Finale of a Quartet:
Hints on Supernova Formation

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Type *Ia* Supernovae

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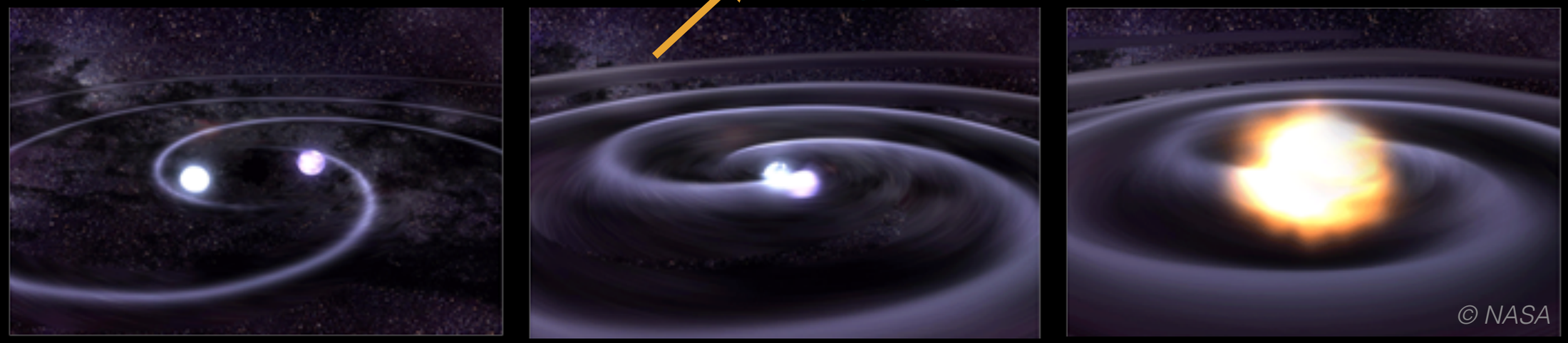
We Know:

- Standard candles
- Thermonuclear explosion of WD matter

We don’t know how they form

How Do Type Ia Supernovae Form?

WD+WD?



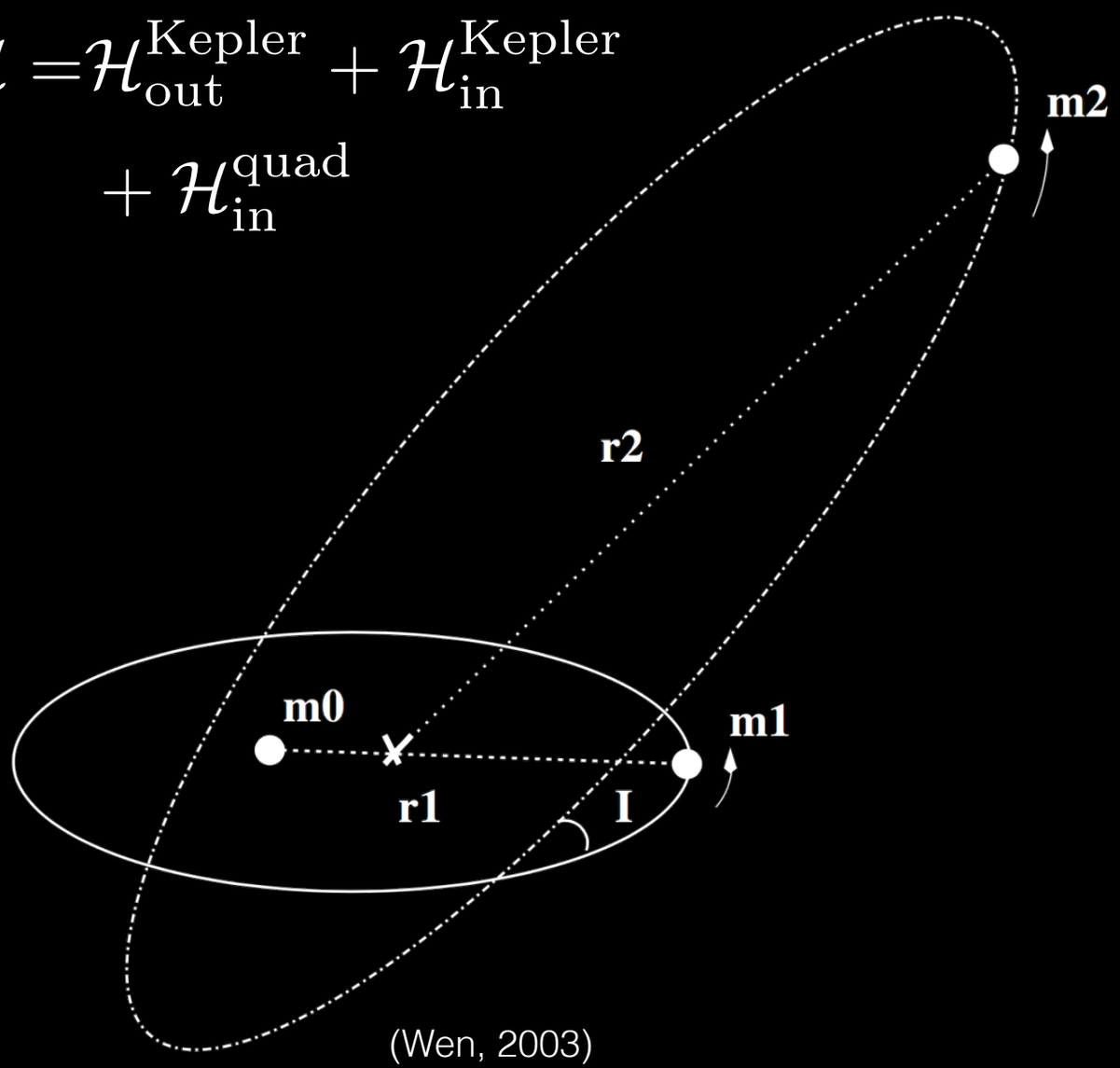
For $t_{\rm merge}<t_{\rm H}$, require $P<0.3$ day for $0.7+0.7 M_\odot$

Question: How to produce compact WD binaries?

Proposal: Triple System

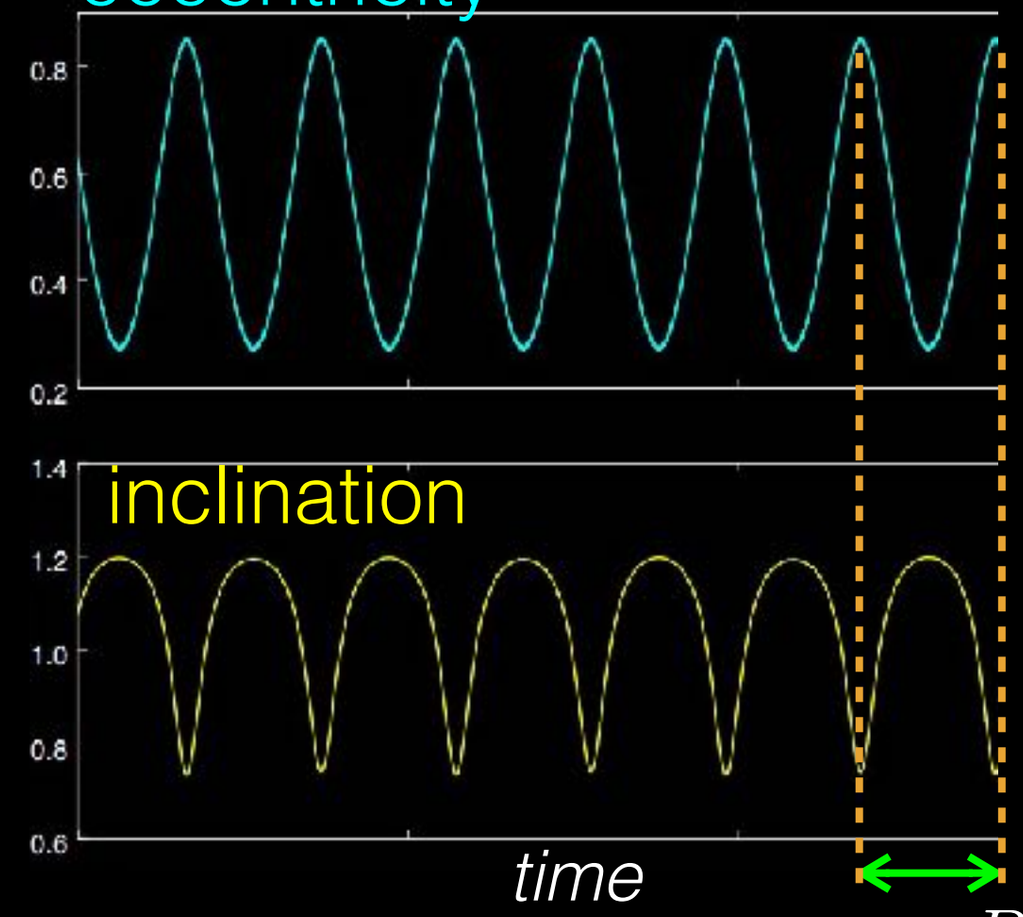
Quadrupole order, Secular

$$\mathcal{H} = \mathcal{H}_{\rm out}^{\rm Kepler} + \mathcal{H}_{\rm in}^{\rm Kepler} + \mathcal{H}_{\rm in}^{\rm quad}$$



(Wen, 2003)

