Class 16 :
Active Galactic Nuclei

ASTR350 Black Holes (Spring 2022)

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RECAP

- Quasars
  - Story of how the early radio sources were localized
  - 3C273 and other quasi-stellar radio sources
  - Basic properties…
    - Luminous (10^{39}W) ➔ source of energy must be efficient
    - Variable (hour-to-hour) ➔ source of energy is small
    - Both conditions satisfied by **black hole accretion**
  - Eddington Luminosity limit
    - Black hole must be sufficiently massive for it's gravity to "hold the source together" despite radiation pressure
    - For 3C273, implies $M>10^8M_{sun}$
    - So, **supermassive black hole accretion**

RECAP

- Accretion Disks....
  - How matter is accreted onto black holes
    - very efficient process for producing energy
  - Need for viscosity and angular momentum transport
  - 'Simple' model predicts the emitted spectrum of the disk
  - Physical viscosity is complex needing sophisticated numerical models.

This class

- Active Galactic Nuclei (AGN) more broadly…
  - Are quasars AGN?
  - How do we recognize an AGN?
  - The appearance of AGN in different parts of the spectrum… we'll come across
    - Jets
    - Accretion disk
    - Disk Coronae

Active Galactic Nuclei

Let’s take this word by word

- Active: shows spectral features different from the normal starlight that dominates galaxies

- Galactic: the object lies in a galaxy (if you look hard enough with enough angular resolution)

- Nuclei: Lies in the center of the galaxy (and >99.9% of the time)- the supermassive black hole 'knows' that it should be at the dynamical center of its 'host' galaxy.


Chandra Deep Field- Almost every object detected by the Chandra X-ray Observatory is an AGN- Roughly 3000 per square degree

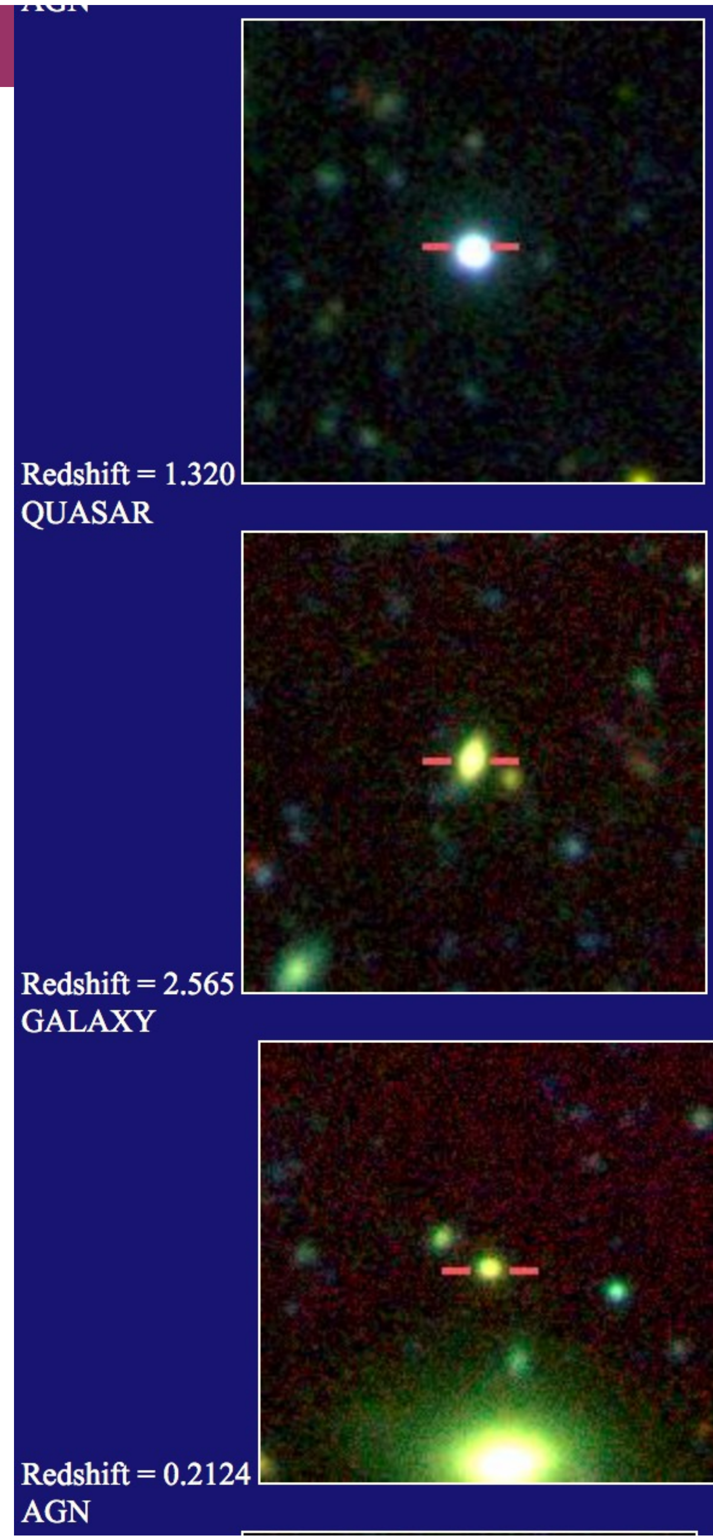
Hubble Deep Field- the sky is filled with galaxies (~10^5 per sq degree)
- which ones are AGN??

X-ray Emission Identifies the AGN

Roughly one galaxy in 100
is an AGN at any one time

Two extreme possibilities: 1. Only 1% of galaxies ever have an AGN and they have it continuously. 2. All galaxies host an AGN at some point, but just in 1% of their lifetimes.

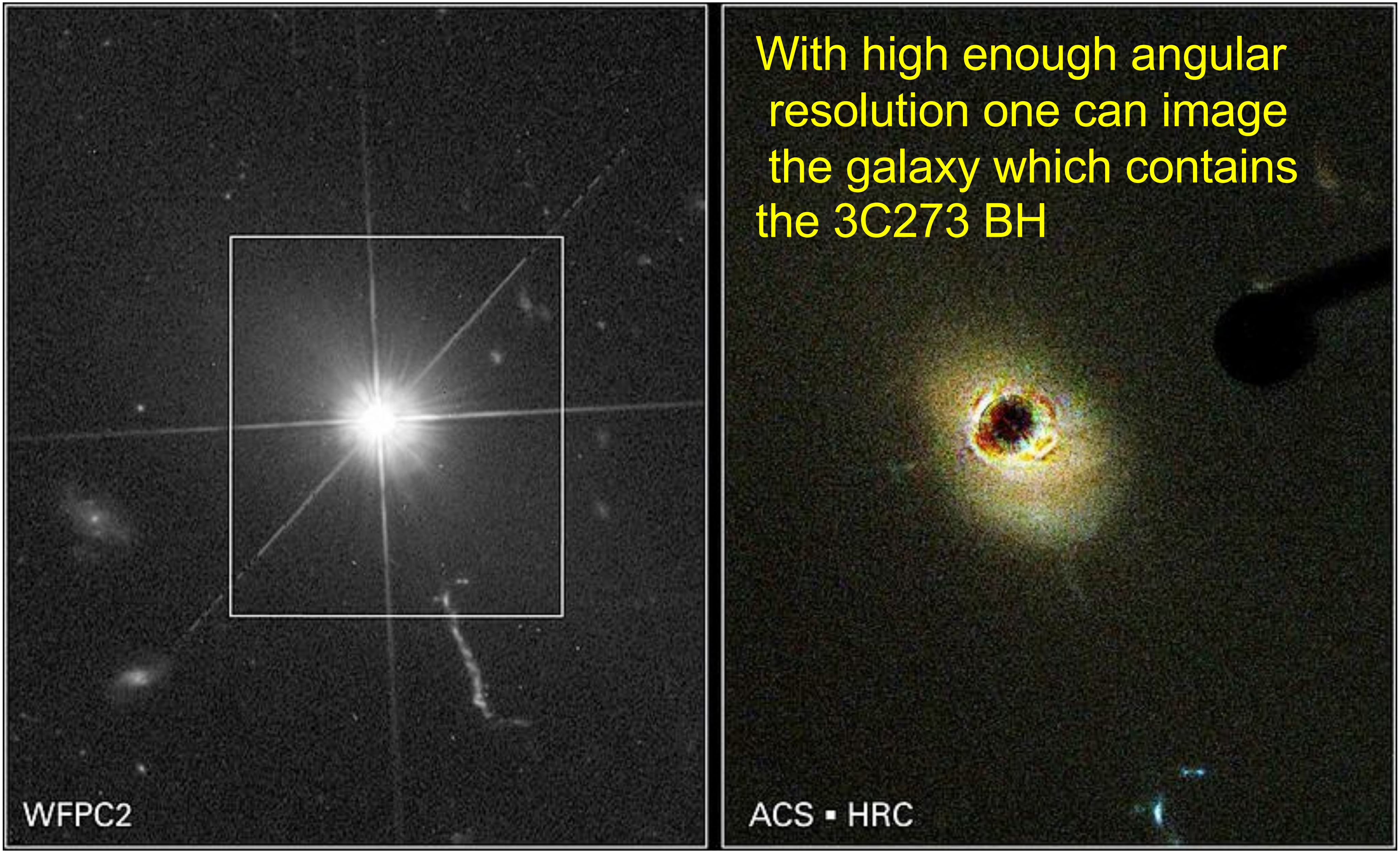
As we shall see later the 'duty cycle' of being an AGN is small, so that most galaxies at some time in their history were an AGN



