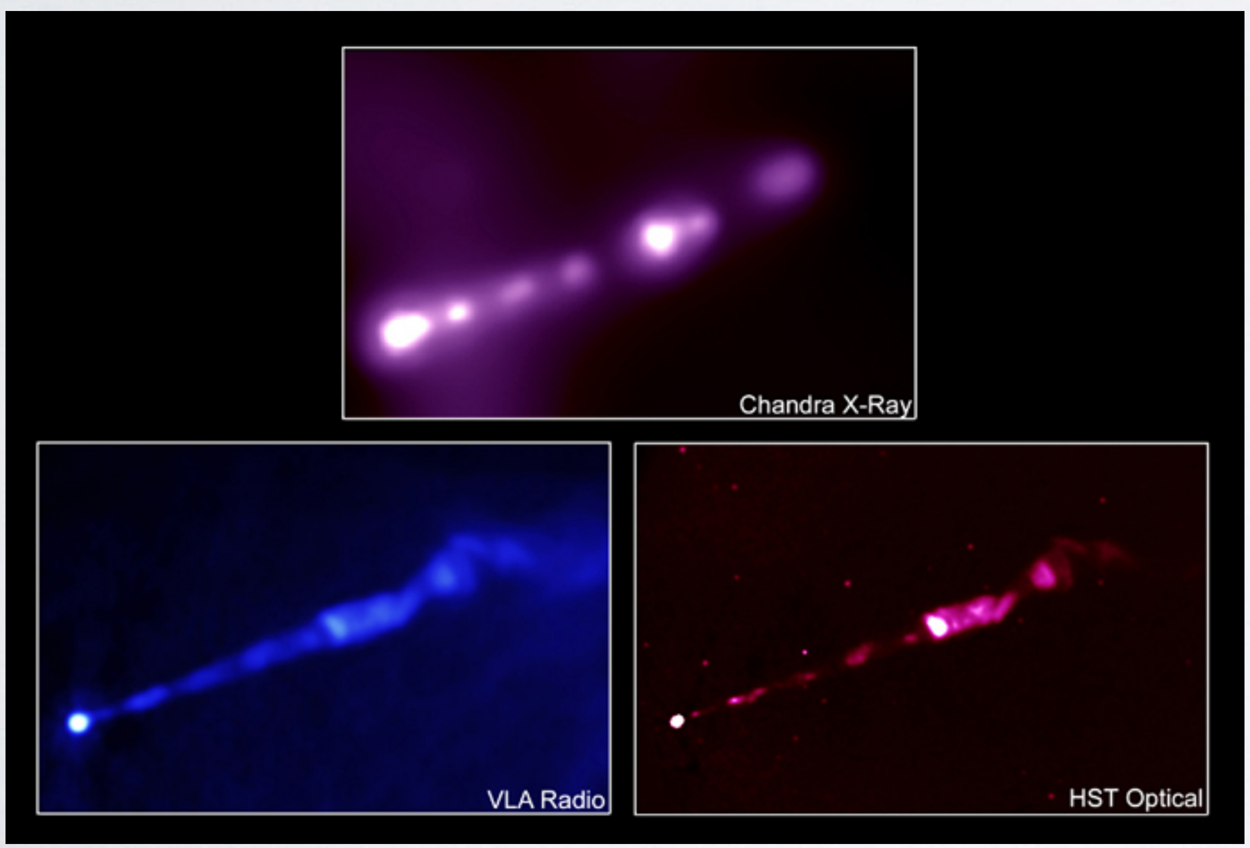
Active Galactic Nuclei (AGN)

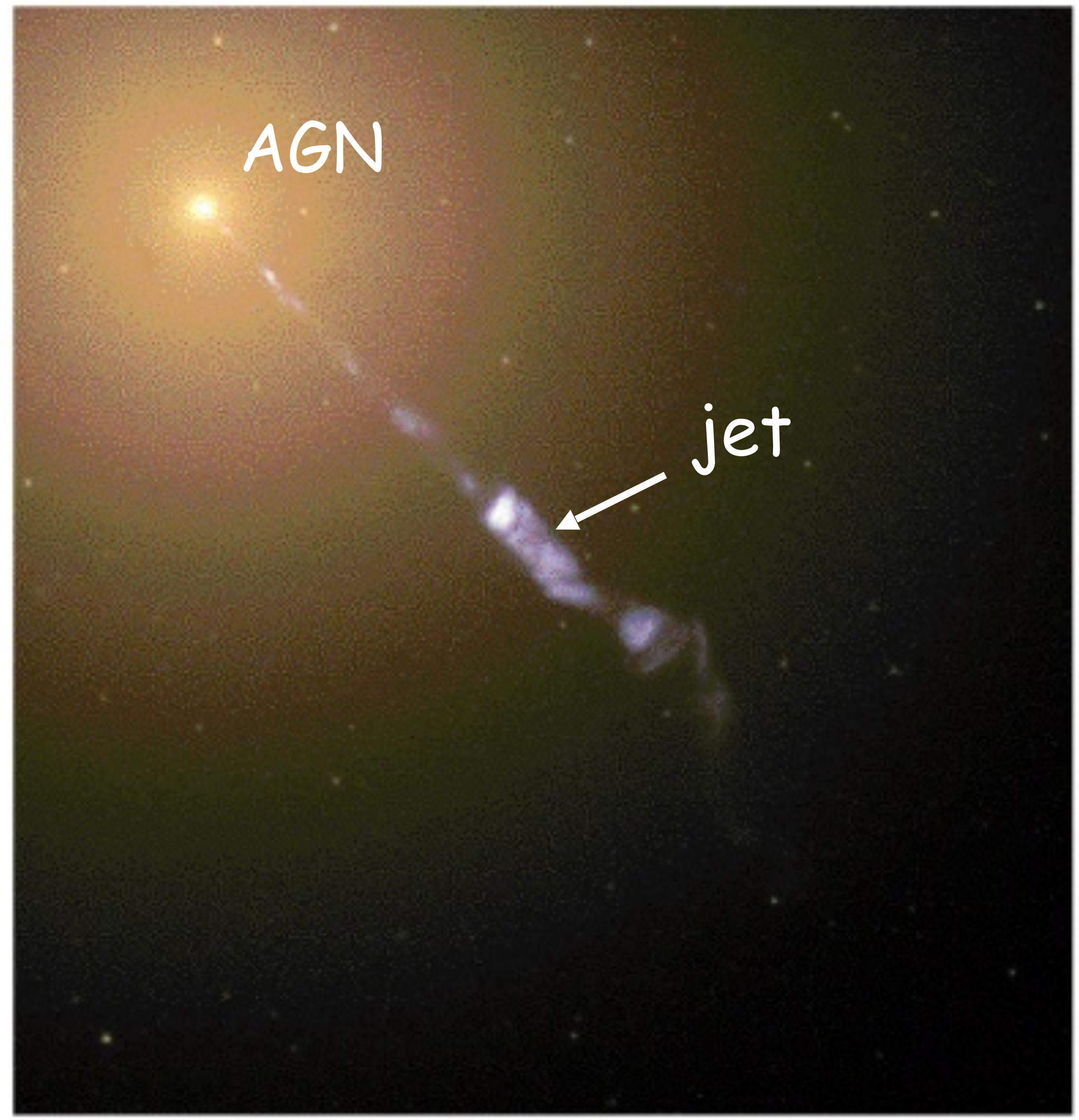
A little history - First Detections of Seyfert Galaxies

1908 – Fath & Slipher detect strong emission lines similar to planetary nebulae with line-width of several 1000 km/s in NGC1068.

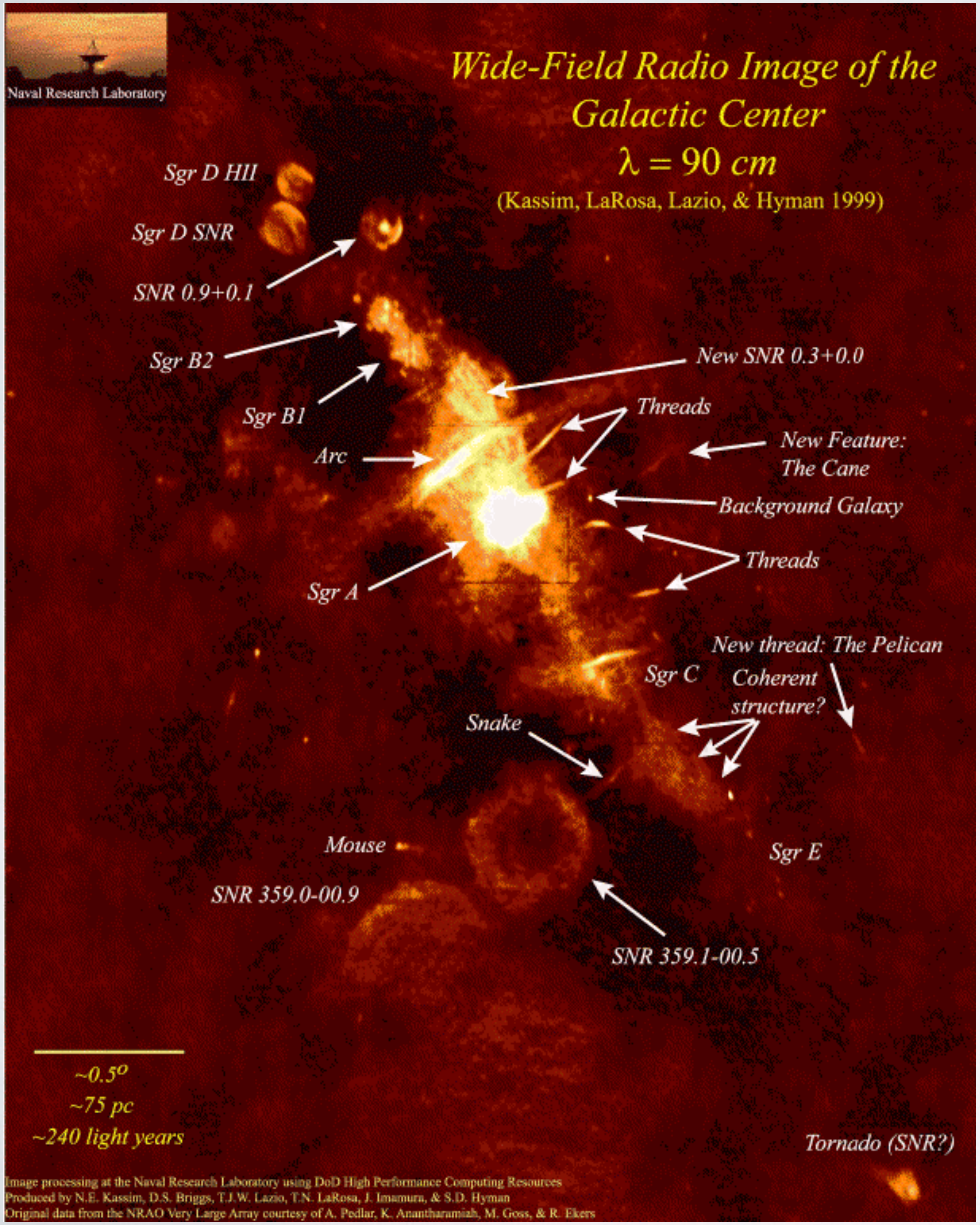
A little history - First Detections of Optical Jets

1913 – Detection of an optical jet in M87 by Curtis

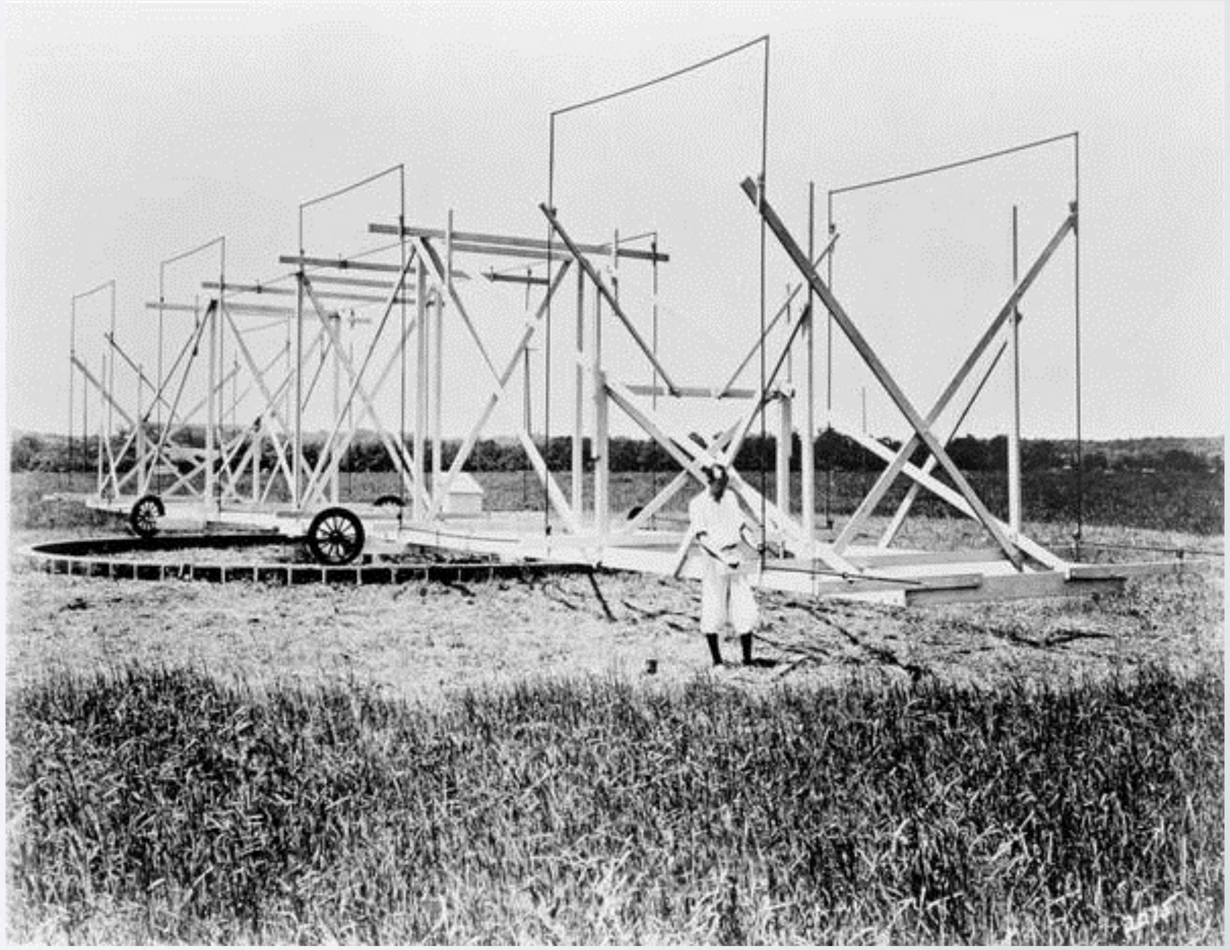


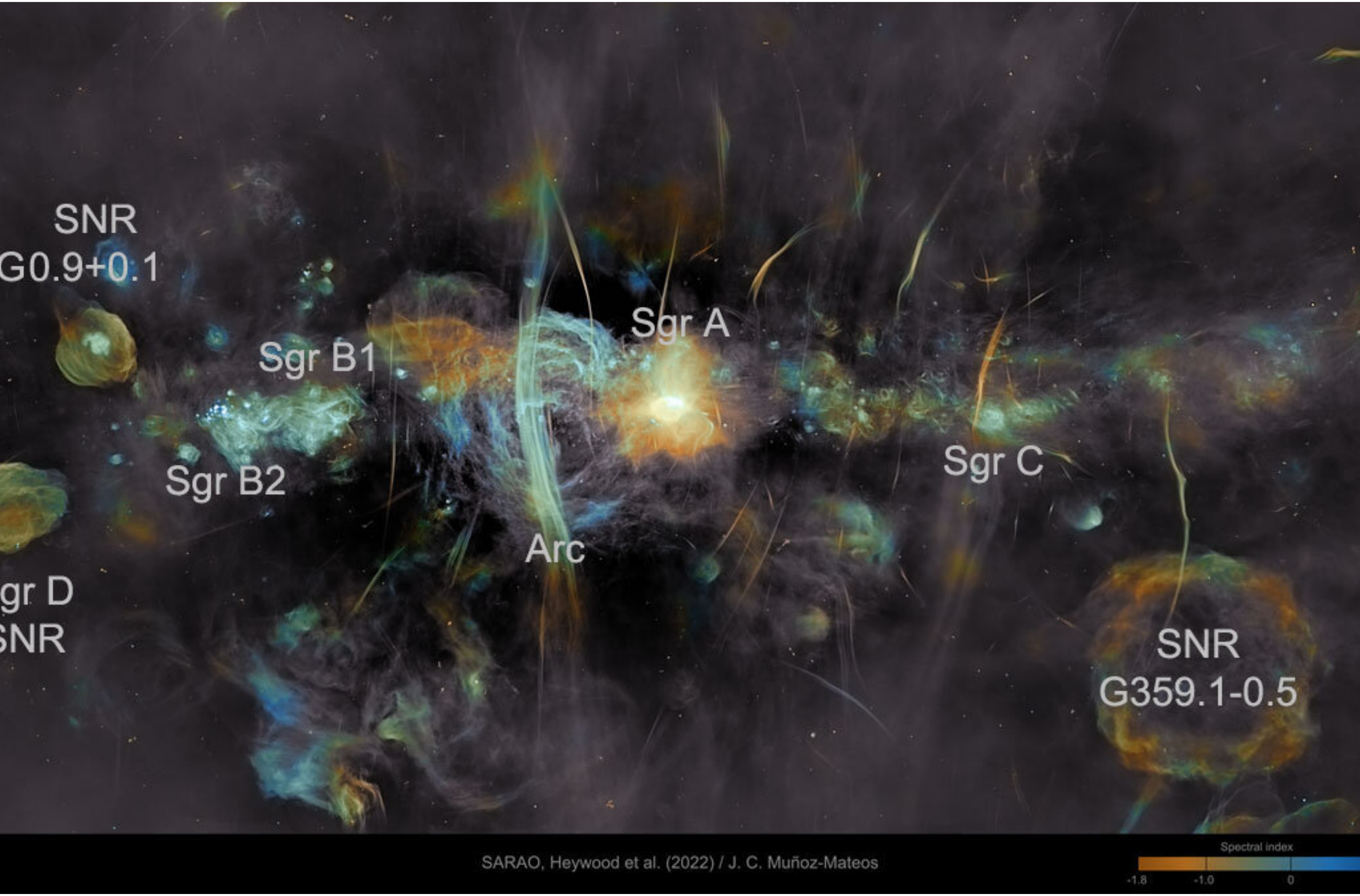


A little history - emission of the Galactic center



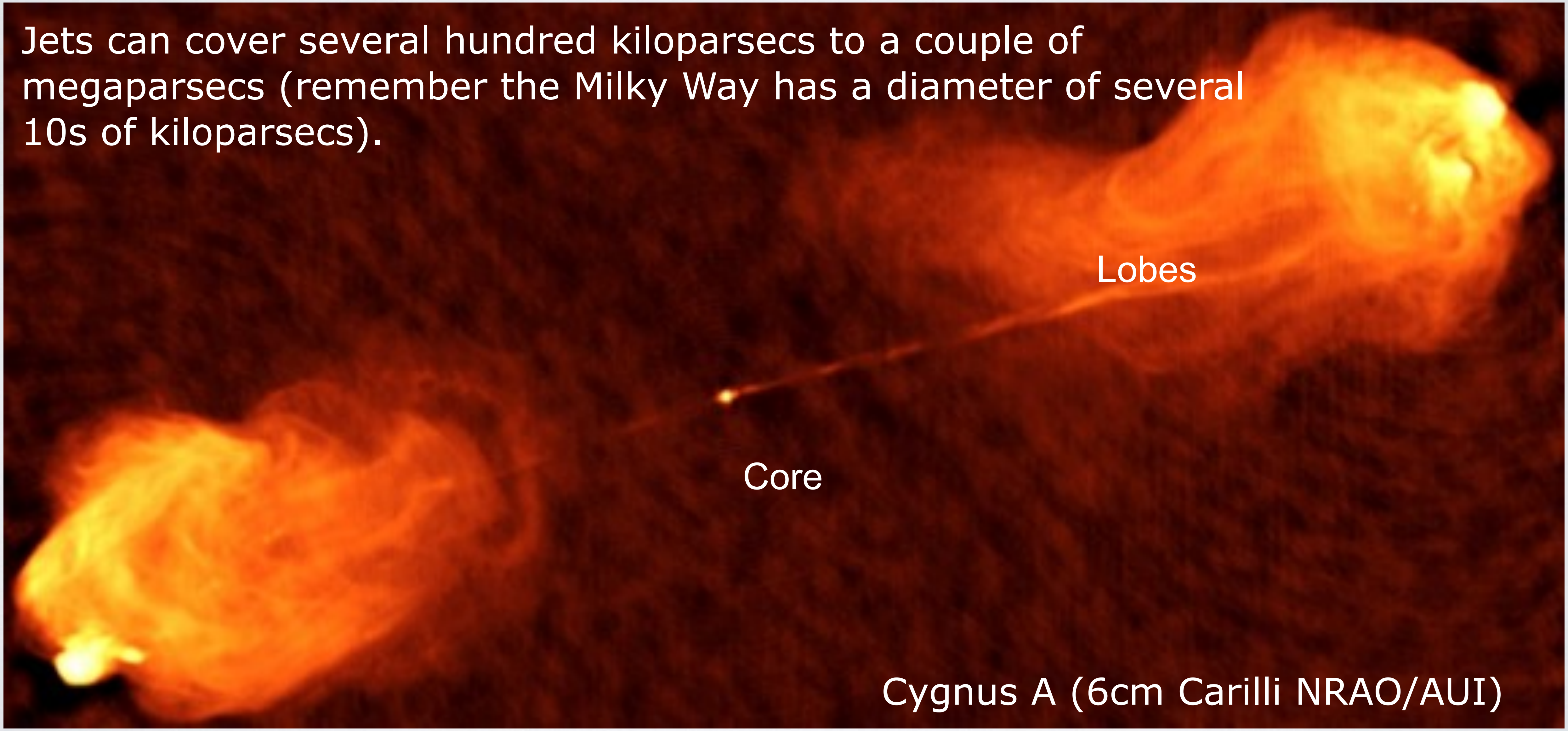
Karl Jansky




SNR
G0.9+0.1
Sgr B1
Sgr B2
Sgr A
Arc
Sgr C
gr D
SNR
SNR
G359.1-0.5
SARAO, Heywood et al. (2022) / J. C. Muñoz-Mateos
Spectral index
-1.8
-1.0
0

A little history - the puzzle of Cygnus A

1953 - discovery of the large linear radio structure in Cygnus A centered around the central brightest galaxy of a cluster



First Radio Surveys

Early radio surveys played a crucial role in discovering quasars

- 3C and 3CR Third Cambridge Catalog (Edge et al. 1959) at 159 Mhz (>9Jy). Basis for extragalactic radio astronomy, cosmology and discovery of Quasars
- PKS Parkes (Australia, Ekers 1959) survey of southern sky at 408 Mhz (>4Jy) and 1410MHz (>1Jy).
- 4C 4th Cambridge survey (today 8C). Deeper/smaller
- AO Aricibo Occultation Survey (Hazard et al. 1967). Occultation by moon (high positional accuracy)

Discovery of Quasars

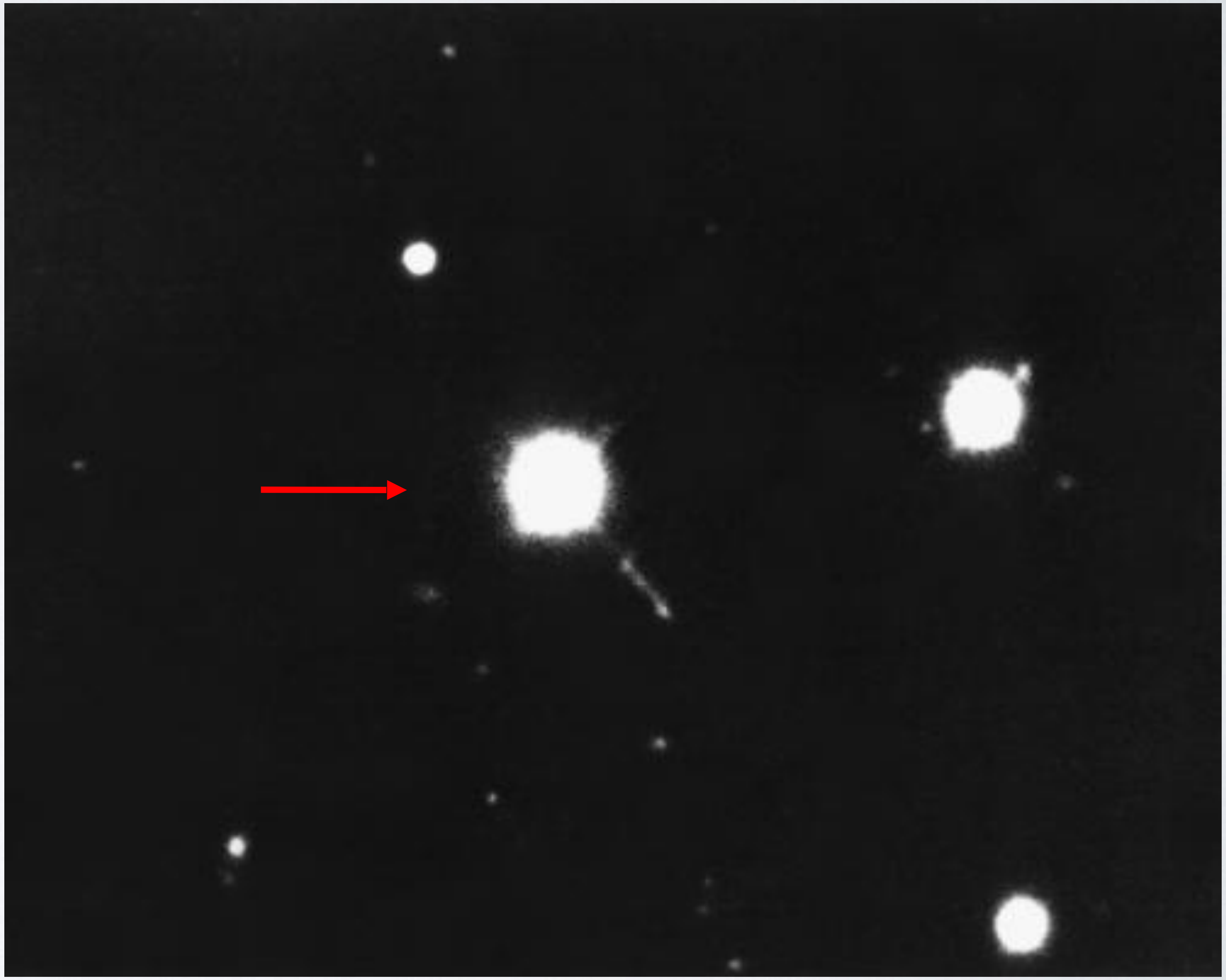
3C273

The 273rd radio source in the Cambridge Catalog

Compact radio source looks like a star except for that wisp of light!

