The First Spectroscopically Resolved Orbit of a Supermassive Binary Black Hole

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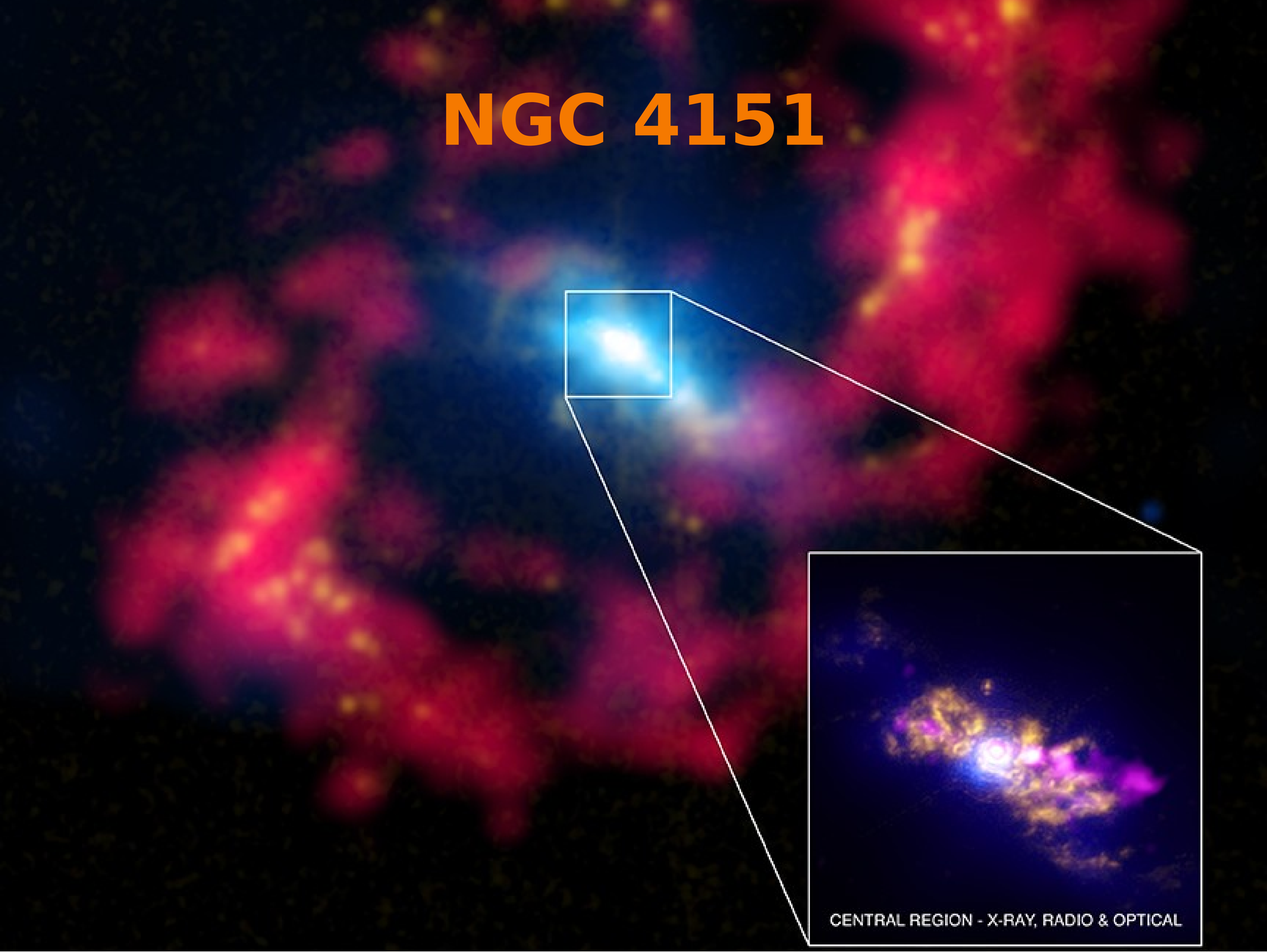
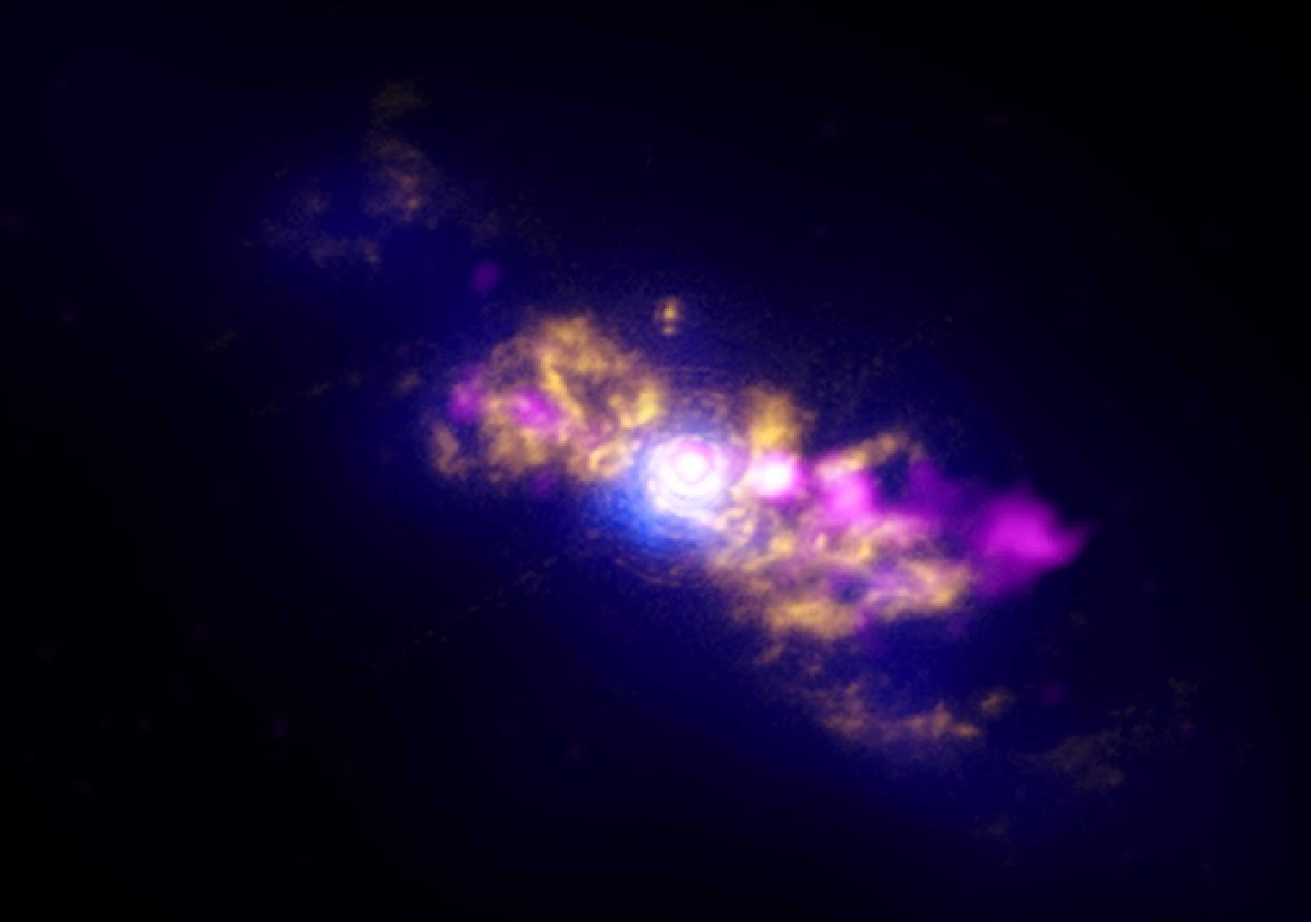
- **Here we present an observational evidence for the first spectroscopically resolved sub-parsec orbit of a supermassive binary system** in the core of Seyfert galaxy NGC 4151.

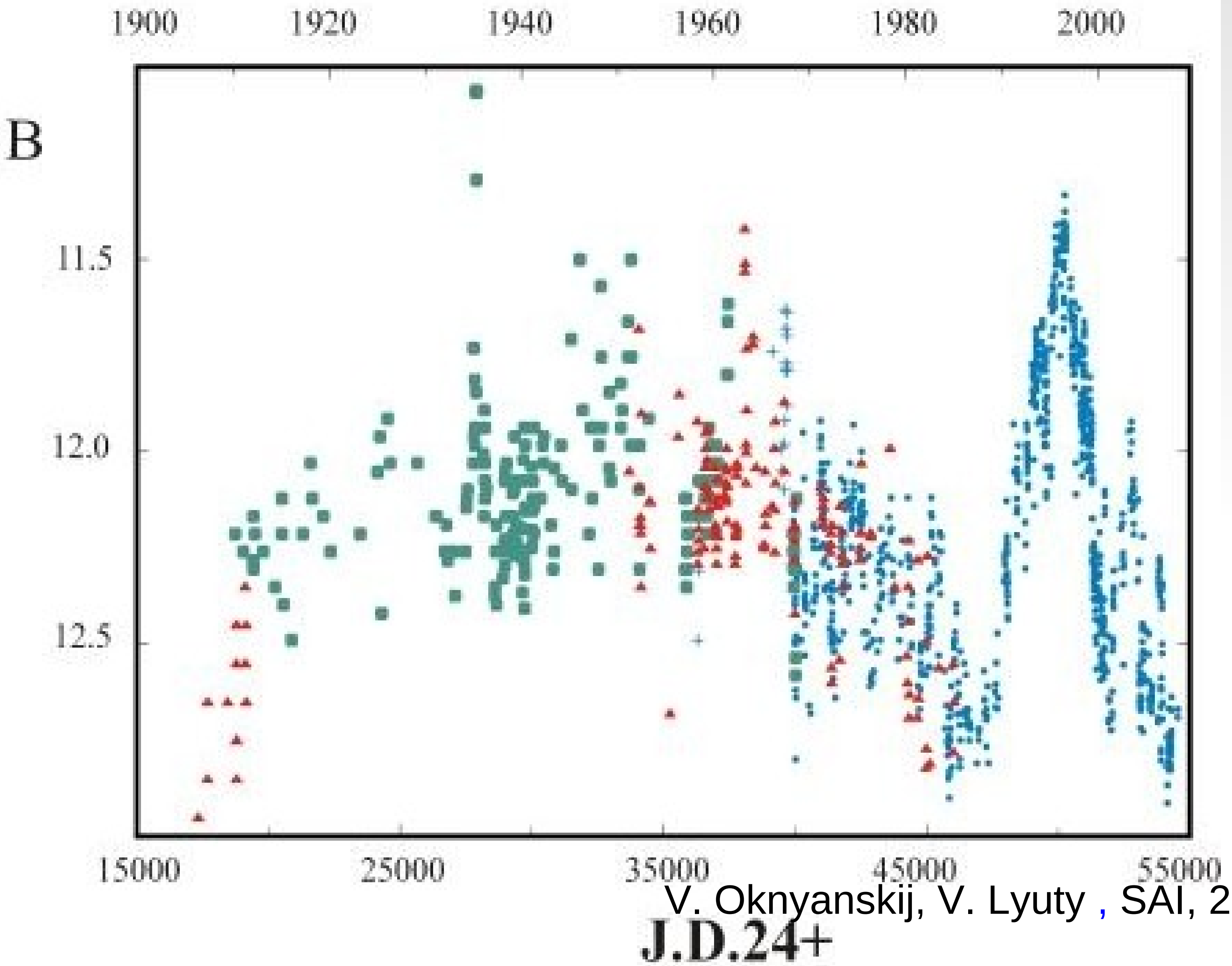
- Using a method similar to those typically applied for spectroscopic binary stars we obtained radial velocity curves of the supermassive binary system, from which we calculated orbital elements and made estimates about the masses of components.

