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Observational determination of the Eddington ratio in AGN

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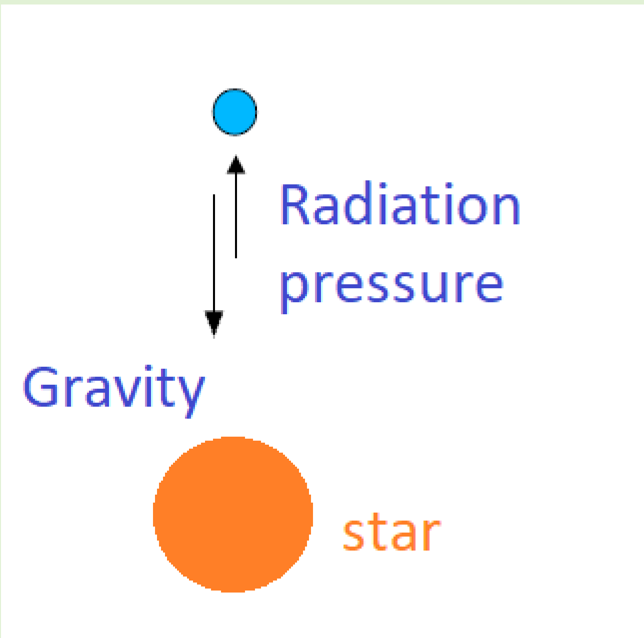
Eddington luminosity



Radiation flux $$F = \frac{L}{4\pi r^2}$$

Force acting on electron $$\frac{F}{c}\sigma_T$$

Gravitational force acting on proton $$\frac{GMm_p}{r^2}$$

Force balance: $$L_{Edd} = \frac{4\pi GM m_p c}{\sigma_T}$$

- Eddington luminosity does not depend on the radius.
- Classical limit is for fully ionized pure hydrogen atmosphere
- Pair-dominated medium would have L_{Edd} lower by factor 1830!

Estimating Eddington ratio

To estimate the Eddington ratio:

L/L_{Edd}

We simply need to measure L and M.

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

In cgs units

$L_{Edd} = 1.26 \times 10^{38}\ (M/M_s)$ erg/s

Why to talk here about Eddington ratio ?

The transition between

standard accretion disk

and

slim disk

happens approximately at

L/L_{edd} = 0.3.

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

In cgs units

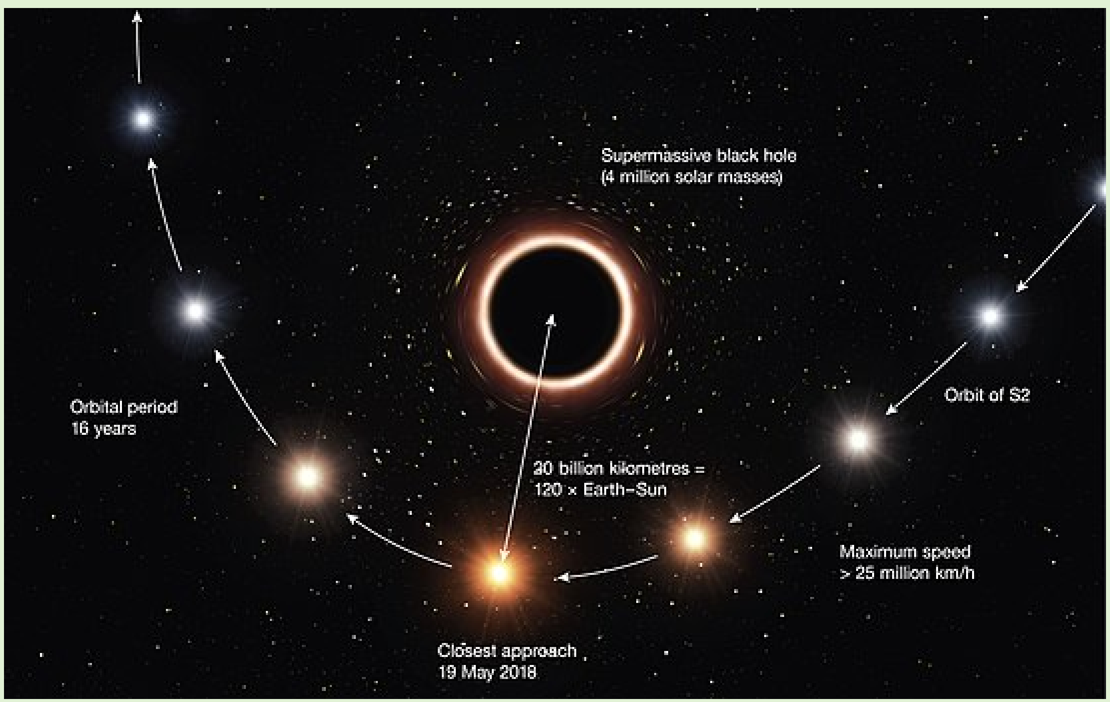
L_{Edd} = 1.26 x 10^{38} (M/M_s) erg/s

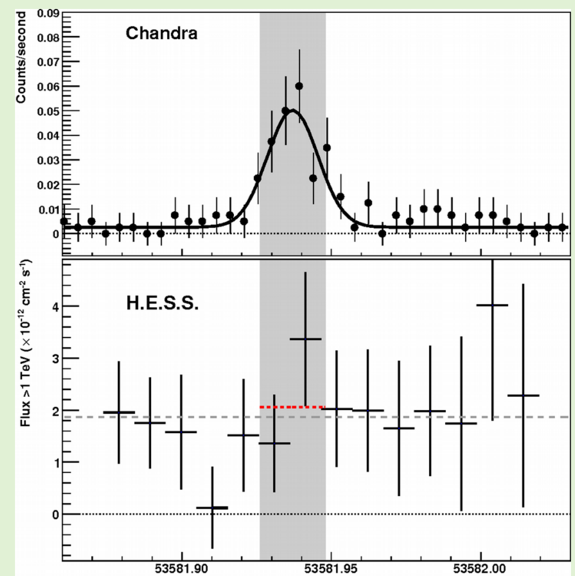
Range of Eddington ratios in astronomy

Sgr A*: $L = 10^{33} - 10^{35}$ erg/s

$M_{BH} = 4 \times 10^{6} M_{s}$

$L/L_{Edd} = 3 \times 10^{-11} - 3 \times 10^{-9}$





Range of Eddington ratios in astronomy

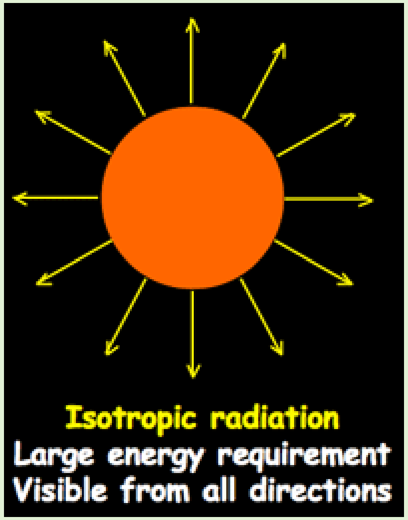
Gamma-ray burst: $E = 10^{52} - 10^{55}$ erg

