The Oort Cloud

Hans Rickman

The seminal paper: Oort (1950)

THE STRUCTURE OF THE CLOUD OF COMETS SURROUNDING THE SOLAR SYSTEM, AND A HYPOTHESIS CONCERNING ITS ORIGIN,

BY J. H. OORT

The combined effects of the stars and of Jupiter appear to determine the main statistical features of the orbits of comets.

From a score of well-observed original orbits it is shown that the "new" long-period comets generally come from regions between about 50000 and 150000 A.U. distance. The sun must be surrounded by a general cloud of comets with a radius of this order, containing about 10^{11} comets of observable size; the total mass of the cloud is estimated to be of the order of 1/10 to 1/100 of that of the earth. Through the action of the stars fresh comets are continually being carried from this cloud into the vicinity of the sun.

- Oort considered the ***barycentric orbits of long-period comets before entry into the planetary system***, found by numerical integrations (E. Strömgren, G. Fayet): "***original orbits***"

The Oort Spike

- Oort found a strong ***pile-up in the 1/a range next to the parabolic limit*** for a sample of 19 orbits
- He concluded that *passing stars inject comets from a very distant "cloud"* into observable orbits

TABLE I

Distribution of original semi-major axes
(a in Astronomical Units)

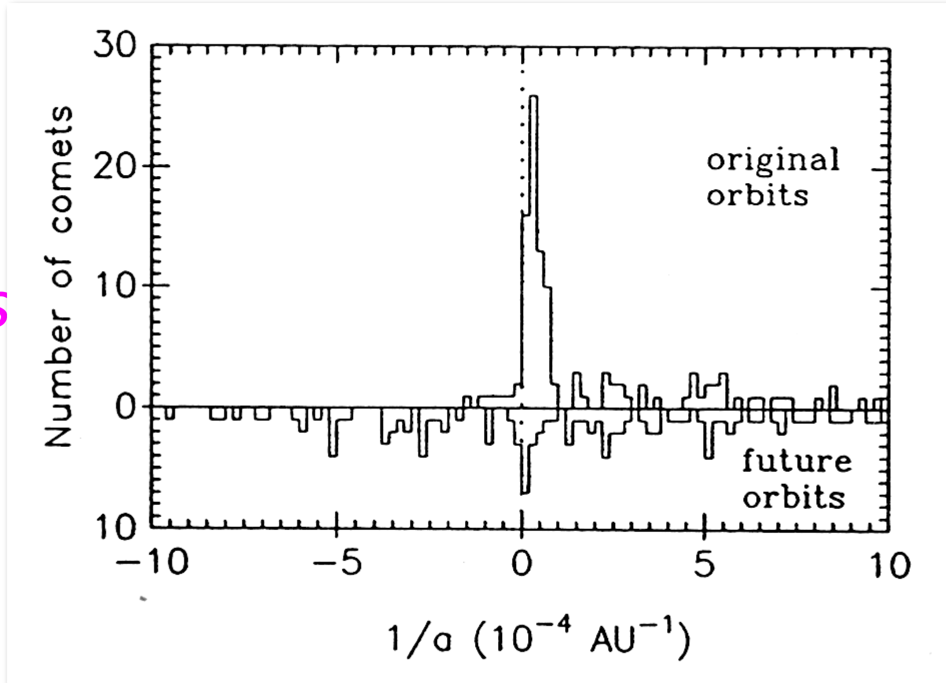
$1/a$	n
$<$ ·000 05	10
·000 05 – 10	4
10 – 15	1
15 – 20	1
20 – 25	1
25 – 50	1
·000 50 – 75	1
$>$ ·000 75	0

Oort (1950)

The Oort Cloud

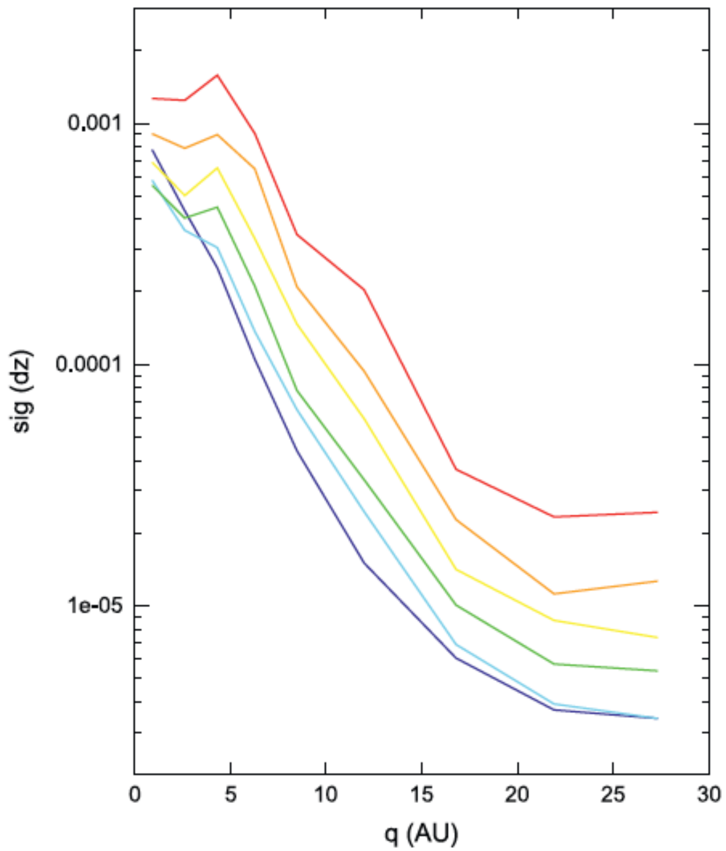
- ***Entering into the planetary system, the comets have a strongly peaked distribution of 1/a***
- *But planetary perturbations wipe out the spike*
- *The comets of the spike are not returning – they are* ***newcomers from a very distant reservoir***

"New" and "Old" comets



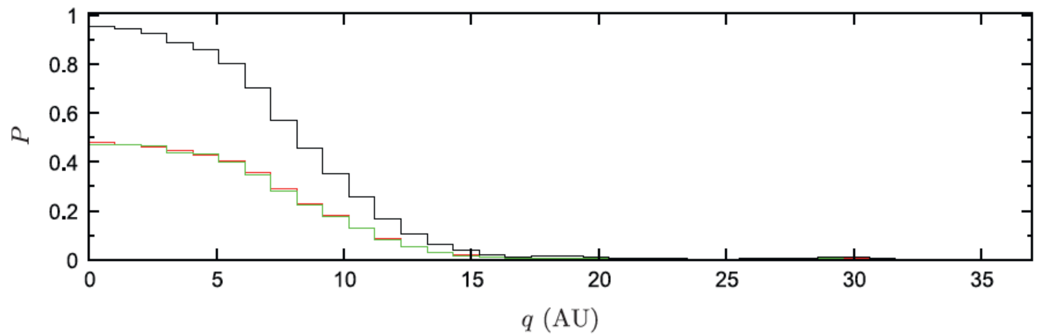
More recent sample of orbits

The Loss Cone



σ(Δ(1/a)) vs q for different inclination ranges

Loss cylinder (loss cone)



