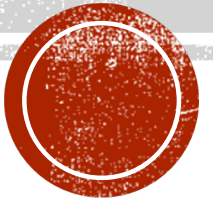
JETS OF BLACK HOLES



Lecture 11, Introduction to Black Hole Astrophysics (PHYS480)

Hsiang-Yi Karen Yang, NTHU, 5/11/2021

ANNOUNCEMENTS

- HW5 is due today.
- Please search for black hole news for the oral presentation and paste the news link here:

https://docs.google.com/spreadsheets/d/1_aYyMj1wf_uGheZ7zp_hvthmy4mdmPwIxFDdZOMG-nc/edit?usp=sharing

- For the final team report (research proposal), please start discussing with your teammates and gather ideas! Due date: 6/11 (Fri) at 5pm on iLMS.

PREVIOUS LECTURE...

- Advancement in technology (adaptive optics, interferometry with long baselines) has allowed us to study Sgr A* with unprecedented details and learn about SMBHs
- Currently, Sgr A* is a dormant SMBH with occasional flares
- We might see accretion events from gas clouds like G2, but unlikely to see tidal disruption of stars by Sgr A*
- Tidal disruption events (TDEs)
  - A star would be disrupted by tidal forces when it passes within the tidal disruption radius
  - About half of the materials would fall back, form accretion disks, and shine
  - Predicted lightcurve follows a $t^{-5/3}$ decay and can be super-Eddington
- Evidences (X-ray light echoes, Fermi bubbles) suggest elevated past activity of Sgr A*
- GR effects have been confirmed. EHT image of Sgr A* is coming soon!

THIS LECTURE

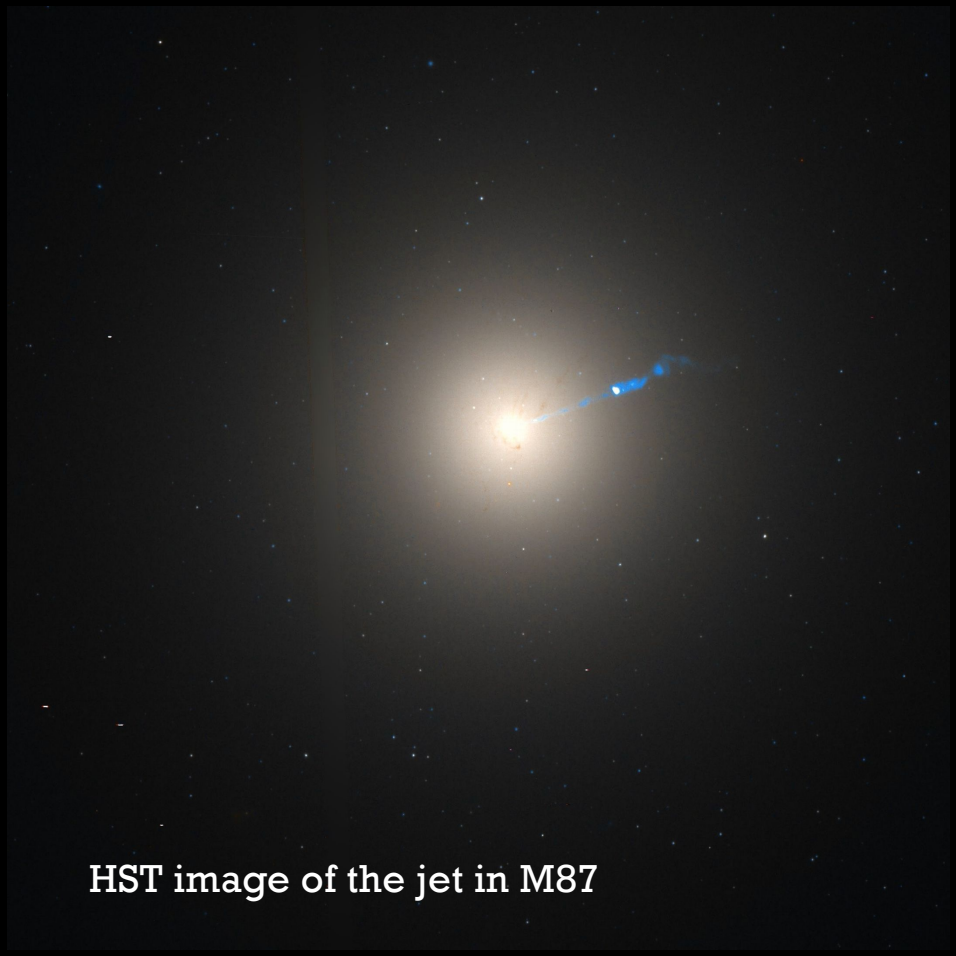
- Overview of jets
- Observed properties of BH jets
- How do we know jets are relativistic?
- The many different looks of jets
- How are jets produced?
- How do jets propagate to large distances?
- Open questions

OVERVIEW OF BH JETS

Astronomy and astrophysics [edit]

Main article: List of unsolved problems in astronomy

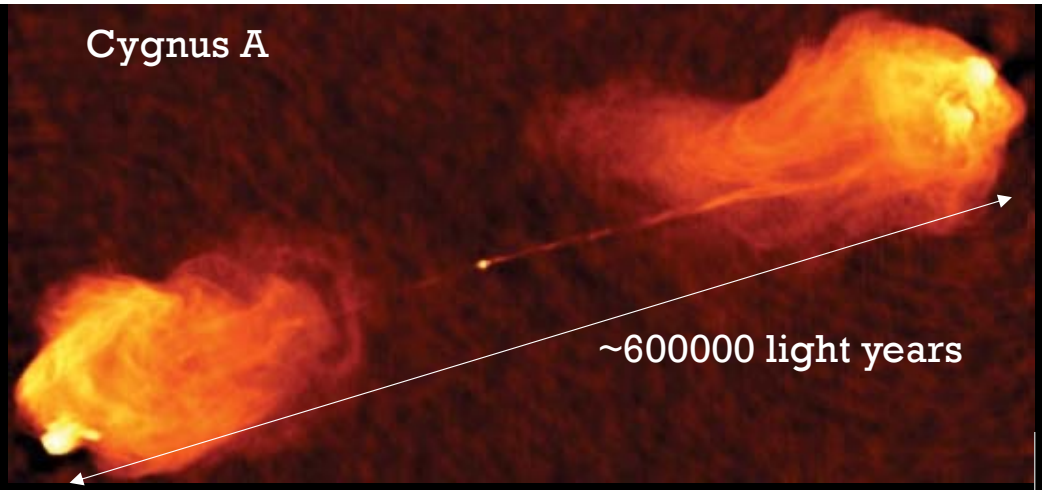
- Astrophysical jet: Why do only certain accretion discs surrounding certain astronomical objects emit relativistic jets along their polar axes?

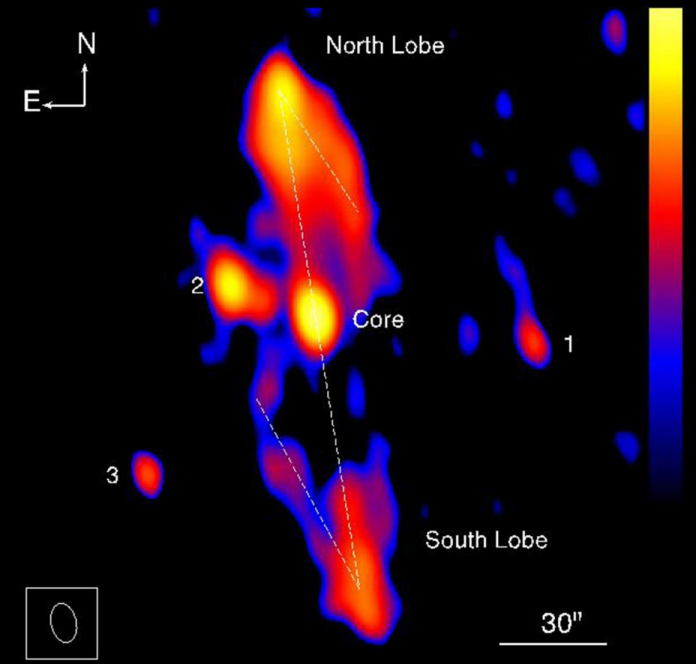


HST image of the jet in M87

Heber Curtis in 1918: "curious straight ray … apparently connected with the nucleus by a thin line of matter."

