

Gravitational microlensing as a probe for dark matter

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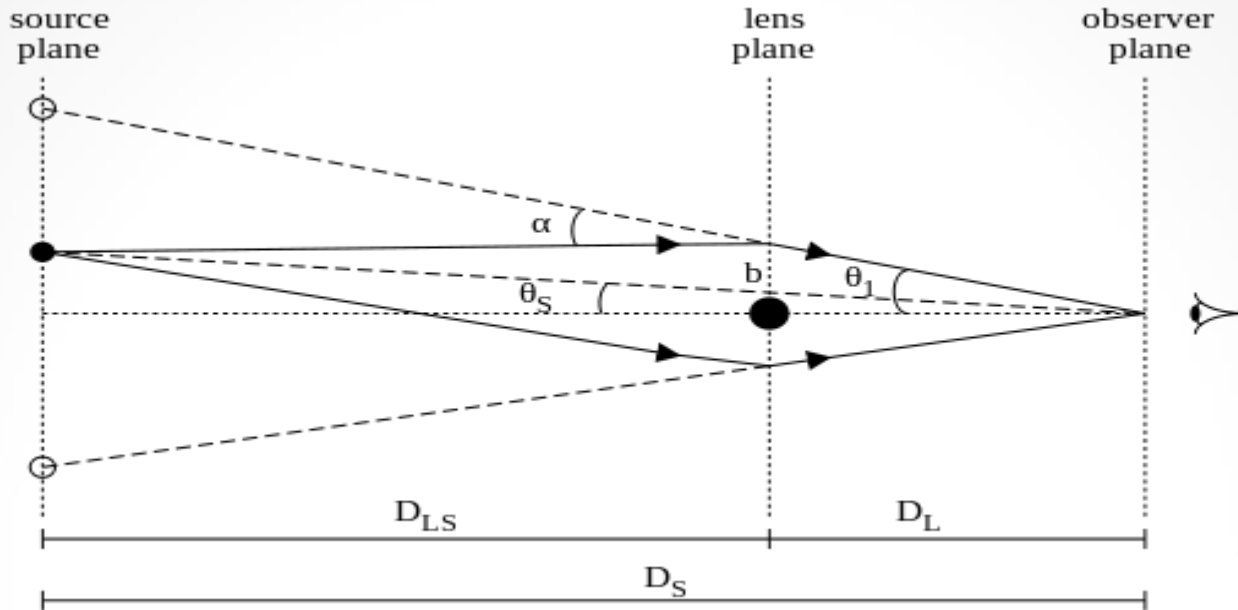
28th Texas Symposium on Relativistic Astrophysics

Introduction

We study the statistics of light curves of a small source images microlensed by a stochastic system of point masses-stars and extended clumps. The latter objects represent models of the dark matter (DM) micro-halos by means of simple analytical formulas. The effective size of each clump is assumed to be 5 or 10 Einstein radii according to its mass. For each set of initial parameters (optical depth of microlensing, external shear, size of the clump) we generated an ensemble of magnification patterns considering spatially homogeneous distribution of microlenses. We derived autocorrelation functions of light curves for different relative contributions of “DM clumps” with total optical depth $\sigma_{\text{tot}} = 0.3$ and different external shear $\gamma = 0.1, 0.2, 0.3$. Two main models have been studied: (i) independent clumps and point masses, and (ii) concentric point masses surrounded by the clumps. We found that the effect of the shear varies significantly for different models (i) and (ii).

Mao et al. (2004), McKean et al. (2007), Oguri (2005).

Gravitational microlensing



- Lens equation for microlensing

$$y = Ax - R_E^2 \sum_{i=1}^N \frac{x - x_i}{|x - x_i|^2},$$

$$A = \begin{bmatrix} 1 - \gamma + \sigma_{cont} & 0 \\ 0 & 1 + \gamma + \sigma_{cont} \end{bmatrix}, \sigma_{cont} = 0$$

- Total microlensed flux

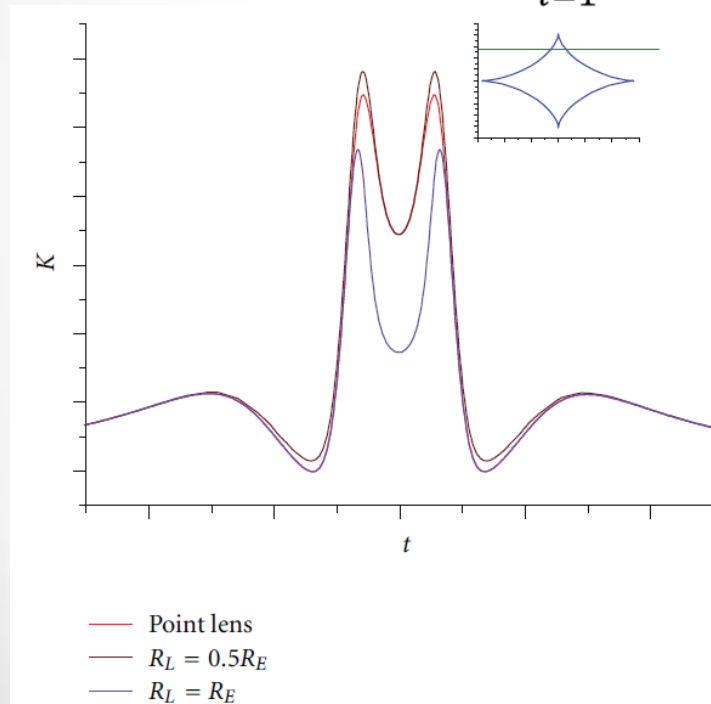
$$F(Y) = \iint K(y) I(y - Y) dy_1 dy_2$$

where point source amplification $K(y) = \sum_i K_i(y)$

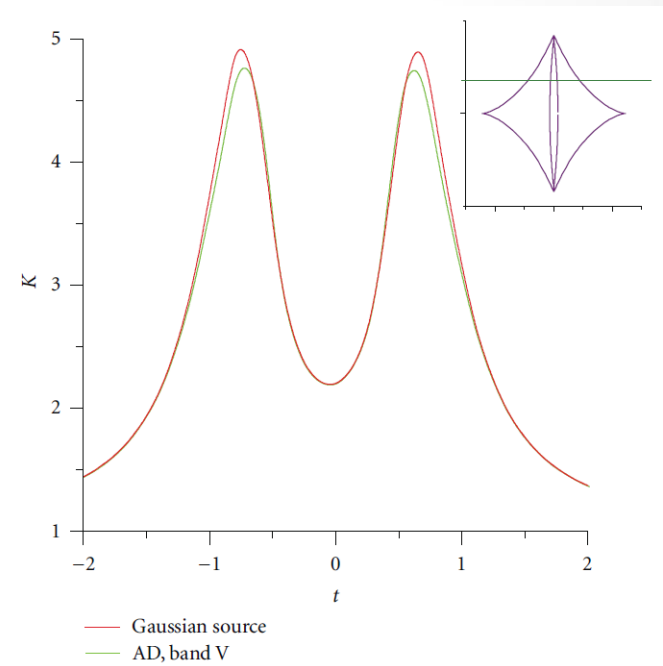
DM clumps as subhalo structures

- Equation of microlensing for DM clumps ($R_{c,i}$ - clump "size")

$$y = Ax - \sum_{i=1}^N \left[\frac{qR_{E,i}^2(x - x_i)}{|x - x_i|^2} + \frac{(1 - q)R_{E,i}^2(x - x_i)}{(|x - x_i|^2 + R_{E,i}^2)} \right],$$

