Radio Galaxies and their Powerful Jets

Jodi Christiansen,

Cal Poly, San Luis Obispo

jlchrist@calpoly.edu

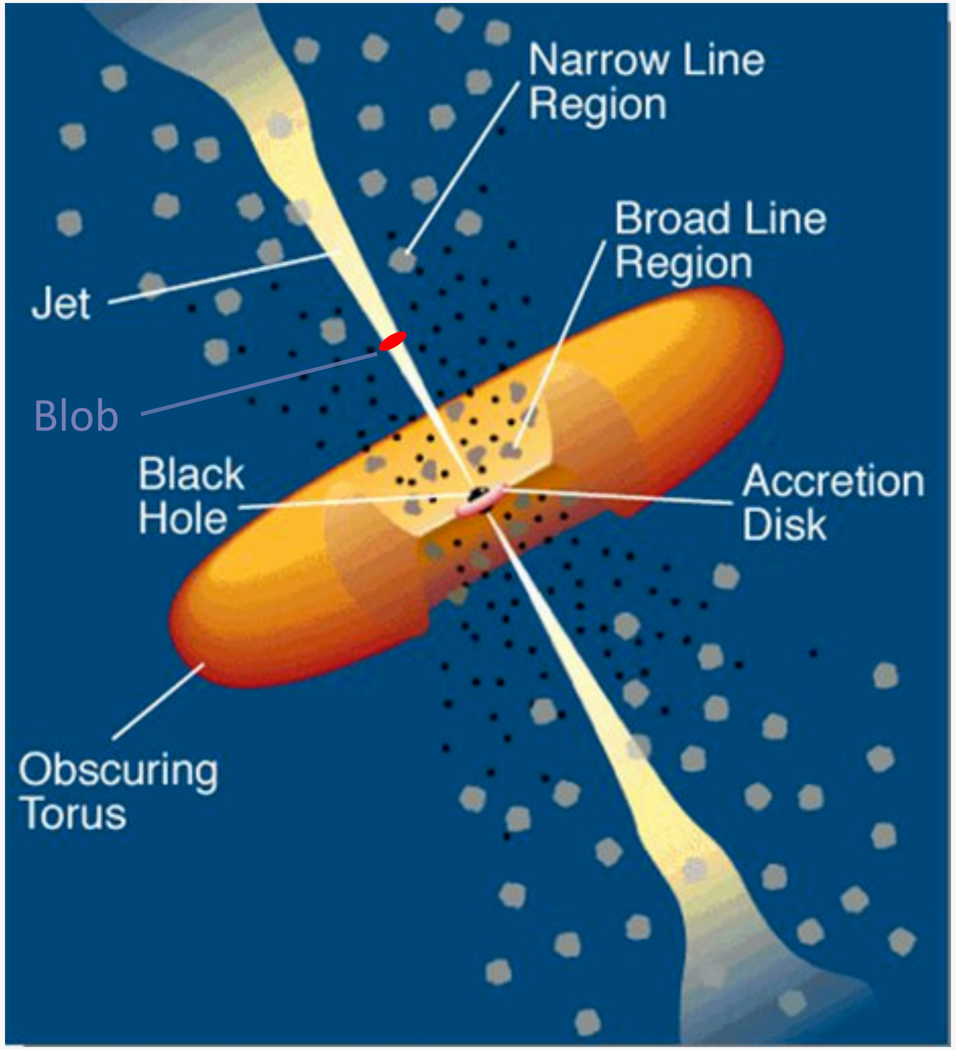
Outline

- Taxonomy of Active Galactic Nuclei (AGN)
- Physics in the jets: E&M and Special Relativity
- Example VERITAS observations of the Radio Galaxy 3C 264

Taxonomy of Active Galaxies (AGN)

Taxonomy of Active Galaxic Nuclei (AGN)

- Most large galaxies have a supermassive black hole at their center.
- Accretion disk & Obscuring Torus of molecules
- Hot gas → high velocity → doppler broadened molecular emission lines
- Cooler gas → low velocity → narrow molecular emission lines
- Jets of particles are emitted from the poles of the blackhole.
  - Blobs of electrons(e-, e+) or hadrons (n,p,pion) are injected into the jet.
  - Magnetic fields
  - Knots of radiation along the jet have also been observed.
  - Terminal Clouds

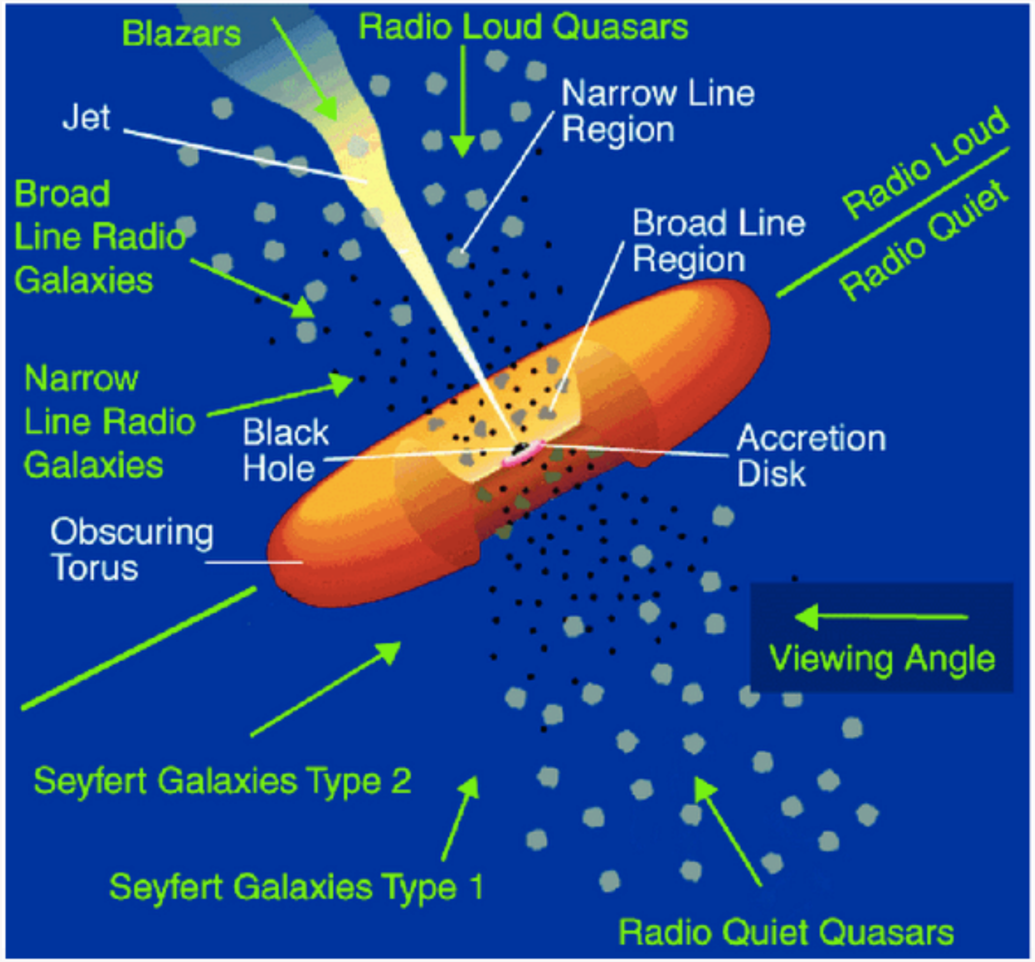


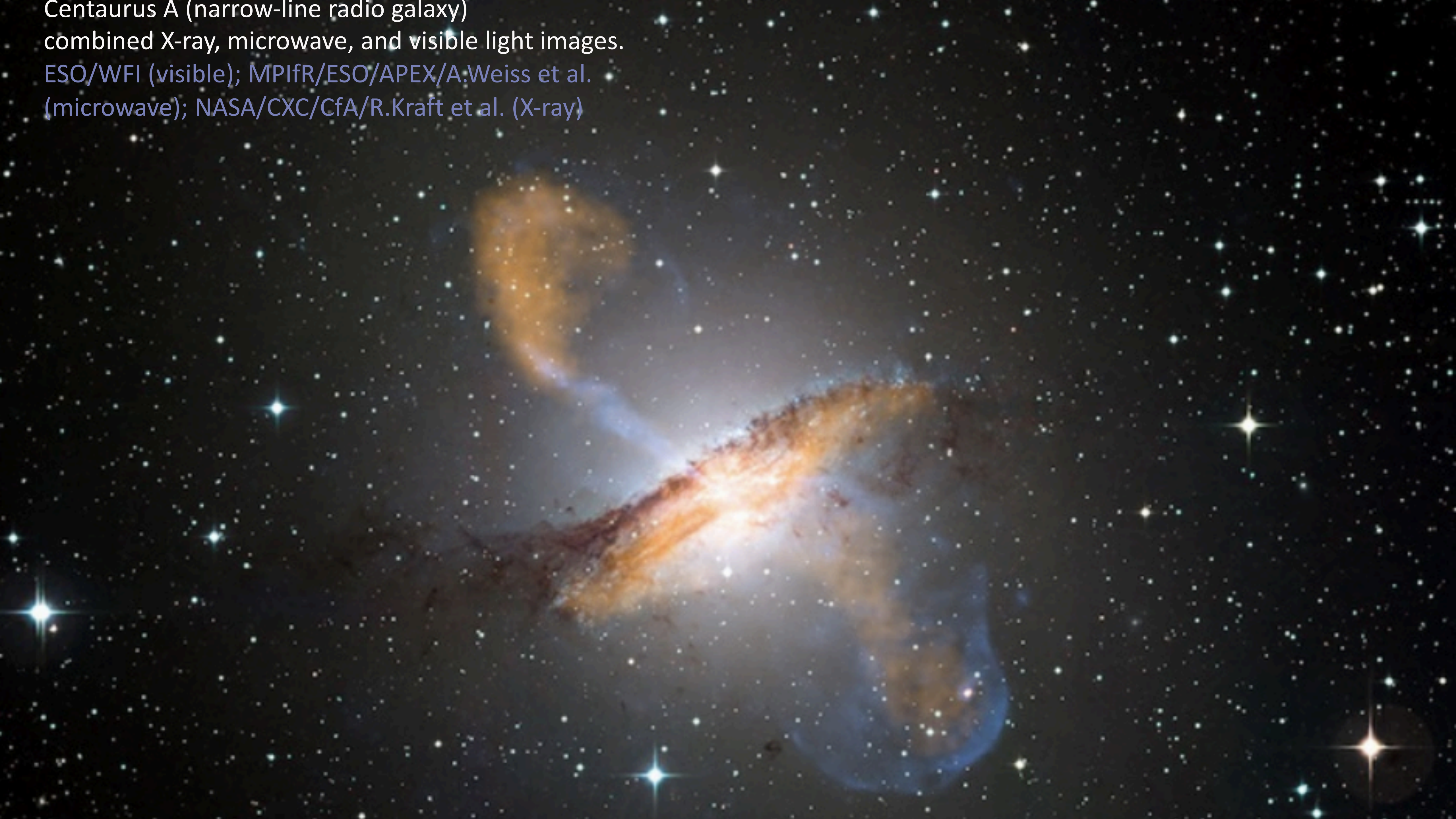
Taxonomy of Active Galaxic Nuclei (AGN)

- Astronomers observed spectra long before they knew about the taxonomy …
- Unique spectra were given different names.
- Beware. As more observations are made, the classifications are sometimes changed in the literature.

- I am interested in the Jets, so I study Blazars and Radio-Loud Quasars.

- Jets take on a variety of shapes.



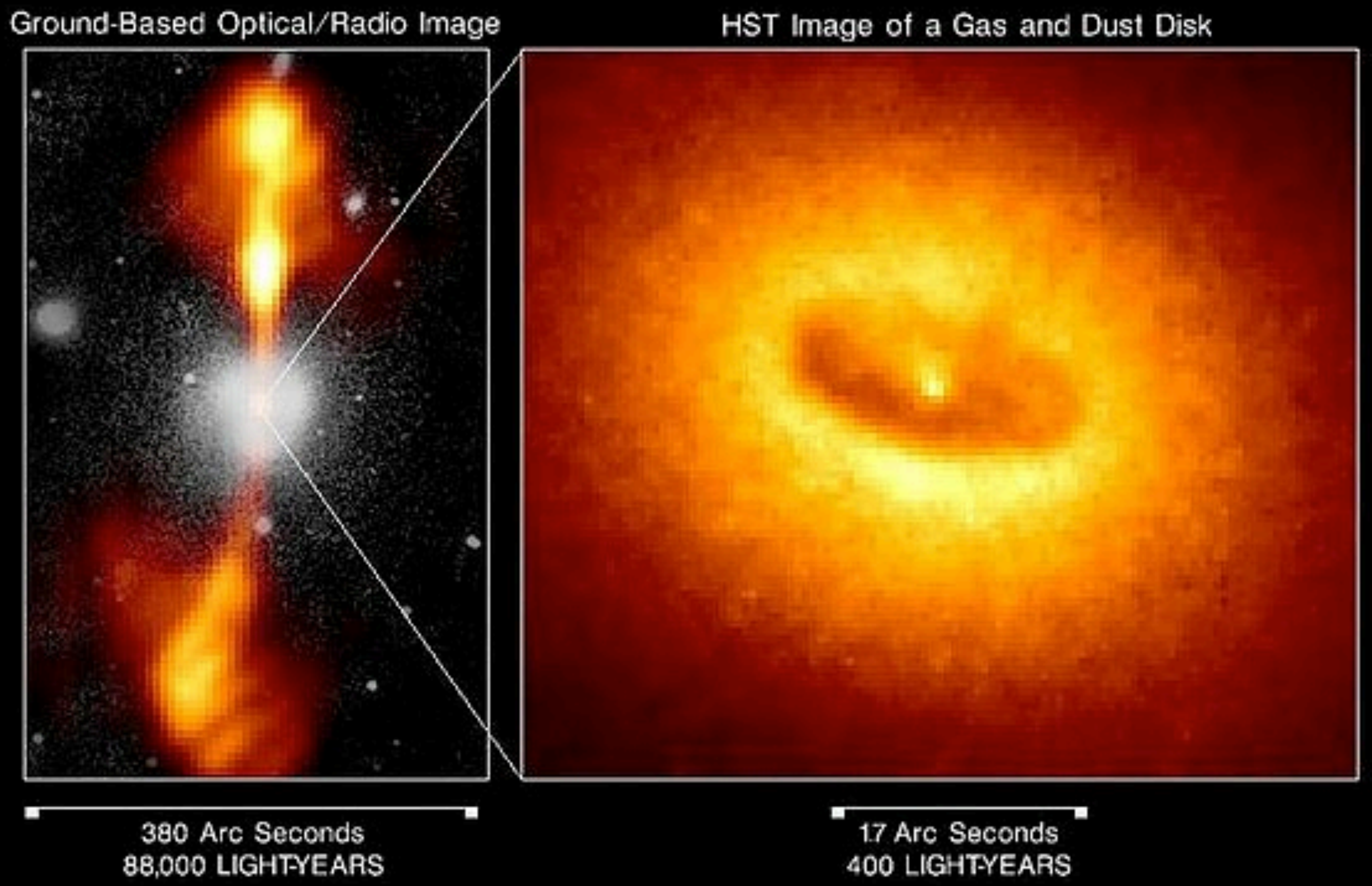


Centaurus A (narrow-line radio galaxy)
combined X-ray, microwave, and visible light images.
ESO/WFI (visible); MPIfR/ESO/APEX/A.Weiss et al. (microwave); NASA/CXC/CfA/R.Kraft et al. (X-ray)