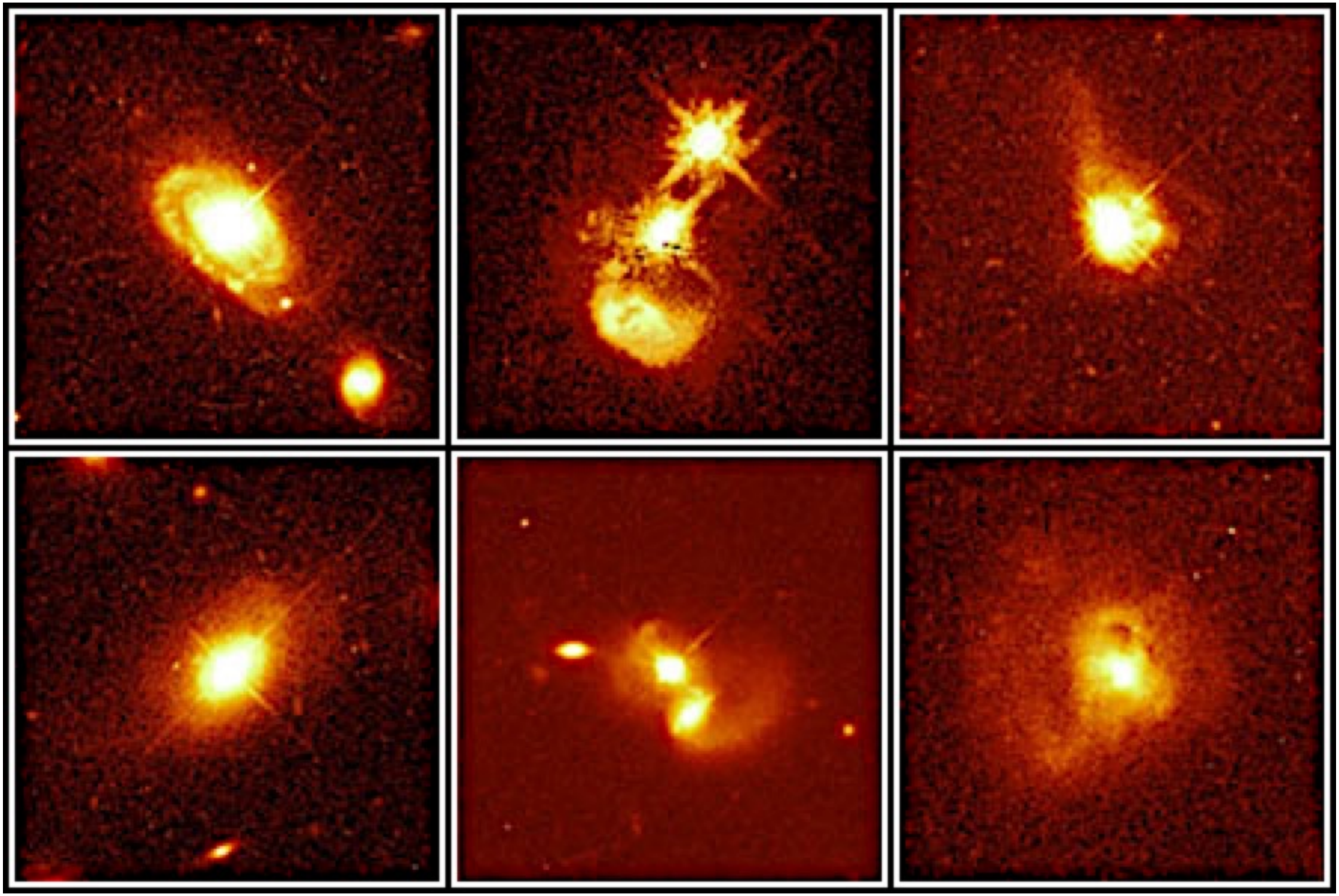
II : AGN and quasars

- Basic question…
  - Previously, we discussed the arguments for why quasars like 3C273 are accreting supermassive black holes…
  - … but are we really sure that they are AGN?
    - <u>and what do we mean by that</u>?
- This point was actively debated as recently as the 1990s
  - Remaining doubt was put to rest by the Hubble Space Telescope.
  - AGN lie at the center of galaxies

The galaxy around 3C273…



Hubble Space Telescope Images of Quasar Showing Host Galaxies

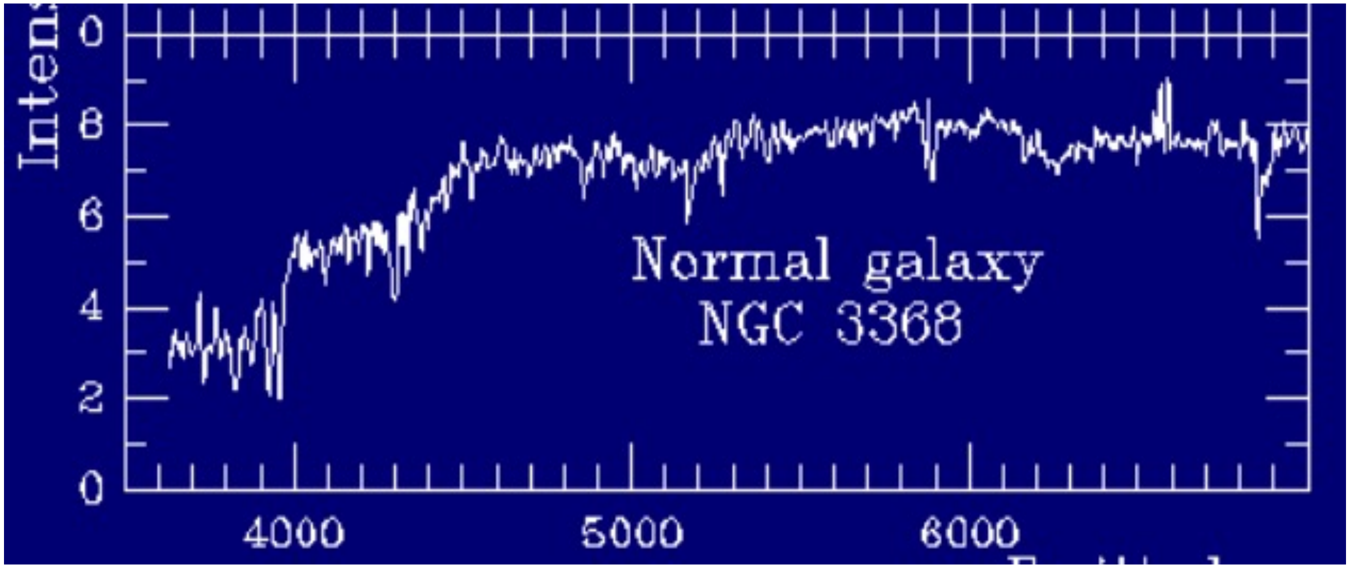


Other Properties of Active Galactic Nuclei

Have a 'non-stellar' spectrum- the emission from the accretion disk does NOT look like light from a star

