Spectral lines and supermassive black hole mass measurements

Luka Č. Popović

Astronomical Observatory, Belgrade, Serbia

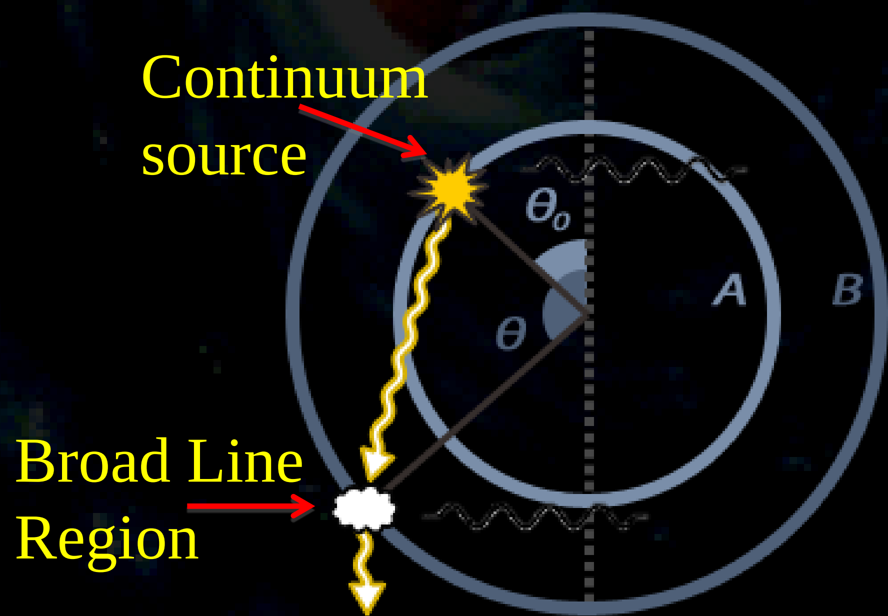
12 SCSLSA, SS: AGN VARIABILITY DEVOTED TO A. I. SHAPOVALOVA

- 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 asumption that the BLR gas is photoionized by** continu

Continuum and line variability.



Time delay between continuum and line photon.

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

- 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

DP 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

NL Sy1

- 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

Binary 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

CL 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 …

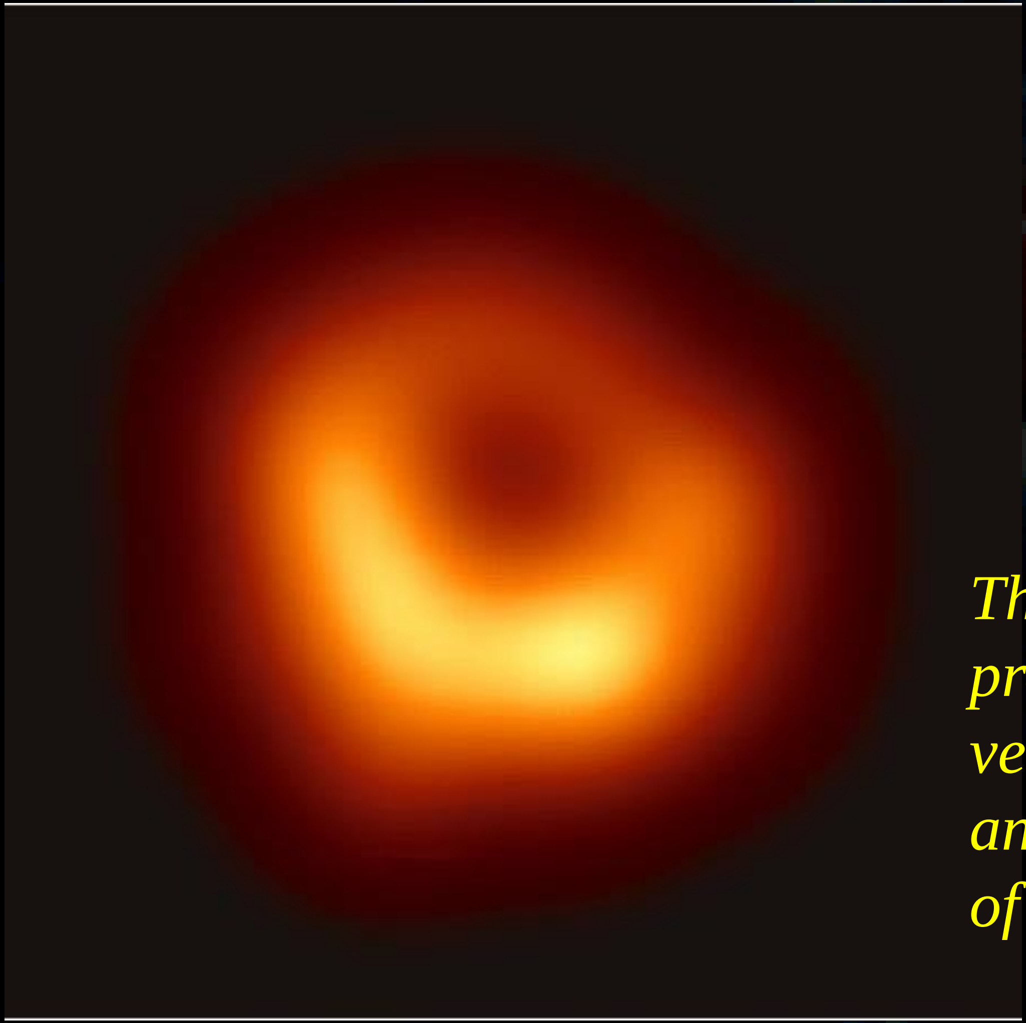
Long-term monitoring

BH mass measurement

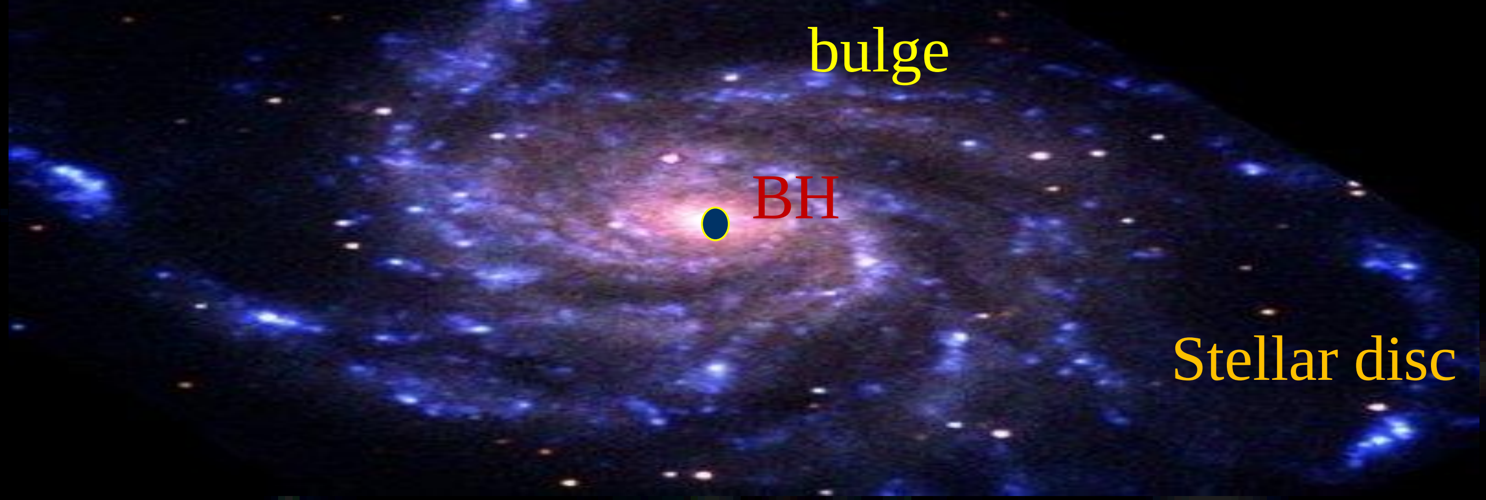
- PIs: Alla I. Shapovalova (Russia)

- 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 …

Measure SMBH masses, why?
AGN – M87



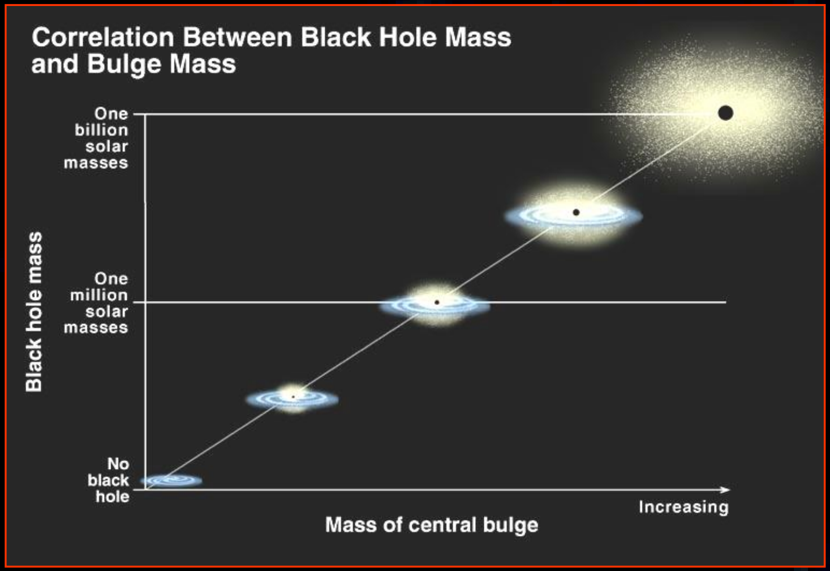
The Event Horizon Telescope project, researchers captured the very first image of a black hole, and it's the beast lurking in the core of galaxy M87.

