Gravitational Wave
Physics and Astronomy
Genesis

YITP long-term workshop
Multi-Messenger Astrophysics in the Gravitational Wave Era
September 24 - October 25 2019,
Yukawa Institute for Theoretical Physics, Kyoto University

On supernovae in binary systems

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collaboration with
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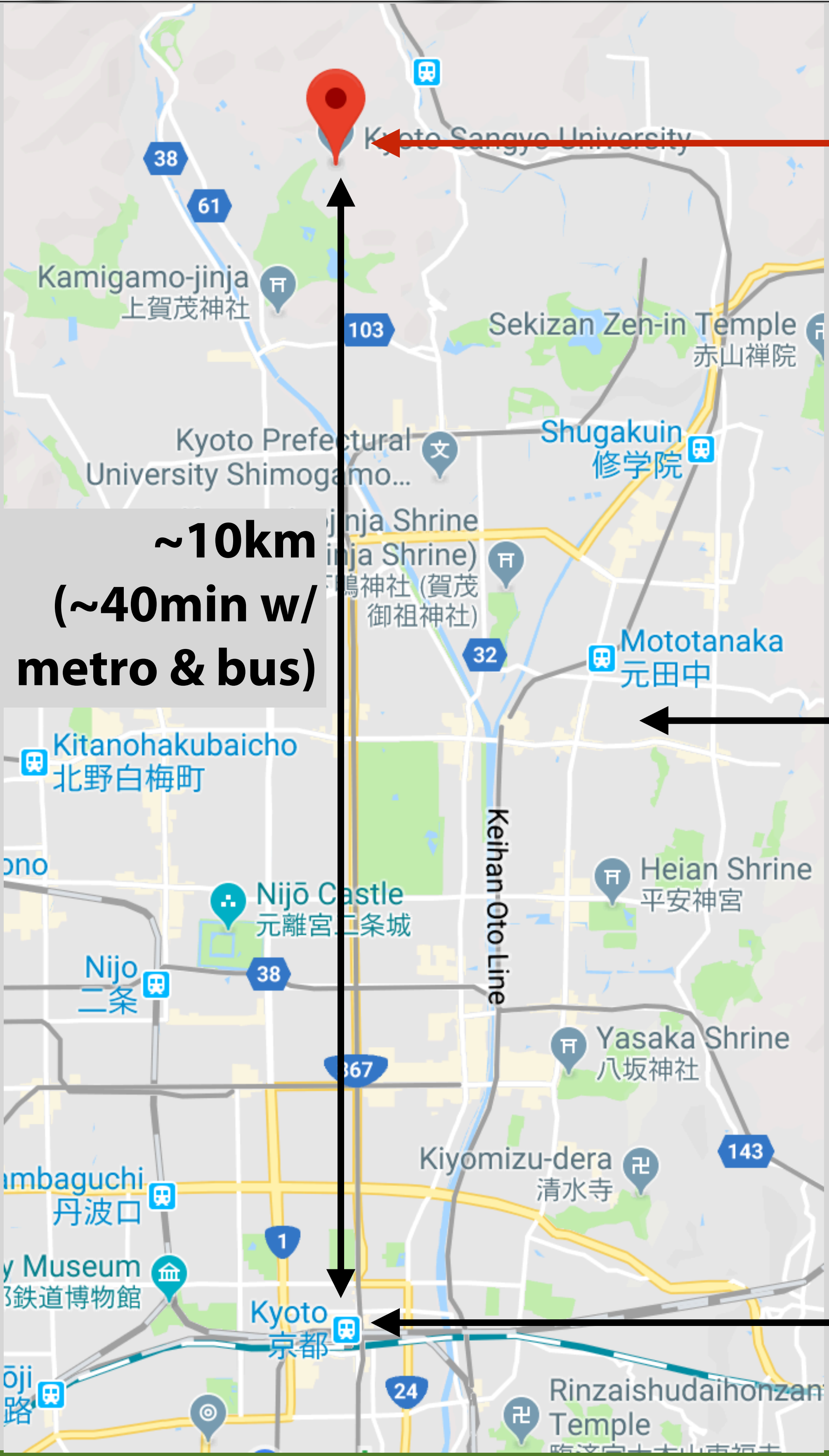
Kyoto Sangyo University（京都産業大学）



Kyoto Sangyo University

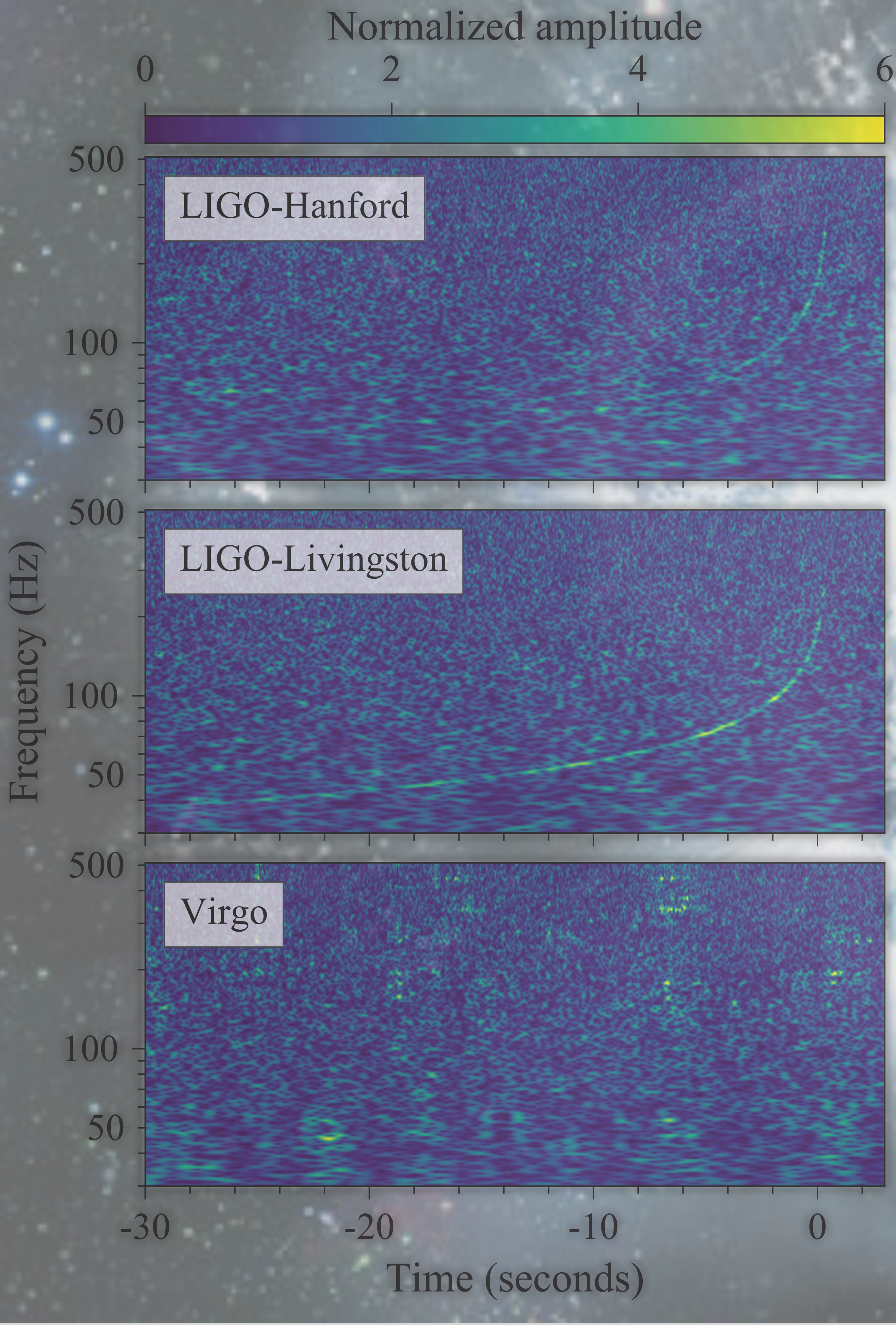
~10km (~40min w/ metro & bus)

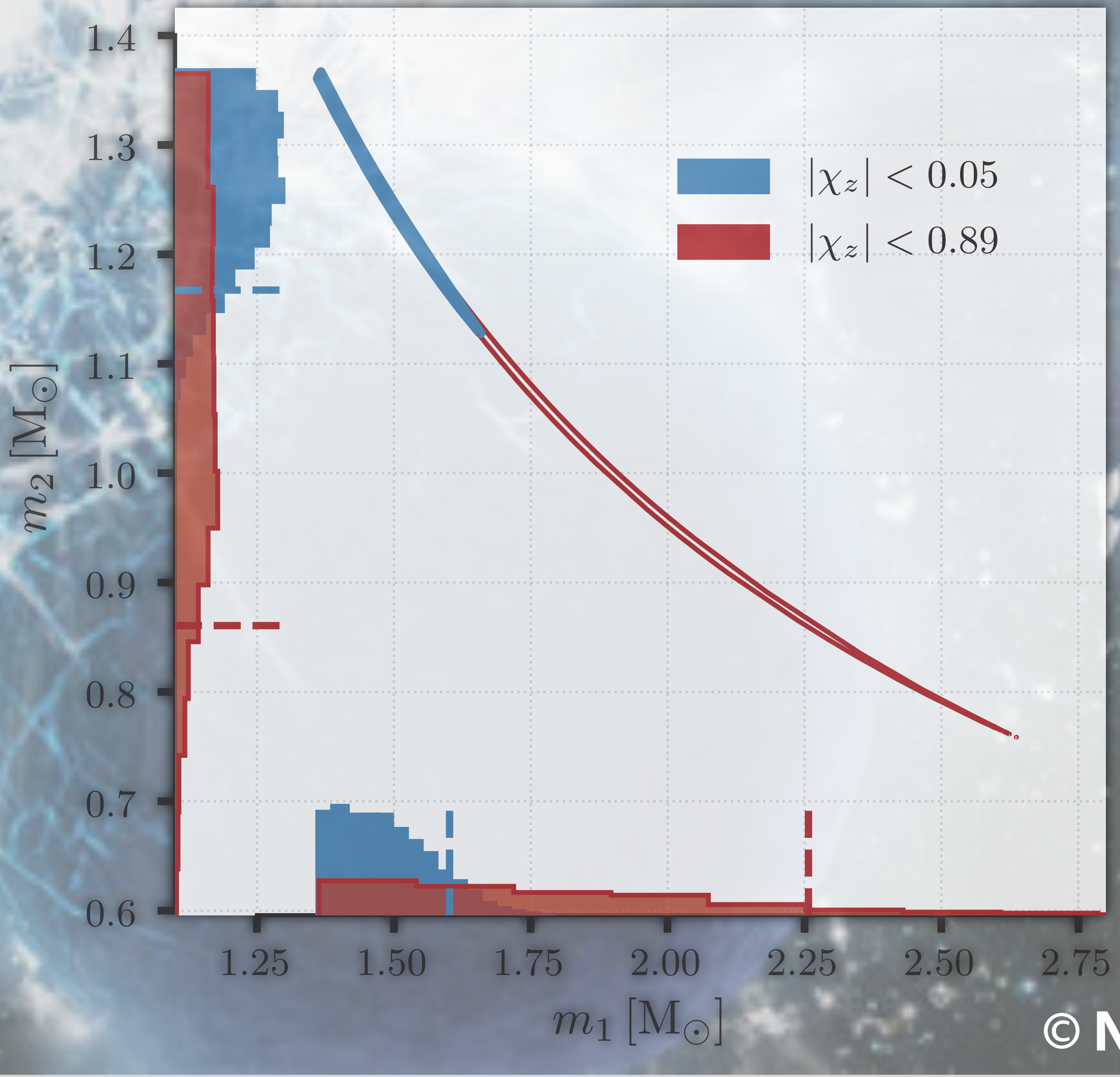
YITP (here)

Kyoto Station

GW170817: Death of neutron stars

LIGO-Virgo, PRL 119, 161101 (2017)





