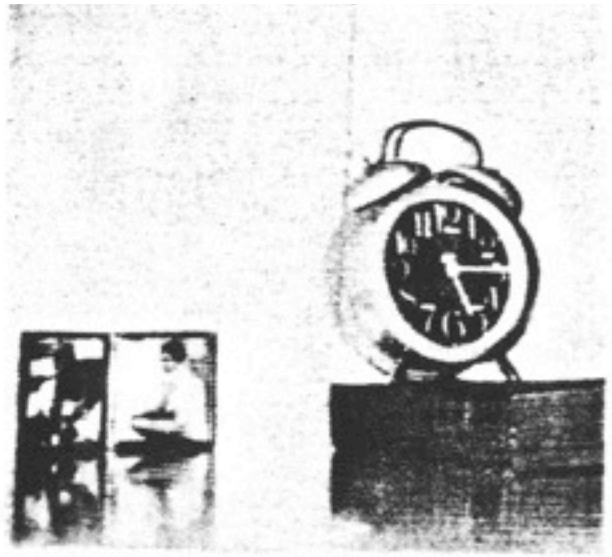
Why is the phase more important in reconstructing the image than the amplitude?



Interferometer measures the "Visibility", which is the Fourier Transform of the source brightness distribution

$|V_{clock}|\ e^{-i2\pi\theta_{clock}}$ $\rightleftharpoons$

$|V_{Cronkite}|\ e^{-i2\pi\theta_{Cronkite}}$ $\rightleftharpoons$



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$|V_{clock}| \, e^{-i2\pi\theta_{clock}}$ ⇅

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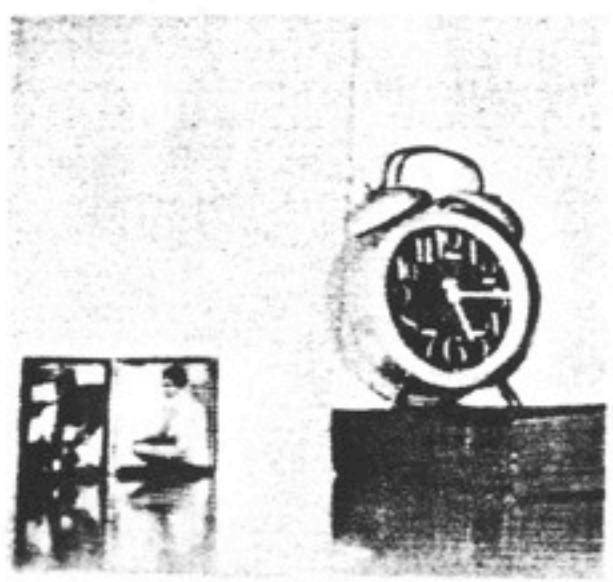
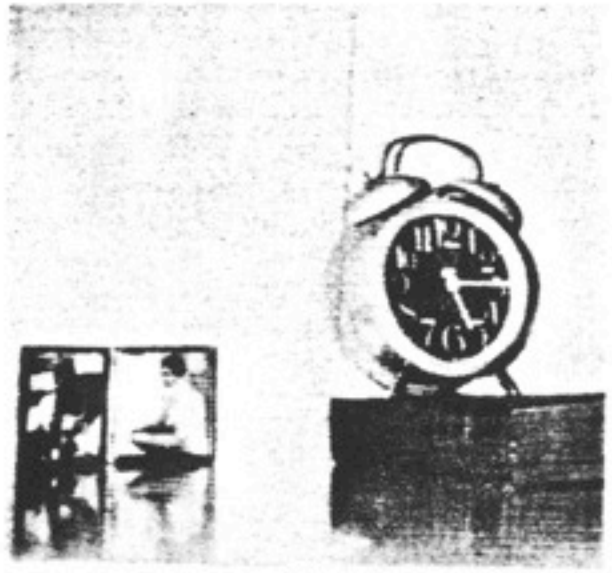
In a computer we Fourier Transform the “Visibility” to recover An image of the source



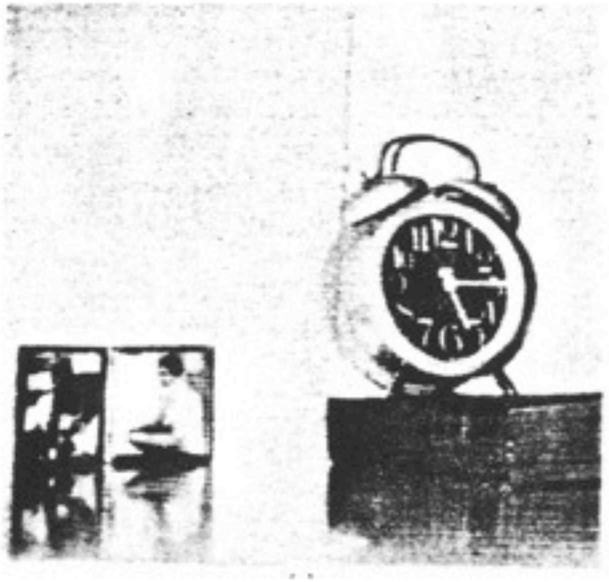


$\Updownarrow$

$|V_{clock}|\ e^{-i2\pi\theta_{clock}}$

$\Updownarrow$

$|V_{Cronkite}|\ e^{-i2\pi\theta_{Cronkite}}$



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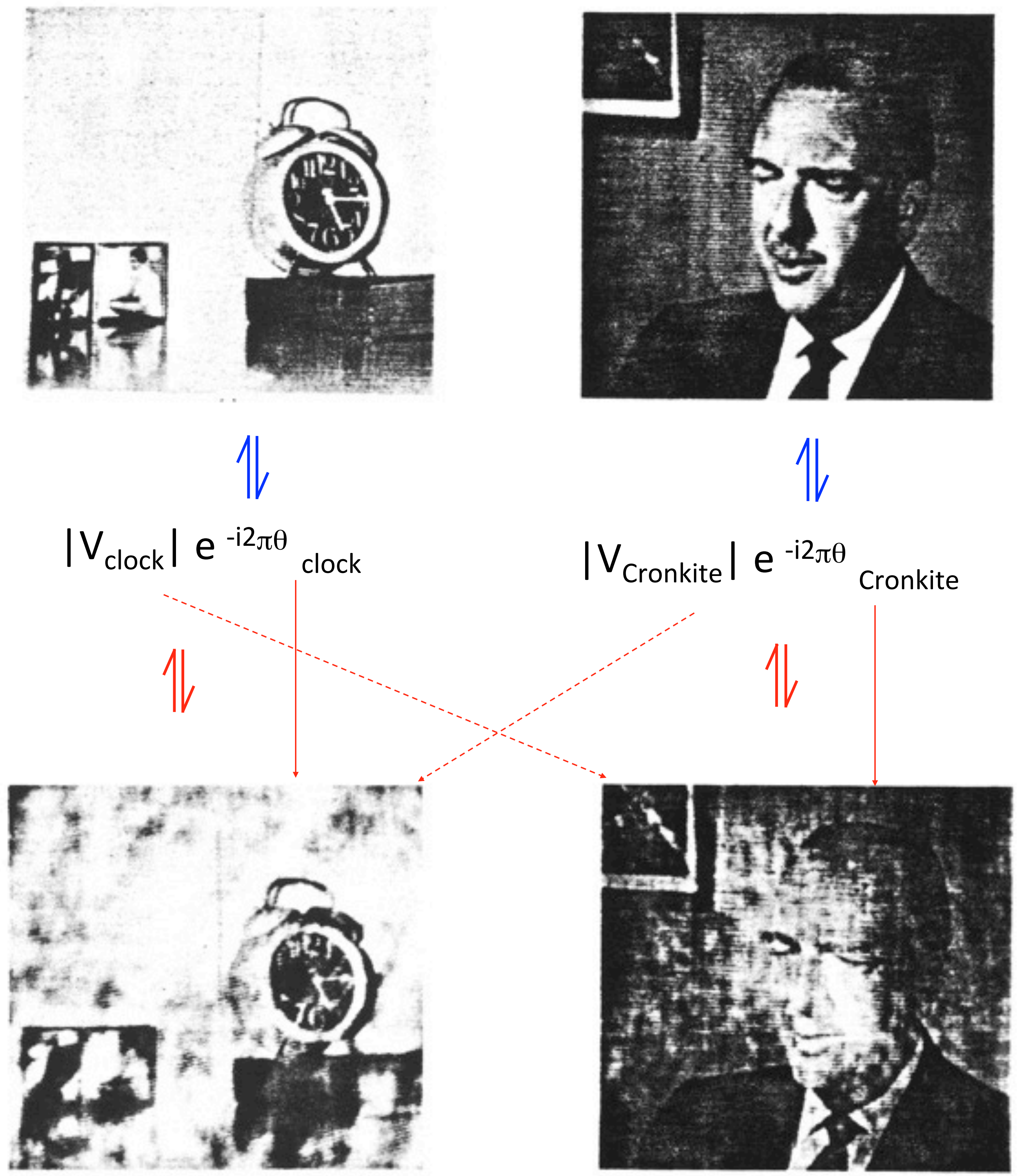
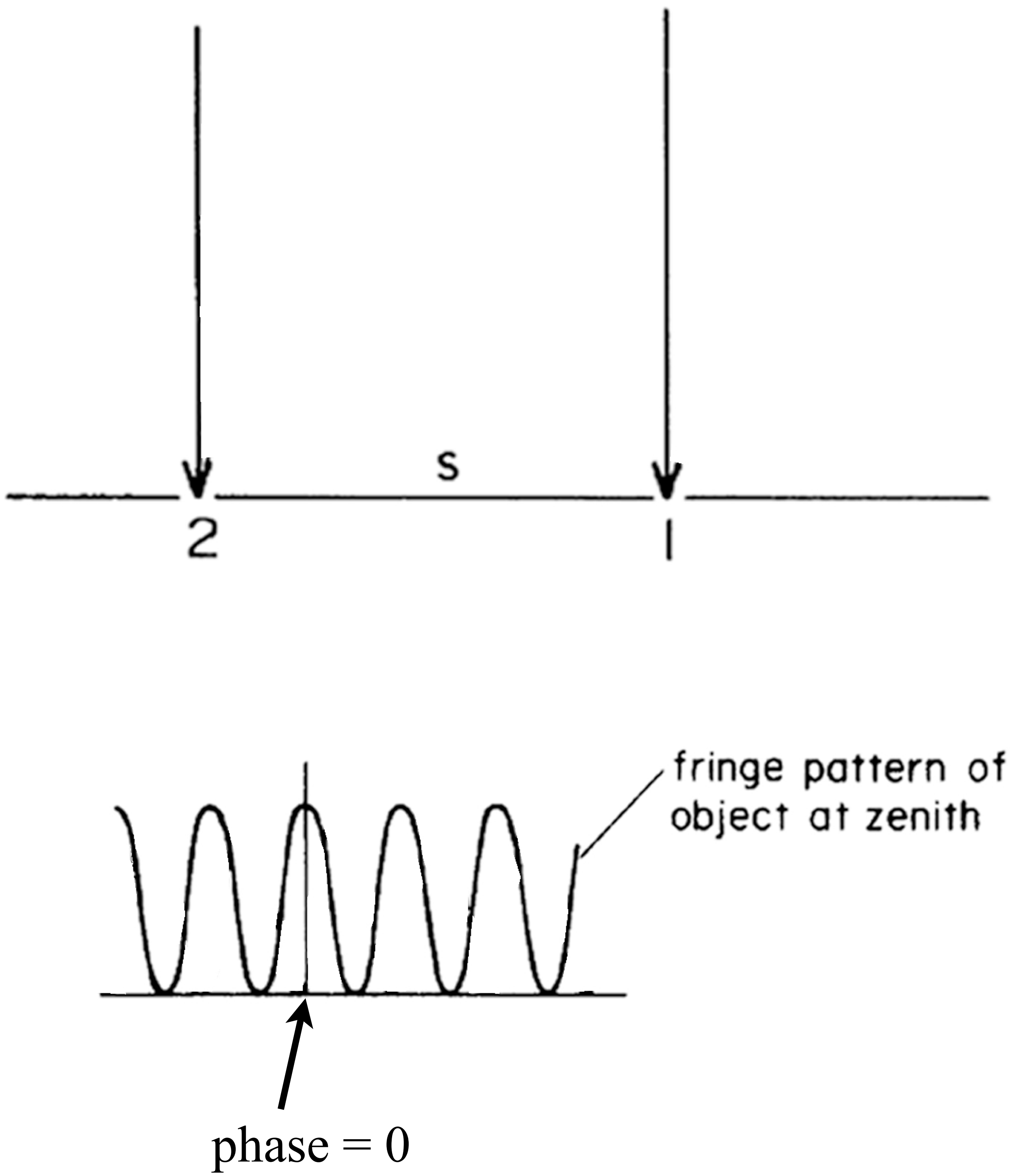


Oppenheim & Lim Proc. IEEE 69, 529-541 (1981).

Interferometry (Radio, Infra-red, or Optical)



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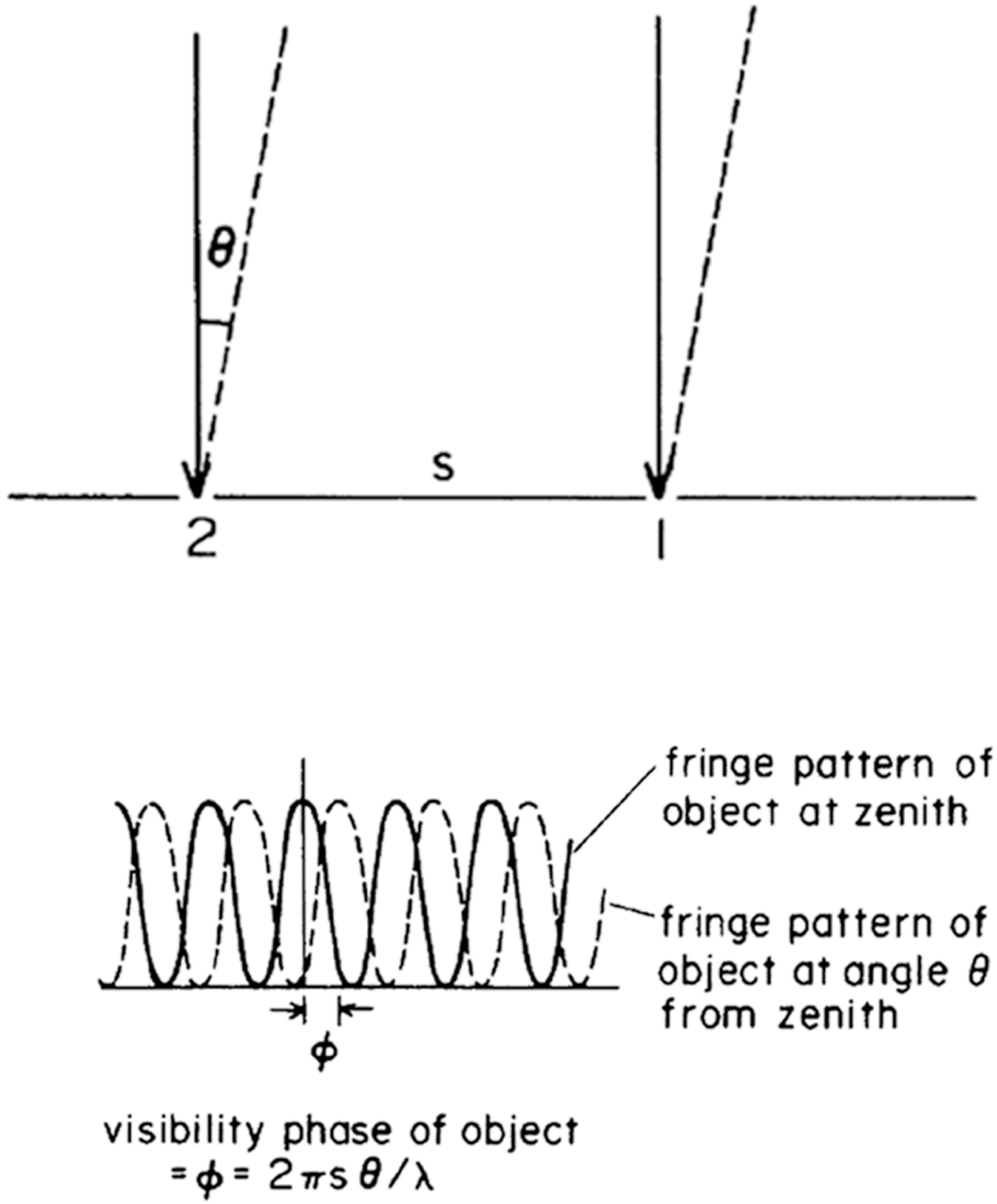
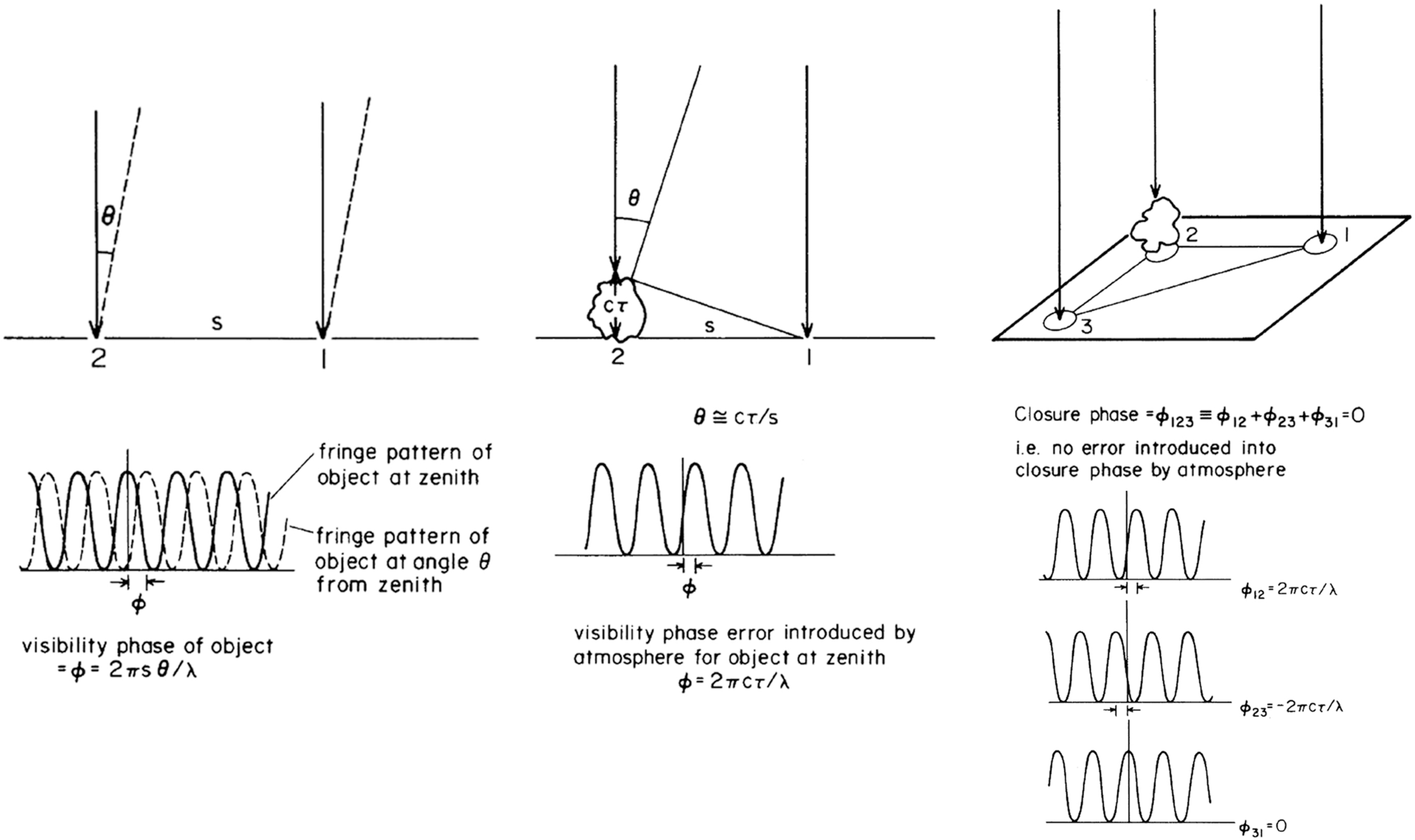


Closure Phase & Hybrid Mapping



Rogers et al, 1974, ApJ, 193, 293
Wilkinson, Readhead, Purcell & Anderson 1977, Nature, 269, 764
Readhead & Wilkinson 1978, ApJ, 223, 75
Readhead, Walker, Pearson, Cohen 1980, Nature, 285, 173

