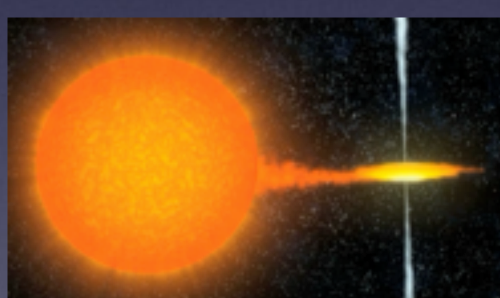
Probing Core Collapse with Binaries



Vicky Kalogera
Northwestern U.

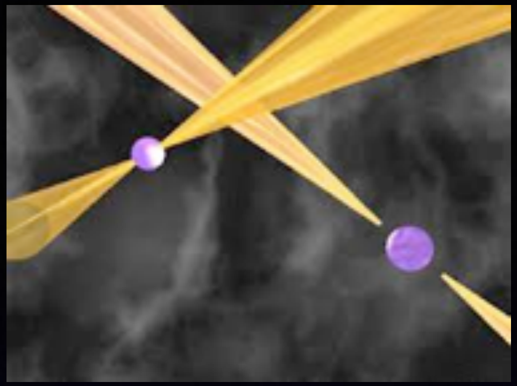
Key Questions

- Can We Constrain the SN mechanism ?
- What is the Origin of SN kicks ?
- Do Black Holes Receive Kicks ?

Key Questions

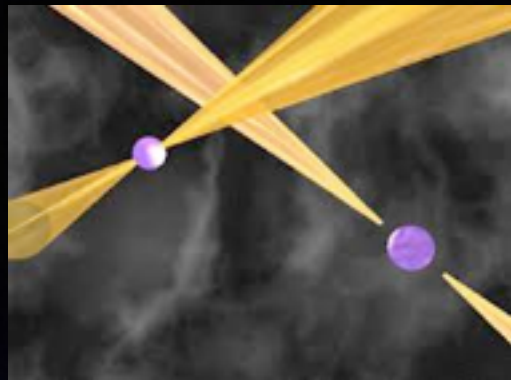
- Can We Constrain the SN mechanism ?
- What is the Origin of SN kicks ?
- Do Black Holes Receive Kicks ?

  - Progenitor Mass at SN ?
  - SN Kick Magnitude ?



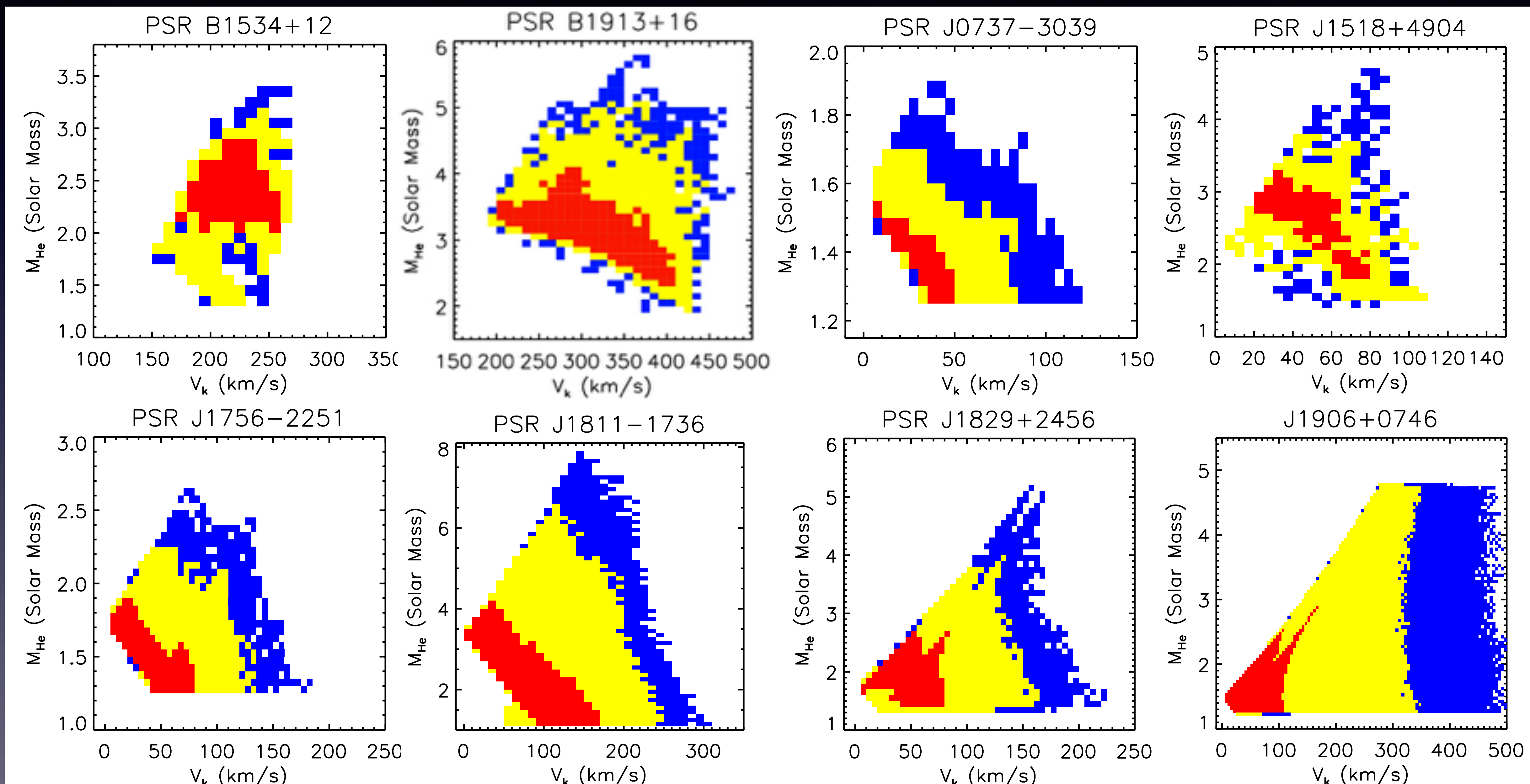
Double Neutron Stars

Double Neutron Stars



Wong et al 2010

Progenitor Mass at SN



SN Kick Magnitude

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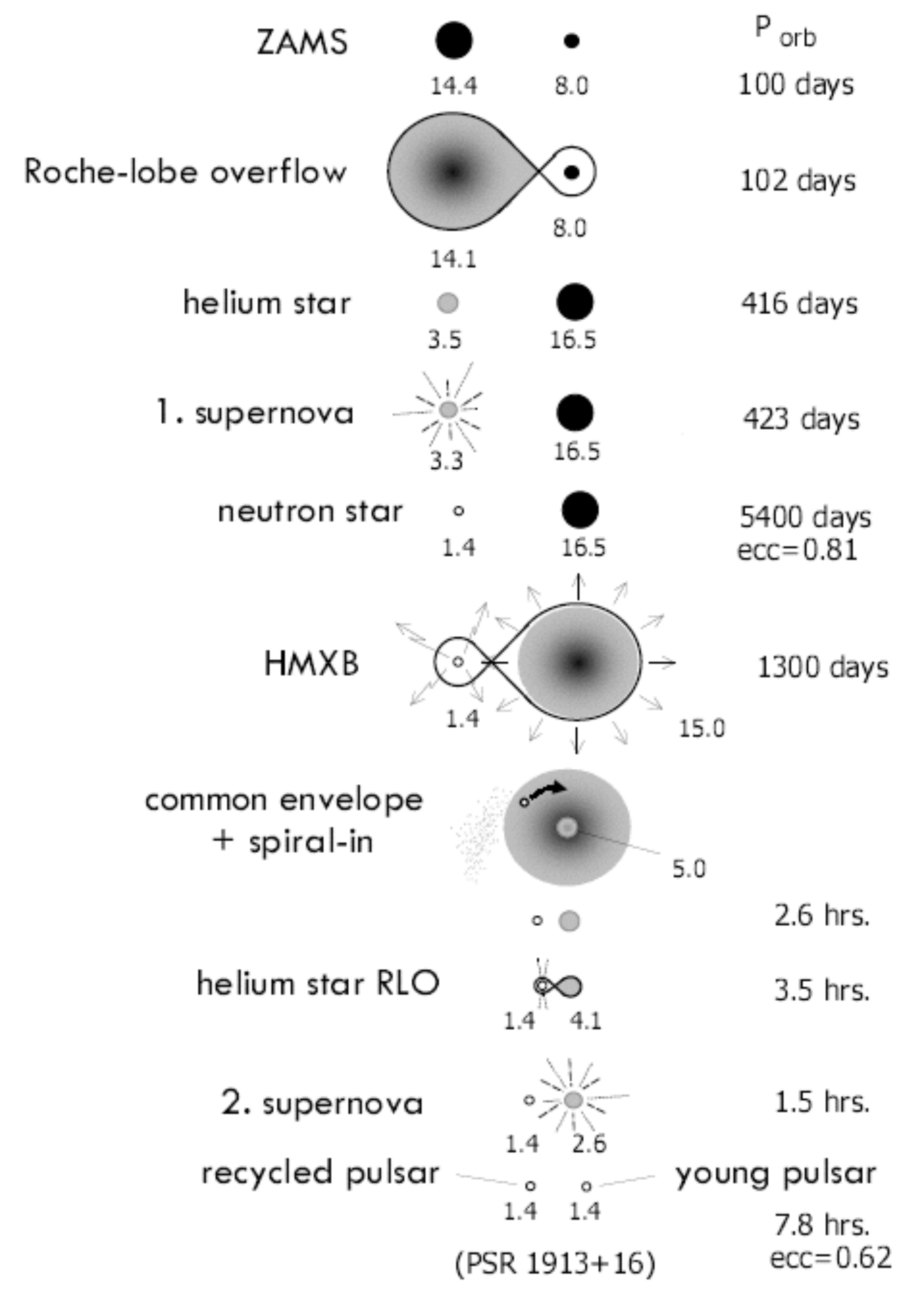
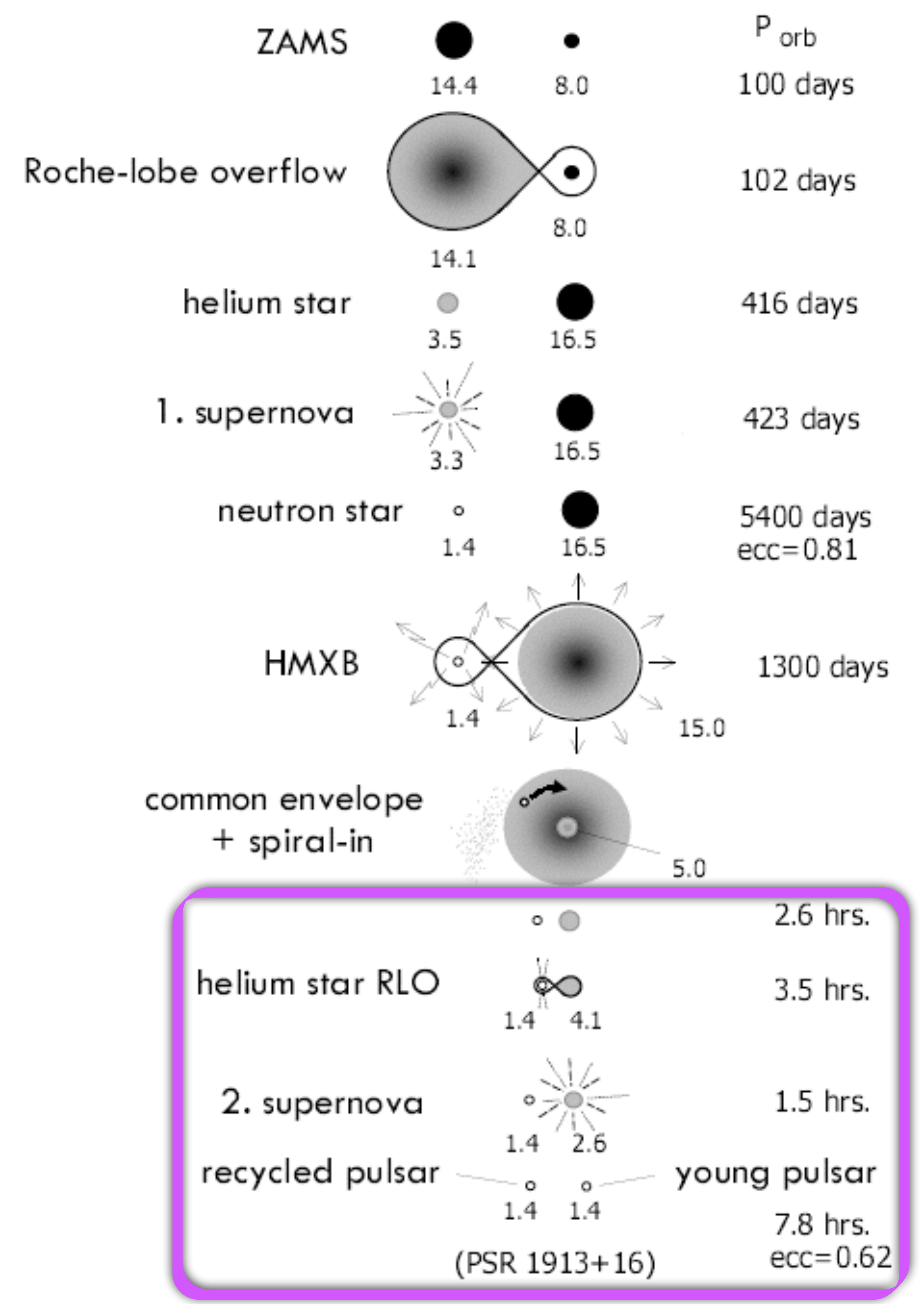
Tauris & van den Heuvel 2004

