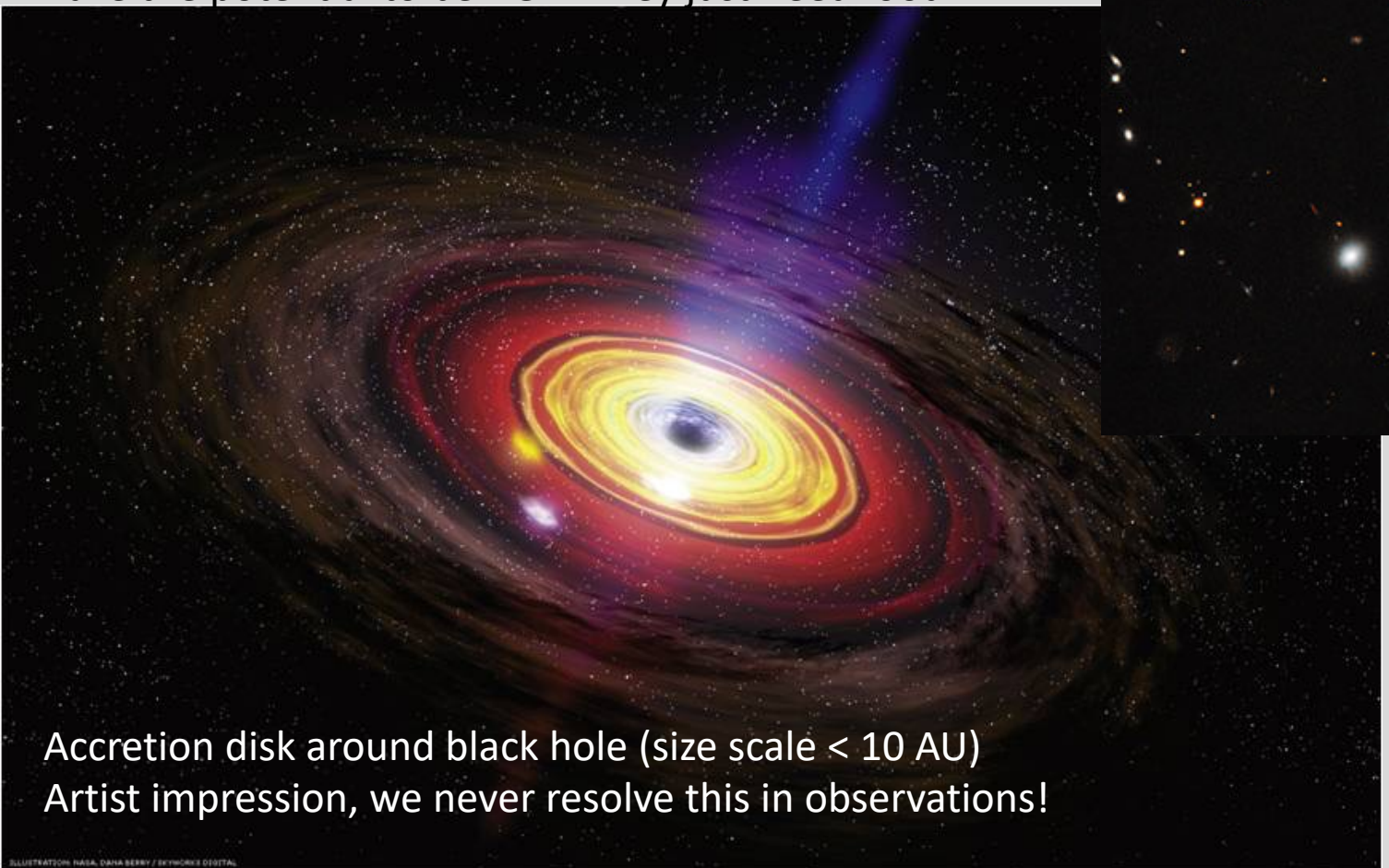
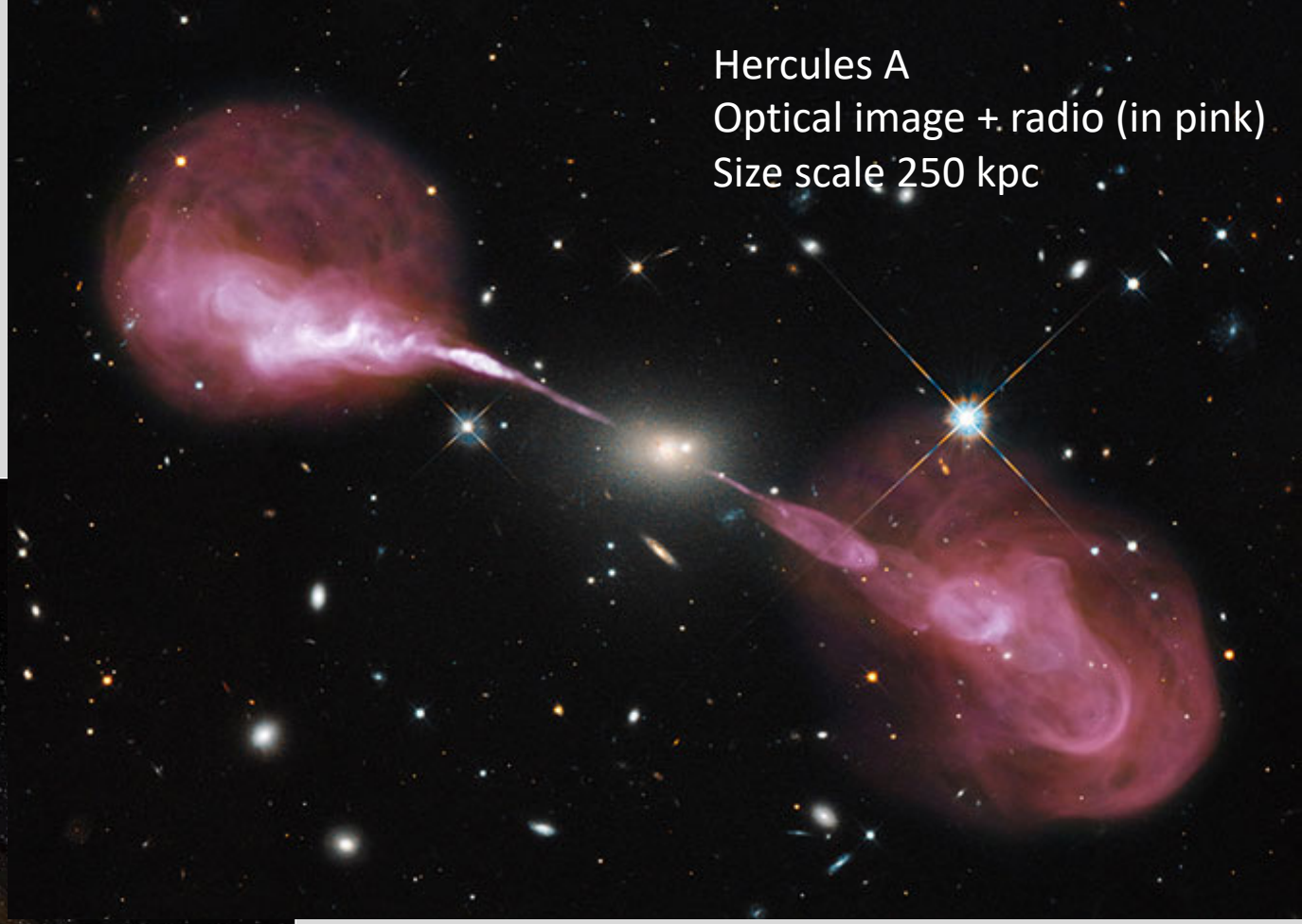
Active Galactic Nuclei (AGN)

Powered by accretion of matter onto a supermassive black hole (SMBH) in the nucleus of a galaxy.

Most bright galaxies have central SMBHs, so they have the potential to be AGN. They just need food….



Accretion disk around black hole (size scale < 10 AU)
Artist impression, we never resolve this in observations!



Hercules A
Optical image + radio (in pink)
Size scale 250 kpc

These images show a factor of 10^{10} difference in scale!

The central AGN is always an unresolved point source; we observe its total light and have to infer its physical properties.

