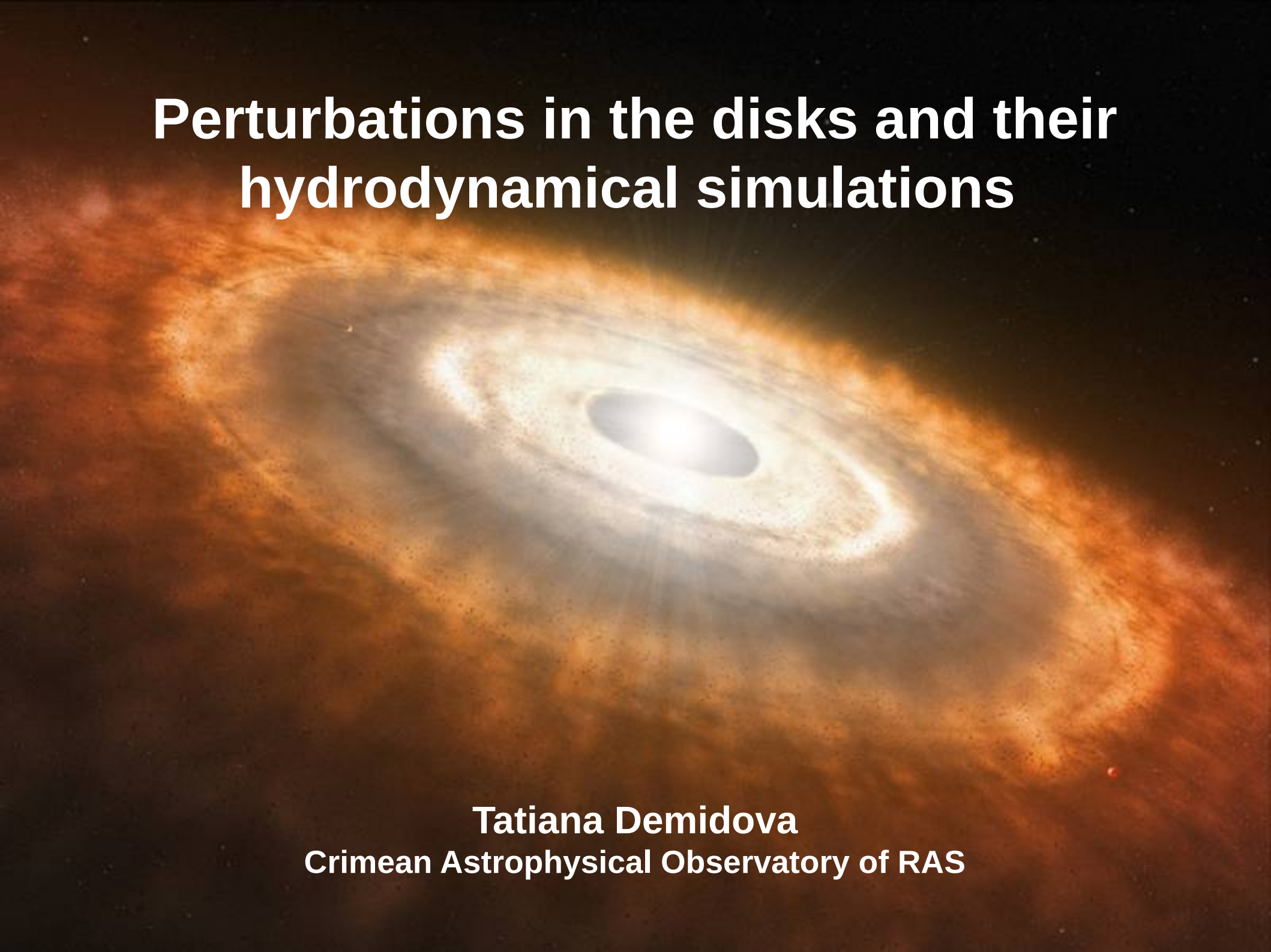
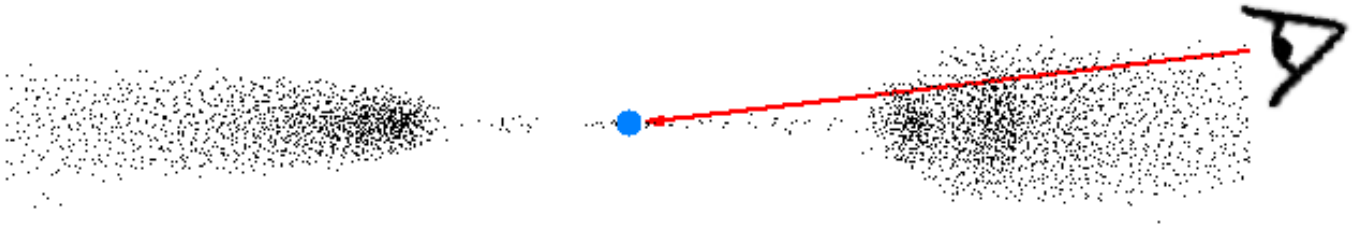
Perturbations in the disks and their hydrodynamical simulations



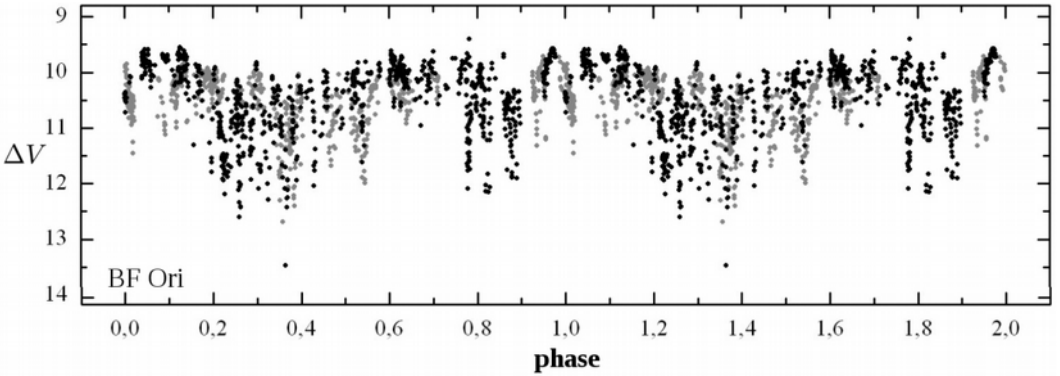
Tatiana Demidova
Crimean Astrophysical Observatory of RAS

The cyclic activity of UX Ori type stars

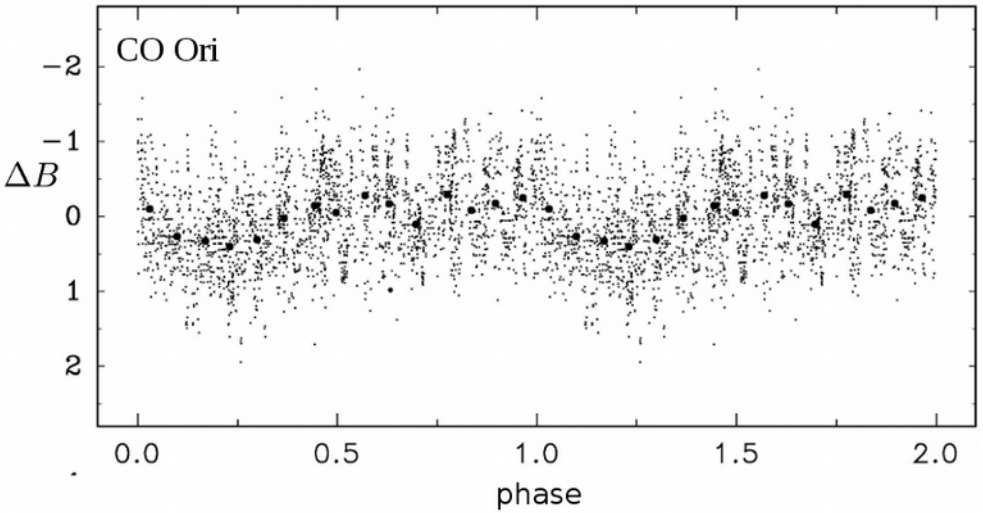
Grinin et al. (1991)



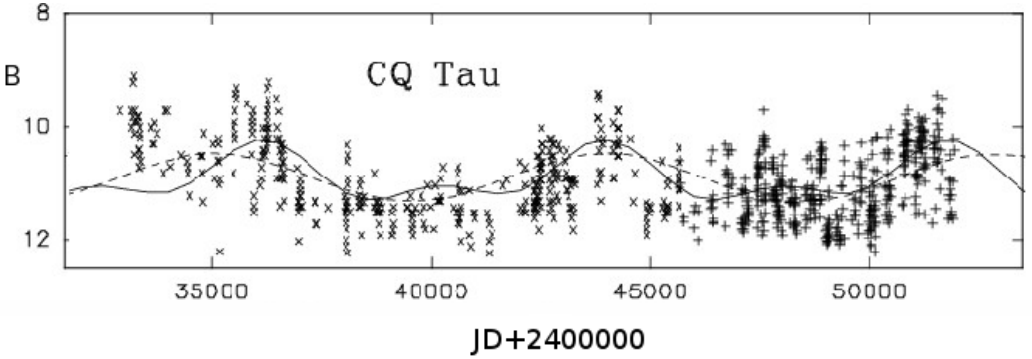
Grinin et al. (2010)

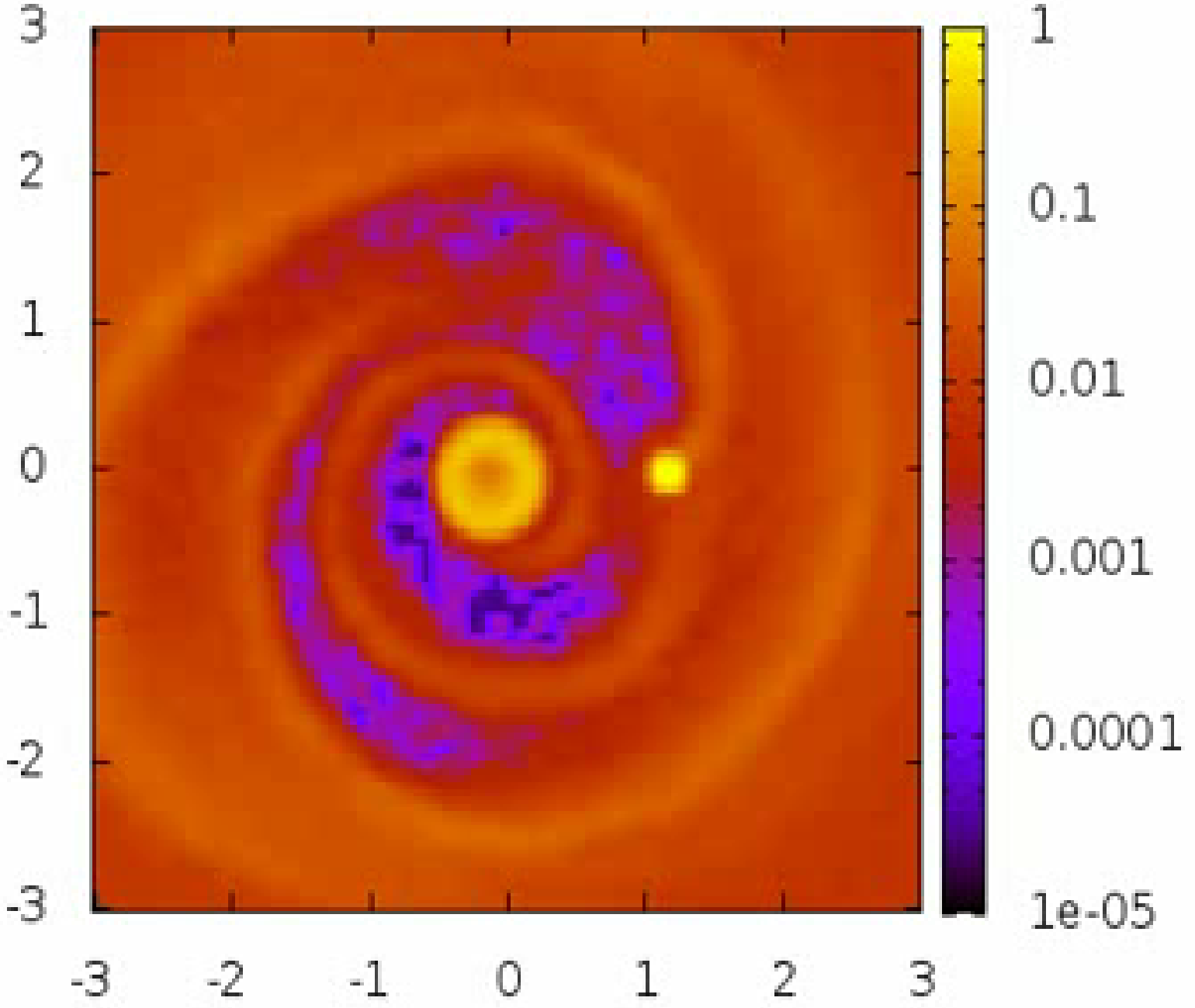


Rostopchina et al. (2007)