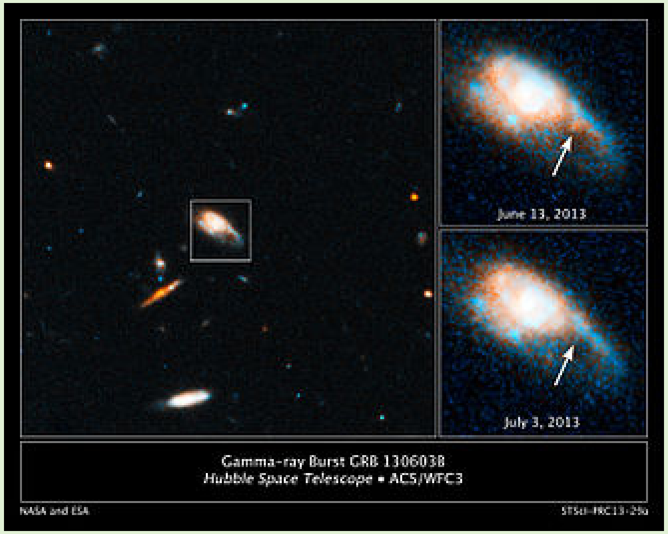
Duration = 0.1 – 1000 s

$L = 10^{53}$ erg/s

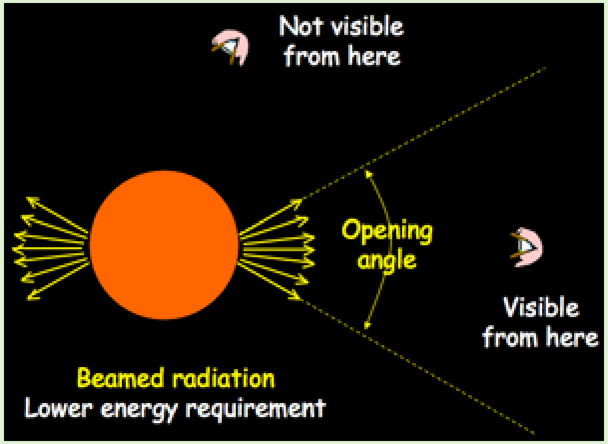
$M_{BH} = 10\, M_{s}$

$L/L_{Edd} = 7 \times 10^{13}$





Phenomenon of a hypernova (collapse of a massive star - long gamma-ray bursts) and a kilonova (collision of two neutron stars – short gamma-ray bursts).



Poeple radiate at Eddington luminosity

Temperature T = 310 K
Surface area S = 1.5 x 10^4 cm
L = sigma T^4 S = 2 x 10^9 erg
L/L_{Edd} = 0.3

Conclusion: the value
L/L_{Edd} = 0.3
Is important! People are strongly connected with the slim disk problem.

Eddington ratio in a quasar sample

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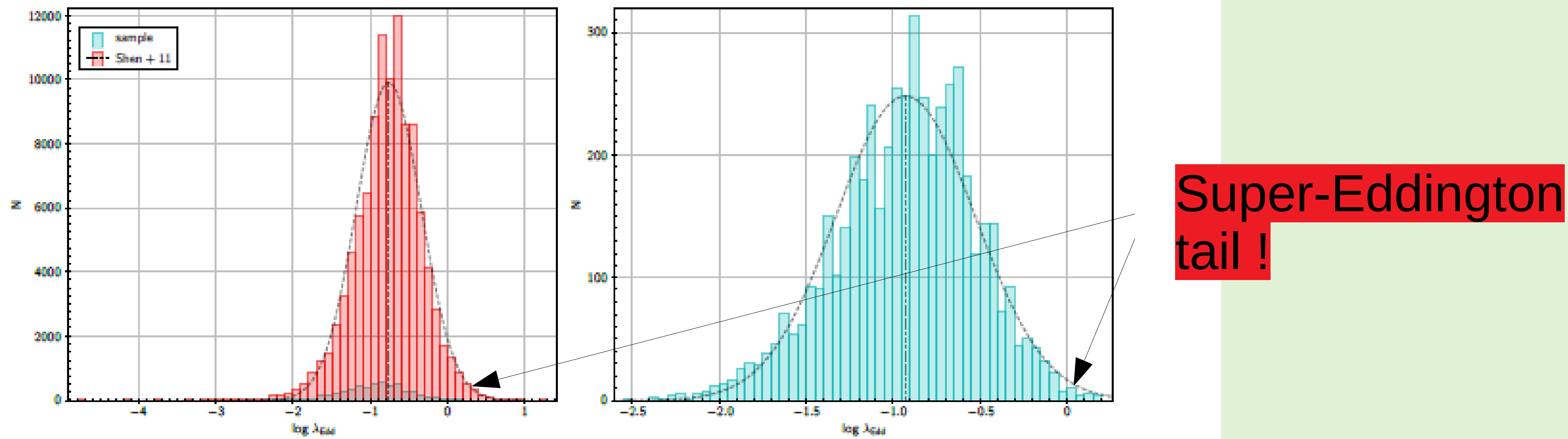


Figure 3. (a) Distribution of the λ_{Edd} from (Shen et al. 2011a) (in red). The error-limited sample (in turquoise) is shown underneath the whole distribution. The fitted gaussian has $\bar{x}$ = -0.769176, σ = 0.42134285. (b) An enlarged version of the error-limited sample. The fitted gaussian has $\bar{x}$ = -0.93127483, σ = 0.40046898.

Panda, Czerny et al. 2018

Quasars are by definition the brightest AGN so they do not cover low values, and peak on average at about 0.1. However, the higher accuracy sample shows somewhat less of the super-Eddington sources.

This poses a general question: how accurately we measure the Eddington ratio in AGN?

How Shen et al. did it? Black hole mass

$$\log\left(\frac{M_{\mathrm{BH,vir}}}{M_\odot}\right) = a + b\log\left(\frac{\lambda L_\lambda}{10^{44}\ \mathrm{erg\ s^{-1}}}\right) + 2\log\left(\frac{\mathrm{FWHM}}{\mathrm{km\ s^{-1}}}\right)$$

Monochromatic luminosity at adopted wavelength

Full Width Half Maximum of a chosen emission line

Mysterious coefficients

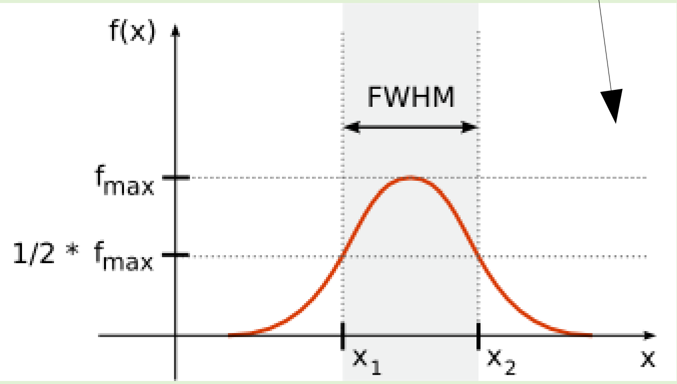
$(a, b) = (0.672, 0.61)$, MD04; Hβ

$(a, b) = (0.505, 0.62)$, MD04; Mg II

$(a, b) = (0.910, 0.50)$, VP06; Hβ

$(a, b) = (0.660, 0.53)$, VP06; C IV

$(a, b) = (0.860, 0.50)$, VO09; Mg II.



How Shen et al. did it? Black hole mass.

$$M_{\rm BH} = f\left(\frac{\Delta V^2 R}{G}\right)$$

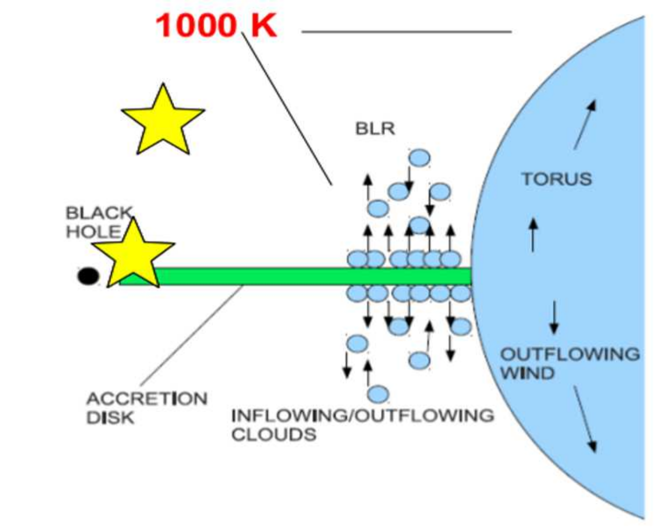
We thus need velocity, radius, and the virial factor to use the Keplerian motion for determination of a black hole.