- Our analysis shows that periodic variations in the light and radial velocity curves can be accounted for an eccentric, sub-parsec Keple-rian orbit of a 15.9-year period.

- Given the large observational effort needed to reveal this spectroscopically resolved binary orbital motion we suggest that many such systems may exist in similar objects even if they are hard to find.


NGC 4151
CENTRAL REGION - X-RAY, RADIO & OPTICAL

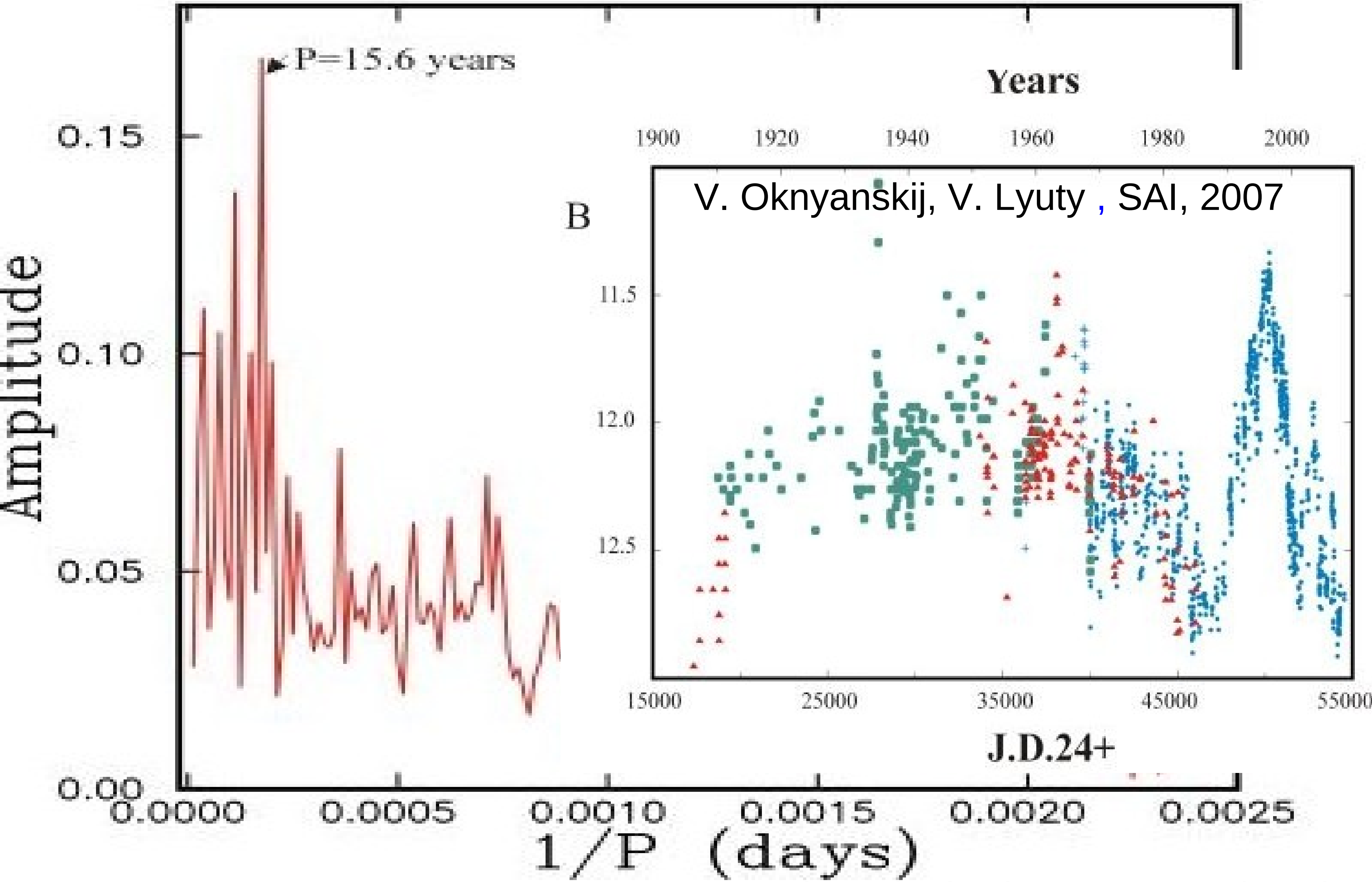




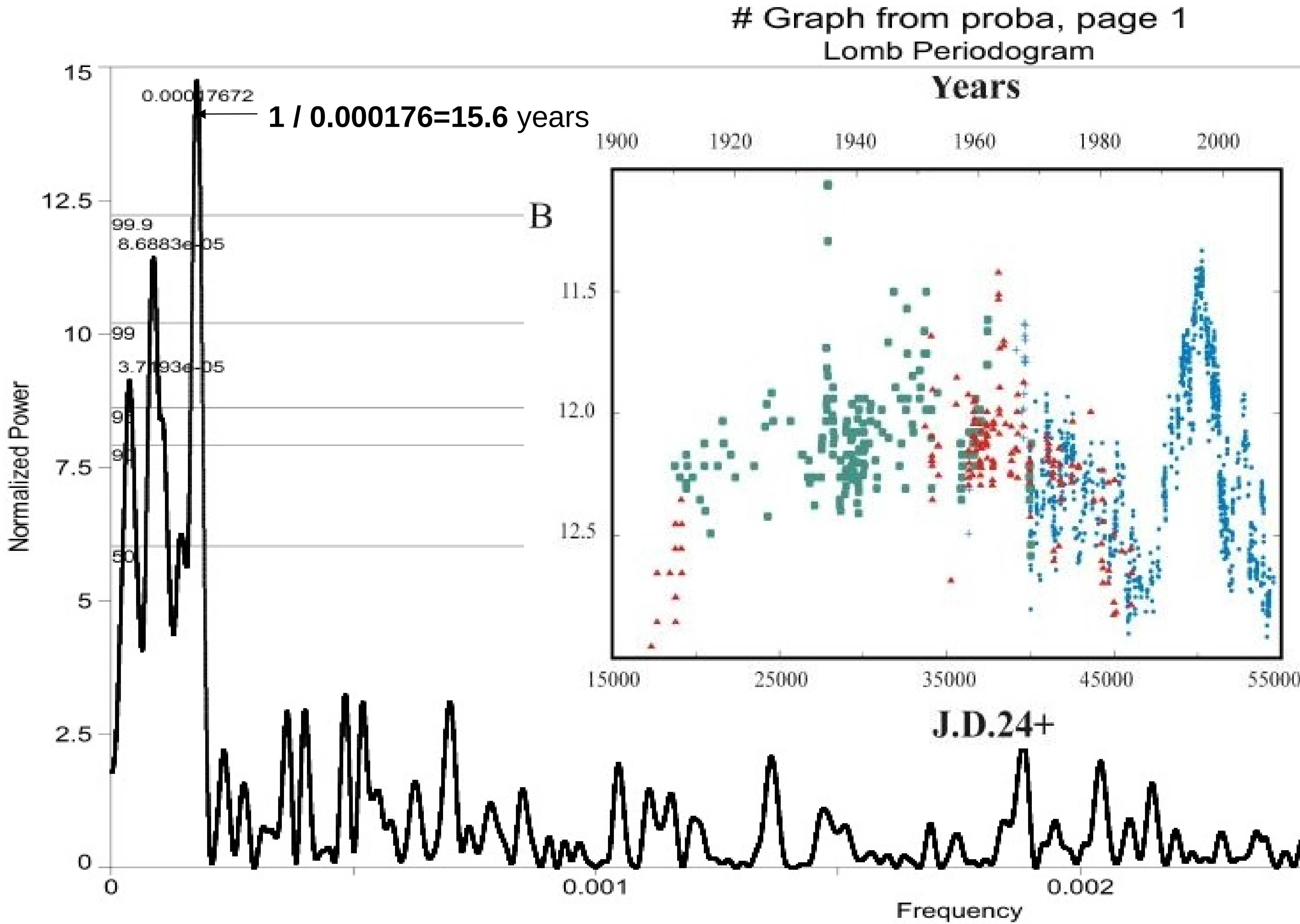
V. Oknyanskij, V. Lyuty , SAI, 2007

Lightcurve of NGC4151 for 100 years

NGC 4151 variability during 100 year period