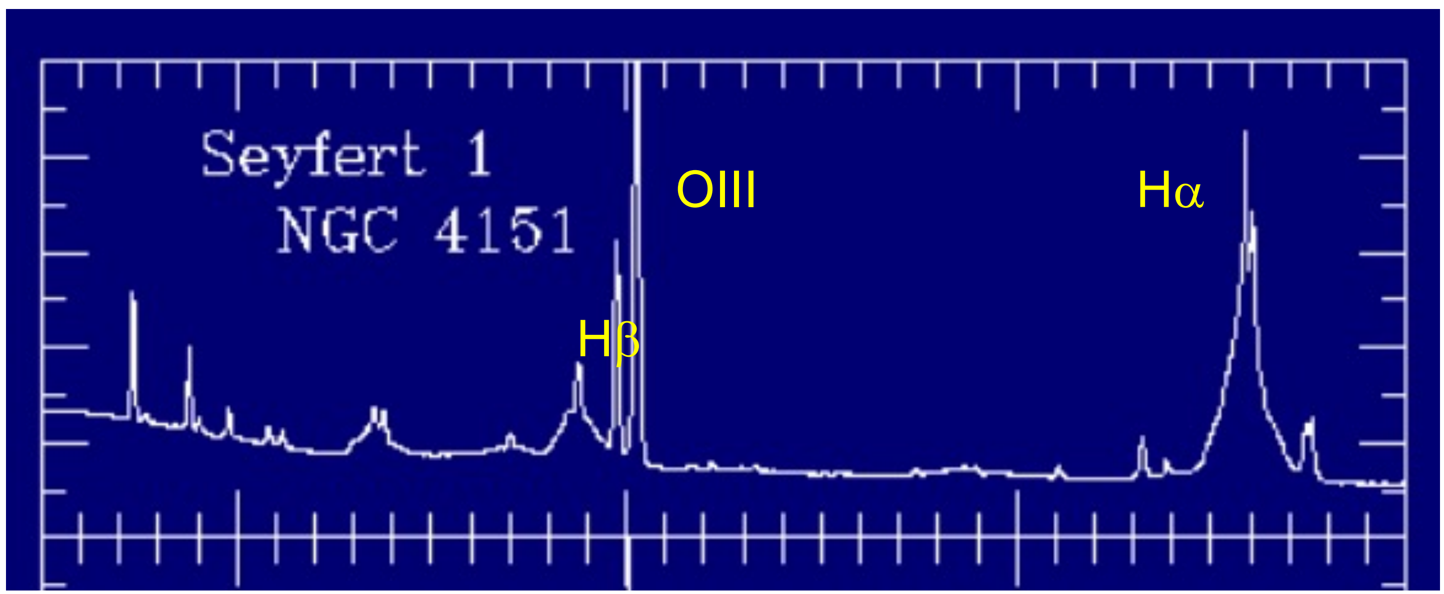
- Normal stars have a roughly blackbody spectrum with relatively little emission in the radio, infrared , x-ray or gamma-ray spectral bands
    - AGN can emit lots of energy in these bands
- AGN have a much broader spectrum often emitting across the entire electromagnetic spectrum from radio through gamma-rays.
    - Not all of this radiation comes from the accretion disk
- AGN frequently show high amplitude variability

Comparison of Optical Spectra of a Normal galaxy and an AGN



Light dominated by emission from stars- no strong lines

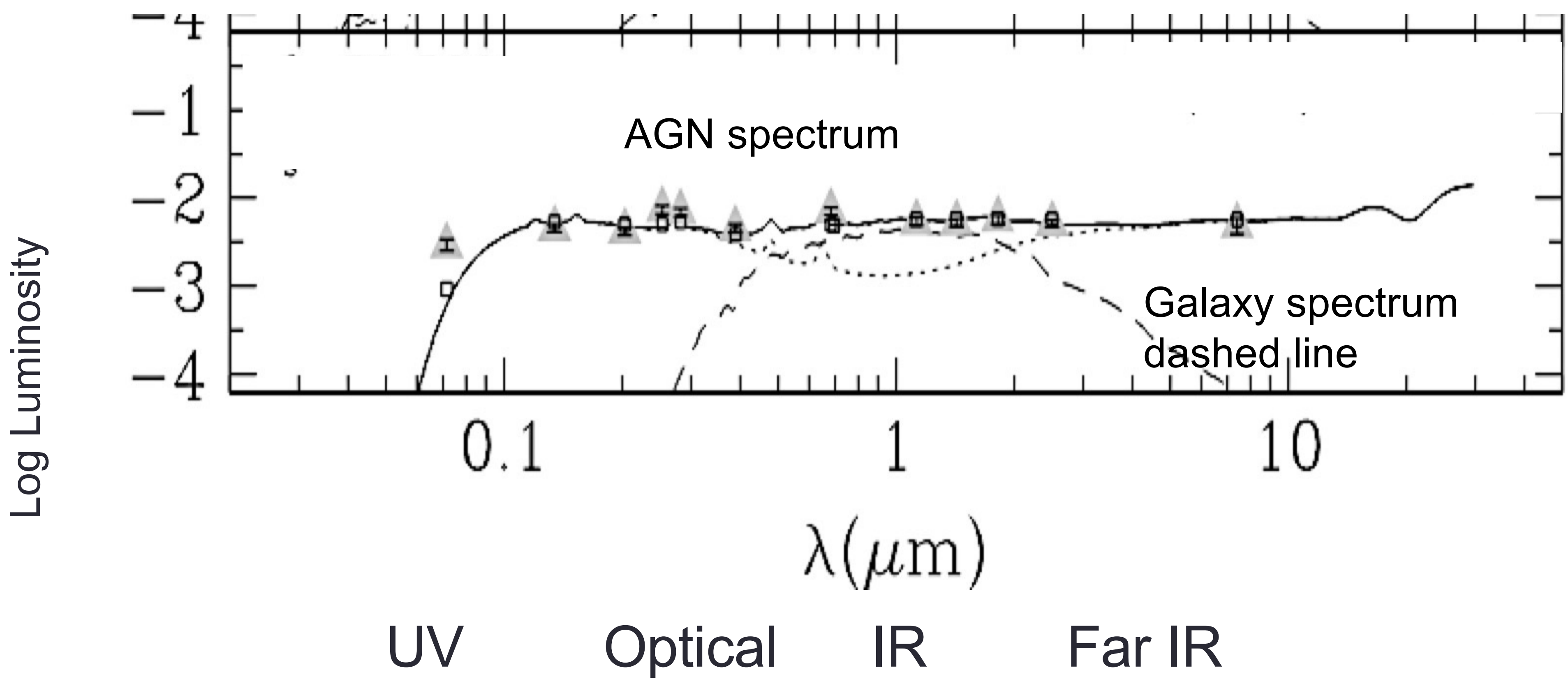
Light dominated by emission from BH- strong lines