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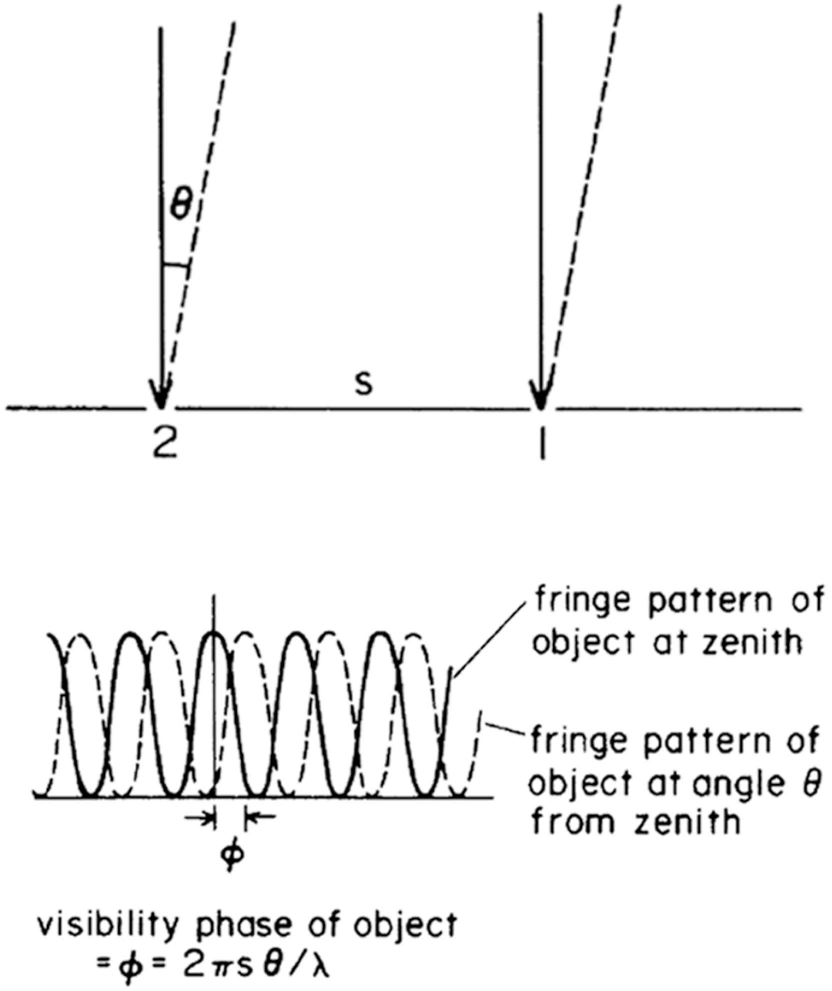
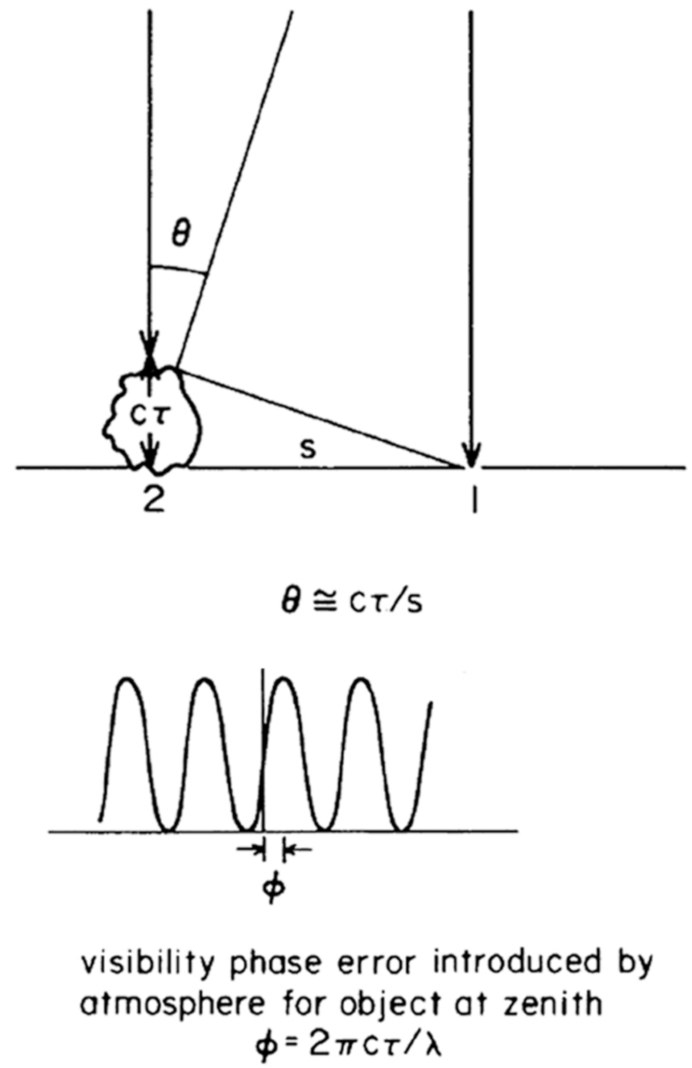
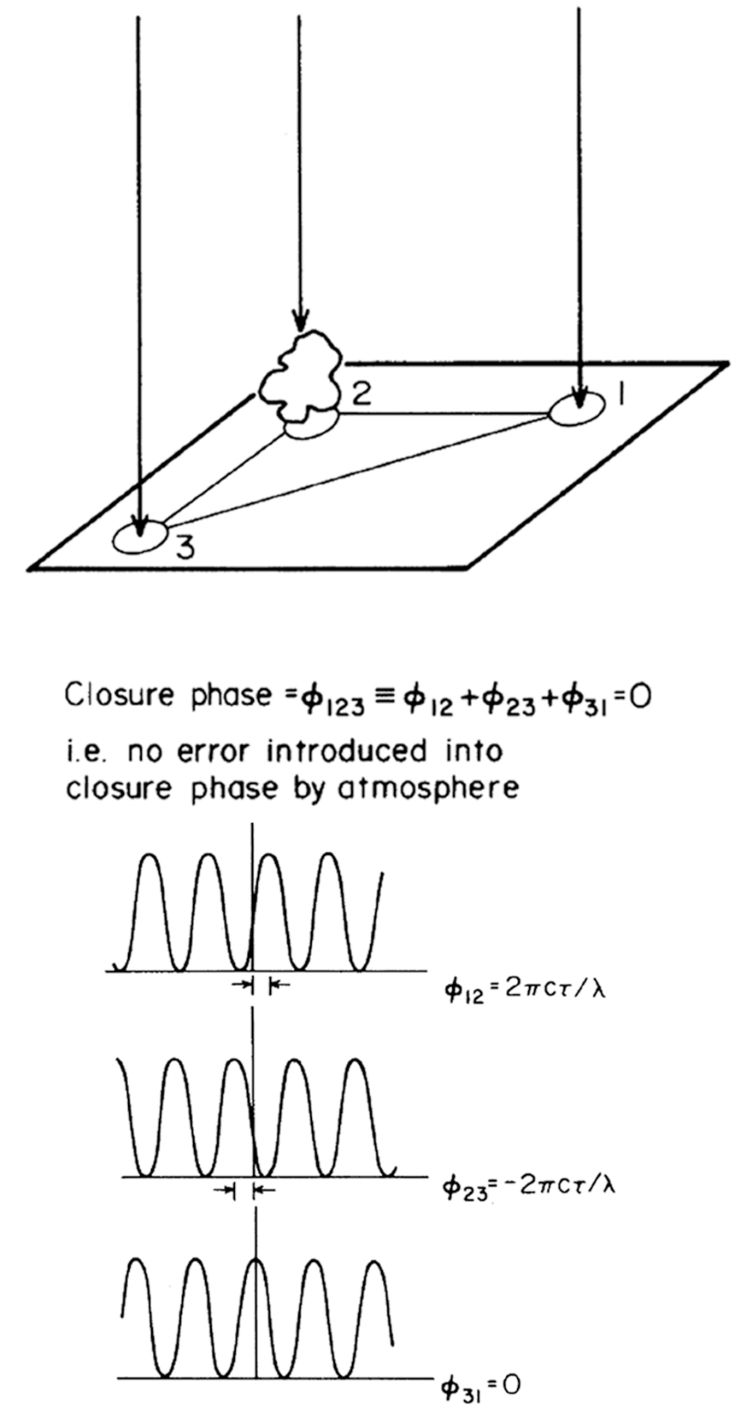




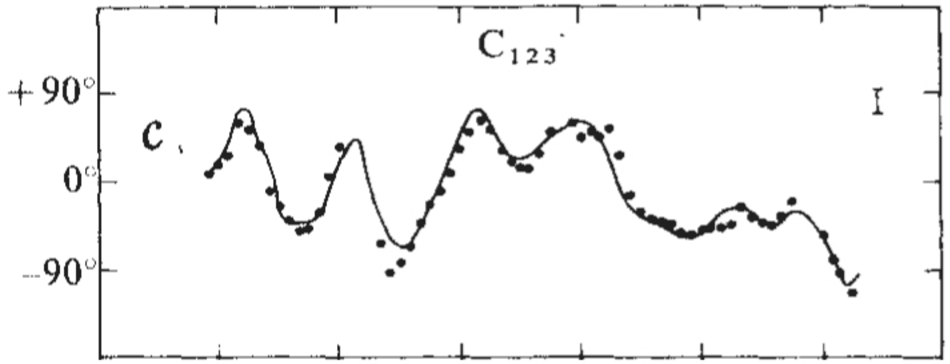


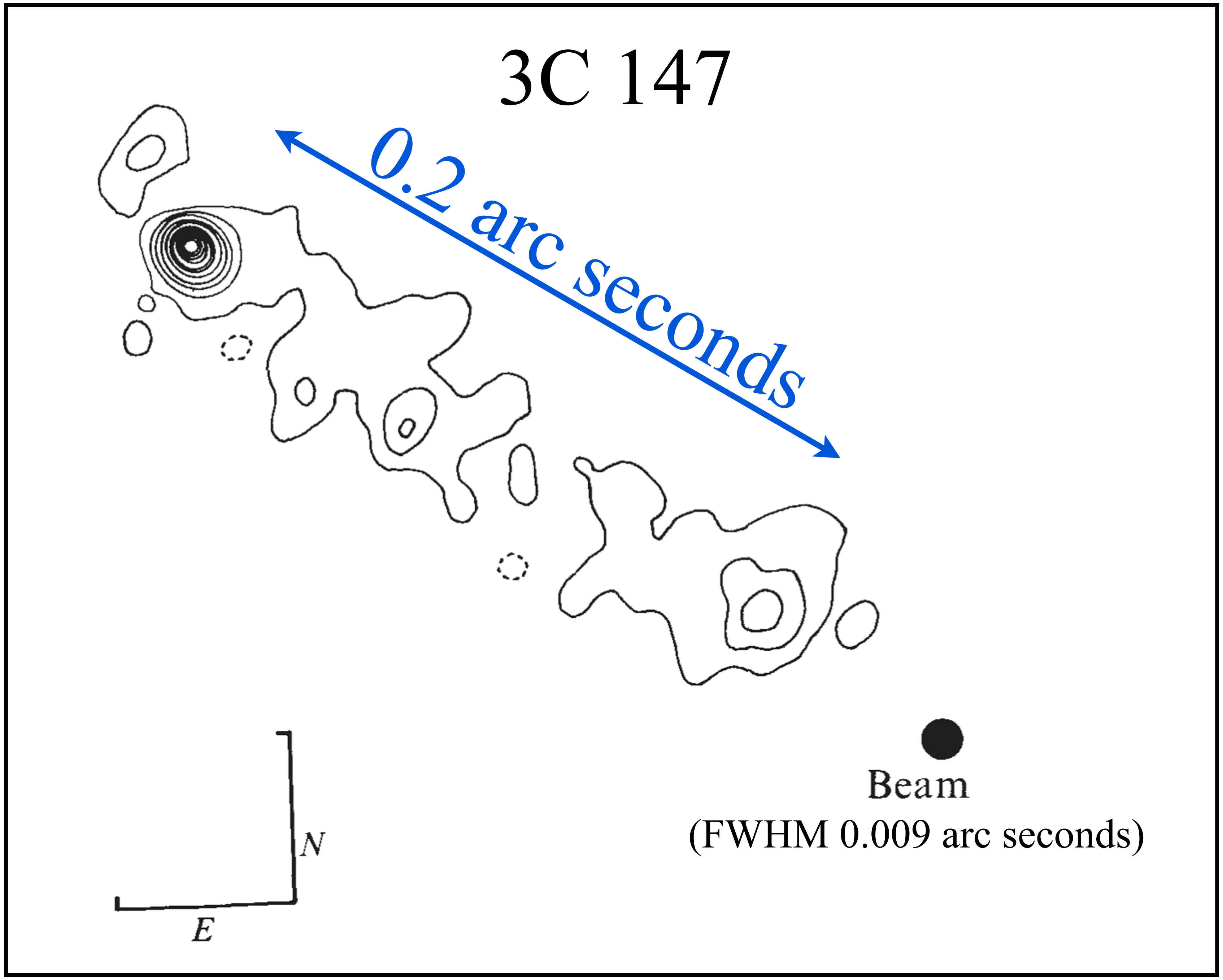
Ryle suggested blind tests

Rogers et al, 1974, ApJ, 193, 293
Wilkinson, Readhead, Purcell & Anderson 1977, Nature, 269, 764
Readhead & Wilkinson 1978, ApJ, 223, 75
Readhead, Walker, Pearson, Cohen 1980, Nature, 285, 173

The first proper (i.e. coherent) diffraction-limited astronomical image made *at any frequency* with resolution << 1 arc second was made using **"closure phase"** in 1976 with VLBI at 609 MHz - these were called "Hybrid Maps" and antedated "Self Calibration", which was developed independently by Fred Schwab at the VLA, 4 years later

Hybrid Map made from observations at 4 telescopes: OVRO, NRAO, Ft. Davis Texas, & Jodrell Bank





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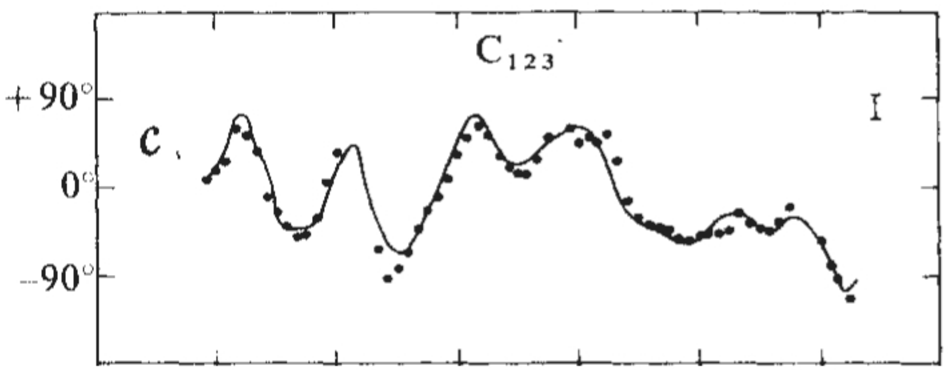
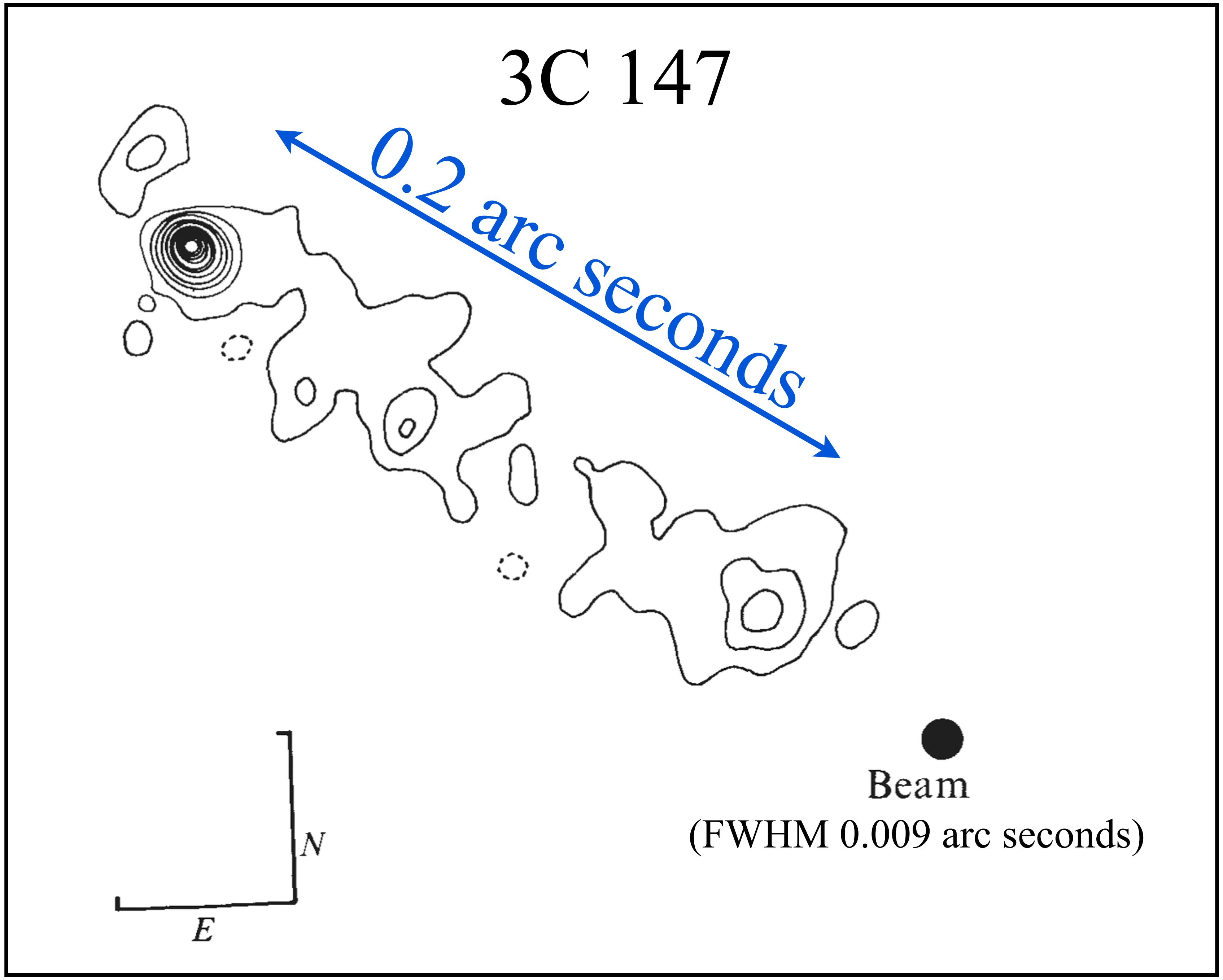
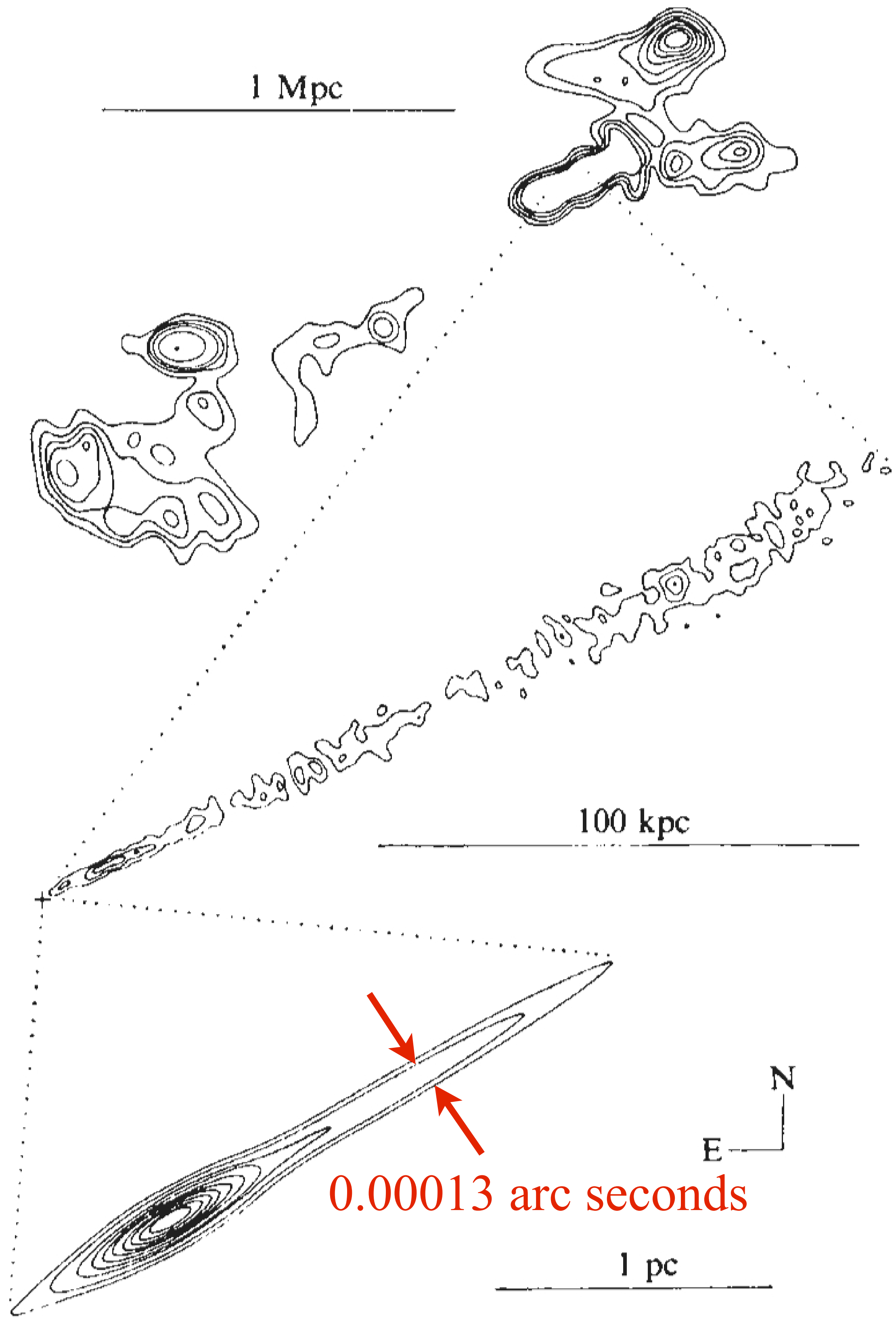




Remarkably - this first hybrid map “said it all” - the nuclear radio components of AGN are asymmetric one-sided jets - we see it here for a quasar, but then we hit it lucky and found the perfect radio galaxy: NGC6251

Wilkinson, Readhead, Purcell & Anderson 1977, Nature, 269, 764

Fig. 2 The radio source associated with NGC6251, showing the disposition of the nuclear and outer jets relative to the total source. The upper two contour maps are taken from Waggett *et al.*[1], the nuclear component has the contours of the adopted model described in the text.