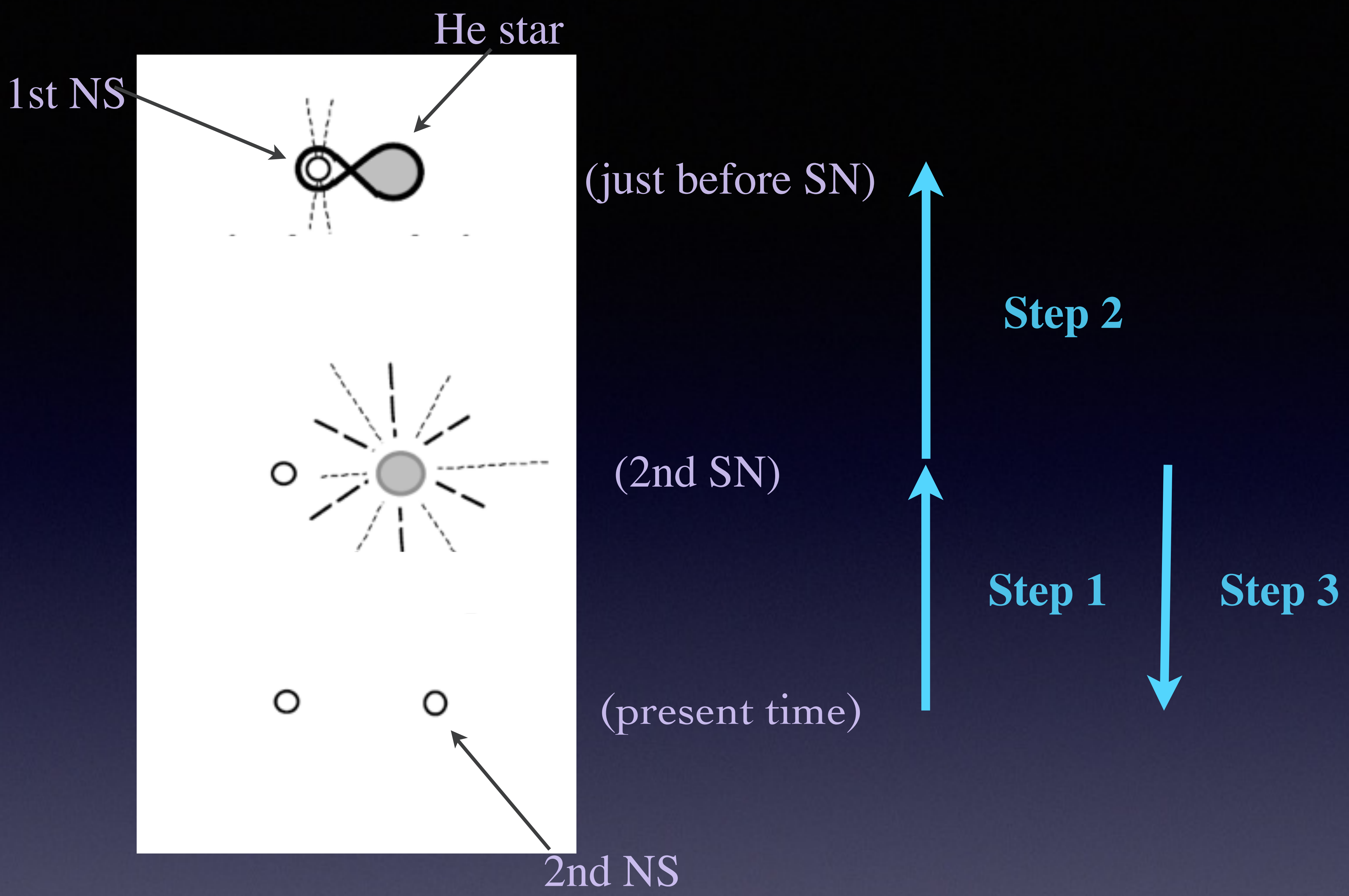
NS-NS Formation Channel



Tauris & van den Heuvel 2004

NS-NS Formation Channel





Step 1:

Step 2:

Step 3:

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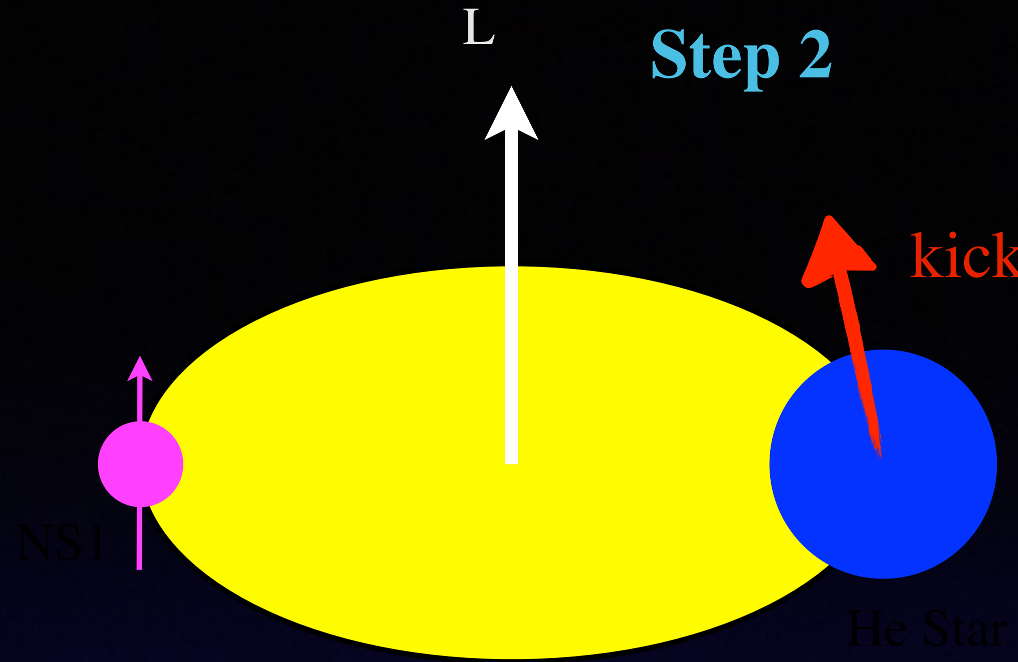
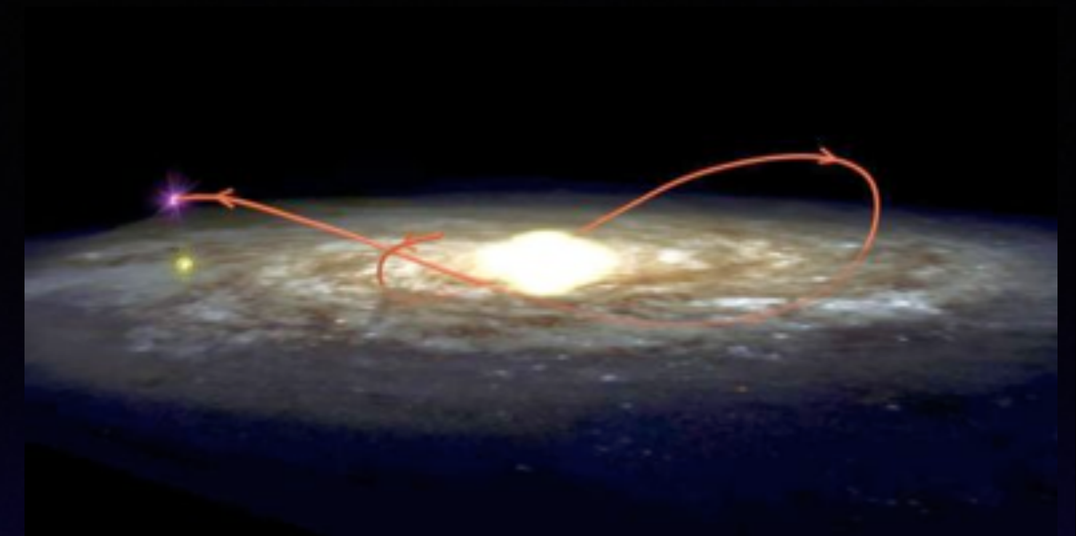
Step 1

Step 2



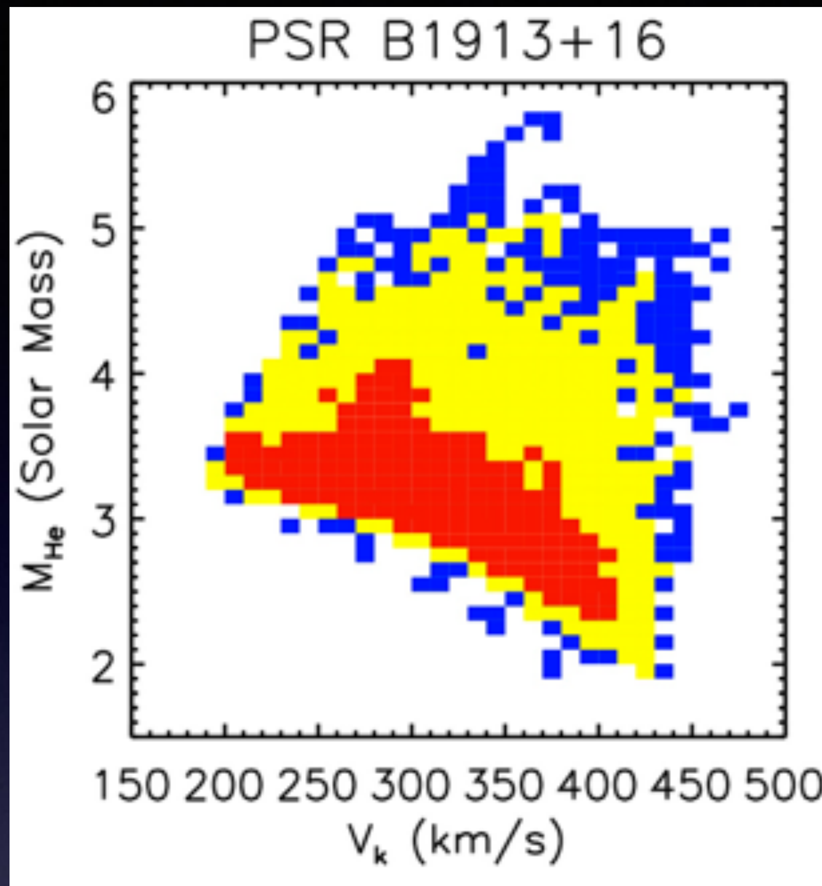
Step 3



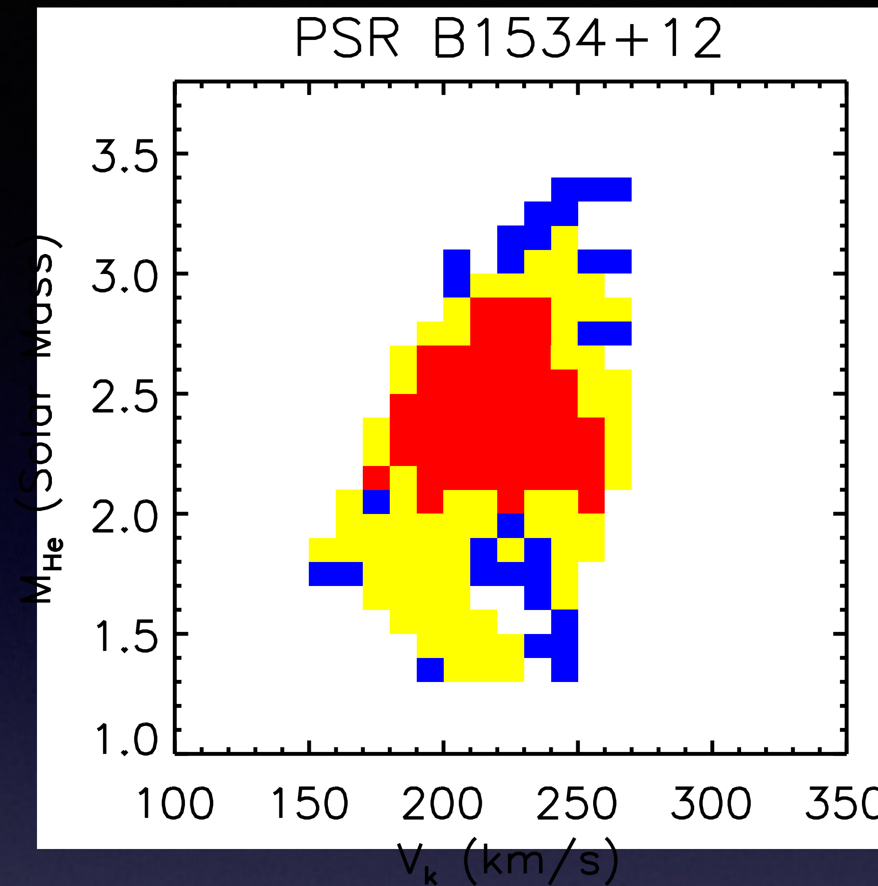
Observational Constraints:

- NS Masses, current A and e, PSR age
- Spin-Orbit Tilt Angle (for B193, B1534, J0737 only)
- Sky Location, Distance, Proper Motion

(Wong et al. 2010)