Comparison of Optical Spectra of Normal Galaxies and AGN

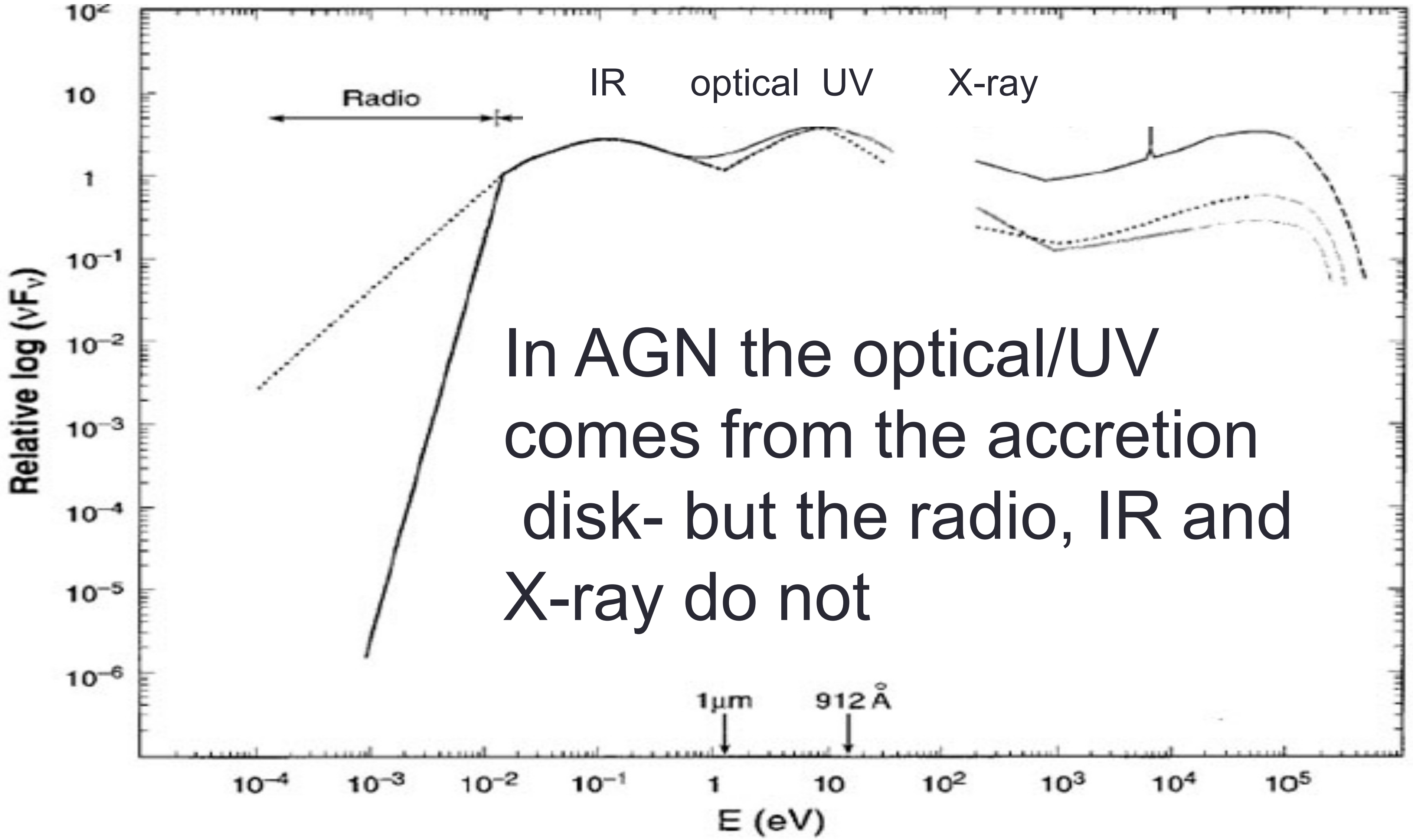
This graph shows the spectral energy distribution (SED) from the UV to mid-IR

Notice the vertical scale- AGN have roughly equal energy per wavelength interval while spectra of galaxies is more concentrated



AGN Spectra are very broad-

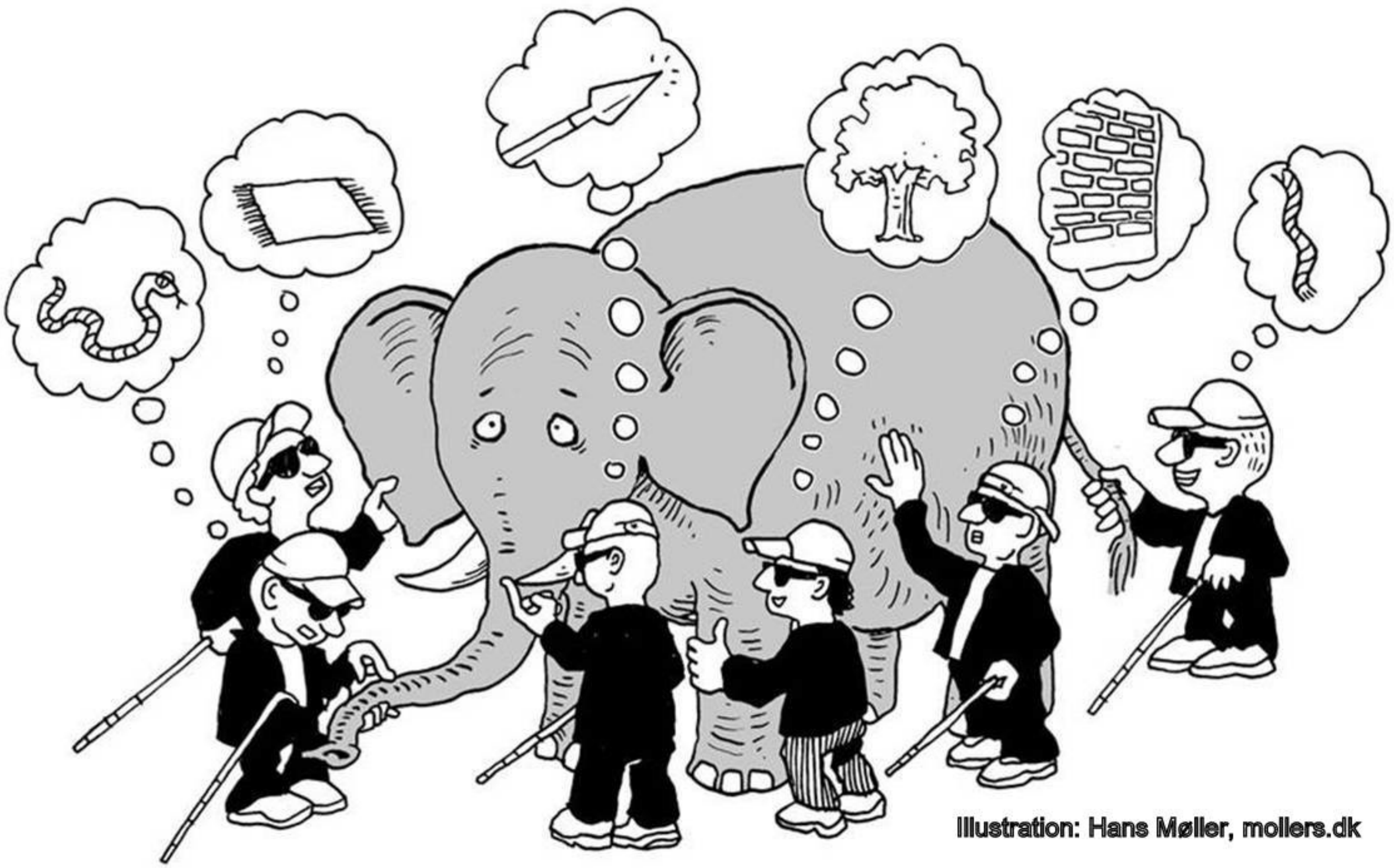
Emitting from the radio to the high energy x-ray