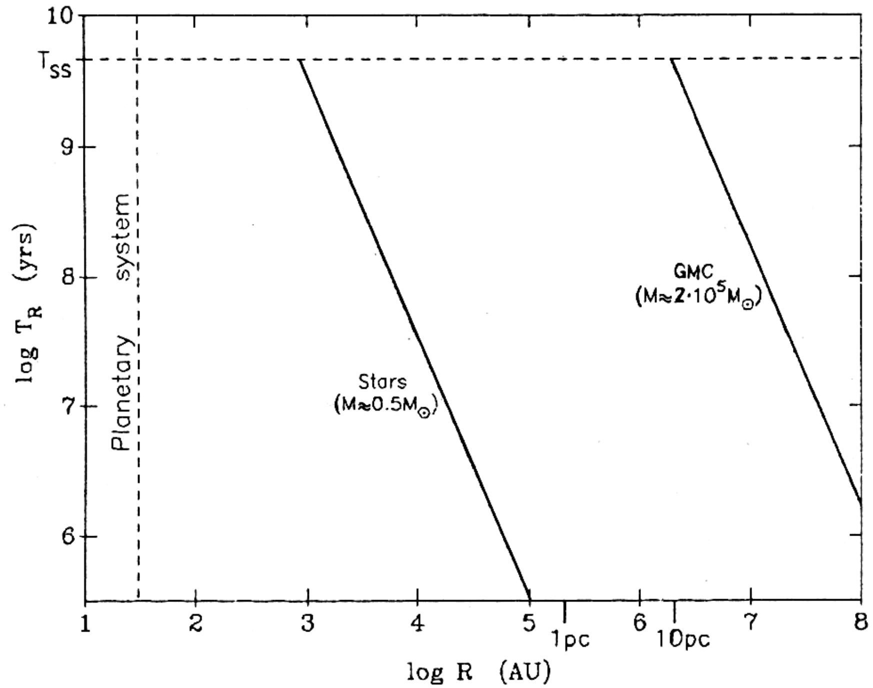
Probability for new comets to be kicked out of the defining range of 1/a vs q

Fouchard et al (2013)

Stellar encounters

Why do the new comets have a>10⁴ AU?

- Stellar encounters then occur on the time scale of one orbital period, injecting comets deep inside the loss cylinder
- For much smaller orbits the stellar encounter time scale is much longer than the period

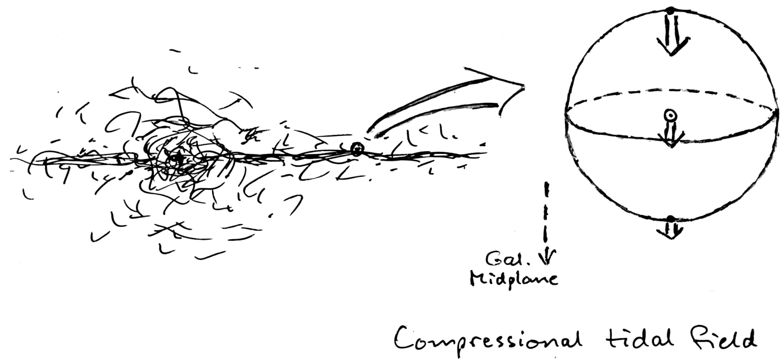


Encounter time scales vs minimum distance

Galactic tides

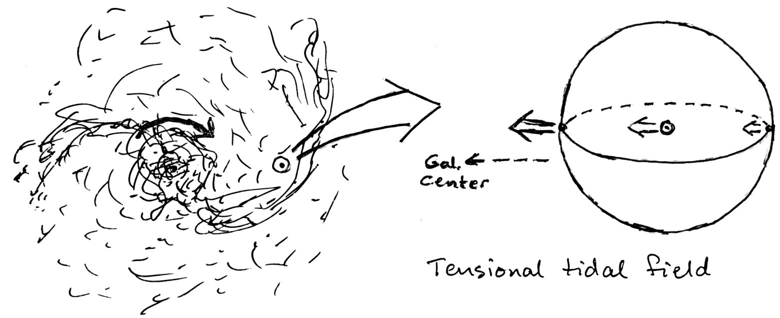
- ***The disk tide***

- Gravitational potential of the Galactic disk
- Induces *regular oscillations of q* and i_G (small enough a)



- ***The radial tide***

- In-plane, central force field of the Galaxy
- Changes also the semimajor axis and *may eject comets*



Tidal theories of the 1980's

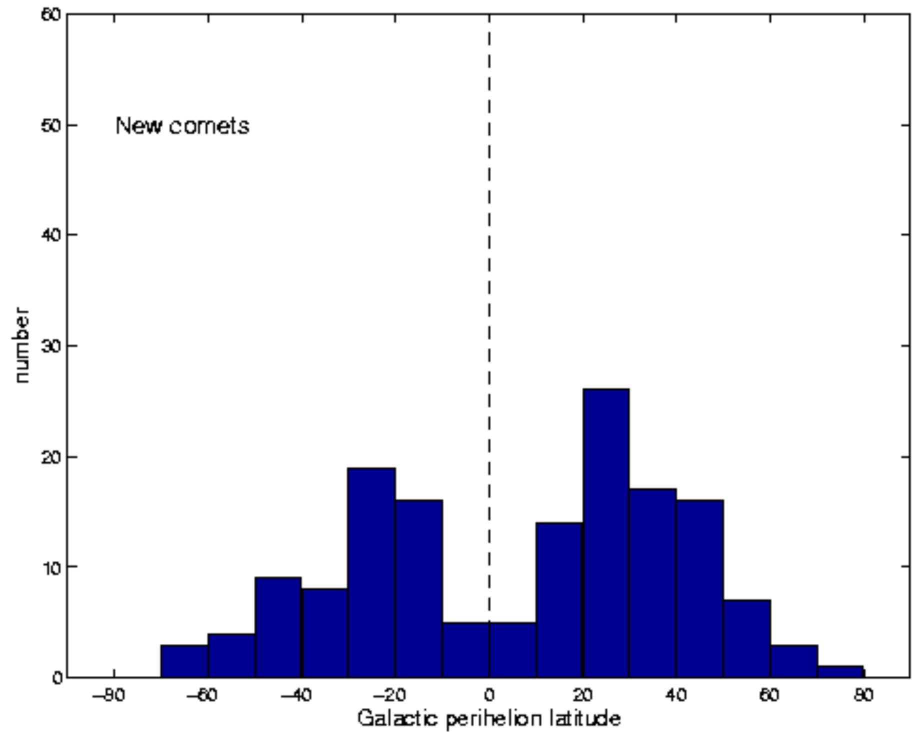
- Several authors identified the ***q oscillations of the disk tide*** as an important mechanism to inject comets into the loss cylinder
- Heisler & Tremaine (1986) developed an *analytic theory of the regular disk tide* by orbital averaging