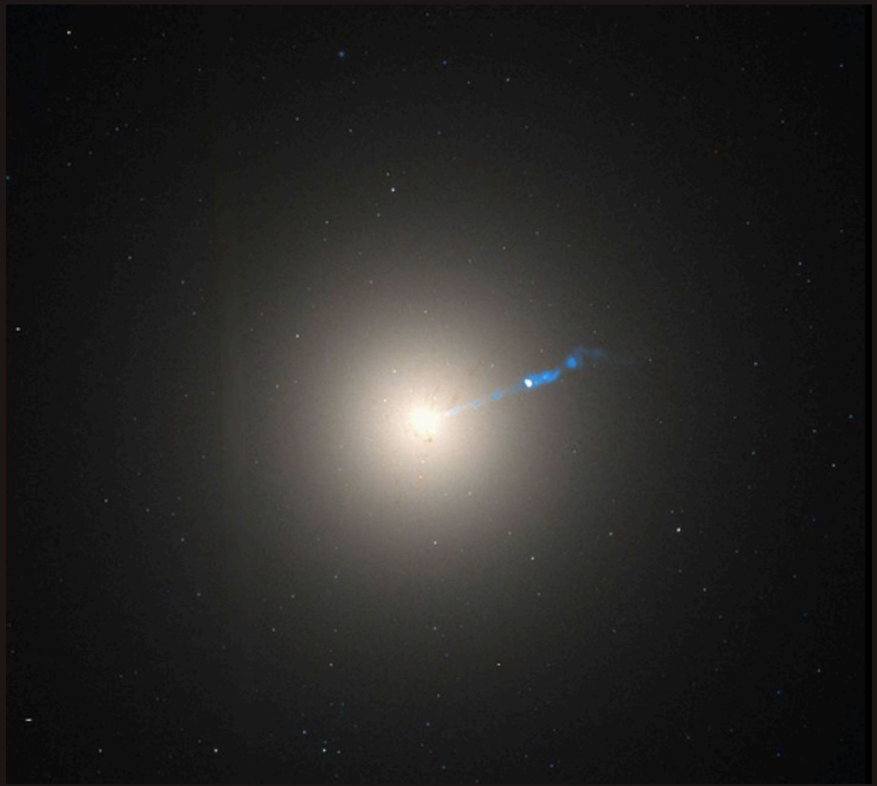
Core of Galaxy NGC 4261

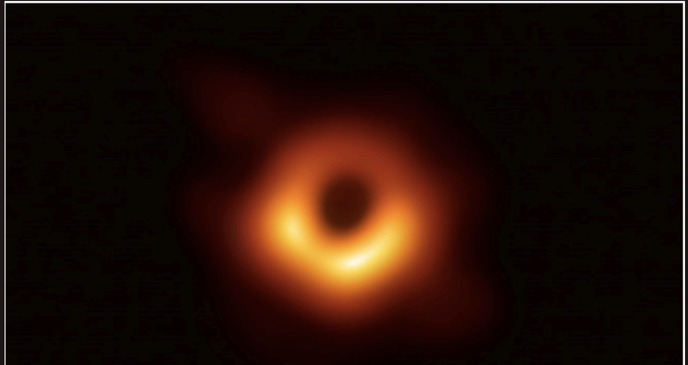
Hubble Space Telescope

Wide Field / Planetary Camera

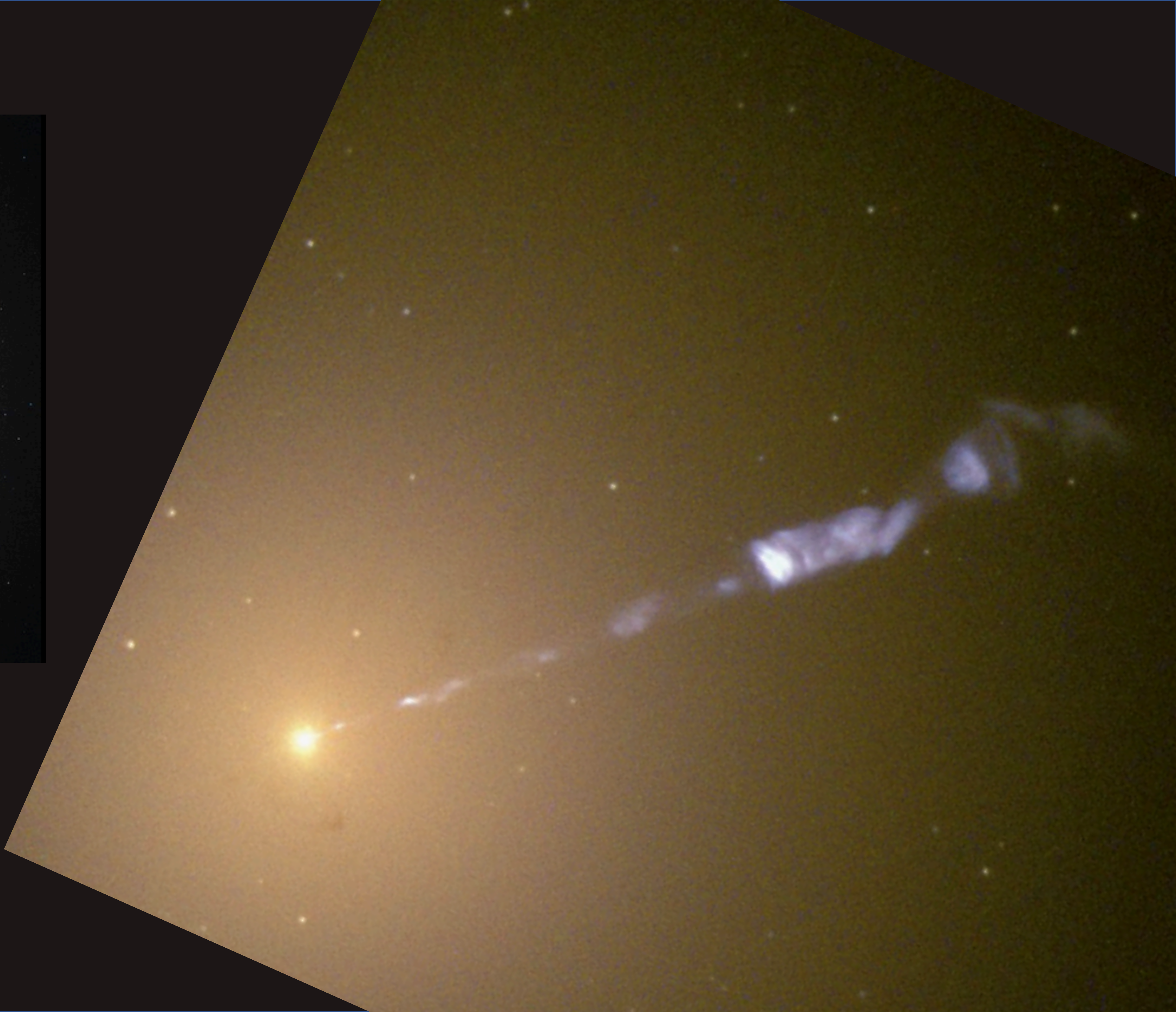


M87
Optical (Hubble Space Telescope)

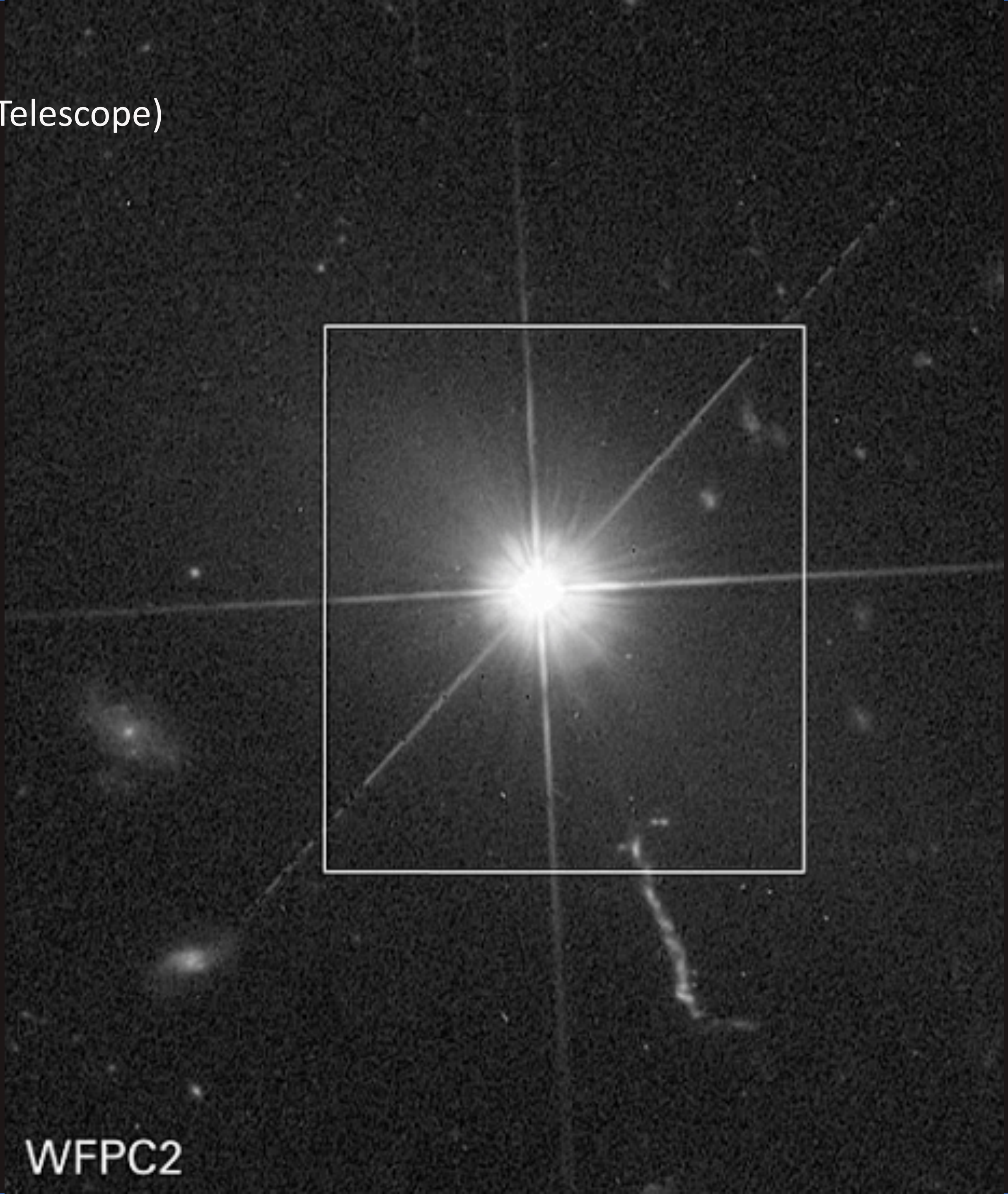




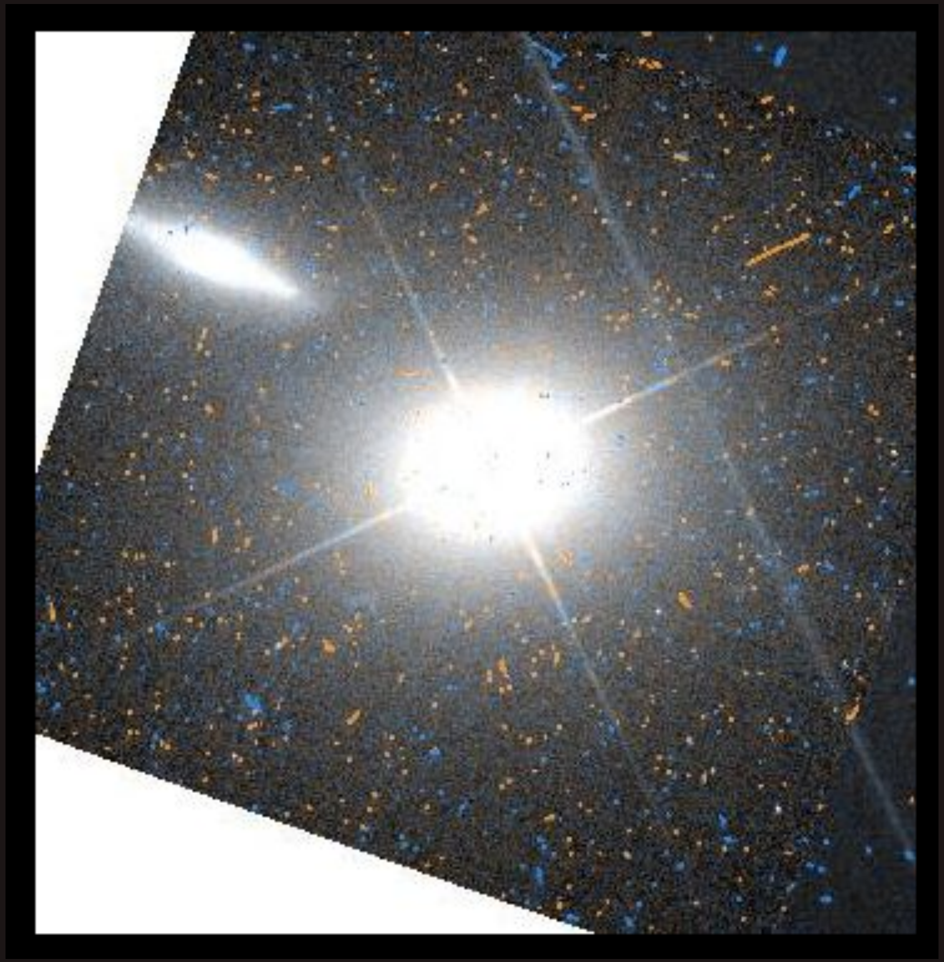
Radio (Event Horizon Telescope)

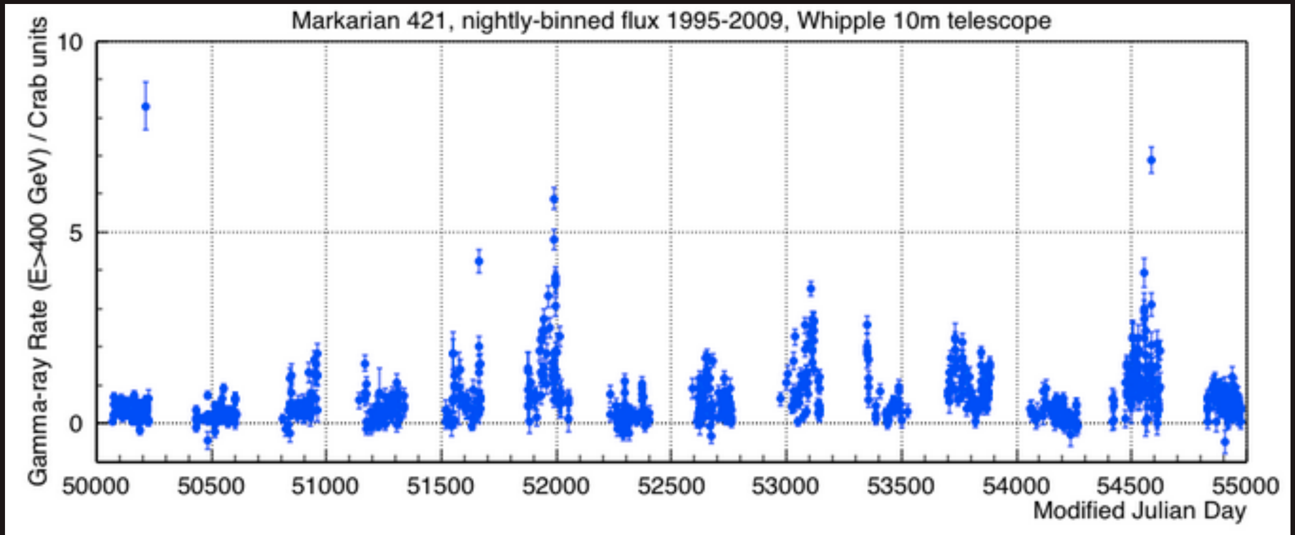


Radio Quasar: 3C 273
Optical (Hubble Space Telescope)



Blazar: Mrk 421
Optical (Hubble Space Telescope)





Physics Processes

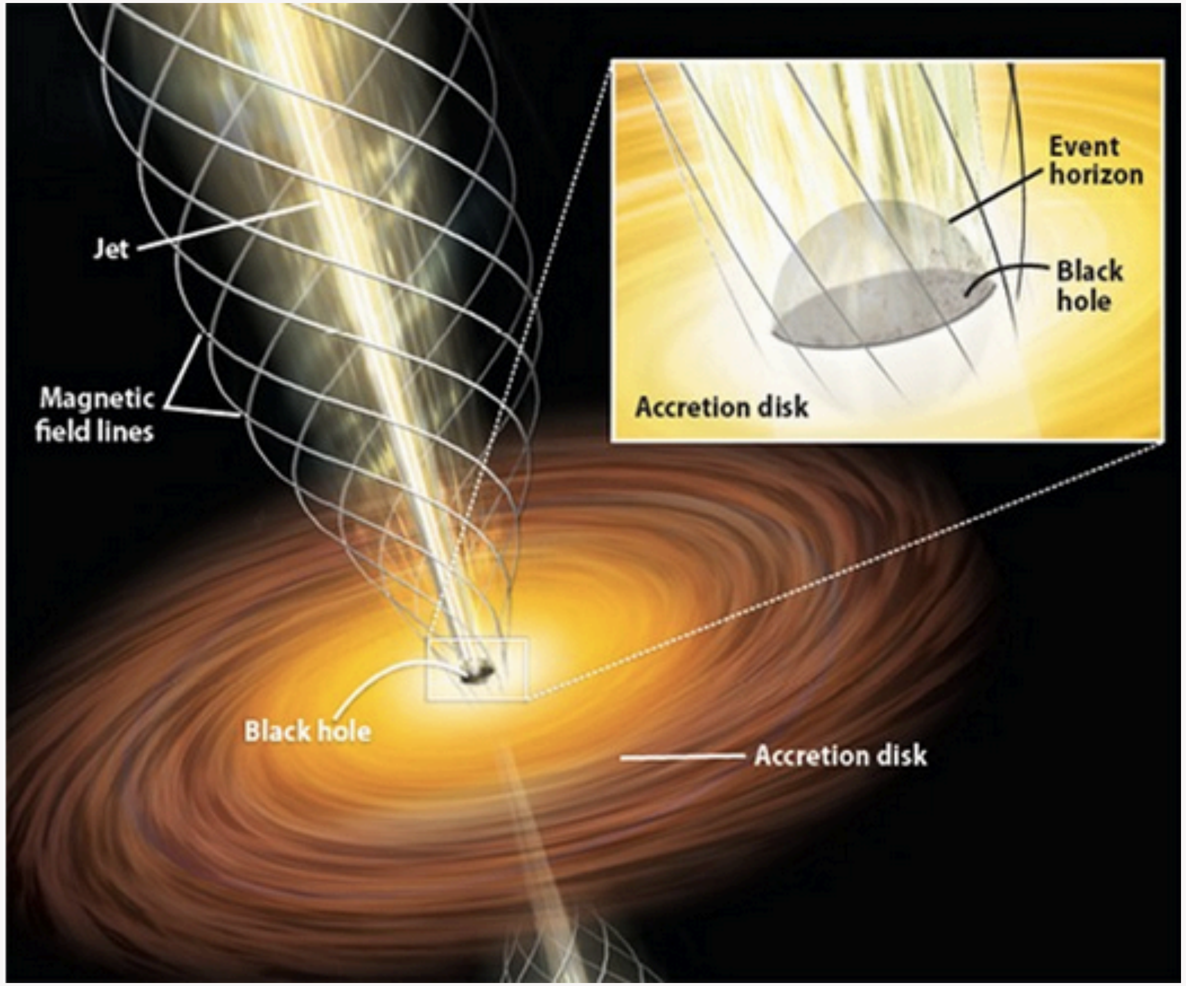
- Particle Injection
- Jets are highly collimated.
- Features are “seen” by their variability time scale.
- Spectra

Particle Injection into the Jet

This is one of the important research questions that is not yet answered.

The jet shows us that a tremendous amount of energy is transported away from the black hole.

- Is the source of particles coming from the accretion disk?
- Is the source of particles coming from the black hole via strong magnetic fields?



