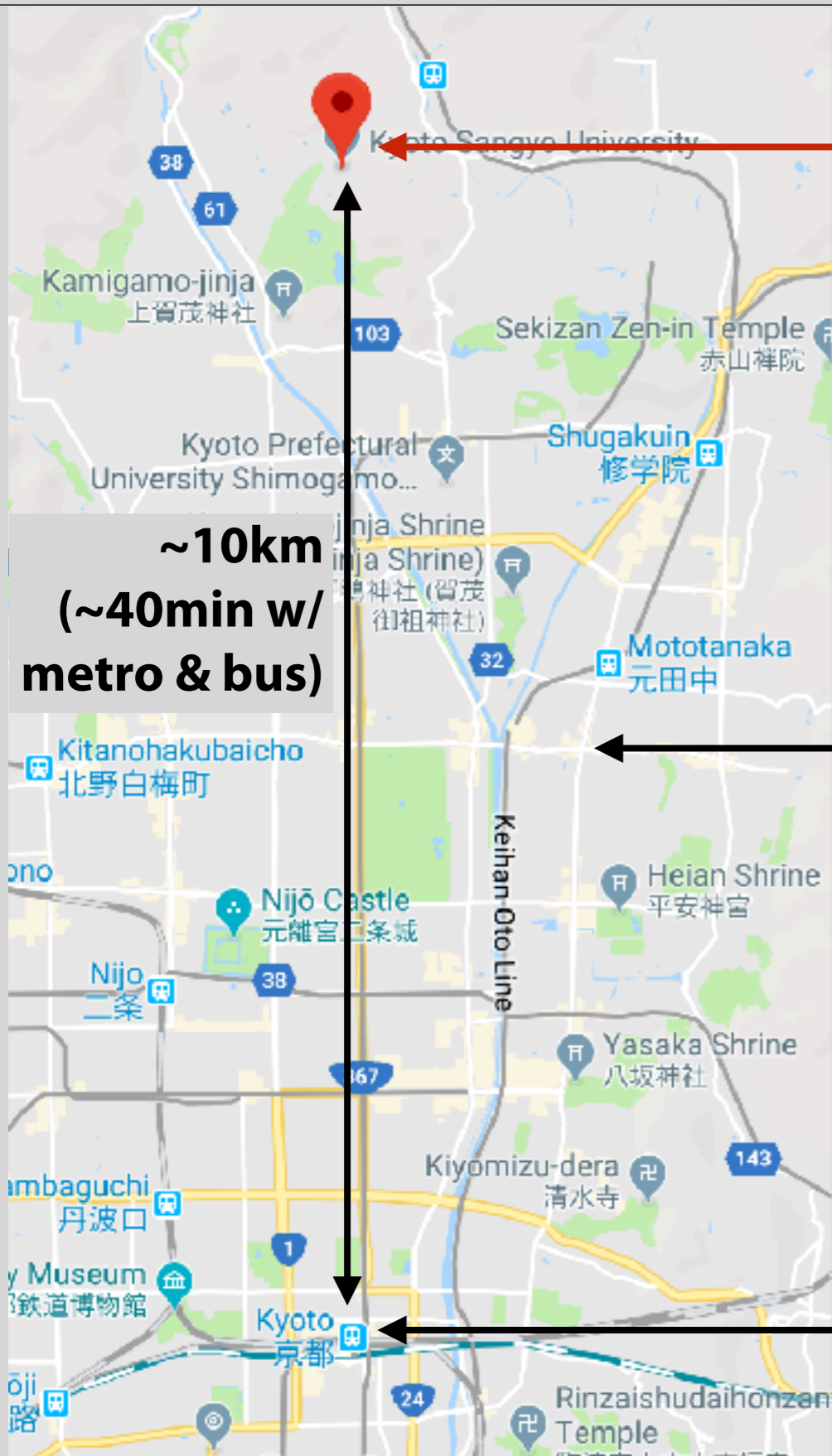# On supernovae in binary systems

Yudai Suwa

（Kyoto Sangyo University）

collaboration with
T. Yoshida (Tokyo), M. Shibata (Kyoto/AEI), H. Umeda (Tokyo),
K. Takahashi (Bonn), K. Kashiyama (Tokyo)
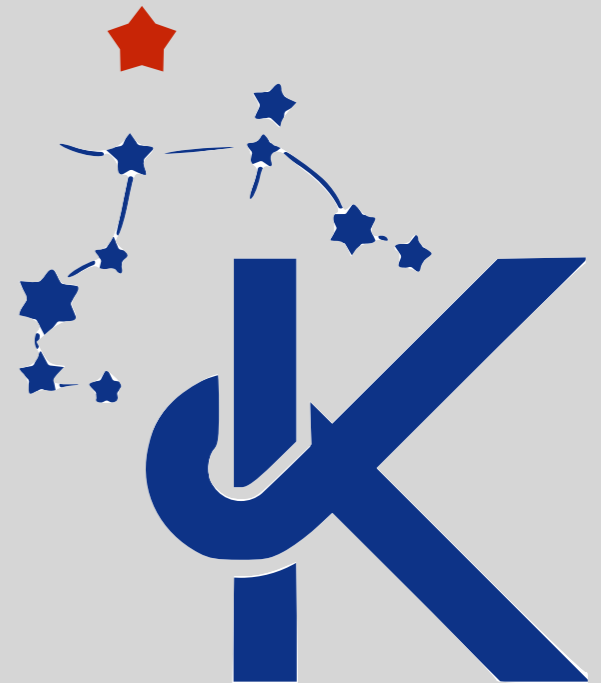
Kyoto Sangyo University（京都産業大学）

WR 104

→ **Kyoto Sangyo University**

**~10km
(~40min w/
metro & bus)**

← **Kyoto University**
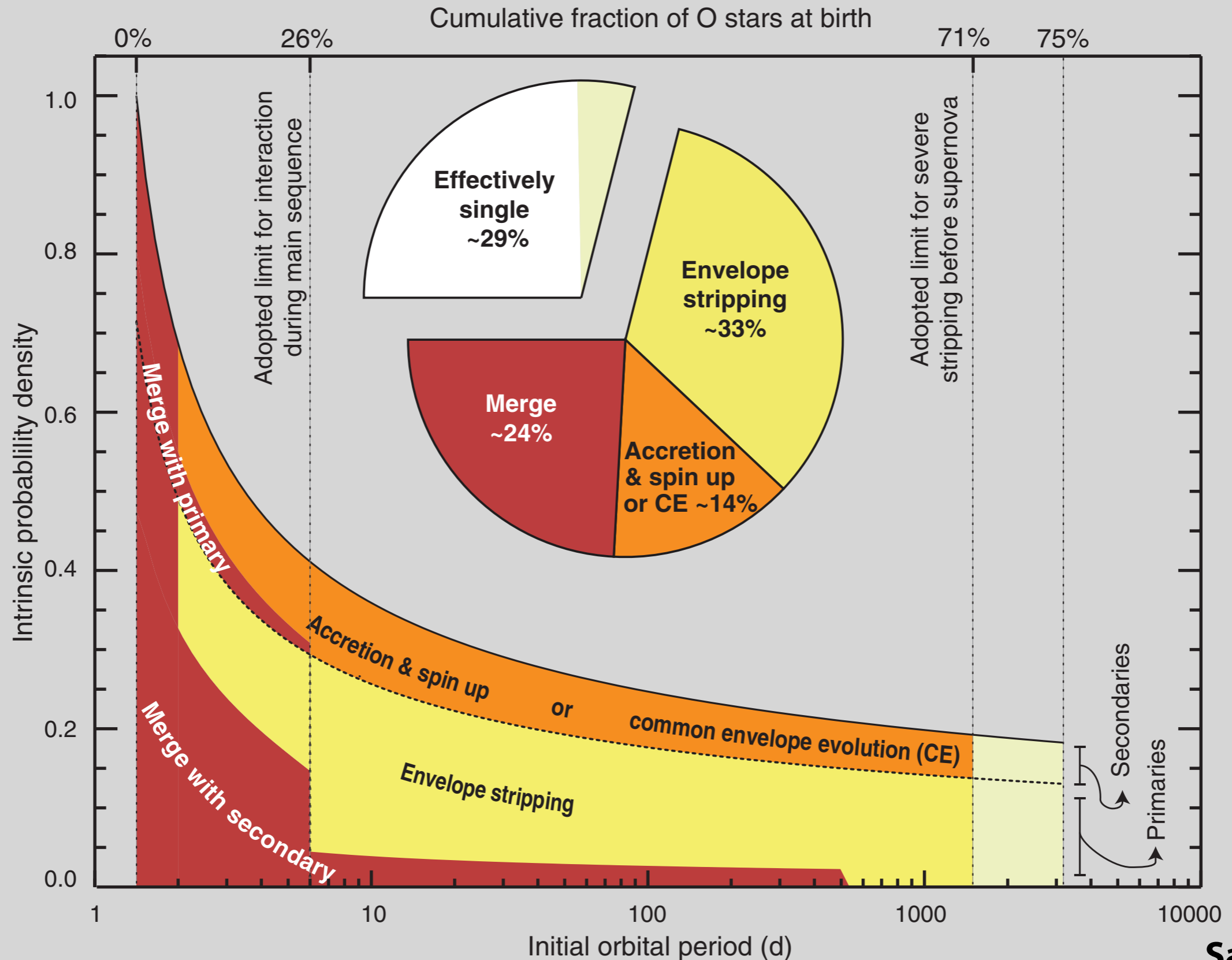
← **Kyoto St**

Long-term workshop
*"Multi-messenger astrophysics
in the GW era"*
(24 Sep.-25 Oct. 2019)

