超新星爆発と連星系

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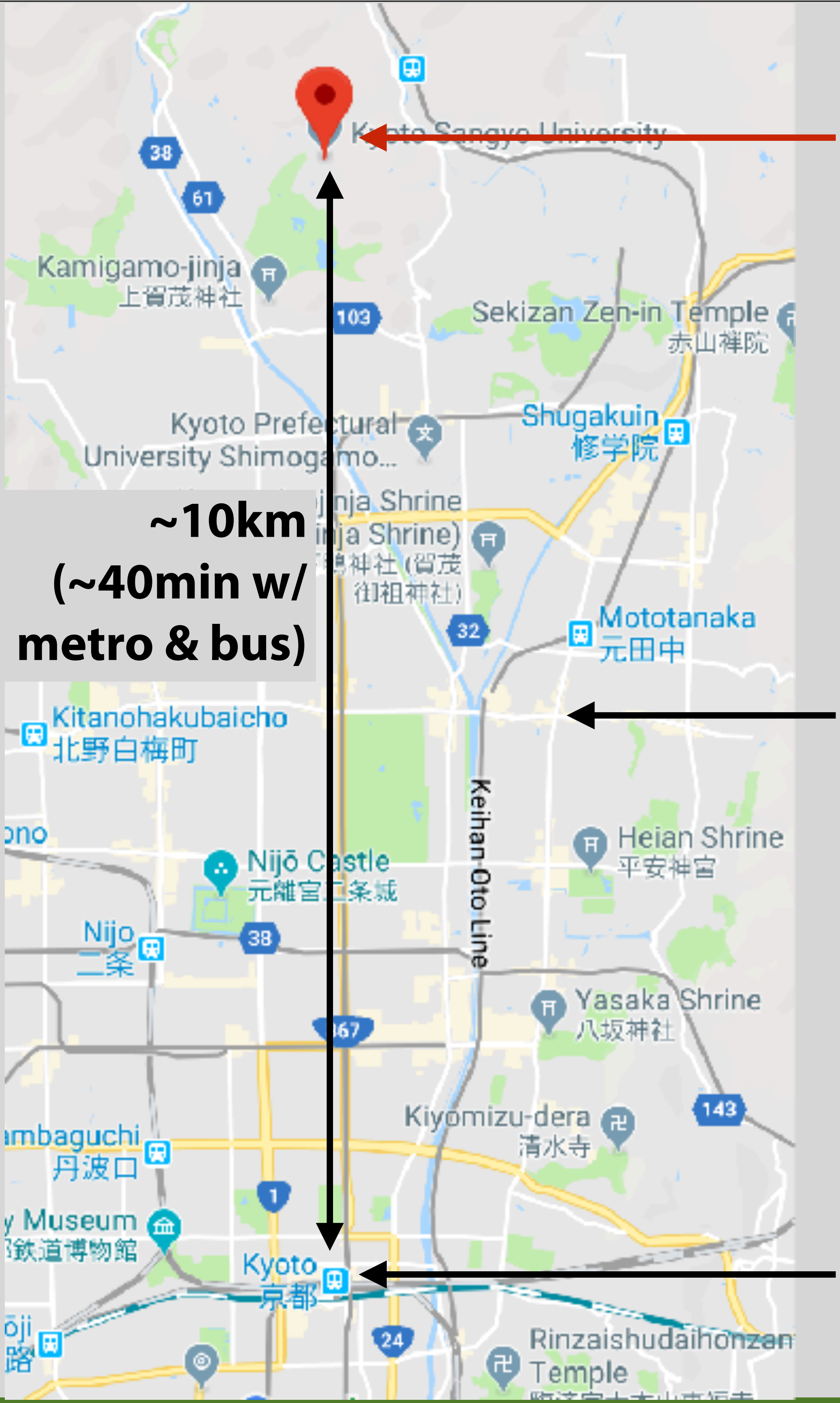


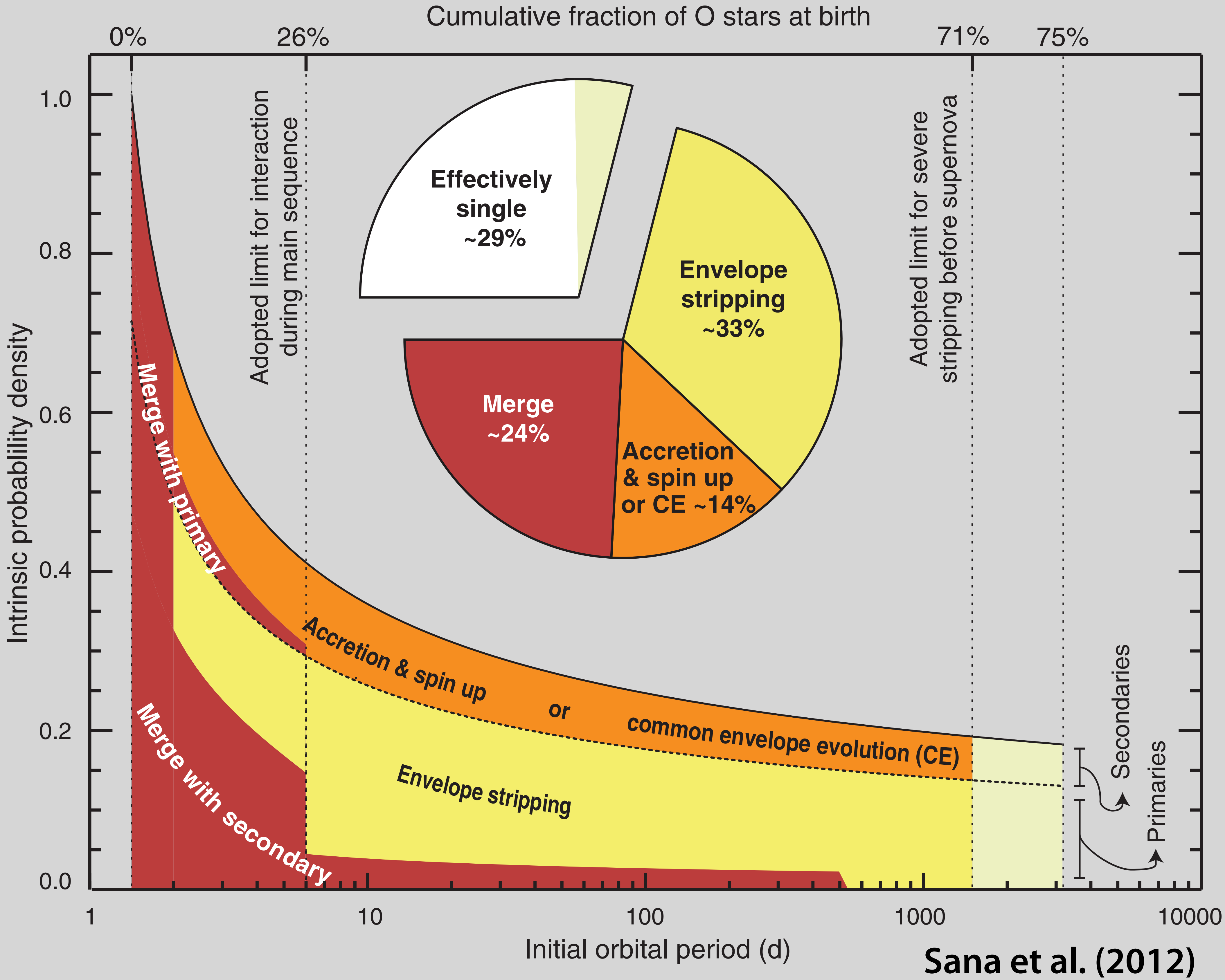
~10km (~40min w/ metro & bus)

Kyoto Sangyo University

Kyoto University

Kyoto Station

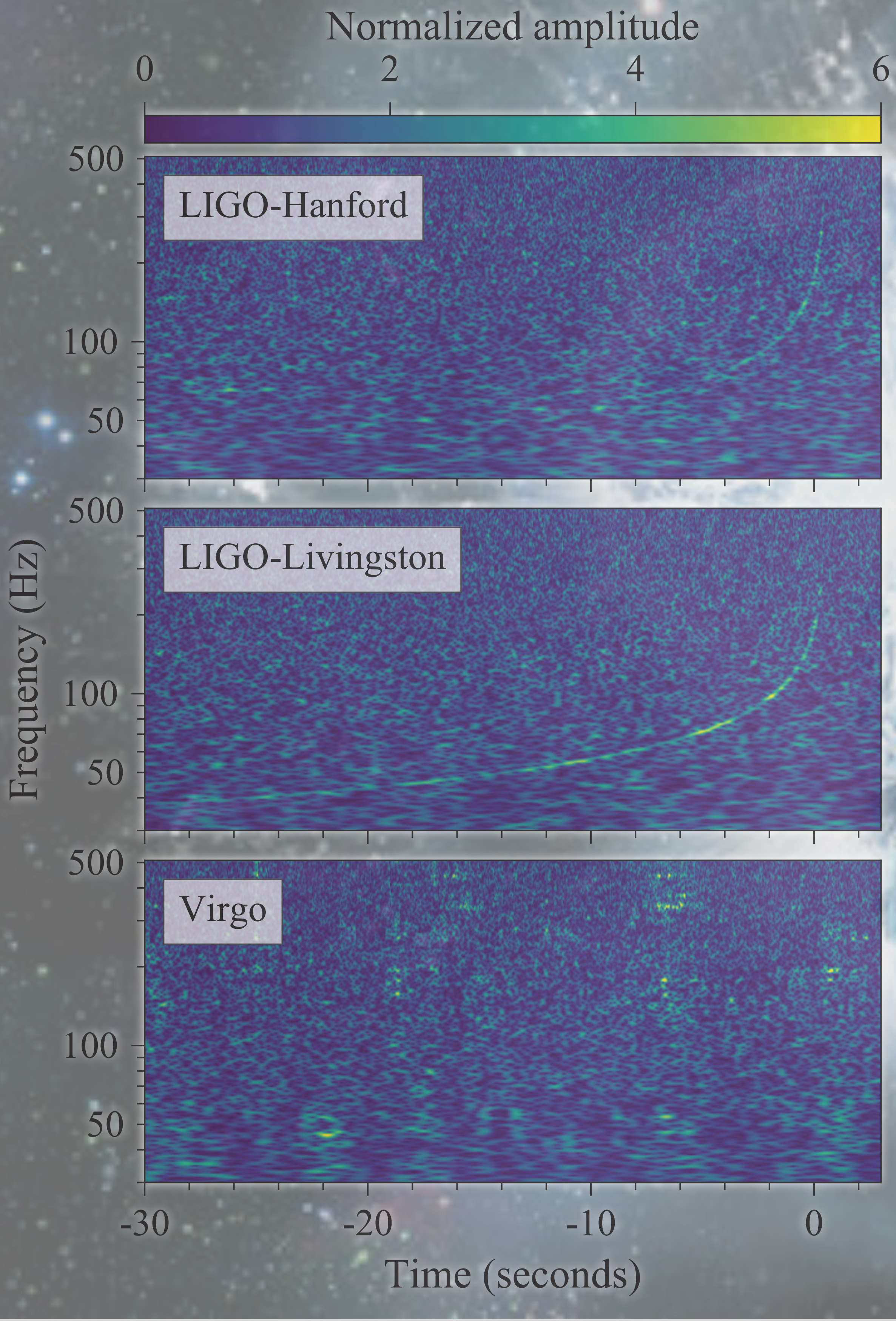
Fraction of interacting binary is high

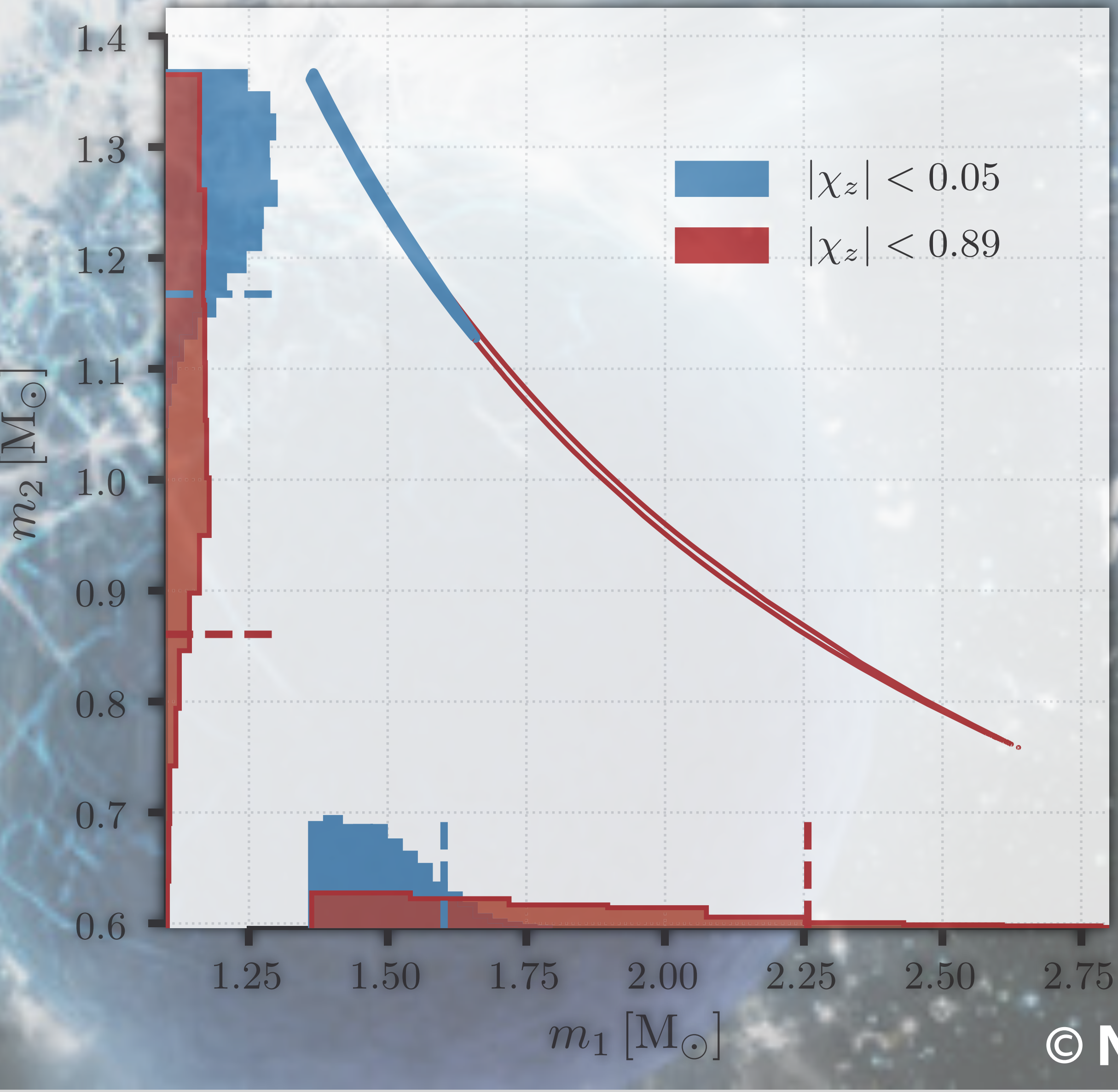


Sana et al. (2012)