Readhead, Cohen & Blandford 1978, Nature, 272, 131

Very soon after the first ultra-high resolution image of a quasar nucleus **using closure phase** we got this VLBI image of the nuclear radio component in the elliptical galaxy NGC 6251 again **using closure phase**

Like 3C147 this was a one-sided jet, beautifully aligned and **pointing in the same direction** as the large-scale one-sided jet - without the closure phase not only would the image have been much less constrained but we also would not have known which way the nuclear jet was pointing

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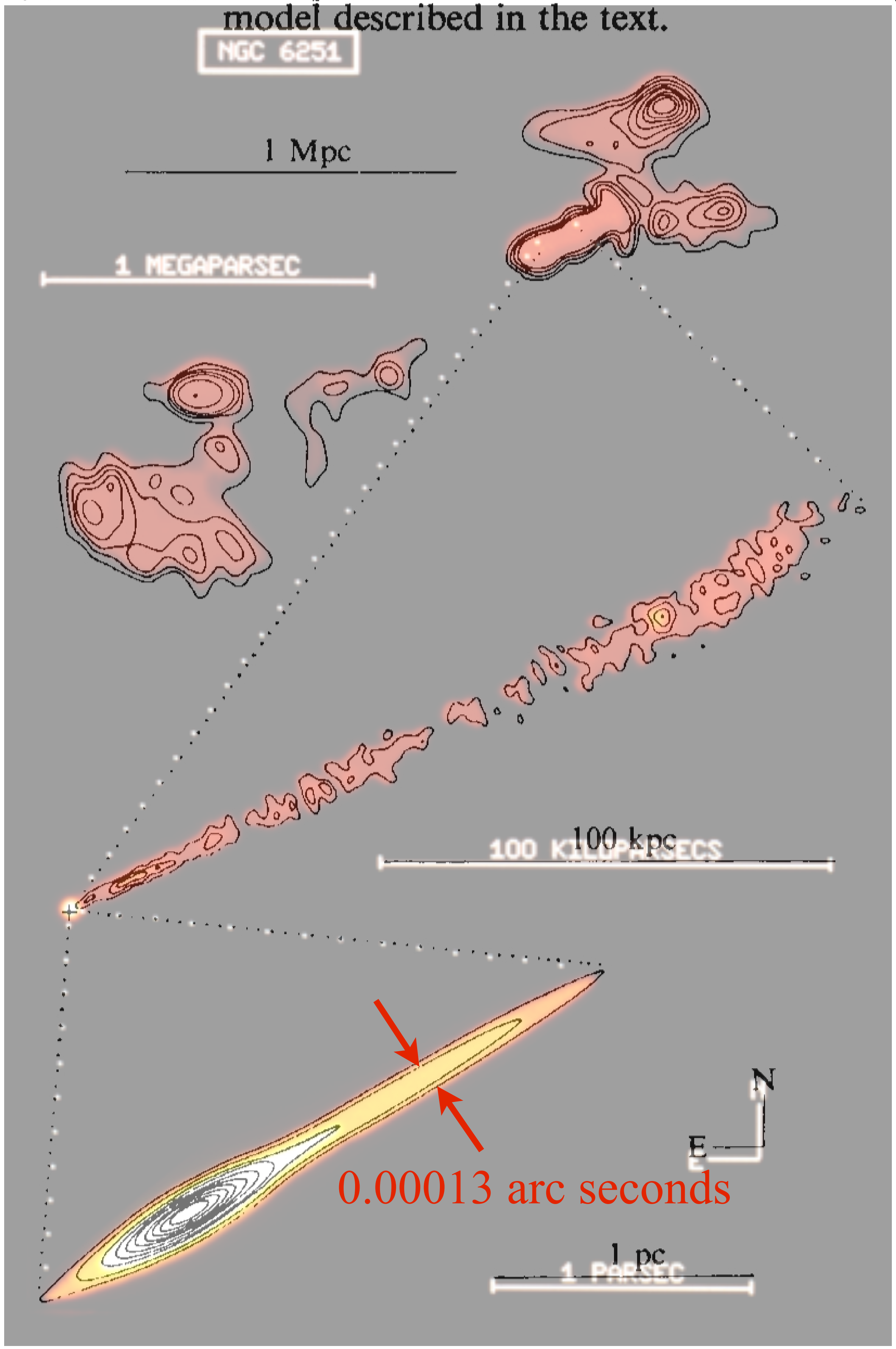

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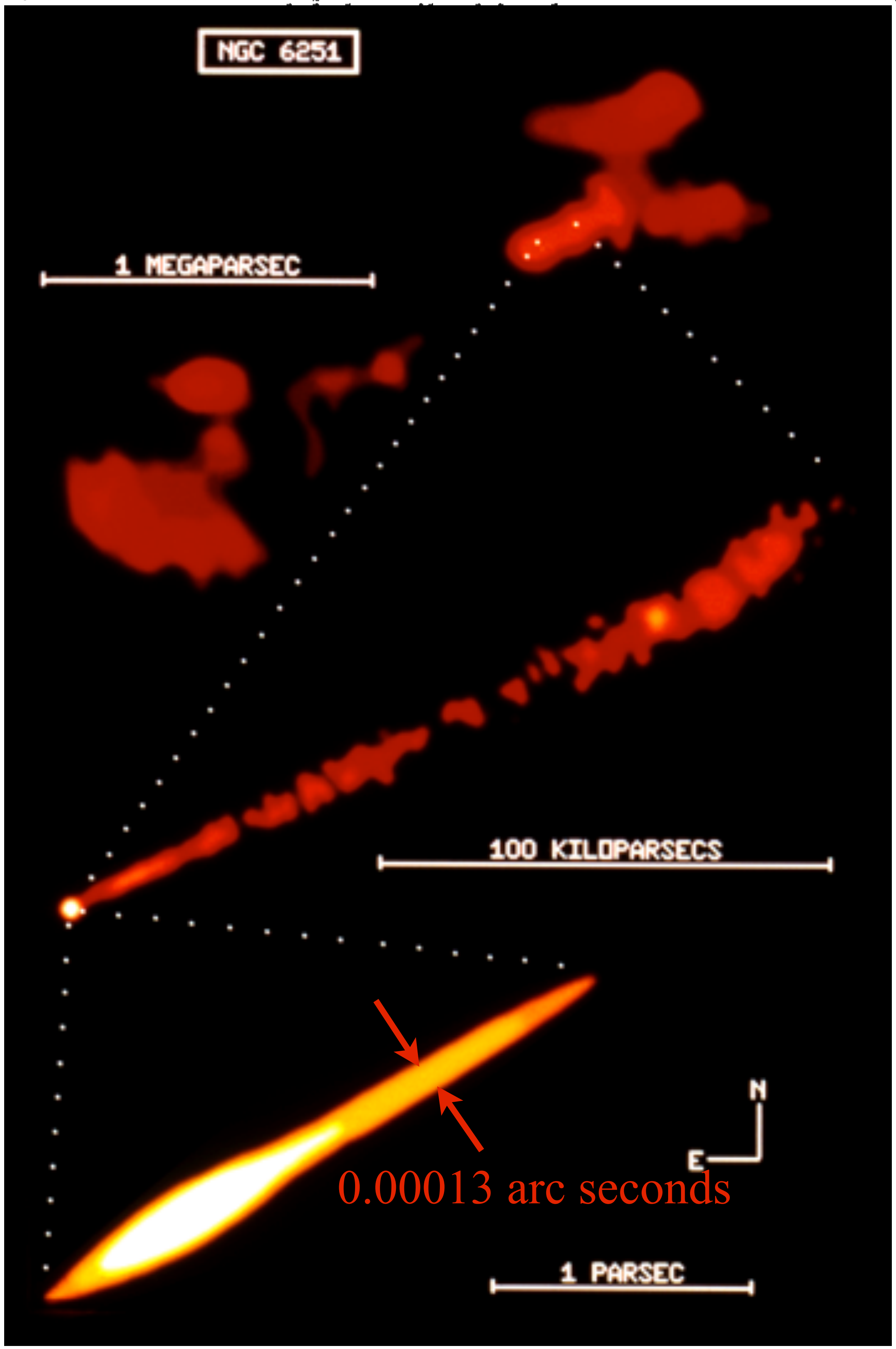

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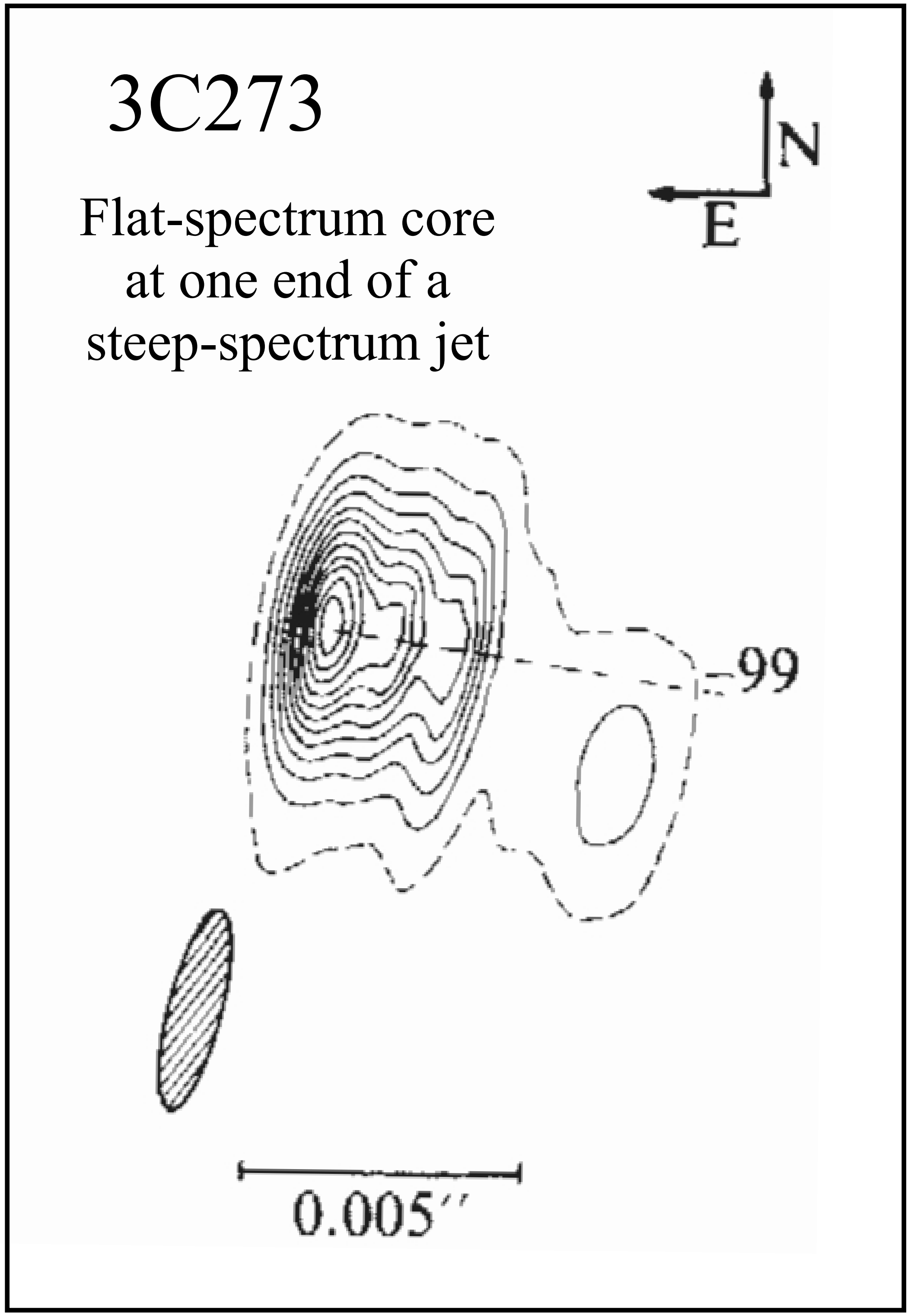


Readhead, Cohen, Pearson & Wilkinson 1978, Nature, 276, 768

Lynden Bell 1977, Nature, 270, 396:
"Hubble's Constant Derived From Superluminal Motion"
H_0 = 110 +/- 10 km $^{s-1}$ Mpc^{-1}

The first hybrid map of a superluminal source: 3C273 in 1977.
Important: Skepticism about SLM in community
Longair, Lynden Bell, Ryle, Webster . . .

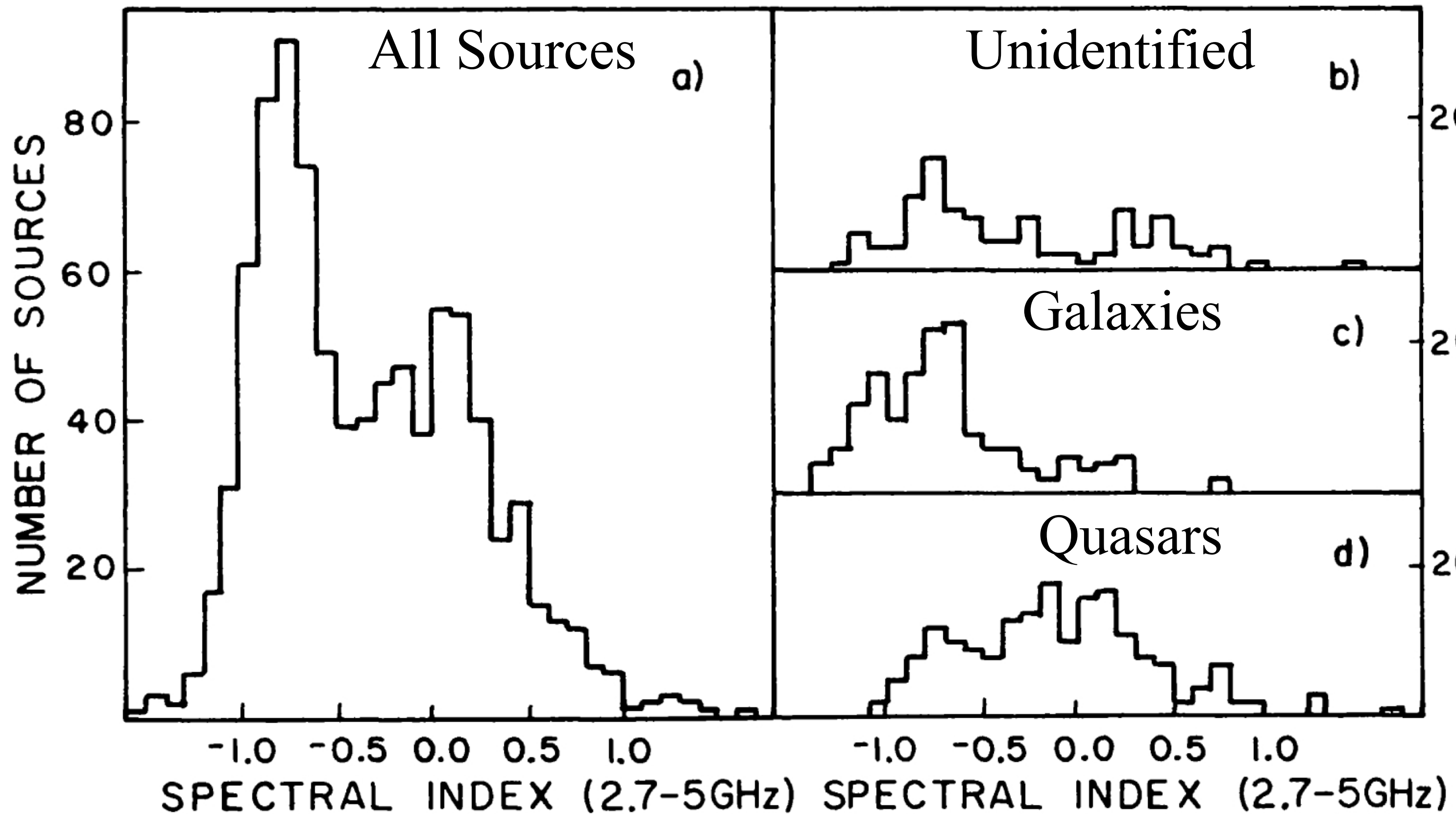
Webster "this map shifts the burden of proof from the believers to the non-believers in SLM".

Lynden Bell Nature paper explaining superluminal motion as actually not being superluminal but two components moving close to c at right angles to the los and a larger Hubble Constant. He was visiting Caltech and when I showed him that 3C 273, like 3C147 and NGC 6251, was a one-sided jet he agreed that these are objects in which the material is moving relativistically almost along the line of sight towards us.

Multi-frequency observations soon showed that these objects had a flat spectrum core at one end of a steep-spectrum jet.

All of these results were directly a result of closure phase hybrid mapping - so I think that "MATISSE" and "GRAVITY", which will combine all four antennas into six interferometers, with 3 independent closure phases and two independent closure amplitudes are very important on the VLT.

The SIV 5 GHz Survey



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Pauliny-Toth et al. 1978, AJ, 83, 451 - The SIV (5 GHz) Radio Survey

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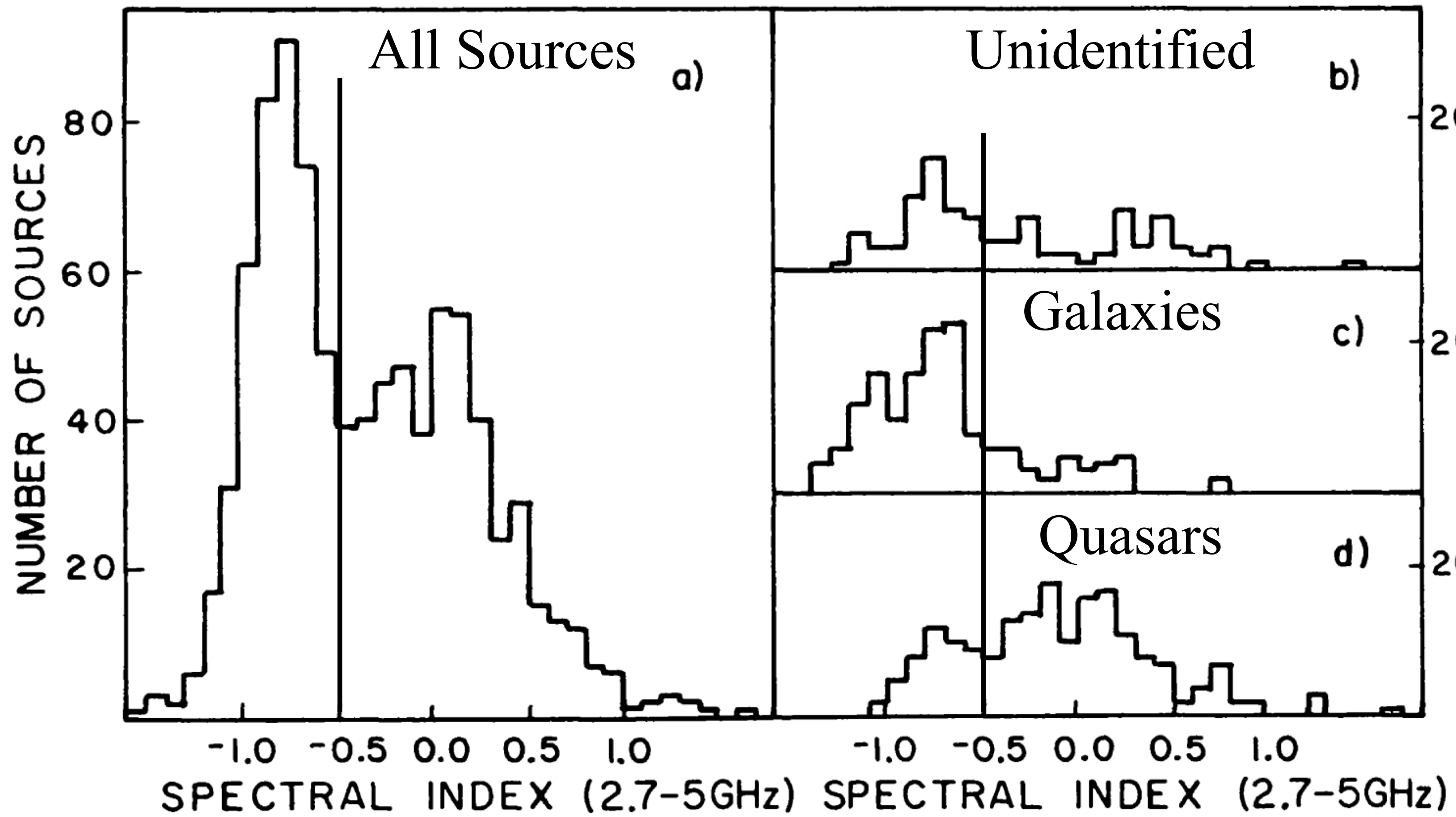