$$|\Delta q| \propto q^{1/2} \cdot a^{7/2} \cdot |\sin 2\beta_G|$$

Tidal change of q per orbital revolution due to the disk tide

Imprint of the disk tide

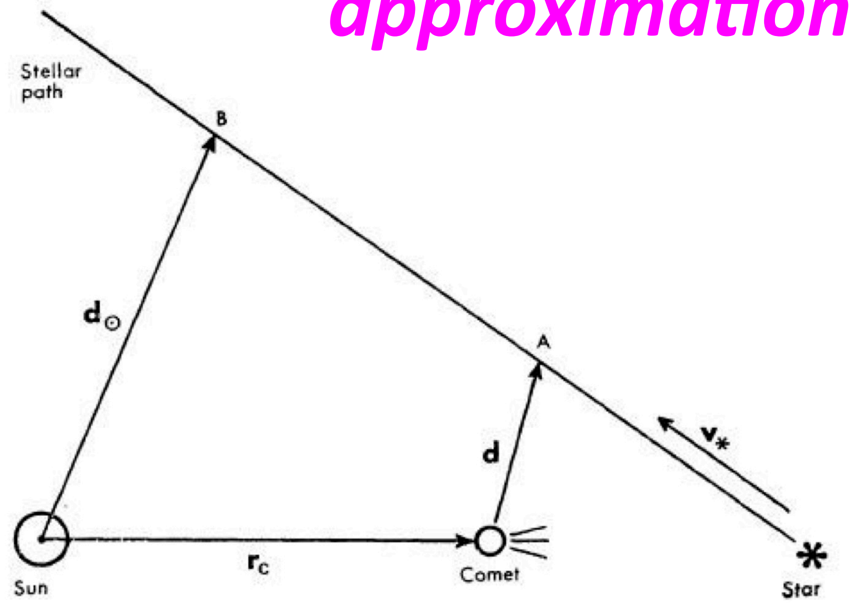
- Delsemme (1987) recognized *a* *double-peaked distribution of Galactic latitudes of perihelia* of new comets, indicating the *importance of the disk tide for comet injection*

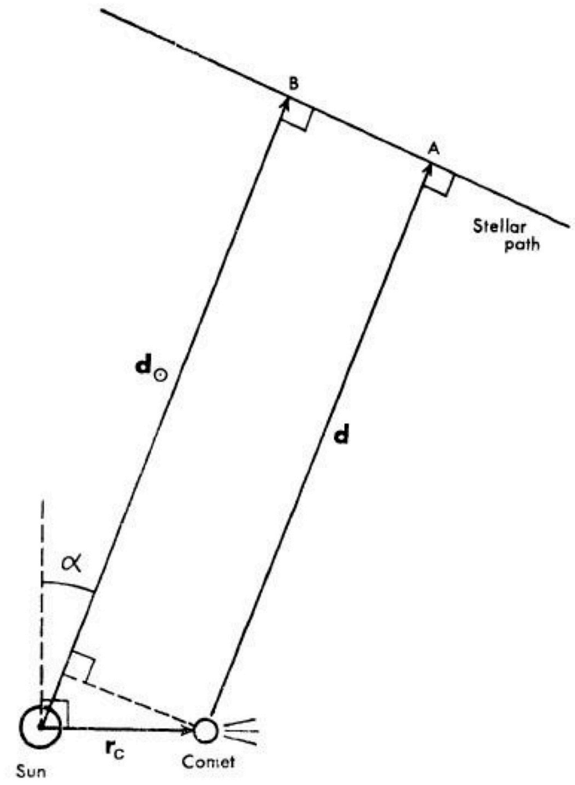


recent orbital statistics

Stellar encounters

Classical impulse approximation





$$\Delta \mathbf{V}_c = \frac{2GM_*}{V_*}\left\{\frac{\hat{\mathbf{d}}_c}{d_c} - \frac{\hat{\mathbf{d}}_\odot}{d_\odot}\right\}$$

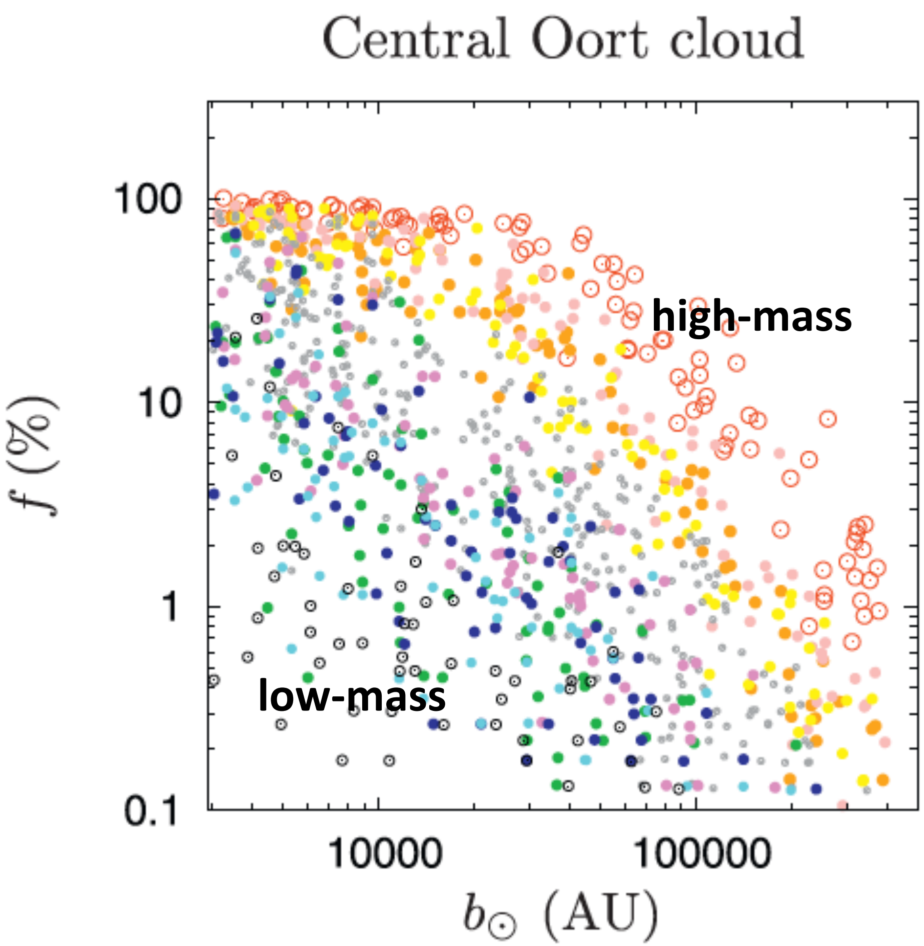
$$\Delta \mathbf{V}_c \approx \frac{2GM_* r_c \sin\alpha}{V_* d_\odot^2} \cdot \hat{\mathbf{d}}_\odot$$