AGN: Optical Spectra

extreme ultraviolet

Strong emission lines: photoionized gas

High ionization emission lines (triply ionized carbon, 4x ionized nitrogen, etc): “hard” ionization source, meaning something emitting very energetic photons.

far ultraviolet

Very blue continuum: not stellar

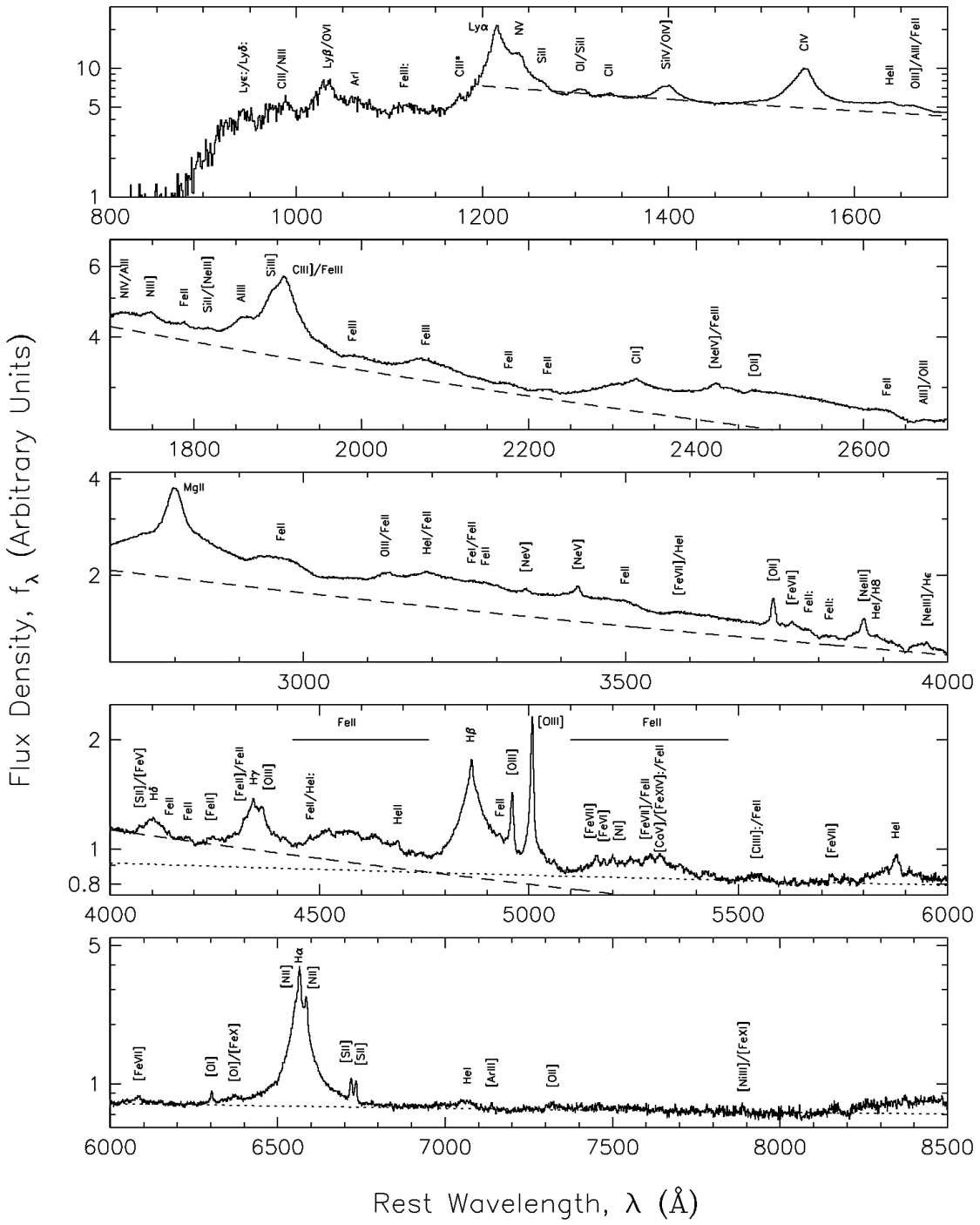
near ultraviolet

Very broad line widths: $\Delta V > 10{,}000$ km/s

Gas-phase metallicity: solar-ish

optical blue

optical red



“median composite” AGN spectrum

(vanden Berk+ 01)

AGN: Luminosity across the entire spectrum

Shang+ 11

Things to note:

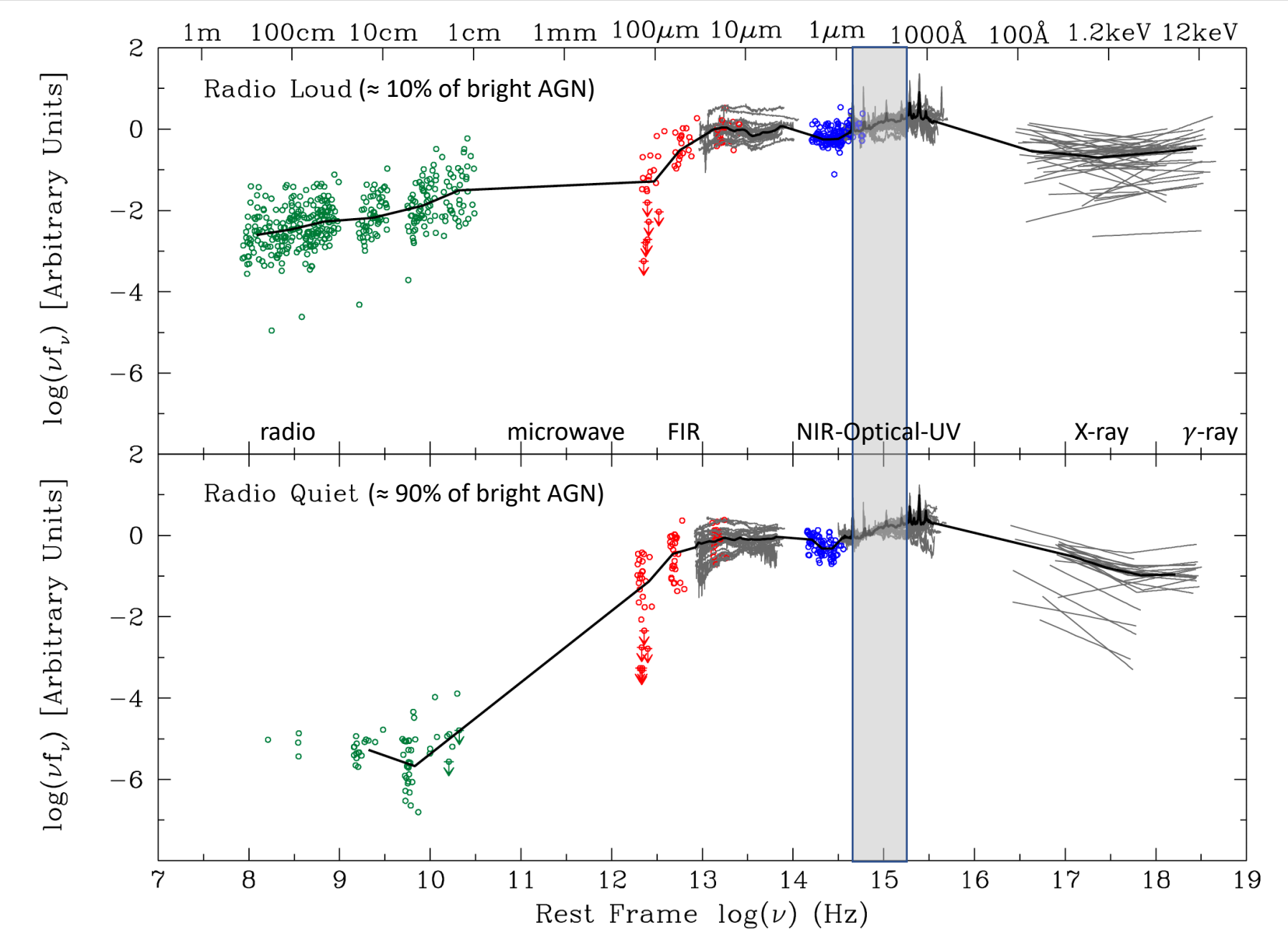
High energy sources!

- Lots of UV emission
- Lots of X-ray emission

Differences in radio emission

- Radio Loud (top)
- Radio Quiet (bottom)

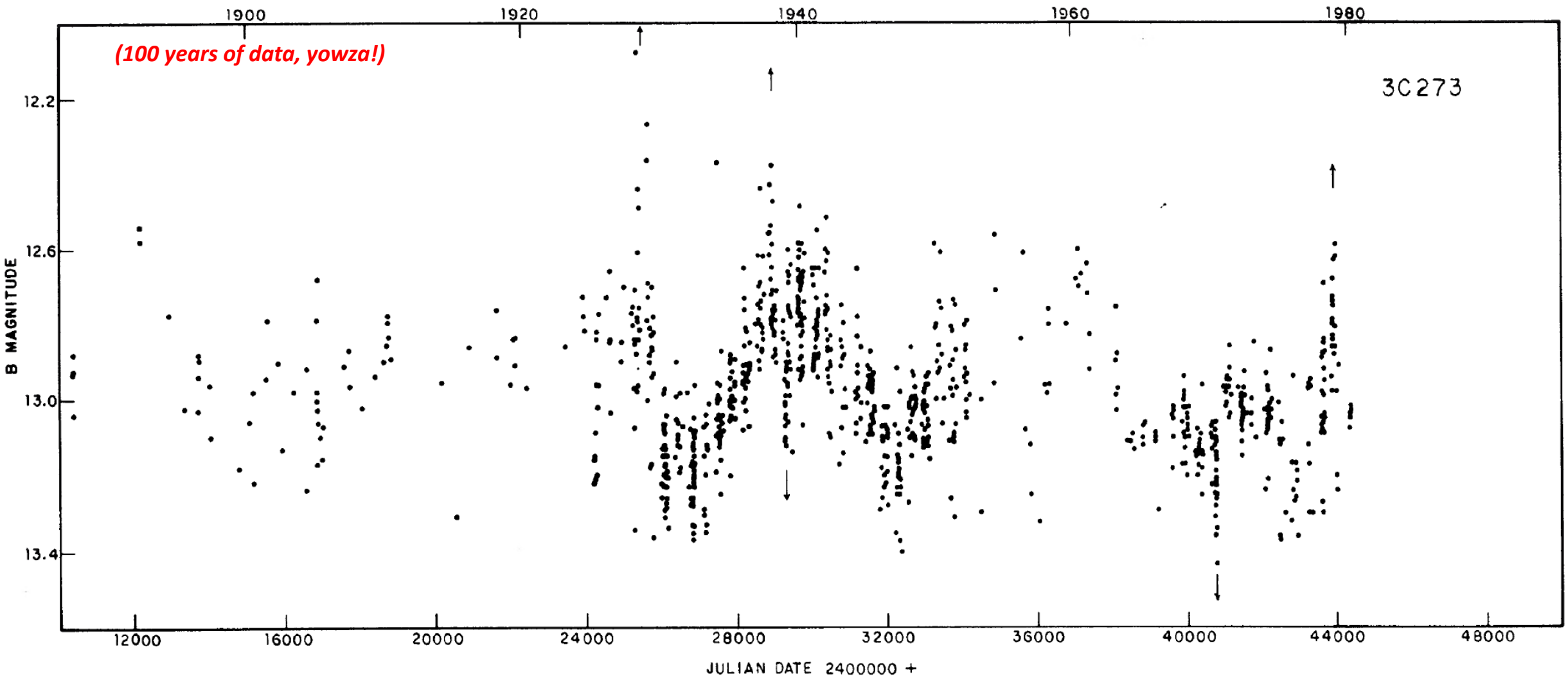
About 10% of bright AGN are radio loud.