For spherical distribution of the clouds f = sqrt(3)/2 (Netzer)

For flatter distribution of the BLR clouds:

$$f = \left[4\left(\sin^2 i + (H/R_{\rm BLR})^2\right)\right]^{-1}$$

(Collin et al. 2006) and depends on the viewing angle to an individual object…



Additionally, there is a discussion whether FWHM is a good measure of delta V, and many people favor dispersion sigma.

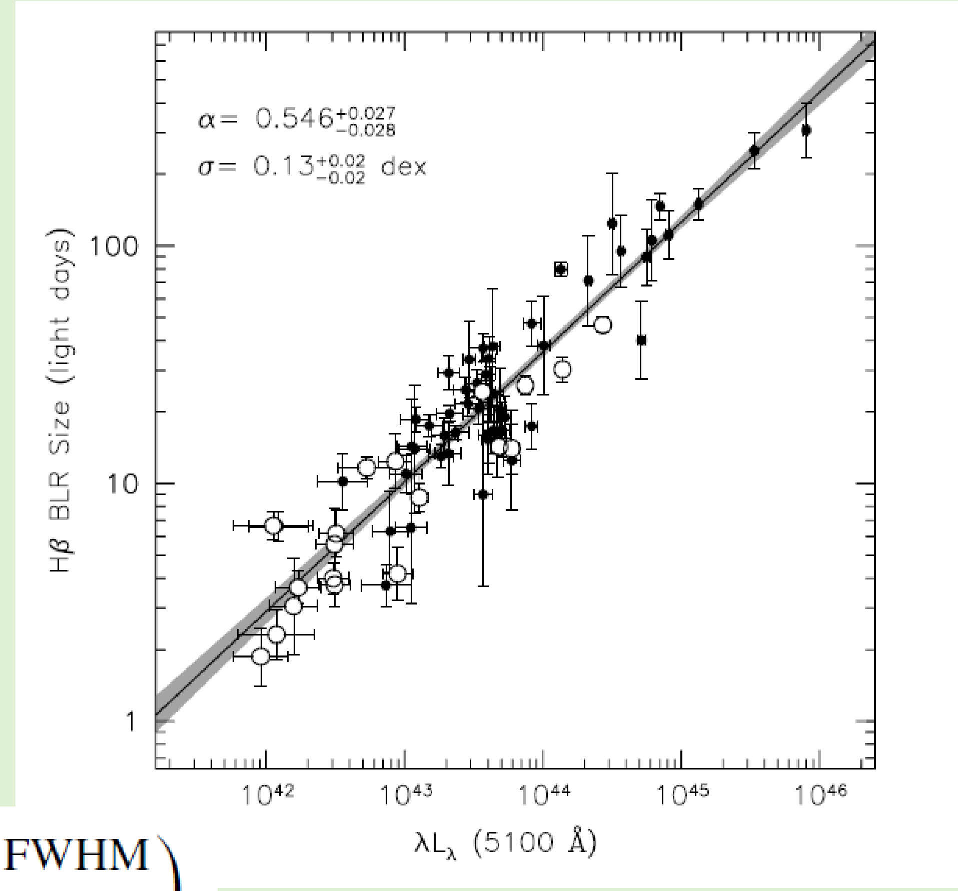
$$\log\left(\frac{M_{\rm BH,vir}}{M_\odot}\right) = a + b\log\left(\frac{\lambda L_\lambda}{10^{44}\,{\rm erg\,s^{-1}}}\right) + 2\log\left(\frac{\rm FWHM}{\rm km\,s^{-1}}\right)$$

How Shen et al. did it? Black hole mass.

$$M_{\rm BH} = f\left(\frac{\Delta V^2 R}{G}\right)$$

We still need radius. Here helps a discovery of the luminosity-radius relation (Peterson 1993, Kaspi et al. 2000). In the paper by Bentz et al. (2013) is looks like quite a tight relation:

$$\log(R_{\rm BLR}/1\ \text{lt-day}) = K + \alpha \log(\lambda L_\lambda/10^{44}\ \text{erg s}^{-1}).$$



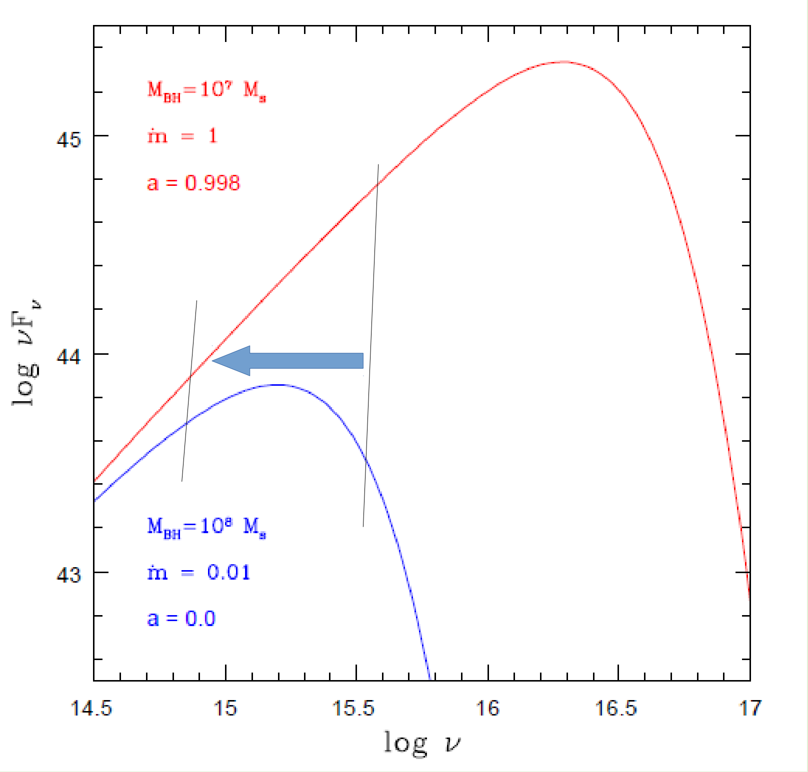
Combining the previous and the current page results we get indeed:

$$\log\left(\frac{M_{\rm BH,vir}}{M_\odot}\right) = a + b\log\left(\frac{\lambda L_\lambda}{10^{44}\ \text{erg s}^{-1}}\right) + 2\log\left(\frac{\text{FWHM}}{\text{km s}^{-1}}\right) \quad (2)$$

but the coefficents can be a matter of debate.

Why BLR radius should scale with the monochromatic flux?