Thus, a change in angular momentum and perihelion distance

Basics of Oort Cloud dynamics

- *Stellar encounters randomize the phase space distribution of Oort Cloud comets*
- For an integrable disk tide (a < 40,000 AU), there is a phase space domain, where q_{min} of the tidal cycle is < 5 AU (observable). This is the ***Tidally Active Zone*** (Fouchard et al 2011)
- In the long-term evolution of the Oort Cloud, ***the stellar encounters keep the TAZ population in steady state***

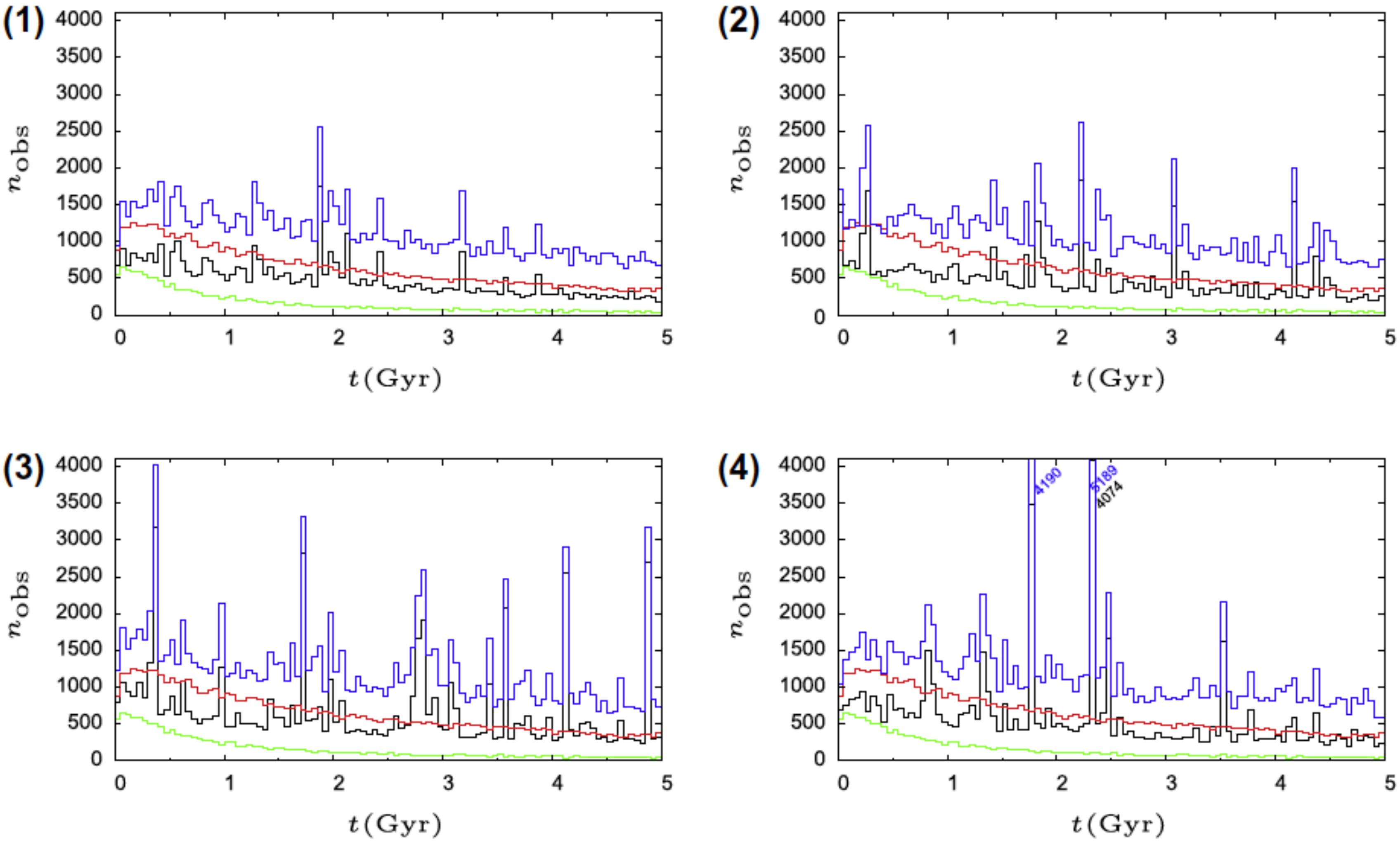
TAZ filling efficiency



Symbols: spectral types of stars

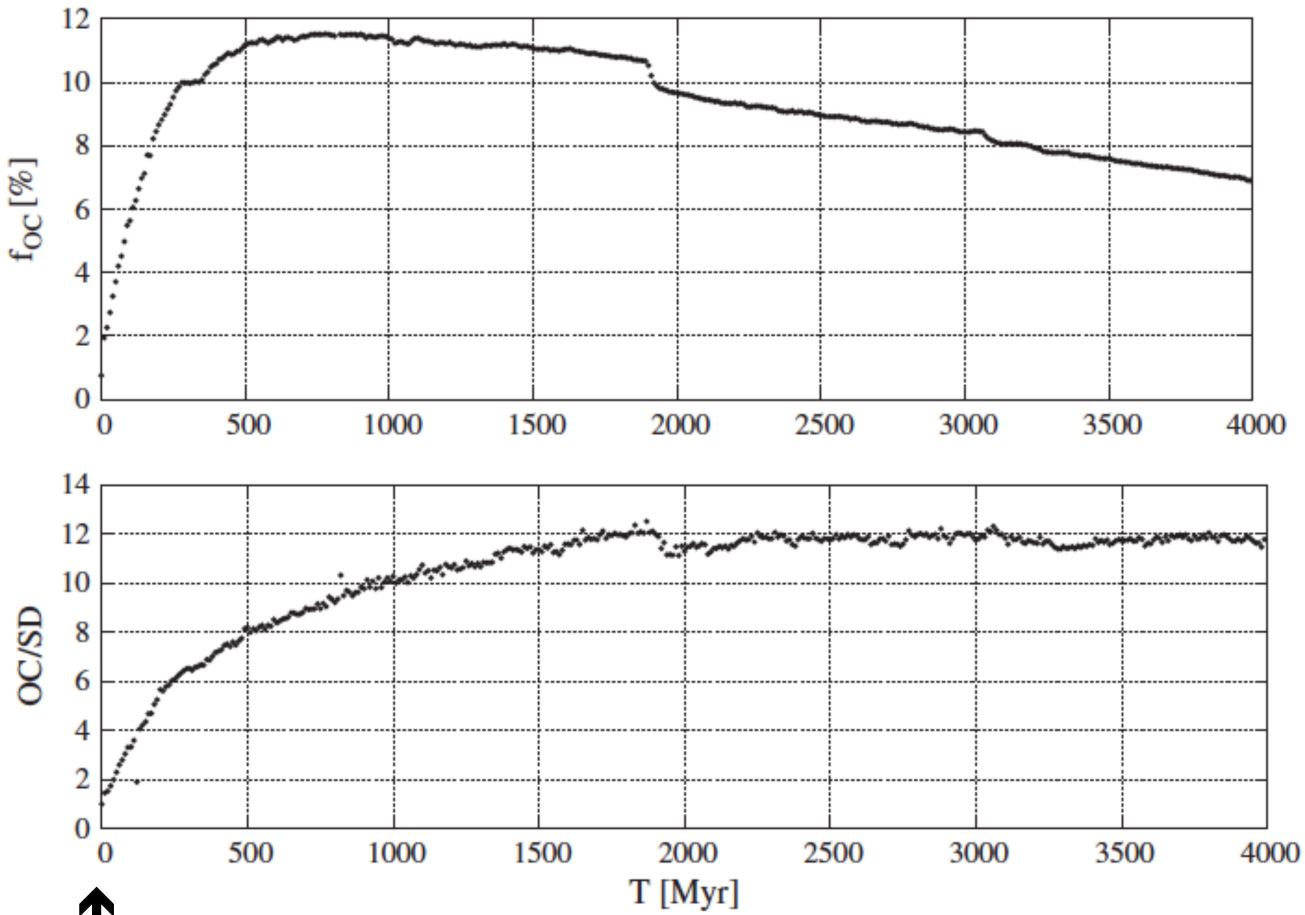
Fouchard et al (2011)

