中性子星形成と超新星

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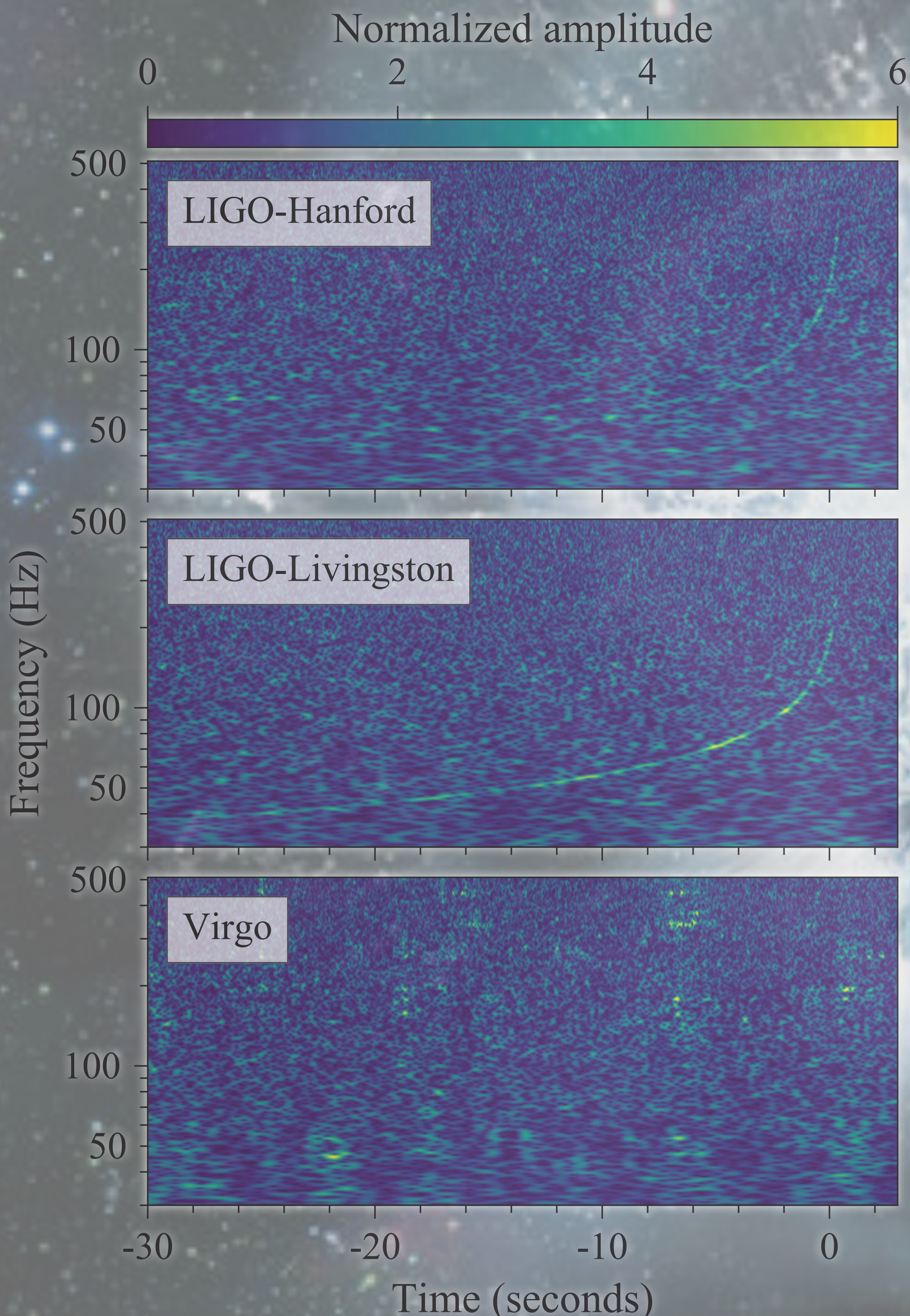
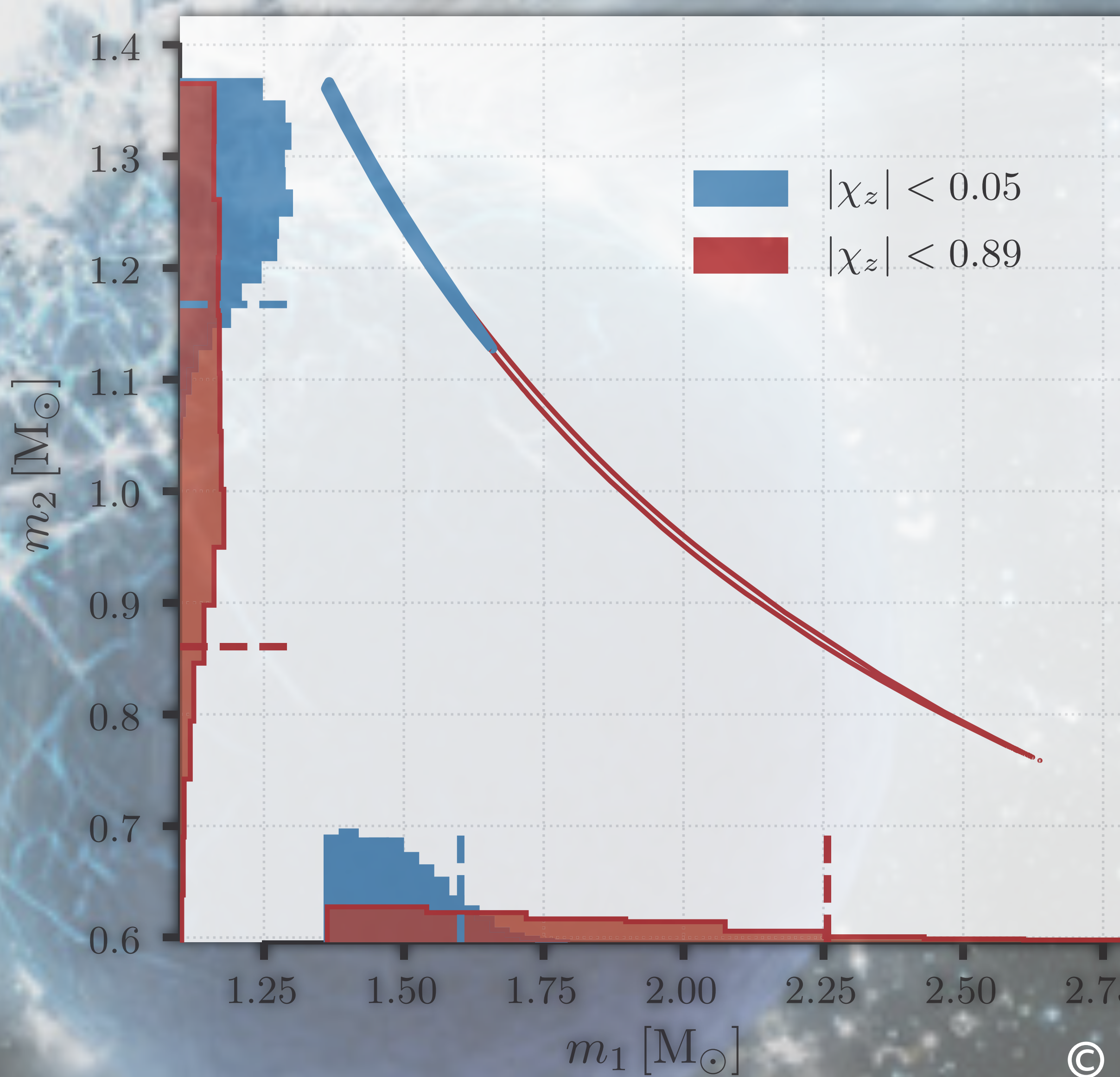
GW170817: Death of neutron stars

LIGO-Virgo, PRL 119, 161101 (2017)

see talks by Fujibayashi-san. Yamazaki-san





2017 is memorial year for NS

- **0 year from GW170817 observation** ***(NS death)*** [LIGO-Virgo]

- **30 years from SN1987A observation** ***(possible NS birth)***
  [Kamiokande+]

- **50 years from pulsar discovery** ***(NS confirmation)*** [Hewish-Bell]

- 43 years from discovery of binary neutron stars [Hulse-Taylor]
- 83 years from theoretical prediction of neutron star [Baade-Zwicky]
- 85 years from discovery of neutron [Chadwick]
- 97 years from theoretical prediction of neutron [Rutherford]

Back in 1983

中性子星の物性的諸問題
集　録

昭和58年10月27日～29日

物性研究所短期研究会

目　次

Agenda

0. supernova modeling

Observable of NS:

