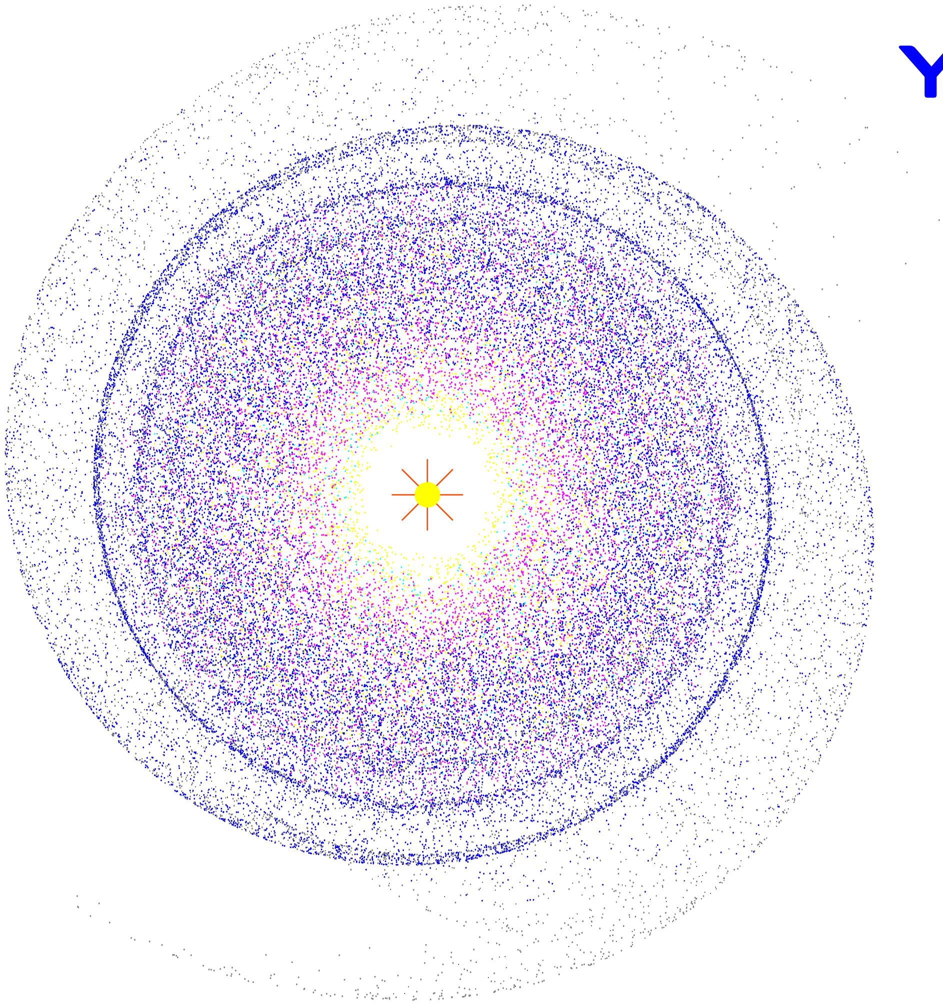

Gravitationally Triggered Planet Formation in Young Stellar Clusters

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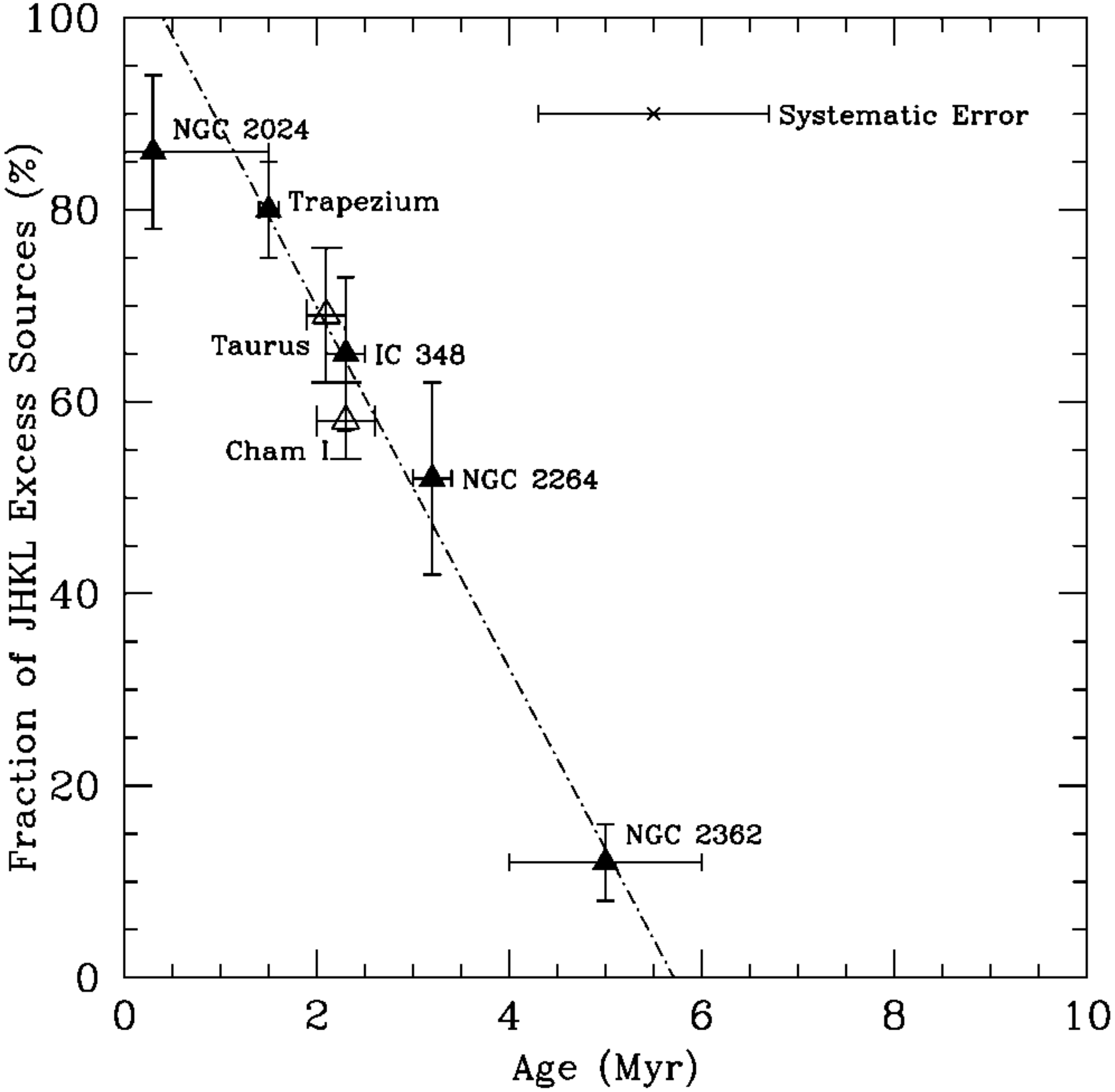
Motivation