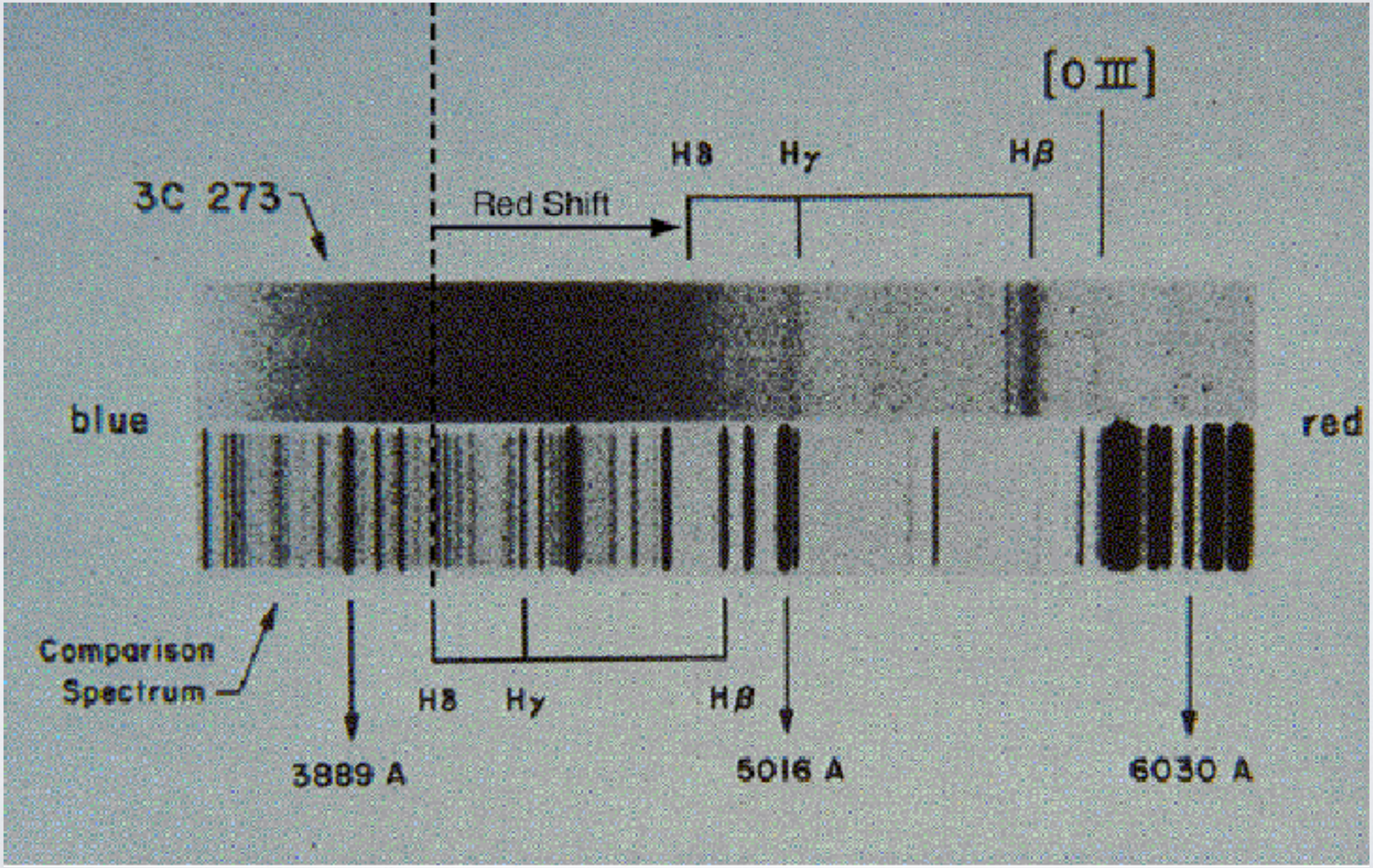
Maarten Schmidt measured a redshift of $z=0.158$

Early attempts to find galaxies associated with quasars failed



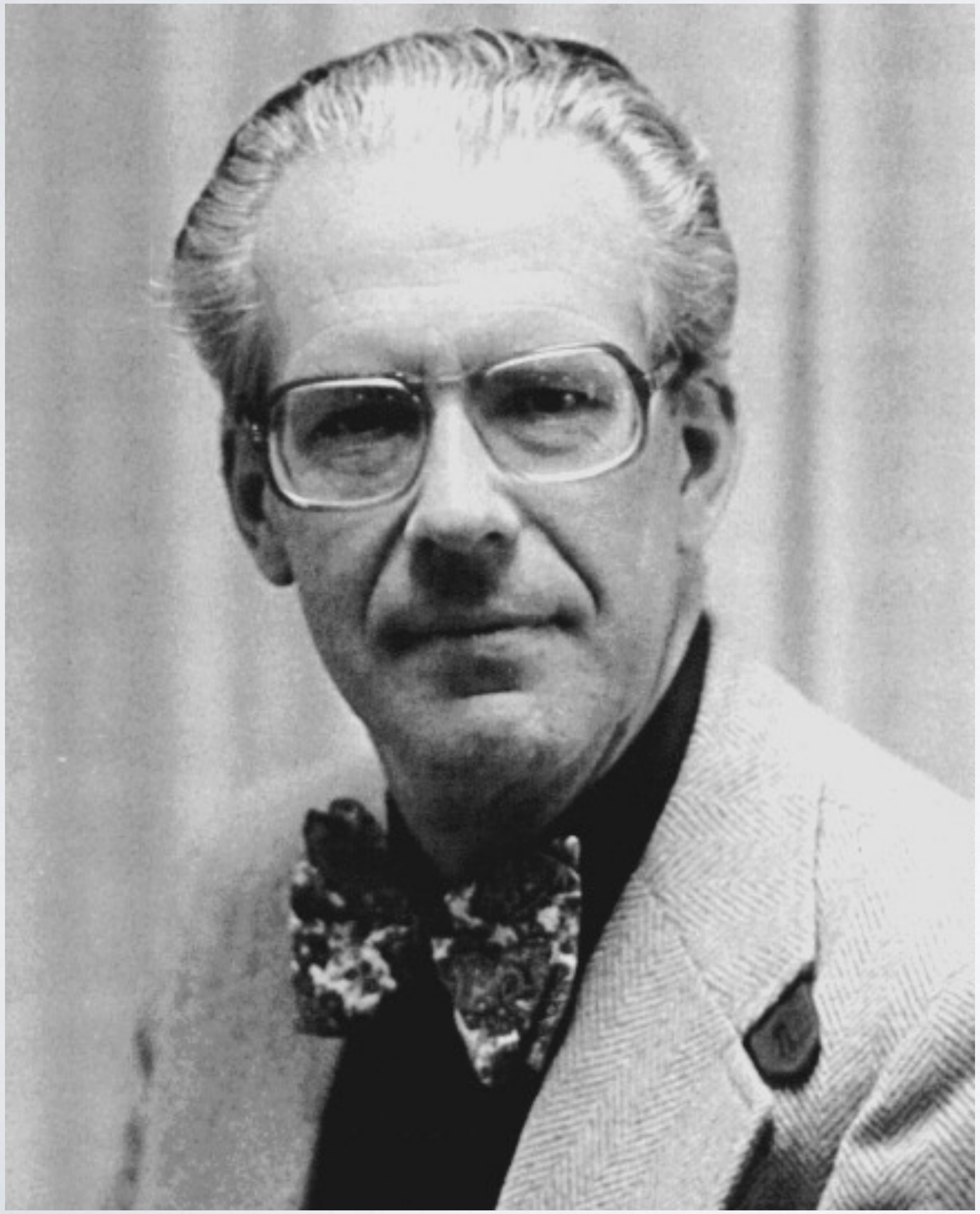
Discovery of Quasars

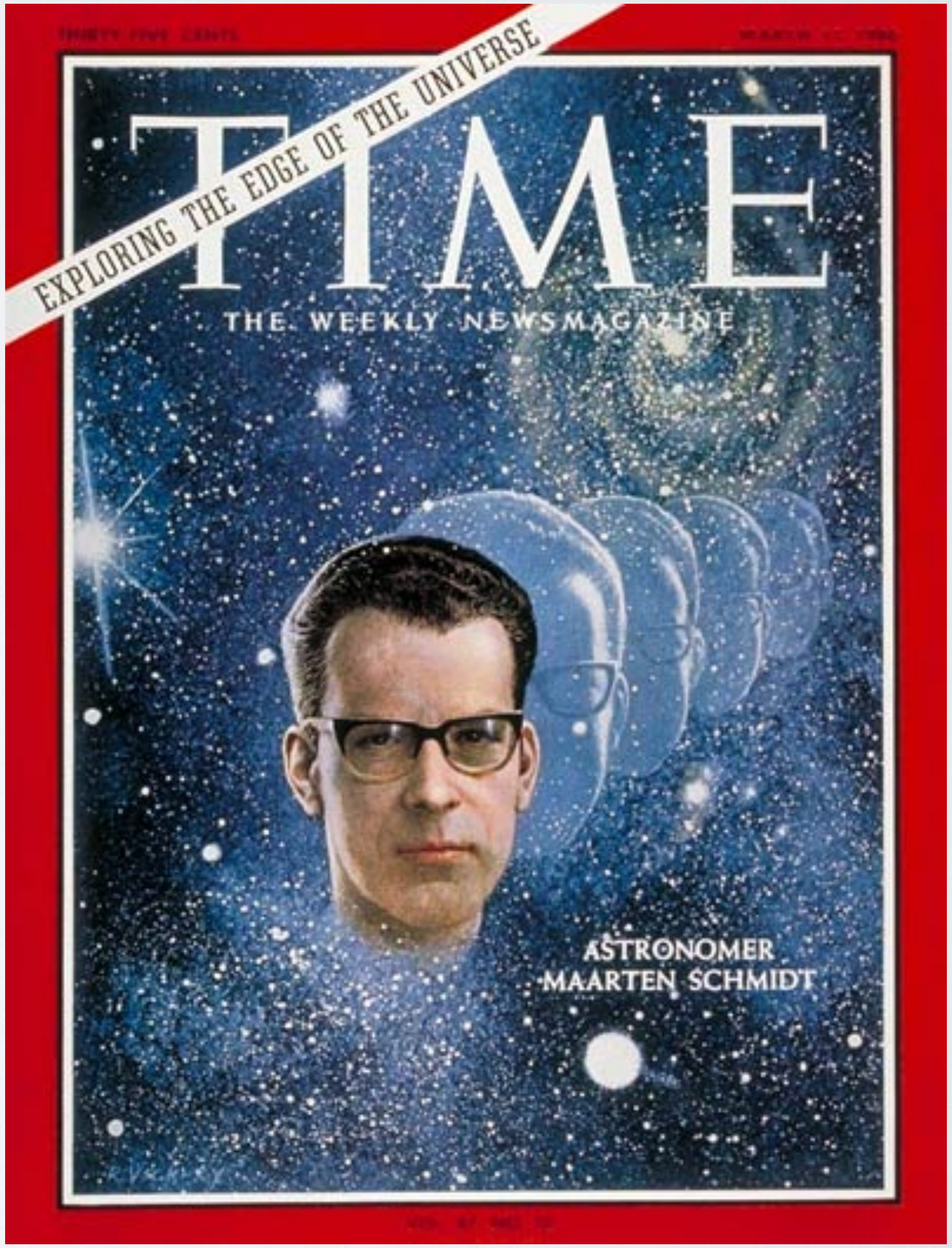
Broad emission lines at "strange" positions



Discovery of Quasars

Maarten Schmidt





Discovery of Quasars

- 1964 – Schmidt studied sufficient quasars to find:

- Star-like, associated with radio sources
- Time-variable in continuum flux
- Large UV fluxes
- Broad emission lines
- Large redshifts

Not all quasars have all these properties

Discovery of Quasars

Why is this object at redshift of 0.158 so special?

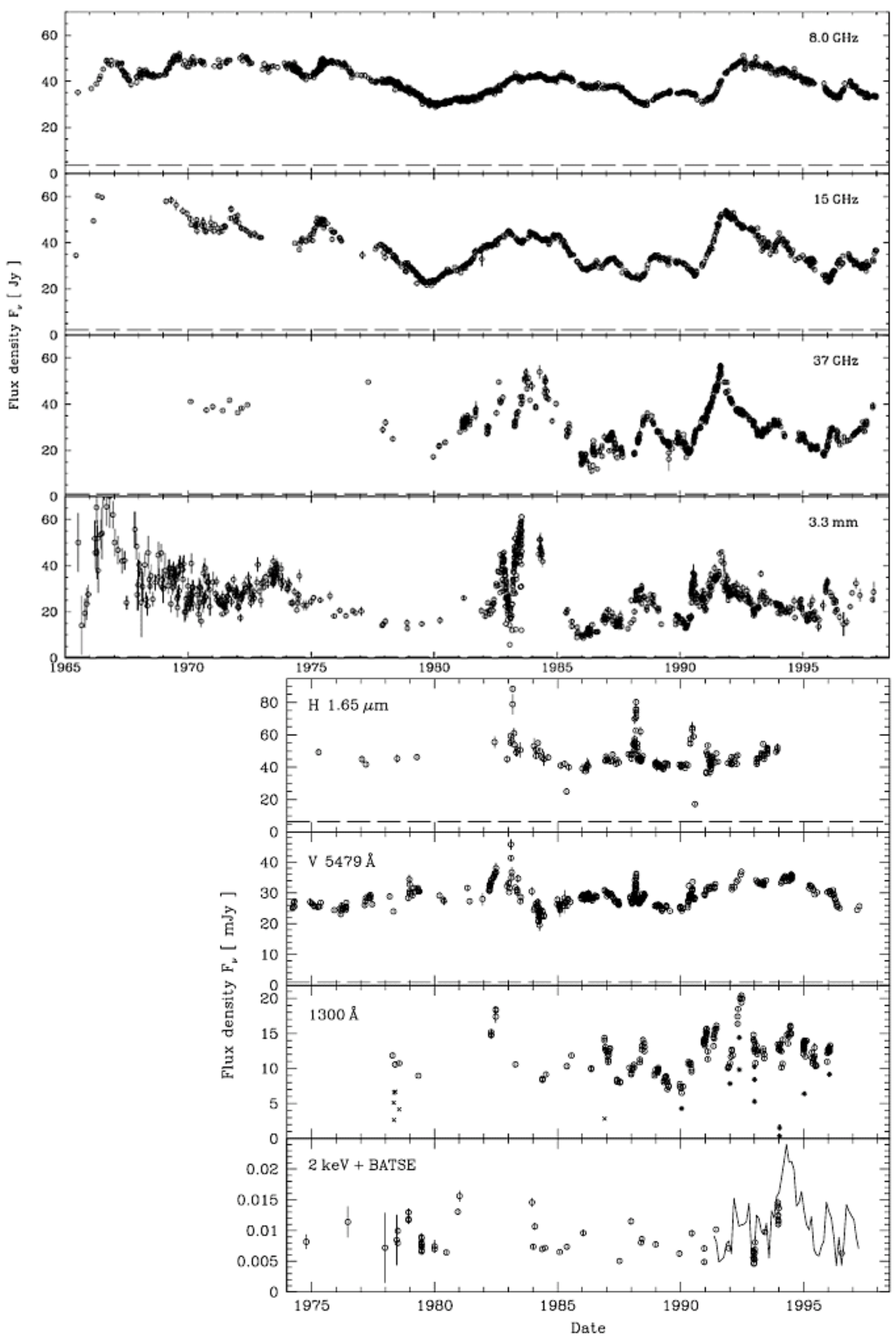
$z = \Delta\lambda/\lambda_{0,}$ then it follows that $d = cz/H_0 = \sim 470\ h_0^{-1}$ Mpc

$m - M = 5 \log(d/\text{Mpc}) + 25$

For B =13.1th magitude => $M_B = -23.3 + 5 \log(h_0^{-1})$

(The Milk Way is ~ -19.7 =>

3C273 is $2.512^{3.6} \sim 30$ times brighter)



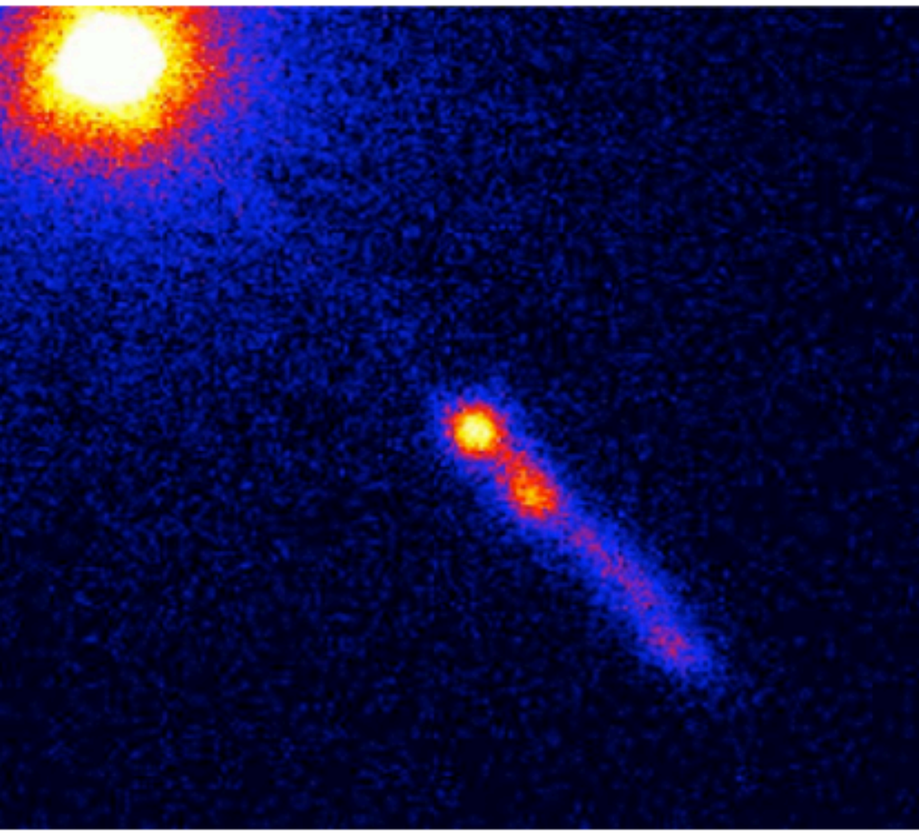
Quasar Variability

- Quasars are variable in every waveband and emission lines
- Variability time-scale can be days to months
- Hence size of emission regions is light-days to light-months (an object cannot vary in brightness faster than it takes light to cross the object).
- a variability of an hour implies a size of $l < c\Delta t \sim 7.2$ AU (less than Saturn's distance from the Sun)

Twinkle, twinkle, quasi-star,
Biggest puzzle from afar.
How unlike the other ones,
Brighter than a trillion Suns.
Twinkle, twinkle, quasi-star,
How I wonder what you are!

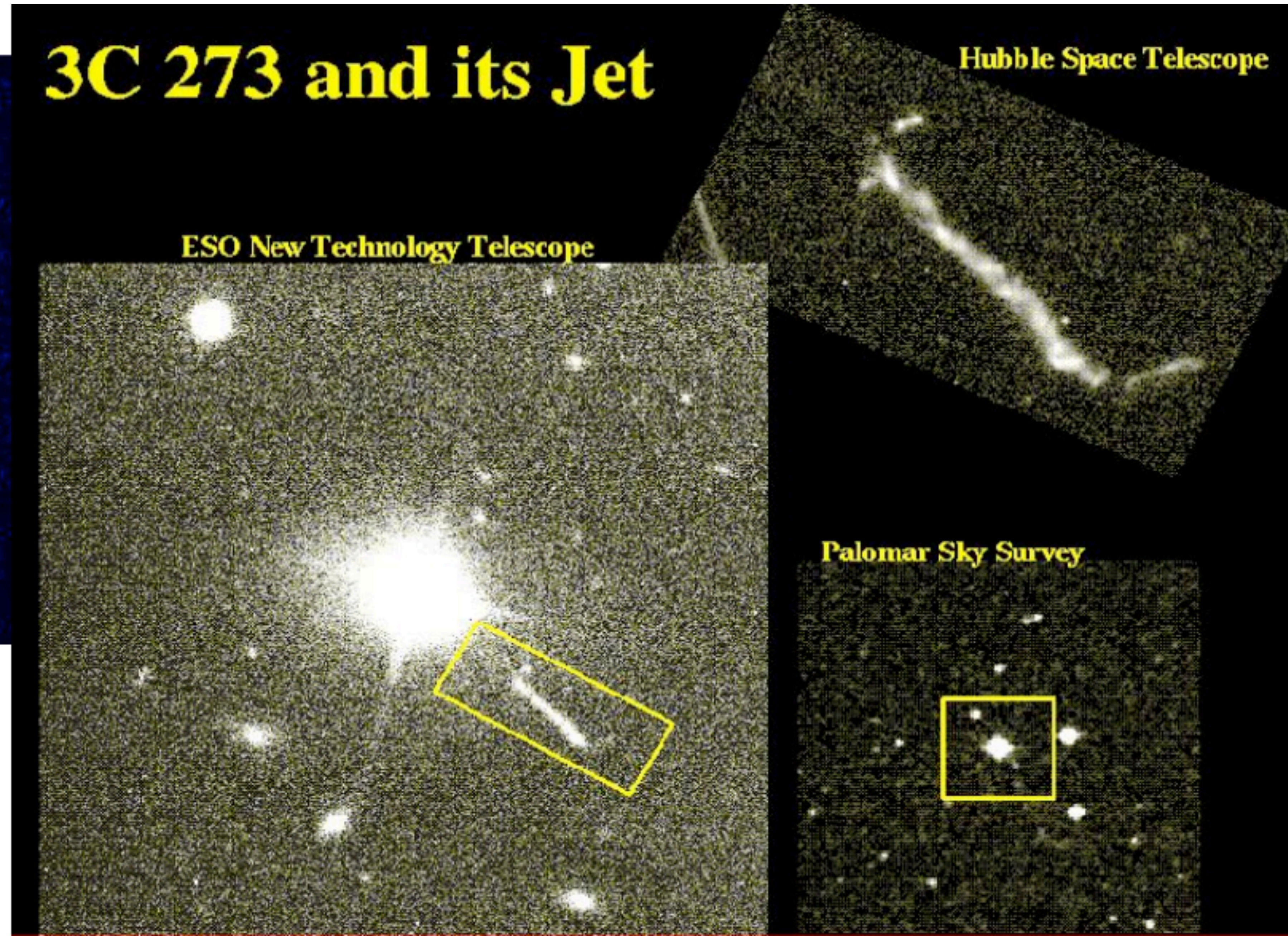
George Gamow

A more detailed view of the jet of the nearest quasar



X-ray image

(Chandra satellite)



AGN taxonomy: Quasars & QSOs

Quasar/QSR = Quasi Stellar Radio-source,
QSO = Quasi-Stellar Object

- Very luminous compact (10^{45}–10^{49} erg/s) centers of galaxies, which outshine their host (typical field galaxy 10^{44}erg/s)
- Highly variable across the electromagnetic spectrum
- Optical spectra similar to much fainter Seyfert 1 nuclei, with the exception that the narrow lines are generally weaker.

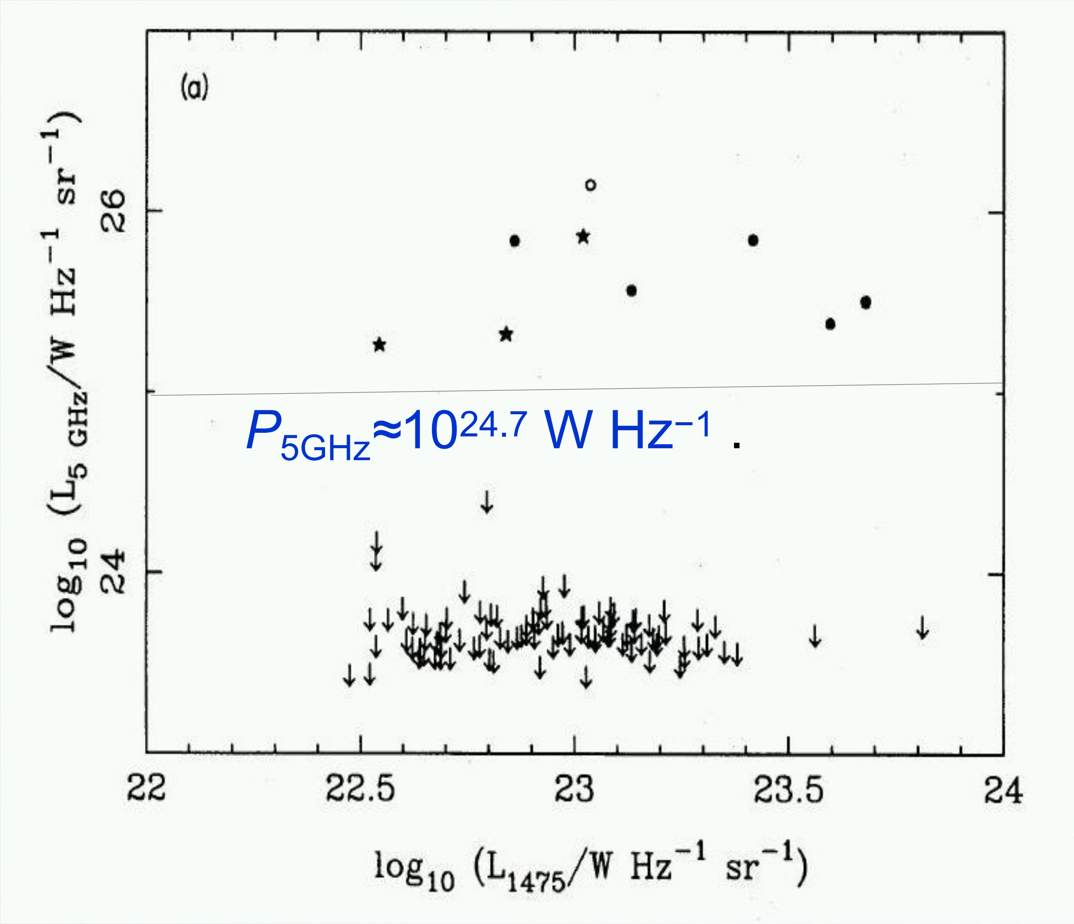
Two varieties:

- Radio-loud QSOs (Quasars or RL QSOs)
- Radio-quiet QSOs (or RQ QSOs)

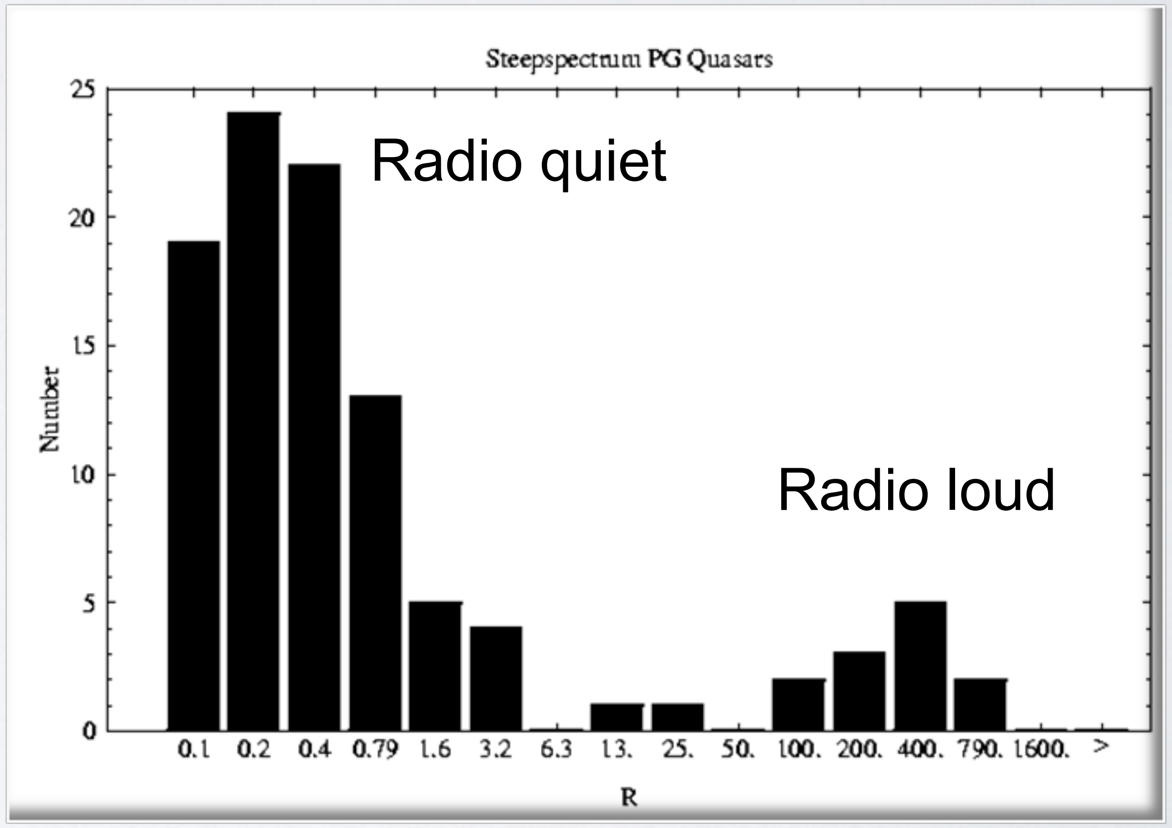
Transitions at $P_{5GHz} \approx 10^{24.7}$ W Hz^{-1} sr^{-1} / RL QSOs are 5−10% of the total of QSOs.

