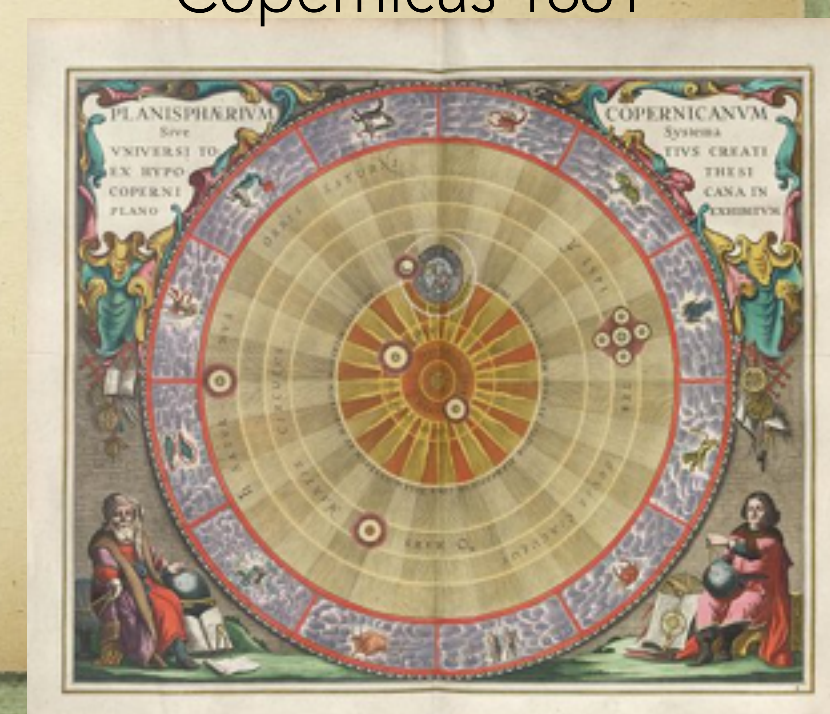
Post-formation dynamical evolution

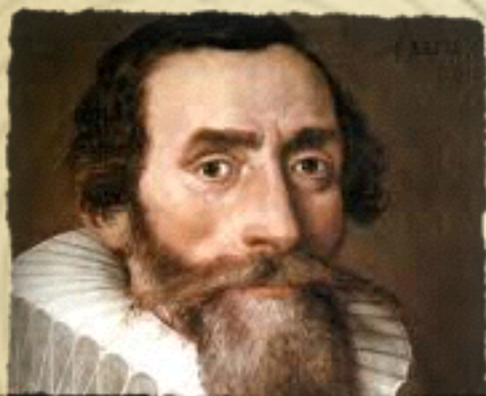
Smadar Naoz
UCLA

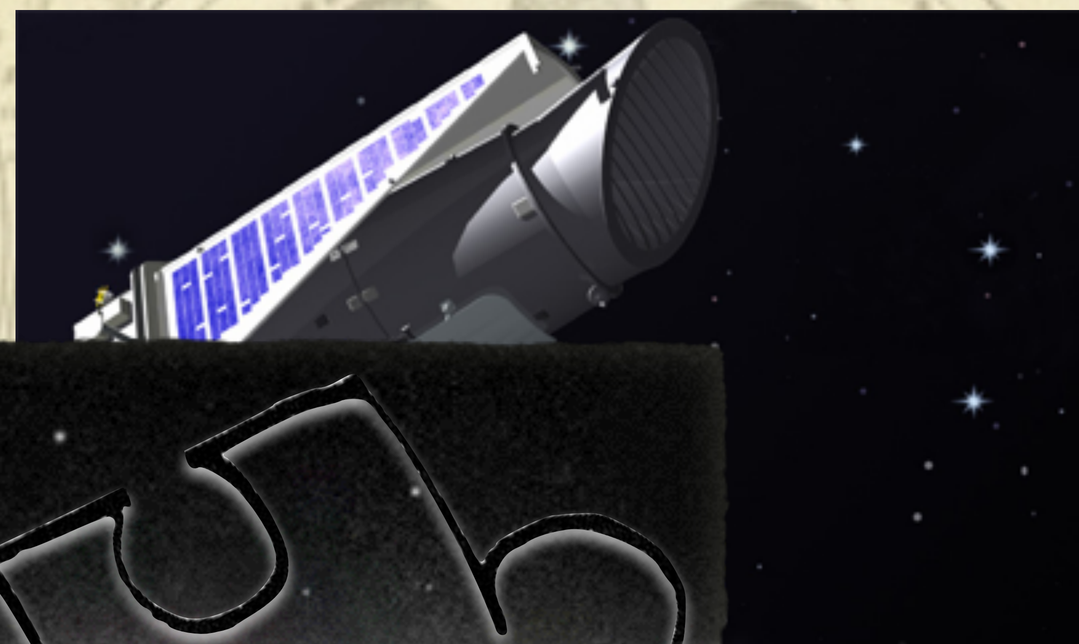
Sagan Workshop
July 2015

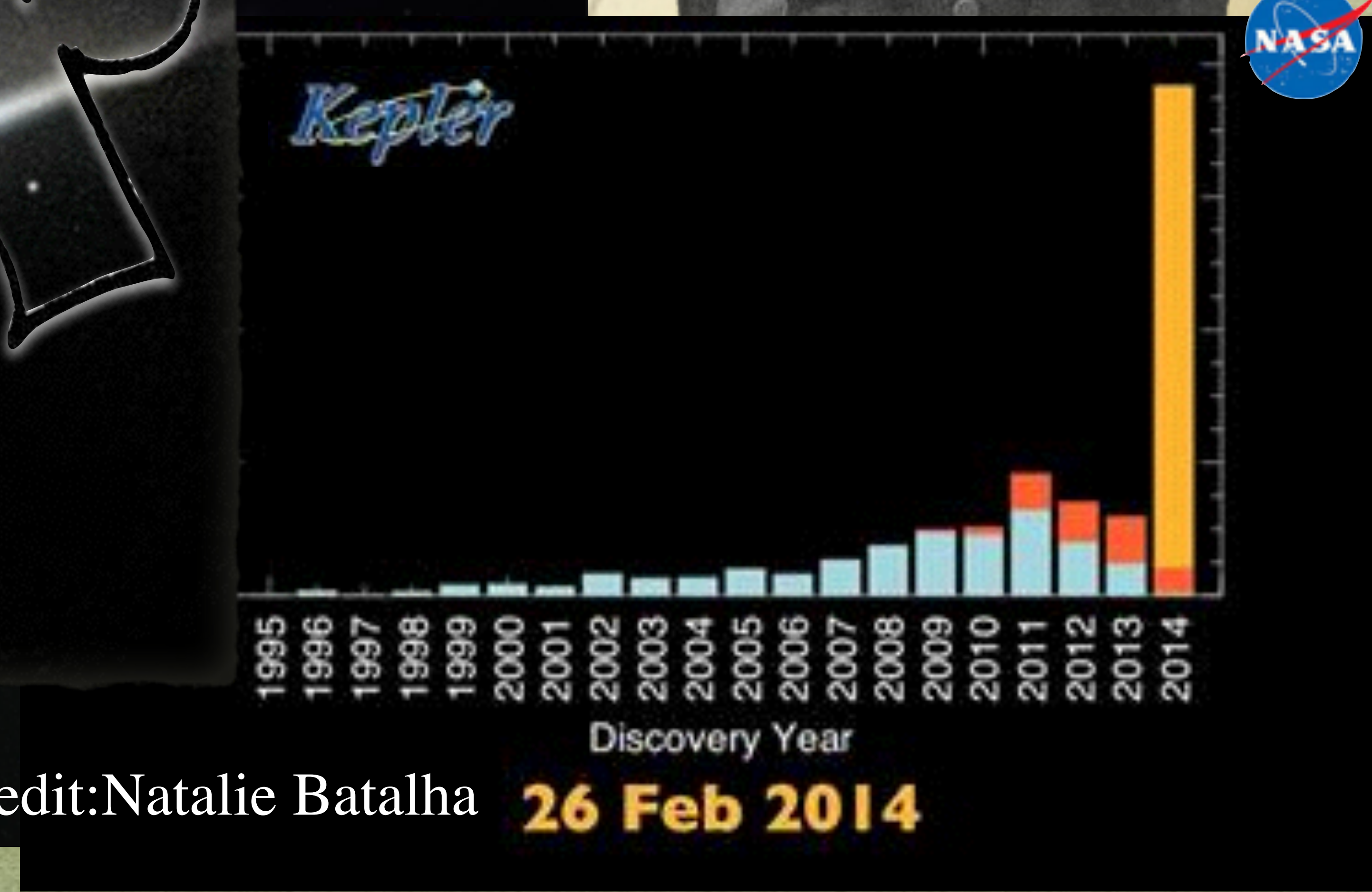
Copernicus 1661



AstroDynamics

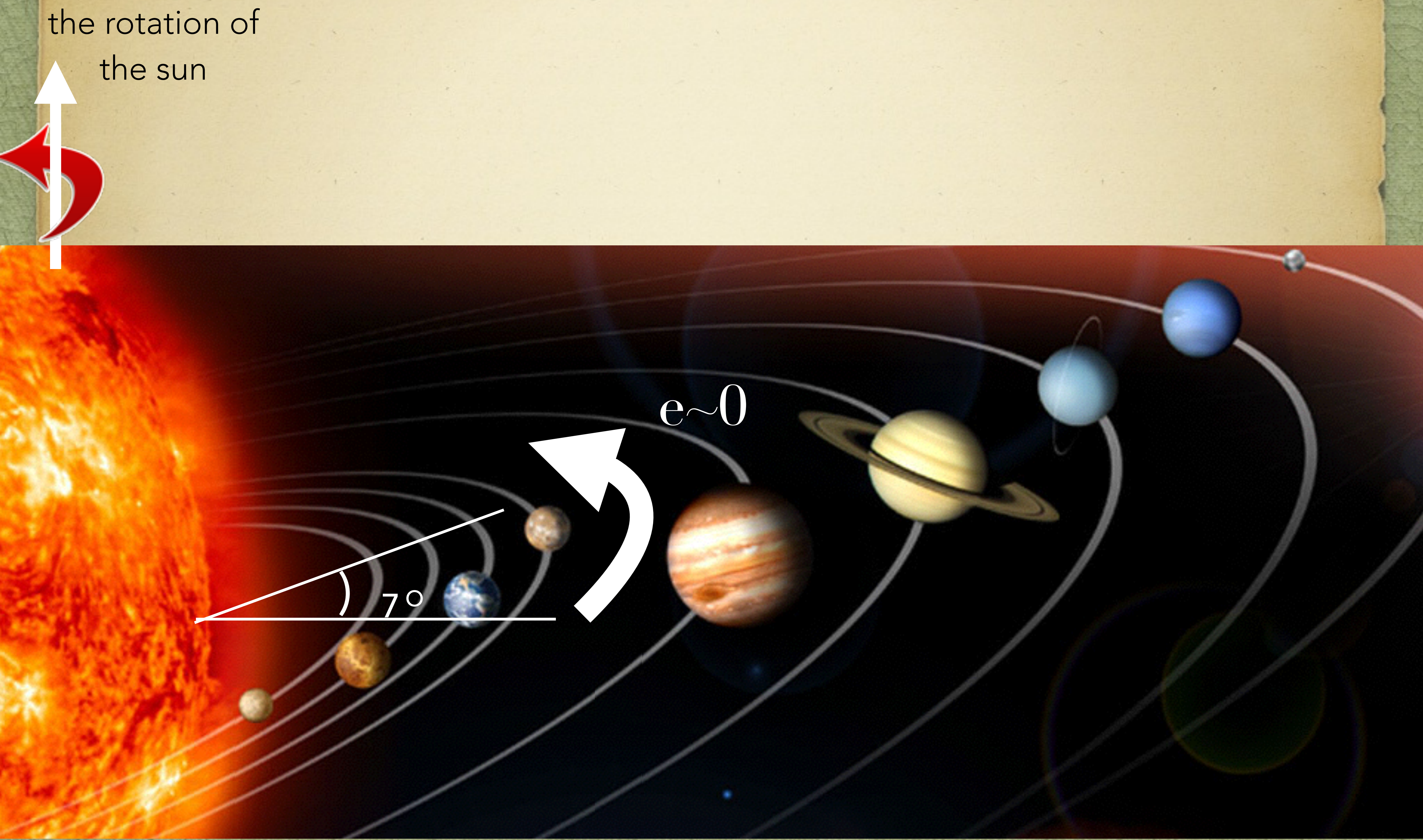






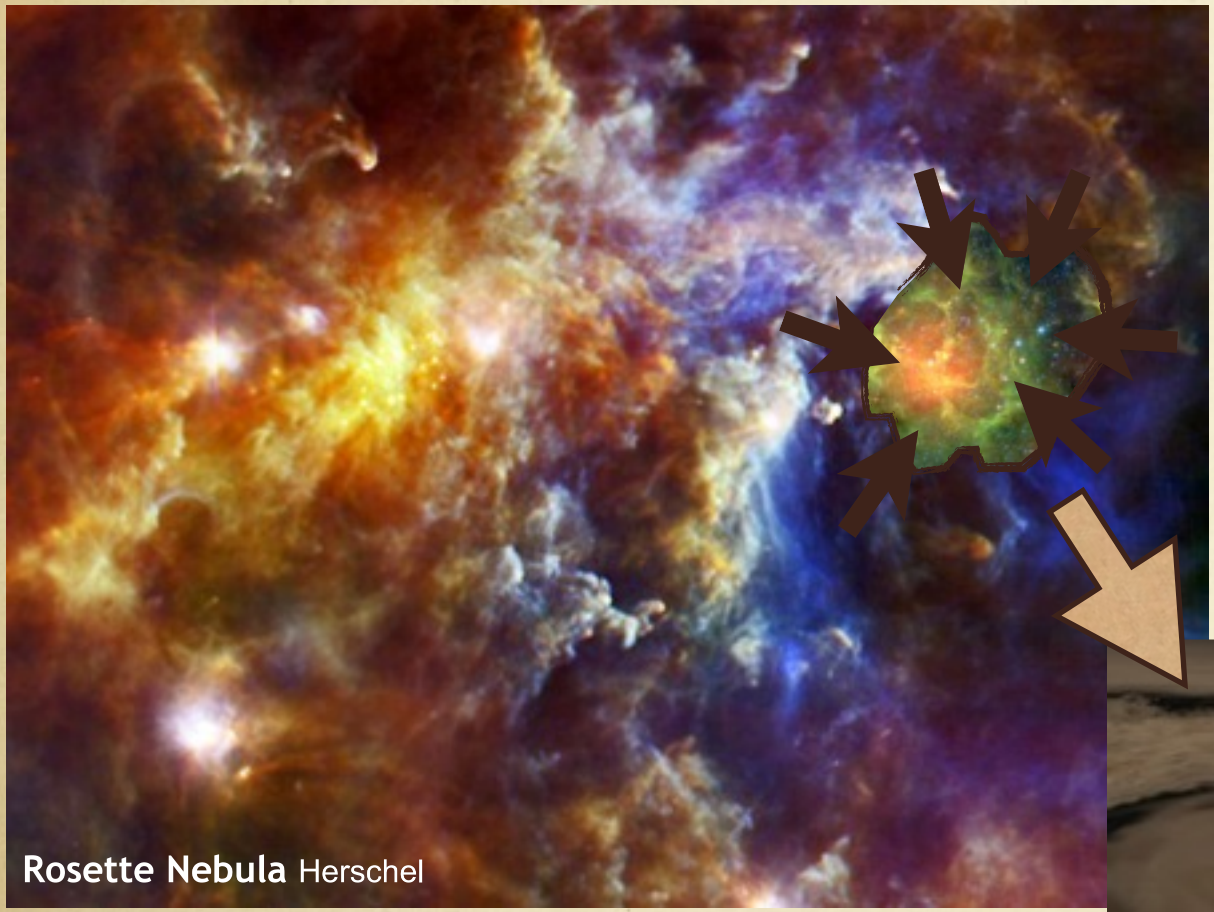
credit:Natalie Batalha

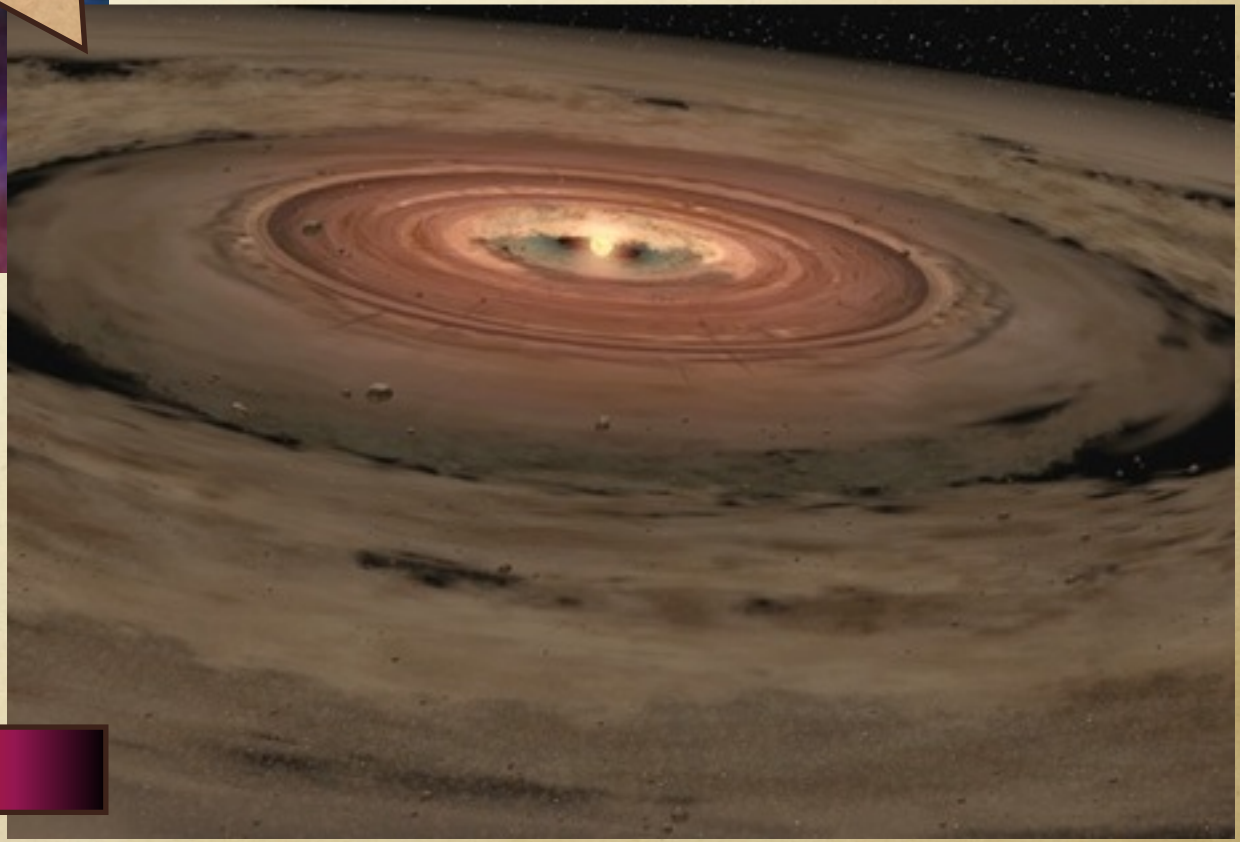
Our solar System

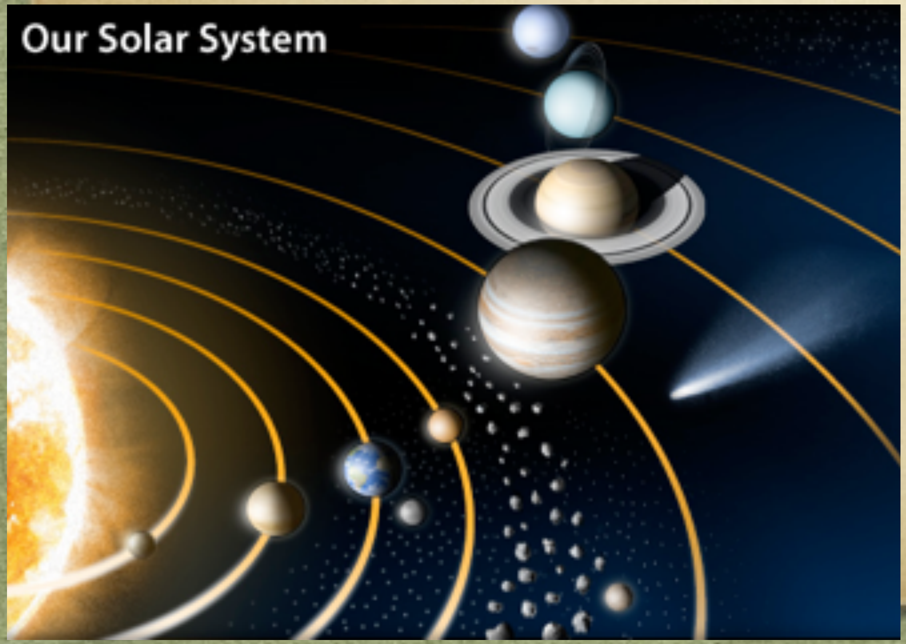


Our solar System

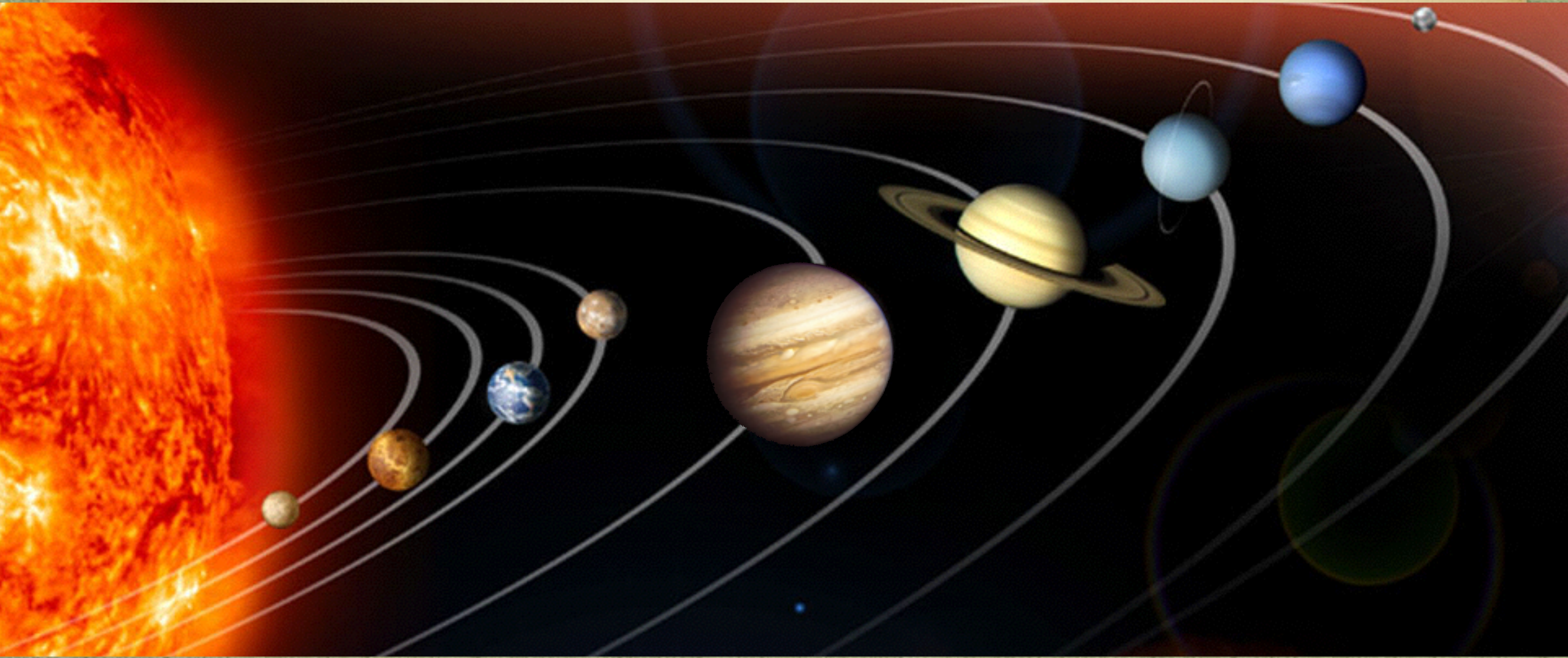
Formation story







Other solar systems



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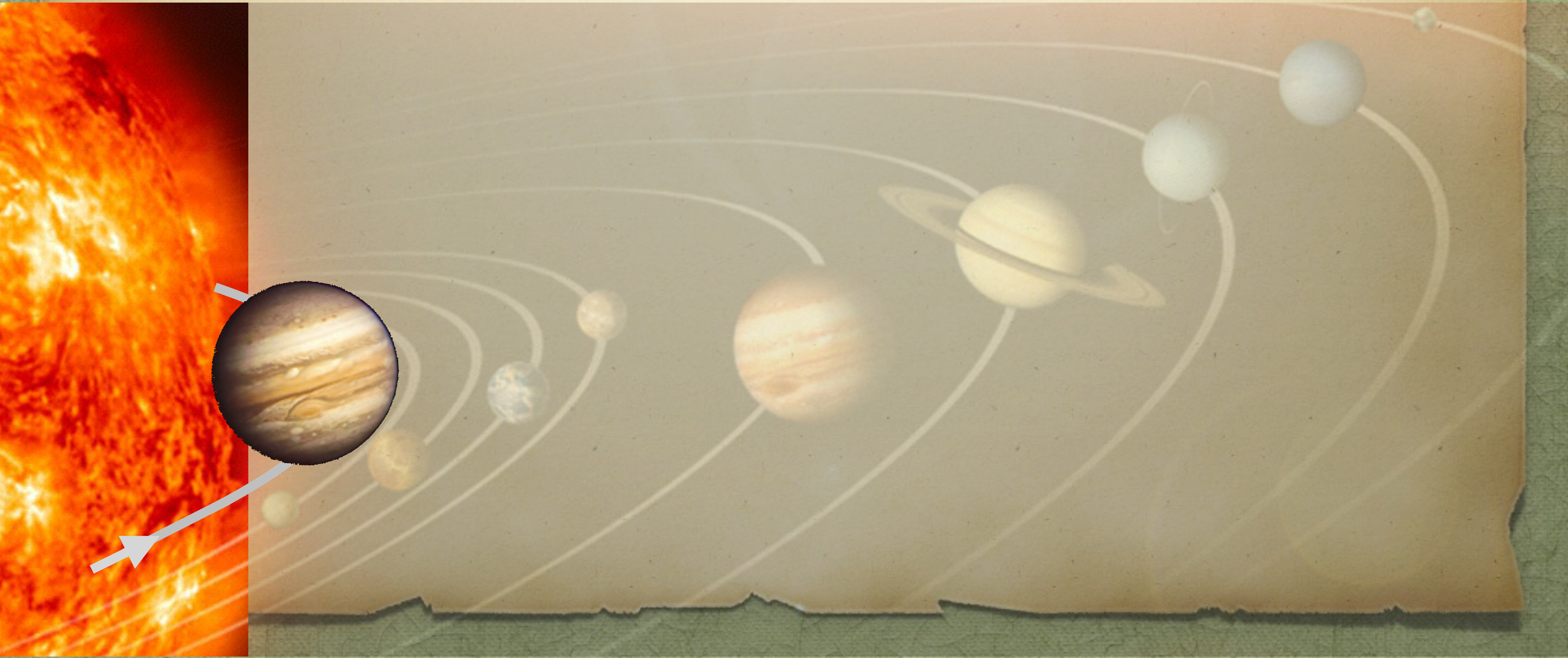

