Evolution of MU69
from a binary planetesimal into contact
via Kozai-Lidov oscillations and nebular drag

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DSP 2020

Funding

AAG – 2020, 2010

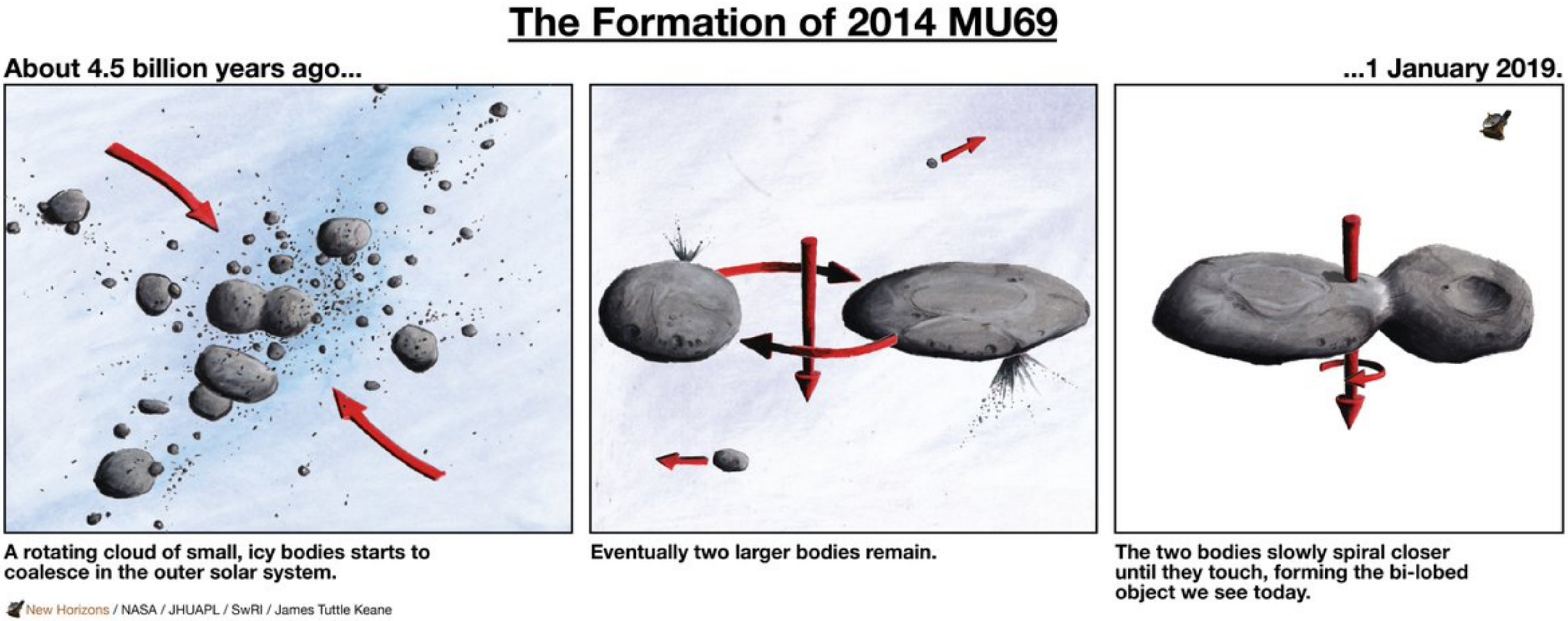
TCAN – 2020
NFDAP – 2019
XRP – 2016, 2018

NRAO - 2017

HST - 2016

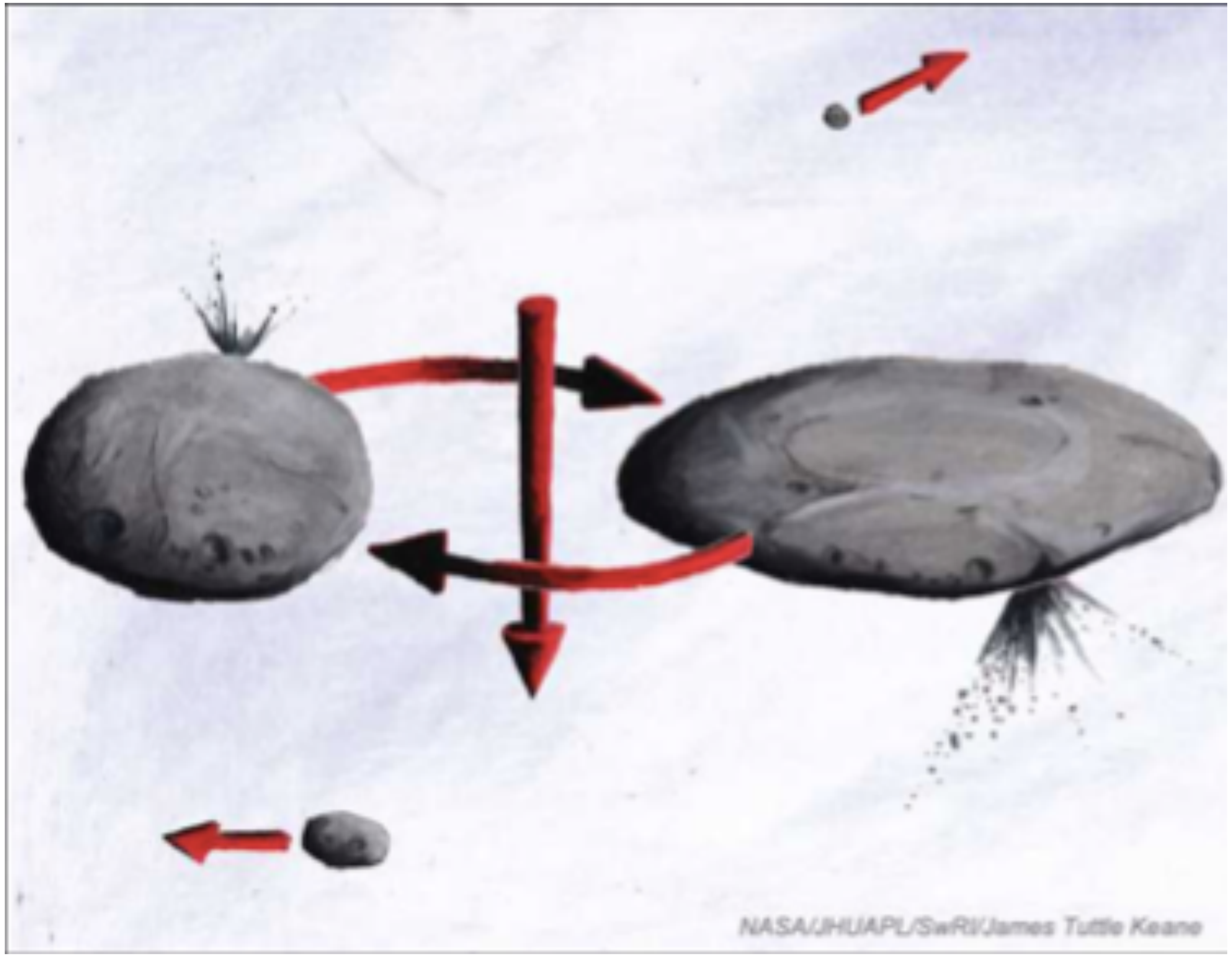
Computational Facilities

The Cartoon Image



Sketch by J.T. Keane

Hardening



Sketch by J.T. Keane

Angular momentum loss via nebular drag

gravity *drag*

$$\ddot{\boldsymbol{r}}_1 = -Gm_2 \frac{(\boldsymbol{r}_1 - \boldsymbol{r}_2)}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|^3} - \frac{\dot{\boldsymbol{r}}_1}{\tau_1}$$

$$\ddot{\boldsymbol{r}}_2 = -Gm_1 \frac{(\boldsymbol{r}_2 - \boldsymbol{r}_1)}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|^3} - \frac{\dot{\boldsymbol{r}}_2}{\tau_2}$$

