Increasing knowledge and understanding of dynamical history of the observed Oort spike comets.

Piotr A. Dybczyński
in cooperation with
Małgorzata Królikowska and Filip Berski

International Workshop on Comets
in Honor of Hans Rickman
Paris – Meudon, 17 – 19 May 2016

To investigate the nature of the Oort Cloud, the reservoir for long-period and Halley-type comets, we need to determine the original orbits of a large number of comets before they entered the planetary region …

From: Luke Dones, Ramon Brasser,
Nathan Kaib, and Hans Rickman,
Space Sci Rev (2015) 197

But we think it is not enough, in many cases we may and should go at least one step further.

With precise original orbits (and their uncertainties) in hand we should try to follow the past trajectory of LPCs, at least down to the previous perihelion or some adopted “escape” distance.

Of course the same can be done with future orbits to show the LPCs fate.

Our contemporary understanding of stellar and Galactic perturbations acting on LPCs outside the planetary zone is quite satisfactory, as we show in the remaining part of this presentation pointing, among others, to the Hans Rickman contribution in this field .

Augmented with the new data from Gaia mission (hopefully available soon) this should significantly increase our ability to describe the source or sources of LPCs.

Vol. 27 (1976), No. 2

STELLAR PERTURBATIONS OF ORBITS OF LONG-PERIOD COMETS AND THEIR SIGNIFICANCE FOR COMETARY CAPTURE

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Approximate expressions for the heliocentric impulse gained by a long-period comet from stellar passages at different distances are derived. The frequency of stellar passages and its dependence on the passage distance is investigated. The relative importances of different passage distances over very long time intervals are discussed. Expected values of the transverse component of the impulse gained from stellar perturbations during one revolution are estimated for different values of the aphelion distance. The resulting dispersions of the perihelion distance and inclination are computed. They are found to influence the initial stages of cometary capture from the Oort cloud but have a very small effect on the capture efficiency.

Возмущение орбит долгопериодических комет от звезды и его значение для кометного захвата

Определяются приблизительные выражения для гелиоцентрического импульса присбретаемого долгопериодической кометой вследствие прохождения звезды на различных расстояниях. Исследуется частота этих прохождений и ее зависимость от расстояния. Обсуждаются долговременные значения прохождений на различных расстояниях. Для различных расстояний афелия сделаны оценки ожидаемых значений поперечного компонента импульса приобретаемого кометой от возмущений в течение одного оборота. Вычисляются окончательные значения дисперсии расстояния перигелия и наклона орбиты. Найдено, что эти возмущения оказывают влияние на захват кометы из облака Оорта, но их воздействие на эффективность захвата очень мало.

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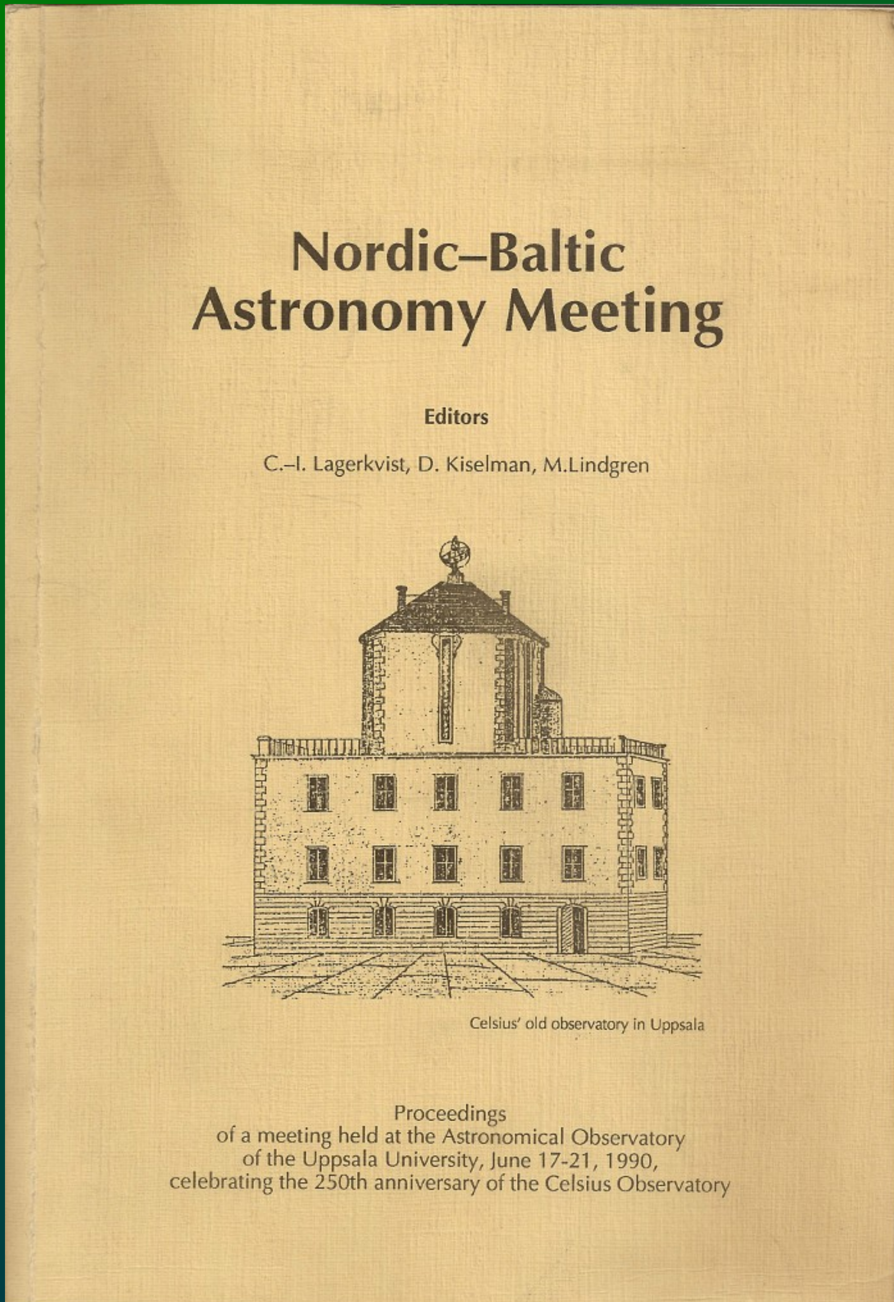

Celsius' old observatory in Uppsala

STELLAR PERTURBATIONS OF THE OORT CLOUD COMETARY ORBITS

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ABSTRACT

Two metods for calculating stellar perturbations of cometary orbits in the Oort cloud are compared and discussed. These are: impuls approximation and numerical integration of the restricted three body problem.
Basing on numerical experiments the possibility of producing observable comets by a single star approach is also discused.

In following table we present as an example results for a star with $M_* = 2\ M_\odot$, V_∞ = 10km/s and the minimal distance from the Sun 90000 AU.

$Q_* \setminus q_*$	1000 AU	10000 AU	40000 AU	80000 AU
100000 AU	$1.9\cdot10^{-4}$ $\pm0.4\cdot10^{-4}$	$3.9\cdot10^{-6}$ $\pm2.3\cdot10^{-6}$	$4.5\cdot10^{-7}$ $\pm2.1\cdot10^{-7}$	$3.6\cdot10^{-7}$ $\pm1.8\cdot10^{-7}$
80000 AU	$4.4\cdot10^{-5}$ $\pm1.9\cdot10^{-5}$	0	0	
40000 AU	0	0		WHOLE CLOUD:
10000 AU	0			$3.5\cdot10^{-7} \pm 1.8\cdot10^{-7}$

IMPULSE APPROXIMATION IMPROVED

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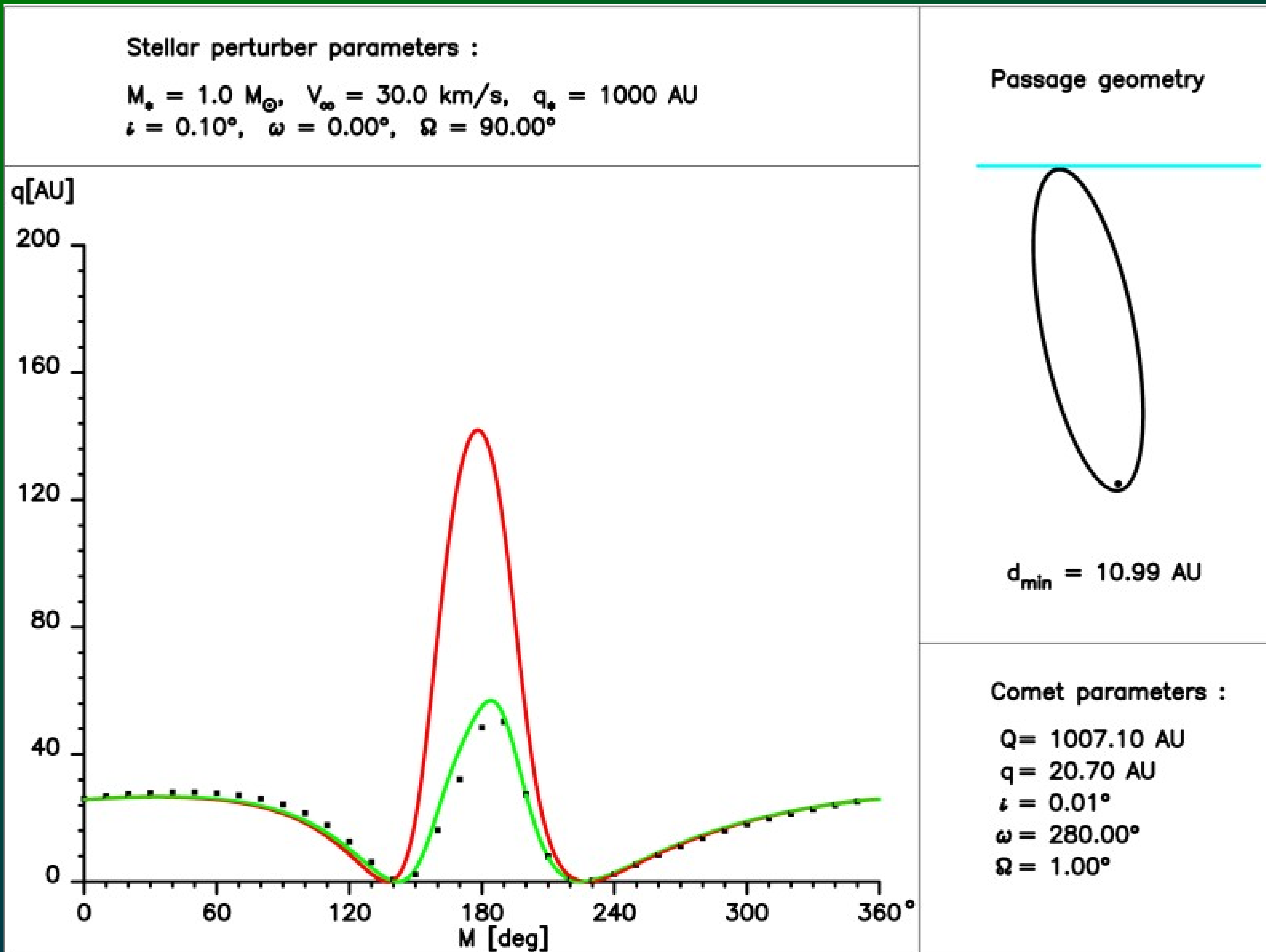
Abstract. Improved formulas of impulse approximation method for stellar perturbations are derived. The method proposed involves a deflection of the stellar path. It is also applicable to an arbitrary time interval. A comparison of the classical vs improved method is presented both in qualitative discussion and numerical results for Oort cloud cometary orbits.

Key words: Impulse approximation, stellar perturbations, Oort cloud.

Celestial Mechanics and Dynamical Astronomy **58:** 139–150, 1994.



Stellar perturber parameters :
M* = 1.0 M⊙, V∞ = 30.0 km/s, q* = 1000 AU
i = 0.10°, ω = 0.00°, Ω = 90.00°
q[AU]
200
160
120
80
40
0
0
60
120
180
240
300
360°
M [deg]
Passage geometry
dmin = 10.99 AU
Comet parameters :
Q= 1007.10 AU
q= 20.70 AU
i = 0.01°
ω = 280.00°
Ω = 1.00°

Earth, Moon, and Planets (2006)
DOI 10.1007/s11038-006-9113-7

Algorithms for Stellar Perturbation Computations on Oort Cloud Comets

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Abstract. We investigate different approximate methods of computing the perturbations on the orbits of Oort cloud comets caused by passing stars, by checking them against an accurate numerical integration using Everhart's RA15 code. The scenario under study is the one relevant for long-term simulations of the cloud's response to a predefined set of stellar passages. Our sample of stellar encounters simulates those experienced by the Solar System currently, but extrapolated over a time of 10^{10} years. We measure the errors of perihelion distance perturbations for high-eccentricity orbits introduced by several estimators – including the classical impulse approximation and Dybczyński's (1994, *Celest. Mech. Dynam. Astron.* **58**, 1330–1338) method – and we study how they depend on the encounter parameters (approach distance and relative velocity). We introduce a sequential variant of Dybczyński's approach, cutting the encounter into several steps whereby the heliocentric motion of the comet is taken into account. For the scenario at hand this is found to offer an efficient means to obtain accurate results for practically any domain of the parameter space.