Shahkovskoi et al., (2005)

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-2
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-2
-1
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1
2
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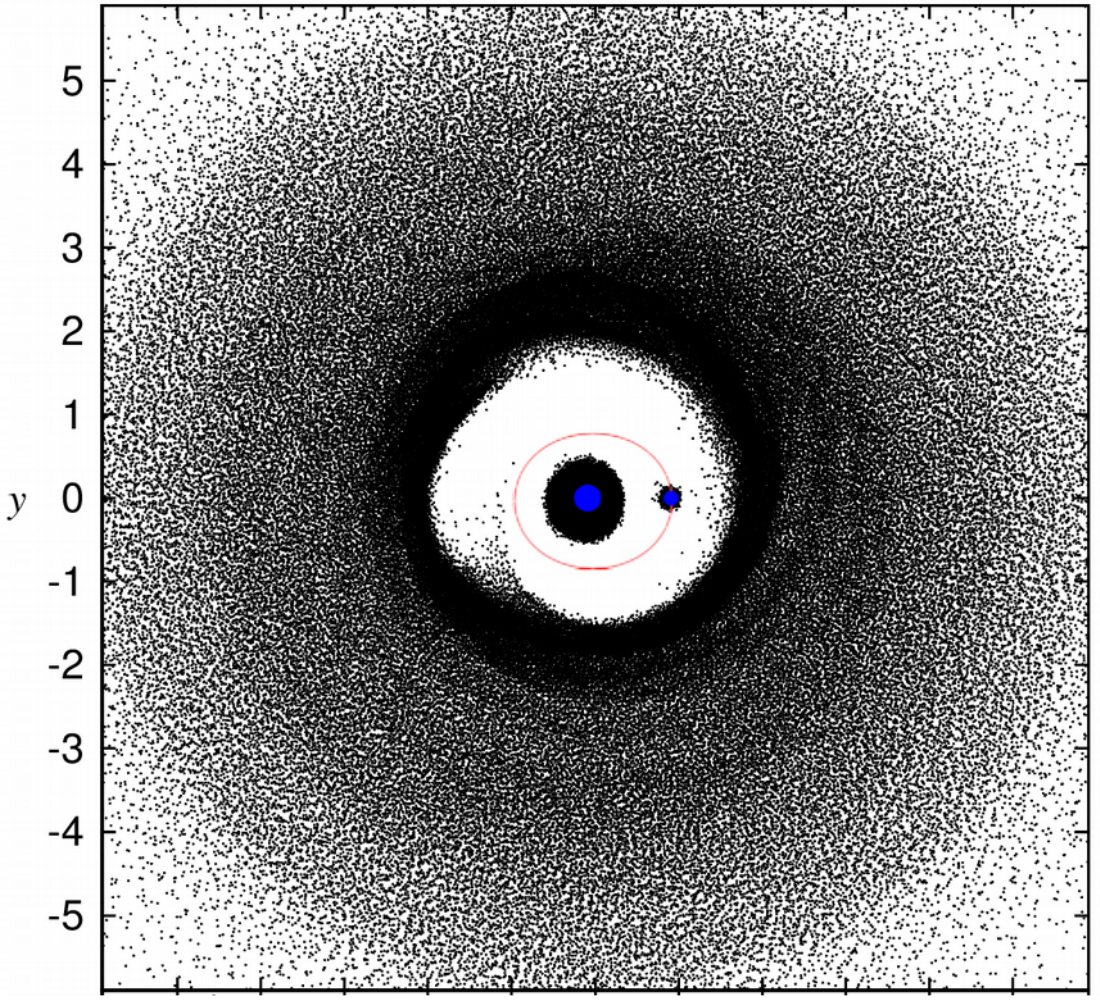
0.01
0.001
0.0001
1e-05

3D hydrodynamic simulations with SPH method



Herbig Ae star

$$M_1 = 2\,M_\odot$$

Companion

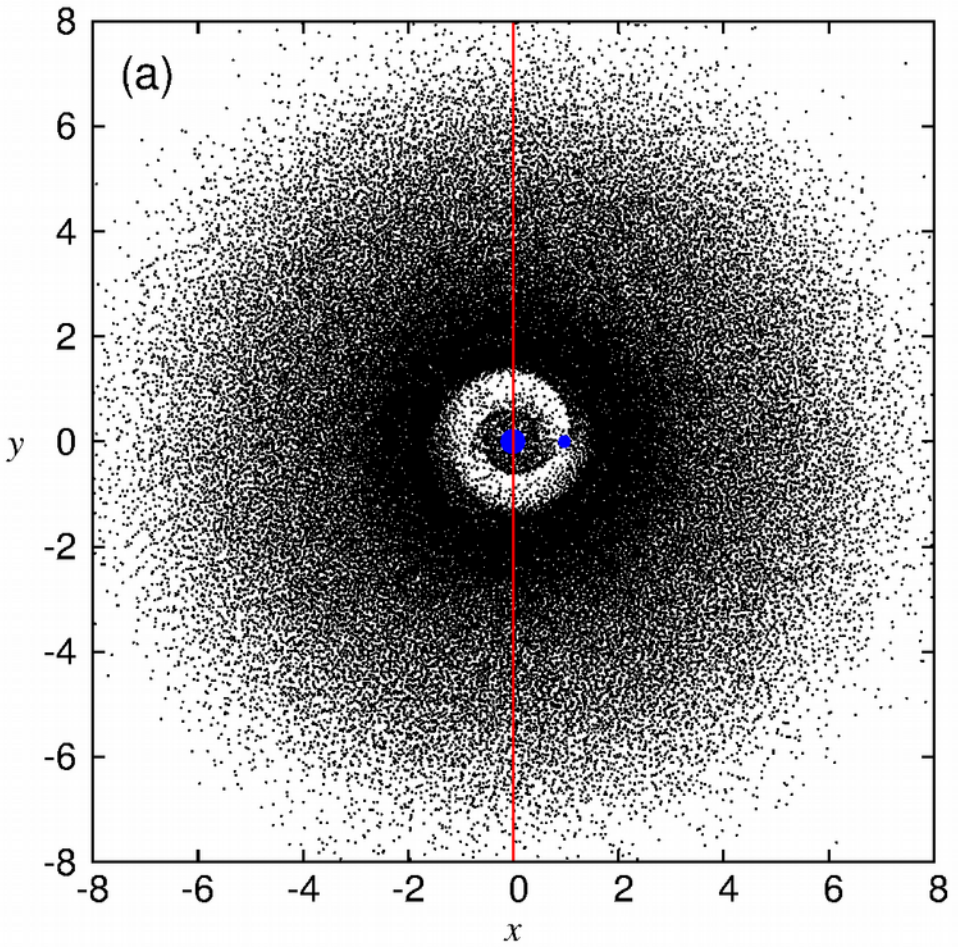
$$q = M_2 : M_1 = 0.1\text{-}0.003$$

$$e = 0.0\text{-}\ 0.3$$

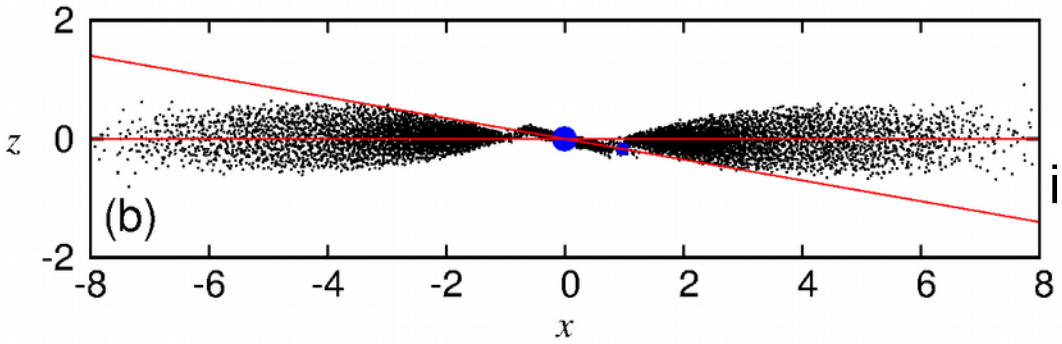
Protoplanetary disk

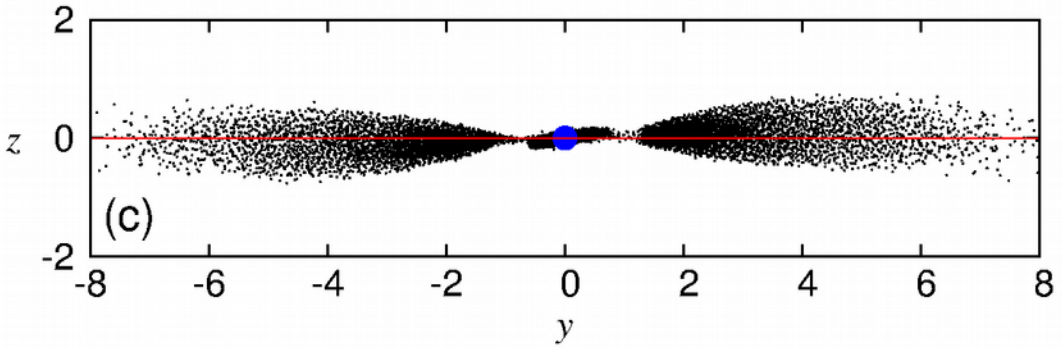
$$N = 2\text{-}\ 5 \cdot 10^5$$

The model where the companion orbit misaligned with the disk plane: Grinin et al. 2010