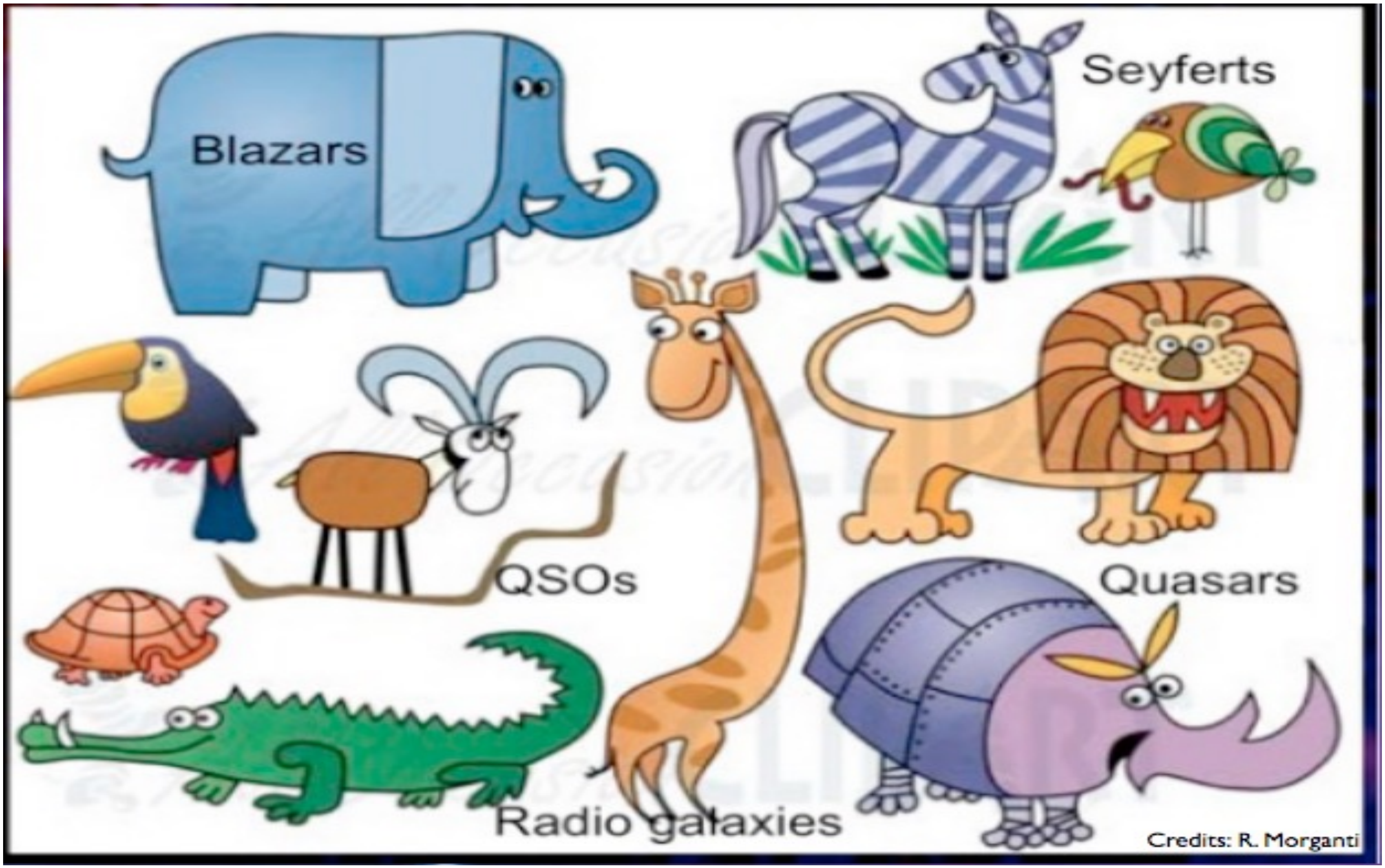
In AGN the optical/UV comes from the accretion disk- but the radio, IR and X-ray do not

III : What do AGN look like?

Each of these blind men in an astronomer working in a different wavelength band (X-ray, optical,UV, radio etc)- or a theoretician. Each has an idea of what an AGN should 'look' like- this is called a 'selection effect'



Some more detail- the AGN Zoo



What Do these Names Mean?

The wide range of names that astronomers use for AGN are based on a variety of reasons- many historical

1) How they were discovered- e.g. **quasar** (quasi-stellar radio source)
2) who discovered them- e.g.**Seyferts** discovered by Carl K. Seyfert, in 1944- there are 2 types (I and II) which have different optical and x-ray spectra
3) A physical property

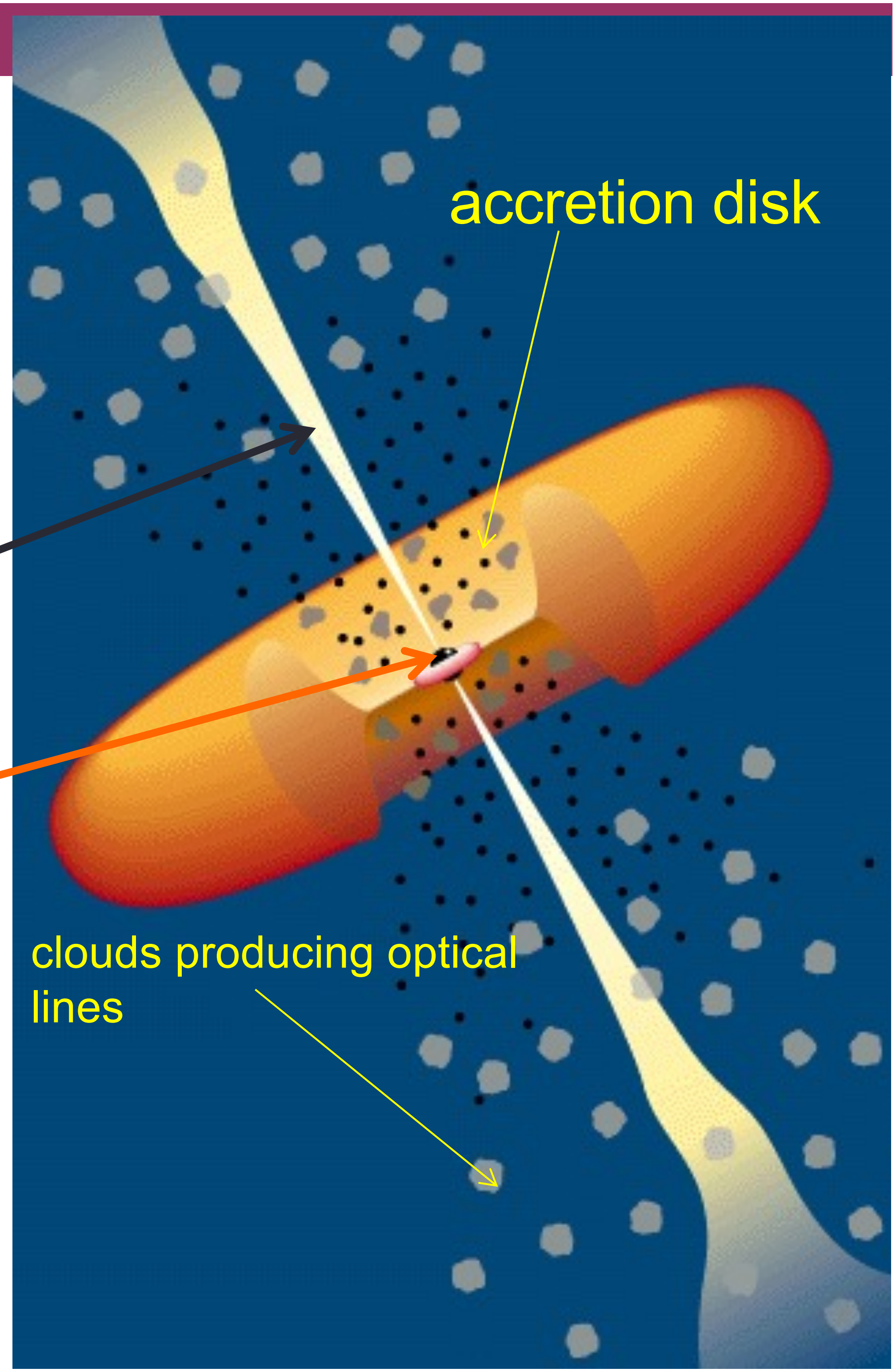
e.g. **blazars**, strong γ-ray emitters and highly variable

radio galaxy: a galaxy which is luminous in the radio part of the electromagnetic spectrum

Despite which property has controlled the name these are all radiating supermassive black holes

Why do they 'look' so different?

