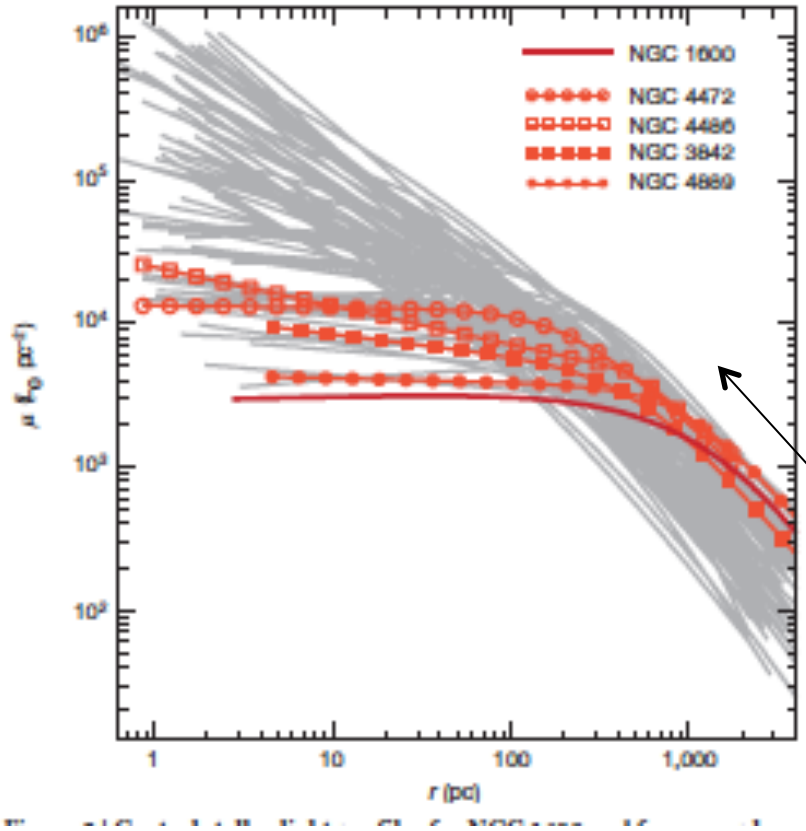
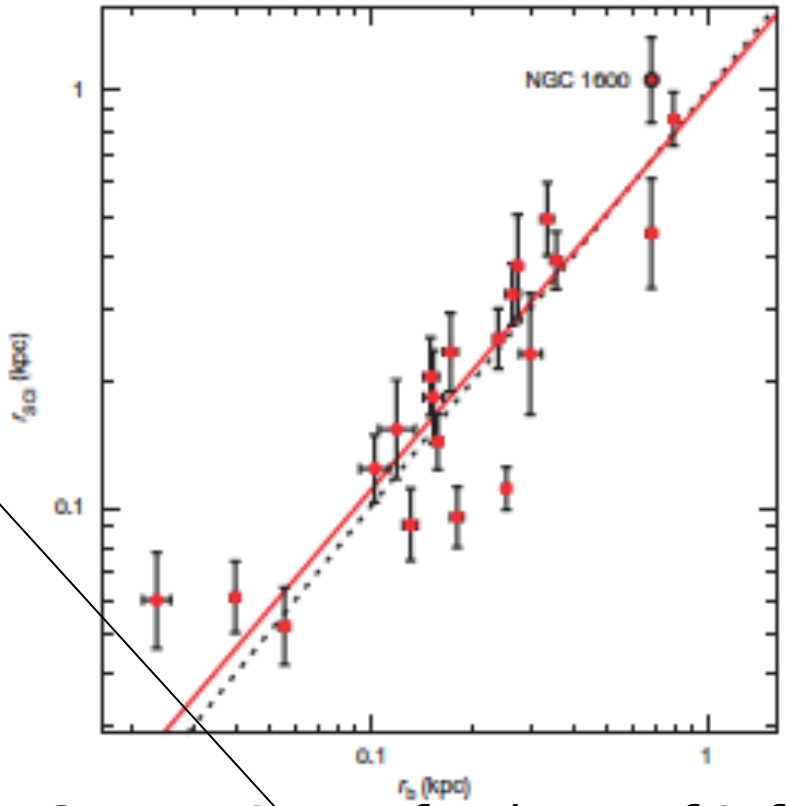
Strong gravity and accreting black holes

- The AGN Zoo
- Black Hole systems
  - The spectrum of accreting black holes
  - X-ray “reflection” from accretion disks
  - Strong gravity effects in the X-ray reflection spectrum

A 17-billion-solar-mass black hole in a group galaxy with a diffuse core- expressed by the media as 'Surprise! Gigantic Black Holed Found in Cosmic backwater"





Comparison of sphere of influence of BH with galaxy core radii

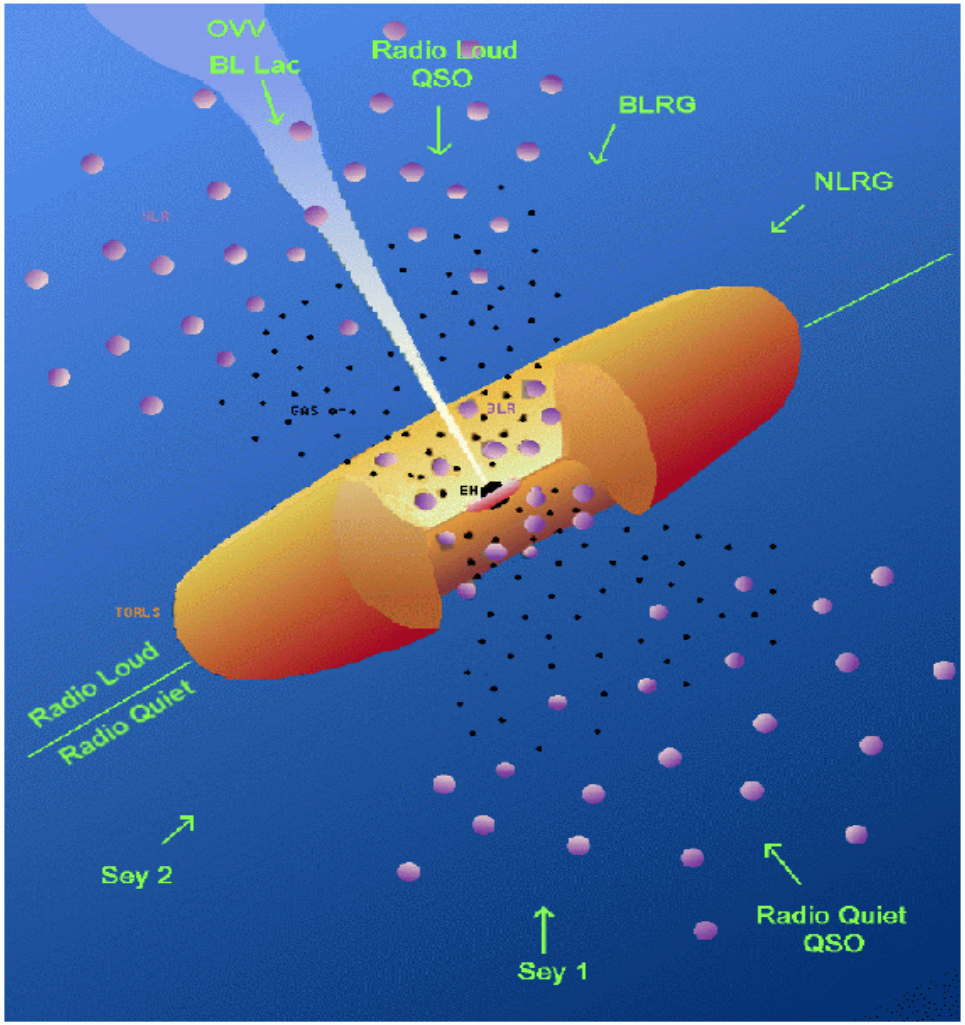
Nature Magazine April 2013

- Against the law-Behaviours proposed for black holes conflict with the laws of physics.
  - News Feature poses the conundrum: will an astronaut who falls into a black hole be crushed or burned to a crisp? The answer ... according to physicists in 2013 is .. a let-down: they don't know.
  - physicists gathered at CERN last month to address the mysterious fate of our unfortunate astronaut. ... The physics is complicated but the take-home message is: if the astronaut fries, then Einstein's framework of general relativity goes up in smoke with it; if the astronaut is crushed and torn by the black hole's internal variation in gravity, then quantum mechanics is wrong.
  - So which is it, relativity or quantum theory; heaven or hell? Debate continues.
  - "this shakes the foundations of what most of us believed about black holes", said Raphael Bousso, a string theorist .. as he opened his talk at the meeting. "It essentially pits quantum mechanics against general relativity, without giving us any clues as to which direction to go next."
  - http://www.bbc.com/earth/story/20150525-a-black-hole-would-clone-you.... most read story on BBC Earth in 2015!

AGN- Alias Active Galactic Nuclei

- AGN are 'radiating' supermassive black holes-
  - They go by a large number of names (Seyert I, Seyfert II, radio galaxies, quasars, Blazars etc etc)
  - The names convey the observational aspects of the objects in the first wavelength band in which they were studied and thus do carry some information

- See http://nedwww.ipac.caltech.edu/level5/Cambridge/Cambridge_contents.html for an overview