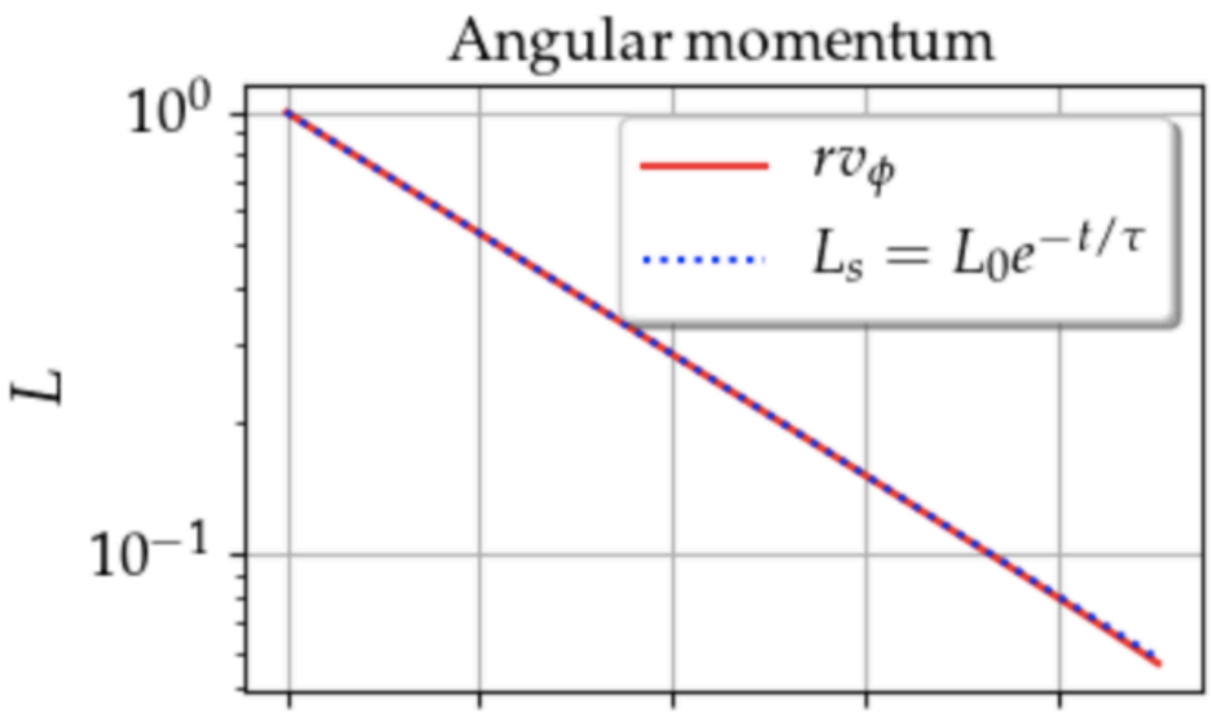
Solve for angular momentum:

$$r\ddot{\phi} + 2\dot{r}\dot{\phi} = -\frac{r\dot{\phi}}{\tau}$$

$$\frac{dh}{dt} = -\frac{h}{\tau}$$

Exponential decay of angular momentum !

$$h = h_0 e^{-t/\tau}$$



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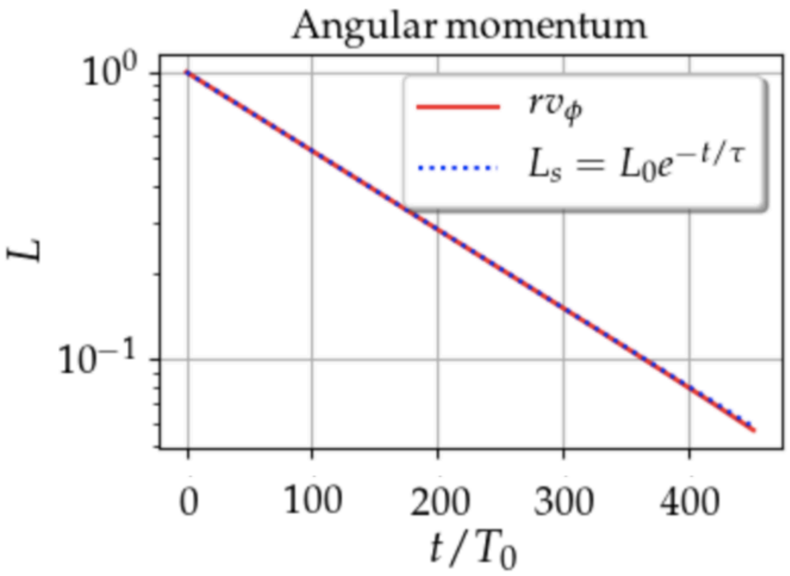
Analytical solution

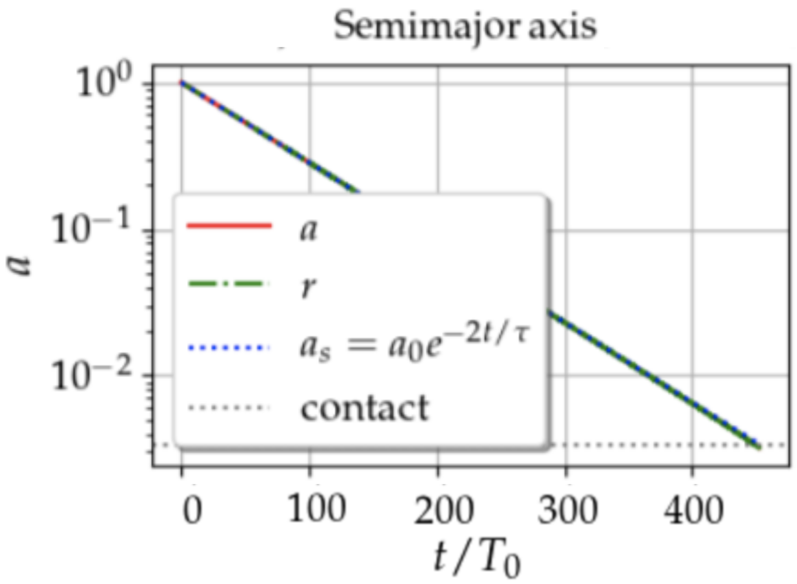
Exponential decay of angular momentum

$$h = h_0 e^{-t/\tau_{\rm eff}}$$



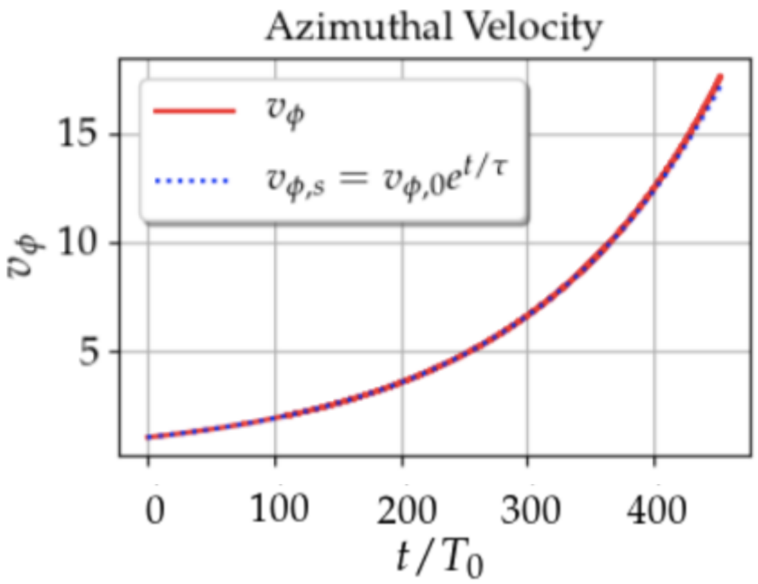
Exponential decay of energy

$$a = a_0\, e^{-2t/\tau_{\rm eff}}$$



Exponential increase of orbital velocity

$$v_\phi = v_{\phi,0}\, e^{t/\tau_{\rm eff}}$$



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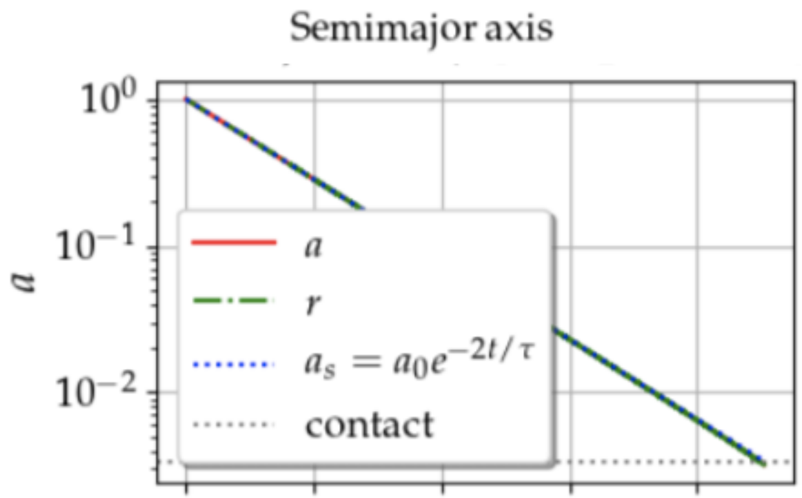
Getting quantitative…