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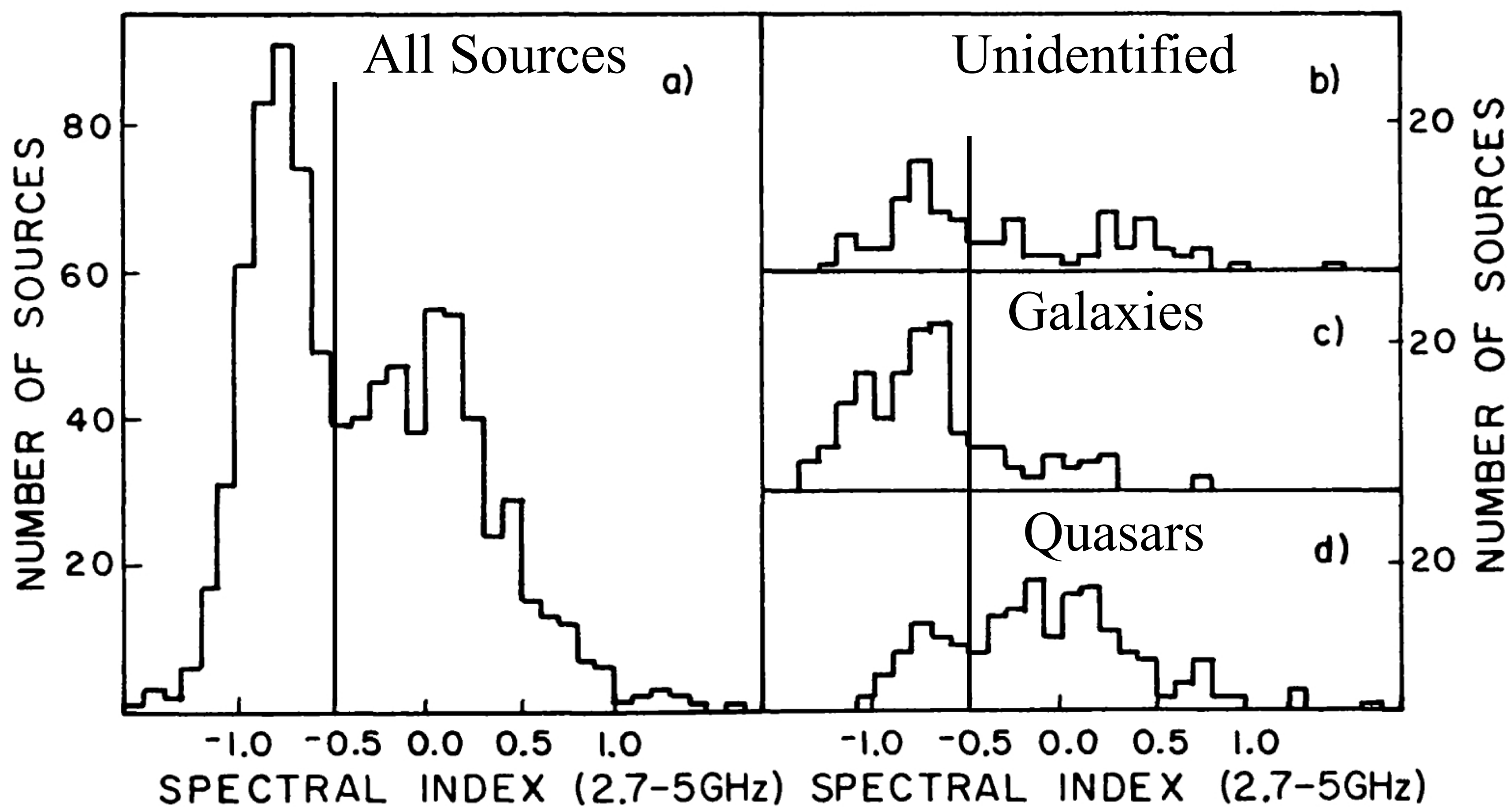

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For about 18 months this was a major spanner in the works: How could one possibly unify the extended steep-spectrum sources with the compact flat-spectrum sources? But then it suddenly became blindingly obvious!

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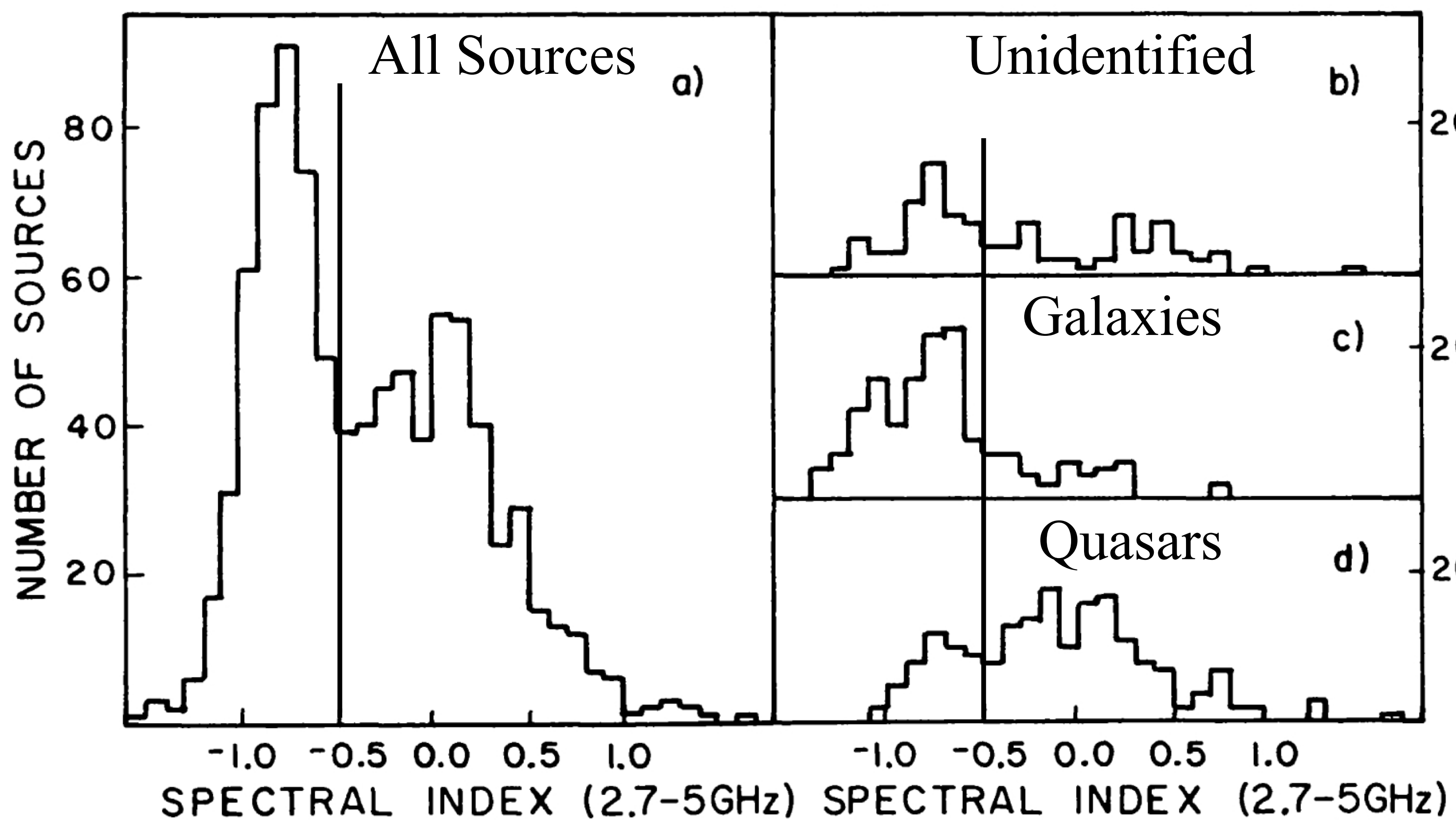

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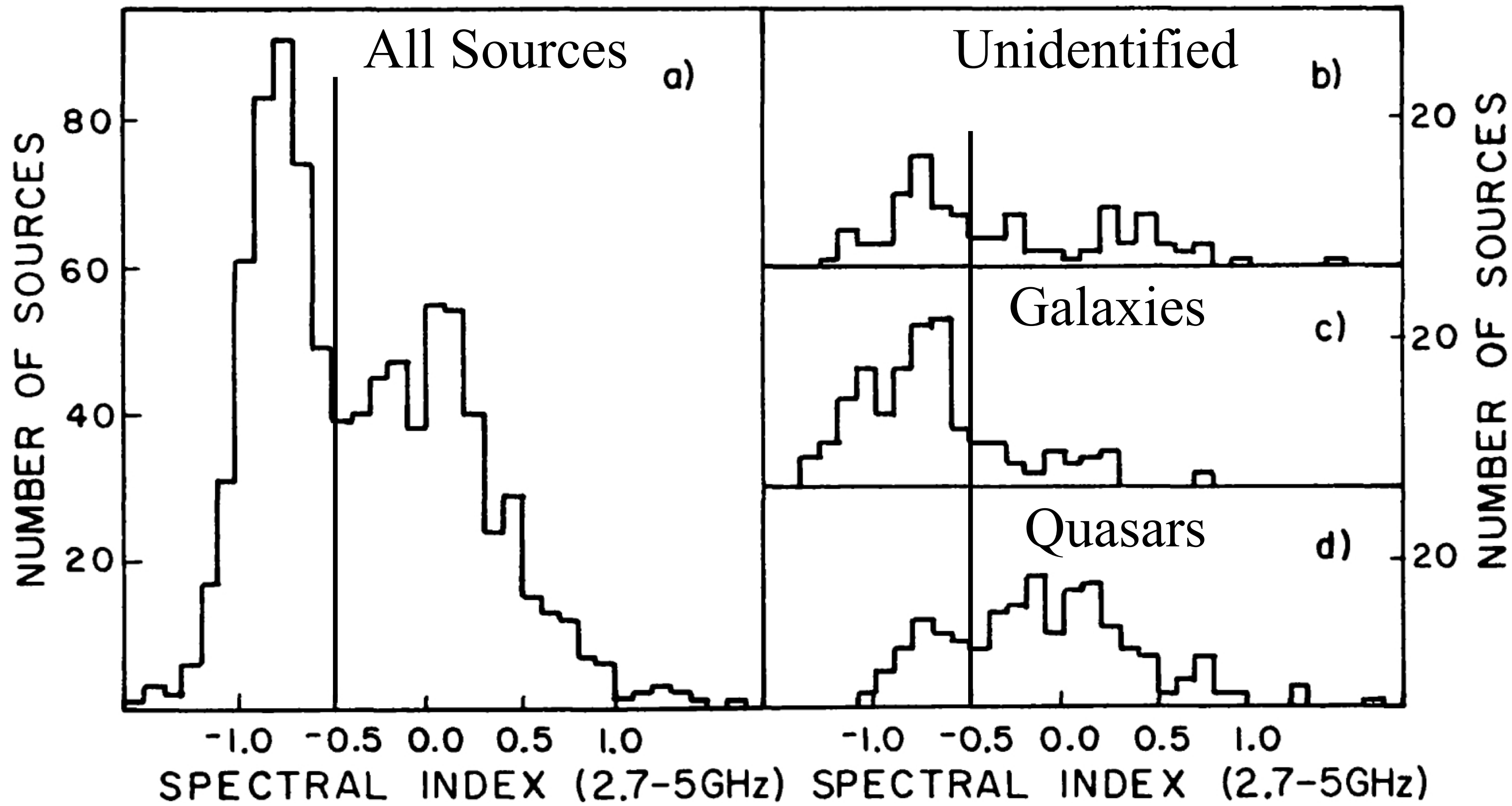

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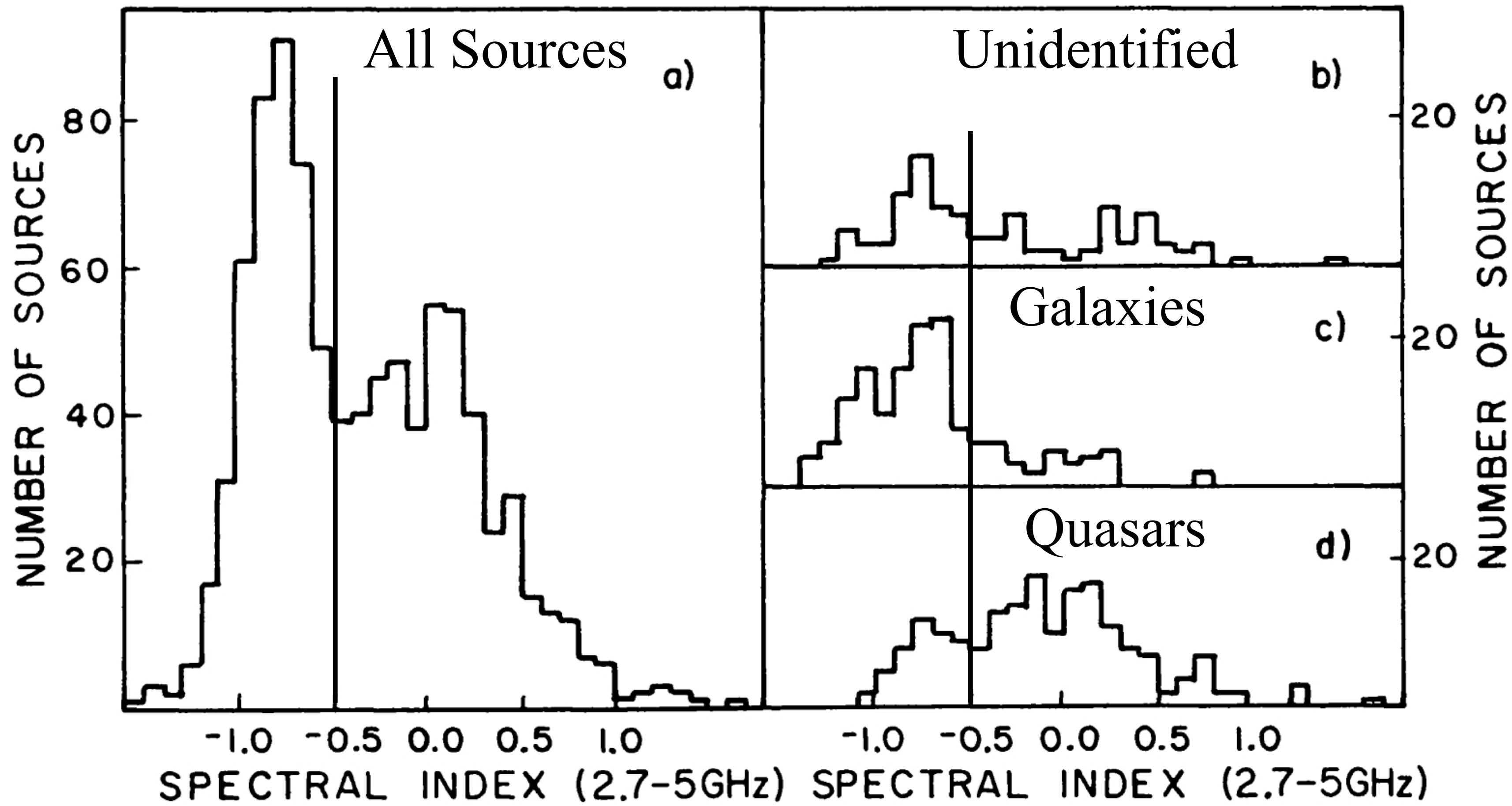

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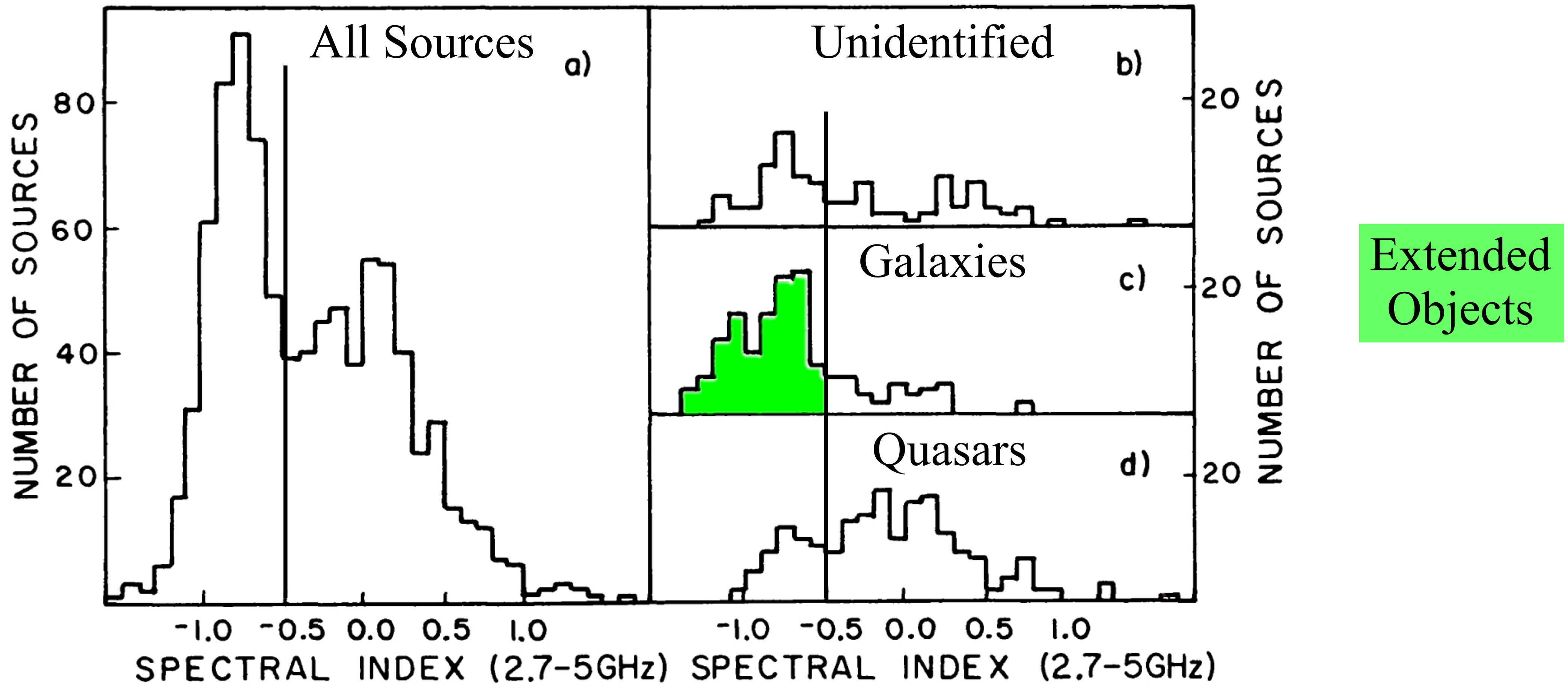

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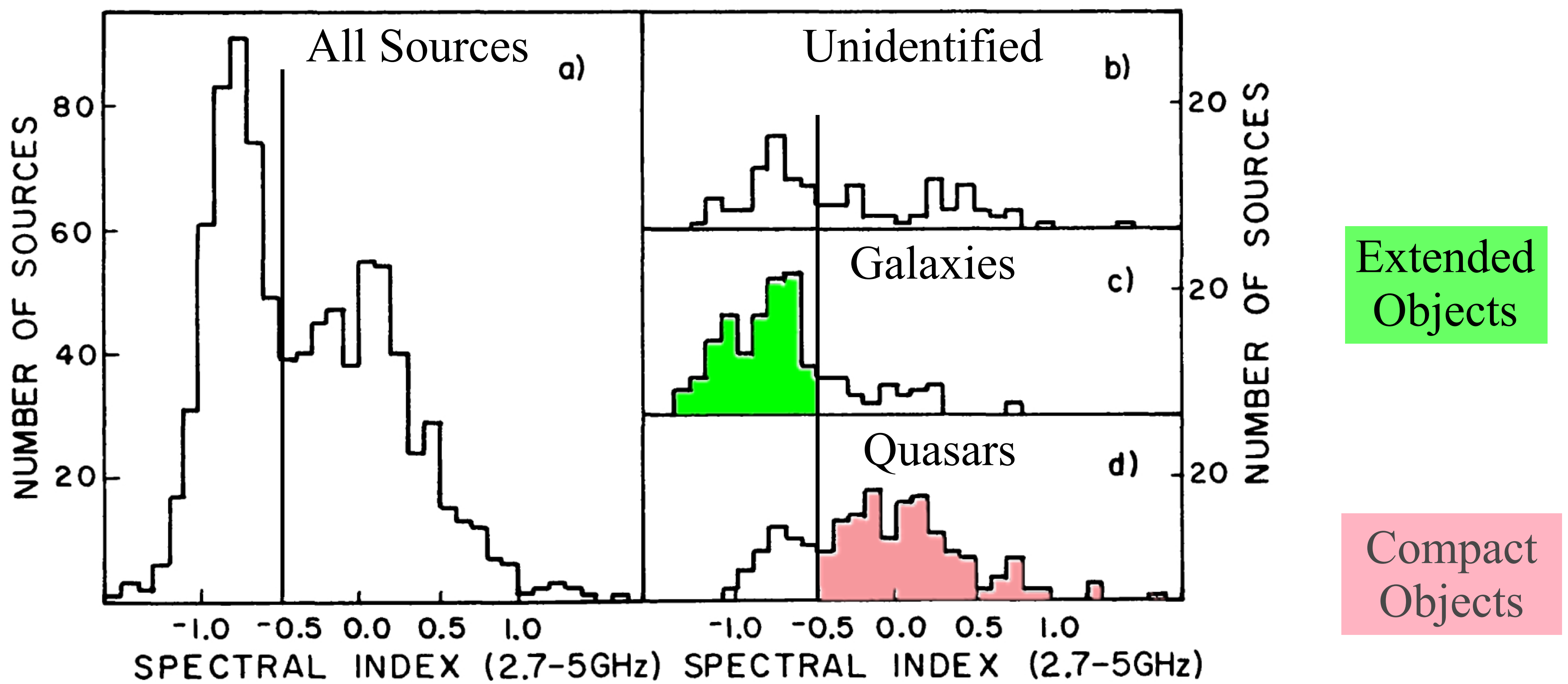