GW170817: Death of neutron stars

LIGO-Virgo, PRL 119, 161101 (2017)





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DNS

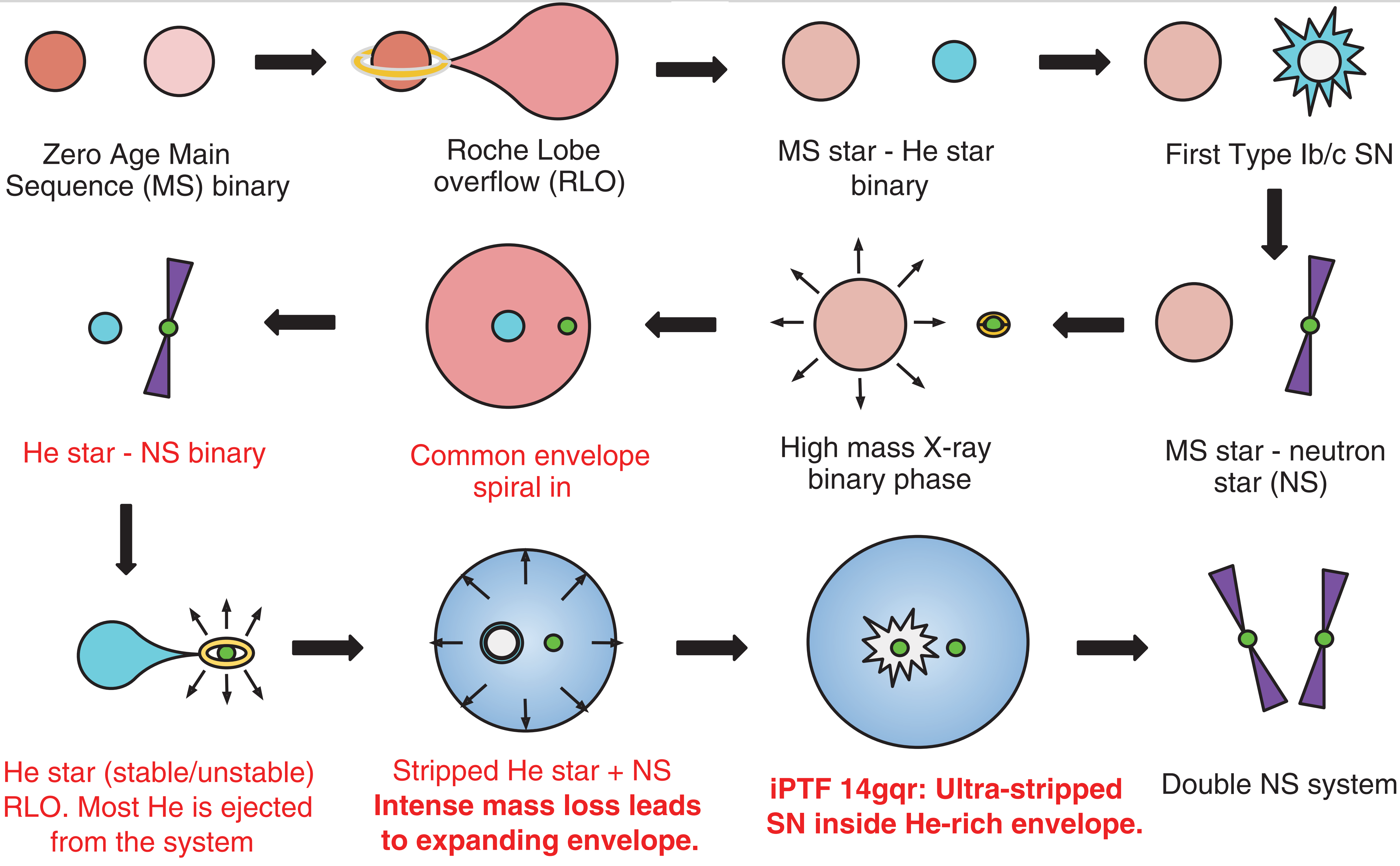
- **In the Galaxy, six systems are expected to merge within cosmic age (~13.8Gyr=1.38×10^{10}yr)**
  - **Merger time =>1.2×10^{8}yr $(a_0/10^{11}\mathrm{cm})^4(m/2.8M_\odot)^{-3}$**
    -> $a_0 < 3 \times 10^{11}$cm is needed
    NB) The distance of Sun-Earth is 1AU=1.5×10^{13}cm, $R_\odot = 7 \times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

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

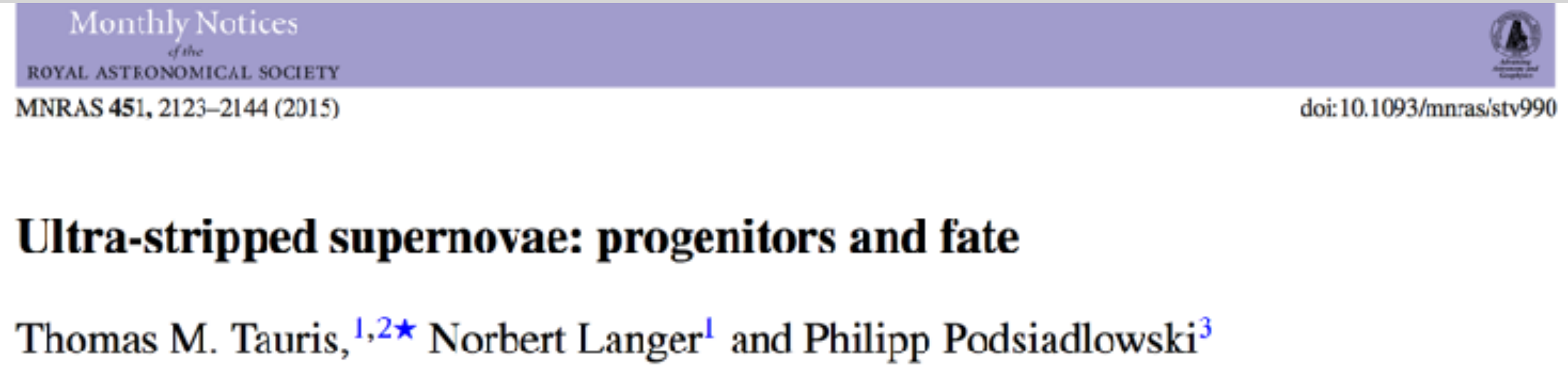
Intense mass loss leads to expanding envelope.

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)

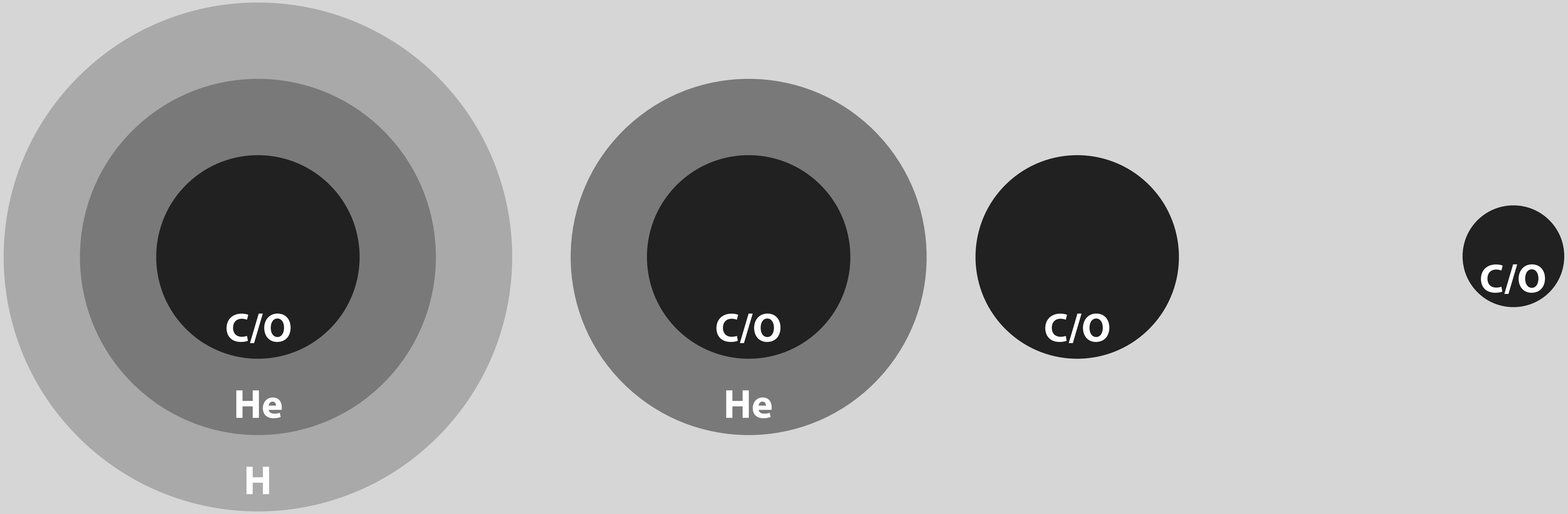
doi:10.1093/mnras/stv990

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.”*

Ultra-stripped supernovae?