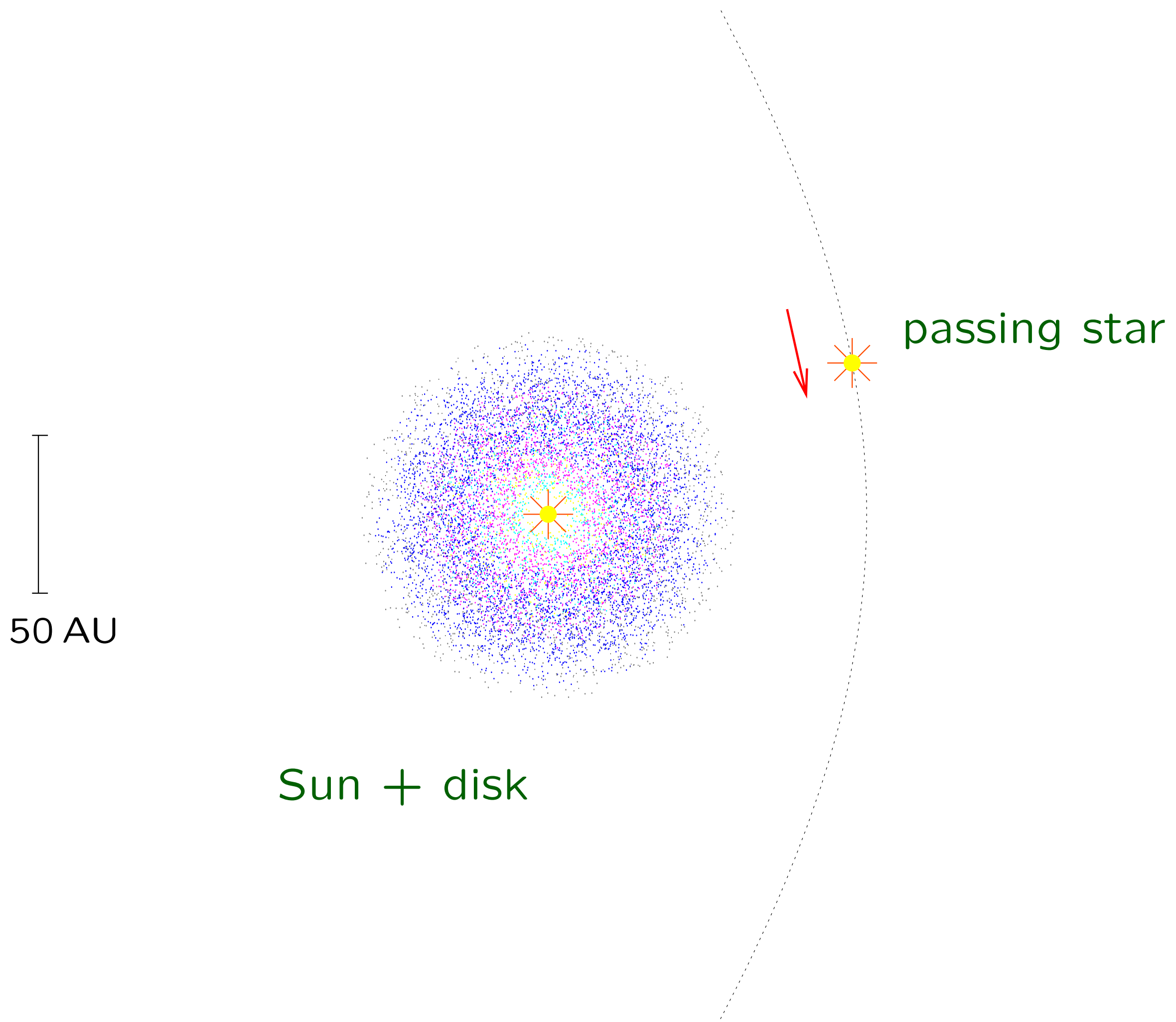
- Formation times of Uranus and Neptune typically about 100 Myr in standard coagulation model (starting with collision of planetesimals, D. J. Hollenbach et al., 2000)

- Lifetime of circumstellar disks less than about 6 Myr (Haisch, Lada & Lada, 2001) $\Rightarrow$ too short

- But Uranus and Neptune *do* exist $\Rightarrow$ new idea needed!