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Table 1 Morphology, overall size, change in position angle and redshift of the objects in the sample*

Object	Z	D (kpc)	Type	ΔPA (deg)
NGC6251	0.023	2,900	S	≤4
3C111	0.0485	270	S	≤4
3C390.3	0.0561	320	S	≤5
3C405 (Cygnus A)	0.0565	190	S	≤4
3C236	0.0989	5,700	S	≤3.5
3C273	0.158	70	C	40
3C147	0.545	5	C	25
3C345	0.594	25	C	45
3C380	0.691	40	C	20

Data either taken from text or from refs 1–5.
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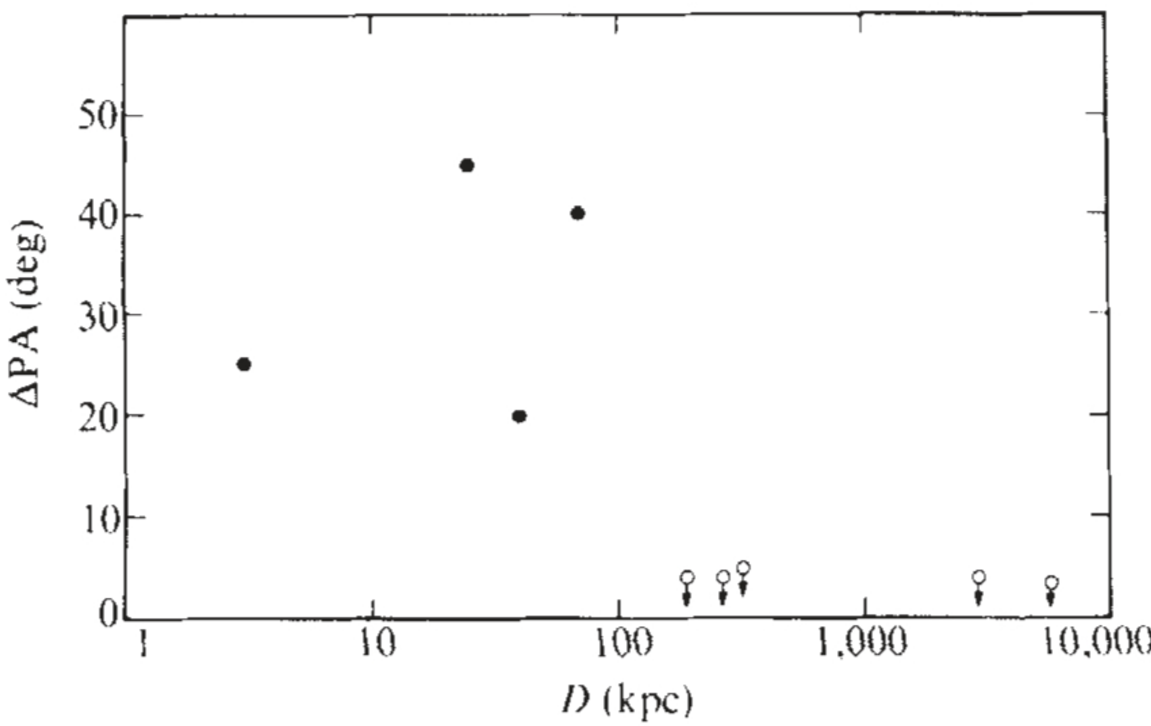

Fig. 3 The change in position angle (ΔPA) versus overall size (D) for the sources listed in Table 1: ○, type S sources; ●, type C sources.

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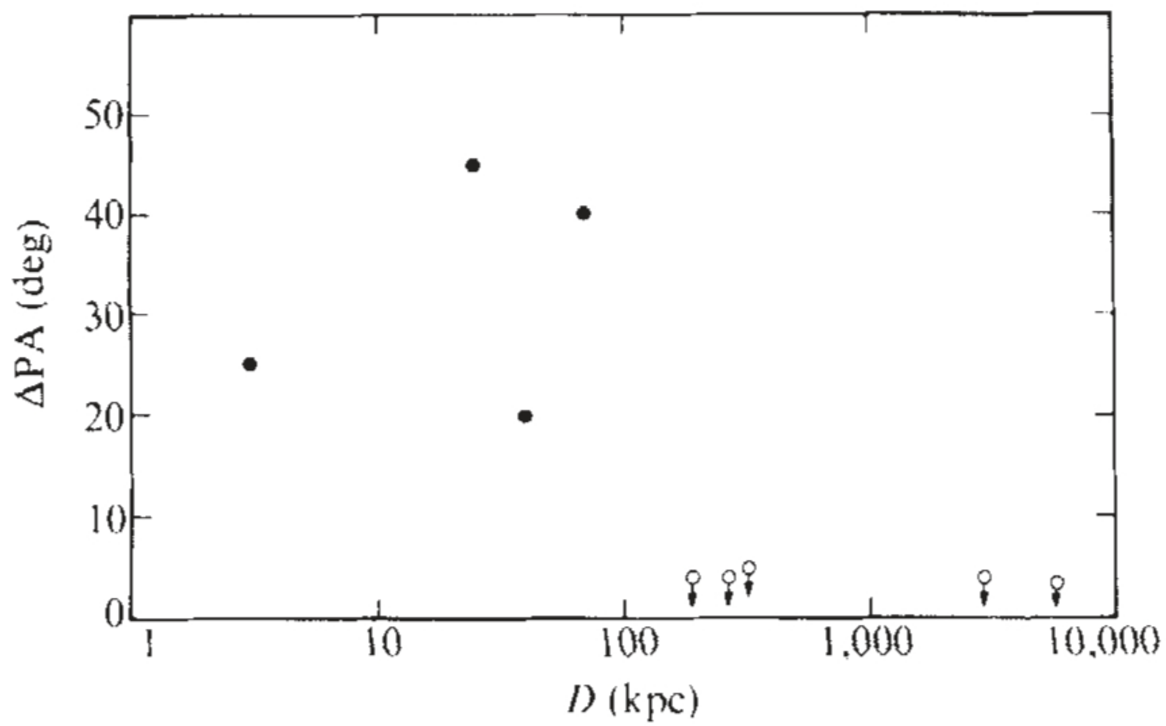

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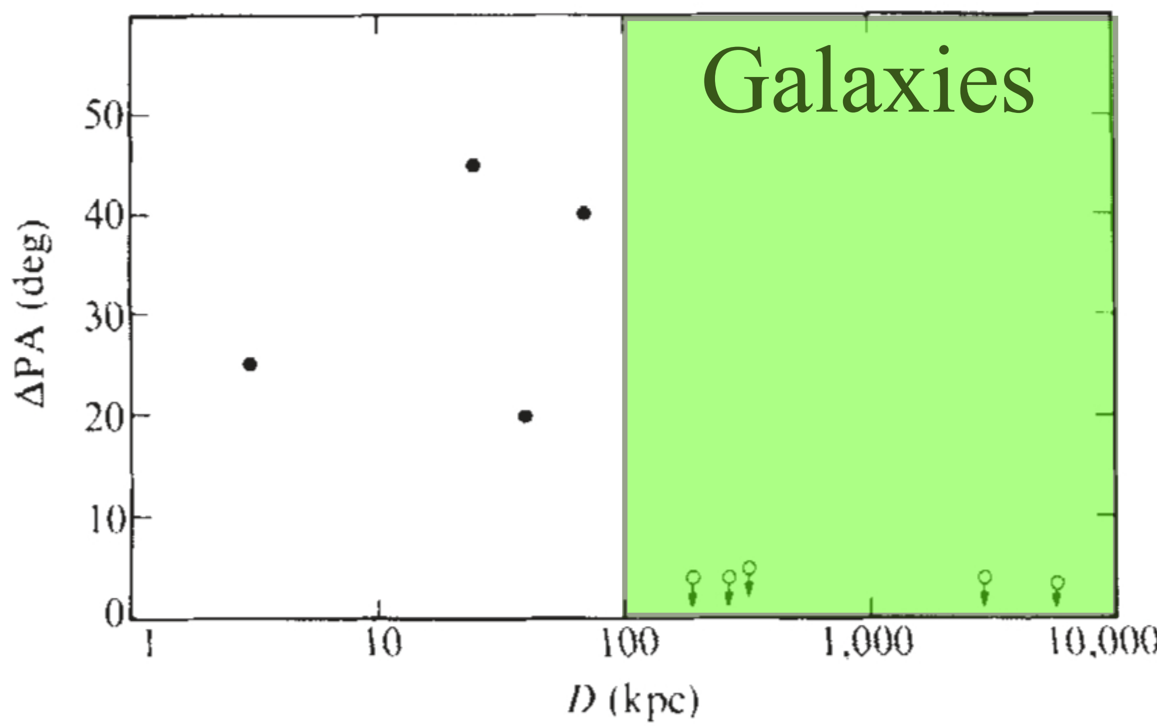

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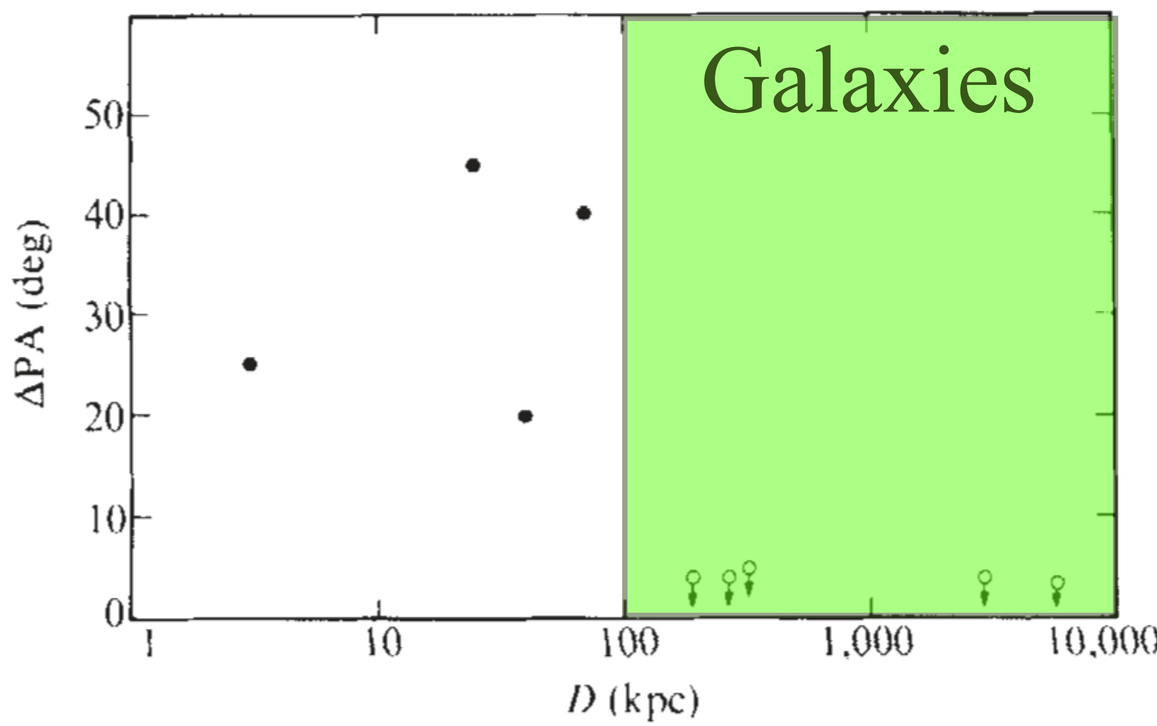

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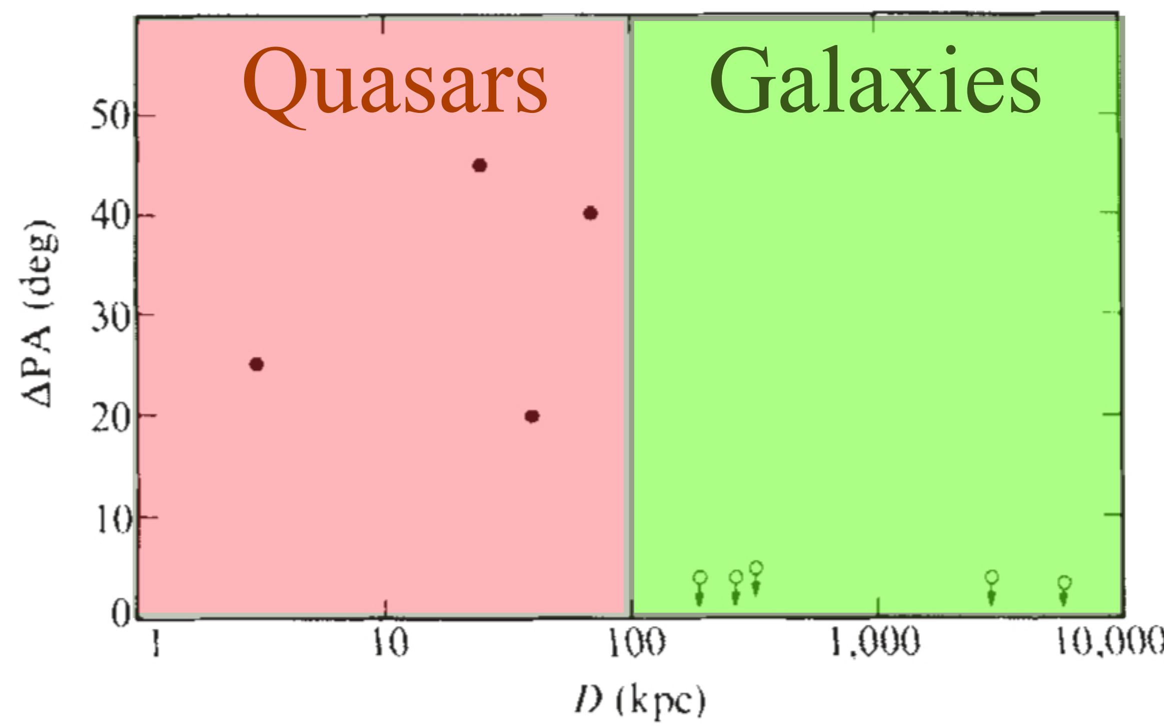
3C390.3	0.0561	320	S	≤5	
3C405 (Cygnus A)	0.0565	190	S	≤4	
3C236	0.0989	5,700	S	≤3.5	
3C273	0.158	70	C	40	Quasars
3C147	0.545	5	C	25	
3C345	0.594	25	C	45	
3C380	0.691	40	C	20	

Data either taken from text or from refs 1–5.
* Assuming $H = 50$ km s^{-1} Mpc^{-1} and $q_0 = 1/2$.



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Galaxies

Quasars

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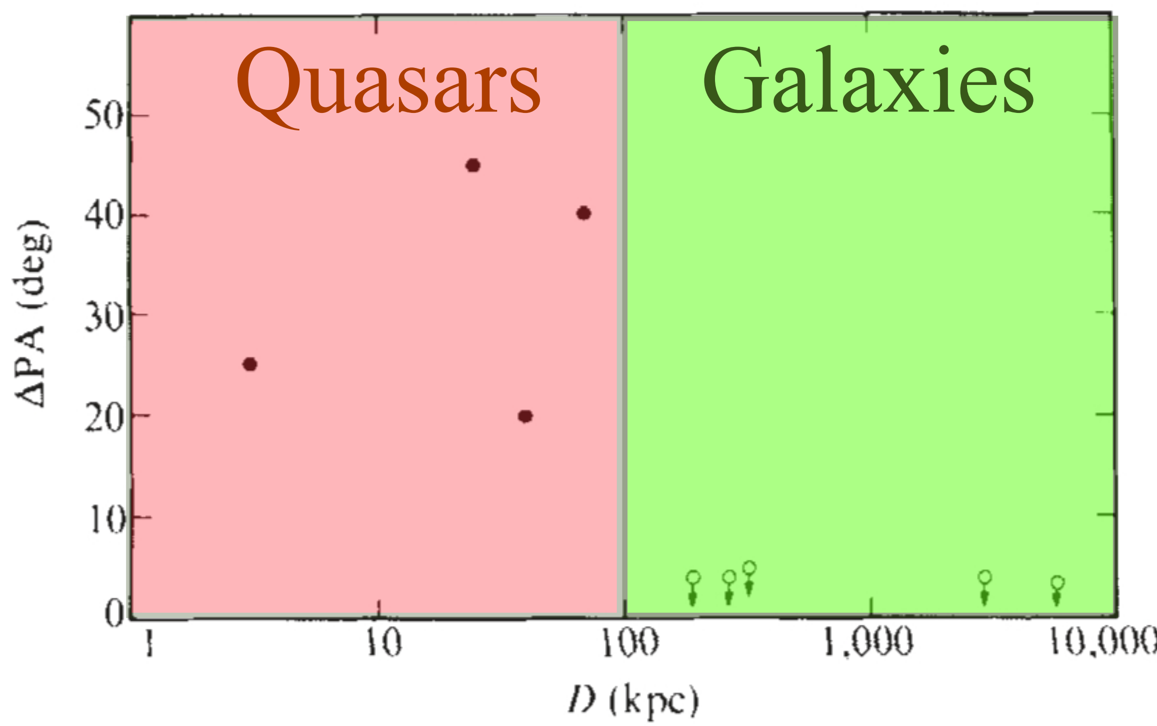

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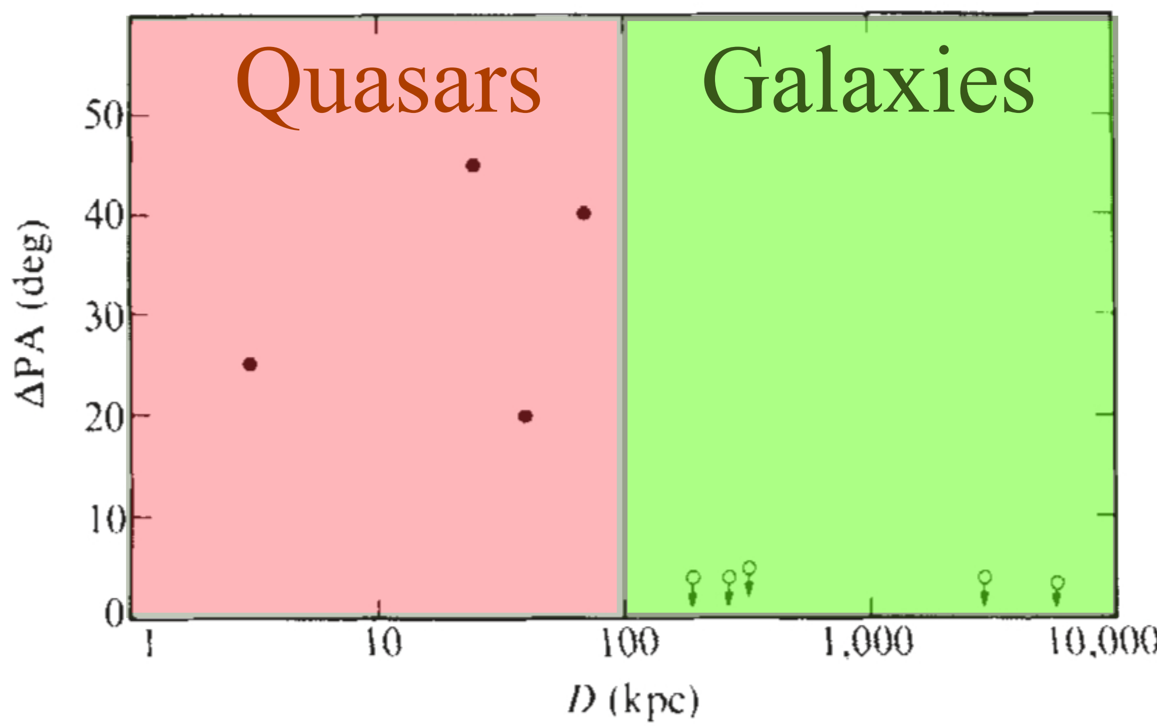

