



Spectral lines and supermassive black hole mass measurements

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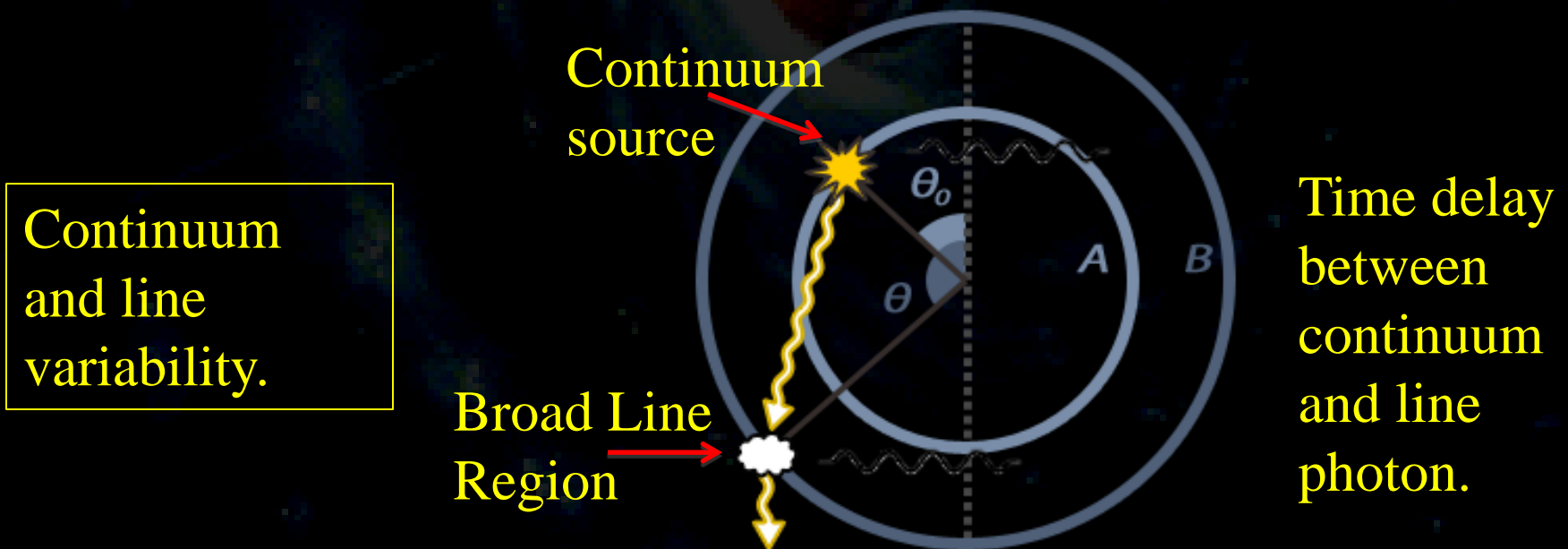
**12 SCSLSA, SS: AGN VARIABILITY
DEVOTED TO A. I. SHAPOVALOVA**

- 50 papers, 25 in leading astronomical journals
- Afanasiev, Popović, Shapovalova 2019, MNRAS, 482, 4985
- Shapovalova, Popović, Afanasiev, Ilić, Kovačević et al. 2019, MNRAS, 485, 4790 (NGC 3516 – just appeared)



Monitoring programs - size of the BLR, geometry of the BLR

- Monitoring programs (see e.g. Shapovalova+, Popovic+ 2008–2014)
 - reverberation mapping
 - based on the assumption that the BLR gas is photoionized by continuum



Alla's monitoring program - Observations

- 6m + 1m telescopes - SAO RAS (Russia)
- 2.1 m telescope - Guillermo Haro Observatory, Cananea, Sonora, Mexico
- 2.1 m telescope - Observatorio Astronómico Nacional, San Pedro Martir, Baja California, Mexico



Long-term monitoring

All AGN

- PIs: Alla I. Shapovalova (Russia)
- constantly observing well known AGN:
 - NGC 5548 – 9 years (Shapovalova+ 2004, Ilić 2007, Popović+2008)
 - NGC 4151 – 11 years (Shapovalova+ 2008, 2009, 2010a)
 - NGC 7469 -20 years (Shapovalova + 2017)
 - 3C390.3 – 13 years (Shapovalova+ 2010b, Popović+ 2011, Jovanović+ 2010)
 - Arp 102B – 12 years (Shapovalova+2013, Popovic+ 2014 , A&A)
 - Ark 564 – 11 years (Shapovalova+ 2012, ApJS)
 - OSO E1821+643 -24 years (Shapovalvova+2016)
 - NGC 3516 -22 years (Shapovalova + 2019)
- Study of variability: continuum flux, line shapes, line fluxes ...

Long-term monitoring

Sy 1

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Long-term monitoring

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Long-term monitoring

Binary
AGN

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Long-term monitoring

CLAGN

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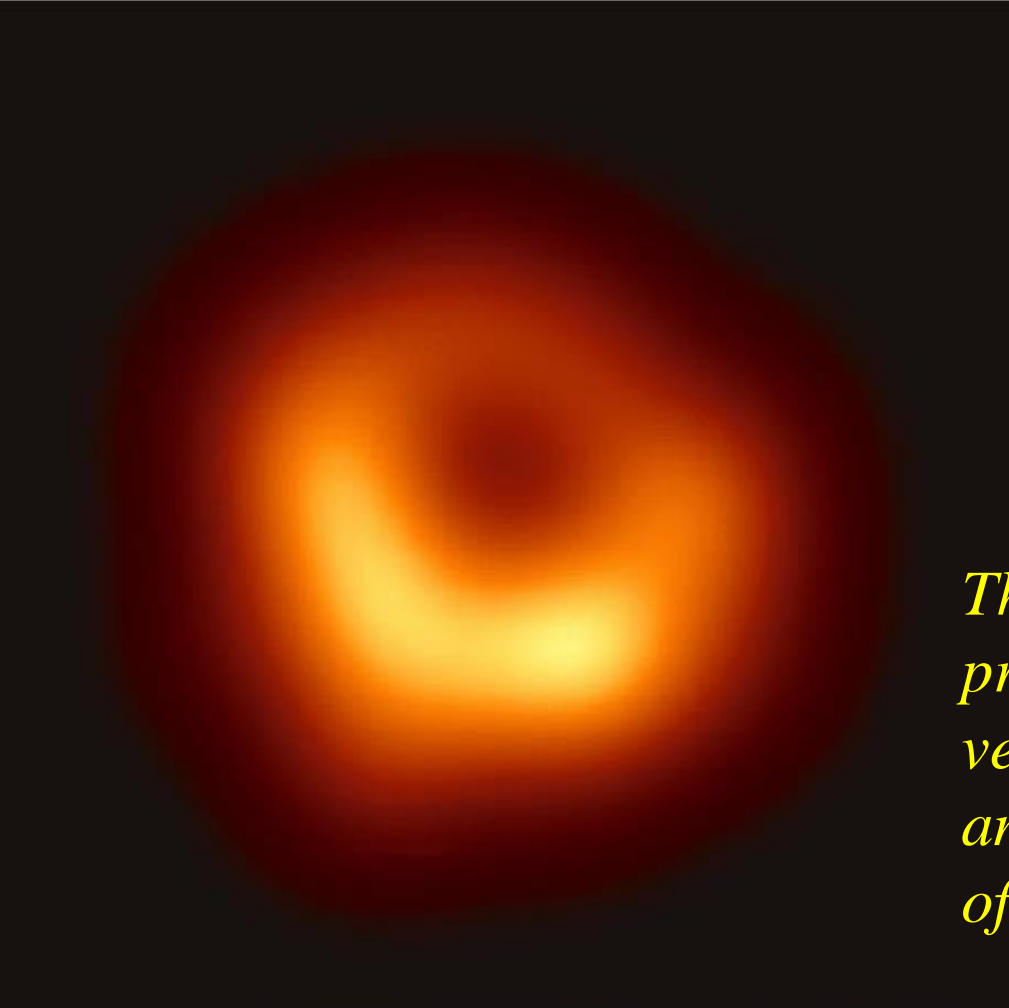
Long-term monitoring

BH mass
measurement

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Measure SMBH masses, why?

AGN – M87



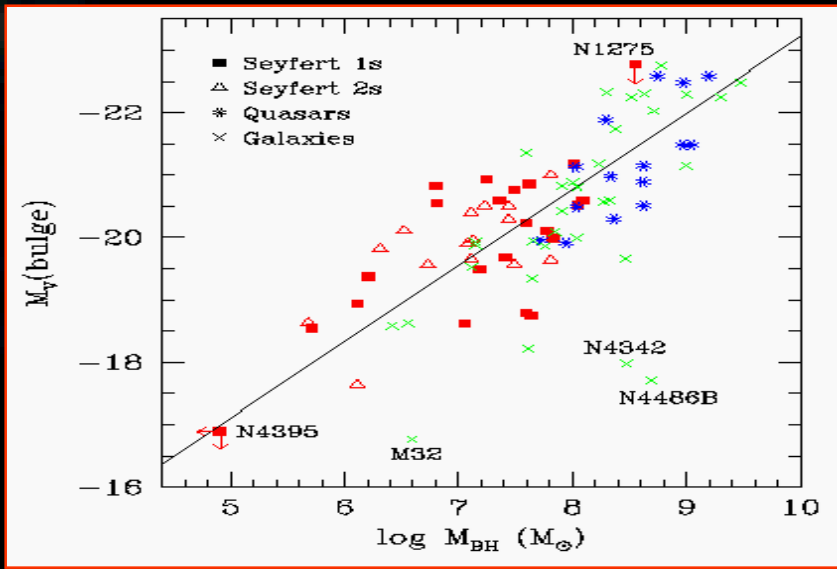
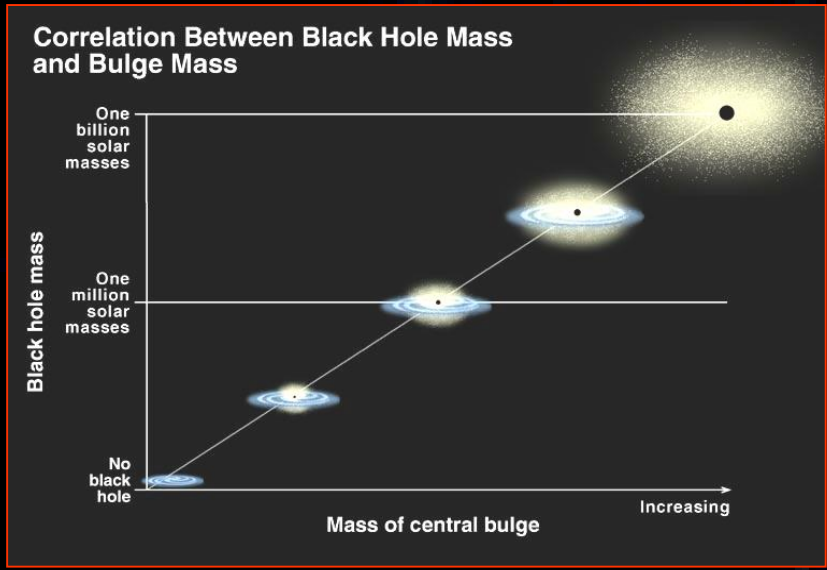
The Event Horizon Telescope project, researchers captured the very first image of a black hole, and it's the beast lurking in the core of galaxy M87.