Keywords: comets, impulse approximation, Oort cloud, stellar encounters

DYNAMICAL INFLUENCES ON THE

COMETS OF THE OORT CLOUD

by

Julia Heisler

A.B., Princeton University
(1982)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS OF THE

DEGREE OF

DOCTOR OF PHILOSOPHY

IN PHYSICS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1986

$$\ddot{x} = \frac{-\mu}{r^3} x$$

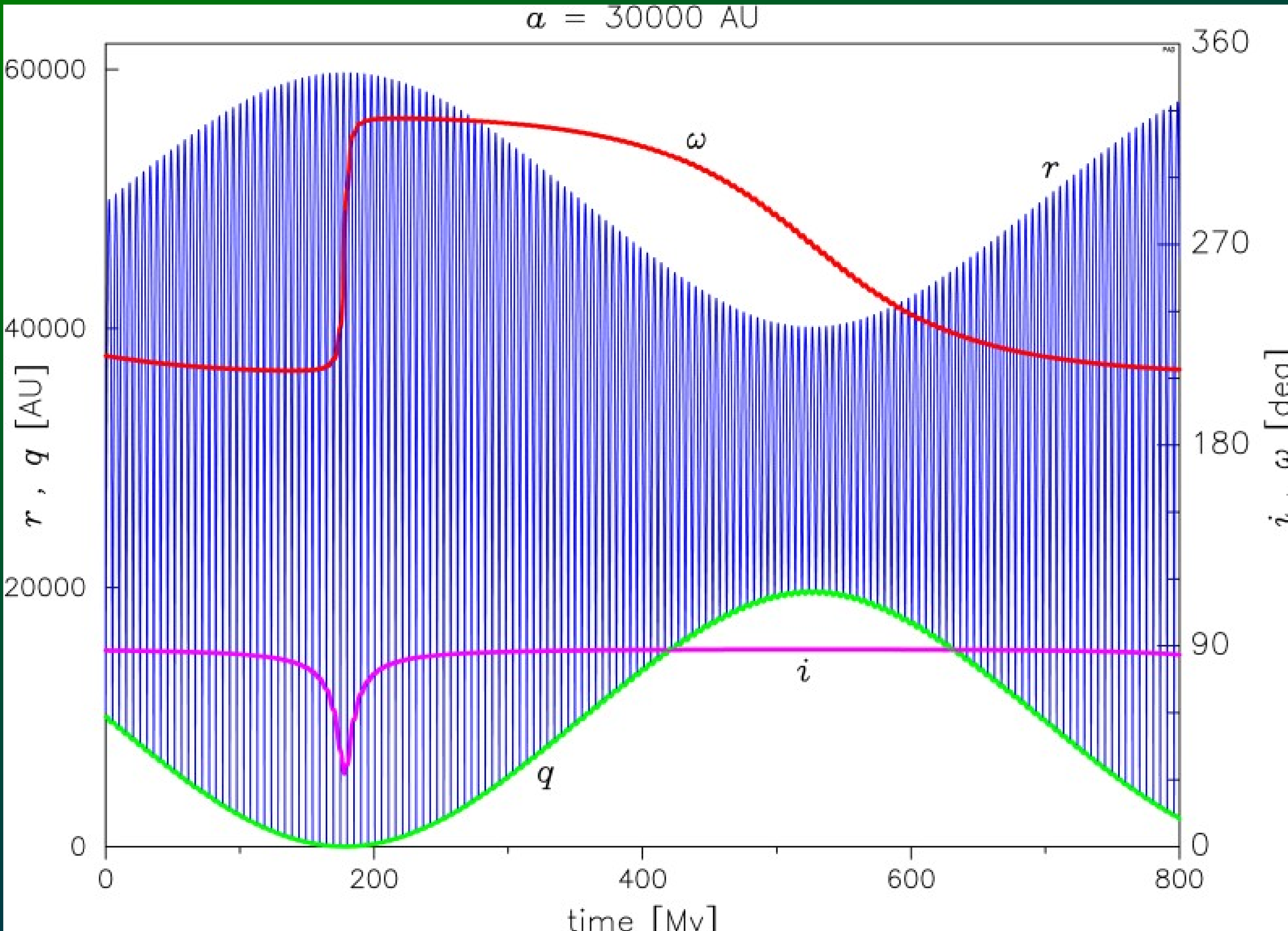
$$\ddot{y} = \frac{-\mu}{r^3} y$$

$$\ddot{z} = \frac{-\mu}{r^3} z - 4\pi G \rho z,$$

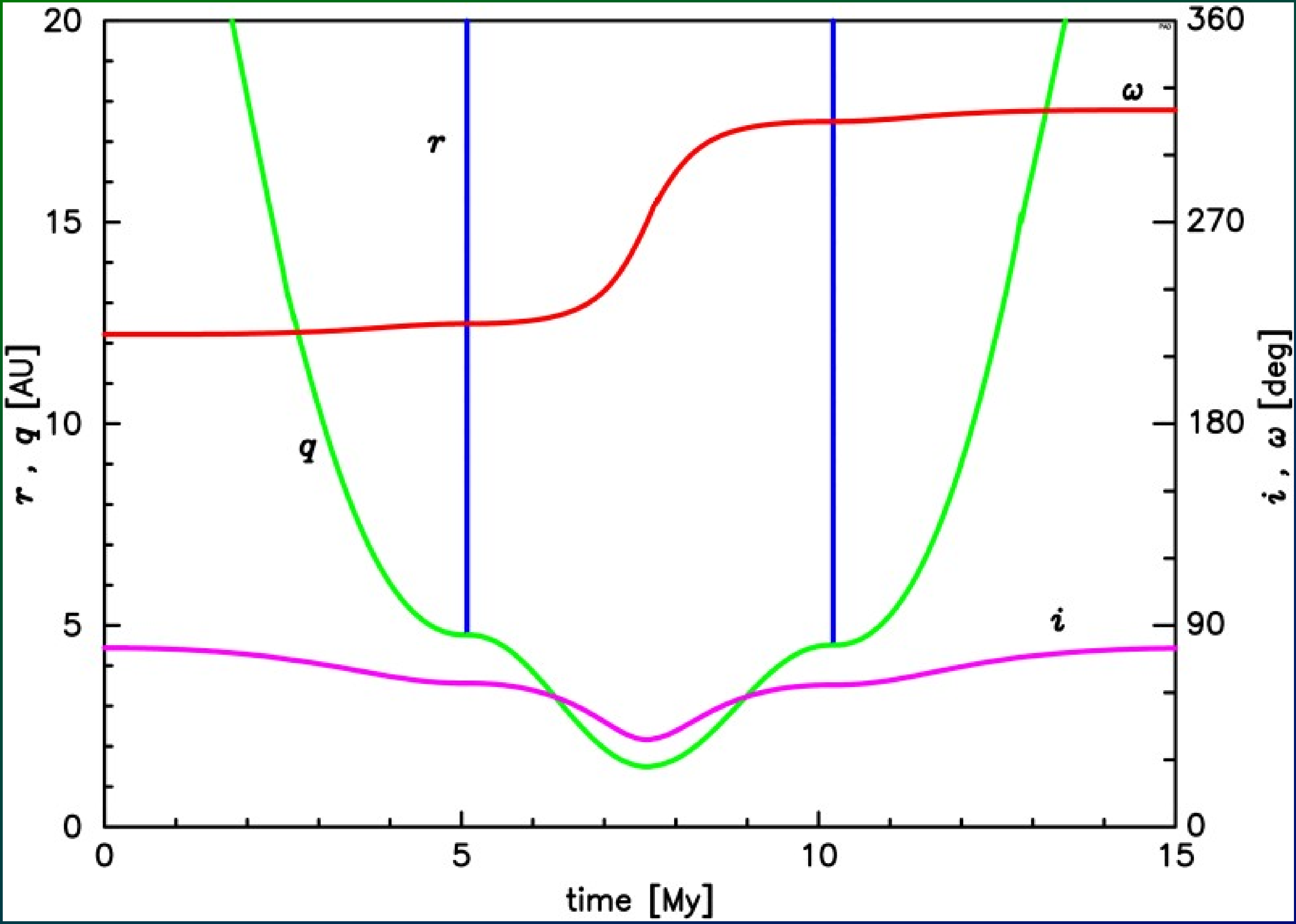
$$\mathbf{F} = -\frac{\mu}{r^3}\mathbf{r} + (A - B)(3A + B)x'\hat{x}' - (A - B)^2 y'\hat{y}' - [4\pi G\rho_0 - 2(B^2 - A^2)]z\hat{z}. \quad (6)$$

We take $A = 13$ km sec^{-1} kpc^{-1}, $B = -13$ km sec^{-1} kpc^{-1} (Gunn, Knapp, and Tremaine, 1979), and $\rho_0 = 0.185 \pm 0.02 M_\odot/\mathrm{pc}^3$ (Bahcall, 1984). With these parameters the coefficients of $x'\hat{x}'$ and $y'\hat{y}'$ are smaller than the coefficient of $z\hat{z}$ by a factor of 15, and the term proportional to $B^2 - A^2$ is zero. Thus, in a first approximation, we may drop all terms involving A and B from Eq. (6). The remaining forces may be derived from a potential

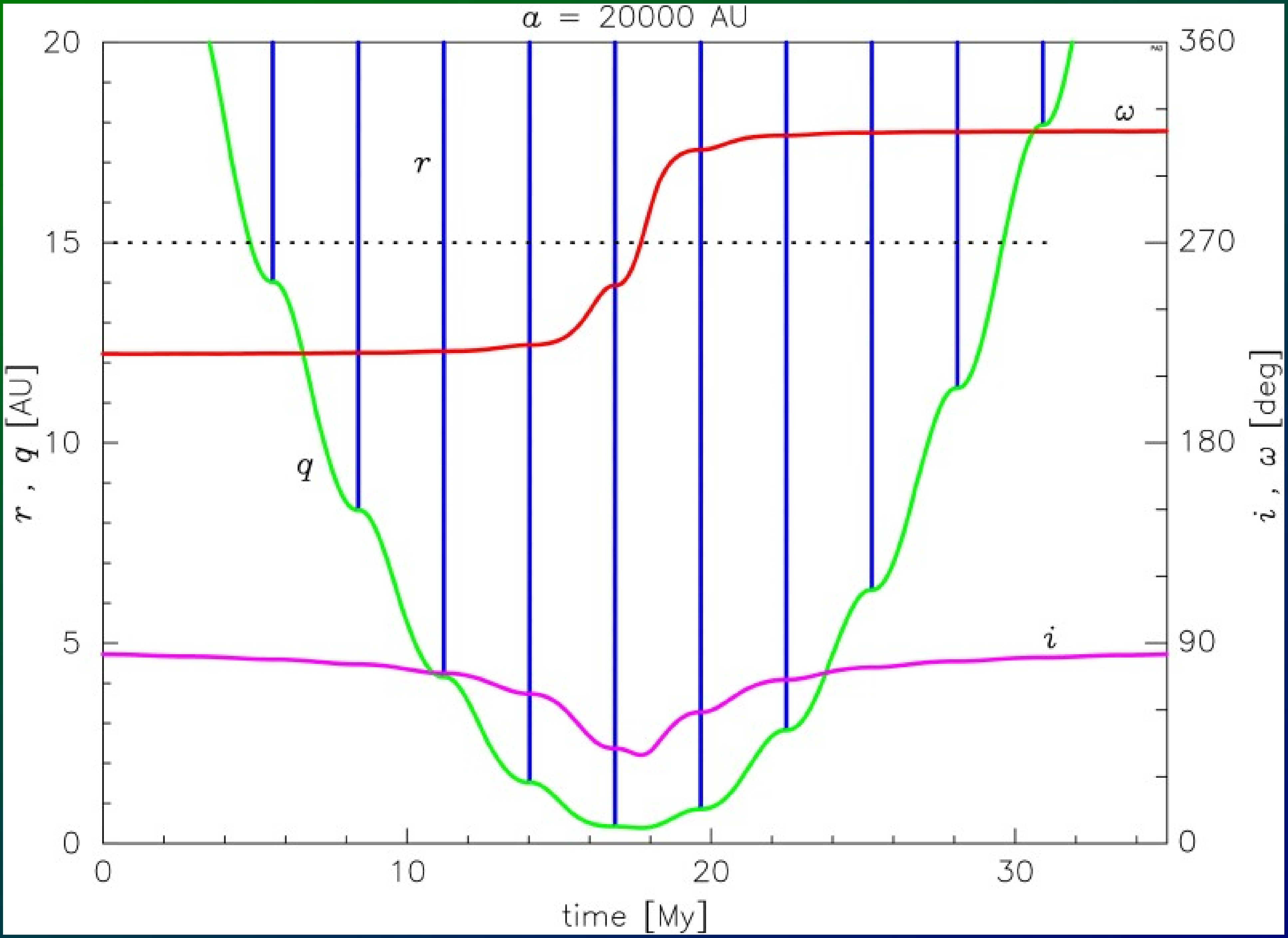
$$U(x, y, z) = -\frac{\mu}{r} + 2\pi G\rho_0 z^2. \quad (7)$$