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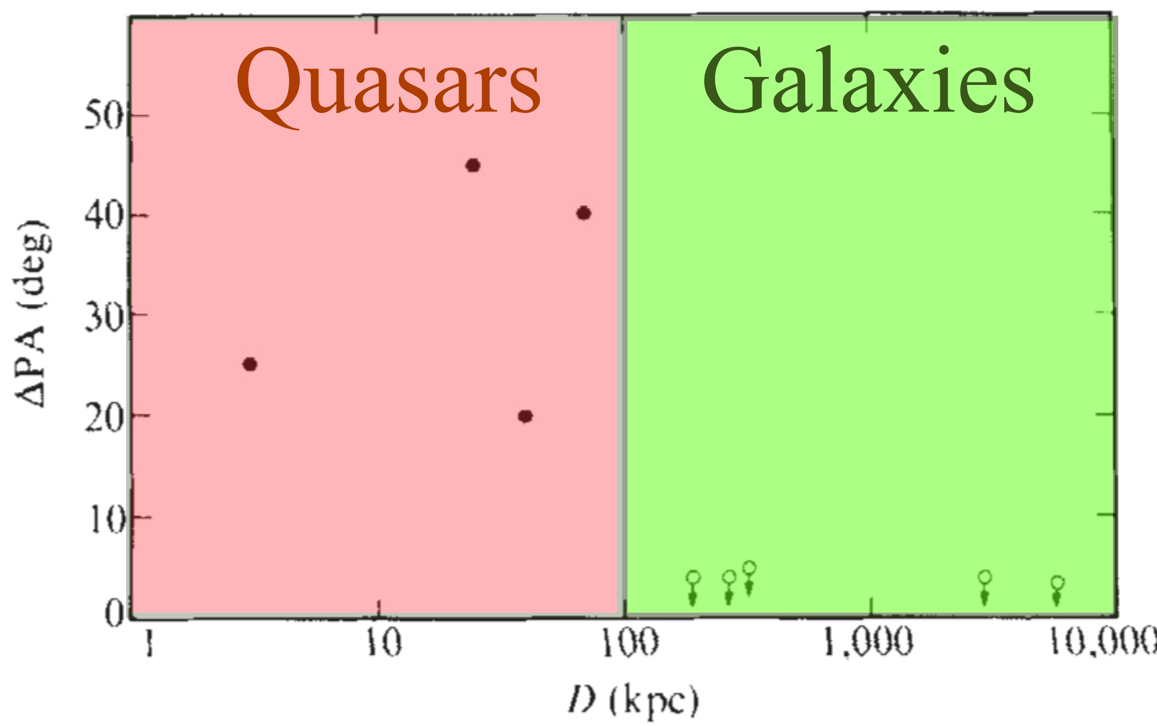

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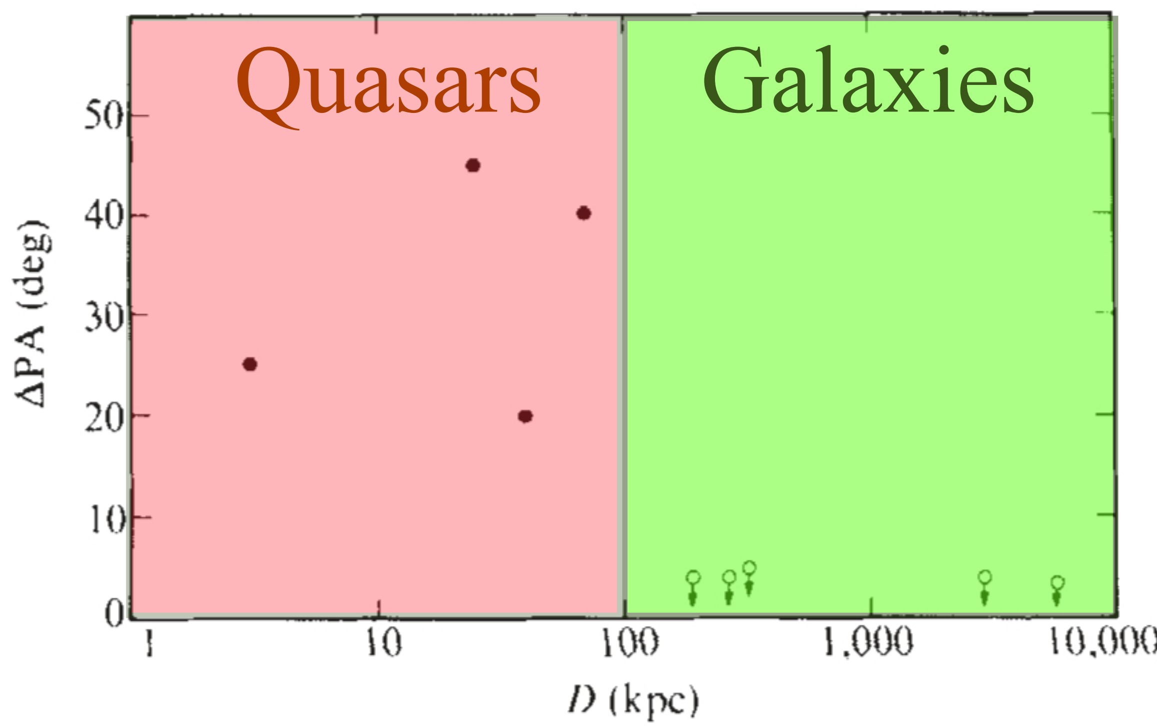

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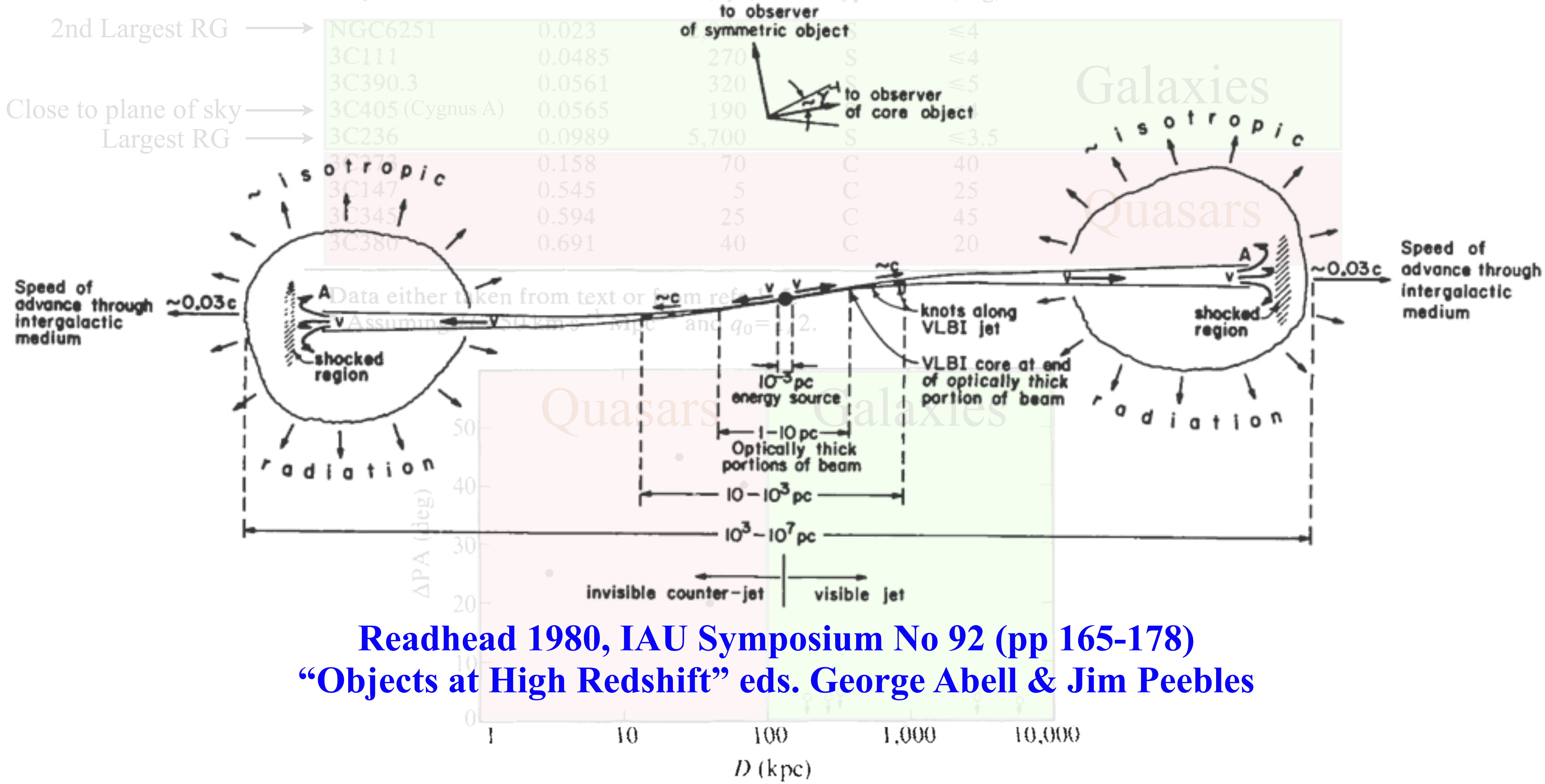

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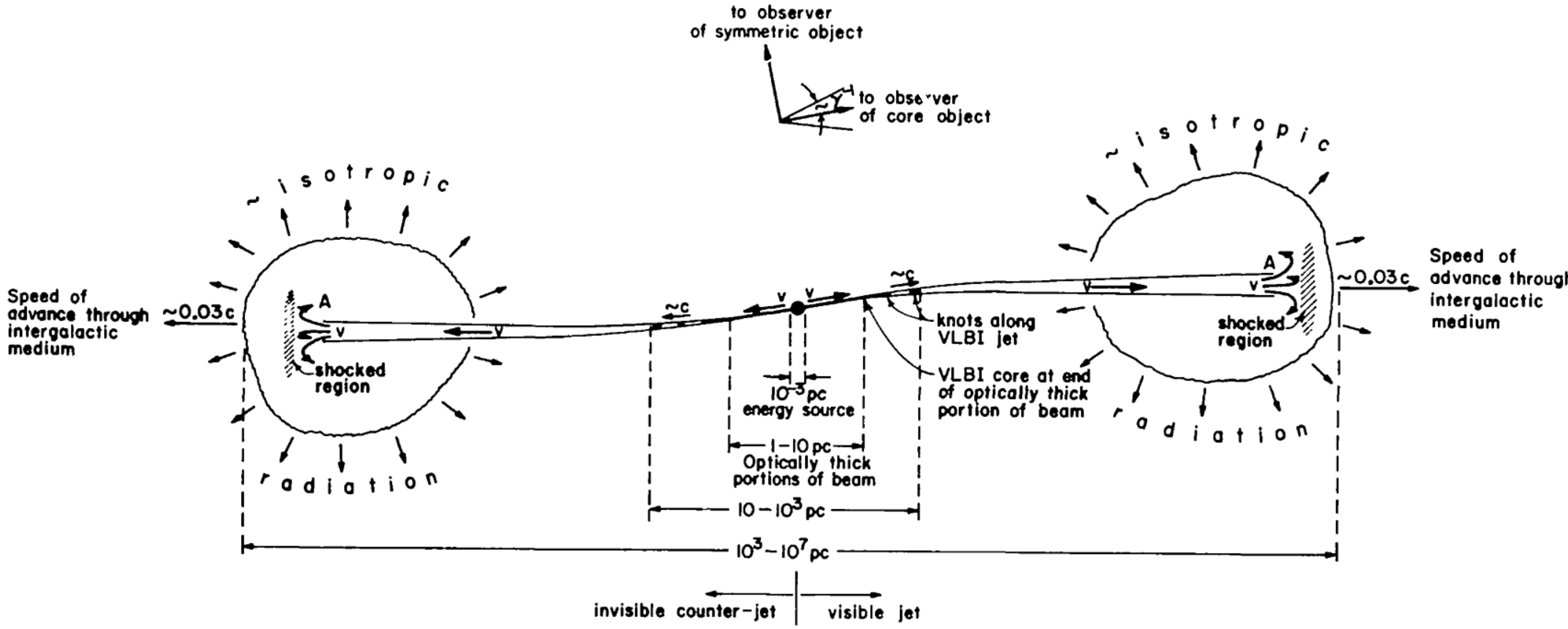

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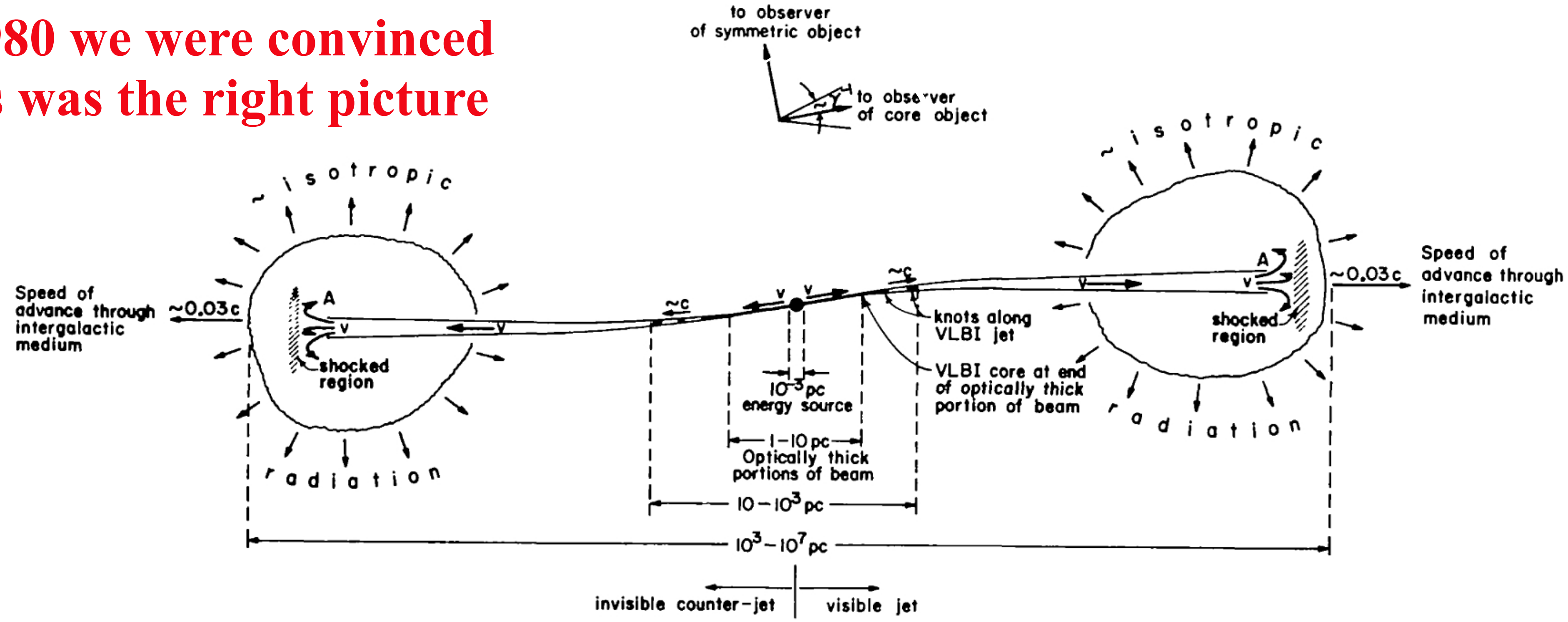
So by 1980 we were convinced that this was the right picture



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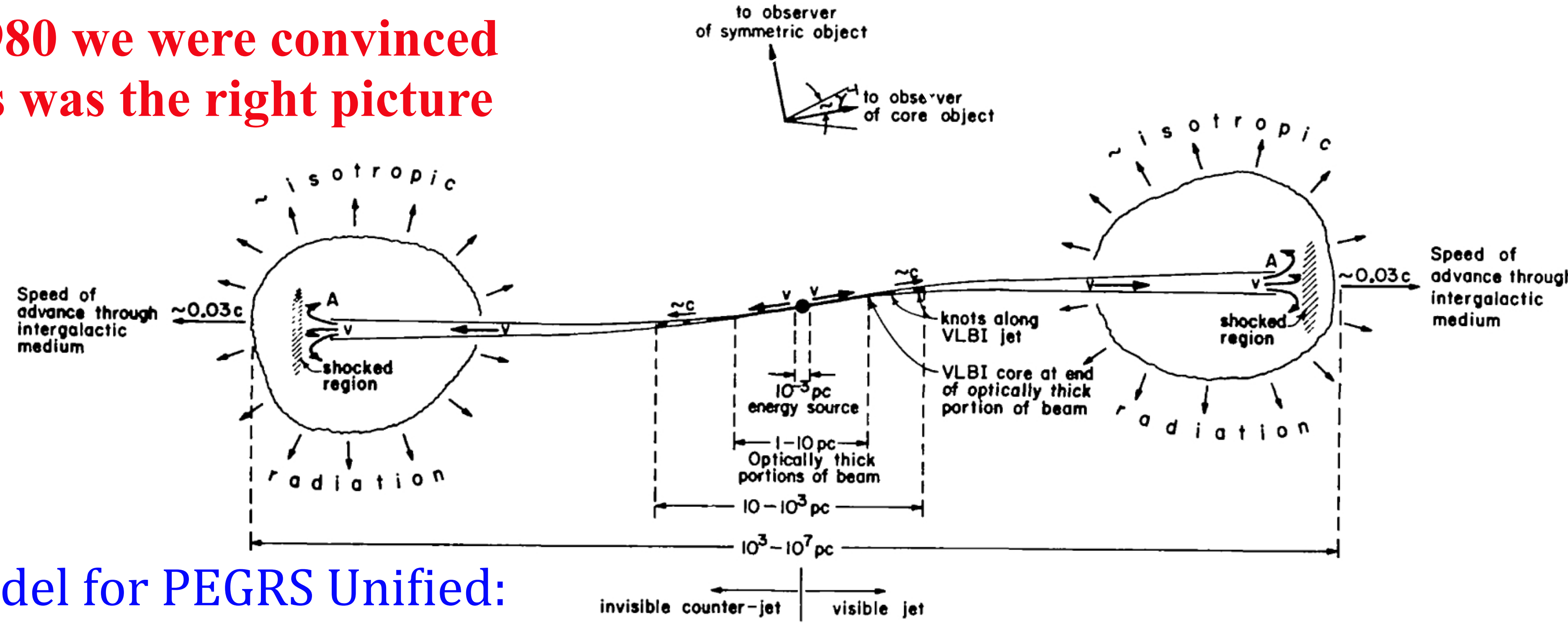

So This Model for PEGRS Unified:

1. Compact Sources with the Extended Sources

2. Flat-Spectrum Sources with the Steep-Spectrum Sources

3. Asymmetric Sources with Symmetric Sources

4. Sources with curved jets with the sources with straight jets

5. Nearby sources with the distant sources

6. Sources with nuclear jets showing superluminal motion with sources with nuclear jets not showing superluminal motion

7. Sources showing rapid variability with those not showing rapid variability

8. Radio-Quiet Quasars with Radio-Loud Quasars (only partially correct - see next)

9. Radio Galaxies with Quasars BUT did not explain the fact that Radio Galaxies have narrow emission lines while Quasars have broad emission lines - this completely baffled us!

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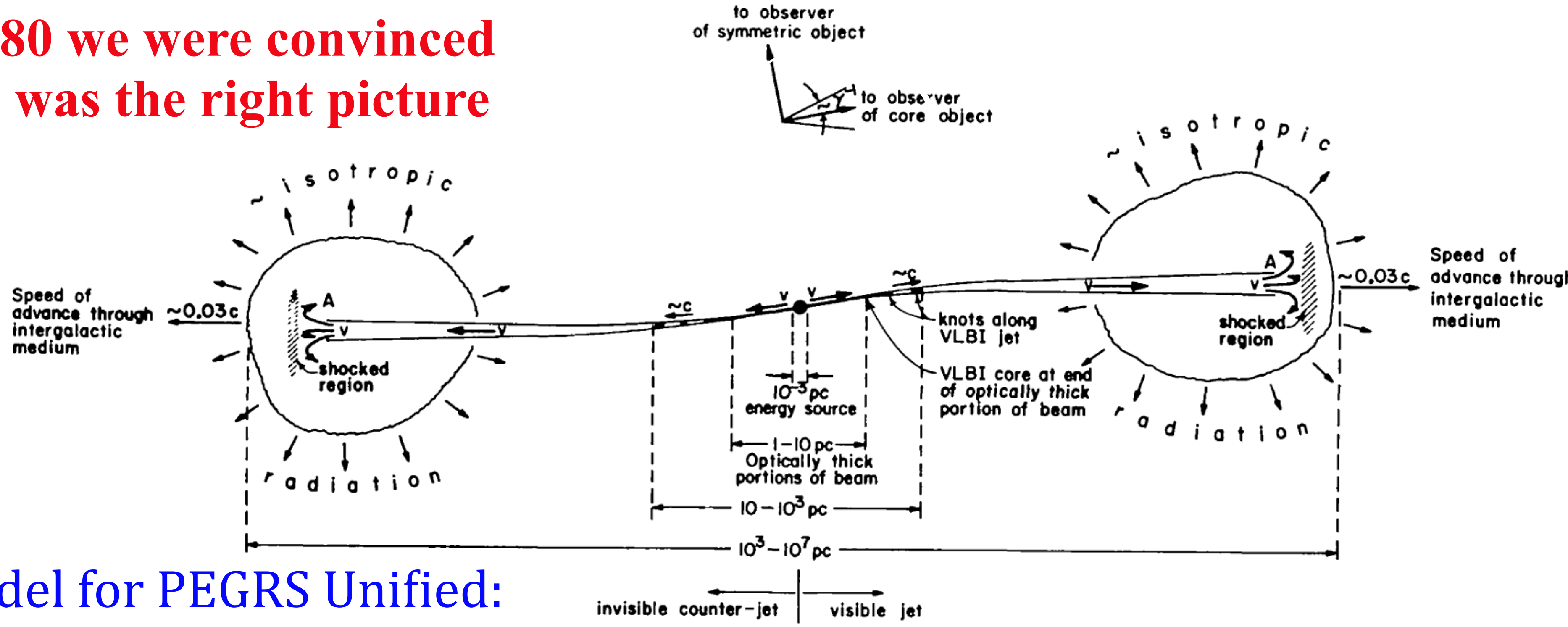

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This is why to us the Torus was the last (not the first) MAJOR piece of the Unification Puzzle!

