White Dwarf Planets

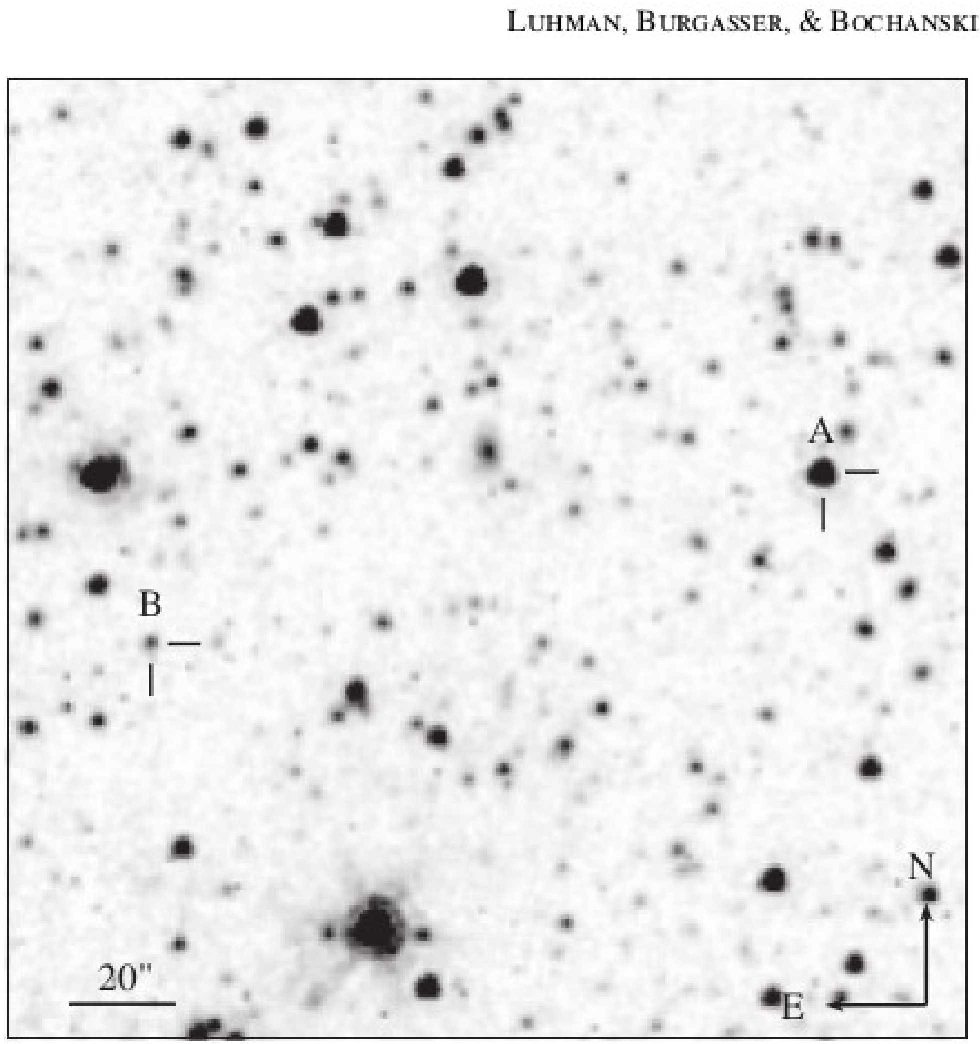

Figure 2. IRAC 4.5 μm image of WD 0806-661 A and B ($3' \times 3'$).

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White Dwarf Planets

- Stellar Evolution Overview

- Single-planet evolution (Mustill & Villaver 2012, *Foretellings of Ragnarök: World-engulfing Asymptotic Giants and the Inheritance of White Dwarfs,* ApJ accepted, arXiv:1210.0328)

- Multi-planet evolution (Veras, Mustill, Bonsor & Wyatt, *Full-Lifetime Planetary Scattering Simulations of Two Massive Planets,* in prep)