$i = 0^\circ$ - 30°

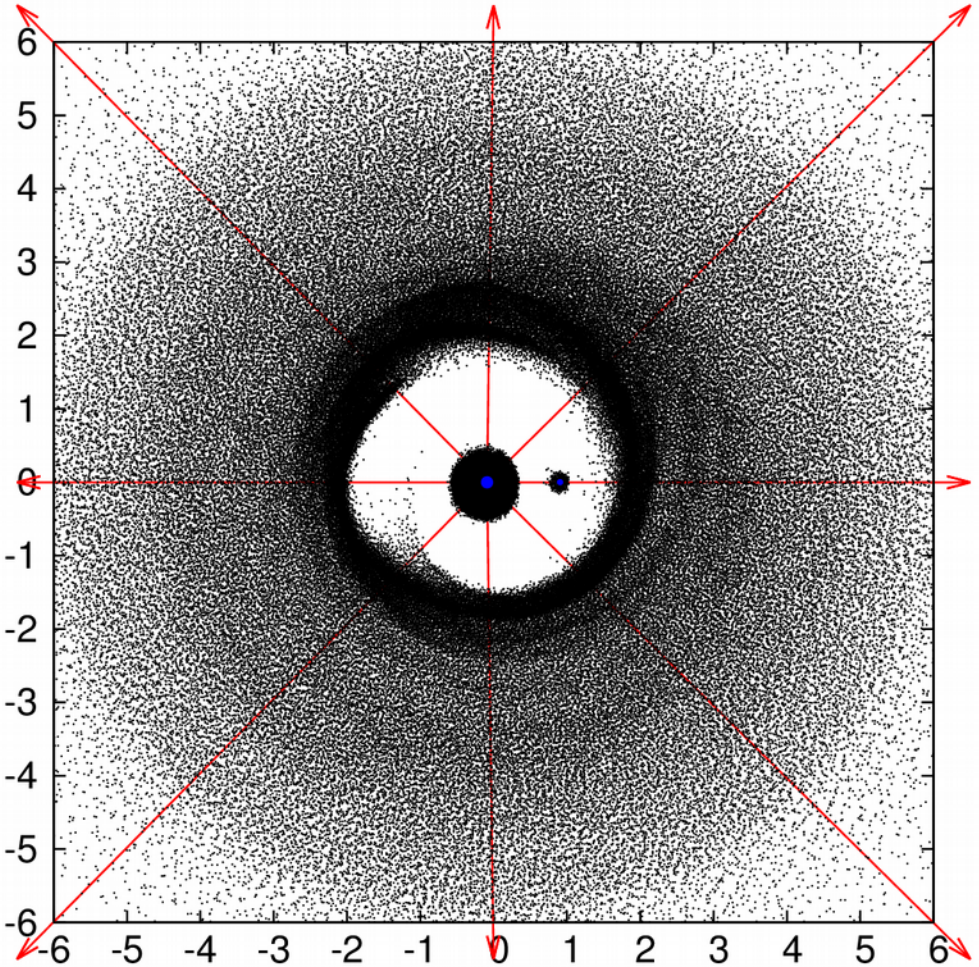


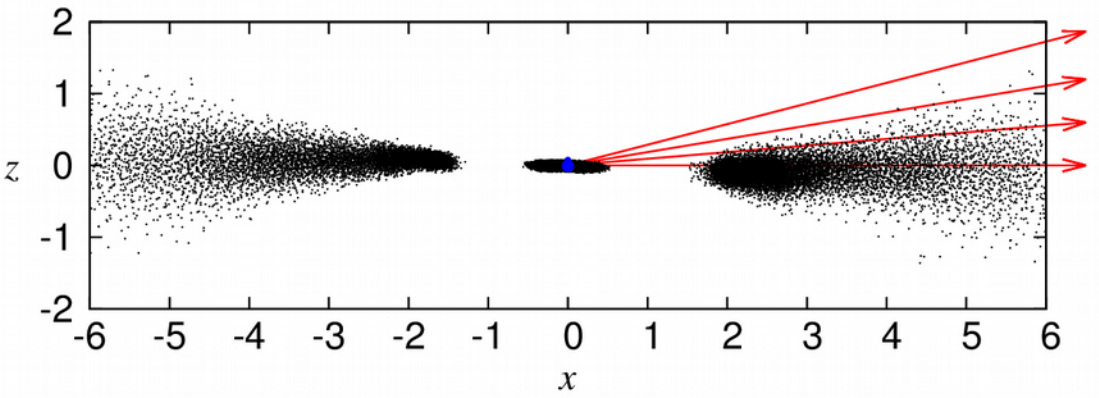


Previous paper: Larwood and Papaloizou (1997) explained the tilt of the inner part in β Pic disk.

The calculation of the column density

Sotnikova & Grinin (2007); Demidova et al. (2010); Grinin et al. (2010)

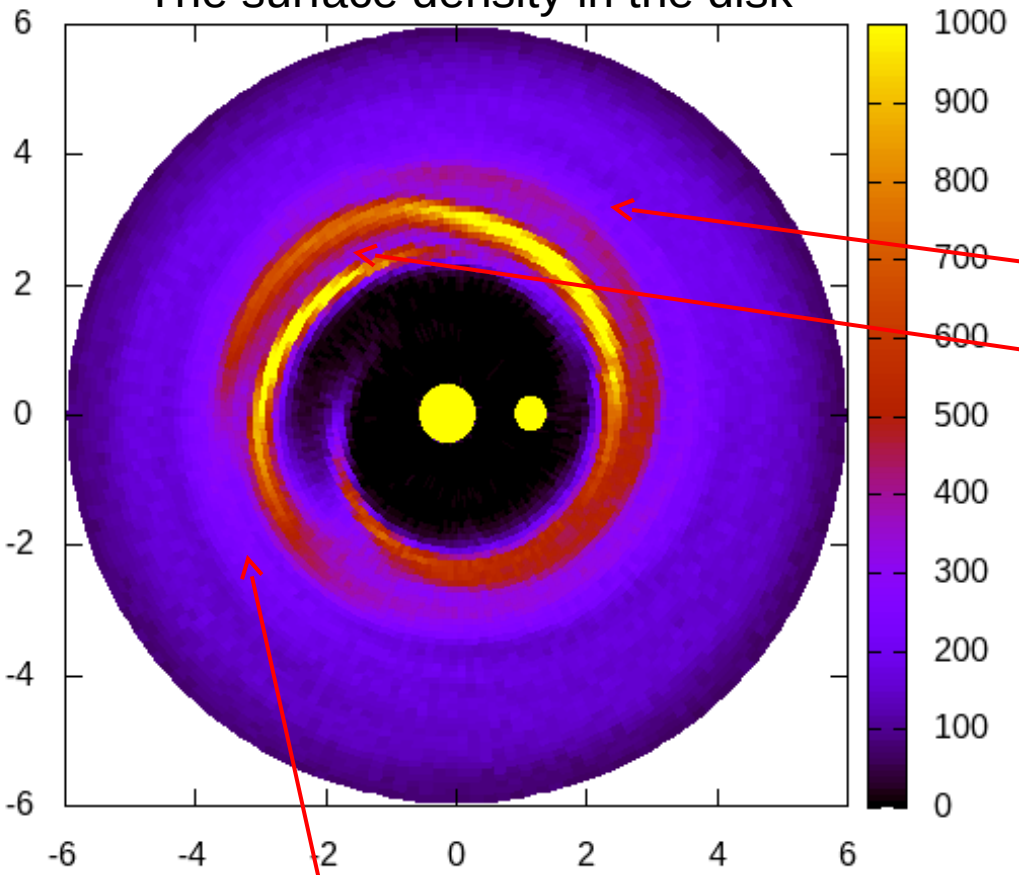




Azimuth angle of the line of sight from x axis with a step 45°.
The inclination — from disk plane with a step 5°.

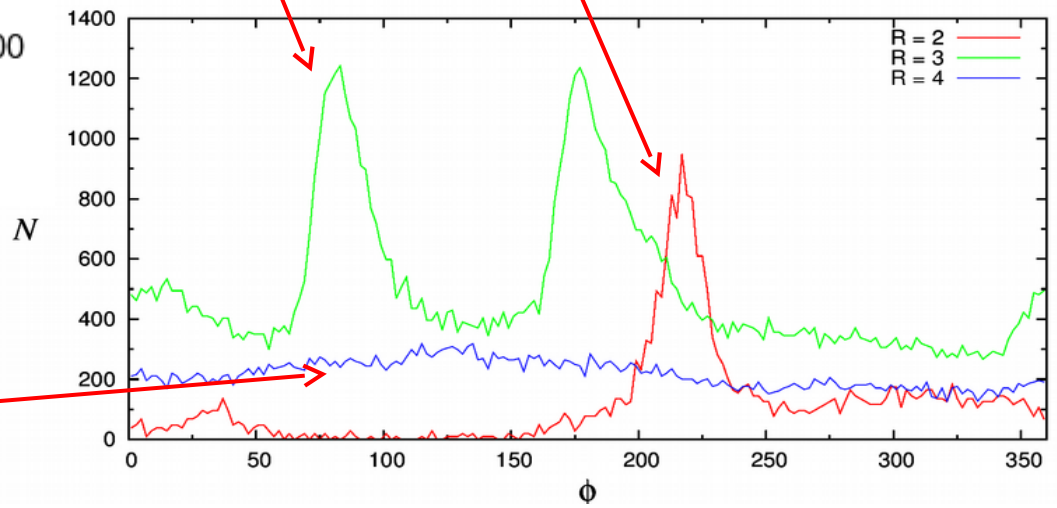
The structures in the common disk

The surface density in the disk



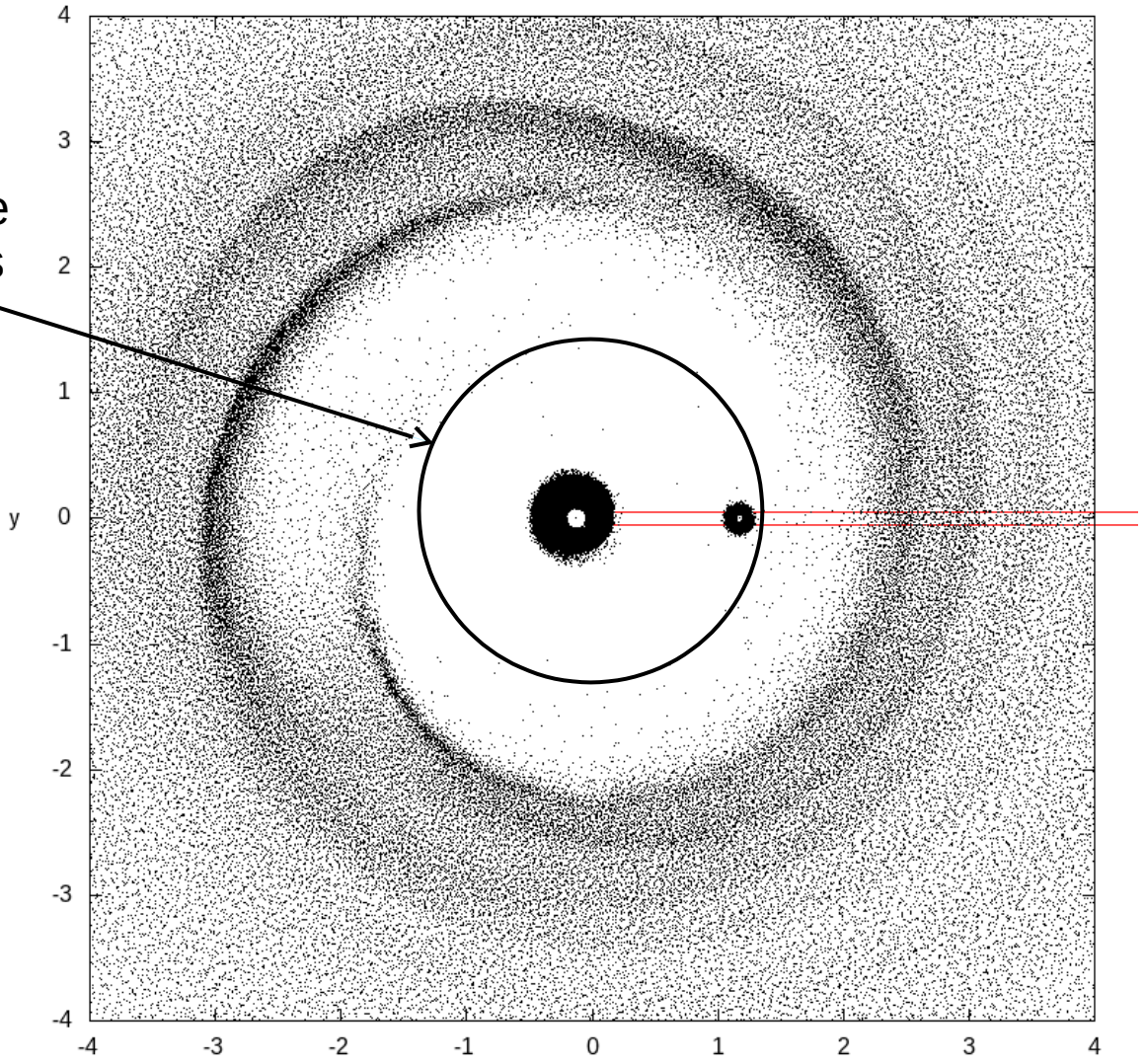
The spiral structures in the inner part of the common disk

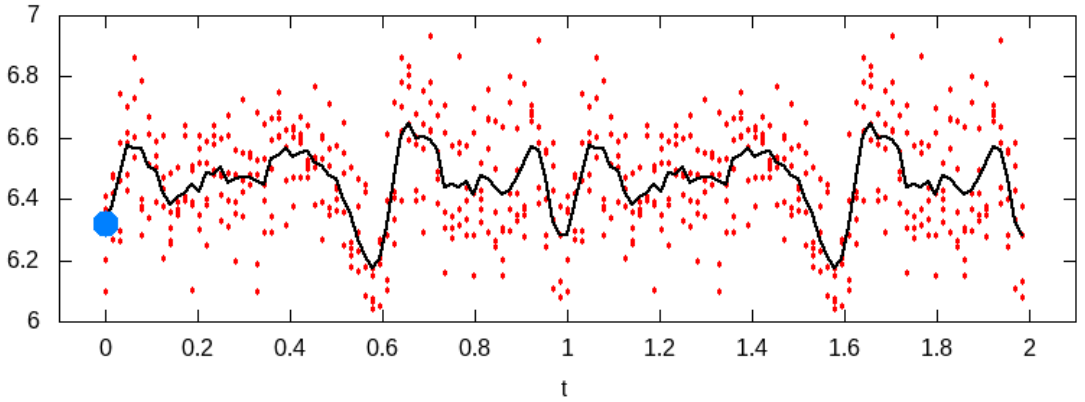
The homogeneous periphery of the common disk