You don't have to take my word for it!

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These conclusions must be regarded as tentative, based as they are on a heterogeneous sample. However, **they do suggest a powerful unifying theory of extragalactic radio sources** (Blandford and Rees, 1978a; Readhead, Cohen, Pearson, and Wilkinson, 1978; Scheuer and Readhead, 1979; Blandford and Konigl, 1979b; Orr and Browne, 1982; and Sec. II). This is that the majority of extragalactic radio sources are fueled by twin relativistic jets that emerge from the environs of a compact spinning object. These jets span a wide range of intrinsic powers. Jets that are pointed toward us are Doppler brightened and comprise the majority of the compact sources. Jets that are not aligned close to our line of sight comprise the extended sources in which most of the flux comes from the isotropically emitting double components. In this model most jets are intrinsically curved to some degree but the bending is exaggerated by projection effects in the compact sources. The halo emission associated with compact sources comes from a low-luminosity double component seen along the symmetry axis. Finally, superluminal expansion is caused by relative motion between the stationary optically thick regions in the innermost parts of the jet and inhomogeneities advected along with the outflowing material, both components being subject to strong Doppler boosting.

an attempt at unification that did not pan out at the time was

Superluminally expanding radio sources and the radio-quiet QSOs

P. A. G. Scheuer
Mullard Radio Astronomy Observatory, Madingley Road, Cambridge, UK

A. C. S. Readhead
California Institute of Technology, Pasadena, California 91125

1979, Nature, 277, 182

The recent findings in Kimball et al, 2011 (ApJL 739, 39) and Condon et al. 2014 (ApJ 768, 37) demonstrate very clearly that there are two populations of radio-quiet quasars:

1. The population described by Scheuer and Readhead of quasars viewed at angles to the los > $1/\gamma$, and
2. A population of radio-quiet quasars in star-forming galaxies with no significant radio contribution from the active nucleus where the radio emission comes from star formation and supernovae

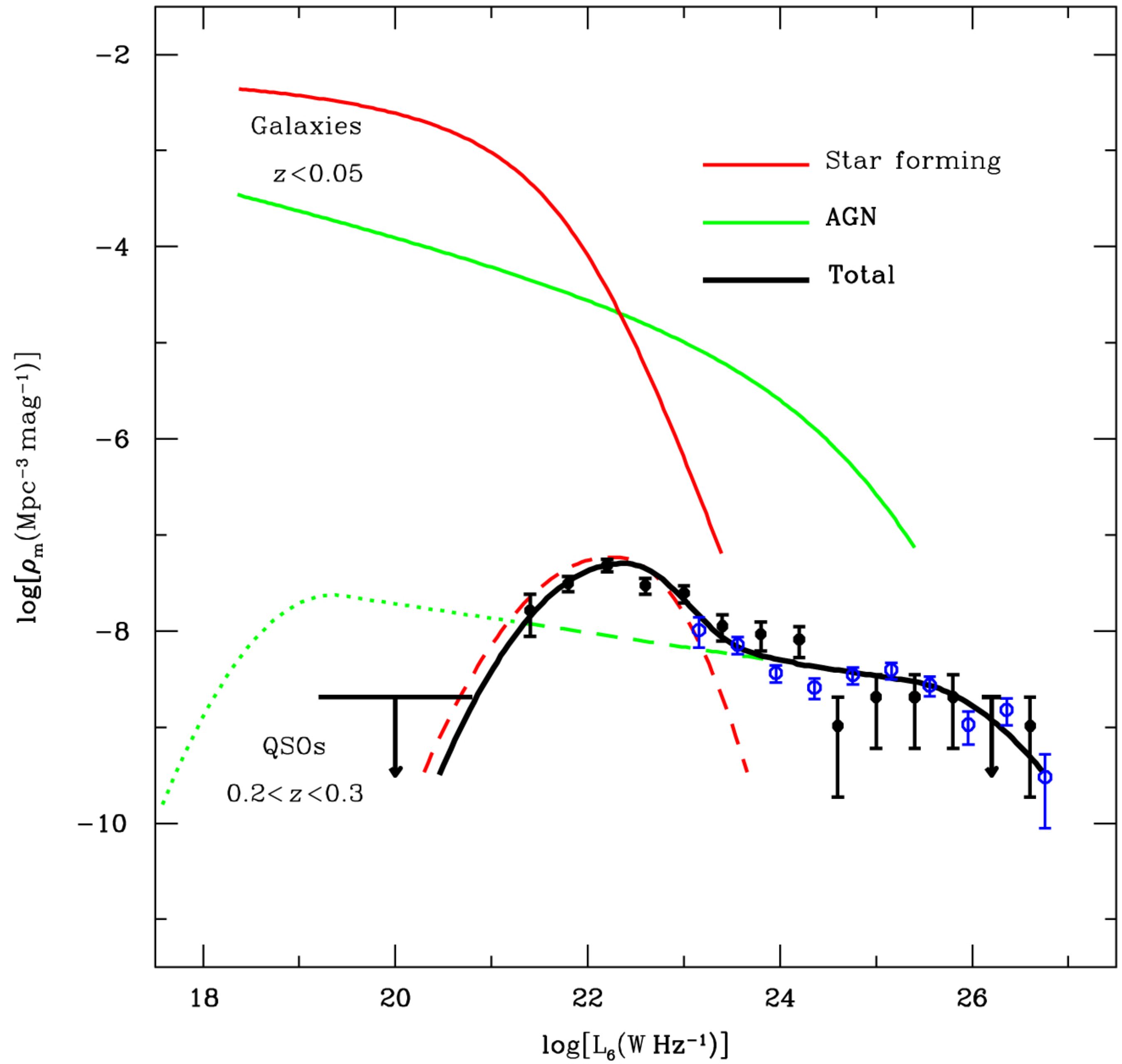

Figure 2. Our models for the spectral luminosity functions of $0.2 < z < 0.3$ QSOs are compared to the 1.4 GHz luminosity function of nearby galaxies (Condon et al. 2002) transformed to 6 GHz with an assumed spectral index of −0.7. Radio sources powered primarily by star formation are shown with a solid red curve and those powered by AGNs as a solid green curve. Solid black points correspond to our EVLA data; open blue points correspond to NVSS sources. The dashed green curve is an extrapolation of the high-radio-luminosity QSOs to low luminosities, using the slope determined from the NVSS data. The dashed red curve represents the spectral luminosity function of QSO hosts that are powered primarily from star formation, constrained by the EVLA data. The upper limit symbol at $\log[L_6(\mathrm{W\,Hz^{-1}})] \sim 20$ represents the six EVLA non-detections. While it is not certain that all of the non-detections have luminosities this low (see Figure 1), this upper limit constrains the most conservative estimate of the RLF falloff (see the text for details). The black curve is the calculated luminosity function for QSOs whose radio sources are powered by both AGNs and star formation in their host galaxies. The total area under the black curve is constrained by the number of SDSS QSOs in the volume-limited ($0.2 < z < 0.3$) sample.

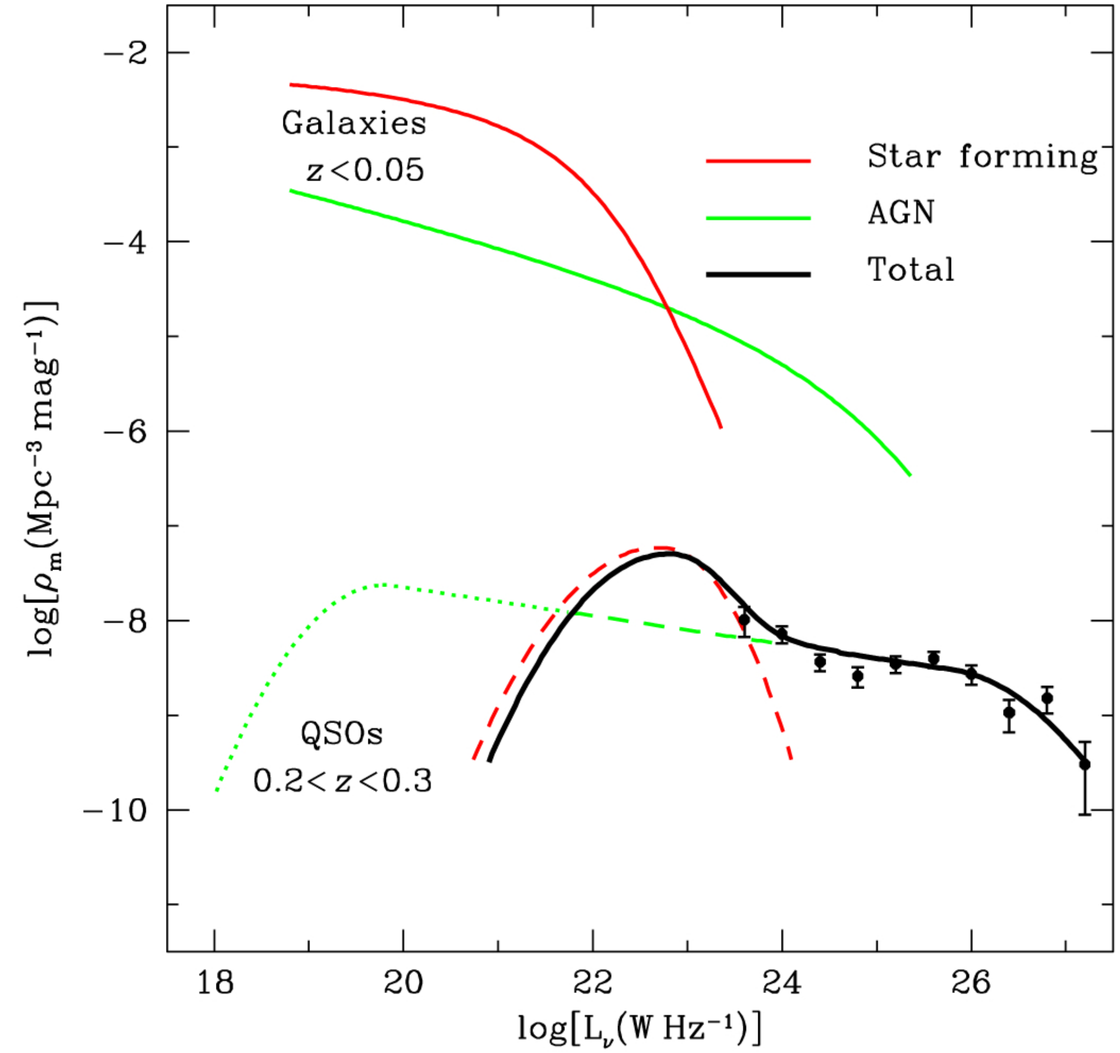

Figure 6. Comparison of the 1.4 GHz luminosity functions of nearby galaxies whose radio sources are powered primarily by star formation (continuous red curve) or by AGNs (continuous green curve) with our model for the luminosity function of $0.2 < z < 0.3$ QSOs (black curve). The data points are from Figure 4 with $\log[\rho_m(\mathrm{Mpc^{-3}\ mag^{-1}})$ lowered by 0.20 to correct for density evolution (Section 2.3). The green dashed line is the power-law extrapolation of the AGN-only contribution, and the green dotted curve shows how this extrapolation might be truncated so the number of AGNs does not exceed the total number of QSOs. The red dashed curve shows the luminosity function of the starbursts only. The black curve is the convolution of the AGN and starburst curves.

Ken Kellermann 5/3/15:

All QSOs must contain a SMBH (to explain the strong OIR luminosity), so the question remains: Why are only a small fraction radio loud? Many years ago you and Peter Scheuer suggested a clever explanation – Doppler boosting. But, for two reasons it seemed not relevant. Firstly, the beaming model predicts a very flat detection rate, whereas all observations found a steeper detection rate. I now realize that previously determined detection rates included the high end of the RQ population which rises steeply. If the analysis is confined to the strongest radio sources, the detection rate is consistent with beaming.

Second, problem is with a typical Lorentz factor of say 10, the radio emission is beamed into a solid angle ~ 0.01 sr. So for an isotropic beam we would only expect about 0.1% of optically selected QSOs to be strong radio sources, whereas typically 10 to 15 % are found to be RL. But gamma~10 is characteristic of radio selected strong radio sources. In a volume limited randomly oriented sample, the typical Lorentz factor is closer to one, and so the beaming angle is much broader.

Kellermann, Condon, Kimball, Perley, & Ivezic (in preparation)

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I don't think these developments before 1980 detract at all from the significance of the torus - that was clearly a major breakthrough - but I do think that they reveal a much longer and richer history of the Unification of AG than many working in this field today are aware of.

The Event Horizon Telescope (EHT) is one of THE most important physics experiments today but it is not easy!

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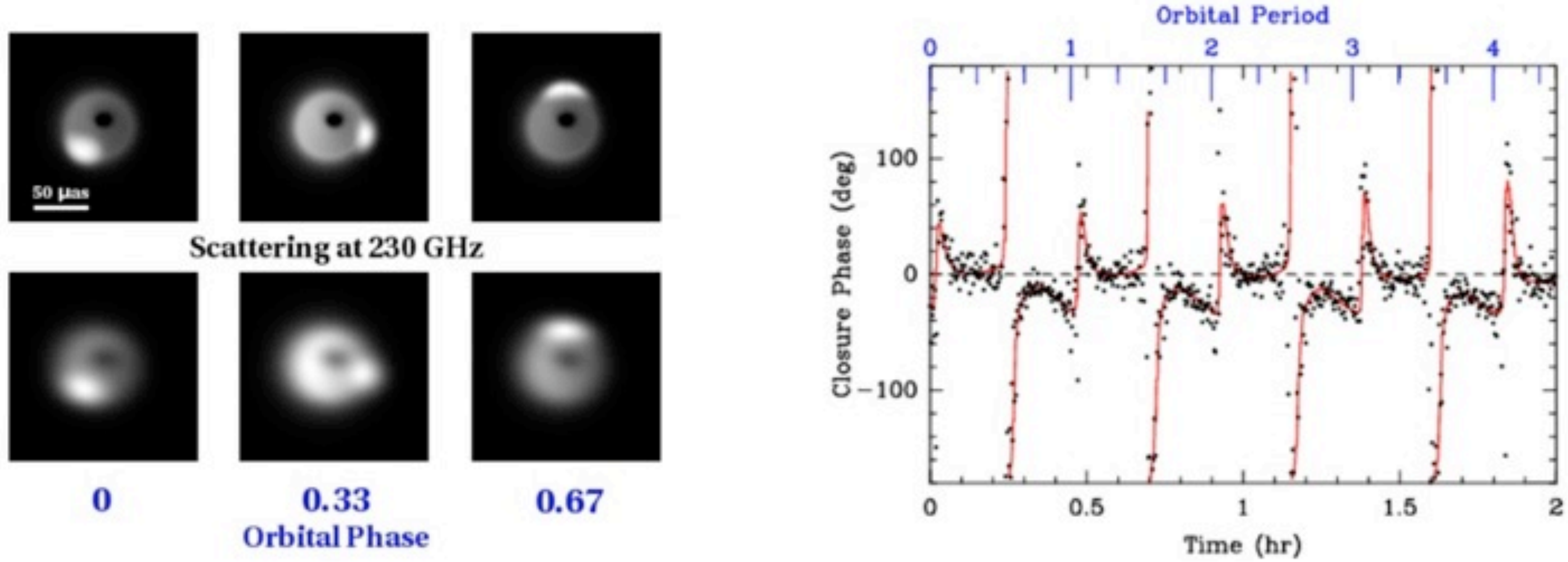
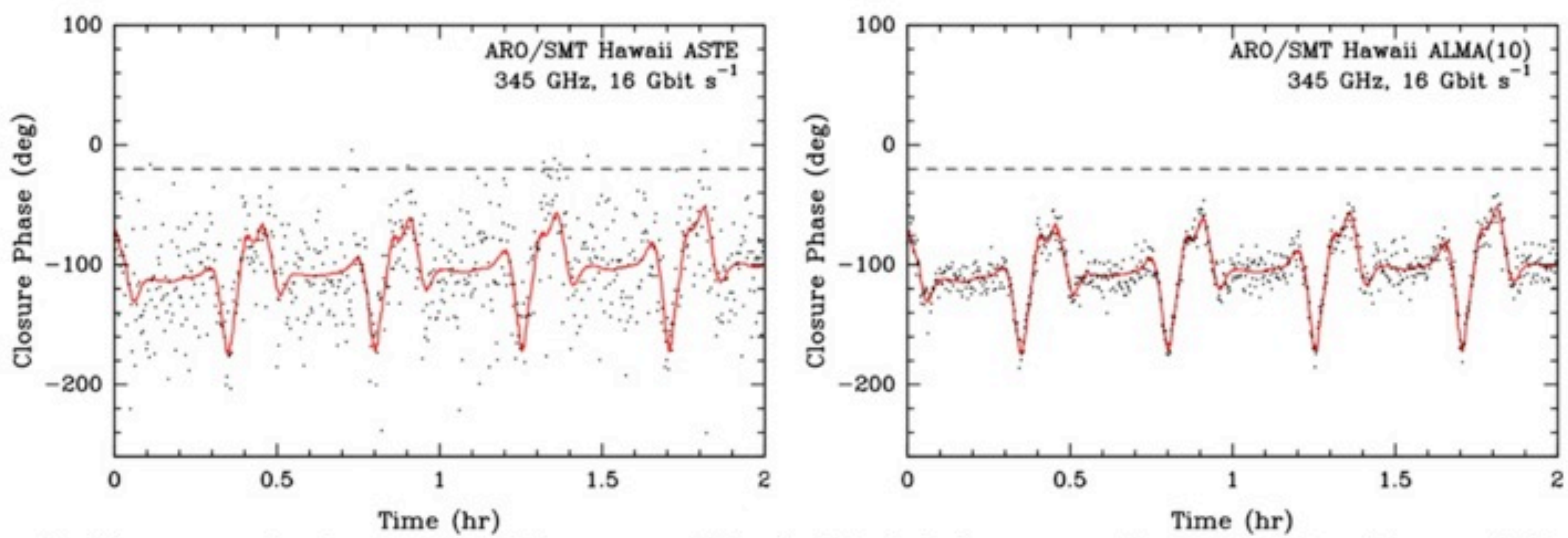


Figure 4: *Signature of a hot-spot orbiting the SgrA* black hole. The left panel shows a quiescent Radiatively Inefficient Accretion Flow (RIAF) model for a non-spinning 4x10^6 solar mass black hole, and a hot spot orbiting at the Innermost Stable Circular Orbit (ISCO), with a disk inclination of 60 degrees from line of sight. The raw model is shown for 3 orbital phases in the top three figures, and the bottom three show the effects of scattering by the ISM. VLBI closure phase (the sum of interferometer phase over a triangle of baselines) is non-zero when asymmetric structure is present. The right panel shows 1.3mm wavelength VLBI closure phases every 10-seconds on the ARO/SMT-Hawaii-CARMA triangle with the model phases shown as a red curve (Doeleman et al. 2009).*



Amplitudes can be hard to calibrate - so how well an one do with closure phases alone?