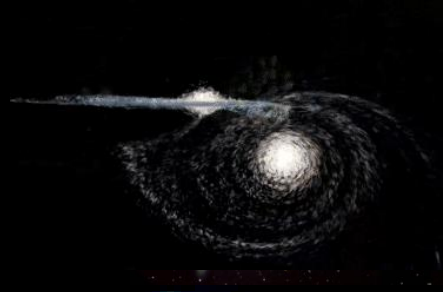
Black Hole - Bulge Relation

$$M_{\text{BH}} = 0.2 \% M_{\text{bulge}}$$

$$M_{\text{BH}} \propto M_{\text{bulge}}^{1.74}$$



Coevolution of black holes and galaxies



- Galaxy merger



- Normal galaxy

Hierarchical growth



Gas inflows



Galaxy formation and evolution



AGN feedback

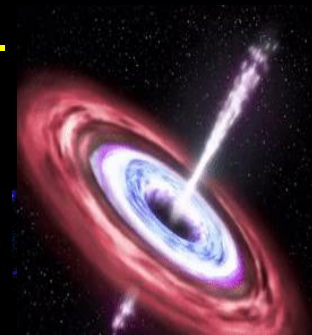
- Starburst and AGN starting phase



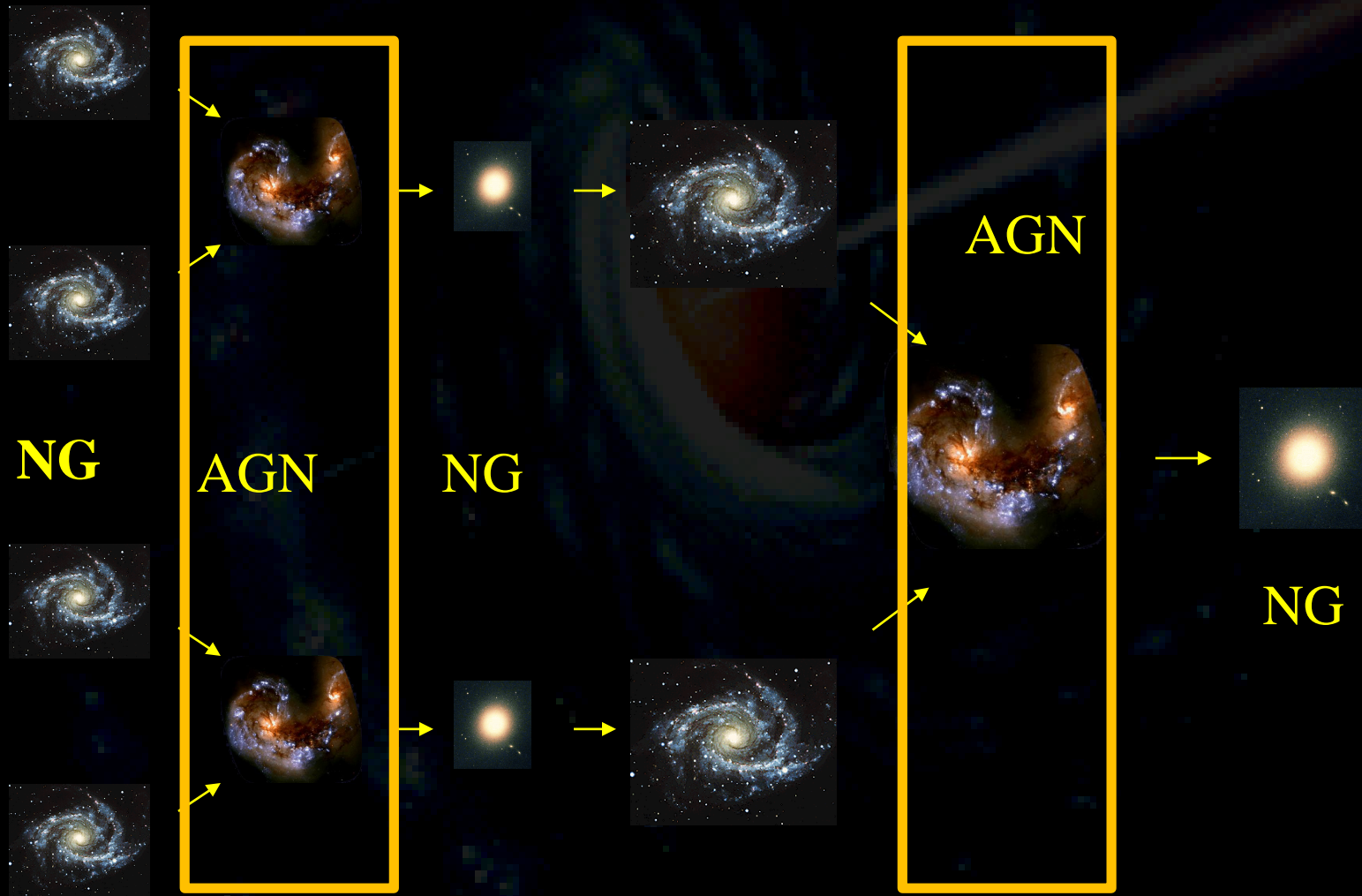
Growth of BH



- AGN - quasar



Hierarchical Galaxy Formation

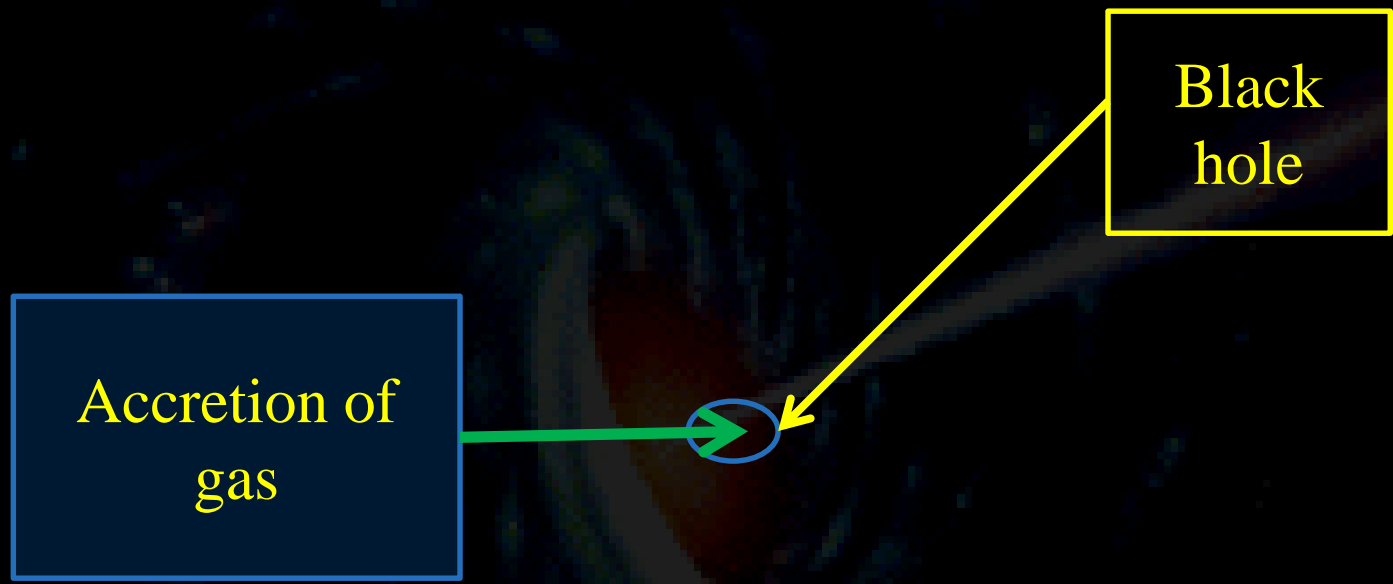


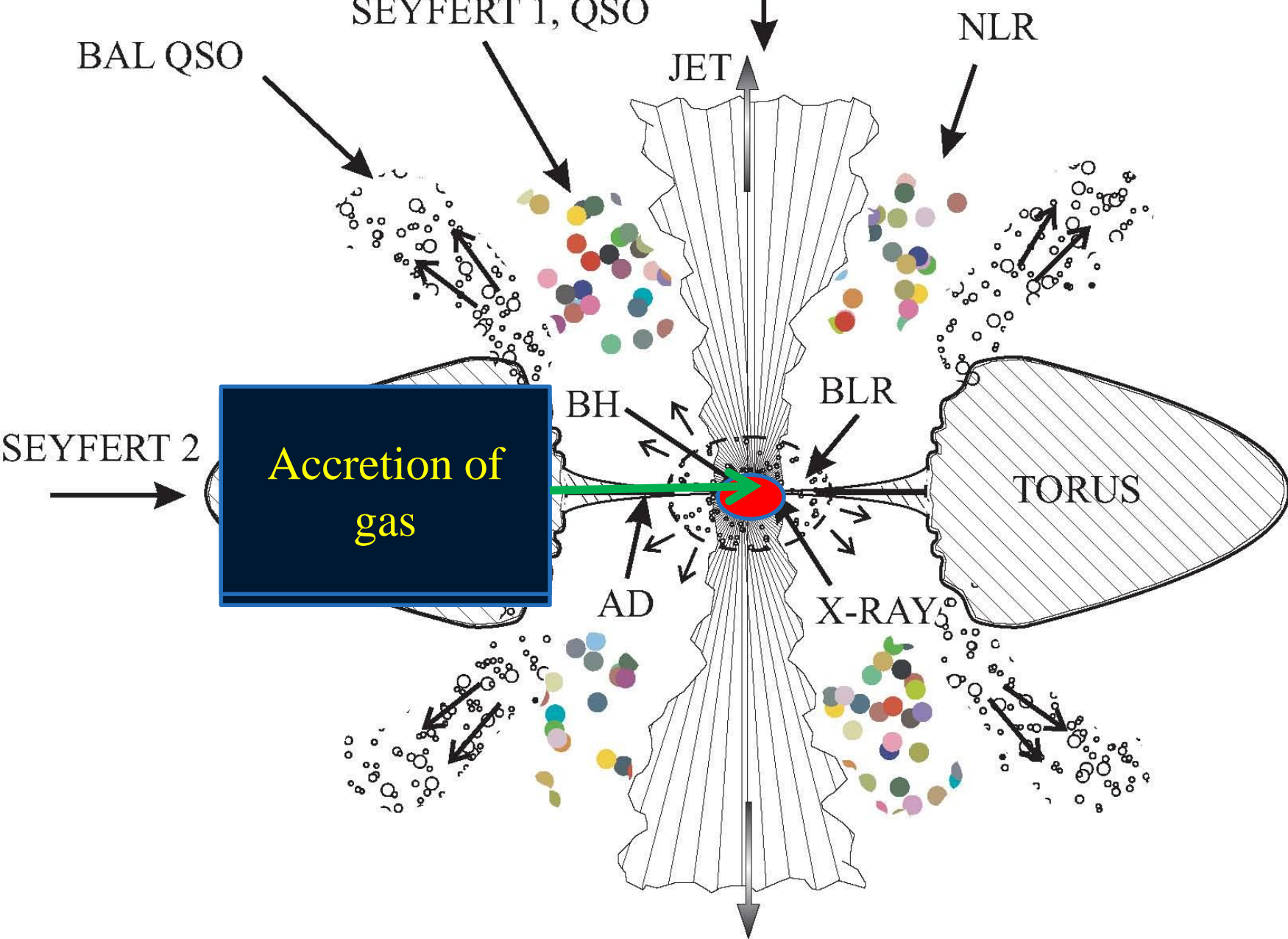
AGN phase is very good for
SMBH measurements, why?