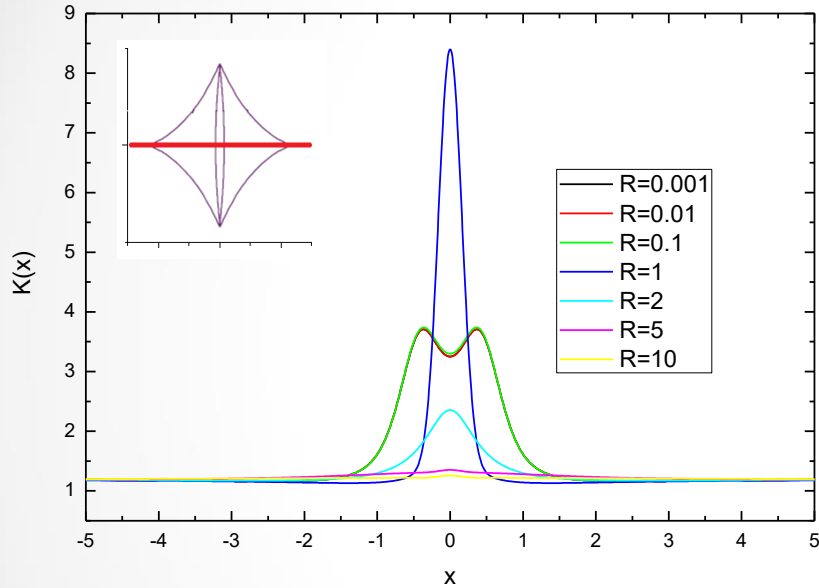


Usual Chang-Refsdal lens

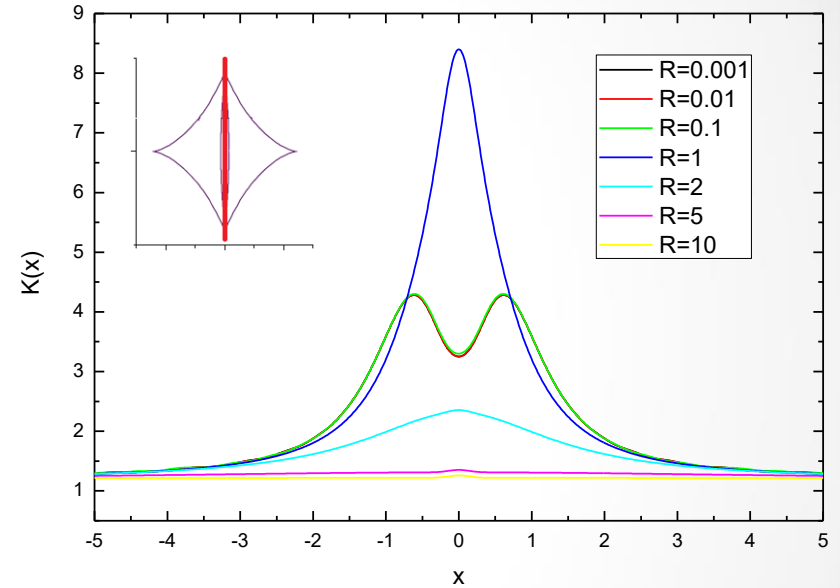


Chang-Refsdal lens with clumps instead of the point microlens

Clumps' sizes



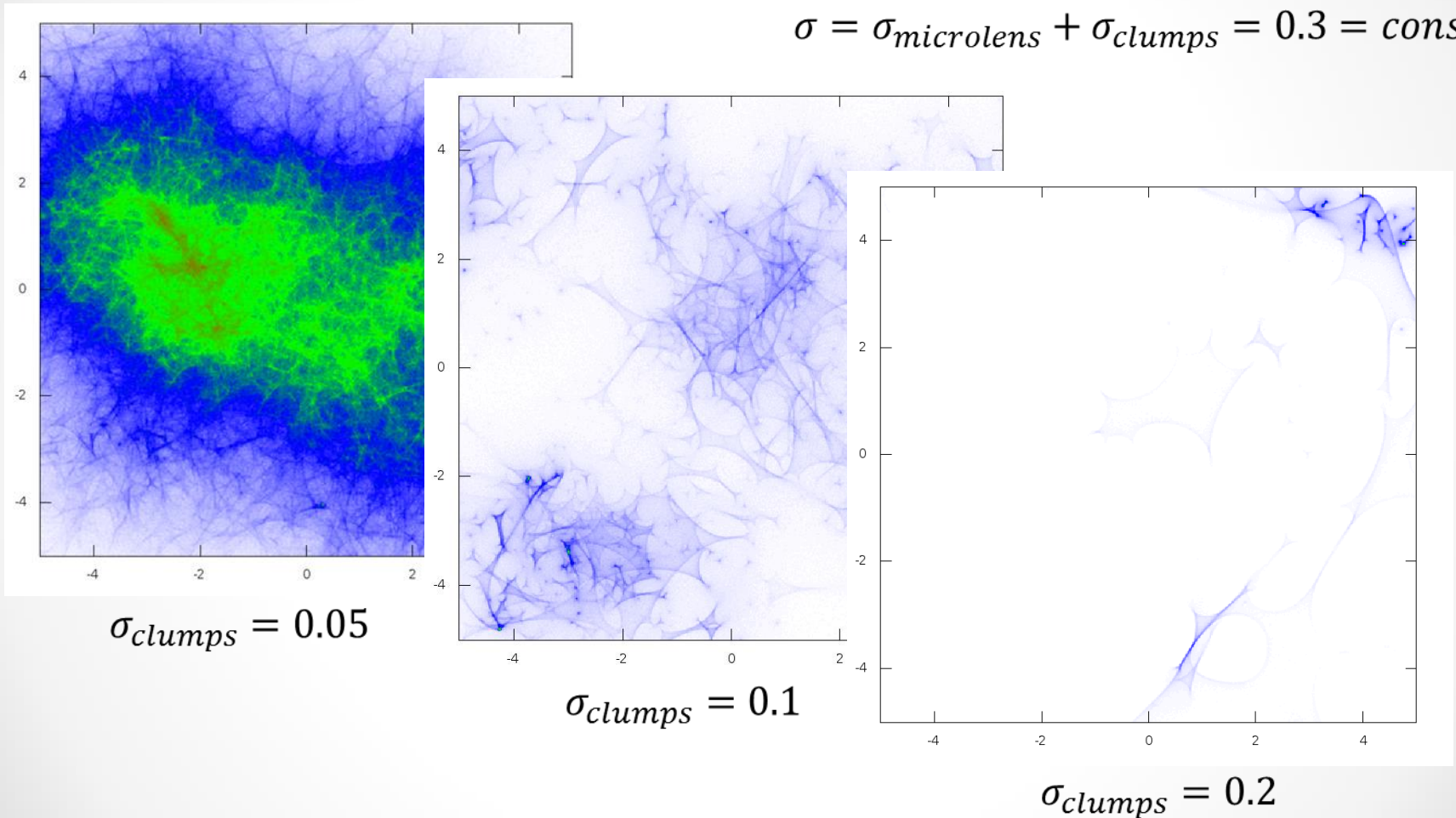
Light curves calculated for single clump with different sizes. The movement of the source has the same direction with the external shear.



