Supernovae as birth sites of neutron stars

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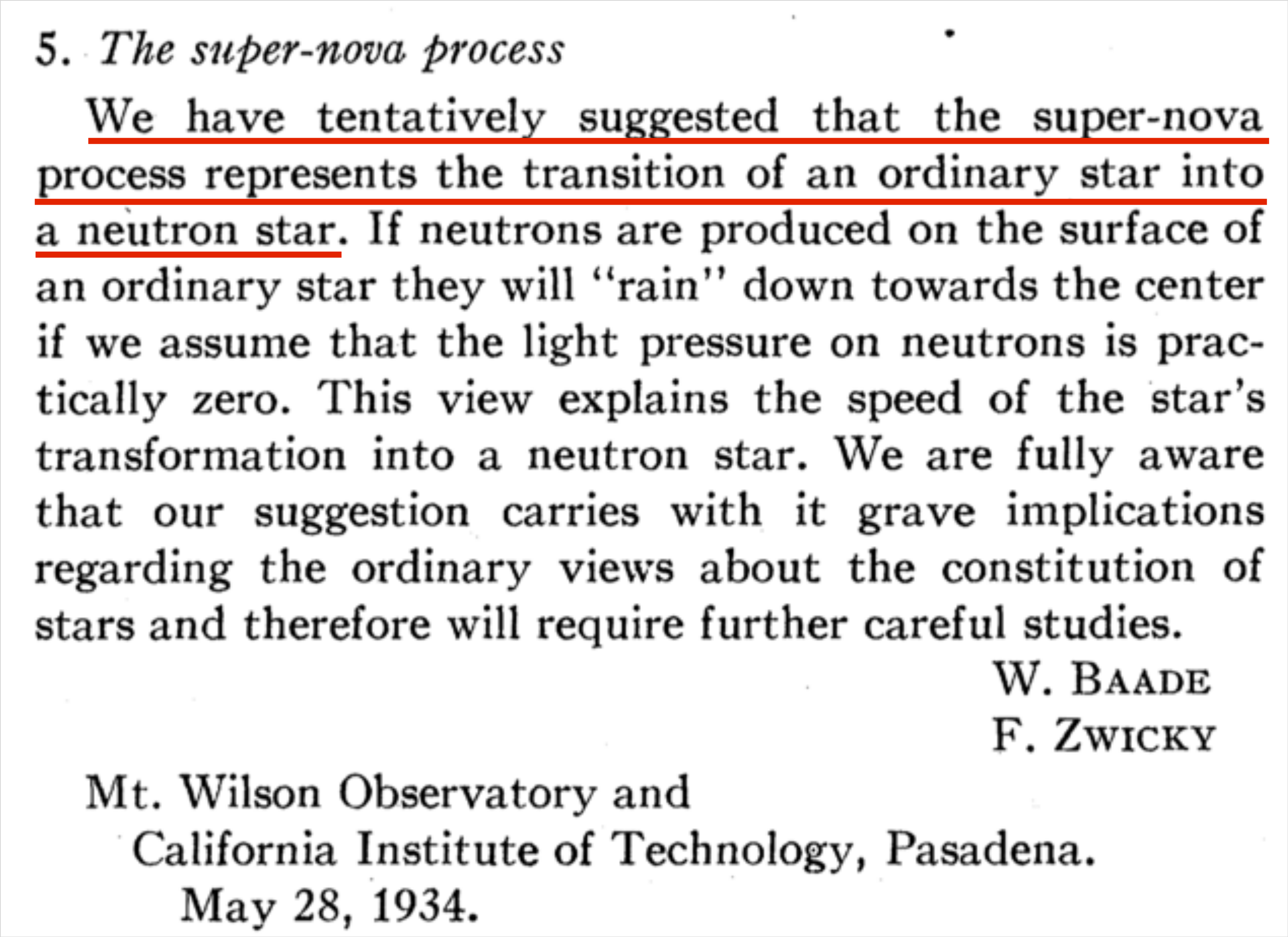
First of all

- Thank you very much for coming to Kyoto and participating our long-term workshop!
- Hope you have enjoyed life in Kyoto
- Please come back again
- last but not least:
  please acknowledge this long-term workshop when you declare new papers which are originated from here

Supernovae make neutron stars



5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE
F. ZWICKY

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

Baade & Zwicky 1934

Contents

- **What we should explain with SN simulations**
- **NS formation**
- **Binary NS formation**
- **Magnetar formation**

What we should explain with SN simulations

Key observables characterizing supernovae

- **Explosion energy:** $\sim 10^{51}$ erg
- **Ni mass:** $\sim 0.1 M_\odot$
- **Ejecta mass:** $\sim M_\odot$

related

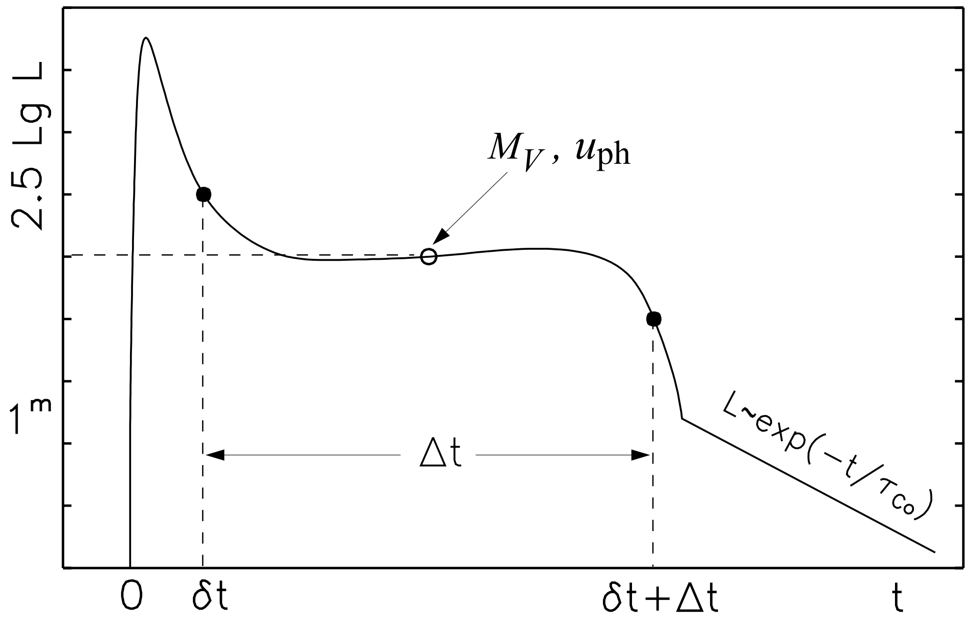
- **NS mass:** $\sim 1 - 2\ M_\odot$

measured by fitting SN light curves

measured by binary systems

final goal of first-principle (*ab initio*) simulations

Explosion energy and Ni amount

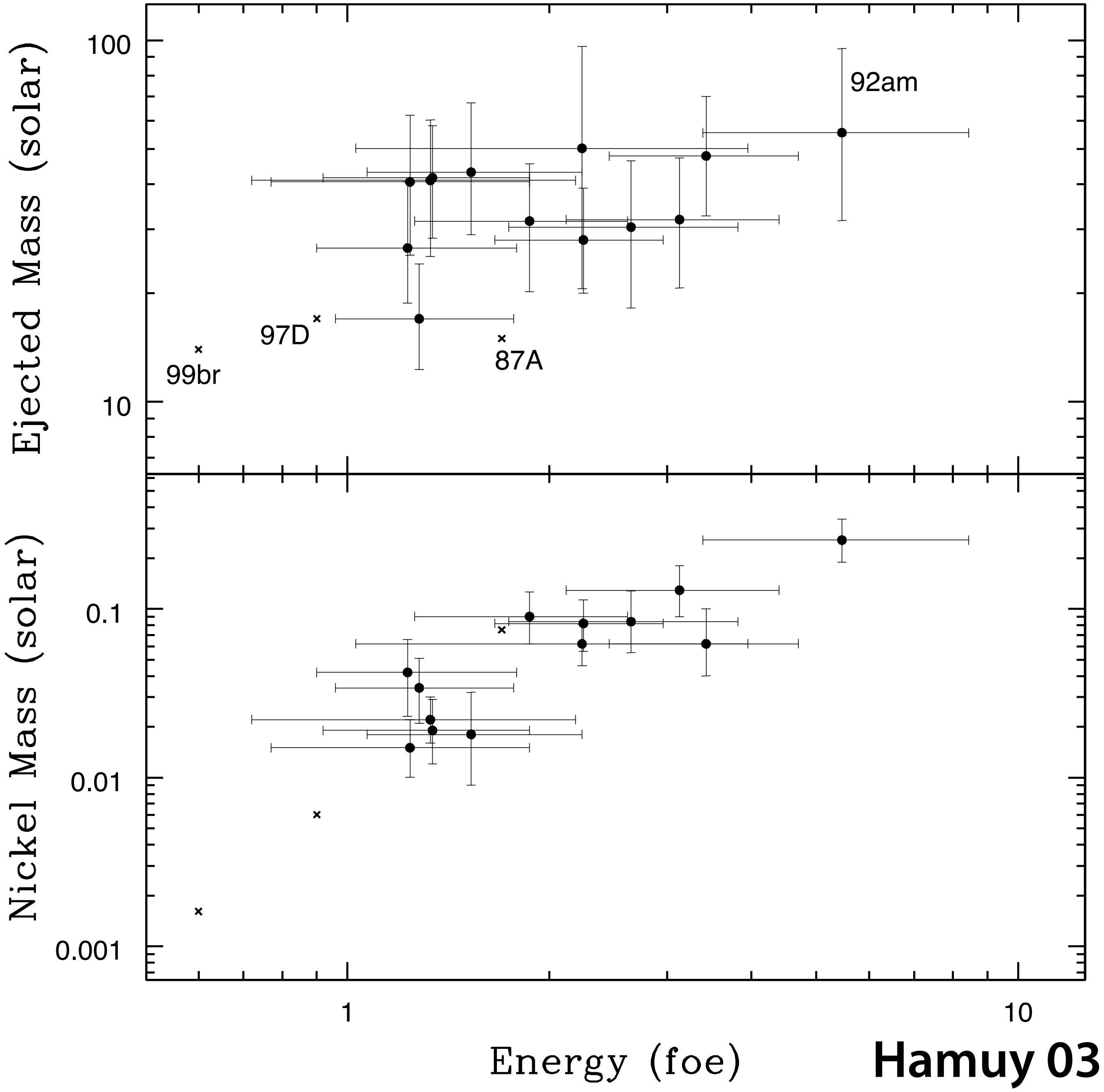


$$\lg E = -0.135 M_V + 2.34 \lg \Delta t + 3.13 \lg u_{\rm ph} - 4.205,$$

$$\lg \mathcal{M} = -0.234 M_V + 2.91 \lg \Delta t + 1.96 \lg u_{\rm ph} - 1.829,$$

$$\lg R = -0.572 M_V - 1.07 \lg \Delta t - 2.74 \lg u_{\rm ph} - 3.350,$$

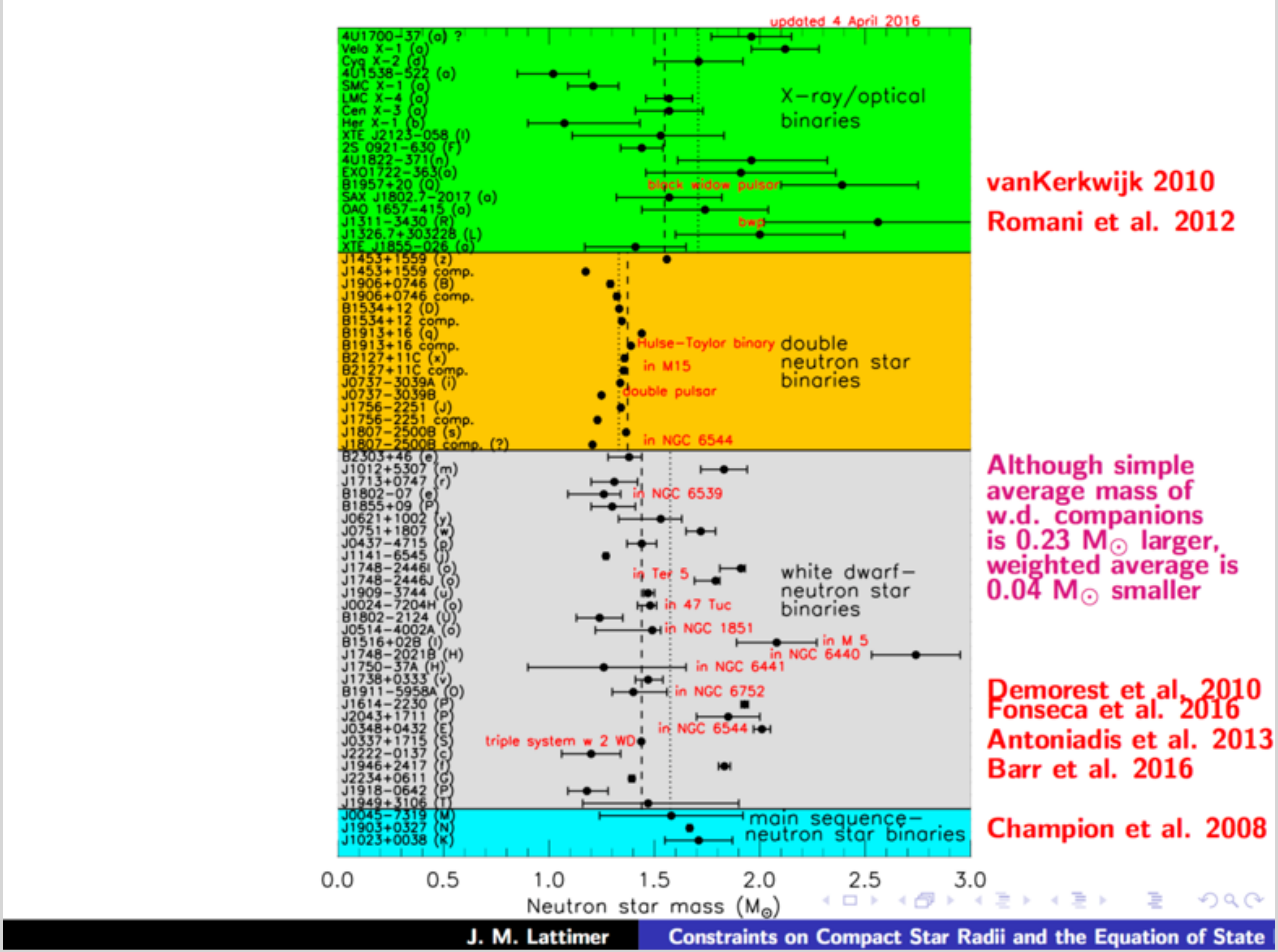
Nadyozhin 03



Hamuy 03

foe=fifty-one-erg, 10^{51} erg

NS mass measurement



vanKerkwijk 2010

Romani et al. 2012

Although simple average mass of w.d. companions is 0.23 $M_\odot$ larger, weighted average is 0.04 $M_\odot$ smaller