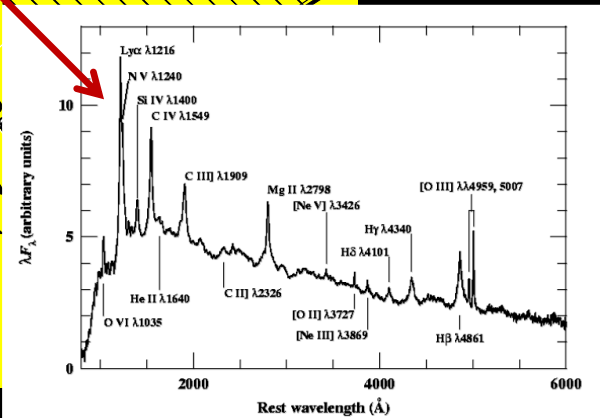
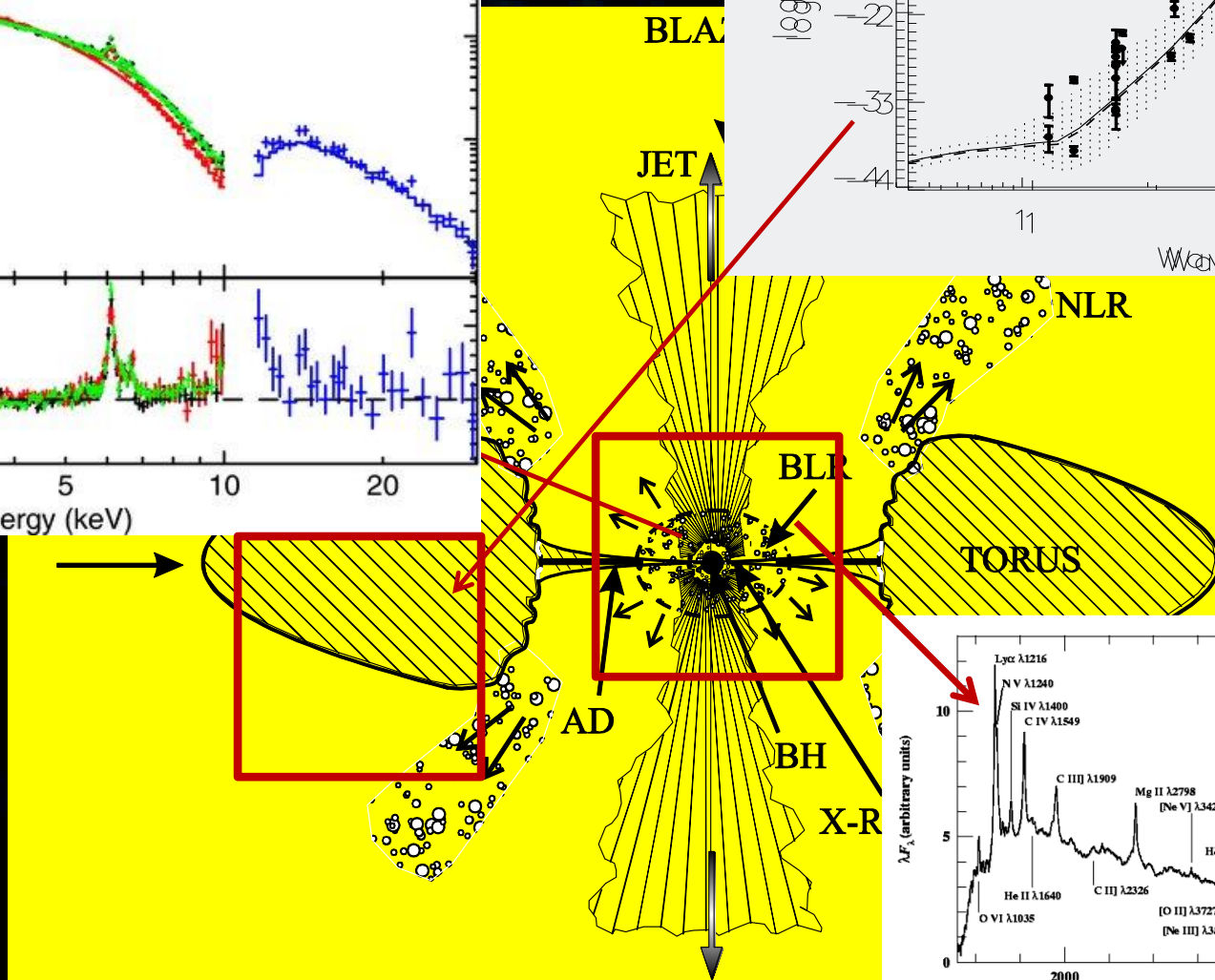
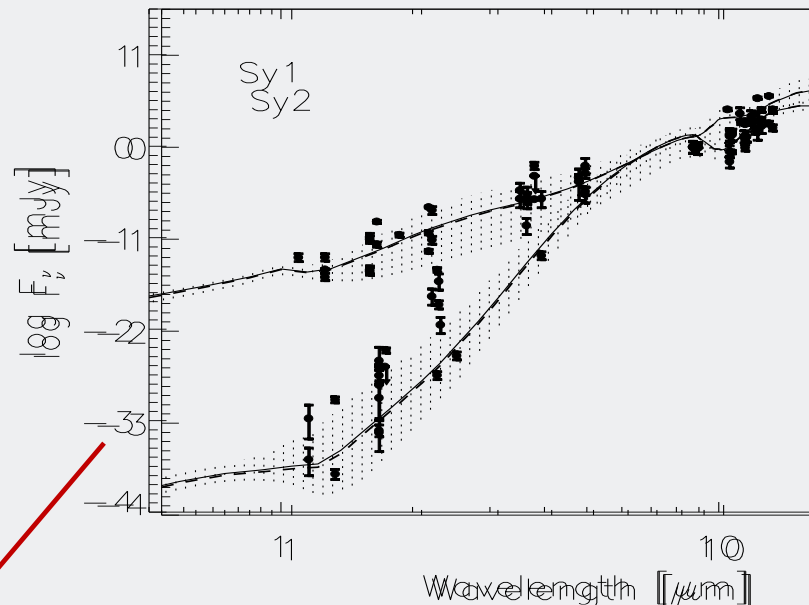
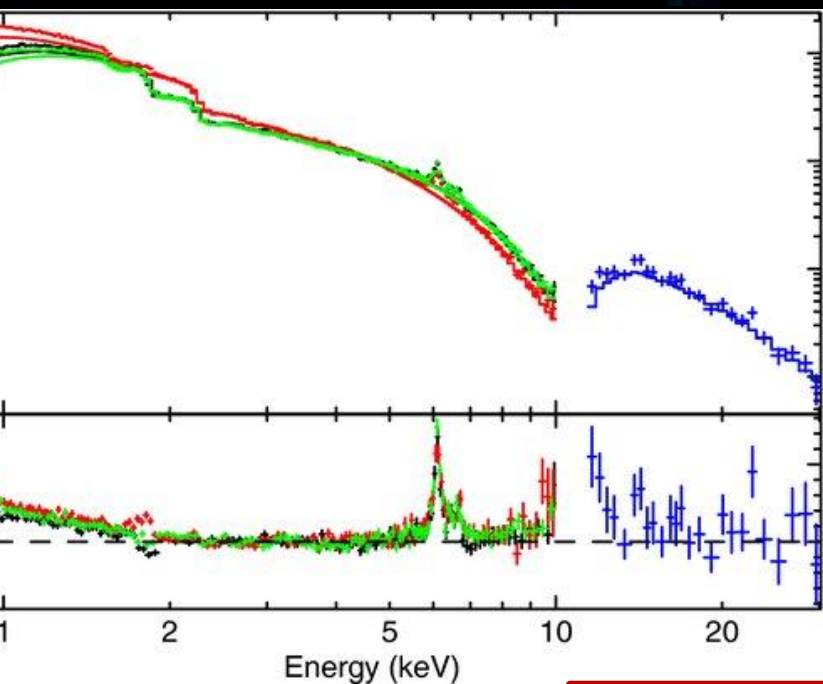
What is an AGN?

- AGN = central SMBH + gas

AGN model - unification





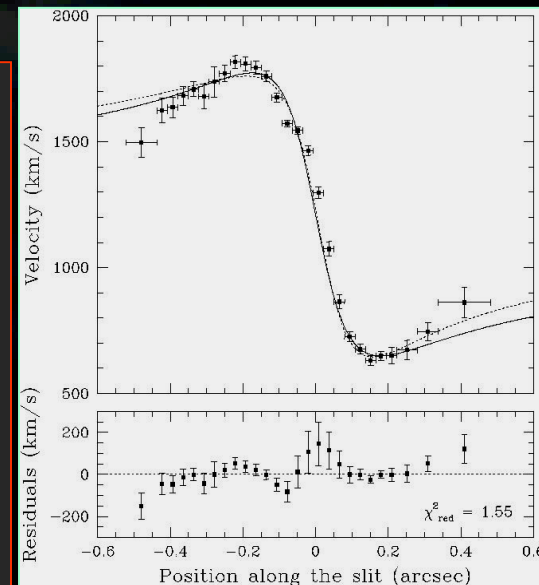
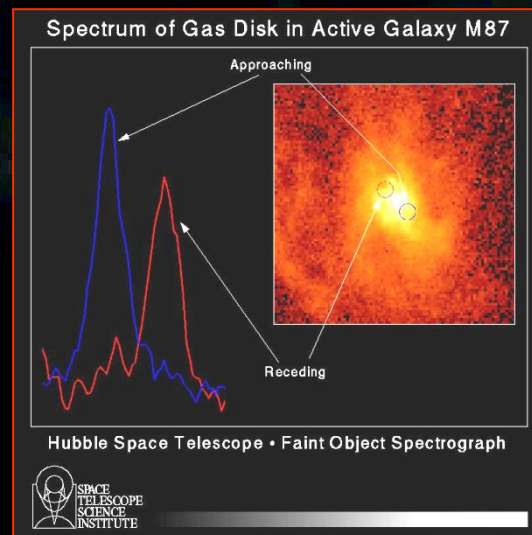
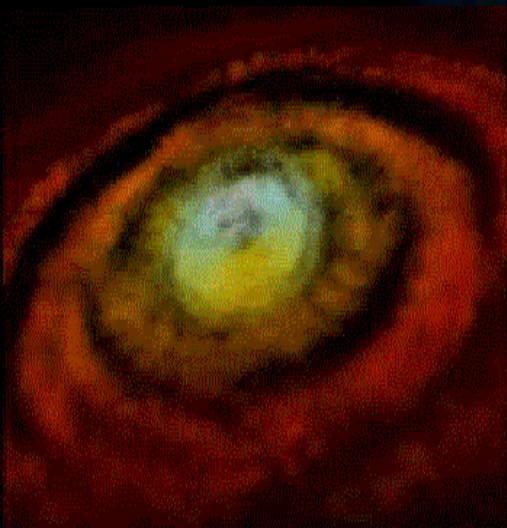


Spectral lines & SMBH mass measurements

- X-ray, Fe $K\alpha$ line
- UV/Optical spectral band – a number of broad emission lines which are emitted from broad emission region (BLR)

Measuring the mass of SMBH in AGNs

- Several methods (stellar dynamics, gas dynamics, masers, reverberation): Direct and indirect (see Peterson 2014 SSRRev)
- Line shift and width as indicator of gas motion



To measure the black hole mass –
virialization: M vs. R , v



$$v = \sqrt{\frac{GM_{BH}}{R_{EC}}}$$

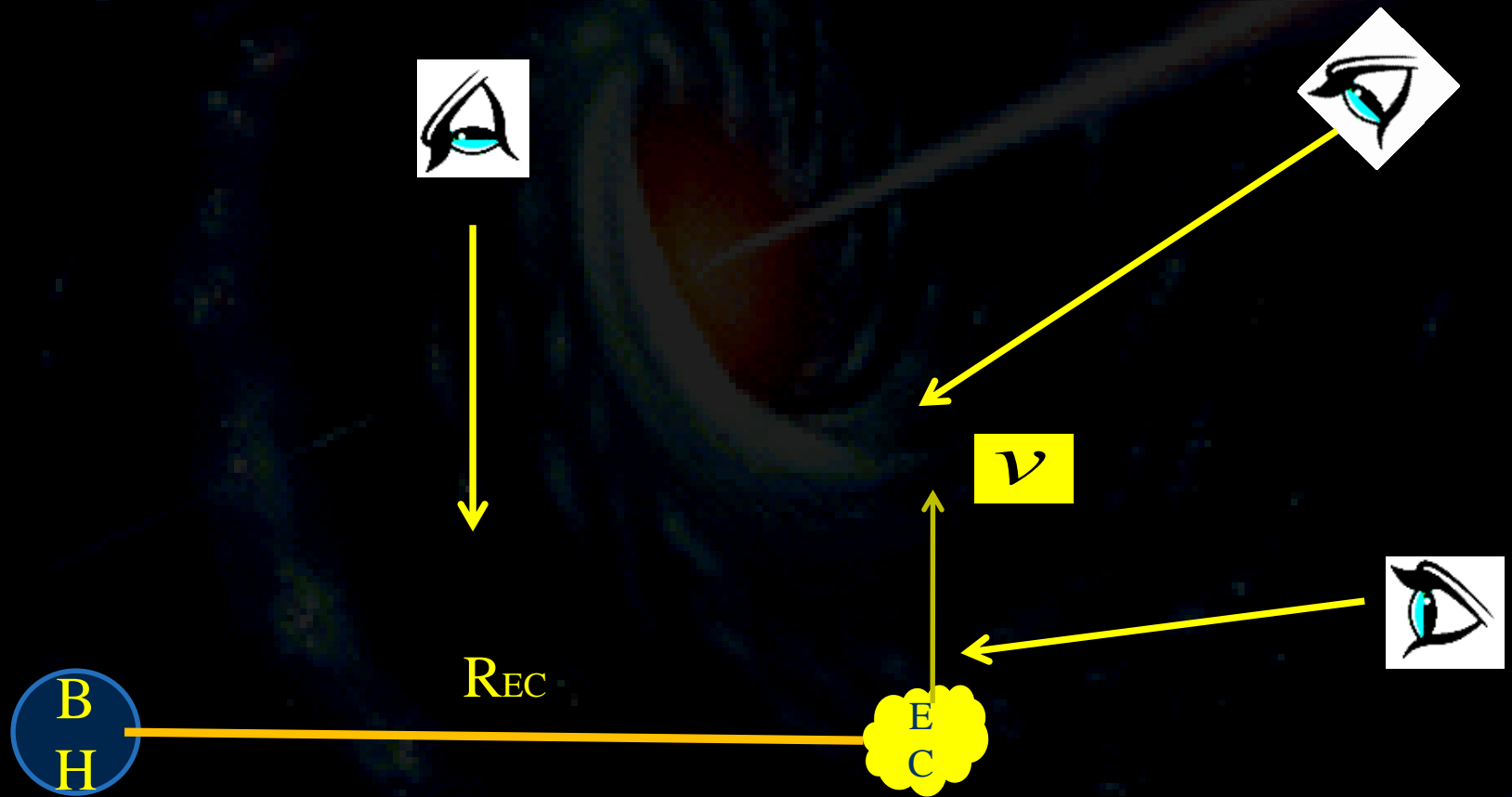


$$M_{BH} = \frac{R_{EC}v^2}{G}$$

First ideas from 1970s and 1980s

- Single-epoch measurements (Dibai ideas, see Bochkarev & Gaskell 2009, *AstL* 35, 287)
- Connect the line width with velocity and find line emitting radius using time lag between continuum and broad line flux variability -reverberation (see Peterson 1993 *PASP*, 105, 247)
- Present status: Several groups & several telescopes (reverberation in different spectral bands)