Light curves calculated for single clump with different sizes. The movement of the source is orthogonal to the external shear.

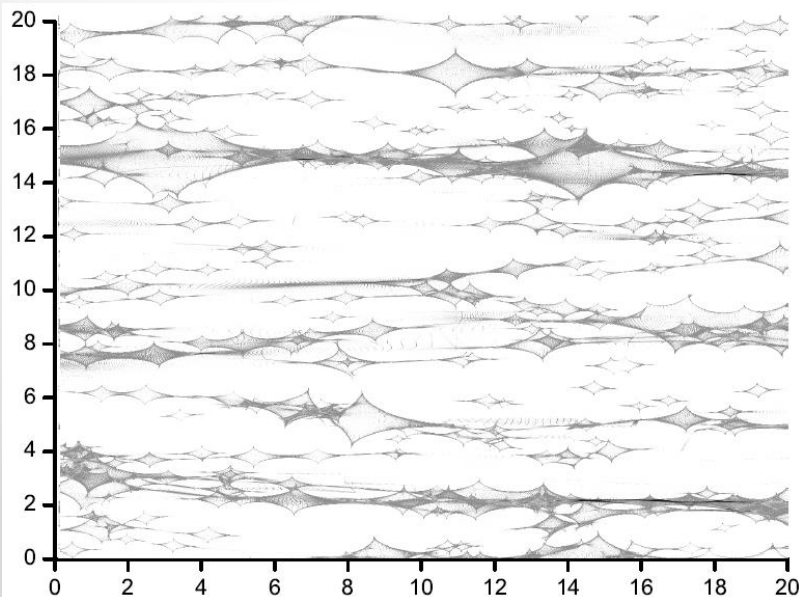
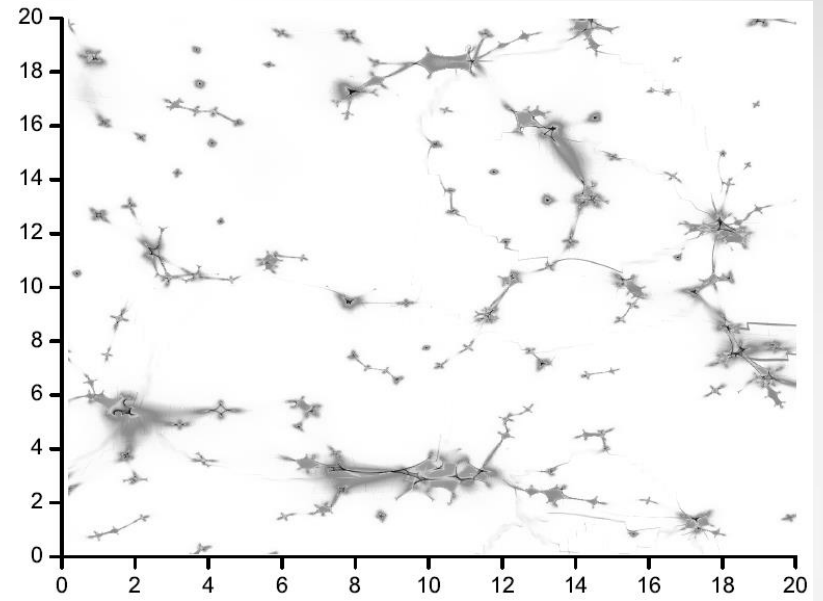
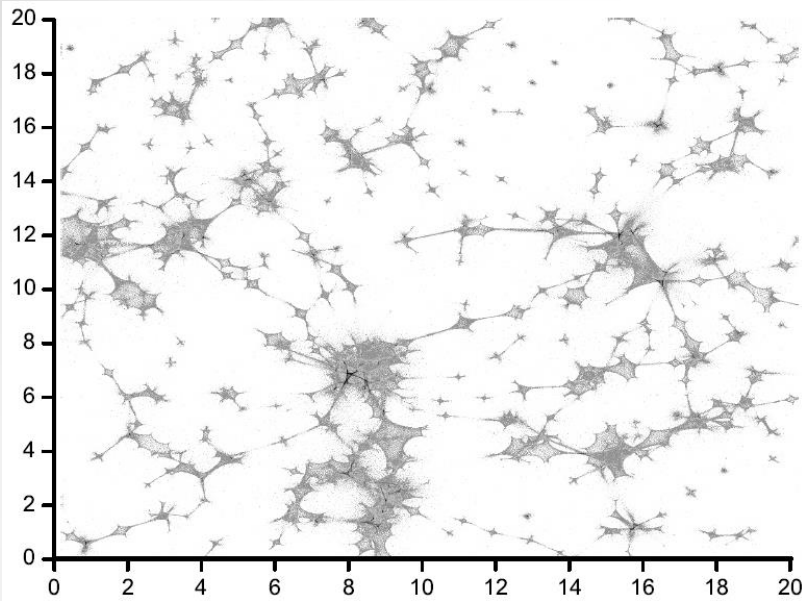
DM clumps impact on gravitational microlensing

$$\sigma = \sigma_{microlens} + \sigma_{clumps} = 0.3 = const$$



Magnification patterns calculated for the same positions of the microlenses but with different optical depths of the clumps.

