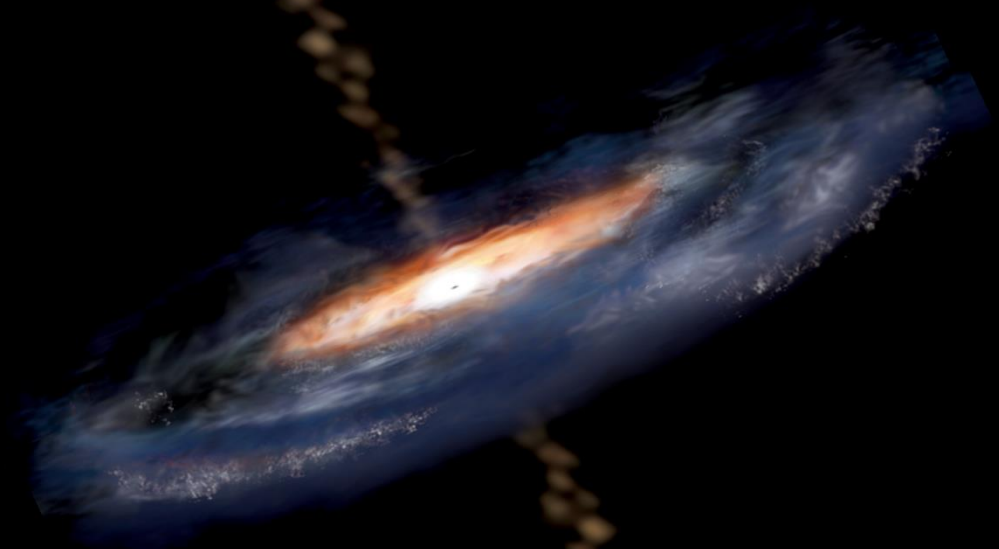


# Reverberation responses in light curves of quasars



**Berdina L.A. & Tsvetkova V.S.**

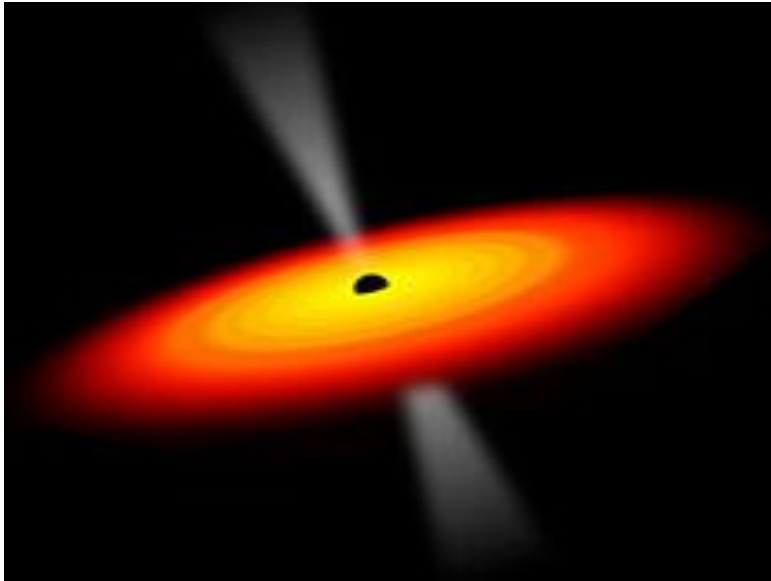
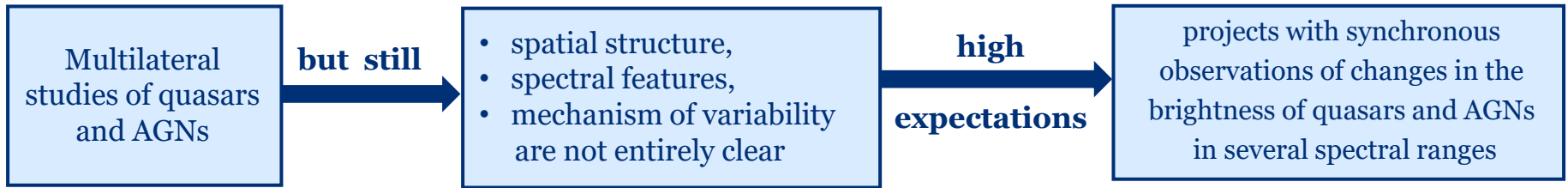


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**Kharkov, Ukraine**

# Quasar model



The **quasar model** (Shakura and Sunyaev, 1973):

- a geometrically thin optically thick accretion disk
- a supermassive black hole in the center

The **accretion disk temperature** along the disk radius (Krolik et al, 1991):

$$T \sim R^{-3/4}$$

Dependence of inter-band **time delays on wavelength**:

$$\tau \sim \lambda^{4/3}$$

for an accretion disk with the temperature  $T \sim R^{-3/4}$  (blackbody radiation)

## REVERBERATION MAPPING

Measuring the time delays between the brightness fluctuations in different parts of the spectrum

Investigation of the spatial structure of quasars and AGNs with a very high resolution