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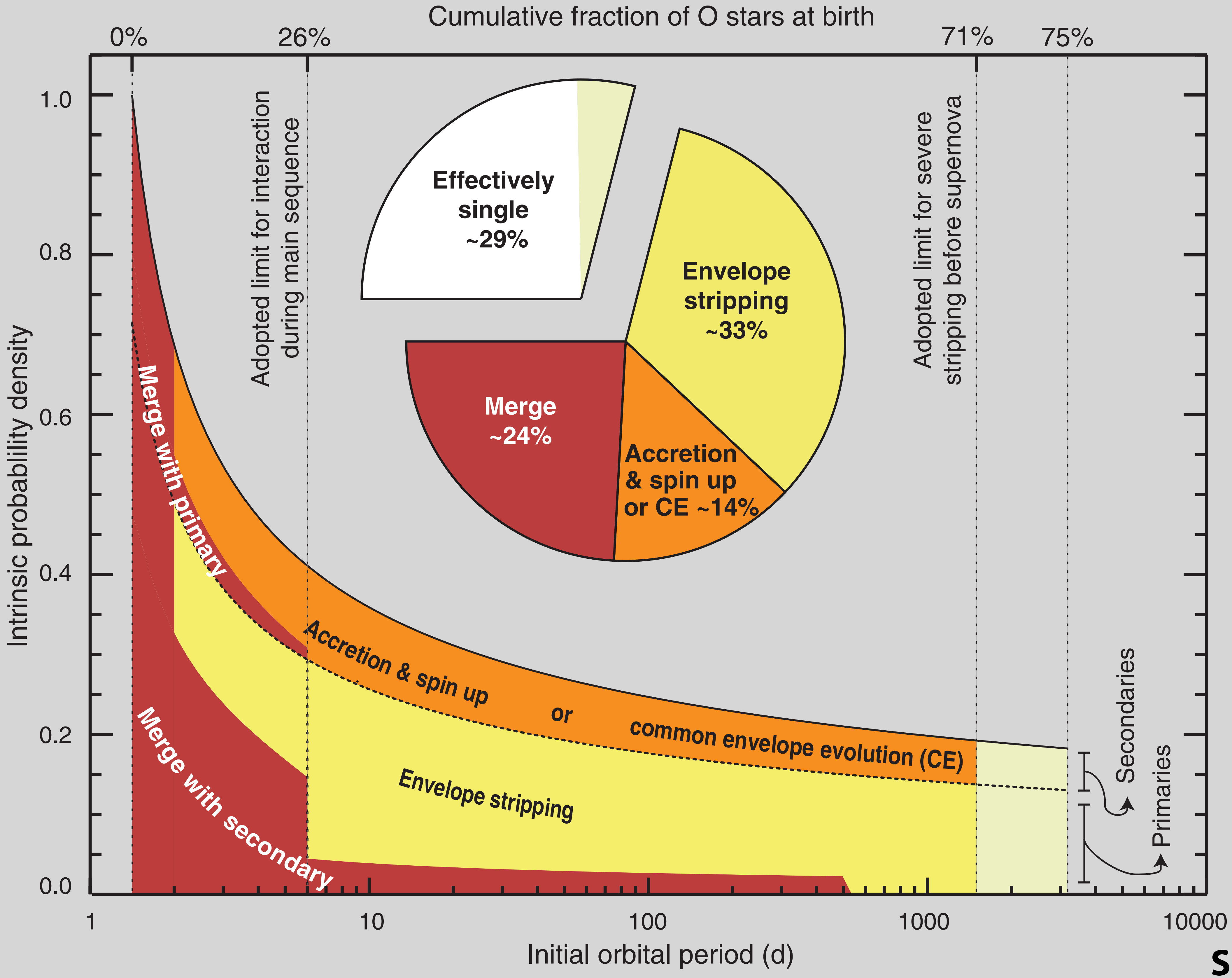
Fraction of interacting binary is high



Sana+ 2012

DNS

- **In the Galaxy, seven systems are expected to merge within cosmic age (~13.8Gyr=1.38×10^{10}yr)**
  - Merger time: 1.2×10^{8}yr $(a_0/10^{11}\mathrm{cm})^4(m/2.8M_\odot)^{-3}$

    → $a_0<3\times10^{11}$cm is needed for $t_{\mathrm{merge}}<13.8$Gyr

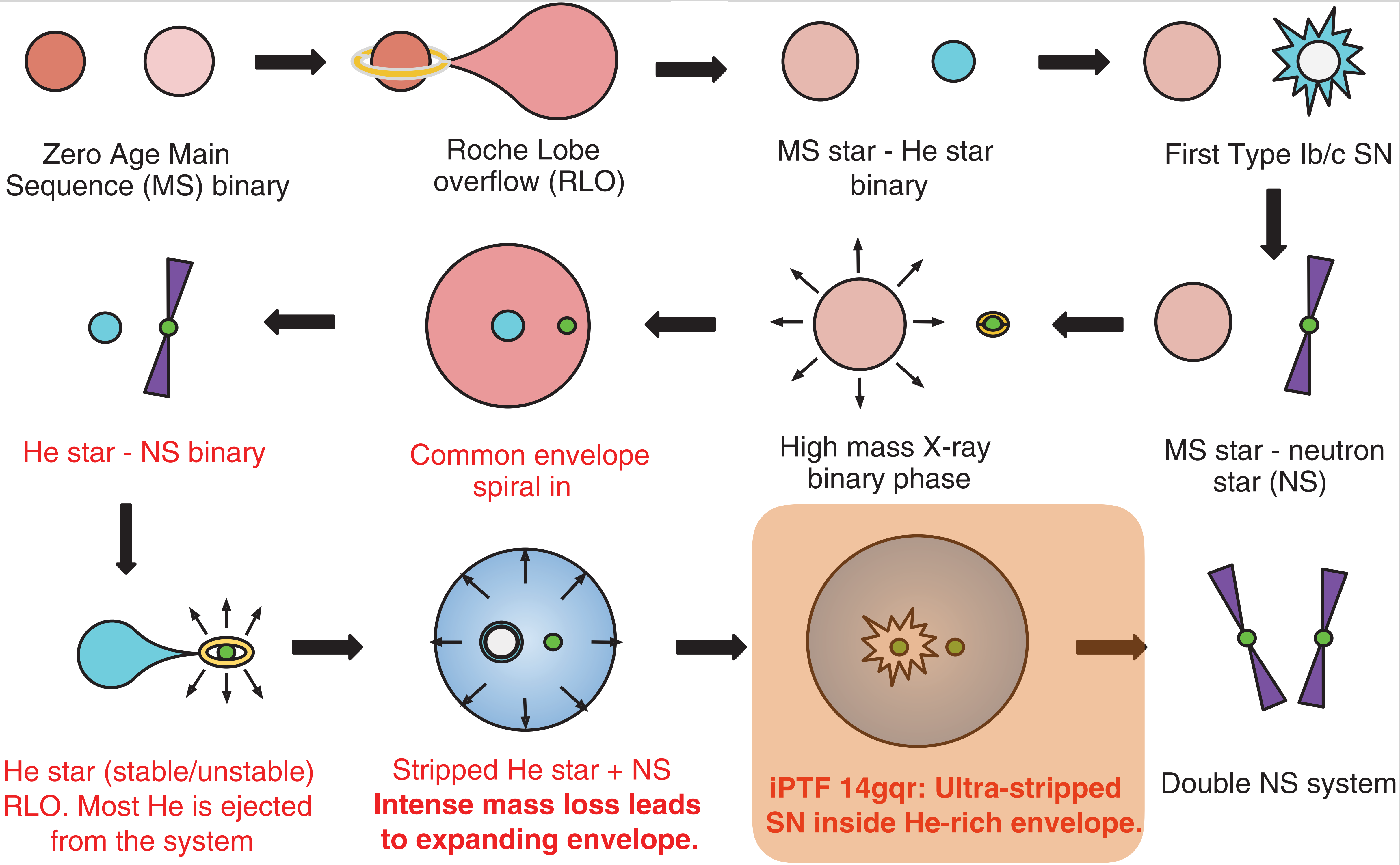
    NB) The distance of Sun-Earth is 1AU=1.5×10^{13}cm, $R_\odot=7\times10^{10}$cm

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

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

1. SNe in 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

MS star - neutron star (NS)

High mass X-ray binary phase

Common envelope spiral in

He star - NS binary

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?

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

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

Ultra-stripped supernovae: progenitors and fate

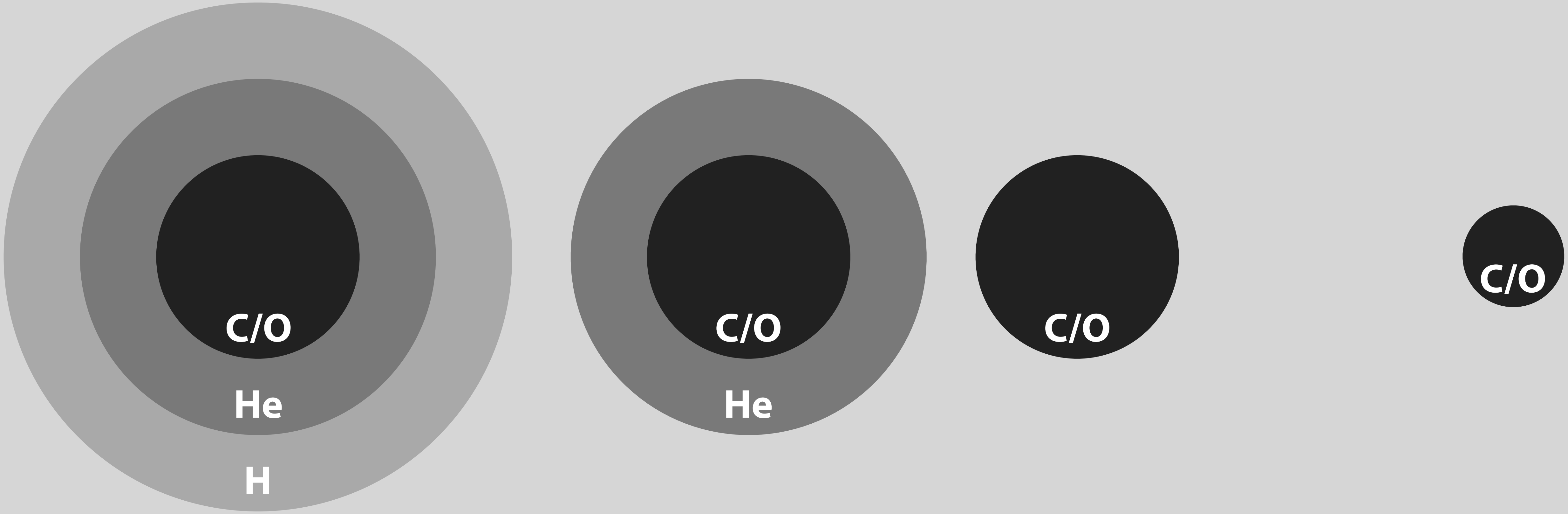
Thomas M. Tauris,[1,2]★ Norbert Langer[1] and Philipp Podsiadlowski[3]

- *“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.”*

see Thomas’s talk in YKIS19

http://www2.yukawa.kyoto-u.ac.jp/~mmgw2019/slide/3rd/Tauris.pdf

Ultra-stripped supernovae?



