Neutron-Star and Black-Hole Kicks

Philipp Podsiadlowski (Oxford)

- most neutron stars (and some black holes) are observed to receive a natal kick in the the event that formed them (asymmetric explosion)
- understanding supernova kicks is essential for understanding various types of binaries
- supernova kicks constrain supernova physics

Evidence for Large Supernova Birth Kicks

- single radio pulsars have large space velocities (Lyne & Lorimer 1994; Hobbs et al. 2005): $\sigma_{\rm v} = 265\,{\rm km\,s^{-1}}$ without evidence for a low-velocity component
- some double-NS systems (DNSs) appear to require large kicks (Fryer & Kalogera 1997)
- PSR J0045−7319 (Kaspi et al. 1996): retrograde companion
- Be/X-ray binaries with large eccentricities (Verbunt, van den Heuvel, Bildsten)

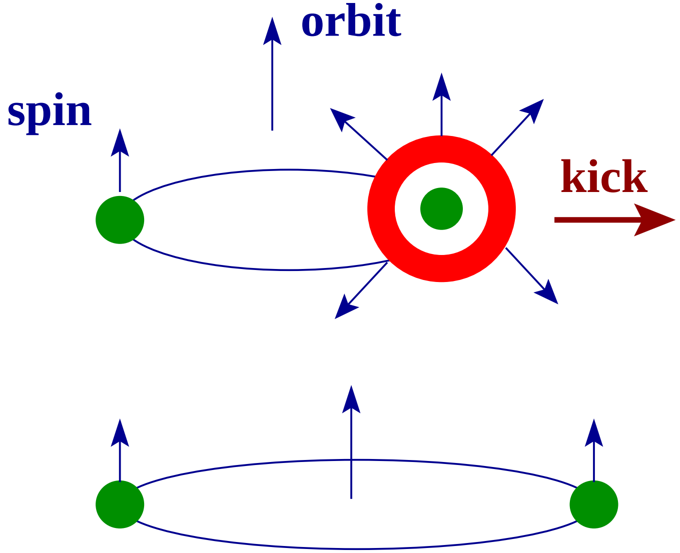
Evidence for Low Supernova Birth Kicks

- neutron star retention in globular clusters (e.g. Pfahl, Ivanova)
- the existence of wide Be/X-ray binaries with low eccentricities (e.g. X Per) (Pfahl)
- DNSs with low eccentricities (van den Heuvel, Dewi)
- the spin period – eccentricity relation of DNSs (Dewi)
- preference for low-kick NSs in binaries?

Kicks and Binary Orbits

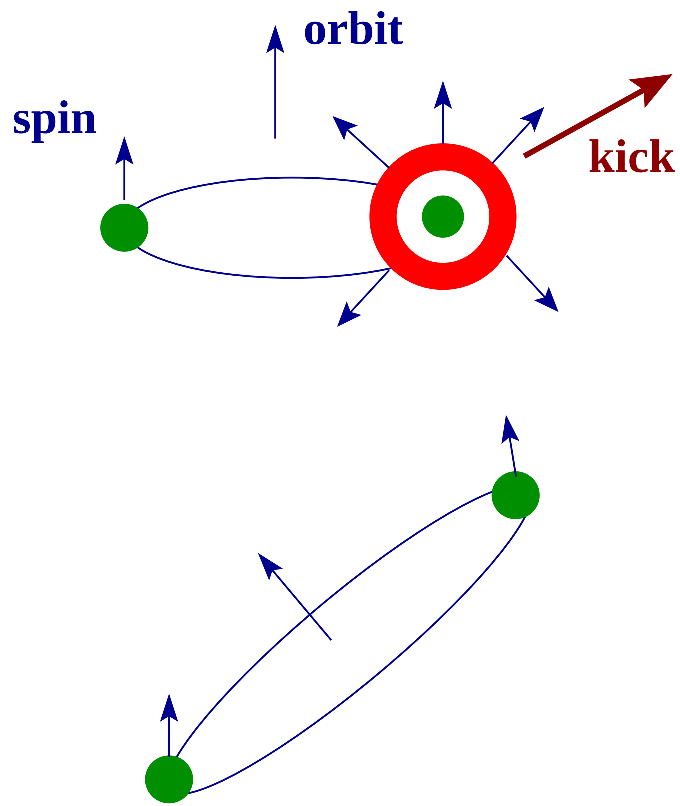
Blaauw Kick

- only due to supernova mass loss



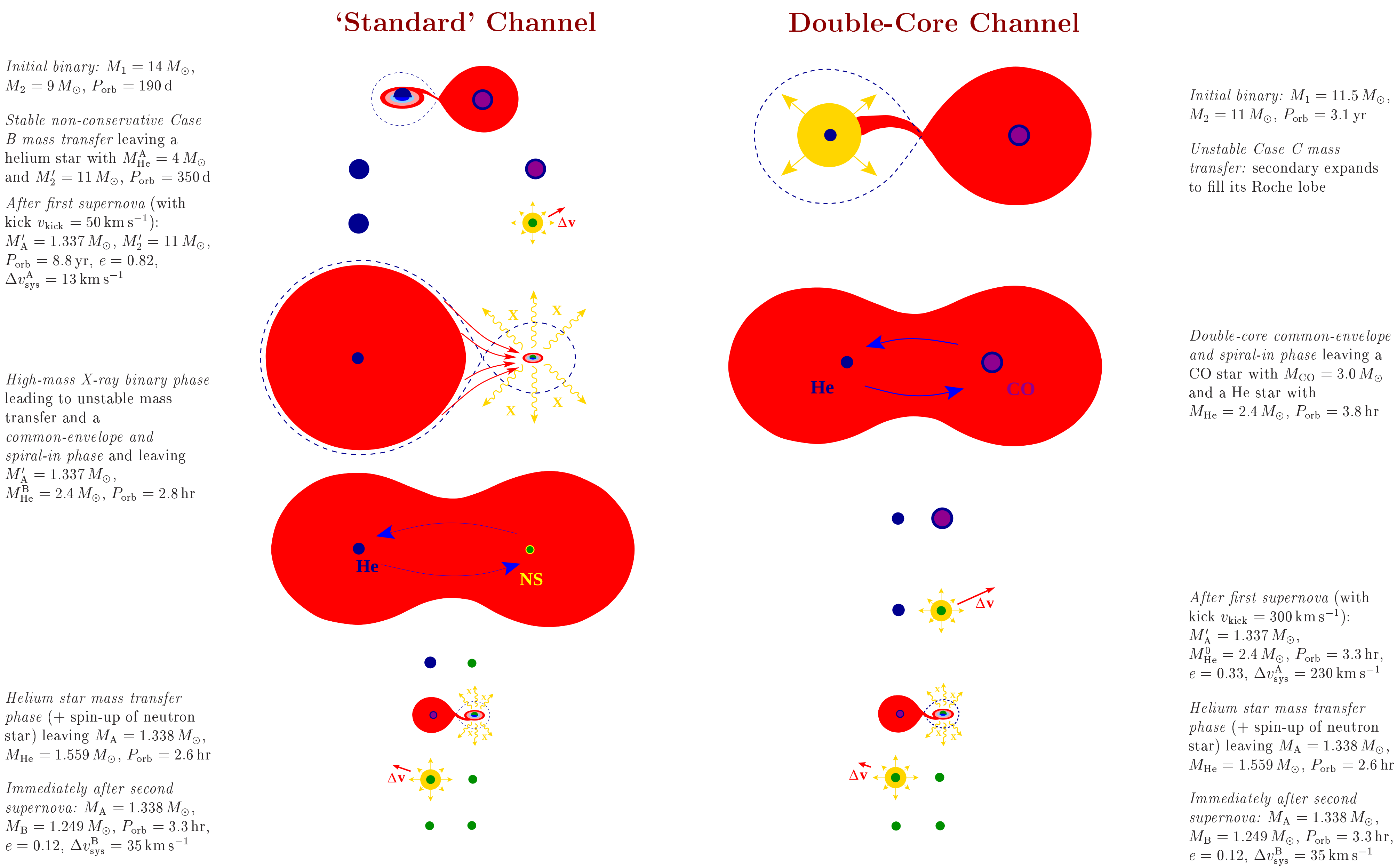
- orbit increases
- spin + orbit remain aligned
- disruption if more than half the mass is lost