Magnification maps with shear



The amplification maps ($\sigma_{tot} = 0.3, \kappa = 5$):

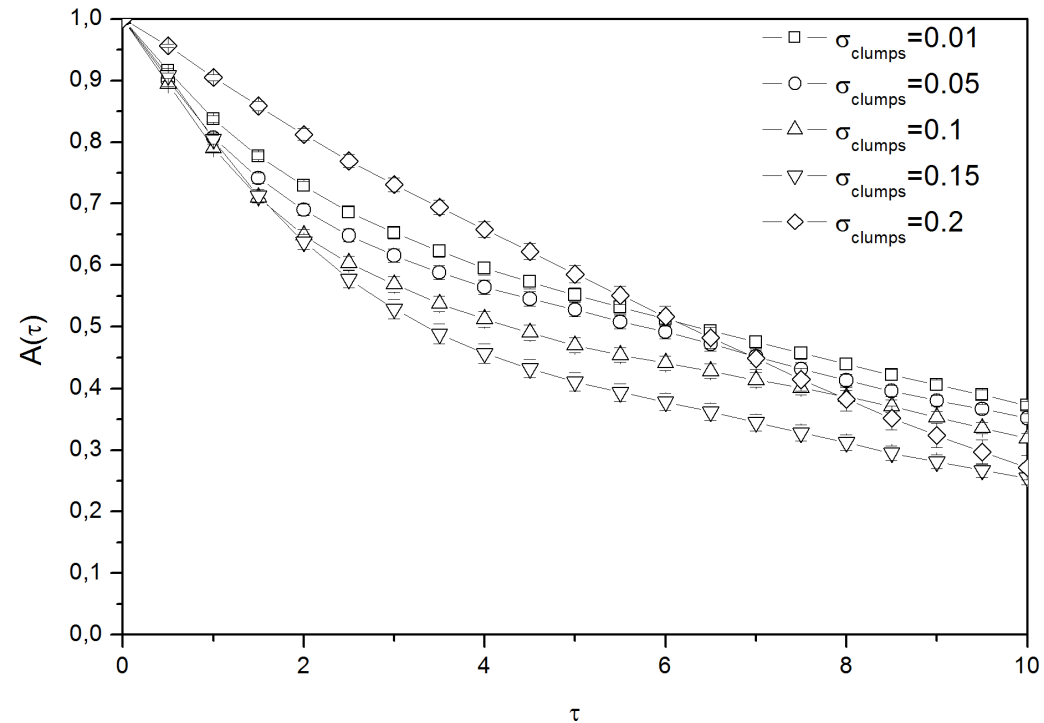
Top-left: $\sigma_{cl} = 0, \gamma = 0$

Top-right: $\sigma_{cl} = 0.2, \gamma = 0$

Bottom-left: $\sigma_{cl} = 0.2, \gamma = 0.5$

Calculations of autocorrelation functions

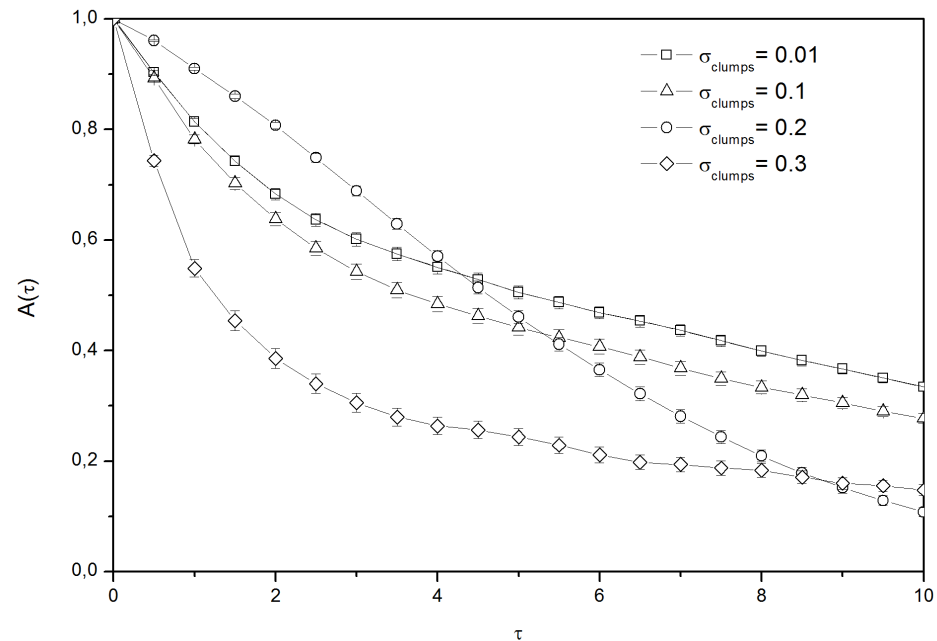
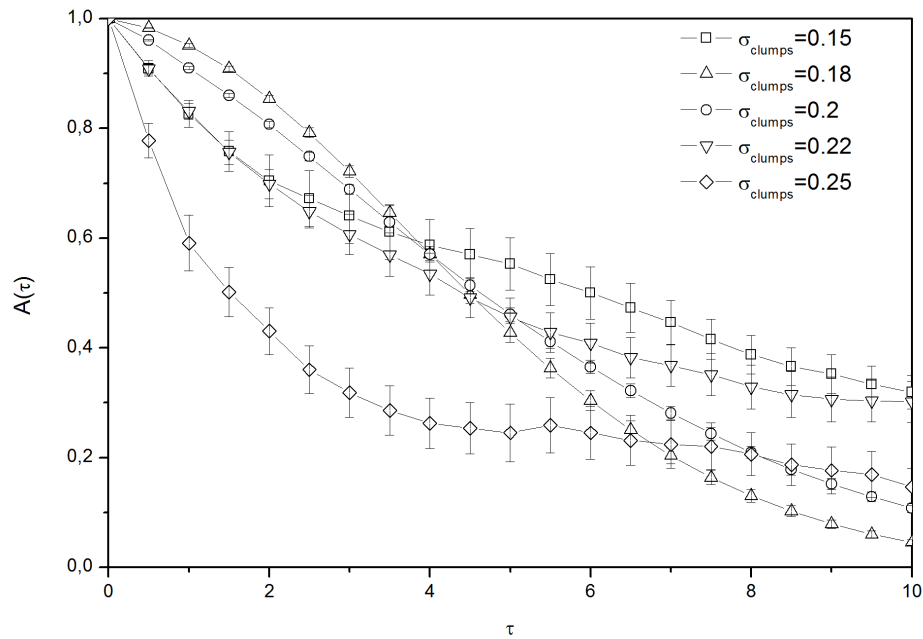
Parameter	Value
Source radii ($R_{1/2}$)	$0.2 R_E$
Trajectory length	$20 R_E$
Optical depths (σ_m)	0.3 (total)
Optical depths (σ_{clumps})	0.01-0.2
Realizations number	100
Clumps size (R_c)	$5 R_E; 10 R_E$
Resolution	$1.25 \cdot 10^7 \text{ pixels}$
Clumps mass parameter (q)	0.5



$$A(\tau) = \langle K(t)K(t-\tau) \rangle (\Delta K)^{-2}, \quad \Delta K = \sqrt{\langle [K(t)]^2 \rangle}$$