The surface density at the fixed radius in dependence of the azimuth angle

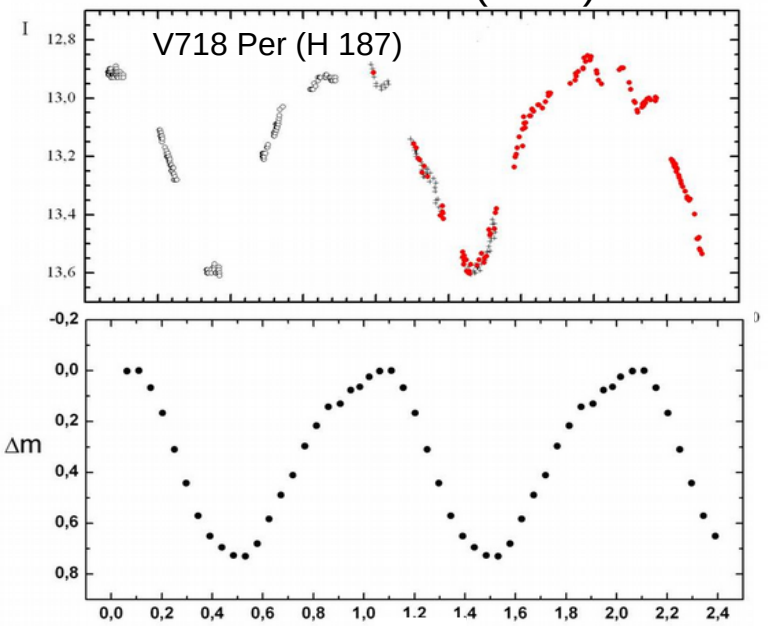
The circumstellar and companion disk inside the sublimation radios of dust



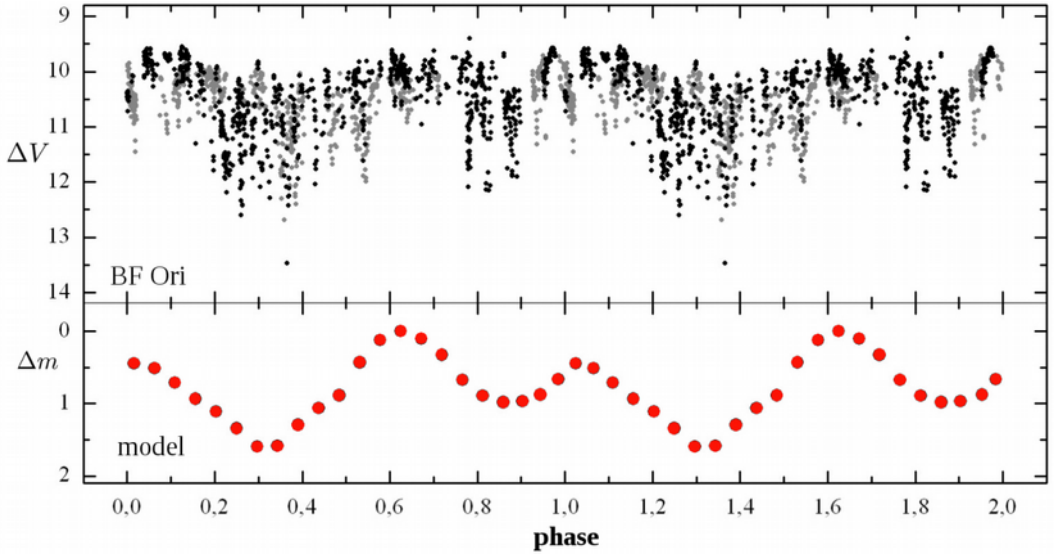


Results

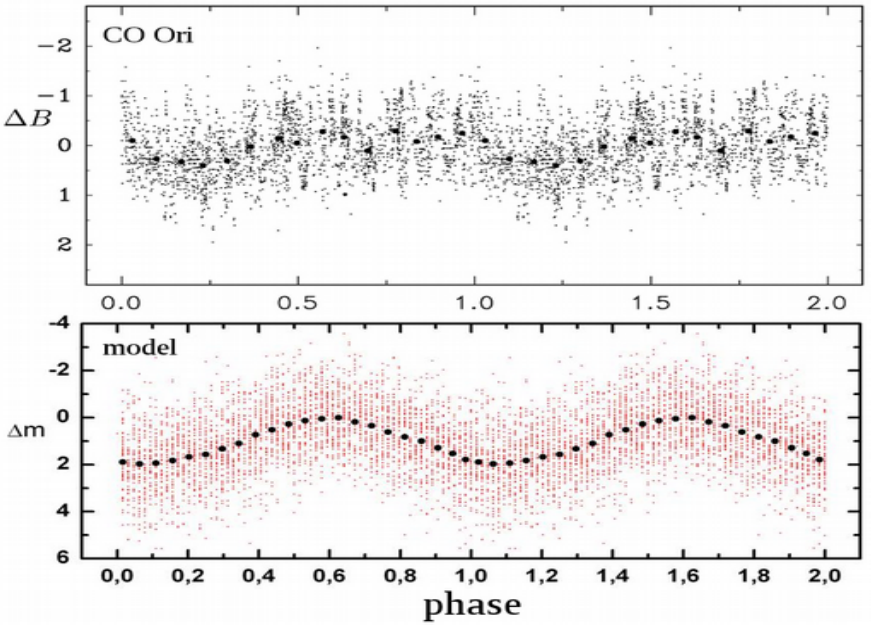
Grinin et al. (2008)



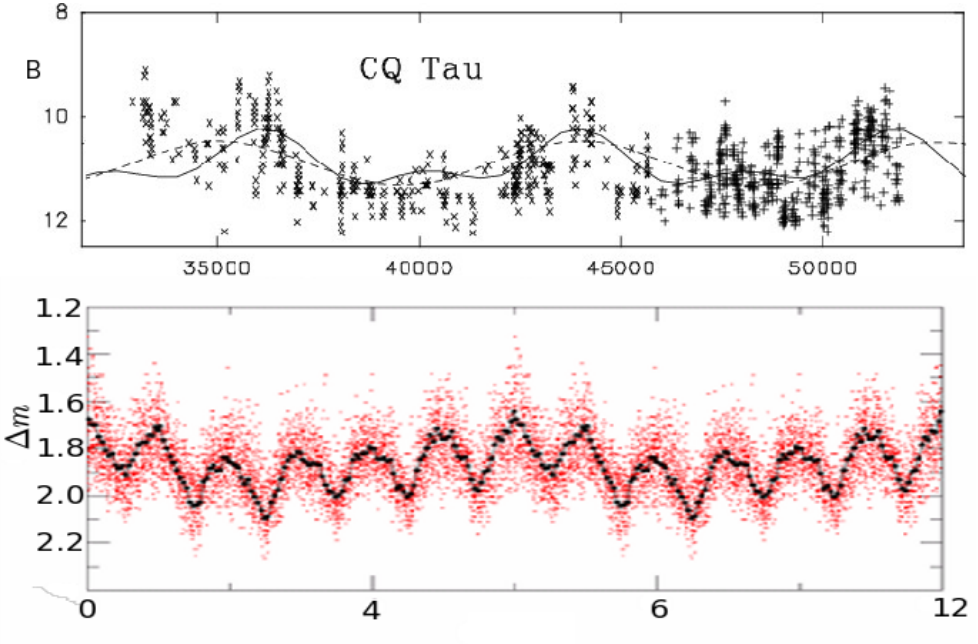
Grinin et al. (2010); Demidova et al. (2010)



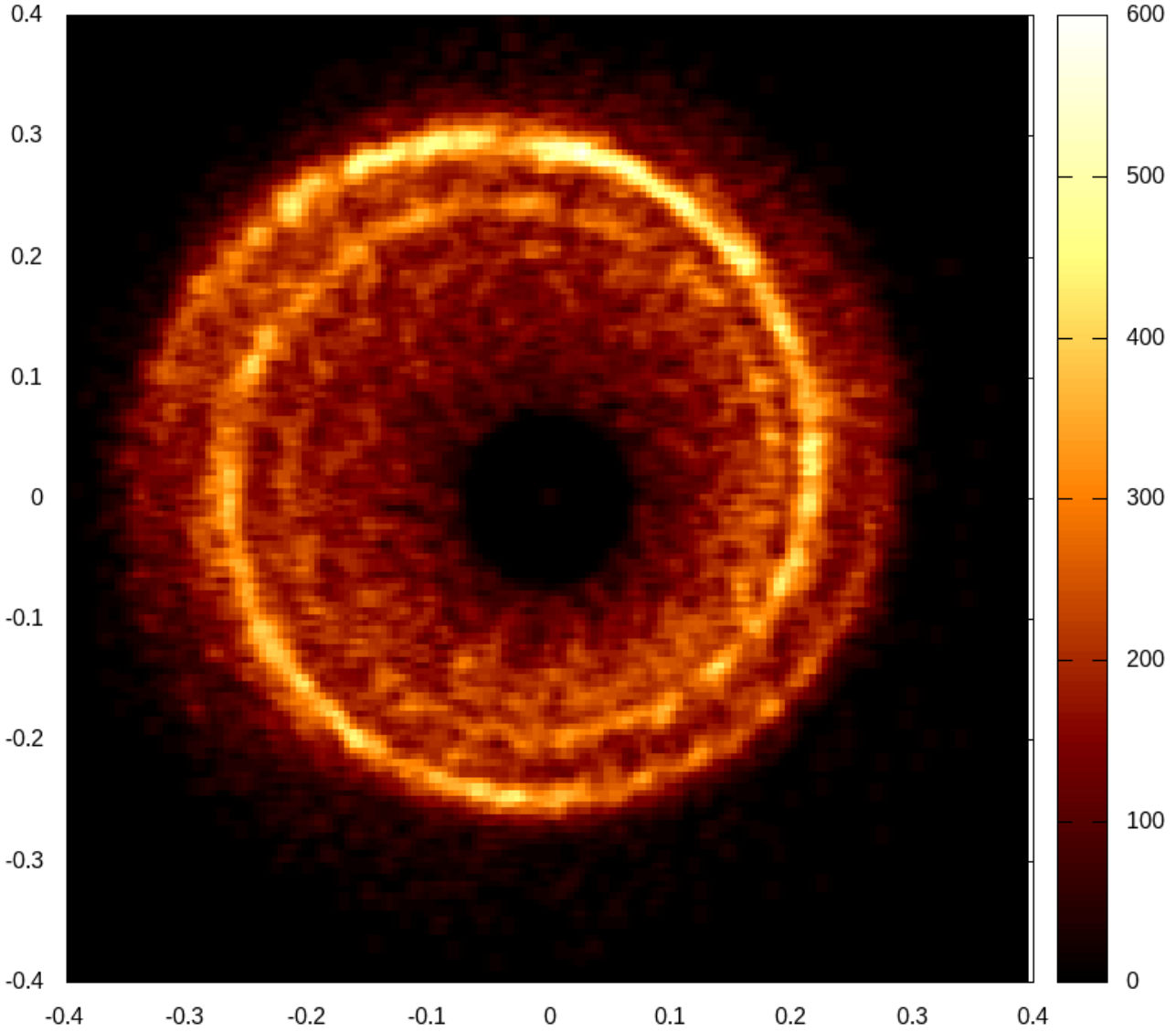
Rostopchina et al. (2006); Demidova et al. (2010)



Shahkovskoi et al. (2005); Demidova et al. (2010)