Quasars & QSOs

There is a large gap in radio power between RL and RQ varieties of QSOs (Kellerman et al. 1989, Miller et al. 1990)



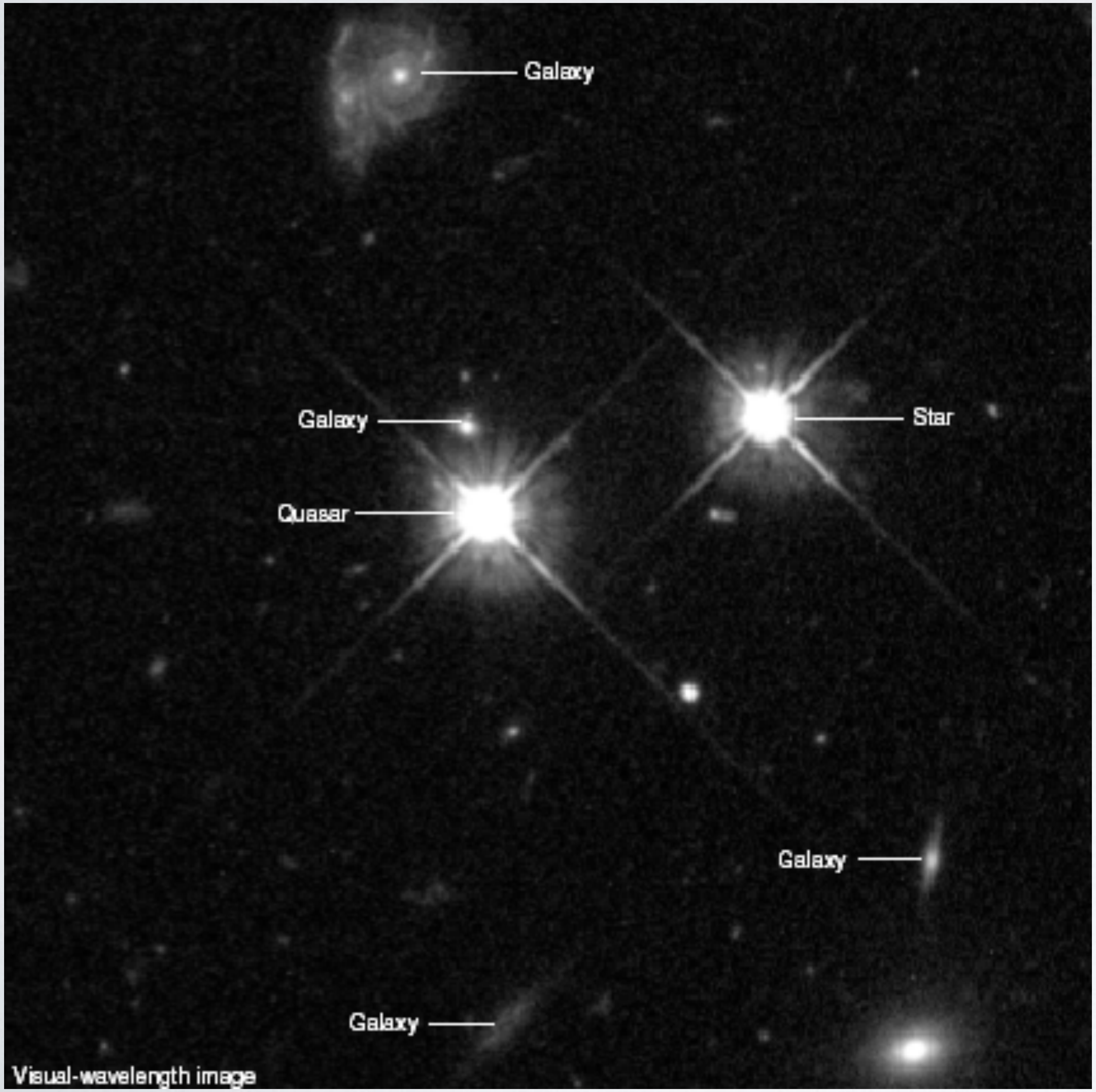
(Miller et al. 1990)



R=radio/optical flux

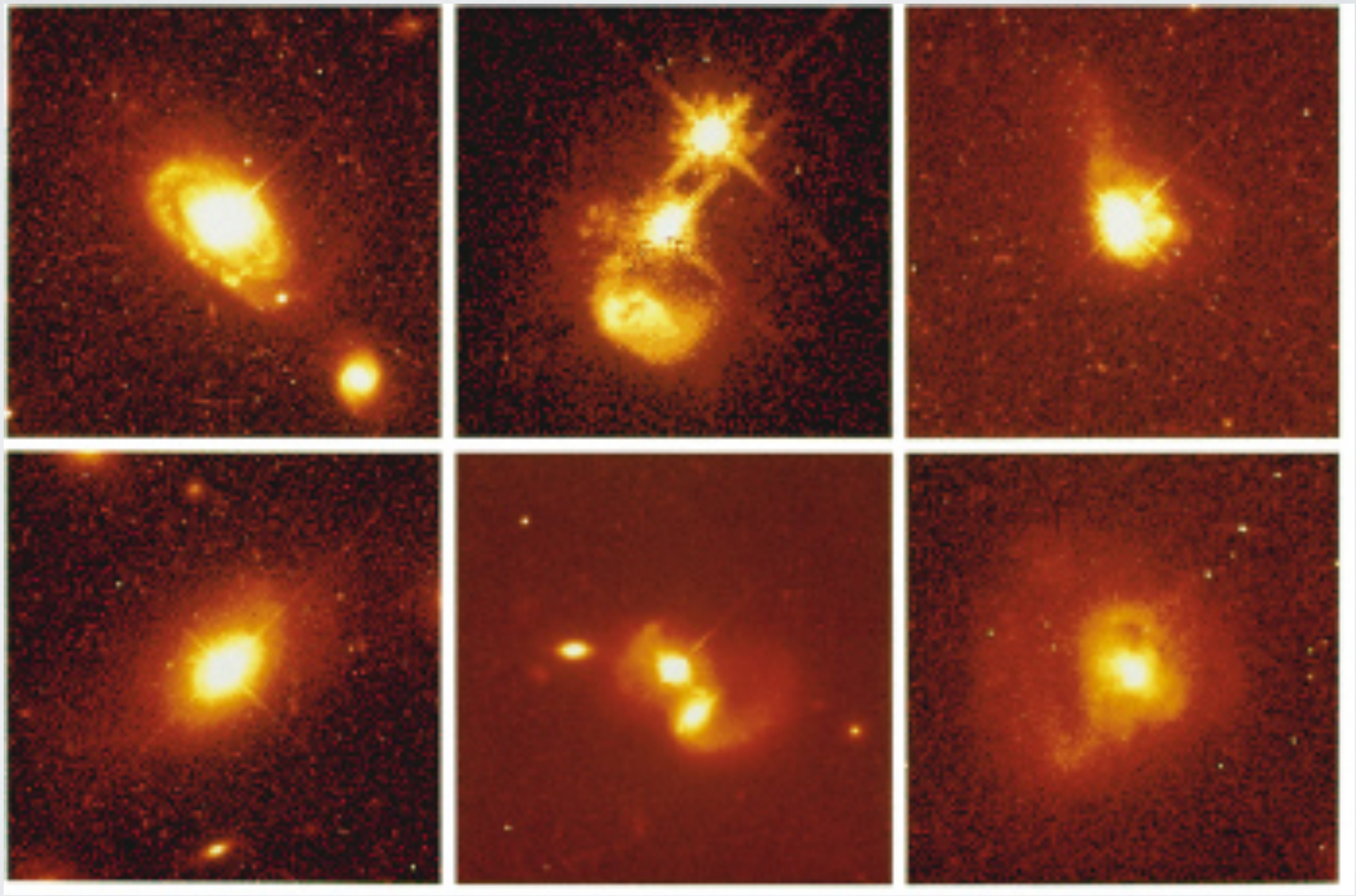
Falcke, Sherwood, Patnaik (1996)

Some examples of QSOs

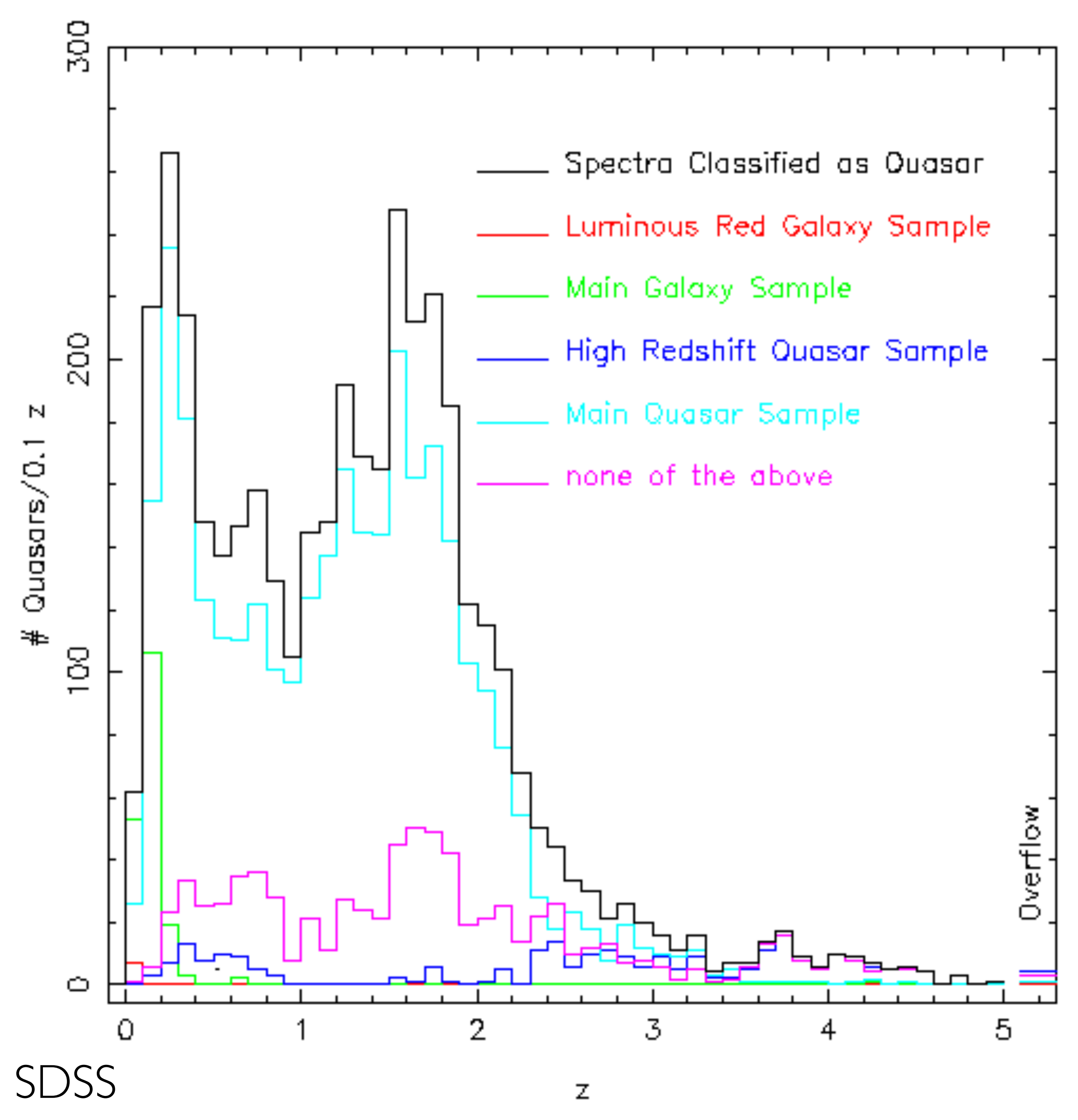


QSOs often outshine their host galaxies which can be difficult to detect!

Quasars host-galaxies often show interactions



Redshift Distribution of Quasars

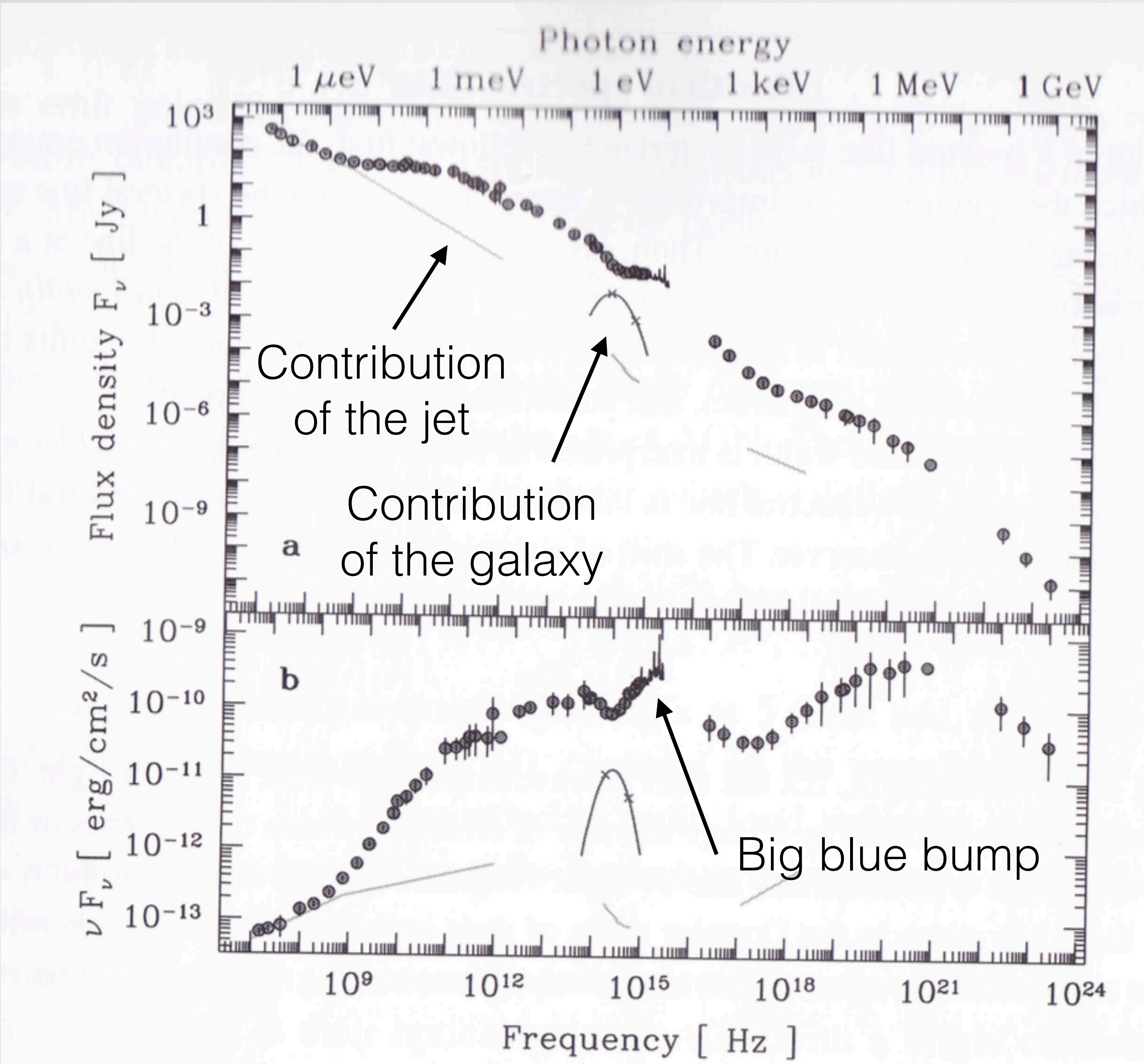


- The quasar redshift distribution seems to peak around z~2.

- This is not only a selection effect, but seems real, even after bias corrections.

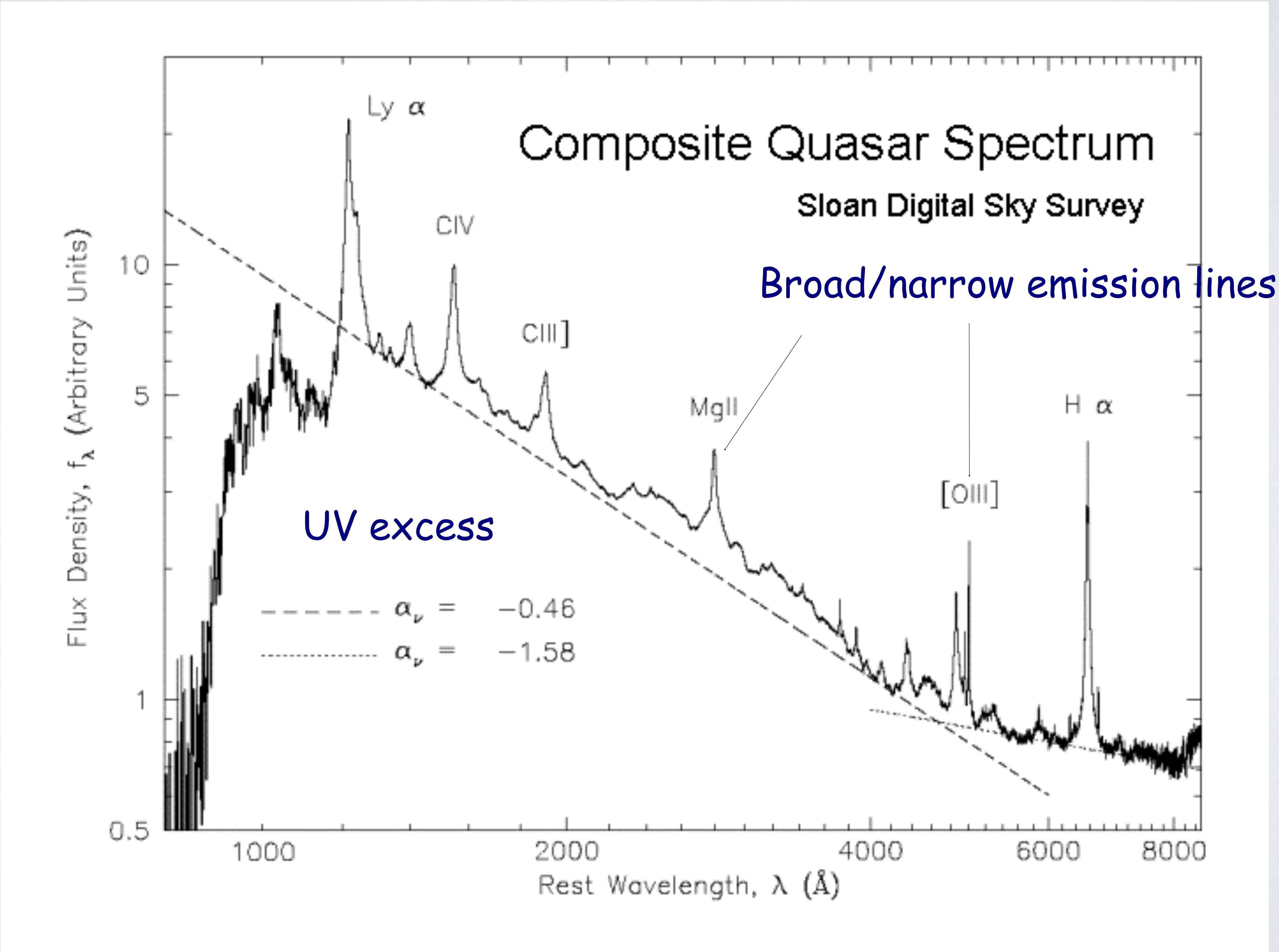
- This could be related to the formation of galaxies and LSS and the star-formation history.

Broad band spectral energy distribution of 3C273



- The flux of 3C273 per logarithmic interval is constant over more than 10 orders of magnitude in frequency!

Quasar Composite Optical/UV Spectrum



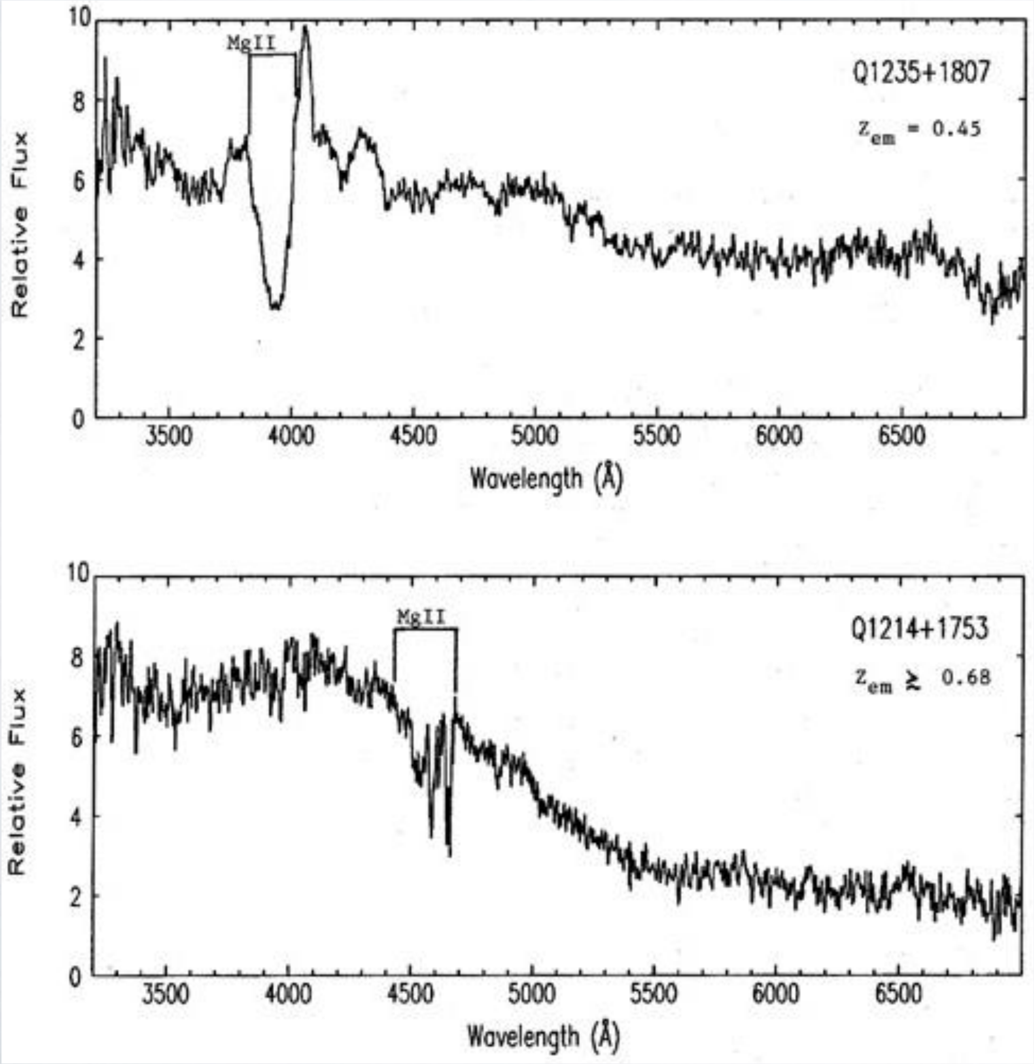
QUASARS

- Quasars are very luminous compact (10^{45}–10^{49} erg/s) centers of galaxies, which outshine their host (typical field galaxy 10^{44}erg/s)
- Highly variable across the electromagnetic spectrum
- Out of 10^4 known quasars only about 10% are radio loud

BAL QSO

BAL QSOs = Broad Absorption Line QSOs

Otherwise normal QSOs that show deep blue-shifted absorption lines corresponding to resonance lines of C IV, Si IV, N V.



