Promenljivost sjaja aktivnih galaktičkih jezgara i priroda njihove aktivnosti

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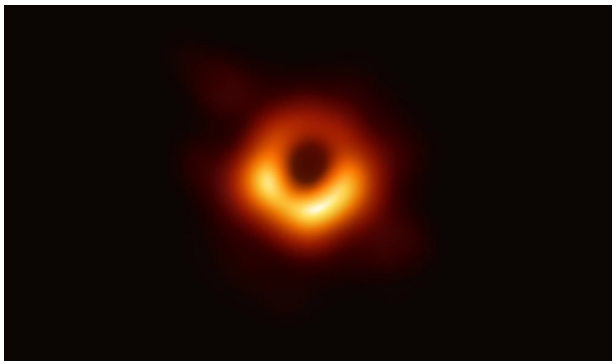


M87, EHT Collaboration 2019

Saradnici

Luka Popović, Anđelka Kovačević

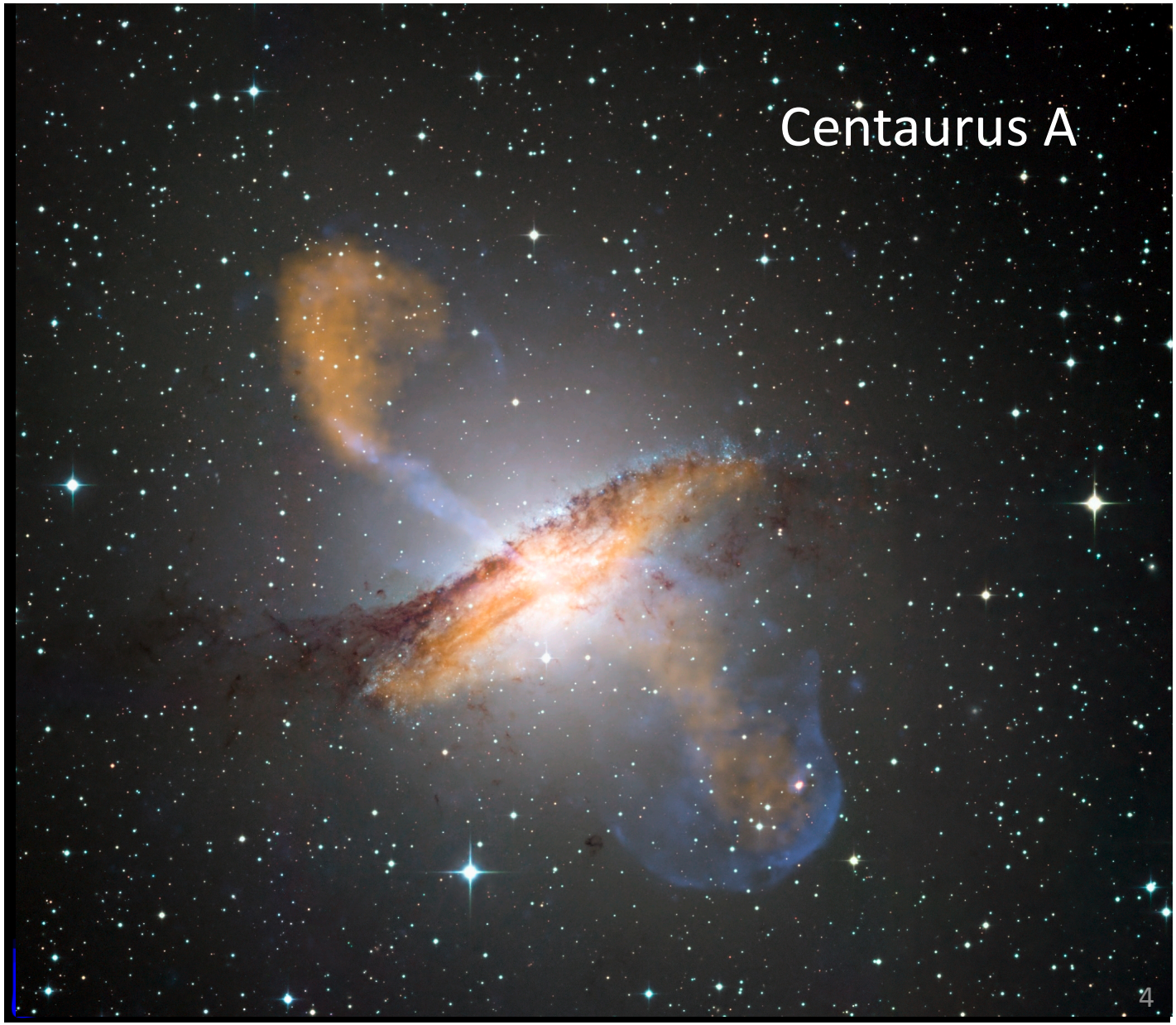
Saradnici

Foto, 12th SCSLSA, Vrdnik, 2020

- Nemanja Rakić, Isidora Jankov, Milica Vučetić, Bojan Arbutina, Dejan Urošević, Saša Simić, Slađana Marčeta-Mandić, Jelena Kovačević-Dojčinović, Vlada Srećković,Edi Bon, Nataša Bon, Marko Stalevski, Djordje Savić, Milan Dimitrijević …
- Alla Shapovalova, Stefano Ciroi, Piero Rafanelli, Wolfram Kollatschny, Alexander Burenkov, Vahram Chavushyan, Giovanni La Miura, Gisella de Rosa, Alexei Moiseev, Victor Osknyansky, Paola Marziani, Daniel Asmus, Elena Shablovniskaya, Victor Afanasiev…

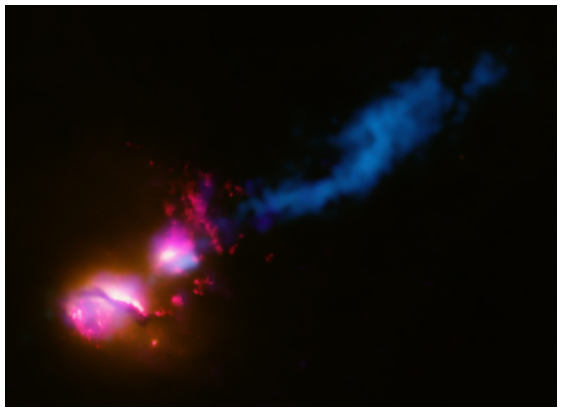
Aktivna Galaktička Jezgra (AGJ)=kvazari

*važno: centar i dalje teško može direktno da se posmatra!



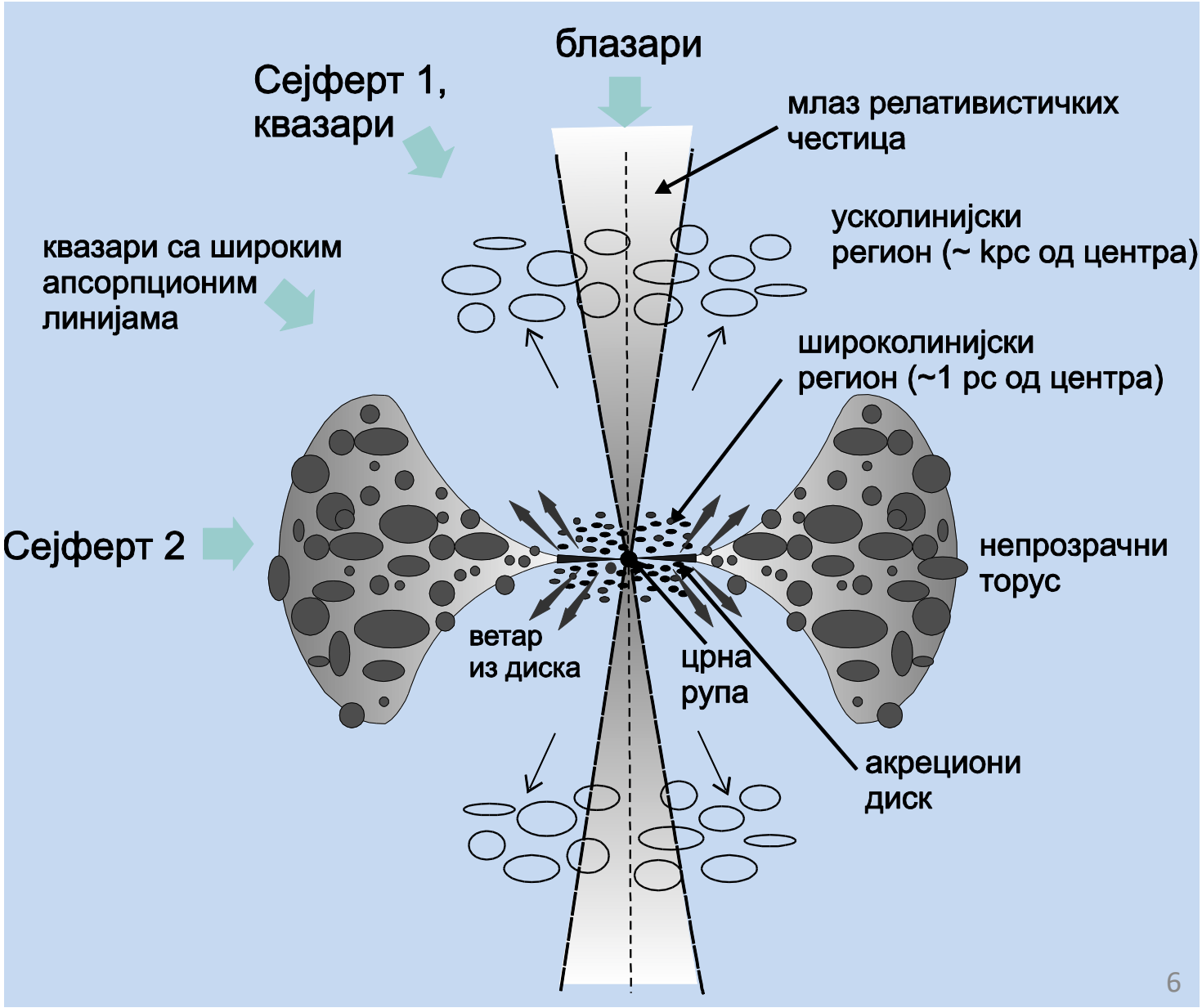
AKTIVNA GALAKTIČKA JEZGRA (AGJ)

- posmatrane karakteristike AGJ :
  - kompaktna veličina
  - ogroman sjaj: do 10^{15} puta sjaj Sunca
  - zrače na svim talasnim dužinama
  - intenzivne široke i uske emisione linije
  - promenjivost fluksa (~1 dan!)
  - najjači radio-izvori
  - polarizovano zračenje



Jedinstveni model AGJ

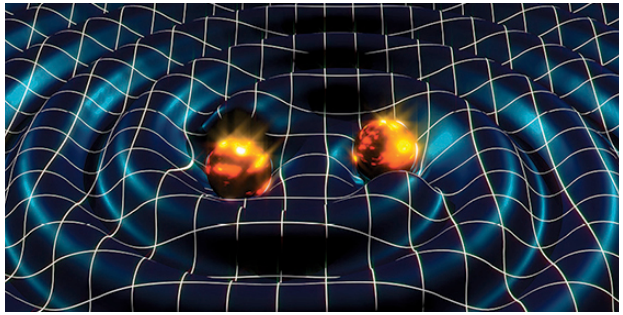
- supermasivna crna rupa
  - od milion do 10 milijardi Msun
- akrecioni disk
- emisioni regioni koji emituju široke i uske emisione linije
- “torus” prašine
- mlazevi relativističkih elektrona



Značaj AGJ/kvazara

M87, EHT Collaboration, 2019

- Formiranje i evolucija galaksija
  - aktivnost u galaksijama – verovatno prisutna u svakoj galaksiji u nekoj fazi evolucije
  - sve (velike)galaksije imaju u svom jezgru supermasivnu crnu rupu
    - kako nastaju? kako rastu?
- "multimessenger" astronomija: gravitacioni talasi
  - potraga za dvojnim supermasivnim crnim rupama
    - teško ih je naći na malim skalama (e.g. Popović+12, Komossa+03, Ge+12, Benitez+18)
    - važnost spektroskopije (Bon+12,16, Liu+16) i analize periodičnosti u fotometrijskim krivama sjaja (Graham+09,17, Kovačević+2019)
- osnovni cilj astronomije → nove metode za merenje rastojanja koristeći kvazare
  - npr. koristeći UV i optičke široke emisione linije (e.g. Watson+11, Marziani+20)

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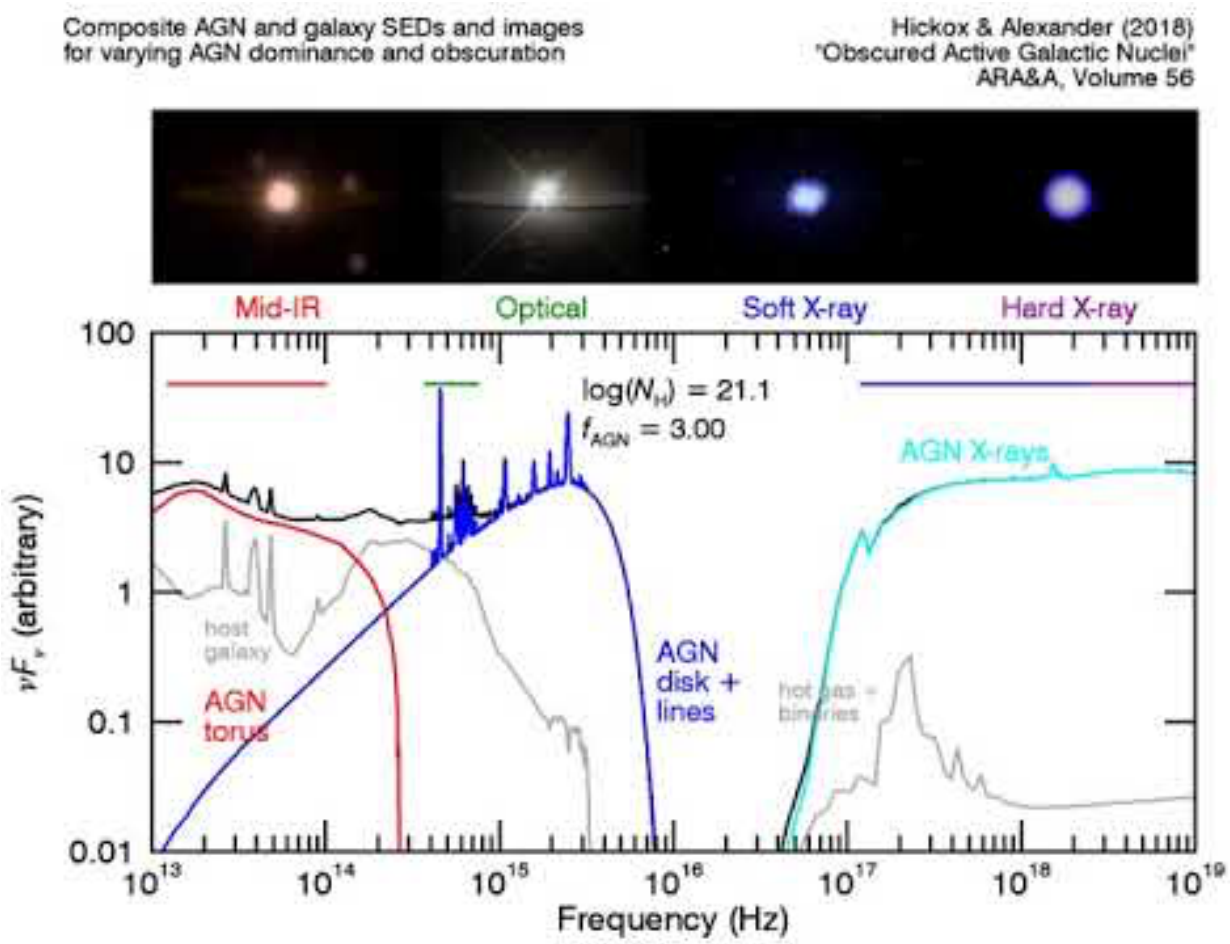
A šta možemo da posmatramo?

