Light curve modeling of eclipsing binary stars

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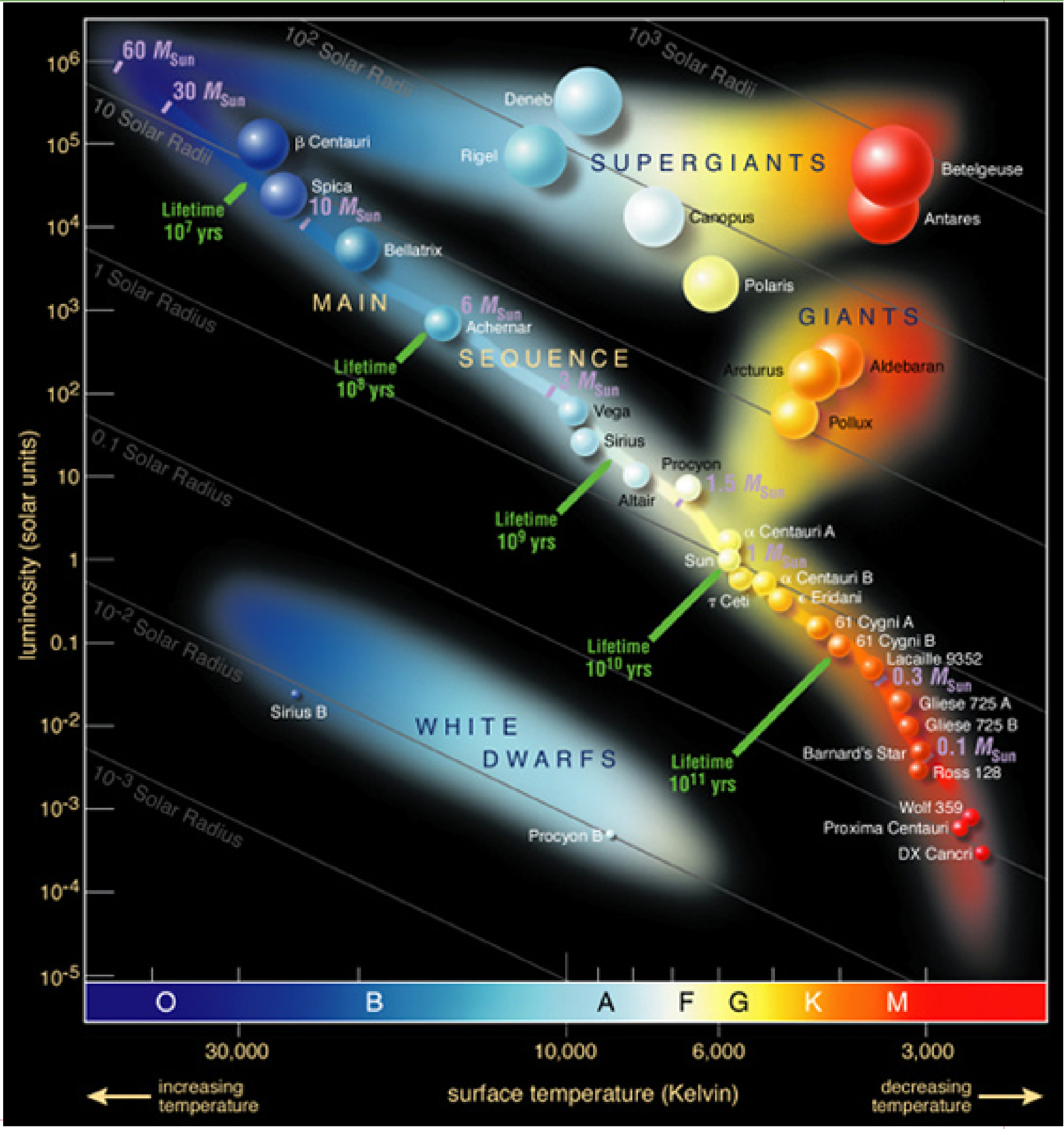
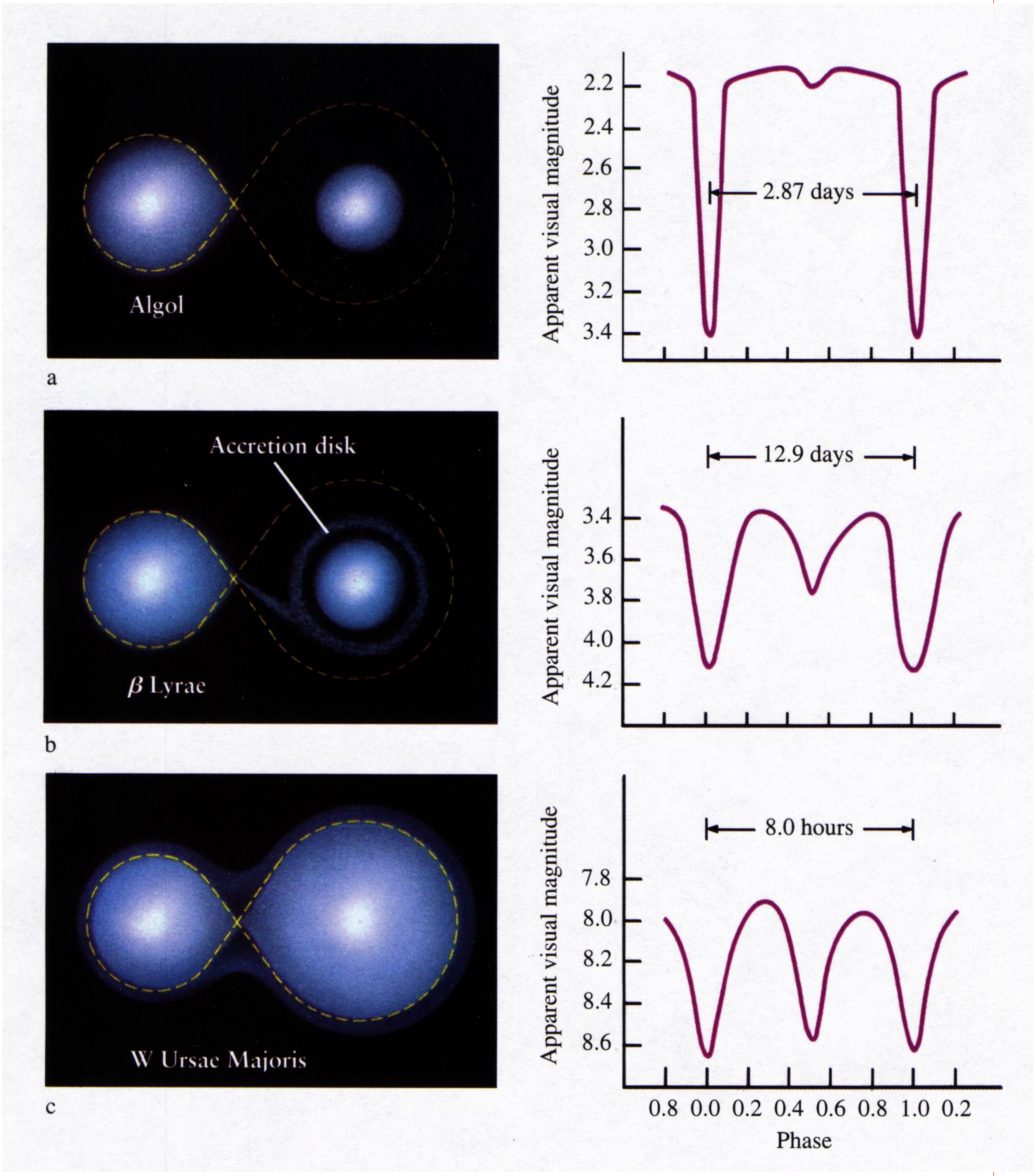
Binary stars

- physical variables
  - pulsating stars
  - mass, radius, temperature
- optical variables
  - binary stars (↔ visual binaries)
  - multiple stellar systems
  - (exoplanets)



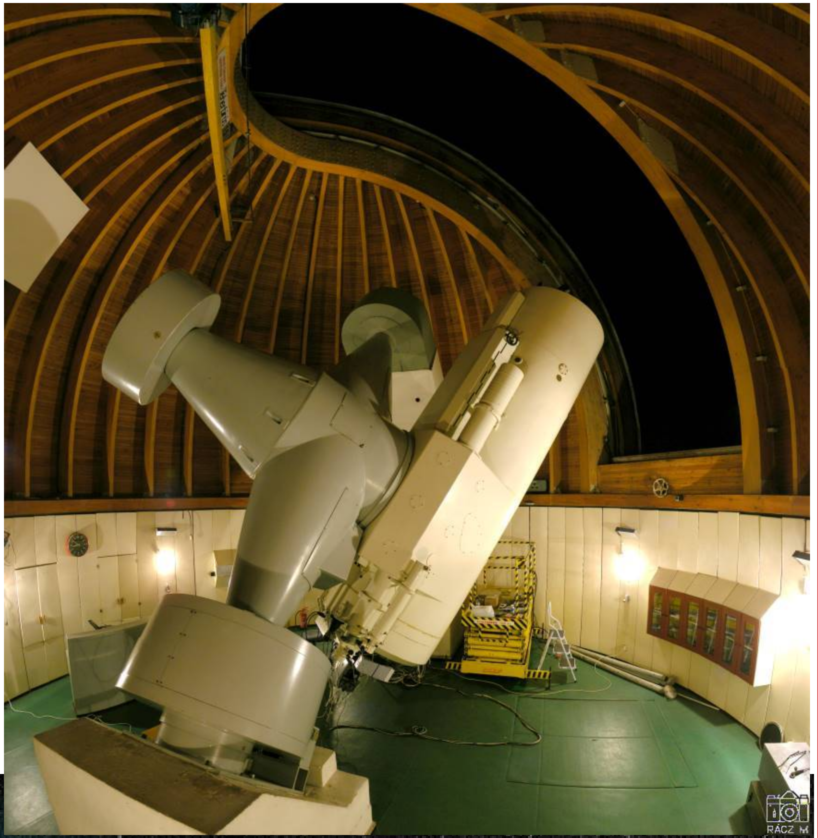
Binary stars

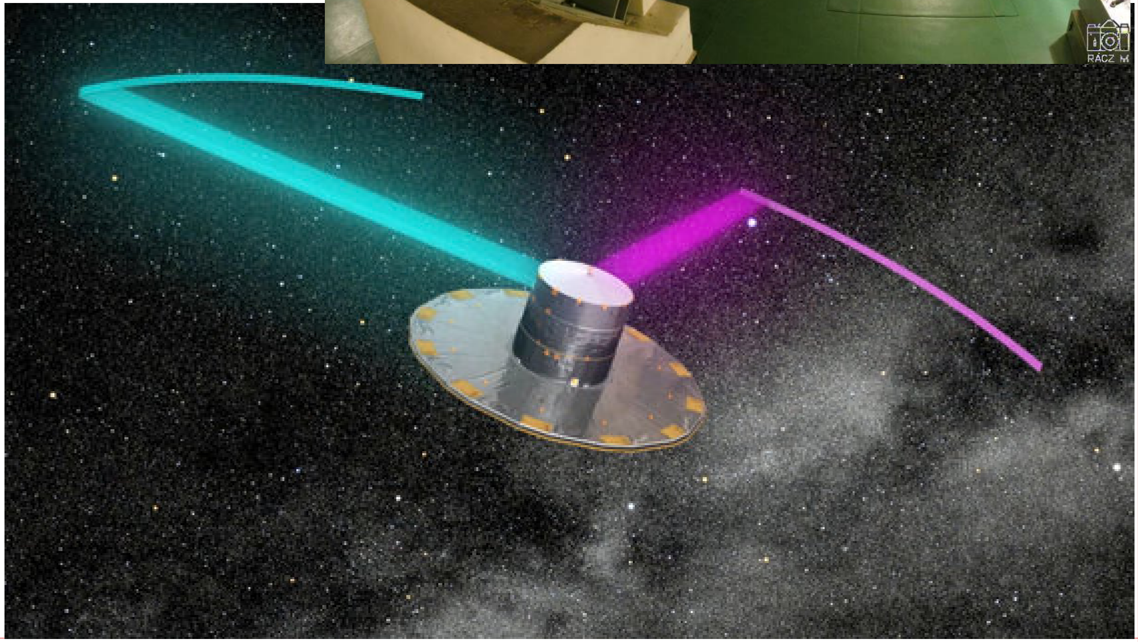
- primary
  - star, minimum
- secondary
  - star, minimum
- orbits
  - circular
  - eccentric
- distance
  - close
  - detached
  - semi-detached
- physical parameters
  - mass, radius, temperature



Observing binaries

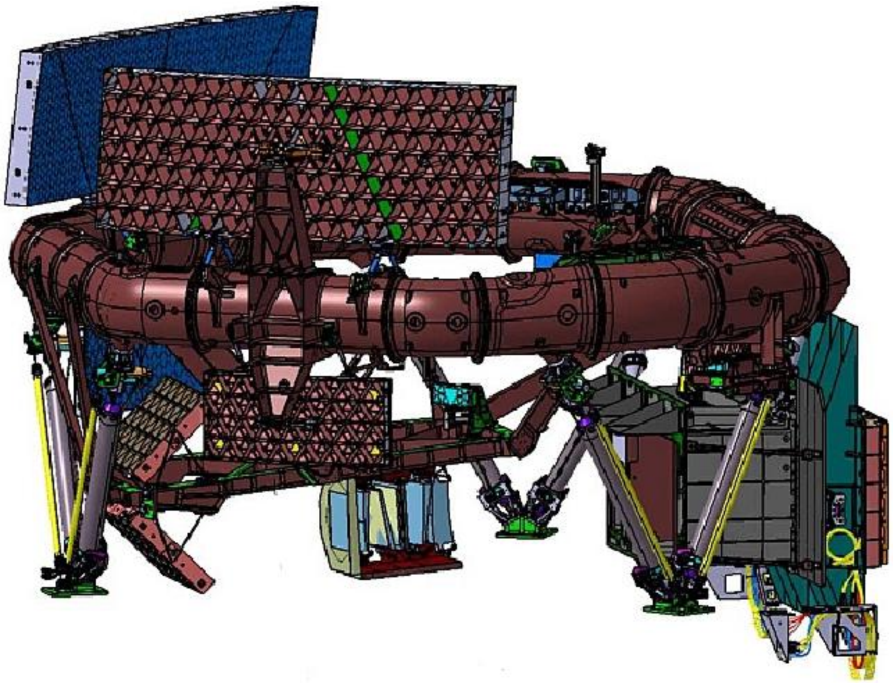
- **ground based observations**
  - **MTA CSFK KTM CSI – Piszkéstető**
  - **ELTE GAO – Szombathely**
  - **Baja Observatory – Baja**
- **space missions**
  - **GAIA (petabytes of data during 5 years operational period)**
  - **Kepler (K2)**
  - **CoRoT**





Observing and modeling binaries

- there are a lot of space missions
- there are a lot of binary and multiple system
- → we get a lot of data
- this requires automated light curve modelling and analysing packages
  - Phoebe (Wilson-Devinney code)
  - binary → multiple systems
  - paralelization (CPU, GPU).



Complex Analysis of Today's and Future Space Photometry of Multiple Stellar and Planetary Systems

- **PI: Dr. Tamás Borkovits**
  - **15 years development (binary and triple stellar systems)**
- **Dr. Emese Forgács-Dajka, senior researcher**
  - **N-body on GPU, CPU/GPU development**
- **János Sztakovics**
- **Tamás Hajdu**

Modelling binary stellar systems

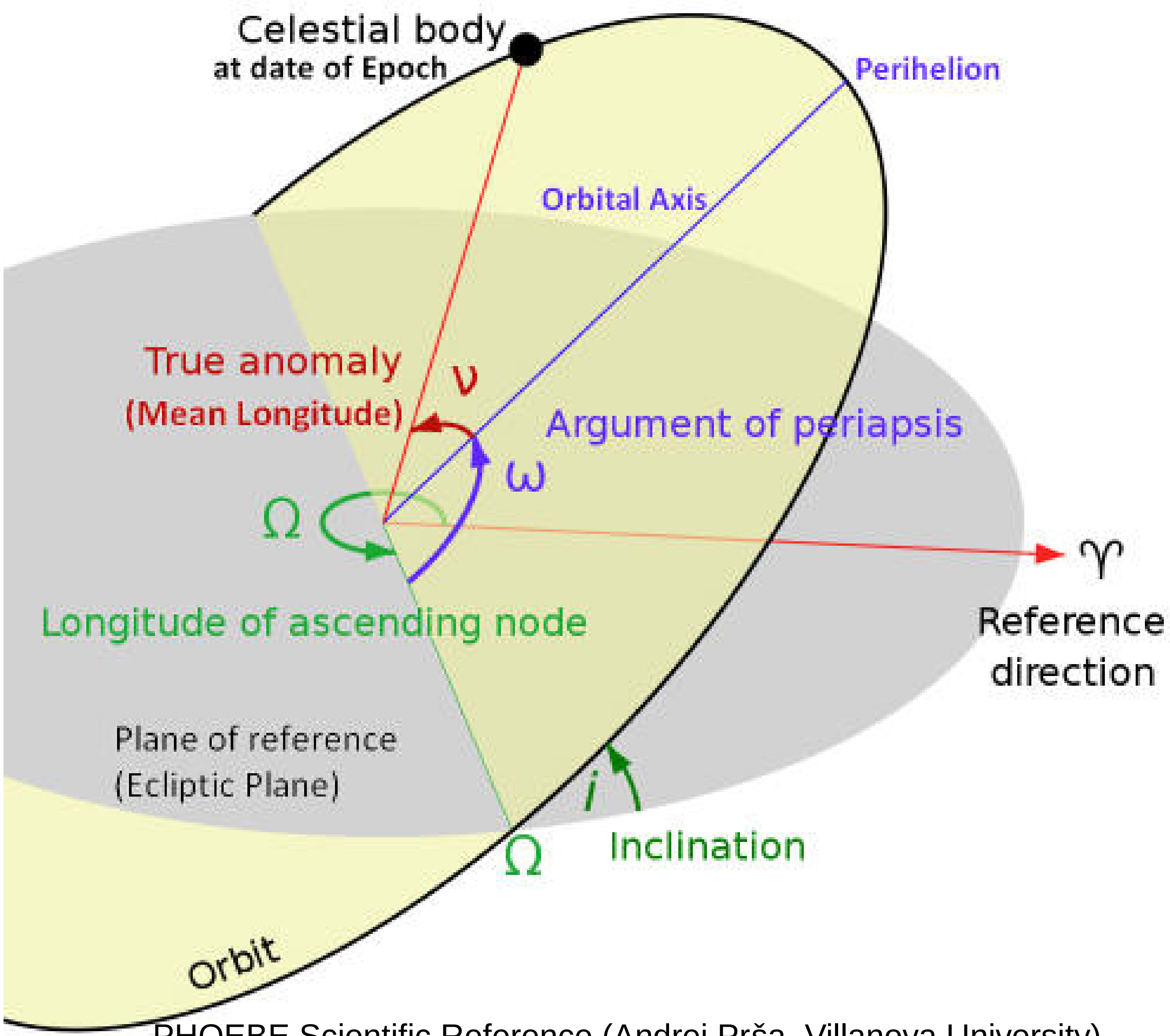
- **Now we have Tamás Borkovits's code for modelling binary and triple, hierarchical triple stellar systems and two gravitationally bound binary systems.**
  - **We would like to**
    - **refine some parts of it**
    - **change some algorithms for more accurate ones**
    - **standardize, modularize the different parts of the code for mutual interoperability**
    - **accelerate computation by means of GPU paralelization**
    - **involving multiple stellar systems and exoplanet systems also**

Modelling binary stellar systems

- Why it is useful to modelling binary and multiple stellar systems?
  - to determine the stars' physical parameters
    - masses (generally only an upper limit of them)
  - potential field → inner structure of the star
    - star evolution
  - orbital elements (like as semi-major axis) and stellar type define the habitable zone

Orbital elements

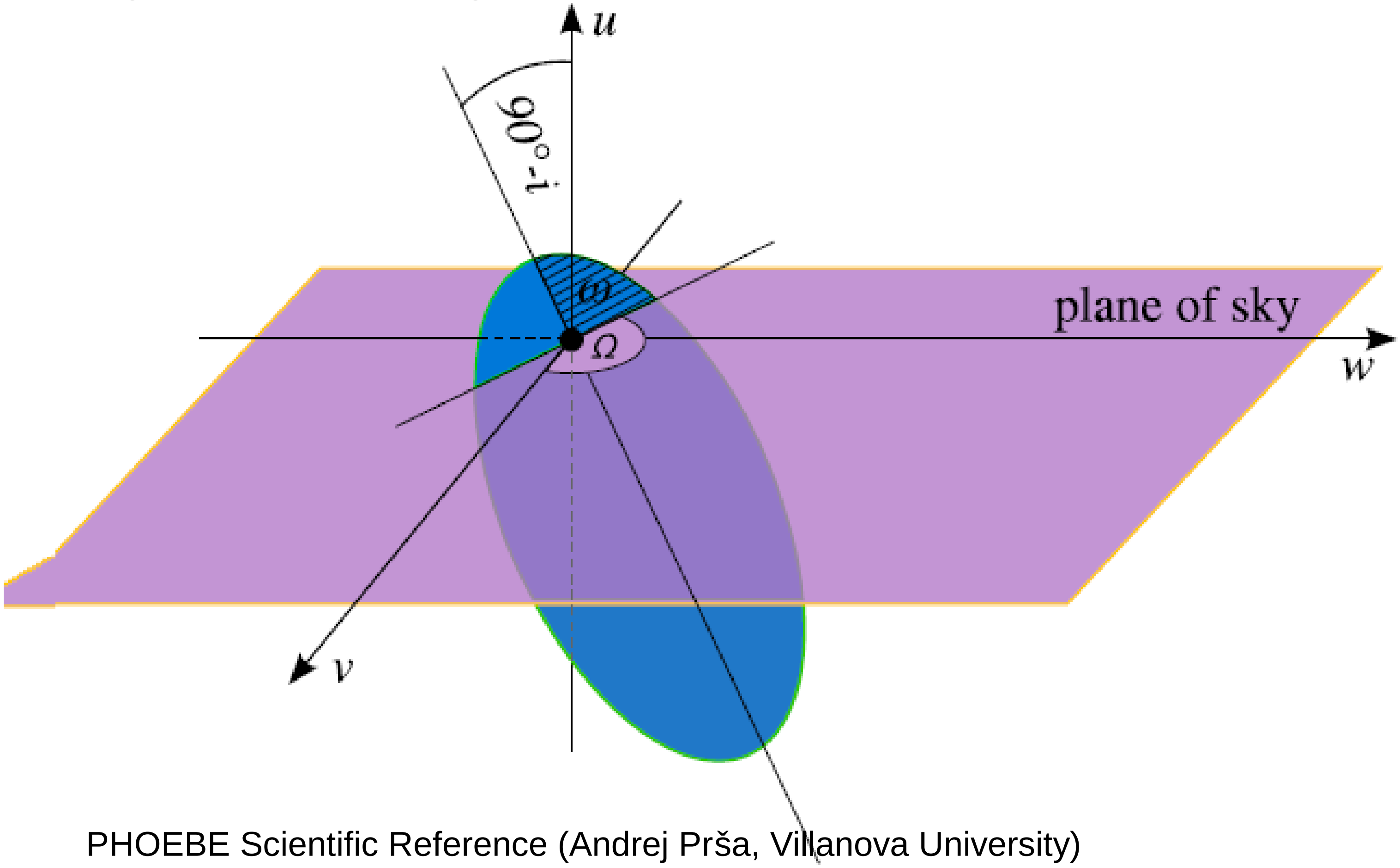
- Initial parameters:
  - orbital parameters
    - eccentricity
    - semi-major axis
    - inclination
    - argument of pericentre
    - longitude of ascending node
    - time of periastron passage
  - stellar parameters
    - radius, mass
    - effective temperature
      - based on Kurutz atmospheric model



PHOEBE Scientific Reference (Andrej Prša, Villanova University)

Orbital parameters

- **stellar positions are calculated by solving Kepler equation with Newton-Raphson method**
- **we using a co-rotating system in the center the primary star**



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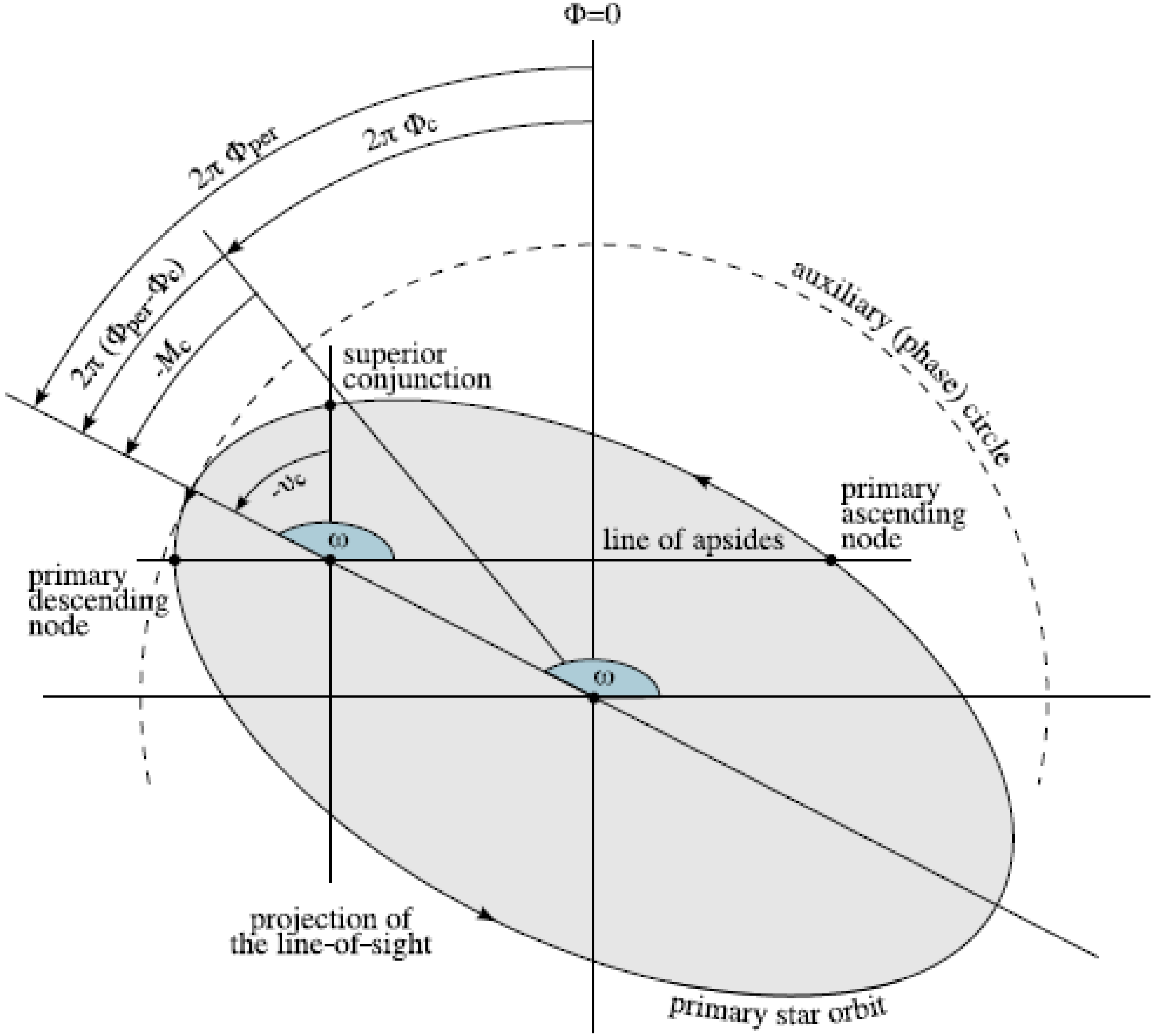
Orbital parameters



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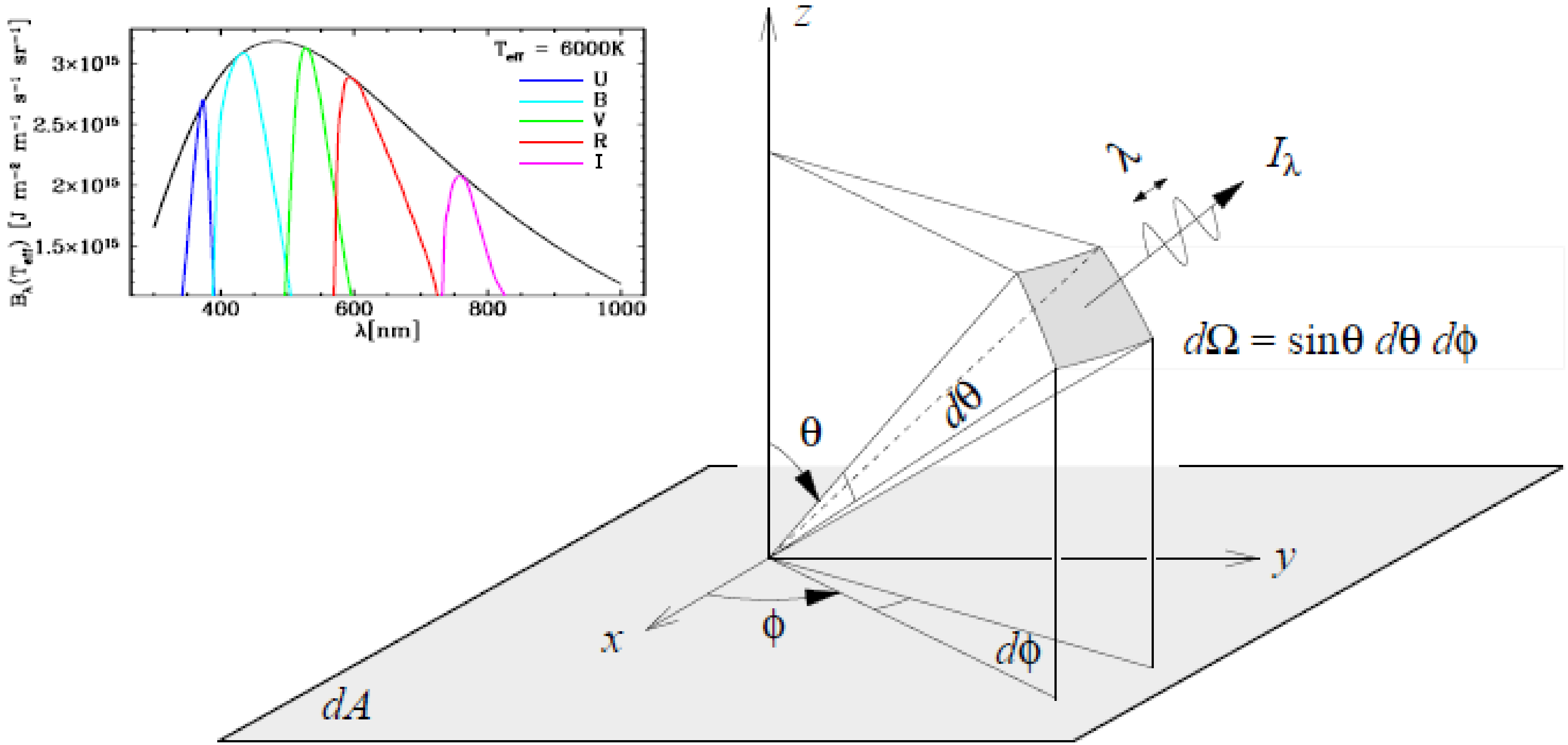
Radiative properties

- **we can calculate the emitted intensity for every surface element**



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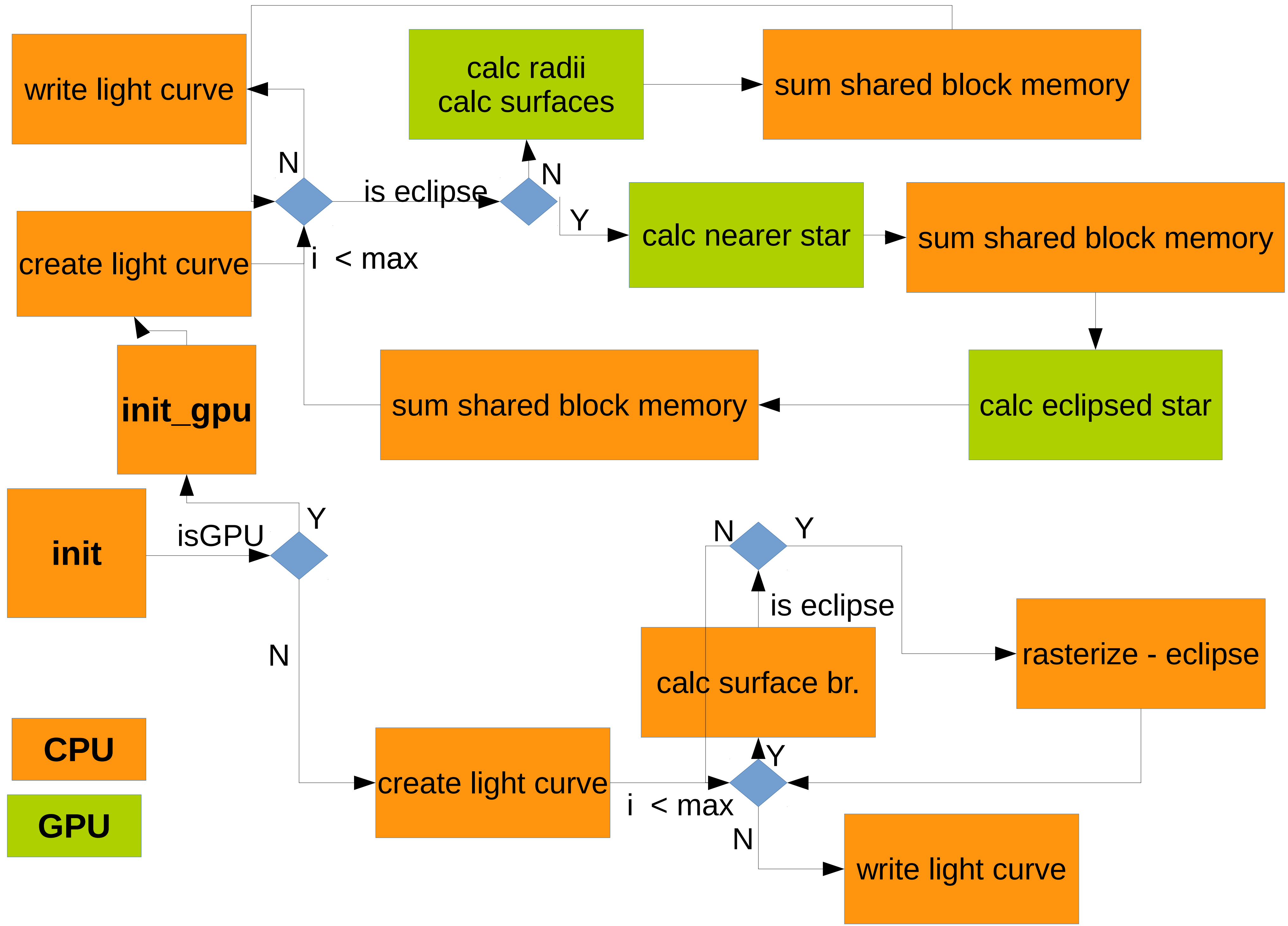


write light curve
calc radii
calc surfaces
sum shared block memory
N
is eclipse
N
Y
calc nearer star
sum shared block memory
create light curve
i < max
init_gpu
sum shared block memory
calc eclipsed star
init
isGPU
Y
N
Y
is eclipse
rasterize - eclipse
calc surface br.
N
CPU
GPU
create light curve
Y
i < max
N
write light curve

init_gpu

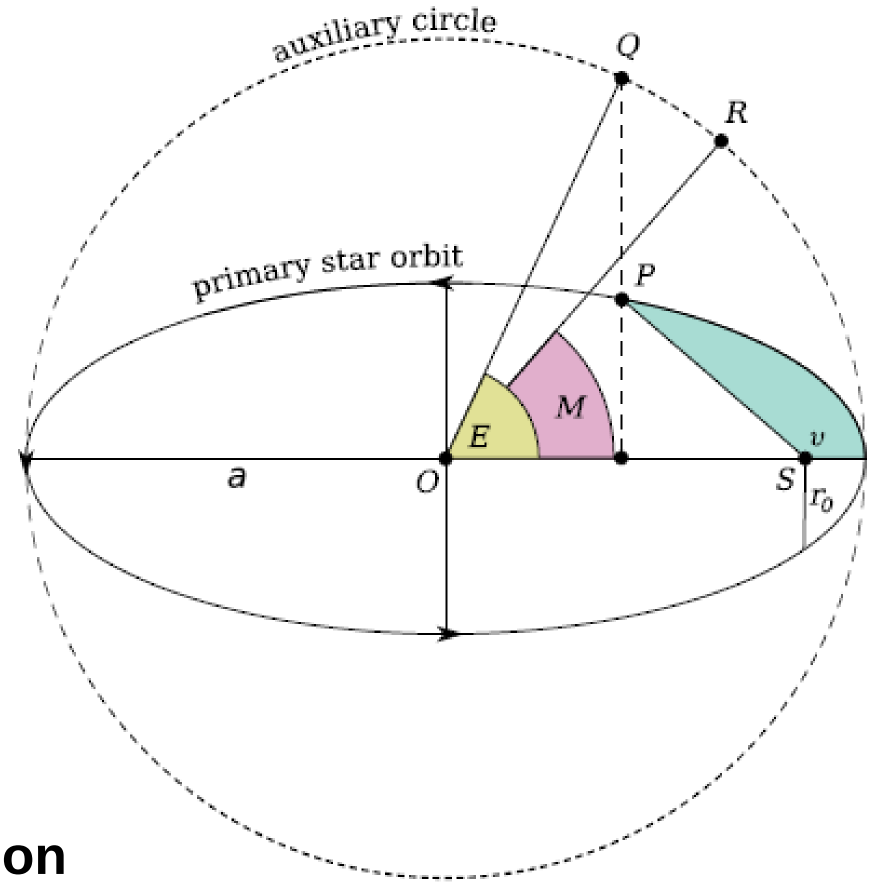
- **load parameters**
- **calculate surface grid**
- **solve Kepler equation with Newton-Raphson method**

$$M = E - e\sin(E)$$

- **calculate initial surface element positions in the plane of orbit**
- **and in the plane of sky.**

calc surface br.

- **calculate:**
  - **norm vector**
  - **surface area**
  - **cos(gamma)**
  - **temperature**
  - **gravity acceleration**



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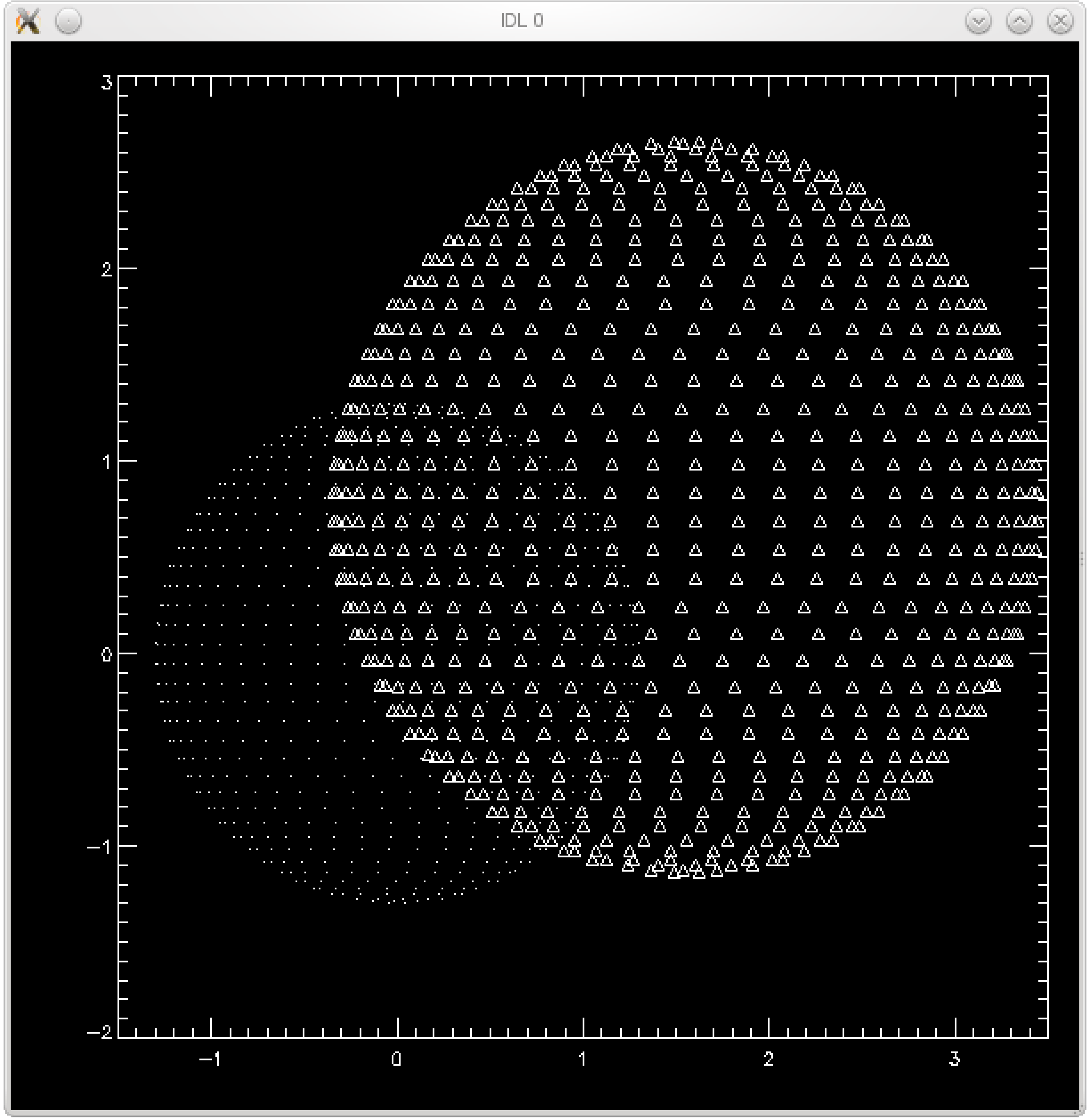
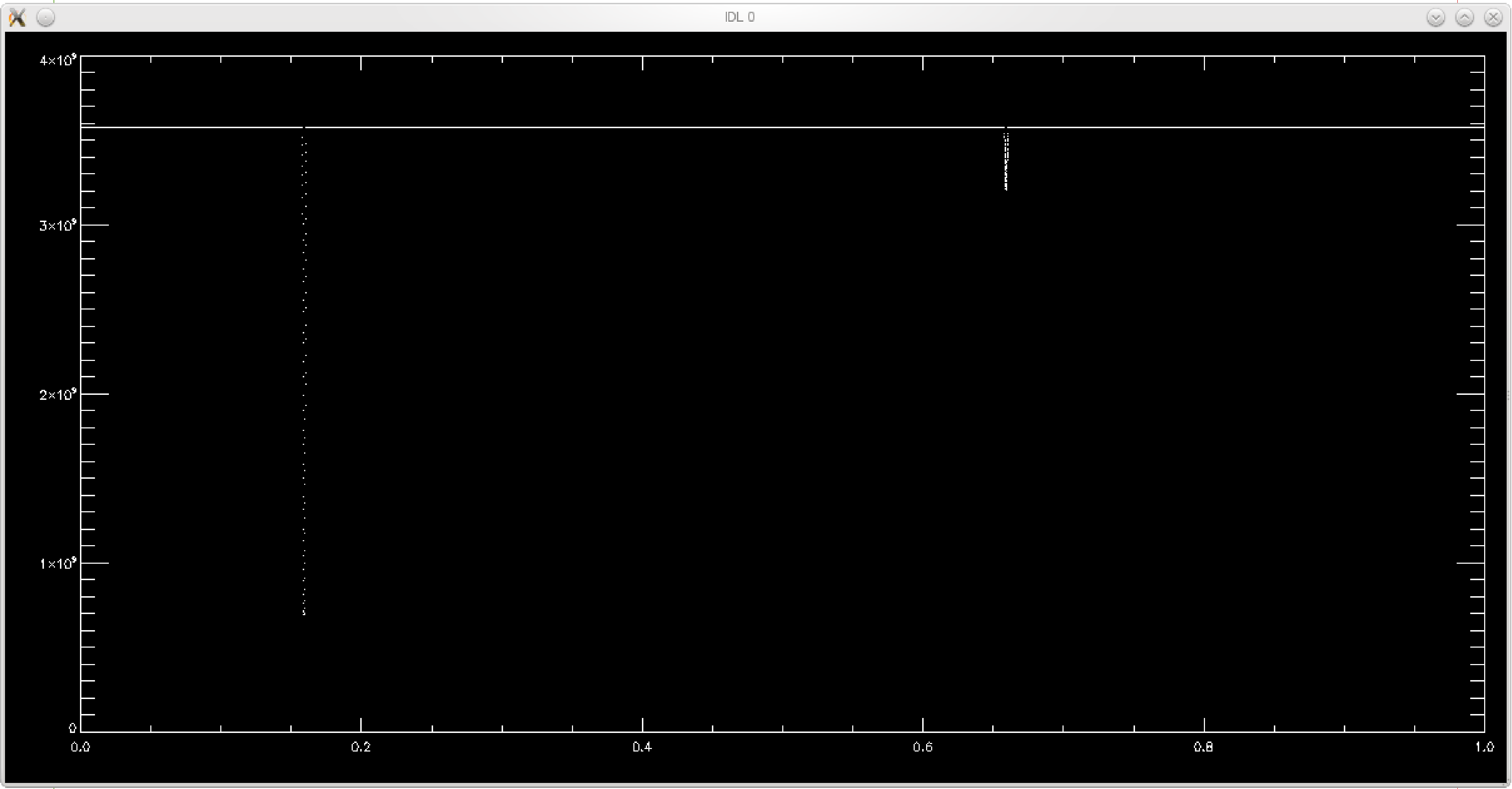
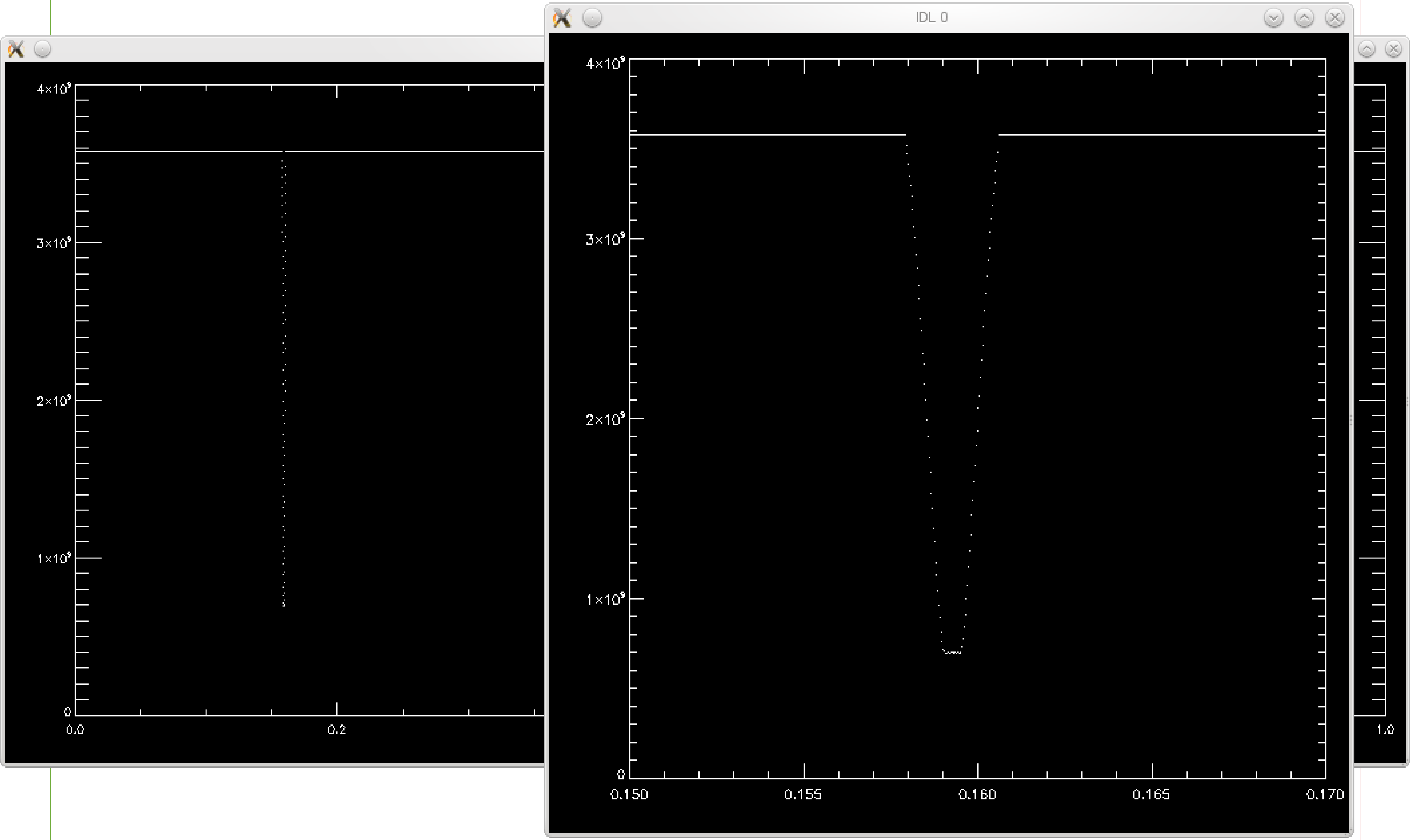
Surface grid



Lightcurve



Lightcurve



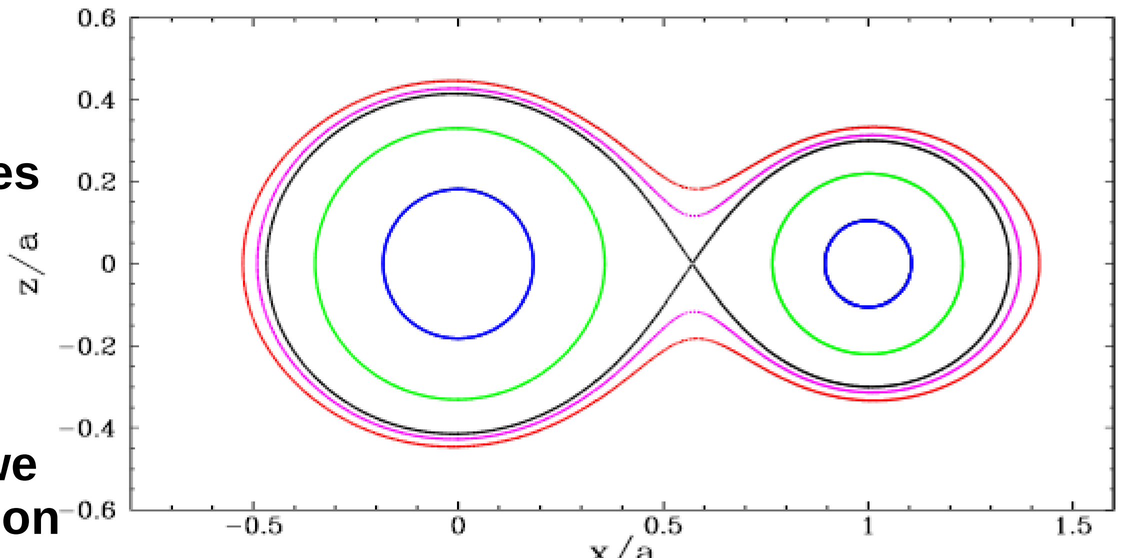
The Roche model

Dimensionless gravitational potential:

$$\Omega = \frac{1}{\rho} + q\left(\frac{1}{\sqrt{\delta^2+\rho^2-2\rho\lambda\delta}} - \frac{\rho\lambda}{\delta^2}\right) + \frac{1}{2}F^2\left(1+q\right)\rho^2\left(1-\nu^2\right)$$

where:

- q **the ratio of the secondary and primary star masses**
- δ **distance / semi-major axes**
- ρ **radius / semi-major axes at a surface element**
- λ, ν **functions of polar angles**
- F **ratio between the rotational and orbital angular velocity**
- **To calculate surface radii we have to use Newton-Raphson or/and Brent's method**



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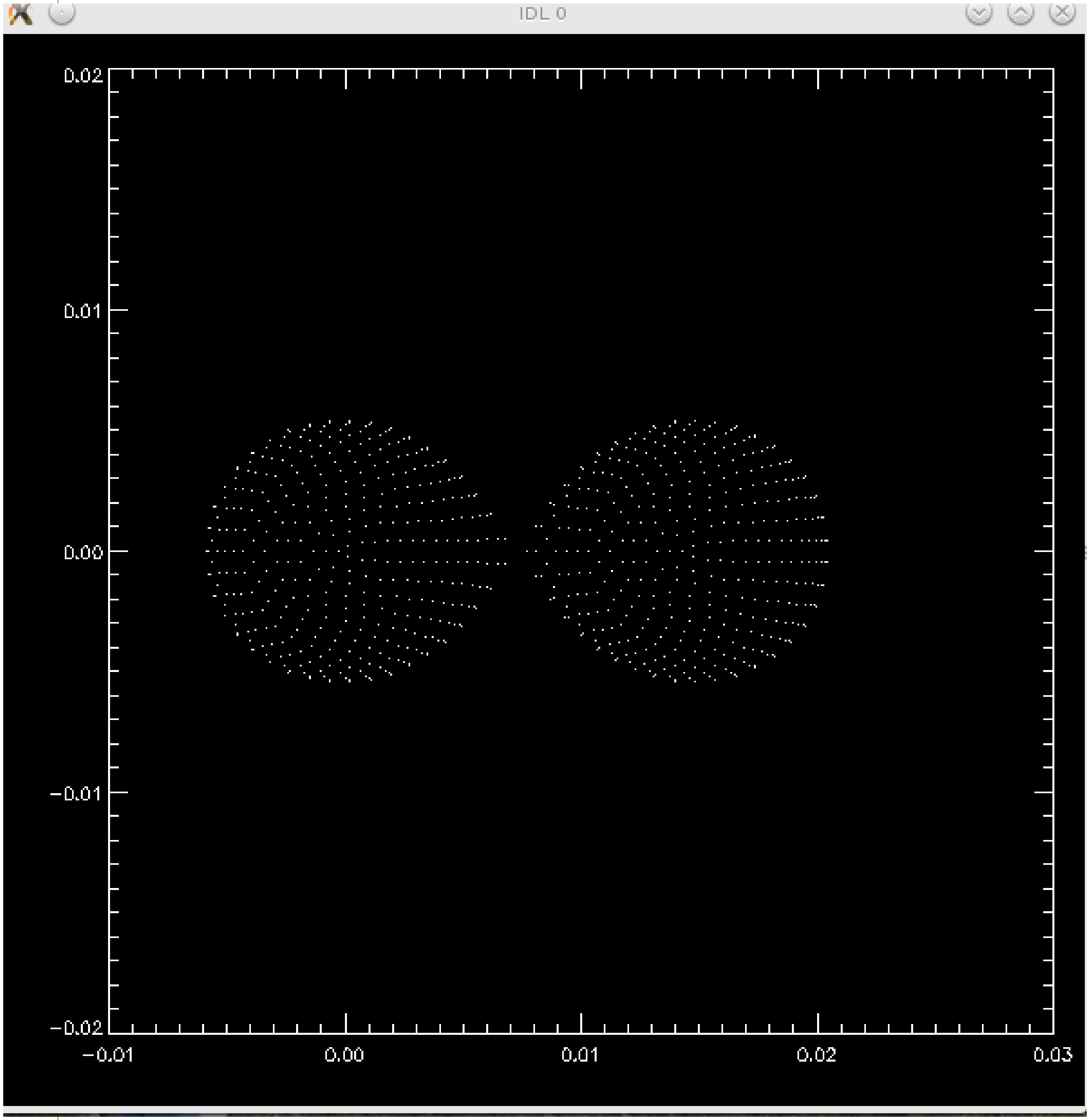

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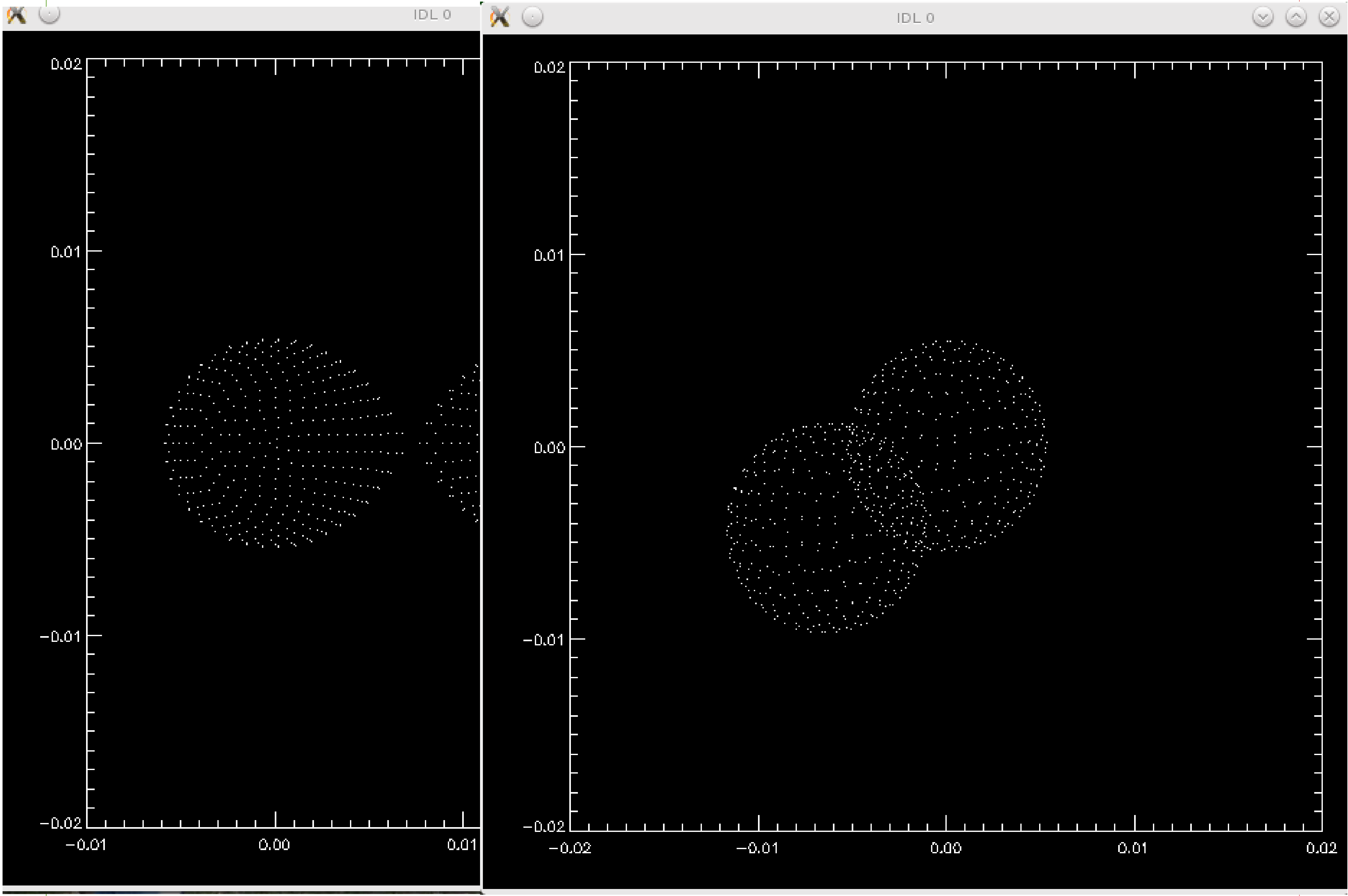
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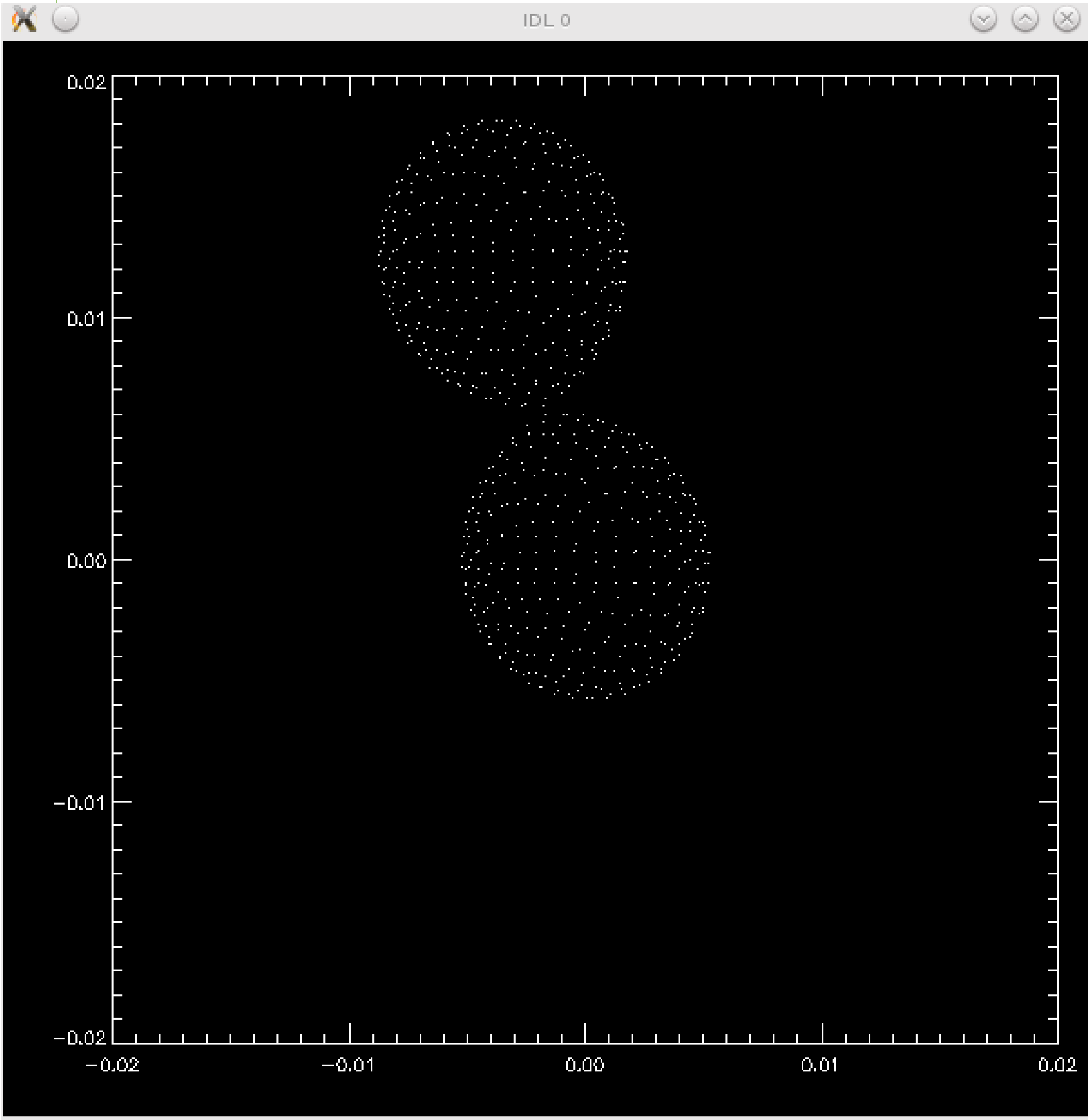

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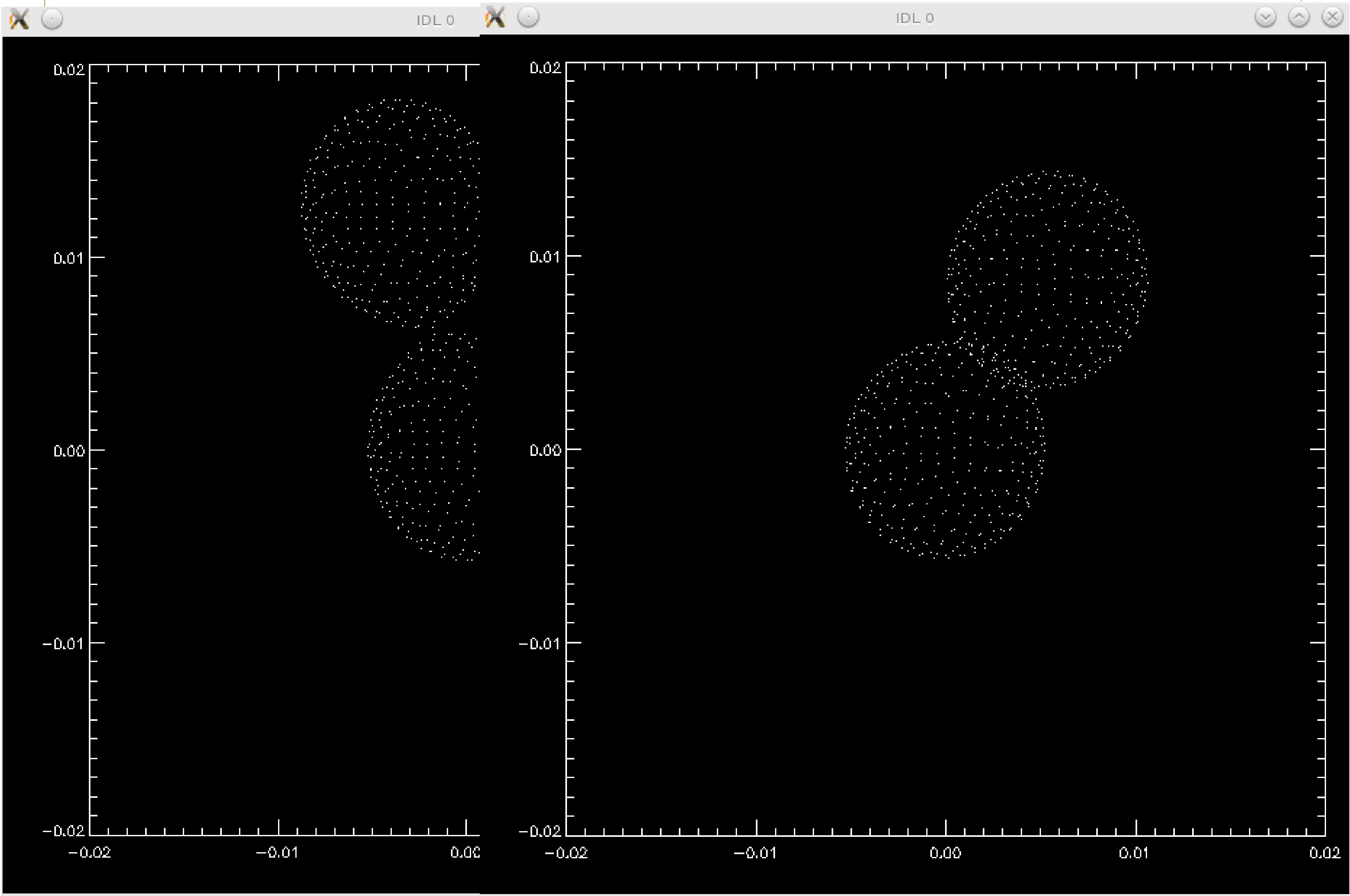
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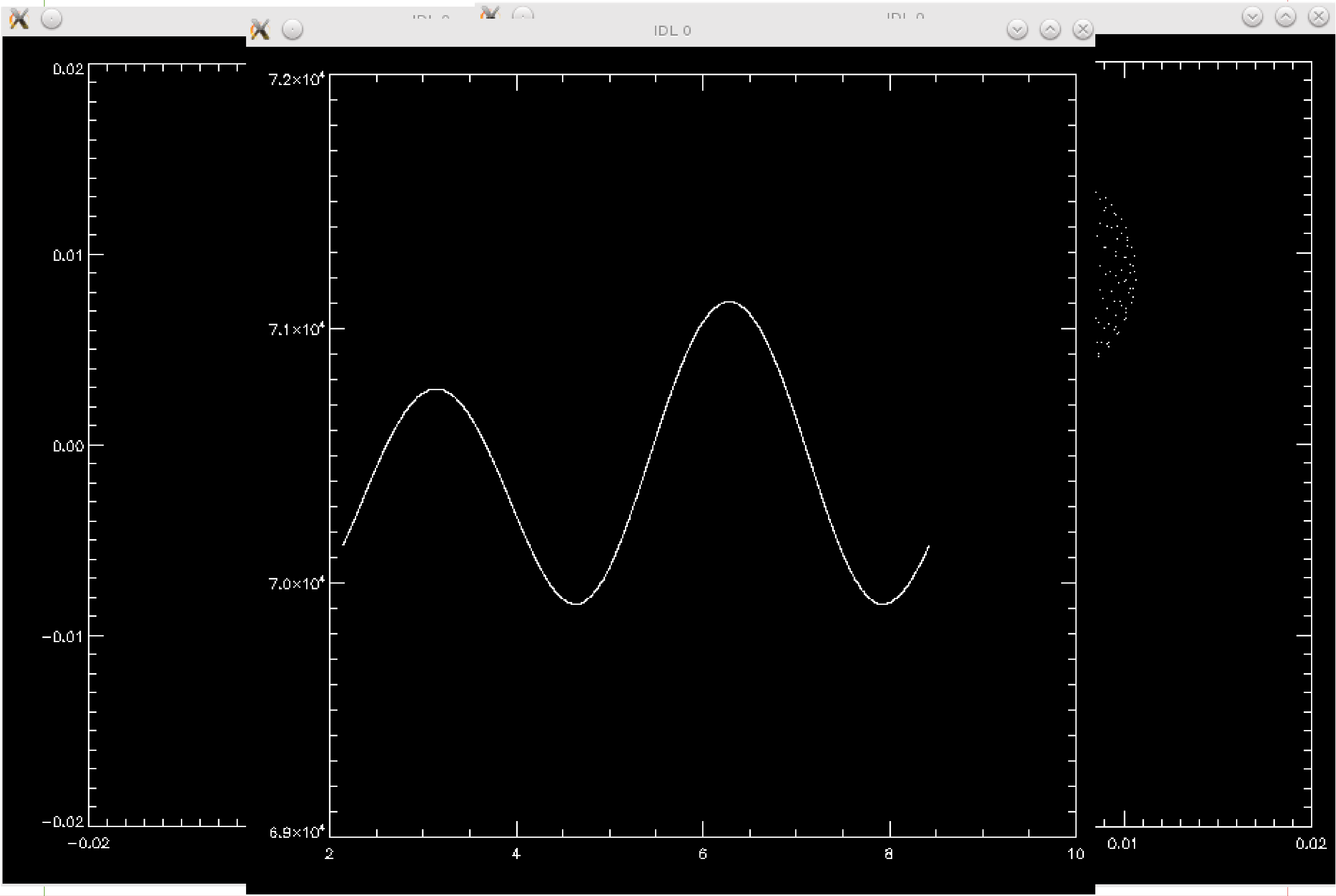
IDL 0
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7.1×10⁴
7.0×10⁴
6.9×10⁴
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4
6
8
10
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0.01
0.00
−0.01
−0.02
−0.02
0.01
0.02

Computational prices

CPU 1
Intel Core i7-4770 3.4 GHz
4 cores, hyperthreading enabled

GPU 1
NVIDIA GeForce GT 620
compute capability: 2.1
1024 threads/block

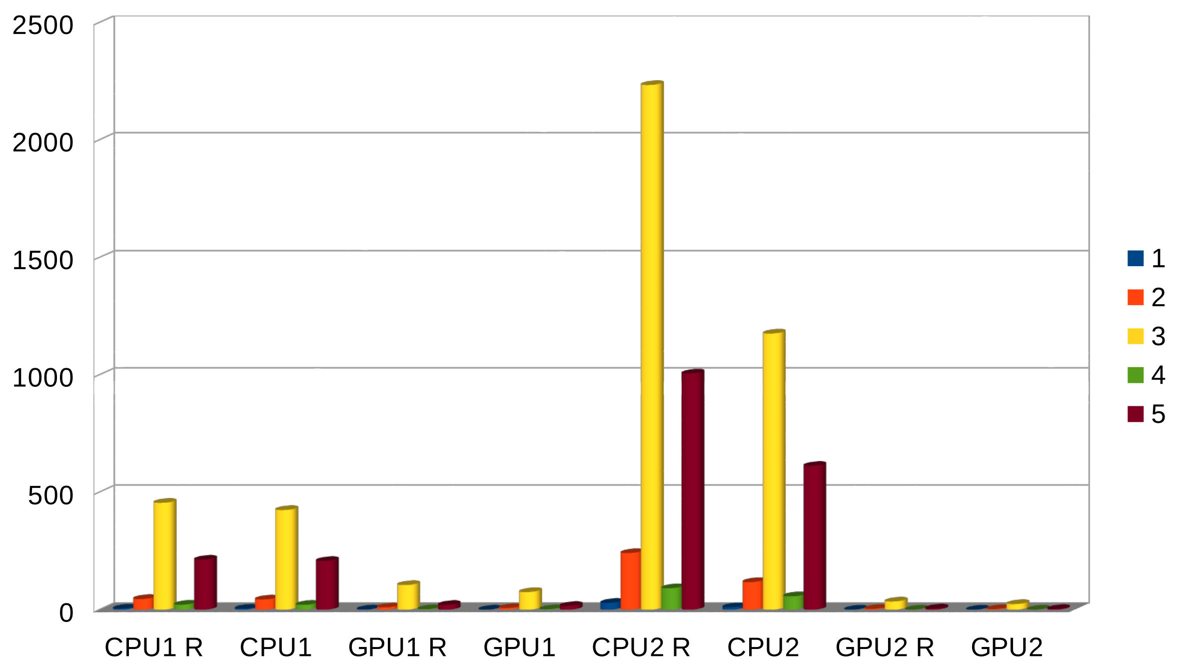
CPU 2
Intel Core i7 920 2.67 GHz
4 cores, hyperthreading enabled

GPU 2
NVIDIA GeForce GTX 980
compute capability: 5.2
1024 threads/block

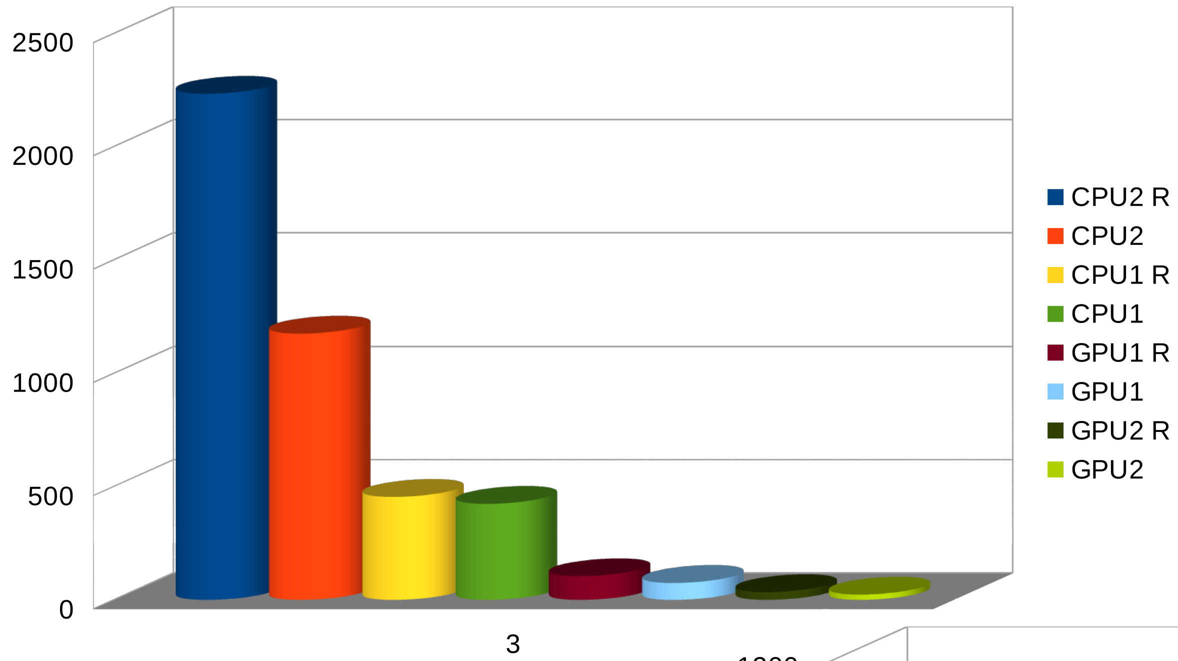
Case ID	Number of orbital positions	Number of theta grid points	number of surface elements
1	360	40	1348
2	3 600	40	1348
3	36 000	40	1348
4	360	60	3012
5	3600	60	3012

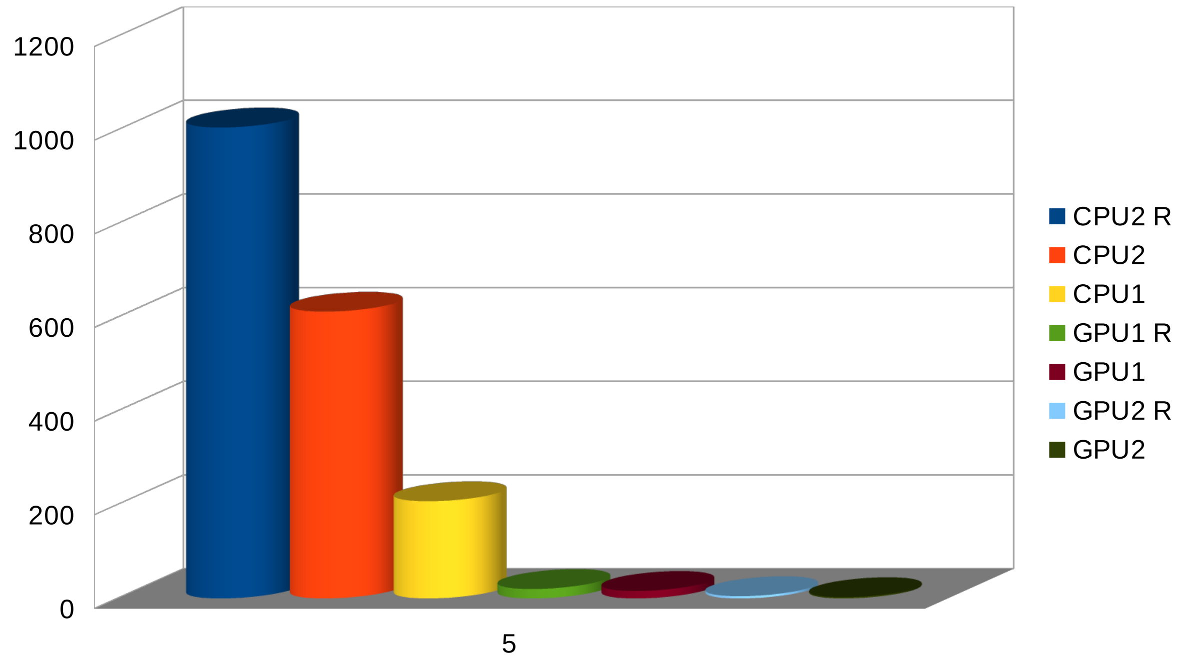
Computational prices

configuration	CPU1		GPU1		CPU2		GPU2	
With Roche- model	√	X	√	X	√	X	√	X
1	4,42	4,37	0,959	0,733	28,98	9,92	0,363	0,276
2	45,43	43,33	9,575	6,953	241,16	117,37	3,389	2,402
3	454,82	424,12	104,82	74,826	2234,2	1175,5	34,659	23,597
4	21,17	20,65	2,042	1,792	91,01	56,92	0,518	0,354
5	212,94	207,67	20,373	15,949	1005,8	612,42	4,955	2,880



Computational prices





Other features

- tidal distortions of close binaries (Roche - model)
- gravity darkening
- limb darkening
- reflection
- light-time variation
- the inverse problem
  - orbital and stellar parameters from the light (and radial velocity) curve
  - using Markov chain Monte Carlo
  - multiple stellar system and exoplanet modelling
  - GUI for setting initial parameters

Acknowledgements

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- János Sztakovics
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Thank You for Your Attention