AGN: Highly variable

On years-long timescales: *stellar populations cannot do this!*
No periodicity or regularity

Angione & Smith 1985



AGN: Highly variable

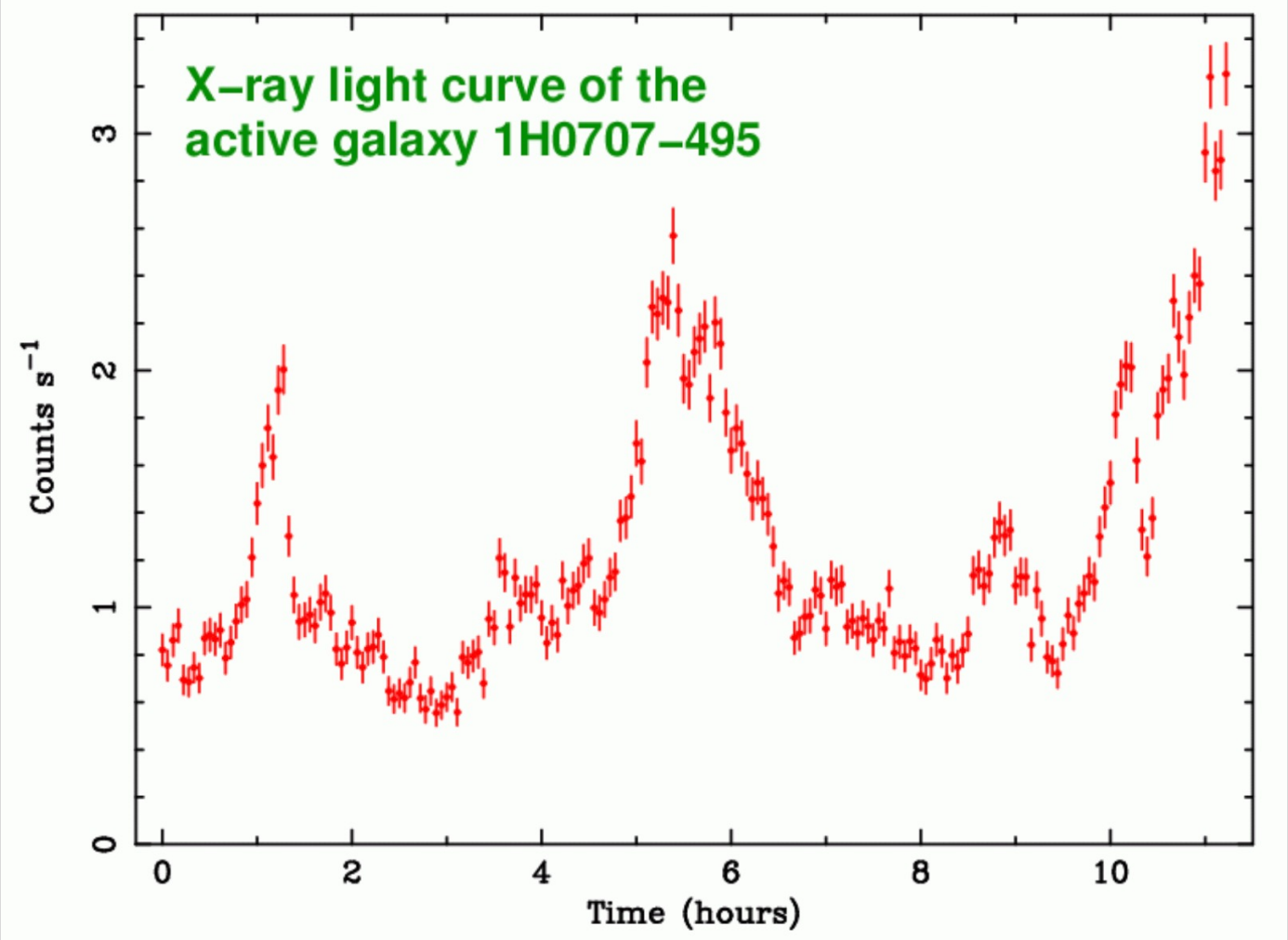
Variability stronger and even more rapid at shorter wavelengths / higher energies: on the scale of minutes!

Remember causality: if an object changes brightness, its size must be smaller than the light travel time:

$$R \leq c\Delta t$$

3C273: hour-timescale variability, so $R \lesssim 7$ AU! That's like having $L \approx 10^{13}\ L_\odot$ crammed inside the solar system.

courtesy Niel Brandt



AGN: Luminosity density and the Eddington Limit

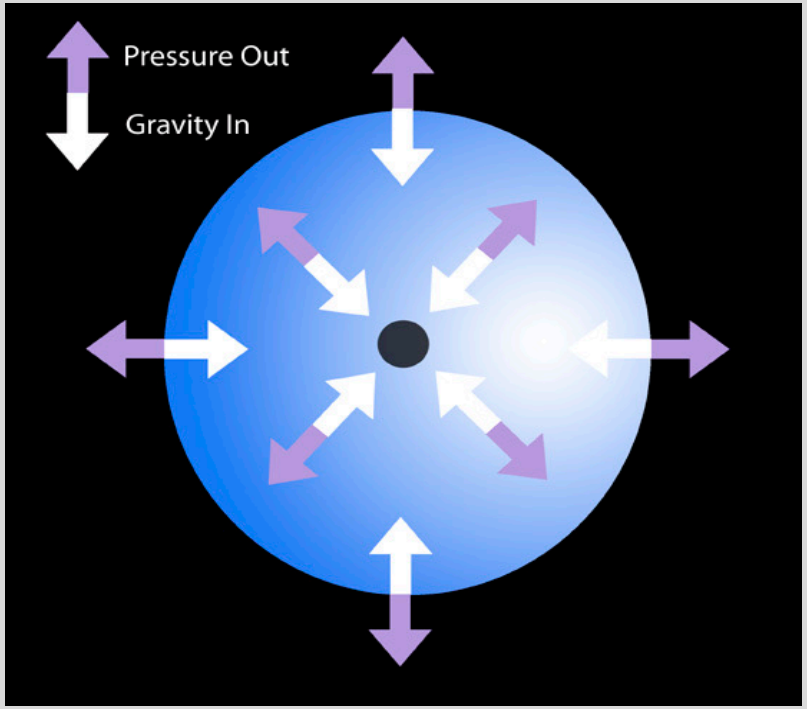
Consider an electron in the ionized gas, at a distance R from the central source which has a luminosity L. That electron feels a radiation pressure from the photons of

$$P_{rad} = \frac{L}{4\pi R^2 c}$$

and so the outward force is given by

$$F_{rad} = \sigma_T P_{rad} = \frac{\sigma_T L}{4\pi R^2 c}$$

where σ_T is the Thomson cross-section for scattering of light by an electron.