Demorest et al. 2010

Fonseca et al. 2016

Antoniadis et al. 2013

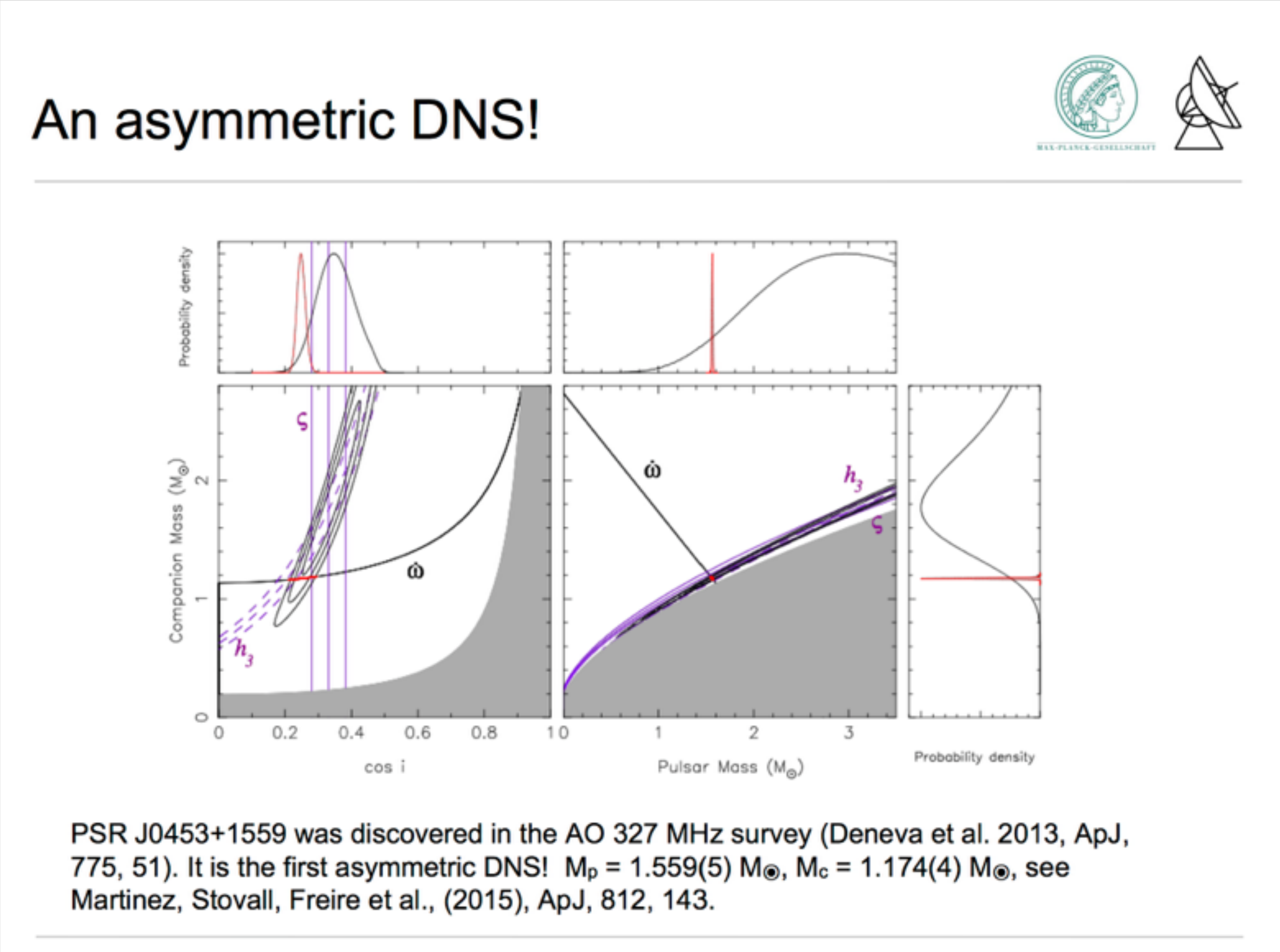
Barr et al. 2016

Champion et al. 2008

J. M. Lattimer | **Constraints on Compact Star Radii and the Equation of State**

From Lattimer's talk in conference week

NS mass measurement



An asymmetric DNS!

PSR J0453+1559 was discovered in the AO 327 MHz survey (Deneva et al. 2013, ApJ, 775, 51). It is the first asymmetric DNS! $M_p = 1.559(5)\ M_\odot$, $M_c = 1.174(4)\ M_\odot$, see Martinez, Stovall, Freire et al., (2015), ApJ, 812, 143.

From Freire's talk in conference week

Key observables characterizing supernovae

- **Explosion energy:** $\sim 10^{51}$ **erg**
- **Ni mass:** $\sim 0.1 M_\odot$
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related

- **NS mass:** $\sim 1 - 2\ M_\odot$

measured by fitting SN
light curves

measured by
binary systems

final goal of first-principle (*ab initio*) simulations

What do simulations solve?

Numerical Simulations

Hydrodynamics equations

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi,$$

$$\frac{de^*}{dt} + \nabla \cdot \left[\left(e^* + P \right) \mathbf{v} \right] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_E,$$

$$\frac{dY_e}{dt} = Q_N,$$

$$\triangle \Phi = 4\pi G \rho,$$

Solve simultaneously

Neutrino Boltzmann equation

$$\begin{aligned} &\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) + \frac{1}{r} \right] \left(1 - \mu^2 \right) \frac{\partial f}{\partial \mu} \\ &+ \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) - \frac{v}{cr} \right] E \frac{\partial f}{\partial E} \\ &= j \left(1 - f \right) - \chi f + \frac{E^2}{c \left(hc \right)^3} \\ &\times \left[\left(1 - f \right) \int R f' d\mu' - f \int R \left(1 - f' \right) d\mu' \right]. \end{aligned}$$

ρ: density, v: velocity, P: pressure, Φ: grav. potential, e^*: total energy, Y_e: elect. frac., Q: neutrino terms

f: neut. dist. func, μ: $\cos\theta$, E: neut. energy, j: emissivity, χ: absorptivity, R: scatt. kernel

What the community has done

- **Multi-D (2D/3D) hydro. simulations in cooperation with multi-energy neutrino transfer (since 2006)**
- **Explosions obtained!**
  - phase transition from qualitative research (explode or not) to quantitative research (comparison w/ observations)
- **Many systematics are under investigation**
  - EOS
  - MHD
  - GR
  - 6D properties of neutrino transfer
  - initial condition
  - etc.

What the community has't done yet

- **Not enough explosion energy (E~10^{50} erg)**
- **Not enough ^{56}Ni**
- **No full GR (magneto-)hydro. simulations with spectral neutrino transfer**
- **No 7D-neutrino transfer with hydrodynamics**
- **No consistent treatment of neutrino oscillation in transfer equation**
- **etc…**

^{56}Ni production

- M(^{56}Ni)=O(0.01)$M_\odot$
- T>5x10^9 K is necessary for ^{56}Ni production

Woosley+ 02

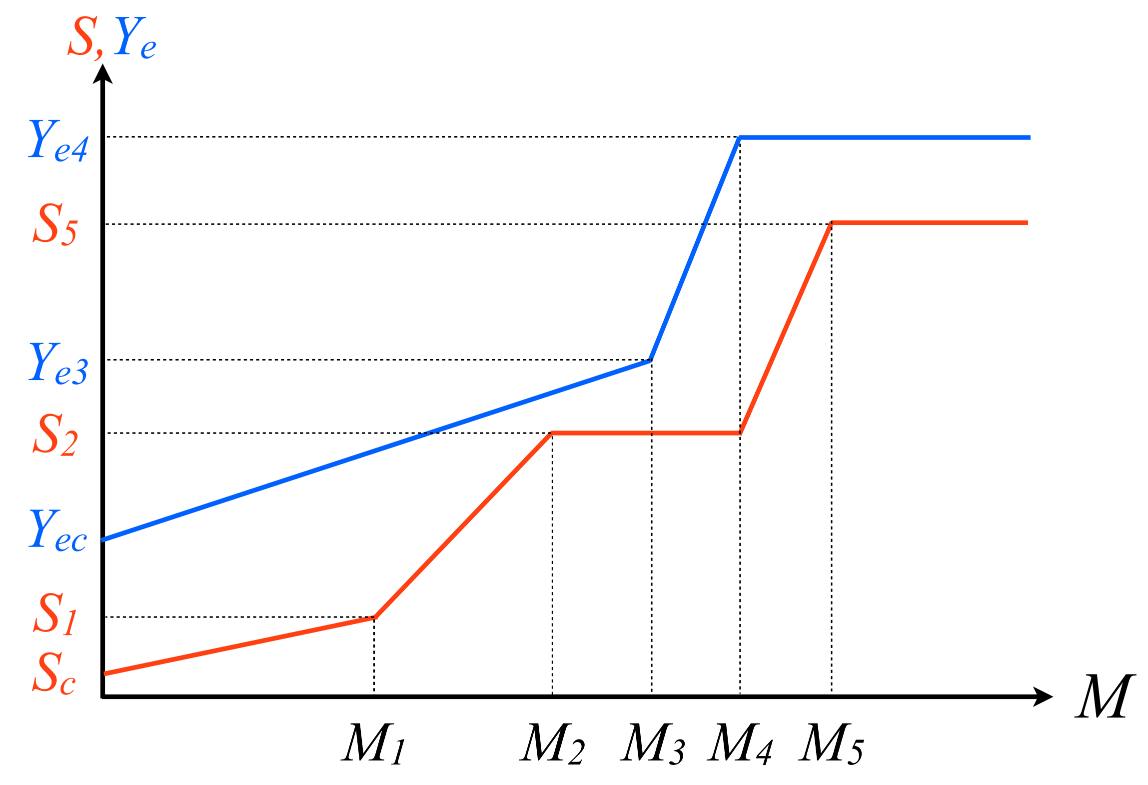
  - $E=(4\pi/3)r^3 aT^4 \Rightarrow T(r_{sh})=1.33\times10^{10}(E/10^{51}\mathrm{erg})^{1/4}(r_{sh}/1000\mathrm{km})^{-3/4}$ K
  - With E=10^{51}erg, $r_{sh}<3700$km for T>5x10^{9}K
- ^{56}Ni amount is more difficult to explain than explosion energy
  - Explosion energy can be topped up late after the onset of explosion (~O(1)s)
  - ^{56}Ni should be synthesized just after the onset of the explosion (before shock passes O(1000)km, i.e. O(0.1) s)
- It would be a benchmark test for explosion simulations