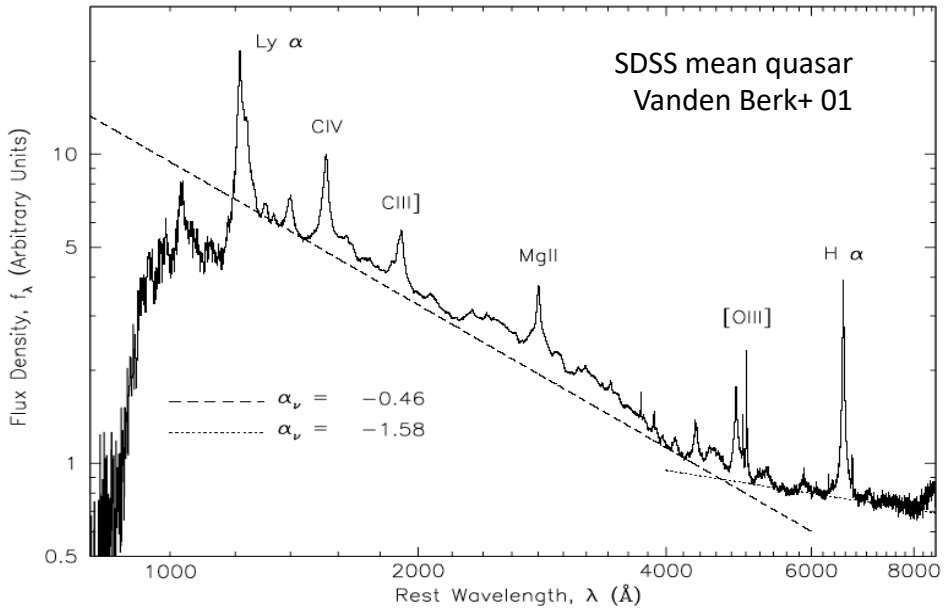
- spektar na svim talasnim dužinama
- sve tehnike
  - fotometrija
  - spektroskopija
  - polarimetrija

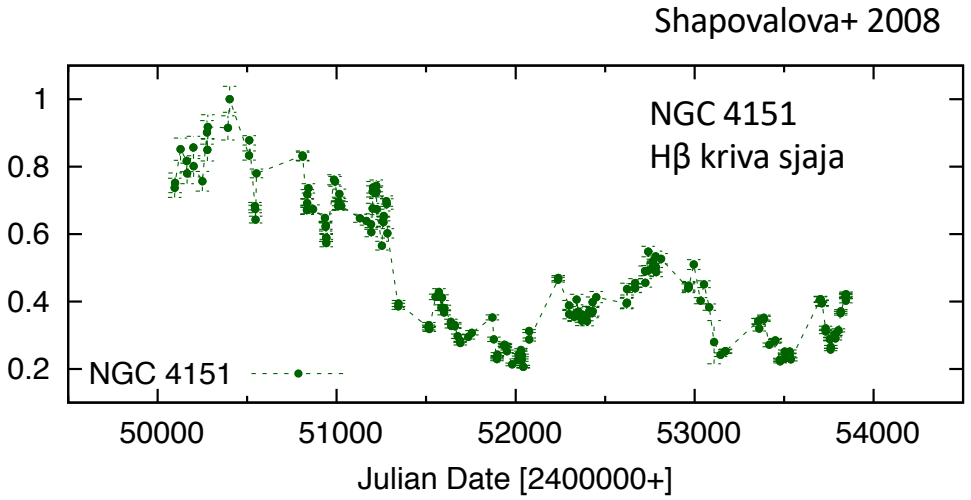


Optička spektroskopija AGJ

Široke emisione linije (širina i preko 10,000 km/s)
- Različiti stepeni jonizacije
- Kompleksni profili
- Moćan alat za dijagnostiku fizičkih i kinematičkih uslova

Sve se menja!
- fluks kontinuuma i u linijama
- profili linija
- ponekad ekstremna promenjivost



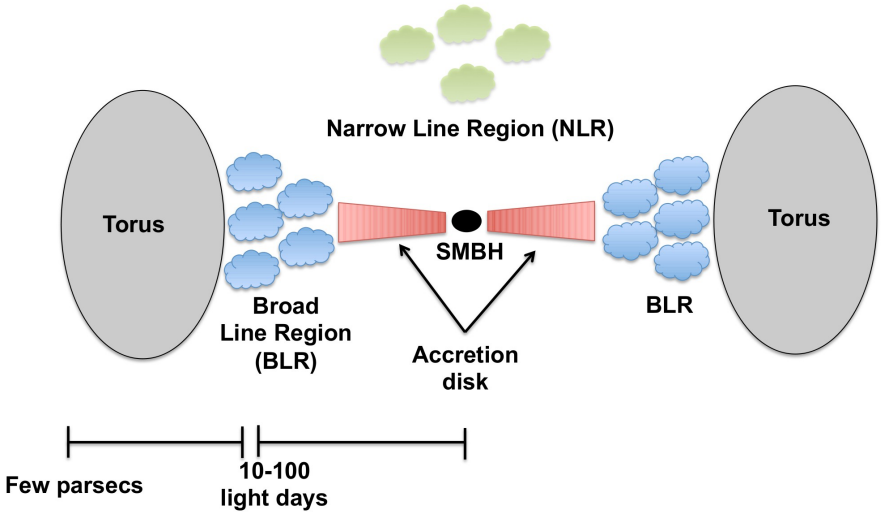


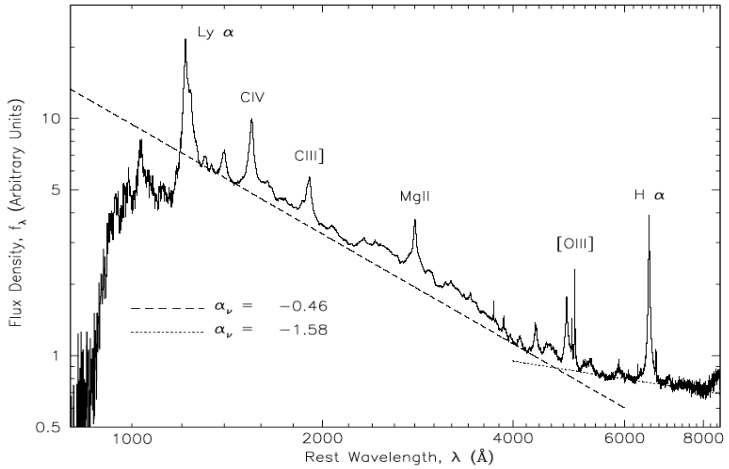
Emisioni gas u AGJ

- **tip 1 AGJ** – sa širokim emisionim linijama
  → širokolinijska oblast (***Broad Line Region - BLR***)

- kako znamo da postoji BLR? NE ZNAMO!
  → imaging: VLT- GRAVITY (10 μas, Sturm+ 18), budući ELTs
  → **spektroskopija i dalje jako važna**

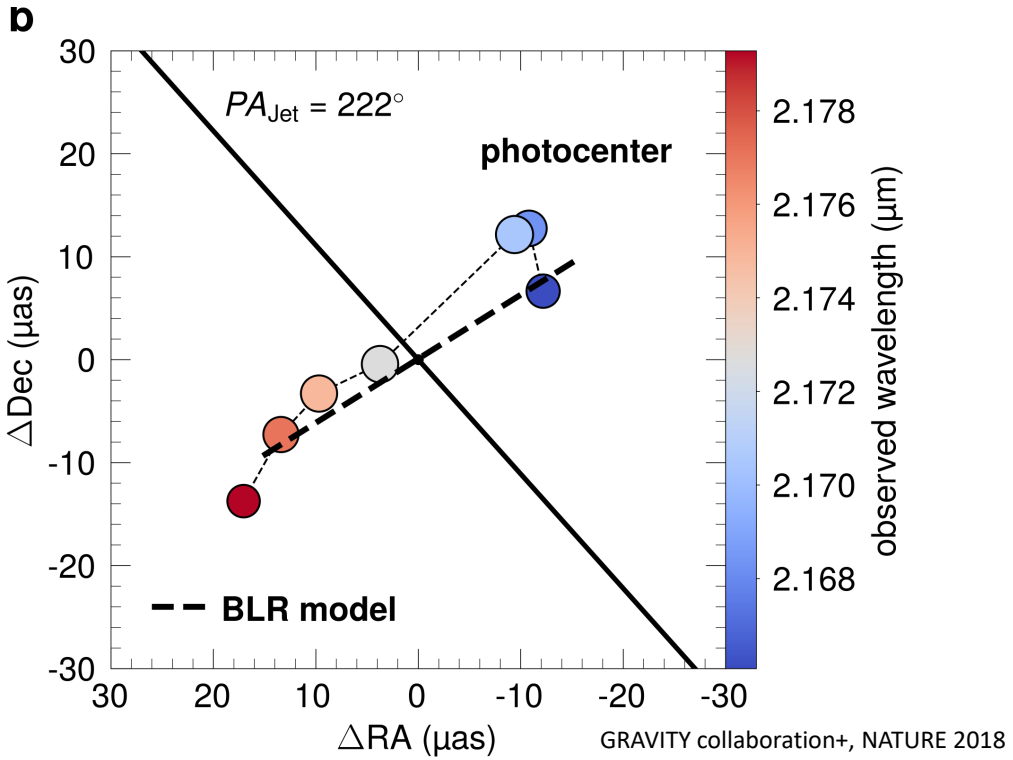
- BLR fizika i geometrija i dalje nisu u potpunosti istražene
  → koja je temperatura gasa i gustine? (Ilić+12)
  → da li je BLR gravitaciono vezana za crnu rupu? (Popović+2019)
  → kakva su kretanja gasa, rotacija ili izbacivanje? (e.g. Wang+17)
  → koji je nagib ovog regiona prema posmatraču? (e.g. Afanasiev+18)





Prostorna → vremenska rezolucija

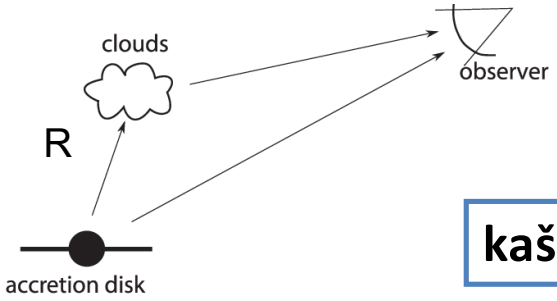
- Oblasti gasa u blizini supermasivne crne rupe je skoro nemoguće direktno posmatrati sa postojećim optičkim teleskopima (osim w/GRAVITY, Sturm+2018)
  → **spectroscopy still important tool**
- ali možemo da posmatramo u vremenskom domenu (kao i pomoću spektropolarimetrije, npr. Afanasiev et al. 2019), i da dobijemo:
  - Dimenzije BLR
  - Kinematku gasa
  - Masu supermasivne crne rupe



GRAVITY collaboration+, NATURE 2018

Reverberaciono mapiranje (RM)

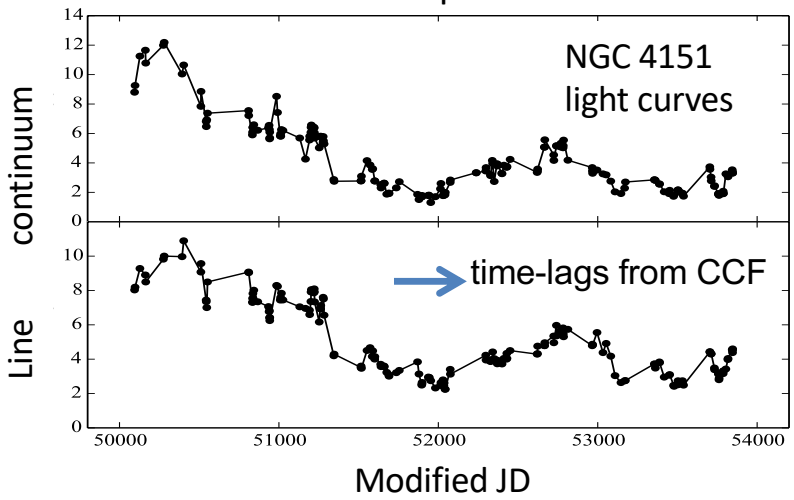
- postoji kašnjenje *(time-delay)* između fluksa kontinuuma i linije



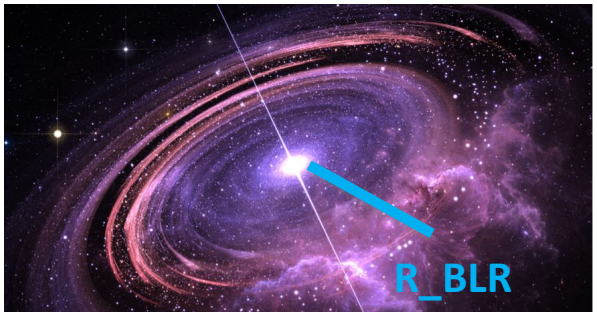
Lyutyi & Cherepashchuk, 1972;
Blandford & McKee, 1982;
Gaskell & Sparke, 1986

kašnjenje τ = dimenzija R

Shapovalova+ 2008



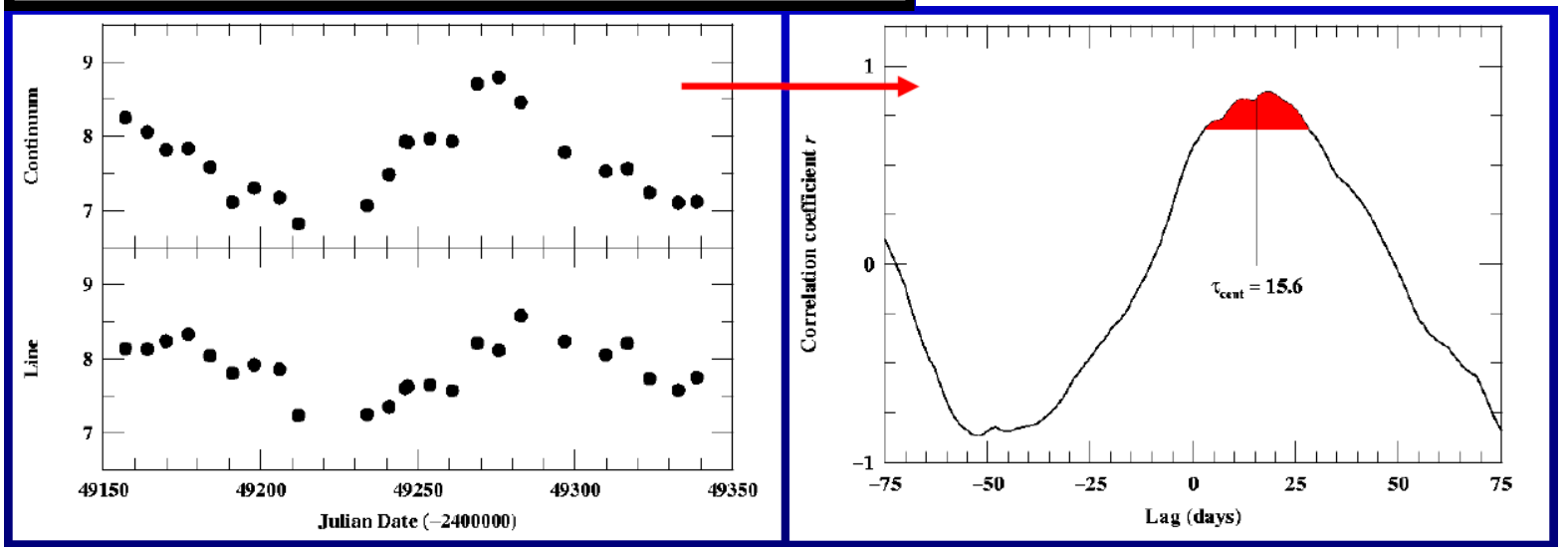
- urađeno za 100ak AGJ: direktno merenje **dimenzija širokolinijskog regiona**
(e.g. Kaspi+ 2000, Peterson+ 2004, Bentz+2009, Shapovalova+ 2008-2019)



Reverberaciono mapiranje (RM)

$$\mathrm{CCF}(\tau) = \int_{-\infty}^{\infty} \Psi(\tau')\,\mathrm{ACF}(\tau-\tau')\,d\tau'$$

kros-korelaciona funkcija



- kašnjenje signala u linijama ⇒ dimenzije BLR

Lyutyi & Cherepashchuk 1972, Blandford & McKee 1982, Gaskell & Sparke, 1986, Wandel et al. 1999, Kollatschny et al. 2001, Kaspi 2000, Peterson et al. 2004, Shapovalova et al. 2008…

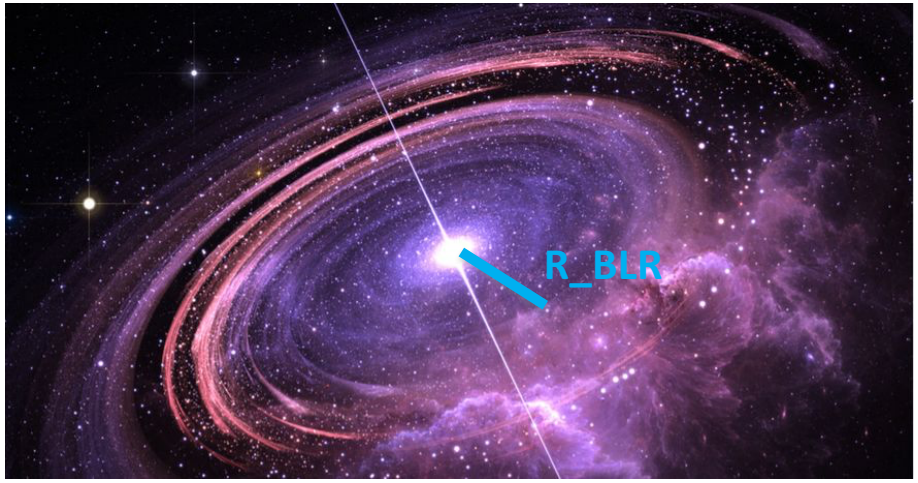
Određivanje mase SMCR iz emisionih linija

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

(Gaskell & Sparke, 1986; Wandel+ 1999; Kaspi+ 2000, 2005; Peterson+ 2004, Bentz+ 2009, itd.)