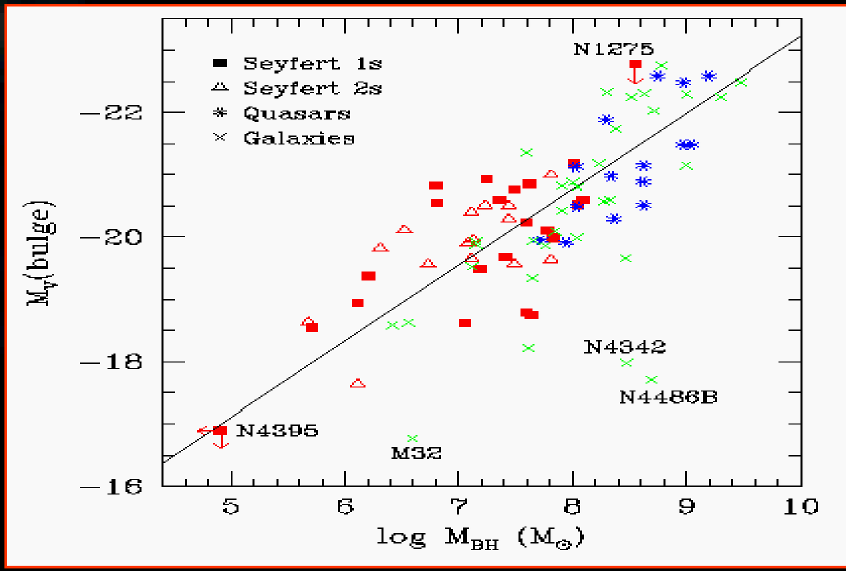


Black Hole - Bulge Relation

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

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





Coevolution of black holes and galaxies

- Galaxy merger

Hierarchical growth

- Normal galaxy

Gas inflows

Galaxy formation and evolution

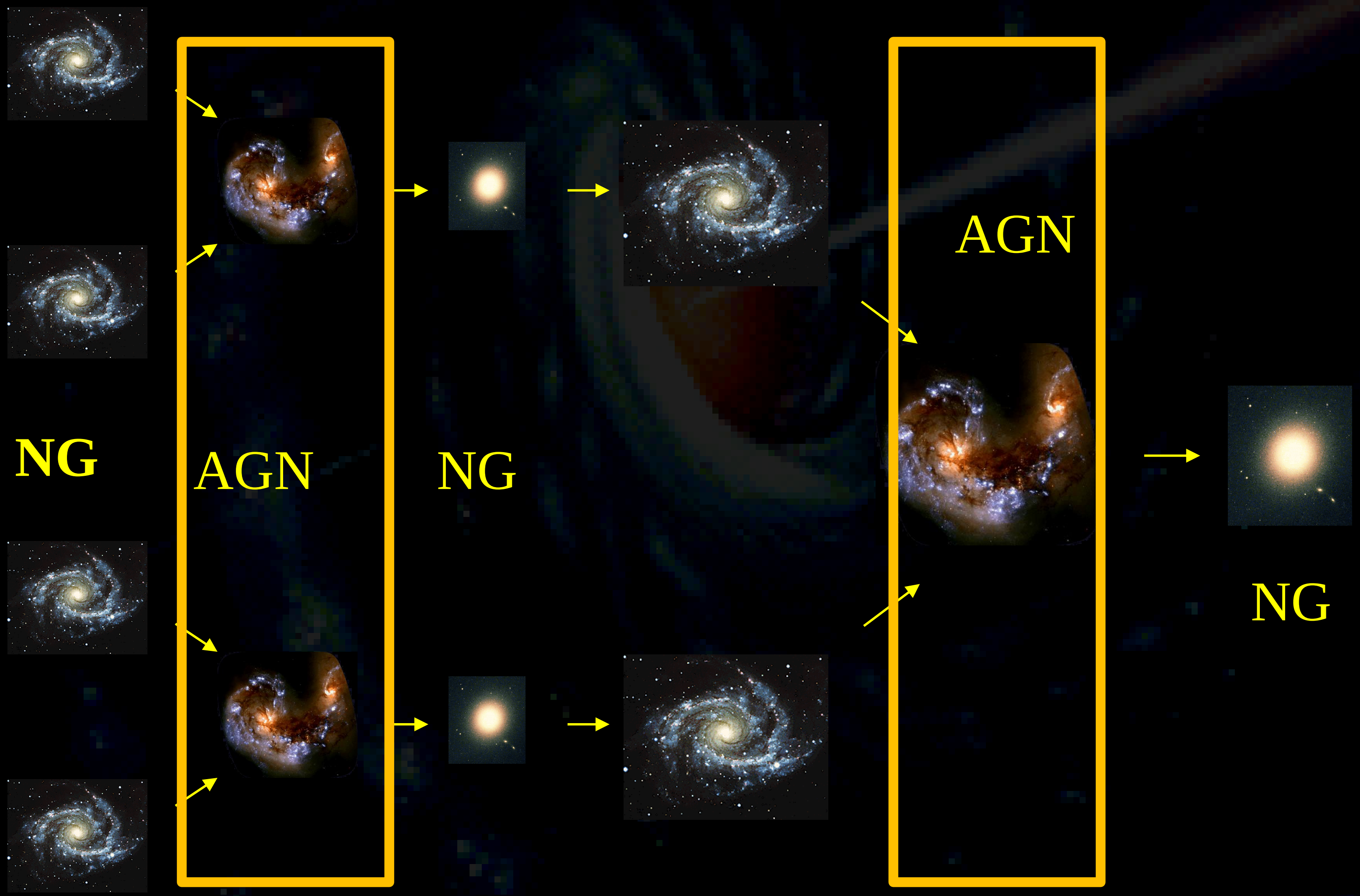
AGN feedback

- Starbrust and AGN starting phase

- AGN - quasar

Growth of BH

Hierarchical Galaxy Formation

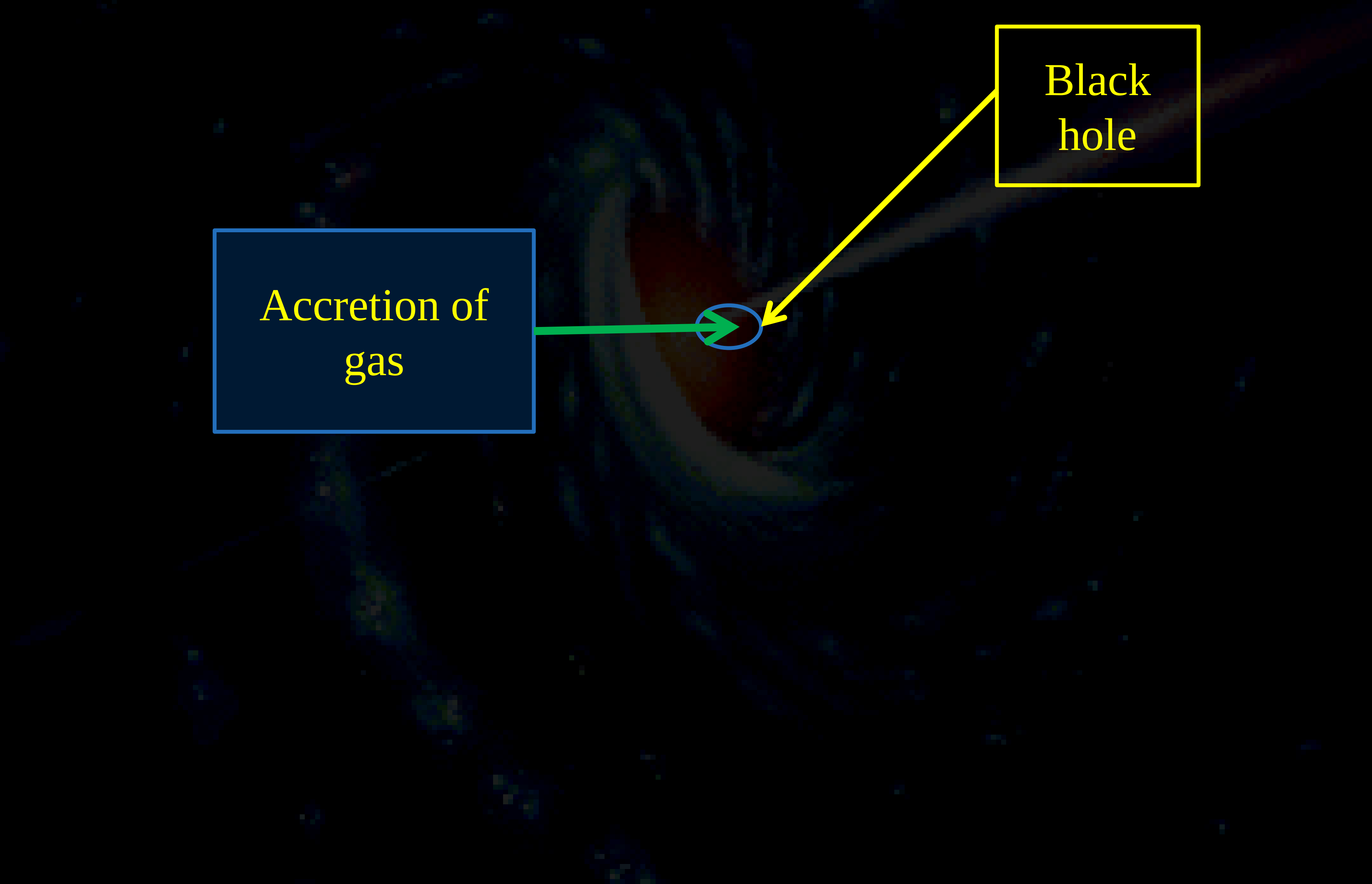


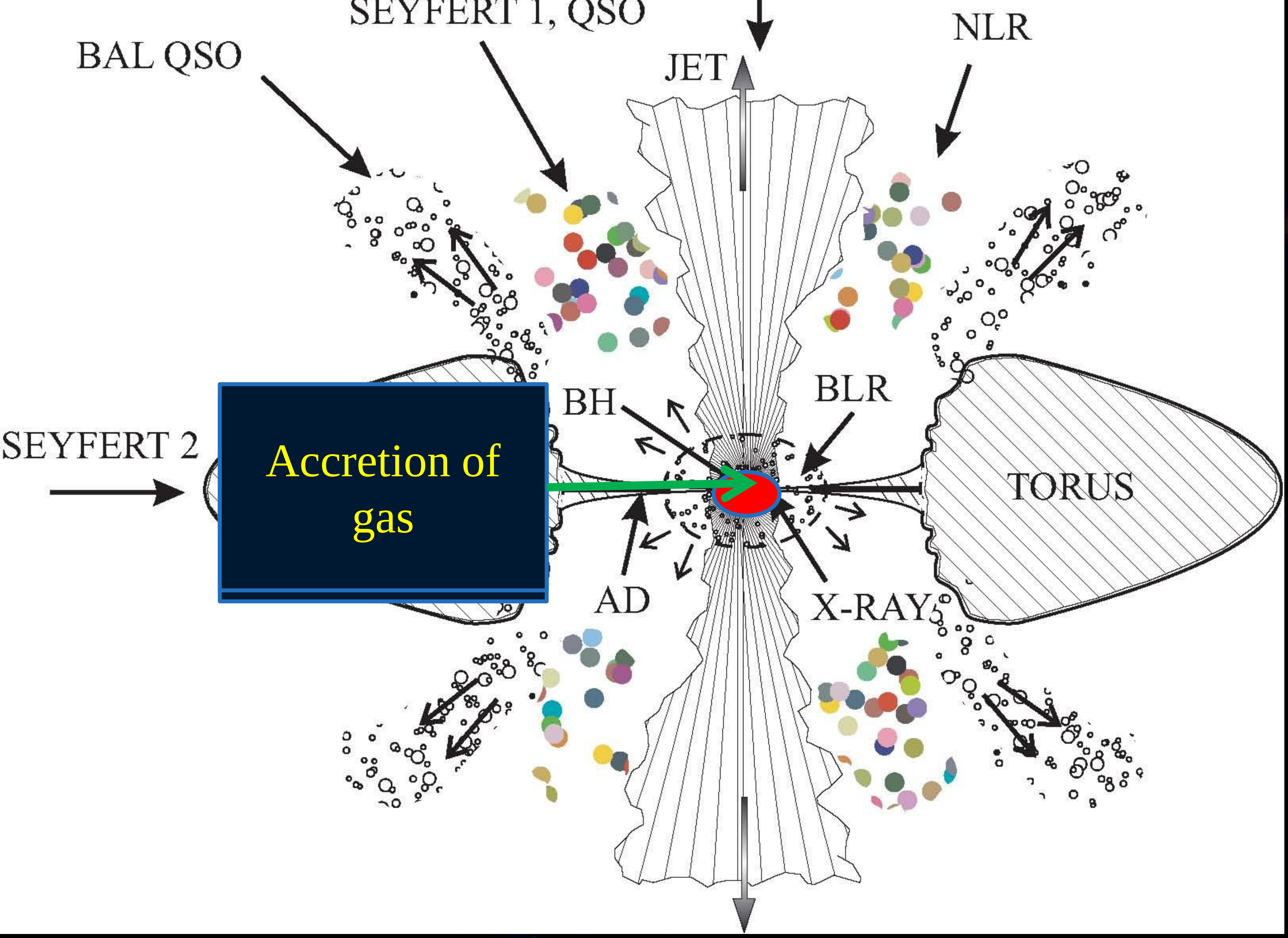
AGN phase is very good for SMBH measurements, why?

What is an AGN?