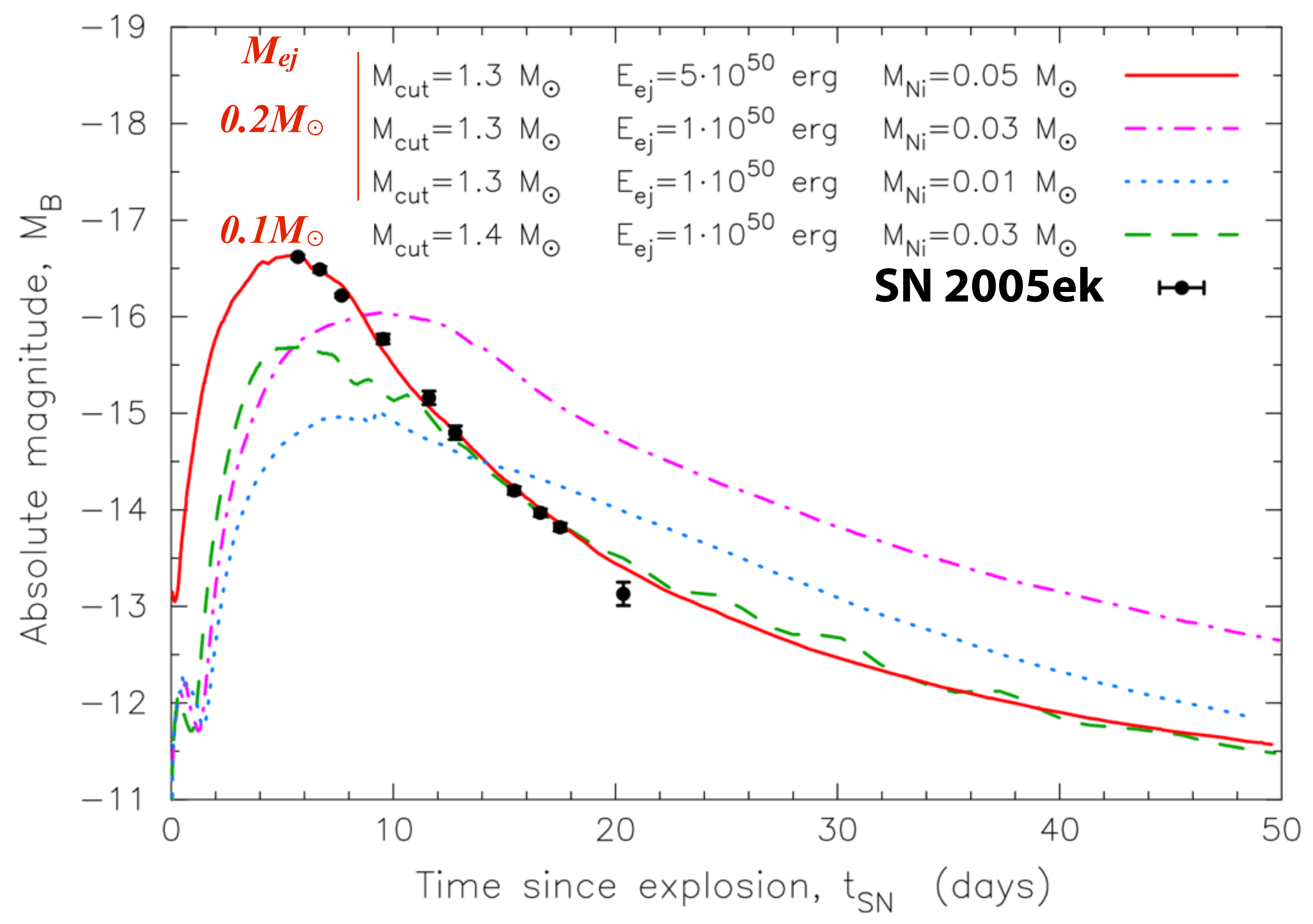
$M_{\rm total}\sim10M_\odot$ $M_{\rm CO}\sim3M_\odot$

$M_{\rm total}\sim5M_\odot$ $M_{\rm CO}\sim3M_\odot$

$M_{\rm total}\sim M_{\rm CO}\sim1.5M_\odot$

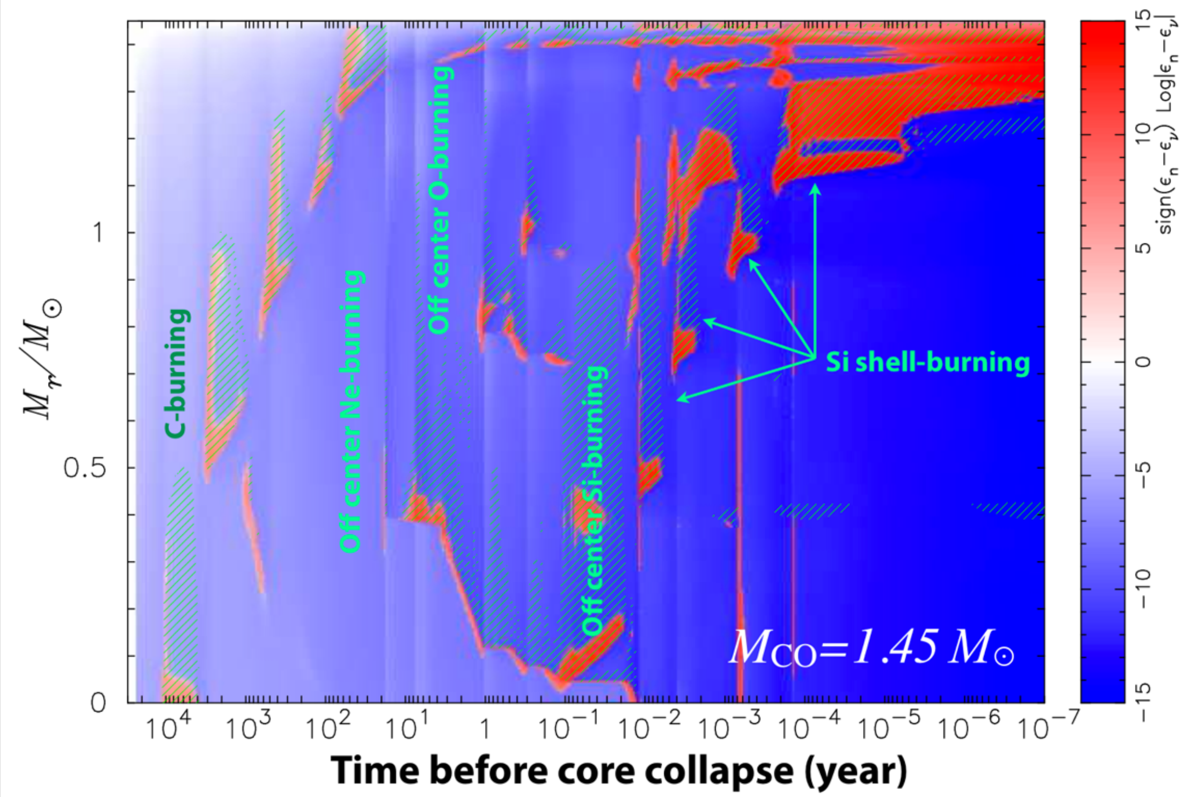
Small ejecta mass

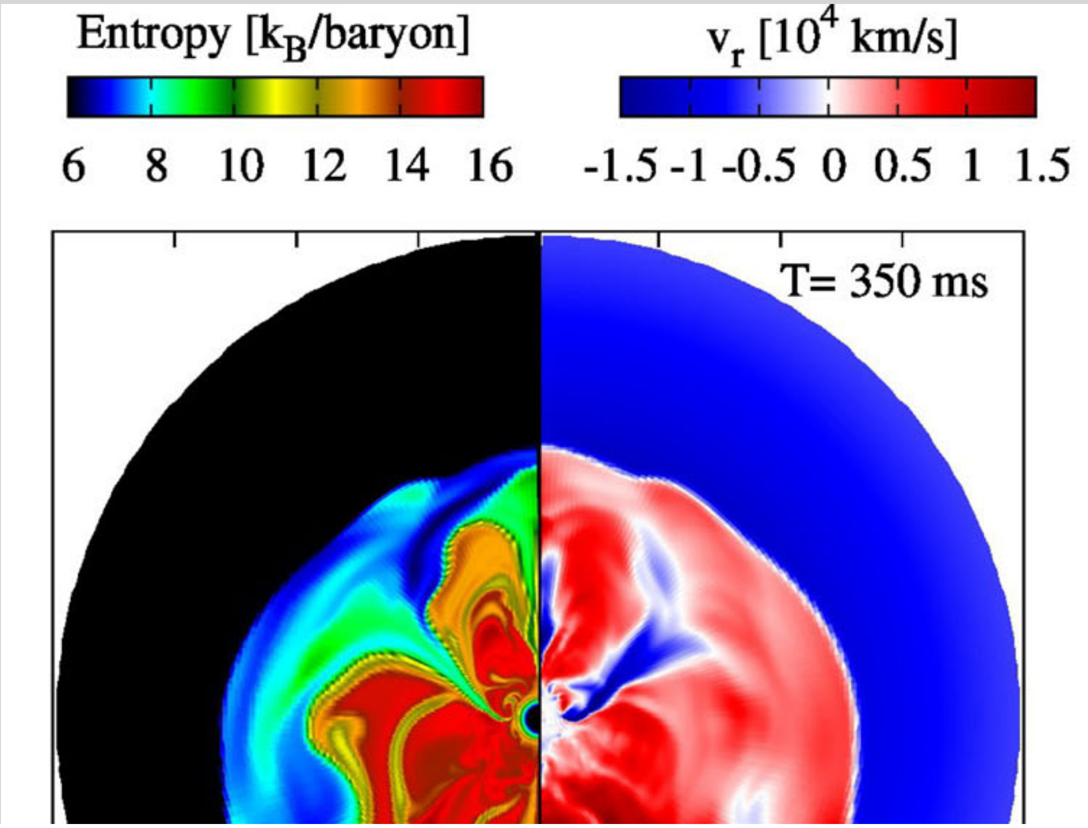
Tauris, Langer, Moriya, Podsiadlowski, Yoon, Blinnikov 2013