Comet showers



Fouchard et al (2014)

Brasser & Morbidelli (2013)



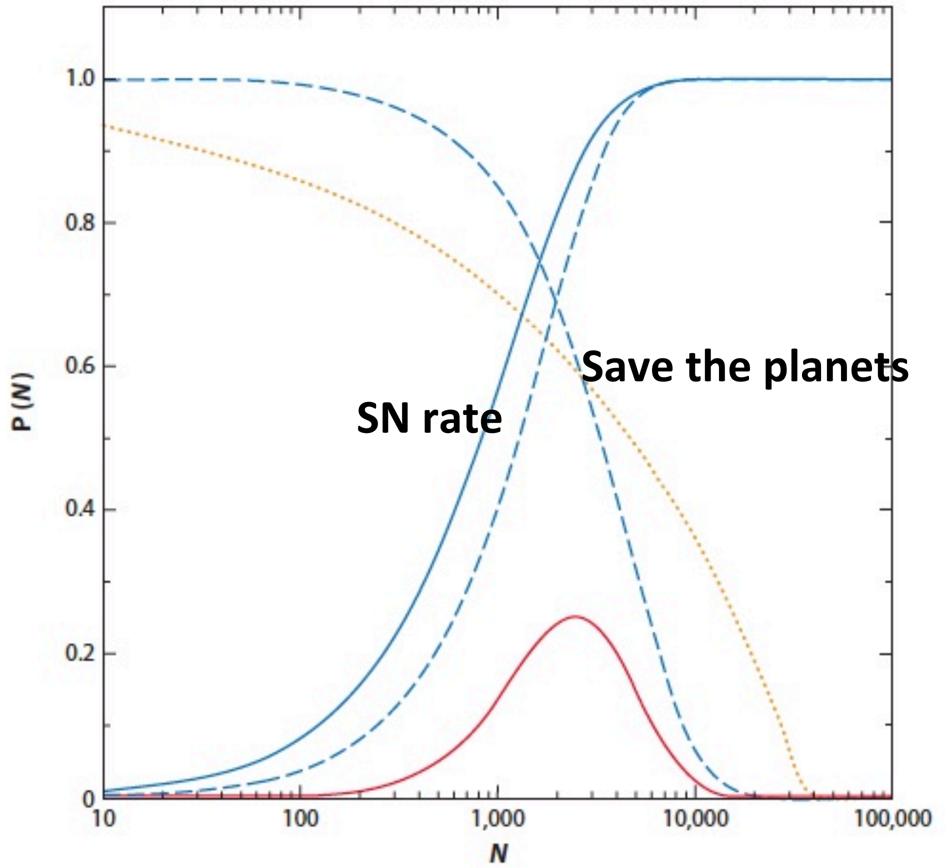
End of migration

Currently, $M_{OC} \approx 7\%$ of M(disk)
M_{SD} is 12 times less

Solar birth cluster

- ***Solar-type stars are born in embedded clusters***

- ***About equal numbers of stars are born in clusters with 10^2, 10^3 and 10^4 members*** *(Lada & Lada 2003)*



Adams (2010)

Oort Cloud and Birth Cluster

- ***If the Oort Cloud was formed very early, and the solar birth cluster was long-lived, would the cloud survive or not?***

- This can be investigated by dynamical simulations!

Nordlander et al (2017)

- ***Assume very early OC formation in a long-lived birth cluster; find out if the cloud survives until the LHB***
- ***High Mass*** (HM: N_0 *= 24000*) or ***Intermediate Mass*** (IM: N_0 *= 2000*) birth cluster assumed
- **Trace *10^3 OC comets* for *400 My*** (100-500 My) in a ***static cluster potential + random stellar encounters*** (select the strongest)
- Perform 10^3 simulations per model (comets and cluster) for statistical robustness