Asymmetric Explosion



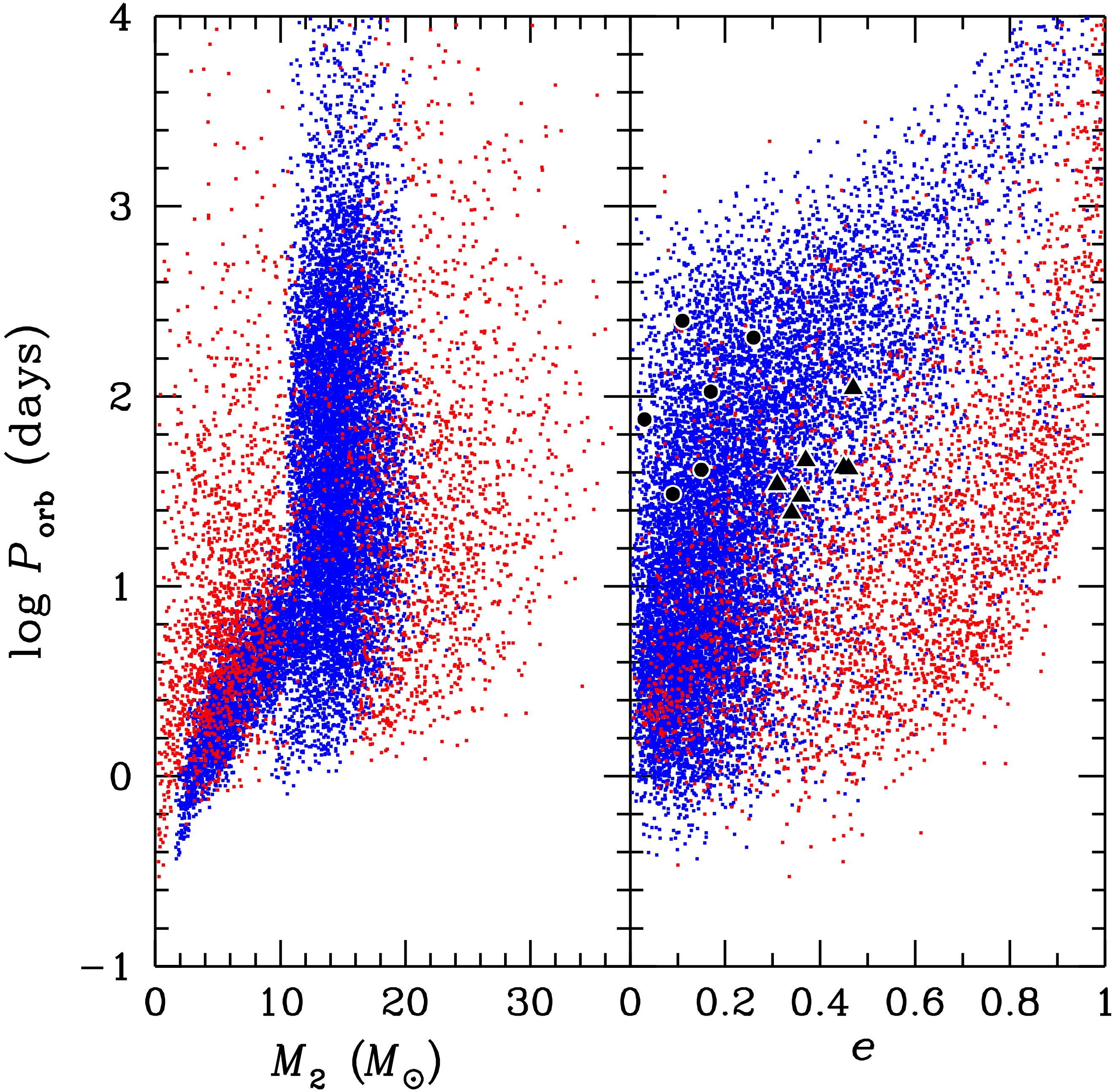
- orbit increases or decreases
- spin/orbit misalignment (retrograde orbits possible)
- system can remain bound that could not otherwise