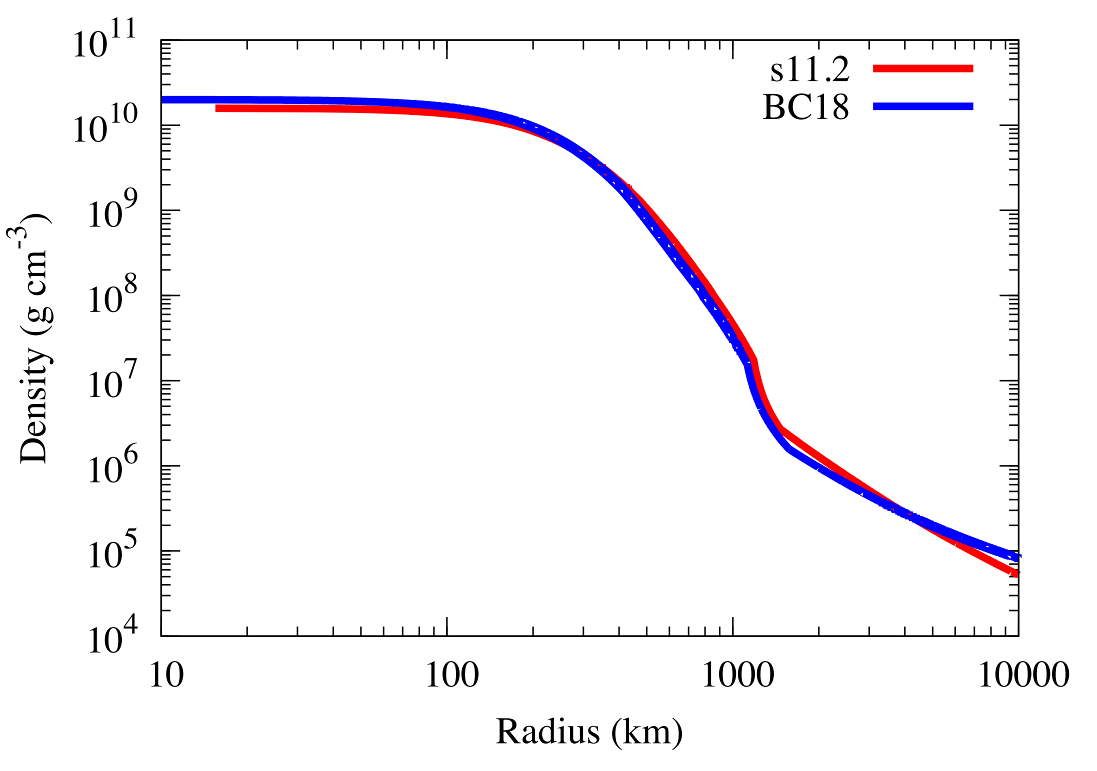
Analytic model for ^{56}Ni

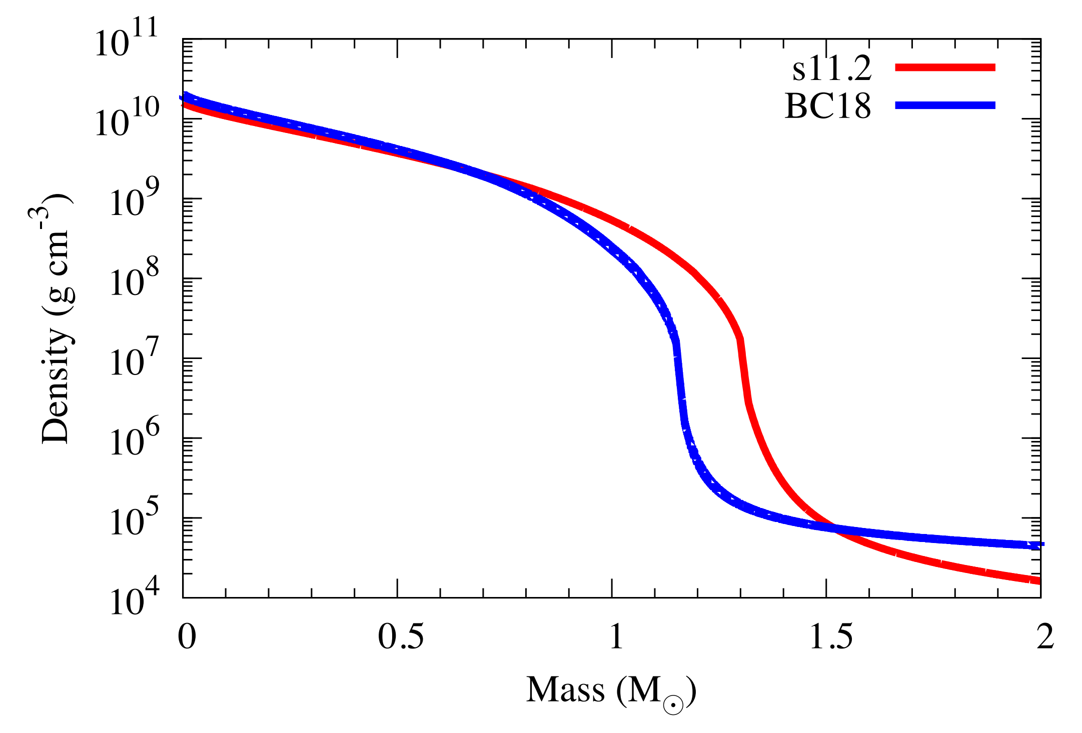
deleted

To solve Ni and expl. ene. problems

[Suwa & Müller, MNRAS, 460, 2664 (2016)]







M_1: the edge of the final convection in the radiative core

M_2: the inner edge of the convection zone in the iron core

M_3: the NSE core

M_4: the iron core mass

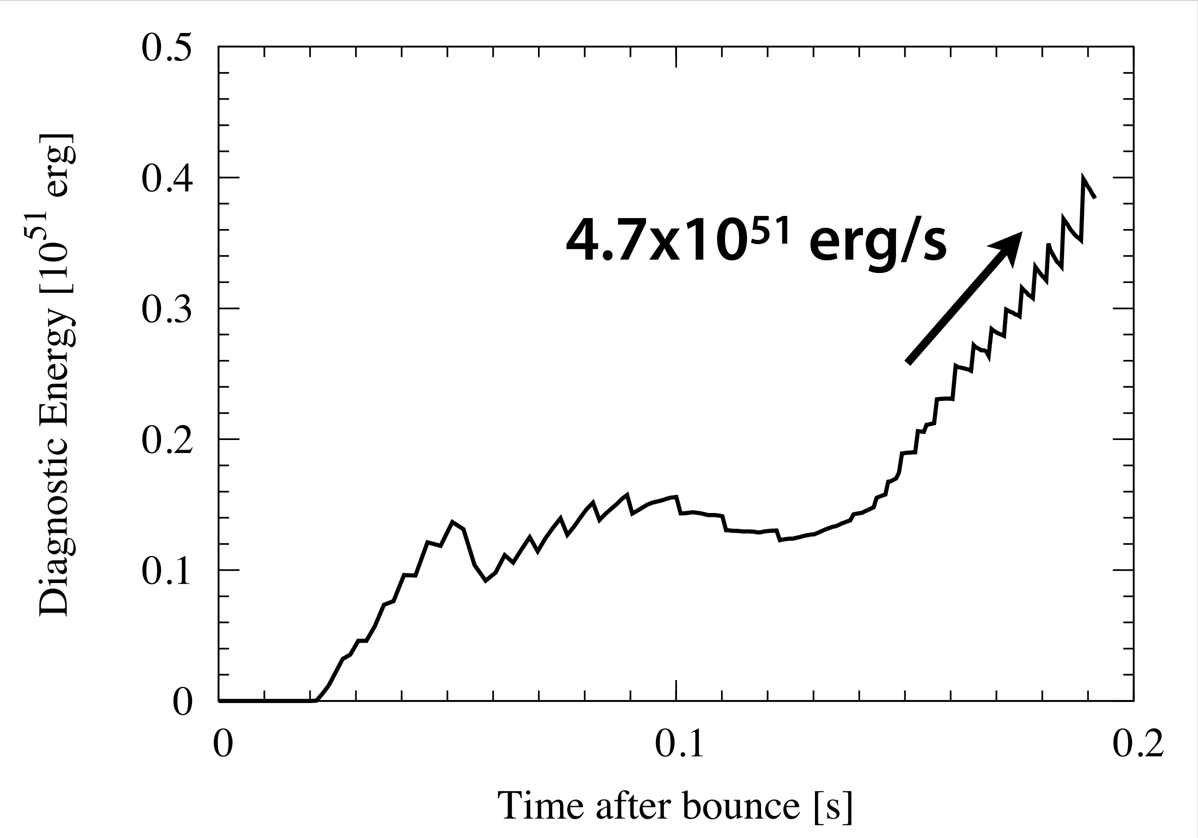
M_5: the base of the silicon/oxygen shell

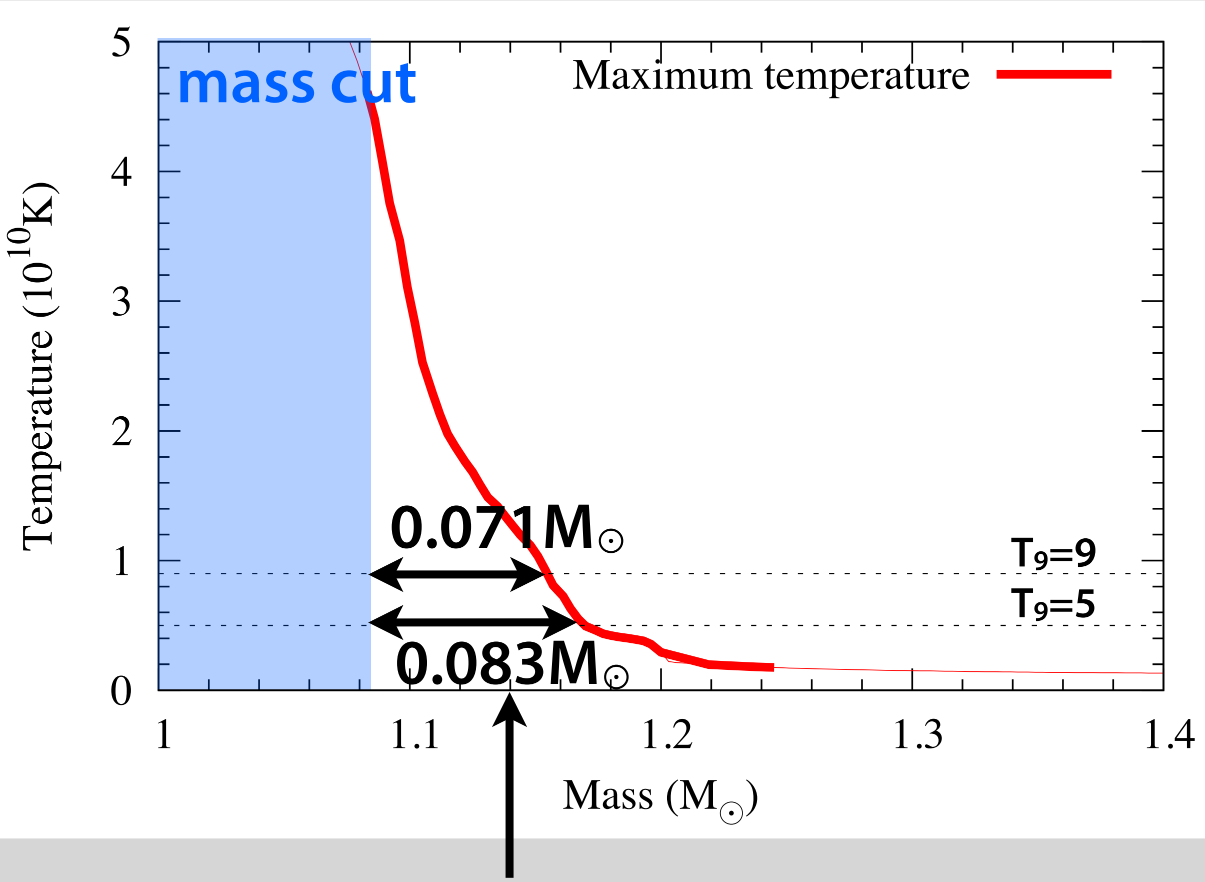
To solve Ni and expl. ene. problems

[Suwa & Müller, MNRAS, 460, 2664 (2016)]

