Supermasivne crne rupe u jezgrima aktivnih galaksija

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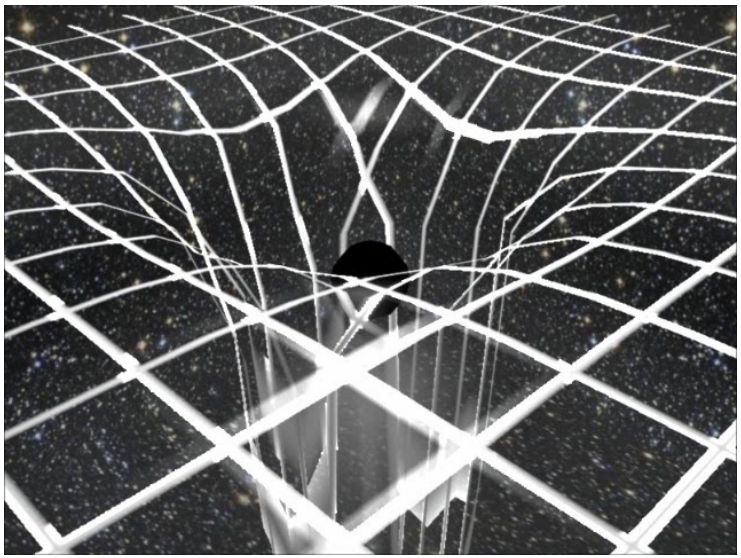
GRUPA ZA ASTROFIZIČKU SPEKTROSKOPIJU ASTRONOMSKE OPSERVATORIJE

Photo from 2008

KAKO UOPŠTE DETEKTOVATI CRNE RUPE?!

- crne rupe:
  - ne emituju zračenje!
  - zato ih zovemo “crne”!
- ALI, centri nekih galaksija emituju snažno zračenje : Aktivna galaktička jezgra



- crne rupe – spin, masa
- emisione linije – širina, pomeraj, intenzitet, oblik profila

U JEZGRIMA AKTIVNIH GALAKSIJA SE NALAZE SUPERMASIVNE CRNE RUPE

OTKRIĆE I PRVA POSMATRANJA

- posmatranja počinju u prvoj deceniji 20tog veka
  - neke galaksije imaju jake emisije u linijama (Habl izveštava o 3 takve galaksije)
- Carl K. Seyfert (1943): u nekim galaksijama posmatra emisione linije visoko-jonizovanih elemenata, jako proširenih profila

OTKRIĆE KVAZARA

- 1960 god: Thomas Matthews & Allan Sandage
- snimili plavičasti zvezdoliki objekat
- neobične emisione linije: neindetifikovane!

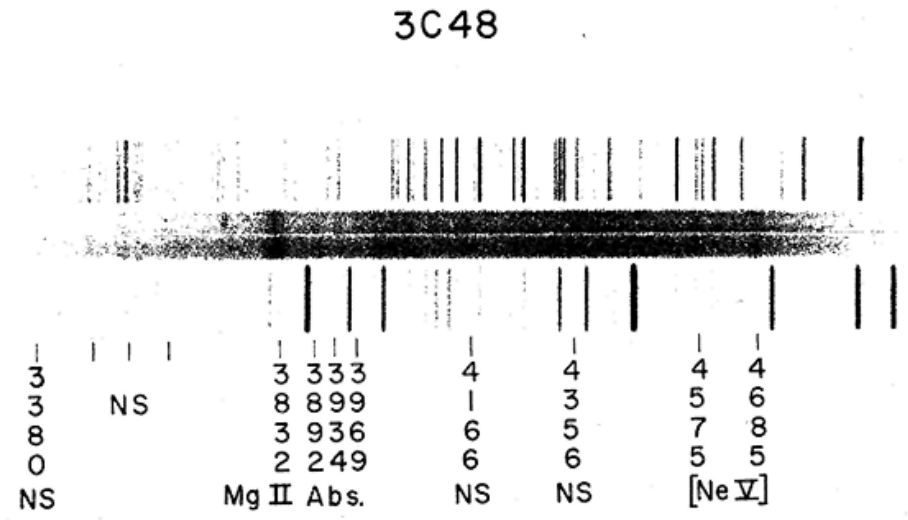
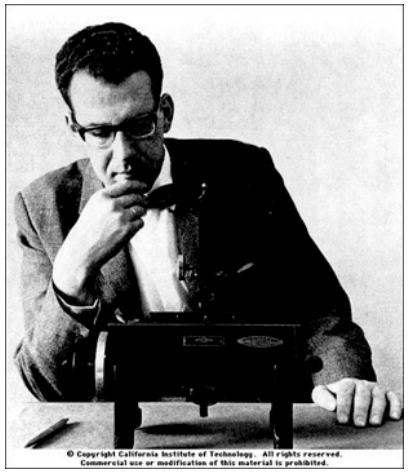


FIG. 3.—Two prime-focus spectra of the quasi-stellar object 3C 48, 190 Å/mm, IIa-O baked; upper November 12, lower December 20, 1960. The symbol *NS* indicates night-sky emission; *Abs.* is absorption. Upper comparison A + Ne, lower H + He + A. Redshifted lines of Mg II and [Ne V] are indicated.

KVAZI-STELARNI RADIO IZVORI: 3C 273



- 1963: određen položaj optičkog izvora koji odgovara radio-galaksiji 3c 273
- 1963: Maartin Schmidt, Mt. Palomar
  - pravi snimak 3c 273: zvezdoliki objekat
  - snima spektar: misteriozne linije odgovaraju dobro poznatim prelazima u atomu vodonika!

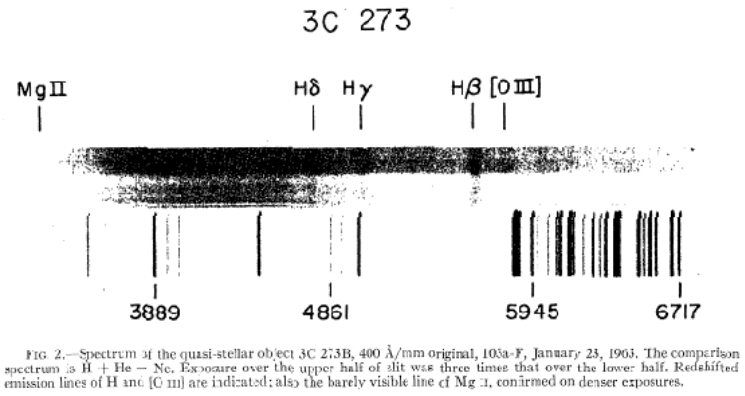
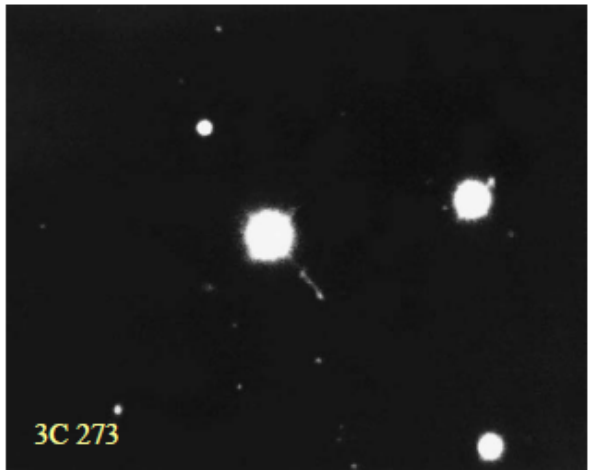
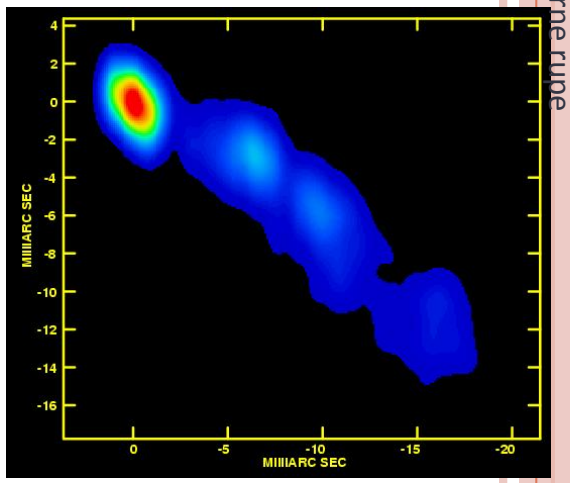
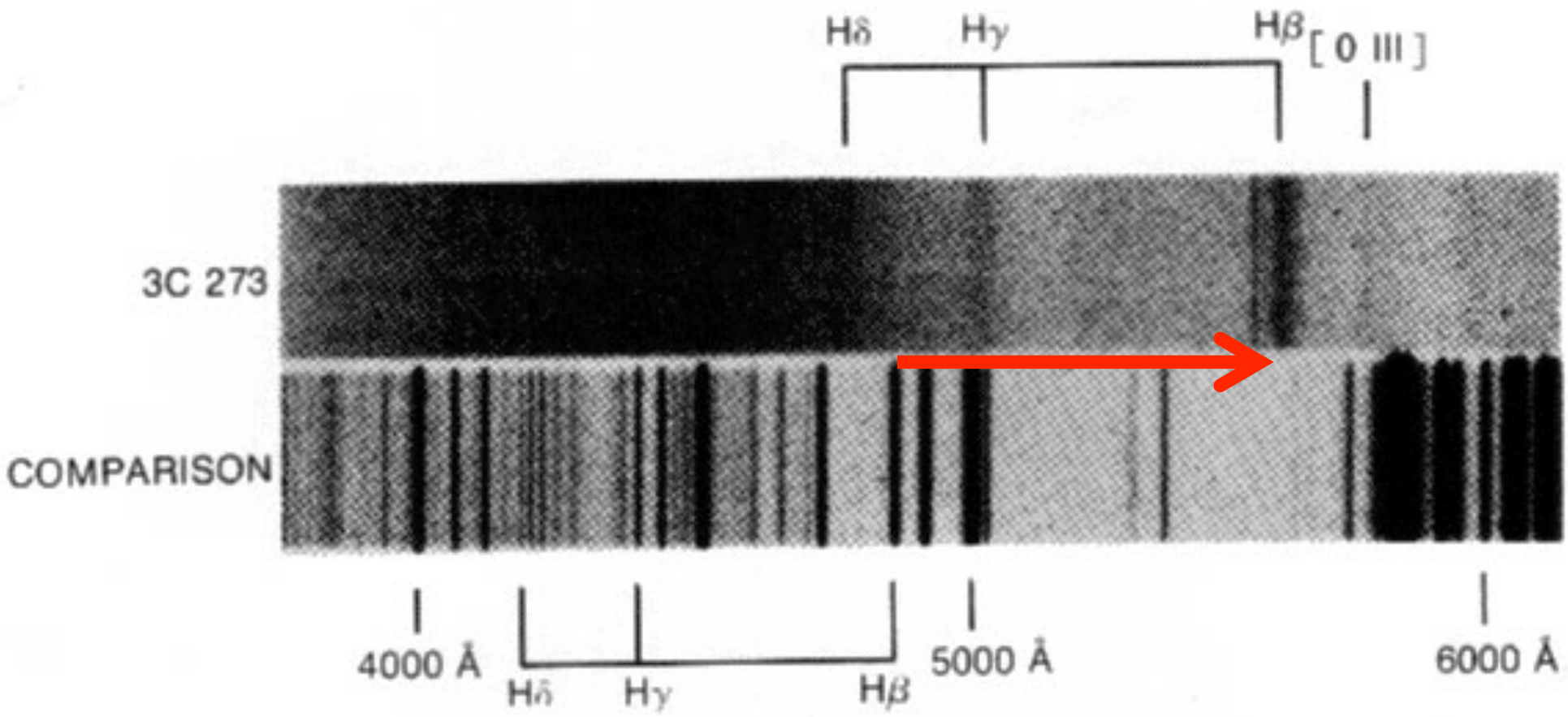


FIG. 2.—Spectrum of the quasi-stellar object 3C 273B, 400 Å/mm original, 103a-F, January 23, 1963. The comparison spectrum is H + He — Ne. Exposure over the upper half of slit was three times that over the lower half. Redshifted emission lines of H and [O III] are indicated; also the barely visible line of Mg II, confirmed on denser exposures.



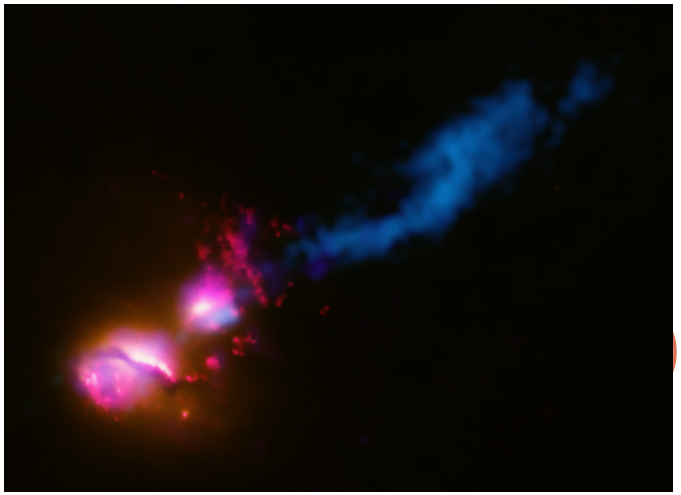


JEDNOSTAVNA INTERPRETACIJA SPEKTRA:
- CRVENI POMAK VODONIKOVIH LINIJA: z=0.158



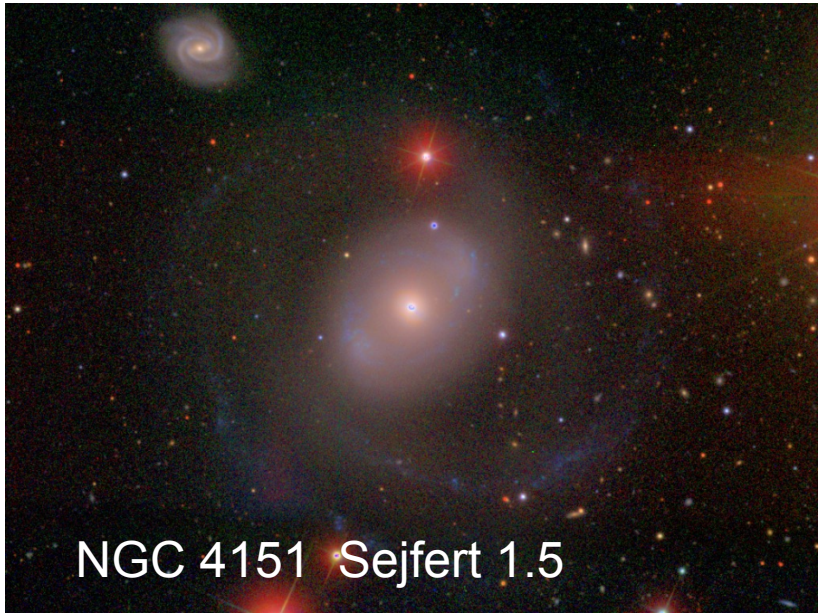
AKTIVNA GALAKTIČKA JEZGRA (AGJ)