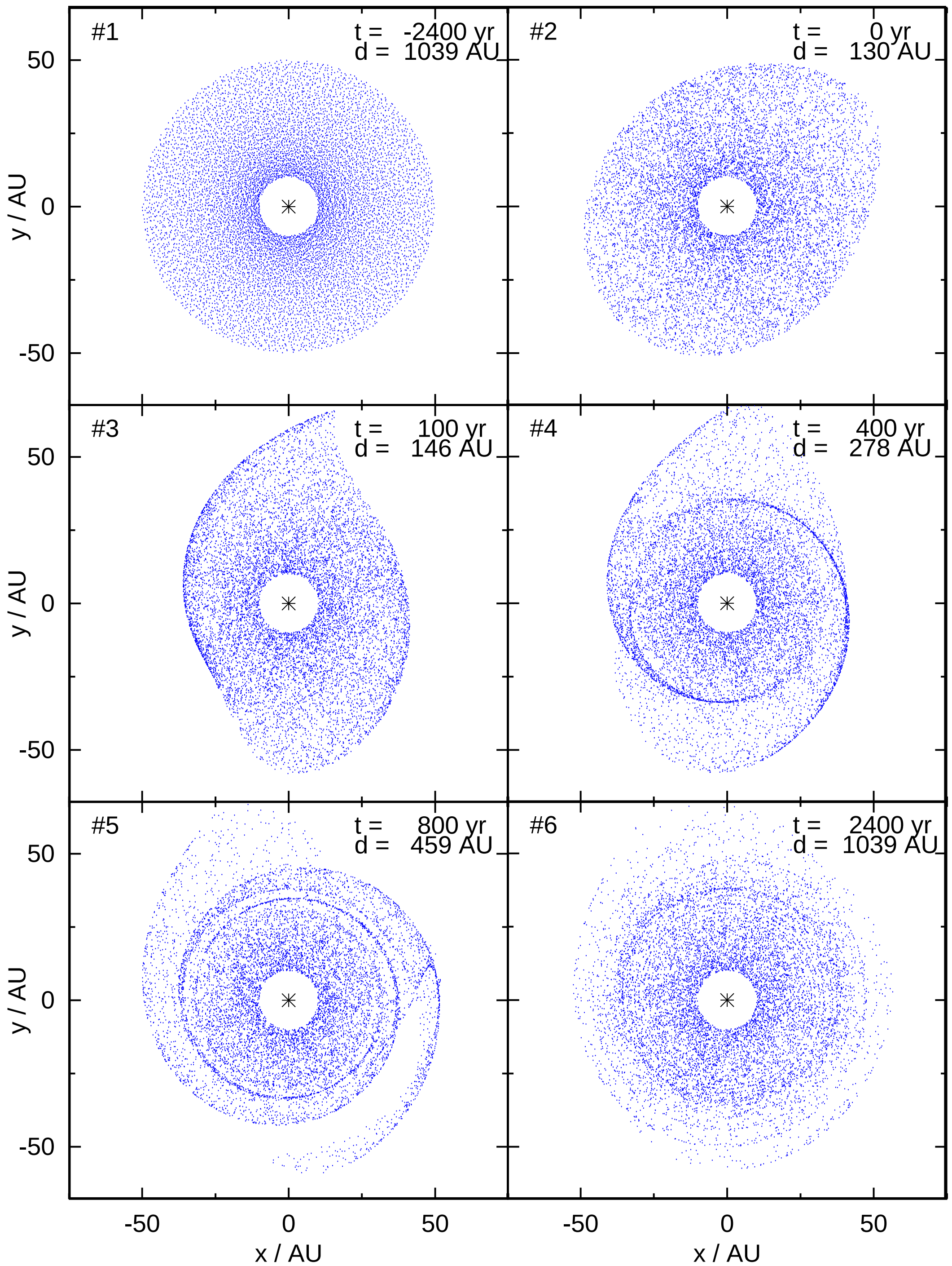


JHKL excess fraction as a function of mean cluster age. The fraction of stars with circumstellar disk is directly given by this excess. *(Haisch, Lada & Lada, 2001)*



Idea

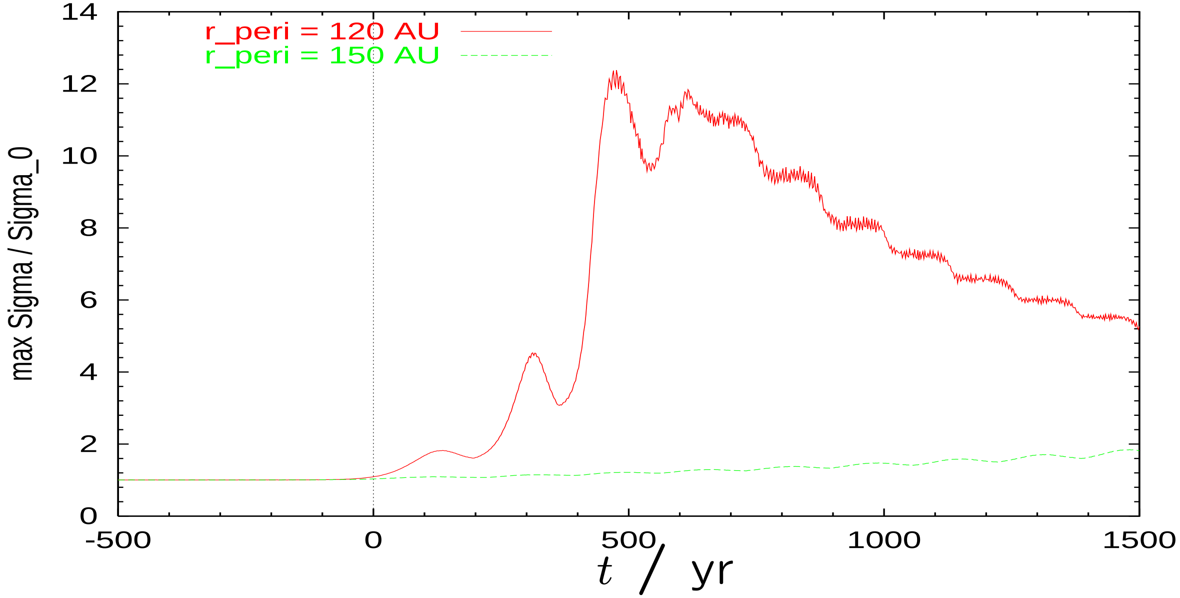
- Planet formation induced by gravitational instabilities (GI's) $\Rightarrow$ much shorter formation time ($\sim 100\,\mathrm{yr}$)
- GI induced by gravitational perturbation due to passing star
- Sun in its early years still member of a stellar cluster – one expects realistic probability of such fly-by



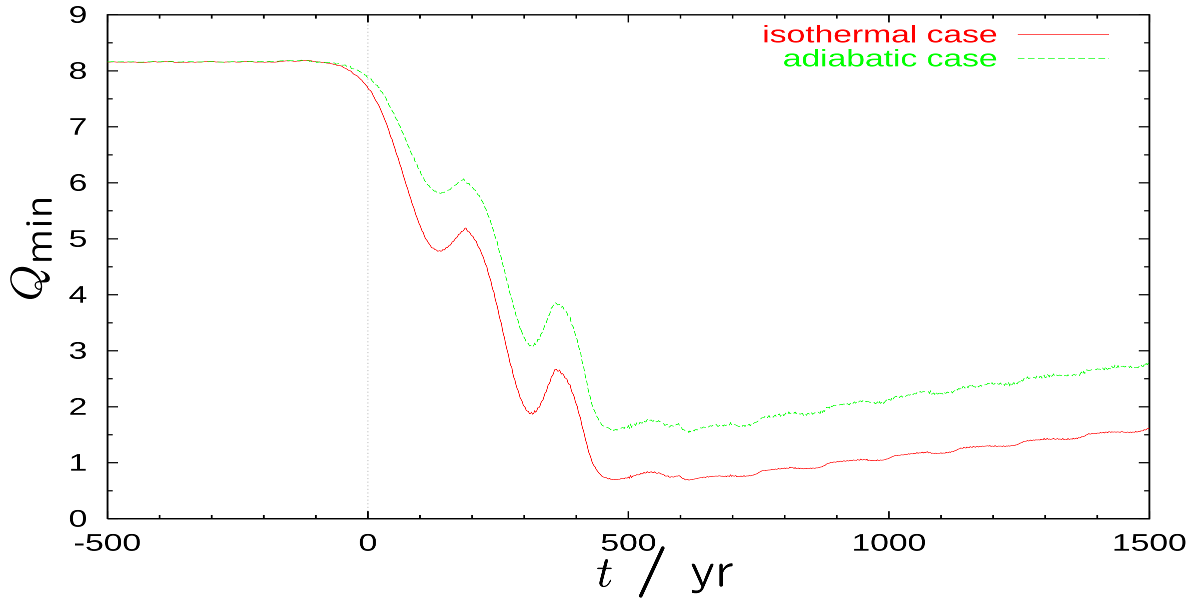
Disk perturbations during a coplanar parabolic fly-by at 130 AU. The mass of the perturber is 0.5 $M_\odot$.