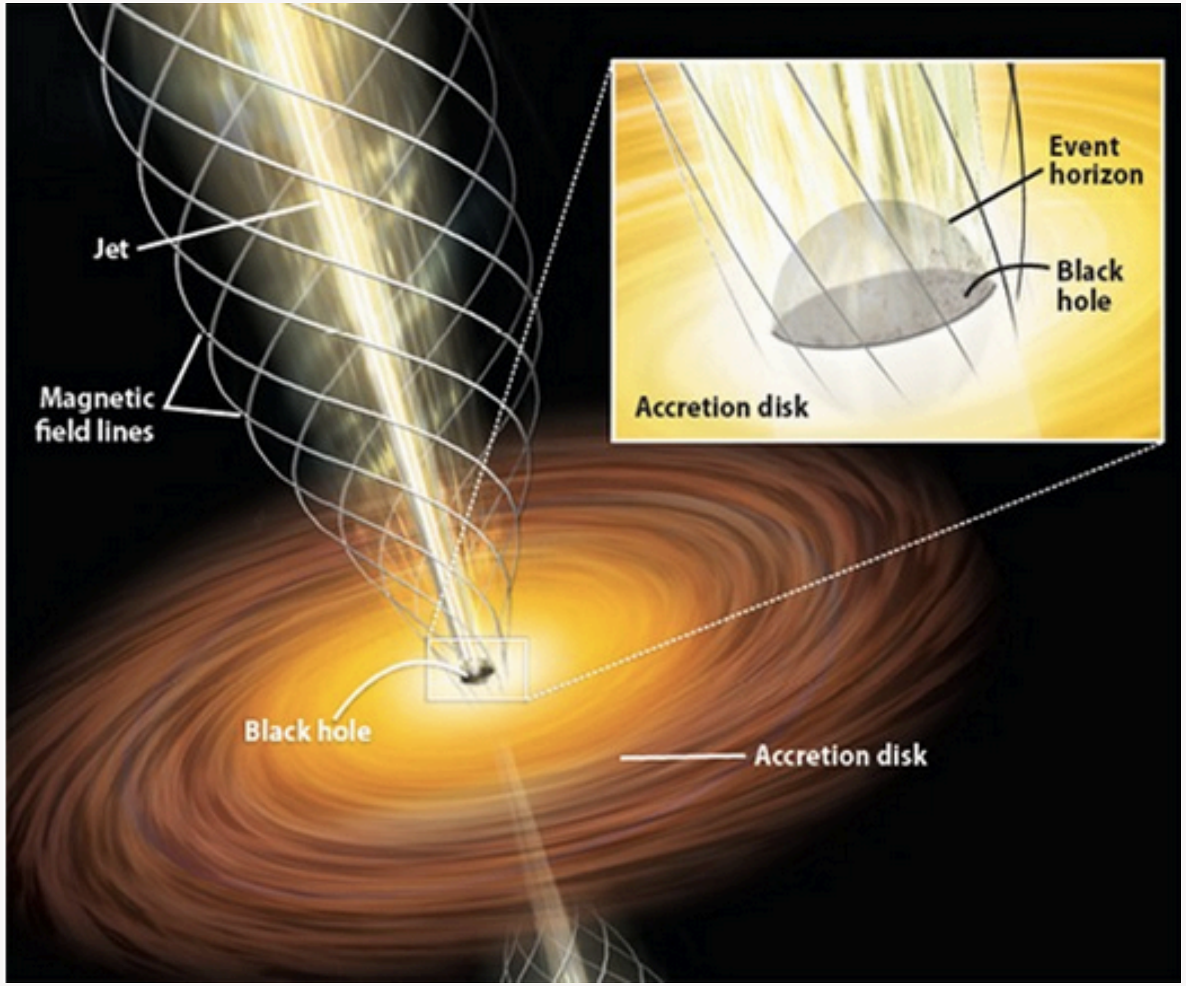
Particle Injection into the Jet

The gas in the accretion disk whirls around the black hole.

- To fall inward, gravitational potential energy must be converted to kinetic energy.

- Viscous flow – there is friction between the gas that slows it down.

- Energy conservation requires a mechanism for dissipating the excess energy. 1. Heat and x-rays, 2. are particles burped into the jet?



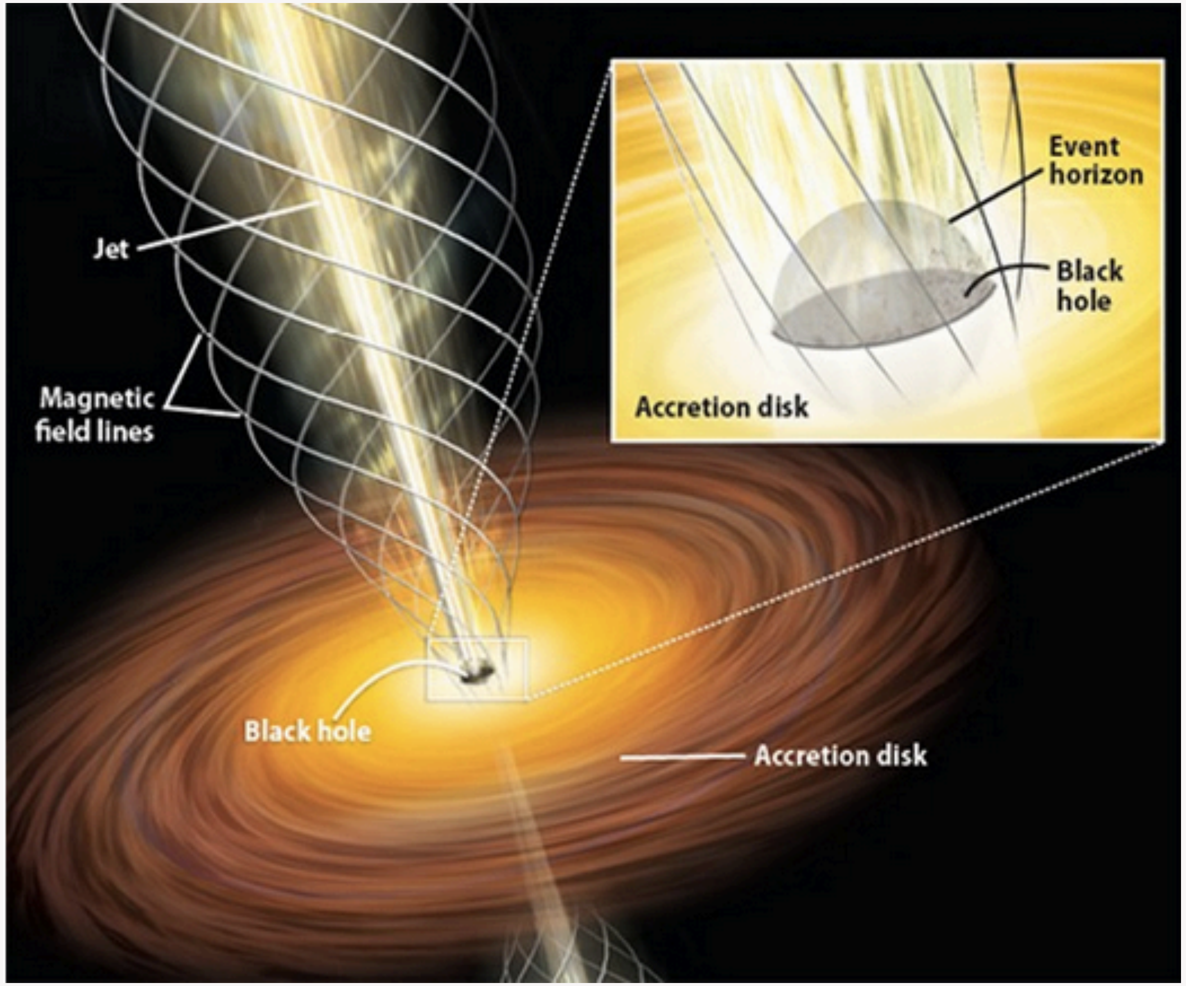
Particle Injection into the Jet

Magnetic Fields are dragged and twisted as the black hole rotates.

- Strong magnetic fields exist where the field-lines tighten.

- Electron-positron pair production can occur on the strong fields.

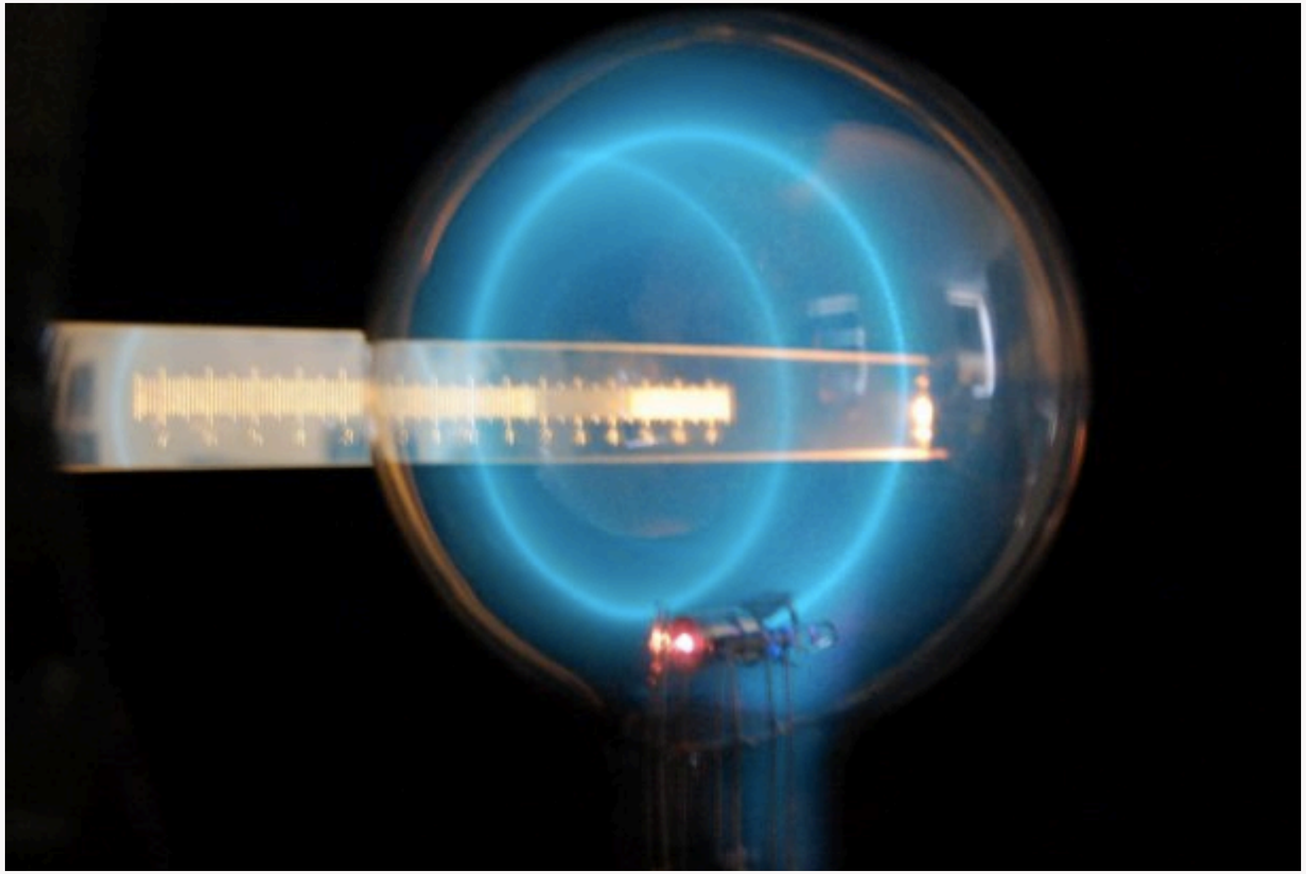
- These are then transported away along the field lines.



Jets are highly collimated by magnetic fields

Particles circulate in a magnetic field: $\vec{F} = q\vec{v}\times\vec{B}$

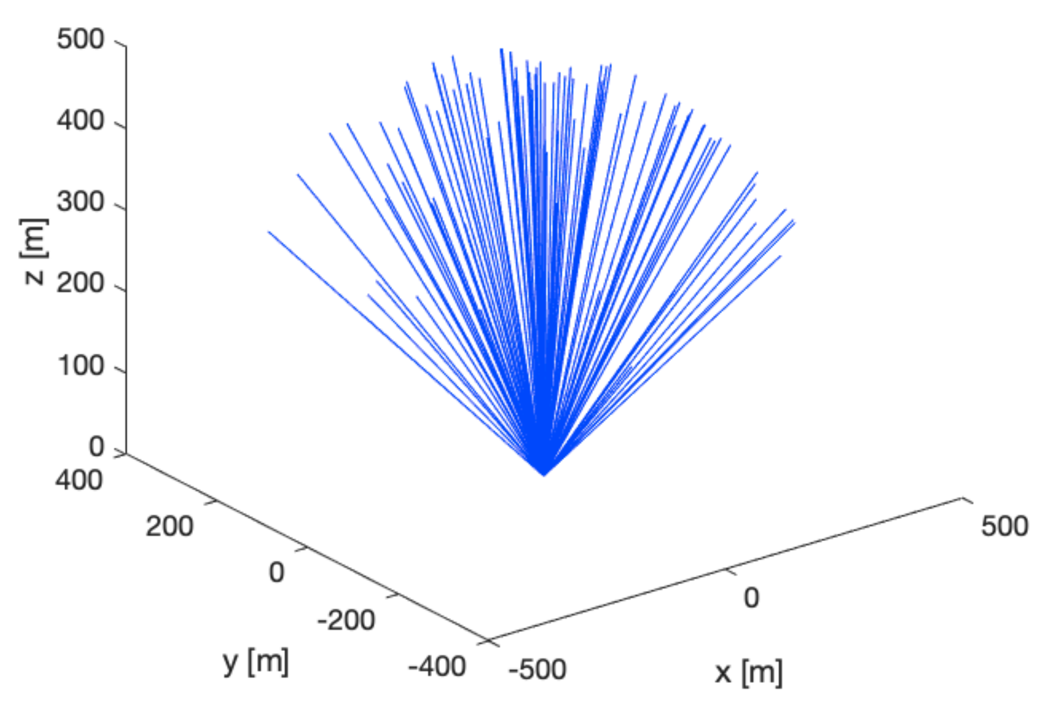
for an electron $q = -e$, for a proton $q = +e$



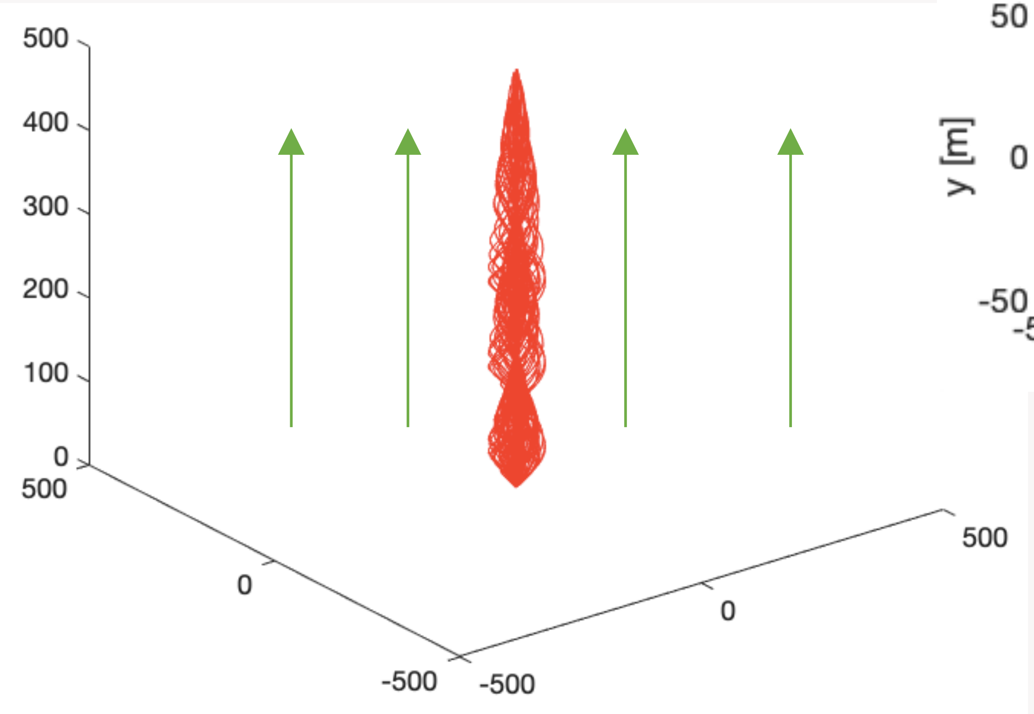
Jets are highly collimated

Particles circulate in a magnetic field: $\vec{F} = q\vec{v}\times\vec{B}$

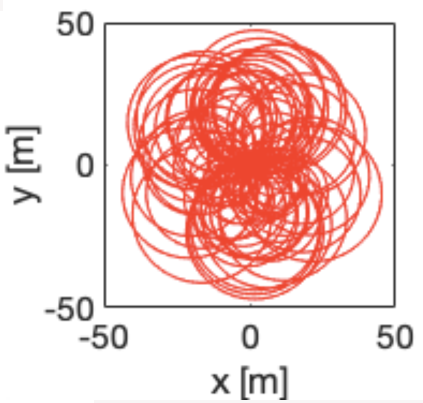
Particle trajectory (no $\vec{B}$)



Particle trajectory (with $\vec{B}$)



View down the beam.



The particles go wherever the magnetic fields direct them.
Jet opening angles are a couple degrees.

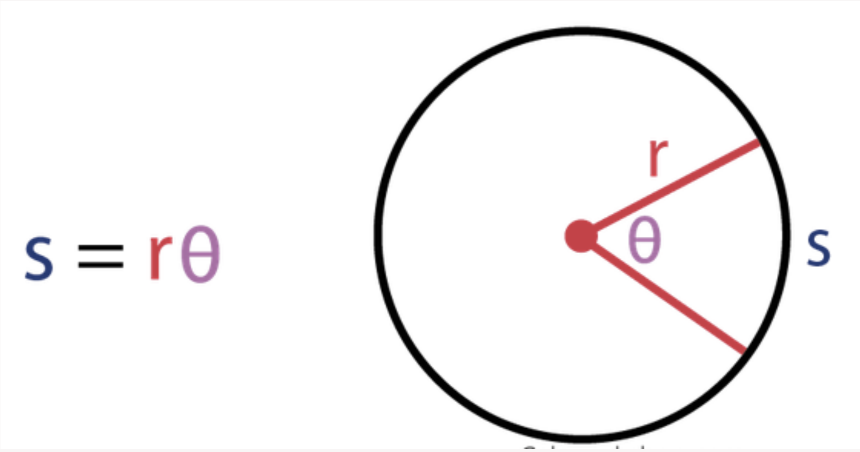
Features are "seen" by their variability time scale.

The core emission region near the black hole is too small to see optically.

$$1° = 60 \; arc \; minutes$$
$$1 \; arc \; minutes = 60 \; arc \; seconds$$

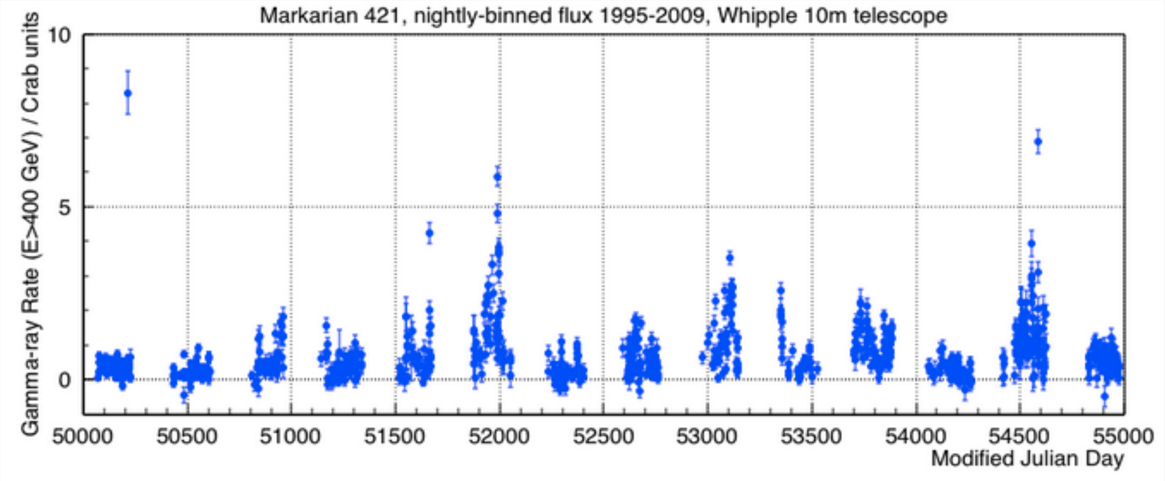
Radio telescopes can distinguish features on a scale of 10^{-3} arc seconds = 1 mas.
That is 1/3600000 of a degree.