1. mass

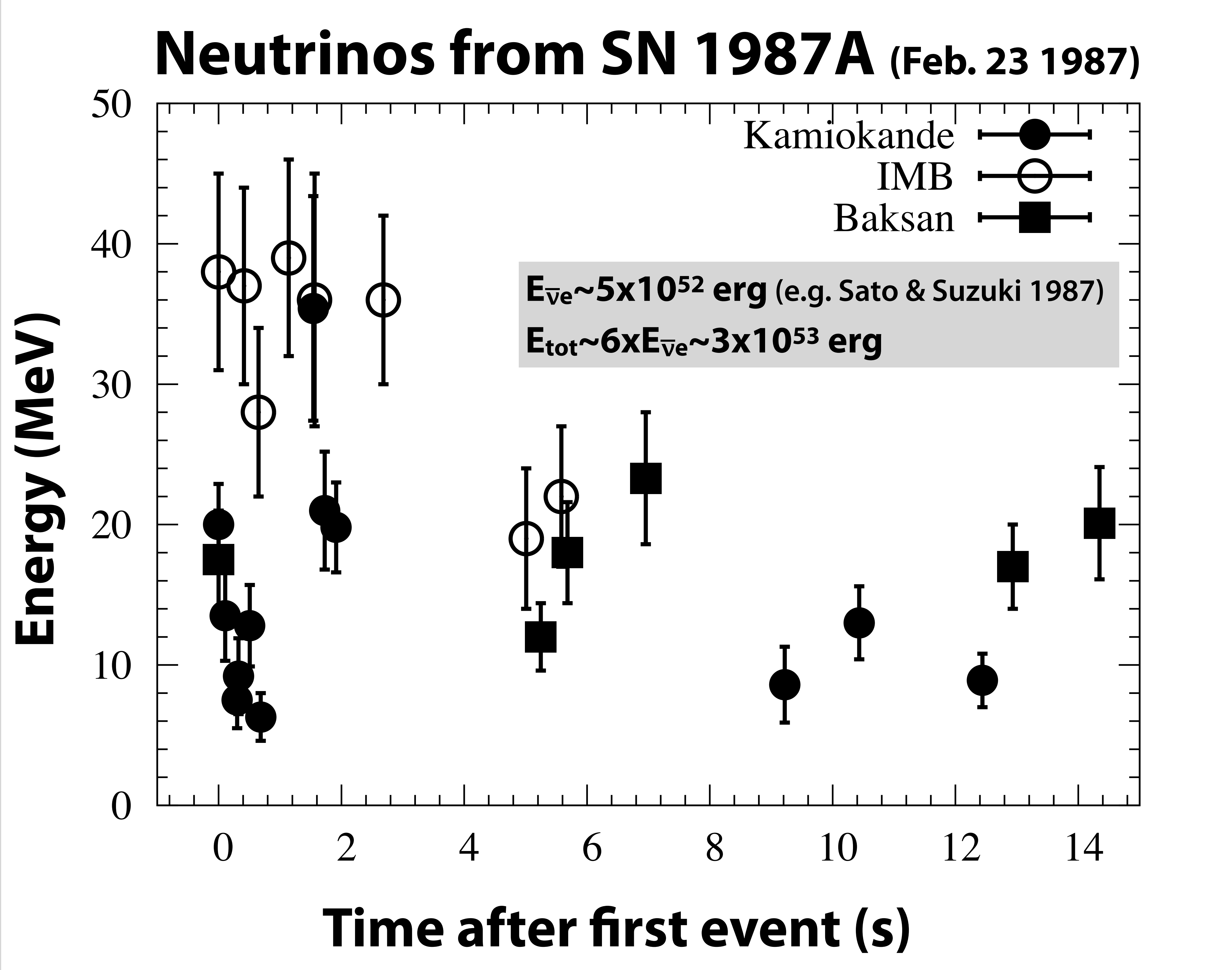
2. spin

3. magnetic fields

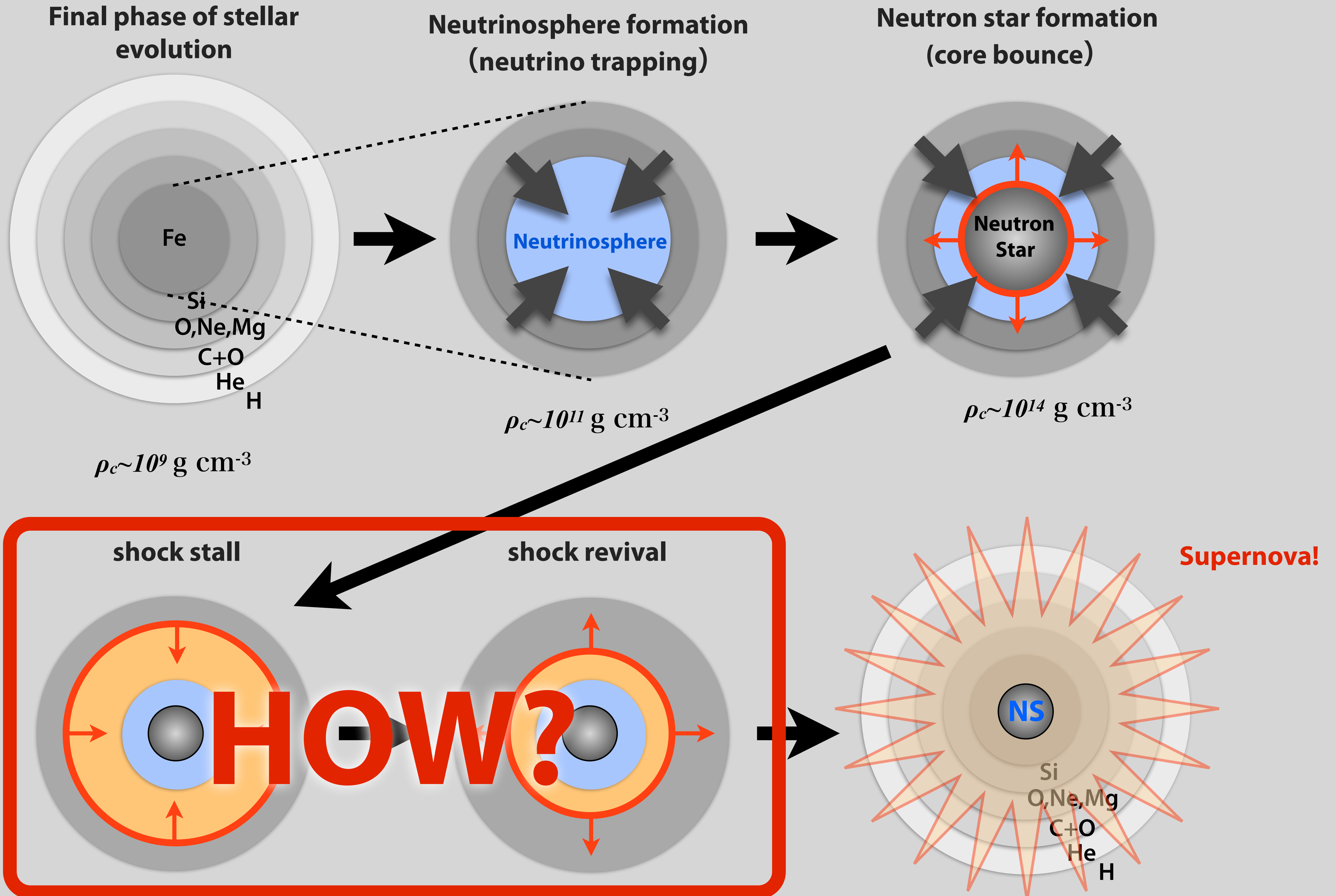
Can we calculate them w/ supernova simulations?

0. SN modeling

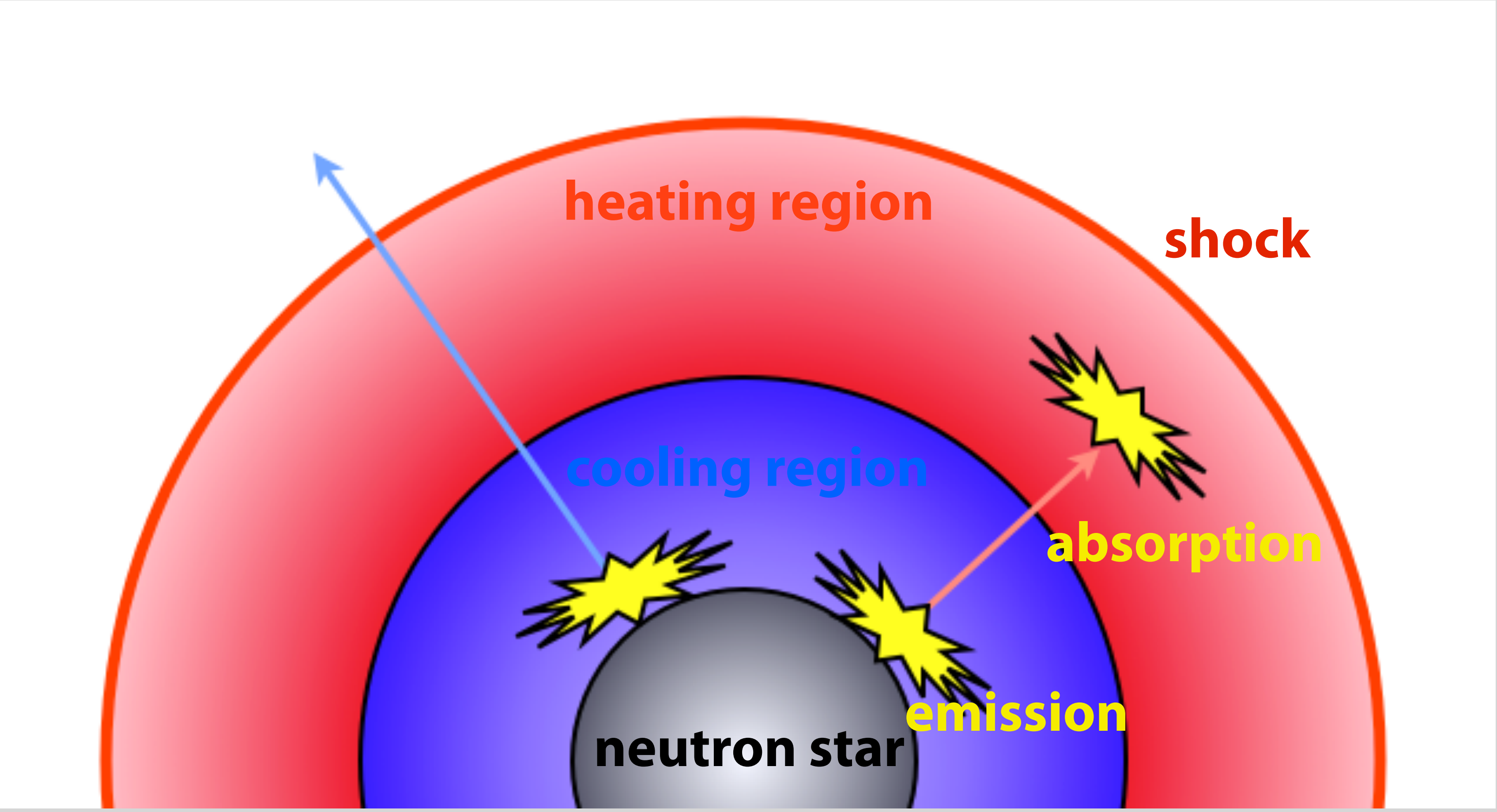
Supernovae are made by neutron star formation