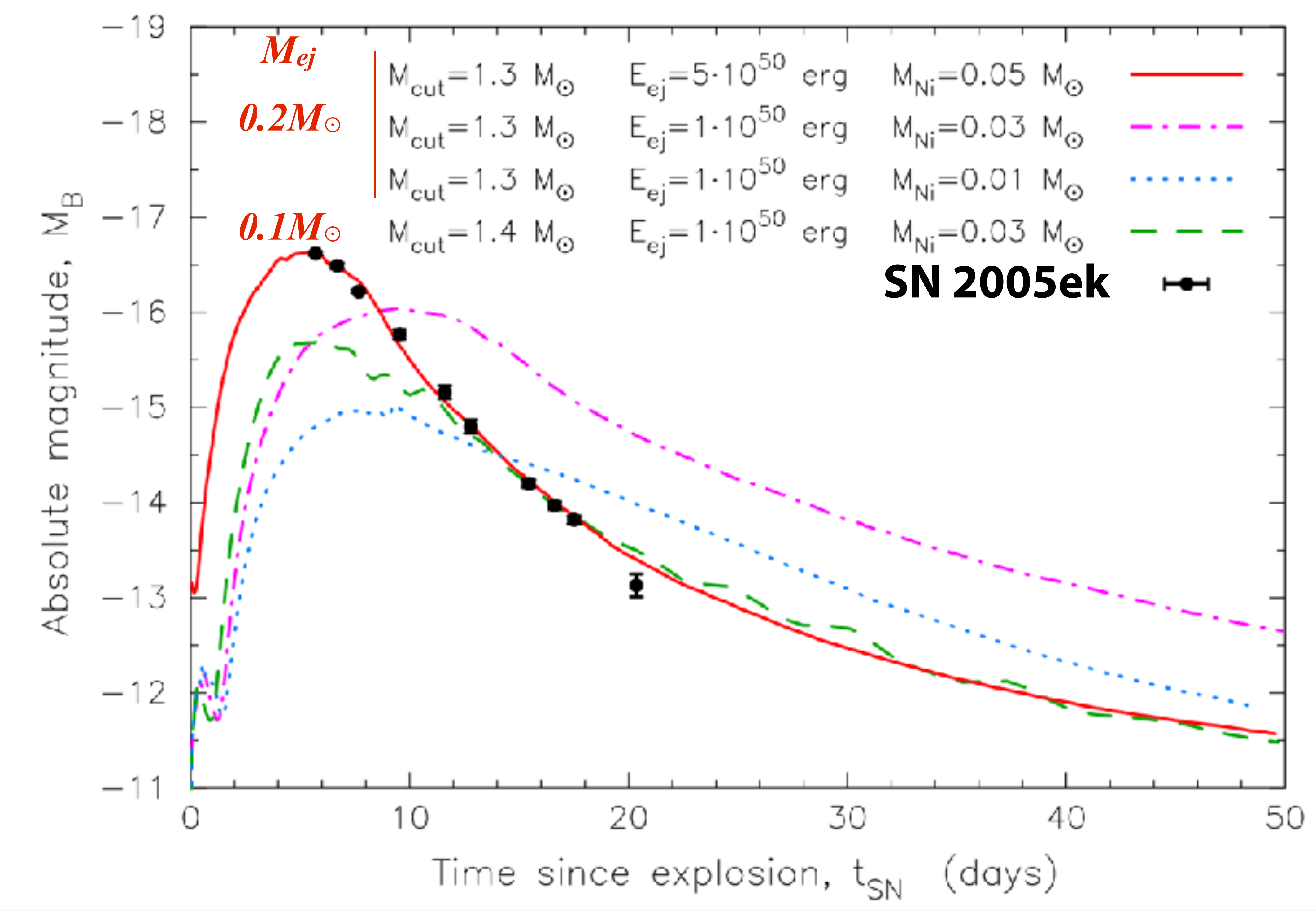


$M_{\rm total}\sim 10M_\odot$ $M_{\rm CO}\sim 3M_\odot$

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

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

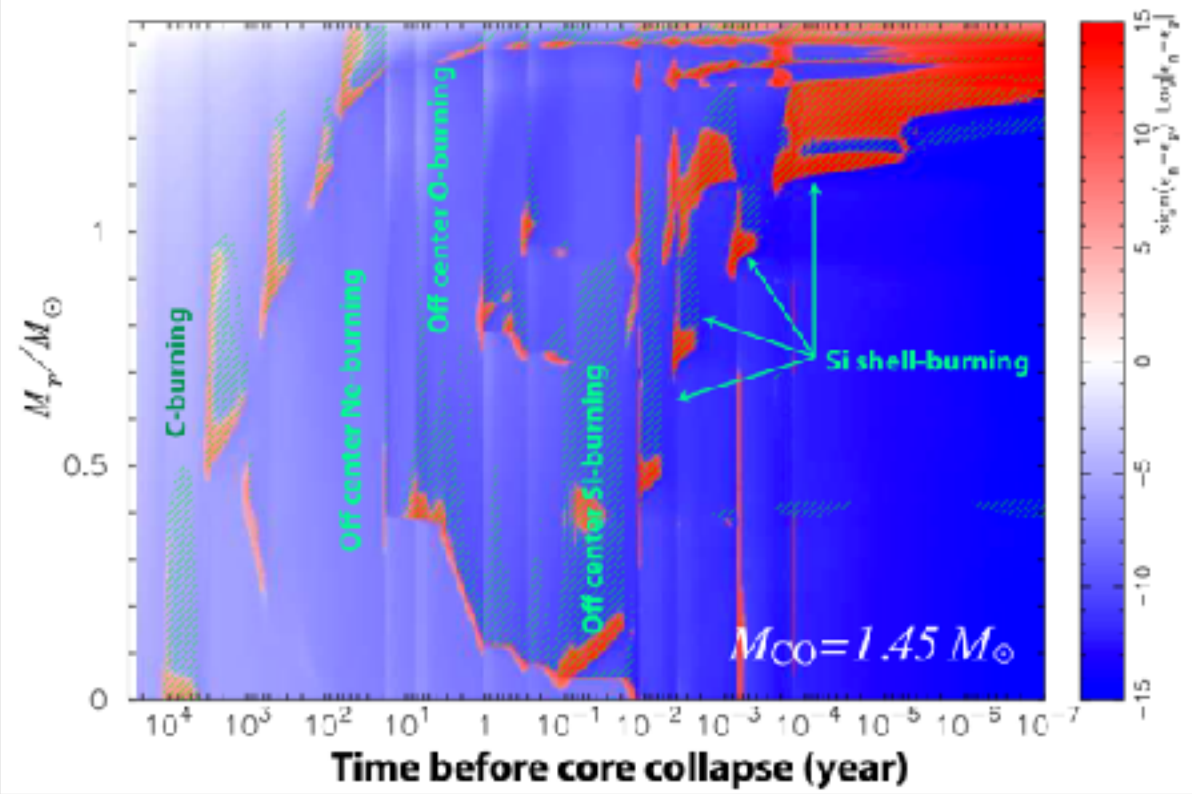
Small ejecta mass

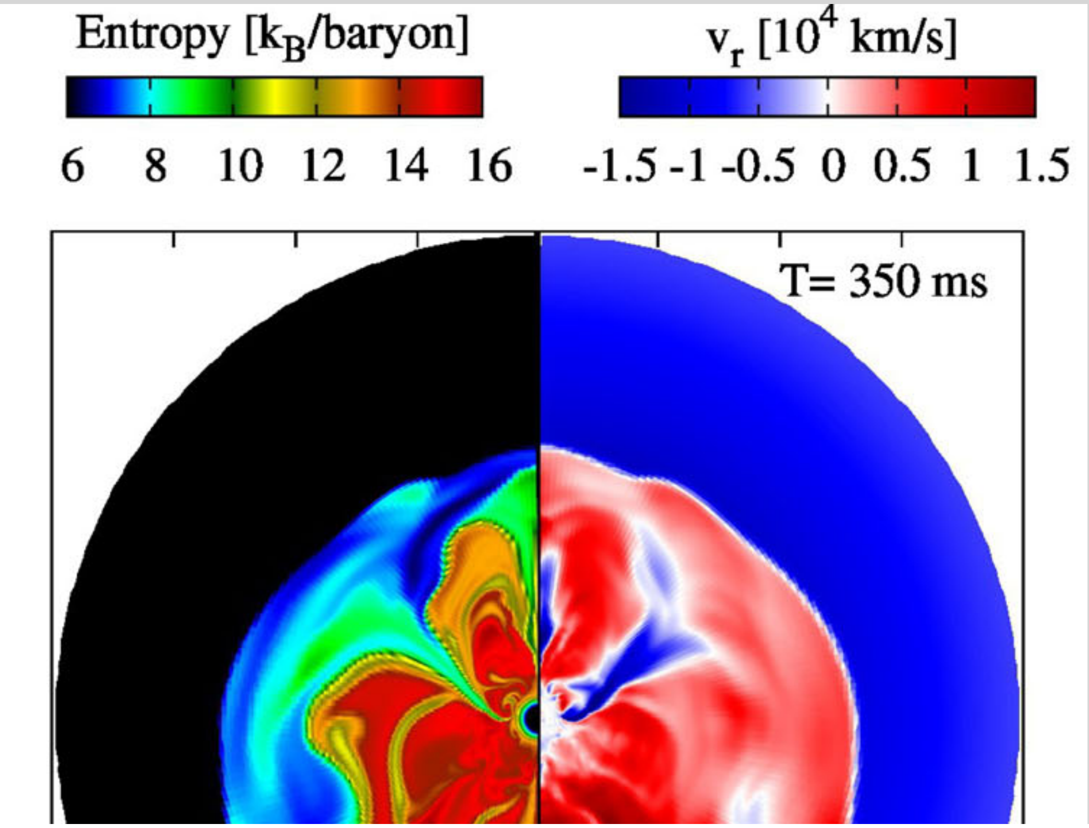


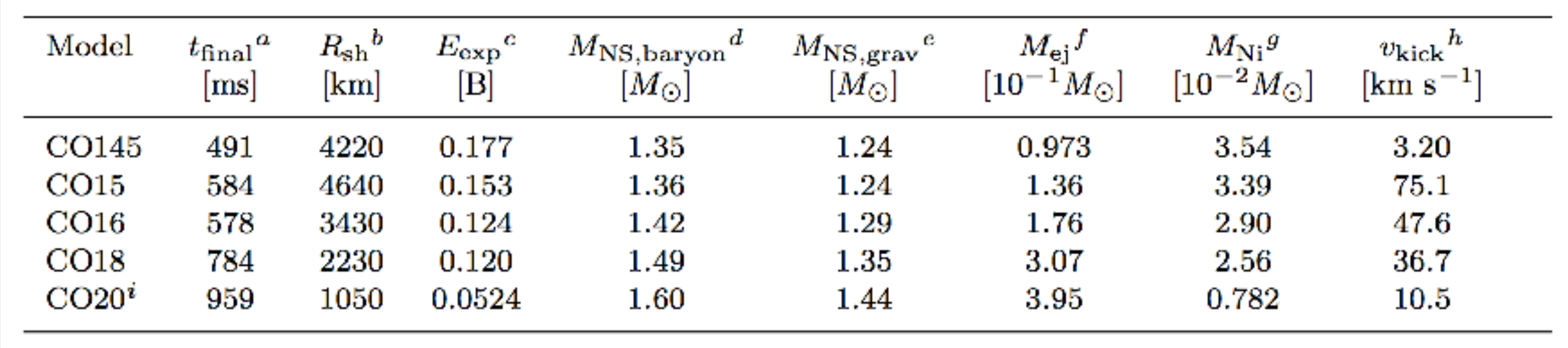
Tauris et al. (2013)

Neutrino-driven explosions of ultra-stripped SN

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







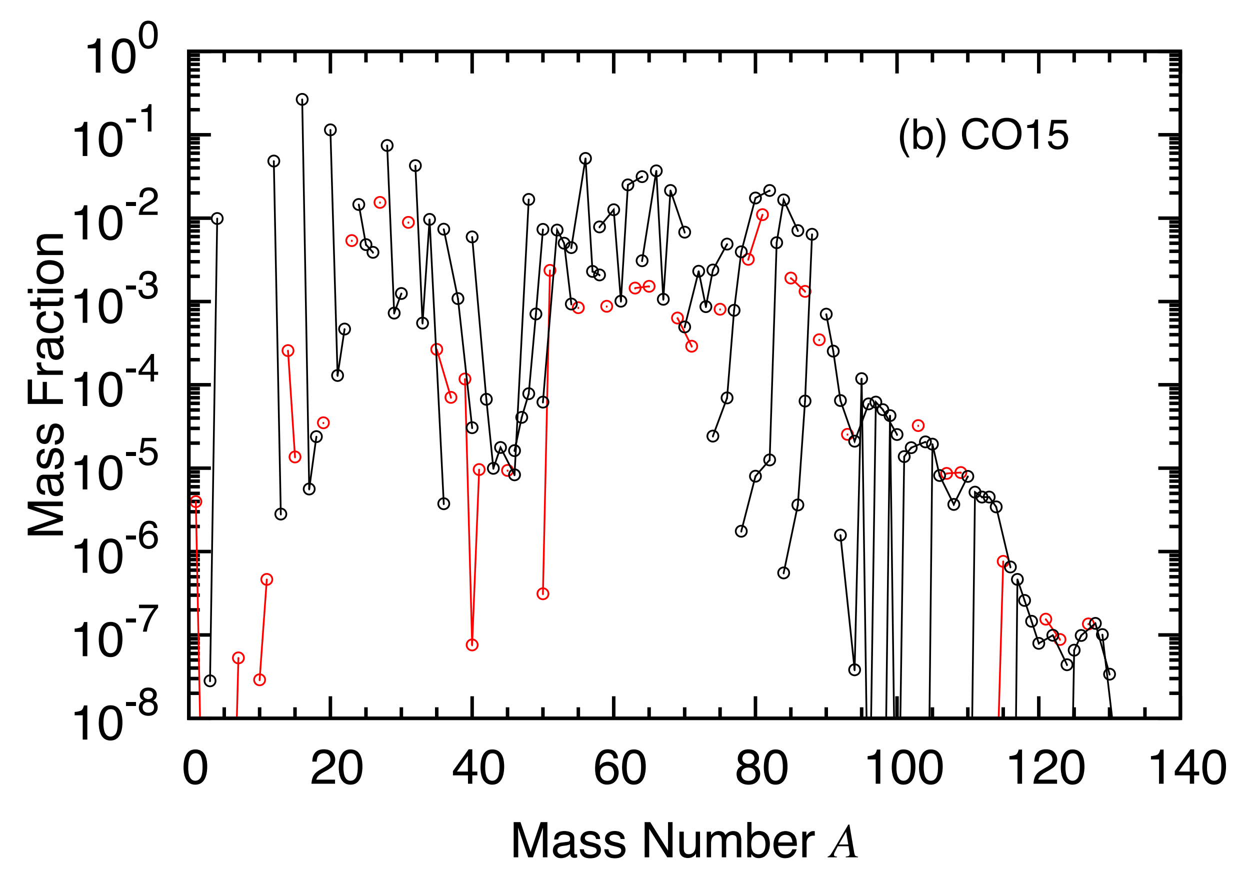
Model	$t_{\rm final}$[a] [ms]	$R_{\rm sh}$[b] [km]	$E_{\rm exp}$[c] [B]	$M_{\rm NS,baryon}$[d] [$M_\odot$]	$M_{\rm NS,grav}$[e] [$M_\odot$]	$M_{\rm ej}$[f] [$10^{-1}M_\odot$]	$M_{\rm Ni}$[g] [$10^{-2}M_\odot$]	$v_{\rm kick}$[h] [km s^{-1}]
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	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