- AGJ fenomen – svuda prisutan!
- osobine 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

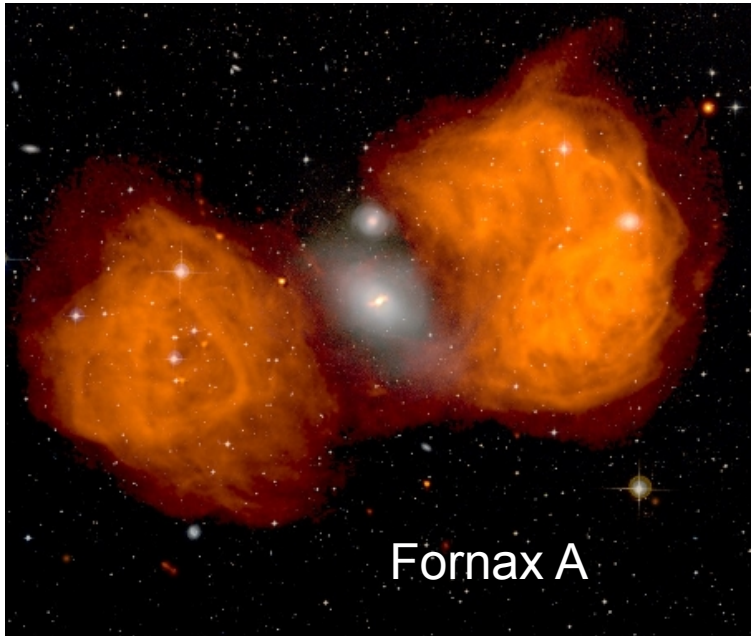


RAZLIČITE VRSTE AGJ

- **Sejfert galaksije**
  spiralne galaksije sa vrlo sjajnim jezgrom; jake emisione linije



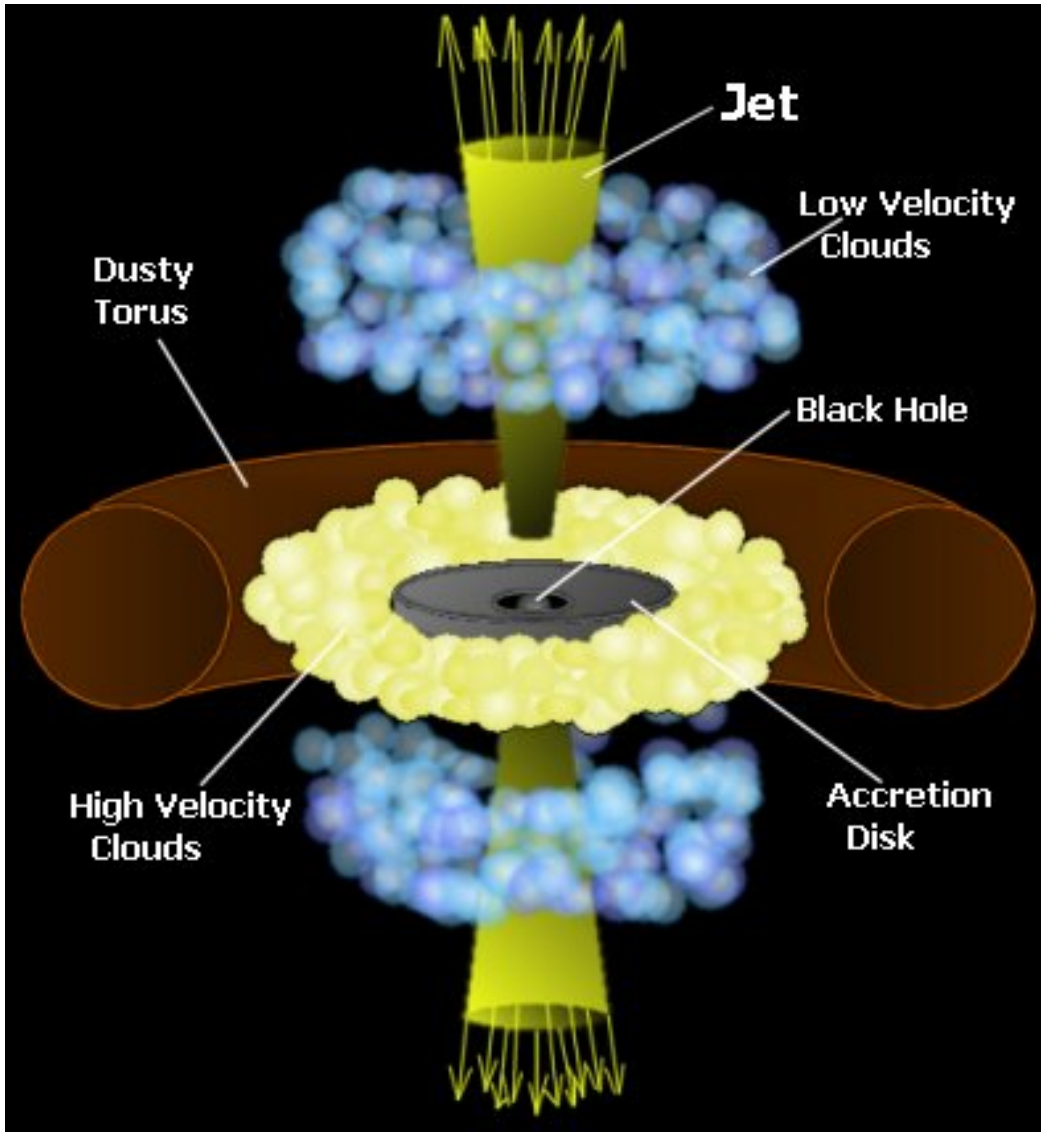
- **Radio galaksije**



- **Kvazari**
  najsjaniji objekti na nebu;

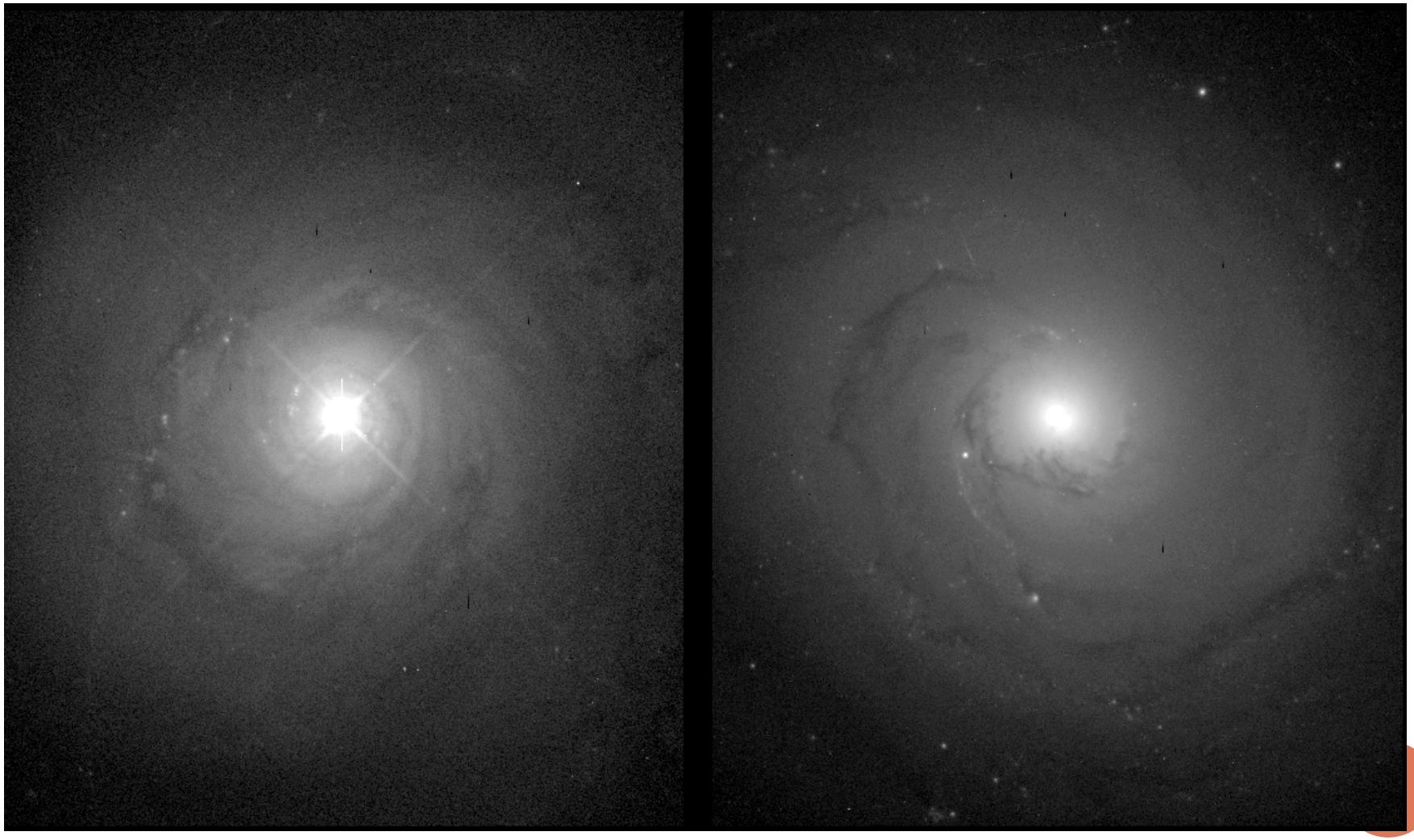
  zapremina veličine Sunčevog sistema izrači energiju oko 10^{12} zvezda!!

STRUKTURA AGJ



- supermasivna crna rupa (od milion do 10 milijardi masa Sunca)
- akrecioni disk
- mehanizam akrecije
- emisioni regioni koji emituju široke i uske emisione linije
- mlazevi relativistič. elektrona

SEJFERT 1 NGC 5548 VS. GALAKSIJA NGC 3227

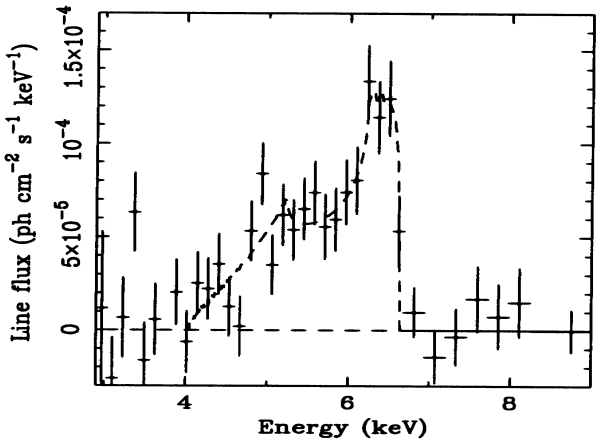


AGJ: CENTAURUS A (ILI NGC 5128)

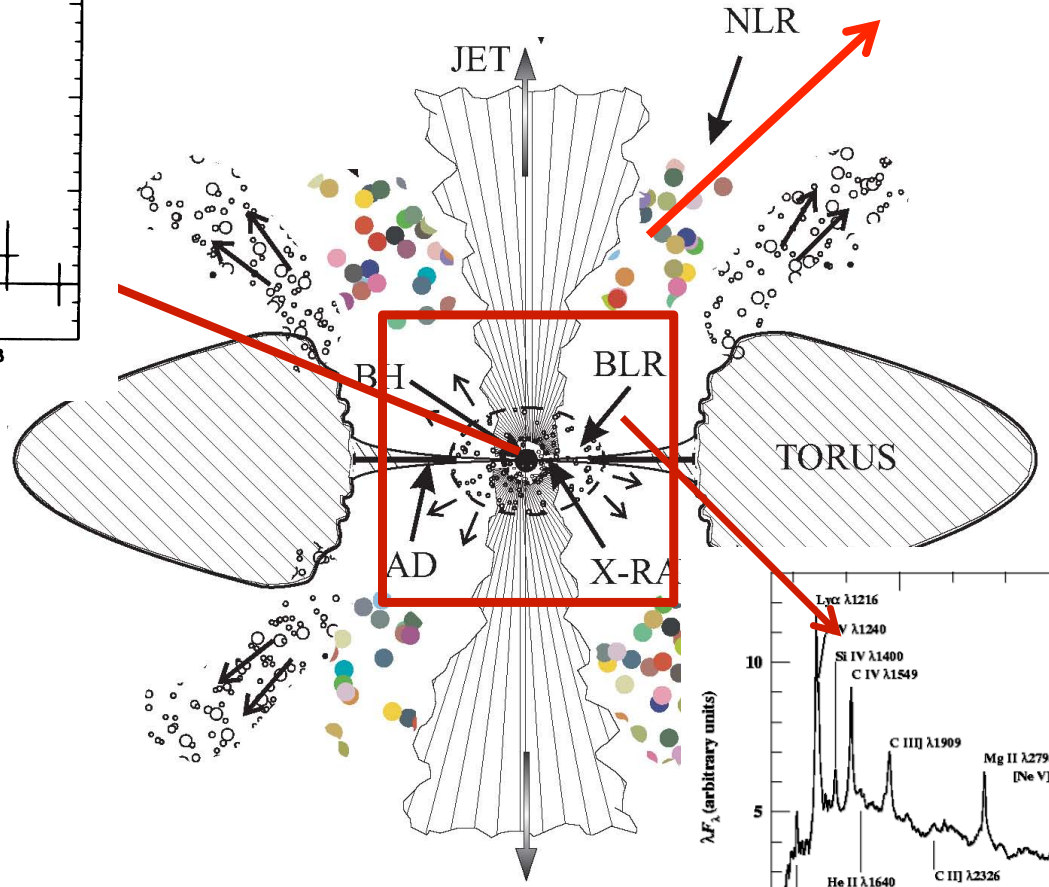
- Radio-slika superponirana na optičku i X-sliku izvora

ODAKLE POTIČU EMISIONE LINIJE?