Kozai-Lidov Mechanism

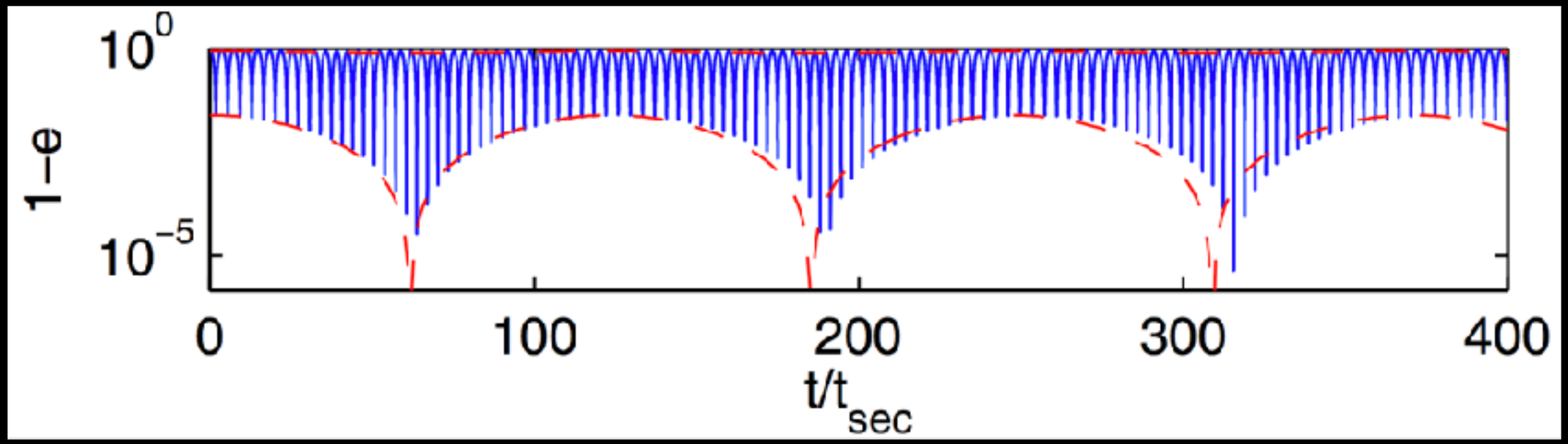


$$t_{\rm KL} \sim \frac{P_{\rm out}^2}{P_{\rm in}}$$

High eccentricity is possibly driven by a distant companion star!

Variants in Triples

- Higher Order Secular Effects

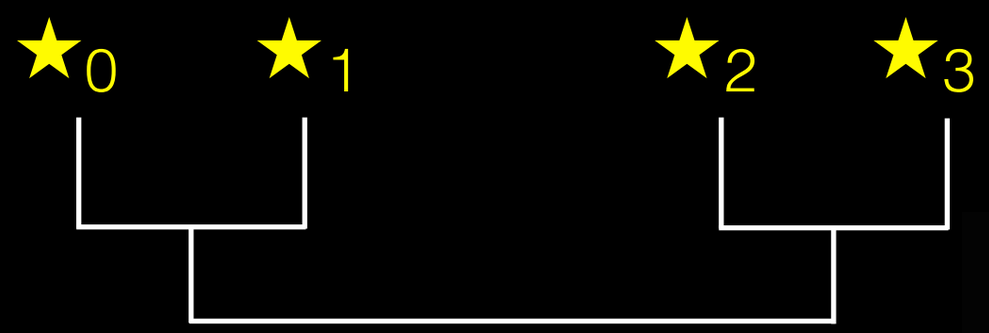


(Katz&Dong, 2011)

- Non-Secular Effects (*e.g.* Katz&Dong, 2012; Antognini *et al.* 2014)
- Mass Loss (*e.g.* Shappee&Thompson, 2012)
- …

Question Still Open

We Propose: Hierarchical Quadruple



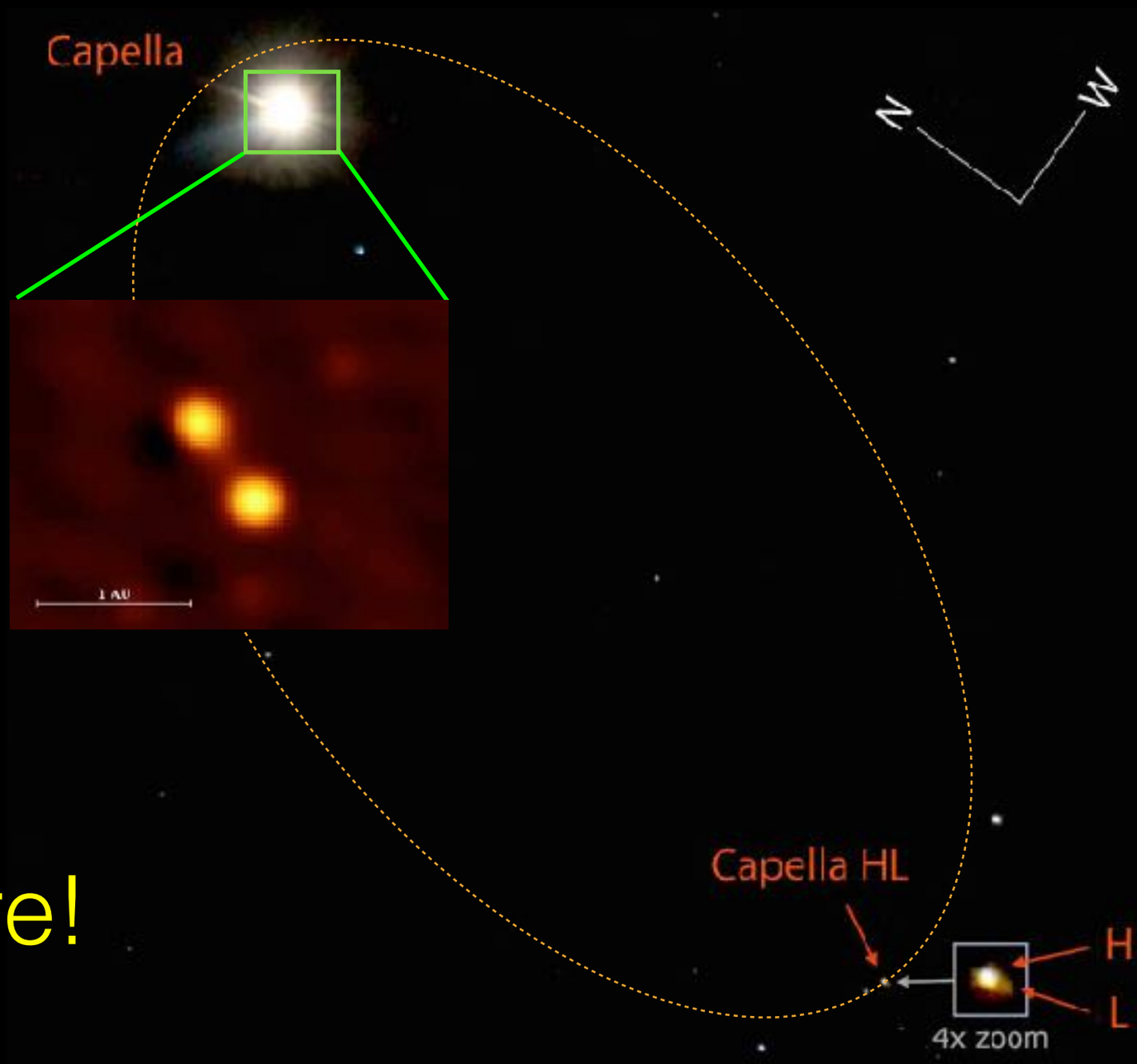
~33%: Binaries

~8%: Triples

~3%: Quadruples

(Raghavan *et al.* 2010)

They are NOT rare!



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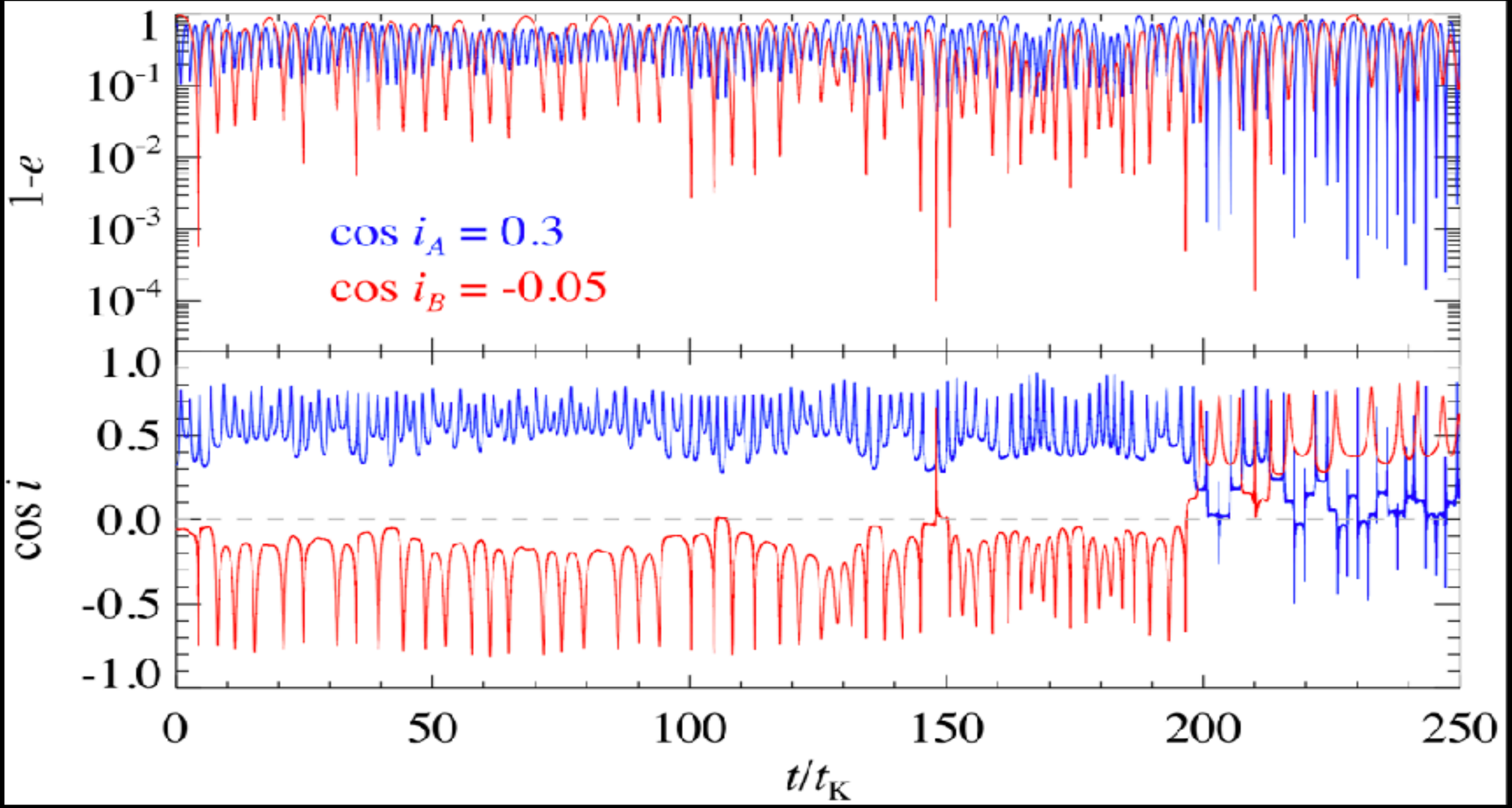
Why Quadruples?

