The Oort cloud: shape and dynamics

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Plan

- The pertubators of the Oort cloud
- The synergy between stellar perturbations and Galactic tides
- Long term simulations: shape of the Oort cloud and observable flux of LPC
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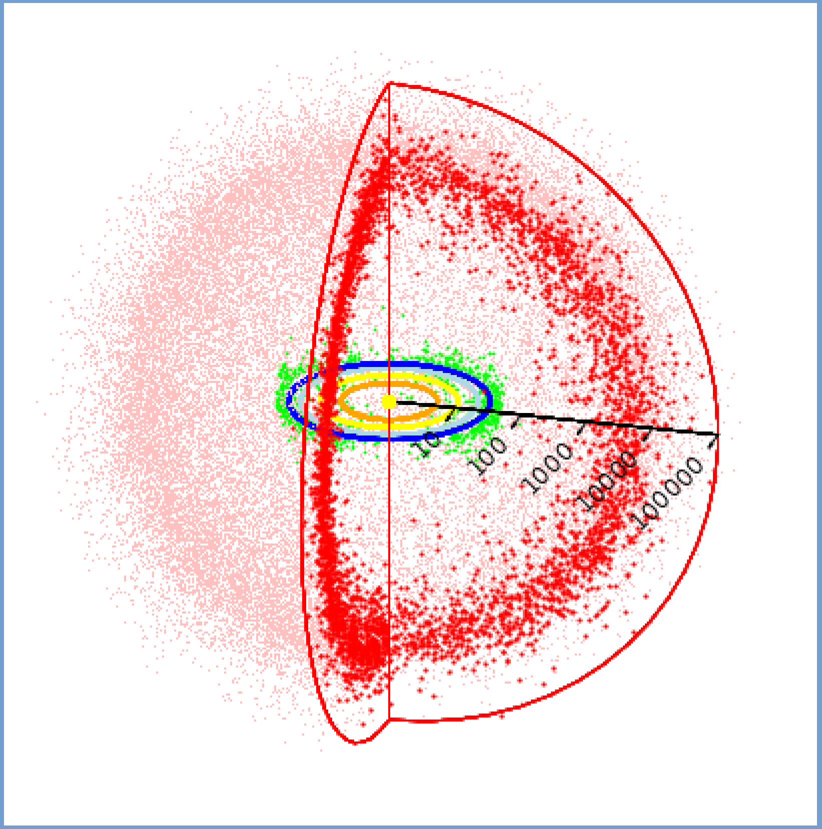
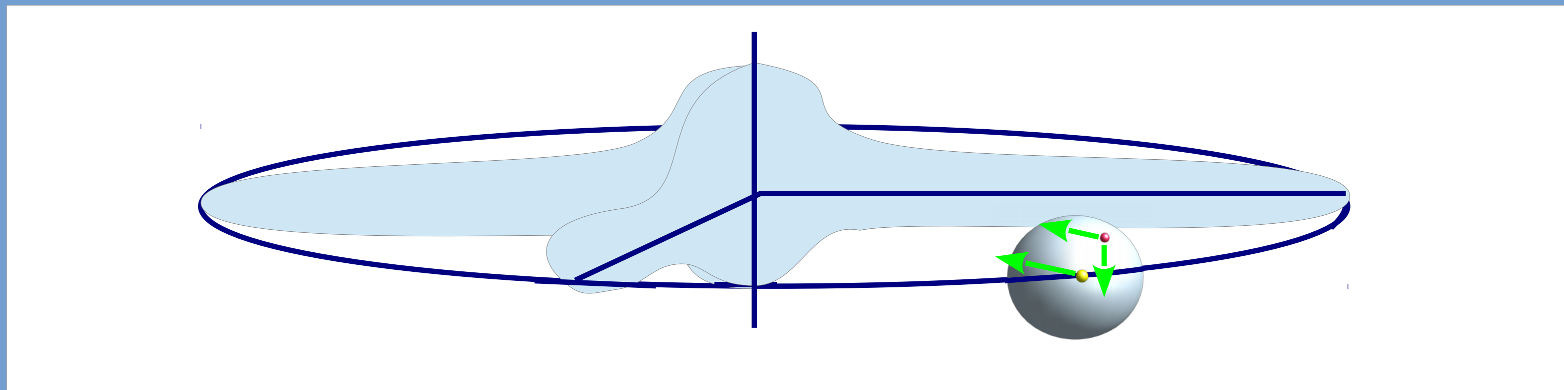
Three main perturbators

- Stellar perturbations caused by a close encounter of the Sun with a passing star ;
- Galactic tides caused by the difference of the gravitational attraction of the entire Galaxy on the Sun and on the comet ;
- Planetary perturbations, when the trajectory of the Oort cloud comets penetrate within the planetary region of the solar system ;
- The Giant Molecular cloud, usually not taken into account, even if they might be efficient perturbators of the Oort cloud.



A model for the Galactic tides



Expression of the force in a rotating frame:

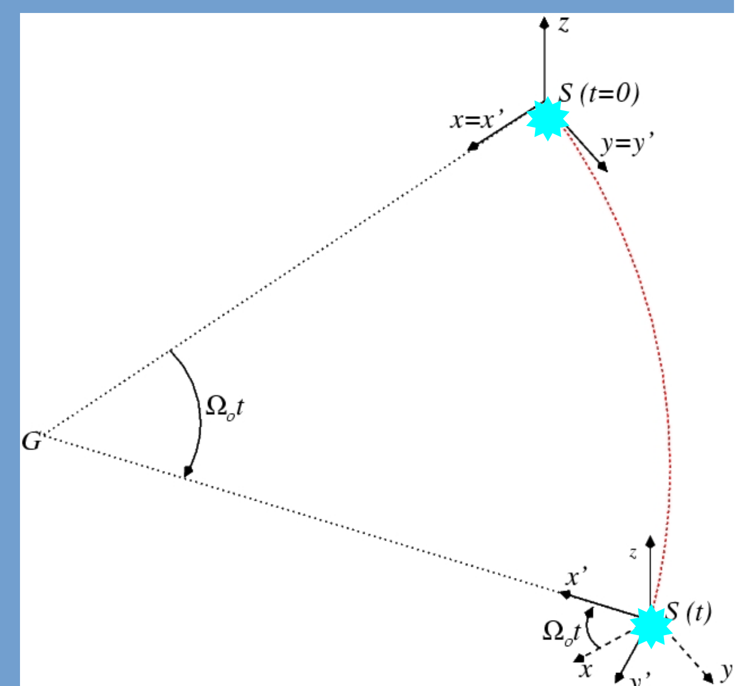
$$F_{Tide} = -\mathcal{G}_1 x'\hat{x}' - \mathcal{G}_2 y'\hat{y}' - \mathcal{G}_3 z\hat{z}$$

where $\mathcal{G}_1 = 7.0707 \times 10^{-16}\,\text{years}^{-2}$

$\mathcal{G}_2 = -\mathcal{G}_1$

$\mathcal{G}_3 = 5.6530 \times 10^{-15}\,\text{years}^{-2}$

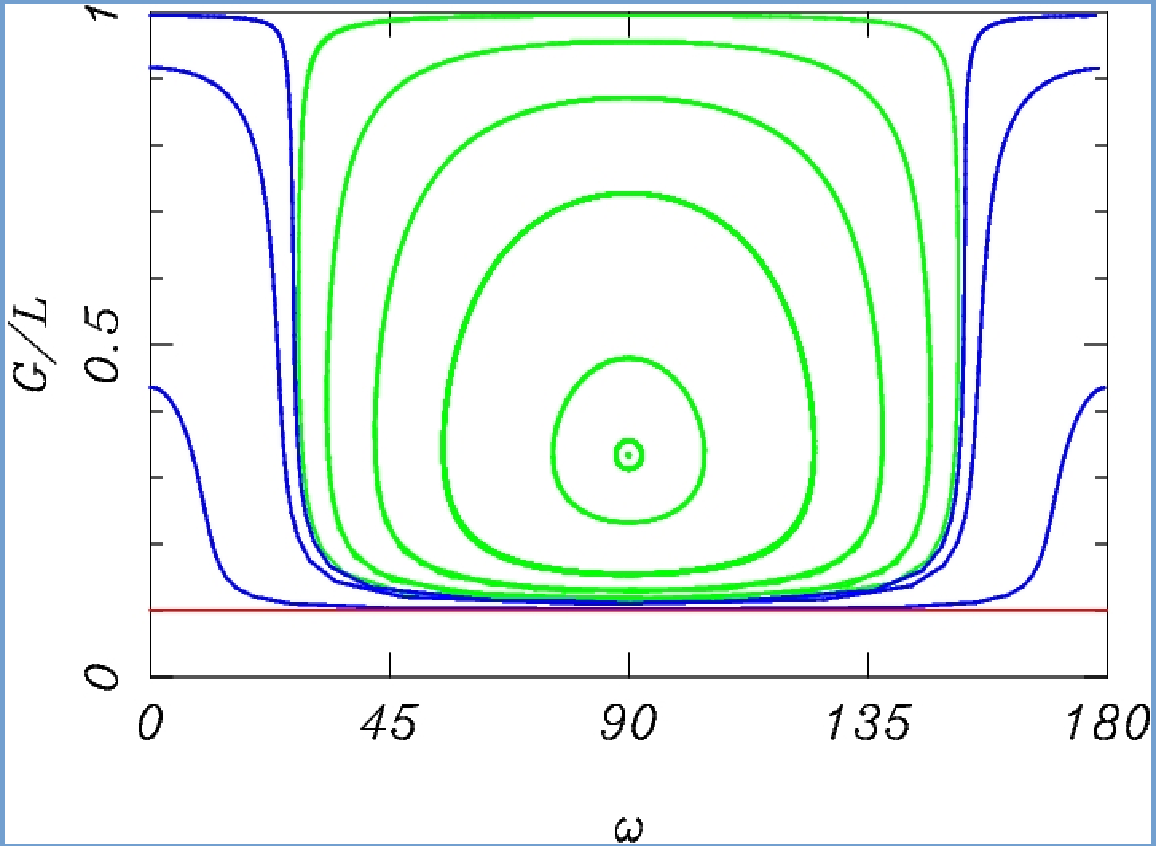
$\Omega_o = -\sqrt{\mathcal{G}_1}$



The Galactic tides: integrable case

- Constants of motion:

$$a = 30\,000 \text{ AU}$$
$$\sqrt{1-e^2}\cos i = 0.1$$



- Period and perturbations strength over one orbital period:

$$P_e \propto P_{orb}^{-1}, \qquad \Delta q \propto a^{7/2}$$

The stellar environment of the Sun

Construction of a sample of random stellar passages with the following criteria according to the stellar type (13 different types are used):

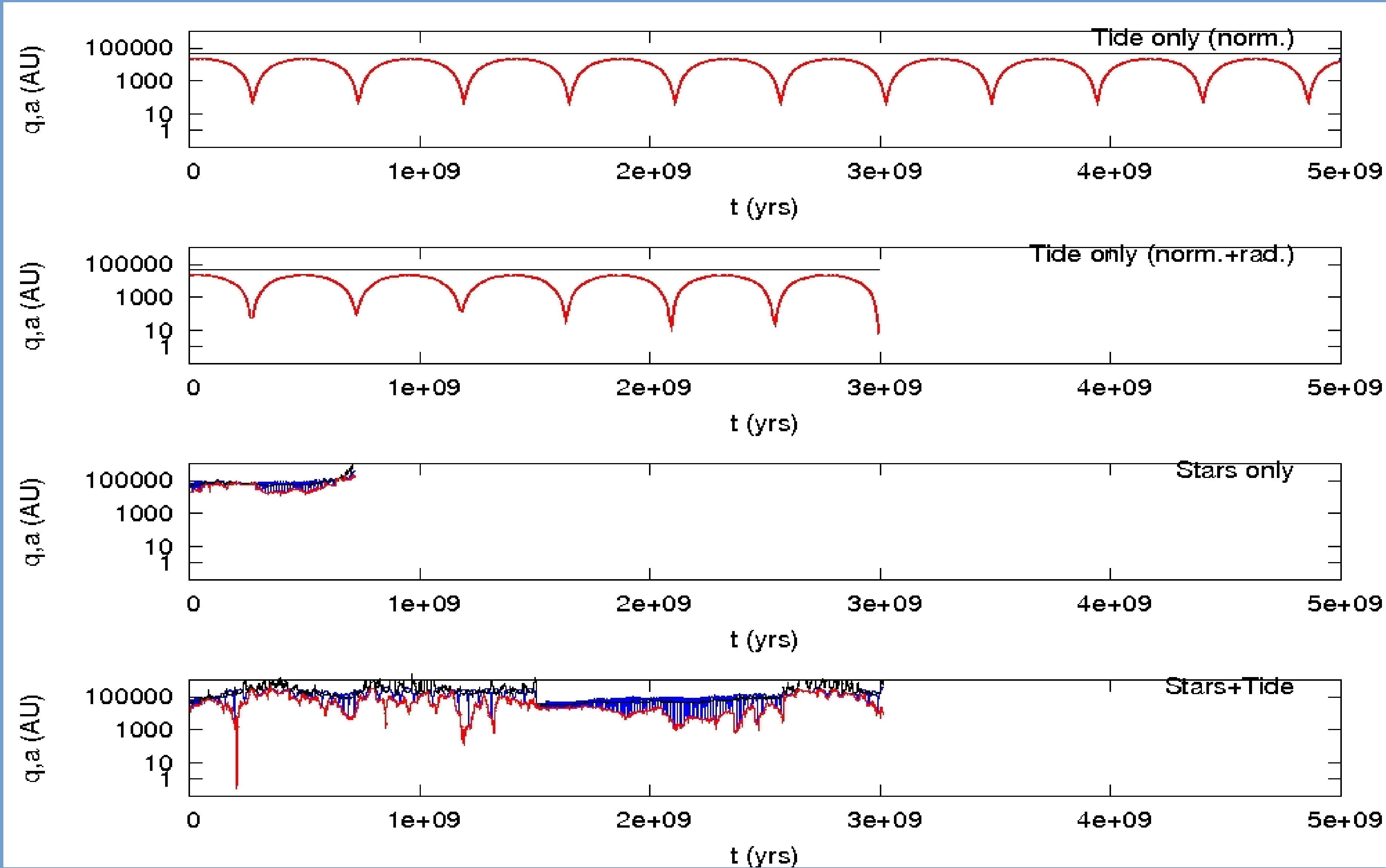
- the stellar mass is fixed;
- speed and time of perihelion passage are chosen randomly respecting the actual observed distribution;
- velocity direction is chosen randomly corresponding to an isotropic distribution.

