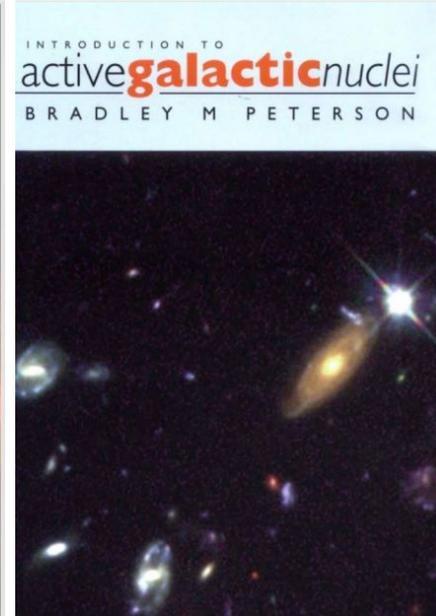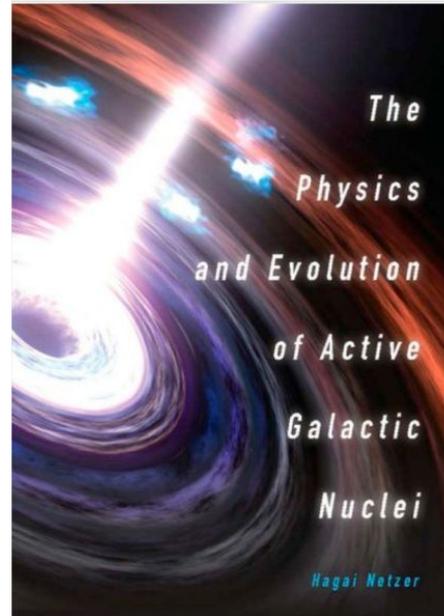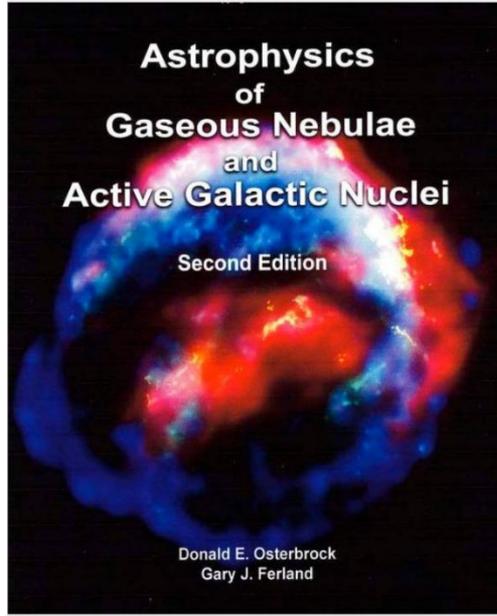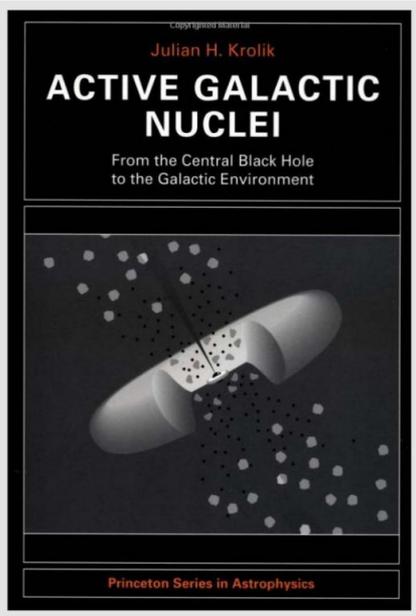# OBSERVATIONAL COSMOLOGY:
ACTIVE GALACTIC NUCLEI

Plus tons of online materials:
- Monaco
- Marconi
- Risaliti
- Brandt (link to lectures)
- Xie
- …

- **1908: Edward Fath notices strong emission lines from H, O, Ne in the nuclear spectrum of NGC 1068. This was way before:**

  - **1915: General relativity**

  - **1916: Schwarzschild solution found, but not fully understood**

  - **Early 1920s: Nebule recognized as extragalactic objects**

- **1917: Vesto Slipher obtains a higher quality spectrum of NGC 1068 and notes its emission lines are unusually broad**

- **1918: Herber Curtis notes in M87 a "curious straight ray ... connected with the nucleus by a thin line of matter"**

- **1924-1929: General realization that nebule (galaxies) are extragalactic – led by Edwin Hubble**

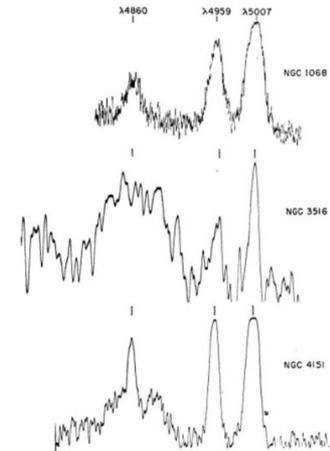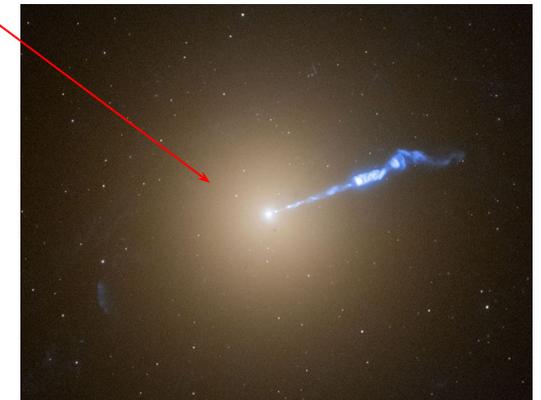- **1926: Edwin Hubble notices the nuclear emission-line spectra of NGC 1068, NGC 4051, NGC 4151**

FIG. 1.—Microphotometer tracings of the emission lines λλ 4860 (Hβ), 4959 and 5007 [O III] in the nebulae NGC 1068, 3516, and 4151.

EARLY HISTORY

- **1939: Grote Reber discovers the radio source Cygnus A**

- **1943: Carl Seyfert shows that a fraction of galaxies have strong, broad emission lines and that these galaxies are especially luminous – now known as "Seyfert galaxies"**

- **1954: Walter Baade and Rudolph Minkowski find the counterpart to Cygnus A at z = 0.057**

- **1963: Maarten Schmidt discovers 3C273 to have z = 0.158**

- **1964: Zeldovich & Novikov and Salpeter speculate about black holes powering quasars**

- **1967: The term "black hole" comes into general use**

- **1968: Donald Lynden Bell notes that many galactic nuclei may contain "collapsed old quasars"**