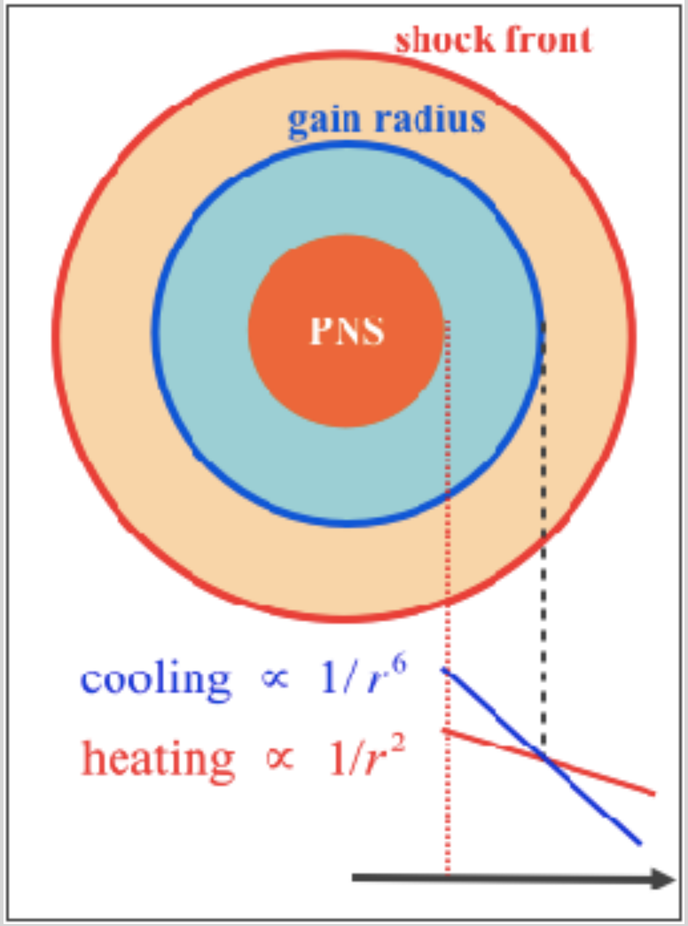


Standard scenario of core-collapse supernovae



Current paradigm: neutrino-heating mechanism





- A CCSN emits *O*(10^{58}) of neutrinos with *O*(10) MeV.
- Neutrinos transfer energy
  - Most of them are just escaping from the system (cooling)
  - Part of them are absorbed in outer layer (heating)
- Heating overwhelms cooling in heating (*gain*) region

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

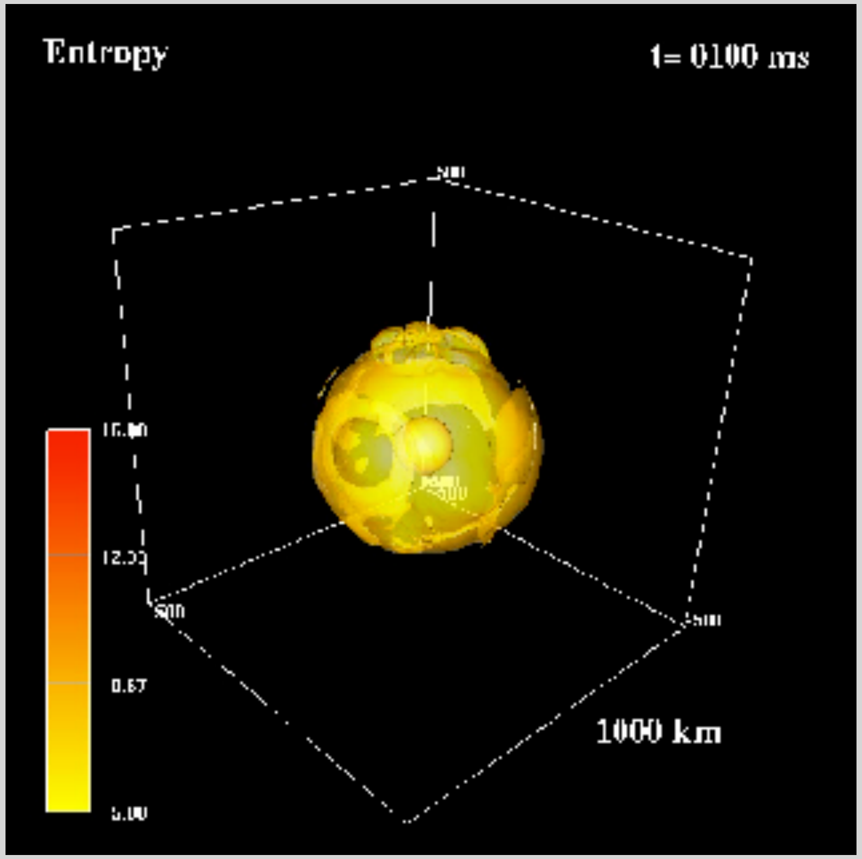
general relativity
Gravity

strong interaction
Nuclear equation of state

electro-magnetic interaction
(Magneto-)hydrodynamics

weak interaction
Neutrino transfer

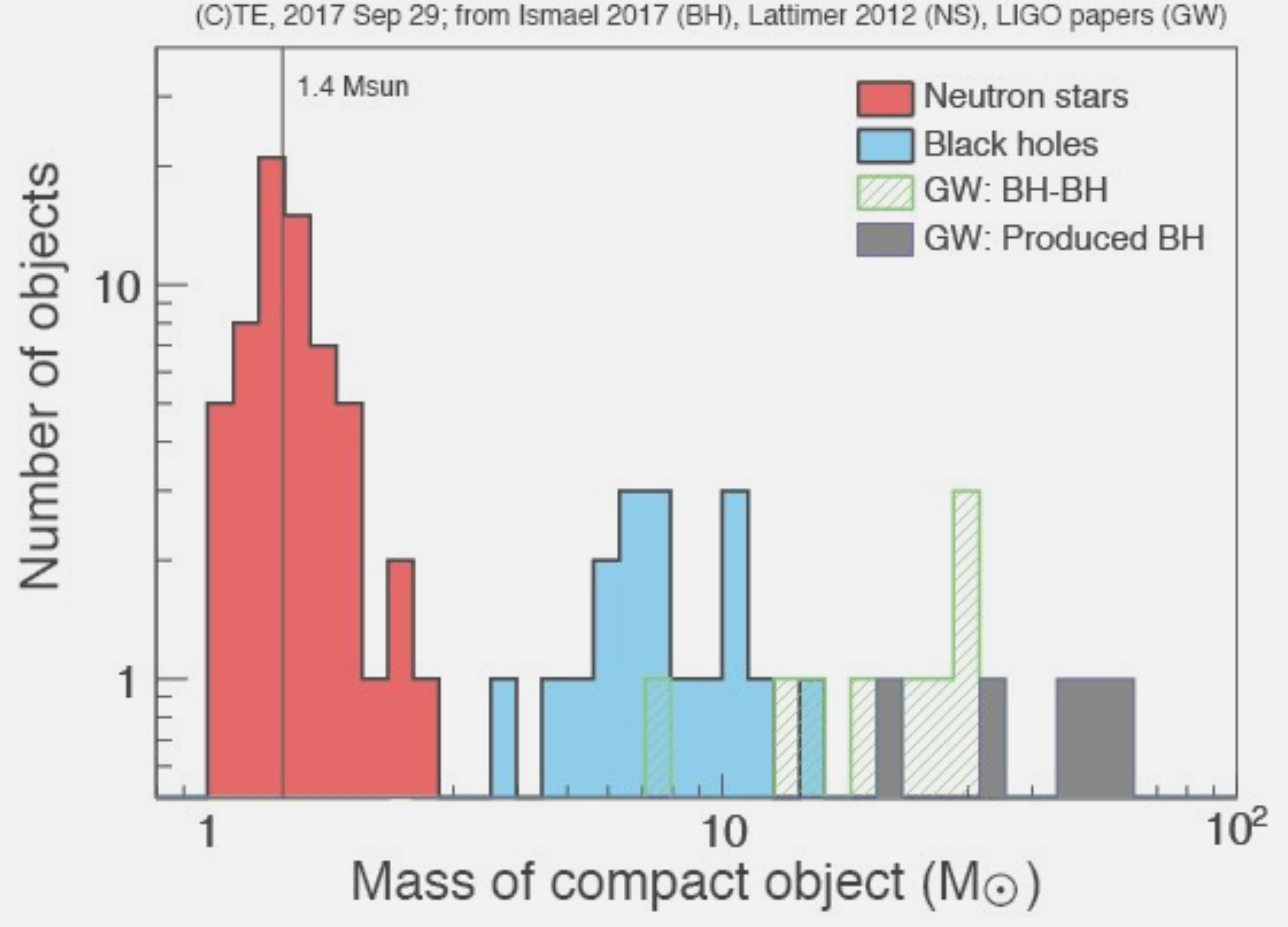
Number of interactions;
$pe^- \leftrightarrow n\nu_e$, $ne^+ \leftrightarrow p\bar{\nu}_e$
$\nu e^\pm \leftrightarrow \nu e^\pm$, $\nu A \leftrightarrow \nu A$, $\nu N \leftrightarrow \nu N$
$\nu\bar{\nu} \leftrightarrow e^-e^+$, $NN \leftrightarrow \nu\bar{\nu}NN$, $\nu\bar{\nu} \leftrightarrow \nu\bar{\nu}$



Takiwaki, Kotake, Suwa (2014)

as first-principles as possible.
parameter free simulation!

