# Kozai effect on planetesimal accretion in inclined binaries

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# Background

- Over 40 planetary systems have been discovered in binary star systems
- Orbital planes randomly distributed if $a_b$>40AU (Hale 1994)
- Spin-orbit misalignment is observed (eg. HD80606b (e=0.93 a=0.47), Wu and Murray 2003; Pont et al. 2009; Winn et al. 2009)

Mean problems in planetesimal accretion: high impact velocity

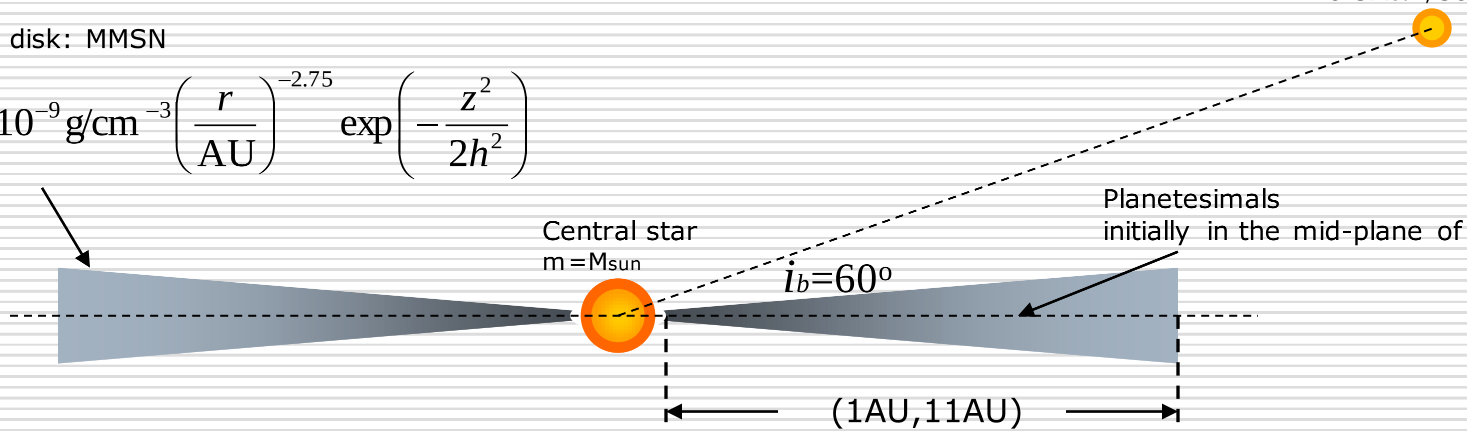
- Kozai effect : $i_c=39.23^o$
- randomization of node longitude

# Model

3D disk: MMSN

$$\rho = 1.4\times10^{-9}\,\mathrm{g/cm}^{-3}\left(\frac{r}{\mathrm{AU}}\right)^{-2.75}\exp\left(-\frac{z^2}{2h^2}\right)$$

Companion: $\vec{r}_b$
0.5Msun, 50AU, $e_b$=0.4




$$\frac{d^2\vec{r}}{dt^2} = -\frac{GM}{r^2}\left(\frac{\vec{r}}{r}\right) + Gm_b\left[\frac{(\vec{r}_b-\vec{r})}{|\vec{r}-\vec{r}_b|^3} - \frac{\vec{r}_b}{r_b^3}\right] + F_{disk}\,(+F_{gasdrag})$$