N-body Simulations (Pejcha *et al*, 2013):



More DOF; can be irregular —> More Mergers?

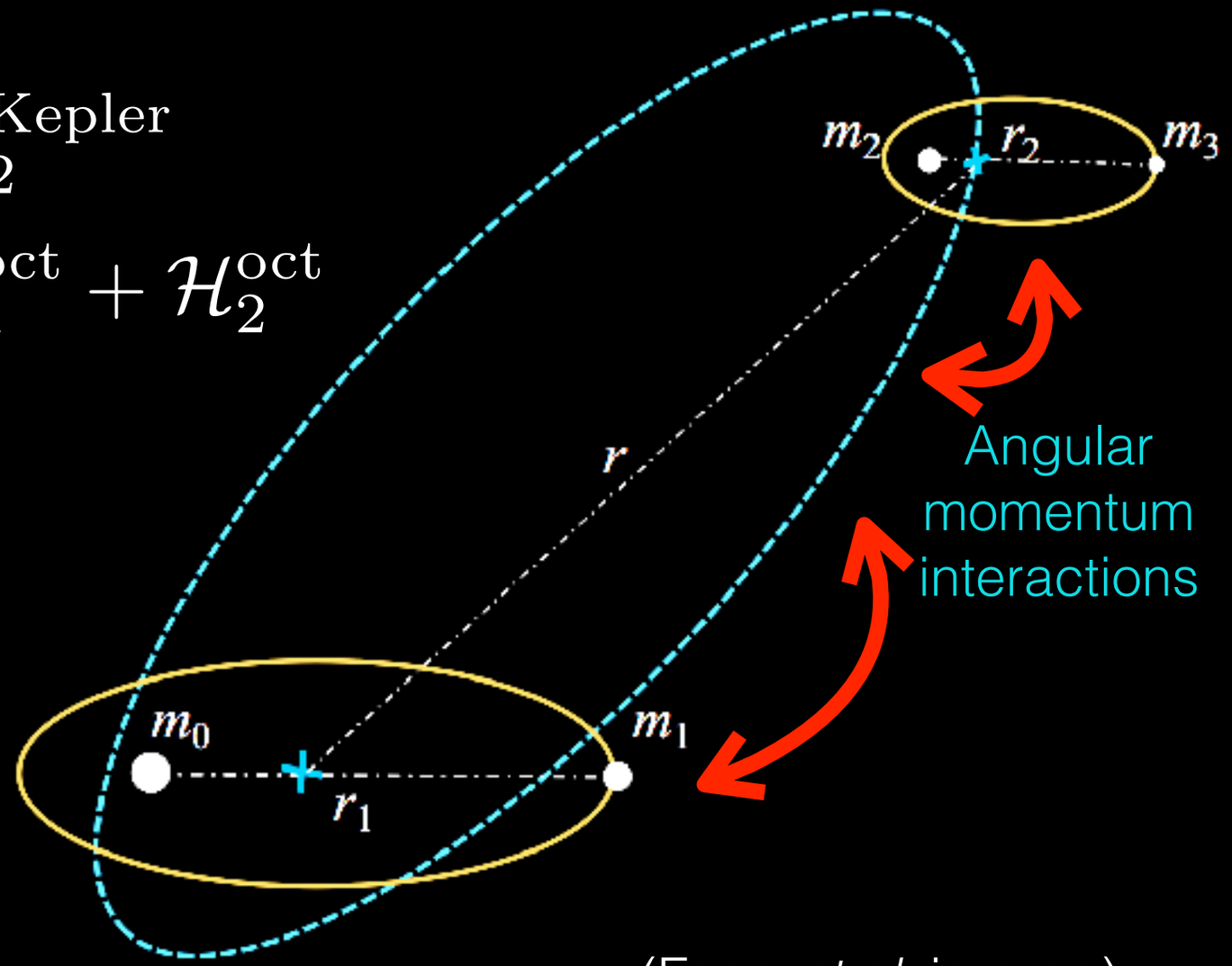
Secular Dynamics of Quads in a Nutshell

$$\mathcal{H} = \mathcal{H}^{\rm Kepler}_{\rm mutual} + \mathcal{H}^{\rm Kepler}_1 + \mathcal{H}^{\rm Kepler}_2 + \mathcal{H}^{\rm quad}_1 + \mathcal{H}^{\rm quad}_2 + \mathcal{H}^{\rm oct}_1 + \mathcal{H}^{\rm oct}_2 + \cdots$$

Orbital Averaging

Canonical Variables:
6 for each orbit

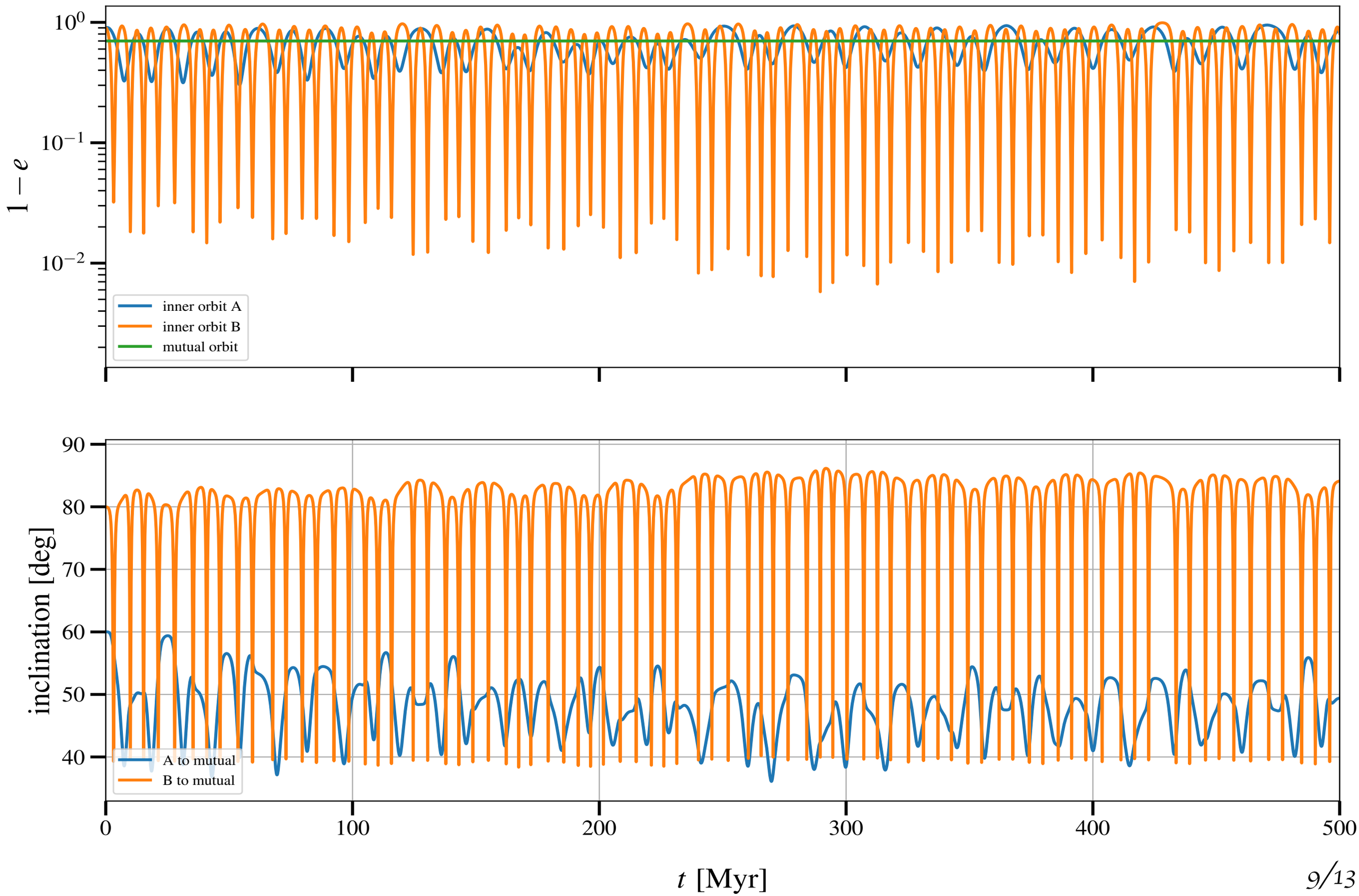
12 coupled secular EoMs in total!



