WS 2004/05

Hochauflösende Radiobeobachtungen aktiver Galaxienkerne

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Max-Planck-Institut
für
Radioastronomie

Jede 2. Woche!

Termine:

Heute

05.11.2004

19.11.2004

03.12.2004

17.12.2004

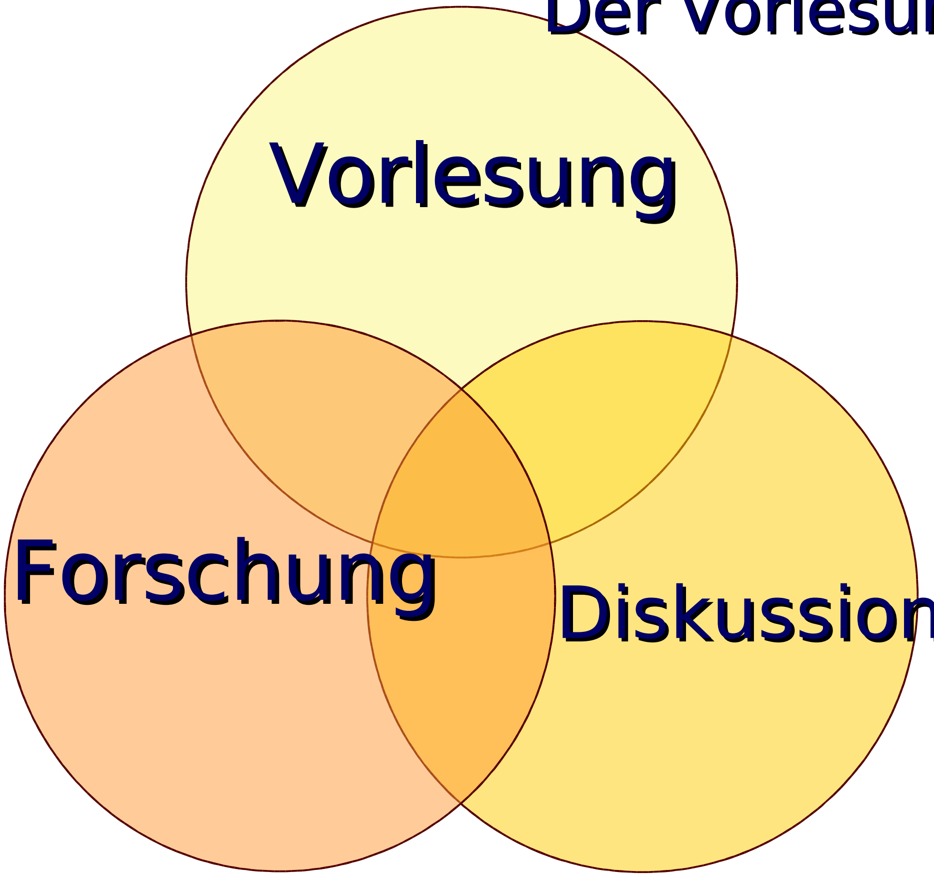
14.01.2005

28.01.2005

11.02.2005

- Geplant: pdf-Version

Der Vorlesung im Internet



Heute: Einführung & Überblick „Aktive Galaxienkerne „

Überblick: Wintersemester 2004/05

- Astrophysik aktiver Galaxienkerne
- Einführung und Überblick
  - Aktive Galaxienkerne
  - Was heißt „aktiv"?
  - Welche Arten gibt es – der Zoo, wichtigste Merkmale
  - AGN Radio-Durchmusterungen
- Handwerkszeug:
  - „beaming"-Scenario
  - Spektrale Energieverteilung Aktiver Galaxienkerne
  - Das Standardmodell: Schwarzes Loch + Akkretionsscheibe +Jet
- Das Jet-Phänomen
  - Jets von pc- zu kpc-Skalen
  - Scheinbar überlichtschnelle Bewegungen
  - Krümmungen & Präzession
  - Polarisation
  - MHD & Jetsimulationen
- Variabilität
  - Überblick: Zeitskalen & Wellenlängen
  - Theoretische Modelle

Überblick: Wintersemester 2004/05

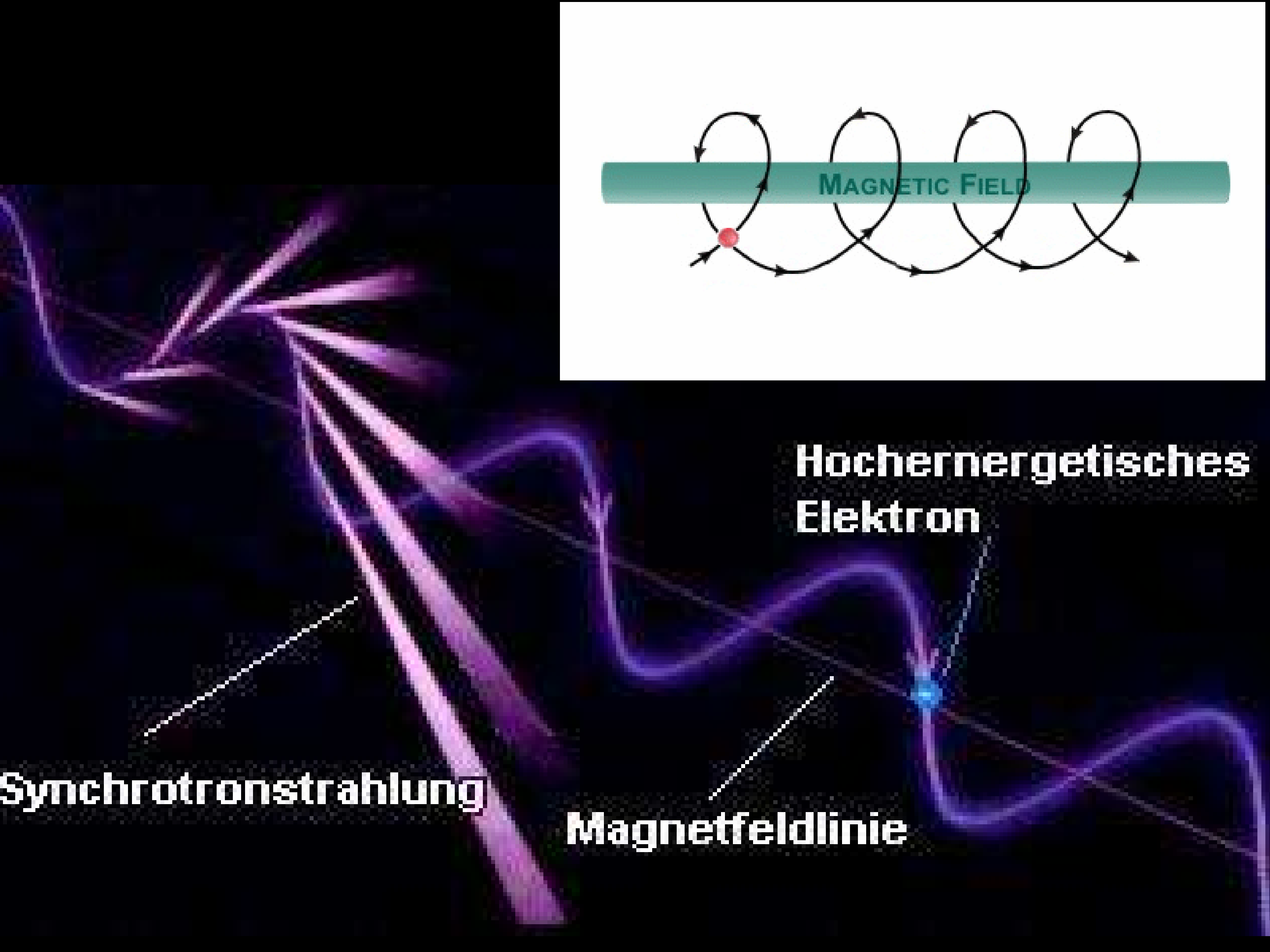
- Astrophysik aktiver Galaxienkerne
  - Kosmologische Evolution der AGN
  - Unsere Milchstraße und die Möglichkeit eines Schwarzen Lochs im Zentrum
  - Vereinheitlichungstheorien
  - Kosmologie mit Aktiven Galaxienkernen
  - Offene Fragen der Erforschung aktiver Galaxienkerne

Literature

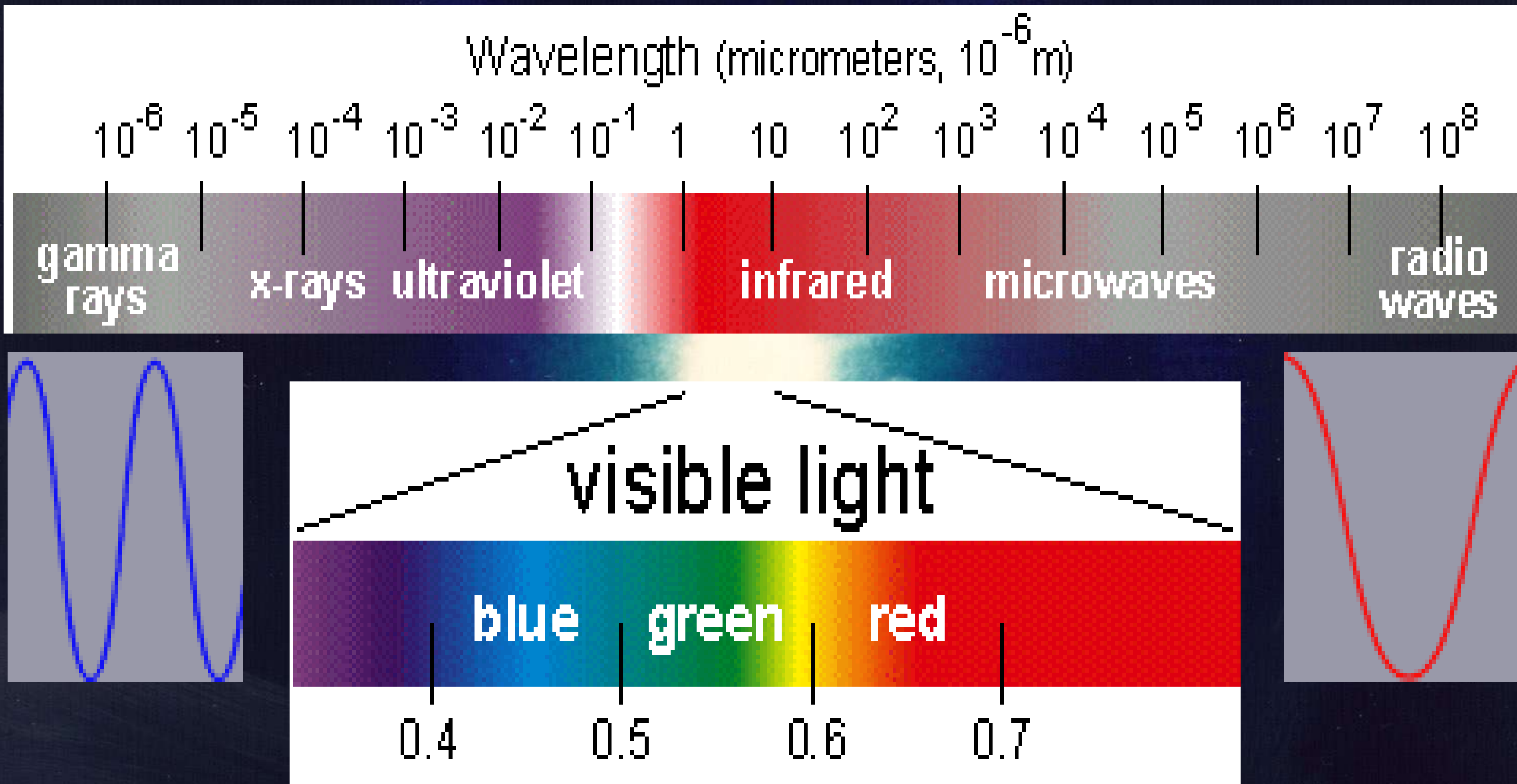
- Books:
  - *Beams and Jets in Astrophysics*, 1991, P.A. Hughes (ed.), Cambridge University Press, Cambridge
  - *Active galactic nuclei*, 1990, R.D. Blandford, 20th SAAS-FEE lectures
  - *An Introduction to Active Galactic Nuclei*, Bradley M. Peterson
  - *Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment*, Julian H. Krolik
  - *Quasars and Active Galactic Nuclei : An Introduction* Ajit Kembhavi & Jayant V. Narlikar

- Articles:
  - *Parsec-Scale Jets in Extragalactic Radio Sources*, J.A. Zensus, *Annu. Rev. Astron. Astrophys. 1997. 35: 607-36*
  - *Theory of Extragalactic Radio Sources*, Begelman, M.C., R.D. Blandford, & M.J. Rees, 1984, *Revs. Modern Physics* **56**, 255

Der „Radiohimmel“


MAGNETIC FIELD
Hochernergetisches
Elektron
Synchrotronstrahlung
Magnetfeldlinie

Radio Emission von kosmischen Objekten: vorwiegend Synchrotron Strahlung

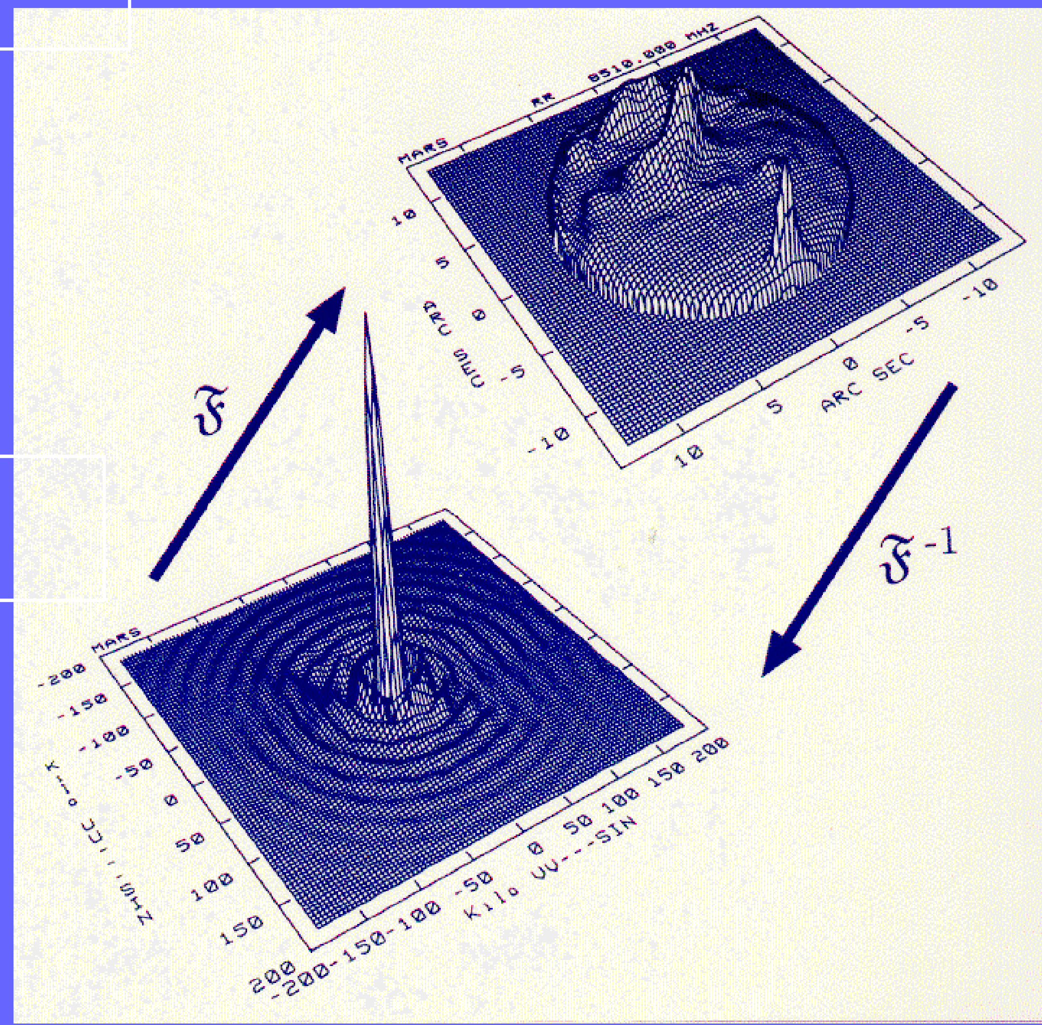


Das Prinzip der Interferometrie

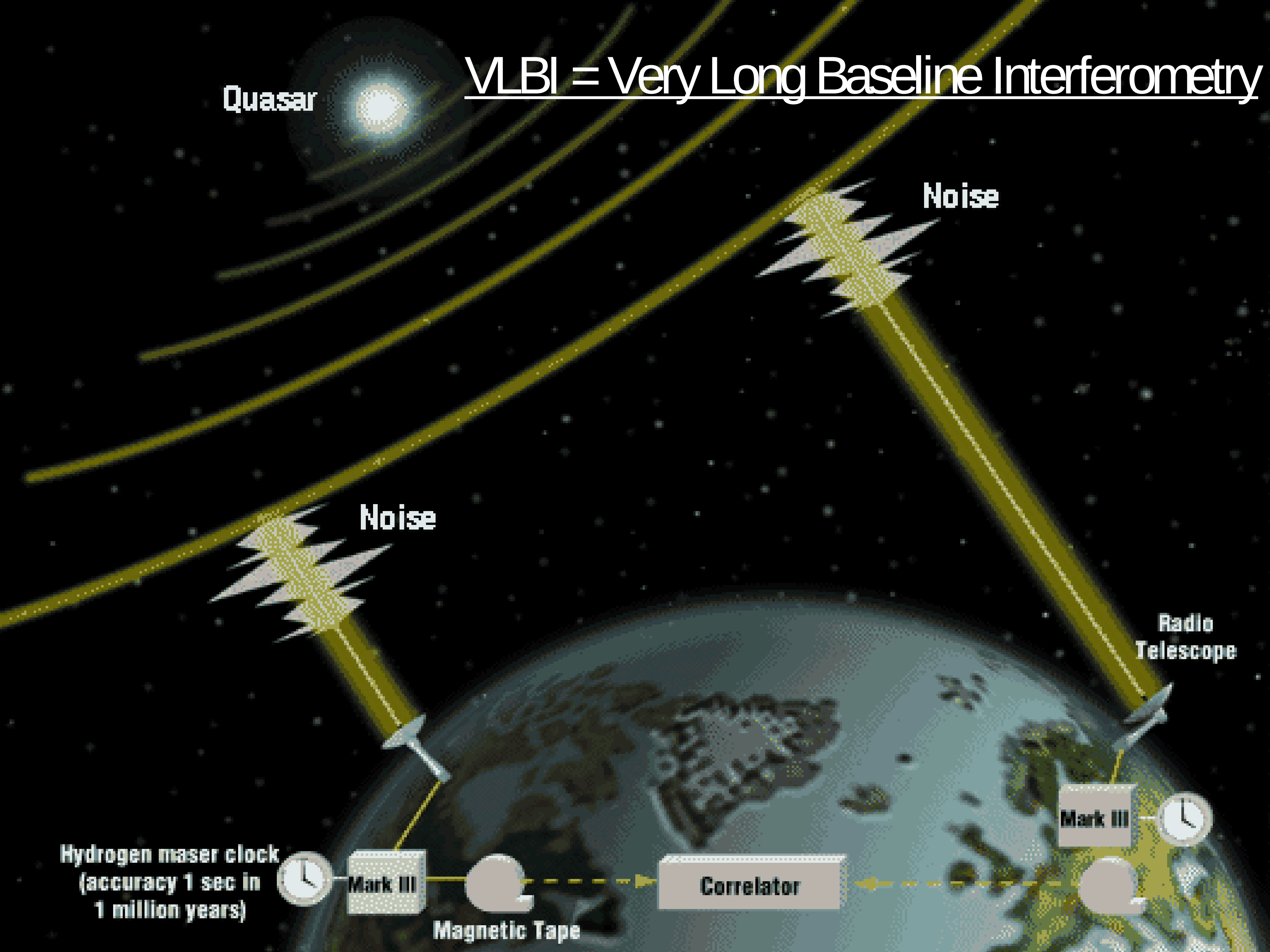
Das Prinzip der Interferometrie: Die Inversion der Kohärenz Funktion

$$V_\nu(u,v) = \int\int I_\nu(l,m)\, e^{-2\pi i(ul+vm)}\, dl\, dm$$

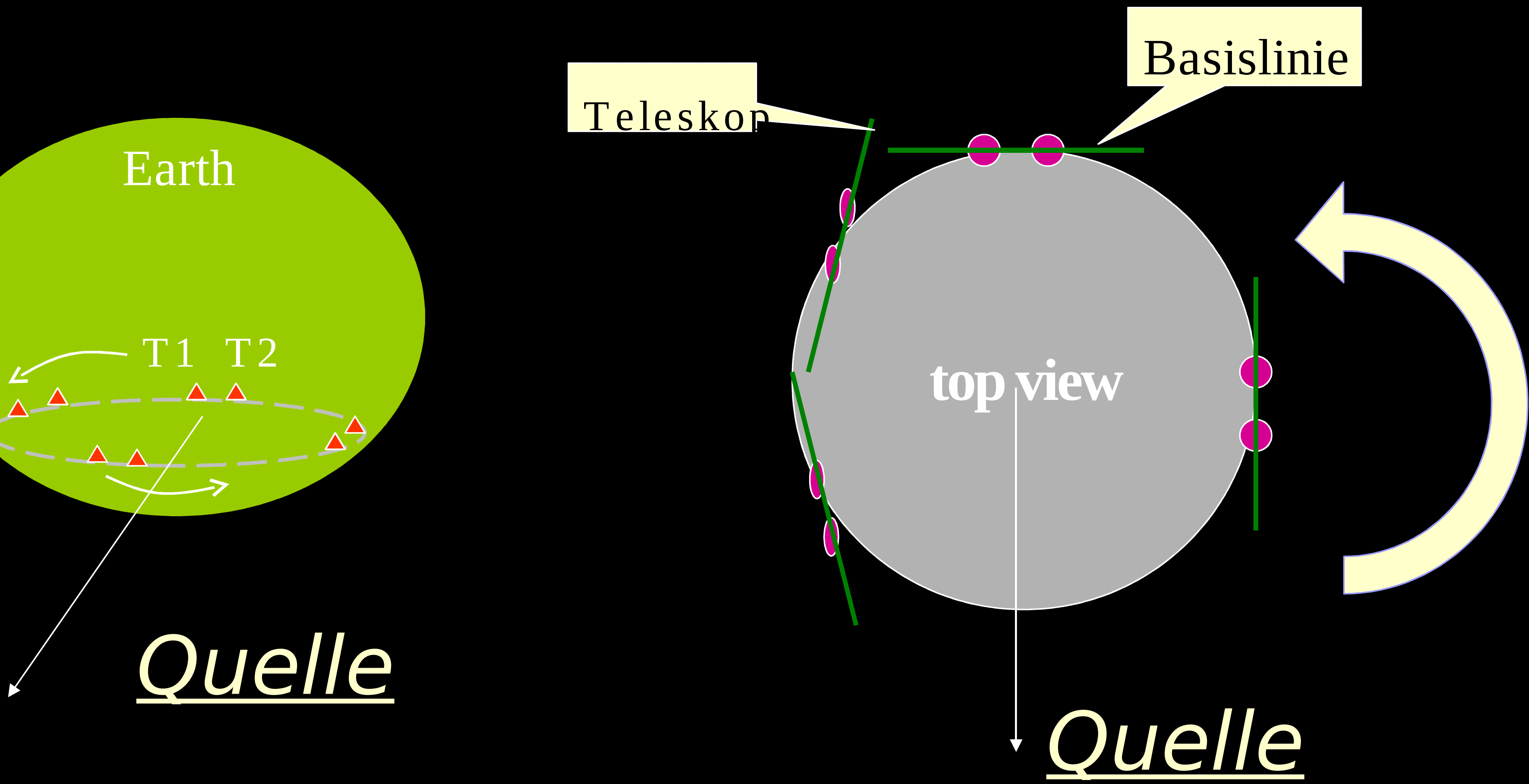
$$I_\nu(l,m) = \int\int V_\nu(u,v)\, e^{2\pi i(ul+vm)}\, du\, dv$$



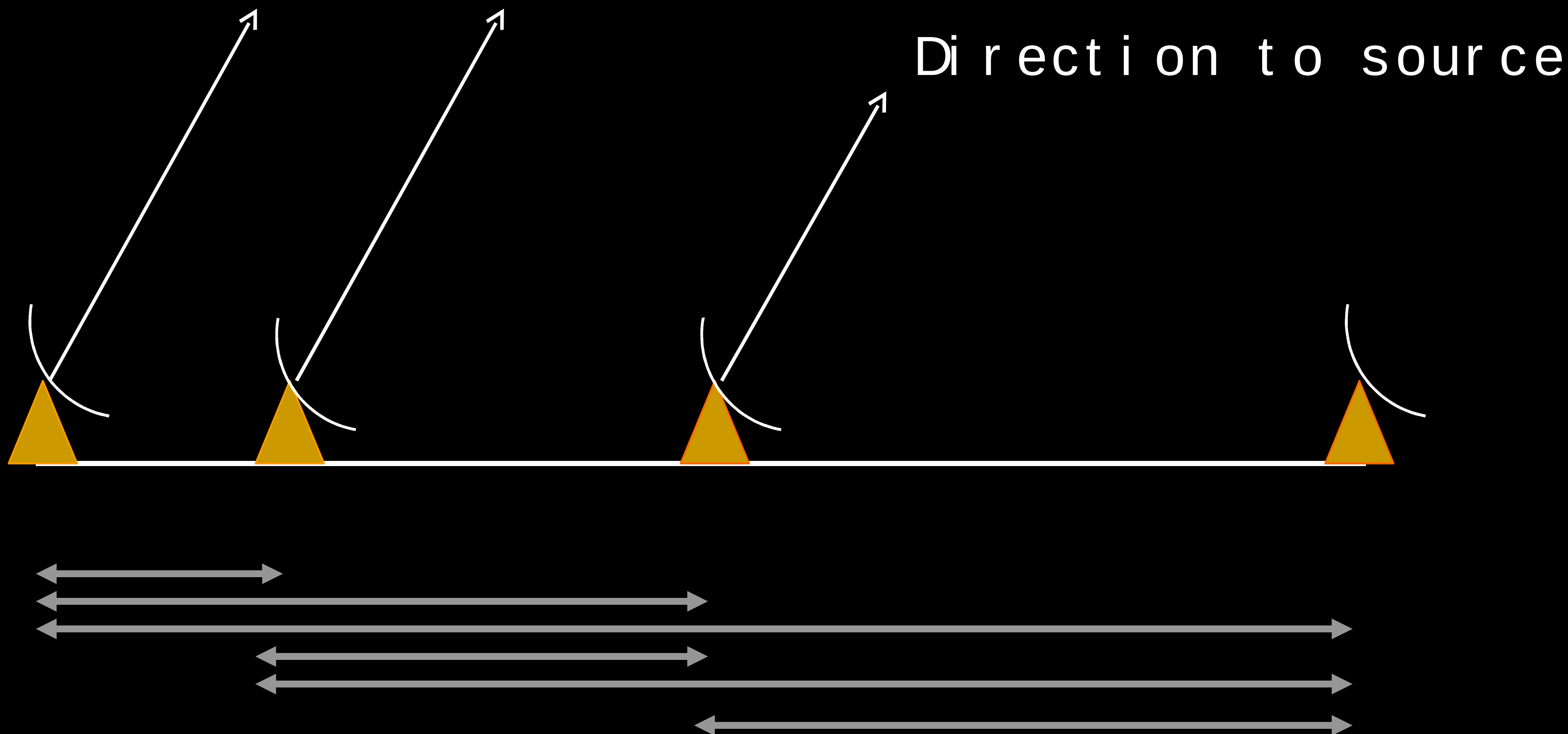
VLBI = Very Long Baseline Interferometry