- **After – AGNs become a topic of widespread study**

Cygnus A @ 5 GHz
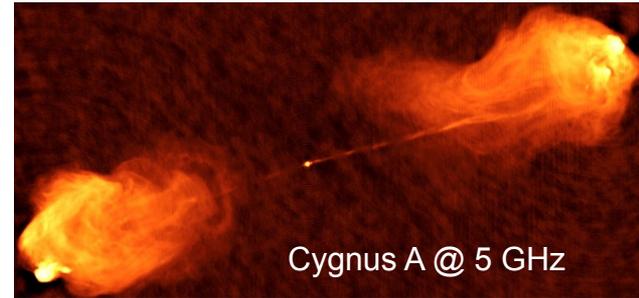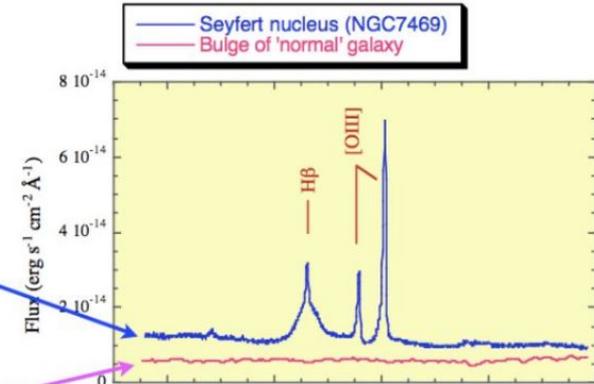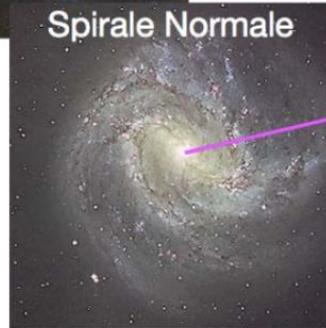
In the local Universe:

- $\sim 10^{-6}$ of massive galaxies contain luminous quasars
- $\sim 5\%$ are moderately luminous AGNs (Seyfert galaxies)
- $\sim 30\%$ show signs of low-level AGN activity

M33 – Normal Galaxy

M100 – Normal Galaxy

3C273 – Active Galaxy

PKS 2349–014 – Active Galaxy
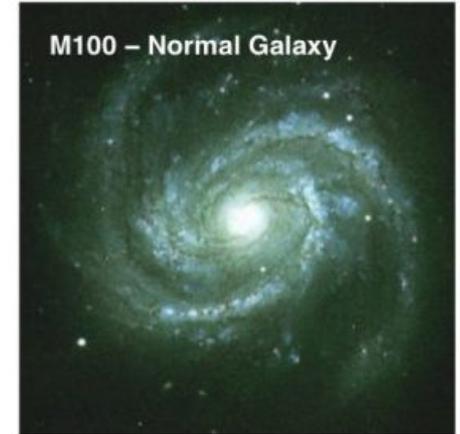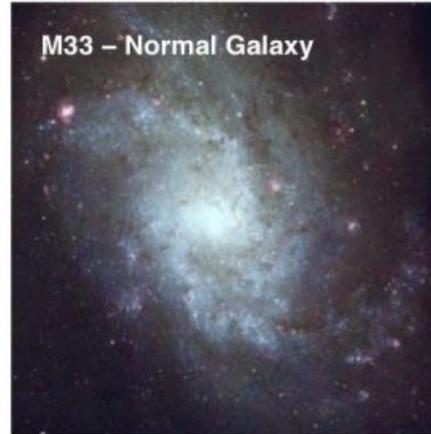
Peculiar spiral galaxies with:

- **Bright, compact nuclei**

- **Strong and broad (permitted) emission lines**

- **These emission lines indicates a ionization level of the gas larger than regular star forming HII regions**

- **The lines can have FWHM>1000 km/s which cannot be explain by stellar motions in galaxies (~few 100s km/s) → this imply gas orbiting very close to a compact massive object**

Peculiar spiral galaxies with:

- **Strong UV continuum**

- **Many Seyferts show a UV excess (big blue bump)**

NGC 4151, by HST
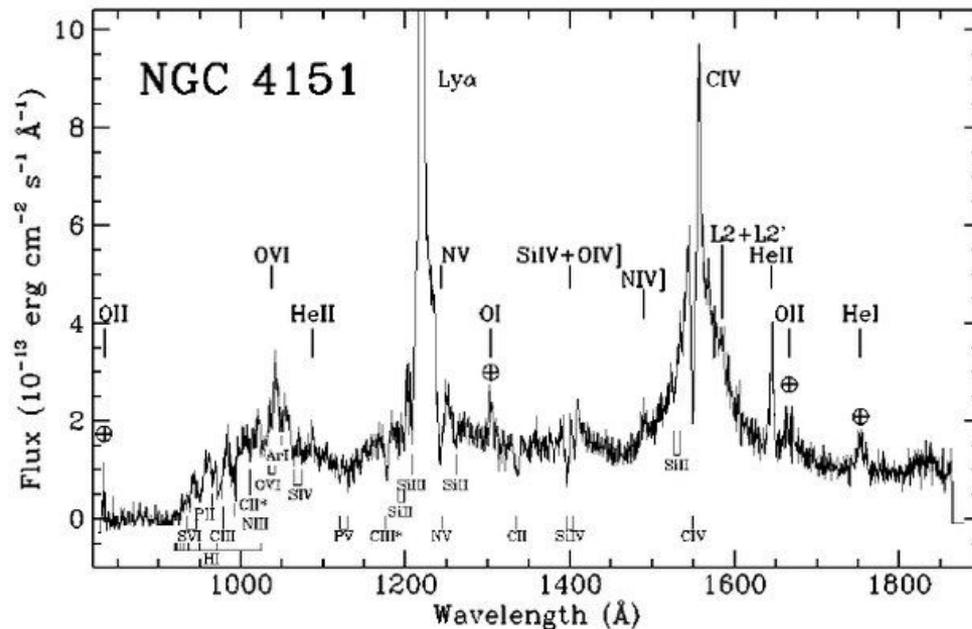
UV spectrum of the Seyfert galaxy NGC 4151 observed with Hopkins UV Telescope

NGC 1068: An obscured Seyfert

- **The core of the galaxy is hidden by dense clouds of gas and dust.**

- **A cone-shaped region of highly ionized gas emanates from the nucleus, shaped by radiation escaping from the nucleus.**

The nucleus is hidden in here
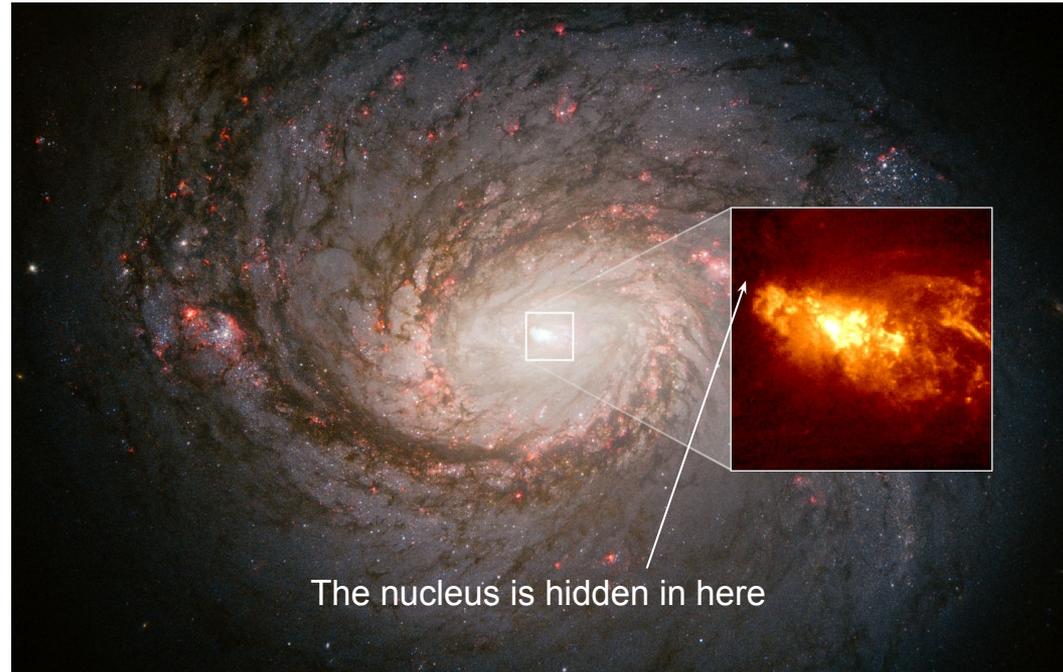
The inset Hubble Space Telescope image resolves hydrogen clouds as small as 10 light-years across within 150 light-years of the core.

