Supernovae from binary systems

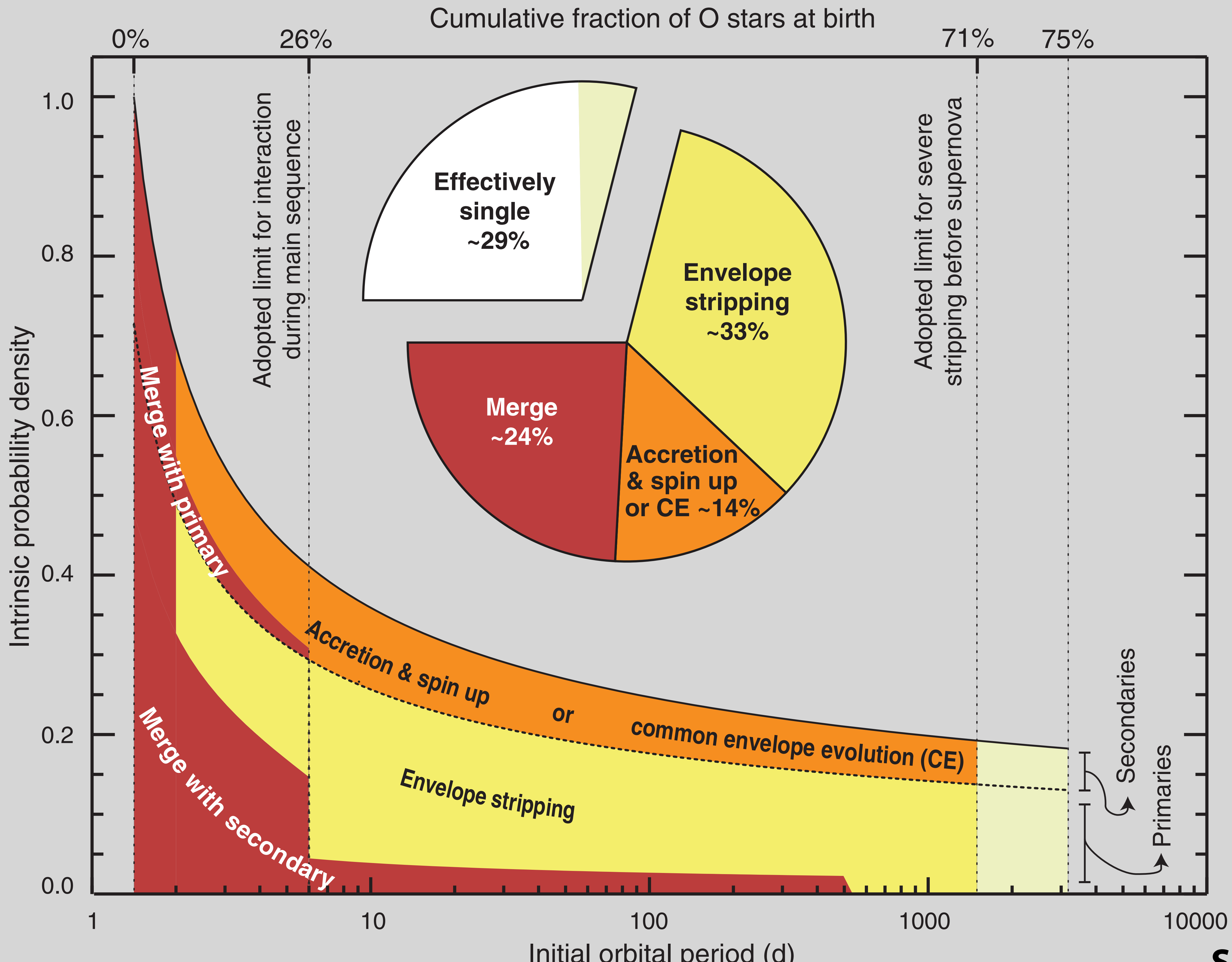
Yudai Suwa

(Kyoto Sangyo University)

collaboration with

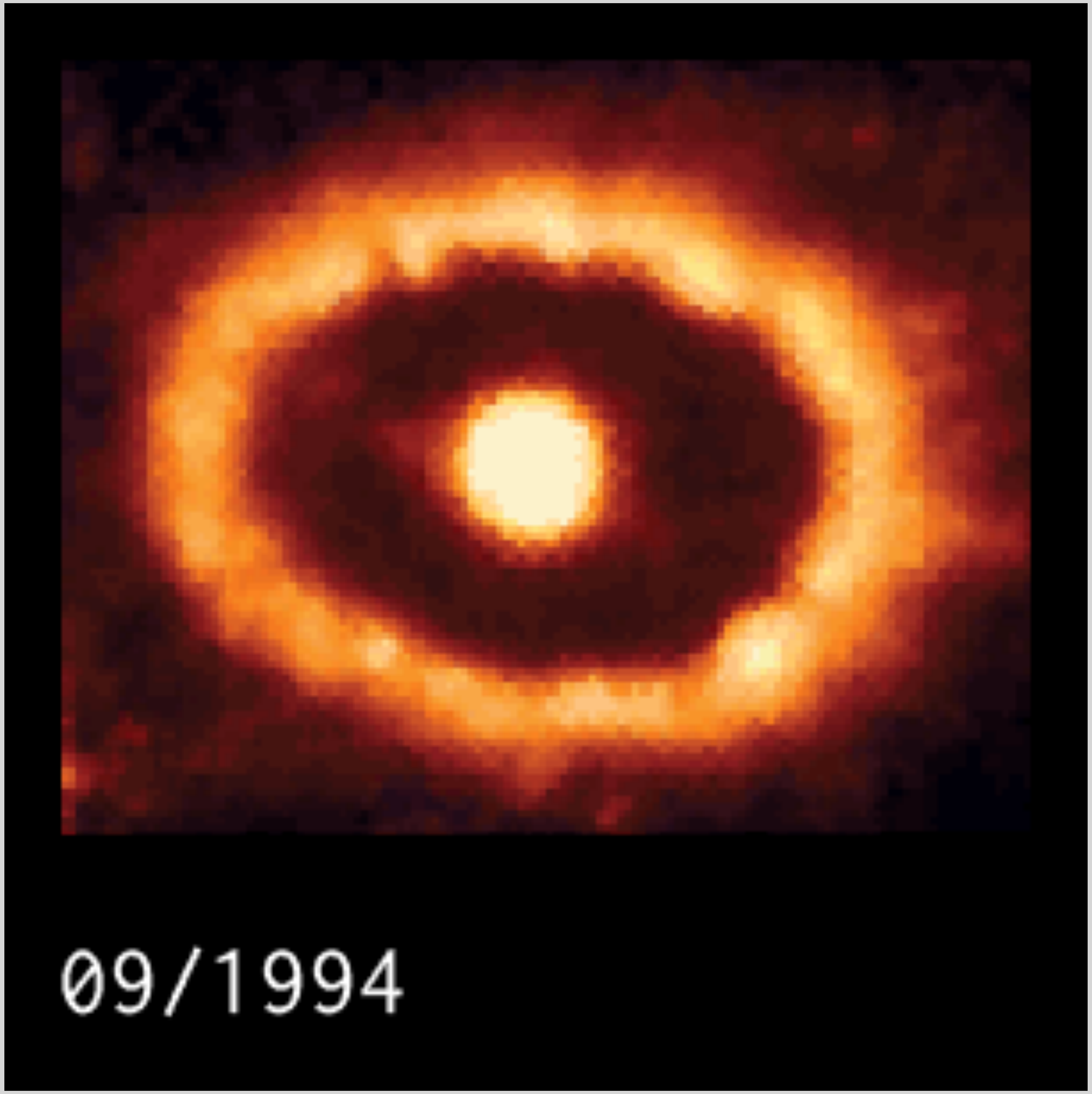
T. Yoshida (Tokyo), M. Shibata (Kyoto/AEI), H. Umeda (Tokyo), K. Takahashi (Bonn)