Time until contact

$$t = \frac{\tau}{2} \ln \frac{a_0}{a}$$

For $a = 0.1\ r_H$ (4000 km), hardening to a_0=20km and $\tau\Omega=10^7$ …

t ~ 100 Myr

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Wind

<u>At initial separation $a \sim$ 4000 km:</u>

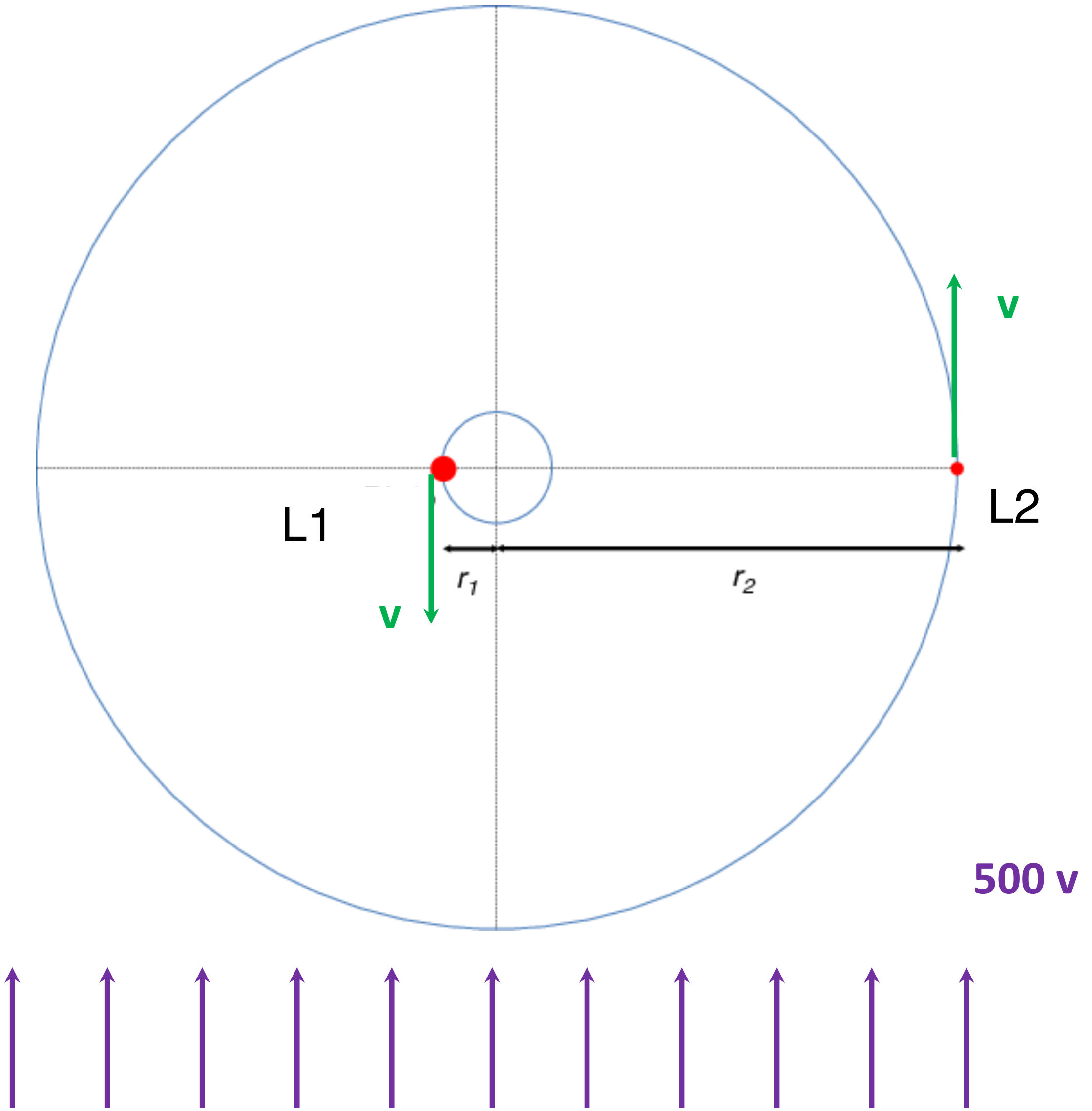
Binary orbital velocity **~ 0.1 m/s**

Solar orbit velocity at 45AU
$\boldsymbol{v_k \sim 4.5}$ **km/s**

Sub-Keplerian pressure support
$v = v_k\,(1-\eta)$
$\eta \sim 0.01$

Headwind velocity (v_k-v):
$\eta v \sim 50$ m/s

Subkeplerian wind on the binary
= 500 times orbital velocity



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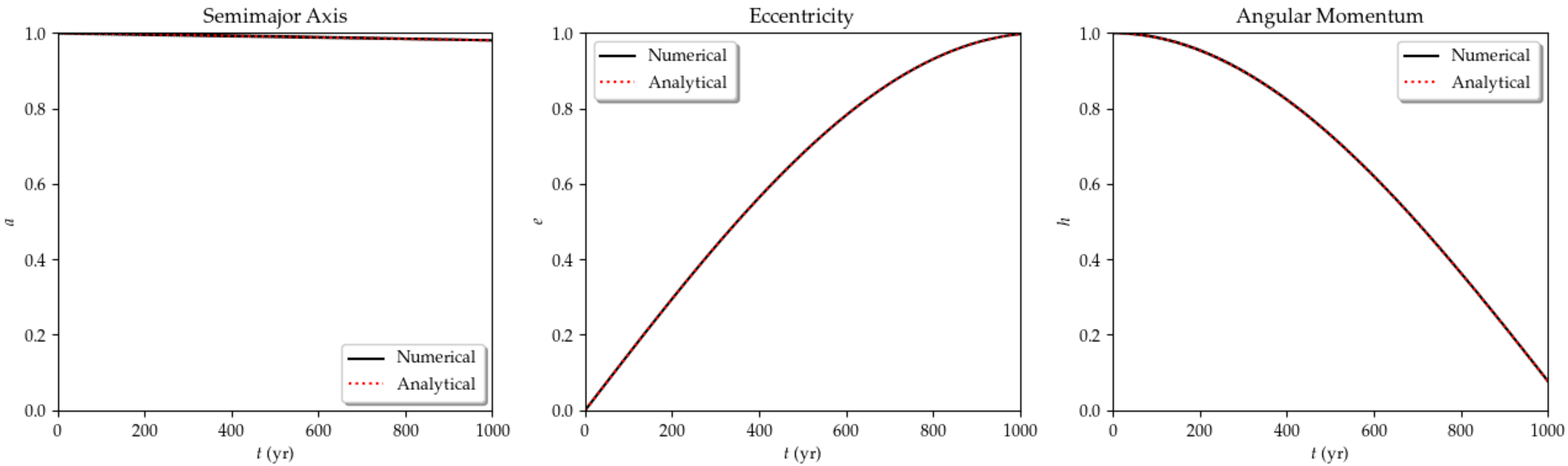
Wind solution