Features:

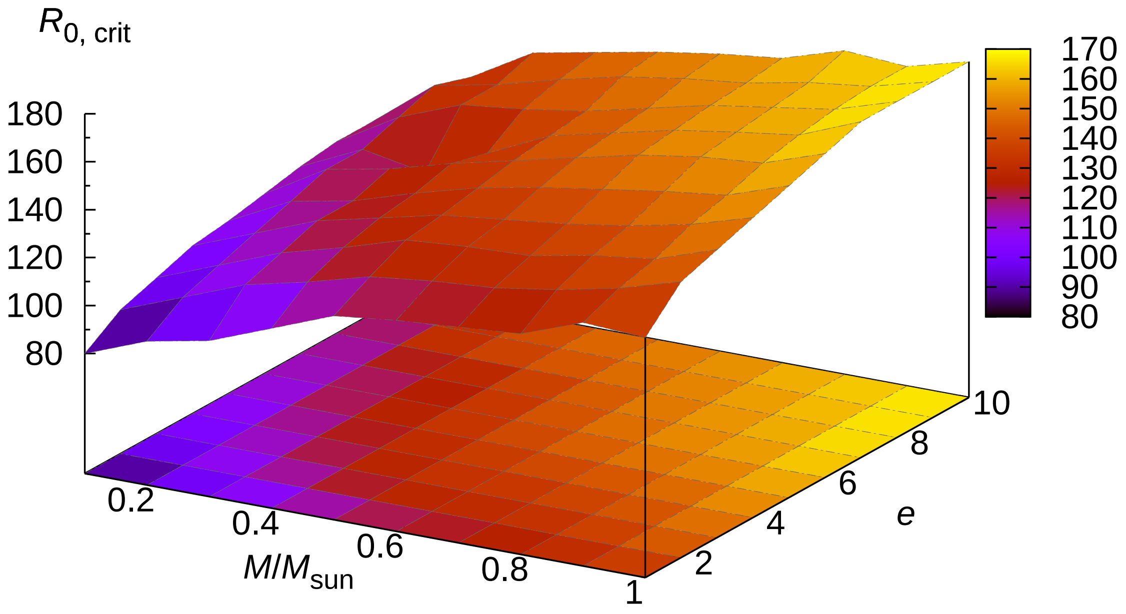
- strong surface density enhancement 400 yr outside 20 AU after closest encounter.
- density run-up easily above ten times the initial surface density
- region below 20 AU relatively unperturbed



Max. compression at $r \approx 25$–30 AU



$Q_{\rm min}(r_p = 120\,\text{AU}, r \approx 25\text{–}30\,\text{AU}, \gamma = 1.00, 1.66)$



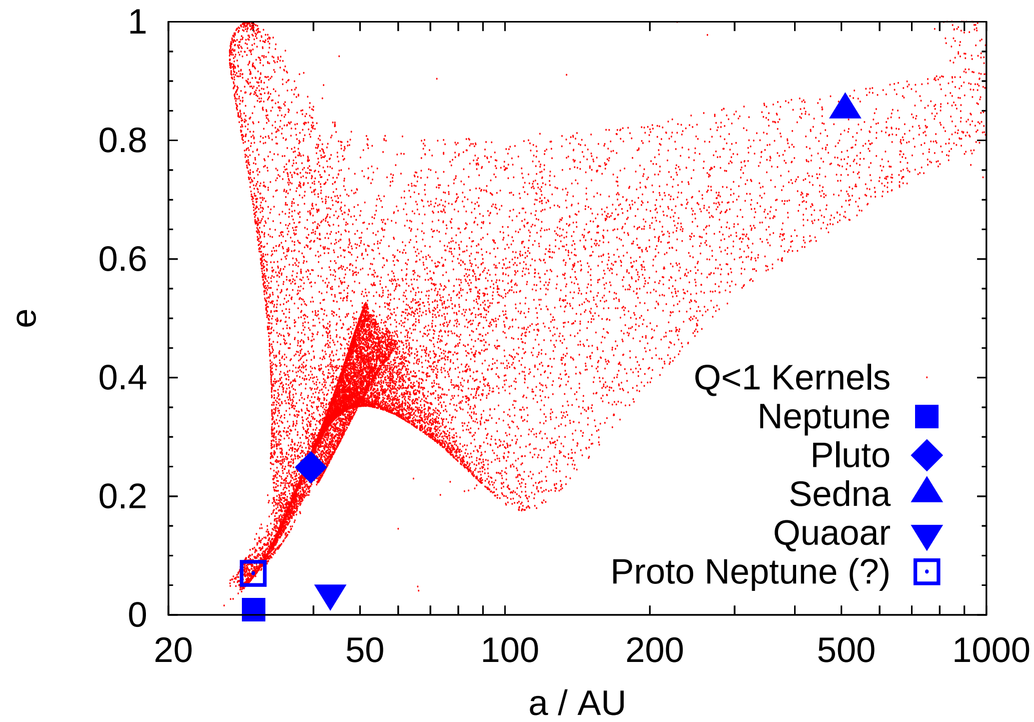
Possible instability region within the $M_\star, e, r_{\mathrm{peri}}$ parameter space. The surface indicates the upper border for r_{peri}, r_{crit}, where $Q < 1$ actually occurs. Grid based on interpolated data points.

Critical Triggering Radius

Two major trends for $M_\star$, e, r_{crit} where $Q < 1$ is likely:

1. increasing perturber mass, and
2. increasing eccentricity $\Rightarrow$ higher angular velocity $\Rightarrow$ more similar to particle velocity (prograde) $\Rightarrow$ stronger coupling

Candidate planet orbits



Distribution of candidate planet semimajor axis a and eccentricity e for a parabolic fly-by with $r_{\text{peri}} = 100\,\text{AU}$. The values for Pluto and Sedna are included as well.

Distribution of q and e of $Q < 1$ kernels in two regions:

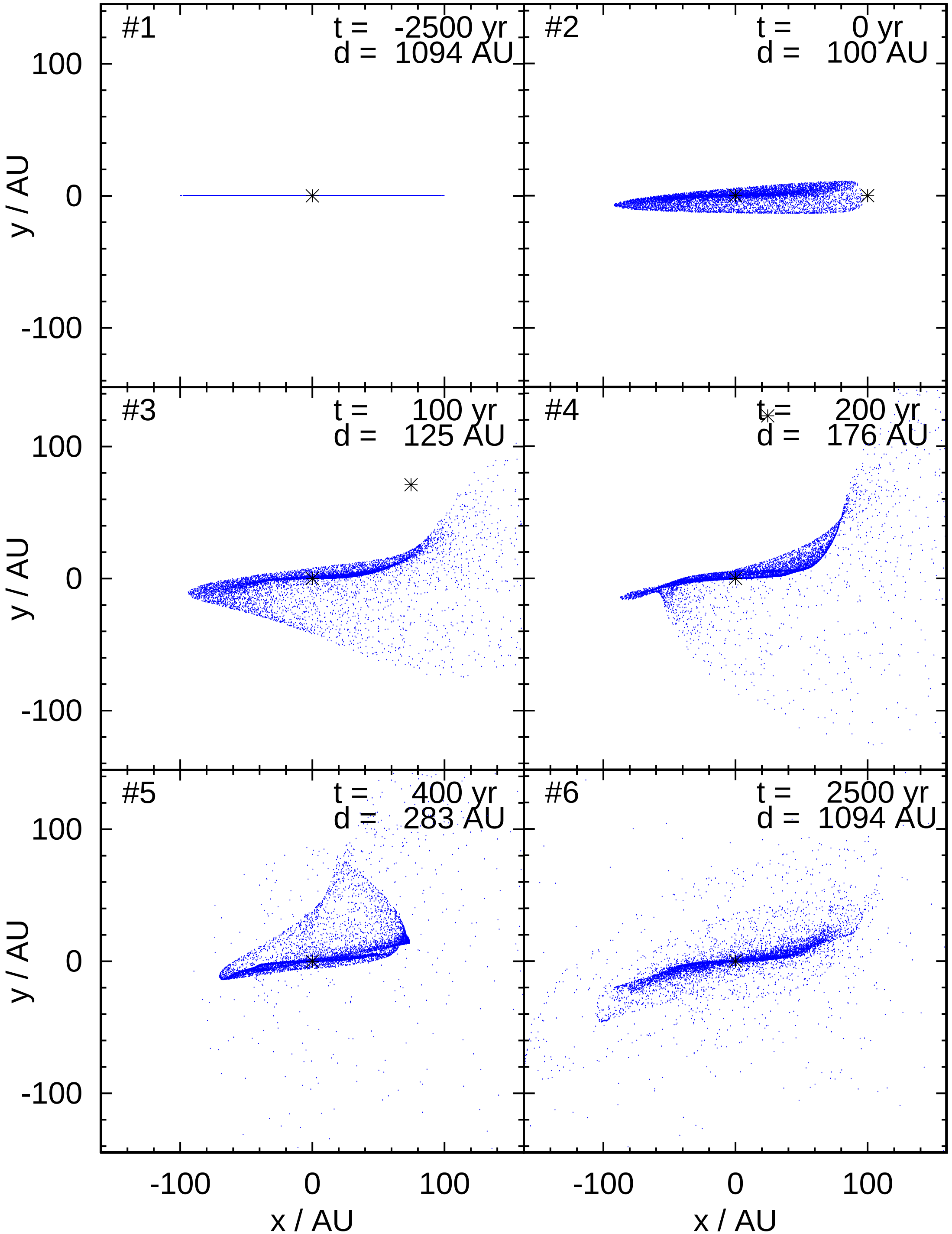
- main population for $30 < a < 500\,\text{AU}$, $0.2 < e < 1$,
- low density trail for $25 < a < 40\,\text{AU}$ and $e < 0.2$.

Sedna's Orbit is close to main population; Neptune near the trail.

$\Rightarrow$ Sedna formed by triggering(?)

Outlook: Current Projects

- minor parameter study using a 3D SPH model to confirm these results
- higher resolution 2D or 3D grid simulations for studying gravitational instabilities
- better estimate of possible resulting protoplanet orbits.

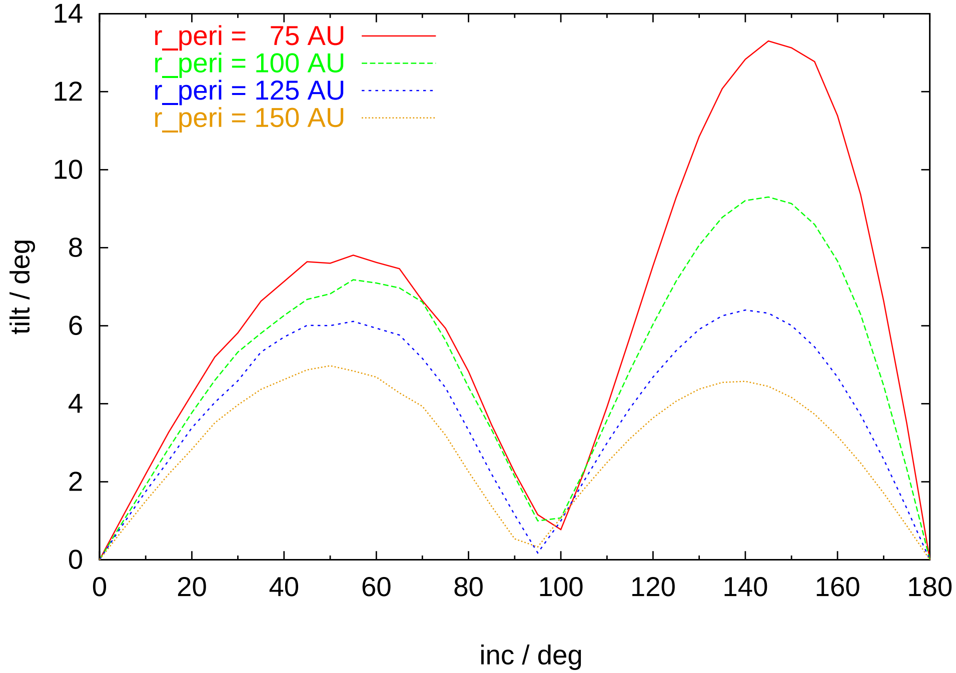


Disk tilt due to an inclined retrograde fly-by.

Flyby parameters:

- Pericenter $r_{\mathrm{peri}} = 100\,\mathrm{AU}$
- Inclination $\imath = 135^\circ$ (retrograde)
- Perturber $m = 0.5\,M_\odot$