week 1: NS physics (EOS, FRB, etc)
week 2: nucleosynthesis, chemical evol.
week 3: YKIS conference
week 4: binary formation and evol.
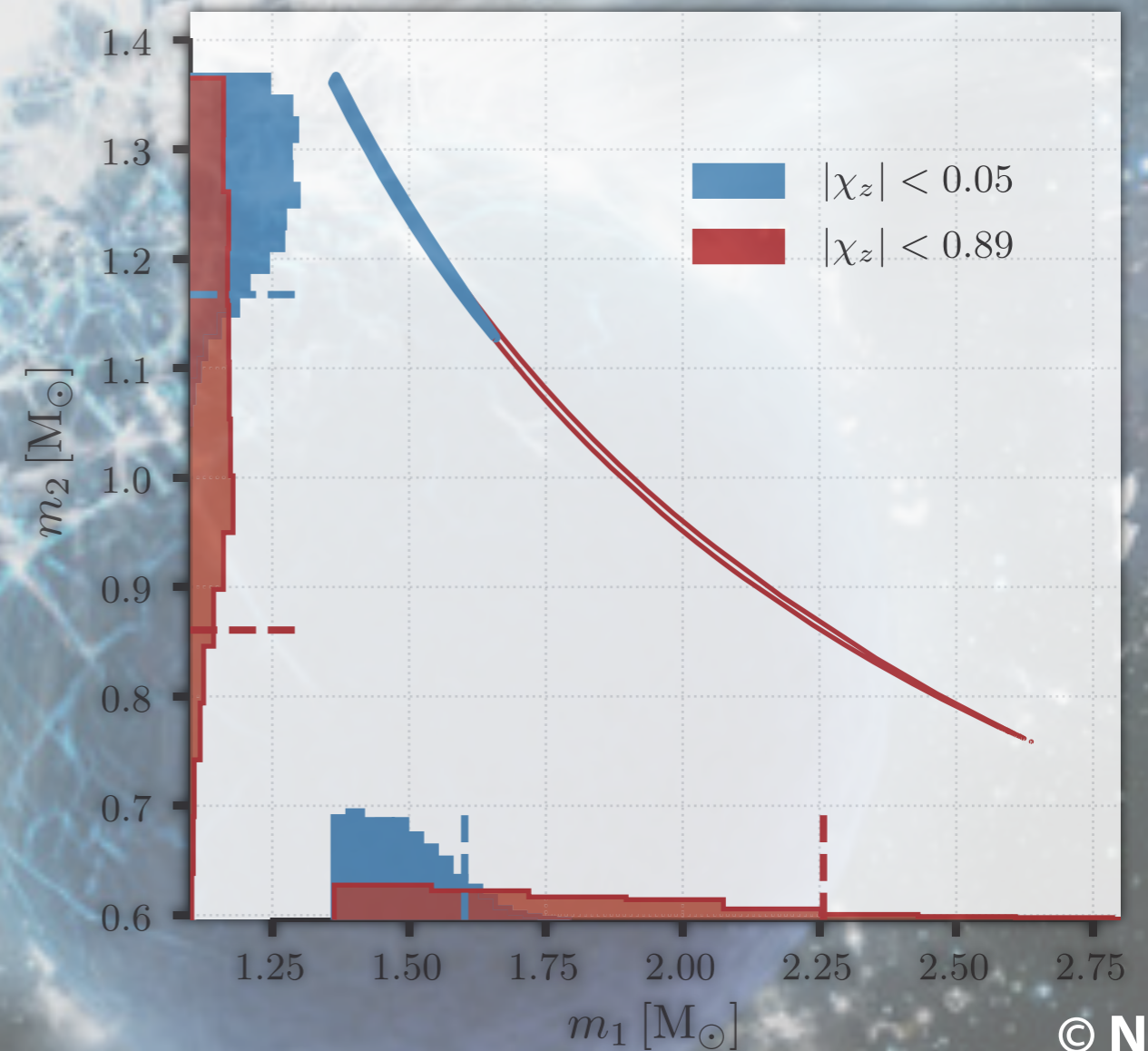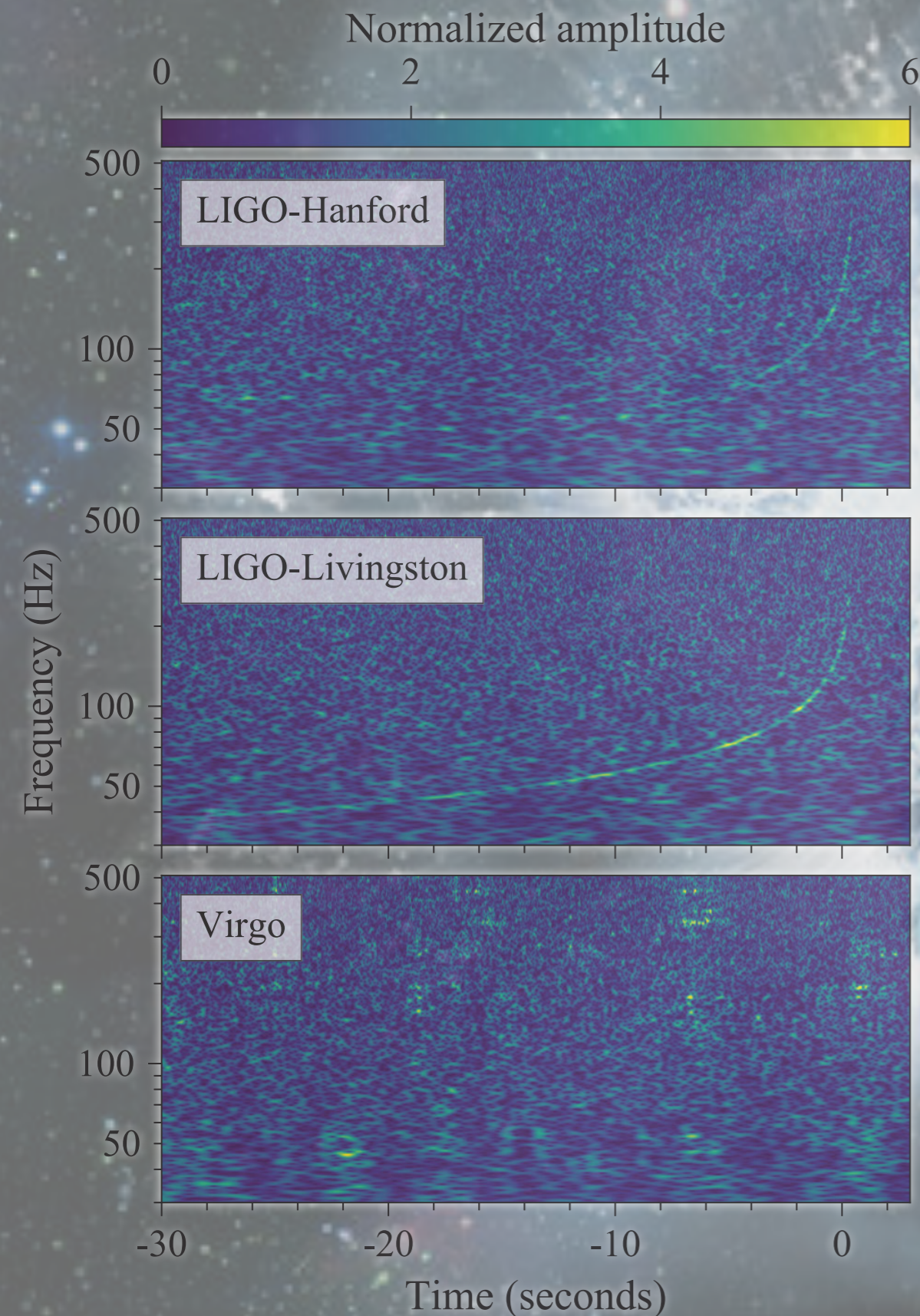week 5: GRB, SN, γ, ν

Registration page will open soon!

Fraction of interacting binary is high

Cumulative fraction of O stars at birth

Effectively single ~29%

Envelope stripping ~33%

Merge ~24%

Accretion & spin up or CE ~14%

Intrinsic probabillity density

Initial orbital period (d)

Merge with primary

Merge with secondary

Accretion & spin up

or

common envelope evolution (CE)

Envelope stripping

Adopted limit for interaction during main sequence

Adopted limit for severe stripping before supernova

Secondaries

Primaries

Sana+ 2012

GW170817: Death of neutron stars
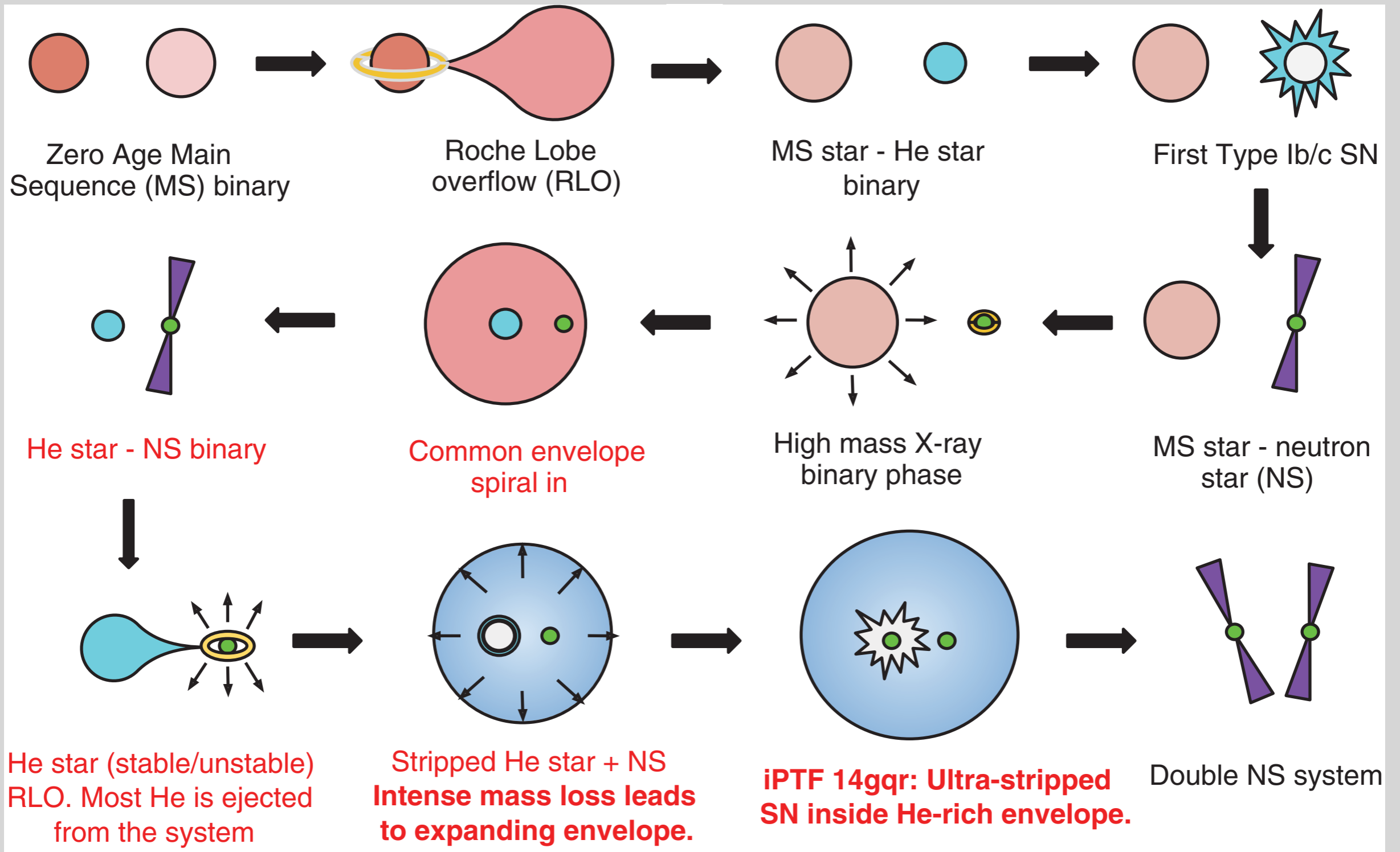
© NASA

DNS

* **In the Galaxy, six systems are expected to merge within cosmic age (~13.8Gyr=1.38×10^{10}yr)**

  * **Merger time =>1.2×10^8yr $(a_0/10^{11} \text{cm})^4 (m/2.8 M_\odot)^{-3}$ -> $a_0 < 3 \times 10^{11}$cm is needed**
    NB) The distance of Sun-Earth is 1AU=1.5×10^{13}cm, $R_\odot = 7 \times 10^{10}$cm

* **Massive stars forming 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

Zero Age Main Sequence (MS) binary → Roche Lobe overflow (RLO) → MS star - He star binary → First Type Ib/c SN

He star - NS binary ← Common envelope spiral in ← High mass X-ray binary phase ← MS star - neutron star (NS)

He star (stable/unstable) RLO. Most He is ejected from the system → Stripped He star + NS **Intense mass loss leads to expanding envelope.** → **iPTF 14gqr: Ultra-stripped SN inside He-rich envelope.** → Double NS system

De et al. 2018

Ultra-stripped supernovae?