1. NS mass from SN



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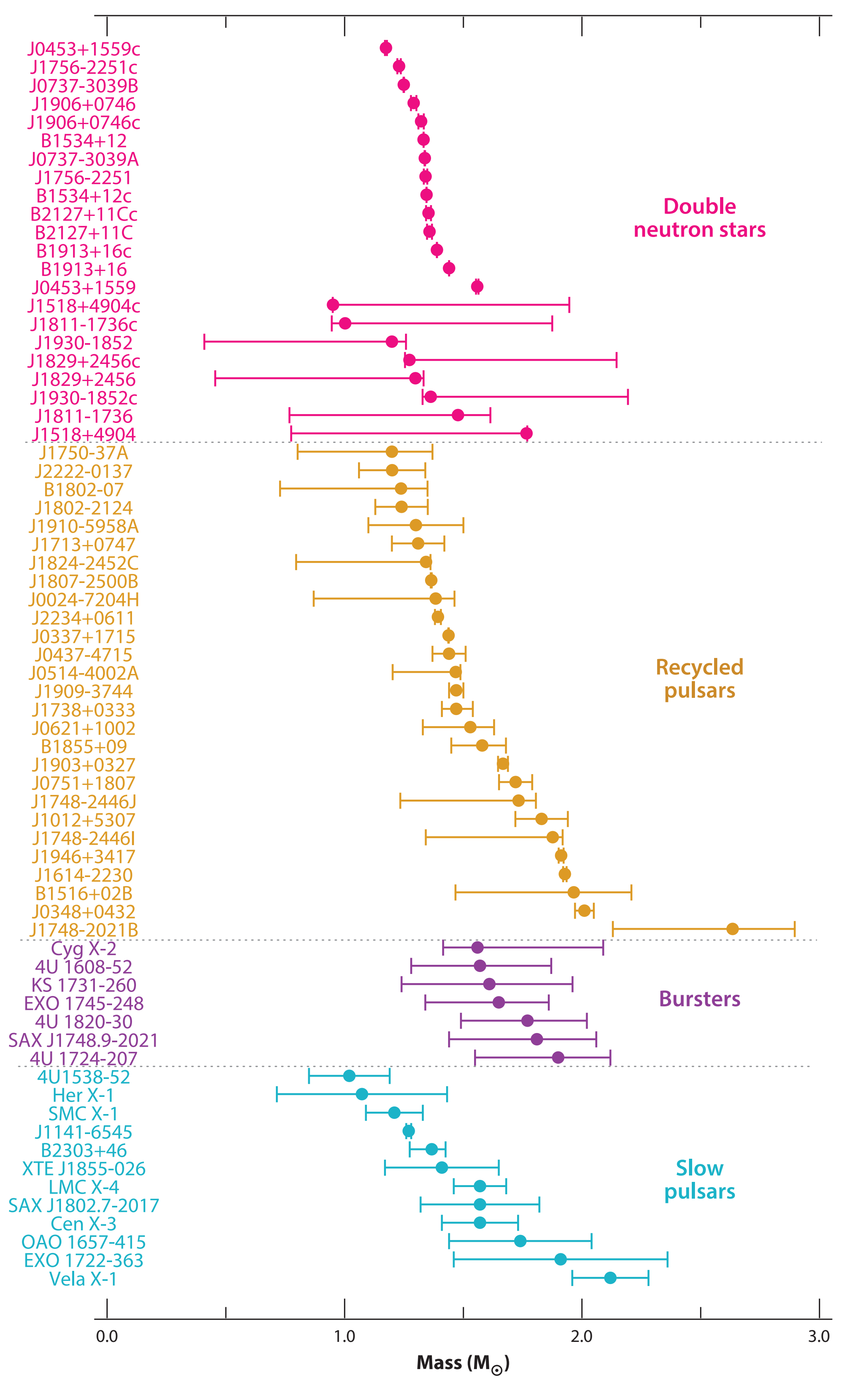
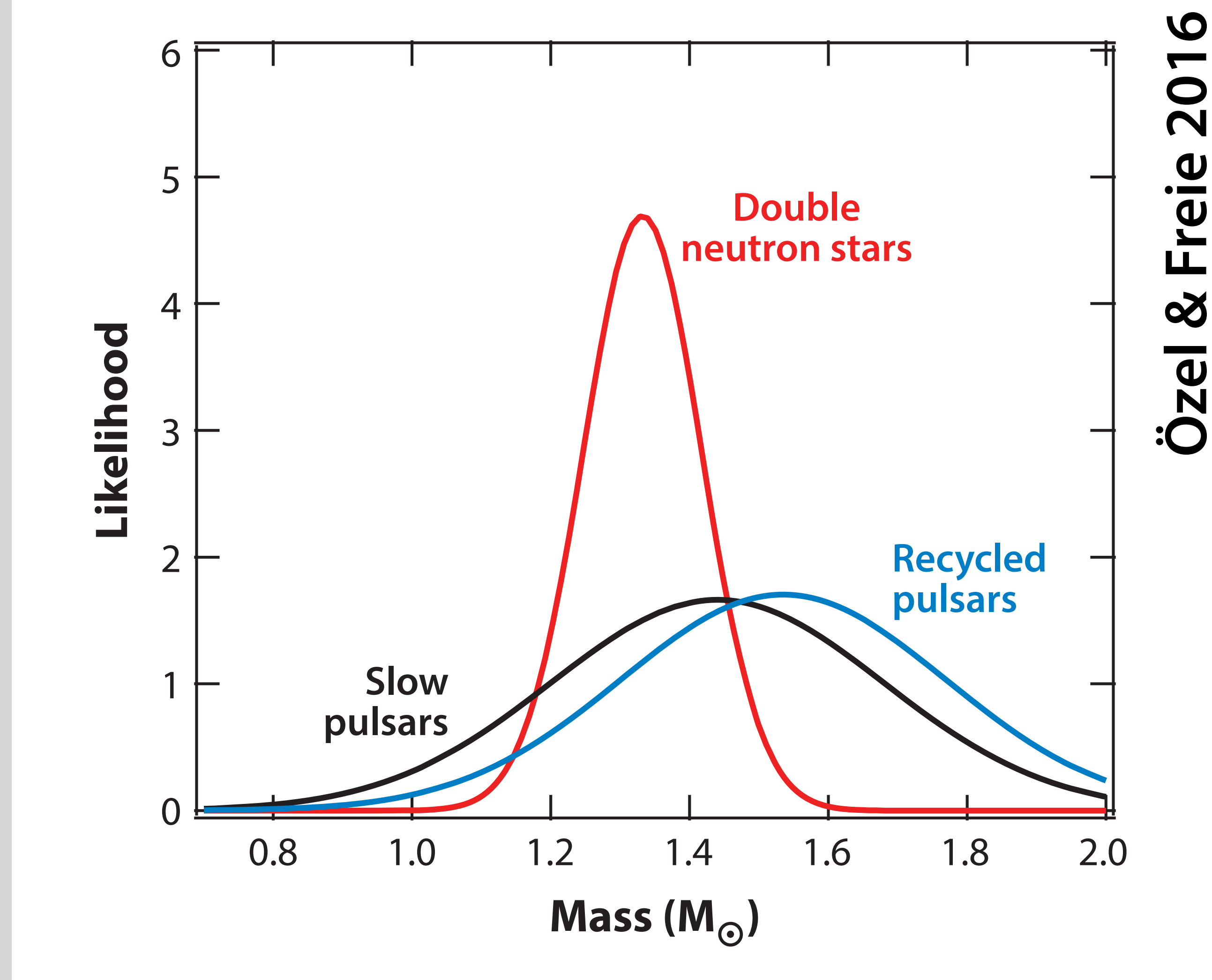
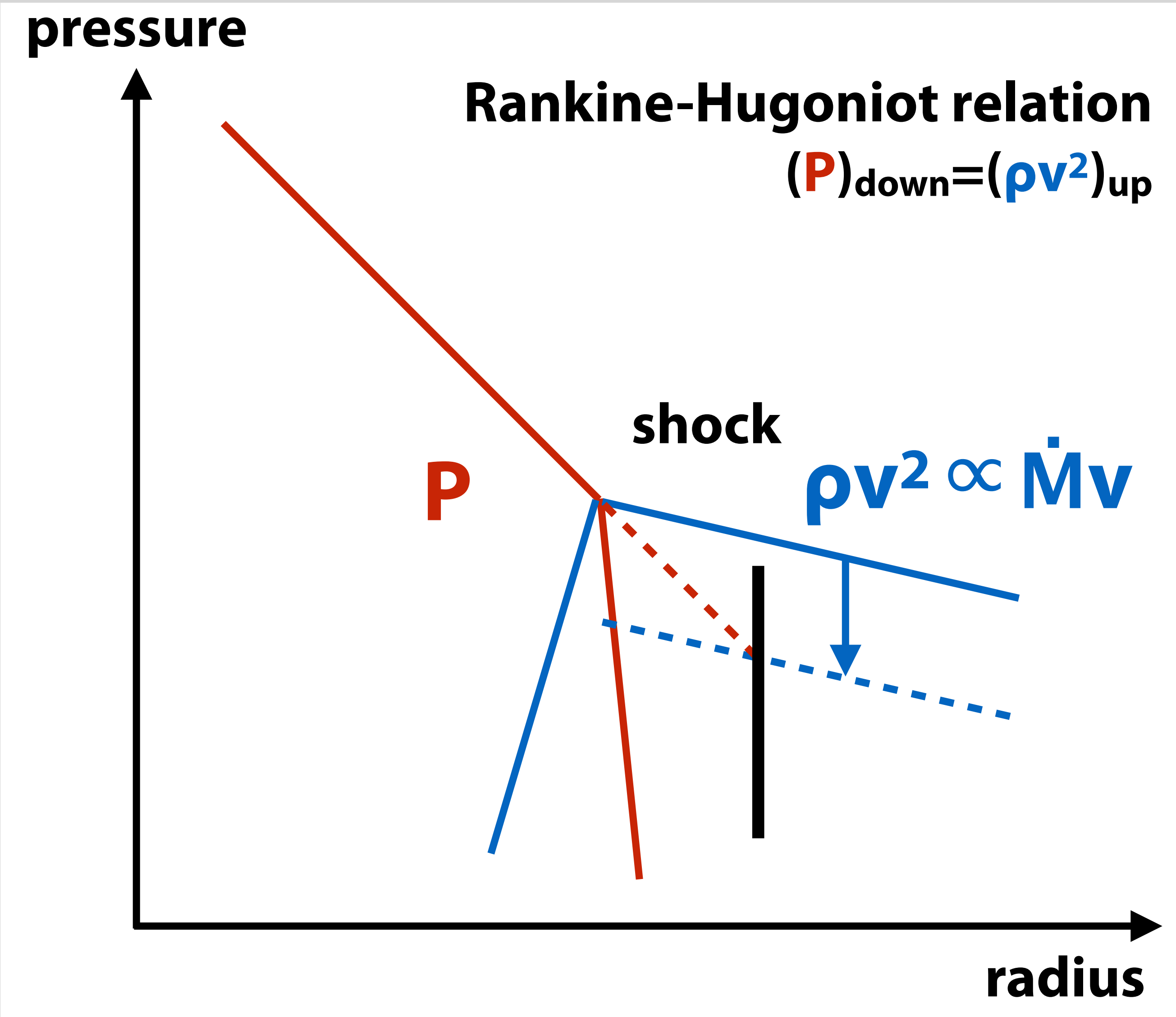
NS mass measurements