Disk tilt by inclined fly-bys

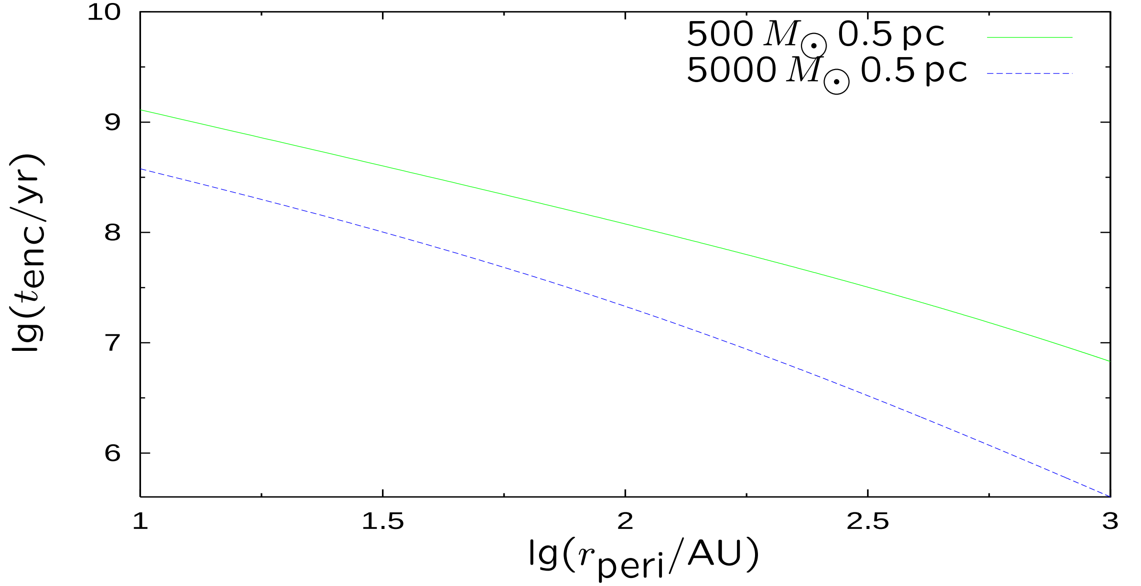


Tilt of the disk after fly-by of a 0.5 $M_\odot$ perturber as a function of inclination and closest distance.

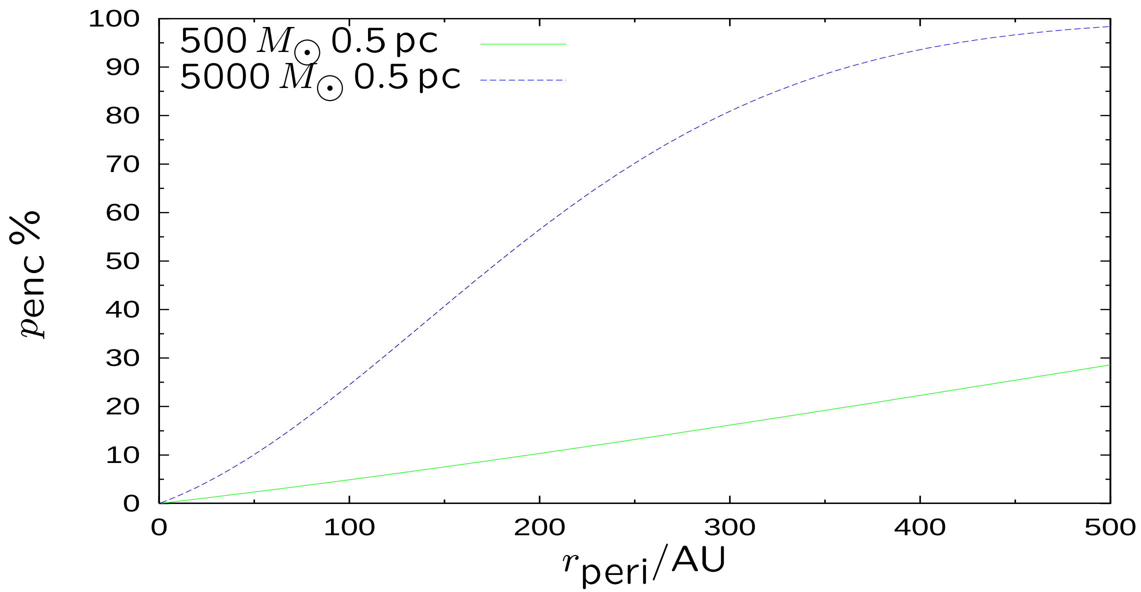
Calculation of angular momentum change of a perturbed disk with 100 AU total radius:

- Closer fly-by $\Rightarrow$ more tilt
- Tilt is maximal for 140° (retrograde) and semi-maximal for 50° (prograde) passages.

(Particles with final semimajor axis $>$ 300 AU have been omitted)



Mean time between two encounters



Probability of close encounters

Dynamics of Stellar Encounters I

The Probability can be estimated by using simplified cluster models (e. g. Plummer).
We assume an open stellar cluster with

- Cluster Mass $M_{\rm cl} \approx 500 M_{\odot}$ ($\Rightarrow N \approx 1000$ stars)
- half-mass radius $R_{0.5} \approx 0.5\,pc$

These parameters yield the characteristic velocity dispersion $\sigma_{\rm ch}$ and the crossing time $t_{\rm cr}$

$$\sigma_{\rm ch}^2 = \frac{2\,E_{\rm kin}}{M_{\rm cl}} \approx 0.384\,\frac{GM_{\rm cl}}{R_{0.5}} t_{\rm cr} \equiv \frac{2\,R_{0.5}}{\sigma_{\rm 1D,ch}} = \frac{2\sqrt{3}}{\sigma_{\rm ch}} R_{0.5} \approx 5.59\,\frac{R_{0.5}^{3/2}}{\sqrt{GM_{\rm cl}}}$$

With common units of measurement:

$$\frac{\sigma_{\rm ch}}{\rm km\,s^{-1}} = 0.0407 \left(\frac{M_{\rm cl}}{M_{\odot}}\right)^{1/2} \left(\frac{R_{0.5}}{\rm pc}\right)^{-1/2}$$

$$\frac{t_{\rm cr}}{\rm Myr} = 83.3 \left(\frac{M_{\rm cl}}{M_{\odot}}\right)^{-1/2} \left(\frac{R_{0.5}}{\rm pc}\right)^{3/2}$$

$\Rightarrow \quad \sigma_{\rm ch} \approx 1.3\,{\rm km/s}\,, \quad t_{\rm cr} \approx 1.3\,{\rm Myr}$

For a more massive Cluster with $M_{\rm cl} = 5000\,M_{\odot}$ we get

$$\sigma_{\rm ch} \approx 3.1\,{\rm km/s}\,, \quad t_{\rm cr} \approx 0.54\,{\rm Myr}$$

Dynamics of Stellar Encounters II

The eccentricity e of the fly-by orbit depends on the periastron radius $r_{\rm peri}$ and the relative velocity before the encounter, which is approximately equal to $\sigma_{\rm ch}$. At given $r_{\rm peri}$, e is

$$e = 2\left(\frac{\sigma_{\rm ch}}{v_{\rm esc}}\right)^2 + 1\ , \quad \text{where} \quad v_{\rm esc}^2 = 2\frac{GM}{r_{\rm peri}}$$

Then the relationship between the impact parameter d and $r_{\rm peri}$ is

$$d = \sqrt{\frac{e+1}{e-1}}\, r_{\rm peri}$$

Given d we can calculate the mean time $t_{\rm enc}$ between two encounters, and the encounter probability $p_{\rm enc}$ within disk lifetime $t_{\rm disk}$

$$t_{\rm enc}(d) = \frac{t_{\rm cr}}{n_{\rm enc}} = \frac{t_{\rm cr}}{N}\frac{R_{0.5}^2}{d^2}$$