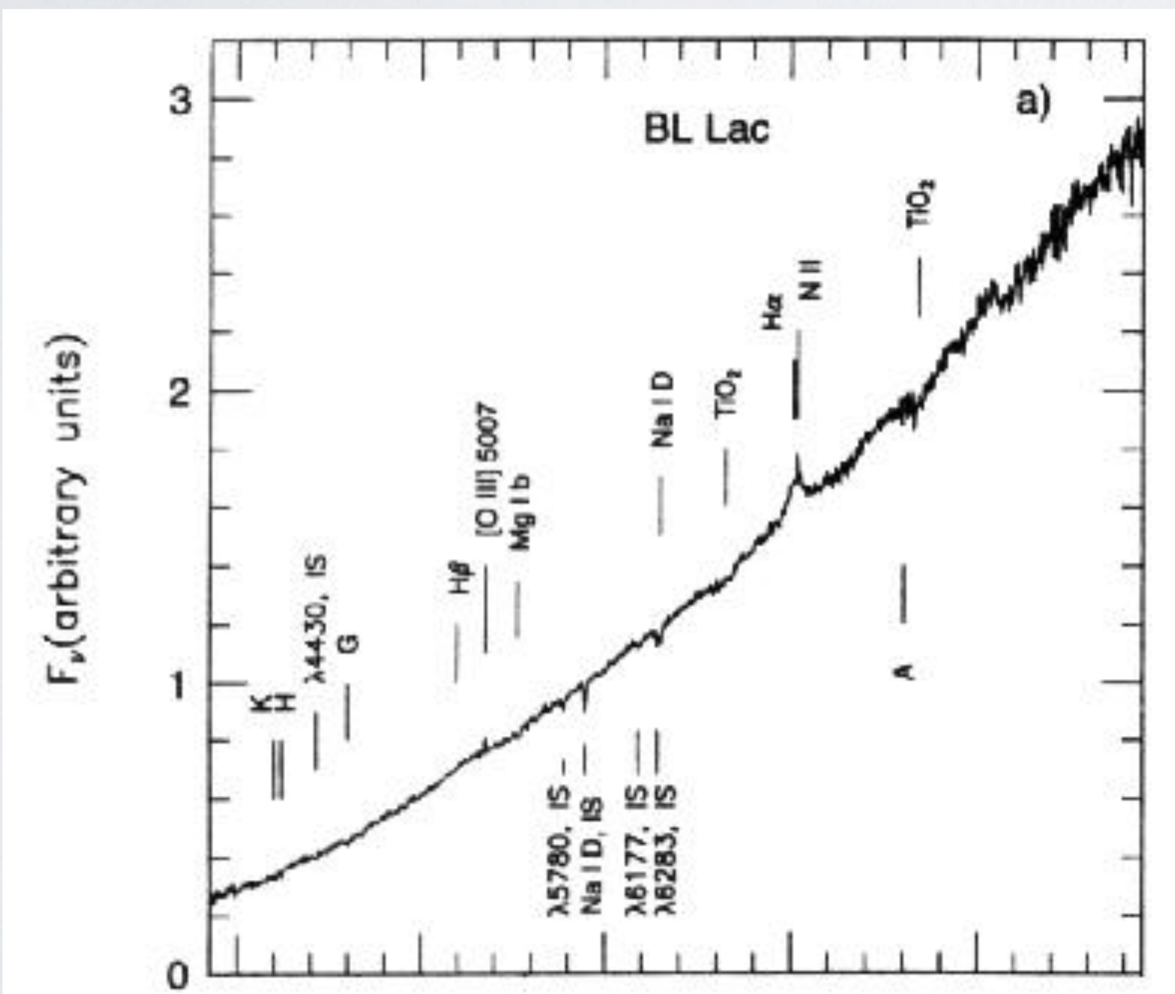
All of them are at $z \geq 1.5$ because the phenomenon is observed in the rest-frame UV. At these redshifts, they are about 10% of the observed population. BAL QSOs tend to be more polarized than non-BAL QSOs.

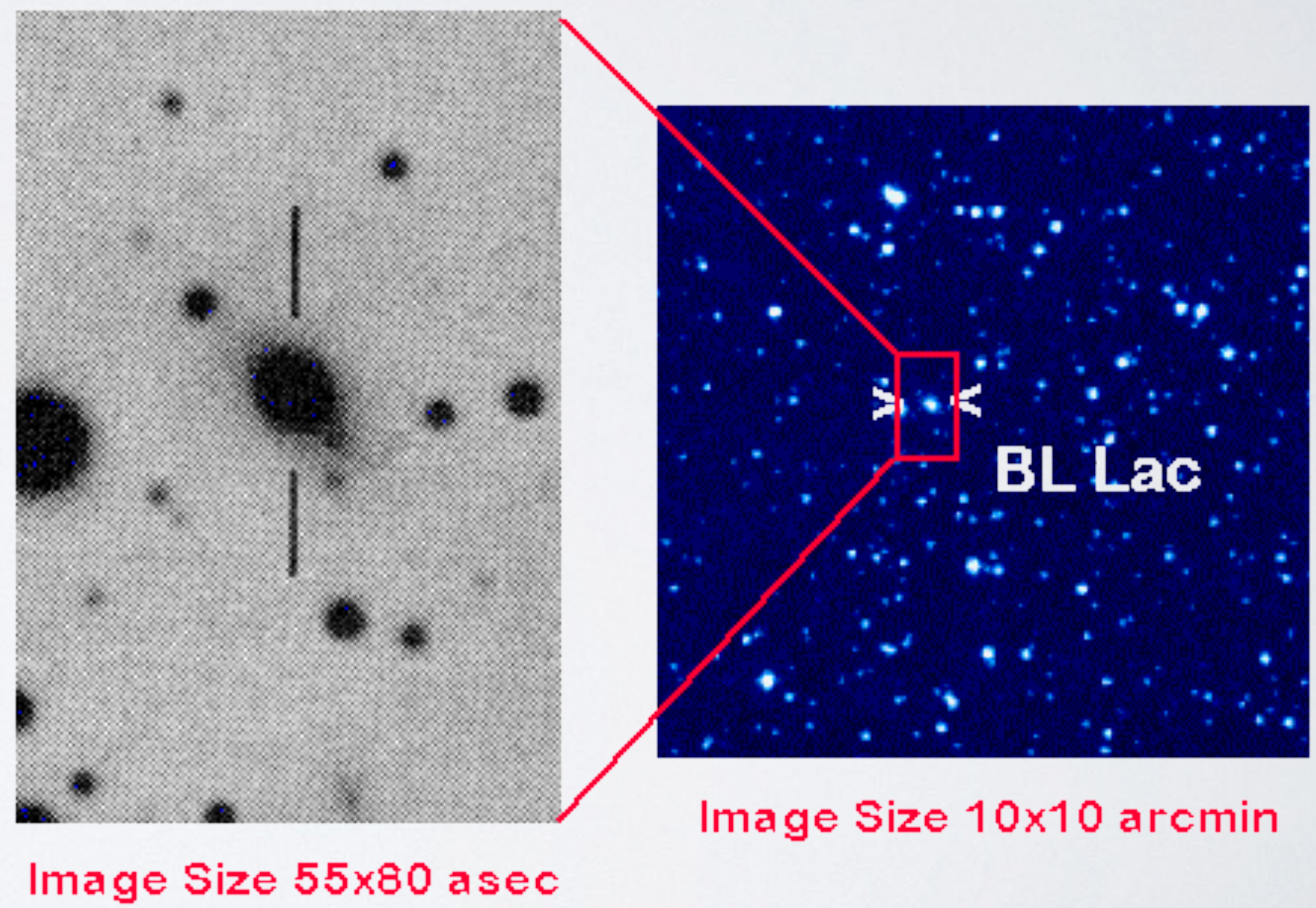
BL Lac objects and blazars

BL Lac: Is the prototype of its class, an object, stellar in appearance, with very weak emission lines and variable, intense and highly polarized continuum. The weak lines often just appear in the most quiescent stages.

Blazars: Encompass BL Lacs and optically violent-variable (OVV) QSOs. These are believed to be objects with a strong relativistically beamed jet in the line of sight. They exhibit the most rapid and largest amplitude variability.

AGN taxonomy: BL Lac





(Vermeulen et al. 1994)

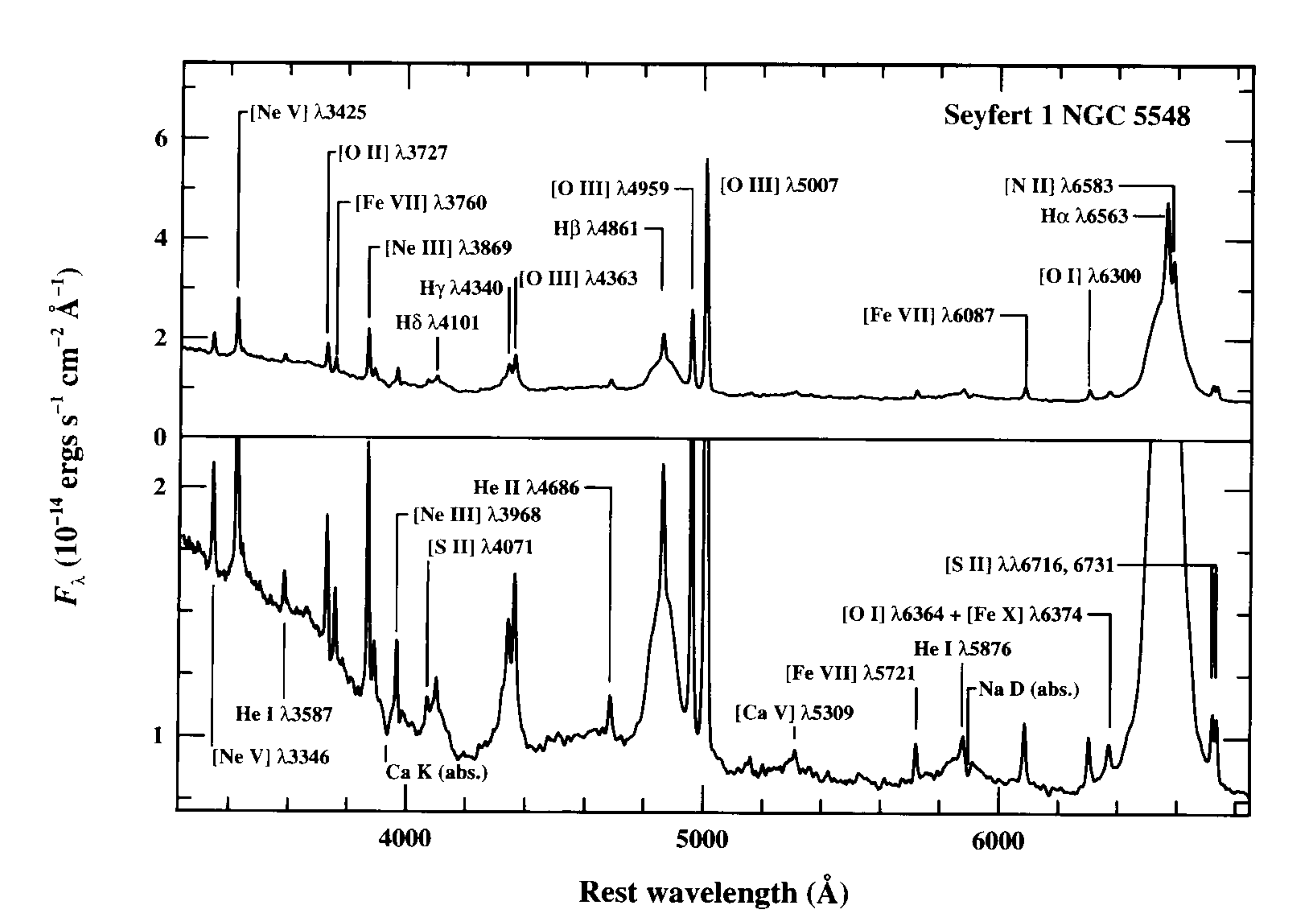
“Re-discovery” of Seyfert Galaxies

1943 – Seyfert finds multiple galaxies similar to NGC1068
(Hence since then they are called by his name)

1959 – Woltjer draws several important conclusions on Seyfert galaxies:

* Nuclei are unresolved (<100pc)
* Nuclear emission last for >10^8 years
  (1/100th spirals is a Seyfert and the Universe is 10^{10} yrs)
* Nuclear mass is very high if emission-line broadening is caused by bound material ($M \sim v^2 r/G \sim 10^{9\pm1}\ M_{sun}$)

Seyfert 1 spectrum



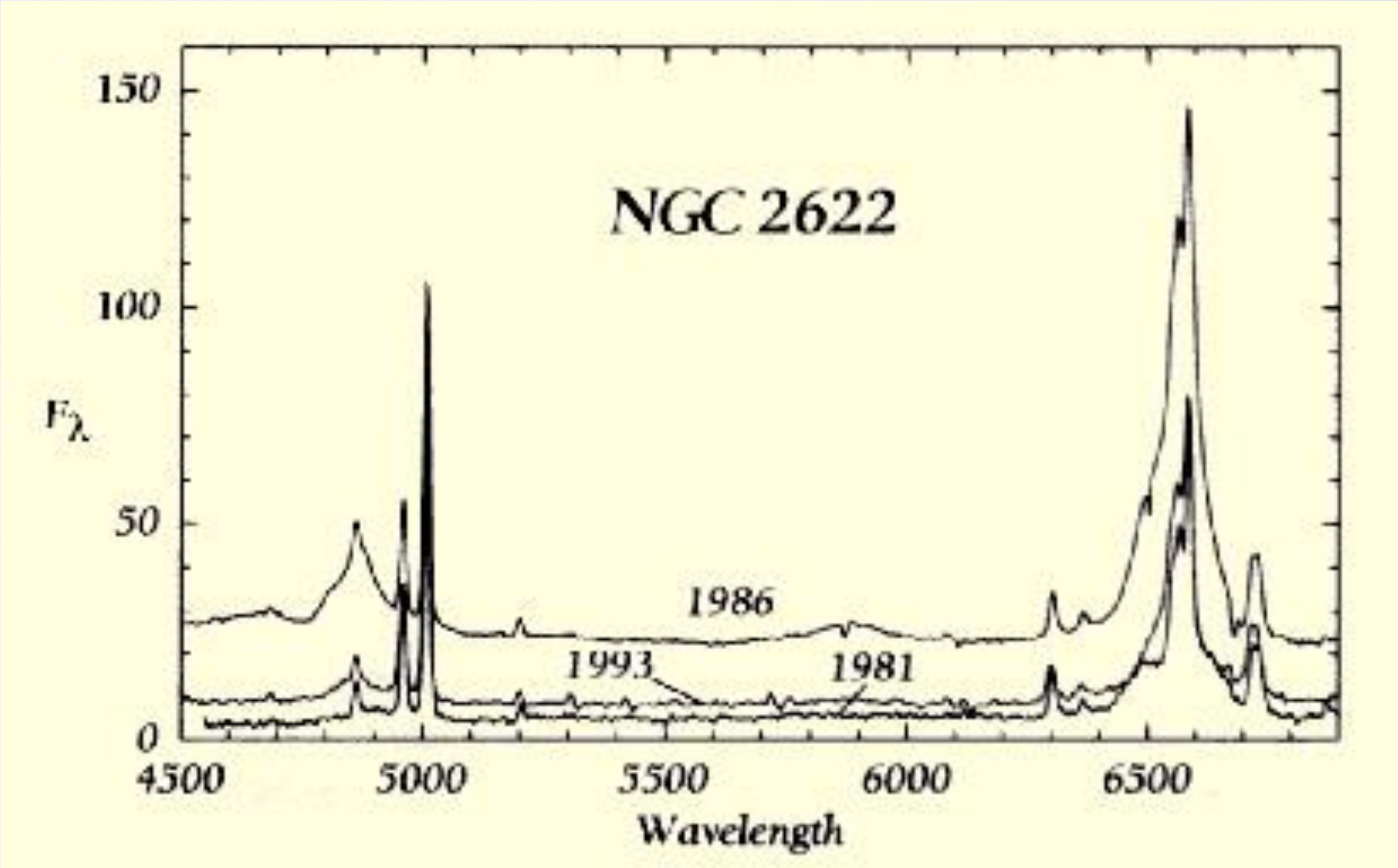
Classification of Seyfert galaxies

Classification based on the width of the optical emission lines

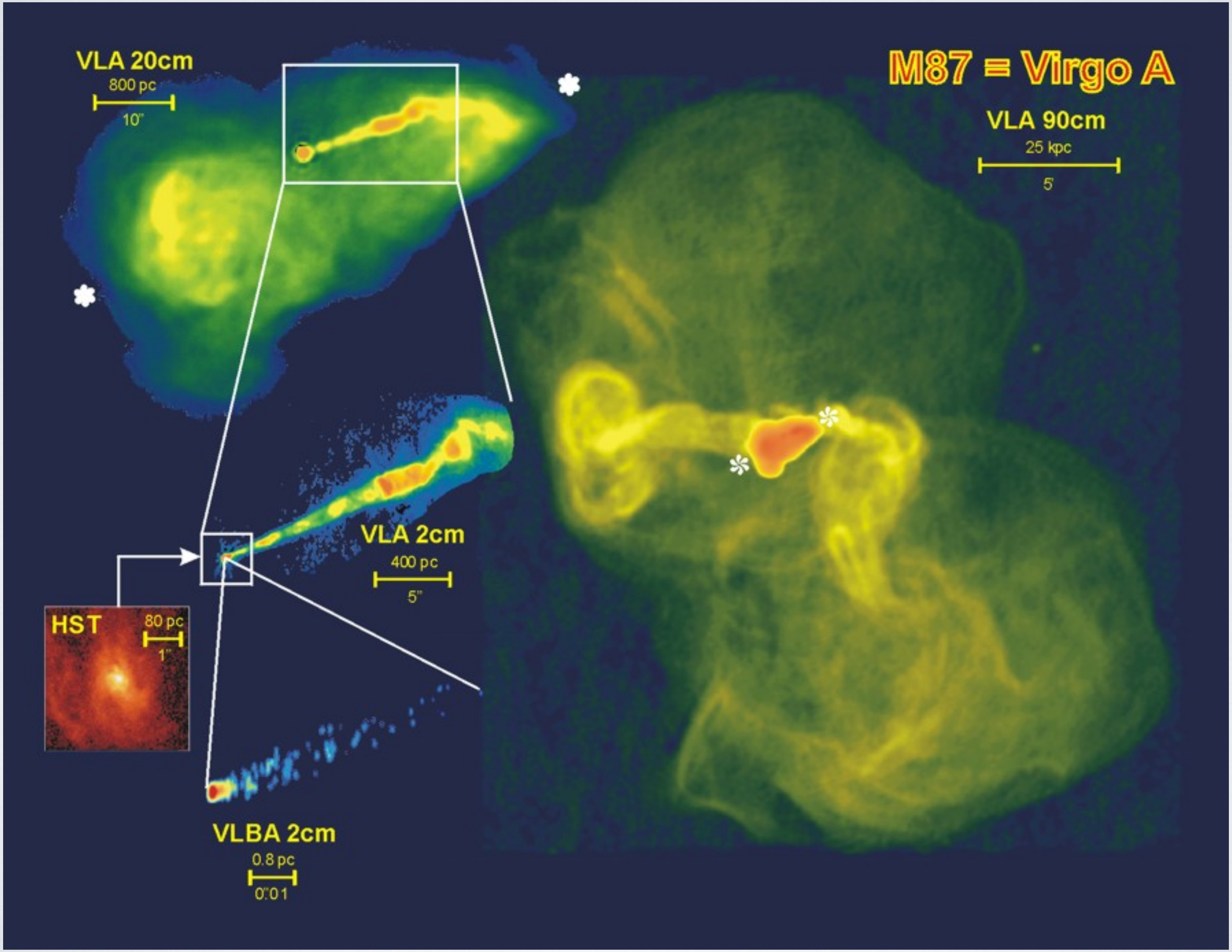
- Sy 1: broad permitted emission lines (Hα, He II, ...), of FWHM $\leq 10^4$ km s^{-1} that originate in a high-density medium ($n_e \geq 10^9$ cm^{-3})
- Sy 2: narrow forbidden emission lines ([OIII], [N II], ...) that originate in a low-density medium ($n_e \approx 10^3 - 10^6$ cm^{-3}) of FWHM $\leq$ few x 100 km s^{-1}
- Sy1.x (1.9, 1.8, ...): increase with the width Hα and Hβ lines.

AGN taxonomy: Seyfert galaxies

The classification for a single object can change with time, due to AGN variability!

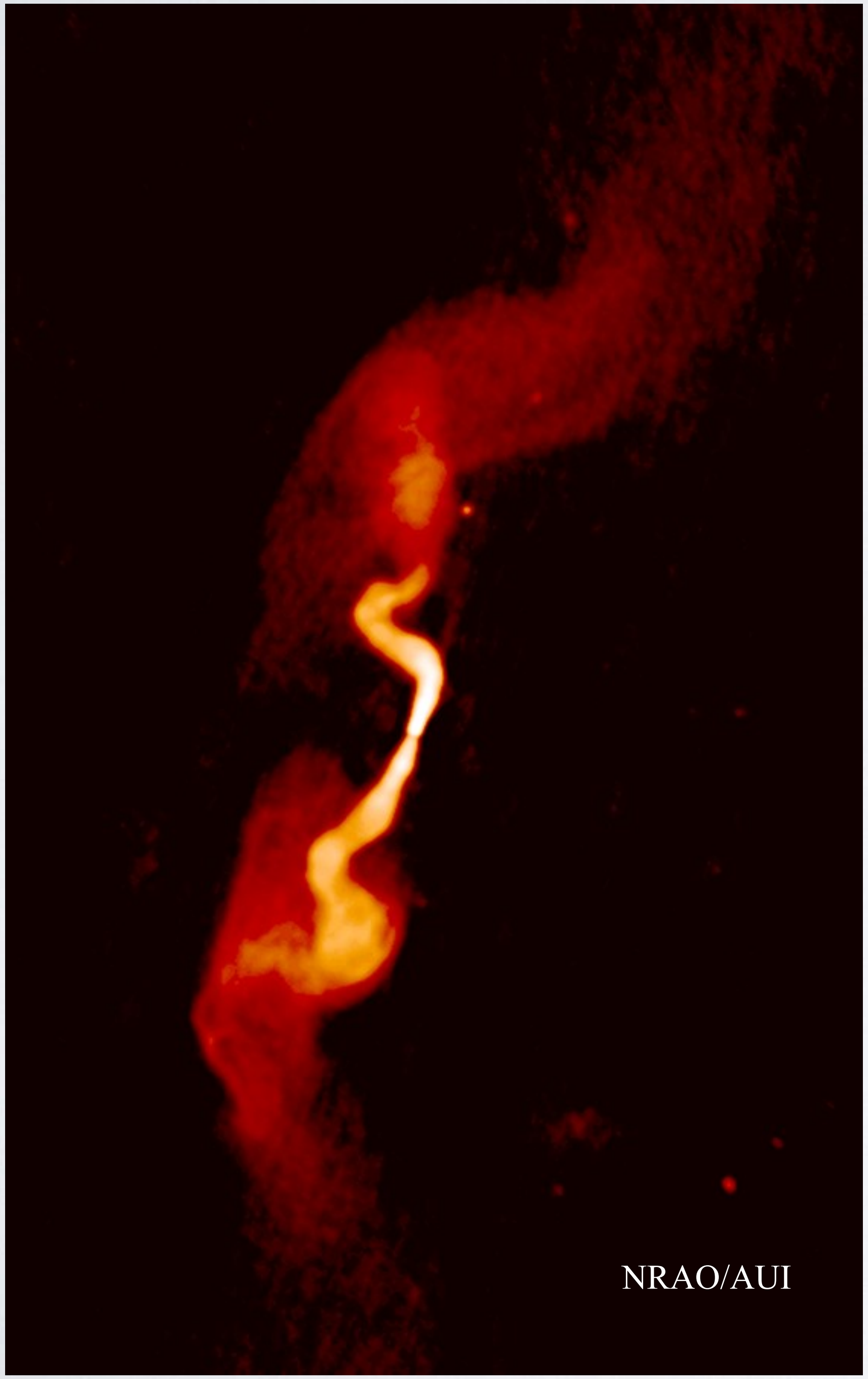


Radio-galaxies

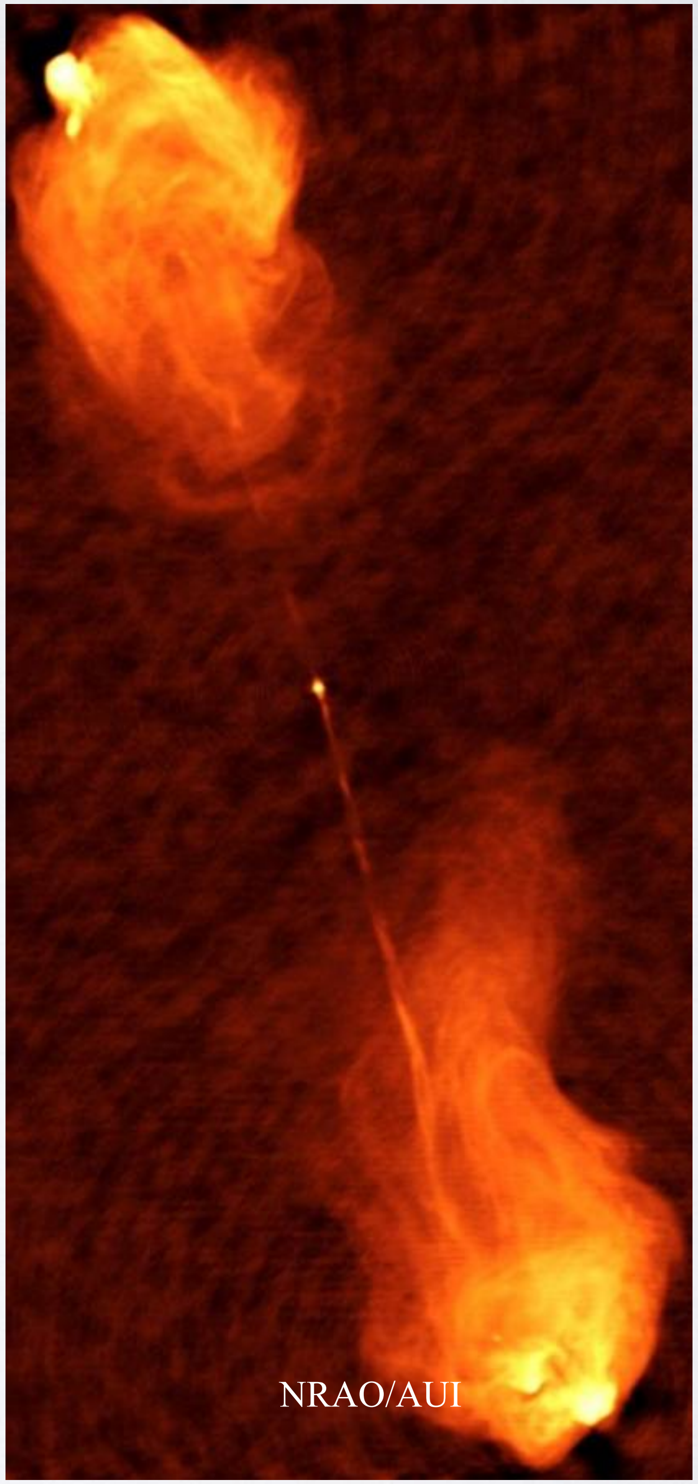


Classes of Radio-Galaxies

- FRI



- FRII



Classes of Radio-Galaxies

Large radio-galaxies with lobes can be divided in two types Fanaroff-Riley (1974):