Urry and Padovani 195

AGN Zoo

"Radio-loud" objects show jets and enormous lobes of relativistic plasma

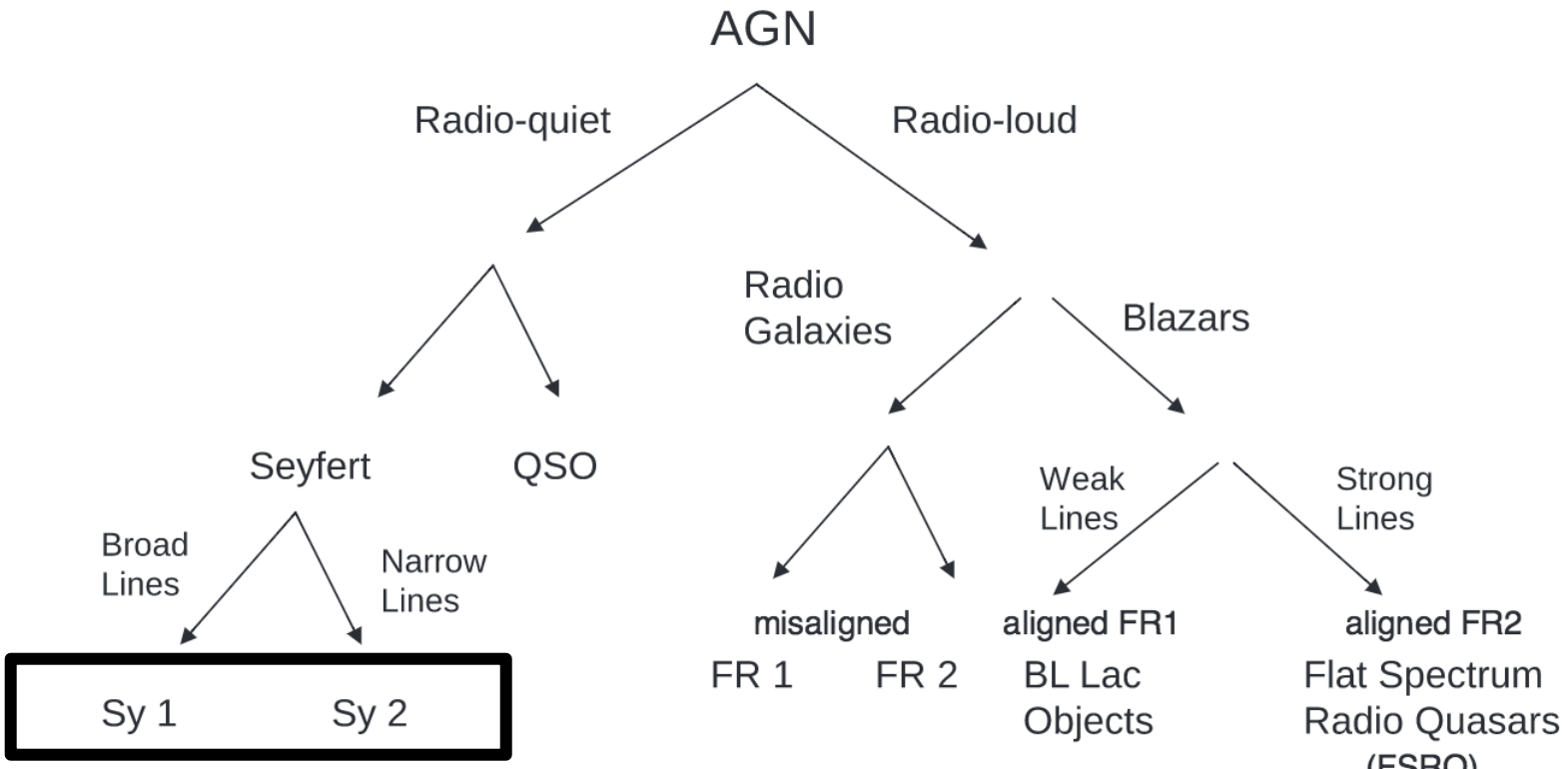
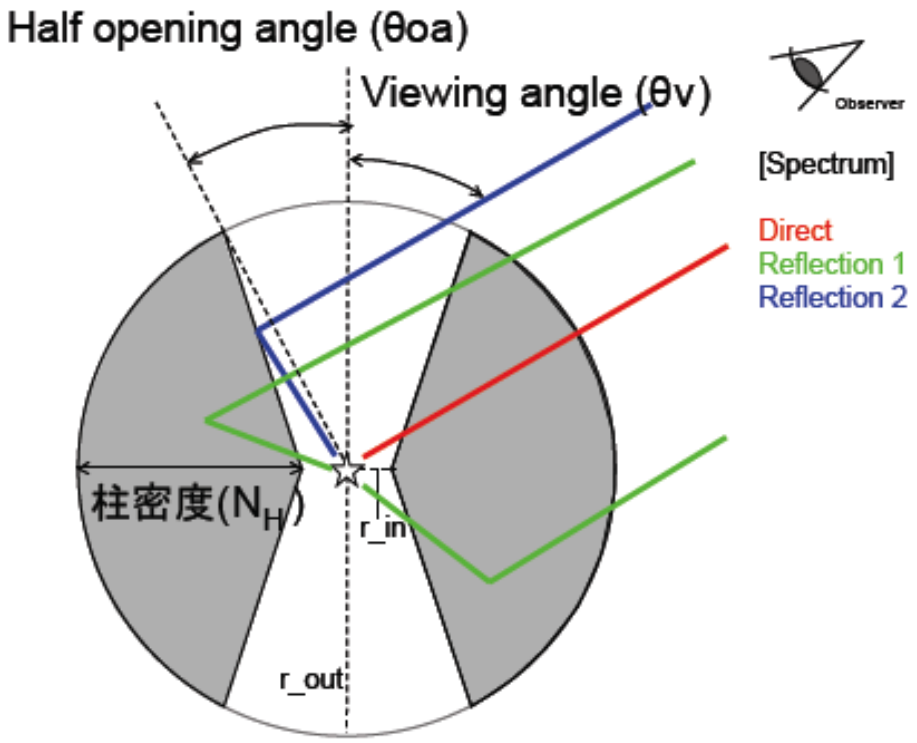


Figure 1. **Observational classification of active galaxies.** AGN are subdivided into classes depending on observational aspects, such as their radio loudness or the presence of optical lines in their spectra. QSO = quasi-stellar objects; Sy1 and Sy2 = Seyfert 1 and 2; FR1 and FR2 = Fanaroff-Riley 1 and 2.

AGN Zoo

- In a simple unification scenario broad-lined (Type 1) AGN are viewed face-on
- narrow-lined (Type 2) AGN
  - the broad emission line region (BELR) the soft X-rays and much of the optical/UV emission from the AD are hidden by the dust

- However there are other complications like jets and a range in the geometry



Radio Loudness	Optical Emission Line Properties		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG { FR I / FR II	BLRG SSRQ FSRQ	Blazars { BL Lacs / (FSRQ)
	decreasing angle to line of sight ->		

Table 1: AGN Taxonomy: A Simplified Scheme.

Radio Loudness	*Optical Properties*		*No Lines*
Radio quiet (weak or no jet)	Type II (narrow forbidden lines) Seyfert 2	Type I (broad permitted lines) Seyfert 1 QSO	
Radio Loud (strong jet)	FR I NLRG FR II	BLRG	Bl Lac Blazars FSRQ
X-ray Properties	Highly Absorbed-strong narrow Fe K line, strong low E emission lines	Not absorbed- or ionized absorber often broad Fe K line-low energy spectrum with absorption lines	Featureless continuum-highly variable γ-ray sources

table 27-2 Properties of Active Galactic Nuclei (AGNs)

Object	Found in which type of galaxy	Strength of radio emission	Type of emission lines in spectrum	Luminosity (watts)	Luminosity (Milky Way Galaxy = 1)
Blazar	Elliptical	Strong	Weak (compared to synchrotron emission)	10^{38} to 10^{42}	10 to 10^5
Radio-loud quasar	Elliptical	Strong	Broad	10^{38} to 10^{42}	10 to 10^5
Radio galaxy	Elliptical	Strong	Narrow	10^{36} to 10^{38}	0.1 to 10
Radio-quiet quasar	Spiral or elliptical	Weak	Broad	10^{38} to 10^{42}	10 to 10^5
Seyfert 1	Spiral	Weak	Broad	10^{36} to 10^{38}	0.1 to 10
Seyfert 2	Spiral	Weak	Narrow	10^{36} to 10^{38}	0.1 to 10

- Some of different classes of AGN are truly different 'beasts' - (e.g. radio loud vs radio quiet) but
- Much of the apparent differences are due to geometry/inclination effects- this is called the Unified Model for AGN (e.g. type I vs Type I radio quiet objects, blazars - radio loud objects observed down the jet)
- The ingredients are: the black hole, accretion disk, the jet, some orbiting dense clouds of gas close in (the broad line region), plus a dusty torus that surrounds the inner disk, some less dense clouds of gas further out (the narrow line region) (adapted from T. Treu)

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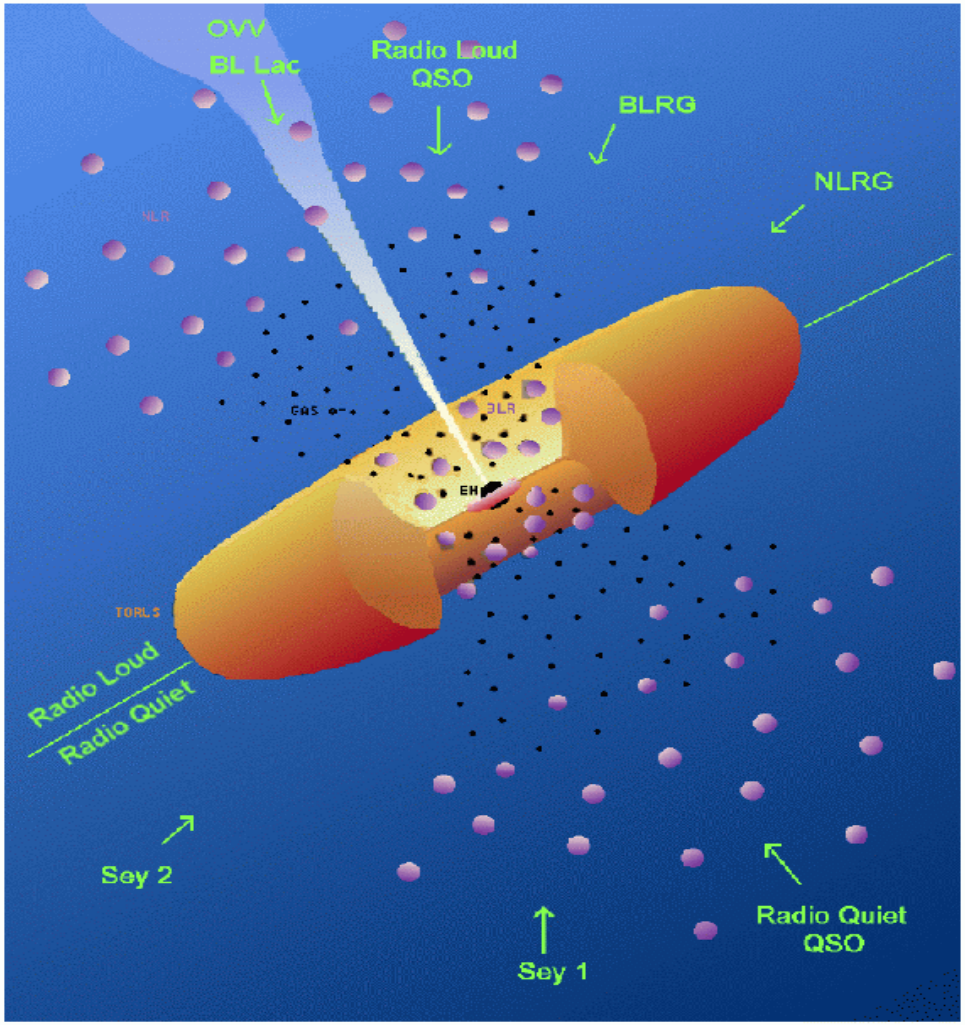
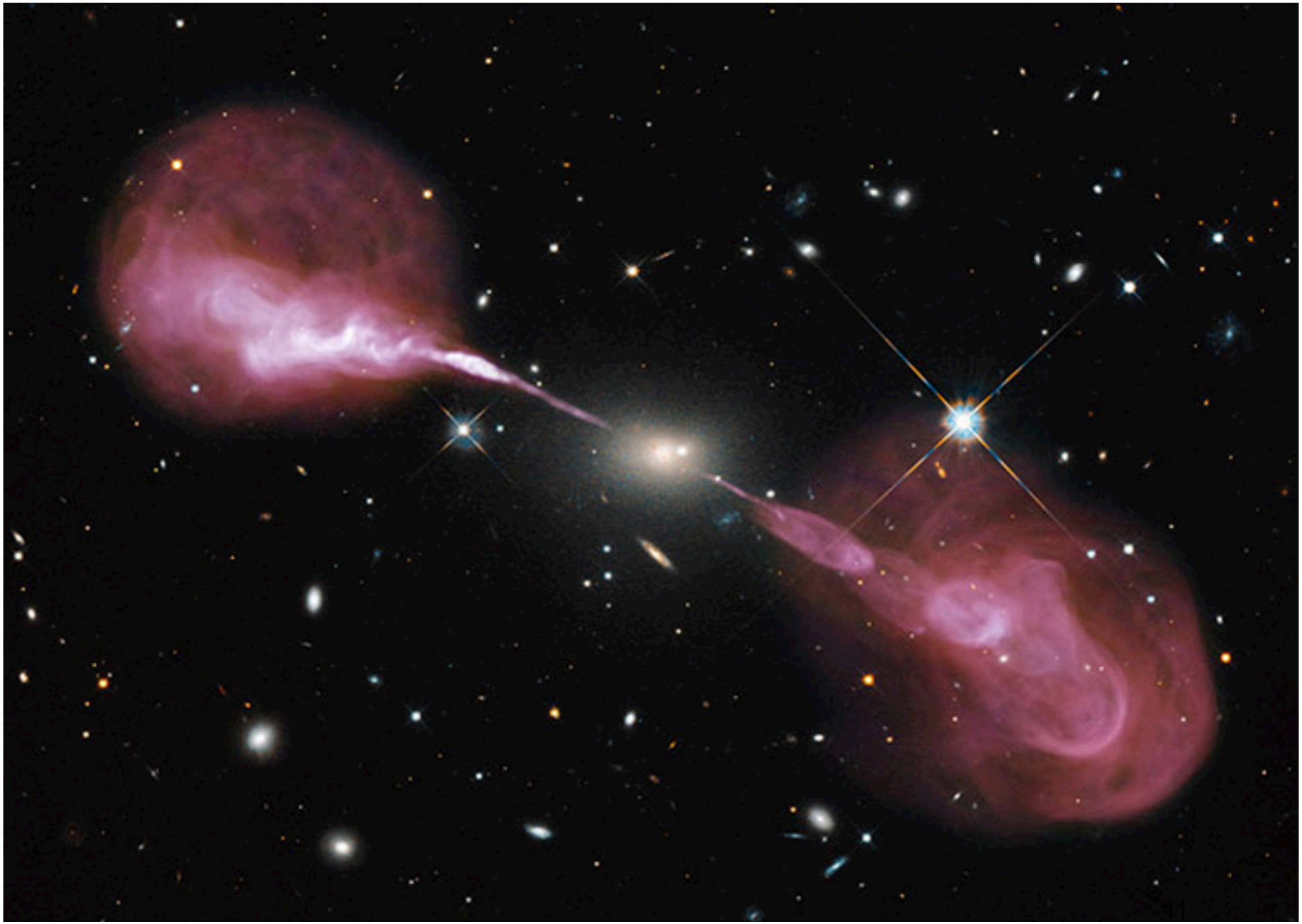