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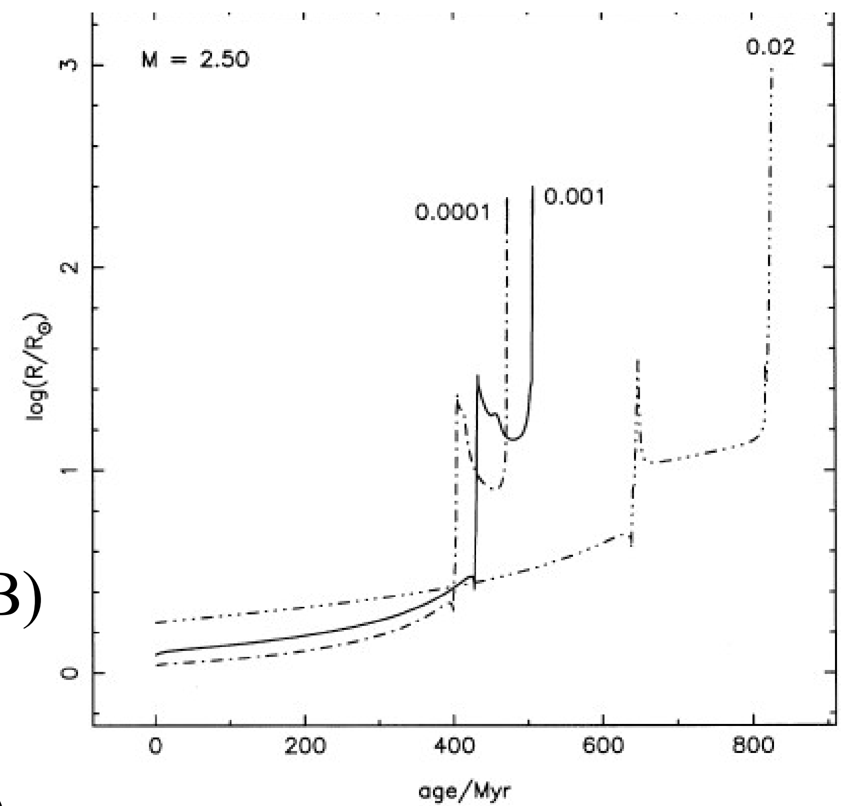
- What planets can we expect around WDs?

- How can we explain WD pollution and discs?

Post-Main Sequence Stellar Evolution

- Hydrogen shell burning: ascend Red Giant Branch (RGB)
  - Radius increases to ~1 AU
  - Maybe mass loss (<~10%)
- Core Helium burning: Red Clump/Horizontal Branch
  - Radius few tenths of an AU
- Hydrogen and Helium shell burning: ascend Asymptotic Giant Branch (AGB)
  - Radius increases to >~1 AU
  - Strong mass loss
- Core left behind as White Dwarf (WD)
  - 1 M_Sol progenitor gives 0.5 M_Sol WD
  - 8 M_Sol progenitor gives 1.4 M_Sol WD



Hurley, Pols & Tout (2000)

Post-Main Sequence Stellar Evolution

Key points:
- Radius expansion
- Mass loss
- Radius increase and mass loss greatest on AGB, so this determines planets surviving to WD

- Planets unlikely to survive engulfment in envelope (Villaver & Livio 2007, Wickramasinghe et al 2010)
- Brown dwarfs could (Nordhaus & Spiegel 2012)

- What is final orbital radius of the closest planet that survives?

Single-planet evolution: mass loss and tides

- Mass loss causes orbit expansion due to angular momentum conservation
- Radius expansion strengthens tides on star: causes orbit to shrink
- Giant stars have large envelope mass and large radius: tides very strong (Zahn 1977)
- We use stellar models of Vassiliadis & Wood (1993)
- Numerically integrate orbital evolution of planets around AGB stars under mass loss and tidal forces