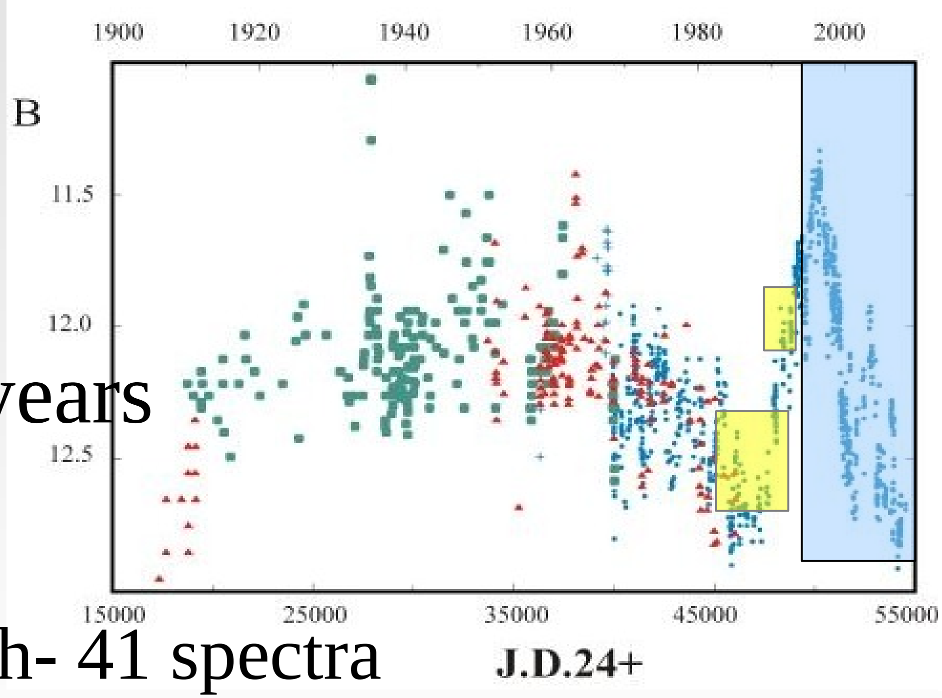


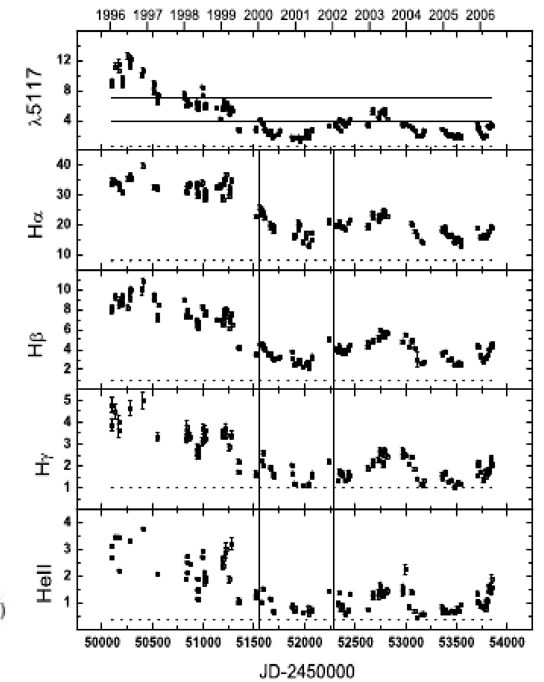
"PeremennyeZvezdy", Prilozhenie, vol. 7, N 28 (2007)



Graph from proba, page 1
Lomb Periodogram
Years
1 / 0.000176=15.6 years
0.00017672
99.9
8.6883e-05
99
3.7193e-05
50
B
1900
1920
1940
1960
1980
2000
11.5
12.0
12.5
15000
25000
35000
45000
55000
J.D.24+
Normalized Power
Frequency
0
0.001
0.002
15
12.5
10
7.5
5
2.5
0

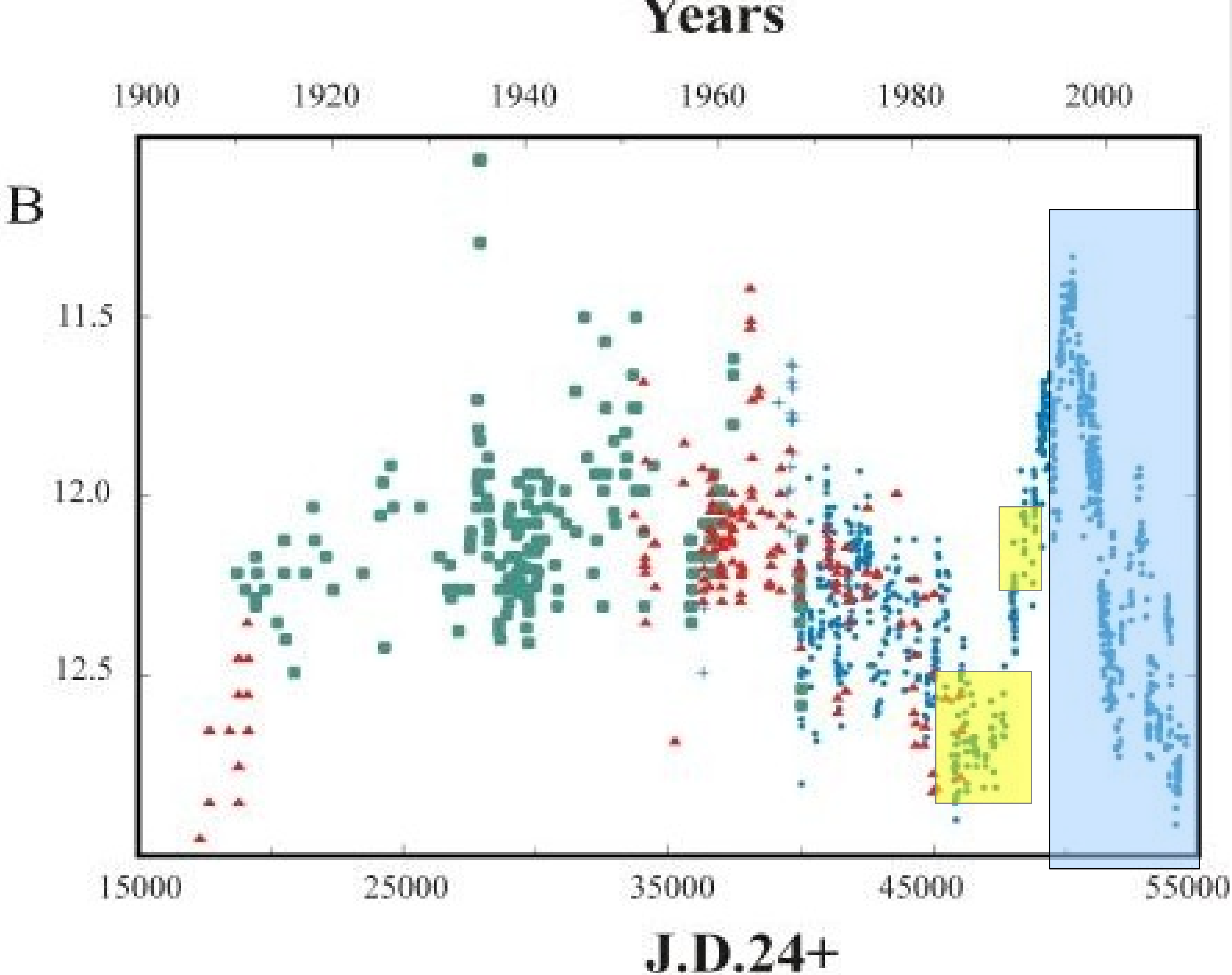
Data:

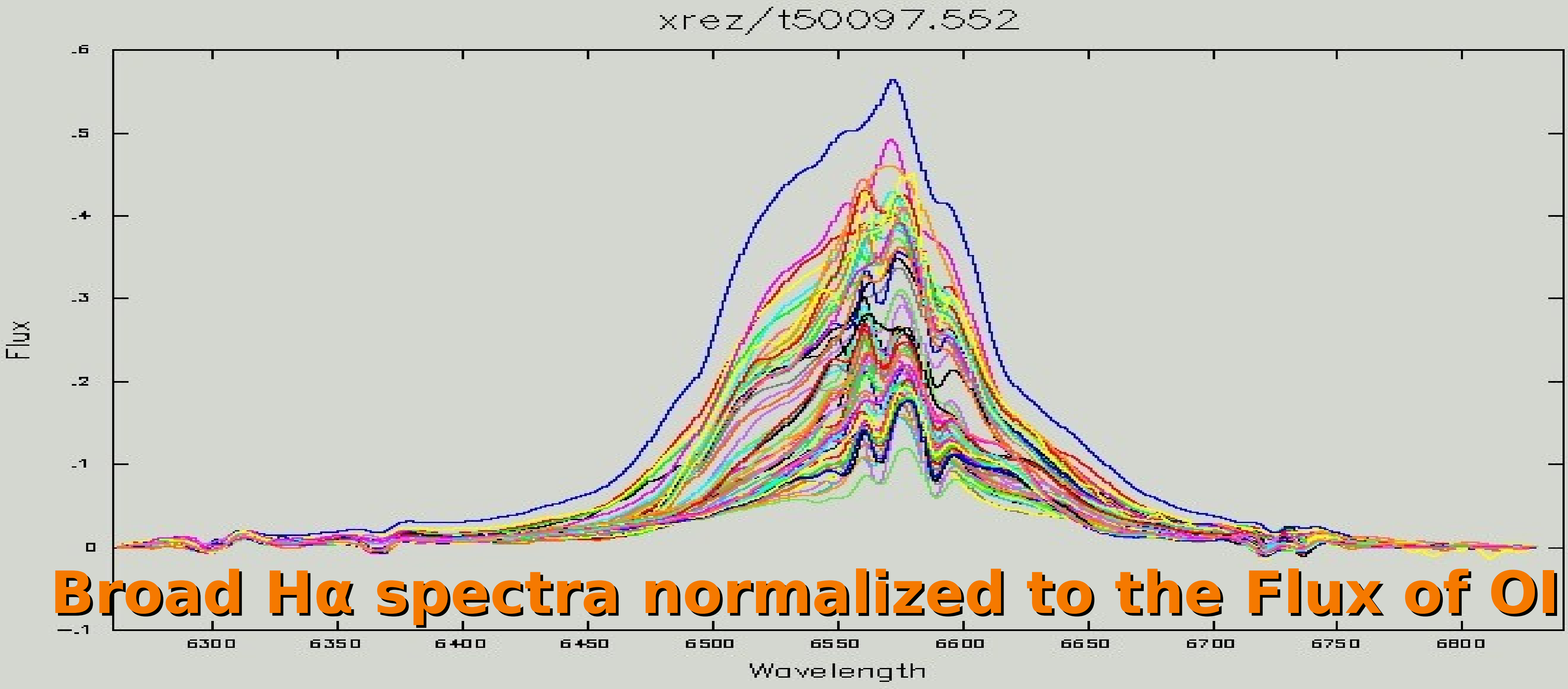




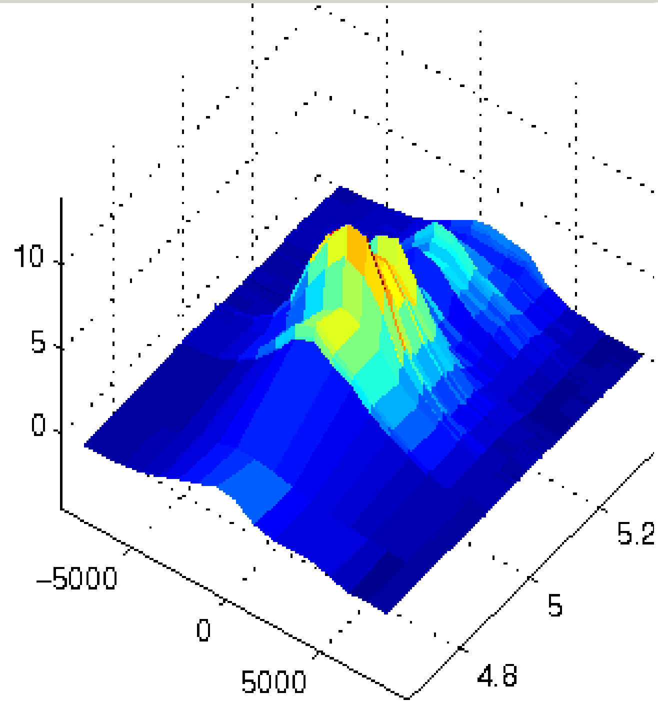
- 115 spectra
- Cover ~ 20 years
- Spectra:
  - AGN Watch- 41 spectra
  - Shapovalova monitoring programe 79 spektara