Urry and Padovani 195

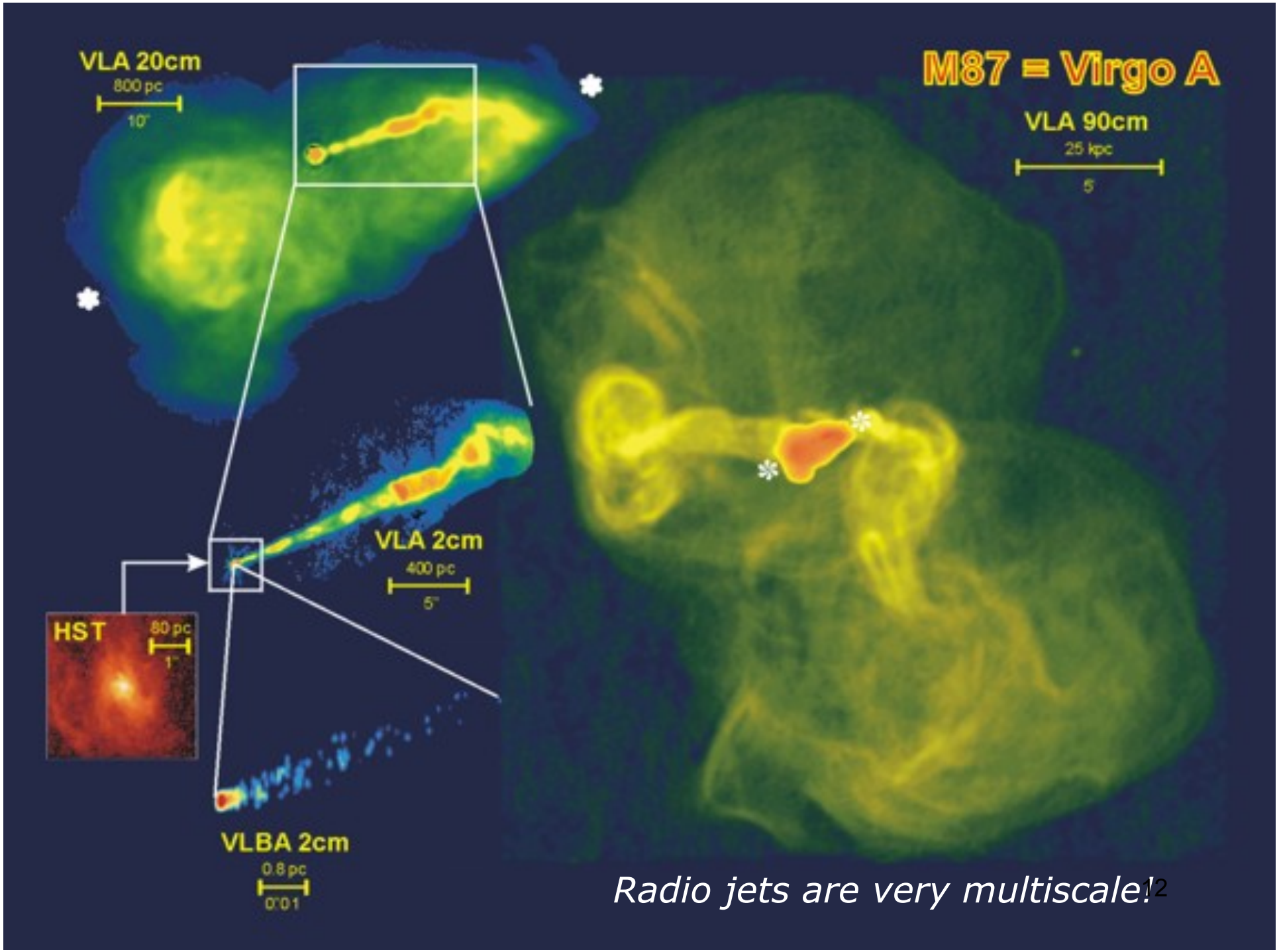
III : AGN Unification

General comments

- *AGN are diverse… they have a vast range of properties*
- *In general, there are three "axes" to consider…*
- *Luminosity*
  - *Range from <1040 erg/s to ~1048 erg/s*
  - *Fundamental parameter controlling this is **mass accretion rate***
  - *Powerful objects called quasars (historically, AGN found before galaxy)*
- *Level of obscuration*
  - *In some objects, can see all of the way down to the SMBH*
  - *In other objects, view at some wavelengths is blocked by column of obscuring material (some objects are blocked at all wavelengths)*
  - *Level of obscuration connected to **viewing inclination***
- *Presence of powerful relativistic (radio) jets*
  - *Radio-loud AGN : generate powerful jets, seen principally via synchrotron radiation in the radio band*
  - *Radio-quiet AGN : lack these powerful jets (often possess weak jets)*
  - *Fundamental parameter controlling jet production **unknown (maybe black hole spin; or magnetic field configuration)***

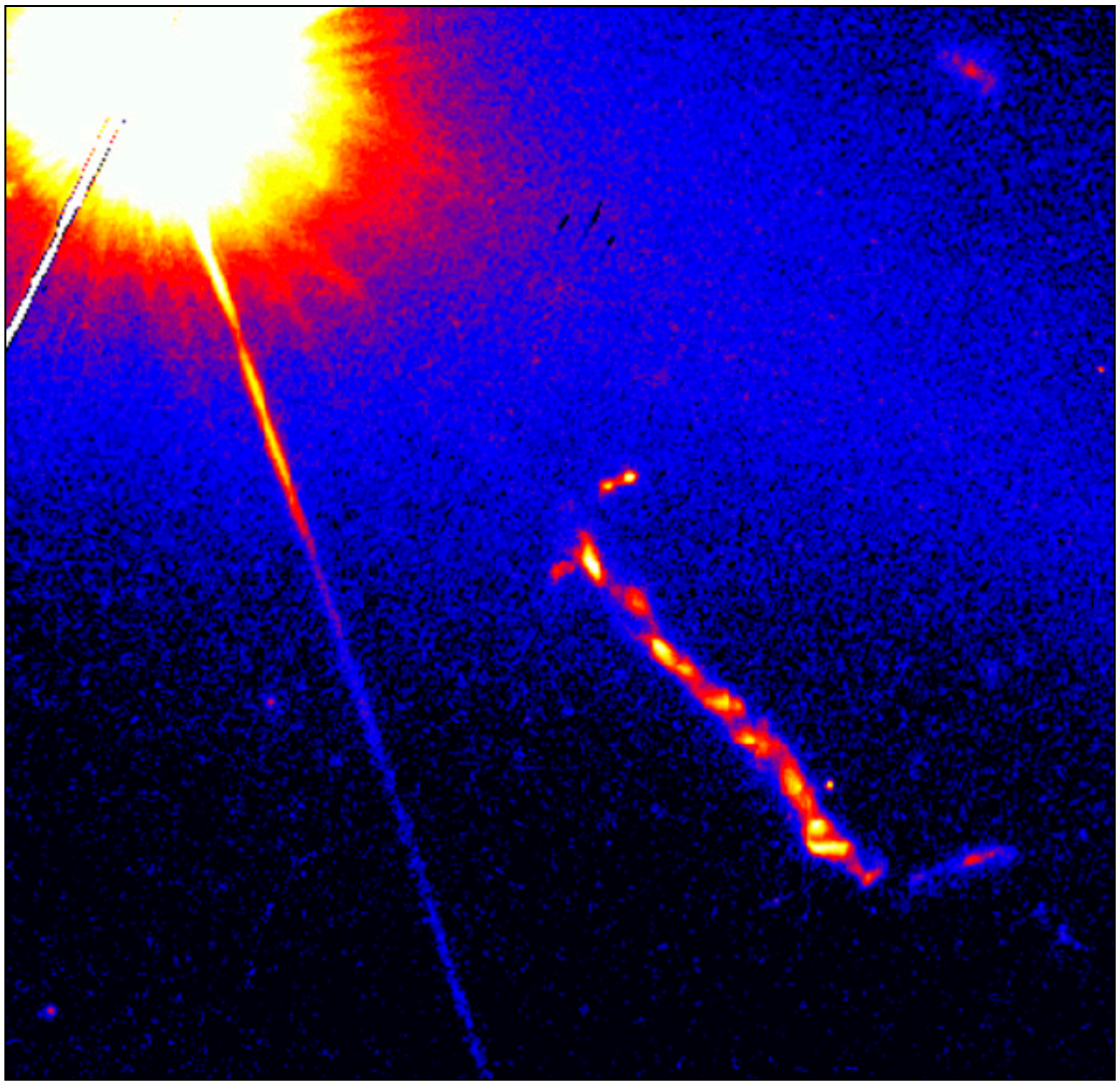


Hercules-A



Radio jets are very multiscale!