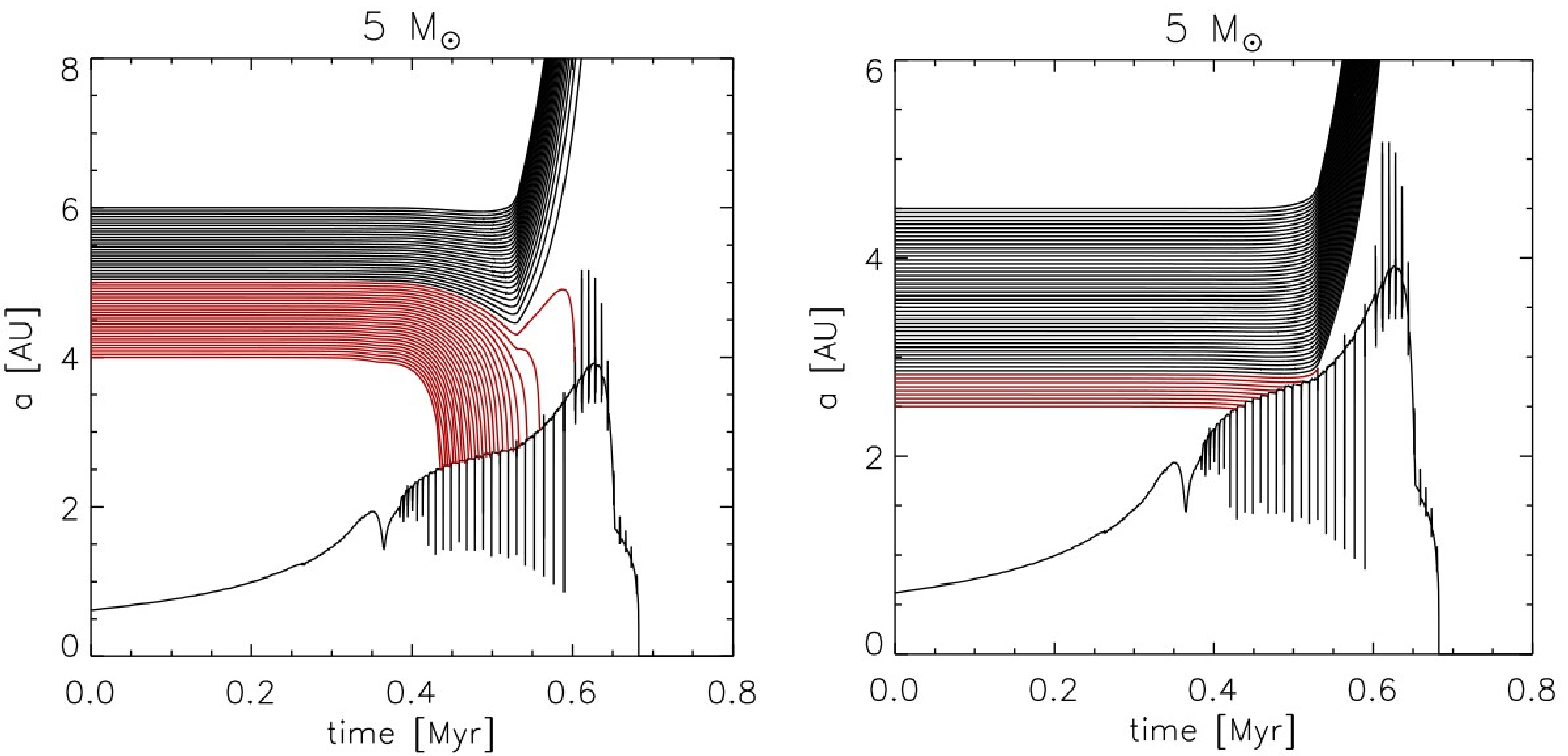
$$\dot{a} = -a\frac{\dot{M}_\star + \dot{M}_{\rm pl}}{M_\star + M_{\rm pl}},$$

$$\dot{a} = -\frac{a}{9t_{\rm conv}}\frac{M_{\rm env}}{M_\star}\left(1+\frac{M_{\rm pl}}{M_\star}\right)\frac{M_{\rm pl}}{M_\star}\left(\frac{R_\star}{a}\right)^8 \times\left[2f_2 + e^2\left(\frac{7}{8}f_1 - 10f_2 + \frac{441}{8}f_3\right)\right]$$

$$\dot{e} = -\frac{e}{36t_{\rm conv}}\frac{M_{\rm env}}{M_\star}\left(1+\frac{M_{\rm pl}}{M_\star}\right)\frac{M_{\rm pl}}{M_\star}\left(\frac{R_\star}{a}\right)^8 \times\left(\frac{5}{4}f_1 - 2f_2 + \frac{147}{4}f_3\right).$$