Opposing that force is the inward pull of gravity, which attracts both protons and electrons, which are coupled via electrostatic forces:

$$F_{grav} = -\frac{GM(m_p + m_e)}{R^2} \approx -\frac{GMm_p}{R^2}$$

To remain bound, $F_{grav} > F_{rad}$, or:

$$\frac{GMm_p}{R^2} \geq \frac{\sigma_T L}{4\pi R^2 c}$$

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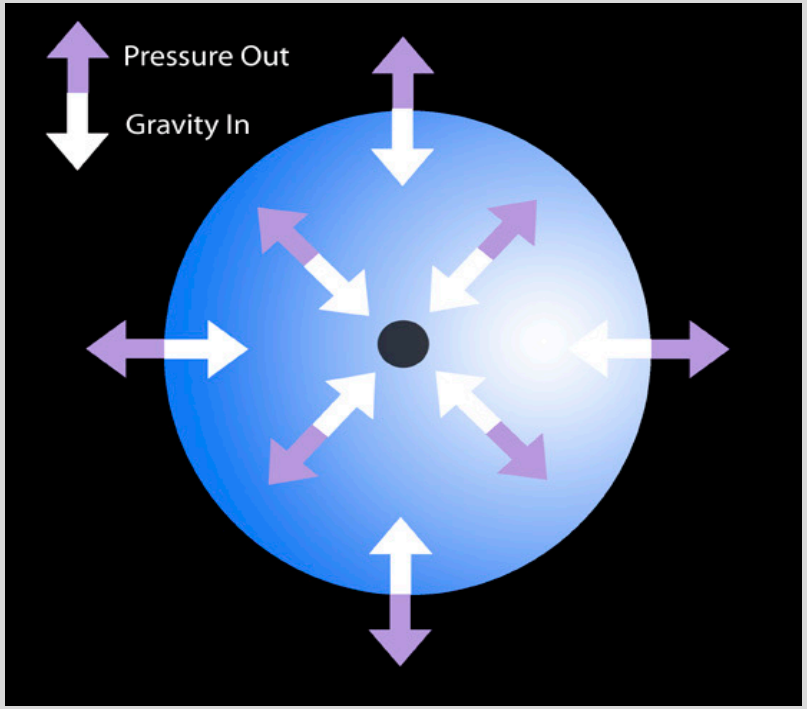
Two options to solve this:

Solve for luminosity: For an object of a given mass, if it is to stay bound the luminosity cannot exceed the ***Eddington luminosity***:

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} = 3.2\times10^4 \left(\frac{M}{M_\odot}\right) L_\odot$$



Solve for mass: If you observe a certain luminosity, the object must have at least a certain mass, the ***Eddington mass***, to stay bound:

$$M_{Edd} = \frac{\sigma_T L}{4\pi G m_p c} = 3.1\times10^{-5} \left(\frac{L}{L_\odot}\right) M_\odot$$

Note: we didn't assume anything specific about it being an AGN. The Eddington limit applies to stars, novae, etc – anything dense and luminous!

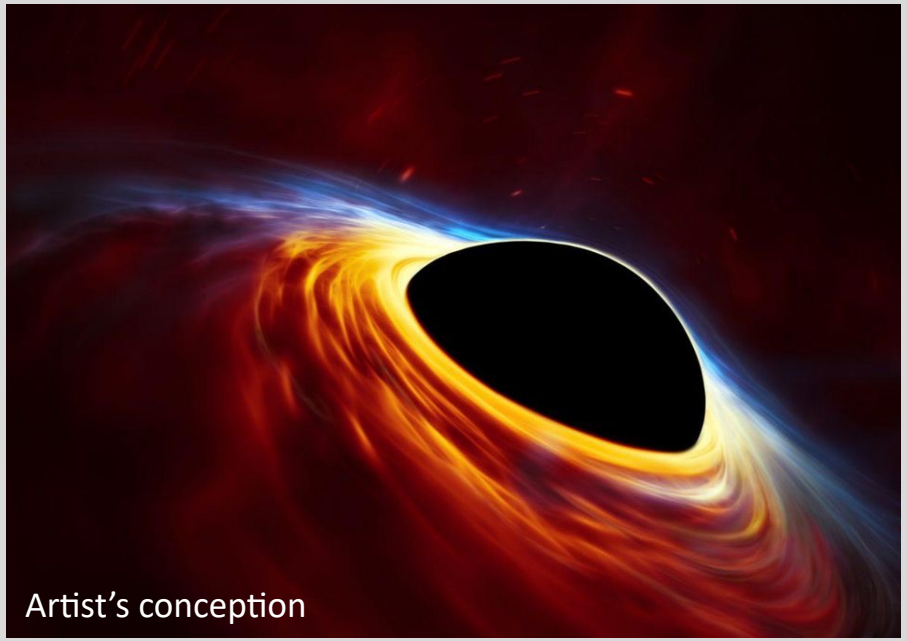
3C273 Revisited

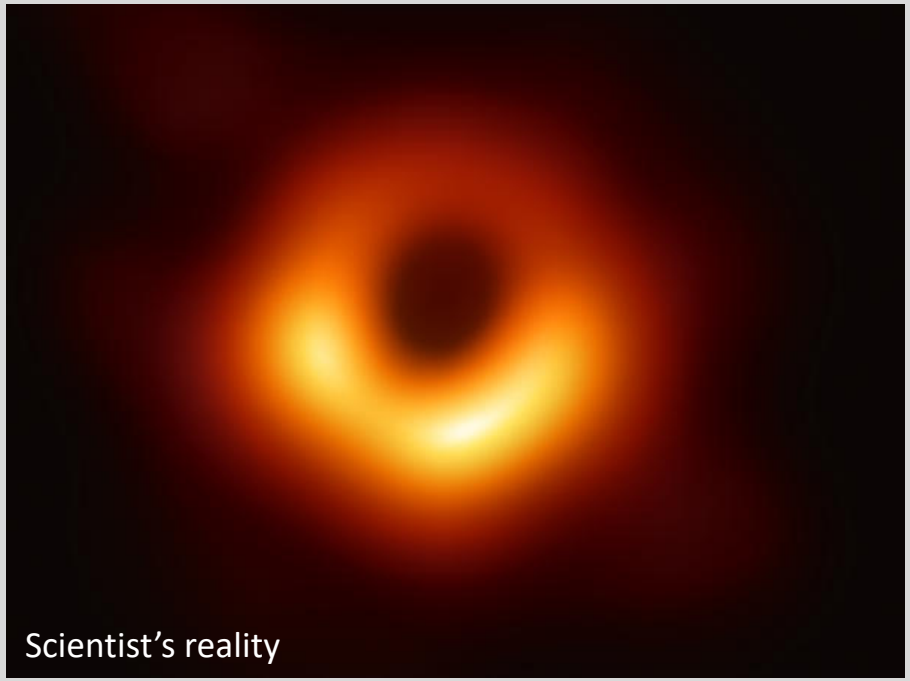
- Variability puts it size at R $\lesssim$ 7 AU.
- It has a luminosity of $L \approx 10^{13}\ L_{\odot}$. It can't be radiating in excess of the Eddington luminosity or it would be flying apart.
- If $L \leq L_{Edd}$, then $M \geq 3{\times}10^{8}\ M_{\odot}$

Now consider the Schwarzchild radius of a black hole:

$$R_s = \frac{2GM}{c^2} = \frac{2(4.43{\times}10^{-3})(3{\times}10^{8})}{(3{\times}10^{5})^2} = 3{\times}10^{-5}\ \mathrm{pc} = 6\ \mathrm{AU}$$

Sounds like a black hole to me!

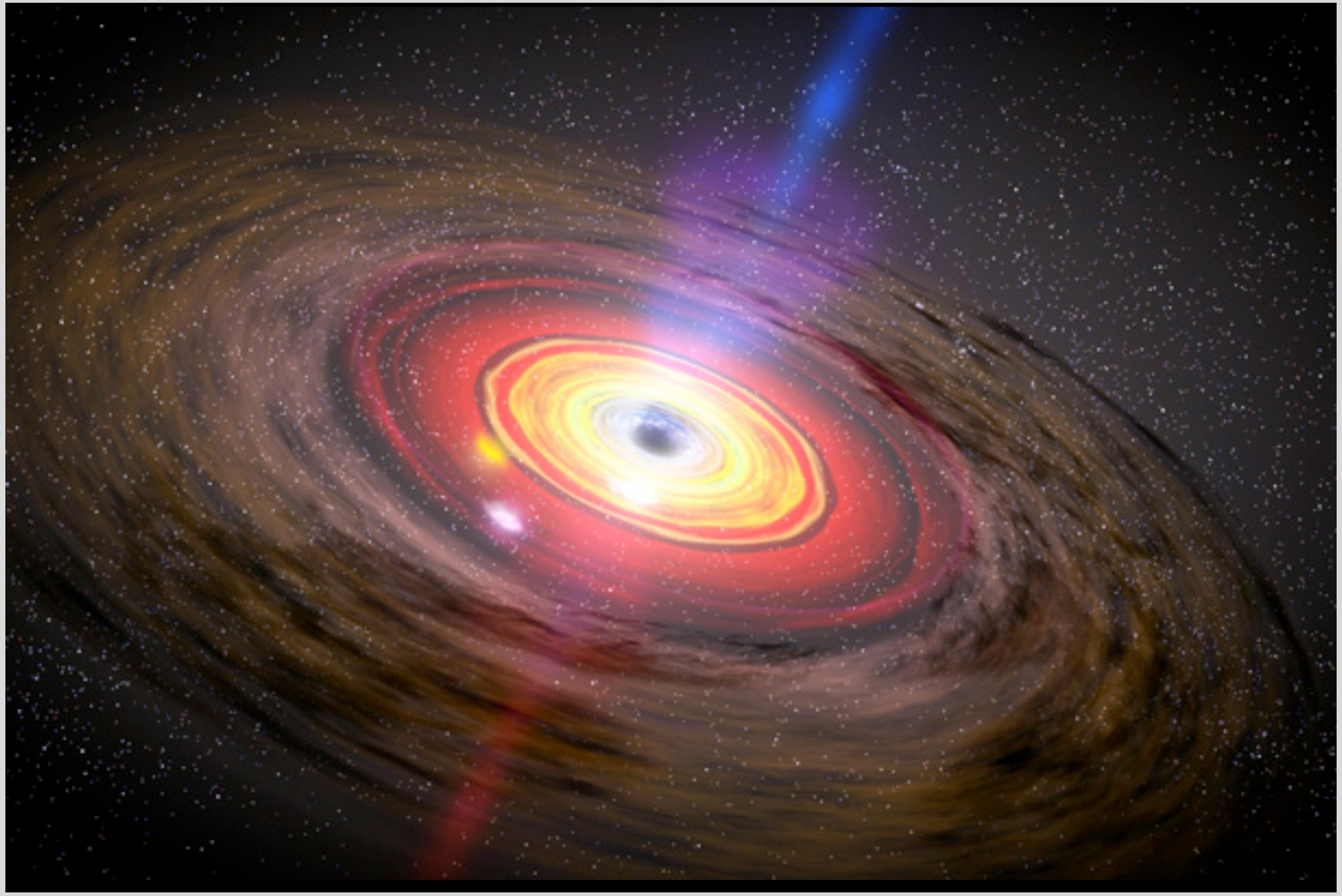

Artist's conception


Scientist's reality

Basic Physical Picture: Black Hole Accretion

- Infall of material onto a supermassive black hole (SMBH).
- Angular momentum + dissipation of vertical gas motion ⇒ formation of an accretion disk (solar system scales!)
- Gas viscosity/friction ⇒ gas spirals inward to SMBH
- Very efficient conversion of gravitational potential energy to heat and radiation.