Problems: measuring Rec and velocity => inclination



Broad emission lines (BLR) - reverberation

Very close to the Black hole

Virialization: $R_{BLR} \sim c\tau$, τ – time lag

between continuum and line flux

line widths \sim rotational velocity

$$M_{BH} = f \frac{R_{BLR} v^2}{G}$$

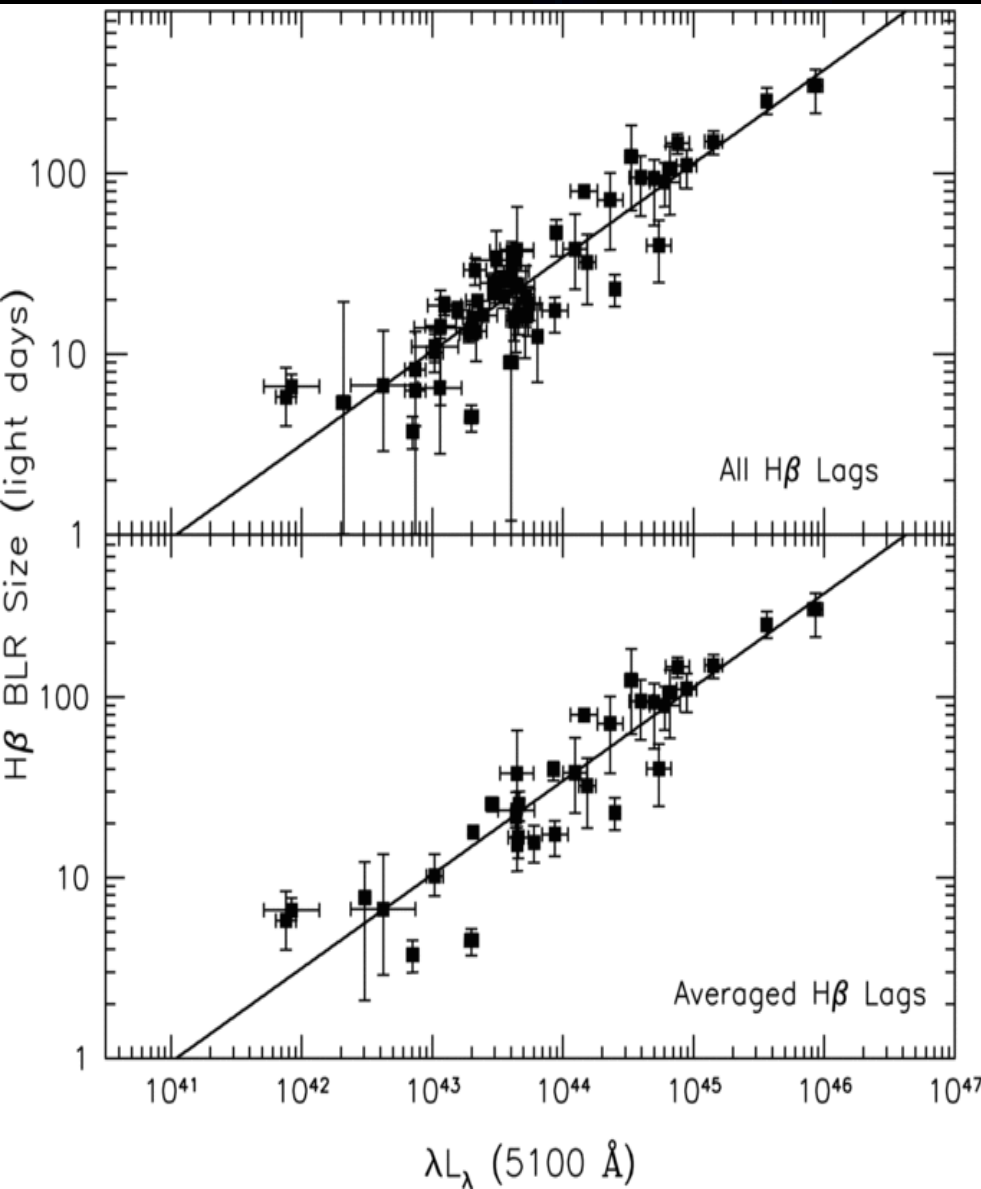
calculated from broad line widths

Dimensions of BLR => reverberation

Geometry, orientation of BLR

Reverberation

- Find the relation between R_{blr} and L_{cont}

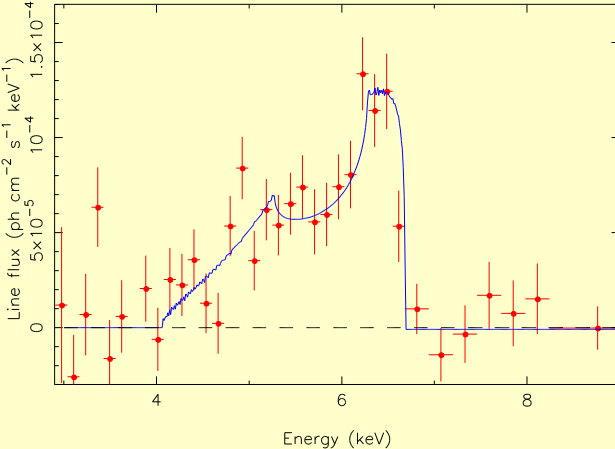


To find f coefficient, then from single epoch observation we can estimate SMBH! Only to measure L_{cont} and FWHM of broad lines, see e.g. Bentz et al. 2009

$$\log(R_{\text{BLR}}) = K + \alpha \log(\lambda L_{\lambda}(5100 \text{ \AA})),$$

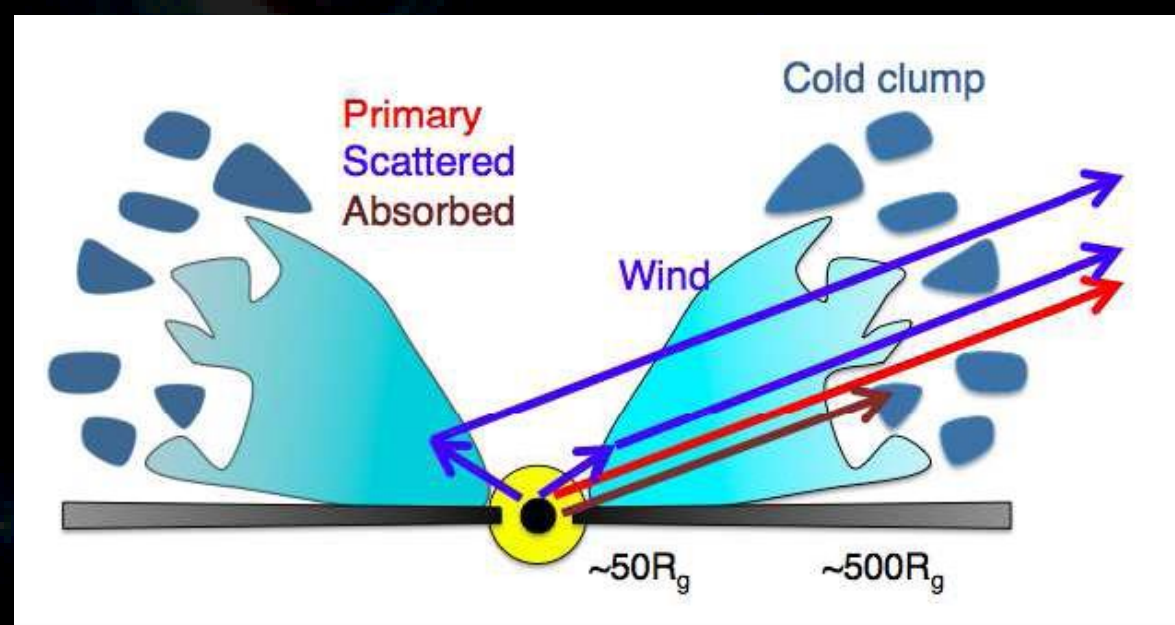
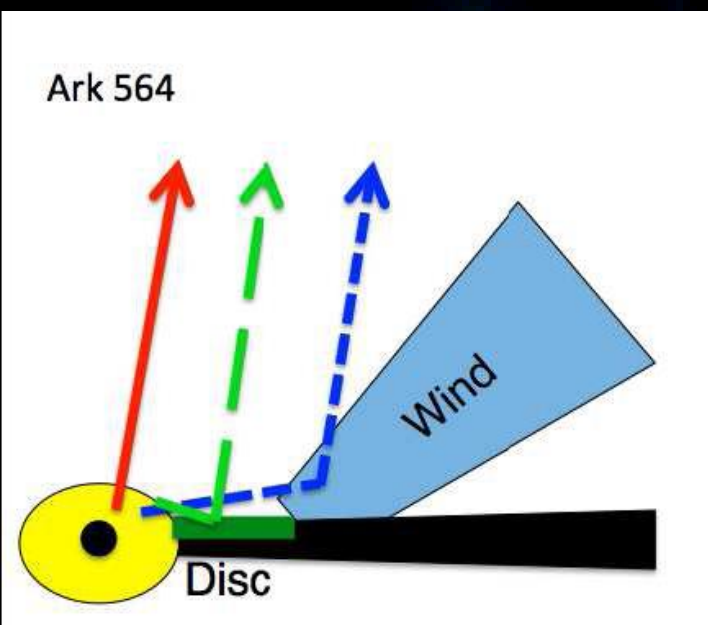
Loli Martínez-Aldama et al. 2019, cosmological application

Reverberation in different lines – different dimensions, different problems



E.g. broad Fe $K\alpha$ spectral line (e.g. Mizumoto et al. 2019, MNRAS)

Short timescale lags around $\sim 5 R_g/c$



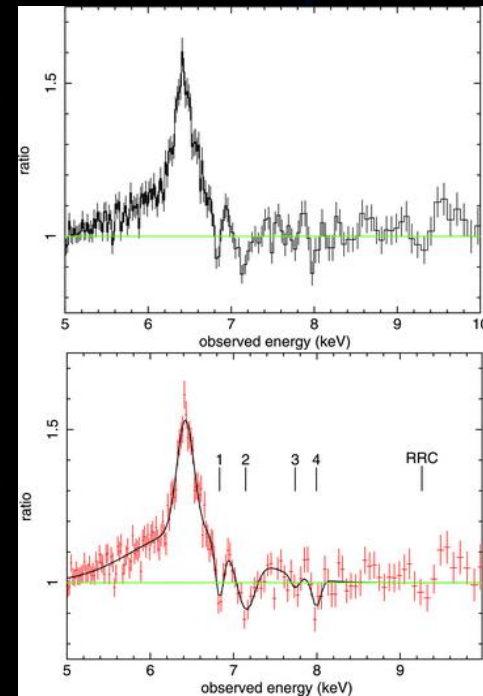
Broad Fe $K\alpha$ spectral line - reverberation

Several works (see Ballantyne et al. 2005, Miller et al. 2010ab, Legg et al. 2012, Frederick et al. 2018, Lobban et al. 2018, Chainakun et al. 2019, etc.), see Uttley et al. 2014, A&Arv,22 for more details

Short lags are likely to be produced by a fast ($0.2c$) outflowing, highly ionised wind at $50 - 100 R_g$ (see Mizumoto et al. 2019)

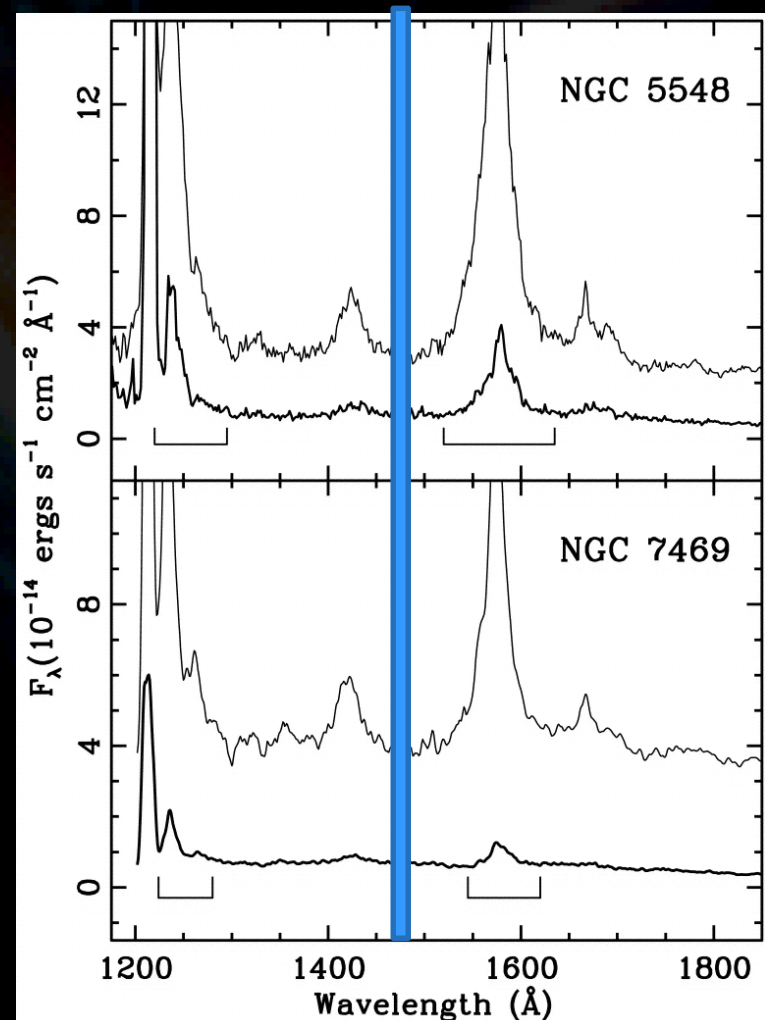
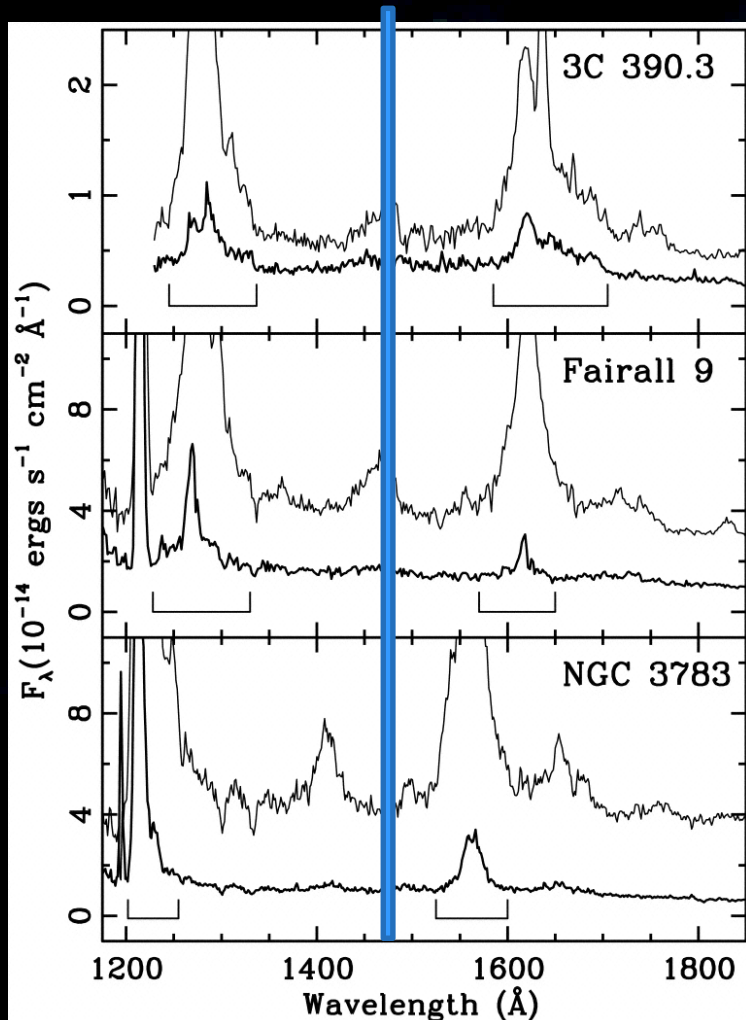
VIRIALIZATION?