197 906 stellar passages within 400,000 AU from the Sun in 5 Gyr are thus defined during a 5 Gyr time span with the following characteristics:

Type	Mass ($M_\odot$)	Enc. Freq.	V (km/s)	σ (km/s)
gi	4	0.06	49.7	17.5
B0	9	0.01	24.6	6.7
A0	3.2	0.03	27.5	9.3
A5	2.1	0.04	29.3	10.4
F0	1.7	0.15	36.5	12.6
F5	1.3	0.08	43.6	15.6
G0	1.1	0.22	49.8	17.1
G5	0.93	0.35	49.6	17.9
K0	0.78	0.34	42.6	15
K5	0.69	0.85	54.3	19.2
M0	0.47	1.29	50	18
M5	0.21	6.39	51.8	18.3
wd	0.9	0.72	80.2	28.2

Example I

a
q
r



Tide only (norm.)
Tide only (norm.+rad.)
Stars only
Stars+Tide
q,a (AU)
100000
1000
10
1
0
1e+09
2e+09
3e+09
4e+09
5e+09
t (yrs)

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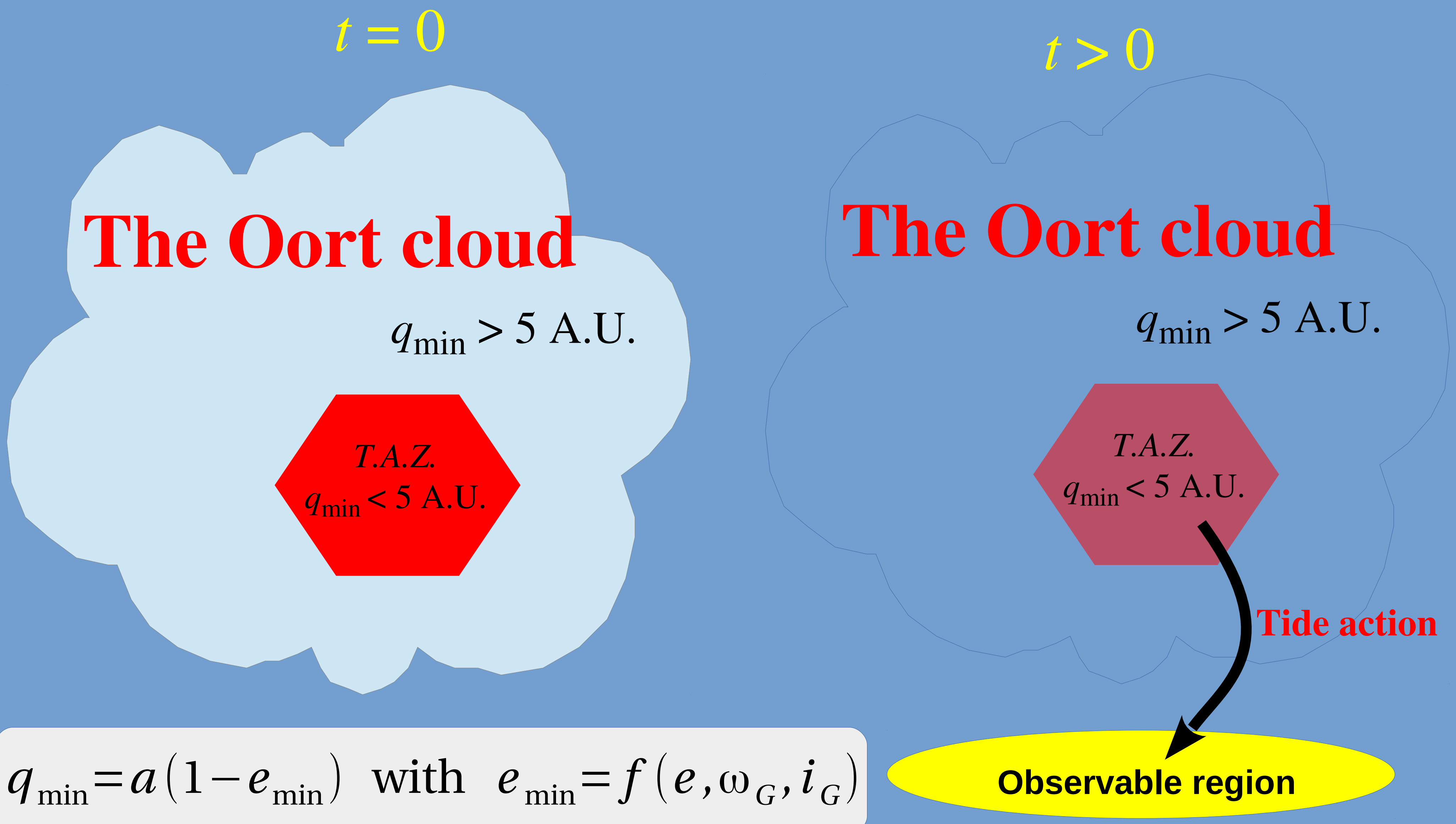
The Tidal Active Zone

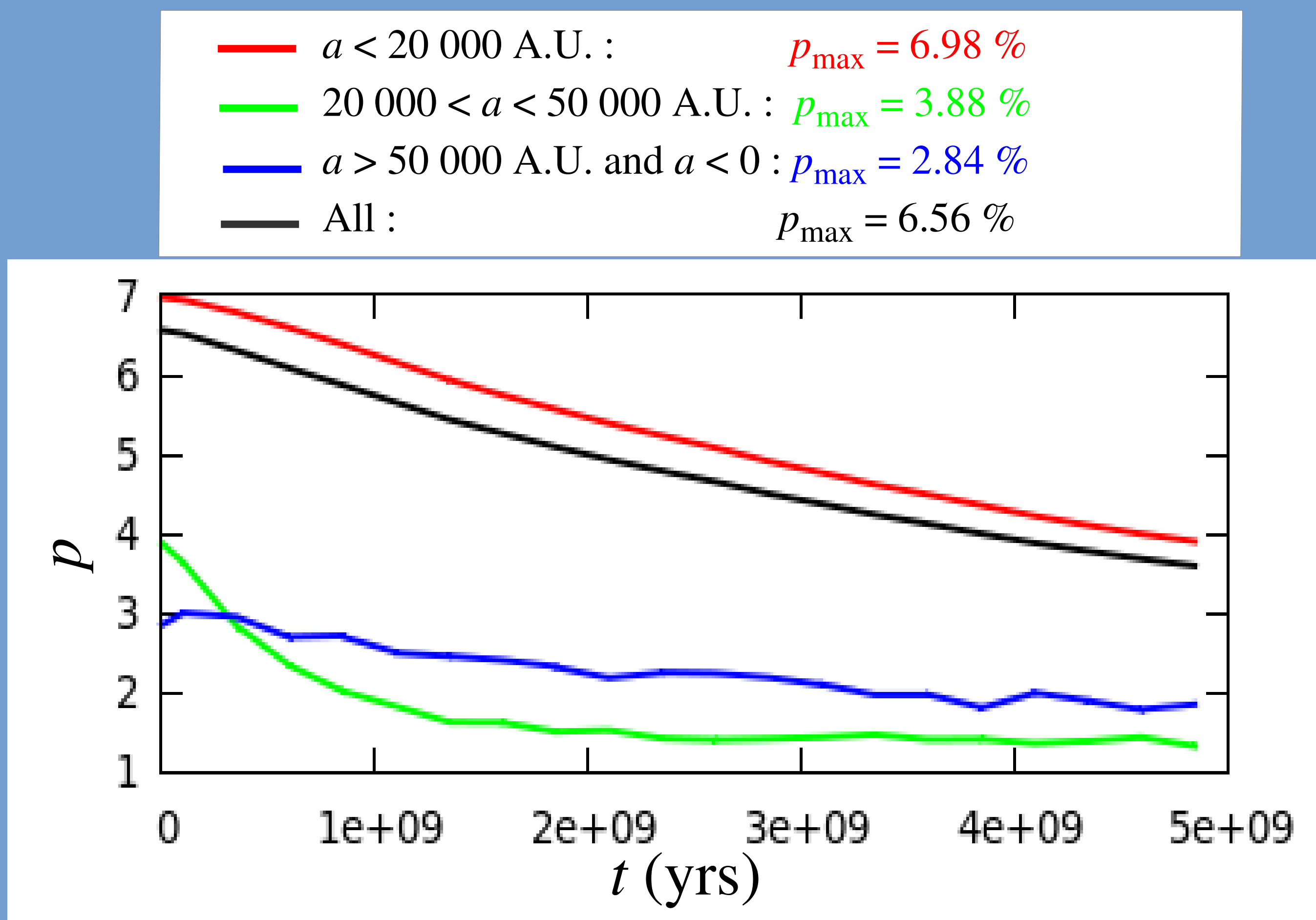


$$q_{\min} = a(1 - e_{\min}) \quad \text{with} \quad e_{\min} = f(e, \omega_G, i_G)$$