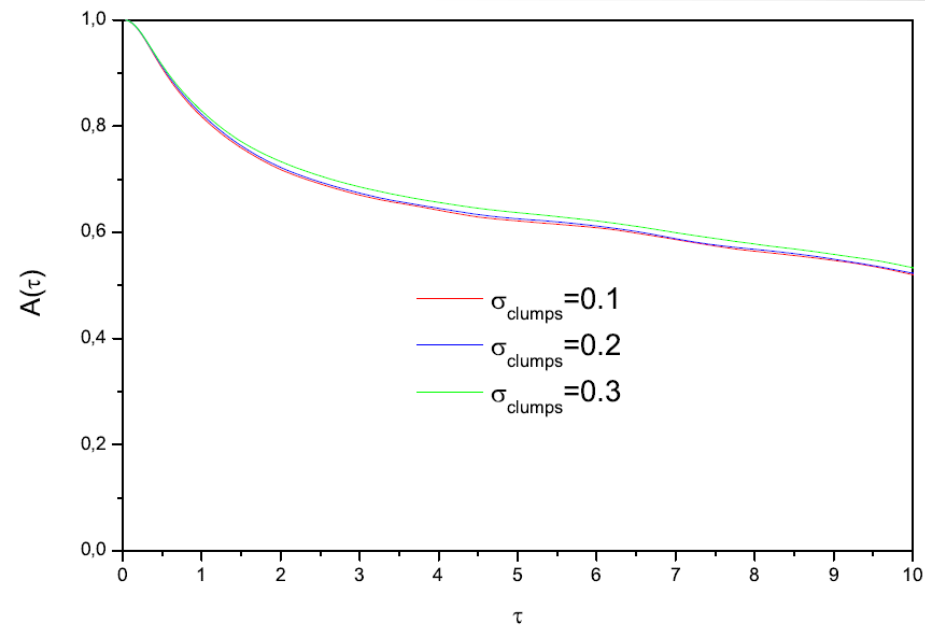
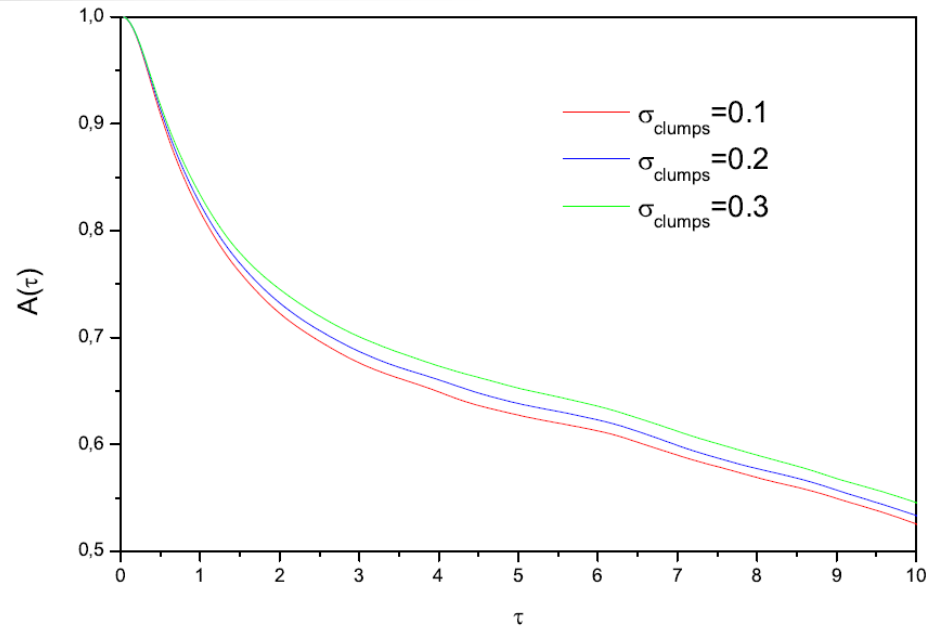
Averaged autocorrelation functions for light curves for cases with different clumps optical depth in case $R_c = 10 R_E$ (clumps are independent of the point masses)