The accretion disk is what creates the energy the AGN is emitting.



Compare efficiency of energy production:

- Chemical energy production (i.e. fire): ≈ 10^{-8} % of rest mass converted to energy

- Nuclear fusion in stars: 0.7% of rest mass converted to energy

- SMBH accretion: ≈10% of rest mass converted to energy

AGN Jets

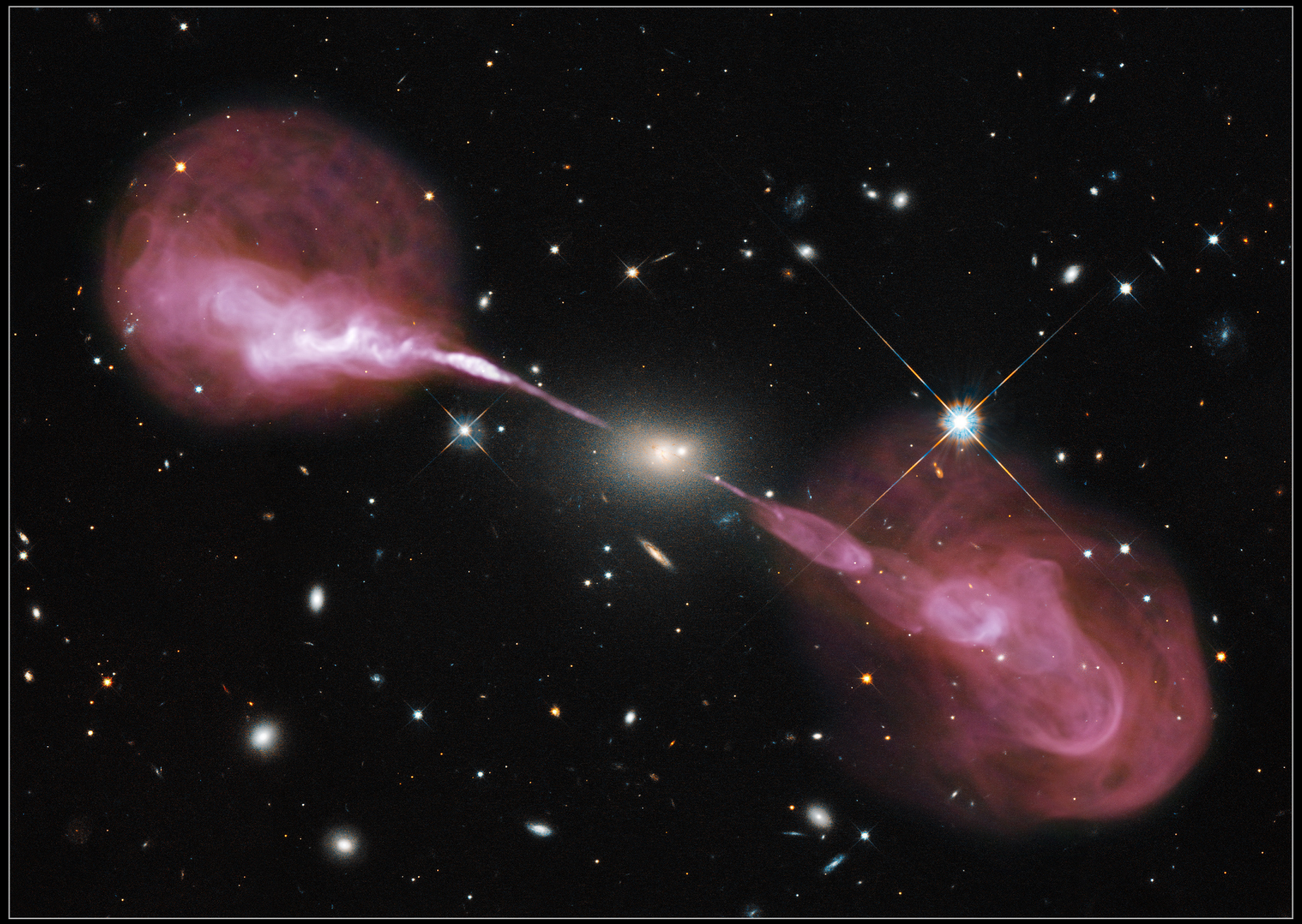
Again, ≈ 10% of AGN are radio-loud and have radio jets/lobes.

These features extend far outside optical galaxy: >100s of kpc to ≈ Mpc in size.

Color image: HST optical
Pink: VLA Radio continuum

Note misalignment of galaxy and jet!

Radio Galaxy Hercules A



Hubble Heritage

NASA, ESA, NRAO • *HST* WFC3/UVIS • VLA • STScI–PRC12–47

Centaurus A

Nearby (≈3.6 Mpc) peculiar elliptical

Composite image:

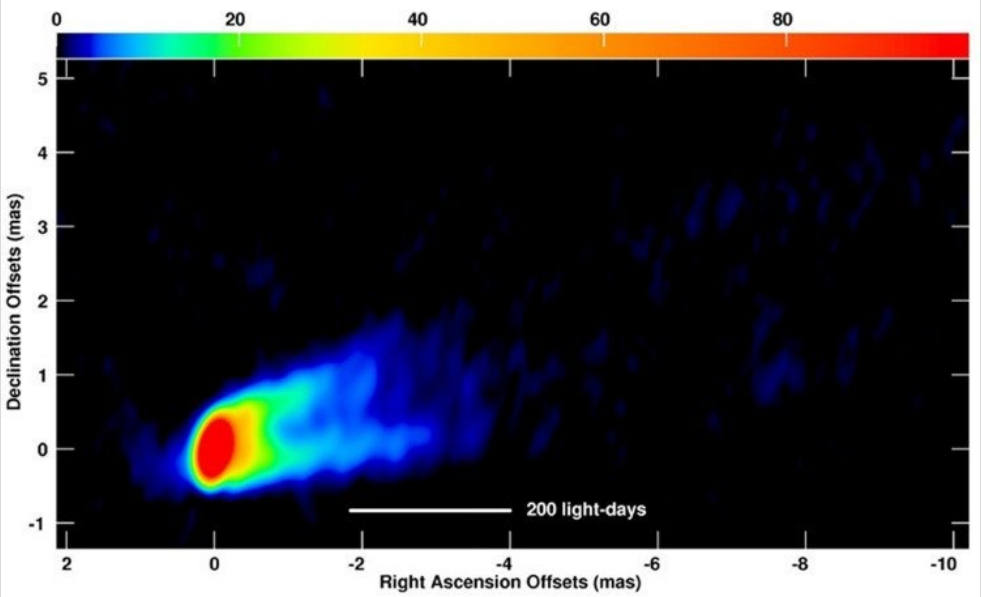
- optical
- X-ray (blue)
- radio (orange)