- **teorema virijala**:
  ako je gas gravitaciono vezan za crnu rupu, možemo odrediti njenu masu iz brzine gasa i rastojanja od centra

- **Recept za masu crne rupe**:
  1. brzina gasa iz širine linija
  2. dimenzije BLR iz reverberacija
  3. *faktor f* (geometrija BLR)

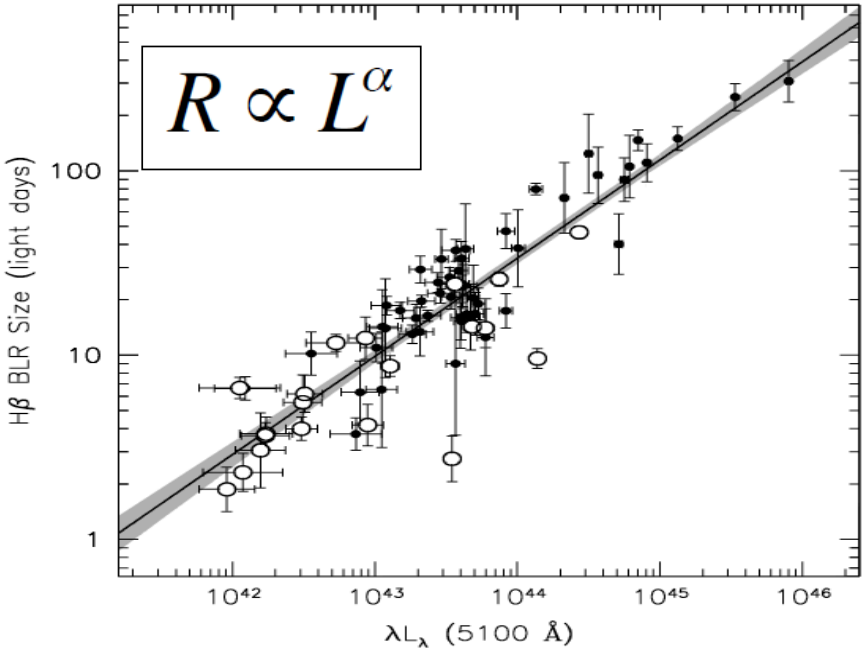


Emprijska relacija radijus-sjaj

- ”Radius-Luminosity” R-L relacija

(e.g. Kaspi+ 2000, Peterson+ 2004, Bentz+2009, Bentz+2013, etc.)

- možemo odrediti masu supermasivne crne rupe iz samo jednogh posmatranja
  - i tako za milione objekata (primena u pregledima neba, npr. SDSS)
  - kad znamo masu, možemo odrediti stepen akrecije, Edingtonov sjaj, itd.



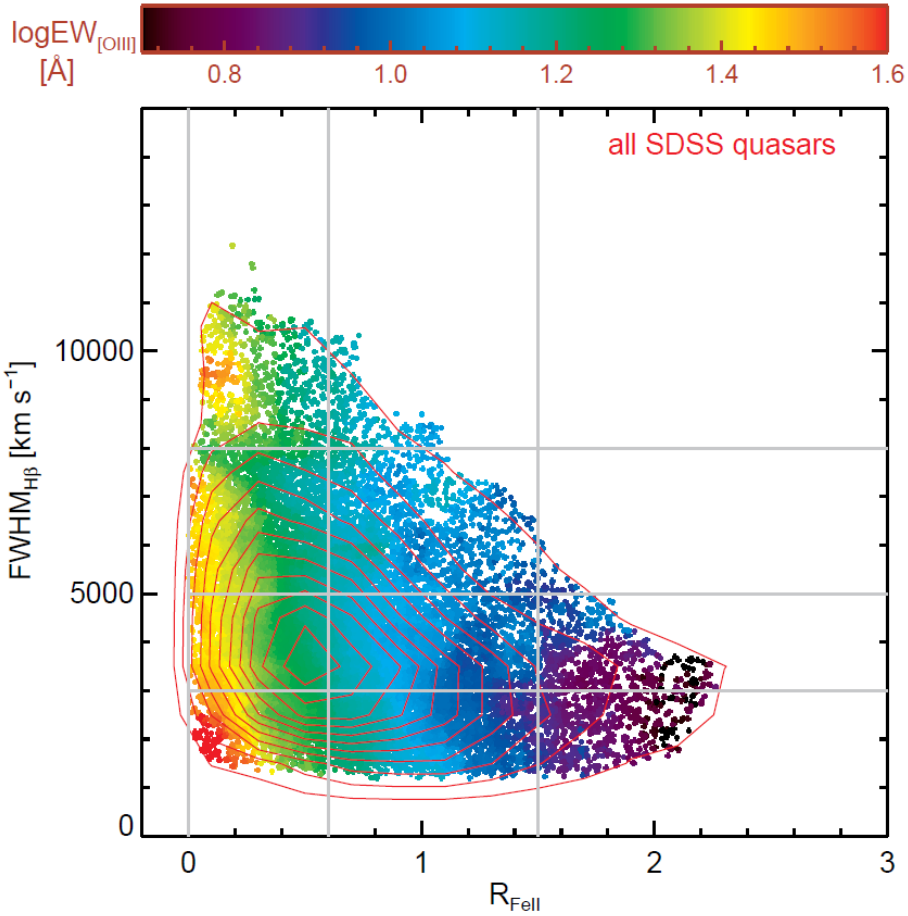
“Glavni niz” kod kvazara

Boroson & Green (1992)

- primena analize glavnih komponenti (Principal component analysis – PCA)
- definisan Eigenvector 1 kao anti-korelacija između EW [O III] λ5007 i EW FeII λ4570

Sulentic et al. (2000)

- definišu Eigenvector 1 parametarski prostor → analogon HR dijagrama
- postojanje glavnog niza kvazara
- stepen akrecije (Edingtonov odnos) verovatno stoji iza toga

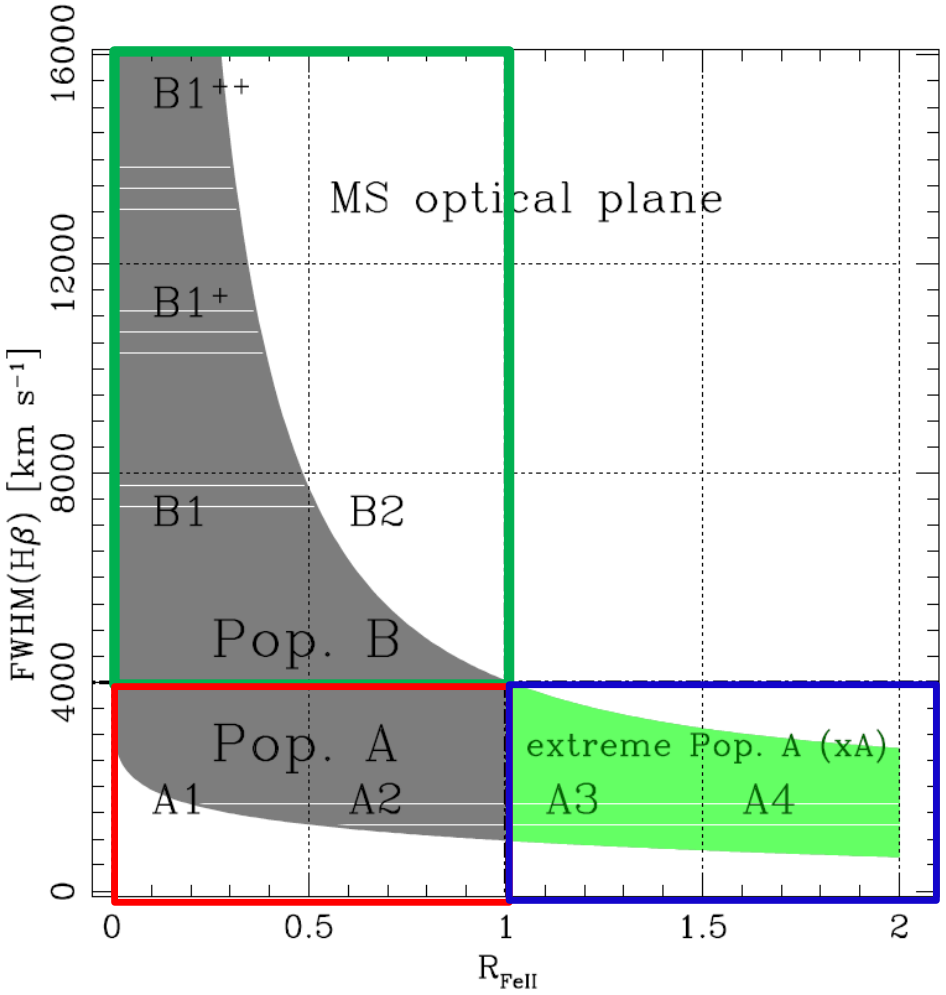


Shen&Ho, 2014, Nature

Populacije kvazara

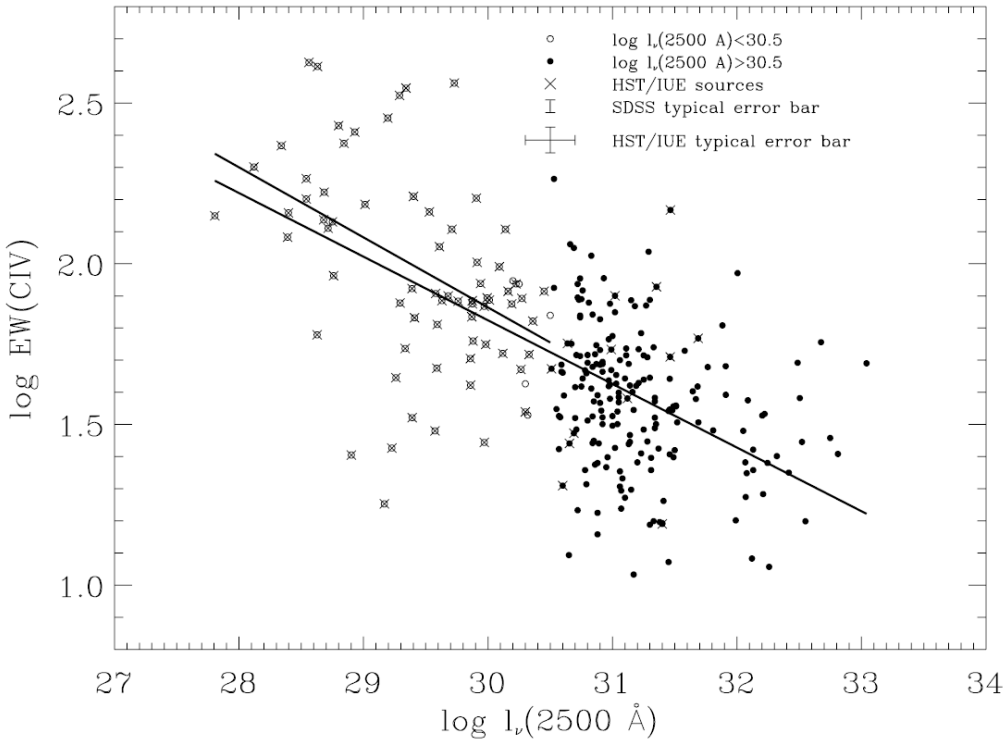
Podela na osnovu širine Hβ linije i jačine FeII linija (e.g. Sulentic et al. 2000, Marziani et al. 2018, N.Bon+2019)

- Populacija A
  - FWHM Hβ < 4000 km/s
  - $\boldsymbol{R}\mathbf{FeII}$ < 1
- Populacija B
  - FWHM Hβ > 4000 km/s
- Populacija xA
  - FWHM Hβ < 4000 km/s
  - $\boldsymbol{R}\mathbf{FeII}$ > 1

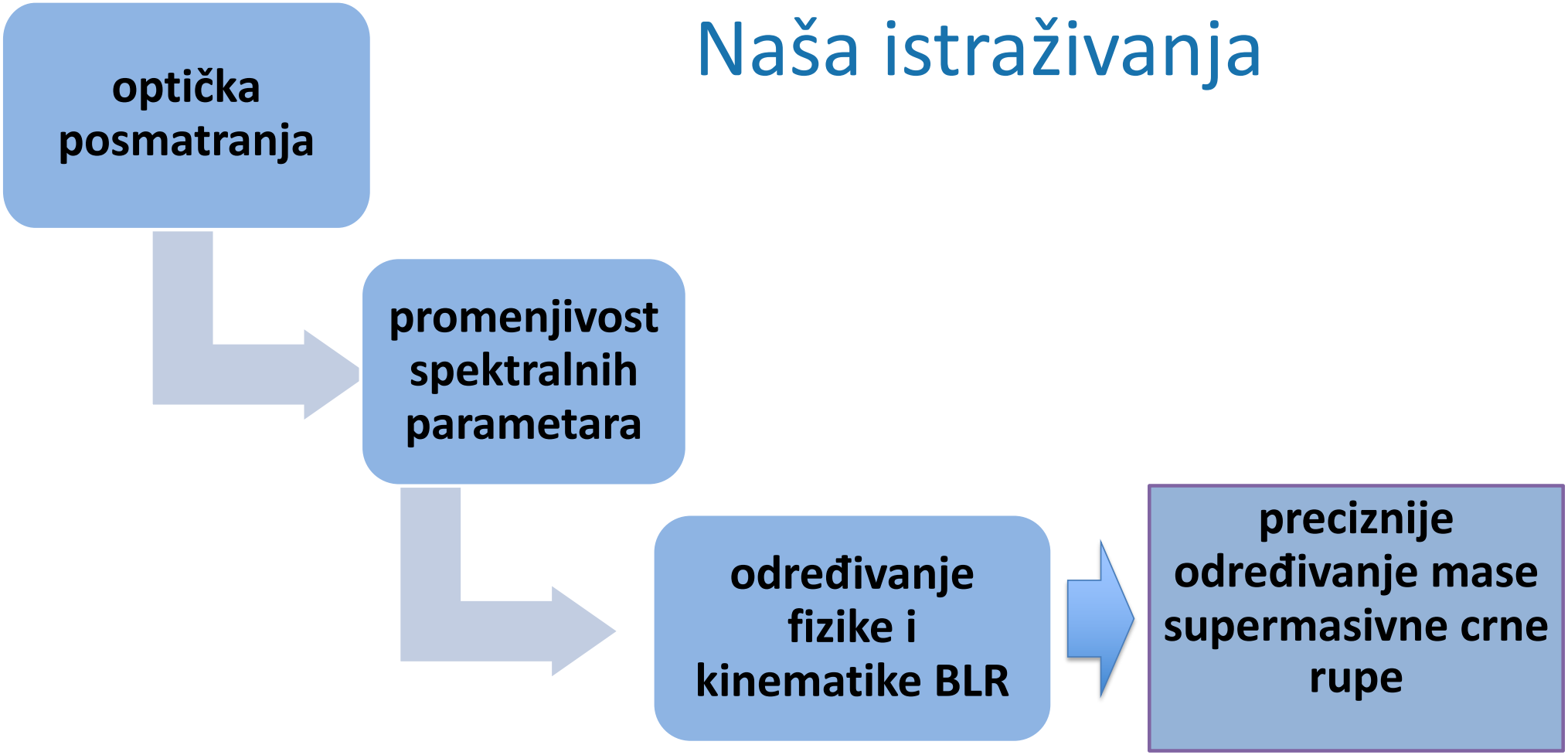


Baldvinov efekat

- **Baldwin (1977)**
  - Anti-korelacija između ekvivalentne širine C IV linije i luminoznosti kontinuuma
  - primećeno i kod drugih linija, pre svega širokih (Rakić+2017), ali i uskih linija