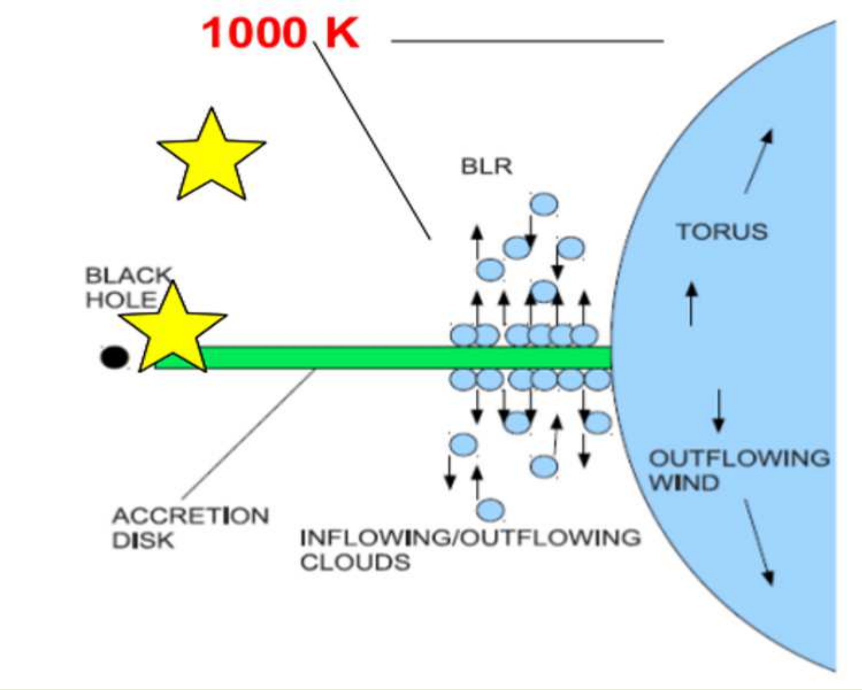
This observational statement is by no means clear. Previously it was expected that the BLR radius scales with the ionizing flux. Monochromatic flux is not the same even for the simplest (Novikov-Thorne) model of an accretion disk.



Two models with similar monochromatic flux but widely different bolometric luminosity and ionizing flux.

BLR radius can scale with the monochromatic flux - FRADO

We (Czerny & Hryniewicz 2011) developed a model of the BLR formation which is based on dust as a source of radiation pressure lifting up the material from the disk (FRADO – Failed Radiatively Accelerated Dusty Outflow). Such a model does predict the relation



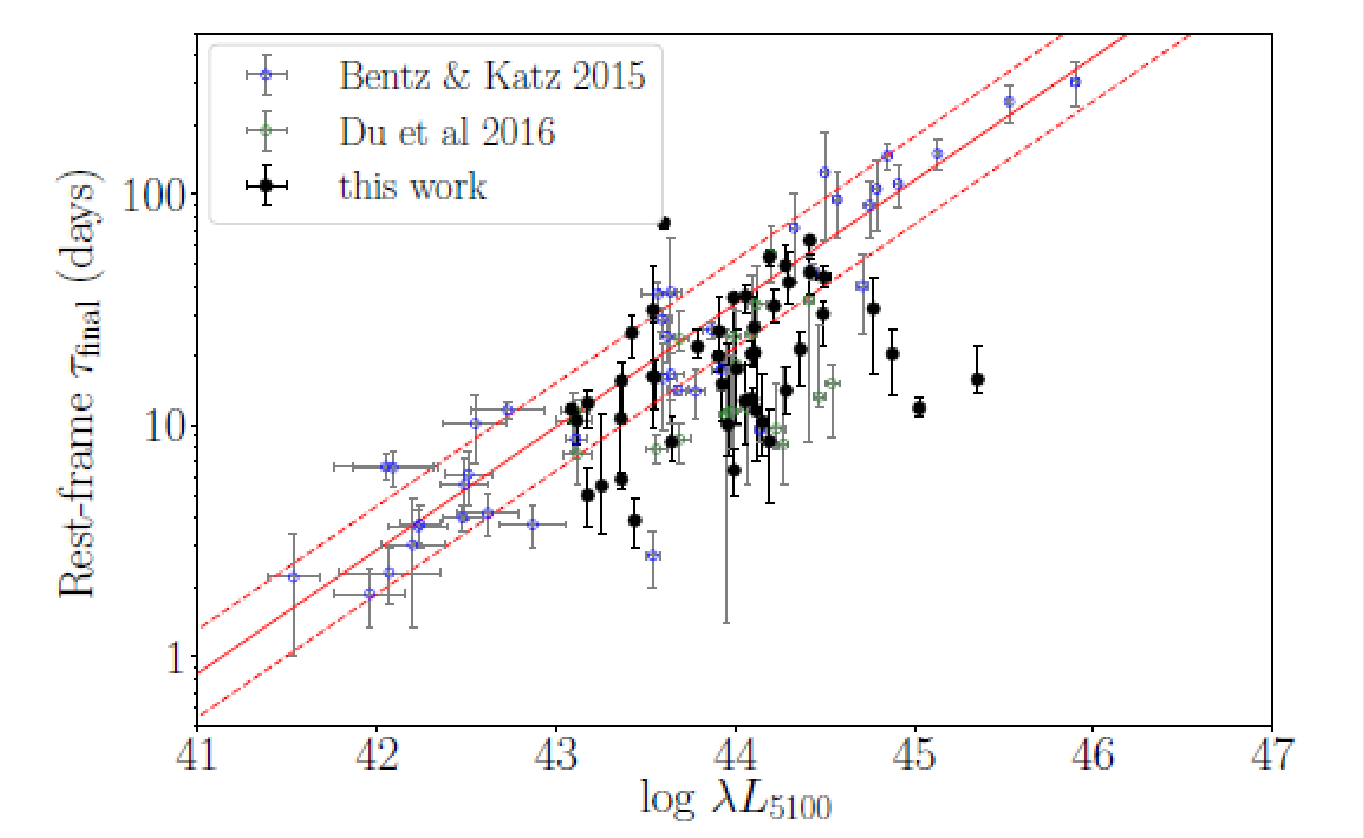
$$\log R_{BLR} = 1.47 + 0.5 \log L_{44,5100} \quad \text{[days]}$$

(Czerny et al. 2016)

Now the constant 1.47 depends on general on the dust sublimation temperature and the second coefficient is precisely 0.5 (accretion disk theory).

Recent problems

Most recent time delay observations from SDSS-RM do not support the size luminosity scaling:



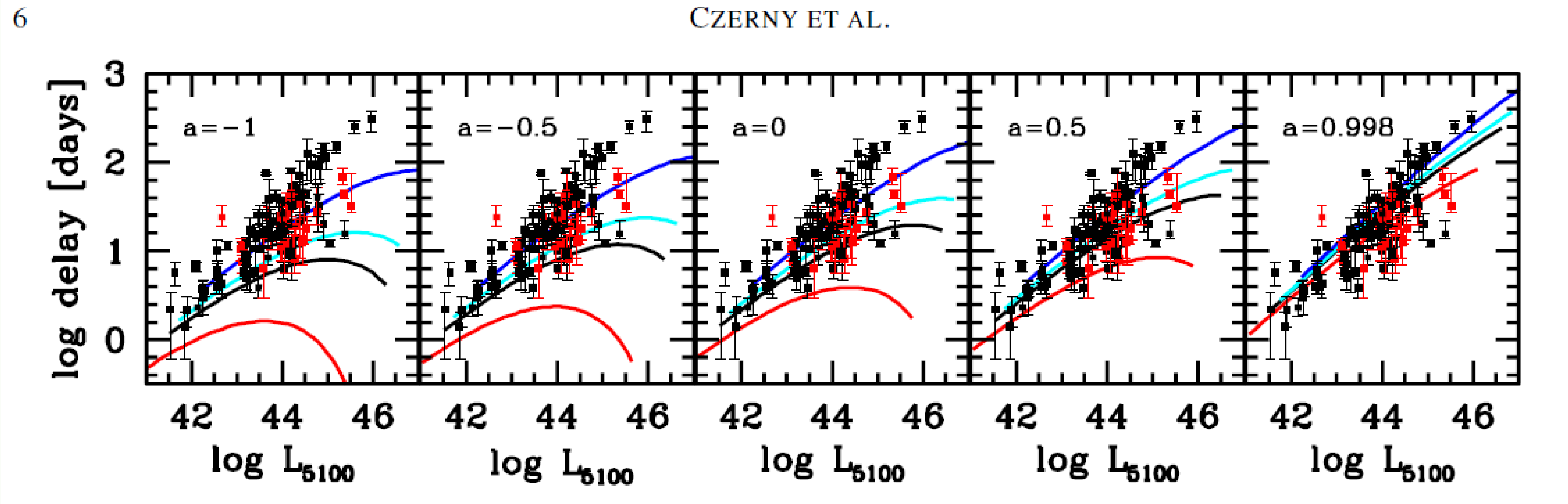
Some of the outliers are super-Eddington (?) sources (Du sample) but others are not.