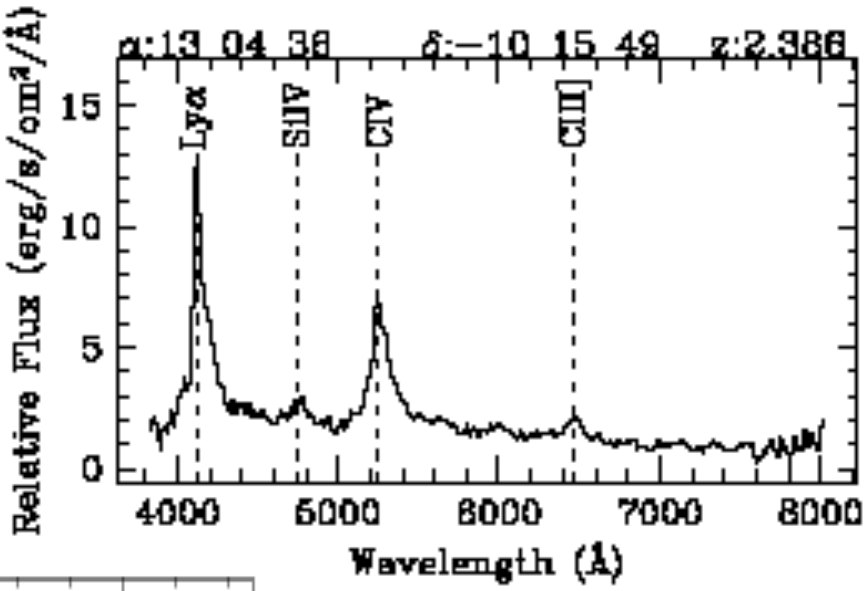
Examples:
Powerful quasar 3C273

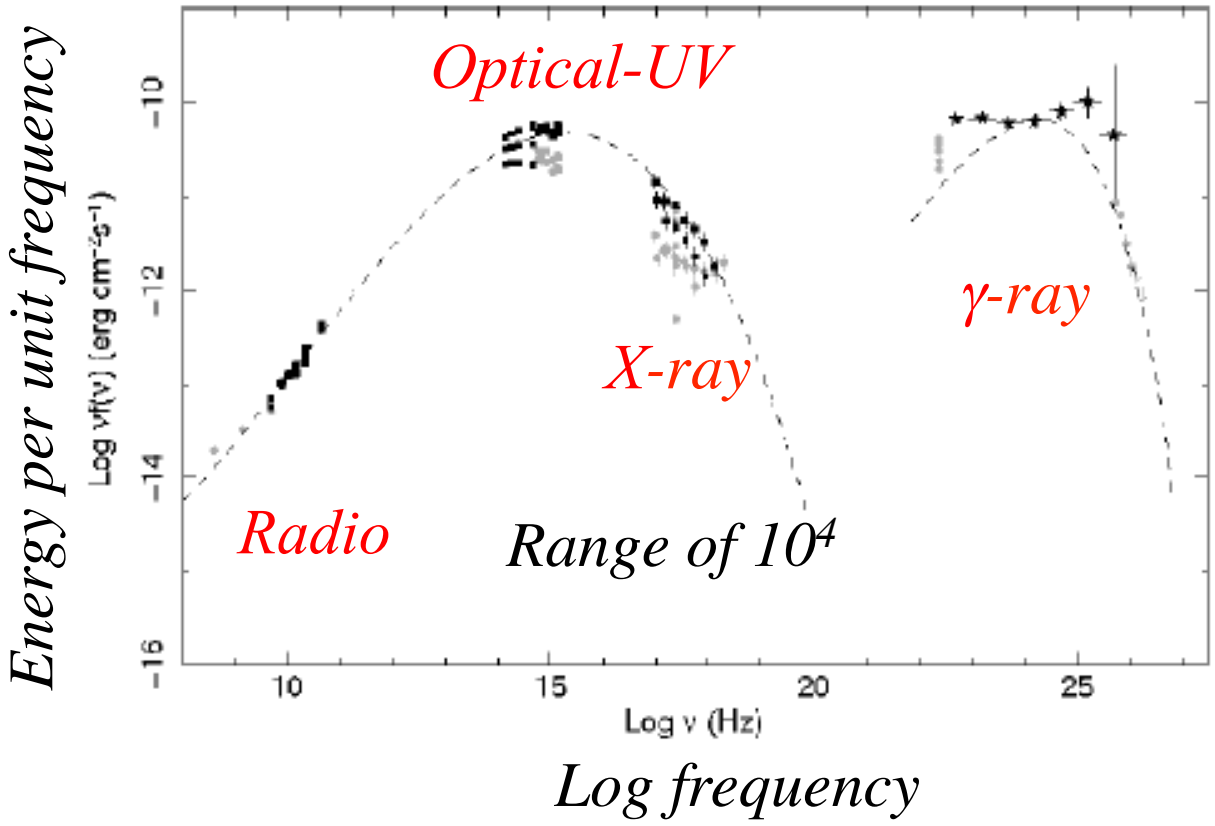


HST

Broad Band Properties of AGN

- **Broad band continuum- very different from stars or galaxies**
- **Strong UV lines not seen in stars ….**
- Can be very variable





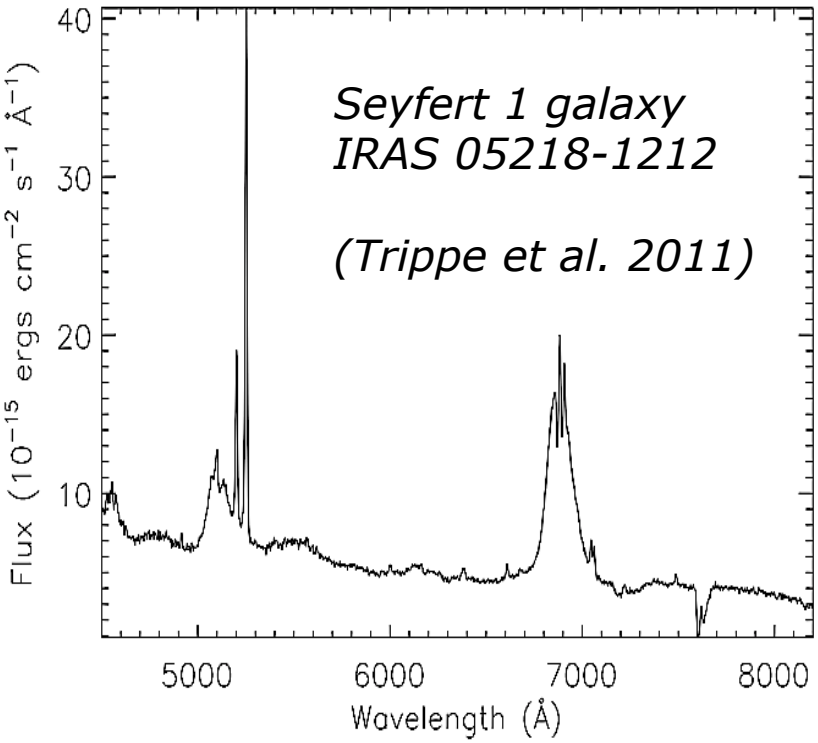
Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

A large fraction of the total observed energy appears in the γ-ray band (due to relativistic beaming)

AGN Unification

Broad line (type-1) objects

- Blue optical/UV continuum
- Broad optical/UV lines
  - Emission lines from permitted (not forbidden) transitions
  - Photoionized matter $n>10^9 cm^{-3}$
  - BLR lines FWHM~2000-20000 km/s
- Narrow optical/UV lines
  - Emission lines from both permitted and forbidden transitions
  - FWHM~500km/s
  - Sometimes spatially resolved 0.1-1kpc