WHAT IS WITH THE UV LINES?



The UV broad lines

- Ly α , CIV (see e.g. Michael & Fromerth 2000)



Ly α and CIV

- Line profiles, disk-wind model (see e.g. Chiang & Murray 1996), wind has very important influence on line shape-intensity (variability)
- E.q. CIV, Mejía-Restrepo et al. 2016, connecting Mg II with CIV! Correction for the wind contribution!

$$M_{\text{BH}} (\text{Mg II})_{\text{pred}} = 5.71 \times 10^5 \left(\frac{L_{1450}}{10^{44} \text{ erg s}^{-1}} \right)^{0.57} \times \left(\frac{\text{FWHM (C IV)}}{10^3 \text{ km s}^{-1}} \right)^2 \times \left(\frac{L_{\text{P}} (\text{C III})}{L_{\text{P}} (\text{C IV})} \right)^{-2.09} \quad (7)$$

The UV and optical broad lines

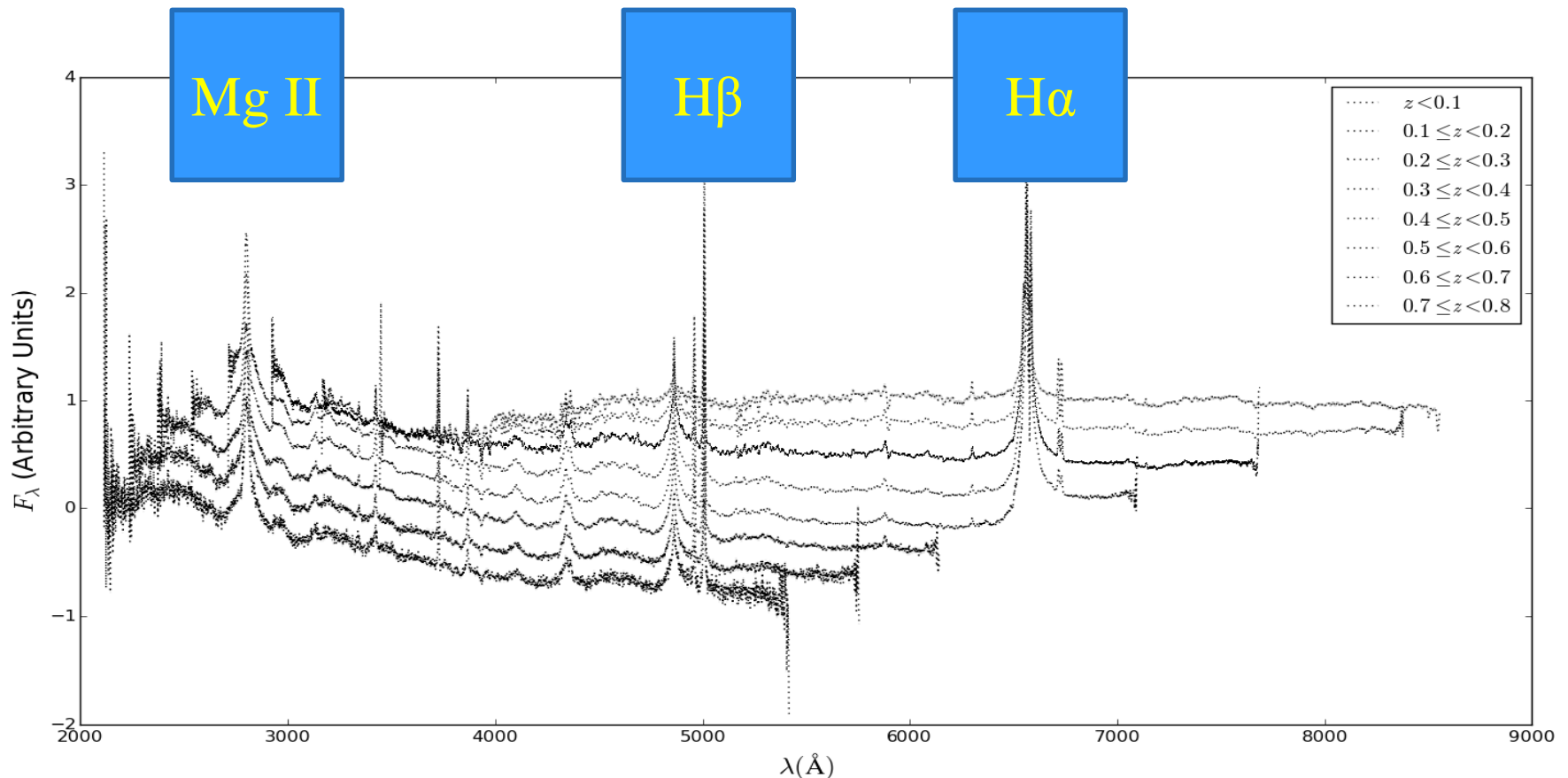
- $Ly\alpha$, CIV, CIII], Mg II, H β , H α
- Wind & disk , or high- and low-ionization lines (see e.g. Marziani 2019)
- Usually, H β Reverberation Measurements and then calibrating Mg II–based SMBH mass measurement (see Bahk et al. 2019)
- Then calibrating CIV, CIII] using Mg II line (see e.g. Mejía-Restrepo et al. 2016)

The UV and optical broad lines

- Ly α , CIV, CIII], Mg II, H β , H α
- H α – probability for forming line is high, and the shape and variability may be affected by different effects
- H β is promising=>H β can be used for calibration (see e.g. Popovic et al. 2019)
- Mg II?

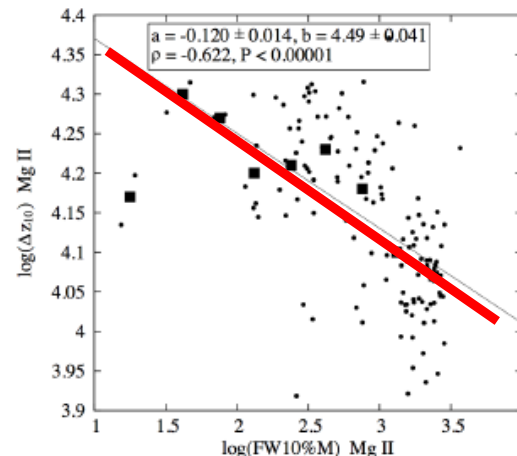
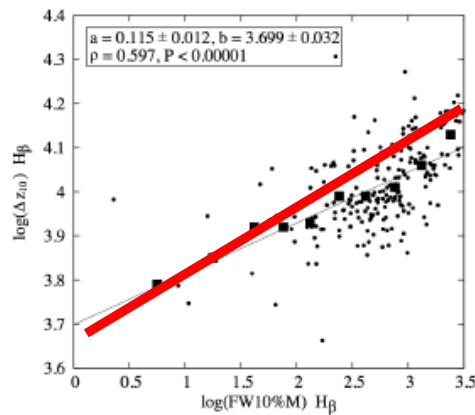
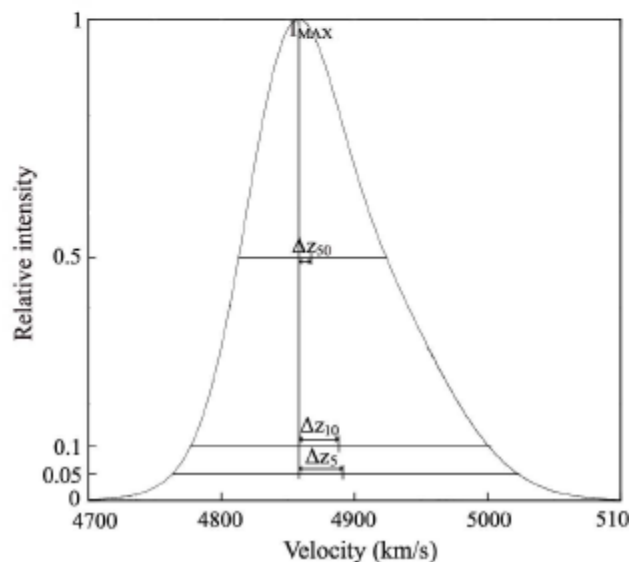
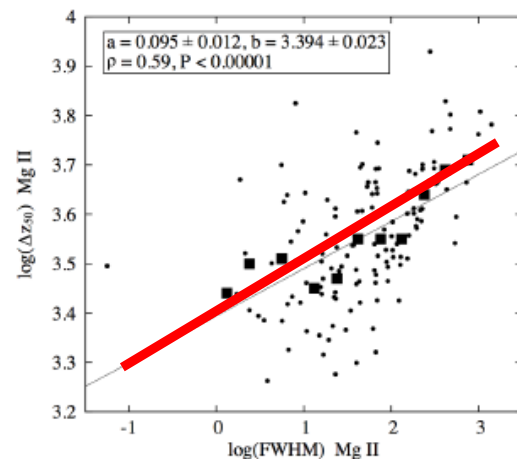
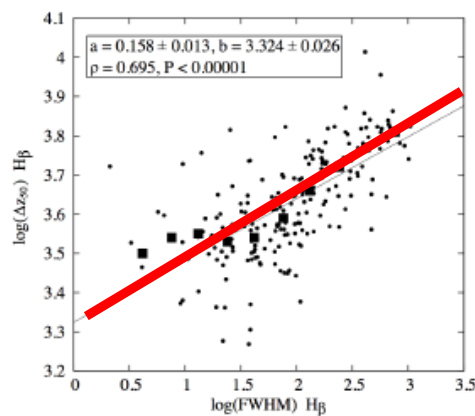
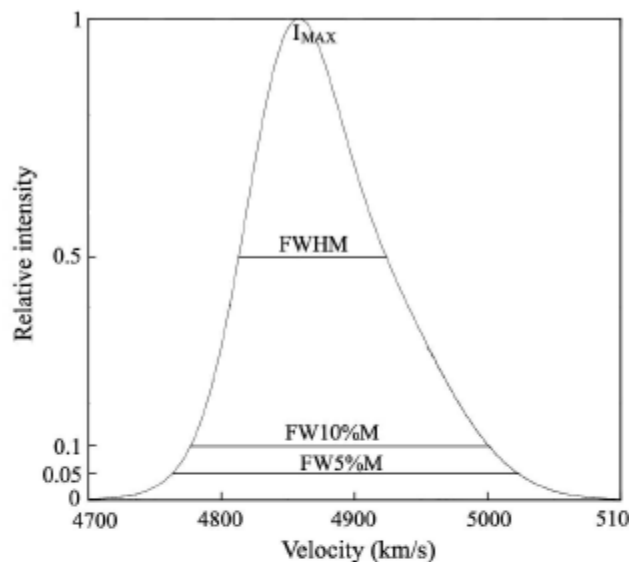
Very important

- Measure SMBHs on different cosmological scales, e.g in optical different lines (SDSS) at different redshift (Poll & Wadadekar 2017, MNRAS)