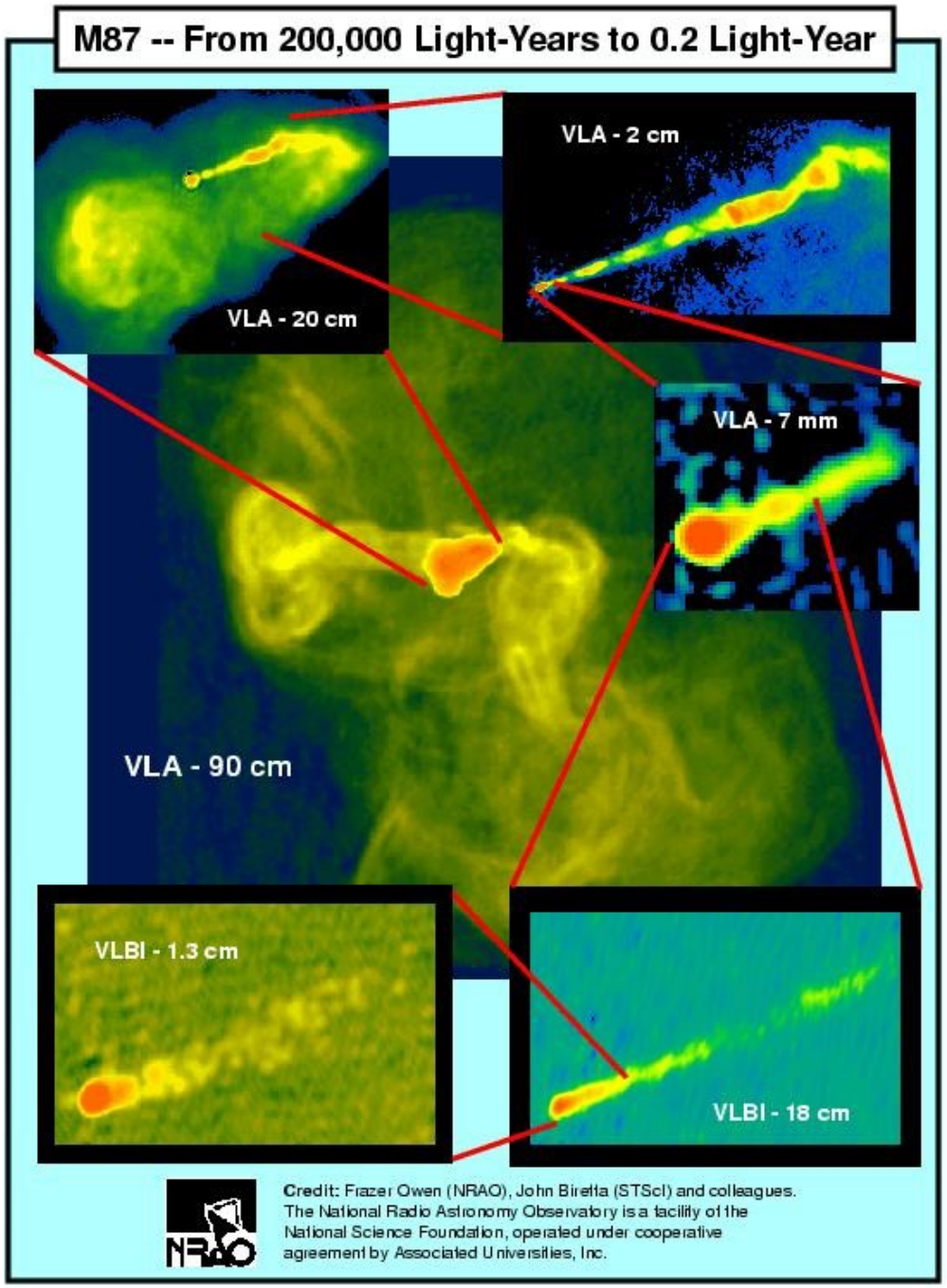
M87 jets: multiscale

Jets are collimated across many scales, until breaking up in outer regions.

Implies they must be stable in orientation over 10^7–10^8 yrs

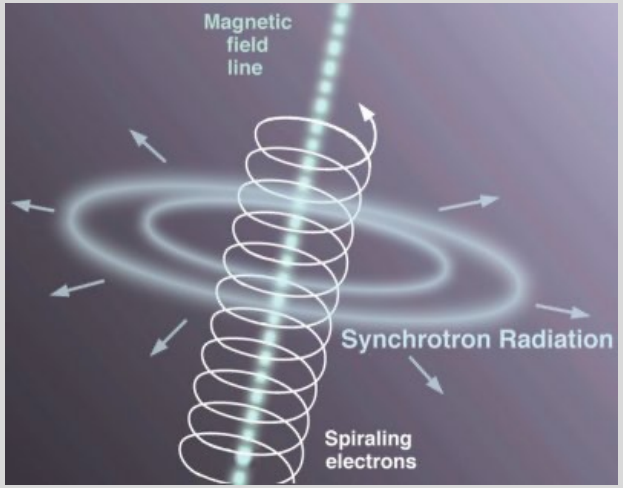
Lister+ 18



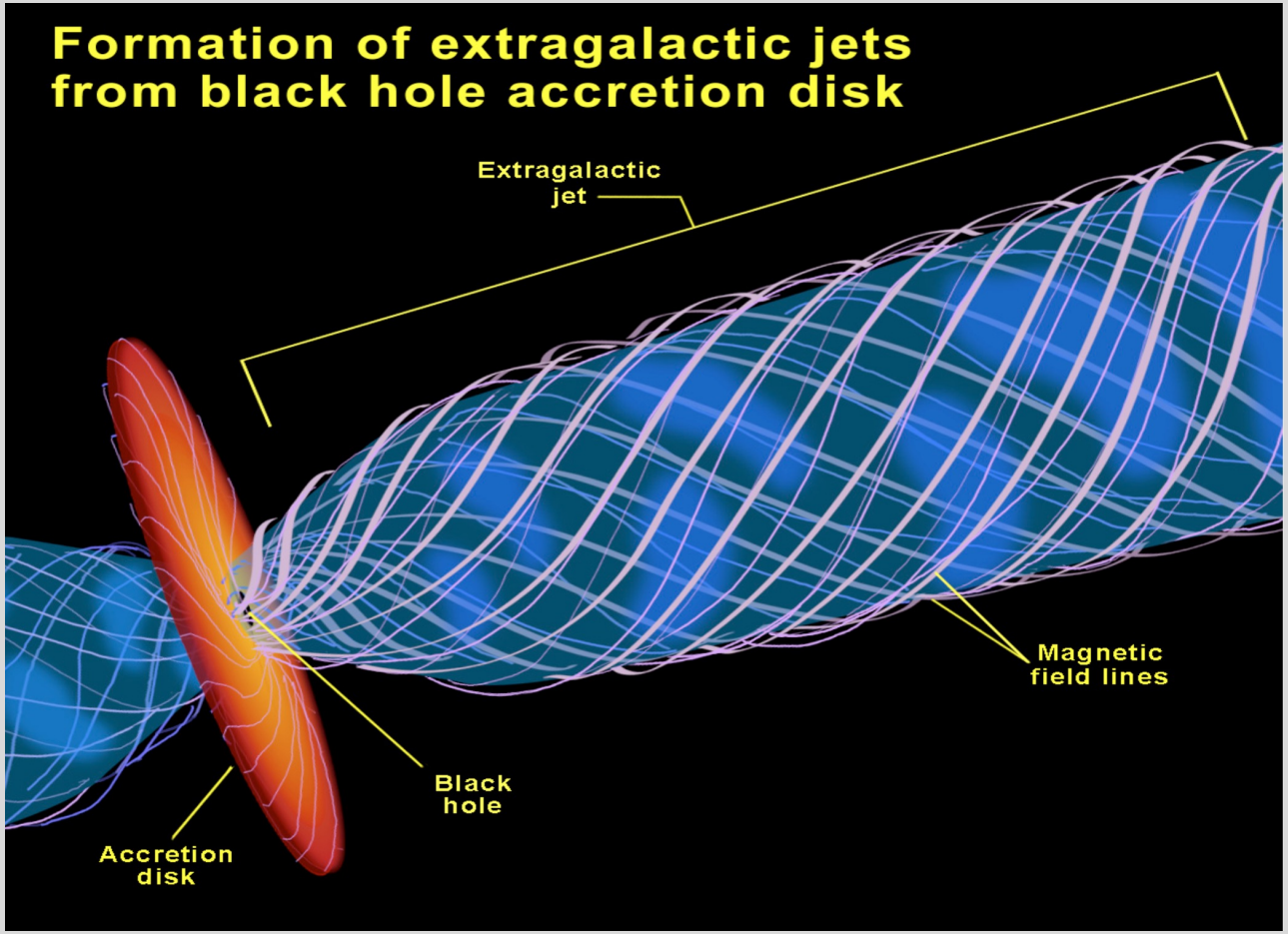


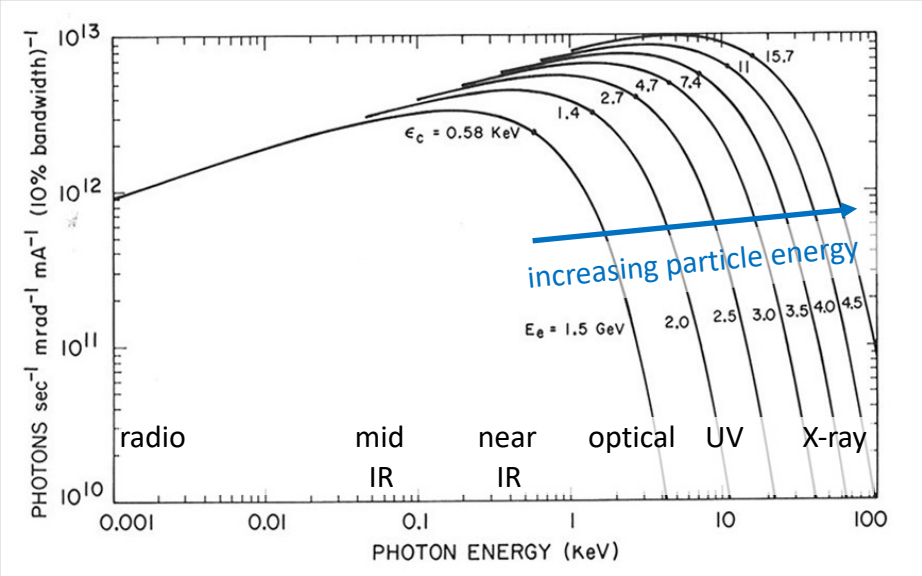
Radio jets: physical mechanism

Magnetic fields generated in the accretion disk are wound up and relativistic charged particles flow outwards, spiraling around the field lines.