(Fang *et al*, in prep)

[(Star+Star) + (Star+Star)]: Both irregular behavior

(Fang *et al*, in prep)



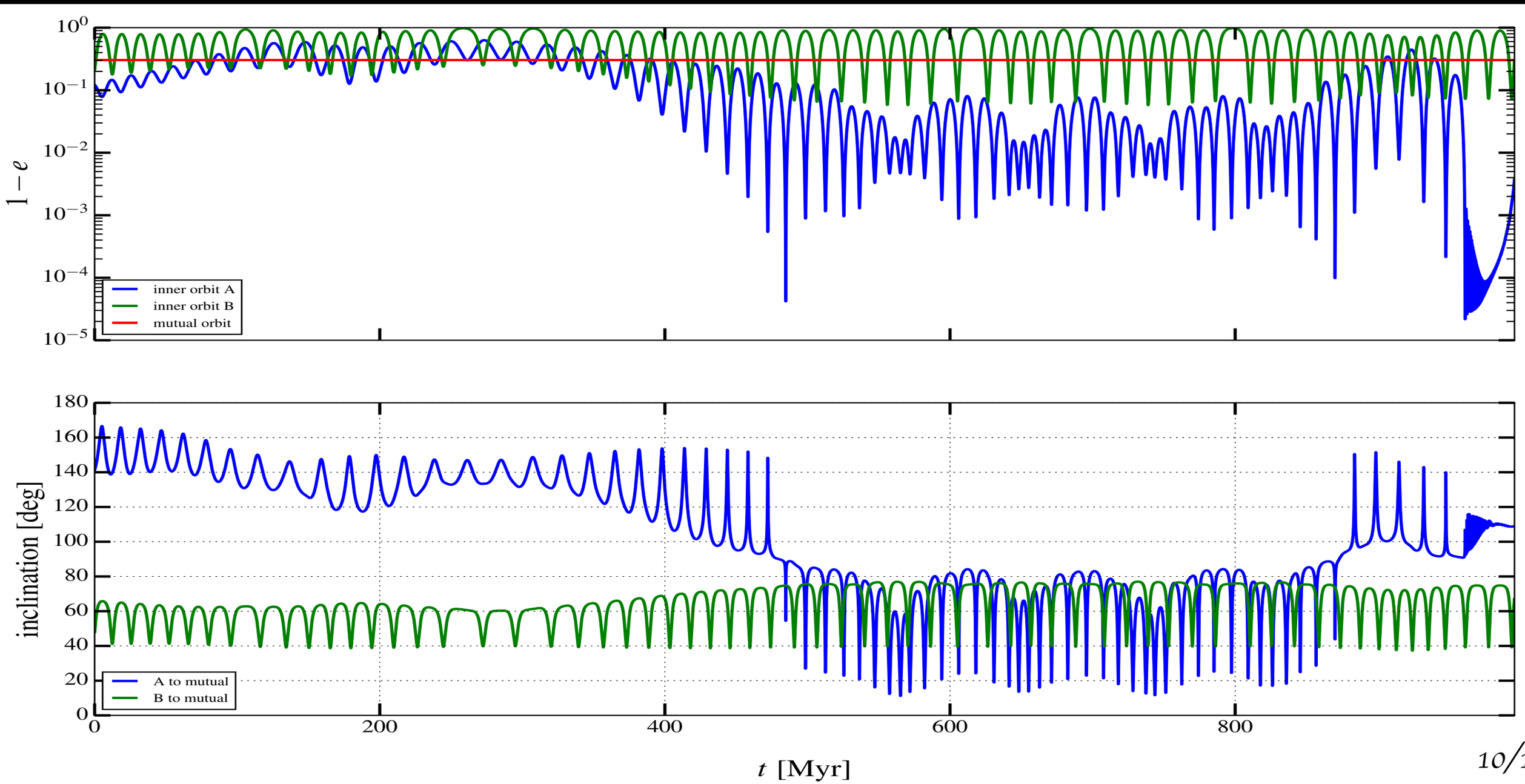
WD-WD in Quads

Effects Included:

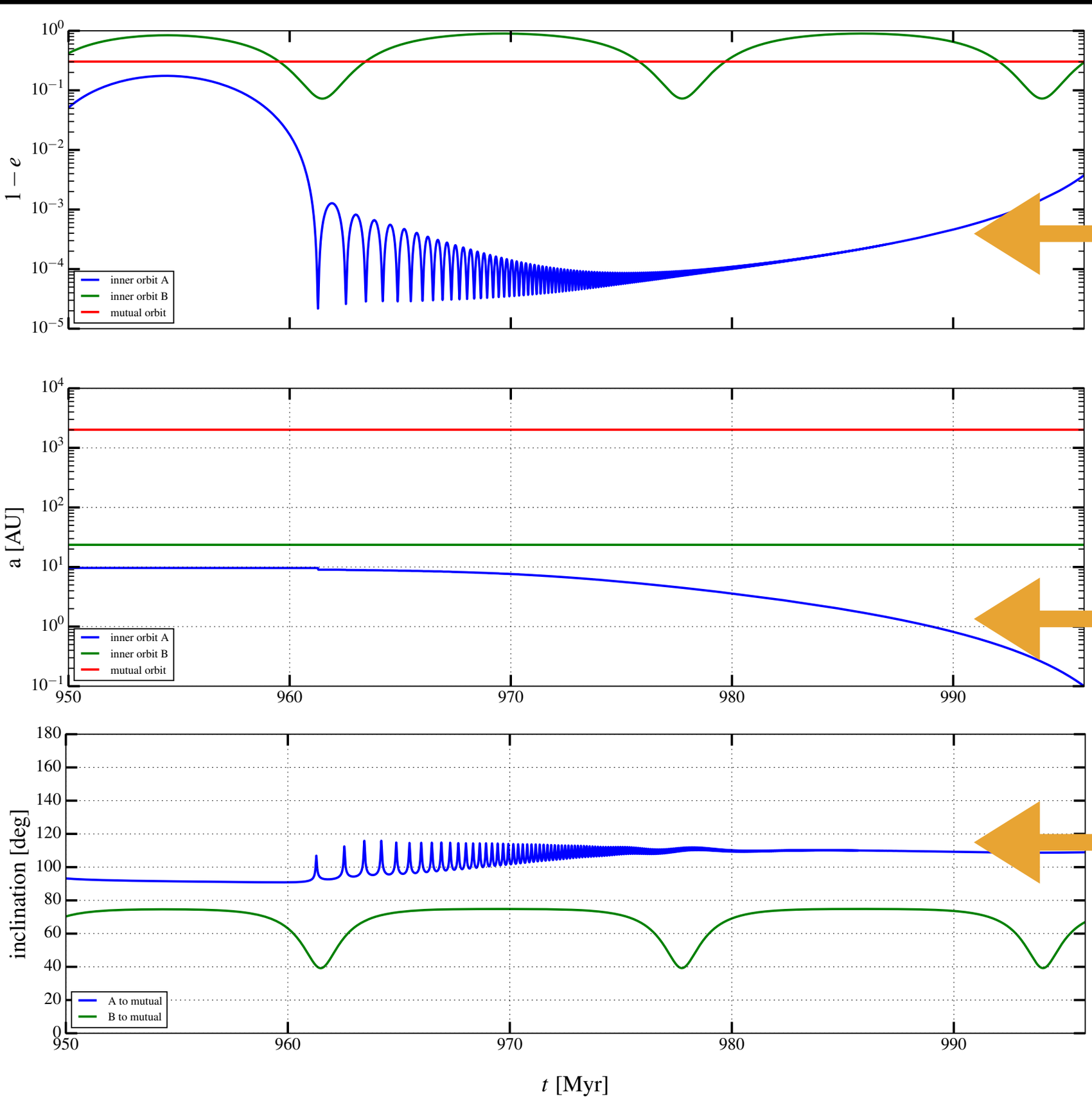
Secular: Quadrupole + Octupole
GR: 1PN precession + GW
Tide: precession + dissipation

Example of
Orbital Decay

(Fang *et al*, in prep)