For a galaxy that is 1 Mpc away,
$r \;= 1 \; Megaparsec$ (Mpc)
Size of features that can be resolved
$s \sim 0.005$ pc
~ 1000X the distance to the sun.



Features are "seen" by their variability time scale.

Blazar intensity is variable on short time scales: 5 min., 1 day, 1 month.



The observed duration, Δt is the relativistic dilated time.

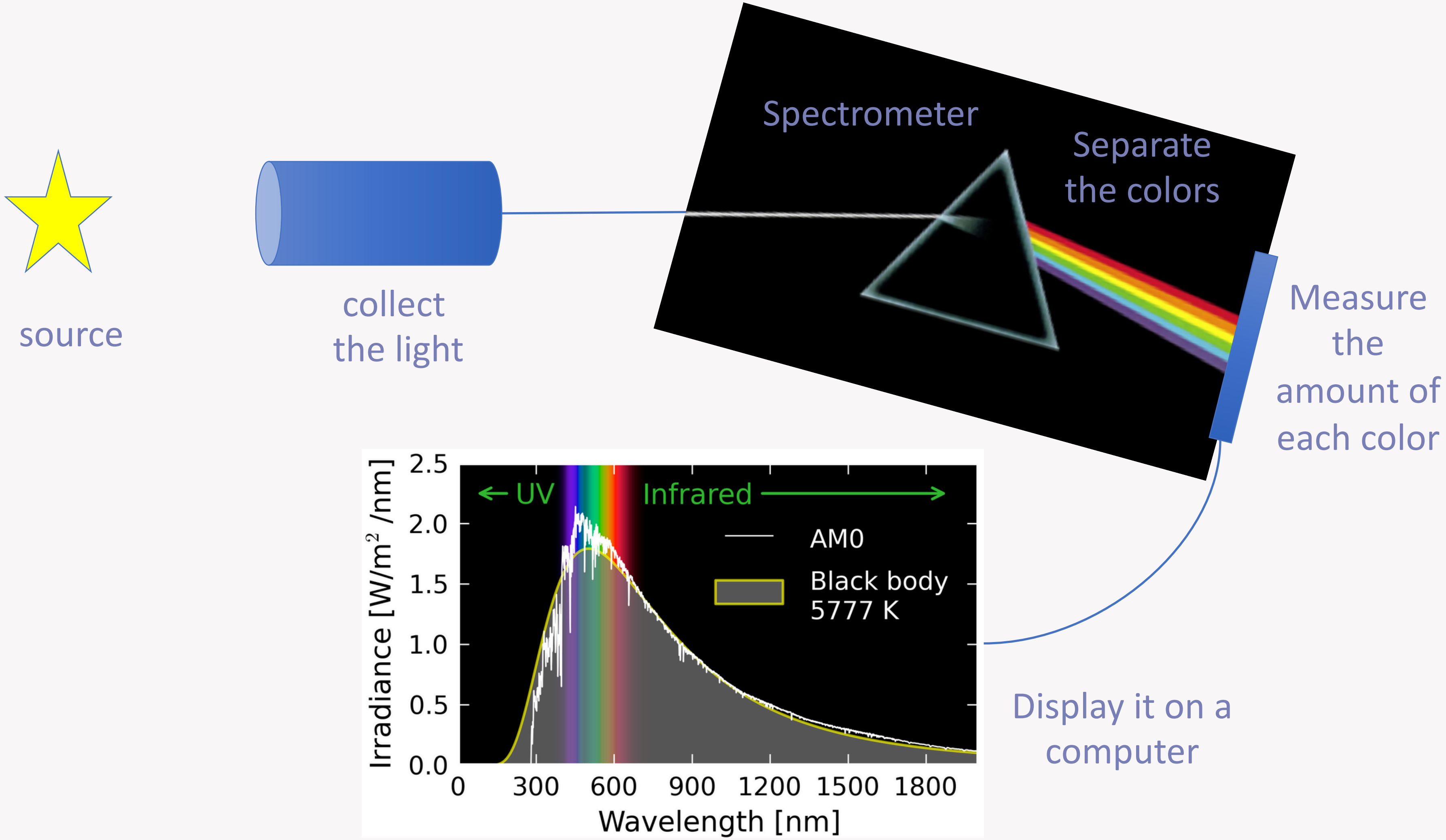
In the Jet's rest frame, the duration is $\Delta t_0 = \Delta t/\gamma$ where $\gamma = 1/\sqrt{1 - v^2/c^2}$

Jet velocities can be VERY close to the speed of light. $\gamma = 1000$ is not uncommon.

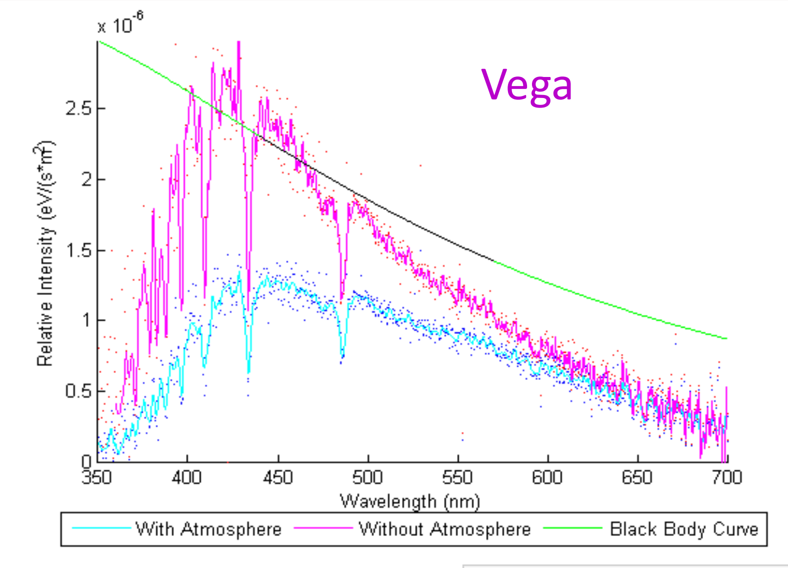
A 5 min. flare corresponds to a region $d = c \times \Delta t_o$ ~ 0.0006X the distance to the sun.

Even a month-long variability is a small region: d ~ 180X the distance to the sun.

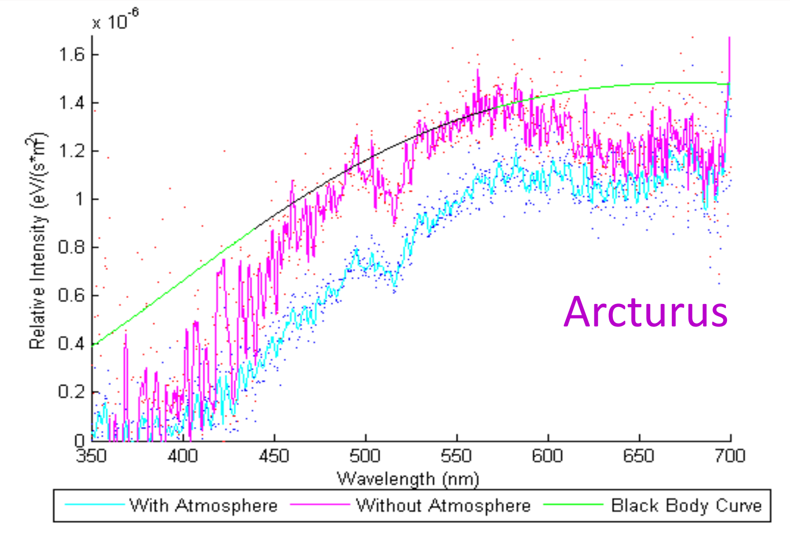
Spectral Colors



Spectral colors depend on Physics

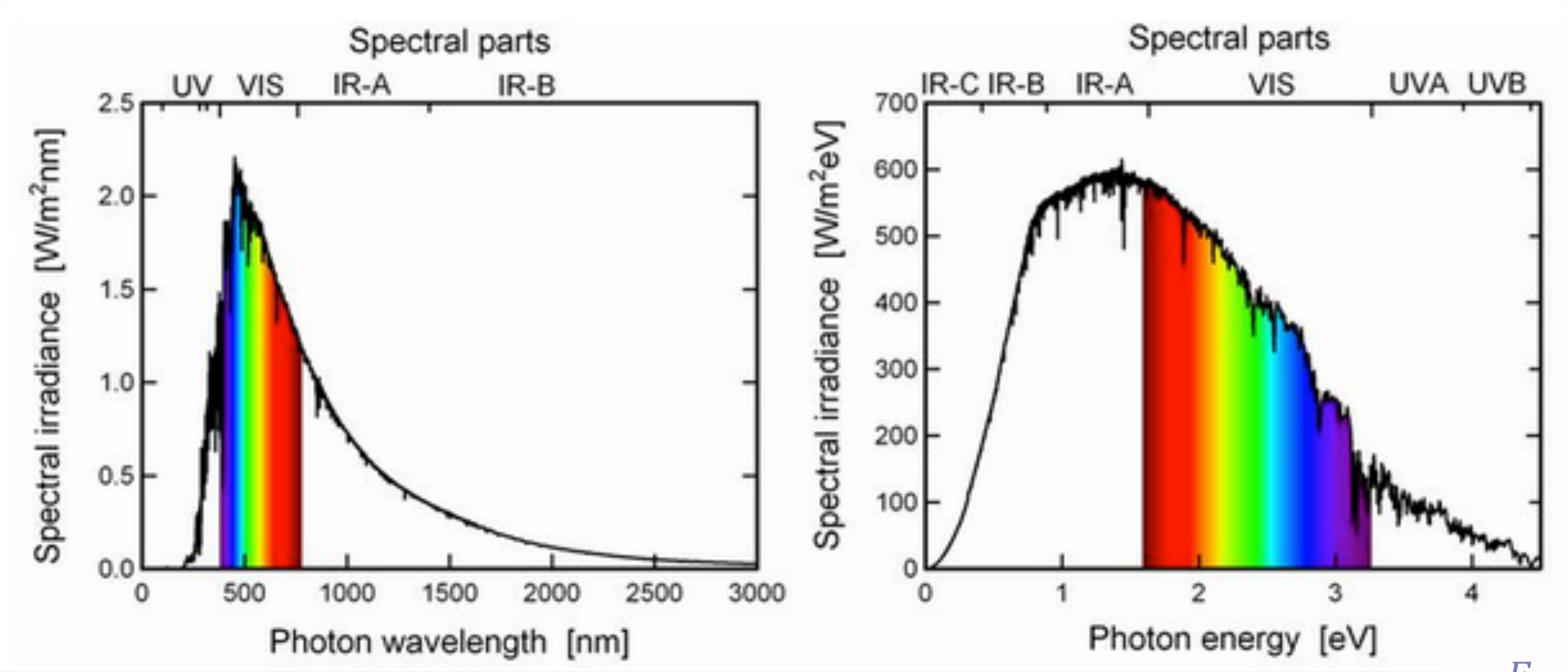


Optical image of Arcturus (DSS2 / MAST / STScI / NASA)



Vega through Celestron CGEM DX 1100 @ F6.3, Canon T3i, Televue 4X Powermate, ISO 800, 60 sec exposure

Thermal Spectrum: colors depend on temperature

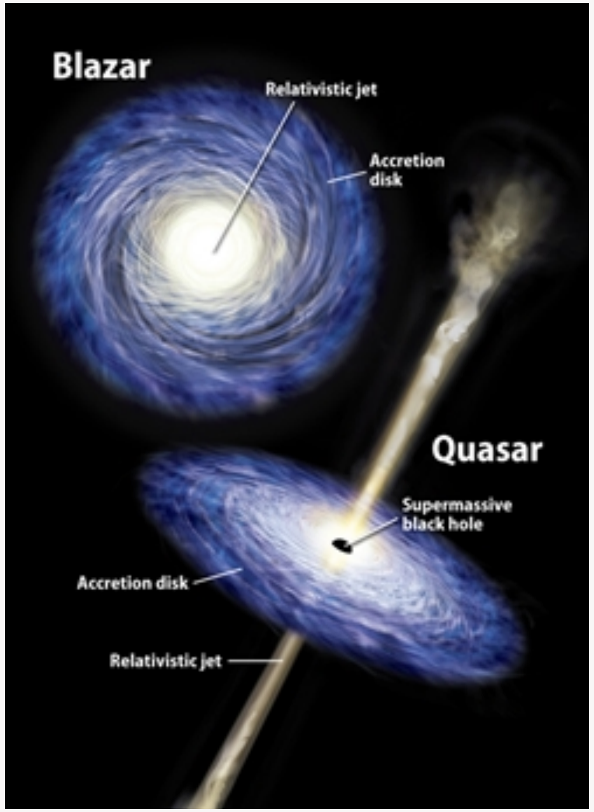


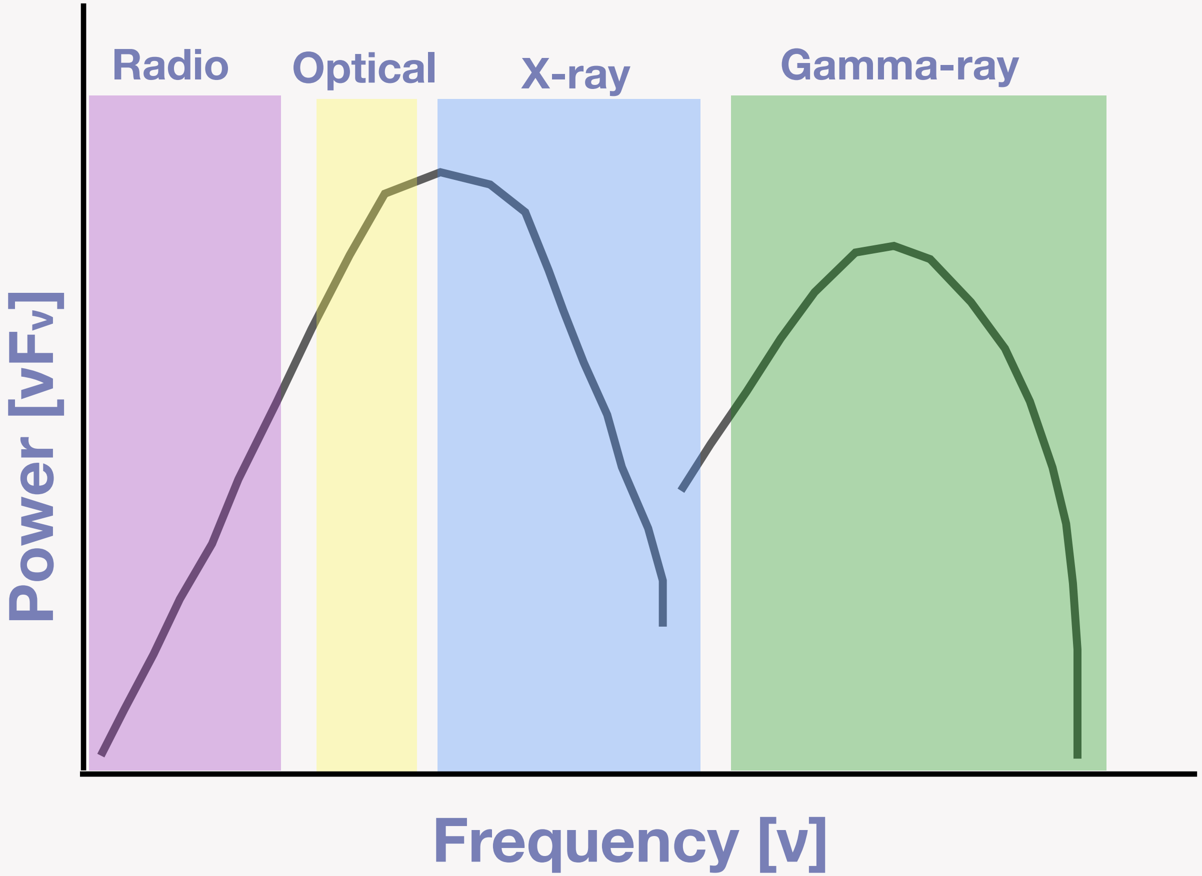
$$E = hf = \frac{hc}{\lambda}$$

Short wavelengths don't occur in the thermal spectrum

- x-ray wavelength<0.1 nm Energy > 12,400 eV
- gamma-ray wavelength<0.001 nm Energy> 124,000 eV

Blazars Spectrum: view down the barrel

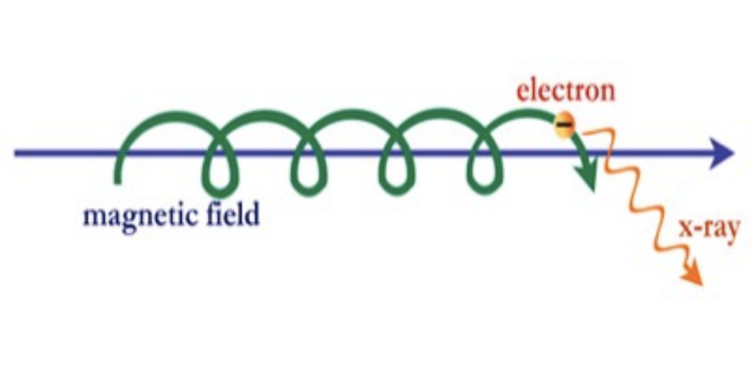




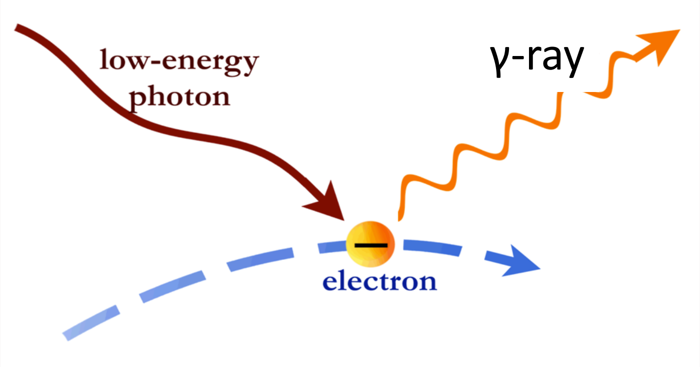
Takeaway Lesson:
Whenever the spectrum changes, there is a new physical process in play!