Fraction of interacting binary is high



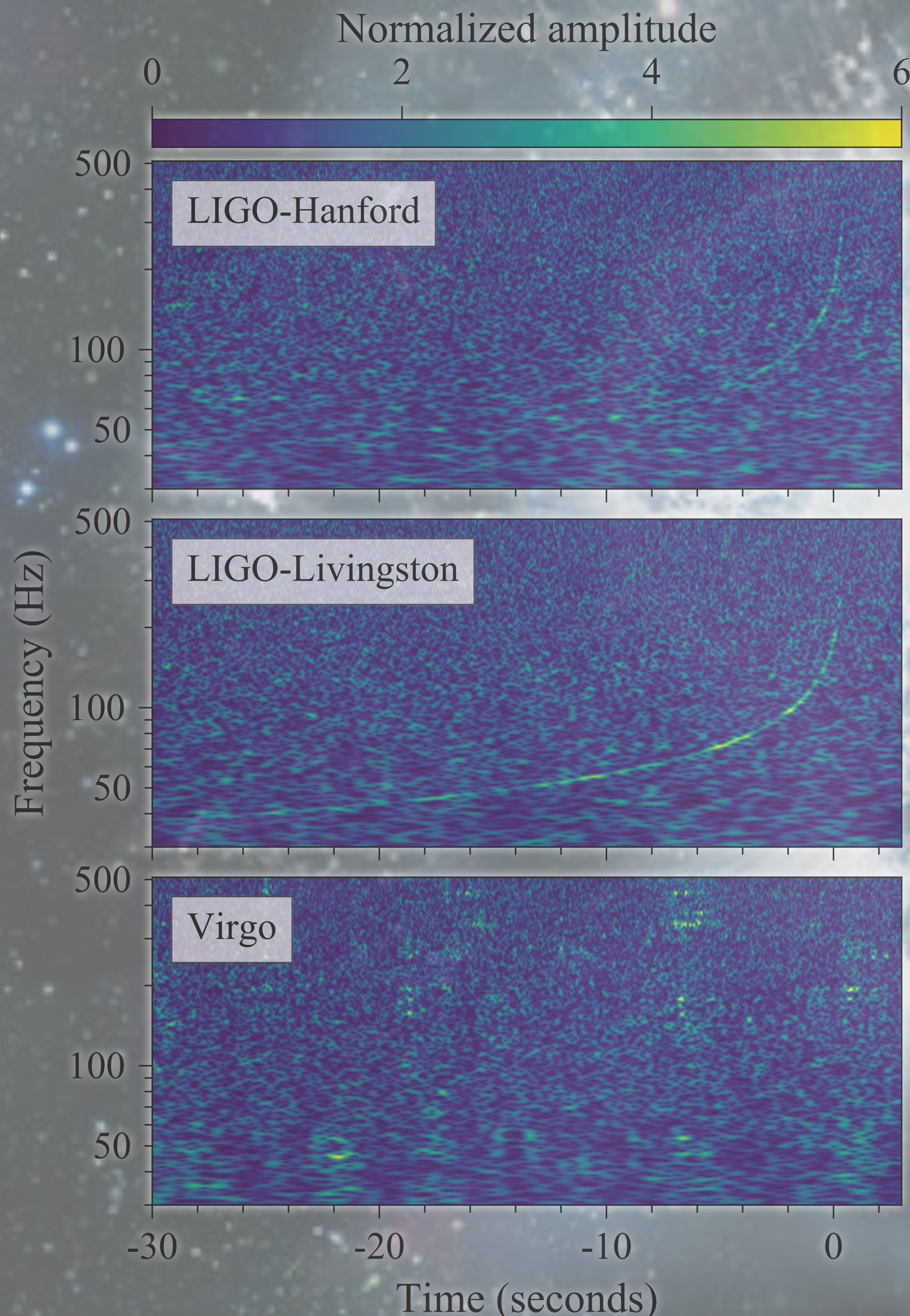
Sana+ 2012

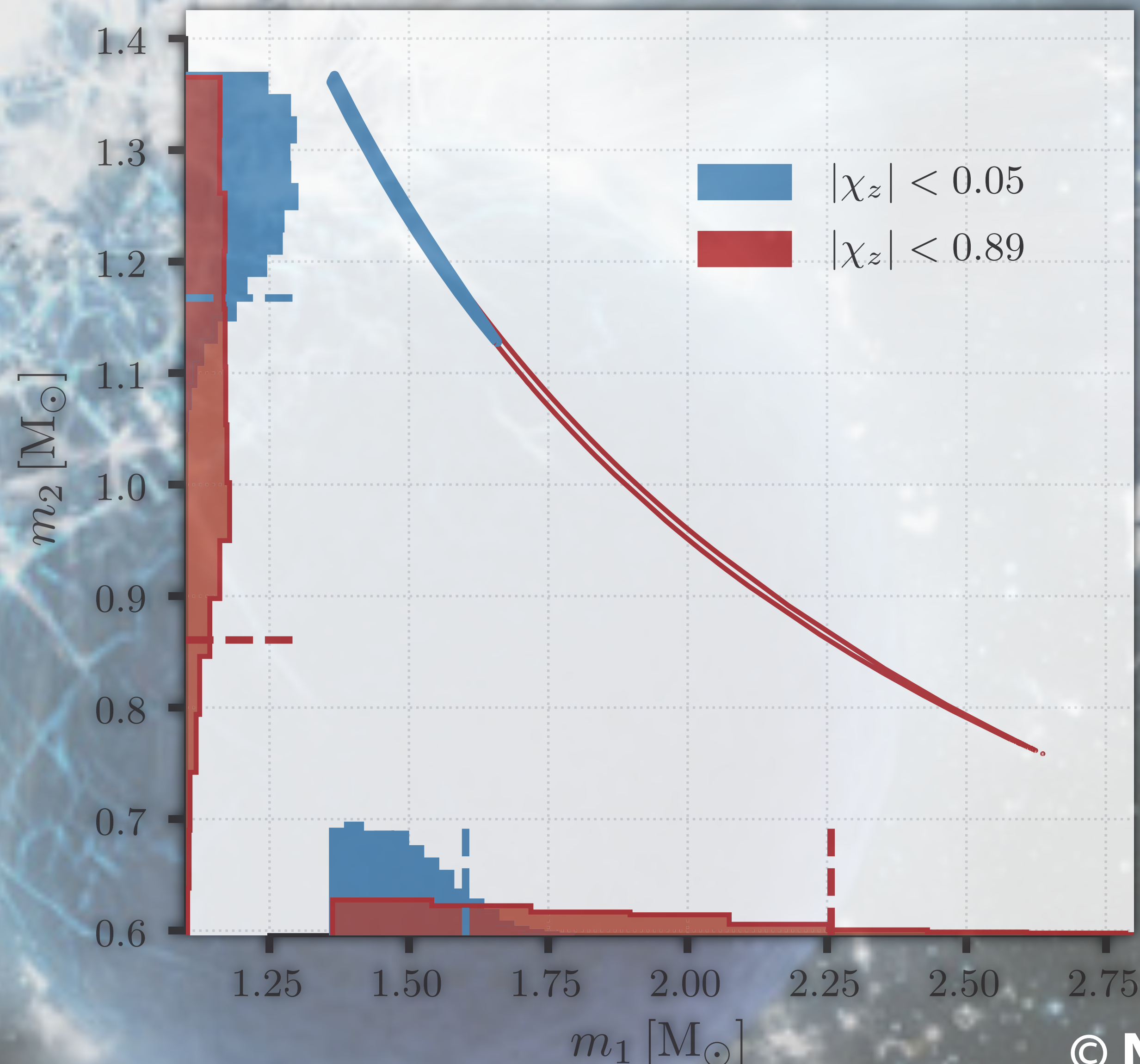
SN after stellar merger?



GW170817: Death of neutron stars

LIGO-Virgo, PRL 119, 161101 (2017)





© NASA

DNS

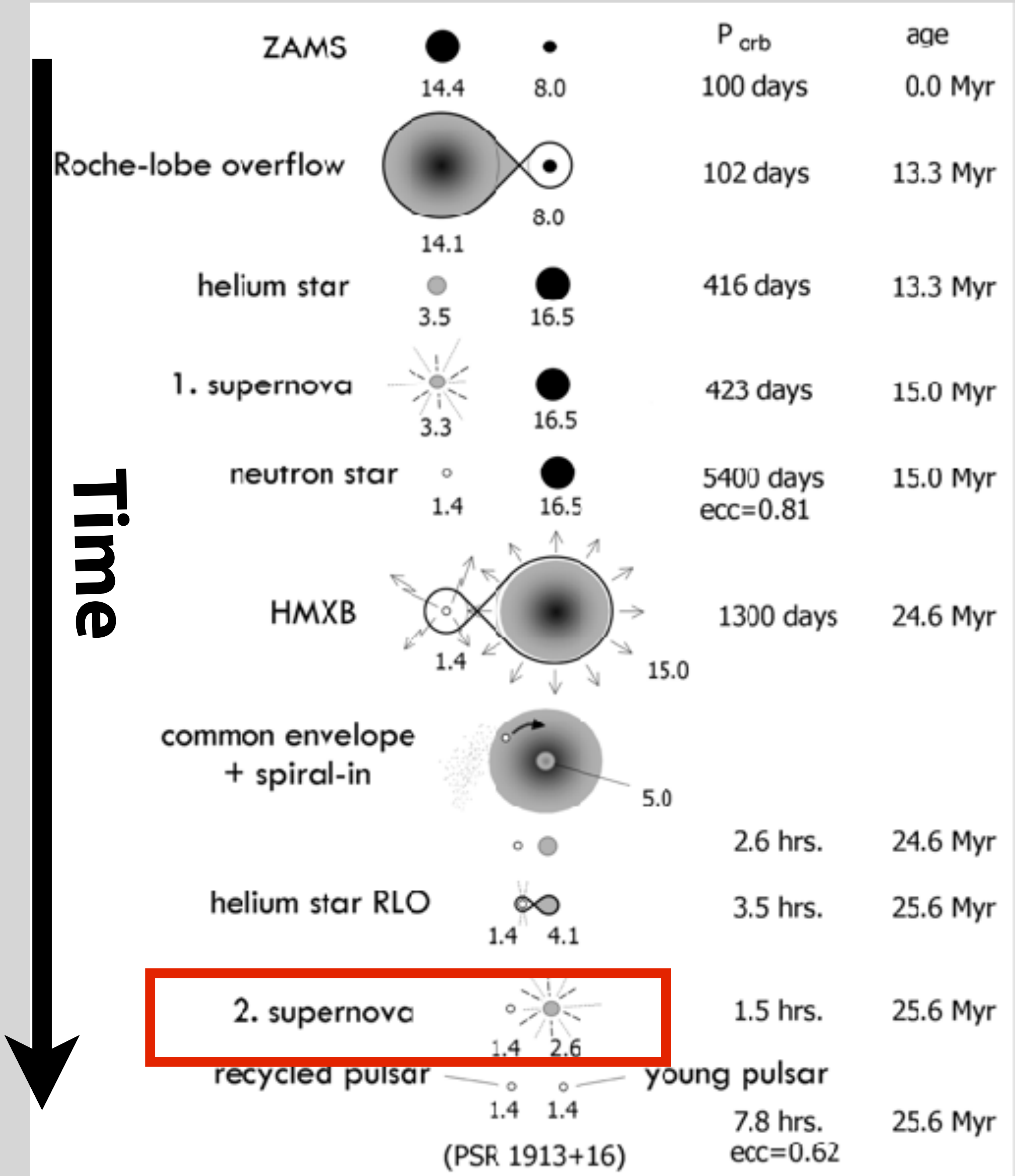
- **In the Galaxy, six systems are expected to merge within cosmic age (~13.8Gyr=$1.38\text{x}10^{10}$yr)**
  - Merger time is given by $1.2\text{x}10^{8}$yr $(a_0/10^{11}\text{cm})^4(m/2.8M_\odot)^{-3}$
    -> $a_0<3\text{x}10^{11}$cm is needed
    NB) The distance of Sun-Earth is 1AU=$1.5\text{x}10^{13}$cm, $R_\odot=7\text{x}10^{10}$cm

- **Massive stars forming such close binary systems must have experienced *close binary interactions*!**

- **Do they make canonical supernovae? Probably, not.**

1. SNe from binary systems

How to make close DNSs?: binary evolutions



Tauris & van den Heuvel 2006

- **There are *two* SNe**
  - first one may be usual (type-Ibc or type II)
  - second one explodes after close binary interactions, e.g. common envelope phase (if they are close enough)
- **How does a second SN look like? Is there any difference from normal SNe?**

Ultra-stripped supernovae?

- **Tauris, Langer, Podsiadlowski (2015)**

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 451, 2123–2144 (2015) doi:10.1093/mnras/stv990

Ultra-stripped supernovae: progenitors and fate

Thomas M. Tauris,[1,2]★ Norbert Langer[1] and Philipp Podsiadlowski[3]

- *"We therefore suggest to define ultra-stripped SNe as exploding stars whose progenitors are stripped more than what is possible with a non-degenerate companion. In other words, ultra-stripped SNe are exploding stars which contain envelope masses $\lesssim 0.2\ M_\odot$ and having a compact star companion."*

Ultra-stripped supernovae?