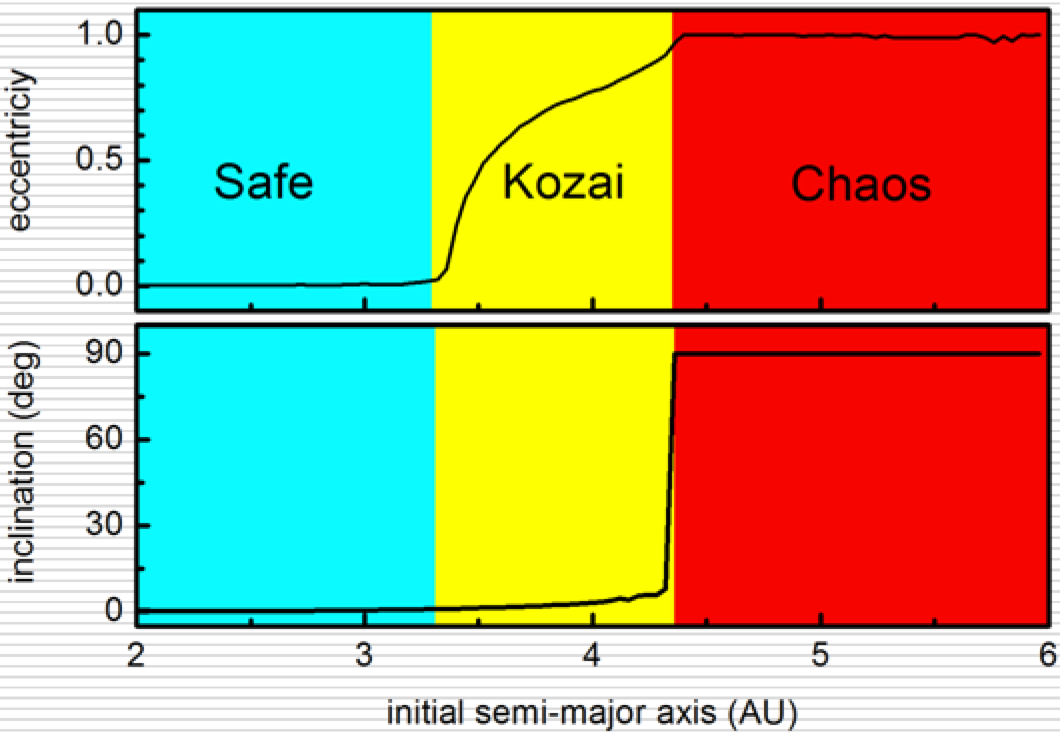
$F_{disk}$: gravitational force of the disk. numerical integration and interpolation

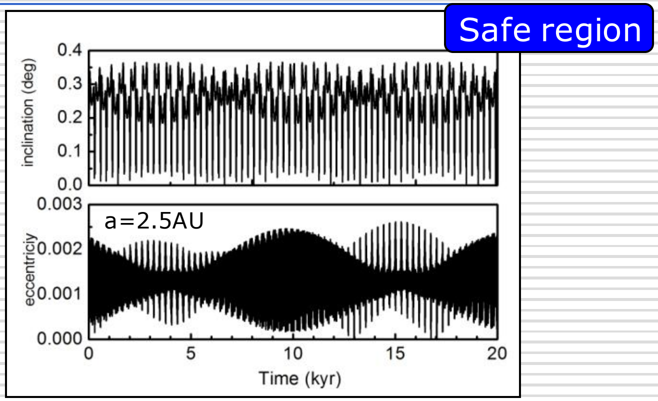
$$F_{gasdrag} = -\frac{3\rho C_d}{8\rho_p R_p} v\vec{v}$$

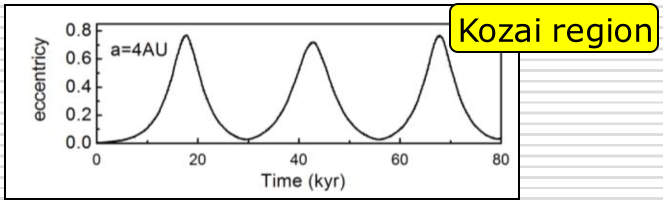
Ignore the interaction between the disk and the companion

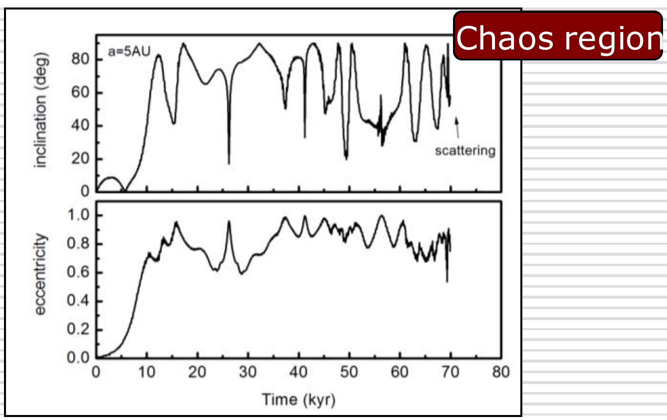
# 3 types of motion

Considering the potential of the disk:




eccentricities and incliantions are small in safe region

# Secular motion

Perturbing function:

$$R = na^2\left(T(a)e^2 - S(a,i)\right) + na^2 A(a)\left(e^2 - cee_b\cos\varpi - i^2 + 2i_b\cdot i\cos\Omega\right) + \text{const.}$$