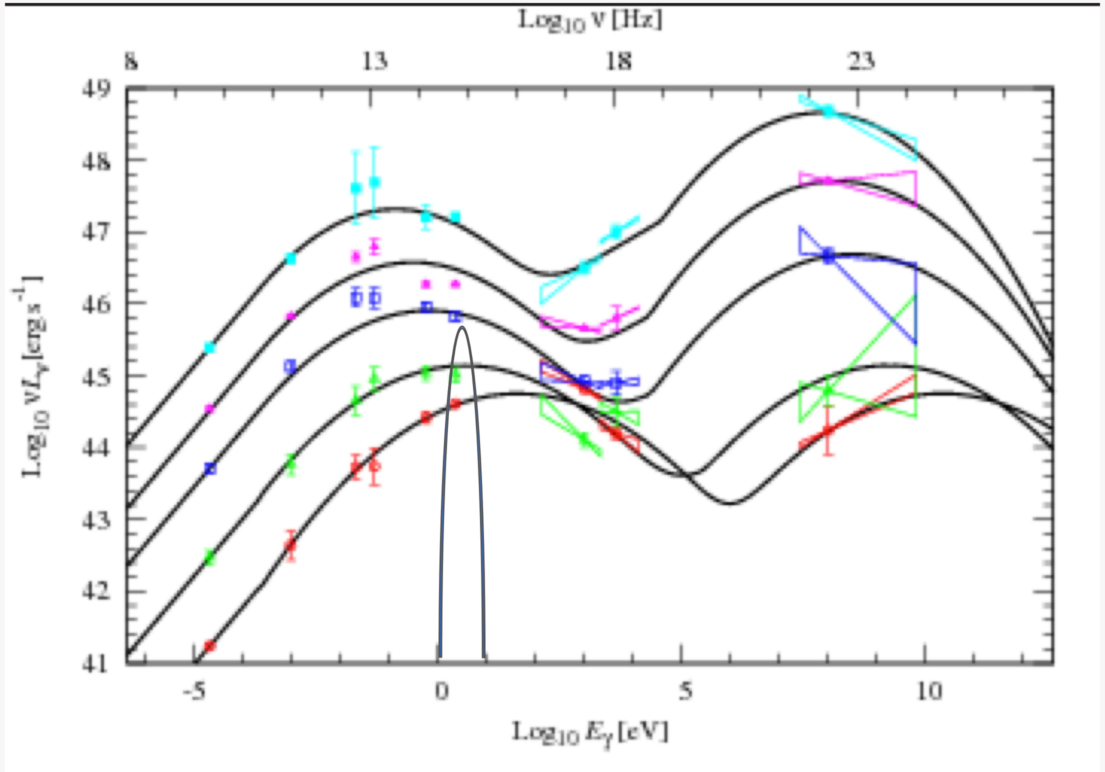
Blazar Spectra:

Magnetic Fields: $\vec{F} = q\vec{v}\times\vec{B}$

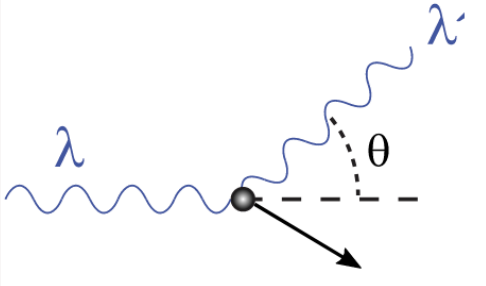


Inverse Compton Scattering



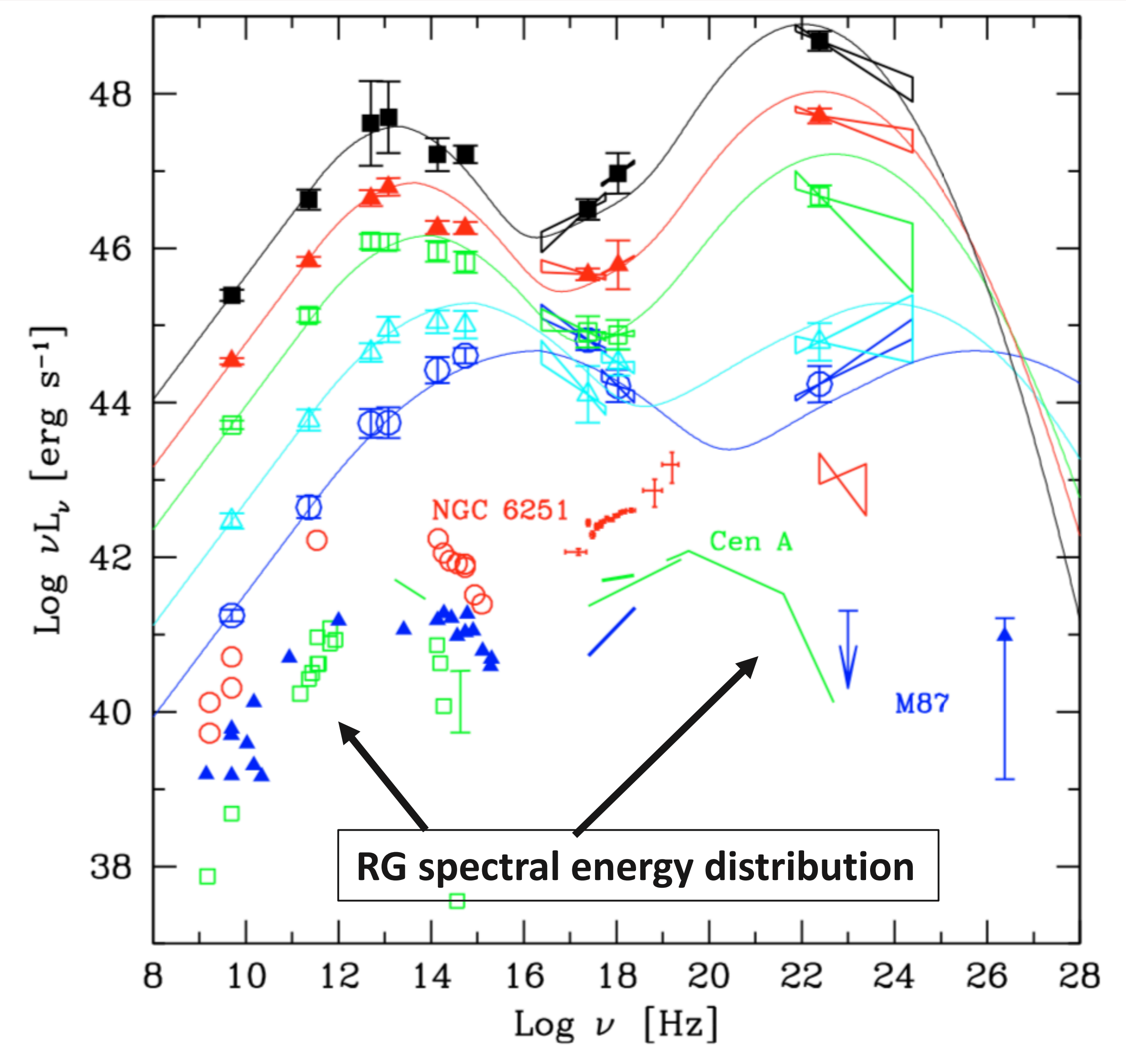


Compton Scattering



Radio Galaxies are an off-axis view of the Jet

- Radio Galaxies are identified by an extended jet feature in radio observations.
- Off-axis (We can see Jet structure!)
- Doppler beaming less likely. (Dimmer!)
- VHE emission is less likely to be detected at large distances. (Closer!)
- Viewed through external photon fields. (Spectrum is messy!)
- About 70 Blazars have been identified with VHE emission compared to 5 or possibly 6 radio galaxies. (Only 5 or 6 examples)



Example: 3C 264

VERITAS Discovery of VHE Emission from the Radio Galaxy 3C 264: A Multi-Wavelength Study

Paper is accepted for publication in Astrophysical Journal
https://arxiv.org/abs/2005.03110

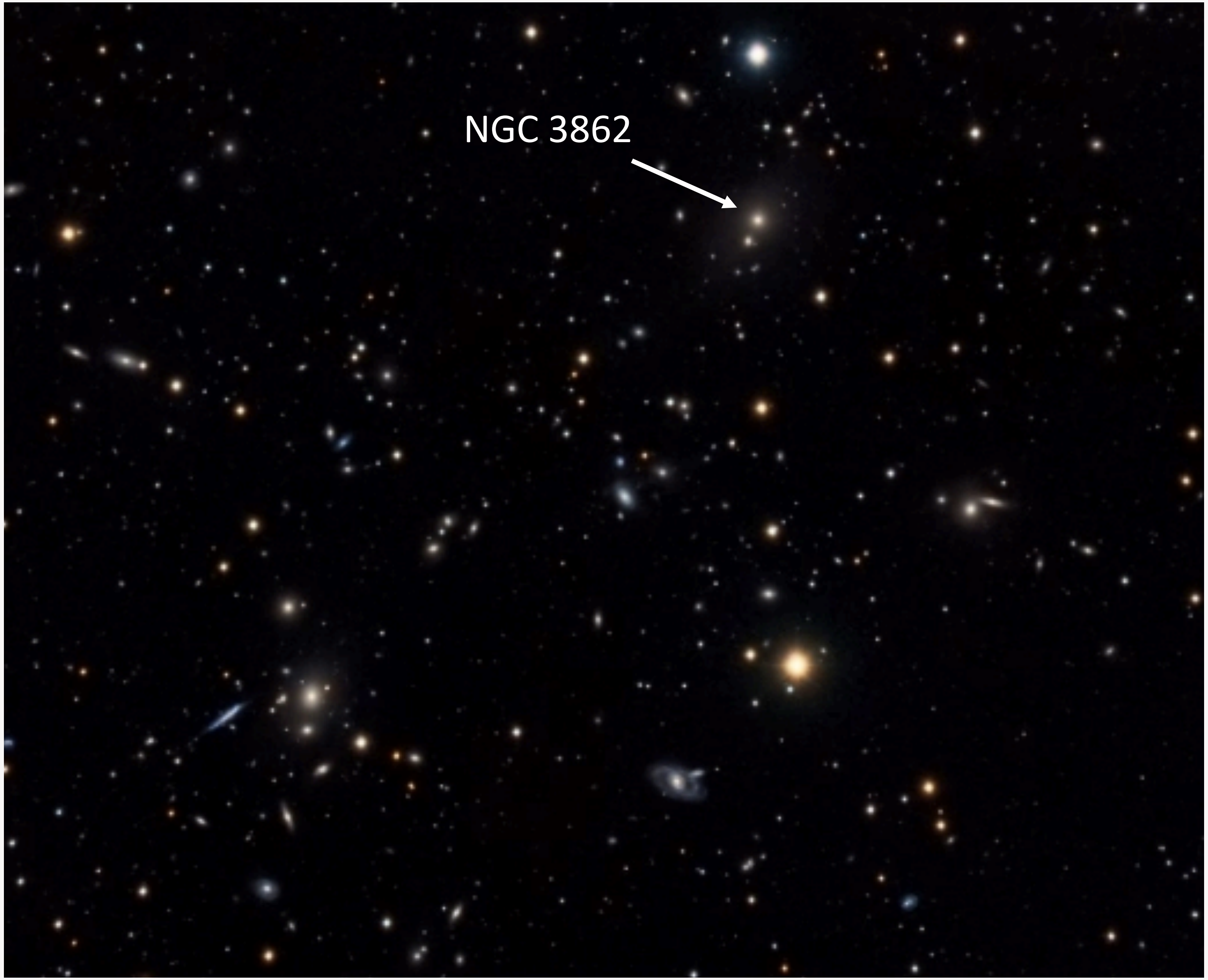
3C 264

The most recent addition to the VHE emitting Radio Galaxies.

Relatively close

- z = 0.02
- 91 Mpc.

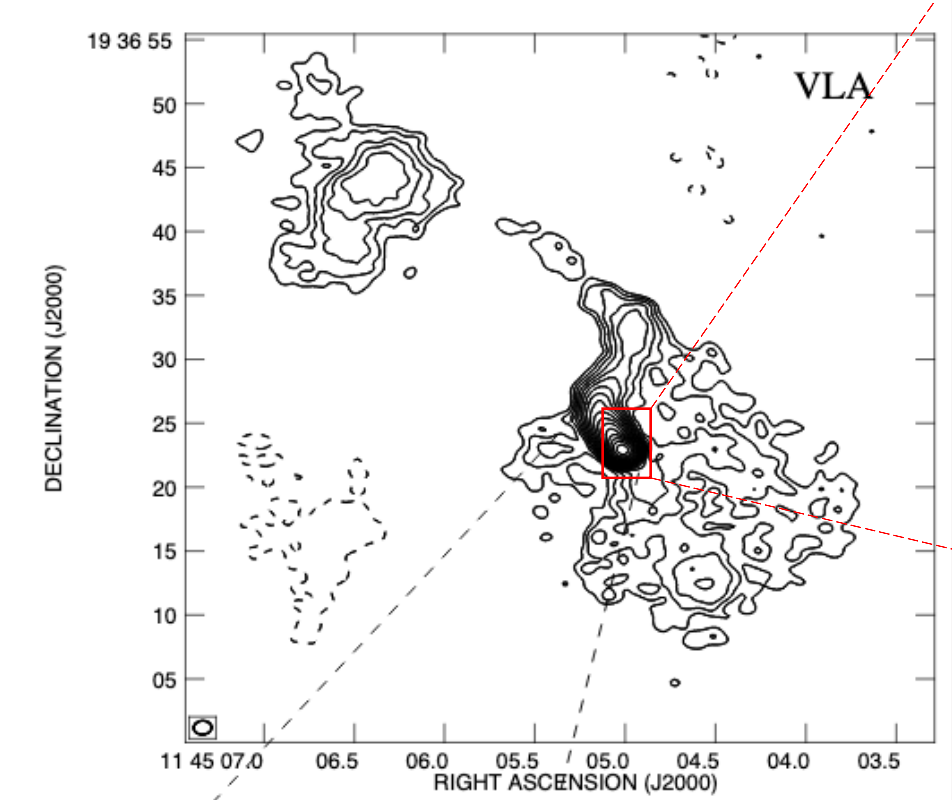
Leo Cluster

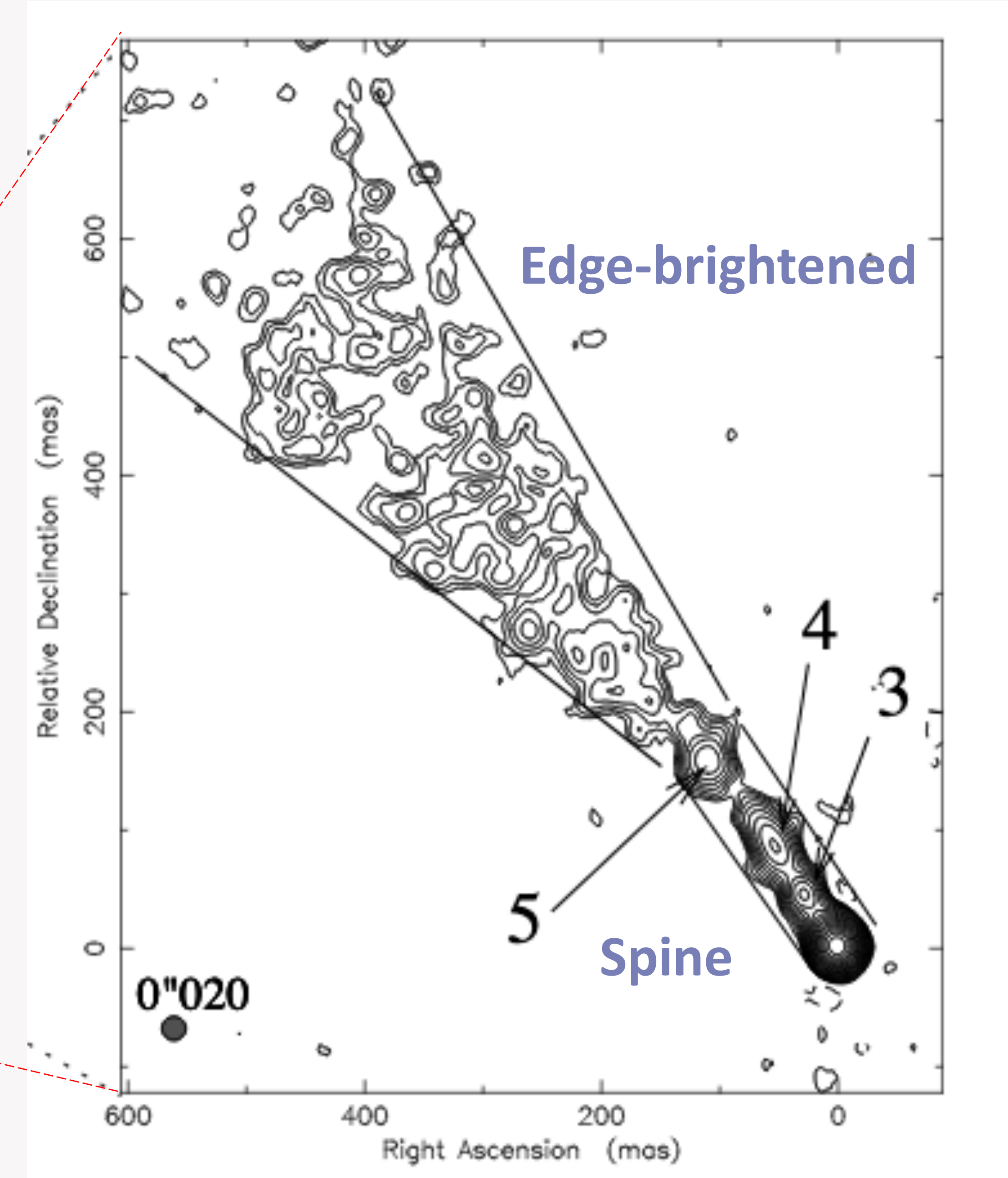


3C 264 Radio Features

Prominent jet (Lara 1999)

- Spine brightened jet at the Core
- Edge-brightened jet with knots after 10° bend
- Wiggling jet
- Terminal blob 28’’ from the core.