M_{total}~$10M_\odot$ M_{CO}~$3M_\odot$

M_{total}~$5M_\odot$ M_{CO}~$3M_\odot$

M_{total}~M_{CO}~$1.5M_\odot$

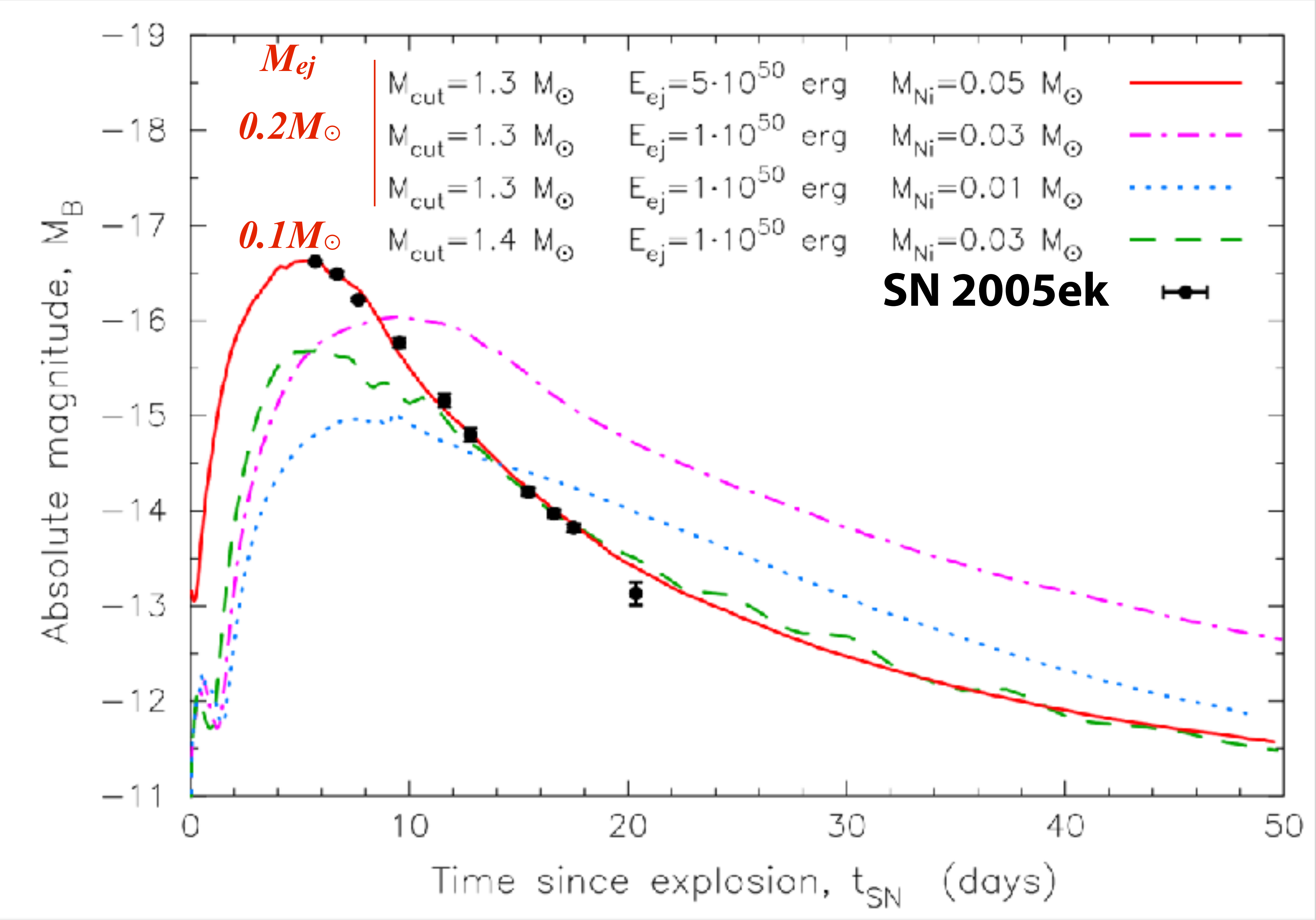
type II SN
M_{ej}~$10M_\odot$

type Ibc SN
M_{ej}~$3M_\odot$

ultra-stripped SN
M_{ej}~$0.1M_\odot$

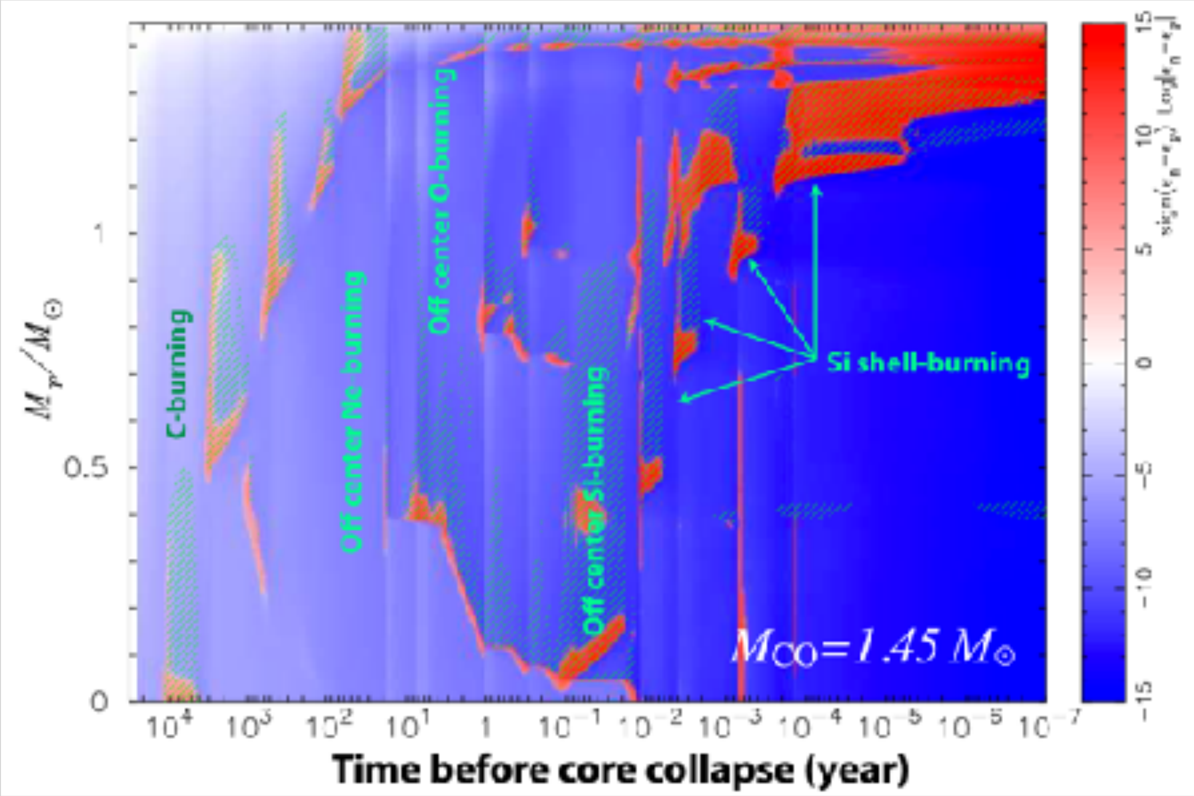
Small ejecta mass

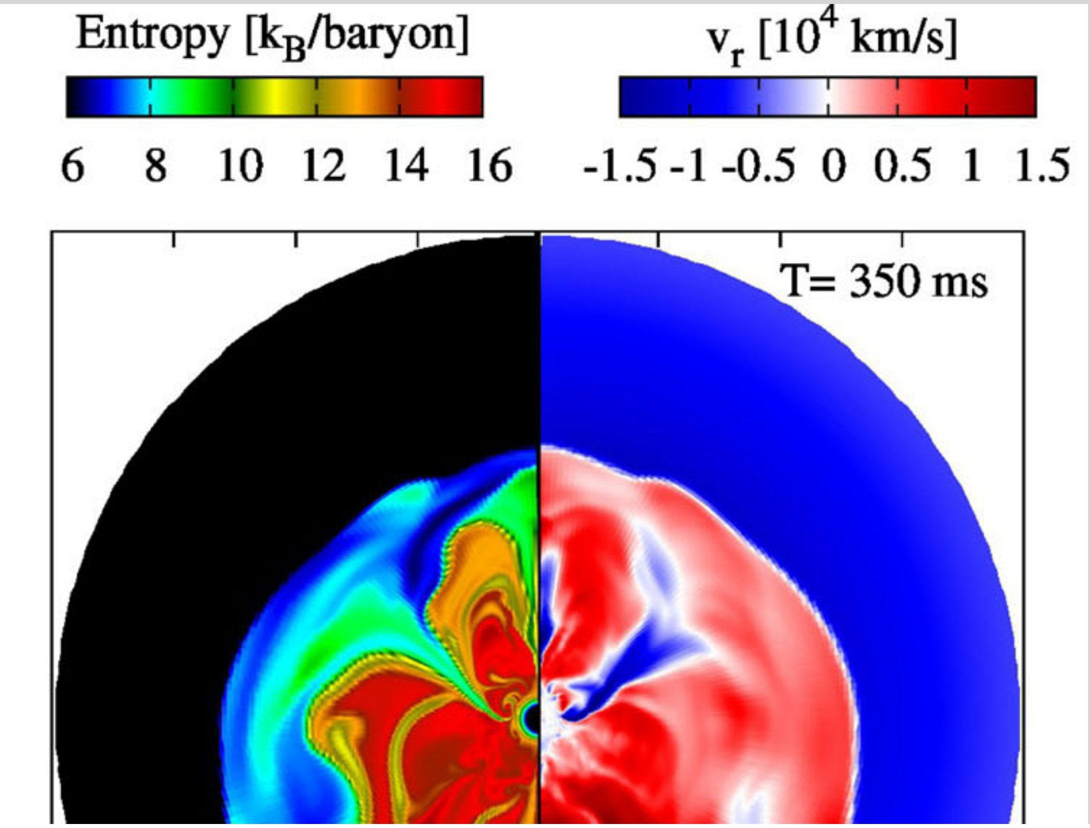
Tauris, Langer, Moriya, Podsiadlowski, Yoon, Blinnikov 2013



Neutrino-driven explosions of ultra-stripped SN

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, 454, 3073 (2015)]





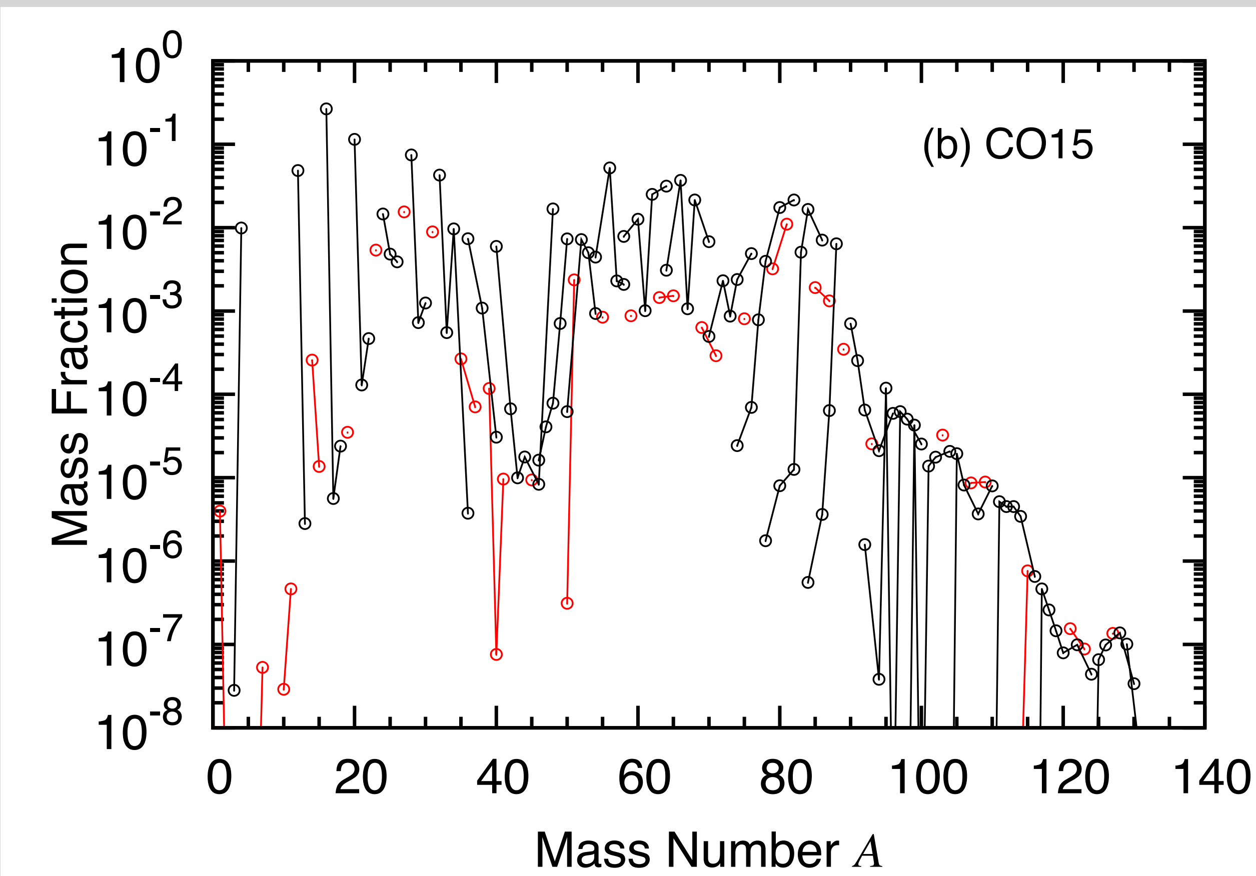
Model	$t_{\rm final}$[a] [ms]	$R_{\rm sh}$[b] [km]	$E_{\rm exp}$[c] [B]	$M_{\rm NS,baryon}$[d] [$M_\odot$]	$M_{\rm NS,grav}$[e] [$M_\odot$]	$M_{\rm ej}$[f] [$10^{-1} M_\odot$]	$M_{\rm Ni}$[g] [$10^{-2} M_\odot$]	$v_{\rm kick}$[h] [km s^{-1}]
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	0.153	1.36	1.24	1.36	3.39	75.1
CO16	578	3430	0.124	1.42	1.29	1.76	2.90	47.6
CO18	784	2230	0.120	1.49	1.35	3.07	2.56	36.7
CO20[i]	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

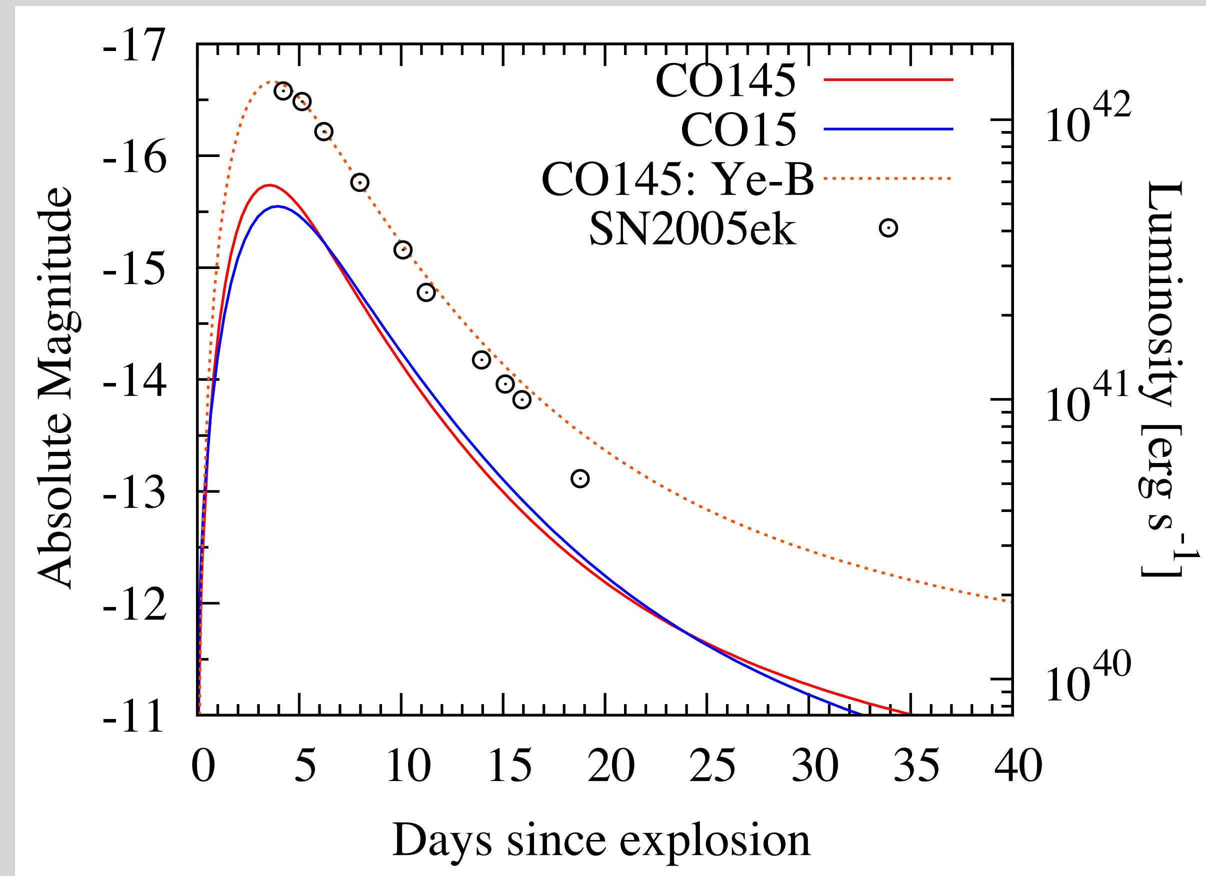
Ejecta mass~*$O(0.1)M_\odot$*, NS mass~*$1.4\ M_\odot$*, explosion energy~*$O(10^{50})$* erg, Ni mass~*$O(10^{-2})\ M_\odot$*; everything consistent w/ Tauris+ 2013

see also Moriya et al. (2017), B. Müller et al. (2018)