WD-WD in Quads



Circularization

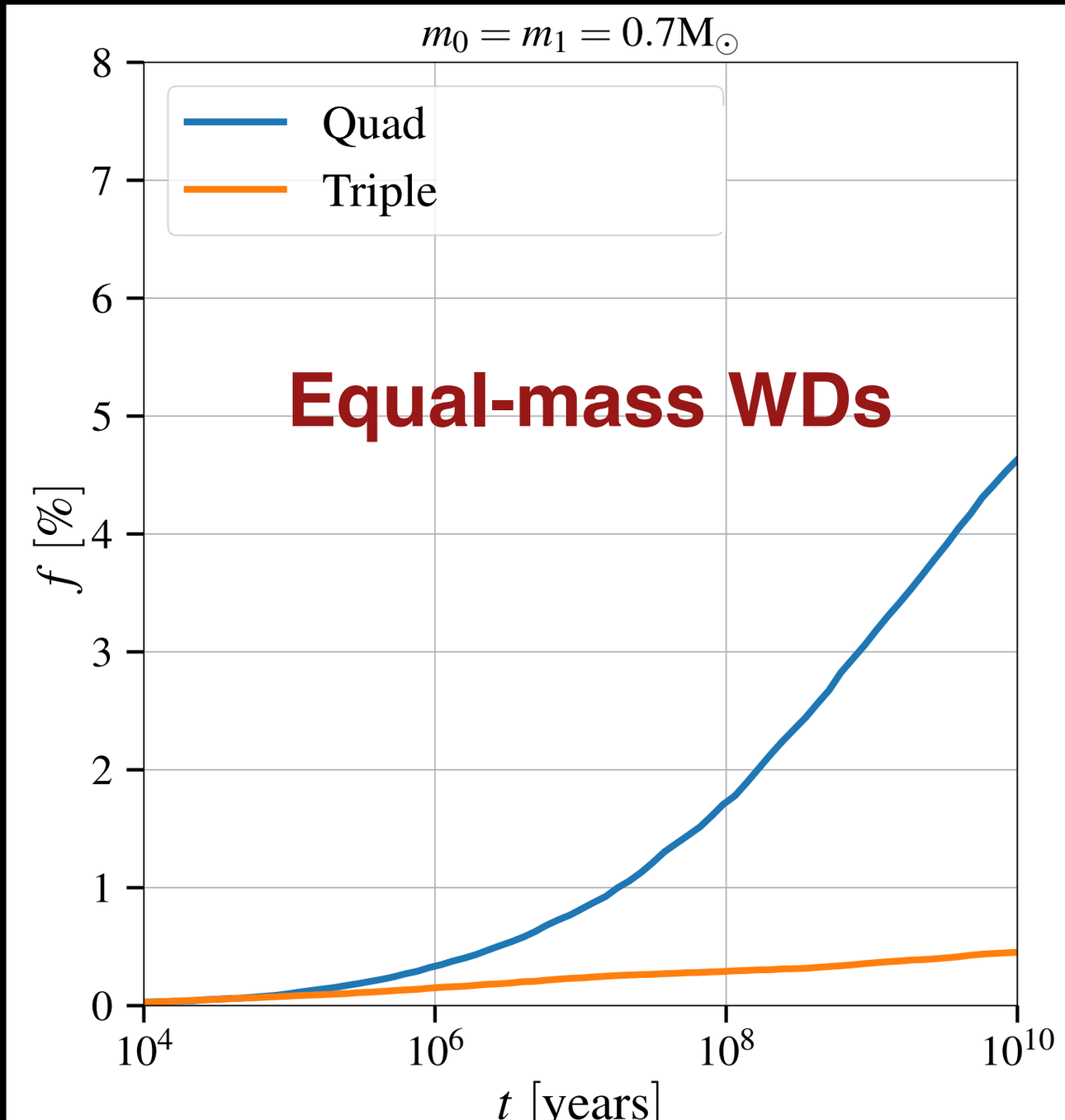
Orbit shrinks

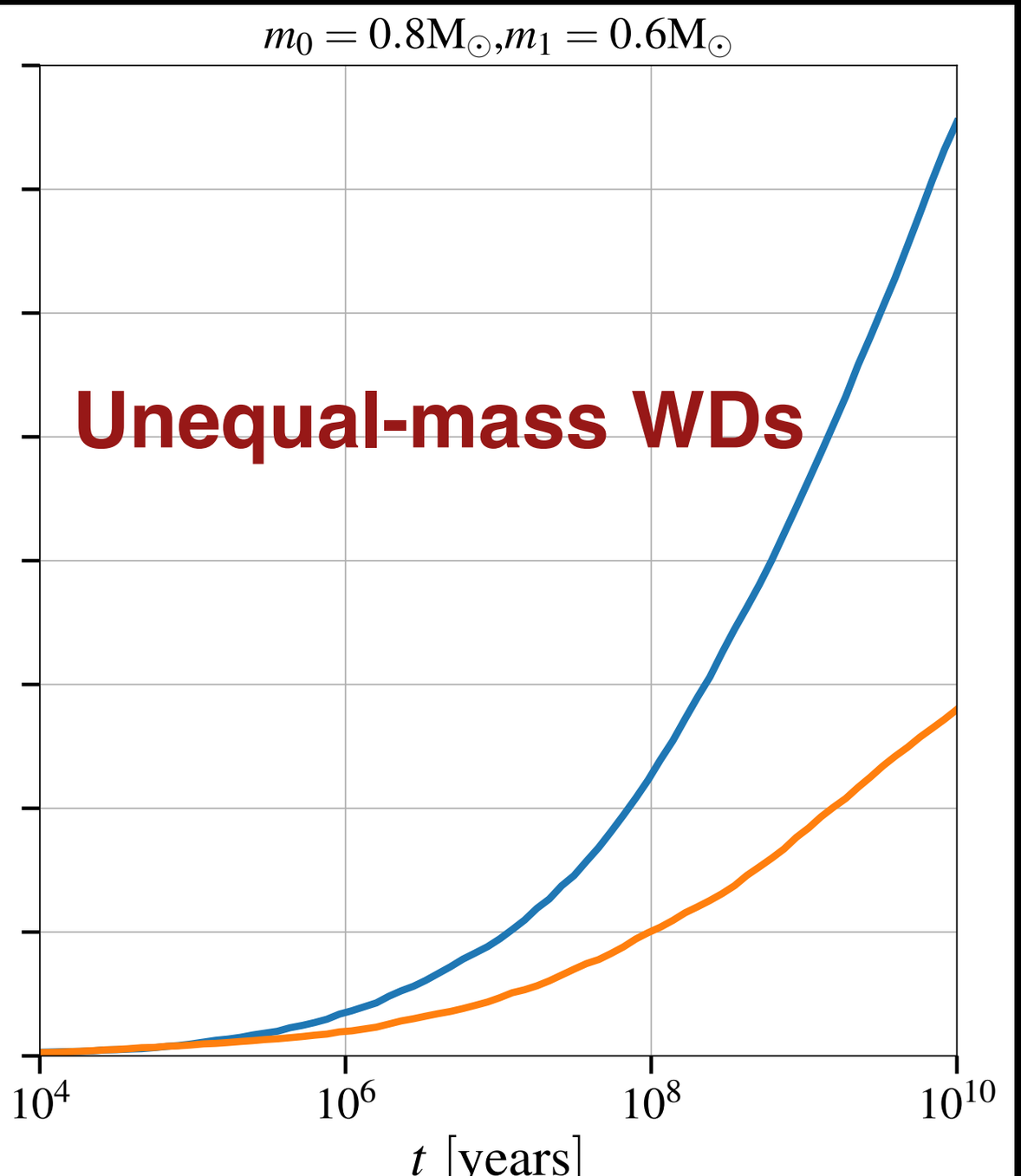
Inclination Freezes

(Fang *et al*, in prep)

WD-WD in Quads

Full Run: 10^5 sys, orbital sizes/shapes sampled





Quadruples provide much more mergers than triples in secular calculations!

(Fang *et al*, in prep)

Summary

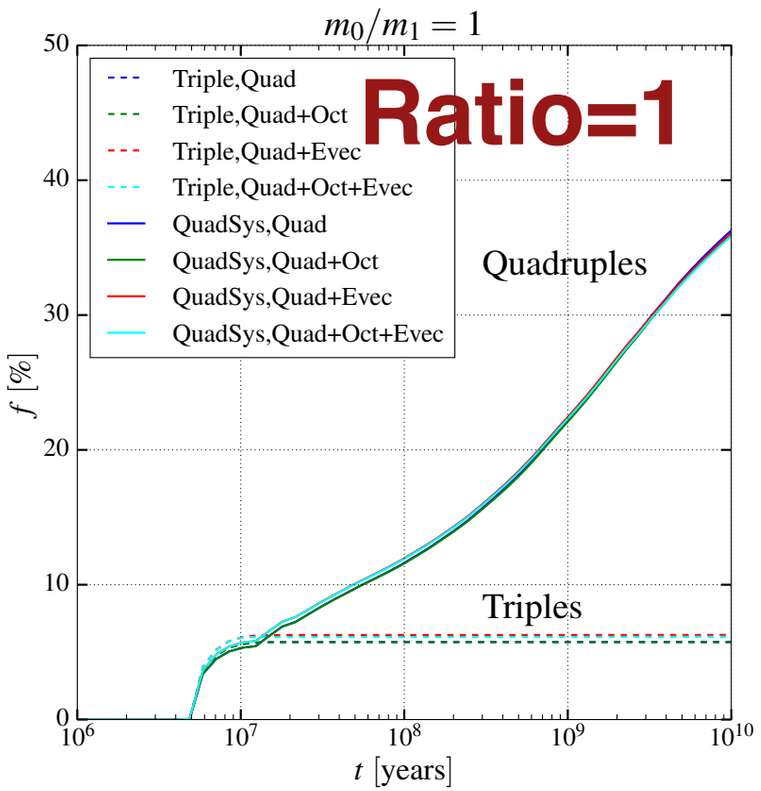
Hierarchical Quadruple Systems:

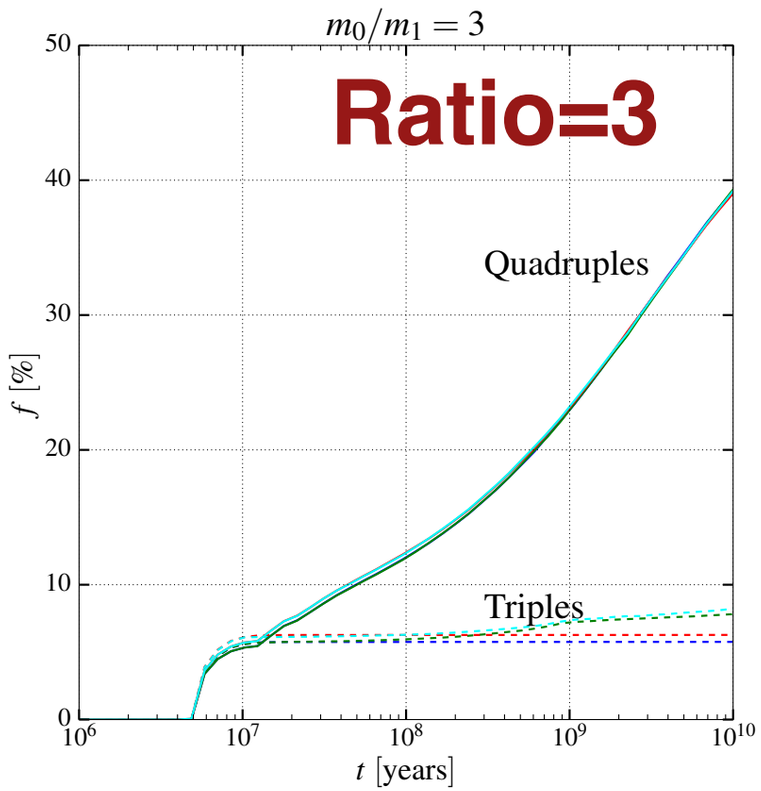
- **Much richer secular dynamics than triples**
- **Higher high-e fraction, hence more compact objects or mergers**
- **Might contribute significantly to WD-WD mergers, hence (possibly) SN Ia rate**