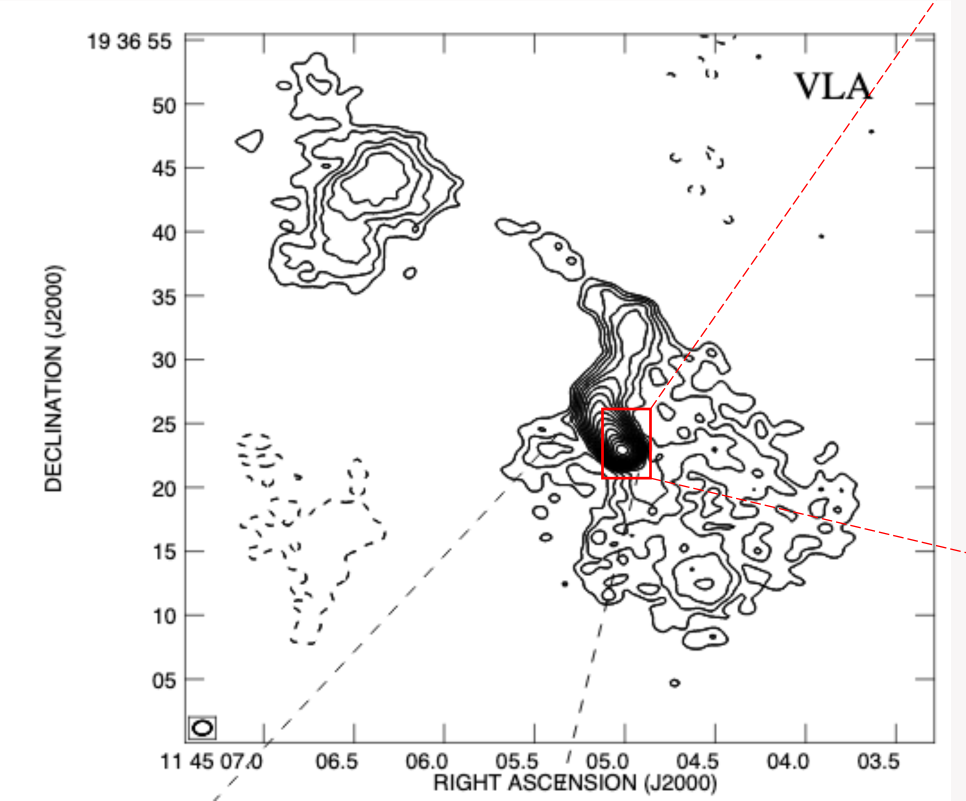


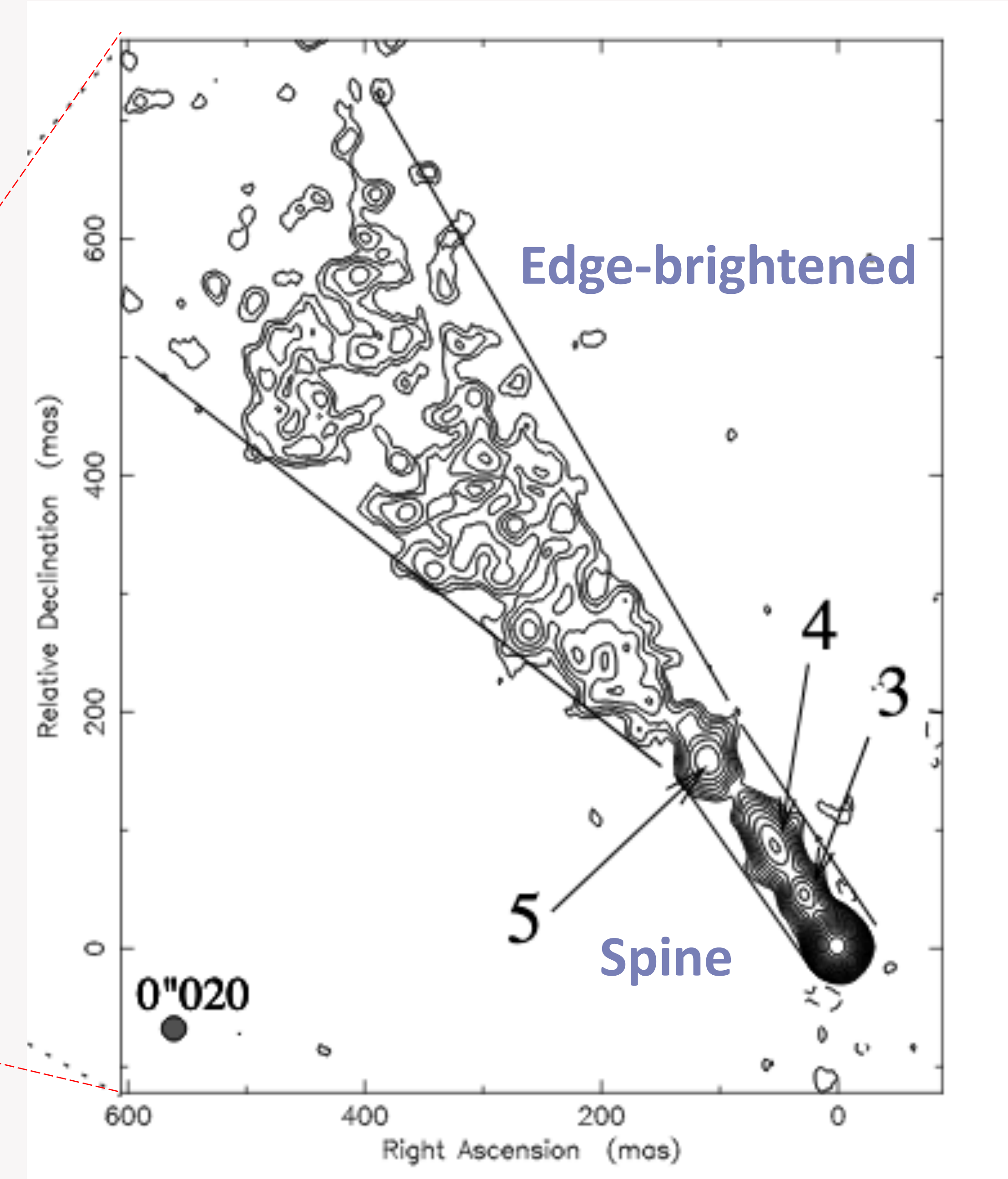


3C 264 Radio Features

This view is a projection of something coming nearly, but not exactly straight at us.

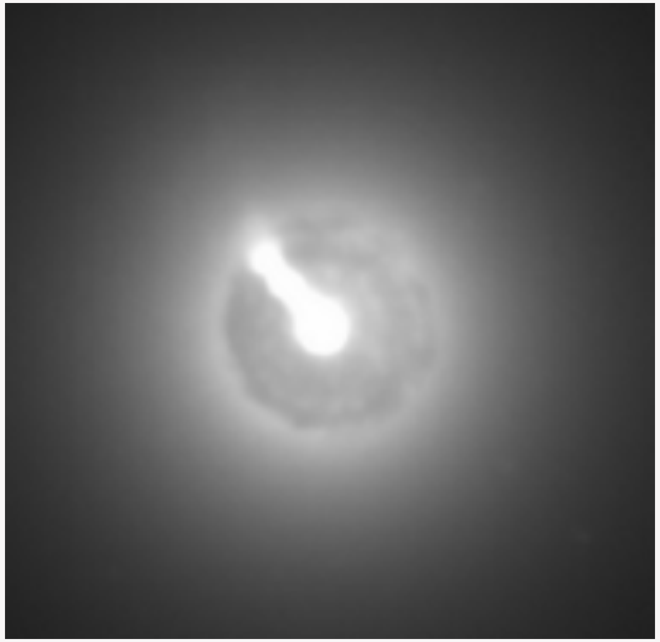
Inclination angle $< 20°$, likely $\sim 8°$

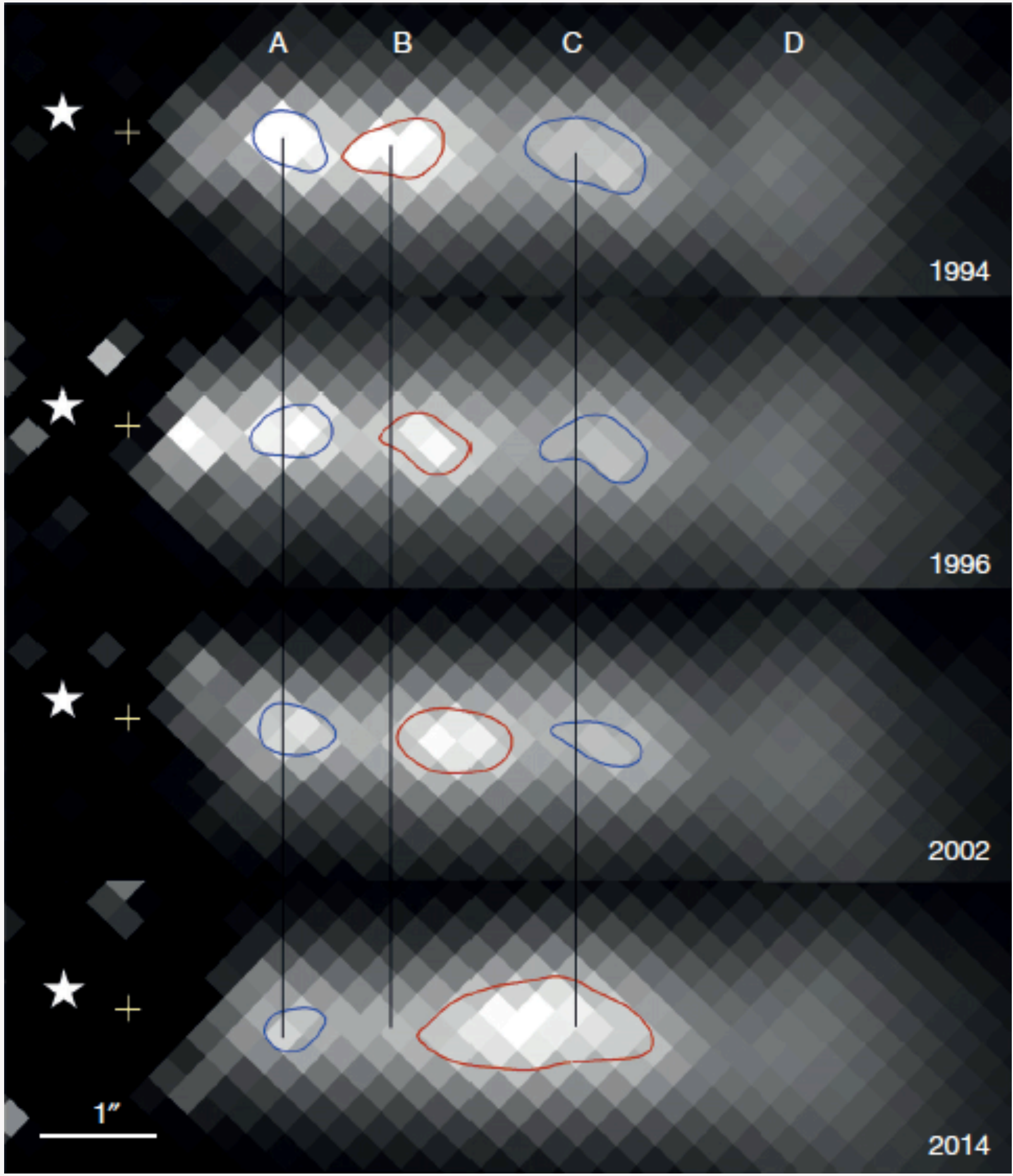




3C 264 Optical Features

- HST ACS/WFC
  Meyer (2015)





- Bubble or possibly disk
- First ~90° wiggle in the radio jet is at the radius of the bubble.
- Knots are synchrotron emission located just past the 10° bend in the jet.

3C 264 Optical Knots

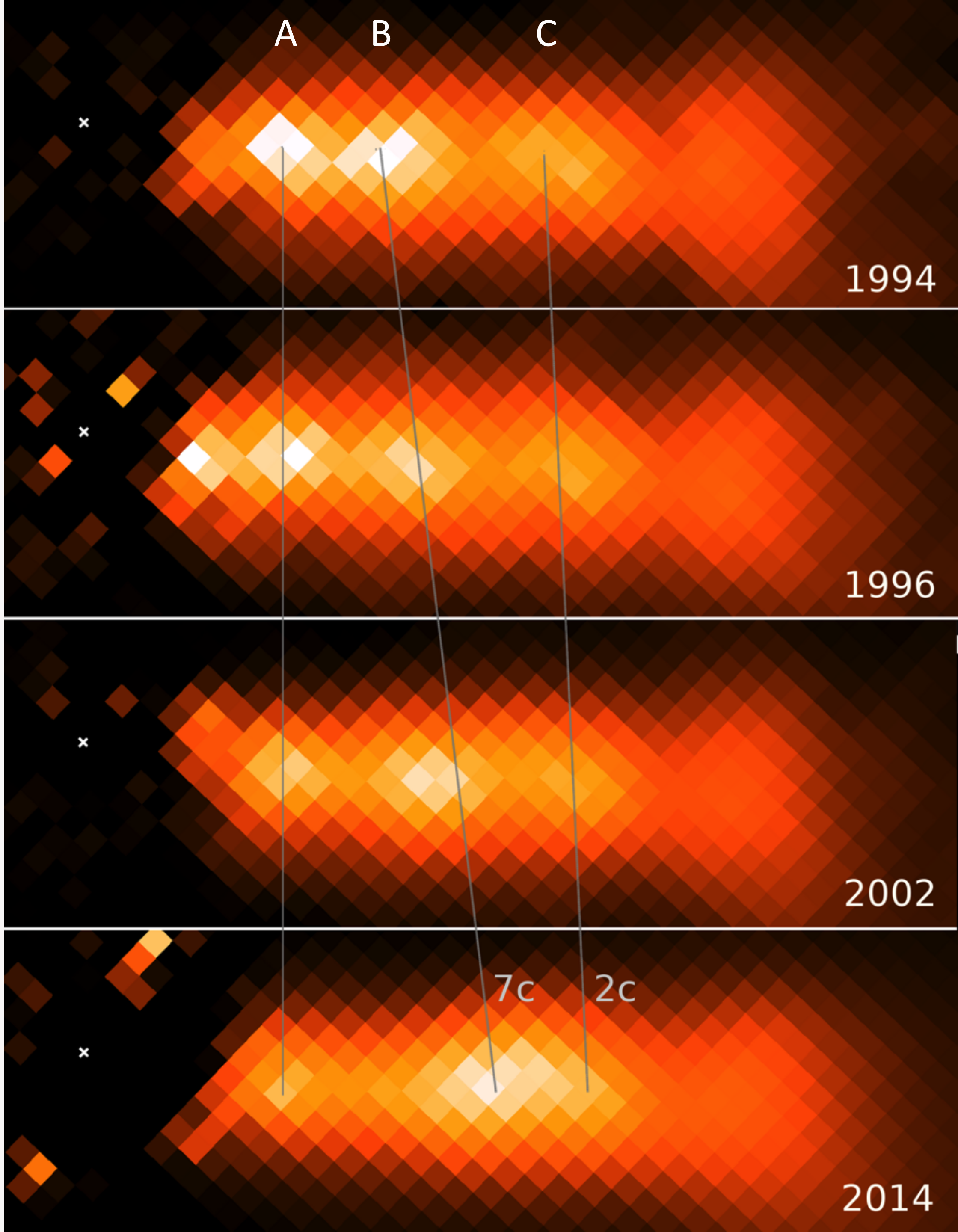
- VERITAS observations were motivated by the HST proper motion study (Meyer 2015)
- Knot A is stationary.
- Knot B has apparent speed of $(7 \pm 0.8)c$
- Colliding with Knot C in 2014.
- Significant brightening is observed.
- 30 years for collision to go to completion.
- VERITAS:

  ~9.2 h observation in 2017

  ~3 h observation in 2018 yield $> 3\sigma$ excess.

  + 35 h follow-up.

  ~ 10.3 h observation in 2019



3C 264 VERITAS Discovery of VHE emission

VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264

ATel #11436; ***Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration***
on ***17 Mar 2018; 00:25 UT***
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

Tweet Recommend 50

We report the VERITAS discovery of very-high-energy emission (VHE; >100 GeV) from the FRI radio galaxy 3C 264, also known as NGC 3862. Nearly 12 hours of quality selected data, collected by VERITAS between 09 February 2018 and 16 March 2018 (UTC), were analyzed. Preliminary results yield an excess of 60 gamma-ray events above background at the position of the source, corresponding to a statistical significance of 5.4 standard deviations. Our preliminary flux estimate (E>300 GeV) is (1.3 ± 0.2)e-12 cm^-2 s^-1, or approximately 1% of the Crab Nebula flux above the same threshold. The Fermi-LAT 3FHL catalog (Ackermann et al. 2017 ApJS 232, 18) lists a photon index of 1.65 ± 0.33 for 3C 264 which, when extrapolated to the VHE band, is consistent with the VERITAS detection. At a redshift of 0.0217, 3C 264 is a

Follow-Up Observations were quickly scheduled

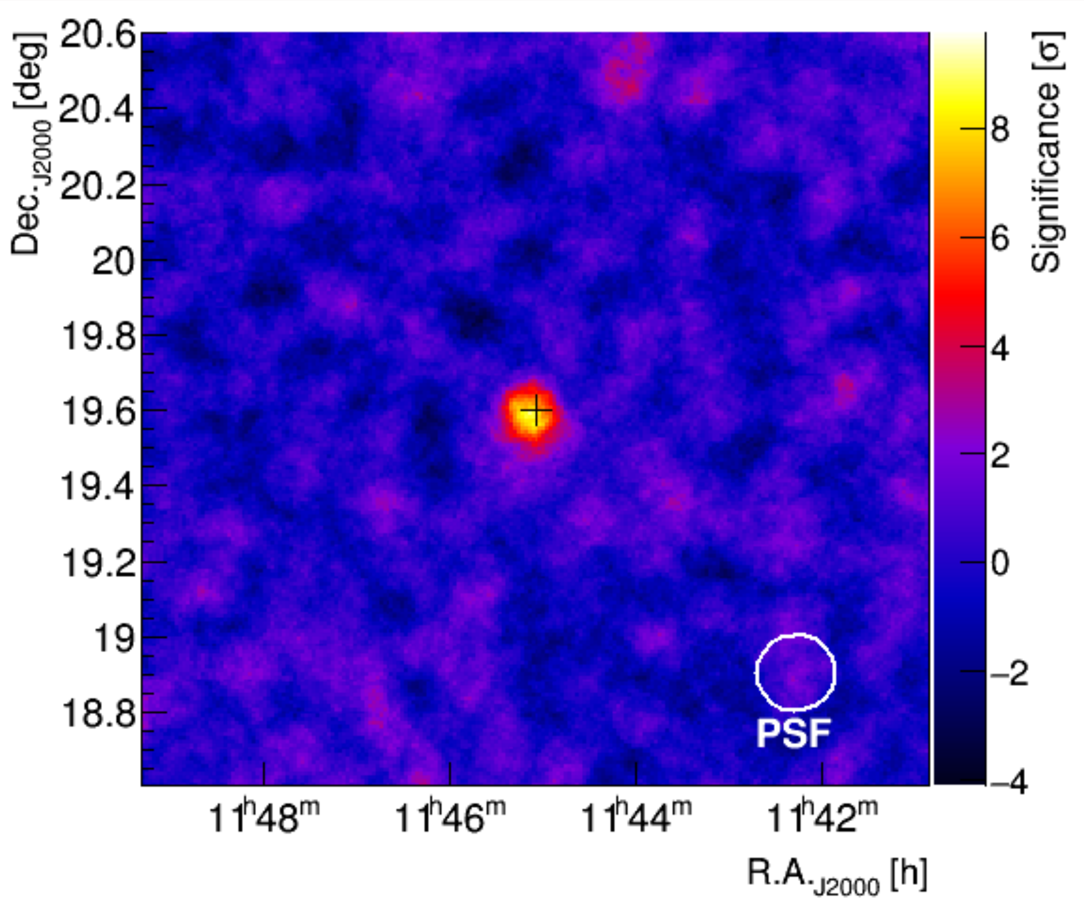


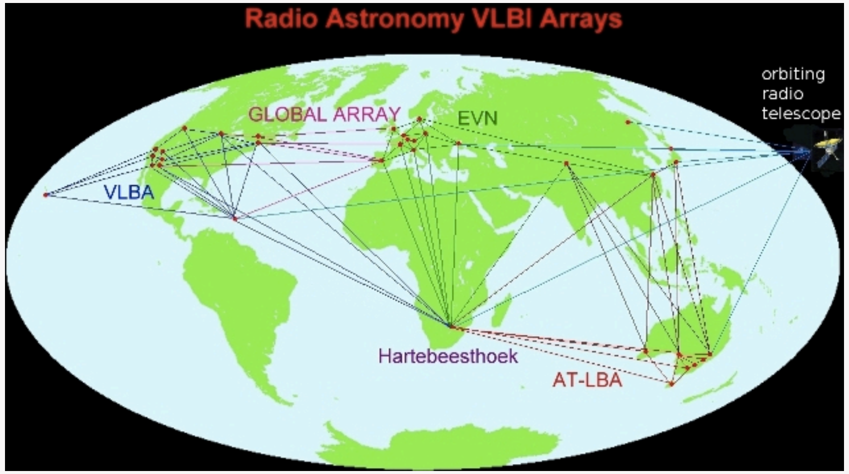
Image-Template Analysis: 7.8σ detection
ITM gave 30% more signal and went into the publication.