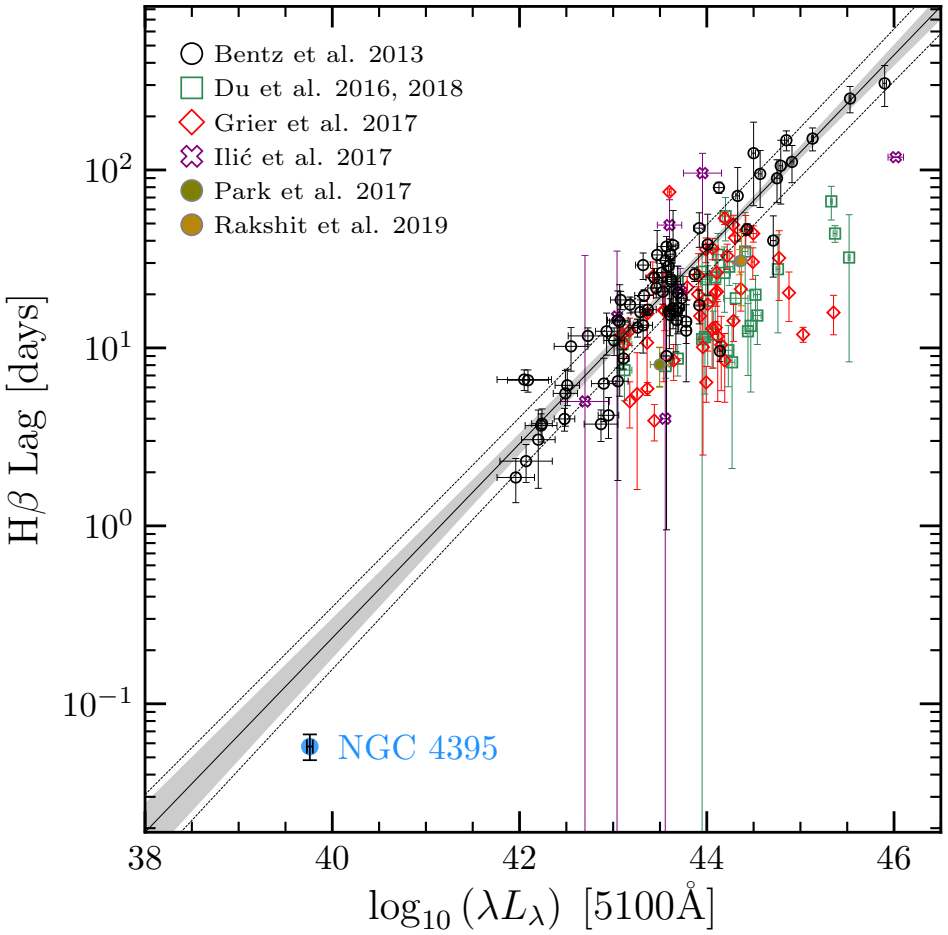
Naša istraživanja



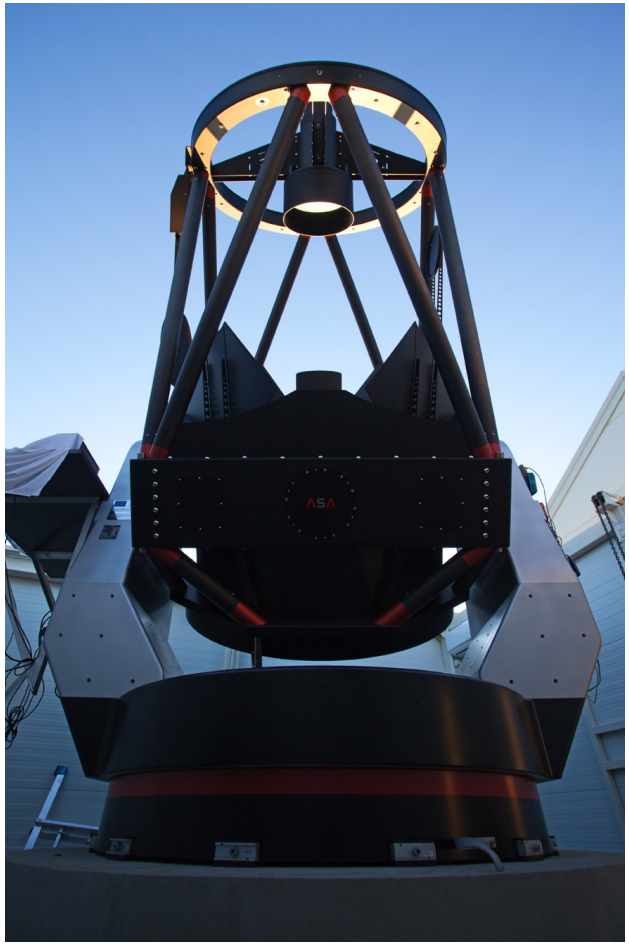
Istraživanja crnih rupa srednjih masa

- "Variability and the size-luminosity relation of the intermediate mass AGN in NGC 4395"
  Hojin Cho, Jong-Hak Woo et al. 2020, ApJ
  - prihvaćen juče ☺

- posmatranja na AS Vidojevica 1.4m, u maju 2017
- kašnjenje u Ha liniji ~80min
- masa crne rupe ~ 10^4 M_{sun}



AS Vidojevica, Srbija



- Teleskop Milutin Milanković
- D=1.4m, F=11.2
- fotometrije
- planovi: spektroskopija
  polarimetrija
- vidojevica.aob.rs

Naša dugoročna kampanja

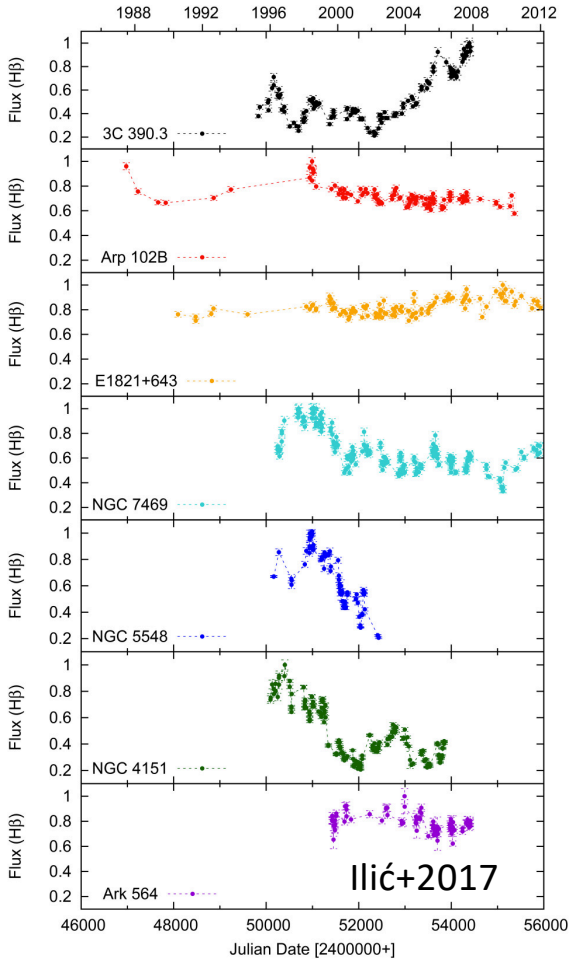
(1941 – 2019)

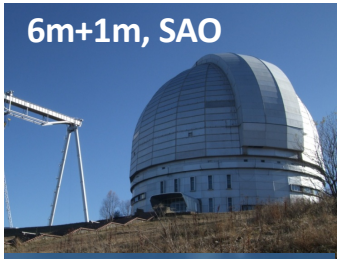
- PIs: **Alla Shapovalova (RUSIJA)**
  Vahram Chavushyan (MEKSIKO)
  - 6m + 1m teleskopi - SAO RAS (Russia)
  - 2.1m teleskop - Guillermo Haro Observatory (Mexico)
  - 2.1m teleskop - Observatorio Astronómico Nacional, San Pedro Martir (Mexico)
  - 3.5m + 2.2m teleskopi – Calar Alto Observatory (Spain) – posmatranja od W.Kollatschny

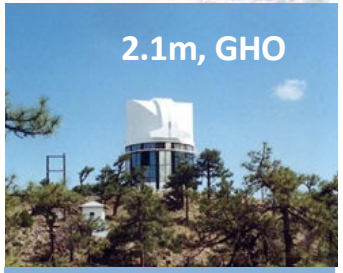
*dugoročna=decenije

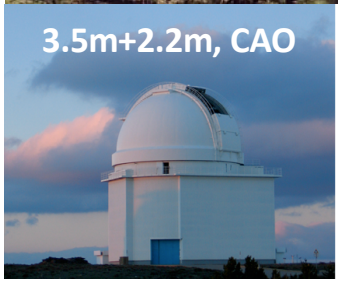
Dugoročna RM kampanja (Shapovalova et al.)

- **Seyfert 1s:**
  NGC 5548 – 9+ years (Shapovalova+ 2004, Ilić 2007, Popović+2008, Bon+2016)
  NGC 4151 – 11+ years (Shapovalova+ 2008, 2010a, Ilić+2010, Bon+ 2012)
  NGC 7469 – 20 years (Shapovalova+2017)
  NGC 3516 – 22 years (Shapovalova+2019)
- **Narrow Line Seyfert 1:**
  Ark 564 – 11 years (Shapovalova+ 2011, Shapovalova+ 2012)
- **Double Peaked Line AGNs (DPLs):**
  3C 390.3 – 13 years (Shapovalova+ 2001, 2010b, Popović+2011, Jovanović+ 2010, Kovačević+ 2014);
  Arp 102B – 12 years (Shapovalova+13, Popović+ 14, Kovačević+ 14, Ilić+15, Rakić+ 17)
- **Quasar, a binary black hole candidate:**
  E1821+643 – 25 years (Shapovalova+2016, Kovačević+2017, Kovačević+2018, Ilić+2019, in prep.)





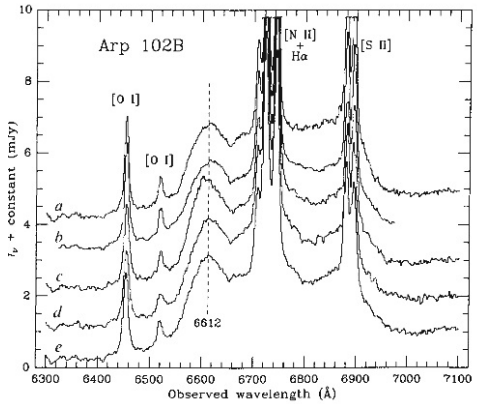


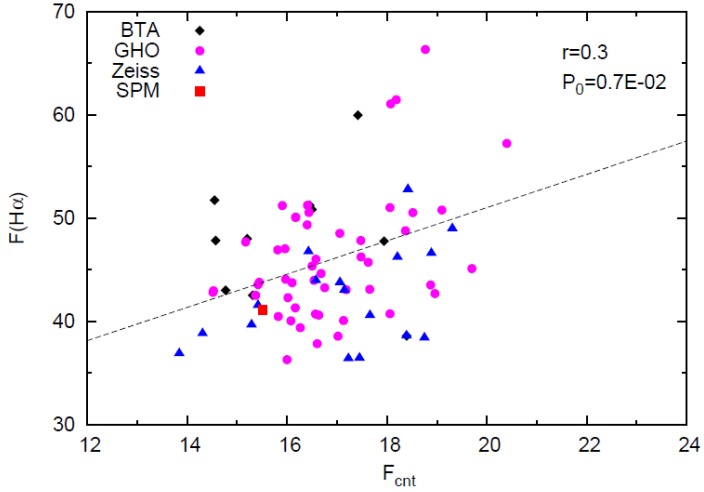


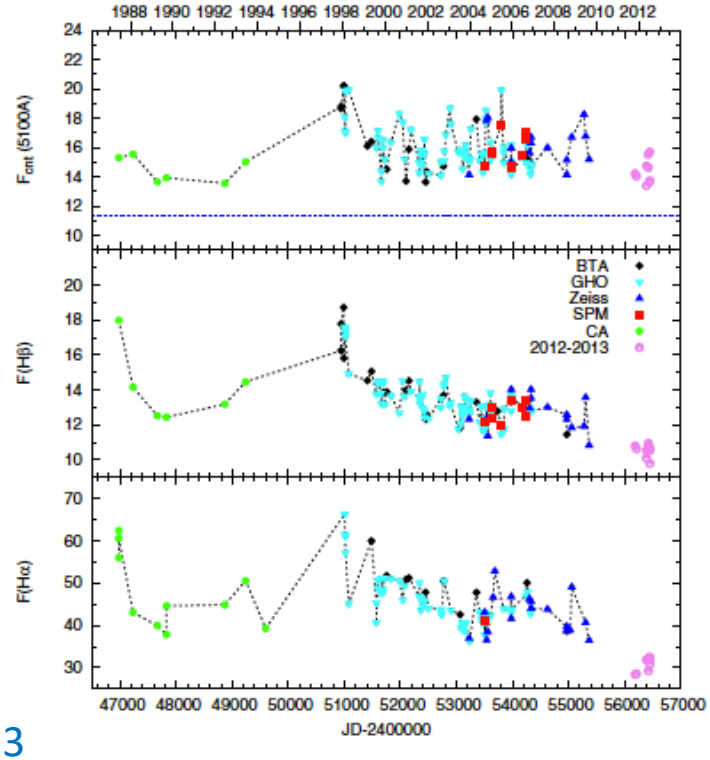
Arp 102B

- prototype of double-peaked broad emission lines (Hα and Hβ)
- 12 years of data
- week correlation between the line and continuum flux

Halpern & Filippenko 1991





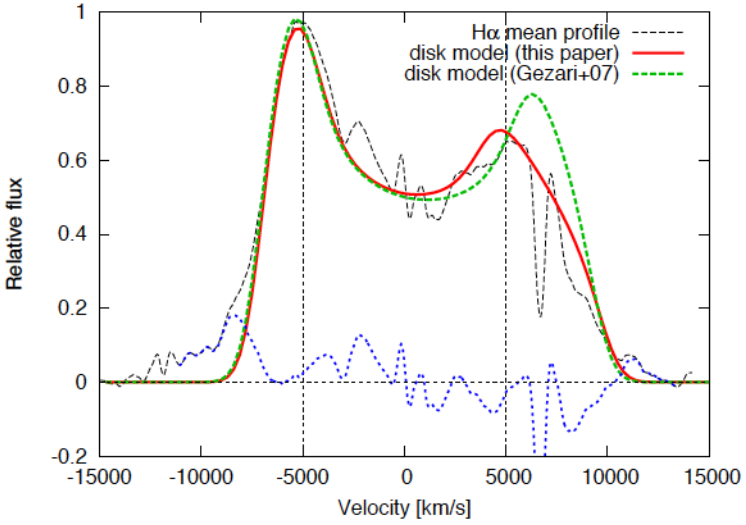


Shapovalova et al. 2013

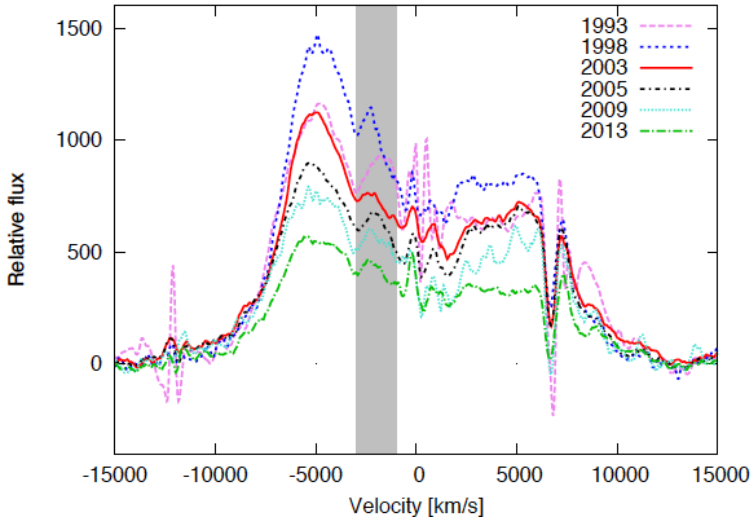
Arp 102B: is there an accretion disk seen in broad lines?

large distance between the peaks (~ 11,000 km s^{-1}) indicates fast rotating disk, that is probably close to the black hole

Left - the mean normalized Hα profile fitted with the disk model



Right – bump in Hα profile at ~-2000km/s (an outflow?) during higher activity state

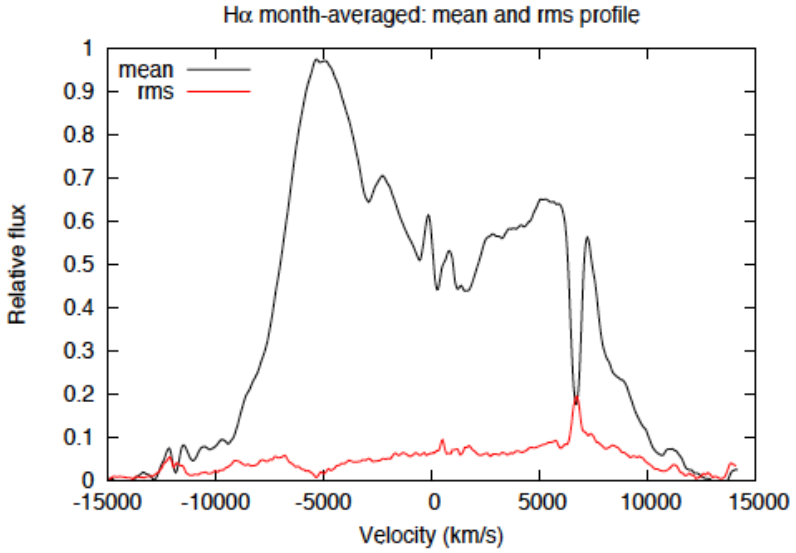


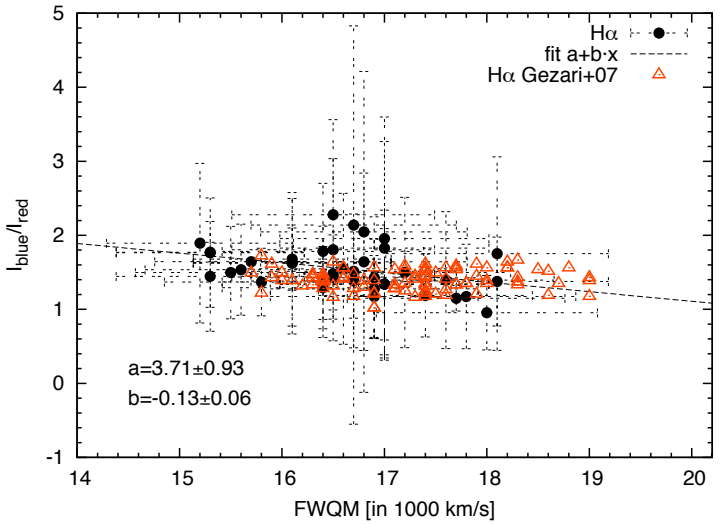
Popović, Shapovalova, Ilić, et al. 2014

Arp 102B: is there an accretion disk seen in broad lines?