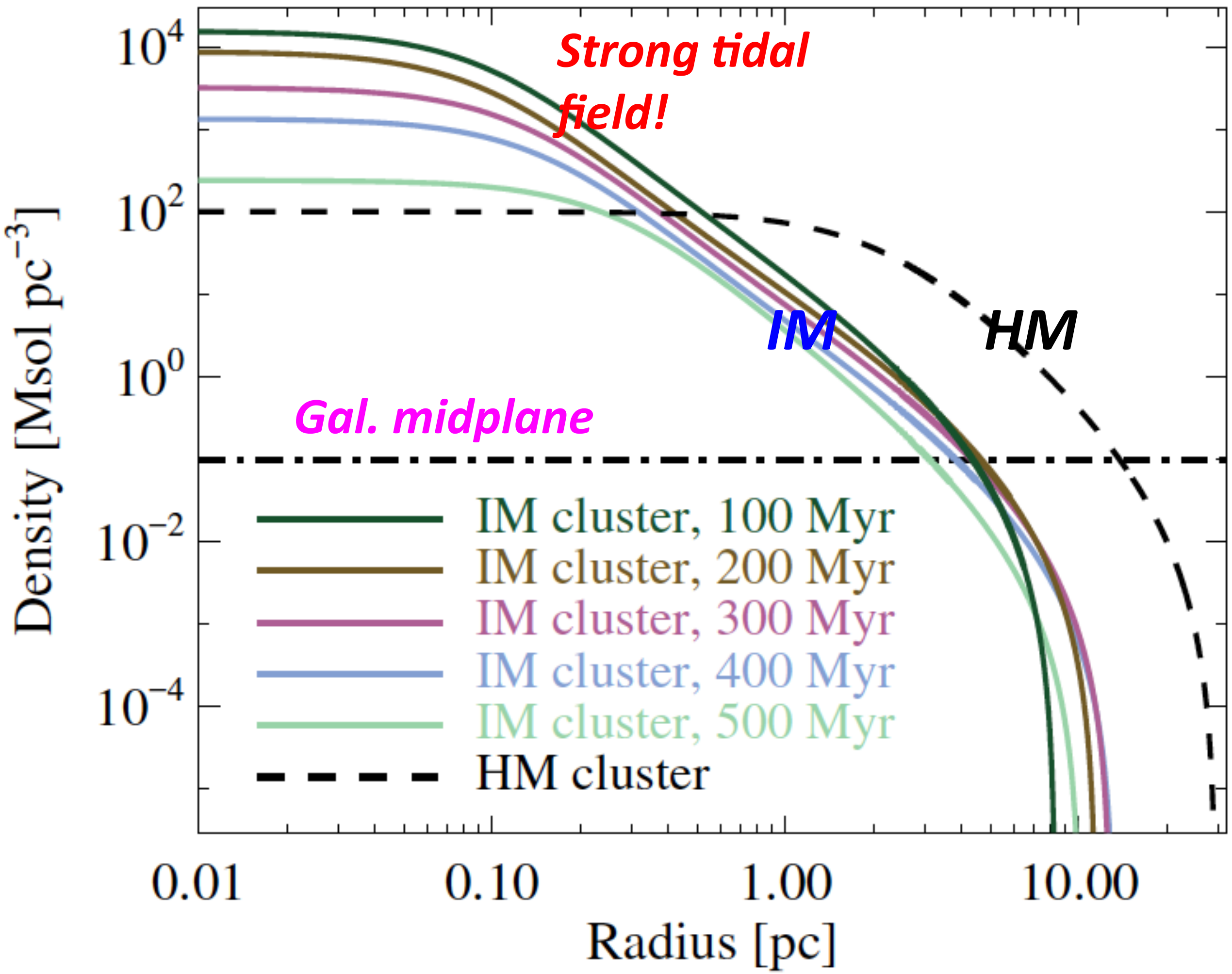
Cluster model

- The most general distribution function for a relaxed stellar cluster with central symmetry is

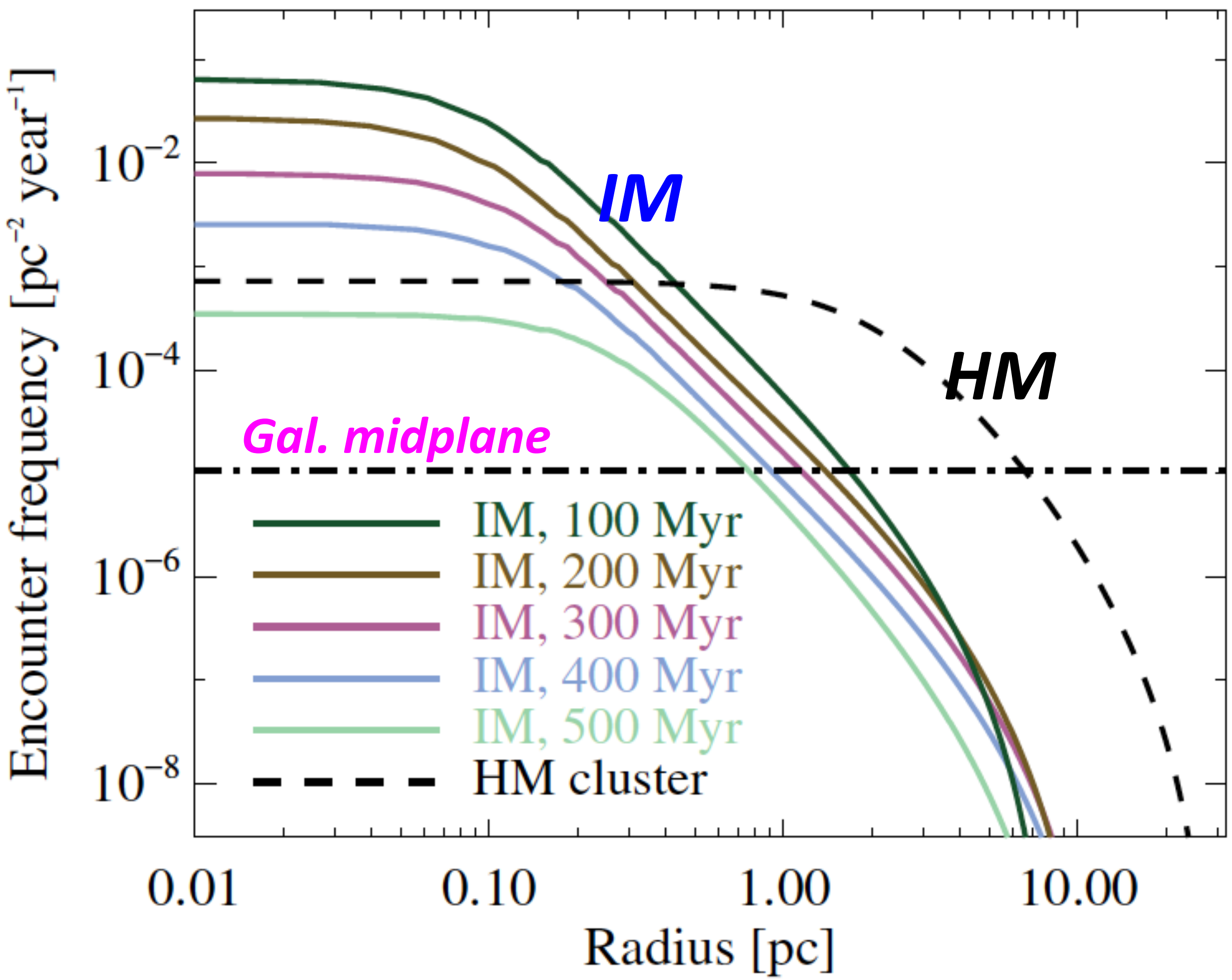
$$\varphi(E) = \begin{cases} a\left\{e^{b(E_{\mathrm{t}}-E)} - 1\right\} & E < E_{\mathrm{t}} \\ 0 & E \geq E_{\mathrm{t}} \end{cases}$$ *(King 1966)*

- ***No mass segregation; no binaries!***
- ***HM model:*** adapted to the young M67 (static)
- ***IM model:*** sequence of 16 static King models computed for evolving cluster (*N* = 1700 $\longrightarrow$ 300) with constant mass distribution