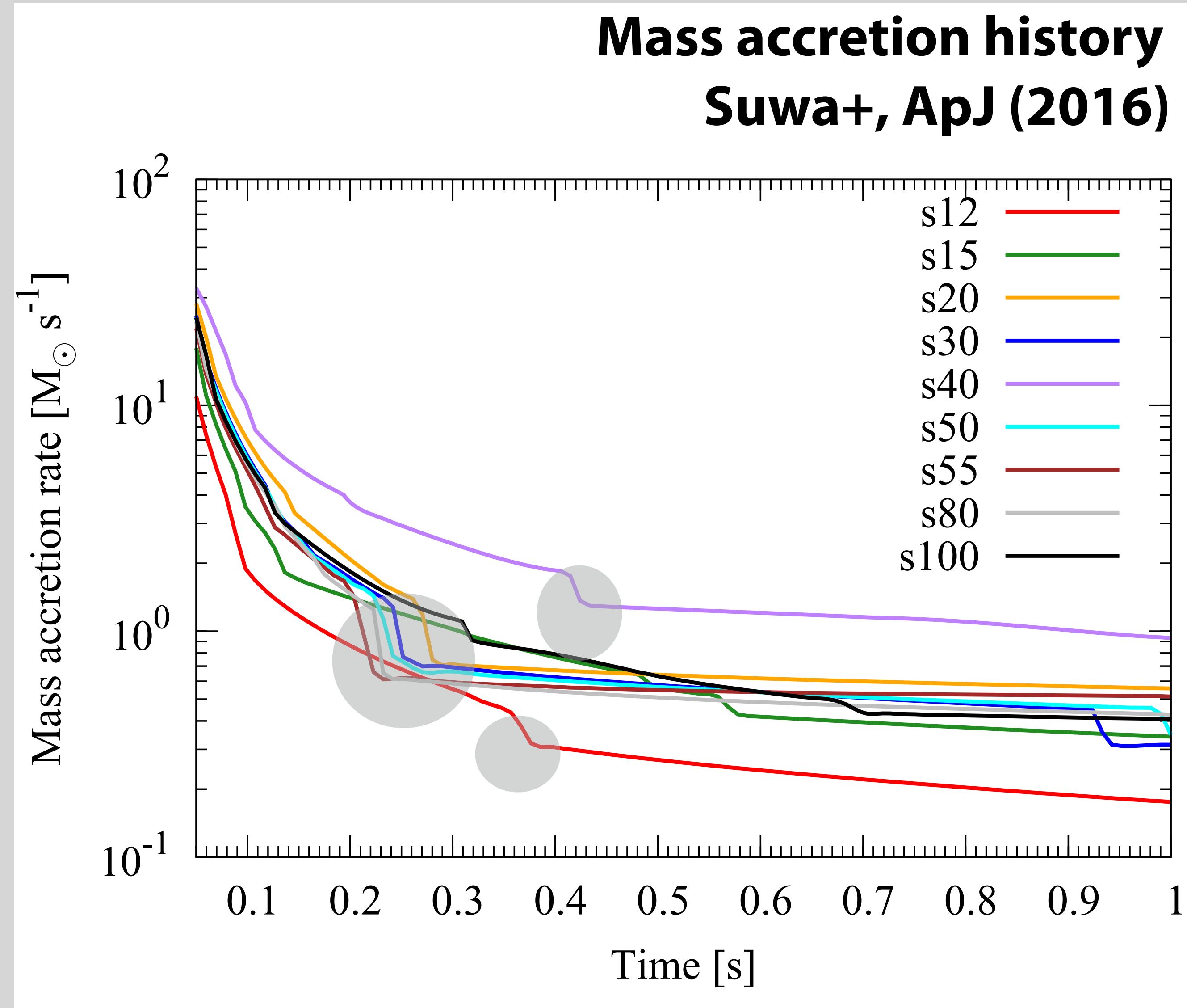




- **>2500 pulsars have been found in the Galaxy**
- **10% in the binary system -> mass measurement possible**
  - **11 double NSs**