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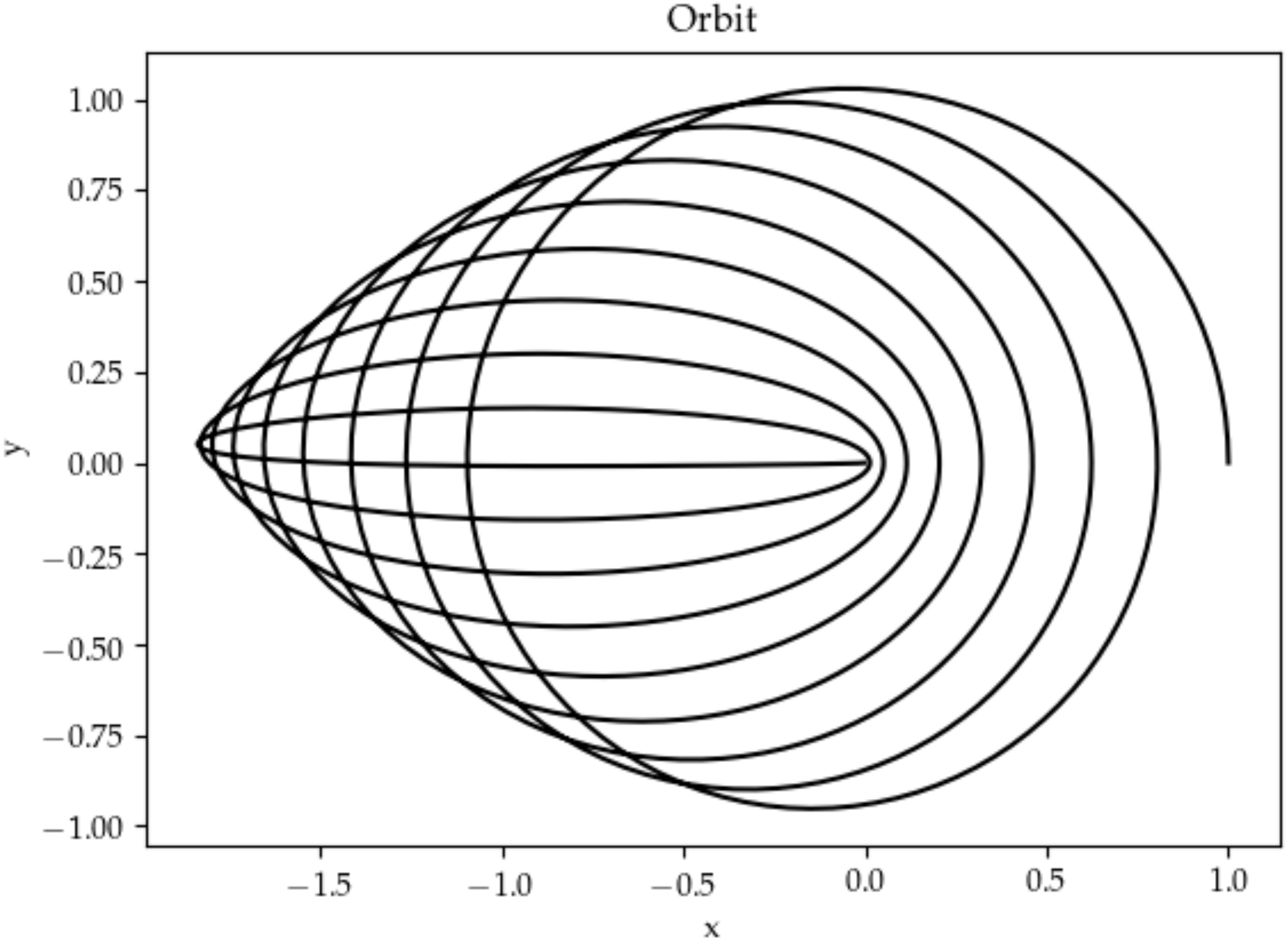
Wind solution



Angular momentum loss at constant energy.

Eccentricity increase at constant semimajor axis

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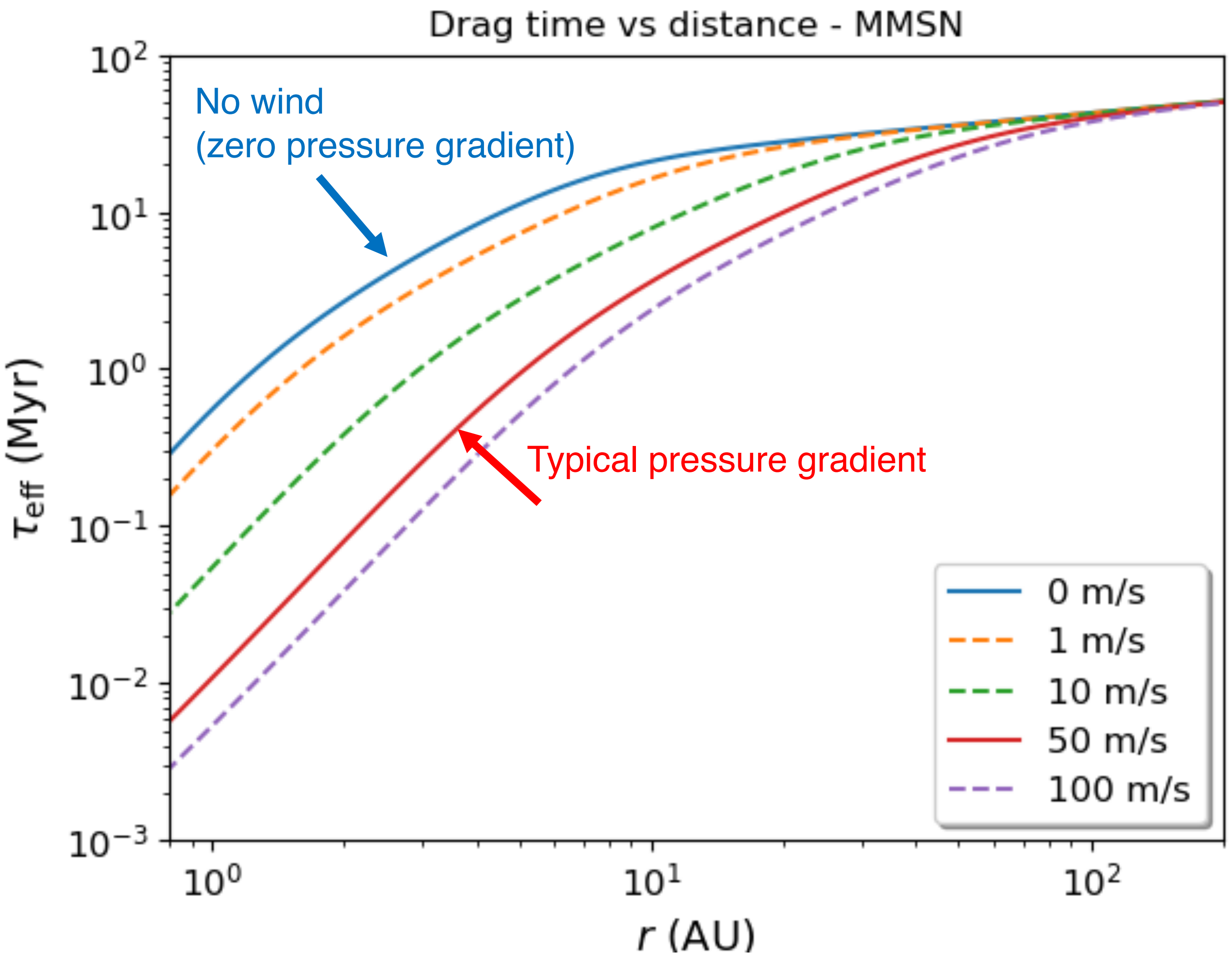
Timescales



Wind has a strong effect in the distances of the asteroid belt.

Little effect in the Kuiper belt.