This is a problem for the black hole mass measurement. Error on radius might be by a factor of 4.

Grier et al. (2017)

Recent problems

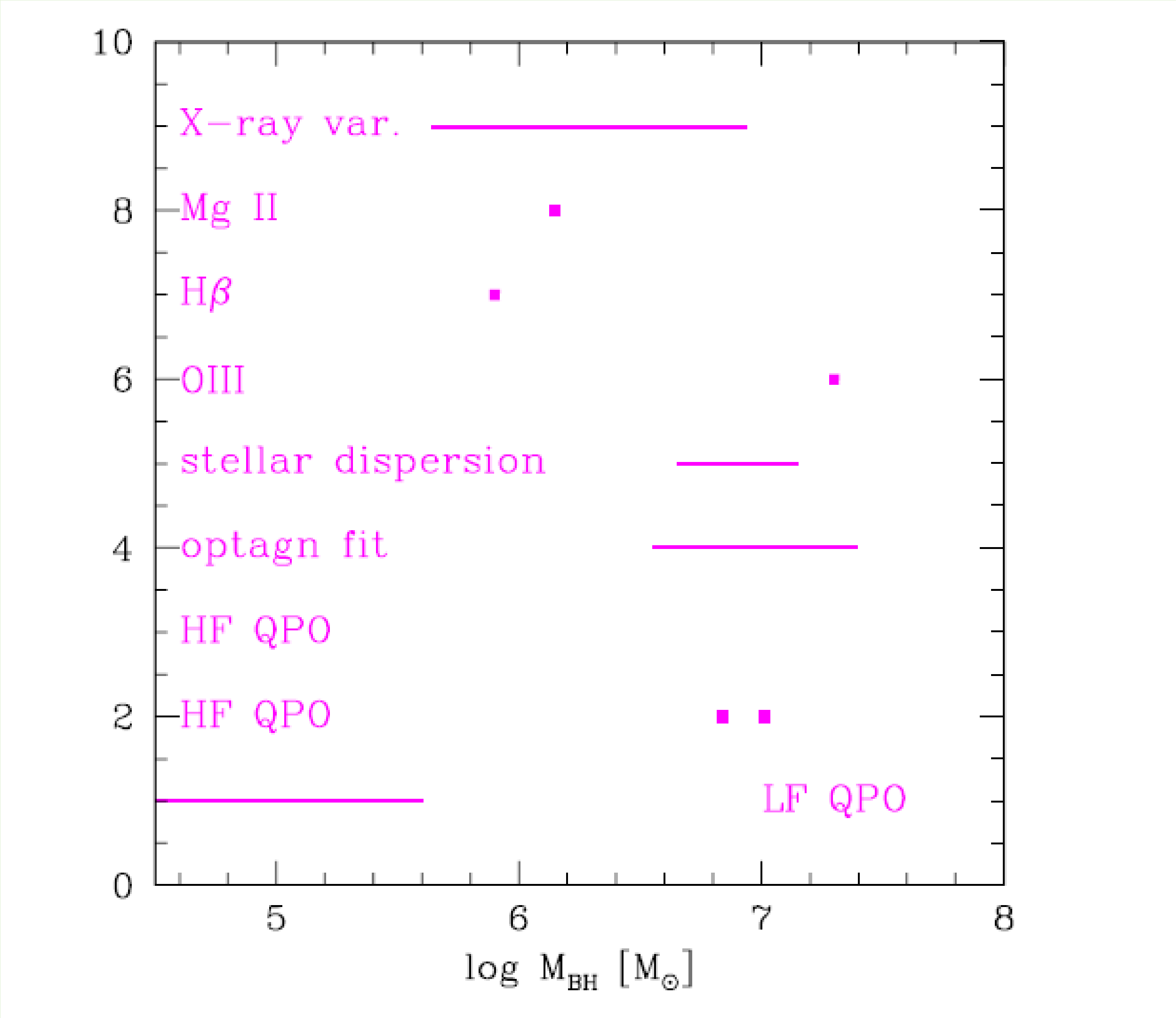
We can model this behaviour going back to the idea that BLR responds to the ionizing flux instead of being fixed by the reservoir of matter due to action of radiation pressure:



Czerny et al. 2018 (submitted)

But the problem of the black hole mass measurement remains, unless those time delays are measured incorrectly (too short campaign).

Independent tests of black hole mass determination



We attempted to determine the black hole mass in a NLS1 object RE J1034+396.

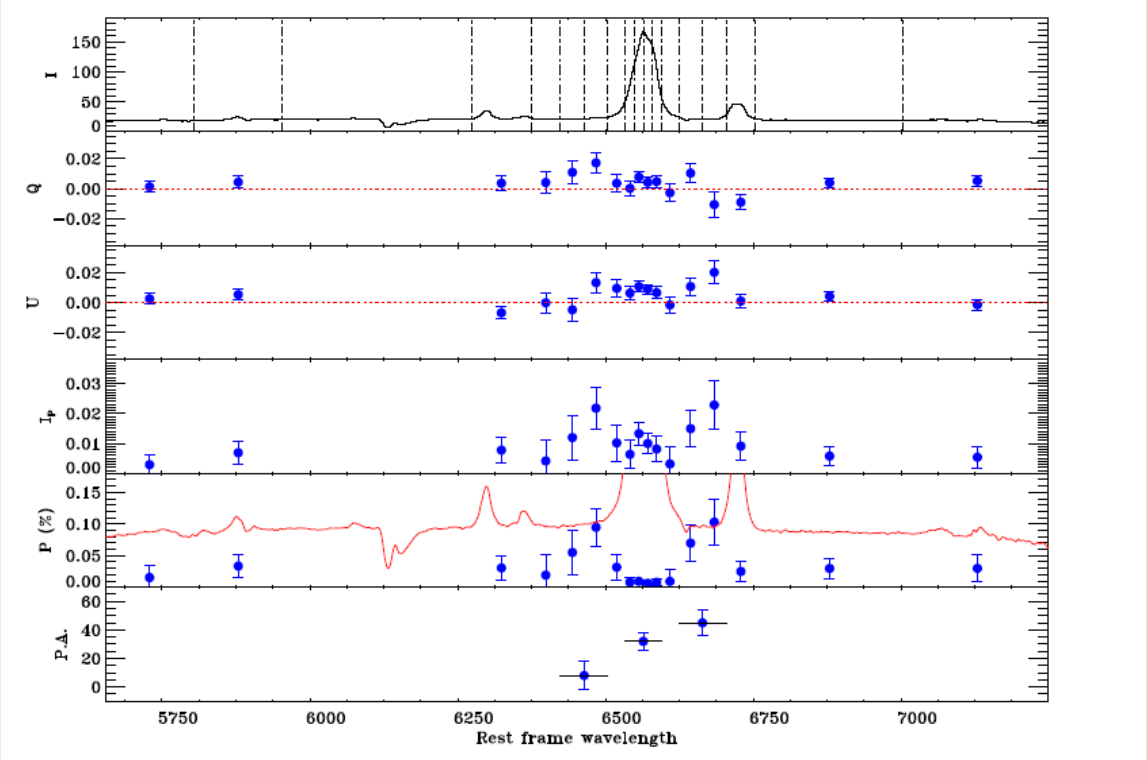
We see a range of results from 5.6 to 7.4 in log M. This is the uncertainty by a factor 8 with respect to the mean value.