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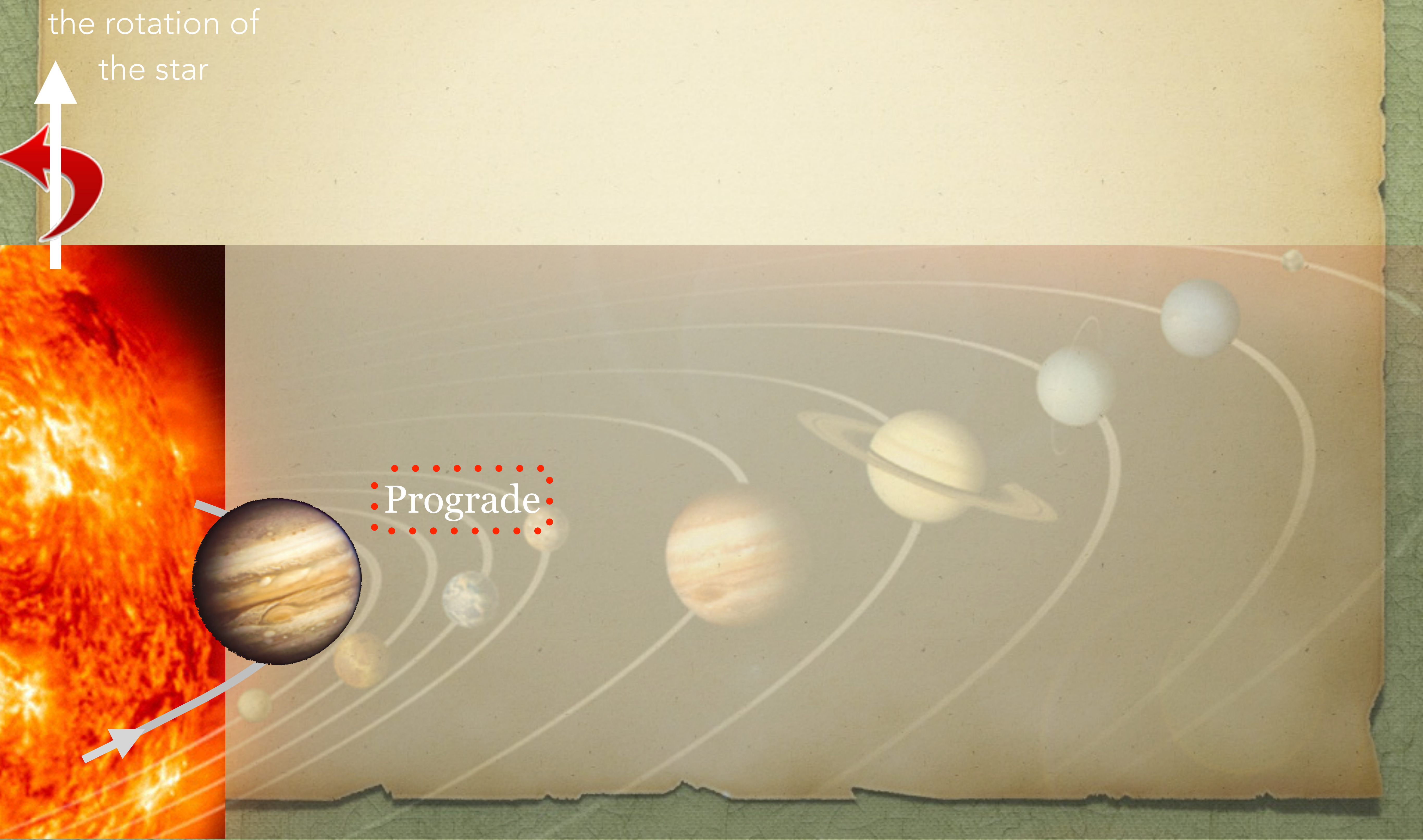

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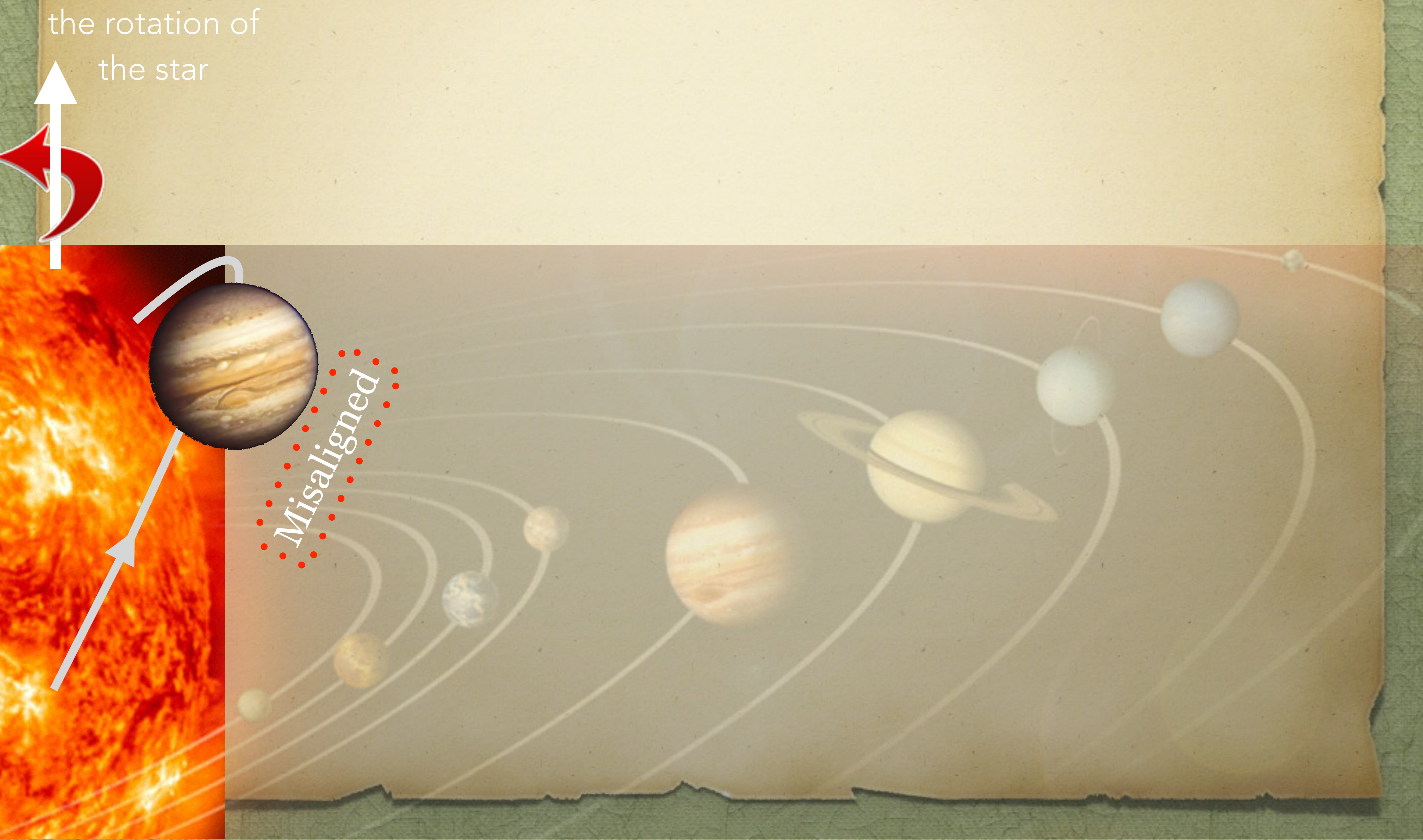
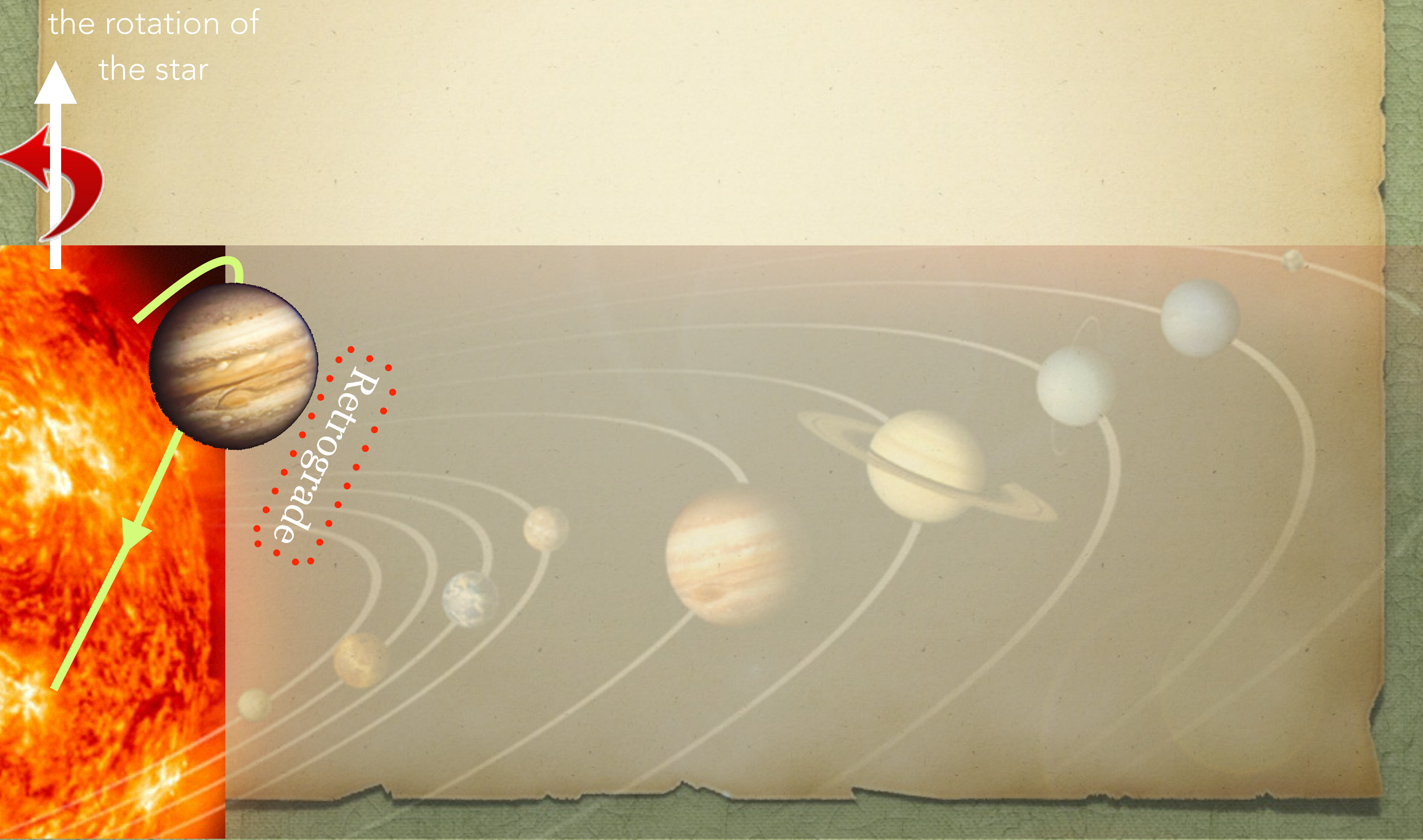


Other solar systems

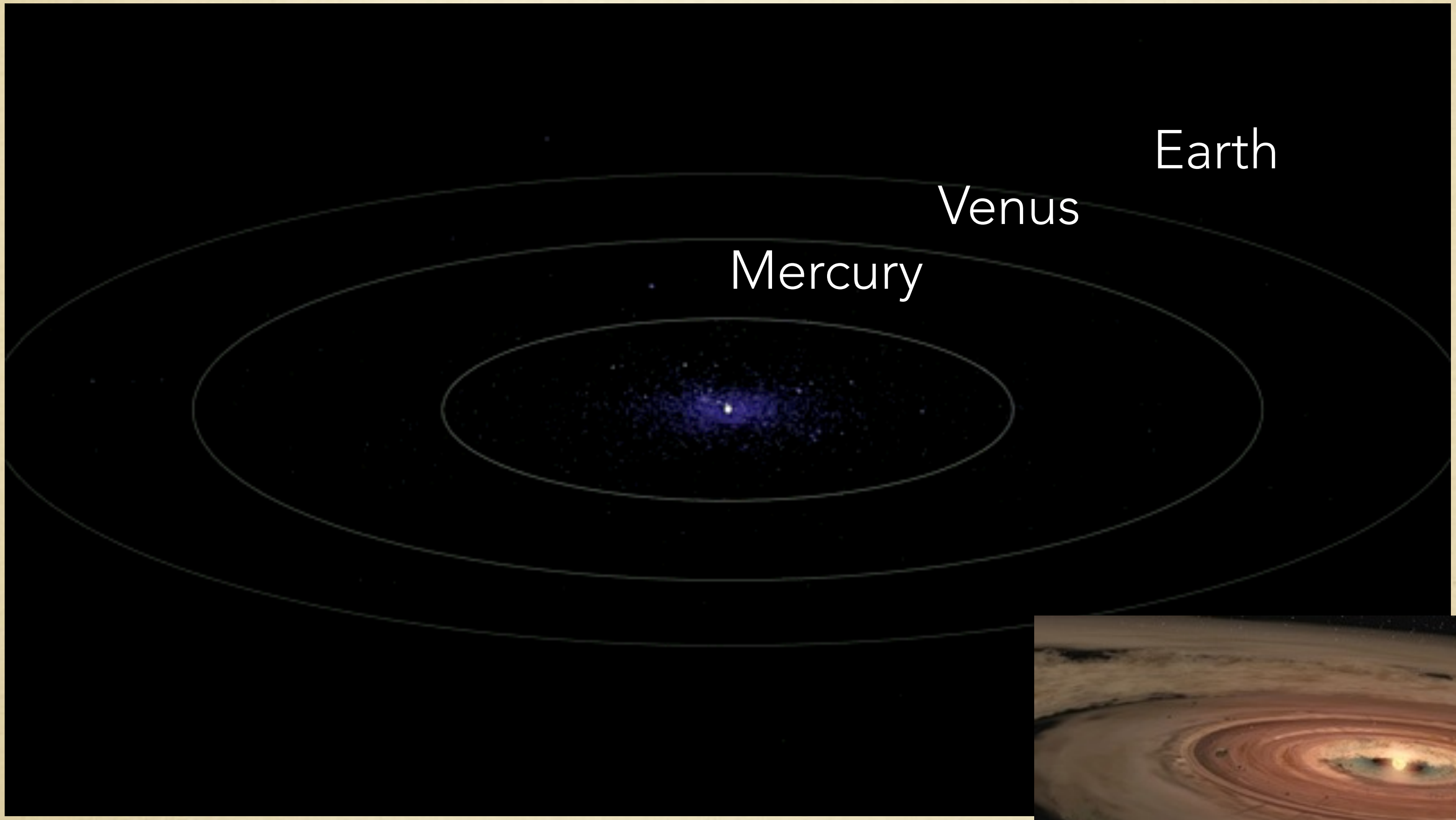


Other solar systems

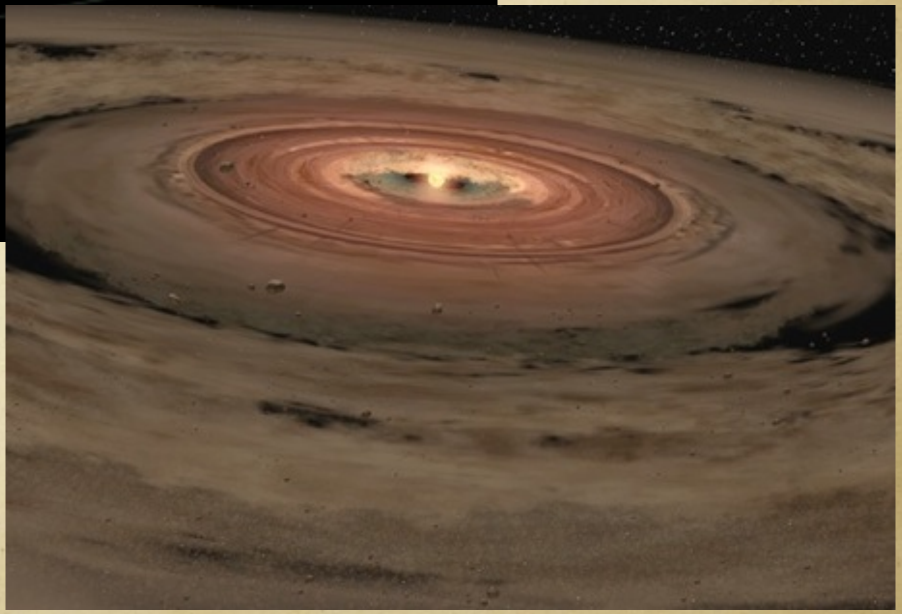
Kepler planet candidates are in a very close orbit

90% of all planets and planet candidates are in a very close orbit

Illustration of the planets and planet candidates as if they orbit a single star



movie by Alex Parker



Astrodynamics is alive!

Selected dynamical processes

- Planet-Planet scattering
- Mean motions resonances
- “Classical” secular evolution
- The eccentric Kozai-Lidov (EKL) mechanism

Selected dynamical processes

- **Planet-Planet scattering**
- Mean motions resonances
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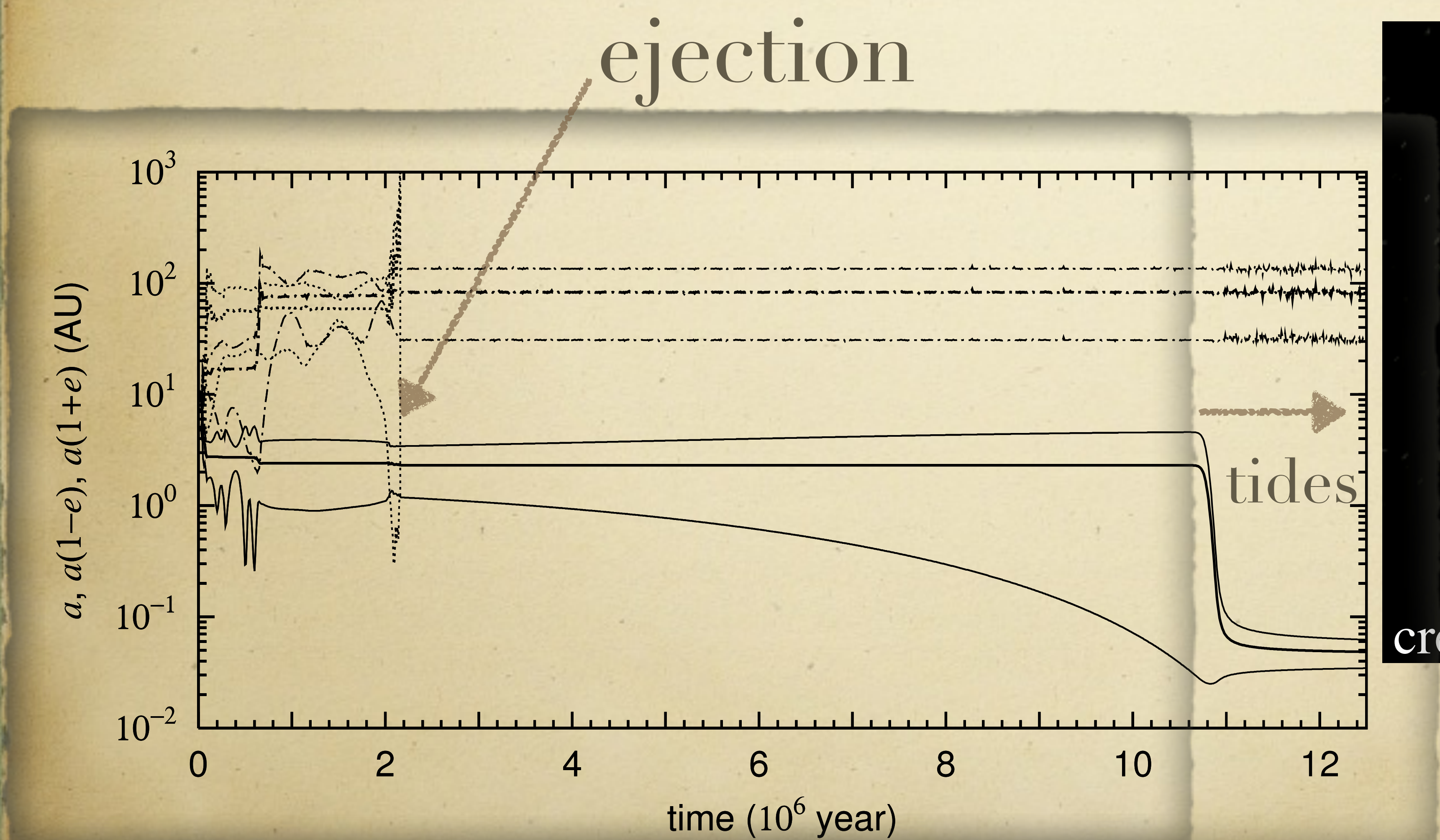
Post evolution dynamics in planetary systems

Short Time Scale

larger than orbital

1. Scattering events Rasio & Ford 1996

~Packed systems, outcome: inclined, eccentric, ejection



Nagasawa et al 2008

credit: Fred Rasio

Selected dynamical processes

- Planet-Planet scattering
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- “Classical” secular evolution
- The eccentric Kozai-Lidov (EKL) mechanism

Post evolution dynamics in planetary systems

Orbital Time Scale

Resonances

2. Mean Motion Resonances $\frac{P_1}{P_2} \sim \frac{n}{m}$

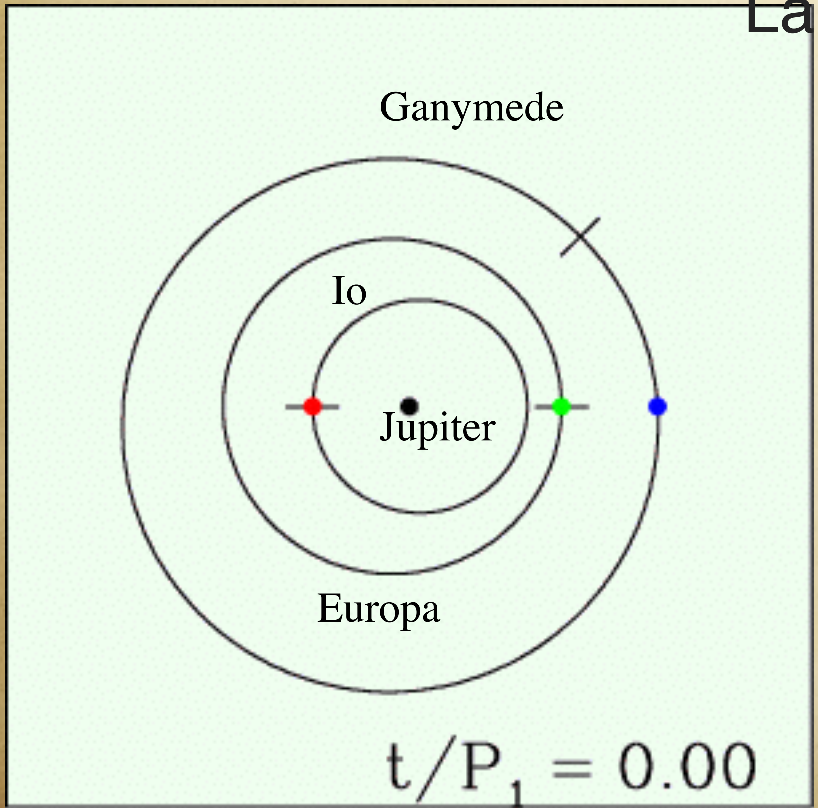
outcome: in most cases lead to unstable config.

sometimes we stable config.

Galilean Satellites

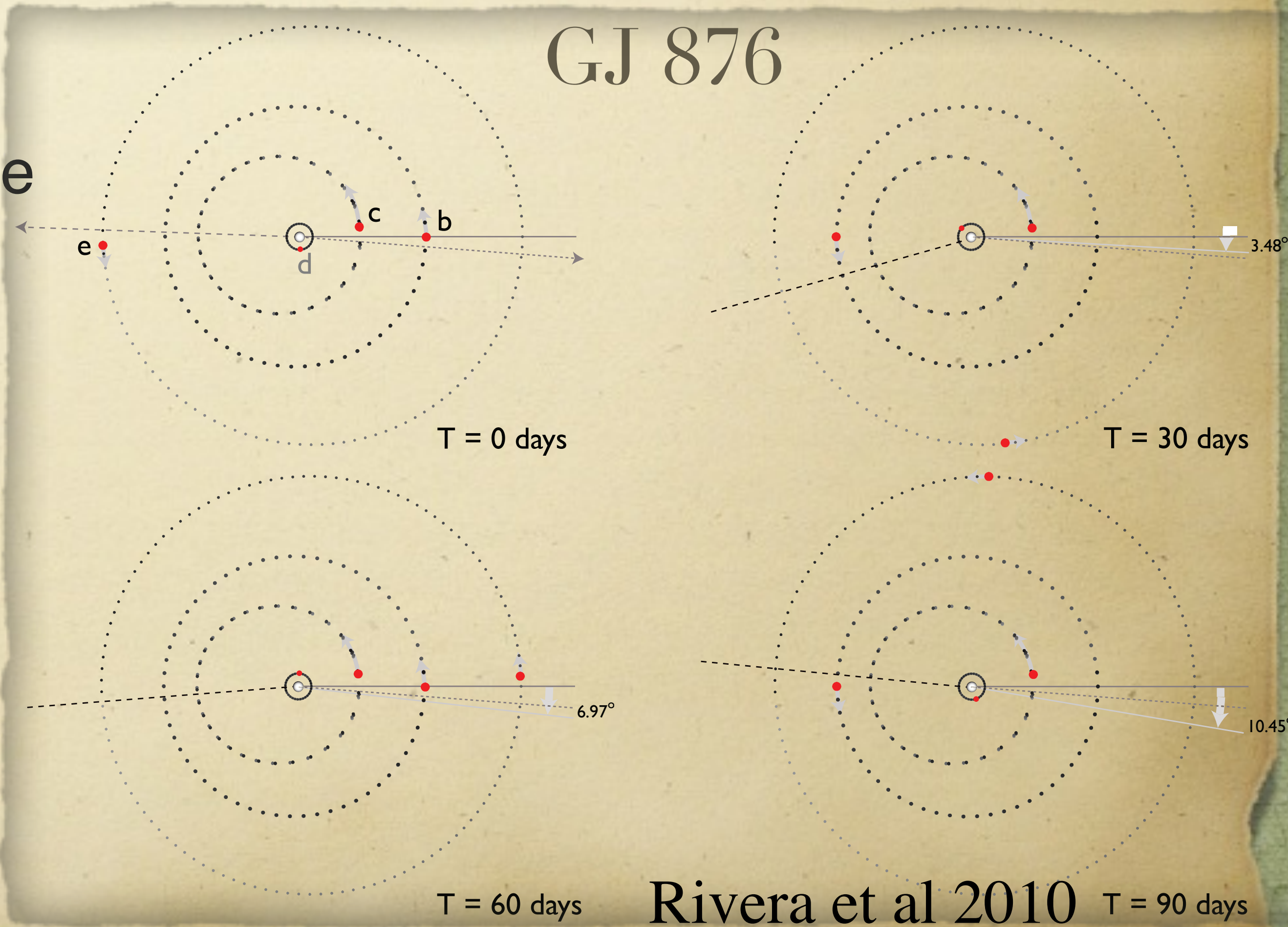
Io, Europa, and Ganymede 1:2:4

Laplace resonance



movie credit: Man Hoi Lee's home page

GJ 876



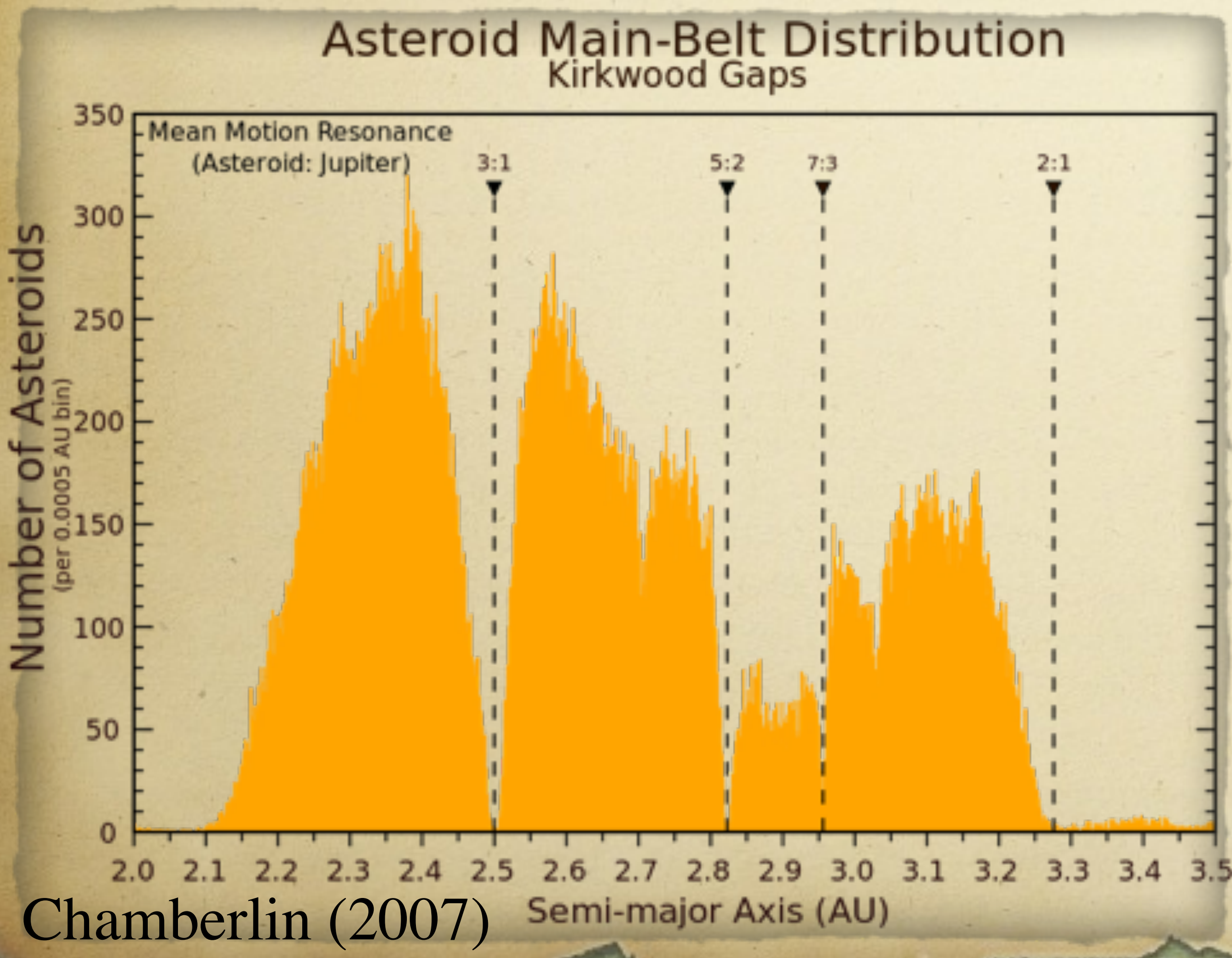
Rivera et al 2010

Post evolution dynamics in planetary systems

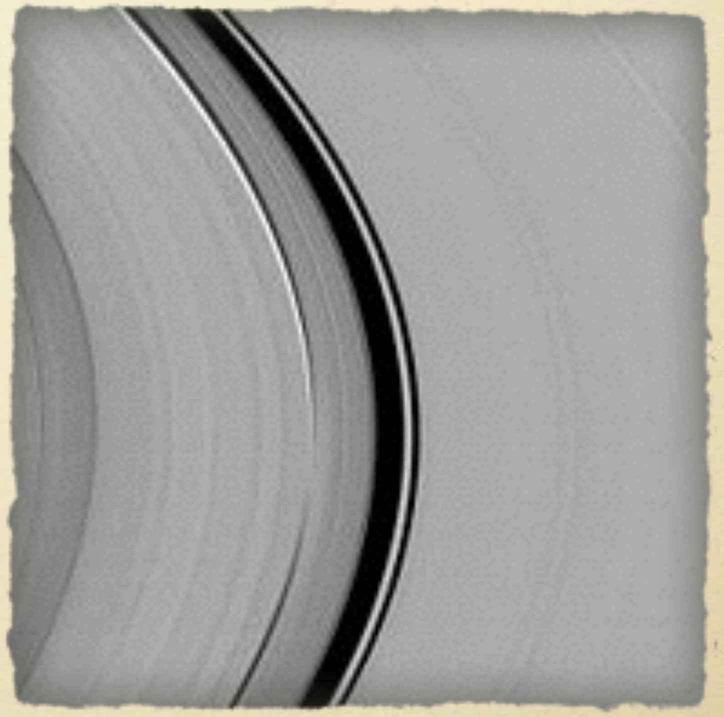
Resonances

2. Mean Motion Resonances $\frac{P_1}{P_2} \sim \frac{n}{m}$

unstable config:



Chamberlin (2007)



Post evolution dynamics in planetary systems

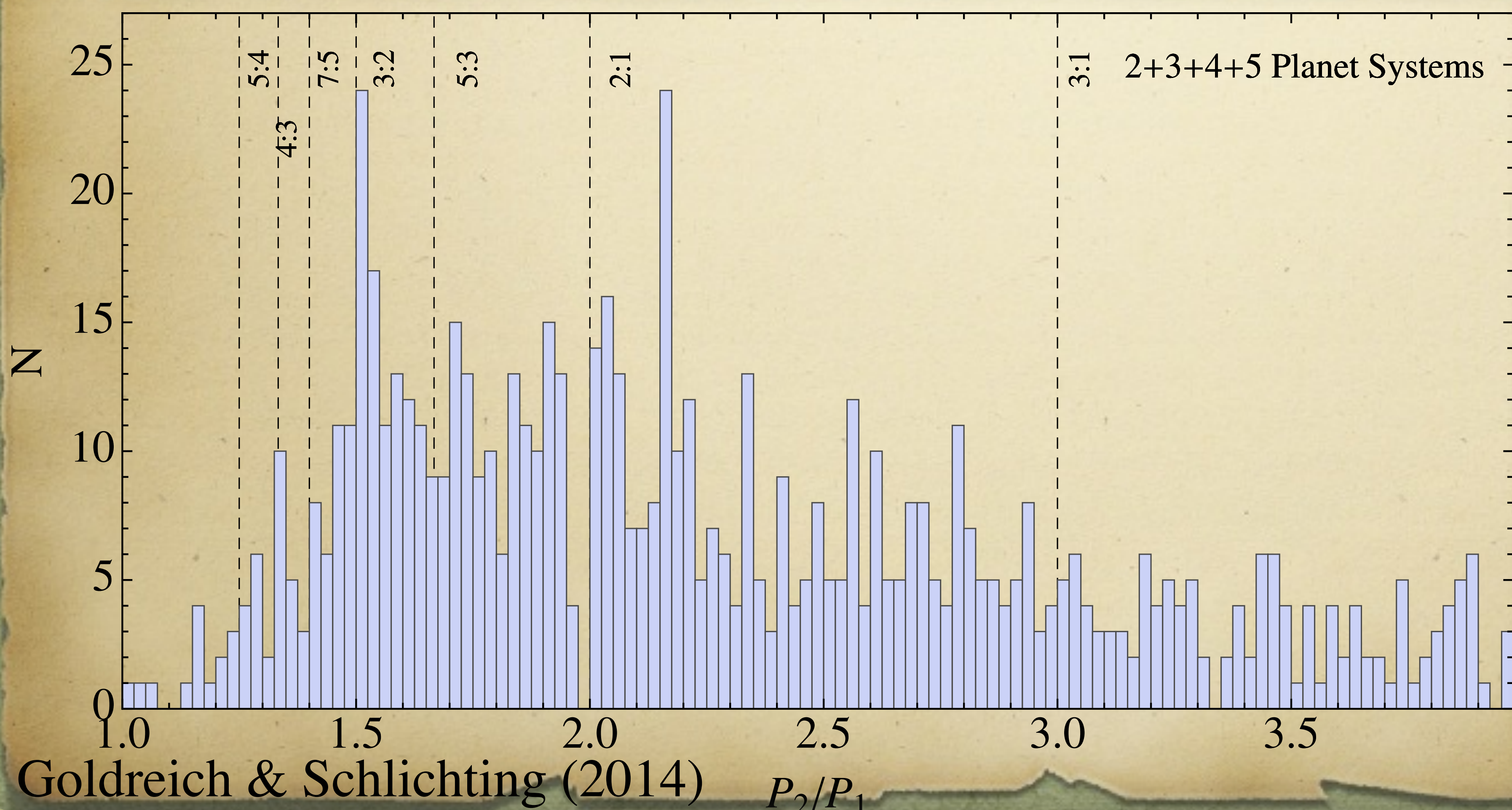
Resonances

Extrasolar….

2. Mean Motion Resonances $\frac{P_1}{P_2} \sim \frac{n}{m}$

Problem: predicted migration rates: most planets in resonances.

But reality …



Goldreich & Schlichting (2014)

Few possible explanations:

- Accretion of mass e.g., Petrovich et al (2013)
- Dissipation (maybe tides?) Lithwick & Wu (2012), Batygin & Morbidelli (2013)
- Resonance capture is temporary Goldreich & Schlichting (2014)
- and more ….

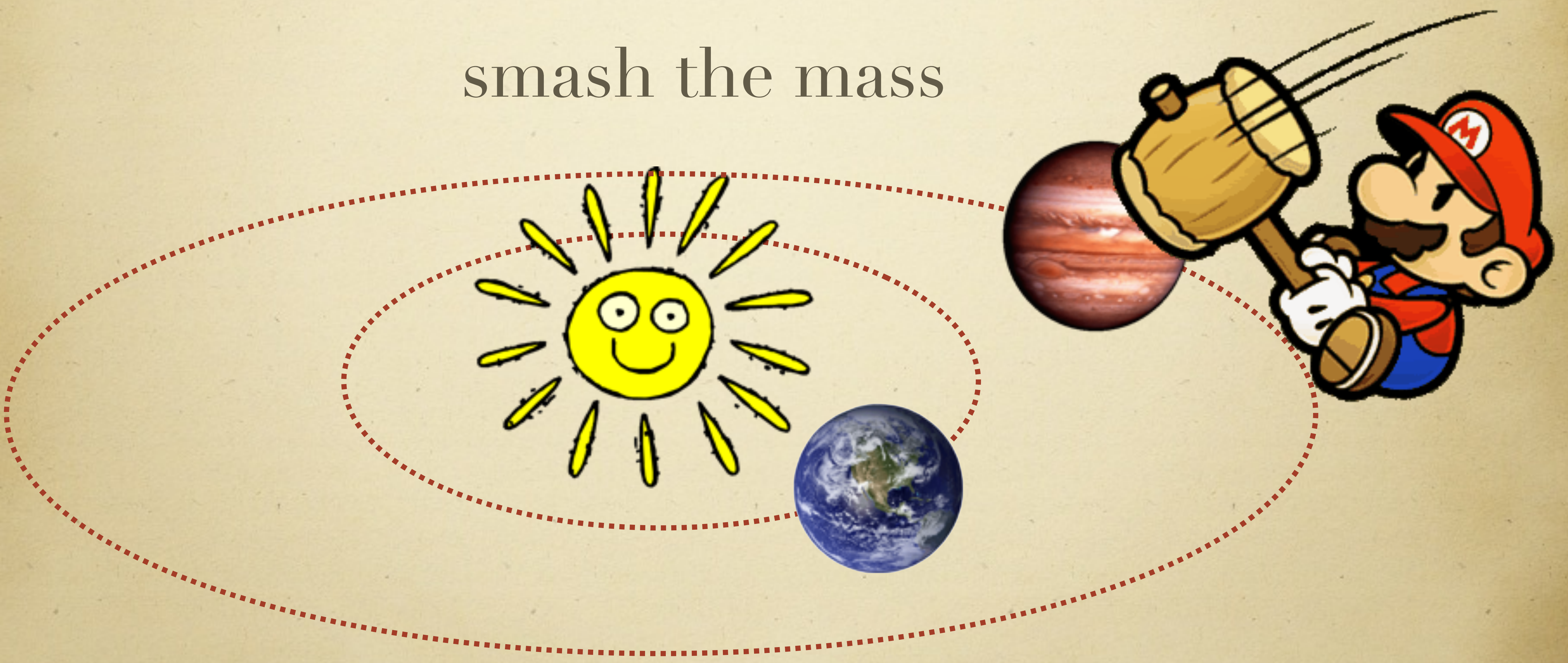
Selected dynamical processes

- Planet-Planet scattering
- Mean motions resonances
- **“Classical” secular evolution**
- The eccentric Kozai-Lidov (EKL) mechanism

Post evolution dynamics in planetary systems

3. The secular interactions

smash the mass



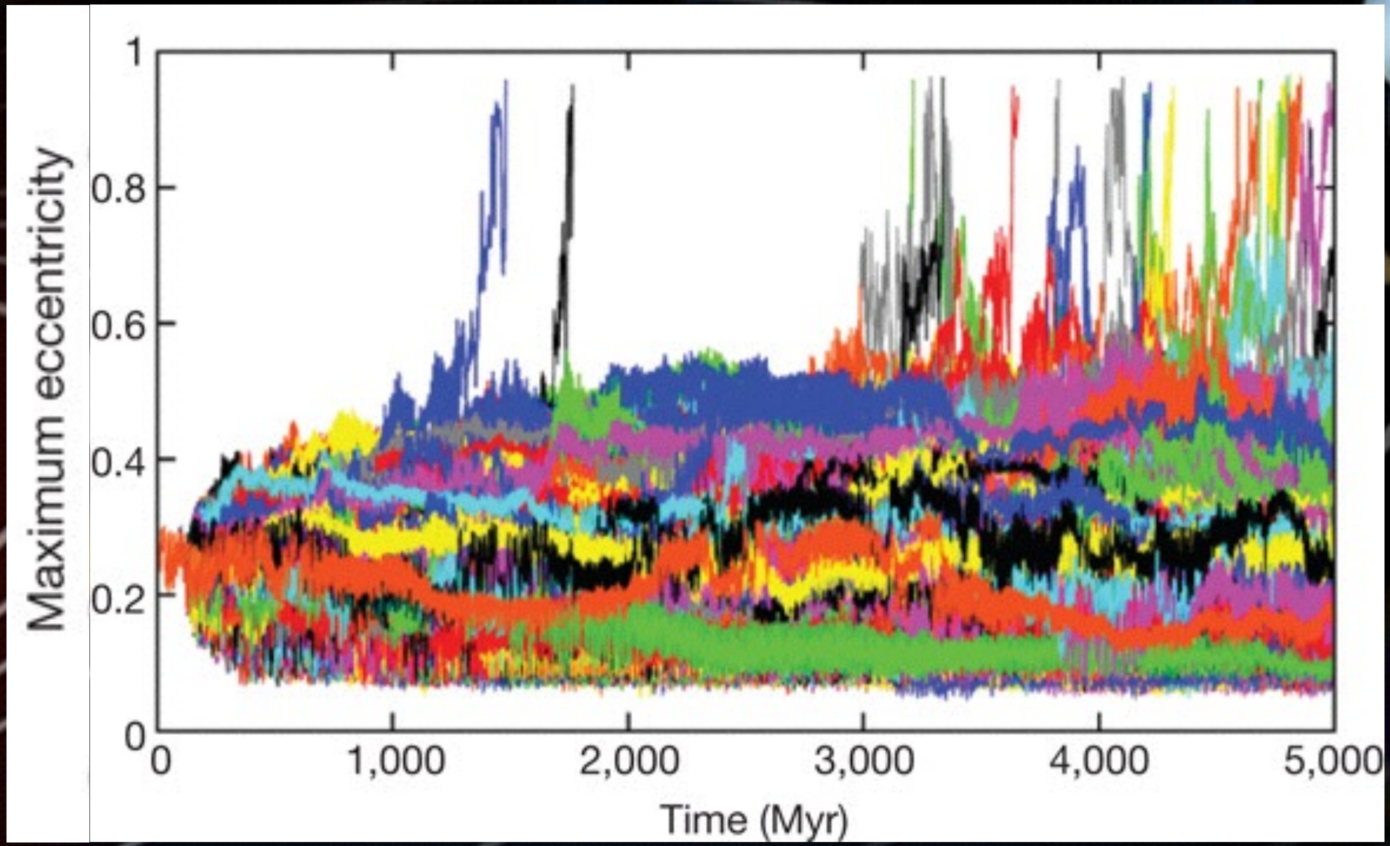
Post evolution dynamics in planetary systems

Long Time Scale

3. The secular interactions

~circular orbits, concentric, coplanar

Laskar & Gastineau (2009)



Selected dynamical processes

- Planet-Planet scattering
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- “Classical” secular evolution
- **The eccentric Kozai-Lidov (EKL) mechanism**

Post evolution dynamics in planetary systems

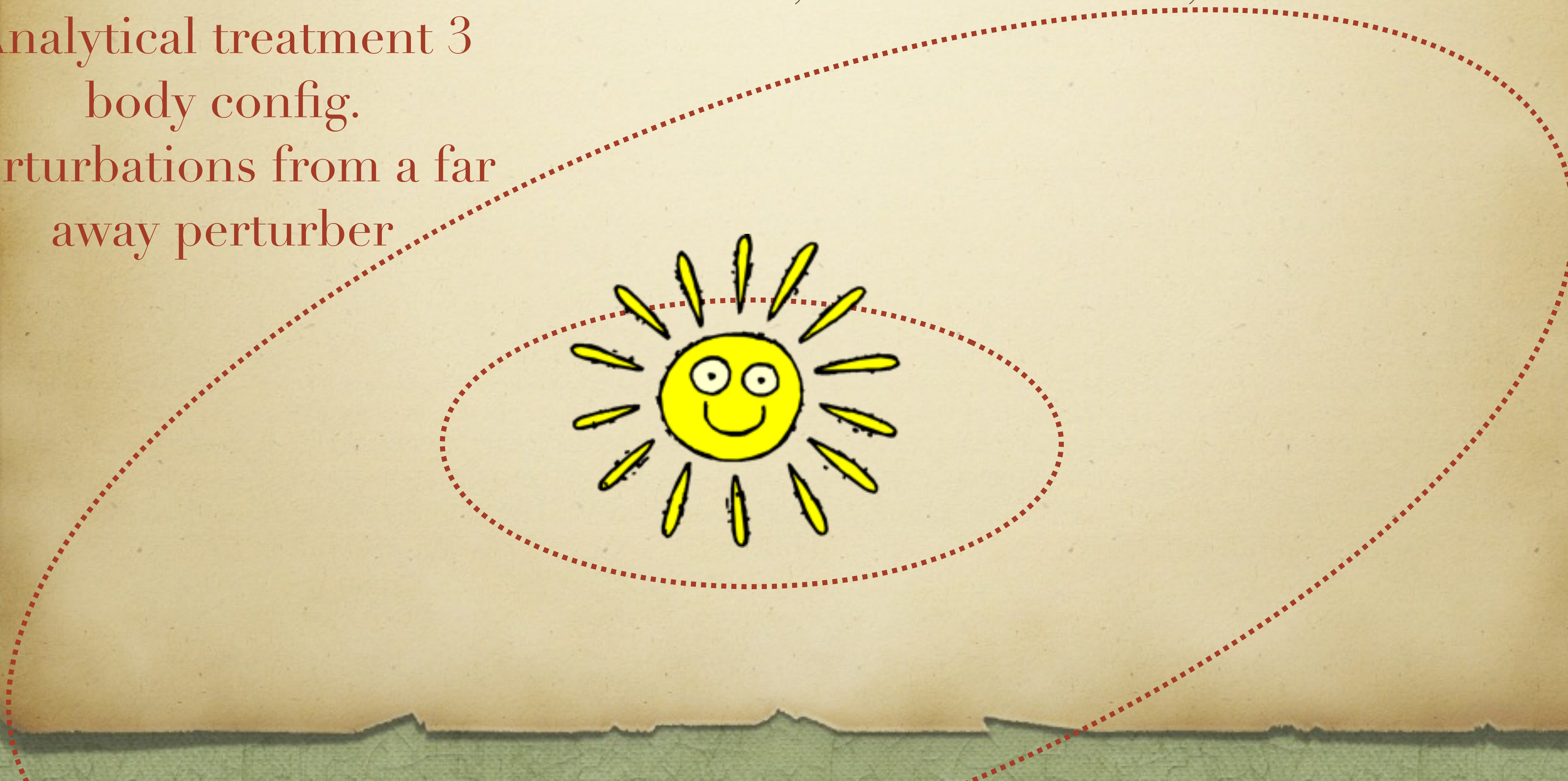
Long Time Scale

4. The secular interactions

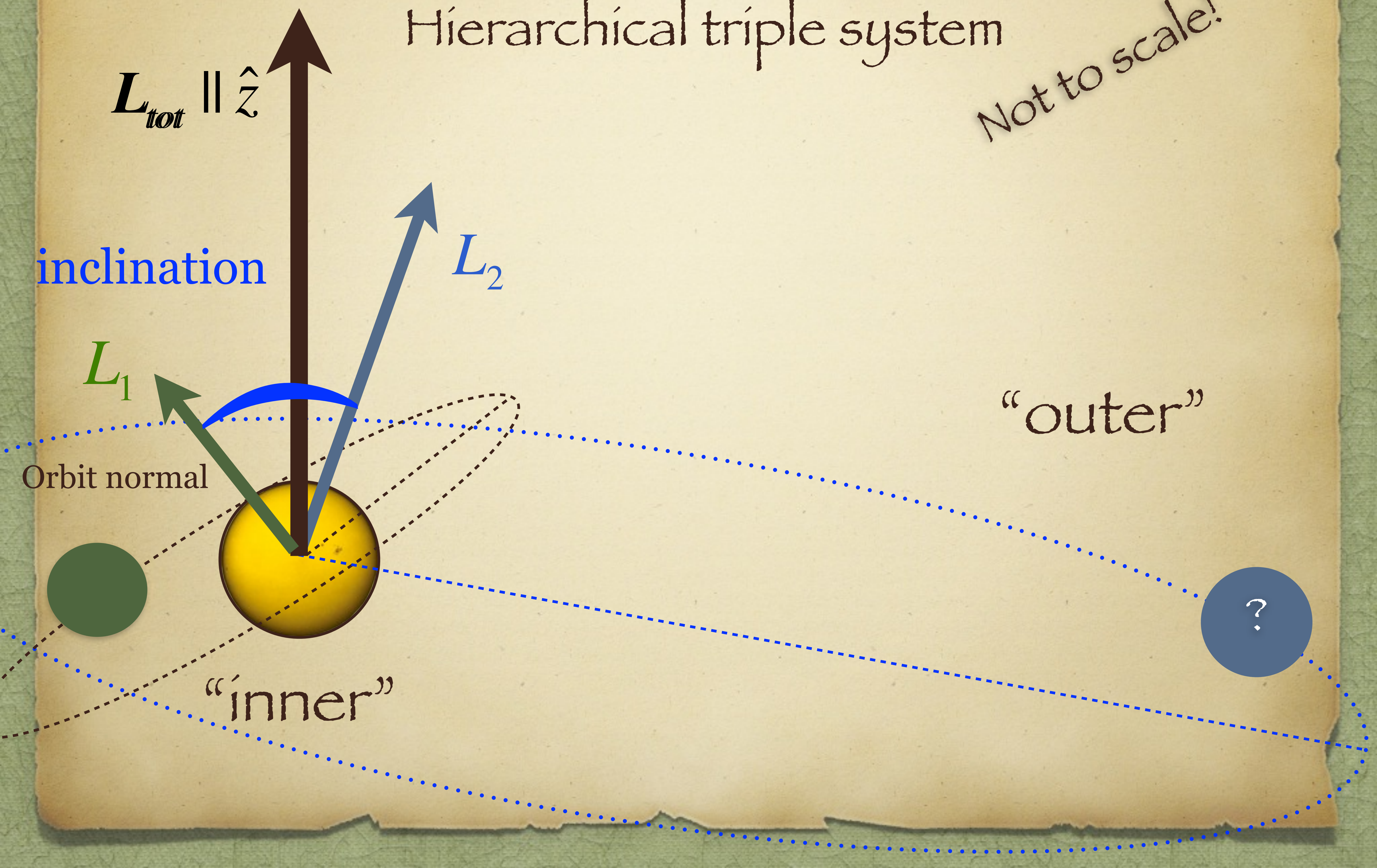
~can be eccentric, hierarchical, inclined

Analytical treatment 3 body config.

Perturbations from a far away perturber



The Kozai-Lidov Formalism

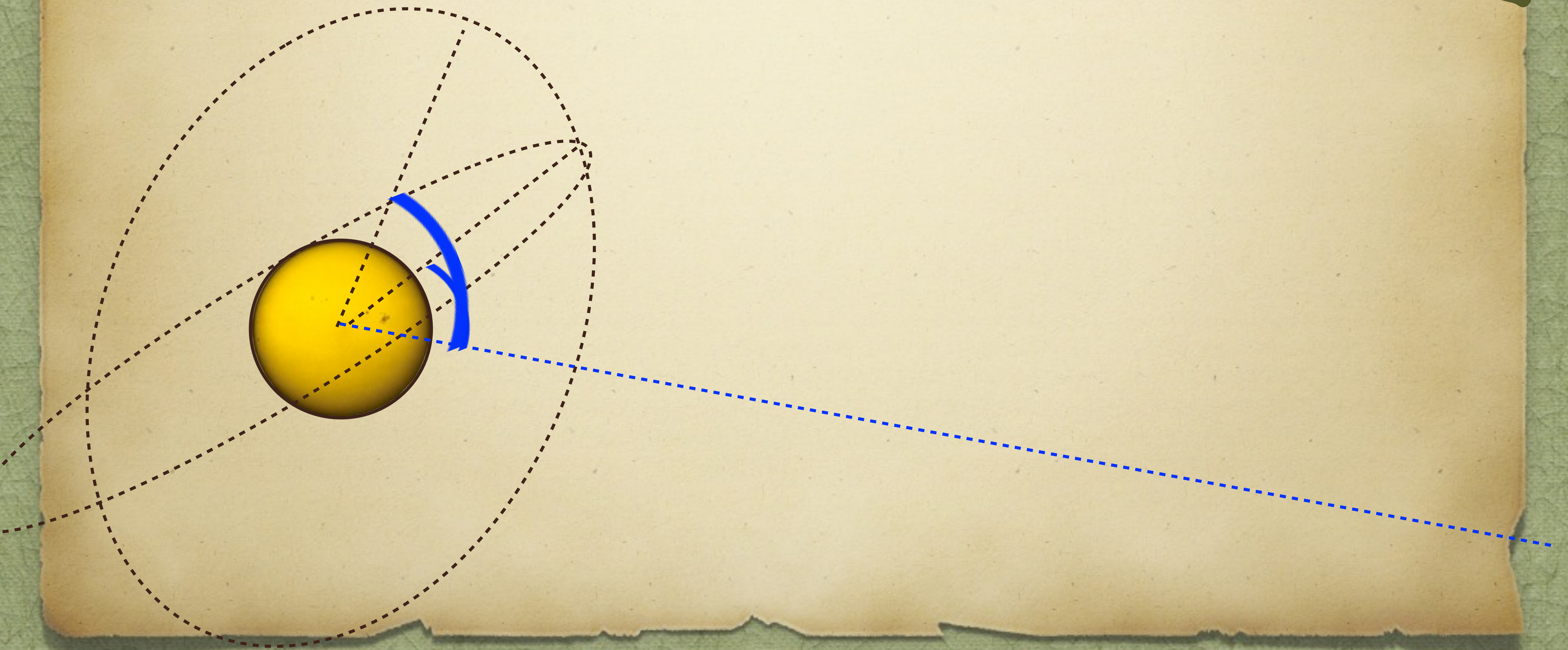


The Kozai-Lidov Formalism

The eccentricity and inclination oscillate

Kozai 1962, Lidov 1962

For initially inclined system ≳ 40°



The Kozai-Lidov Formalism

The eccentricity and inclination oscillate

Kozai 1962, Lidov 1962

Conservation of the z component of angular momentum for both the inner outer orbits

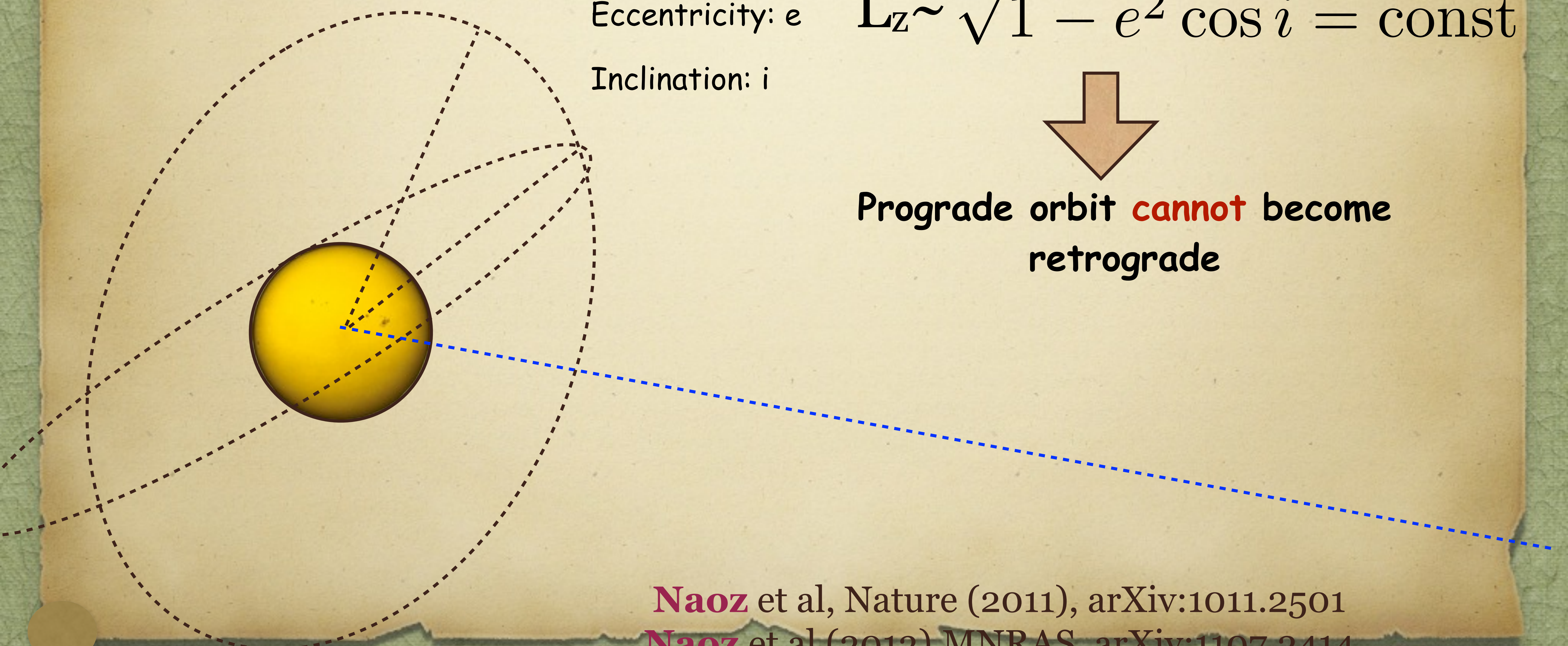
The orbital elements:

Eccentricity: e

Inclination: i

$$L_z \sim \sqrt{1-e^2}\cos i = \text{const}$$

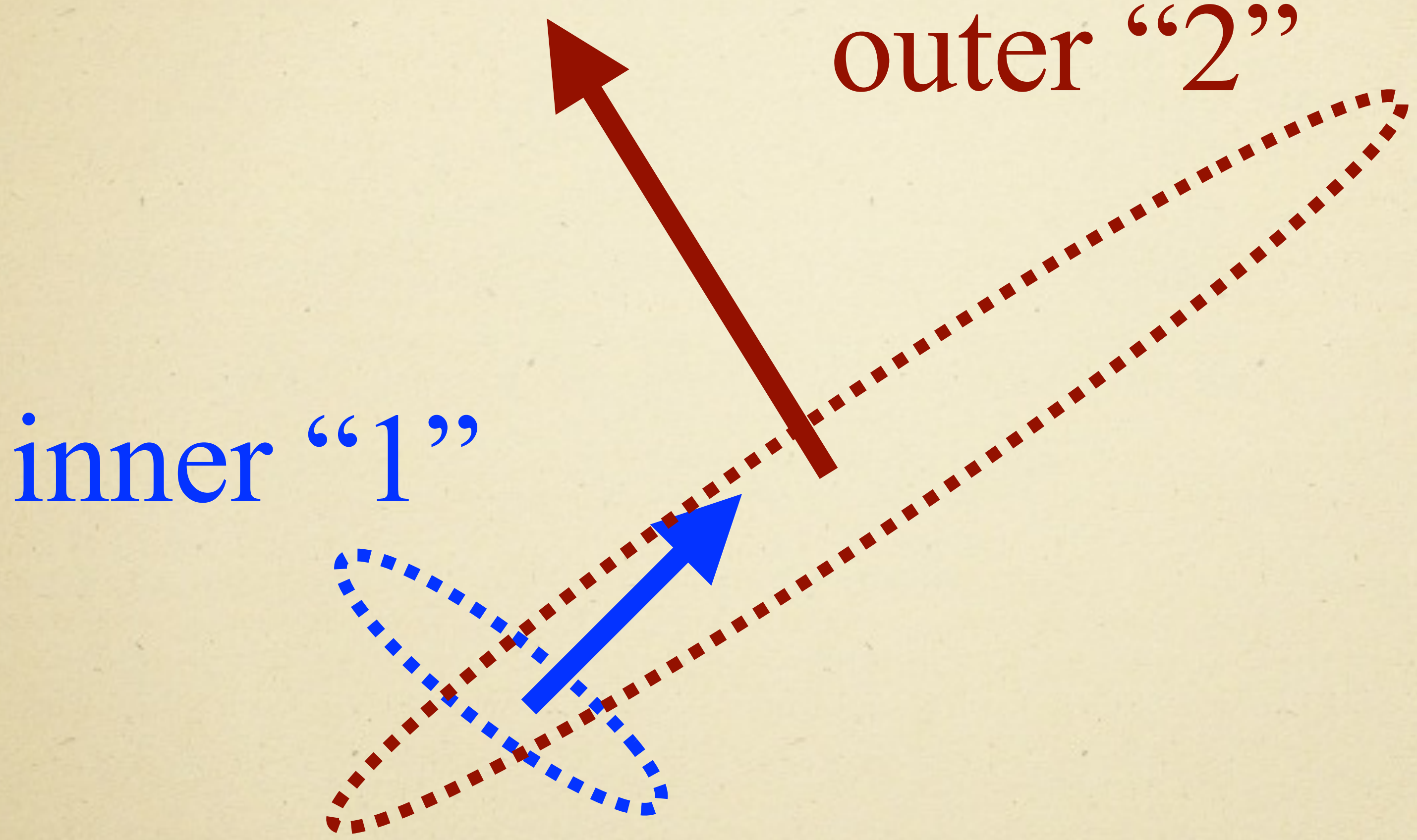
Prograde orbit cannot become retrograde



Naoz et al, Nature (2011), arXiv:1011.2501

Naoz et al (2013),MNRAS, arXiv:1107.2414

Is it constant?



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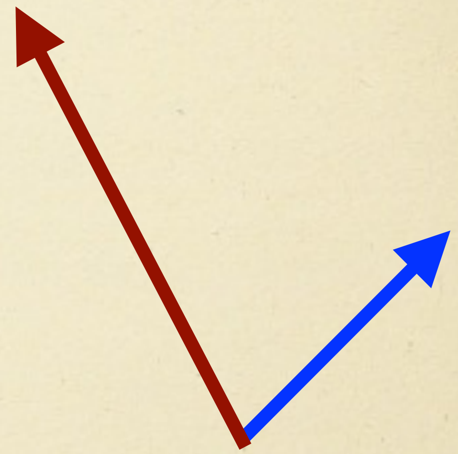

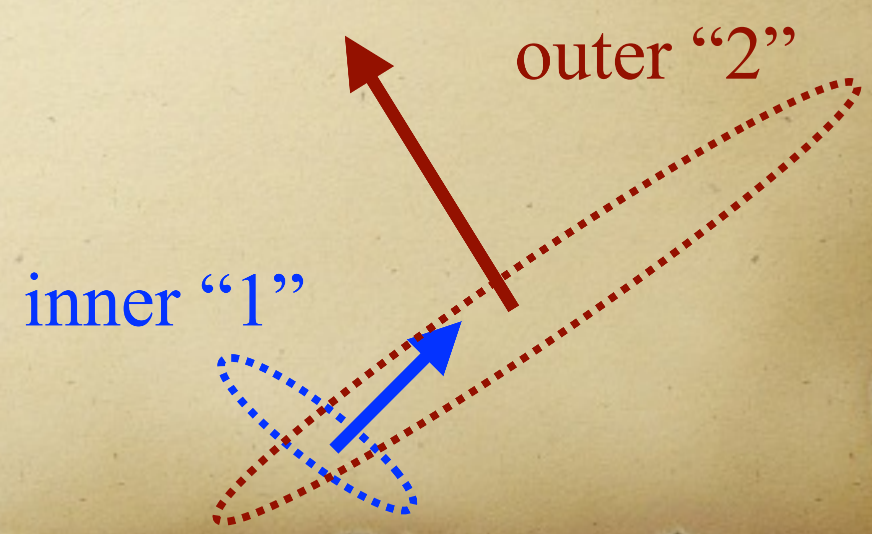

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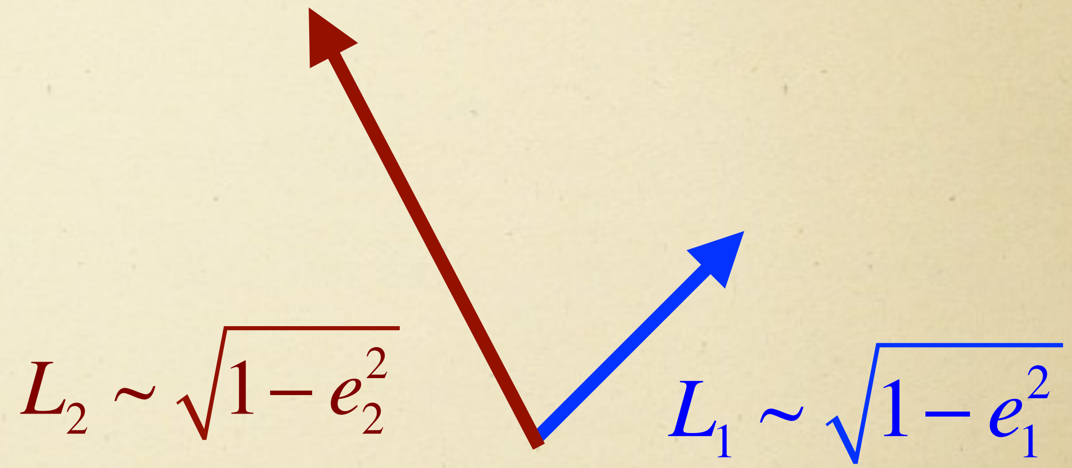
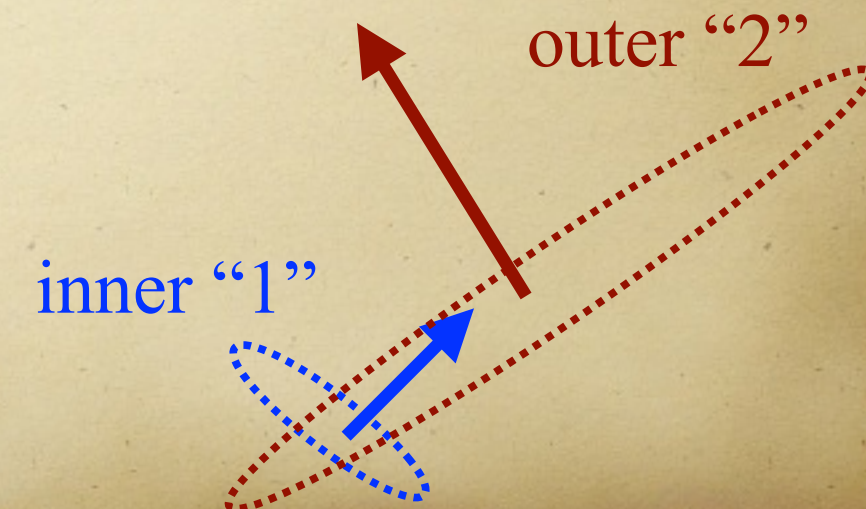
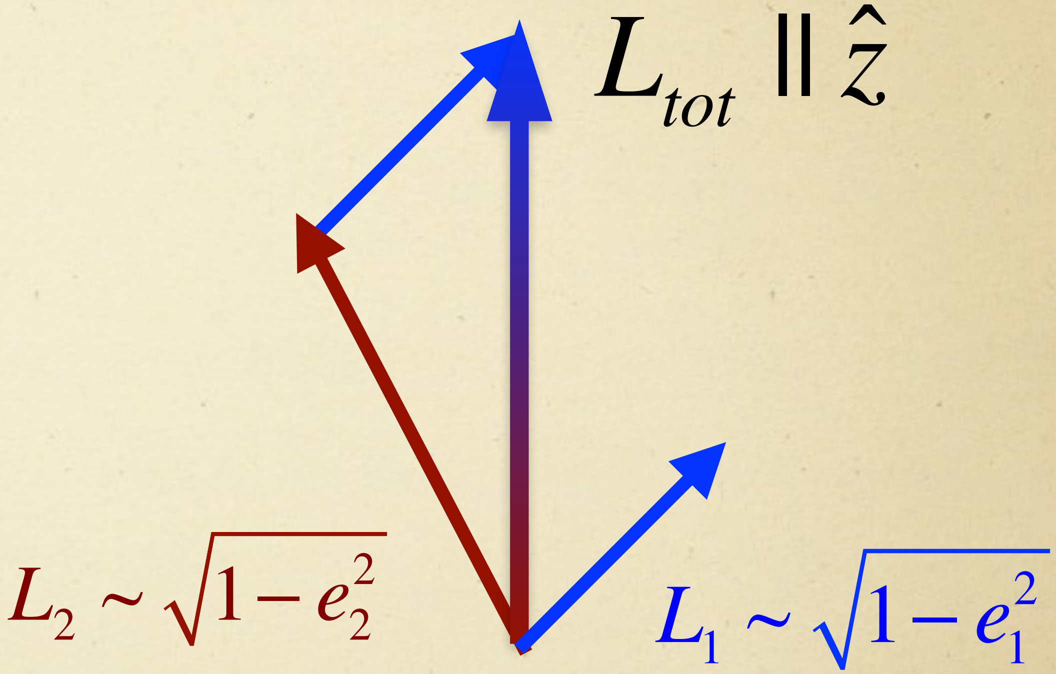


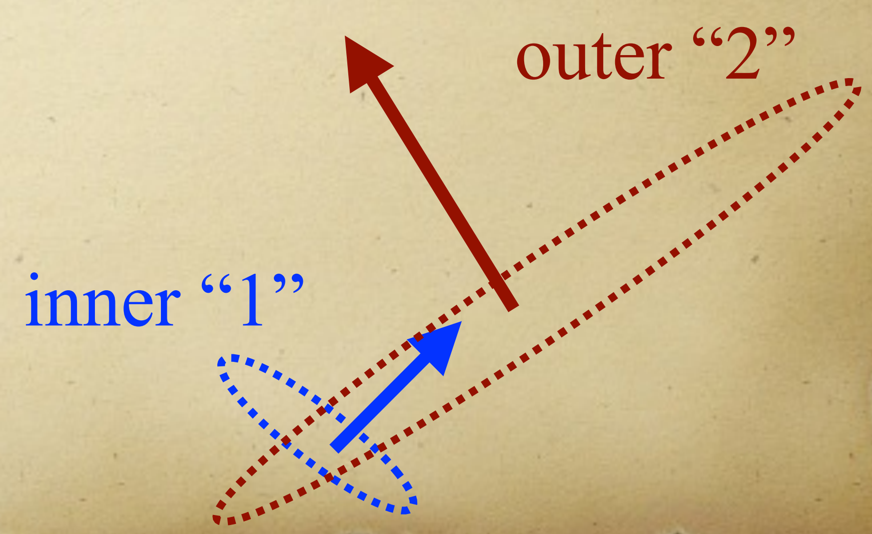


Is it constant?

Adding vector …

$$\vec{L}_{tot} = \vec{L}_1 + \vec{L}_2$$





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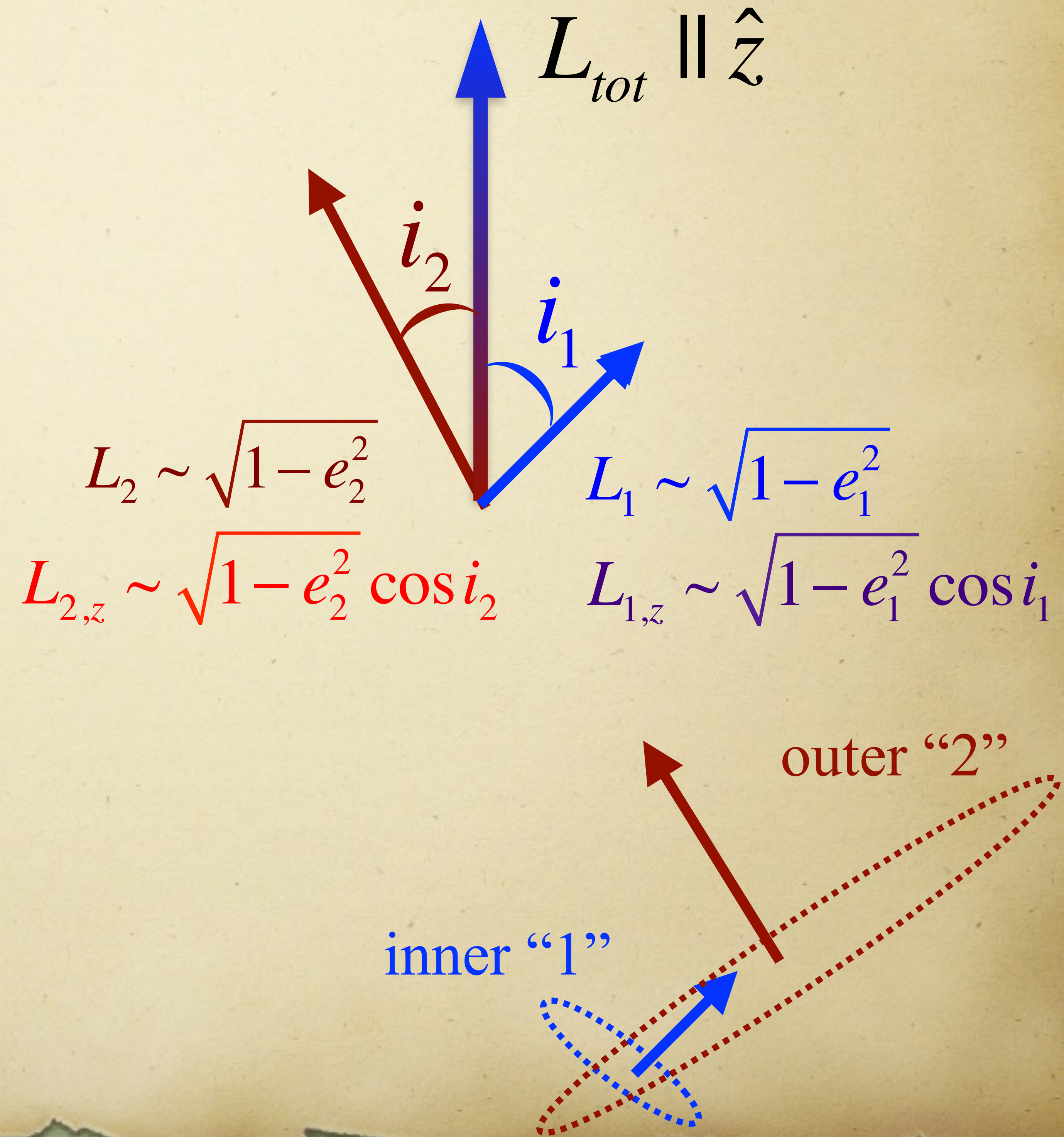

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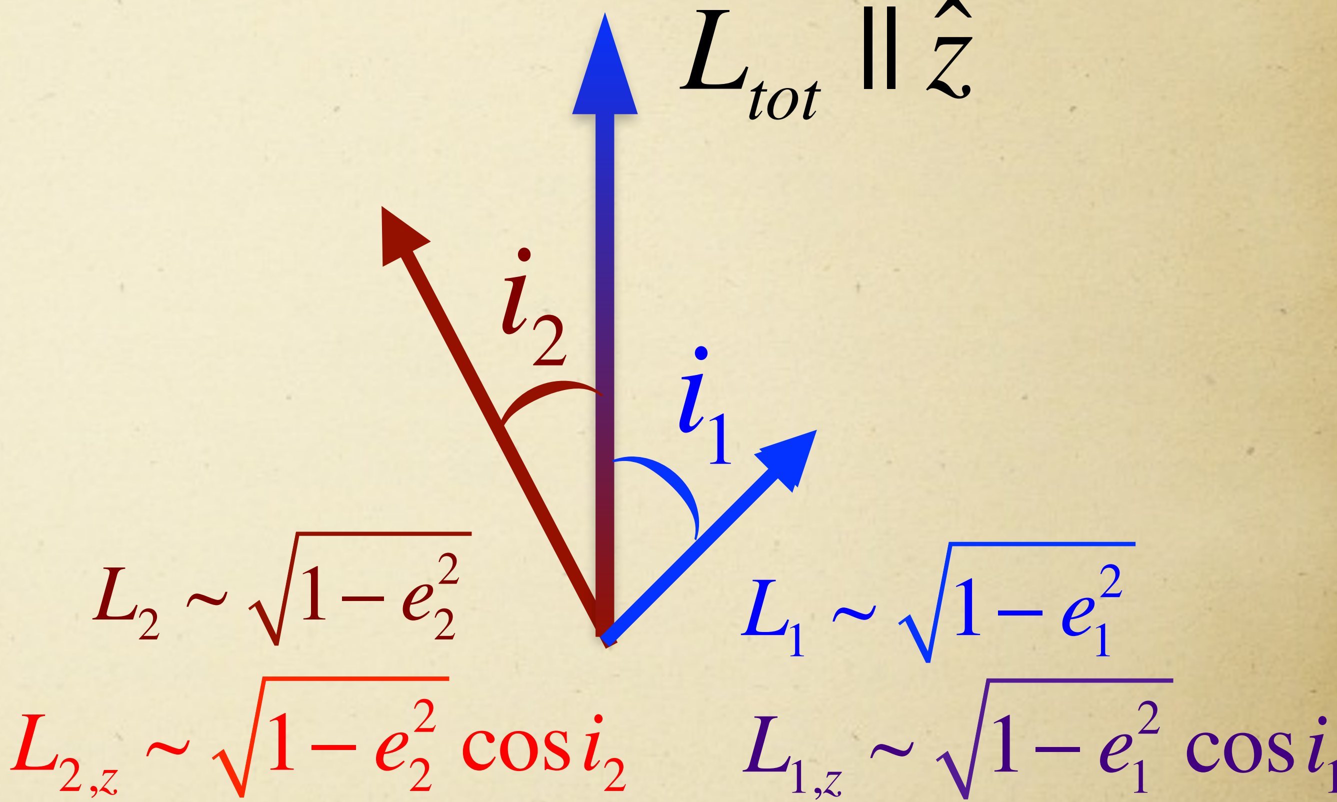
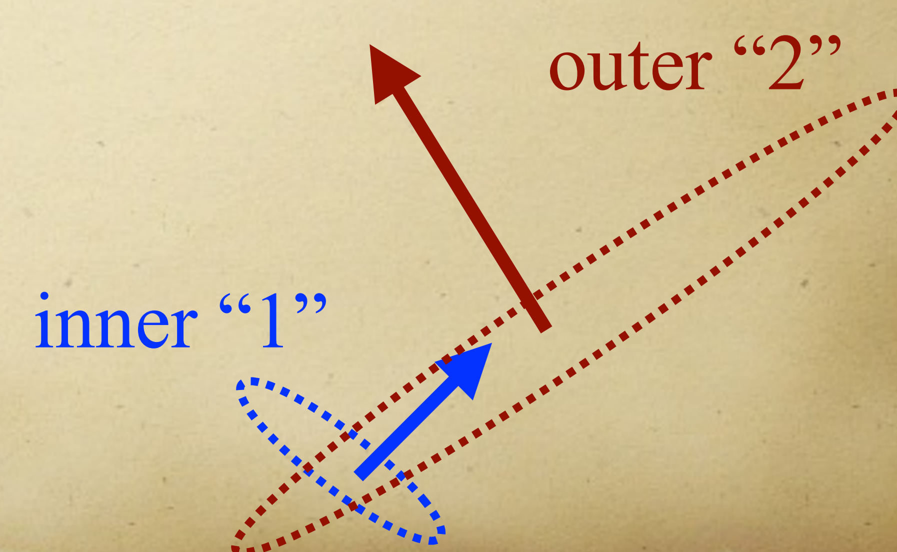
$$L_2^2 = L_{tot}^2 + L_1^2 - 2L_{tot}\underbrace{L_1 \cos i_1}_{L_{1,z}}$$





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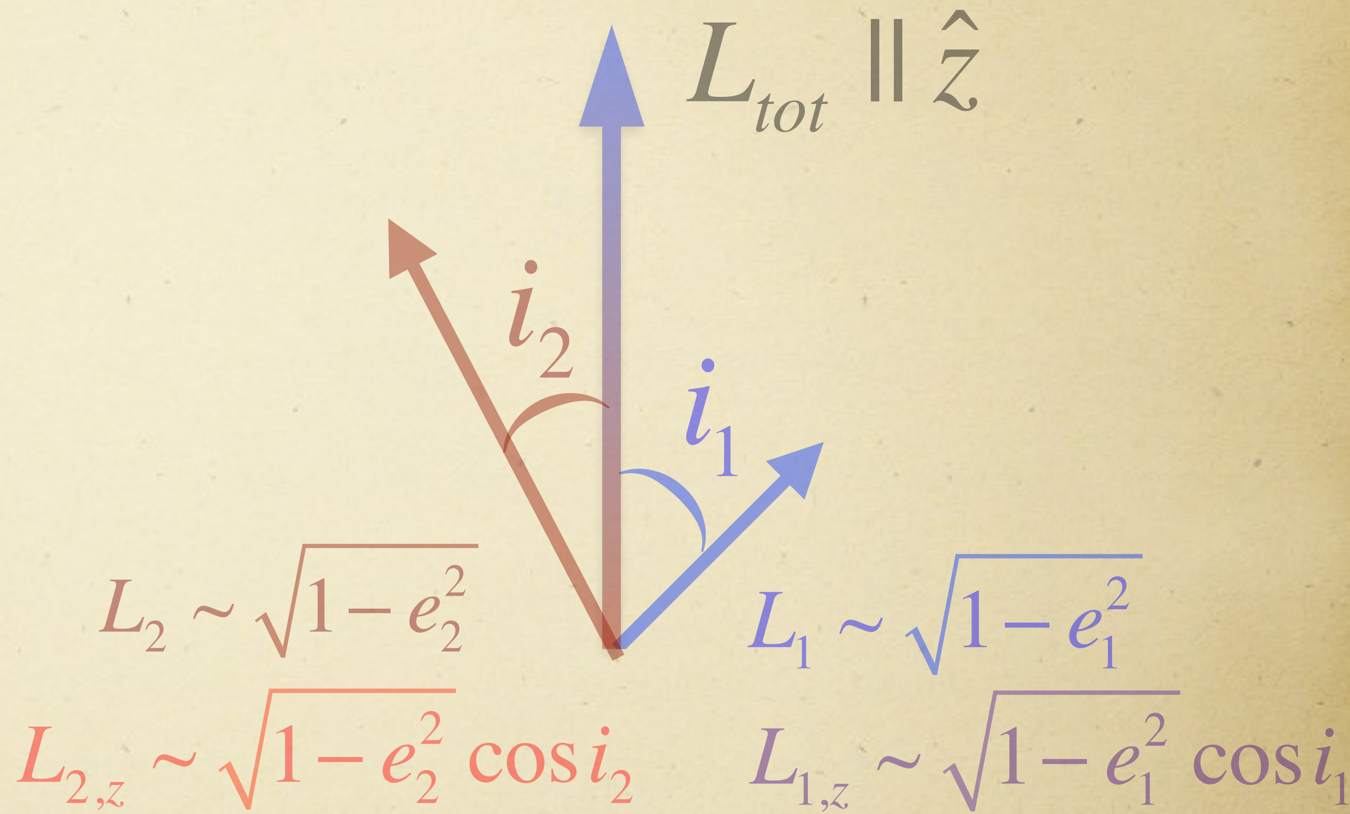

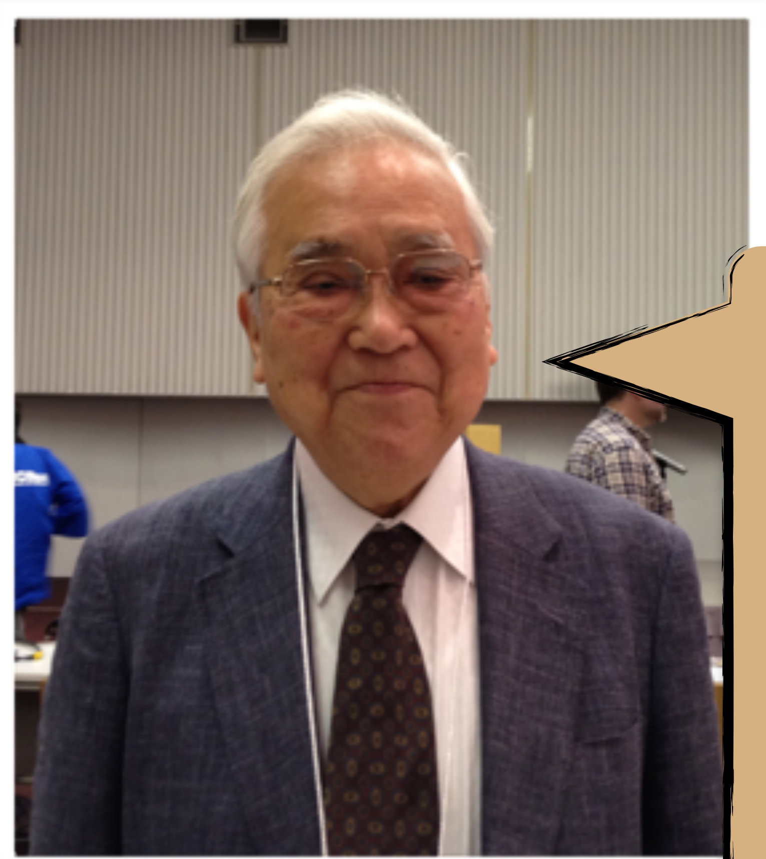

Yoshihde Kozai

THE ASTRONOMICAL JOURNAL VOLUME 67, NUMBER 9 NOVEMBER 1962

Secular Perturbations of Asteroids with High Inclination and Eccentricity

Yoshihide Kozai*
Smithsonian Astrophysical Observatory, Cambridge, Massachusetts

(Received August 29, 1962)

Secular perturbations of asteroids with high inclination and eccentricity moving under the attraction of

Is it constant?

Adding vector ...

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$$\vec{L}_2 = \vec{L}_{tot} - \vec{L}_1$$

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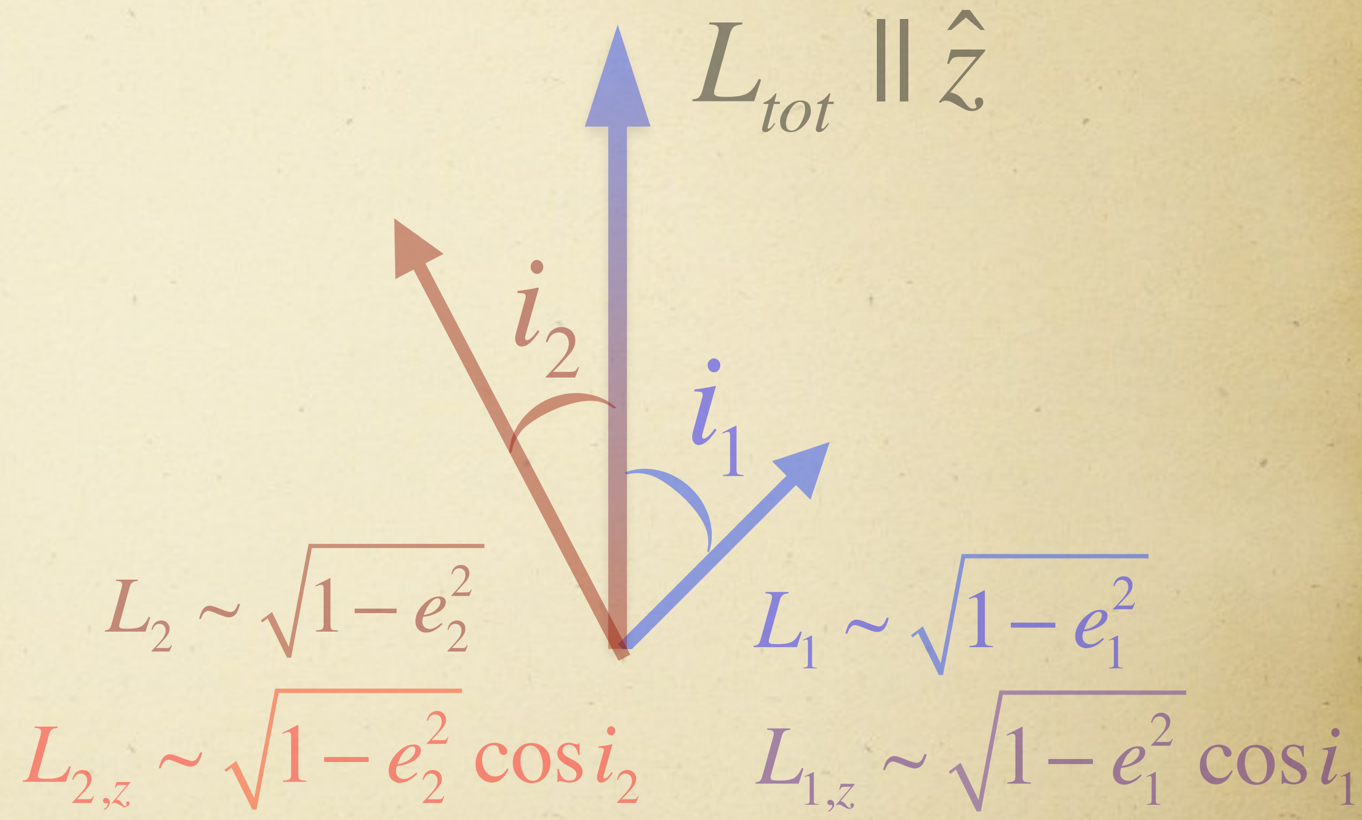
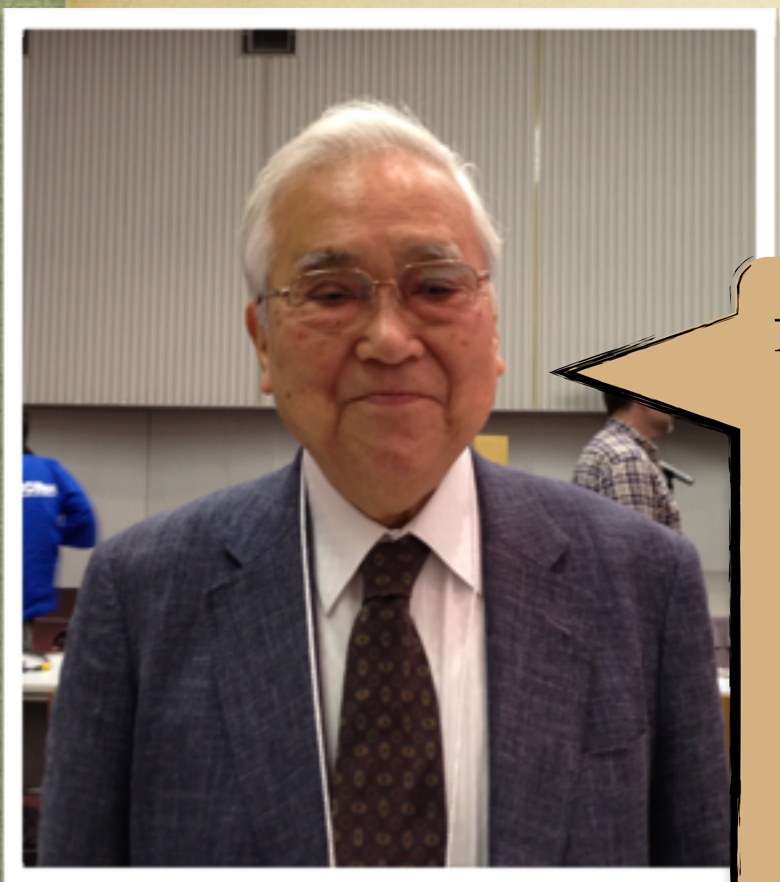
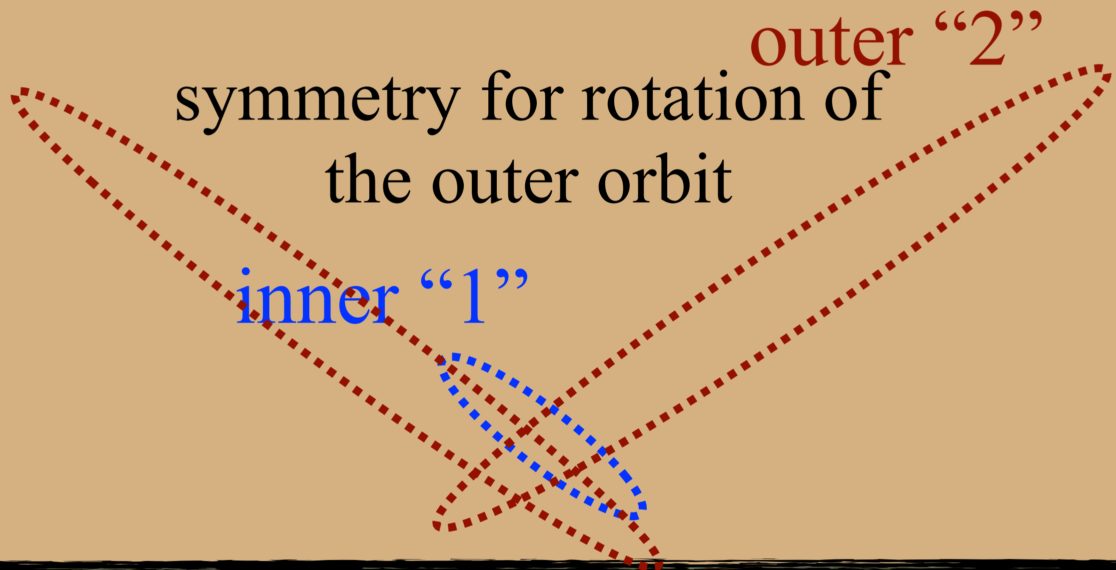




Yoshihde Kozai

for the quadrupole approx. ~ $(a_1/a_2)^2$:

$L_2 = Const.$



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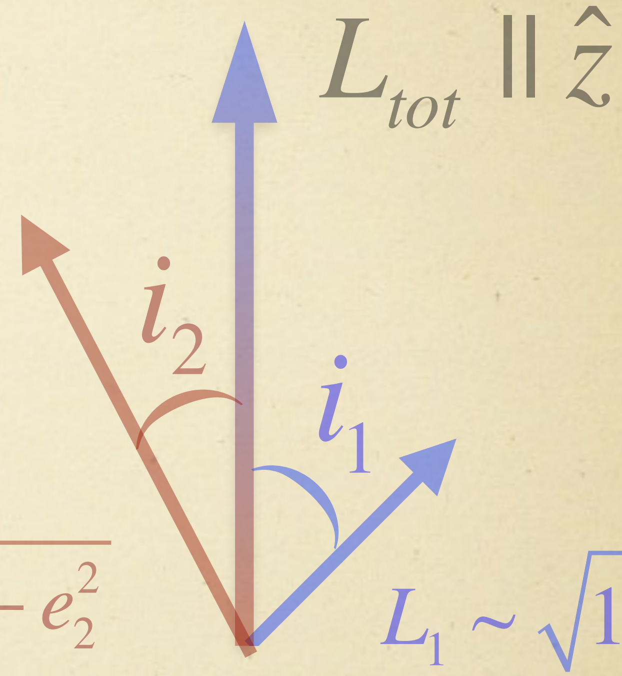
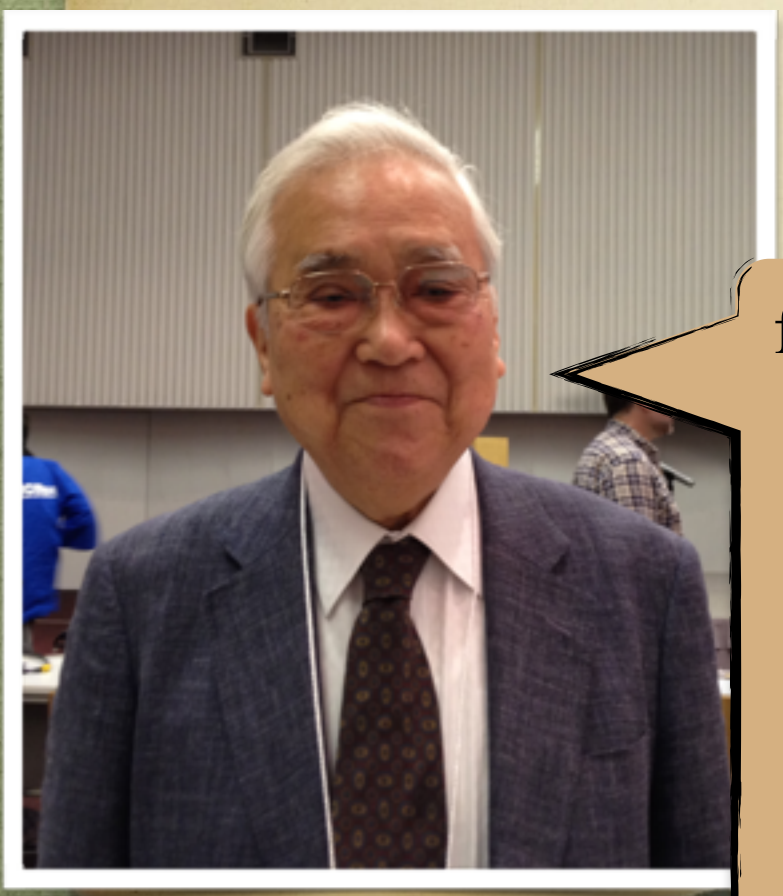


$L_2 \sim \sqrt{1-e_2^2}$ $\quad L_1 \sim \sqrt{1-e_1^2}$

$L_{2,z} \sim \sqrt{1-e_2^2}\cos i_2$ $\quad L_{1,z} \sim \sqrt{1-e_1^2}\cos i_1$



Yoshihde Kozai

for the quadrupole approx. $\sim (a_1/a_2)^2$:

$L_2 = Const.$

$L_{1,z} = Const.$

$L_{2,z} = Const.$

$L_1 \neq Const.$ $\quad \mathcal{H}_{quad}(\omega_1)$

Is it constant?

Adding vector …

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$$\vec{L}_2 = \vec{L}_{tot} - \vec{L}_1$$

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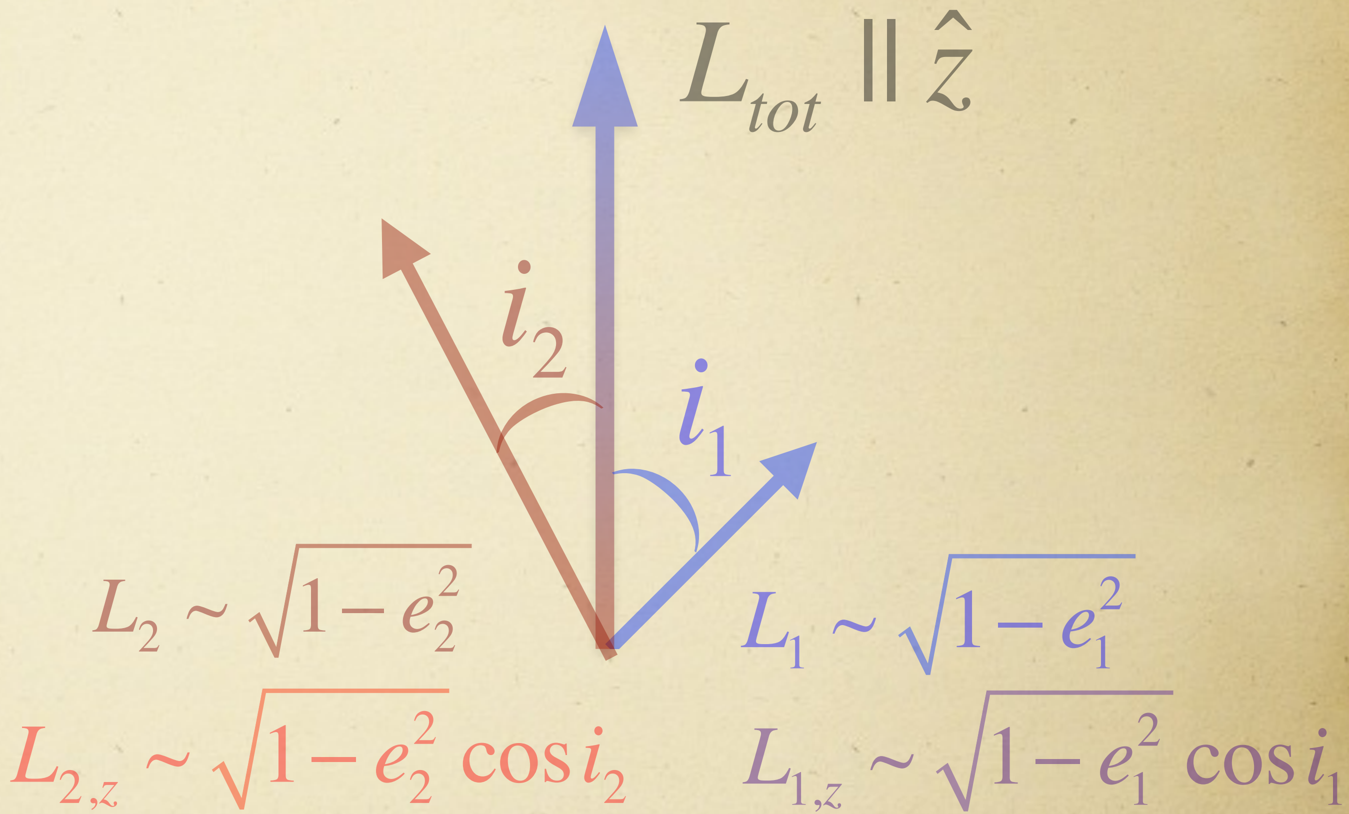


for the quadrupole approx. $\sim (a_1/a_2)^2$:

$L_2 = Const.$

$L_{1,z} \neq Const.$

$L_{2,z} \neq Const.$

$L_1 \neq Const.$

$$\mathcal{H}_{quad}(\omega_1, \underbrace{\Omega_1 - \Omega_2}_{\pi})$$

$$\left.\frac{df}{fx}\right|_{x=2} \neq \frac{df(x=2)}{dx}$$

Naoz et al, Nature (2011), arXiv:1011.2501

The Kozai-Lidov Formalism EKL

The eccentricity and inclination oscillate

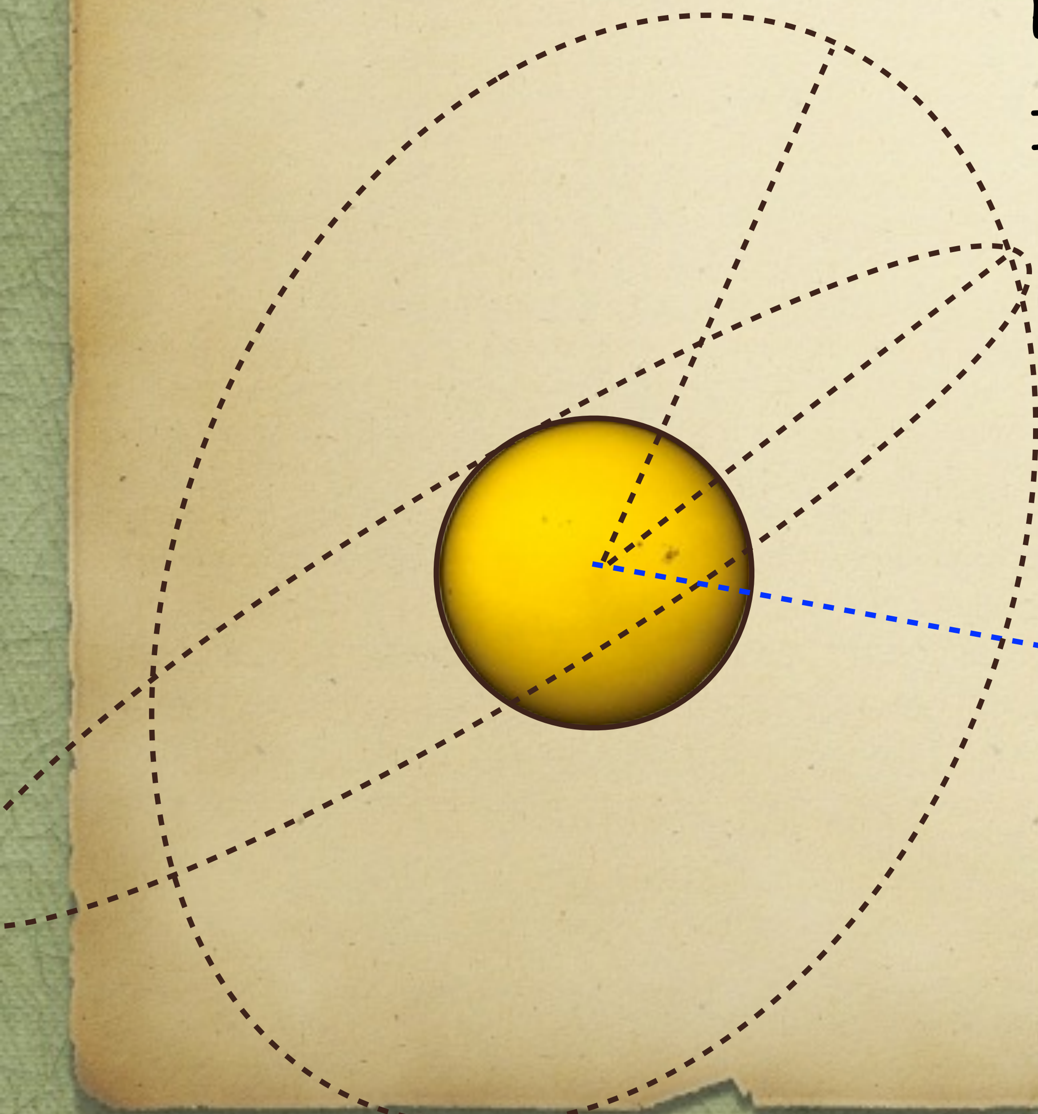
Conservation of the z component of angular momentum for both the inner outer orbits

The orbital elements:

Eccentricity: e

Inclination: i

$$L_z \sim \sqrt{1-e^2}\cos i = \text{const}$$



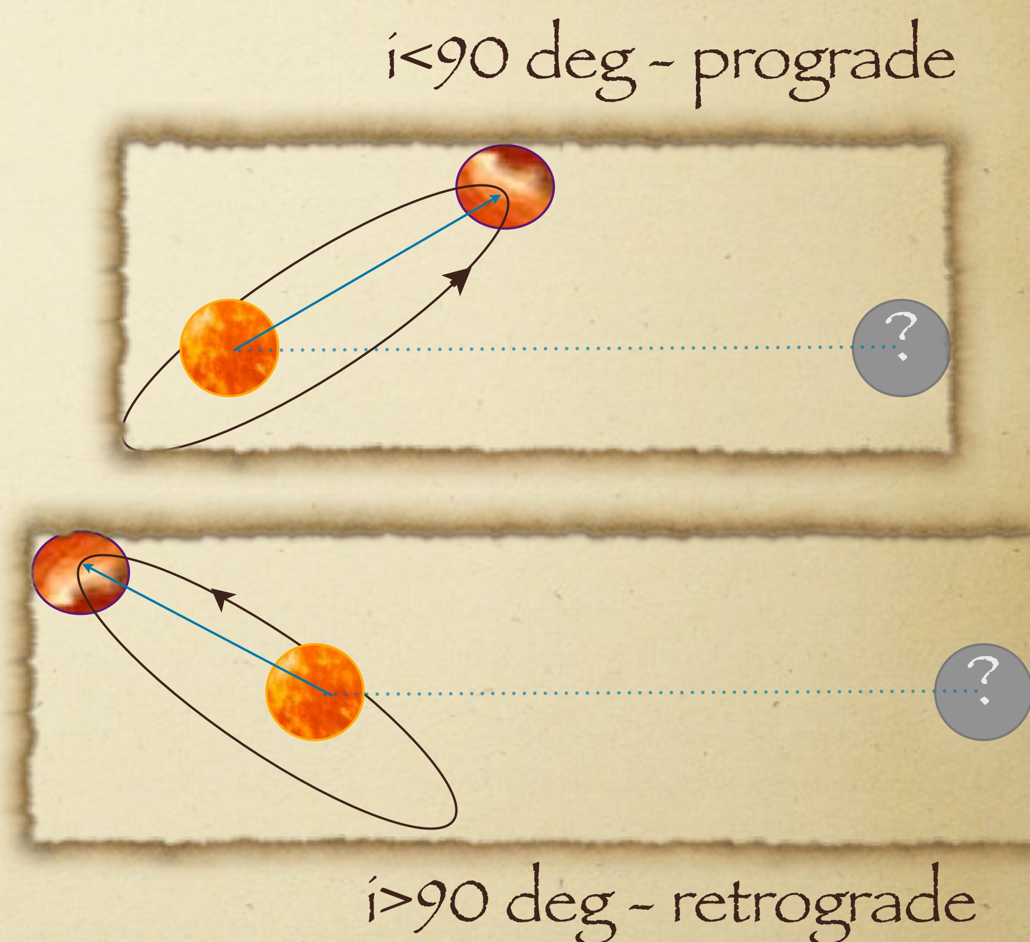
L_{z1} conserved only to lowest order (quadrupole) and for a test particle (massless planet)!

Naoz et al, Nature (2011), arXiv:1011.2501
Naoz et al (2013),MNRAS, arXiv:1107.2414

Our treatment

The eccentric Kozai-Lidov mechanism - KEL

- Allow for the z-component of the angular momenta of the inner and outer orbit to change - already at the quadrupole level
- Expanding the approximation to the octupole level (**e.g., Ford et al 2000, Blaes et al 2002 - <u>already done before us</u>!!!**)
- Both the magnitude and orientation of the angular momentum can change



larger parts of the parameter space

Naoz et al, Nature (2011), arXiv:1011.2501
Naoz et al (2013), MNRAS, arXiv:1107.2414

for test particle approx. see:
Lithwick & **Naoz** (2011), ApJ, arXiv:1106.3329
Katz, Dong Malhotra (2011), arXiv:1106.3340

Lets…flip the planet

point mass limit

Lets…flip the planet

Example system: a_1=6AU, a_2=100AU, m_1=1.M_{sun} M_2=1M_j, M_3=40M_j i=65 deg secular dynamics + GR

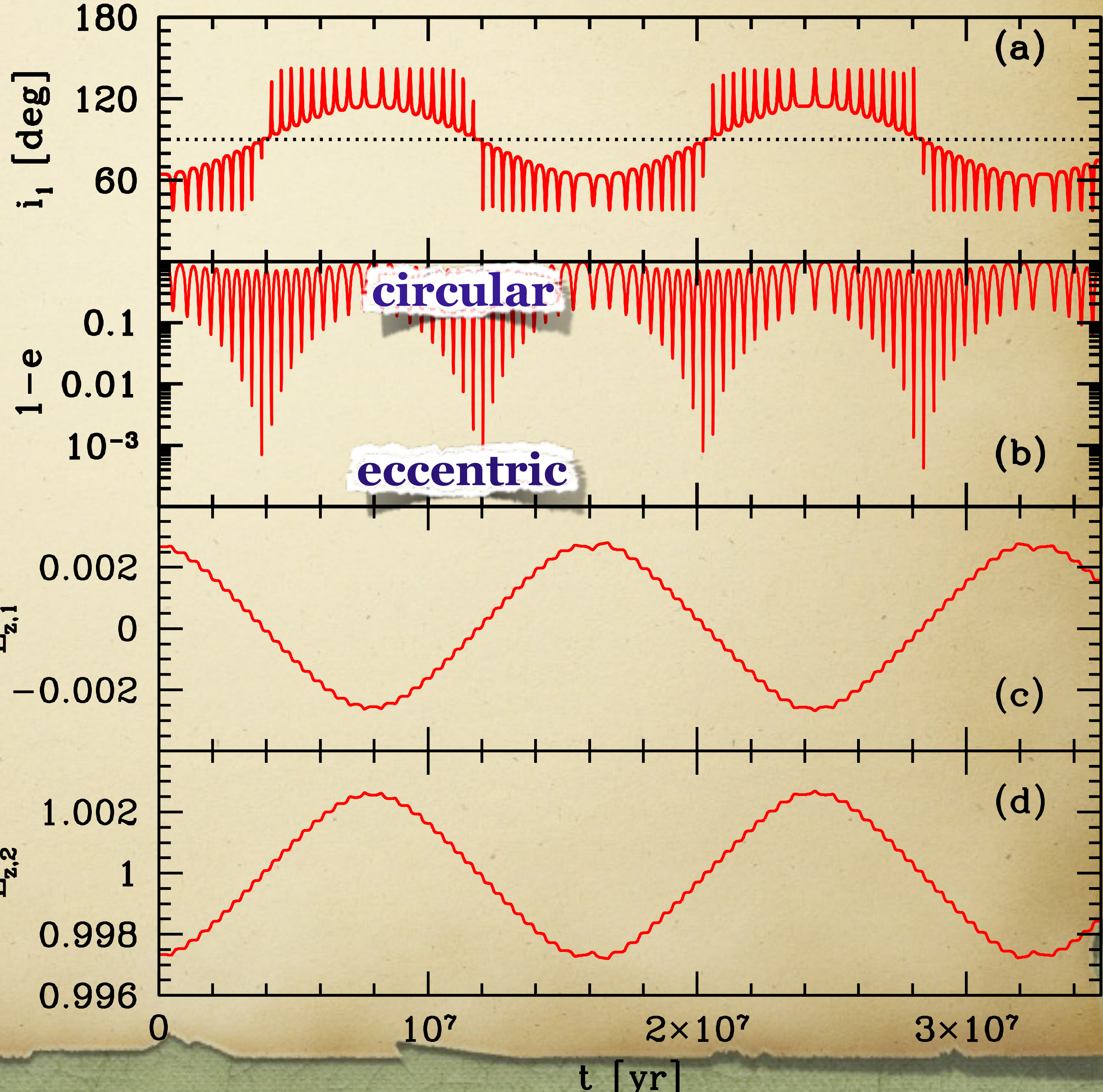
GR effects: e.g., Ford et al 2000, Naoz, Kocsis, Loeb, Yunes 2013

(a) inner orbit inclination

(b) inner orbit eccentricity

(c) inner orbit z-com. angular momentum

(d) inner orbit z-com. angular momentum



Naoz et al, Nature (2011)

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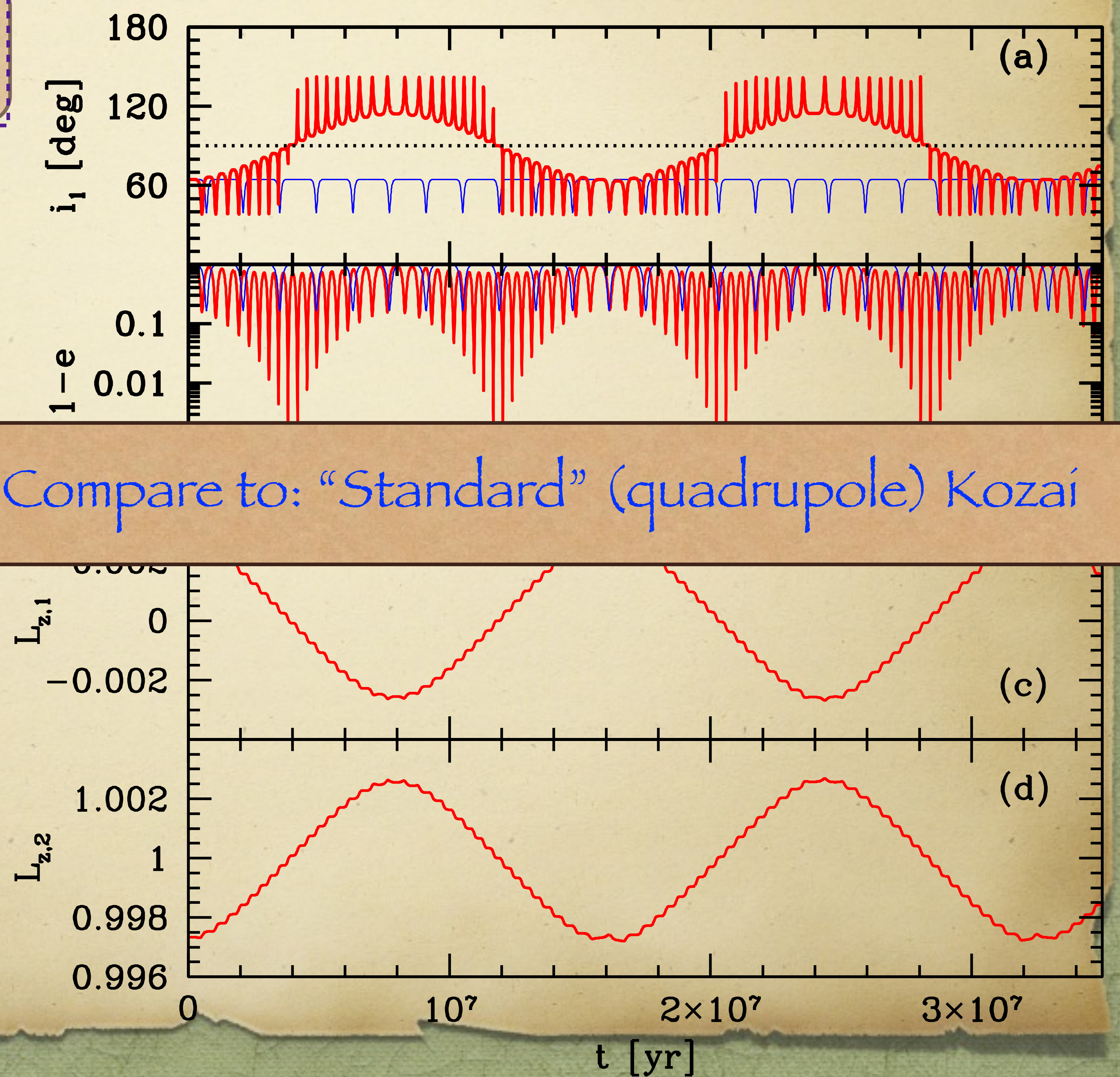
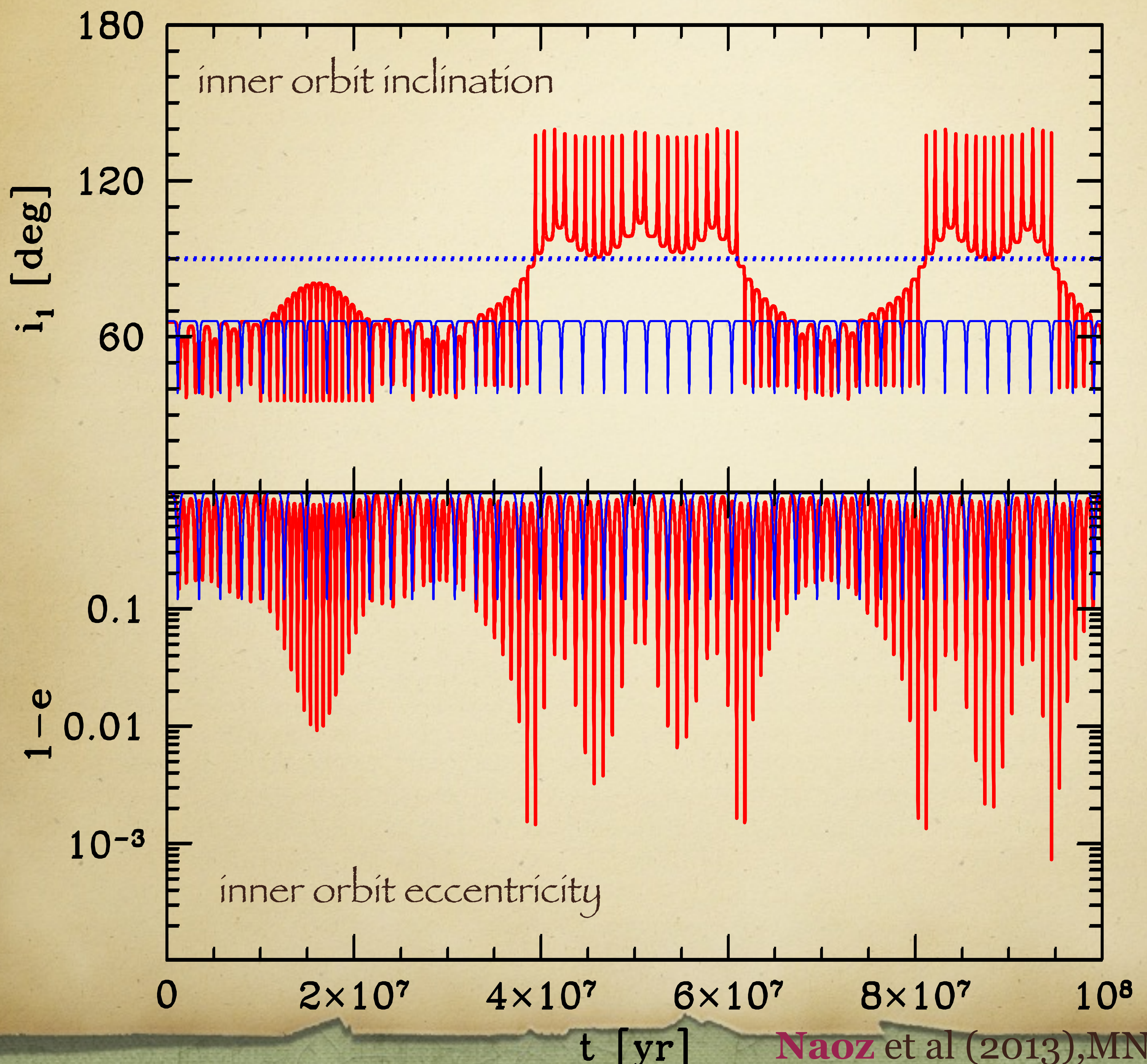


Compare to: “Standard” (quadrupole) Kozai

Naoz et al, Nature (2011)

EKL



$M_1 = 1\ \mathrm{M}_\odot$
$M_2 = 1\ \mathrm{M}_J$
$M_3 = 4\ \mathrm{M}_J$

$a_1 = 5$ AU
$a_2 = 51$ AU

$i = 71°$

Naoz et al (2013),MNRAS, arXiv:1107.2414

Question

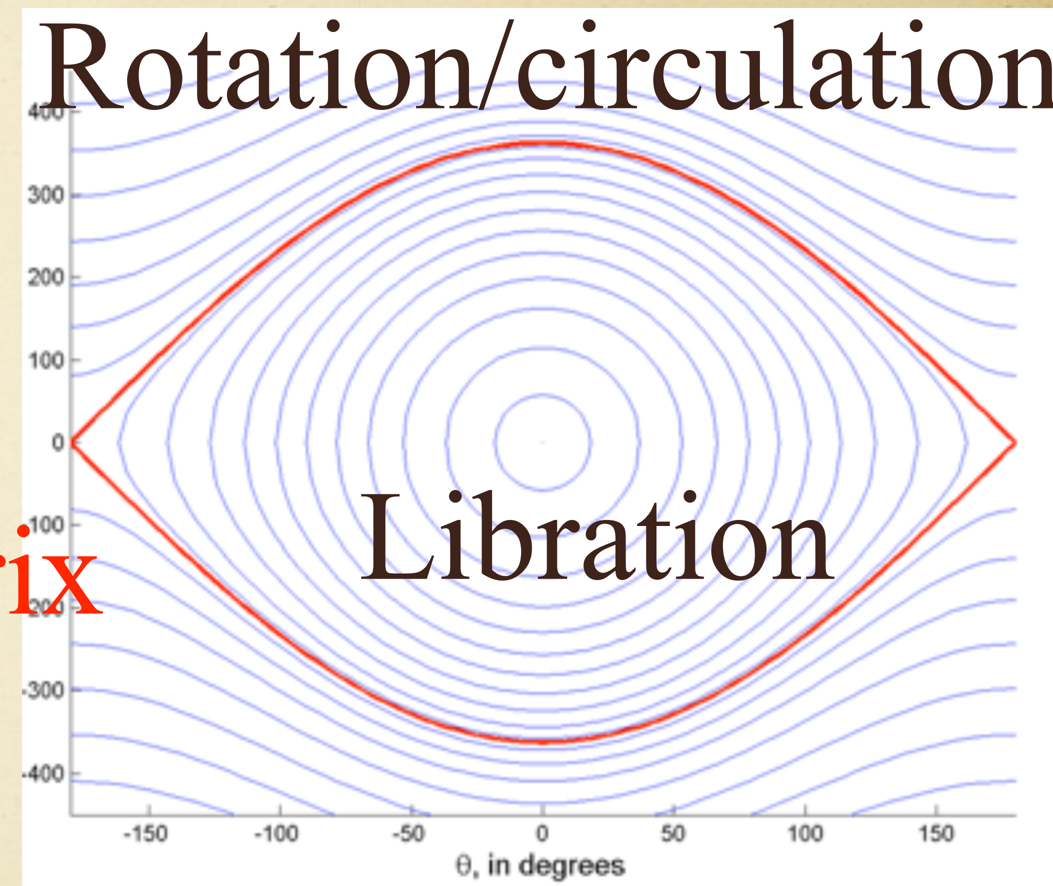
- Why high inclination $>40^{o}$?
- Is high inclination required also in the EKL mechanism?
- What about chaos?

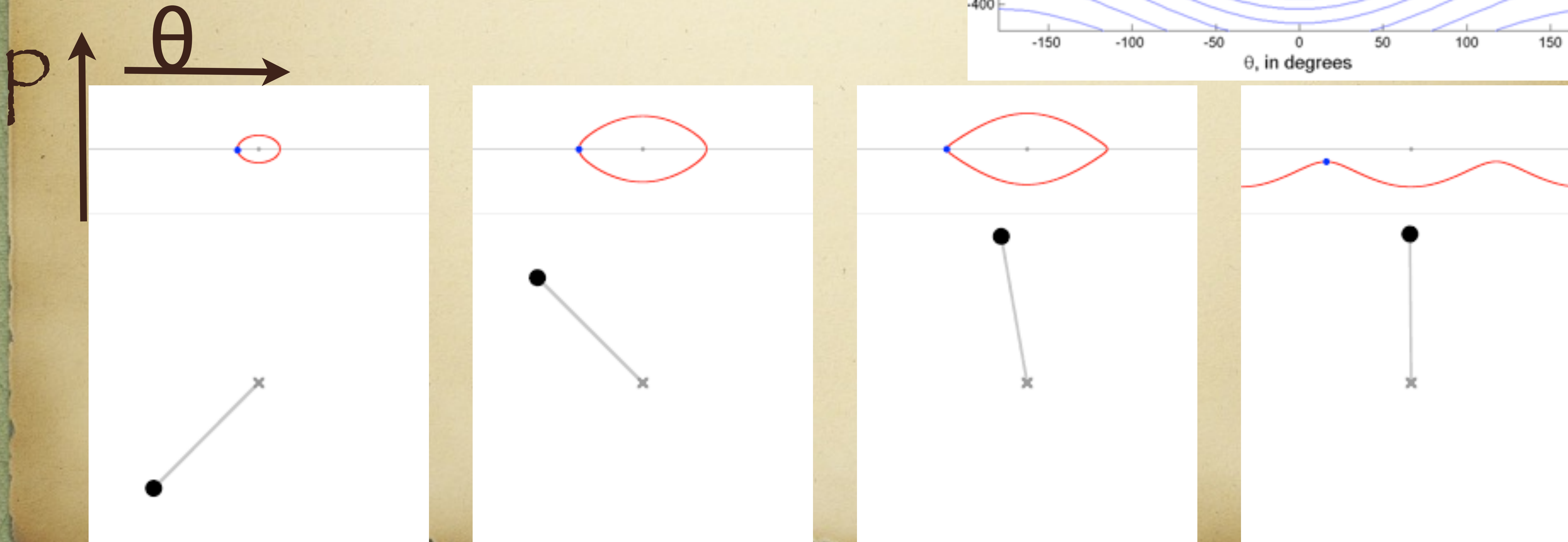
EKL and the Pendulum

The Pendulum

$$H(\theta, p) = \frac{p^2}{2mL} - mgL\cos\theta$$

The separatrix

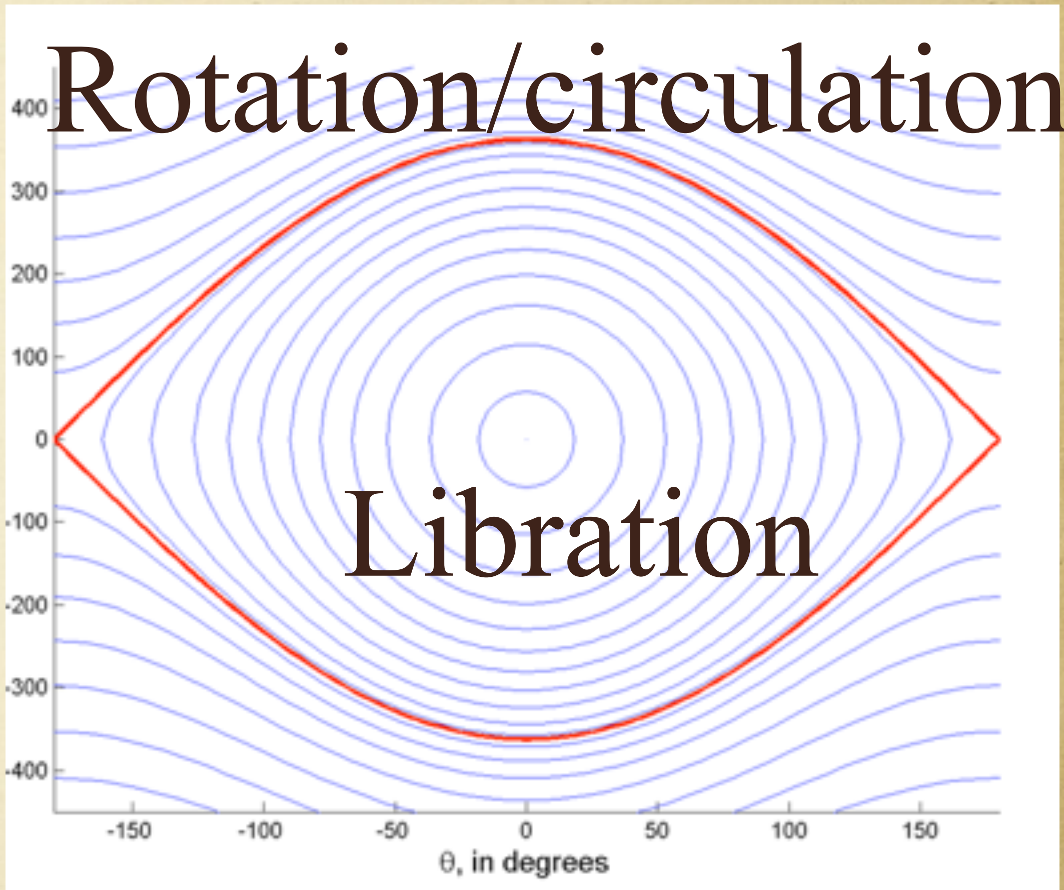




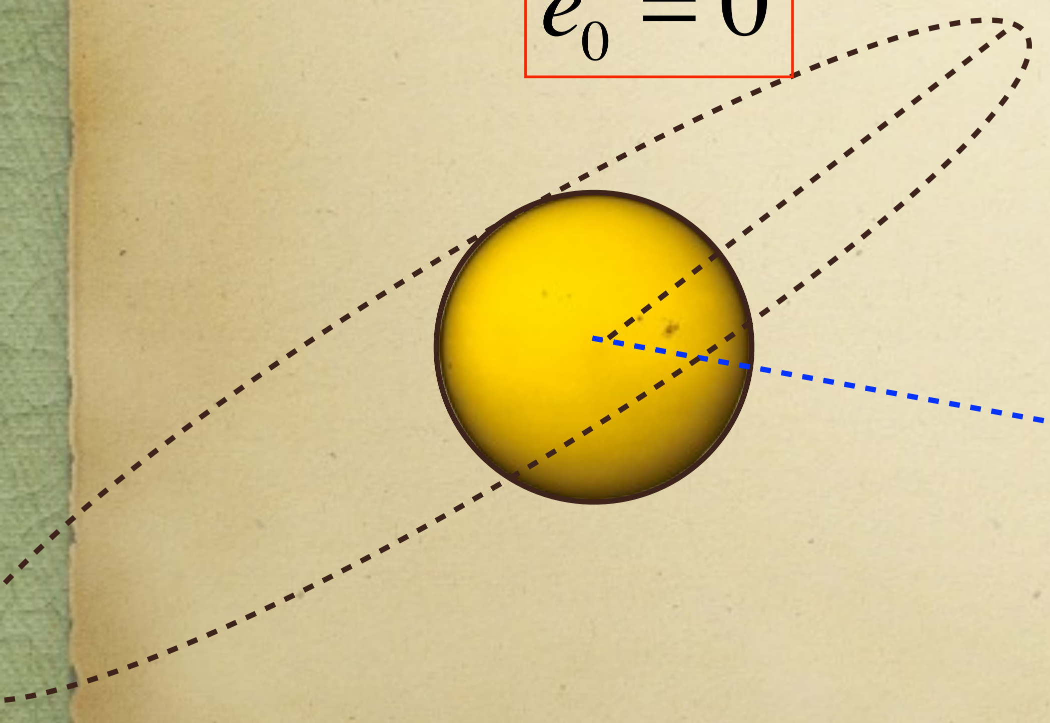
θ_0=45° θ_0=135° θ_0=170°

EKL and the Pendulum

Quadrupole test particle limit:



$e_0 = 0$

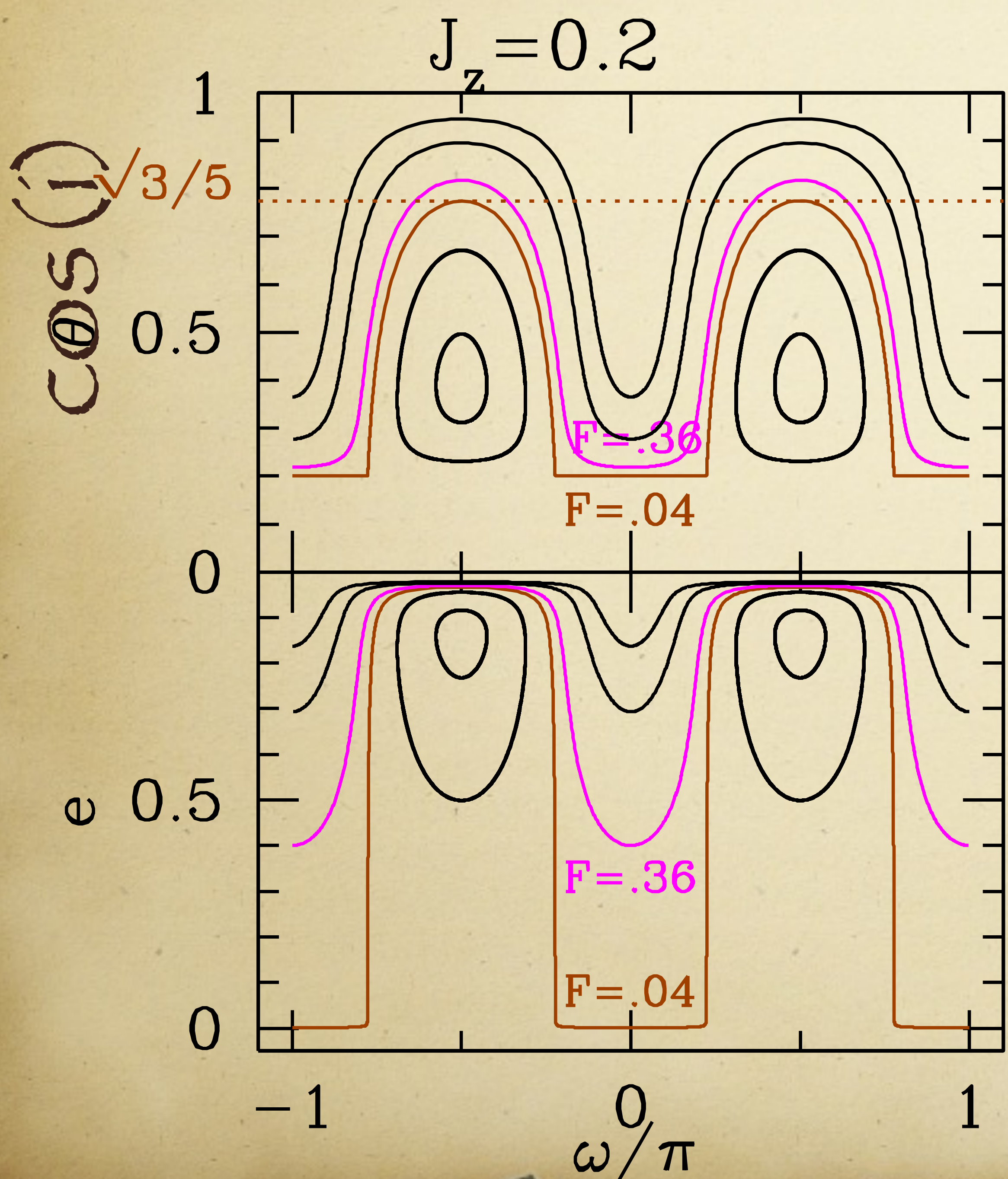


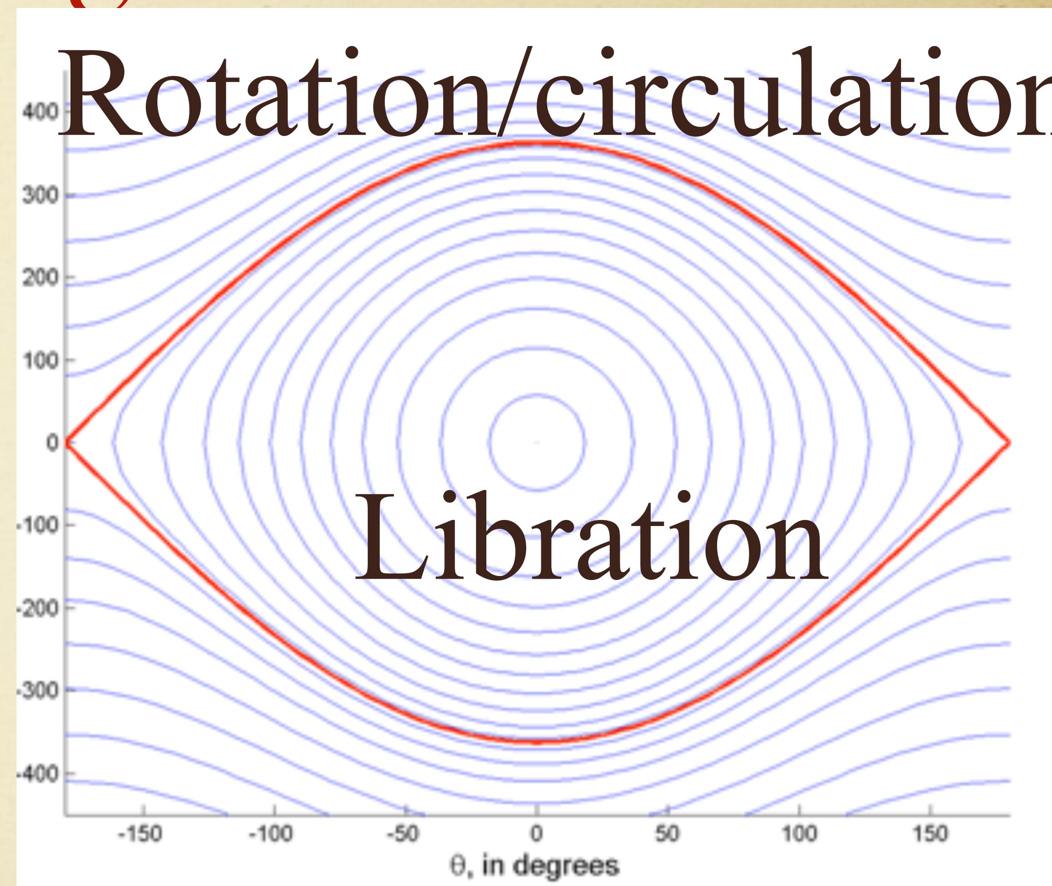
circular outer orbit

Lithwick & **Naoz** (2011), ApJ

Q: Why 40 - 140 degrees limits?

Quadrupole test particle limit:





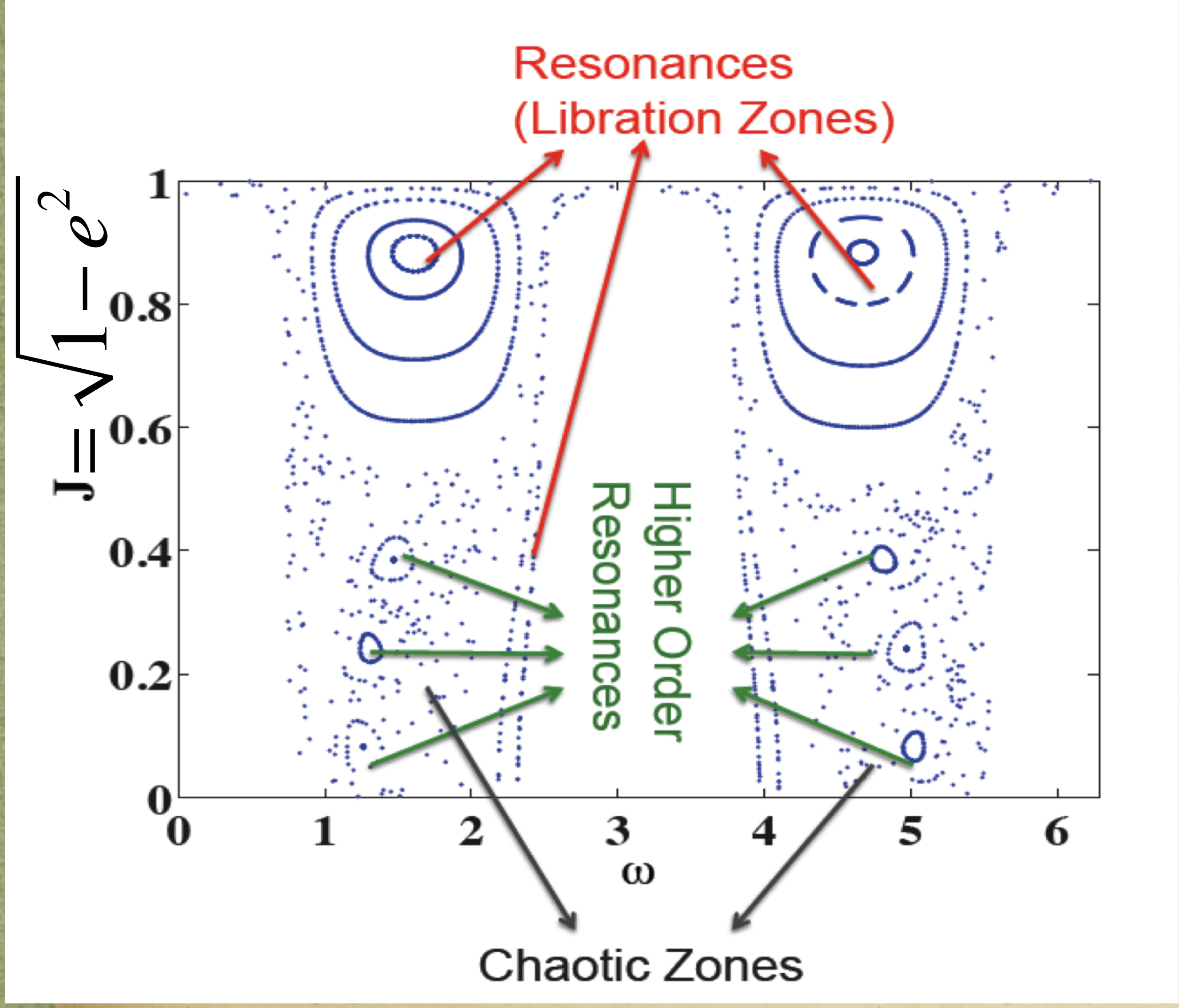
A: The separatrix has:

$$e_0 = 0, \cos i_0 = \sqrt{\frac{3}{5}}$$

Lithwick & **Naoz** (2011), ApJ

Q: Is the 40 - 140 degrees limits hold?

A: No



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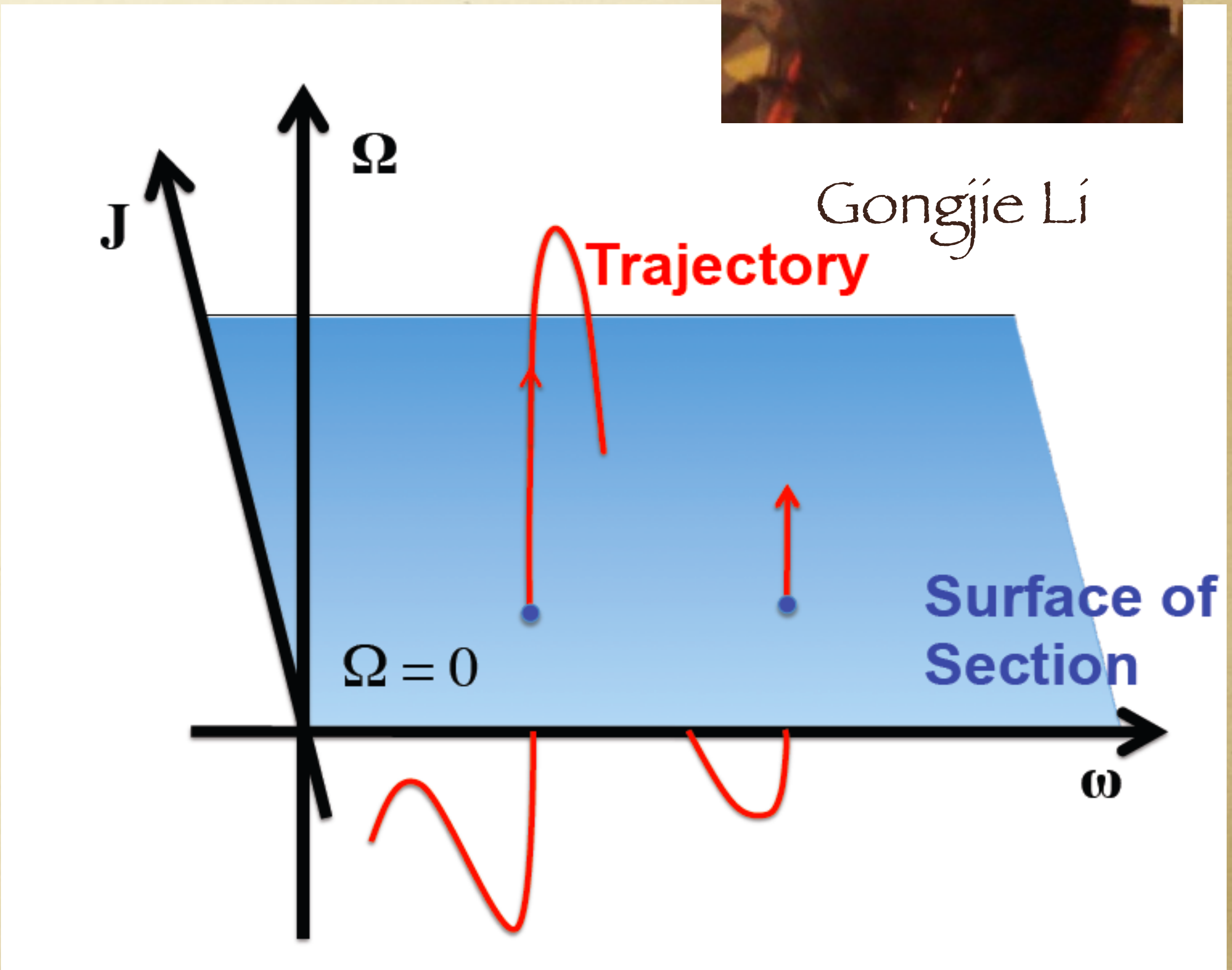

Li, **Naoz,** Kocsis, Loeb 2014, ApJ arXiv:1310.6044

Li, **Naoz,** Holman, Loeb 2014, ApJ arXiv:1405.0494

Q: Is the 40 - 140 degrees limits hold?

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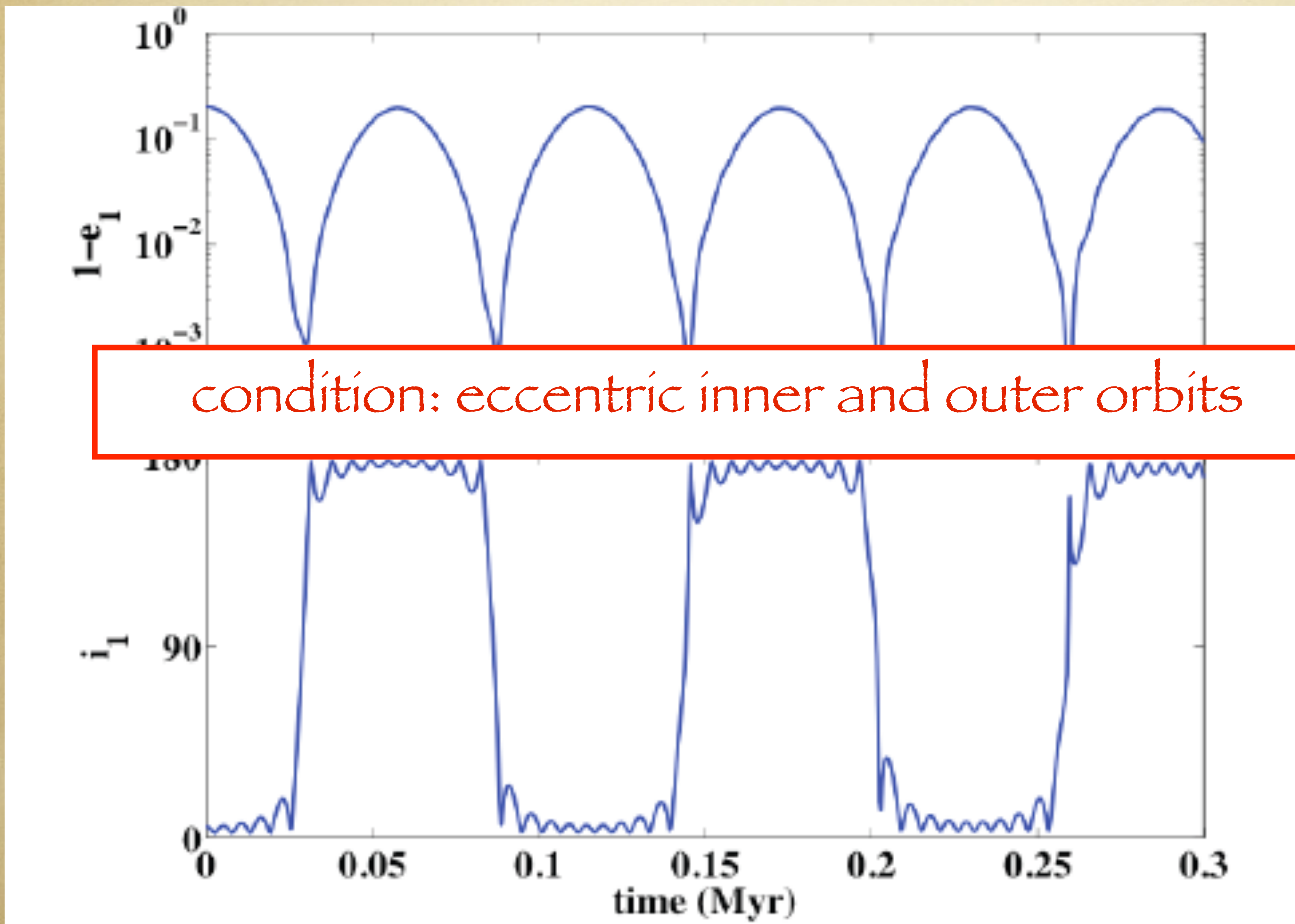

condition: eccentric inner and outer orbits

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$\omega_1 = 0^\circ, \Omega_1 = 180^\circ,$

$e_2 = 0.6, a_1 = 4AU, a_2 = 50AU$

$e_1 = 0.8, i = 5^\circ$

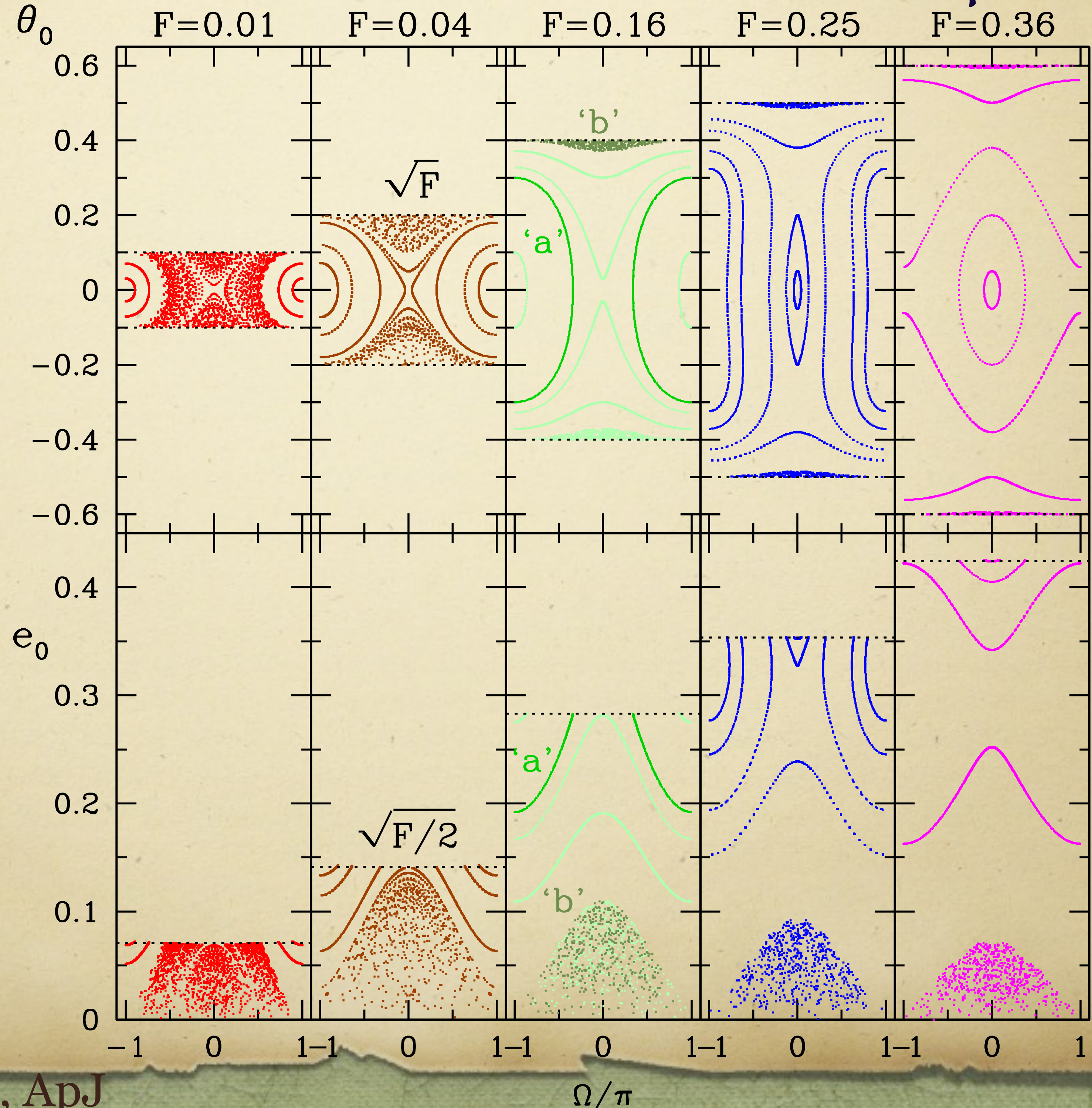
$m_1 = 1M_\odot, m_2 = 1M_J, m_3 = 0.3M_\odot$

Li, **Naoz,** Kocsis, Loeb 2014, ApJ arXiv:1310.6044

Li, **Naoz,** Holman, Loeb 2014, ApJ arXiv:1405.0494

Q: Why Chaos?

A: Octupole - chaotic behavior crossing the separatrix



chaos in these systems:Holman, Touma & Tremaine (1997)

Lithwick & **Naoz** (2011), ApJ

Maximum eccentricity and initial conditions

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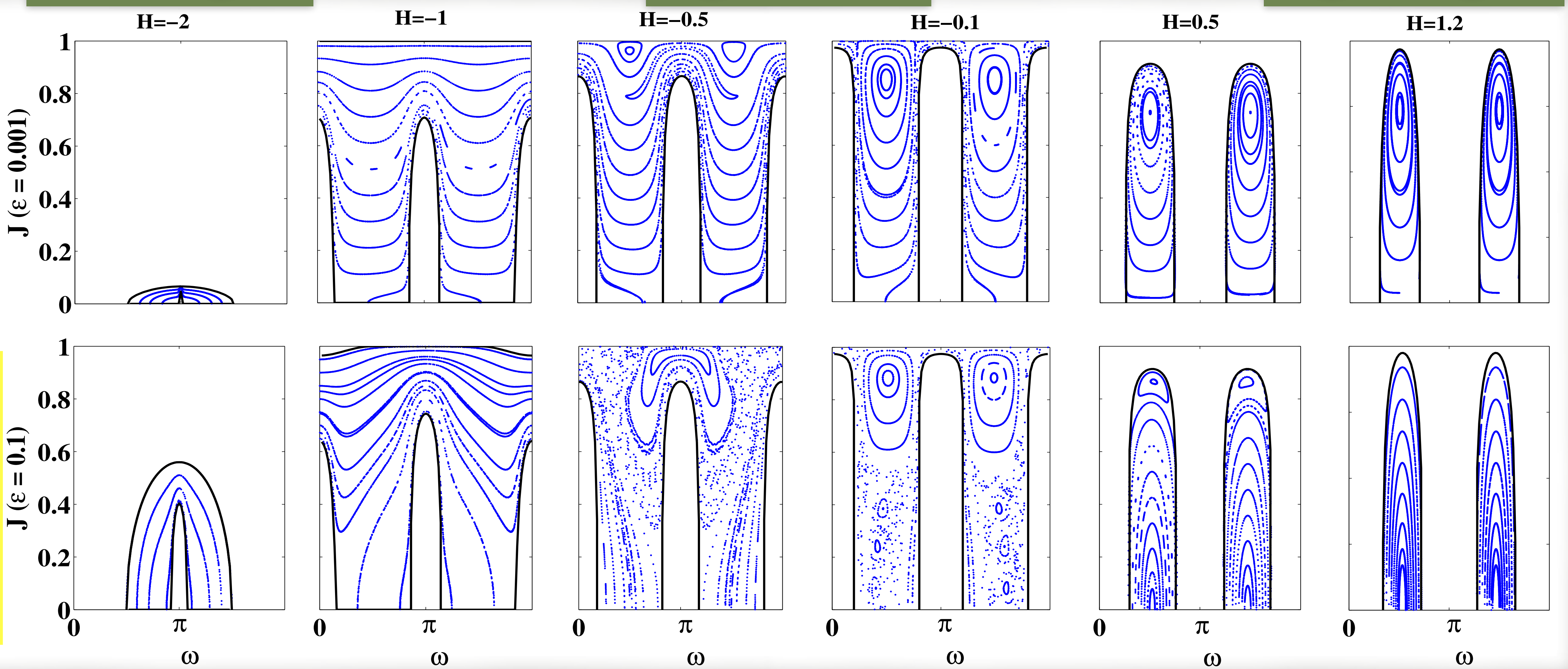
Low i High e

High i Low e

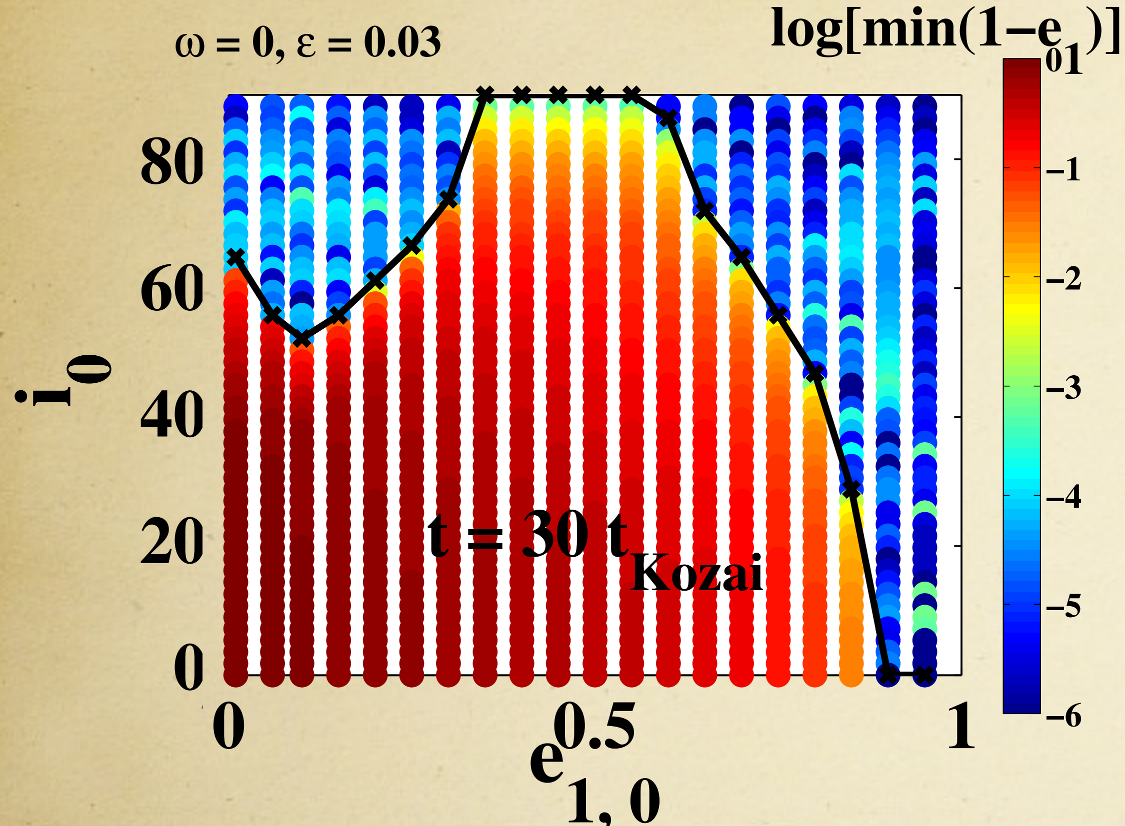
High i High e



octupole plays important role

Li, **Naoz,** Holman, Loeb 2014, ApJ, arXiv:1405.0494

Eccentricity spikes



Maximum eccentricity at the test particle regime

Li, **Naoz** et al, (2014), ApJ 785, 116 + ApJ 791, 86

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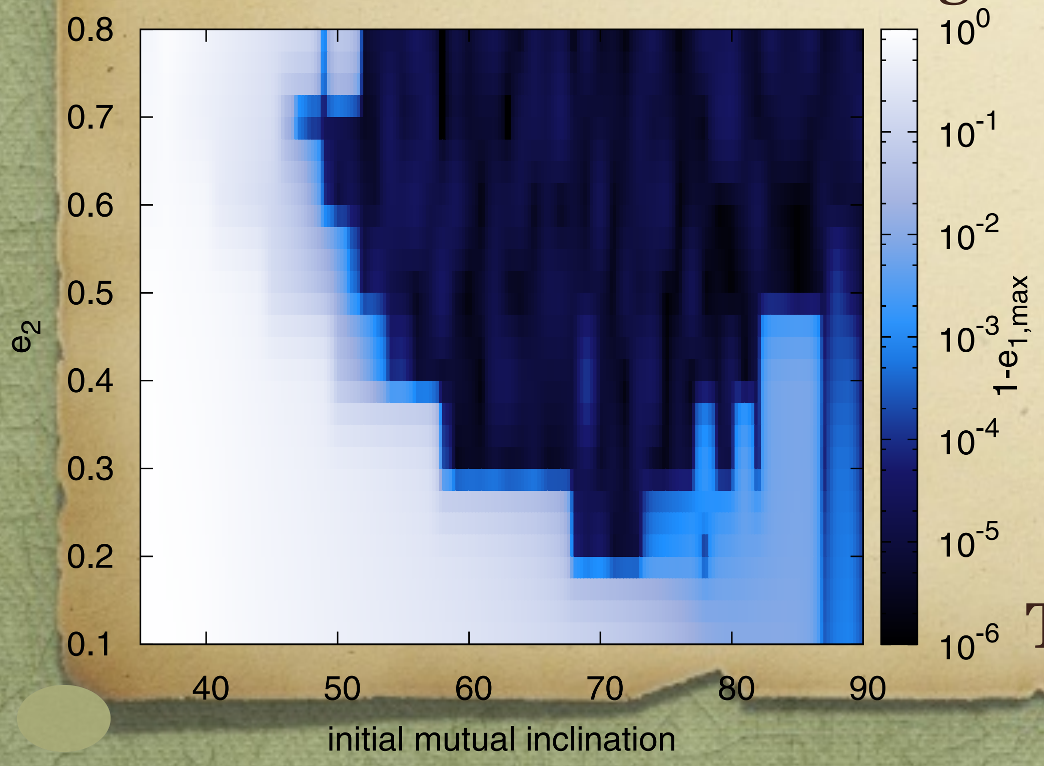
Maximum eccentricity outside the test particle regime



Ian Lizarraga

Jean Teyssandier

Teyssandier, **Naoz**, Lizarraga Rasio (2013), ApJ 779, 166

Astrodynamics is alive!