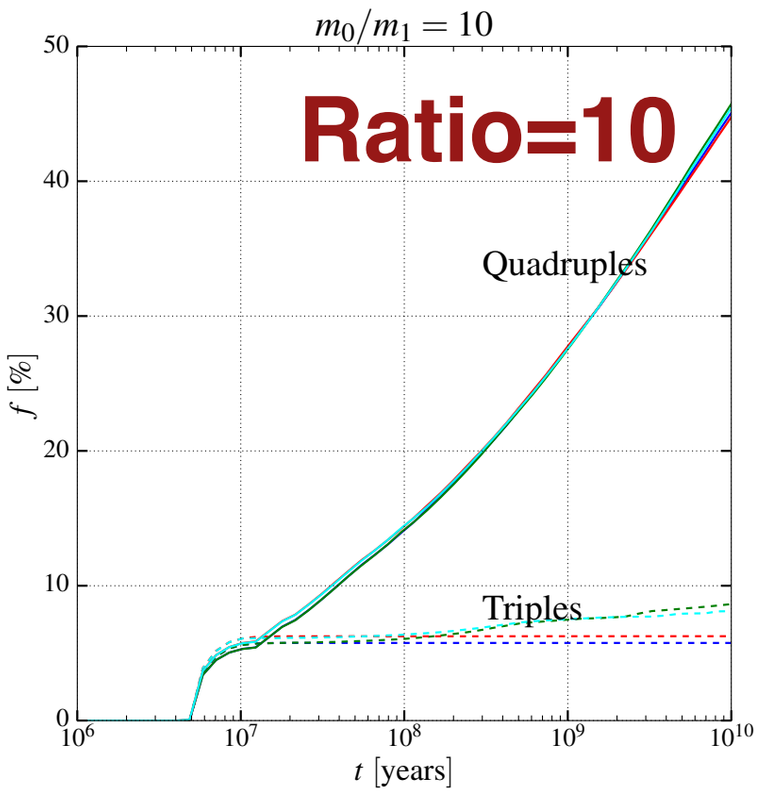
© Space Engine

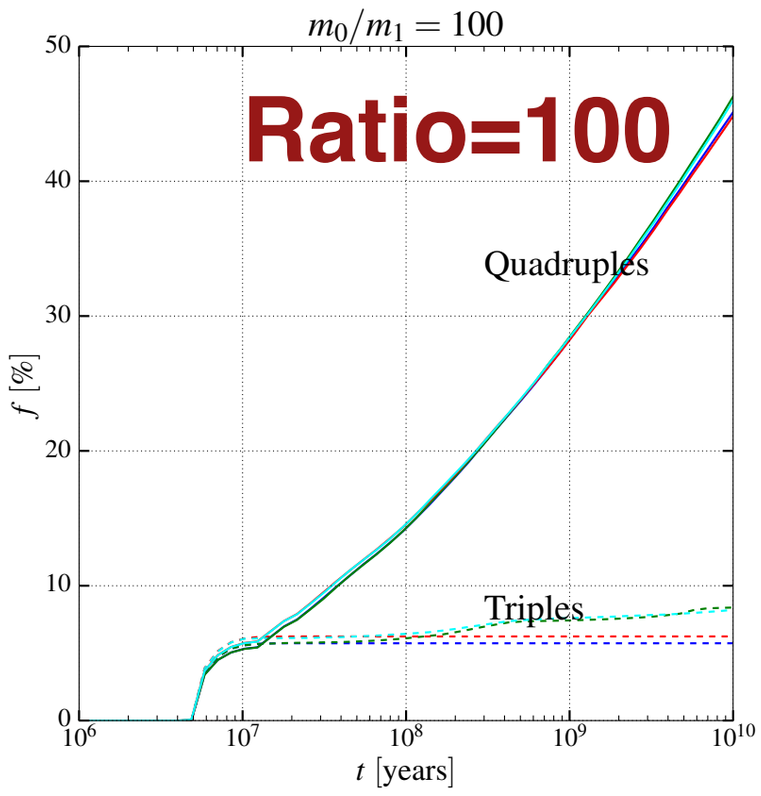
BACKUP SLIDES

Quadruples *vs.* Triples



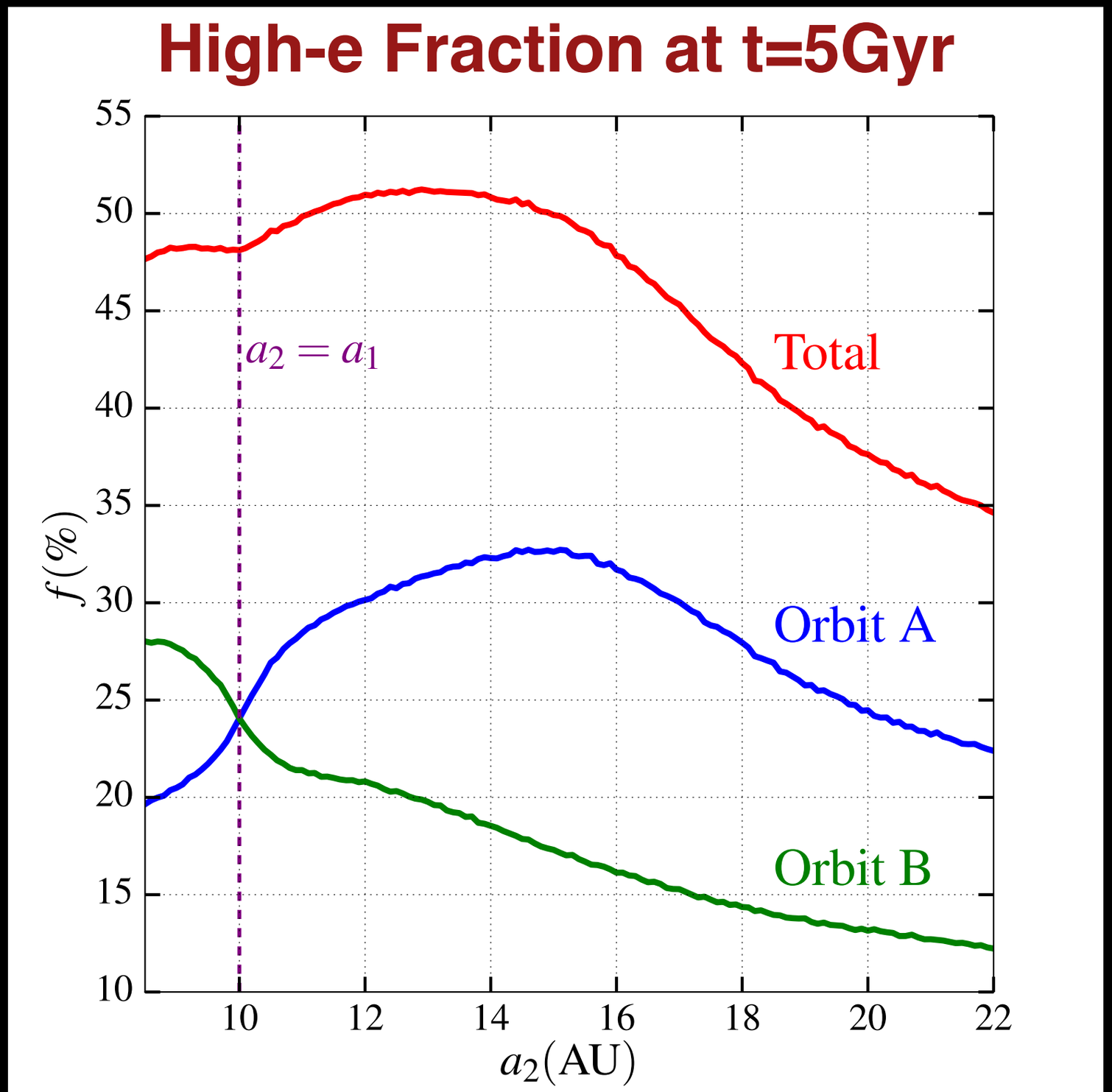






True for different mass ratios!

Quadruples *vs.* Triples

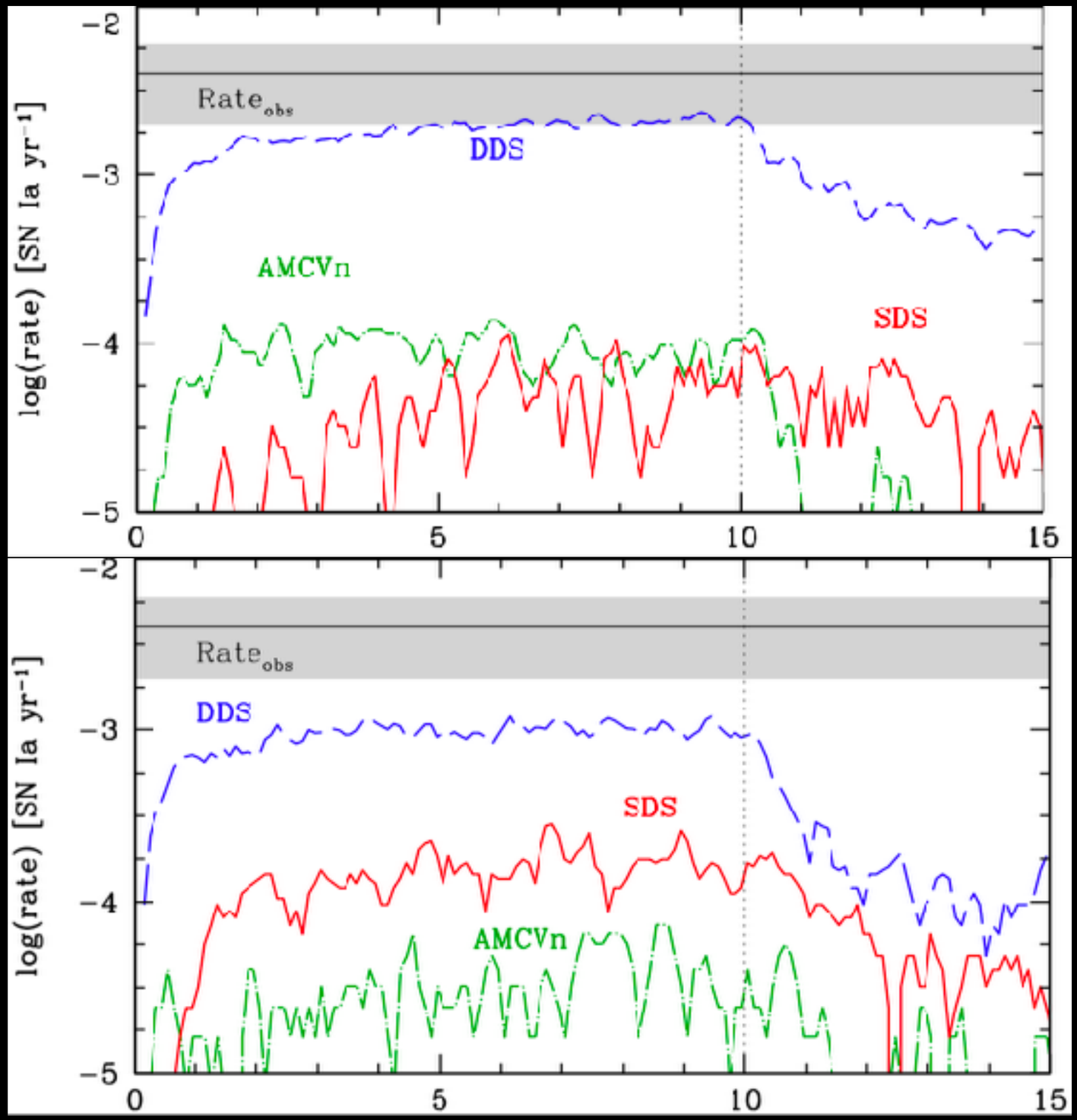


True for different orbital sizes!