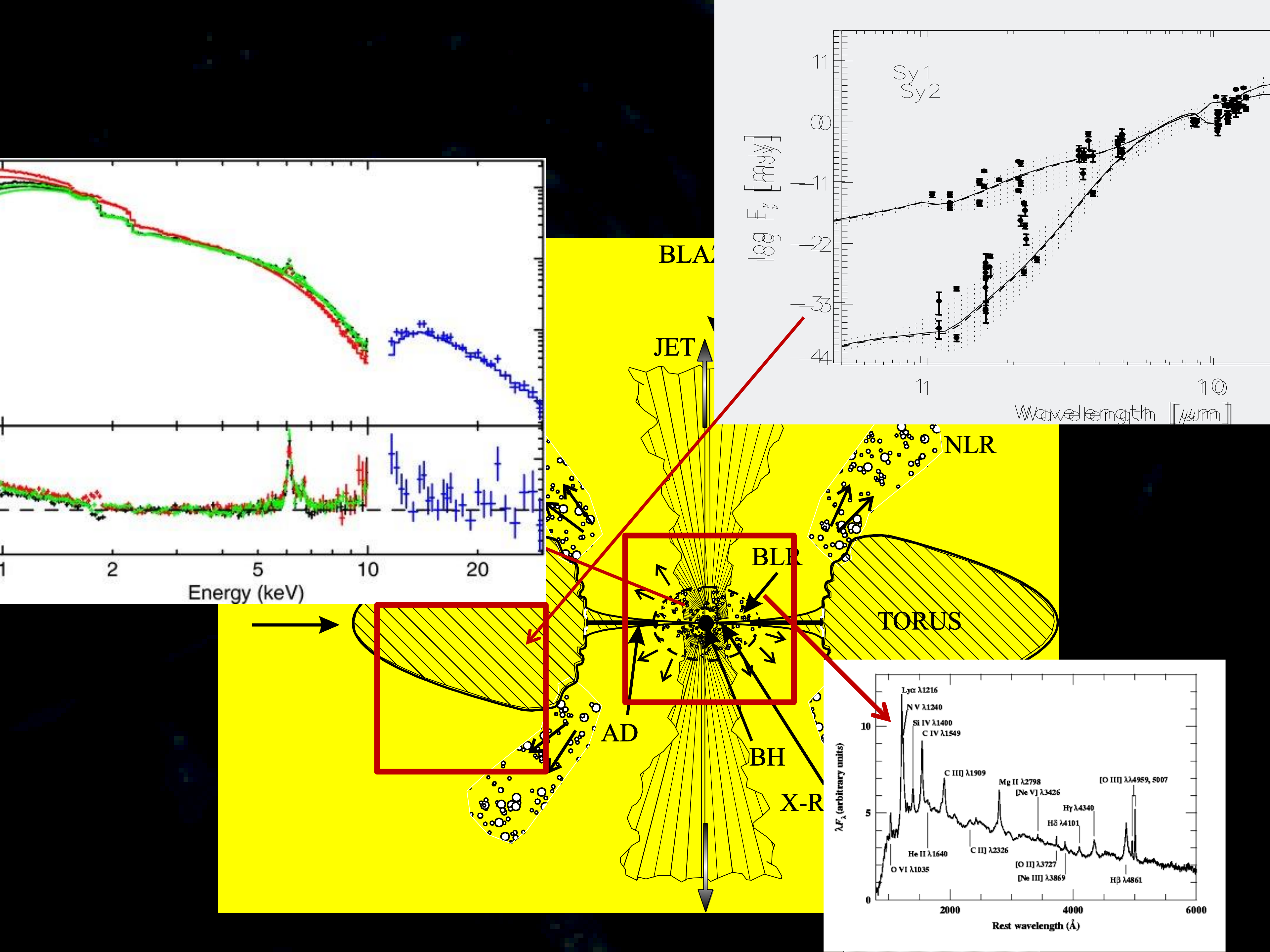
- AGN = central SMBH + gas

AGN model - unification





SEYFERT 1, QSO
BAL QSO
JET
NLR
BH
BLR
SEYFERT 2
Accretion of gas
TORUS
AD
X-RAYS



Energy (keV)
1
2
5
10
20
Sy1
Sy2
log F_ν [mJy]
Wavelength [μm]
1
10
JET
NLR
BLR
TORUS
AD
BH
Lyα λ1216
N V λ1240
Si IV λ1400
C IV λ1549
C III] λ1909
Mg II λ2798
[Ne V] λ3426
[O III] λλ4959, 5007
Hγ λ4340
Hδ λ4101
He II λ1640
C II] λ2326
[O II] λ3727
[Ne III] λ3869
Hβ λ4861
O VI λ1035
λF_λ (arbitrary units)
Rest wavelength (Å)

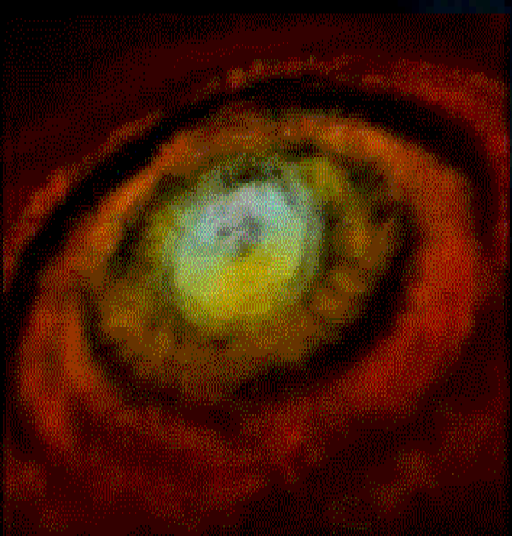
Spectral lines & SMBH mass measurements

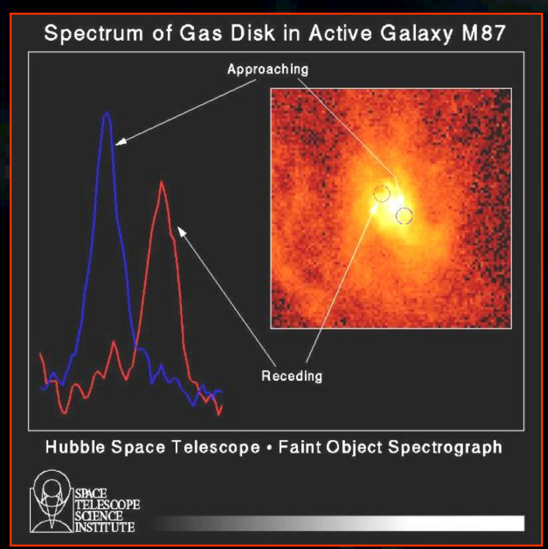
- X- ray, Fe Kα line
- UV/Optical spectral band – a number of broad emission lines which are emitted from broad emission region (BLR)

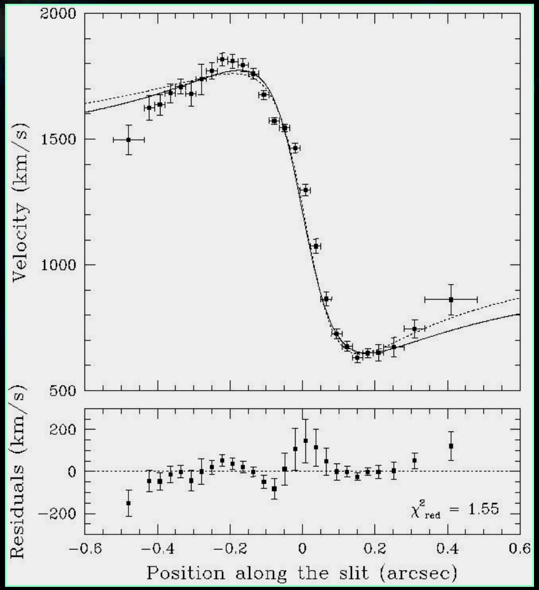
Measuring the mass of SMBH in AGNs

- **Several methods (stellar dynamics, gas dynamics, masers, reverberation): Direct and indirect (see Peterson 2014 SSRev)**

- **<u>Line shift and width as indicator of gas motion</u>**







Macchetto et al. (1997)

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

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

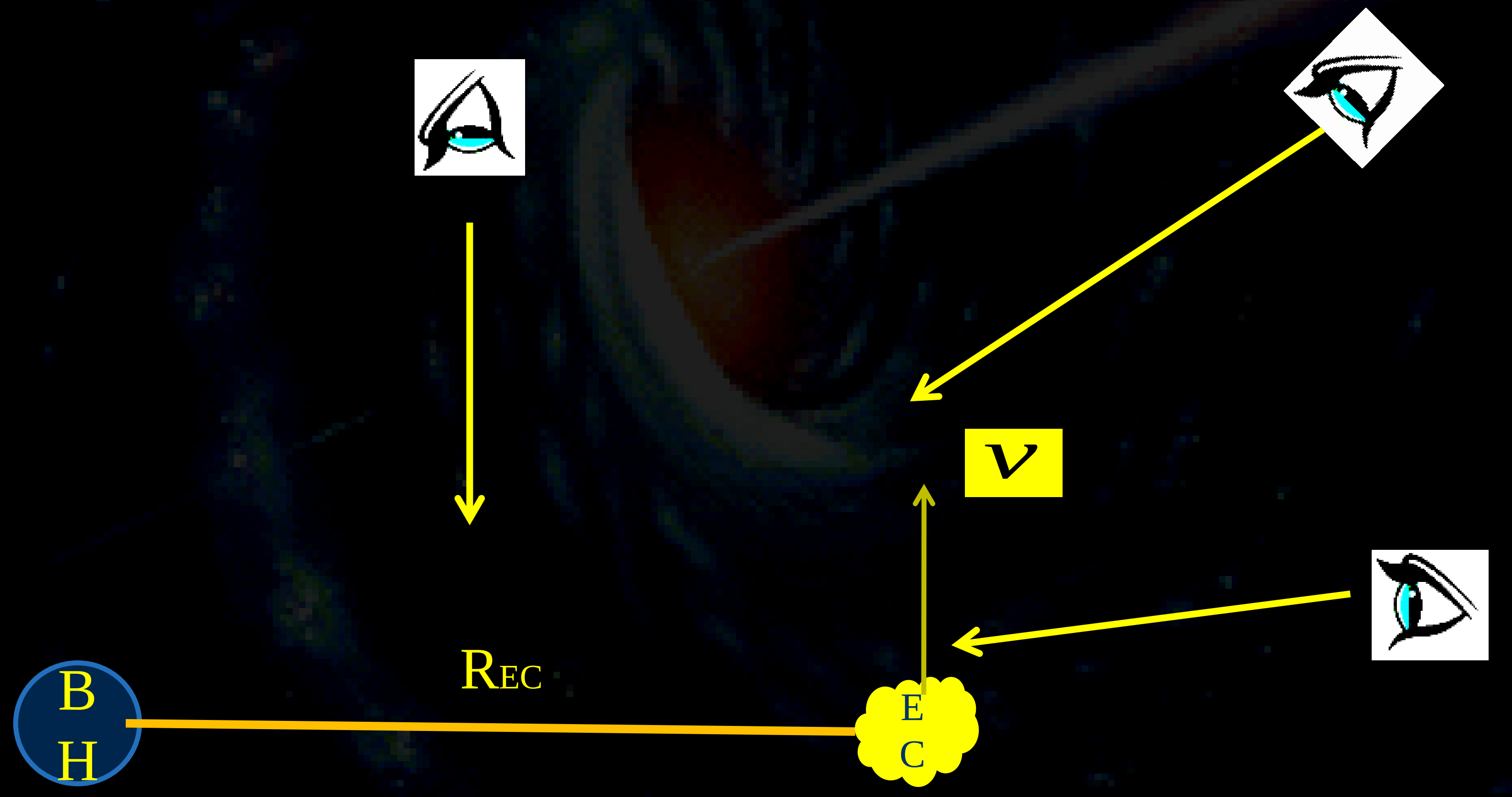
$$\Rightarrow$$

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

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: measureng Rec and velocity => inclination