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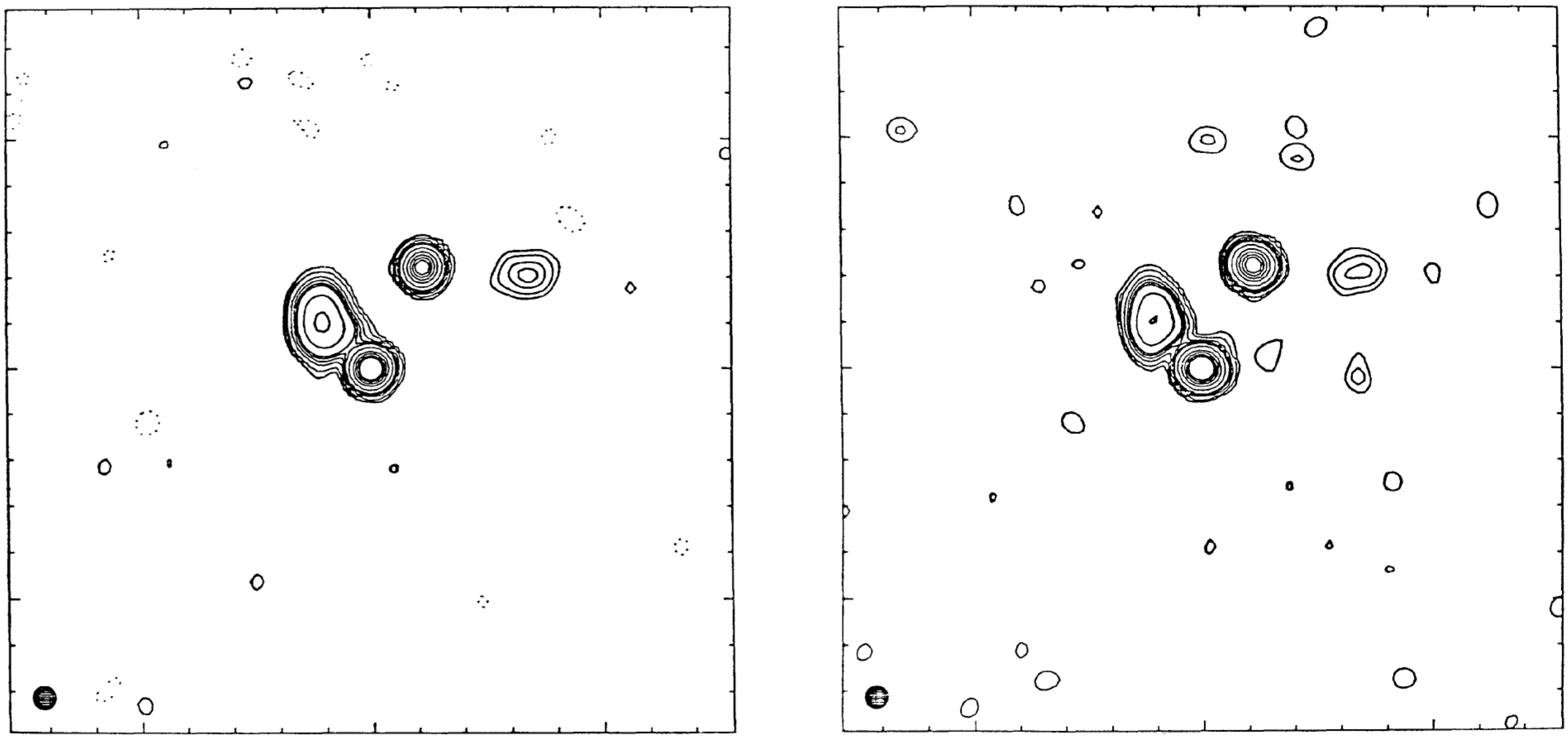
Blind Test

Test Object

Image reconstructed from closure phases alone from observations with 10 antennas



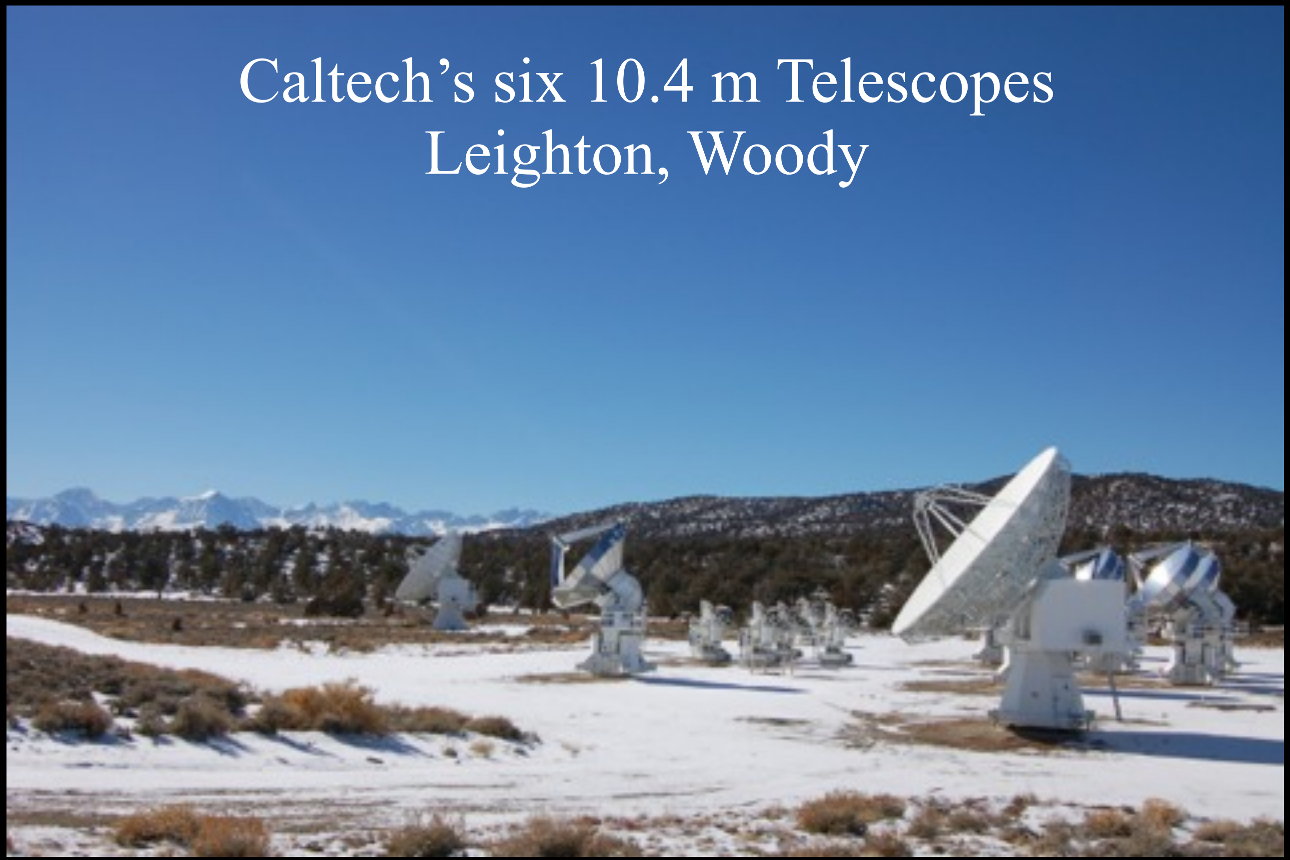
Readhead, Nakajima, Pearson, Neugebauer, Oke & Sargent, 1988 AJ, 95, 1278

We need the EHT to be able to probe the event horizon with extreme sensitivity

Sensitivity is the key

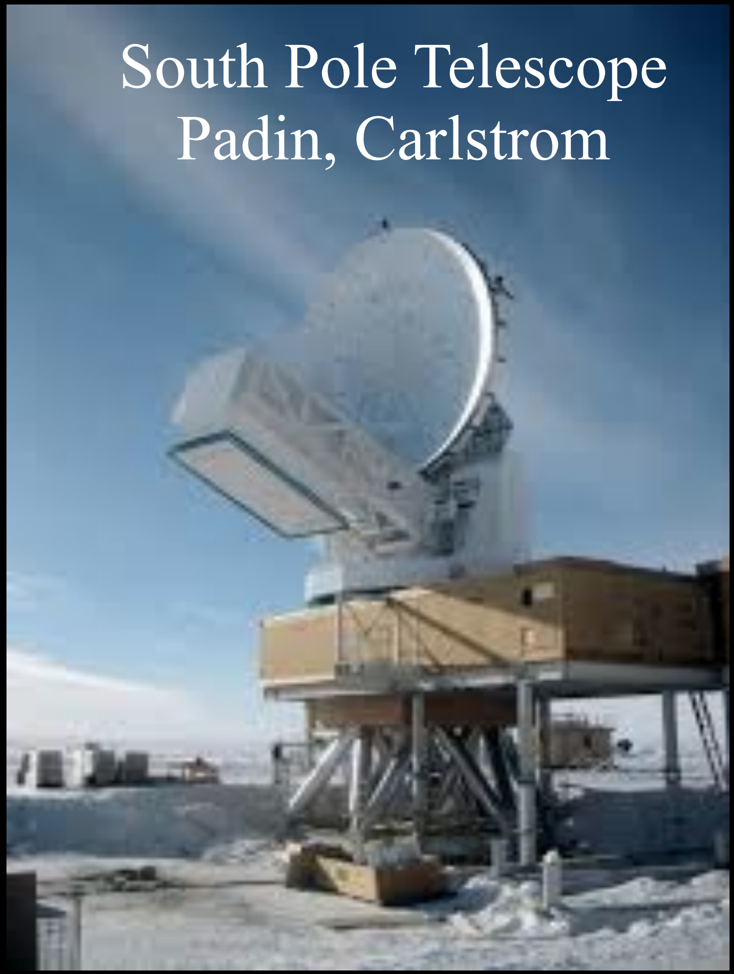
In the 70s when we were probing AGN we had the advantage of large telescope - these are very important

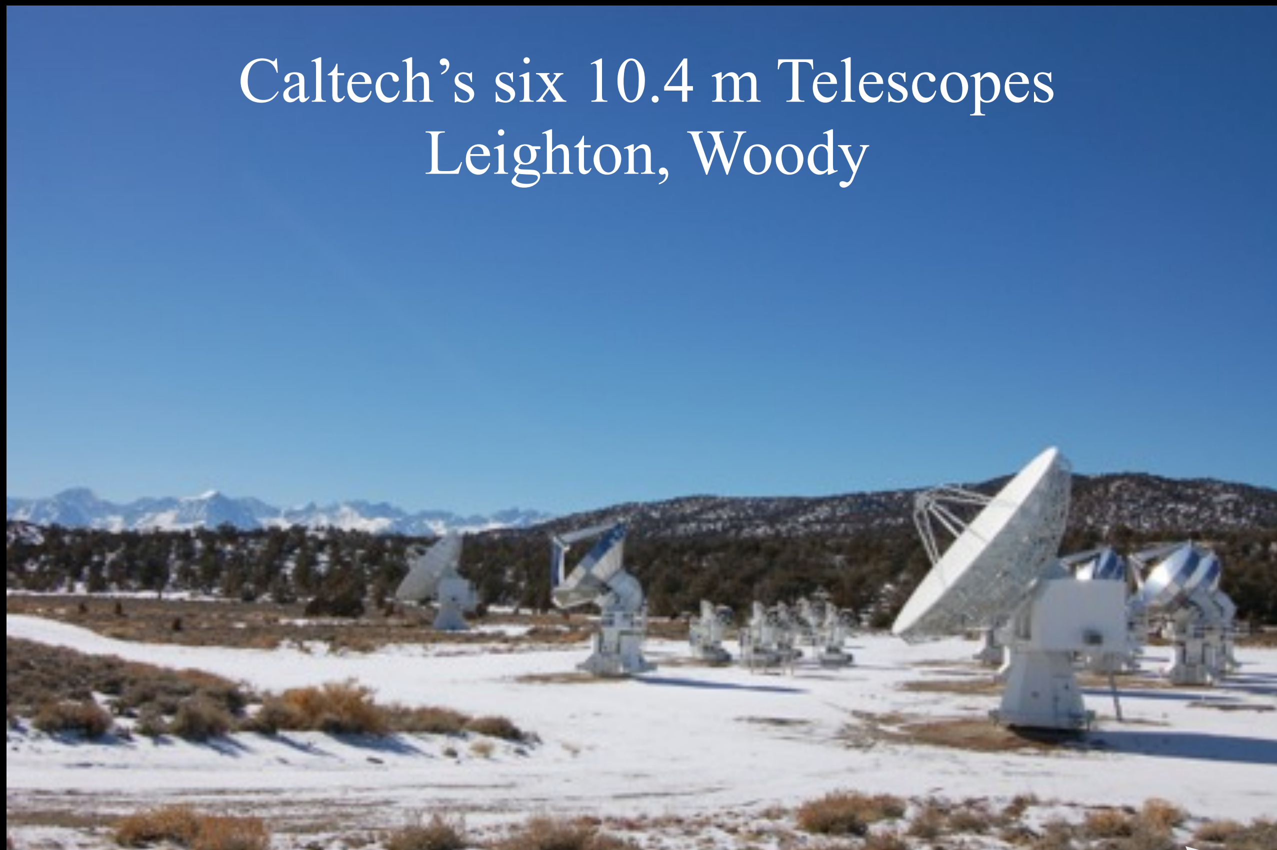
The Importance of Southern Africa is obvious from the (u,v) coverage it will provide - but we need a large ~25 m telescope there


Caltech's six 10.4 m Telescopes
Leighton, Woody

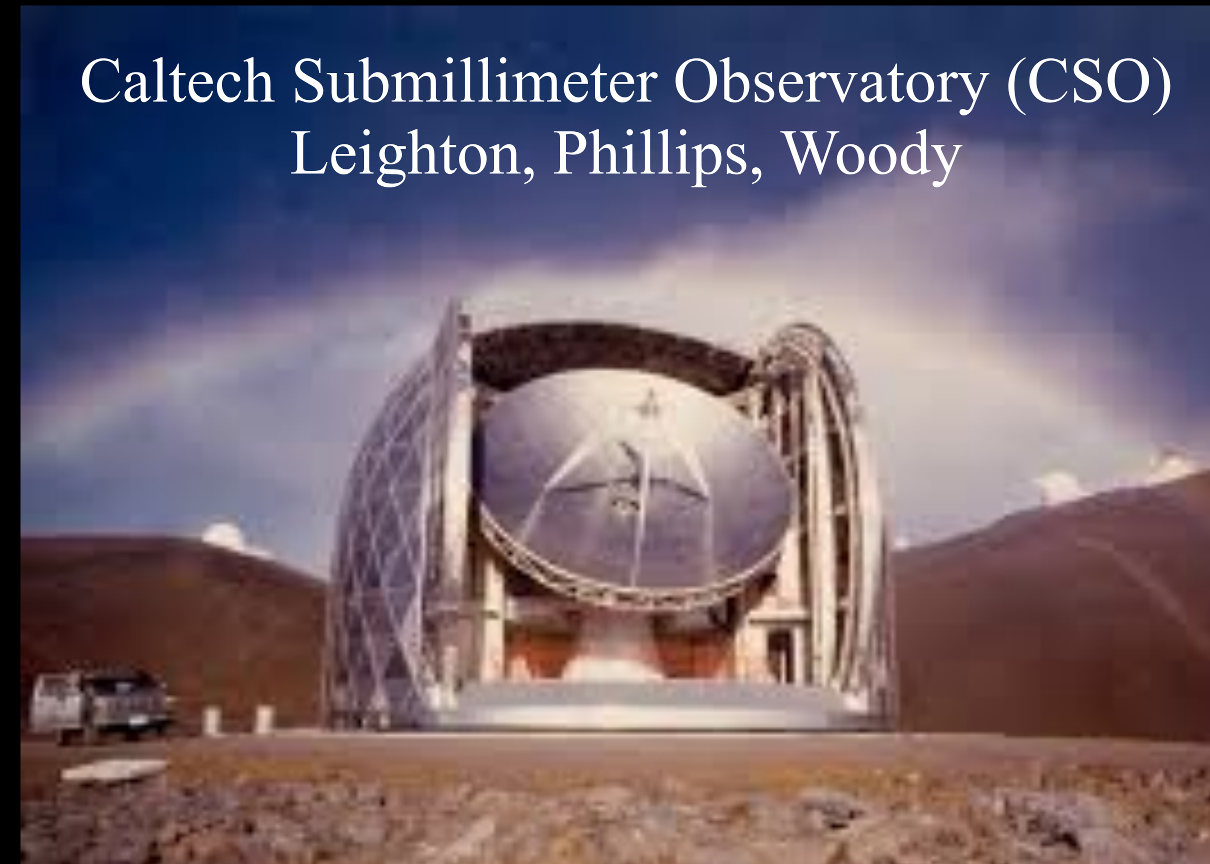

Caltech Submillimeter Observatory (CSO)
Leighton, Phillips, Woody


Caltech's Cosmic Background Imager (CBI)
Padin, Readhead


South Pole Telescope
Padin, Carlstrom

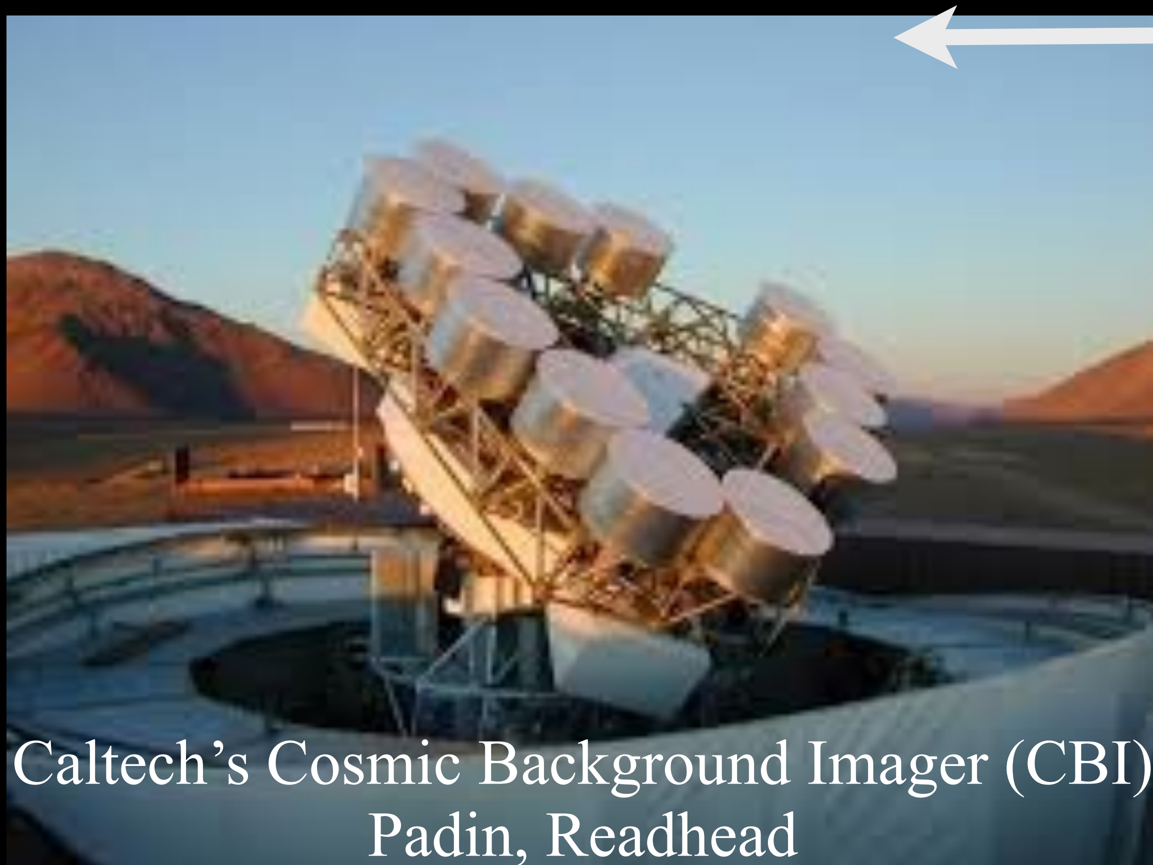


Caltech's six 10.4 m Telescopes
Leighton, Woody



Caltech Submillimeter Observatory (CSO)
Leighton, Phillips, Woody

Designed and built at Caltech then disassambled shipped and re-assambled on site



Caltech's Cosmic Background Imager (CBI)
Padin, Readhead

South Pole Telescope
Padin, Carlstrom

Steve Padin's
Caltech Sub-millimeter Survey Telescope (CSST)

Completely novel design
free-standing - no dome - designed for windy site
active control of surface
low maintenance
limited sky coverage (1 radian in az and el)

A 30 meter telescope operating to 345 GHz for $15M
scales as $D^{8/3}$ and $\lambda^{1/2}$
e.g. a 25 m antenna operating to 235 GHz would cost $7m
built in house at Caltech, or in South Africa, or in Germany

Inexpensive mount for a large millimeter-wavelength telescope

S. Padin

California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA (spadin@caltech.edu)

Received 3 April 2014; revised 27 May 2014; accepted 30 May 2014;
posted 2 June 2014 (Doc. ID 209561); published 4 July 2014

A telescope mount with a single-point force support at the center of gravity of the primary mirror is proposed in order to eliminate much of the structure and cost of a large, millimeter-wavelength telescope. The single-point support gives repeatable thermal and gravitational deformation, so the surface of the primary can be controlled based on lookup tables for elevation and temperature. The new design is most appropriate for a survey telescope because locating the support above the vertex of the primary limits the range of motion of the mount to about 1 rad. A 30 m diameter, $\lambda = 850$ μm telescope with the proposed mount is a factor of 4 lighter than a design with a conventional elevation-over-azimuth mount, and roughly half the cost.

OCIS codes: (350.1260) Astronomical optics; (110.6770) Telescopes; (220.4880) Optomechanics.
http://dx.doi.org/10.1364/AO.53.004431

Applied Optics, 2014, 53, 4331

Thank You!