3C 264 VERITAS Discovery of VHE emission

Follow-Up Observations:

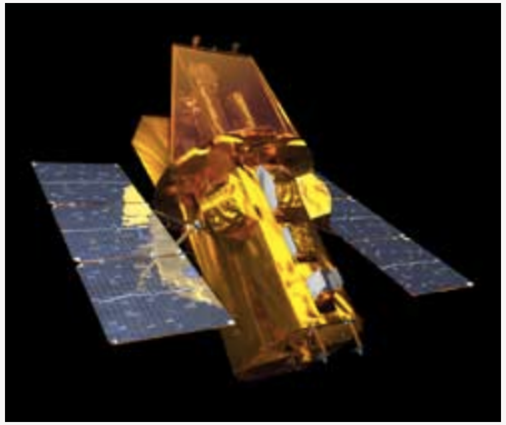
Very Large Array - Radio (DDT - 2018 April

Very Large Baseline Interferometer - radio (MOJAVE + DDT – 2018 Mar 30)



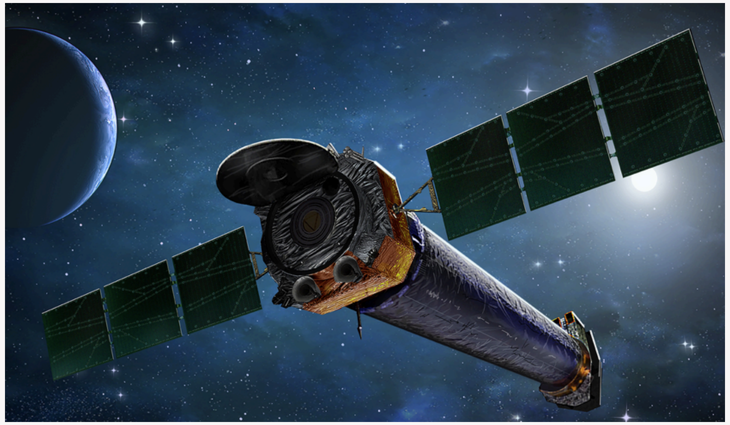
Fermi – gamma-rays

Swift – x-ray



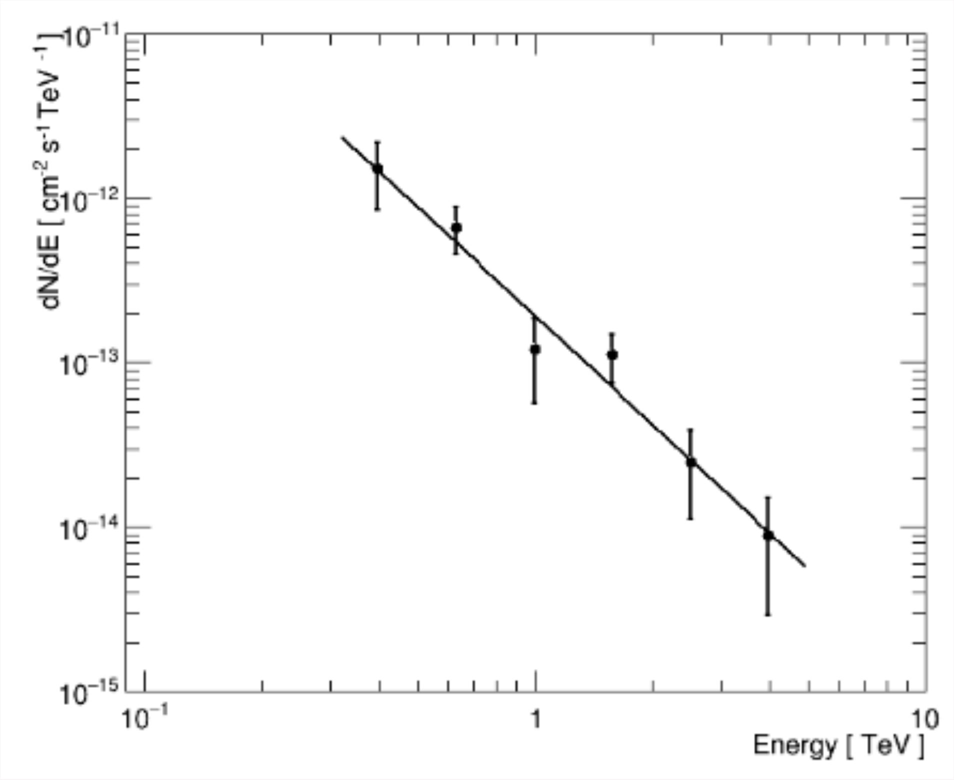
Hubble Space Telescope - Optical (GO, PI: Meyer – 2018 Mar 24)

Chandra – x-ray (DDT – 2018 April 04)



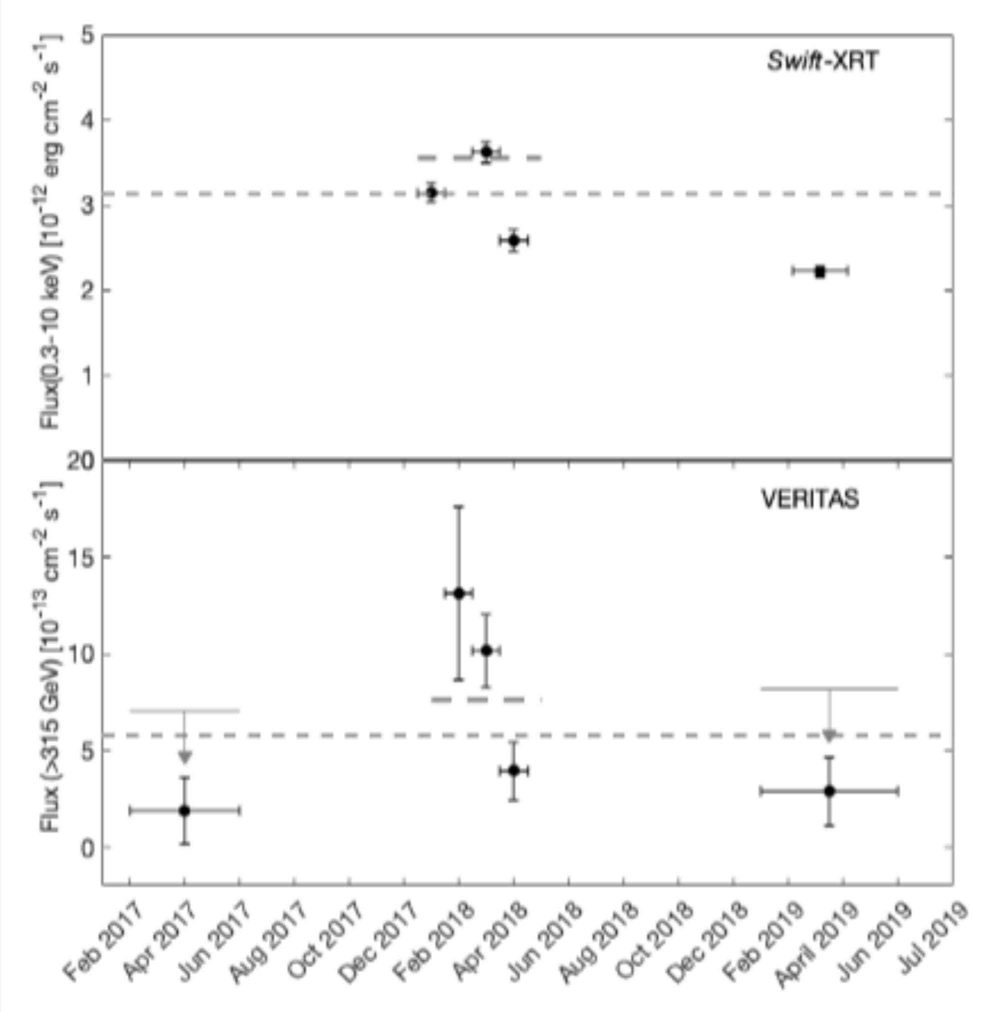
3C 264 VERITAS, VHE Gamma-rays

VERITAS Spectrum



Hard spectrum in 2018

VERITAS Light Curve



Elevated flux in Feb/March 2018

3C 264 –MWL Data, Gamma-ray

Fermi LAT

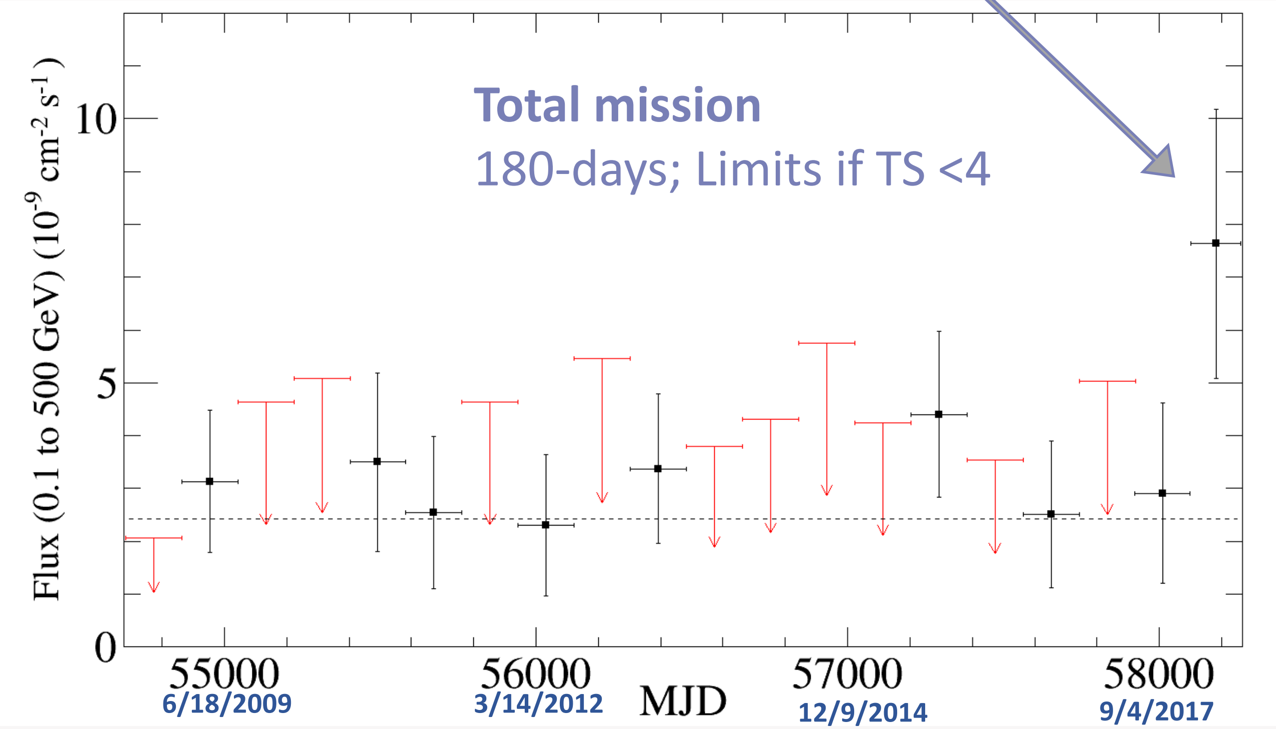
- Brighter in early 2018

  Fermi solar panel issues resulted in lower statistics in 2018.

  - Safe mode began on March 16, 2018
  - Normal operations resumed on April 8, 2018

- Hard spectrum from 10-yrs of data:

VHE flux increase in 2018



Tyrel Johnson (NRL), Fermi-LAT collaboration

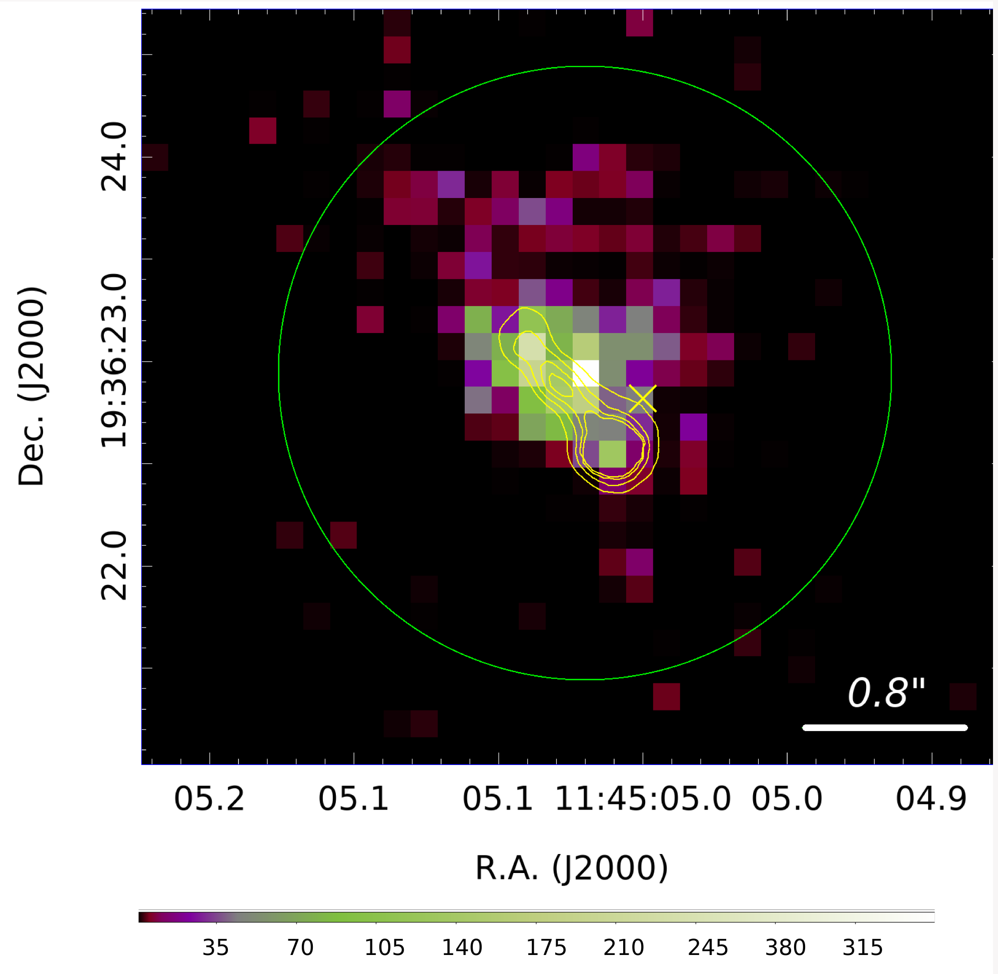
3C 264 – MWL Data, X-ray

Chandra DDT (15 ks, 30’x30’, April 4, 2018)

- Extended emission detected.
- Yellow contours show reasonable agreement between HST and Chandra.
- Factor 2 brightening compared to Perlman 2010

Swift XRT

- Steady emission (green circle)



3C 264 -MWL Data, Optical

Hubble Space Telescope

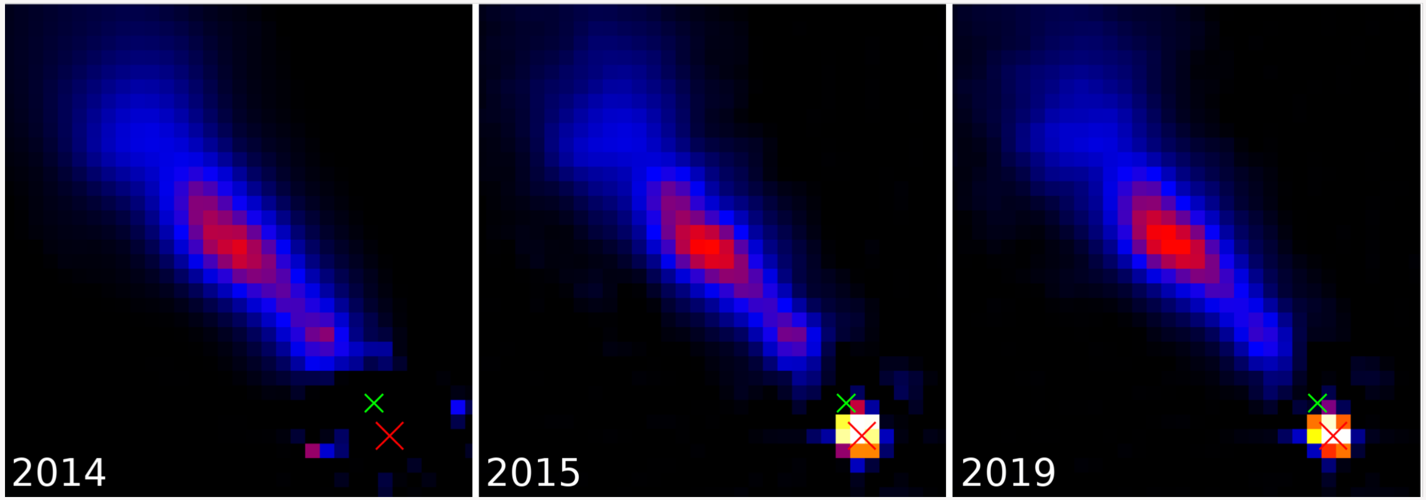
Imaging

- Light from galaxy & inner disk/bubble is subtracted.
- Linear brightening
- Change in shape expected because of the B/C knots are interacting.