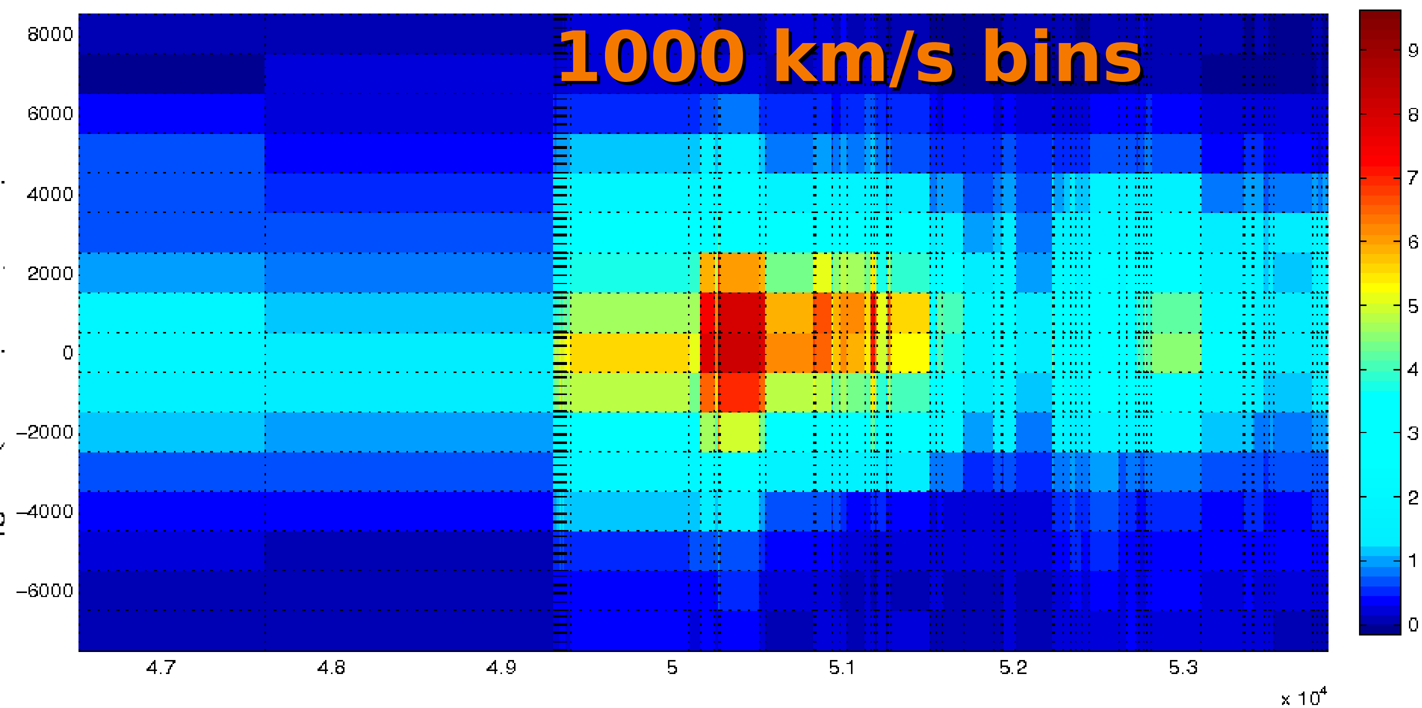
  (using 6m, 2.1m and **1 m** telescopes)
  - Asiago - 1 spectrum (using **1.8m**)
  - Palomar - 1 spectum
- Reduced to the same resolution $\sigma_g = \frac{\sqrt{\sigma_{p_1}^2 - \sigma_{p_2}^2}}{2.354}$.
- Normalized to the flux of OI 6300 A


Years
1900
1920
1940
1960
1980
2000
B
11.5
12.0
12.5
15000
25000
35000
45000
55000
J.D.24+

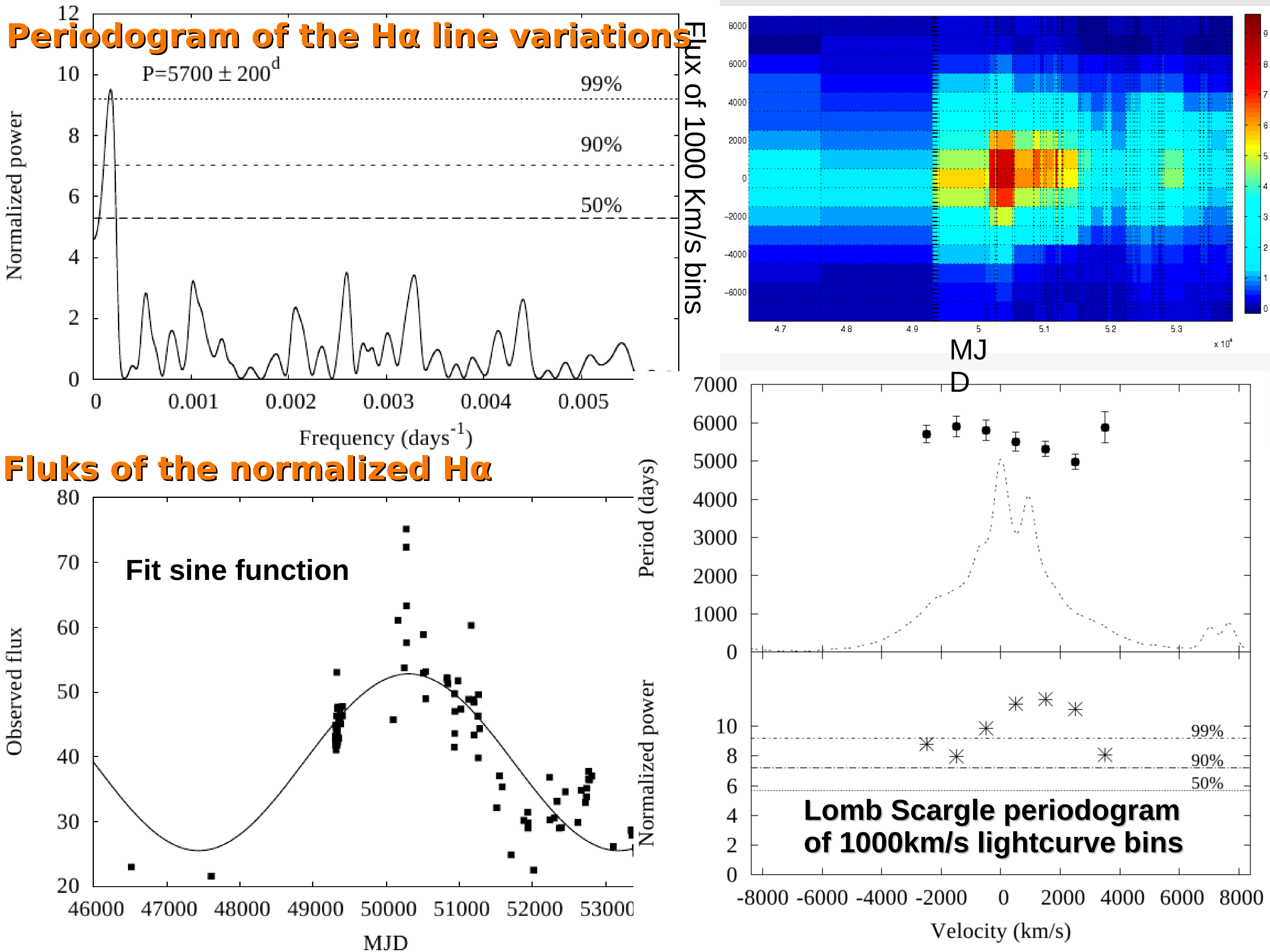


xrez/t50097.552
Flux
Wavelength
Broad Hα spectra normalized to the Flux of OI





1000 km/s bins
x 10^4



Periodogram of the Hα line variations
P=5700 ± 200d
99%
90%
50%
Normalized power
Frequency (days-1)
Flux of 1000 Km/s bins
MJD
x 10^4
Fluks of the normalized Hα
Fit sine function
Observed flux
MJD
Period (days)
Normalized power
99%
90%
50%
Lomb Scargle periodogram
of 1000km/s lightcurve bins
Velocity (km/s)

Relevant timescales

- Binary BH
- Blob of a gas
- Binary BLR

Orbital Period:

$$P \approx 1.7 r_{16}^{-\frac{3}{2}} M_8^{-\frac{1}{2}} \mathrm{yr} \tag{1}$$

Geodetic precession (Begelman et al. 1980):

$$T_P \approx 600 r_{16}^{-\frac{5}{2}} (\frac{M}{m}) M_8^{-\frac{3}{2}} \quad \mathrm{yr} \tag{2}$$

Seems very long...