https://physik.unibas.ch/~liebend/download/

Agile-IDSA: 1D/GR/neutrino-radiation hydro code, publicly available



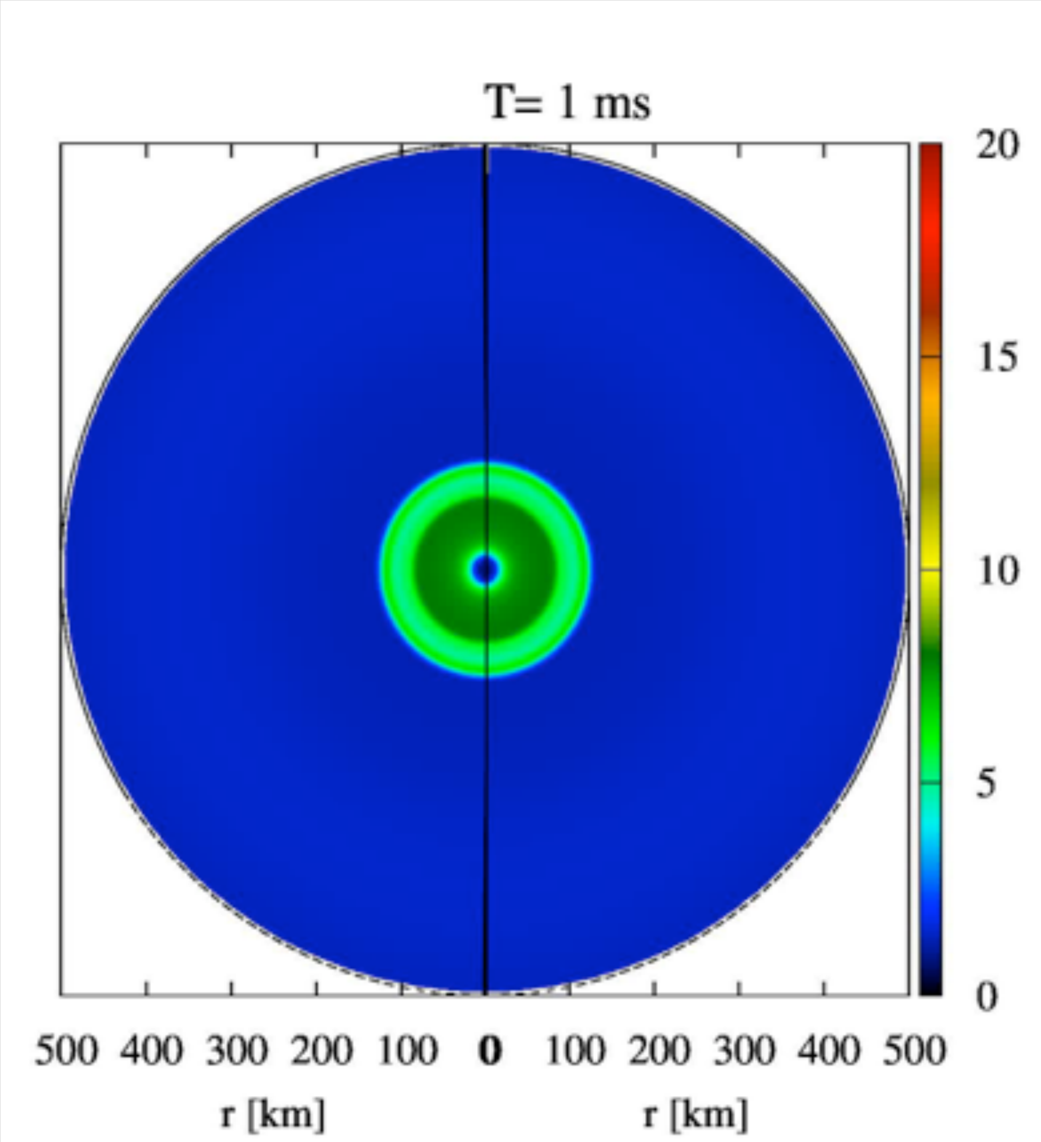


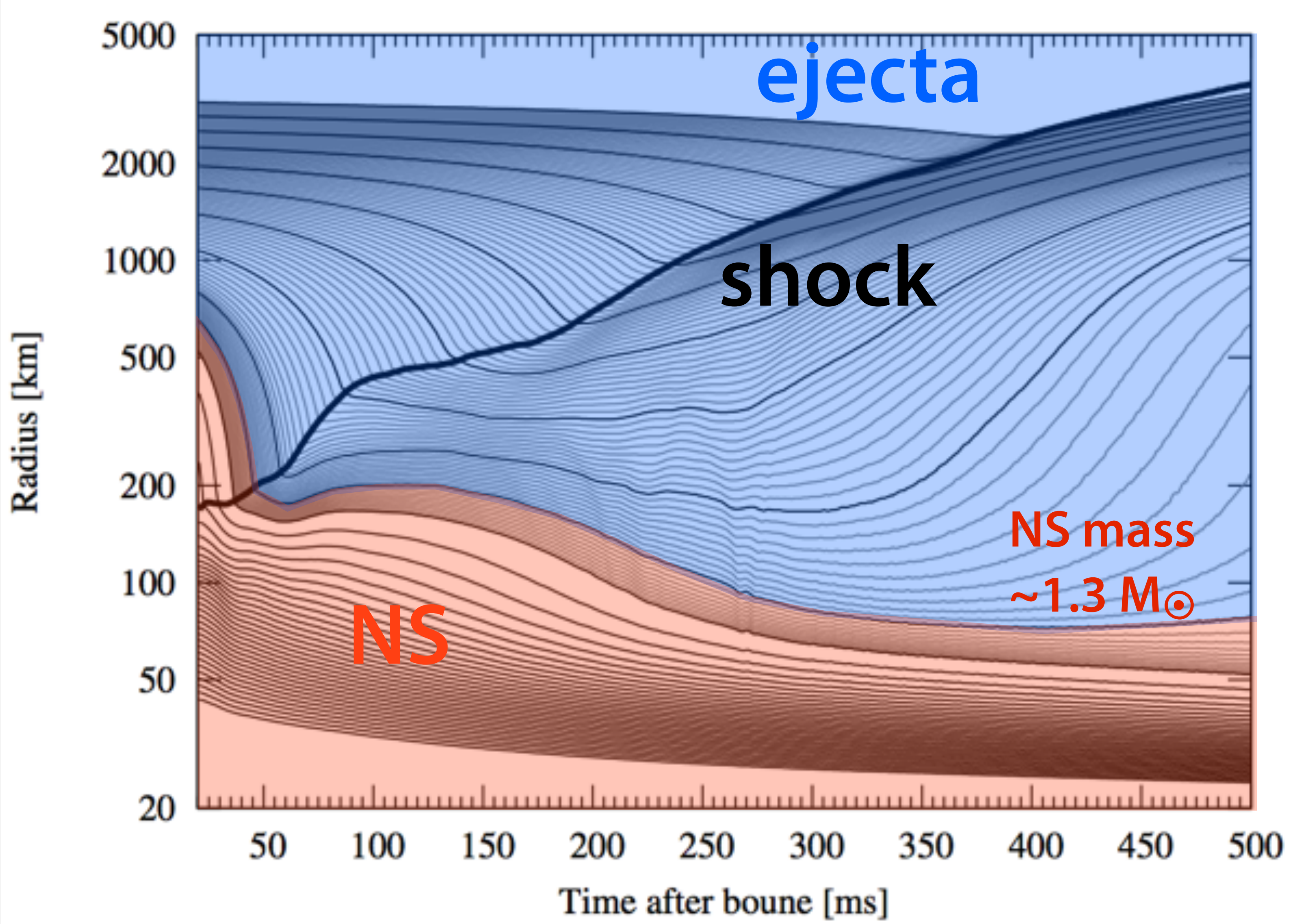
approx. ^{56}Ni mass

NS formation

From SN to NS

[Suwa, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ, **764**, 99 (2013); Suwa, PASJ, **66**, L1 (2014)]

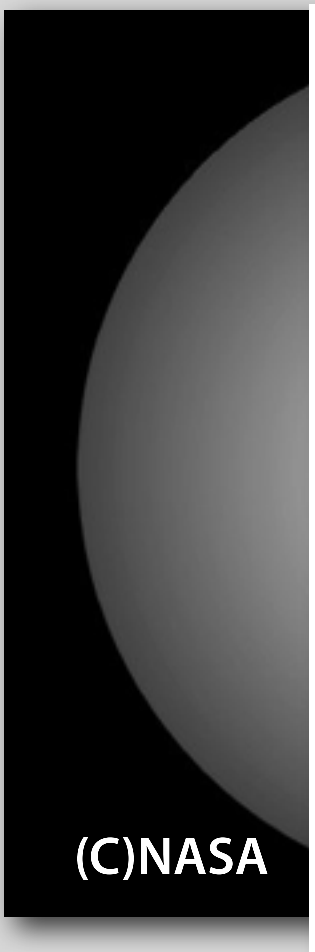




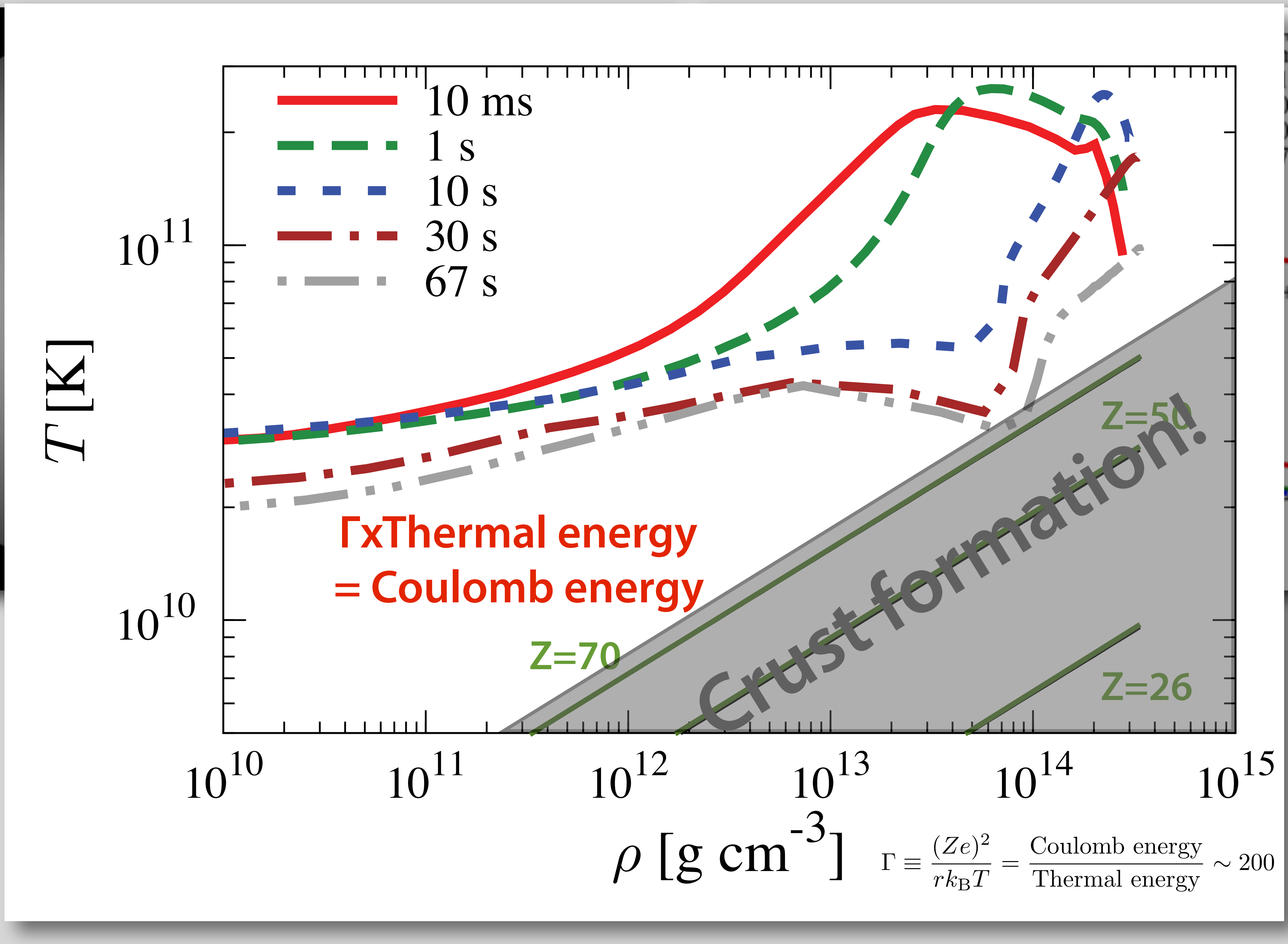
- **Progenitor:** $11.2\ M_\odot$ (Woosley+ 2002)
- **Successful explosion! (but still weak with** E_{exp}~10^{50} **erg)**
- **The mass of NS is** $\sim 1.3\ M_\odot$
- **The simulation was continued in 1D to follow the PNS cooling phase up to ~70 s p.b.**

From SN to NS

[Suwa, PASJ, 66, L1 (2014)]



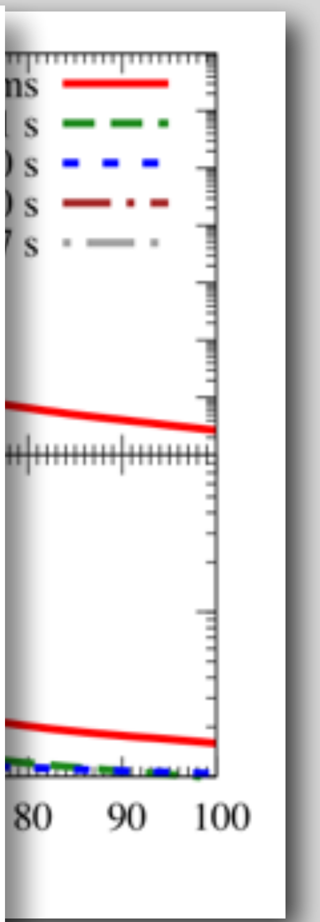
(C)NASA



ΓxThermal energy = Coulomb energy

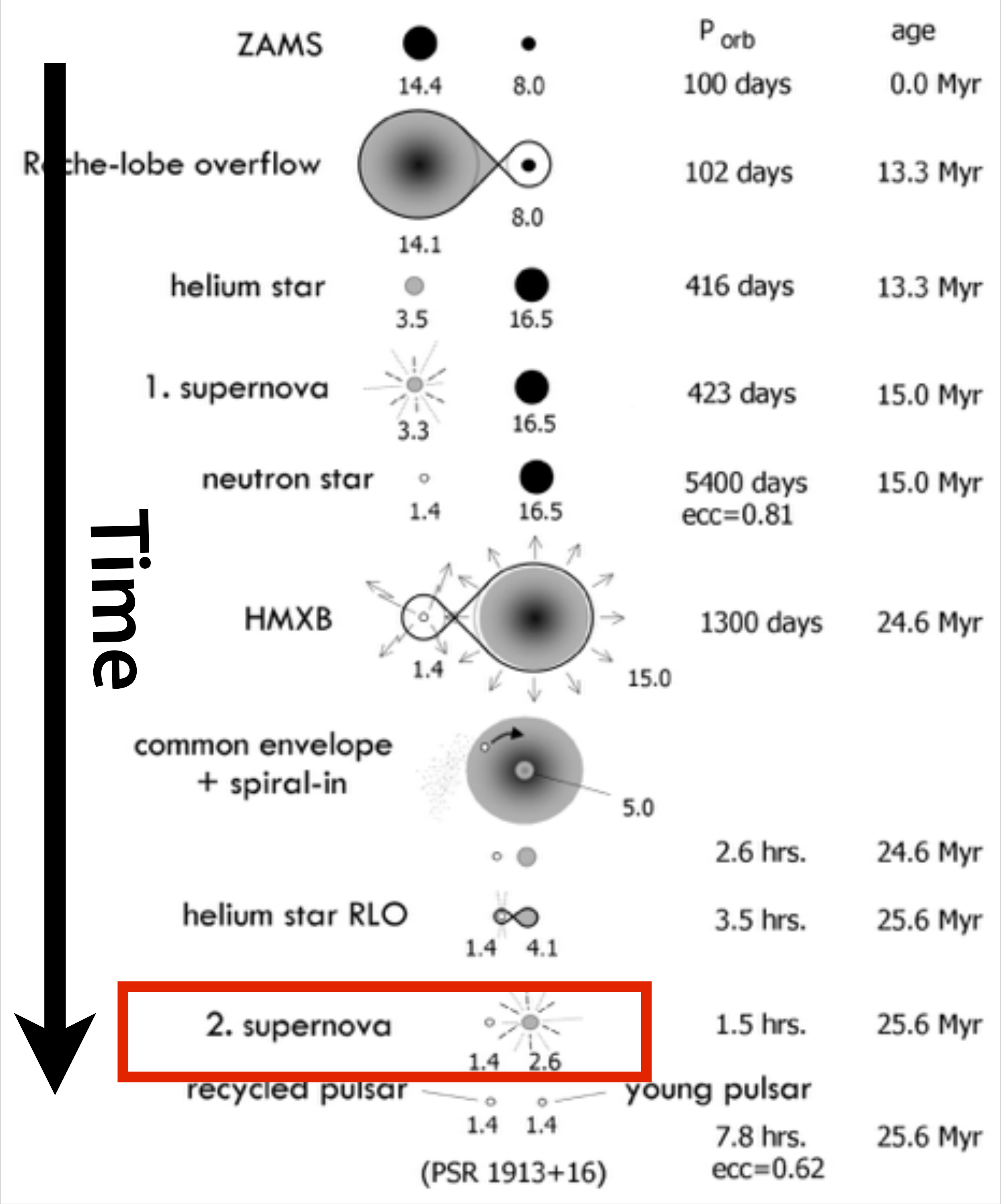
Crust formation!

$$\Gamma \equiv \frac{(Ze)^2}{r k_{\rm B} T} = \frac{\text{Coulomb energy}}{\text{Thermal energy}} \sim 200$$