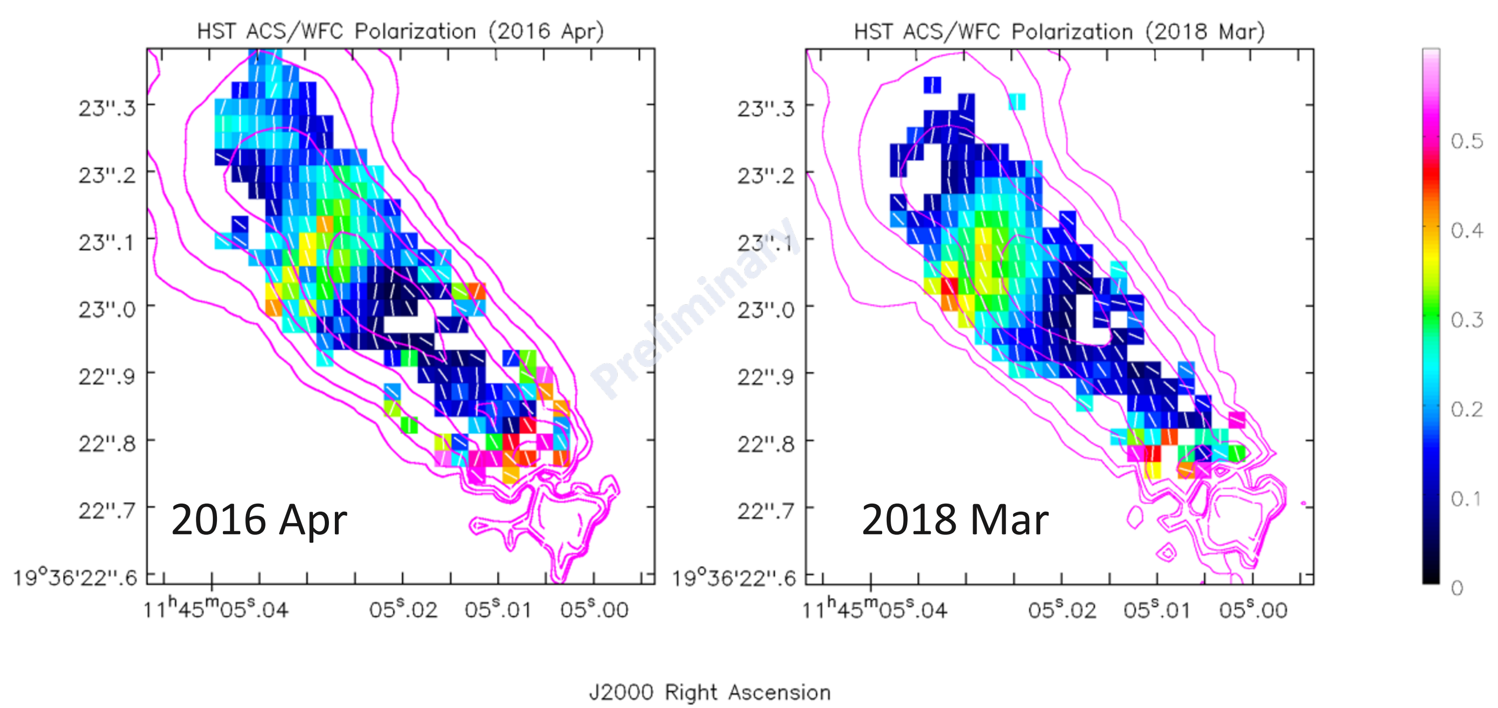
ACS/WFC Polarization

- Polarization structure consistent between 2016 and 2018.
- Higher polarization downstream of knot B/C collision zone in 2018.

HST Images



HST Polarization



3C 264 – MWL Data, Radio

VLA DDT (Jet with Knots)

- Polarization structure consistent between 2015 and 2018
- No evidence in polarization for a strong shock.

VLBI DDT (Jet at Core)

- March 2018
- High fractional linear polarization may be indicative of a transverse shock that is accelerating e-.

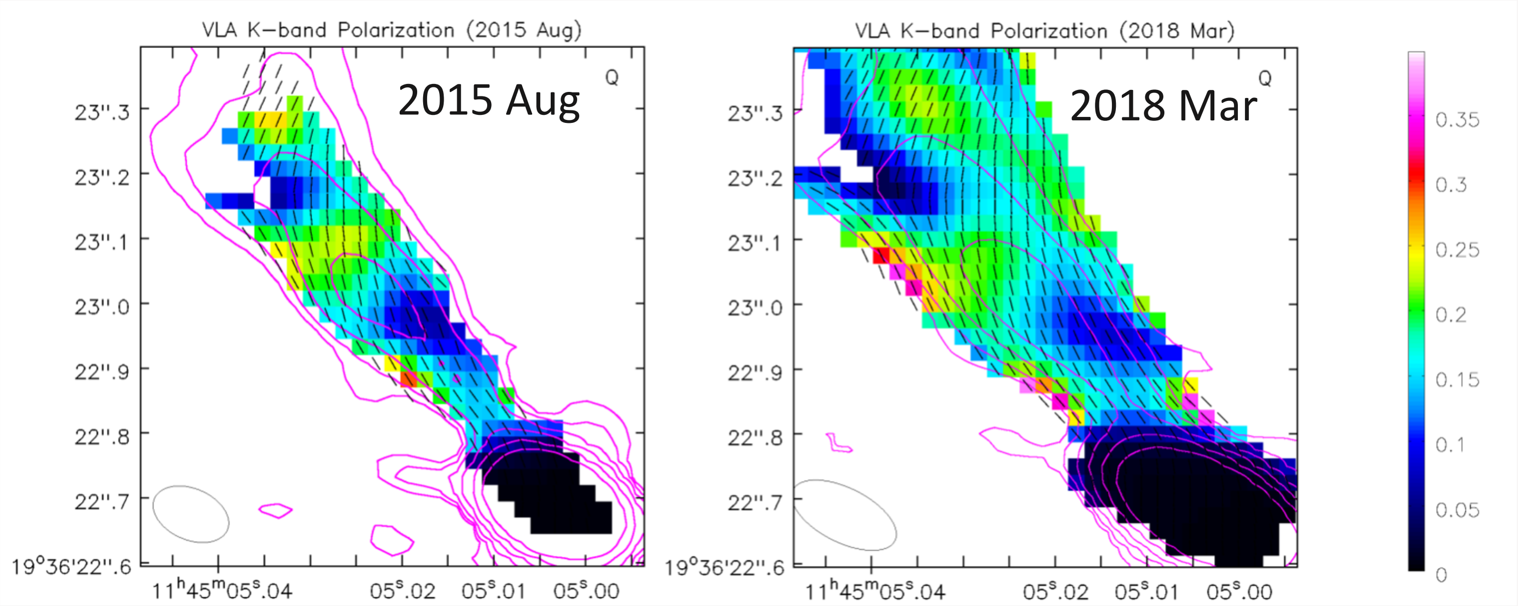
Flare lasted about a month.

→ 5.2X distance to the sun.

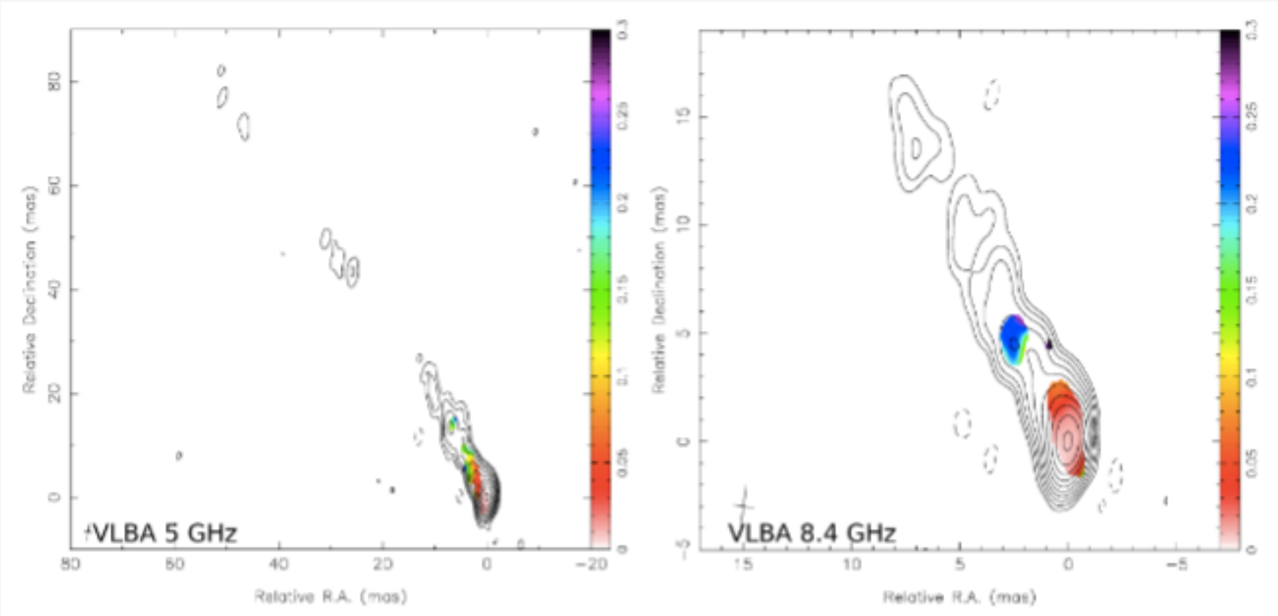
→ 1.5e-3 mas

Emission region is in the Core.

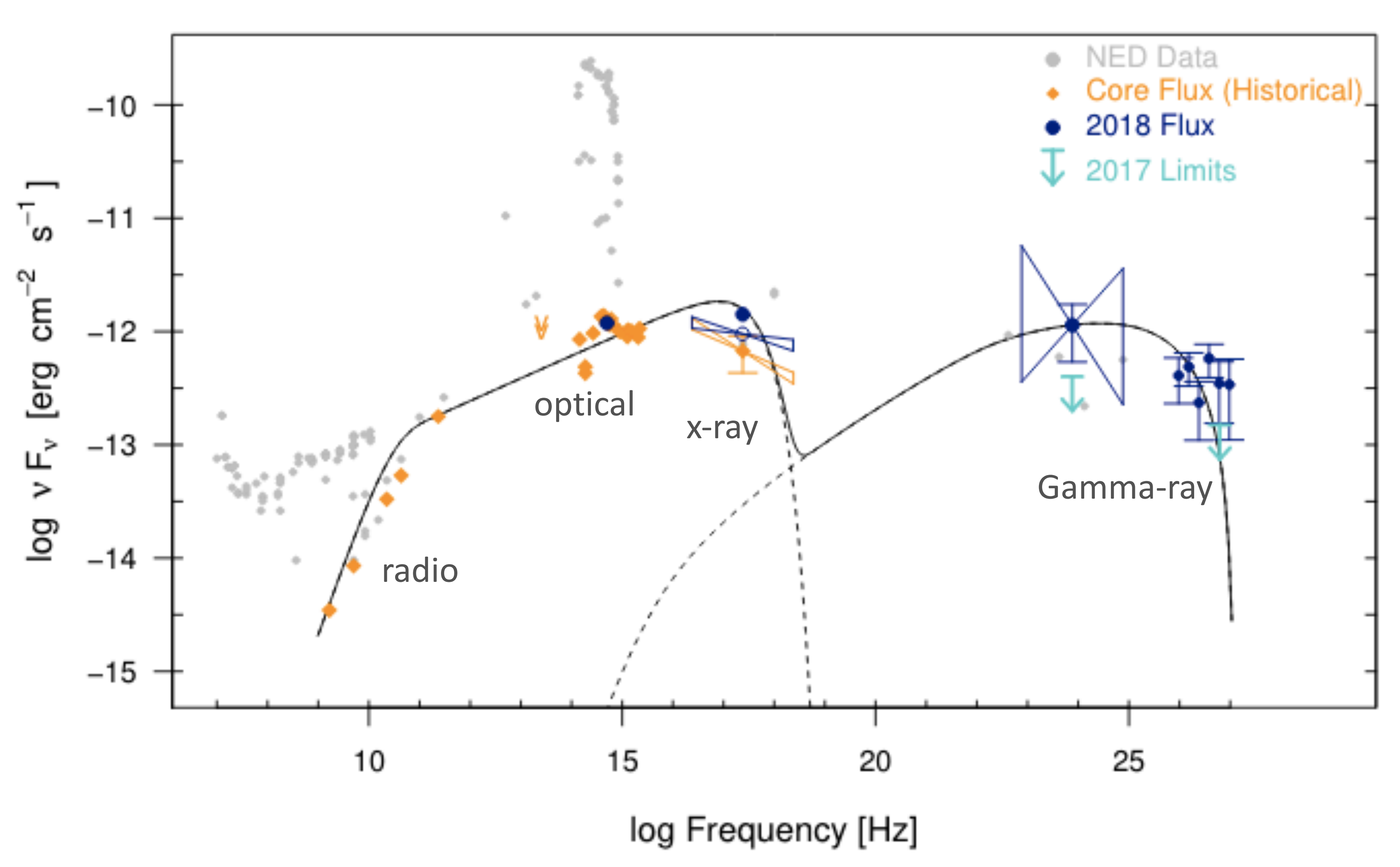
VLA Polarization Maps



VLBI (9 participating telescopes)



3C 264 – MWL Spectrum



Conclusions

- 3C 264 has a complex jet morphology, kinematics, and Spectrum.
- Provides a new observational angle to study the physics of Radio-Galaxy Jets.
- Strong evidence for a Jet powered by a supermassive black hole.
- Strong evidence for magnetic confinement of the electrons in the jet, as well as synchrotron and inverse Compton emissions.

- The time-scale of the elevated VHE Gamma-ray emission in 2018 leads us to conclude that the gamma-rays were produced in the Core of the jet.

- The interaction of knots B and C has so far only enhanced the optical and x-ray emission. No significant brightening in radio, or gamma-rays.

Personal Journey

Grew up in Hawthorne, CA (Los Angeles)

I played all day every day and did very little homework.
I'm a Christian and interested in faith and science issues.
I was good at math and music, bad at reading and spelling.
Graduated 4th in my high school class of 450, without much college preparation.

Started college as a Math Major

Switched major to physics because it was more interesting than pure math.

However, I'm no Einstein and I secretly wondered when the professors would tell me to go back to math.

I was the only female in my class of 23 physics majors.

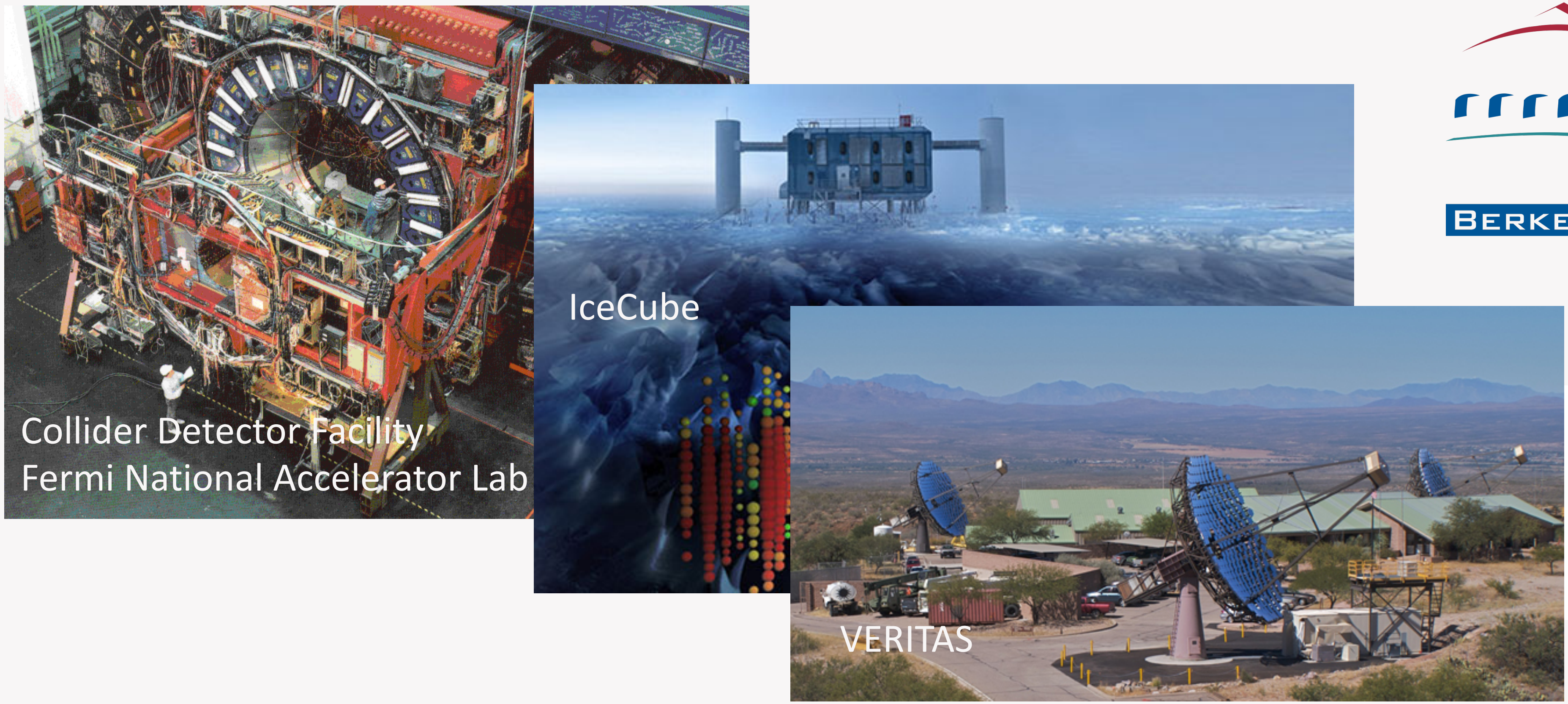
It wasn't until I was in my mid-late 30s before I figured that no one was going to tell me to quit doing physics.

Personal Journey

Harvey Mudd College

The University of Wisconsin Madison

Brandeis



Berkeley Lab

Cal Poly Mustangs