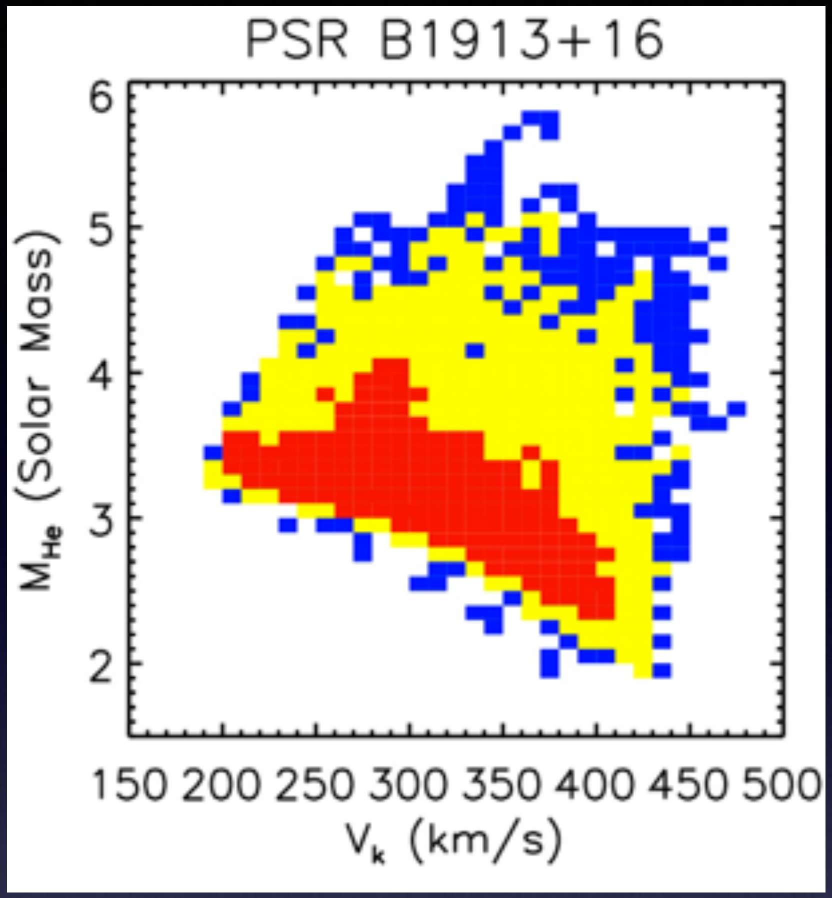
red = 60%
yellow = 90%
blue = 95%



V
M

V
M

(Wong et al. 2010)



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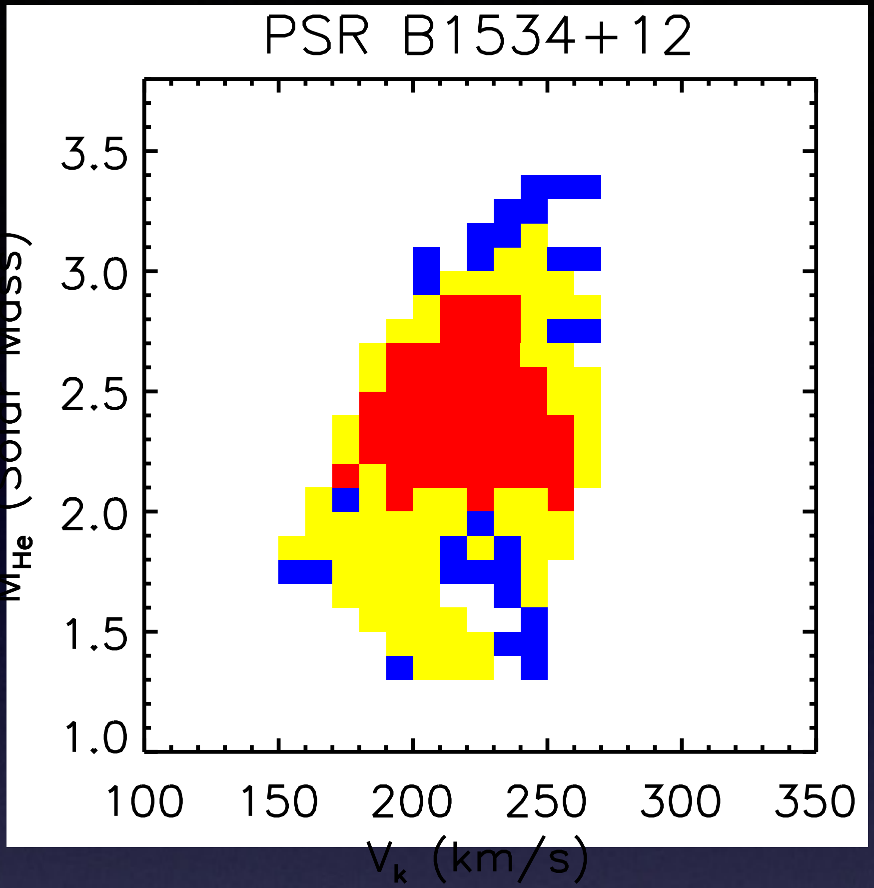


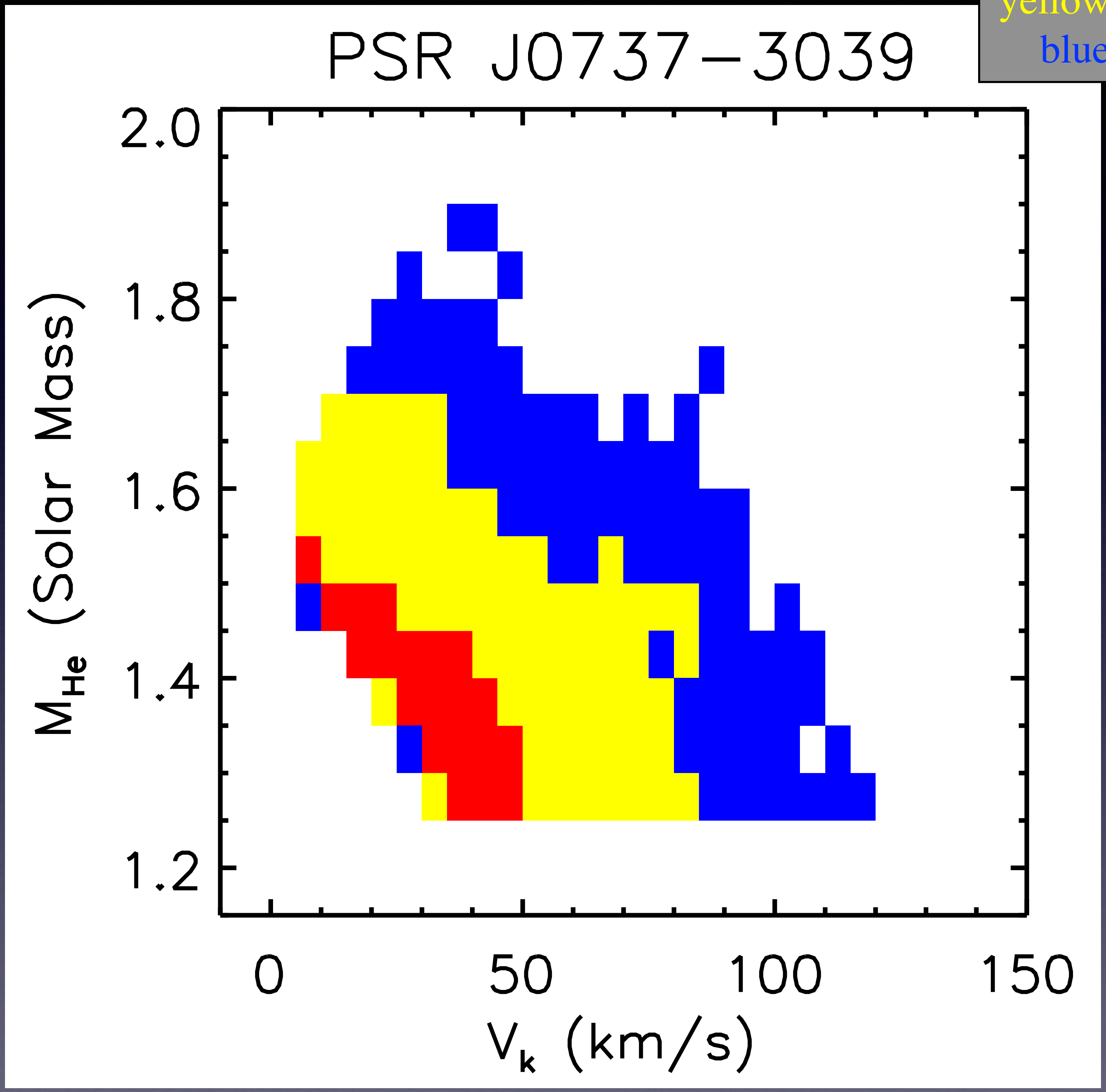
V
M

V
M

NS2 formed in an Fe core collapse supernova

(Wong et al. 2010)

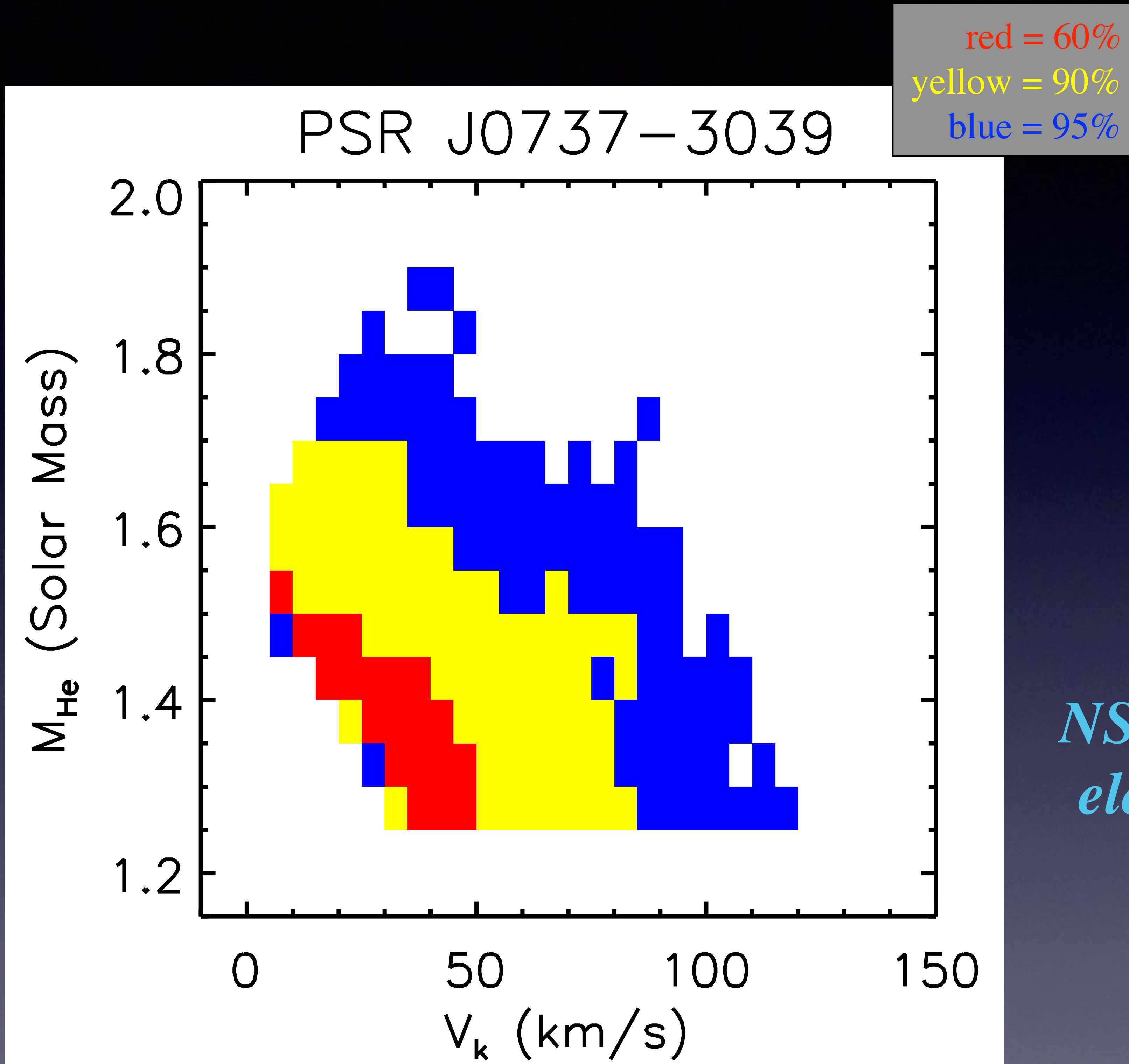
red = 60%
yellow = 90%
blue = 95%



V

M

(Wong et al. 2010)