# Gravitational time delays

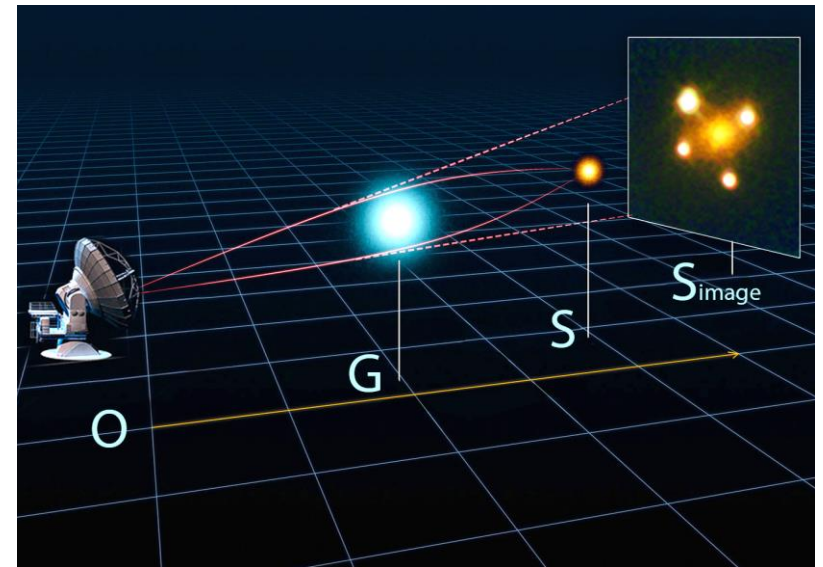
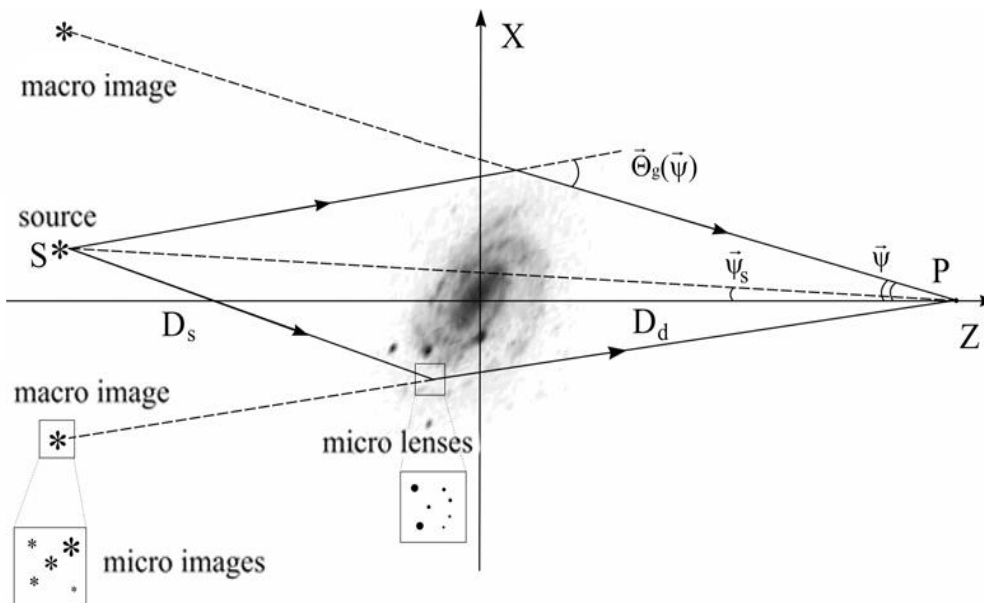
Depending on the mutual location of a source, lens and observer, and specific spatial distribution of the lens gravitational potential, the observer may see:

two images of the same quasar

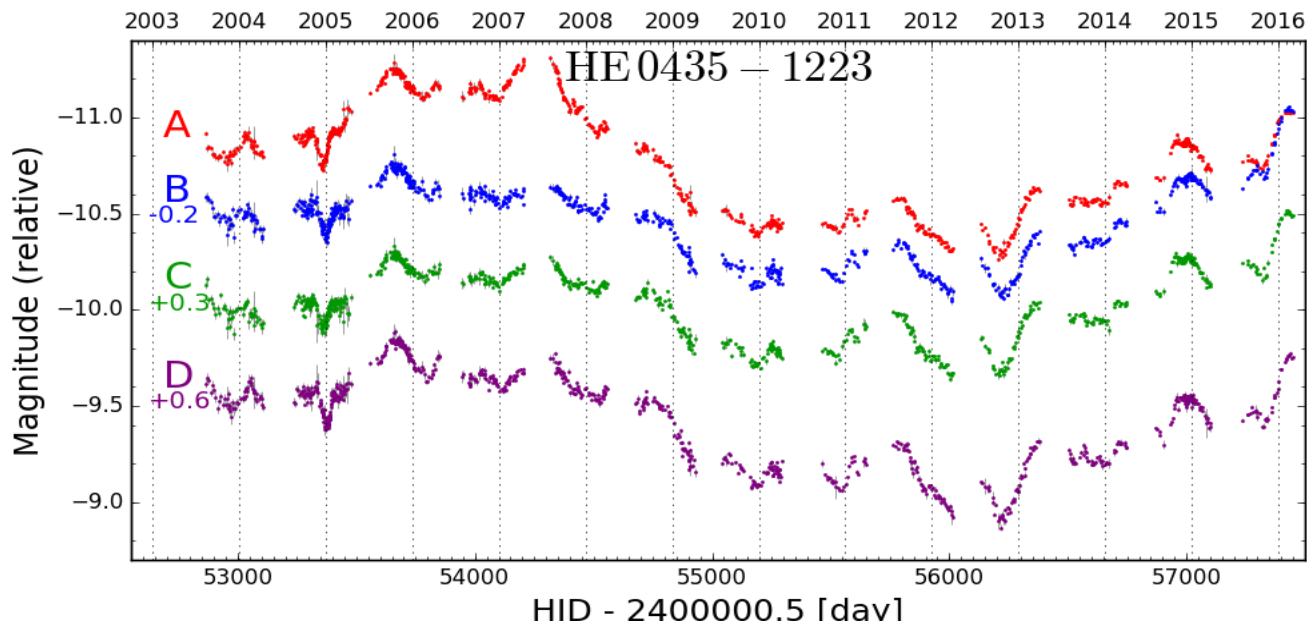
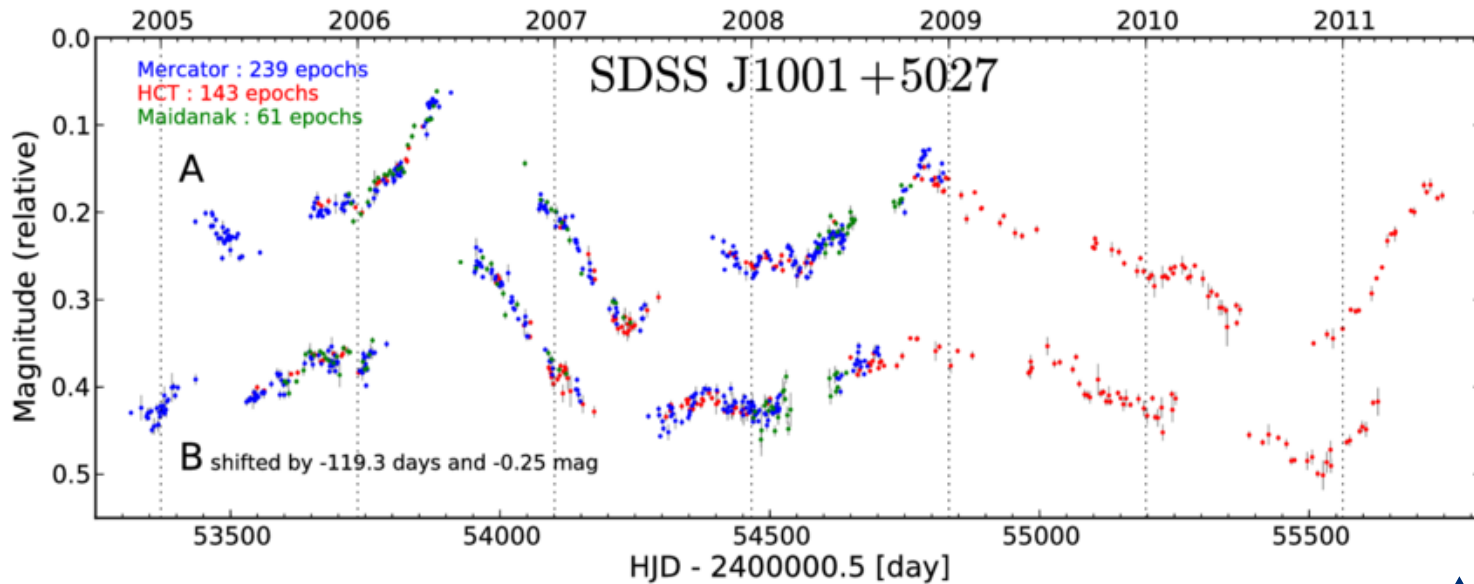
various distortions of the source

four images of the same quasar

light from the images passes different paths to the observer, the fluctuations of quasar's brightness between images is registered shifted in time - the time delays



# Examples of macroimages light curves



SDSS J1001+5027  
R. Kumar et al., 2013

QSO HE0435-1223,  
COSMOGRAIL project

# Reverberation mapping

**first**, the measurement of the light travel times between a quasar's central region responsible for the hard continuum radiation and a broad emission line region (Blandford & McKee 1982).

**labour-intensive  
spectral observations**

**large instruments**

**photometric RM:** photometry in two spectral bands, with one of them containing an emission line and the other one free of it

(Edri et al 2012; Bachev et al. 2014; Jiang et al. 2015)

## REVERBERATION MAPPING

Measuring the time delays between the brightness fluctuations in **different parts of the spectrum**

Obtaining **direct estimates of distances** between the quasar regions responsible for radiation in different spectral bands

Estimating the mass of the central black hole and the accretion rate, studying the temperature changes along the radius of the accretion disk

## INTERNATIONAL PROJECTS:

- **SDSS-RM** (Sloan Digital Sky Survey Reverberation Mapping), Grier C. et al. 2017
- **STORM** (Space Telescope and Optical Reverberation Mapping), Fausnaugh et al. 2018
- **LAMP** (Lick AGN Monitoring Project), Pancoas et al. 2019

# *Method for determination of the time delays*

## THE ESSENCE OF THE PROPOSED METHOD



- Representation of light curves in the form of series **expansions in orthogonal polynomials**.
- Construction of an **orthonormal basis** specified at a discrete set of unevenly spaced data points (dates of observations) with the use of **Gramm-Schmidt orthogonalization procedure** - for utilizing the useful properties of the orthogonal-polynomial regressions (the **Legendre polynomials** - for the computational stability).