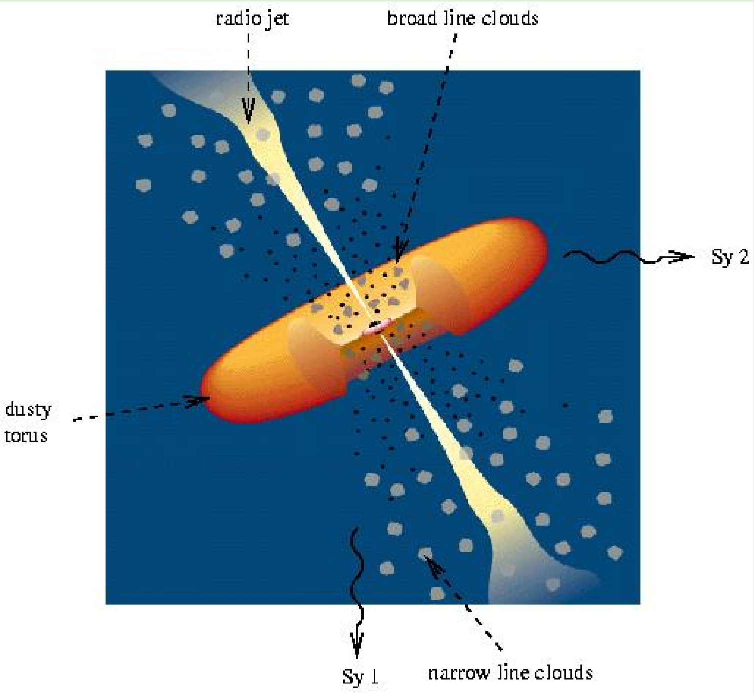
Reverberation measurement for this source of a time delay is still to come, the campaign is under way (Jian-Min Wang, private communication).

Czerny et al. (2016)

Other surprises in black hole mass determination

Viewing angle in AGN is limited by the torus. Turbulence decreases the dependence of the line width on the viewing angle but...





The line width of 1500 km/s in the unpolarized flux increased up to 9000 km/s when measured in polarized light. Mass revised by a factor 36 !

Baldi et al. (2016)

How Shen et al. did it? Luminosity

Observations of quasars in SDSS are done in a finite wavelength range, and precise determination of the luminosity is usually done close to the interesting line (monochromatic flux).

The bolometric luminosity is thus obtained assuming:

$L_{bol} = L_{5100}*9.26$

Or

$L_{bol} = L_{3000}*5.15$

or

$L_{bol} = L_{1350}*3.81$

Sometimes people measure the 2-10 keV flux in X-rays, and then calculate

$L_{bol} = L_{2\text{-}10\ keV}*27$

And this is it.

Observationally, this is based on the averaged broad band spectra *(Richards et al. 2006)*.

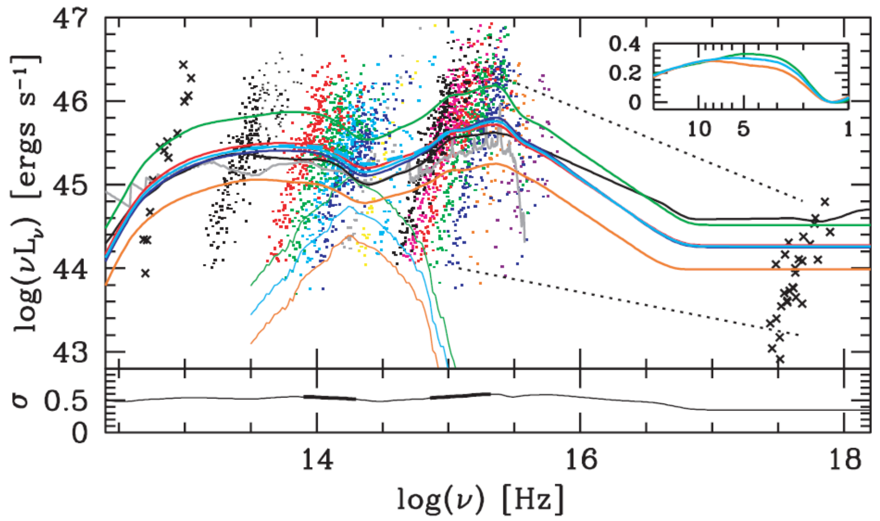


FIG. 11.—Mean quasar SEDs and the data used to construct them. The points show the data; the lines show the mean SEDs. From left to right: *black crosses*, MIPS70; *black points*, MIPS24/ISO15; *red points*, $S_{8.0}$; *green points*, $S_{5.8}$; *cyan points*, $S_{4.5}$; *blue points*, $S_{3.6}$; *gray points*, *K*; *yellow points*, *H*; *cyan points*, *J*; *black points*, *z*; *magenta points*, *i*; *red points*, *r*; *green points*, *g*; *blue points*, *u*; *orange points*, *n*; *purple points*, *f*; *black crosses*, X-ray. The dotted lines show the range of α_{ox} with luminosity for the luminosity extremes of our sample (Strateva et al. 2005). From top to bottom (at 10^{14} Hz) the thick solid lines are color coded as follows: *green*, optically luminous SDSS quasars; *red*, optically red SDSS quasars; *cyan*, all SDSS quasars; *blue*, optically blue SDSS quasars; *black*, Elvis et al. (1994) radio-quiet mean SED; *gray*, Hatziminaoglou et al. (2005) mean SED (normalized to Elvis et al. 1994 at 1 μm); *orange*, optically dim SDSS quasars. The near-IR luminous/dim composites are nearly identical to the optical composites. The thin green, cyan, and orange curves show the host galaxy contribution assuming $(L_{Bol}/L_{Edd}) = 1$ (see eq. [1]) for the elliptical galaxy composite spectrum of Fioc & Rocca-Volmerange (1997). The dashed cyan curve shows the effect of ignoring the host contribution. The inset at the upper right zooms in on the MIR region of the spectrum. The three curves are normalized at 1.3 μm, and the *y*-axis shows relative luminosity (νL_ν), while the *x*-axis is in microns. The bottom panel shows the 1 σ error array (dex) for our overall mean SED. Those frequencies where over 100 quasars contribute to the mean SED are shown as thicker line segments and are relatively unaffected by the gap-repair process.

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And this is it.

Theoretically, this does not make sense. The normalization of the disk spectrum at long wavelengths (i.e. monochromatic flux) depends on M*Mdot, while bolometric luminosity depends on Mdot and spin...

?