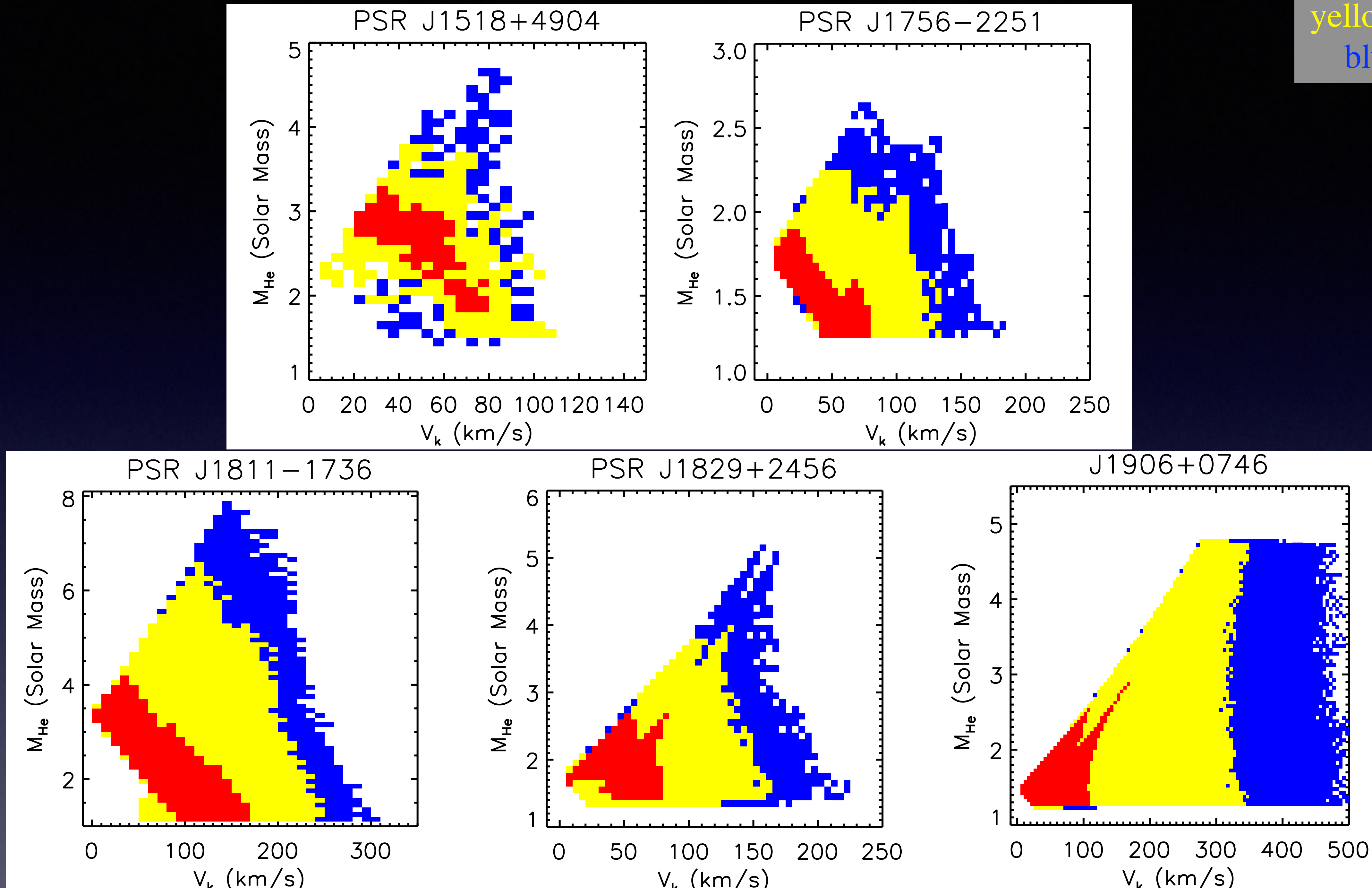
V

M

↓

NS2 (pulsar B) formed in an electron capture supernova

red = 60%
yellow = 90%
blue = 95%



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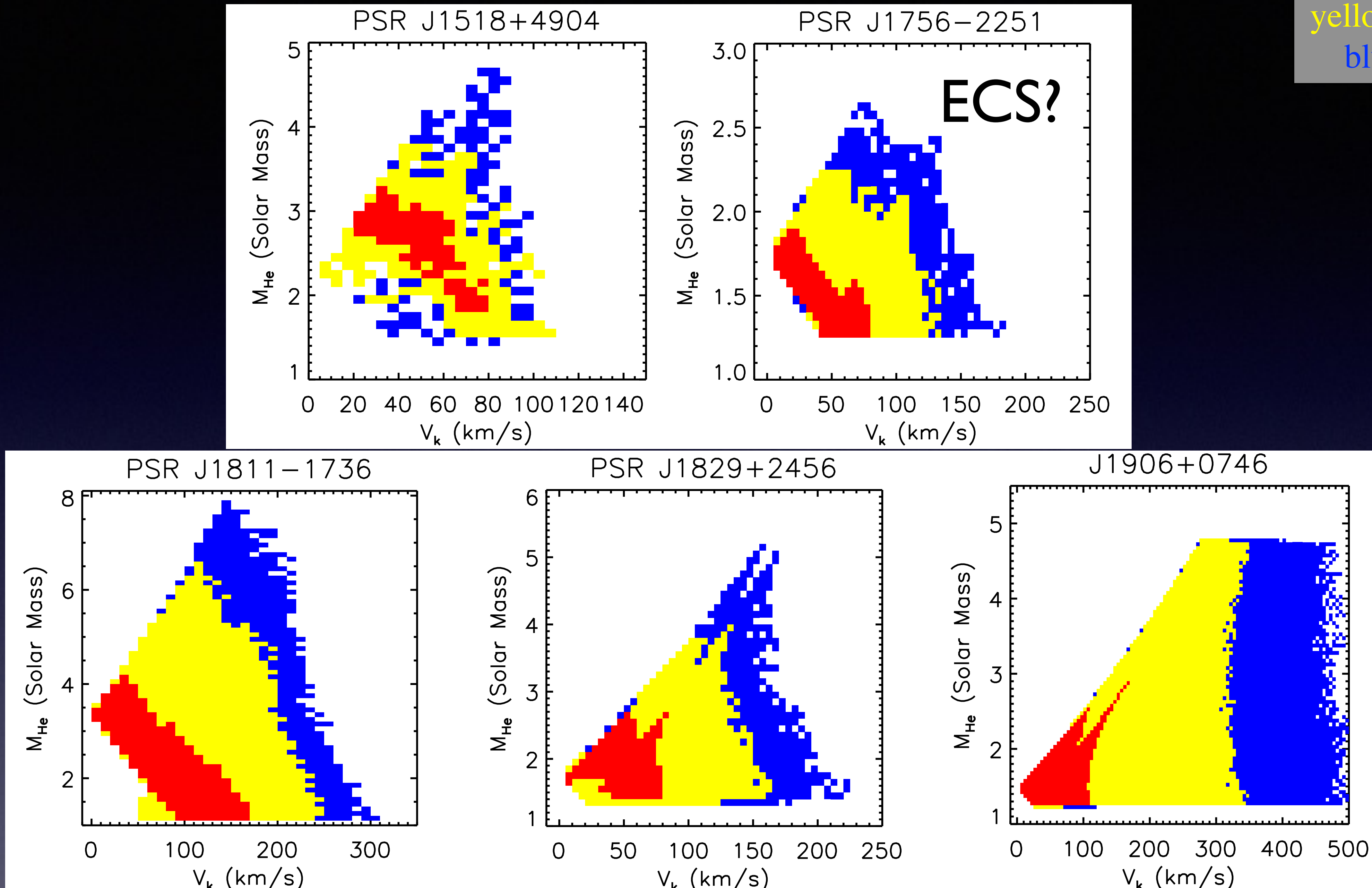

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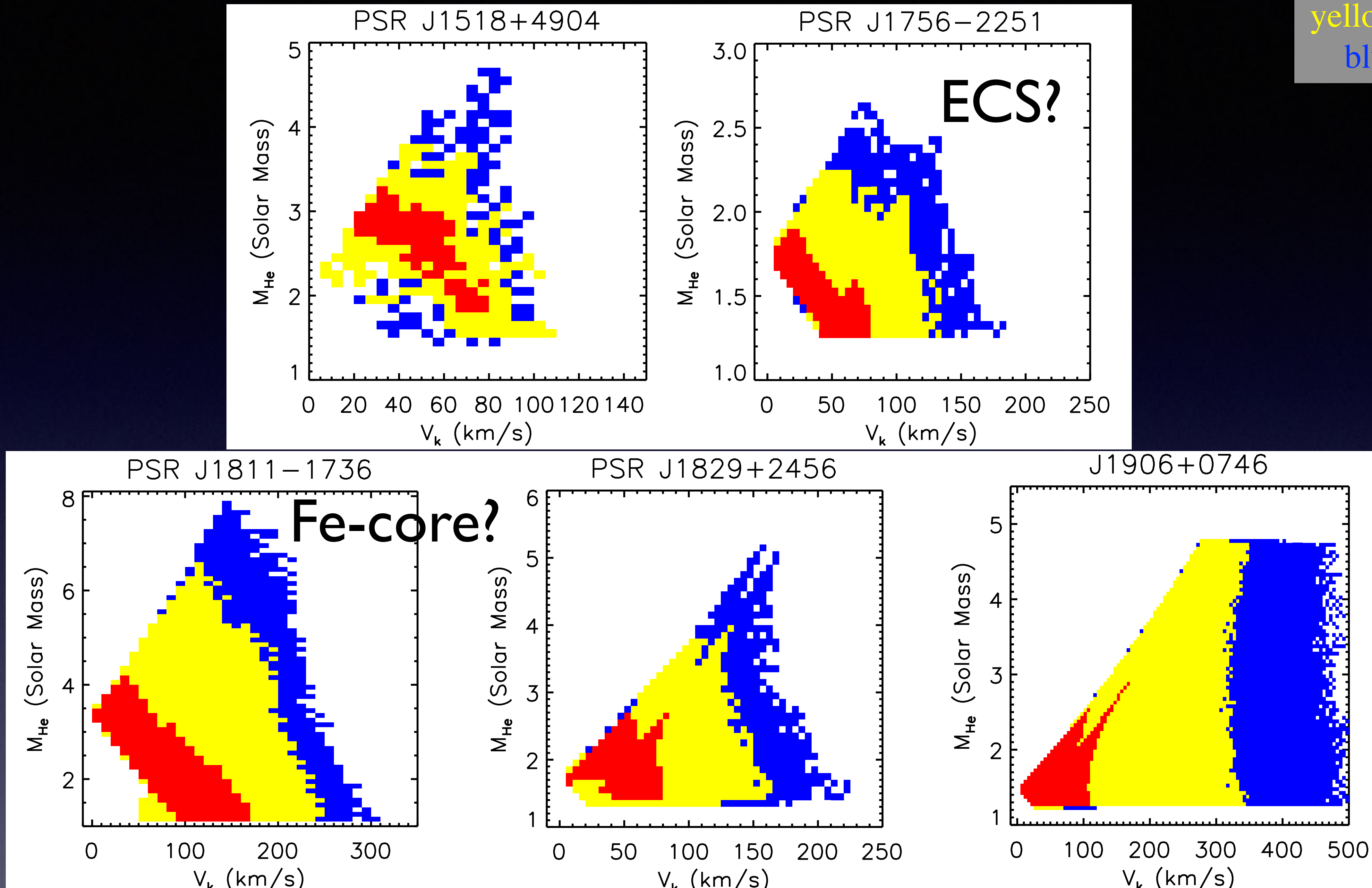

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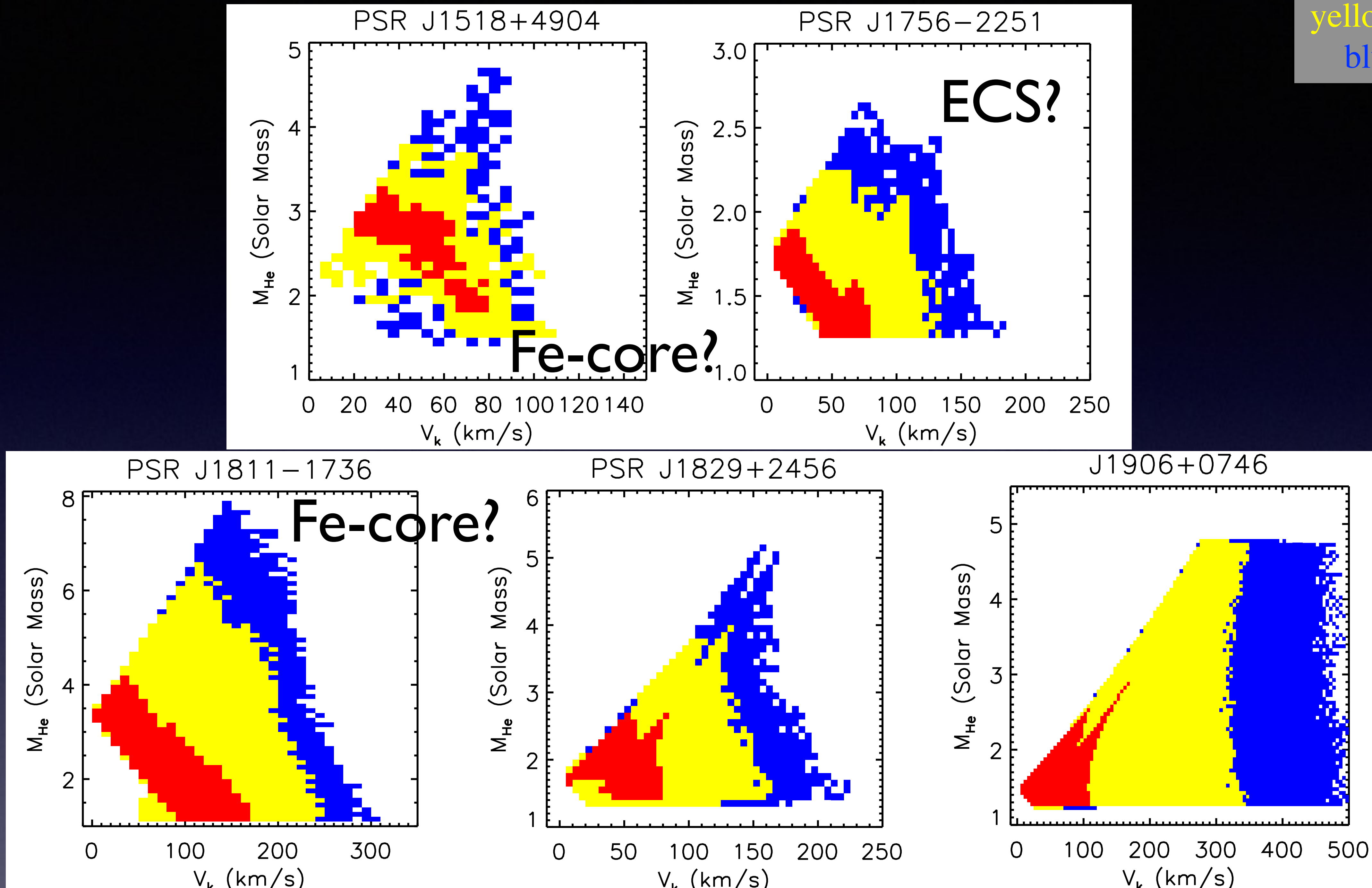
yellow = 90%
blue = 95%