Accretion disk precession (Katz 1997; see also derivation by Pringle):

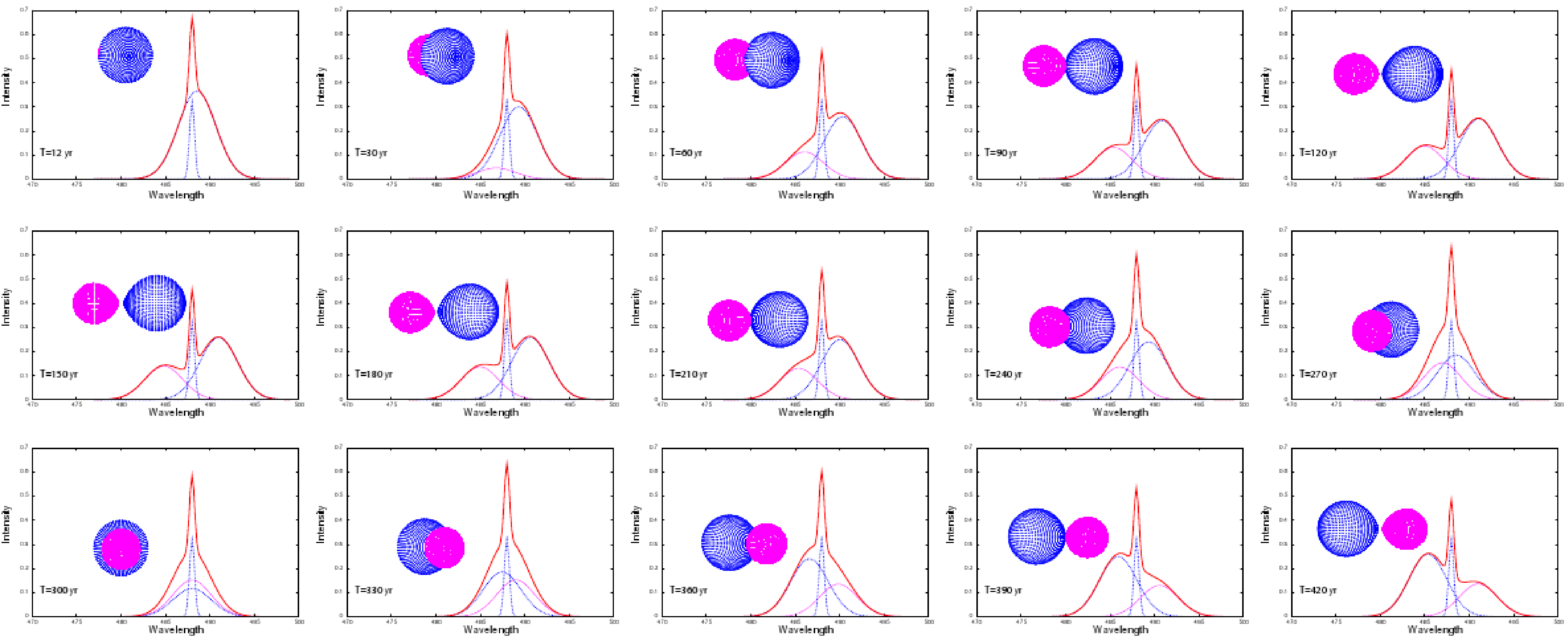
$$T_{P,AD} \approx 23 \cdot r_{16}^{3} (\frac{M}{m})^{\frac{1}{2}} m_6^{-\frac{1}{2}} R_{d,16}^{-\frac{3}{2}} \frac{1}{\cos\theta_0} \quad \mathrm{yr} \tag{3}$$

R_d is the AD radius, all the other symbols have obvious meaning. This last period is most interesting and is associated to a precession much faster than the geodetic precession of the BH spin around the total angular momentum of the systems.

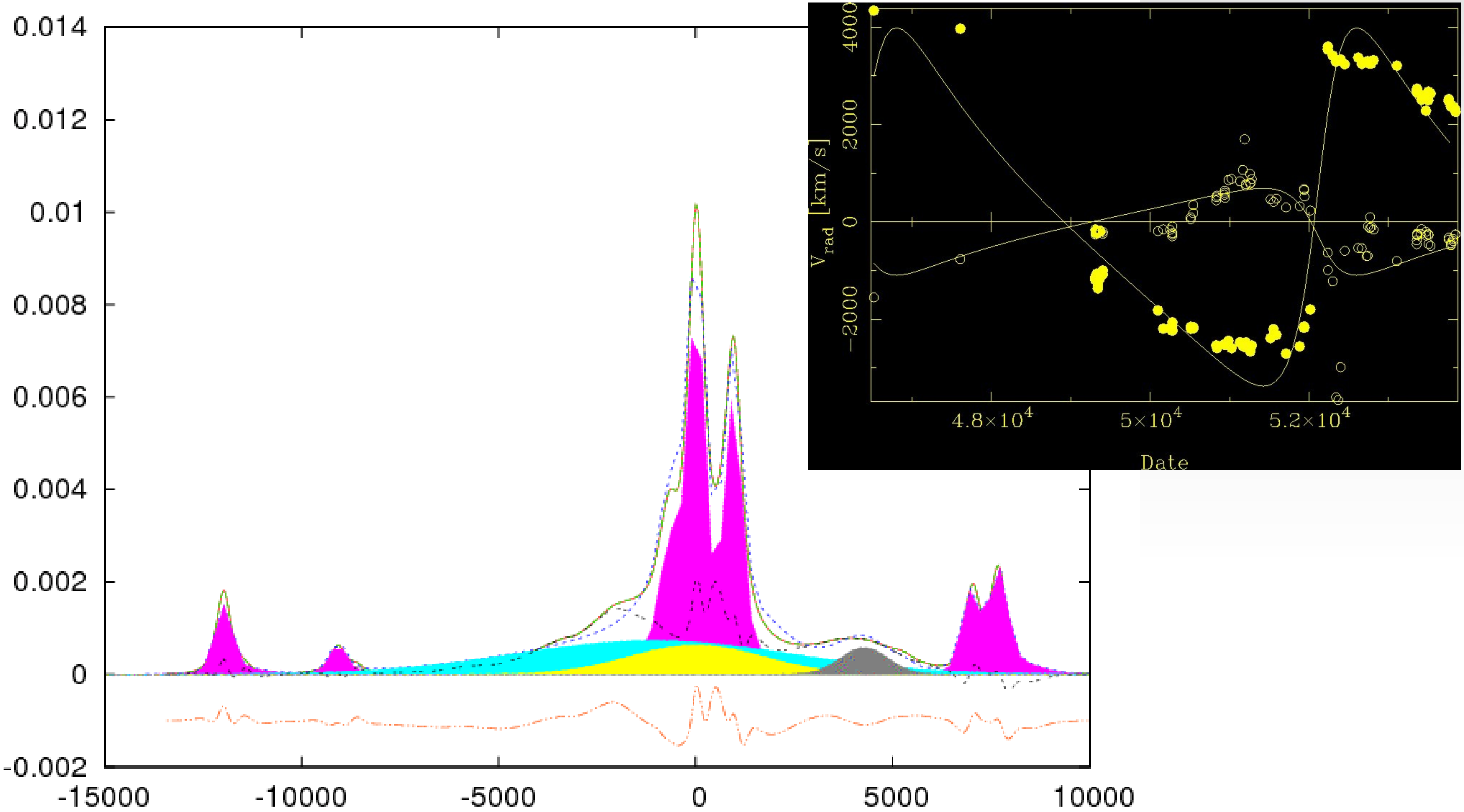
Warped accretion disk (due to radiation force) precession (following Pringle 1992):

$$T_{\mathrm{P,warp}} \approx 13.6 \cdot (M_{\mathrm{ion.gas},-2}) M_7^{\frac{1}{2}} R_{\mathrm{d},10^3\mathrm{R_g}}^{\frac{1}{2}} L_{44}^{-1} \quad \mathrm{yr} \tag{4}$$

The idea: as the coalescing binary reaches an orbital diameter similar to the broad line region, two separate peaks will be seen in the broad line profiles, which track the separate objects in velocity, in analogy to a stellar spectroscopic binary.



L.C. Popovic , New Astronomy Reviews (2012)



THE MODEL :