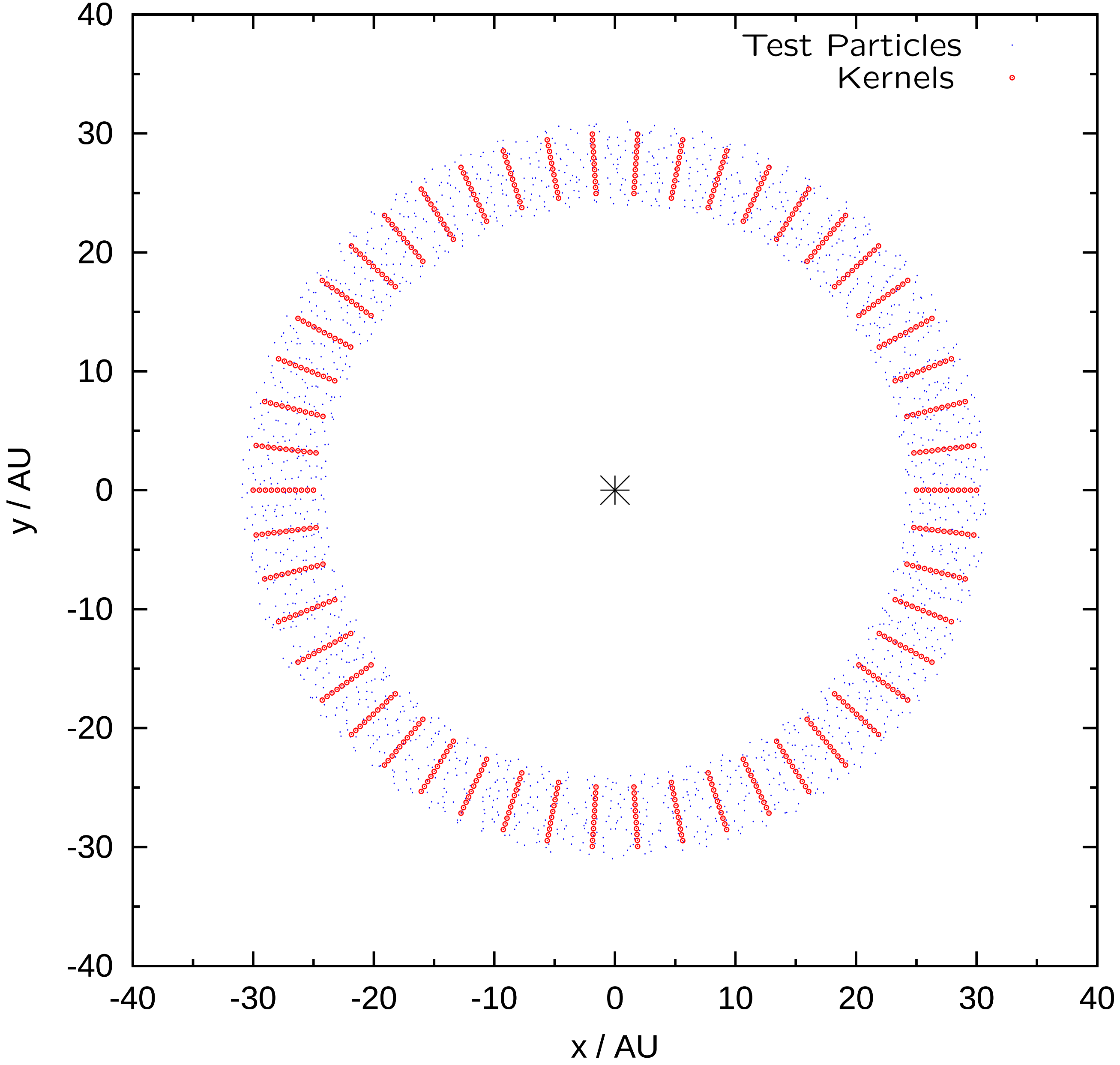
$$\frac{t_{\rm enc}}{\rm Myr} = \frac{3.5\cdot 10^{12}}{N}\left(\frac{M_{\rm cl}}{M_\odot}\right)^{-1/2}\left(\frac{R_{0.5}}{\rm pc}\right)^{7/2}\left(\frac{b}{\rm AU}\right)^{-2}$$

$$\boxed{p_{\rm enc} = 1 - e^{-\frac{t_{\rm disk}}{t_{\rm enc}}}}$$

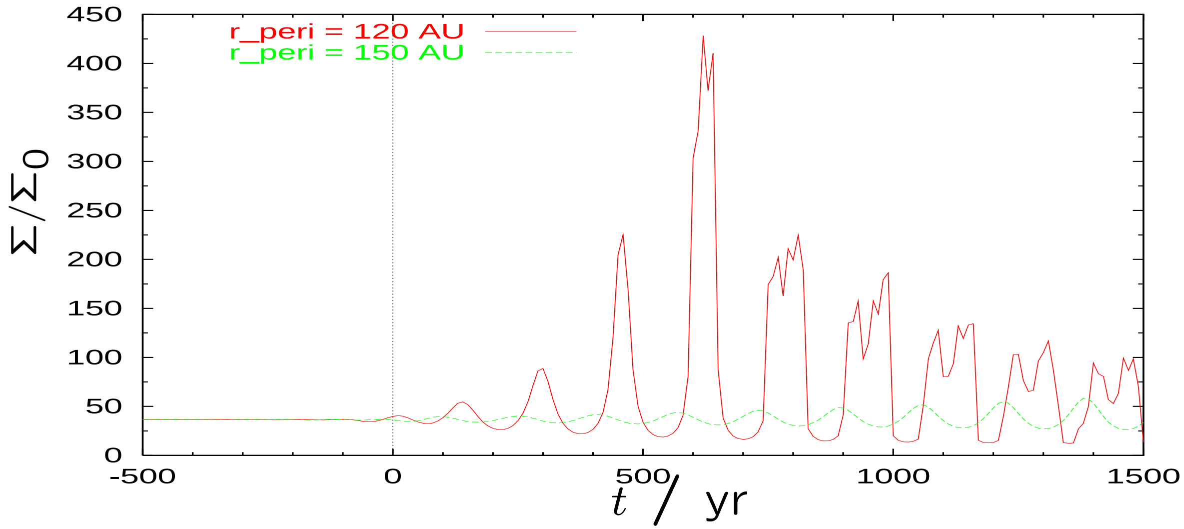
Particle Density

Two methods:

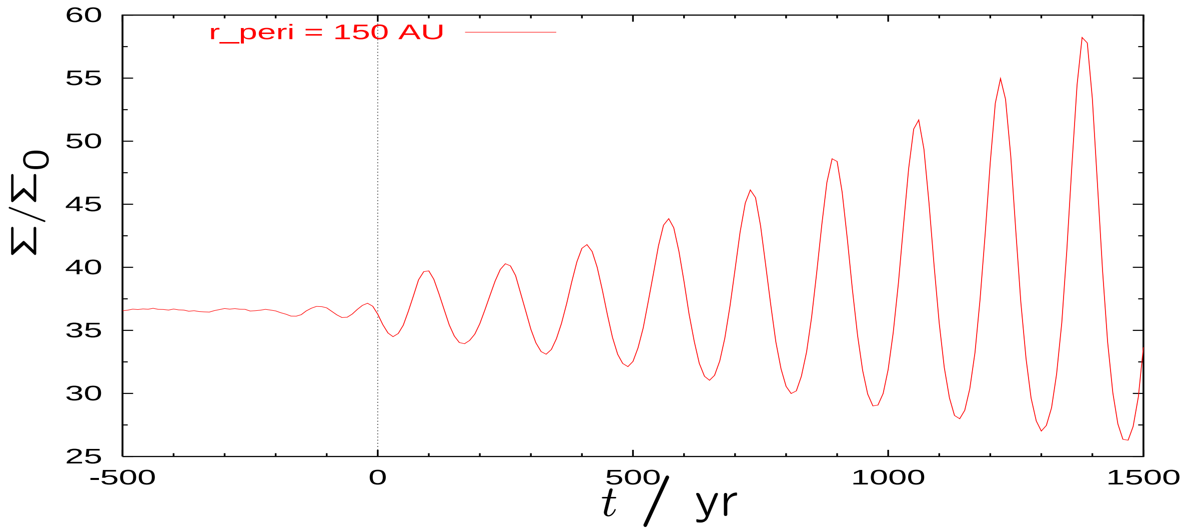
- fixed grid $\Rightarrow$ global density distribution
  - gives overall view when using 2-D colour plot (not yet implemented)
  - but limited information about local conditions
- "test volume" around selected test particles (using kernel functions)
  - information about selected "mass boxes"
  - but limited spatial information



Initial positions of kernels within the scanned area of the particle disk, which ranges from 24 to 31 AU. The Kernels are distributed between 25 and 30 AU

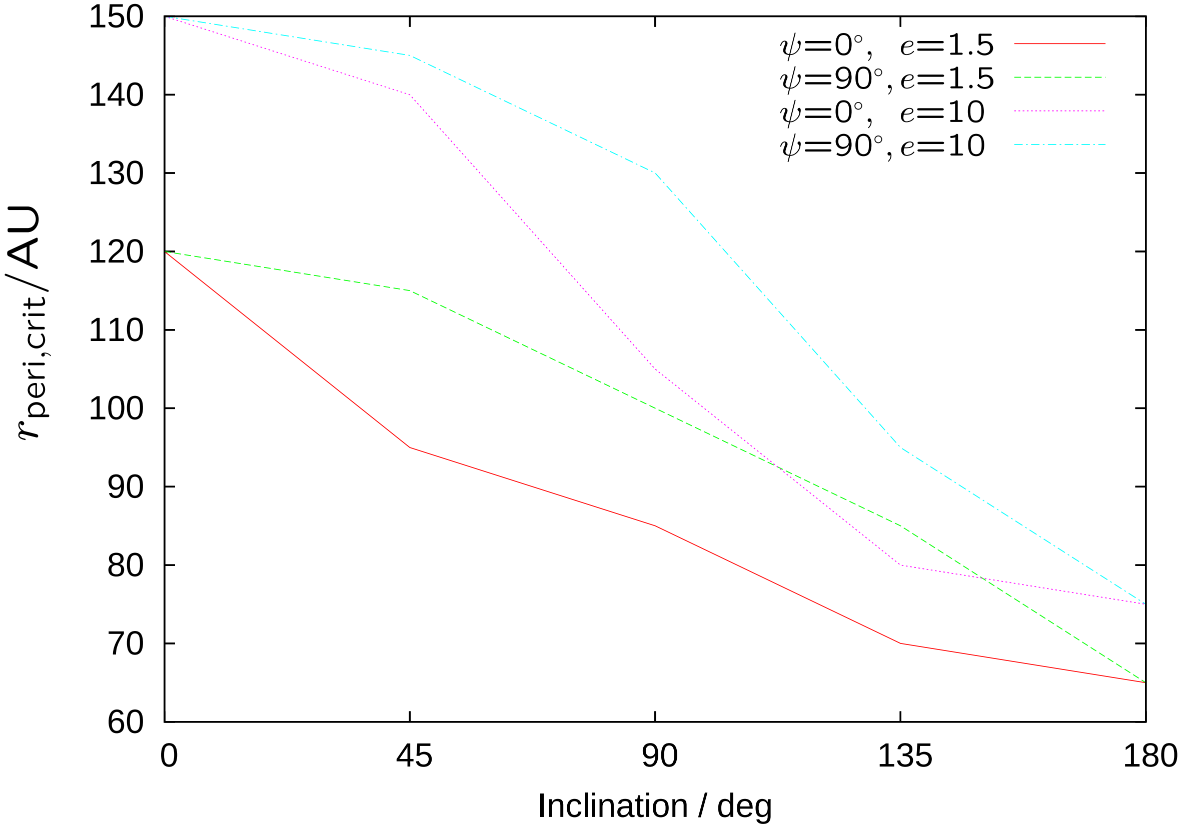


Surface density vs time at $r \approx 30\,\mathrm{AU}$



Surface density vs. time at $r \approx 30\,\mathrm{AU}$ for $r_p = 150\,\mathrm{AU}$

Inclined Encounters



$r_{\text{peri,crit}} = r_{\text{peri}}$ with $Q_{\text{min}} < 1$ for $M_\star = 0.5\,M_\odot$, $e = 1.5$ and $e = 10$ and different inclinations. ψ is the longitude of the encounter.

- $Q_{\text{min}} < 1$ also possible in retrograde fly-bys
- $r_{\text{peri,crit}}$ about half of that for prograde events.
- $r_{\text{peri,crit}}$(inc) monotonically falling

The Role of Cooling

- Cooling prevents compressed perturbed area from re-expansion

- Rough estimate using polytropic equation of state:

  - Best case: Cooling dominates
    $\Rightarrow \gamma = 1$

  - Worst case: No cooling at all
    $\Rightarrow \gamma = 5/3$

- Locally Q decreases strongly
  ($\Rightarrow$ induces gravitational fragmentation)

Disk stability

- Gravitational stability depends on
  - surface density Σ
  - temperature vs. velocity dispersion v_s (sound velocity in gaseous disks)
  - epicyclic frequency κ (orbital frequency in Keplerian disks)
- Toomre parameter:

$$Q = \frac{v_s\,\kappa}{\pi G \Sigma}$$

- Gravitational instabilities occur for Q below about 1.5–1.7
- Dynamic timescale of a disk region:

$$t_{\mathrm{dyn}} = \sqrt{\frac{3\pi}{32 G \rho}} \approx 10^2\ \mathrm{yr} \quad \text{for} \quad \rho \approx 10^{-12}\ \mathrm{g/cm^3}$$