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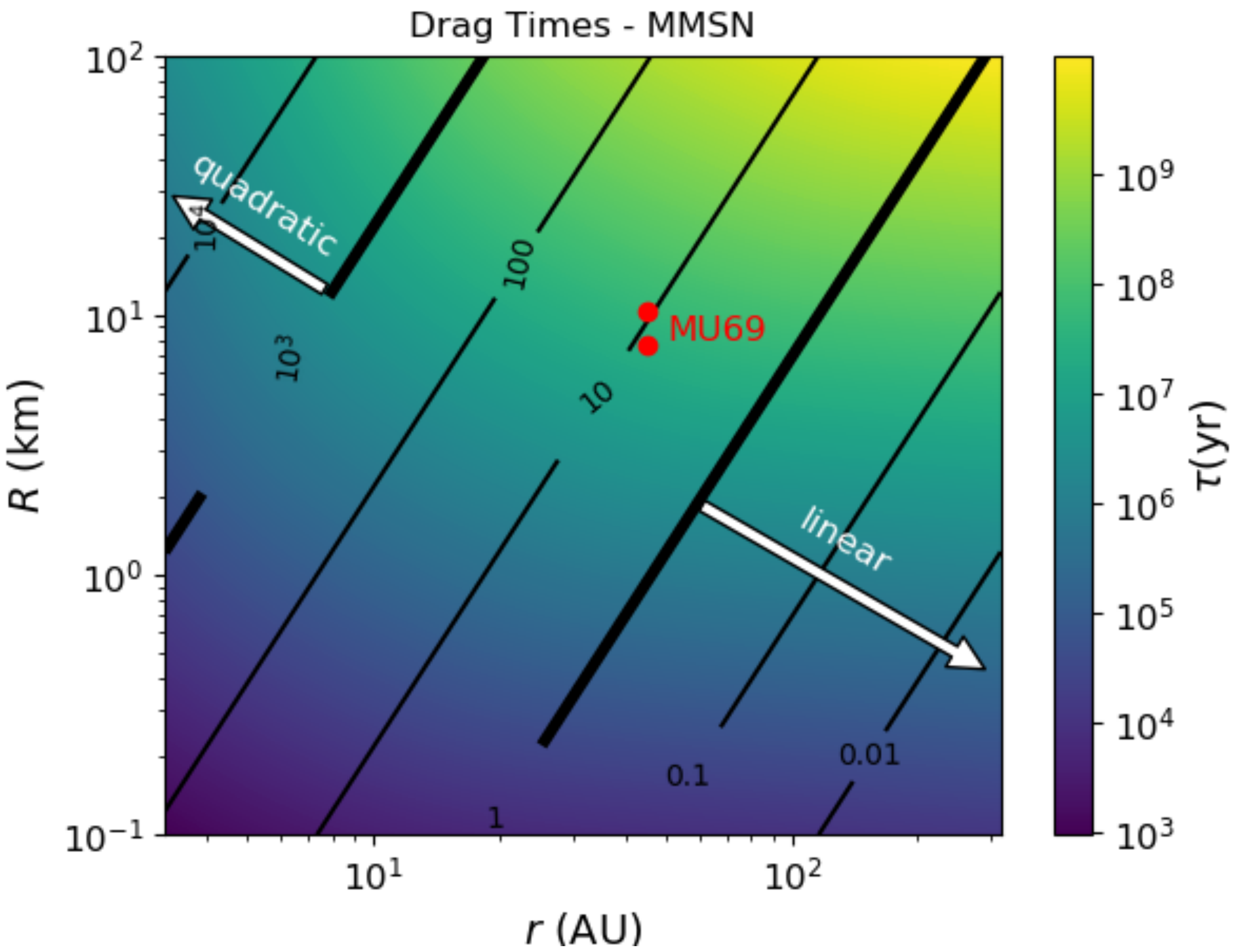
Linear vs quadratic drag



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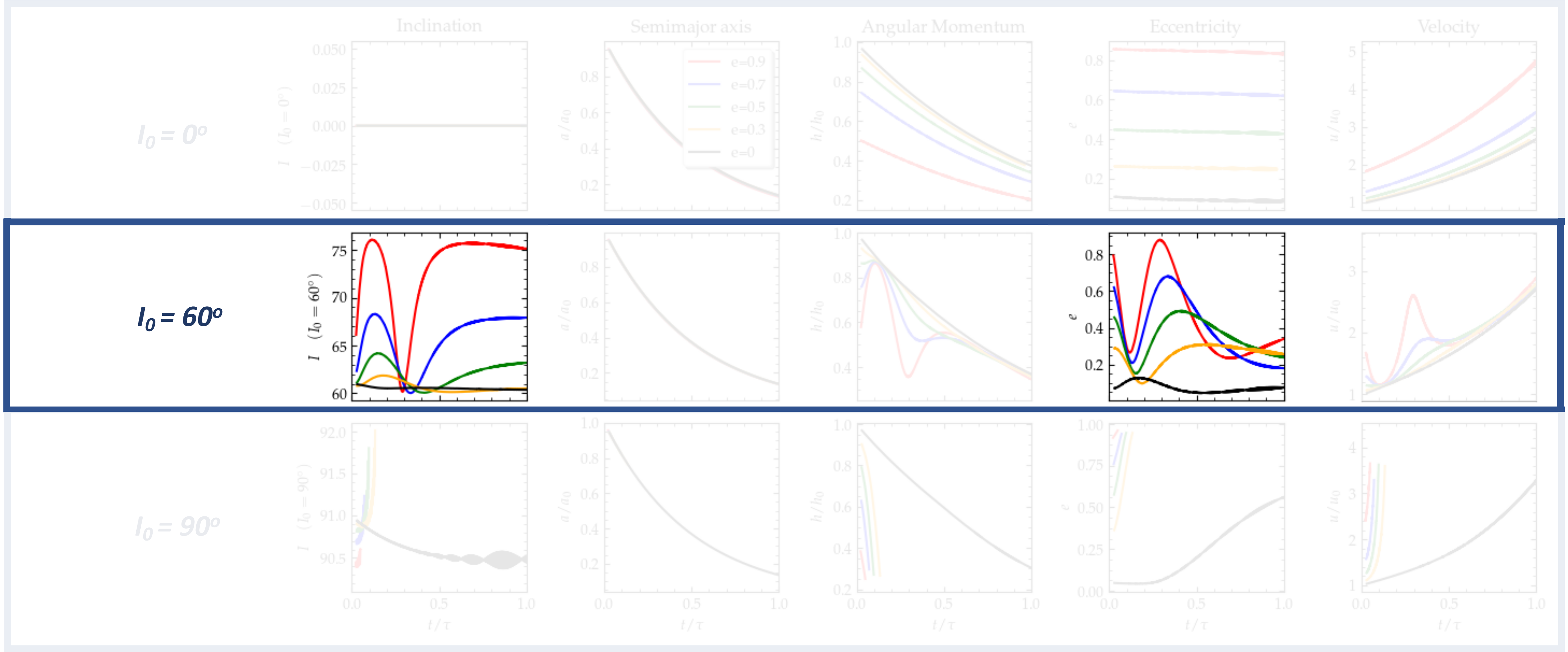
Effect of Inclination



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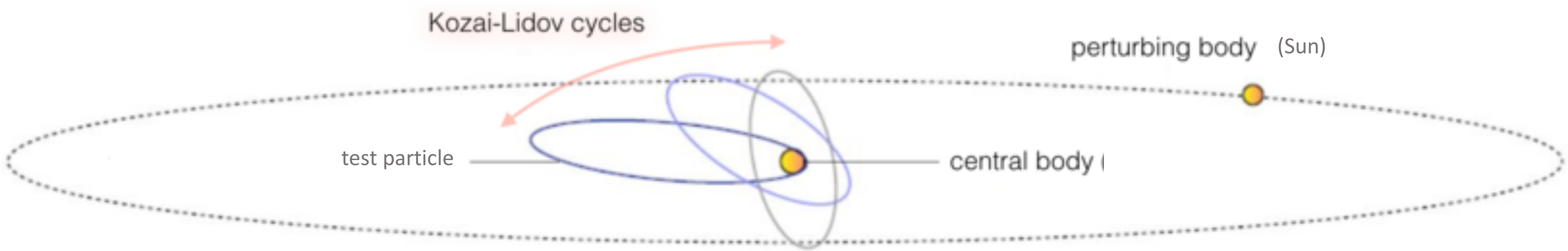
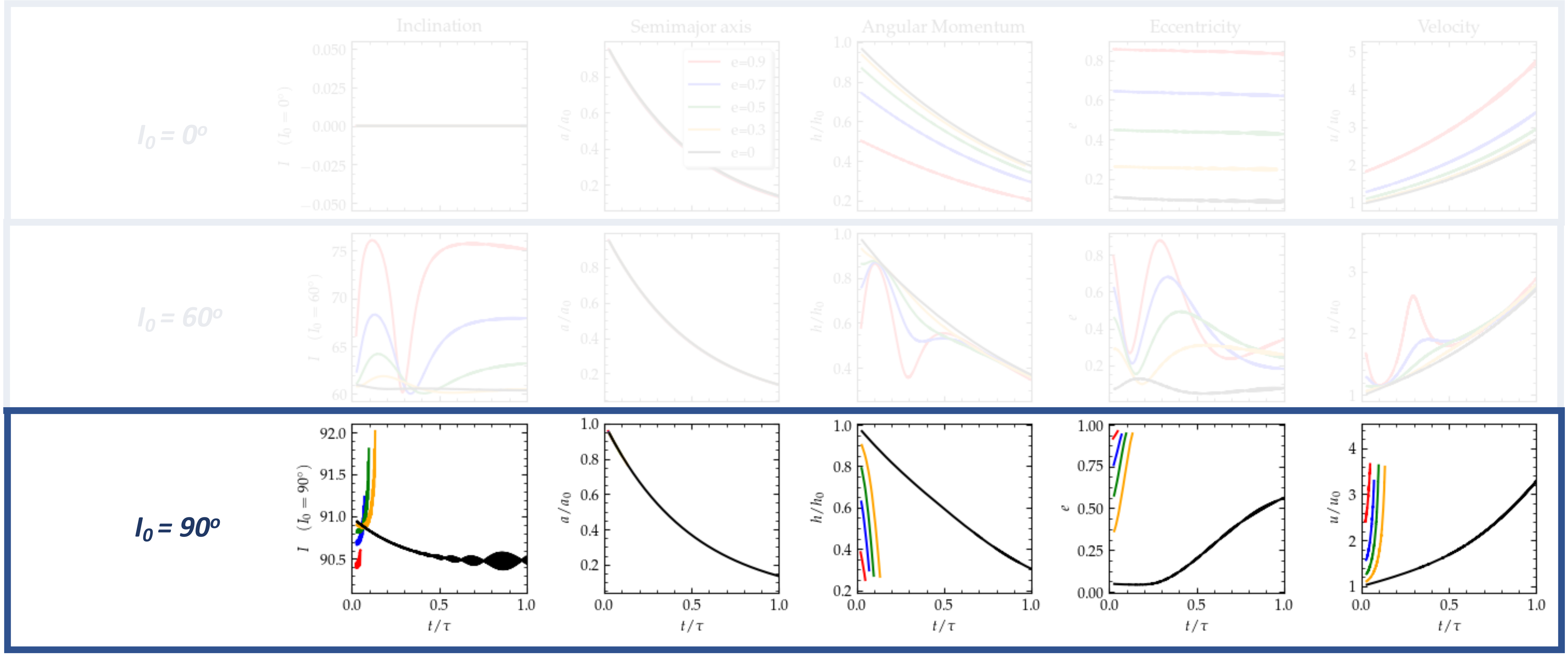
Kozai-Lidov Oscillations