Synchroton emission



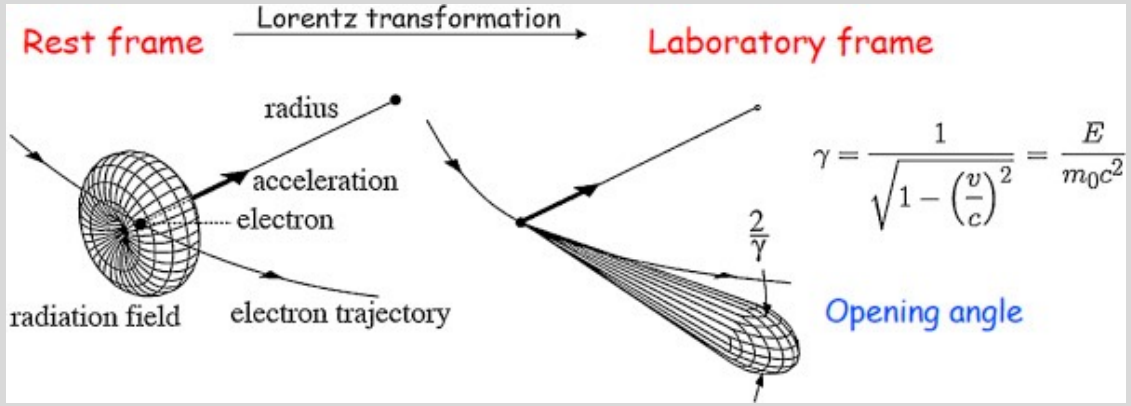


Synchroton spectrum:
power law at radio wavelengths

Radio jets: relativistic beaming

At low velocities, synchrotron radiation is emitted orthogonal to the direction of acceleration.

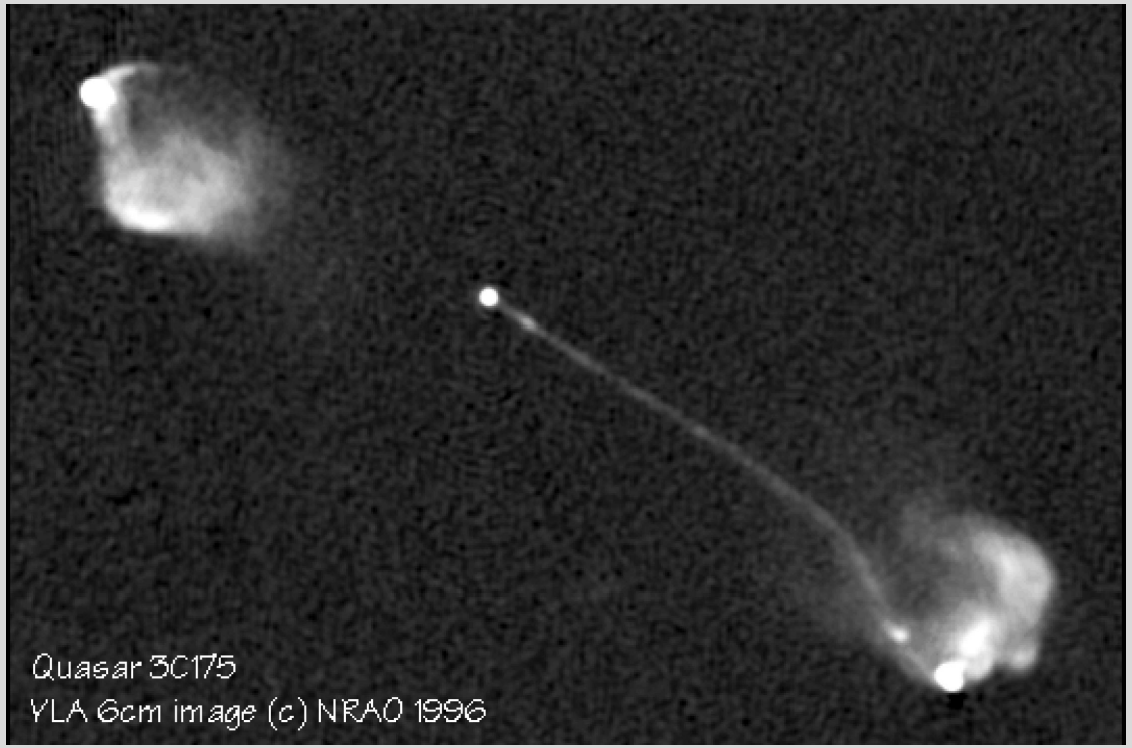
At relativistic velocities, the radiation is forward-beamed along the trajectory of the particle's motion



This leads to some jets appearing one-sided

- Approaching jet: boosted in brightness
- Receding jet: dimmed

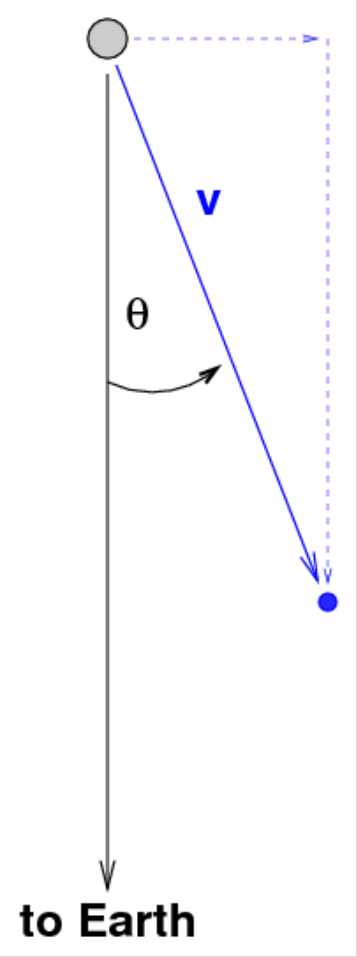
Don't see this effect in the lobes, so they are not so relativistic.



Radio jets: superluminal motion

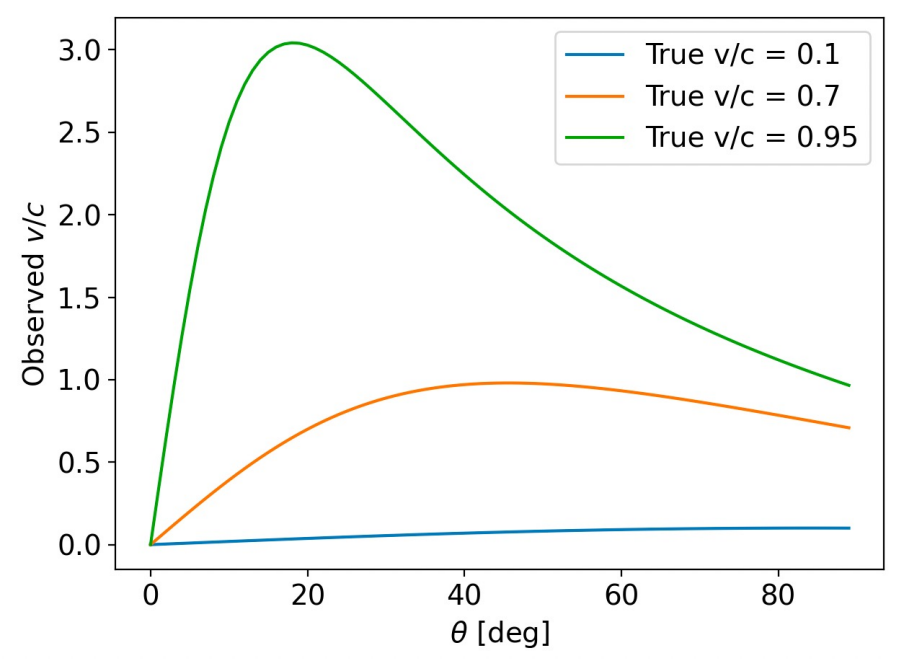
Blobs in jets often show faster-than-light motion.