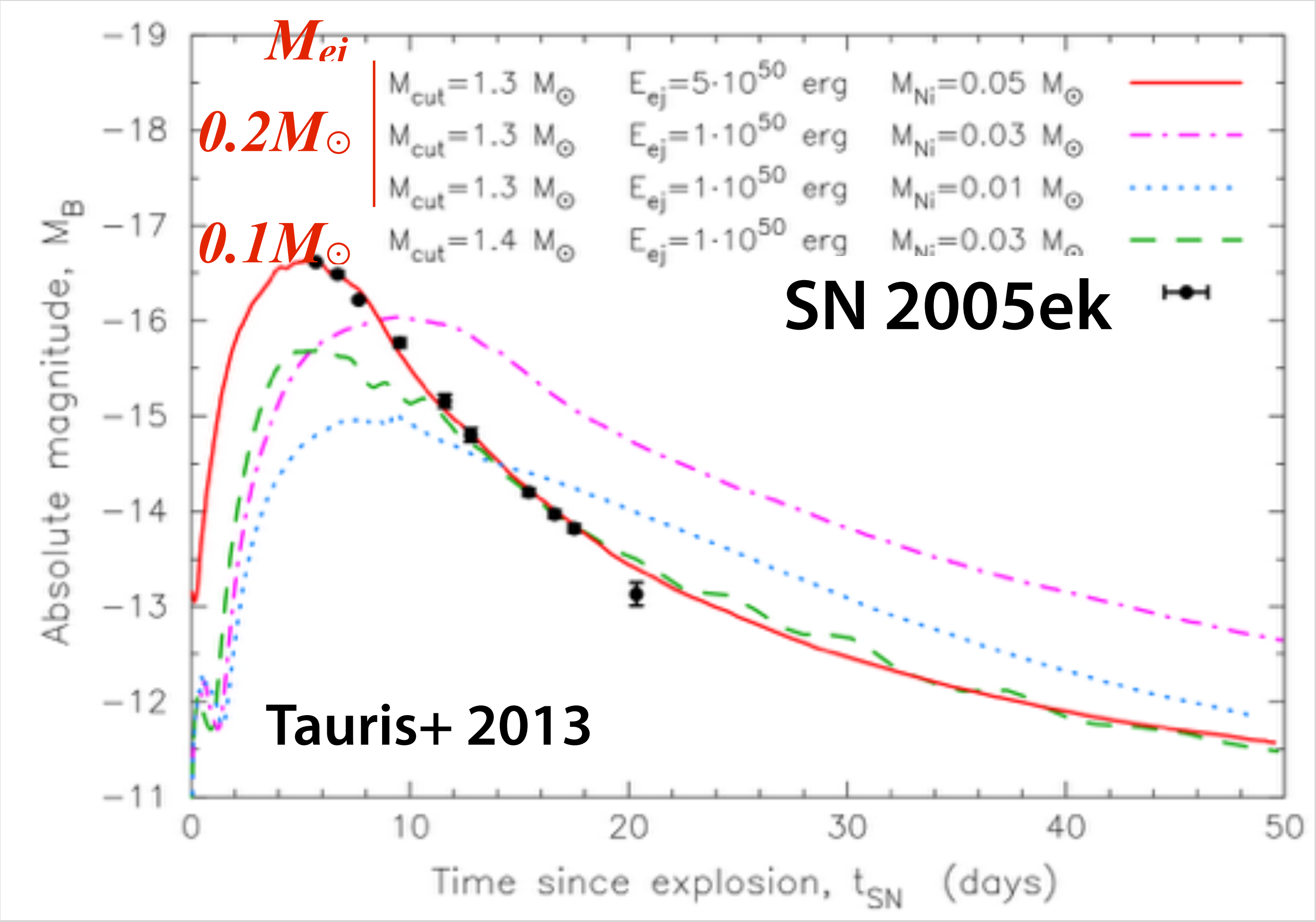


Binary NS formation

How to make binary NSs?



Tauris & van den Heuvel 2006

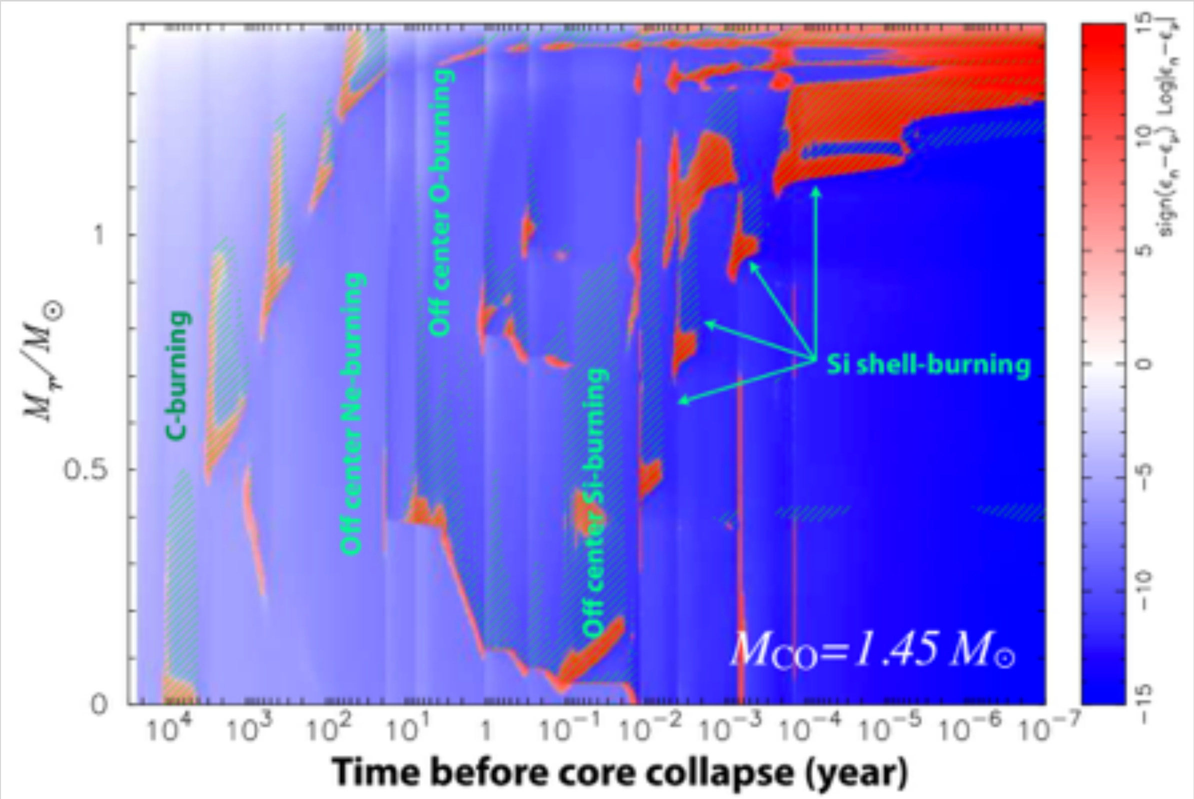


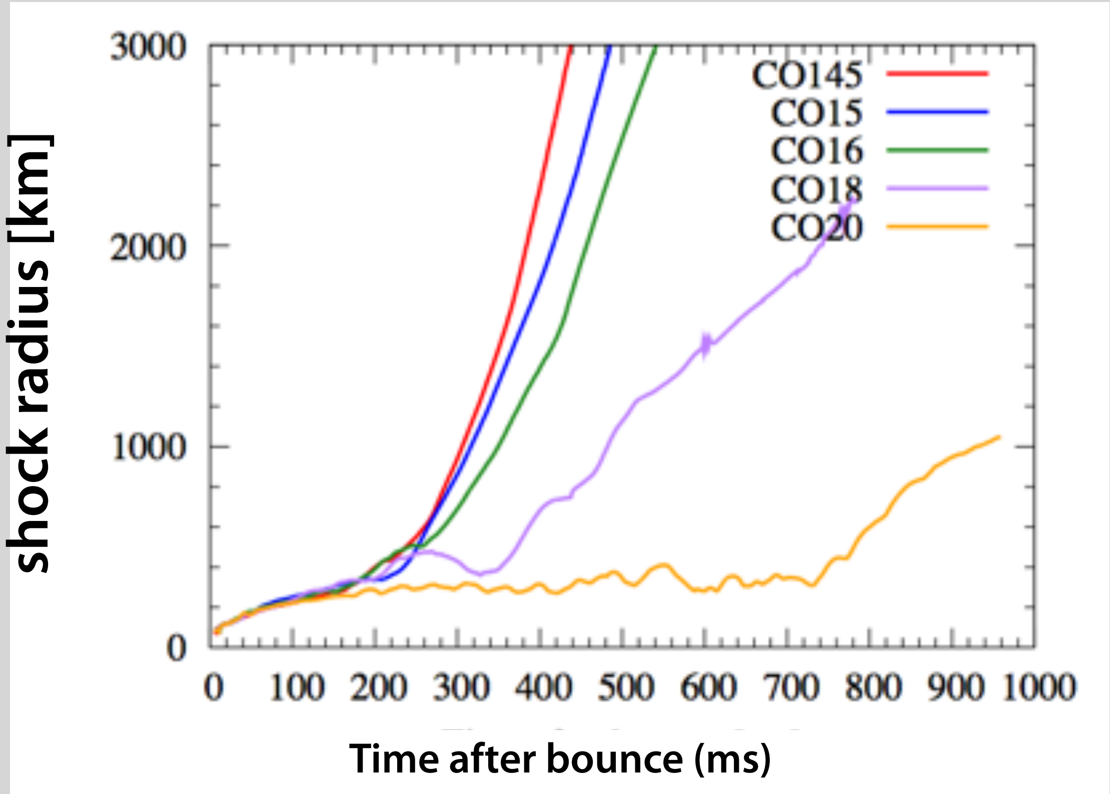
- new class of SNe
- rapidly evolving light curve -> very small ejecta mass
- possible generation sites of binary neutron stars

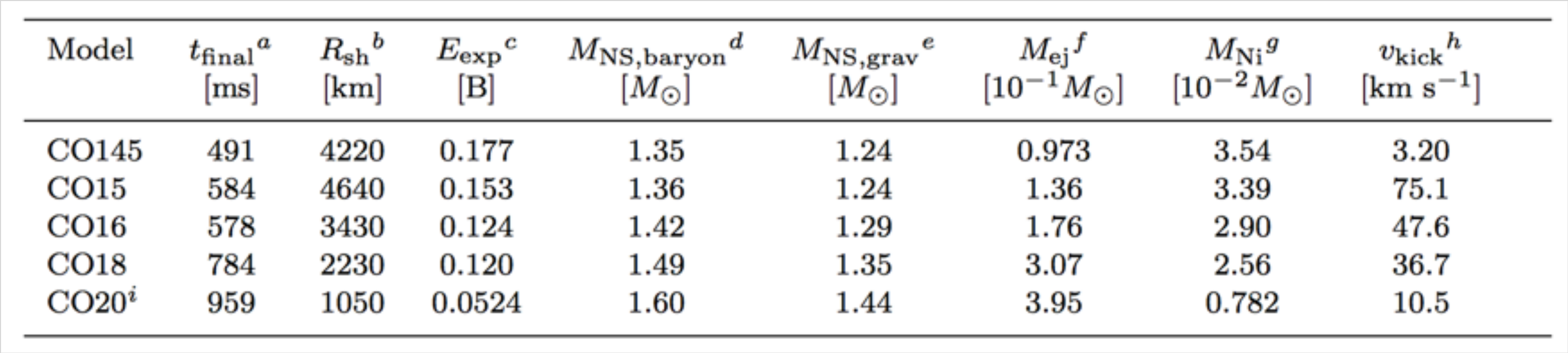
(synergy w/ gravitational wave!)

Ultra-stripped type-Ic supernovae

[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

Magnetar formations

Magnetar

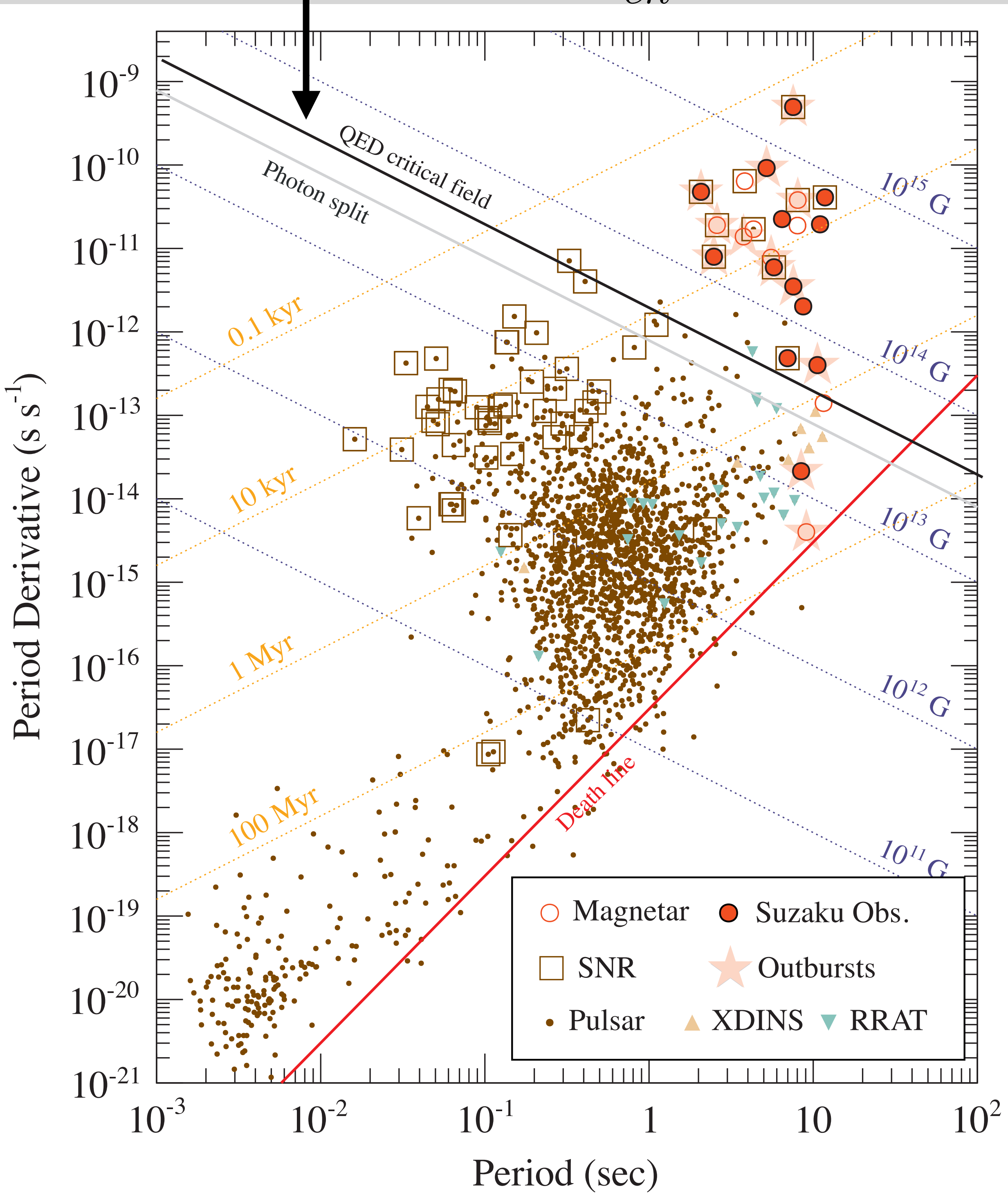
$$B_s \propto \sqrt{P\dot{P}}$$

$$B_Q = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\mathrm{G}$$

- Subclass of neutron stars
- Soft Gamma Repeater (SGR)
- Anomalous X-ray Pulsar (AXP)
- Surface magnetic field from P&$\dot{P}$ ~$10^{14\text{-}15}$ G (>B_Q=4.4x10^{13}G)
- rotation period ~2-12s
- 29 magnetars: 15 SGRs (including 4 candidates), 14 AXPs (including 2 candidates) as of 24/3/2016.

http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

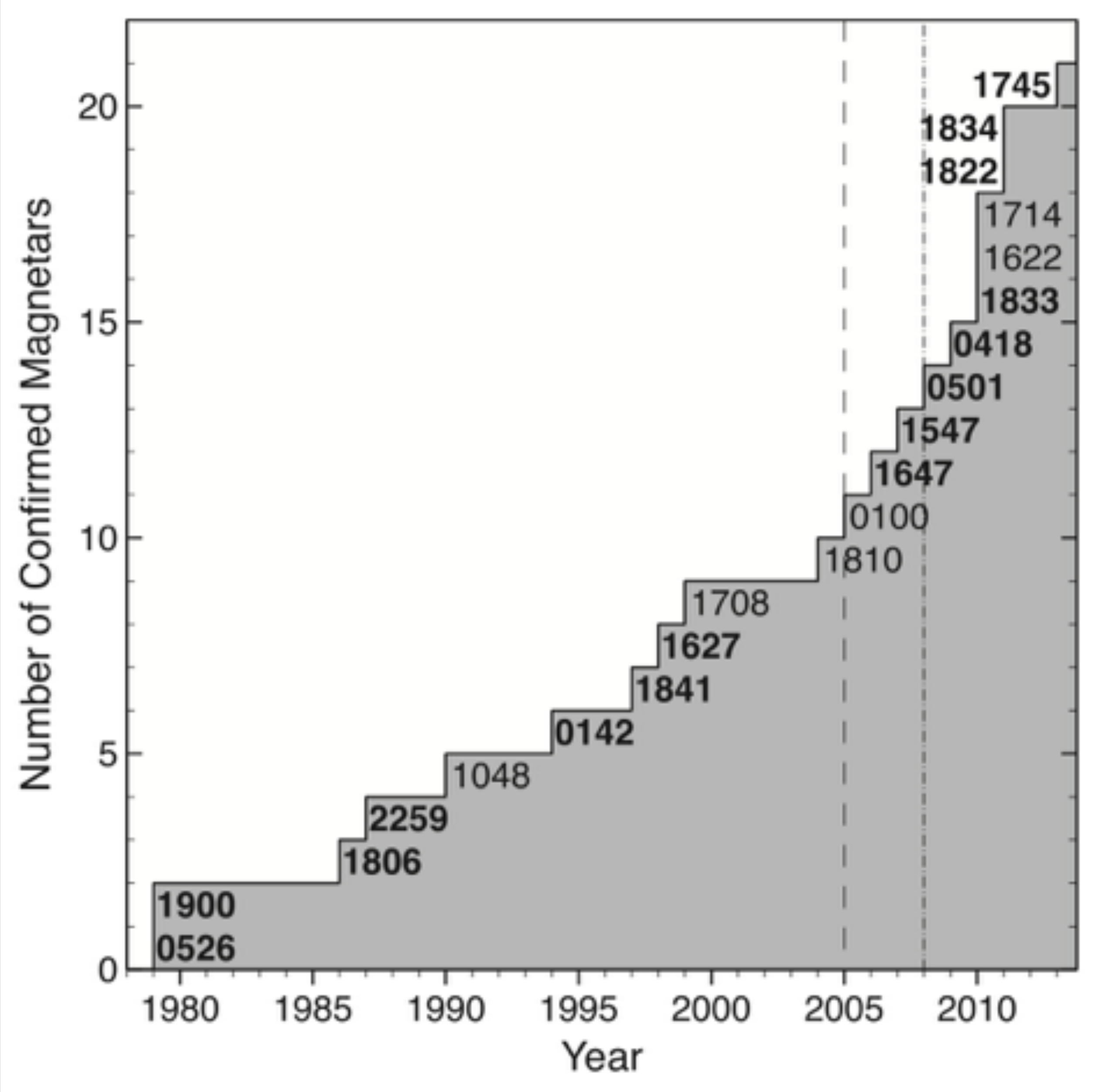
(first report was in 1979)



Enoto, Shibata, Kitaguchi, Suwa+, submitted

Magnetar birth rate

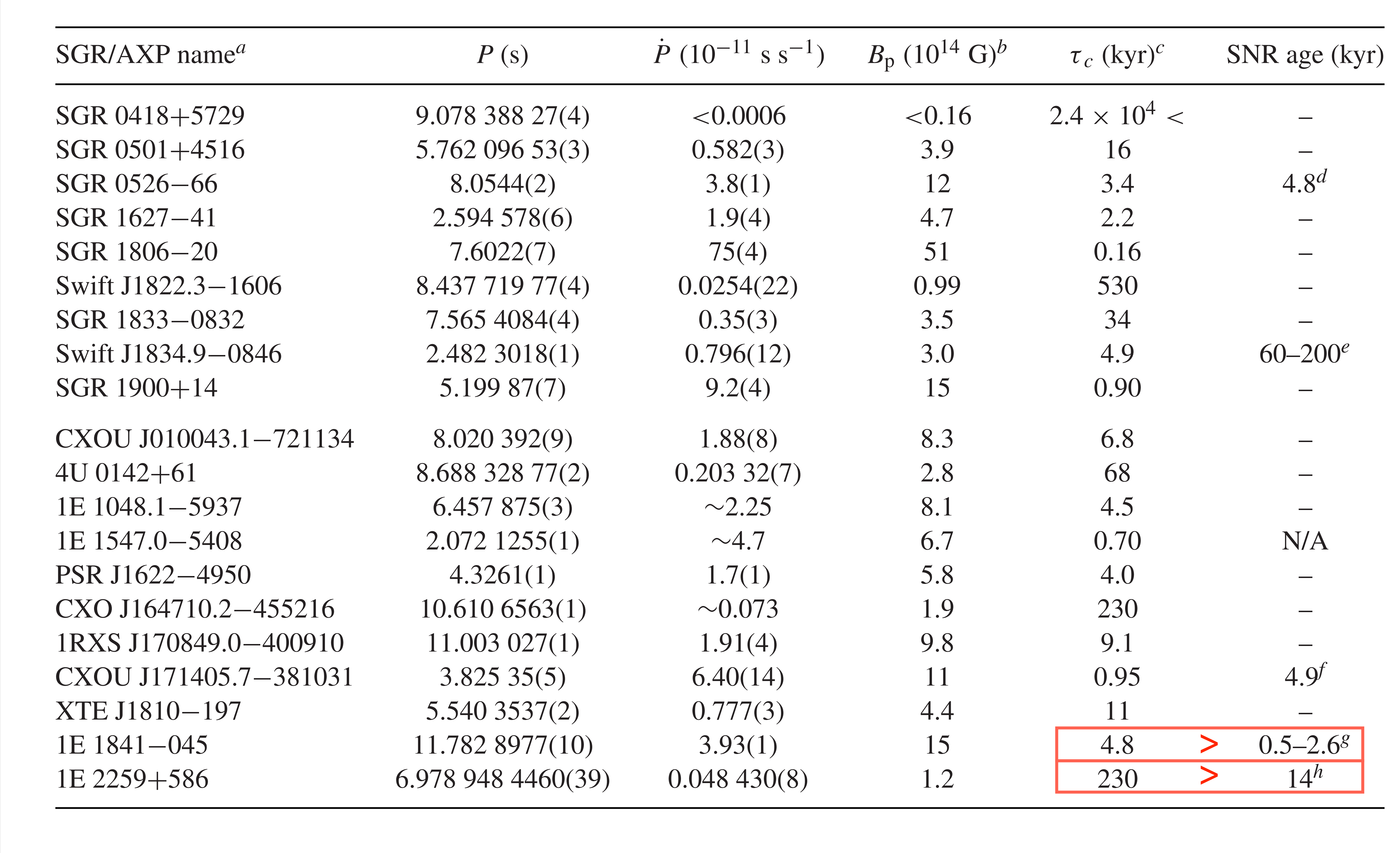
- N_{mag}~30 (SGRs & AXPs) found in our Galaxy so far
- typical age: $\tau_c \sim 10^4$ years (estimated by characteristic age; $P/2\dot{P}$)
- typical birth rate: $N_{mag}/\tau_c \sim 10^{-3}$ year^{-1}~0.1 SN rate
    - ~10% of SNe generate magnetars?
    - observationally, N_{mag} is increasing by ~1/year
    - 100% of SNe generated magnetars at 100 years from now?



Olausen & Kaspi 14

Magnetars & SNRs

[Suwa & Enoto, MNRAS, 443, 3586 (2014)]

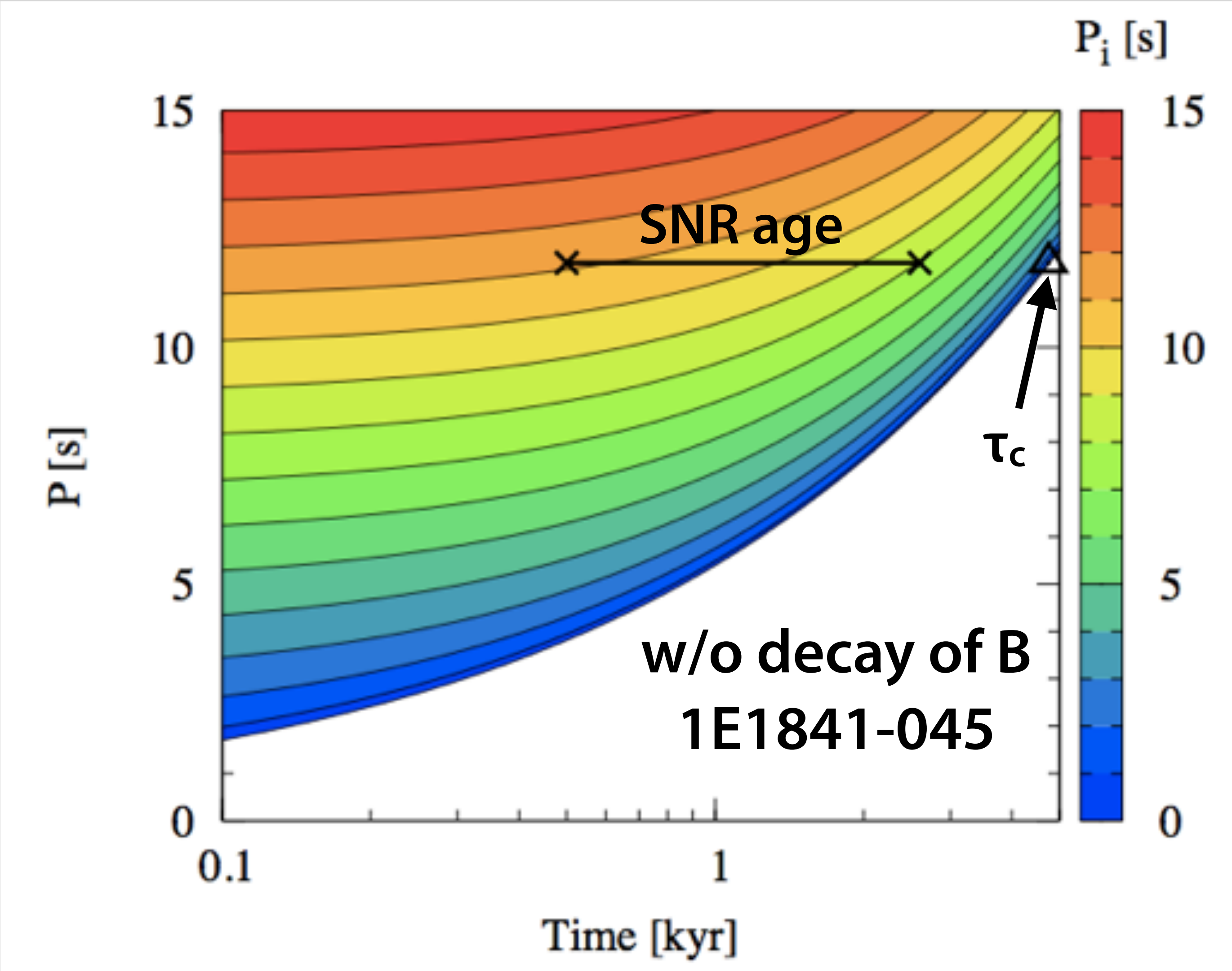


SGR/AXP name[a]	P (s)	$\dot{P}$ (10^{-11} s s^{-1})	B_p (10^{14} G)[b]	τ_c (kyr)[c]	SNR age (kyr)
SGR 0418+5729	9.078 388 27(4)	<0.0006	<0.16	$2.4 \times 10^4 <$	–
SGR 0501+4516	5.762 096 53(3)	0.582(3)	3.9	16	–
SGR 0526−66	8.0544(2)	3.8(1)	12	3.4	4.8[d]
SGR 1627−41	2.594 578(6)	1.9(4)	4.7	2.2	–
SGR 1806−20	7.6022(7)	75(4)	51	0.16	–
Swift J1822.3−1606	8.437 719 77(4)	0.0254(22)	0.99	530	–
SGR 1833−0832	7.565 4084(4)	0.35(3)	3.5	34	–
Swift J1834.9−0846	2.482 3018(1)	0.796(12)	3.0	4.9	60–200[e]
SGR 1900+14	5.199 87(7)	9.2(4)	15	0.90	–
CXOU J010043.1−721134	8.020 392(9)	1.88(8)	8.3	6.8	–
4U 0142+61	8.688 328 77(2)	0.203 32(7)	2.8	68	–
1E 1048.1−5937	6.457 875(3)	∼2.25	8.1	4.5	–
1E 1547.0−5408	2.072 1255(1)	∼4.7	6.7	0.70	N/A
PSR J1622−4950	4.3261(1)	1.7(1)	5.8	4.0	–
CXO J164710.2−455216	10.610 6563(1)	∼0.073	1.9	230	–
1RXS J170849.0−400910	11.003 027(1)	1.91(4)	9.8	9.1	–
CXOU J171405.7−381031	3.825 35(5)	6.40(14)	11	0.95	4.9[f]
XTE J1810−197	5.540 3537(2)	0.777(3)	4.4	11	–
1E 1841−045	11.782 8977(10)	3.93(1)	15	4.8	> 0.5–2.6[g]
1E 2259+586	6.978 948 4460(39)	0.048 430(8)	1.2	230	> 14[h]

see also Olausen & Kaspi 14

Spin evolution

[Suwa & Enoto, MNRAS, **443**, 3586 (2014)]

