Formation of SNe Ia by Direct Collisions of White Dwarfs

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Introduction

- Type Ia supernovae (SNe Ia)
  - Cosmological 'standard candles' : tight correlation between intrinsic peak luminosity and post-peak brightness decline rates (Phillips 1993)
  - Powered by the decay of ^{56}Ni produced from the explosion of CO white dwarfs (WDs)

- Scenarios for the formation of SNe Ia
  - Chandrasekhar-mass model (double-degenerate model)

    : Merger of two close WDs through the radiation of gravitational waves (Whelan & Iben 1973, Nomoto 1982, Han & Podsiadlowski 2004)
  - Single-degenerate model or double detonations theory (DDT)

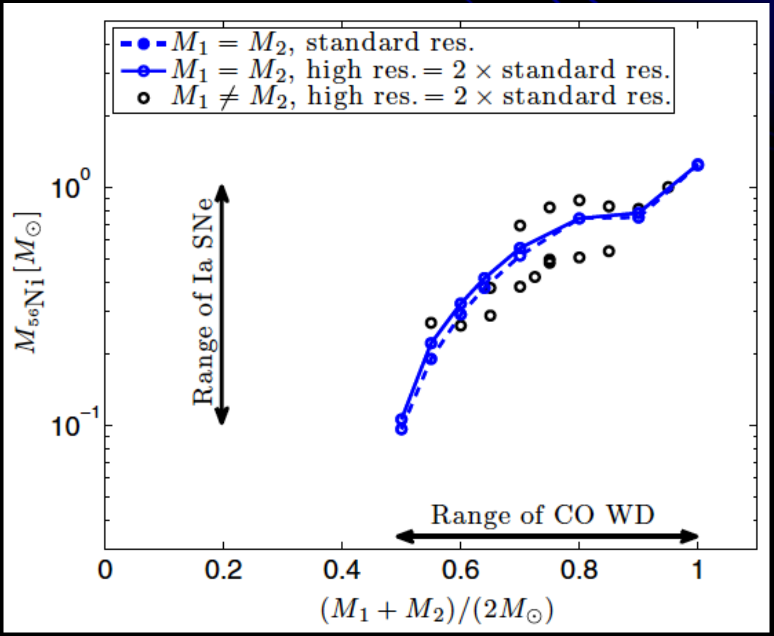
    : By accreting a hydrogen-rich or helium-rich mass from a non-degenerate stellar companion (Iben & Tutukov 1984, Webbink 1984; Iben et al. 1987, Ruiter et al. 2011)
  - WDs collision scenario (Thompson 2011; Katz & Dong 2012; Kushnir et al. 2013)

    : two WDs collide directly, either because of interaction with a tertiary star

    ⇒ eccentric Kozai-Lidov mechanism (EKL)