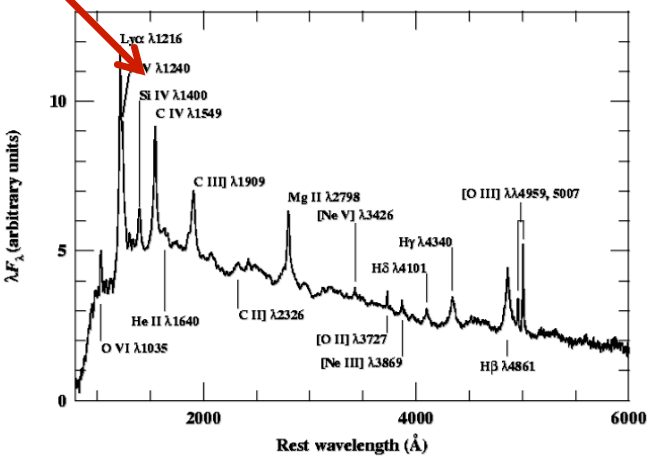
Fe Kα linija u X-domenu



Spektar uskih linija
(iz Narrow Line Region)



Broad Line Region (BLR)

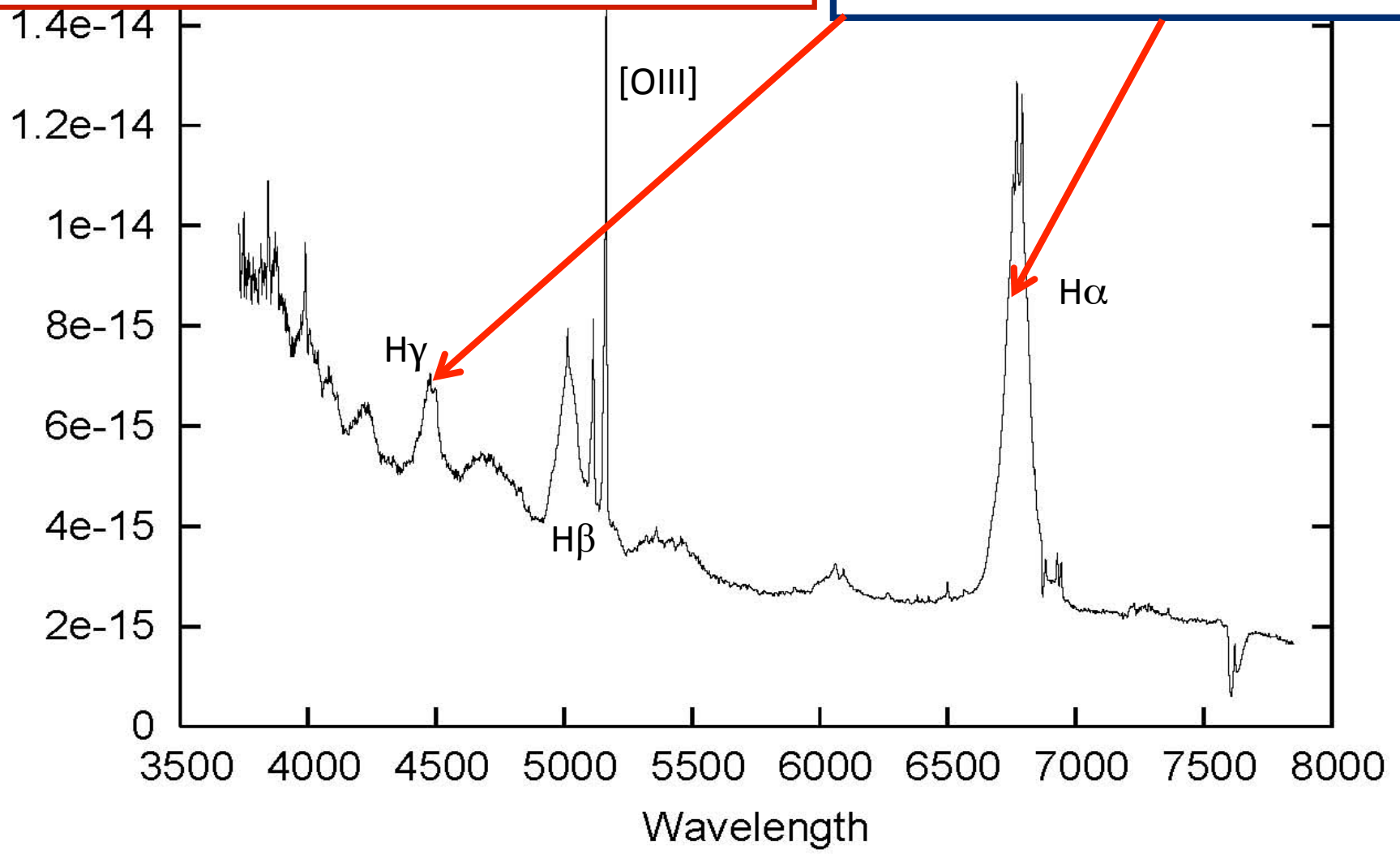


UV/Optički spektar
širokih linija

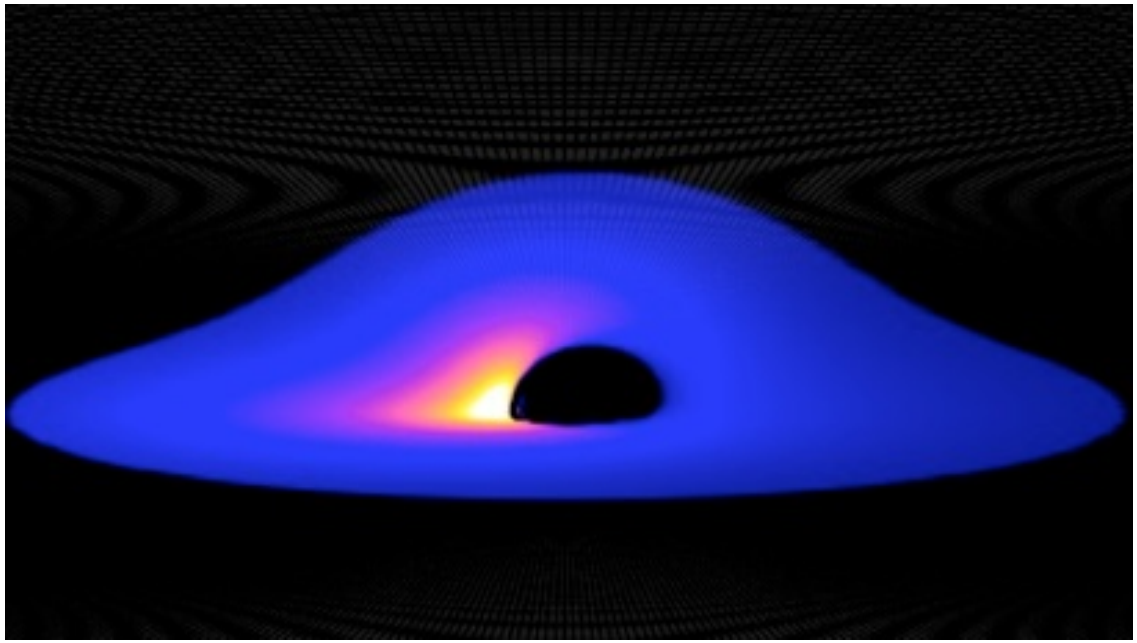
EMISIONE LINIJE

Balemrove linije kod AGJ Mrk 817
(Ilic et al.2006)

Široke emisione linije
- samo iz dozvoljenih prelaza
širina ~ 2000 - 10000 km/s

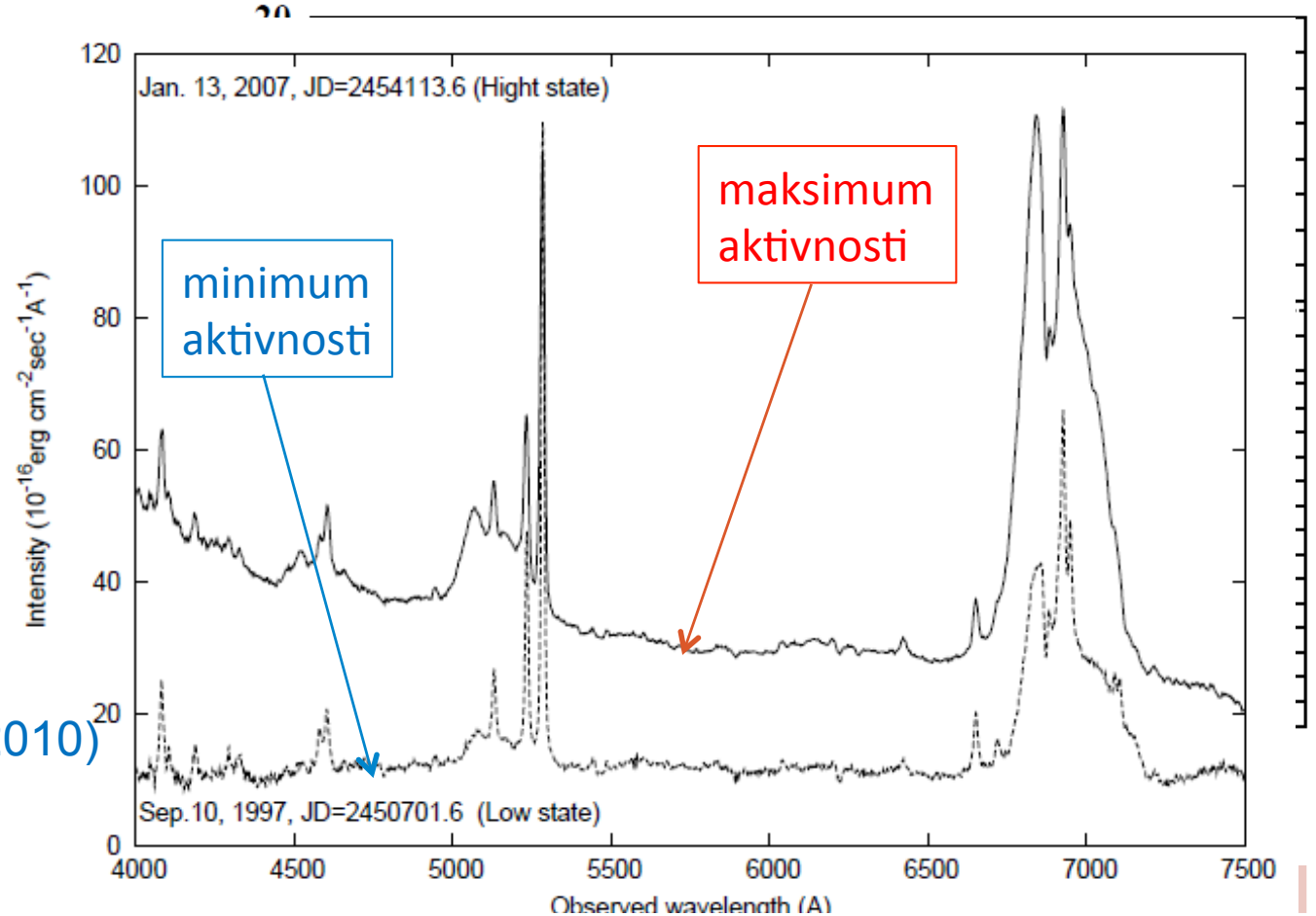


KAKO MOŽEMO PROCENITI MASU CRNE RUPE?



AGJ – PROMENJIVI OBJEKTI

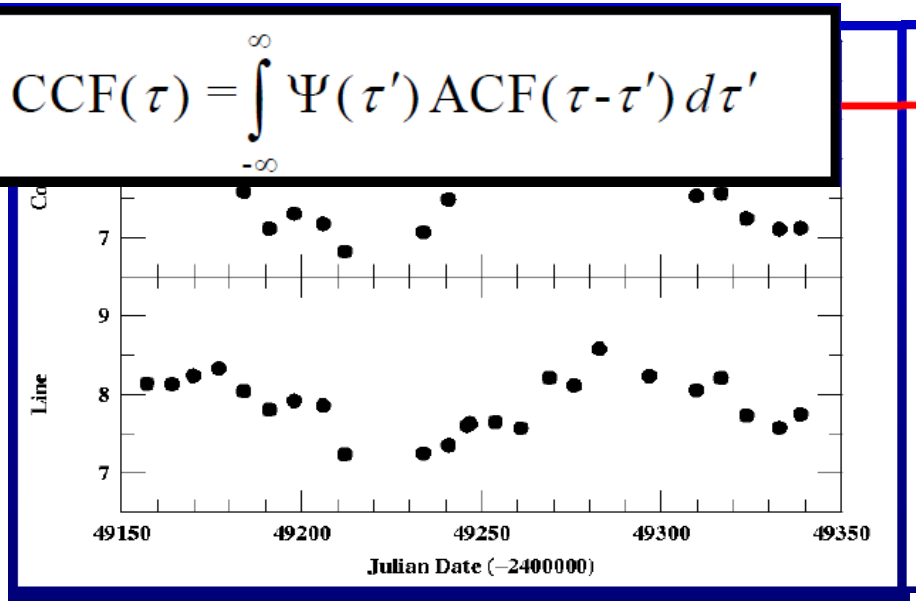
- fluks u liniji i kontinuumu se menja
- velika promena (AGJ tip: tip 1 -> tip 2)

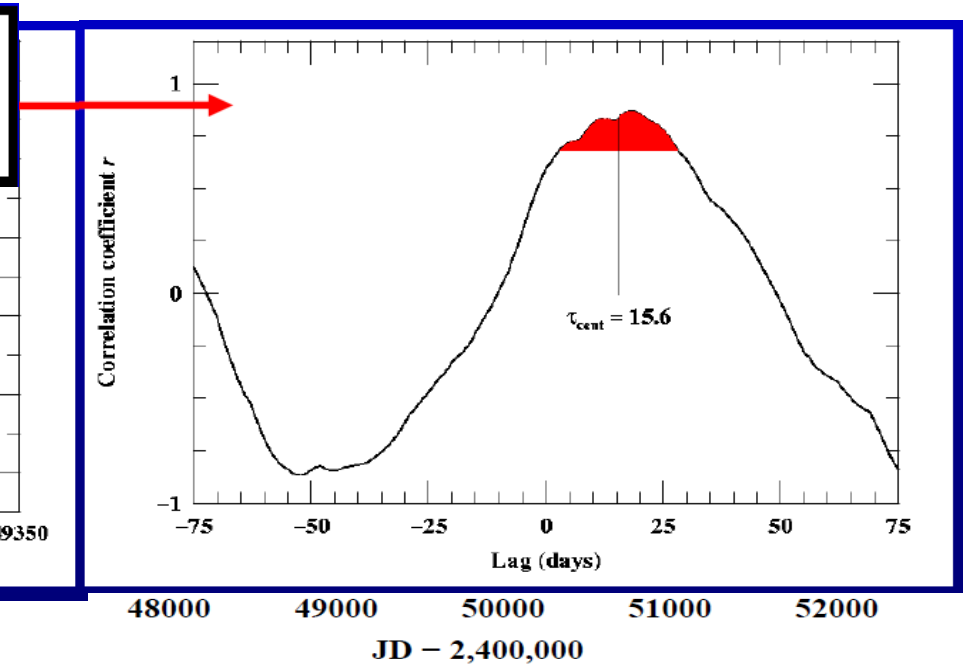


3c390.3 NGC 5548 (Peterso
(Shapovalova et al. 2010)