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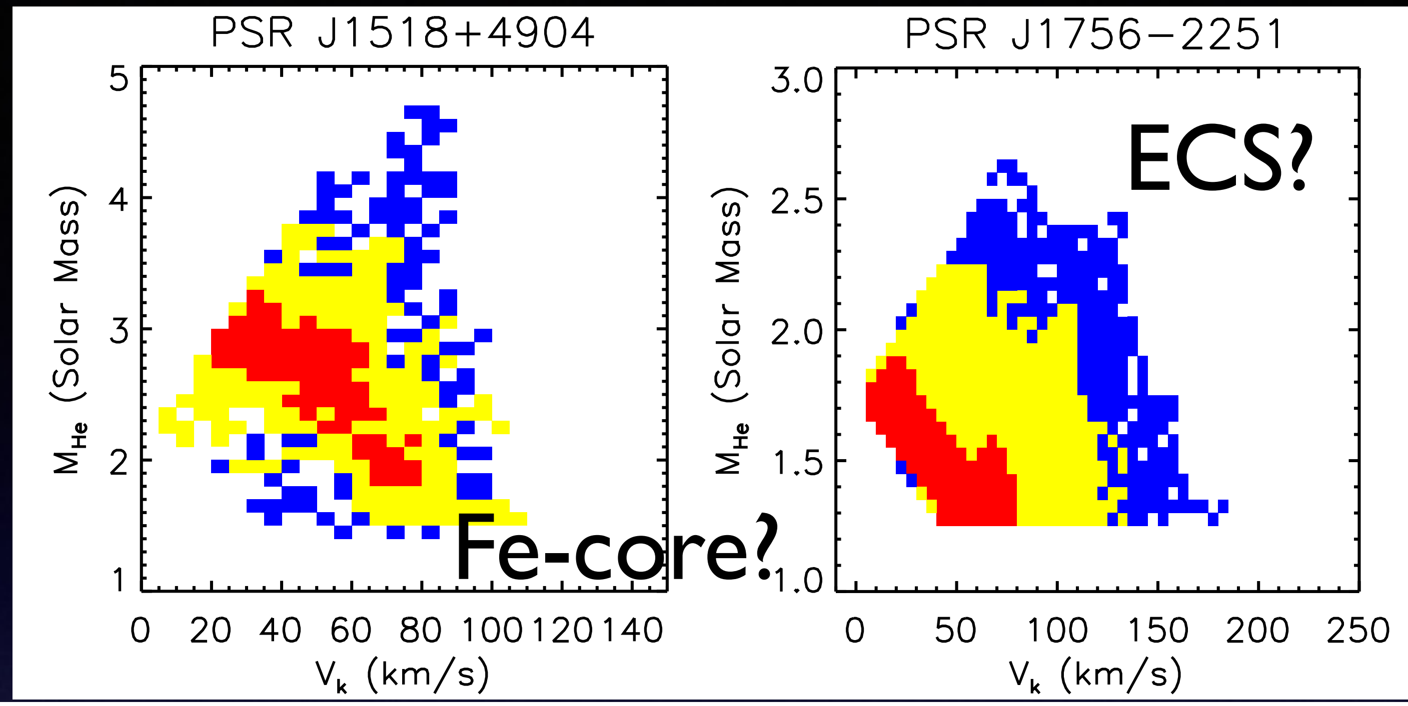

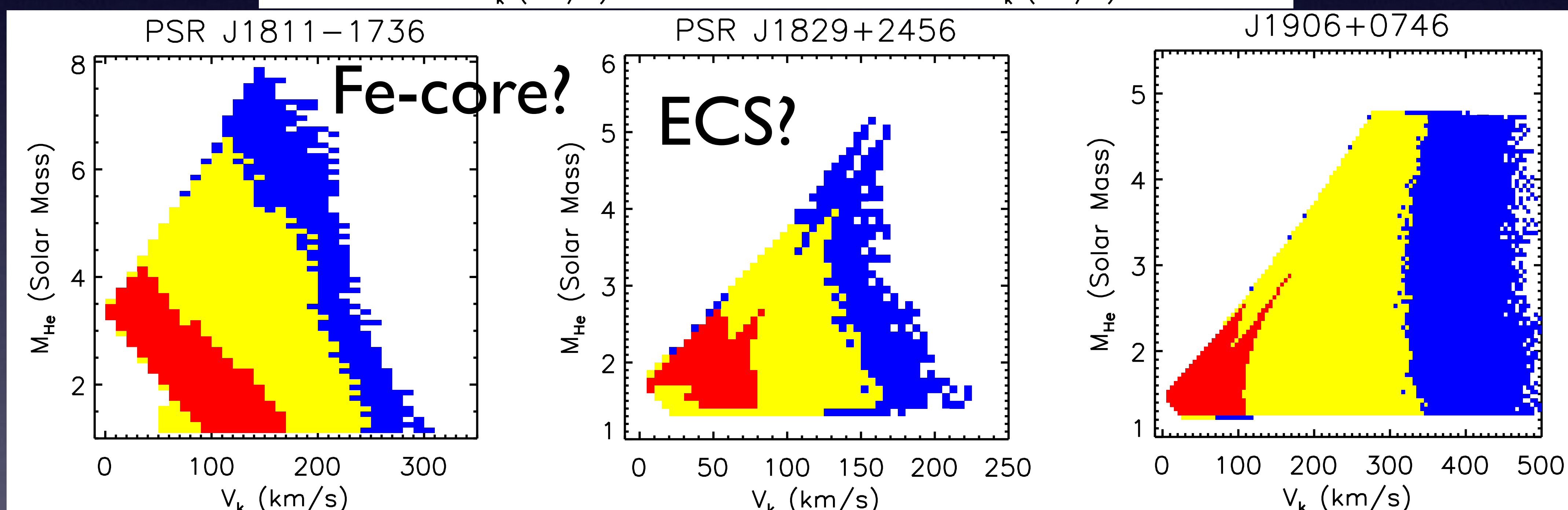

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yellow = 90%
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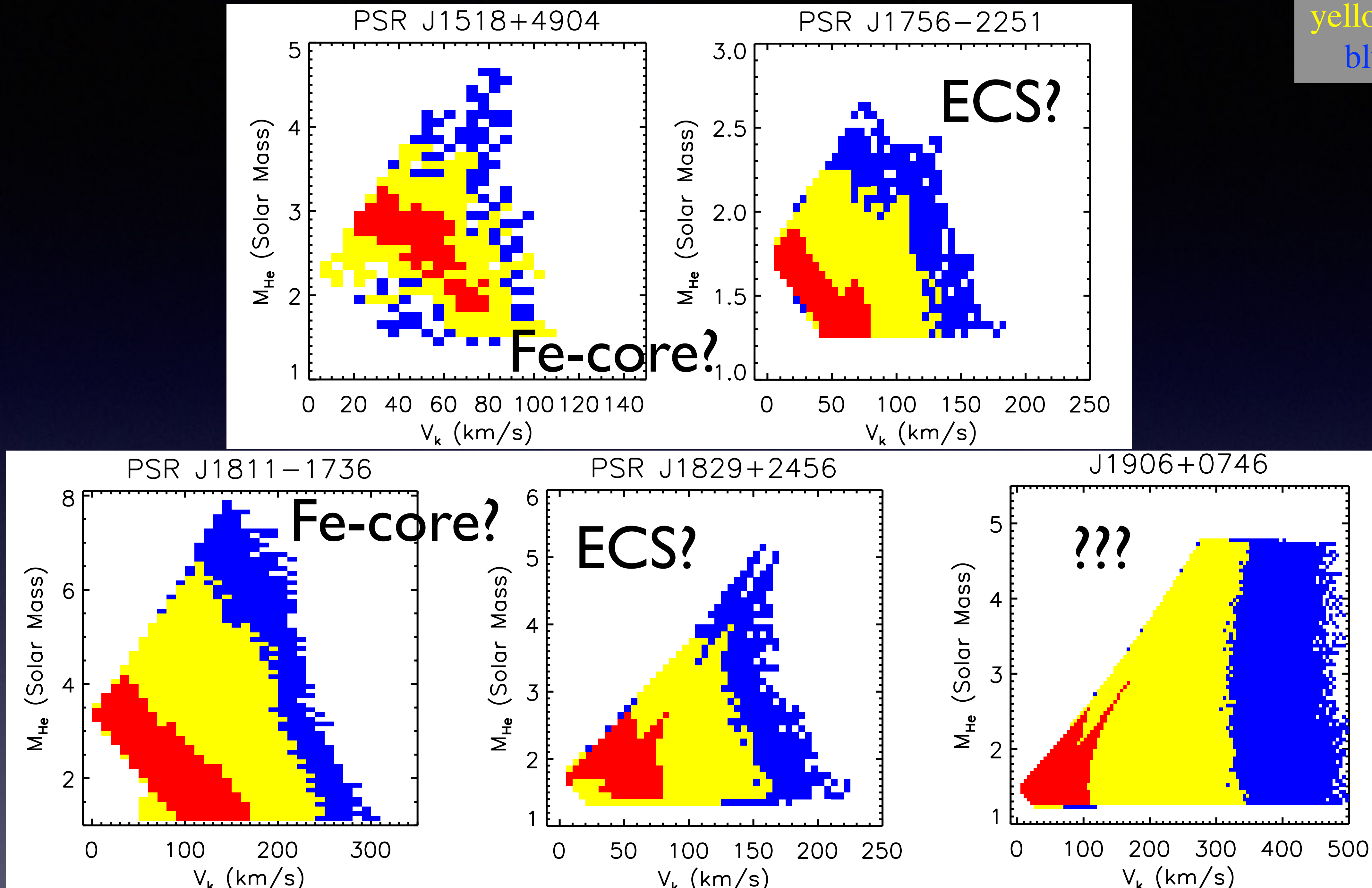
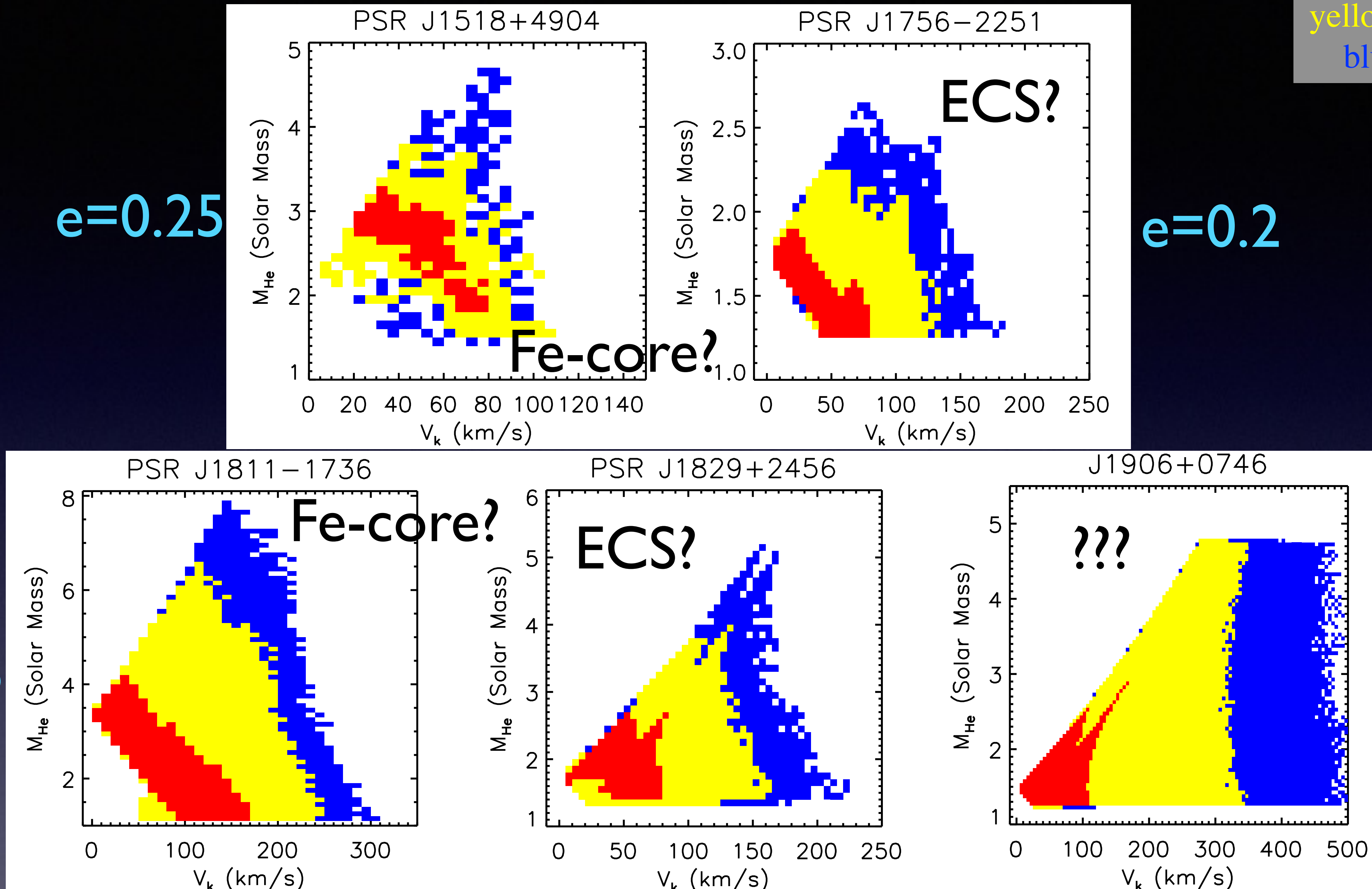




red = 60%
yellow = 90%
blue = 95%

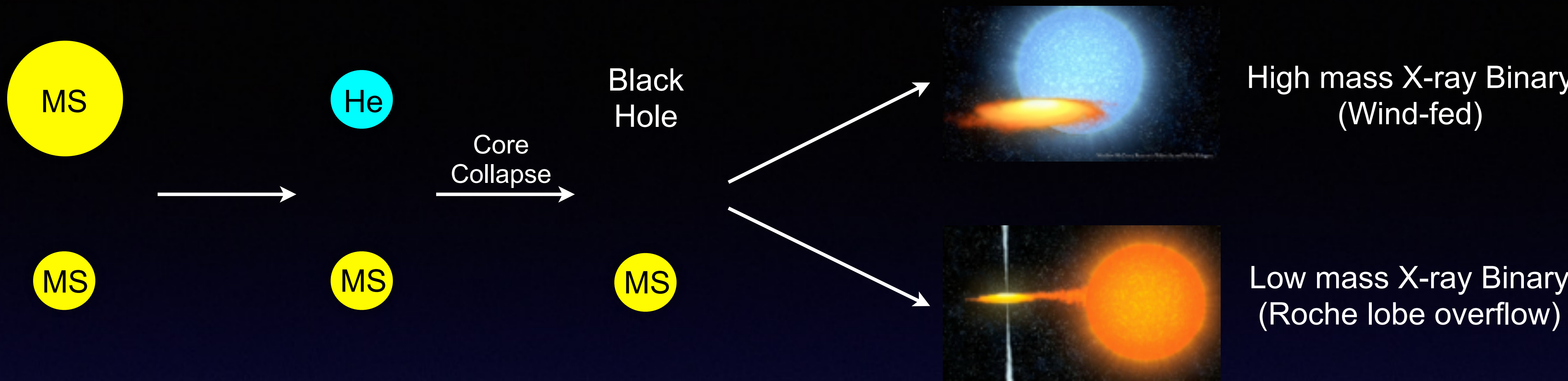
e=0.25

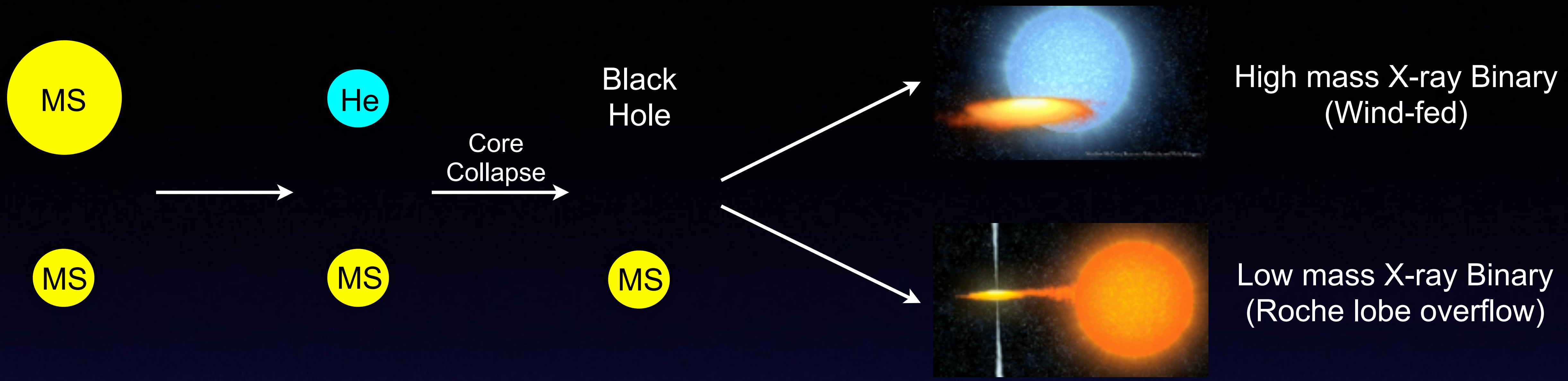
e=0.2

e=0.83

e=0.09

e=0.14


MS
MS
He
MS
Core
Collapse
Black
Hole
MS
High mass X-ray Binary
(Wind-fed)
Low mass X-ray Binary
(Roche lobe overflow)

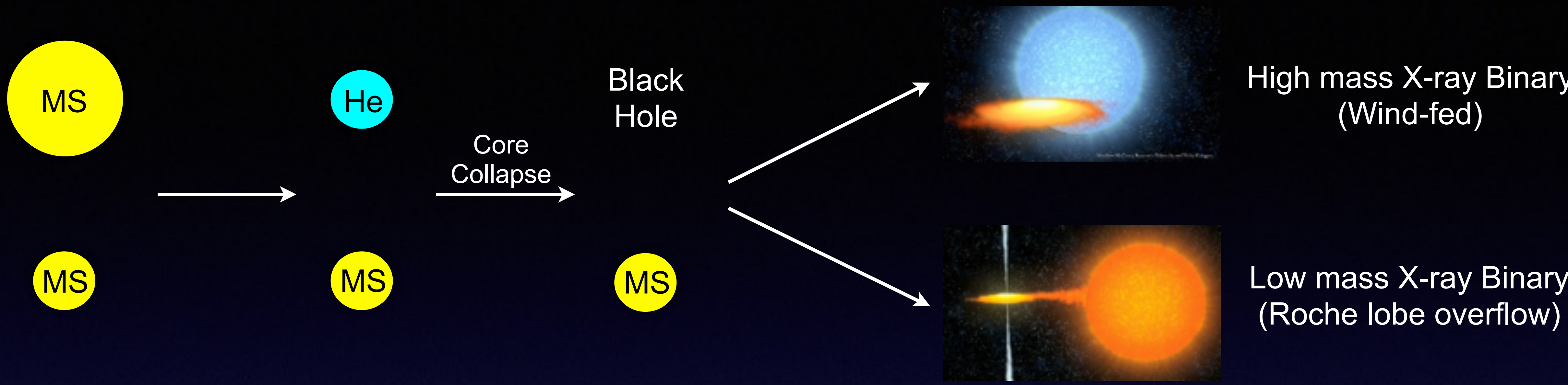


Step 1:

Step 2:

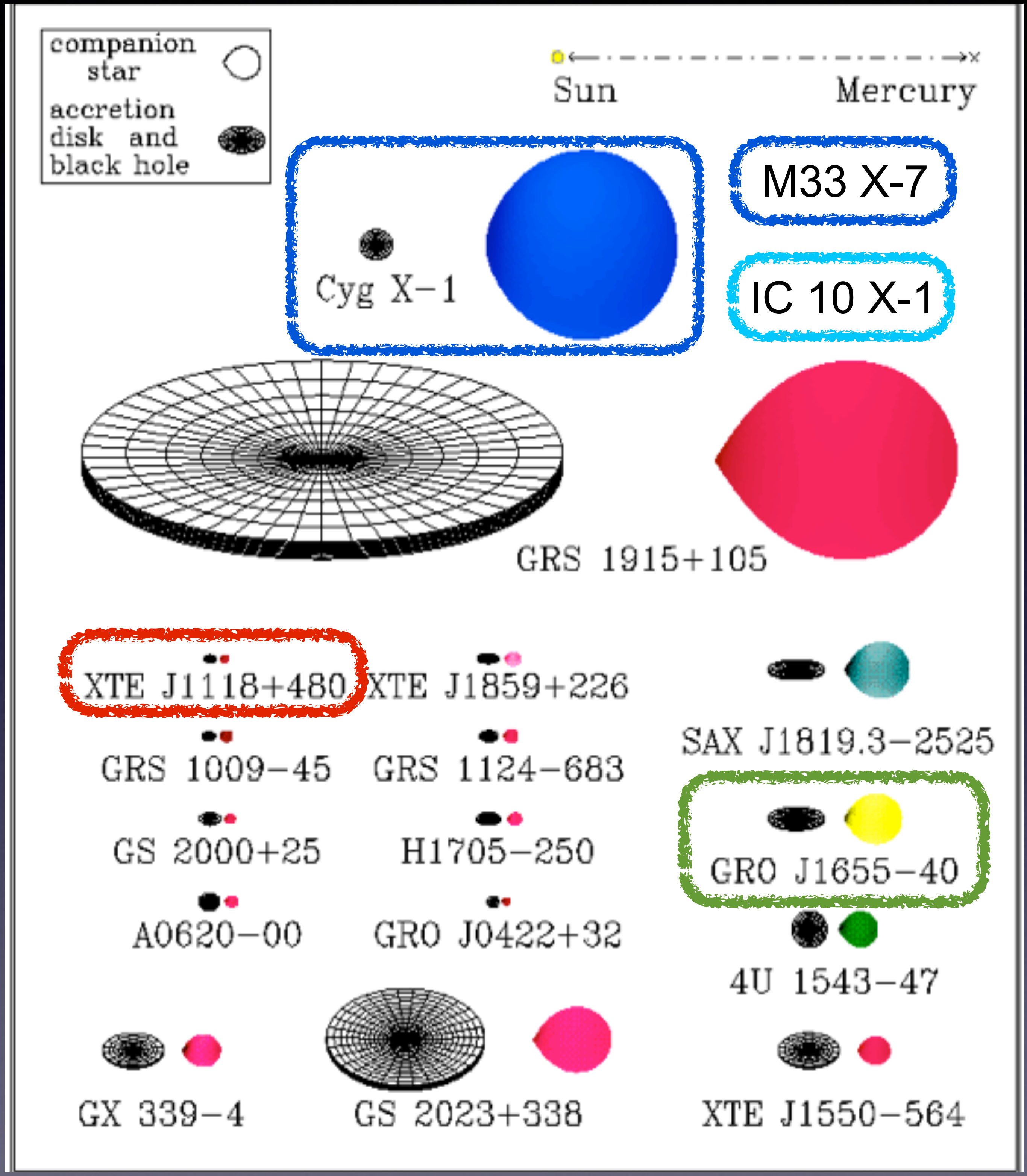
Step 3:

Step 4:



Observational Constraints:

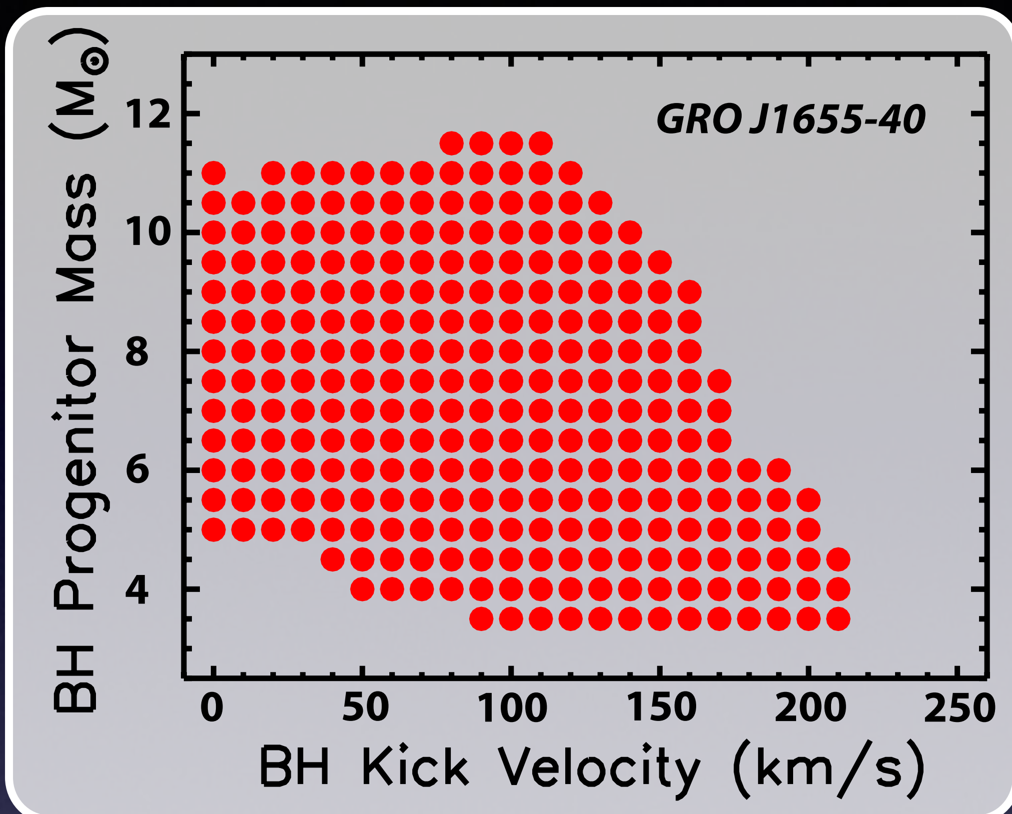
- BH companion L, Teff, and Mass
- BH Mass, Orbital Period
- Proper Motion, Radial Velocity
- Sky Location, Distance



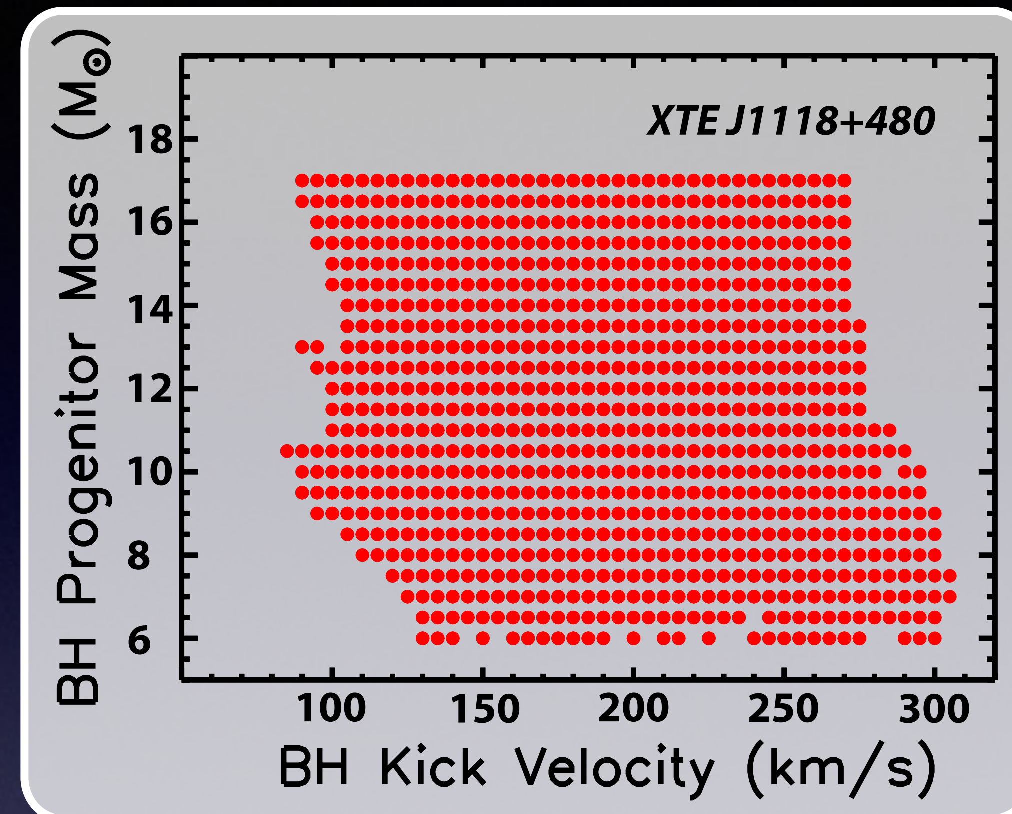
(from Orosz/Bailyn)

BH XRB Results

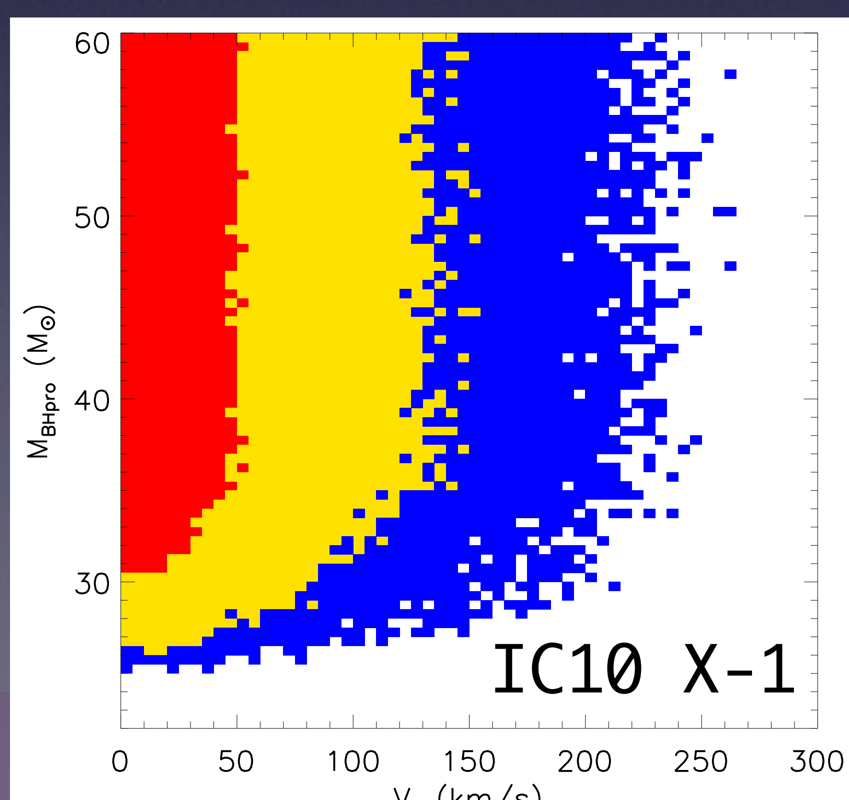
(Willems et al. 2005)



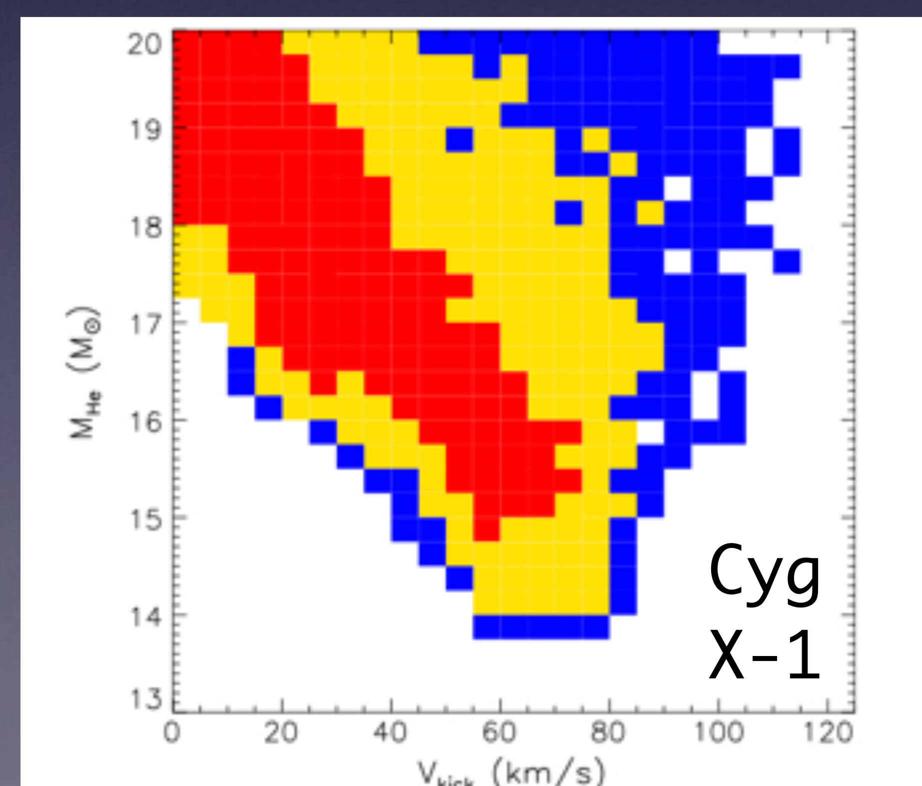
(Fragos et al. 2009)



(Wong et al. 2013)



(Wong et al. 2012)



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BH XRB Results

System	Observed Current BH mass ($M_\odot$)	Post-SN BH mass ($M_\odot$)	Immediate Progenitor mass ($M_\odot$)	Natal Kick (km/s)
GRO J1655-40 (early-type, P>1d)	6.3 ± 0.5 (Greene et al. 2001) 5.4 ± 0.3 (Beer & Podsiadlowski 2002)	5.5 – 6.3 3.5 – 5.4 (Willems et al. 2005)	5.5 – 11.0 3.5 – 9.0 (Willems et al. 2005)	30 – 160 ≤ 210 (Willems et al. 2005)
XTE J1118+480 (late-type, P<1d)	8.0 ± 2.0 (McClintock et al. 2001, Wagner et al. 2001, Gelino et al. 2006)	6.0 – 10.0 (Fragos et al. 2009)	6.5 – 20.0 (Fragos et al. 2009)	80 – 310 (Fragos et al. 2009)
M33 X-7 (wind-fed, H-rich)	13.5 – 20.0 (Orosz et al. 2007, Valsecchi et al.2010)	13.5 – 14.5 (Valsecchi et al.2010)	15.0 – 16.1 (Valsecchi et al.2010)	10 – 850 (Valsecchi et al.2010)
Cygnus X-1 (wind-fed, H-rich)	14.81 ± 0.98 (Orosz et al. 2011)	13.8 – 15.8 (Wong et al. 2012)	15.0 – 20.0 (Wong et al. 2012)	≤ 77 (Wong et al. 2012)
IC 10 X-1 (wind-fed, He-rich)	25 — 39 (Wong et al. 2013)	25 — 39 (Wong et al. 2013)	32 - 60 (Wong et al. 2013)	≤ 130 (Wong et al. 2013)

Some BHs must have received a kick at formation

Probing the Kick Mechanism?

What do BH Kick Magnitudes Correlate with?

- BH mass?
- He-star mass?
- mass loss at core collapse? (absolute/fractional?)

What is the underlying shape of the global correlation?

Can we probe the kick mechanism?

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What do BH Kick Magnitudes Correlate with?

- BH mass?
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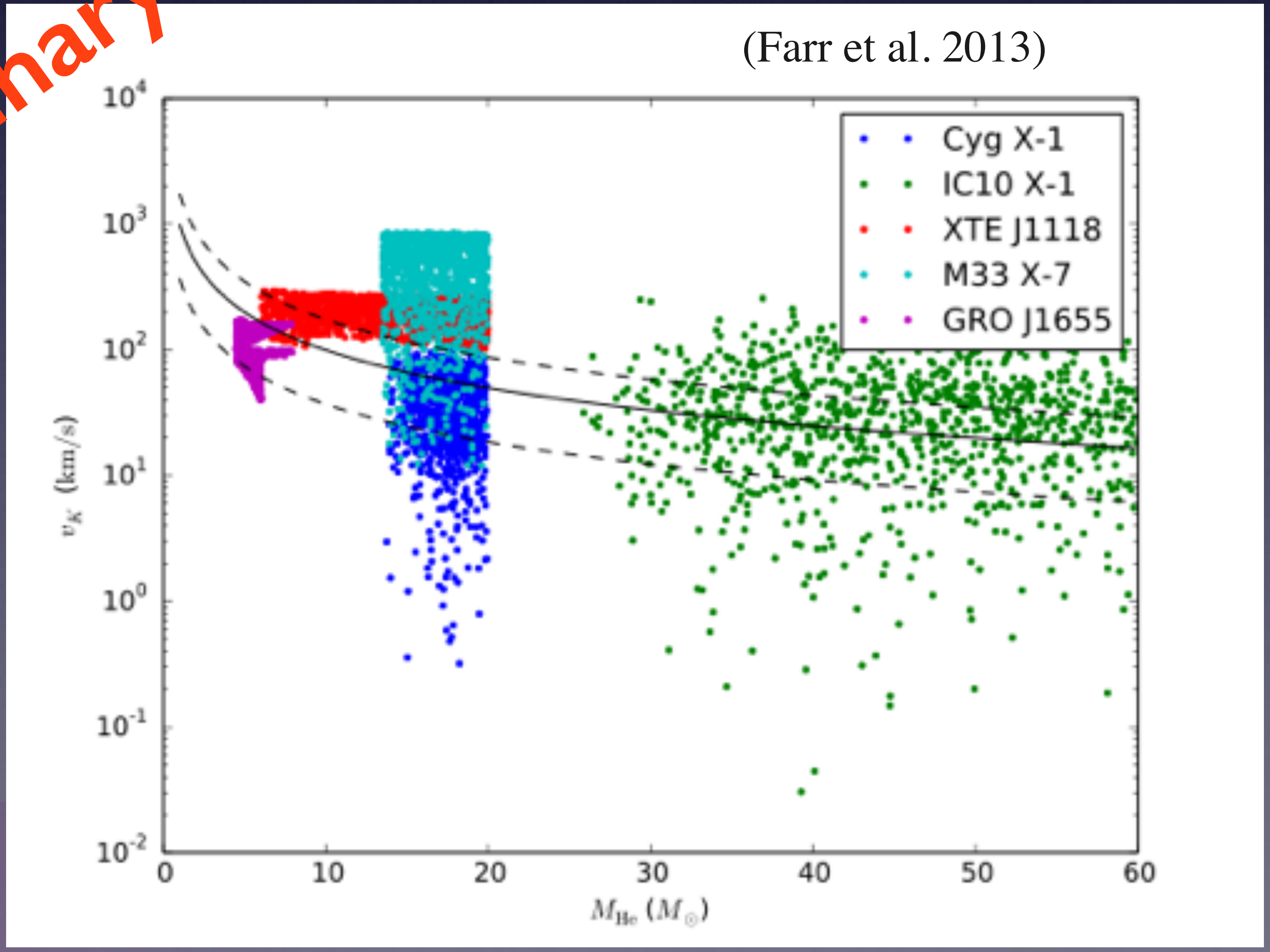
preliminary



best f(M_{He}):

Maxwellian kick distribution with:

$\langle V_k \rangle \sim 1/M_{He}$

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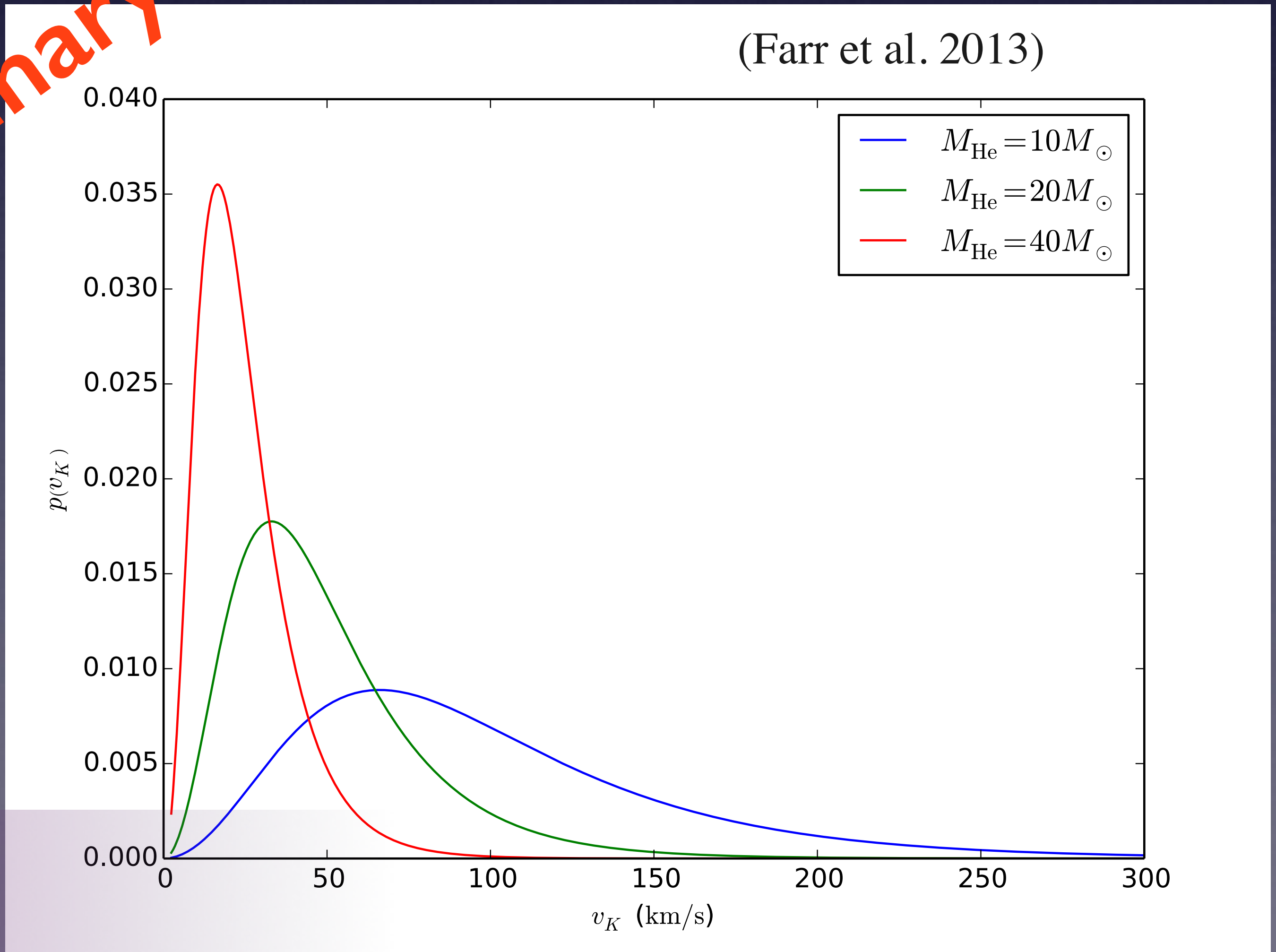

best f(M_{He}):

Maxwellian kick distribution with:

$\langle V_k \rangle \sim 1/M_{He}$

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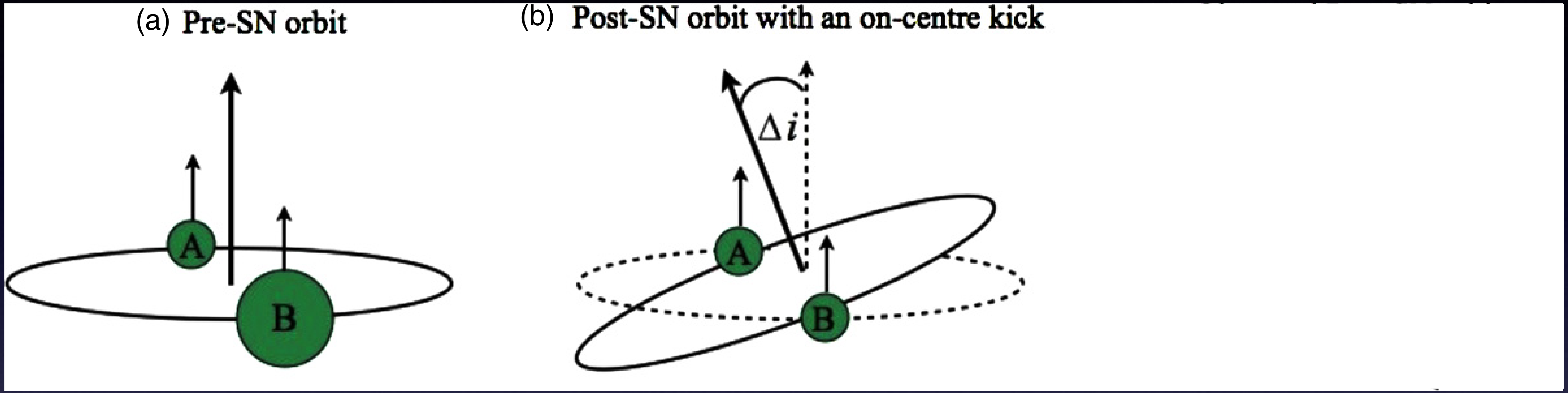
The Double Pulsar

The Double Pulsar

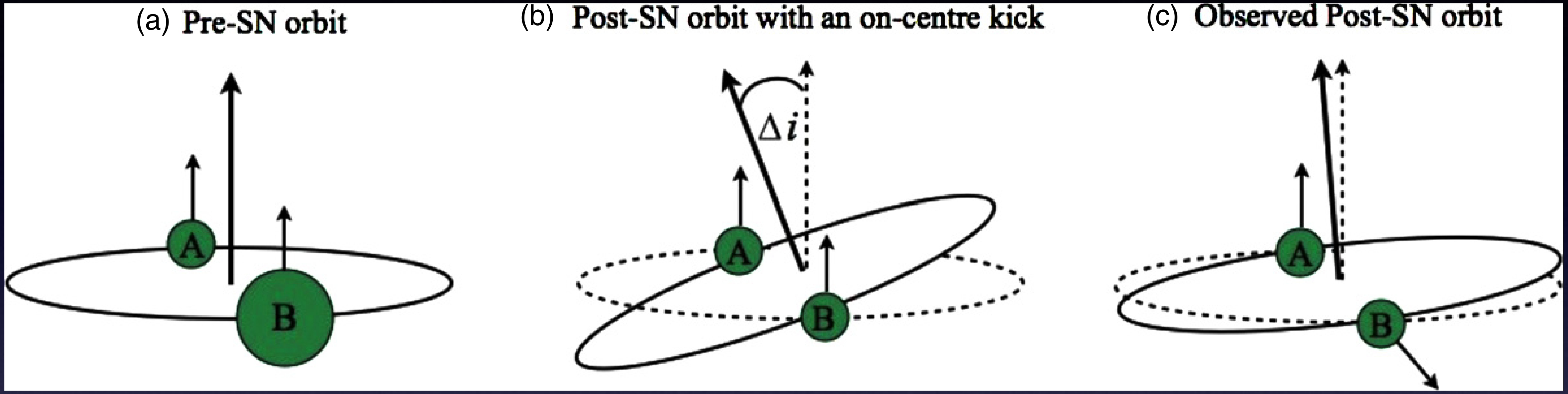
Farr et al. 2011



If kick imparts only
linear momentum:
PSRs A and B should be closely aligned

The Double Pulsar

Farr et al. 2011



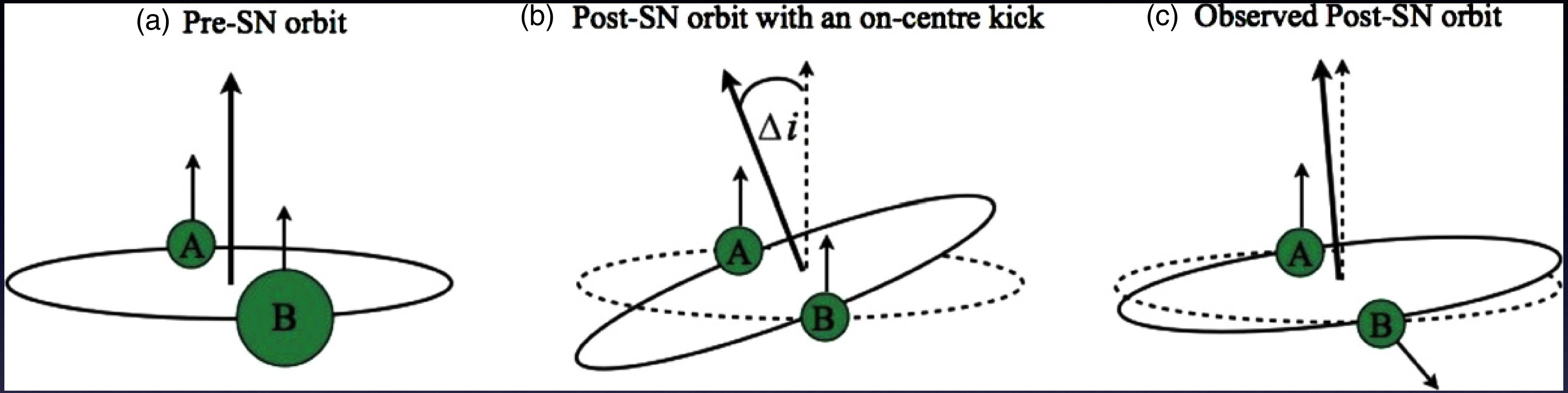
Spin-Orbit Tilts Measured:

PSR A: < 14 deg (Ferdman et al. 2008)

PSR B: 130 +- 1.3 deg (Lyutikov & Thompson 2005; Breton et al. 2008)

The Double Pulsar

Farr et al. 2011



Spin-spin misalignment:

- requires AM production during SN collapse
- if spin & kick linked physically,

an off-center `bulk' kick is required too (~2-5km)

All Thanks to:

Will Farr

Tassos Fragos

Francesca Valsecchi

Kyle Kremer

Tsing-Wai Wong

Bart Willems

SIMONS FOUNDATION

NSF NASA

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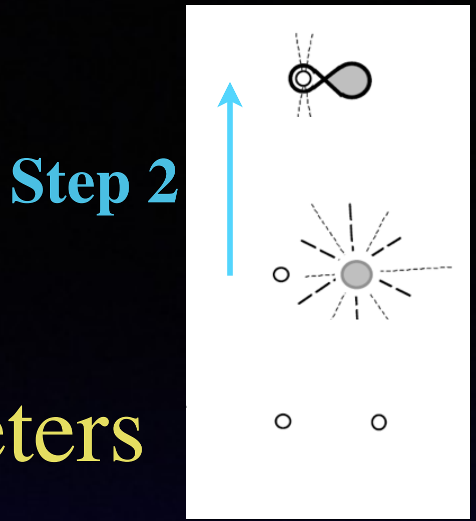
C I E R A

Table 1
Parameters of the Eight Known DNS in Our Galaxy

System	α[a]	δ[b]	D[c]	μ_α[d]	μ_δ[e]	τ_c[f]	M_1[g]	M_2[h]	A_{cur}[i]	e_{cur}[j]	θ_t[k]
PSR B1534+12[r1]	15 37 09.96	11 55 55.55	1.02	1.34(1)	−25.05(2)	250	1.3332(10)	1.3452(10)	3.28	0.274	25(155) ± 3.8
PSR B1913+16[r2]	19 15 28.00	16 06 27.40	8.3(1.4)	−3.27(35)	−1.04(42)	110	1.4408(3)	1.3873(3)	2.80	0.617	18(162) ± 6
PSR J0737−3039[r3]	07 37 51.25	−30 39 40.71	1.15	−3.82(62)	2.13(23)	210	1.337(5)	1.250(5)	1.26	0.0878	<15[l]
PSR J1518+4904[r4]	15 18 16.80	49 04 34.25	0.625	−0.67(4)	−8.53(4)	20000	$0.72^{+0.51}_{-0.58}$	$2.00^{+0.58}_{-0.51}$	24.7	0.249	...
PSR J1756−2251[r5]	17 56 46.63	−22 51 59.40	2.5	−0.7(2)	...	443	1.312(17)	$1.258^{+0.018}_{-0.017}$	2.70	0.181	...
PSR J1811−1736[r6]	18 11 55.03	−17 36 37.70	6.0	...	...	1830	$1.62^{+0.22}_{-0.55}$	$1.11^{+0.53}_{-0.15}$	40.7	0.828	...
PSR J1829+2456[r7]	18 29 34.60	24 56 19.00	1.2	...	...	12400	$1.14^{+0.28}_{-0.48}$	$1.36^{+0.50}_{-0.17}$	6.36	0.139	...
PSR J1906+0746[r8]	19 06 48.67	07 46 28.60	5.4	...	...	0.112	1.365(18)	1.248(18)	1.75	0.0853	...

Step 2: Orbital Dynamics at Core Collapse



- random magnitude and direction of natal kick
- map post-SN binary parameters to pre-SN parameters using conservation of E
- constraints:
  a) survival of the binary
  b) mass ratio between NS1 and immediate progenitor of NS2
  c) spin—orbit misalignment angle (for