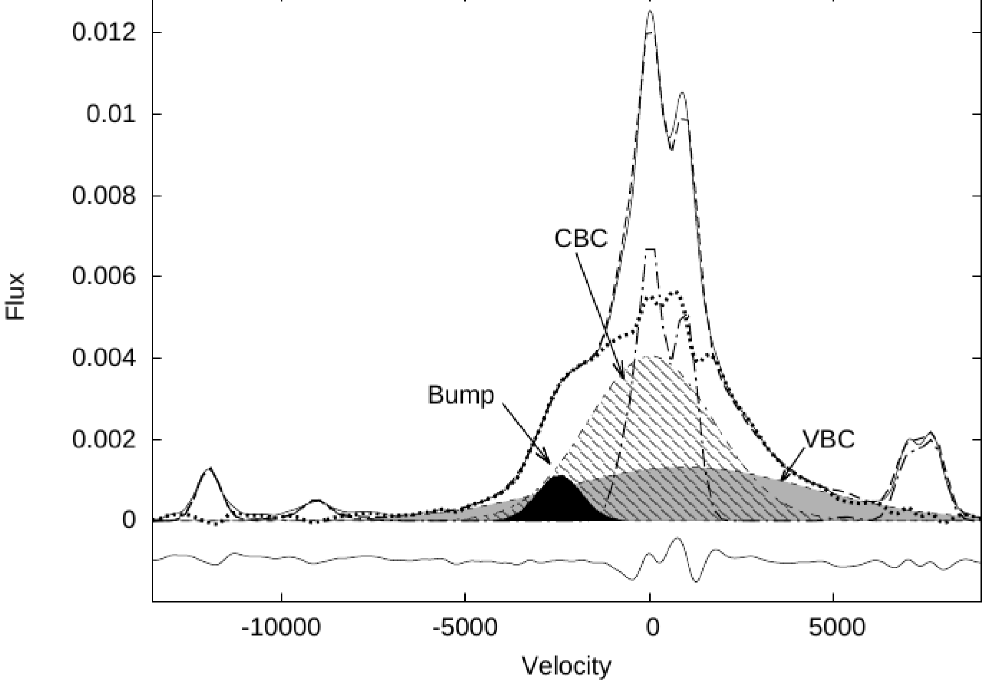
Sum of Gaussians

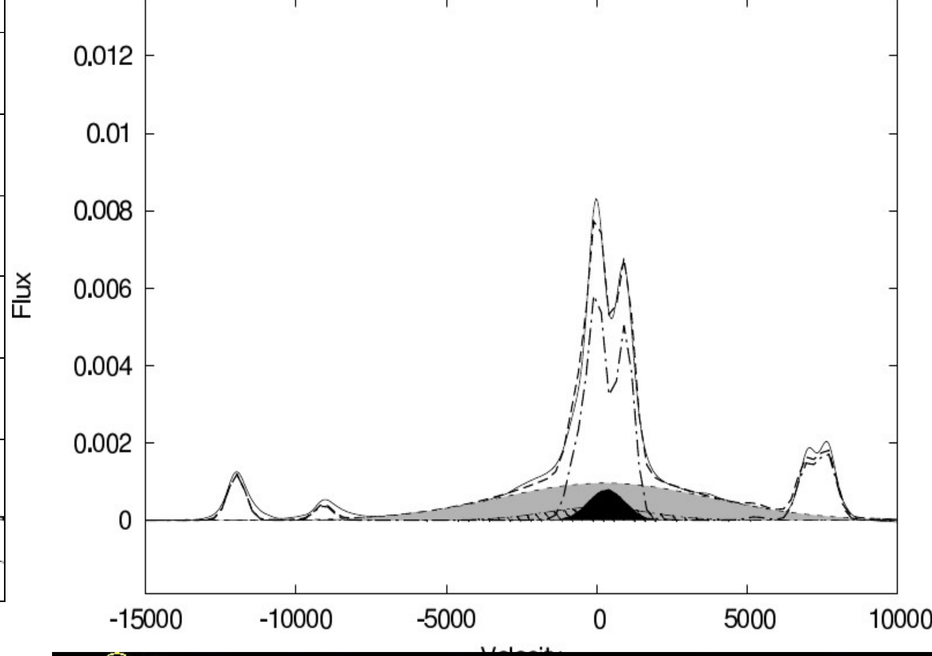
σ_{VBC} = 3400 km / s

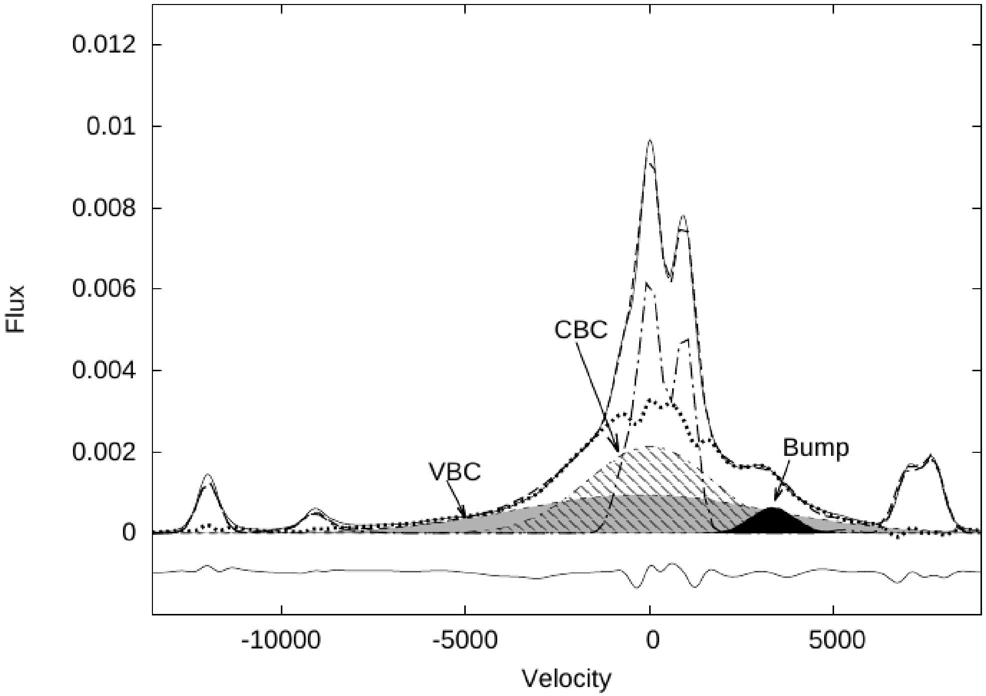
σ_{CBC} = 1700 km / s

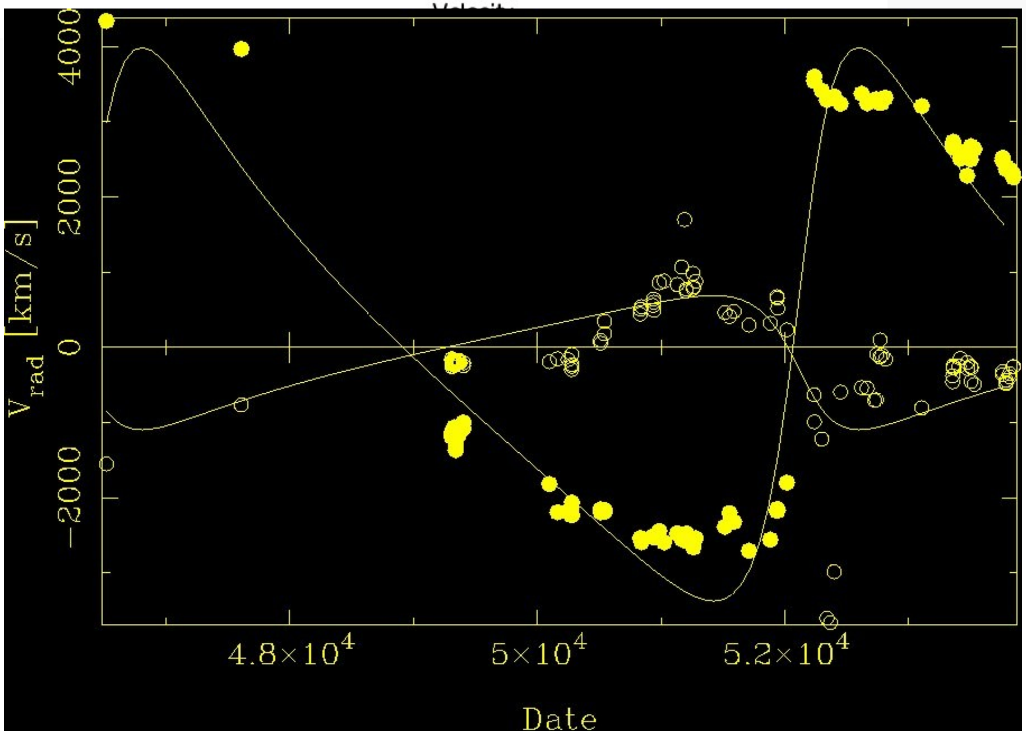
σ_{Bump} = 600 km / s

Narrow line template

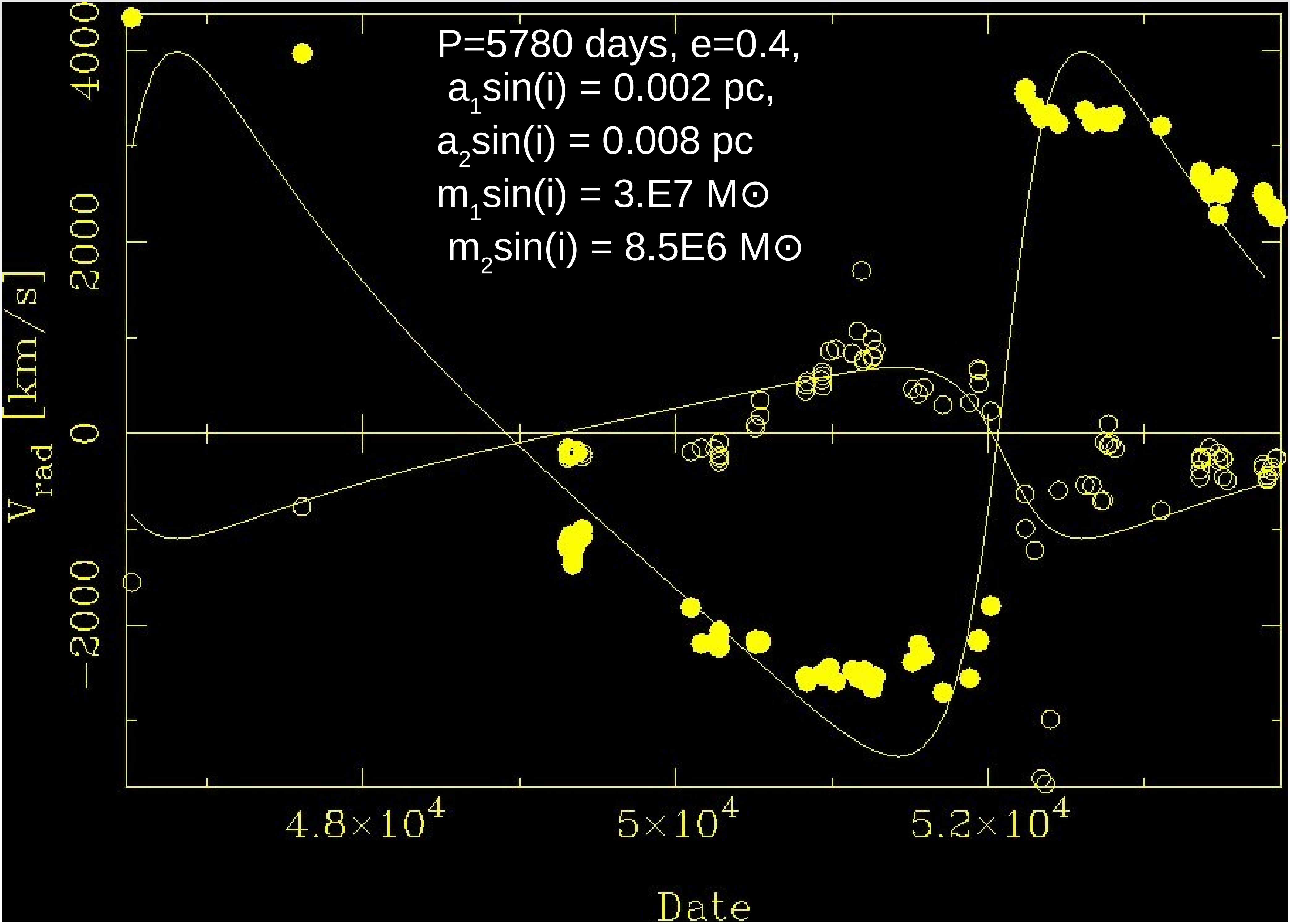








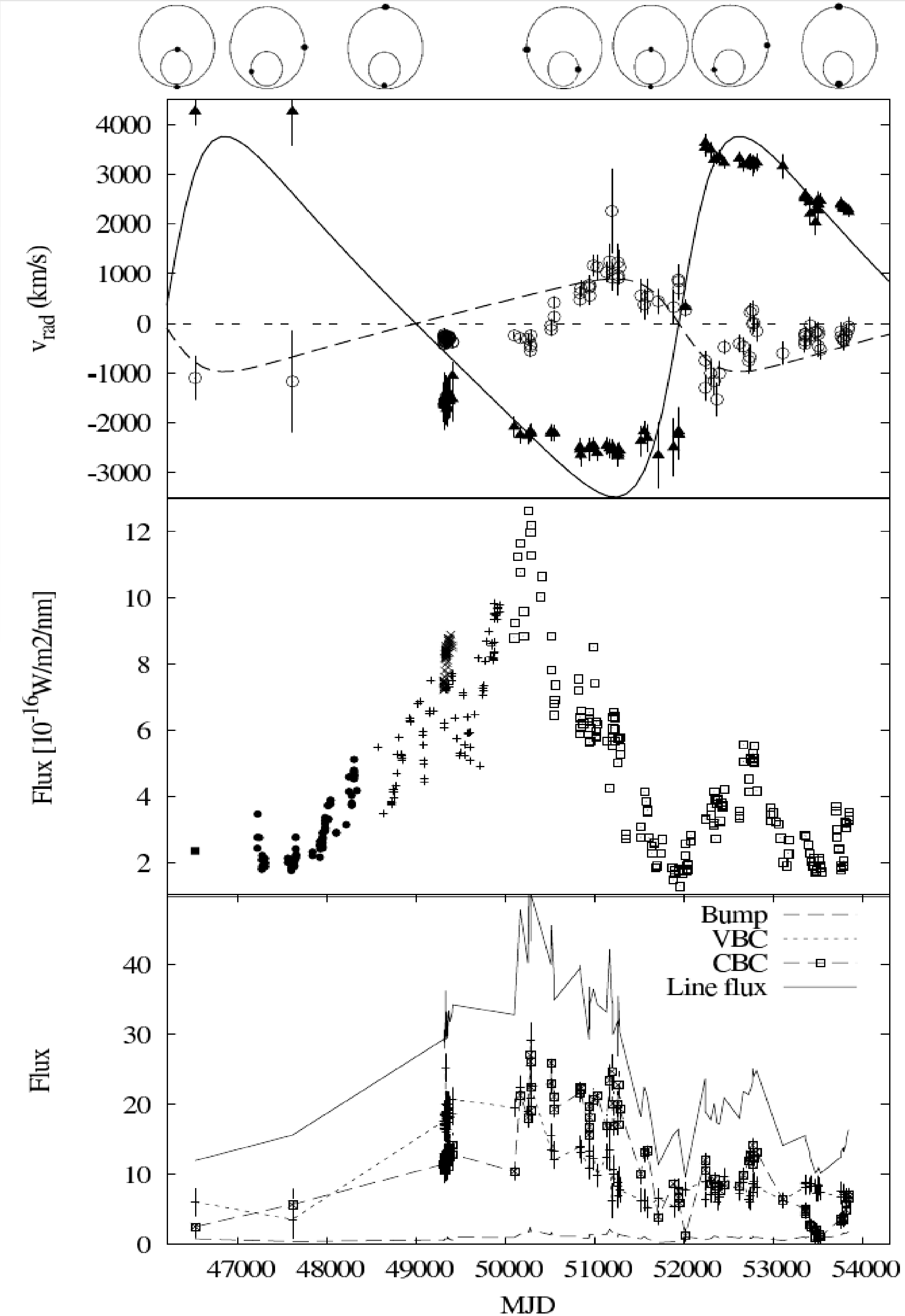
The radial velocity curve was immediately consistent with orbital motion (a fortunate coincidence) that we are able to see a sudden change in the radial velocity. It is however what is expected and observed in many binaries with highly eccentric orbits