ASTROPHYSICAL JETS



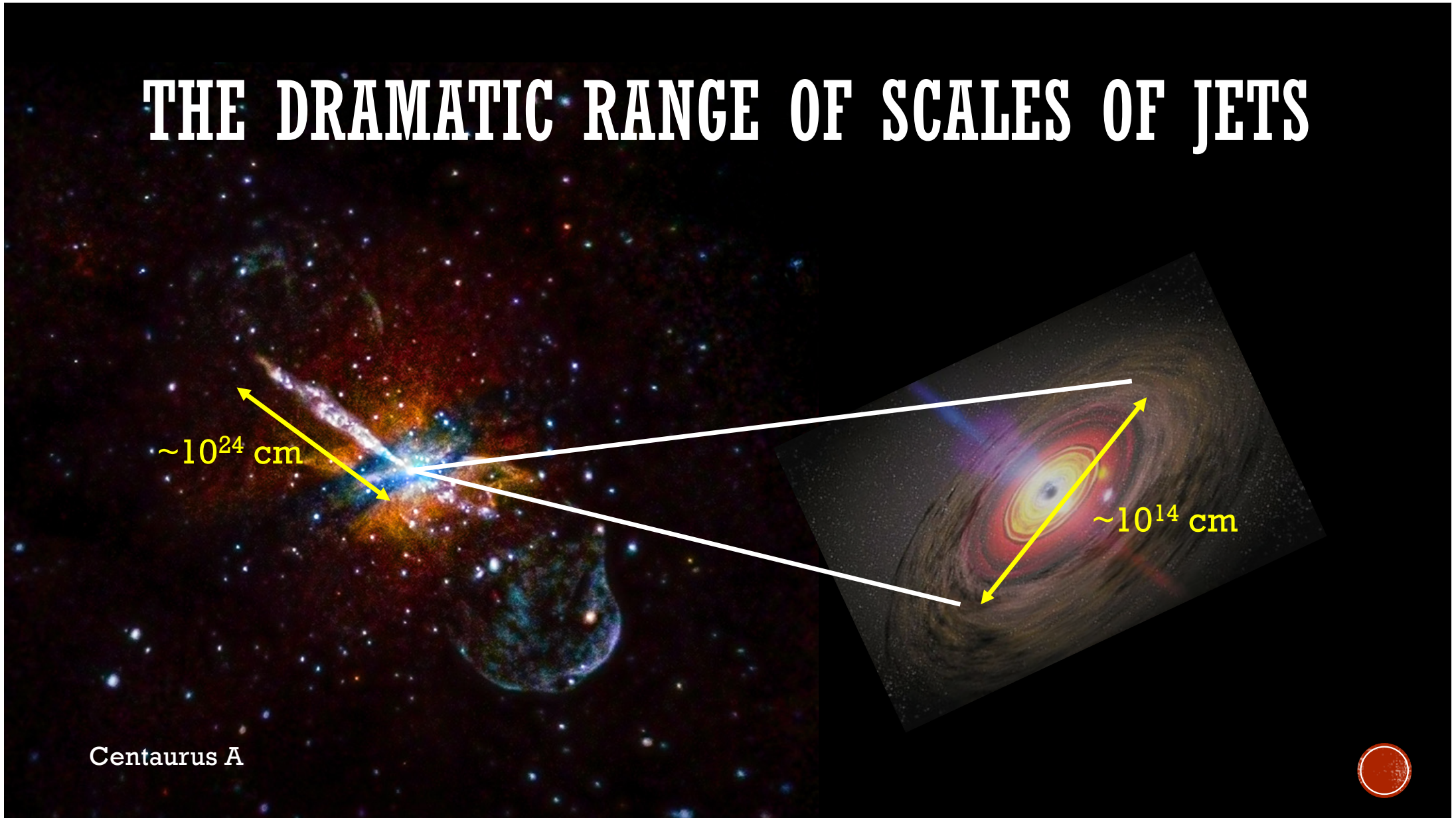


Jets from X-ray binary / Microquasar

Jets from Young Stars · HH1/HH2 HST · WFPC2

PRC95-24c · ST ScI OPO · June 6, 1995 · J. Hester (AZ State U.), NASA

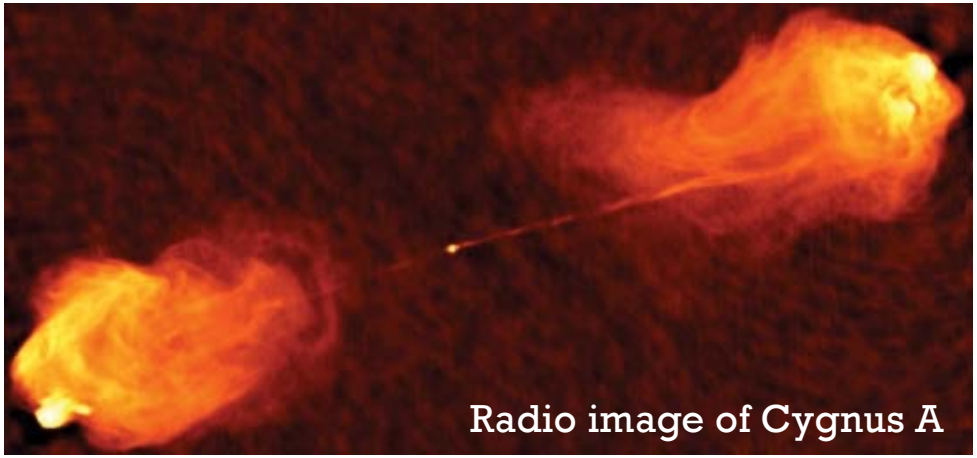
THE DRAMATIC RANGE OF SCALES OF JETS

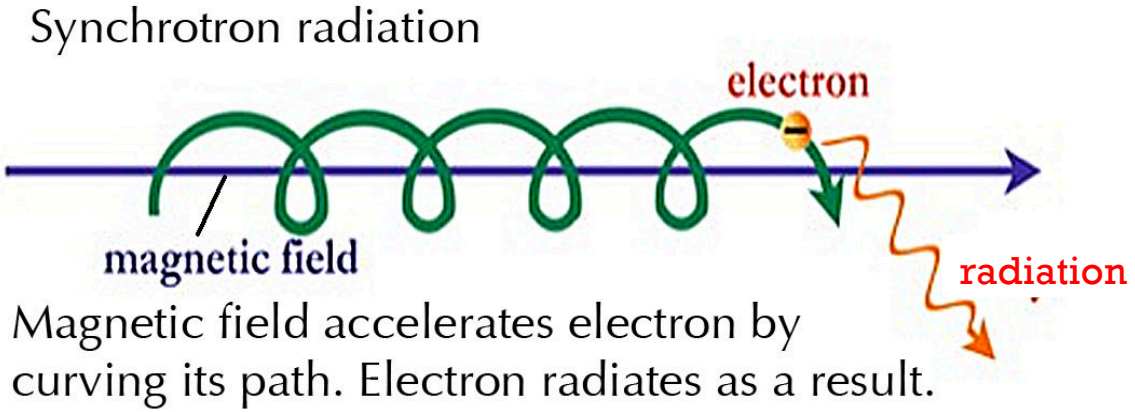


BASIC PROPERTIES OF BH JETS

- Jets occur in ***~10%*** of AGN and slowly-accreting X-ray binaries
- Typically observed in ***radio***, sometimes optical/X-ray/gamma-rays
- Primary emission mechanism -- ***synchrotron radiation*** when relativistic particles gyrate around magnetic field lines
- ***Relativistic*** with typical Lorentz factor $\gamma \sim 10$ or $v \sim 0.995c$

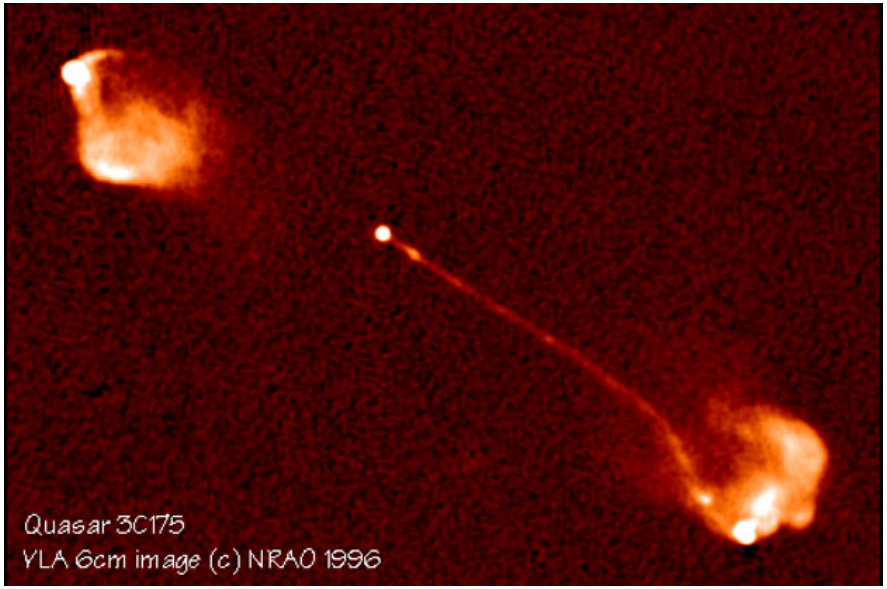
$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

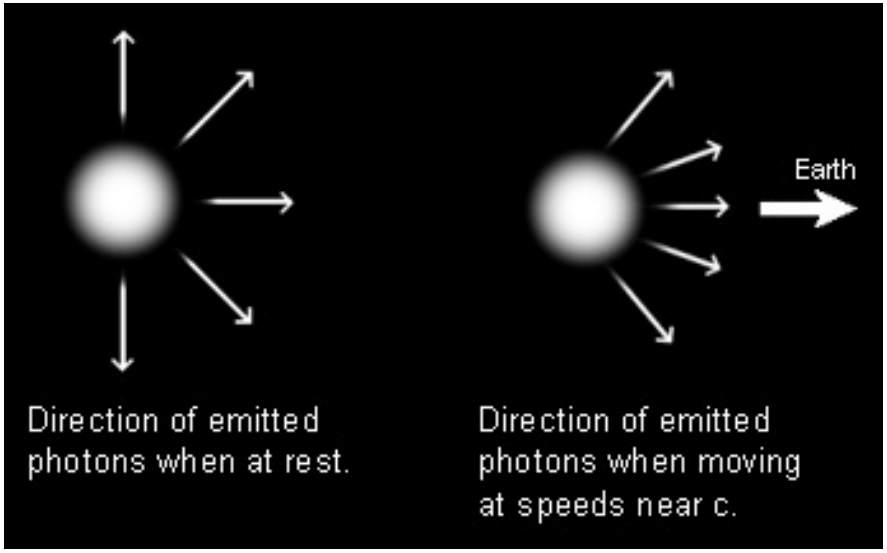

Radio image of Cygnus A

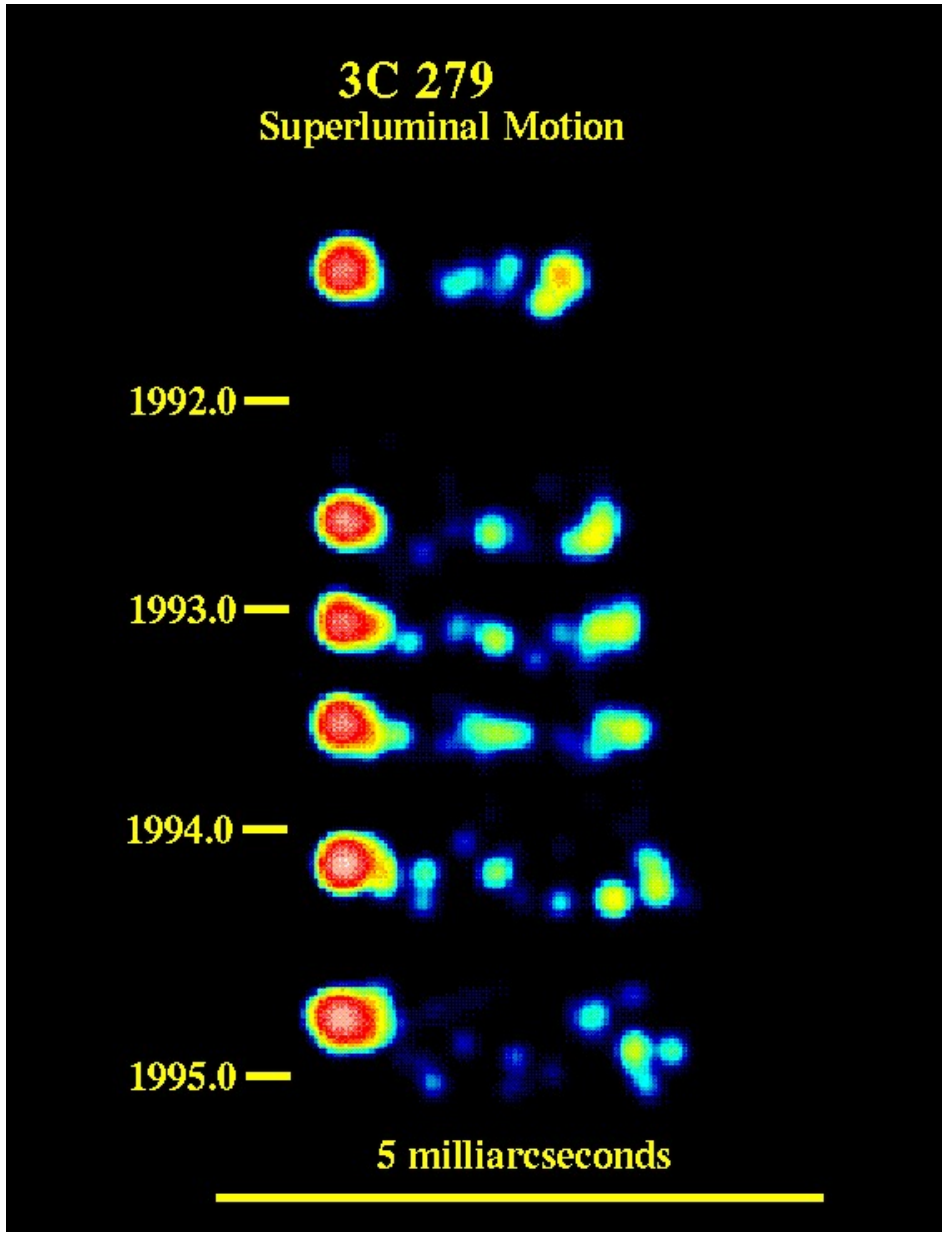


HOW DO WE KNOW JETS ARE RELATIVISTIC?

- Many jets appear to be ***one-sided*** (e.g., M87, Centaurus A)!
- Such powerful jets should be created symmetrically
- In fact, the approaching jet appears much brighter than the receding jet – ***relativistic beaming (Lecture 2)***
  - ***Relativistic aberration*** -- when an emitting object moves close to light speed, the light rays would be beamed in the direction it is moving
  - ***Relativistic Doppler's effect*** – approaching photons would be blue-shifted, i.e., shifted to higher energies



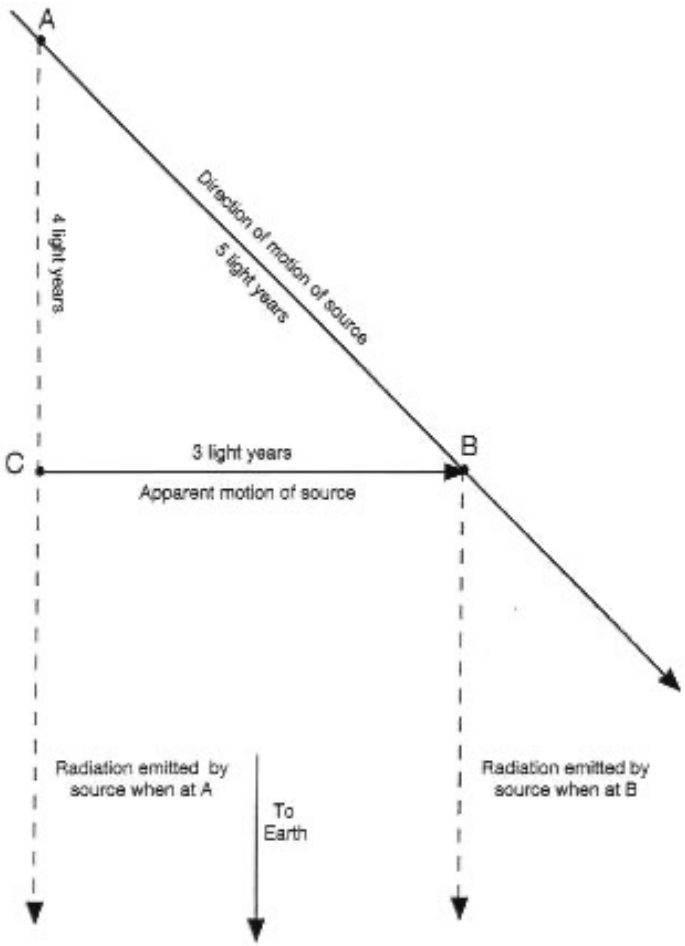




HOW DO WE KNOW JETS ARE RELATIVISTIC?