Nucleosynthesis yields and light curves

[Yoshida, Suwa, Umeda, Shibata, Takahashi, MNRAS, **471**, 4275 (2017)]





NB) This is one-zone model based on Arnett (1982).
Detailed radiation transfer calculations will be done.

Implications

- **small kick velocity due to small ejecta mass**

- **small eccentricity (e~0.1), compatible with binary pulsars J0737-3039 (e=0.088 now and ~0.11 at birth of second NS)**
Piran & Shaviv 05

- **event rate (~0.1-1% of core-collapse SN)** Tauris+13, 15, Drout+ 13, 14
    - **SN surveys (e.g., HSC, PTF, Pan-STARRS, and LSST) will give constraint on NS merger rate**

see also talk by Paz

Summary

* **Ultra-stripped SN might be second explosion in close binary forming double NSs**

* **To test this conjecture, we performed**
  * stellar evolution calculations of bare C/O cores
  * hydrodynamics simulations for neutrino-driven explosions

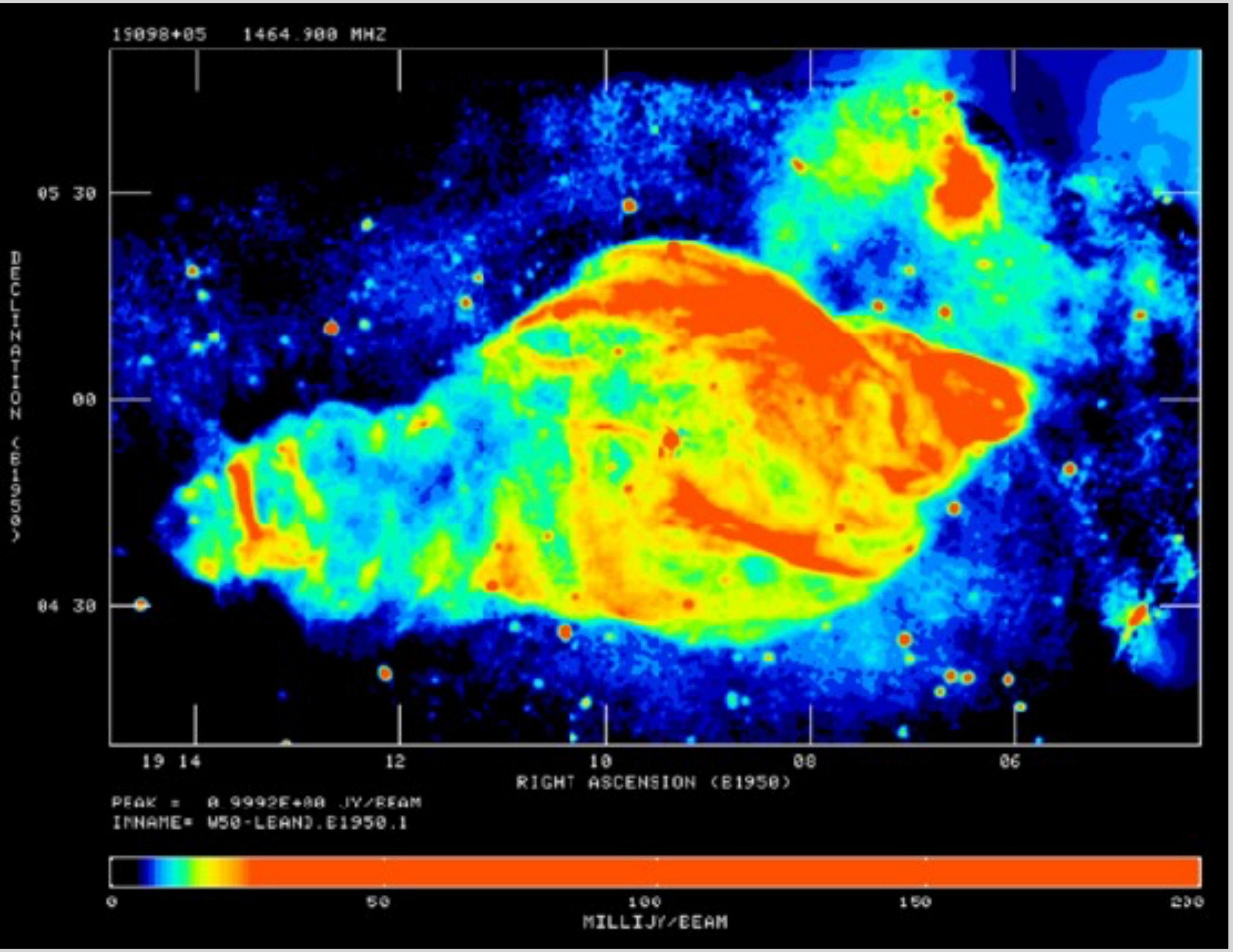
* **Compatible with parameters explaining observations**

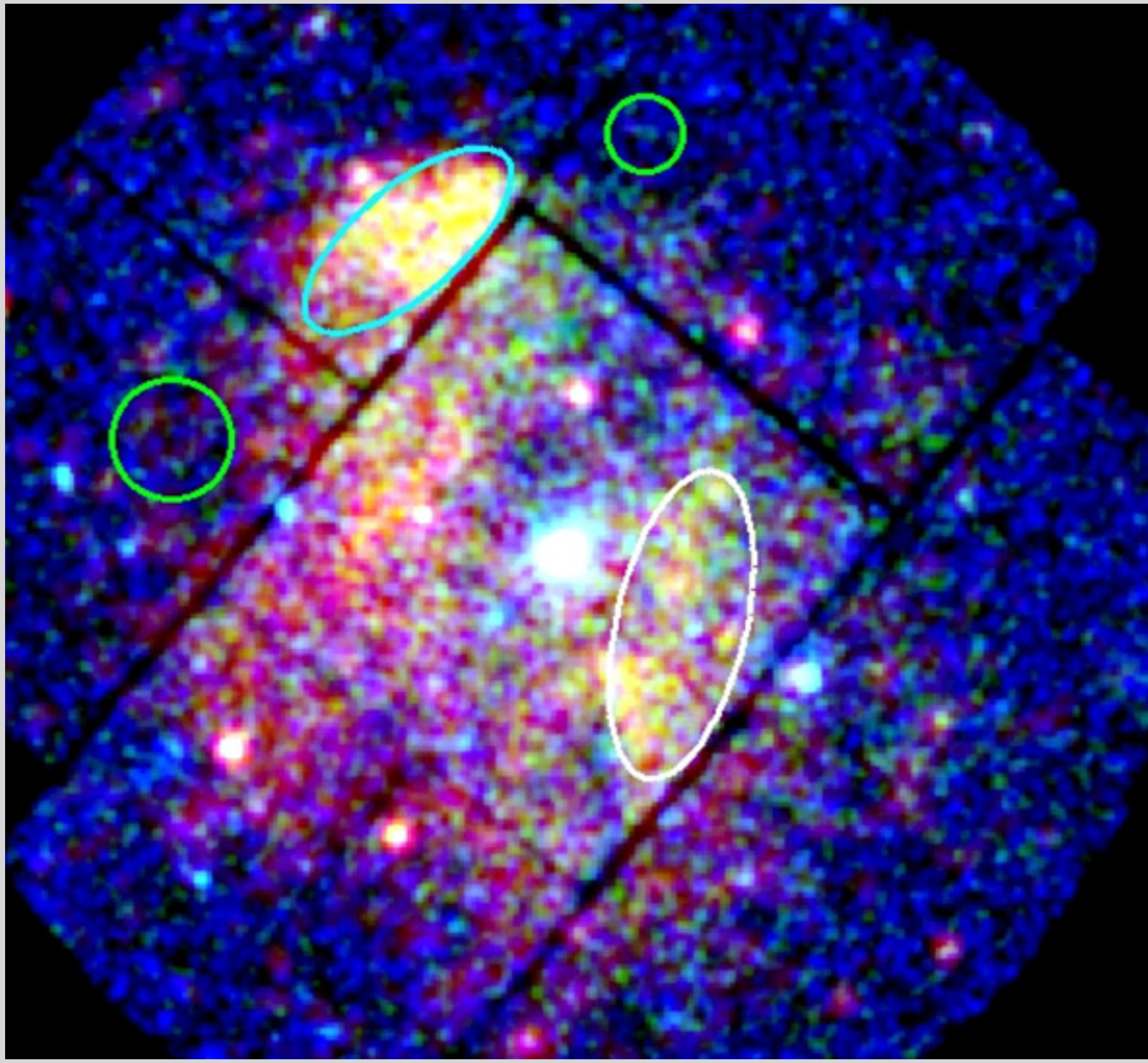
  Drout+ 13, Tauris+13
  * $E_{exp}=O(10^{50})$ erg
  * $M_{ej}\sim O(0.1)\ M_\odot$
  * $M_{Ni}\sim O(10^{-2}) M_\odot$
  * $M_{NS}\sim 1.2\text{-}1.4 M_\odot$ (gravitational)

Gamma-ray binaries in SNRs

SS433 & SNR W50A
Dubner+ (1998)

1FGL J1018.6–5856 & SNR G284.3-1.8
Williams+ (2015)