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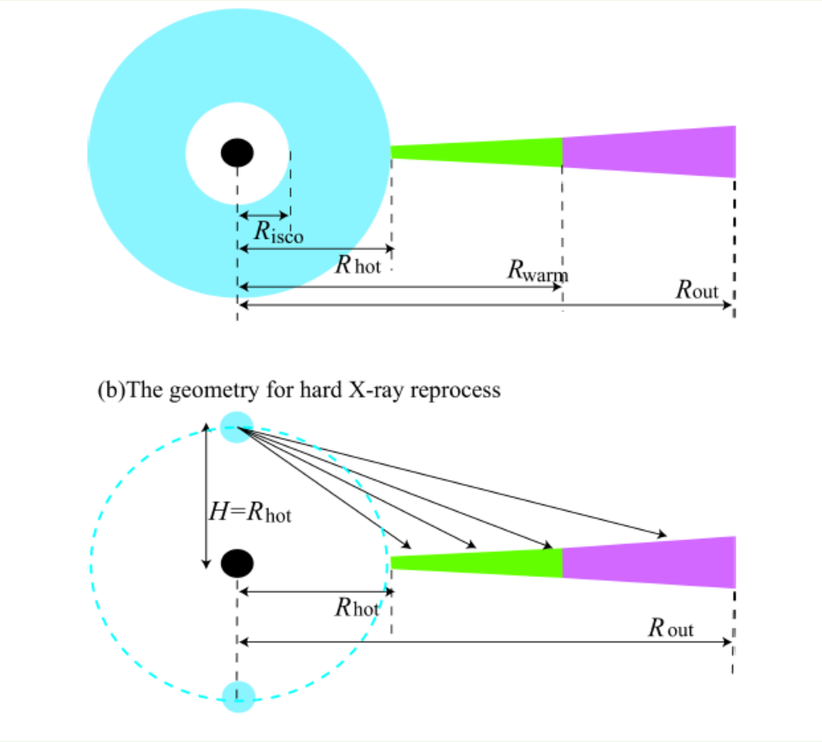
However, observationally motivated model of the Spectral Energy Distribution (SED) proposed by Kubota & Done (2018) contains three components
- compact corona
- warm corona (see Czerny et al. 2003, Rozanska et al. 2015)
- outer cold disk



All set for the Novikov-Thorne dissipation profile.

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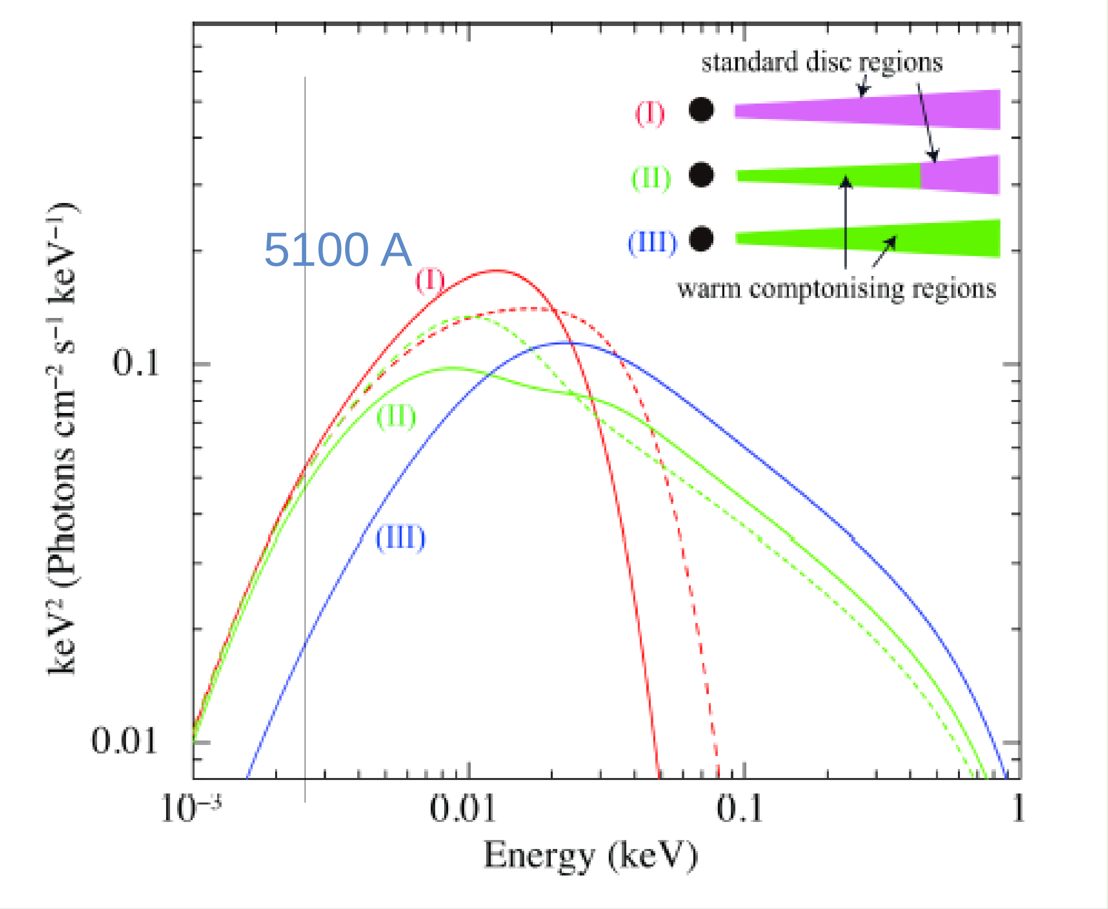


Few examples from Kubota & Done set for non-rotating black hole (a = 0).

Summarizing the Eddington ratio accuracy in AGN

On average for a single object:

Black hole mass – factor 3

Bolometric luminosity – factor 2

Together – factor 3.6

But in the case of particularly problematic individual sources it can be much worse !

The average values for large samples would depend on the systematic errors. Viewing angle, virial factor, bolometric correction – probably 50% to 100%.

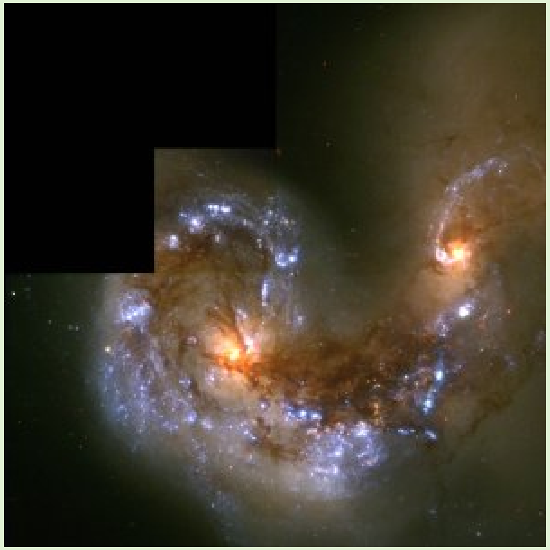
Uncertainty of Eddington ratio in other objects

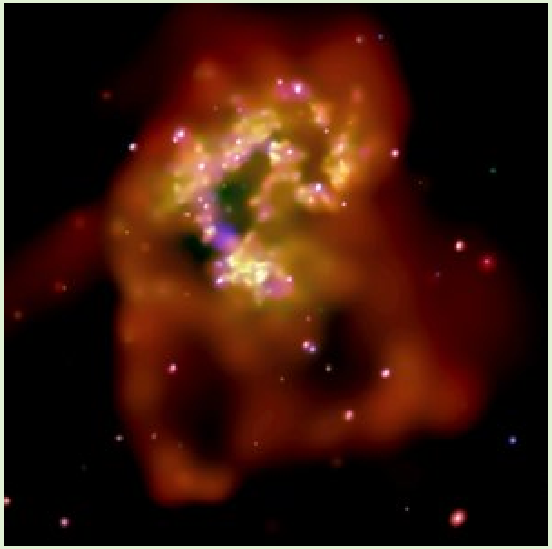
Uncertainty in AGN is in general not drammatic. The worst case is with Ultra-luminous X-ray sources (ULX).

Those are sources with luminosities between the values typical for ANG and typical for binary black holes.