Current understanding of SN

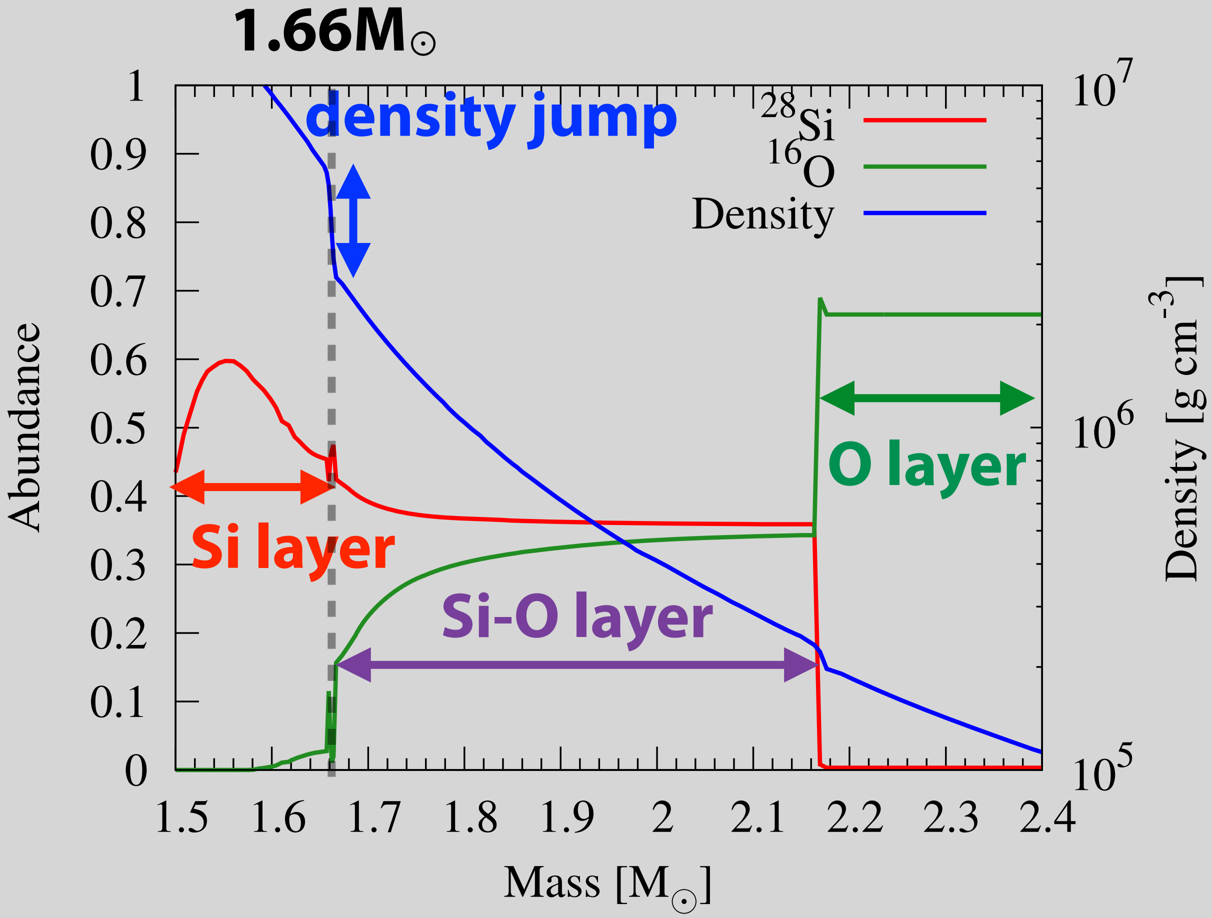




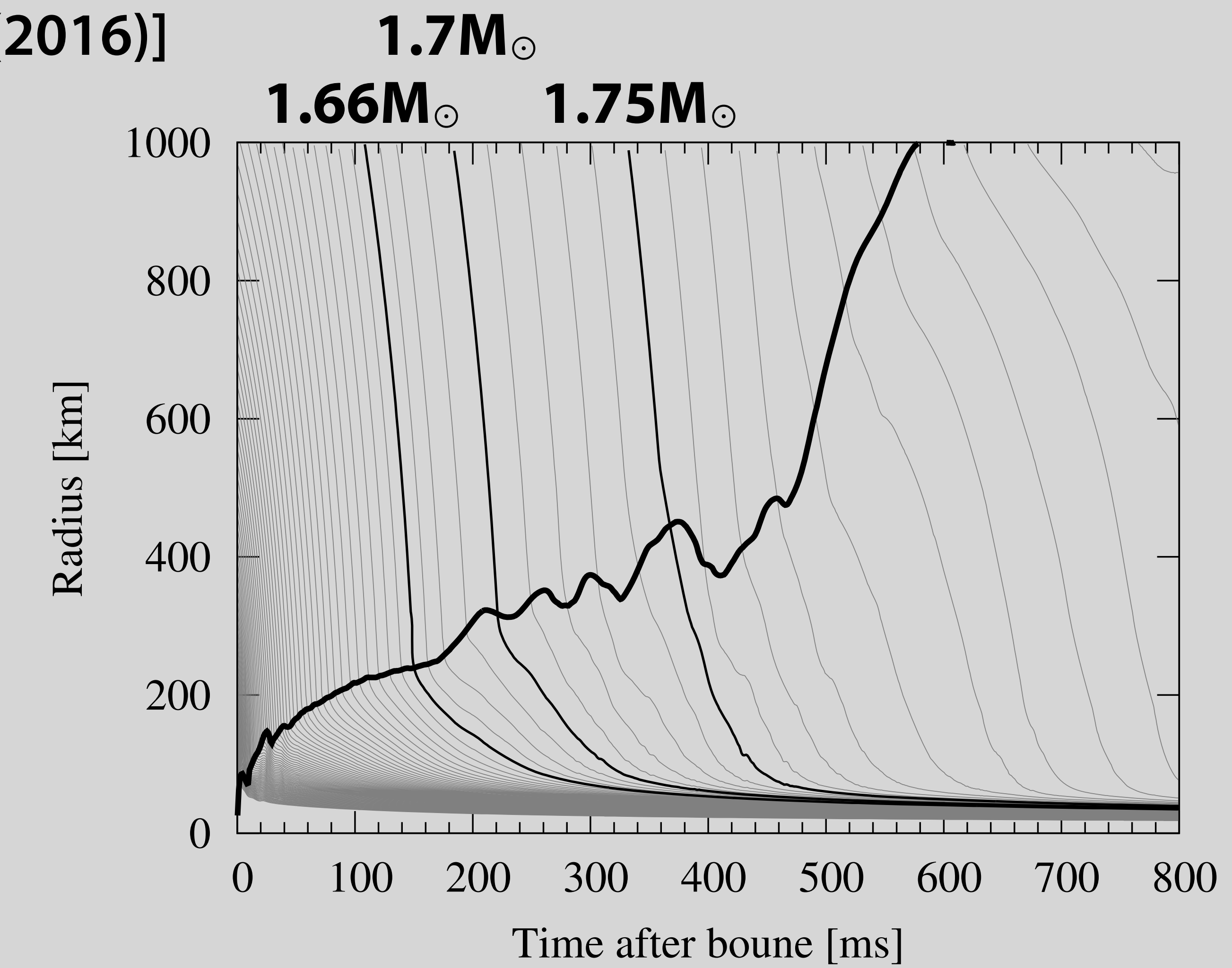
- Shock position is given by force balance between thermal pressure (down stream) and ram pressure (up stream)
- Since ram pressure is related to mass accretion rate, a drastic change of $\dot{M}$ changes shock and leads to explosion

When is SN shock launched?

[Suwa, Yamada, Takiwaki, Kotake, ApJ, 816, 43 (2016)]