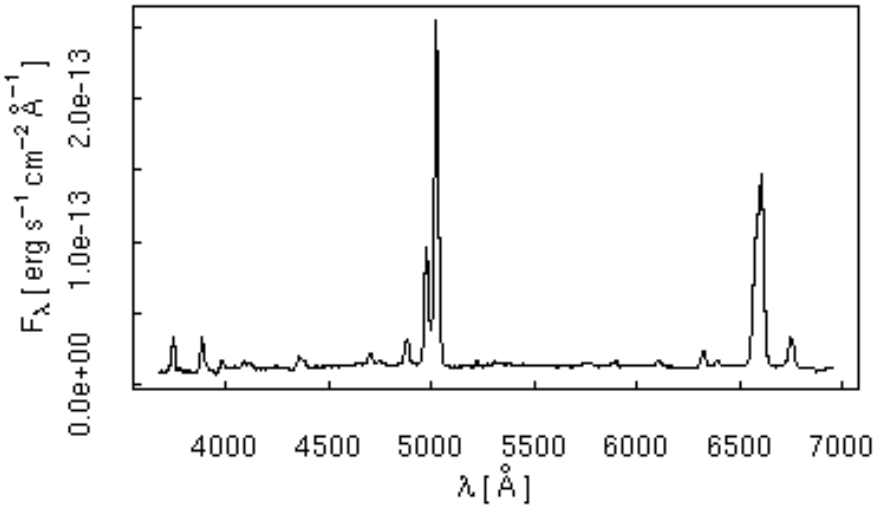


- **Overall spectrum reveals unabsorbed/unreddened nucleus**

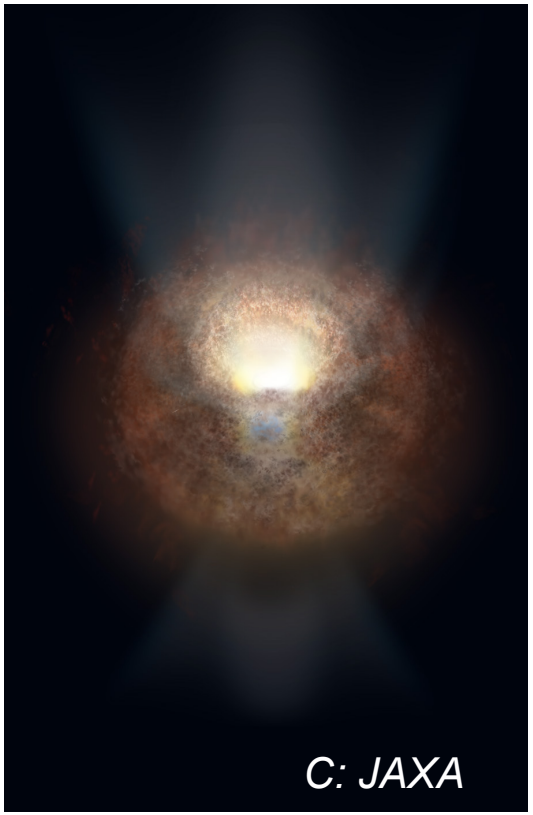
AGN Unification

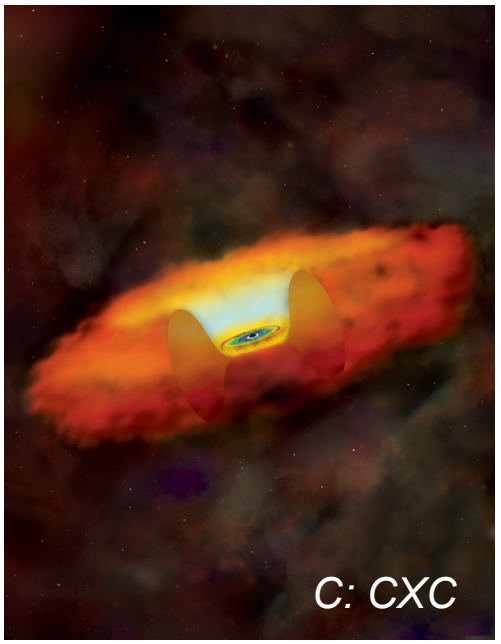
Narrow line (type-2) objects

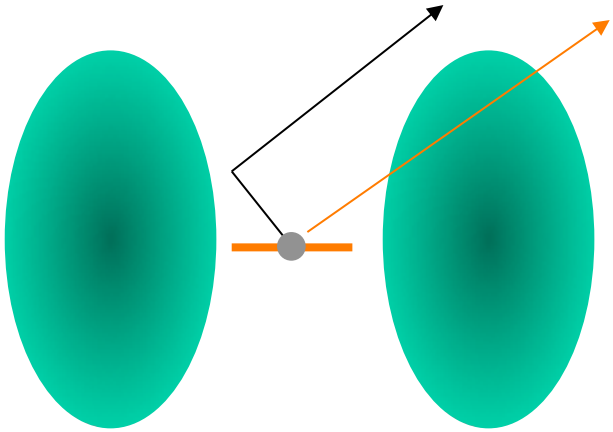
- Reddened Optical/UV continuum
- Emission line spectrum
  - "Full light" spectrum only shows narrow optical/UV lines
  - Broad optical/UV lines seen in polarized light… shows that there is a hidden broad line region **seen in scattered light** (Antonucci & Miller 1985)
- **X-ray spectrum usually reveals highly absorbed nucleus (NH>10^{22}cm-2)**
- type II **do not have broad lines and have a weak or absent 'non-stellar' continuum**
- **Depending on the type of survey and luminosity range ~50% of all AGN are of type II**