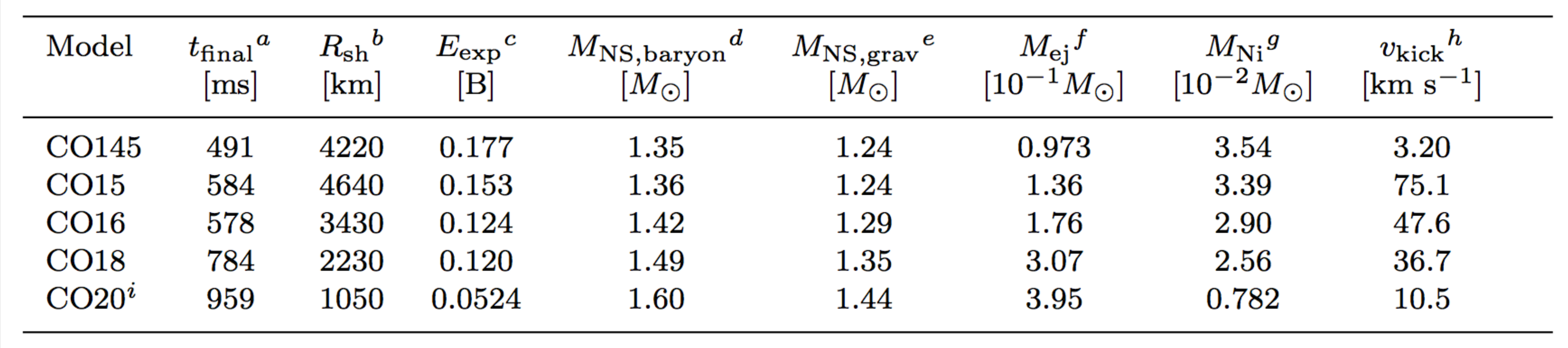


Neutrino-driven explosions of ultra-stripped SN

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







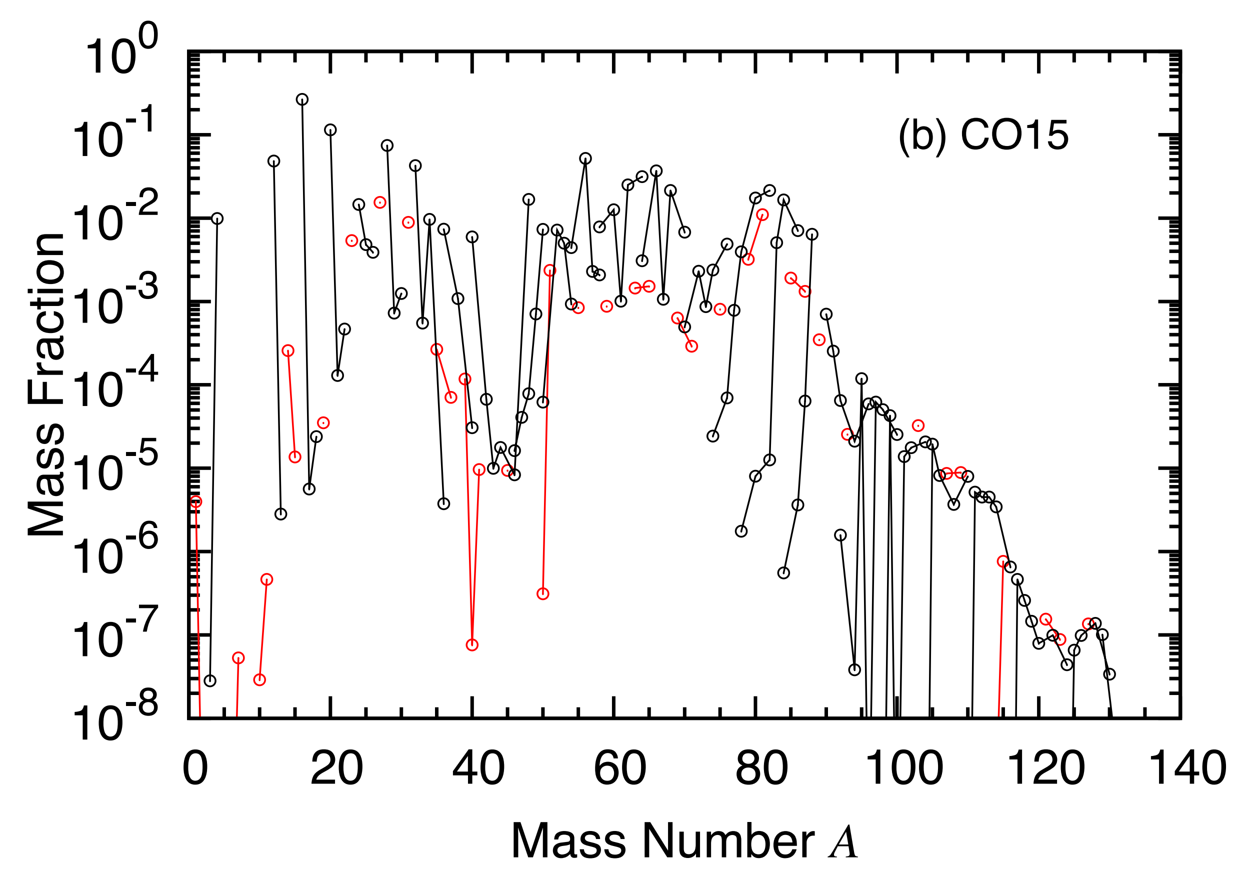
Model	$t_{\rm final}{}^a$ [ms]	$R_{\rm sh}{}^b$ [km]	$E_{\rm exp}{}^c$ [B]	$M_{\rm NS,baryon}{}^d$ [$M_\odot$]	$M_{\rm NS,grav}{}^e$ [$M_\odot$]	$M_{\rm ej}{}^f$ [$10^{-1}M_\odot$]	$M_{\rm Ni}{}^g$ [$10^{-2}M_\odot$]	$v_{\rm kick}{}^h$ [km s^{-1}]
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	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

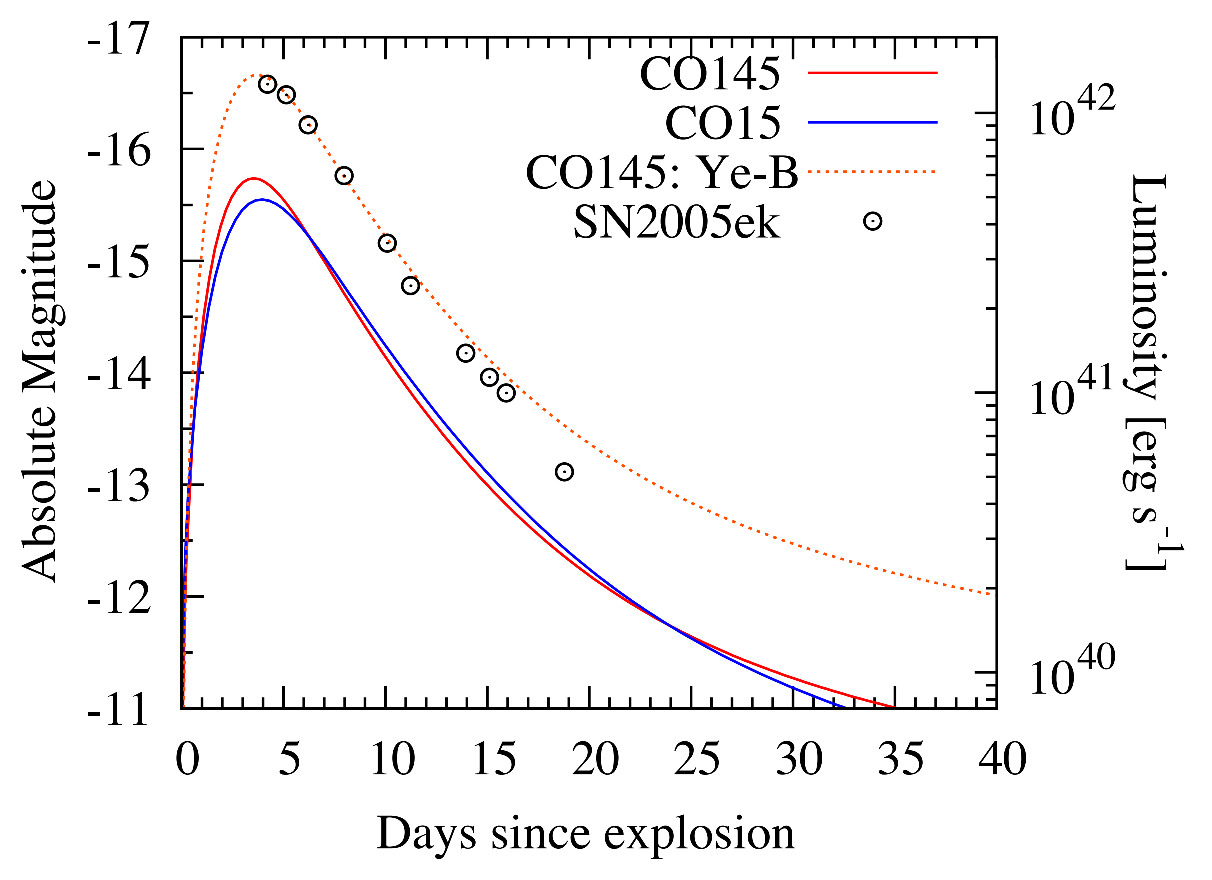
Ejecta mass~*$O(0.1)M_\odot$*, NS mass~*$1.4\,M_\odot$*, explosion energy~*$O(10^{50})$* erg, Ni mass~*$O(10^{-2})\,M_\odot$*; everything compatible w/ Tauris+ 2013

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

iPTF 14gqr / SN2014ft

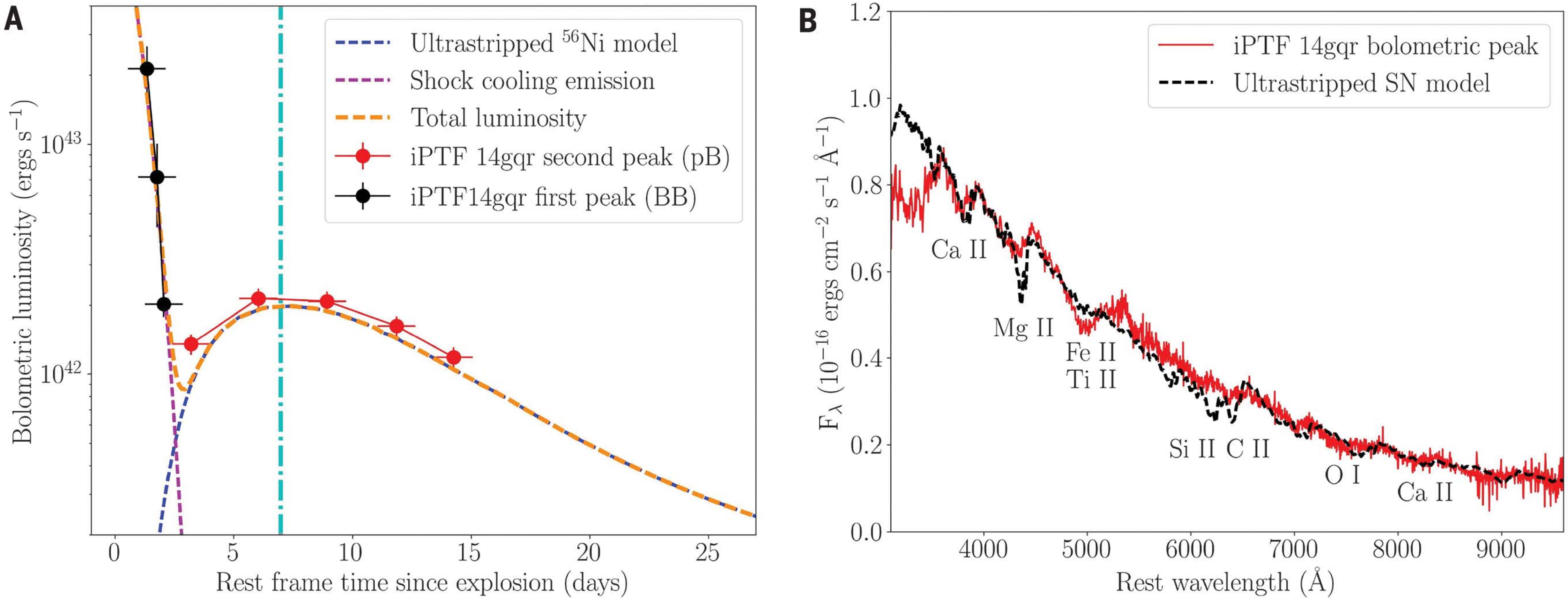
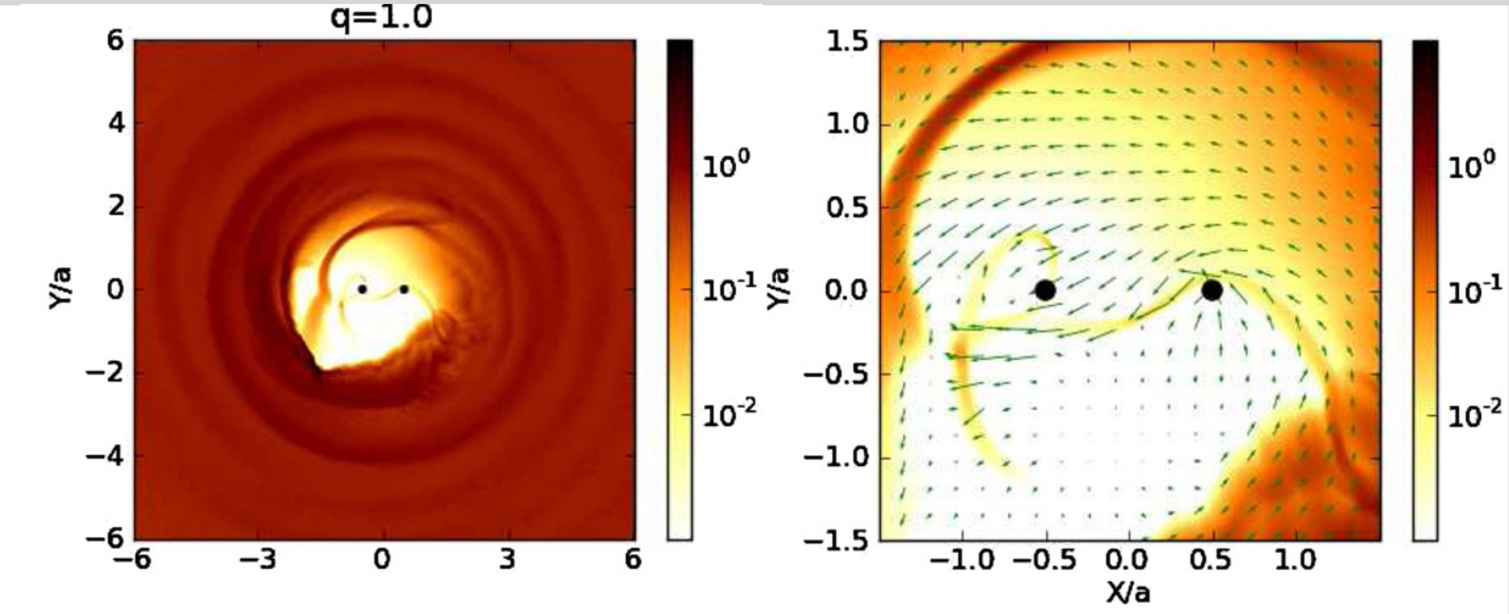
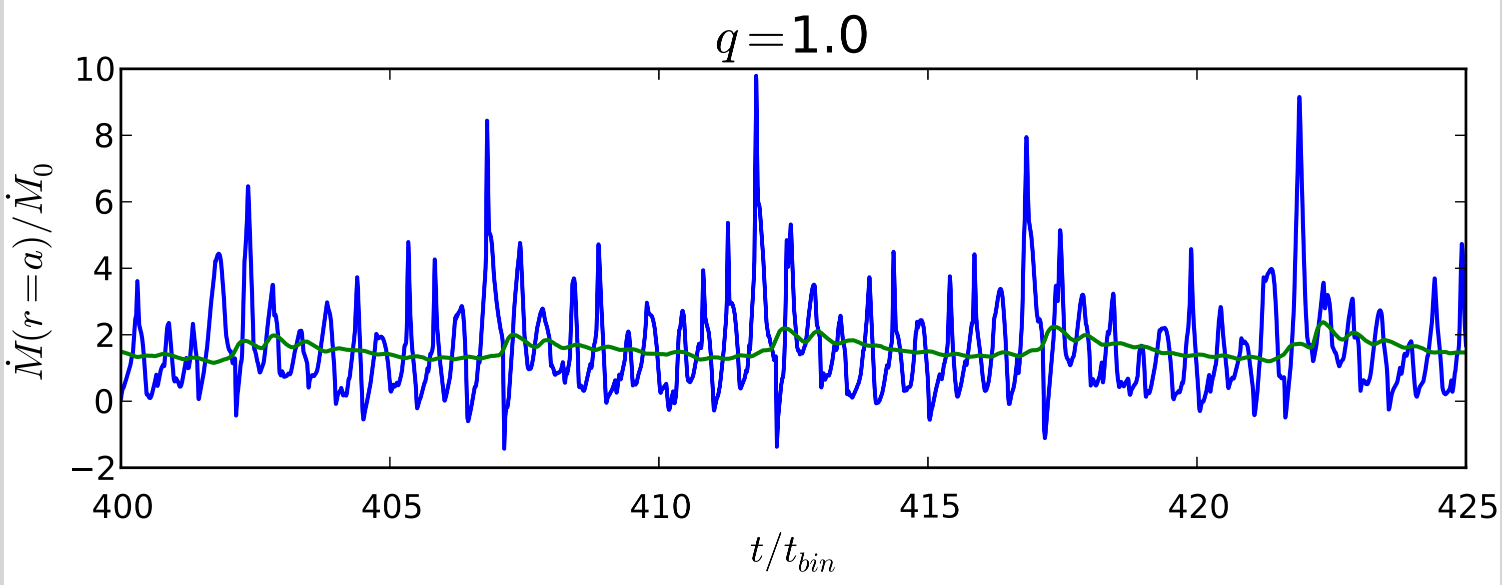