Density profiles



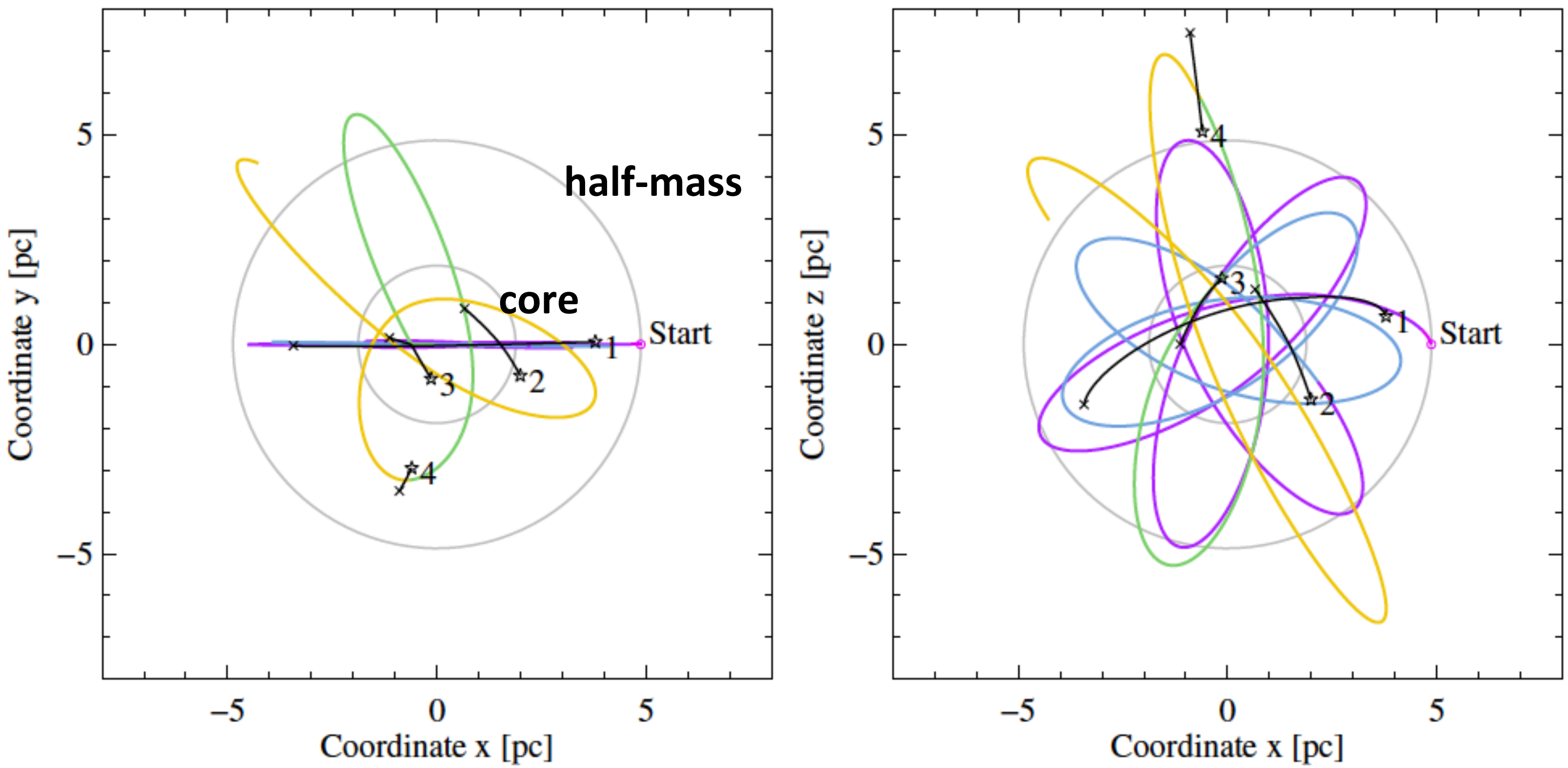
Encounter frequency



Simulations

- Initialize three groups of comets with ***a* = *5000*, *10000* and *20000* AU** and thermalized eccentricities
- Each group has *1000 comets*
- Start the Sun with random *E* and *L* defining the initial rosette orbit
- Integrate the effects of the ~20 strongest ***stellar encounters*** on the Sun and comets, and the ***cluster tide*** all the time
- Derive statistical results for *1000 simulations*

The solar orbit



HM cluster, first 80 Myr of one simulation

Comet escape

- ***Unlinked*** – ***comets reach distances > 1 pc from the Sun***

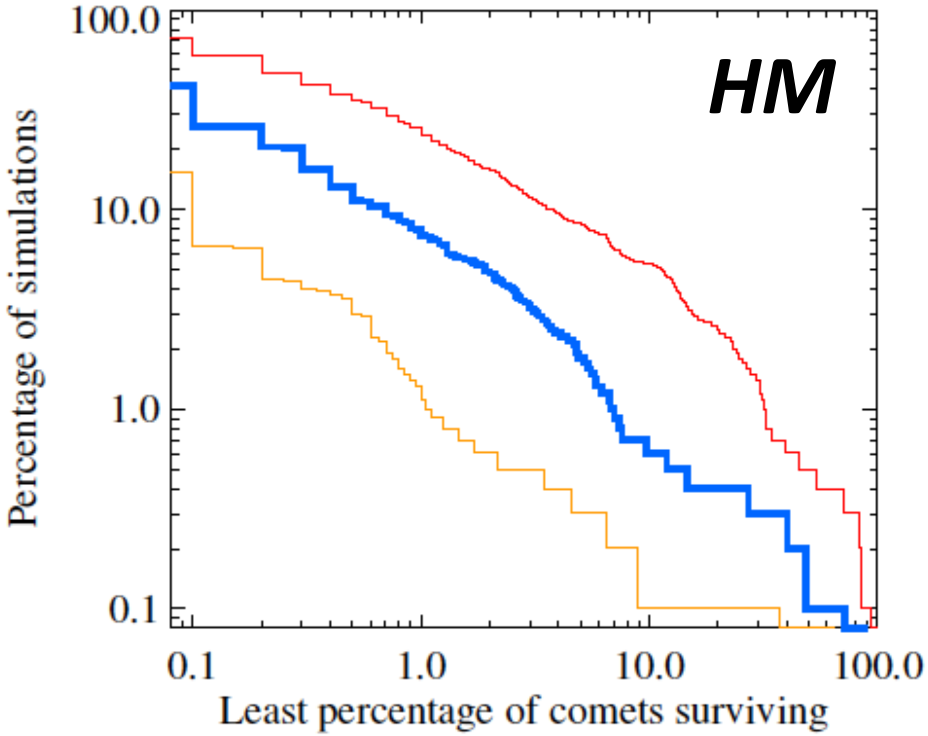
– *Mechanism:* impulse imparted by a stellar encounter, or energy perturbation by a non-integrable cluster tide