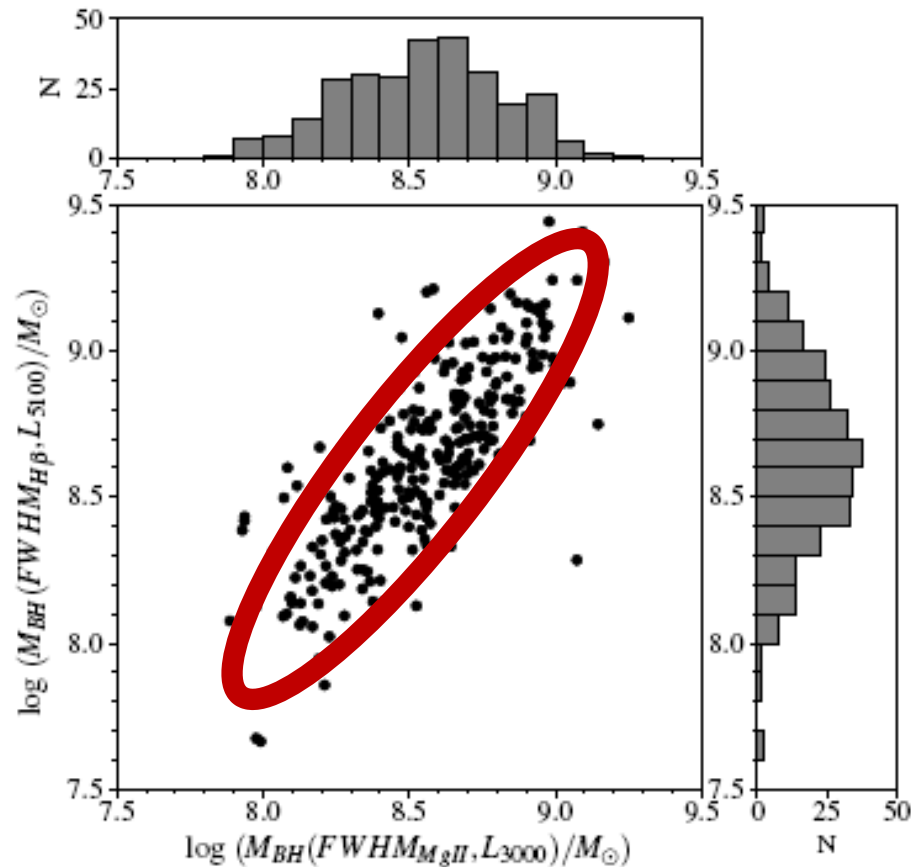
Difference between Mg II and H β , shift and width

- Jonic et al. 2016, z vs. FWHM



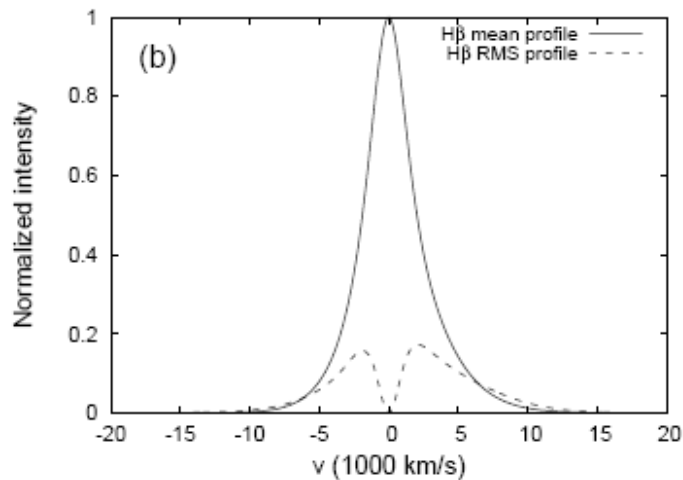
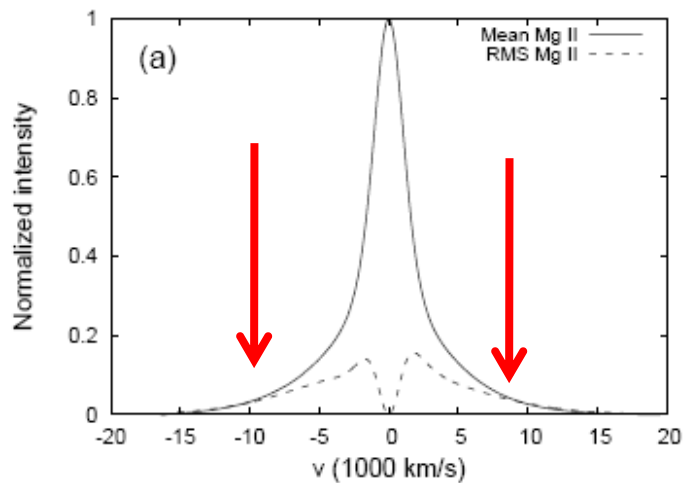
Mg II and H β

- Popovic, Kovacevic-Dojcinovic & Marceta-Mandic 2019, MNRAS, 484, 3180
- A sample of 285 type 1 AGN, covering both lines

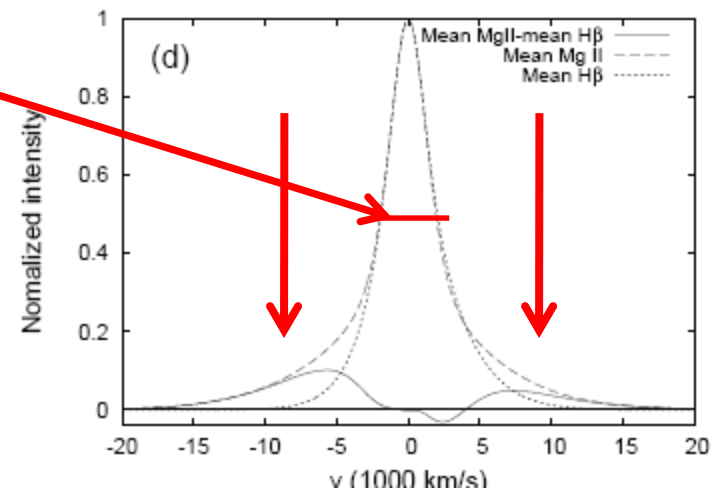
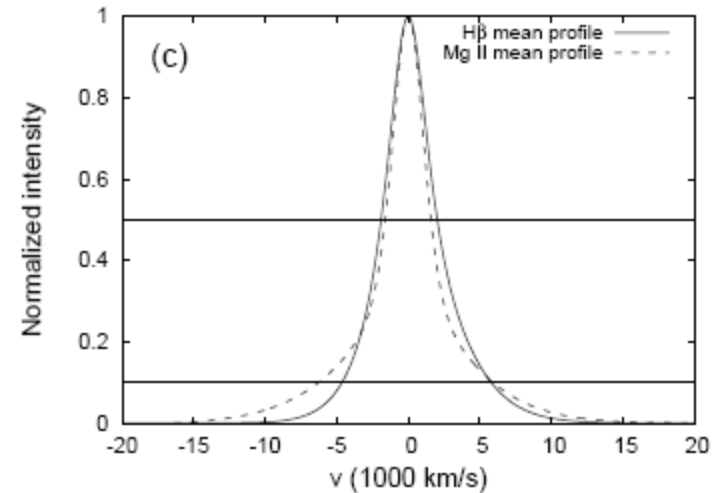


Seems to be good, but...

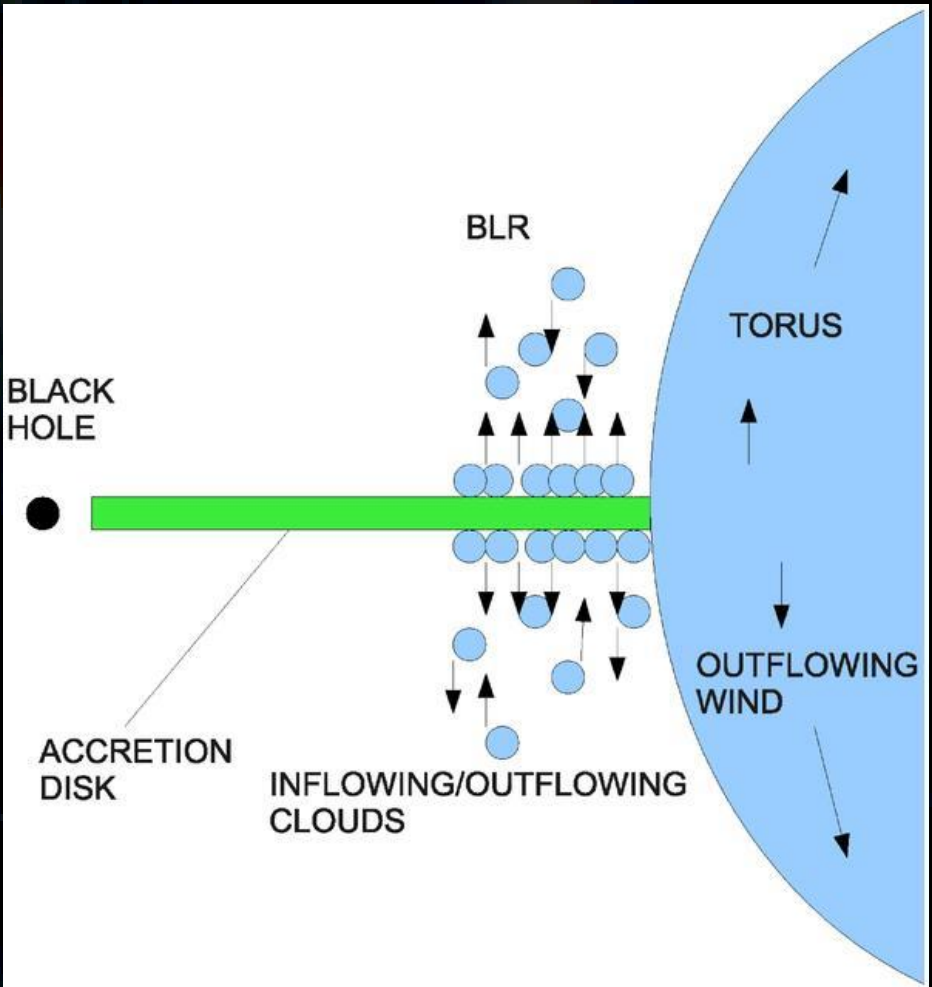
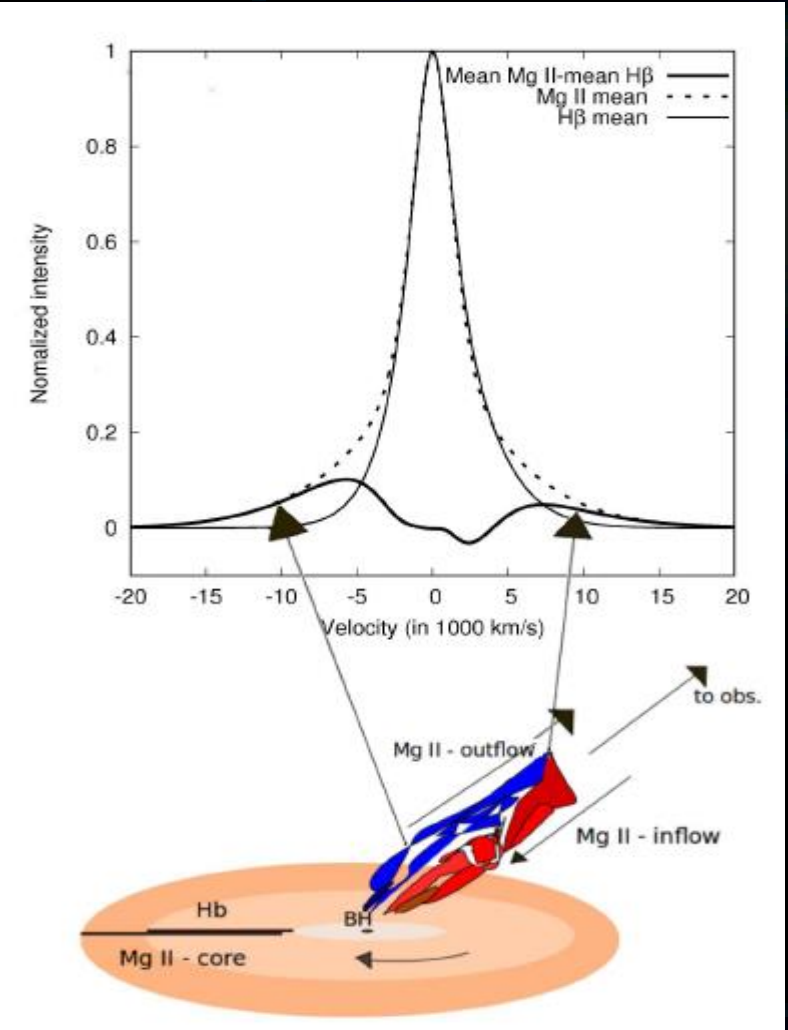
- Virialization in MgII and H β broad lines – line profiles (Popovic et al. 2019)