P=5780 days, e=0.4,
$a_1 \sin(i)$ = 0.002 pc,
$a_2 \sin(i)$ = 0.008 pc
$m_1 \sin(i)$ = 3.E7 M⊙
$m_2 \sin(i)$ = 8.5E6 M⊙
V_{rad} [km/s]
4000
2000
0
−2000
4.8×10^4
5×10^4
5.2×10^4
Date

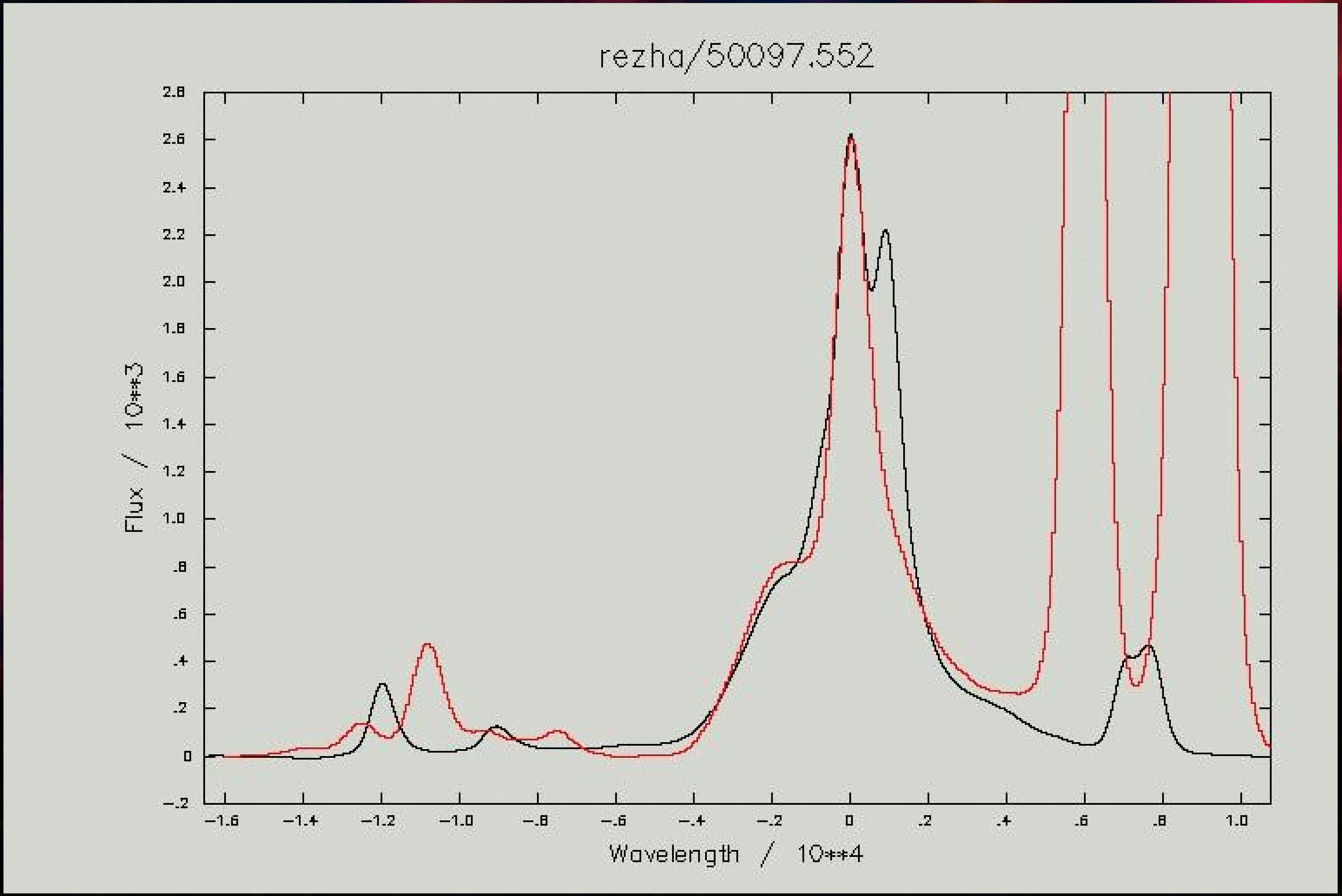
Radial velocity curves (top)

Lightcurve of Hα line (middle)

Lightcurves of each Gaussian component flux (bottom)



Hα & Hβ overplot



Conclusions

This work presents:

- *an analysis of previously published data of NGC 4151*
- *and argues that the pattern of H-alpha line flux variability and*
- *H-alpha line profile changes*
- *are indicative of a supermassive binary black hole.*

The derived orbit is eccentric (e = 0.42) with a period of P = 5780 days and longitude of pericenter $\omega \approx 95^{\circ}$

$$a_1 \sin i = 0.002 \text{ pc}, \qquad a_2 \sin i = 0.008 \text{ pc}$$

$$m_1 \sin^3 i = 3 \cdot 10^7\, M_\odot \quad \text{and} \quad m_2 \sin^3 i = 8.5 \cdot 10^6\, M_\odot$$

– where i is inclination of the orbital plane

The inclination of 65° yields semimajor axes of 0.0024 pc and 0.0094 pc, while the masses of each component are

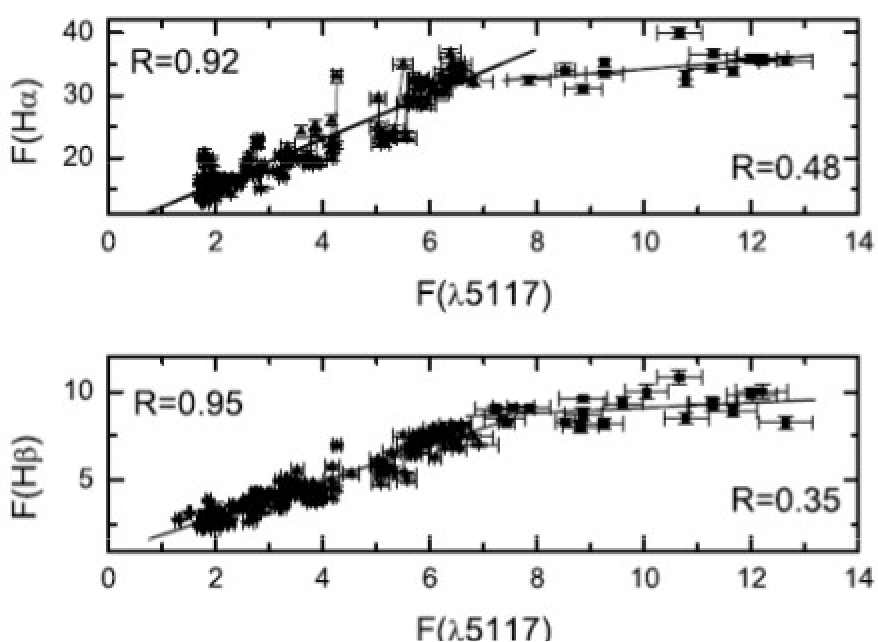
$$4.4 \cdot 10^7\, M_\odot \quad \text{and} \quad 1.2 \cdot 10^7\, M_\odot$$