- High-resolution observations of jets show that there are knots moving away from center
- Knots appear to move faster than the speed of light!
- Apparent speed could be up to ~40c !??
- This is called ***superluminal motions*** **(超光速運動)**

SUPERLUMINAL MOTIONS

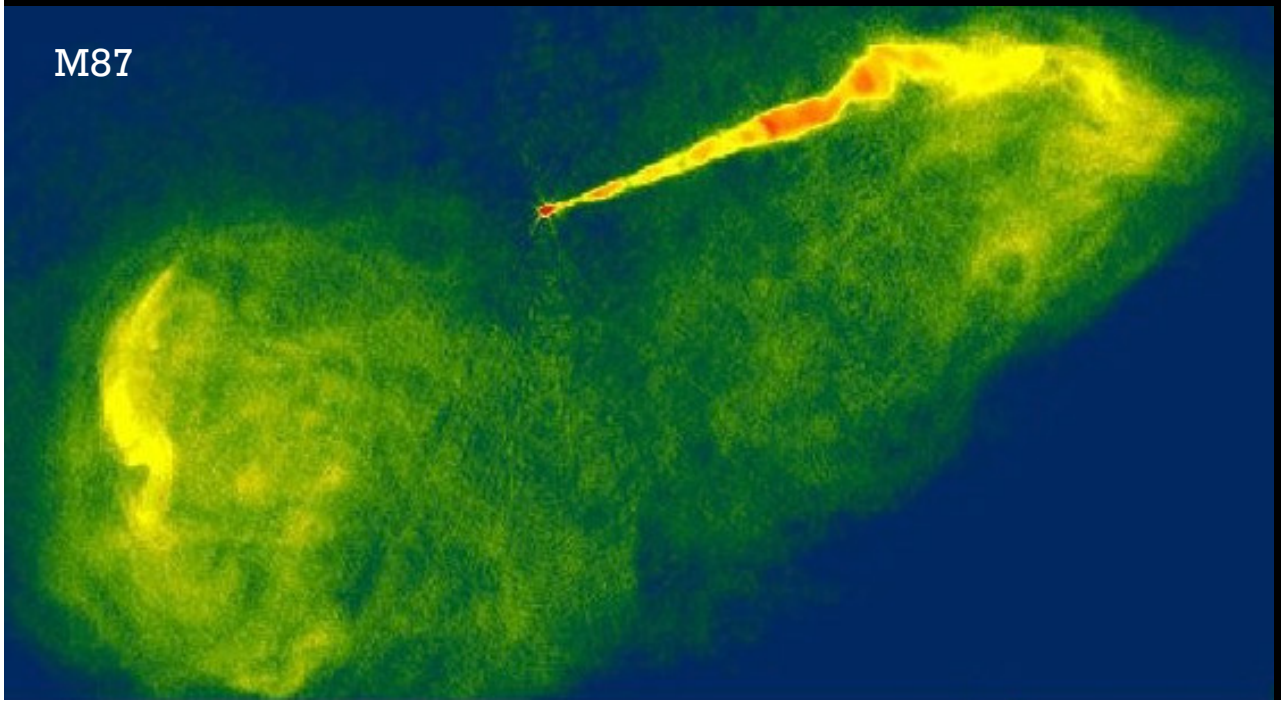


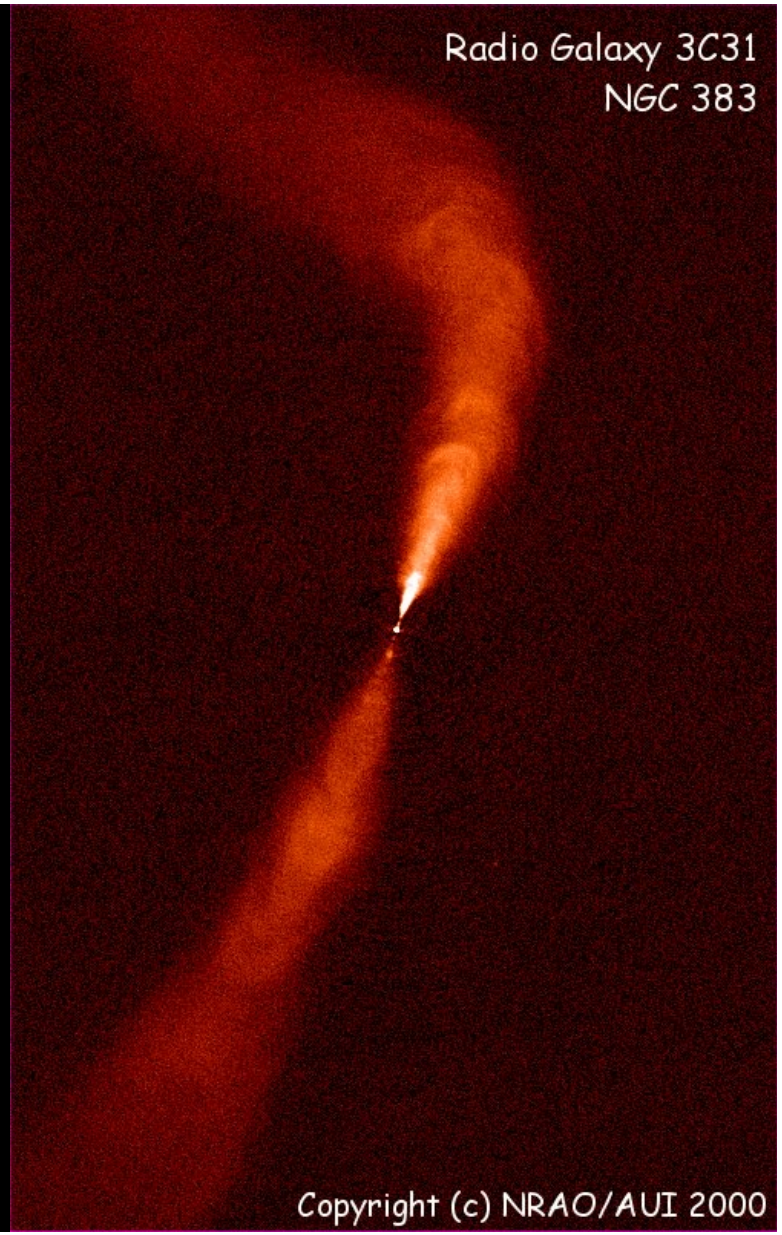
- Assuming an emitting object is moving at ~light speed from A to B, where the distance between A and B is 5 light years
- Assuming we are observing the object from Earth, the apparent speed = (distance on the sky) / (time between photons received on Earth)
- Distance on the sky = BC = 3 light years
- ***Time between photons = 1 year*** (because the photon emitted at A is ***delayed*** by 4 years)
- So the apparent speed = 3c!
- This is strong evidence for relativistic speed!

MANY LOOKS OF JETS

THE MANY LOOKS OF JETS

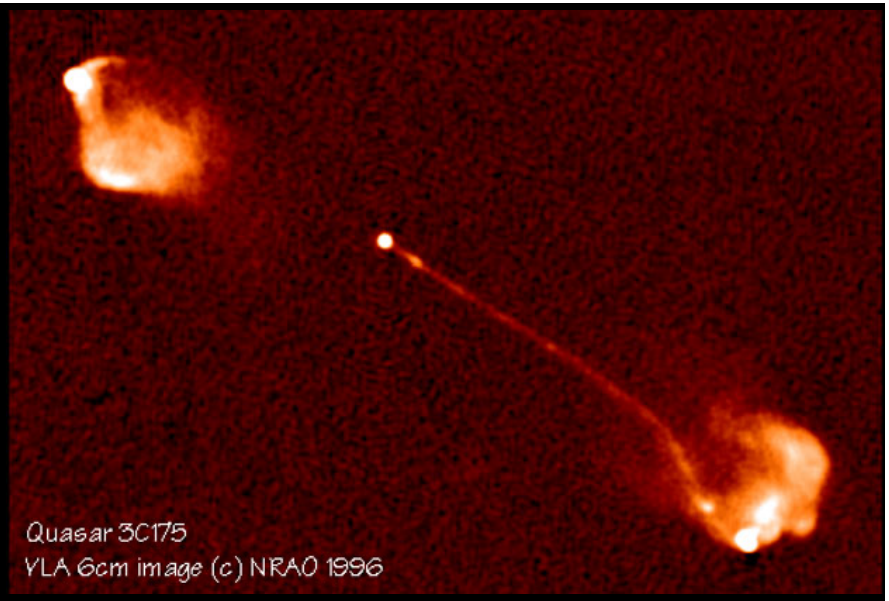
- Some start bright and then darken to edge