- double-peaked line: disk models gives size of ~500Rg, but there is no big change in the line profile
- a stable disk?

- weak anticorrelation btwn. blue-to-red peak vs. FWQM
- disk models suggest the opposite

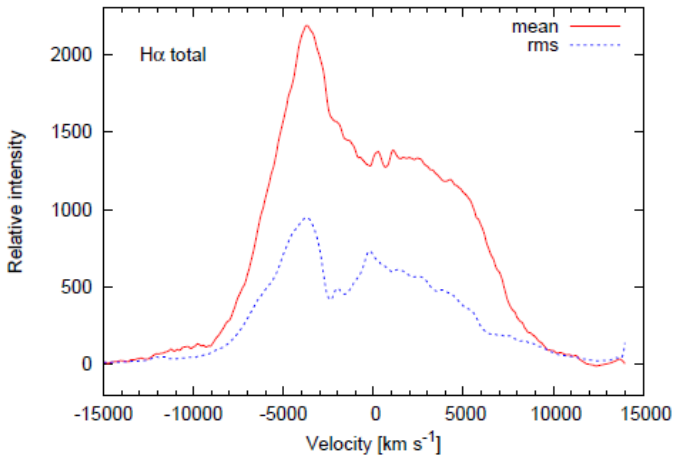


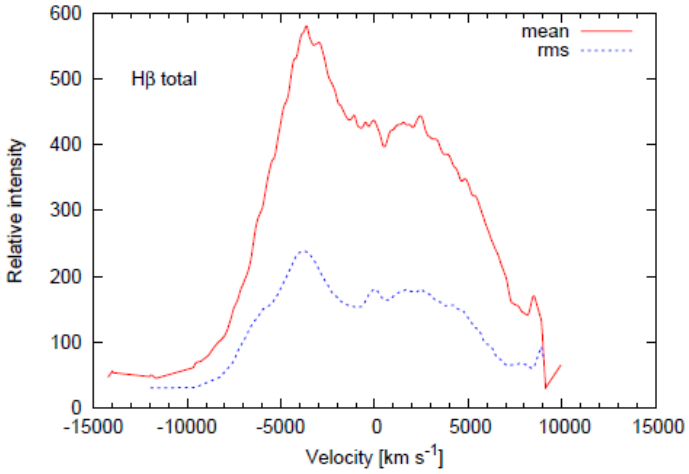


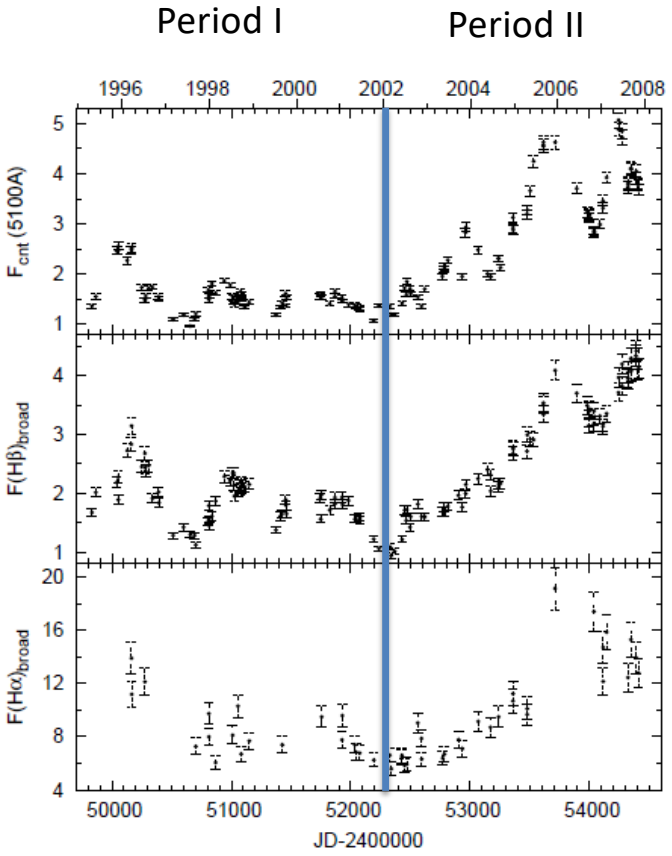
Popović, Shapovalova, Ilić, et al. 2014

3c390.3

- double-peaked broad line
  (Eracleous & Halpern 1994)
- 13 years of data
- stratified BLR (Hα ~ 120 l.d. Hβ ~ 95 l.d.)
- strongly variable line profiles ⇒ several different complex BLR models suggested: binary, disc precession, disk perturbation, etc.



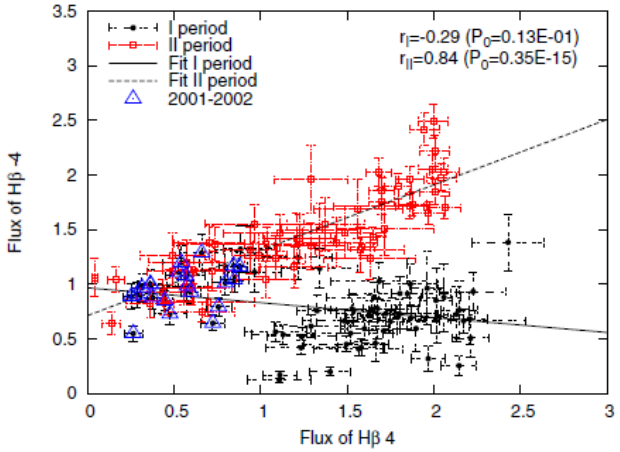




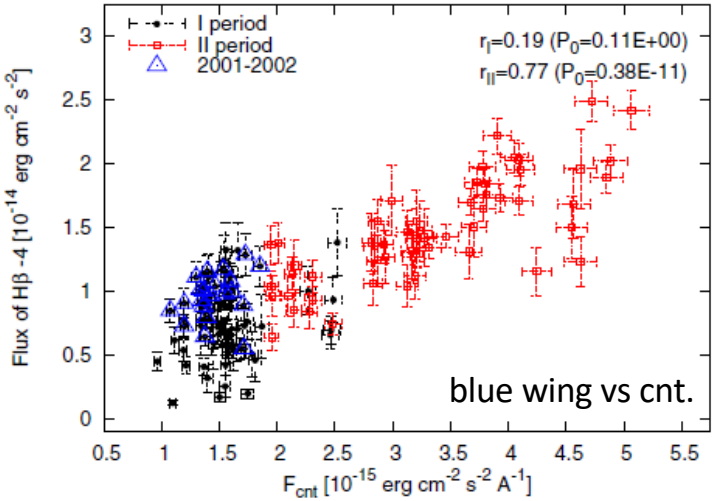
Shapovalova et al. 2010

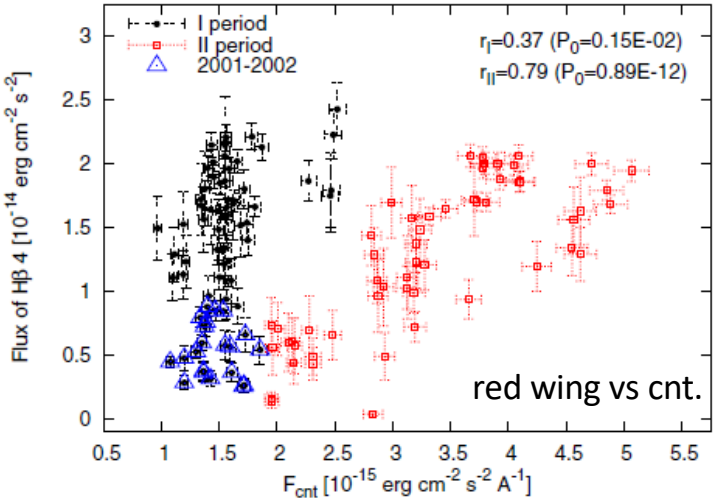
3c390.3 – Hβ line

- blue and red wings of Hβ ↔ segments -4 and +4
- Period I (**black**) and II (**red**): different response of line wings to the continuum variations



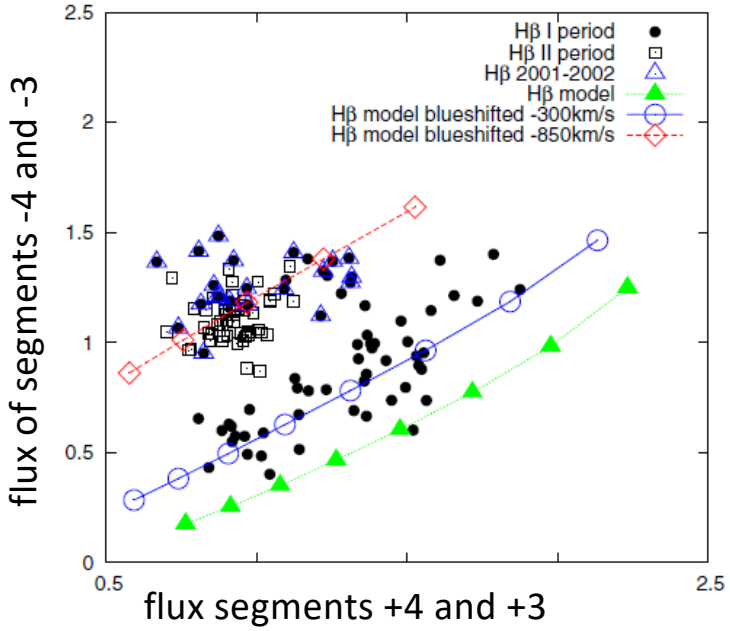
Popović, Shapovalova, Ilić, et al. 2011, A&A, 528,130



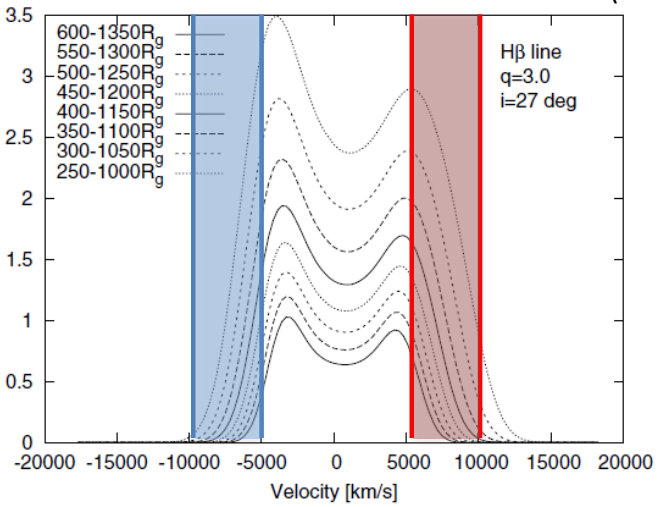


3c390.3 – models

- part of the disc that is emitting lines is shifting along the radius



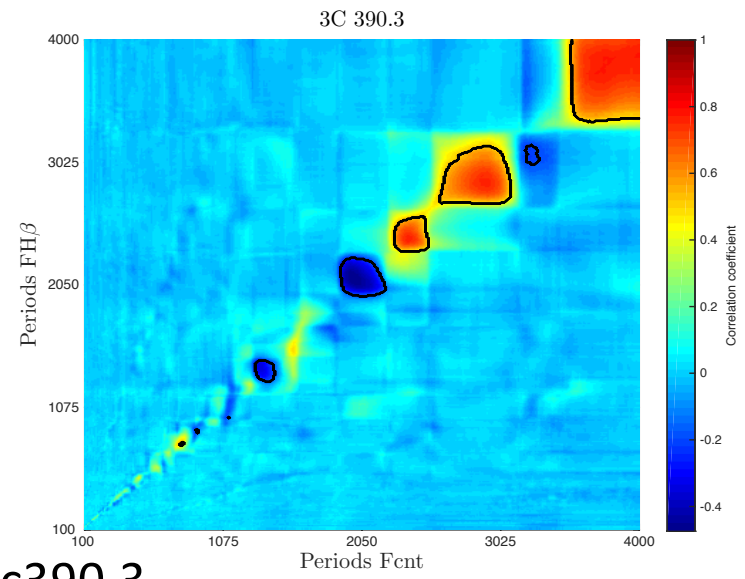
Disk model of Chen et al. (1989)



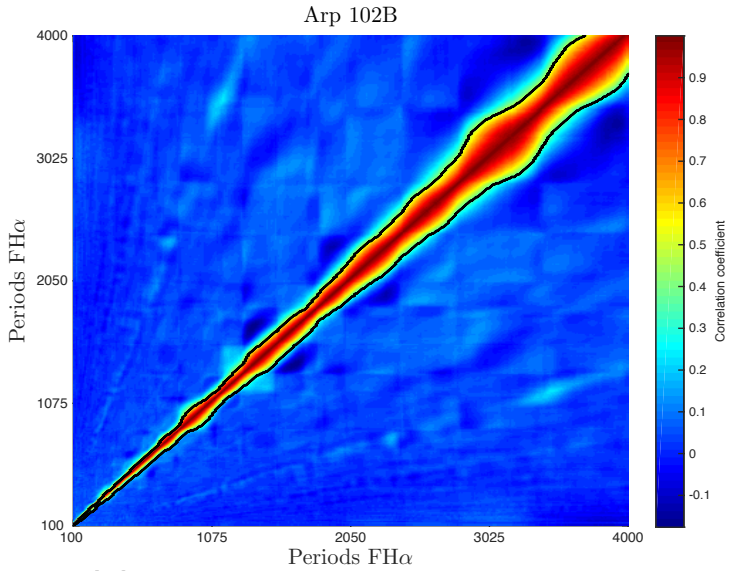
- models vs. observations
- **Period I**: the change can be explained with the change of the line-emitting disk radius
- **Period II** (when burst starts): line-emitting disc radius is fixed

Popović, Shapovalova, Ilić, et al. 2011

- new method to detect oscillatory patterns in long-term light curves



3c390.3



Arp102B

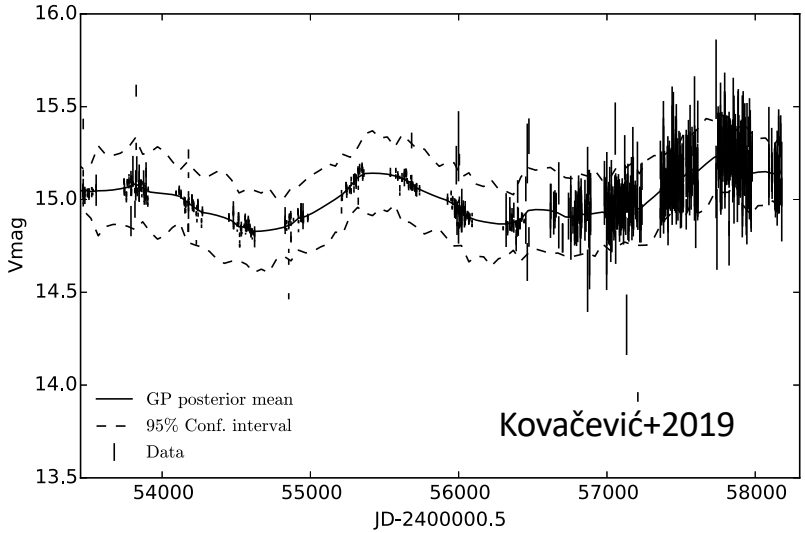
- Both are double-peaked line emitters
- The underlying topology of their oscillations mechanisms is different, suggesting different physical backgrounds

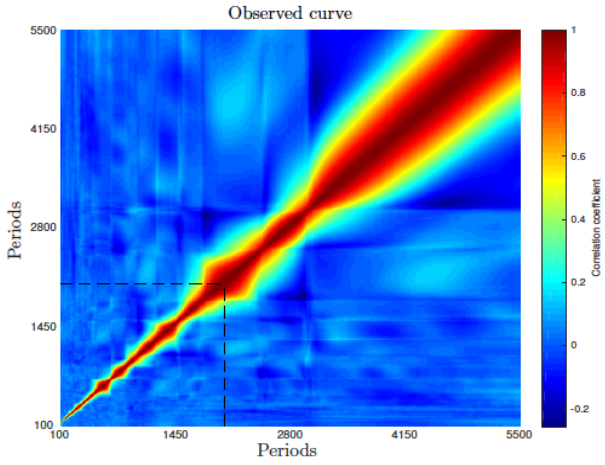
Kovačević et al. 2018, 2019

Hunt for parsec-scale SMBH binaries

- time-domain photometry of AGN (see e.g. with CRTS, Graham+2017)
  - → famous case: binary SMBH candidate **PG1302-102** (Graham+2015, Liu+2018)

- novel hybrid method to search for periodic oscillatory behavior
  - → applies continuous wavelet transform and correlation coefficients on Gaussian-processed light curves (see Kovačević+ 2018, for details)
  - → could be explained with the model of binary SMBH with the perturbation in accretion disk temperature (see Kovačević+ 2019 for details)