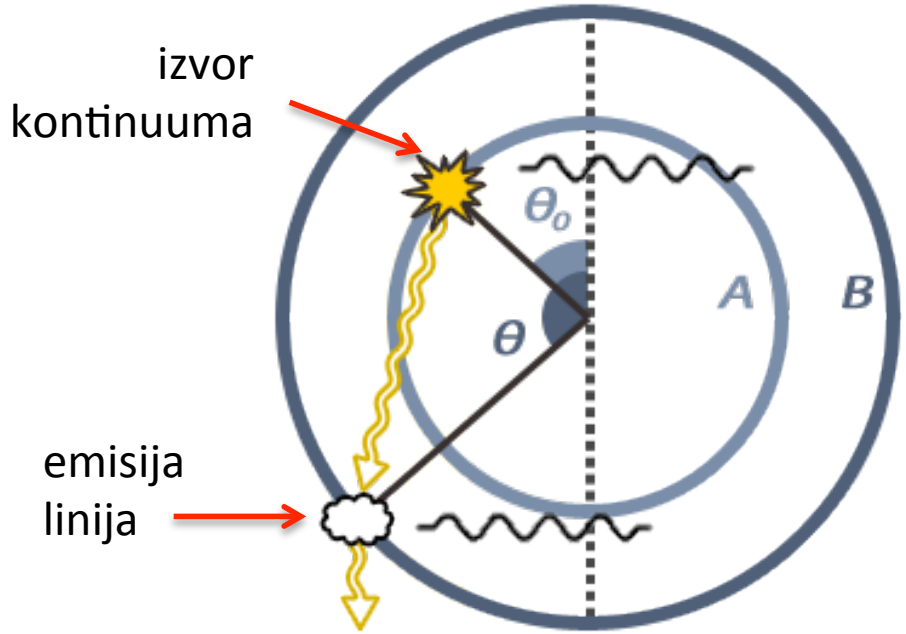
AGJ – REVERBERACIJA

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





NGC 5548 (Peterson et al. 2002)



vremensko kašnjenje fotona u liniji u odnosu na foton kontinuuma

PROCENA MASE CRNE RUPE

potrebe su:

- optičke emisione linije
- osobine regiona koji emituje linije: brzine i dimenz

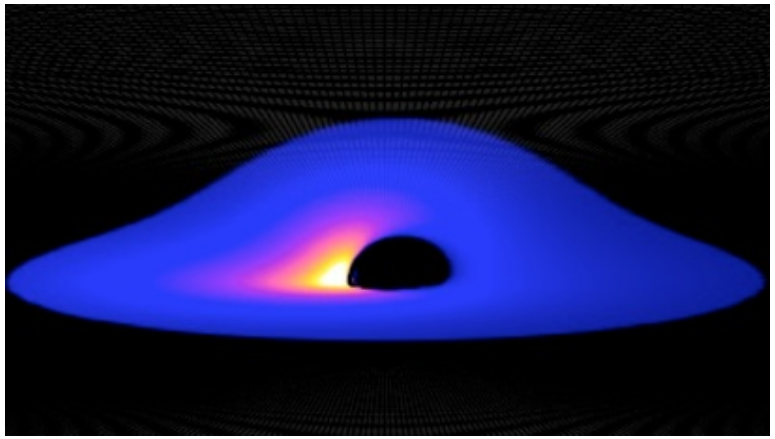
Te ma ala

BLR GEOMETRY

BLR DIMENSIONS

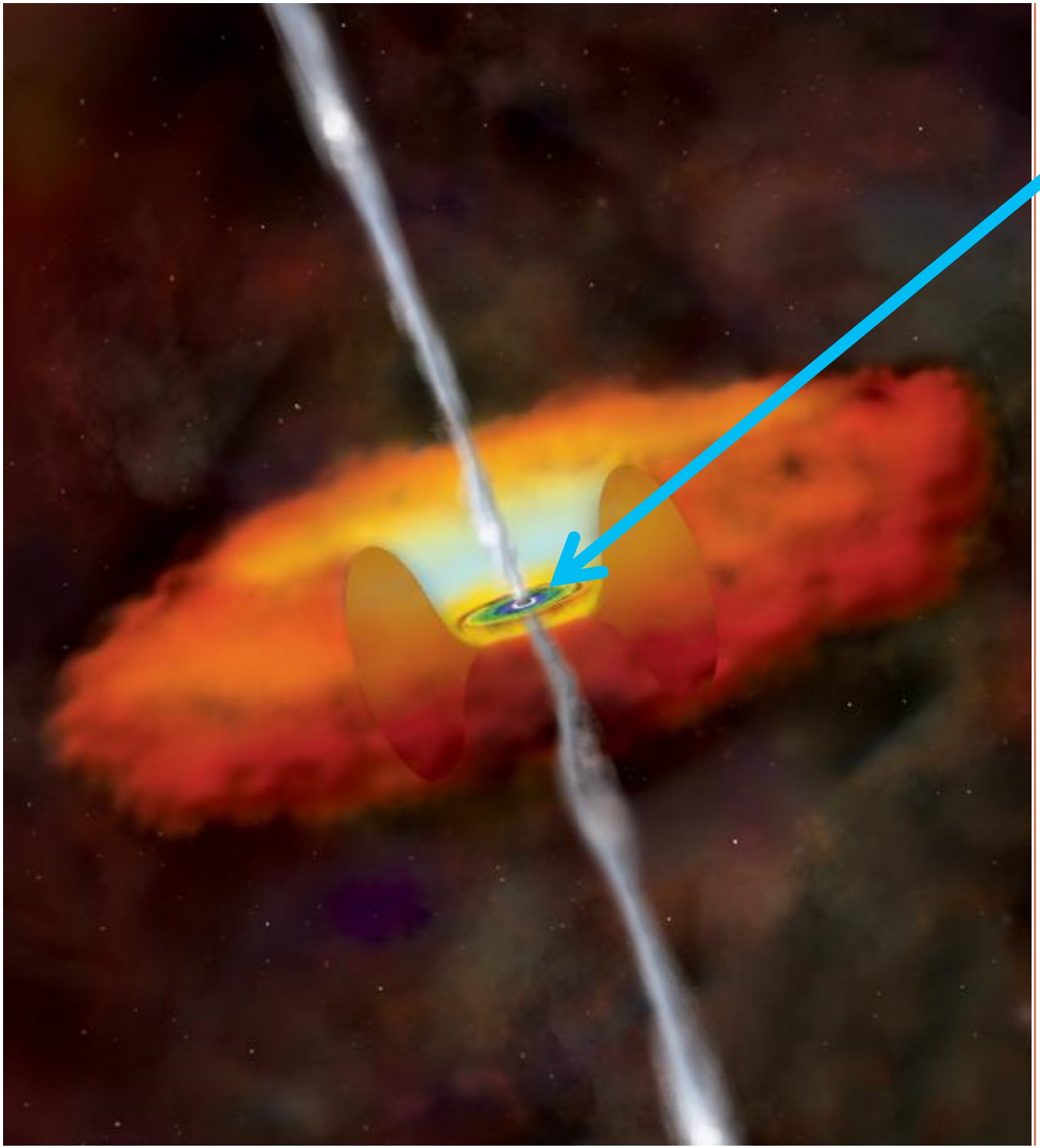
BLR KINEMATICS

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



(Wandel+ 1999; Kaspi+ 2000, 2005; Peterson+ 2004, Bentz+ 2009)

- pretpostavka: Fotojonizacija



da bi procenili masu M_{BH} neophodne su nam osobine regiona koji emituje široke emisione linije

DUGOGODIŠNJA POSMATRANJA AGJ

- Alla I. Shapovalova (Russia)
  Vahram H. Chavushyan (Mexico)
- konstantna posmatranja poznatih AGJ:
  - NGC 5548 – 9 years (Shapovalova+ 2004, Ilić 2007, Popović +2008)
  - NGC 4151 – 11 years (Shapovalova+ 2008, 2009, 2010a)
  - 3C390.3 – 13 years (Shapovalova+ 2010b, Popović+ 2011, Jovanović+ 2010)
  - Ark 564 – 11 years (Shapovalova+ 2012)
  - Arp 102B – 12 years (Shapovalova+2013, Popović+ 2014)
- proučavanje promenjivosti: fluks kontinuuma i linija, oblik profila, modeli, itd.

POSMATRANJA

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

NGC 4151

- izuzetno promenjiv izvor i u kontinuumu i u linijama (e.g. Peterson 1988; Sergeev et al. 2001)

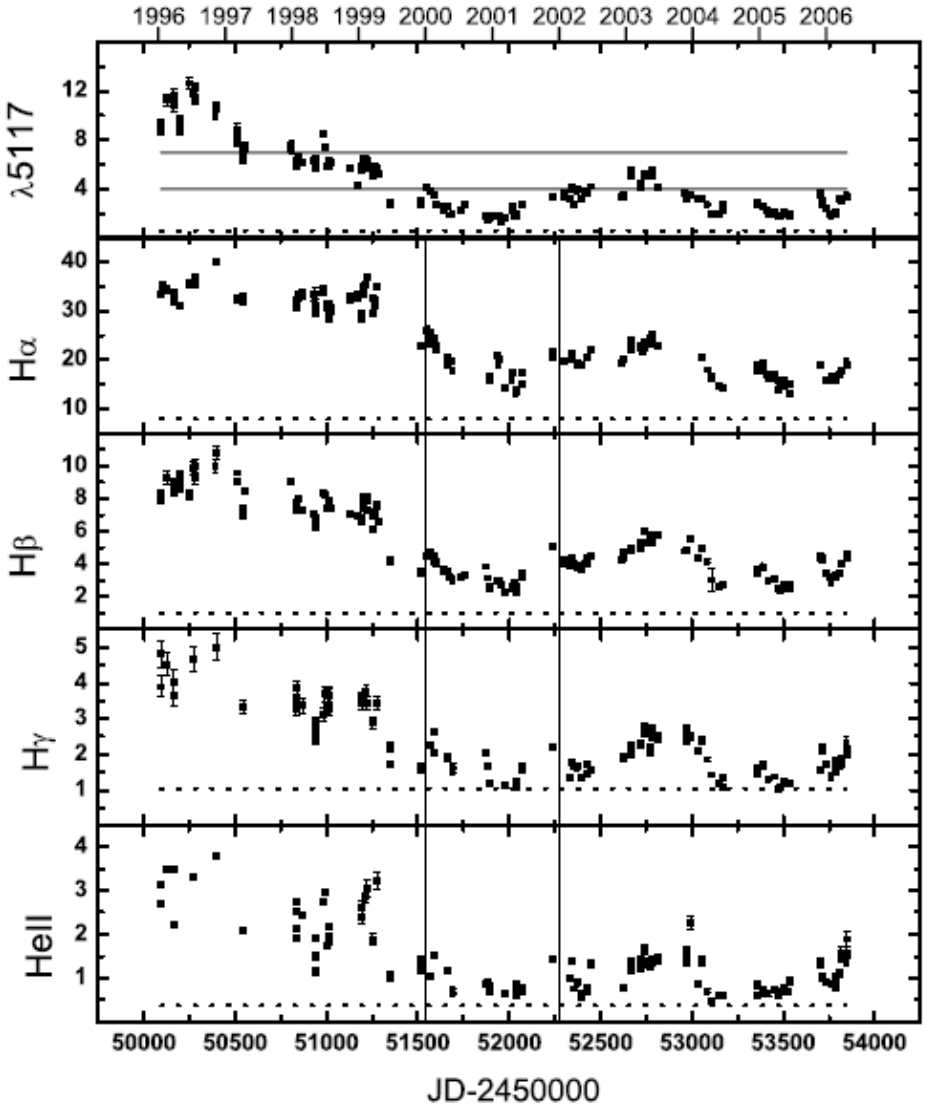
- posmatrano 11 god
- CCF analiza krive sjaja

⇒izuzetno kompaknto BLR

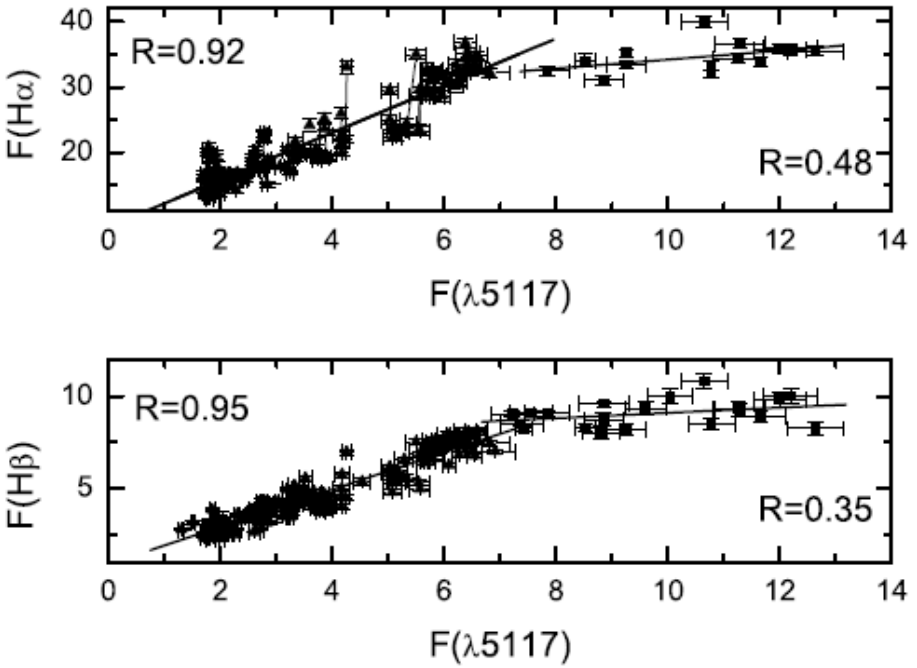
⇒vremensko kašnjenje:
~ 0-2 svetlosna dana!!