Fig. 5. Comparison of iPTF 14gqr to theoretical models of ultra-stripped SNe. (**A**) Bolometric light curve of iPTF 14gqr shown with a composite light curve consisting of ultra-stripped type Ic SN models (*28*) and early shock-cooling emission (*25*). The blue dashed line corresponds to the ^{56}Ni 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

How to confirm binarity?: time variability

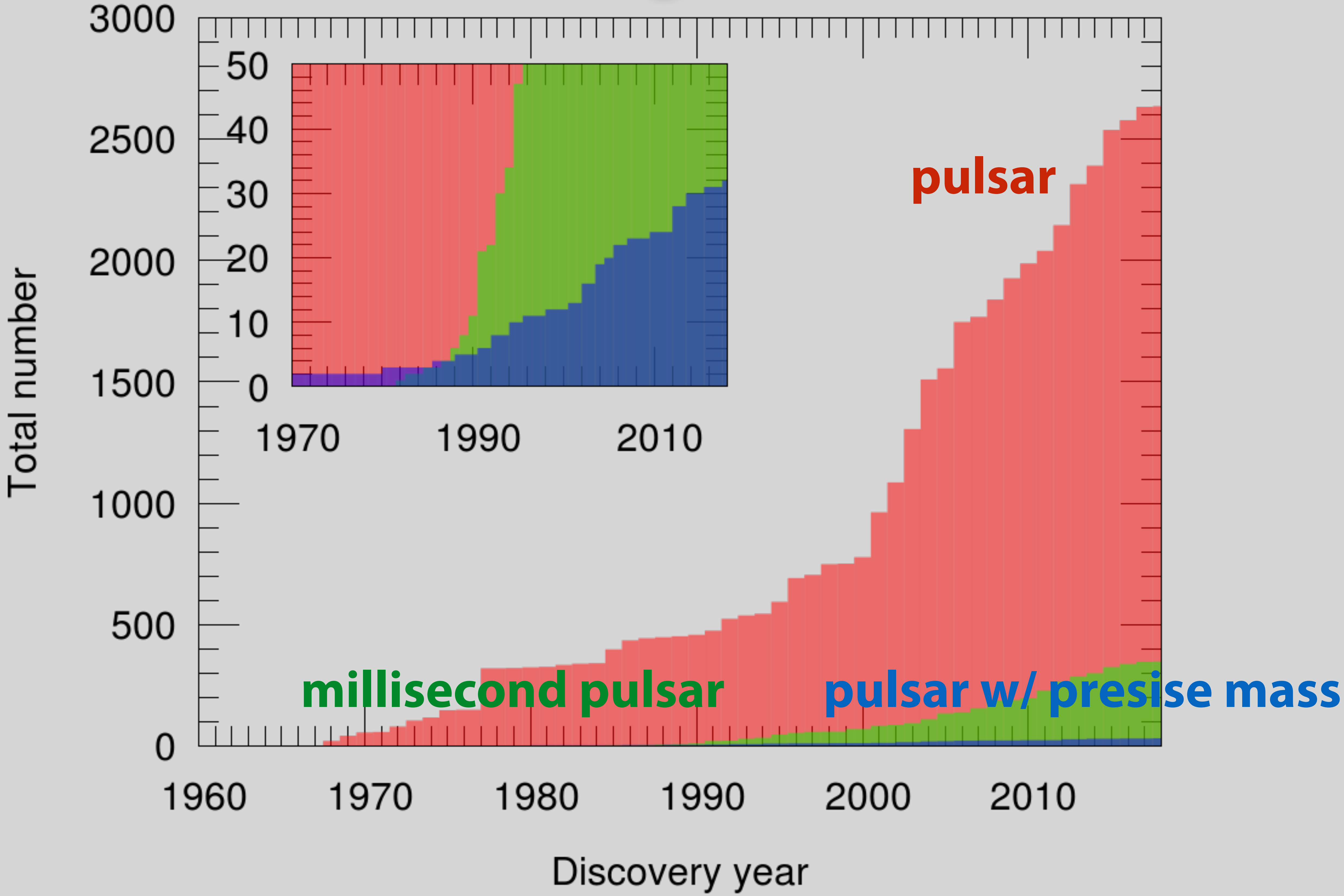




Farris et al. 2014

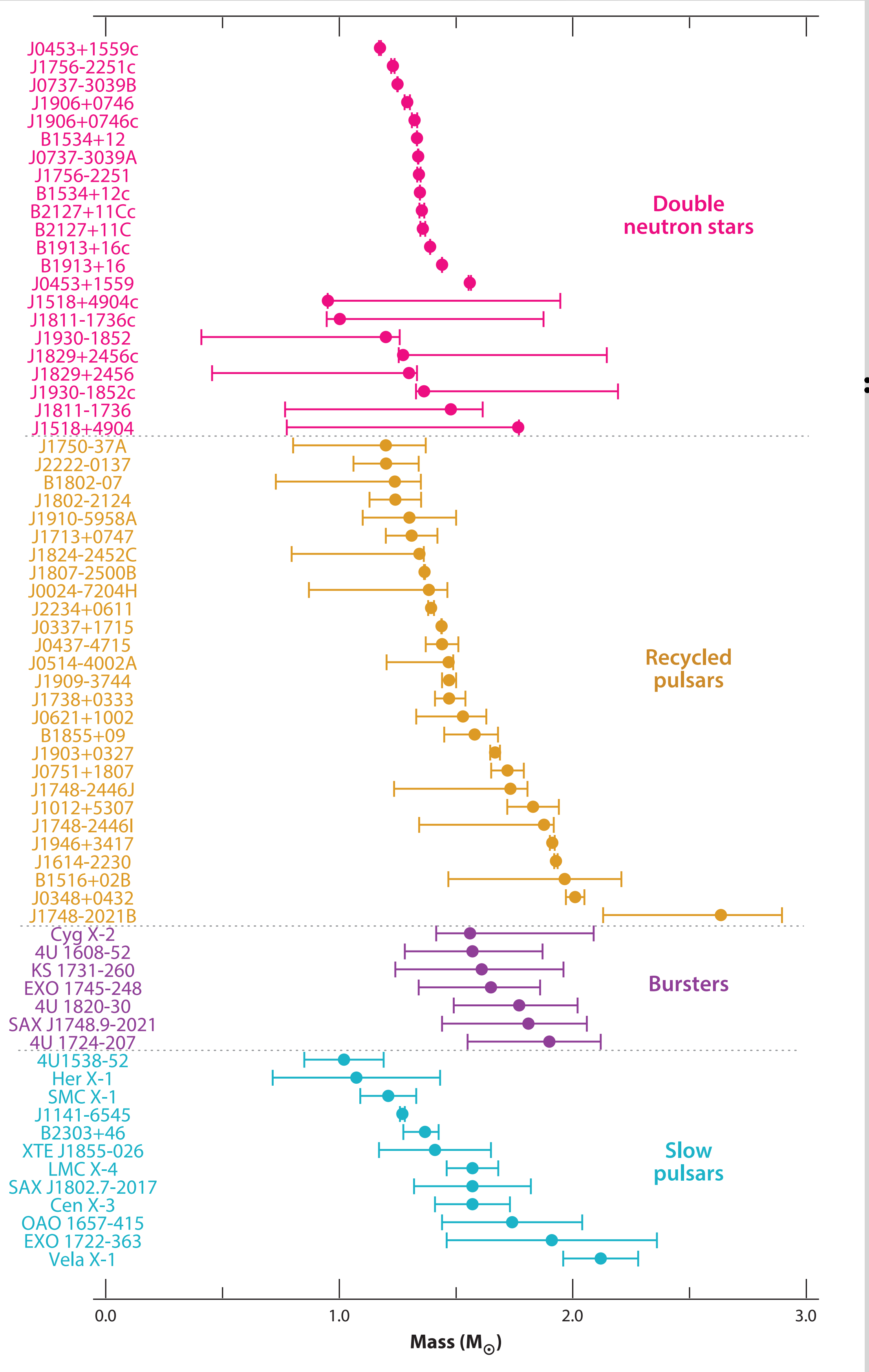
2. Minimum NS mass in binary systems

Pulsar number is increasing

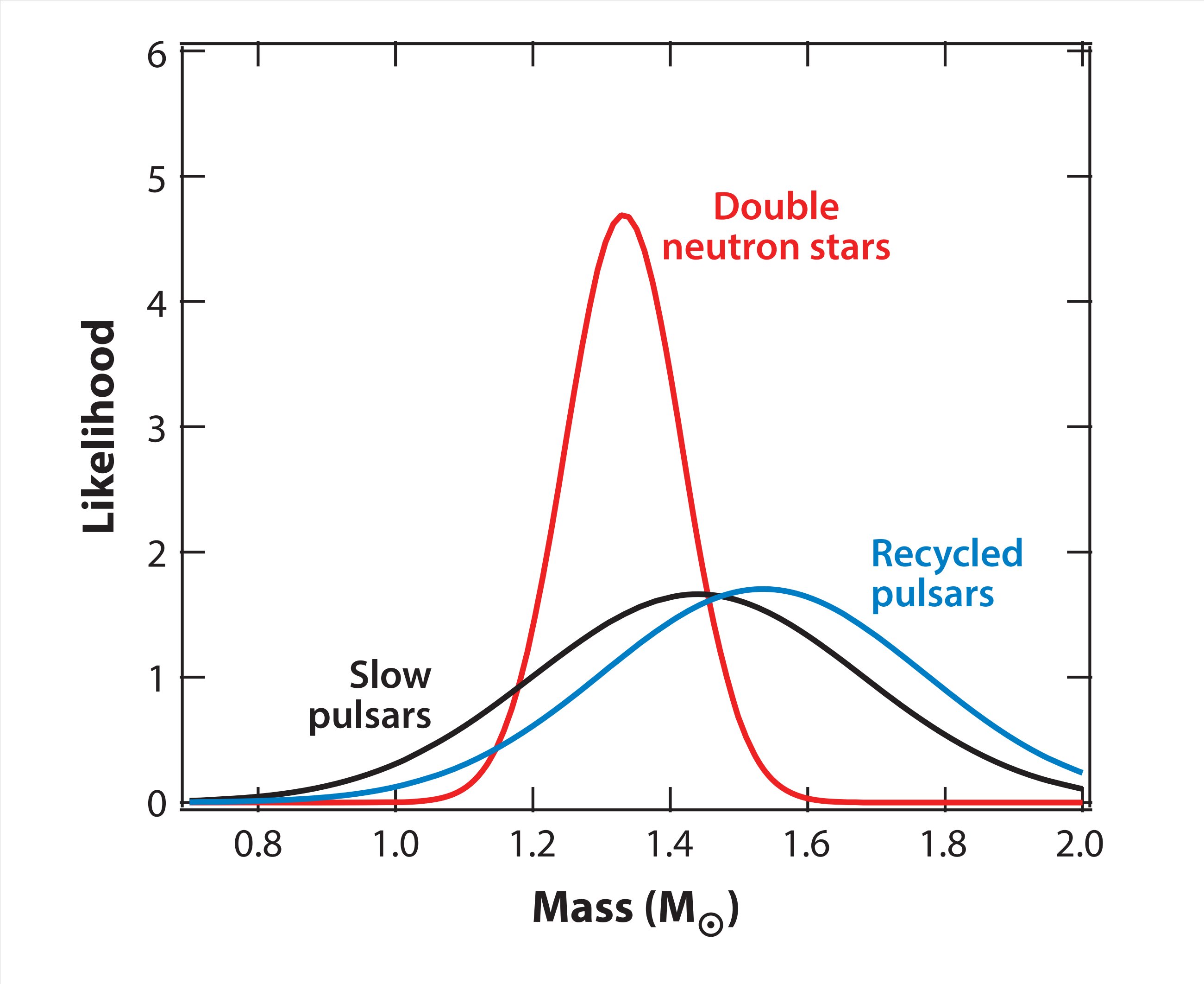


compiled data from ATNF pulsar catalog and P. Freire's table