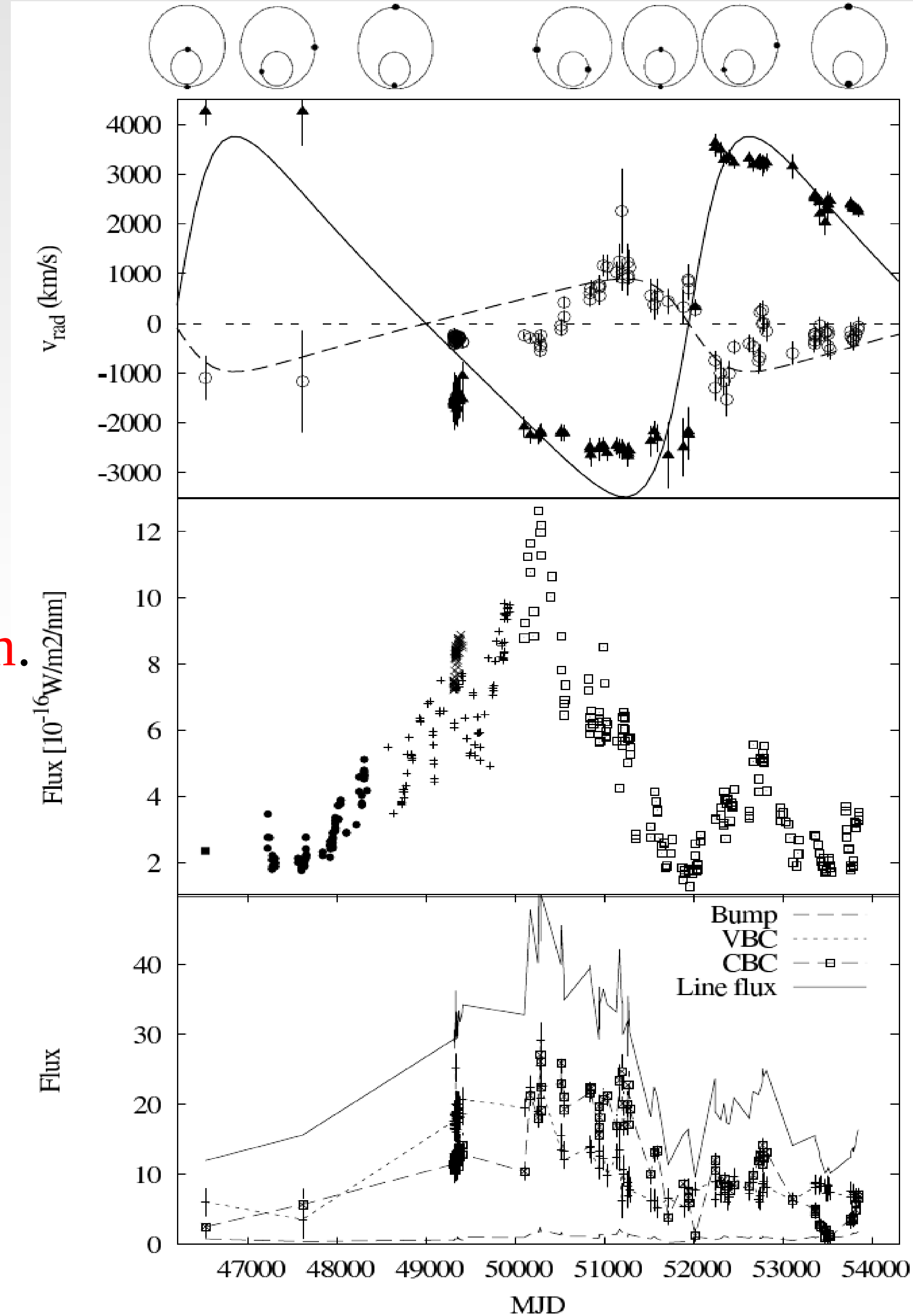
The derived period is in agreement with previous studies of optical variability in NGC 4151 (Oknyanskij et al 1978; Oknyanskij & Lyuty 2007; Guo et al. 2006), also indicating existence **of previous cycles** (see Oknyanskij et al. 1978)

In the case that the secondary object is with a mass much smaller than the primary component, then its orbit would be defined with the bump component only, implying the distance of about 0.01 pc, and the same period (about 15.9 years and eccentricity of about 0.4)

The flux **maximum in the lightcurve** correspond to **the approaching phase of a secondary component**.

We speculate that the periodic variations in the Hα line shape and flux are due to shock waves generated by the **supersonic motion of the components** through the surrounding medium.





If the phenomenology outlined by our analysis is general for all similar AGN then an important question arises:

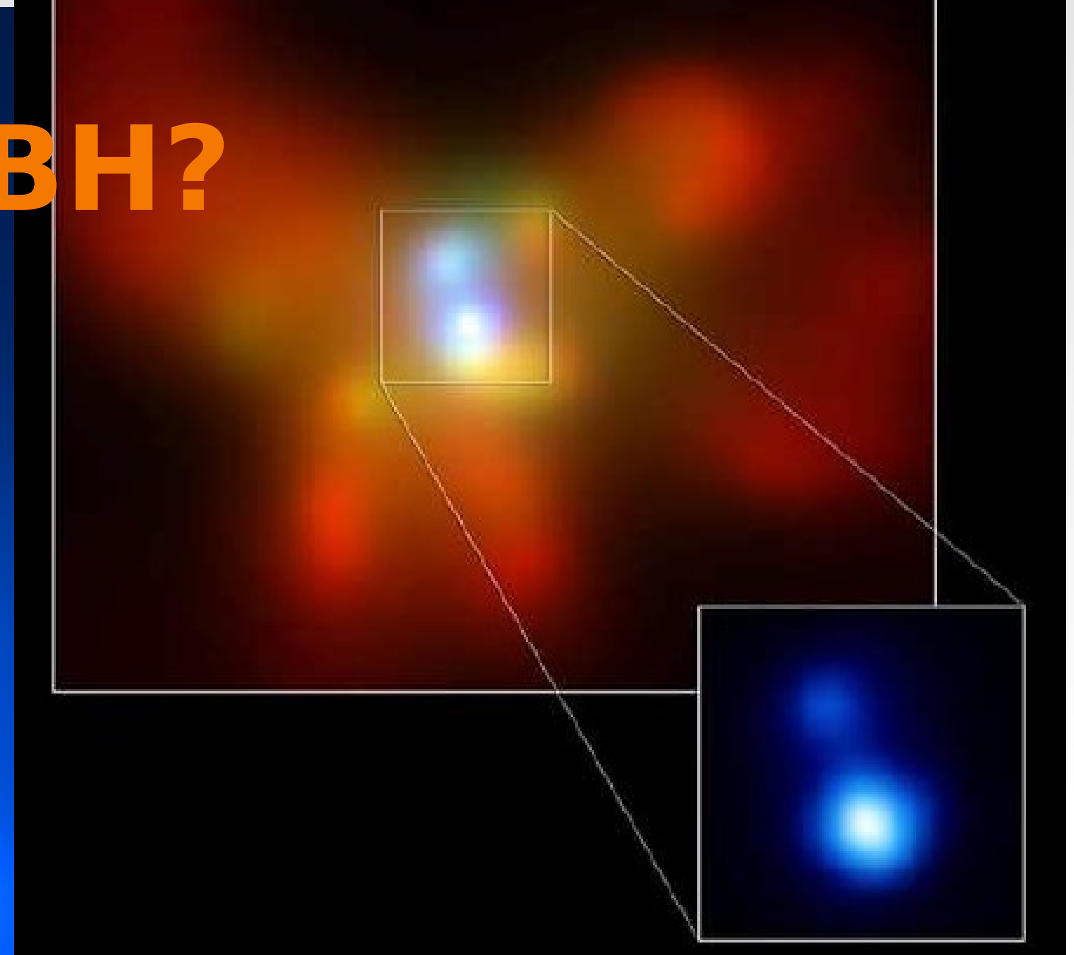
is binarity a necessary condition for AGN ignition?

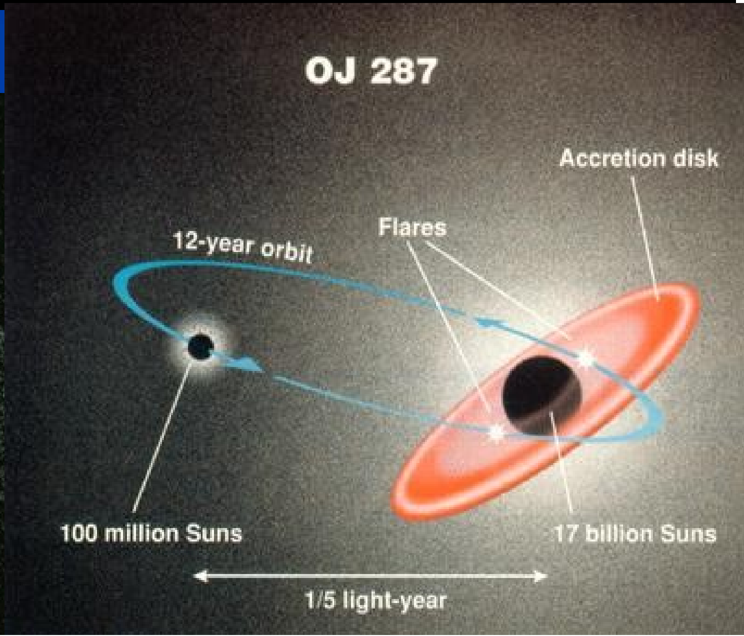
Support for such an assumption could be related to changes in spectral type (Sy1–Sy1.5-Sy2) manifested by NGC 4151. The activity type of the galaxy changes from Sy1 to Sy1.5 when it is most active (Shapovalova et al. 2008) and to Sy2 at its deep minimum phase, as it was in 1984 (Penston and Perez 1984; Lyutyj et al. 1984). Different spectral types may be possible only at a certain phase of orbital motion in the binary SMBH.

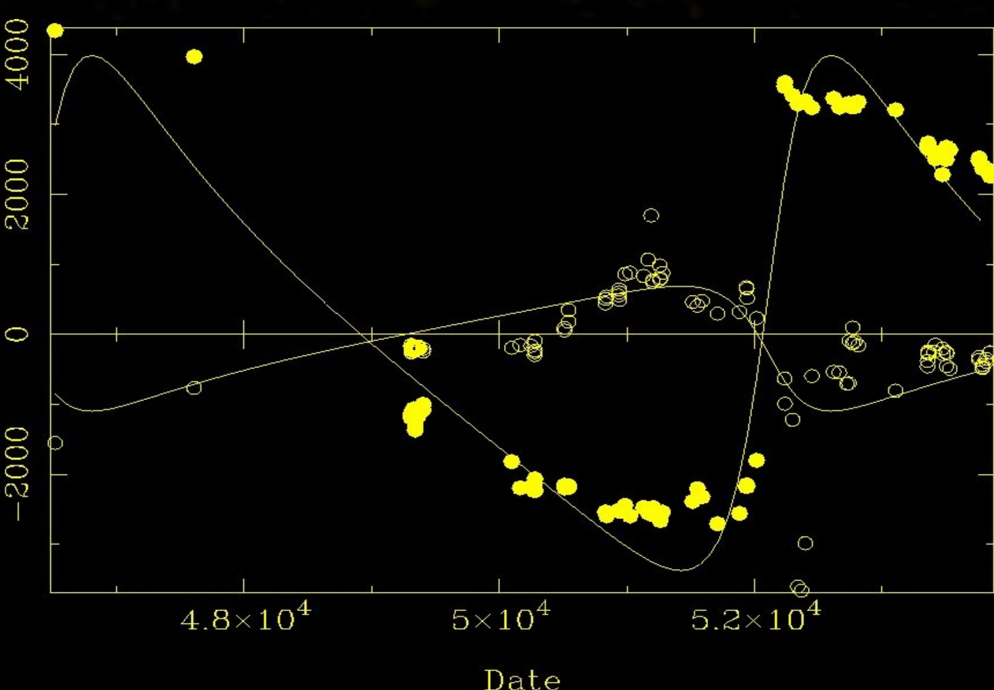
This opens a question whether the different activity types of active galaxies correspond to different orbital phases of such systems and whether the binarity is a necessary condition for the activity switch-on.

SBBH?

- Double peak ?
- Periodical variability
- Visually binary: NGC6420
  Chandra X-ray (Kamosa et al.2003)
- Binary quasars
- Binary bi cone jets **(3C75)**
- Spectroscopically resolved orbit (NGC 4151)







Thank you for attention