Shapovalova+ 2008, A&A, 486, 99

Shapovalova+ 2010, A&A, 509, 106



NGC 4151



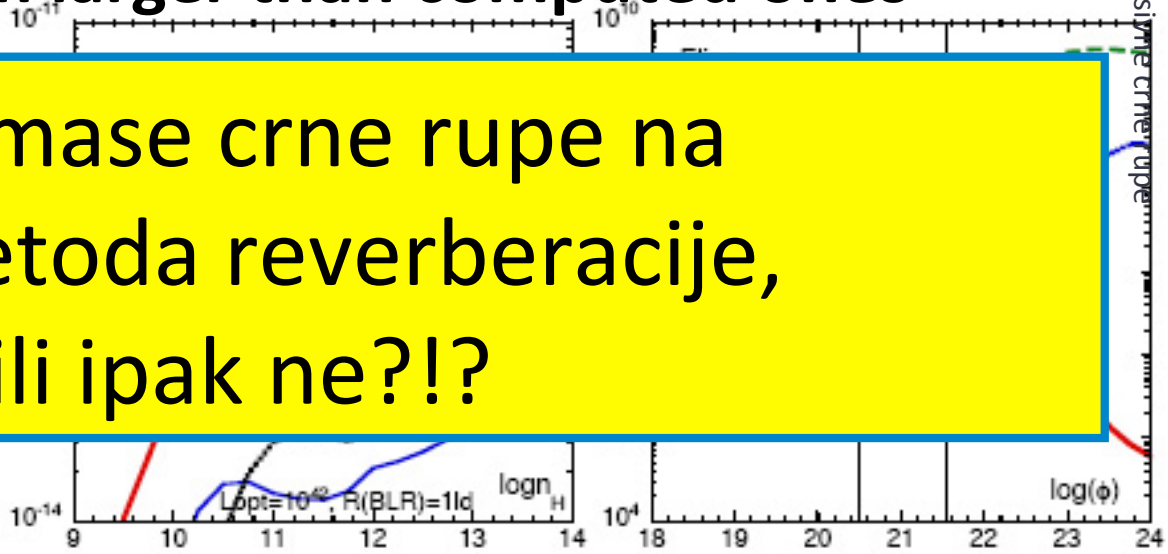
- saturacija fluksa u liniji za velike vrednosti kontinuuma

$F_{obs}(H\beta)=(2.3\text{-}9.8)\times10^{-12}$erg cm^{-2}s^{-1}

- na osnovu fotojonizacionog modela izračunate vrednosti fluksa u liniji za odgovarajući fluks kontinuuma ⇒ **observed line flux much larger than computed ones**

Procena mase crne rupe na osnovu metoda reverberacije, da ili ipak ne?!?

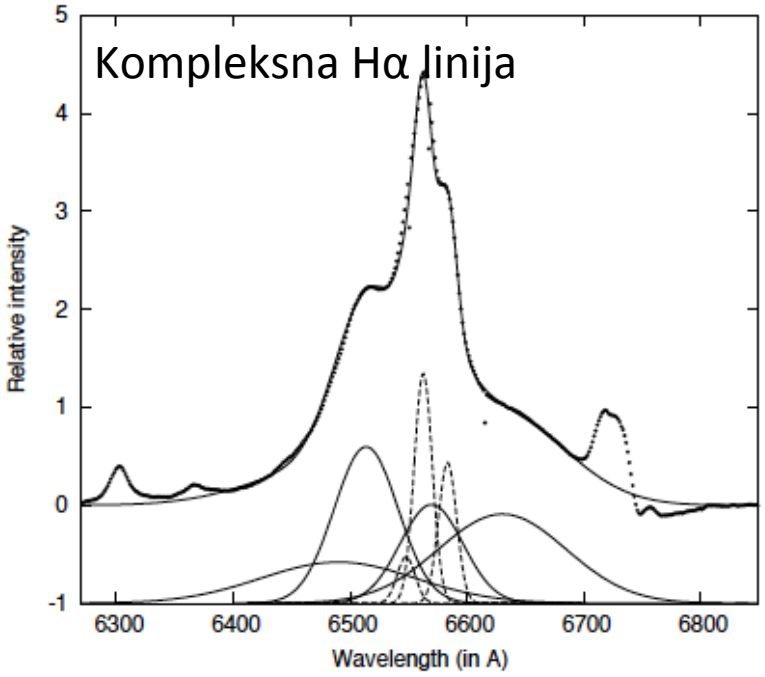
Shapovalova, Popović, et al. 2008, A&A, 486, 99

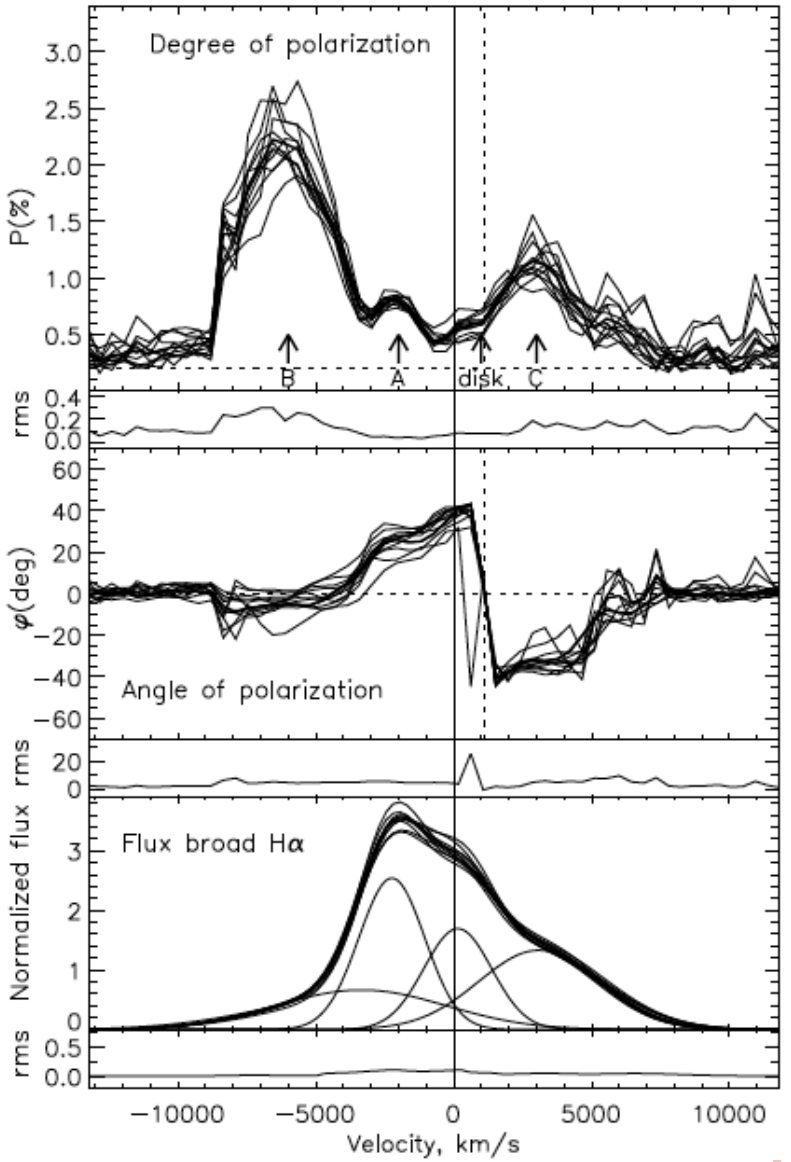


Fluks linije vs. koncentracija (levo) i jonizujući fluks (desno)

DA LI POMAŽE POLARIZACIJA ŠIROKIH LINIJA?

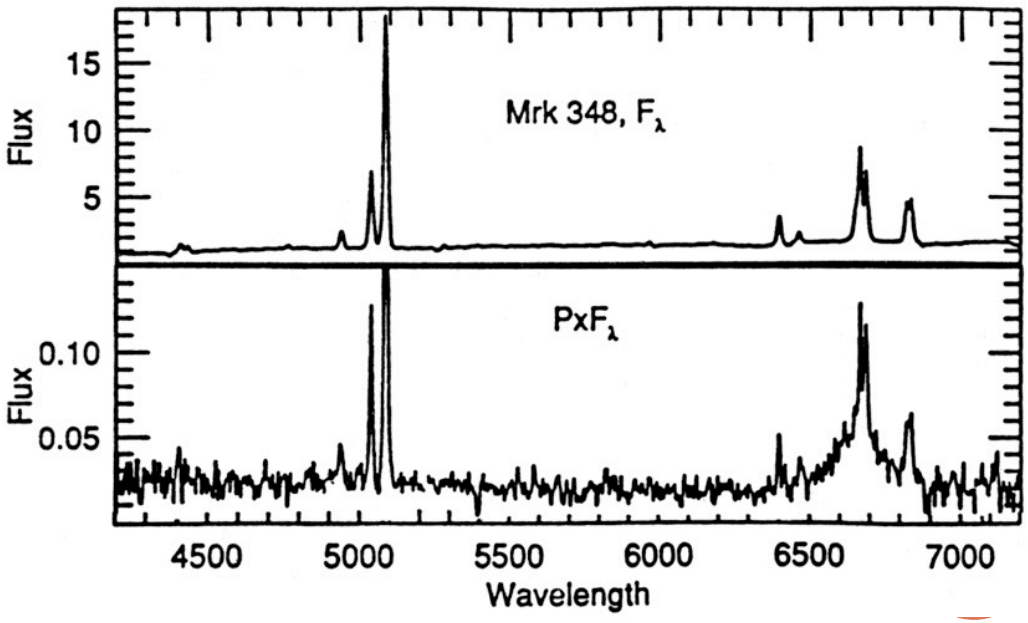
- primer galaksije Mrk 6
- spektro-polarimetrijska posmatranja sa 6m SAO teleskopom (Afanasiev+ 2014)



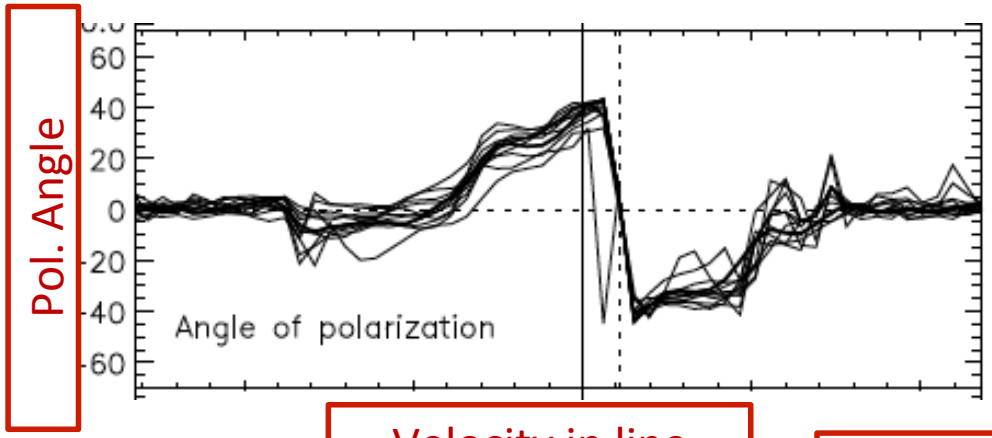


AGJ POLARIZACIJA: POSMATRANJA U OPTIČKOM DOMENU

- poređenje polarizaciju u kontinuumu i linijama, provera unificiranog modela AGJ
- potraga za širokim linijama u polarizaciji kod AGJ tipa 2
- **Procena mase crne rupe?**