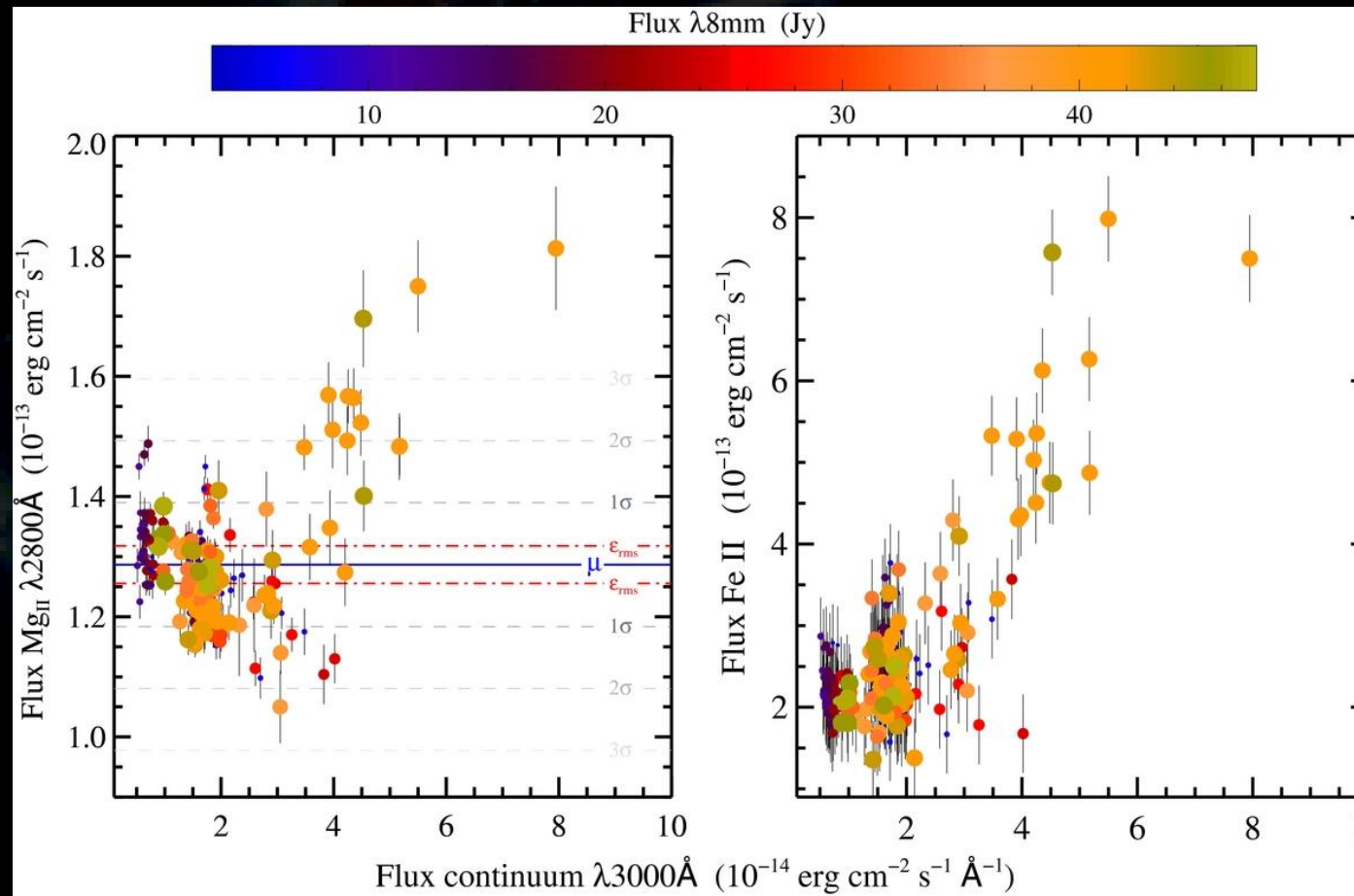
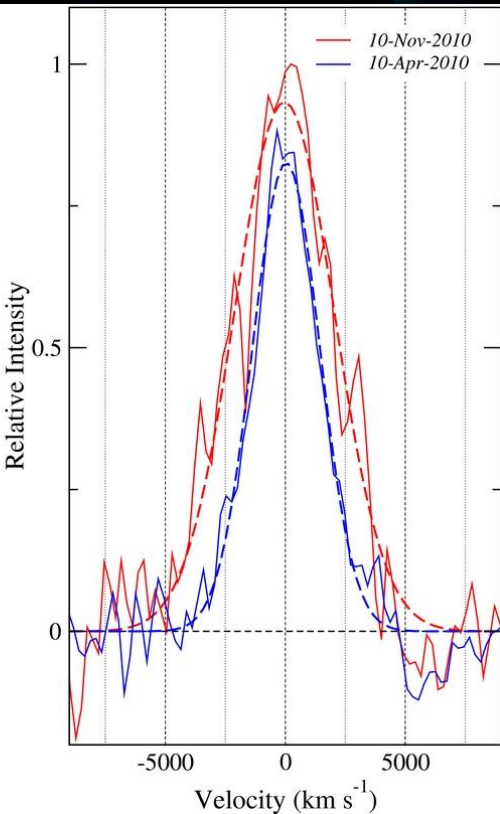
Same
width-
shape-
geometry
?

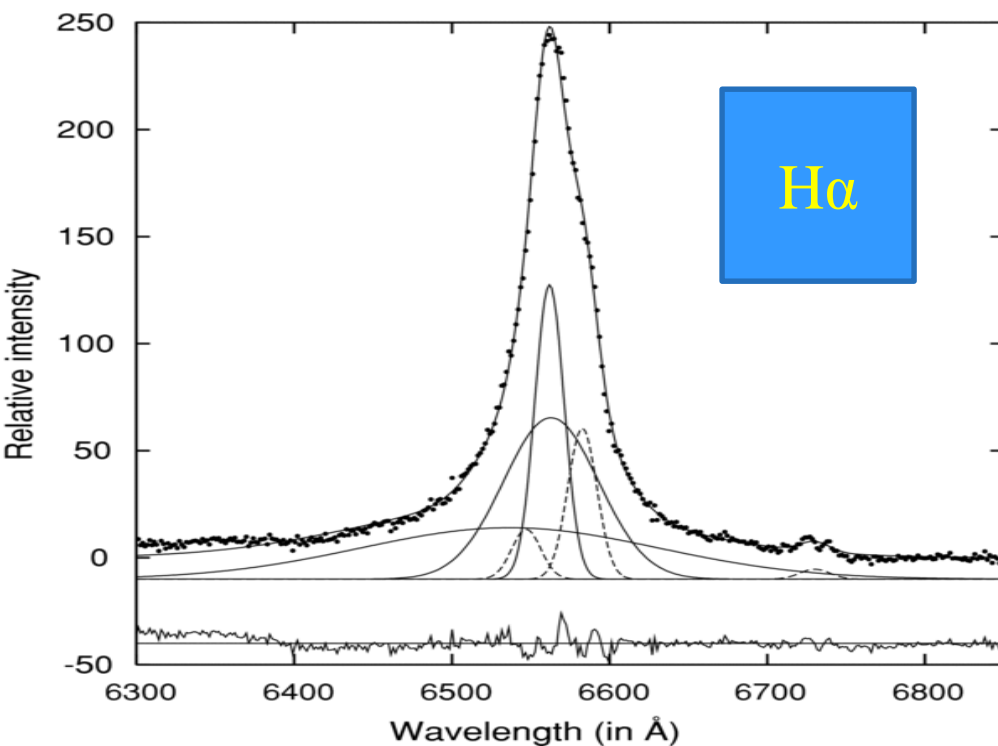
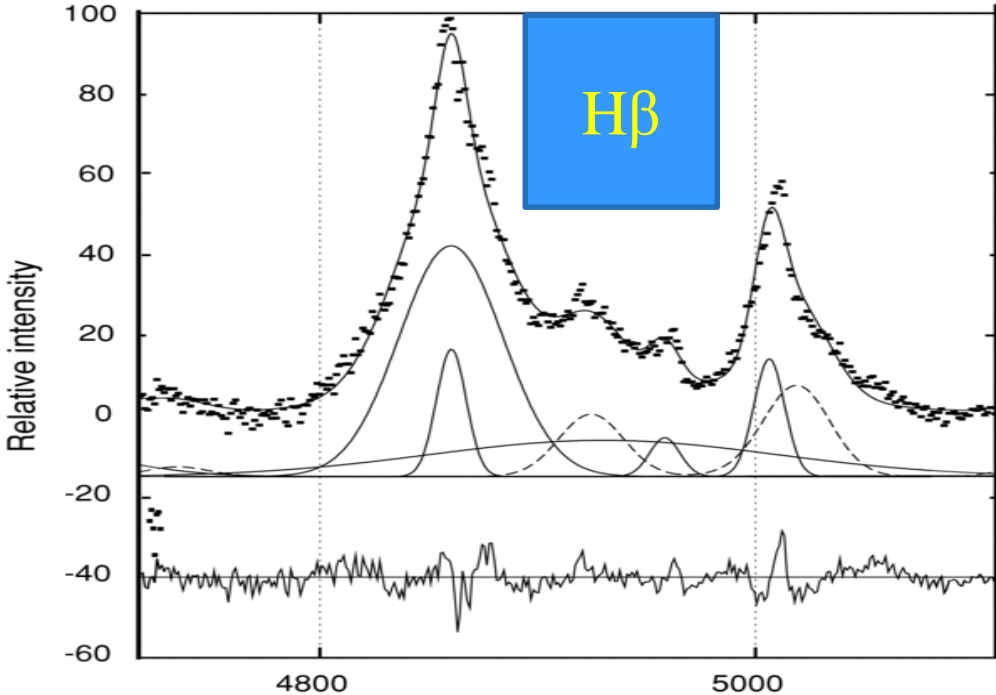


- Virialization in whole Mg II is a problem (Popovic et al. 2019), fountain-like region contribution to the Mg II wings, vertical motion see Czerny & Hryniewicz 2011, Kollatschny & Zetzl 2013, Czerny et al. 2017



- Mg II very broad (Popovic et al. 2019) contribution of the ‘fountain-like’ region, see Leon-Tavares 2013. Be careful with huge FWHM, and without Lorentz-like profile (bumps in the Mg II wings)