Ultra-stripped supernovae: progenitors and fate

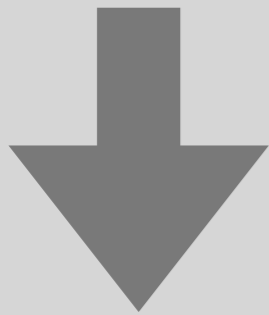Thomas M. Tauris,[1,2]★ Norbert Langer[1] and Philipp Podsiadlowski[3]

* *"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?

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

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

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

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

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

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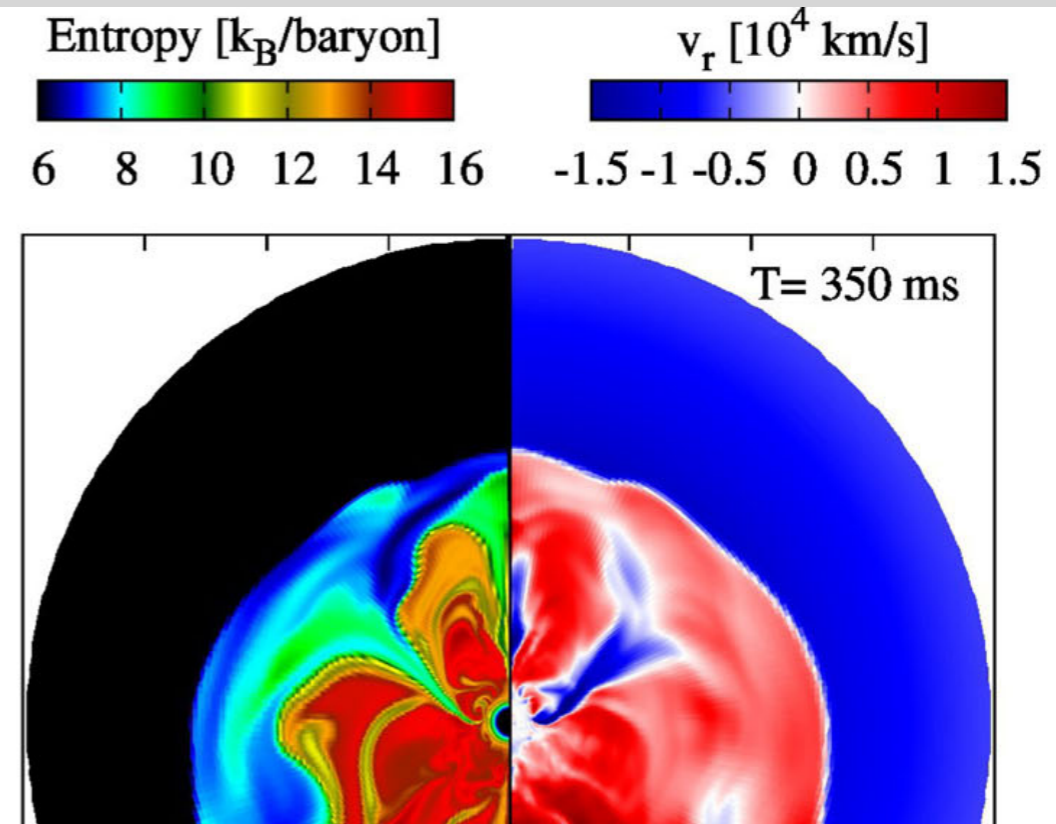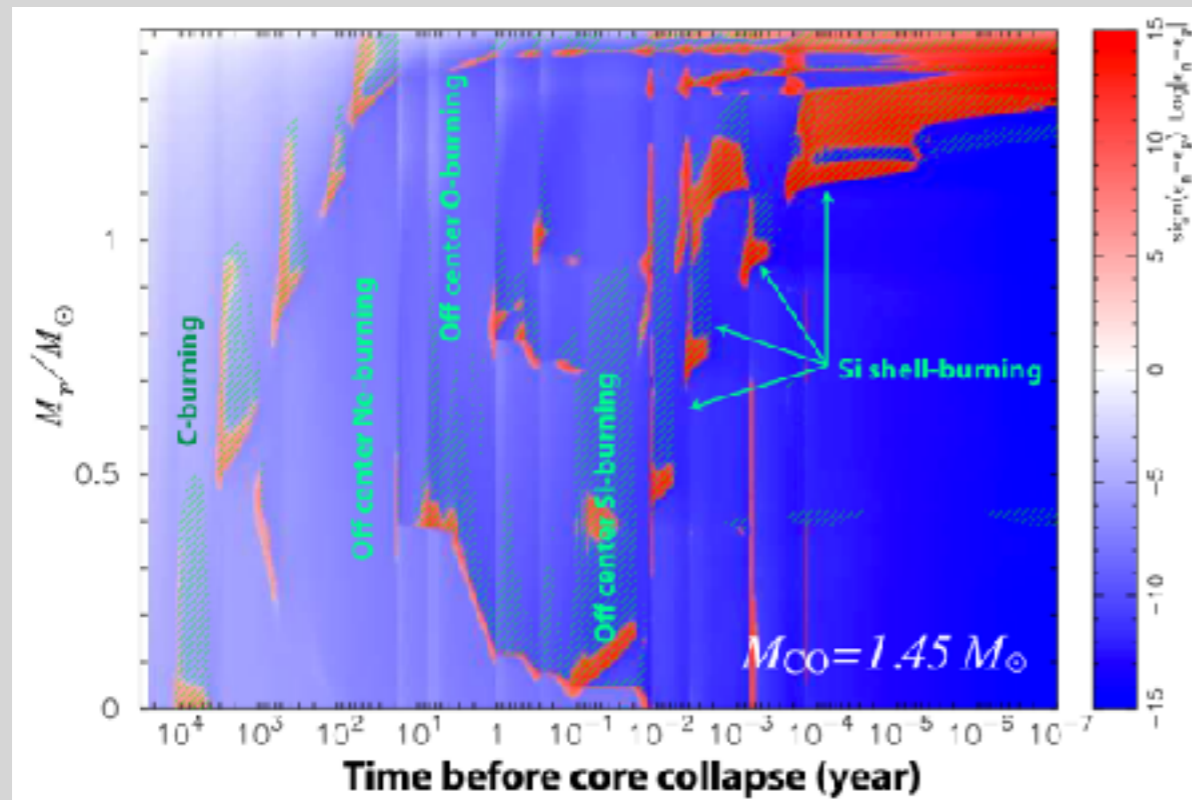$M_{ej} \sim 0.1 M_\odot$

Small ejecta mass

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

Neutrino-driven explosions of ultra-stripped SN

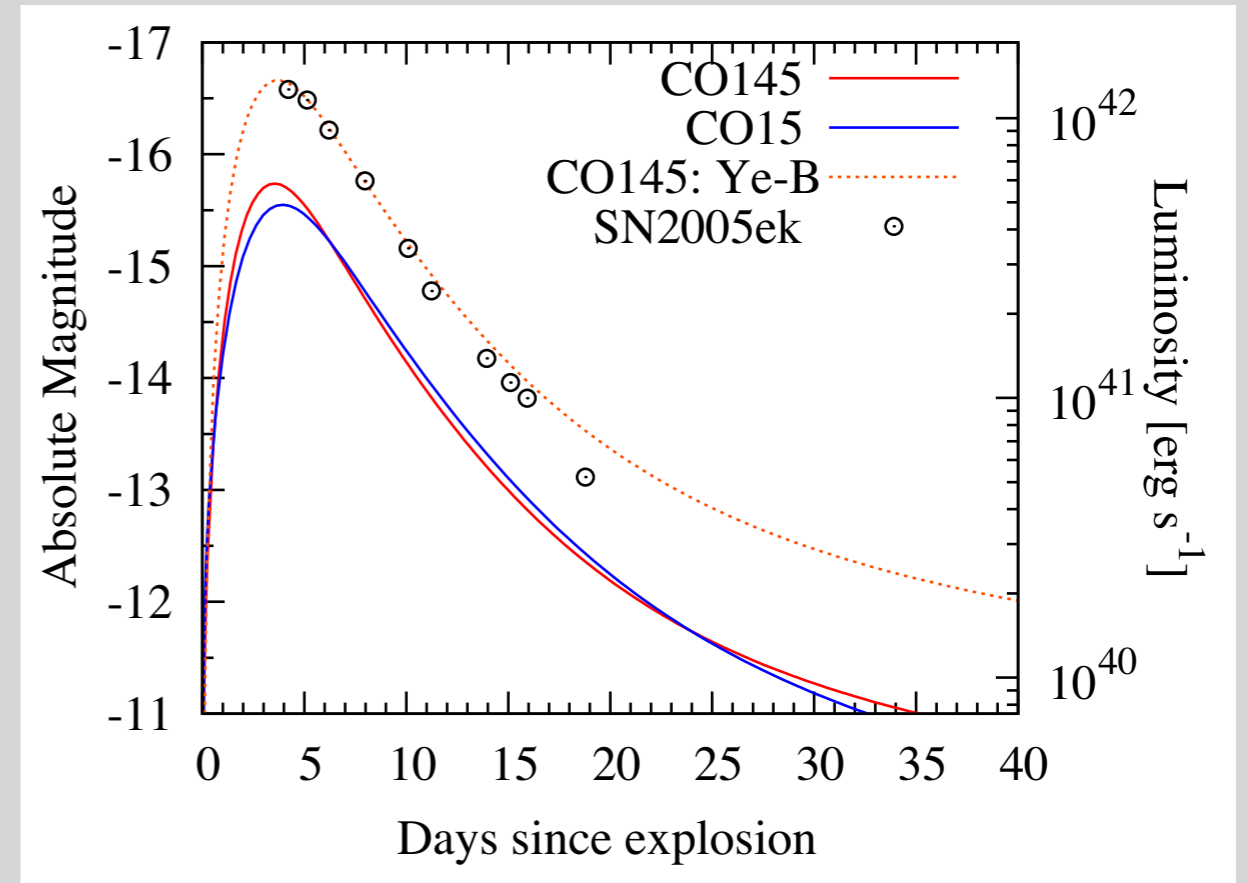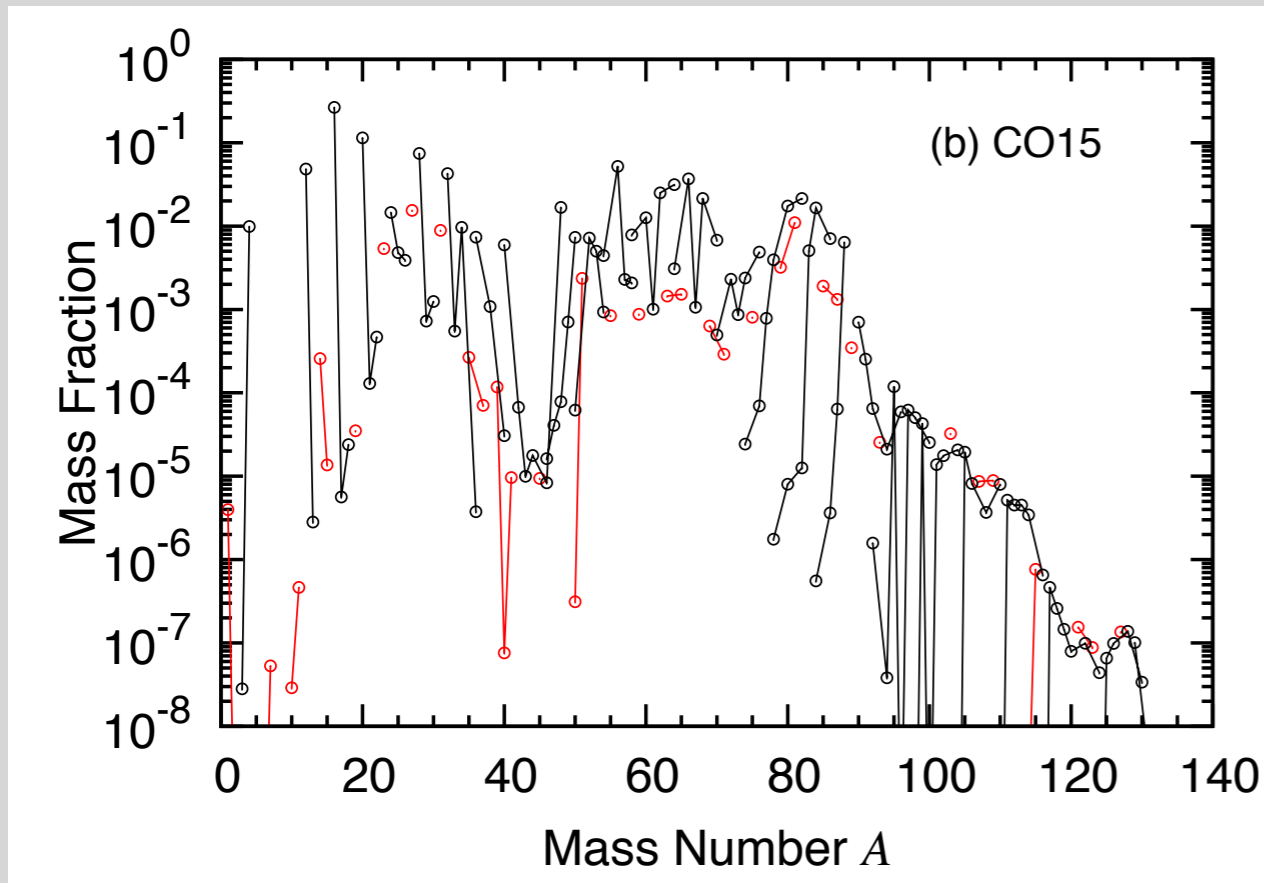**[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, 454, 3073 (2015)]**