Orientation, geometry and jets



III. : Radio Selection

- Radio See 'jets' and 'lobes' as well as nucleus
- Jets 'feed' the lobes (a lot more in next lecture)
  - **Jets are tightly focused flows of <u>very</u> energetic matter from immediate environment of black holes**
  - Jet flows have relativistic velocities…
    - Speeds up to γ=10-20 (>0.99c)- this is the special relativity γ
    - Accelerated to these speeds close to black hole
  - Can extend to enormous distances
- BUT, not all AGN have jets
  - Radio-loud AGN (10%) : Have jets and are radio bright
  - Radio-quiet AGN (90%) : No obvious jets and radio dim
- Remarkable example is Cygnus A /3C405… the brightest radio source in the sky! **But 230Mpc distant**

III : Optical/UV of AGN

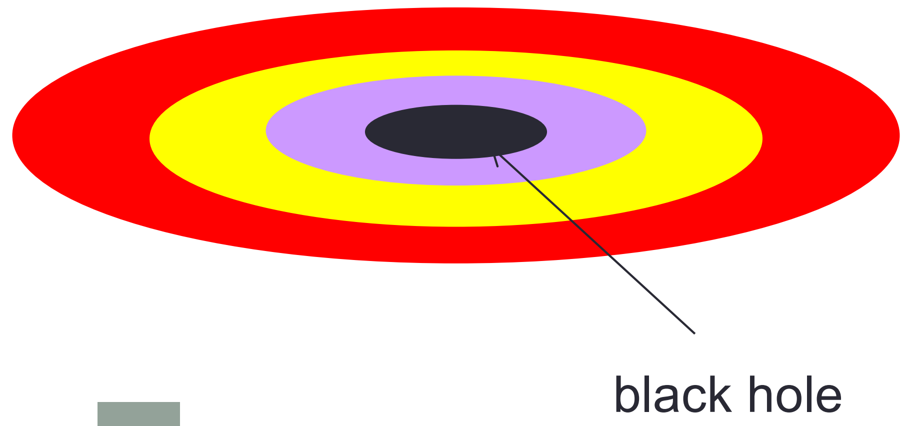
- Optical/UV emission dominated by accretion disk emission
  - Emission is “black body” locally, but sum of black bodies is a much broader spectrum (NOT like stars)
  - i.e. disk is glowing because it is hot and dense
    - hotter towards center, cooler at larger radii

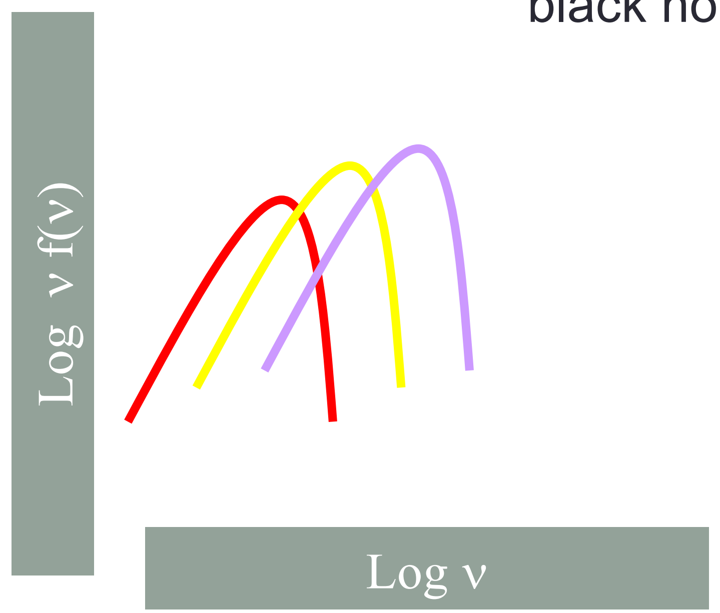
- Comparison of stellar-mass black holes and AGN
  - Stellar mass BHs… disk is T_{max}~10^7K, glows in X-rays
  - AGN… disk is T_{max}~10^5K, glows in optical/UV

- Sometimes, also get optical emission from jet

Spectra of accretion disc flow

- The innermost radius (purple) depends on whether it is a Kerr or Schwarzschild black hole
- Kerr black holes have a hotter innermost temperature for a fixed black hole mass and accretion rate
- Big black holes are 'cooler' than low mass ones with maximum temperature proportional to $M_{BH}^{-1/4}$
- Stellar mass BHs disks shine mainly in x-ray and supermassive black holes disk in optical/UV