Ausnutzen der Erdrotation

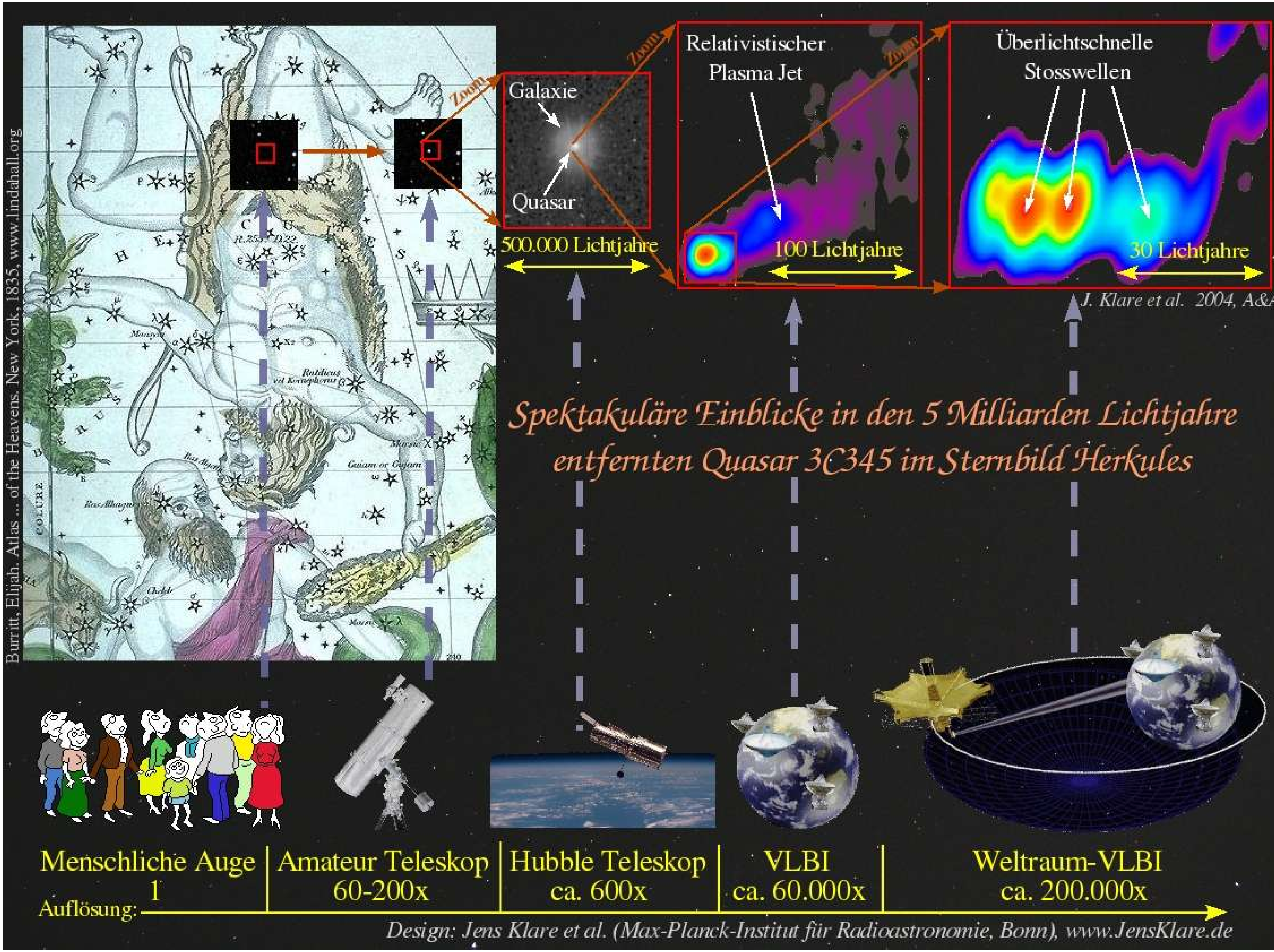


Need to measure the cross-correlation over as many spacings as possible



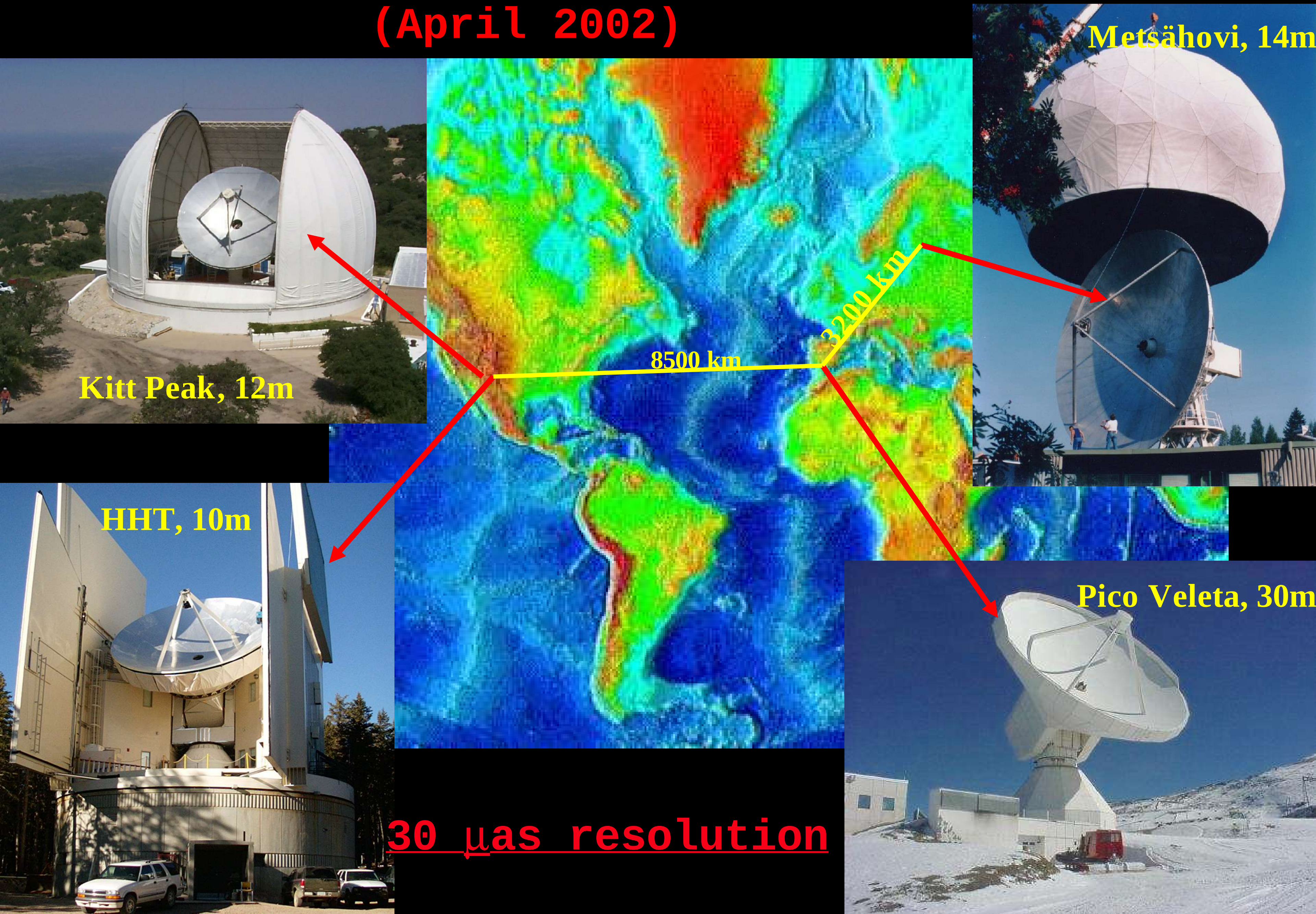
For n antennas, we get $n(n+1)/2$ spaci

The Global VLBI - Array
EVN
HSA
VLBA


Burritt, Elijah. Atlas ... of the Heavens. New York, 1835, www.lindahall.org
Zoom
Galaxie
Quasar
500.000 Lichtjahre
Zoom
Relativistischer
Plasma Jet
100 Lichtjahre
Zoom
Überlichtschnelle
Stosswellen
30 Lichtjahre
J. Klare et al. 2004, A&A
Spektakuläre Einblicke in den 5 Milliarden Lichtjahre
entfernten Quasar 3C345 im Sternbild Herkules
Menschliche Auge
1
Amateur Teleskop
60-200x
Hubble Teleskop
ca. 600x
VLBI
ca. 60.000x
Weltraum-VLBI
ca. 200.000x
Auflösung:
Design: Jens Klare et al. (Max-Planck-Institut für Radioastronomie, Bonn), www.JensKlare.de

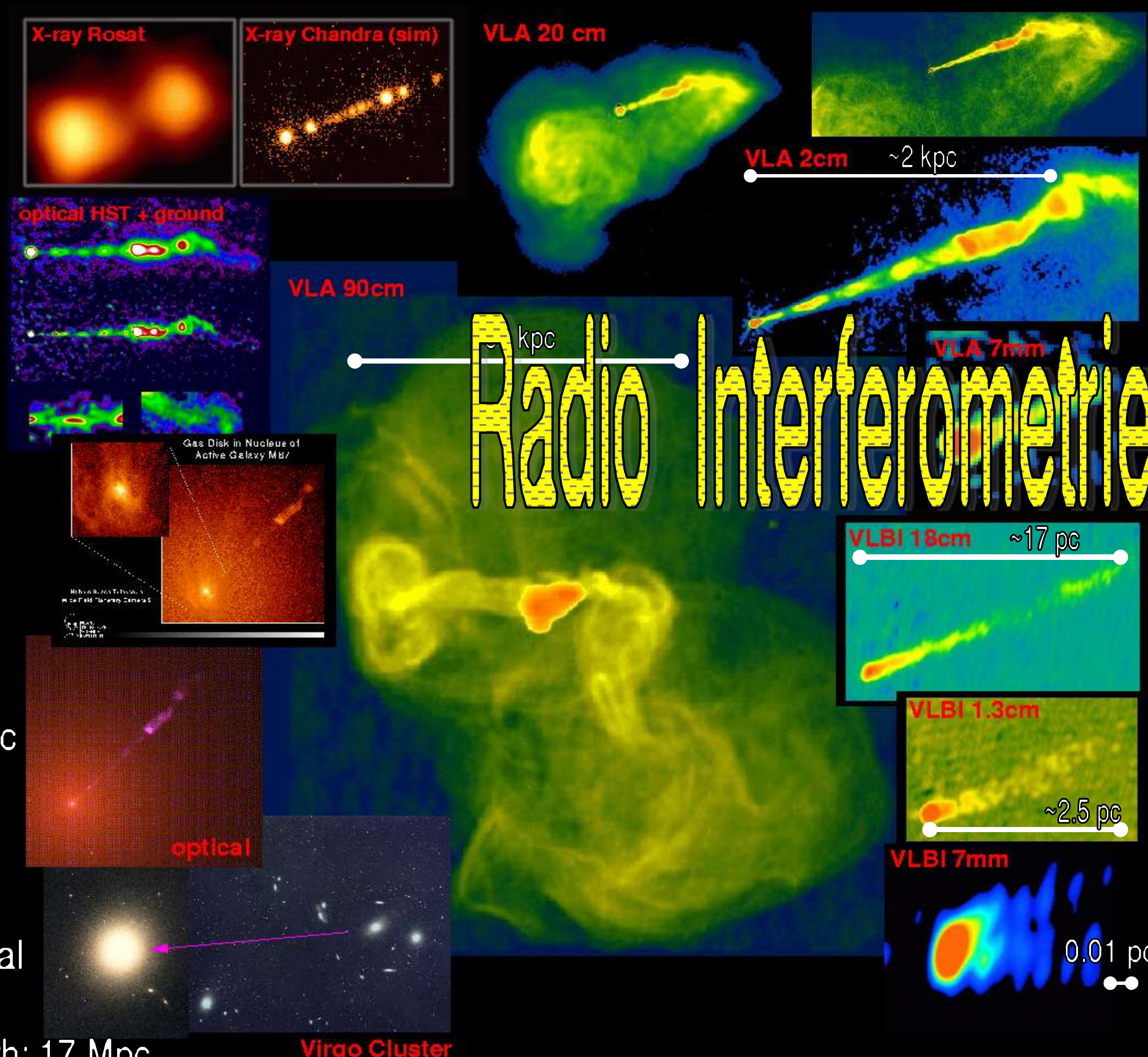
First Transatlantic VLBI fringes at 147 GHz:

(April 2002)



30 µas resolution

M87 (Virgo A) - From half a million light years to 0.1 light years

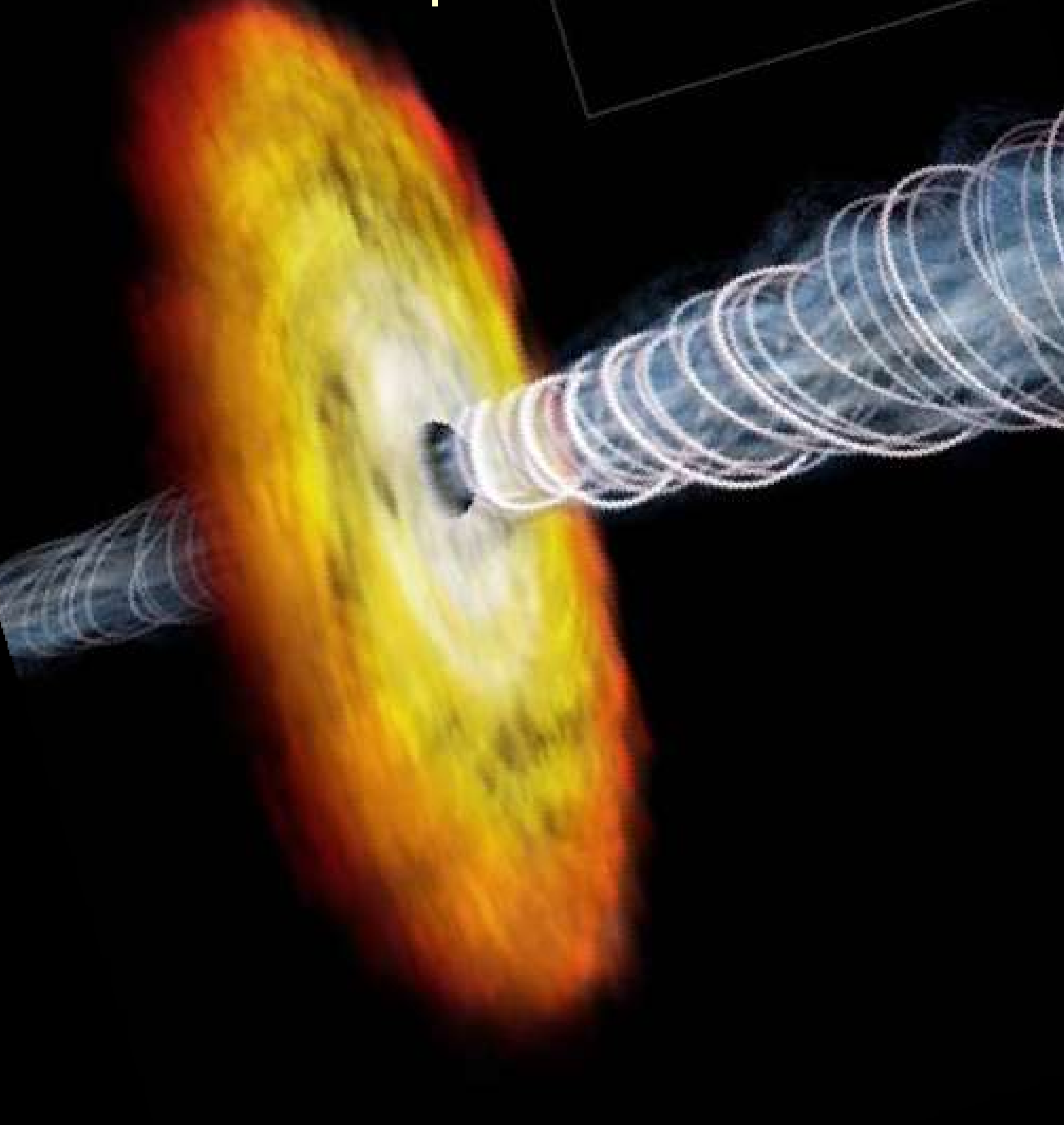


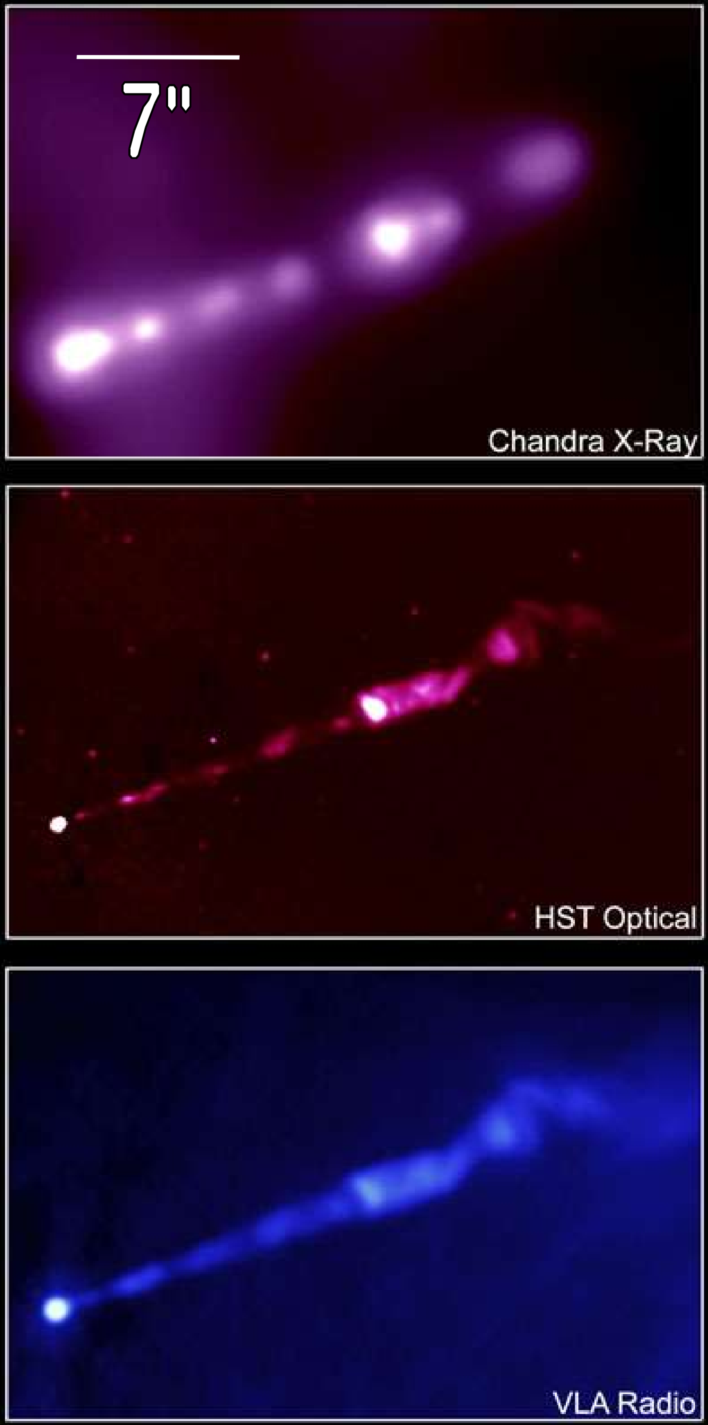
2 kpc

100 kpc total

distance from Earth: 17 Mpc

„Jets have a knotty problem!“

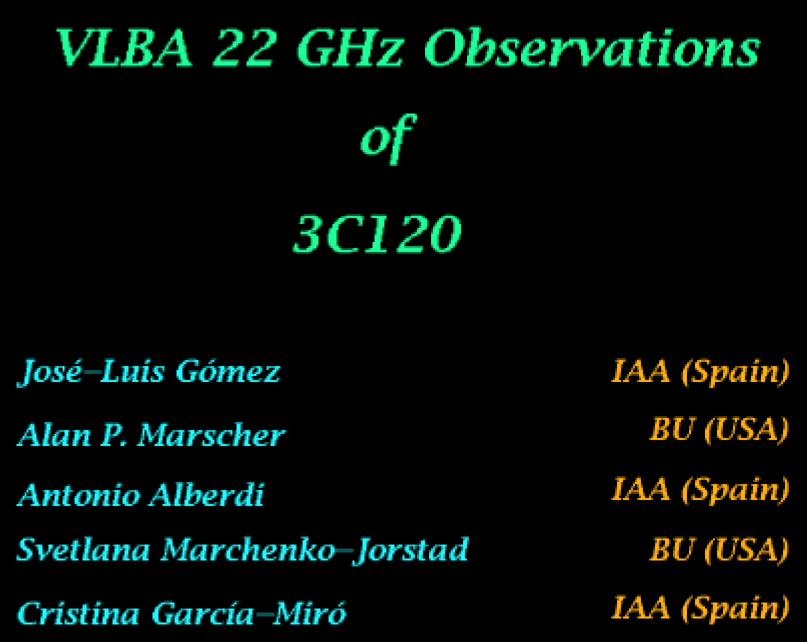




Superluminal motion in AGN

3C120 monitored in a dedicated campaign

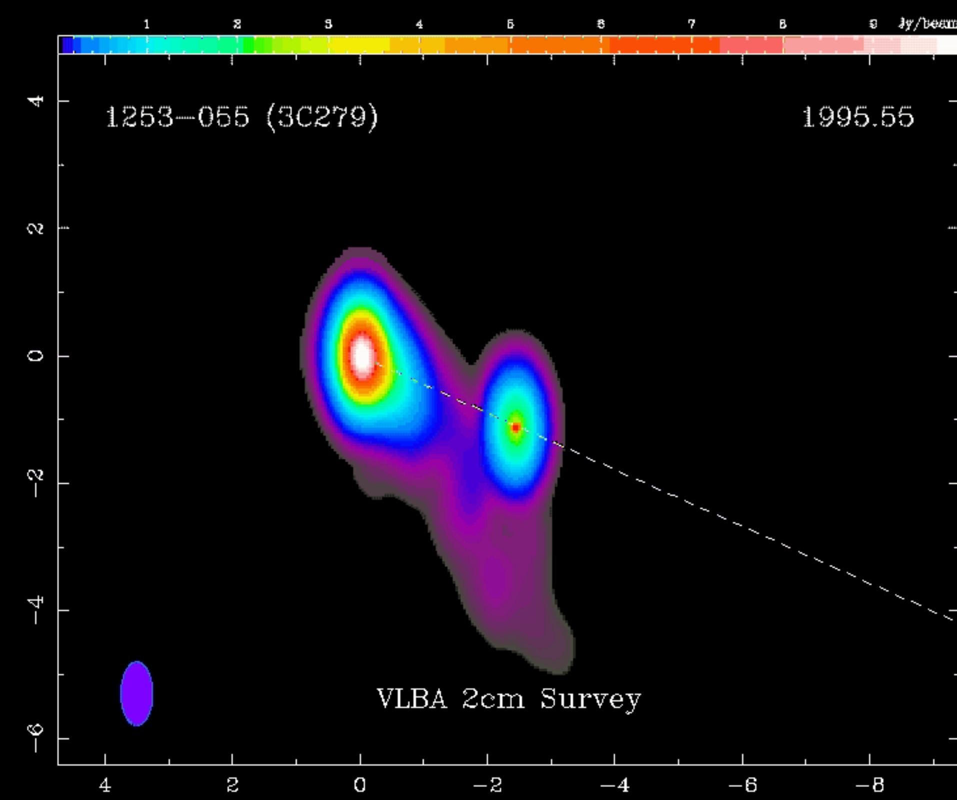
-Complex jet kinematics in total intensity (contours) and polarization (color).
-Superluminal motion, edge brightening, polarization angle rotation, etc. allow to study the jet physics (MHD) in finest details.



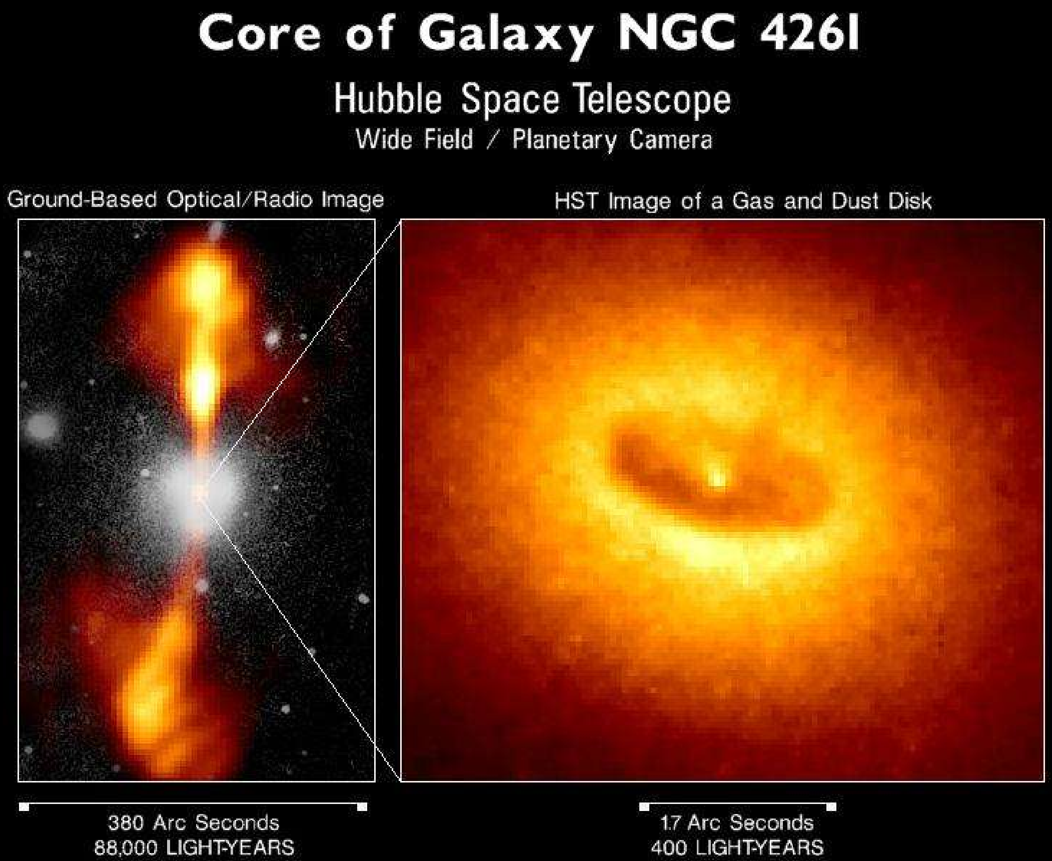
3C279 in the 2cm Survey

-Change in the trajectory of a jet component of the quasar 3C 279; change in speed and direction
-change in trajectory might be collimation event

Homan et al.