Note: if kick along spin axis → retrograde orbits impossible

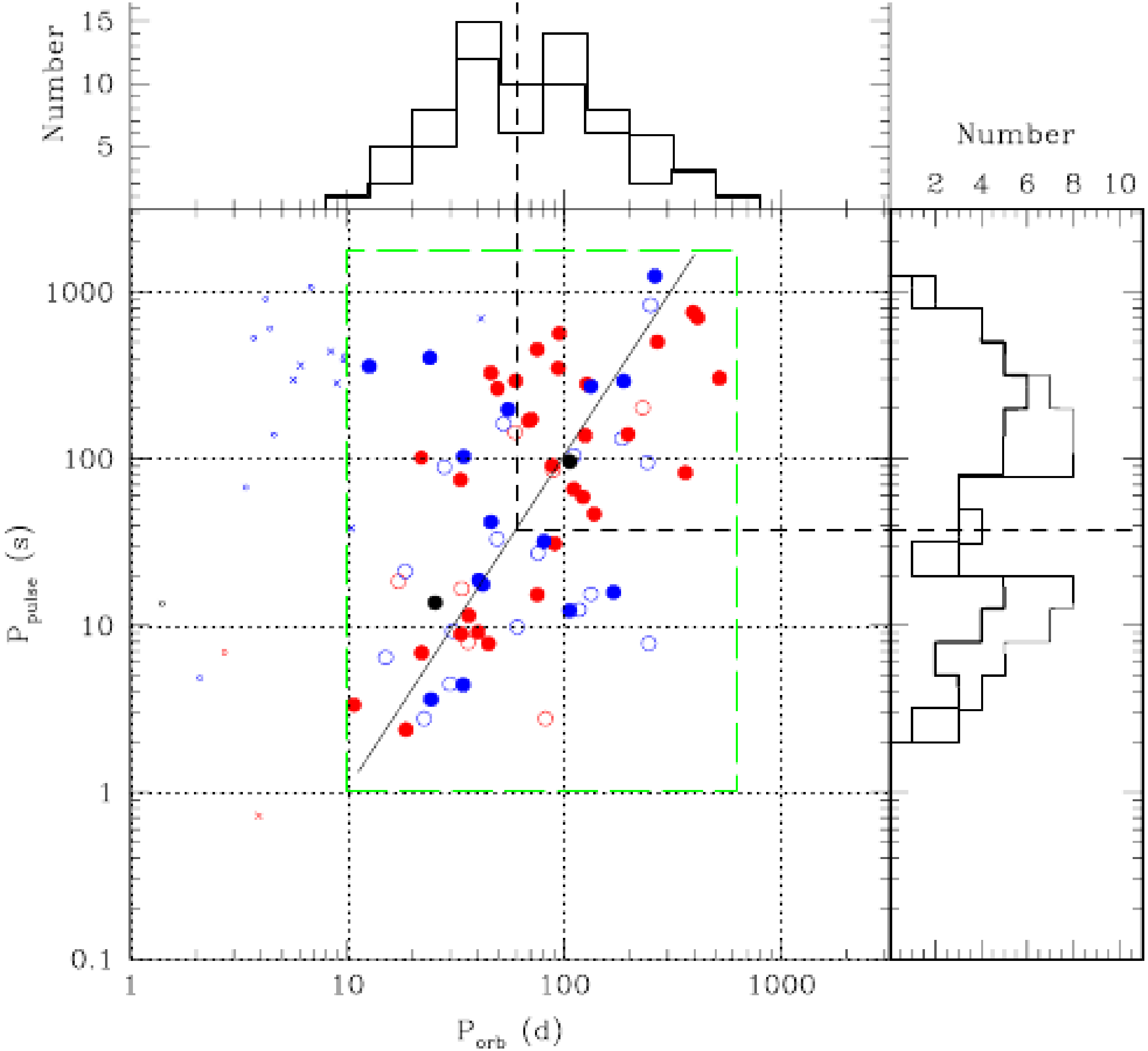


‘Standard’ Channel
Double-Core Channel
Initial binary: $M_1 = 14\,M_\odot$, $M_2 = 9\,M_\odot$, $P_\mathrm{orb} = 190\,\mathrm{d}$
Stable non-conservative Case B mass transfer leaving a helium star with $M_\mathrm{He}^\mathrm{A} = 4\,M_\odot$ and $M_2' = 11\,M_\odot$, $P_\mathrm{orb} = 350\,\mathrm{d}$
After first supernova (with kick $v_\mathrm{kick} = 50\,\mathrm{km\,s^{-1}}$): $M_\mathrm{A}' = 1.337\,M_\odot$, $M_2' = 11\,M_\odot$, $P_\mathrm{orb} = 8.8\,\mathrm{yr}$, $e = 0.82$, $\Delta v_\mathrm{sys}^\mathrm{A} = 13\,\mathrm{km\,s^{-1}}$
Δv
X
High-mass X-ray binary phase leading to unstable mass transfer and a *common-envelope and spiral-in phase* and leaving $M_\mathrm{A}' = 1.337\,M_\odot$, $M_\mathrm{He}^\mathrm{B} = 2.4\,M_\odot$, $P_\mathrm{orb} = 2.8\,\mathrm{hr}$
He
NS
Helium star mass transfer phase (+ spin-up of neutron star) leaving $M_\mathrm{A} = 1.338\,M_\odot$, $M_\mathrm{He} = 1.559\,M_\odot$, $P_\mathrm{orb} = 2.6\,\mathrm{hr}$
Immediately after second supernova: $M_\mathrm{A} = 1.338\,M_\odot$, $M_\mathrm{B} = 1.249\,M_\odot$, $P_\mathrm{orb} = 3.3\,\mathrm{hr}$, $e = 0.12$, $\Delta v_\mathrm{sys}^\mathrm{B} = 35\,\mathrm{km\,s^{-1}}$
Initial binary: $M_1 = 11.5\,M_\odot$, $M_2 = 11\,M_\odot$, $P_\mathrm{orb} = 3.1\,\mathrm{yr}$
Unstable Case C mass transfer: secondary expands to fill its Roche lobe
Double-core common-envelope and spiral-in phase leaving a CO star with $M_\mathrm{CO} = 3.0\,M_\odot$ and a He star with $M_\mathrm{He} = 2.4\,M_\odot$, $P_\mathrm{orb} = 3.8\,\mathrm{hr}$
He
CO
After first supernova (with kick $v_\mathrm{kick} = 300\,\mathrm{km\,s^{-1}}$): $M_\mathrm{A}' = 1.337\,M_\odot$, $M_\mathrm{He}^0 = 2.4\,M_\odot$, $P_\mathrm{orb} = 3.3\,\mathrm{hr}$, $e = 0.33$, $\Delta v_\mathrm{sys}^\mathrm{A} = 230\,\mathrm{km\,s^{-1}}$
Helium star mass transfer phase (+ spin-up of neutron star) leaving $M_\mathrm{A} = 1.338\,M_\odot$, $M_\mathrm{He} = 1.559\,M_\odot$, $P_\mathrm{orb} = 2.6\,\mathrm{hr}$
Immediately after second supernova: $M_\mathrm{A} = 1.338\,M_\odot$, $M_\mathrm{B} = 1.249\,M_\odot$, $P_\mathrm{orb} = 3.3\,\mathrm{hr}$, $e = 0.12$, $\Delta v_\mathrm{sys}^\mathrm{B} = 35\,\mathrm{km\,s^{-1}}$

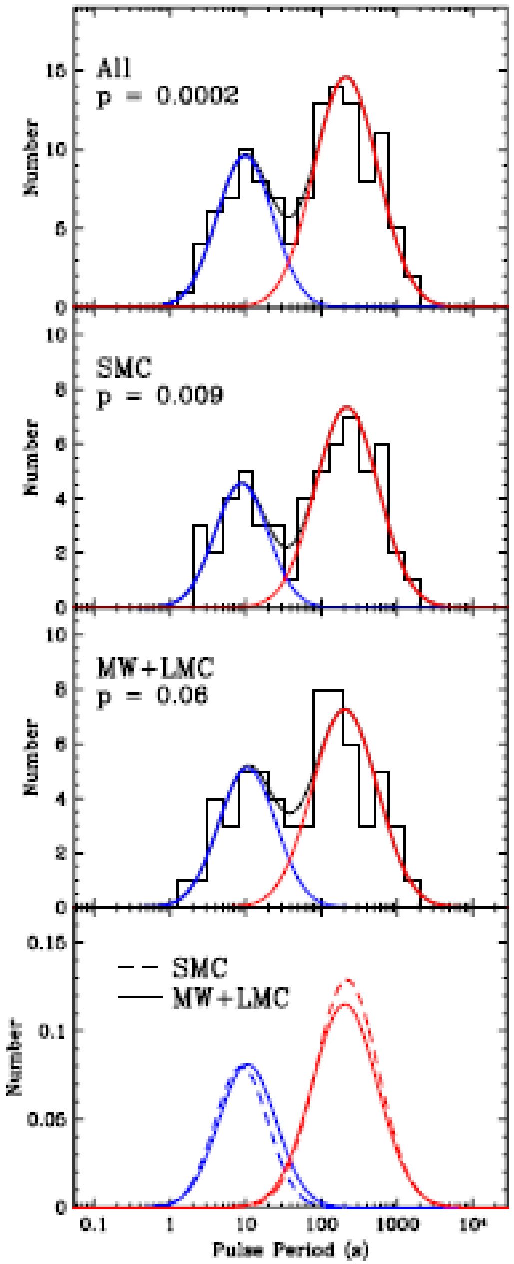
Low eccentricity HMXBs (Pfahl+ 2002)



Knigge, Coe & Podsiadlowski (2011)



Knigge, Coe & Podsiadlowski (2011)

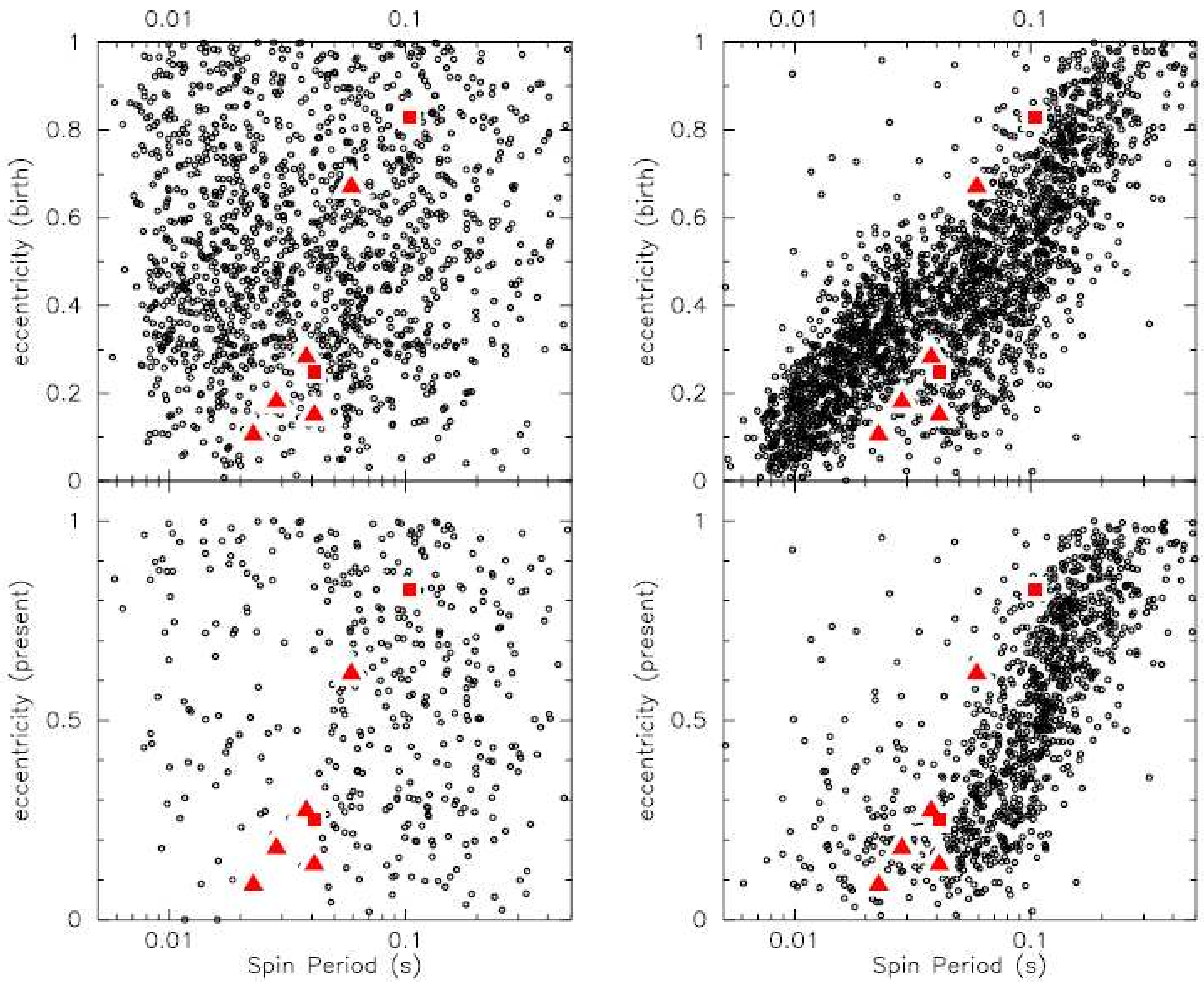


- spin period may be a better proxy for NS formation channel (?)
- comparable numbers of Fe core collapse and e-capture NSs
- Be X-ray binaries may be useful for constraining NS formation and the formation of double NS binaries

QUESTION: why is the spin distribution bimodal?

- different magnetic fields for different collapse modes?
- mis-alignment effects?
- understanding wind accretion seems essential

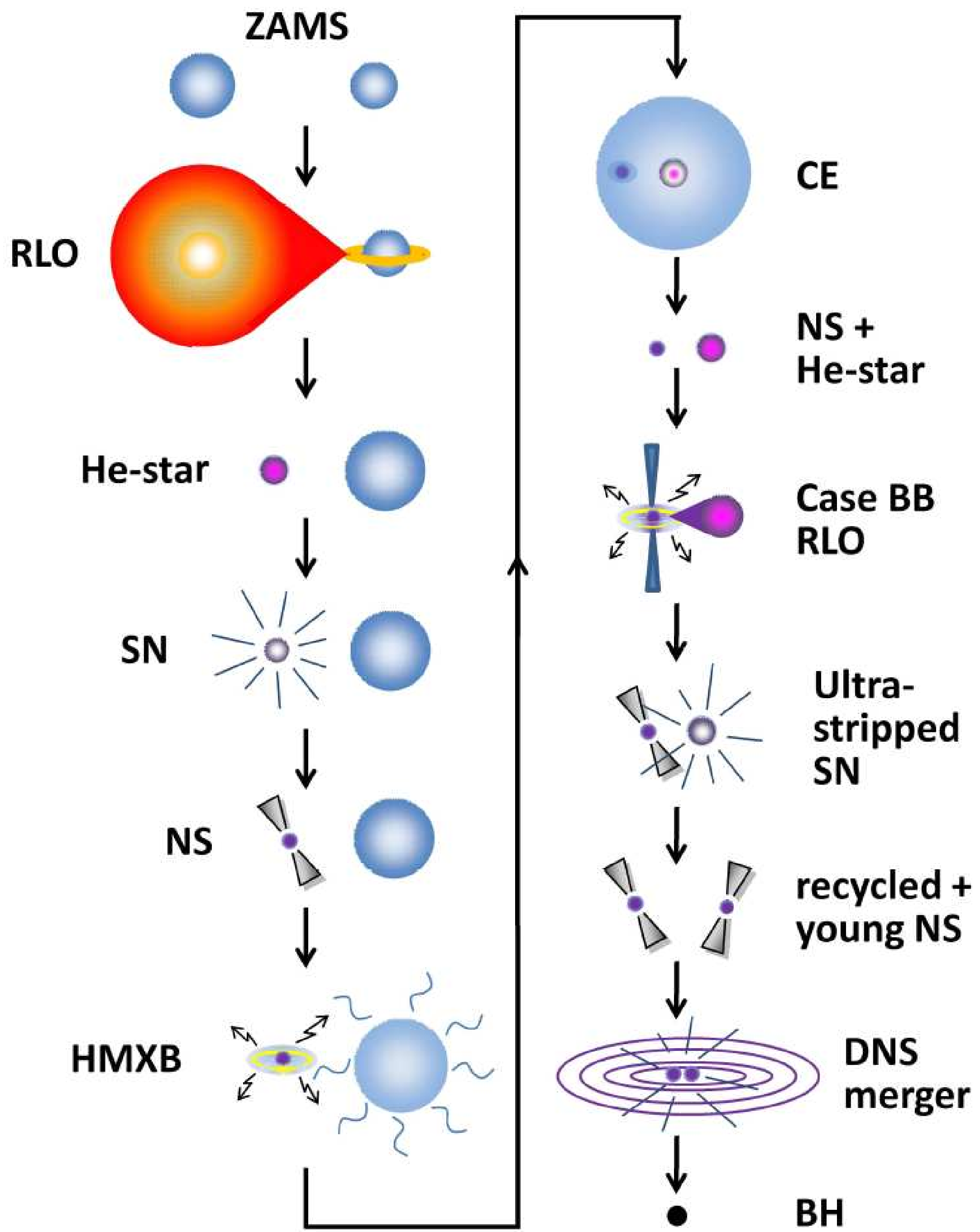
The spin – eccentricity relation for DNSs (McLaughlin+ 2005, Faulkner+ 2005)



(a) $\sigma_2 = 190$ km s^{-1}

(b) $\sigma_2 = 20$ km s^{-1}

Dewi, Podsiadlowski & Pols (2005)


ZAMS
RLO
He-star
SN
NS
HMXB
CE
NS +
He-star
Case BB
RLO
Ultra-
stripped
SN
recycled +
young NS
DNS
merger
BH

Tauris+ (2017)

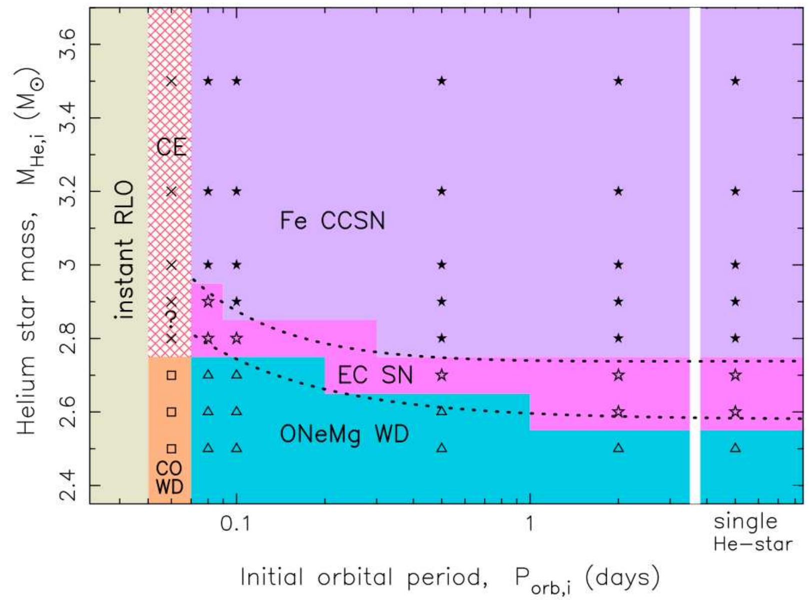
Case BB Mass Transfer and Ultrastripped Supernovae

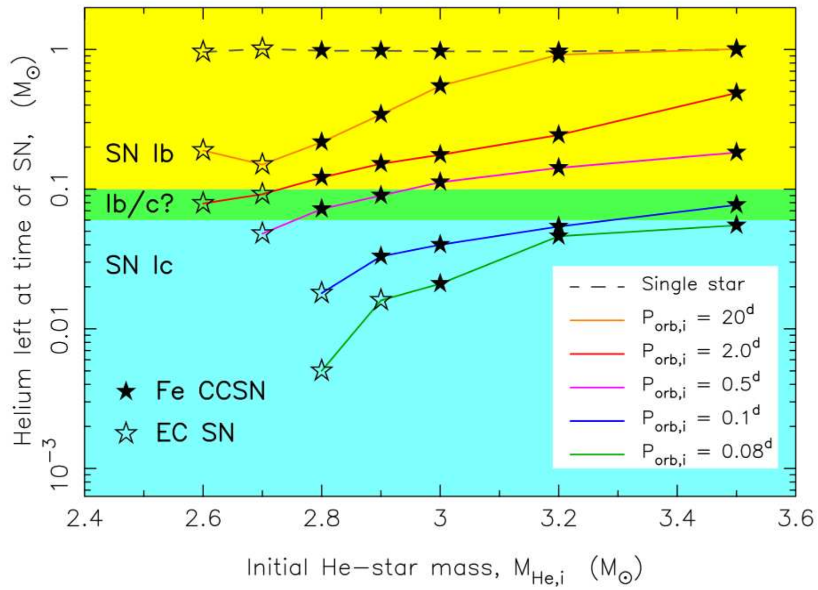
Tauris, Langer & Podsiadlowski (2015)

- low-mass He stars experience case BB mass transfer
- produces ultrastripped SN progenitors with very low ejecta masses ($\sim 0.1\,M_\odot$)
- produces e-capture supernovae and core-collapse supernovae with very low iron-core masses

$\rightarrow$ low-kick neutron stars

- short supernova transient



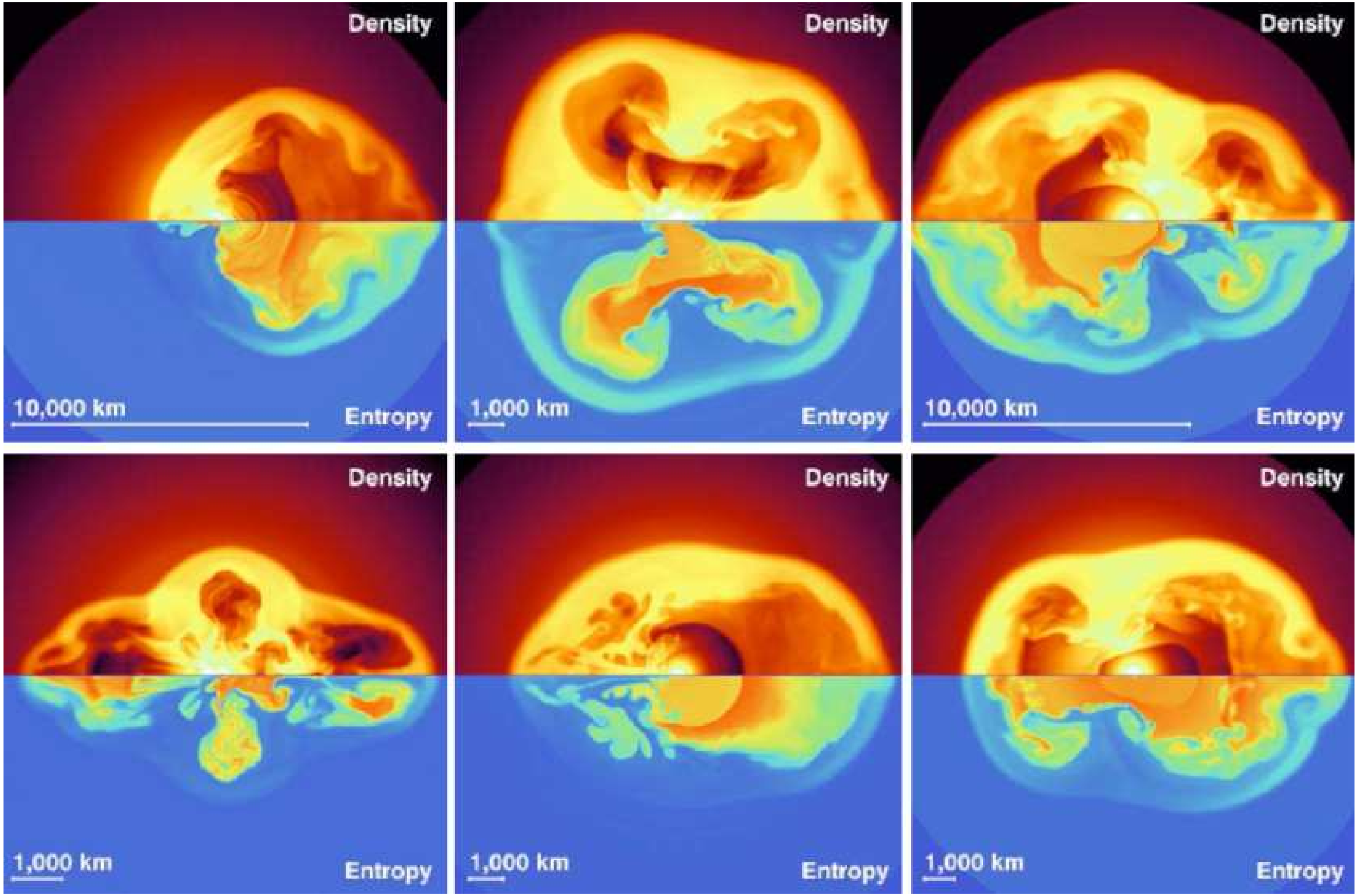


The origin of supernova kicks

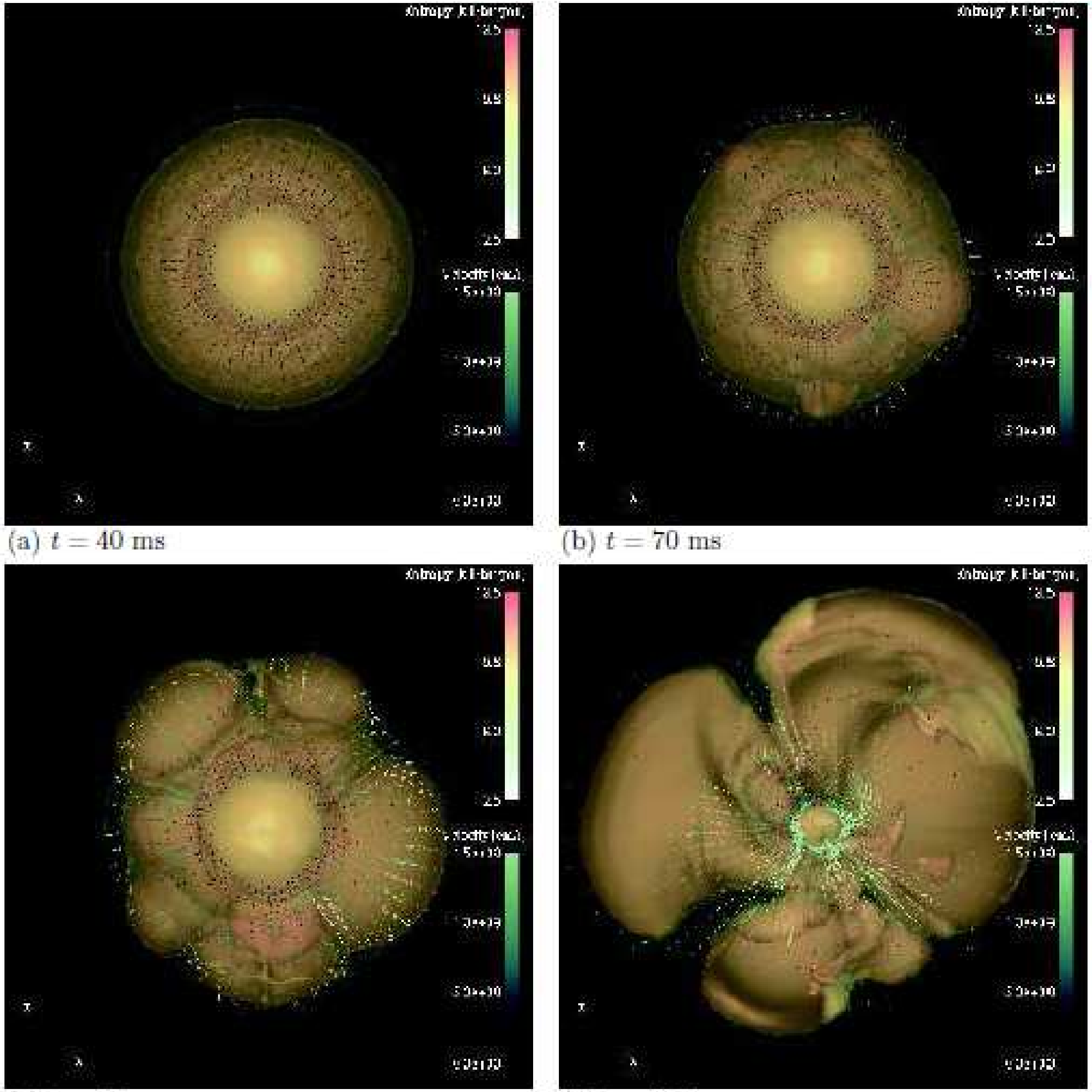
- dramatic recent progress in neutrino-driven core-collapse simulations
- supernova kicks produced by standing accretion shock instability (SASI) (Blondin, Mezzacappa, Foglizzo, Janka)
- driven by advective-acoustic instability
- $l = 1$ instability
- comes in two flavours:
  - ▷ sloshing instability ($m = 0$)
  - ▷ spiral mode ($m = \pm 1$)
- can produce kicks of a few $100\,\mathrm{km\,s^{-1}}$ if the collapse phase lasts $\gtrsim 500\,\mathrm{ms}$ (many growth timescale)
- can torque the proto-NS and produce the pulsar spin ($P_{\rm spin} \sim 100 - 200\,\mathrm{ms}$) (Blondin & Mezzacappa 2007)

Sloshing Instability

$(l = 1,\ m = 0)$



(Janka, Scheck, Foglizzo)



(a) $t = 40$ ms

(b) $t = 70$ ms

(c) $t = 80$ ms

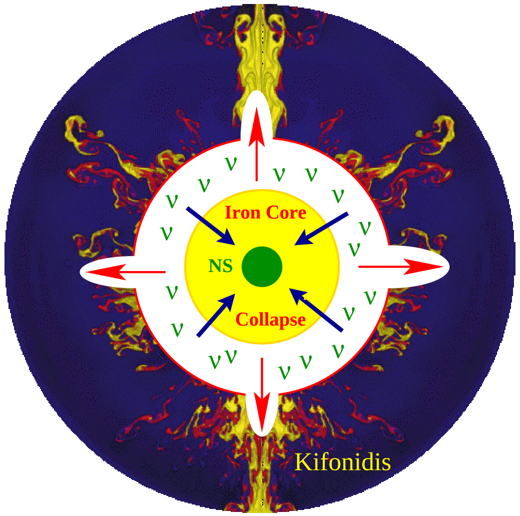
(d) $t = 350$ ms

Iwakami et al. (2008)

Neutron Star Formation

Iron core collapse

- inert iron core ($> M_{Ch}$) collapses
  - ▷ presently favoured model: delayed neutrino heating to drive explosion



Electron-capture supernovae

- occurs in degenerate ONeMg core
  - ▷ at a critical density ($4.5 \times 10^9\,\mathrm{g\,cm^{-3}}$), corresponding to a critical ONeMg core mass ($1.370 \pm 0.005\,M_\odot$), electron captures onto ^{24}Mg removes electrons (pressure support!)

→ triggers collapse to form a low-mass neutron star

note: essentially the whole core collapses

→ easier to eject envelope/produce supernova

→ no significanct ejection of heavy elements

▷ "fast" explosion → low SN kick (Podsiadlowski, Langer+ 2004)

The Double Pulsar (PSR J0737-3039)

- $P_{orb} = 2.4\,h$, $M_A = 1.338\,M_\odot$ ($P_A = 22.7\,ms$), $M_B = 1.249\,M_\odot$ ($P_B = 2.77\,s$)
- lower-mass pulsar formed in e-capture supernova?
- circumstantial evidence:
  - ▷ low mass of $1.249\,M_\odot$ close to expected mass from e-capture SN
  - ▷ evidence for low kick: low eccentricity, low space velocity, Pulsar A spin aligned with orbital axis (no geodetic precession)

note: Pulsar B not aligned if kicks induces torque (Blondin & Mezzacappa 2007)

Black-Hole Kicks

(Brandt/Podsiadlowski, White/van Paradijs,
Nelemans/Yonker/Repetto, Mirabel, Fragos/McClintock)

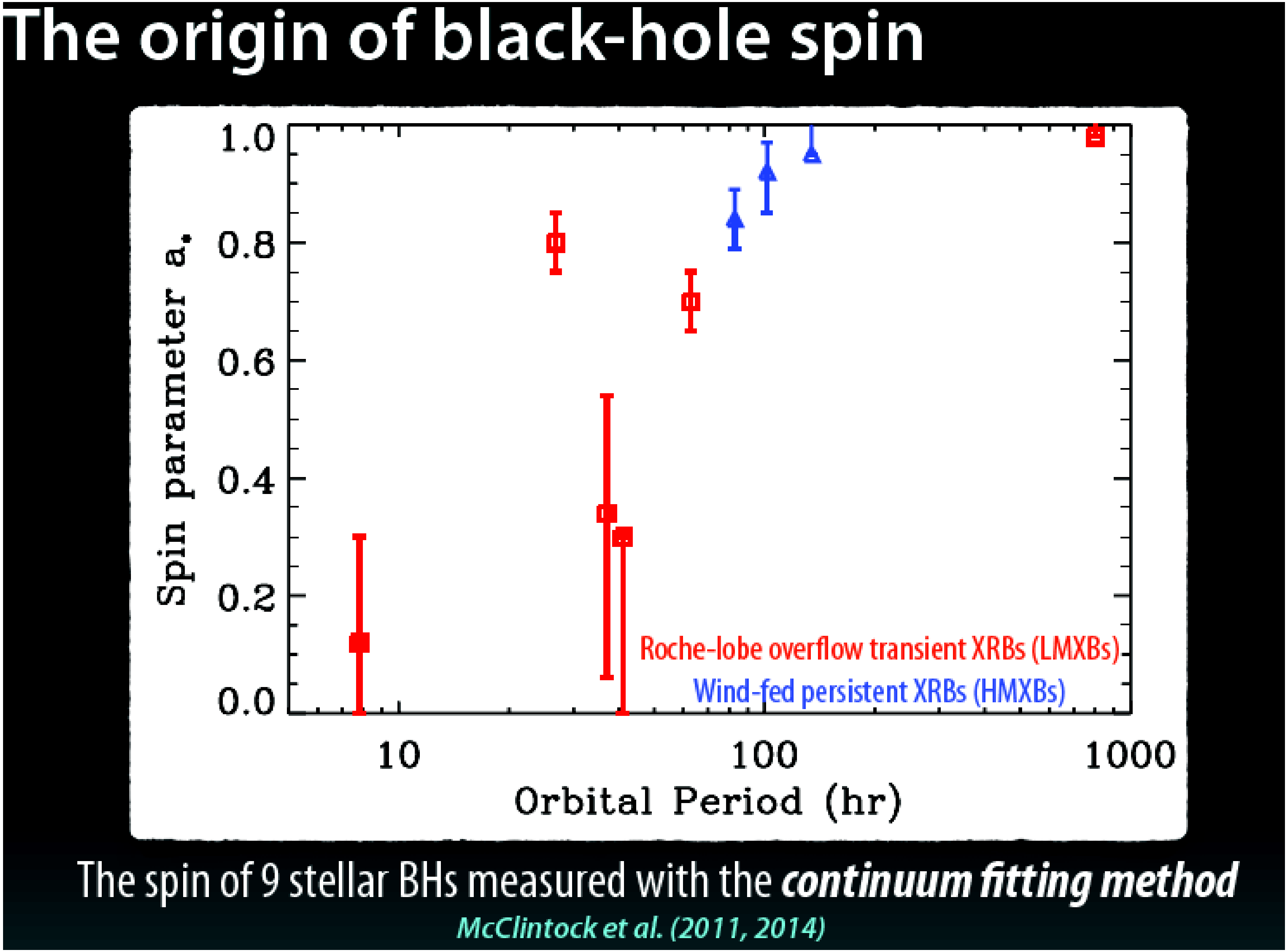
Black-hole binaries with large kicks

- GRO J1655-40, XTE J1188+480: $v_{kick} \gtrsim 100\,km/s$
- relatively low-mass BHs: $M_{BH} \sim 6\,M_{\odot}$
- companion polluted by supernova material $\rightarrow$ successful (weak?) supernova (formation by fallback?)