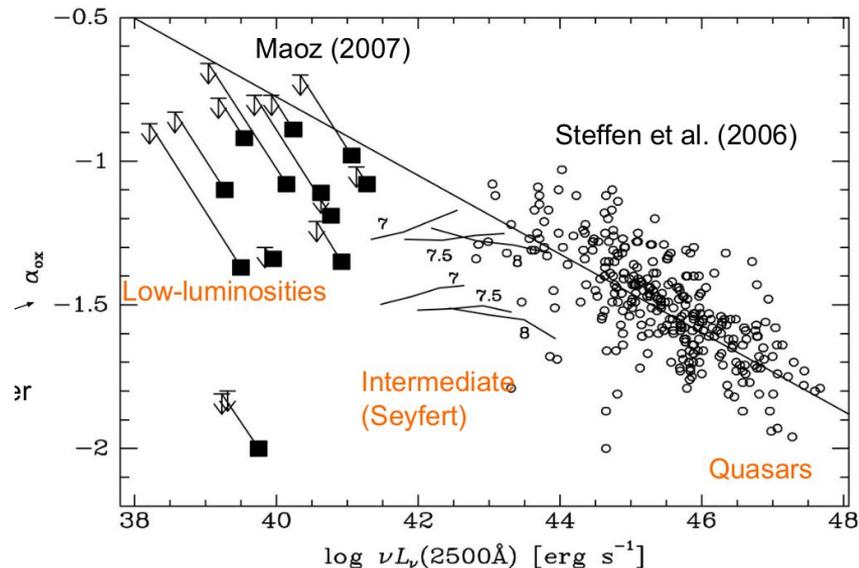**5 MAIN OBSERVED PROPERTIES:**

1. **Broad range of luminosities, reaching very large values**

2. **Strong and broad optical/UV emission lines**

3. **Emission over a very broad band**

4. **Variability**

5. **Particle Jets**

Broad range of luminosities:

- **Span more than 9 orders of magnitude in luminosity**

- **There is no strict lower limit on luminosity; e.g., even the black hole at the center of our Galaxy shows some intermittent activity at very low levels (comparable with 10^{33} in the plot).**

- **At very low luminosities, the distinction between active and normal galaxies is largely semantic → There is no clear bimodal separation of properties.**

- **There is a maximum observed luminosity, and we believe that we have found examples of the most luminous AGNs that exist (i.e., the most luminous quasars) → They outshine their own galaxy by factors of 100-1000s and can easily be detected to high-z**
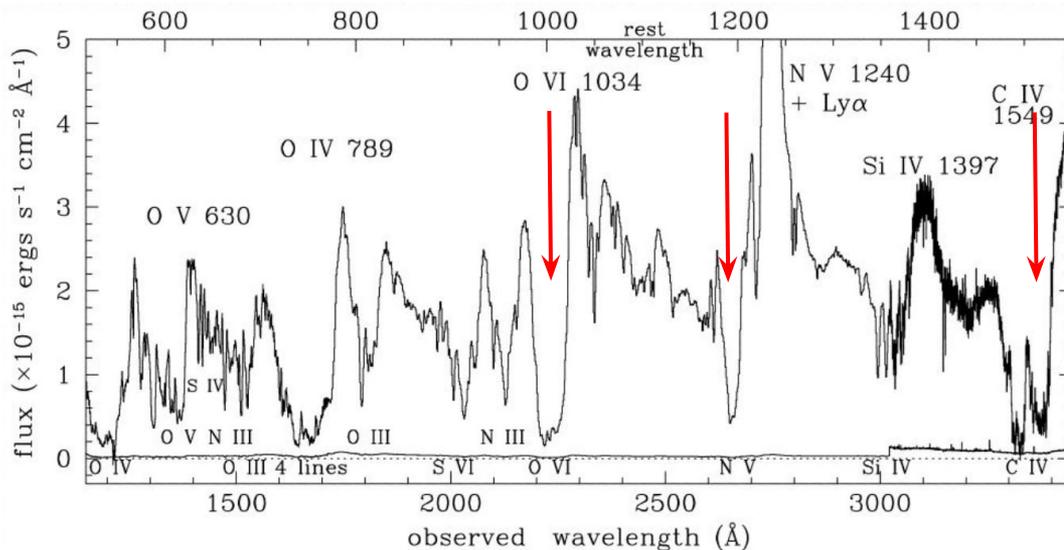
Strong and board optical/UV emission lines:

- **Indicate the presence of ionized nebular gas**

- **The gas is photo-ionized by the bright central source**

- **The line widths exceed the thermal limits, indicating doppler broadening from bulk motions**

    - **wide range of velocities, up to ~25000 km/s**

- **There are broad lines and narrow lines, indicating a stratified ionized gas structure in the AGN**

    - **BL e.g. balmer, He I, He II, but not forbidden lines → dense and compact regions**

    - **NL e.g. [OIII], [NII] → less dense region farther from the nucleus**

Stacked AGN spectra from SDSS

Strong and board optical/UV emission lines:

- **Abundances are about solar or slightly super-solar (very difficult measurements)**

- **Sometimes AGNs present blue-shifted absorption lines:**

  - **Indicate the presence of absorbing outflowing gas along the LOS**

  - **The absorption lines can be very board → velocities of ~10^3-10^4 km/s**

Emission over a very broad band:

- **The AGN spectrum can span more than 10 orders of magnitude in frequency:**

  - **~10% of the AGN have strong radio emission (radio loud vs radio quite)**

- **The spectrum is typically much flatter w.r.t. e.g. the one from stellar emission**