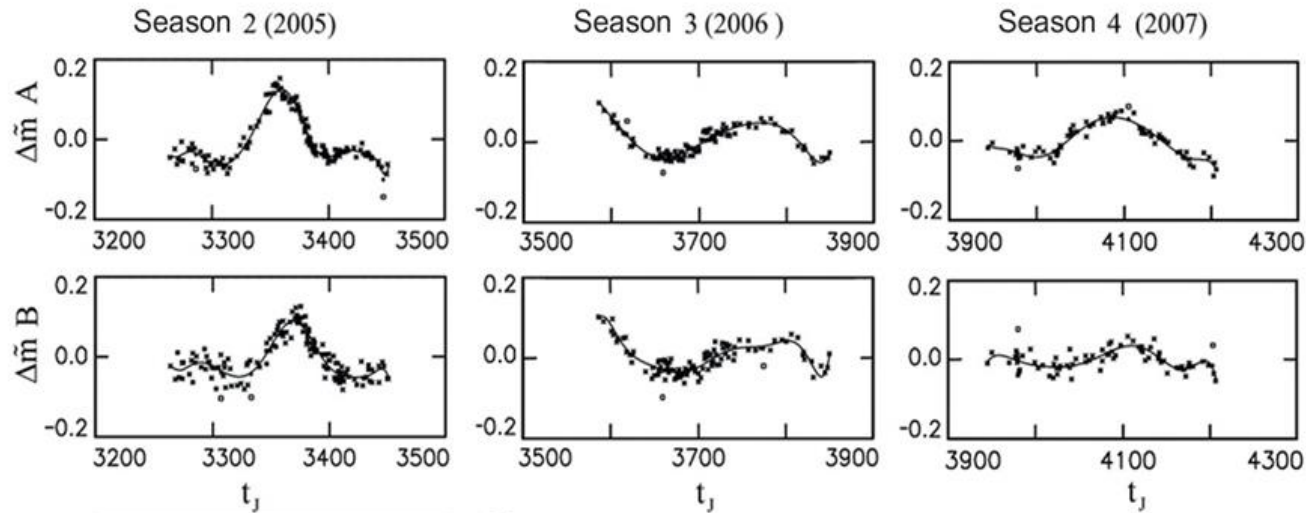
## ADVANTAGES OF THE PROPOSED METHOD



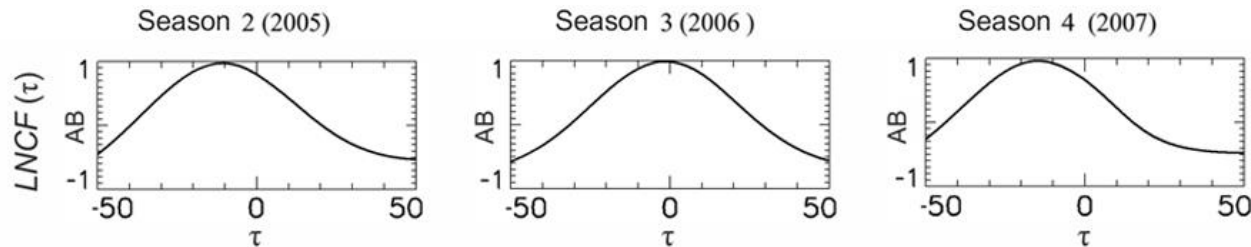
- an opportunity to **eliminate or add any** term of the polynomial approximation of a light curve without a necessity to recalculate the rest of the expansion coefficients.
- a simple way to **release** the light curves from the component of variability resulted **from microlensing effects** in the case of the so-called slow microlensing.

# Method for determination of the time delays

- I. Representation of light curves in the form of series expansions in Legendre polynomials at a discrete set.
- II. Calculation of the approximating polynomials for a pair of light curves at quasi-continuous reference points.



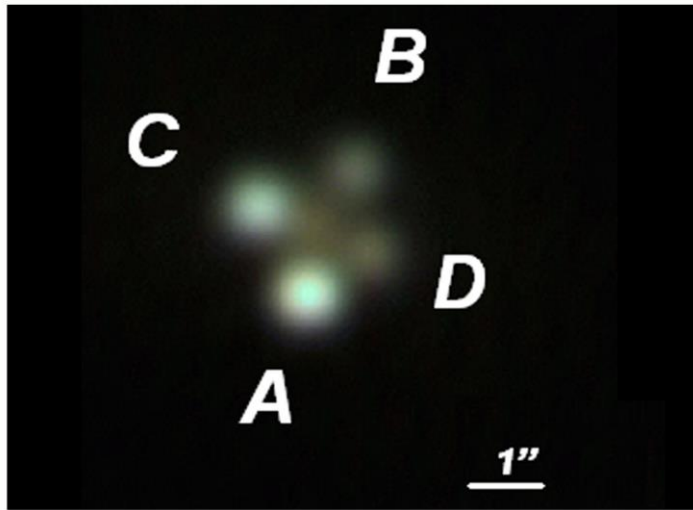
- III. Calculation of the cross-correlation functions for pairs of light curves represented by their approximations.



- IV. The time delay - the time shift between the light curves, where the cross-correlation function reaches its maximum.