Light curves autocorrelations



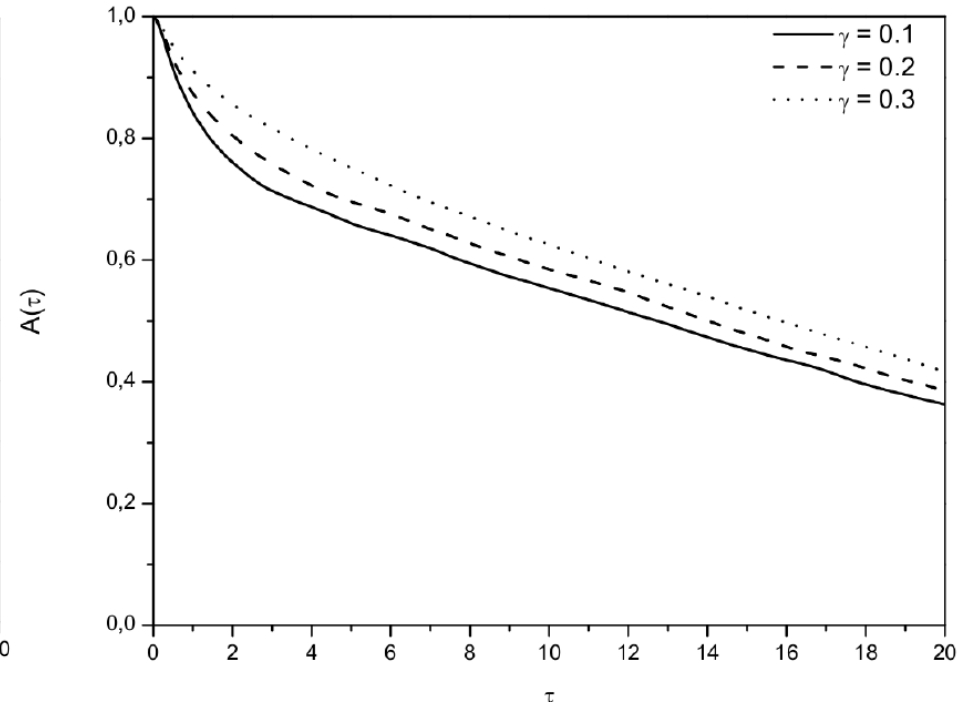
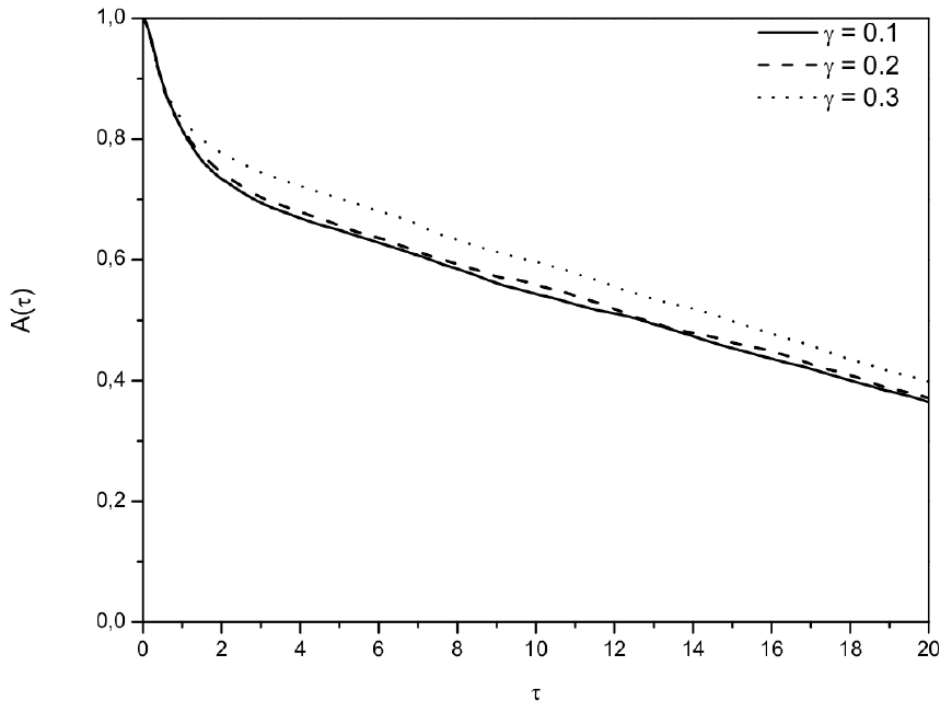
Averaged autocorrelation functions for light curves for cases with different clumps optical depth in case $R_c = 5 R_E$ (clumps are independent of the point masses)

Light curves autocorrelations



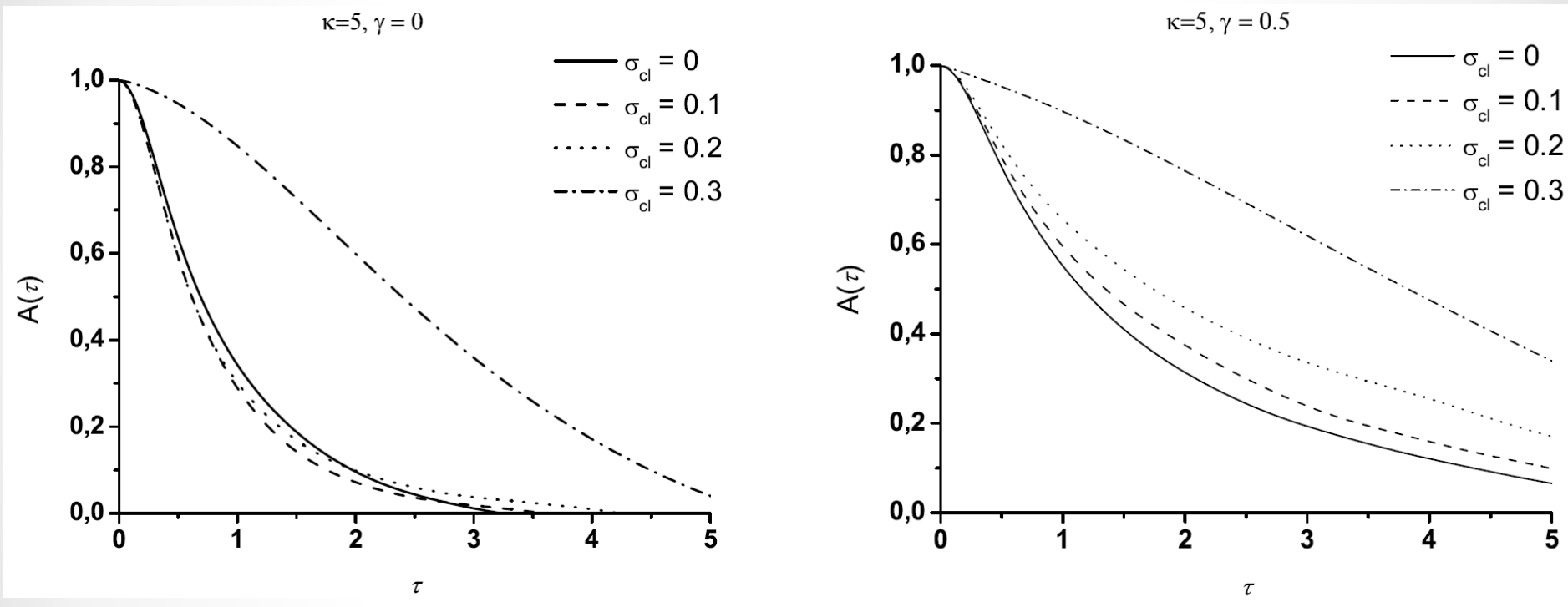
Averaged autocorrelation functions for light curves for cases with different clumps optical depth in case $R_c = 5 R_E$ (*left*) and $R_c = 10 R_E$ (*right*) (clumps located around the point mass)