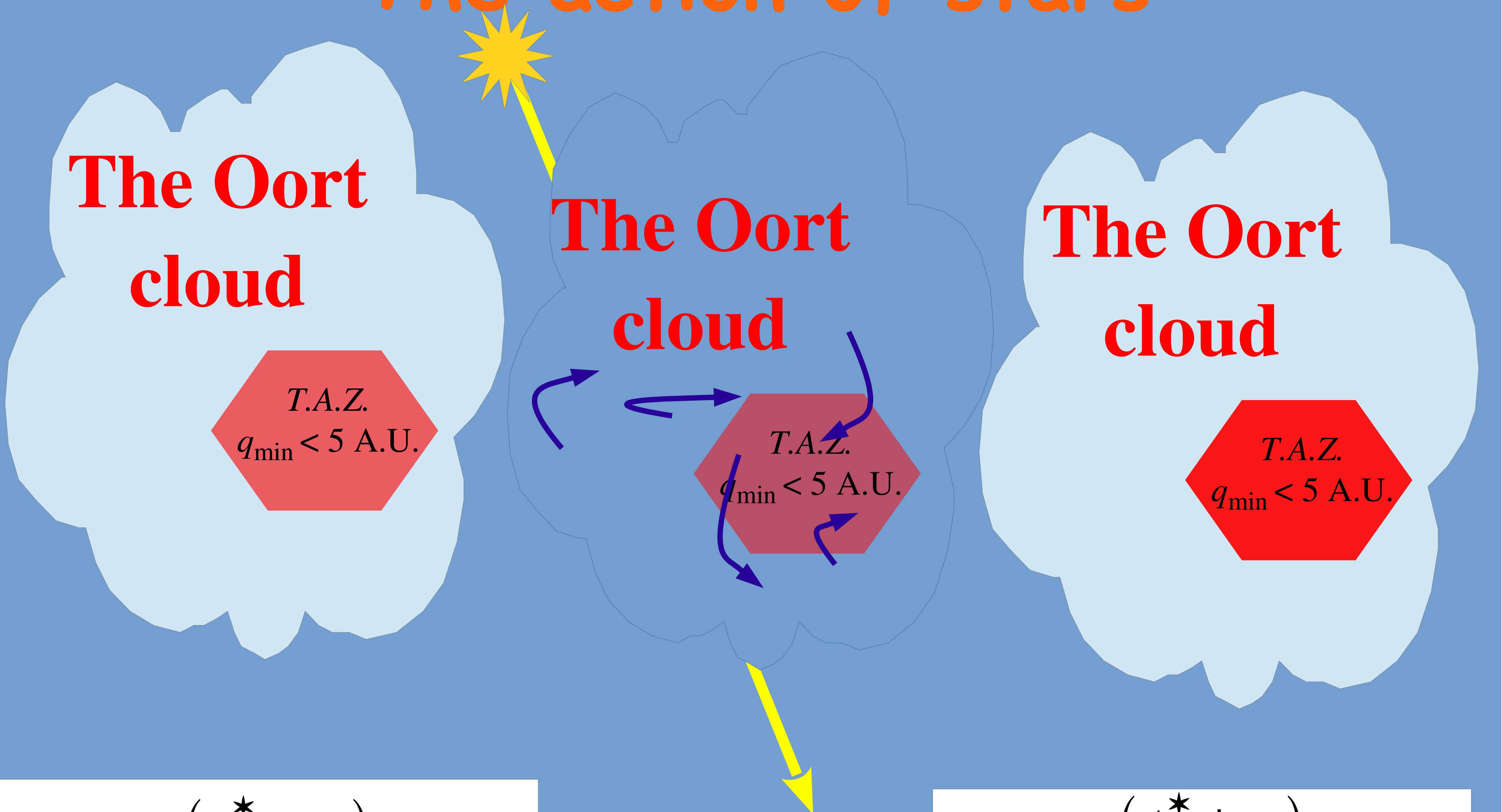
Population in the Tidal Active Zone in the case of an initial thermalized population

We consider the percentage of comet in the Tidal Active Zone given by:

$$p = N_{TAZ} / N_{Oort} \times 100$$



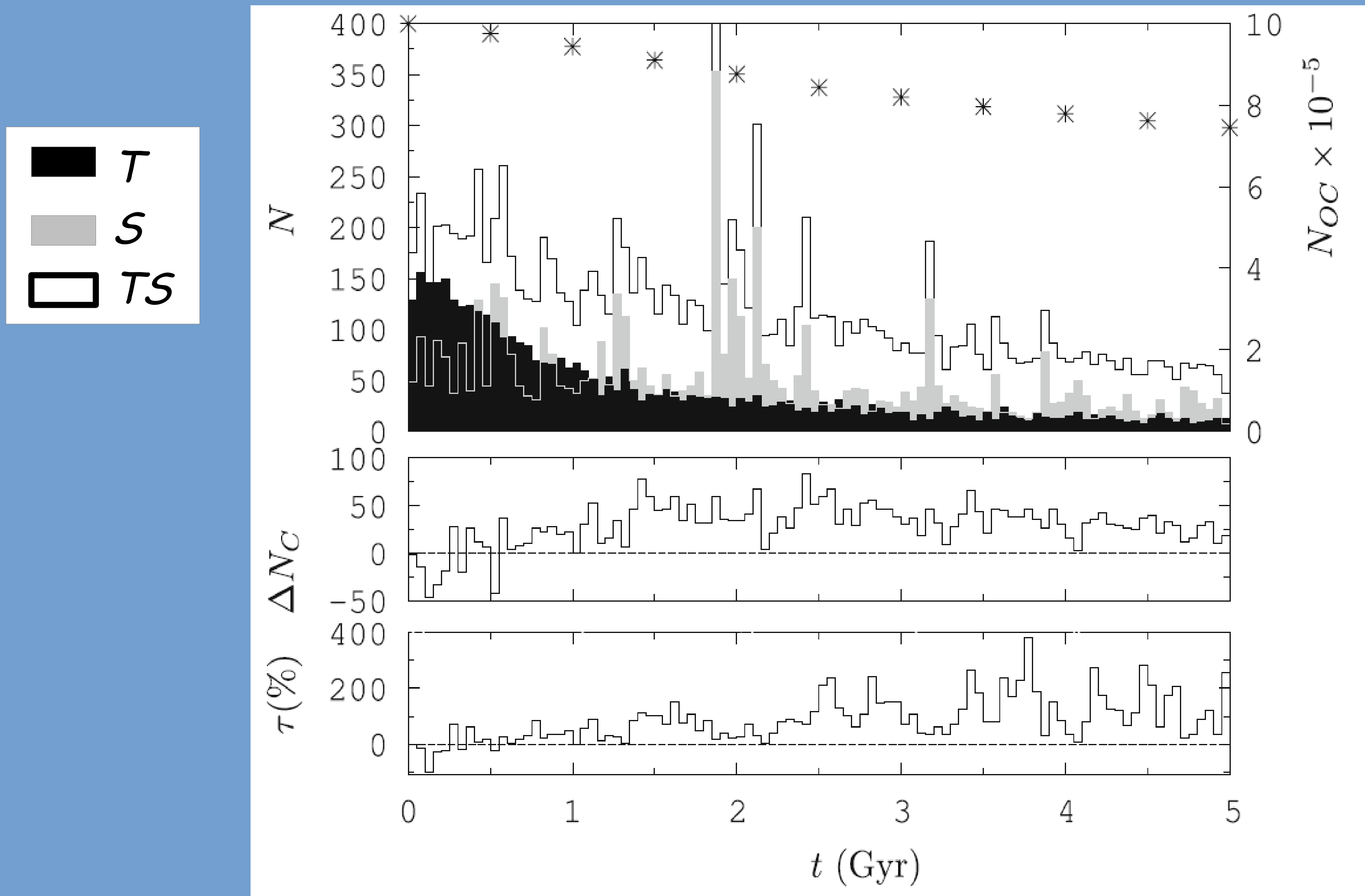
The action of stars



$$\tau_i = \frac{p(t^\star - \epsilon)}{p_{max}} \times 100$$

$$\tau_f = \frac{p(t^\star + \epsilon)}{p_{max}} \times 100$$

The long term synergy



After 2 Gyr there is a strong synergy between the tides and stellar perturbations

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Initial conditions and simulations

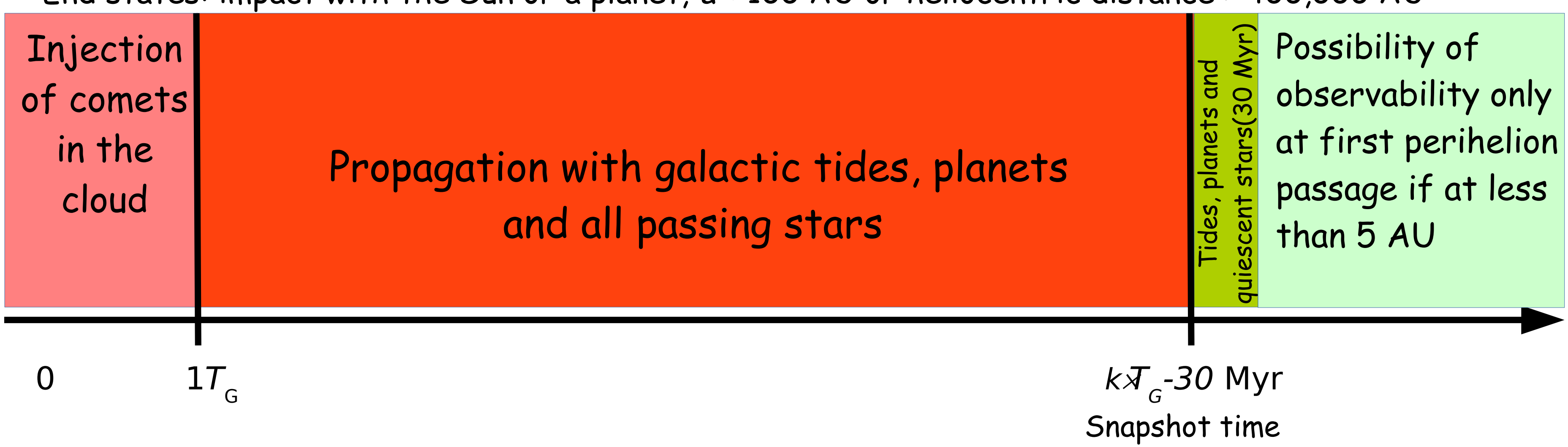
Initial conditions:

10^7 comets randomly chosen with the following uniform distributions:

- perihelion distance q between 15 and 32 AU
- ecliptical inclination i between 0° and 20°
- orbital energy for semi-major axis a between 1,100 and 50,000 AU
- uniform distribution of M,ω and Ω between 0° and 360°.

Propagation:

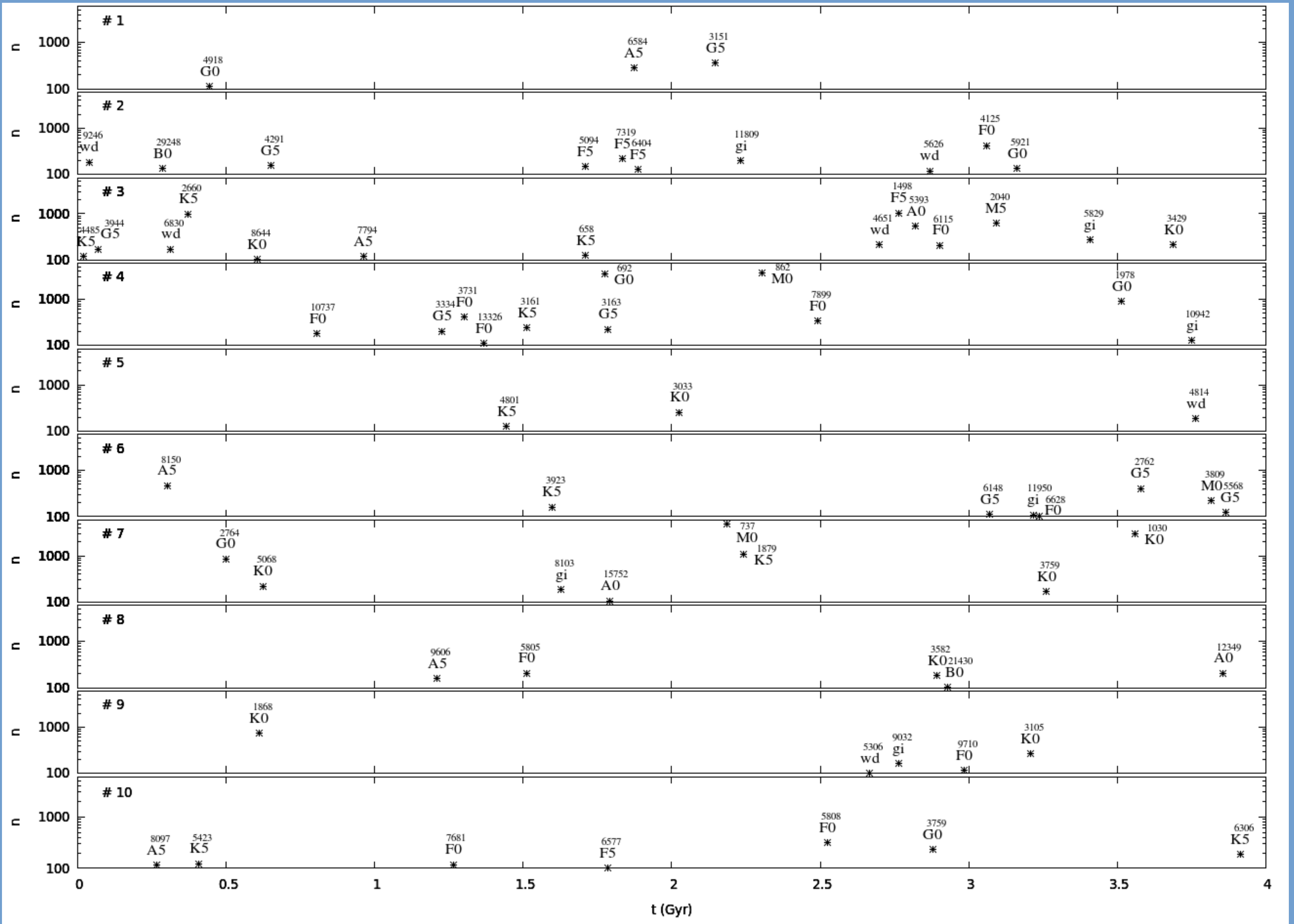
End states: impact with the Sun or a planet, a < 100 AU or heliocentric distance > 400,000 AU



NB: T_G is the orbital period of the Sun around the galactic centre ($1T_G \approx 236$ Myr)

5 different snapshots of the Oort cloud between 4.02 and 4.96 Gyr => as if we had modelled the evolution of 5×10^7 comets.