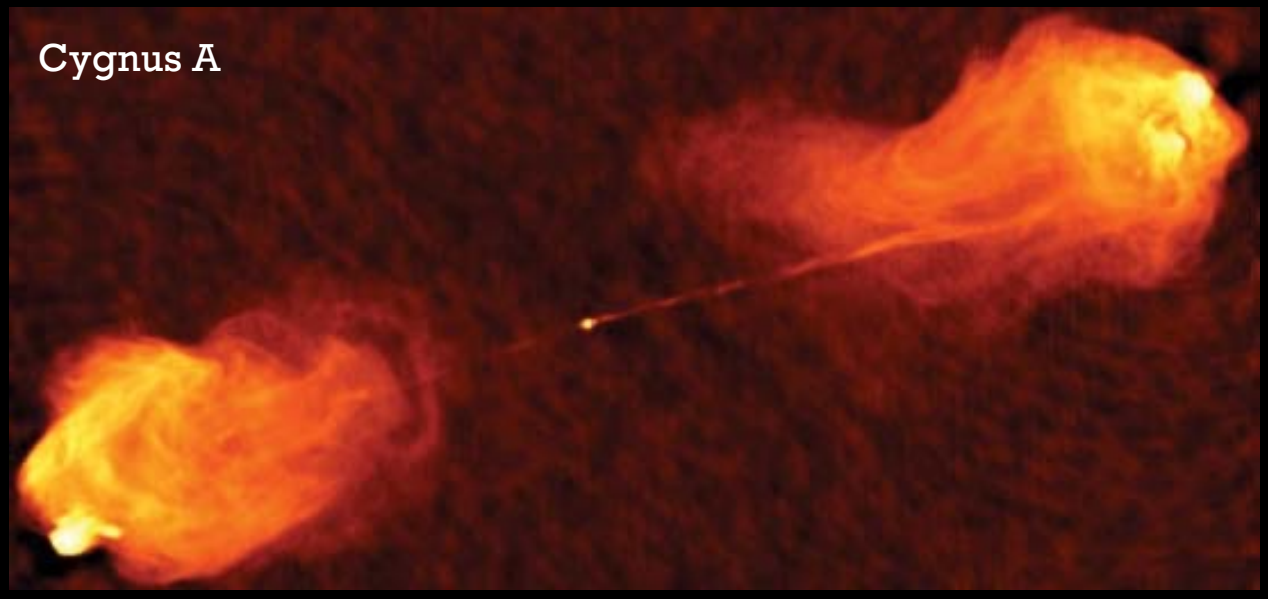


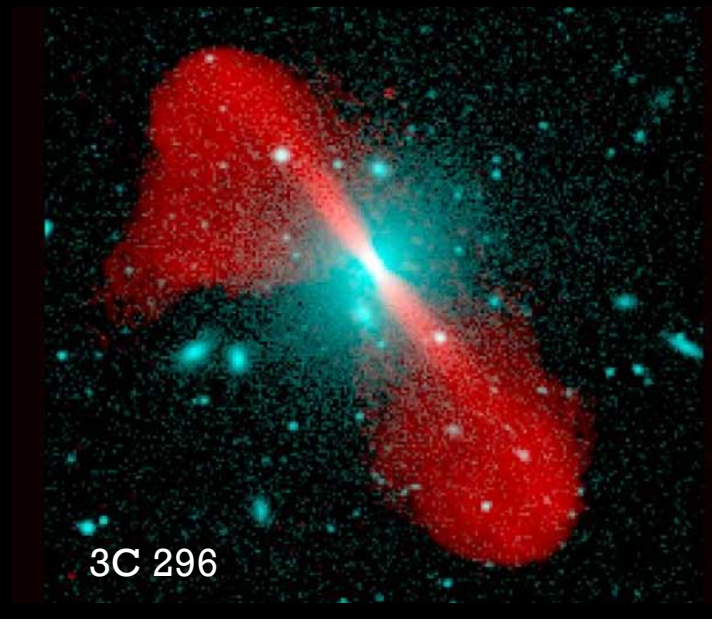


THE MANY LOOKS OF JETS

- Some start dim and then brighten to edge



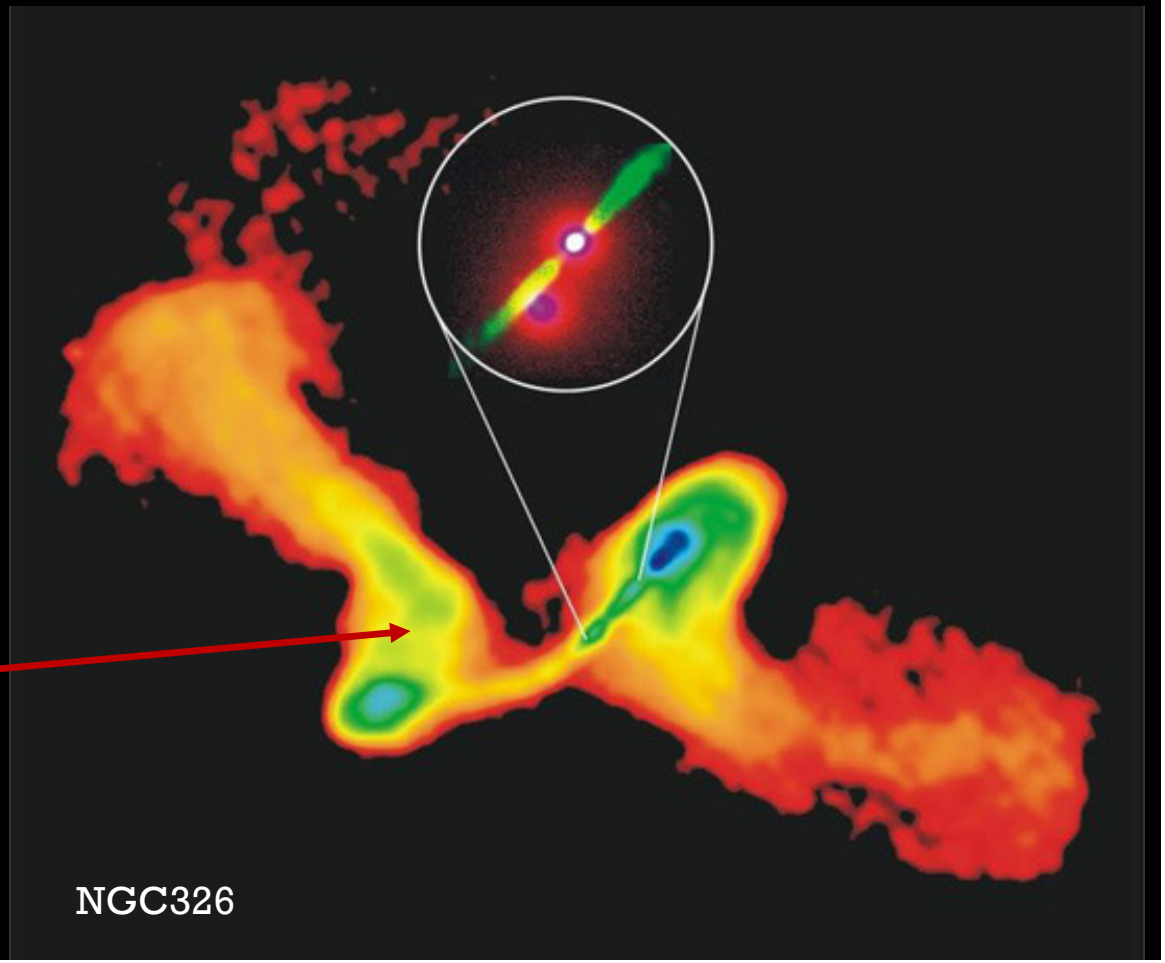




THE MANY LOOKS OF JETS

- Some just look weird!

- ***The X-shaped radio galaxies could form due to jet reorientation or interactions with motions in the ambient gas***



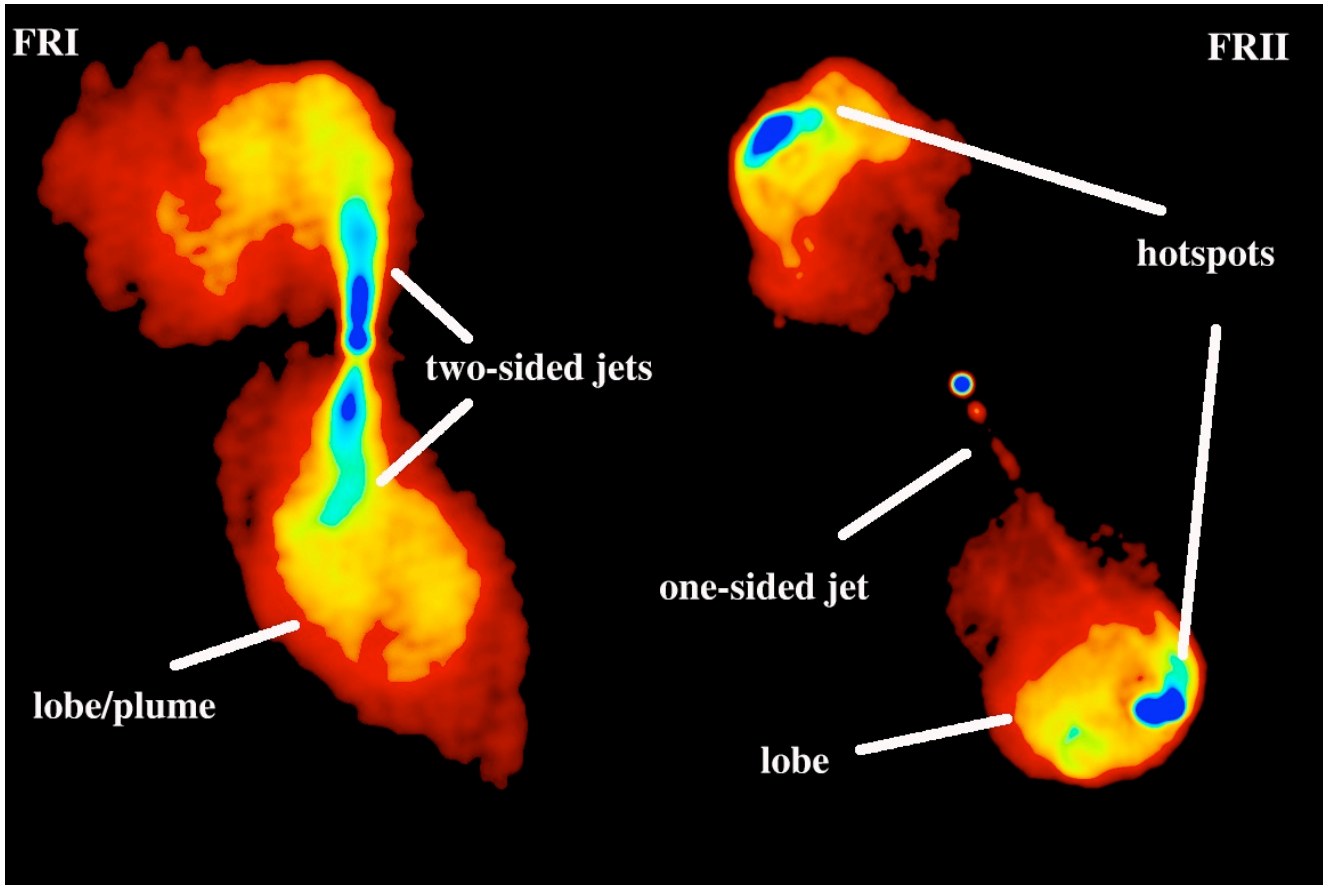
THE MANY LOOKS OF JETS

- Some just look weird!

- ***The "head-tail" radio sources are swept back because the galaxy is moving through the ambient medium***

TWO TYPES OF RADIO GALAXIES -- FRI & FRII

- Fanaroff-Riley (FR) types (1974)
- ***FRI***:
  - Brighter towards center
  - Two-sided jets
  - Plumes (羽狀結構) /lobes
  - Lower jet power (L_{bol} <~ 10^{42} erg/s)
- ***FRII***:
  - Edge-brightened
  - One-sided jets
  - Lobes (瓣狀結構)
  - Hot spots
  - Higher jet power (L_{bol} >~ 10^{42} erg/s)