Shear impact on autocorrelation functions



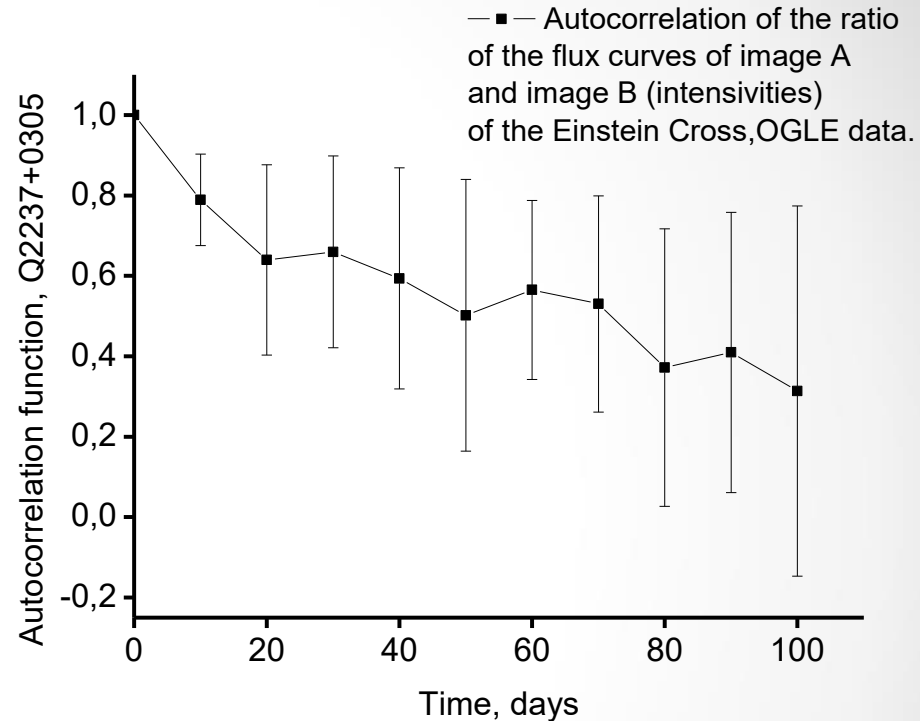
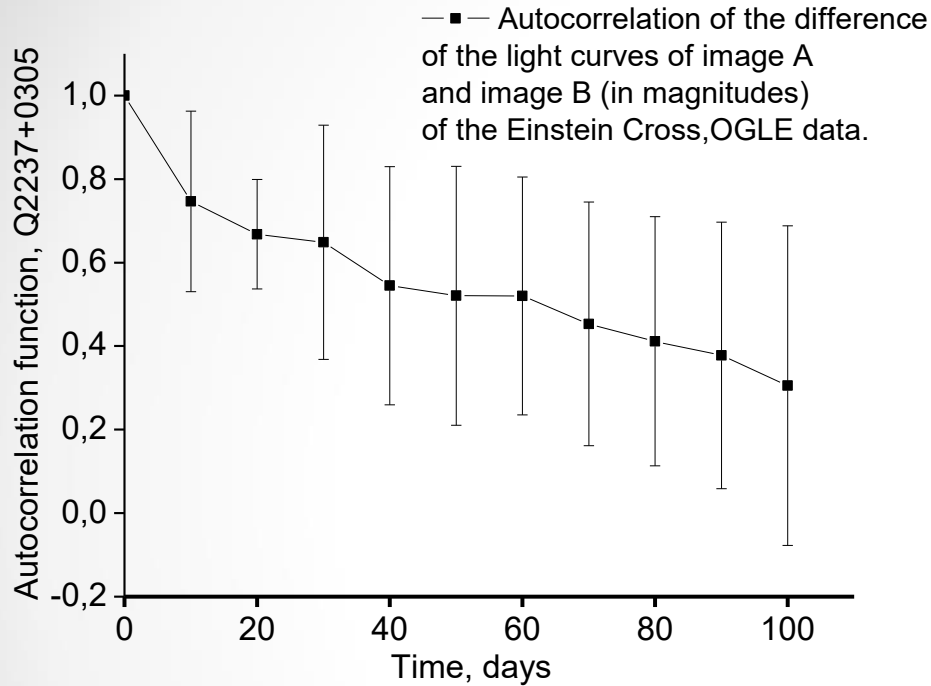
Autocorrelation functions of the amplification curves calculated for “point masses + clumps” system with external shear, $\sigma_{tot} = 0.3$, $\sigma_{cl} = 0.2$, $\kappa = 5$ (left), $\kappa = 10$ (right) (clumps are independent of the point masses).

Shear impact on autocorrelation functions



Autocorrelation functions of the amplification curves calculated for "point masses + clumps" system, $\sigma_{tot} = 0.3$, $\kappa = 5$ (clumps located around the point mass).

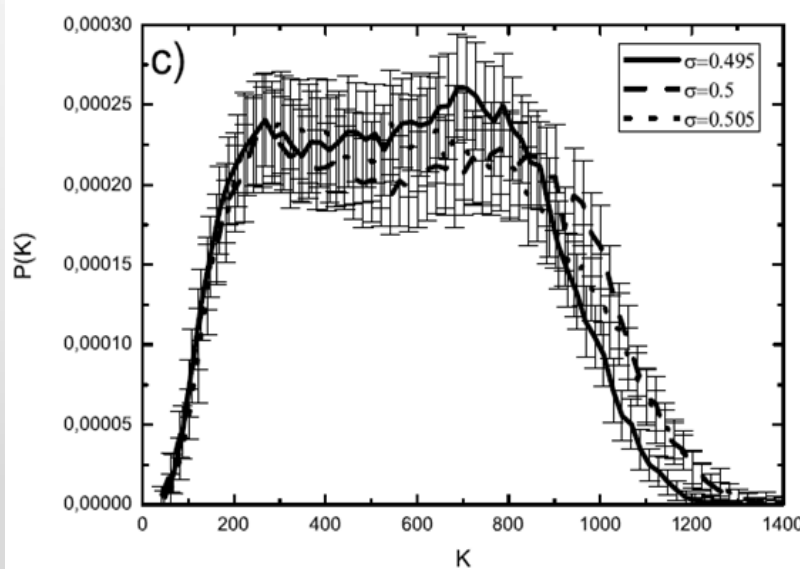
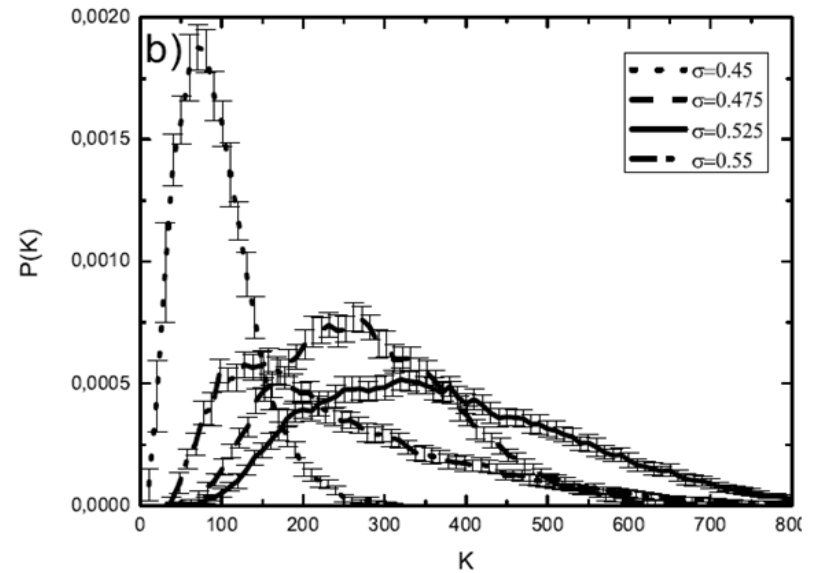
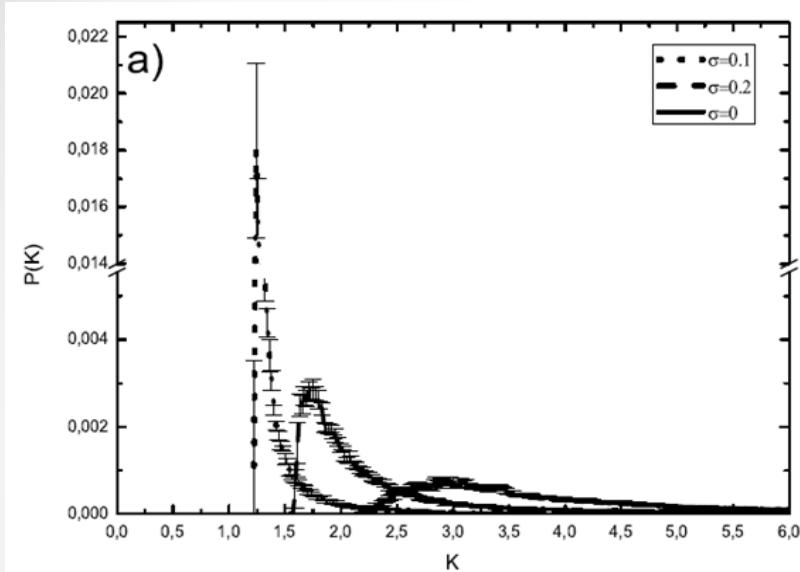
Observational data