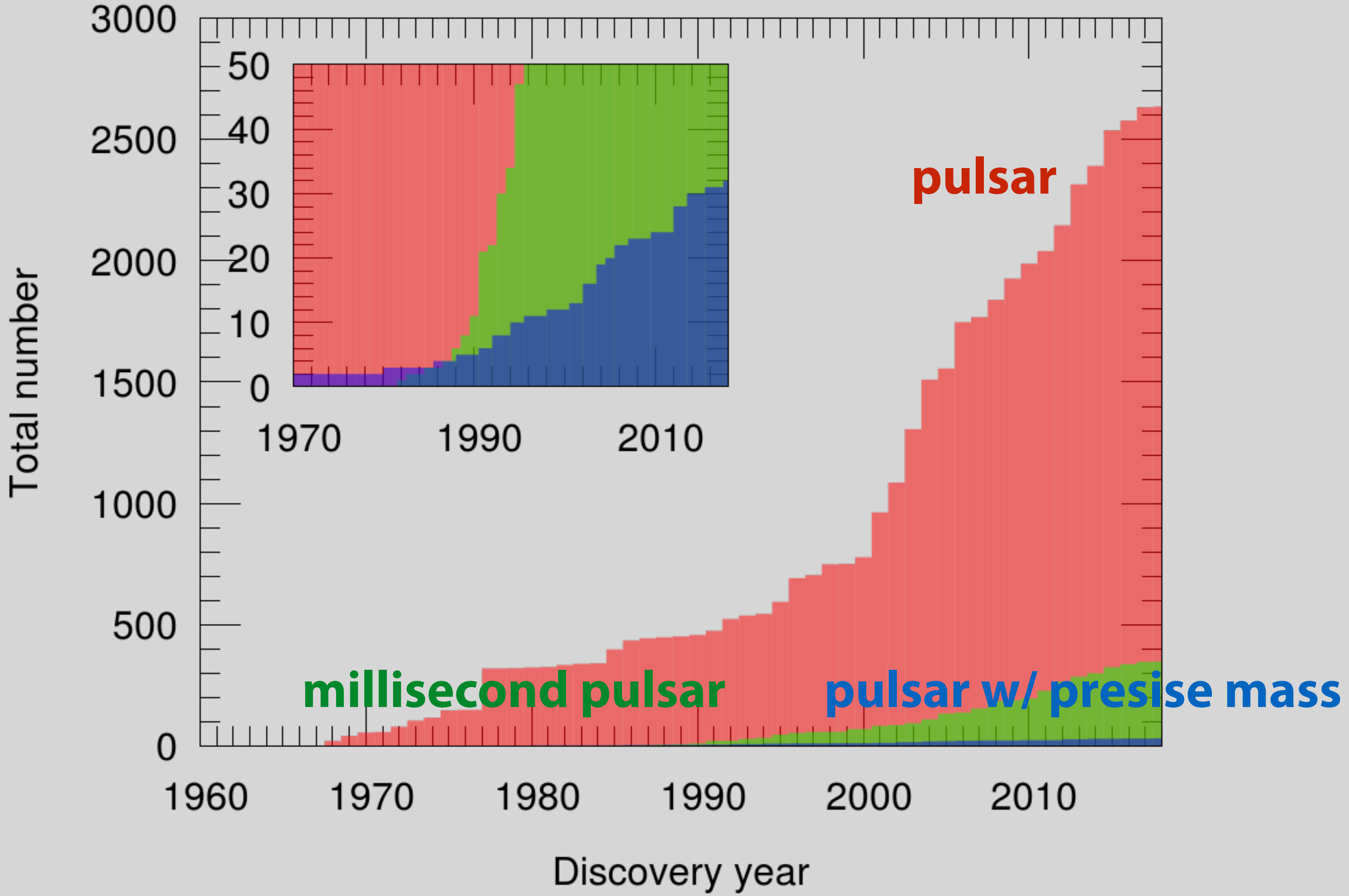




(c) Image courtesy of NRAO/AUI

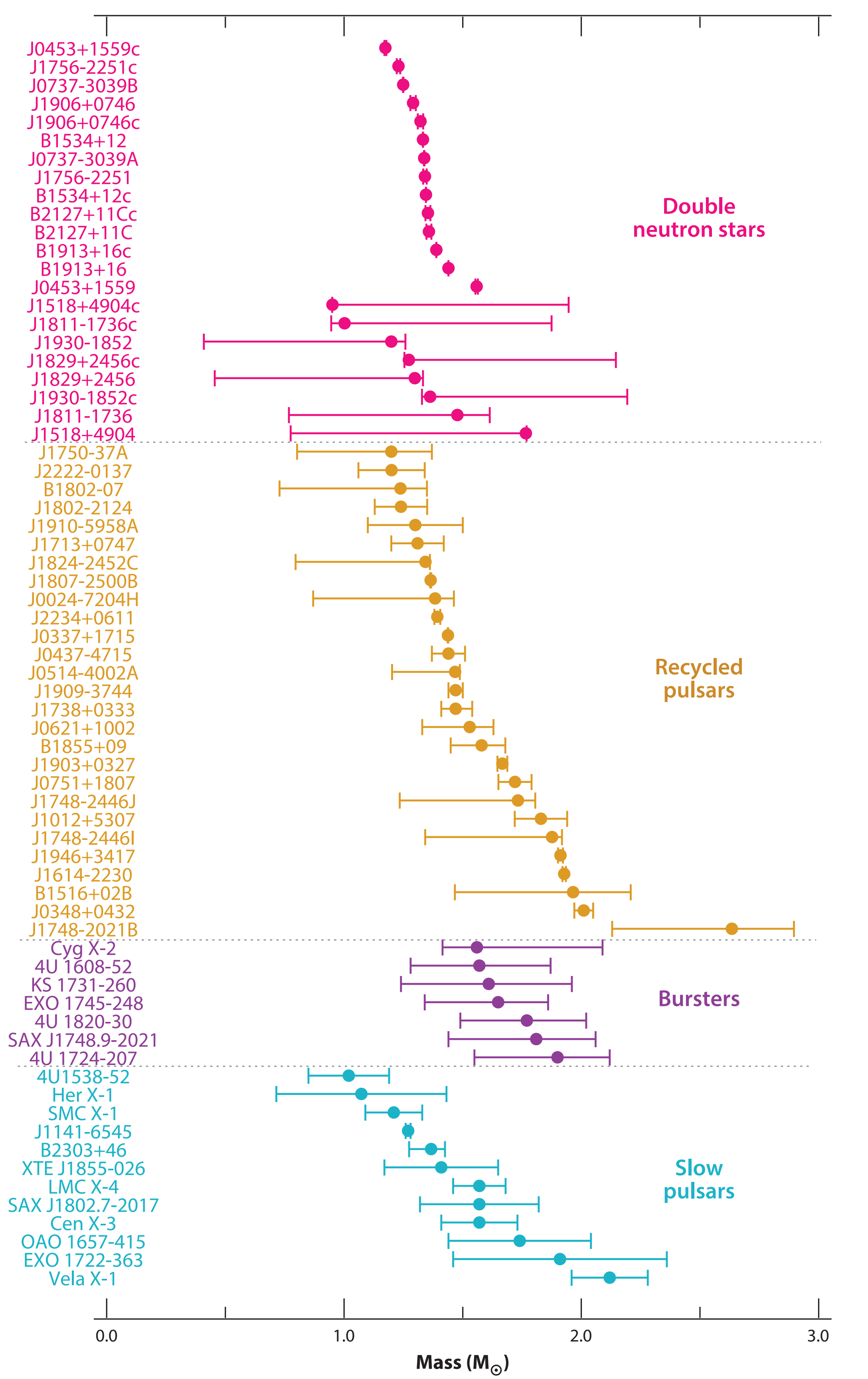
2. Minimum NS mass from binary systems

Pulsar number is increasing

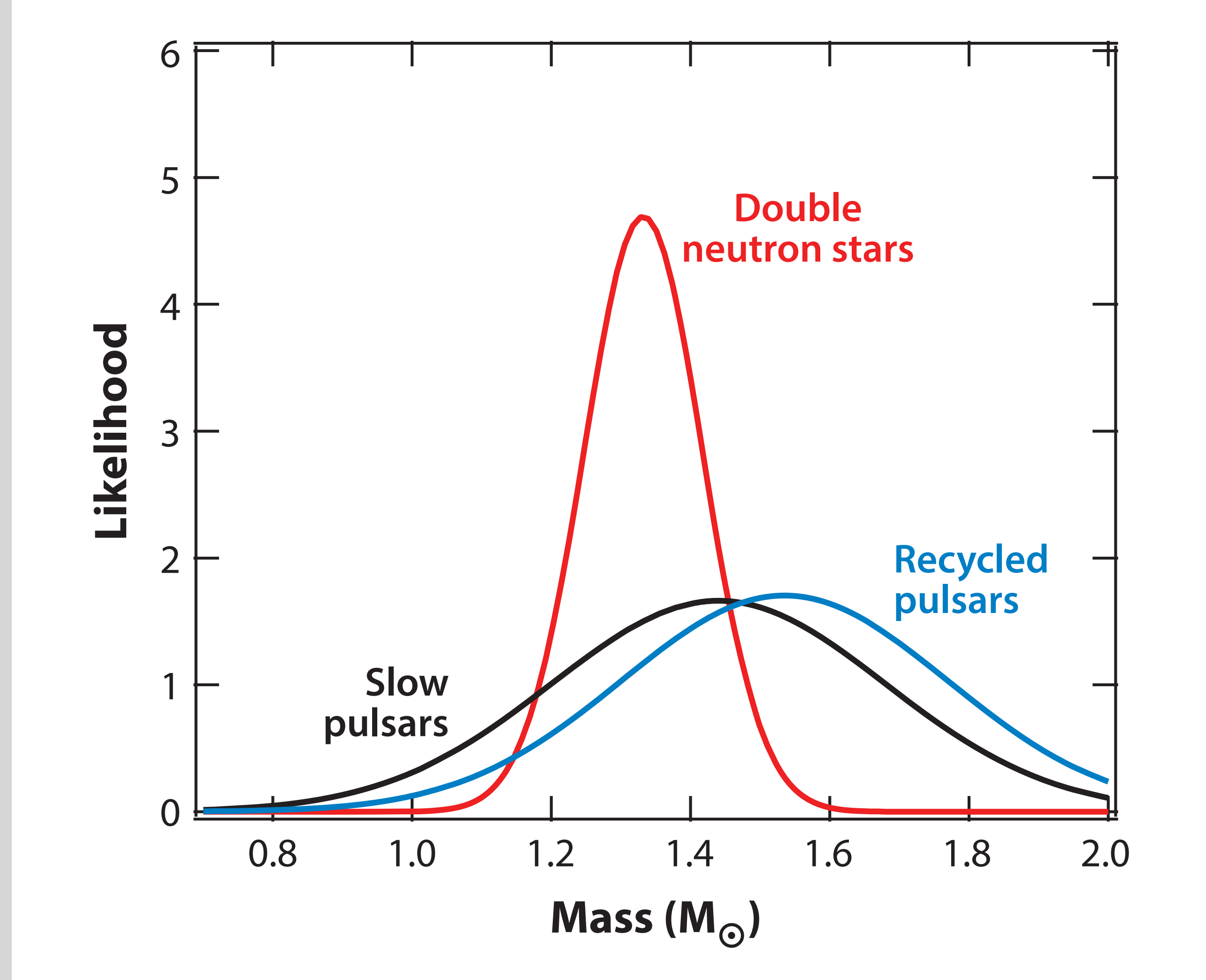


compiled data from ATNF pulsar catalog and P. Freire's table

NS mass measurements



Özel & Freie 2016

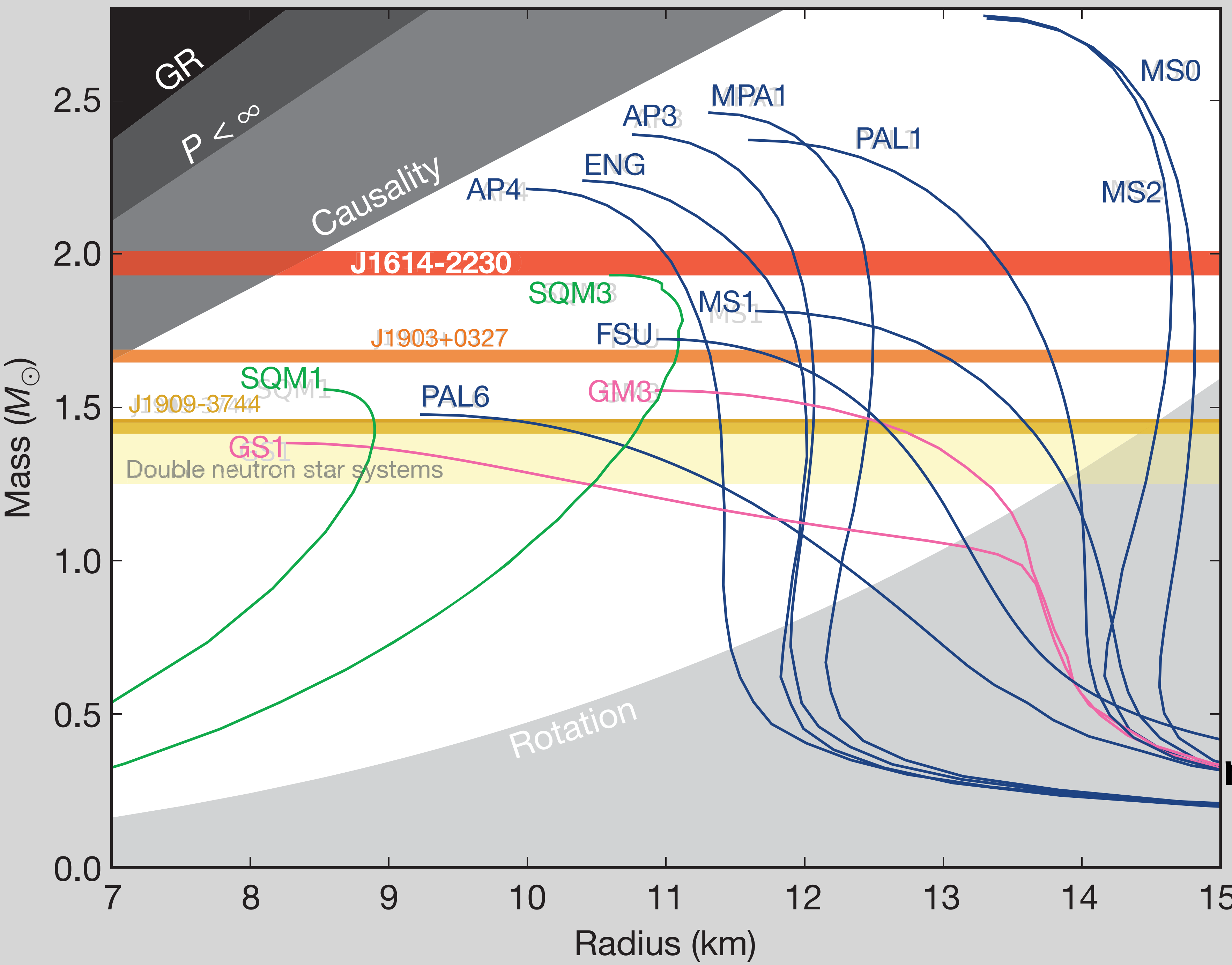


- >2600 pulsars have been found in the Galaxy
- 10% in the binary system
  →mass measurement possible
  - 15 double NSs so far [Tauris+ 2017]

http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Massive NSs tell us nuclear physics