  - **Regular galaxy spectra peak in the ~optic in correspondence of the peak of the BB stellar emission**
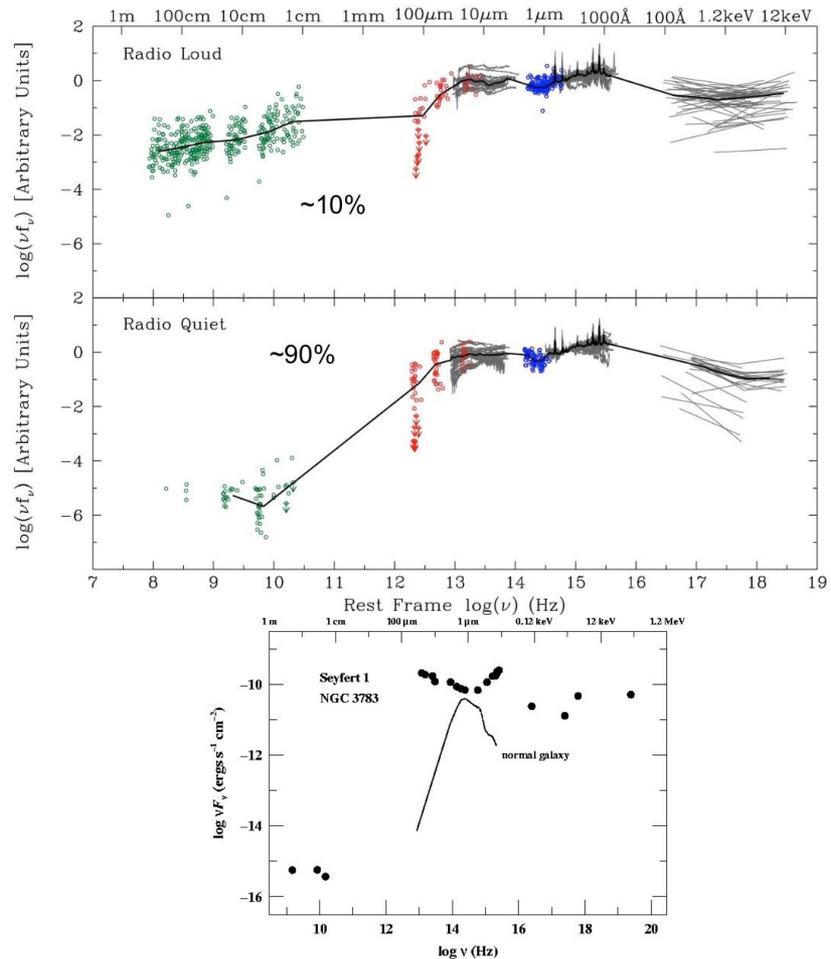
Variability:

- **The variability is generally chaotic without a clear period**
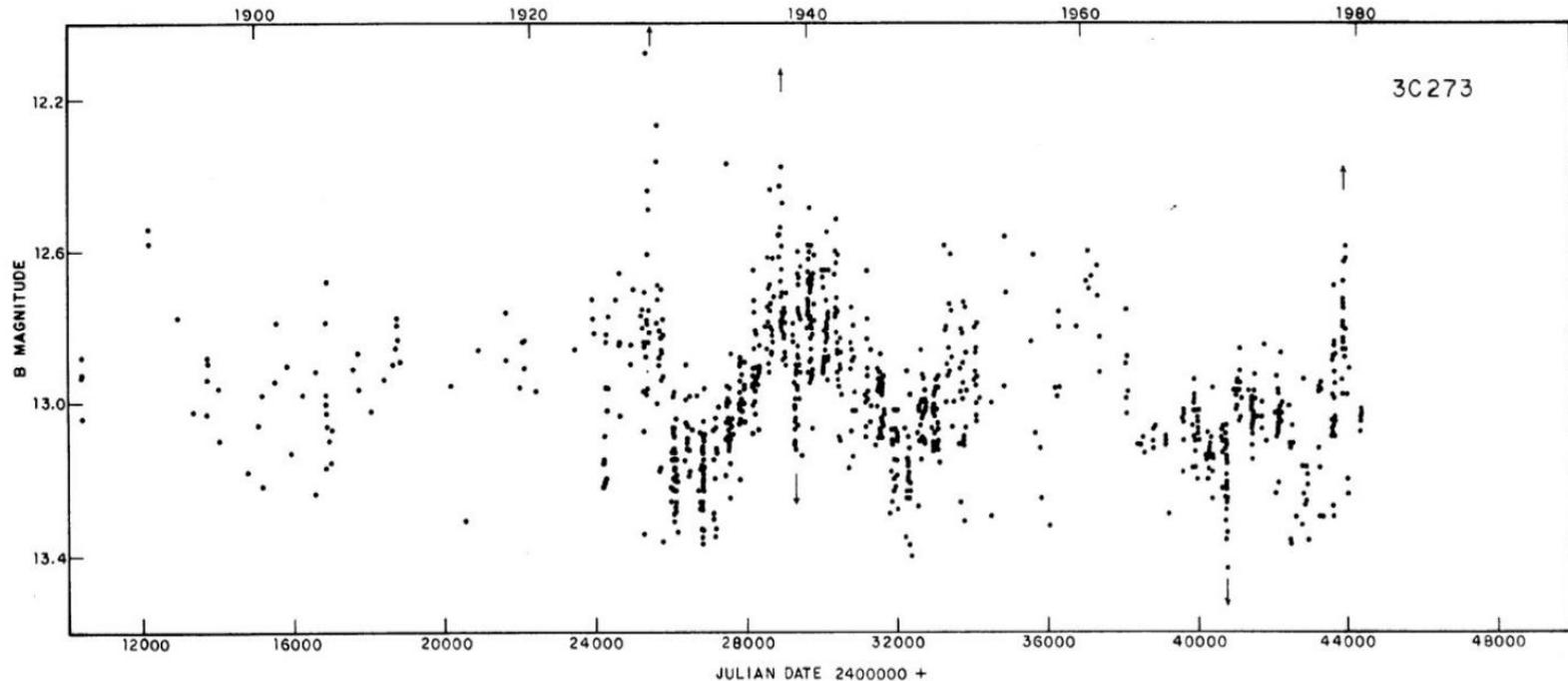
100 year of 3C 273

Continuum variability:

- **Coherent at all wavelengths**
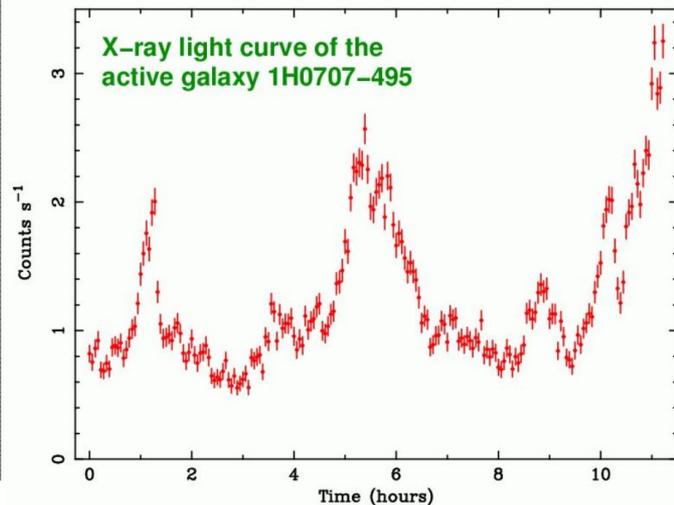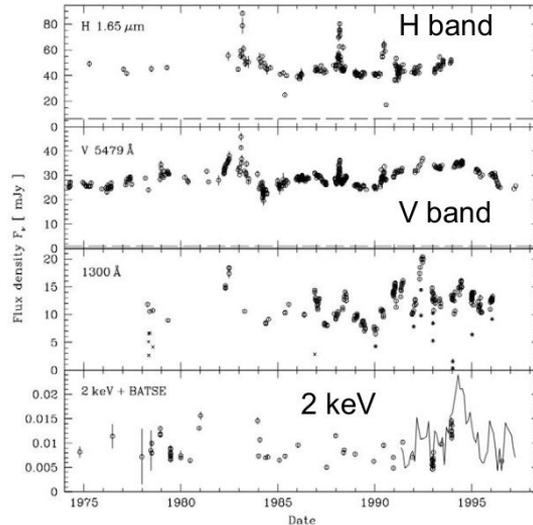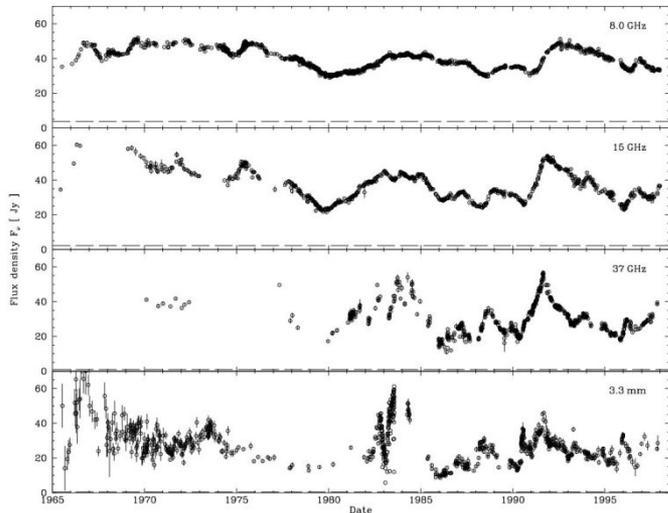
- **Increases – larger and quicker variations – as one moves to higher frequencies**
    - **In the X-ray observed variability on timescales down to minutes**
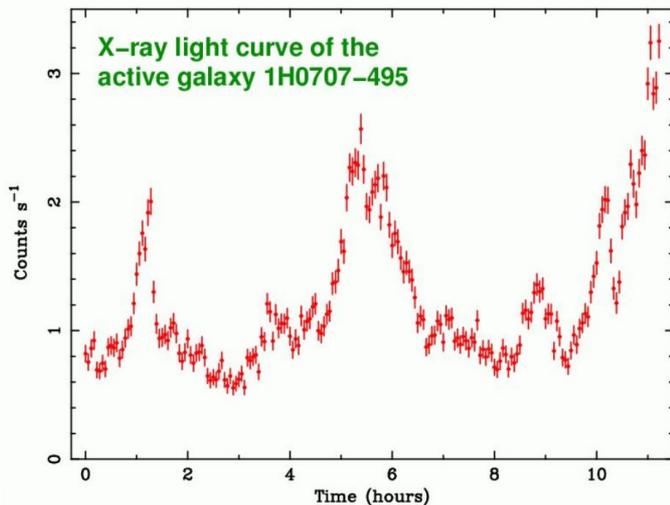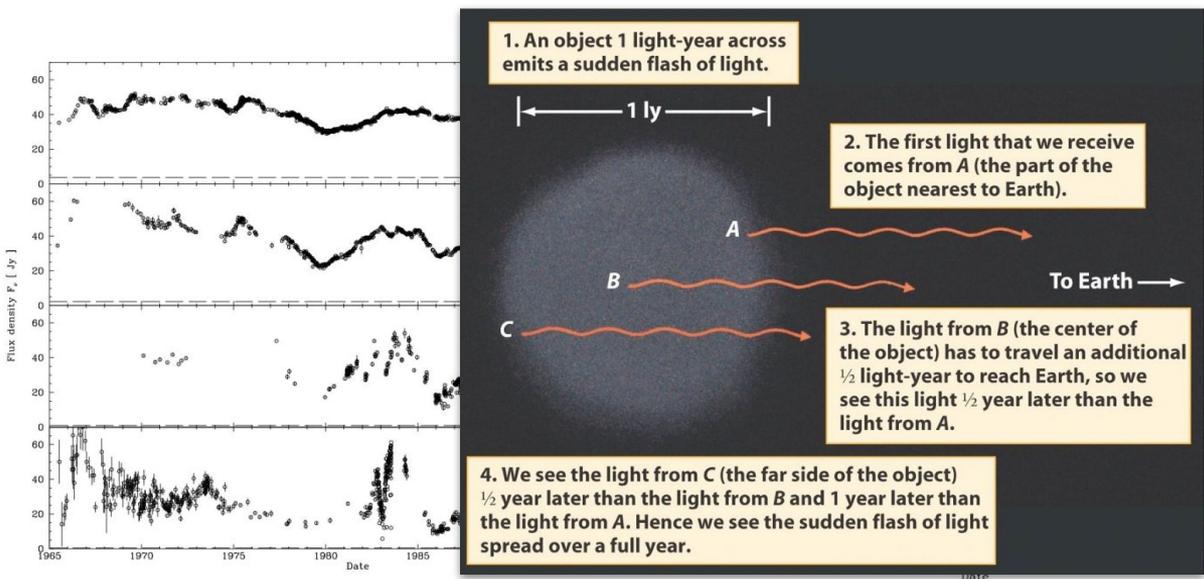
Continuum variability:

- **Coherent at all wavelengths**

- **Increases – larger and quicker variations – as one moves to higher frequencies**

  - **In the X-ray observed variability on timescales down to minutes → emission region of the size of light-hours or less**
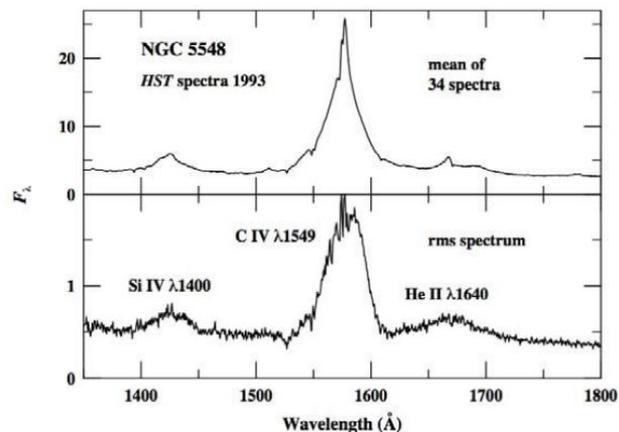
Emission Line variability:

- **The broad emission lines also vary, generally following the continuum with a lag.**

  - **This leads to the idea of a purely geometric time delay due to the different regions emitting the continuum and the EL (→ reverberation mapping technique)**

C IV Variability in NGC 5548

Hβ Variability of Markarian 335

Figure 4. The top panel shows the mean spectrum computed from 34 HST spectra of the variable Seyfert 1 galaxy NGC 5548[40]. The lower panel shows the rms spectrum based on variations around this mean. The rms spectrum thus isolates the variable components of the spectrum. Fluxes are in units of 10^{-15} ergs s^{-1} cm^{-2} Å^{-1}.
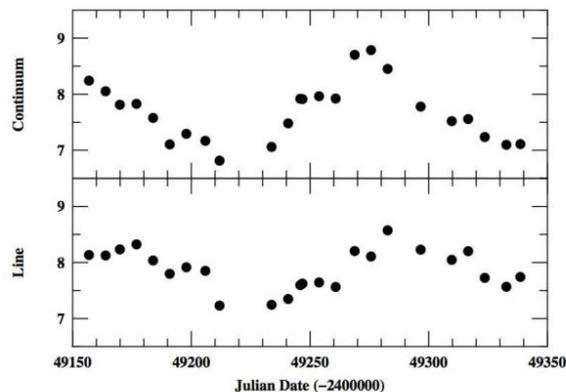
Figure 23. The Hβ emission-line and optical continuum fluxes for Mrk 335, as shown in Fig. 22, are plotted as a function of time. It is clear from the figure that the continuum and emission-line fluxes are well-correlated, and that the correlation can be improved by a linear shift in time of one time series relative to the other. The optimum linear correlation occurs by shifting the emission-line light curve backwards by 15.6 days.