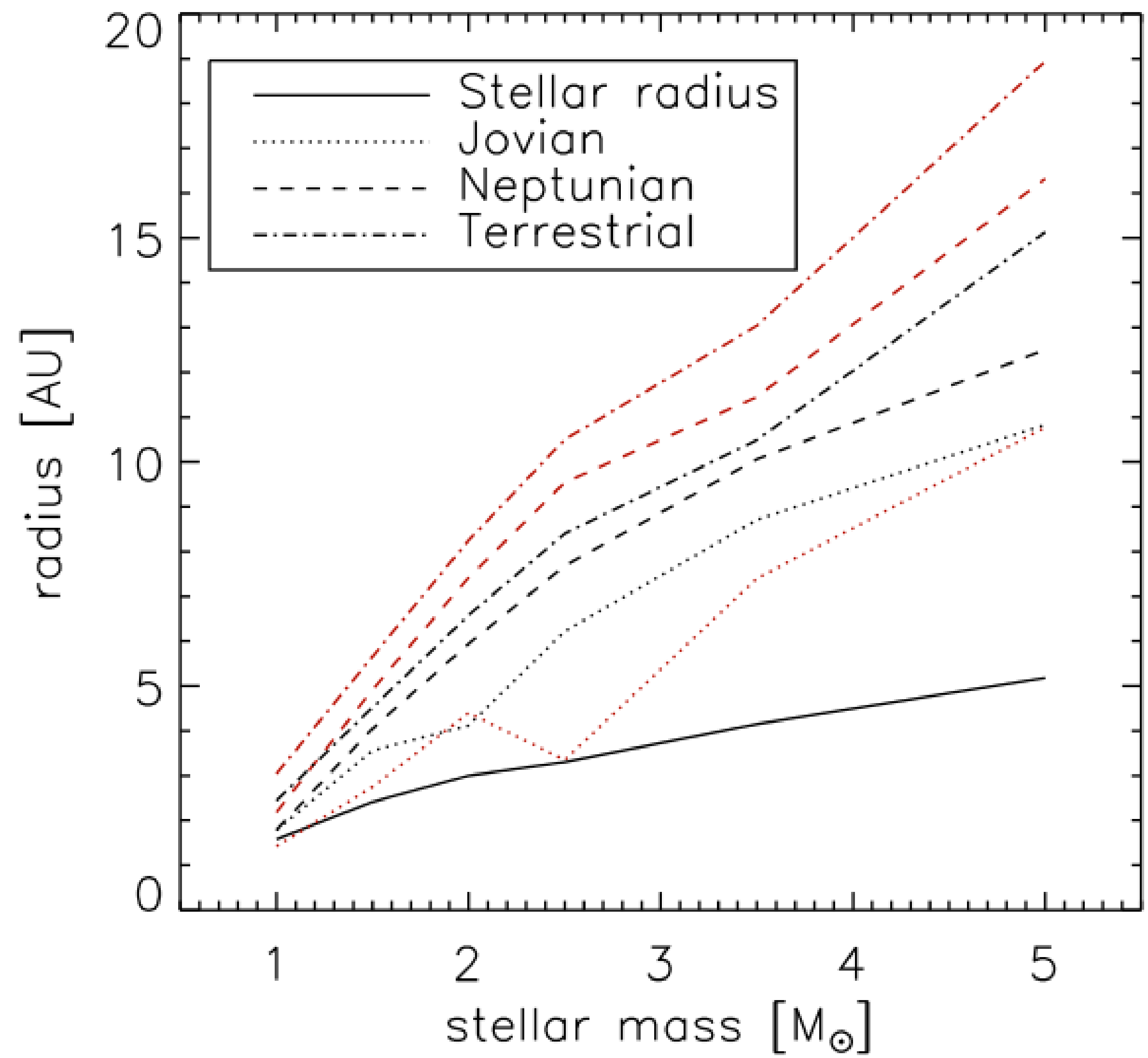
Single-planet evolution: mass loss and tides

- Jovian planets: stellar tides strong
- Terrestrial planets: stellar tides weak



Single-planet evolution: mass loss and tides

- The closest surviving planets
- Planets that did not get engulfed end up beyond this radius
- WD planets unlikely closer than this
- Unless scattered inwards later...



Multi-planet evolution: mass loss and scattering

- Decreasing stellar mass
- Increasing planet:star mass ratio
- Stronger interactions between planets
- Instability possible in previously stable systems

Multi-planet evolution: mass loss and scattering

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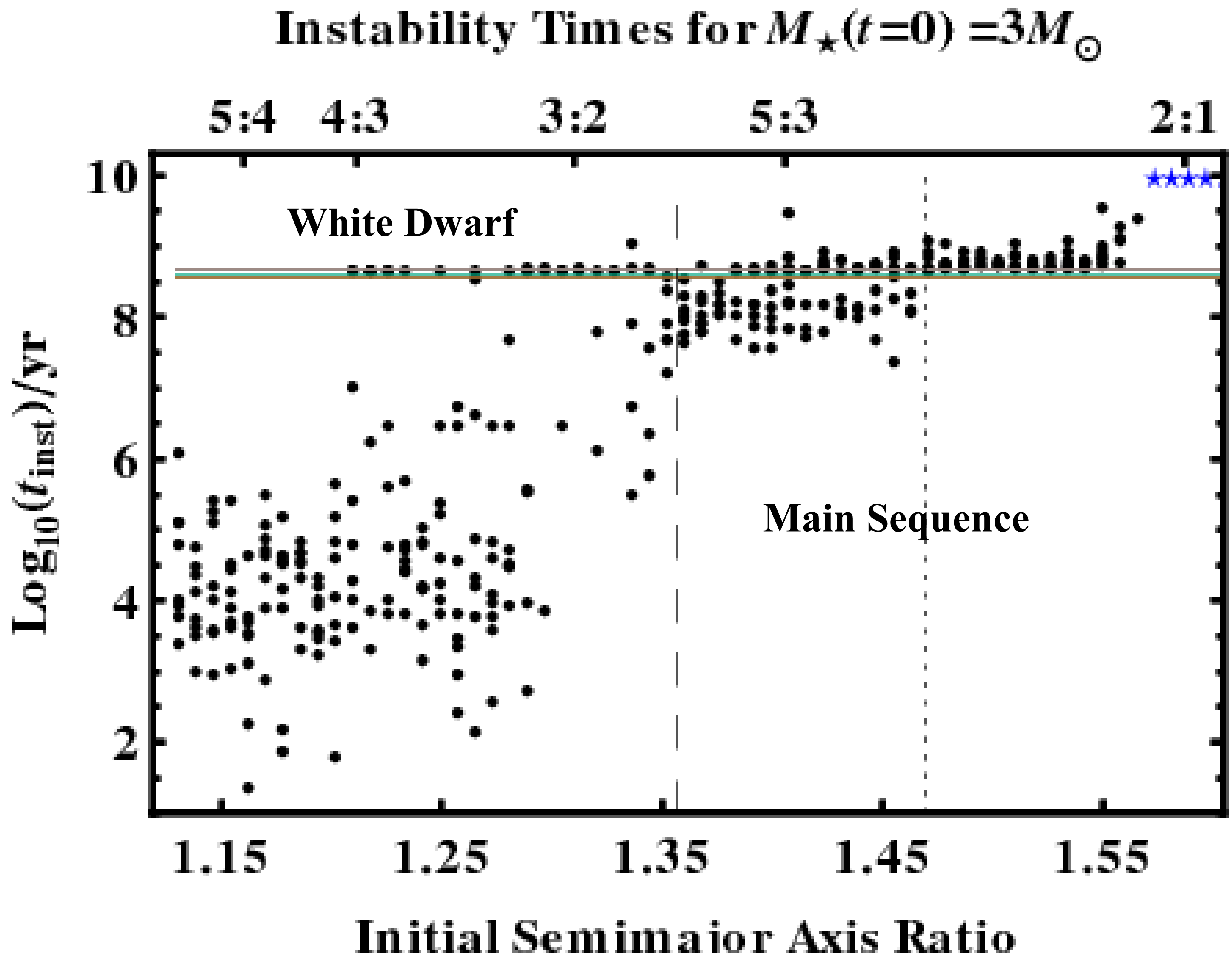
Study with numerical integrations