Model	t_{final}[a] [ms]	R_{sh}[b] [km]	E_{exp}[c] [B]	$M_{NS,baryon}$[d] [$M_\odot$]	$M_{NS,grav}$[e] [$M_\odot$]	M_{ej}[f] [$10^{-1}M_\odot$]	M_{Ni}[g] [$10^{-2}M_\odot$]	v_{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 compatible 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.
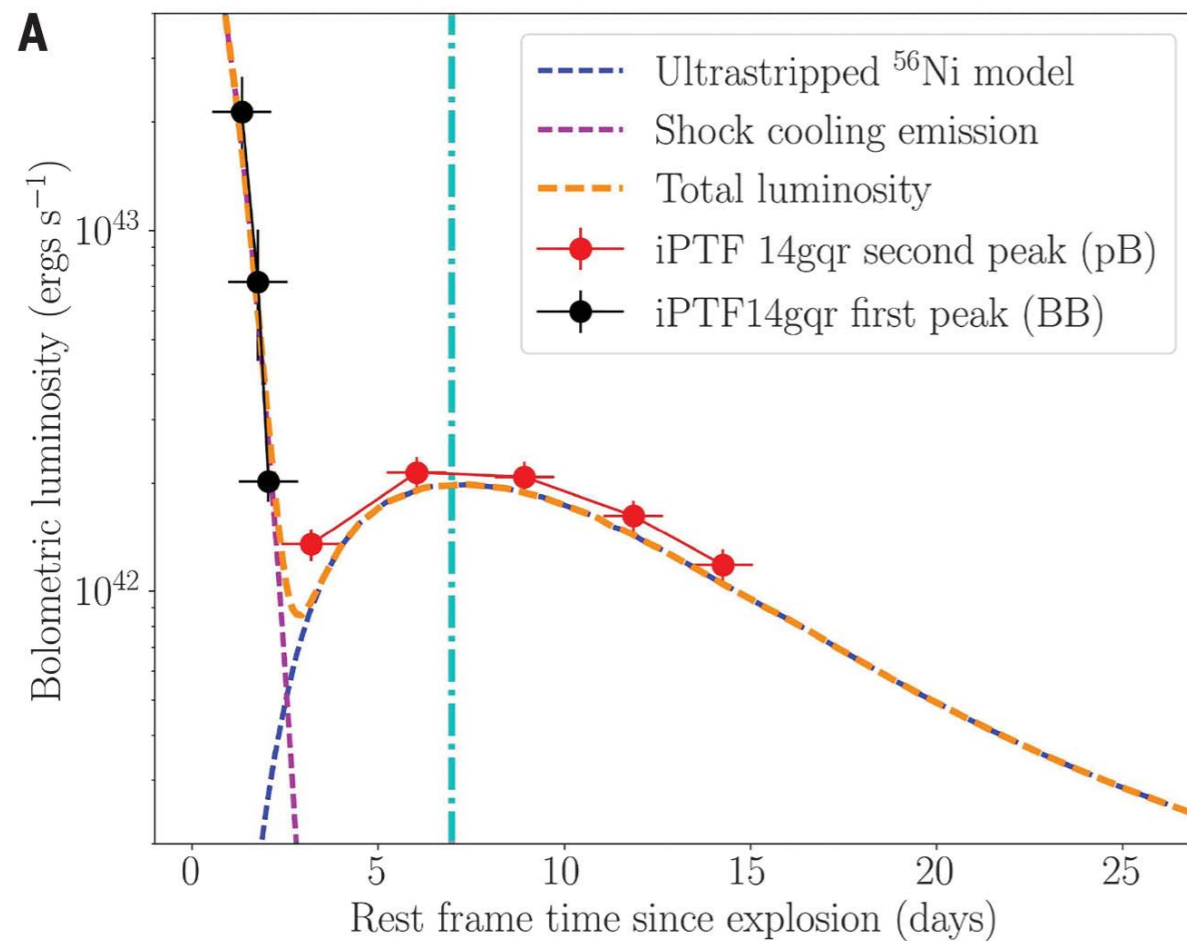
Implications

* **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/ZTF, Pan-STARRS, and LSST) will give constraint on rate**