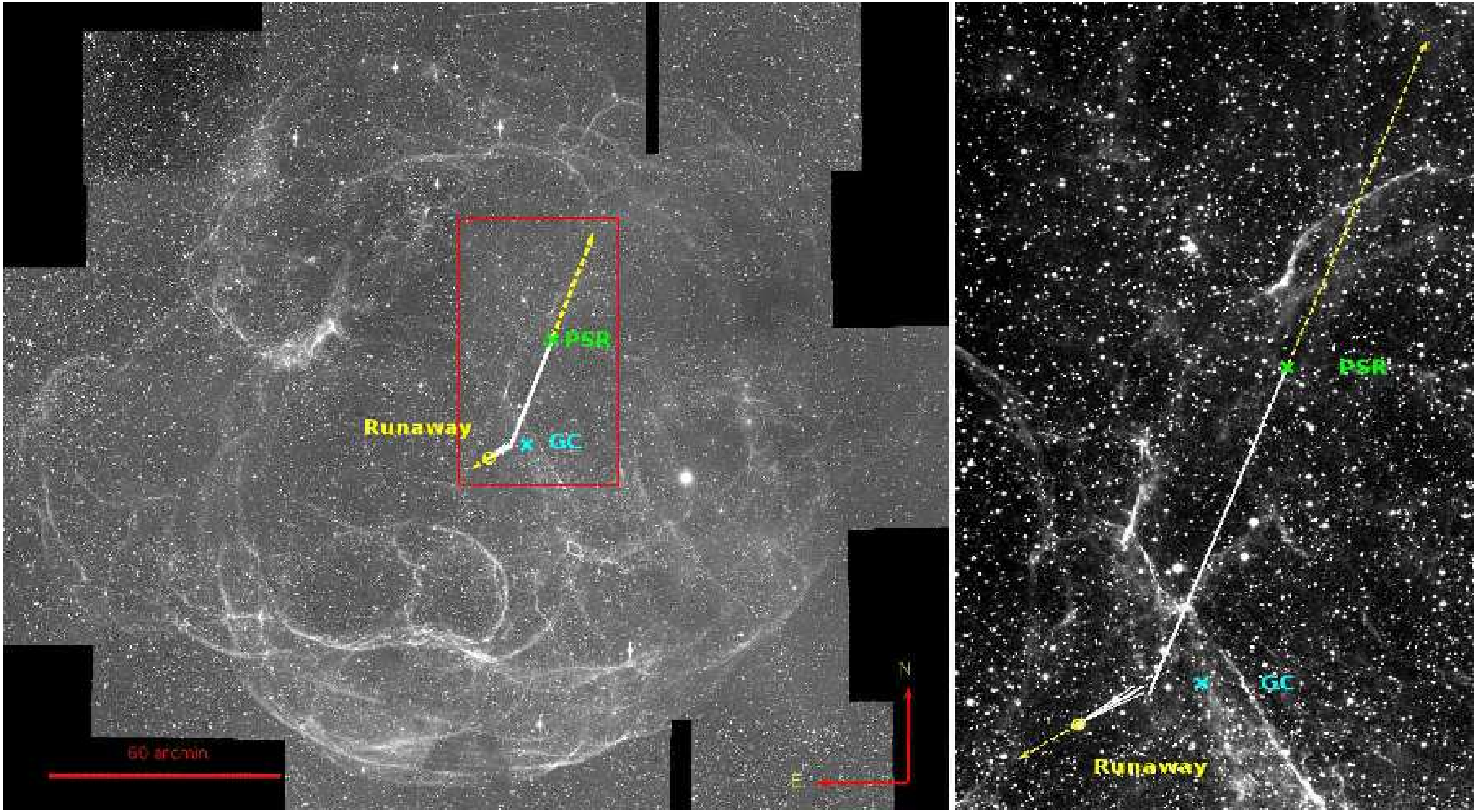
Black-hole binaries with low kicks

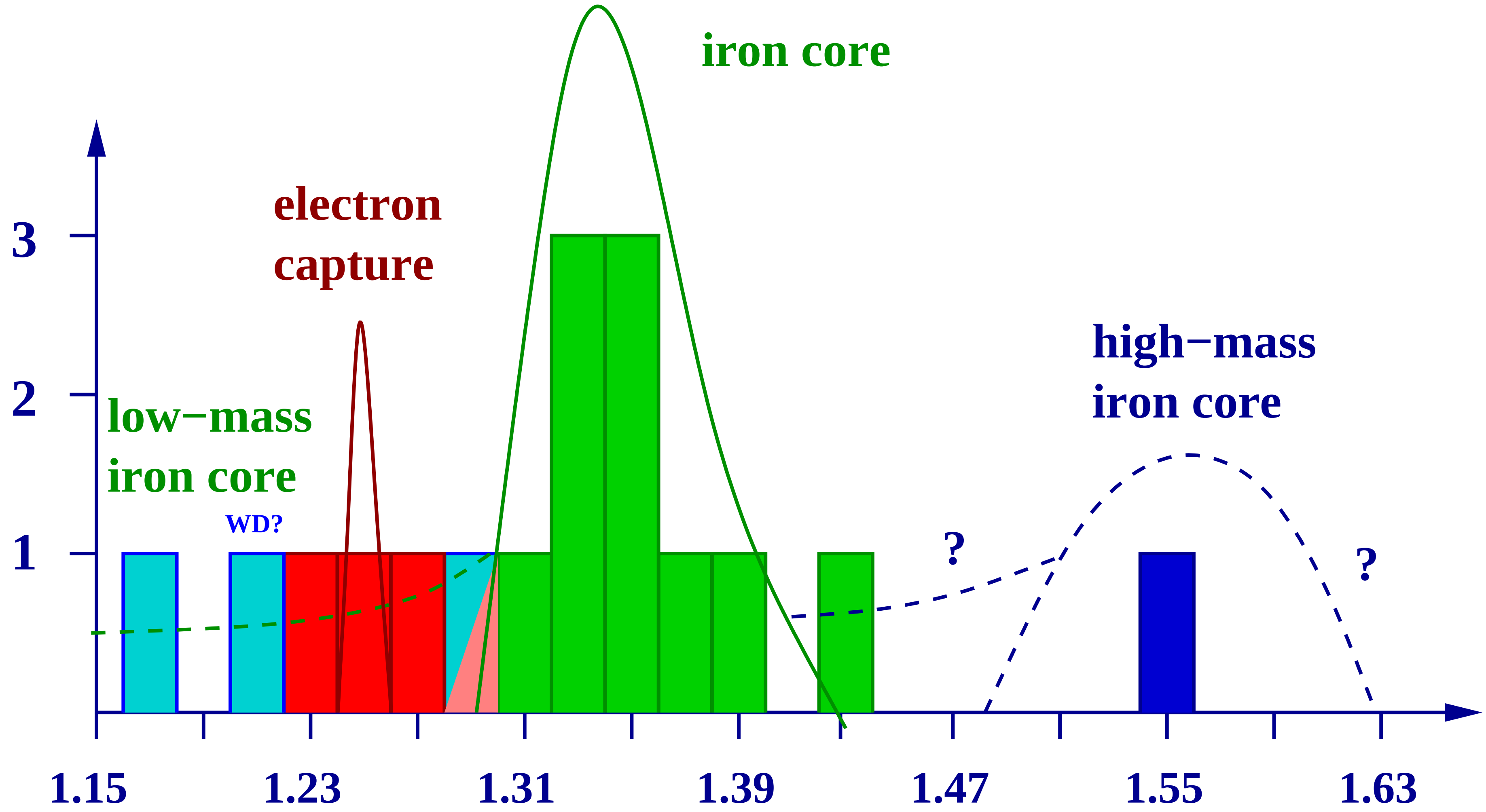
- mostly in HMXBs (e.g. Cyg X-1)
- more massive BHs: $M_{BH} \gtrsim 10\,M_{\odot}$
- no supernova? "fast" collapse?

From Fragos (2017):



Runaway star in SNR S147 Dincel+ (2015)



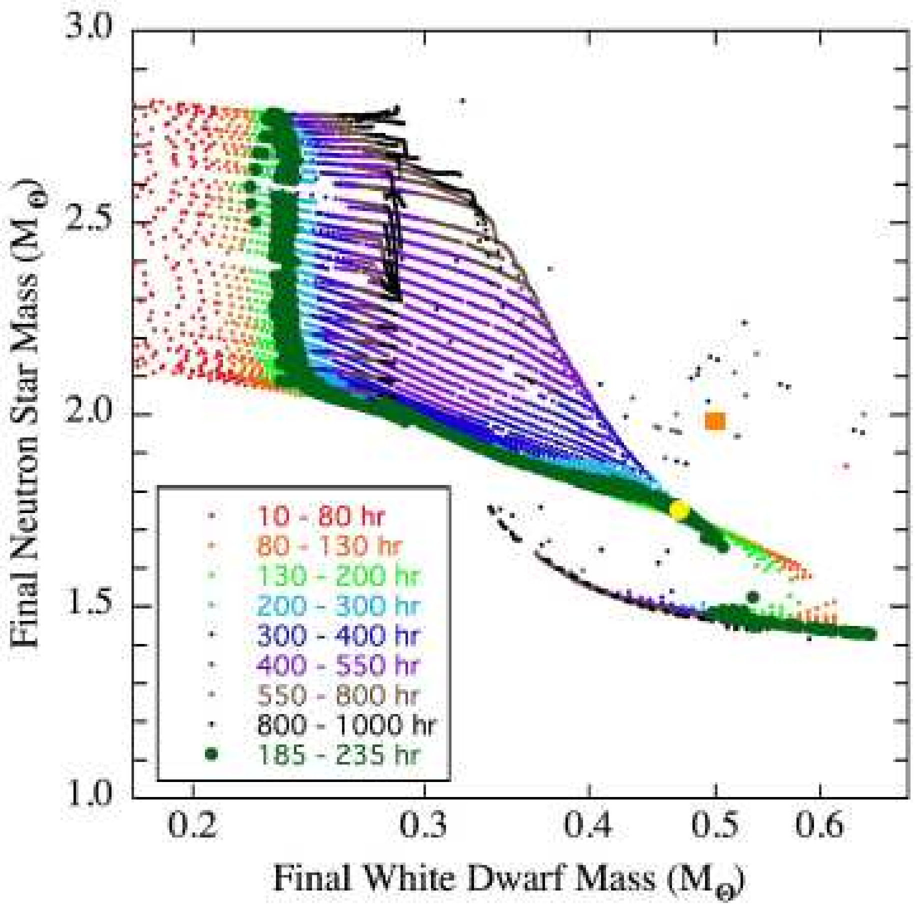


iron core
electron
capture
high−mass
iron core
low−mass
iron core
WD?
?
?
3
2
1
1.15
1.23
1.31
1.39
1.47
1.55
1.63

Evidence for Massive Neutron Stars at Birth

- Demorest et al. (2010): PSR 1614-2230
  - ▷ $M_{NS} = 1.97 \pm 0.04\,M_\odot$, $M_{WD} = 0.5\,M_\odot$
  - ▷ massive WD requires intermediate-mass progenitor (Lin et al. 2011; Tauris et al. 2011)

  → relatively massive NS at birth ($> 1.6\,M_\odot$)
- some HMXBs (e.g. Vela X-1; van Paradijs+)
- binary ms pulsars (Antoniadis+ 2015)



Lin, Rappaport, Podsiadlowski (2011)

Possible Explanations (Suggestions)

- massive NSs reflect the masses of single NSs (e.g. case C mass transfer)
- massive NSs originate from masses just below the NS/BH dividing line (indication from compactness parameter?)

Observations: Not all neutron stars are born with large kicks

- Be X-ray binaries (Pfahl+ 2002)
- NS+NS binaries (DNSs) (van den Heuvel)

Conjecture I: Supernova kicks depend on the duration of the explosion phase (Podsiadlowski, Langer + 2004)

- large kicks: "normal" iron cores
- small kicks
  - ▷ low-mass iron cores (e.g. from ultrastripped binaries, → Tauris, Mazzali)
  - ▷ electron-capture supernovae in ONe cores
- difference between single stars and binaries

Conjecture II: Supernova kicks increase with neutron-star mass

- more compact collapsing cores → longer explosion phase → larger NS masses (explosion energy?)
- consistent with observations and recent calculations?

Conjecture III: Neutron star masses and supernova kicks are systematically smaller in close binaries (Case A/B) than for single stars/wide binaries (case C)

- systematically smaller core masses in systems that lose the H-rich envelope in case A/B mass transfer

  Implications

  - ▷ larger binary survival probability in first supernova → DNS merger rate