NS mass measurements



Özel & Freire 2016

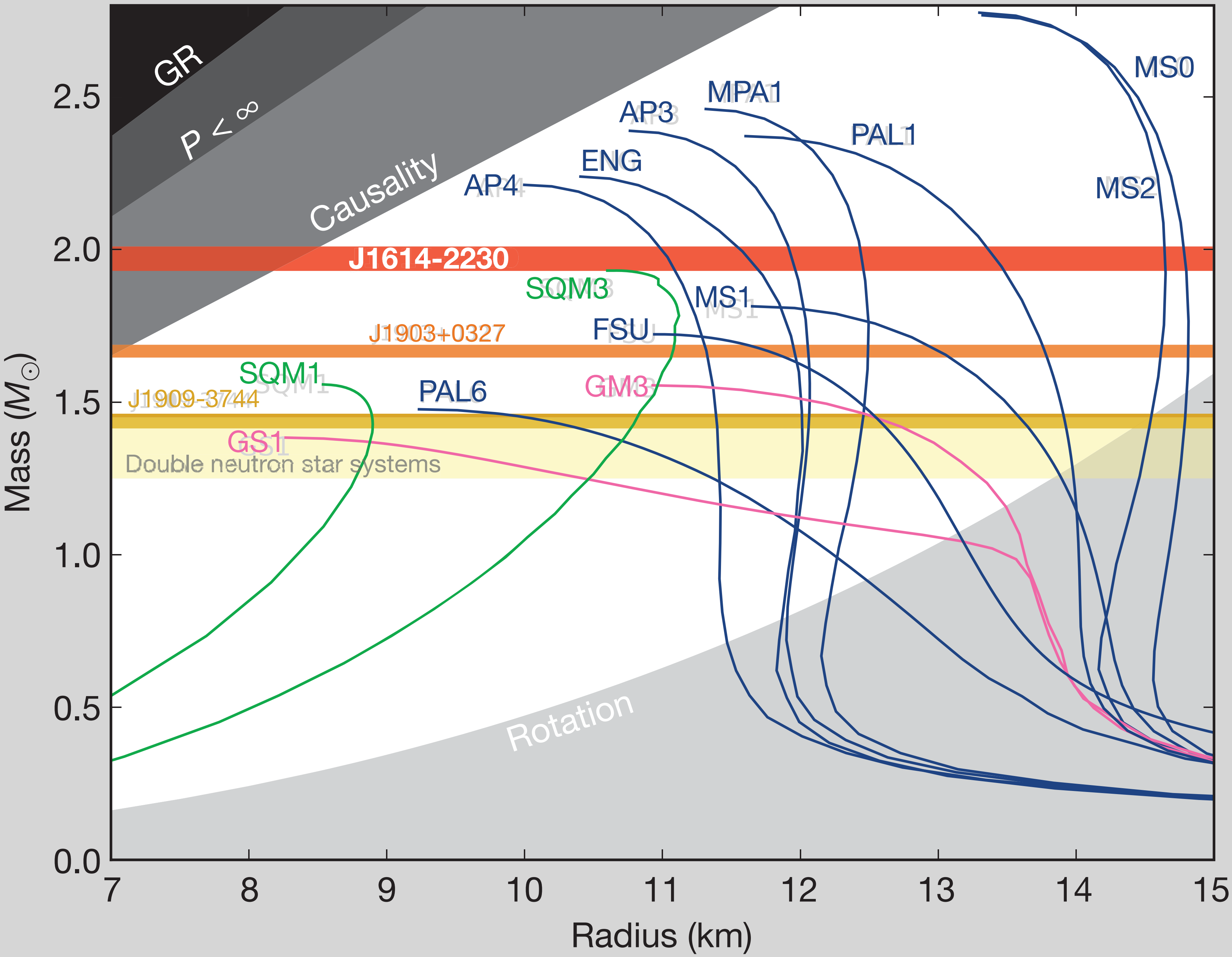


- **>2700 pulsars have been found in the Galaxy**
- **10% in the binary system**
  →mass measurement possible
  - **15 double NSs so far** [Tauris+ 2017]

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

Massive NSs tell us nuclear physics

Demorest+ 2010



←$1.97 \pm 0.04 M_\odot$

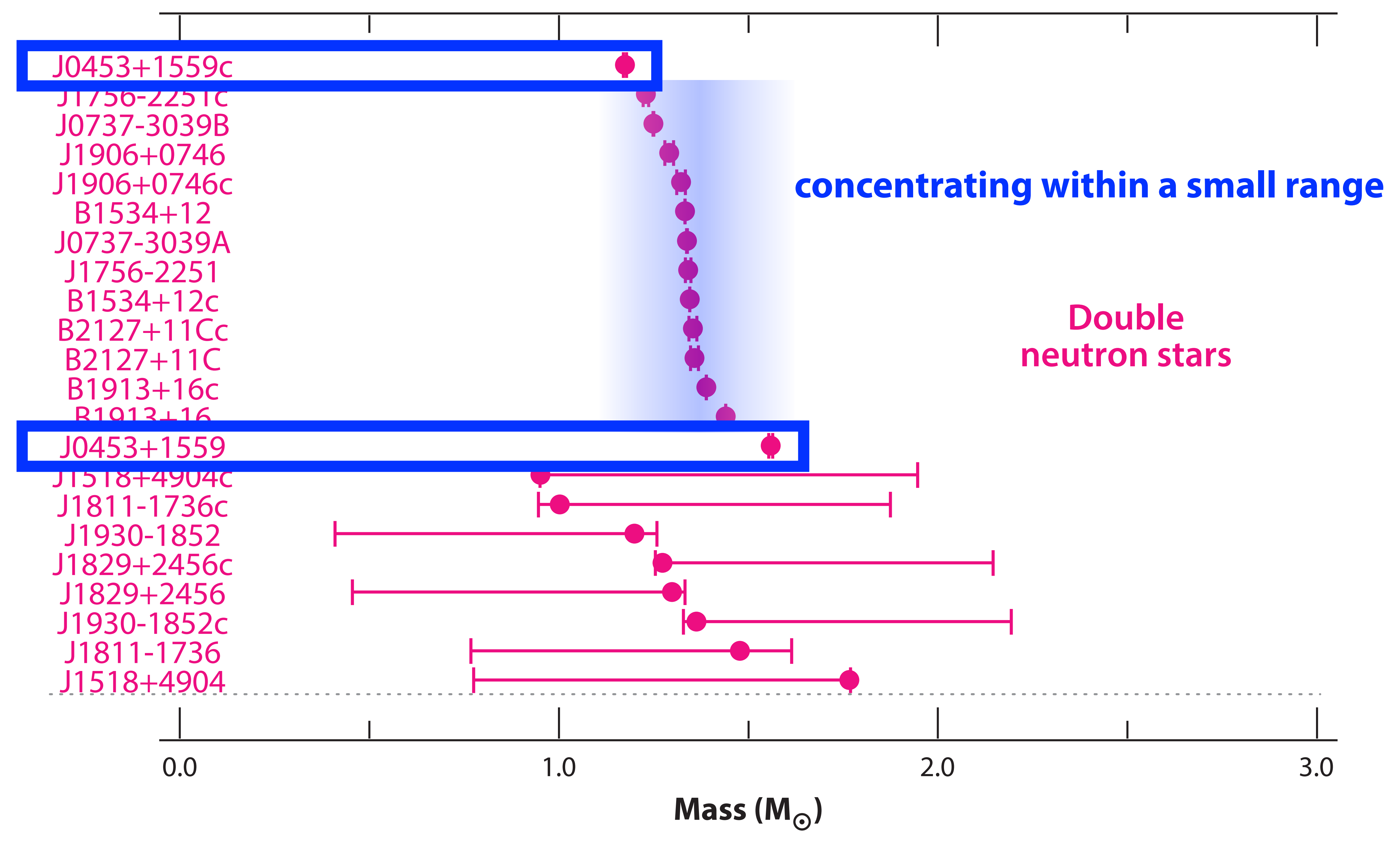
NB) mass estimation was updated by Arzoumanian+ 2018 as $1.908 \pm 0.016 M_\odot$

Other massive NSs were reported by Antoniadis+ (2013), J0348+0432, $2.01 \pm 0.04 M_\odot$ by Cromartie+ (2019), J0740+6620, $2.14 \pm 0.1 M_\odot$

How about low-mass one?