Effect of Inclination



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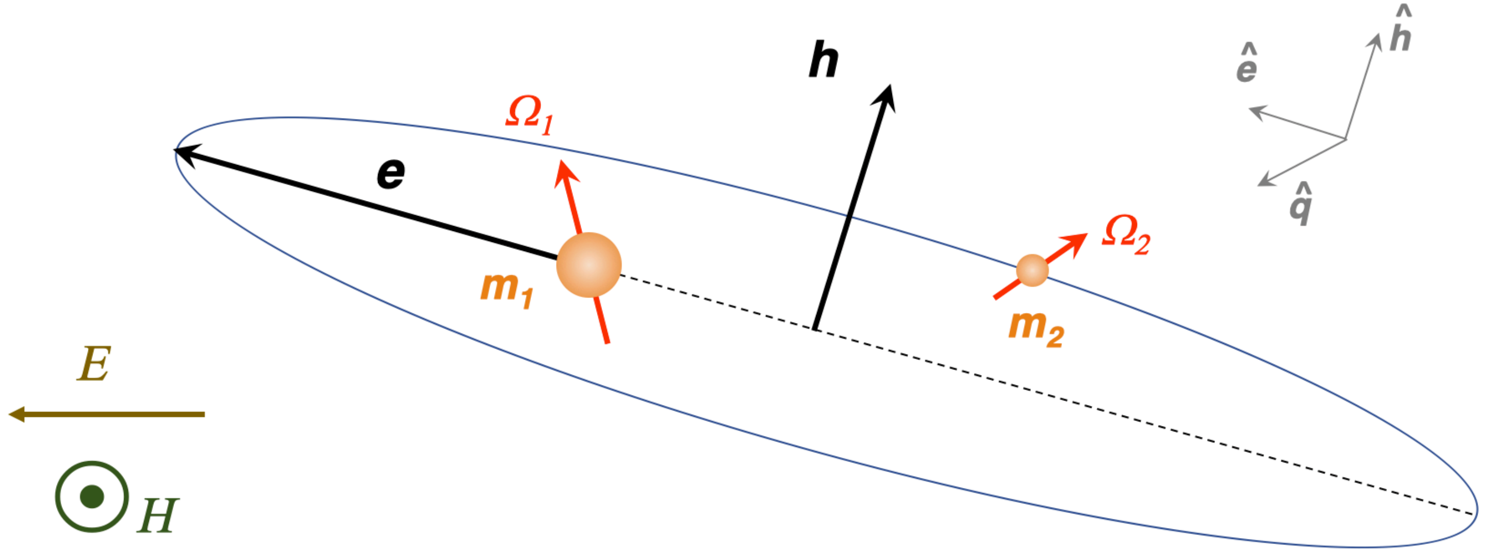
Kozai + Tidal Friction + Drag

$$
\begin{aligned}
\frac{de}{dt} &= -e\left[V_1 + V_2 + V_d + 5\left(1-e^2\right)S_{eq}\right],\\
\frac{dh}{dt} &= -h\left(W_1 + W_2 + W_d - 5e^2 S_{eq}\right),\\
\frac{d\hat{\boldsymbol{e}}}{dt} &= \left[Z_1 + Z_2 + \left(1-e^2\right)\left(4S_{ee} - S_{qq}\right)\right]\hat{\boldsymbol{q}}\\
&\quad - \left[Y_1 + Y_2 + \left(1-e^2\right)S_{qh}\right]\hat{\boldsymbol{h}},\\
\frac{d\hat{\boldsymbol{h}}}{dt} &= \left[Y_1 + Y_2 + \left(1-e^2\right)S_{qh}\right]\hat{\boldsymbol{e}}\\
&\quad - \left[X_1 + X_2 + \left(4e^2 + 1\right)S_{eh}\right]\hat{\boldsymbol{q}},\\
\frac{d\boldsymbol{\Omega}_1}{dt} &= \frac{\mu_r h}{I_1}\left(-Y_1\hat{\boldsymbol{e}} + X_1\hat{\boldsymbol{q}} + W_1\hat{\boldsymbol{h}}\right),\\
\frac{d\boldsymbol{\Omega}_2}{dt} &= \frac{\mu_r h}{I_2}\left(-Y_2\hat{\boldsymbol{e}} + X_2\hat{\boldsymbol{q}} + W_2\hat{\boldsymbol{h}}\right).
\end{aligned}
$$



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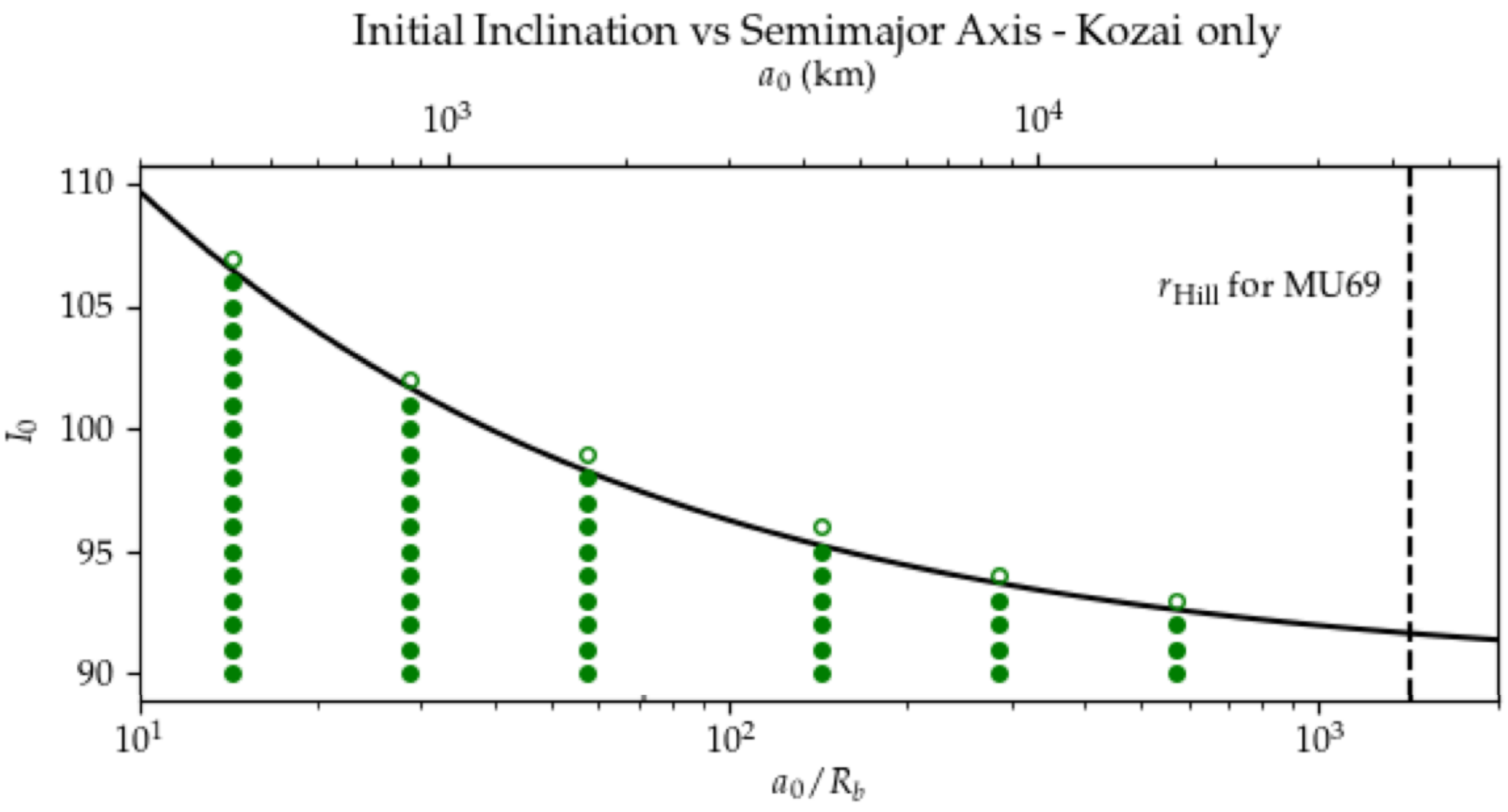
Critical Inclination