(a) Abundance distribution and density structure

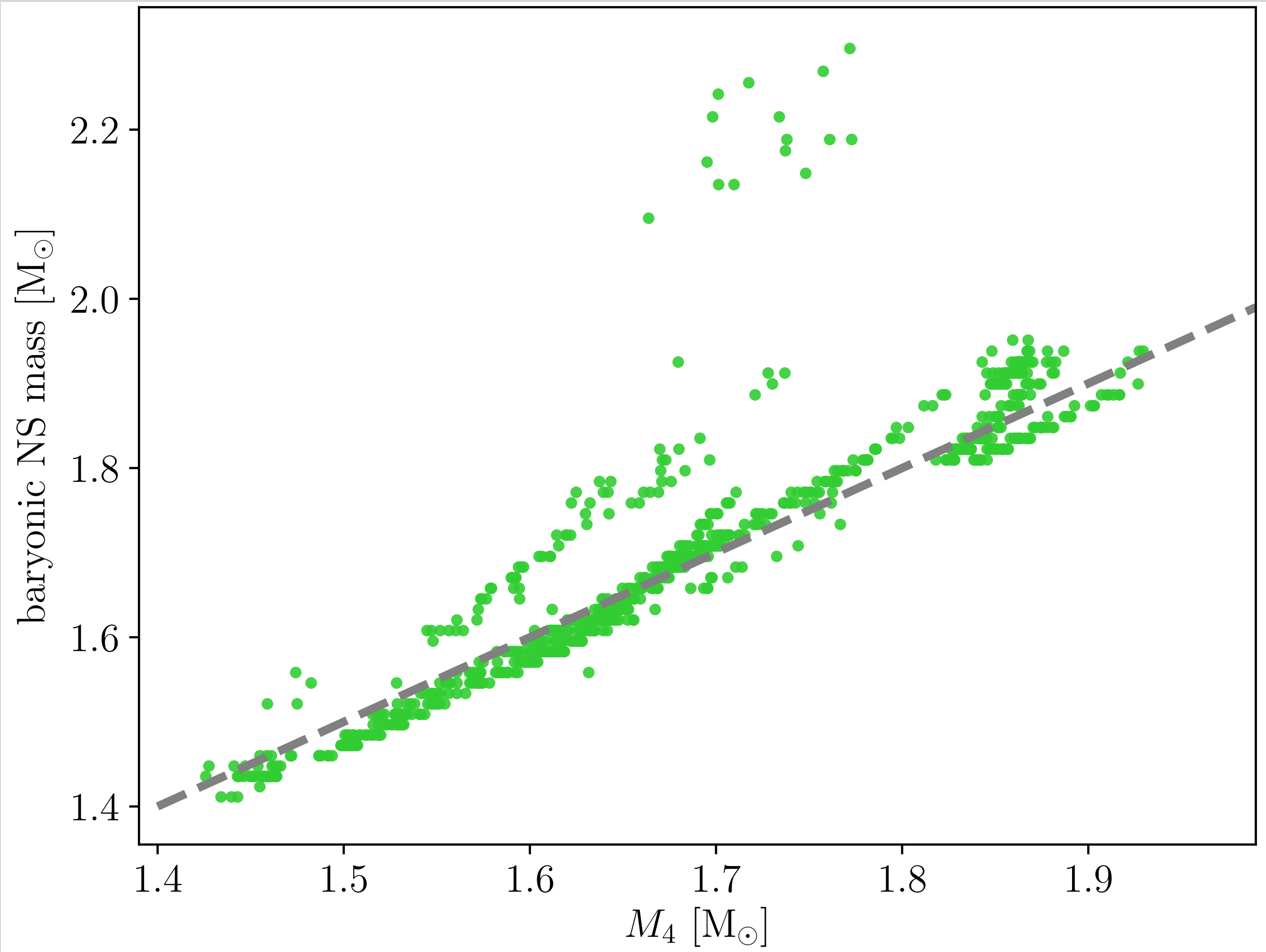


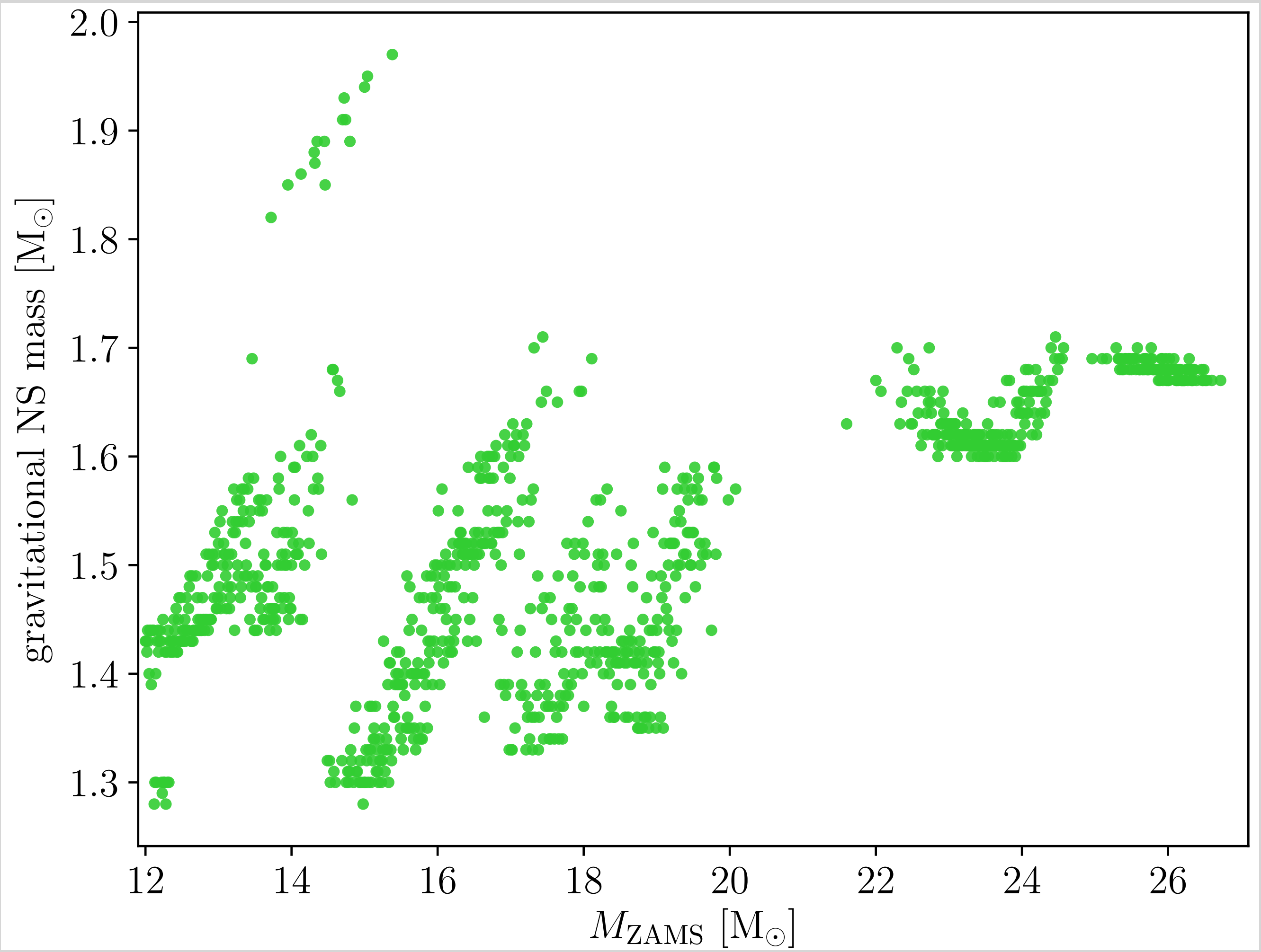
(b) Time evolution of mass coordinate and shock

- **When the mass shell of Si/Si-O interface run across the shock, several oscillations ensue in the shock radius**
- **Aided by turbulence driven by convection and SASI, the shock is eventually launched**

Progenitor structure and NS mass

Sukhbold+, arXiv:1710.03243



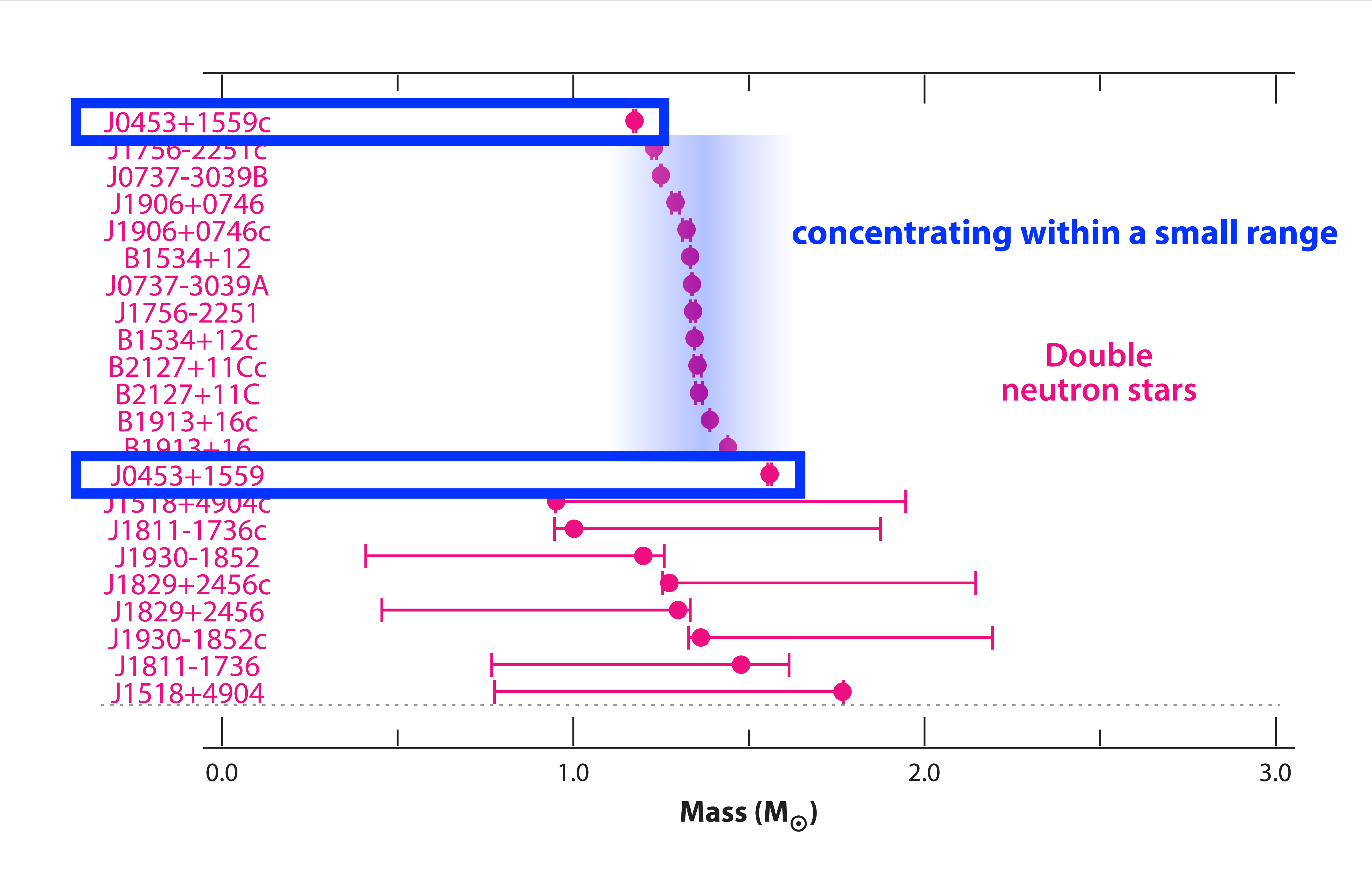


~$M_{Si/Si\text{-}O}$

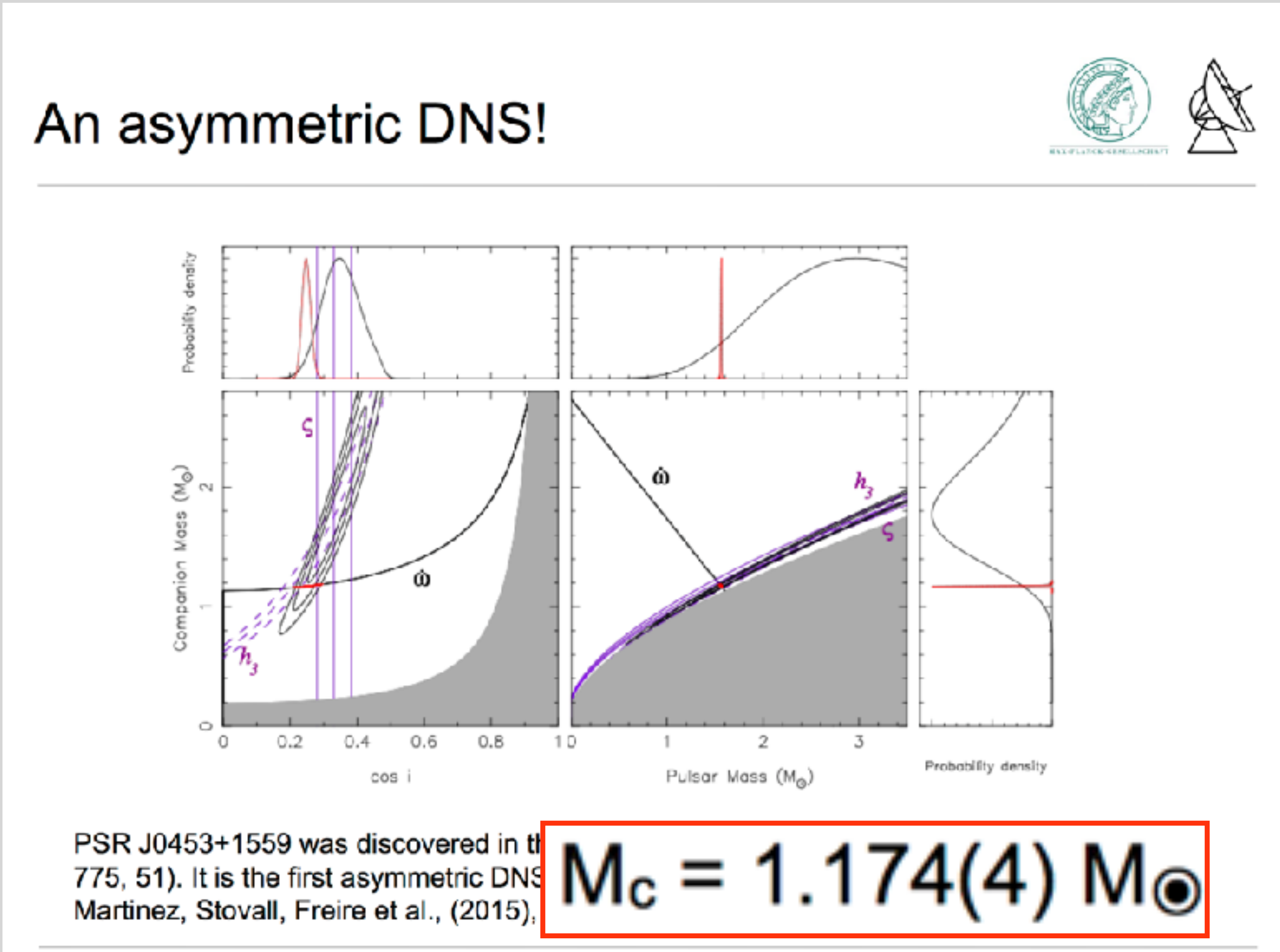
NB) The estimation is NOT based on hydrodynamics simulation, but on phenomenological model of Müller+ (2016)

see poster by Nakamura-san

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 ($M_\odot$)