Double NSs

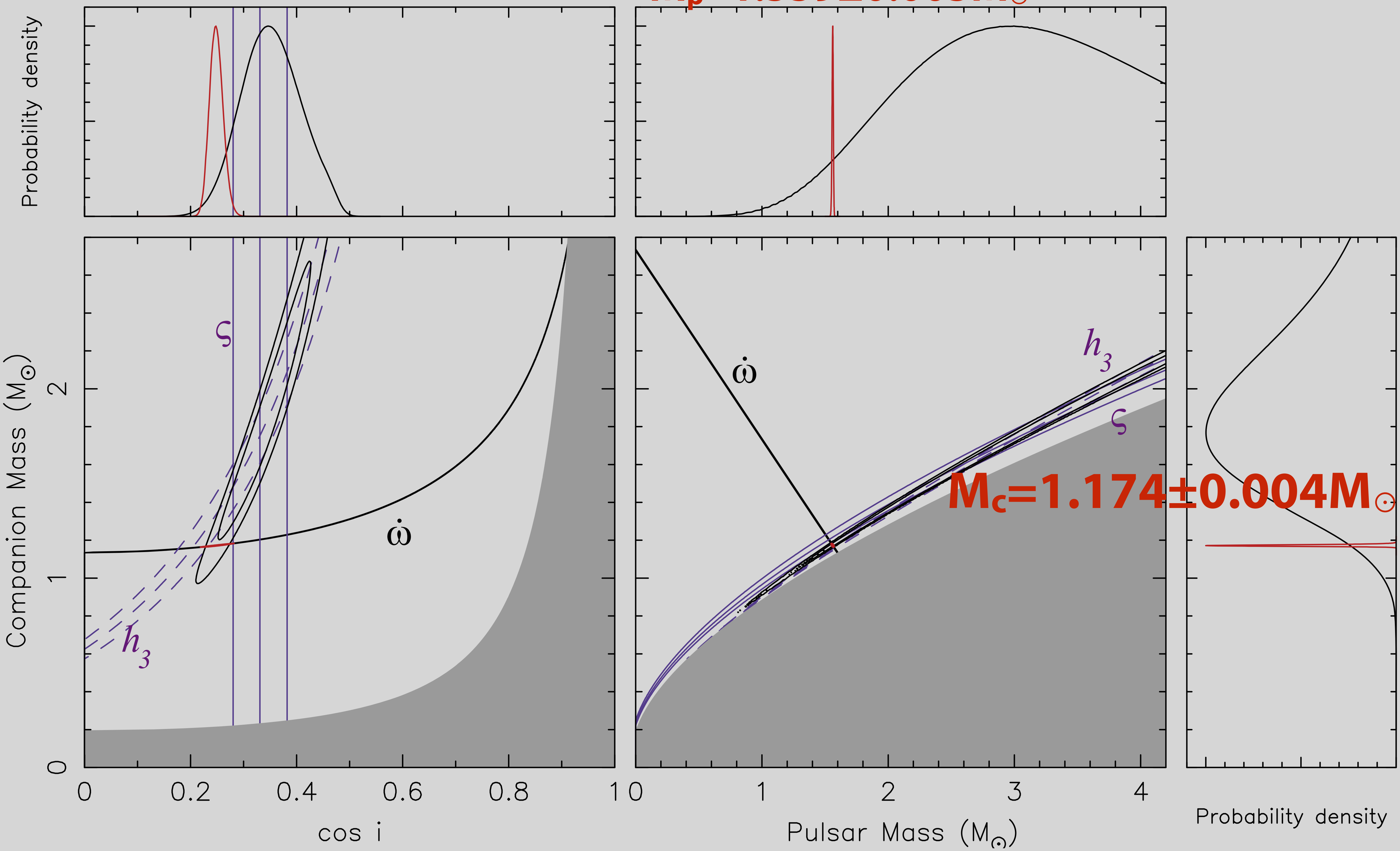
Özel & Freire 2016



First asymmetric DNS system

Martinez+ 2015

$M_p = 1.559 \pm 0.005 M_\odot$



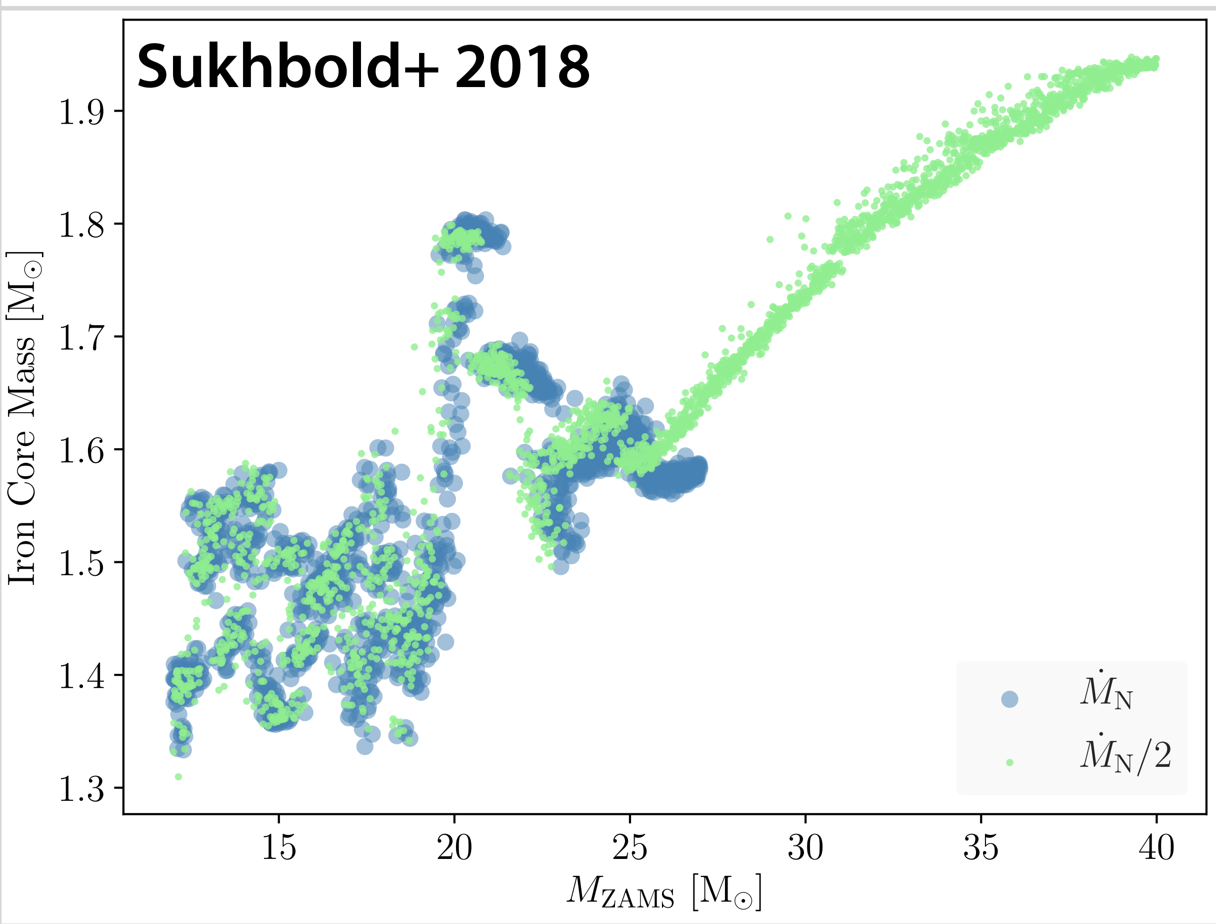
$M_c = 1.174 \pm 0.004 M_\odot$

A low-mass NS

- **M_{NS}=1.174$M_\odot$!** (NB, it's gravitational mass, while 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

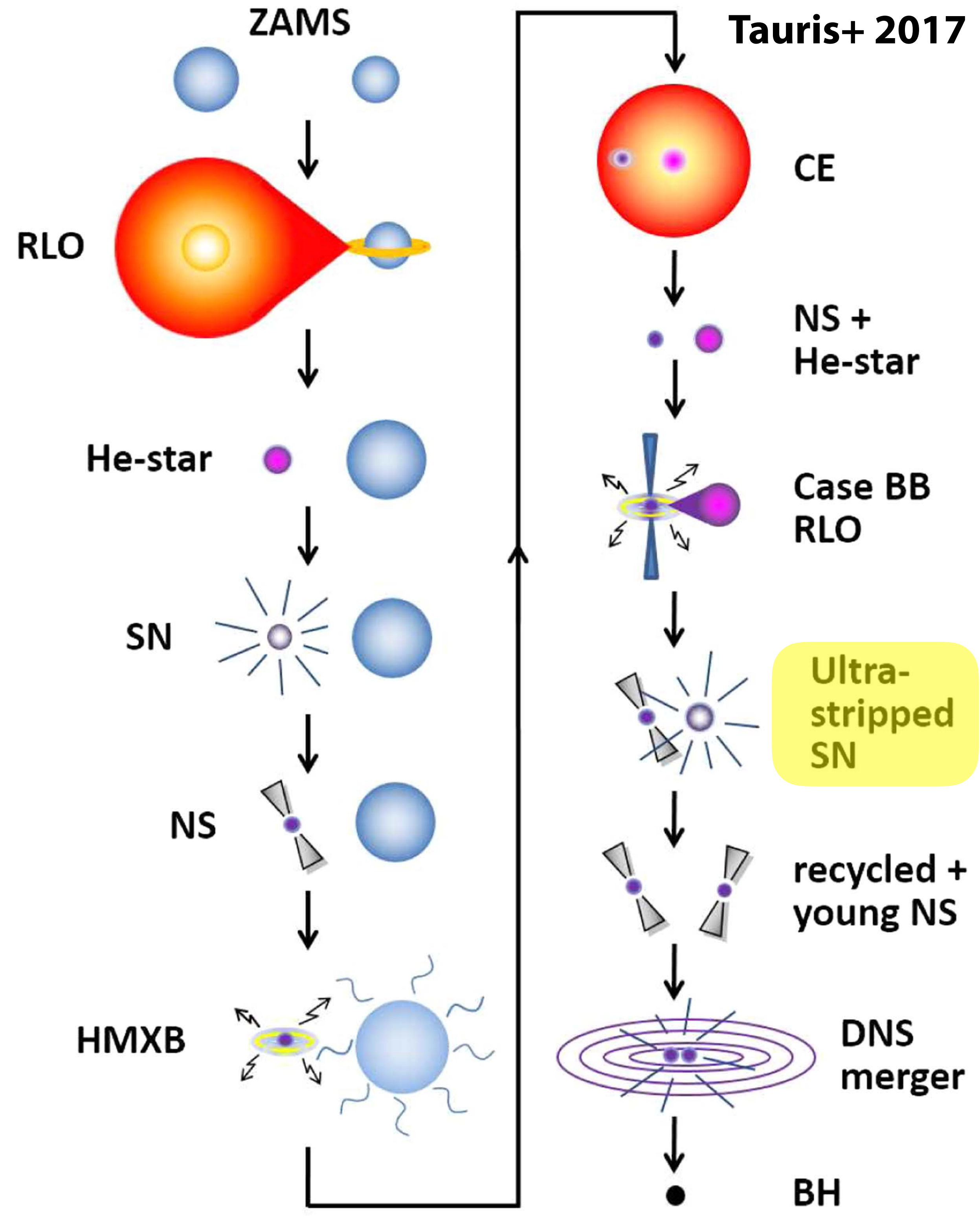
- **How to make it?**
  - a small iron core of massive star? (typically M_{Fe}~1.4–1.8$M_\odot$)