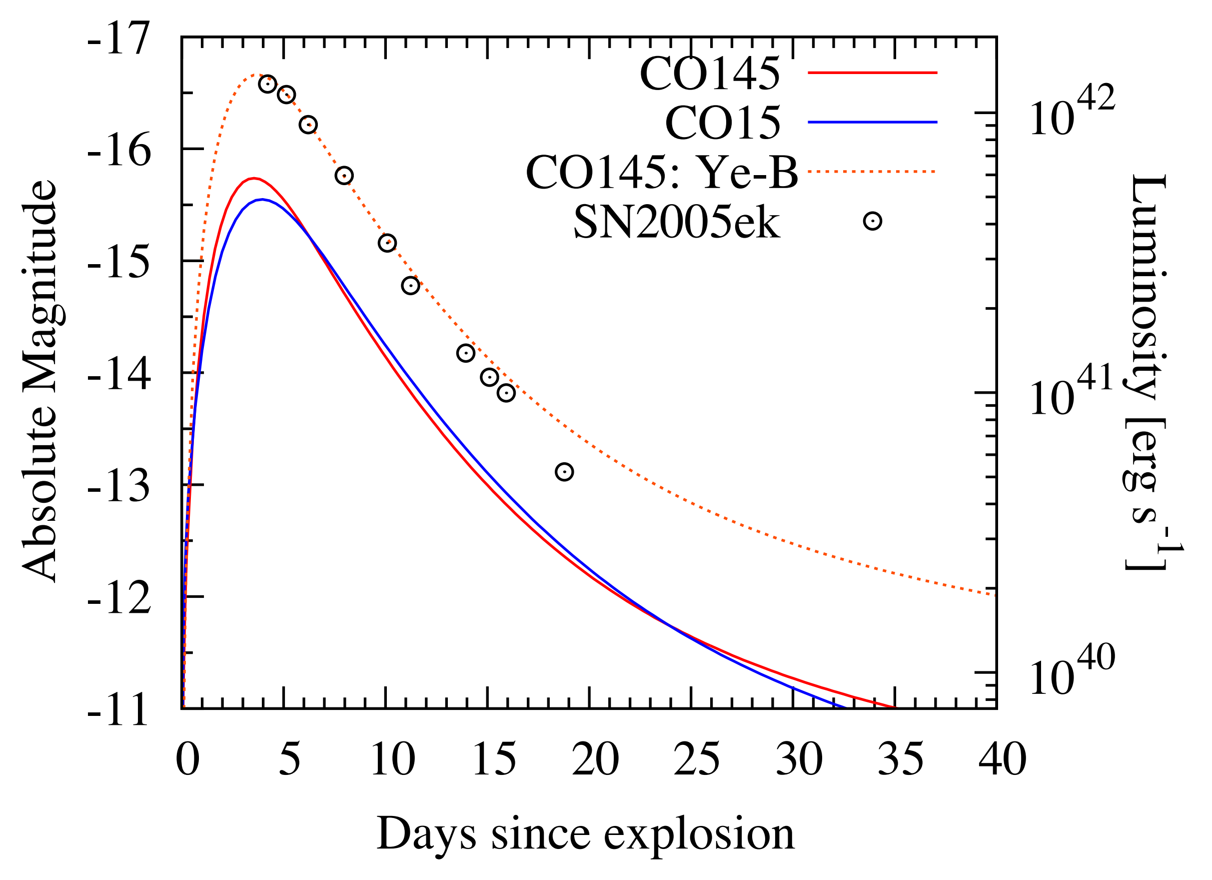
Ejecta mass~*O(0.1)M*⊙, NS mass~*1.4 M*⊙, explosion energy~*O(10^{50})* erg, Ni mass~*O(10^{-2}) M*⊙; everything compatible w/ Tauris+ 2013

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

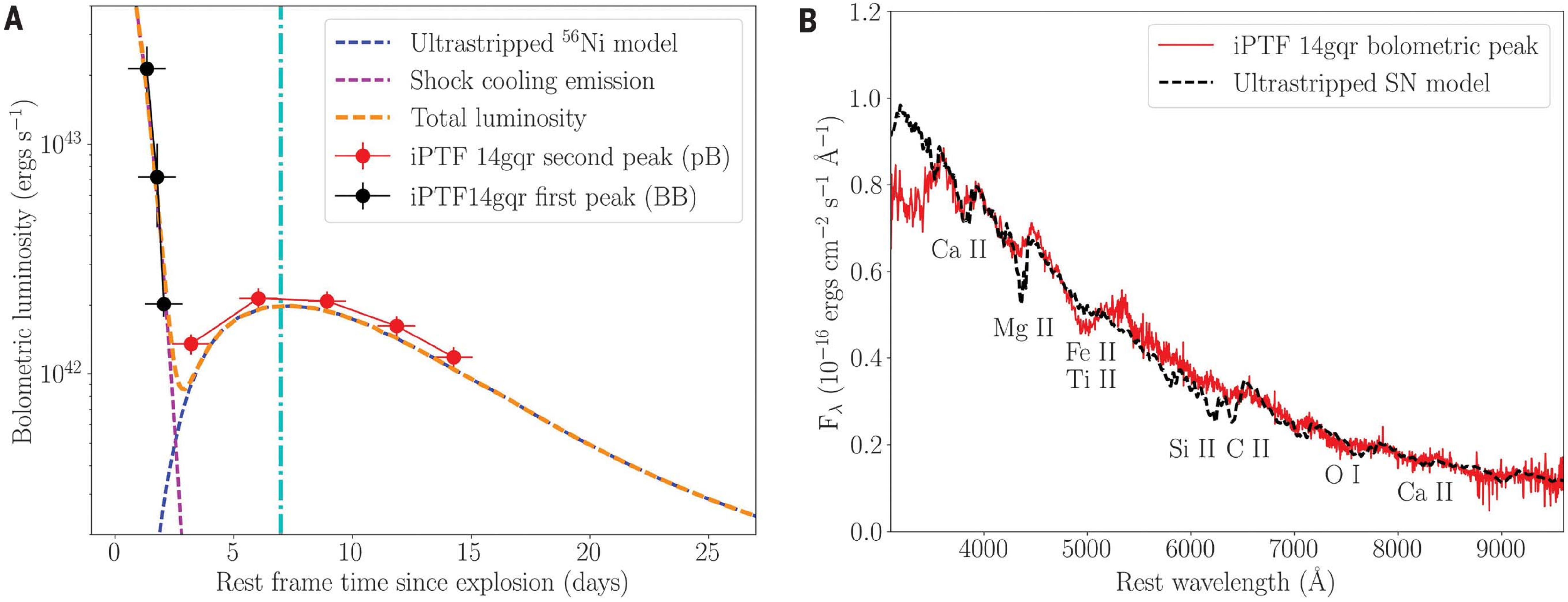
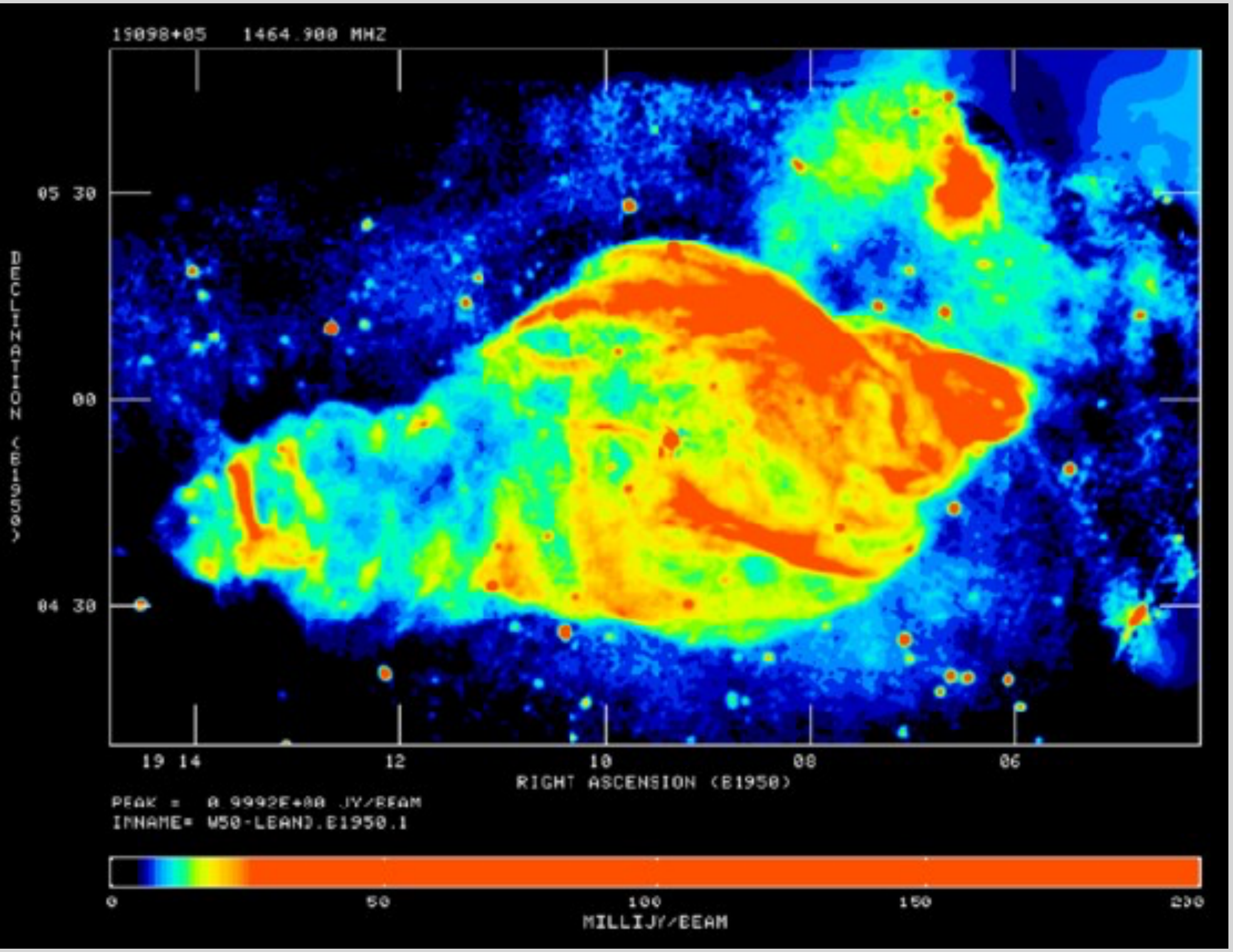


Fig. 5. Comparison of iPTF 14gqr to theoretical models of ultra-stripped SNe. (**A**) Bolometric light curve of iPTF 14gqr shown with a composite light curve consisting of ultra-stripped type Ic SN models (*28*) and early shock-cooling emission (*25*). The blue dashed line corresponds to the ^{56}Ni powered peak in the ultra-stripped SN models for $M_{\mathrm{ej}} = 0.2\,M_\odot$, $M_{\mathrm{Ni}} = 0.05\,M_\odot$, 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)

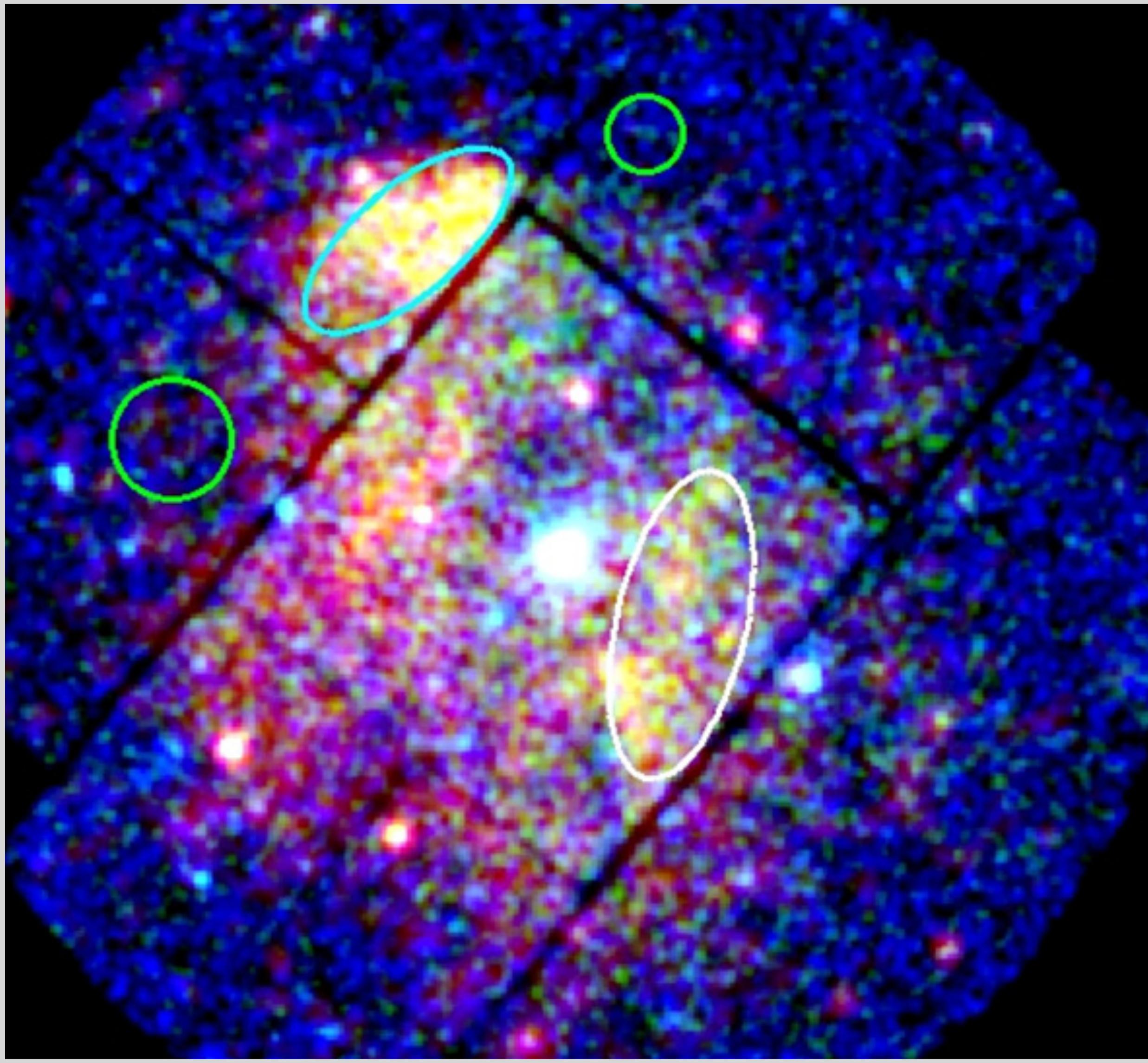
Gamma-ray binaries in SNRs

SS433 & SNR W50A
Dubner et al. (1998)