Proposal: Common Envelope Evolution

- Orbit rapidly shrinks in CE phase
- Underpredict short time-delay SN rate
- Depend on CE evolution physics, …

Unclear



(Ruiter *et al*, 2009)

Proposal: Triple System

$$e_{\max} = \sqrt{1 - \tfrac{5}{3}\cos^2 i}$$

$$t_{\rm GW} \sim a_1^4 (1 - e_1^2)^{7/2}$$

Largely shorten merger time

(*e.g.* Peter, 1964; Blaes *et al*, 2002)

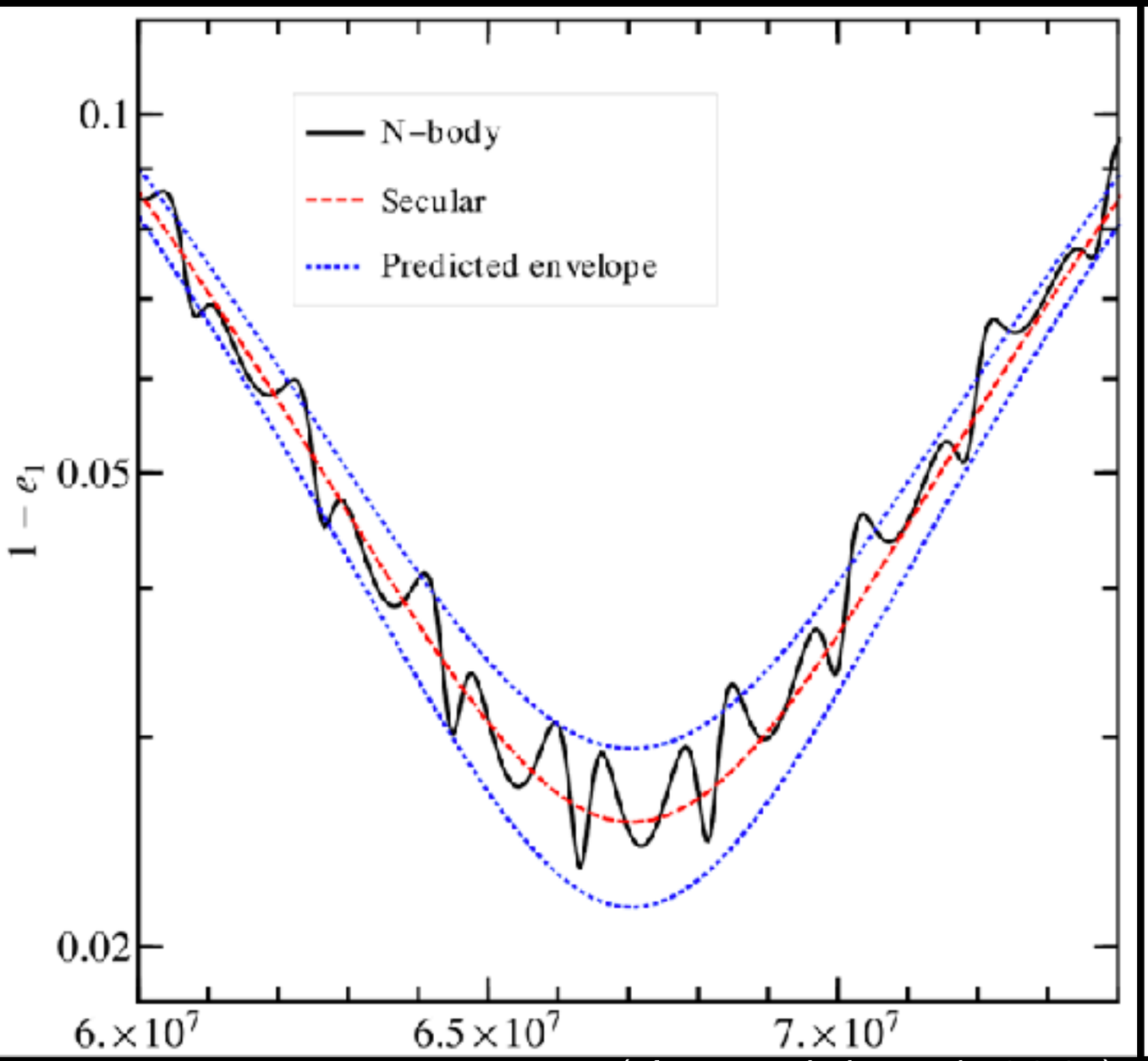
Thompson (2011): $t_{\rm merge} \sim \cos^6 i$

Concerns:

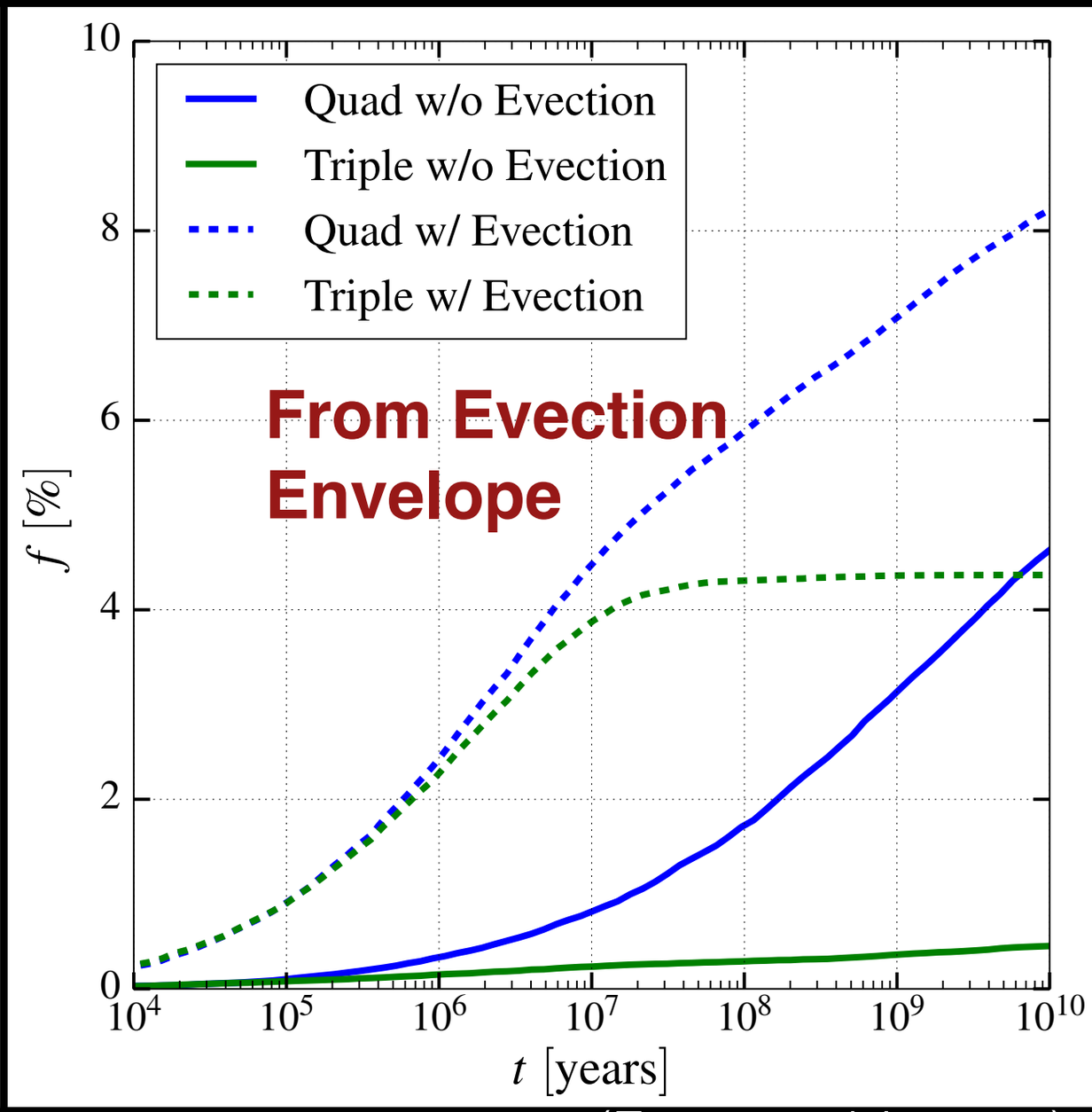
- Require high initial inclination
- Mergers in main sequence: not helpful to SN Ia

Issue

Non-secular: Evection —> Direct Collisions



(*Antognini et al. 2014*)