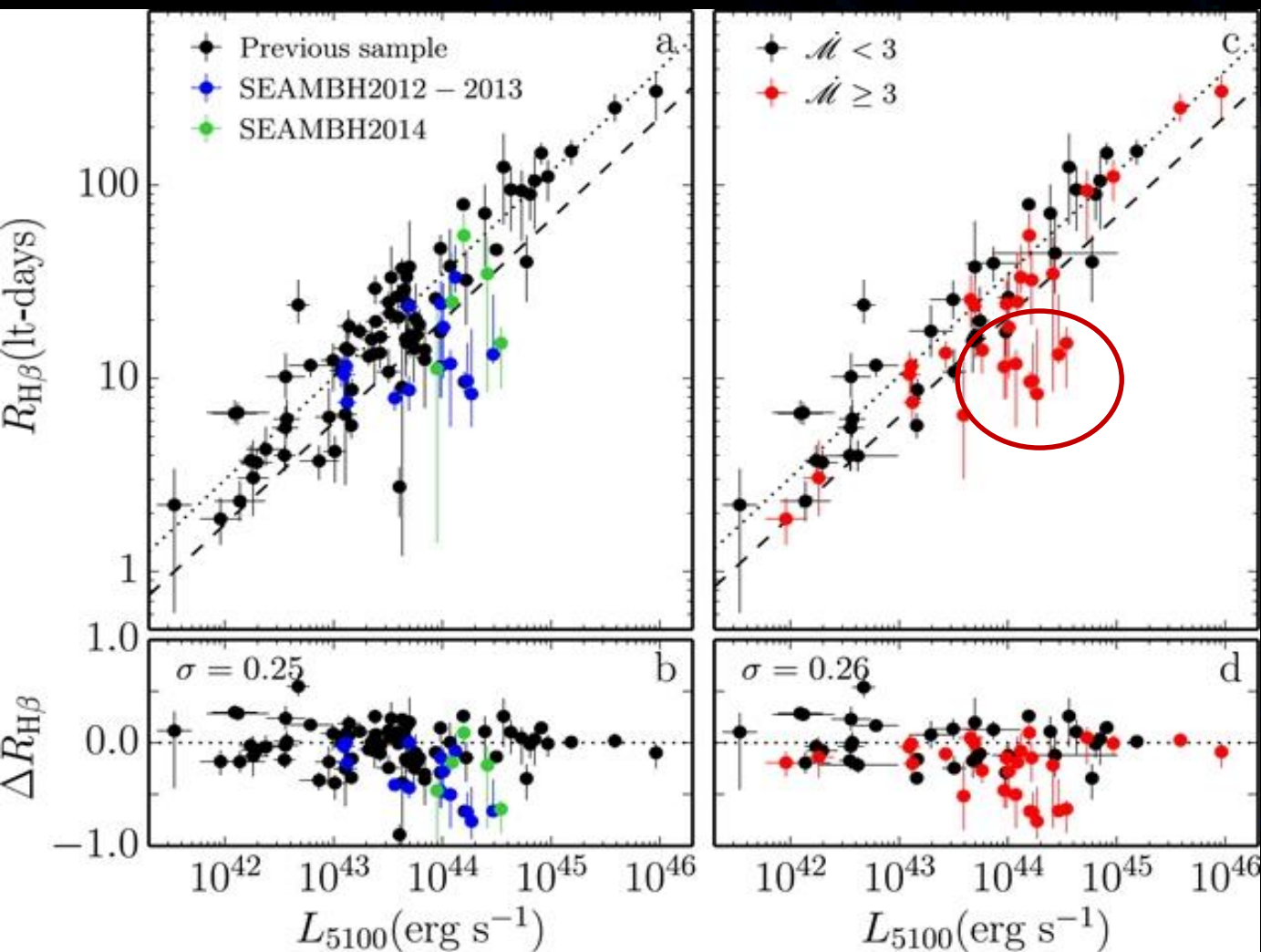


Some problems

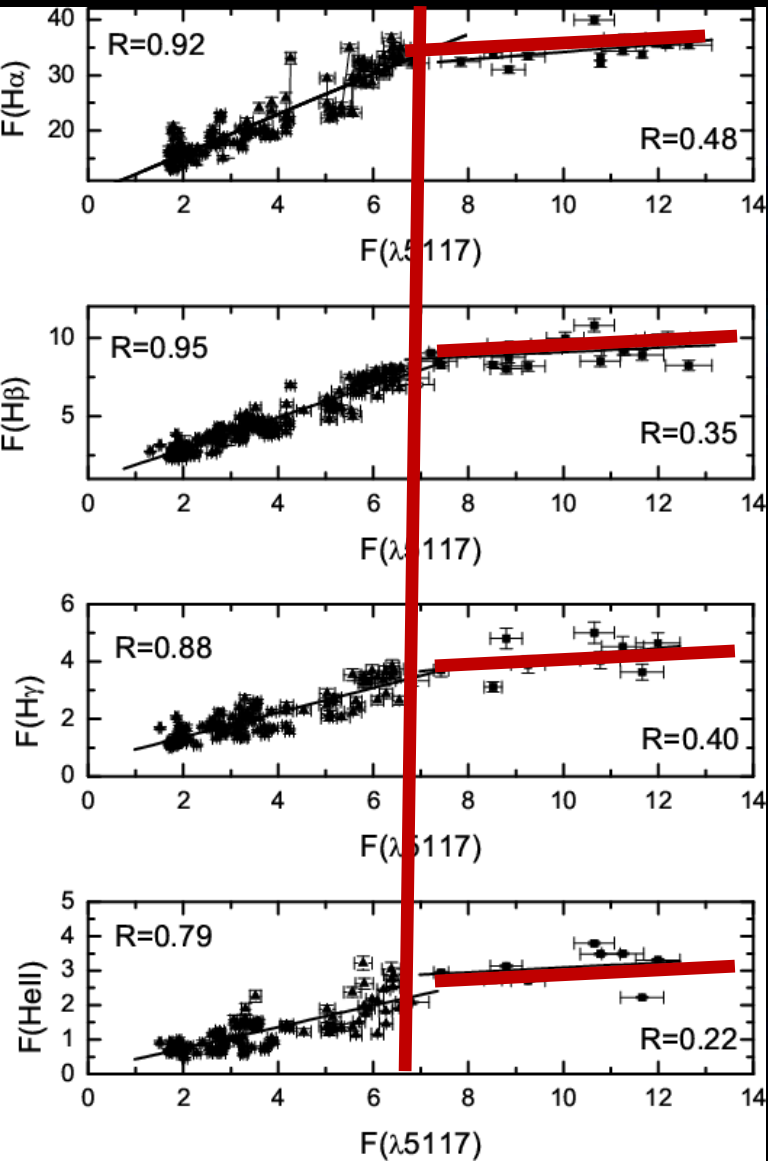
- $H\beta$ seems to be virialized (not so big vertical motion, NL Sy1?), but several problems:

- - complex BLR and accretion rate (Bozhana, Paola)

Problem with broad H β line, as e.g. Difference between Pop A and Pop B (Sulentic, Marziani), i.e. with High Accretion Rates in AGN. Size–Luminosity Scaling Relation for the BLR, see Du et al. 2016 ApJ 825 126 6

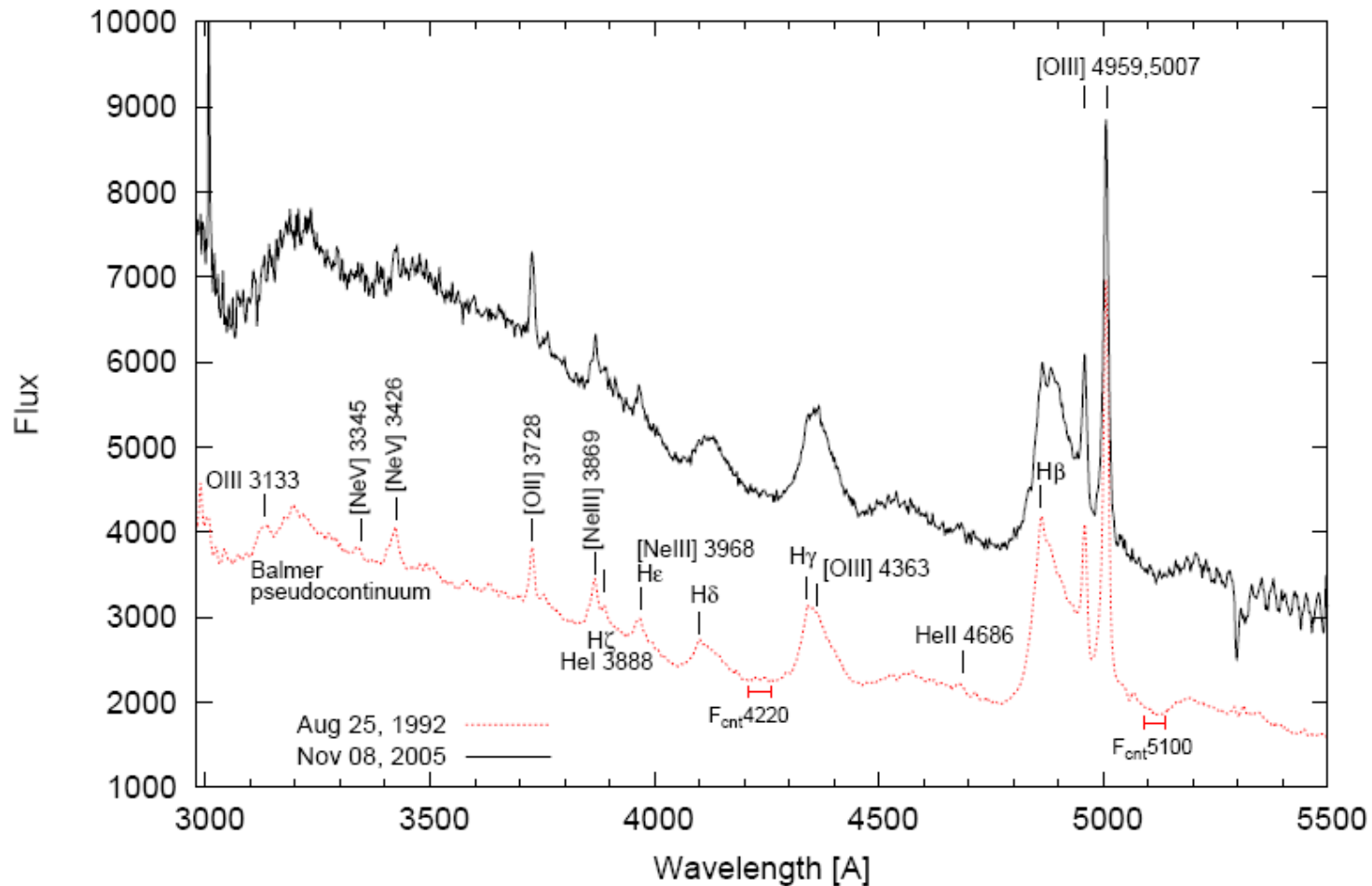


Continuum vs. line variability (e.g NGC4151, Shapovalova et al. 2008)



- - variability and changing look AGN (Gisella, Andjelka, Paola, Marco ...)
- Response the line to the continuum variability
- -Binary (Pu, Sasha, Edi, Wolfram)

E1821+643 – SMBBHs, Shapovalova et al. 2016



Polarization in the broad lines Equatorial scattering (Afanasiev & Popovic 2015, Afanasiev, Popovic, Shapovalova 2019)– more in talk of Elena & Victor

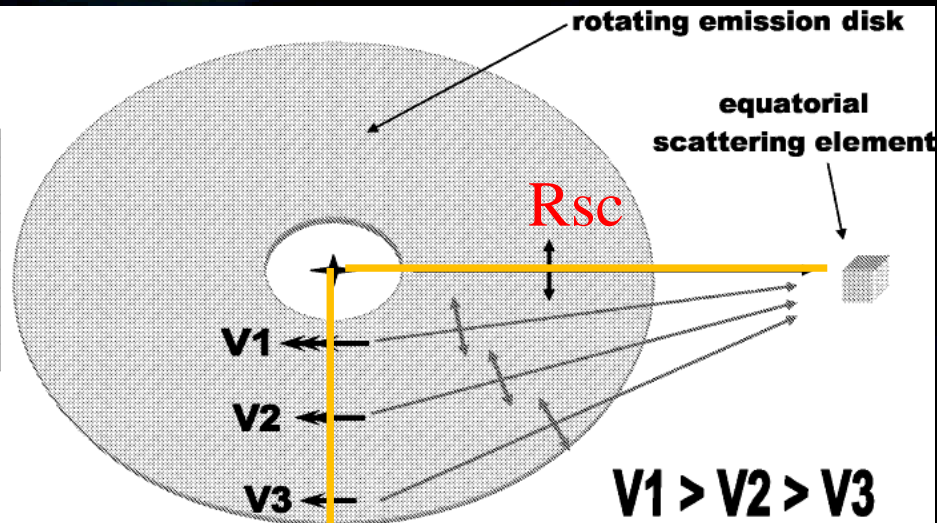
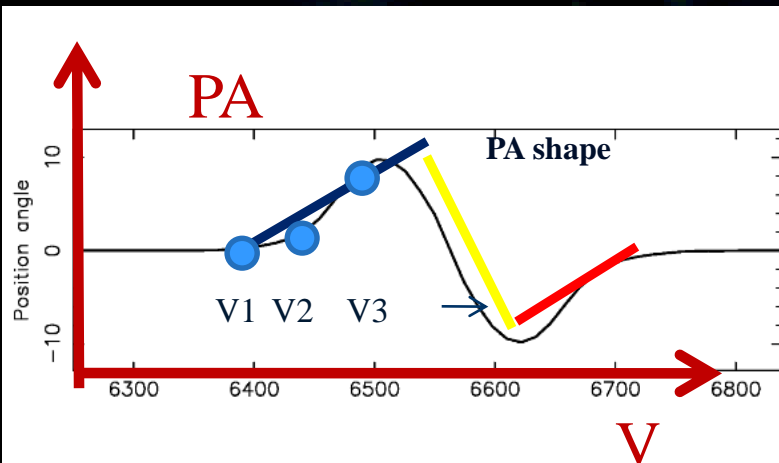
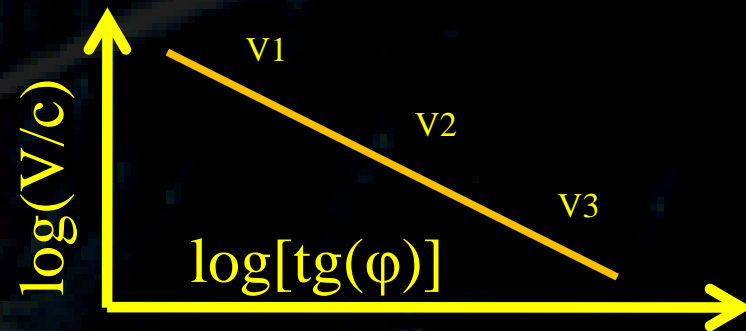
$$v_i = \sqrt{\frac{GM_{BH}}{R_{SC} \tan(\varphi_i)}},$$

$$\log(v_i) = a - b \log(\tan(\varphi_i)),$$

$$b = 0.5$$

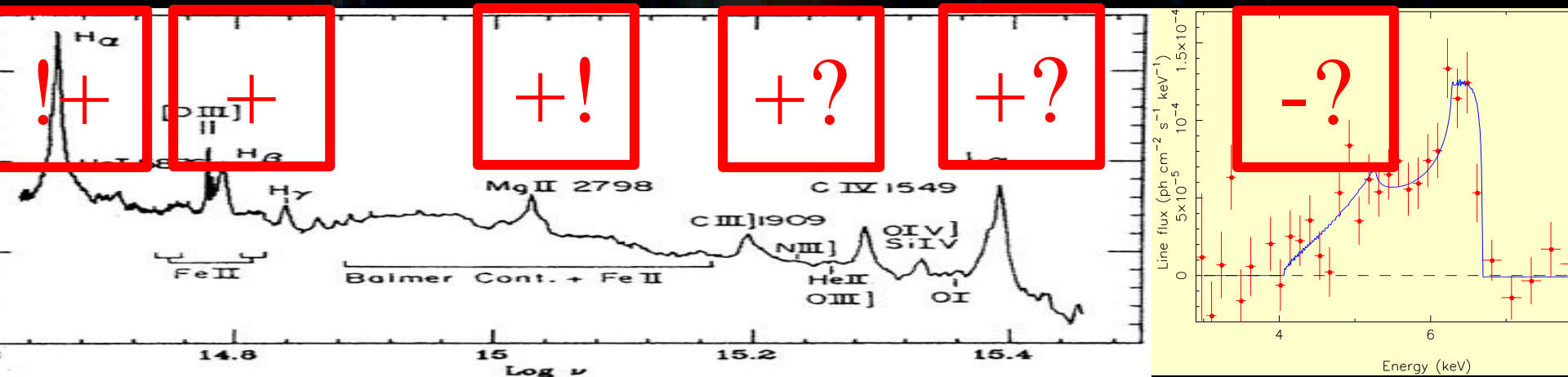
$$a = f\left(\frac{M_{BH}}{R_{SC}}\right)$$

$$v = \sqrt{\frac{GM_{BH}}{R_{EC}}}$$



Conclusions

1. Lines for SMBH measurements
2. Fe K and UV lines?
3. Optical H β seems to be the best one



Thank you for your attention