Interpretation:

- Accretion onto intermediate black Hole mass object M_{BH} = 1000 – 10^5 M_s
- Super-Eddington accretion onto a neutron star or a 10 M_s black hole
- Beamed emission





ULXs in Antennae interacting galaxies

Periodic pulsations detected in some of ULX strongly suggest a neutron star (Bachetti et al. 2014)

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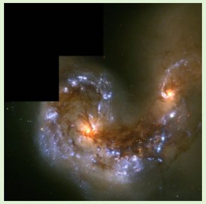
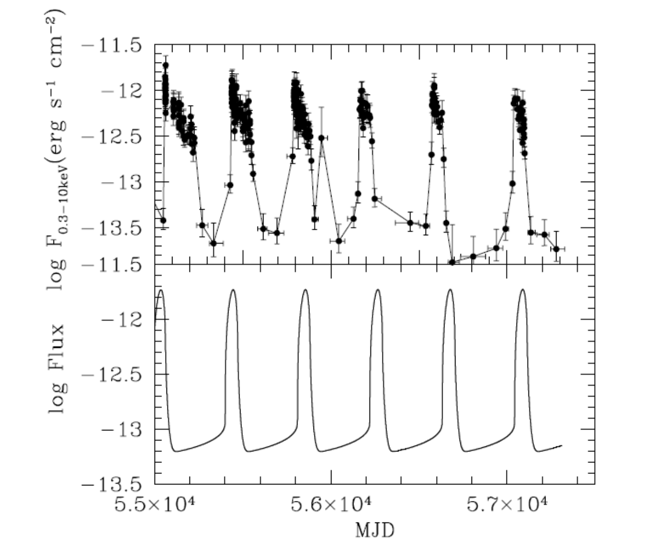
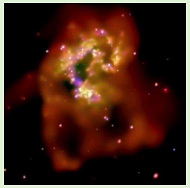
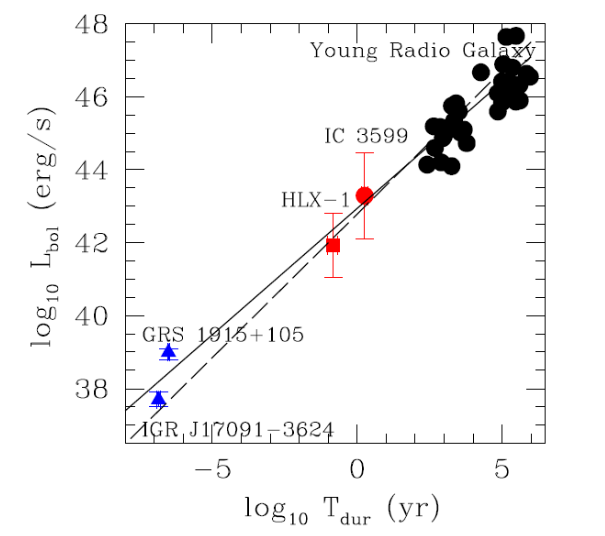






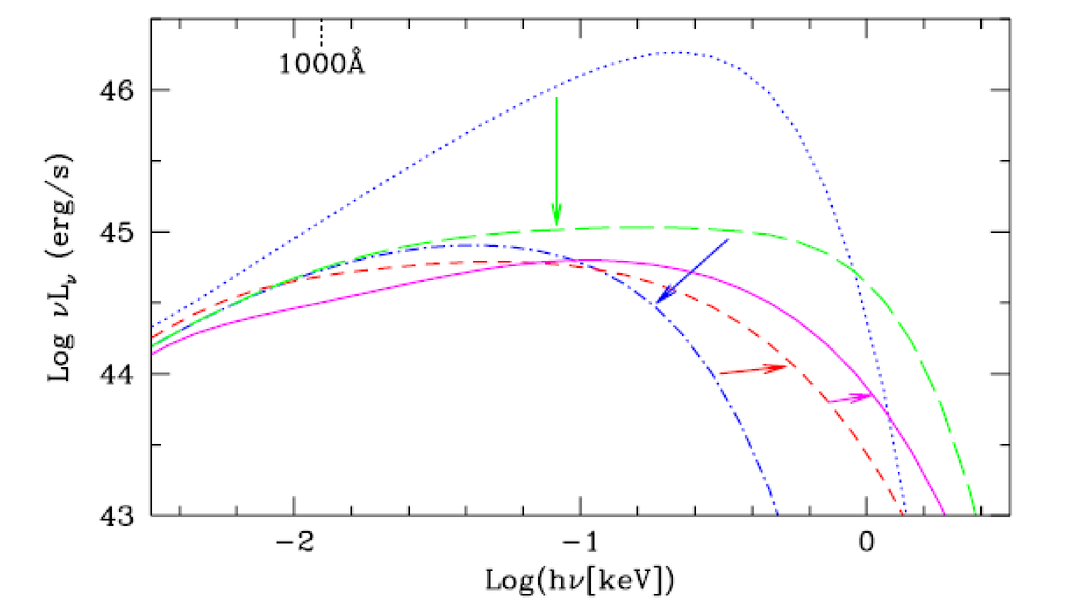


In HLX- 1 periodic outbursts in timescales of 400 days suggest an IMBH with M_{BH} = 10^5 Ms (Wu, Czerny et al. 2016).

Why do we care about the Eddington ratio?

- The transition from standard to slim disks happens at L/L_{edd} = 0.3, and the disk spectrum becomes redder

Kawaguchi (2003)



AGN spectra are frequently redder, but another reason for that can be extintion, magneticaly-driven or line-driven outflow, or warm corona….

- Super-Eddington accretion in general leads to outflows

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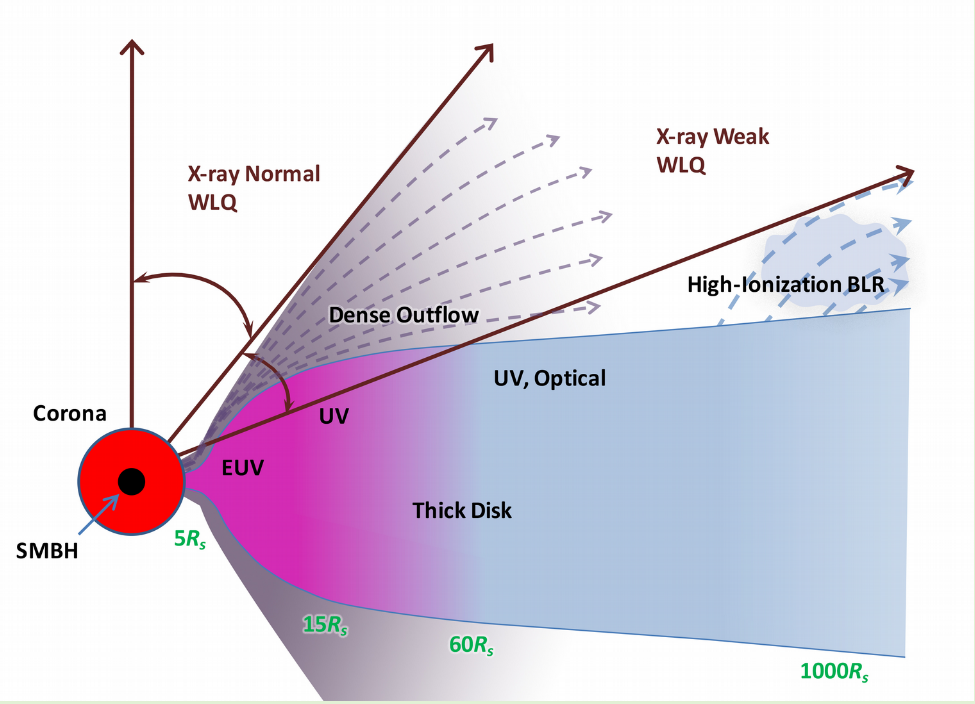

- Super-Eddington accretion in general leads to outflows

In ion tori or slim disks there is a force balance perpendicular to the disk surface, but the tangential part of the radiation pressure will still power some outflow

Summary

- Observational determination of the Eddington ratio in AGN is still uncertain by a factor of a few (at least)
- Consistent development of the theory as well as methods of black hole mass determination are necessary since the mechniasms of modification of optical/UV AGN slope are highly degenerate