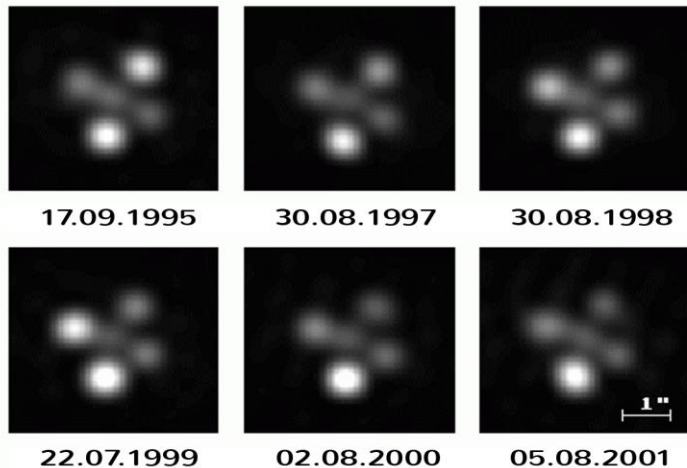


# QSO 2237+0305 (Einstein Cross)

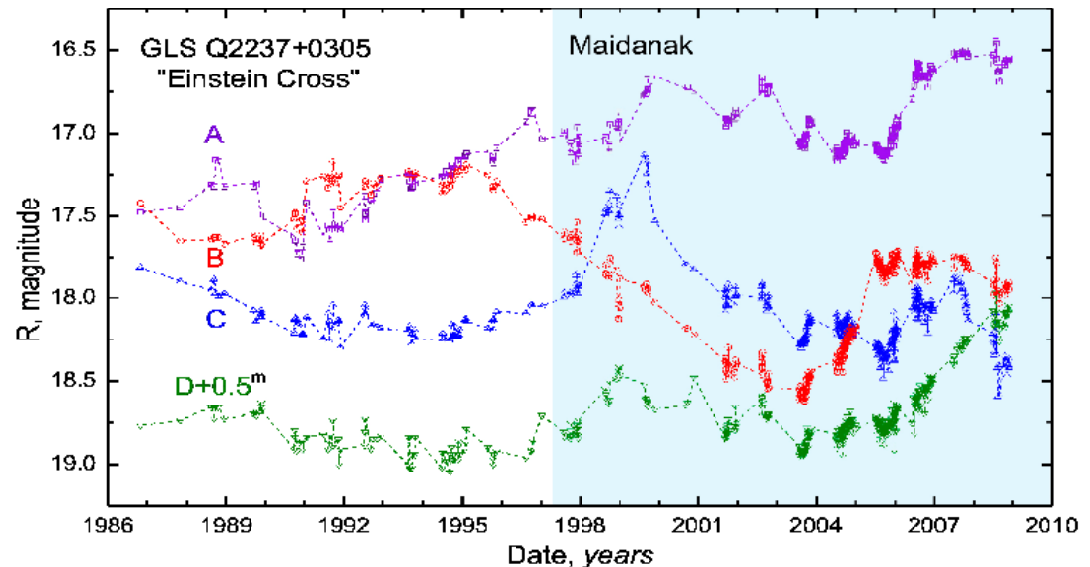


QSO 2237+0305 - a quadruple gravitational lens system with a quasar at  $z=1.69$  seen through the galaxy at  $z=0.039$ .

The **color image** QSO 2237+0305 in 1999 synthesized from three monochrome images of a superb quality taken in **filters V, R and I** with the Maidanak 1.5-meter telescope (obtained by V.Vakulik, Institute of Astronomy of V.N Karazin National University, Kharkov, Ukraine).



Changes of mutual brightness of the quasar components caused by microlensing events (data of monitoring in 1995-2001 from the Maidanak Observatory (A&A 420, 2004).



Light curves of all the four components of QSO 2237+0305. Observations carried out at the 1.5-meter telescope of the Maidanak Observatory are shown at the blue background (Dudinov V. et al. 2011)



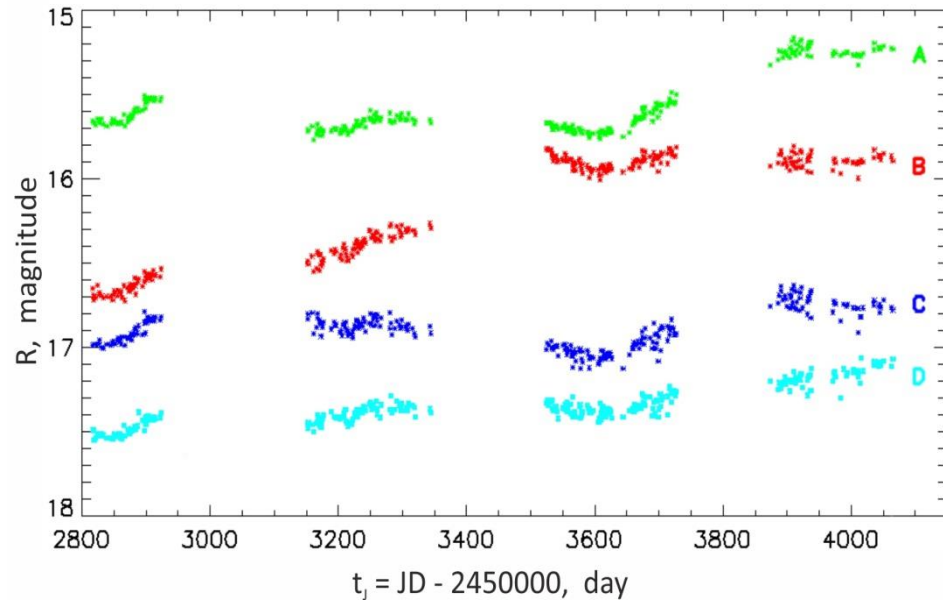
# Time delays for Q2237+0305 - R light curves

The new more **accurate** estimates of the **gravitational time delays** between components in Q2237+0305 with our new method (Tsvetkova et al. 2016).

Time delays, hours	R, our results Dudinov et al., 2011	Bar accounted Schmidt et al., 1998	SIE lens model Wertz & Surdej, 2014	NSIE+ $\gamma$ model Wertz & Surdej, 2014
$\Delta t_{AB}$	$4.5 \pm 1.9$	2.0	$2.6 \pm 0.7$	$2.51 \pm 0.52$
$\Delta t_{AC}$	$- 14.22 \pm 1.66$	- 16.2	$- 17.97 \pm 0.7$	$- 18.01 \pm 0.62$
$\Delta t_{AD}$	$- 2.73 \pm 4.61$	- 4.9	$- 5.38 \pm 0.7$	$- 5.41 \pm 0.43$
$\Delta t_{BC}$	$- 19.0 \pm 1.56$	( - 18.27 )	( - 20.57 )	( - 20.52 )
$\Delta t_{BD}$	$- 2.97 \pm 3.96$	( - 6.9 )	( - 7.98 )	( - 7.92 )
$\Delta t_{CD}$	$19.31 \pm 2.76$	( 11.3 )	$12.59 \pm 0.7$	$12.6 \pm 0.58$

The obtained results **are consistent with the most recent theoretic predictions** (e.g., Schmidt et al. 1998, Wertz & Surdej 2014).