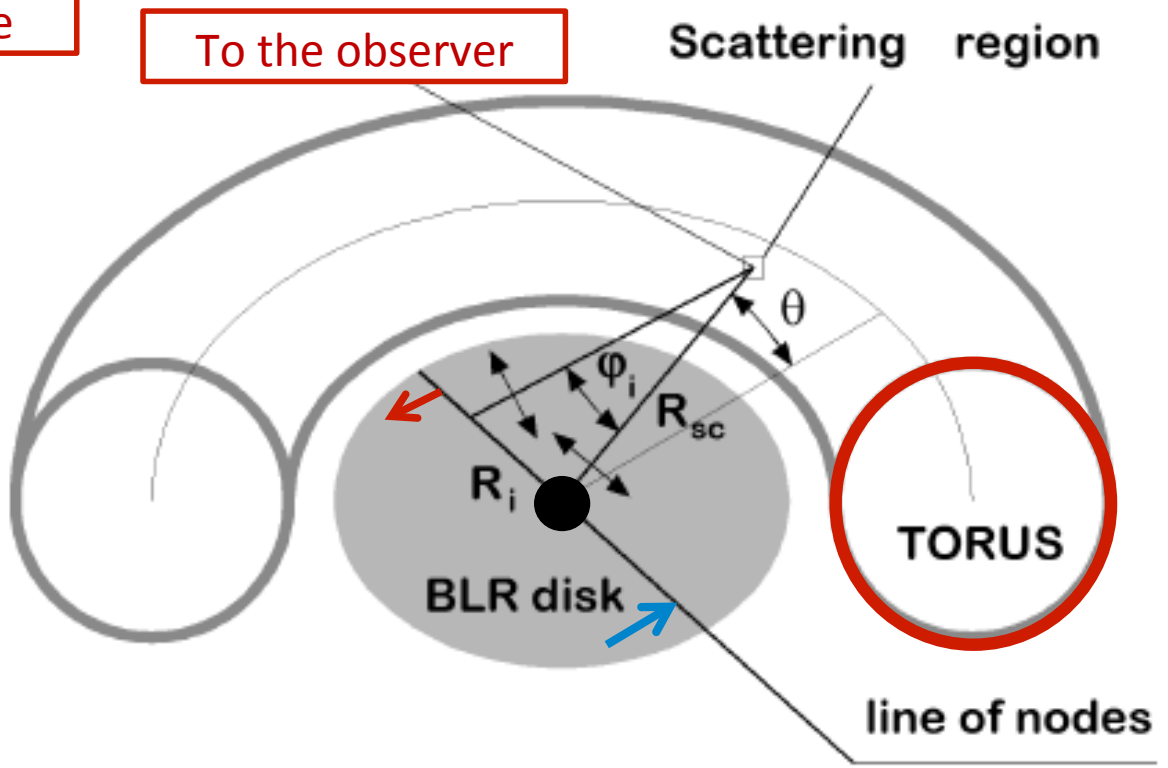


EKVATORIJALNO RASEJANJE KOD MRK 6



$$\log\left(\frac{V_i}{c}\right) = a - b \cdot log(\tan(\varphi_i))$$

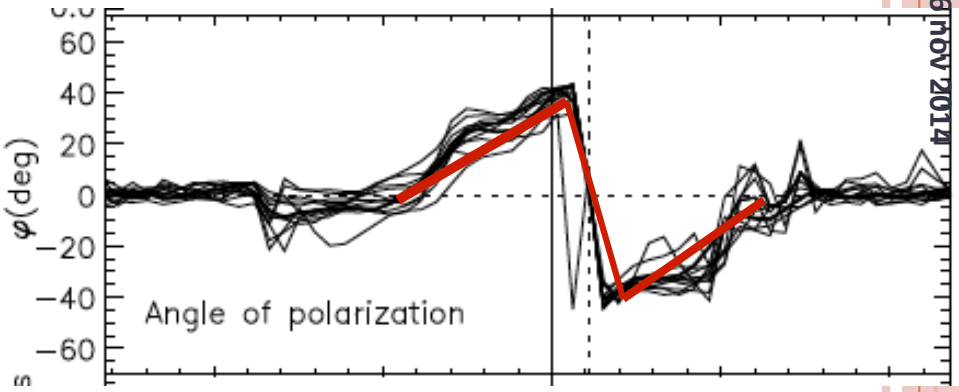
$$R_i = R_{sc} \cdot \tan(\varphi_i)$$

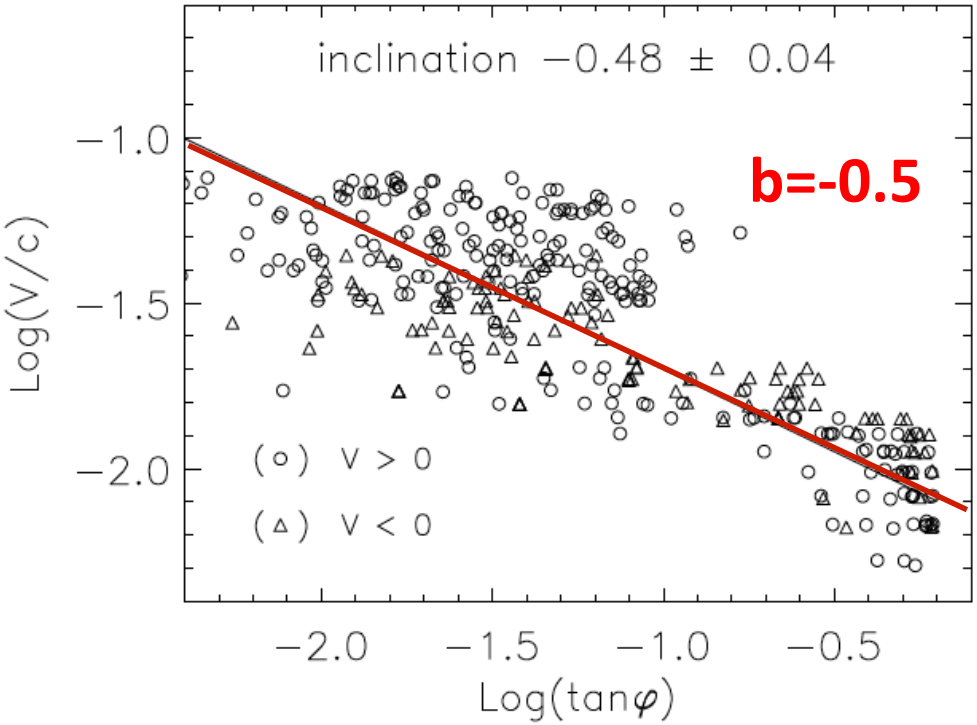


- Keplerovsko kretanje u BLR
- Ekvatorijalna polarizacija: rasejanje na unutrašnjoj strani torusa

Keplerovsko kretanje u BLR
(Afanasiev et al. 2014)

V VS. TAN(Φ) – DAJE DIREKTAN DOKAZ KEPLEROVSKOG KRETANJA GASA U BLR KOD MRK 6





$$\log\left(\frac{V_i}{c}\right) = a - b \cdot log(\tan(\varphi_i)),$$

Iz parametra a, dobija se masa crne rupe

$$a = 0.5 \log\left(\frac{GM_{BH}\cos^2(\theta)}{c^2 R_{sc}}\right)$$

NOVI METOD ZA PROCENU MASE CRNE RUPE

(AFANASIEV, POPOVIC, SHAPOVALOVA, BORISOV, ILIC, 2014)

$$M_{BH-kep} = 10^{2a}\frac{c^2 R_{sc}}{G\cdot\cos^2(\theta)} = 1.78\cdot 10^{2a+10}\frac{R_{sc}}{cos^2(\theta)}M_{\odot}$$

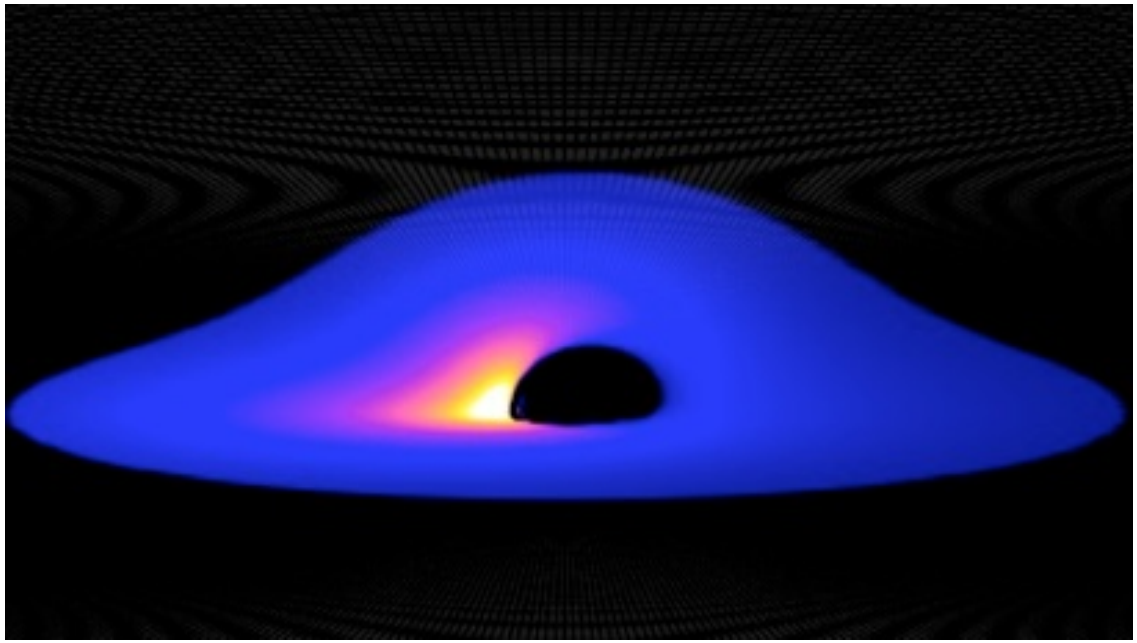
R_{sch}~ 0.18 pc ~ 220 svetlosnih dana (Kishimoto et al. 2011)

Uz pomoć spektro-polarimetriijskih posmatranja procenjena je masa supermasivne crne rupe kod Mrk 6

$$M_{BH-kep} = 1.16\times 10^{8} M_{sun}$$

Dobro slaganje sa reverberaciom: 1.3 - 1.8 $\times 10^8 M_{sun}$

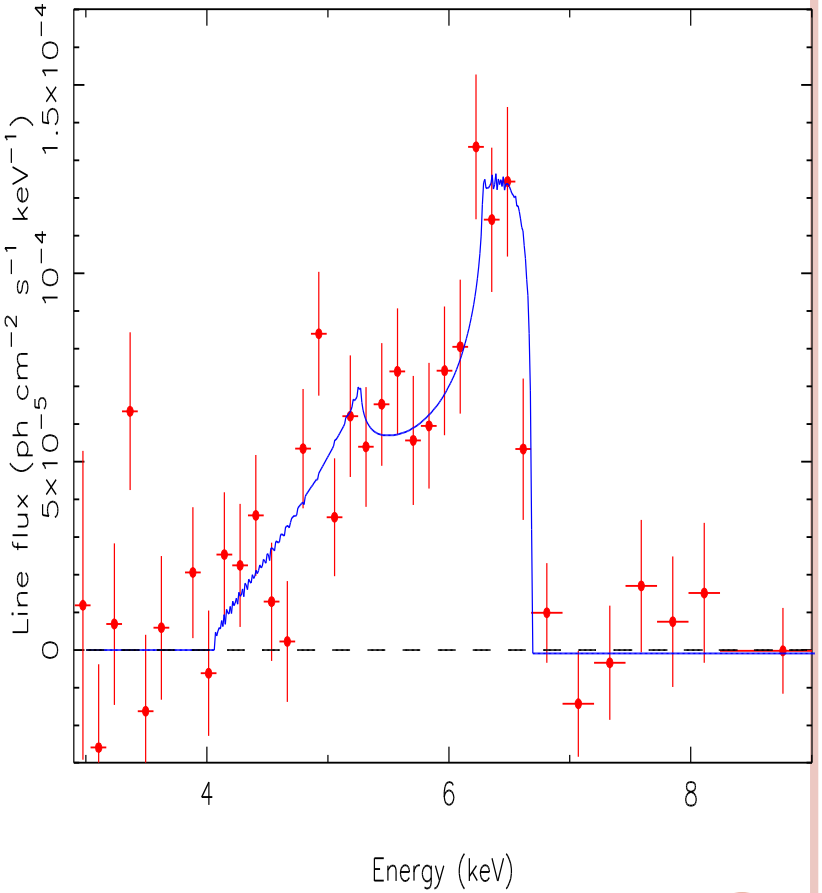
KAKO MOŽEMO PROCENITI SPIN CRNE RUPE?



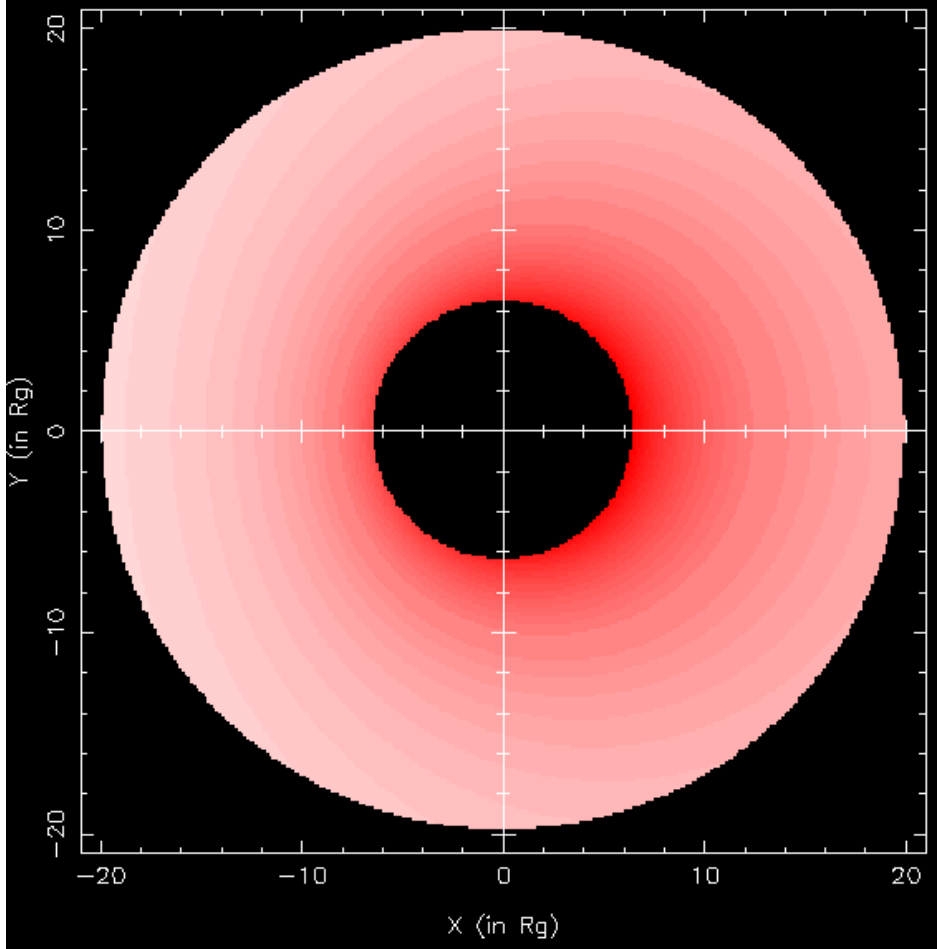
- modeliranje Fe K alpha linije u X-domenu, E=6.4 KeV

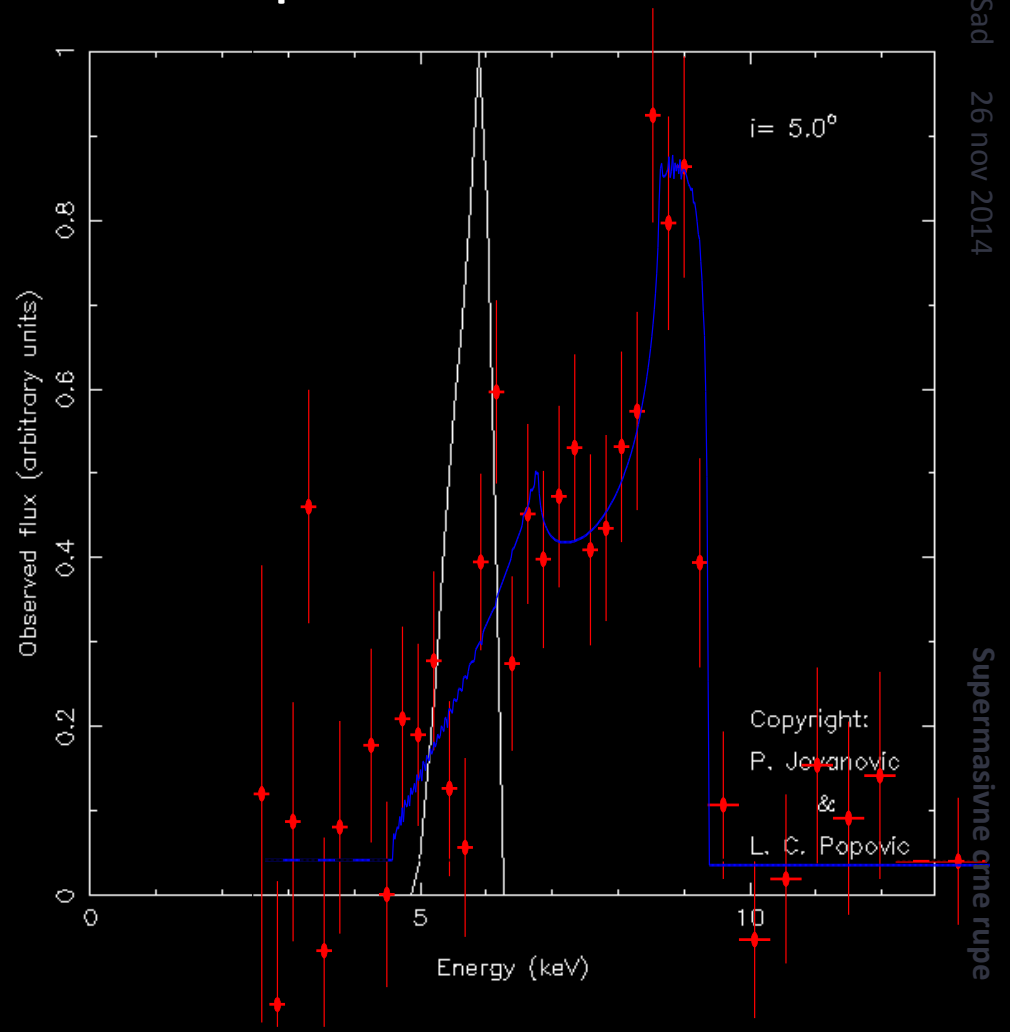
ZNAČAJ FE K ALPHA LINIJE?