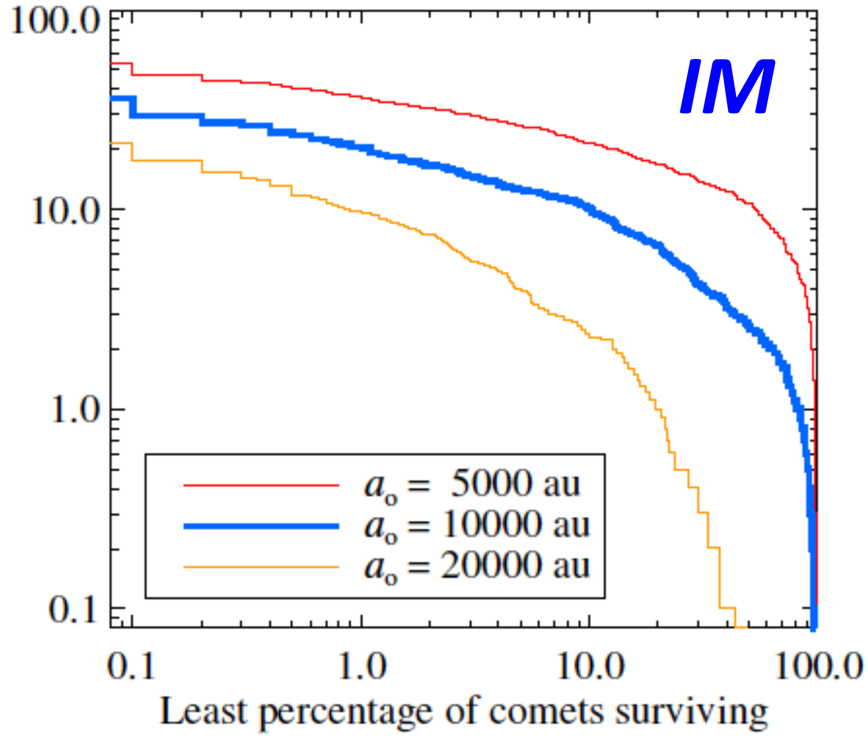
- ***Loss cone entry*** – ***comets enter within 5 AU of the Sun***

– *Mechanism:* angular momentum drain by the cluster tide, or by impulse imparted by a stellar encounter

Loss of comets

Median survival probability of OC comets ~ 0.1%



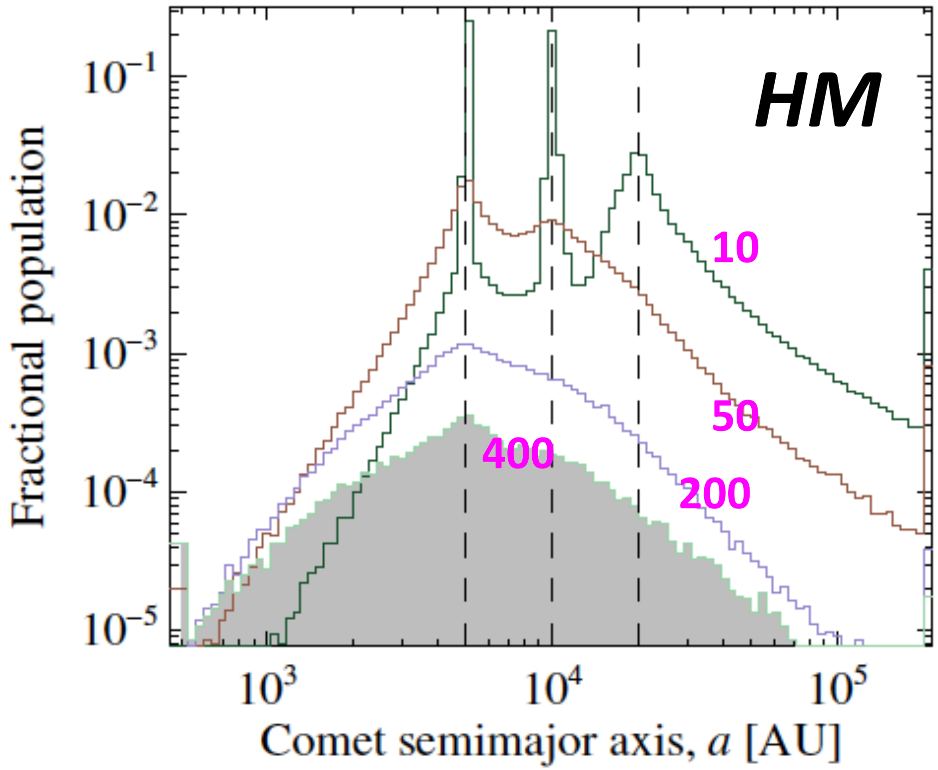


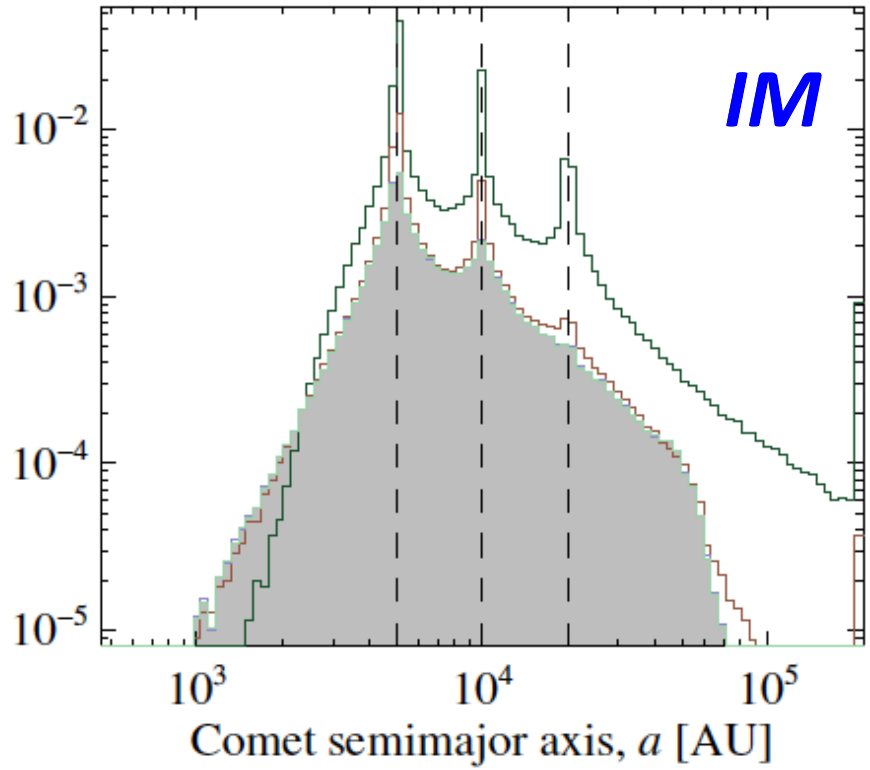
Here, the inner group survives at 10% level in almost 10% of the simulations

Here, there is a chance of significant survival, if the Sun avoids the central core

OC energy distribution

Four snapshots at times = X Myr, averaged





The Sun remains in the cluster: 94%

The Sun remains in the cluster: 5%

The OC gets fossilized, when the Sun leaves the cluster