- Contact
- ○ No contact



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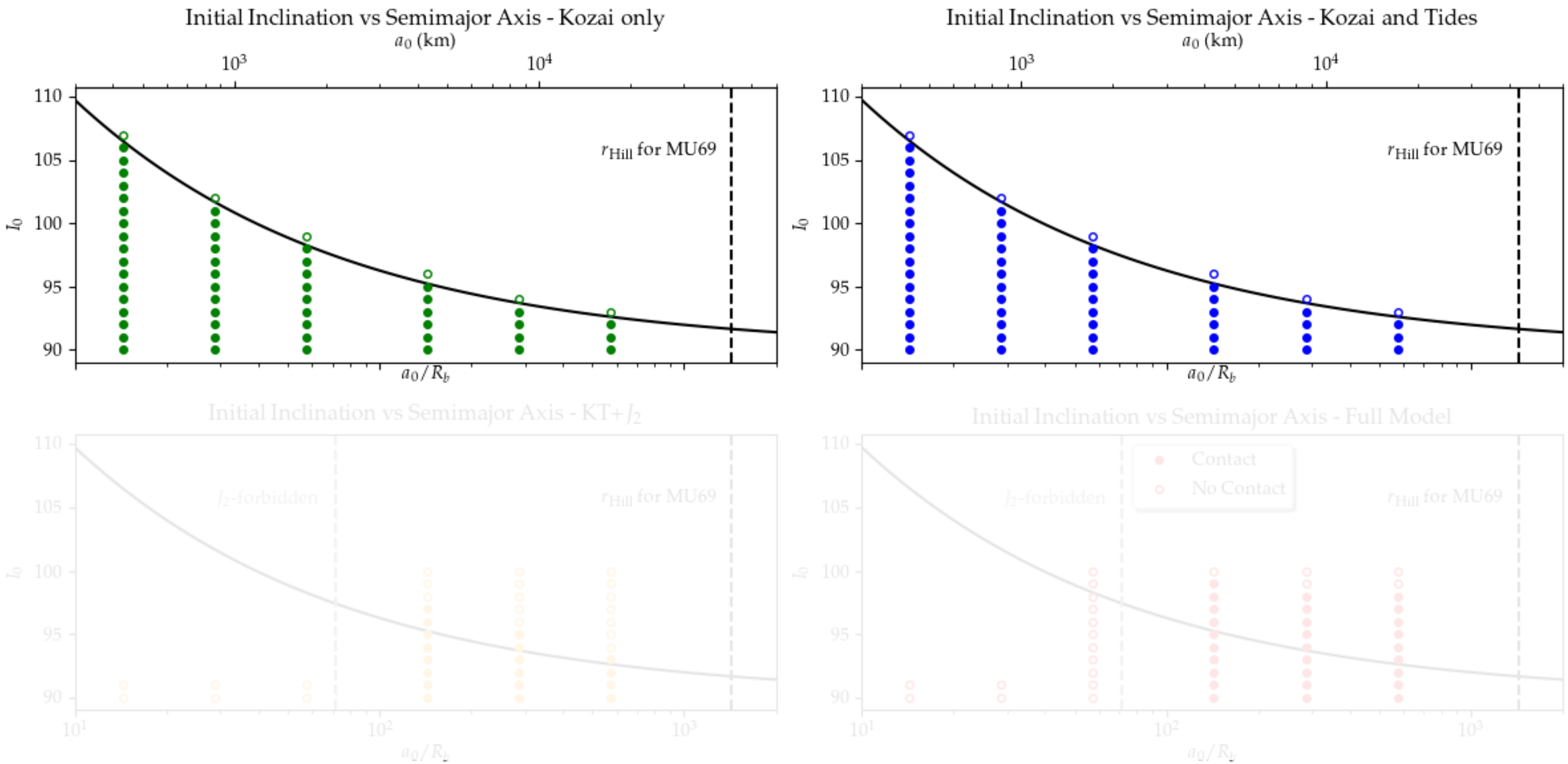
Kozai + Tidal Friction + Drag



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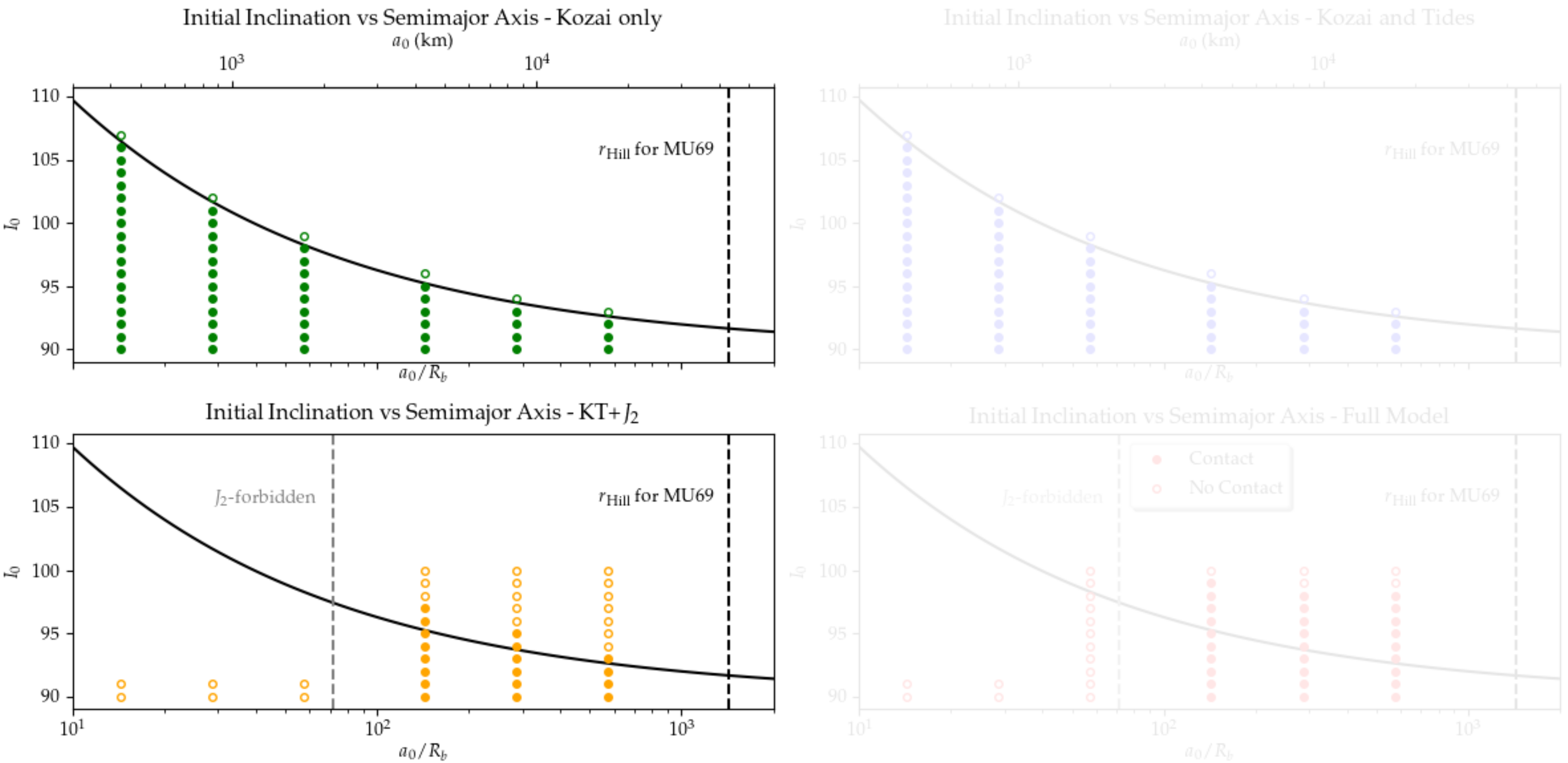
Kozai + Tidal Friction + Drag