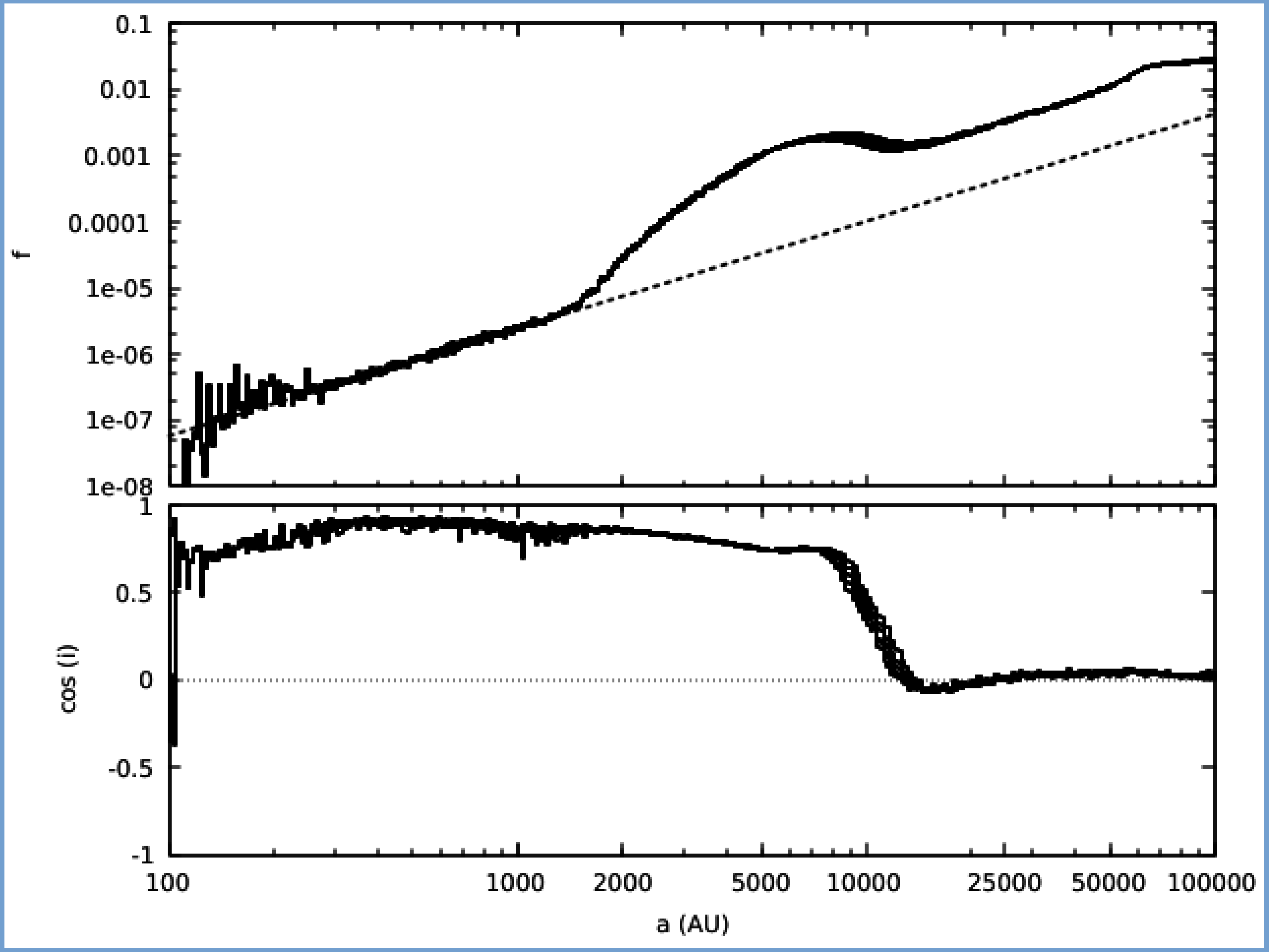
The 10 stellar sequences



The final shape, without stellar perturbations - I

Five different snapshot times between 4 Gyr and 5 Gyr :

- The distributions overlap
- Two regimes:
  - below ≈ 1,500 AU a transport regime caused by planetary perturbations
  - beyond ≈ 1,500 AU, distribution shaped by the interaction between galactic tides and planetary perturbations.



Some properties of the Galactic tides

The period of the perihelion is directly obtained from the orbital parameters and is inversely proportional to the orbital period :

$$P_p = \frac{1}{P_{\mathrm{orb}}} f(e, i_G, \omega_G)$$

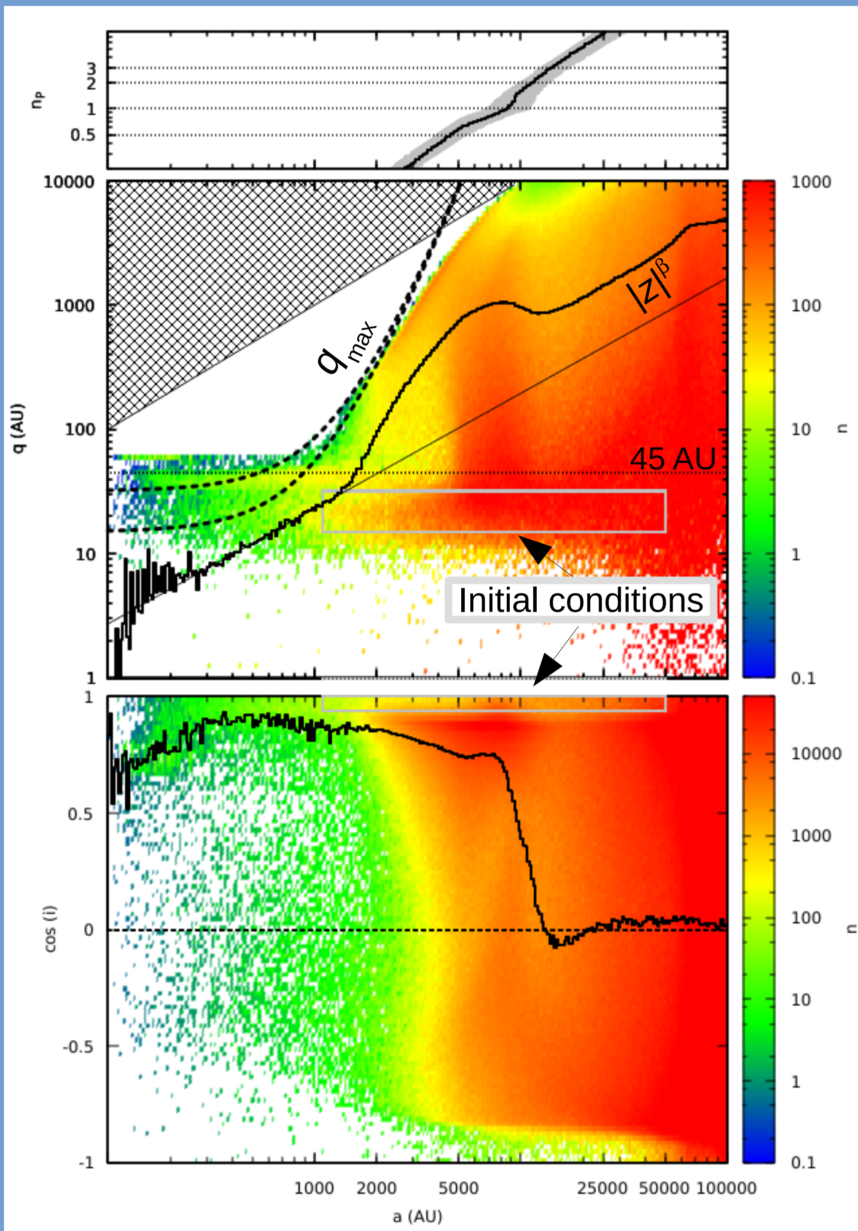
For each comet, we will consider the number of perihelion cycle during Δt :

$$n_p = \frac{\Delta t}{P_e}$$

If $\Delta t \ll P_e$ and $e \approx 1$, one can estimate the maximal and the median value of the perihelion distance that a comet can reach starting from q_0 according to its semi-major axis :

$$q_{\max} = \left(\sqrt{q_0} + \frac{5\sqrt{2}\,\mathcal{G}_3}{8\mu} a^2 \Delta t \right)^2 \quad q_{\mathrm{med}} = \left(\sqrt{q_0} + \frac{5\sqrt{2}\,\mathcal{G}_3}{24\mu} a^2 \Delta t \right)^2$$

The Final shape without stellar perturbations - II



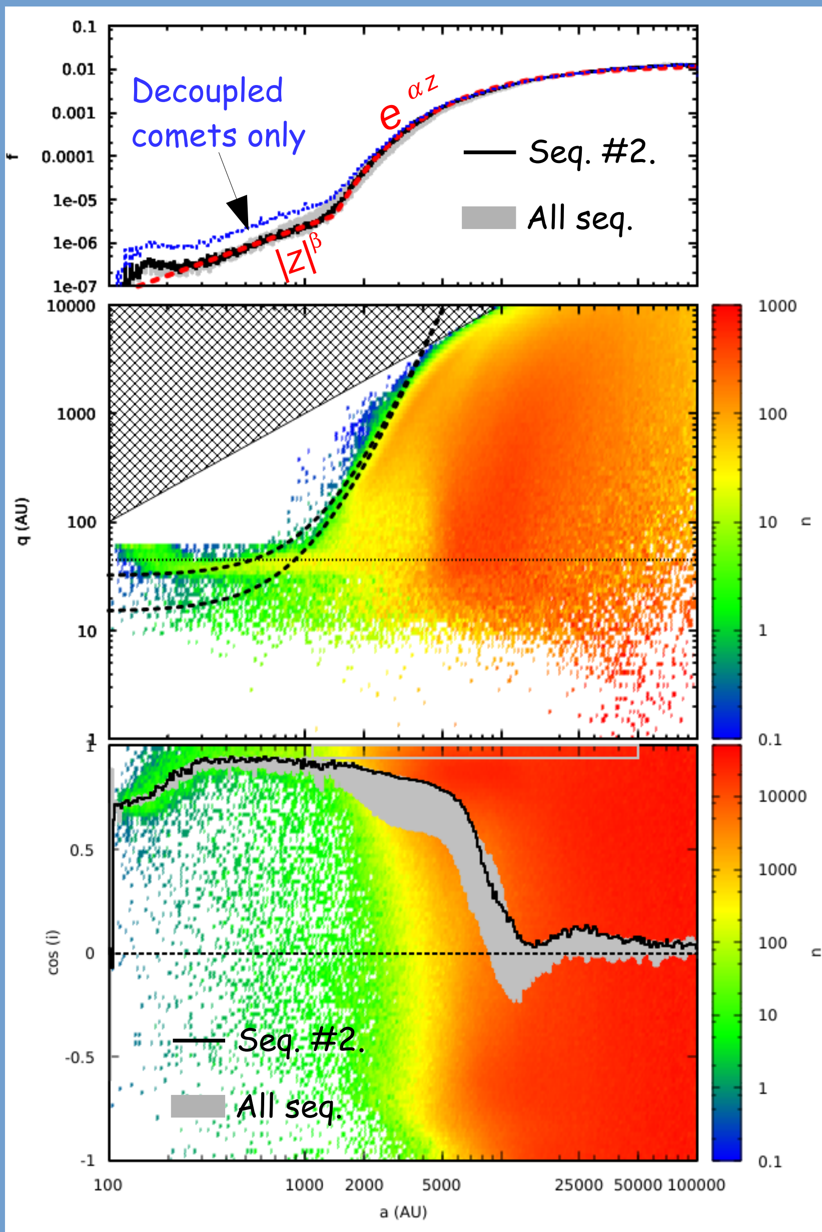
The knee at about 1,500 AU is well explained by the q_{max} behaviours : it occurs when the tides are able to remove the perihelion from the planetary region in about 4.5 Gyr

In the transport regime (a < 1,500 AU) the orbital energy distribution is well approximated by a power law μ $|z|^{\beta}$, with β=-1,62 $\pm$ 0.3

In the tidal region, the main features are:

- For 5,000 < a < 10,000 AU : the perihelion distances are on their decreasing branch leading back to the planetary region. For 7,000 < a < 11,000 AU, $n_p \approx 1$ meaning that most of the comets have performed a complete cycle => depletion of the Oort cloud caused by the planets. When *a* increases the time spent by the comets in the planetary region decreases given less chance to planetary ejection.
- The (cos I, a) diagram highlights a wave structure well explained in Higuchi et al. (2007).