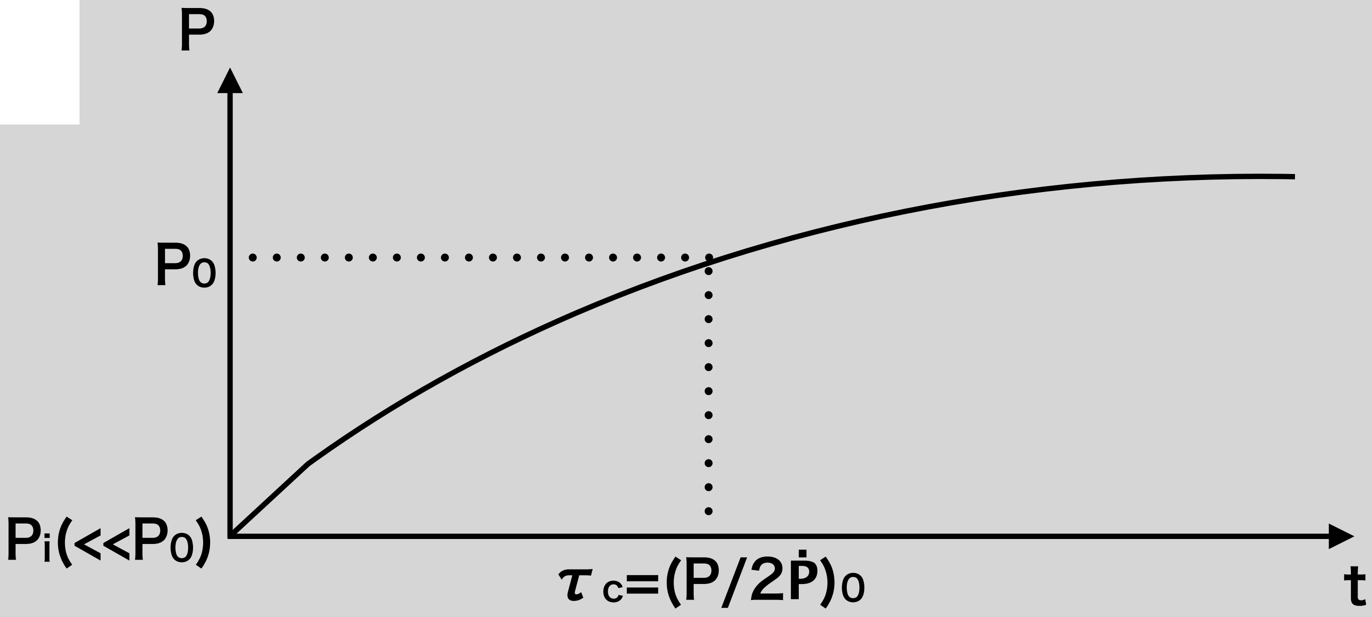


Canonical dipole radiation predicts

$$P = P_i \left(1 + \frac{2P^2}{P_i^2}\frac{t}{T}\right)^{1/2}$$

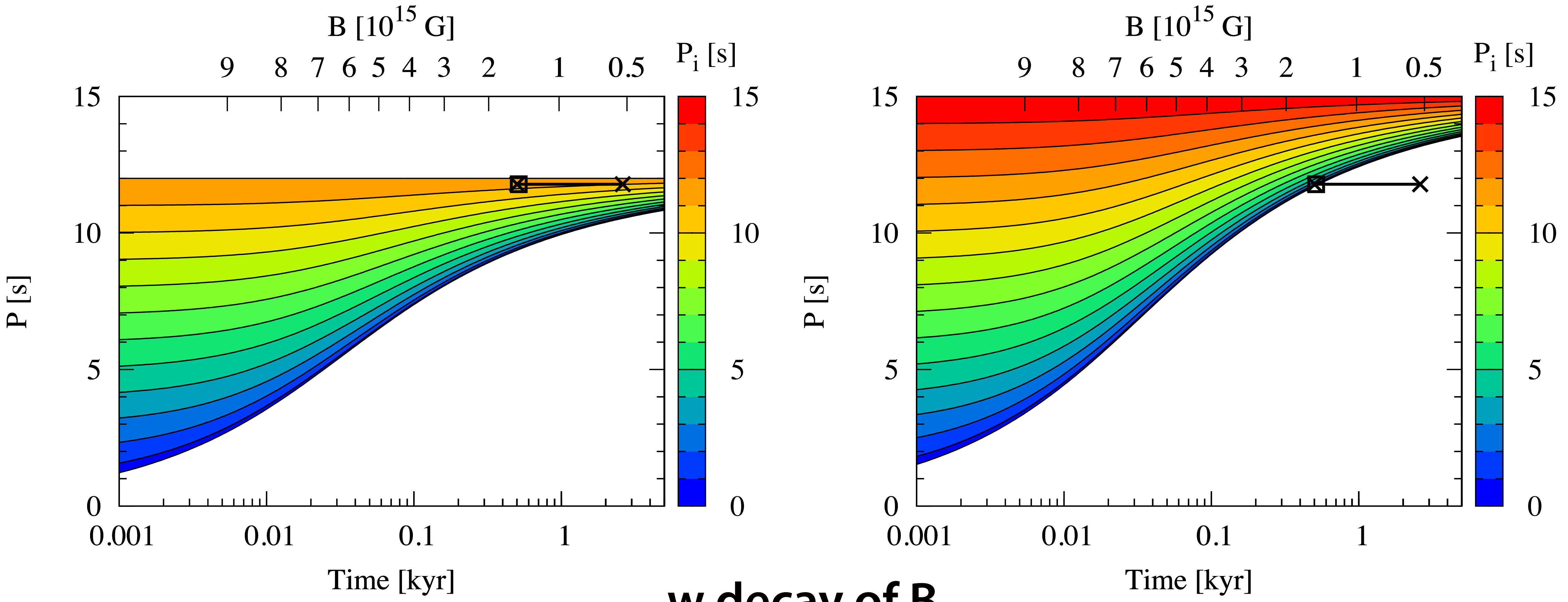
Spin-down timescale

$$T = \frac{P}{\dot{P}} = \frac{3Ic^3P^2}{2\pi^2 B_p^2 R^6 \sin^2\alpha}$$
$$= 145\,\mathrm{yr}\left(\frac{B_p}{10^{15}\,\mathrm{G}}\right)^{-2}\left(\frac{R}{10\,\mathrm{km}}\right)^{-4}\left(\frac{M}{1.4\,M_\odot}\right)\left(\frac{P}{1\mathrm{s}}\right)^2$$



Spin evolution

[Suwa & Enoto, MNRAS, **443**, 3586 (2014)]



w decay of B

(a) $P_\infty = 12$ s

(b) $P_\infty = 15$ s

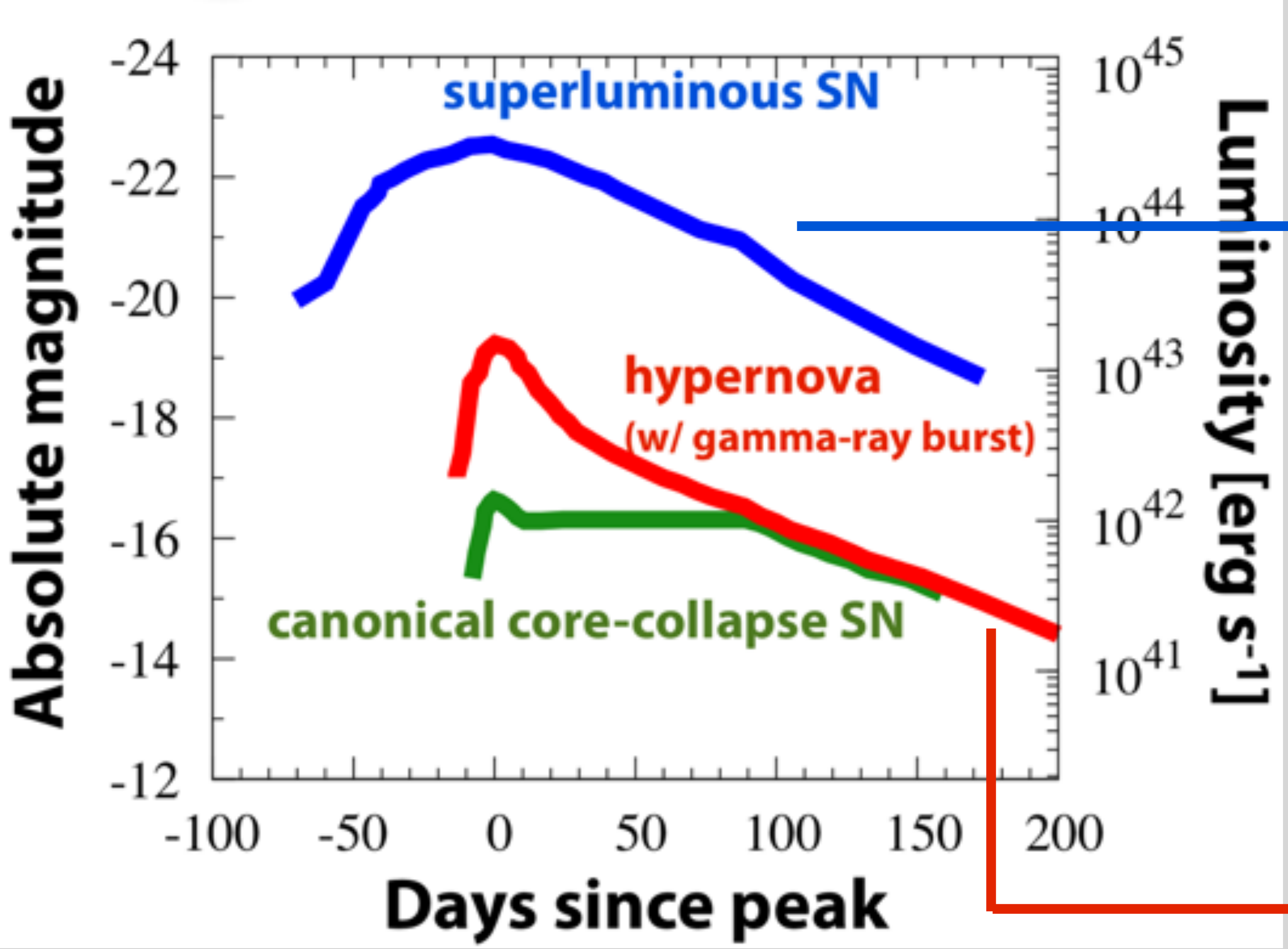
Recently favored model
Dall'Osso+ 12
Pons+ 13

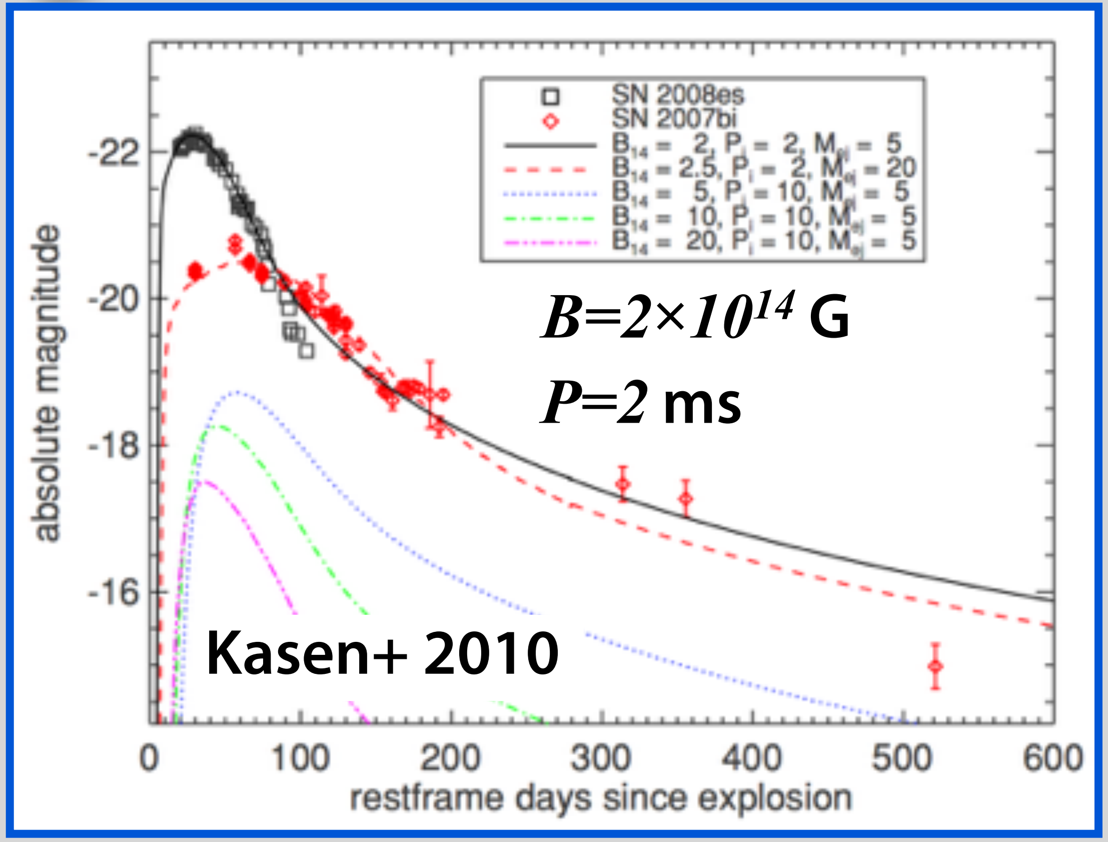
$$P^2(t) = P_\infty^2 - (P_\infty^2 - P_i^2)\left(1 + \frac{t}{\tau_d}\right)^{(\alpha_B-2)/\alpha_B}$$

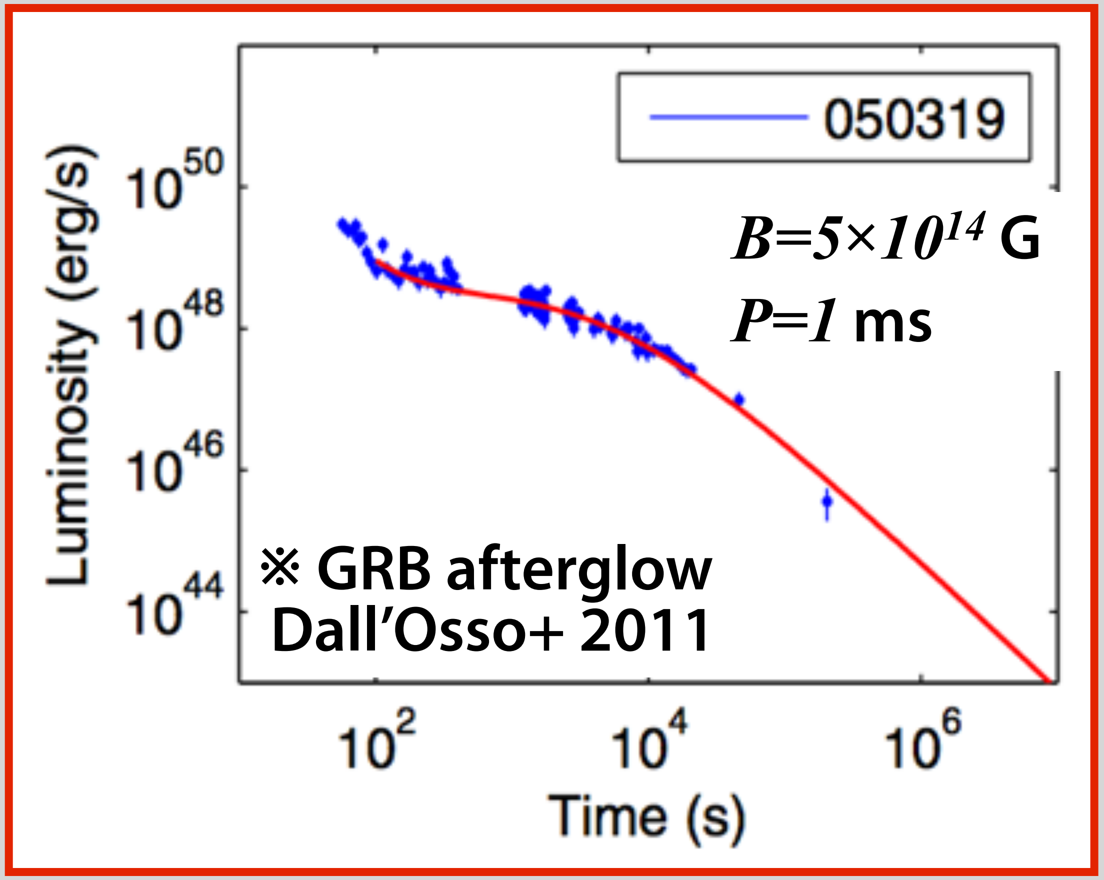
$$B_p(t) = \frac{B_i}{(1 + t/\tau_d)^{1/\alpha_B}}$$

Colpi+ 00
Dall'Osso+ 12

Magnetar formation and bright transients







- SLSNe and GRB afterglows can be fitted by strongly magnetize NS (magnetar) model
- ALL models based on dipole radiation formula ($L\sim B^2P^{-4}$, $\Delta t\sim B^{-2}P^2$)
- $B\sim O(10^{14})$G, $P\sim O(1)$ms

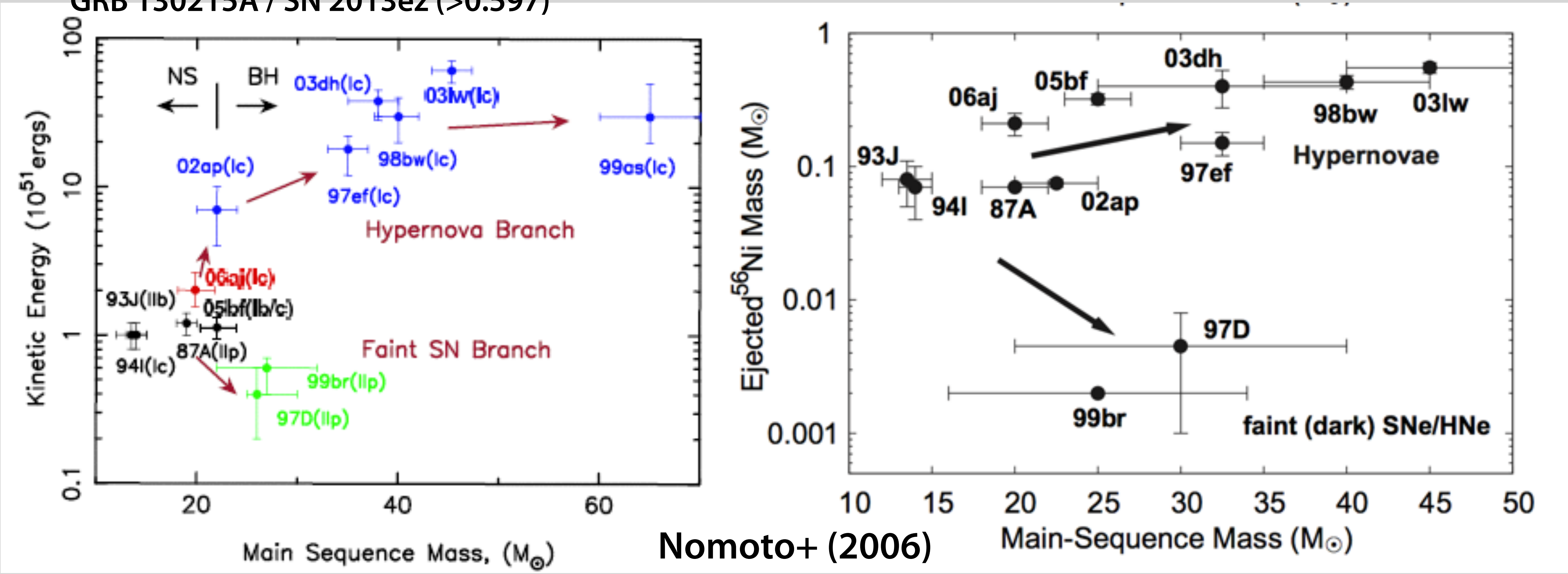
GRBs and SN Ic-bl

GRB -SN association

Modjaz+, arXiv:1509.07124

GRB	SN
GRB 980425	SN 1998bw (z=0.0085)
GRB 030329	SN 2003dh (0.1685)
GRB 031203	SN 2003lw (0.1006)
GRB 060218	SN 2006aj (0.0335)
GRB 091127	SN 2009nz (0.490)
GRB 100316D	SN 2010bh (0.0591)
GRB 101219B	SN 2010ma (0.55)
GRB 120422A	SN 2012bz (0.2825)
GRB 130427A	SN 2013cq (0.3399)
GRB 130702A	SN 2013dx (0.1450)
GRB 130215A	SN 2013ez (>0.597)

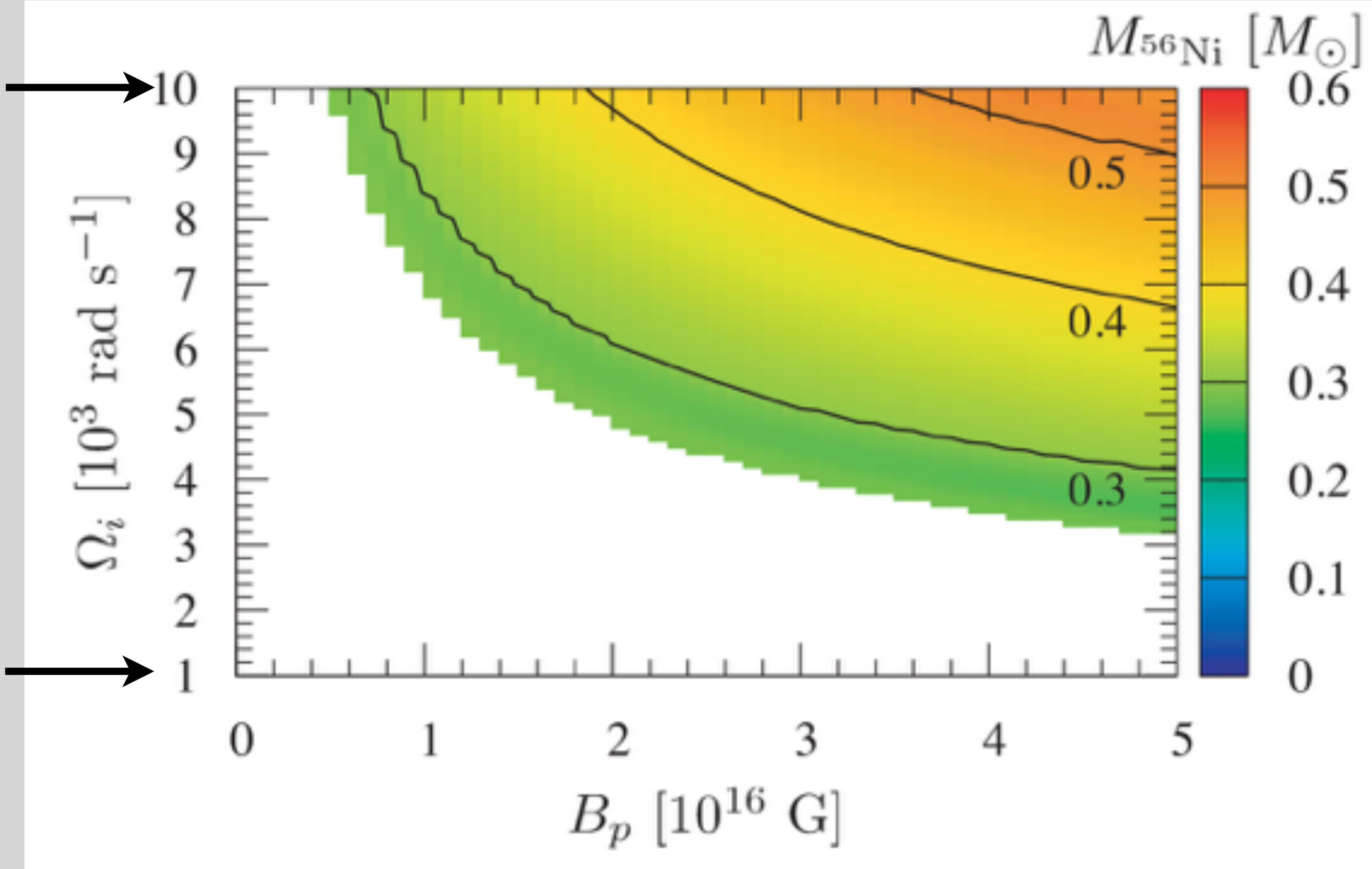
- GRBs are associated with SNe, which are more energetic, $E_{exp}\sim10^{52}$ ergs, than canonical SNe ($\sim10^{51}$ erg), called SN Ic-bl (broad line) or "hypernovae" (HNe)
- To explain the brightness of SN Ic-bl/HNe, we need $O(0.1)M_\odot$ of ^{56}Ni



Nomoto+ (2006)

Magnetar formation and ^{56}Ni

[Suwa & Tominaga, MNRAS, **451**, 4806 (2015)]



P=*0.6* ms

P=*6* ms

$$L_w = 6.18 \times 10^{51}\,\mathrm{erg\,s^{-1}} \times \left(\frac{B_p}{10^{16}\,\mathrm{G}}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^6 \left(\frac{\Omega}{10^4\,\mathrm{rad\,s^{-1}}}\right)^4.$$

$$T_d = \frac{3Ic^3}{B_p^2 R^6 \Omega_i^2} = 8.08\,\mathrm{s} \left(\frac{B_p}{10^{16}\,\mathrm{G}}\right)^{-2} \left(\frac{R}{10\,\mathrm{km}}\right)^{-6} \times \left(\frac{\Omega_i}{10^4\,\mathrm{rad\,s^{-1}}}\right)^{-2} \left(\frac{I}{10^{45}\,\mathrm{g\,cm^2}}\right).$$

- To make consistent model for GRB & SN Ic-bl/HN, we need O(0.1)$M_\odot$ of ^{56}Ni to explain optical components
- Postshock temperature of shock driven by magnetar dipole radiation should be $>5\times10^9$ K
- For $M_{\mathrm{Ni}}>0.2\ M_\odot$, $(B/10^{16}\mathrm{G})^{1/2}(P/1\ \mathrm{ms})^{-1}>1$ is necessary, which is inconsistent with model parameters fitting GRB afterglow

Magnetar and SLSNe

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Contents

- What we should explain with SN simulations
- NS formation
- Binary NS formation
- Magnetar formation