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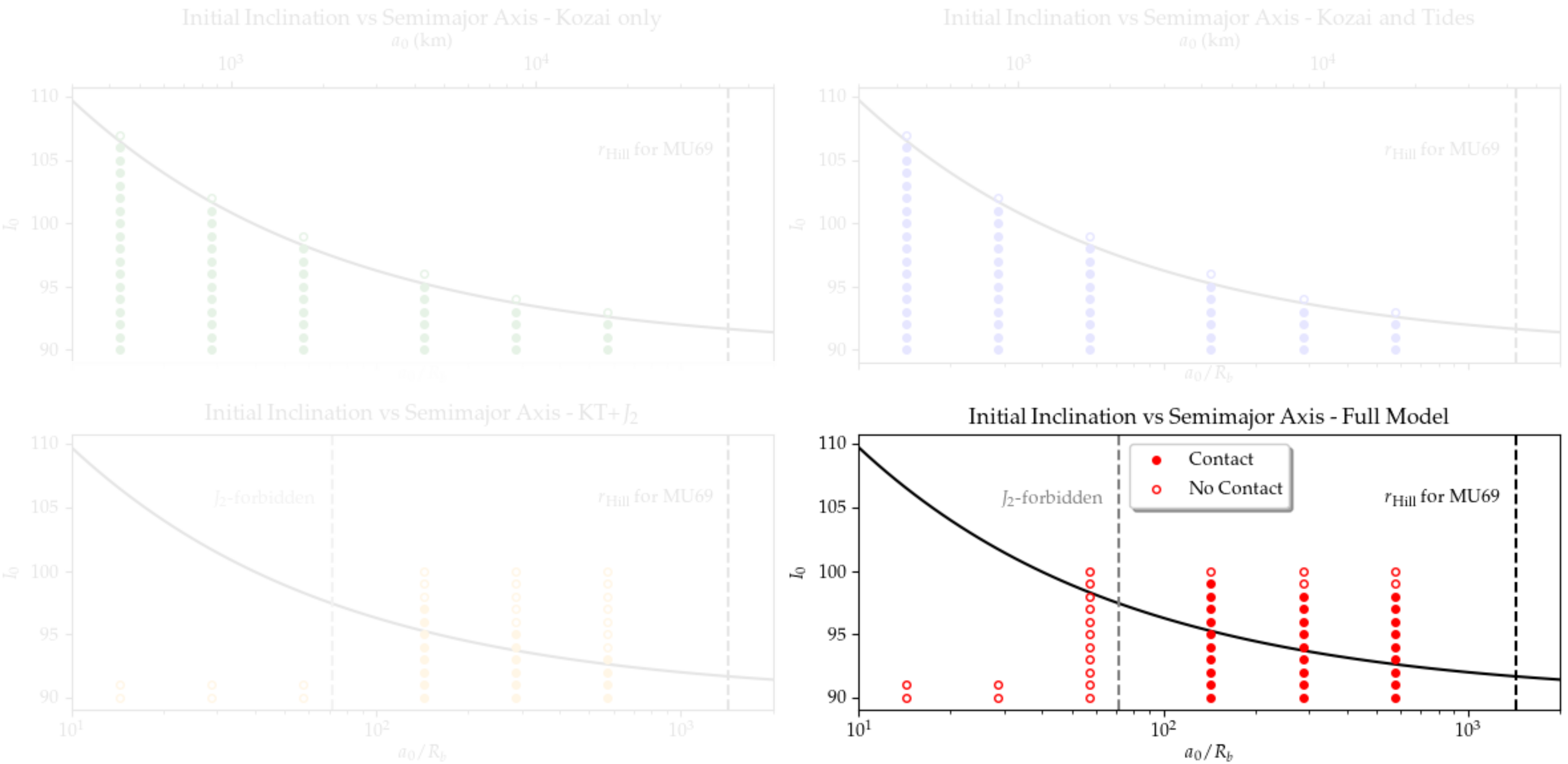
Kozai + Tidal Friction + Drag



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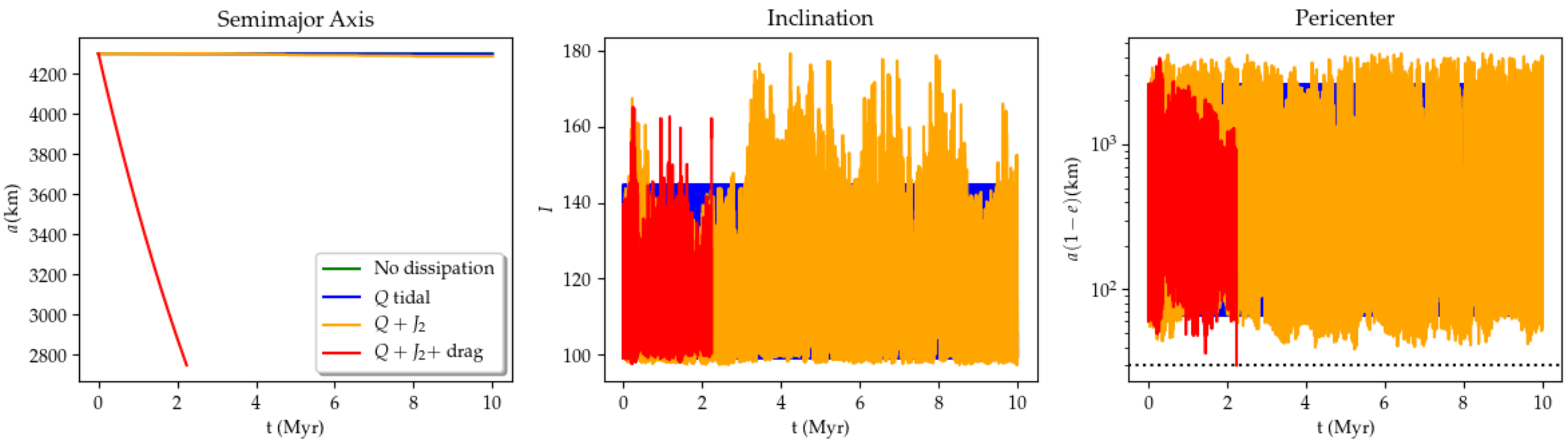
Effect of Drag



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Conclusions

- Solved the binary planetesimal problem with gas drag
- Implemented the solution into a Kozai plus tidal friction code
- Contact possible in the asteroid belt within 0.1 Myr (depleted of binaries)
- Contact via Kozai cycles in the Kuiper belt, orbits become grazing
- Window of contact increased by J_2 and drag

- Model predictions:
  - ~ 10% of KBCC binaries should be contact binaries
  - Velocities at contact should be about 3-4 m/s
- Open questions:
  - Single-averaged (or N-body) needed to reproduce final inclinations
  - Combine our model with single-averaged Kozai (or N-body)

...1 January 2019.

The two bodies slowly spiral closer until they touch, forming the bi-lobed object we see today.

Sketch by J.T. Keane

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