Particle Jets:

- **About 10% of the AGN emit powerful particle jets extending from pc to Mpc scales**

- **These produce strong linearly polarized radio emission via synchrotron radiation (radio loud AGNs)**
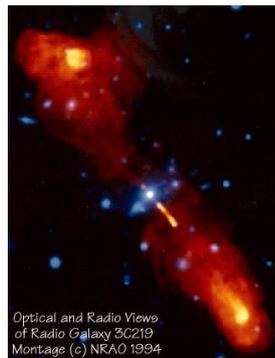
Optical and Radio Views of Radio Galaxy 3C219 Montage (c) NRAO 1994
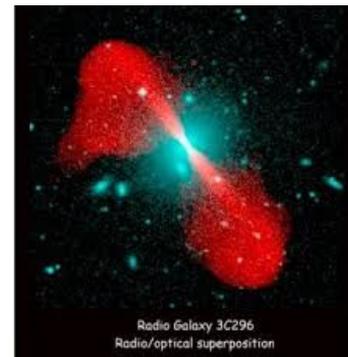
Radio Galaxy 3C296 Radio/optical superposition

Visible light

X–ray light

Infrared light

Radio light

Multi–wavelength image

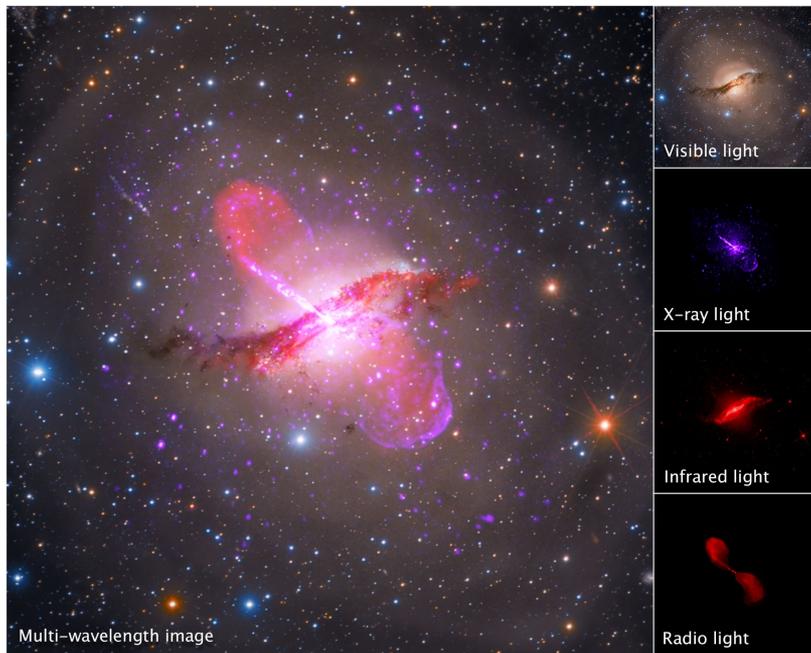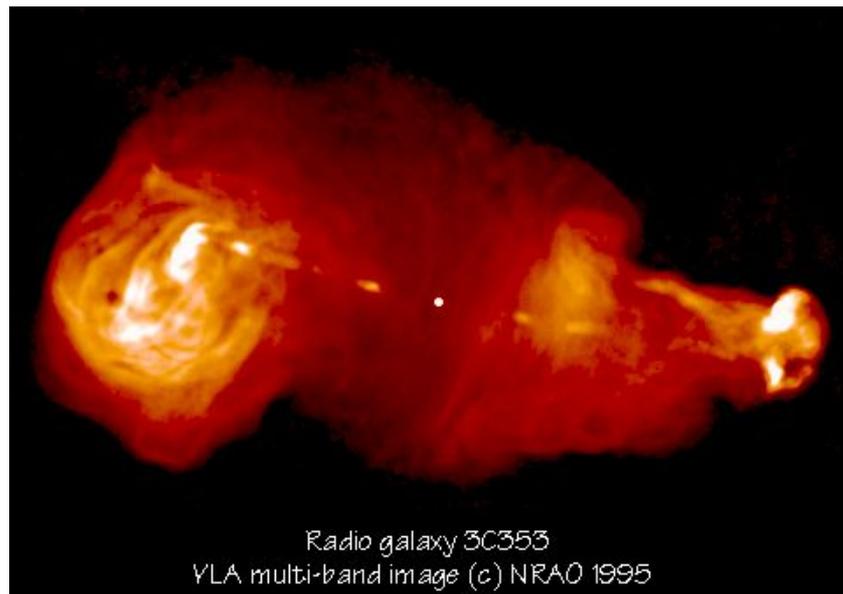Radio galaxy 3C353 VLA multi-band image (c) NRAO 1995

Particle Jets:

- **About 10% of the AGN emit powerful particle jets extending from pc to Mpc scales**

- **These produce strong linearly polarized radio emission via synchrotron radiation (radio loud AGNs)**

- **Jets also seen in Optical, X-ray (inverse Compton scattering), gamma-rays (blazars)**

- **Cosmological relevance:**

  - **Inject energy in the interstellar and intracluster medium (10^{58} - 10^{61} erg in radio lobes)**

  - **Regulate star formation (AGN feedback)**

  - **Affect galaxy evolution**
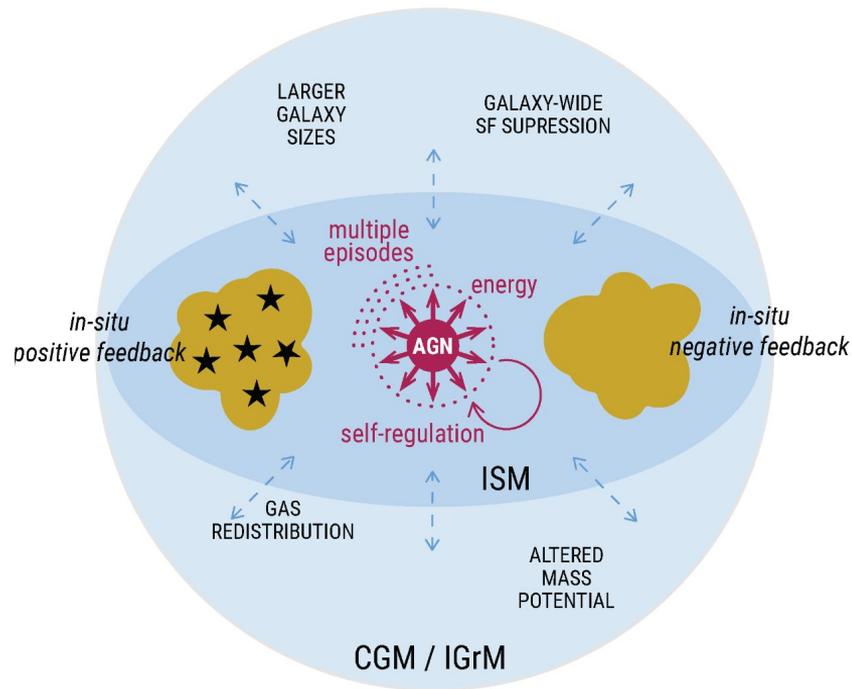
Particle Jets:

- **The particle jets can produce characteristic pattern when interacting with the surrounding medium**

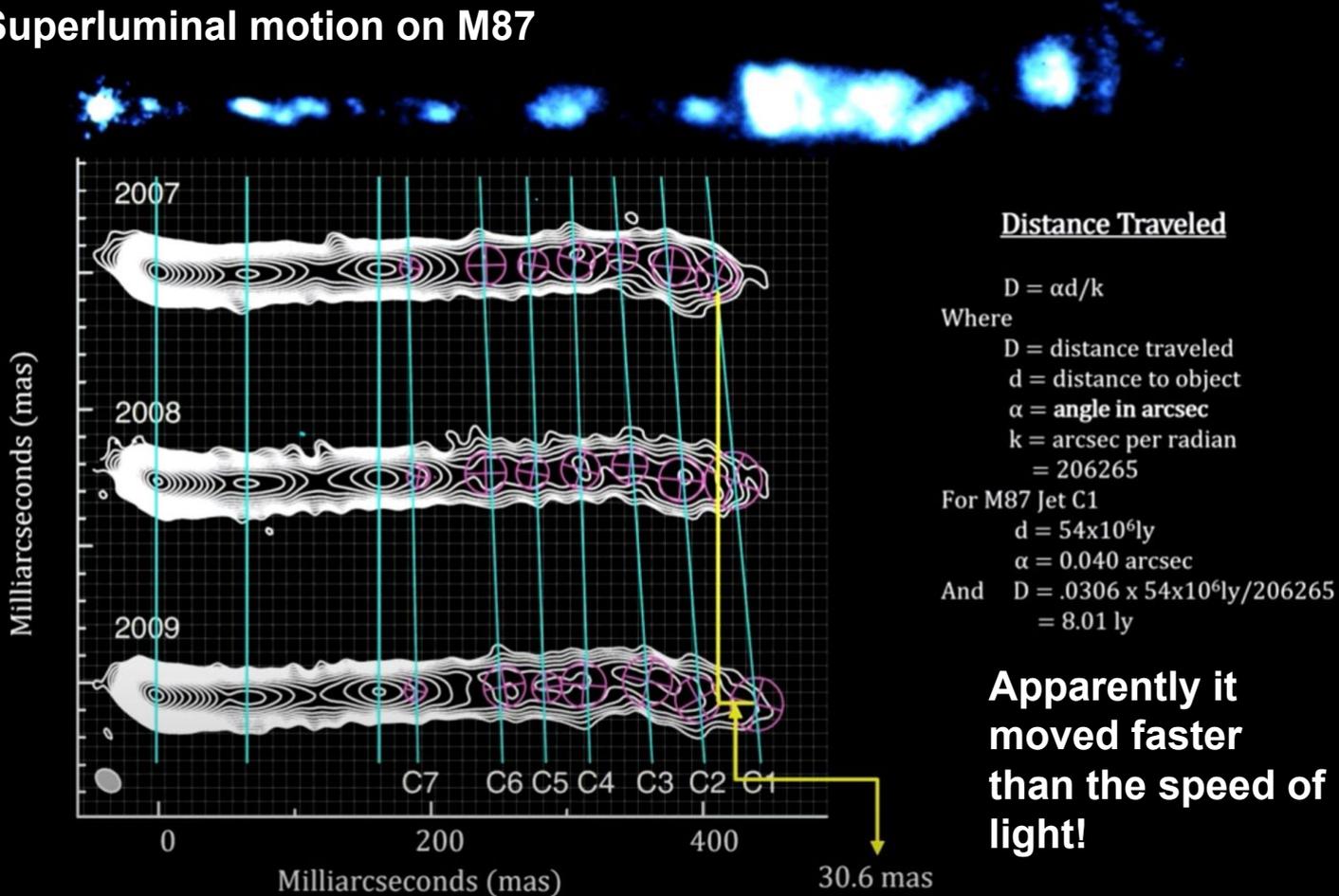- **The direction of the jets is stable over a very long timescale → imply a stable "gyroscope" that keep the pointing fixed**
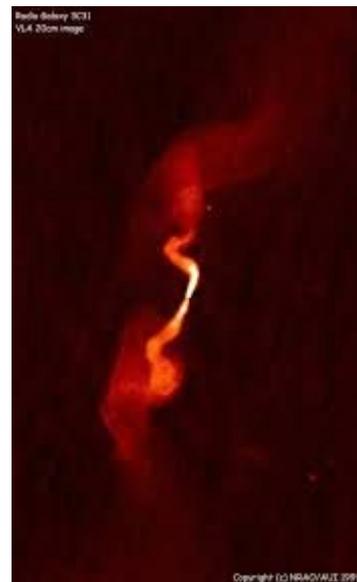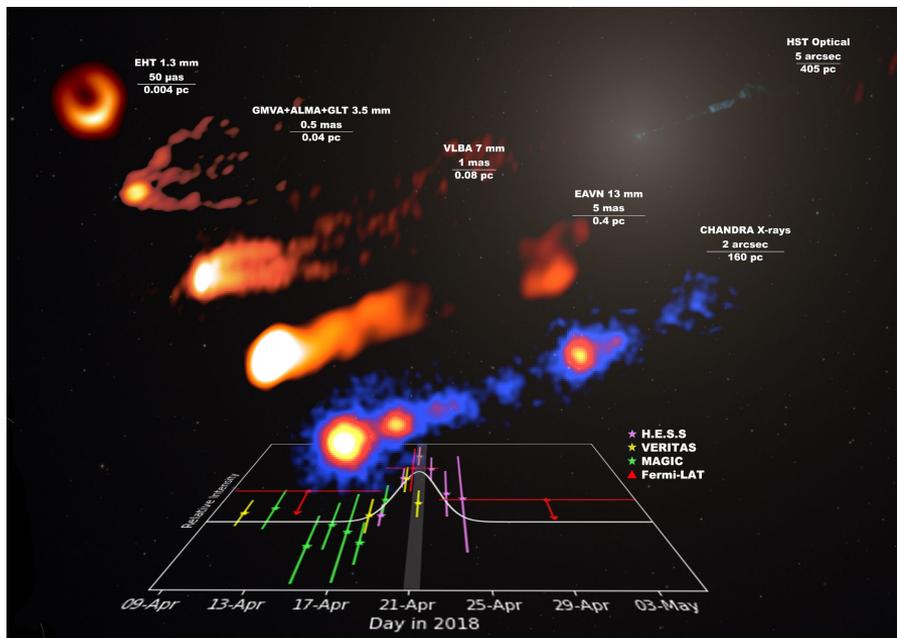
NGC 1265 "Cosmic Skywriting" - In Perseus Cluster

Superluminal motion on M87

Distance Traveled

$$D = \alpha d / k$$

Where

D = distance traveled
d = distance to object
α = **angle in arcsec**
k = arcsec per radian
= 206265

For M87 Jet C1

$d = 54 \times 10^6 \text{ ly}$
α = 0.040 arcsec

And $D = .0306 \times 54 \times 10^6 \text{ ly} / 206265$
= 8.01 ly

Apparently it moved faster than the speed of light!

Superluminal motions:

- **Suppose a source emits flashes 1 day apart, while moving toward us at 0.8c**

- **Flashes emitted 1 day apart are received 0.2 days apart**
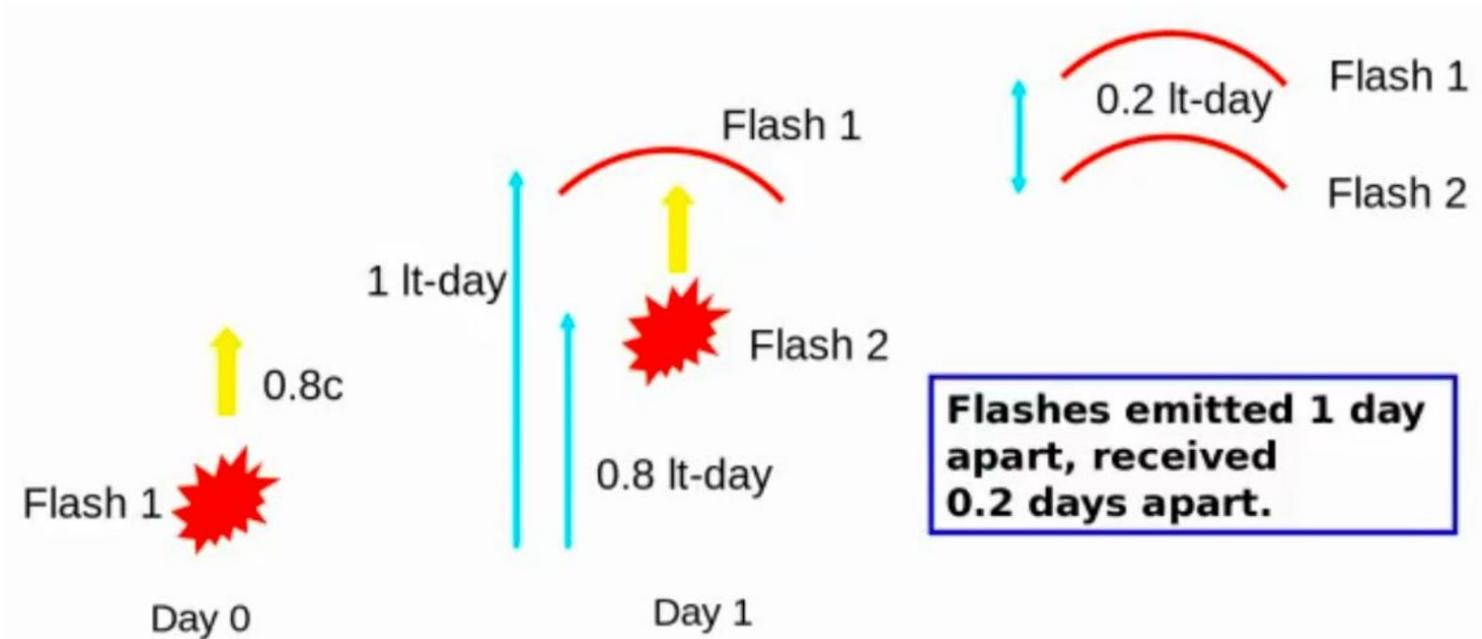
Superluminal motions:

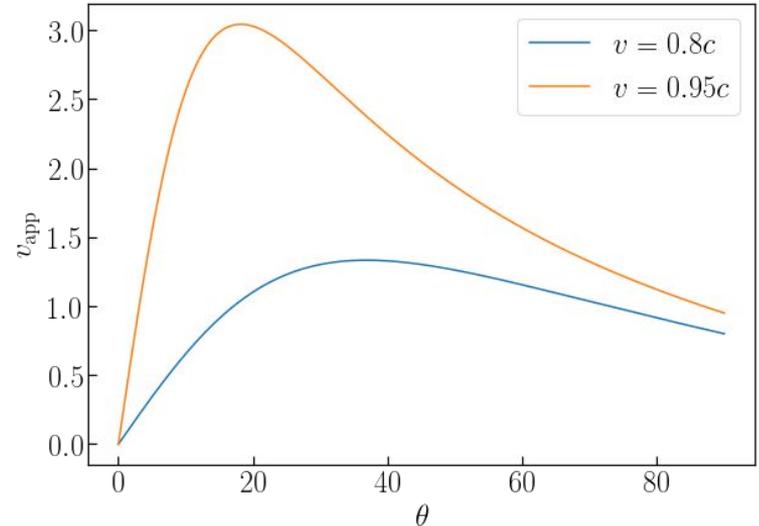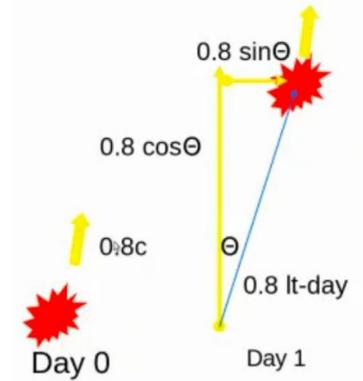- **Consider a continuously glowing blob, moving almost toward us at v =0.8c with an inclination of ϑ**

- **In 1 day, the blob traveled a distance 0.8 c t_{day}, but the apparent travel time – i.e. the observed Δt between the light emitted at t_0 and t_{day} – is $\Delta t = (1 - 0.8 \cos \vartheta) t_{day}$.**

- **The projected distance on the sky plane is:**

$$\Delta x = 0.8 \ c \ t_{day} \ \sin \vartheta$$

- **The apparent speed on the sky plane is:**

$$\Delta x / \Delta t = c[\ 0.8 \sin \vartheta \ / \ (1 - 0.8 \cos \vartheta)]$$

Superluminal motion on M87

Let

$\delta t = (t_2 - t_1)$

$D = v\,\delta t$

θ = the viewing angle

$D' = v\delta t \sin\theta$

D_L = the long distance to the object at point B

φ = the milliarcsec movement angle

$t_1' = t_1 + (D_L + D\cos\theta)/c$ Arrival time of signal emitted at t_1

$t_2' = t_2 + D_L/c$ Arrival time of signal emitted at t_2

$\delta t' = (t_2' - t_1')$

Then

$\delta t' = \delta t(1 - (v/c)\cos\theta)$

$\delta t = \delta t'/(1 - (v/c)\cos\theta)$

$v = D/\delta t$ True jet velocity

$v' = D'/\delta t'$ Apparent jet velocity

$v' = v\sin\theta/(1 - (v/c)\cos\theta)$

$v = v'/(\sin\theta + (v/c)\cos\theta))$

We observe

$\theta = 14°$

$\varphi = 30.6$ mas

$\delta t' = 2$ yr

We calculate

$D' = 8.01$ ly

$v' = 4c$

$v = 4c/(\sin 14 + (4c/c)\cos 14)$

$= .97c$

$\delta t = 2\text{yr}/(1 - (4c/c)\cos 14)$

$= 66.7$ yr

B at t_2

$v\delta t = D$

$D' = v\delta t\sin\theta$

D_L

φ

O

D_L

C $v\delta t\cos\theta$

θ

A at t_1