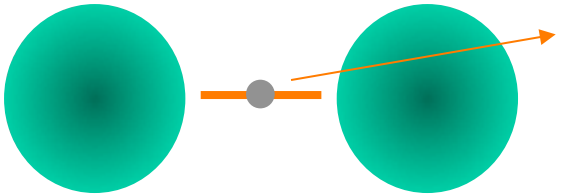


Some Variation in Geometry









- Effects of geometry can be seen in the spectra

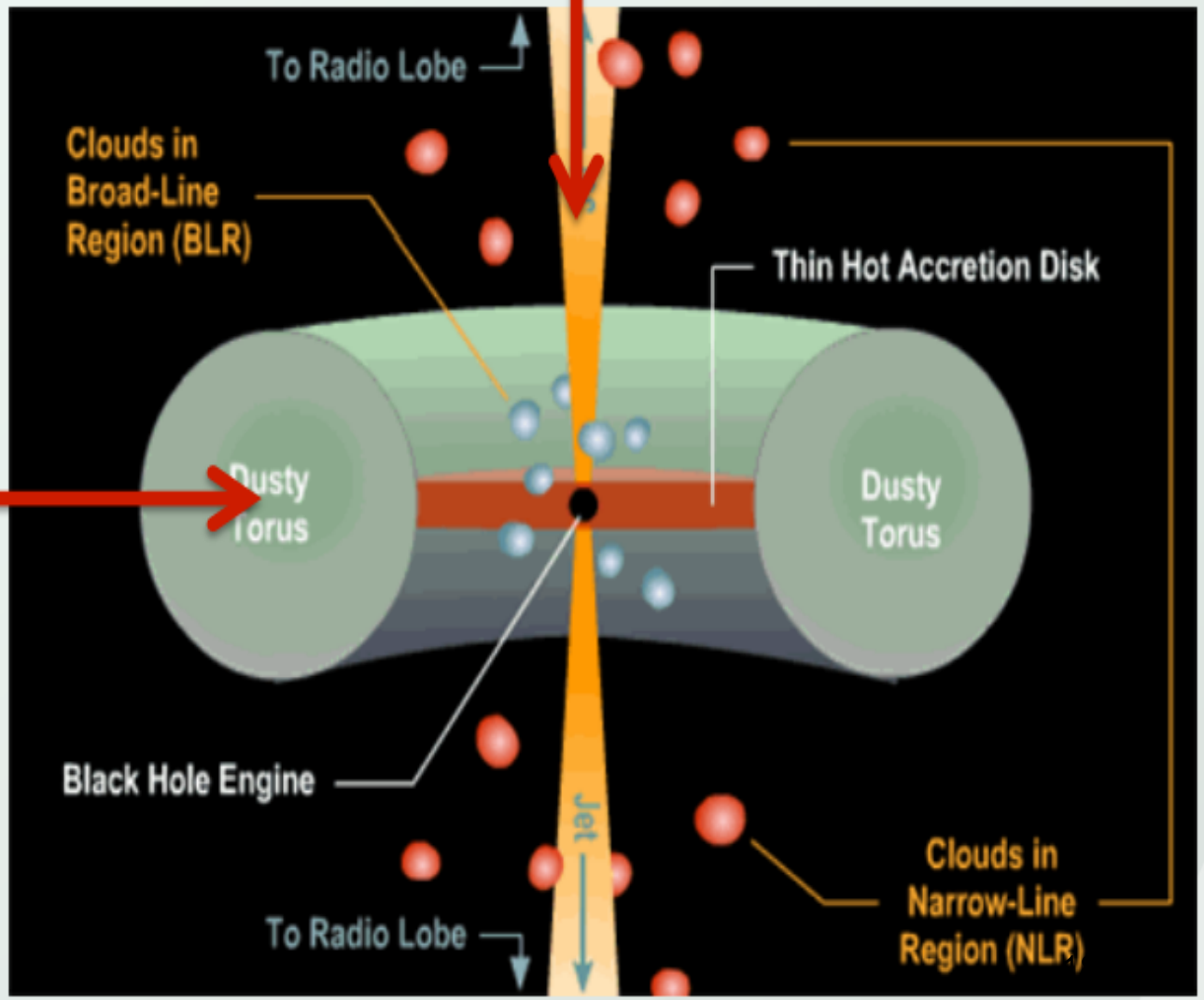
UNIFICATION MODEL of AGN

DUSTY TORUS

TYPE 1

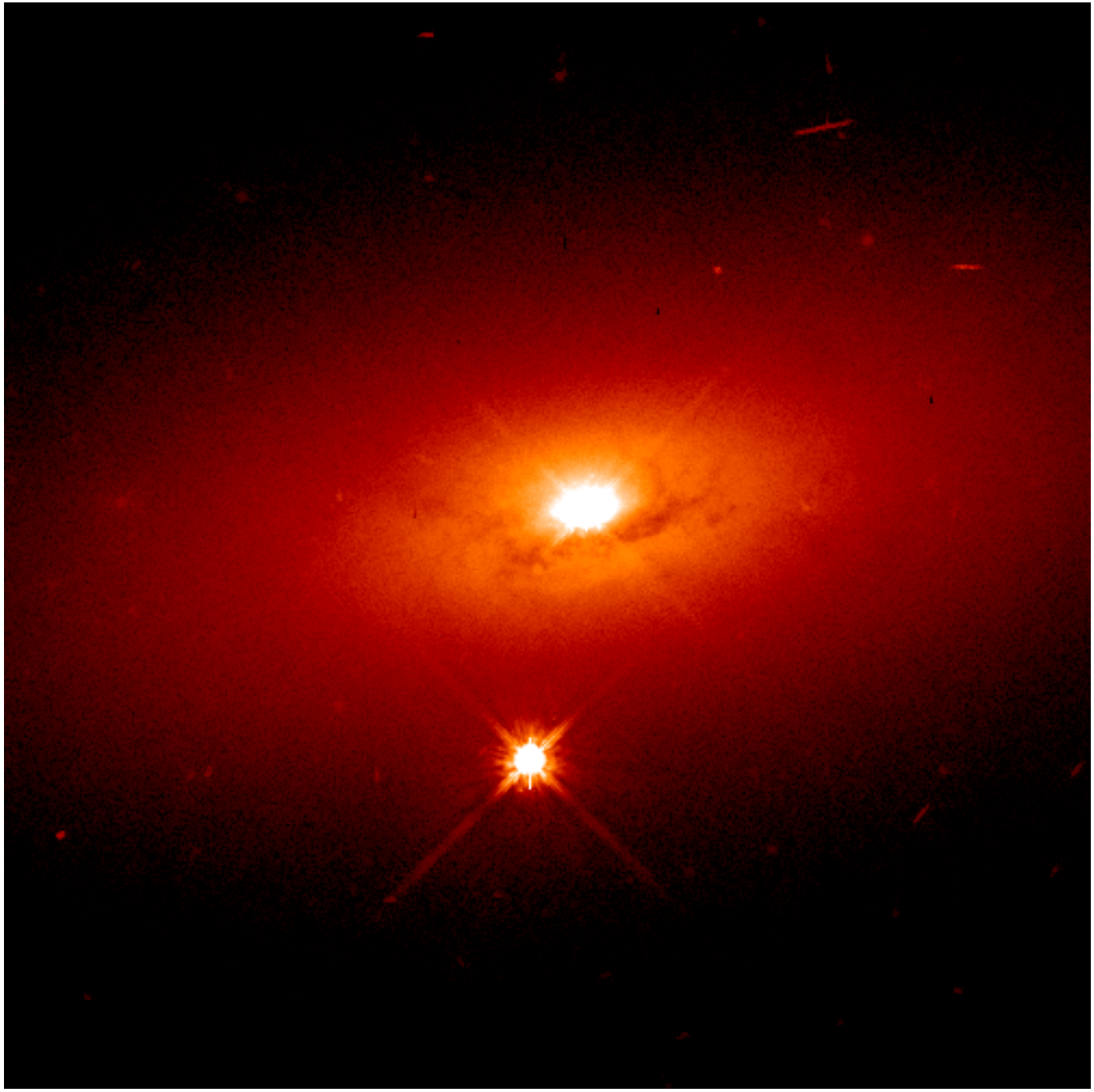
TYPE 2

orientation effect



- Anna Feltre

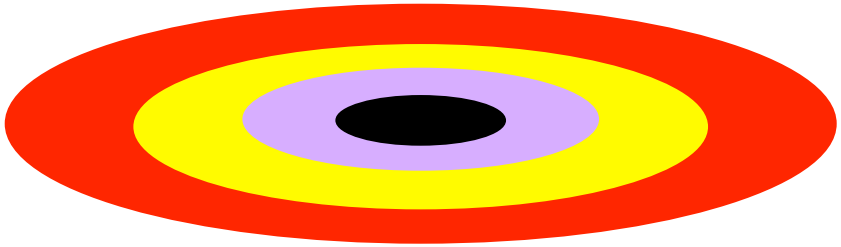
Spectra of accreting black holes

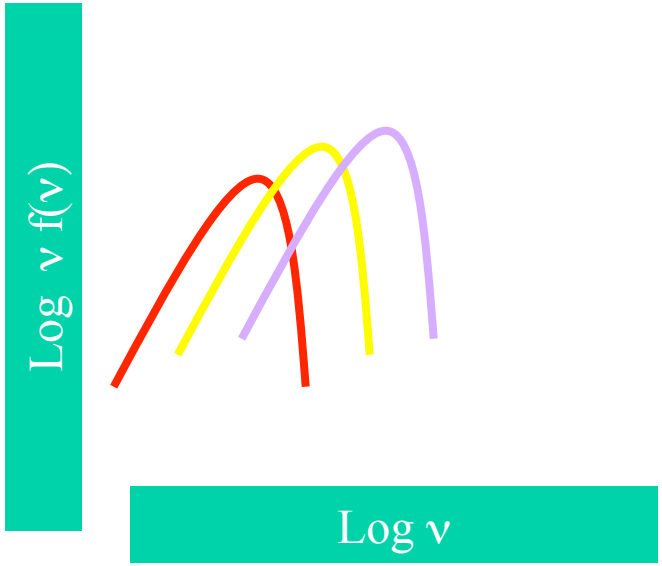


Spectra of accretion flow: disc-

C. Done

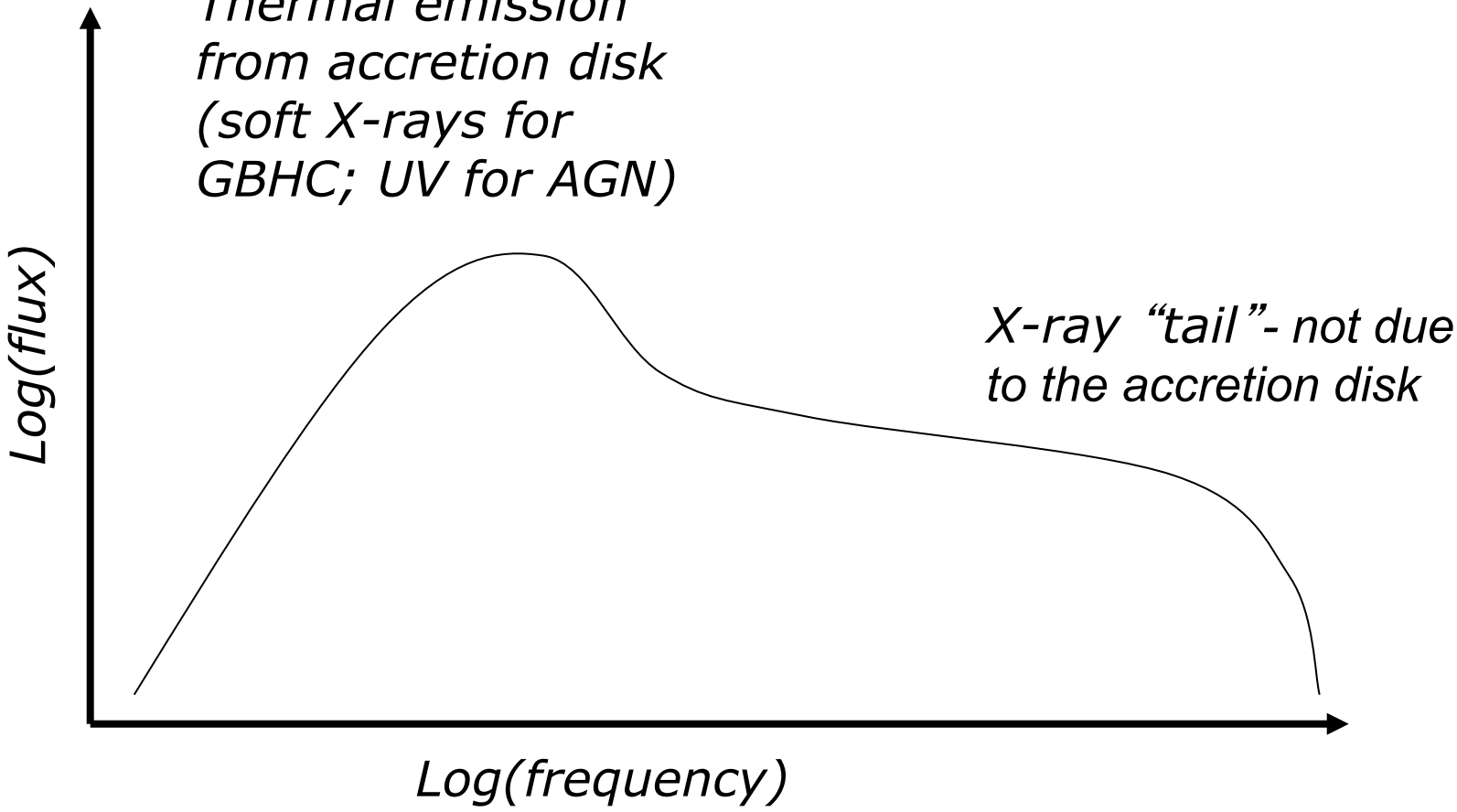
- Differential Keplerian rotation
- Viscosity : gravity → heat
- Thermal emission: $L = A\sigma T^4$
- Temperature increases inwards
- GR last stable orbit gives minimum radius R_{ms}
- a=0: $T_{max} = (M/M_\odot)^{-1/4} (L/L_{Edd})^{1/4}$
  - 1 keV (10^7 K) for 10 $M_\odot$
  - 10 eV (10^5 K) for 10^8 $M_\odot$
- a=0.998 $T_{max} \sim 2.2\ T_{max}$ (a=0)
- AGN: UV disc, ISM absorption, mass more uncertain. XRB…





What Do Broad Band Spectra of Black Holes Look Like

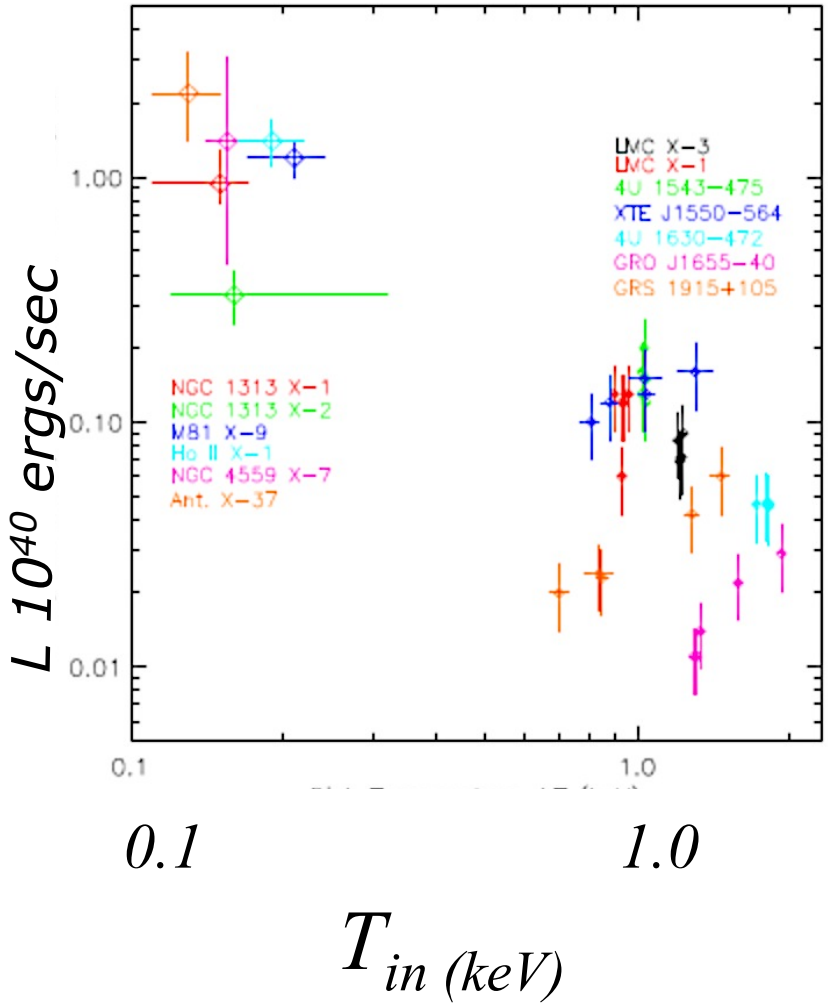
$T \sim \mathscr{M}^{1/4} M^{-1/4}$

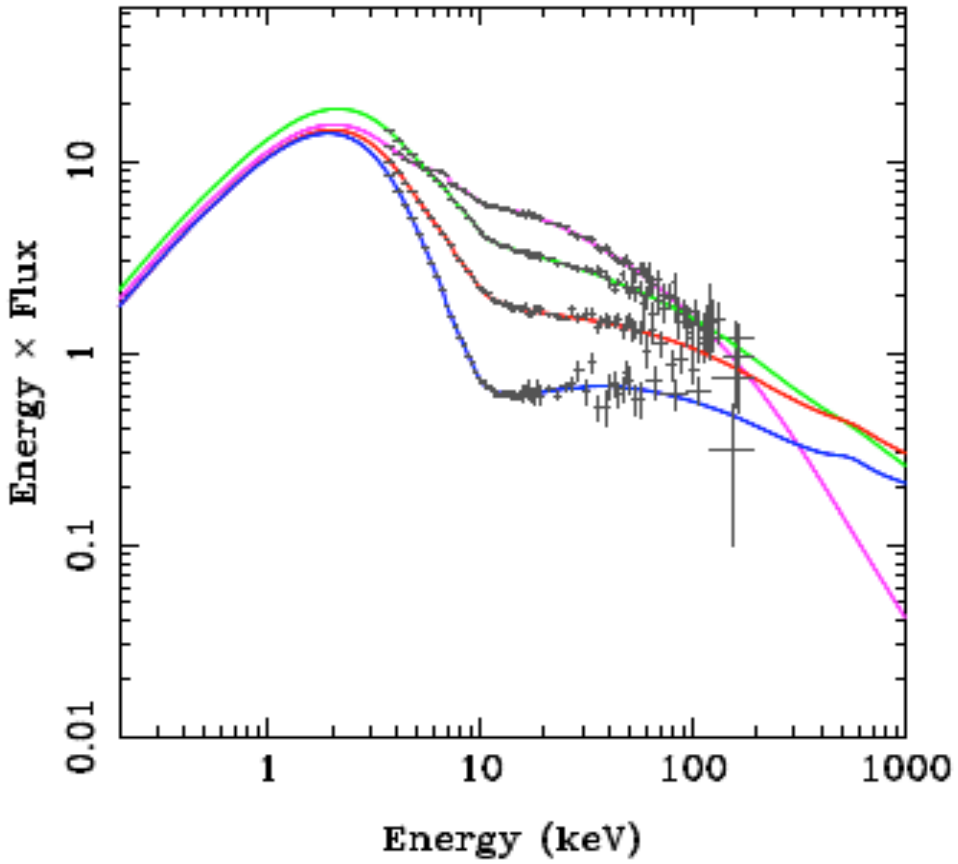


Galactic Black Holes

- Relatively low mass and so the disk are 'hot'