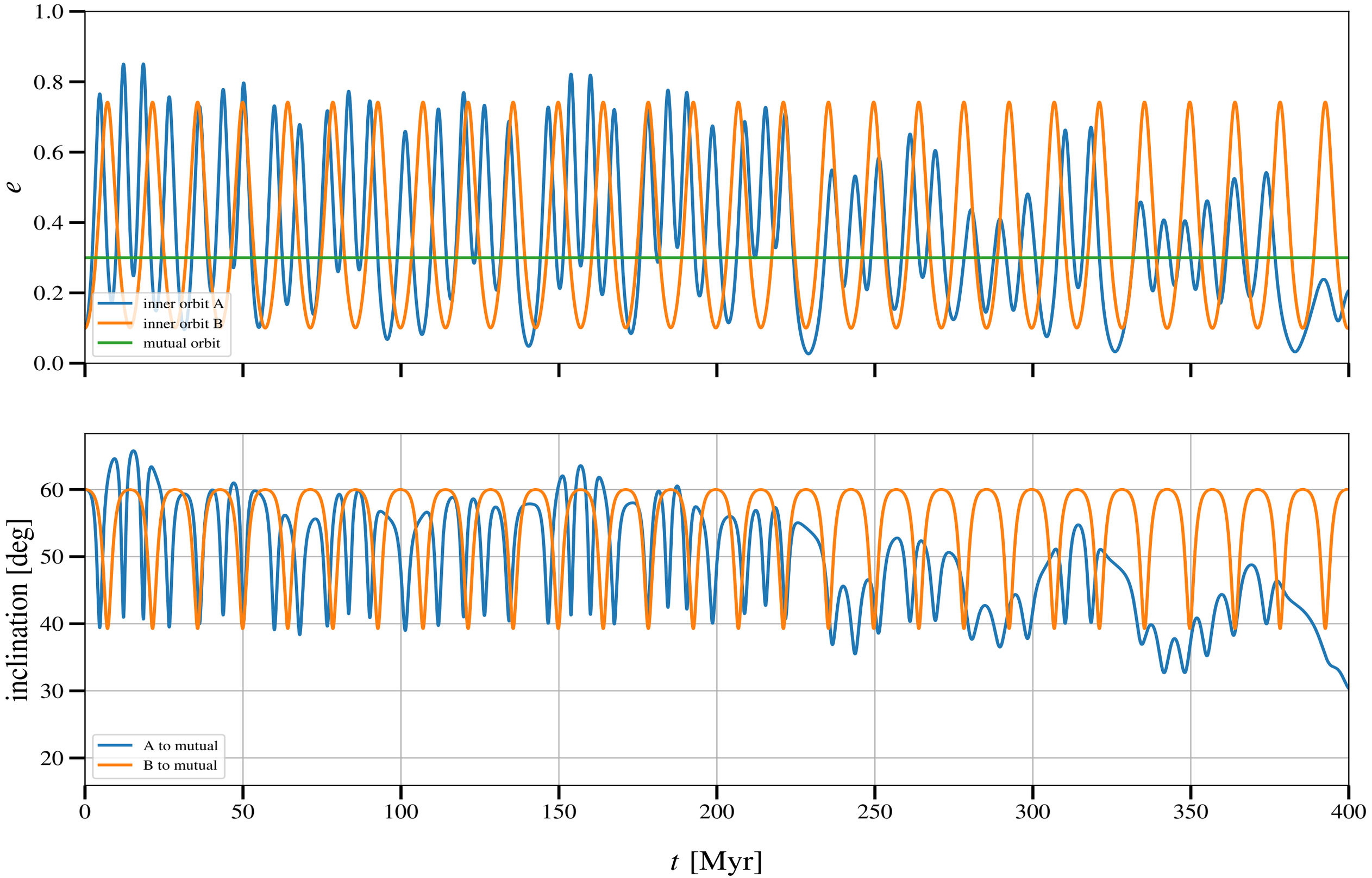


(Fang *et al*, in prep)

More careful evection treatment needed!

[(Star+Planet) + (Star+Star)]: Regular *vs* irregular behavior

(Fang *et al*, in prep)



Quadruples *vs.* Triples

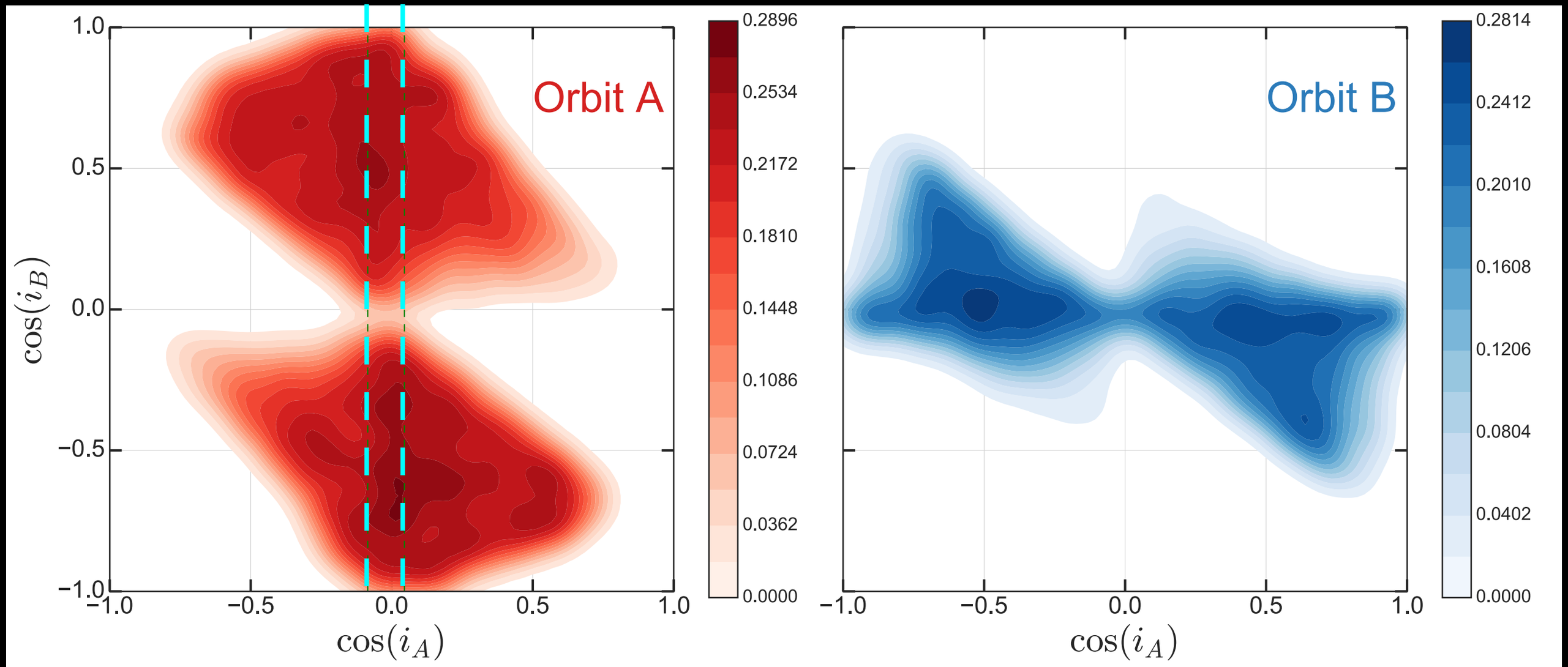
100,000 Systems with Random Orientations

Stop at 10Gyr or when $r_{\rm peri}<6R$

Constraint for triple limit

m: (1+1)+(1+1)$M_\odot$
a: 10,15,1000AU
e: 0.1, 0.1, 0.3

(Fang *et al*, in prep)

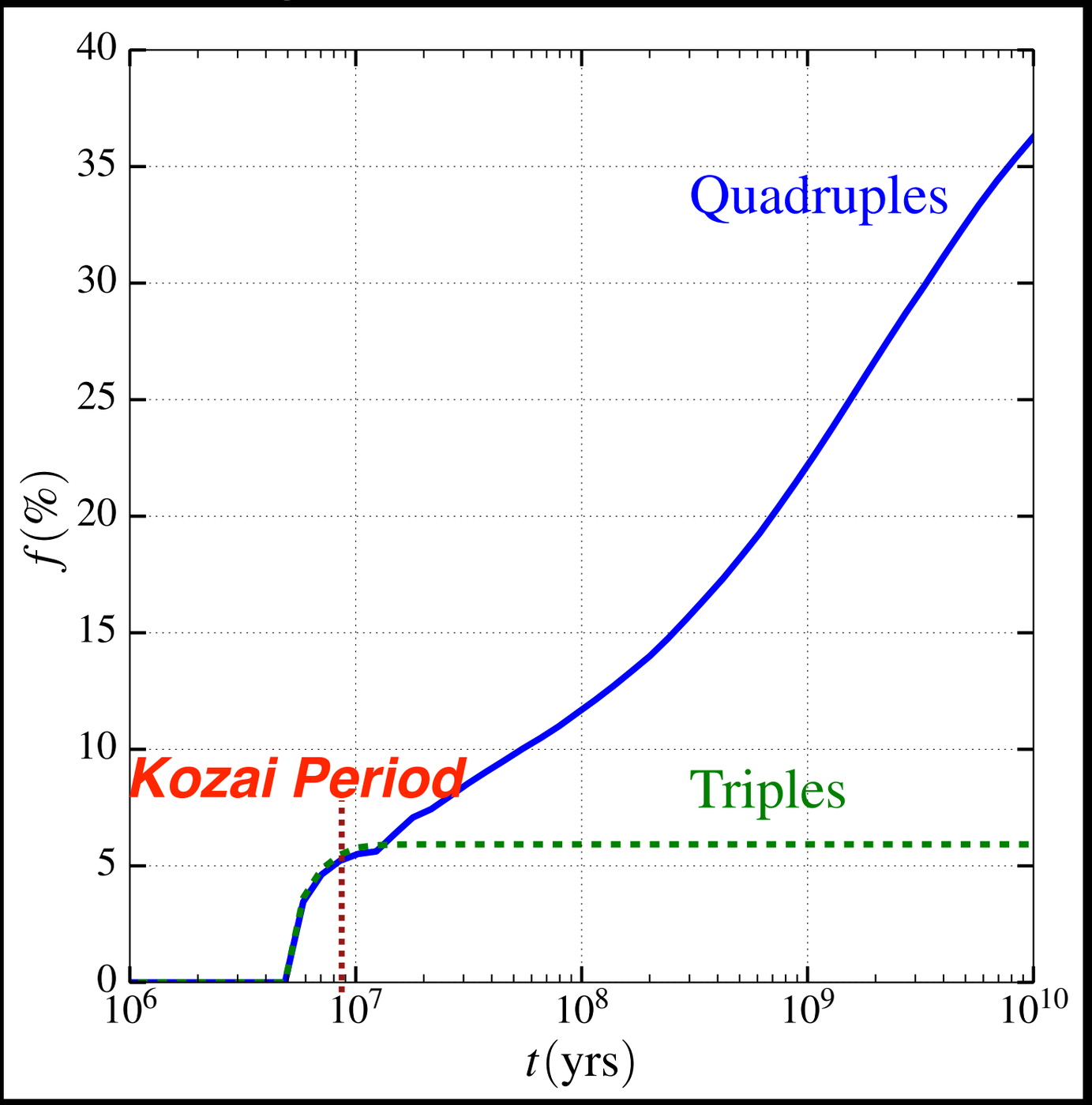


Quadruples: Much weaker requirement for inclination

Quadruples *vs.* Triples

100,000 Systems with Random Orientations

High-e fraction vs. time



Quads At Quad Order:

- Much higher fraction
- Near linear growth in $\log(t)$

Are they true for other orbital configurations?

Yes!

- mass ratios
- orbital sizes

(Fang *et al*, in prep)