Demorest+ 2010



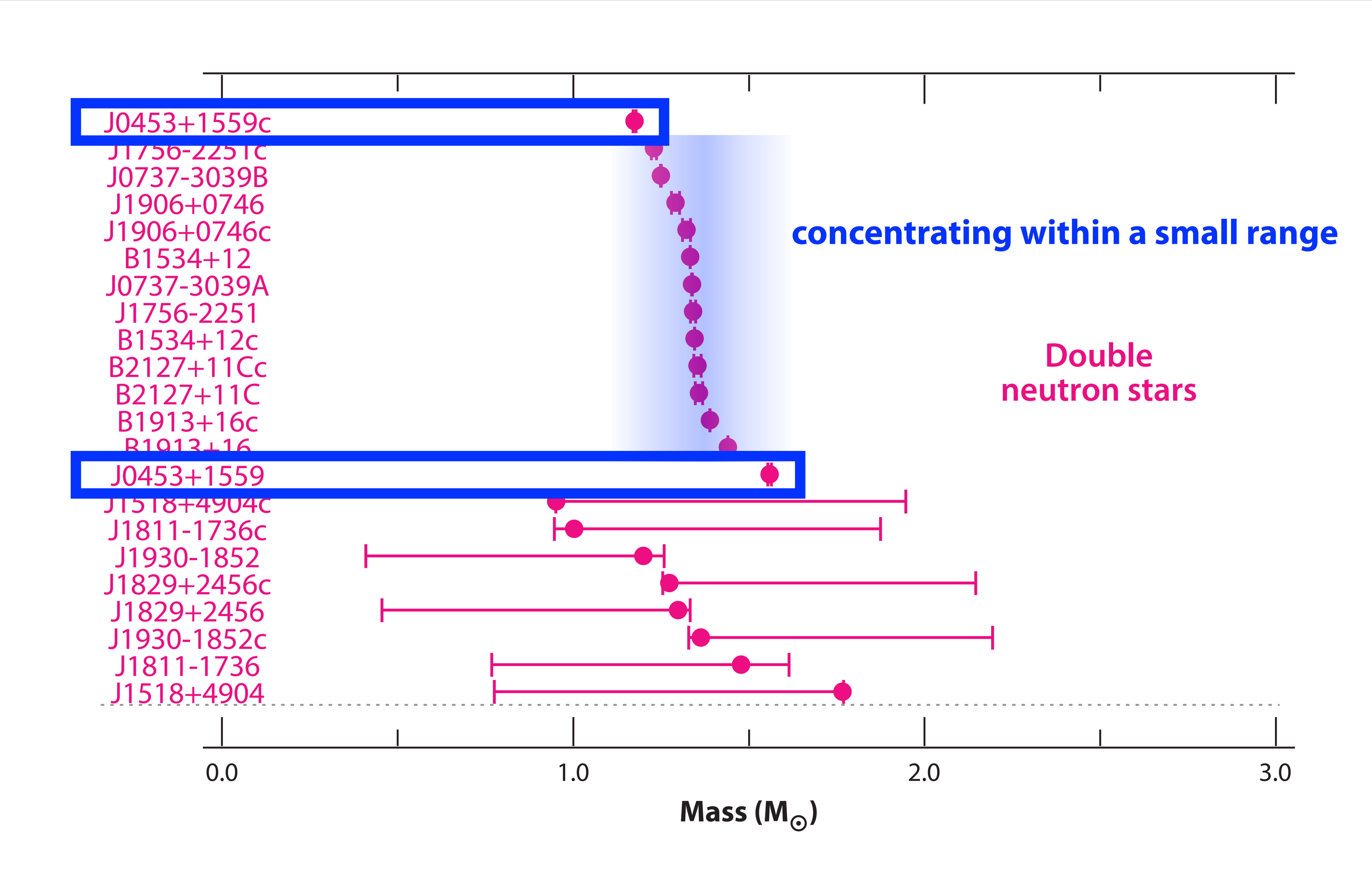
←1.97±0.04M$_\odot$

NB) mass estimation was updated by Fonseca+ 2016 as 1.928±0.017M$_\odot$

Another massive NS was reported by Antoniadis+ (2013), J0348+0432, 2.01±0.04M$_\odot$

So, what does a small NS tell?

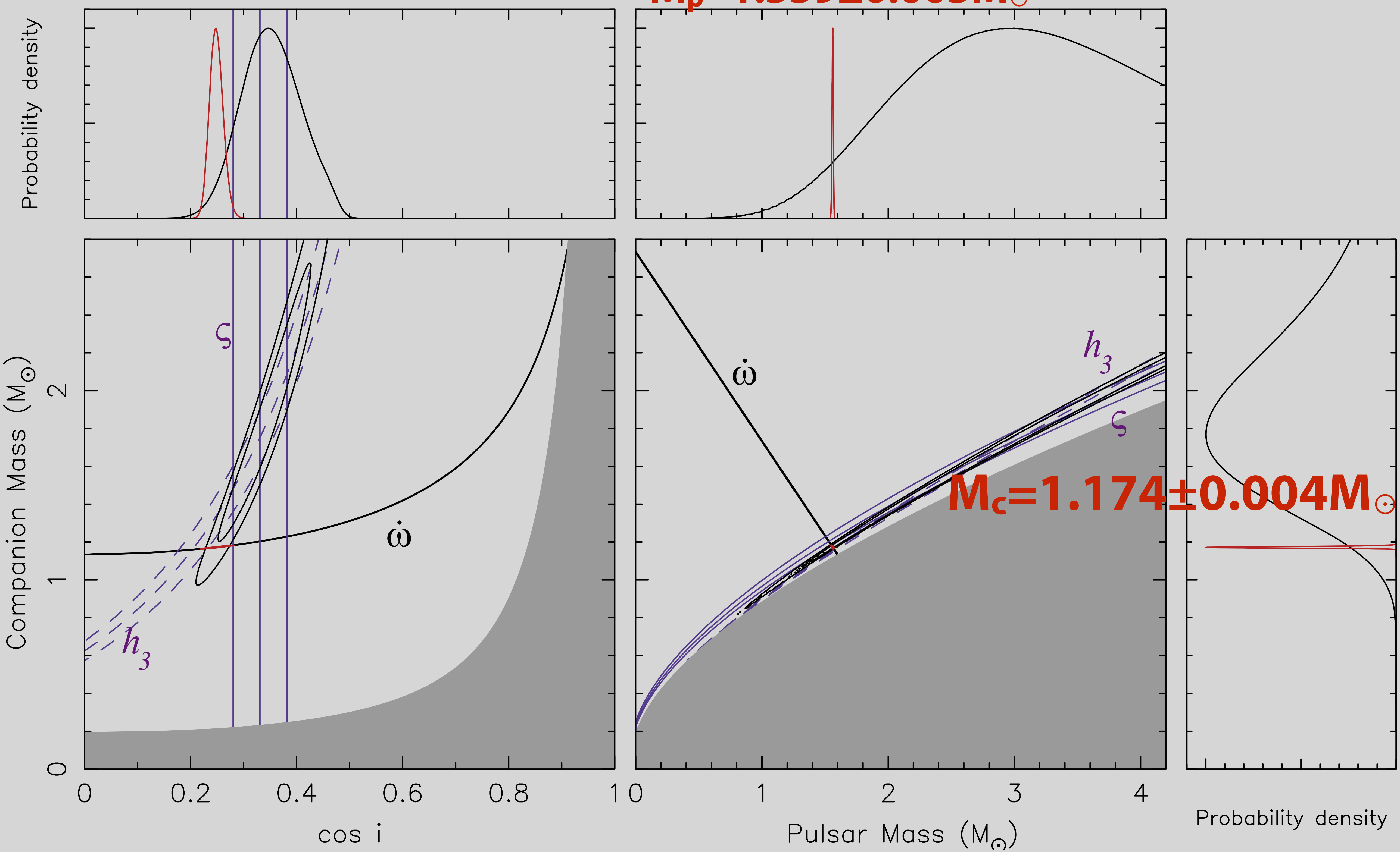
Double NSs


J0453+1559c
J1756-2251c
J0737-3039B
J1906+0746
J1906+0746c
B1534+12
J0737-3039A
J1756-2251
B1534+12c
B2127+11Cc
B2127+11C
B1913+16c
B1913+16
J0453+1559
J1518+4904c
J1811-1736c
J1930-1852
J1829+2456c
J1829+2456
J1930-1852c
J1811-1736
J1518+4904
concentrating within a small range
Double
neutron stars
0.0
1.0
2.0
3.0
Mass ($M_\odot$)

First asymmetric DNS system

Martinez+ 2015

$M_p=1.559\pm0.005M_\odot$



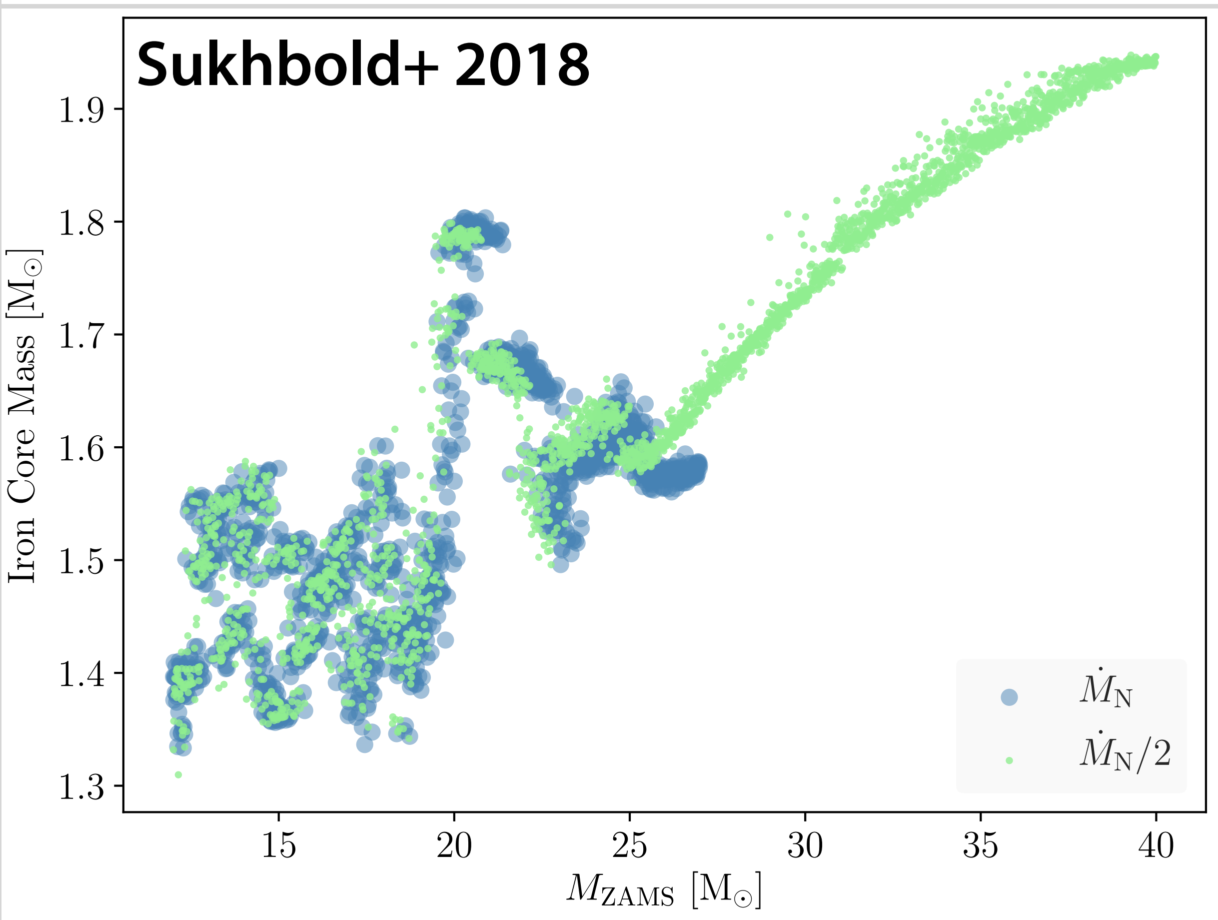
$M_c=1.174\pm0.004M_\odot$

A low-mass NS

- **M_{NS}=1.174$M_\odot$!** (NB, it's gravitational mass, baryonic mass is ~1.28$M_\odot$)