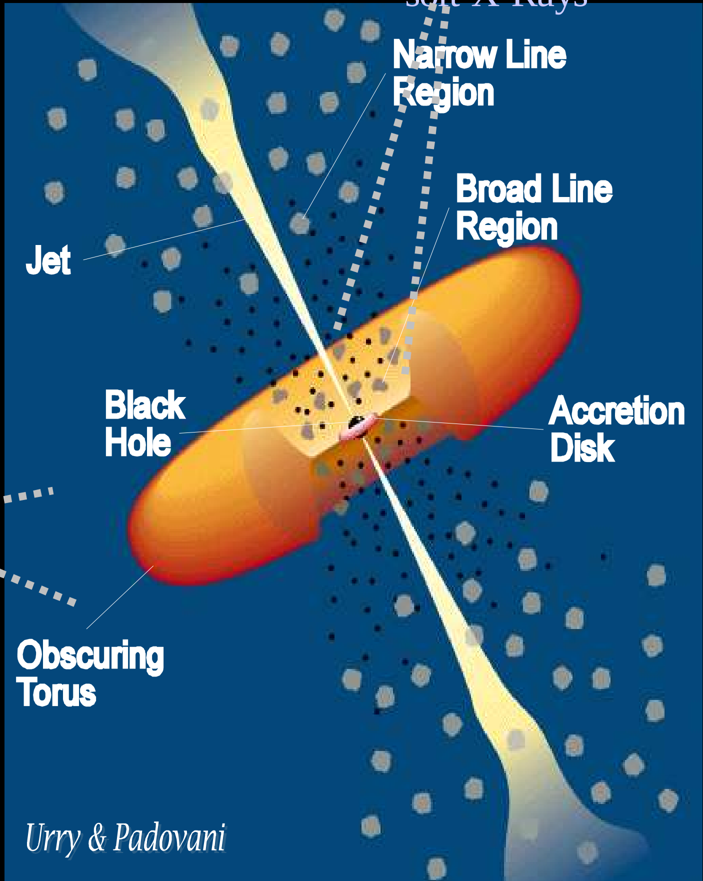
The Current Paradigm of AGN-Activity



NGC 4261, Jaffe et al. (1996)

Type 1:

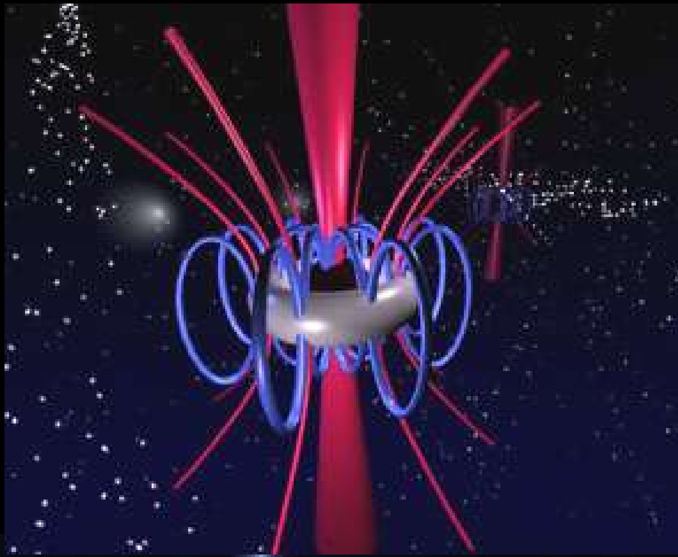
One-Sided Jets;
Broad and Narrow Line Region;
No absorption of soft X-Rays

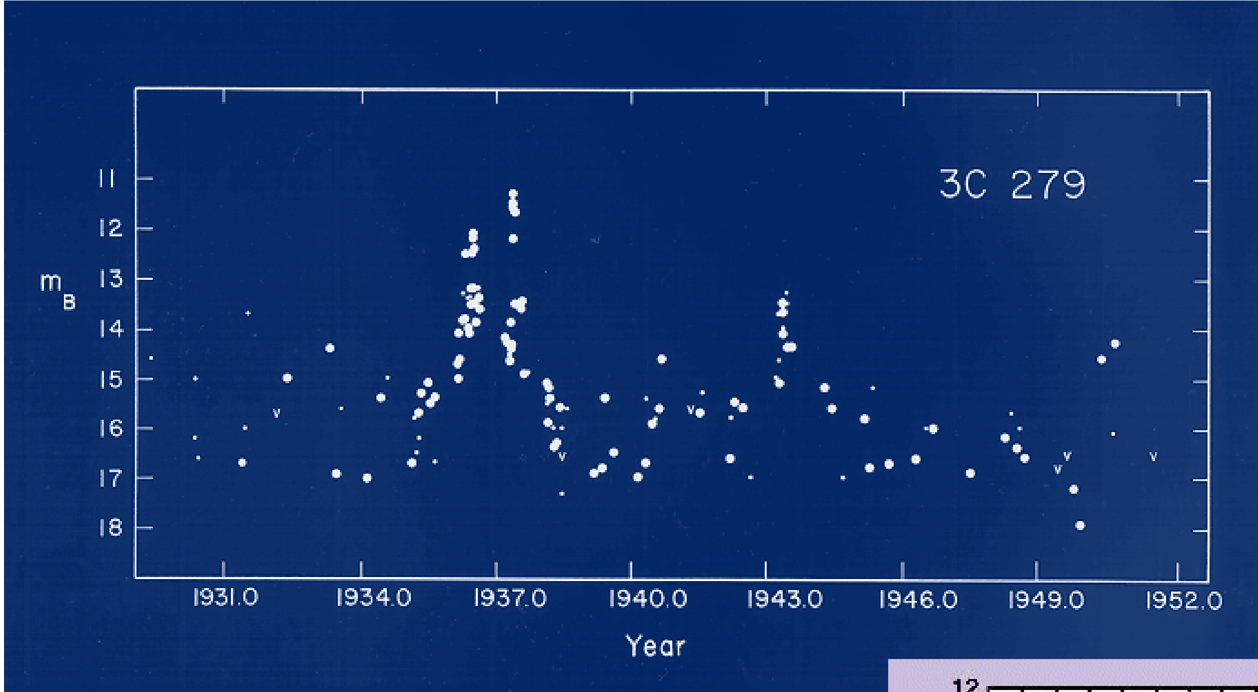


Type 2:

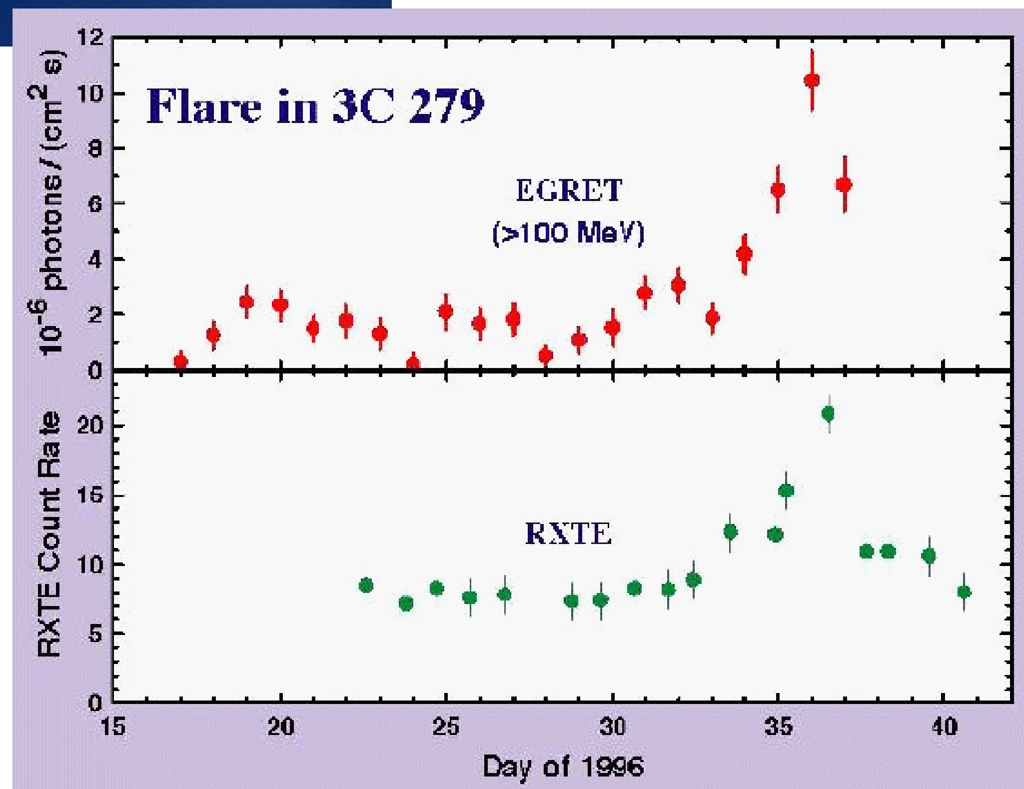
Two-Sided Jets;
Free-Free Absorption;
Narrow Line Region;
Strong Absorption of soft X-Rays

Die Verbindung zwischen Jet und Schwarzem Loch : ????

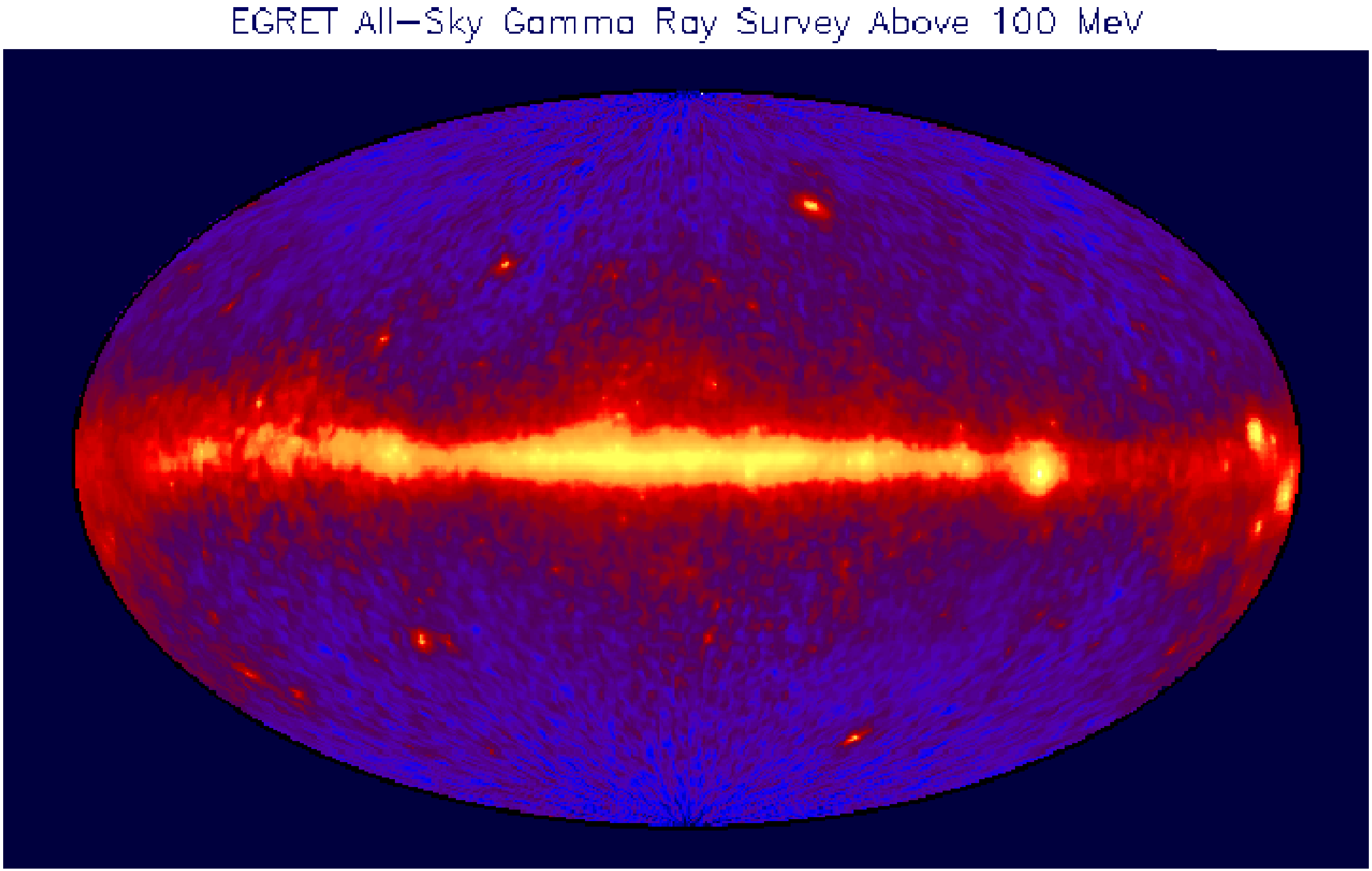




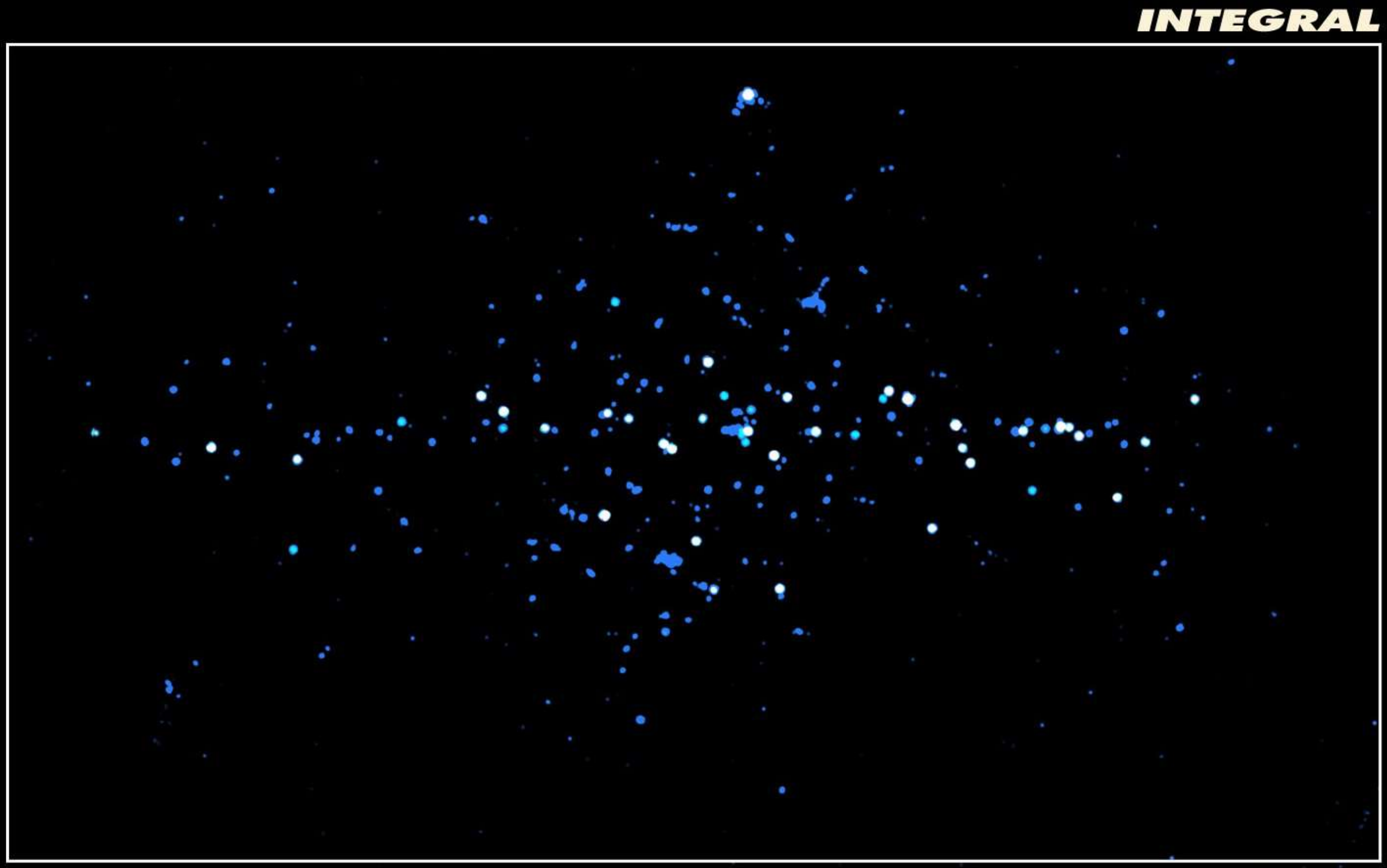
Historische Aufnahmen!
Harvard Survey plates,
Eachus & Liller



EGRET:



INTEGRAL: resolving the gamma-ray background

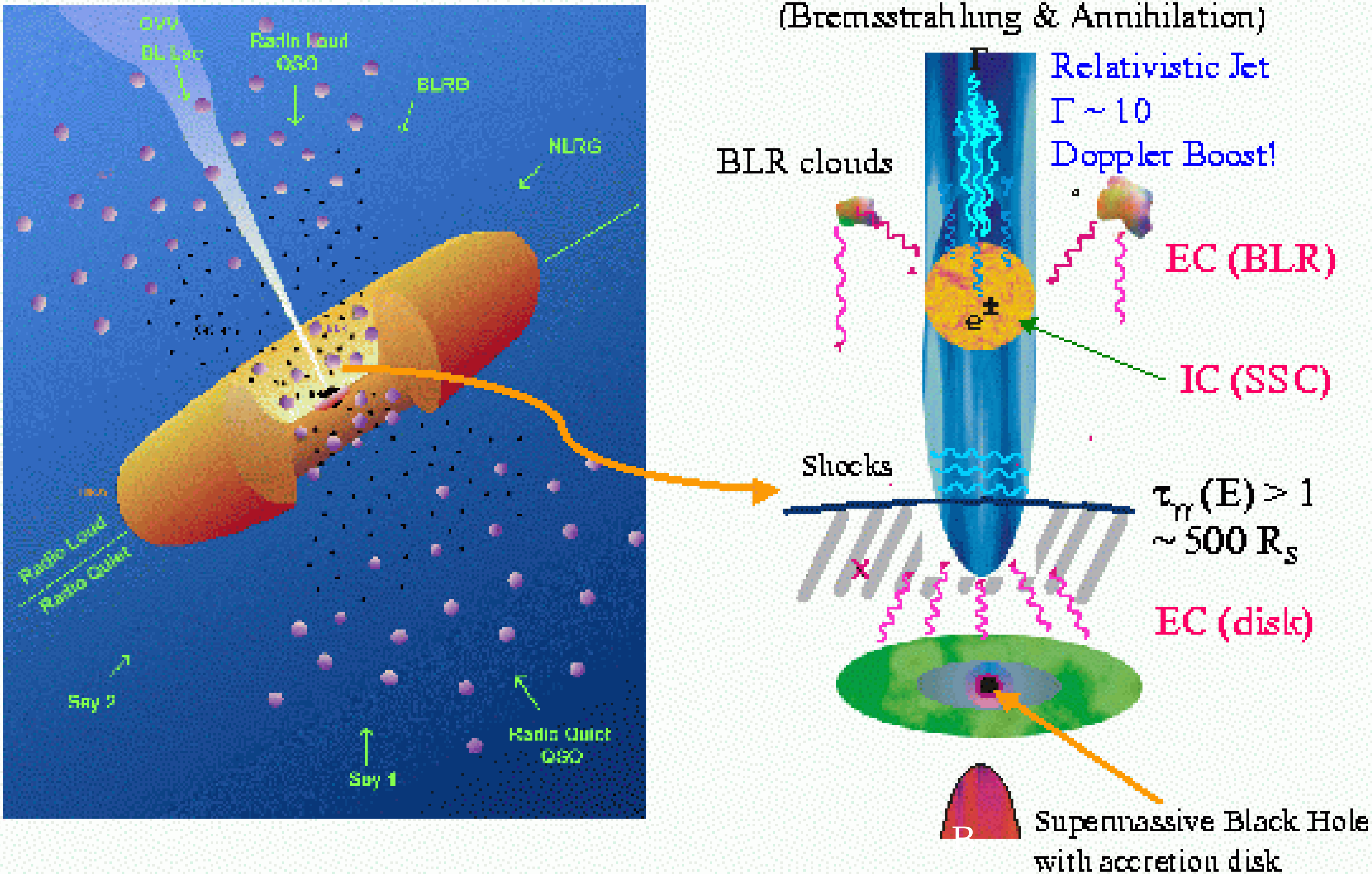


Where does the radiation come from?

AGN Modell:

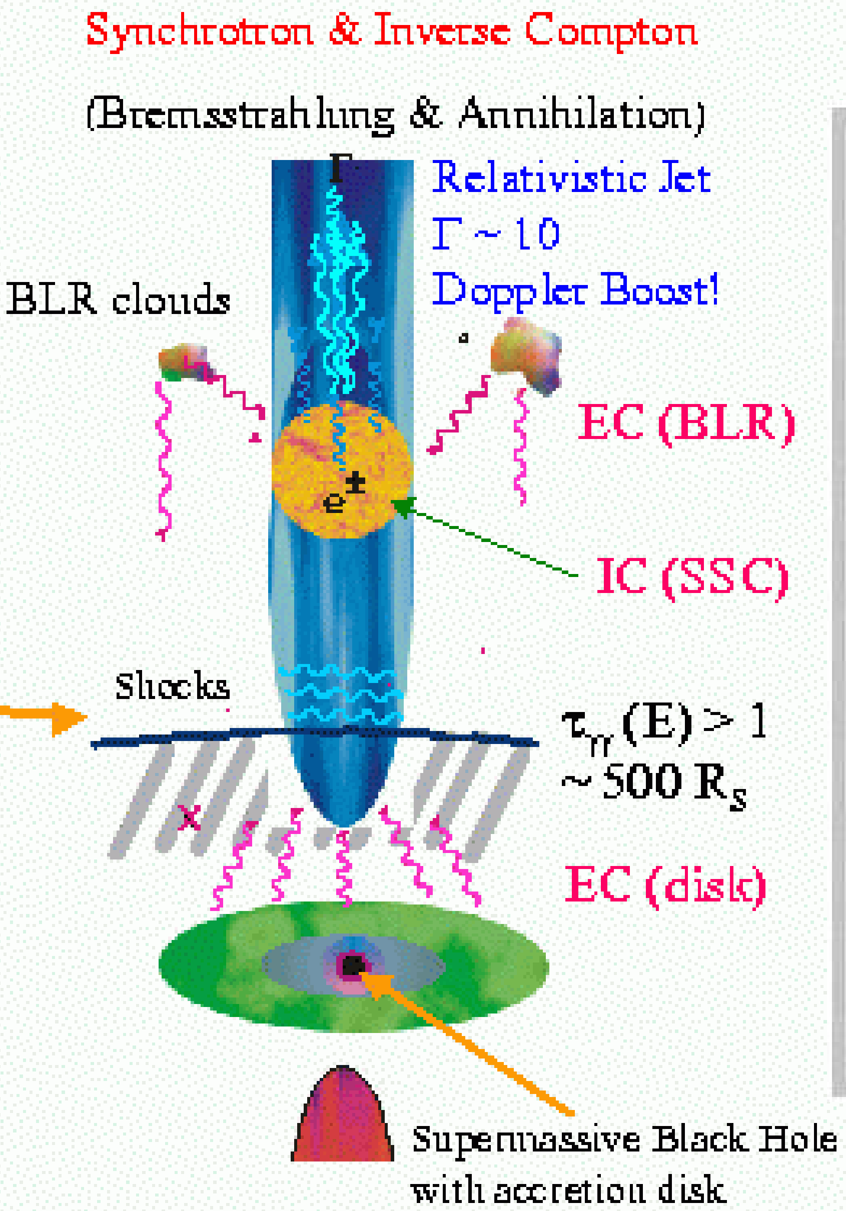
Synchrotron & Inverse Compton

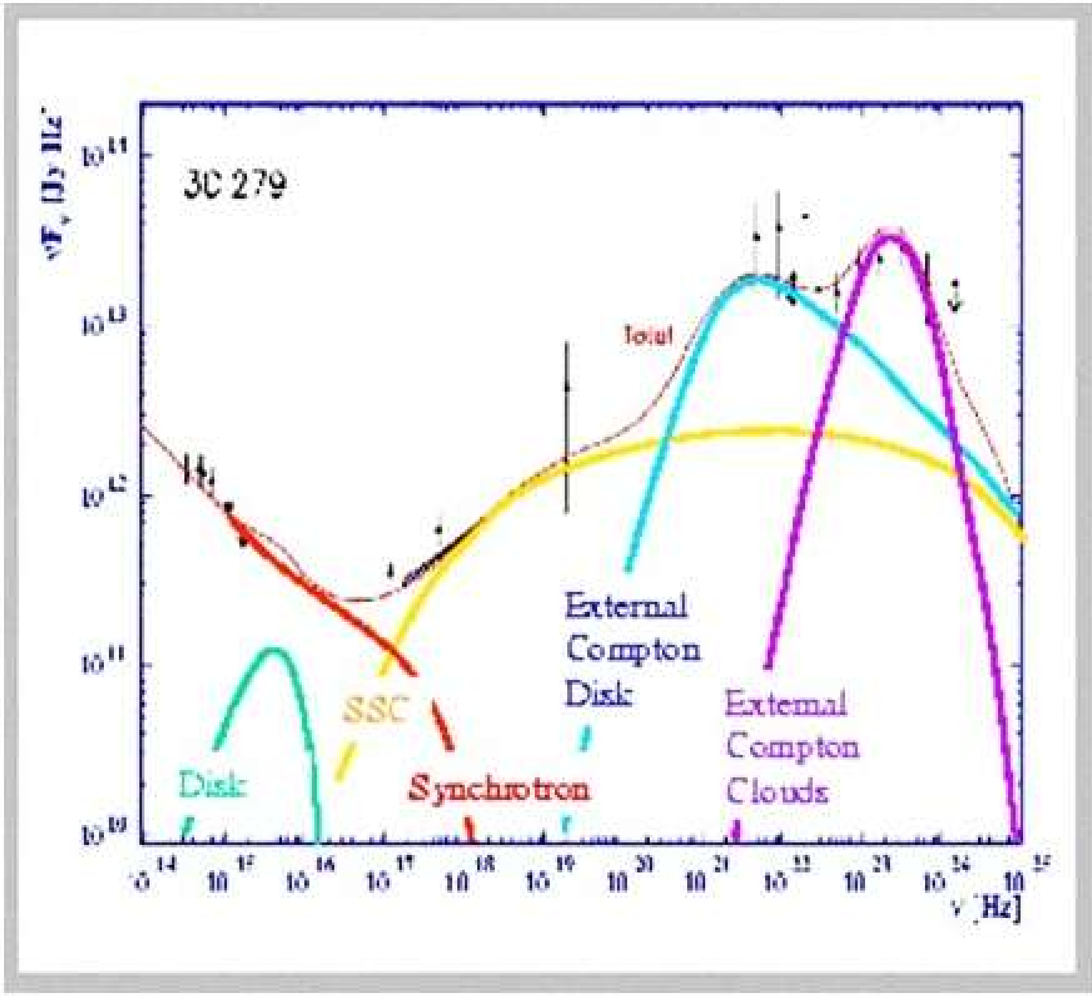
(Bremsstrahlung & Annihilation)



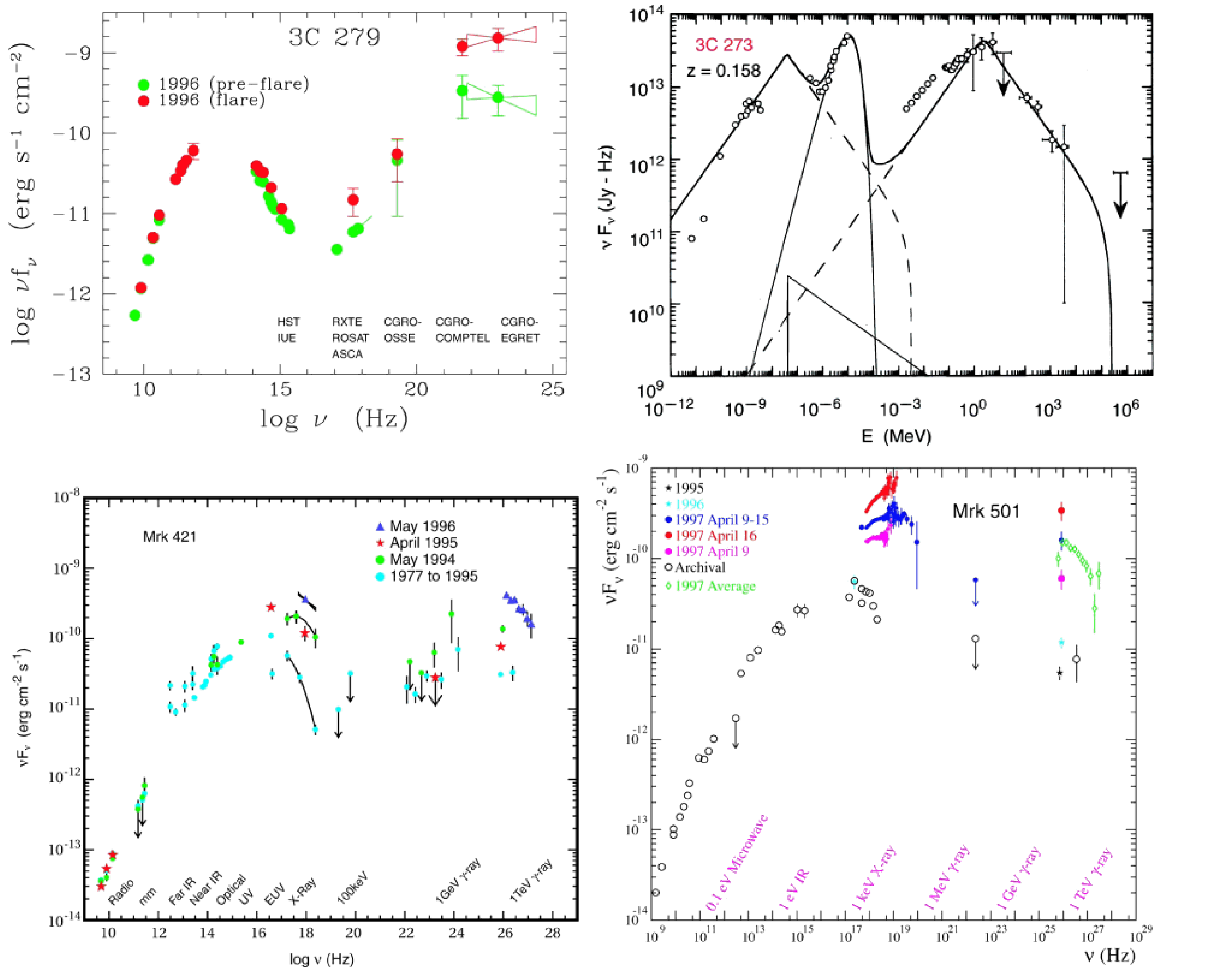
Boettcher et al.

Where does the radiation come from?