# QSO 2237+0305 – *R*, *I* and *V* light curves

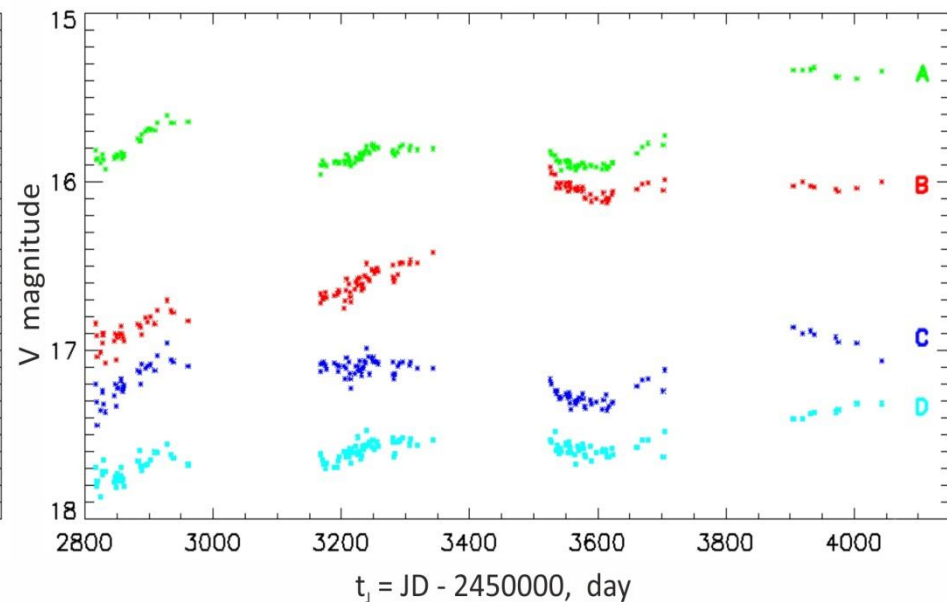
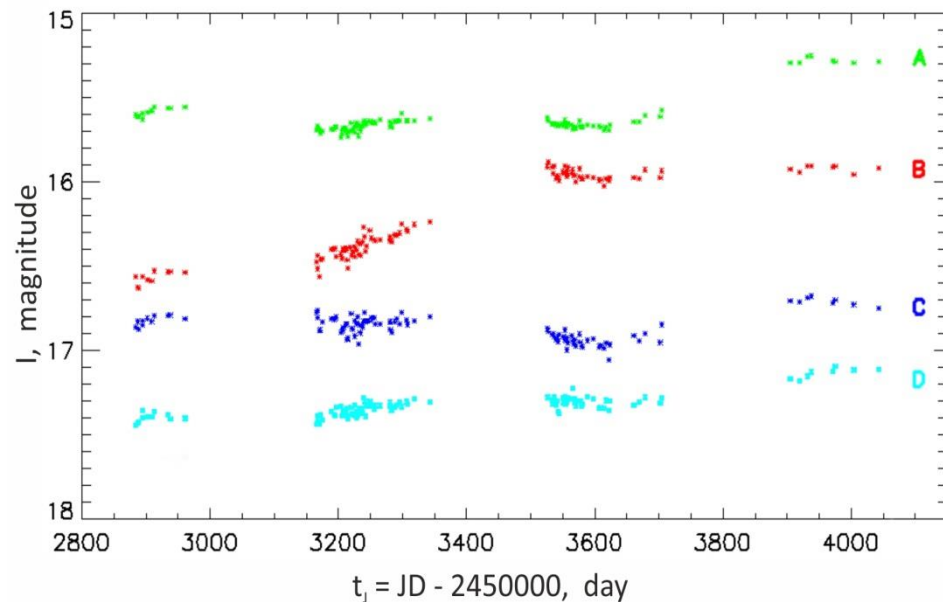


The light curves of the QSO 2237 + 0305 system for **2003–2006 seasons** in filters ***V***, ***R*** and ***I*** of the Johnson-Cousins photometric system as part of the long-term monitoring program at the **1.5-meter telescope of the Maidanak Observatory** from 2001 to 2009 :

$$I (\lambda_{\text{eff}} = 879.7\text{nm})$$

$$V (\lambda_{\text{eff}} = 547.7\text{nm})$$

$$R (\lambda_{\text{eff}} = 634.9\text{nm})$$



The photometry are available on the site: <http://www.astron.kharkov.ua/databases/index.html>

# Time delays between the RV, IR and IV pairs of light curves

**Inter-band time delays** of the Q2237+0305 quasar between the RV, IR and IV pairs of light curves of the **2004 season**:

Season 2004	$\Delta t_{R-V}$	$\Delta t_{R-V}^{ABC}$	$\Delta t_{I-R}$	$\Delta t_{I-R}^{ABC}$	$\Delta t_{I-V}$	$\Delta t_{I-V}^{ABC}$
Comp A	$9.14 \pm 2.51$	$7.18 \pm 2.81$	$2.21 \pm 1.07$	$3.18 \pm 1.37$	$5.67 \pm 2.21$	$6.67 \pm 2.34$
Comp B	$6.68 \pm 2.31$		$3.89 \pm 1.08$		$6.81 \pm 1.91$	
Comp C	$5.61 \pm 2.38$		$4.49 \pm 0.53$		$7.76 \pm 2.37$	

**Inter-band time delays** of the Q2237+0305 quasar between the RV, IR and IV pairs of light curves of the **2005 season**:

Season 2005	$\Delta t_{R-V}$	$\Delta t_{R-V}^{ABC}$	$\Delta t_{I-R}$	$\Delta t_{I-R}^{ABC}$	$\Delta t_{I-V}$	$\Delta t_{I-V}^{ABC}$
Comp A	$7.31 \pm 2.06$	$6.25 \pm 1.97$	$0.63 \pm 0.83$	$0.63 \pm 1.36$	$7.69 \pm 1.39$	$6.72 \pm 2.28$
Comp B	$5.64 \pm 2.35$		$0.89 \pm 1.81$		$5.83 \pm 2.48$	
Comp C	$5.82 \pm 0.62$		$0.36 \pm 1.19$		$6.57 \pm 2.42$	

**Inter-band time** of the Q2237+0305 quasar between the RV, IR and IV pairs of light curves **averaged over components and seasons**:

Season 2004 - 2005	$\Delta t_{R-V}^{ABC}$	$\Delta t_{I-R}^{ABC}$	$\Delta t_{I-V}^{ABC}$
Comp ABC	$6.71 \pm 2.46$	$1.71 \pm 1.86$	$6.73 \pm 2.31$

\* time delays in the observer's coordinate system

# Reliability of the results

- **excellent agreement** between the time delay estimates obtained **independently** for different macroimages and for two different seasons;
- our estimates of the time delays between filters R and V for seasons 2004 and 2005 are **consistent with the results** obtained by Koptelova et al. (2010) for season 2003:

**5.1- 5.6 days for component A and 5.1-5.2 days for component C;**

- if the detected proximity of the  $\Delta t_{RV}$  and  $\Delta t_{IV}$  delays is real, the time delay between filters I and R must be short enough - this is just what we see in our results - the **time delay between filters I and R is close to the level of errors.**

Season 2004	$\Delta t_{R-V}$	$\Delta t_{R-V}^{ABC}$	$\Delta t_{I-R}$	$\Delta t_{I-R}^{ABC}$	$\Delta t_{I-V}$	$\Delta t_{I-V}^{ABC}$
Comp A	9.14 ± 2.51	7.18 ± 2.81	2.21 ± 1.07	3.18 ± 1.37	5.67 ± 2.21	6.67 ± 2.34
Comp B	6.68 ± 2.31		3.89 ± 1.08		6.81 ± 1.91	
Comp C	5.61 ± 2.38		4.49 ± 0.53		7.76 ± 2.37	

Season 2005	$\Delta t_{R-V}$	$\Delta t_{R-V}^{ABC}$	$\Delta t_{I-R}$	$\Delta t_{I-R}^{ABC}$	$\Delta t_{I-V}$	$\Delta t_{I-V}^{ABC}$
Comp A	7.31 ± 2.06	6.25 ± 1.97	0.63 ± 0.83	0.63 ± 1.36	7.69 ± 1.39	6.72 ± 2.28
Comp B	5.64 ± 2.35		0.89 ± 1.81		5.83 ± 2.48	
Comp C	5.82 ± 0.62		0.36 ± 1.19		6.57 ± 2.42	

# Standard accretion disk model by Shakura & Sunyaev

The radius  $R_\lambda$  at which the disk temperature matches the wavelength  $\lambda_{eff}$  in the maximum of the blackbody radiation (thin accretion disk model by Shakura & Sunyaev):

$$R_\lambda = \left( \frac{45G\lambda^4 M_{BH} \dot{M}}{16\pi^6 hc^2} \right)^{1/3} \xrightarrow{\substack{\text{dimensionless quantities} \\ \tilde{M}_{BH} = M_{BH} / (10^9 M_\odot), \tilde{\lambda} = \lambda / 1\mu m \\ \dot{M} = L / \eta c^2}} R_\lambda = 9.7 \cdot 10^{15} \left( \frac{\lambda_{rest}}{1000} \right)^{4/3} \cdot \left( \frac{M_{BH}}{10^9 M_\odot} \right)^{2/3} \cdot \left( \frac{L}{\eta L_E} \right)^{1/3}$$

$M_{BH}$  – black hole mass and  $\dot{M}$  – accretion rate;  
 $\lambda$  – the rest-frame effective wave lengths of the corresponding filters;  
 $L$  и  $L_E$  – luminosity and Eddington luminosity limit;  
 $\eta$  – accretion efficiency



**Poindexter & Kochanek (2010);**  
**Morgan et al. (2010)**

**Estimation of the time delay** for two wavelengths expected from the standard thin accretion disk model by Shakura & Sunyaev (for a **simplified reprocessing model**: annual zones; quasar observed “face-on”):

$$\Delta t_{R-V} = \frac{K}{c} \cdot M_{BH}^{2/3} \left( \frac{L}{\eta L_E} \right)^{1/3} \cdot \left( \tilde{\lambda}_R^{4/3} - \tilde{\lambda}_V^{4/3} \right)$$

The values of the **inter-band time delays predicted by a standard thin accretion disk model** (Shakura & Sunyaev) for  $M_{BH} = 9 \cdot 10^8 M_\odot$  (Morgan 2010):

$$\Delta t_{RV} \approx 0.15 \text{ days} \quad \Delta t_{IR} \approx 0.3 \text{ days} \quad \Delta t_{IV} \approx 0.45 \text{ days}$$

# Comparison the measured time delays and predicted theoretically

Rest-frame **time delays** obtained from **observational data**:

Season 2004 – 2005	$\hat{\Delta t}_{R-V}^{ABC}$	$\hat{\Delta t}_{I-R}^{ABC}$	$\hat{\Delta t}_{I-V}^{ABC}$
Comp ABC	$2.49 \pm 0.92$	$0.64 \pm 0.69$	$2.51 \pm 0.86$

$$\hat{\Delta t} = \frac{\Delta t_{R-V}}{1 + z_Q}$$

**Time delays** predicted by a **standard thin accretion disk model**  
Shakura and Sunyaev :

$$\Delta t_{RV} \approx 0.15 \text{ days} \quad \Delta t_{IR} \approx 0.3 \text{ days} \quad \Delta t_{IV} \approx 0.45 \text{ days}$$



$$M_{BH} = 9 \cdot 10^8 M_\odot$$

**(Morgan 2010)**

- **project STORM (Space Telescope and Optical Reverberation Mapping)** - Fausnaugh M. et al. (2016)  
=> the measured inter-band time delays are significantly larger than those expected from the standard thin accretion disk model (Shakura & Sunyaev);
- **Morgan et al. (2010)** => to eliminate the observed discrepancy, it's necessary to make changes in the values of the parameters of standard thin accretion disk model: the mass of the black hole  $M_{BH}$ , the accretion efficiency  $\eta$ , and/or the ratio of luminosity to the Eddington limit;
- **Jaroszynski et al. (1992)** => were the first to assume the existence of an extended structure in the accretion disk of Q2237+0305 from the microlensing analysis ;
- **Witt & Mao (1994), Vakulik et al. (2007), Shulga et al. (2014)** => similar conclusions (from microlensing events)

# Analysis and interpretation of results

In the classic work of Shakura and Sunyaev (1973), the authors admitted a **possibility of a supercritical accretion regime** that leads to formation of an **extended optically thick scattering envelope** on the accretion disk periphery :

Radius of scattering envelope

$$R_{eff} \simeq 3 \cdot 10^2 \dot{m}^{51/22} m^{10/11} \alpha^{-17/11} A^{8/11} (cm)$$

Effective temperature of scattering envelope

$$T_{eff} \simeq 2 \cdot 10^{10} \dot{m}^{-15/11} m^{-2/11} \alpha^{10/11} A^{-6/11} (^\circ K)$$

**dimensionless quantities:**

mass  $m = M/M_\odot$  and accretion rate  $\dot{m} = \dot{M}/\dot{M}_{cr}$ ,

A - a ratio of energy losses in the Compton radiation to those in free-free transitions

( $10 < A < 300$  under physical conditions of interest)

$\alpha$  - efficiency of the angular momentum transport in the accreting matter

In the **optical spectral range** (low-frequency range at the temperature  $T_{eff}$ ), the **radius** near which the envelope becomes opaque exceeds considerably  $R_{eff}$  :

Optical envelope radius

$$R_{opt} \simeq 10^7 \alpha^{-3/4} \left( \frac{10^6 \text{ }^\circ K}{T} \right)^{3/8} \left( \frac{10^{15} \text{ Hz}}{\nu} \right)^{1/2} \dot{m}^{9/8} m^{3/4} (cm)$$



# Analysis and interpretation of results

$R_{\text{opt}}$ (cm)	$R_{\text{optV}}$	$R_{\text{optR}}$	$R_{\text{optI}}$
$\alpha=0.015; A=50$	$9.56 \cdot 10^{16}$	$1.02 \cdot 10^{17}$	$1.21 \cdot 10^{17}$
$\alpha=0.05; A=50$	$2.57 \cdot 10^{16}$	$2.77 \cdot 10^{16}$	$3.25 \cdot 10^{16}$
$\alpha=0.01; A=100$	$1.71 \cdot 10^{17}$	$1.84 \cdot 10^{17}$	$2.17 \cdot 10^{17}$
$\alpha=0.05; A=100$	$2.97 \cdot 10^{16}$	$3.19 \cdot 10^{16}$	$3.74 \cdot 10^{16}$

The values of  $R_{\text{opt}}$ , calculated for sets of parameters  $\alpha$  and  $A$  for the black hole mass  $9 \cdot 10^8 M_{\odot}$  and dimensionless accretion rate  $17$  (Morgan et al. 2010)

Corresponding estimates of time delays for the three pairs of filters V, R and I

$\Delta t$ (days)	$T_{\text{eff}}, (K)$	$\Delta t_{\text{RV}}$	$\Delta t_{\text{IR}}$	$\Delta t_{\text{IV}}$
$\alpha=0.015; A=50$	$0.25 \cdot 10^5$	2.79	6.94	9.74
$\alpha=0.05; A=50$	$0.77 \cdot 10^5$	0.75	1.87	2.62
$\alpha=0.01; A=100$	$0.12 \cdot 10^5$	5.07	12.45	17.46
$\alpha=0.05; A=100$	$0.53 \cdot 10^5$	0.87	2.15	3.02

The values of time delays are consistent with the results of this work at the values of parameters  $\alpha$  and  $A$ :

$$\alpha = 0.015 \text{ and } A = 50$$

$\alpha$  - efficiency of the angular momentum transport in the accreting matter;  
 $A$  - a ratio of energy losses in the Compton radiation to those in free-free transitions.

# Conclusions

- The **method elaborated** in our group earlier provided reliable estimates of the inter-band time delays for QSO 2237+0305.
- The **measured time delays** between the flux variations in different filters are an order of magnitude **larger** than the delays values based on a standard thin accretion disk model (Shakura and Sunyaev , 1973).
- The discrepancy between the measured time delays and predicted theoretically can be explained by the fact that the black hole is accreting matter in a **moderately super-critical regime**. Shakura and Sunyaev showed that such regime may result in creating an extended **scattering envelope**.
- Having used the analytical expressions obtained by Shakura-Sunyaev, we made calculations for quasar QSO 2237+0305 with the black hole mass  $M_{BH} = 9 \cdot 10^8 M_{\odot}$  and show that the inter-band time delay values obtained by us from the data of observations for some parameters of the supercritical regime are consistent with **the existence of scattering envelope**. The reverberation responses which we observe may arise in quasar's regions located more than  $10^{16}$  cm from the central black hole.

*Thank you for your attention!*