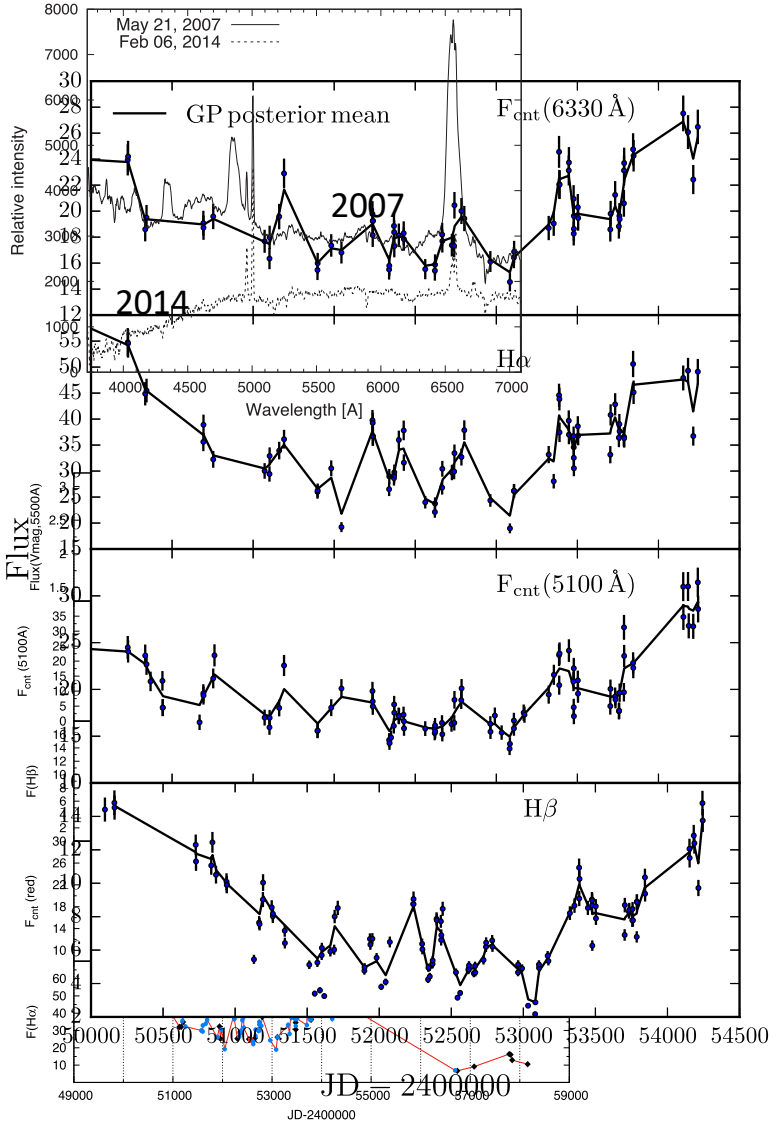




NGC 3516

- 22 years of data
- **extreme variability**: disappearance of broad lines in 2014

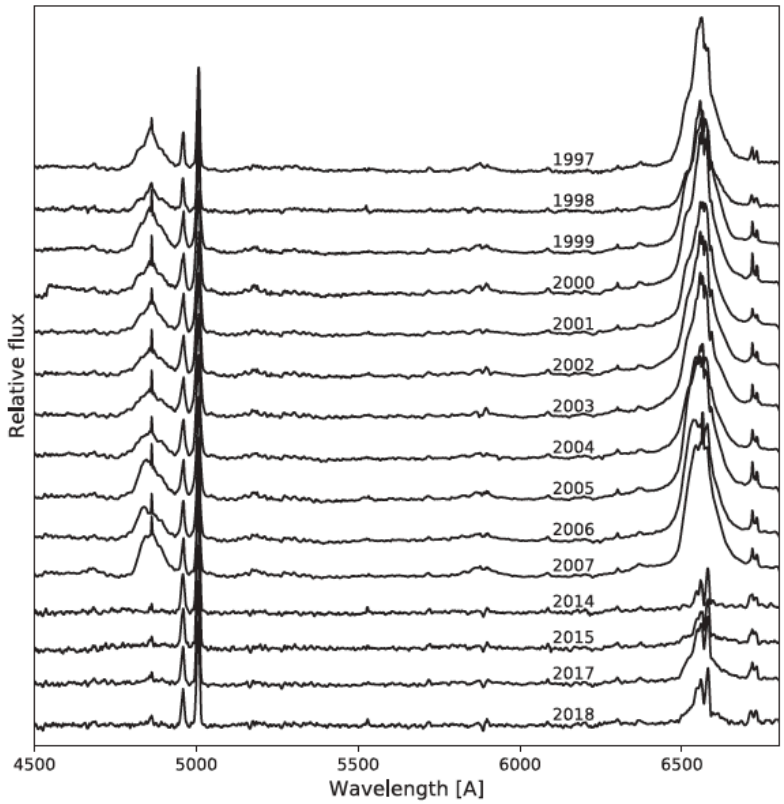
- large gap in light curves → used data until 2007
- applied Gaussian processes to get simulated light curves
- time-delays:
  15-17 days for both Hα and Hβ



Shapovalova et al. 2019

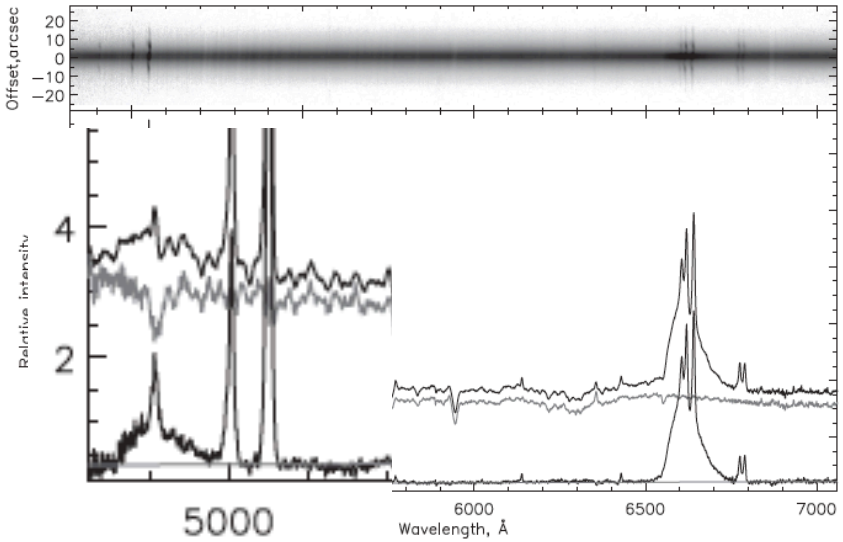
NGC 3516: **changing-look** AGN

- extreme variability:
  - appearance or disappearance of broad lines within few years
- confirmed: changing-look AGN
- what is the cause?
  - variable accretion rate
  - variable obscuration
  - tidal disruption event
  - hot topic e.g. LAMOST has found 21 new CL AGN (Yang et al. 2018)
- why are important?
  - perfect cases to study the connection btw. AGN and its host galaxy
  - important to understand AGN evolution

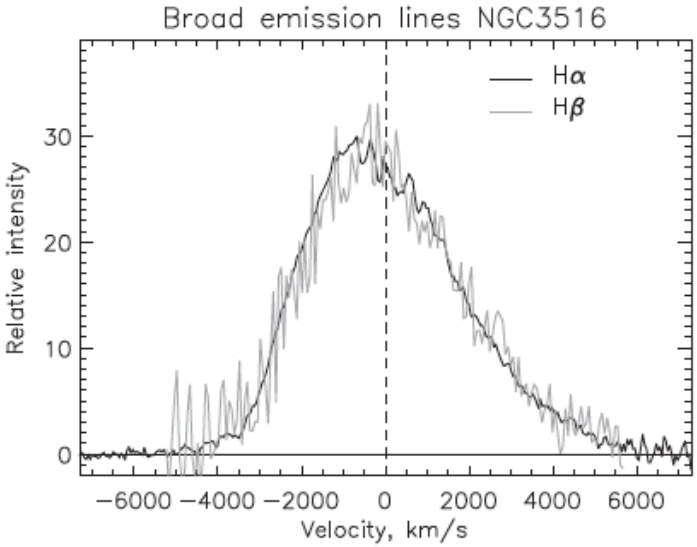


Shapovalova et al. 2019

6m BTA observation w/SCORPIO in 2017



- in 2017: the object is still in low state, but broad component starts to appear
- subtracted the off-slit spectrum of the host-galaxy



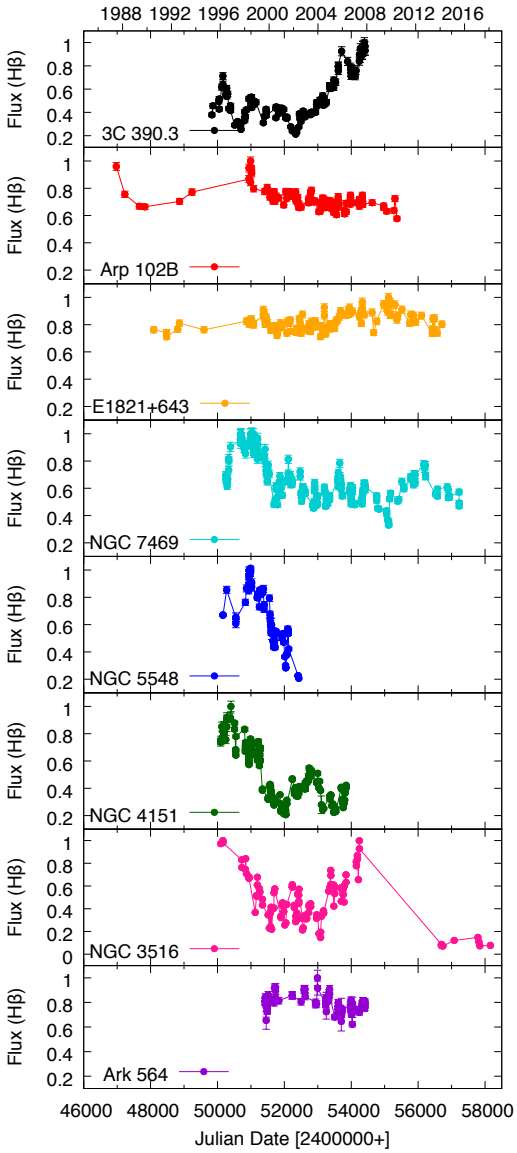
- Hα and Hβ profiles are the same
- blueshift and red asymmetry

Shapovalova et al. 2019

Rezime rezultata

- odradili smo dugoročna posmatranja nekoliko AGJ tipa 1, sa različitim spektralnim karakteristika
  - sve krive sjaja su dostupne on-line

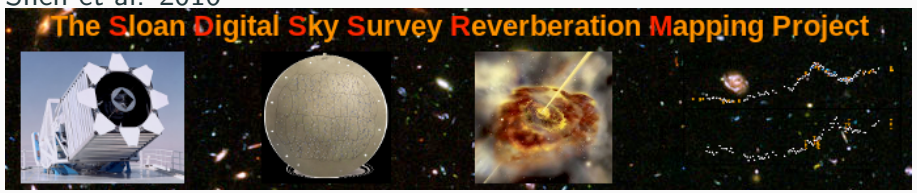
- odredili smo dimenzije BLR i masu SMCR
- struktura BLR je vrlo kompleksna
- **dugoročne** promene u krivama sjaja
  - skrivene periodičnosti
  - različite dinamičke oscilacije
  - *changing-look* fenomen
- dugoročno praćenje AGJ je značajno



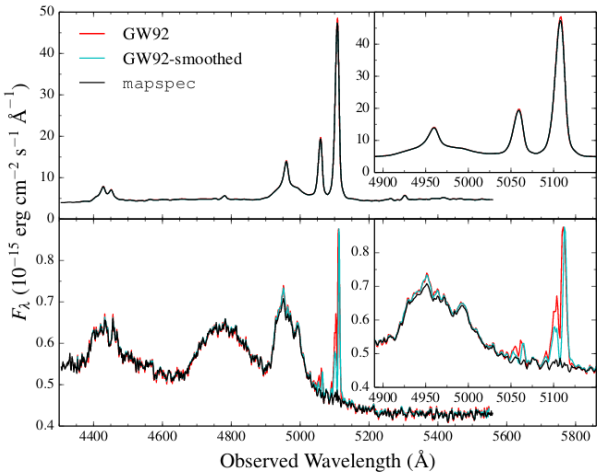
Optička promenjivost na većem uzorku AGJ

- **student doktorskih studija: Nemanja Rakić**
- podaci iz Sloan Digital Sky Survey (SDSS) baze
- ~ 100 objekata iz SDSS RM kampanje
- 48 epoha po objektu u ~ 3godine

Shen et al. 2016

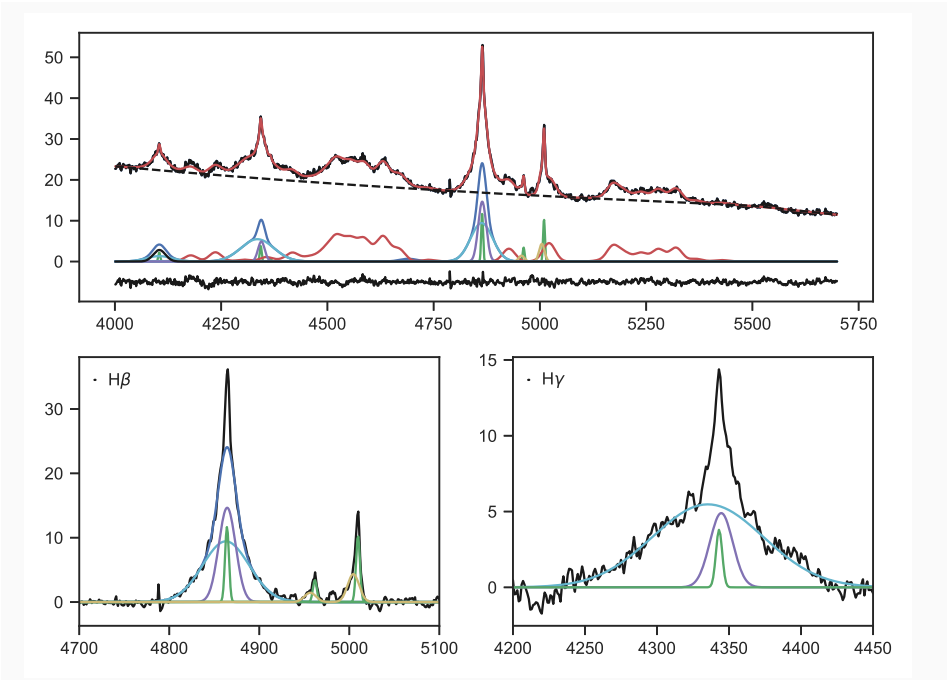


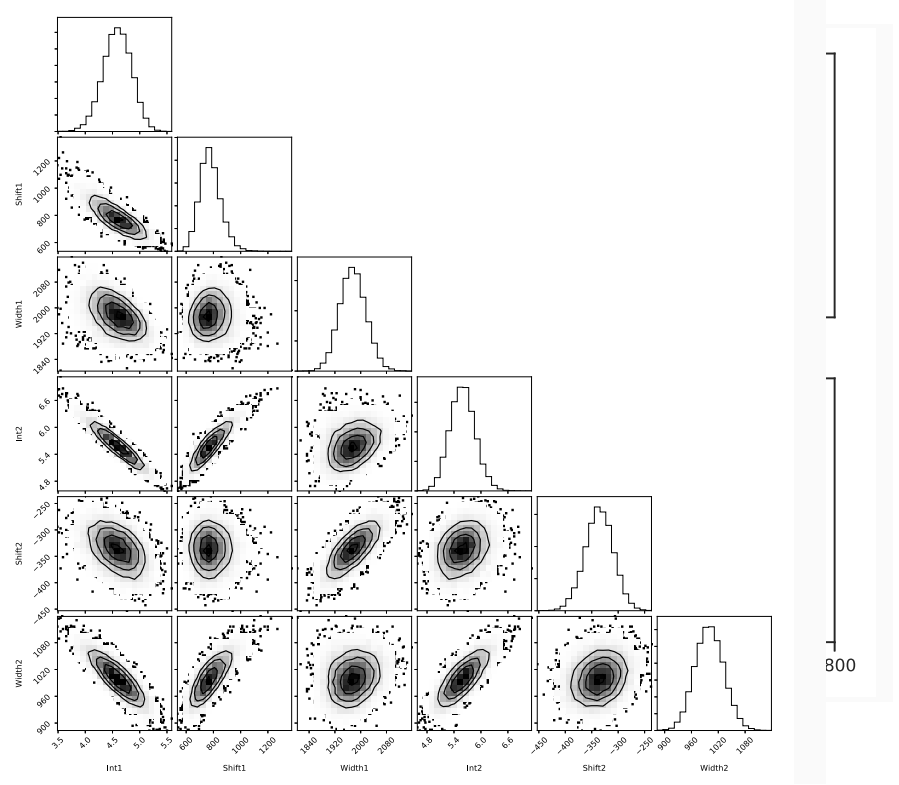
- cilj: precizno merenje fluksa linija i kontinuuma, i testiranje postojanja korelacija (npr. **Baldwin effect**)
- napredna interna kalibracija podataka
  - apsolutna kalibracija na [OIII] linije (Fausnaugh 2016)
  - oduzimanje uticaja okolne galaksije



Optička promenjivost na velikom uzorku AGJ

- **student doktorskih studija: Nemanja Rakić**
- razvoj alata za automatsko kompleksno fitovanje emisionog spectra (python sherpa package, Burke et al. 2019, MCMC za procenu grešaka fita)