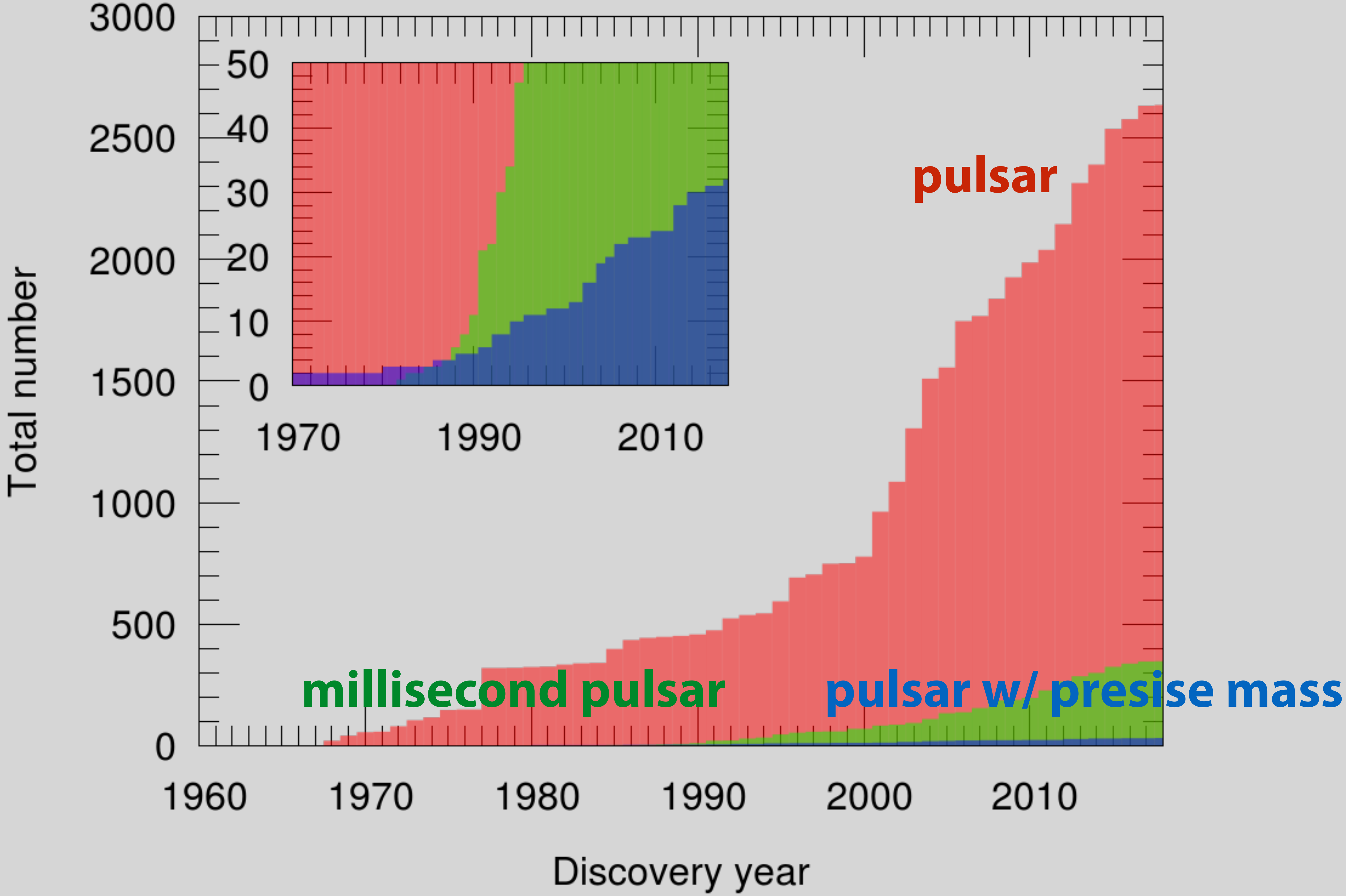
(c) Image courtesy of NRAO/AUI

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



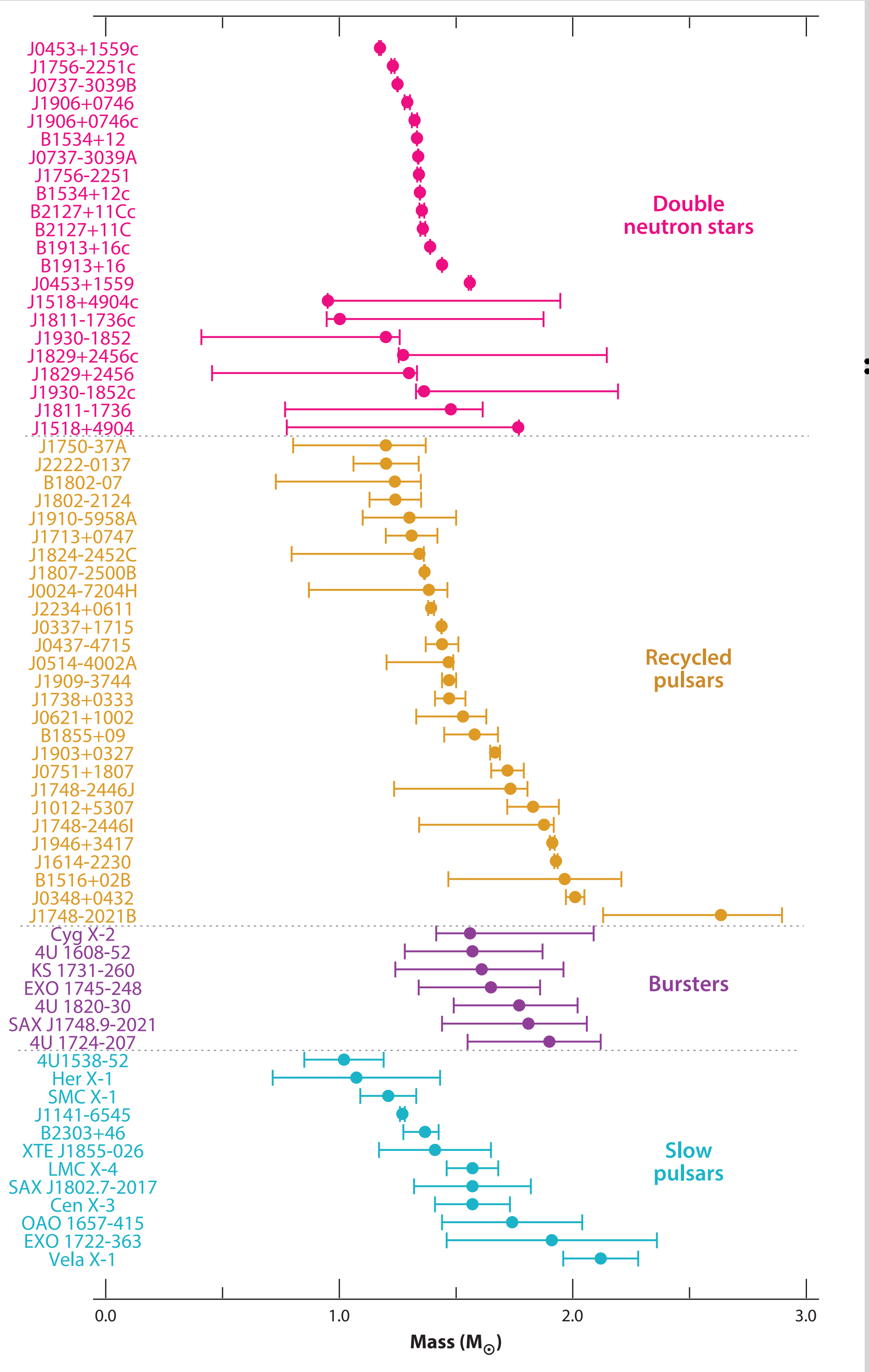
2. Minimum NS mass from binary systems

Pulsar number is increasing

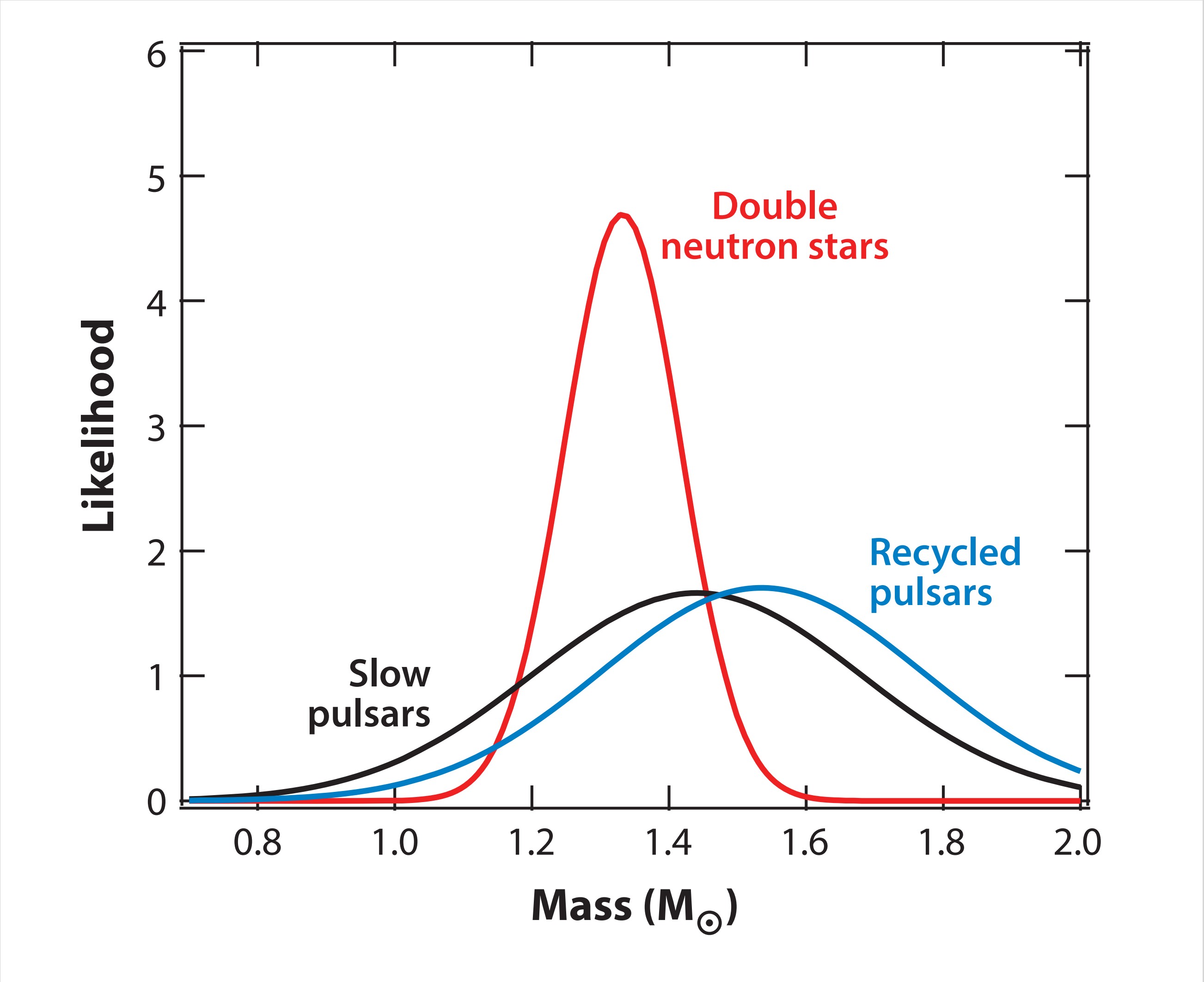


compiled data from ATNF pulsar catalog and P. Freire's table

NS mass measurements



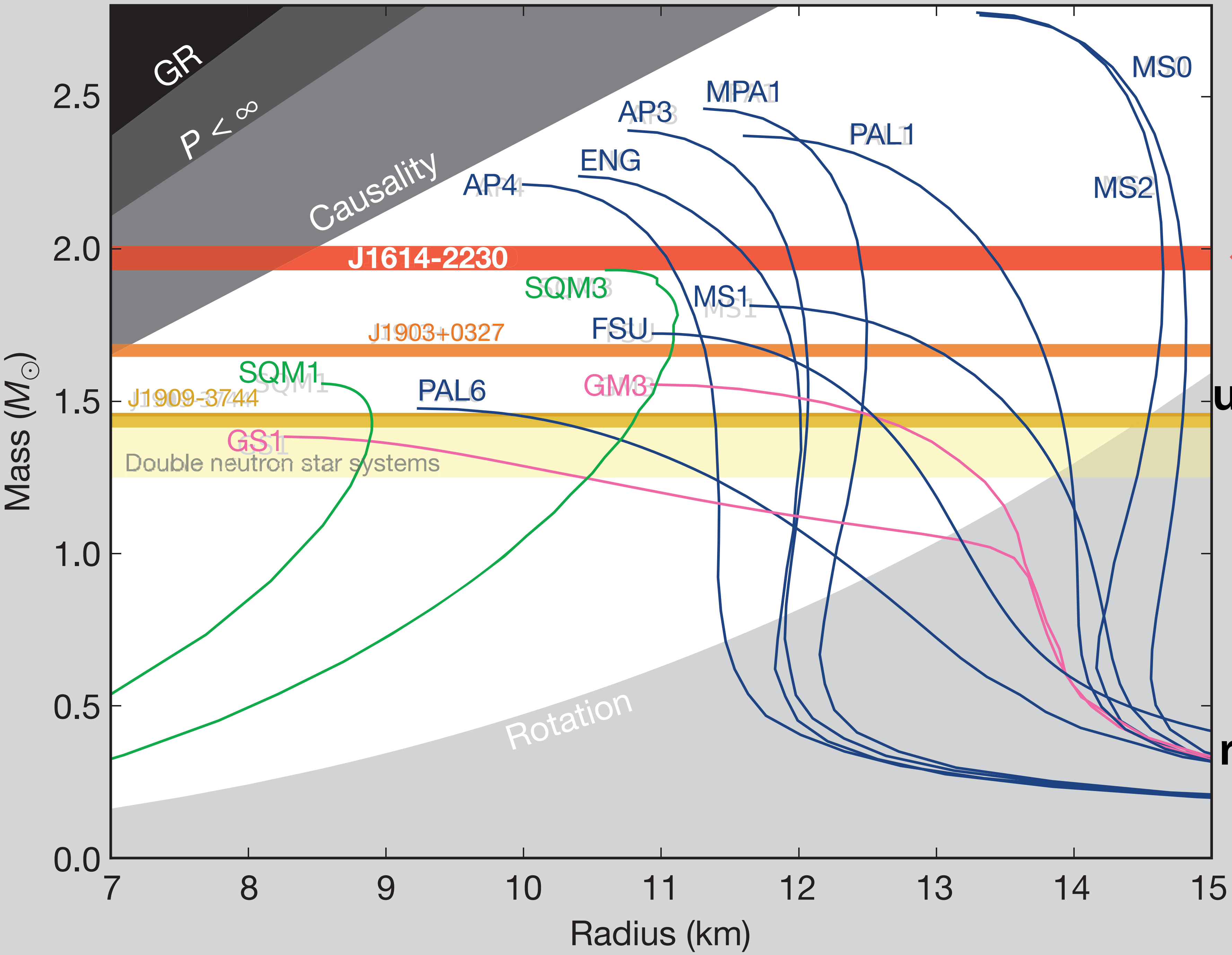
Özel & Freie 2016



- **>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⊙

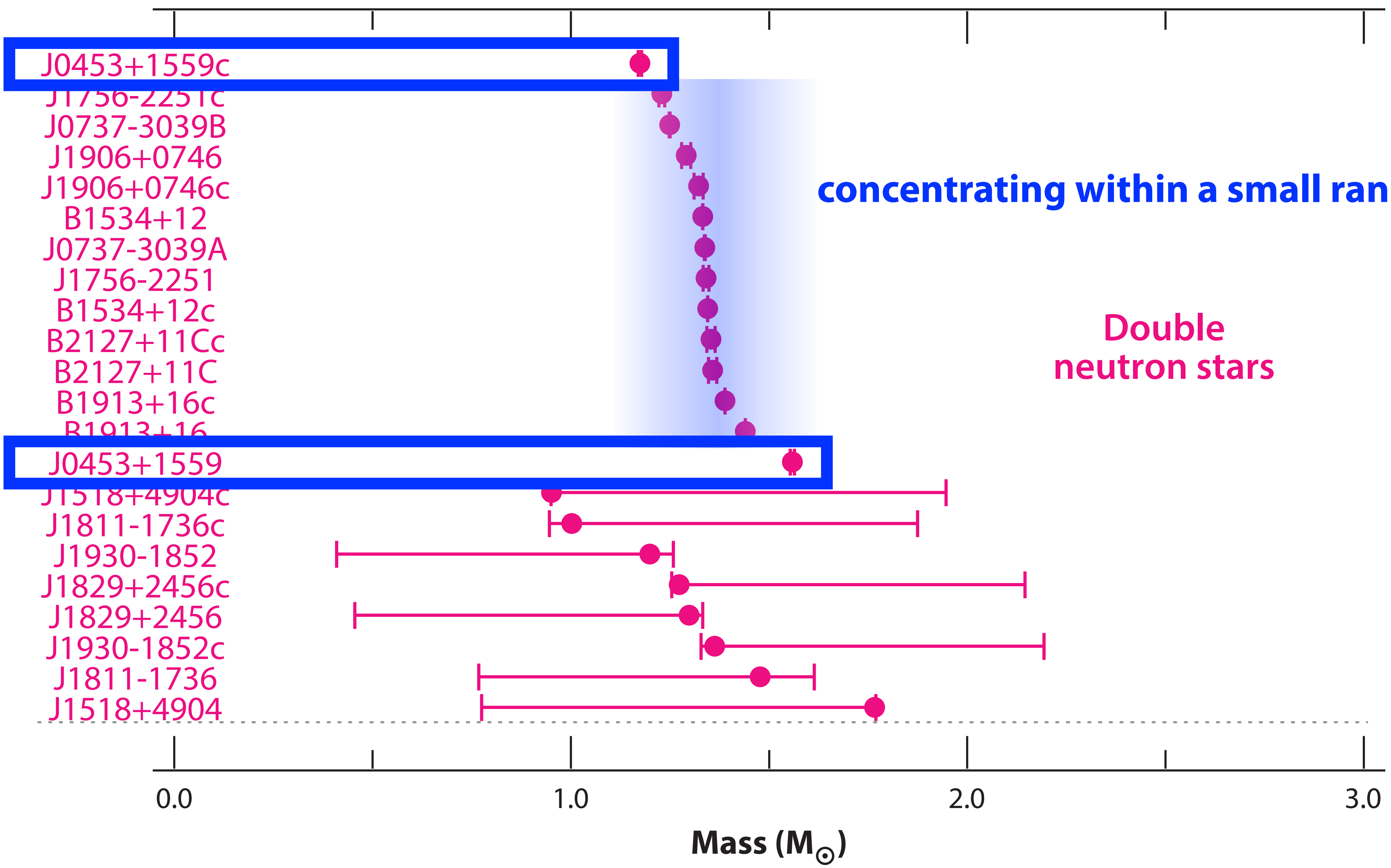
NB) mass estimation was updated by Arzoumanian+ 2018 as 1.908±0.016M⊙

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

How about low-mass one?

Double NSs

Özel & Freie 2016



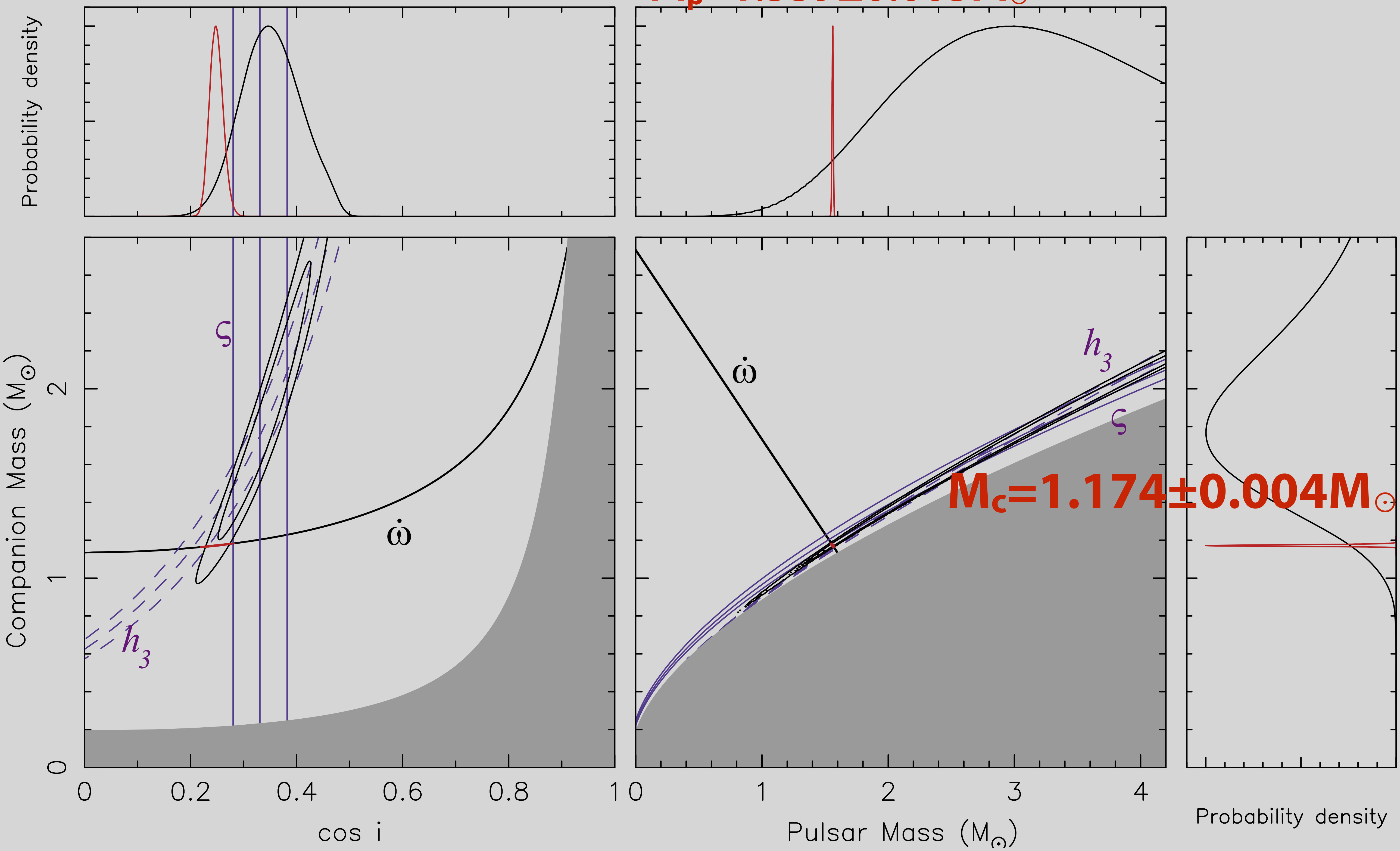
concentrating within a small range

Double neutron stars

First asymmetric DNS system

Martinez+ 2015

M_p=1.559±0.005$M_\odot$



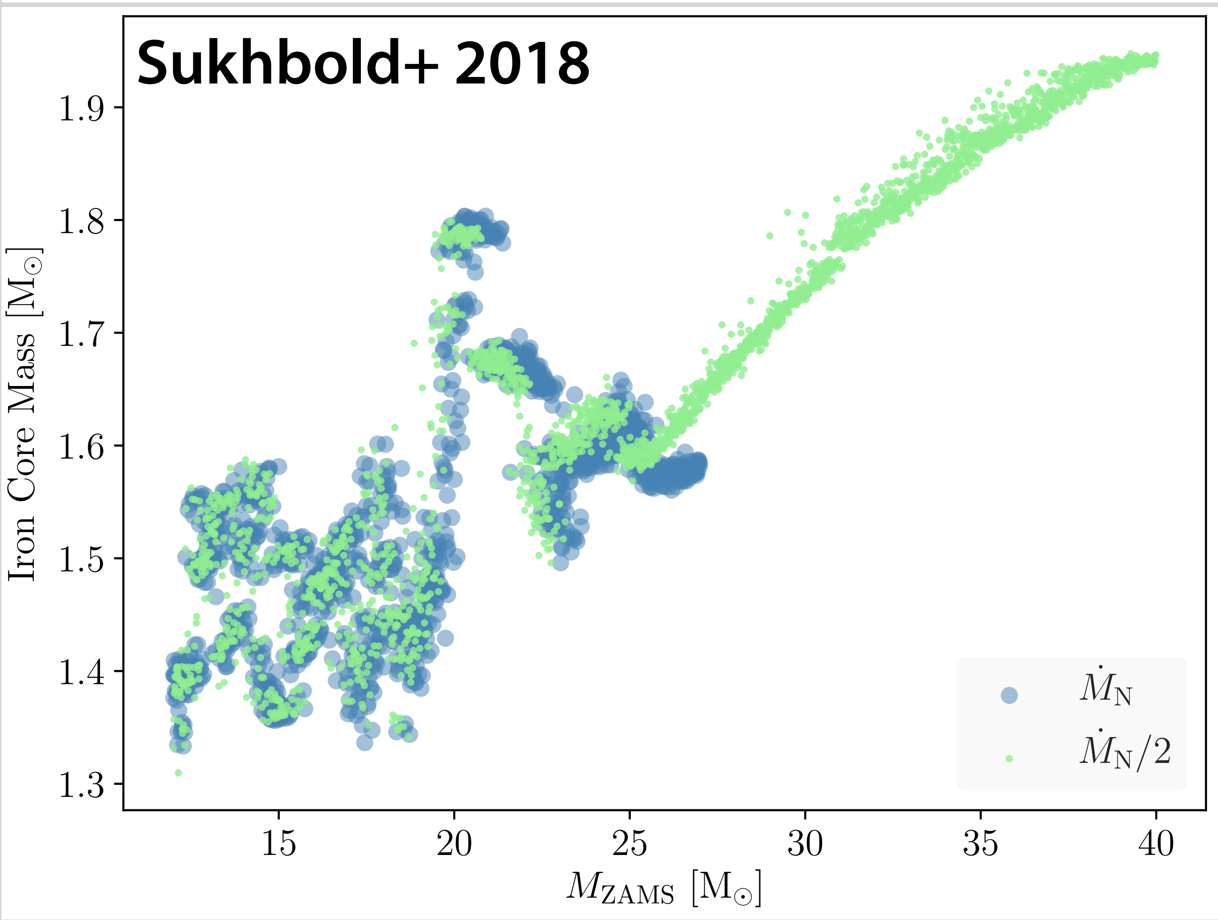
M_c=1.174±0.004$M_\odot$

A low-mass NS

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

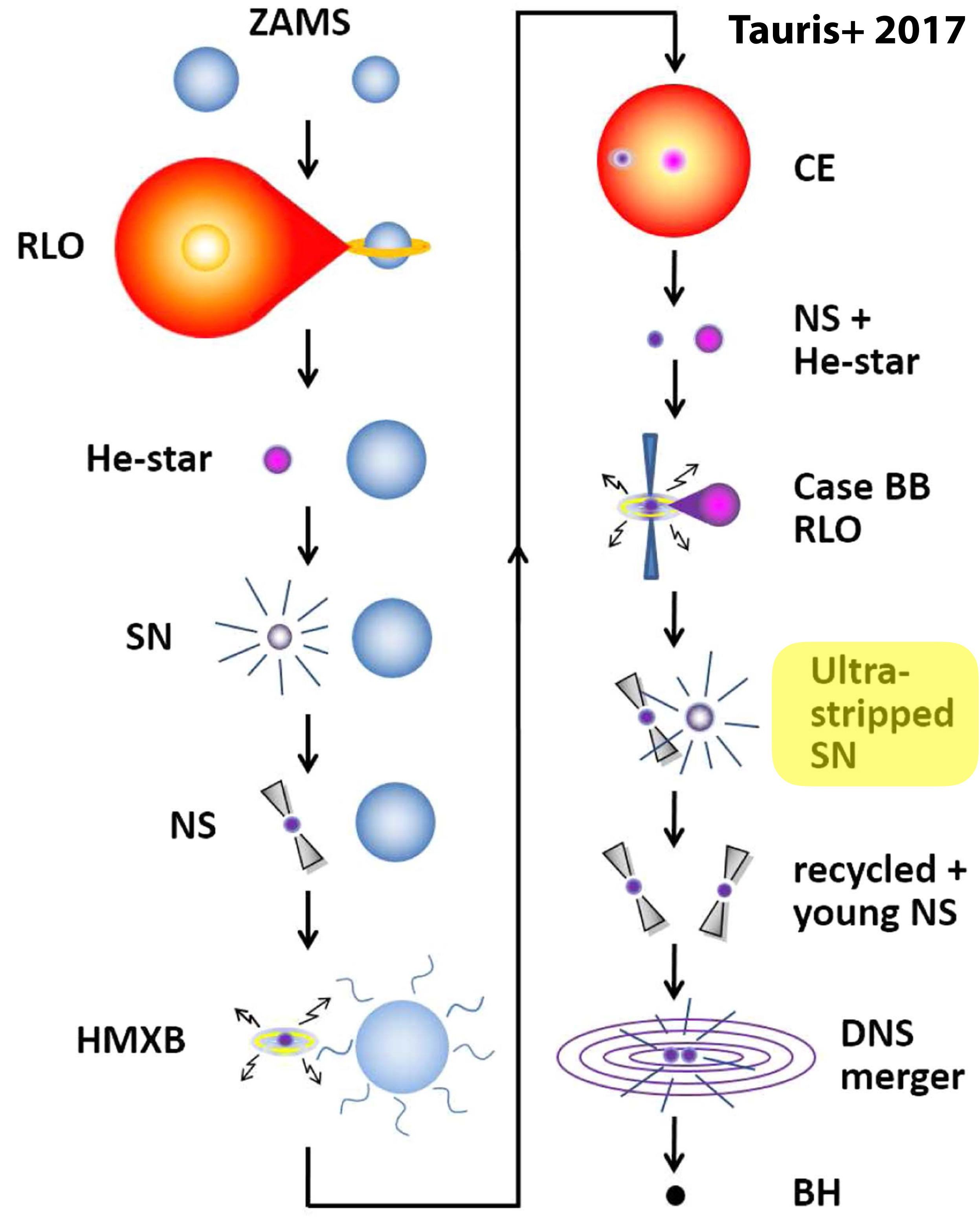
- **Is it a white dwarf? Maybe no**
  - a large eccentricity (e=0.112) is difficult to explain by slow evolution into a WD

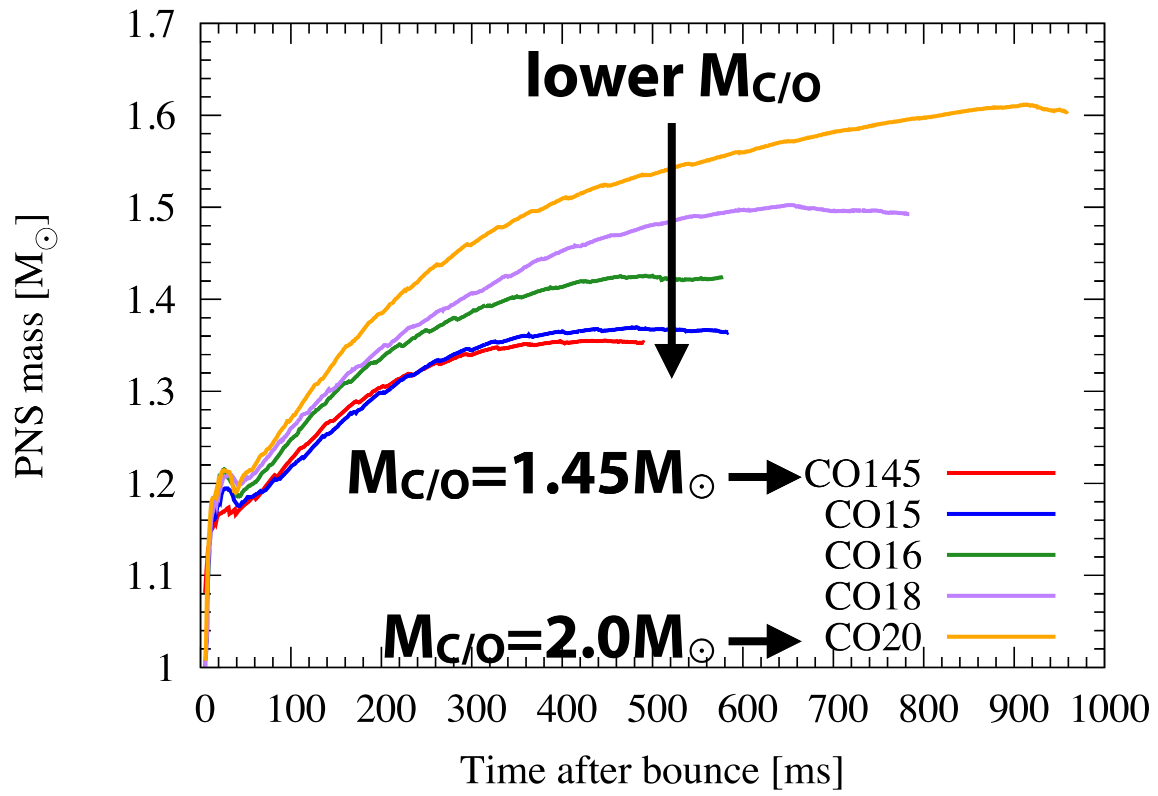
- **How to make it?**
  - a small iron core of massive star? (typically M_{Fe}~1.4–1.8$M_\odot$)

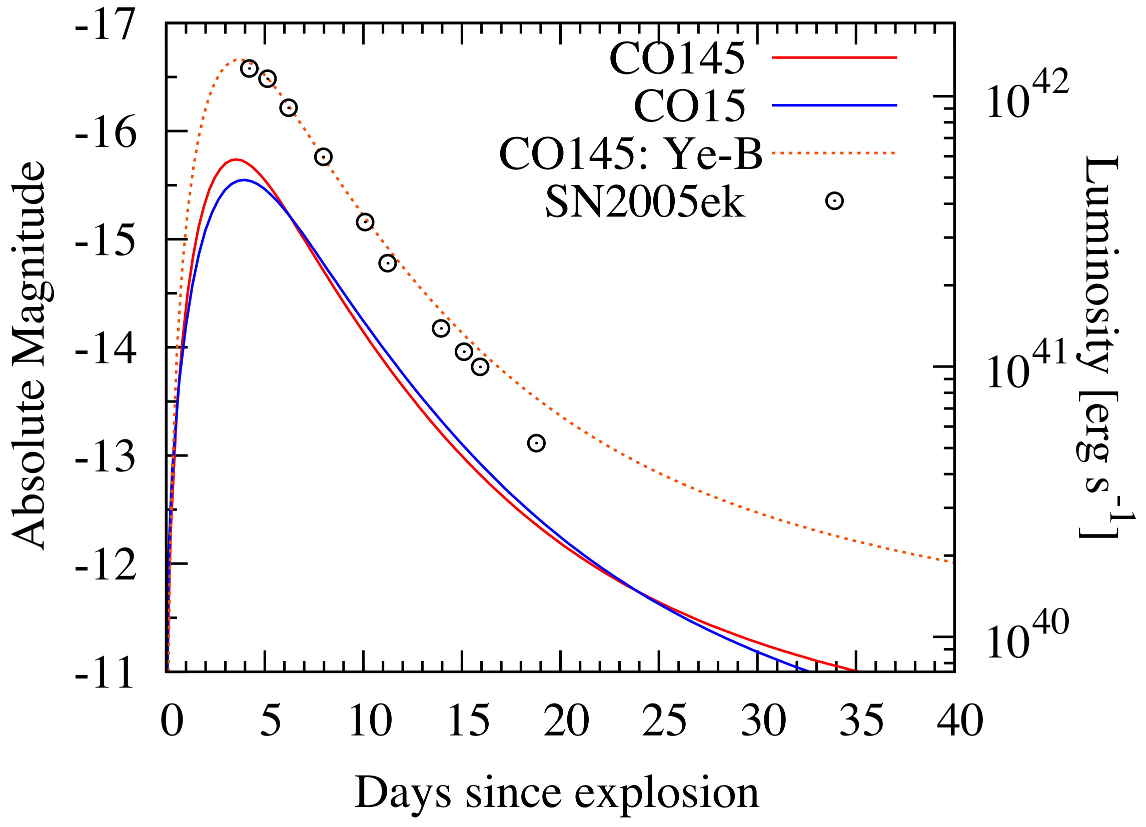


A path toward a low mass NS?: Ultra-stripped SN

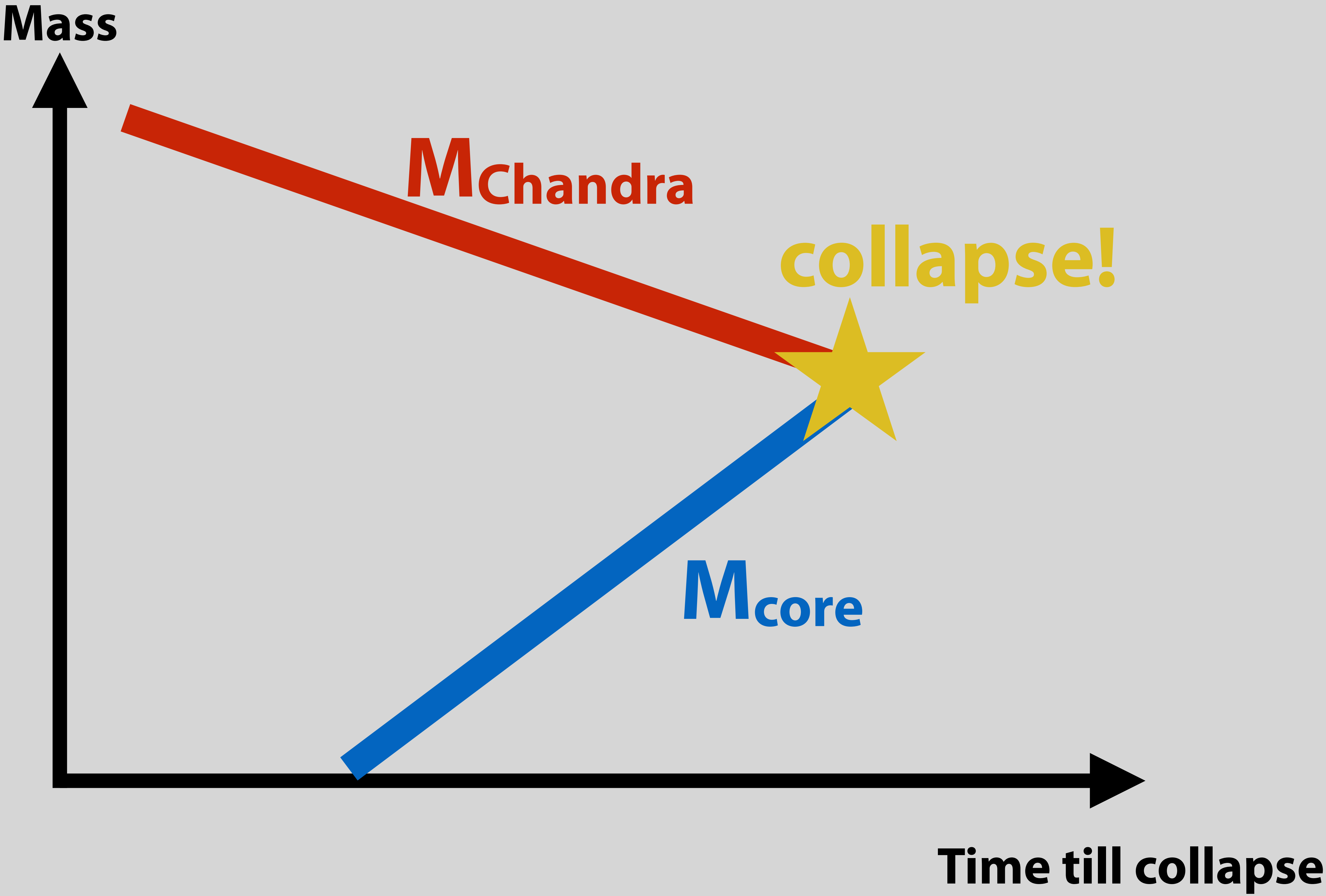
[Suwa+, MNRAS, **454**, 3073 (2015); Yoshida+, MNRAS, **471**, 4275 (2017)]