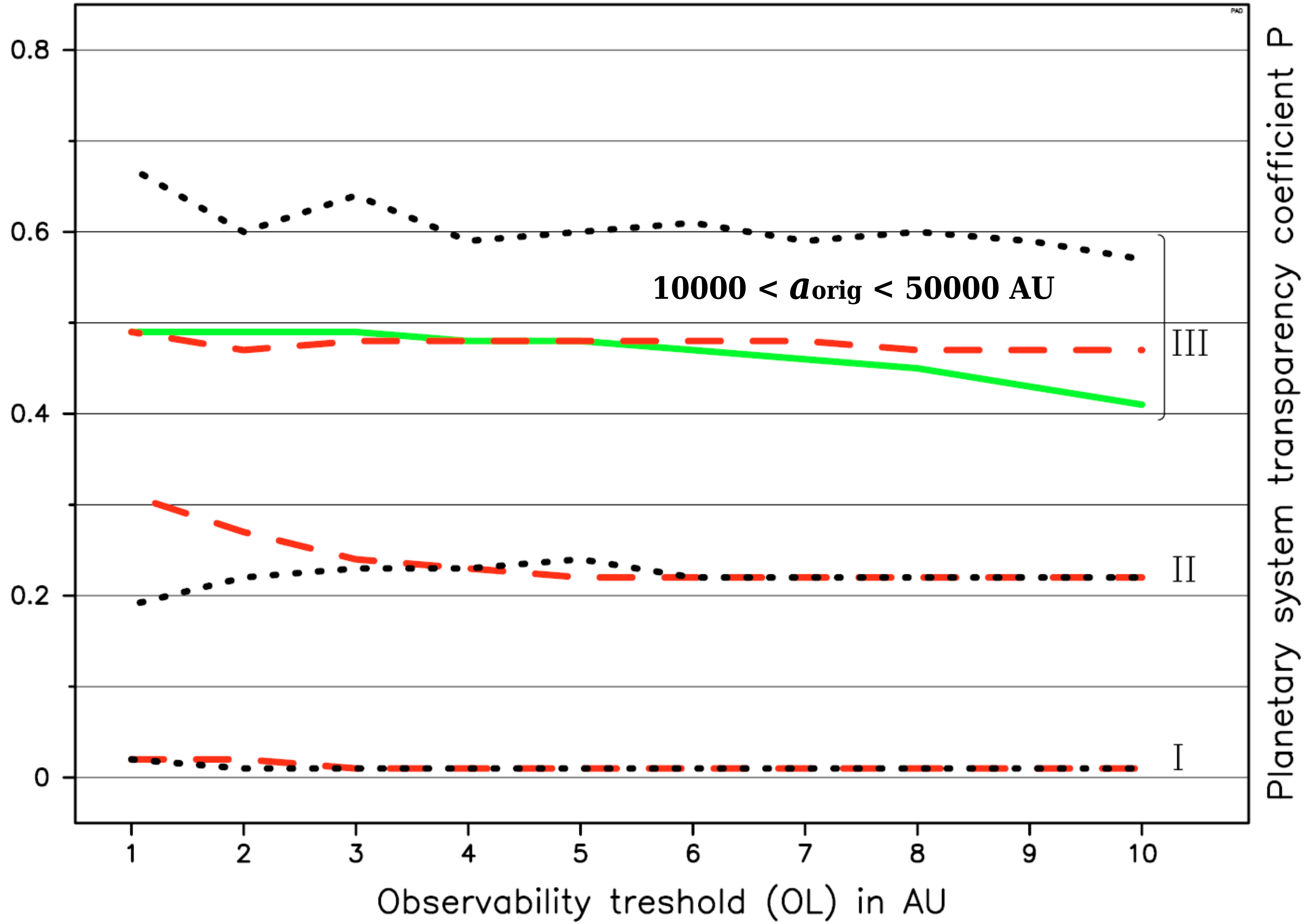
a = 30000 AU
60000
40000
20000
0
r , q [AU]
360
270
180
90
0
i , ω [deg]
ω
r
i
q
0
200
400
600
800
time [My]



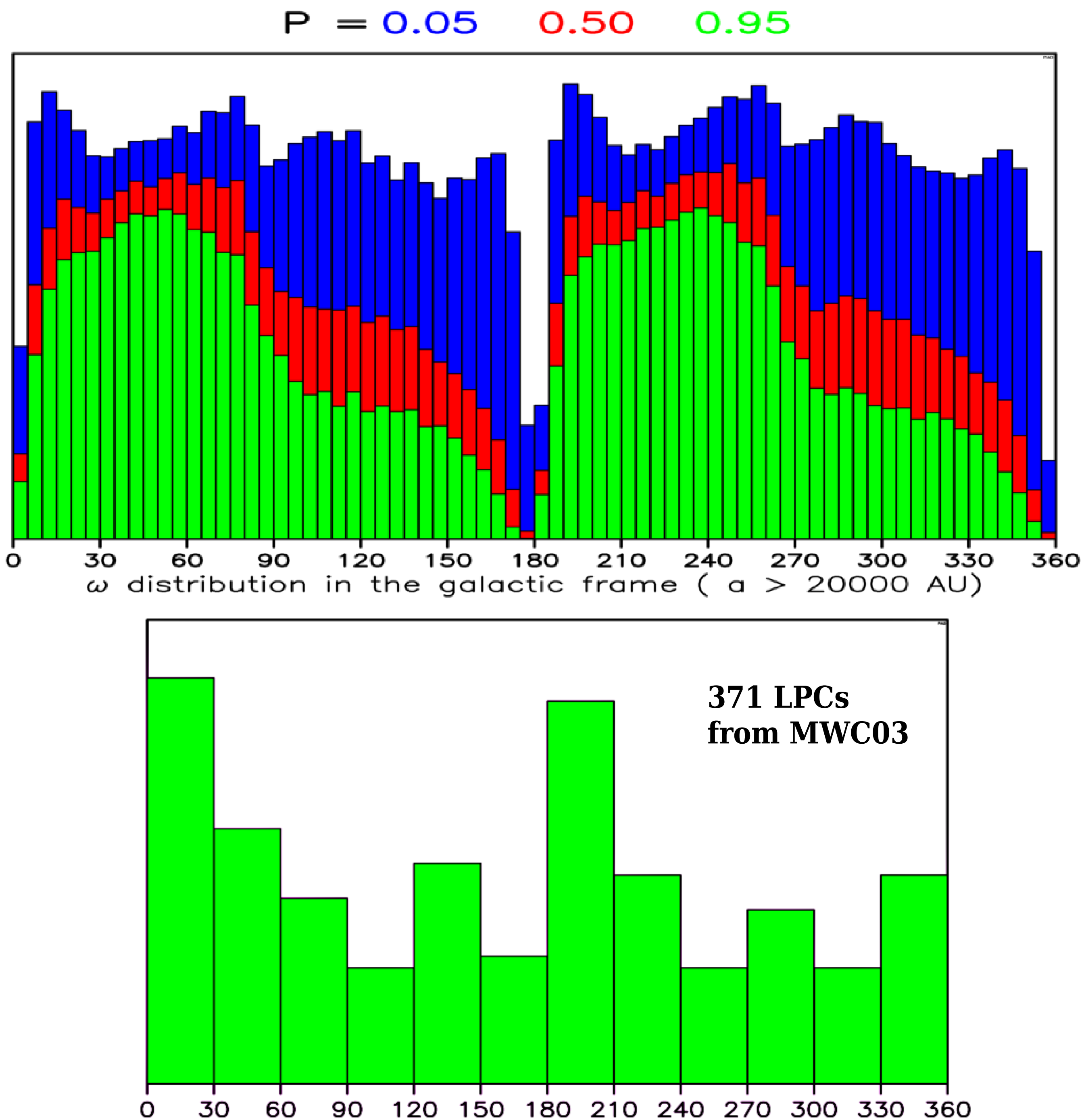
20
15
10
5
0
360
270
180
90
0
r , q [AU]
i , ω [deg]
r
q
ω
i
0
5
10
15
time [My]



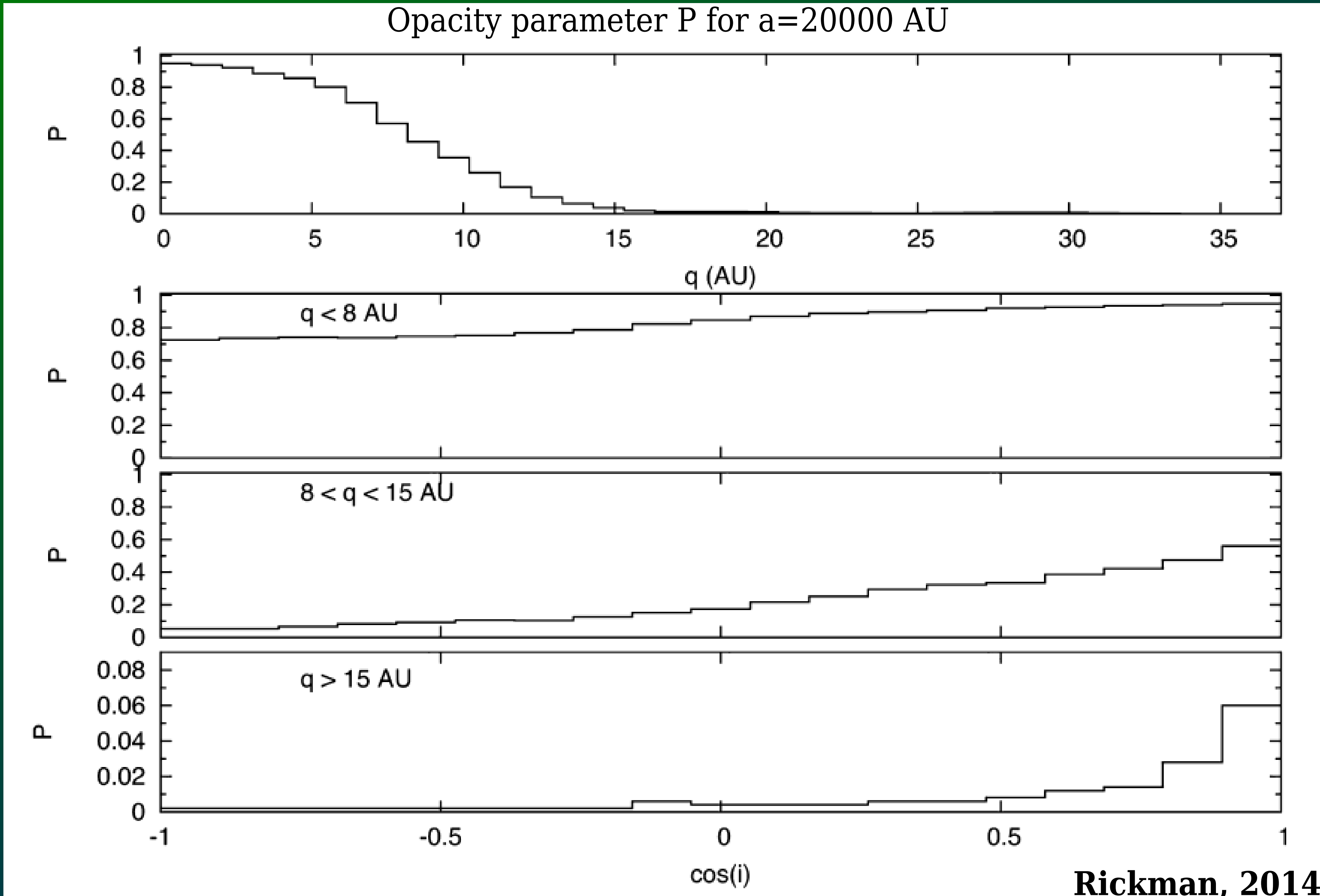
a = 20000 AU
r , q [AU]
i , ω [deg]
time [My]
r
q
ω
i
0
5
10
15
20
0
90
180
270
360
0
10
20
30