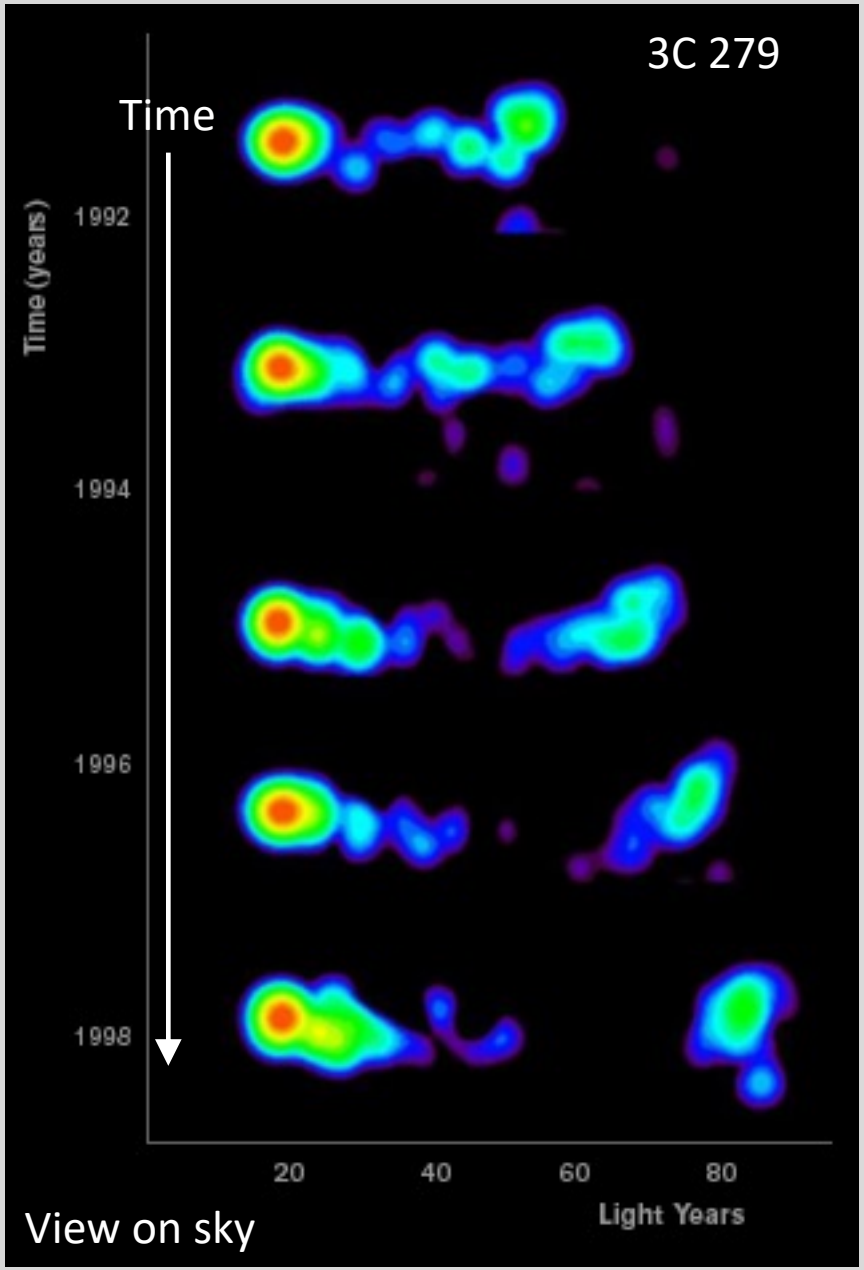
e.g., 3C 279: $V_{obs} \approx 3c$



If the jet is pointed at an angle θ to the line of sight, the observed speed on the sky is given by

$$(v/c)_{obs} = \frac{(v/c)\sin\theta}{[1-(v/c)\cos\theta]}$$



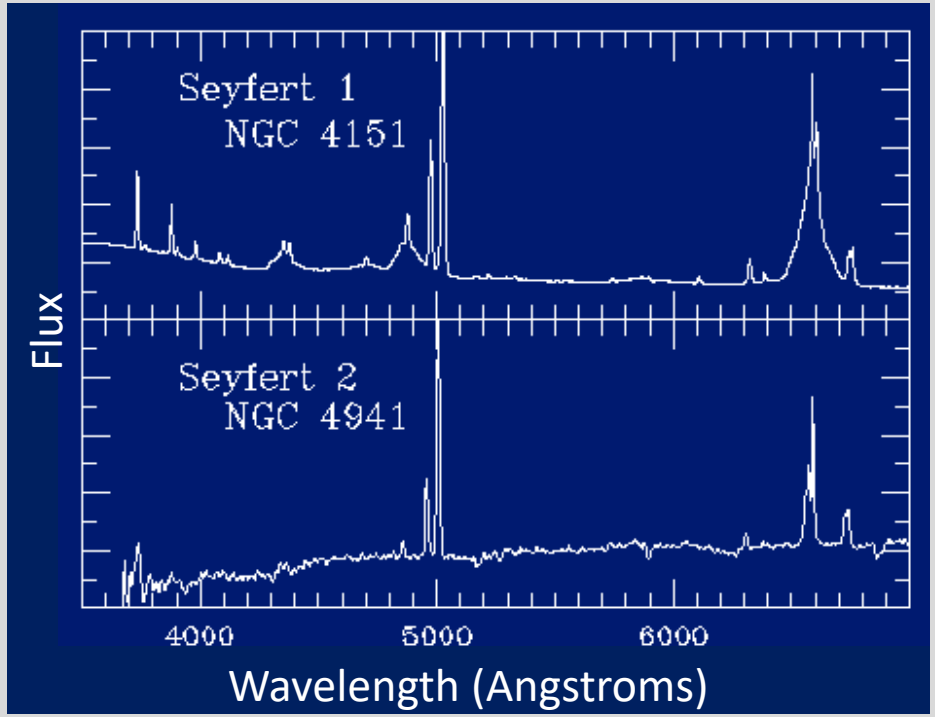


The Unified Model for AGN

Accretion disk is embedded inside a dusty torus of material, which blocks optical light. In the optical, can only see light from the accretion disk at angles where the torus doesn't obscure.

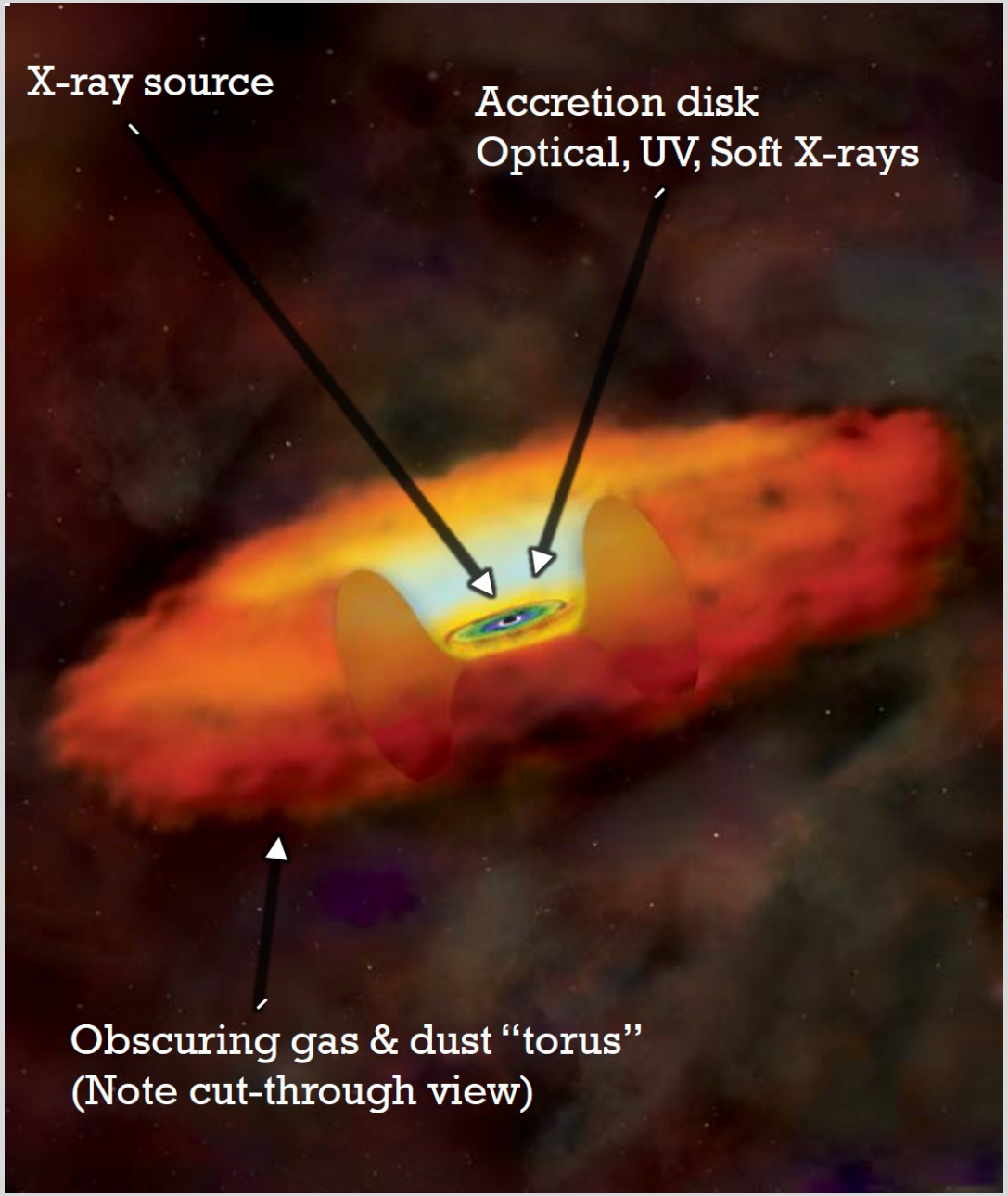
X-rays are not blocked by dust, so all AGN show X-rays.

Type 1 / Type 2 dichotomy: The difference between Type 1 (broad + narrow emission lines) and Type 2 (narrow lines only) AGN is due to *viewing angle*.



courtesy Bill Keel

0.1-100 light year scales:



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- Gas moves very fast inside torus ($V^2 \propto GM/R$), so this is the **broad-line region.**
- In the larger scale environment outside the torus gas moves more slowly, so this is the **narrow-line region**.
- If we view from angles that can see into the center, we see a Type 1 AGN: broad+narrow lines plus blue continuum from hot accretion disk at center.
- If our view of the center is blocked by the dusty torus, we see a Type 2 AGN: narrow lines only.

0.1-100 light year scales: