Suppression of extreme orbital evolution in triple systems with short-range forces

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Triple systems

- Three-body systems are ubiquitous in astrophysics ~25%

  ---Planet-satellite systems

  ---Exoplanet systems (Hot jupiters)

  ---Black holes in dense stellar clusters

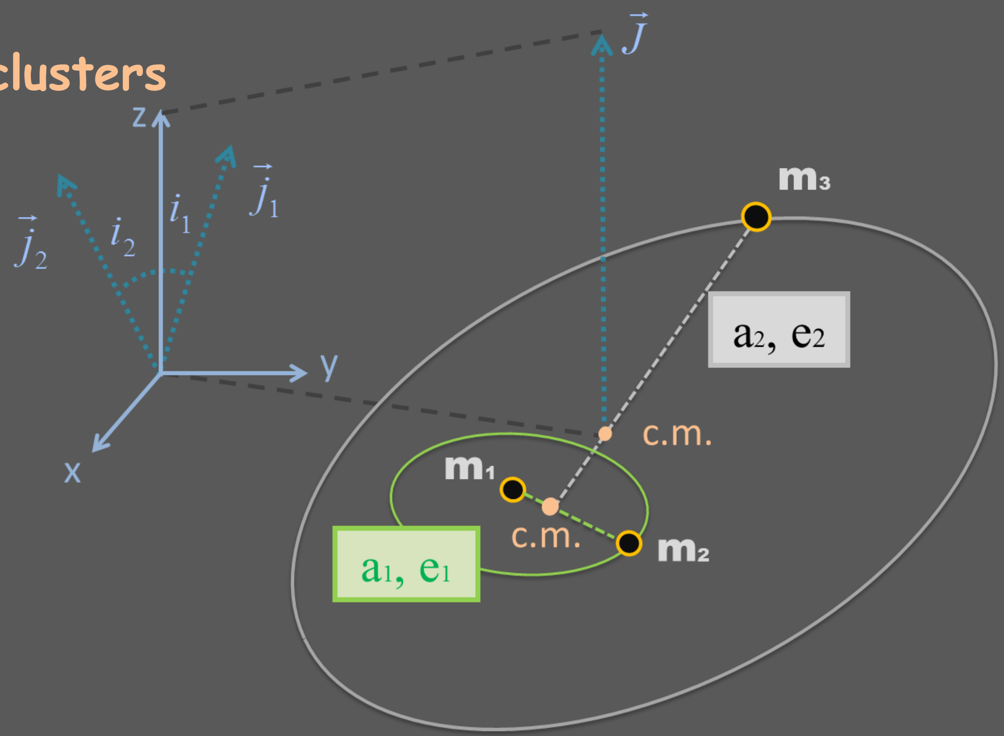
  …

- Hierarchical triple

  ---Inner binary

  ---Outer binary

  ---Stable



Lidov-Kozai oscillations

Hamiltonians

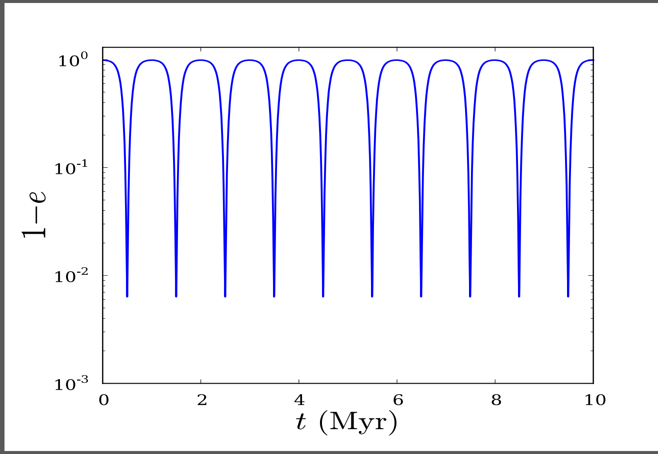
Theory

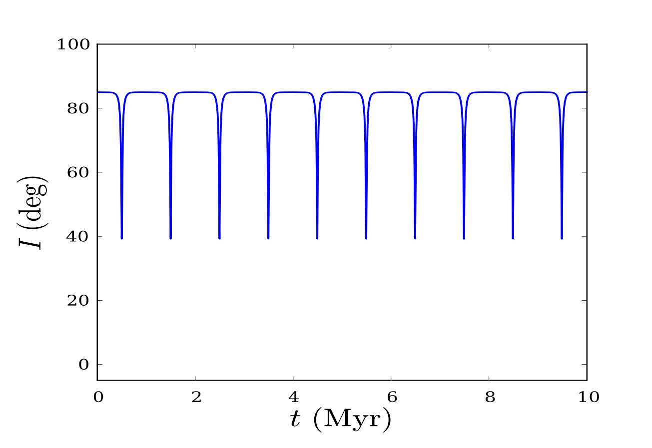
$$
\begin{cases}
H = -\dfrac{Gm_1m_2}{2a_1} - \dfrac{Gm_3(m_1+m_2)}{2a_2} + \Phi \\
\Phi = -\dfrac{G}{a_2}\displaystyle\sum_{l=2}^{\infty}\left(\dfrac{a_1}{a_2}\right)^l m_1m_2m_3 \dfrac{m_1^{l-1} - (-m_2)^{l-1}}{(m_1+m_2)^l}\left(\dfrac{r_1}{a_1}\right)^l \left(\dfrac{a_2}{r_2}\right)^{l+1} P_l(\cos\theta)
\end{cases}
$$

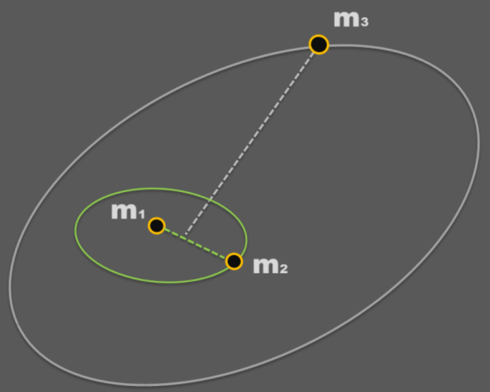
---Eccentricity and inclination oscillations induced if $i > 40°$

---If i large (85-90 degrees), get extremely large eccentricities ($e > 0.99$)

Orbital (secular) evolution





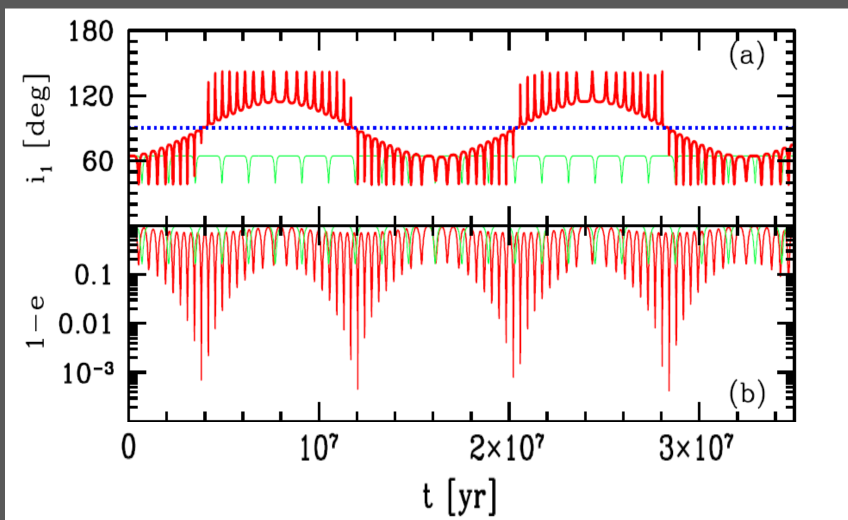


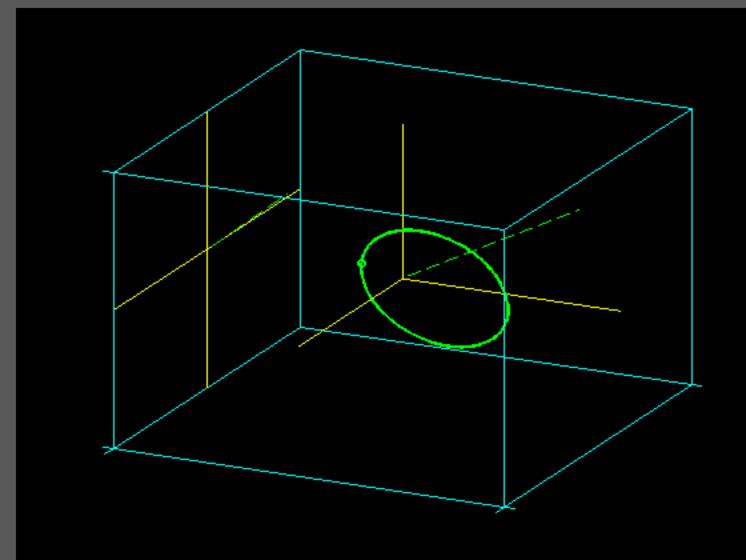
Lidov-Kozai oscillations (Octupole)

- **Orbital evolution**
  e.g. Ford et al 2000; Naoz et al 11; Katz et al 11;
  Lithwick & Naoz 11; Li et al 14; Petrovich 15; Antognini 15

Edit: Naoz

Naoz et al 11

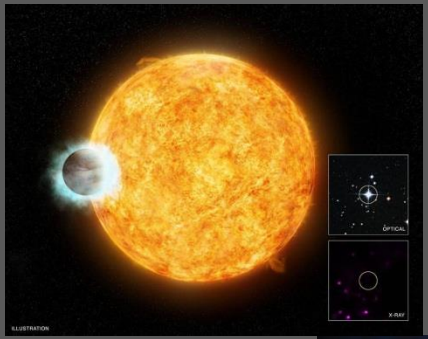




- **Octupole effect**
  --- Very large ***e*** even for modest *i*
  --- L_p can flip with respect to the outer binary

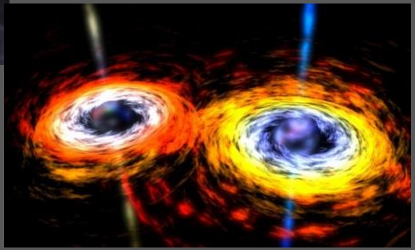
Applications

- The excitation of eccentricities of **exoplanet** systems and the formation of **HJ** through high-eccentricity migration



- The production of **Type Ia supernovae** from white-dwarf binary mergers or direct collisions

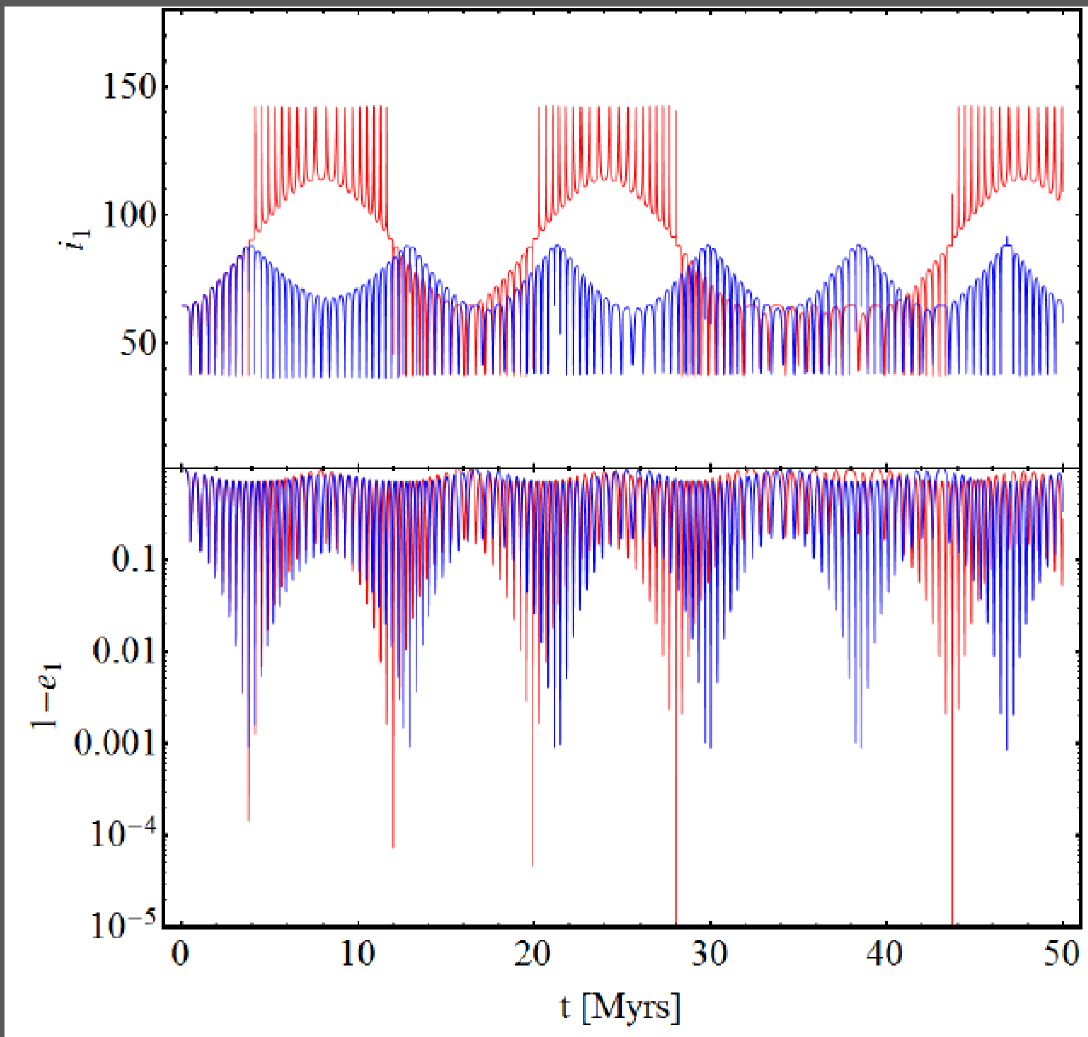
- The formation and merger of **stellar black hole binaries** at the centers globular clusters or galaxies



- The formation and merger of **supermassive black hole binaries**

Short-Range Forces

$m_0=1M_{sun}$, $m_1=1M_J$, $m_3=0.04M_{sun}$, $e_1=0.001$, $e_2=0.6$
$a_1=6$ AU, $a_2=100$ AU



- **Includes:**

(1) precession of periapse (GR)

(2) tidal bulge of the planet induced by the star

(3) planet oblateness (rotation)

- **Effects:**

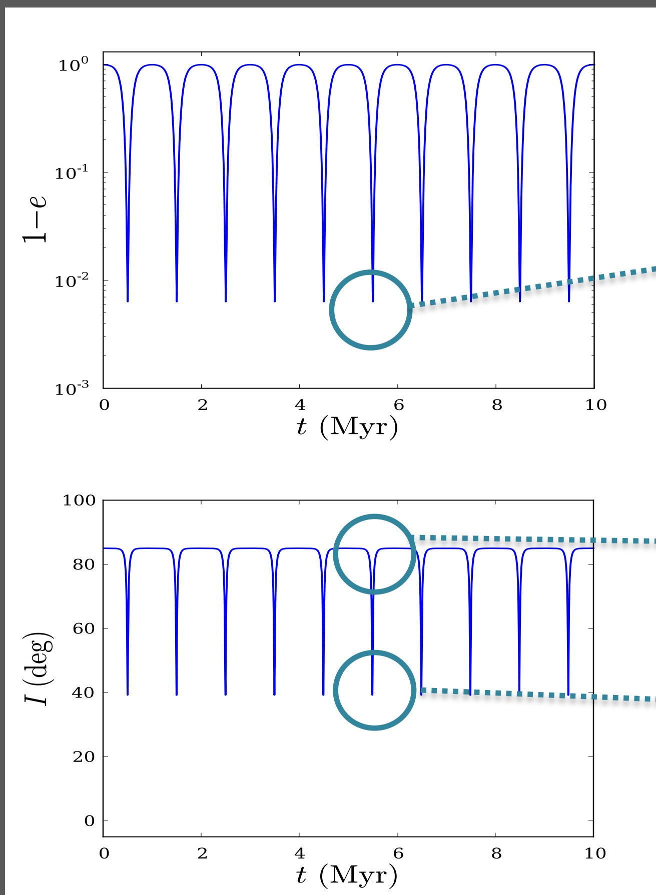
(1) e_{max} is reduced/limited

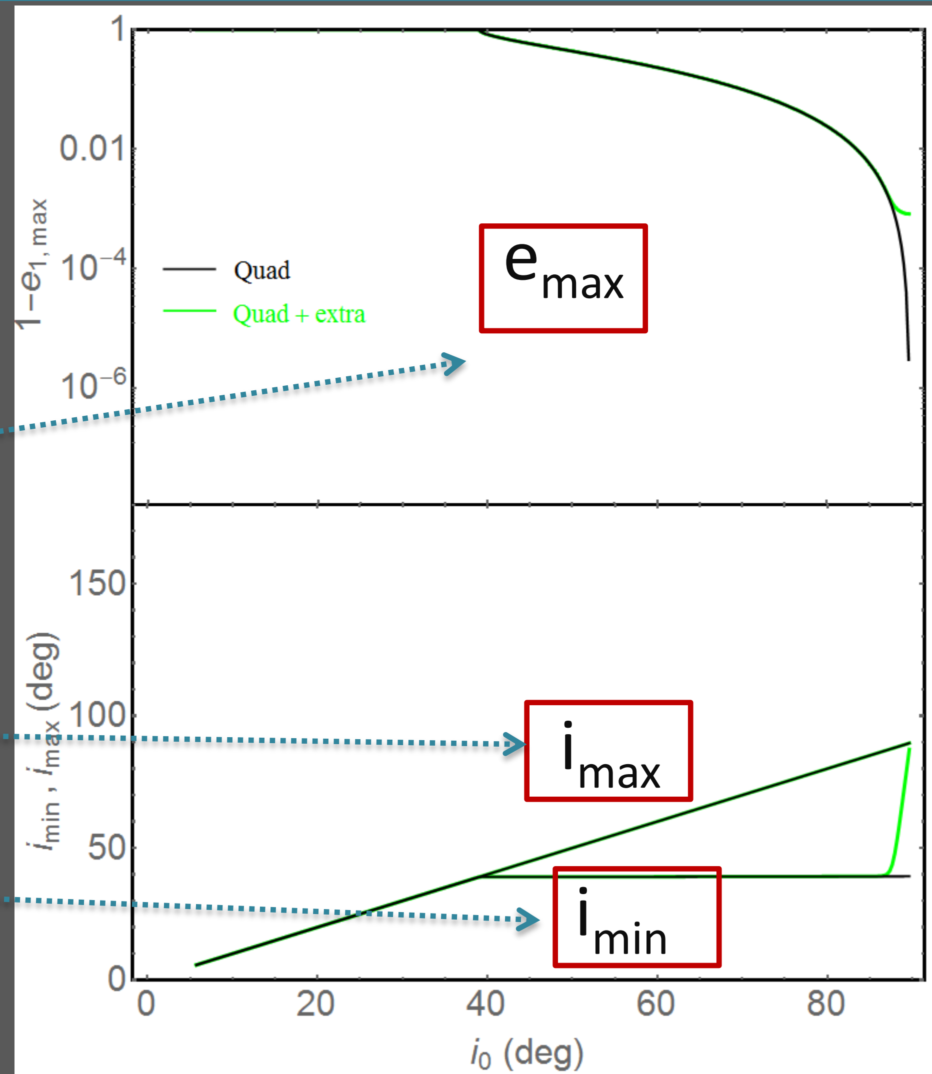
(2) flip is delayed/suppressed

Parameter Survey

m_0=1M_{sun}, m_1=1M_J, m_3=0.04M_{sun}, e_1=0.001, e_2=0.6
a_1=6 AU, a_2=100 AU

- We setup each system by varying the **initial inclination**





Parameter Survey

m_0=1M_{sun}, m_1=1M_J, m_3=0.04M_{sun}, e_1=0.001, e_2=0.6
a_1=6 AU, a_2=100 AU

- **Turn on Octupole →**

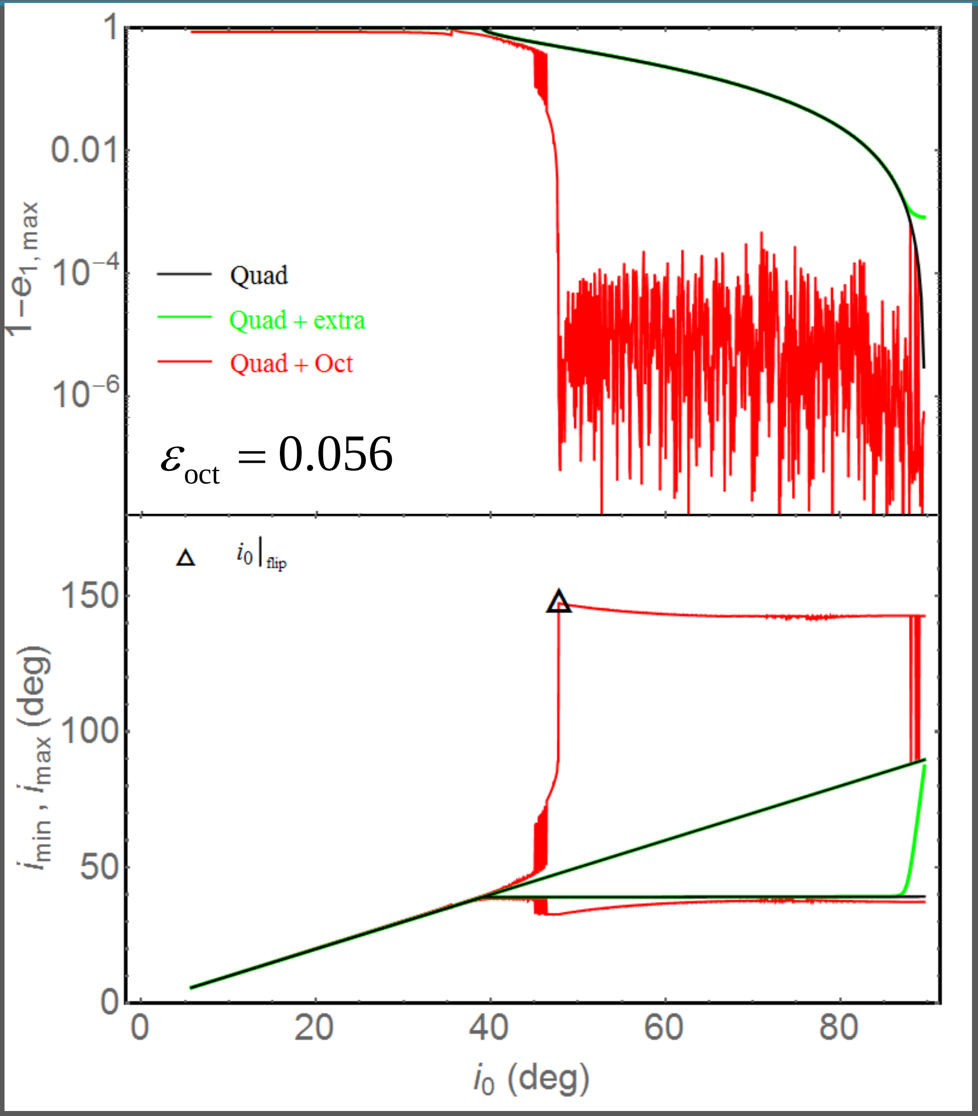
$$\varepsilon_{oct} = \frac{a_1}{a_2}\frac{e_2}{1-e_2^2}$$

Strength of the octupole potential relative to the quadrupole

- **We find →**

--- Very large *e* even for modest *I*

--- L_p can flip with respect to outer binary



Suppression of extreme orbital evolution

- **Turn on SRF →** $\varepsilon_{\rm SRF}$

relative strength of the SRF potential

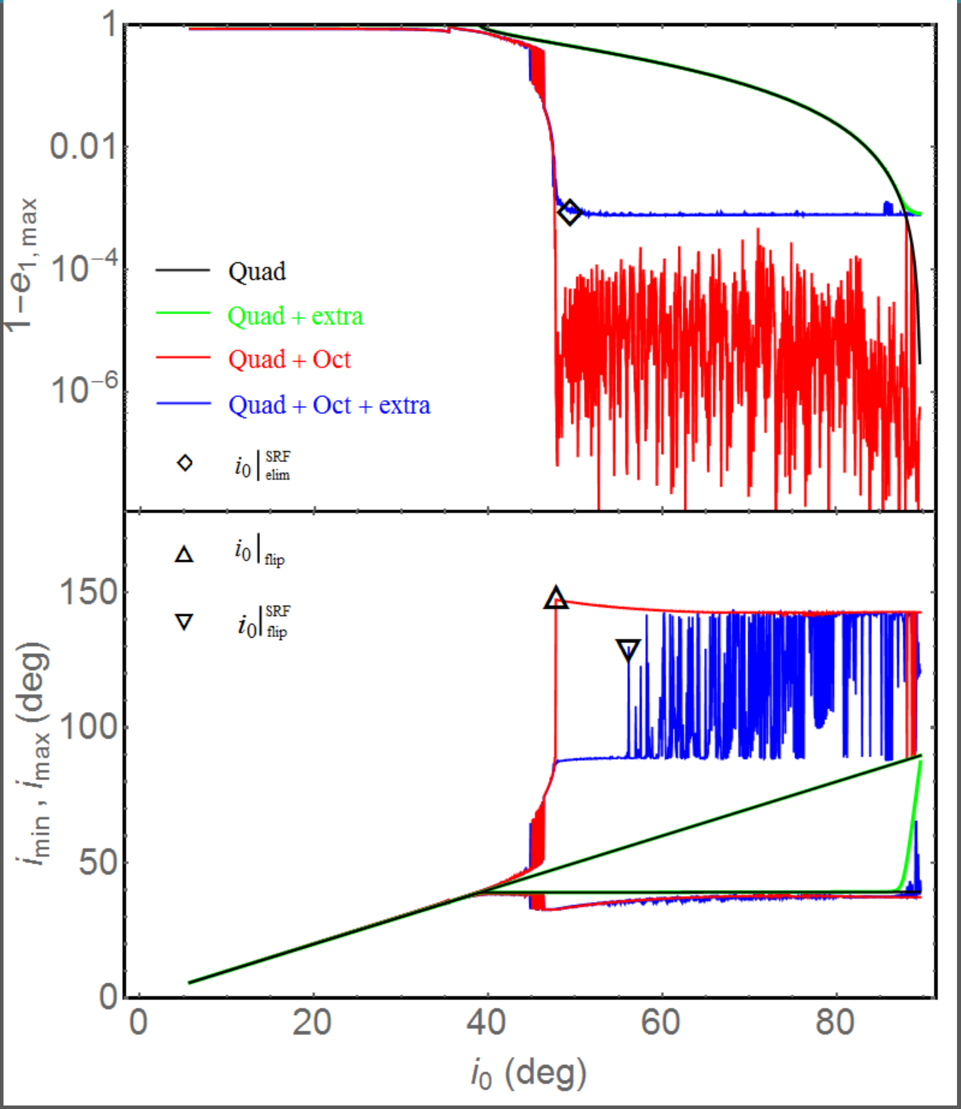
PRM.	$\varepsilon_{\rm Oct}$	$\varepsilon_{\rm GR}$	$\varepsilon_{\rm Tide}$	$\dot{\omega}_{\rm GR}/\dot{\omega}_{\rm K}$	$\dot{\omega}_{\rm Tide}/\dot{\omega}_{\rm K}$
case	0.056	2.93×10^{-4}	1.32×10^{-12}	6.86×10^{-3}	7.28

--- e_{max} is reduced/limited

--- flip is delayed/suppressed

- **Limiting Eccentricity** (analytic) regardless of octupole strength

$$\left[\frac{\dot{\omega}_{\rm GR}}{\dot{\omega}_{\rm K}}+\frac{1}{15}\frac{\dot{\omega}_{\rm Tide}}{\dot{\omega}_{\rm K}}f\left(e_1\right)+\frac{1}{3}\frac{\dot{\omega}_{\rm Rot}}{\dot{\omega}_{\rm K}}\right]_{e_1=e_{\rm lim}}=\frac{9}{8}e_{\rm lim}^2$$



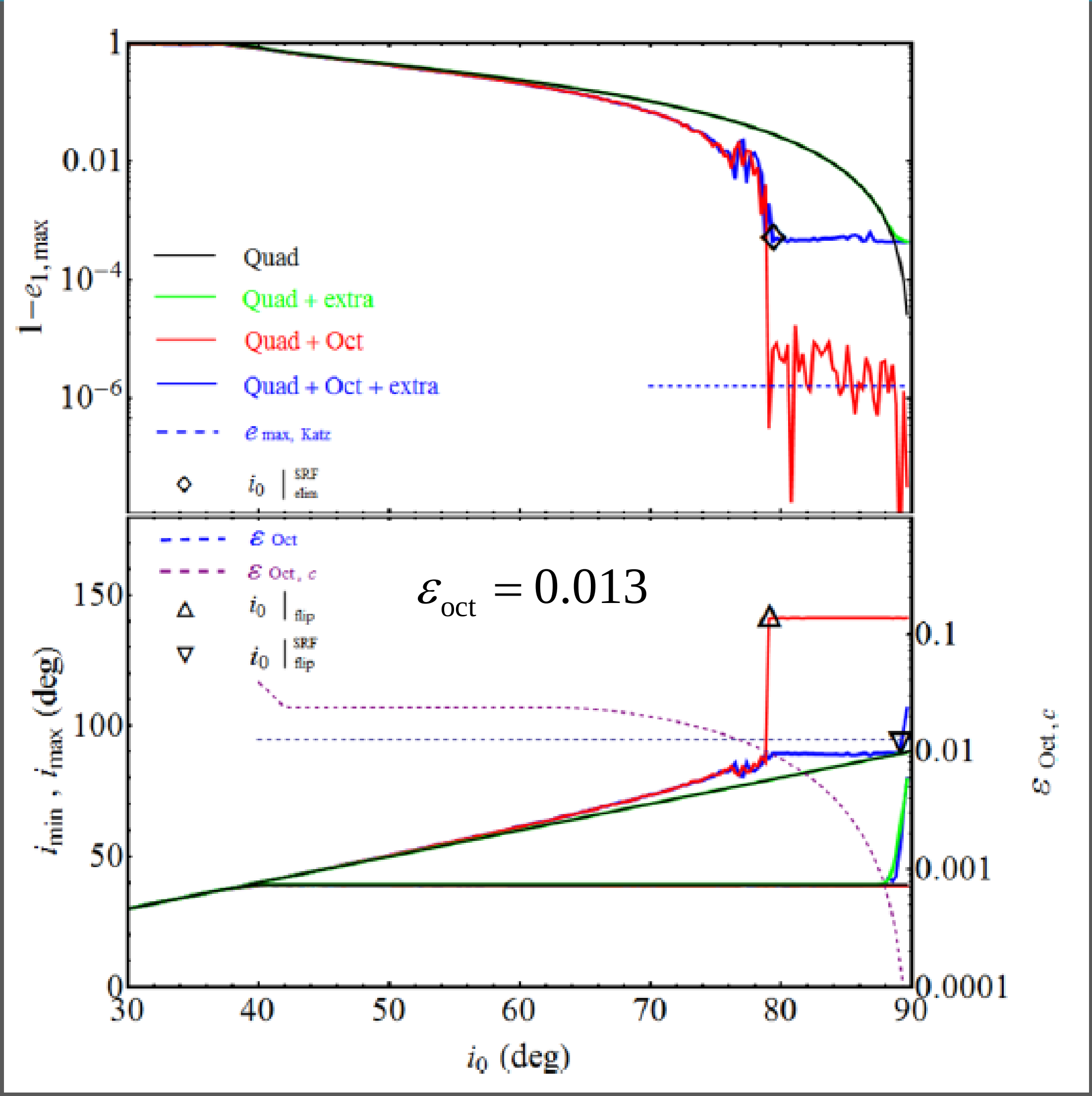
Suppression of extreme orbital evolution

- **Smaller** ε_{oct}

ε_{Oct}	ε_{GR}	ε_{Tide}	$\dot{\omega}_{GR}/\dot{\omega}_{K}$	$\dot{\omega}_{Tide}/\dot{\omega}_{K}$
0.013	2.15×10^{-5}	9.12×10^{-14}	6.74×10^{-4}	7.32

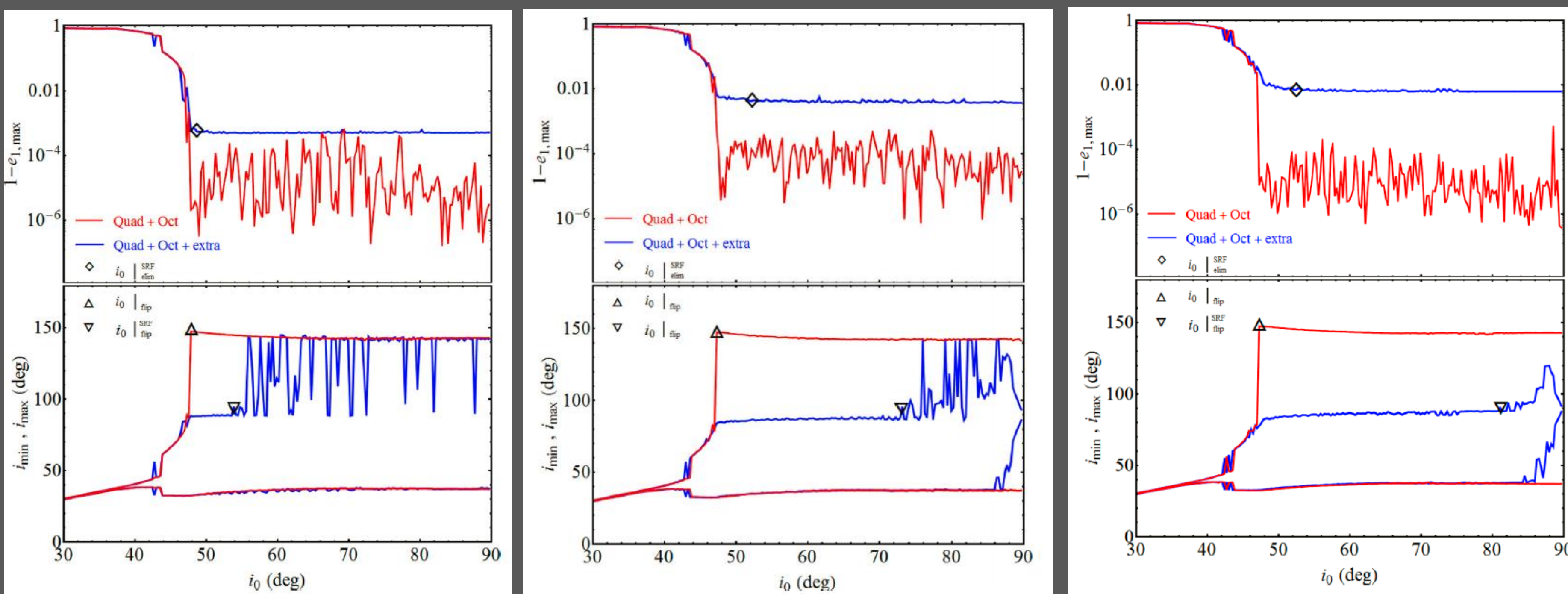
--- window of influence (initial inclinations) become narrow

m_0=1M_{sun}, m_1=1M_J, m_3=1M_{sun}
e_1=0.001, e_2=0.2
a_1=6 AU, a_2=100 AU



Suppression of extreme orbital evolution

- **The relative strength of the SRF become stronger**



m_0=1M_{sun}, m_1=1M_J, e_1=0.001, e_2=0.8

PRM.	ε_{GR}	ε_{Tide}	m_3	a_1	a_2
a	3.96×10^{-5}	1.79×10^{-13}	1	6	200
b	2.37×10^{-4}	1.39×10^{-9}	1	1	33.33
c	2.37×10^{-3}	1.39×10^{-8}	0.1	1	33.33

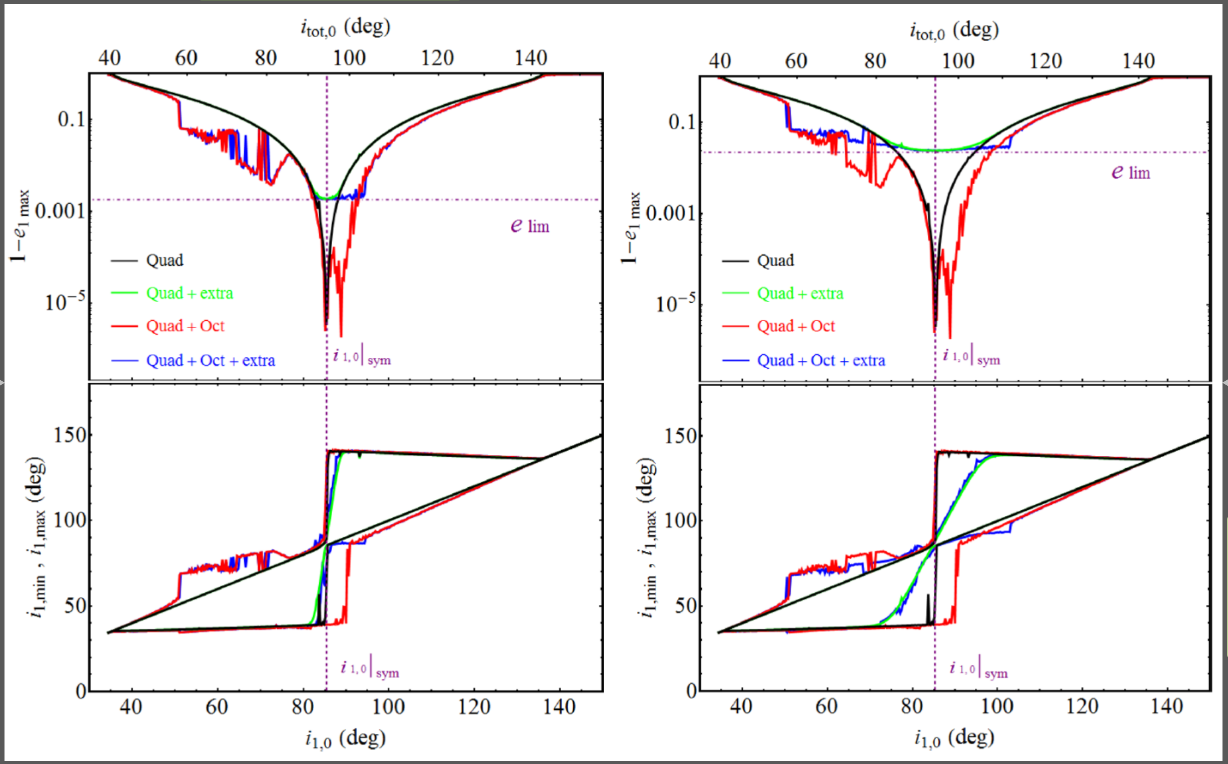
--- window of "flips" become narrow

Parameter Survey

- Comparable-mass cases: (BH/NS/WD/Main sequence star binary)

ε_{Oct}	ε_{GR}	ε_{Tide}	a_1(au)	a_2(au)	$e_{2,0}$	$m_1(M_\odot)$	$m_2(M_\odot)$	$R_1(R_\odot)$
0.022	4.33×10^{-5}	4.00×10^{-11}	1	10	0.5	0.5	1	0.5
0.022	4.33×10^{-5}	4.00×10^{-6}	1	10	0.5	0.5	1	5

$\varepsilon_{oct} = 0.022$



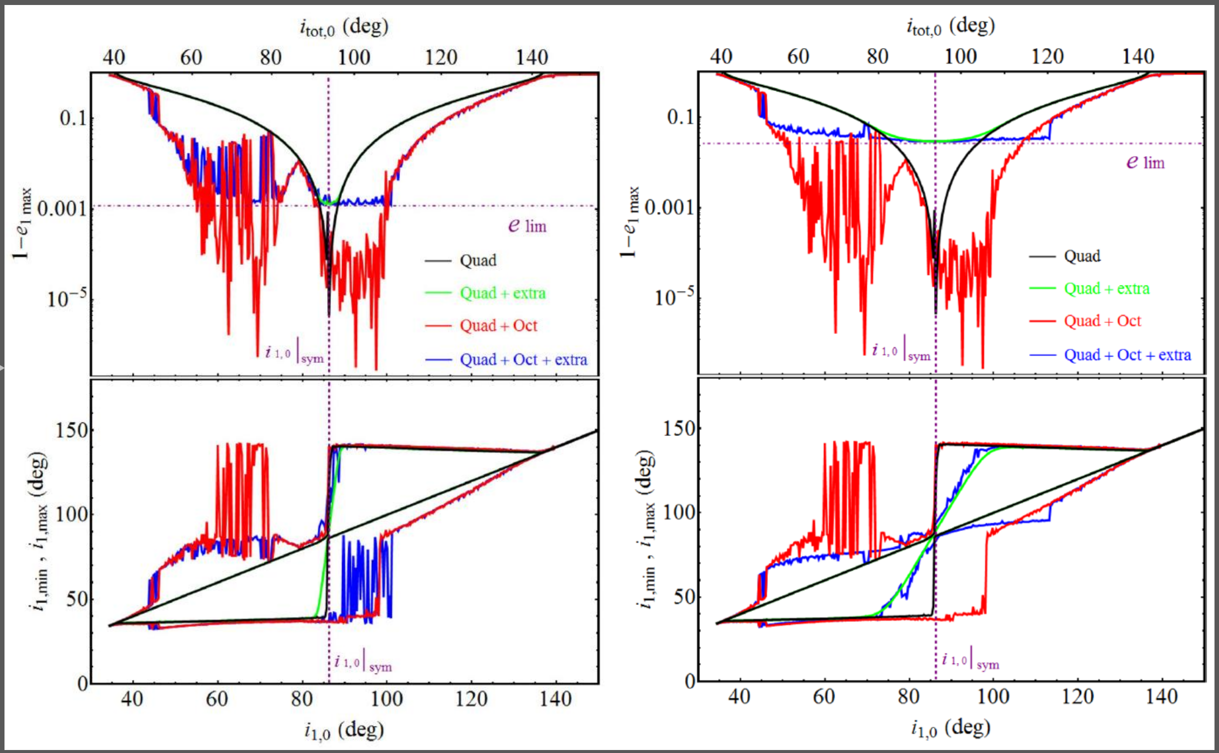
symmetry of eqs. is broken

Parameter Survey

- Comparable-mass cases: (BH/NS/WD/Main sequence star binary)

$\varepsilon_{\rm Oct}$	$\varepsilon_{\rm GR}$	$\varepsilon_{\rm Tide}$	a_1(au)	a_2(au)	$e_{2,0}$	$m_1(M_\odot)$	$m_2(M_\odot)$	$R_1(R_\odot)$
0.042	5.53×10^{-5}	7.64×10^{-12}	1	12	0.6	0.3	0.8	0.3
0.042	5.53×10^{-5}	9.83×10^{-6}	1	12	0.6	0.3	0.8	5

$\varepsilon_{\rm oct} = 0.042$



Conclusions

- The main contribution of the oct. terms to eccentricity and inclination excitation
  --- provides a "window of influence", the width of which grows with ε_{oct} (the importance of the octupole effects)

- The SRFs can indeed affect the orbital evolution in the oct. order

  --- impose a strict upper limit on the maximum achievable eccentricity (regardless of octupole strength)

  Combining the further studies in Kassandra R.A.+16,17, most of the properties of Oct. Kozai dynamics can be understood analytically

  --- With increasing strength of the SRFs, orbital flips are increasingly confined to the region close to I_0=90° (depends on ε_{SRF})

Thank you