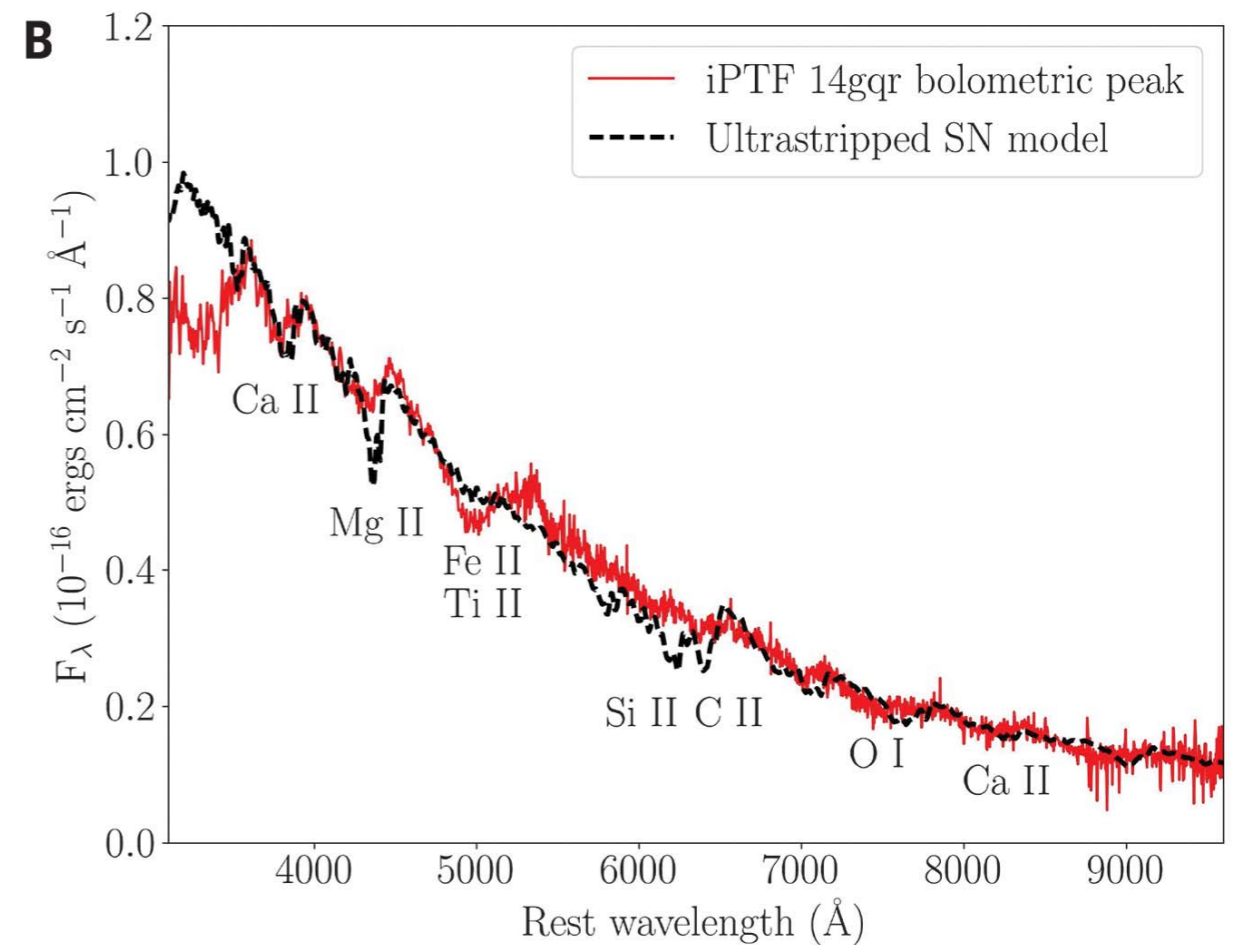# Summary of Part1

* **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)**

Fig. 5. Comparison of iPTF 14gqr to theoretical models of ultra-stripped SNe. (**A**) Bolometric light curve of iPTF 14gqr shown with a composite light curve consisting of ultra-stripped type Ic SN models (28) and early shock-cooling emission (25). The blue dashed line corresponds to the ^{56}Ni powered peak in the ultra-stripped SN models for $M_{ej} = 0.2\,M_\odot$, $M_{Ni} = 0.05\,M_\odot$, and $E_K = 2 \times 10^{50}$ ergs; the magenta line corresponds to the early shock-cooling emission; and the orange line represents the total luminosity from the sum of the two components. Blackbody (BB) luminosities represent the early emission, whereas pseudo-bolometric (pB) luminosities are used for the second peak (12). (**B**) Comparison of the peak photospheric spectra of iPTF 14gqr [the epoch is indicated by the cyan dashed line in (A)] to that of the model in (A). The overall continuum shape, as well as absorption features of O I, Ca II, Fe II, and Mg II, are reproduced (12).
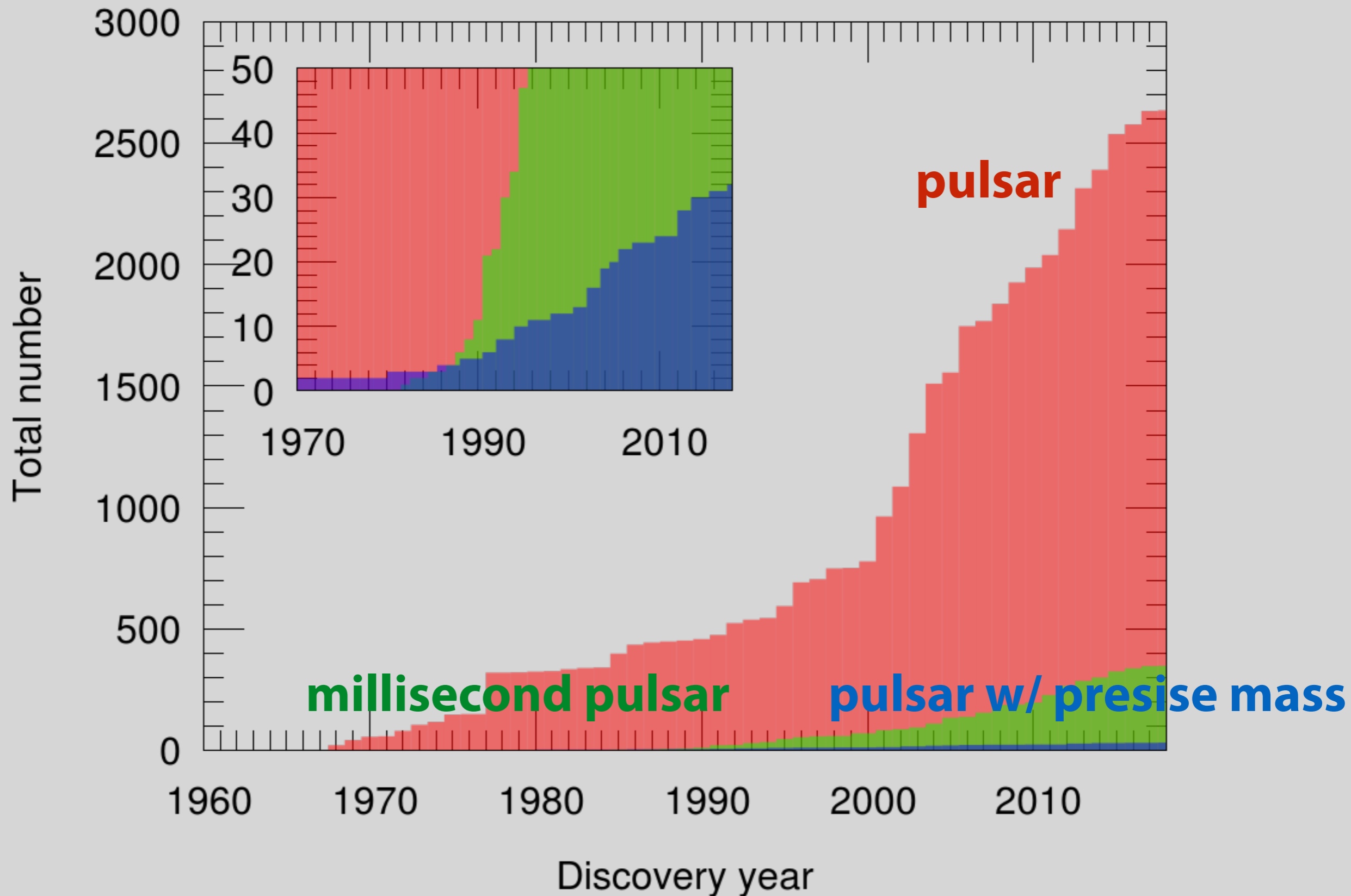
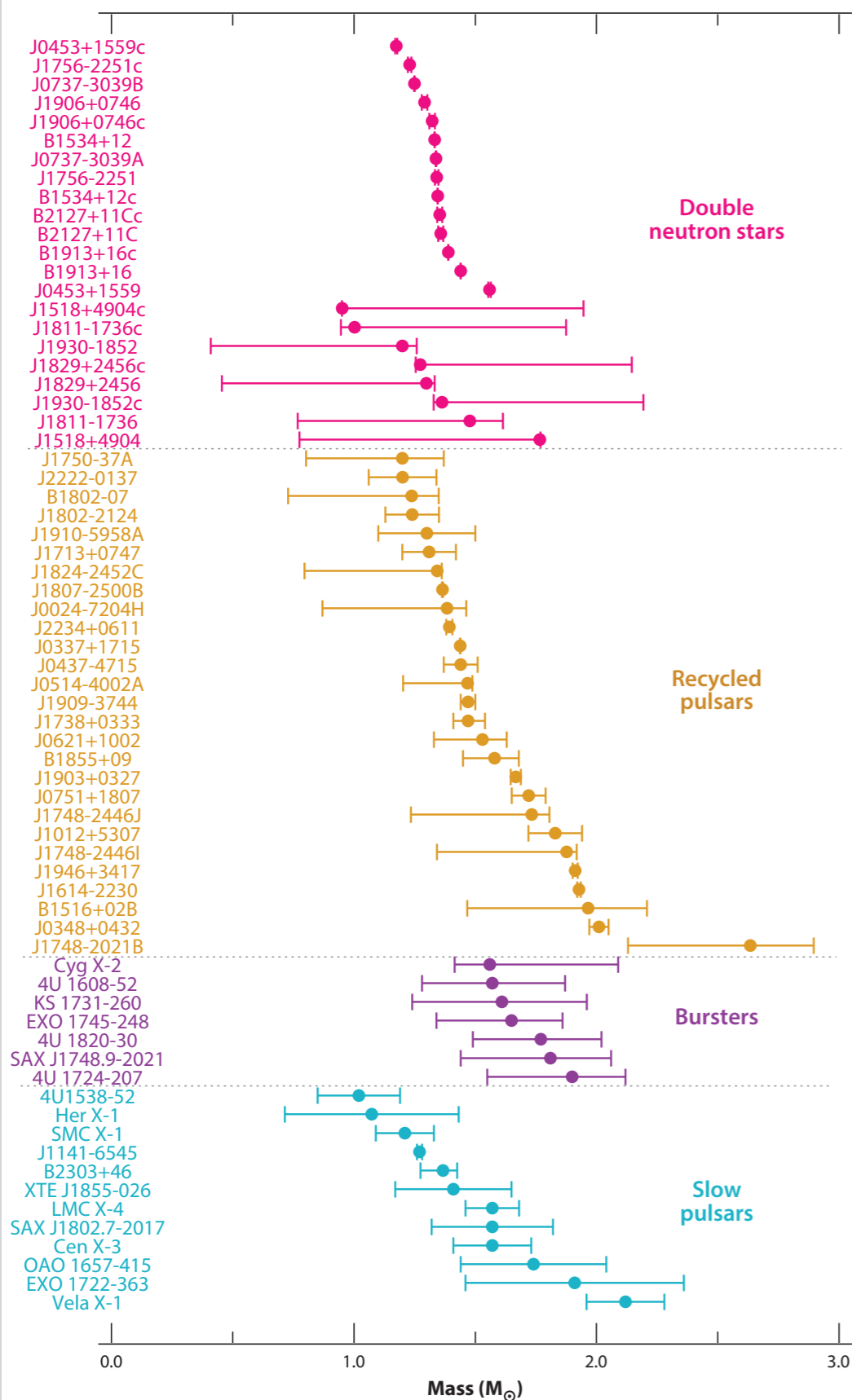De et al. 2018

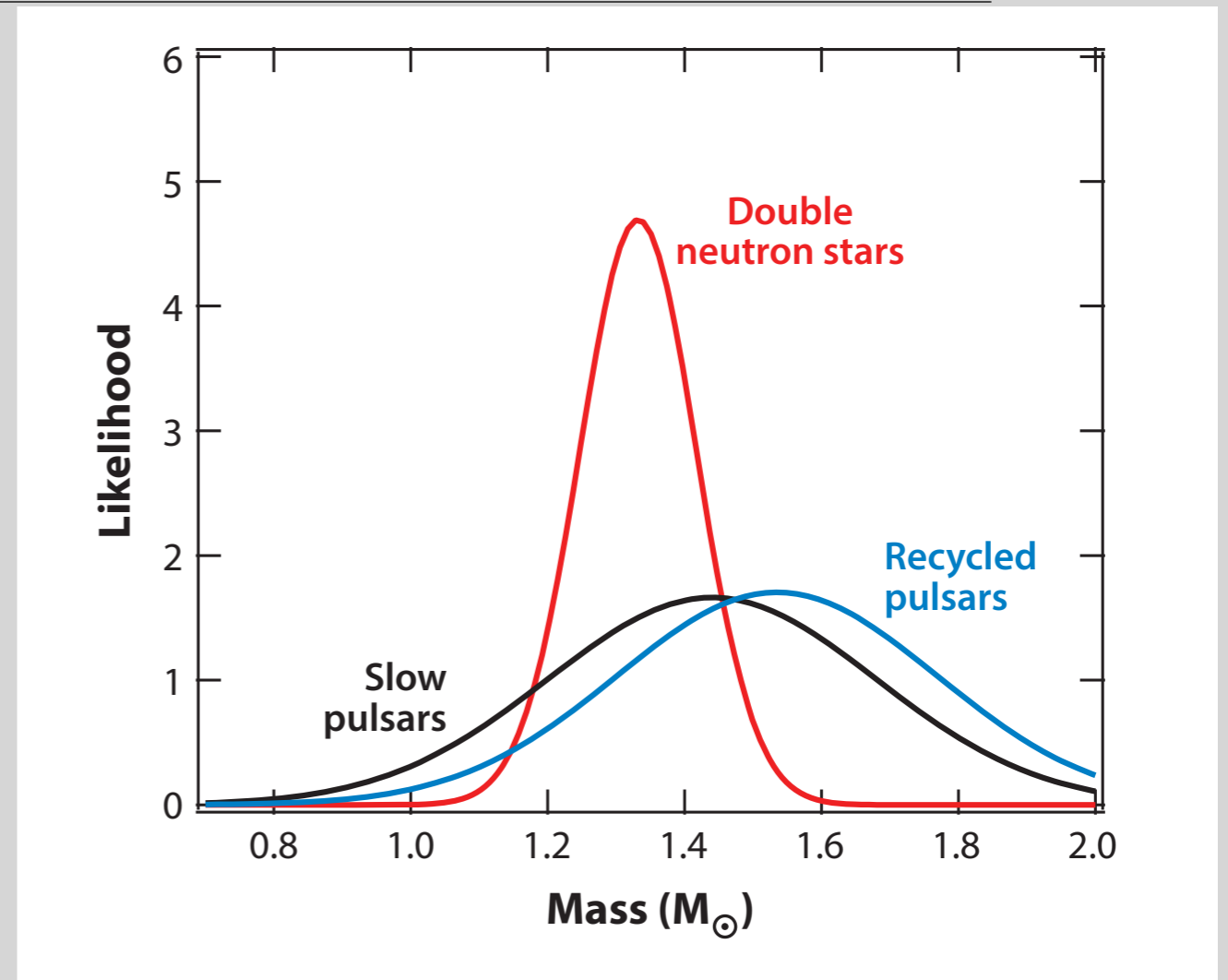# *2. Minimum NS mass from binary systems*

Pulsar number is increasing

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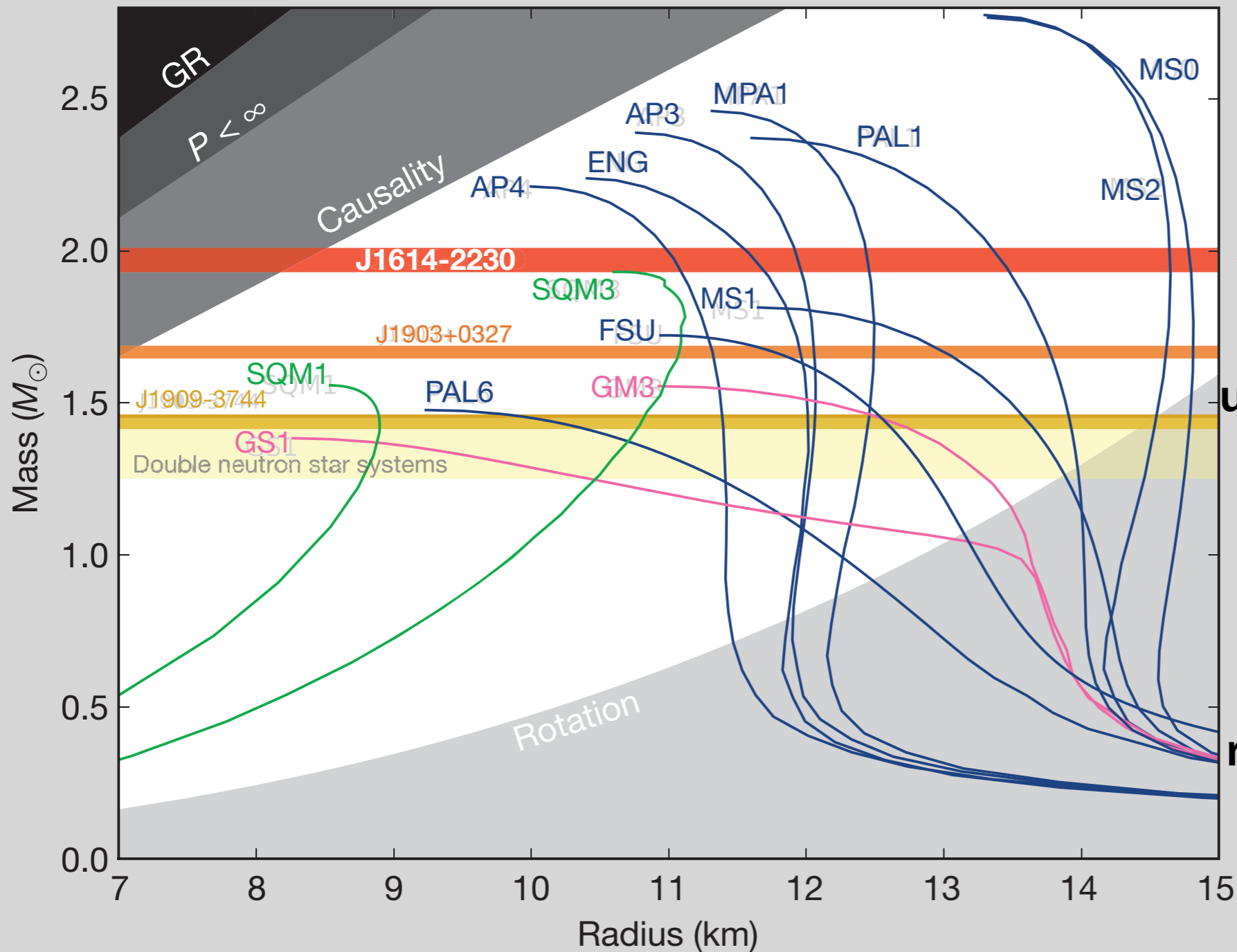
NS mass measurements

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]