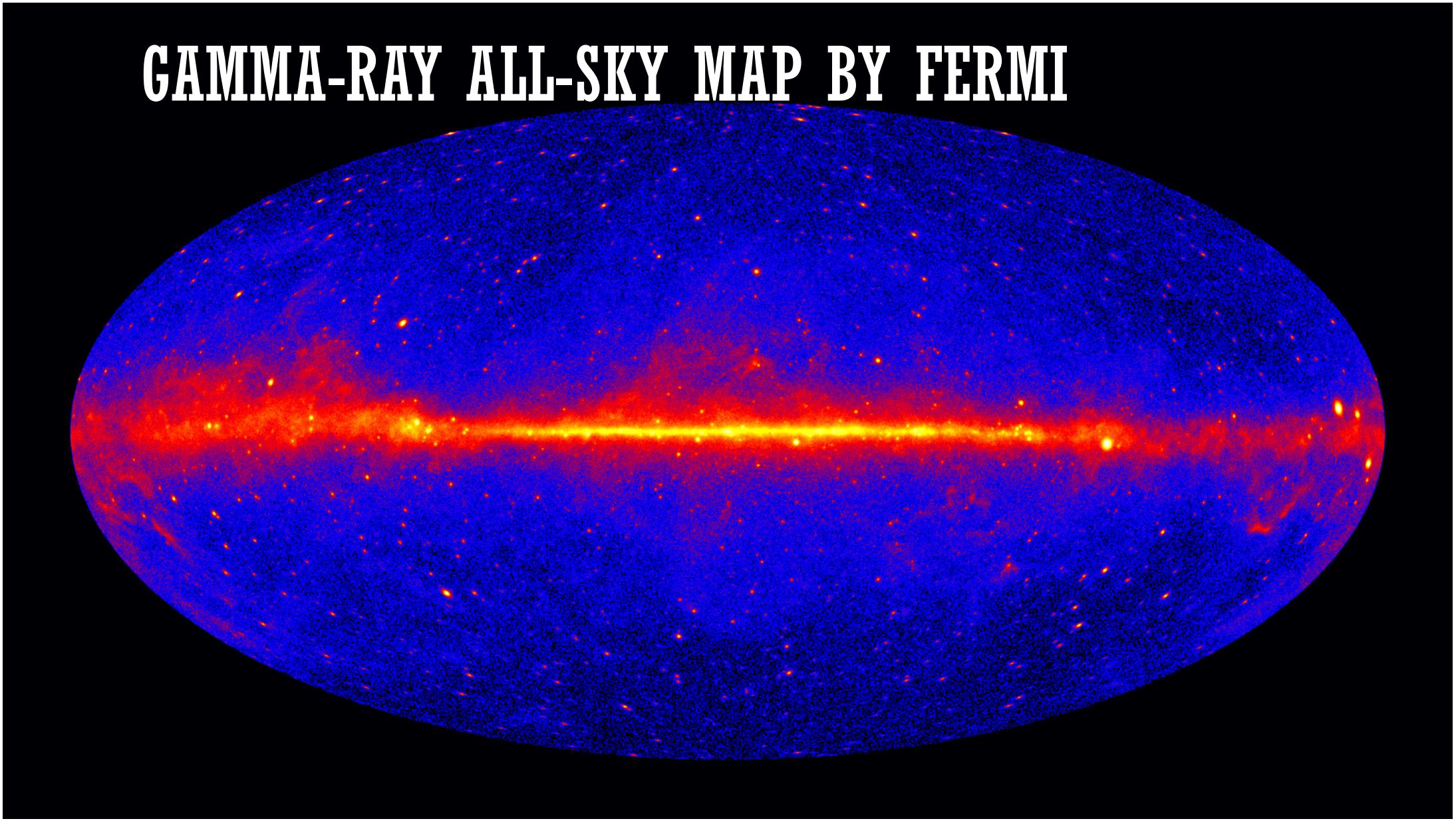


BLAZARS

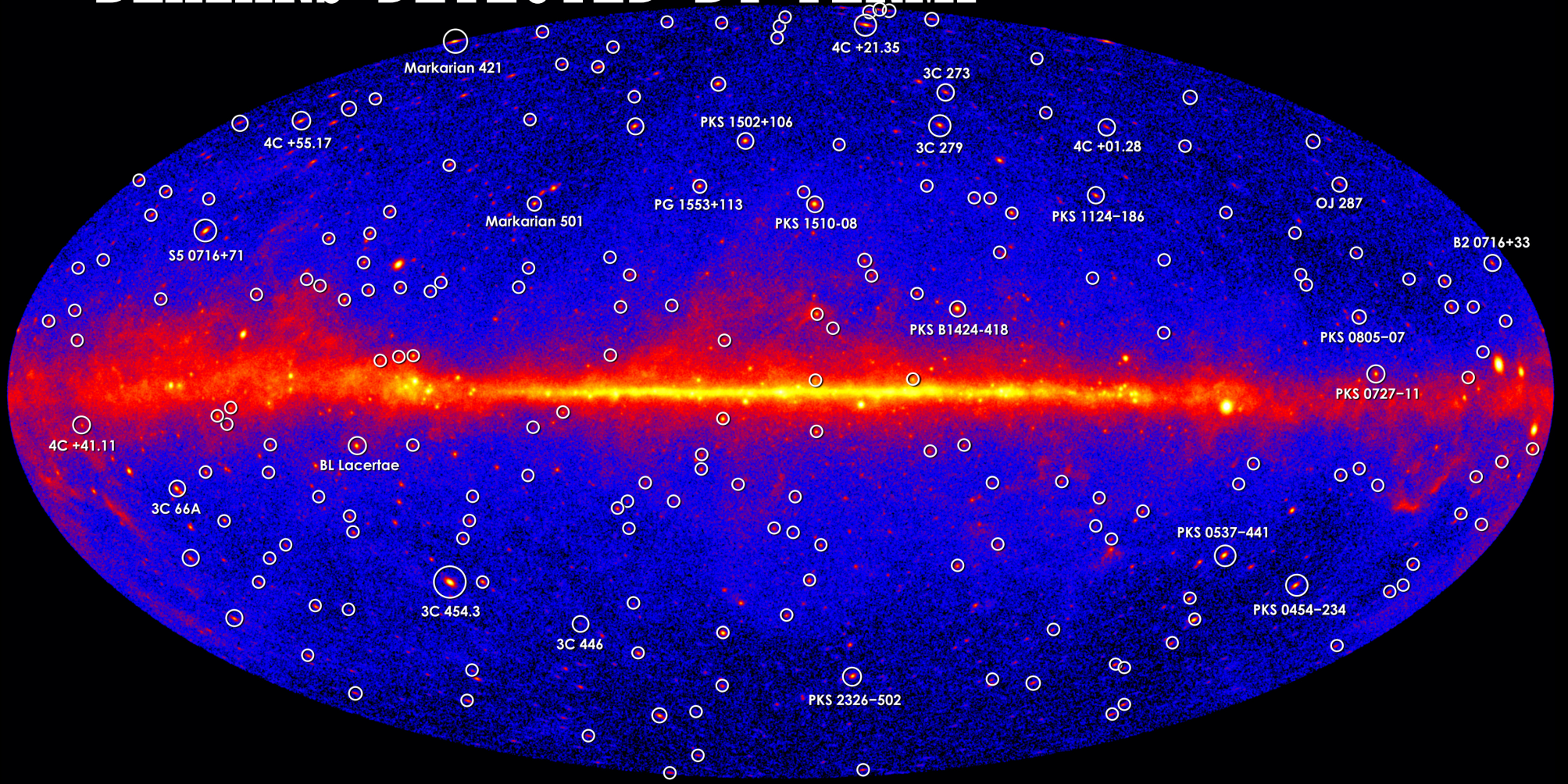
Conception of a blazar

- Blazars are radio-loud AGNs with jets pointing to us
- Very bright due to relativistic beaming
- Highly variable (on hours-days timescales)
- Two types: BL Lac (analog of FRI jets) and FSRQ (flat spectrum radio quasars, analog of FRII jets)
- One of the important sources in the gamma-ray sky

GAMMA-RAY ALL-SKY MAP BY FERMI

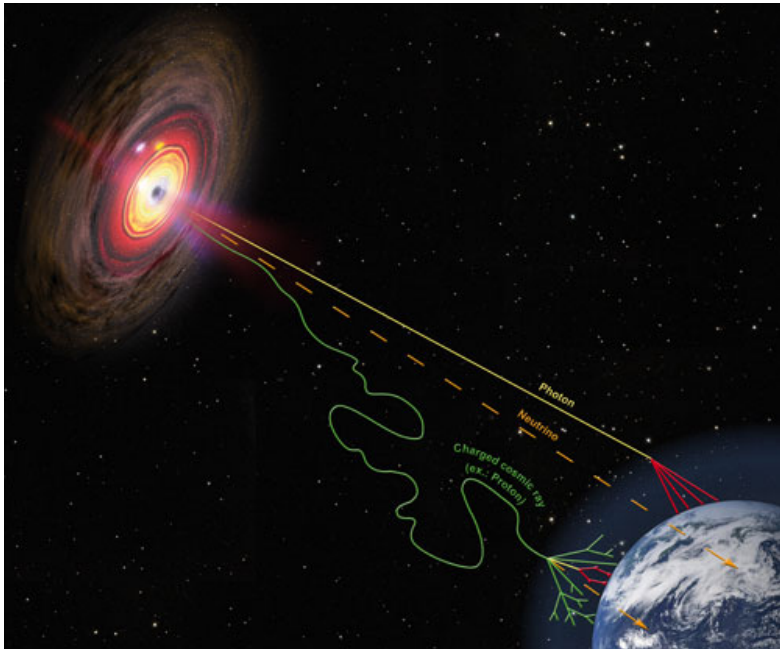


BLAZARS DETECTED BY FERMI



BLAZARS ARE SOURCES FOR HIGH-ENERGY NEUTRINOS

- On Sep. 22, 2017, the ***IceCube*** Neutrino Observatory detected a high-energy neutrino near the constellation Orion
- They sent alerts to the community and ~20 observatories made follow-up observations
- It is detected in gamma-rays, X-rays, optical and radio
- This event was found to coincide with blazar TXS 0506+056
- This is the first evidence that blazars (aka AGN jets) could produce high-energy neutrinos!
- This shows the power of the ***multi-messenger*** astrophysics



Blazar as one source of high-energy cosmic rays and neutrinos

**Read more about this event by clicking here

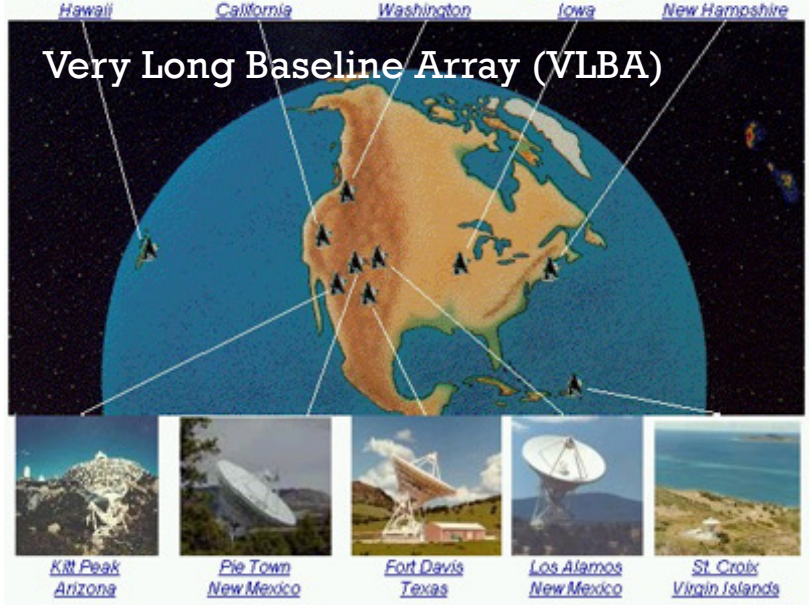
THANKS TO RADIO TELESCOPES

- Telescope resolution limited by diffraction (繞射):