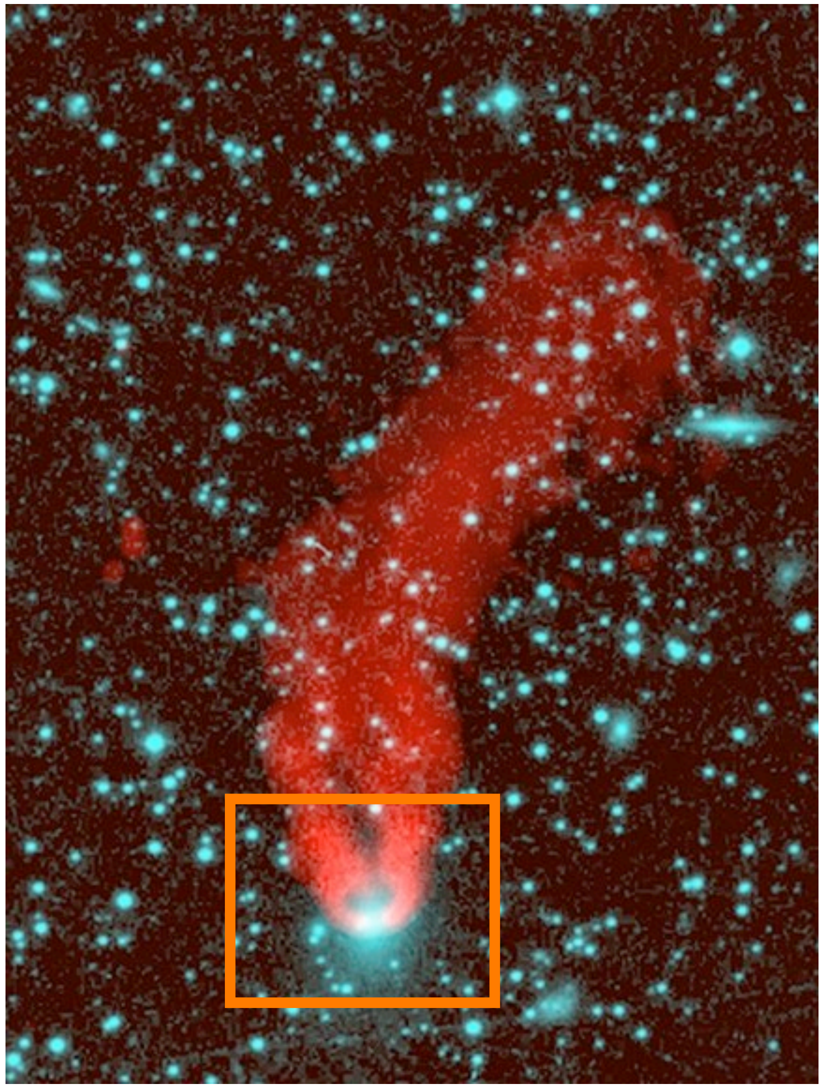
- FR-I
  - -Weaker radio sources that are bright in the center and fainter toward the edges (limb-darkened)
  - -smooth, continuous turbulent double-sided jets
  - -steepest spectrum emission in outer region

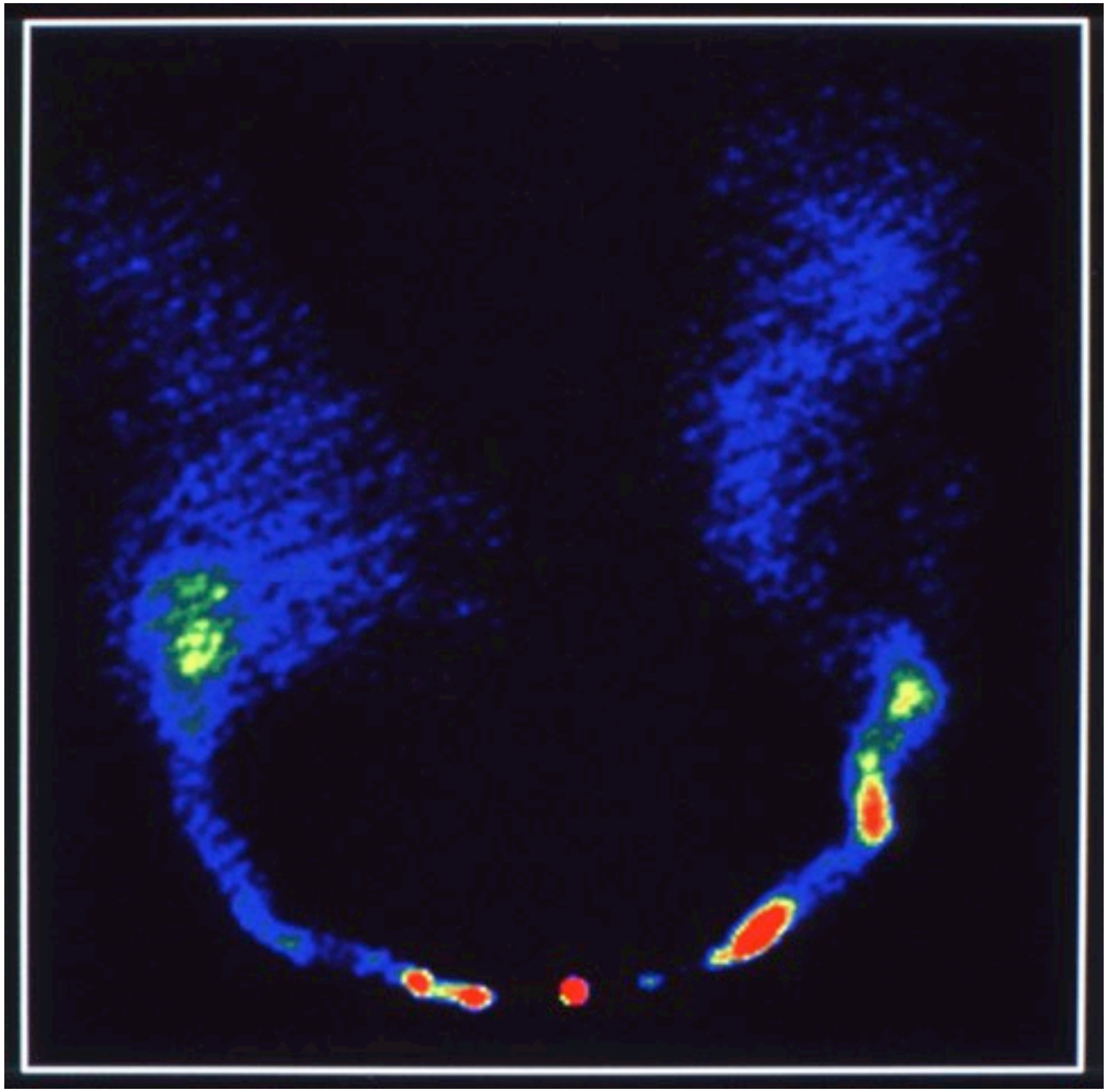
- FR-II
  - -Radio structure with a faint core and bright end-points (limb-brightened)
  - -steepest spectrum emission in inner region
  - -invariably have high luminosities, $P>10^{42}$ erg/s

Radio classification

- Morphological classification
  - Lobe dominated
    - ✳ FR I
    - ✳ FR II
      Jet-power - black hole spin(?), ISM/IGM/ICM density?
  - Core Dominated
    Doppler boosting and/or age
  - Peculiar
    - ✳ Tailed radio sources
      Interaction with ambient cluster medium
- Optical spectra
  - Narrow-line radio galaxies
  - Broad-line radio galaxies (Seyfert I and QSO)
  - Feature less (link to blazars)
    Observed properties dependent on viewing direction due to a torus of dust

3. Tailed radio sources: Morphology due to movement galaxy through (cluster) gas





Radio classification

- Morphological classification
  - Lobe dominated
    - ✳ FR I
    - ✳ FR II
      Jet-power - black hole spin(?)
  - Core Dominated
    Doppler boosting and/or age
  - Peculiar
    - ✳ Tailed radio sources
      Interaction with ambient cluster medium
- Optical spectra
  - Narrow-line radio galaxies
  - Broad-line radio galaxies (Seyfert I and QSO)
  - Feature less (link to blazars)
    Observed properties dependent on viewing direction due to a torus of dust

Some signs of AGN Activity

- Compact (~3pc) luminous centers
- Spectra with strong emission lines
- Strong Non-Thermal Emission
- Strong UV emission from a compact region in the center
- High Variability on time-scales of days to months
- Compact Radio Core
- Extended radio structures (jets, lobes, hot spots)
- Strongly Doppler-broadened emission lines
- X-ray, γ-ray and TeV-emission

(Not all AGN show each of these, but often several of them)

Summary Quasars, radio and Seyfert galaxies

- AGN show emission not easily attributable to stars
- AGN occur both in spirals and E/S0's (Seyferts/Quasars, distinguished mostly in the amount of energy emitted)
- AGN emit energy comparable or larger than all the stars in the host-galaxy, over a wide range of frequencies (including sometimes the radio).
- AGN show strong broad emission lines. Combined with the small emission region this indicates a high central concentration of mass.
- AGN are often highly variable (supporting the small region from which the emission emanates).
- AGN can show linear structures (jet/lobes/hotspots) in the radio of order ~Mpc

Summary Quasars, radio and Seyfert galaxies

Table 8.1 *The main properties of the most important types of AGN.*

Class	Host galaxy	Radio emission	Emission lines	Luminosity (erg s^{-1})
Blazar	E	Strong	Weak	10^{45}–10^{49}
Radio-loud quasar	E	Strong	Broad	10^{45}–10^{49}
Radio galaxy	E	Strong	Narrow	10^{43}–10^{45}
Radio-quiet quasar	S/E	Weak	Broad	10^{45}–10^{49}
Seyfert 1	S	Weak	Broad	10^{43}–10^{45}
Seyfert 2	S	Weak	Narrow	10^{43}–10^{45}

What powers AGN?

To produce $L=10^{45}$ erg/s by O stars, $8\text{x}10^5$ O stars would be required. Assuming an emitting region of $l=10^{-2}$ pc^{-3}, their density would have to be $1.6\text{x}10^{12}$ pc^{-3} (globular clusters 10^6 pc^{-3}) and an average separation would have to be 3800 R_{Sun}.

To produce this luminosity by supernovae would require 10^4 supernovae shining at their peak luminosity!

Arguments in Favour of SMBHs as the Engines of AGN

Theoretical arguments for SMBHs in AGN:

- Radiation pressure: Lower Limit on $M_{\bullet}$
- Radiation Efficiency of Accretion on BHs

Observational evidence for SMBH in Galaxies/AGN hosts:

- High central stellar velocity dispersions
- Megamaser disks
- Radial Velocities from Ionized Gas
- Radial velocities of stars within the spheres of influence of BHs
- Broad Iron (Fe) Kα lines (relativistic accretion disk)
- Sgr A* in the Galactic Center

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Radiation Pressure: BH mass limits

(Long-term) stability of the AGN gas requires that the gravitational force exceeds or equals the radiation pressure from the AGN:

$$F_{grav} > F_{rad}$$

Radiation Force on an electron

$$F_{\text{rad}} = \sigma_e \frac{L}{4\pi r^2 c} \hat{r}$$

Gravitational Force on electron plus proton pair (medium must be neutral)

$$F'_{\text{grav}} = -\frac{GM_\bullet (m_p + m_e)}{r^2} \hat{r}$$

Radiation Pressure: BH mass limits

Eddington Limit:

$$L \leq \frac{4\pi G c m_p}{\sigma_e} M_\bullet \approx 6.31\times10^4 M_\bullet \ \text{erg s}^{-1} \approx 1.26\times10^{38} (M_\bullet / M_{sun}) \ \text{erg s}^{-1}$$

This is known as the Eddington limit, which can be used to establish a minimum for the mass of the BH: $M_{\mathrm{E}} = 8\times10^5 L_{44} \, M_{\mathrm{sun}}$

For typical Seyfert galaxies $L \approx 10^{44}$ erg s^{-1} , so $M_{Sy} \approx 8 \times 10^5 \, M_{sun}$

QSOs $L \approx 10^{46}$ erg s^{-1} , so $M_{QSO} \approx 8 \times 10^7 \, M_{sun}$

The Eddington luminosity is the maximum luminosity emitted by a body of mass $M_\bullet$ that is powered by spherical accretion.

Radiation Pressure: BH mass limits

- Hence, the luminosity of an AGN sets a limit on its mass, independent from size/distance (both radiation pressure and gravity decrease as $1/r^2$)

- This does NOT imply a SMBH, but combined with an upper limits on the volume (e.g. from variability) it can limit alternatives (clusters of compact objects)

- With the Eddington mass $>10^8$ M_{sun} and the size constraints <1pc from variability one can derive a robust lower limit for the central mass density $\rho > 10^8$ M_{Sun} pc^{-3} (for comparison, the central star cluster in our Galaxy $\sim 4 \times 10^6$ M_{Sun} pc^{-3})

WHY BLACK HOLE?

- With the Eddington mass $>10^8\ M_{sun}$ and the size constraints <1pc from variability one can derive a robust lower limit for the central mass density

  $$\rho > 10^8\ M_{sun}\ pc^{-3}$$

- For comparison remember that
  - in our vicinity there are only a few stars within a parsec distance.
  - the central star cluster in our Galaxy has "only" $\sim 4\times10^6\ M_{sun}\ pc^{-3}$
- It was then suggested that the activity in the active nuclei was produced by a accreting black holes.
- NB: The term ``black hole'' was invented by John Wheeler in 1967 well after the concept was invented.

WHAT IS A BLACK HOLE

- A black hole is a concentration of mass so large, that even light cannot escape its gravitational attraction
- A black hole has only two parameters (we ignore charge):
  - the mass $M_{\rm bh}$ and
  - the spin $0 \leq a \leq 1$
- A non-rotating black hole (a=0) is called a Schwarzschild hole
- A rotating black hole ($0 < a \leq 1$) is called a Kerr hole

SCHWARZSCHILD RADIUS ET AL.

- Equating kinetic and potential energy in a gravitating system yields:

$$\frac{1}{2}mv^2 = \frac{GM_\bullet m}{R_S} \overset{v=c}{\Rightarrow} R_S = 2\frac{GM_\bullet}{c^2}$$

- This is called the Schwarzschild radius and defines the event horizon in the Schwarzschild metric (non-rotating black hole).
  - For the mass of the Earth R_S=1 cm.
  - For a quasar with $M_\bullet$=100 Million M_{sun} we have R_S= 2 AU.
- For maximally rotating black hole (a=1) the event horizon is R_g=0.5 R_S

Arguments in Favour of SMBHs as the Engines of AGN

Theoretical arguments for SMBHs in AGN:

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Observational evidence for SMBH in Galaxies/AGN hosts:

- High central stellar velocity dispersions
- Megamaser disks
- Radial Velocities from Ionized Gas
- Broad Iron (Fe) Kα lines (relativistic accretion disk)
- Sgr A* in the Galactic Center

BLACK HOLES AS THE BRIGHTEST REGIONS IN THE UNIVERSE

- Consider a particle falling from infinity onto an object of mass M. When it is stopped at radius r, its energy is radiated away. When mass dm is accreted in time dt, the mass accretion generates a power:

$$L = \dot{U} = G\frac{M}{r}\frac{dm}{dt} = GM\frac{\dot{M}}{r}$$

where we call M-dot the mass accretion rate.

BLACK HOLES AS THE BRIGHTEST REGIONS IN THE UNIVERSE

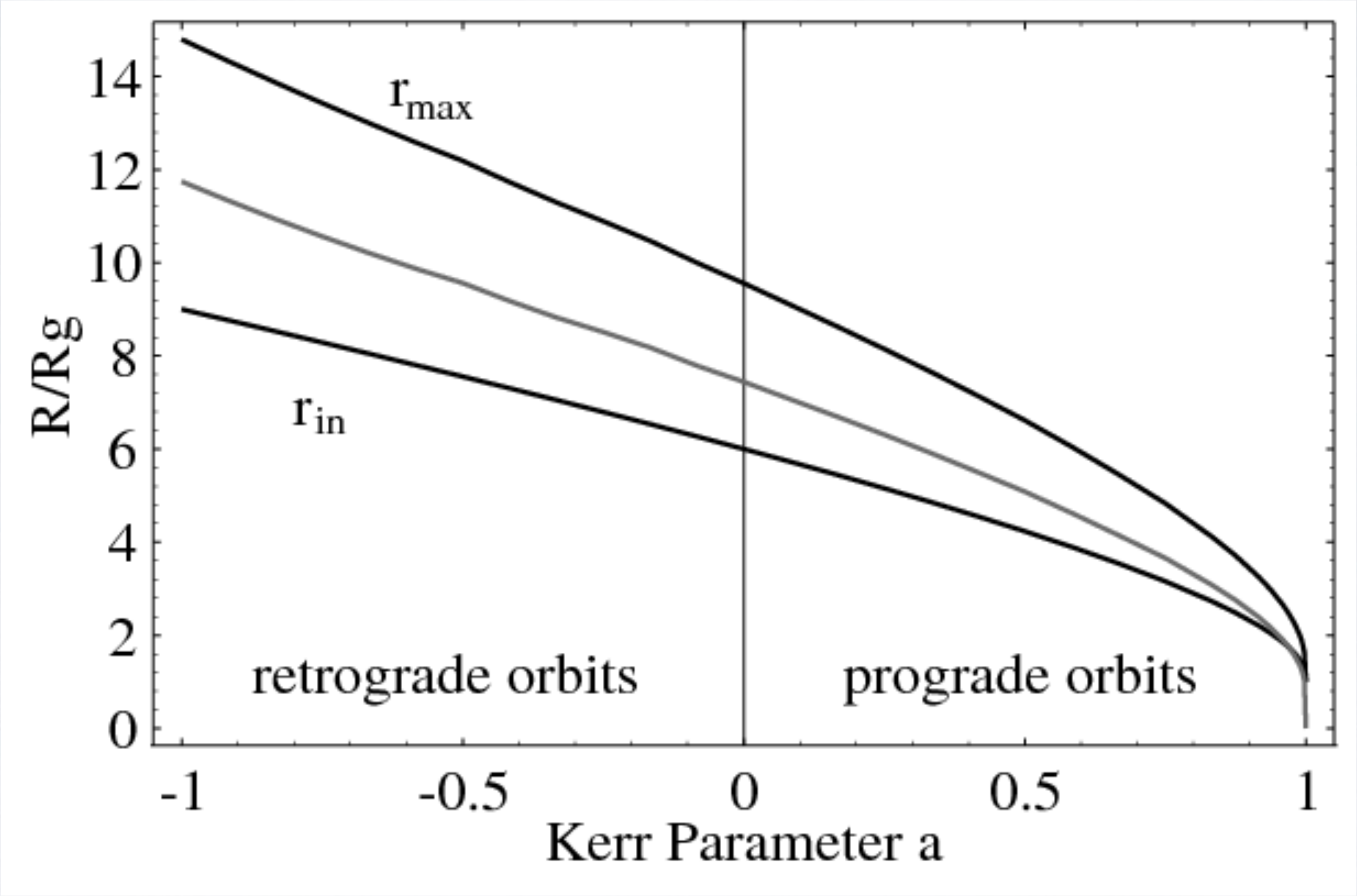
- The characteristic scale of the emitting region is a few gravitational radii, $r \sim r_{in} R_g$ ($R_g = GM/c^2$)

$$L = \frac{G M \dot{M}}{1} \frac{c^2}{r_{in} GM} = \eta \dot{M} c^2$$

- where $\eta = 1/r_{in}$

- Therefore, for energy dissipation near the black hole with, e.g., $r_{in}=10$ (means $10R_g$) we will have $\eta=0.1$ and hence a 10% efficiency in converting rest mass into energy

INNER DISK RADII



- The top line gives the radius of maximal energy dissipation
- The bottom line gives the location of the marginally stable radius, i.e. the inner disk radius
- Values plotted as function of angular momentum *a*

BLACK HOLES AS THE BRIGHTEST REGIONS IN THE UNIVERSE

- The efficiency η will depend on the spin (a) of the black hole:
  - for a=0 (Schwarzschild) we have η =6% and for a=1 (extreme Kerr) we have η =40%!
  - Note that for nuclear fusion we only have η =0.7%.
- For $L_{QSO}=10^{46}$ erg/sec and η =10% we have $Mdot = 2M_{Sun}\ yr^{-1}$
- The Eddington accretion rate also depends on the type of accretion:
  - Spherical accretion: Eddington limit is strictly valid only for this type
  - ADAF (Advection Dominated Accretion Flow): Quasi-spherical accretion where energy is not radiated away, but carried into the black hole (η <<0.1)
  - Disk accretion: much of the radiation escapes along rotation axis. However, strong radiation can induce a disk-wind which becomes significant near the Eddington limit.
- =>At least for very luminous AGN, the Eddington limit is robust.

Arguments in Favour of SMBHs as the Engines of AGN

Theoretical arguments for SMBHs in AGN:

- Radiation pressure: Lower Limit on $M_{\bullet}$
- Radiation Efficiency of Accretion on BHs

Observational evidence for SMBH in Galaxies/AGN hosts:

- High central stellar velocity dispersions
- Megamaser disks
- Radial Velocities from Ionized Gas
- Broad Iron (Fe) Kα lines (relativistic accretion disk)
- Sgr A* in the Galactic Center

M31 – Andromeda: Stellar Kinematics

Sphere of influence of a black hole (gravitational potential of SMBH larger than that of the surrounding stars):

$$R_{\rm infl} \sim \frac{GM_{\rm BH}}{\sigma_*^2} \sim 11.2\,{\rm pc}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{\sigma_*}{200\,{\rm kms}^{-1}}\right)^{-2},$$

- Velocity dispersion increases to 250 km/s toward center
- Radial velocities increase to 200 km/s before passing through center
- Kormendy (1988) derived a mass of about $10^7\ M_{sun}$

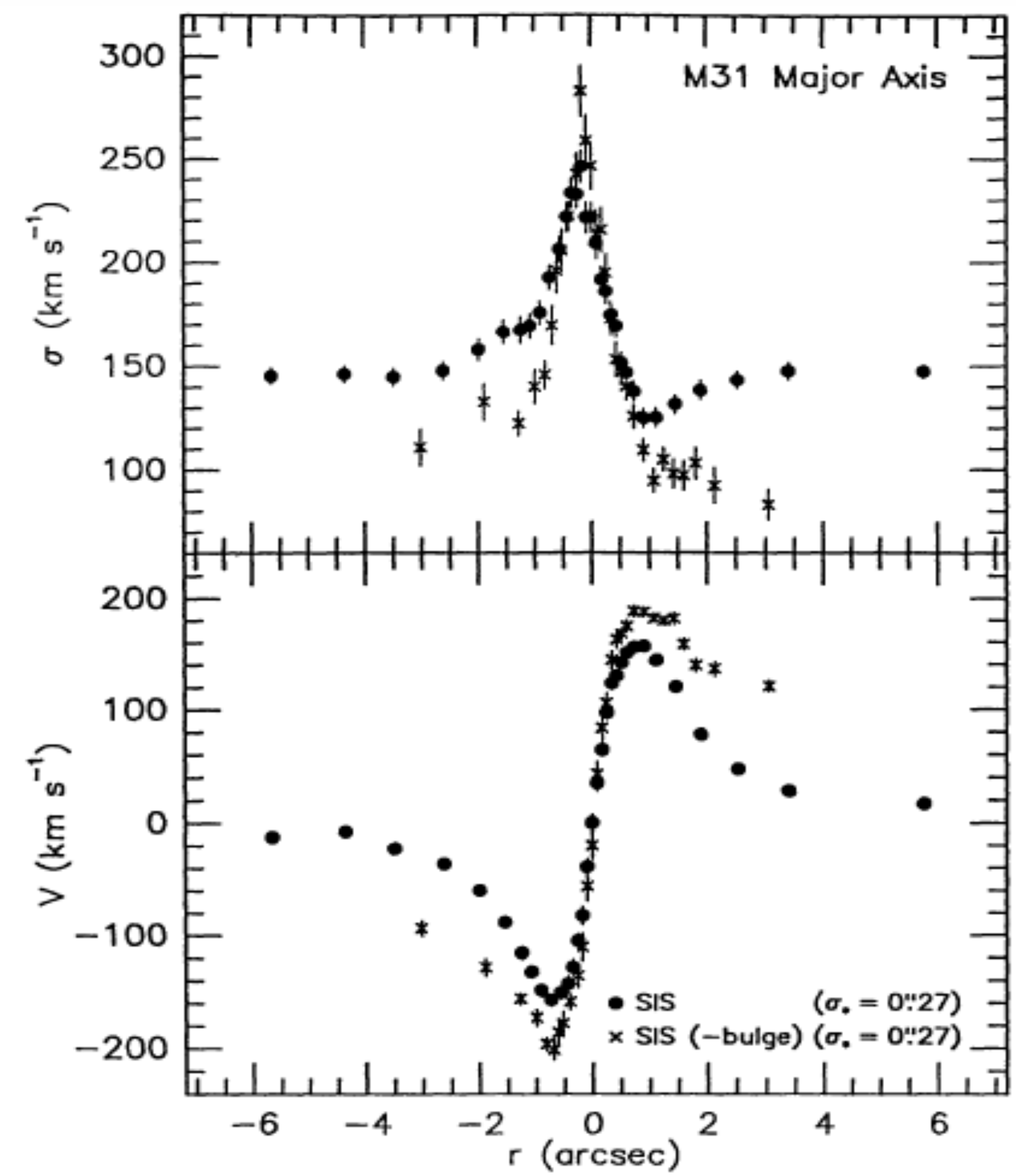
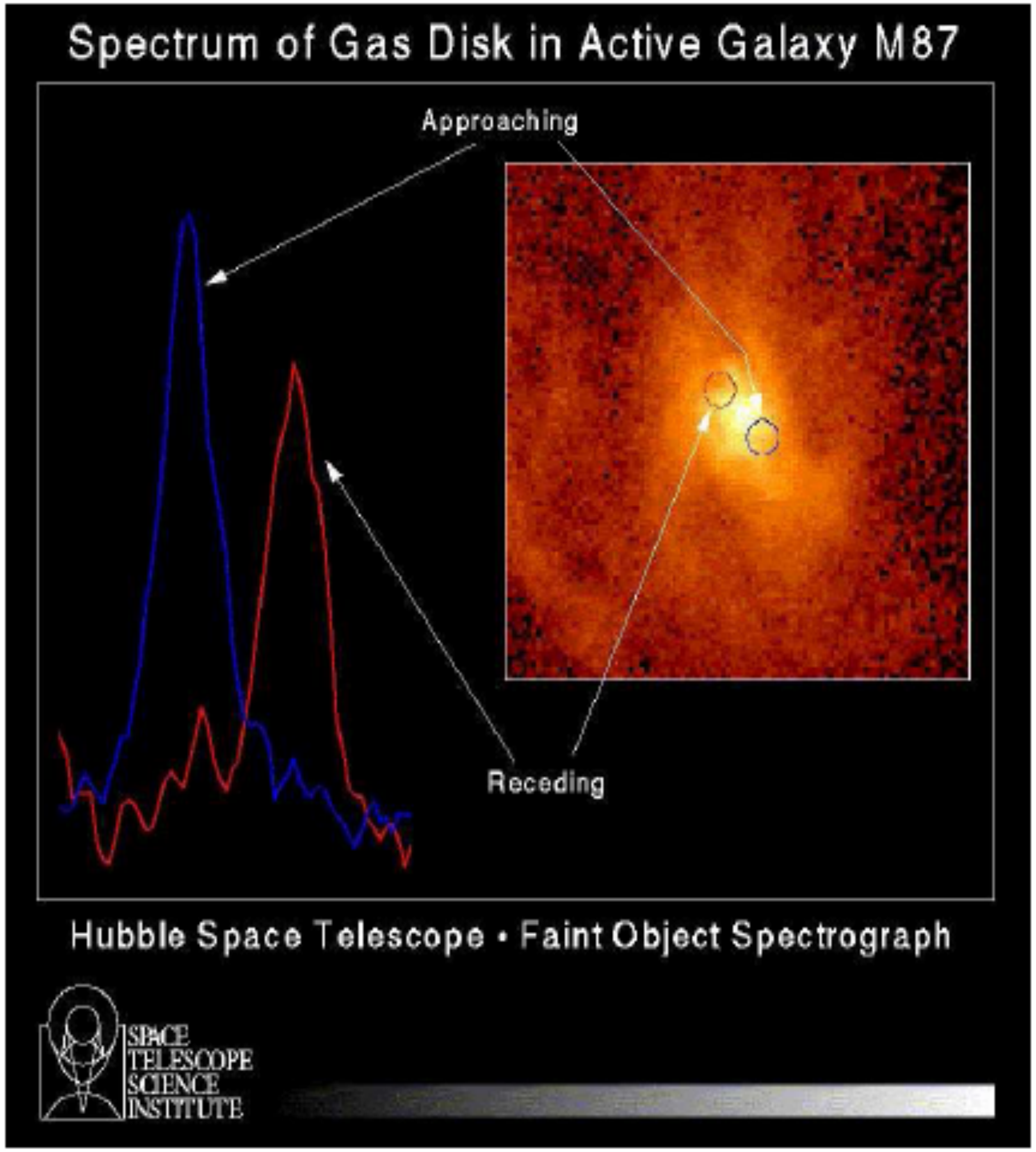


Figure 1. Velocity $V(r)$ (bottom) and velocity dispersion $\sigma(r)$ (top) profiles along the nucleus major axis of M31. (Taken from Kormendy and Richstone 1995).