- Fe K alpha, X-domen, E=6.4 KeV
- široka komponenta dolazi iz akrecionog diska (jako blizu crnoj rupi, oko 10 Rg, Tanaka et al. 1995, Nature)
  - **spin crne rupe**
  - fizika plazme u blizini crne rupe (dejstvo jakog gravitacionog polja)
  - geometrija akrecionog diska



Jovanović & Popović 2008, 2009: nerotirajuća crna rupa

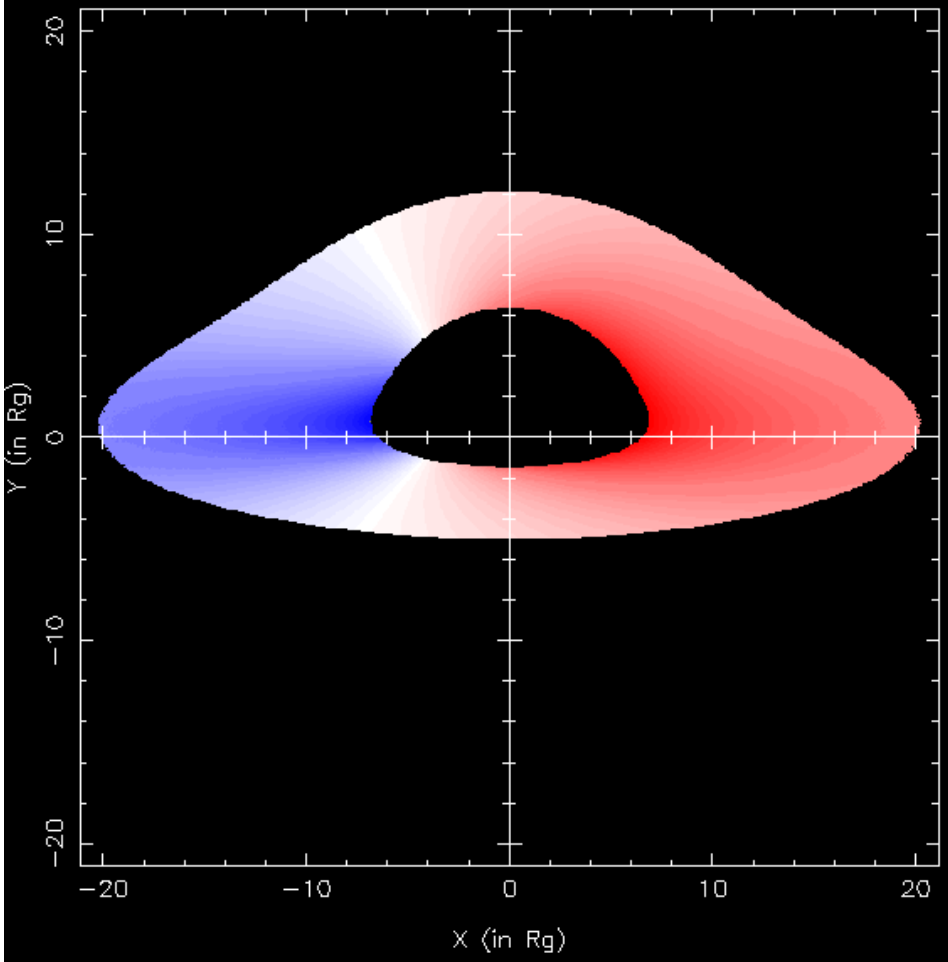


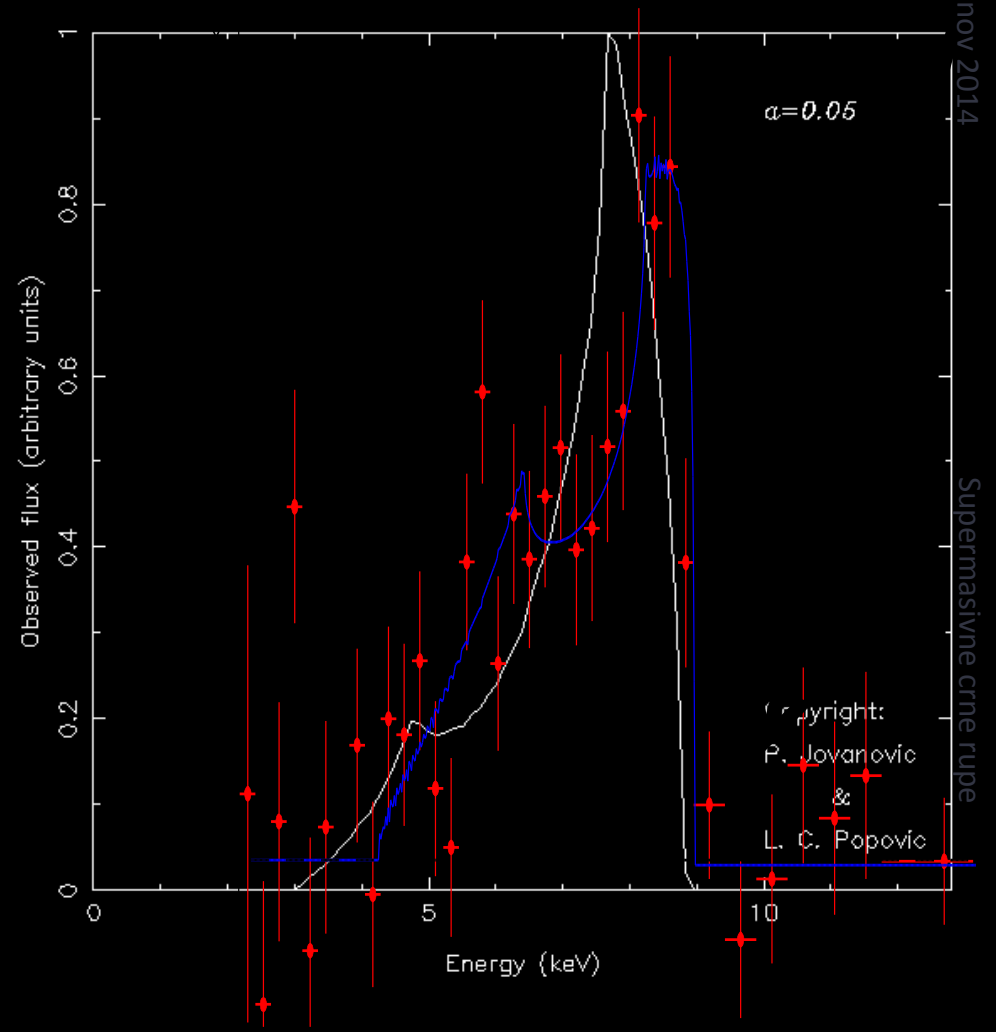


Model akrecionog diska u okolini crne rupe

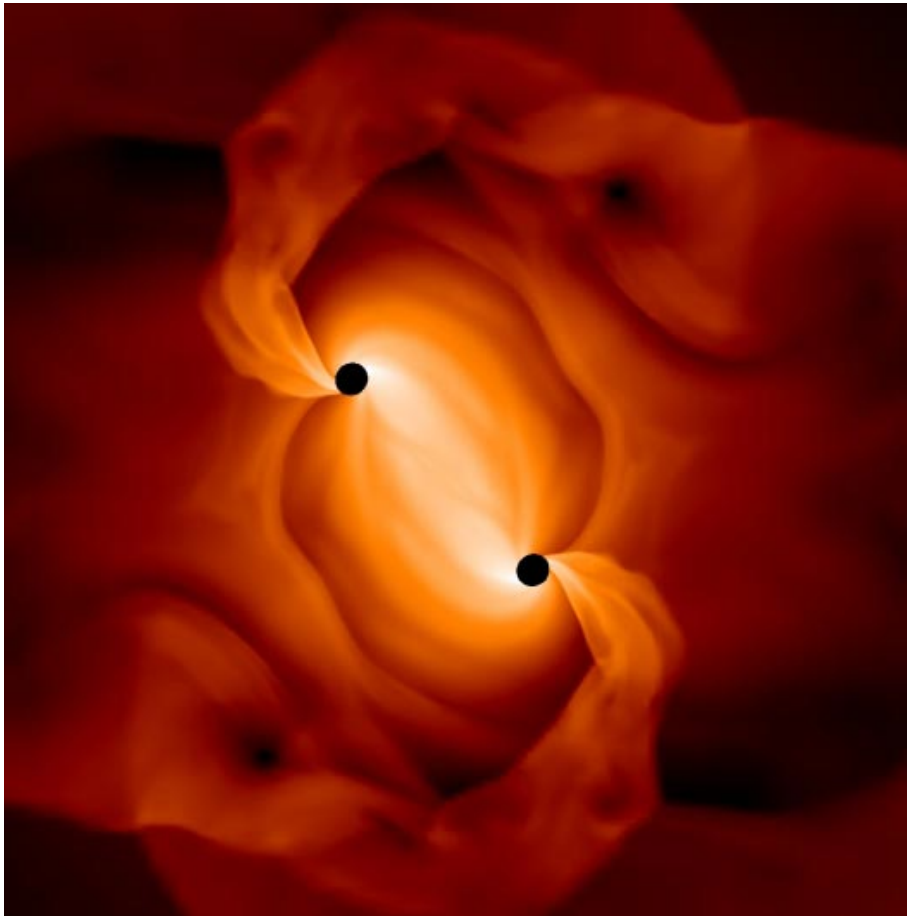
Novi Sad 26 nov 2014 Supermasivne crne rupe

Modeliranje Fe K alpha linije (rotirajuća crna rupa)





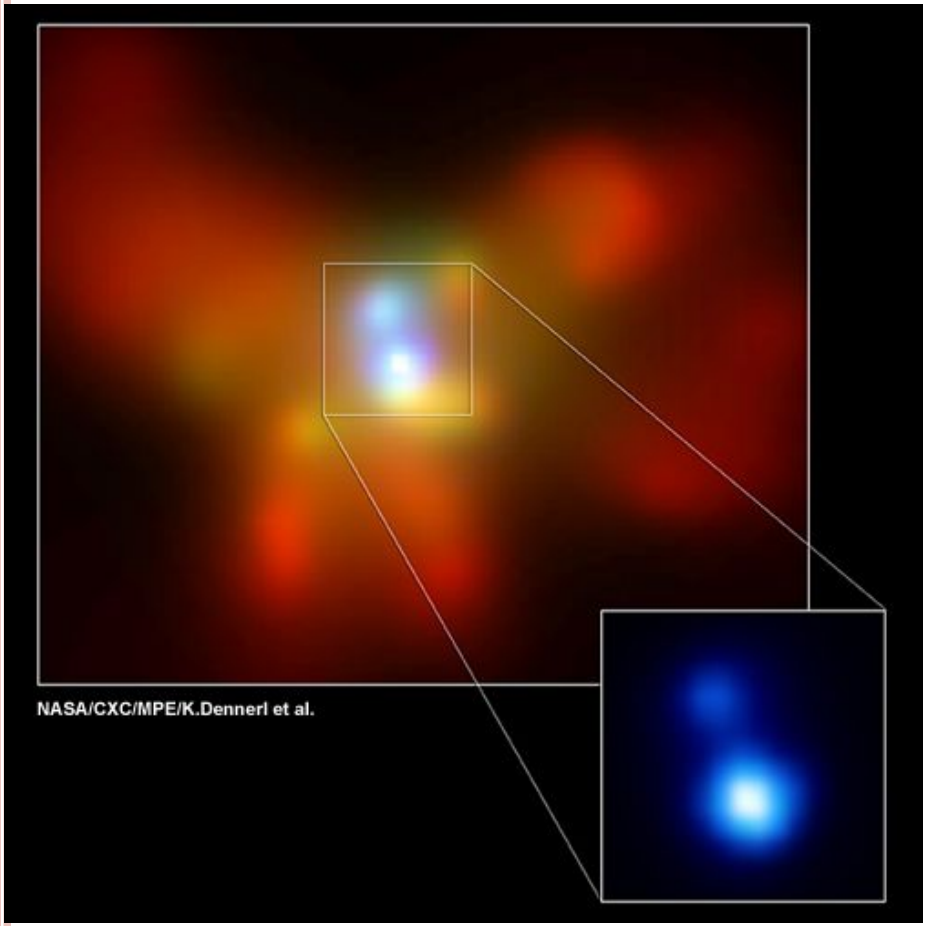
KAKO SE FORMIRAJU SUPERMASIVNE CRNE RUPE?