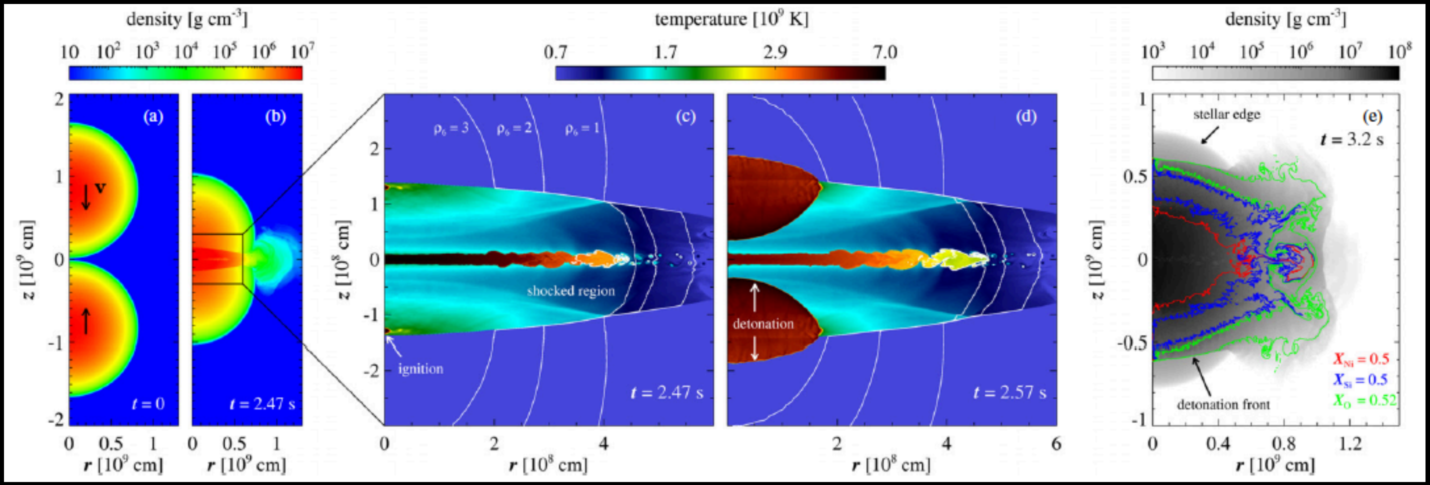
Strong Evidence for Direct Collision

- Converged ^{56}Ni range is produced by WD range (Kushnir et al. 2013)



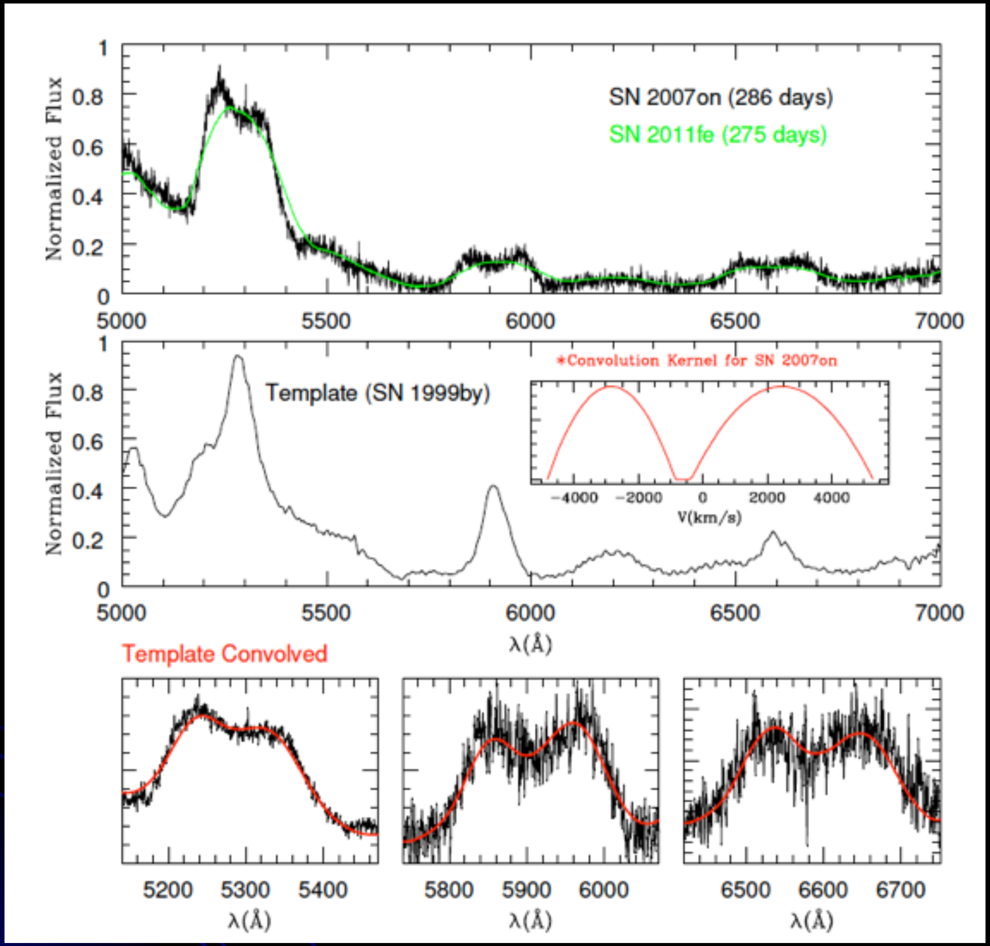
* M_1 and M_2 vary from 0.5 to 1.0 M_{sun}.

* Shock ignition ⇒ Nuclear Detonation

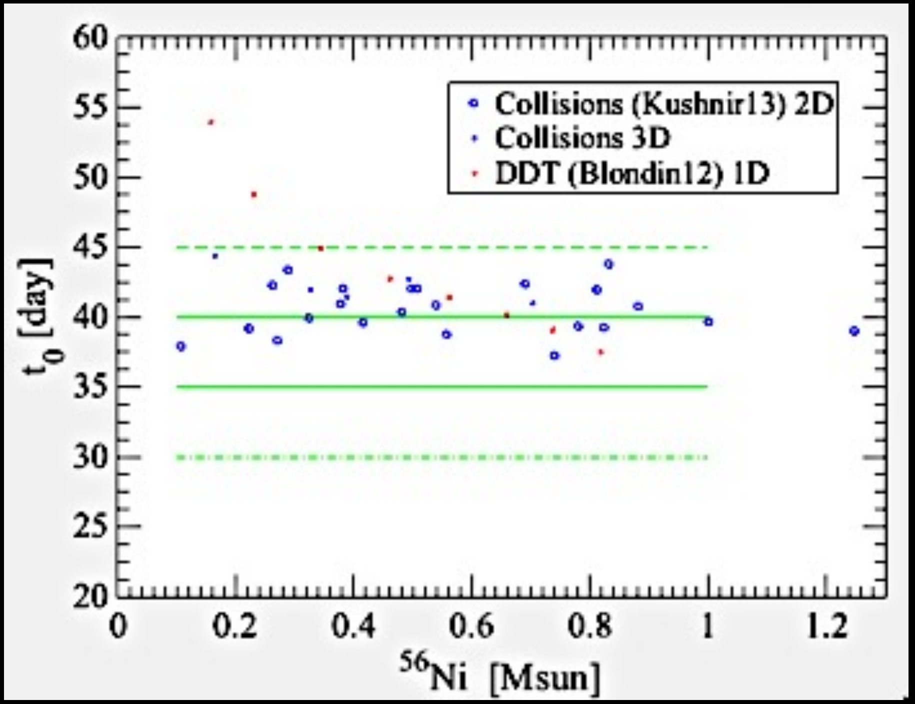


Strong Evidence for Direct Collision

Double peak at nebular line (Dong+15)

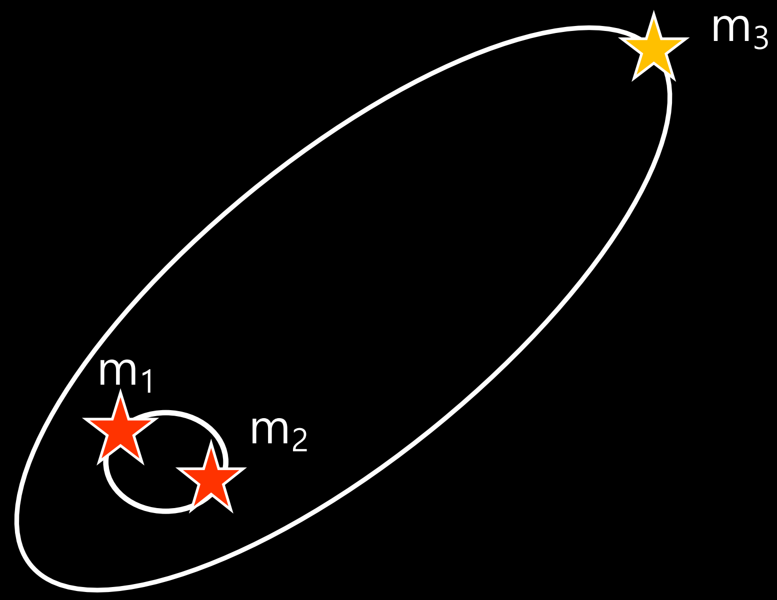


Correct bolometric properties



- t_0 is the transparency time when the optical depth to Compton scattering equals unity, using Arnett's rule (Arnett 1982) and the analytic treatment of Jeffery (1999). ⇒ Relate to average column density of ejecta

Kozai-Lidov Mechanism



$e(m_1\text{-}m_2) \sim 1$

$\Rightarrow$ likely to collisions

Challenges to adopt the Kozai-Lidov theory on the SNe Ia formation

a. Required extreme eccentricity : $1\text{-}e > 10^{-6} \leftarrow a/R_{WD} \sim 10^6 (a/30AU)$

b. Tidal and General Relativistic (GR) effects will prohibit the collision during the slow secular evolution

c. Small fraction of parameter space $\sim(R_{WD}/a)^{1/2}$ available for producing the required extreme eccentricity $1\text{-}e \sim R_{WD}/a$

Eccentric Kozai-Lidov Mechanism

Overcome these Challenges by;

a. Required extreme eccentricity : $1\text{-}e > 10^{-6} \leftarrow a/R_{WD} \sim 10^6(a/30AU)$

⇒ Stochastically achieved the collision after a sufficient amount of orbits, $N \sim a/R_{WD} \sim 10^6(a/30AU)$

b. Tidal and General Relativistic (GR) effects will prohibit the collision during the slow secular evolution

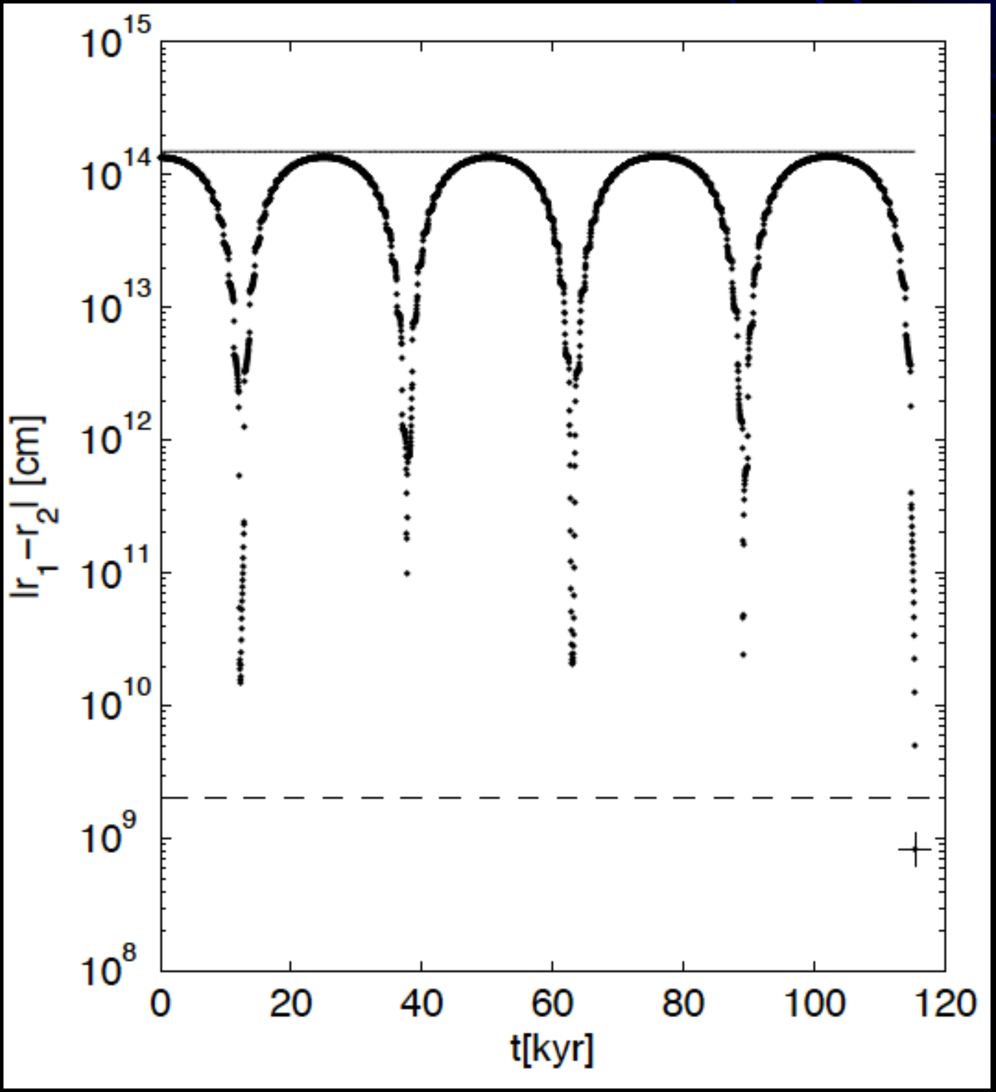
⇒ "Clean" : the perturber is close enough to significantly change the angular momentum of the eccentric binary at the last apocenter prior to the collision, leading to a jump in pericenter separation r_p from several R_{WD} (far enough to avoid GR and tides) to $r_p < 2R_{WD}$ (a head-on collision).

c. Small fraction of parameter space $\sim(R_{WD}/a)^{1/2}$ available for producing the required extreme eccentricity $1\text{-}e \sim R_{WD}/a$

⇒ direct numerical 3-body integration in order to avoid the limitation of standard Kozai-Lidov theory.

Evolution of a Triple System

- Inner binary
  - $m_1=m_2=0.5M_{sun}$
  - a=10AU, e=0.1
- Third body
  - $m_3=0.5M_{sun}$
  - a_{out}=100AU and e_{out}=0.5 (pericenter $r_{p,out}$=5a=50AU)
  - i=98° (95 ° -100 ° similar)

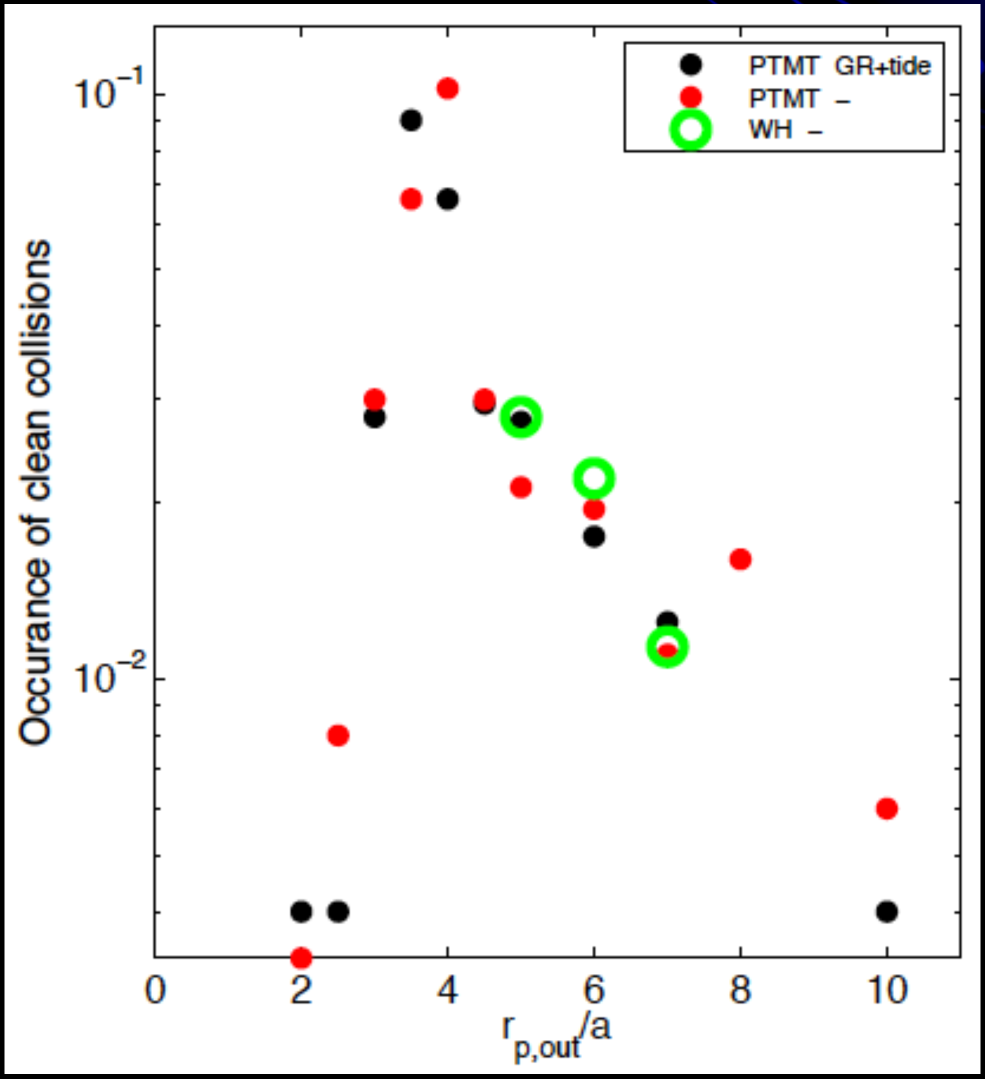


Boaz & Dong 2012

Dependence of Numerical Method

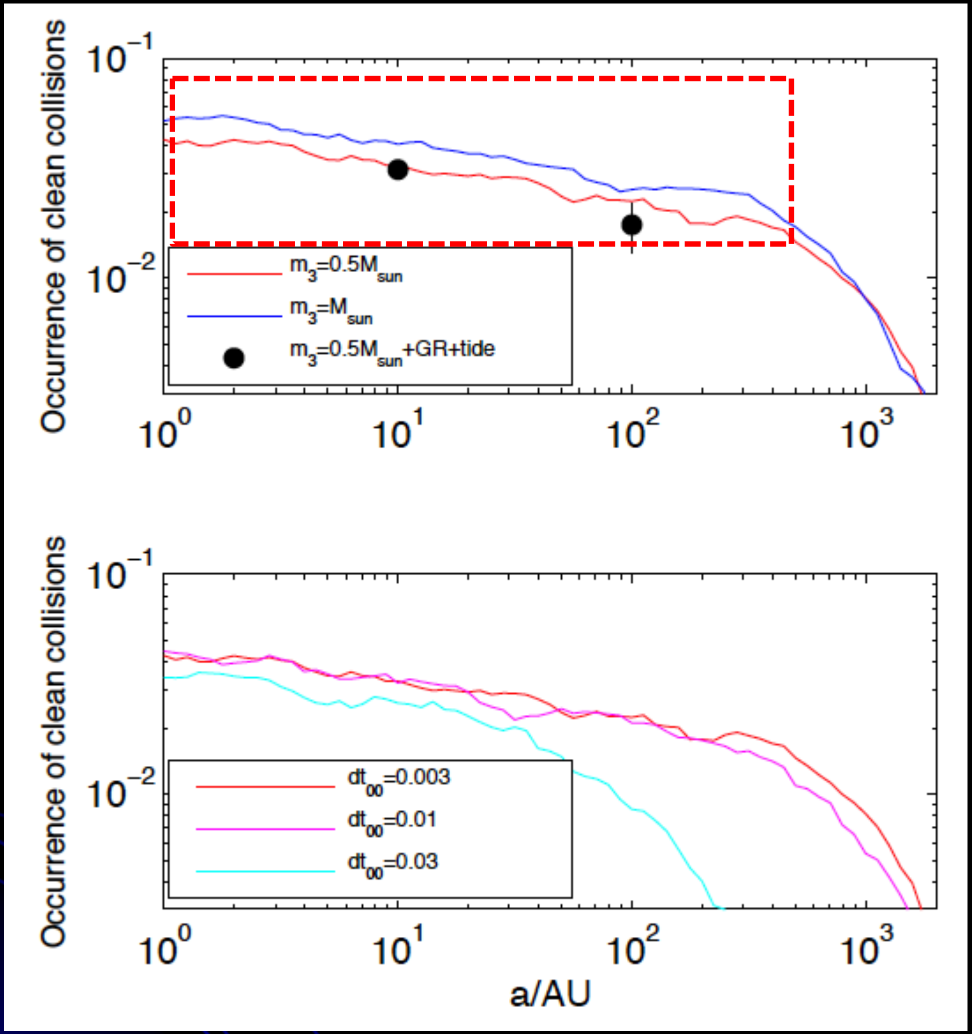
- Newtonian
- Non-Newtonian (with GR+T)

- Dependence of Integrator
  - Preo-Tremaine-Mikkola-Tanikawa
    : Most cases
  - EH (Wisdom-Holman integrator)
    : for sufficiently weak perturbers
    ($r_{p,out} > 5a$)



Boaz & Dong 2012

Dependence of m_3 and a



WDs binary with a=1–300AU

+

Outer perturber with $r_{p,out}/a$=3–10

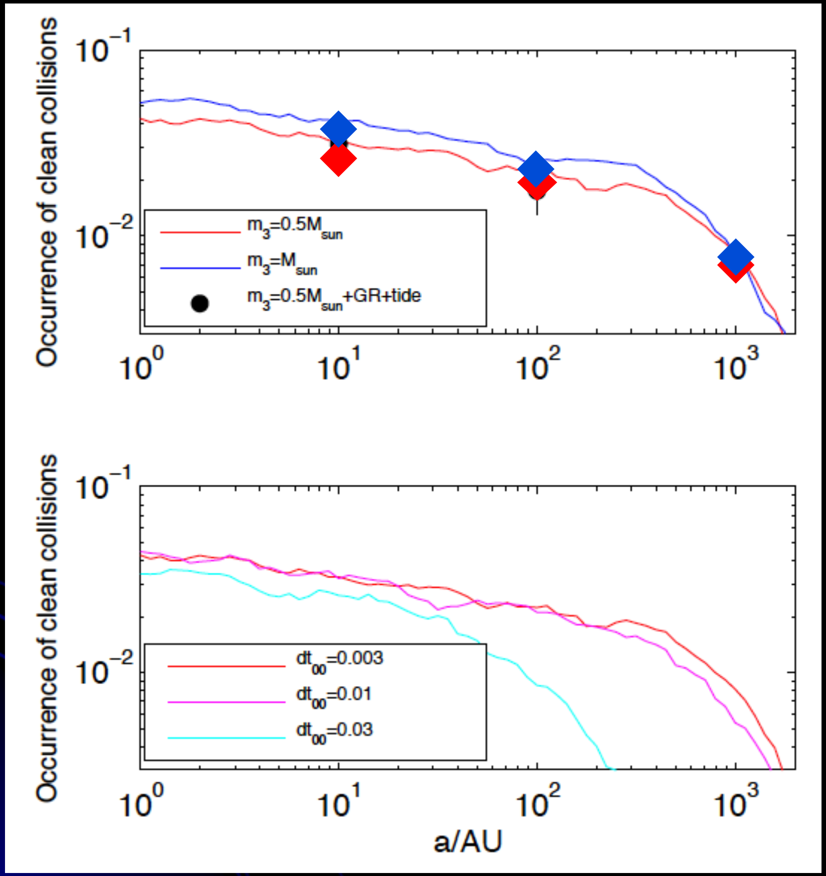
=

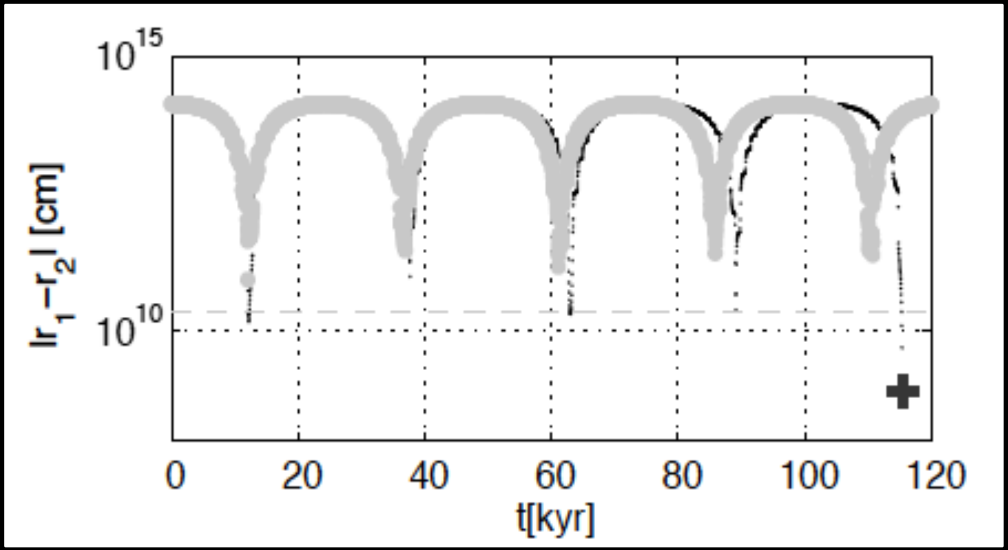
A few percent chance of experiencing a head-on collision within 5 Gyr.

Boaz & Dong 2012

On going work;

- Not enough to explain the fraction of SNe Ia (~only a few %).
- Parametric dependence : m3, i, and other effects





black : i=98 , grey : i=94

m_3=0.4M_{sun}; m_3=0.6M_{sun} (with GR+T)