M87 (Massive Elliptical): Gas Kinematics

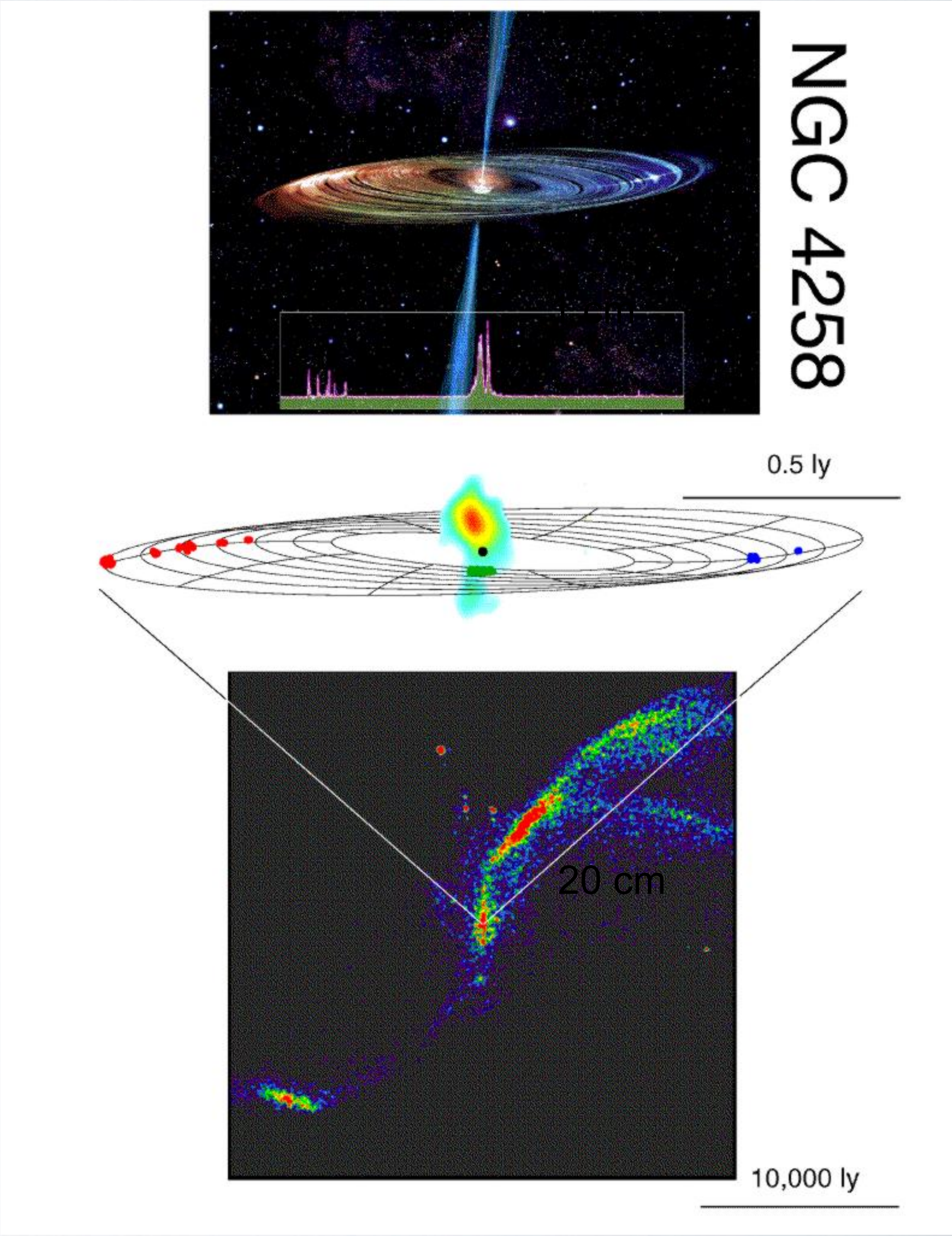
- Radial velocity measurements using spectroscopy of emission lines of ionized gas
- Ford et al. conclude a mass of $2.4 \times 10^9\ M_{sun}$ within the inner 18 parsecs of the nucleus



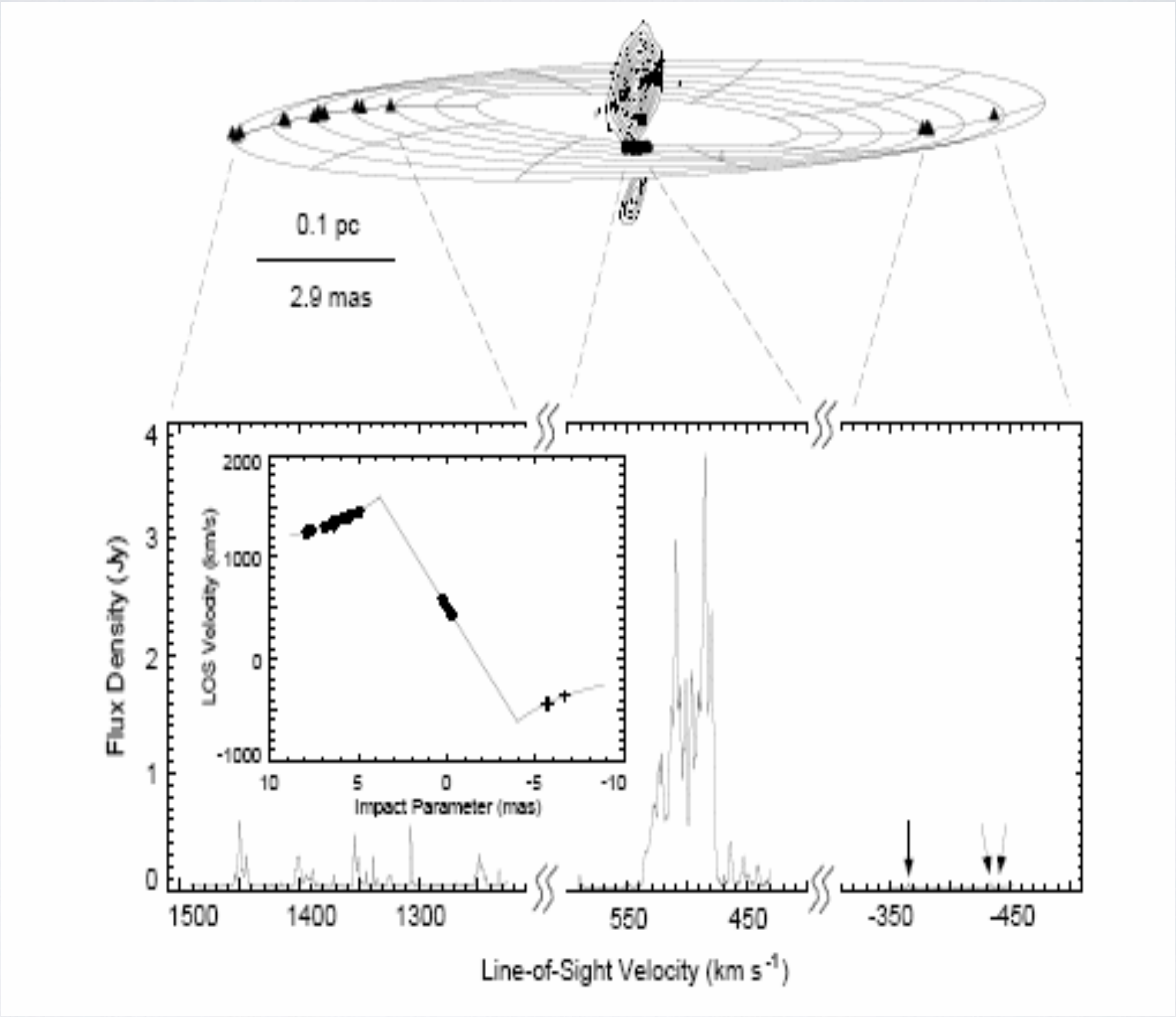
NGC 4258: Megamasers

H_2O megamaser @ 22 GHz detected in NGC 4258 in a warped annulus of 0.14 − 0.28 pc and less than 10^{15} cm of thickness, with a beaming angle of 11° (Miyoshi et al. 1995, Maloney 2002).

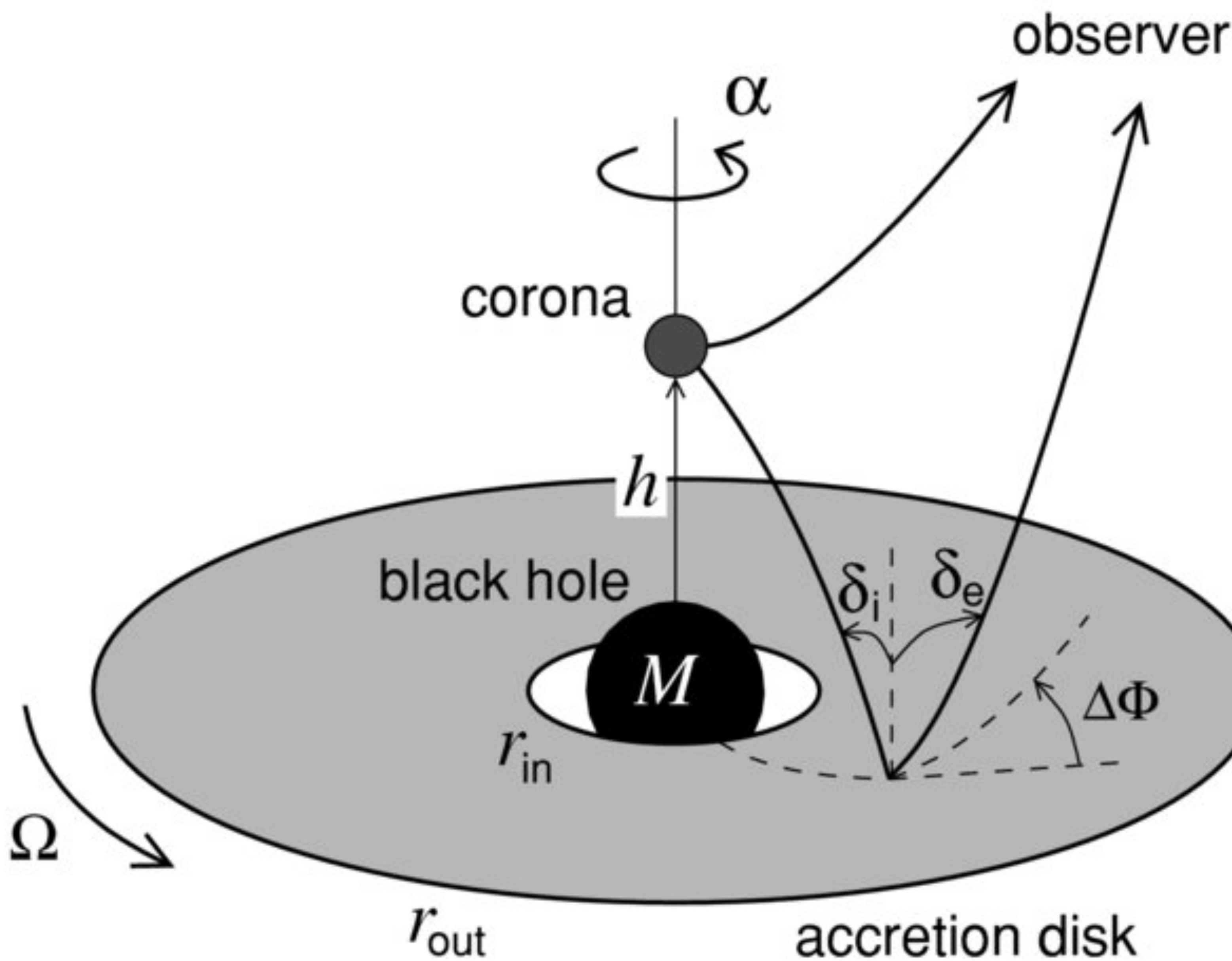
Combining the Doppler velocities (±900km s^{-1}) and the time to transverse the angular distance (0.14 pc) gives the mass of the nucleus $3.9 \times 10^7\ M_{sun}$ within $r \leq 0.012$ pc



NGC 4258: Megamasers



X-ray measurements of the innermost discs of AGN



observer
α
corona
h
black hole
δi
δe
M
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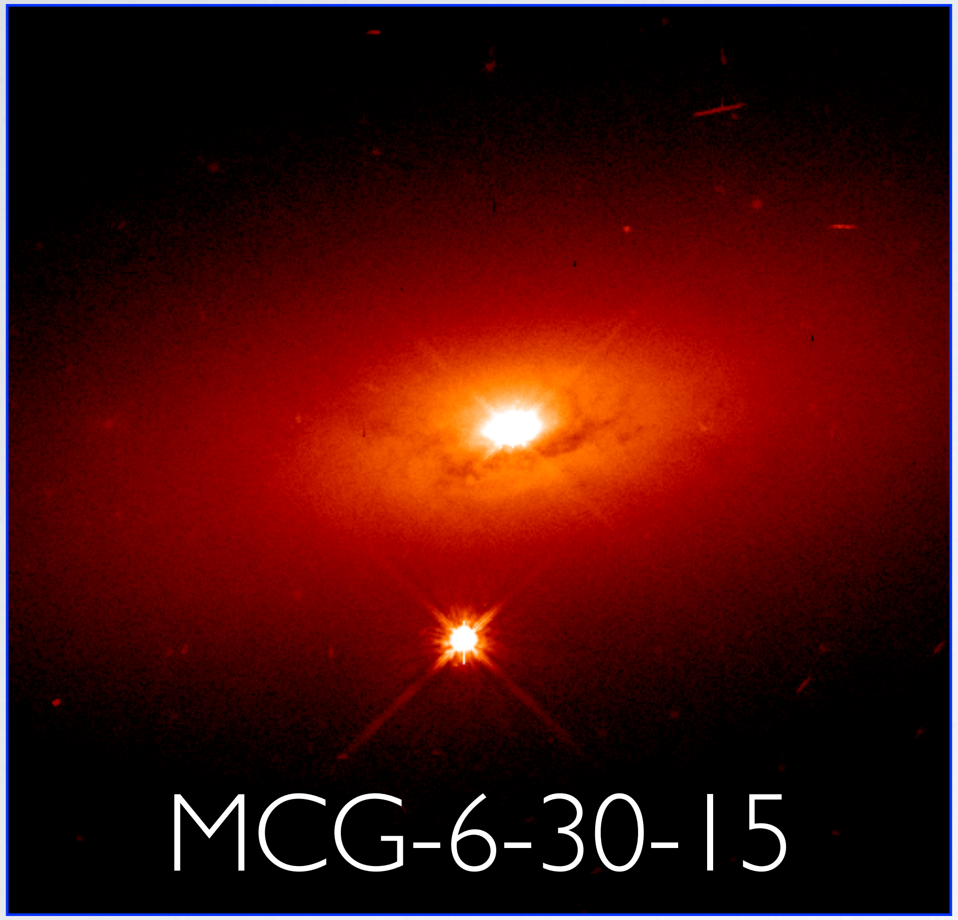
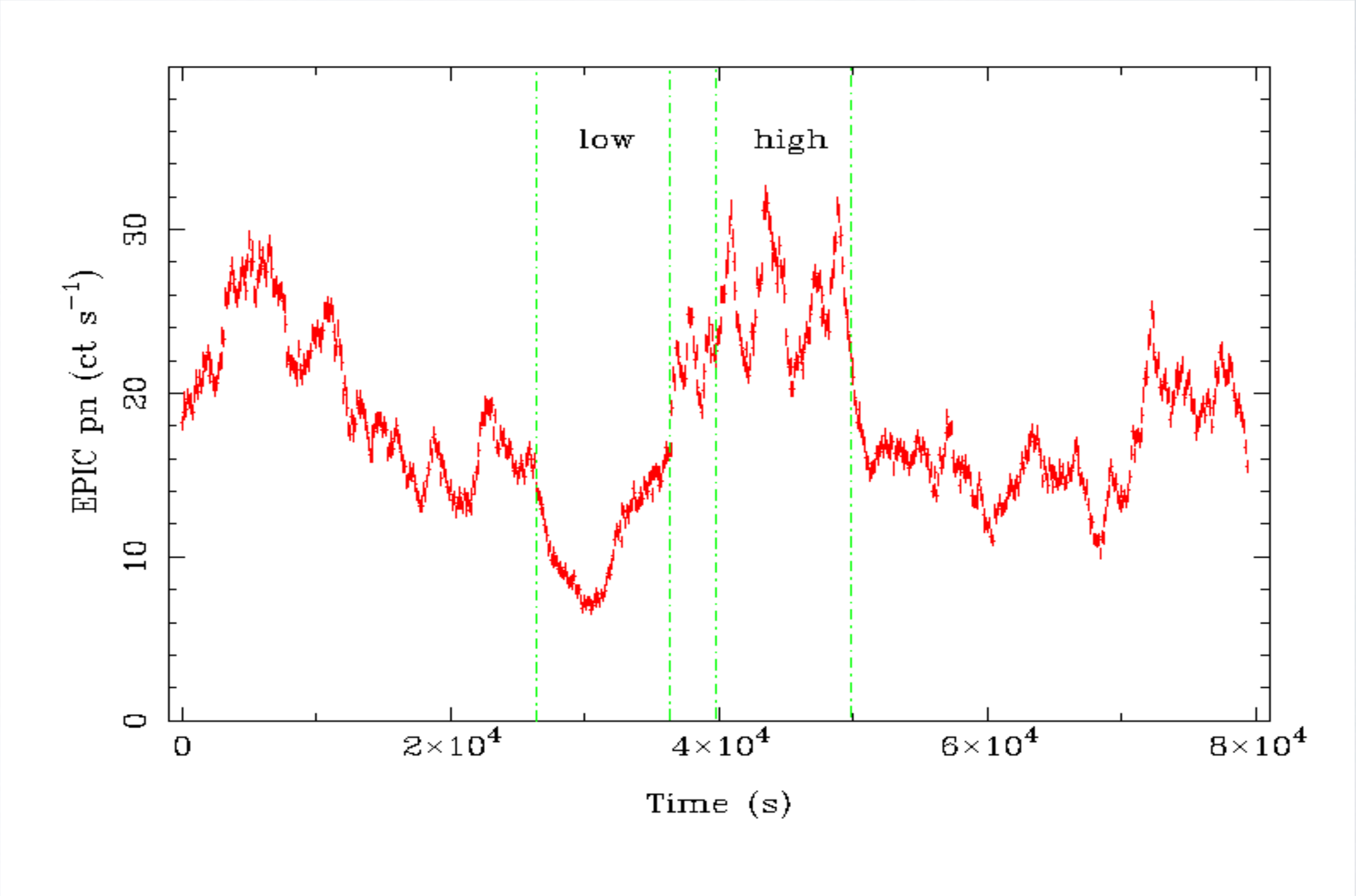
accretion disk

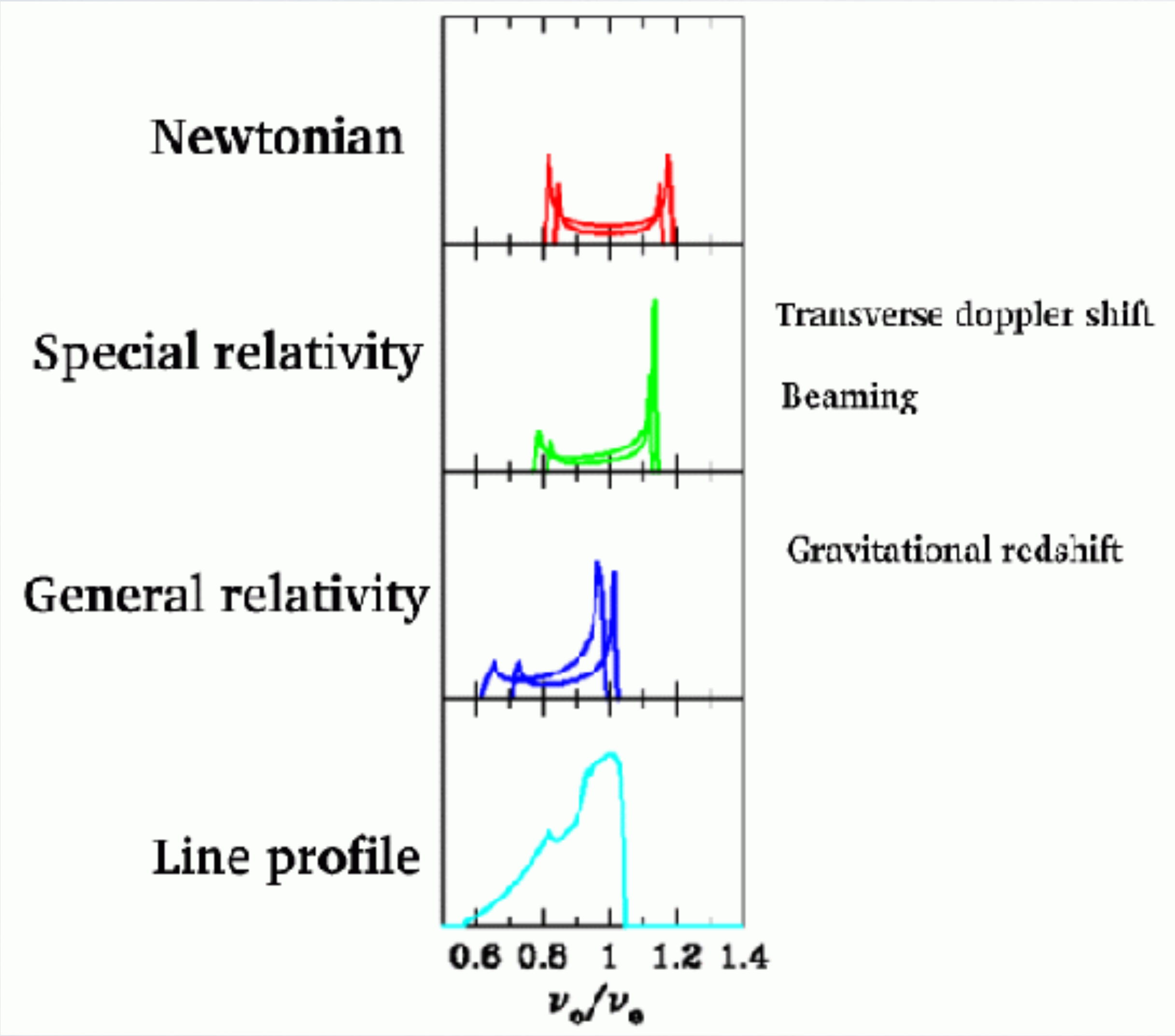
WHY DO WE USE X-RAYS

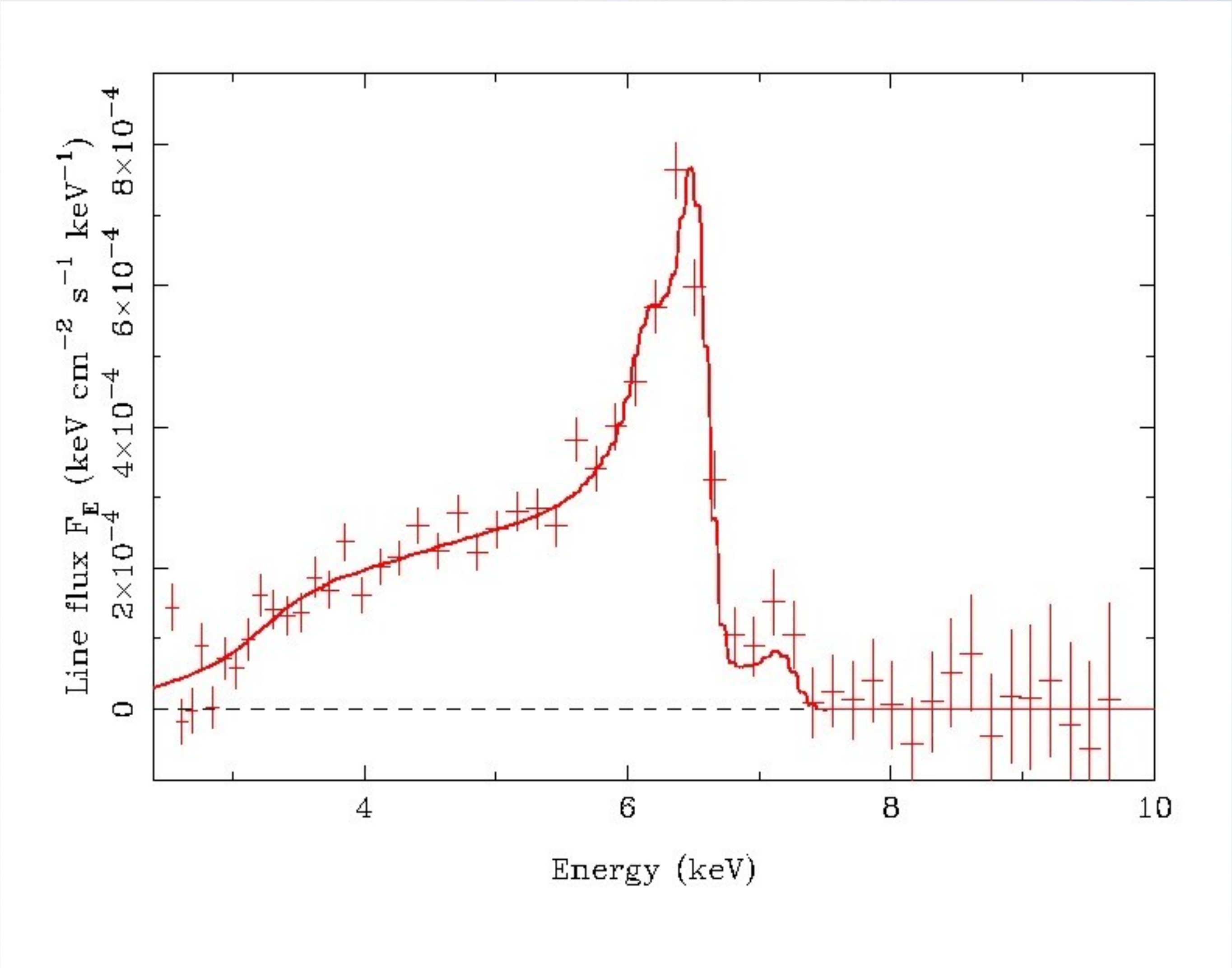




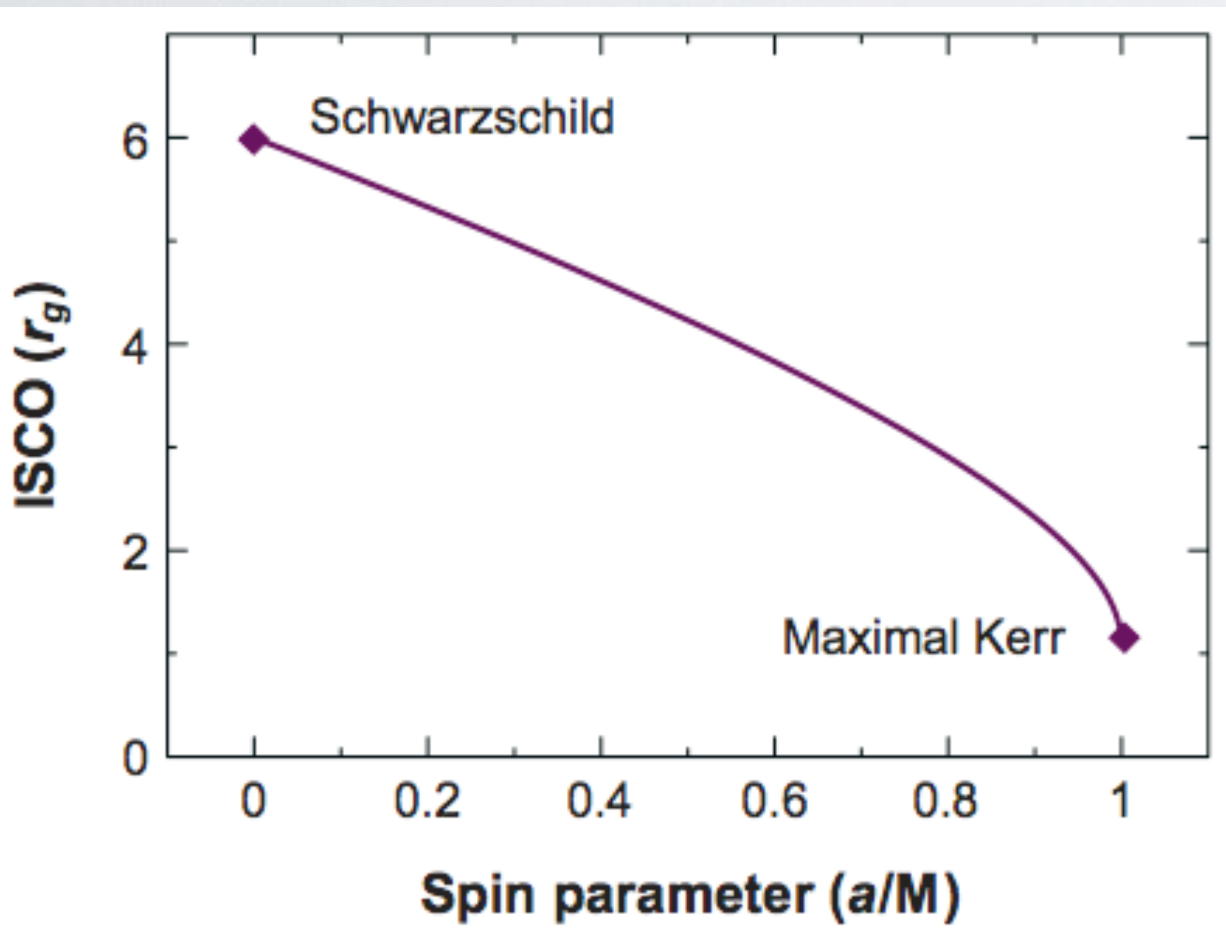
Rapid variability of AGN reveals that the X-ray photons come from the innermost accretion disk!

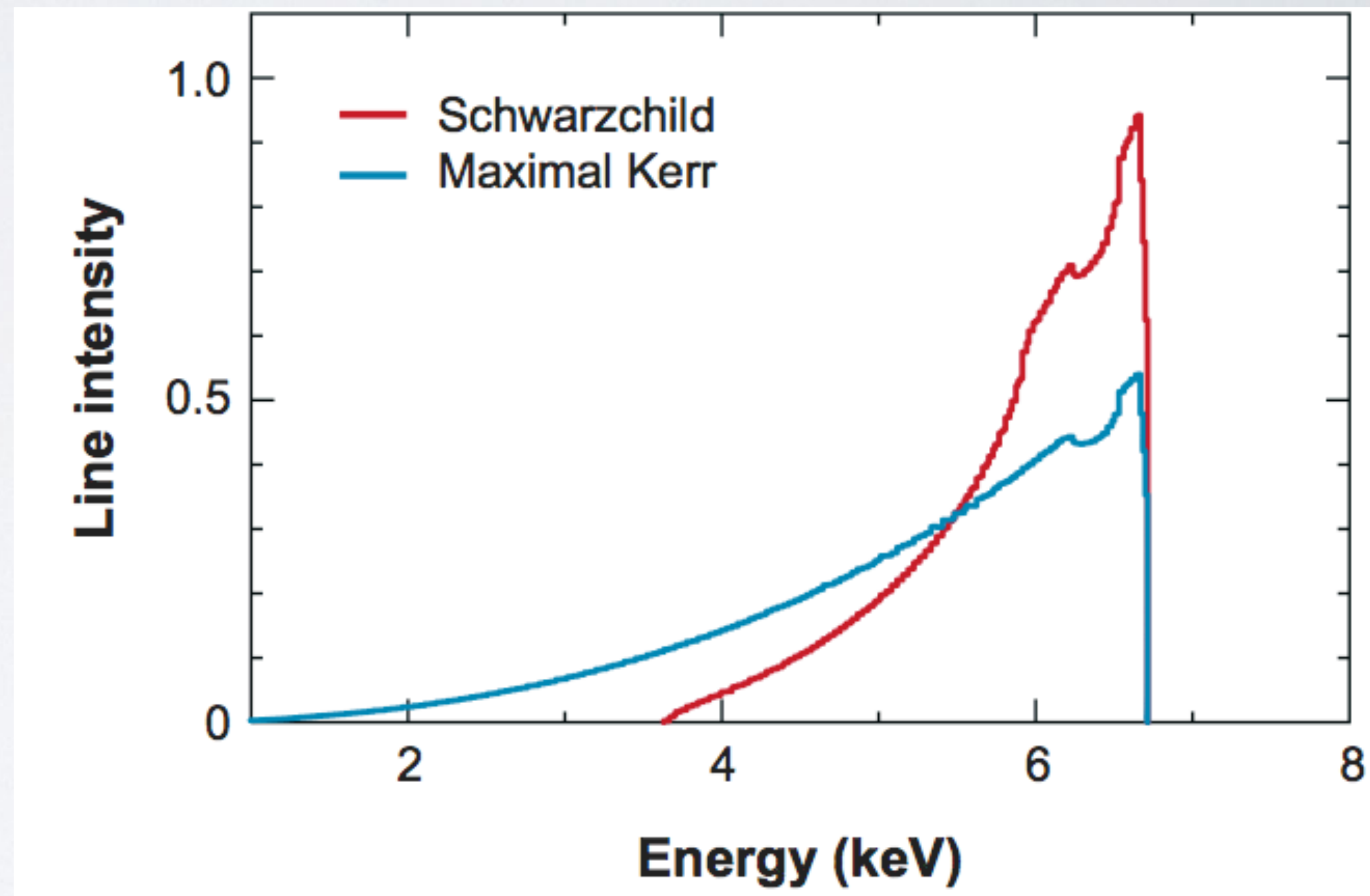
RELATIVISTICALLY BROADENED AND SKEWED EMISSION LINES





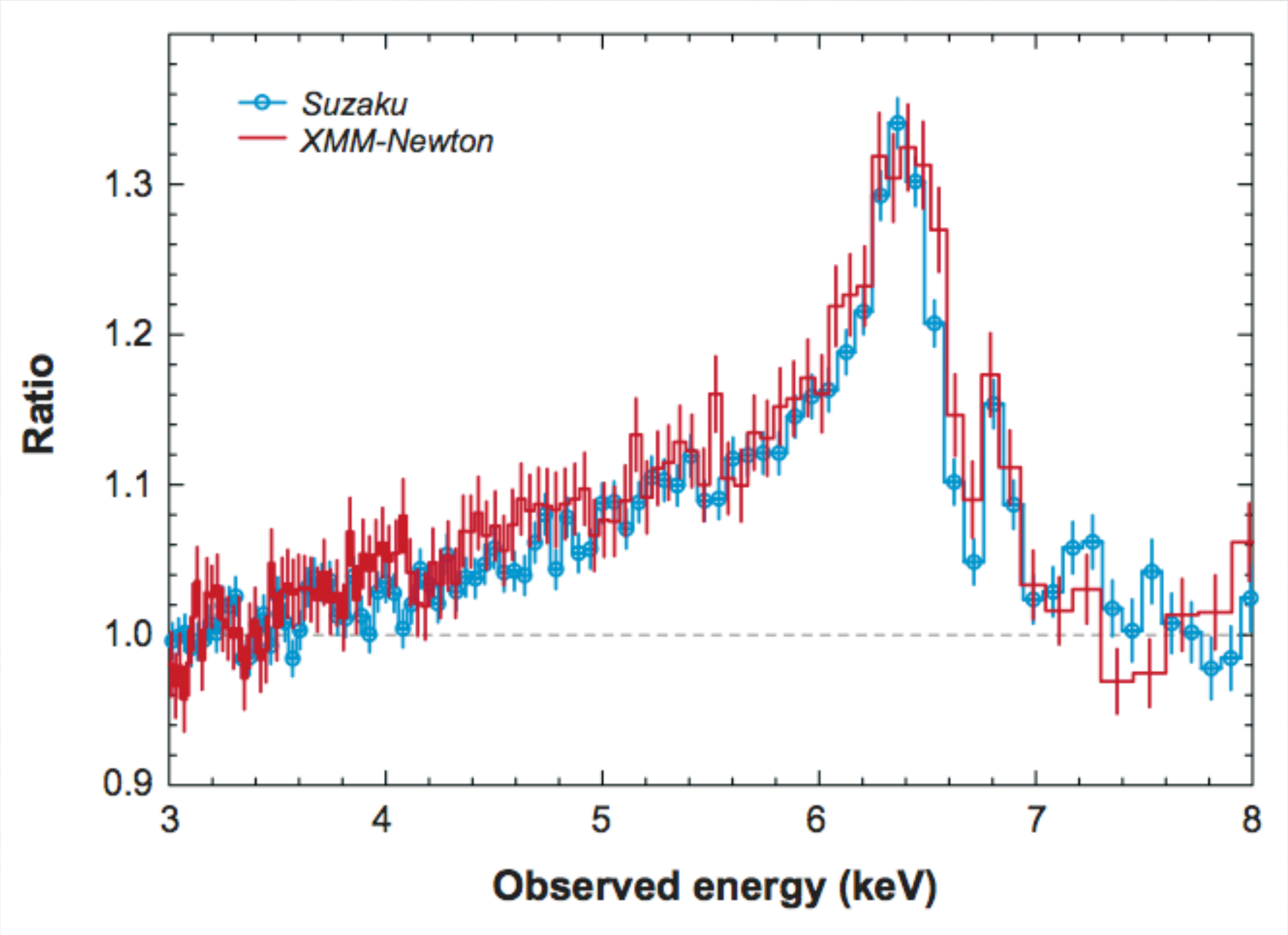
RELATIVISTICALLY BROADENED AND SKEWED EMISSION LINES





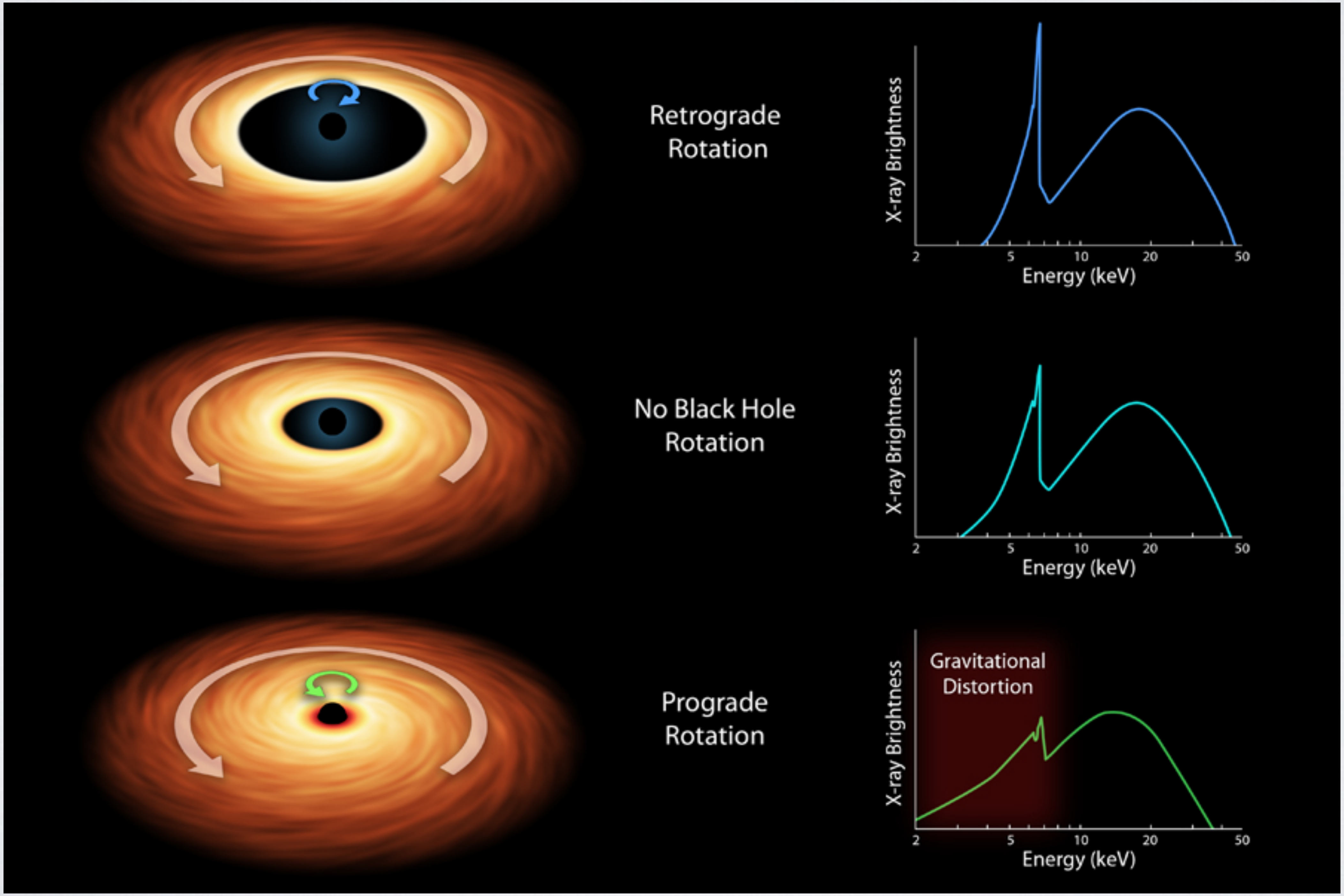
RELATIVISTIC LINE BROADENING IN MCG-6-30-15

- emission very close to black hole ISCO<$2R_g$
- accretion disk oriented at 30^{o} from our l.o.s.
- rotates at 0.989 of maximal Kerr spin



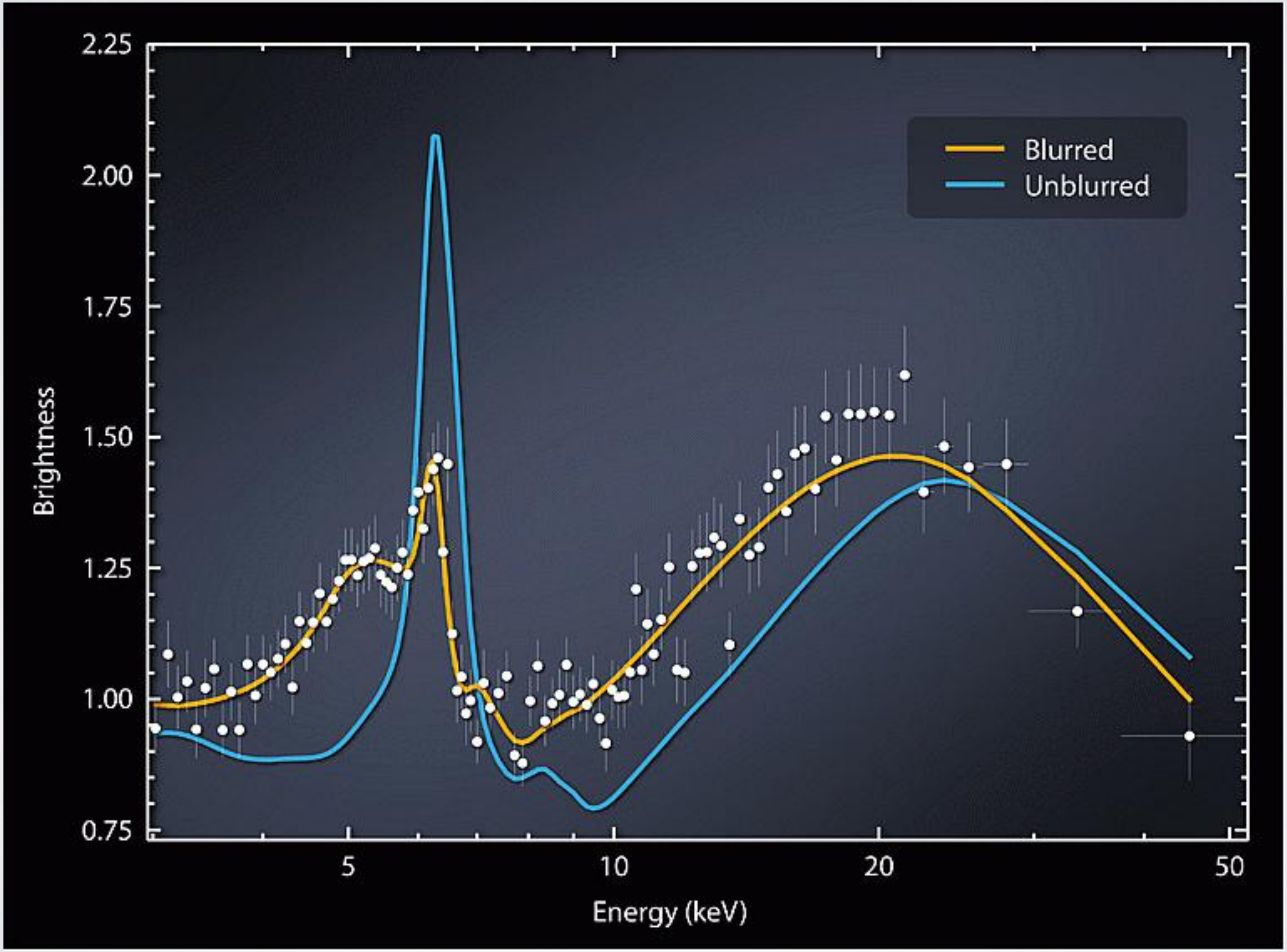
Spin of a Black Hole

Measure radius of the innermost stable circular orbit



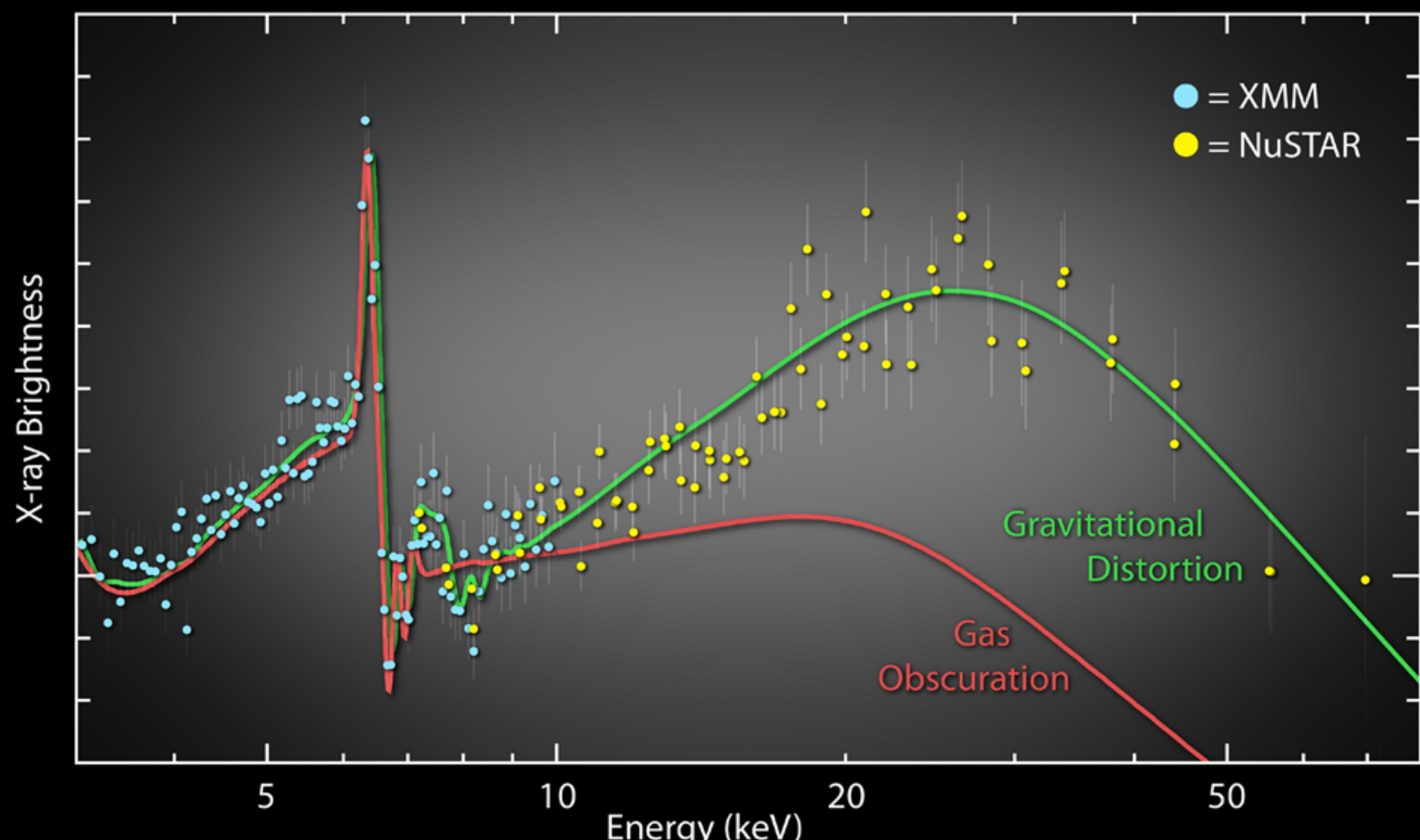
RELATIVISTIC BROAD FE LINE

- Mrk 335



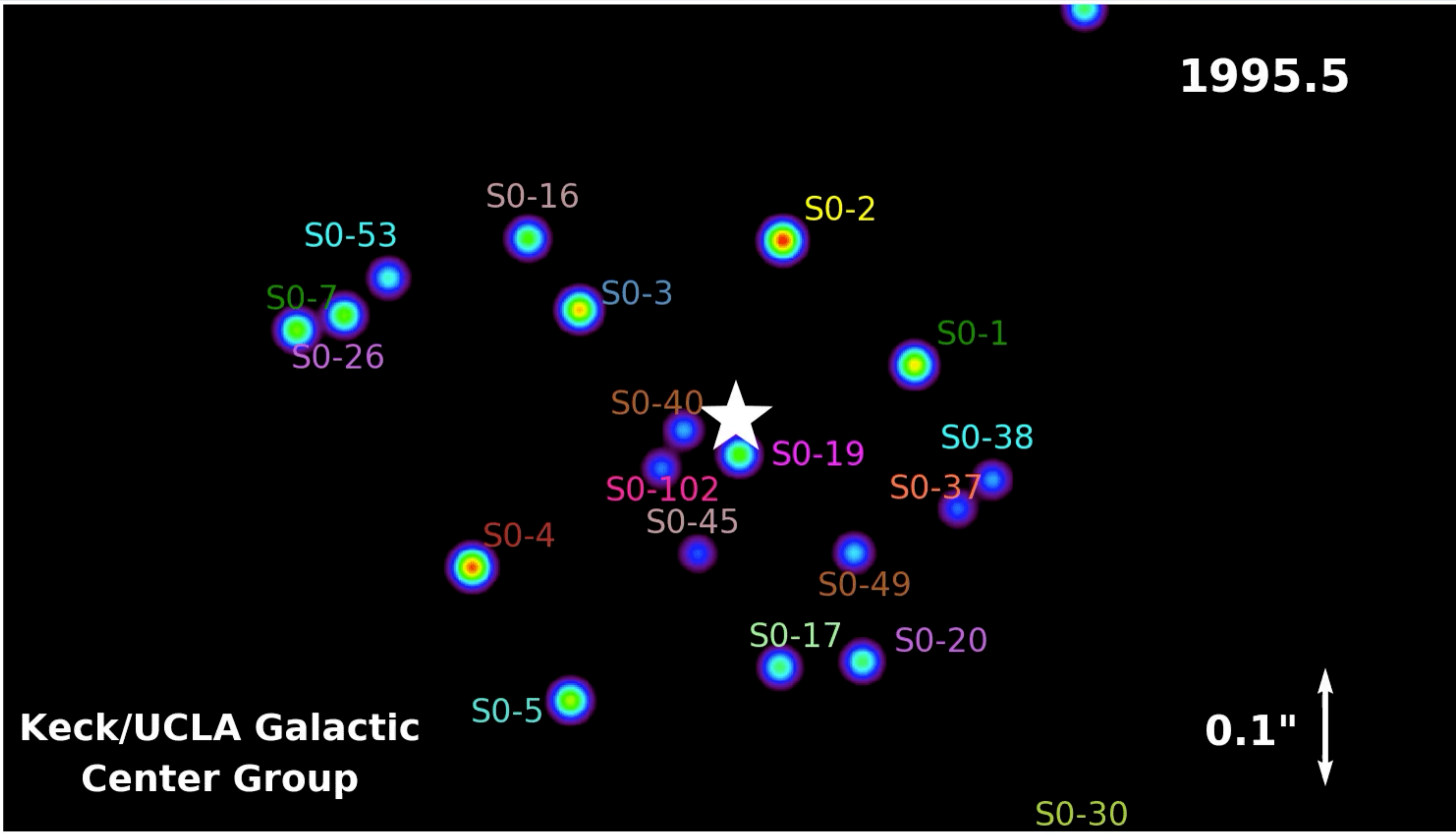
Relativistic Broaden lines

NGC 1365 - not gas obscuration

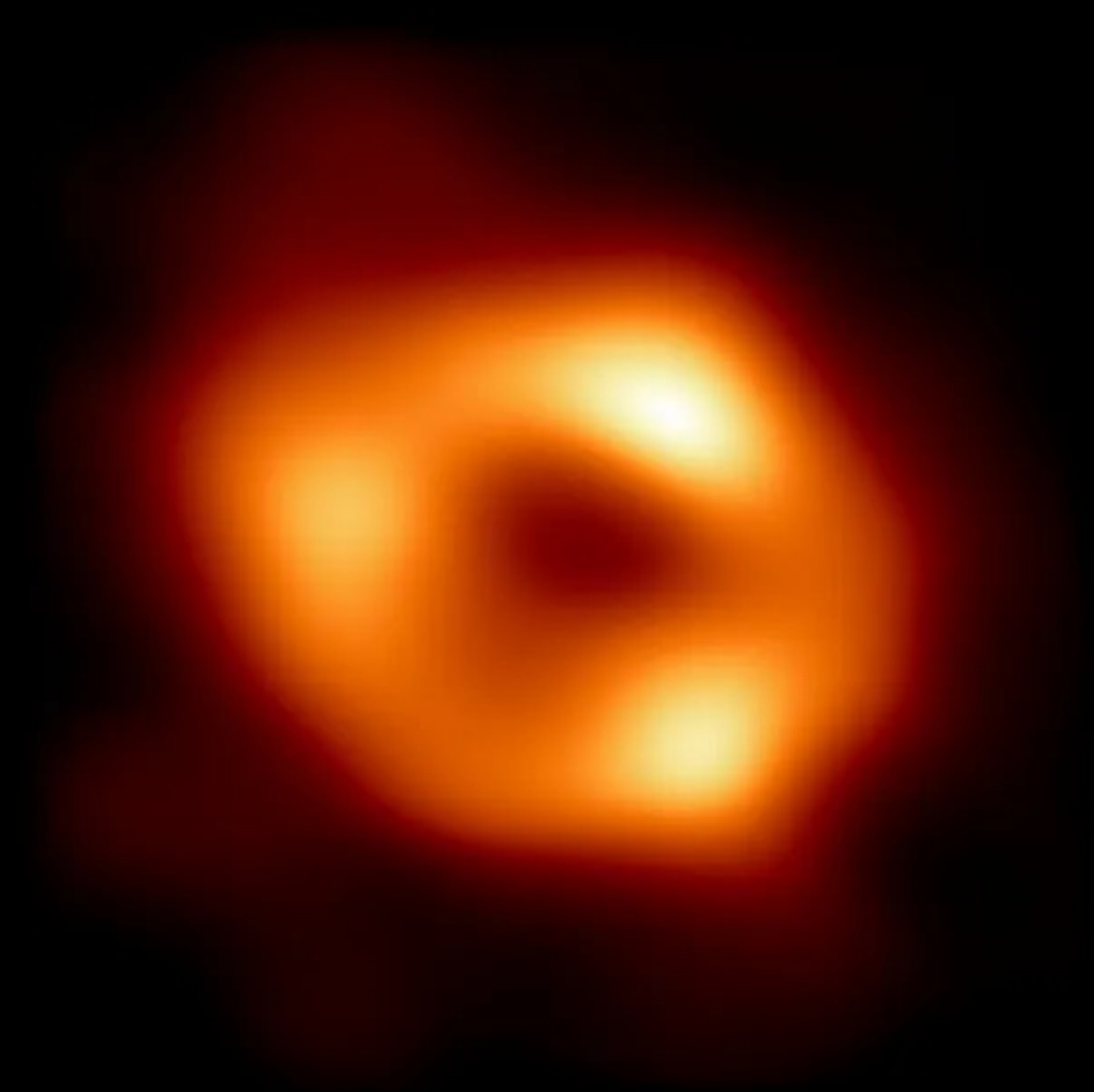


The Galactic Center

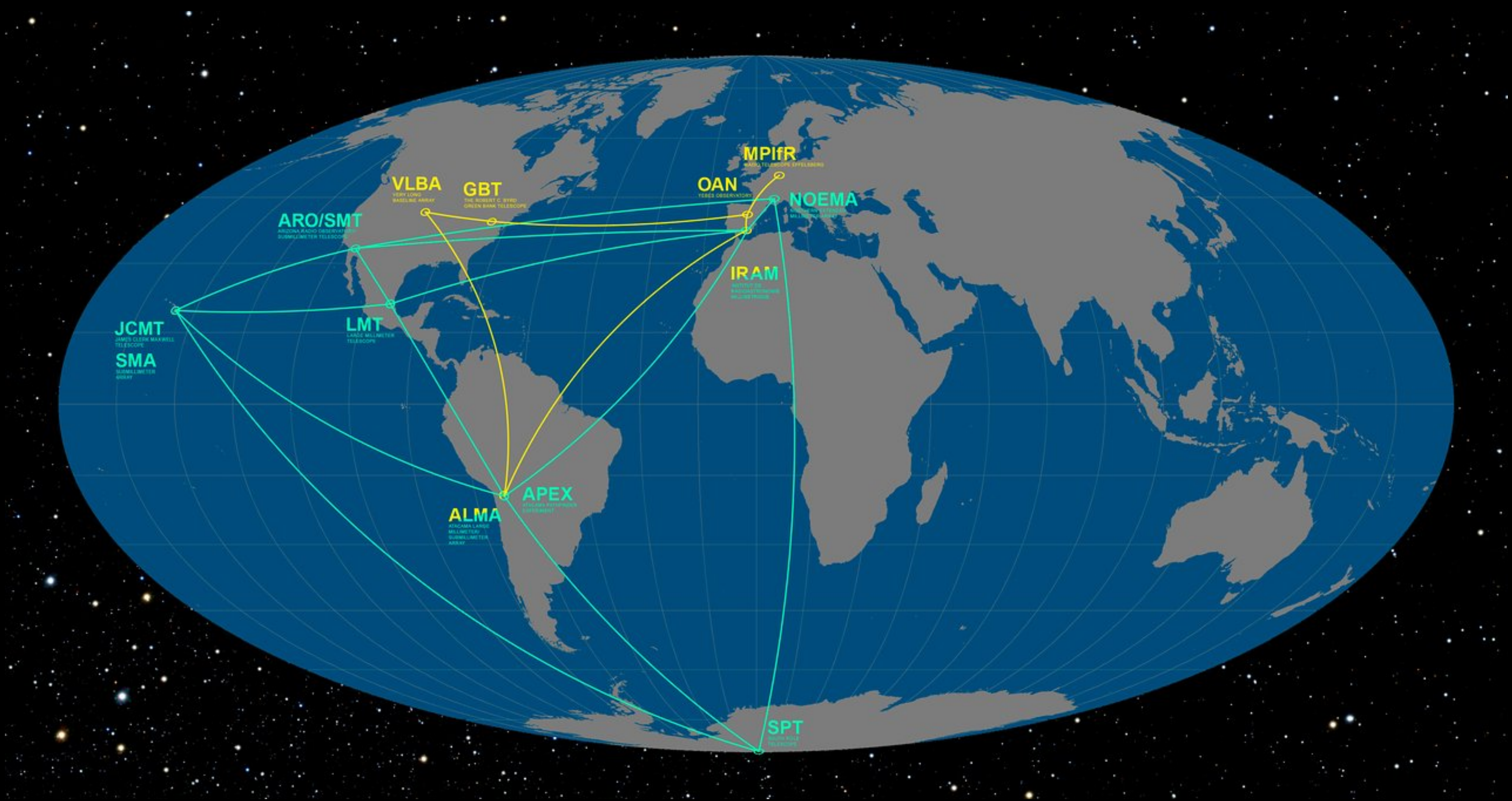
Sagittarius A*

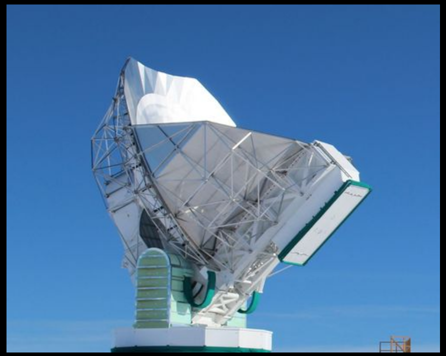


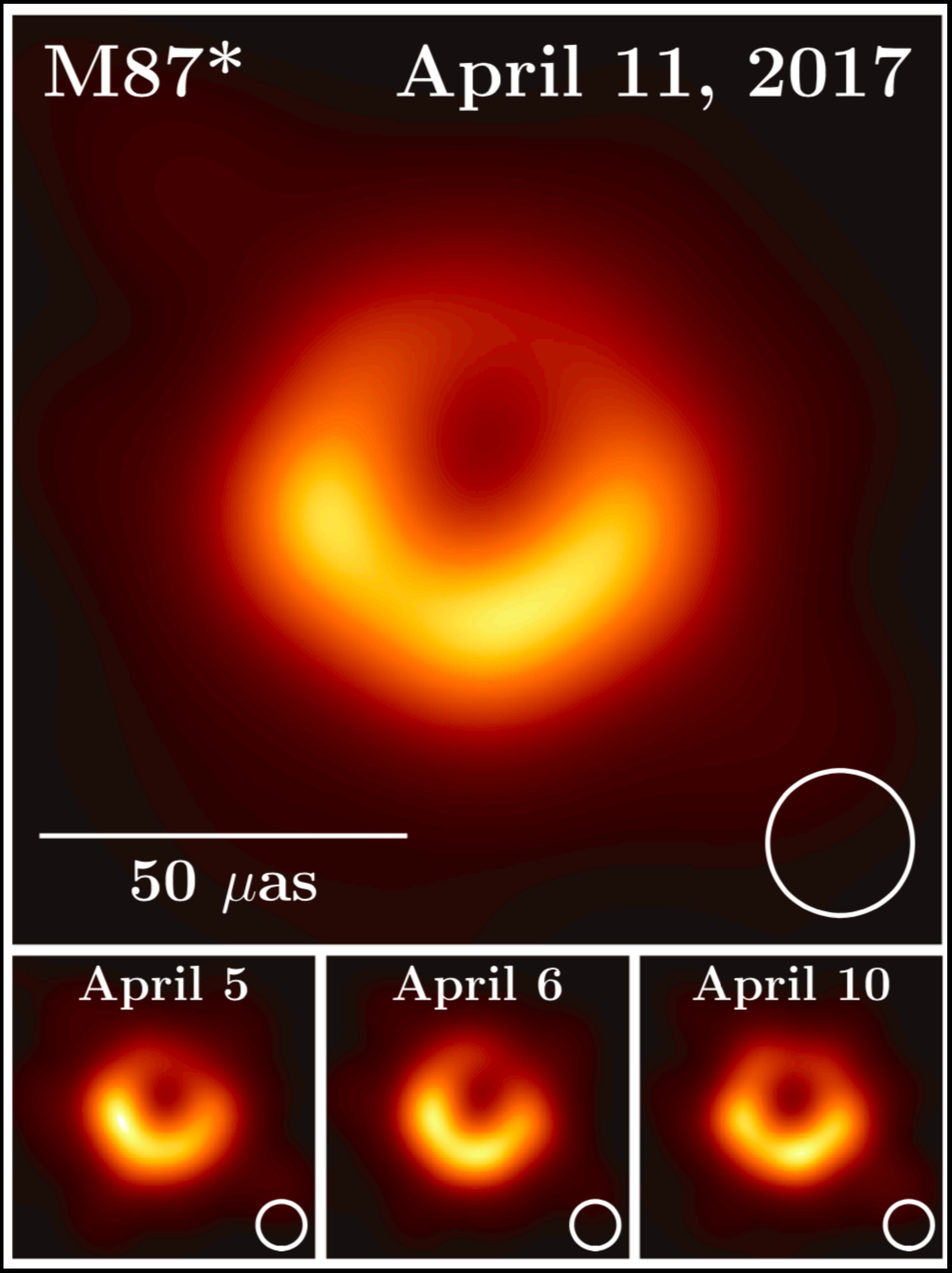
Sagittarius A*

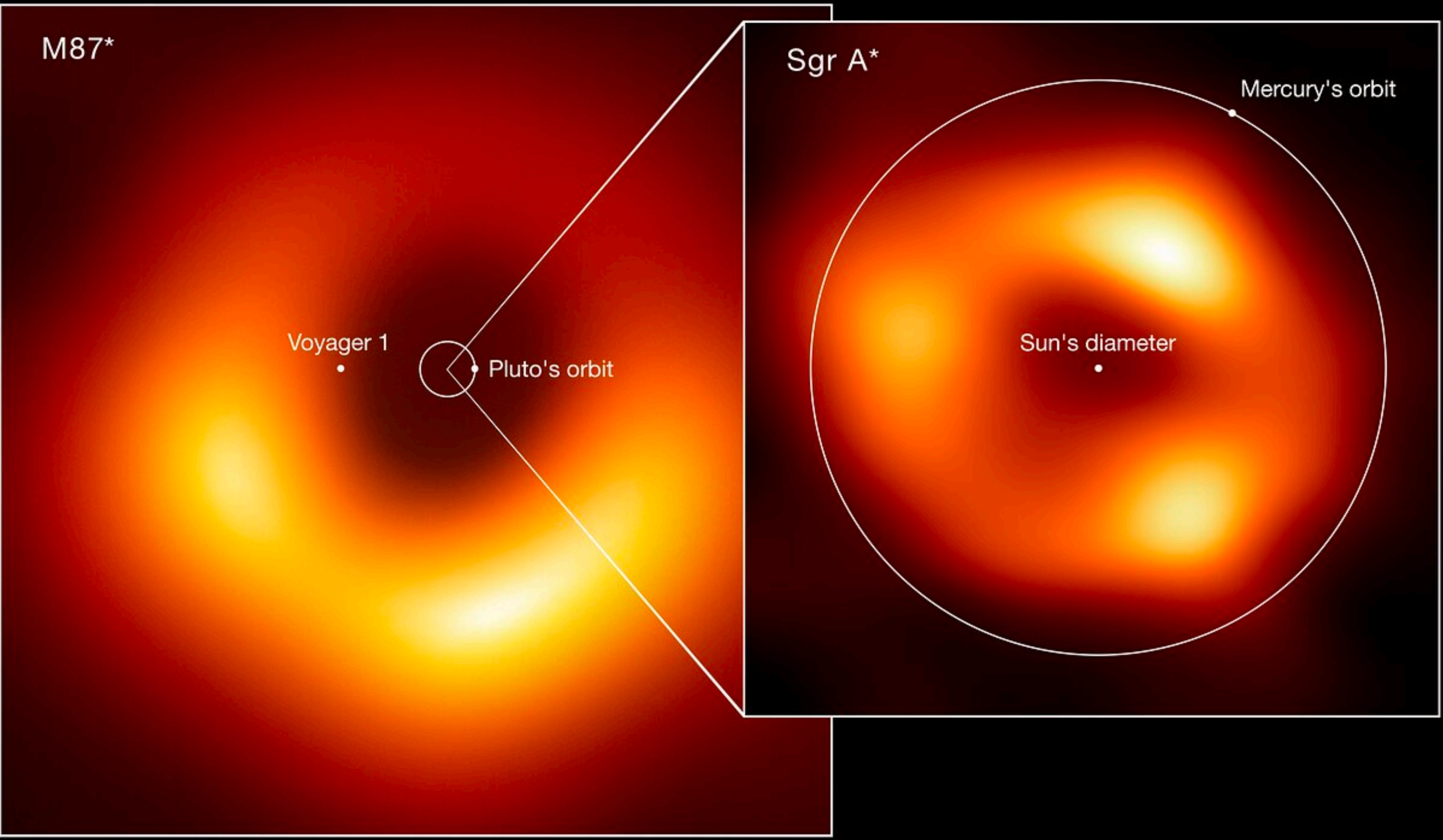


Event Horizont Telescope

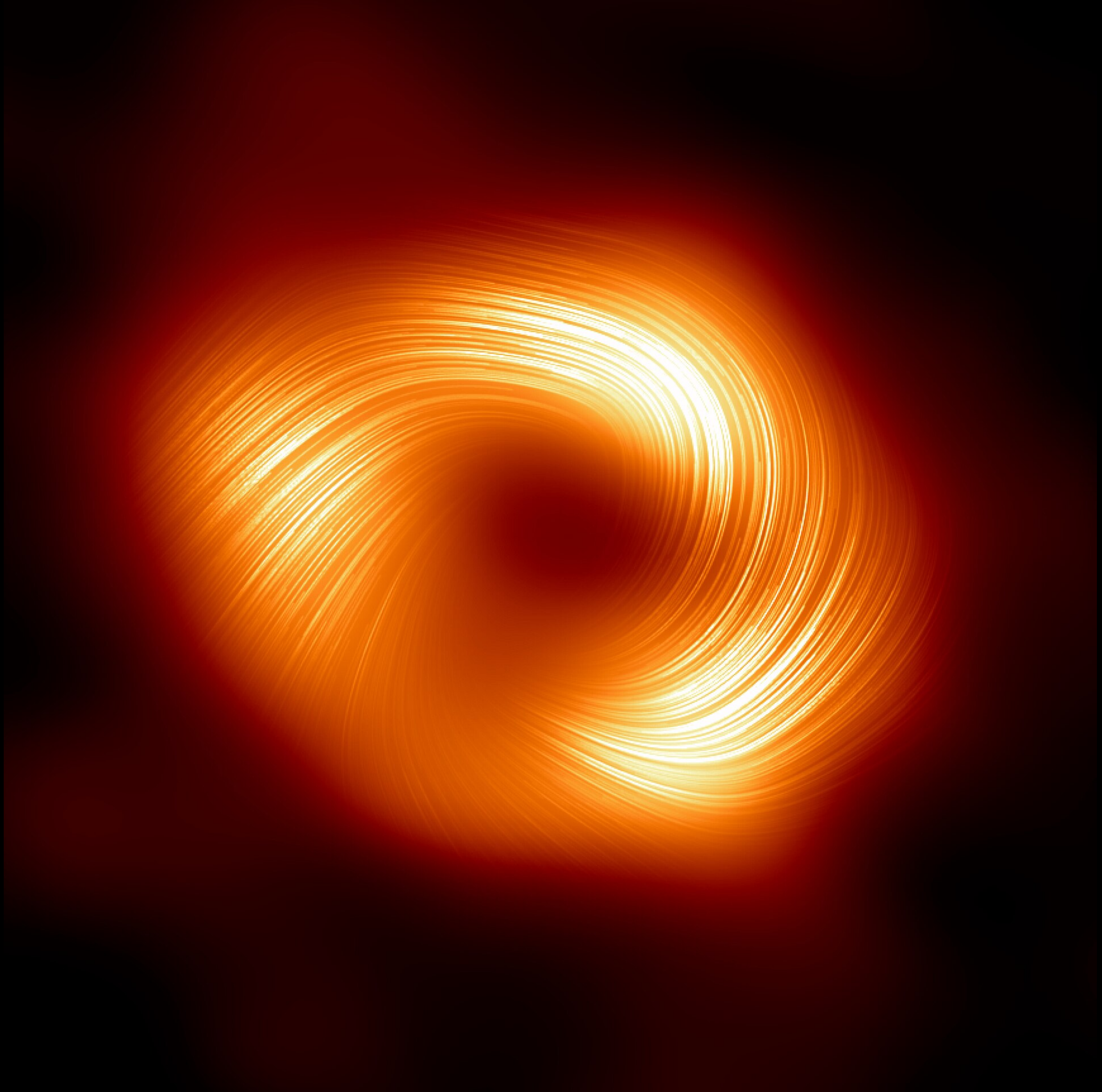


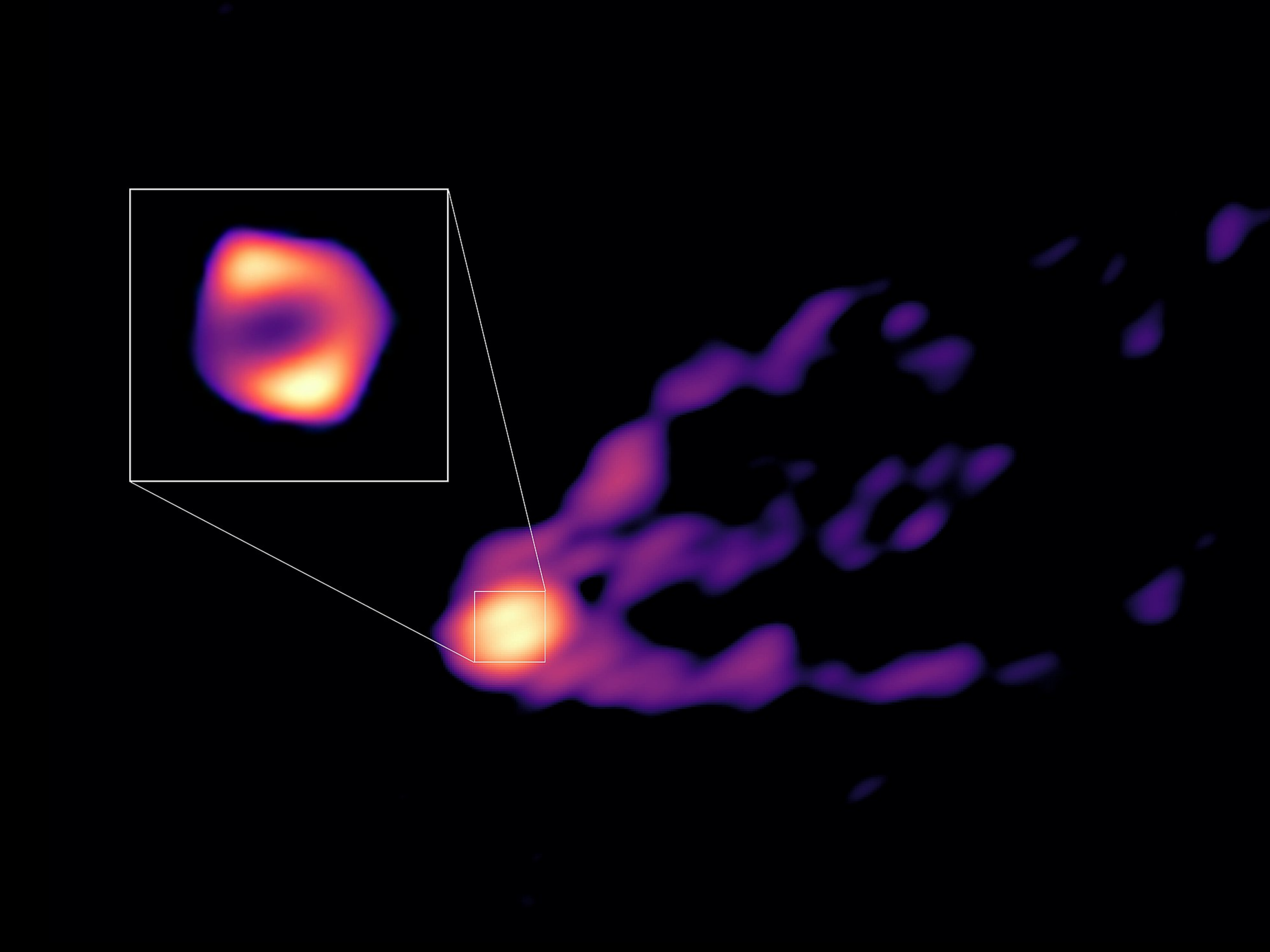



M87*
April 11, 2017
50 μas
April 5
April 6
April 10



M87*
Voyager 1
Pluto's orbit
Sgr A*
Mercury's orbit
Sun's diameter





General Summary

- A massive object is required to avoid highly ionized gas being blown away by radiation pressure.

- The accretion efficiency of SMBH can be 0.06-0.42, avoiding the problem with the "low" nuclear burning efficiency (~0.007) of stars (if they were the cause of AGN)

- Evidence for massive objects (SMBH) come from:
  - Stellar/gas kinematics: Increasing to very small radii
  - Mega-masers: Keplerian velocity of gas disks
  - Broadened Fe lines: Relativistic accretion disks
  - Sgr A*:Individial stellar orbits around Galactic center