- sudari galaksija
- sudari crnih rupa

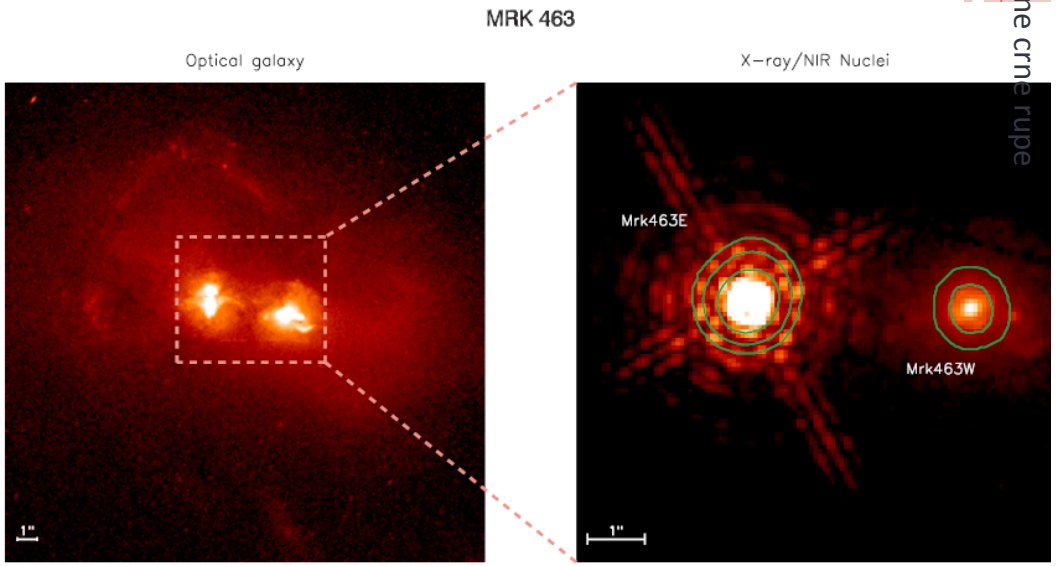
- dvojne crne rupe

SUPERMASIVNE DVOJNE CRNE RUPE



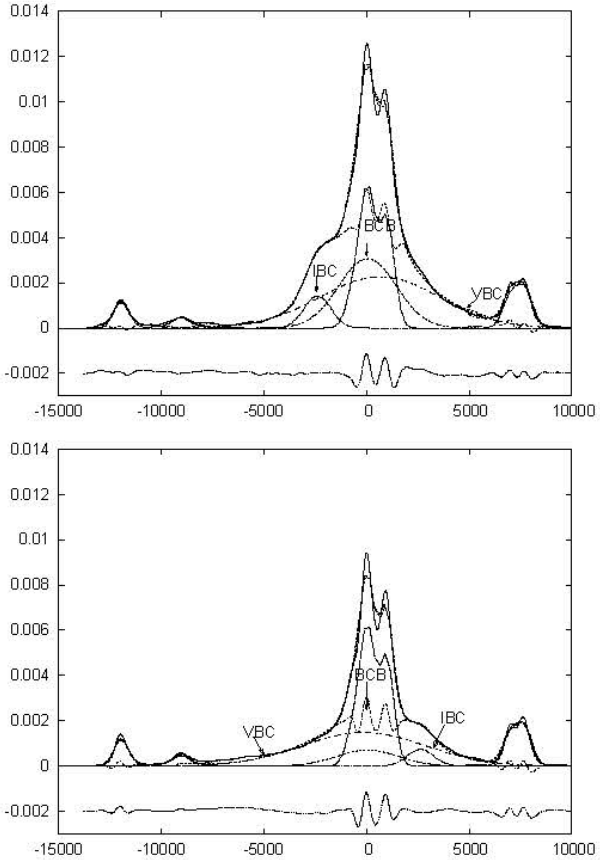
- Dvojna AGJ
  - NGC 6240 (Komossa+ 2003)
  - Mrk 463 (Bianchi+ 2008)

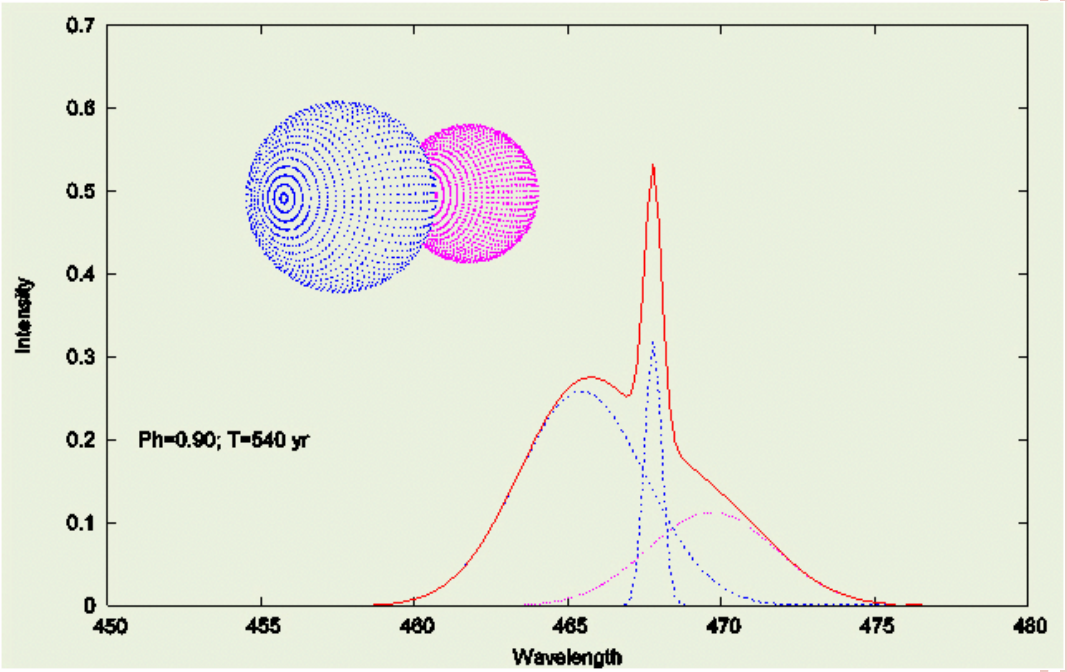
- Problem: detekcija?

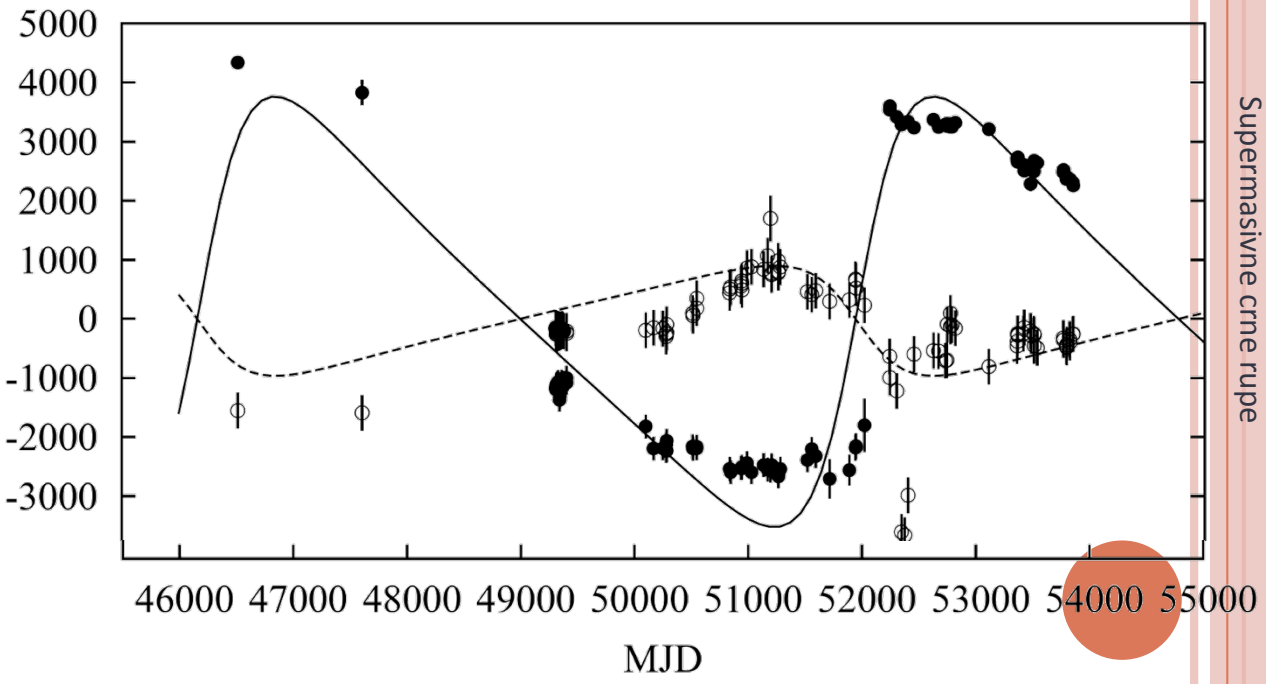


Uticaj dvojnih crnih rupa na emisione linije

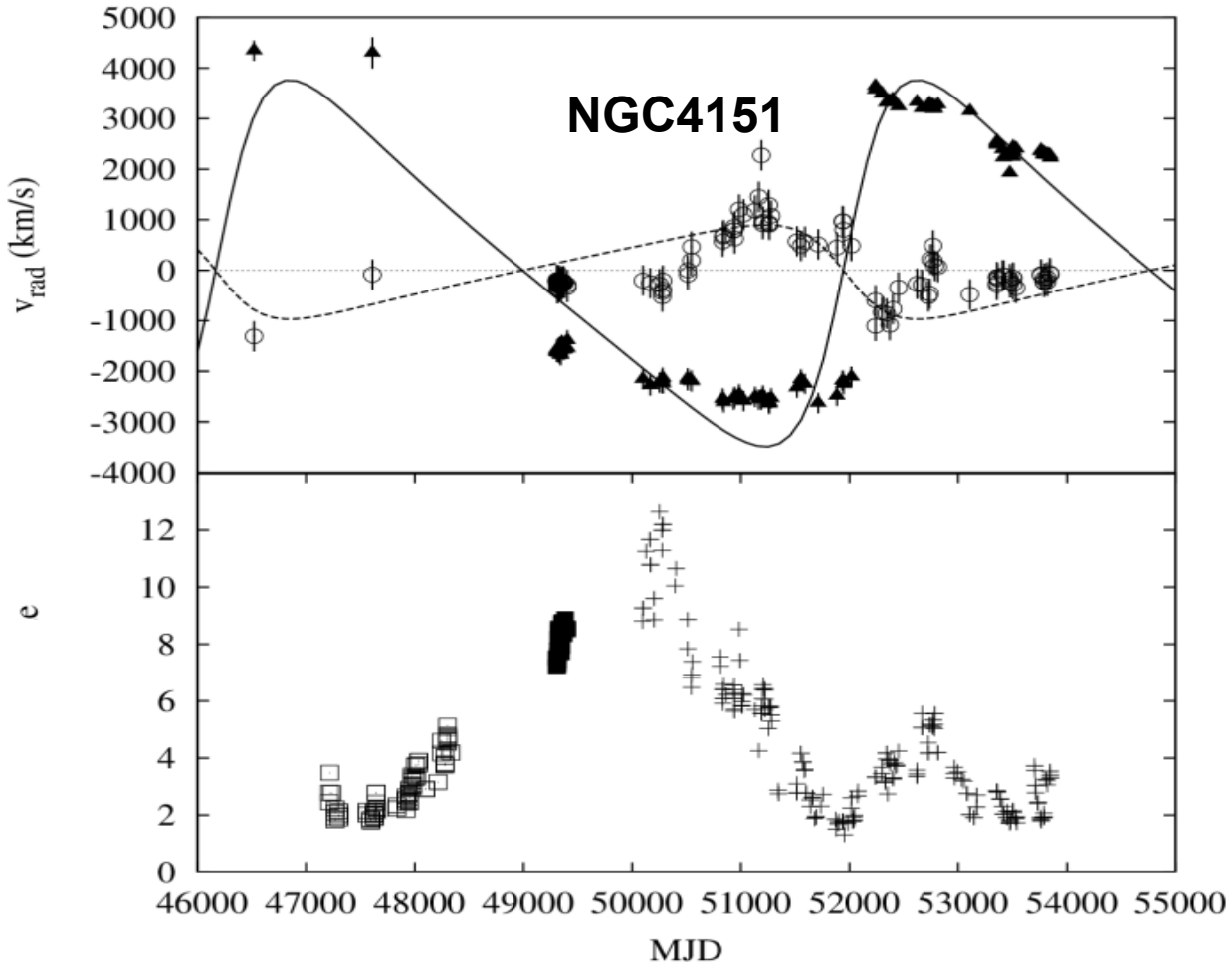
Popović, 2012, NewAR, 56, 74

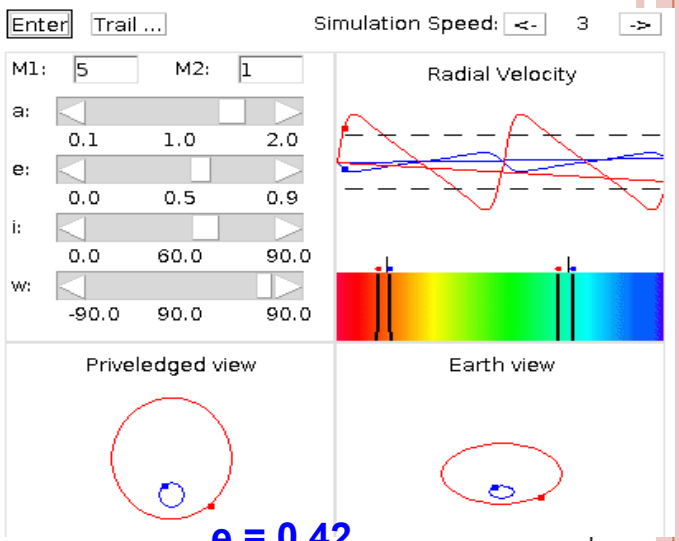






Bon et al. 2012, ApJ, 759, 118





e = 0.42

P = 5780 days (~16y)

ω ≈ 95°

a_1 sin *i* = 0.002 pc,

a_2 sin *i* = 0.008 pc

$m_1 \sin^3 i = 3 \cdot 10^7$ M⊙

$m_2 \sin^3 i = 8.5 \cdot 10^6$ M⊙

***i*=45° => 0.01 pc,**

$4.5 \cdot 10^7$ M⊙

$1.5 \cdot 10^7$ M⊙

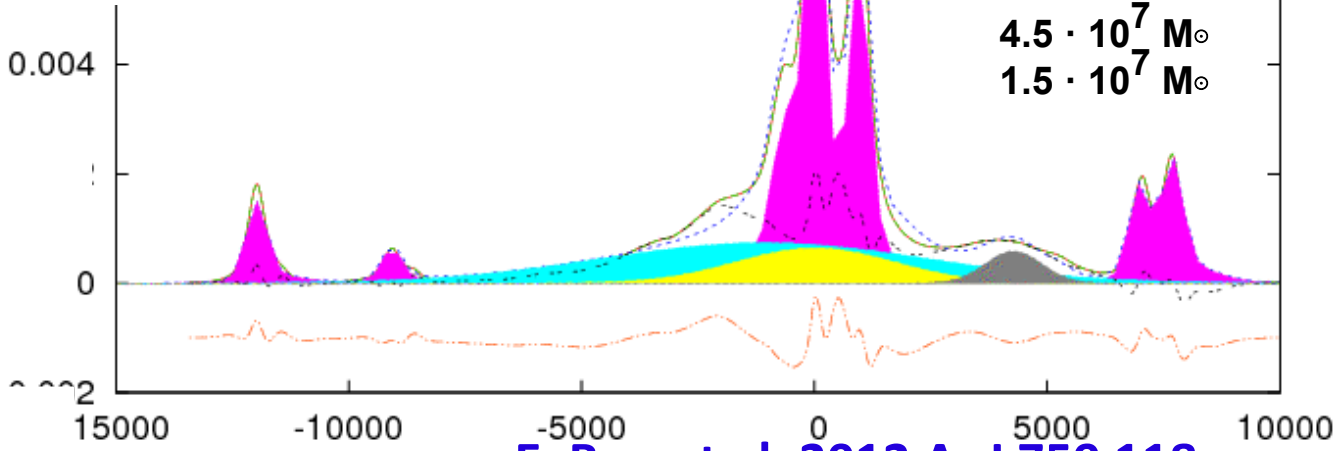
Sum of Gaussians:

σ_{VBC} = 3400 km / s

σ_{CBC} = 1700 km / s

σ_{Bump} = 600 km / s

Narrow line template



- **E. Bon et al. 2012 ApJ 759 118**

Supermasivne crne rupe

Hvala na pažnji!