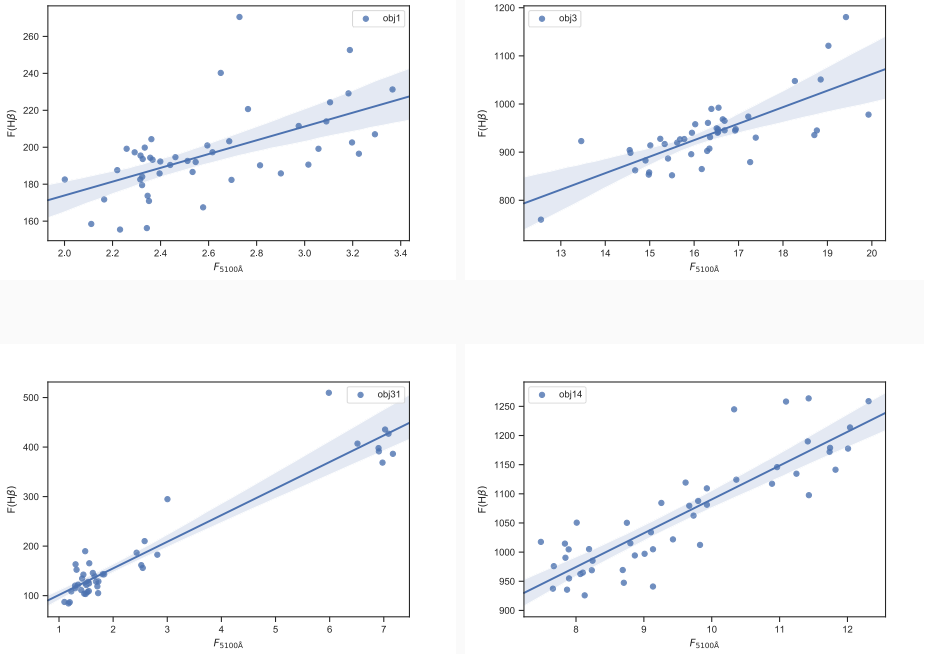




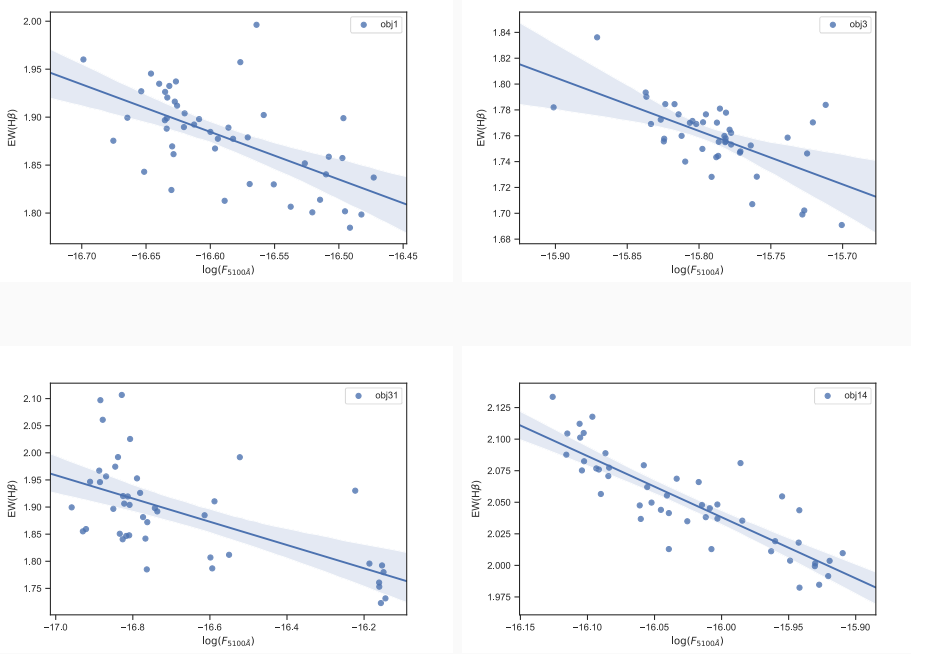
Optička promenjivost na velikom uzorku AGJ

- **student doktorskih studija: Nemanja Rakić**

Flux linije vs. flux kontinuuma



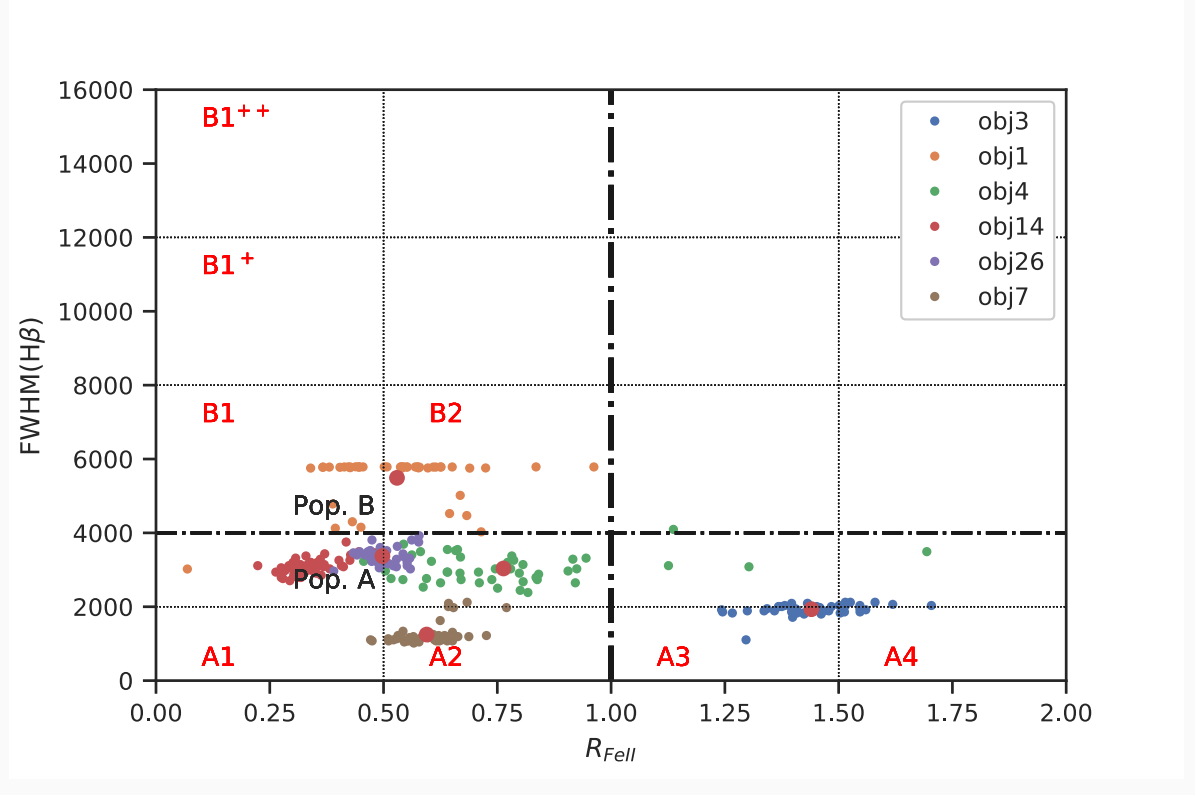
EW linije vs. flux kontinuuma



Rakic, in prep.

Optička promenjivost na velikom uzorku AGJ

- **student doktorskih studija: Nemanja Rakić**

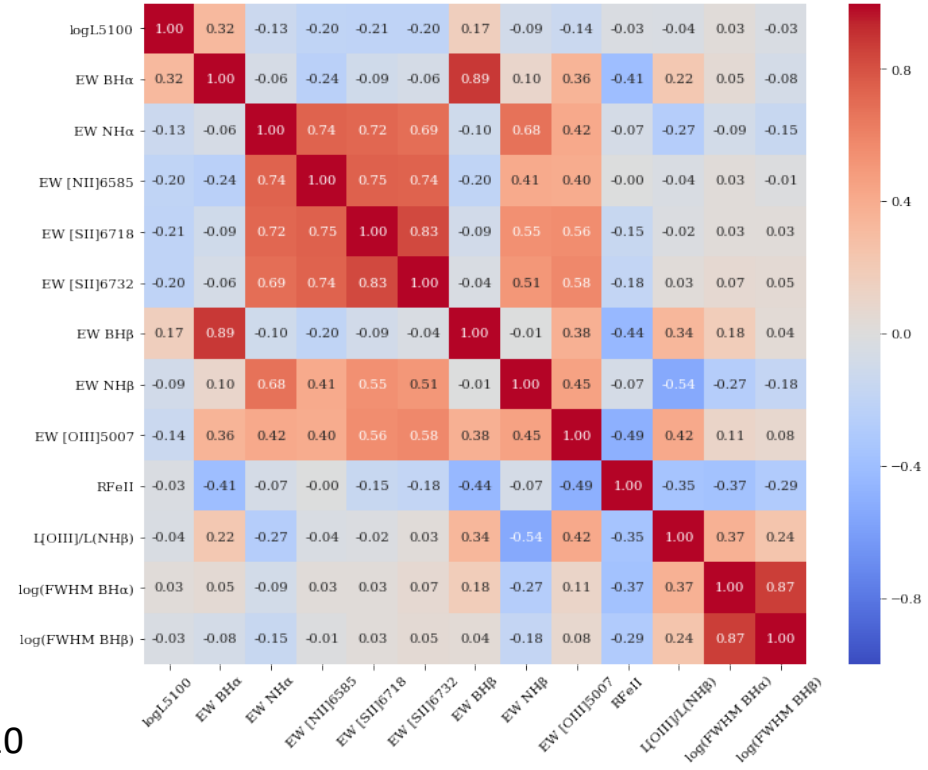


Rakic, in prep.

Ispitivanje korelacija spektralnih karakteristika

- **studentkinja doktorskih studija: Isidora Jankov**

- Podaci iz SDSS: katalog spektralnih parametara Shen et al. 2011 (novija verzija Liu et al. 2019)
- definisan uzorak za z<0.39,
  oko 2,200 objekata (odnosno 3,900):
  Hα, Hβ, [O III] 5007, [N II] 6585, [S II] 6718,6732
- korelaciona matrica potvrđuje Eigenvector 1
  - EW [OIII] vs. R_FeII (r = -0.49)
  - FWHM (Hβ) vs. R_FeII (r = -0.29)

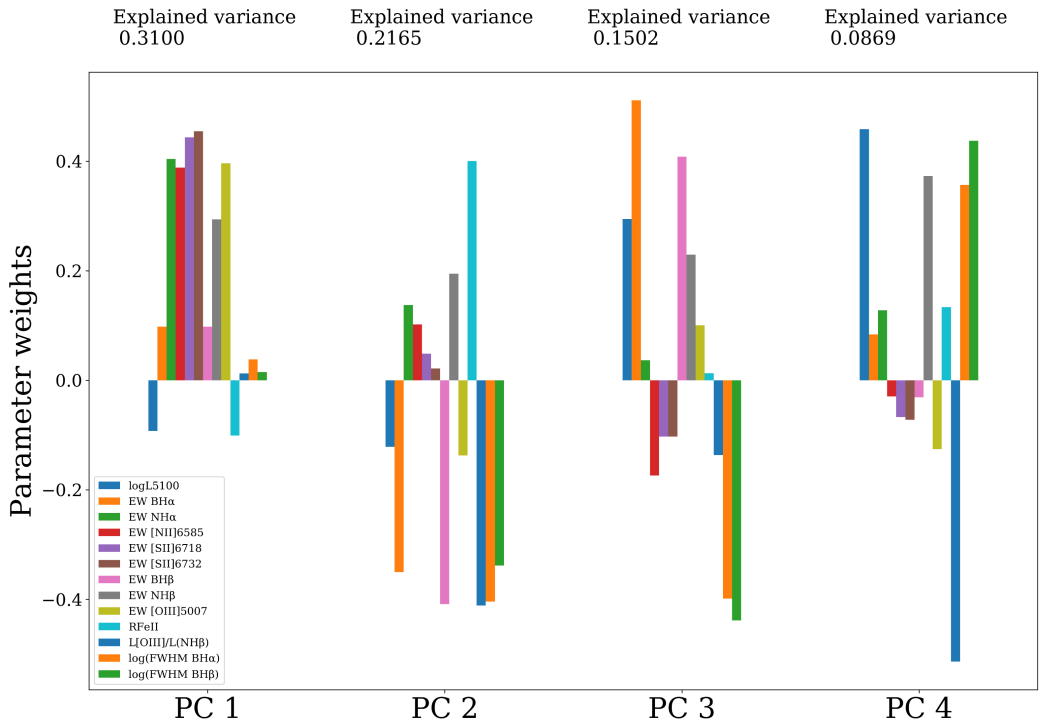


Jankov & Ilić, 2020

Ispitivanje povezanosti spektralnih karakteristika

- **studentkinja doktorskih studija: Isidora Jankov**

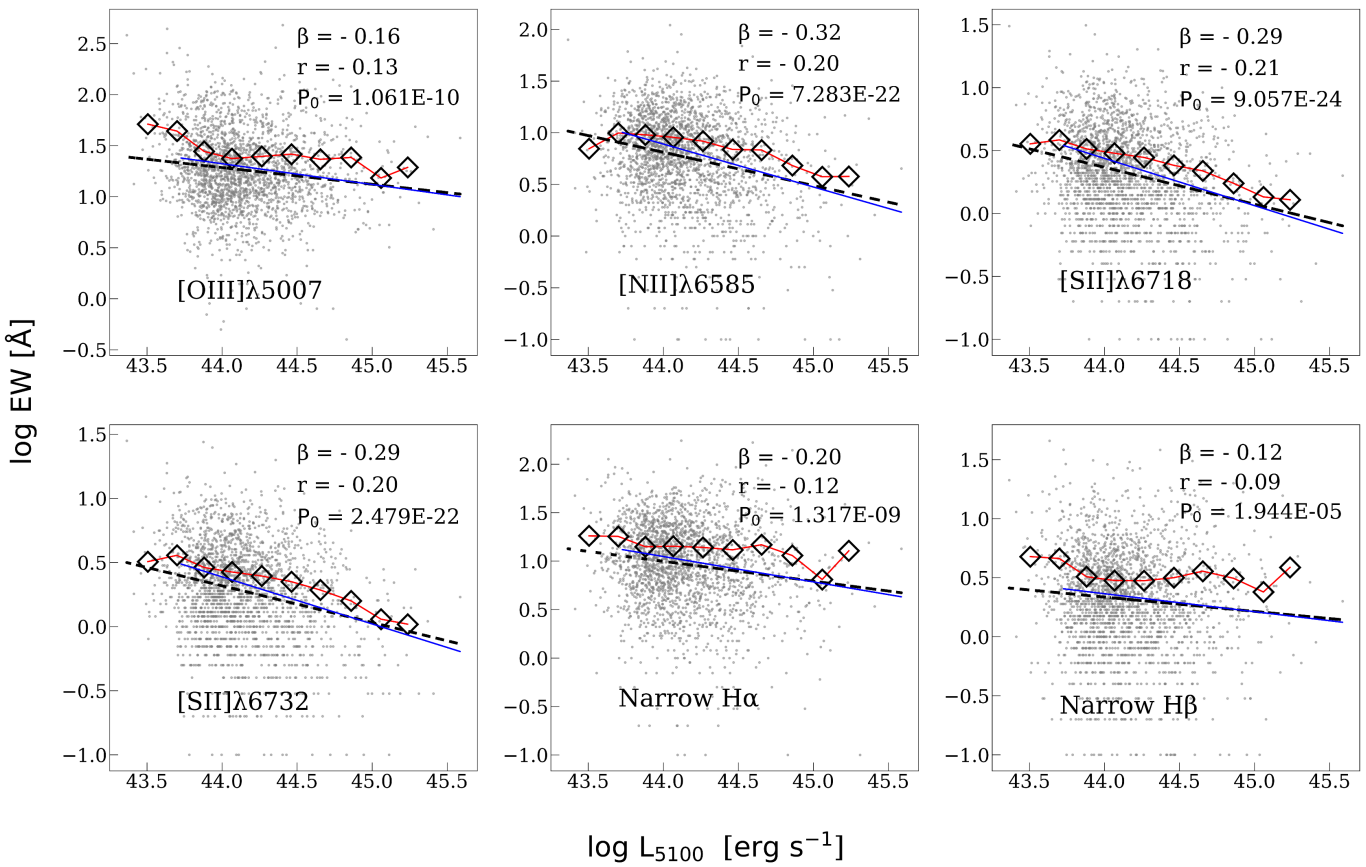
- PCA analiza daje još:
  - PC1 – dominira Baldvinov efekat za uske linije
  - PC2 – Eigenvector 1 korelacije + korelacija FWHM(Hα) vs. $\frac{L[O\ III]}{L(H\alpha)}$ (Baron & Menard, 2019)



Jankov & Ilić, 2020

Baldvinov efekat kod uskih linija

Jankov & Ilić, 2020



log-log zavisnost EW šest razmatranih uskih linija od L_{5100}

- [N II] i [S II] imaju najizraženiji Baldvinov efekat
- Uske Hα i Hβ imaju najmanje izražen Baldvinov efekat