Massive NSs tell us nuclear physics

Demorest+ 2010

←**1.97±0.04M⊙**

NB) mass estimation was updated by Arzoumanian+ 2018 as 1.908±0.016M⊙

Another massive NS was reported by Antoniadis+ (2013), J0348+0432, 2.01±0.04M⊙

How about low-mass one?
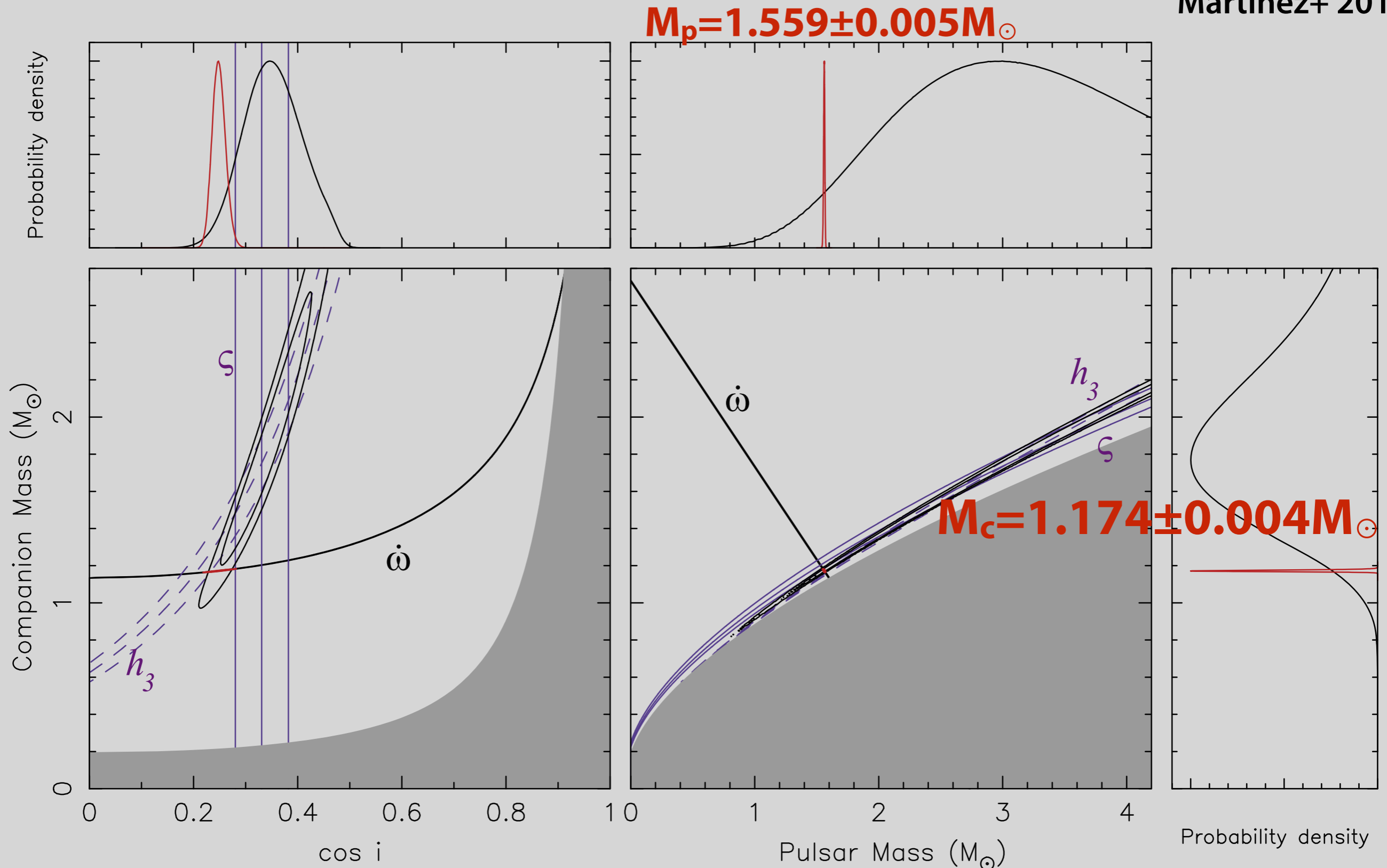
Double NSs

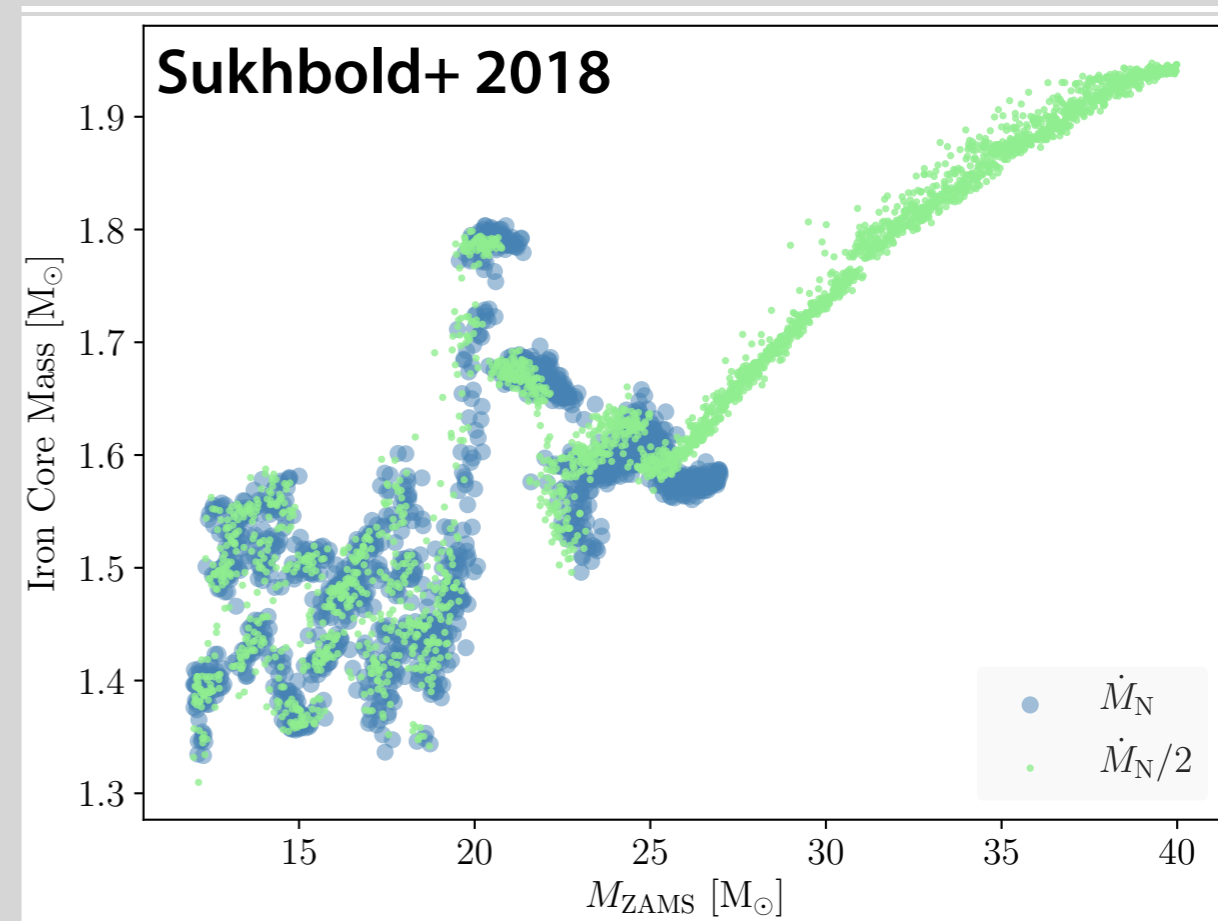concentrating within a small range

Double
neutron stars

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

0.0   1.0   2.0   3.0

Mass (M$_\odot$)

First asymmetric DNS system

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

$M_c=1.174\pm0.004M_\odot$
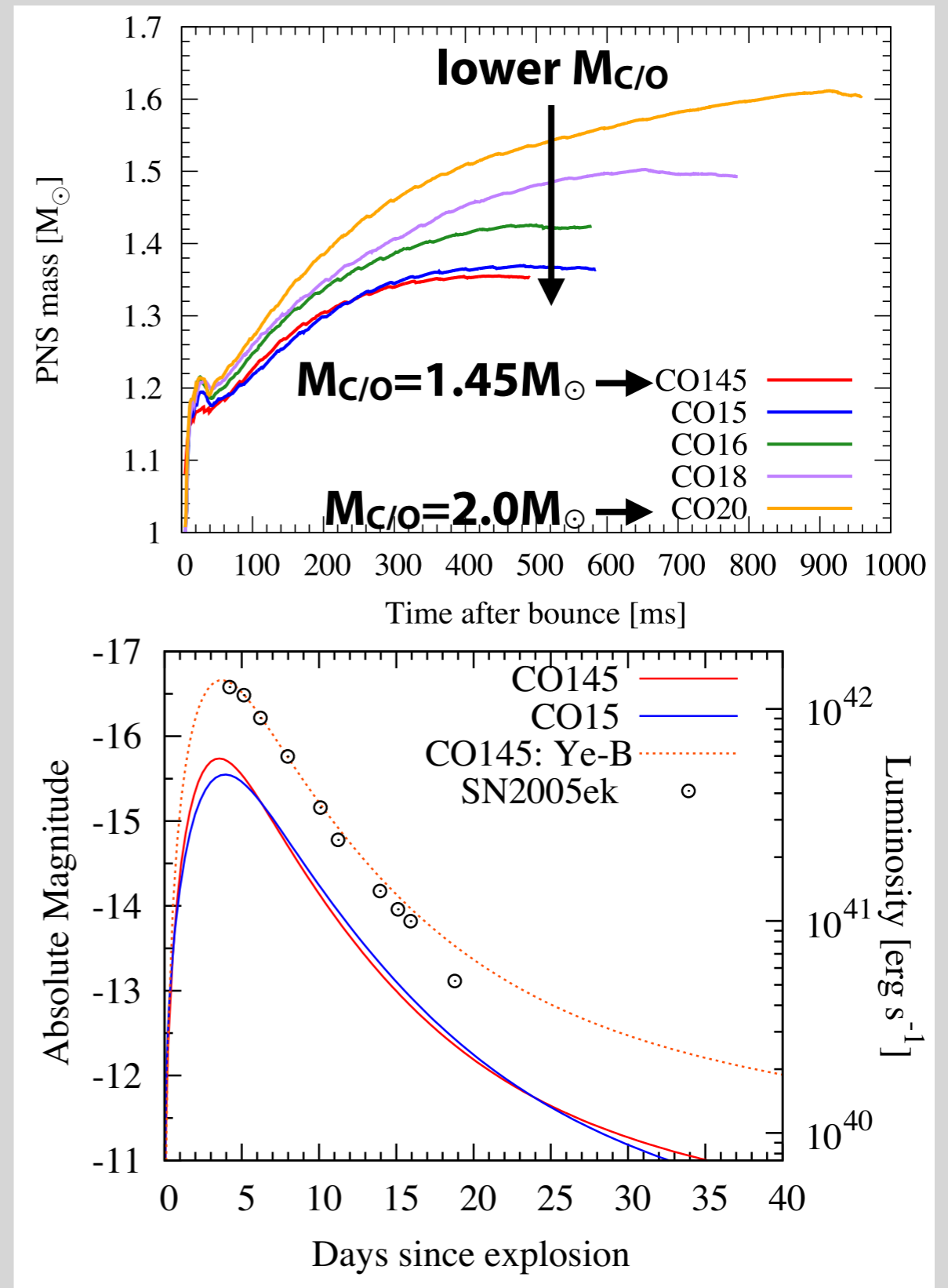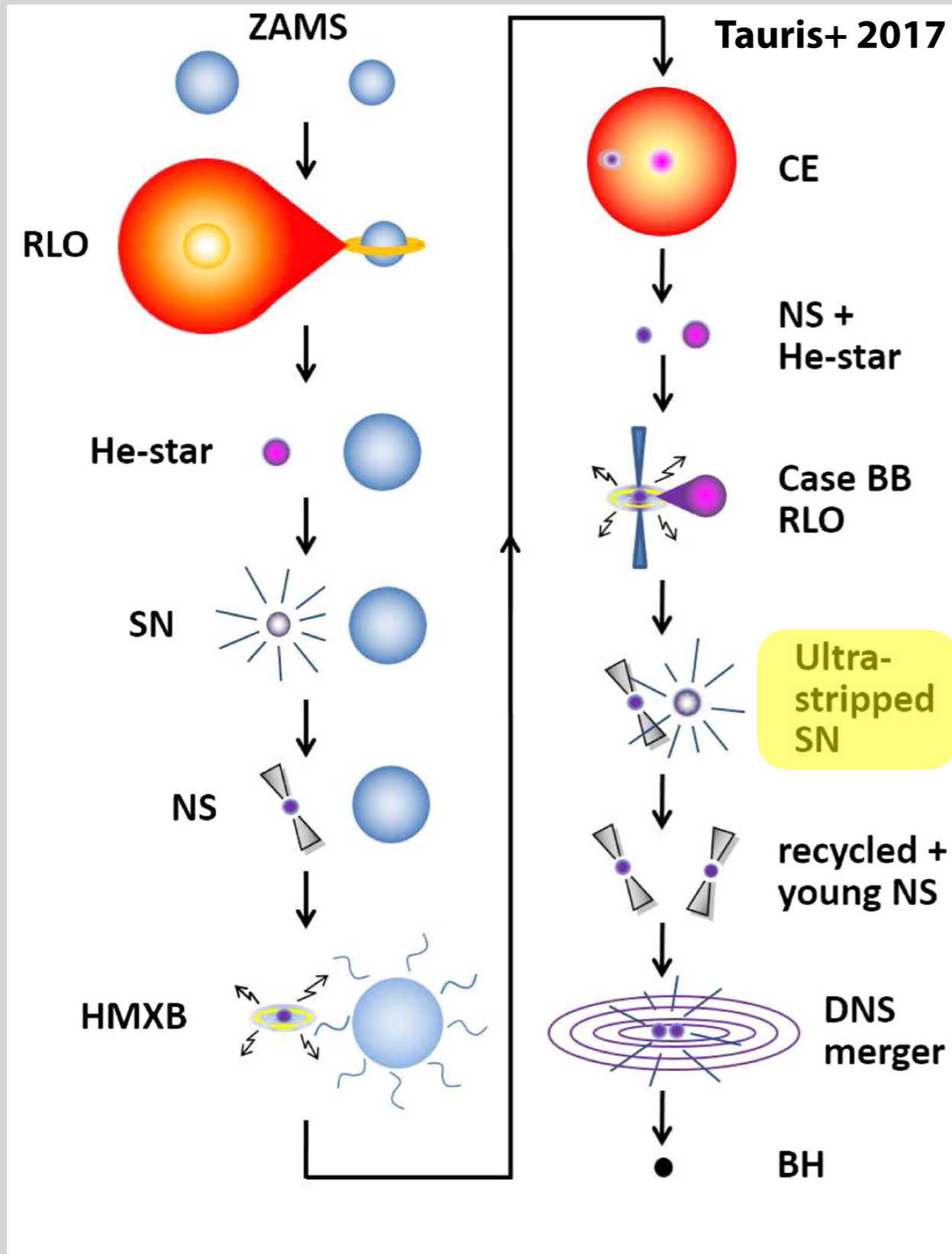
A low-mass NS