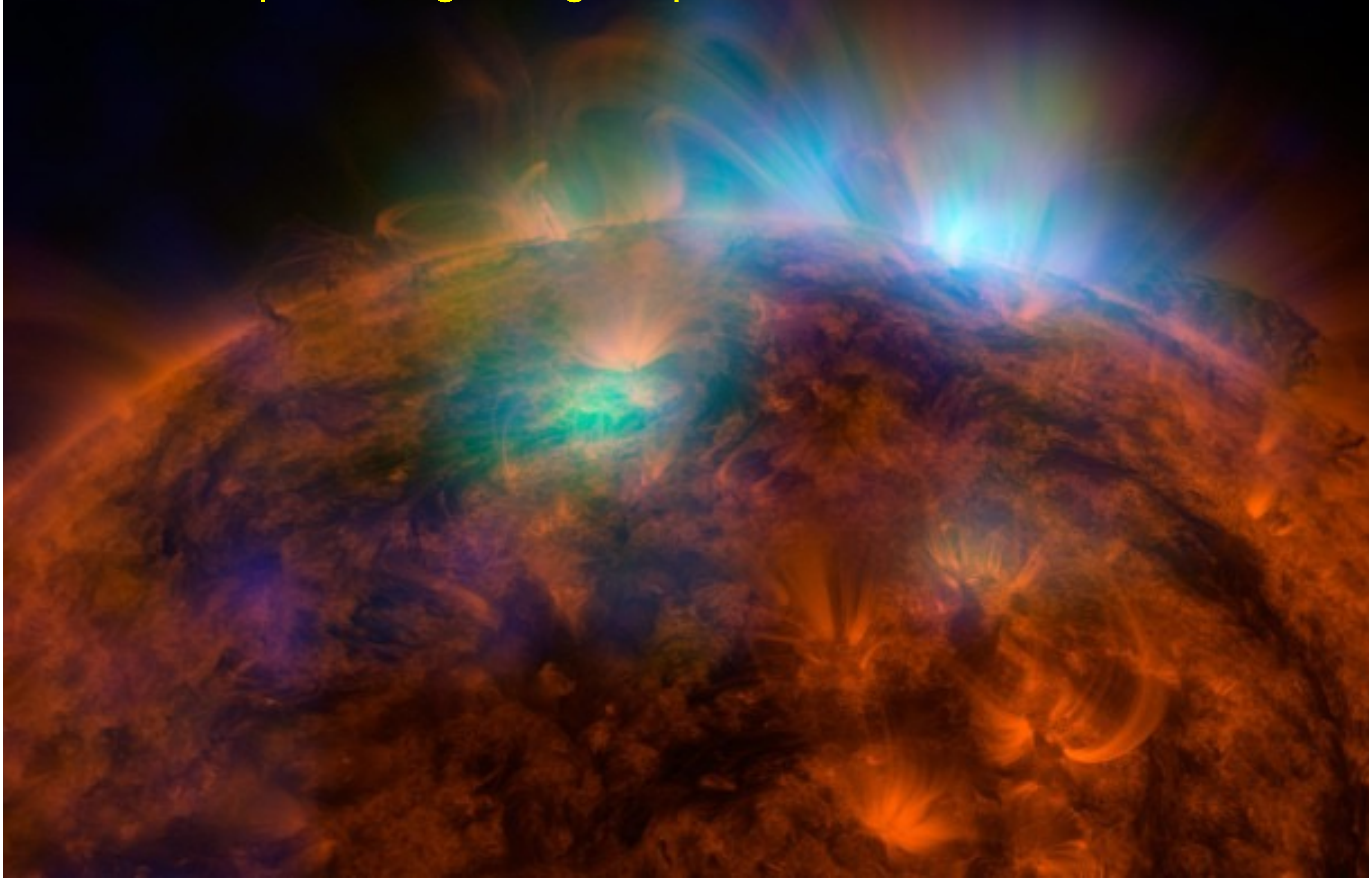




III: X-rays

- Digression/Discussion :
- How hot is the surface (photosphere) of the Sun?
- Does the Sun produce X-rays? If so, how and when?
- What might be similar/different about radiation from the sun compared to an accretion disk?

Active regions on the sun-places where the magnetic field 'reconnects' producing energetic particles- solar flares



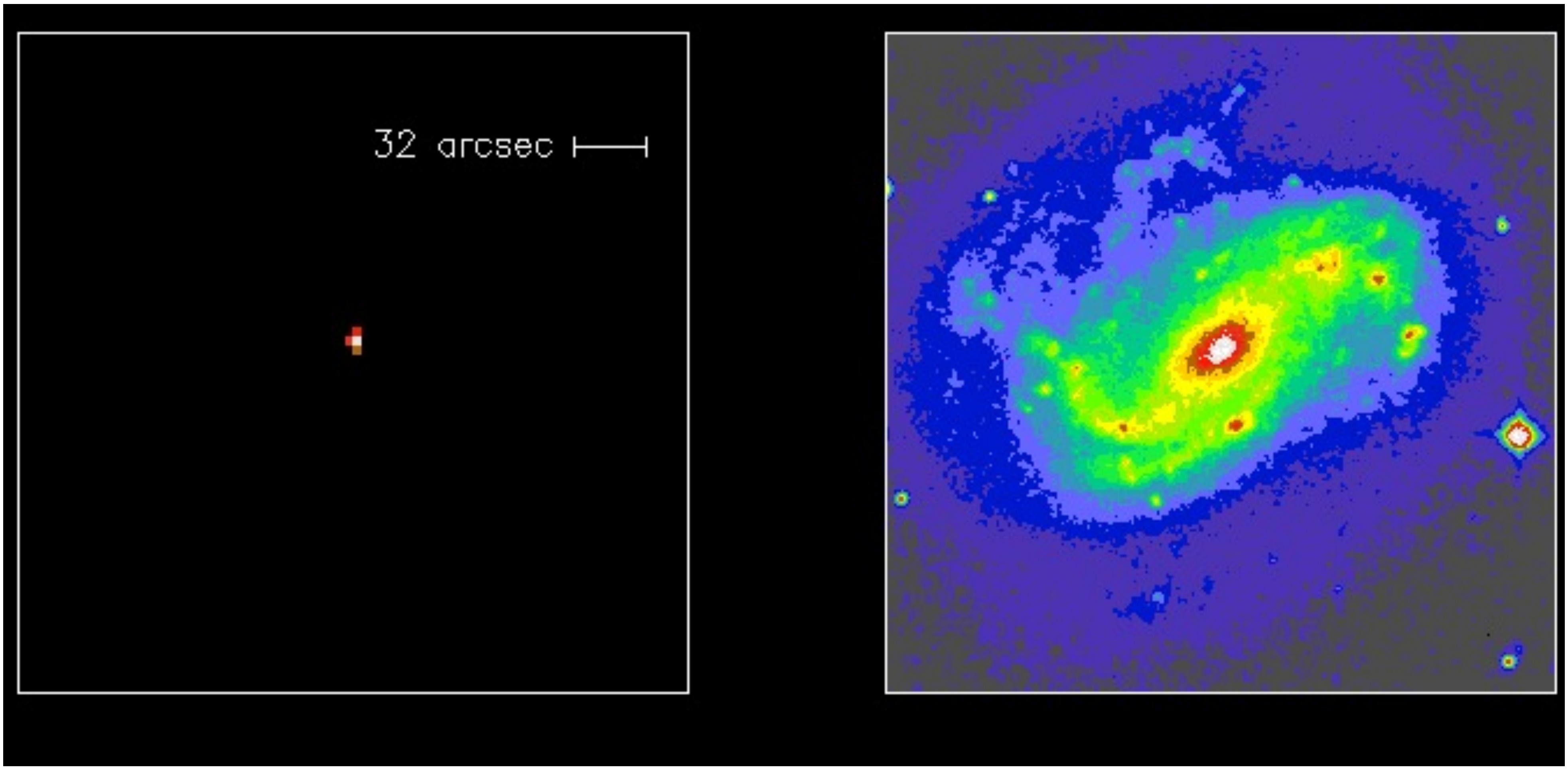
AGN and X-rays

- Almost all AGN are X-ray sources!
- X-rays originate from a "corona" associated with the accretion disk
  - Corona is very hot, $T>10^9K$
  - Shape and size of corona is poorly known but probably $\sim 10\text{-}30R_{Sch}$
  - Energy probably carried from disk into corona by magnetic fields
  - More about this later!
- In radio-loud AGN, some of the X-rays may come from the jet

X-ray selection

X-ray Image Optical image

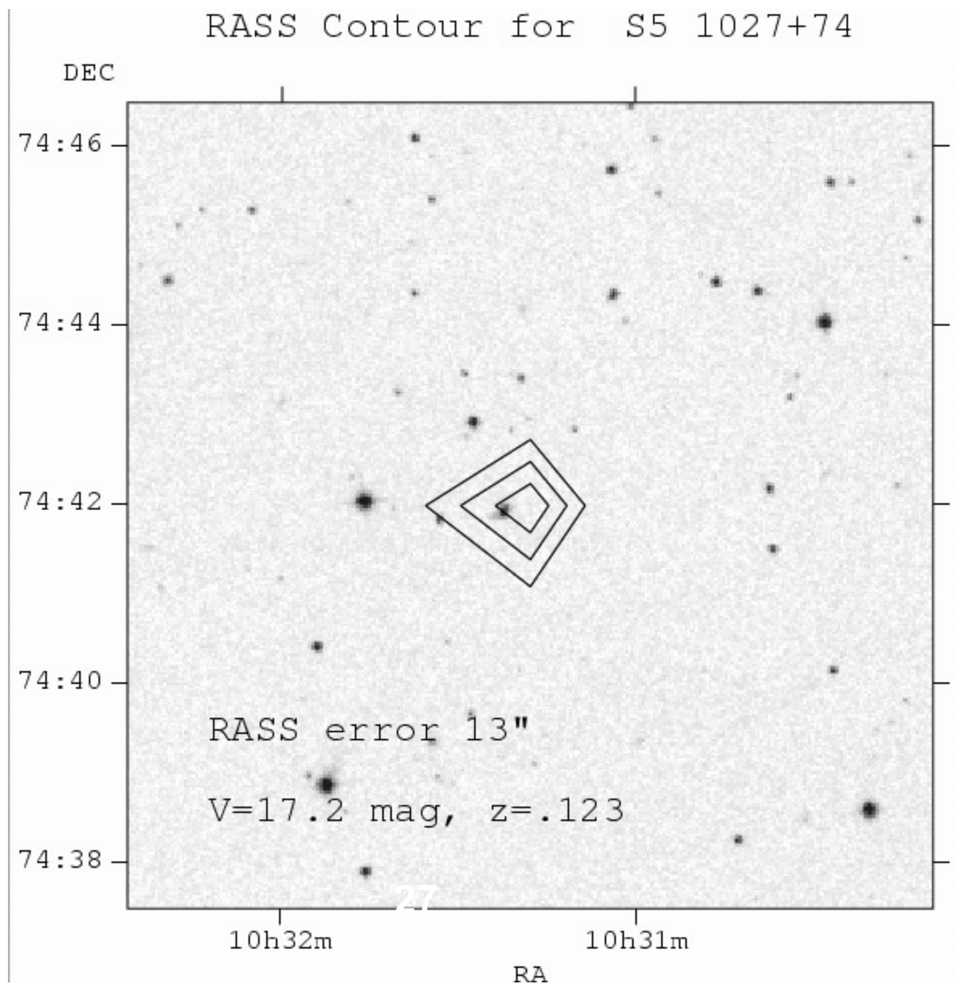
of nearby galaxy NGC4051



X-ray Selection of Active galaxies

- X-ray and optical image of a nearby AGN NGC4051-
- Note the very high contrast in the x-ray image