Plava linija – najbolji linearni fit na uzorak kvazara bez korekcije na L_{5100}

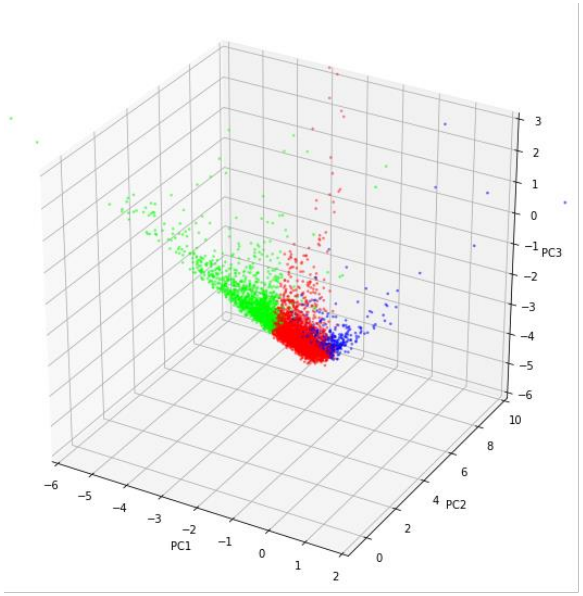
Crna isprekidana linija – najbolji linearni fit na uzorak kvazara sa korekcijom uticaja galaksije domaćina na L_{5100}

Ispitivanje povezanosti spektralnih karakteristika

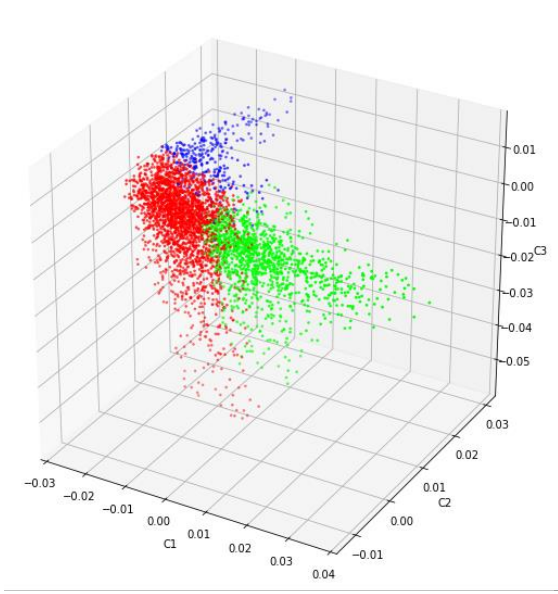
- **studentkinja doktorskih studija: Isidora Jankov**
- osim PCA primena drugih metoda mašinskog učenja, Manifold Learning
  - Isometric Feature Mapping (IsoMap)
  - Locally Linear Embedding (LLE)

Jankov, Ilić, Kovačević, in prep

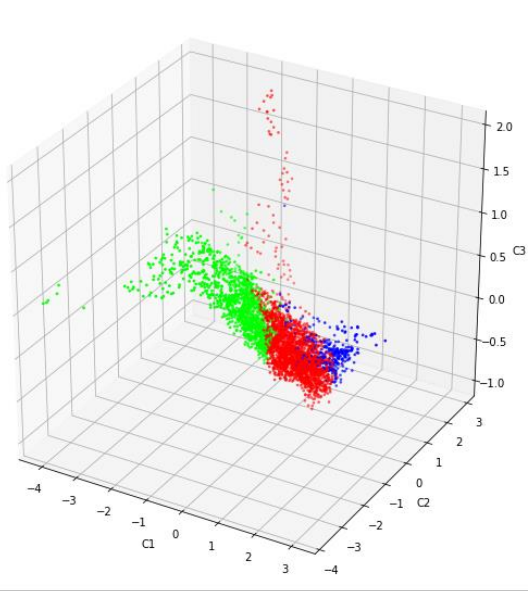
Pop B
Pop A
ExPopA



PCA



LLE



IsoMap

Ispitivanje povezanosti spektralnih karakteristika

- **studentkinja doktorskih studija: Isidora Jankov**
- osim PCA primena drugih metoda mašinskog učenja, Manifold Learning
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Jankov, Ilić, Kovačević, in prep

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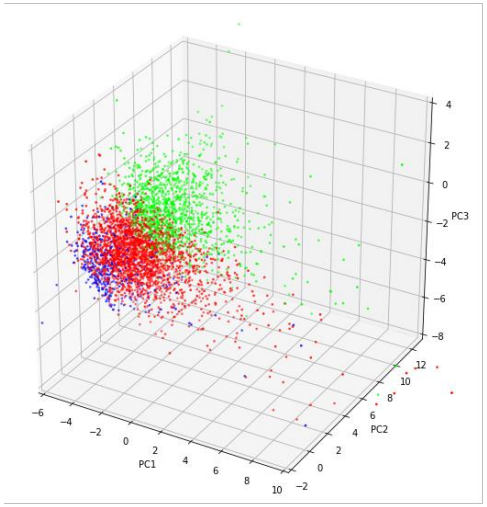
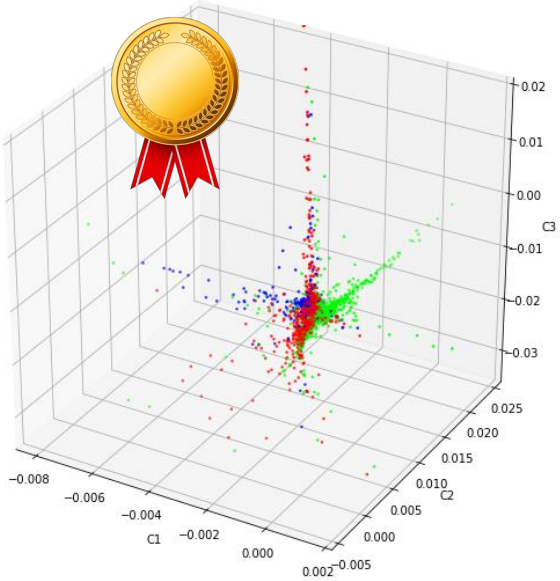
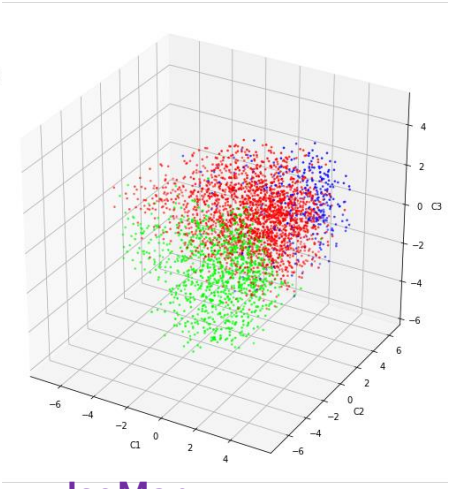


PCA



LLE

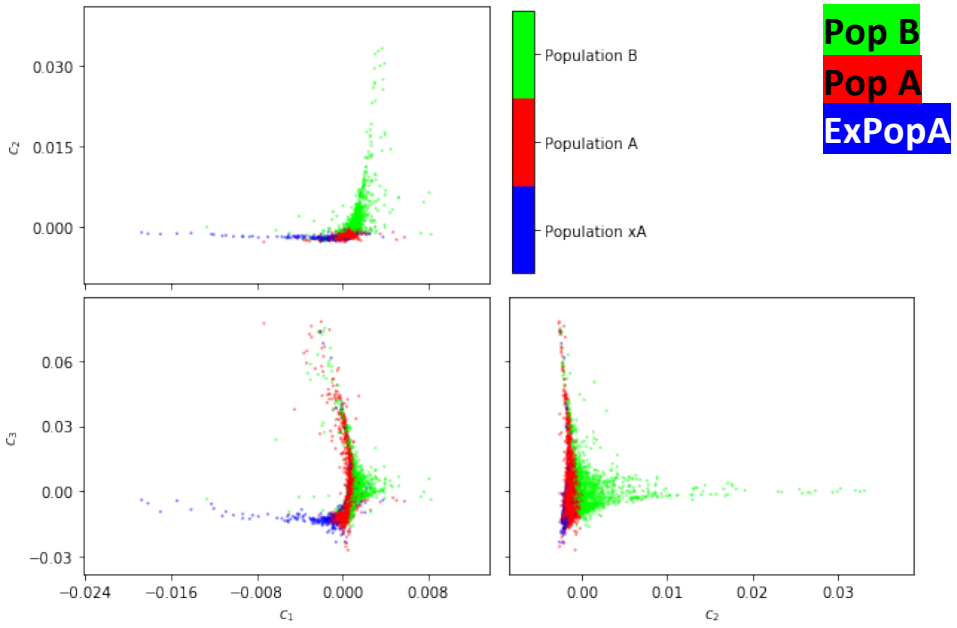


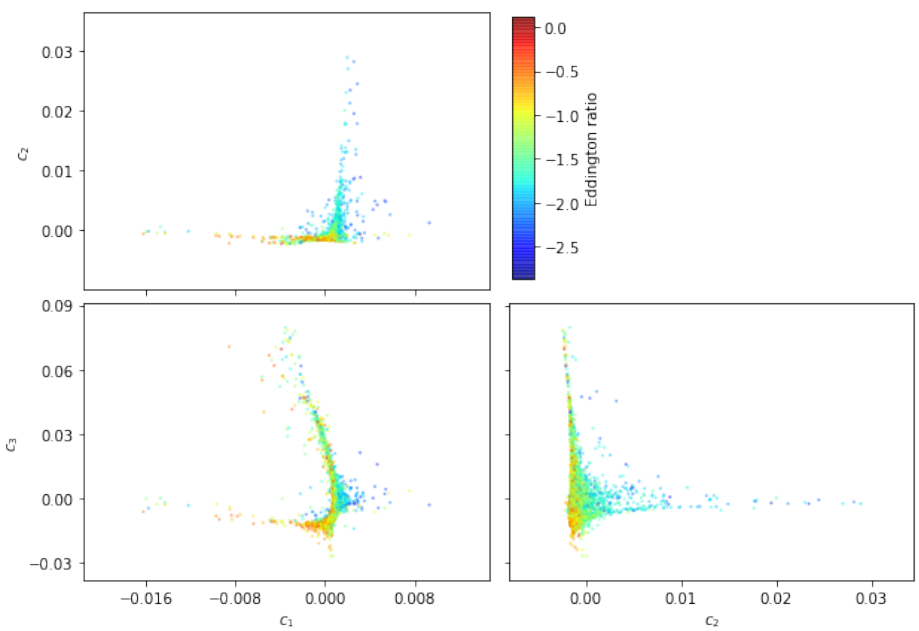
IsoMap

Ispitivanje povezanosti spektralnih karakteristika

- **studentkinja doktorskih studija: Isidora Jankov**

Jankov, Ilić, Kovačević, in prep





Trenutna istraživanja i planovi naše grupe

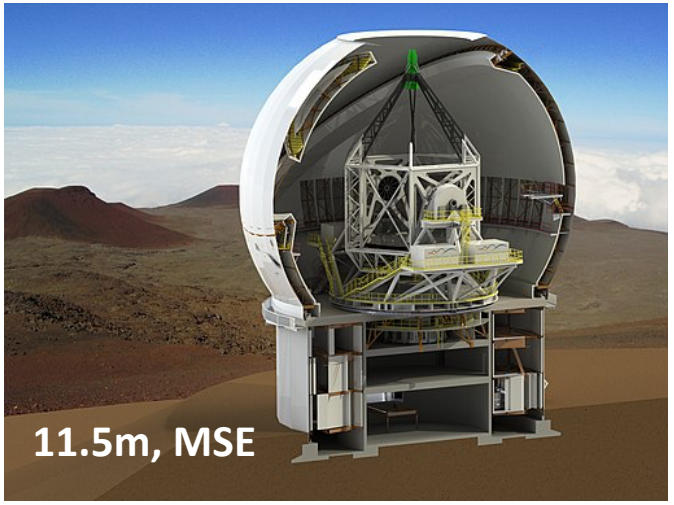
- analiza profila emisionih linija sa ciljem određivanja BLR osobina
- praćenje kratkoročnih i dugoročnih promena u liniji i kontinumu sa ciljem merenja dimenzija BLR, kao i detekciji periodičnih promena (dvojne crne rupe)

- učešće u Manuakea Spectroscopic Explorer projektu - ***reverberation mapping*** kampanja za preko 5000 kvazara na kosmološkim rastojanjima (z~3)

  → određivanje kašnjenja
  → određivanje mase supermasivnih crnih rupa
  za najveći broj kvazara do sada!

(see White paper: Shen et al. 2019)

Maunakea Spectroscopic Explorer



Trenutna istraživanja i planovi naše grupe

- analiza profila emisionih linija sa ciljem određivanja BLR osobina
- praćenje kratkoročnih i dugoročnih promena u liniji i kontinumu sa ciljem merenja dimenzija BLR, kao i detekciji periodičnih promena (dvojne crne rupe)

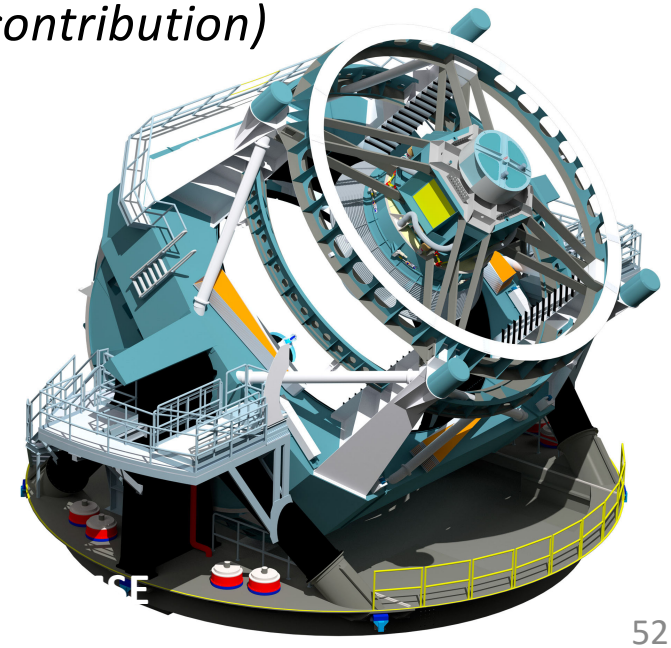
- učešće u Large Synoptic Survey Telescope – LSST (*in-kind contribution)*

  → *ispitivanje oscilacija krivih sjaja*

  → *ispitivanje varijabilnosti i kašnjenja*

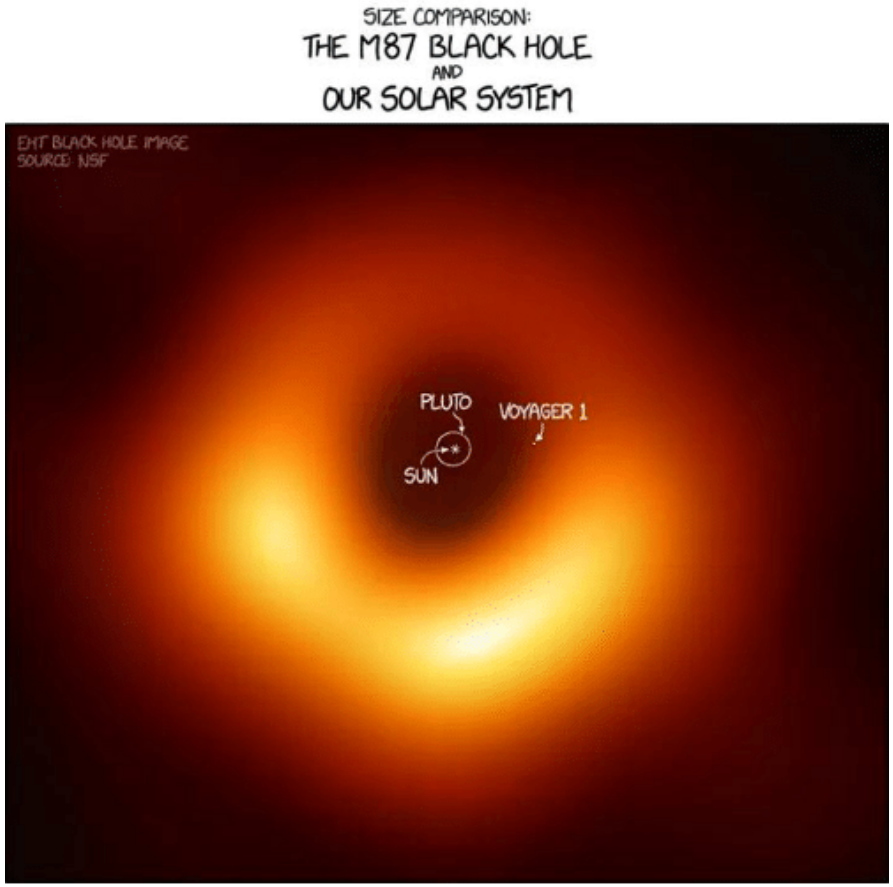
  → *dodatna spektroskopska posmatranja iz naše kampanje*

Vera C. Rubin Observatory



Hvala!

Pitanja?



That black hole you see trending today is very, very big. Here it is compared to the size of our solar system.

L’Oreal Unesco nacionalna stipendija ”Za žene u nauci”

otvoren poziv

rok 31.mart 2020