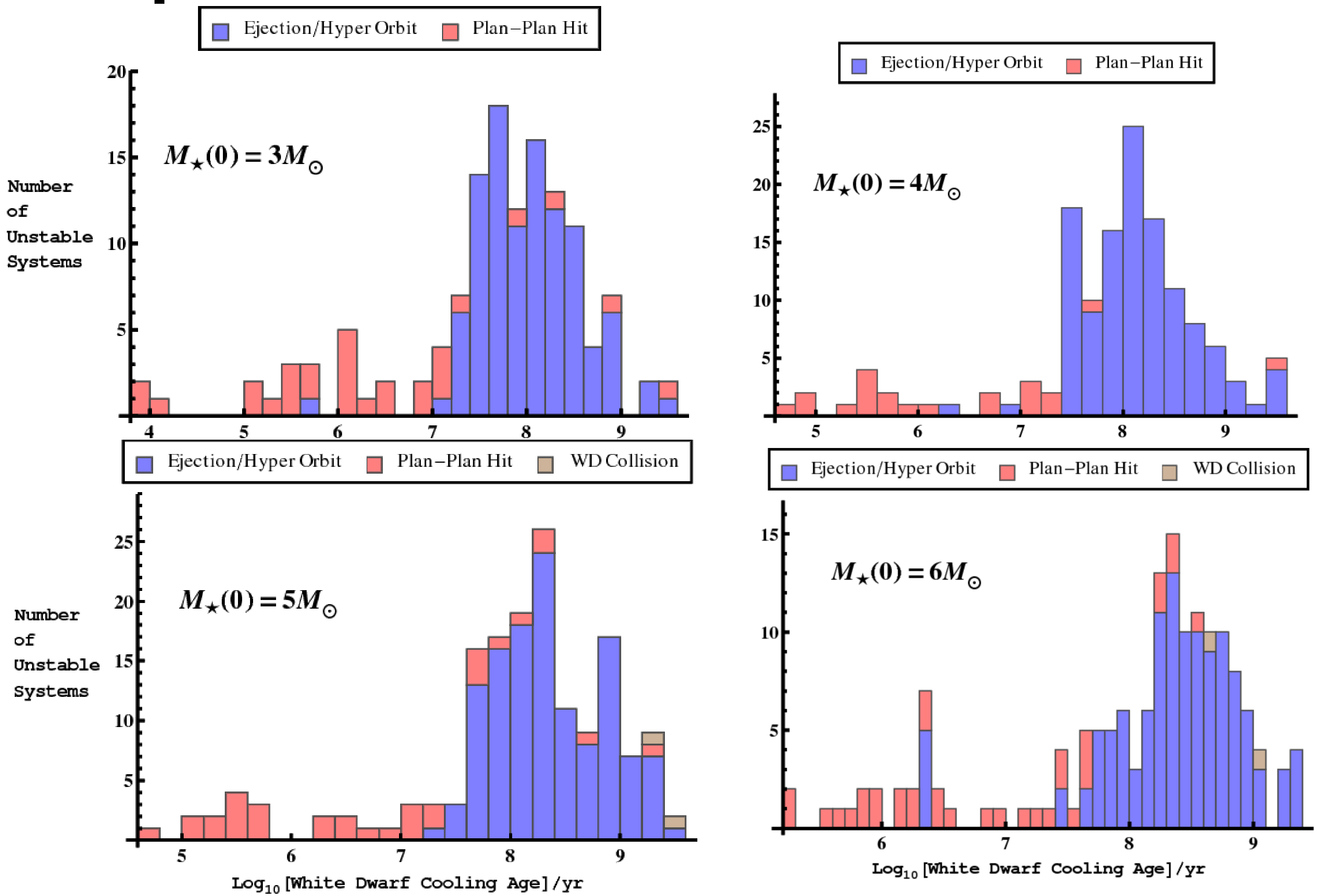
- Modified *Mercury* Bulirsch–Stoer integrator
- 2 Jovian planets, inner at 10 AU (avoids tides)
- Outer at 11 – 16 AU
- Stellar masses 3 – 8 M_Sol
- High but allows integration over whole MS lifetime: integrate each system for 5 Gyr