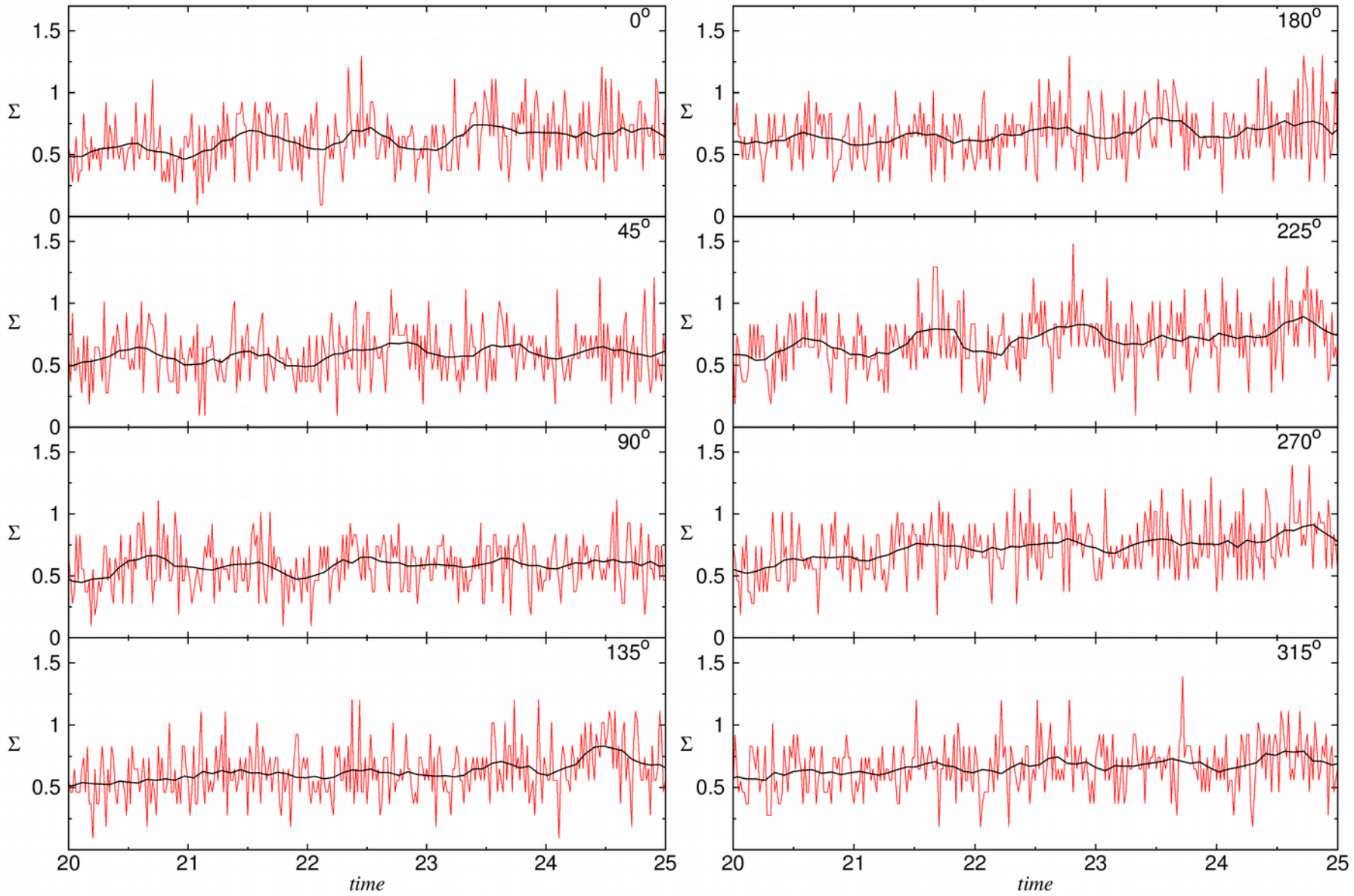
The density waves in the circumstellar disk
(model q = 0.1, e = 0.3, i = 5°):



Two spiral arms arise when the companion pass by the pericenter and its disappear after the companion pass by the apocenter.
Similar results: Nelson (2000); Kley & Nelson (2008)

The column density in the circumstellar disk

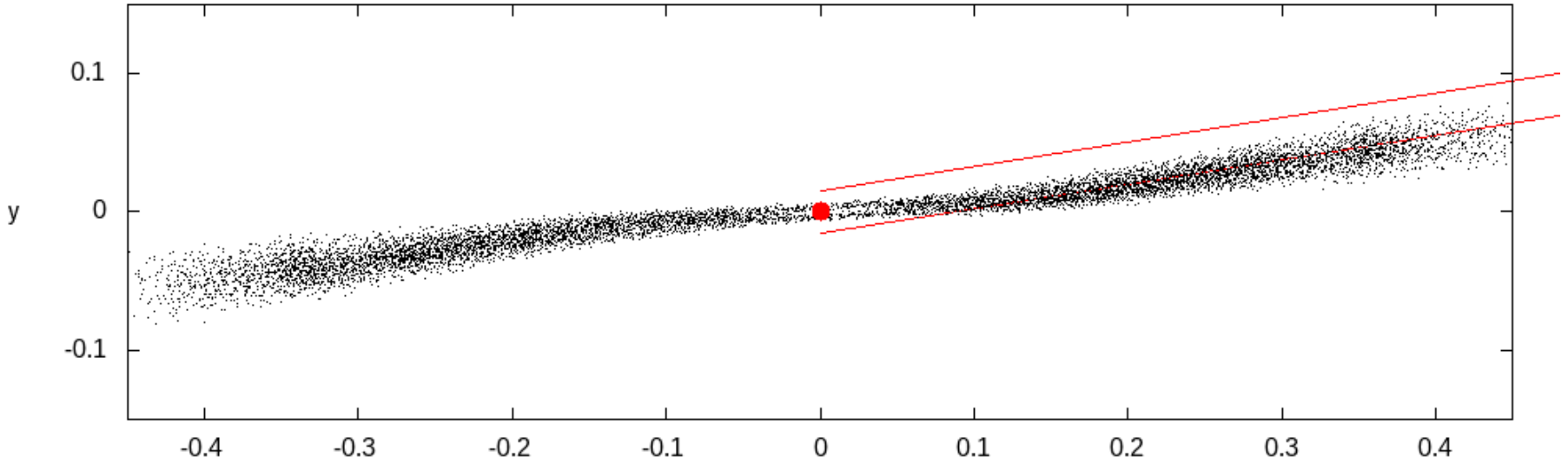
(model q = 0.1, e = 0.3, i = 0°, θ = 10°):

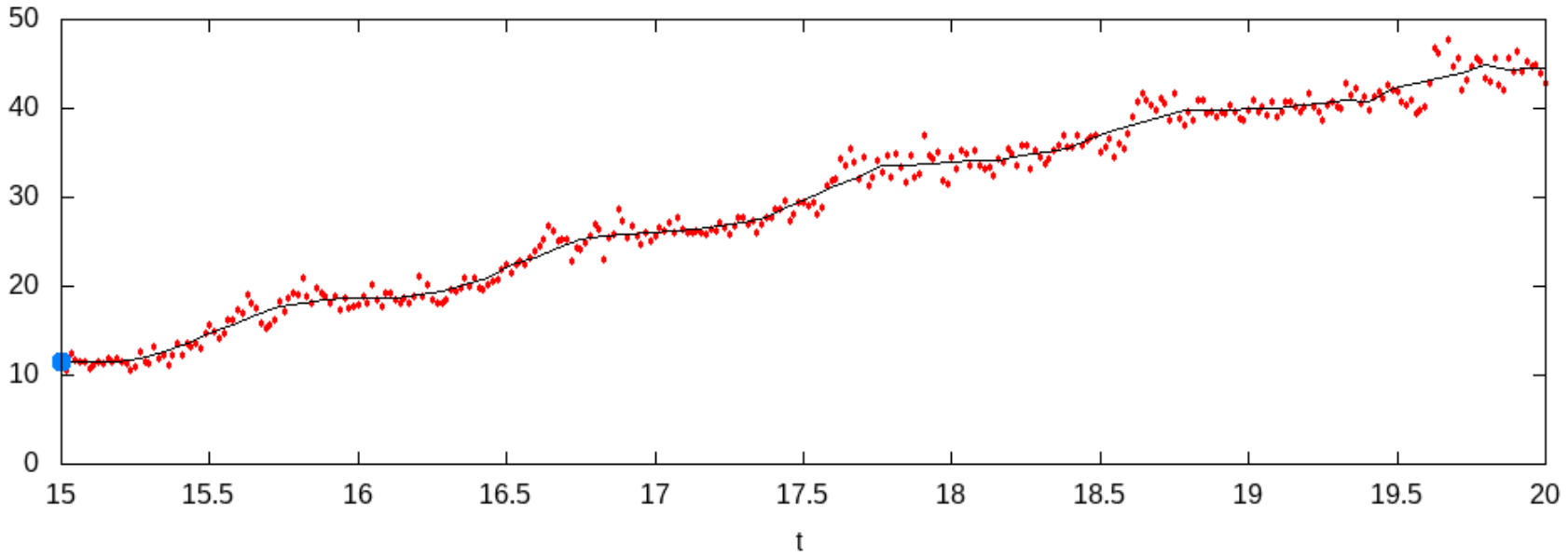


10° is the maximum inclination where the noticeable number of particles lies on the line of sight for the model with the companion orbit coplanar to the disk plane.

The precession of the circumstellar disk

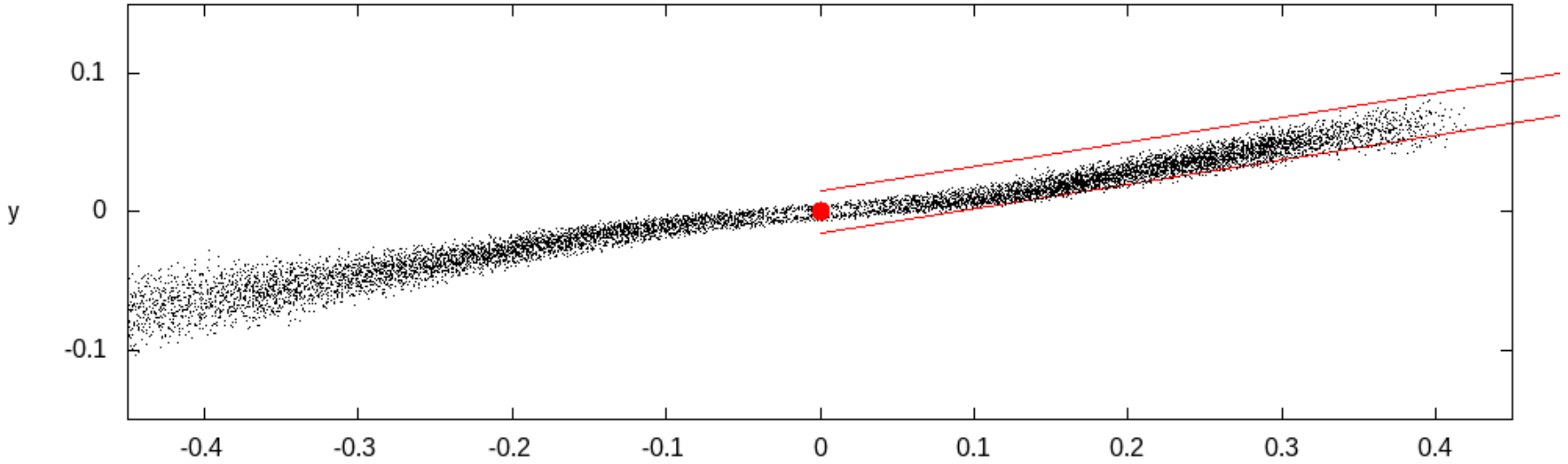
(model q = 0.1, e = 0.3, i = 5°,φ = 0°, θ = 10°):

