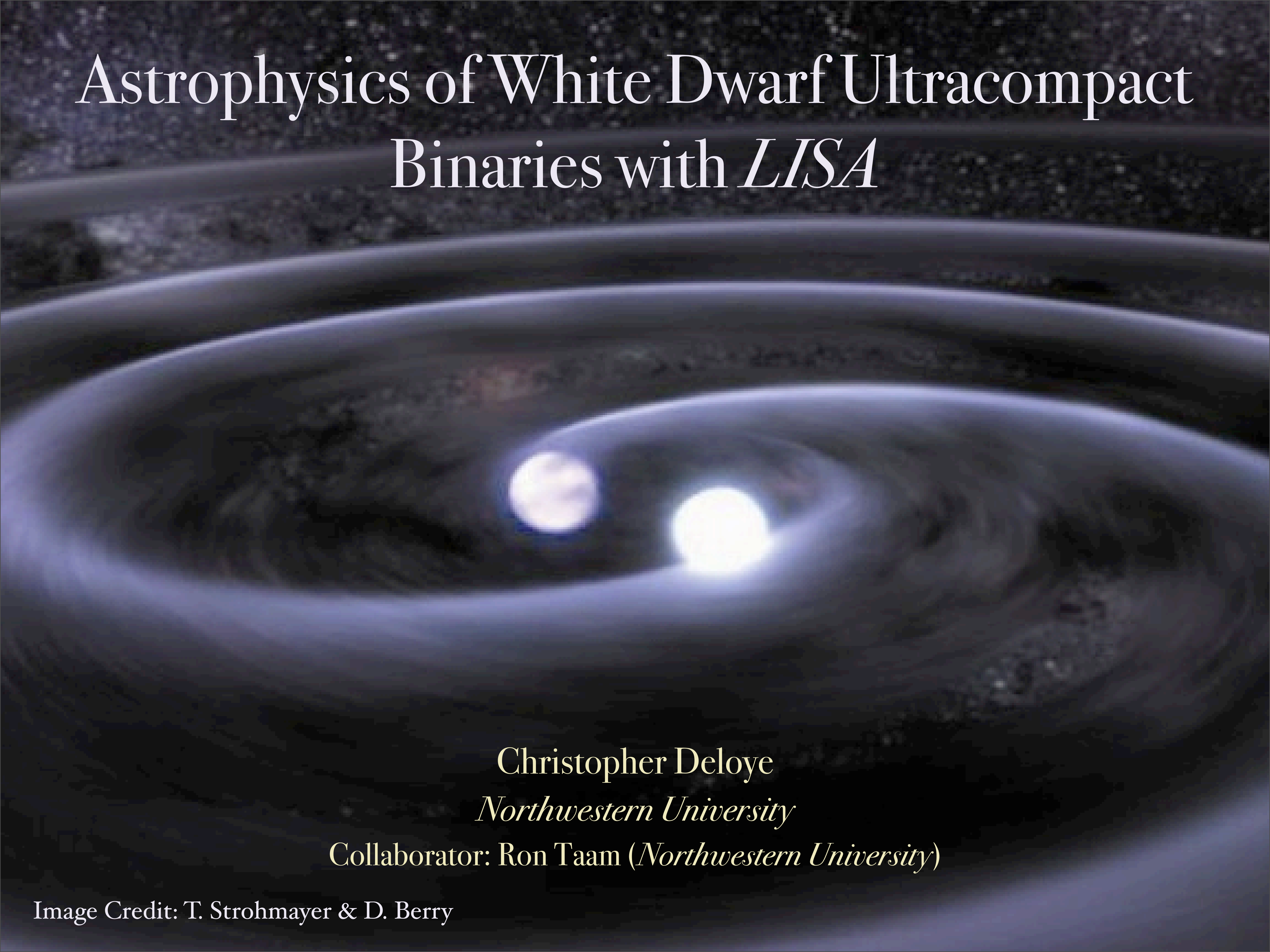
Astrophysics of White Dwarf Ultracompact Binaries with *LISA*



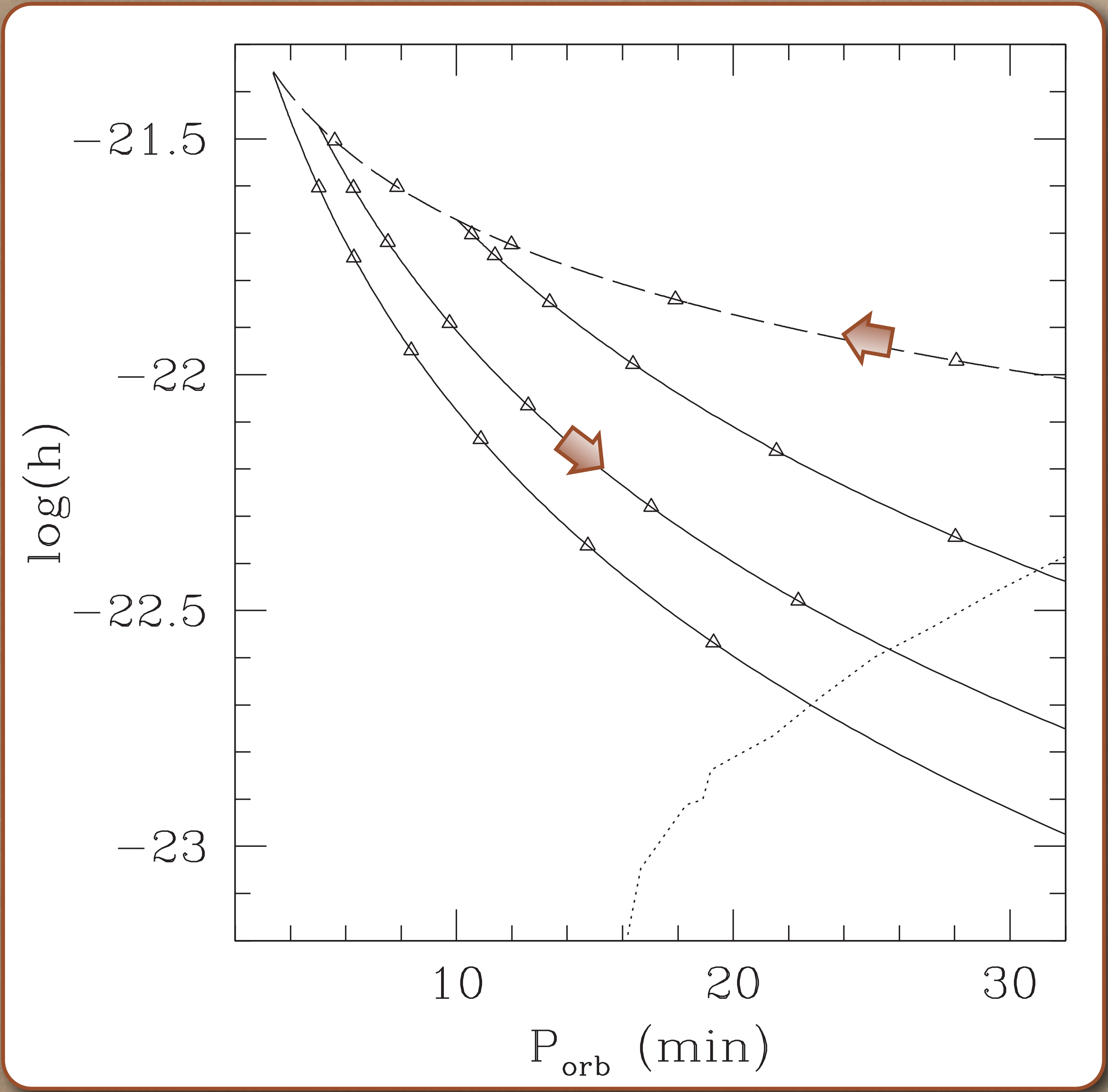
Christopher Deloye
Northwestern University
Collaborator: Ron Taam (*Northwestern University*)

Image Credit: T. Strohmayer & D. Berry

OUTLINE

- Introduction
    - Basics of ultracompact binary evolution.
    - Some open questions.
- Diagnostics of population properties from *LISA* observations.
- Physics important to outcomes at contact that can be probed with *LISA* derived constraints.

ULTRACOMPACT BINARIES WITH WDS: BASIC PICTURE



- Binary evolution driven by gravity wave angular momentum losses.
- Orbital period evolution phases:
  - Inspiral during detached phases (before mass transfer begins).
  - Onset of mass transfer; phase where donor contracts rapidly enough in response to mass loss to drive continued inward evolution.
  - (Some subset of systems) Eventual reversal of P_{orb} evolution once donor's contraction slows and then reverses.
- Component natures:
  - "Accretors": C/O or He WDs.
  - "Donors": C/O WDs, He WDs, or He-burning stars.
- Most systems seen in mass-transferring phase:
  - Longer lived.
  - Accreting systems brighter.

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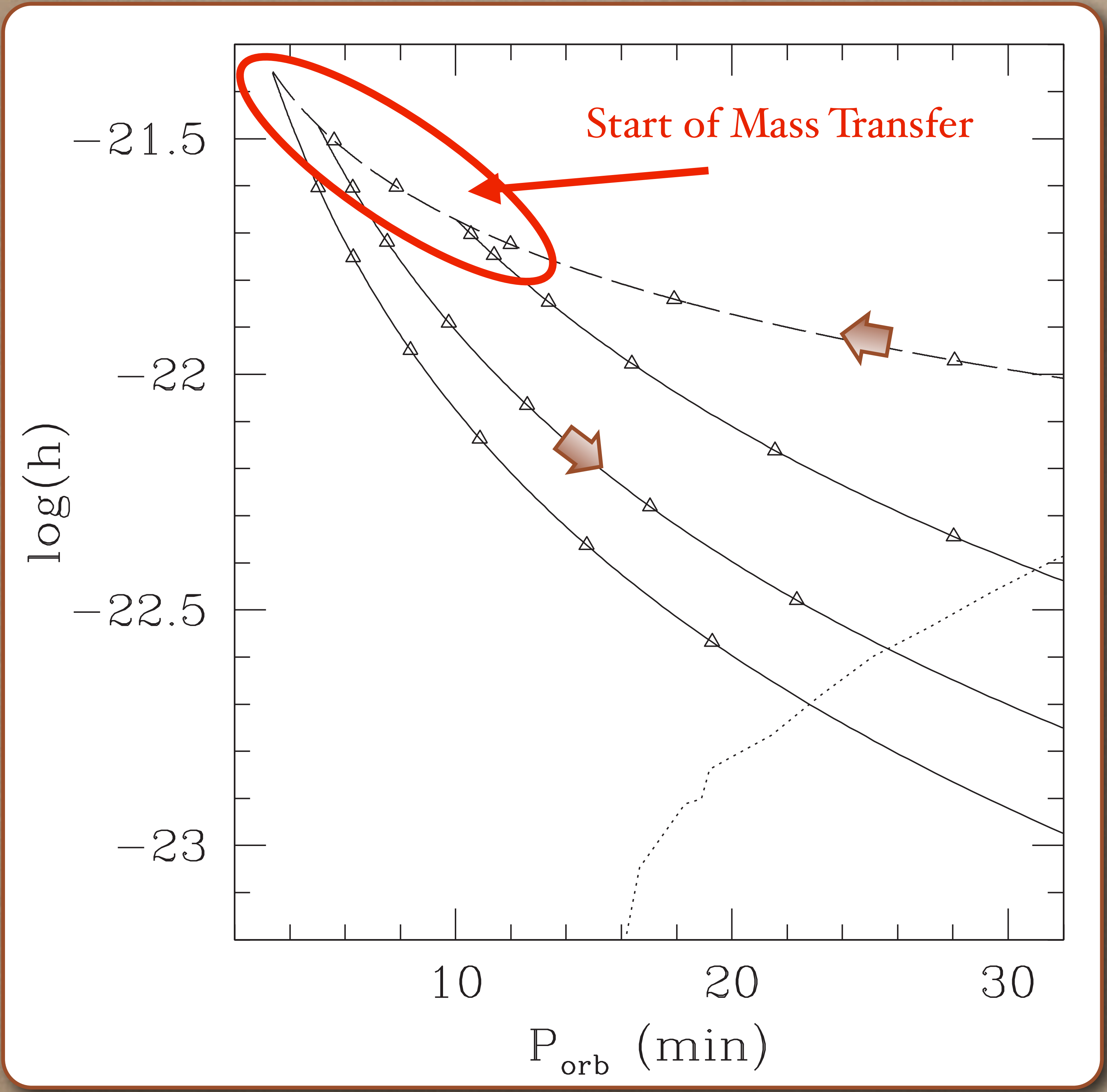

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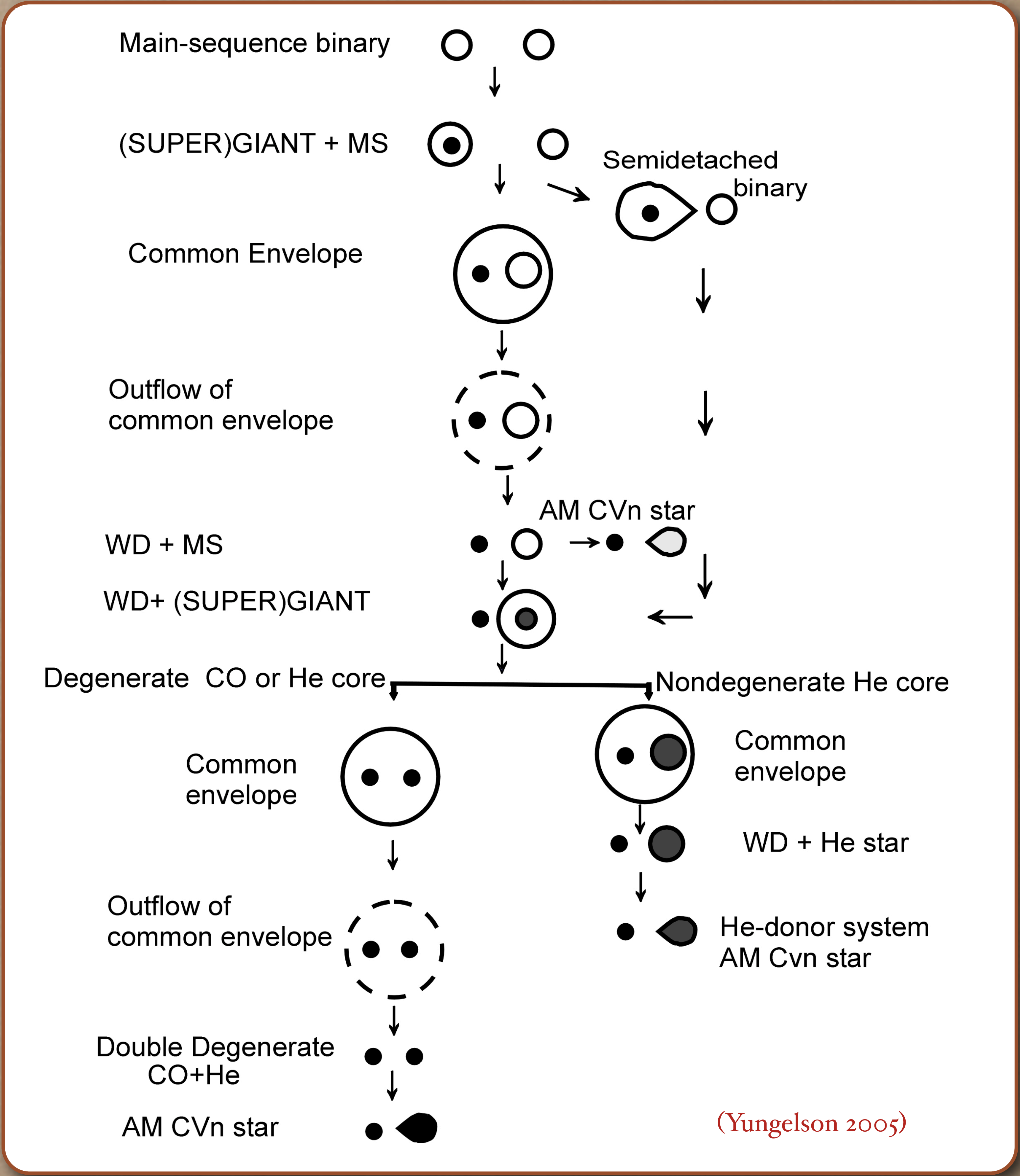
FORMING WD-ULTRACOMPACT BINARIES: PRIOR BINARY EVOLUTION