Multi-planet evolution: mass loss and scattering



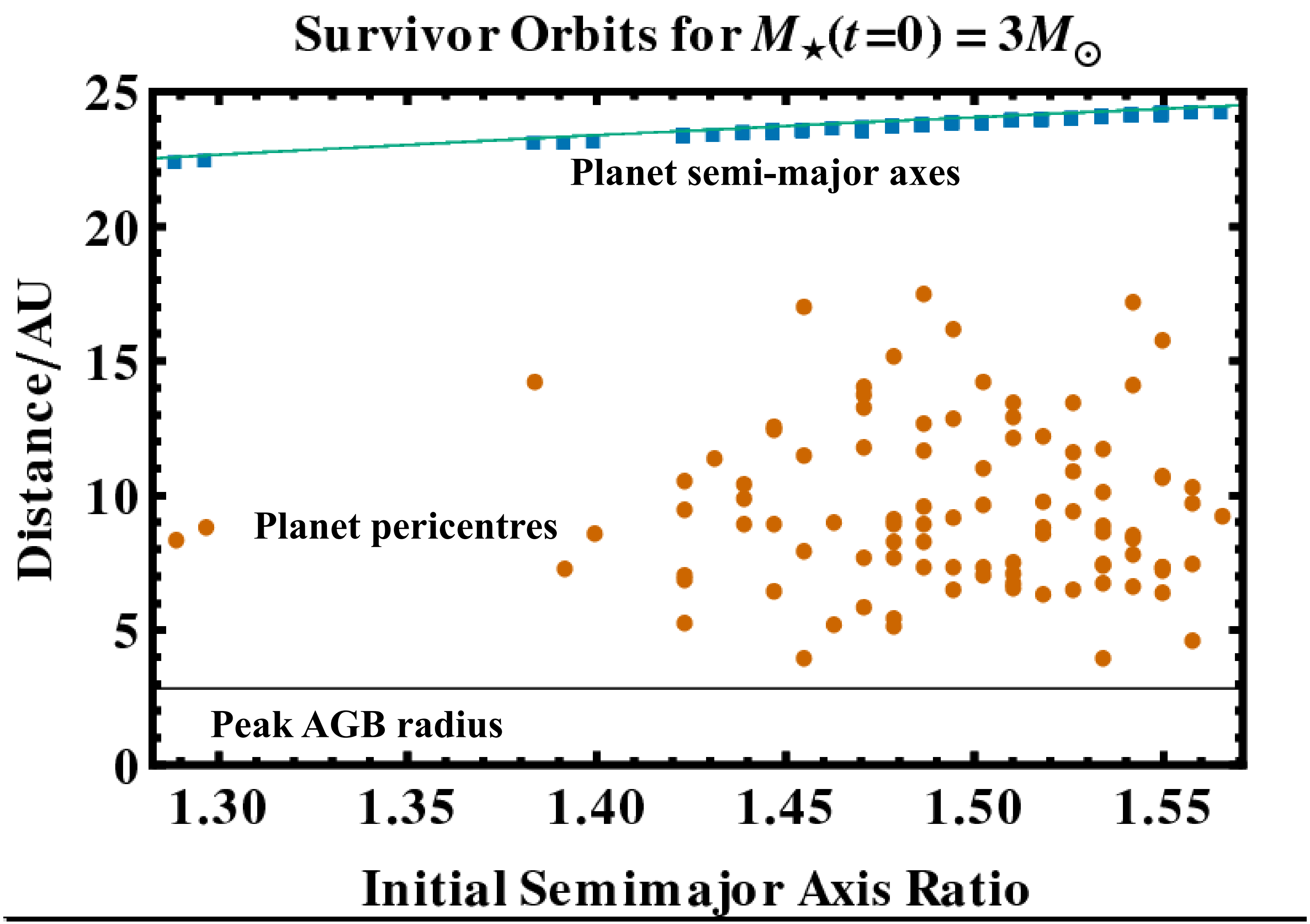
- Many stable systems destabilised by mass loss

Multi-planet evolution: mass loss and scattering



- Instabilities occur at range of times
- Direct pollution by planet uncommon

Multi-planet evolution: mass loss and scattering



- Survivor orbits distant from star
- High eccentricity orbits could destabilise other bodies

Conclusions

- Significant changes to planets' orbits during post-Main Sequence evolution
- Planets within 1 – 5 AU (depending on masses) will be engulfed
- Innermost unengulfed planets at 1 – 3 AU around WDs from 1M_Sol progenitors, at 10 – 20 AU around WDs from 5M_Sol progenitors
- Many multi-planet systems destabilised on WD
- Instability occurs at range of times (up to several Gyr)
- Surviving planets at 10s of AU
- Direct pollution of star by planet uncommon
- High-eccentricity orbits could destabilise other bodies