disk Companion

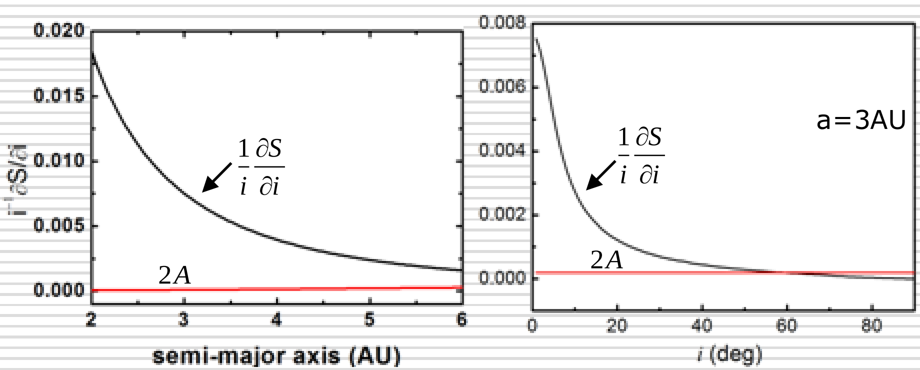
T(a),s(a,i) are obtained by numercial average

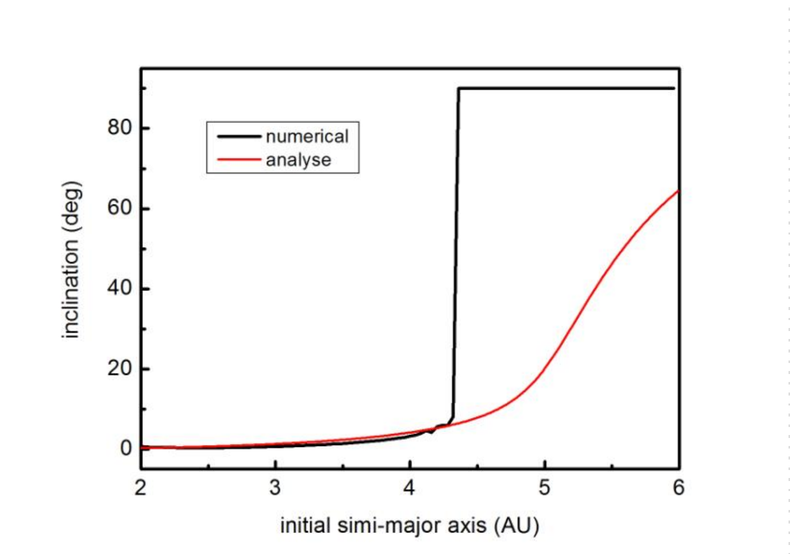
Equation of motion:

$$\frac{dp}{dt} = -\left(\frac{1}{i}\frac{\partial S}{\partial i} + 2A\right)q + 2Ai_b$$

$$\frac{dq}{dt} = \left(\frac{1}{i}\frac{\partial S}{\partial i} + 2A\right)p$$

where $p = i\sin\Omega$, $q = i\cos\Omega$



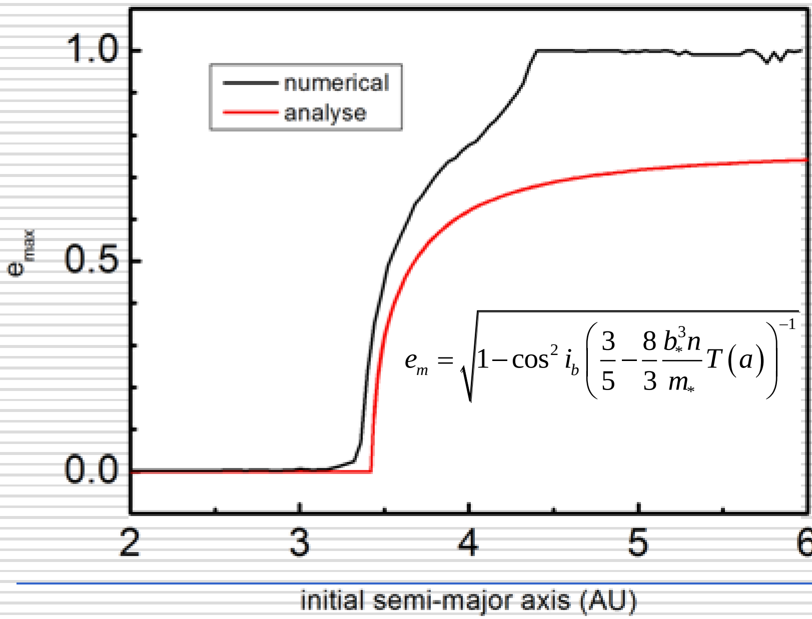



# Kozai effect

$$\frac{d\omega}{dt} \approx \frac{m_b}{b_b^3 n}\frac{3}{4}\left(2-5\sin^2 i \sin^2\omega\right)+2T(a)$$