The Final shape with stellar perturbations



The final distributions of orbital energy has been smoothed in the tidal regime. Indeed, stellar perturbations have broken the tidal perihelion cycle.

This distribution is very robust with the knee between the diffusive and the tidal regime located between 1,000 and 2,000 AU. The tidal regime yield a Boltzmann distribution of orbital energy $\mu\ e^{\alpha z}$, with α between 11,000 and 13,000 according to the stellar seq. Even considering only comets with a < 1,000 AU at some time during the propagation (decoupled comets) the orbital energy distribution conserved the same properties.

The behaviour of the median of cos *i* is more dependent on the stel. seq. as explained in Higuchi and Kokubo (2015). However, whatever is the seq. the cloud is certainly not isotropic for a < 9,000 AU.

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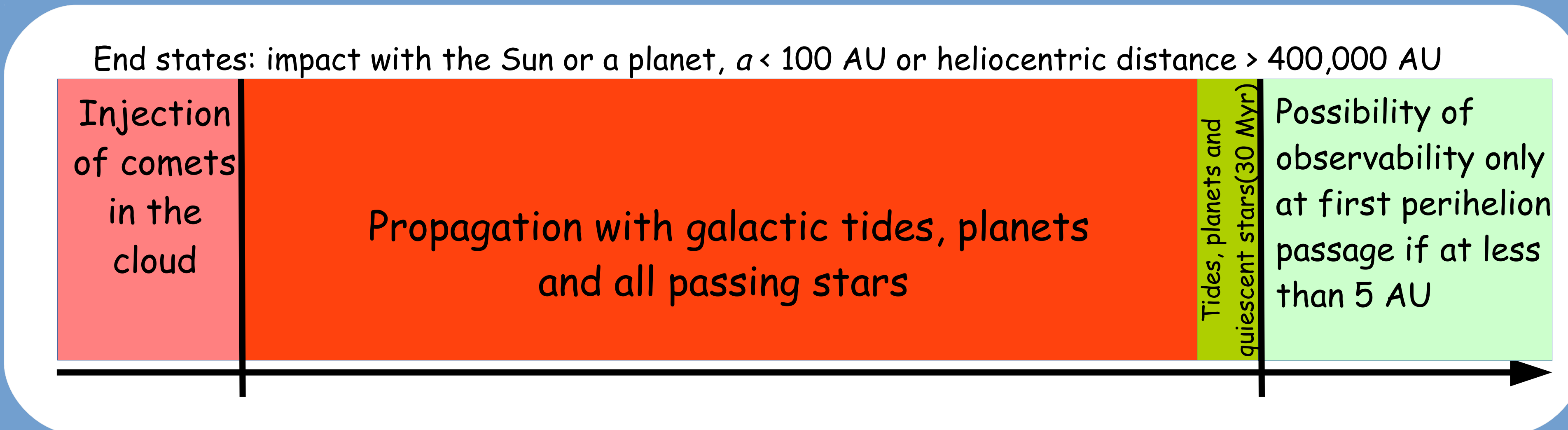
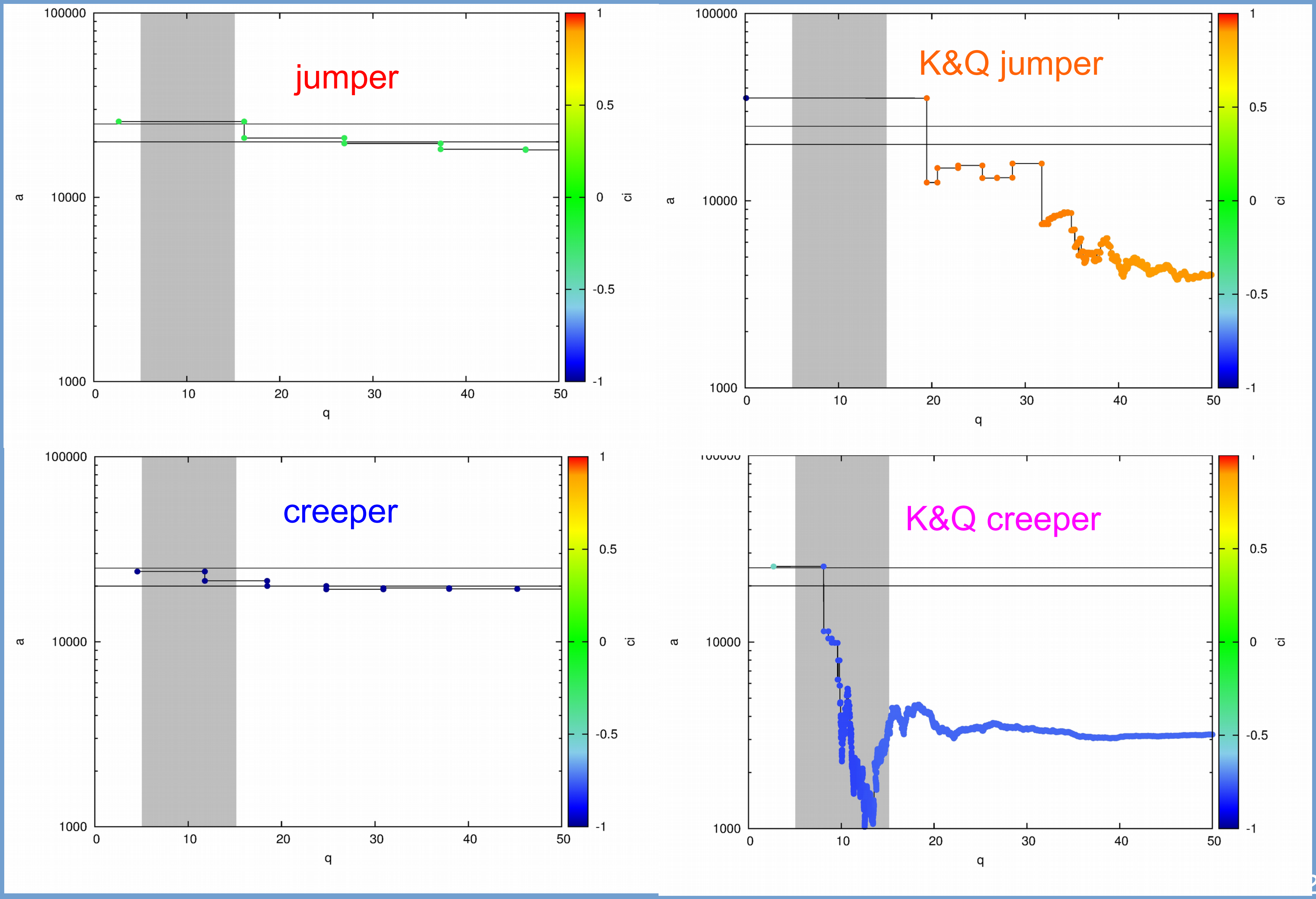
The observable comets



Each observable comet is weighted by : $2 \times 10^4 / P_{orb}$ so that it corresponds to an observable comet per year considering an initial Oort cloud containing 10^{12} comets (Kaib and Quinn 2009, Brasser and Mordbidelli 2013).

The four observable classes



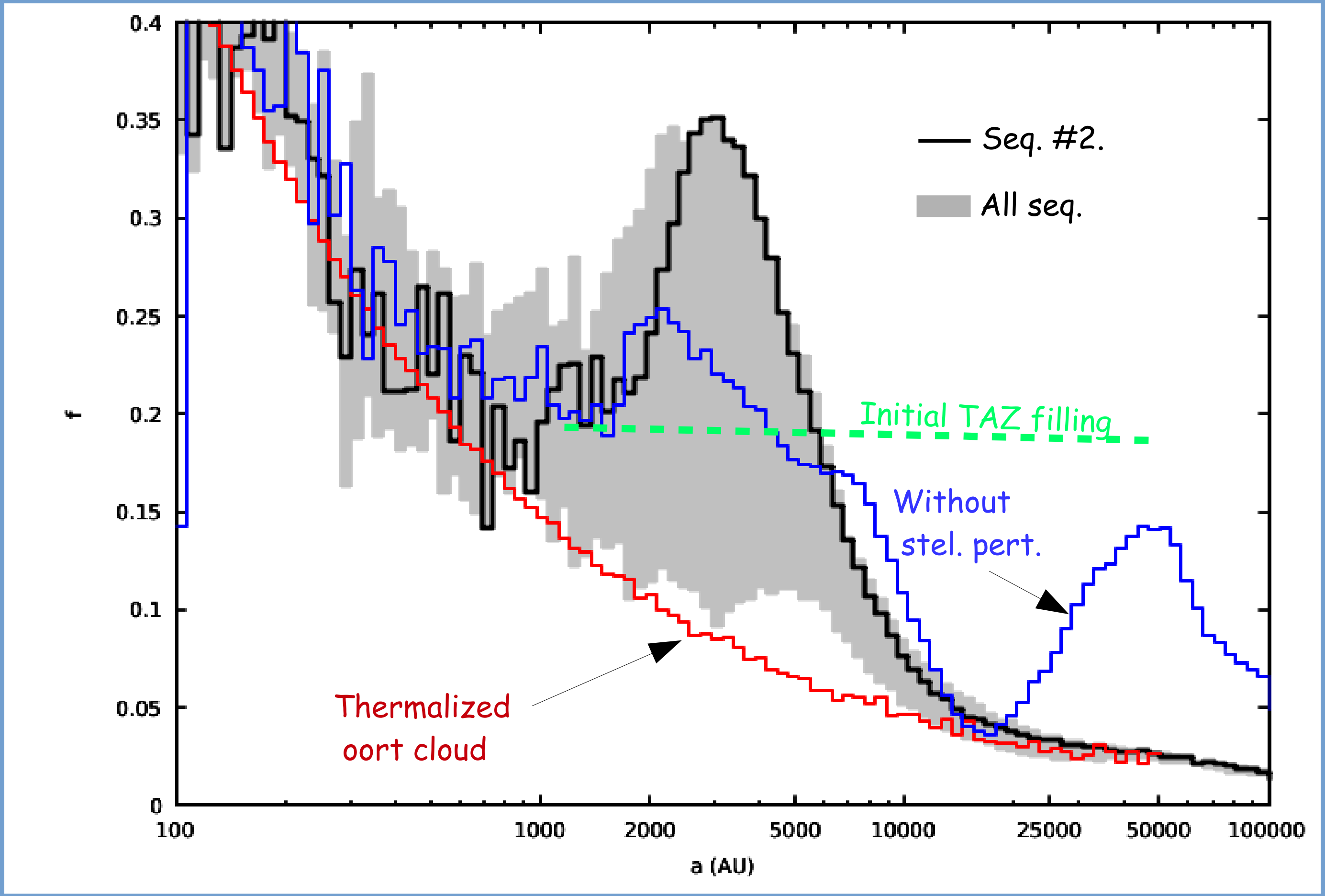
KQ stands for Kaib and Quinn (2009)

Global statistics on the observable comets

mod.	c/yr	j	c	KQ j	KQ c	$a_{0_{50}}$	ret.	$a_{\mathrm{orig}_{25}}$	$a_{\mathrm{orig}_{50}}$
1	4.5	44.9	17.4	1.2	36.5	2412.3	53.3	21092.6	28081.4
2	4.5	41.4	17.8	1.3	39.6	2497.9	49.9	22097.9	28157.0
3	3.3	41.4	17.6	1.1	39.9	2208.5	56.5	21198.6	27828.0
4	3.3	39.8	17.3	0.9	42.1	2230.3	55.0	21837.1	27445.2
5	5.1	40.2	19.2	0.4	40.2	2253.6	54.4	20623.0	27256.7
6	3.9	44.7	16.4	1.3	37.7	2431.9	51.8	22189.7	28562.6
7	3.2	41.8	16.4	1.2	40.5	2343.6	57.6	20120.4	26963.0
8	4.0	43.6	19.1	0.8	36.4	2395.9	57.6	21501.7	28634.6
9	4.4	42.3	18.7	0.7	38.3	2519.9	55.7	22044.8	28458.8
10	5.3	44.1	19.4	0.9	35.6	2328.4	55.4	21400.6	27801.9
TP	8.2	69.8	14.1	2.4	13.6	2266.8	50.6	29660.7	41470.6