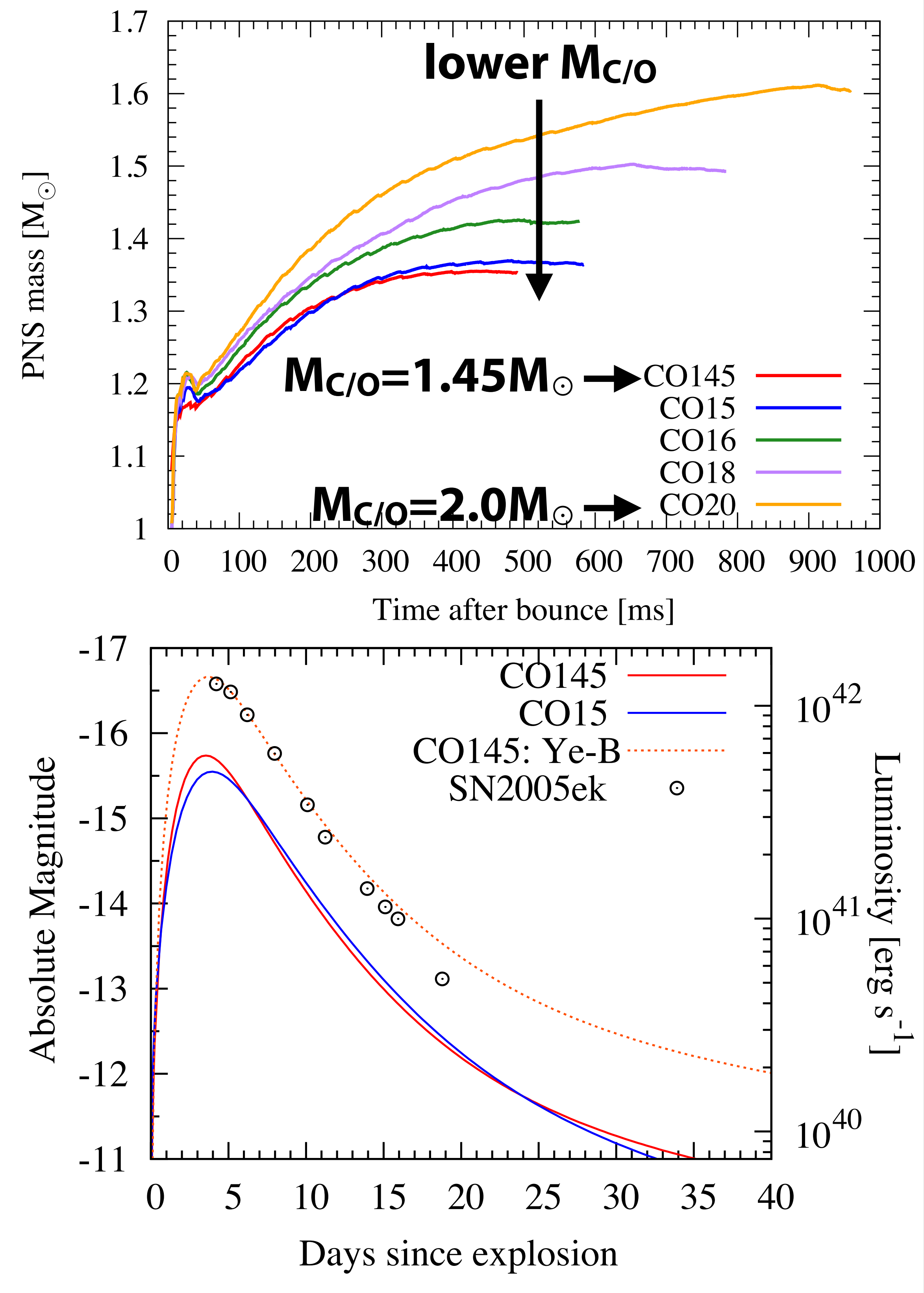


but see also Tauris & Janka, arXiv:1909.12318

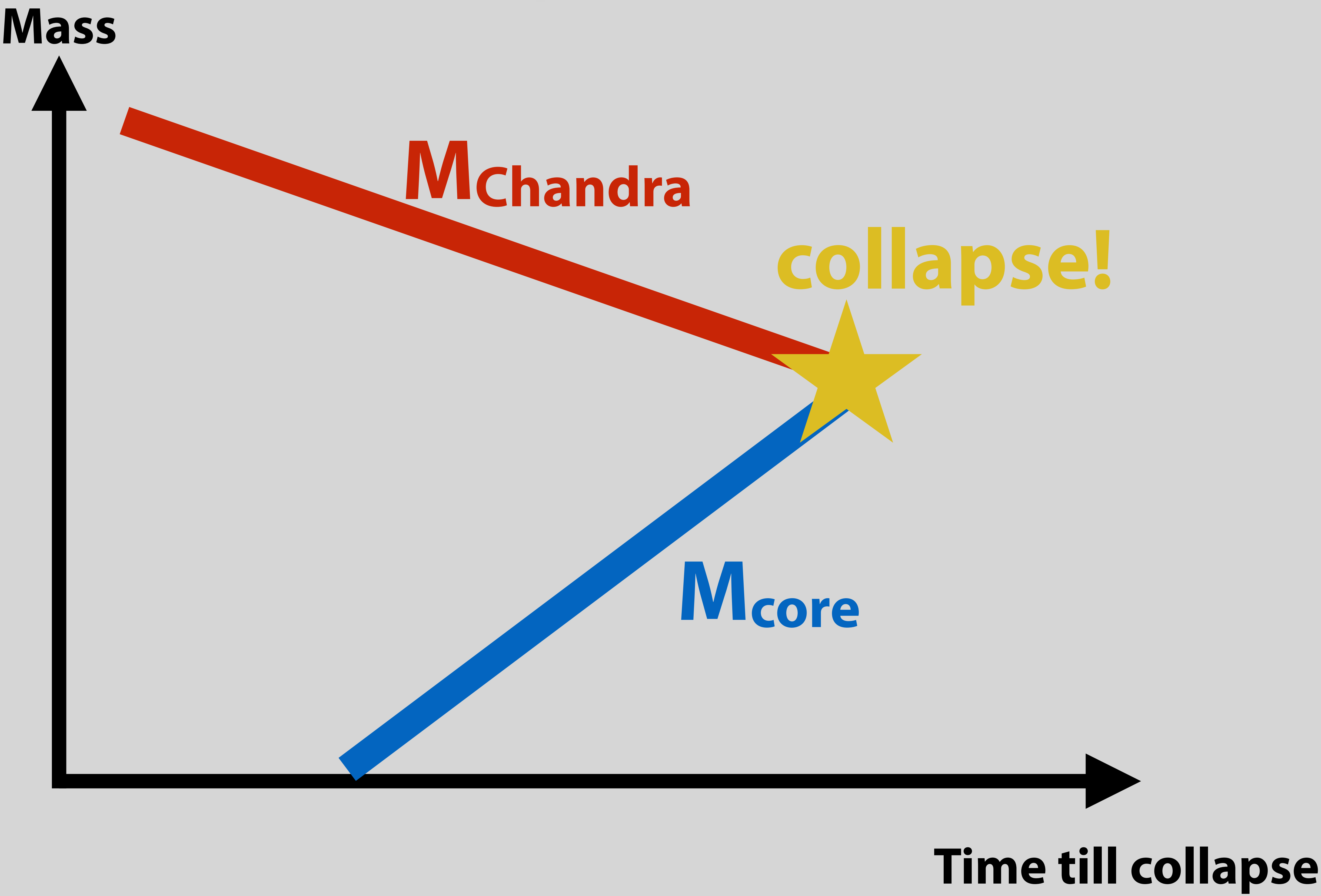
A path toward a low mass NS?: Ultra-stripped SN

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





When does a core collapse?



Modified Chandrasekhar mass

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

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

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

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

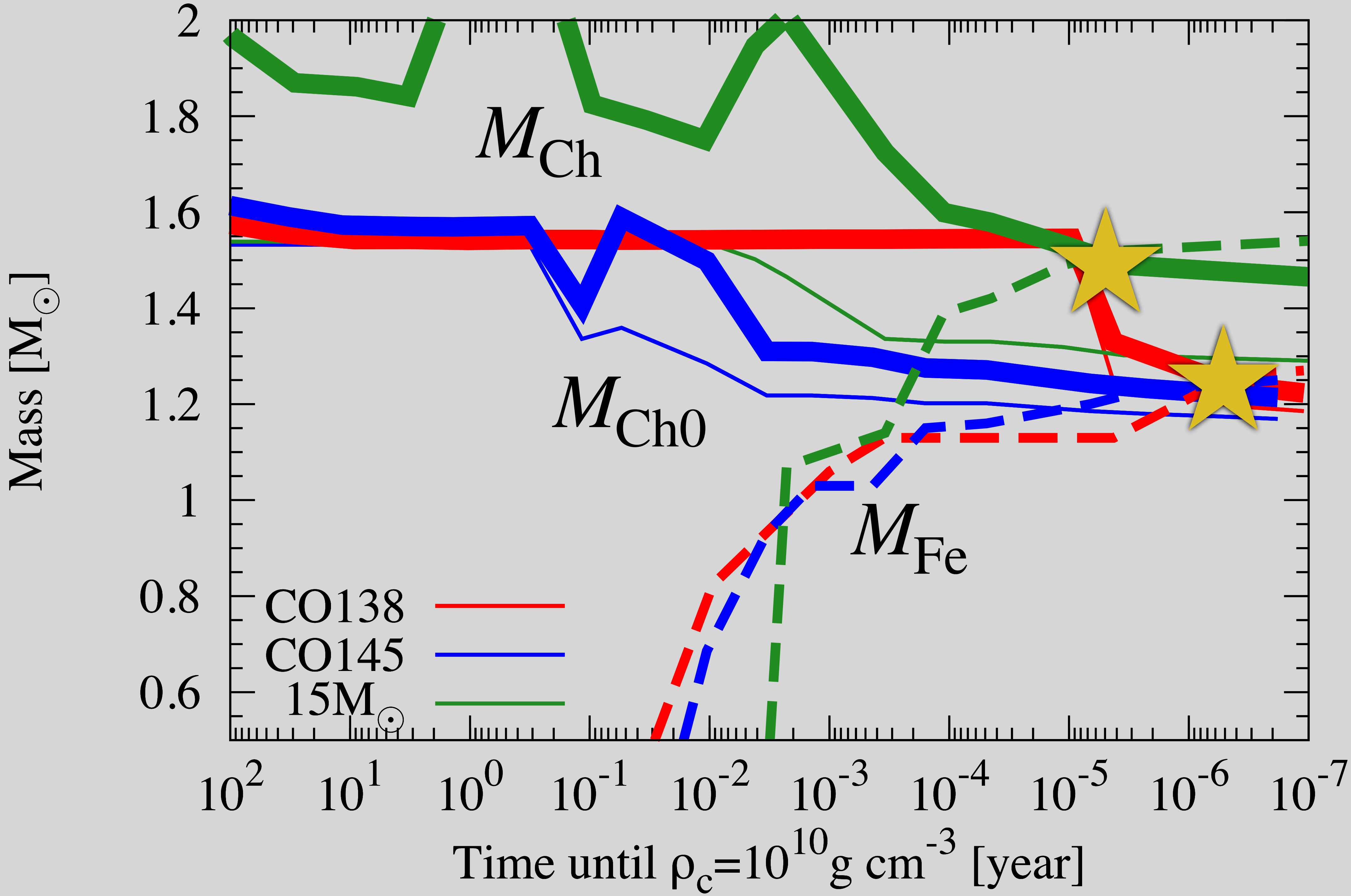
$$s_e = 0.5\rho_{10}^{-1/3}(Y_e/0.42)^{2/3}T_{\rm MeV}$$

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

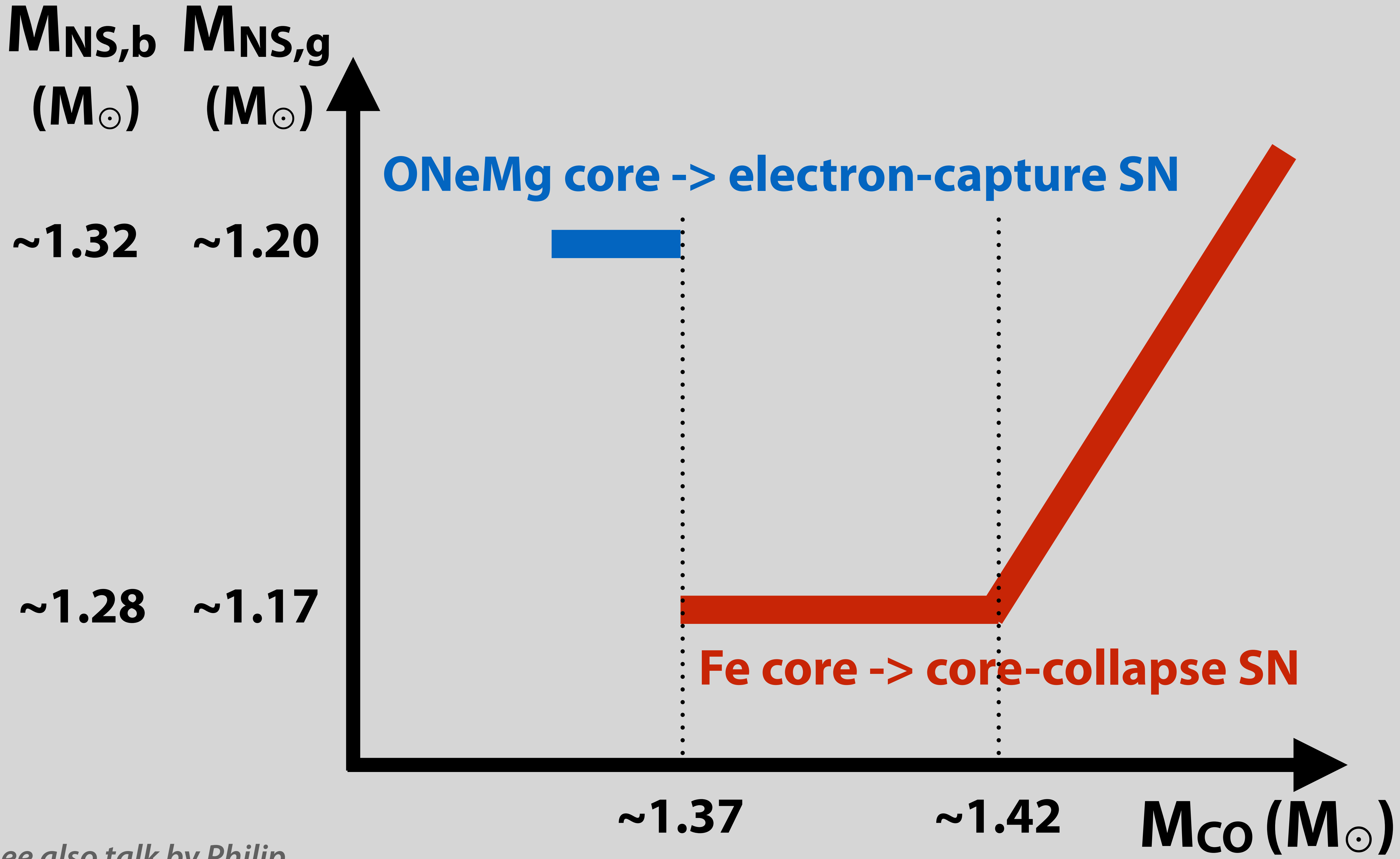
- **Neutrino-radiation hydro. sim**

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



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.