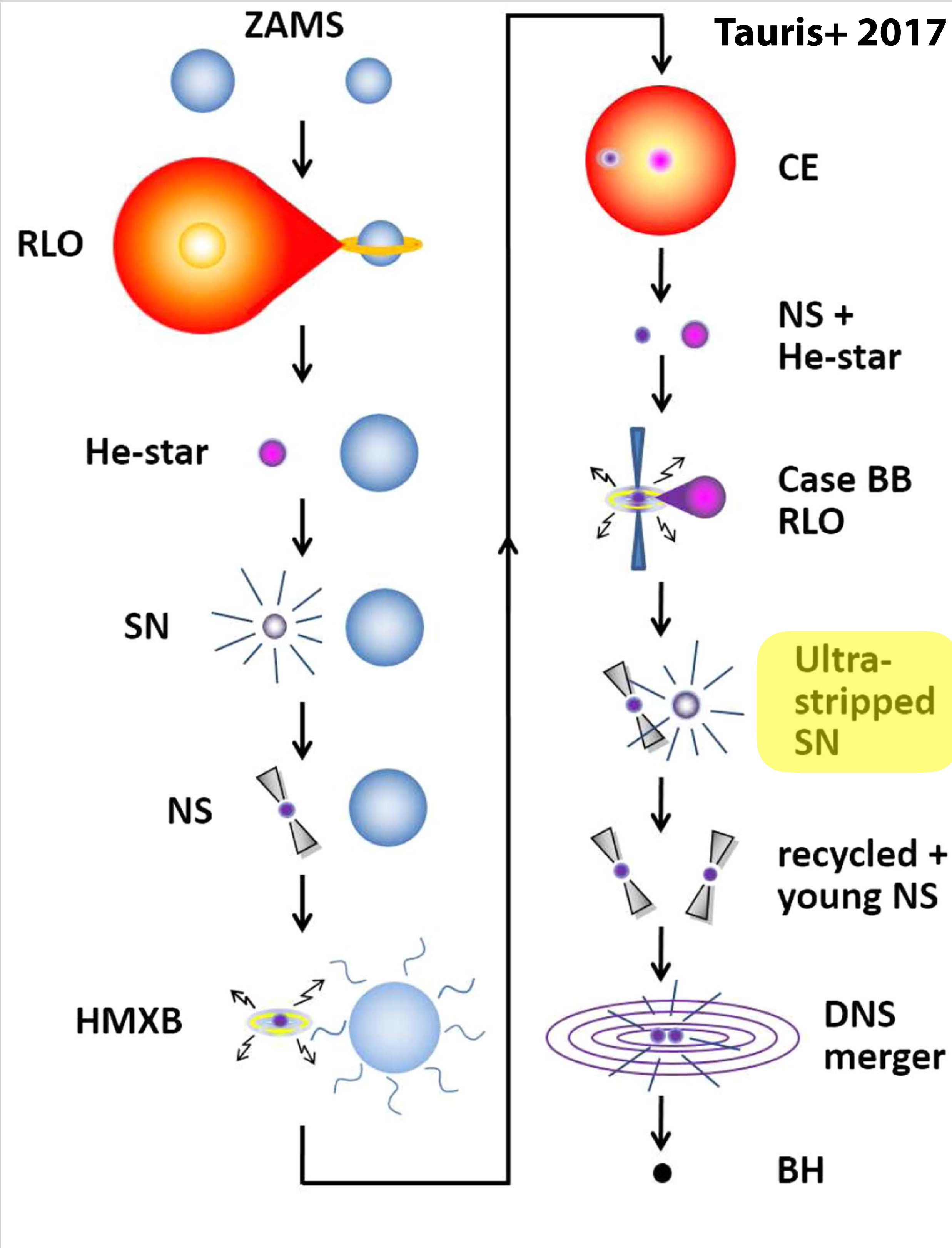
- **Is it a white dwarf? Maybe no**
  - a large eccentricity (e=0.112) is difficult to explain by slow evolution into a WD

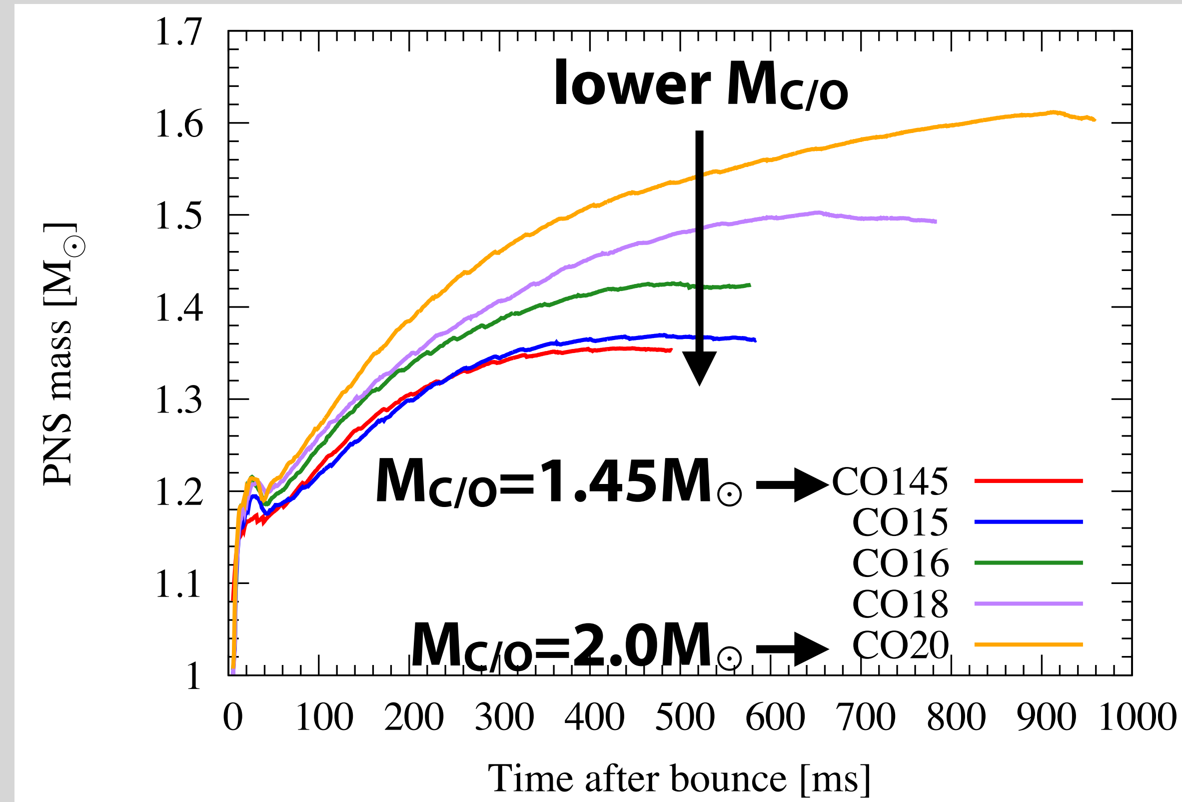
- **How to make it?**
  - a small iron core of massive star? (typically M_{Fe}~1.4–1.8$M_\odot$)
  - getting rid of mass from a NS?