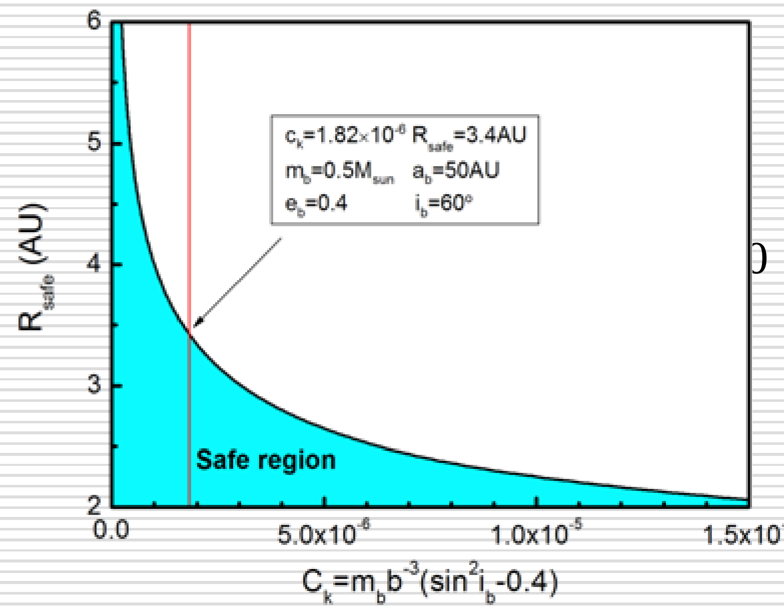
companion — disk

(for small eccentricity;
the xy plane is Companion's orbital plane and
$b_b = a_b\sqrt{1-e_b^2}$ )



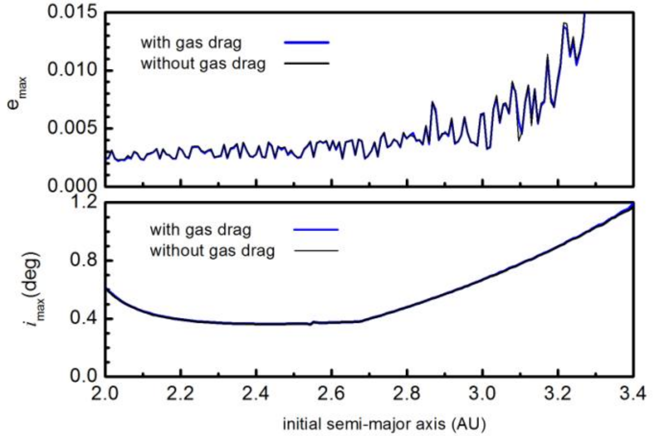

the extension of the safe region can be solved:

$$\frac{8}{15}a^{-3/2}T(a) > \frac{m_b}{b_b^3}\left(\sin^2 i_b - \frac{2}{5}\right)$$

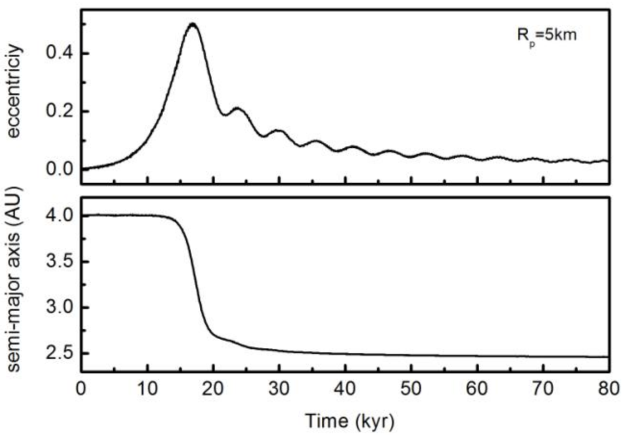


# Gas drag

Safe region:




Kozai region or Chaos region:




Planetesimials have small eccentricities and inclinations

Simulation: 10000 planetesimals 2-3AU

Average impact velocity $<\Delta V> \approx 2\text{m/s}$

- No planetesimal in Kozai region and Chaos region
- Planetesimals quickly migrate into the safe region which might favor planetesimal accretion

# conclusion

- The potential of disk can’t be ignored
- Considering the potential of disk, planetesimals’ eccentricities and inclinations are small in the safe region
- Planetesimals outside of the safe region will quickly migrate into the safe region
- Planet(Isolation mass) can form in safe region

# The end

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Thank you!