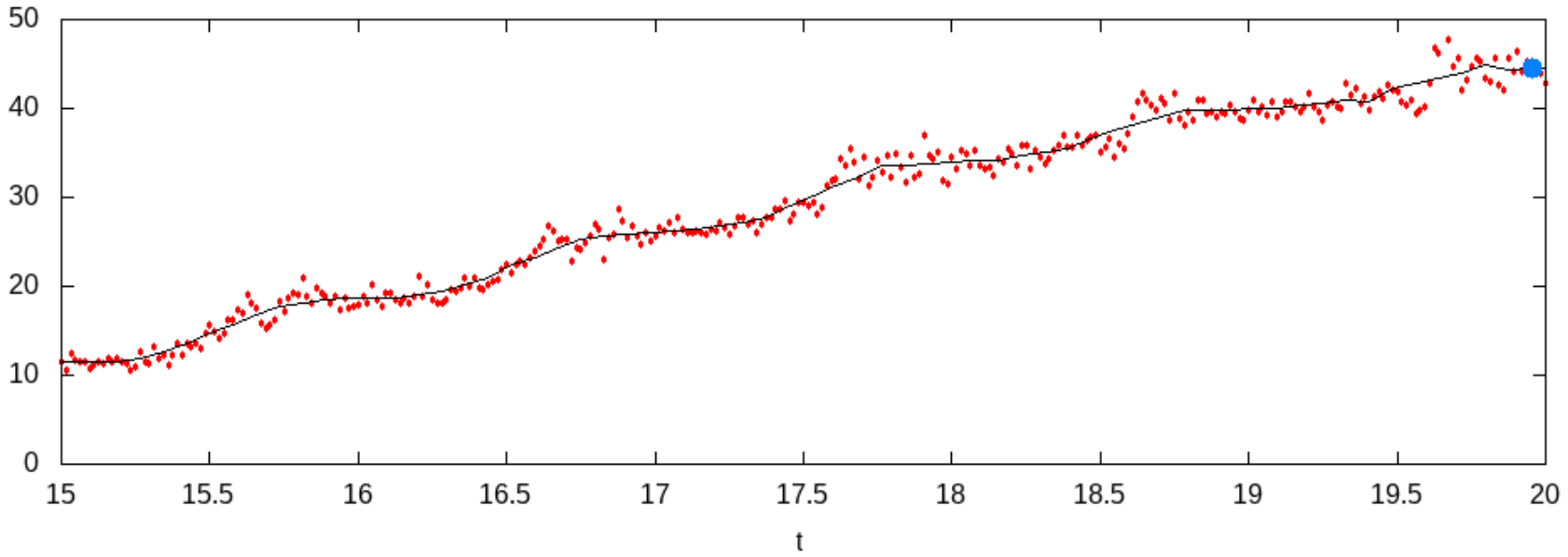




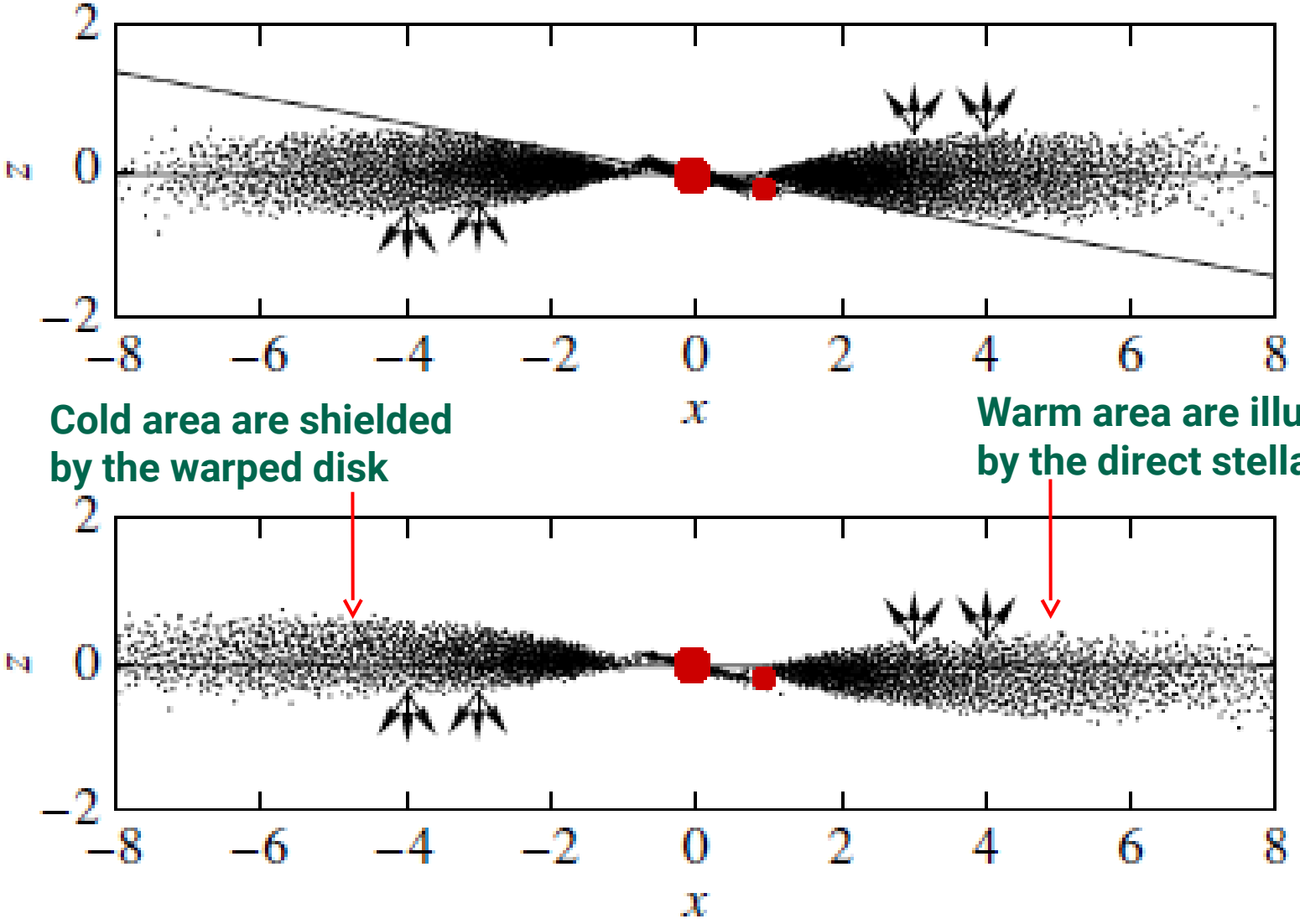
The precession of the circumstellar disk

(model q = 0.1, e = 0.3, i = 5°,φ = 0°, θ = 10°):

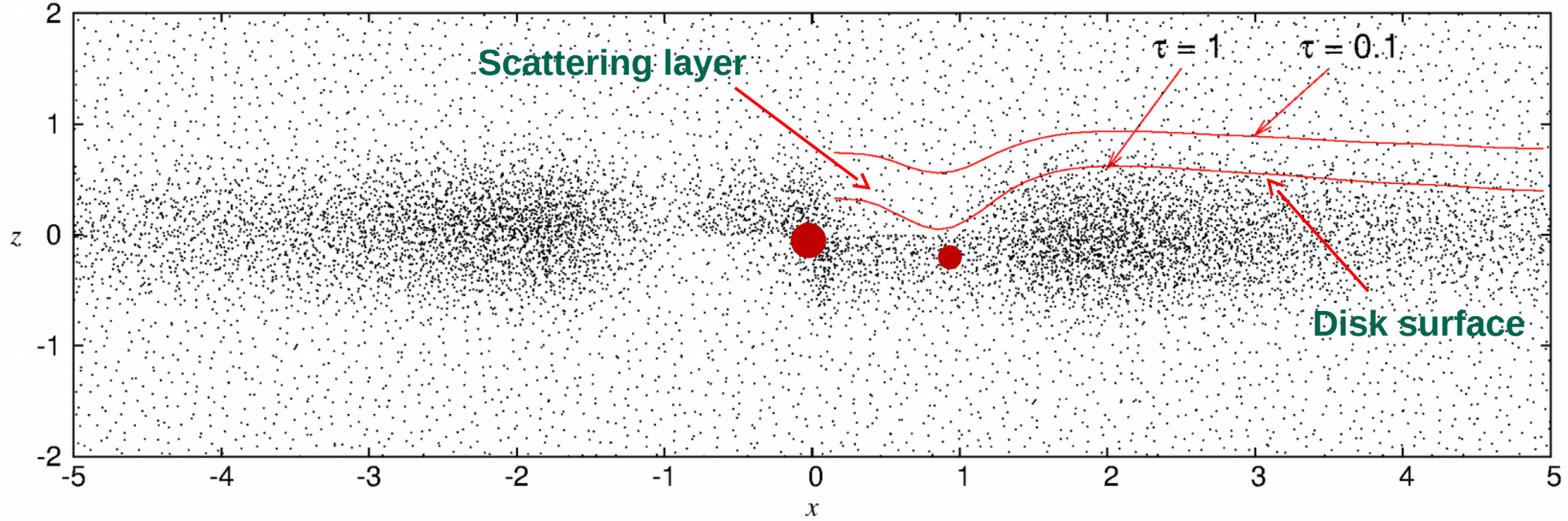




The idea about asymmetric illumination of the outer part disk: Demidova et al. (2013); Demidova & Grinin (2014)



The disk surface definition



Vertical density distribution

$$\rho_z = \rho_0 \cdot e^{-z^2/h^2}$$

Surface density

$$\Sigma_z = \int_z^\infty \rho_z dz$$

Optical depth

$$\tau = \Sigma_z \cdot \kappa$$

k – Opacity

Natta & Whitney (2000)

The calculation of the disks images

Tambovtseva et al. (2006); Demidova & Grinin (2014)

Direct radiation

$$F_s(r', \phi', z') = \frac{L_* e^{-\tau(r', \phi', z')}}{4\pi(r'^2 + z'^2)}$$

Scattered light

$$F_{sc}(r, \phi, z_1) = k_{sc} \int_0^{2\pi} d\phi' \int_{r_s}^{5a} r' dr' \int_{z_1}^{z_2} \frac{F_s(r', \phi', z')}{4\pi |\vec{\mathrm{d}}|^2} \rho(r', \phi', z')\, f(\theta)\, e^{-\tau(r', \phi', z', r, \phi, z_1)} \cos\xi\, dz'$$