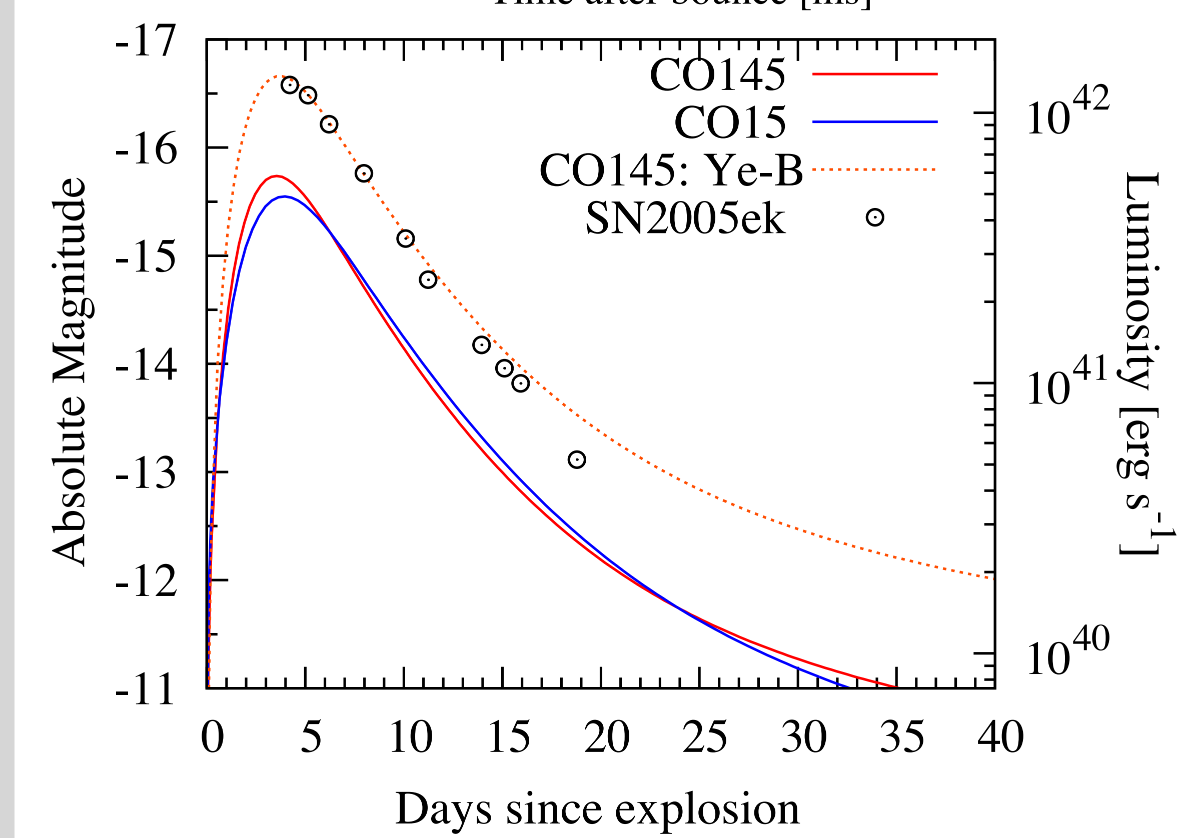


A path toward a low mass NS?: Ultra-stripped SN

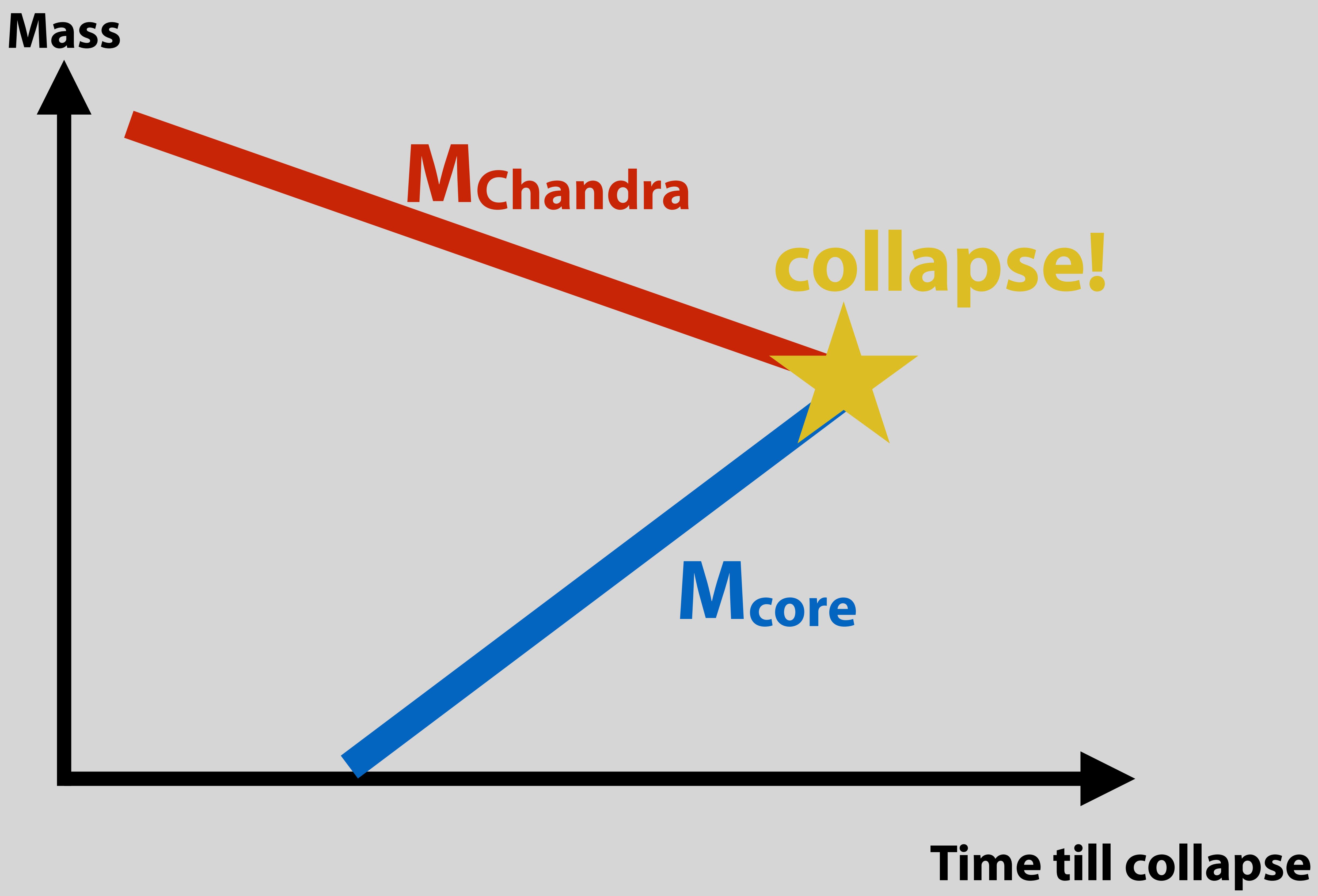
[Suwa+, MNRAS, **454**, 3073 (2015); Yoshida+, MNRAS, **471**, 4275 (2017)]







When does a core collapse?



Modified Chandrasekhar mass

- **Chandrasekhar mass *without* temperature correction**

$$M_{\mathrm{Ch0}}(Y_e) = 1.46 M_\odot \left(\frac{Y_e}{0.5}\right)^2$$

- **Chandrasekhar mass *with* temperature correction**

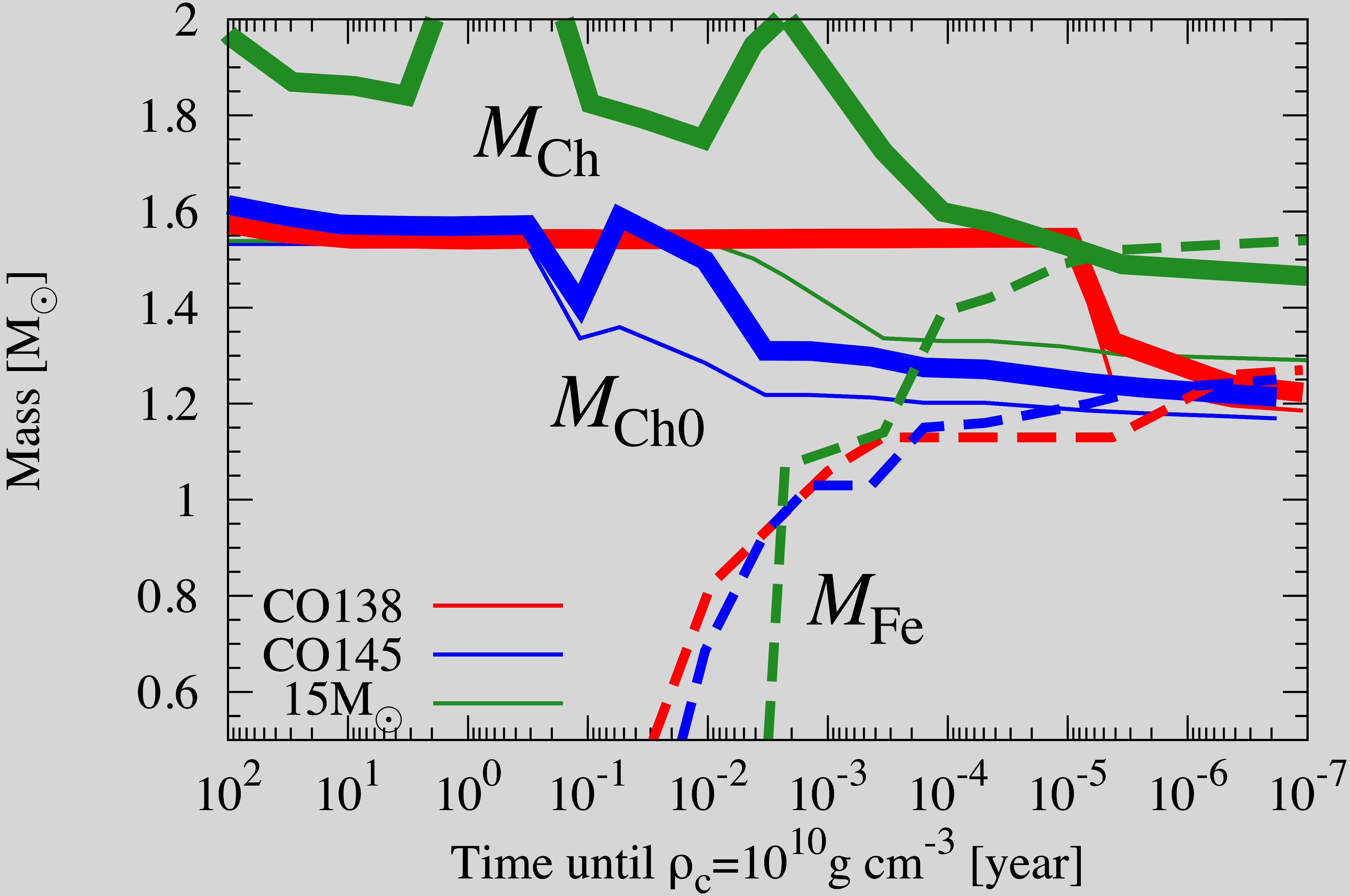
$$M_{\mathrm{Ch}}(T) = M_{\mathrm{Ch0}}(Y_e)\left[1 + \left(\frac{s_e}{\pi Y_2}\right)^2\right]$$

$$s_e = 0.5 \rho_{10}^{-1/3} (Y_e/0.42)^{2/3} T_{\mathrm{MeV}}$$

Baron+ 1990; Timmes+ 1996

- **To make a small core, *low* Y_e and *low* entropy are necessary**

M_{ch} vs. M_{core}



2
1.8
1.6
1.4
1.2
1
0.8
0.6
Mass [M☉]
M_{Ch}
M_{Ch0}
M_{Fe}
CO138
CO145
15M☉
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Time until $\rho_c=10^{10}$g cm^{-3} [year]

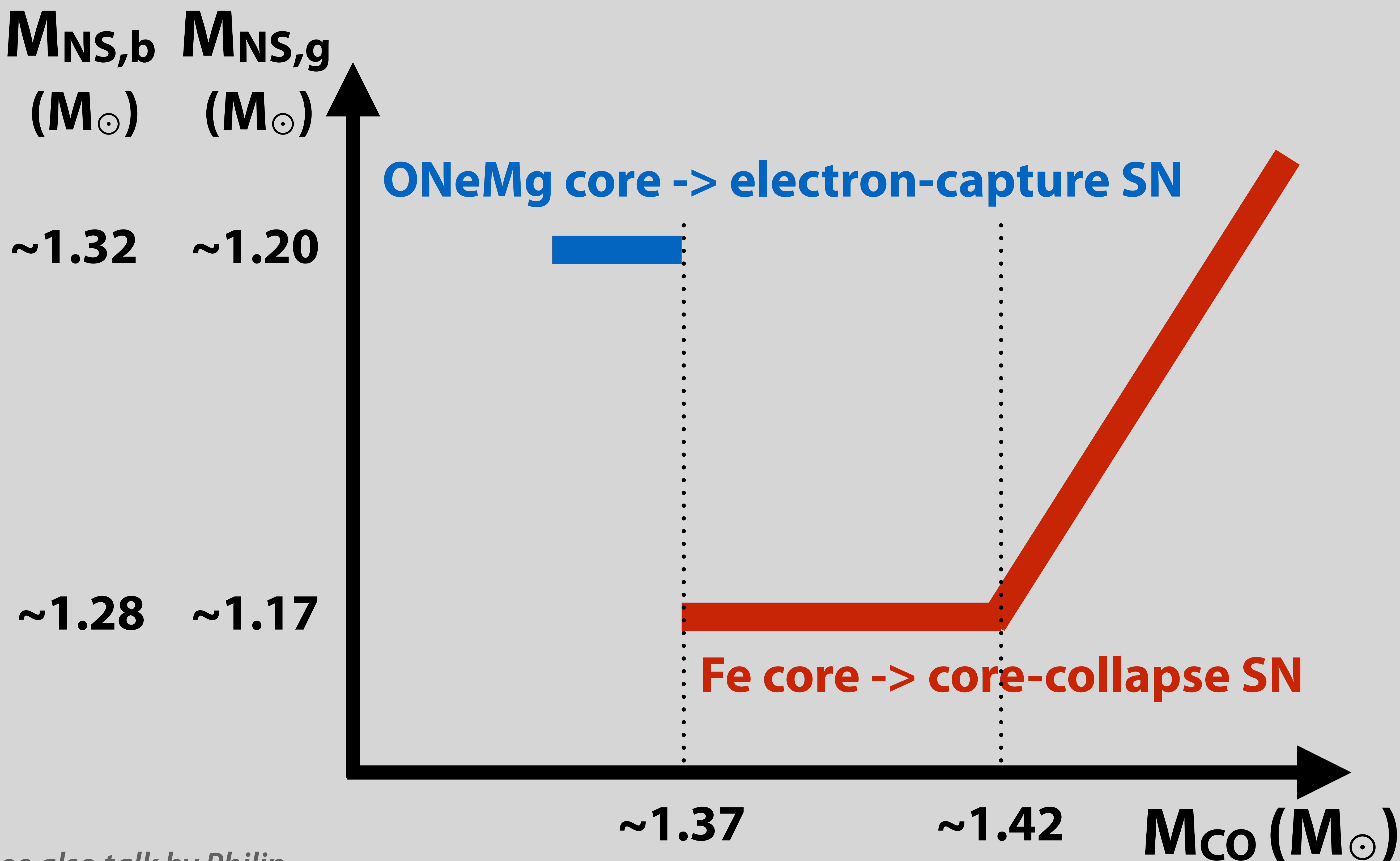
Explosion simulations and NS masses

* **Neutrino-radiation hydro. sim**

Model	M_{CO} ($M_\odot$)	M_{ZAMS} ($M_\odot$)	M_{Fe} ($M_\odot$)	$M_{NS,b}$ ($M_\odot$)	$M_{NS,g}$ ($M_\odot$)
CO137	1.37	9.35	1.280	1.289	**1.174**
CO138	1.38	9.4	1.274	1.296	**1.179**
CO139	1.39	9.45	1.258	1.302	1.184
CO140	1.4	9.5	1.296	1.298	1.181
CO142	1.42	9.6	1.265	1.287	**1.172**
CO144	1.44	9.7	1.234	1.319	1.198
CO145	1.45	9.75	1.277	1.376	1.245

$M_{NS,b}-M_{NS,g}=0.084M_\odot(M_{NS,g}/M_\odot)^2$
(Lattimer & Prakash 2001)

Discussion



see also talk by Philip

Summary

- **A low-mass NS of $M_{NS,g}$=1.174$M_\odot$ was found**
- **Q: *Is it possible to make such a low-mass NS with standard modeling of SN?***
- **A: Yes, it is.**
  - **The minimum mass is ~1.17$M_\odot$.**
  - **If a new observation finds even lower mass NS, we cannot make it. Something wrong.**