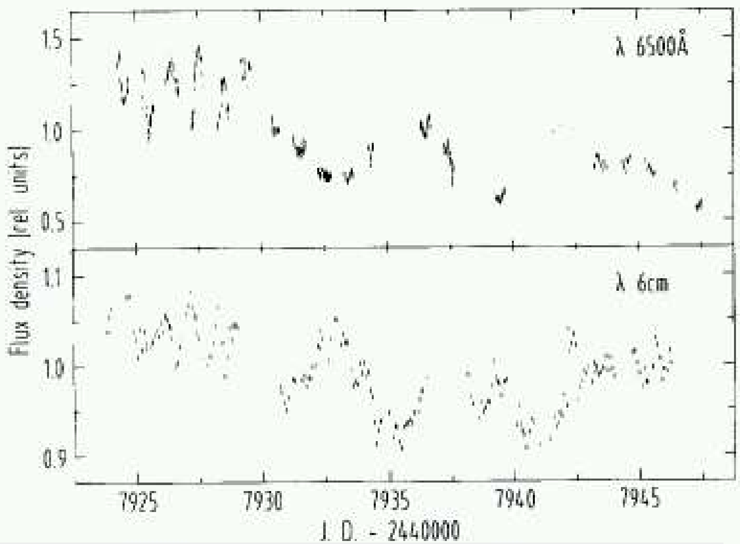




Boettcher et al.



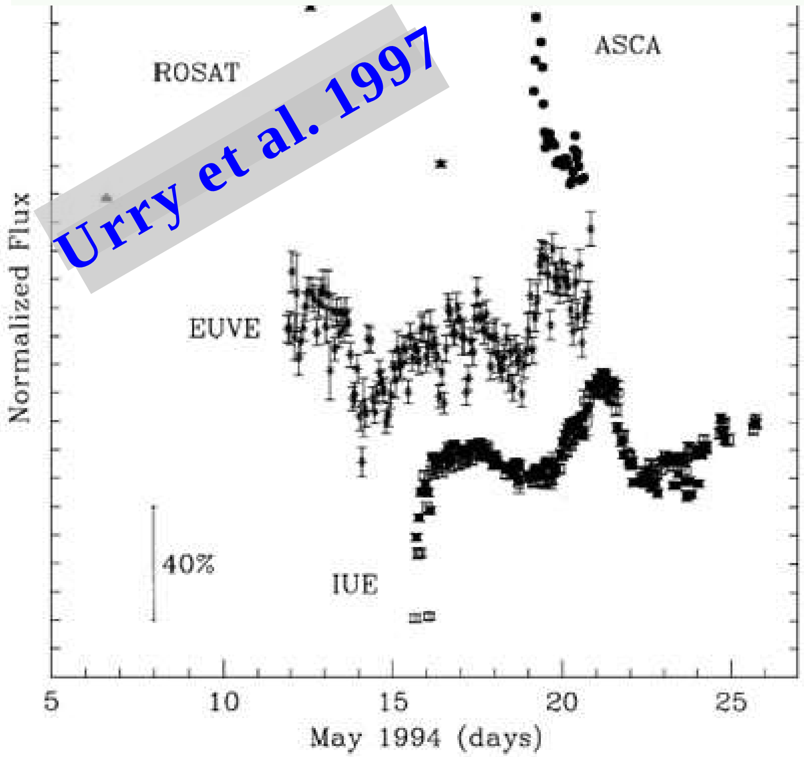
3C 279
1996 (pre-flare)
1996 (flare)
log νf_ν (erg s^{-1} cm^{-2})
log ν (Hz)
HST IUE
RXTE ROSAT ASCA
CGRO-OSSE
CGRO-COMPTEL
CGRO-EGRET
3C 273
z = 0.158
νF_ν (Jy - Hz)
E (MeV)
Mrk 421
May 1996
April 1995
May 1994
1977 to 1995
νF_ν (erg cm^{-2} s^{-1})
log ν (Hz)
Radio
mm
Far IR
Near IR
Optical
UV
EUV
X-Ray
100keV
1GeV γ-ray
1TeV γ-ray
Mrk 501
1995
1996
1997 April 9-15
1997 April 16
1997 April 9
Archival
1997 Average
νF_ν (erg cm^{-2} s^{-1})
ν (Hz)
0.1 eV Microwave
1 eV IR
1 keV X-ray
1 MeV γ-ray
1 GeV γ-ray
1 TeV γ-ray



Quirrenbach et al., 1991, ApJ 372, 71

set to 1, and fractional deviations from the mean are plotted on the y-axis.

- optical/radio correlation in 0716+714 (Wagner & Witzel 1995)
- optical/UV PKS 2155-304 (Edelson et al. 1991)
- UV/X-ray: PKS 2155-304 (Brinkmann et al. 1994)
- optical/Gamma: PKS 1406-076 (Wagner et al. 1995)



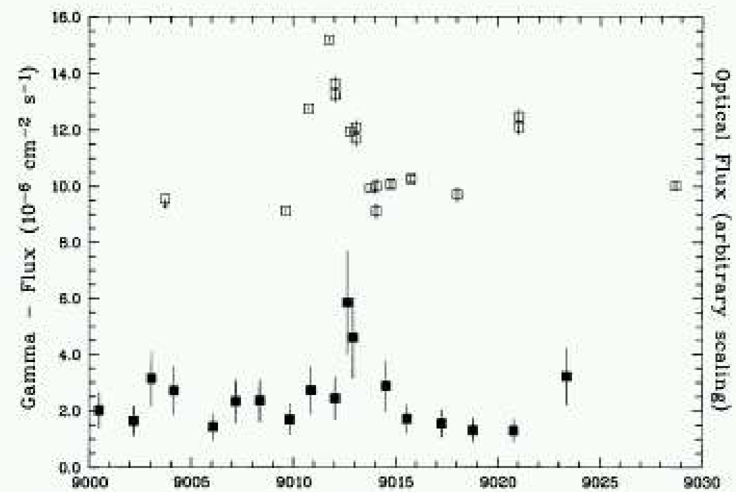
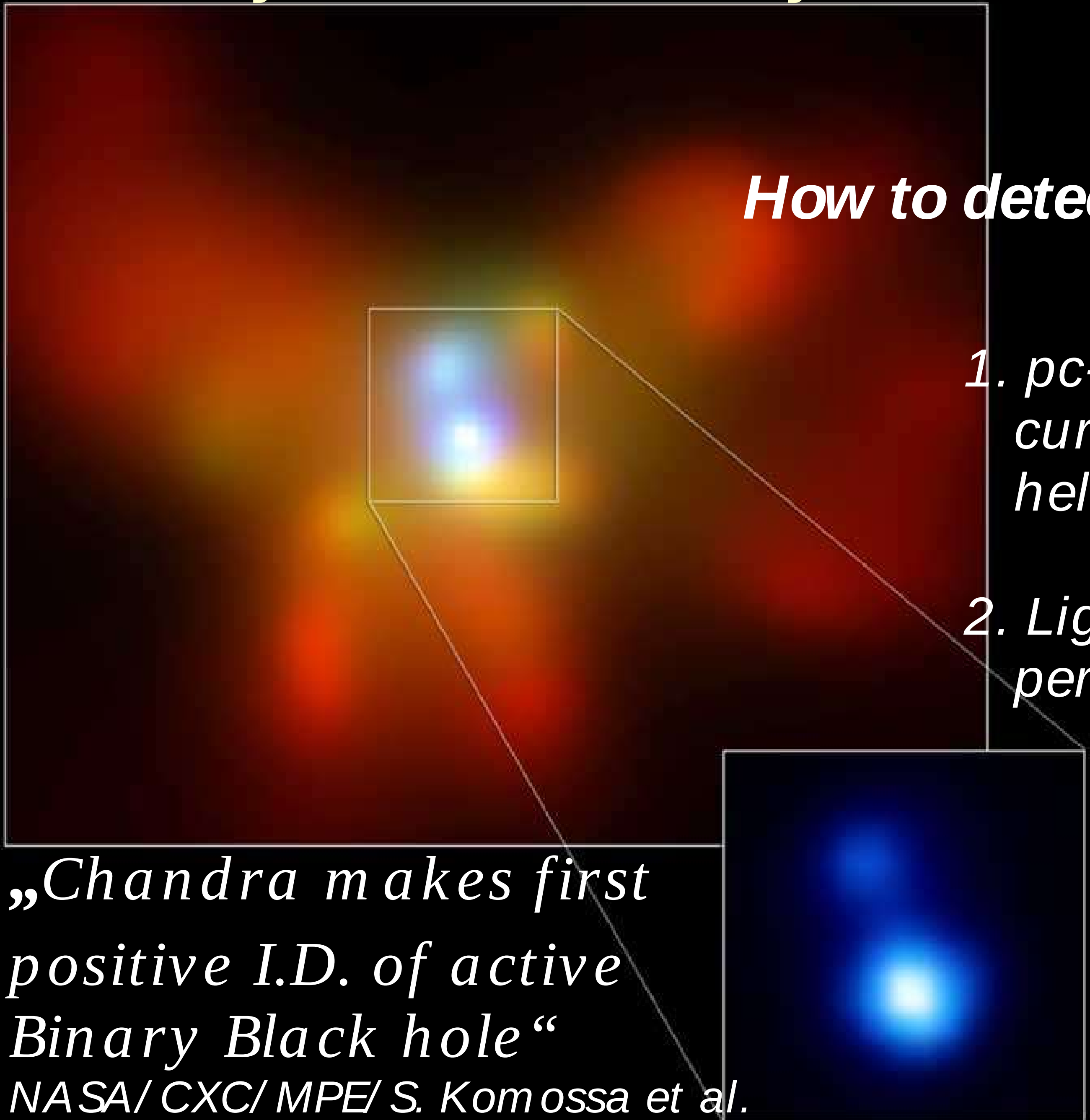


FIG. 4.—Comparison of differential light curves in the optical and gamma-ray regimes. Here the gamma-ray data are shown with a grouping of 10 counts each. The optical intensity (*open symbols*) has an arbitrary scaling.

Wagner et al. 1995, ApJ 454, L97

Binary Black hole Systems in AGN



How to detect these BBHS?

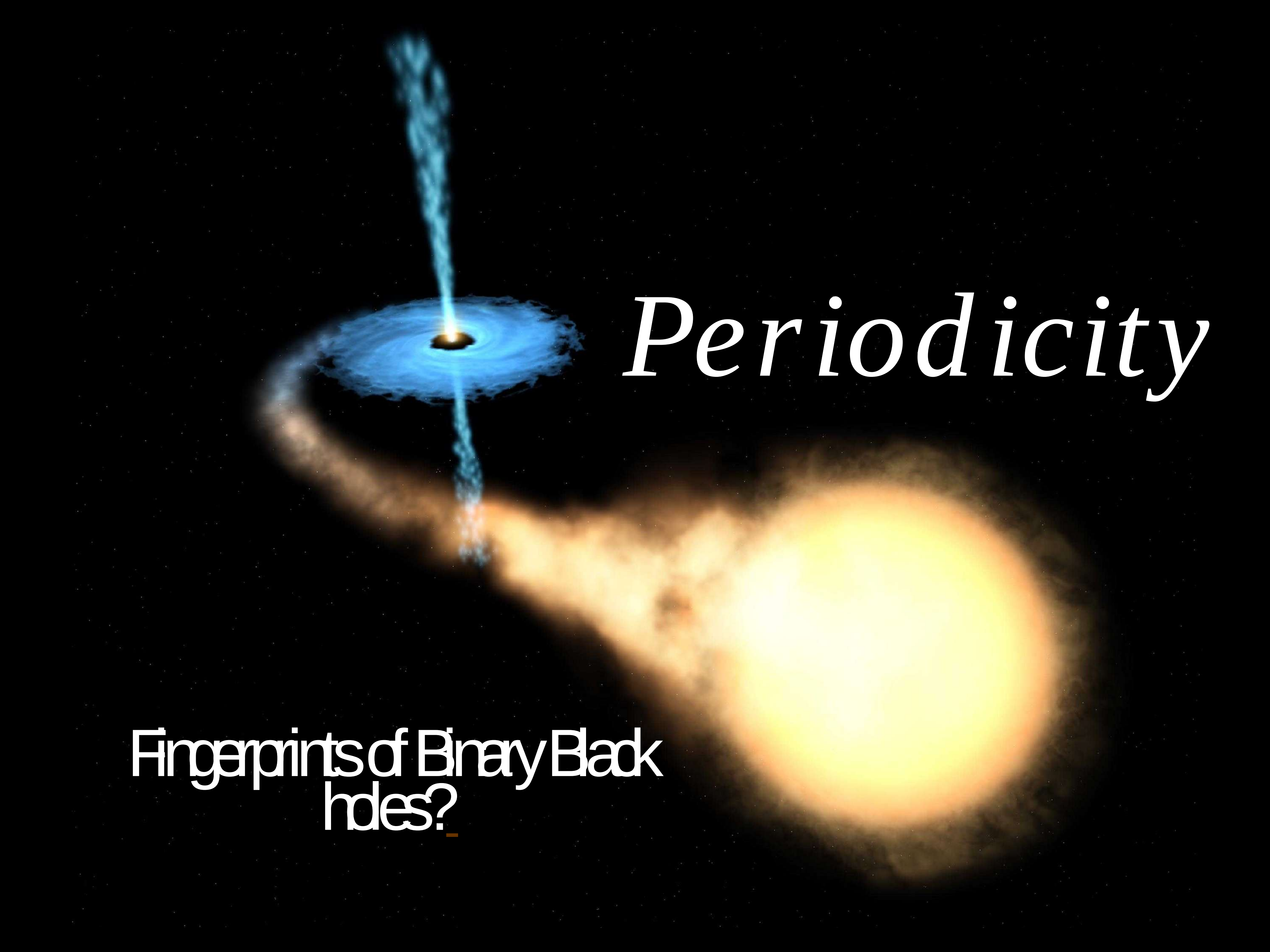
1. pc- scale radio jets: curved jet structures, helicity

2. Light curves: periodic flaring

=> some examples ..

„Chandra makes first positive I.D. of active Binary Black hole“

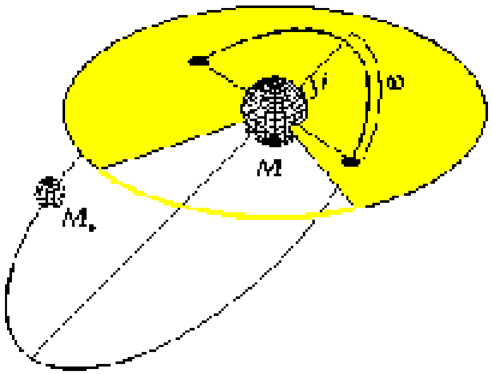
NASA/ CXC/ MPE/ S. Komossa et al.

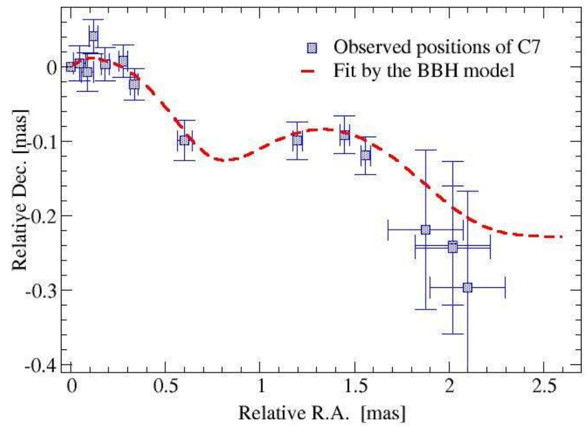


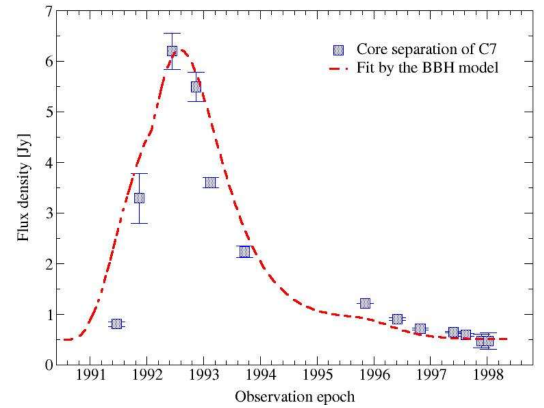
Periodicity

Fingerprints of Binary Black holes?

Binary Black Hole Systems (3C 345)





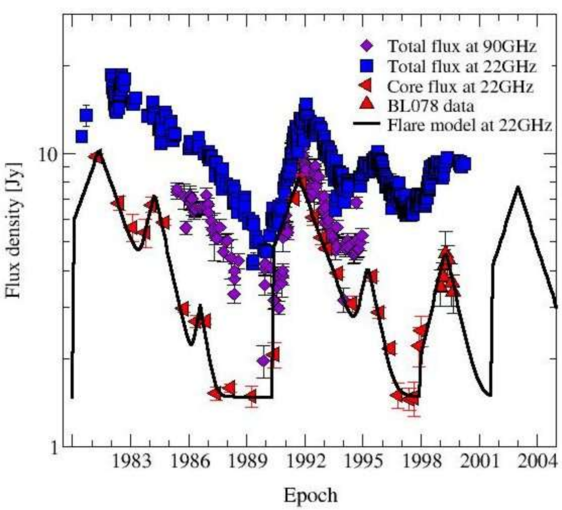


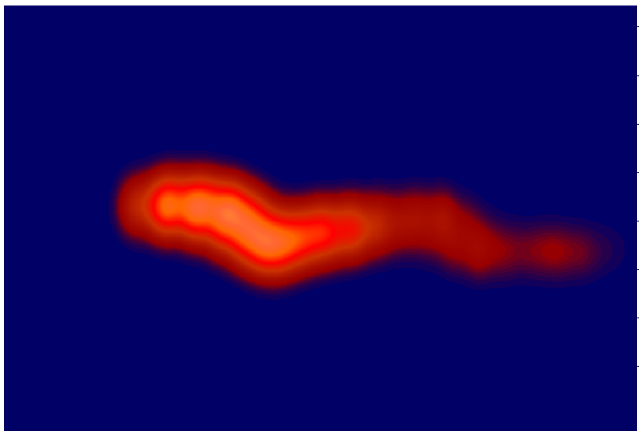
$M_1 = 1\cdot 10^{9}\,M_\odot$, $M_2 = 5\cdot 10^{8}\,M_\odot$

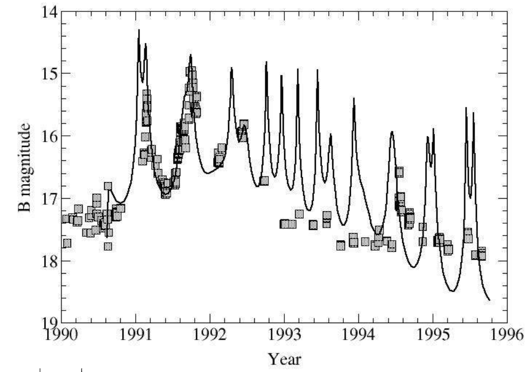
$a_{\rm bin} = 0.3$ pc ([illegible]) $e = 0.1$

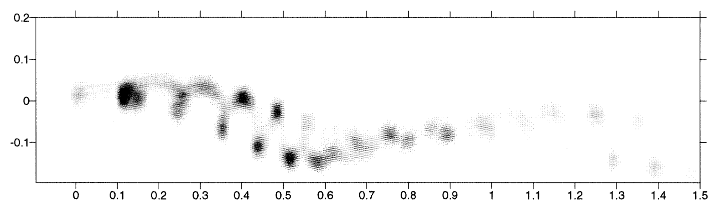
$P_{\rm obs} \approx$ [illegible] yr

$P_{\rm prec} \approx$ [illegible] yr



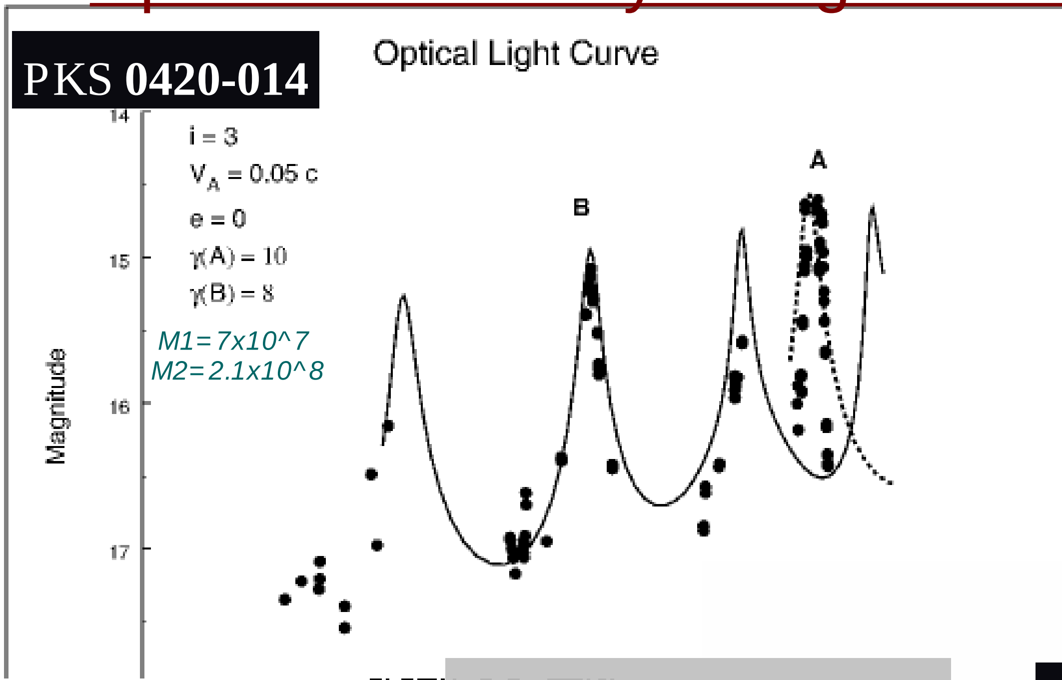






Lobanov & Roland 2002

Optical Flux-density flaring unravels Binary Black holes



PKS 0420-014:

Britzen, et al., 2001,

A&A 374, 748

OJ287: The Rosetta

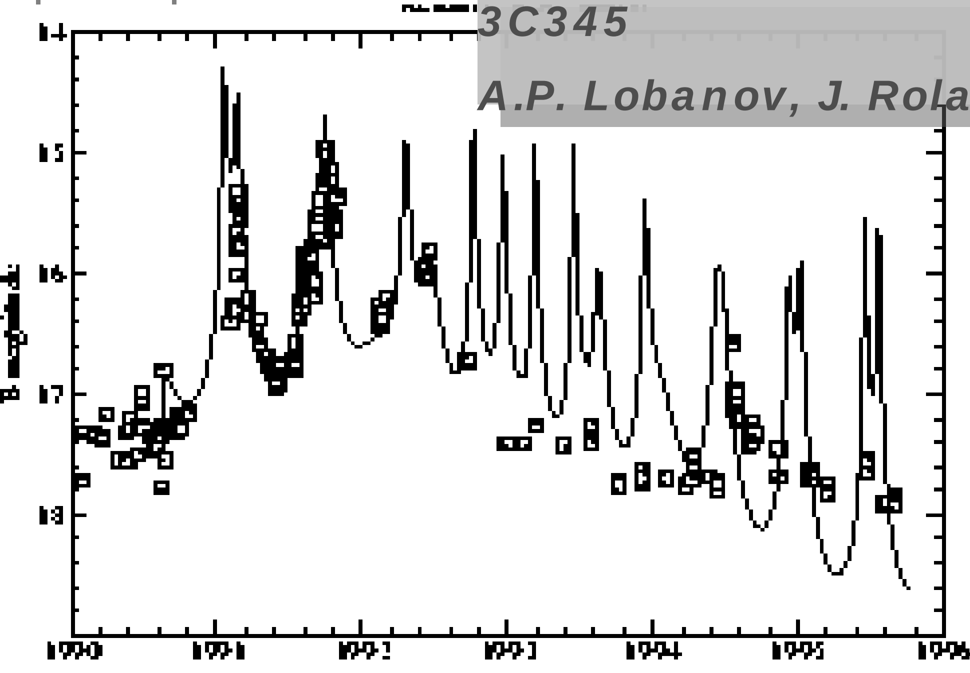
Stone of Blazars

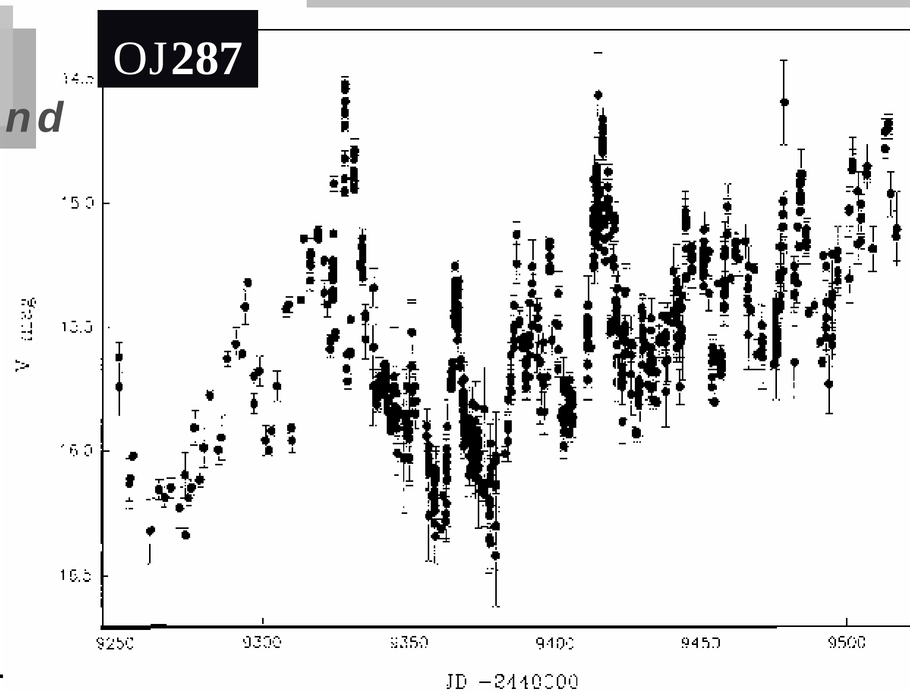
e.g., Takalo 1994,

Abraham 2000, A&A 355, 9

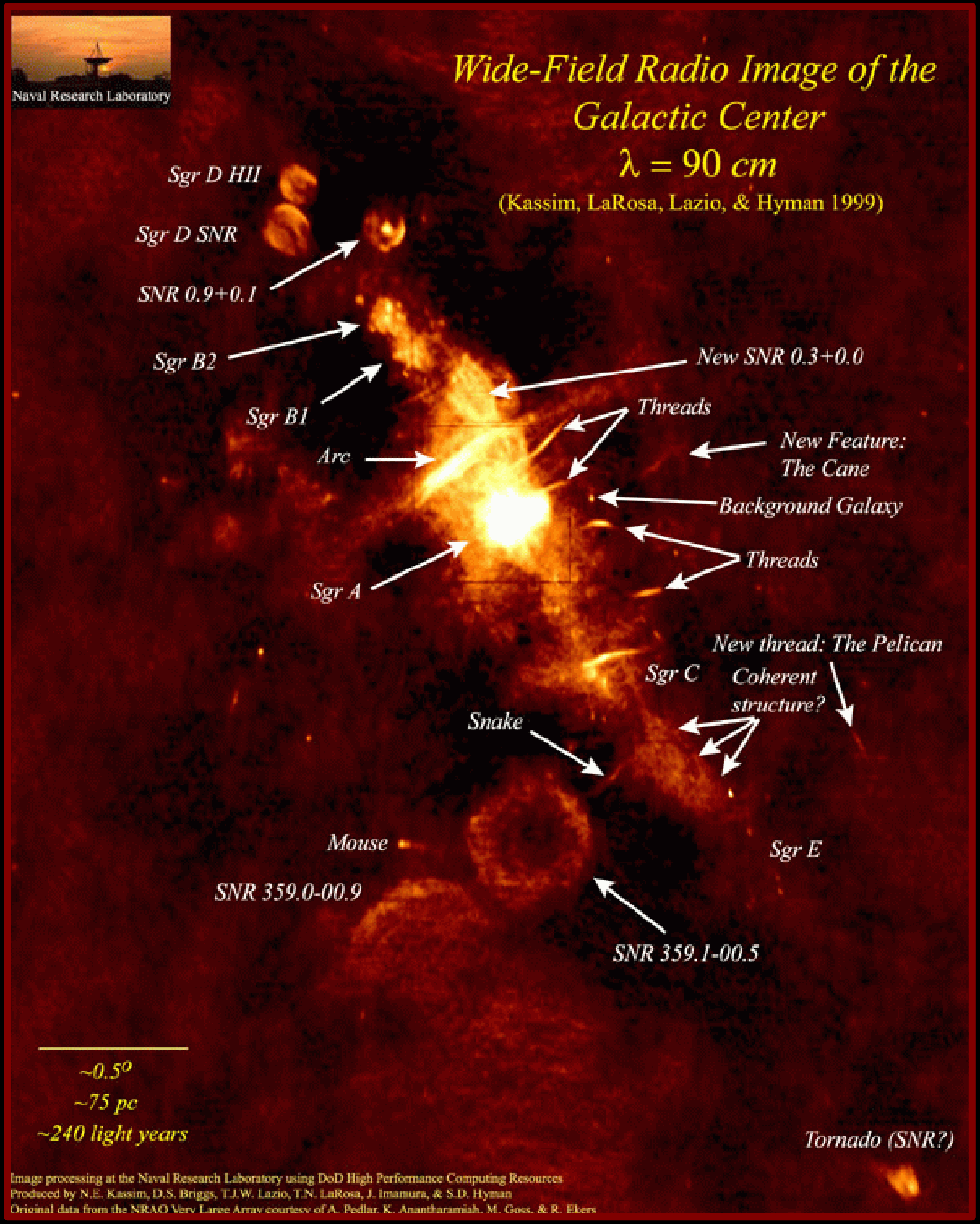
3C345

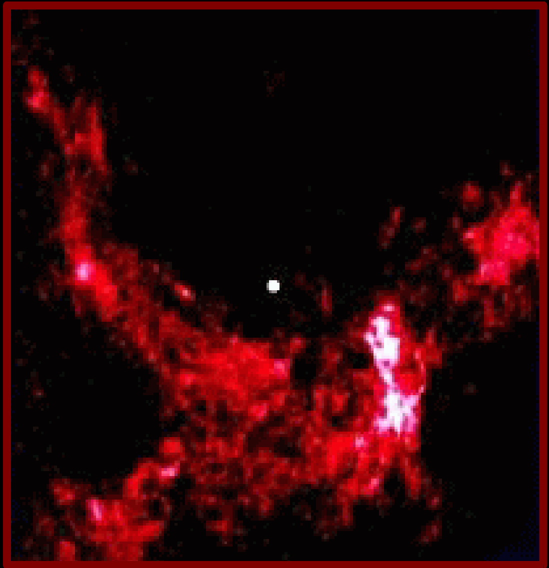
A.P. Lobanov, J. Roland





Center of our Galaxy





Zur Phänomenologie & Historie Aktiver Galaxienkerne

Zur Phänomenologie Aktiver Galaxienkerne

Welche Art von Objekten gehört zu dieser Klasse?

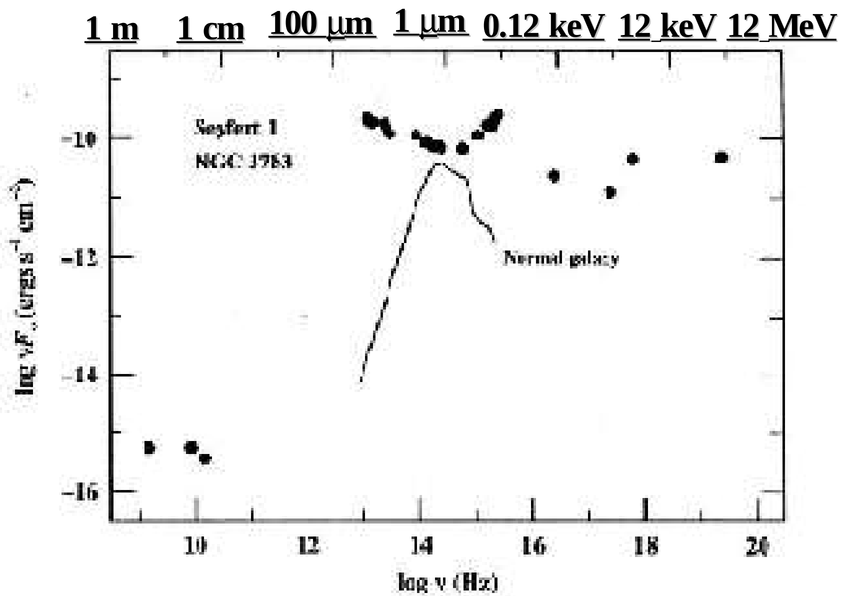
Was bedeutet "aktiv"?

Aktivität sollte meßbar sein!

Was bedeutet "kern"?

....

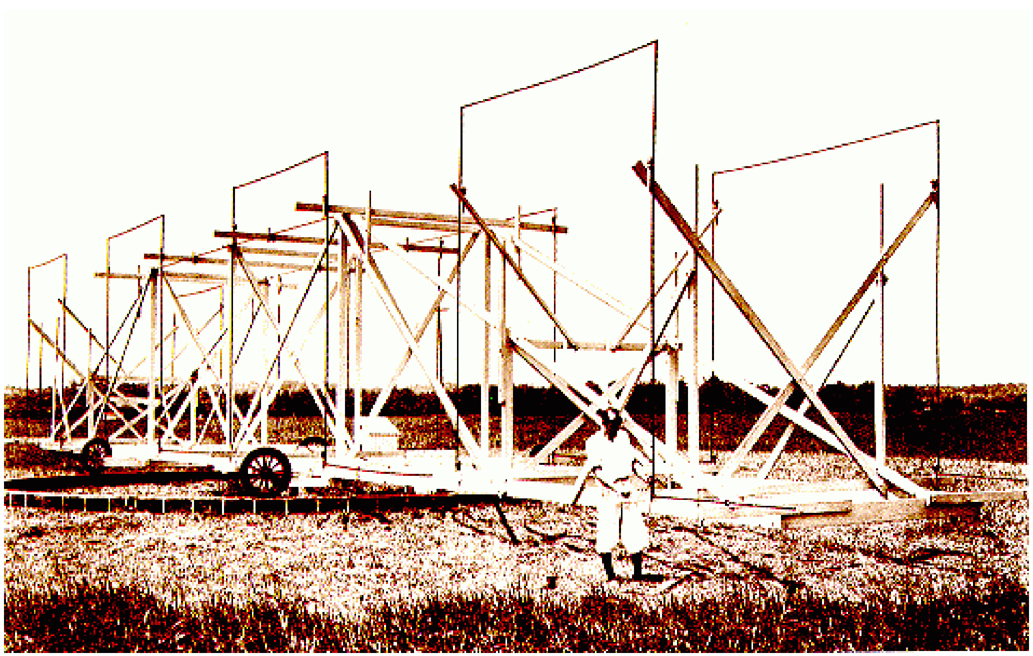
"nicht-thermische Strahlung"

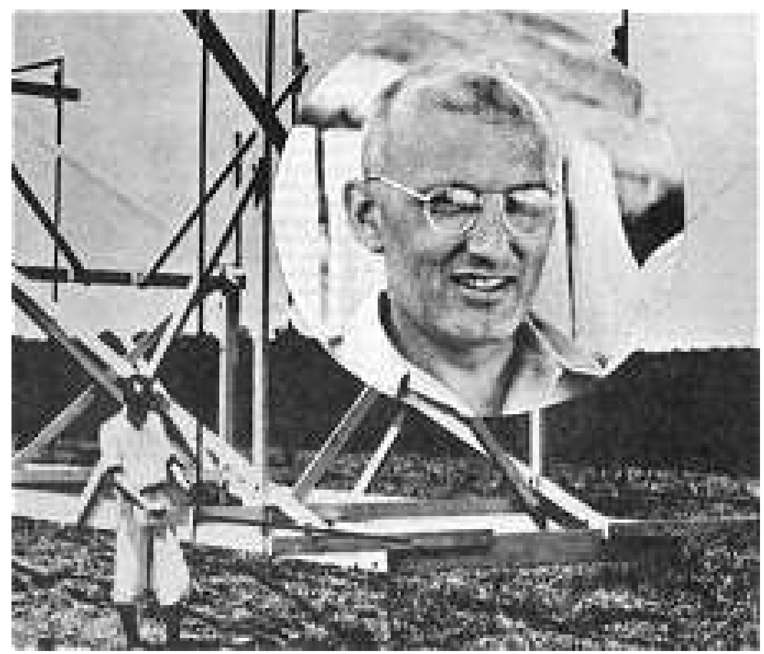


Verschiedene Typen Aktiver Galaxienkerne:

- Radio Galaxies
- Radio Quasars
- BL Lac Objects
- Optically Violent Variables (OVV's)
- Radio Quiet Quasars
- Seyfert 1 Galaxies (Sy 1)
- Seyfert 2 Galaxies (Sy 2)
- Low Ionization Nuclear Emission-Line Regions (LINERS)
- Nuclear H II Regions
- Star Burst Galaxies
- Strong IRAS Galaxies

- 1932: **K.G.Jansky** examines for Bell Laboratories (New Jersey) why transatlantic radiotelephone circuits suffer from a variety of hissing and crackling sounds (interference) wavelength of ~14.6 m); identifies 3 origins:
  - Nearby thunder storms
  - Distant, tropical thunder storms
  - Steady hiss-type static of unknown origin, seemed to reach earth from the direction of the Milky way
- Astronomers did not take notice of this discovery!! (late recognition, unit named after him)





- **Grote Reber** (Illinois)reads about Jansky's work and realizes importance -> builds the world's first dish-shaped radio telescope (1937) of 9.6m (~14°) diameter in his own backyard!! assumes thermal origin of radiation -> receiver for wavelength of 9.1 cm, afterwards for 33cm and finally for 1.87 m, detects celestial radio emission (~2 m), and radio emission from the Galactic plane
- 1939: Reber confirms Jansky and disproves his own ideas about the emission origin
- Publication in ApJ: not noticed by astronomical community!!
- 4 years later: first radio sky maps of the milky way and radio measurements of the sun: start of the radioastronomical research!!
- Reber`s publication appeared during World War II and a copy reached the observatory at Leiden-> Oort is interested

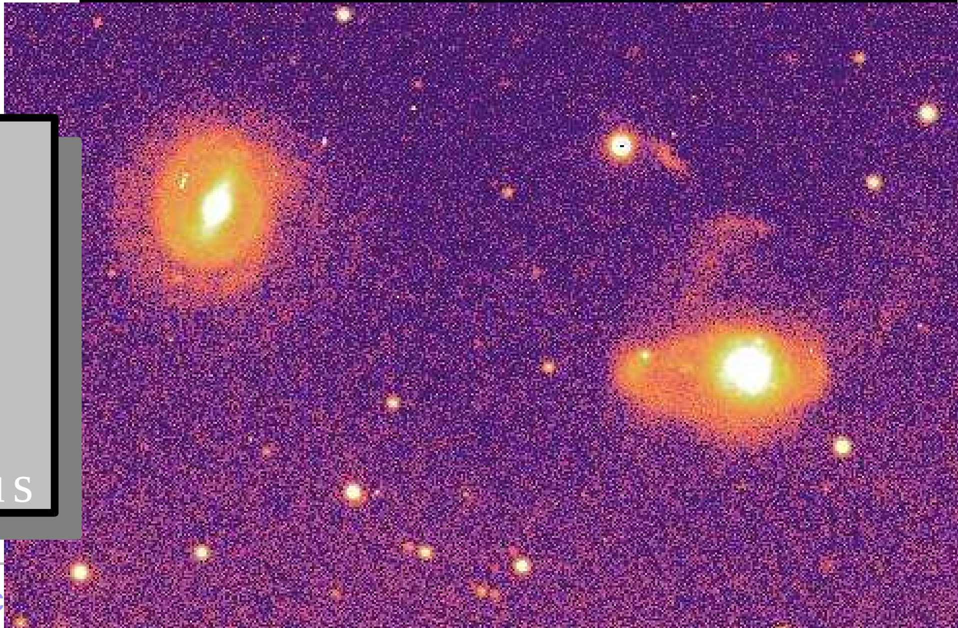
- 1918 Messier 87 reveals surprising jet of luminous matter shootin out of ist interior -> not studied further, 1950s: radio signals detected from M87
- 1943 Carl Seyfert identifies galaxies whose nuclei show unusual spectra -> Seyfert galaxies

C. Seyfert zeigte 1943, daß kleiner Bruchteil von Galaxien seh hellen, 'punktförmigen' Kern besitzen, der auch sehr breite Emissionslinien von Atomen mehrerer Ionisationsgrade emittiert;solche Galaxien heißen heute

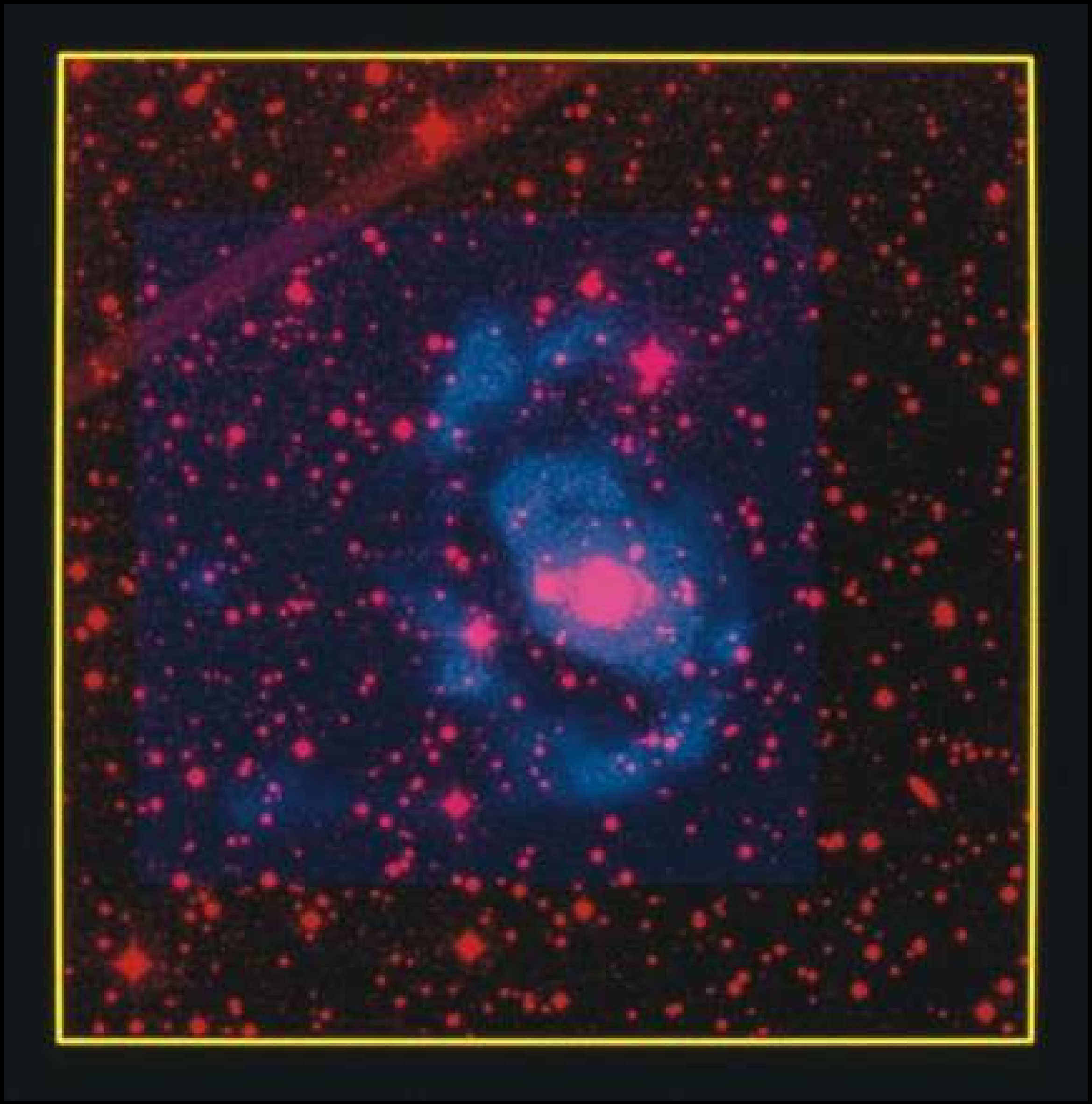
Galaxie im Sternbild Circinus, Typ 2 Seyfert Galaxie. 2 starburst Ringe (Hubble, NASA, A. Wilson et al.)

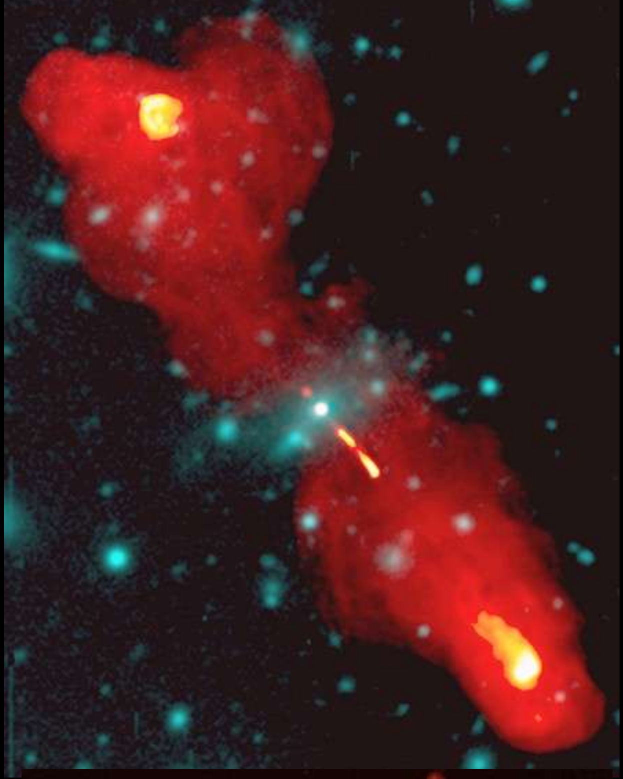
Seyfert-Galaxie NGC 7742 i
Sternbild Pegasus; z=0.0055

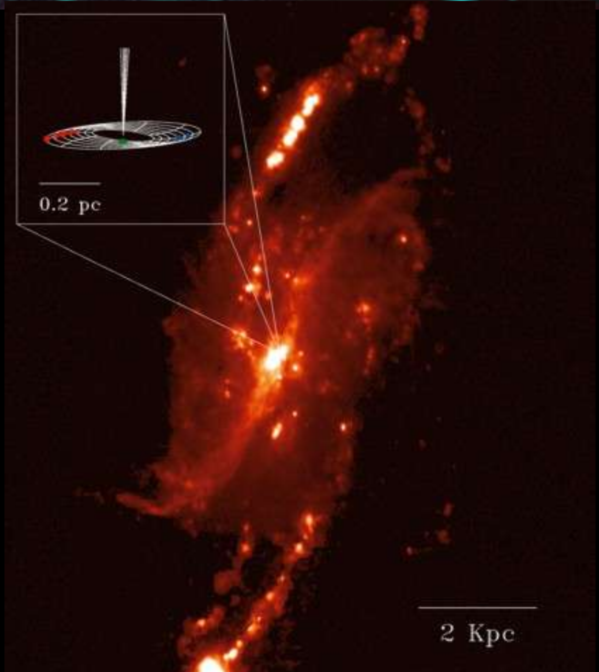
Die Galaxien NGC 7682
(links, z=0.017125):
eine Seyfert-Galaxie und
NGC 7679
(rechts, 0.017139):eine irreguläre
Starburstgalaxie. Terskol, Kaukasus



Seyferts



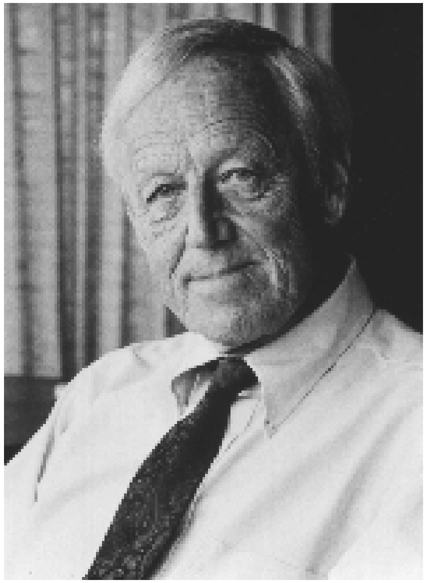




Seyferts

- **Besonderheiten**:
  - große Linienbreiten: typisch einige 1000 km/s (Seyfert Typ 1) oder ca. 500 km/s (Seyfert Typ2) [wenn interpretiert als Doppler-Vebreiterung mit D/ *=v/c!!] (zum Vergleich: Rotationsv. von normalen S's: 200 km/s);* heute Bezeichnung nach Verhältnis von relativer Stärke der schmalen und breiten Komponenten; Beide Komponenten vermutlich aus Akkretionsscheibe; Typ 2 Seyferts: breite Komponente abgeschirmt durch Staub und/oder Winkel zur Sichtlinie. In einigen Typ 2 Seyfert Galaxien kann die breite Komponente in polarisiertem Licht beobachtet werden.
  - Emission im Radio, Infrarot, UV, Röntgen

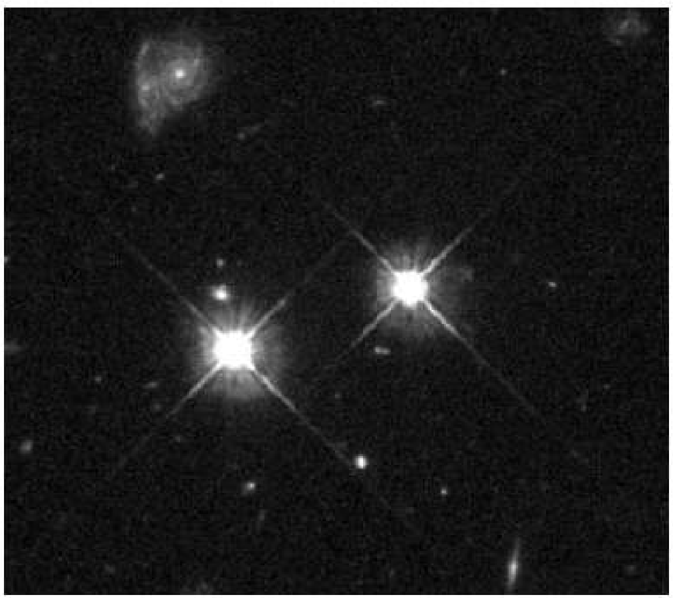
- **1950:** sufficient observations obtained to pose the question concerning the physical nature of the non-thermal component of the cosmic radio radiation:
- **Alfvén** and **Herlofson** (1950): *Synchrotron radiation*, radiation of relativistic electrons, moving on helical trajectories in a magnetic field; stars could be surrounded by extended regions of intense magnetic fields where highly energetic electrons would be continuously injected.



Hannes Alfvén

Zur Geschichte

- 3C und 3CR Kataloge (1961): Durchmusterung des nördlichen (> -22 °) Himmels bei 158 MHz und 178 MHz, Flußlimit S_{min}= 9 Jy
- Matthews & Sandage (1963): 3C48 ist punktförmige Quelle mit *m*=16 mag; komplexes Spektrum, bestehend aus blauem Kontinuum und starken, breiten Emissionslinien, die aber keinem atomaren Übergang zuzuordnen waren -> nicht identifizierbar!!!
  - Quasi-stellar ….



The bright object on the left is a quasar; the one on the right is a star. There is no discernible difference from this image

Image credit: C. Steidel and NASA

Die Geschichte von 3C 273 … und die Erfindung der Mondbedeckungs-Beobachtungen

- **Cyril Hazard**

- **1962 August C. Hazard (University of Sydney) uses new observational technique (lunar occultation) to observe and pinpoint the location of the radio source 3C 273**

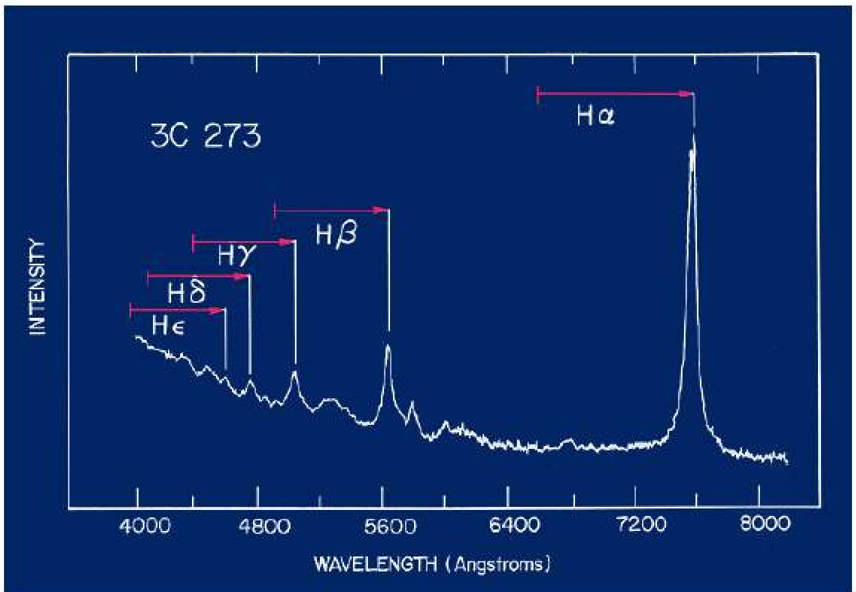
- **Parkes radio telescope**

Zur Geschichte

- Schmidt (1963): Identifikation von **3C273** mit punktförmiger optischer Quelle; Identifikation der Emissionslinien mit der Balmer-Serie des Wasserstoffs, aber mit *extrem hoher Rotverschiebung z*=0.158
  - Gültigkeit des Hubble-Gesetzes vorausgesetzt, die bis dahin mit Abstand weitest entfernte Quelle (D~500 h^{-1} Mpc)
  - absolute Magnitude dann M_B=-25.3+5 log h: 100 Mal heller als normale (Spiral)galaxien
- nach besserer Bestimmung der Positionen der Radioquellen sind in kurzer Folge dann viele solcher ***Quasare (quasi-stellar radio sources = quasars)*** identifiziert worden.

- 1963 February 5 (breakthrough!) M. Schmidt (Caltech) using the 5-meter Hale Telescope on Palomar Mountain, observes the spectrum of 3C 273-> like 3C48, emission lines are at uncommon wavelengths: Schmidt concludes that he is observing a hydrogen spectrum greatly shifted by the Doppler effect; because of starlike appearance: quasi-stellar object, afterwards shortened to quasar

Optical spectrum of 3C273



Optical spectrum of 3C 273 clearly showing the redshifted Balmer lines and the "blue bump" thought to be associated with the accretion disk in 3C273

3C273 has a redshift $z = 0.15839$

3C273: z=0.158; 90% of the radio ene

emitted by jet-like feature; length: 10",

3C273 spectral energy distribution

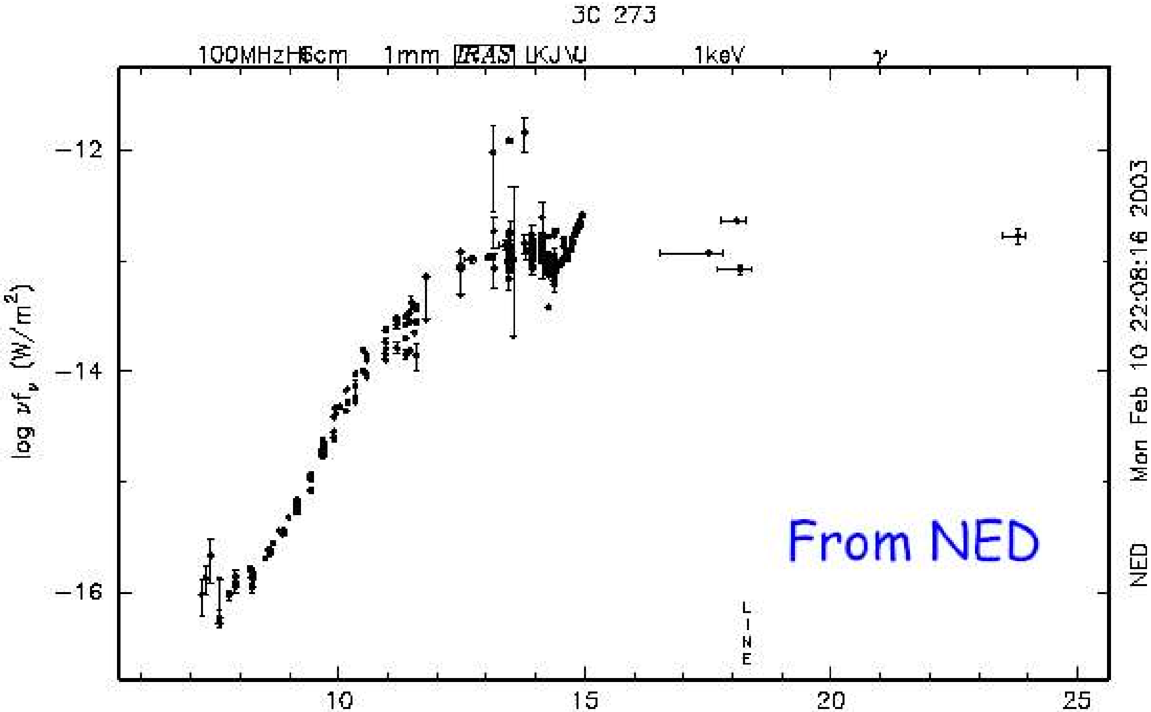
Use fluence: $E_\nu = \nu F_\nu = W\,m^{-2}$ *per log frequency*

The spectral energy distribution of 3C273 from

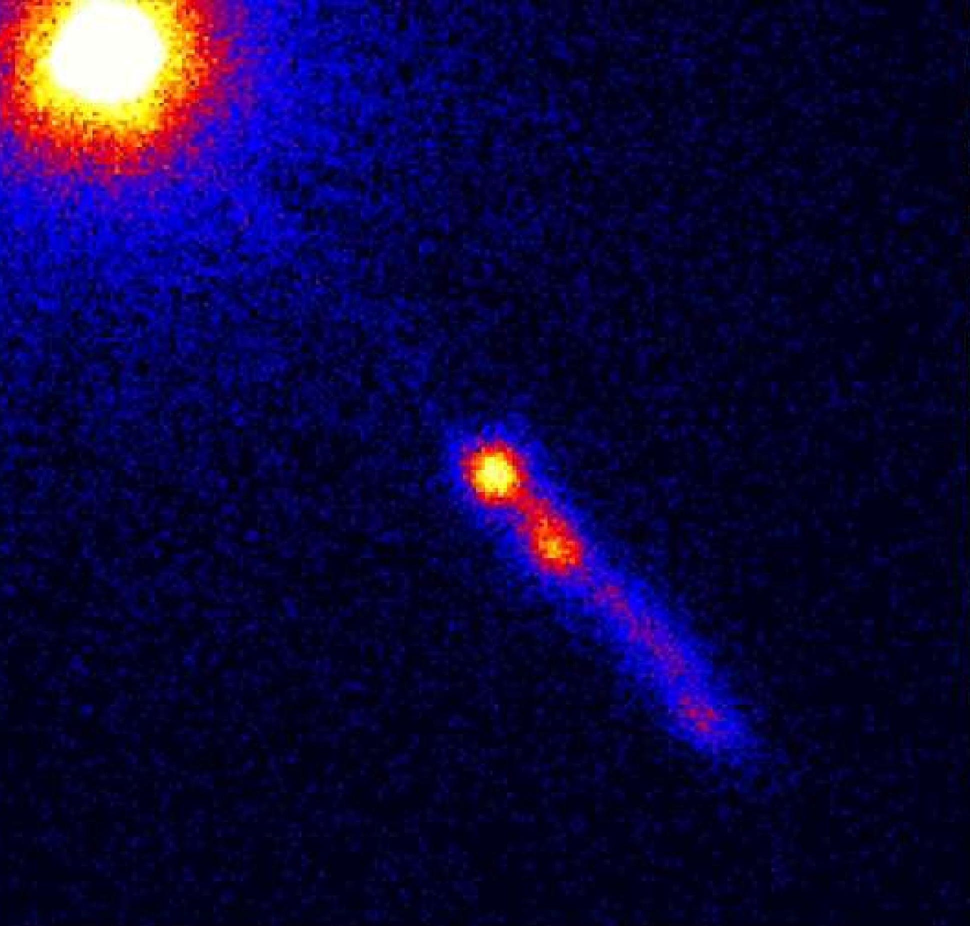
$10^7 - 10^{24}$ *Hz*

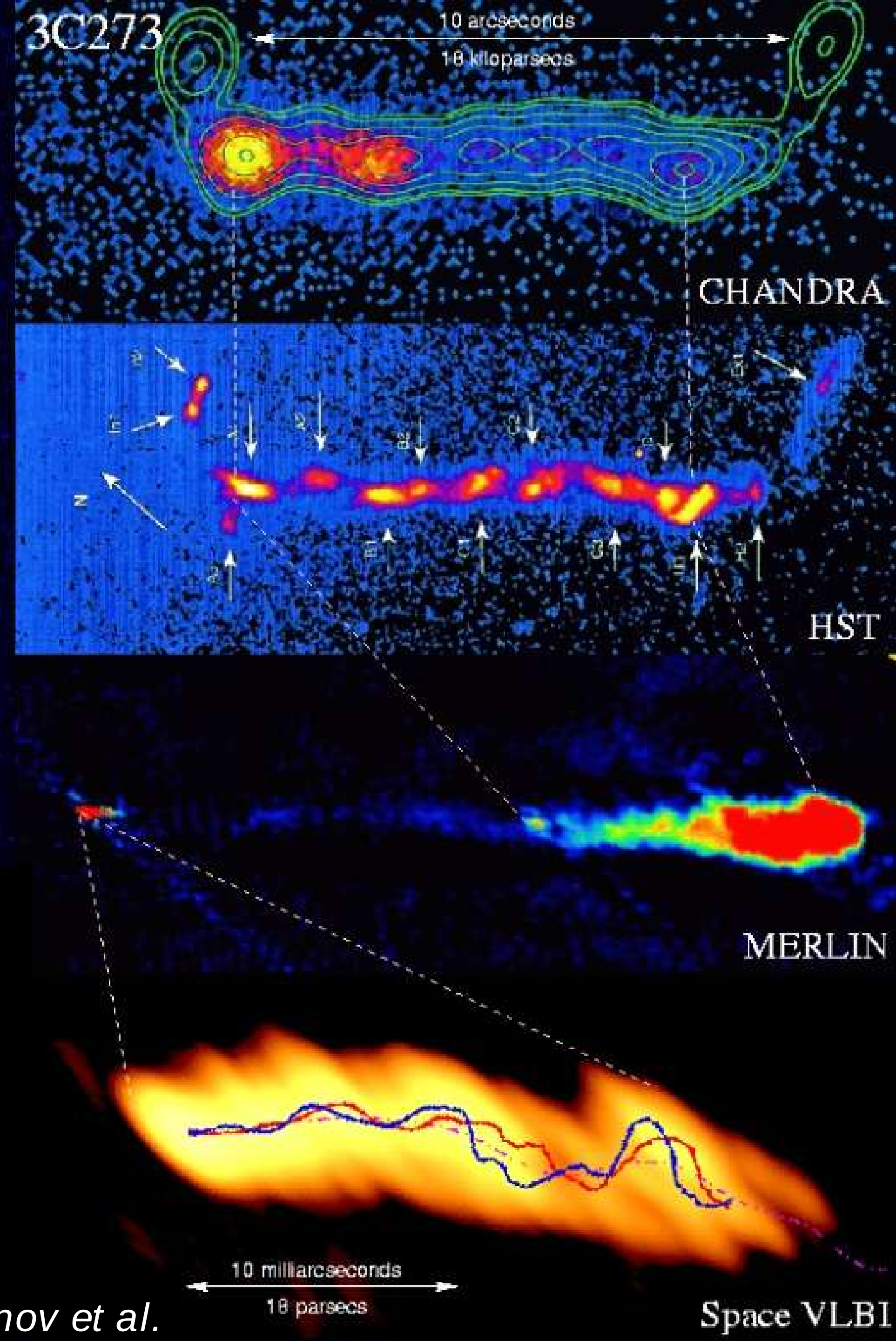
This shows that most of the energy emerges in the region from

10^{12-24} *Hz*



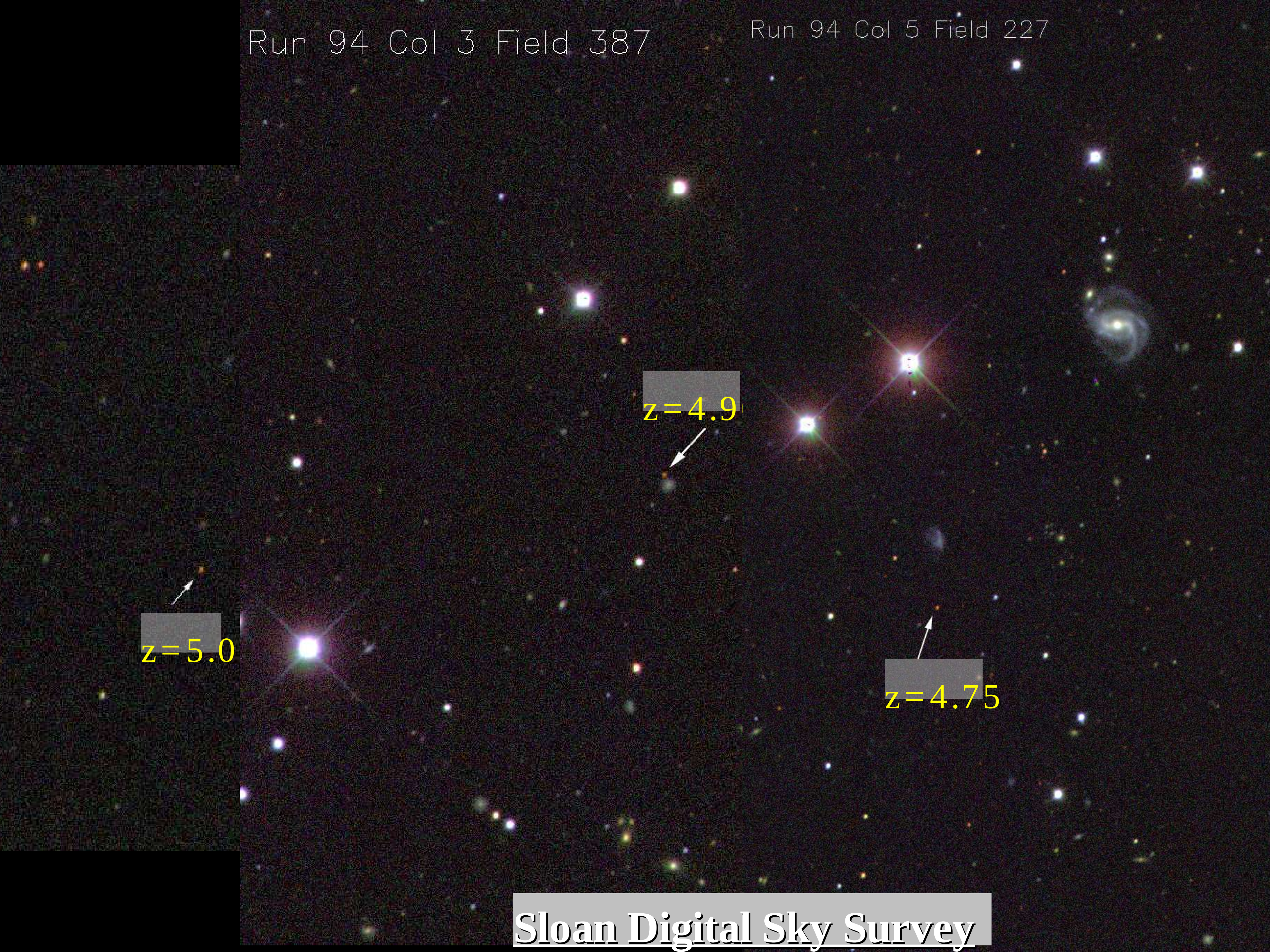
Whilst most of the energy emerges in the IR-γ-ray region of the spectrum, most of the particle energy is in the radio-emitting particles





The „first“ Quasar: 3C273

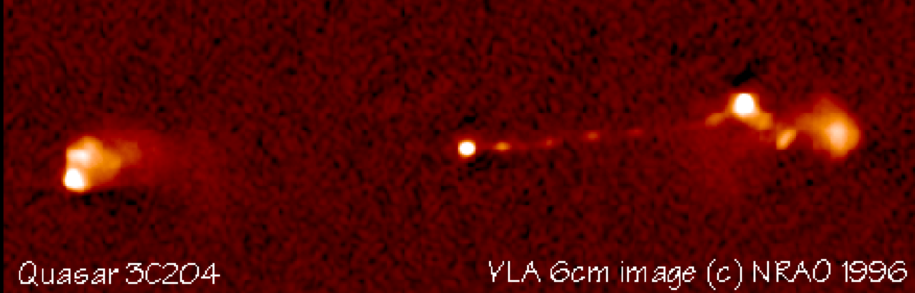
Lobanov et al.

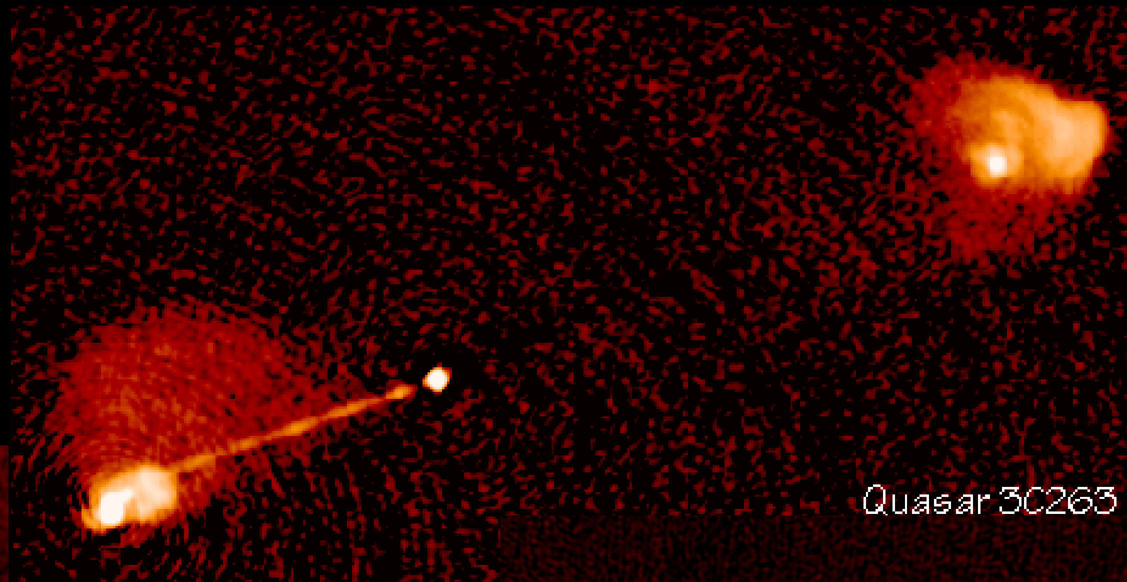

Run 94 Col 3 Field 387
Run 94 Col 5 Field 227
z=4.9
z=5.0
z=4.75
Sloan Digital Sky Survey

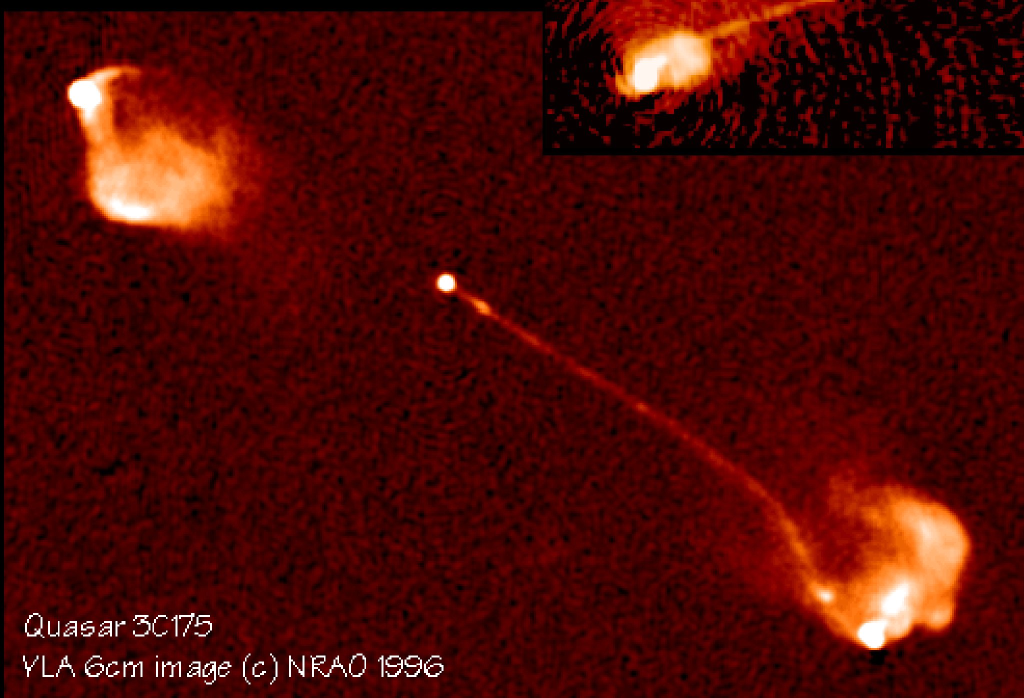
Taonomy of Active Galactic Nuclei

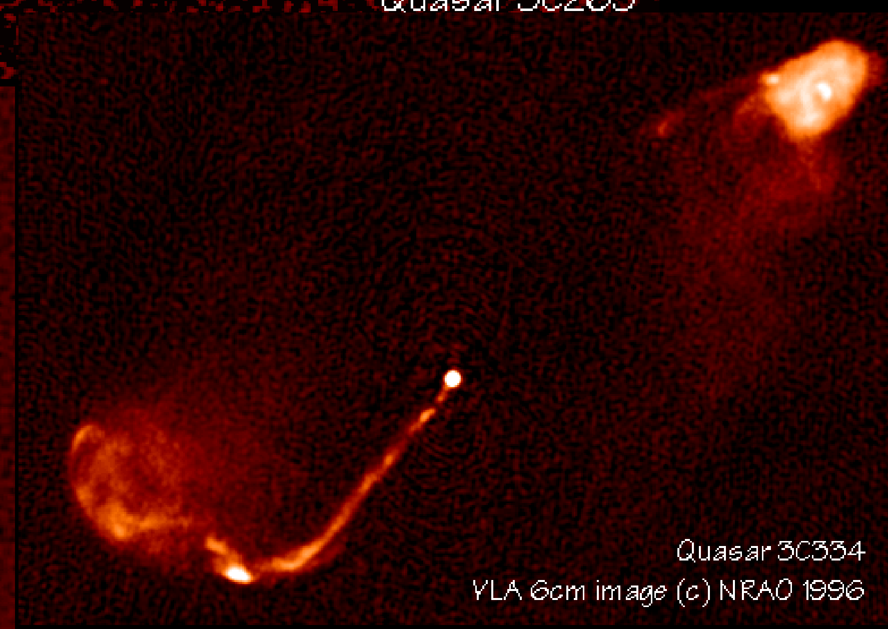
- *Quasars:*
  - *Quasi-Stellare Radio Quellen, optisches Bild isd dominiert durch blaue Farbe (U-B< 0) unaufgelöst (< 1”), leuchtkräftiger (-22, oder -23) Kern mit starken breiten Emissionslinien im optischen Spektrum*
  - *Variabilität des optischen Kerns, lineare Polarisation*
  - *Starke kosmologische Evolution*
  - *Radio: sehr kompakte Komponenten (10^{-3} arcsec), Jets, ...*

Quasars

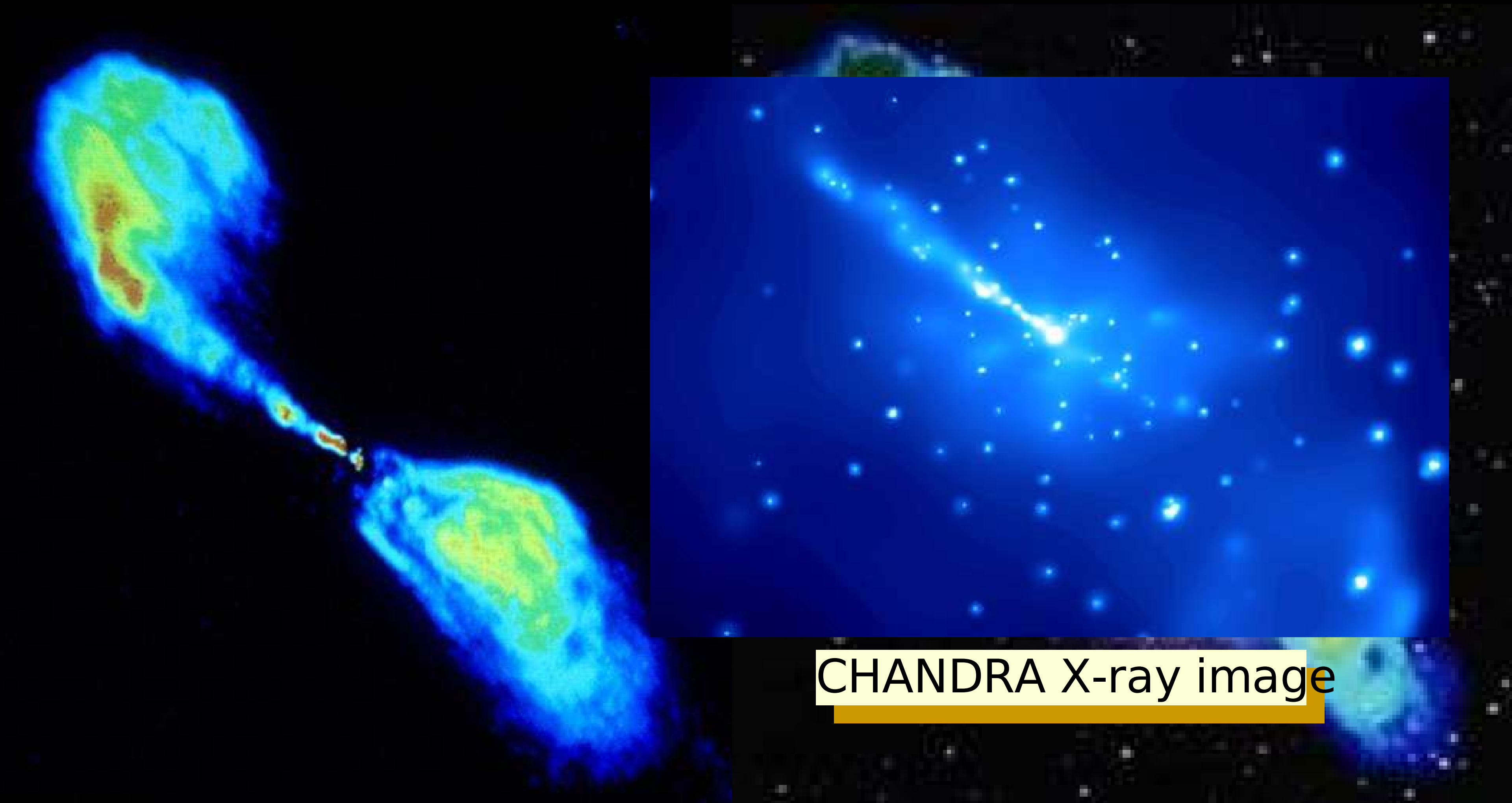

Quasar 3C204
VLA 6cm image (c) NRAO 1996


Quasar 3C263


Quasar 3C175
VLA 6cm image (c) NRAO 1996


Quasar 3C334
VLA 6cm image (c) NRAO 1996

Radio Galaxies



Centaurus A, Radio (left, Burns & Price 1987); Radio+optical
right, Anglo Australian Telescope, VLA); z=0.0006

Centaurus A (NGC 5128)

X-ray, radio, and optical images suggest that the galaxy is in tremendous turmoil with energetic arcs and jets after merging with the barred spiral some 100 million years ago

1. Juni 2004, Infrarot-Beobachtungen

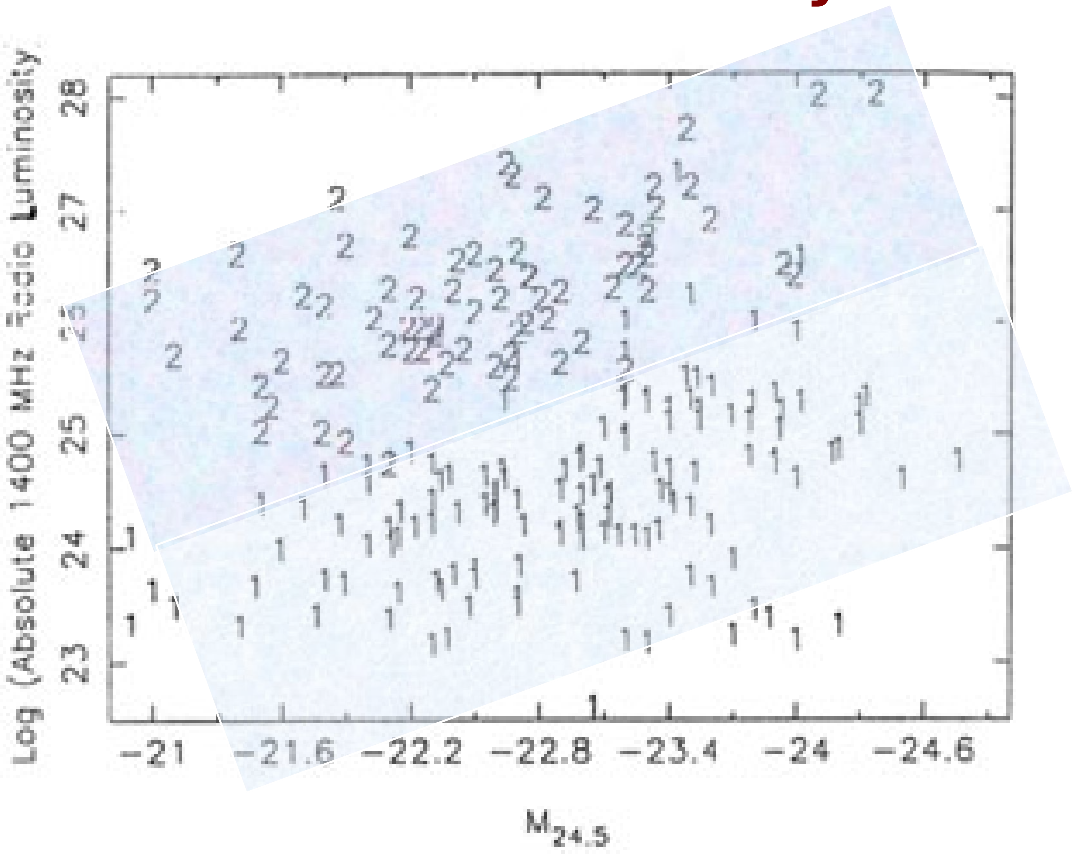
The warped and twisted disk of a spiral galaxy devoured by Centaurus A has dust shaped like a parallelogram around 1,000 ly wide (Spitzer Space Telescope)

X-ray (CXC/NASA/Karovska et al, 2002); radio 21-cm (NRAO/VLA/Schiminovich et al), and continuum (NRAO/VLA/Condon et al); and optical (Digitized Sky Survey/UK Schmidt/STSc

Taxonomy of Active Galactic Nuclei

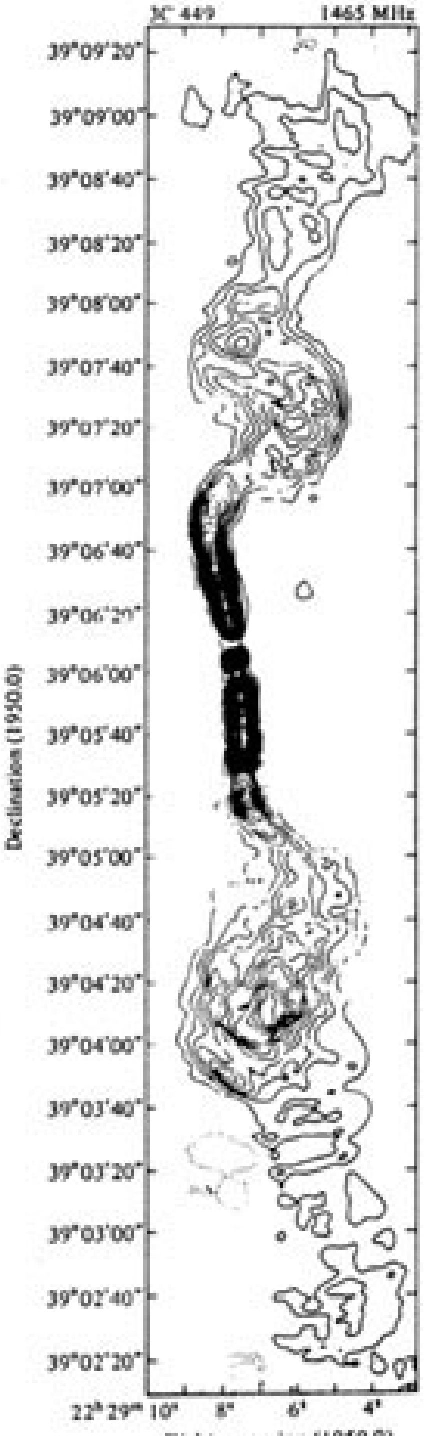
- Radio Galaxien:
  - Leuchtkräftige elliptische Galaxien, starke Emissionslinien
  - Starke kosmologische Evolution (wesentlich größer bei z=2 als lokal)
  - Steiles Spektrum (optisch dünn und ausgedehnt) und flache Spektren (kompact and variabel) (Unterscheidung bei 1 GHz bei =-0.4)
  - Fanaroff und Riley (1974) fanden zwei unterschiedliche Klassen von Radiogalaxien bei 178 MHz: Verhältnis der Entfernungen zw. Den zwei hellsten Spots auf jeder Seite des Kerns zur Gesamtgröße ->
    - in FR II ist das Verhältnis >0.5; in FR I < 0.5
    - Power in FR II > 2 x 10^{26} WHz^{-1}; FR I <2 x 10^{26} WHz^{-1}
  - Substantielle lineare Polarisation in ausgedehnten Quellen (10-30%) => uniform ausgerichtete Magnetfelder

Radio Galaxien: Fanaroff-Riley Klassifikation



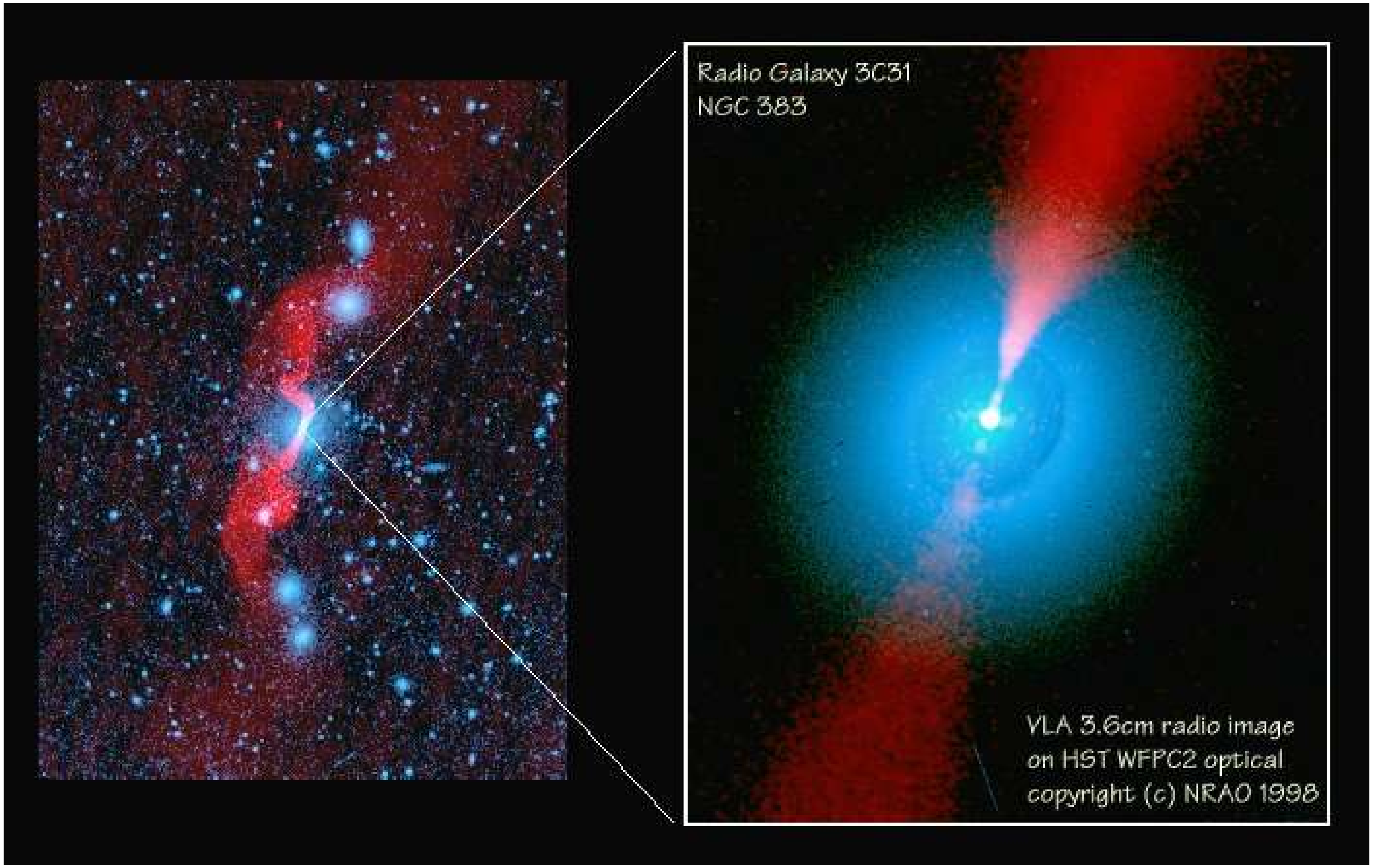
Verteilung der FR I- und FR II Radio Galaxien als Funktion der 1400 MHz Radio Leuchtkräfte und ihrer absoluten B-magnitudes; Owen & Ledlow (1994)

Fanaroff, B. L., & Riley, J. M.
1974. The morphology of extragalactic radio sources of high and low luminosity.
Mon. Not. R. astr. Soc., **167**, 31P-35P.



Fanaroff & Riley Klassifikation

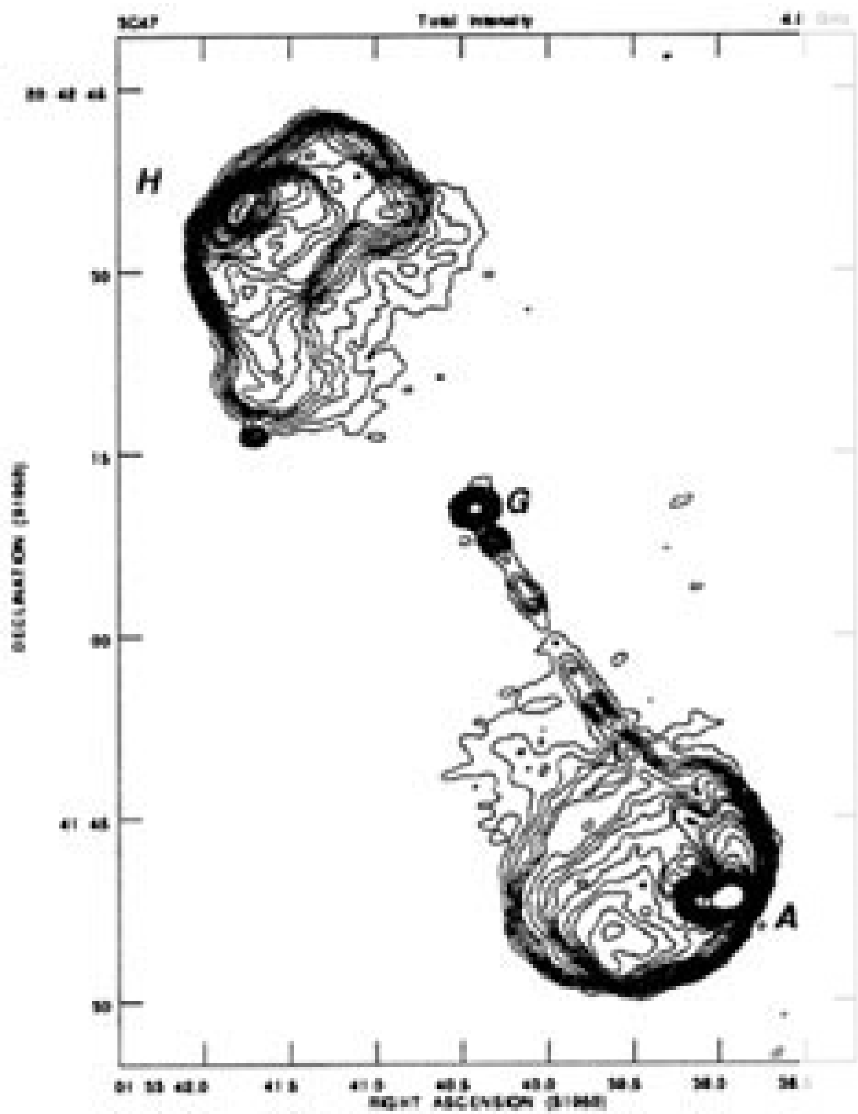
- Fanaroff-Riley Typ I:
  - *starke, zweiseitige Jets, welche in großen Keulenstrukturen enden*
  - *Keulen: steilste (=strahlungsalt) Radiospektren in den von der Muttergalaxie entferntesten Regionen, "edge-darkened"*
  - *die meisten geraden Jets sind einseitig in der Nähe des Kerns (10% der Länge des Jets), aber werden beidseitig nach einigen kpc*
  - *10 % der Gesamtleuchtkraft stammt von den Jets*
  - *große Öffnungswinkel (variieren) der Jets*
  - *Übergang vom Jet zur Keule häufig verbunden mit unstetiger Öffnung der Struktur*
  - *"Loch" zwischen Kern und Start des Jets*



3C 31, Beispiel einer FR I- Radio Galaxie.

Links: 21cm Radio-Emission (VLA) mit einer Auflösung von 5.5 Bogensekunden, stark gestörter Jet, Digitized Palomar Sky Survey in blau.

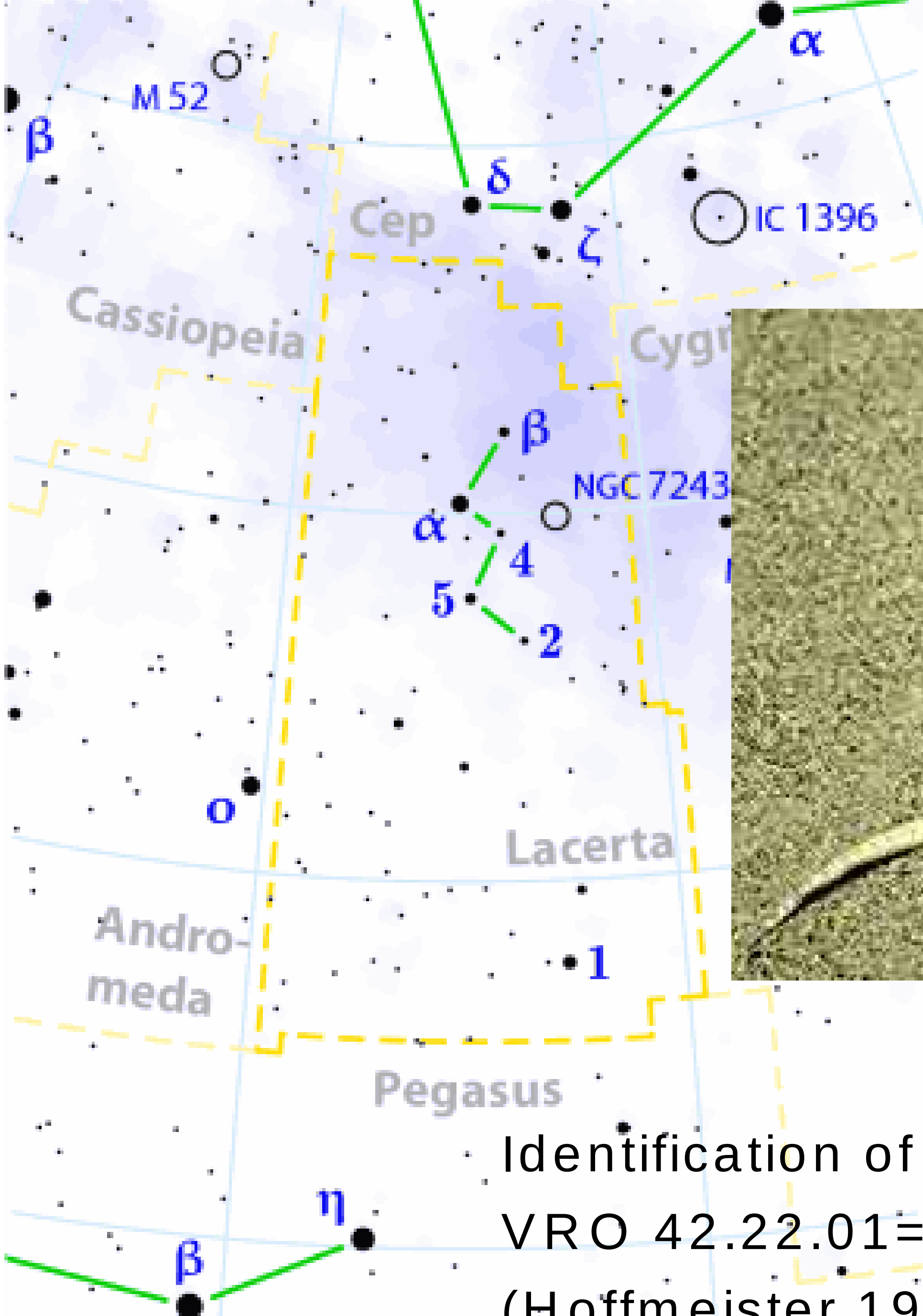
Fanaroff & Riley Klassifikation



Fanaroff-Riley Typ II:

- *die großen Keulenstrukturen sind "edge-brightened", sehr leuchtkräftige "hotspots"*
- *die steilsten Radiospektren werden in den inneren ausgedehnten Regionen gefunden (nahe der optischen Identifikation)*
- *Jet und Kern weniger deutlich sichtbar (Kern + Jet <10%, Jets in <10% gefunden, 80% bei FR I)*
- *einseitige Jets (jet/counter-jet >4:1, Bridle & Perley 1984)*
- *helle Knoten dominieren die Jets*
- *Öffnungswinkel der Jets kleiner*

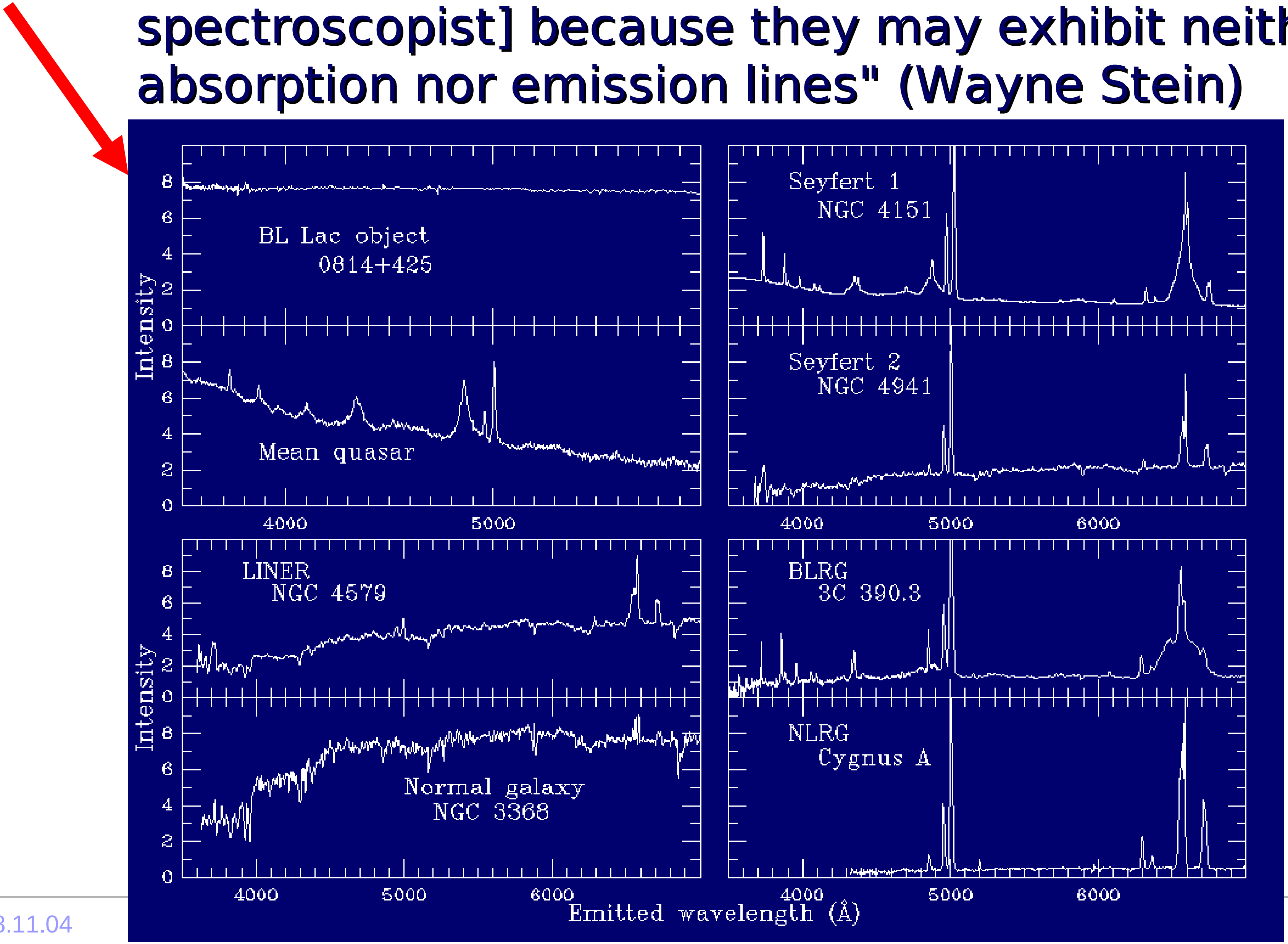
BL Lac=BL Lacertae



Identification of the radio source
VRO 42.22.01=“variable star" BL Lac
(Hoffmeister 1929)

BL Lac Objects

- "totally uninteresting astronomical sources [to the spectroscopist] because they may exhibit neither absorption nor emission lines" (Wayne Stein)

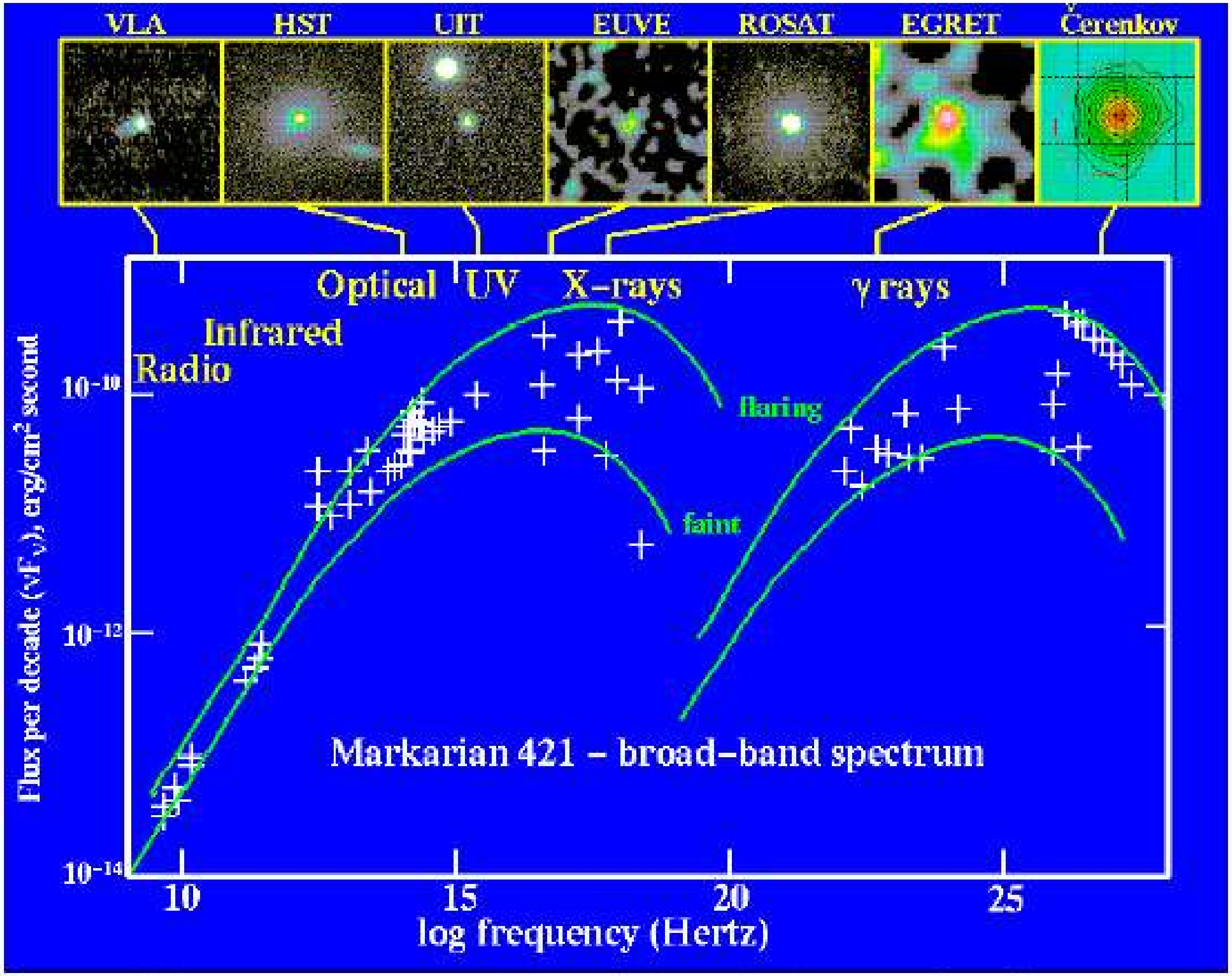


Phenomenology of Active Galactic Nuclei

- *BL Lac Objects:*
  - *Ähneln Flach-Spektrum Radio Quasaren*
  - *Keine breiten optischen Emissionslinien*
  - *Hoch-variabel im Radio, Optischen, Röntgen und Gamma-Bereich*
  - *Starke und stakr variable optische Polarisation*
  - *Schwache kosmologische Evolution*

- *Optically Violent Variables:*
  - *Unterklasse von (hauptsächlich radio) Quasaren mit optischen Charakteristiken wie BL Lac’s, aber mit breiten Emissionslinien (schwächer)*
  - *BL Lac’s + OVV’s= Blazars*

MKN 421 at various wavelengths



http://www.astr.ua.edu/keel/agn/mkn421.html

Images and spectrum of the BL-Lac object MKN 421

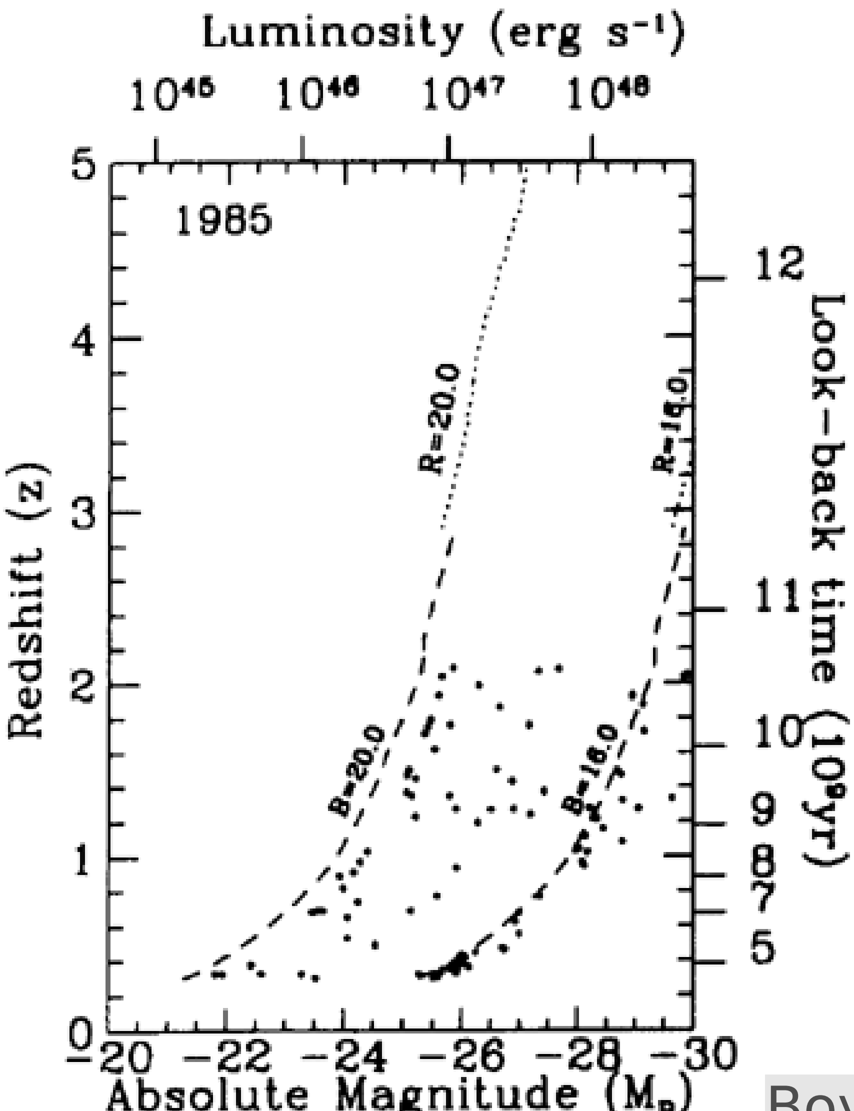
There are no optical emission lines in the spectrum and the object is similar to a point source in all images

MKN 421 is one of a few AGN that emits prodigiously at TeV energies

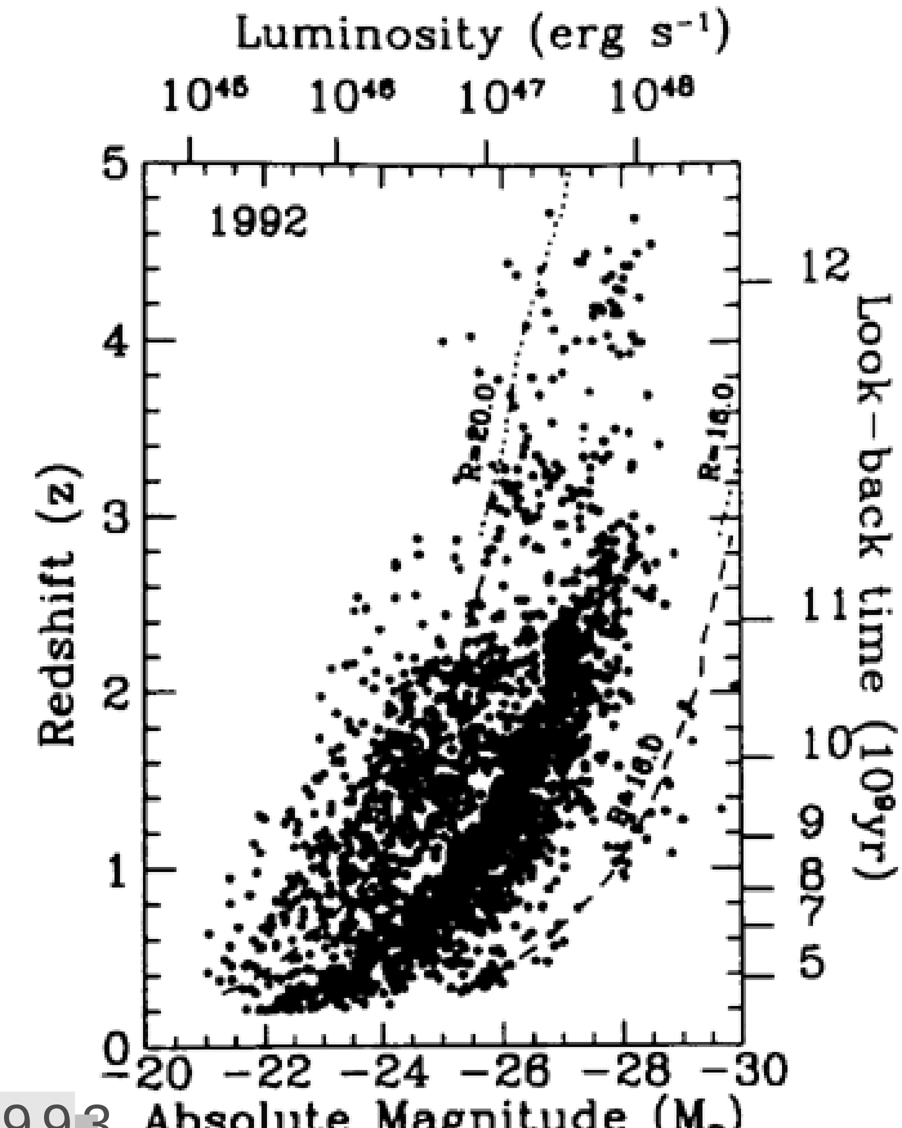
Radio-Durchmusterungen

Die Suche nach Quasaren

1986



1992, Juni



Boyle, 1993

Radio AGN Surveys

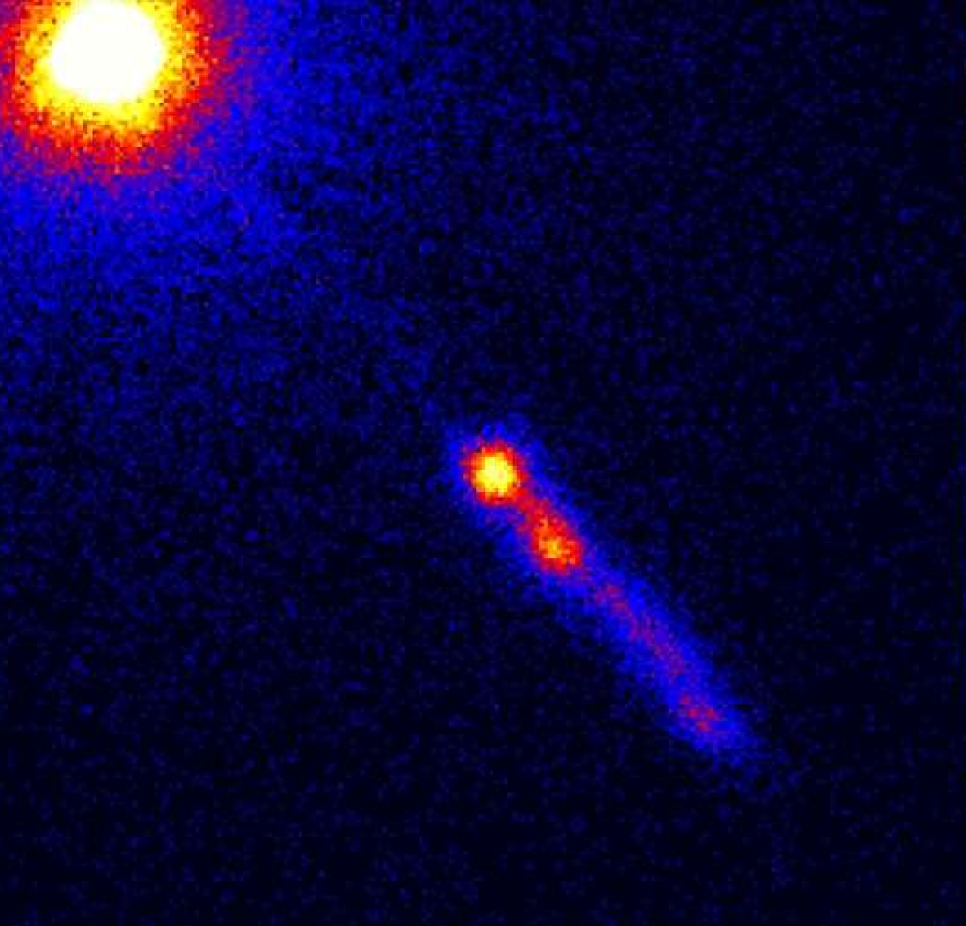
Radio surveys: only 5-10% of AGN are radio-loud

- 3C/3CR: >9Jy@178MHz, ~300 sources, all w/IDs, ~25% AGN
  - 4C-8C (esp. 4C & 7C): decreasing flux limits & areas
  - PKS (Parkes): >0.5Jy@2.7GHz, 15000 deg^2, 5000 sources
  - 1 Jy: 5GHz, nearly complete IDs, good source of BL Lacs,518 s
  - FIRST: >1mJy@1.4GHz, 5000-1000 deg^2, 5" FWHM,

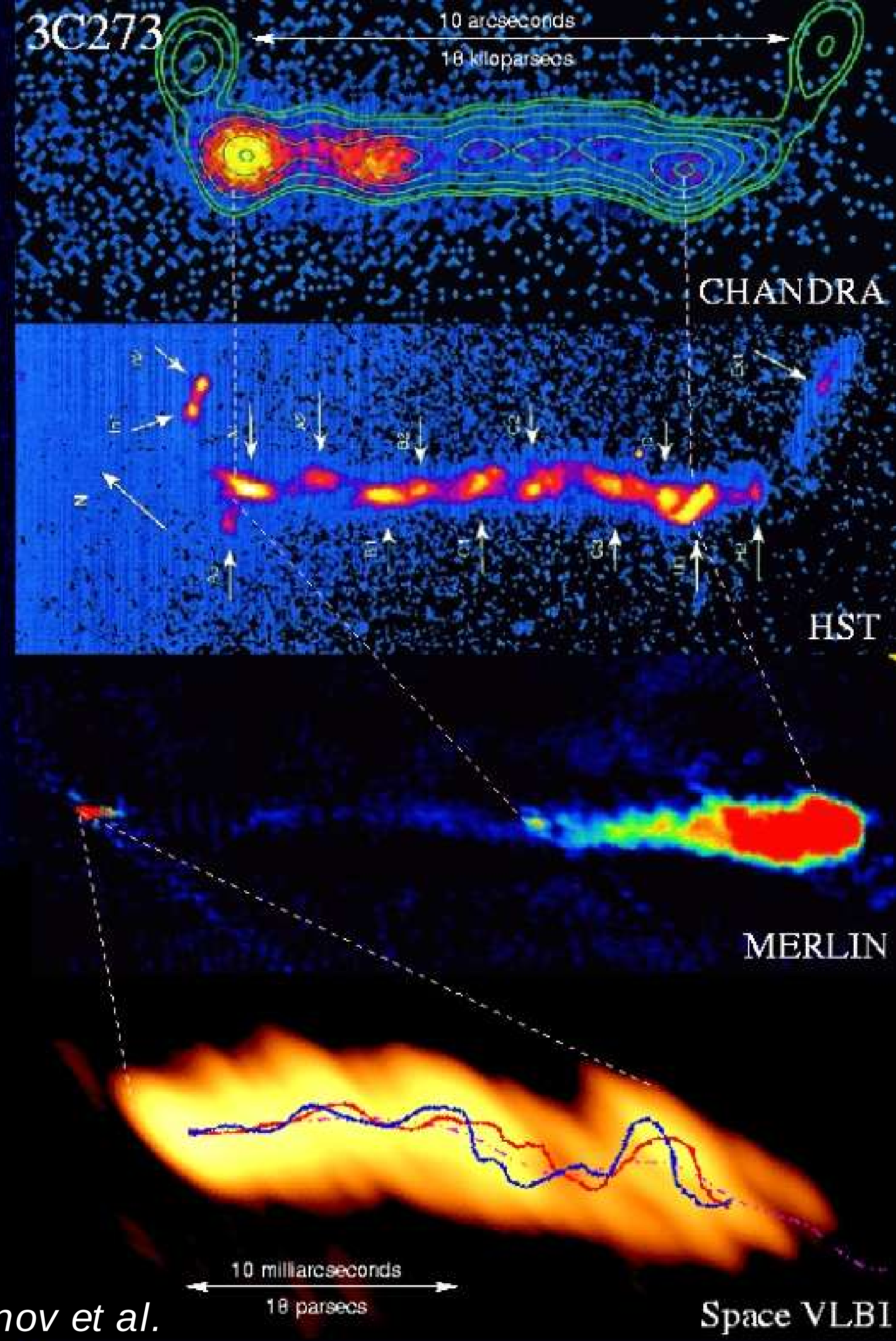
    radio-loud and radio-quiet to z~3 (ditto for NVSS)
  - NVSS: >1mJy@1.4GHz, ~30000 deg^2, 45" FWHM
  - WENSS: north of +30 deg decl. at 326 MHz,

230,000 sources > 18 mJy, total I & linear polarization

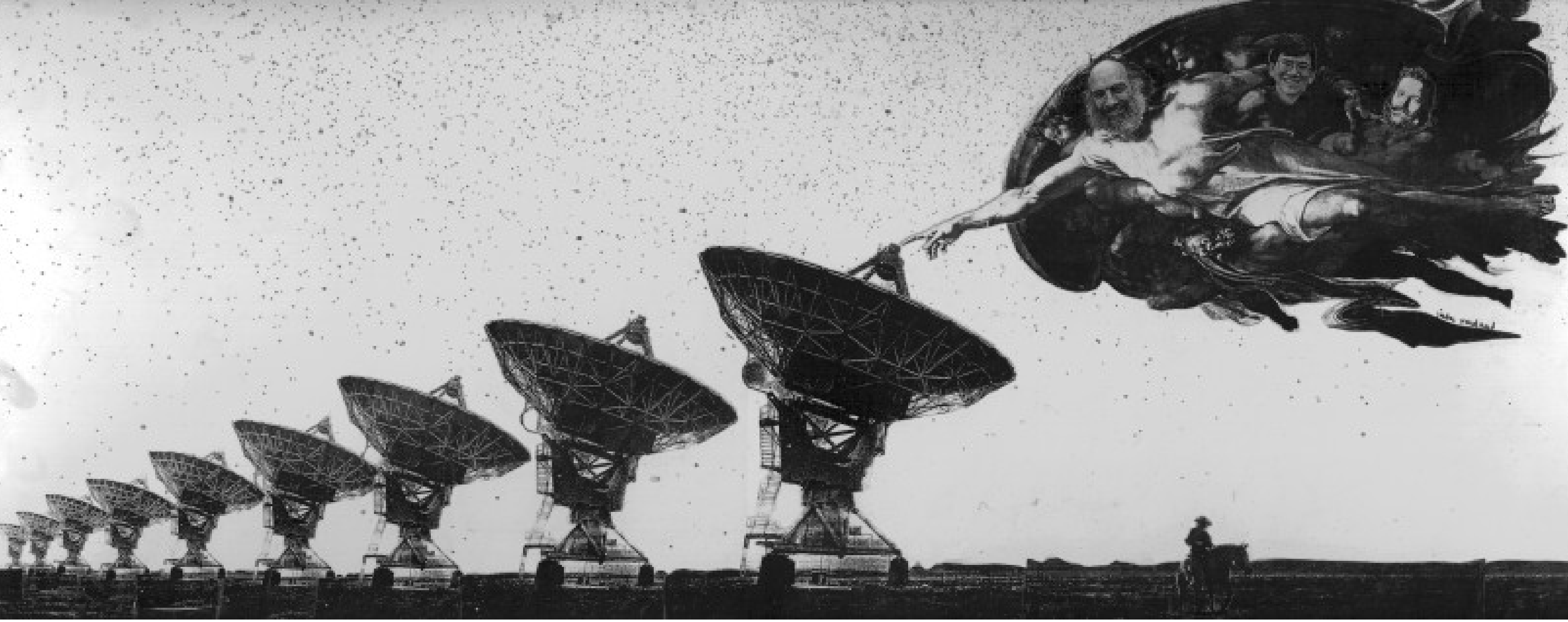
  - MRC (Molonglo): >0.95Jy@ 408MHz, complete followup, SU
  - USS (ultra-steep-spectrum): good for z>2 radio galaxies



The „first“ Quasar: 3C273



Lobanov et al.



The VLA FIRST Survey

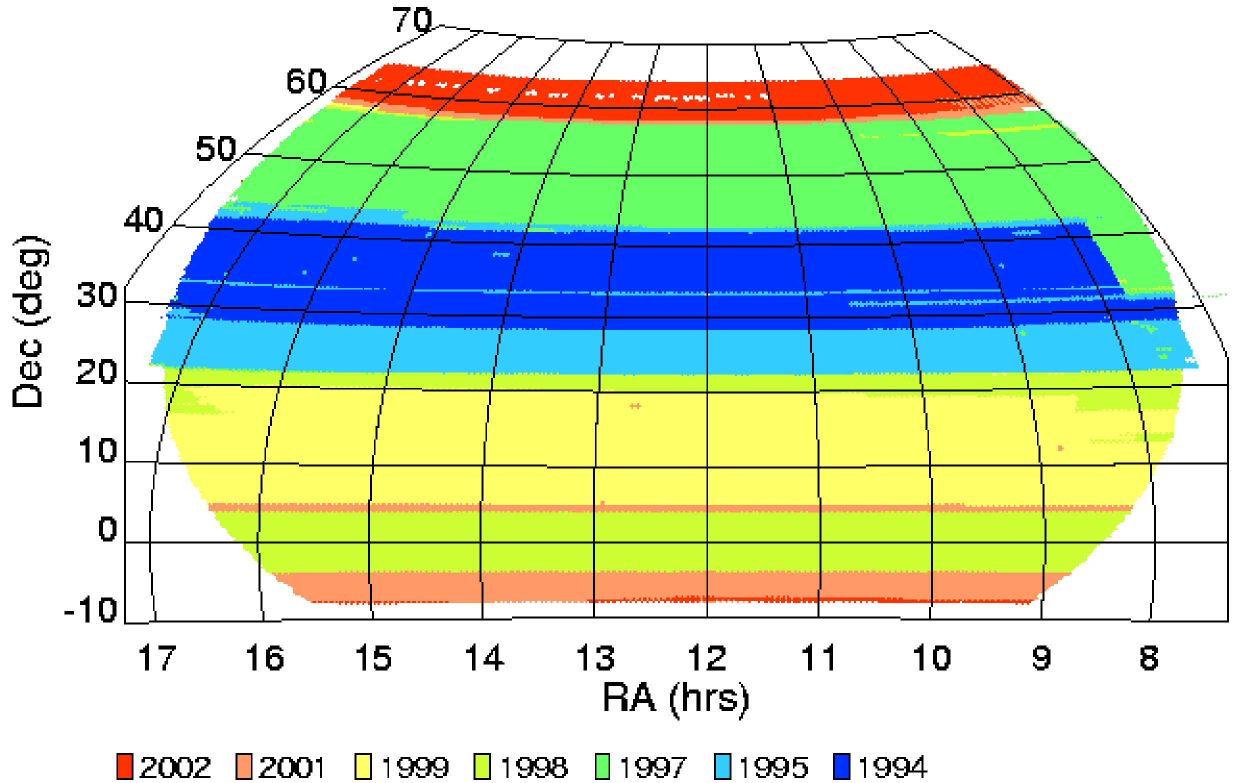
FAINT IMAGES OF THE RADIO SKY AT TWENTY-CENTIMETE

FIRST -- Faint Images of the Radio Sky at Twenty-cm -- is a project designed

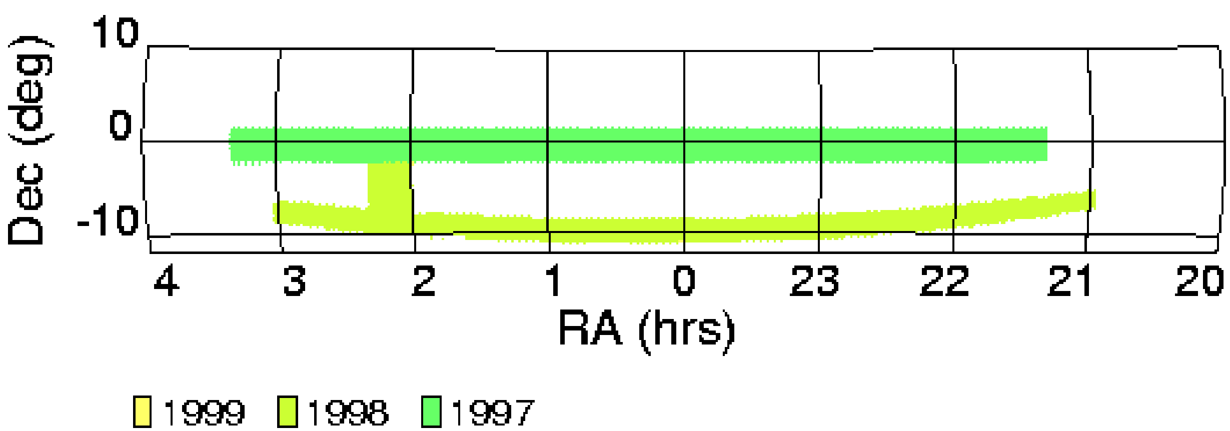
to produce the radio equivalent of the Palomar Observatory Sky Survey over 10,000 square degrees of the North and South Galactic Caps. Using the NRAO Very Large Array (VLA) and an automated mapping pipeline, we produce images with 1.8" pixels, a typical rms of 0.15 mJy, and a resolution of 5". At the 1 mJy source detection threshold, there are ~90 sources per square degree,

~35% of which have resolved structure on scales from 2-30".

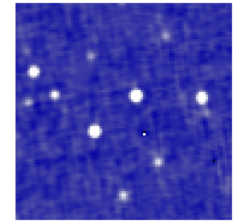
FIRST Survey Northern Sky Coverage, 2003 April 11



FIRST Survey Southern Sky Coverage, 2003 April 11



The NRAO VLA Sky Survey



- The NRAO VLA Sky Survey (NVSS) is a 1.4 GHz continuum survey covering the entire sky north of -40 deg declination. A detailed description appears in the 1998 May issue of The Astronomical Journal (Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693). The principal NVSS data products are:

- A set of 2326 continuum image ``cubes," each covering 4 deg X 4 deg with three planes containing the Stokes I, Q, and U images. These images were made with a relatively large restoring beam (45 arcsec FWHM) to yield the high surface-brightness sensitivity needed for completeness and photometric accuracy. Their rms brightness fluctuations are about 0.45 mJy/beam = 0.14 K (Stokes I) and 0.29 mJy/beam = 0.09 K (Stokes Q and U). The rms uncertainties in right ascension and declination vary from < 1 arcsec for relatively strong (S > 15 mJy) point sources to 7 arcsec for the faintest (S = 2.3 mJy) detectable sources. The completeness limit is about 2.5 mJy.

- A catalog of discrete sources on these images (over 1.8 million sources in the entire survey).

- Processed *(u,v)* data sets. Every large image was constructed from more than 100 smaller "snapshot" images. All of the edited and calibrated single-source *(u,v)* data sets used to make the snapshot images contributing to each large image have been combined into a single multisource *(u,v)* file for users who want to investigate the data underlying the images

=> postage stamp server.

- The 6C survey covers most of the northern hemisphere above a declination

  of 30°, but generally away from the Galactic plane,

  at 151 MHz, with a resolution of 4.2×4.2 cosec(declination) arcmin2 (EW×NS).

- I: declination > 80°, 0h < right ascension < 24h

Baldwin et al. 1985, MNRAS, 217, 717.

- II: 30° < declination < 51°, 08h30m < right ascension < 17h30m

Hales et al. 1988, MNRAS, 234, 919.

- III: 48° < declination < 68°, 05h25m < right ascension < 18h17m

Hales et al. 1990, MNRAS, 246, 256.

- IV: 67° < declination < 82°, 0h < right ascension < 24h

Hales et al. 1991, MNRAS, 251, 46.

- V: 48° < declination < 68°,

  01h34m < right ascension < 6h14m and 17h16m < right ascension < 20h24m

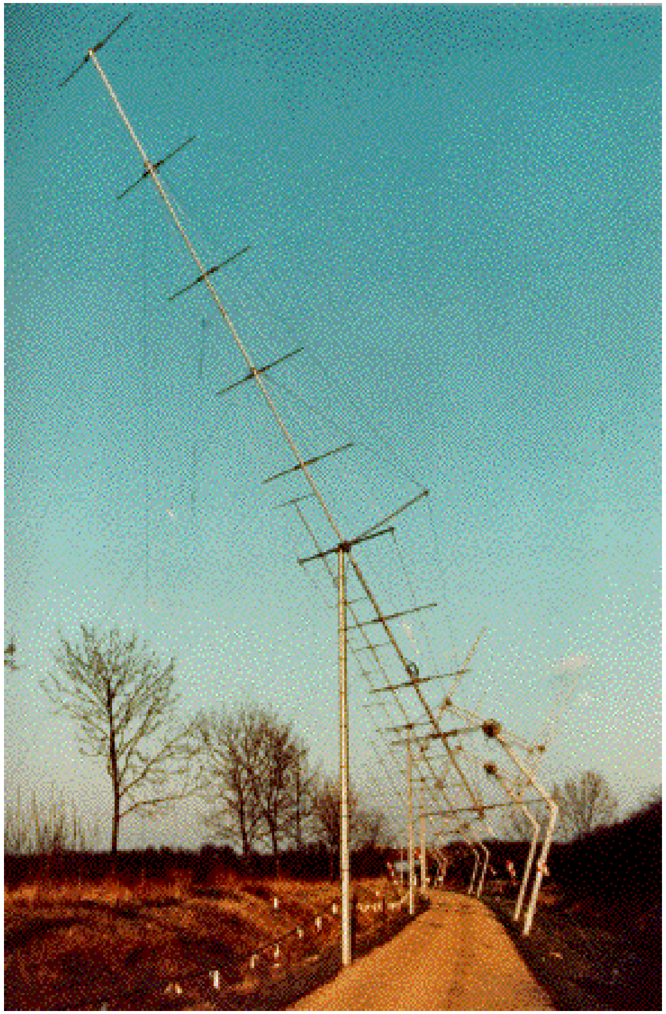
Hales et al. 1993, MNRAS, 262, 1057.

- VI: 30° < declination < 51°,

Cambridge Surveys

A group of the 6C antennas.

(© *Mullard Radio Astronomy Observatory, 1995.*)



A group of the 8C antennas, with the smaller CLFST antennas to the right.

(© *Mullard Radio Astronomy Observatory, 1995.*)

The Westerbork Northern Sky Survey

- The Westerbork Northern Sky Survey (*WENSS*) is a low-frequency radio survey that covers the whole sky

  north of delta=30 degree at a wavelength of 92 or 85 cm to a limiting flux density of approximately 18 mJy (5 sigma).

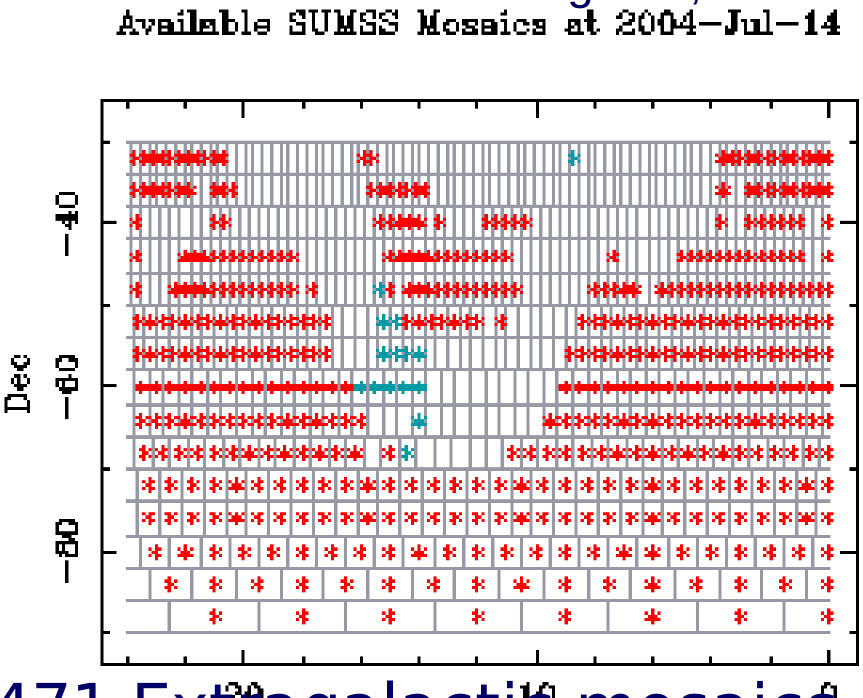
  This survey has a resolution of 54'' x 54'' cosec (delta) and a positional accuracy for strong sources of 1.5''.

- The *WENSS* project is a collaboration between the Netherlands Foundation for Research in Astronomy (NFRA/ASTRON) and the Leiden Observatory.

SUMSS:

SUMSS is a deep radio survey of the entire sky

south of declination -30 degrees, made using the MOST



Molonglo Observatory

Synthesis Telescope

471 Extragalactic mosaics and 15 Galactic mosaics have now been released, covering an area of about 5450 square degrees, **Completion: 90%, expected: 300 000 radio sources**

Radio surveys

Survey	Frequency MHz	Flux Jy	# of sources	ID %	QSR %	$z>1$ %		Additional constraints	
6C/2Jy[a]	151	$2.2<S<4.4$	67	30	24	-		$34<\delta<40$	$08<\alpha<13$
3CR[b]	178	9	298	60	20	15		$-05<\delta$	
3CRR[c]	178	10	173	60	20	15	$b>10$	$10<\delta$	
4C/USS[d]	178	2	46	20	-	30		$20<\delta<40$	$a<-1$
ESO/UTRAO[e]	365	0.25	372	15	-	-		$0<\delta<20$	$a<-1$
B2/1Jy[f]	408	$2>S>1$	59	39	24	20	$b>30$	$34<\delta<40$	$0<\alpha<13$
MCR/1Jy[g]	408	0.9	540	30	25	15	$b>15$	$-30<\delta<-20$	
B3/VLA[h]	408	0.1	1103	30	-	-		$37<\delta<47$	
LBDS[i]	1412	0.001	306	53	20	-		selected areas	
PSR[j]	2700	0.1	1178	67	29	-		selected areas	
MG[k]	5000	0.106	5974	45	24	-	$b>10$	$0<\delta<19.5$	
PR[l]	5000	1.3	65	-	52	26	$b>10$	$35<\delta$	

[a] Baldwin et al 1985, Eales 1985a,b; [b] Bennet 1962, Spinrad et al 1985a; [c] Laing et al 1983; [d] Tielens et al 1979, Chambers & Miley 1990; [e] Douglas et al 1980, Röttgering 1993; [f] Allington-Smith 1982; [g] Large et al 1981, McCarthy et al 1990a; [h] Ficarra et al 1985, Vigotti et al 1989; [i] Windhorst et al 1984a,b; [j] Downes et al 1986, Dunlop et al 1989a; [k] Bennett et al 1986, Lawrence et al 1986.

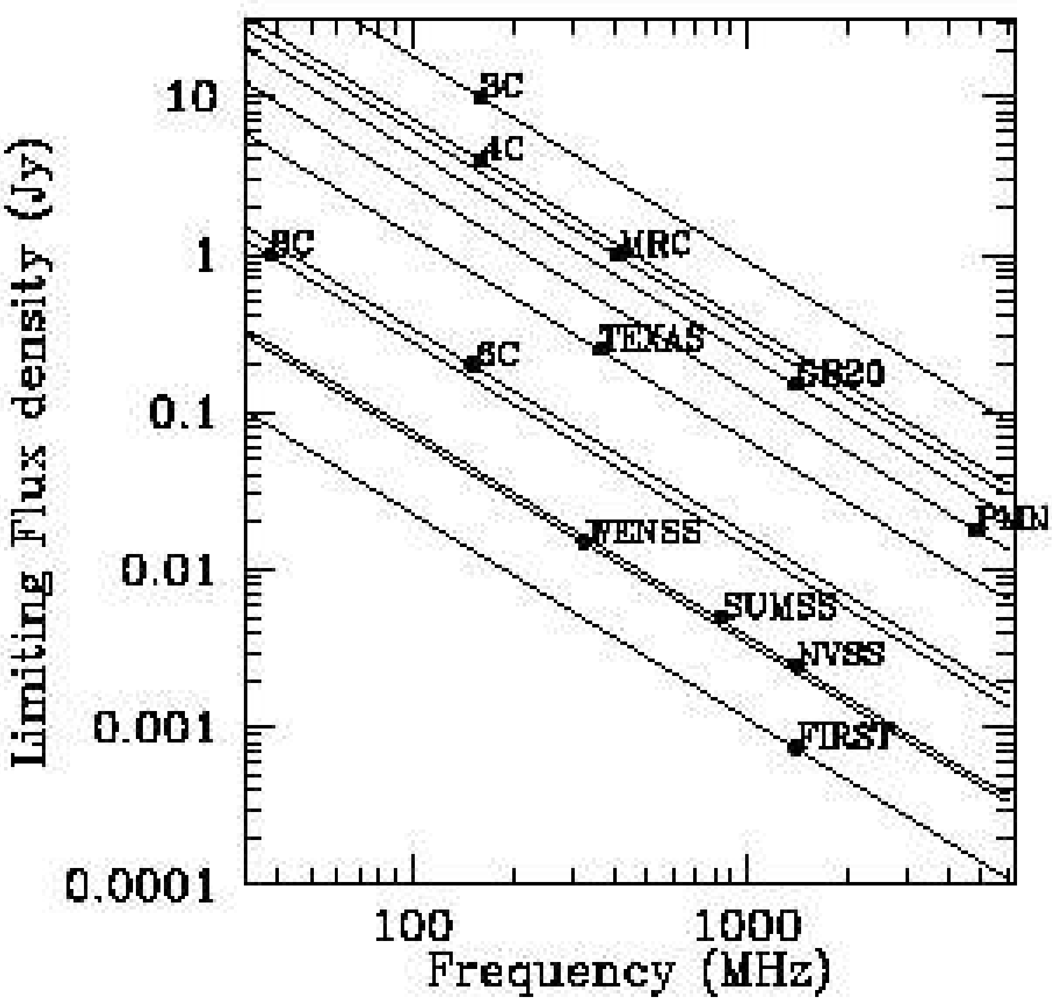


Figure 1. Limiting flux density of all major radio surveys. Lines are of constant spectral indices of −1.3. Note that WENSS and SUMSS are ideally matched to NVSS to construct samples of USS sources.