Autocorrelation functions of light curves of Q2237+0305 based on combined OGLE & Maidanak data sets.

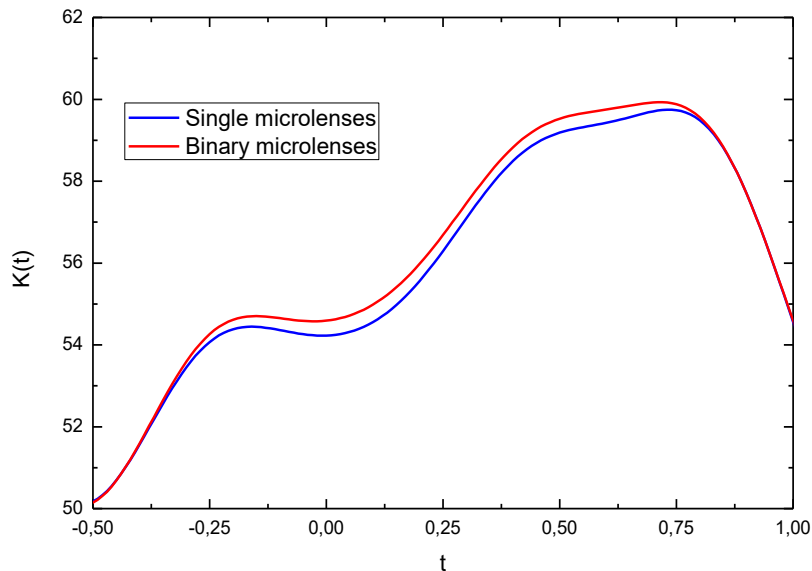
Data: OGLE collaboration, Vakulik et al. (2006)

Distribution of amplifications for different optical depths



Distribution of amplification coefficients for Gaussian source $R1/2 = 0:1$ for various optical depths: a) $= 0:1; 0:2; 0:3$ and the step over K -axis is $\Delta K = 0:02$; b) $= 0:45; 0:475; 0:525; 0:55$ and $\Delta K = 10$; c) $= 0:495; 0:5; 0:505$ and $\Delta K = 20$

Microlensing by binary stars



$\sigma_C=0.4$; $R_{1/2}=0.2$; Gaussian source

$R_{1/2}=0.1$

Relative difference: $\eta = \max_t \left(\frac{|K_i(t) - K_j(t)|}{K_i(t) + K_j(t)} \right)$

$R_{1/2}=0.15$

Parameter	Value
Source radii ($R_{1/2}$)	$0.1 R_E$; $0.15 R_E$; $0.2 R_E$
Trajectory length	$5 R_E$
Optical depths (σ_m)	0.3; 0.4; 0.5
Number of microlenses	1470; 1960; 2450
Power-like parameter (p)	1.5
Limb-darkening (p)	2

$R_{1/2}=0.2$

Model	$\sigma_c=0.3$	$\sigma_c=0.4$	$\sigma_c=0.5$
AD	0.03 ± 0.002	0.03 ± 0.002	0.009 ± 0.0003
GS	0.02 ± 0.001	0.019 ± 0.002	0.007 ± 0.0003
PL	0.02 ± 0.001	0.019 ± 0.002	0.007 ± 0.0002
AD1	0.07 ± 0.003	0.04 ± 0.002	0.013 ± 0.0005
LD	0.019 ± 0.001	0.015 ± 0.002	0.006 ± 0.0002

Model	$\sigma_c=0.3$	$\sigma_c=0.4$	$\sigma_c=0.5$
AD	0.019 ± 0.0013	0.014 ± 0.0006	0.006 ± 0.0002
GS	0.013 ± 0.0009	0.01 ± 0.0004	0.004 ± 0.0001
PL	0.012 ± 0.0008	0.01 ± 0.0004	0.004 ± 0.0001
AD1	0.04 ± 0.002	0.03 ± 0.001	0.009 ± 0.0003
LD	0.012 ± 0.0009	0.008 ± 0.0004	0.004 ± 0.0001

Model	$\sigma_c=0.3$	$\sigma_c=0.4$	$\sigma_c=0.5$
AD	0.012 ± 0.0008	0.009 ± 0.0004	0.005 ± 0.0009
GS	0.009 ± 0.0005	0.006 ± 0.0002	0.004 ± 0.0009
PL	0.009 ± 0.0005	0.006 ± 0.0003	0.004 ± 0.0009
AD1	0.03 ± 0.0012	0.02 ± 0.0009	0.006 ± 0.0002
LD	0.008 ± 0.0005	0.005 ± 0.0002	0.003 ± 0.0009

Conclusions

- We find that there can be a significant difference between ACFs for different types of DM clumps if the clump size is comparable with typical Einstein radii.
- The direction of the motion of the source relatively to external shear has negligible impact on ACFs for both models.
- Our results show that there is a non-monotonous behavior of the ACFs (as a whole) as a function of the clump contribution.
- Impact of any parameters of microlensing in “clumps+point masses” system cannot be distinguished in modern level of photometric observations.

Thank you!