Adapted from Miller et al 2003





$L \sim 7 \times 10^{38}\ f (M_{10})^2 (T_{in})^4$ erg/s

Where M_{10} is the mass in units of 10 $M_\odot$ and T_{in} is in keV

f is a factor taking some physics into account

Reminder of Accretion Disk Spectrum

- Derivation of previous eq
- $L=2\pi R_{in}^2 f(\cos i)^{-1}$; f is the flux from the surface of the disk, R is the radius
- Using the black body law

$L=4\pi\sigma R^2 T_{in}^4$ σ is the Stefan- Boltmann constant

In fitting the spectrum T_{in} is directly observable

We can thus take the 2 equations to get the innermost radius

$R_{in}=\mathrm{sqrt}(L/4\pi\sigma T_{in}^4)$ and

$T_{in}\sim 3 M_{10}^{-1/4}\mathrm{keV}$

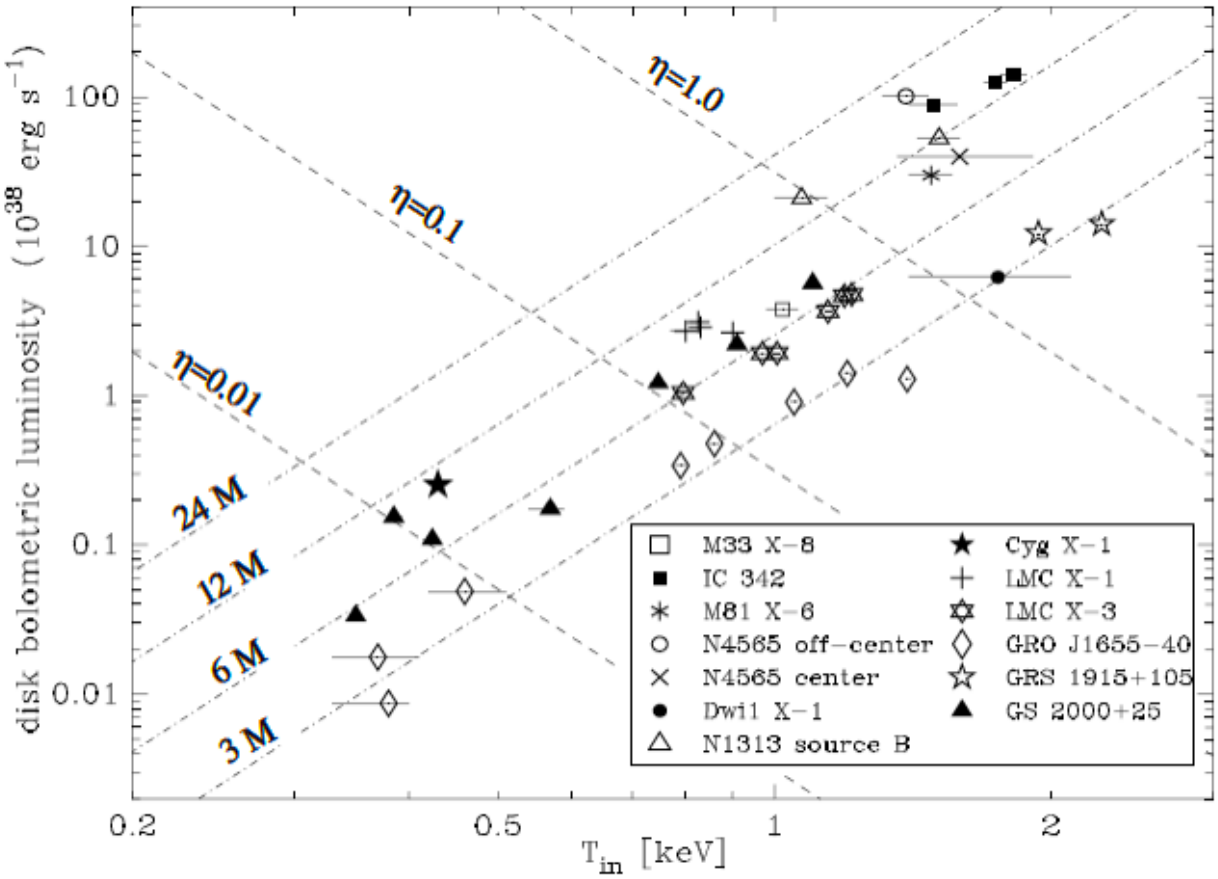
$T(r)=6.3\times10^5 (\dot{M}/\dot{M}_{Edd})^{1/4} M_8^{-1/4} (r/r_s)^{-3/4}$

($\dot{M}_{Edd}$ *is the accretion rate in Eddington units,* $T=T_{in}$ for $r=r_s$)

Real Objects

- Amazingly data for galactic black holes agrees with the simple theory
- E.g assume that M_{BH} does not change and all changes due to changes in $\mathscr{M}$- *if so then expect* $T_{in} \sim \mathscr{M}^{1/4} \sim L^{1/4}$

Makishima et al 2000



Fitted T_{in}

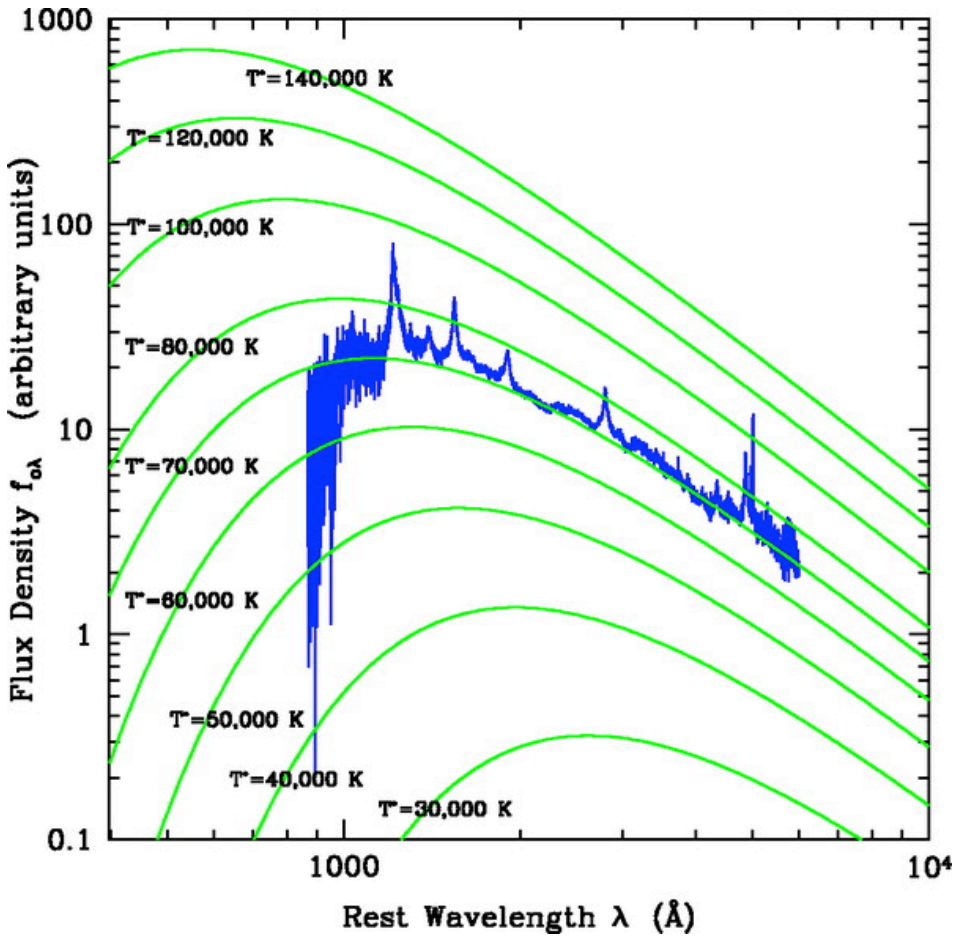
- Accretion Disk fits to AGN spectra

- Broad band spectra are not so simple- what's there in addition to the accretion disk
  - the geometry of the innermost regions
  - brief review of Comptonization

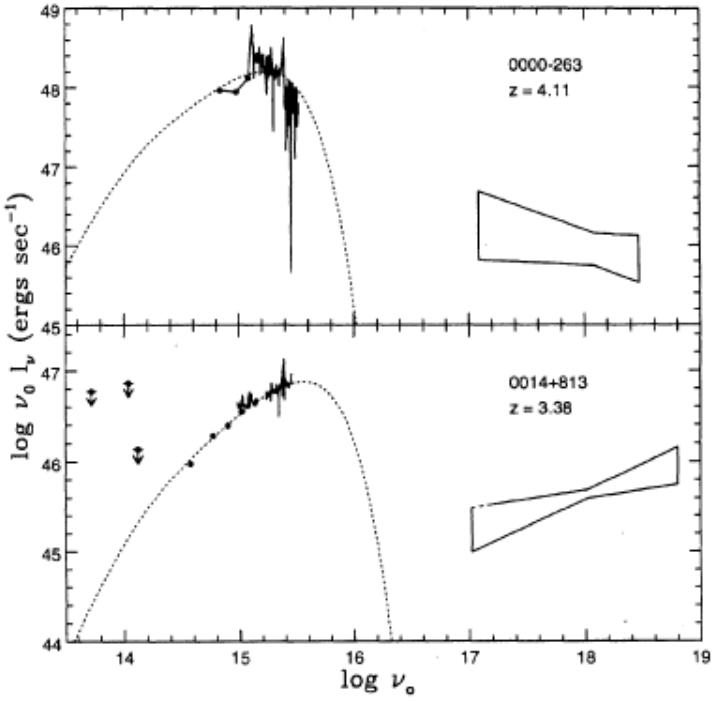
- Effects of 'reprocessing' - the disk 'sees' the hard x-ray radiation and there are measurable effects