Temperature

$$T = \sqrt[4]{F/\sigma}$$

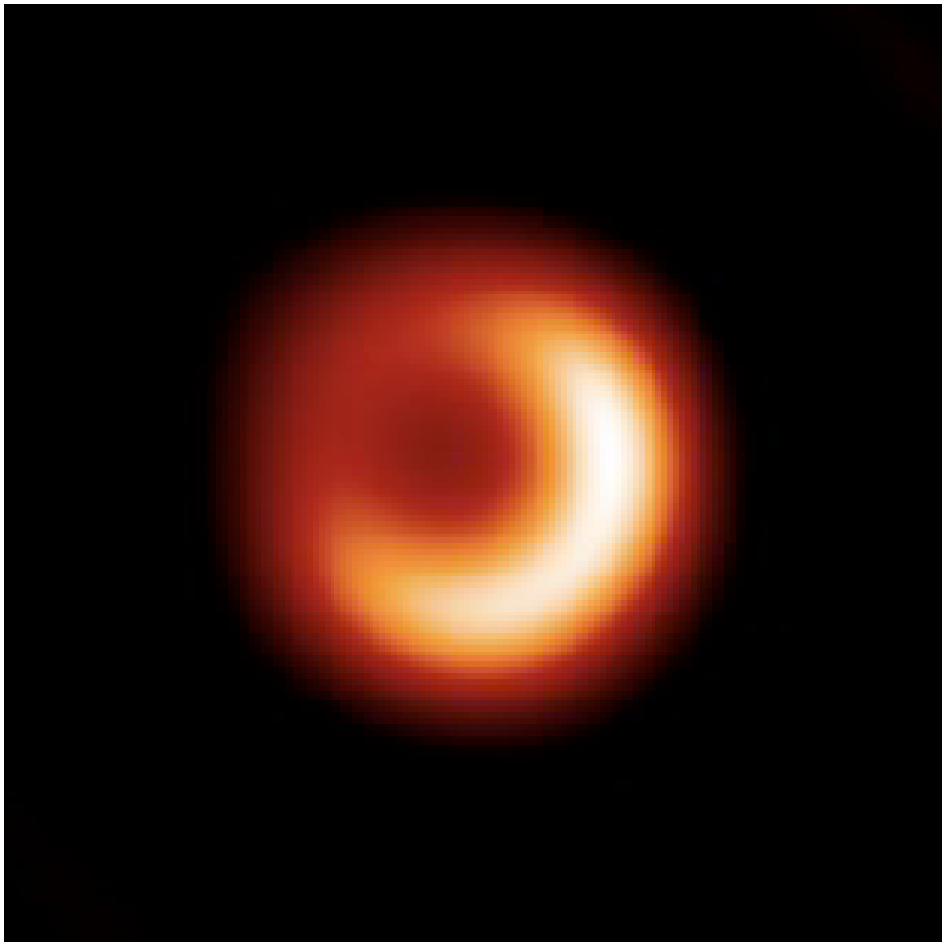
Luminosity

$$L_\lambda = \sum_\lambda B_\lambda(T) \cdot g_\lambda$$

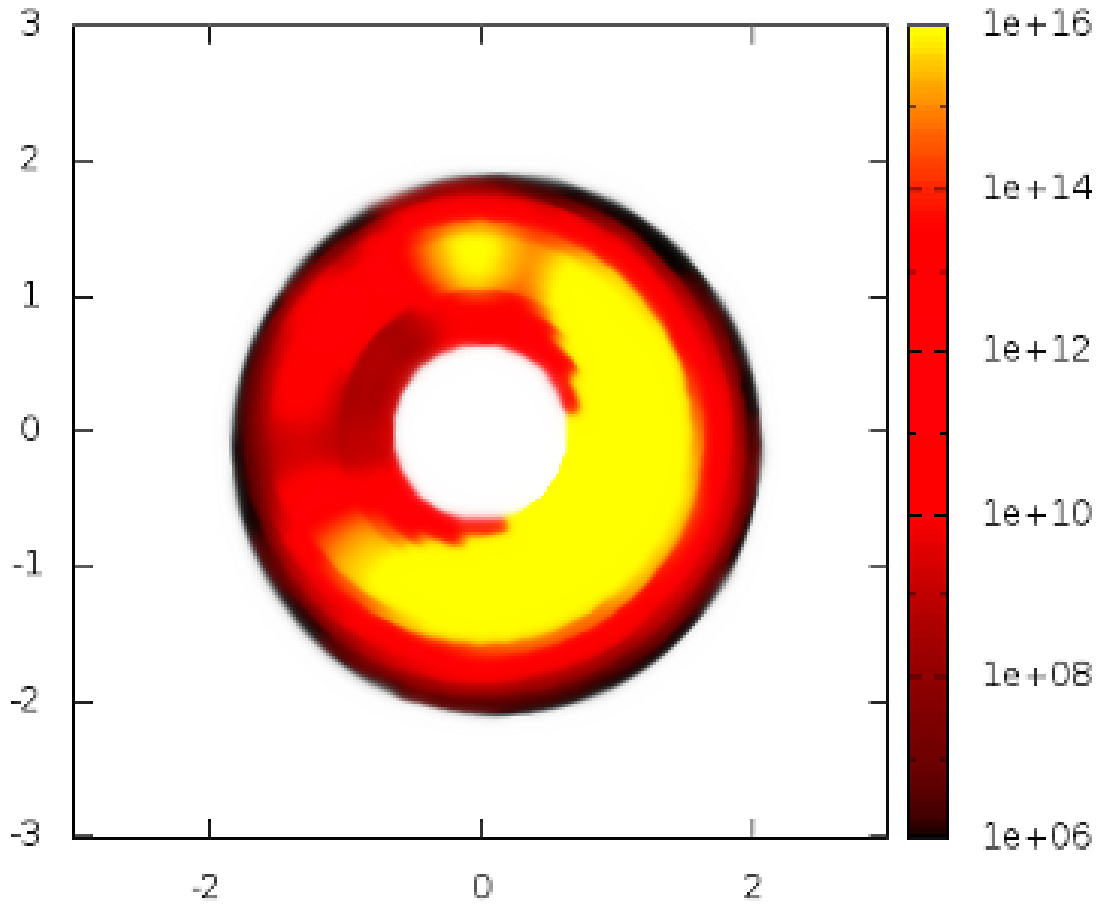
$LkH\alpha 101$

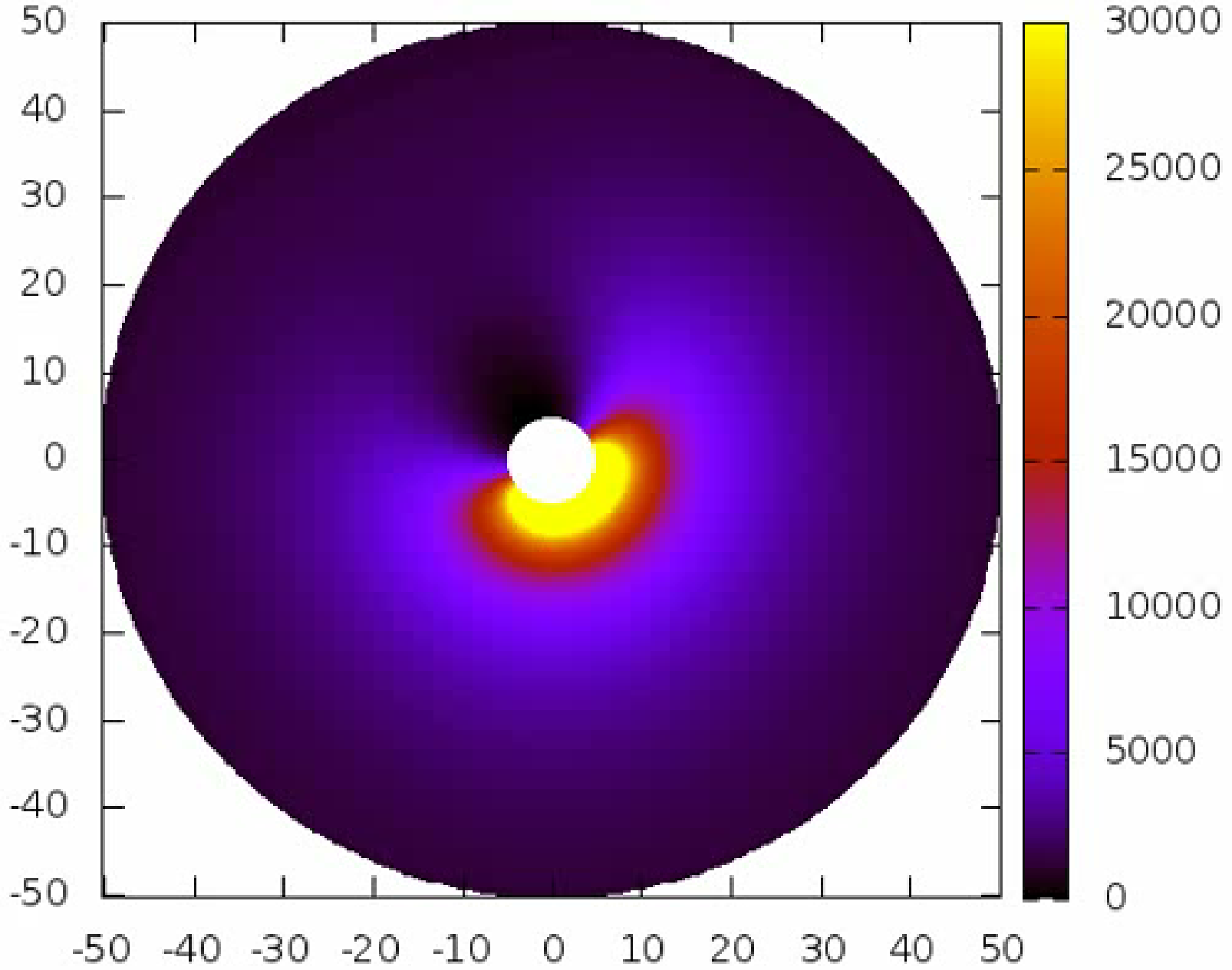
$$L_* = 1300 L_\odot$$

Tuthill et al. (2002)



Demidova et al. (2014)

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-50 -40 -30 -20 -10 0 10 20 30 40 50
30000
25000
20000
15000
10000
5000
0

Collaboration with S.Wolf group

Method – the Monte Carlo-based full 3D continuum radiative transfer code MC3D (Wolf 2003; Wolf et al. 1999).

Dust – spherical dust grains: 62.5% silicate, 37.5% graphite
density of dust: $\rho_d = 2.7\, g/cm^3$
dust grain size distribution: $n(a) \propto a^{-2.5}$
$a \in [\,0.005\,\mu m, 100\,\mu m]$
Ice is not considered.

Primary component

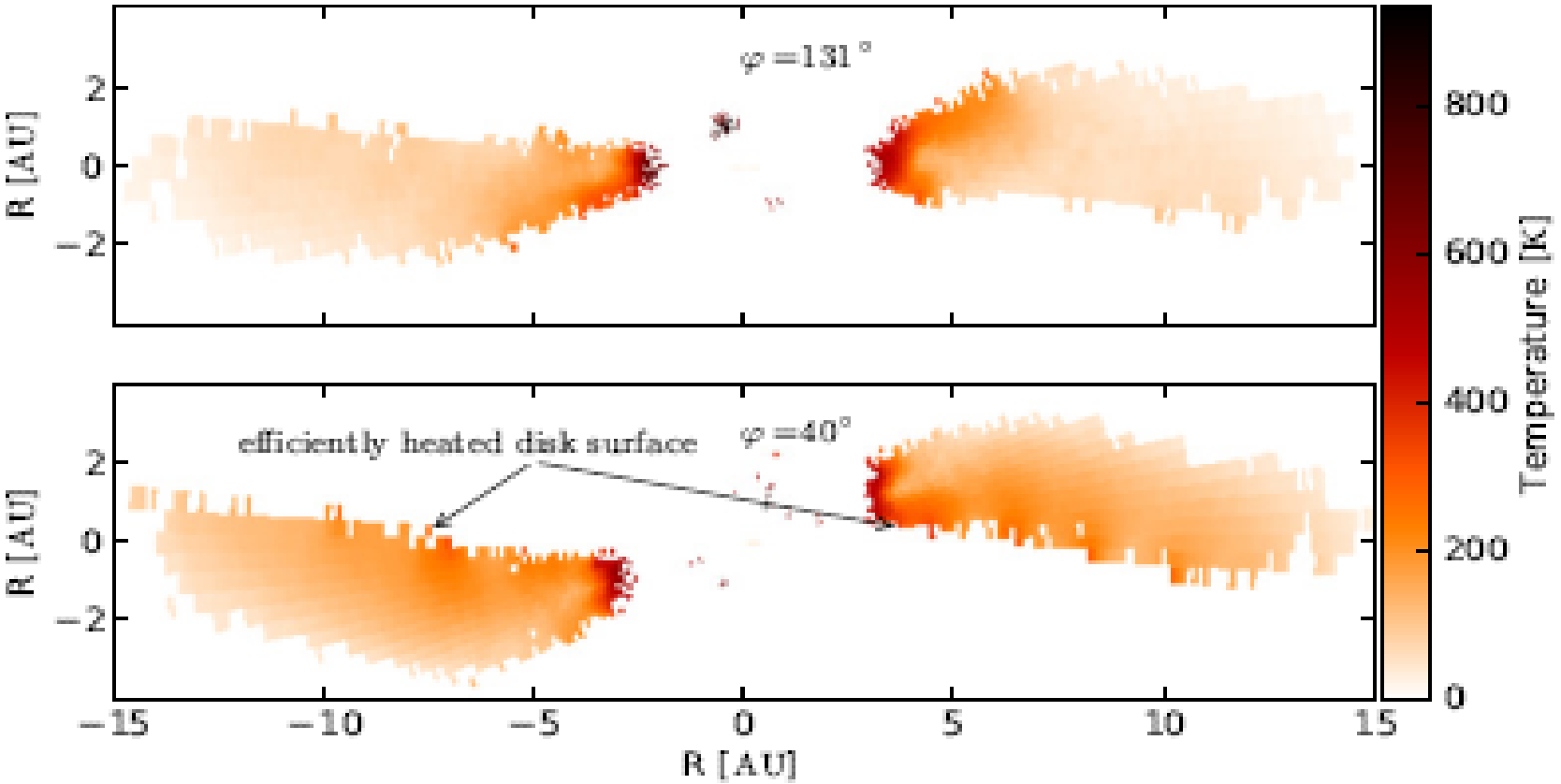
– Herbig Ae star
mass: M = 2 $M_\odot$
luminosity: L = 43 $L_\odot$
temperature: T = 9500 K

Secondary component

q	L [$L_\odot$]	T_{eff} [K]	M [$M_\odot$]
1	43	9500	2.5
0.5	0.95	4000	1.25
0.1	0.7	4000	0.25
0.01	0.003	2700	0.025