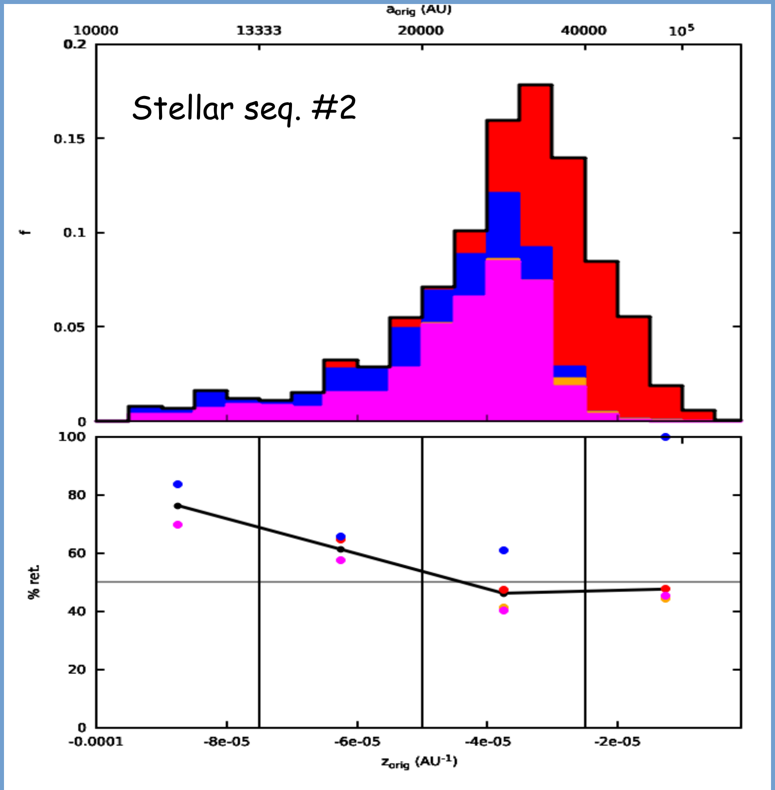
- The production of comets with a total magnitude $H_T < 11$ is consistent with Francis (2005) and Brasser and Morbidelli (2013).
- When stellar perturbations are at work, a majority of comets were in the Jupiter-Saturn barrier at their previous perihelion passage, and the median and the first quartile of the observable comets original semi-major axis have been reduced.
- In almost all cases a small preference for retrograde orbits seems to be observed.

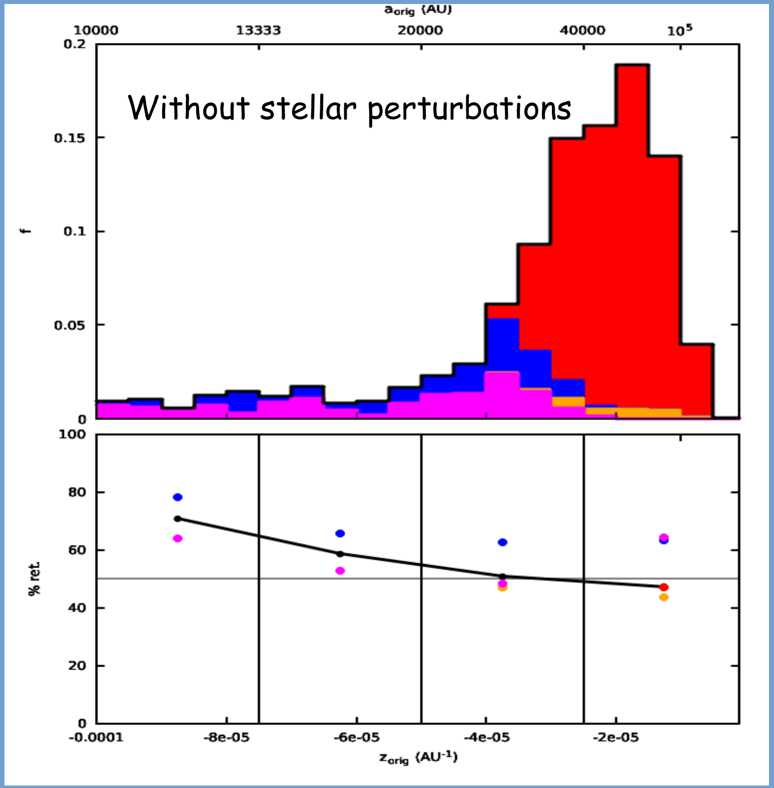
The final TAZ filling



Convergence toward the thermalized cloud for a < 1,000 AU (planetary perturbations) and a > 10,000 AU (stellar perturbations).
Without star the departure from the initial filling for a > 5,000 AU is caused by the depletion of the TAZ by planetary perturbations. This depletion is less efficient for increasing semi-major axis because of the fast transit of the perihelion through the planetary region.

The Oort spike





The spike is shift to smaller semi-major axis when stellar perturbations are at work. The location and preferences of the different observable classes is explainable by the TAZ filling : creepers and KQ creepers are coming from smaller semi-major axis (<20,000 AU, Fouchard et al. 2014) where the TAZ is more filled when stellar perturbations are at work, whereas the jumpers come mainly for a > 25,000 AU, where the tAZ is more filled when the stars are not at work.

As regard the proportion of retrograde orbits, a preference for retrograde orbits is observed when creepers and KQ creepers dominate.

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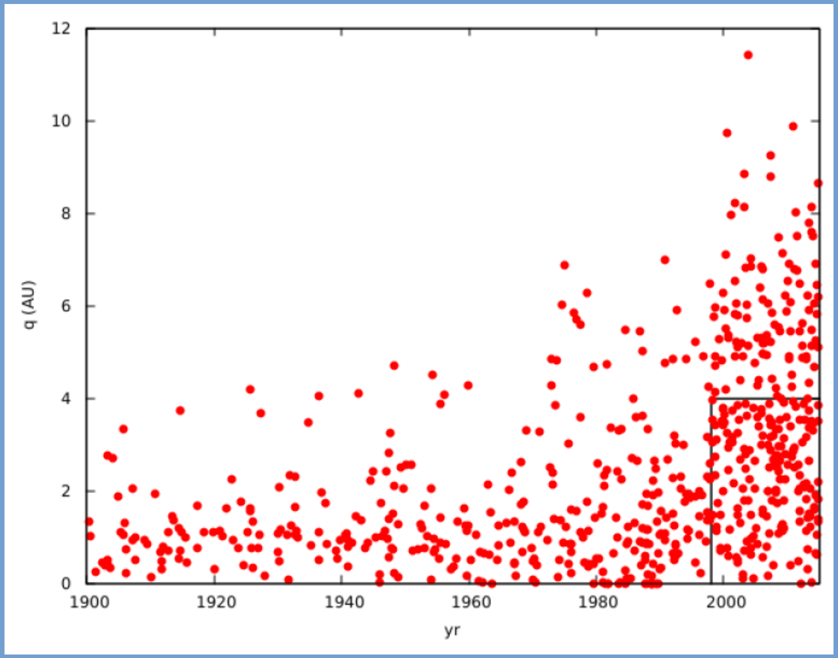
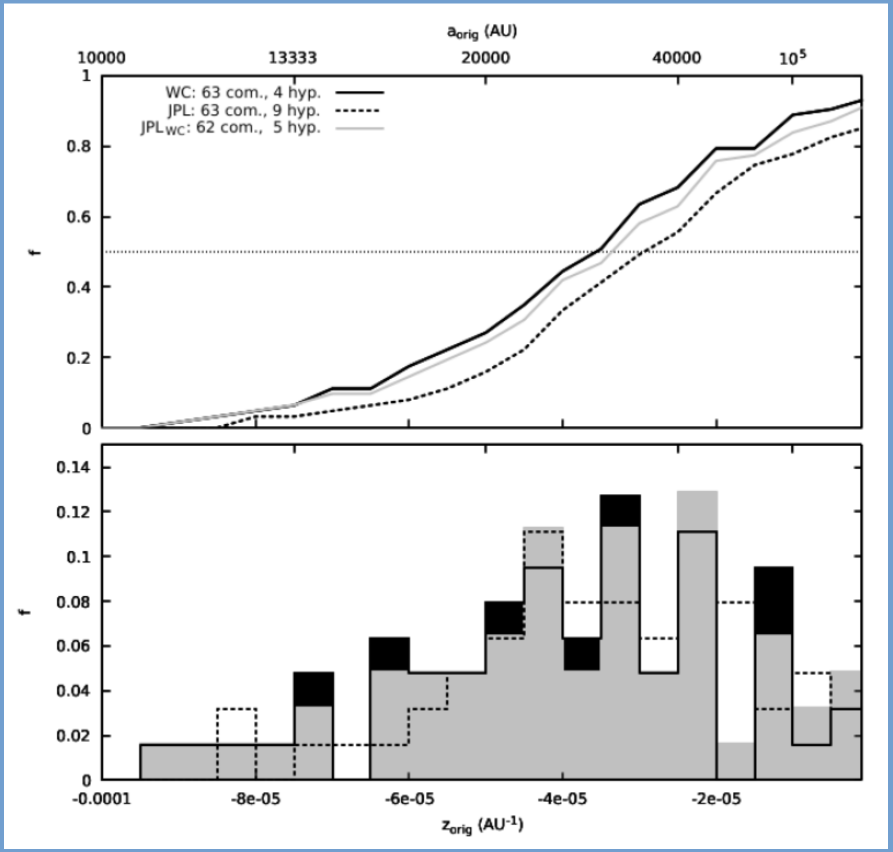
Comparison with observations: the samples of known LPC

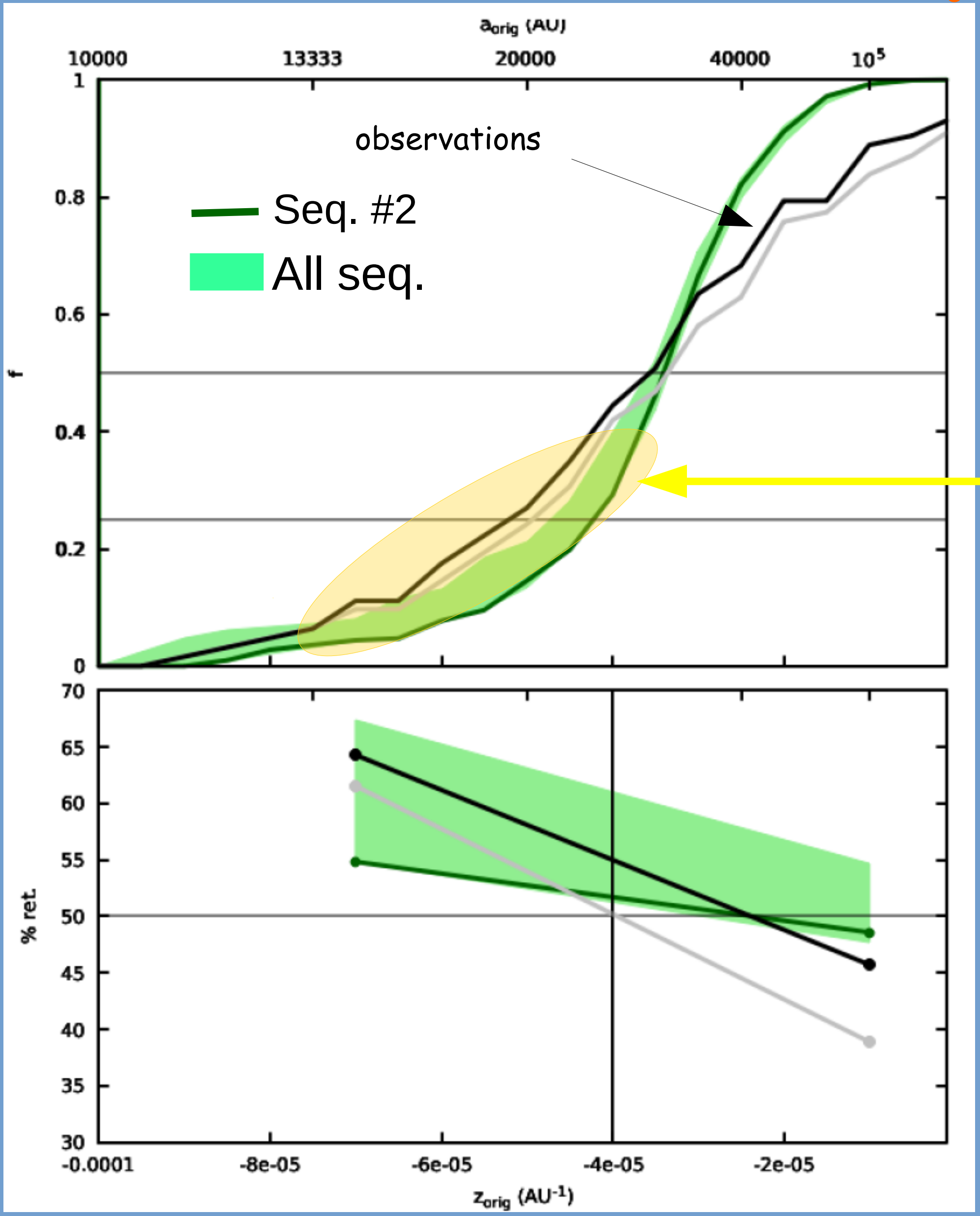




The observed "new" long period comets with total mag. smaller than 11, perihelion distance smaller than 4 au and perihelion passage after 01/01/1998 seems to be complete (JPL sample). This corresponds to 3.6 com/yr. The original orbital energy is taken from the Warsaw catalogue when available (JPL_{WC} sample).