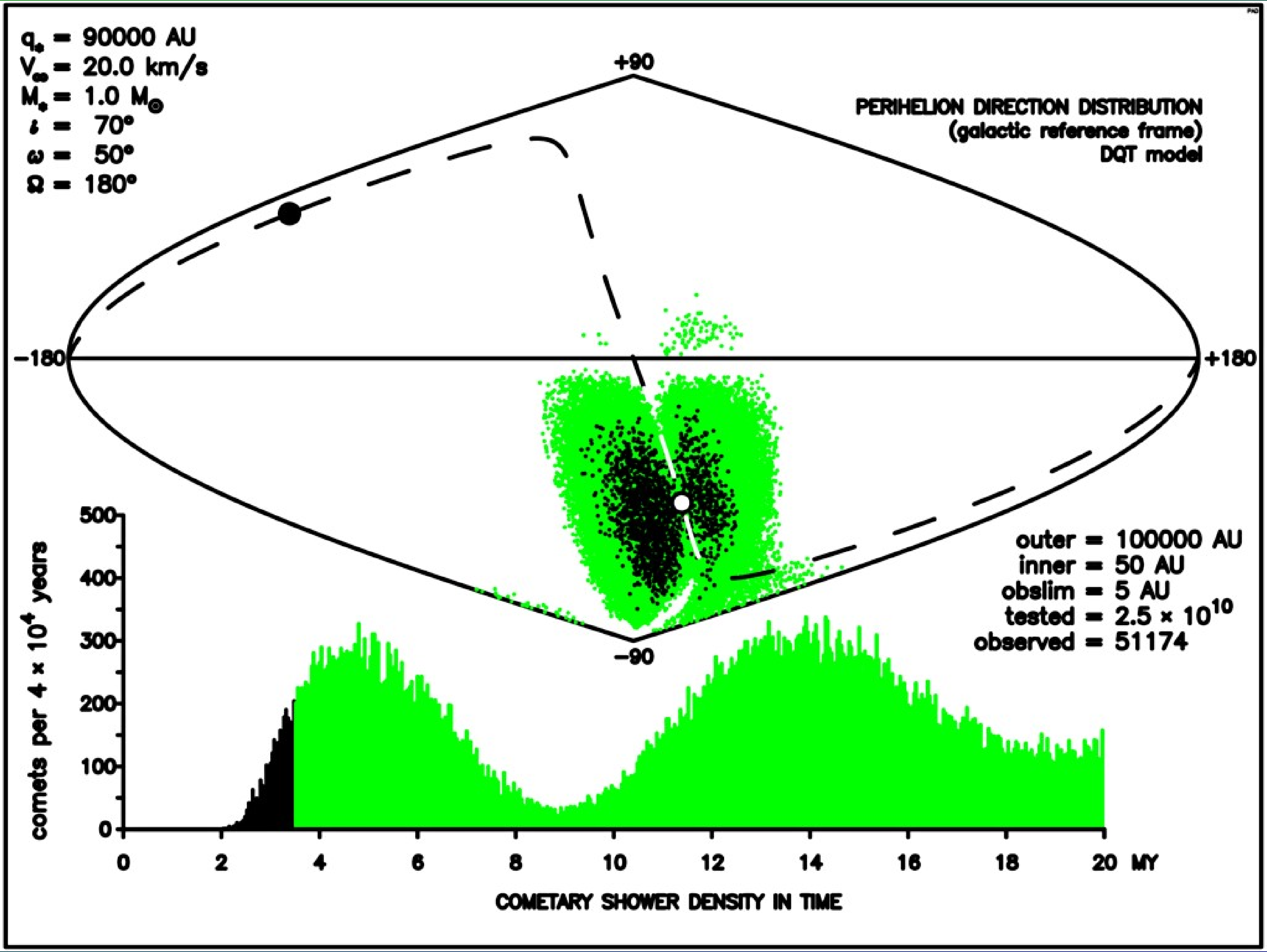


Dybczynski, 2004a



Dybczynski, 2005


Opacity parameter P for a=20000 AU
P
q (AU)
q < 8 AU
8 < q < 15 AU
q > 15 AU
cos(i)
Rickman, 2014



Dybczyński, 2005

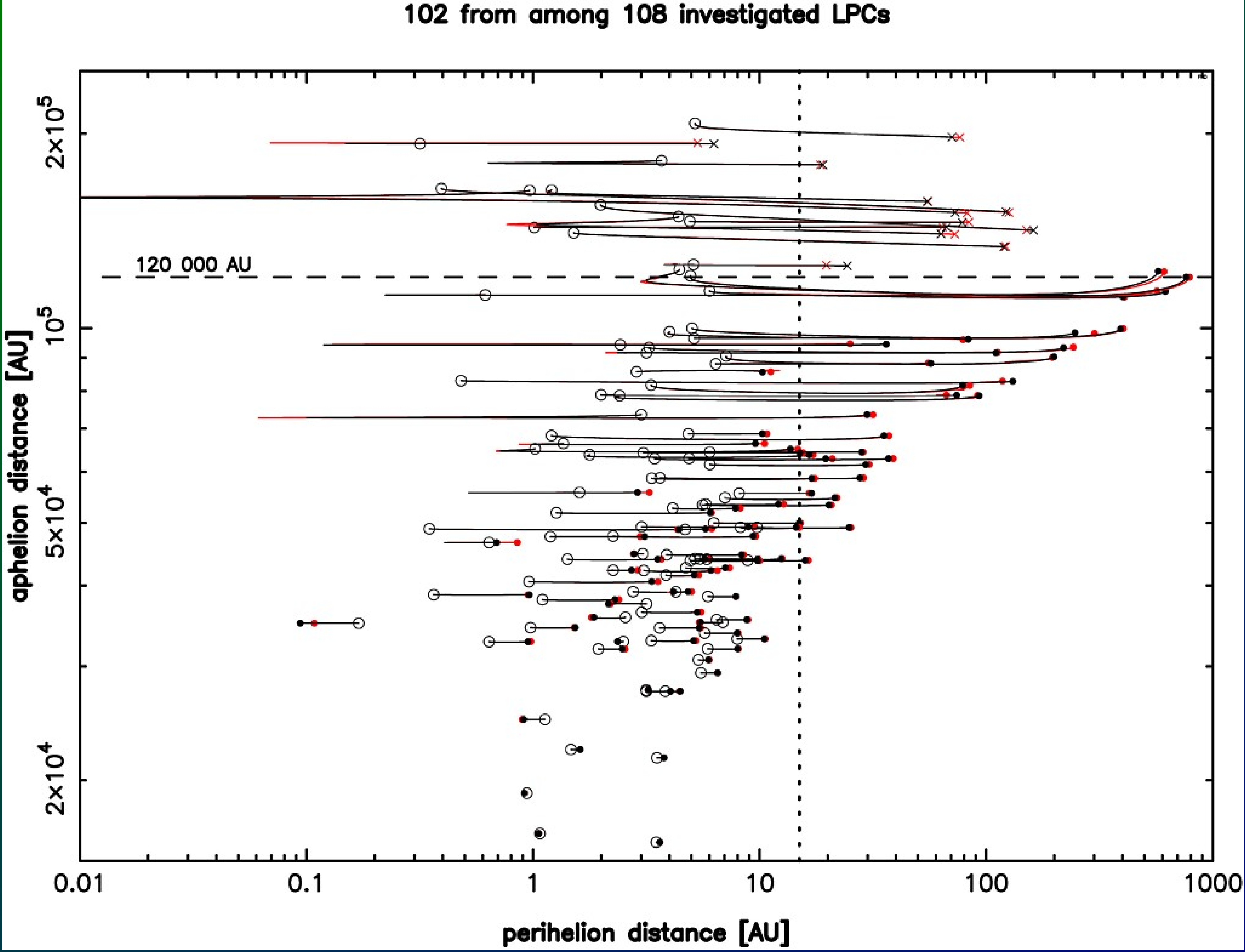
$$\frac{d^2x}{dt^2} = -\frac{\mu M_\odot}{r^3}x - \mathcal{G}_1 x' \cos(\Omega_0 t) + \mathcal{G}_2 y' \sin(\Omega_0 t),$$
$$\frac{d^2y}{dt^2} = -\frac{\mu M_\odot}{r^3}y - \mathcal{G}_1 x' \sin(\Omega_0 t) - \mathcal{G}_2 y' \cos(\Omega_0 t),$$
$$\frac{d^2z}{dt^2} = -\frac{\mu M_\odot}{r^3}z - \mathcal{G}_3 z,$$

Assuming a local density of the galactic disk in the solar neighborhood $\rho_0 = 0.1 M_\odot\ \mathrm{pc}^{-3}$, an angular velocity of the Sun around the Galaxy center $\Omega_0 = B - A = -26\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ and with the approximation $A = -B$ (thus $\mathcal{G}_1 = -\Omega_0^2$), Levison et al. (2001) gives the following values to $\mathcal{G}_1, \mathcal{G}_2$ and $\mathcal{G}_3$:

$$\mathcal{G}_1 = -7.0706 \times 10^{-16}\ \mathrm{years}^{-2},$$
$$\mathcal{G}_2 = -\mathcal{G}_1,$$
$$\mathcal{G}_3 = 5.6530 \times 10^{-15}\ \mathrm{years}^{-2}.$$

The values of $\mathcal{G}_1, \mathcal{G}_2$, and $\mathcal{G}_3$ tell us that the radial component of the tide is almost 10 times smaller than the normal one. This is the reason why in the present study, as well as in many others, the radial component is neglected, i.e., $\mathcal{G}_1 = \mathcal{G}_2 = 0$.

Marc Fouchard, Christiane Froeschlé, Giovanni Valsecchi, Hans Rickman, 2006


102 from among 108 investigated LPCs
120 000 AU
aphelion distance [AU]
perihelion distance [AU]
2×10^5
10^5
5×10^4
2×10^4
0.01
0.1
1
10
100
1000

New dynamical model for simultaneous stellar and Galactic perturbations

see: Dybczyński & Berski, MNRAS, 2015

Galactic potential:
model I from Irrgang et al., A&A, 2013

Table 1. Model I parameters from Irrgang et al. (2013).

Parameter	Value
The distance of the Sun from the Galactic Centre $R_\odot$	8400 pc
Galactic bulge mass M_b	$9.51 \times 10^9\ \mathrm{M}_\odot$
Galactic disc mass M_d	$66.4 \times 10^9\ \mathrm{M}_\odot$
Galactic halo mass M_h	$23.7 \times 10^9\ \mathrm{M}_\odot$
Bulge characteristic distance b_b	230 pc
Disc characteristic distance a_d	4220 pc
Disc characteristic distance b_d	292 pc
Halo characteristic distance a_h	2562 pc
Galactic halo cut-off parameter Λ	200 000 pc
Galactic halo exponent parameter γ	2 (fixed)
Galactic disc matter density near the Sun ρ_o	$0.102\ \mathrm{M}_\odot\,\mathrm{pc}^{-3}$
Galactic rotational velocity of the LSR v_o	$242\ \mathrm{km\,s}^{-1}$

A ($\mathrm{km\,s^{-1}\,kpc^{-1}}$)	15.06	B ($\mathrm{km\,s^{-1}\,kpc^{-1}}$)	−13.74

Numerical integration of the N-body system (Sun + comet + 90 stars or stellar systems) in Galactocentric, non rotating frame.

$$\boldsymbol{R}_\odot = (x_\odot, y_\odot, z_\odot) = (-8400, 0, 17) \text{ pc}$$

$$\dot{\boldsymbol{R}}_\odot = (u, v, w) = (+11.1, +254.24, +7.25) \text{ km s}^{-1}$$
$$= (+11.352, +260.011, +7.41) \text{ pc Myr}^{-1}.$$

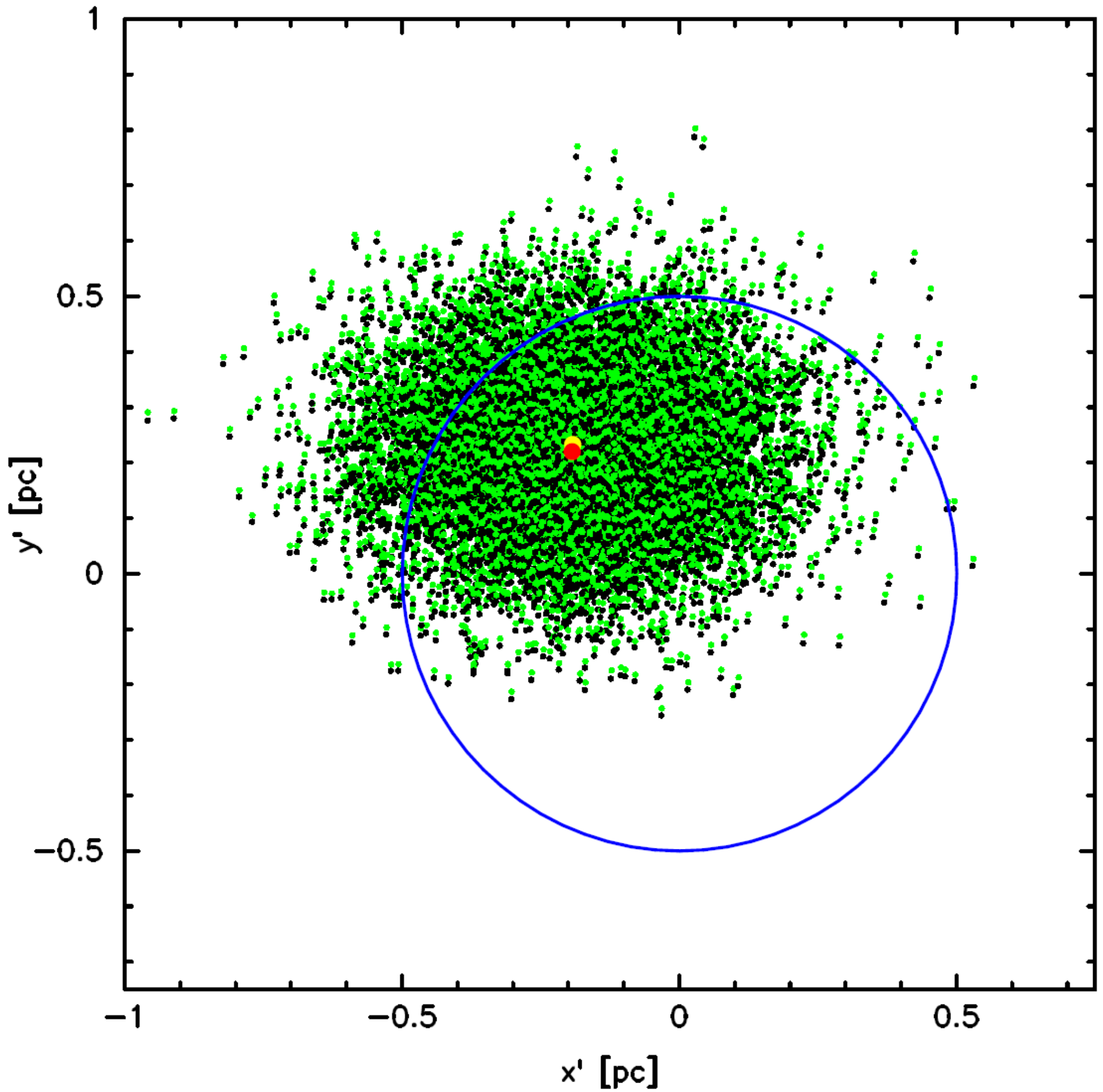


Figure 6. Distribution of the clones of Gliese 710 using $RV = -13.80\,\mathrm{km\,s^{-1}}$.

Dybczyński & Berski, 2015

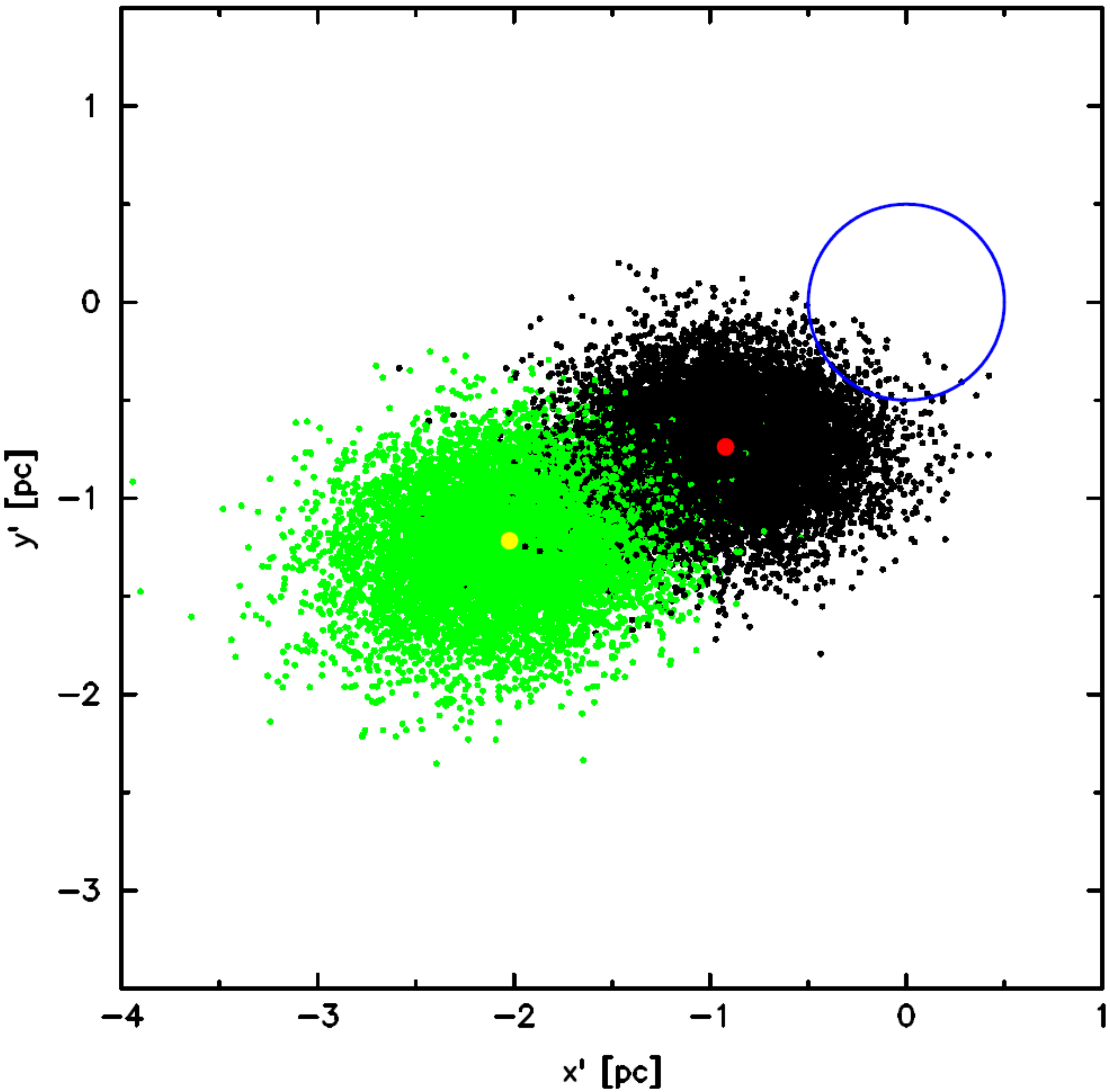


Figure 8. Distribution of the clones of HIP 103738.

Dybczyński & Berski, 2015

Example:

dynamical evolution of

C/2001 C1 LINEAR

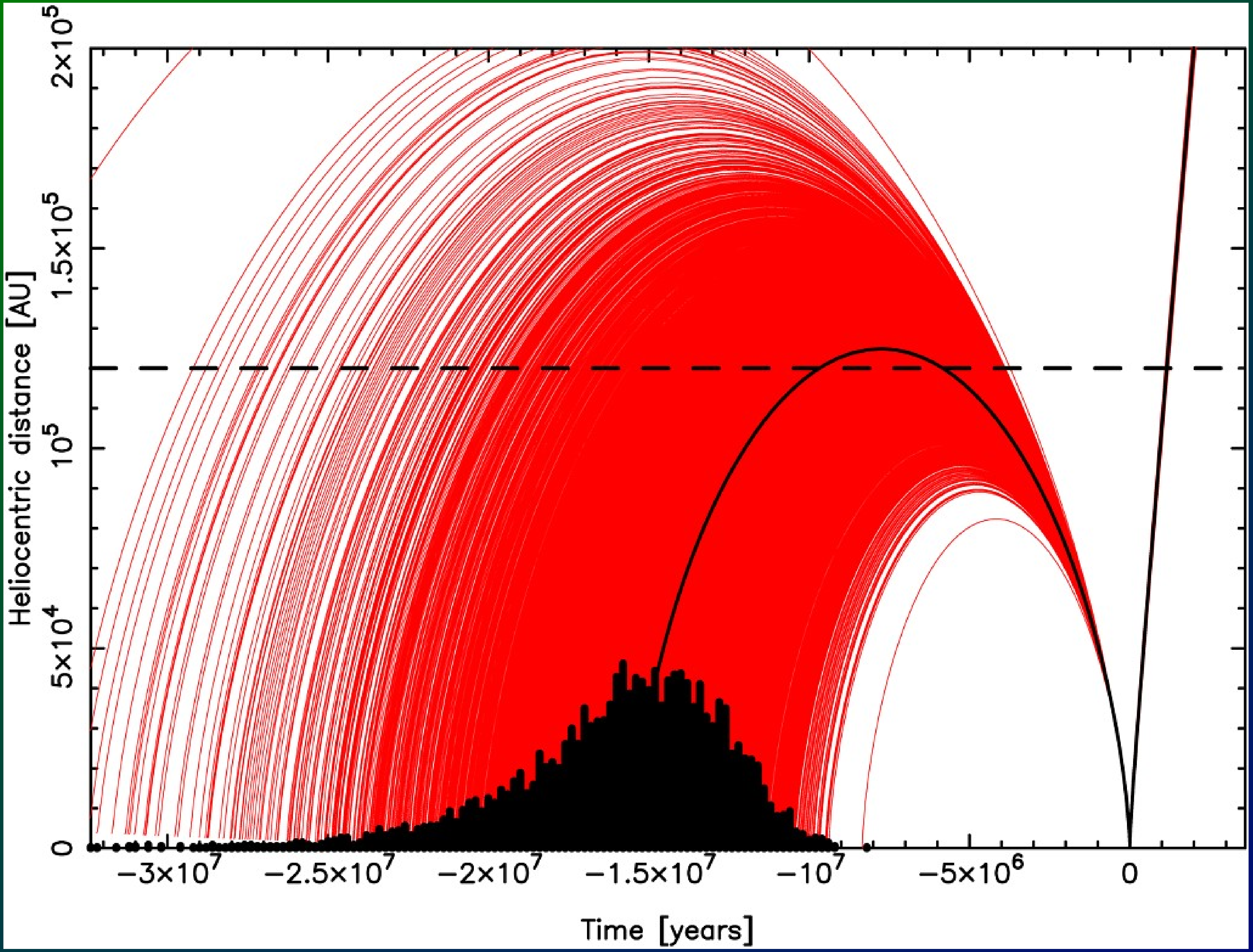
Comet C/2001 C1 LINEAR

number of observations	223
number of residuals	436
data interval	2000 Apr. 29 — 2002 July 3
rms [arcsec]	0.67
orbit quality class	1a

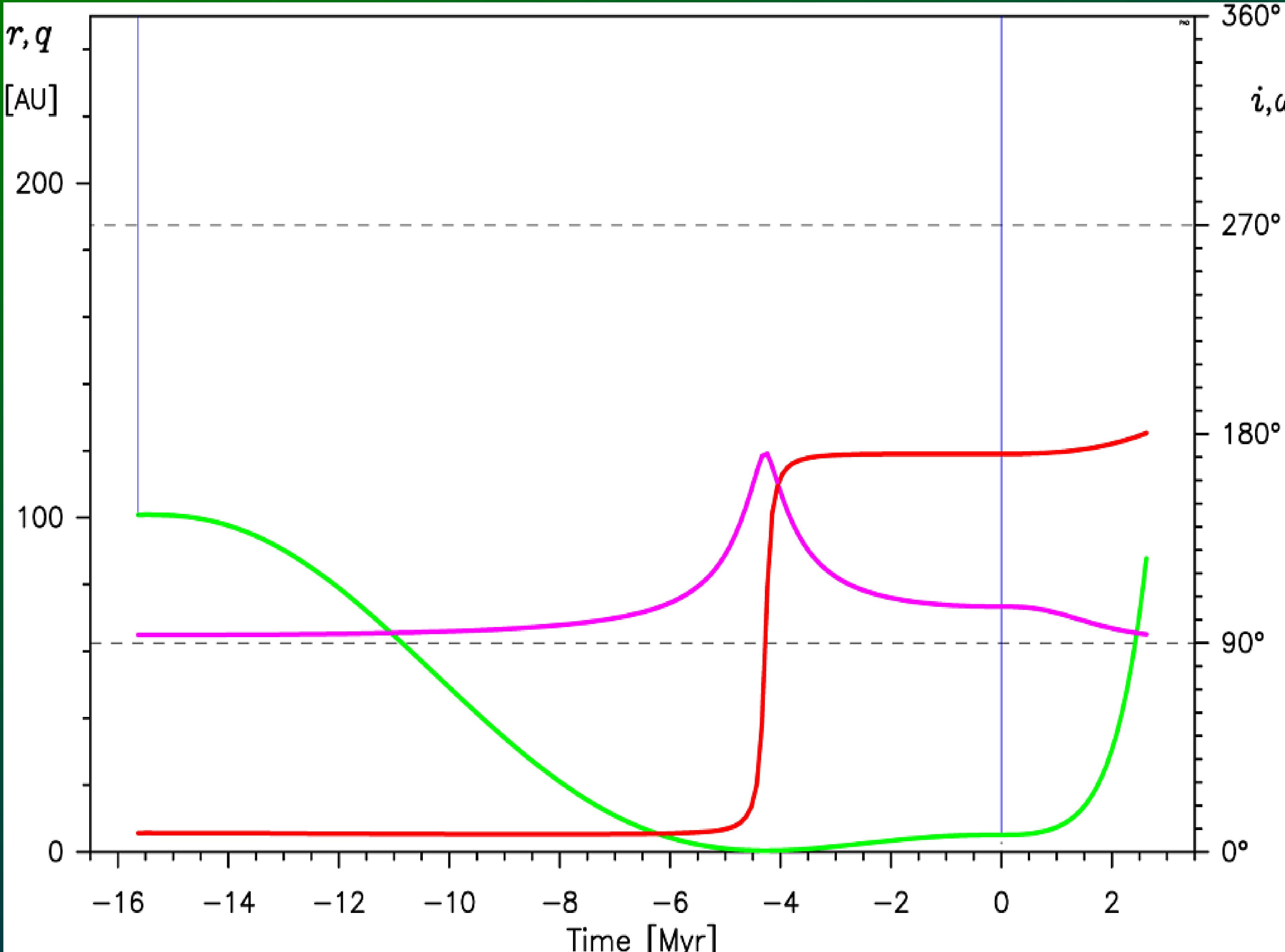
Original orbital elements (barycentric; at 250 au from the Sun)

Epoch (TT)	16960906	
time of perihelion passage (TT)	20020328.801115	± 0.002426
perihelion distance	5.11002022	± 0.00001152
eccentricity	0.99991858	± 0.00001070
argument of perihelion [deg]	219.952566	± 0.000276
longitude of the ascending node [deg]	33.760054	± 0.000013
inclination [deg]	68.910831	± 0.000050
inverse semimajor axis [10^{-6} au^{-1}]	15.93	± 2.09

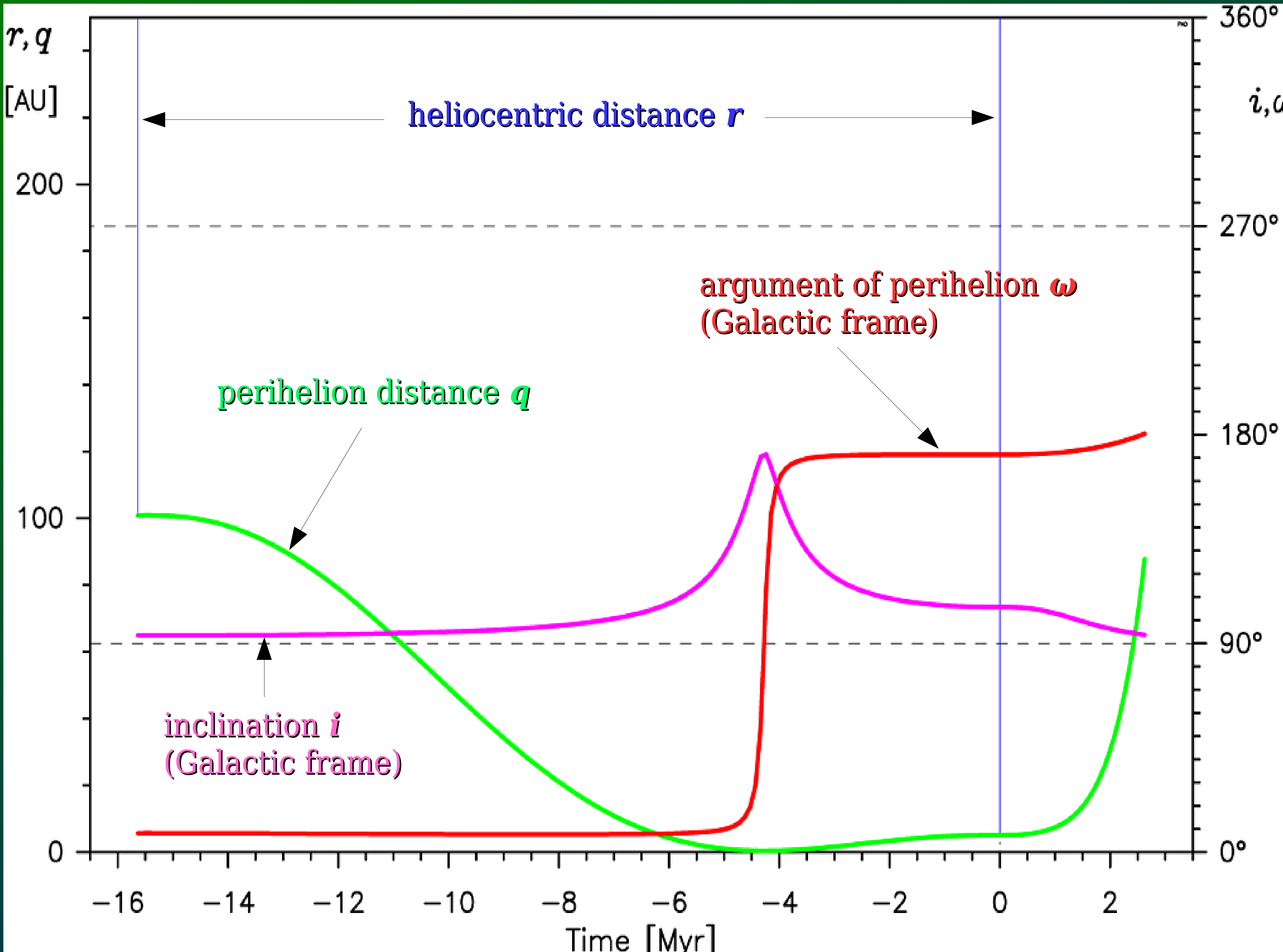
http://ssdp.cbk.waw.pl/LPCs/Catalogue/2001c1.html



5001 VCs of C/2001 C1



Galactic disk tide only.



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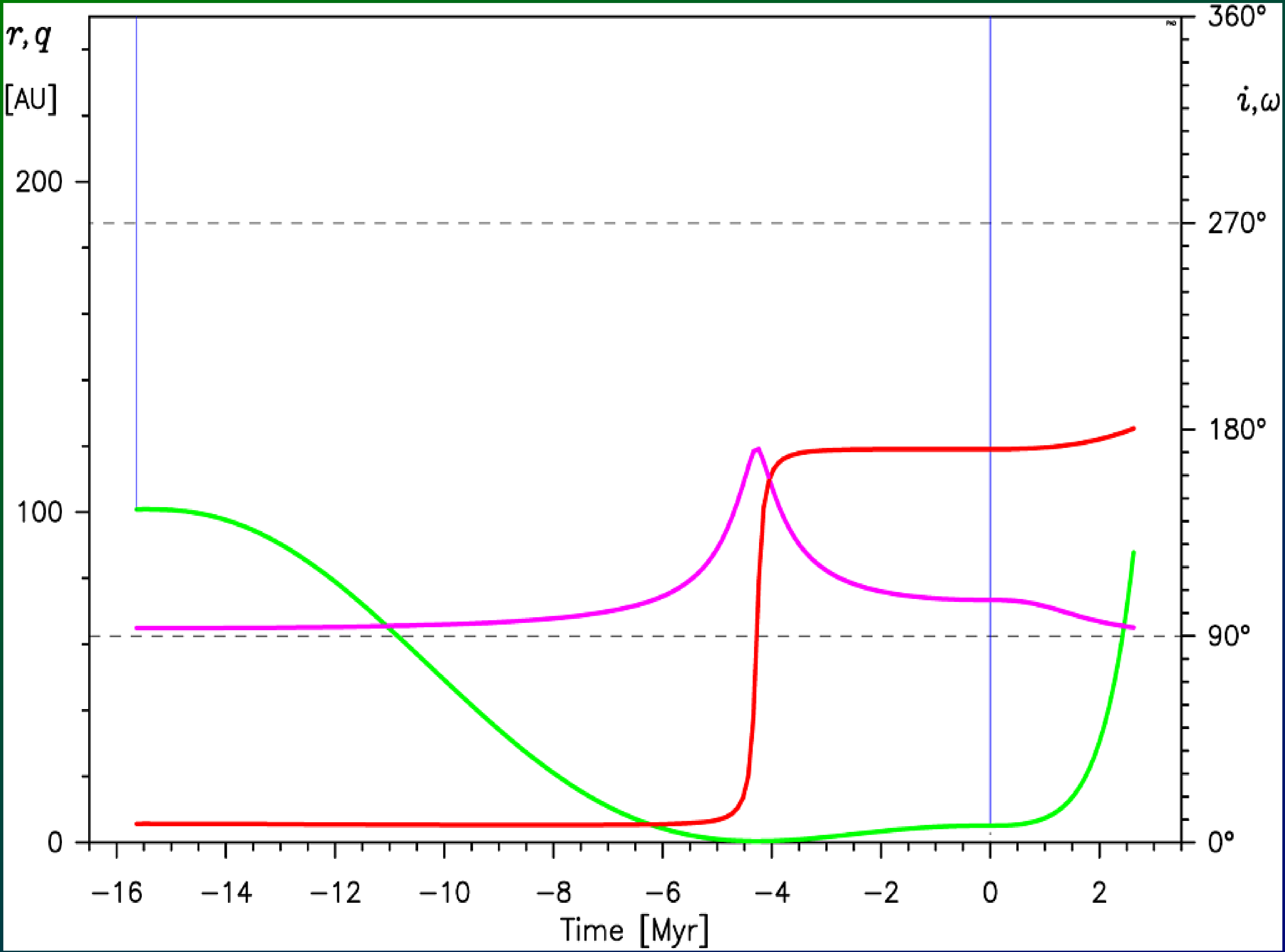
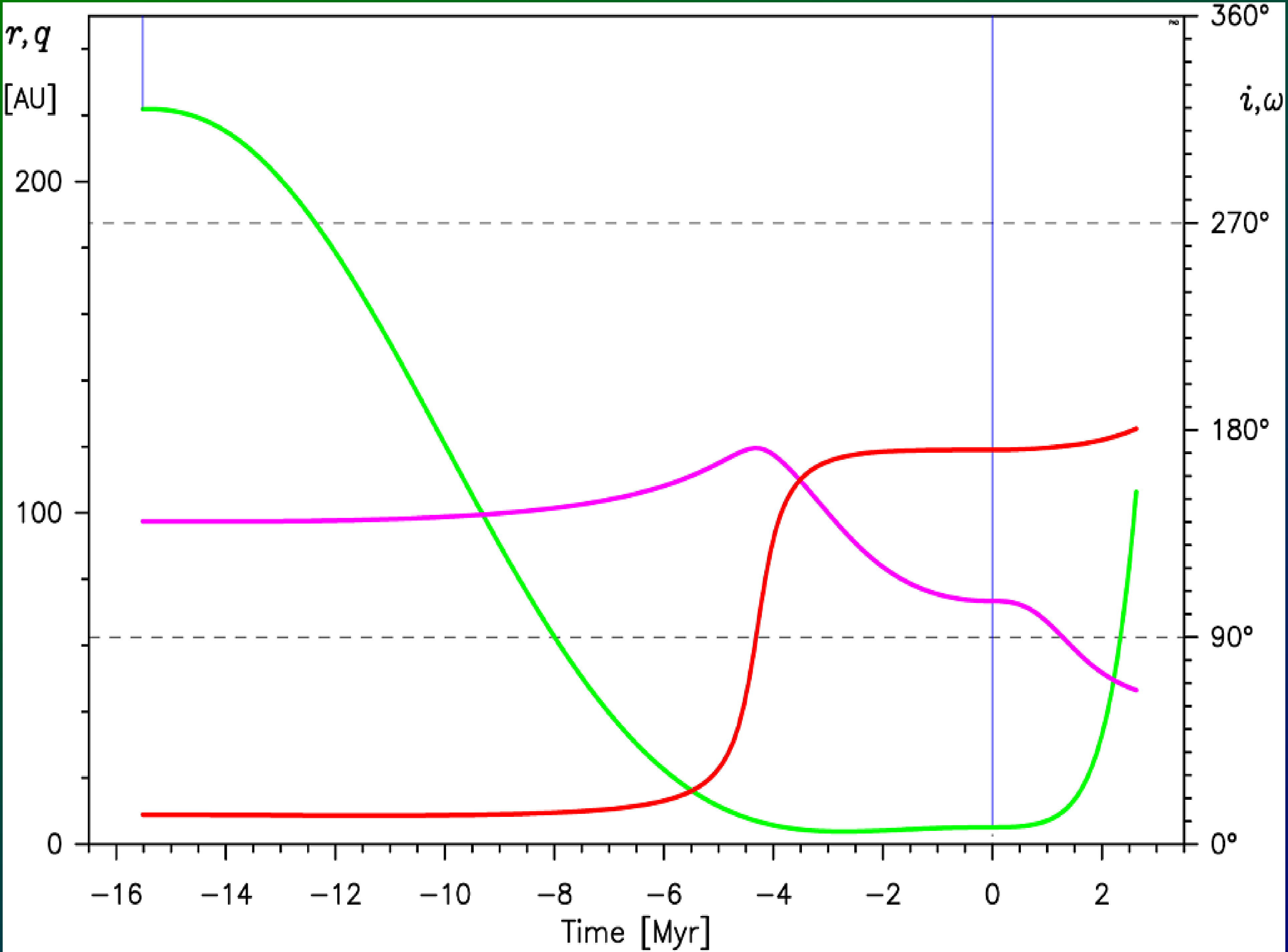
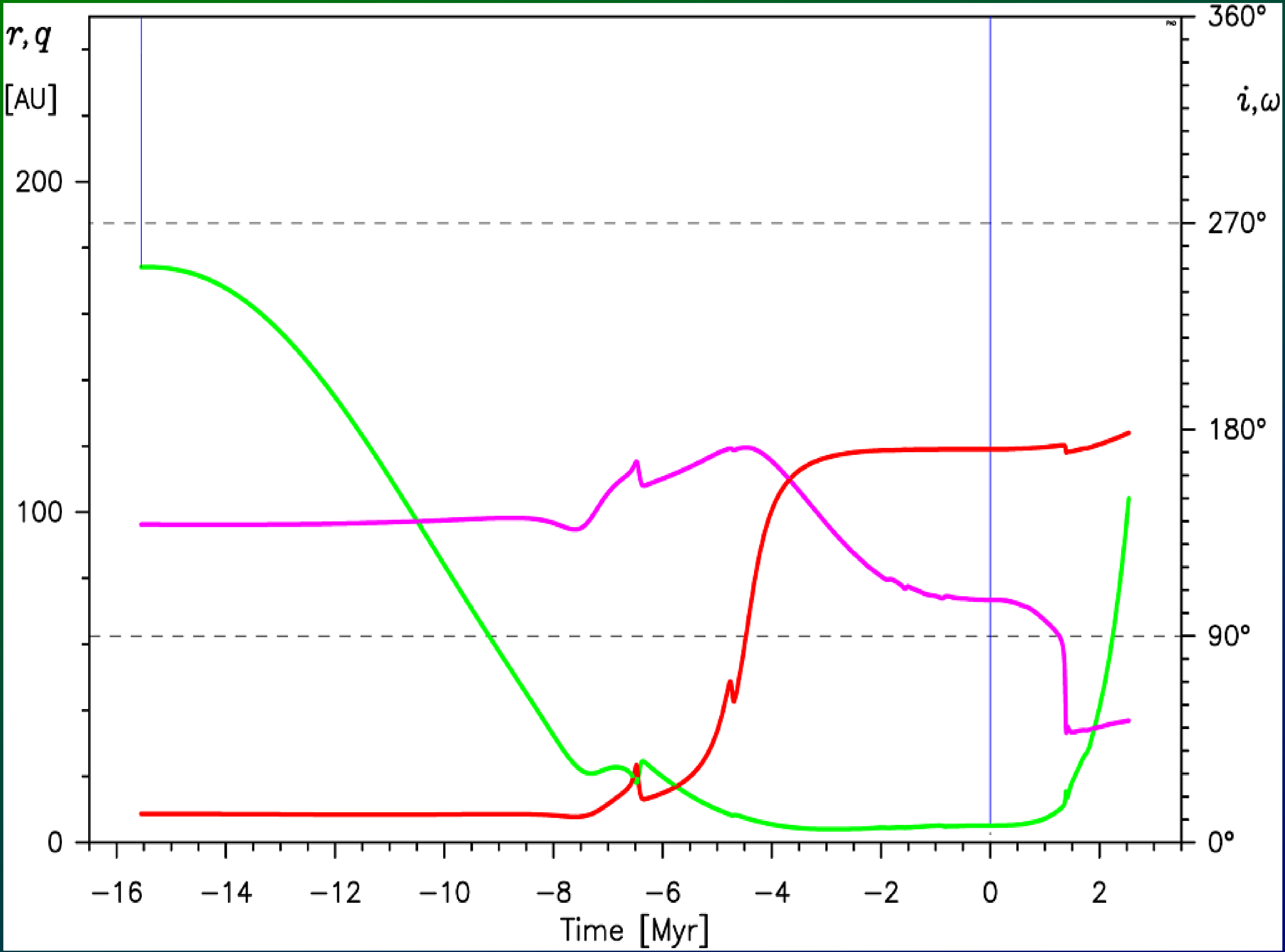


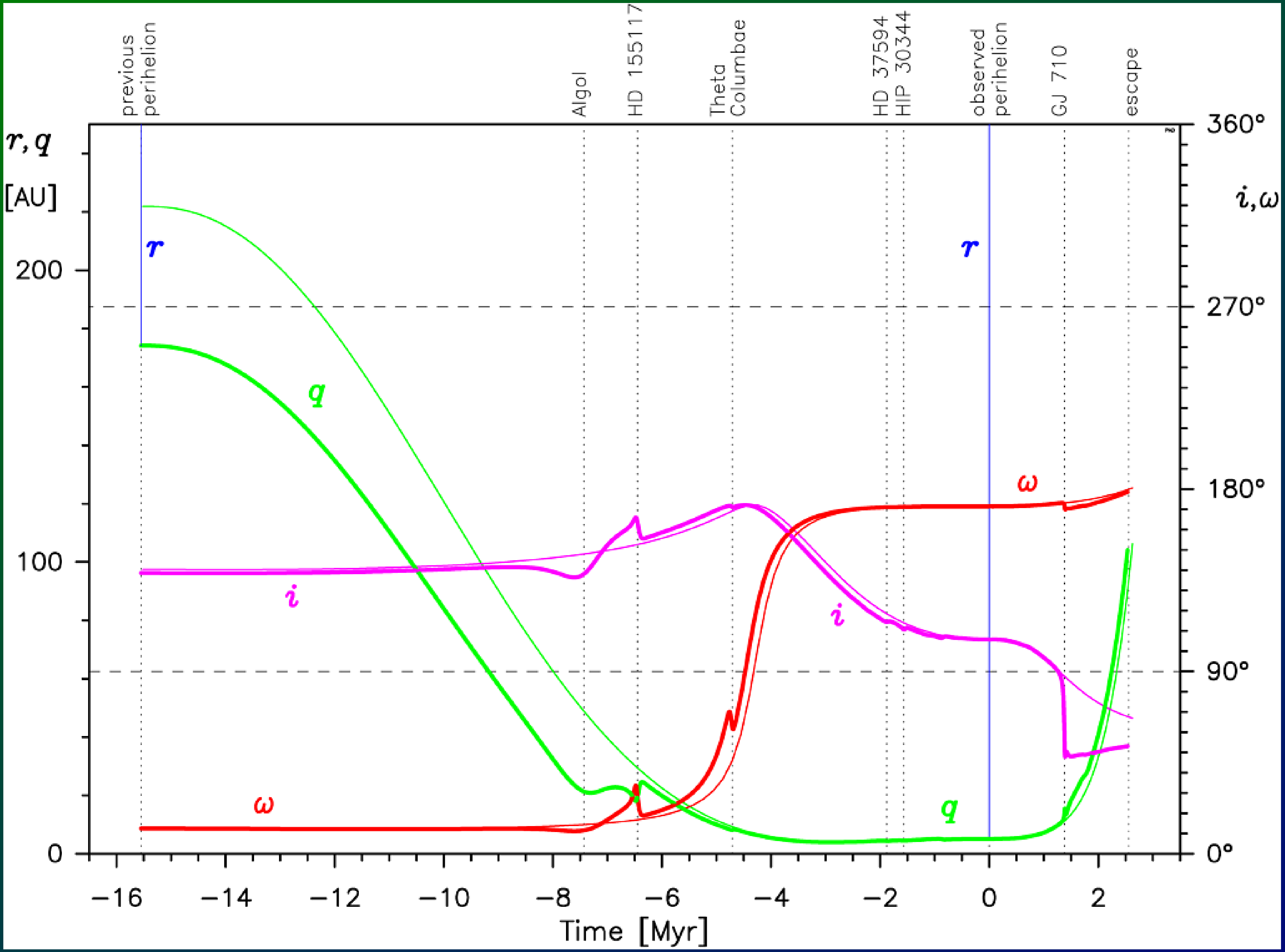
Galactic disk tide only.



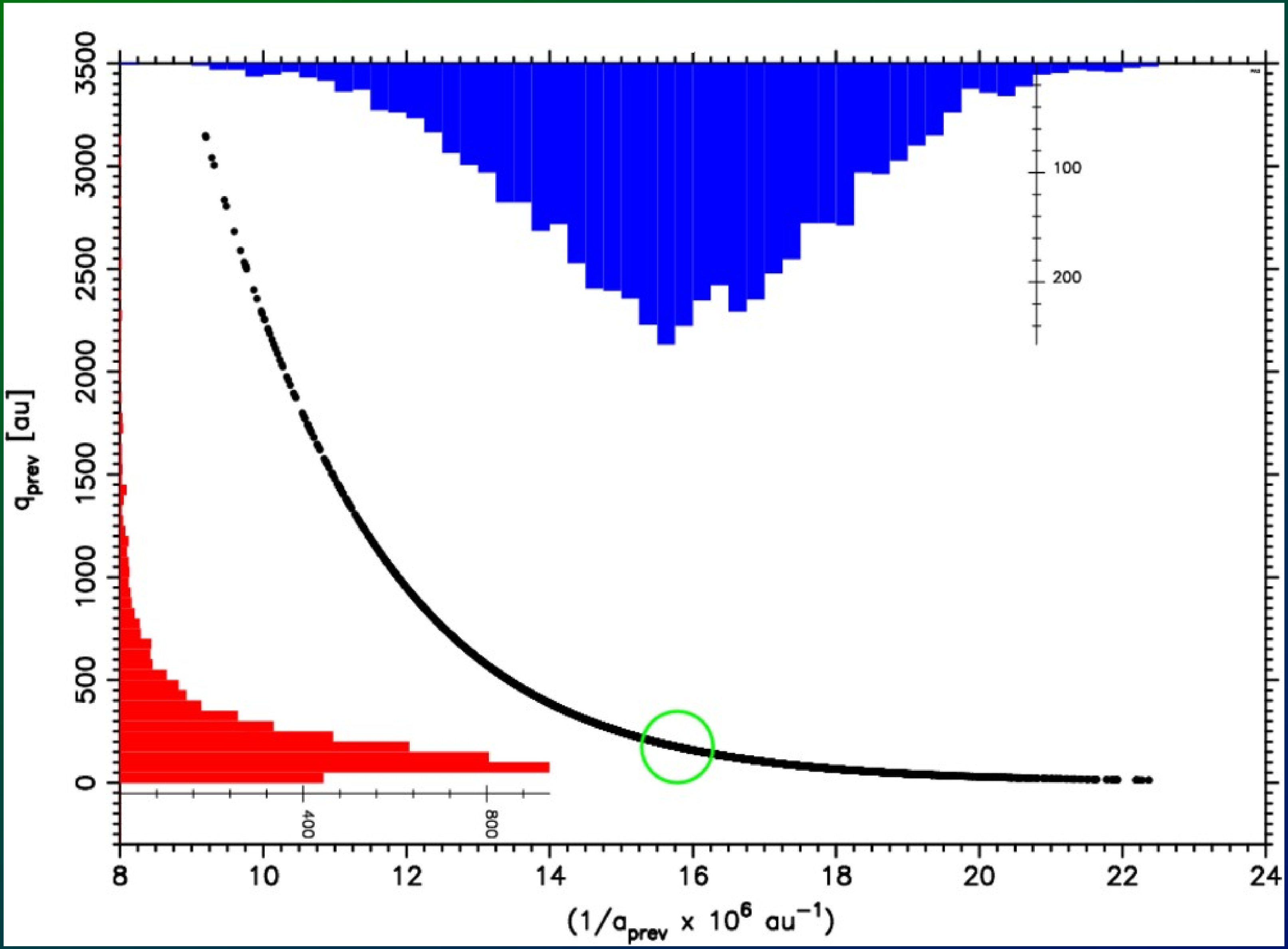
Galactic disk + centre.



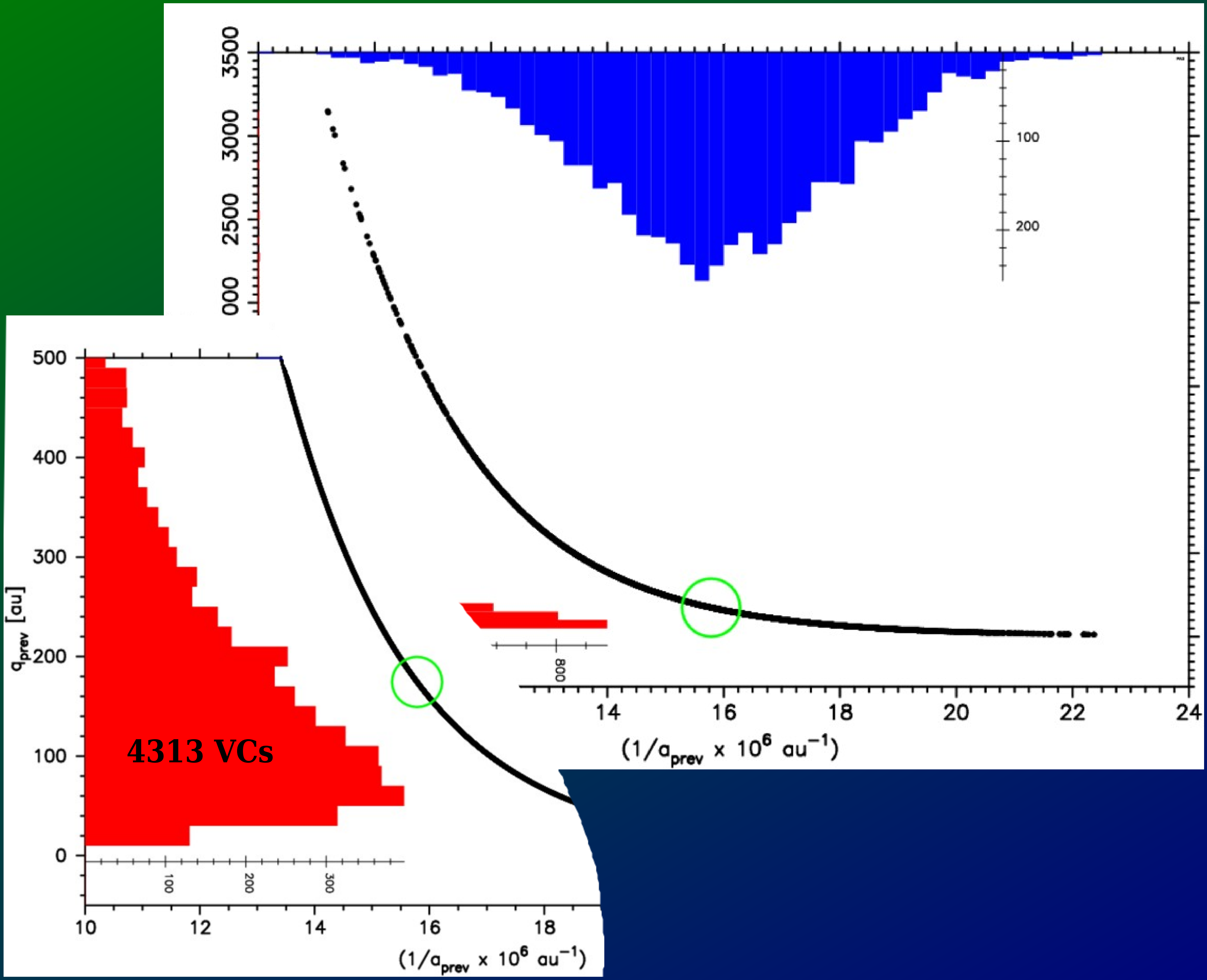
Galactic disk + centre + 90 stars → differential model.



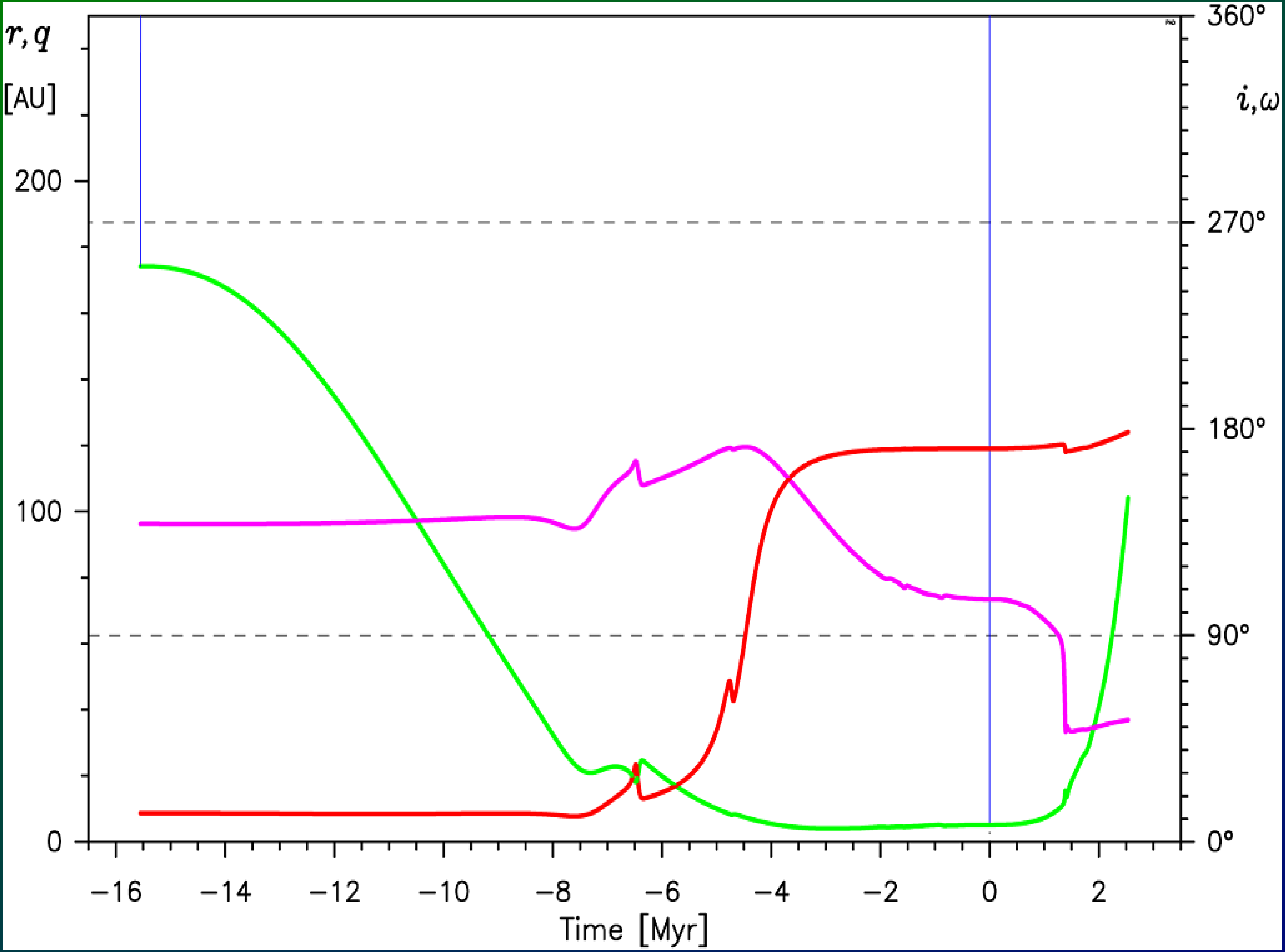
Galactic disk + centre + 90 stars → differential model.



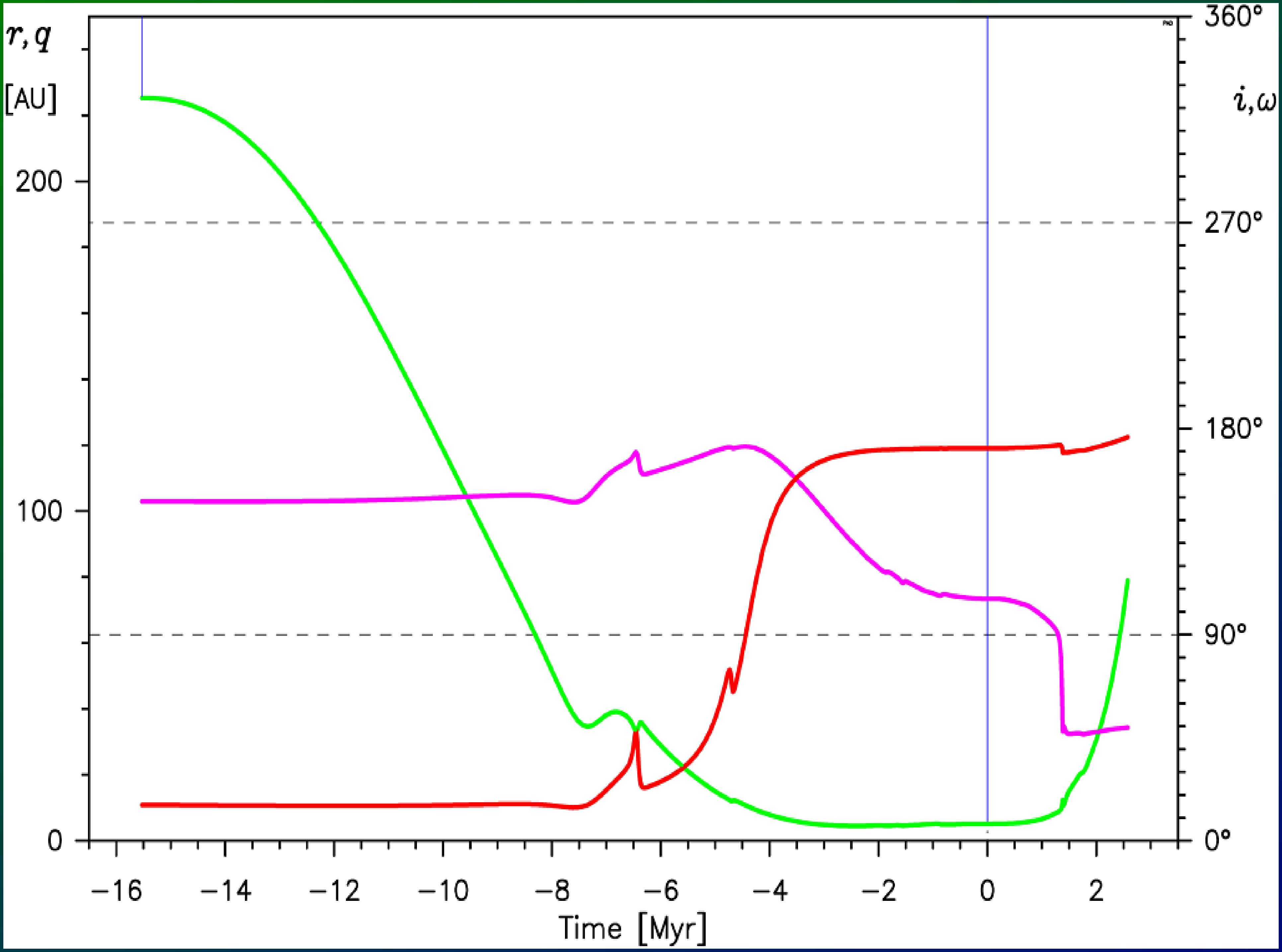
5001 VCs of C/2001 C1 stopped at previous perihelion



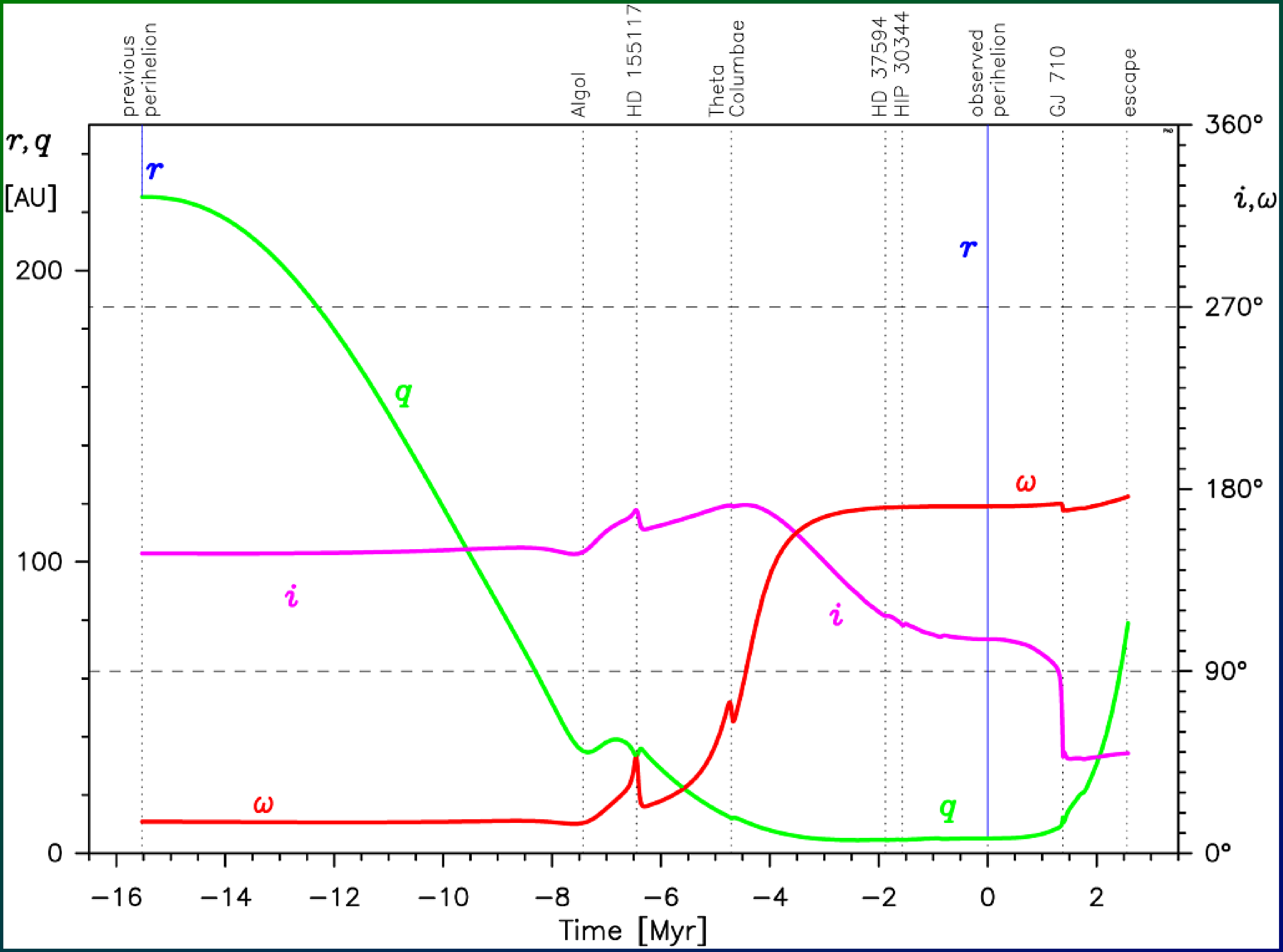
3500
3000
2500
000
100
200
800
14
16
18
20
22
24
$(1/a_{prev} \times 10^6\ au^{-1})$
500
400
300
200
100
0
q_{prev} [au]
4313 VCs
100
200
300
10
12
14
16
18
$(1/a_{prev} \times 10^6\ au^{-1})$



Galactic disk + centre + 90 stars → differential model.



Galactic disk + centre + 90 stars → full model.



Galactic disk + centre + 90 stars → full model.

New Gaia stellar data highly needed !

New Gaia stellar data highly needed !

(this summer ?)

Thank you.