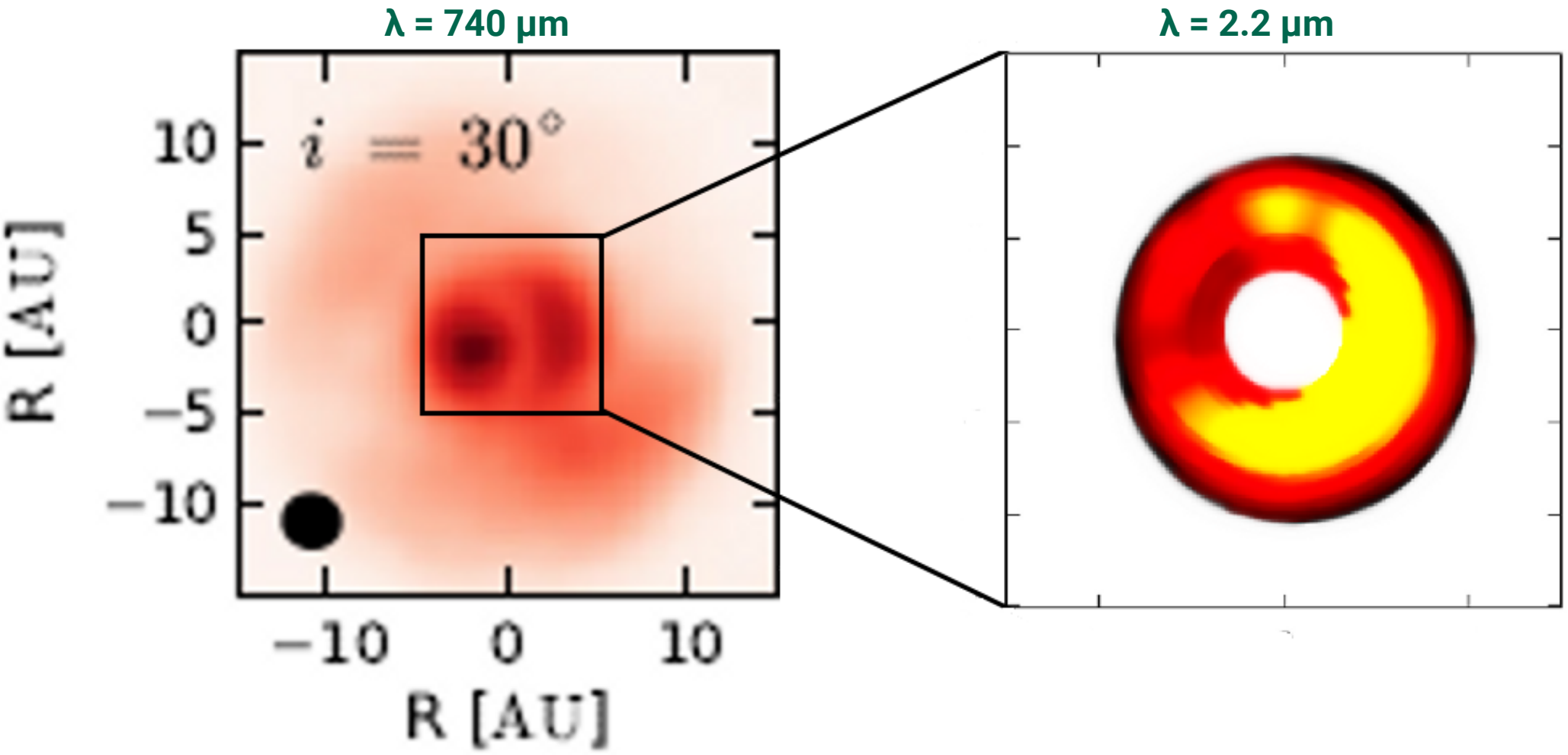
Semimajor axis of the component orbit a = 2 AU

The temperature distribution in the inclined model



Temperature maps along vertical cuts through the density distributions of the disk model with the parameters: **q = 0.1**, **i = 30°**, **e = 0**

The comparison of the images in IR and radiowaves in the inclined model: Ruge et al. 2015

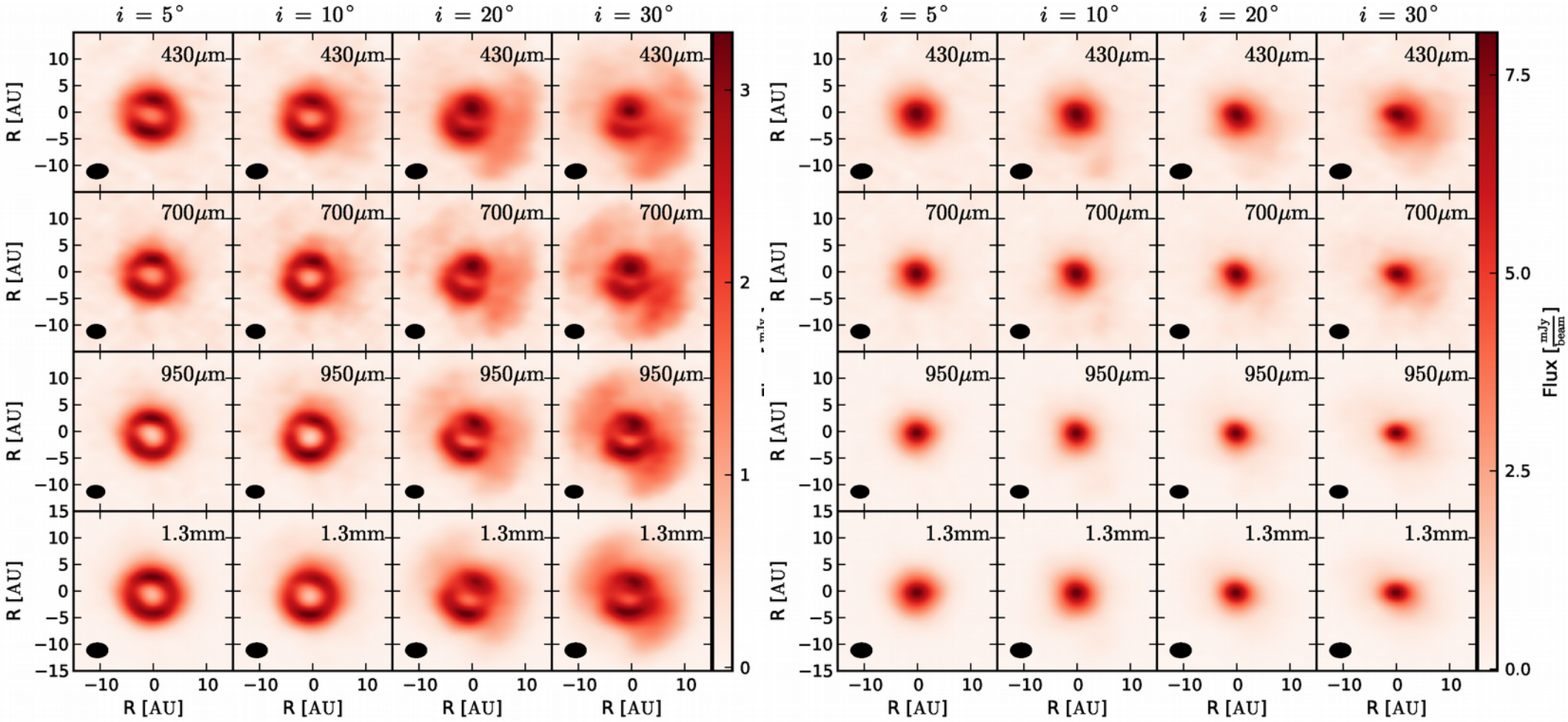


The images in IR band show the inner warm part of the disk, but the radio images can demonstrate the outer part of the disk. Disk is optically thin in radio waves and warm region shielded from an observer can shine through the disk. The “butterfly”-shaped images can be observed. Similar results: Arzamasskiy et al. (2018); Zhu (2018).

Predicted images with ALMA for the inclined models

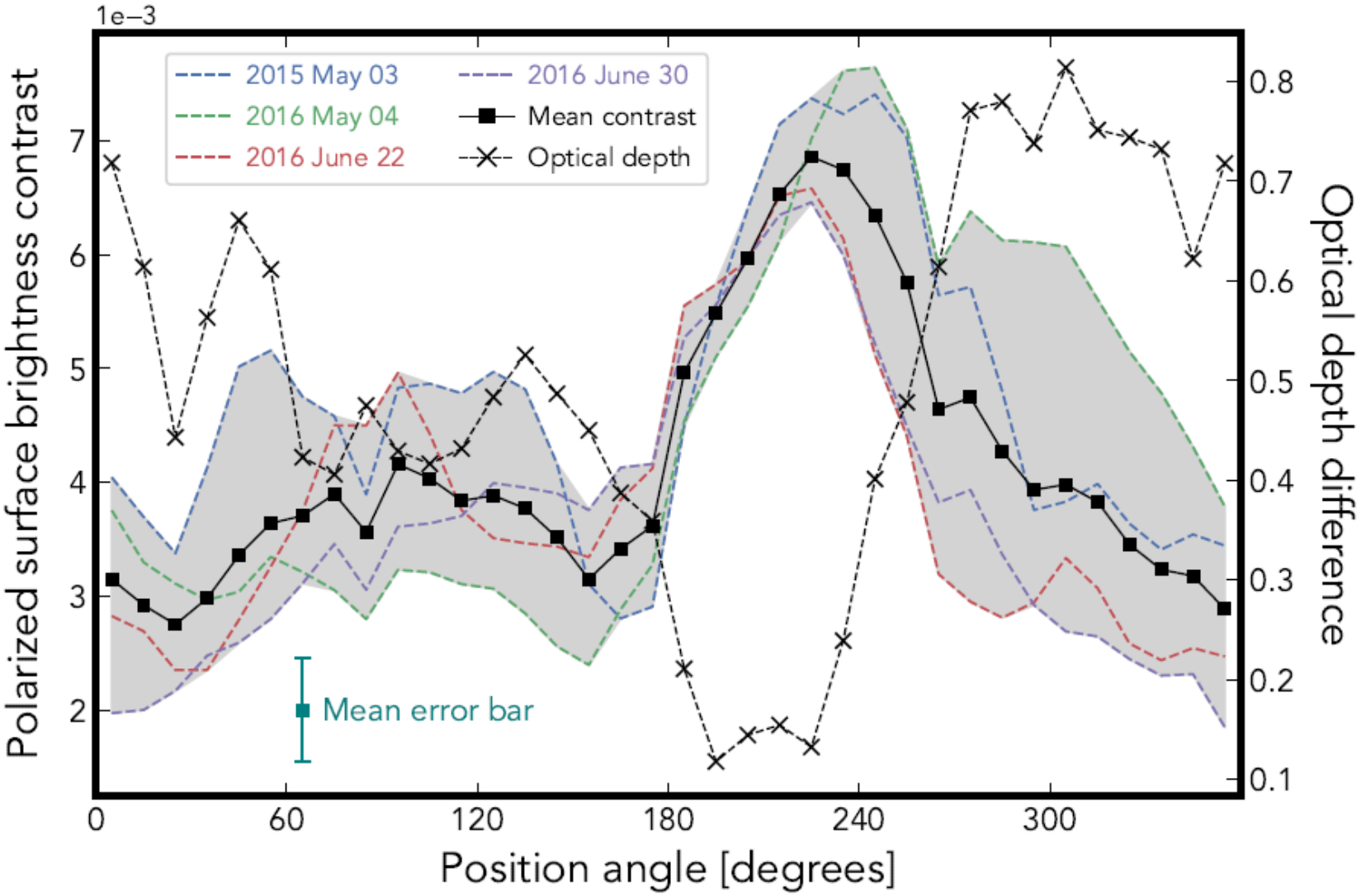
q = 0.1

q = 0.01



If **q = 0.1** the simulated observations appear as rings at low inclinations. This aspect is destroyed if **i > 10°**. If **q = 0.01** the perturbations induced by the component into the disk are not strong enough to be detected in the simulated observations.

Quasi-stationary shadow on the disk



HD 135344B, Stolker et al. (2017)

Conclusions

Signature of an invisible low-mass companion:

1) The cyclic brightness variations of UX Orion type stars;
2) Quasi-stationary shadow on the disk image;
3) “Horseshoe” asymmetry in IR and “butterfly” in a radio image of the disk.