The use of Warsaw catalogue significantly decreases the estimate of the original orbital energy

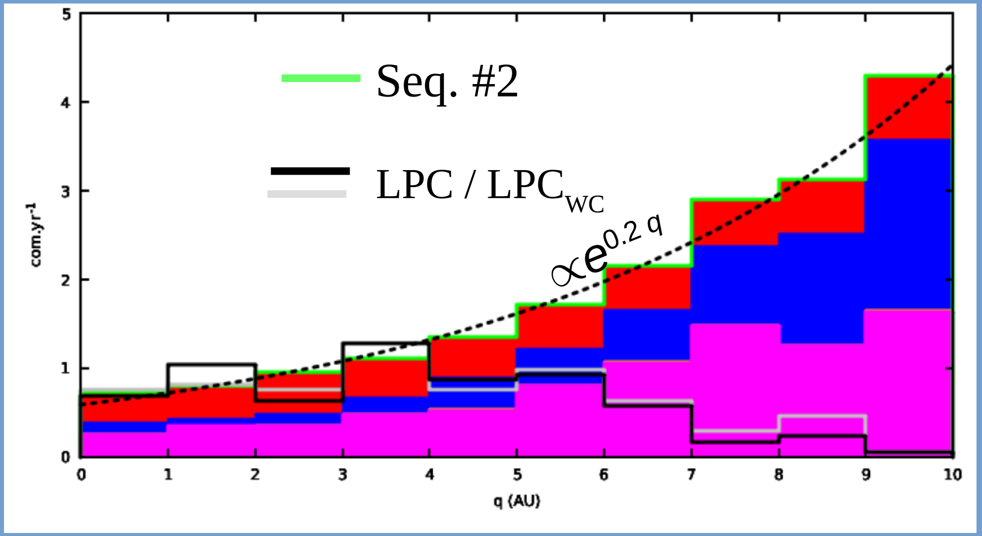
Comparison with observations : the Oort spike

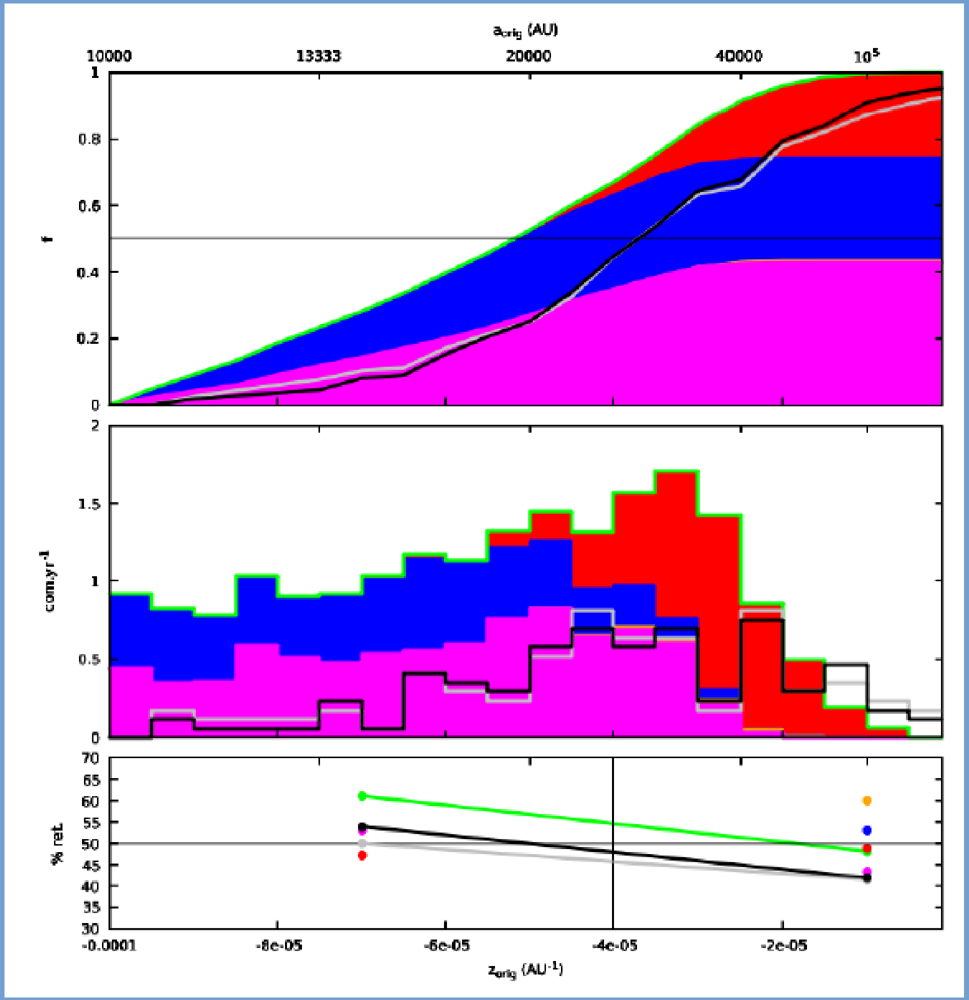


Discrepancy. Caused by :

- Initial conditions ?
- Planet nine ?
- Higher stellar density of low mass stars in the solar neighbourhood ?
- Wrong determination of the original orbital energy ?

Comparison with observations for $q < 10$ AU



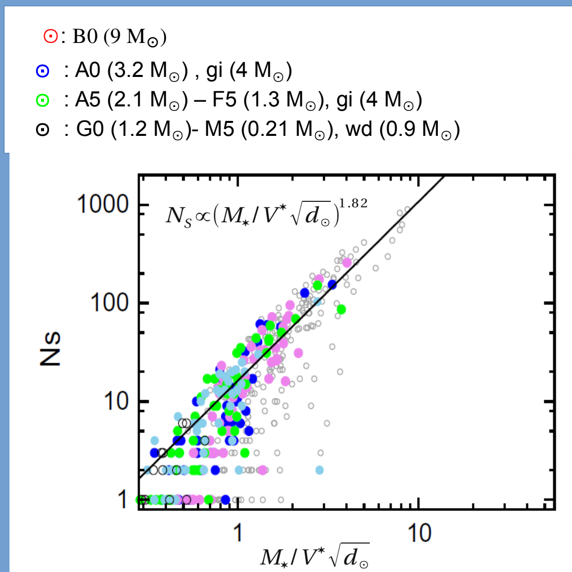


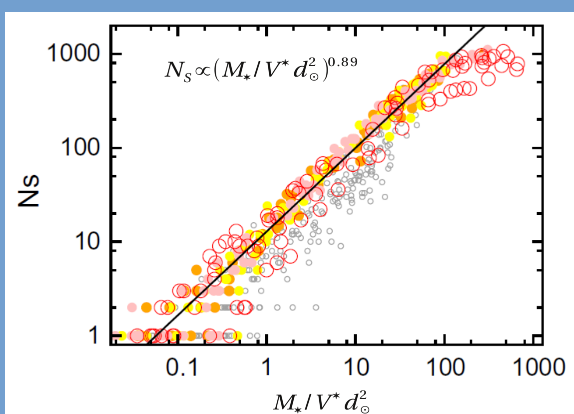
Simulation predict an exponential increase of the number of obs.com. w.r.t. the perihelion distance.

For $q > 5$ au the increase is mainly coming from creepers and KQ creepers with much lower semi-major axis than a typical Oort spike comet.

Thanks !

Global strength of the stellar sequences



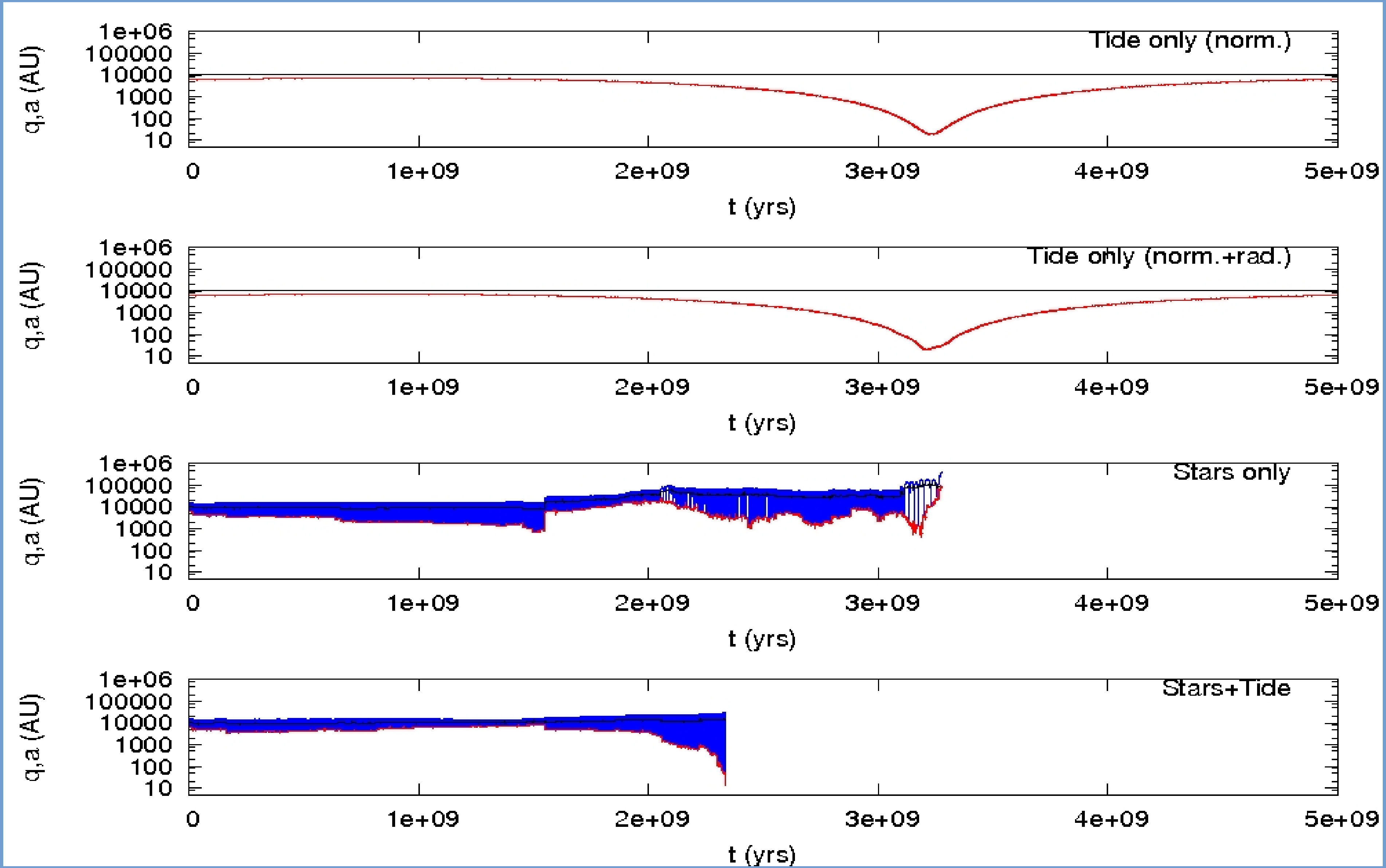


seq. #	$\Sigma_{N_\star > 10} N_\star$	Num. of stars with $N_\star >$ 10	100	500
1	4001.1	142	3	0
2	4612.4	123	10	0
3	8127.5	139	14	4
4	12549.9	129	11	3
5	3917.6	132	3	0
6	4543.4	133	8	0
7	13490.3	140	8	4
8	3562.8	128	5	0
9	4538.7	138	5	1
10	4044.9	130	7	0

The number of comets directly injected at less than 5 AU from the Sun by a single stellar encounter can be estimated by a power-laws. This is used to estimate the global strength of a stellar sequences.