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

* **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?**
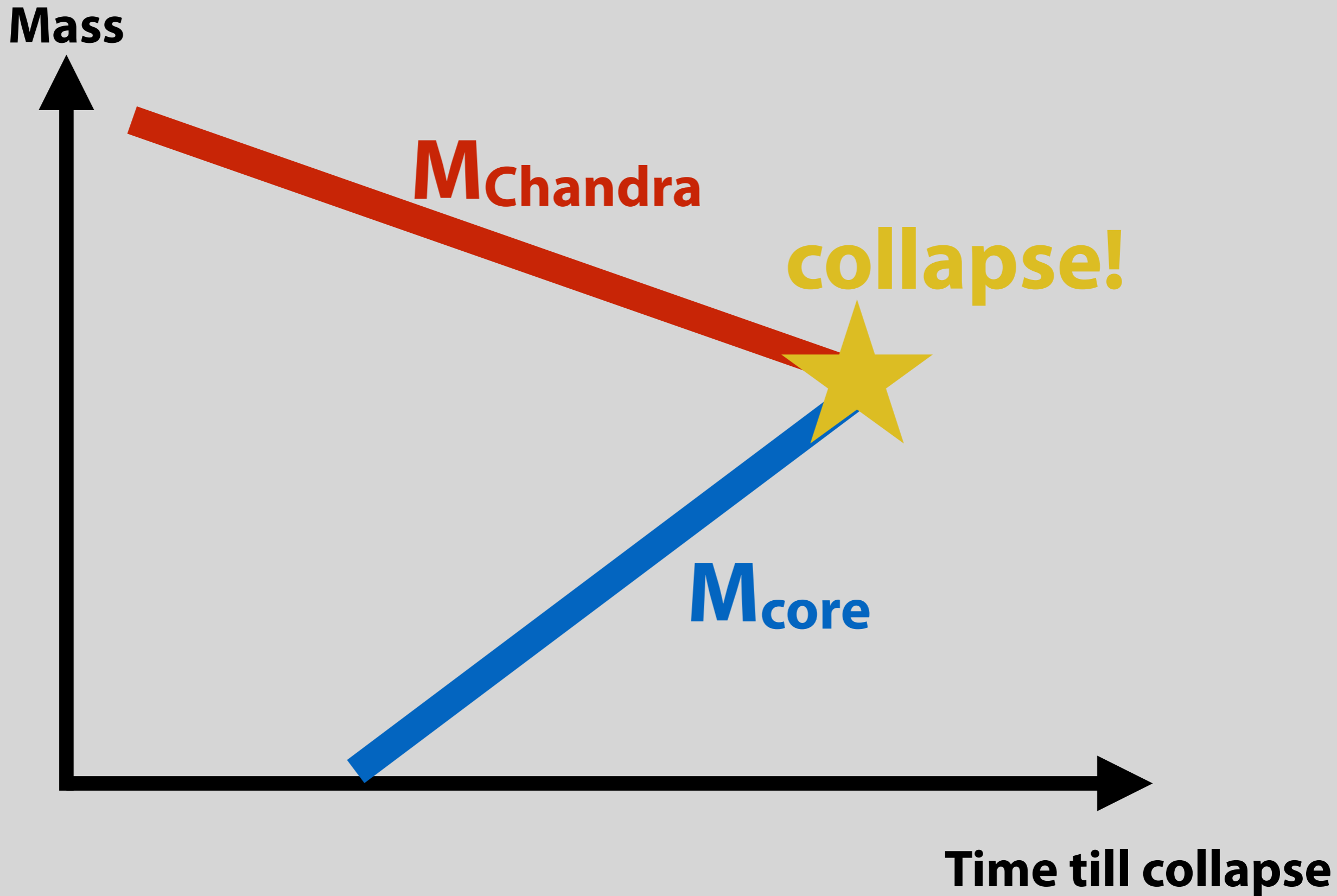 * a small iron core of massive star? (typically M_{Fe}~1.4–1.8M$_\odot$)

Sukhbold+ 2018

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

When does a core collapse?

Modified Chandrasekhar mass

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

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

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

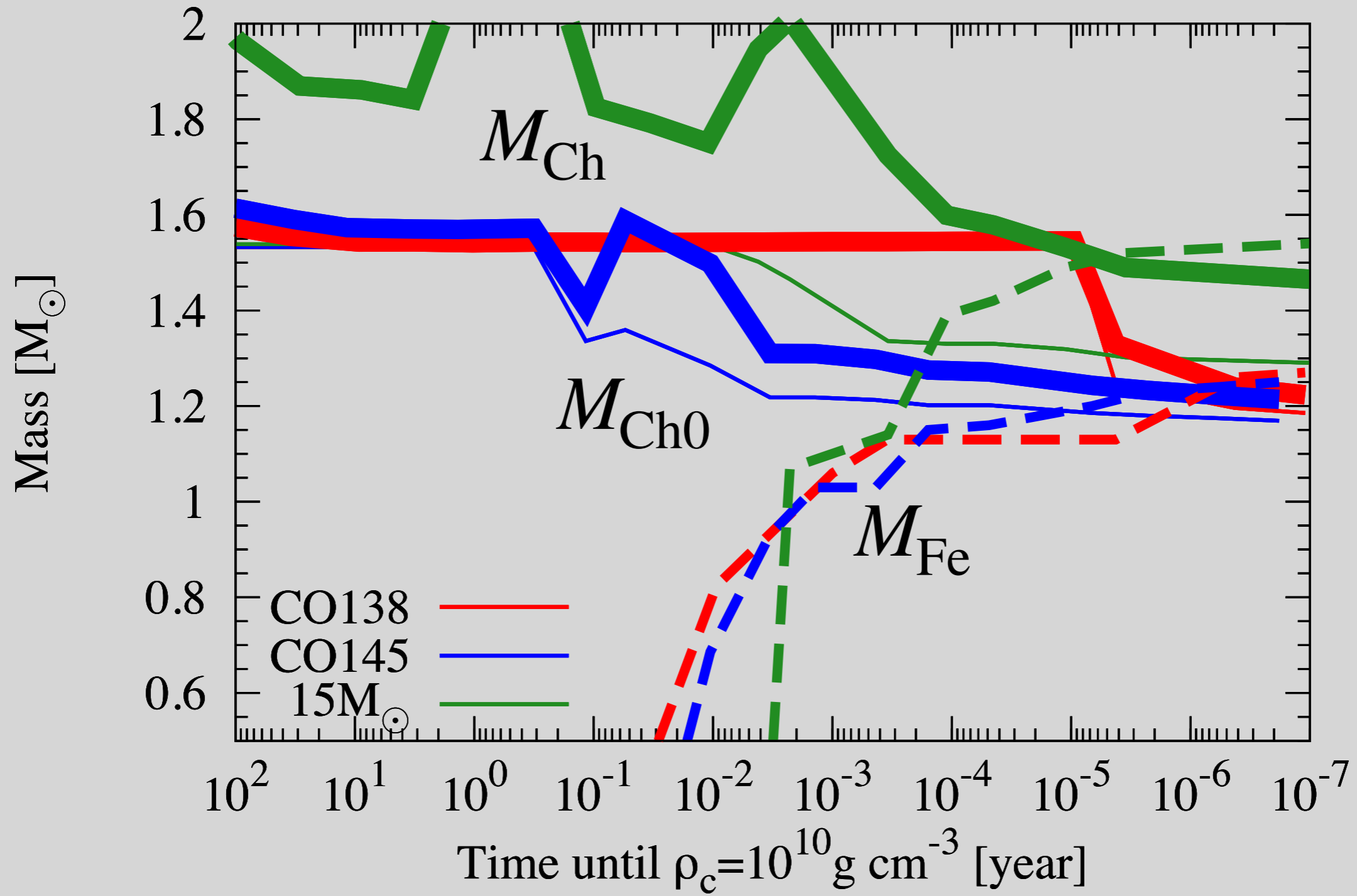$$M_{\text{Ch}}(T) = M_{\text{Ch0}}(Y_e) \left[1 + \left(\frac{s_e}{\pi Y_e} \right)^2 \right]$$

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

Baron+ 1990; Timmes+ 1996

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

M_{ch} vs. M_{core}

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **481**, 3305 (2018)]
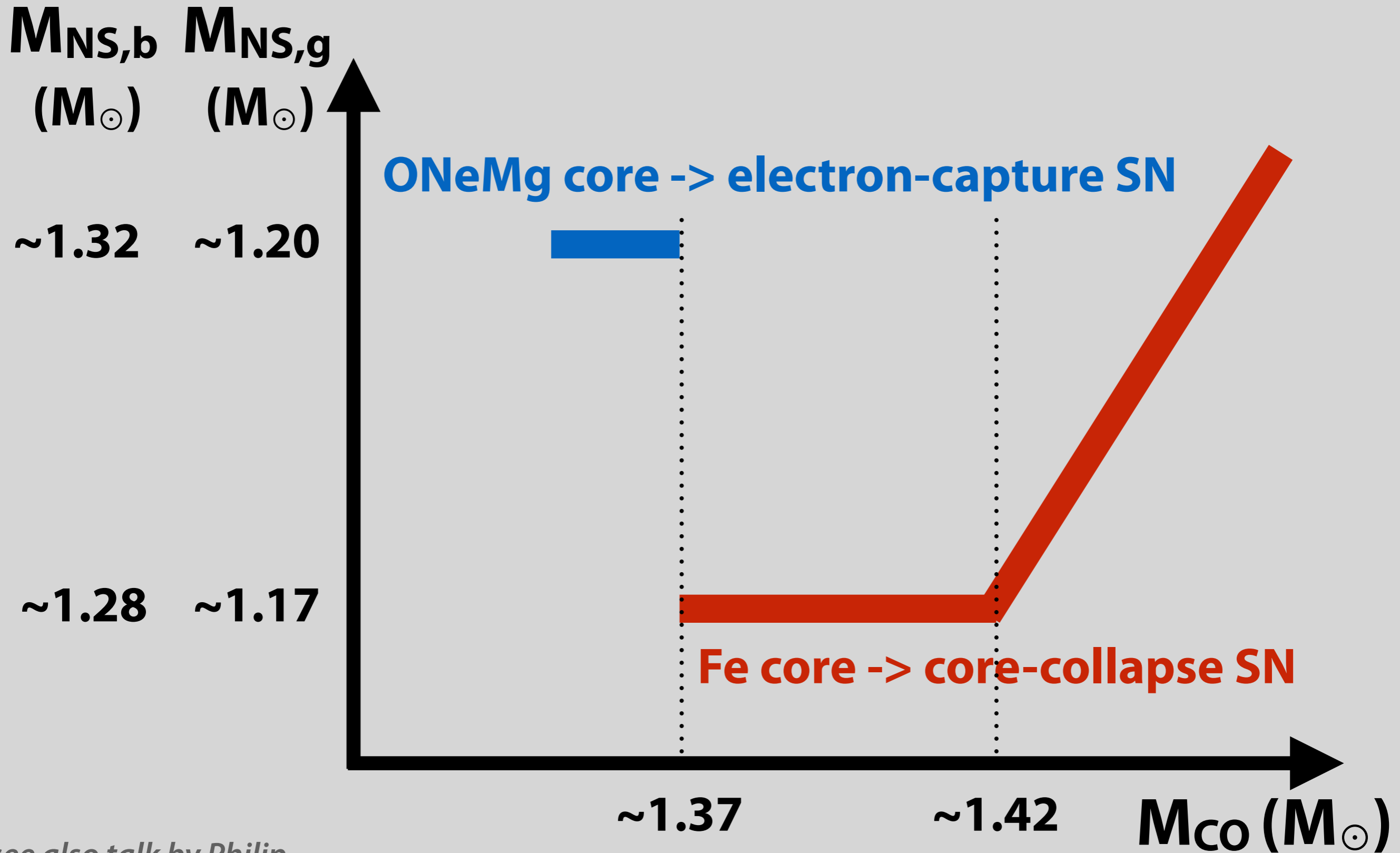
Explosion simulations and NS masses

* **Neutrino-radiation hydro. sim**

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

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

Discussion

$M_{NS,b}$ $M_{NS,g}$
($M_\odot$) ($M_\odot$)

~1.32   ~1.20

ONeMg core -> electron-capture SN

~1.28   ~1.17

Fe core -> core-collapse SN

~1.37   ~1.42 M_{CO} ($M_\odot$)

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.