Rosat x-ray all sky survey image overlaid on sky survey image



Find x-ray AGN via

luminous* pointlike x-ray source in nucleus of galaxy

unique shape of x-ray spectrum

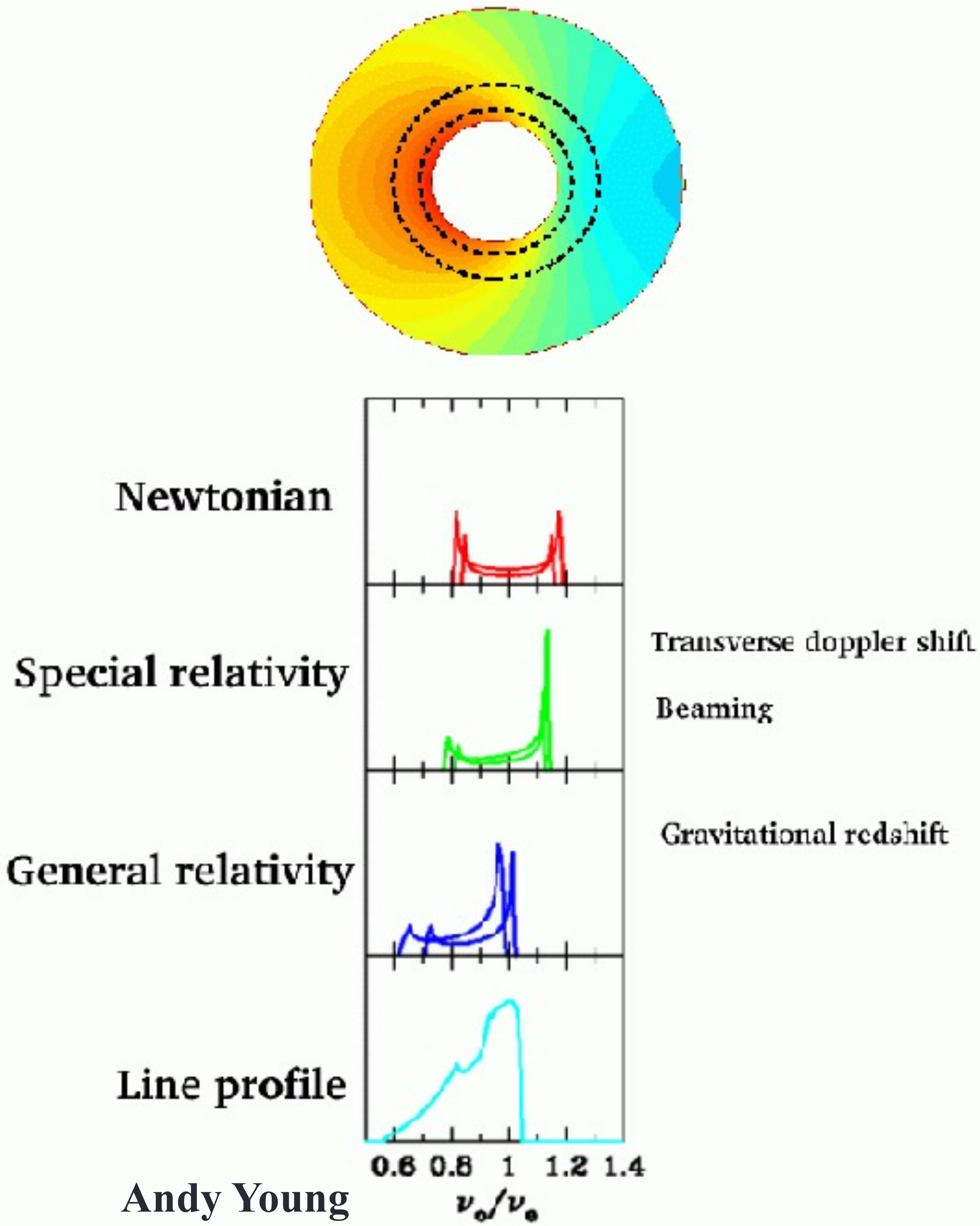
variablity

* much more luminous than an x-ray binary

Spectral Features from Near the Black Hole

It turns out that the only spectral feature from 'near' the black hole ($R<20R_s$) occurs in the X-ray band and is due to iron

This 'line' is shifted and broadened by special and general relativistic effects and is one of the ways we have of measuring spin



Relativistic effects imprint a characteristic profile on the emission line…

Looking at disk at 30^0 angle
Doppler shift is color coded
(Red shift going away from us
blue shift towards us)
See what the addition of special
and general relativity does to line shape

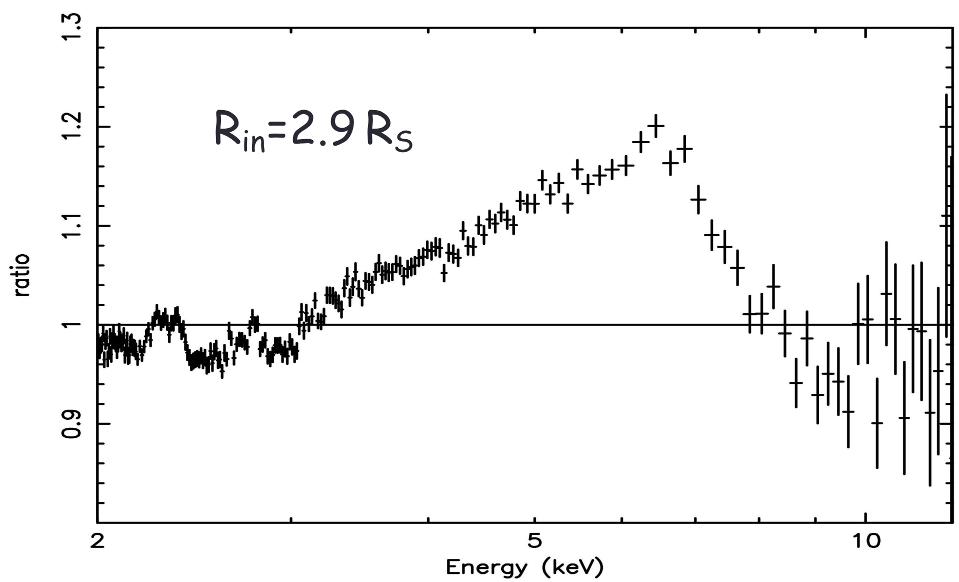
Spin

As we discussed earlier a BH is completely characterized by its spin and mass.

One of the few ways of inferring the spin is to determine the ISCO

The shape of the broad Fe K line is sensitive to how close the gas can get to the BH and thus the ISCO.

GX 339-4 (XMM)



Shape of Fe K line in a galactic BH indicating the innermost region is 2.9 R_S in size