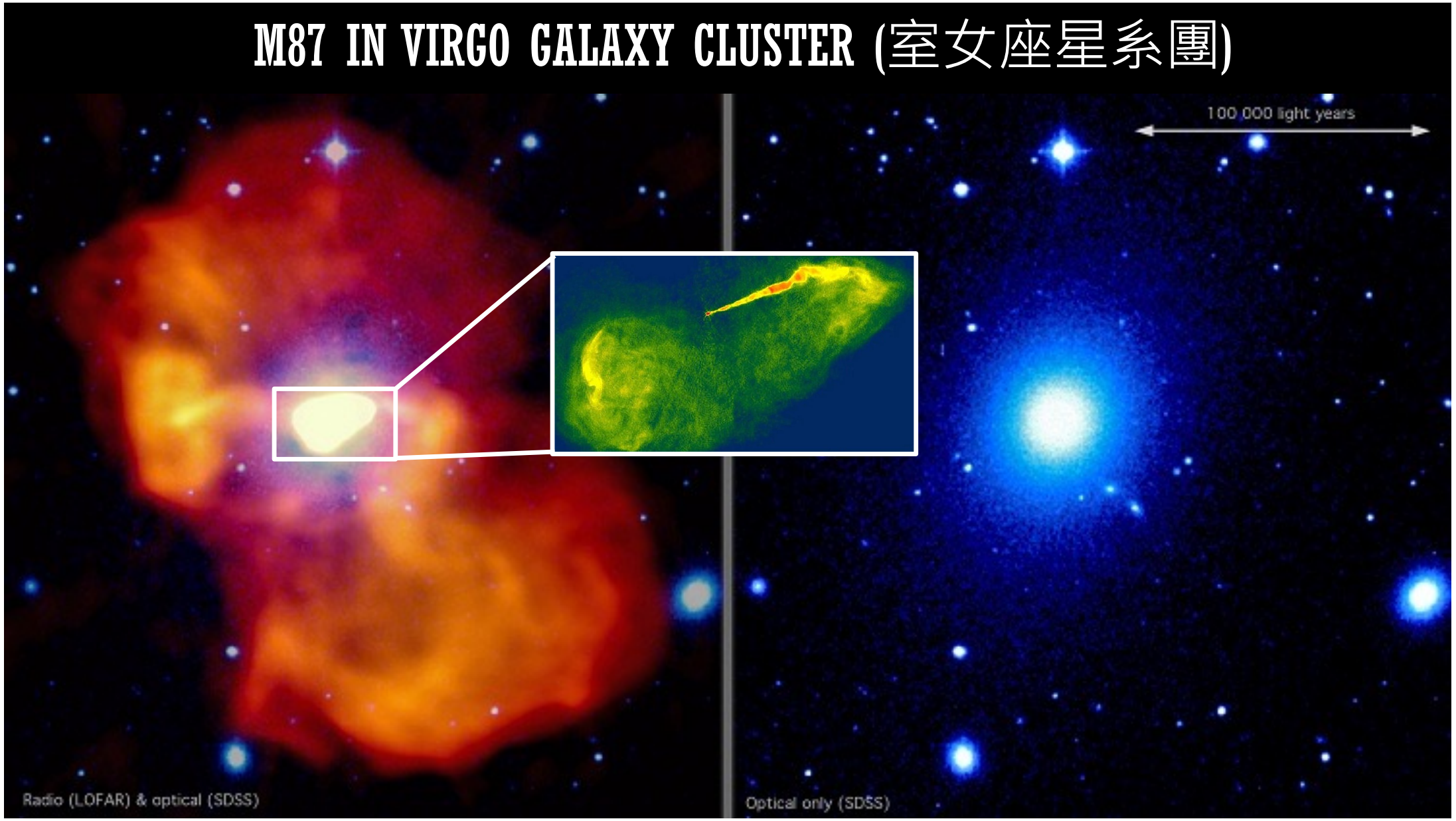
  $\theta \propto \lambda/D$

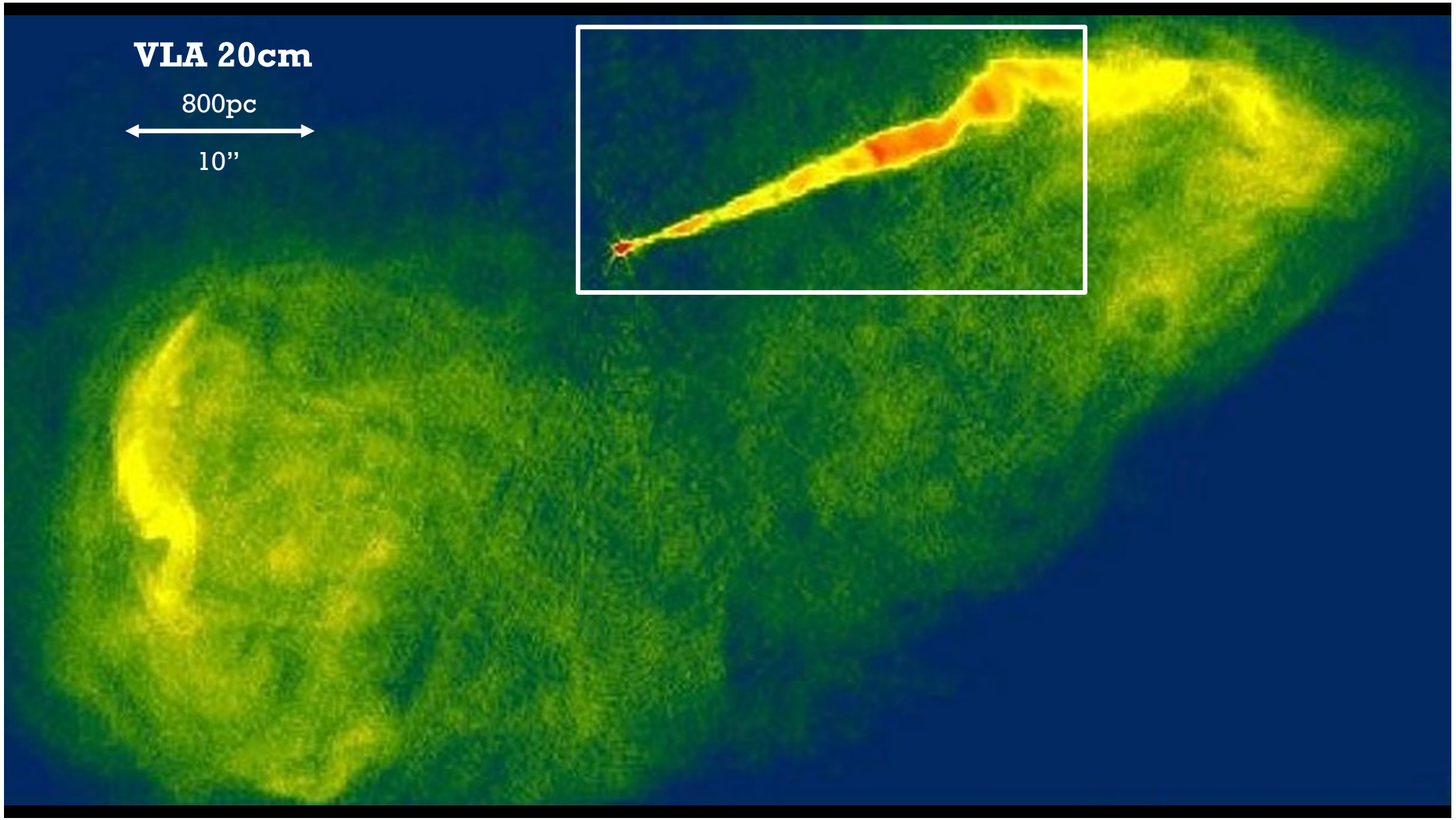
- Can reach higher resolution by observing at shorter wavelengths or by increasing D, e.g., linking radio telescopes across the globe
- Can reach resolutions of <1 milliarcsec using ***Very Long Baseline Interferometry (VLBI)!***

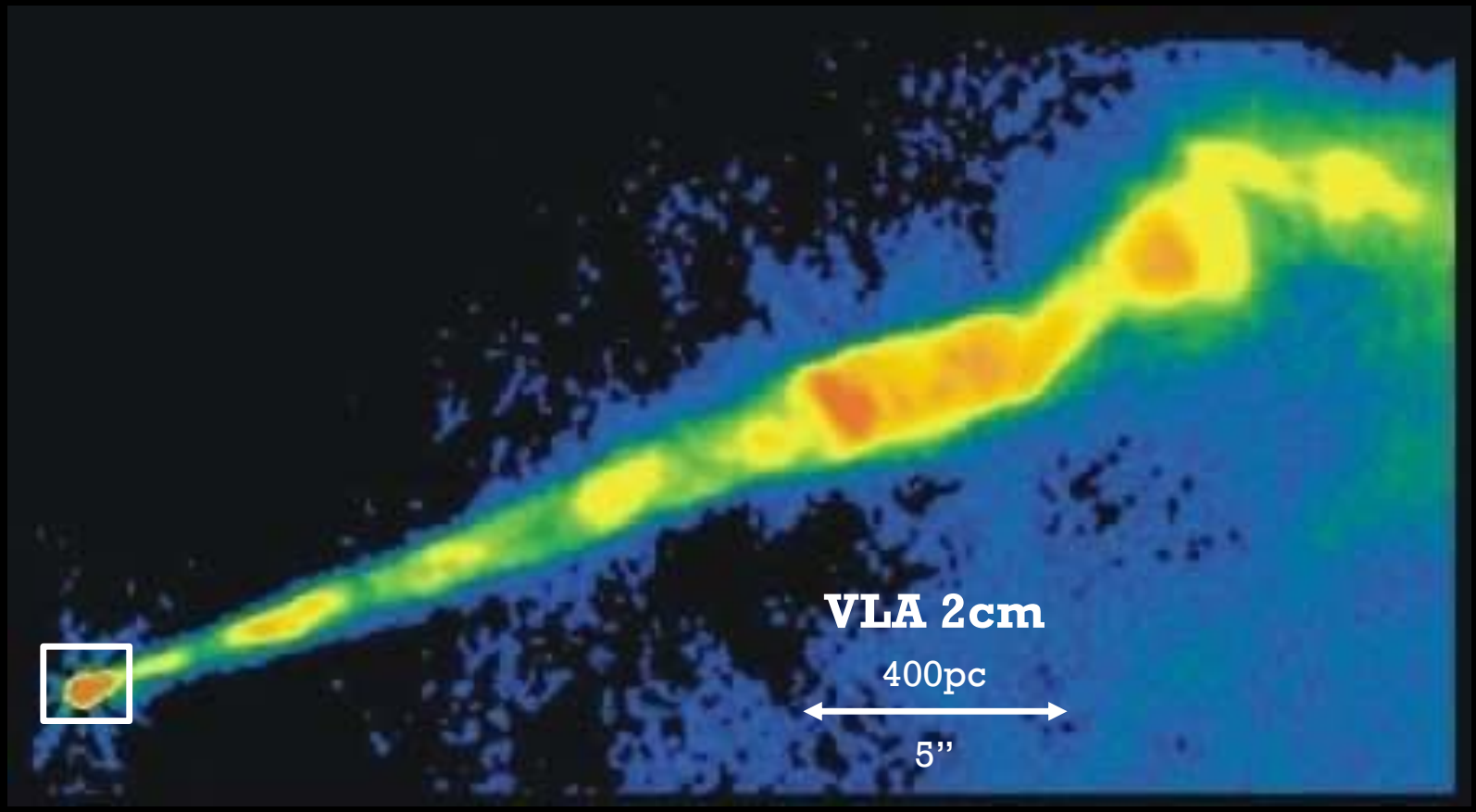
Because of diffraction, a point source would be blurred into a disk, limiting our ability to resolve two sources

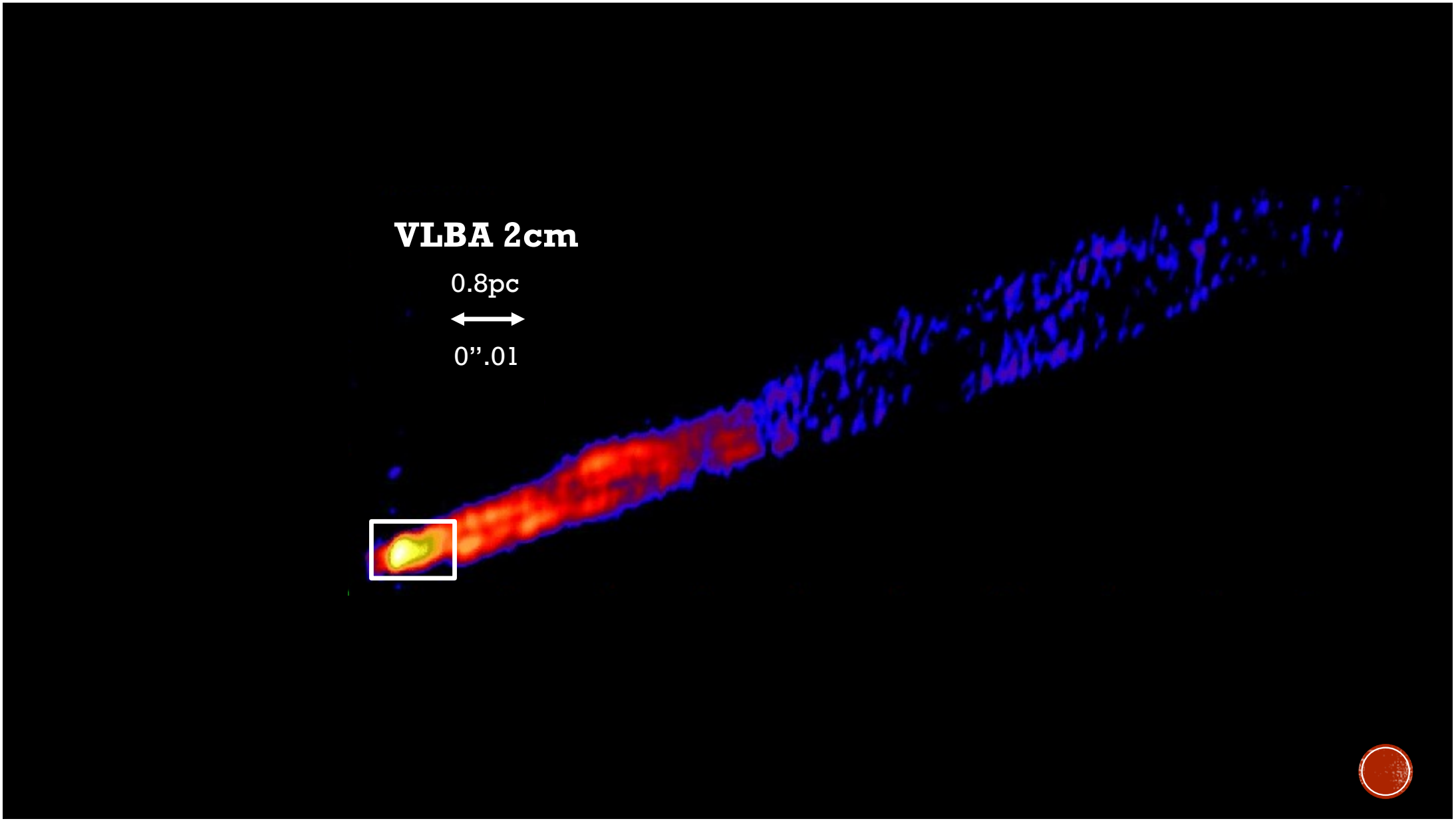


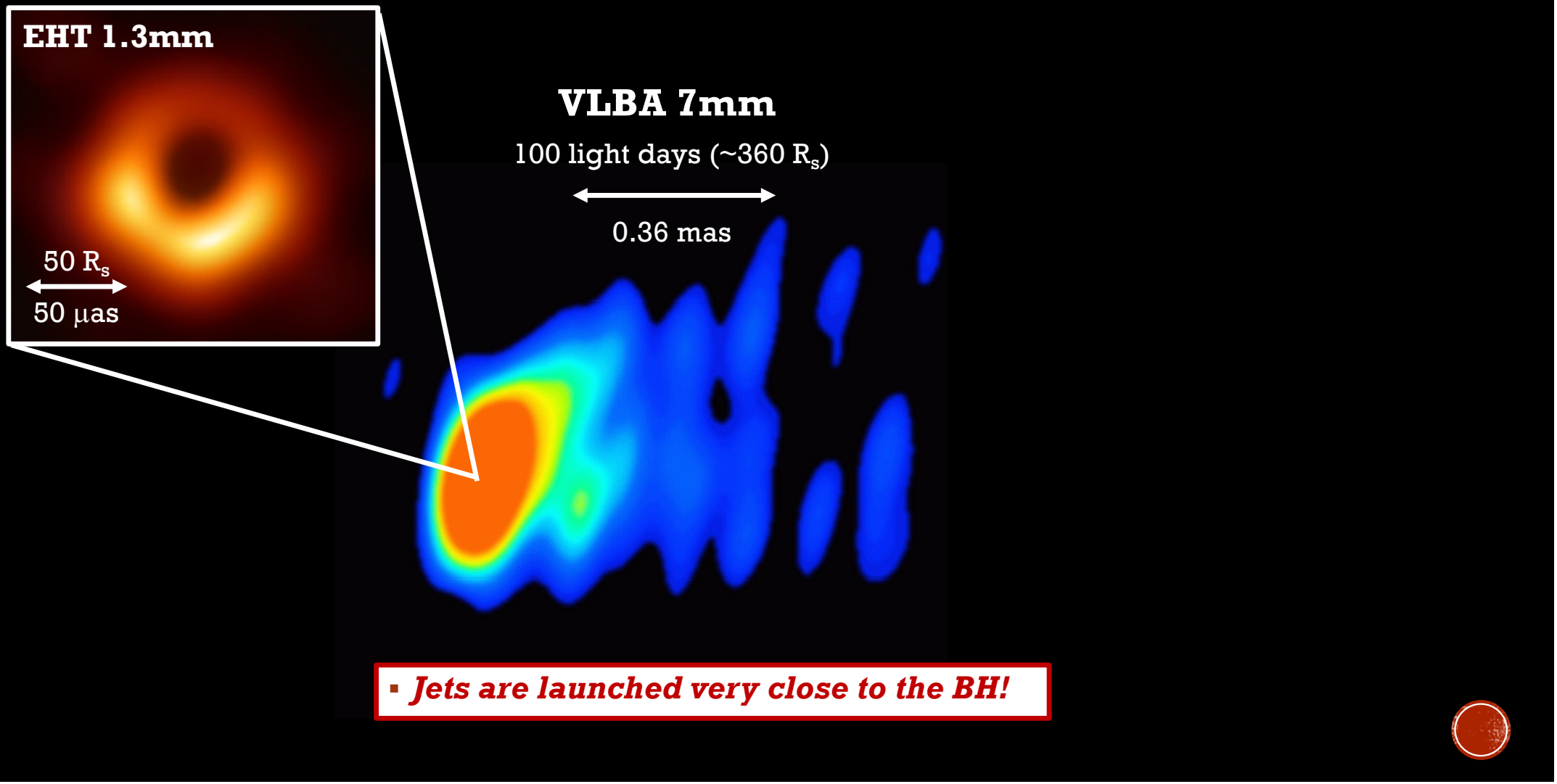
M87 IN VIRGO GALAXY CLUSTER (室女座星系團)




VLA 20cm
800pc
10”


VLA 2cm
400pc
5”

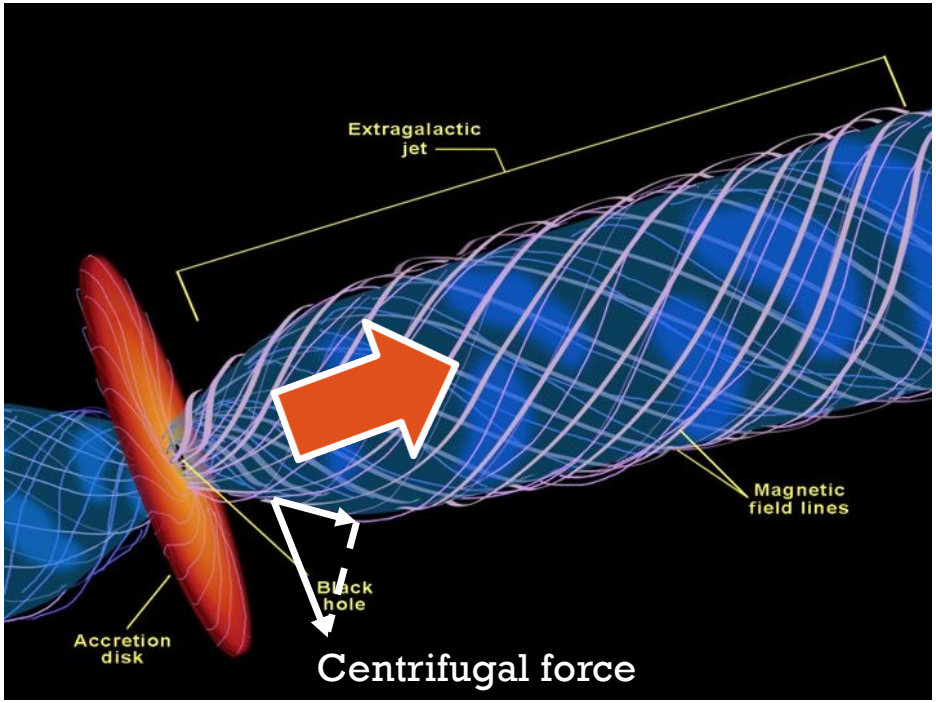

VLBA 2cm
0.8pc
0”.01



- ***Jets are launched very close to the BH!***

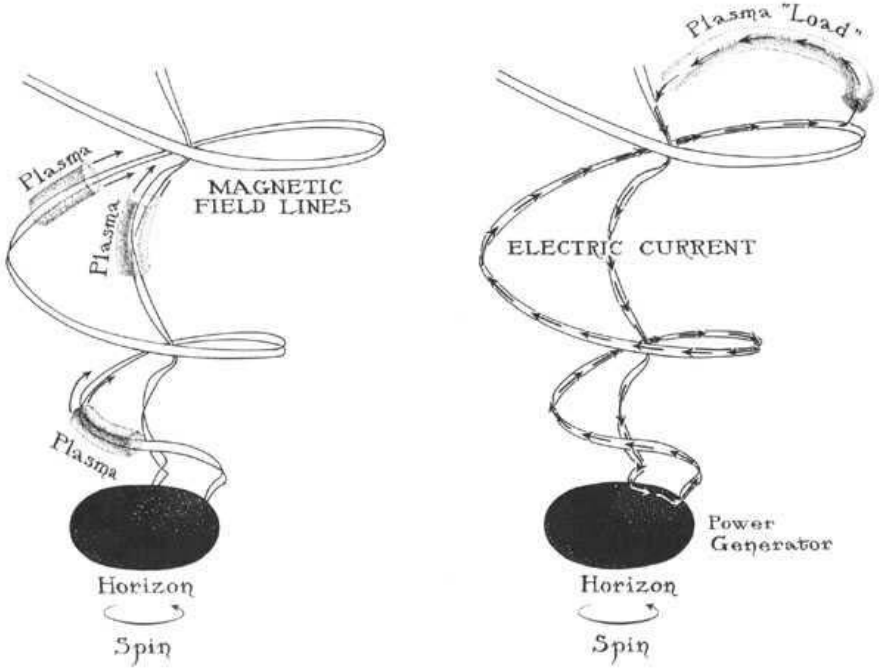
HOW ARE JETS FORMED?

HOW ARE JETS FORMED?



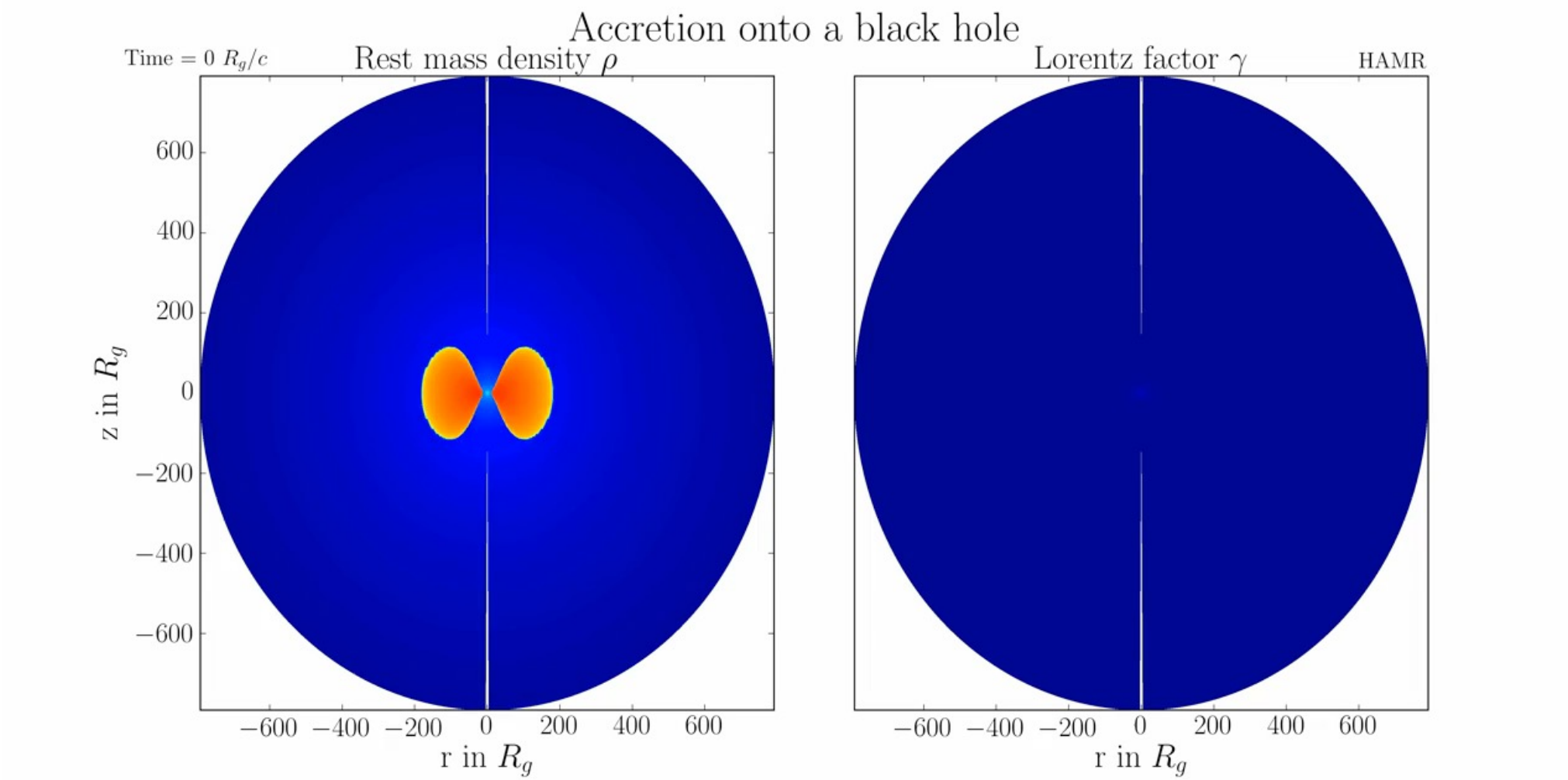
- ***Blandford and Payne (BP) mechanism (1982)*** – outflows driven by ***magneto-centrifugal force***
- As gas in the accretion disk approach the BH, the rotation would drag and twist the magnetic field
- The centrifugal force would fling materials outward along field lines
- The tightly wound magnetic fields would tend to unwind and exert pressure force to accelerate the gas outward
- Jet energy comes from rotational energy of accretion disk

HOW ARE JETS FORMED?



- ***Blandford-Znajek (BZ) mechanism (1977)*** – jets driven by ***BH spin***
- Magnetic field carried by the accretion disk within the ergosphere twisted due to the frame-dragging effect
- Electric field is induced due to the rotating magnetic field lines, developing a voltage difference between the poles and the equator like a battery
- The electric current driven by the voltage drop can extract energy from the BH spin and transformed into outflowing jets
- Jet energy comes from the BH spin energy

GRMHD SIMULATION OF JET LAUNCHING

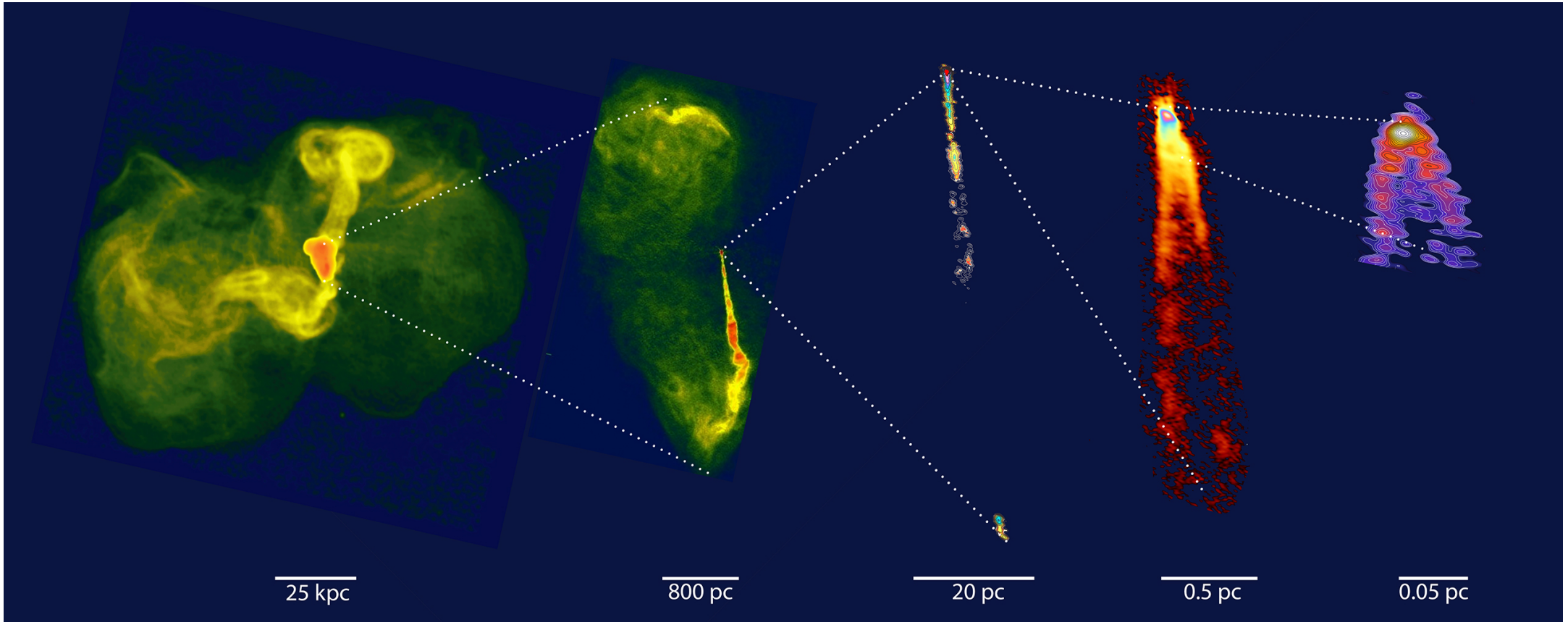


Credit: M. Liska & A. Tchekhovskoy

HOW DO JETS PROPAGATE TO LARGE DISTANCES?

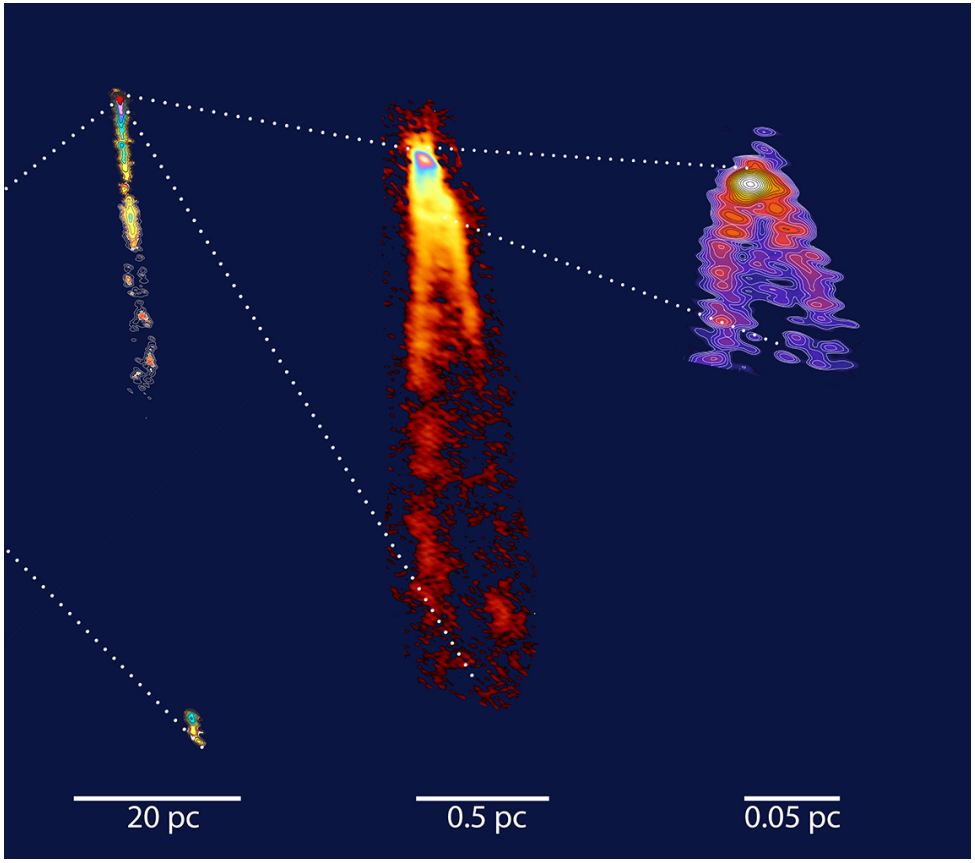
THE EXTREME RANGE OF SCALES OF JETS

For M87, M_{BH} = 6.5x10^9 M_{sun}, d = 16Mpc, 1 milliarcsec ~ 0.1pc ~ 160 Rs, R_{inf} ~ 4x10^5 Rs ~ 300pc



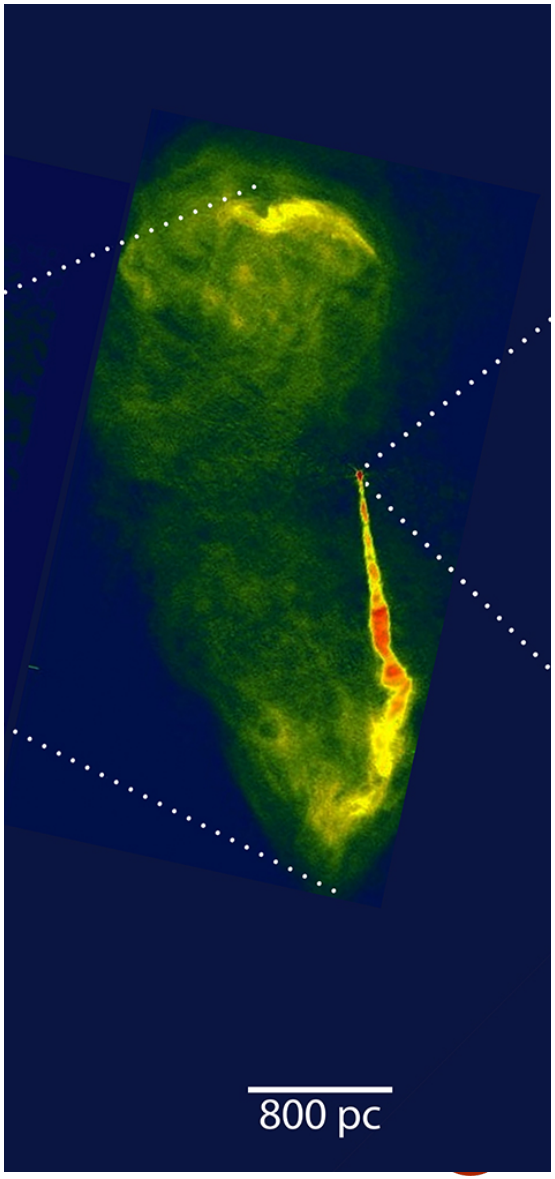
(I) SMALL SCALES -- BLACK HOLE JETS

- ***Black hole jets: Rs < R < R_{inf}***, where R_{inf} is the BH sphere of influence
- On this scale, the jet dynamics is dominated by BH potential & inflow/outflow of the accretion disk
- After jets are launched, they can be further ***accelerated***
  - For example, the M87 jets accelerate from ~0.01c at ~200 Rs to ~6c at R_{inf}, and decelerate afterwards
- On this scale, the jets can be ***collimated*** by outflows from the accretion disk



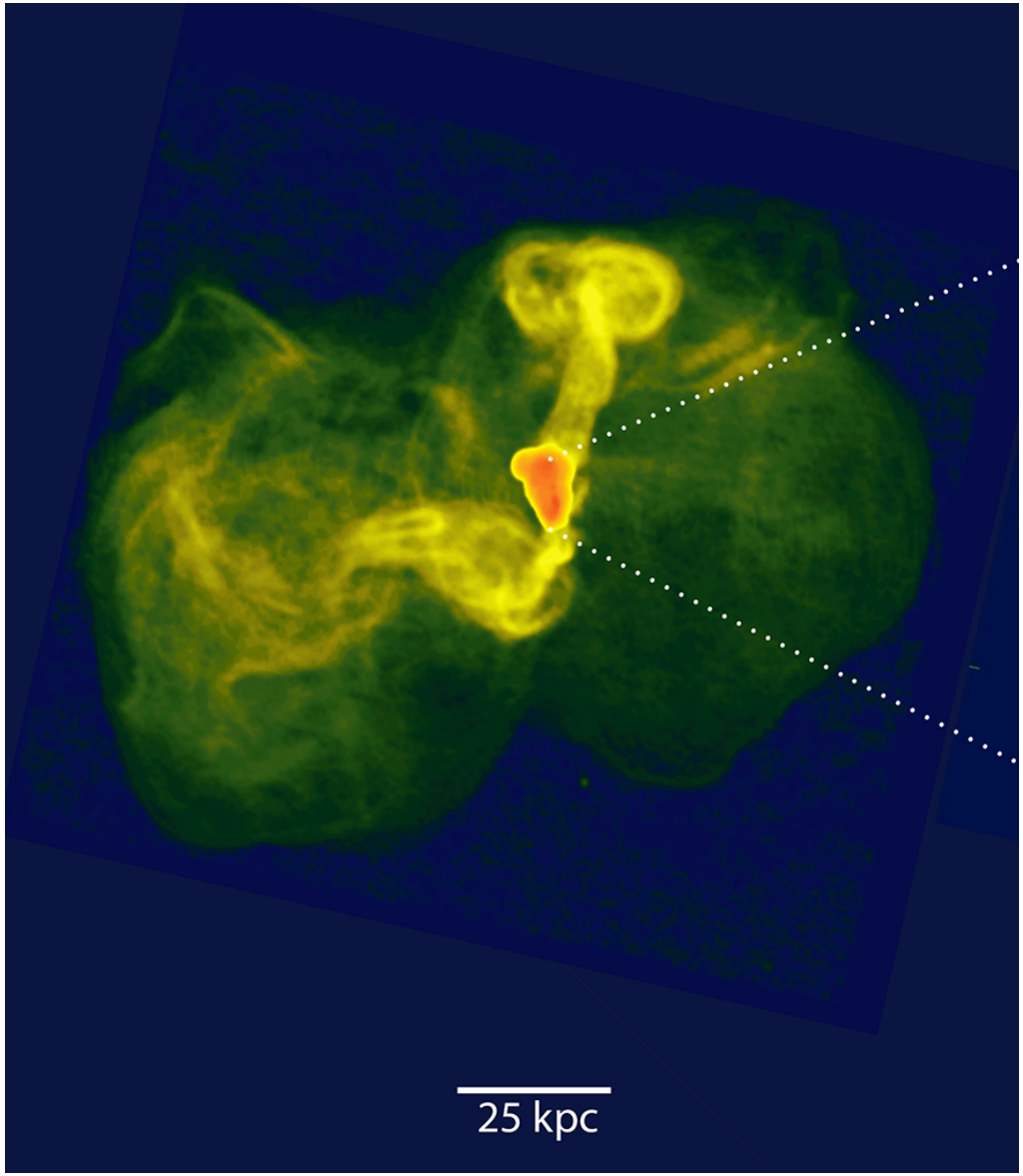
(II) INTERMEDIATE SCALES – GALAXY JETS

- ***Galaxy jets:*** $R_{inf} < R < 0.1\ R_{lobe}$, where R_{lobe} is the size of the lobes
- On this scale, the jet dynamics is dominated by stellar/dark matter potential within the host galaxy
- Many jets show superluminal motions on this scale, meaning that they have been accelerated before reaching R_{inf}



(III) LARGE SCALES – LOBE JETS

- ***Lobe jets: 0.1 R_{lobe} < R < R_{lobe}***
- Controlled by interaction between the jets and the circumgalactic medium
- This is the scale where we could clearly see the morphological difference of FR1 vs. FRII jets



SOME OPEN QUESTIONS

- Observational evidences for BZ or BP mechanisms?
  - No strong evidence for spin dependence of jet power predicted by the BZ theory
- Why do some AGN have jets and others do not? What are the optimal conditions/environments for jet formation?
  - Spin is probably not a sufficient condition; other factors (e.g., magnetic flux) are important too
  - They tend to live in elliptical galaxies (?)

SOME OPEN QUESTIONS

- What is the origin of the FRI/FRII dichotomy? Do all radio galaxies fall into one category or the other?
- What is the composition of the jets (magnetic, high-energy particles, kinetic)? How/where does the energy conversion occur?
- Can we apply what we learned from the M87 jets to other AGN jets in general?
- How do jets affect the formation and evolution of galaxies? (Lecture 12)

SUMMARY

- Jets occur in ***~10%*** of AGN and slowly-accreting X-ray binaries
- Jets emit in radio and other wavebands due to ***synchrotron radiation***
- BH jets are ***relativistic*** because we observe (1) one-sided jets due to relativistic beaming, and (2) superluminal motions
- Jets can look very different due to interactions with the ambient medium
  - ***FRI*** sources: lower power, plumes, edge-darkened
  - ***FRII*** sources: higher power, lobes, edge-brightened, hot spots
- Jet launching mechanisms:
  - ***Blandford-Payne (BP) mechanism***: outflows driven by magneto-centrifugal force from disks
  - ***Blandford-Znajek (BZ) mechanism***: jets powered by BH spin
- Jet propagation (acceleration, collimation, energy conversion) is an extreme multi-scale and complex problem!

PRESENTATIONS 5/11

- Tiny newfound 'Unicorn' is closest known black hole to Earth by Shang-Jing Lin 林上景

https://qrgo.page.link/Tkjy2

- Staring down the throat of an ancient, extremely distant black hole by Ming-Xue Xie 謝明學

https://qrgo.page.link/kceZf

- The Milky-Way's central black hole may have turned nearby red giant stars blue by Shao-Yi Guo 郭紹儀

https://qrgo.page.link/RhNNp