(Yungelson 2005)

FORMING WD-ULTRACOMPACT BINARIES: PRIOR BINARY EVOLUTION

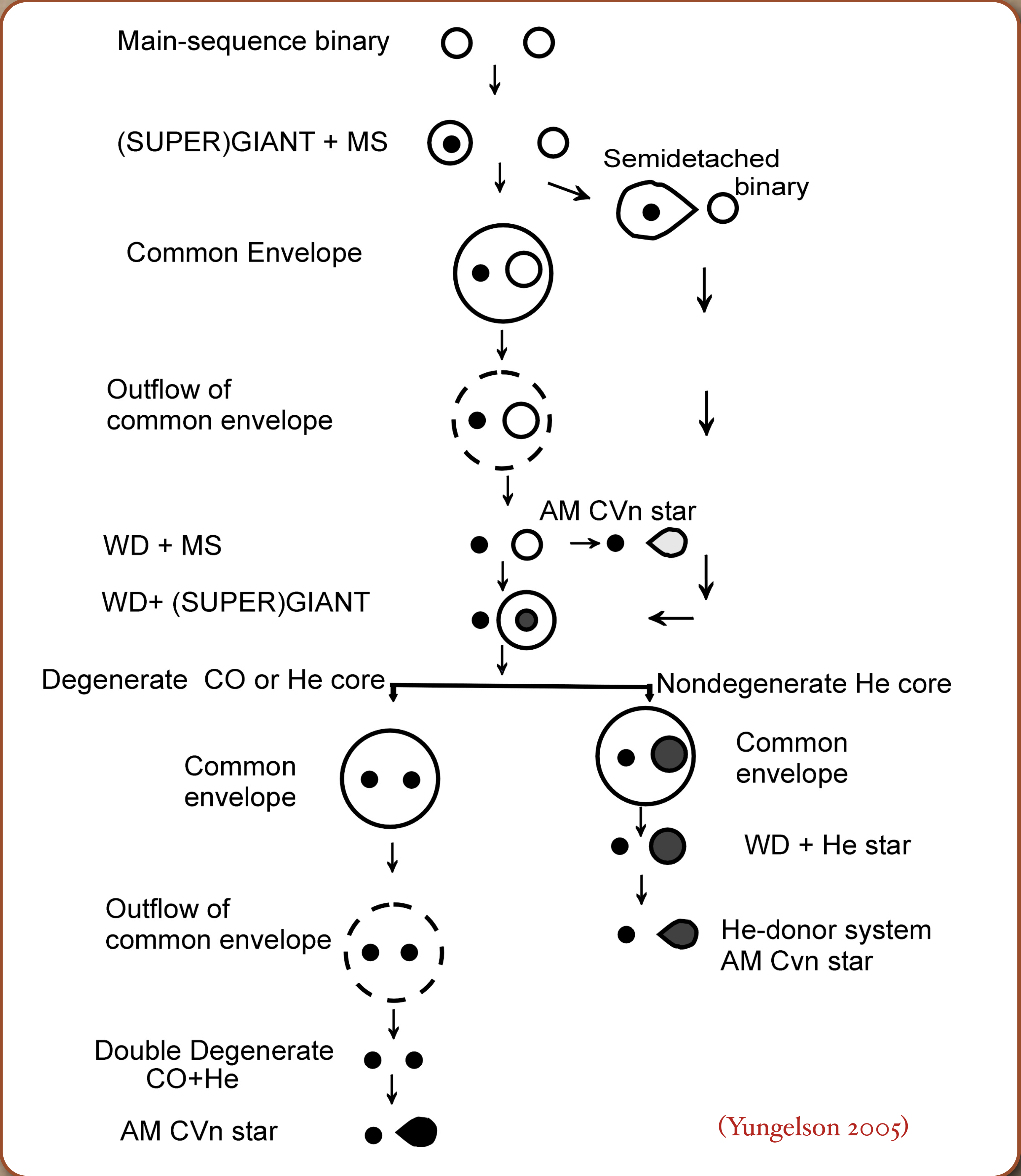
Primordial Binary Parameters:
(M_1', M_2', a')

↓

Binary Evolution Processes

↓

Binary Parameters at Contact:
$[M_{1,i}, M_{2,i}, R_{2,i}, X_{2,i}]$



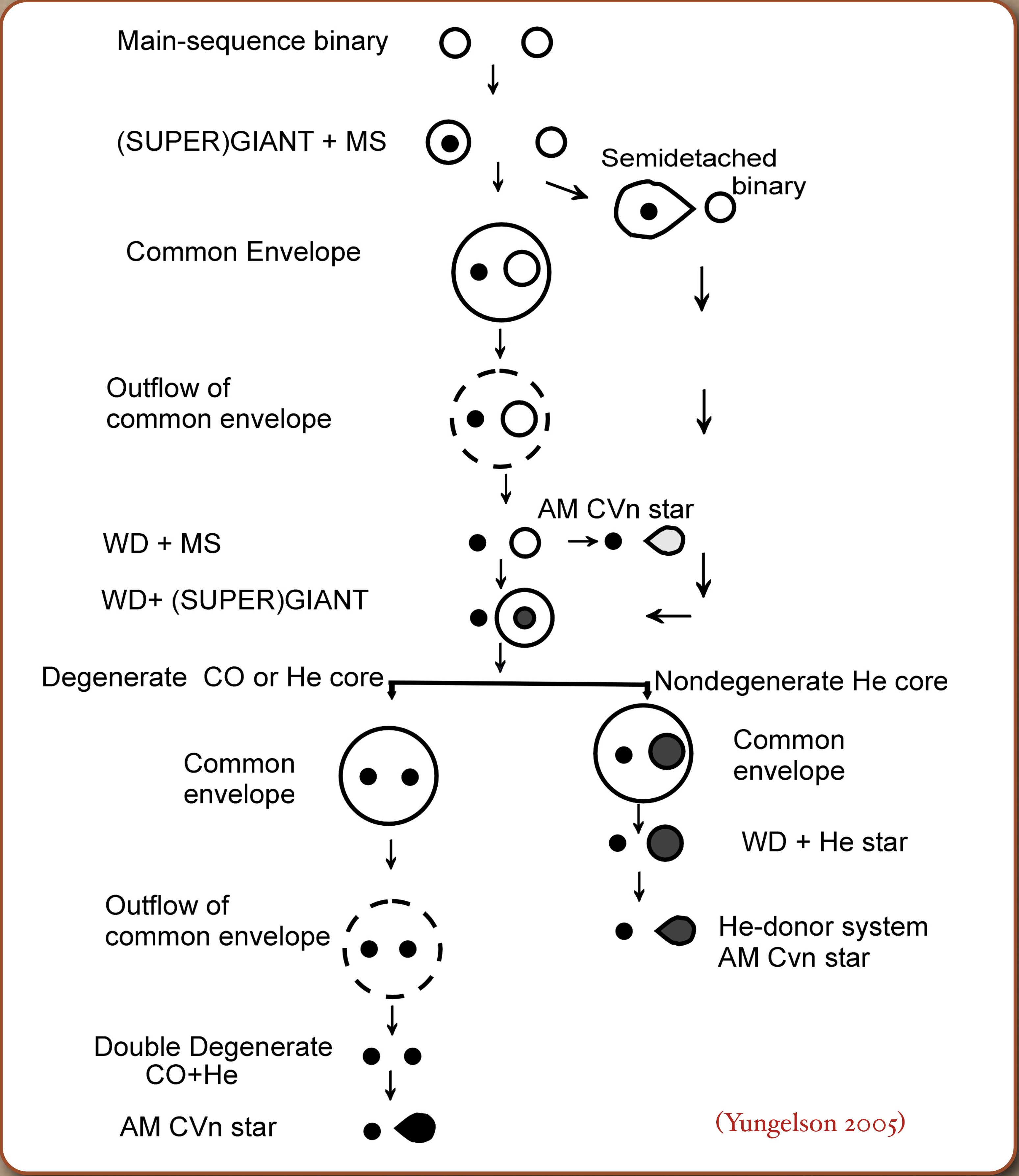
(Yungelson 2005)

FORMING WD-ULTRACOMPACT BINARIES: PRIOR BINARY EVOLUTION

Primordial Binary Parameters:
(M_1', M_2', a')

Theoretically Uncertain

Binary Parameters at Contact:
$[M_{1,i}, M_{2,i}, R_{2,i}, X_{2,i}]$



(Yungelson 2005)

Examples of Possible Contact Outcomes: Proto-AM CVn Binaries

M_1

(C/O or He WD)

M_2

(He "WD")

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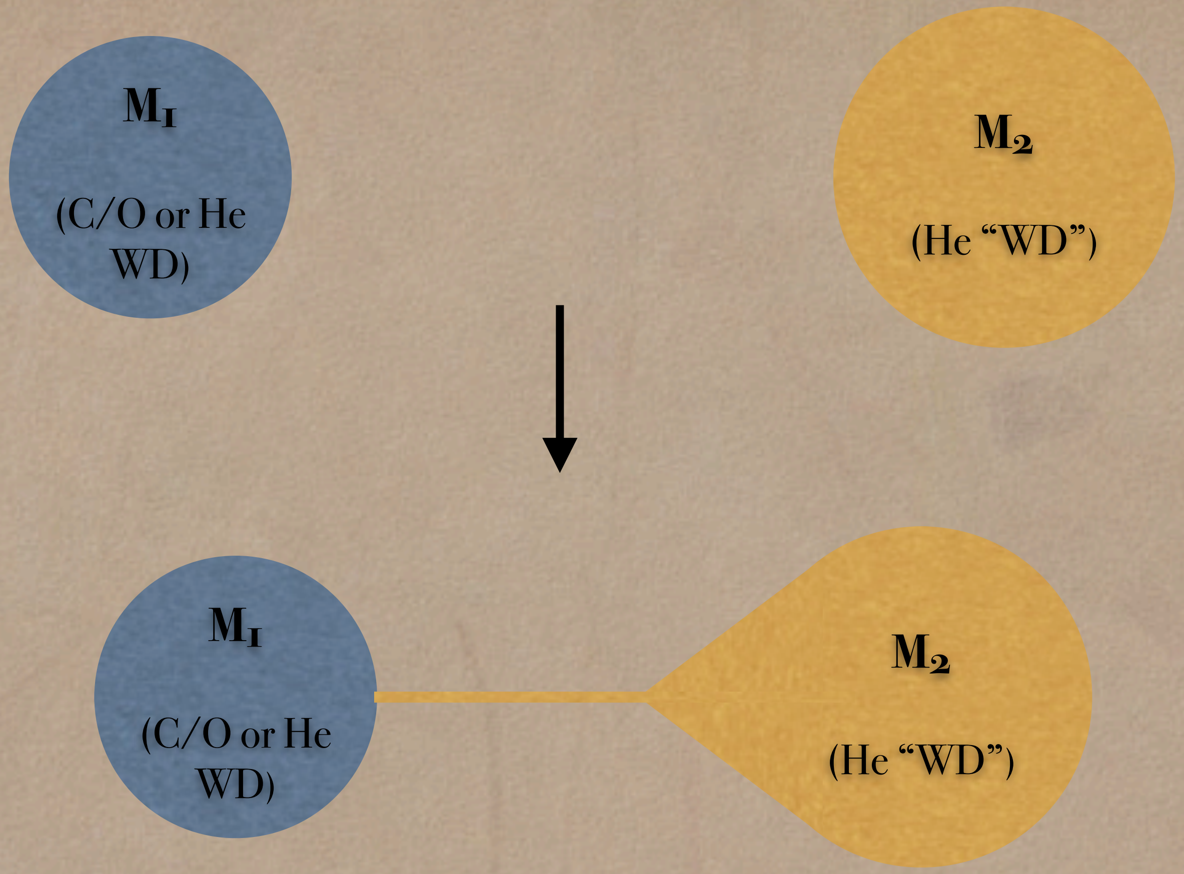

M_1

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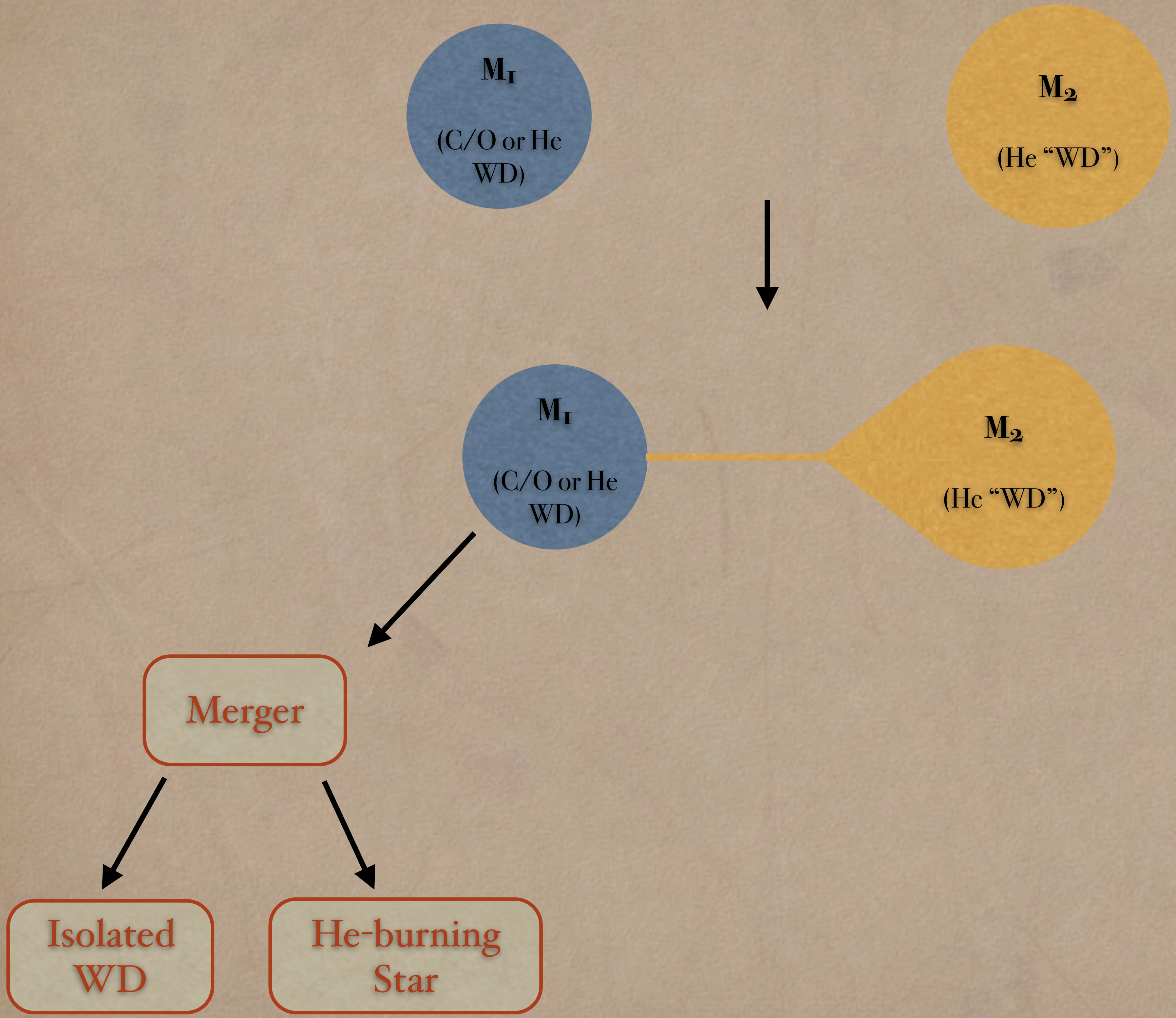
EXAMPLES OF POSSIBLE CONTACT OUTCOMES: PROTO-AM CVN BINARIES



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(C/O or He WD)

M_2

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Merger

Isolated WD

He-burning Star

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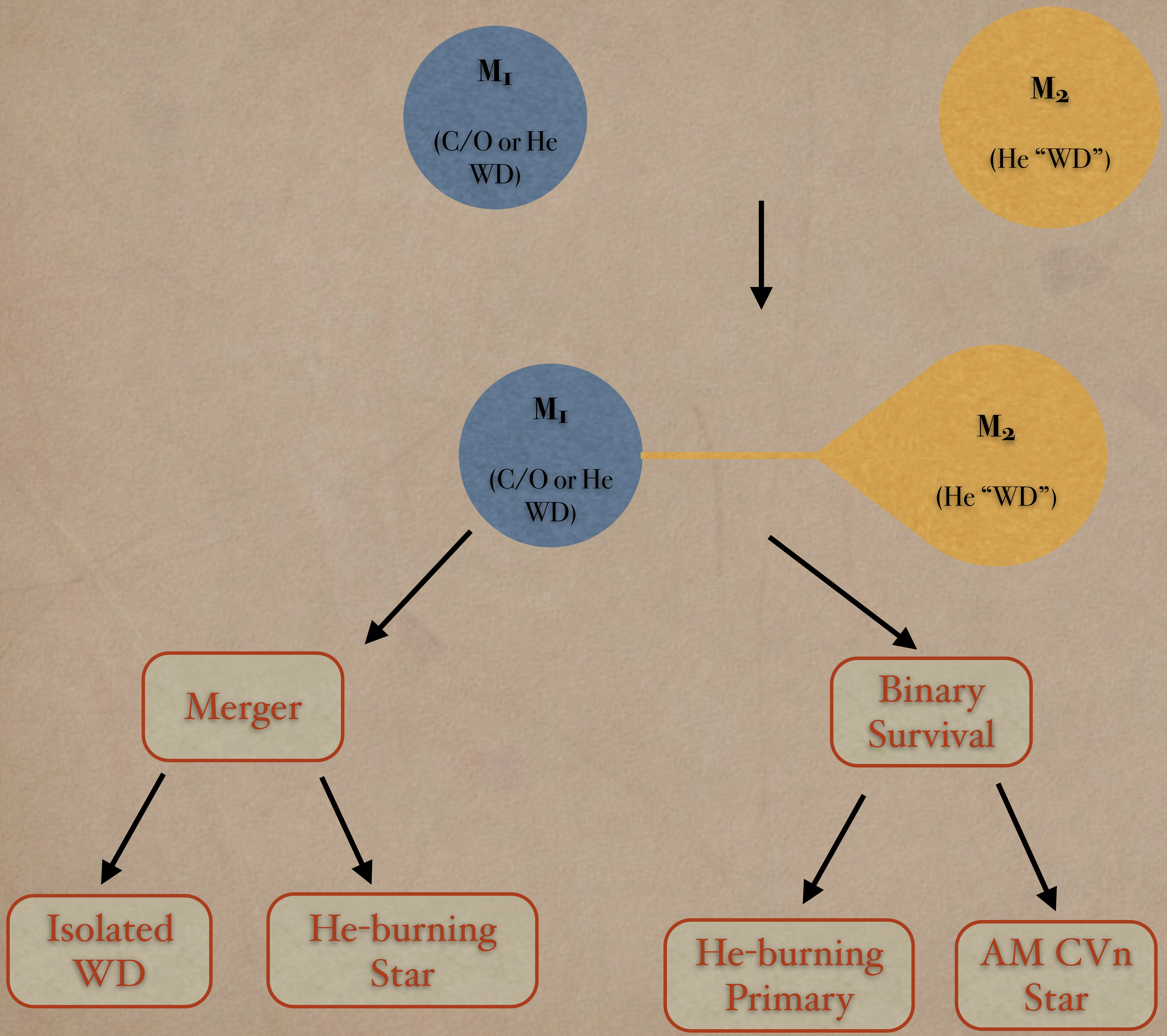

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Merger

Binary Survival

Isolated WD

He-burning Star

He-burning Primary

AM CVn Star

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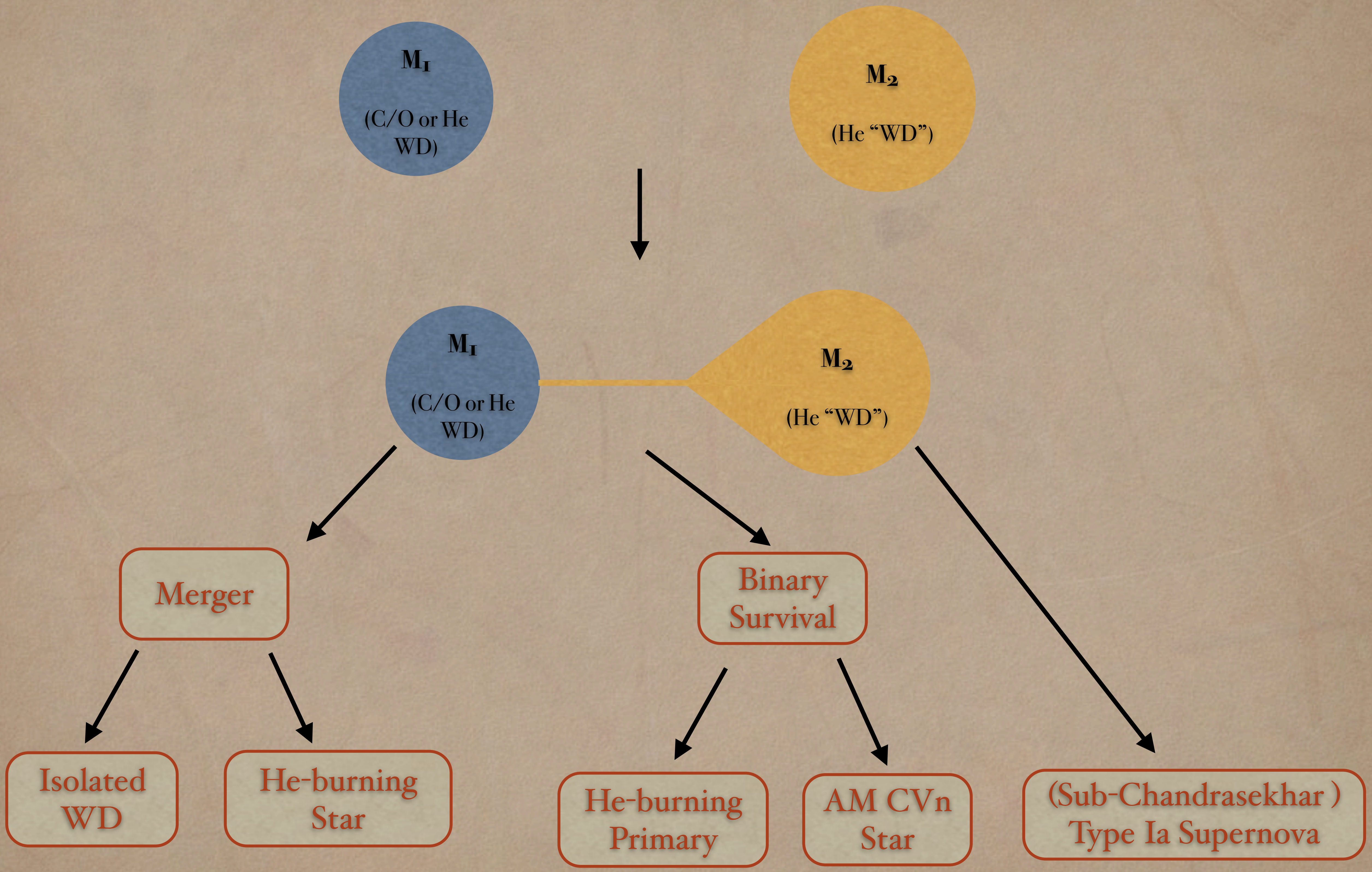

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AM CVn Star

(Sub-Chandrasekhar) Type Ia Supernova

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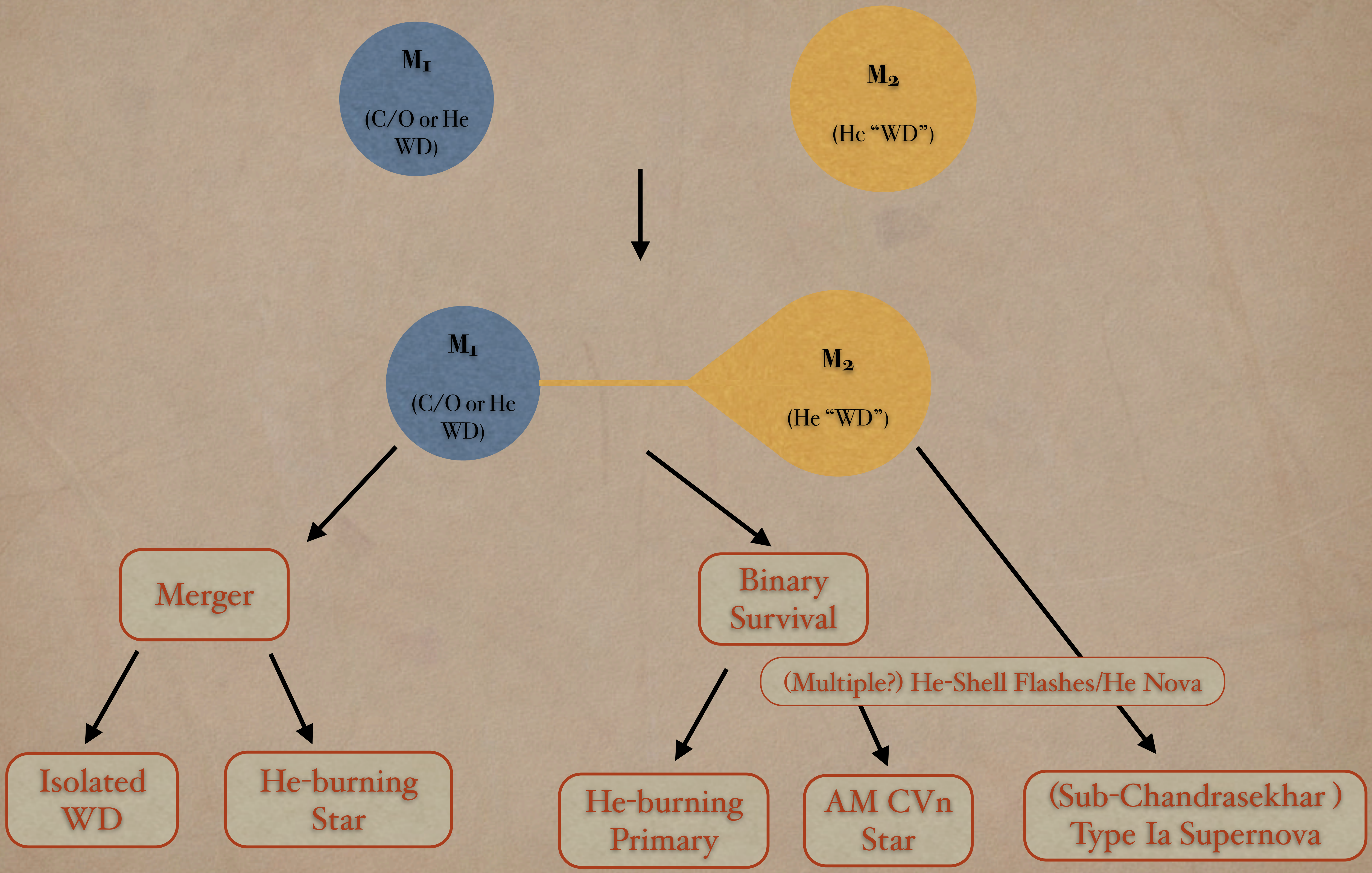

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Merger

Binary Survival

(Multiple?) He-Shell Flashes/He Nova

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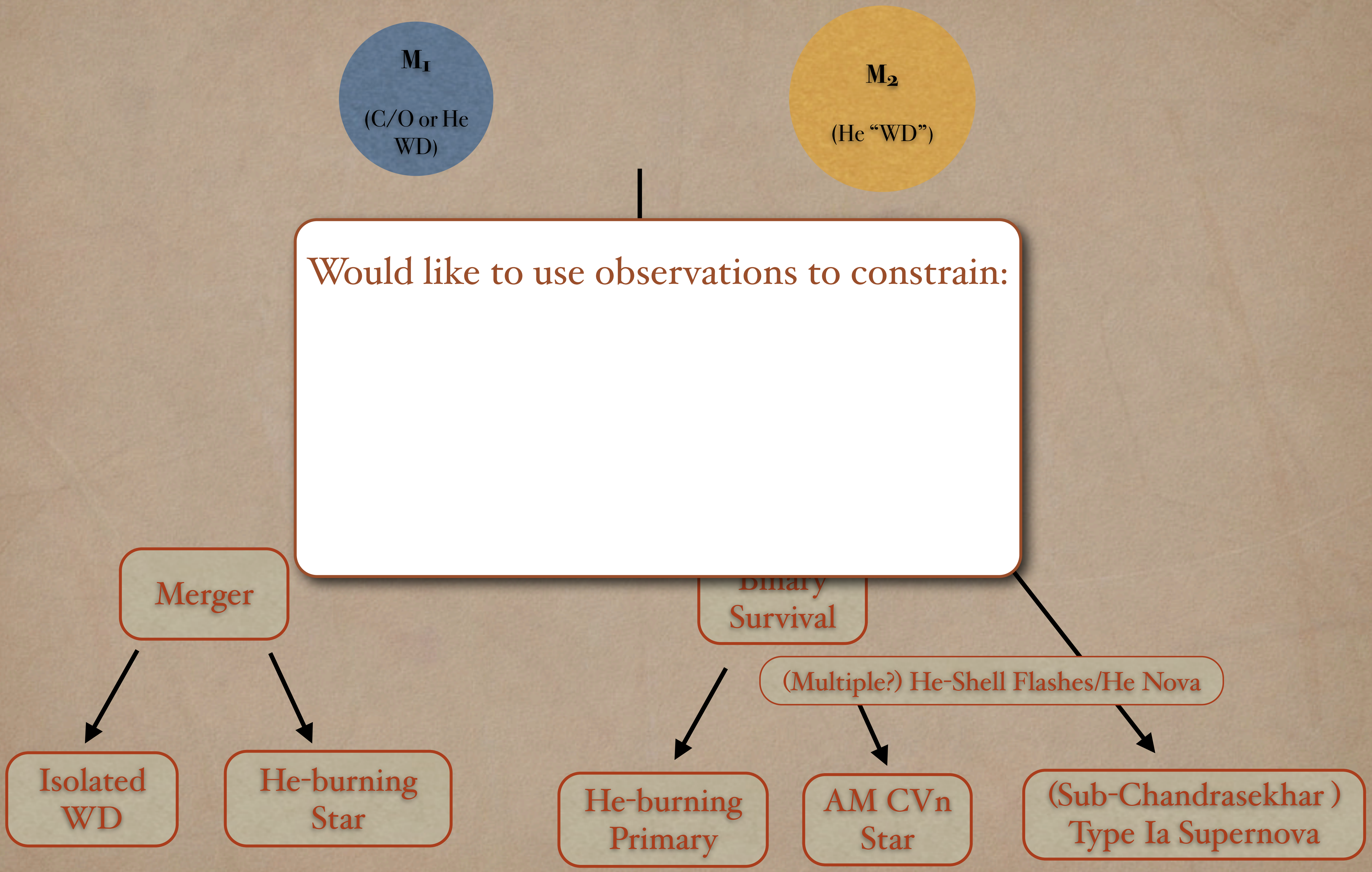
Examples of Possible Contact Outcomes: Proto-AM CVn Binaries



M_1

(C/O or He WD)

M_2

(He "WD")

Would like to use observations to constrain:

Merger

Binary Survival

(Multiple?) He-Shell Flashes/He Nova

Isolated WD

He-burning Star

He-burning Primary

AM CVn Star

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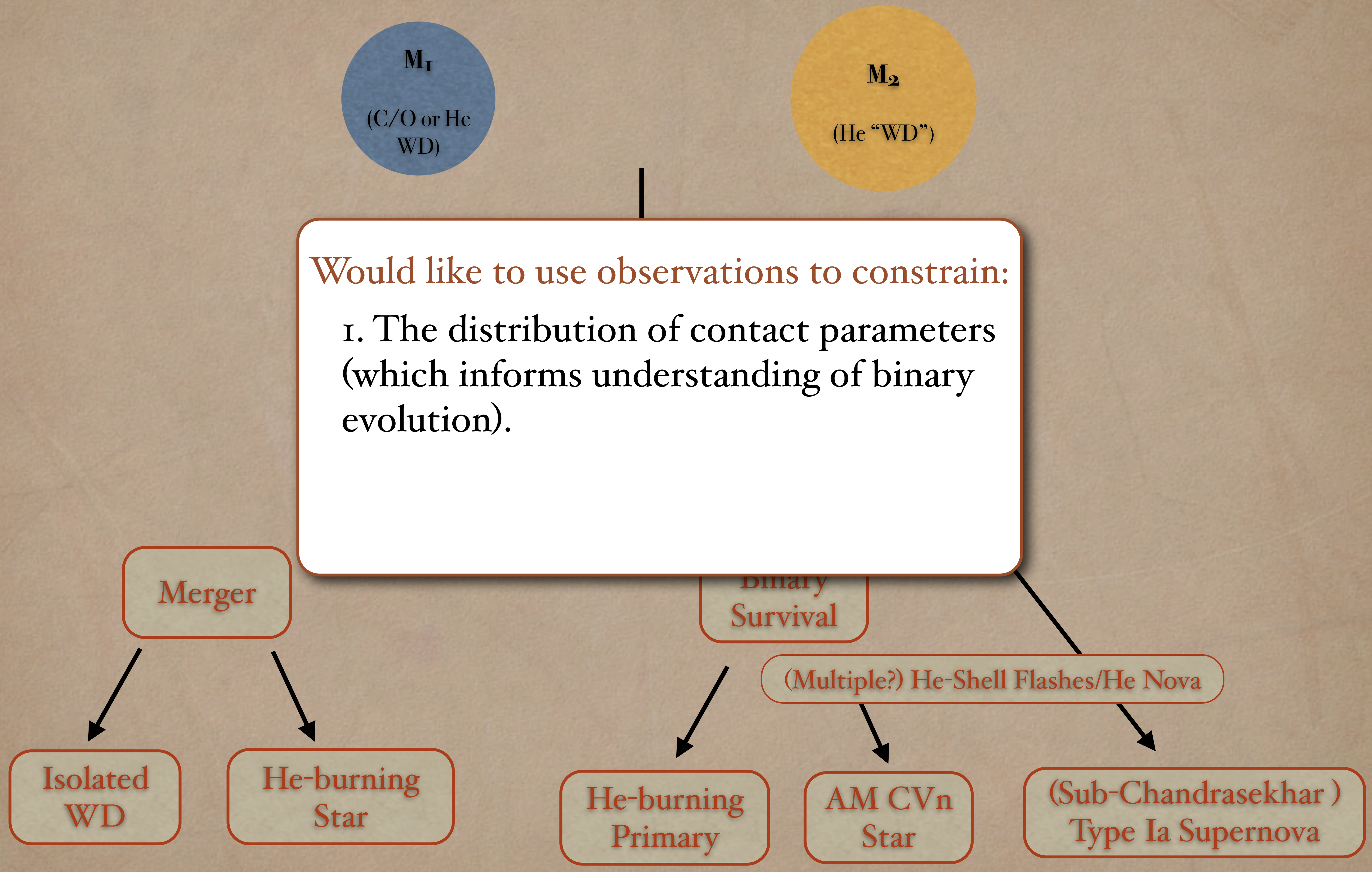

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Merger

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Binary Survival

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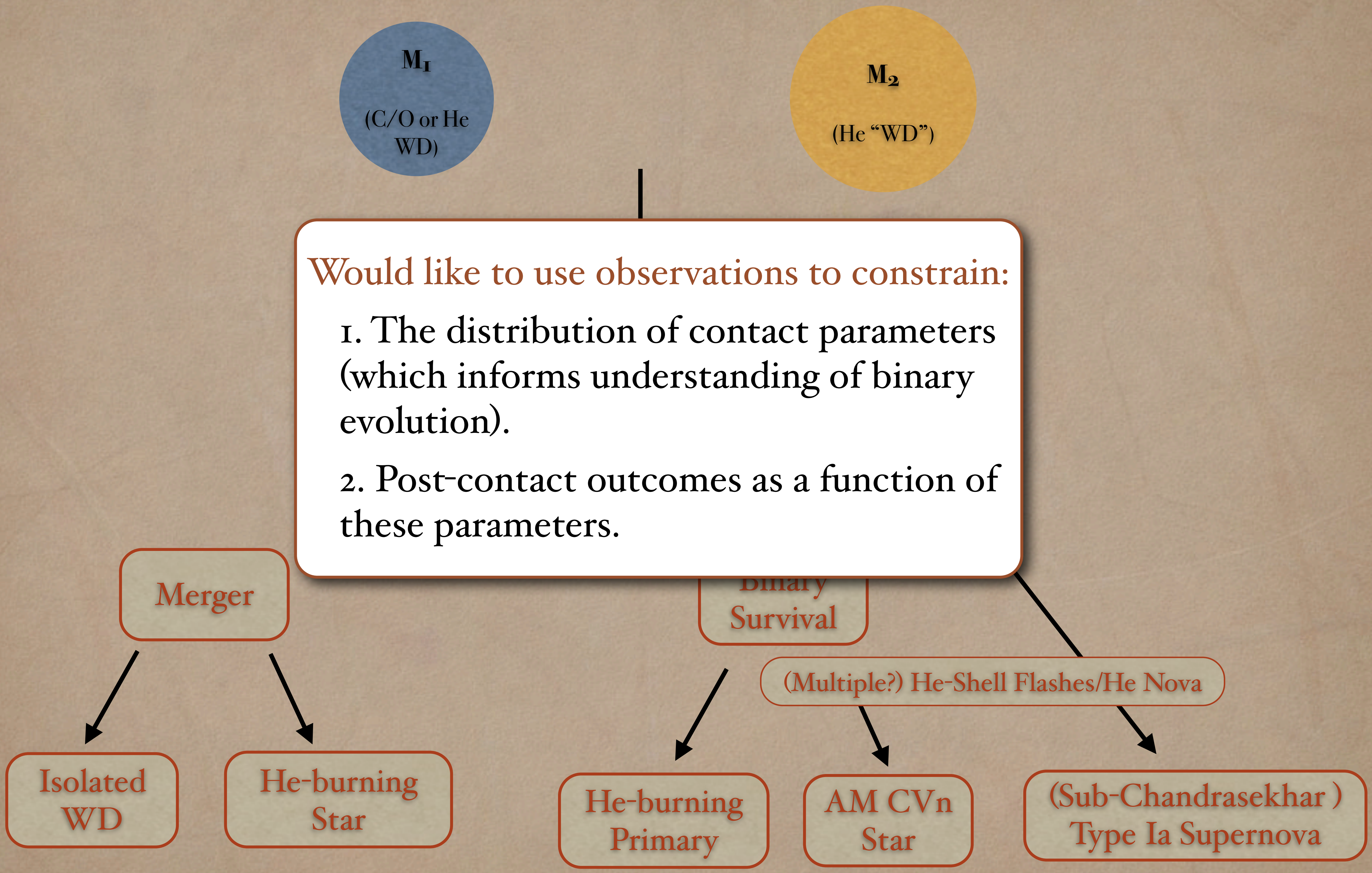
Would like to use observations to constrain:

1. The distribution of contact parameters (which informs understanding of binary evolution).

Examples of Possible Contact Outcomes: Proto-AM CVn Binaries



M_1

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Would like to use observations to constrain:

1. The distribution of contact parameters (which informs understanding of binary evolution).
2. Post-contact outcomes as a function of these parameters.

Merger

Binary Survival

(Multiple?) He-Shell Flashes/He Nova

Isolated WD

He-burning Star

He-burning Primary

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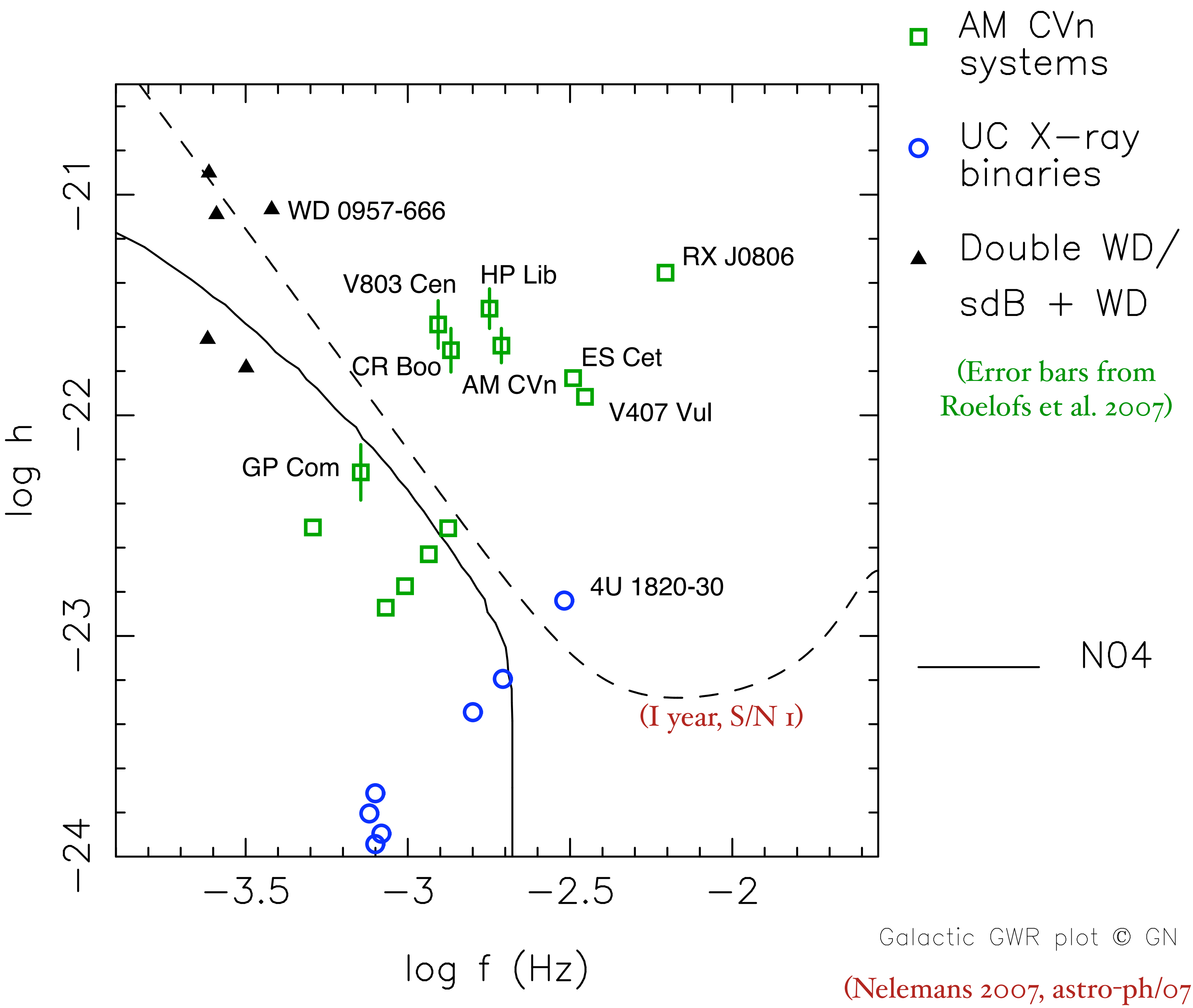
(Sub-Chandrasekhar) Type Ia Supernova

KNOWN SAMPLE OF ULTRACOMPACT BINARIES



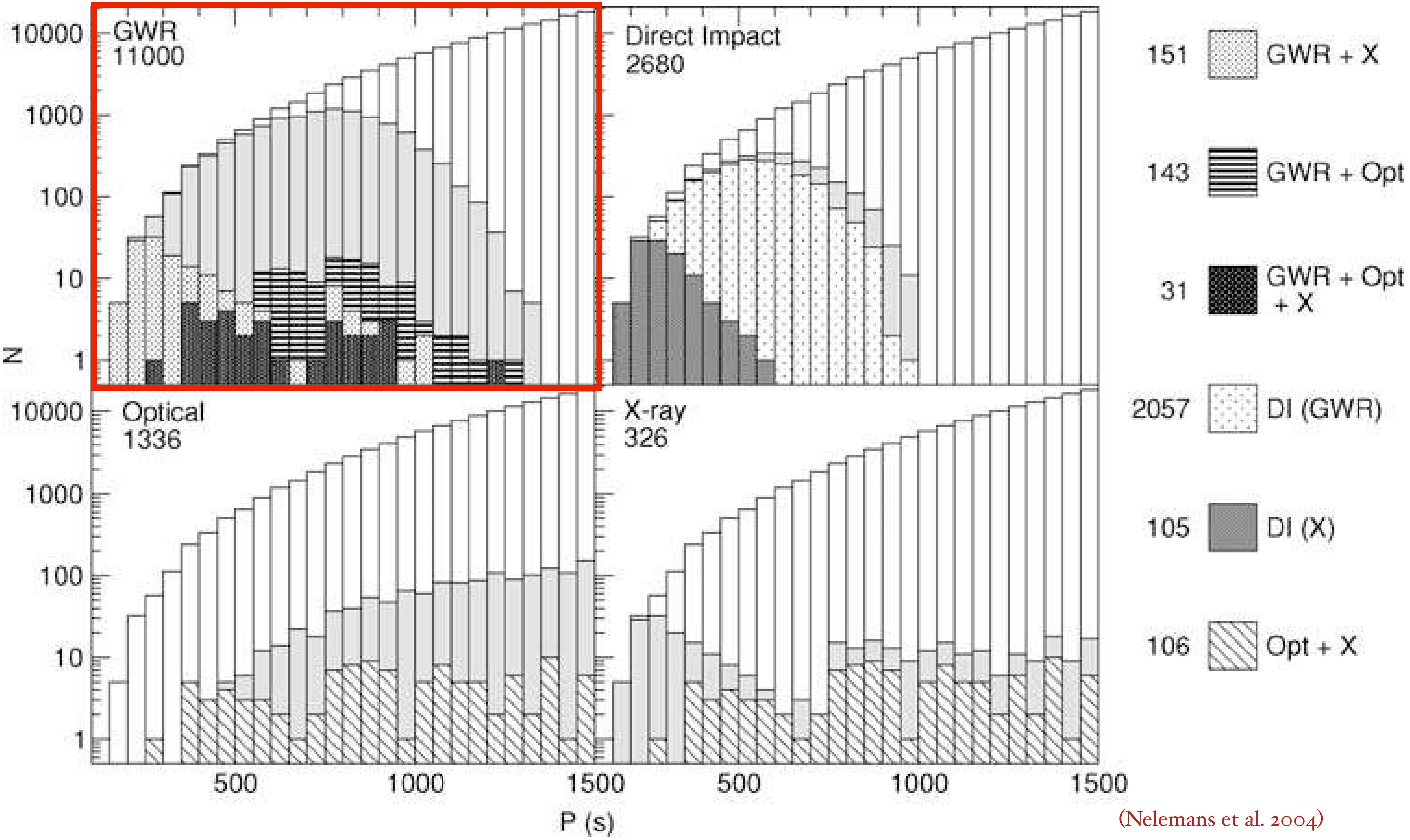
(Error bars from Roelofs et al. 2007)

Galactic GWR plot © GN 2005

(Nelemans 2007, astro-ph/0703292)

- 16-18 AM CVn systems known from EM observations.
- Galactic-Plane surveys expected to turn up ≈ 750 (Nelemans 2007).
- Many AM CVn systems will serve as verification sources for *LISA*.

AM CVn Population as Seen by *LISA*



(Nelemans et al. 2004)

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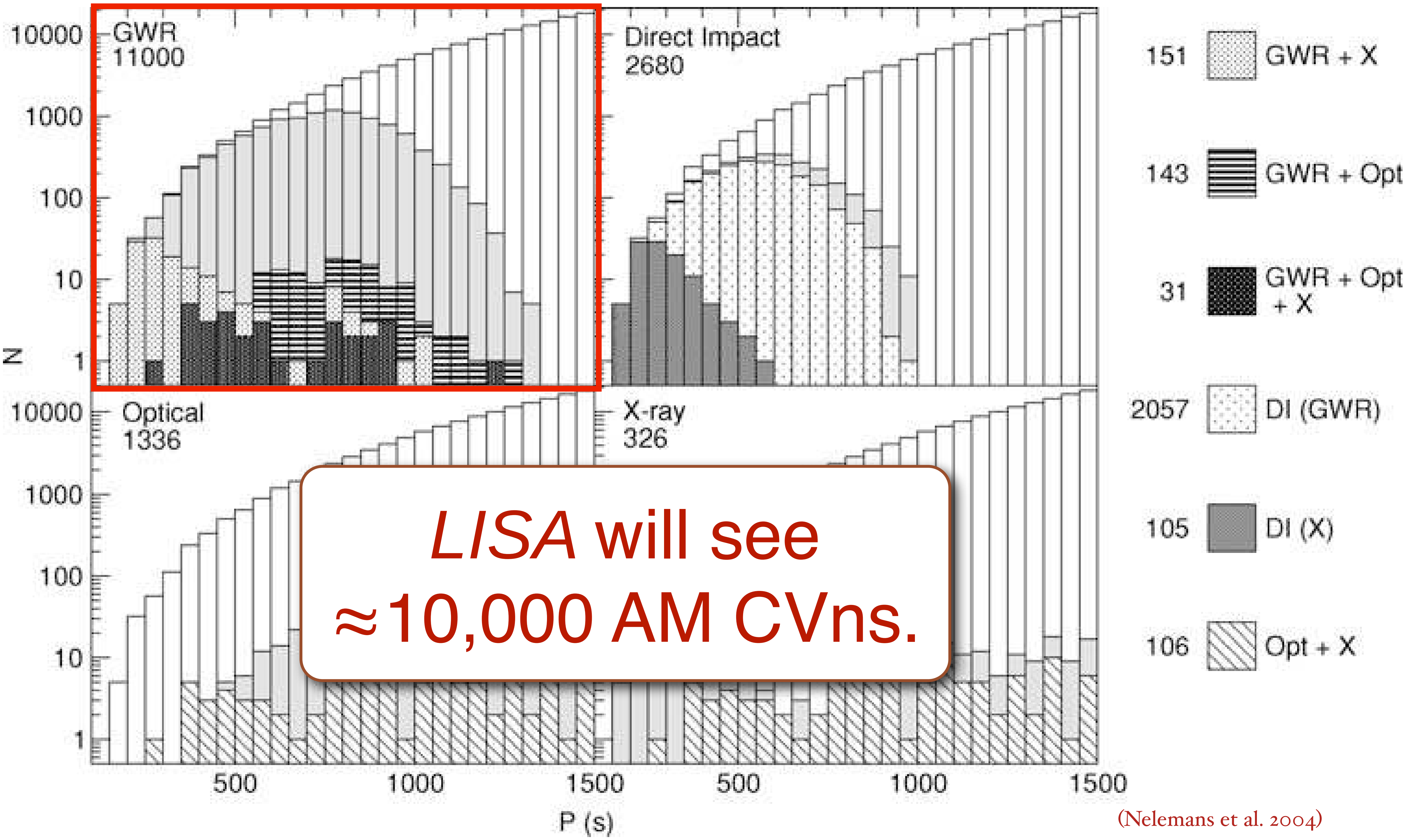
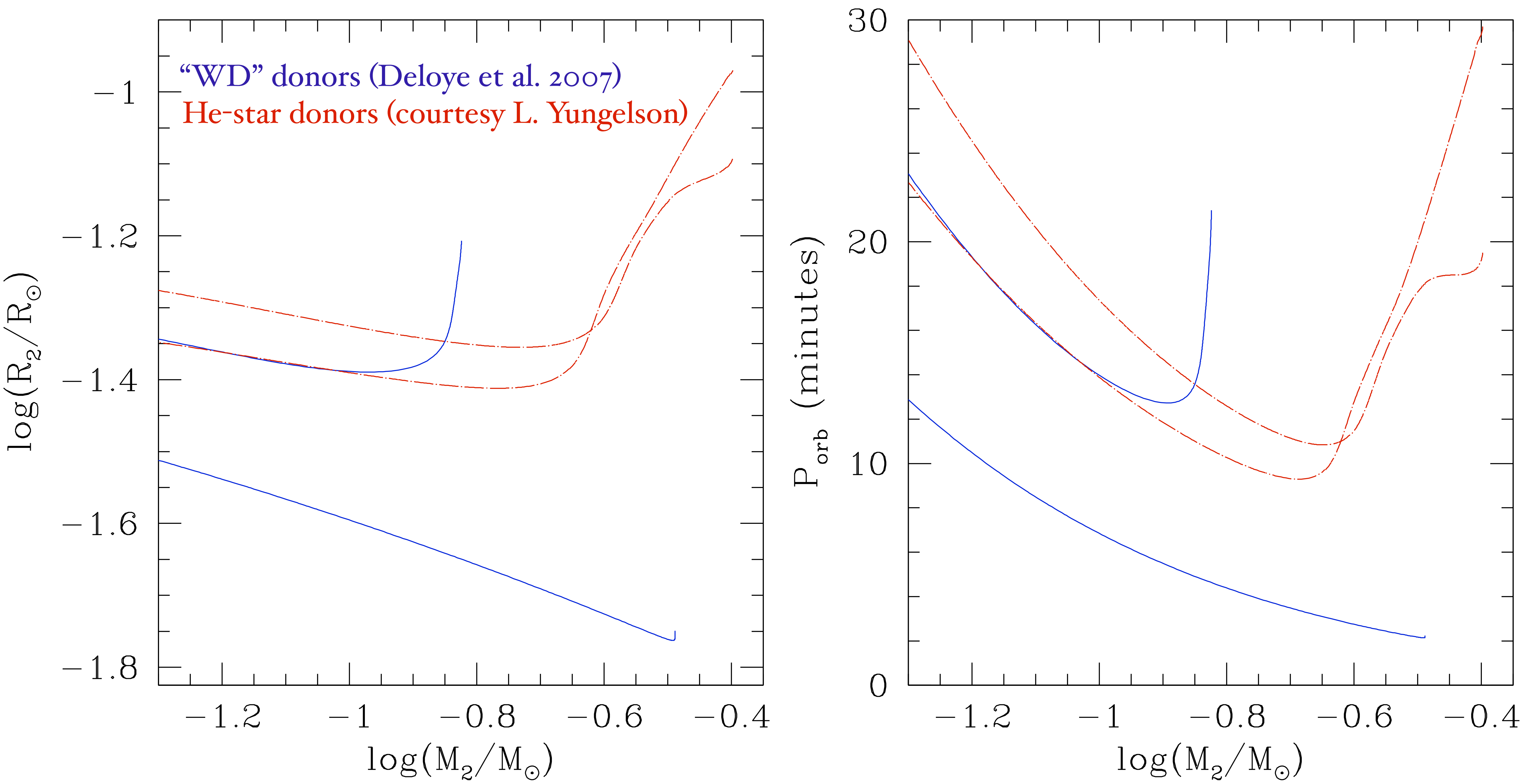


LISA will see ≈10,000 AM CVns.

(Nelemans et al. 2004)

AM CVN (I.E. POST-CONTACT) EVOLUTION DEPENDS ON PRIOR BINARY EVOLUTION



Variations in R_2 evolution set by conditions at contact.

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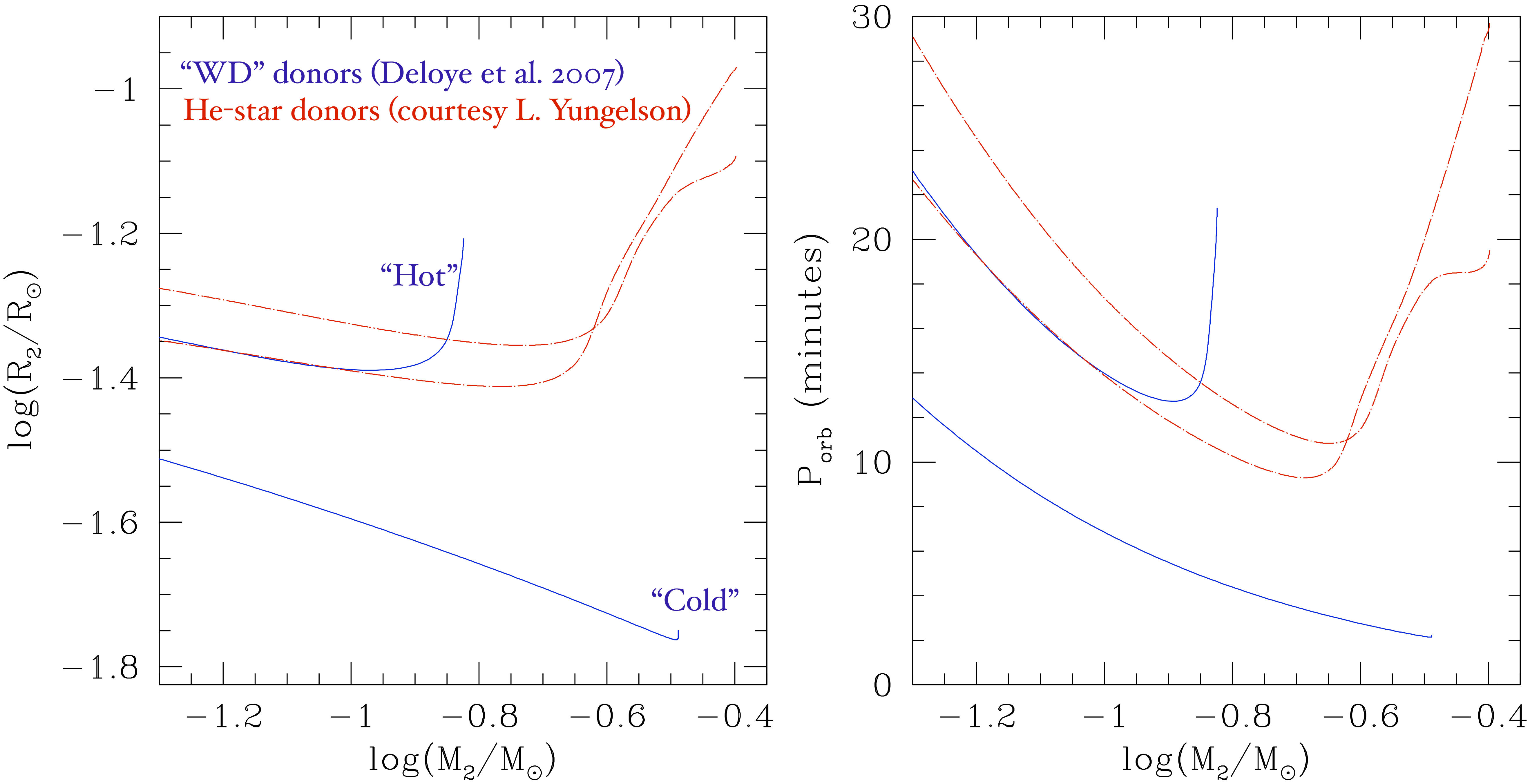

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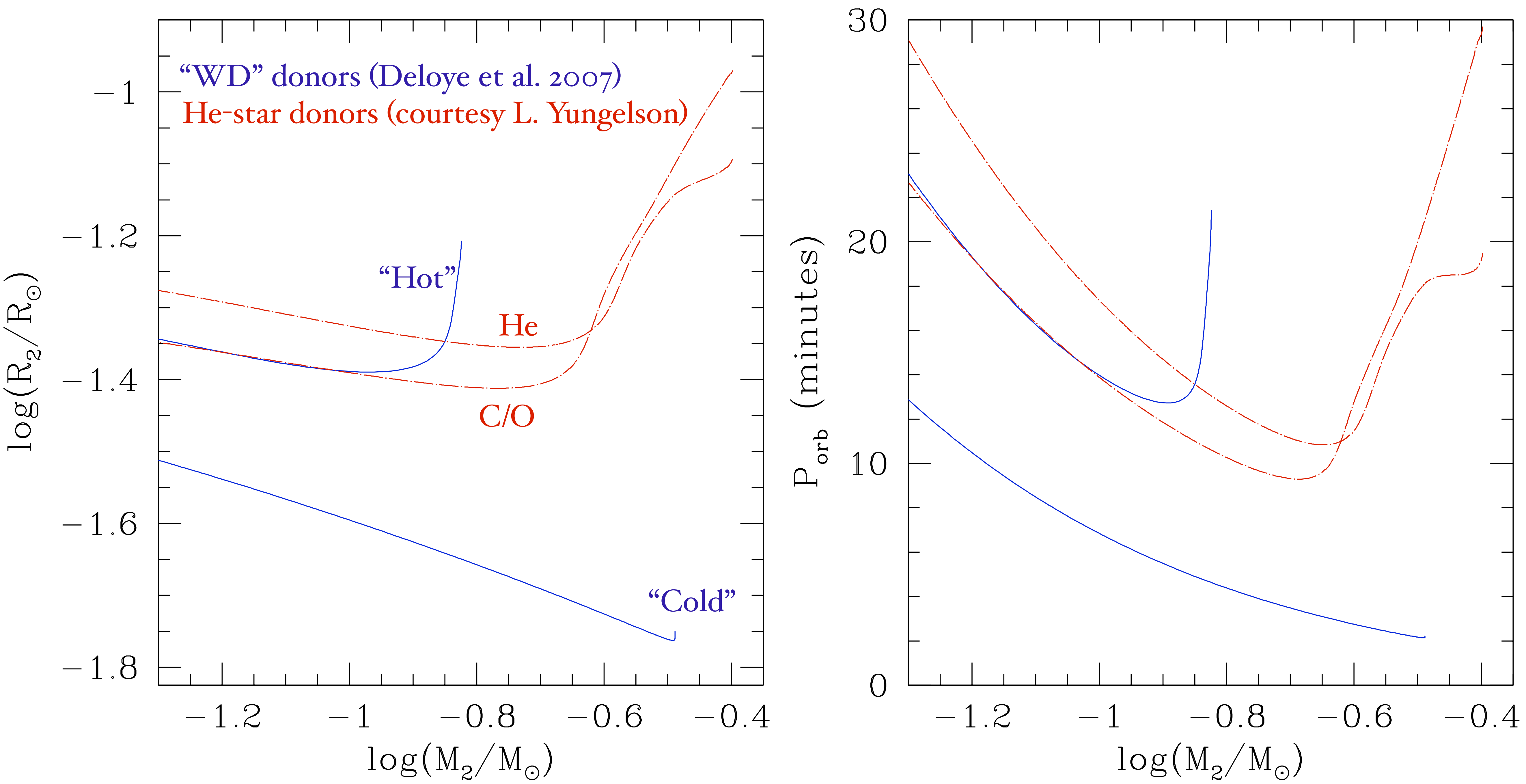

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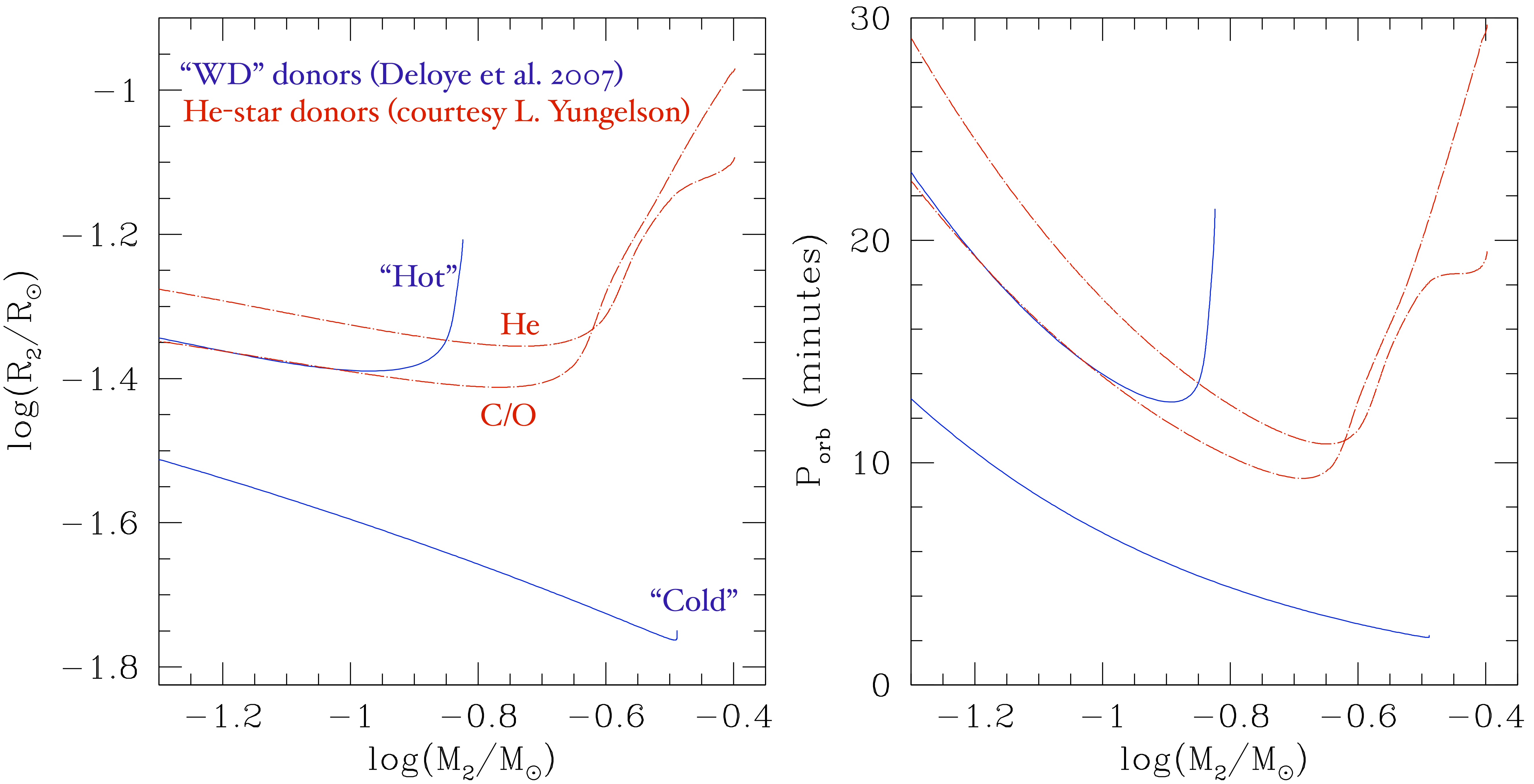
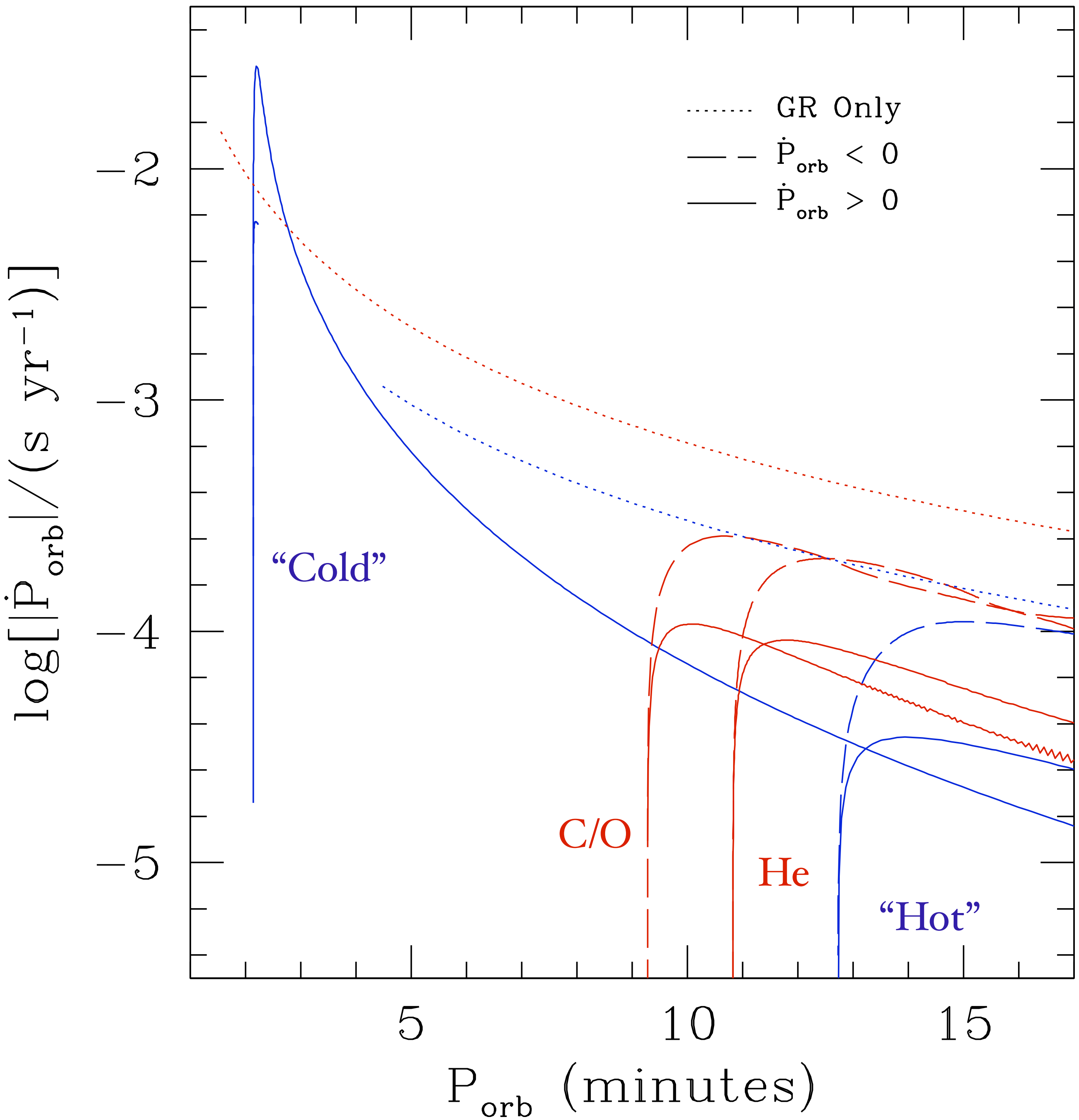


Variations in R_2 evolution set by conditions at contact.

Once mass transfer starts:

$$P_{\rm orb} \approx 53.4 {\rm min} \left(\frac{R_2}{0.1R_\odot}\right)^{3/2} \left(\frac{M_2}{0.1M_\odot}\right)^{-1/2}$$

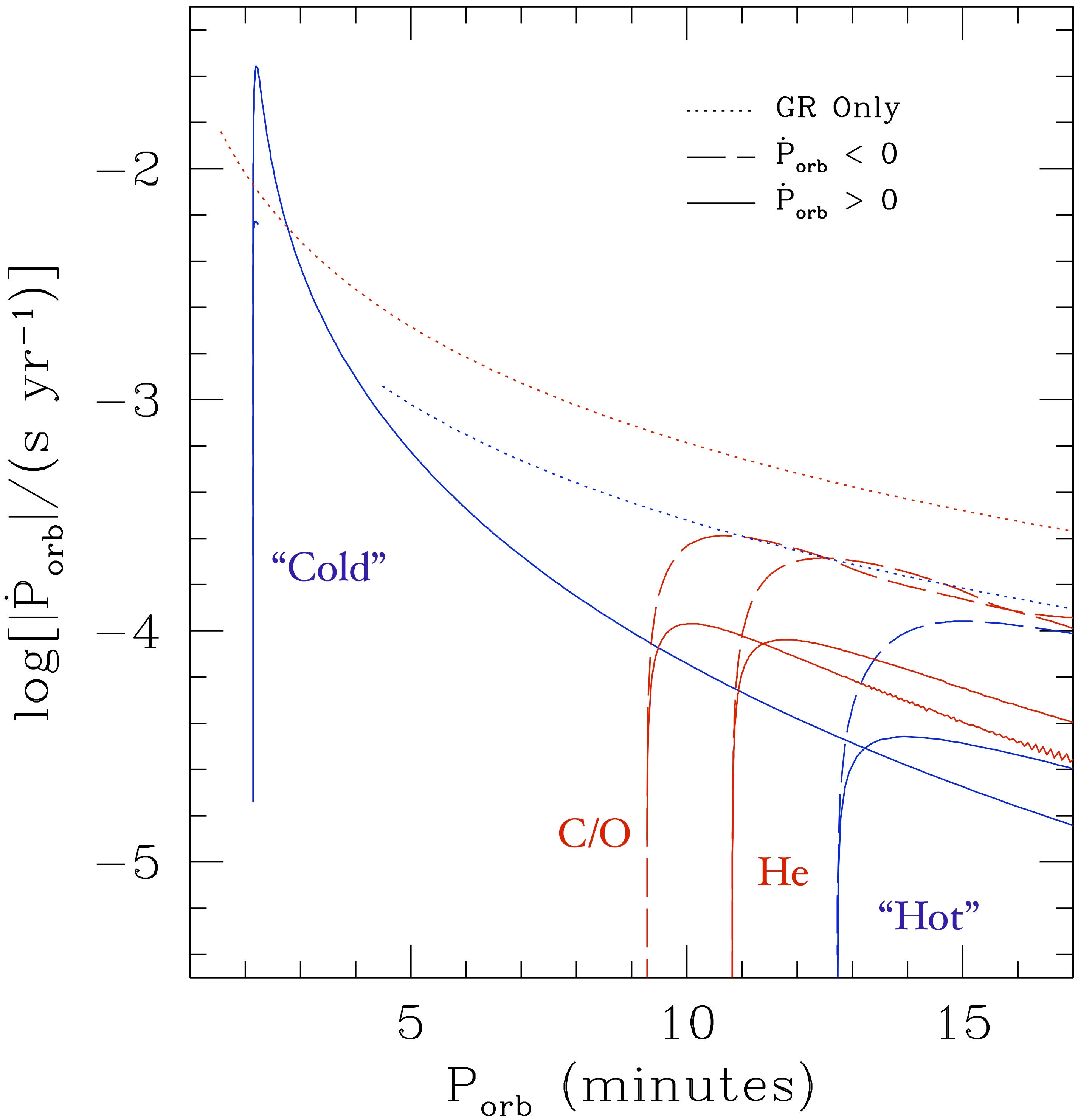
Implications for the Orbital Period Evolution



$$\dot{P}_{\rm orb} = 3P_{\rm orb}\times \left[\left(\frac{\dot{J}}{J}\right)_{\rm GR} - \frac{\dot{M}_2}{M_2}\left(1-\frac{M_2}{M_1}\right)\right]$$

$$\frac{P_{\rm orb}}{\dot{P}_{\rm orb}} \lesssim 10^7 {\rm yrs}$$

IMPLICATIONS FOR THE ORBITAL PERIOD EVOLUTION



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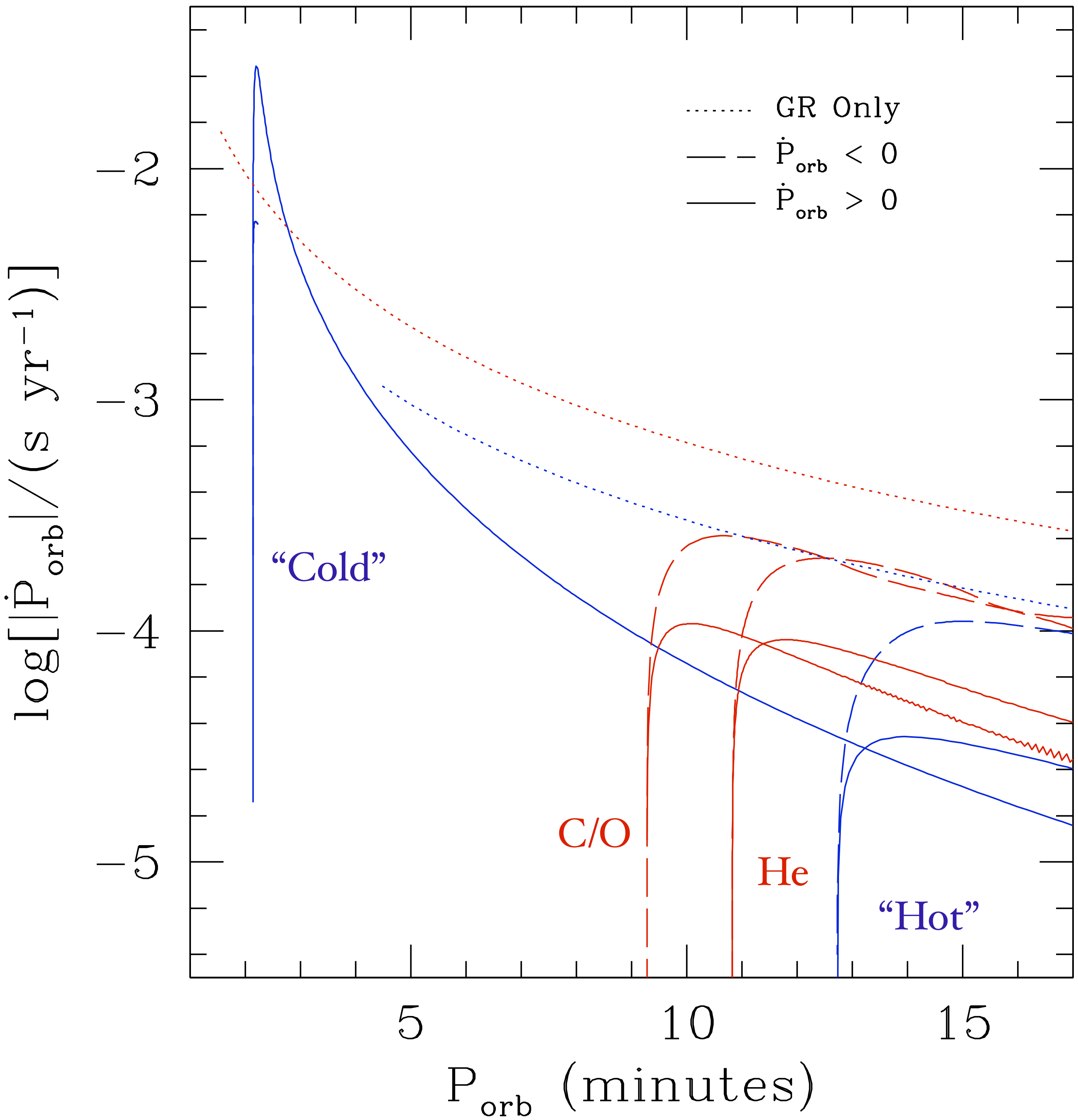

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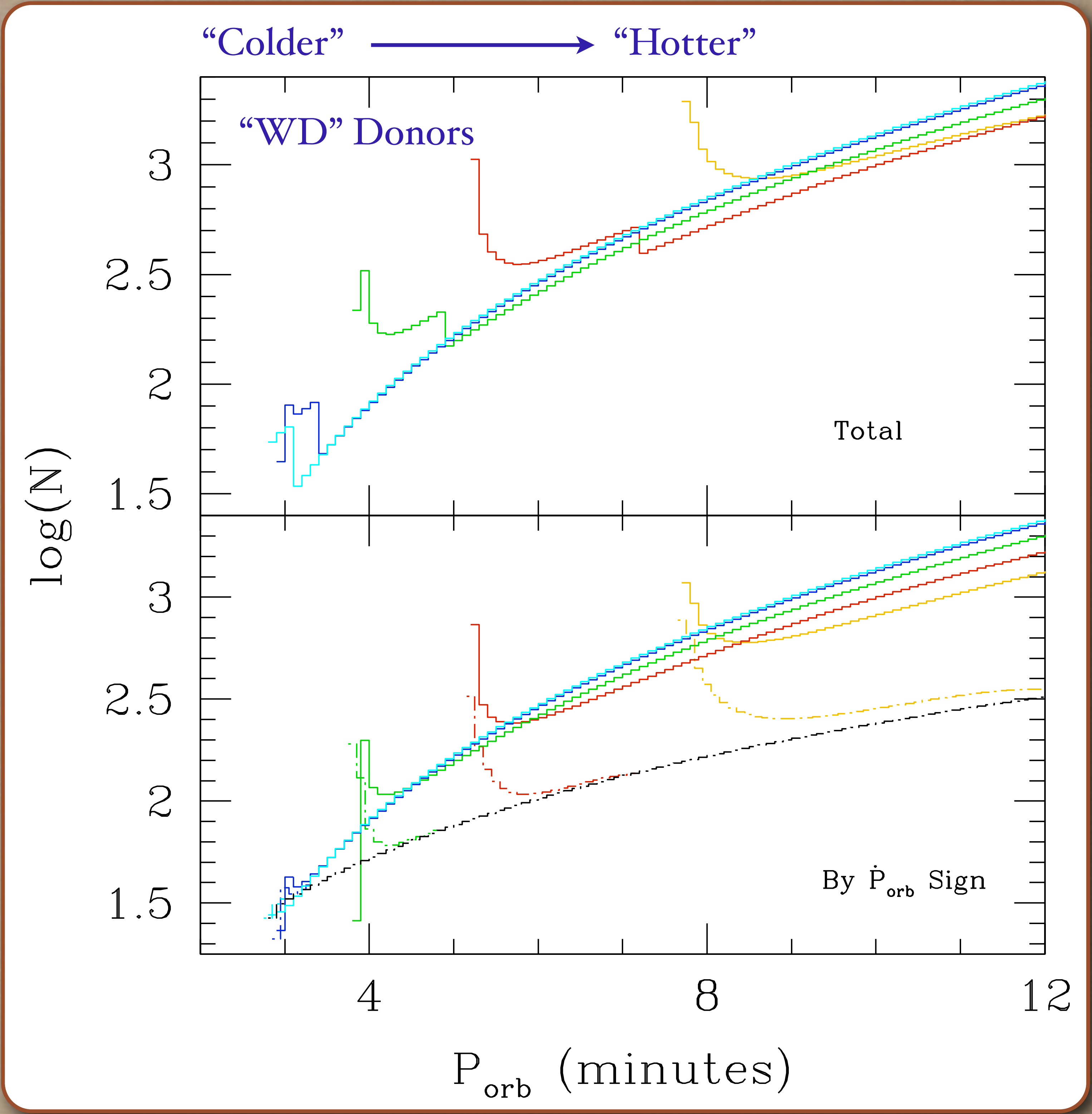
At short periods, $P_{\rm orb}$ distribution of systems is in steady state:

$$n(P_{\rm orb}) \propto \dot{P}_{\rm orb}^{-1}$$

$P_{\rm orb}$ minimum will lead to peaks in $n(P_{\rm orb})$ that are diagnostic of donor's entropy, mass, and composition.

EXAMPLE STEADY-STATE ORBITAL PERIOD DISTRIBUTIONS

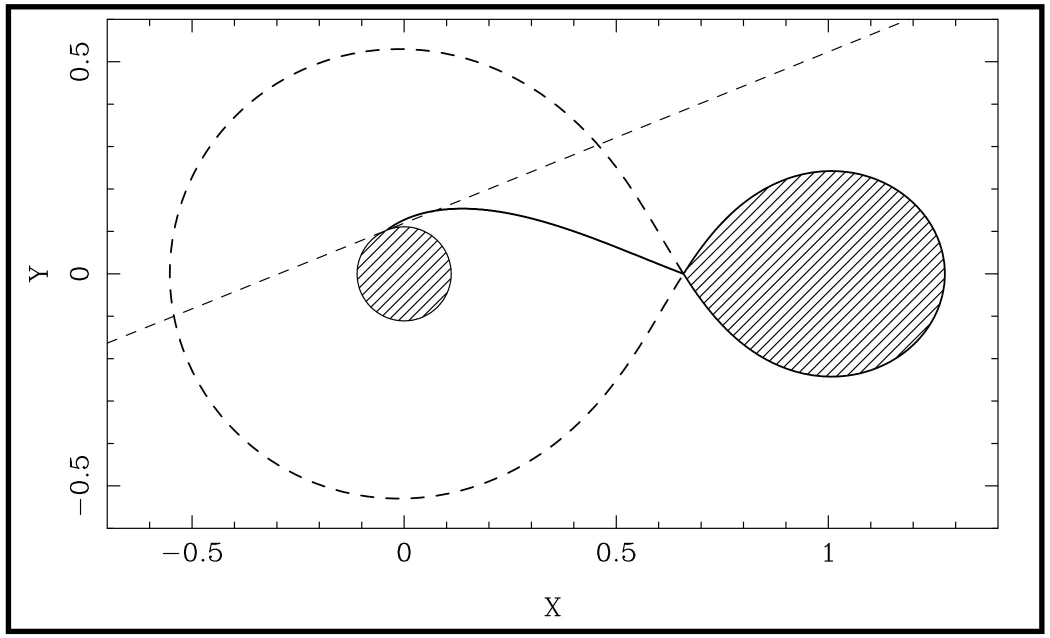
- A system's properties at contact parameterize its relative contribution to the population's orbital period distribution.
- Minimum period peaks will provide an obvious feature that should diagnose which systems survive onset of mass transfer as binaries.
- Key questions:
    - What physics will this probe?
    - How constraining will *LISA* observations be?
        - *(Work in this direction in progress).*



STABILITY OF MASS TRANSFER AT CONTACT: DISK MEDIATED OR DIRECT IMPACT?

Direct Impact Accretion:

With "WD" donors, orbital separation at contact is so close in most systems that accretion stream directly impacts accretor, spinning it up at cost of orbit's *J*.



(Marsh & Steeghs 2002)

Condition for Mass Transfer: $R_2 \approx R_L$

$$R_L \approx 0.46a\left(\frac{M_2}{M_1+M_2}\right)^{1/3}$$

Stability Criteria (Conservative Mass Transfer):

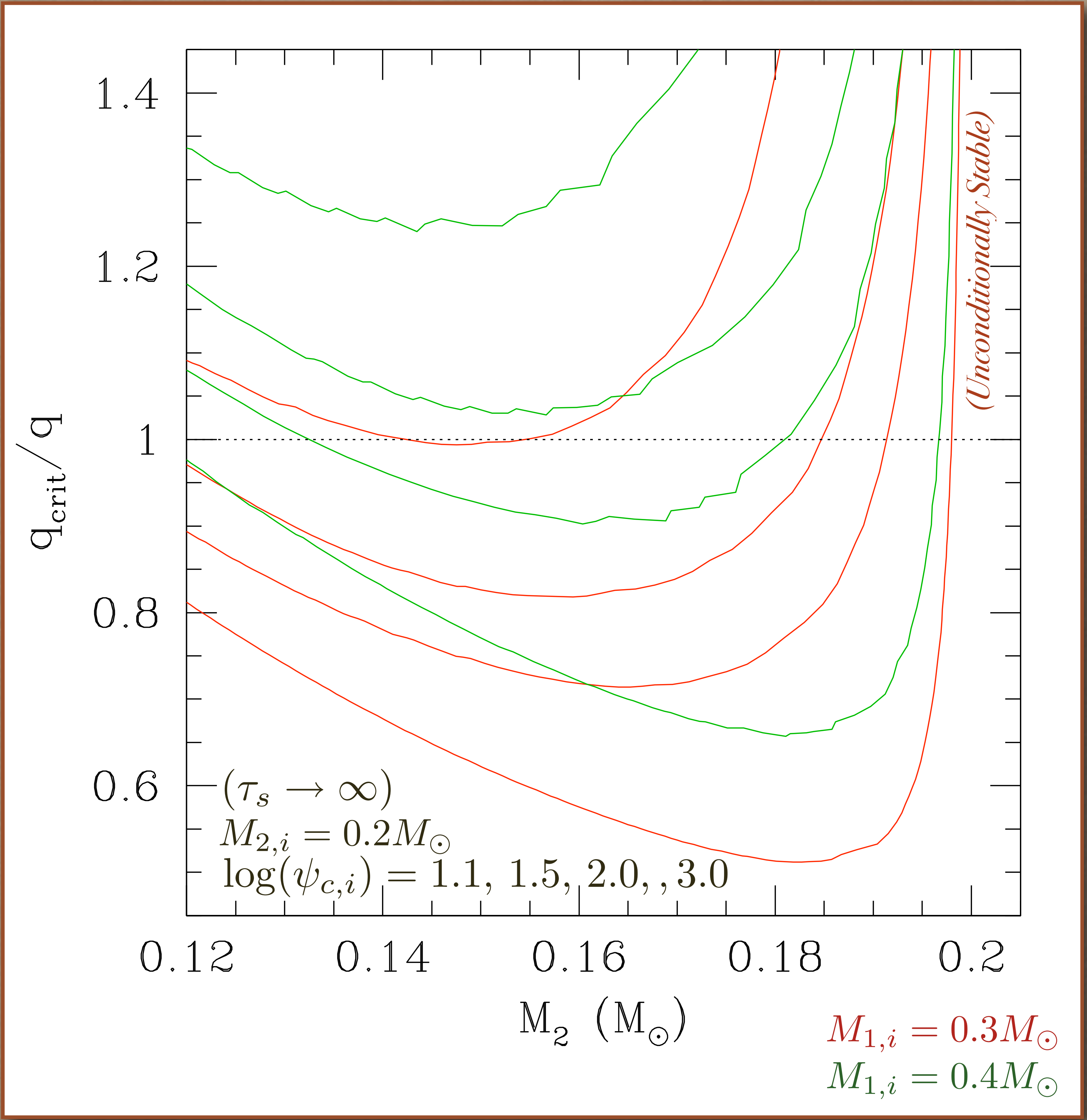
Disk	Direct Impact
$q < \frac{5}{6} + \frac{\xi_2}{2}$	$q < \frac{5}{6} + \frac{\xi_2}{2} - \sqrt{(1+q)r_h}$

$$q \equiv \frac{M_2}{M_1} \qquad \xi_2 = \frac{d\ln R_2}{d\ln M_2}$$

r_h : *parameterizes J lost in accreted matter.*

(Marsh et al. 2004)

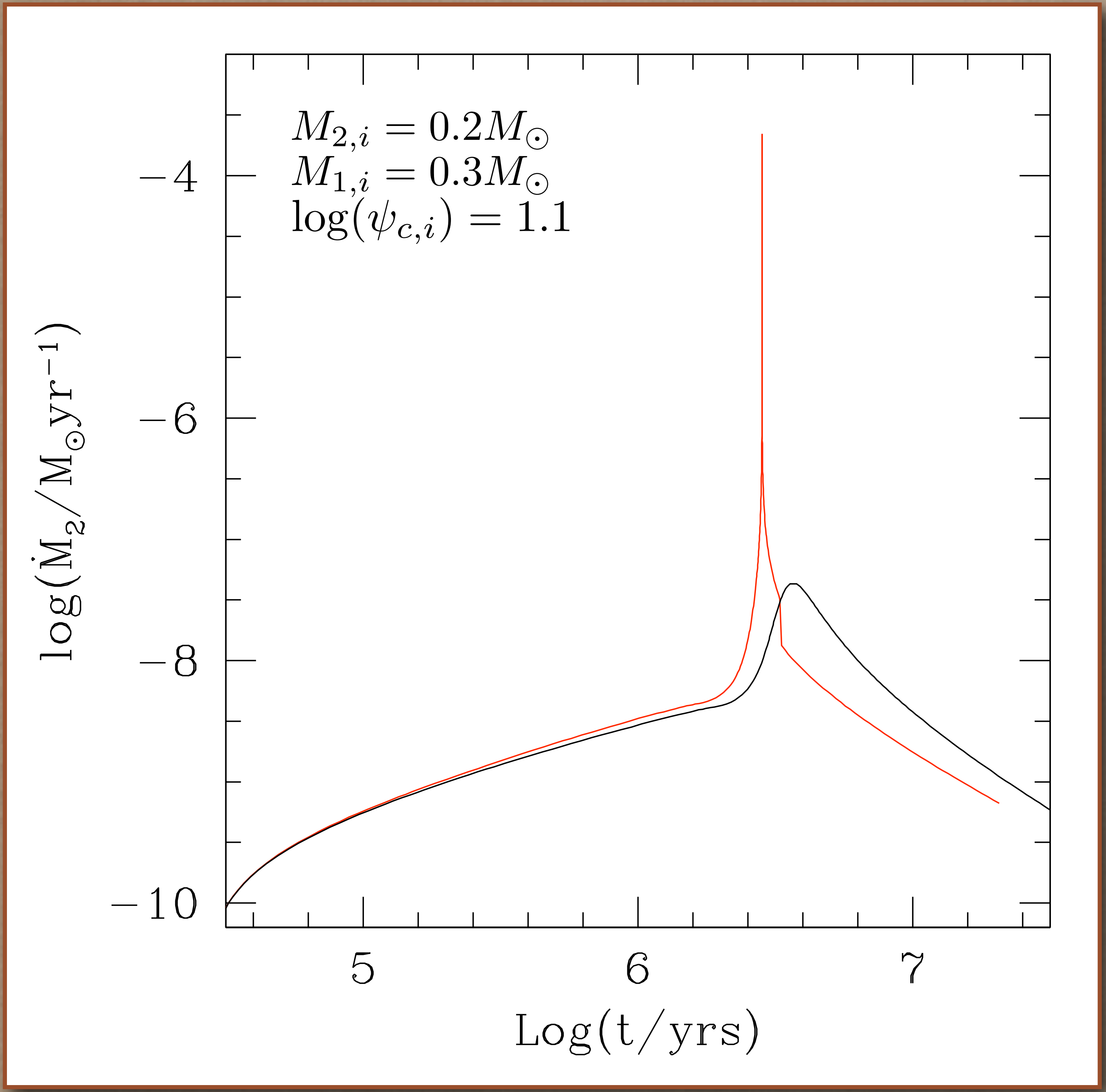
STABILITY OF MASS TRANSFER VS. SYSTEM PARAMETERS



- Systems with:
  - Hotter donors.
  - More massive accretors

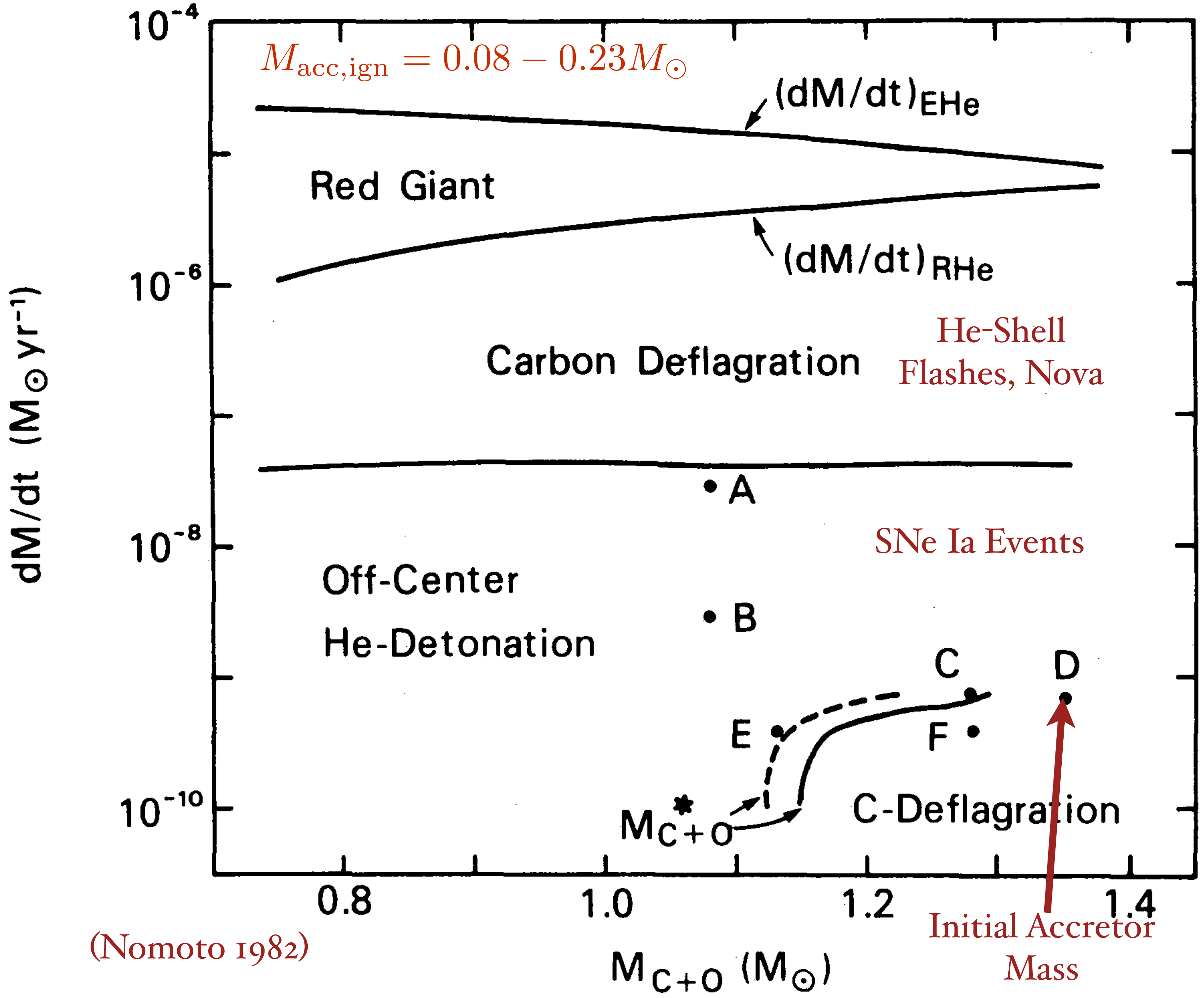
  will avoid mass transfer instabilities.
- If unstable mass transfer produces mergers:
  - P_{orb} distribution will reflect lack of outward contribution from systems with cold donors and less massive accretors.
  - Provide constraints on tidal coupling efficiencies in close WD-WD binaries.

MASS TRANSFER RATE EVOLUTION AND ACCRETED HE IGNITION



- During all phases of mass transfer, accretion rate is evolving.
- Occurrence of instabilities significantly alters mass transfer evolution history.
  - Binaries do not necessarily merge as result of instabilities (Gokhale et al. 2006).
- During early phases of mass transfer, rates of He accretion onto WD high enough for nuclear physics to be relevant.
  - Needs to be taken into account to understand contact phase outcomes.

SUMMARY OF HE IGNITION OUTCOMES AT CONSTANT ACCRETION RATE



$M_{\rm acc,ign} = 0.08 - 0.23 M_\odot$

He-Shell Flashes, Nova

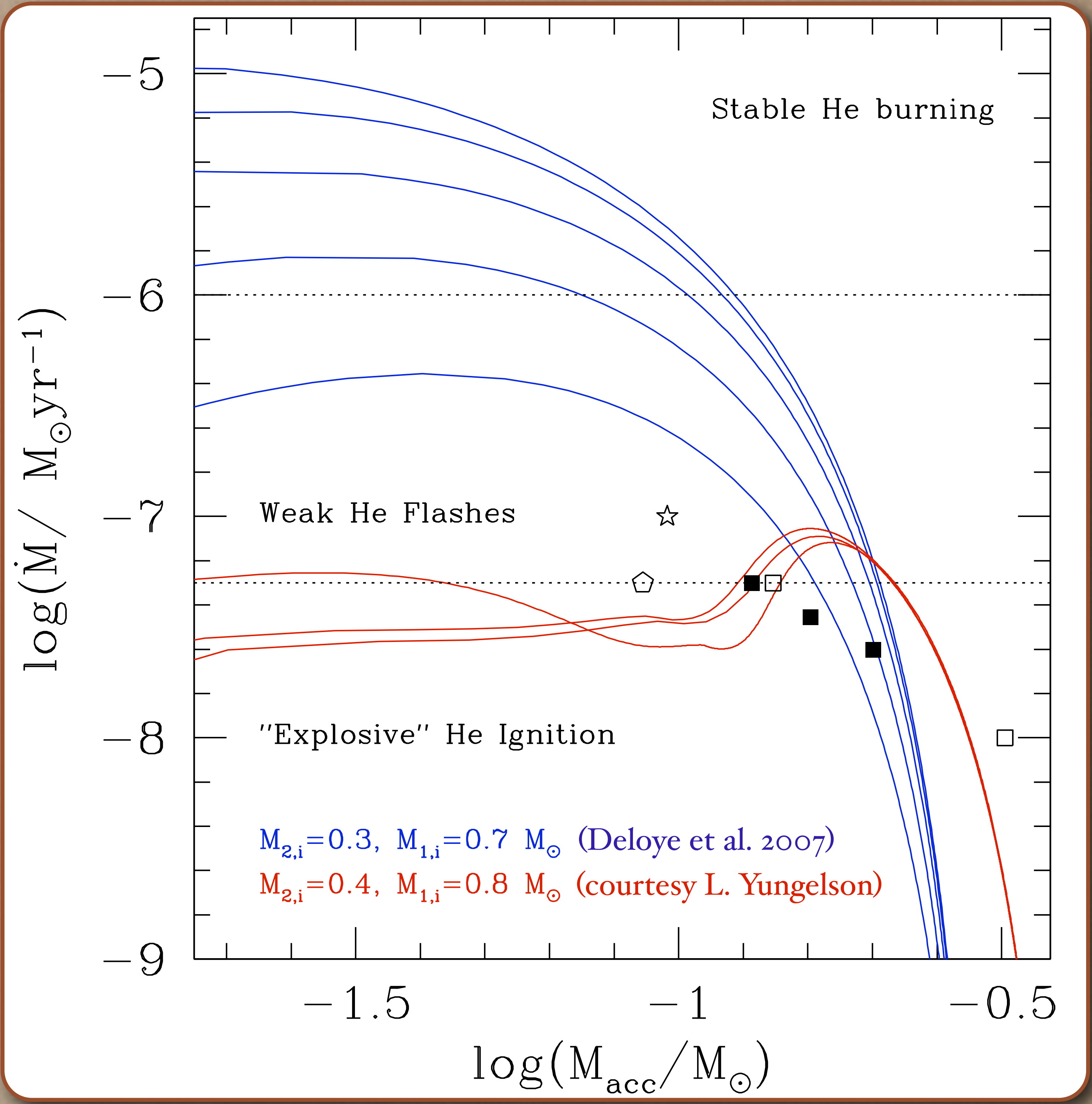
SNe Ia Events

Initial Accretor Mass

(Nomoto 1982)

IGNITION OUTCOMES WITH EVOLVING HE MASS-TRANSFER RATE

- Different donor types produce qualitatively different mass-transfer rate evolution.
  - Alters the nature of any He ignition events that occur on accretor's surface.
- "WD" donors:
  - evolution from stable surface He-burning to phase of (multiple?) He-shell flashes.
  - Some systems may access dynamical explosions (i.e. Type Ia-like Supernovae) (see also Bildsten et al. 2007).
- He-star donors:
  - Probes regime of "stronger" shell-flashes.
  - Many systems also produce dynamical explosions.
- Relevance to *LISA*: which systems produce explosive ignitions destroying the binary and where in their evolution does this occur?



SUMMARY

- With its detailed view of the galactic WD-ultracompact binary population, *LISA* will provide unprecedented constraints on this population's properties and the physics that shapes it.
- Physics important to the outcomes of these system's early contact phase that will be probed include:
  - Mass transfer instabilities at contact and whether these produce mergers.
  - Efficiency of tidal coupling in ultracompact binaries.
  - Outcomes of He-ignition events on the surface of the accretor.
- Laundry list of to-do's (so that all of this could actually be useful):
  - Determine realistic orbital period distributions of WD-ultracompact binaries given population synthesis inputs and examine how each component of population contributes to this distribution.
  - Quantify across the range of system properties which systems avoid mass transfer instabilities at contact.
  - Understand how time-evolving mass transfer rates affect He-ignition events (again as function of system parameters at contact) on the accretor:
    - Which systems lead to accretor detonation?
    - How does this change if systems experiencing unstable mass transfer do not merge as matter of course?