Broad emission lines (BLR) - reverberation

Very close to the Black hole

Virialization: Rblr~cτ, τ – time lag between continuum and line flux

line widths ~ rotational velocity

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

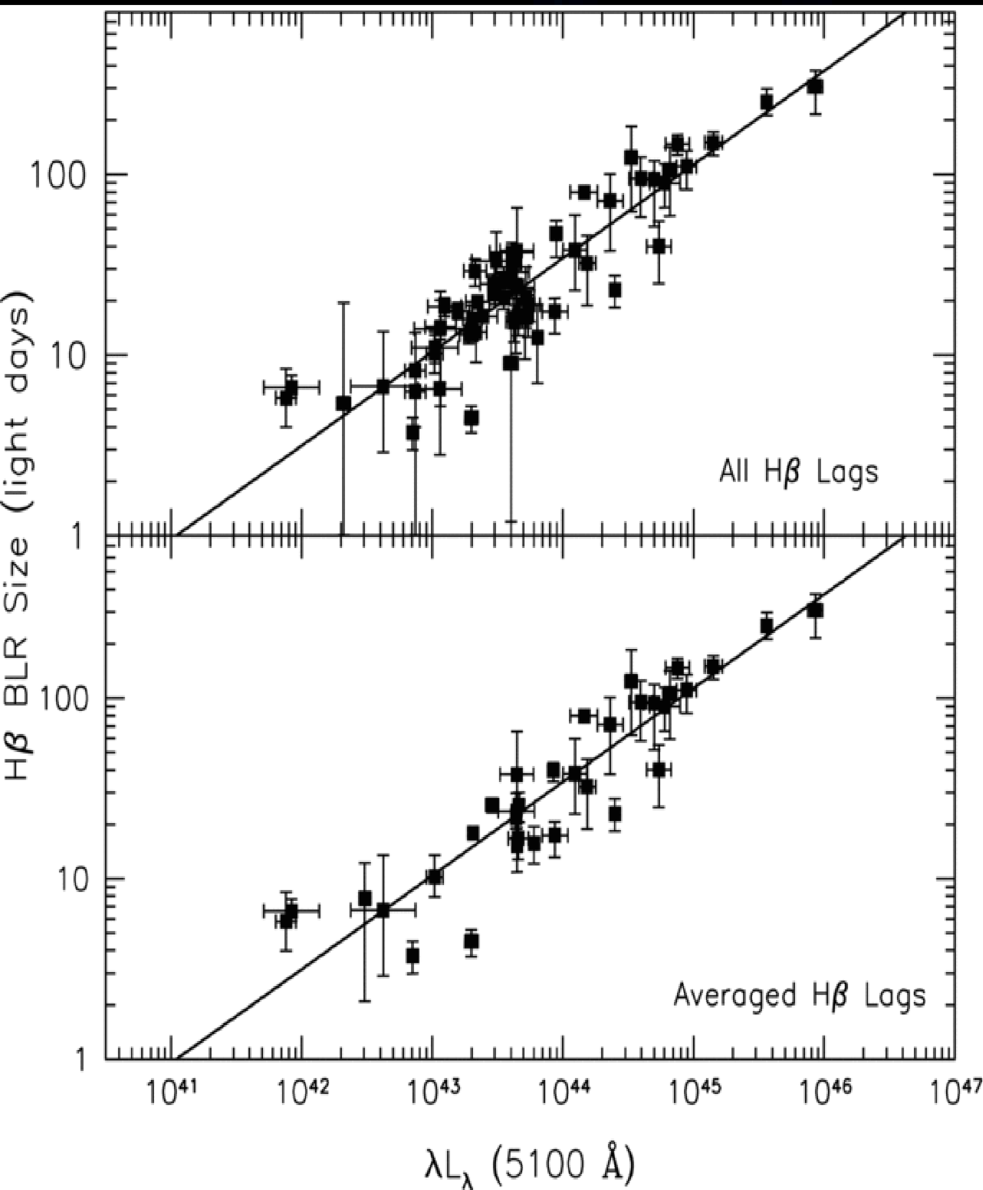
calculated from broad line widths

Dimensions of BLR=>reverberation

Geometry, orientation of BLR

Reverberation

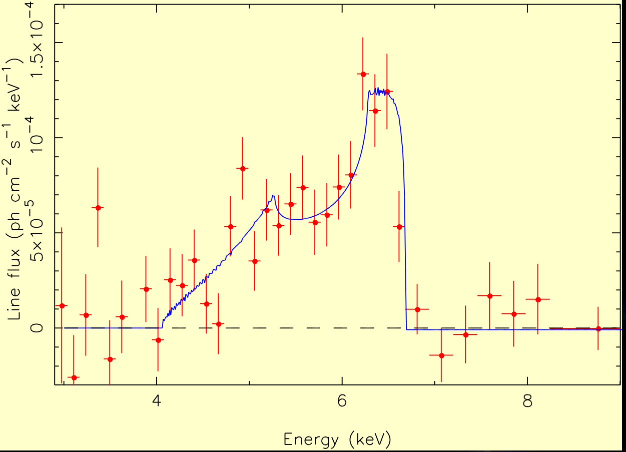
- Find the relation between Rblr and Lcont



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

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

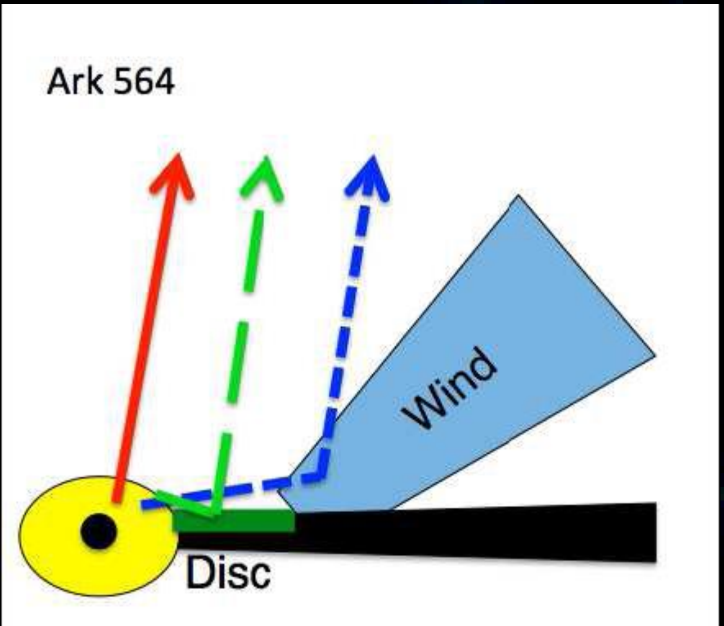
Loli Martínez-Aldama et al. 2019, cosmological application

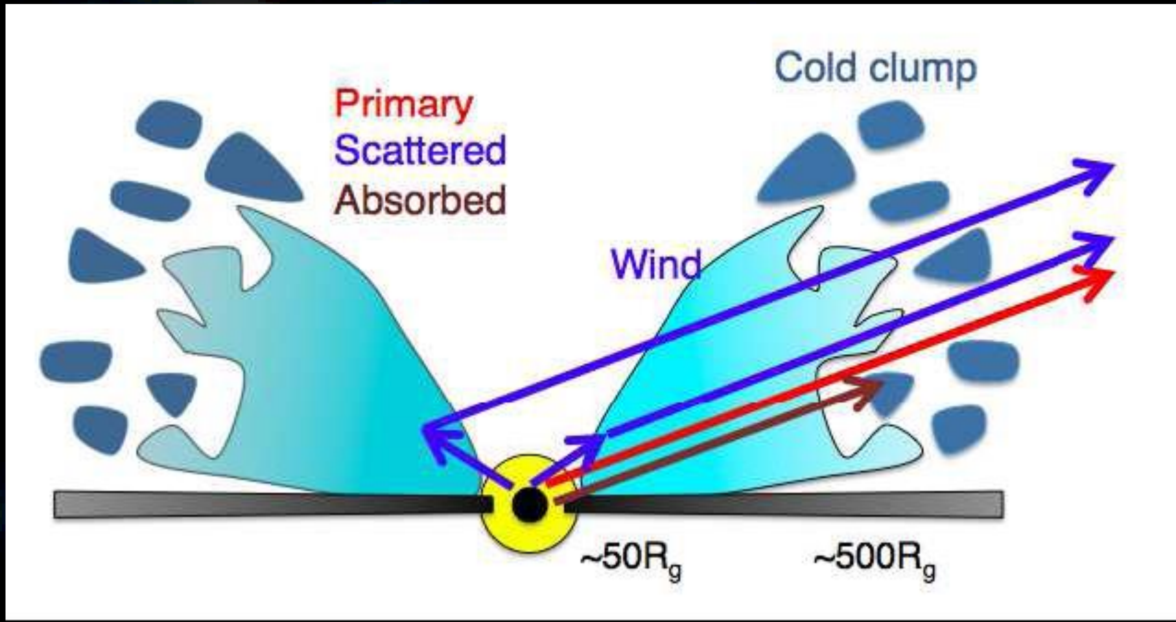


Reverberation in different lines – different dimensions, different problems

E.g. broad Fe Kα spectral line (e.g. Mizumoto et al. 2019, MNRAS)

Short timescale lags around ~ 5 Rg/c





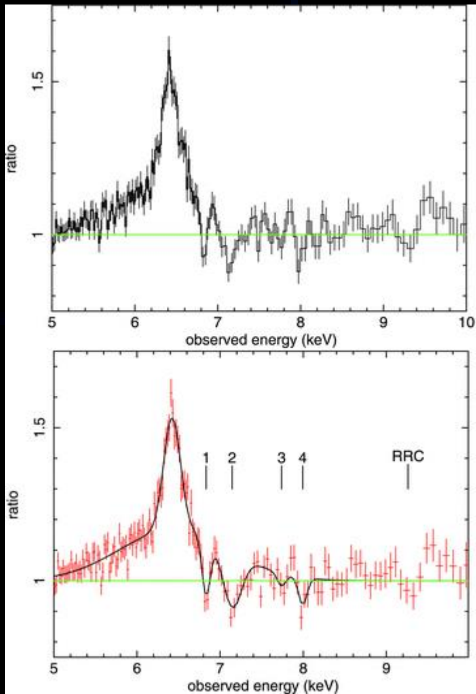
Broad Fe Kα spectral line - reverberation

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 l ikely to be produced by a fast (0.2c) outflowing, highly ionised wind at 50 − 100 Rg (see . Mizumoto et al. 2019)

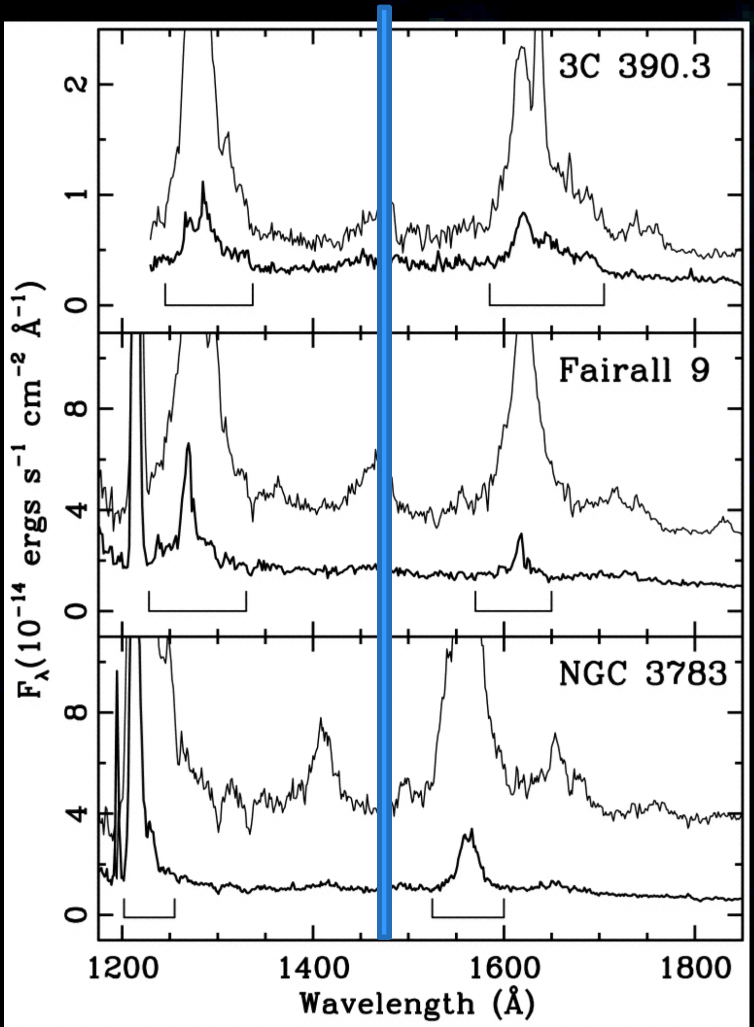
VIRIALIZATION?

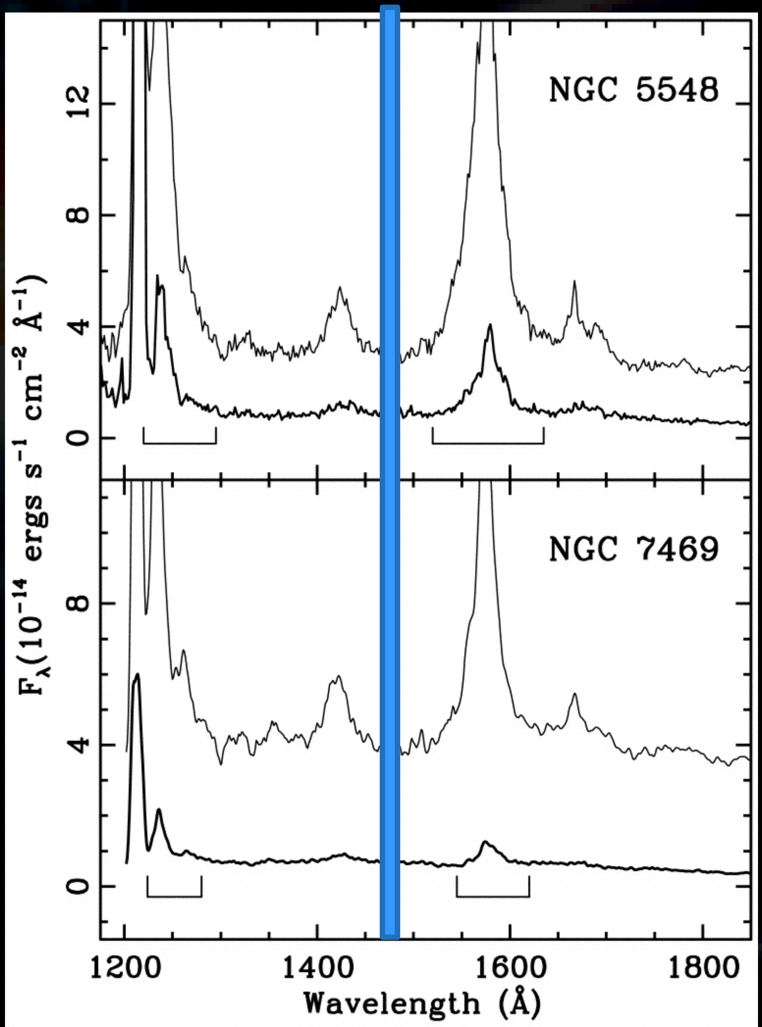
WHAT IS WITH THE UV LINES?



The UV broad lines

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





Lyα and CIV

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

$$M_{\rm BH}\,({\rm Mg\,II})_{\rm pred} = 5.71\times10^{5}\left(\frac{L_{1450}}{10^{44}\,{\rm erg\,s^{-1}}}\right)^{0.57}\times\left(\frac{{\rm FWHM\,(C\,IV)}}{10^{3}\,{\rm km\,s^{-1}}}\right)^{2}\times\left(\frac{L_{\rm P}\,({\rm C\,III]})}{L_{\rm P}\,({\rm C\,IV})}\right)^{-2.09}. \quad (7)$$

The UV and optical broad lines

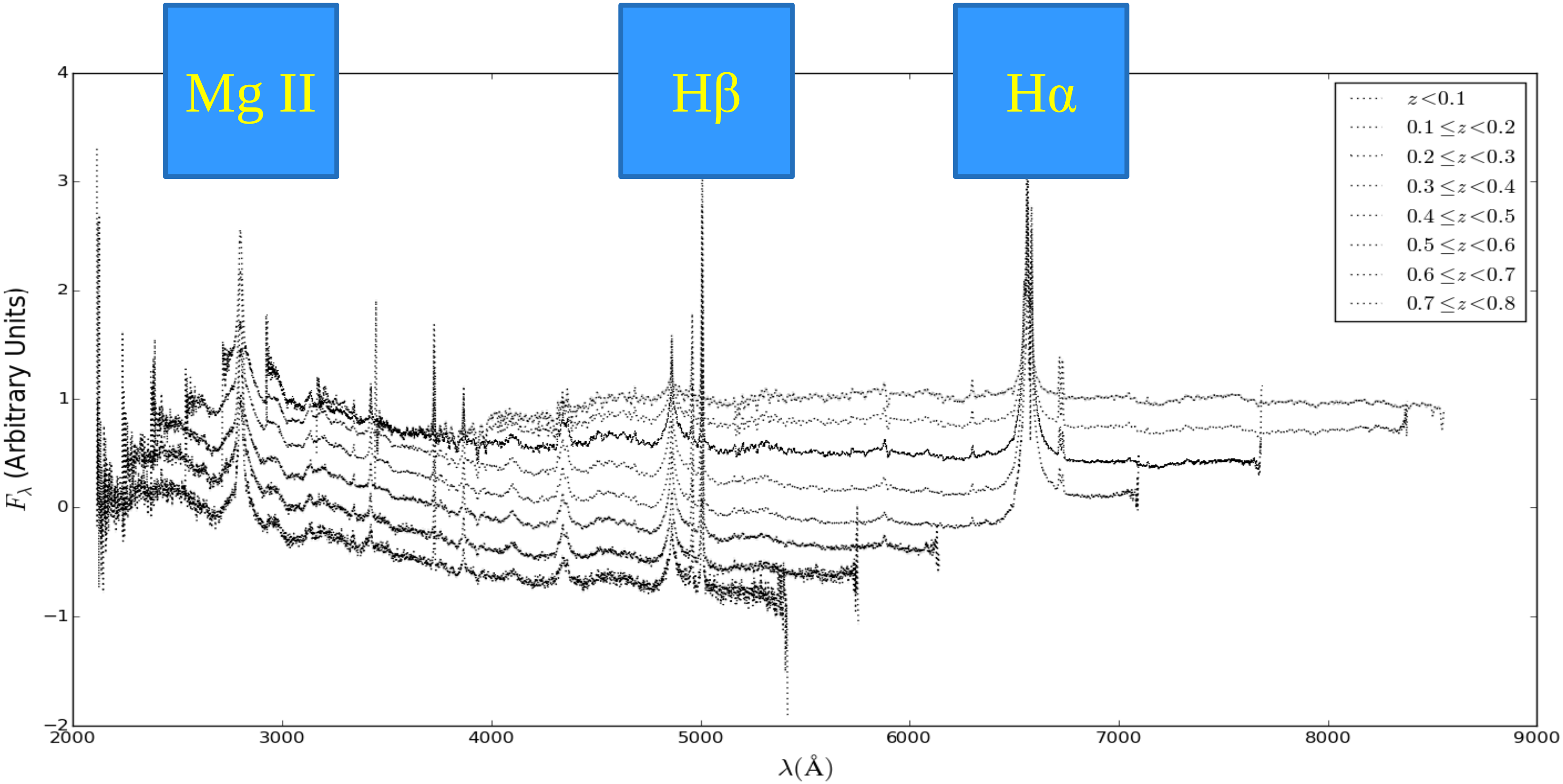
- Lyα, CIV, CIII], Mg II, Hβ, Hα
- Wind & disk , or high- and low-ionization lines (see e.g. Marziani 2019)
- Usually, Hβ Reverberation Measurements and then calibrating Mg II–based SMBH mass measurement (see Bahk et al. 2019)
- Then calibrating CIV, CIII] using Mg II line (see e.g. Mejía-Restrepo et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

The UV and optical broad lines

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

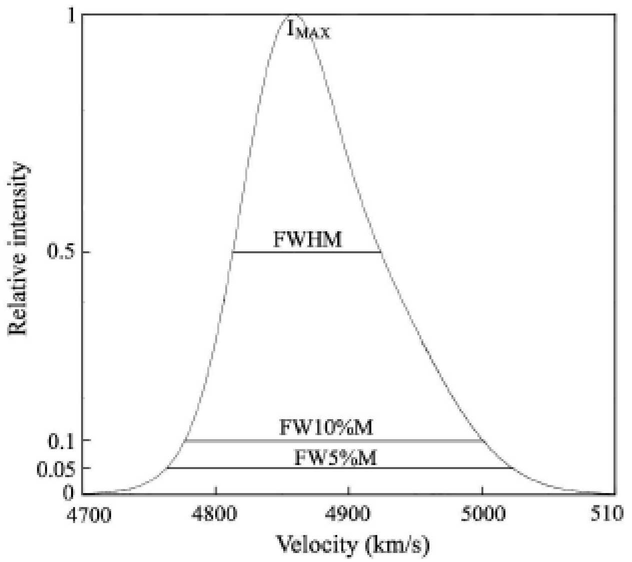
Very important

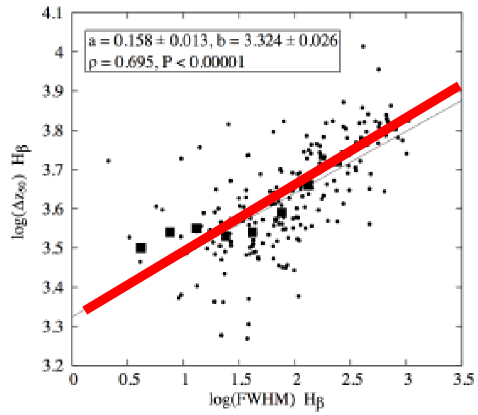
- Measure SMBHs on different cosmological scales, e.g in optical differeent lines (SDSS) at different redshift (Pol1 & Wadadekar 2017, MNRAS)

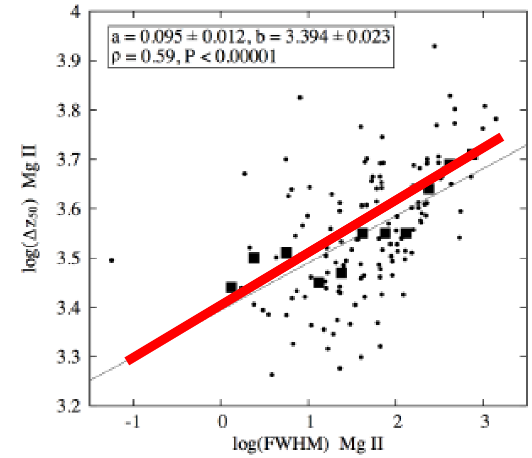


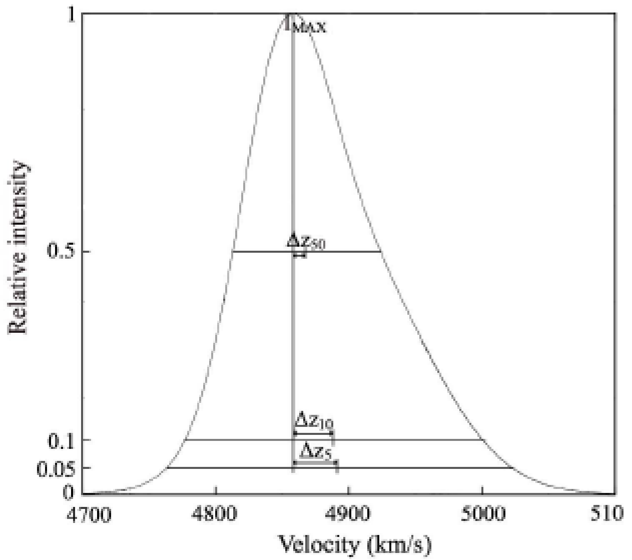
Difference between Mg II and Hβ, shift and width

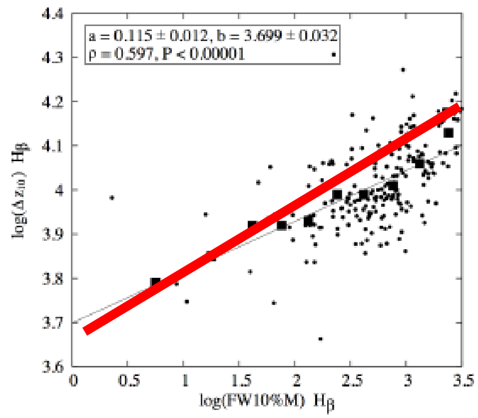
- Jonic et al. 2016, *z* *vs*. FWHM

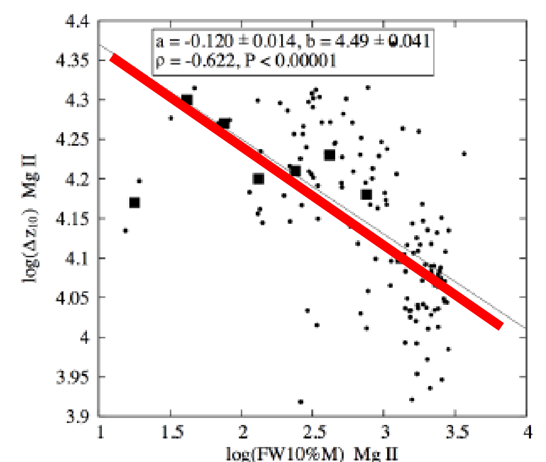






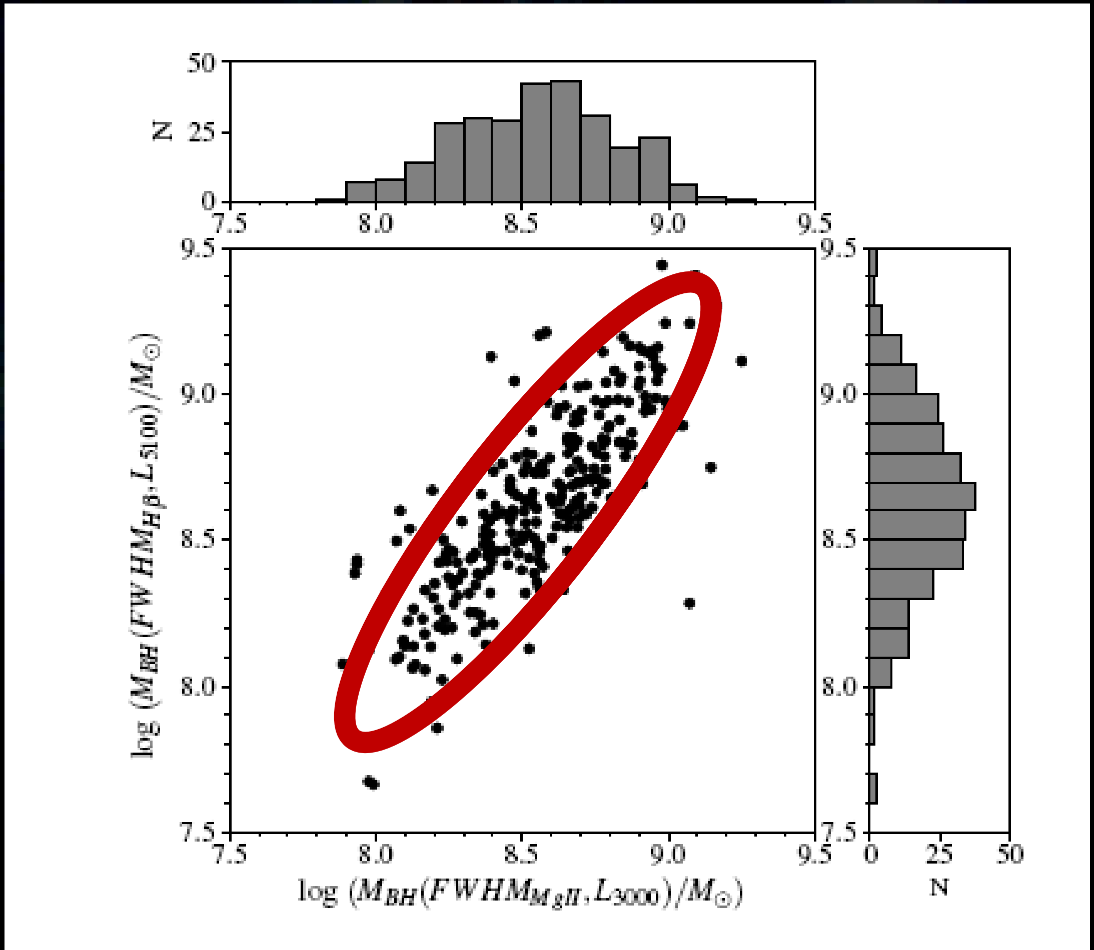






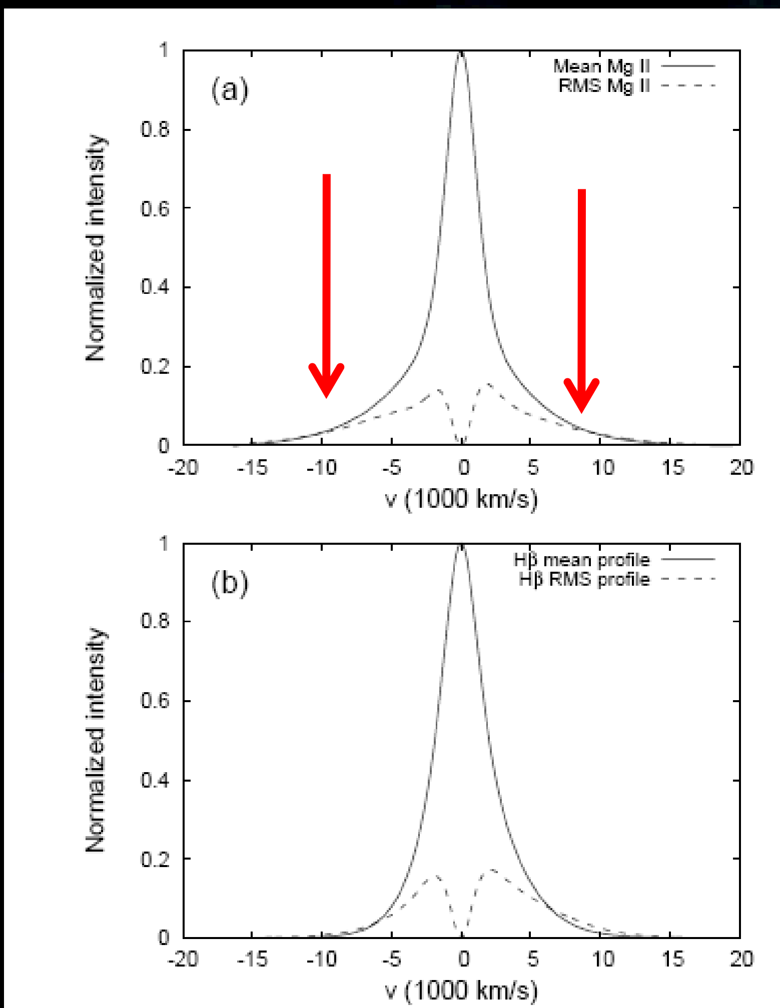
Mg II and Hβ

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

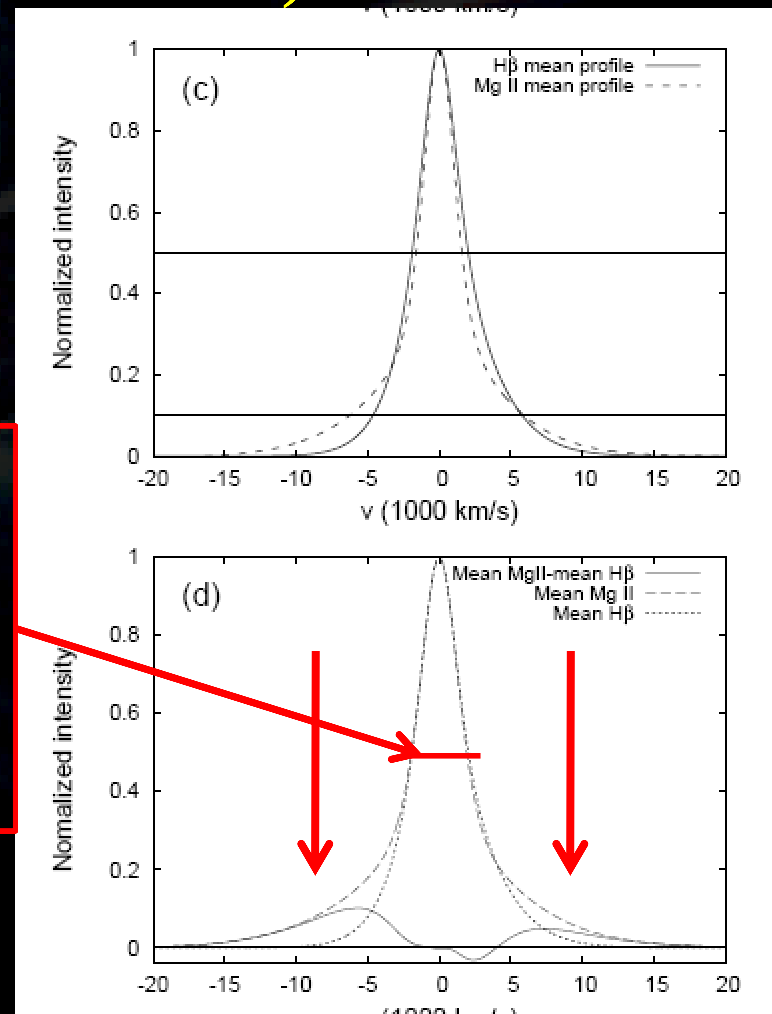


Seems to be good, but...

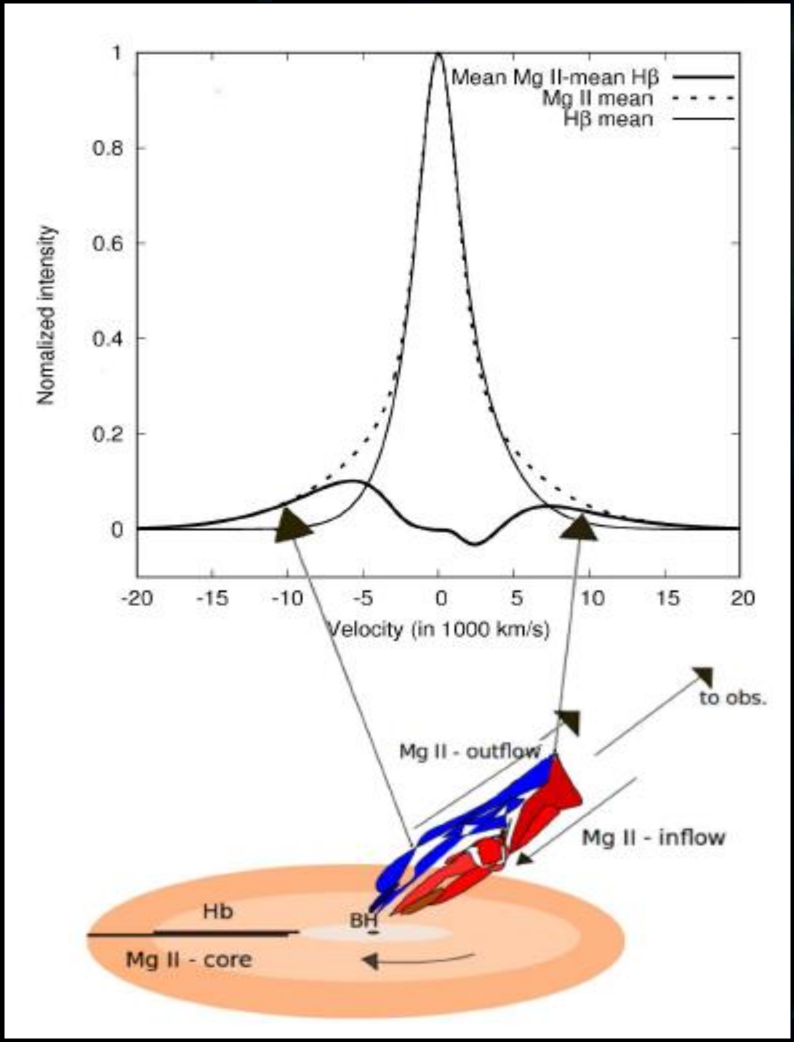
- Virialization in MgII and Hβ broad lines – line profiles (Popovic et al. 2019)

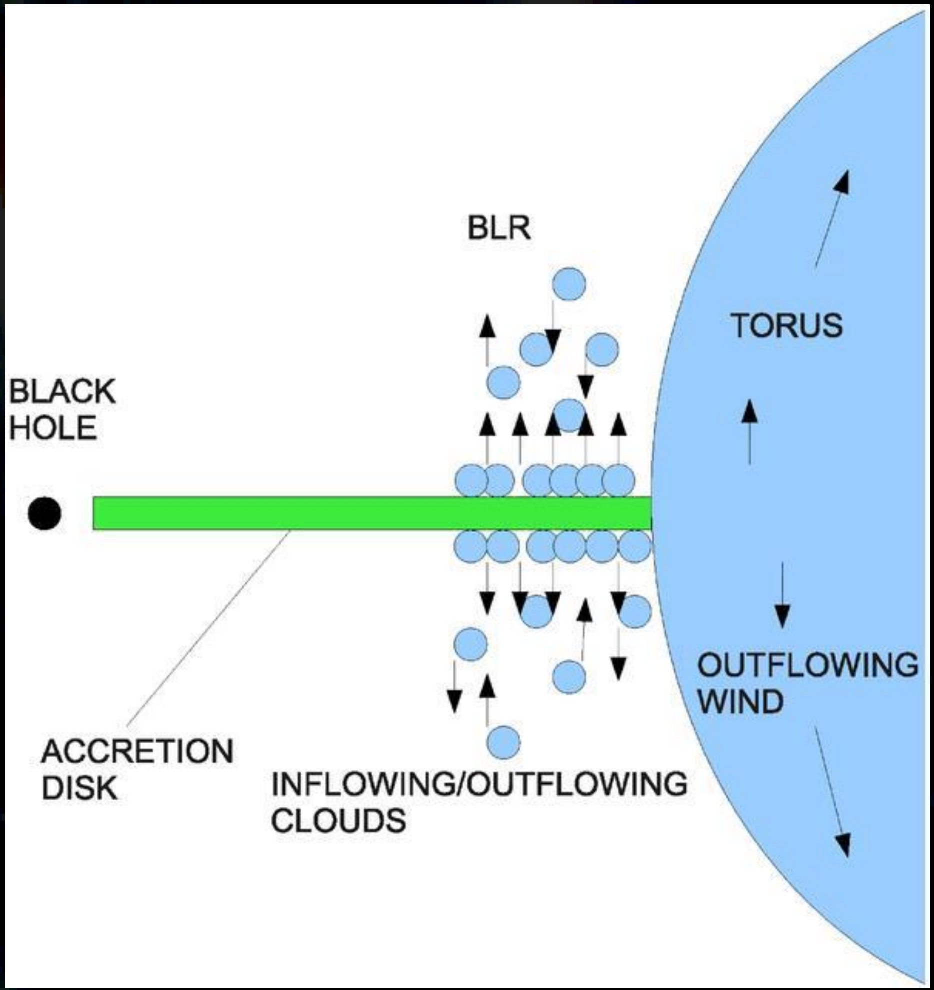


Same width-shape-geometry ?

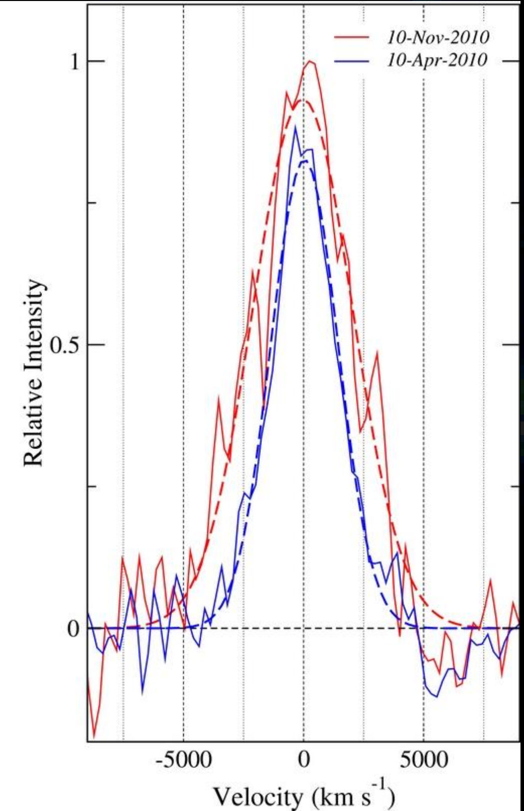


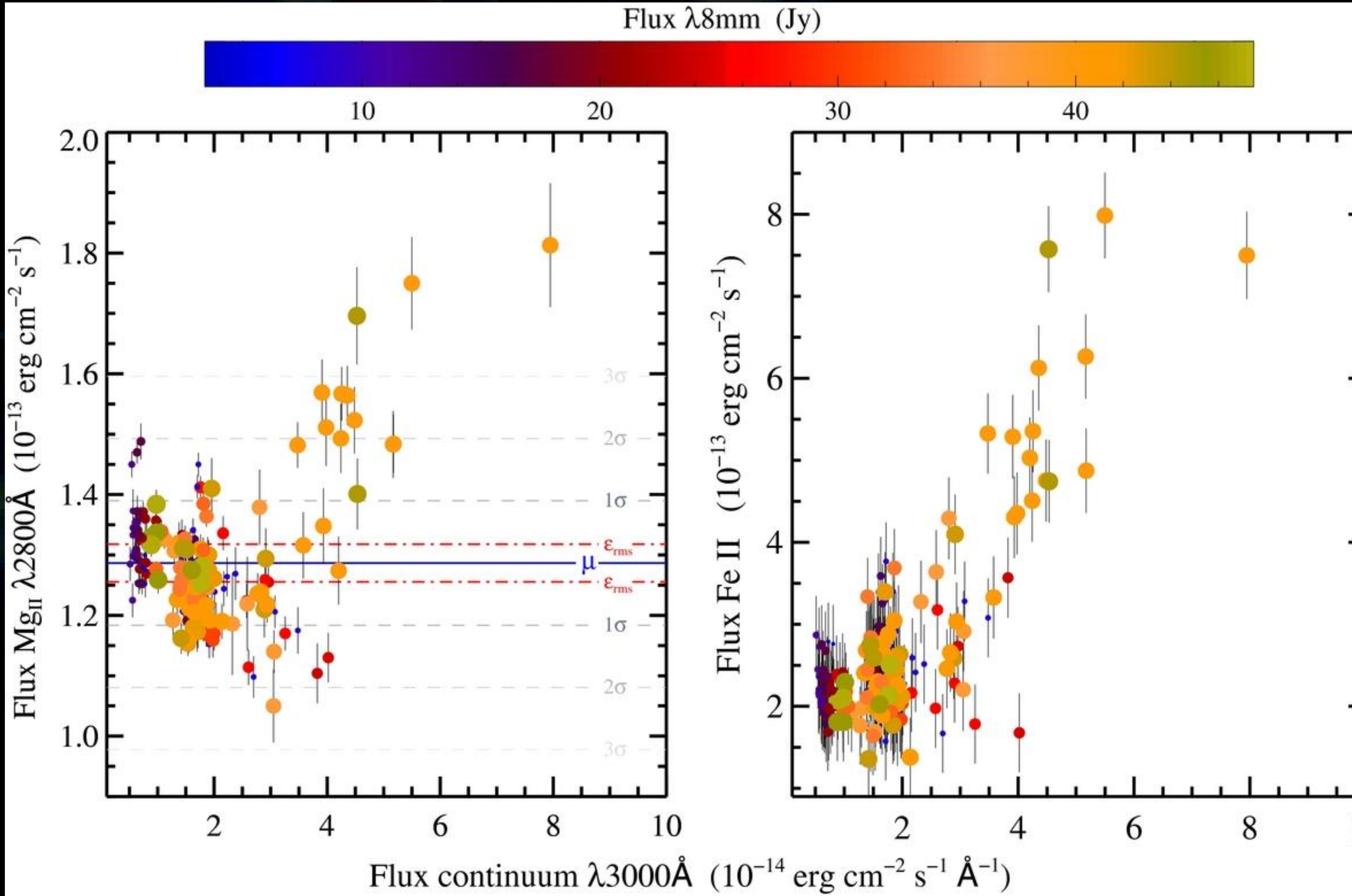
- Virialization in whole Mg II is a problem (Popovic et al. 2019), fountain-like region contribution to the Mg II wings, vertical motion see Czerny & Hryniewicz 2011, Kollatschny & Zetzl 2013, Czerny et al. 2017

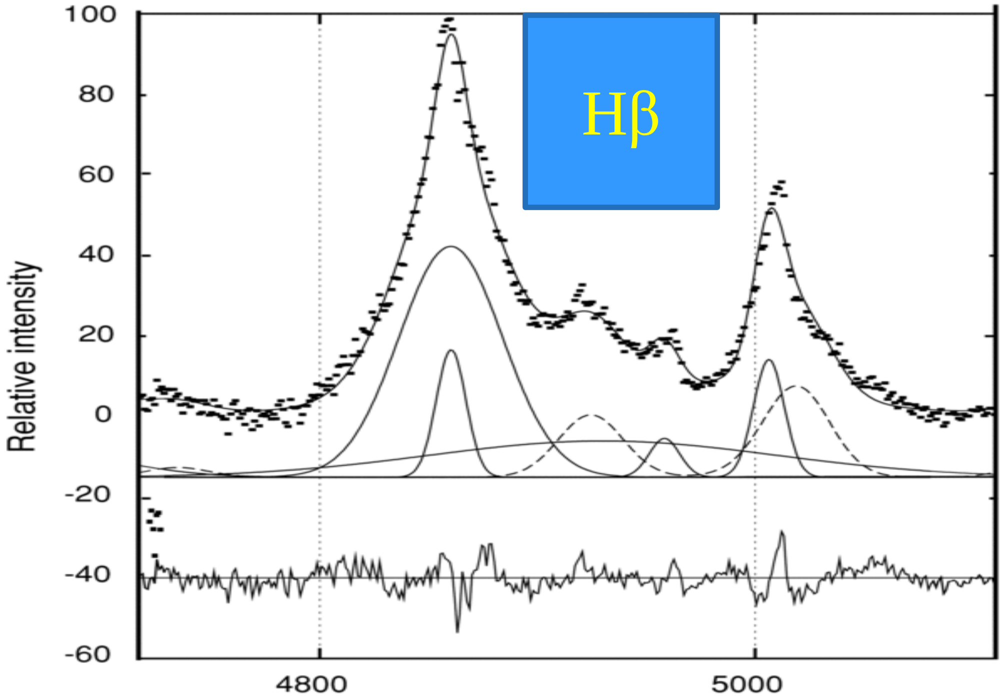


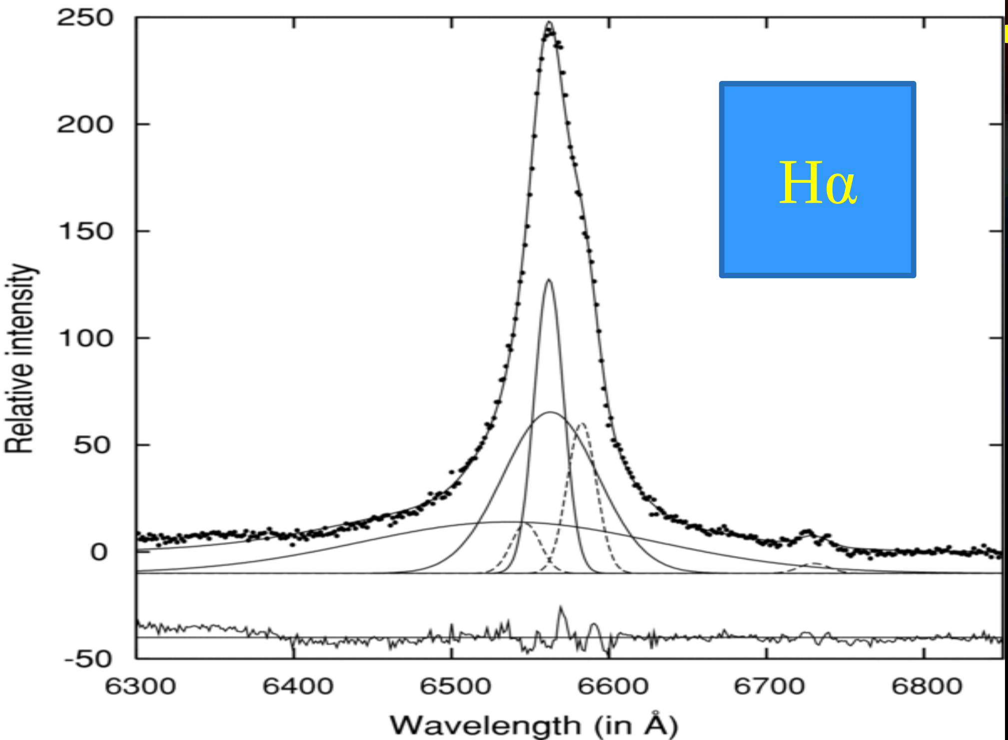


- Mg II very broad (Popovic et al. 2019) contribution of the 'fountain-like' region, see Leon-Tavares 2013. Be careful with huge FWHM, and without Lorentz-like profile (bumps in the Mg II wings)





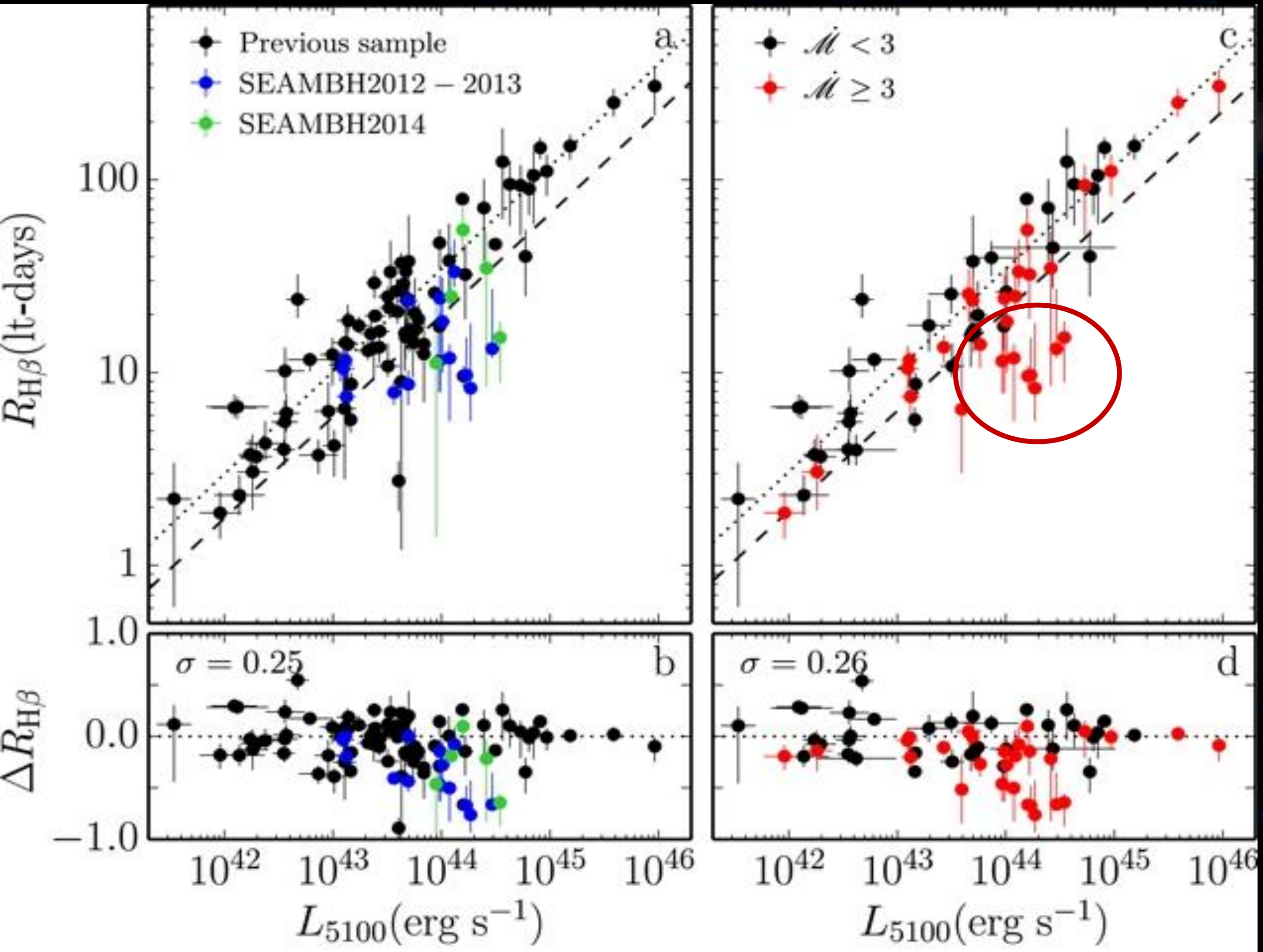




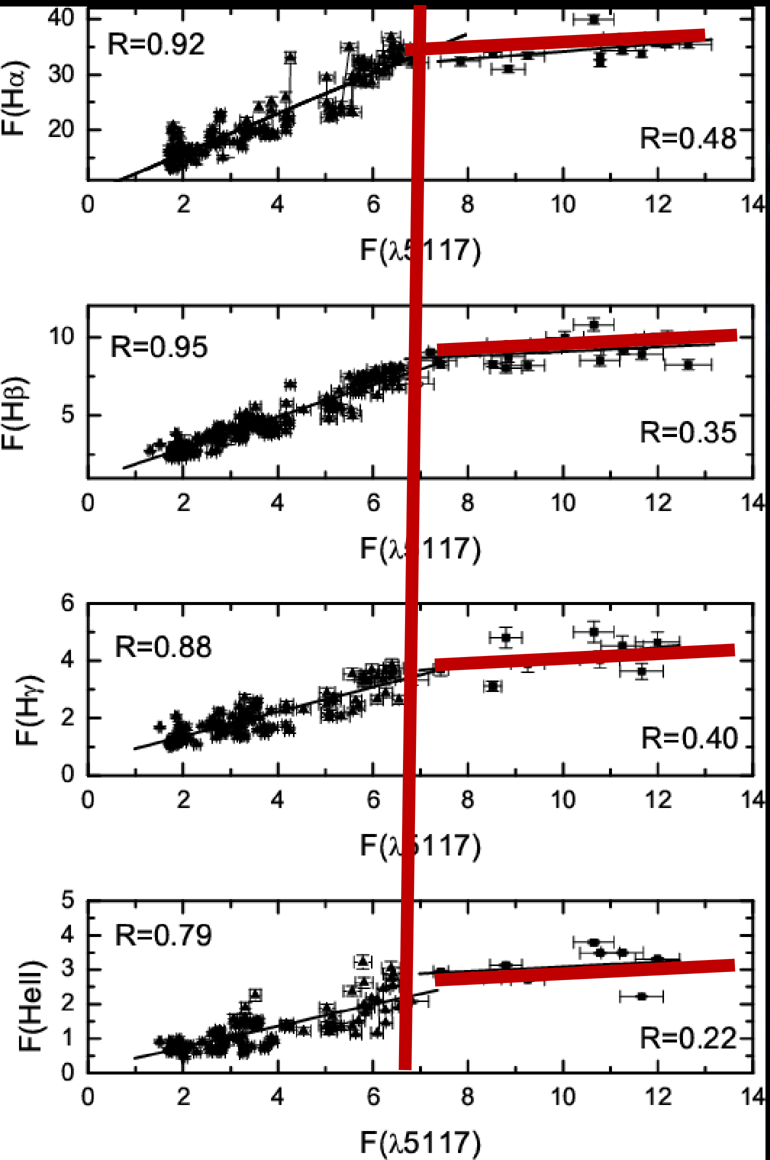
Some problems

- H β seems to be virialized (not so big vertical motion, NL Sy1?), but several problems:
- - complex BLR and accretion rate (Bozhana, Paola)

Problem with broad Hβ line, as e.g. Difference between Pop A and Popb 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

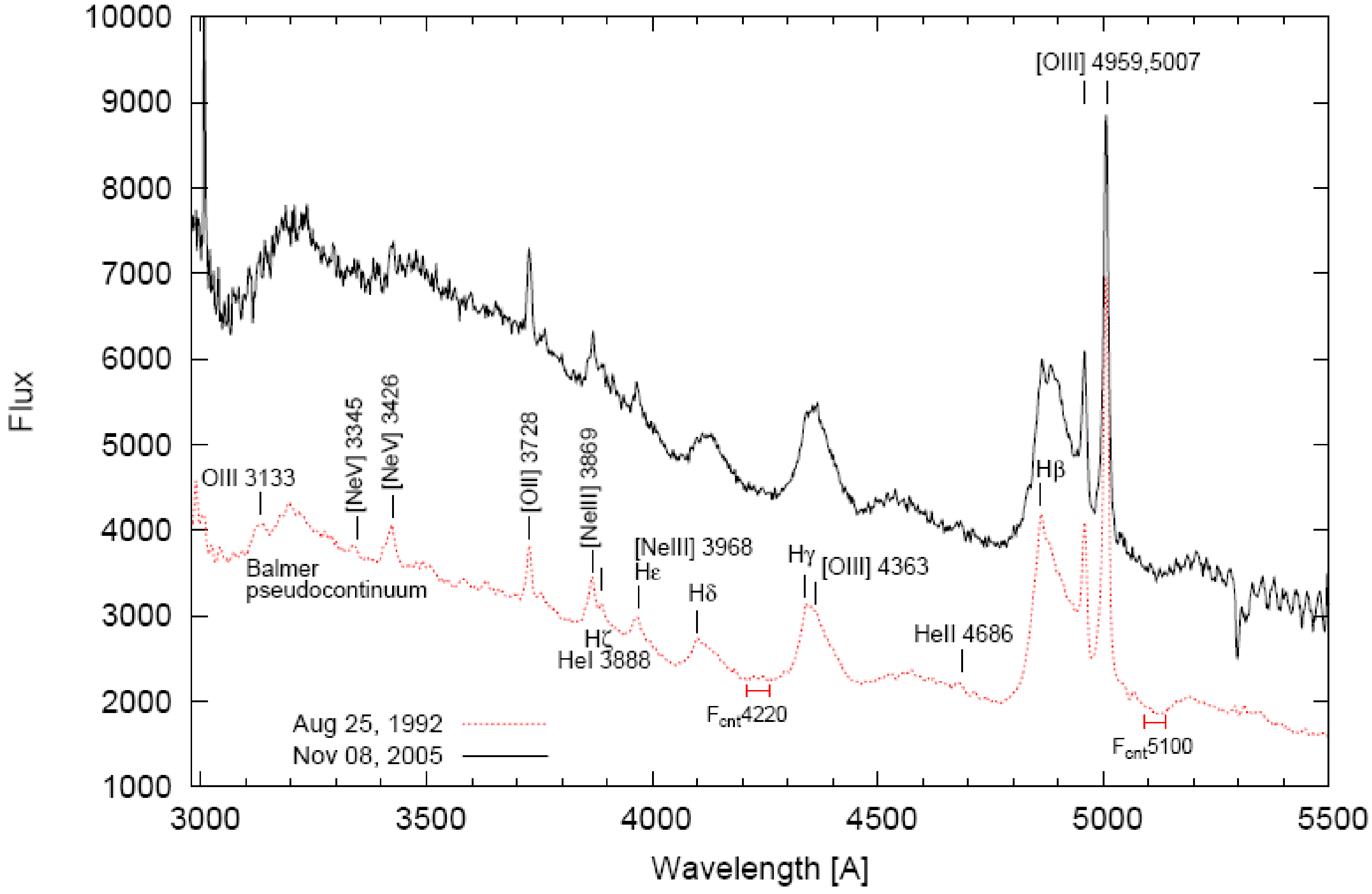


Continuum vs. line variability (e.g NGC4151, Shapovalova et al. 2008)



- - 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



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

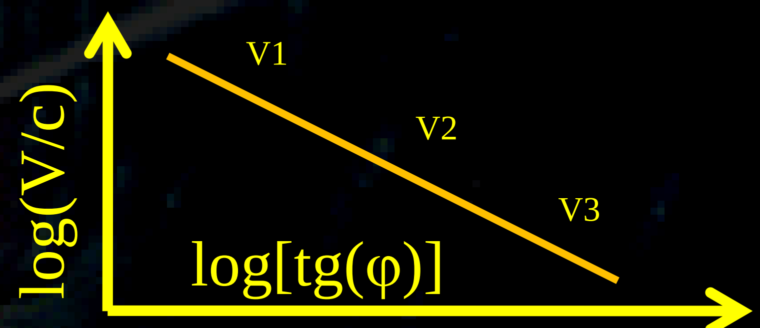
$$v_i = \sqrt{\frac{GM_{BH}}{R_{SC}\tan(\varphi_i)}},$$

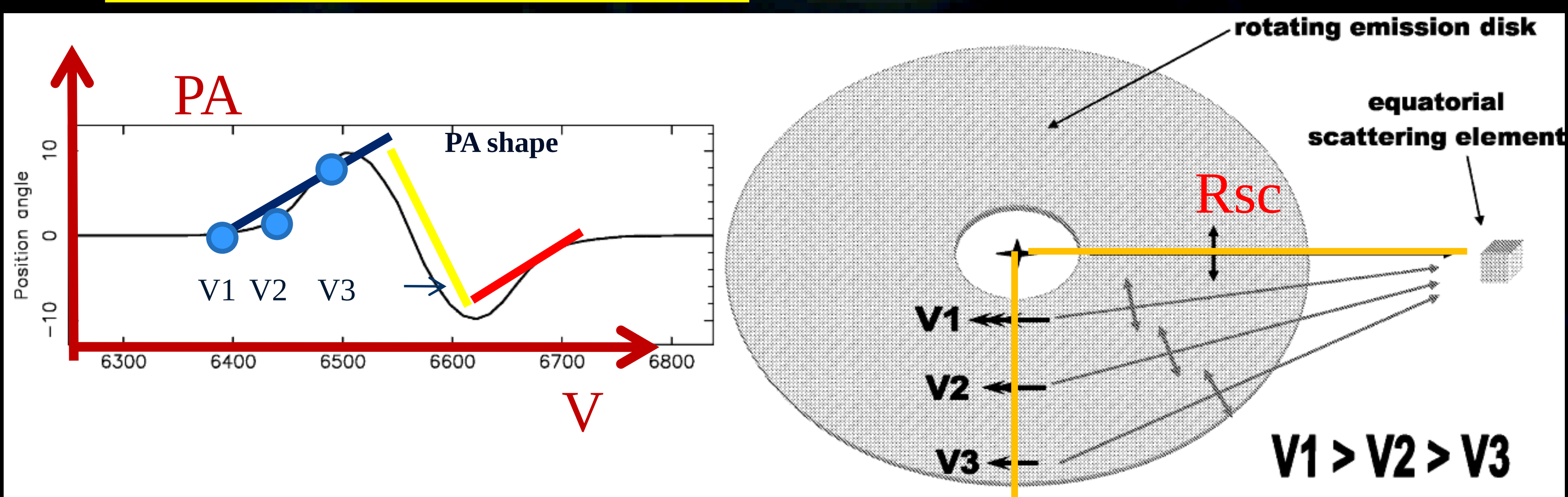
$$\log(v_i) = a - b\log(\tan(\varphi_i)),$$

$$b = 0.5$$

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

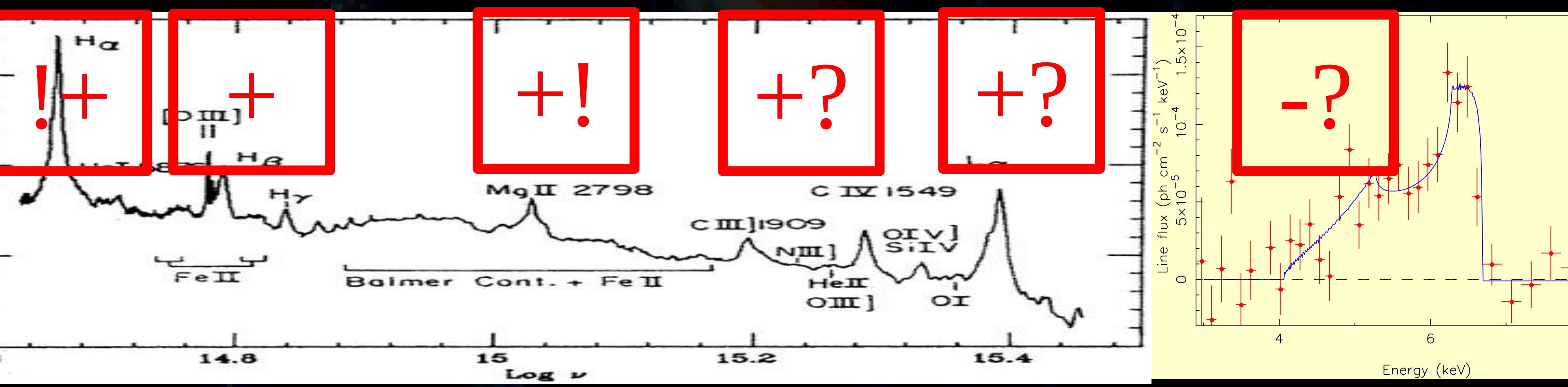
$$v = \sqrt{\frac{GM_{BH}}{R_{EC}}}$$





Conclusions

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



Thank you for your attention