Example II

a
q
r



Tide only (norm.)
Tide only (norm.+rad.)
Stars only
Stars+Tide
q,a (AU)
t (yrs)
1e+06
100000
10000
1000
100
10
0
1e+09
2e+09
3e+09
4e+09
5e+09

Conclusions

Our simulations show that, starting from an extended scattered disc, a steady state is reached, characterized by a two shapes distribution of the orbital energy:

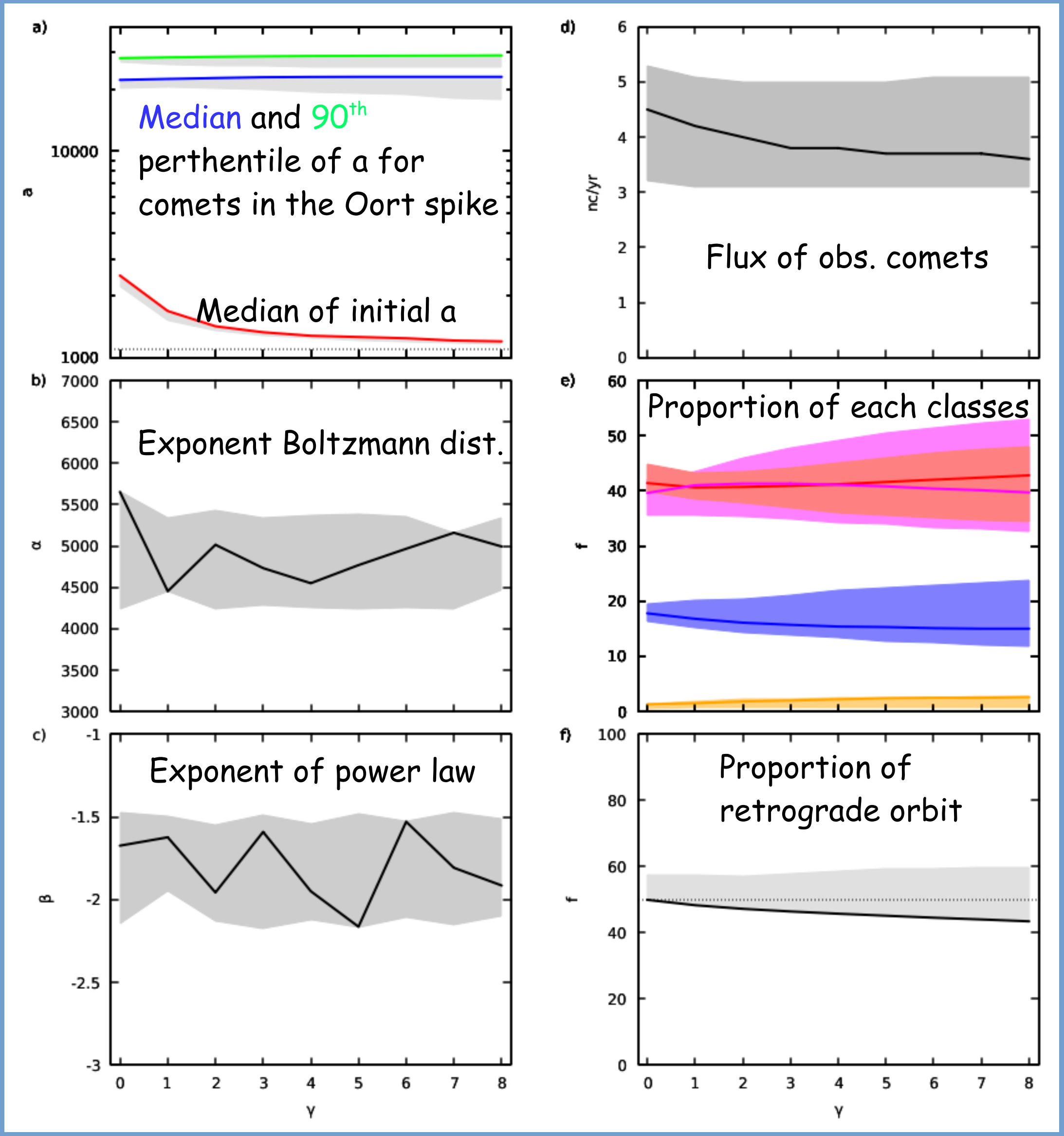
- A power law distribution in a diffusive regime controlled by the planets for a < 1,000 AU
- A Boltzmann distribution in a regime controlled by the Galactic tides for a > 1,500 AU

The transition between the two regimes depends on the stellar sequence used.

As regards the Oort spike, our simulations show that a majority of observable comets were already in the Jupiter - Saturn region one orbital period before observability. This result in consistent with observations (Dybczynski and Krolikowska, 2011). A small preference for retrograde orbits is observed for a < 20,000 AU.

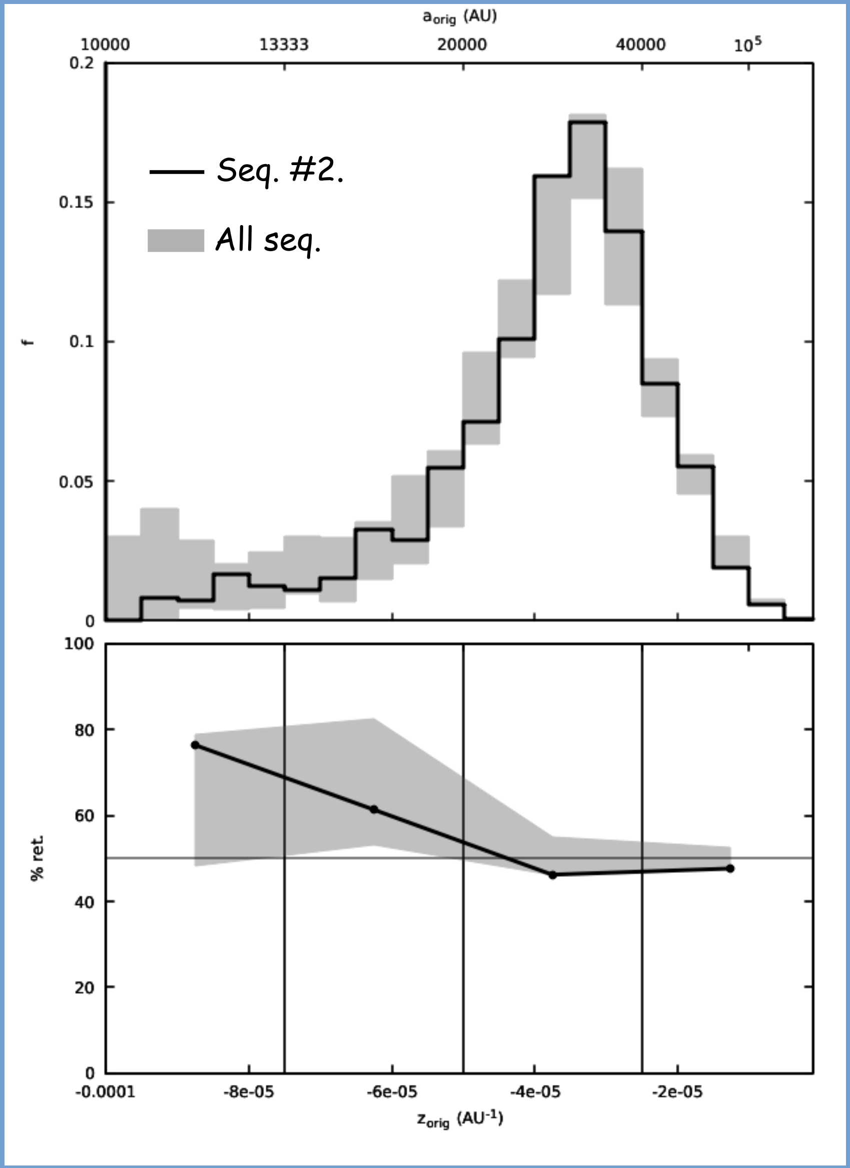
All our results appeared to be rather independent of the initial orbital energy distribution.

Influence of the initial orbital distributions



The original orbital energy distribution is uniform. We simulate distributions proportional to z^{γ} by applying a weight ($\mu\, z_o^{\gamma-1}$) to the comet according to their initial orbital energy z_o.

Oort spike : other stellar sequences



The shape of the spike is rather robust with respect to the stellar sequence used.

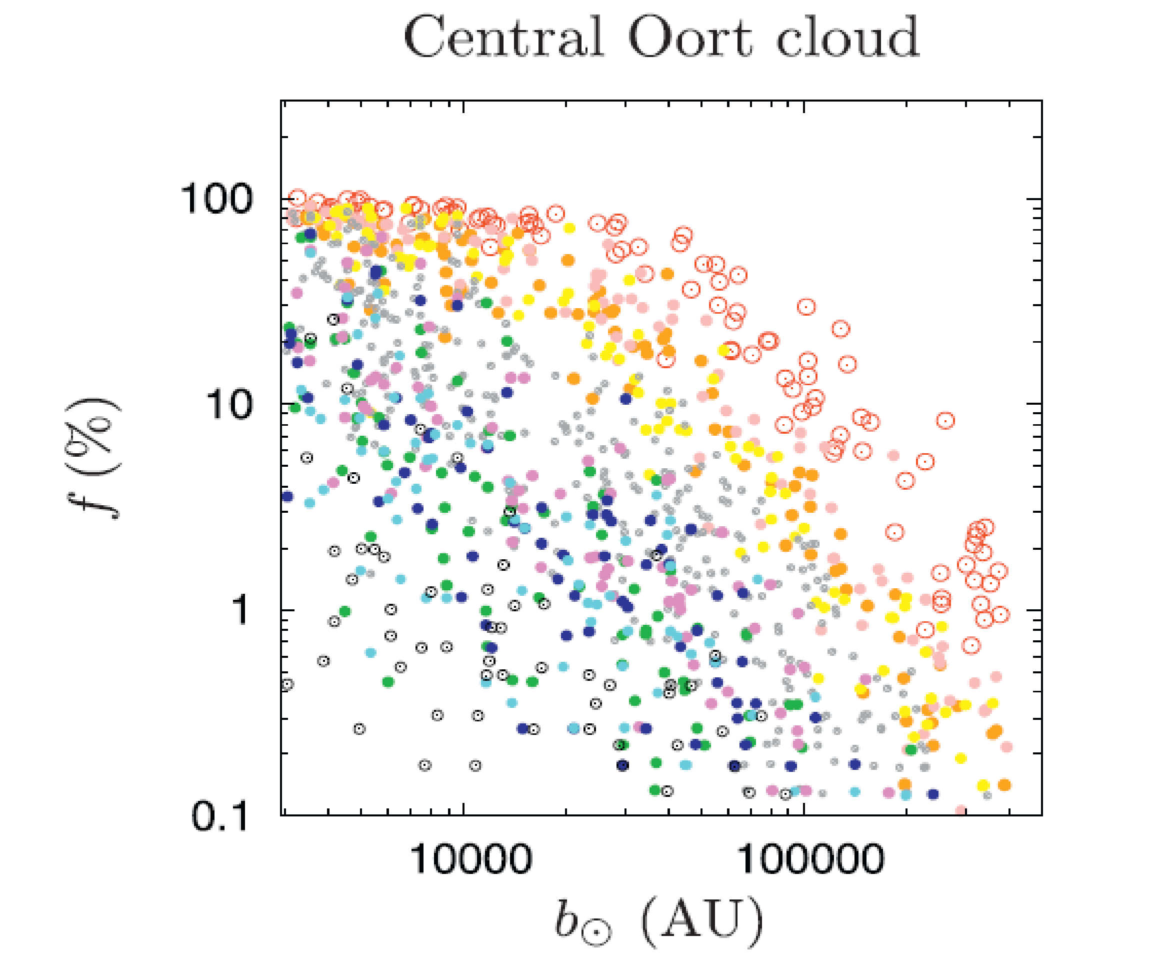
The proportion of retrograde orbits is on the contrary very sensitive to the stellar sequence, mainly for a<20,000 AU. This is mainly caused by statistical fluctuations because of the small number of observable comets.

Feeding of the Tidal Active Zone vs stellar parameters

$\odot$: B0 (9 $M_\odot$) , • : gi (4 $M_\odot$) , • : A0 (1.2 $M_\odot$) , • : A5 (2.1 $M_\odot$)

• : F0 (1.7 $M_\odot$), F5 (1.3 $M_\odot$), G0(1.1 $M_\odot$), G5(0.93 $M_\odot$)

• : K0 (0.78 $M_\odot$), • : wd (0.9 $M_\odot$) , • : K5 (0.69 $M_\odot$) , • : M0 (0.47 $M_\odot$), o : M5 (0.21 $M_\odot$)



Massive stars are able to fill completely the TAZ with much higher impact parameter than low mass stars