AGN

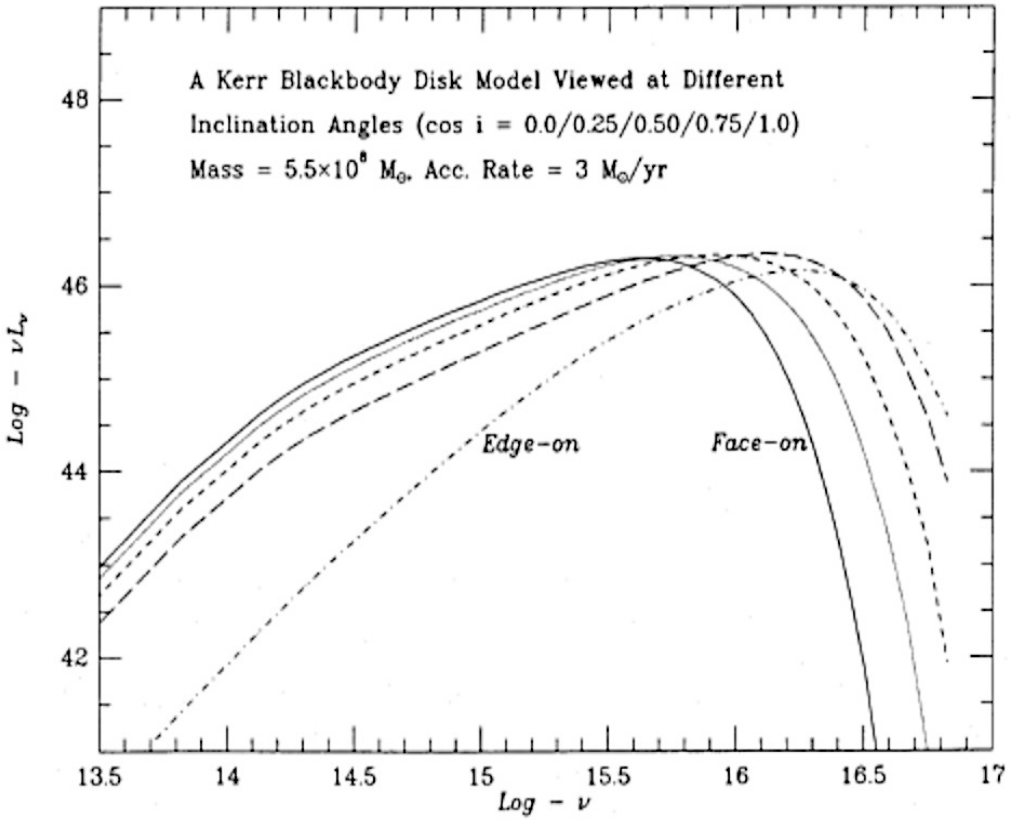
- AGN are very massive and so the predicted spectrum of the accretion disk is 'cool'
- $T \sim 8 \times 10^4$ k for a Eddington limited $M \sim 10^8 M_\odot$ black hole



- Can Fit AGN UV-optical data with accretion disk models

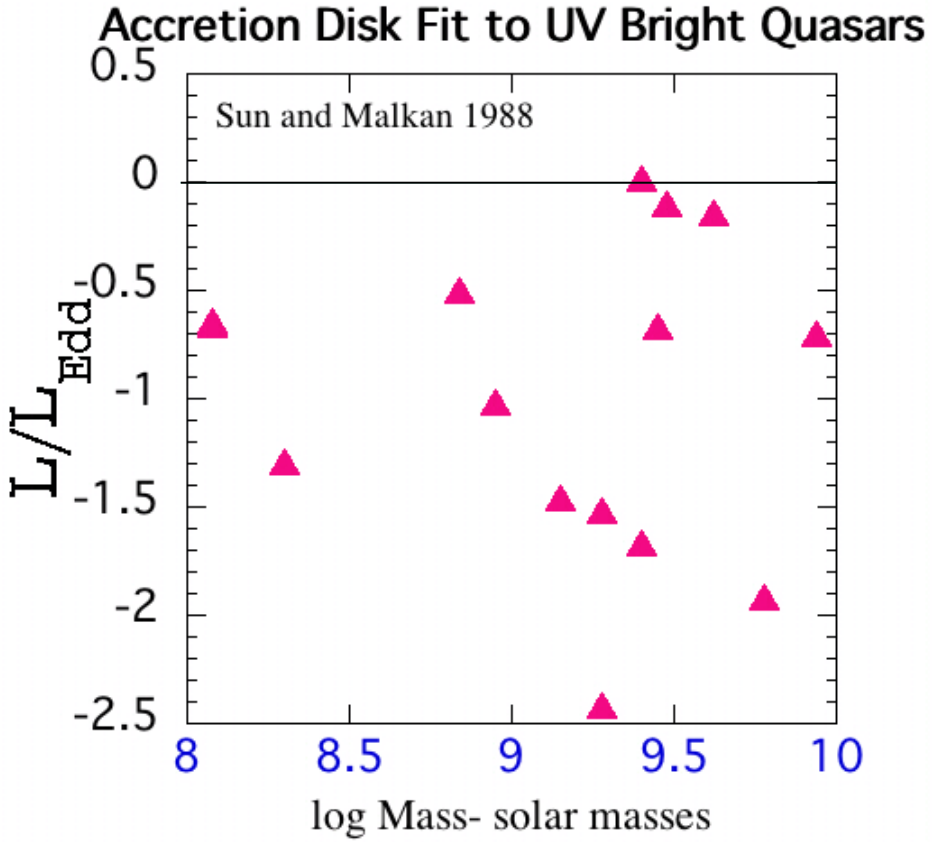


Malkan and Sun 1989

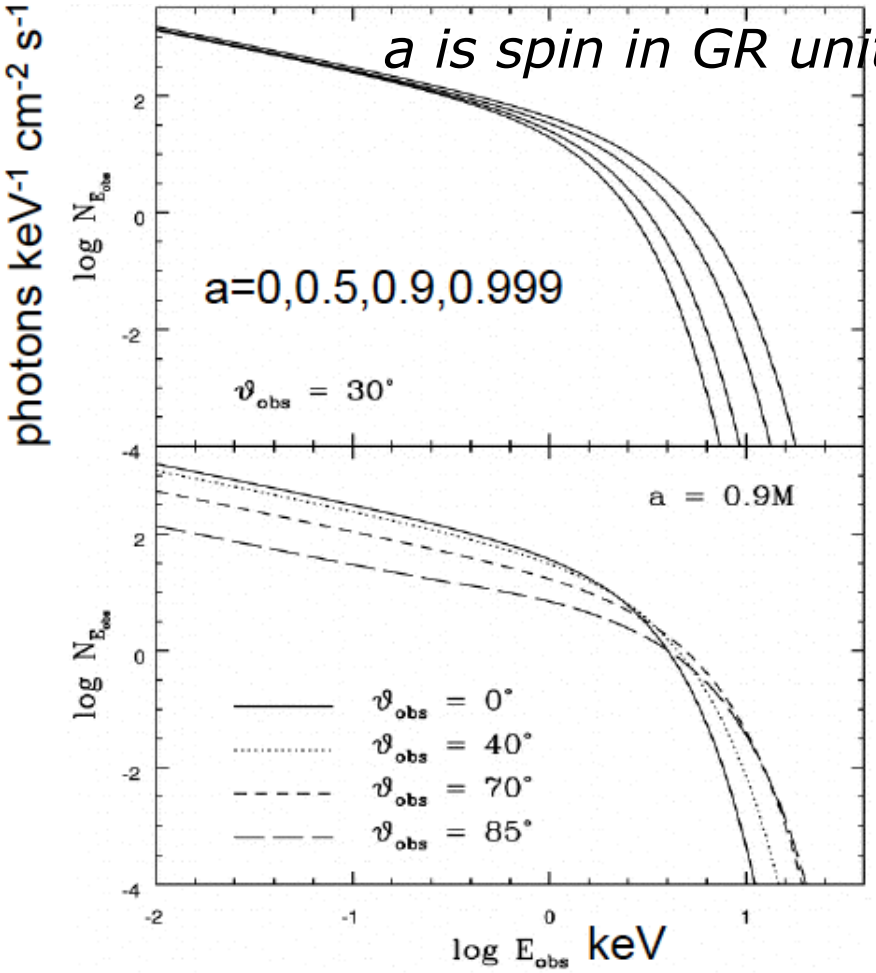


Fitted Parameters for UV Disk Fits

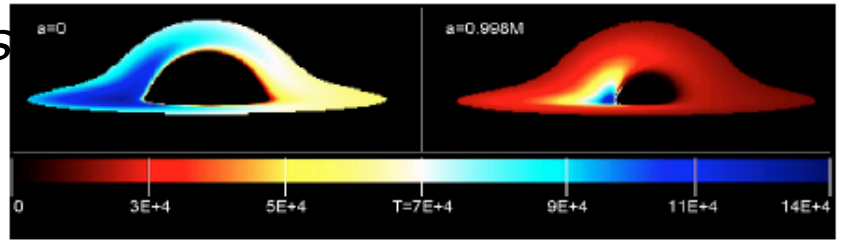
- Results are 'reasonable' but not unique
- Now have independent mass estimates- results can be checked
  - Find that values are not quite right- need more complex accretion disk models (surface is not simple BB, need to include relativistic effects)



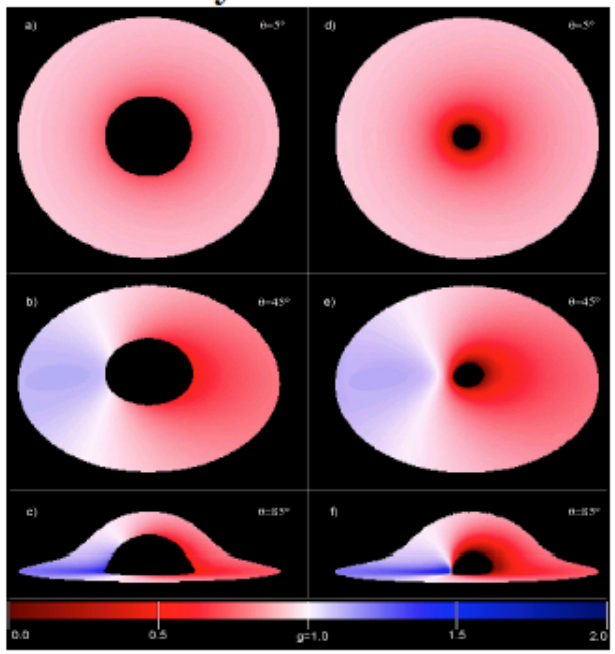
Effects of Strong Gravity (Spin), Inclination Angle on Spectrum of Disk (Merloni 2010)



a is spin in GR units



Courtesy of M. Calvani



Zheng et al. 1997; Li et al. 2005; Shafee et al. 2006; McClintock et al. 2006; Nowak et al. 2008; Steiner et al. 2010; Kubota et al. 2010