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**

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

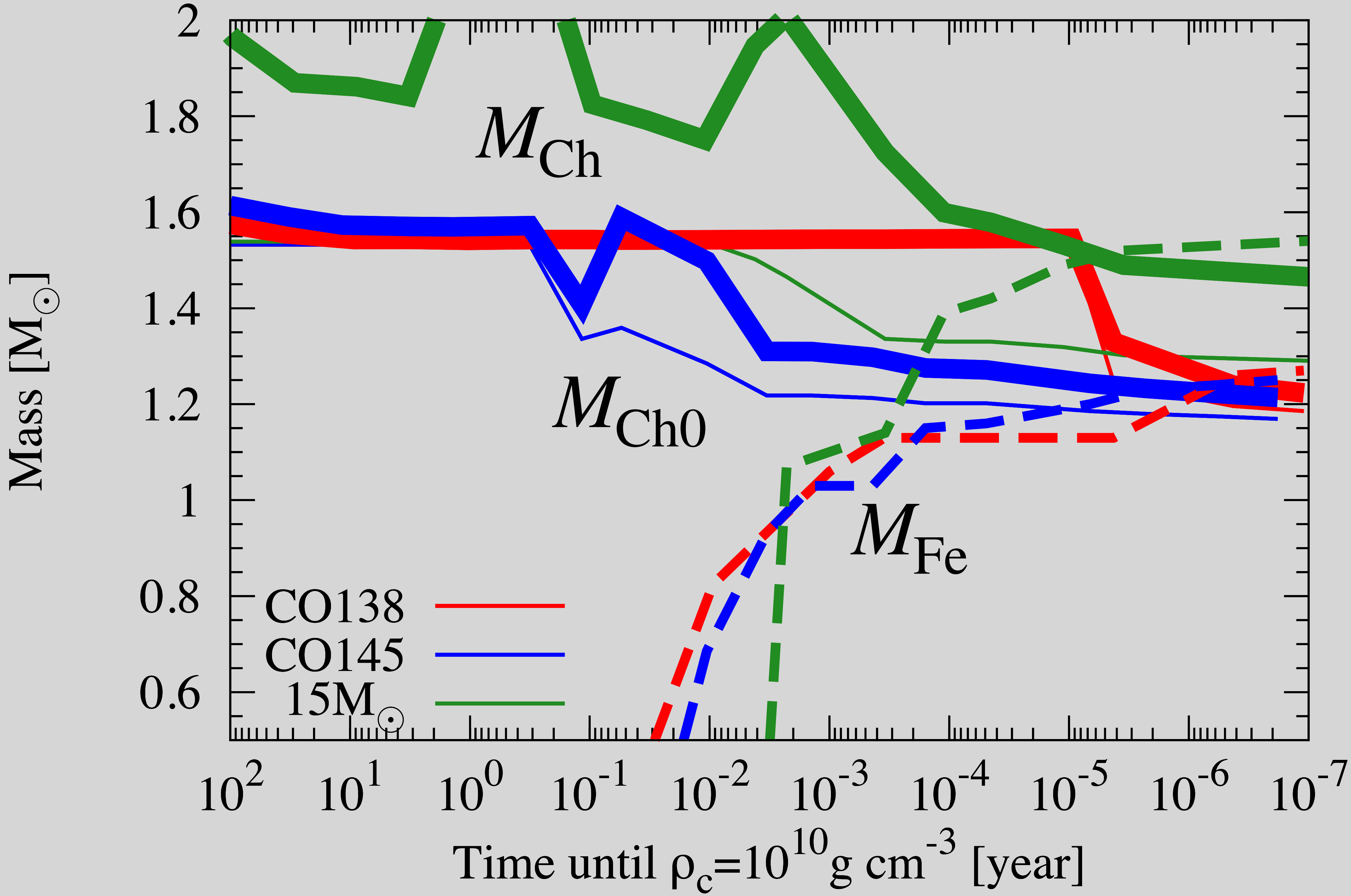
$$s_e = 0.5\rho_{10}^{-1/3}(Y_e/0.42)^{2/3} T_{\rm MeV}$$

Baron+ 1990; Timmes+ 1996

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

M_{ch} vs. M_{core}

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **481**, 3305 (2018)]



What do simulations solve?

stellar evolution

input: $\rho(r), T(r), Z_i(r), v_r(r)$

Numerical table based on nuclear physics
e.g.) 10^3 g cm^{-3} < ρ < 10^{15} g cm^{-3}
0.1 MeV < T < 100 MeV
0.03 < Y_e <0.56

general relativity

Gravity

strong interaction

Nuclear equation of state

electro-magnetic interaction

(Magneto-)hydrodynamics

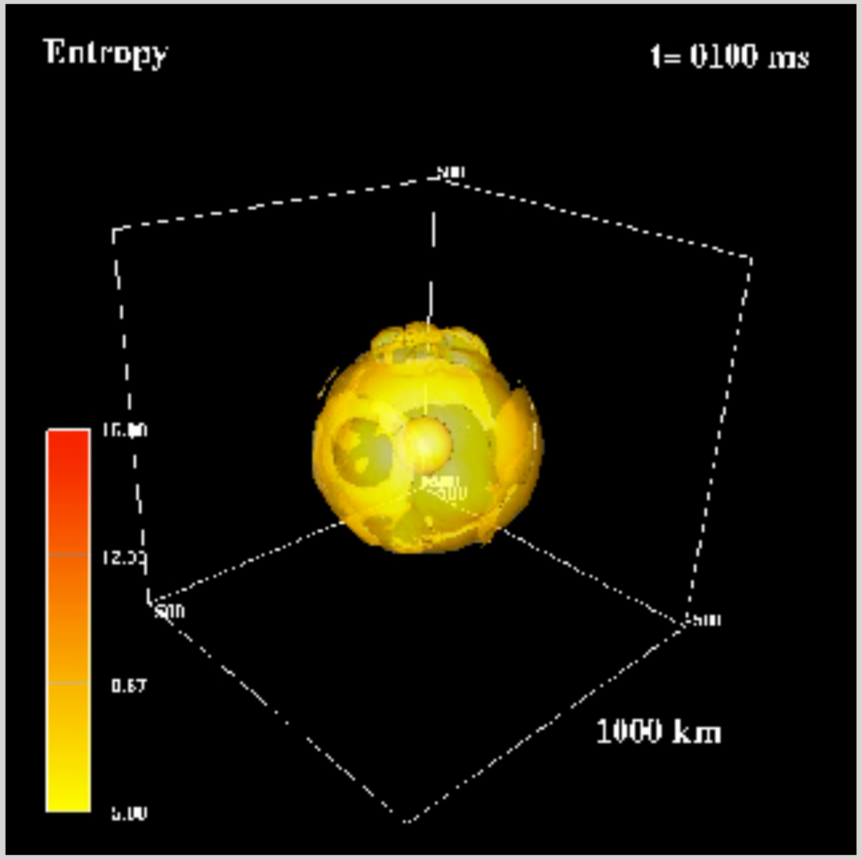
weak interaction

Neutrino transfer

Number of interactions;

pe^- <-> $n\nu_e$, ne^+ <-> $p\bar{\nu}_e$
$\nu e^{\pm}$ <-> $\nu e^{\pm}$, νA <-> νA, νN <-> νN
$\nu\bar{\nu}$ <-> e^-e^+, NN <-> $\nu\bar{\nu}NN$, $\nu\bar{\nu}$ <->$\nu\bar{\nu}$

as first-principles as possible.
parameter free simulation!



Takiwaki, Kotake, Suwa (2014)

Explosion simulations and NS masses

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **481**, 3305 (2018)]

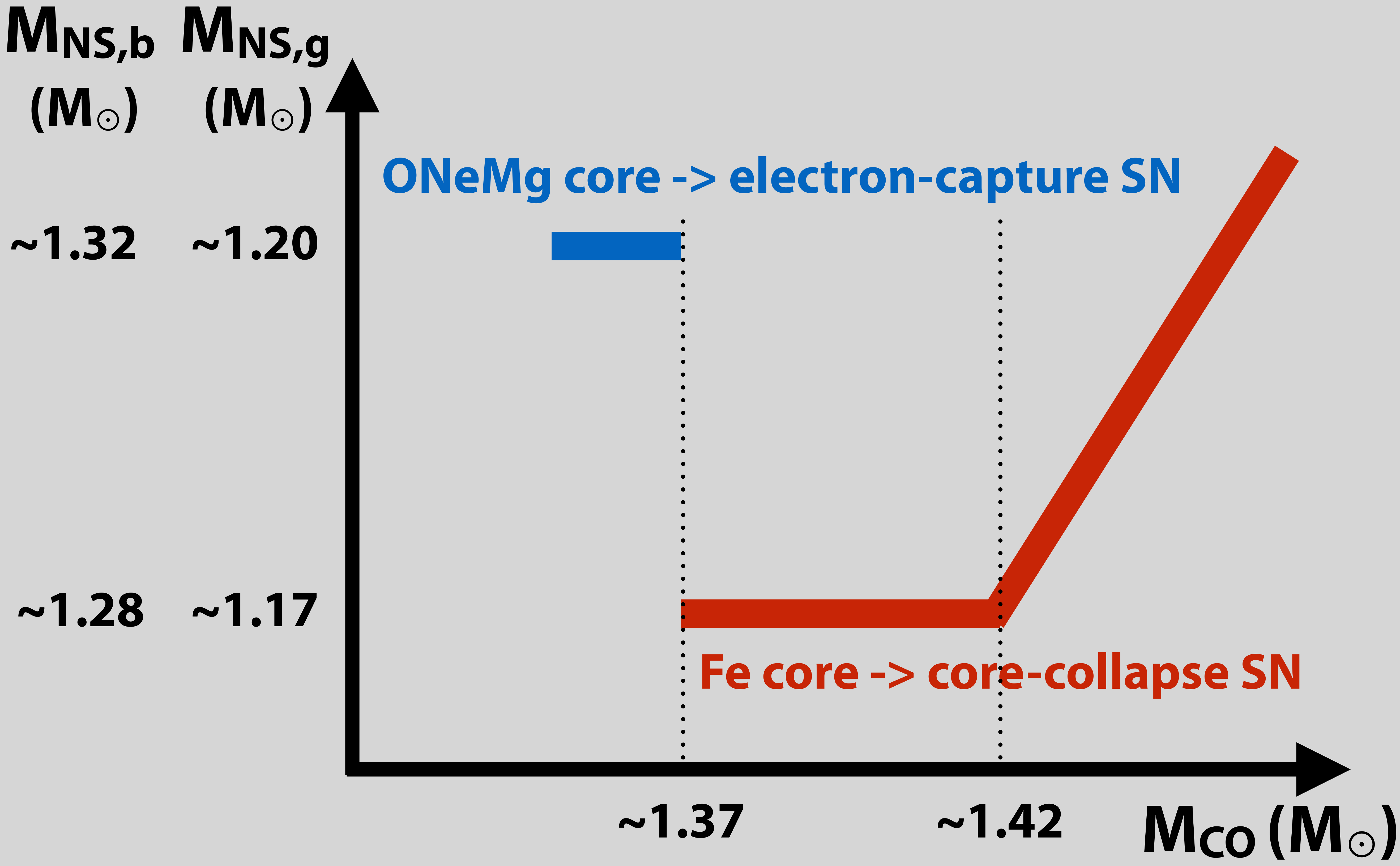
Model	M_{CO} ($M_\odot$)	M_{ZAMS} ($M_\odot$)	$M_{NS,b}$ ($M_\odot$)	$M_{NS,g}$ ($M_\odot$)
CO137	1.37	9.35	1.289	**1.174**
CO138	1.38	9.4	1.296	**1.179**
CO139	1.39	9.45	1.302	1.184
CO140	1.4	9.5	1.298	1.181
CO142	1.42	9.6	1.287	**1.172**
CO144	1.44	9.7	1.319	1.198
CO145	1.45	9.75	1.376	1.245

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

(Lattimer & Prakash 2001)

Discussion

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **481**, 3305 (2018)]



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.