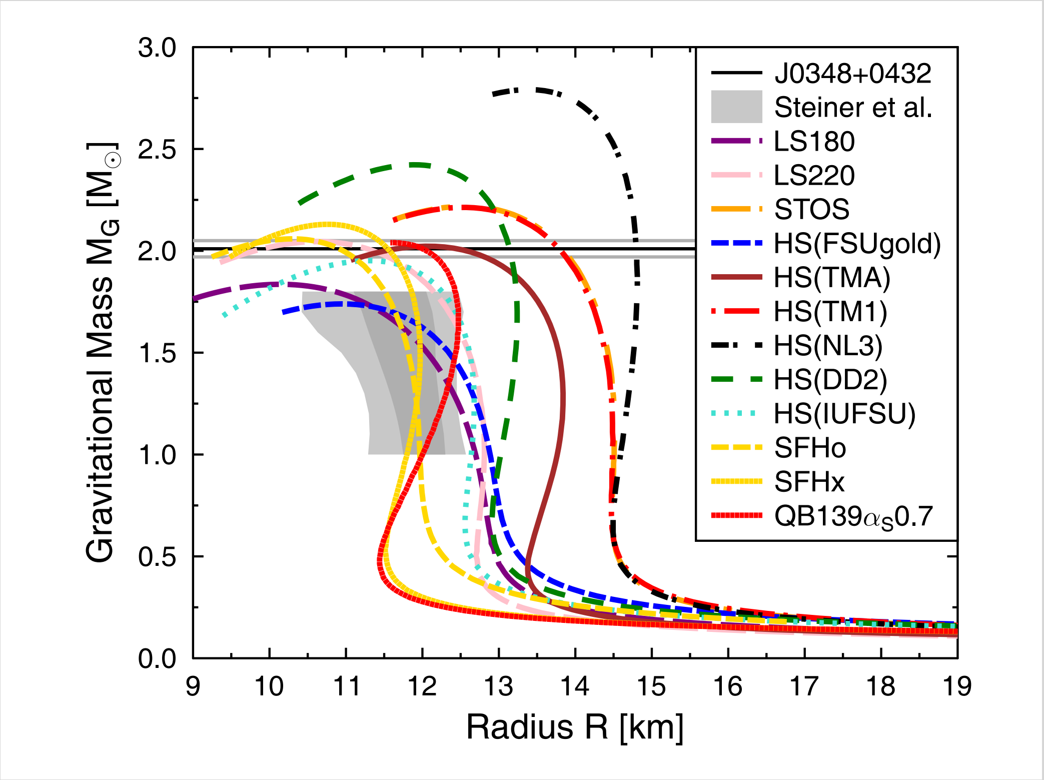
First asymmetric DNS system



From Freire's talk in NPCSM2016@YITP

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_{Ch}=1.46(Y_e/0.5)^2$M_\odot$)
  - getting rid of mass from a NS?

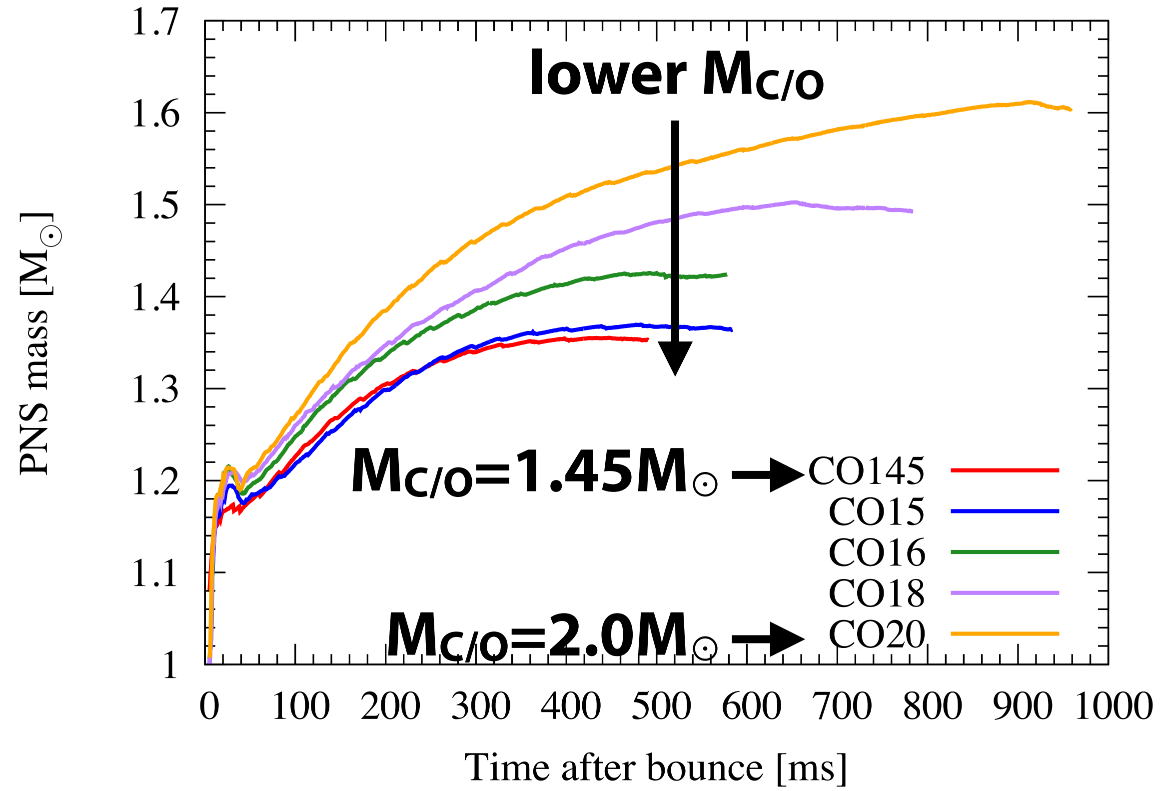


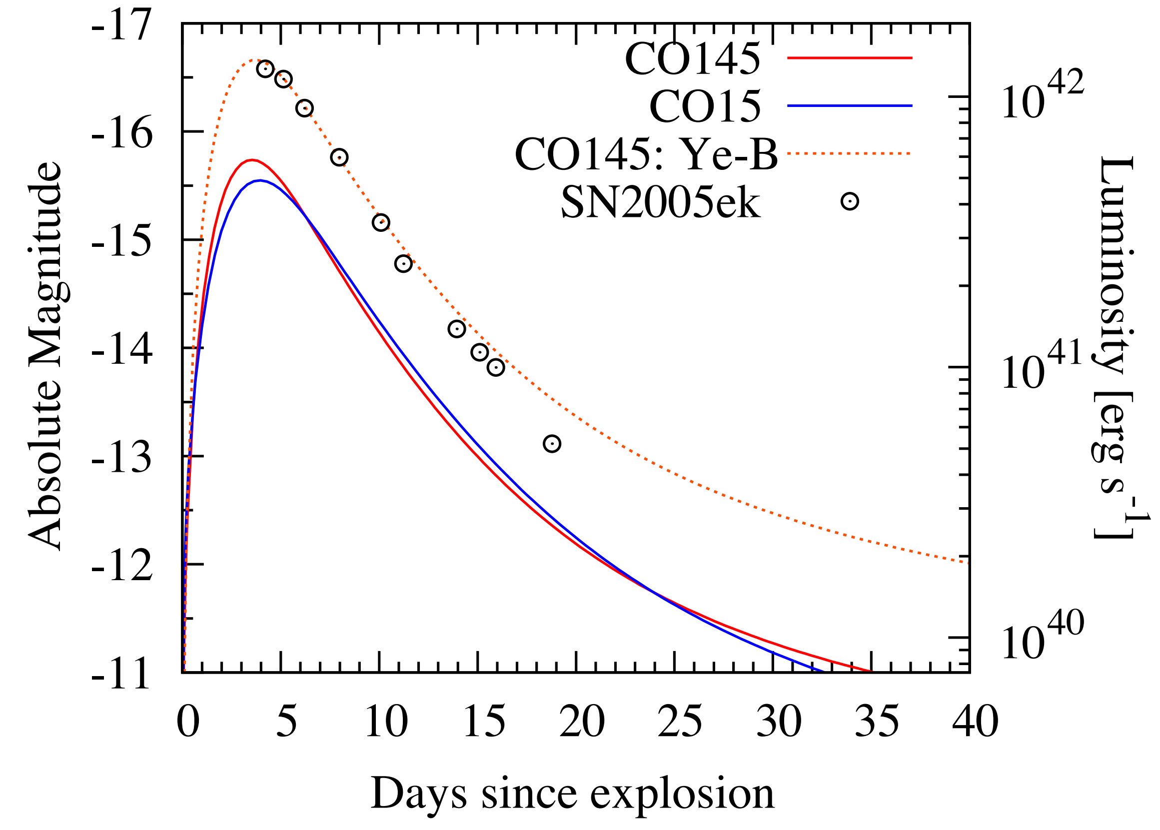
Fischer, Hempel, Sagert, Suwa, Schaffner-Bielich (2014)

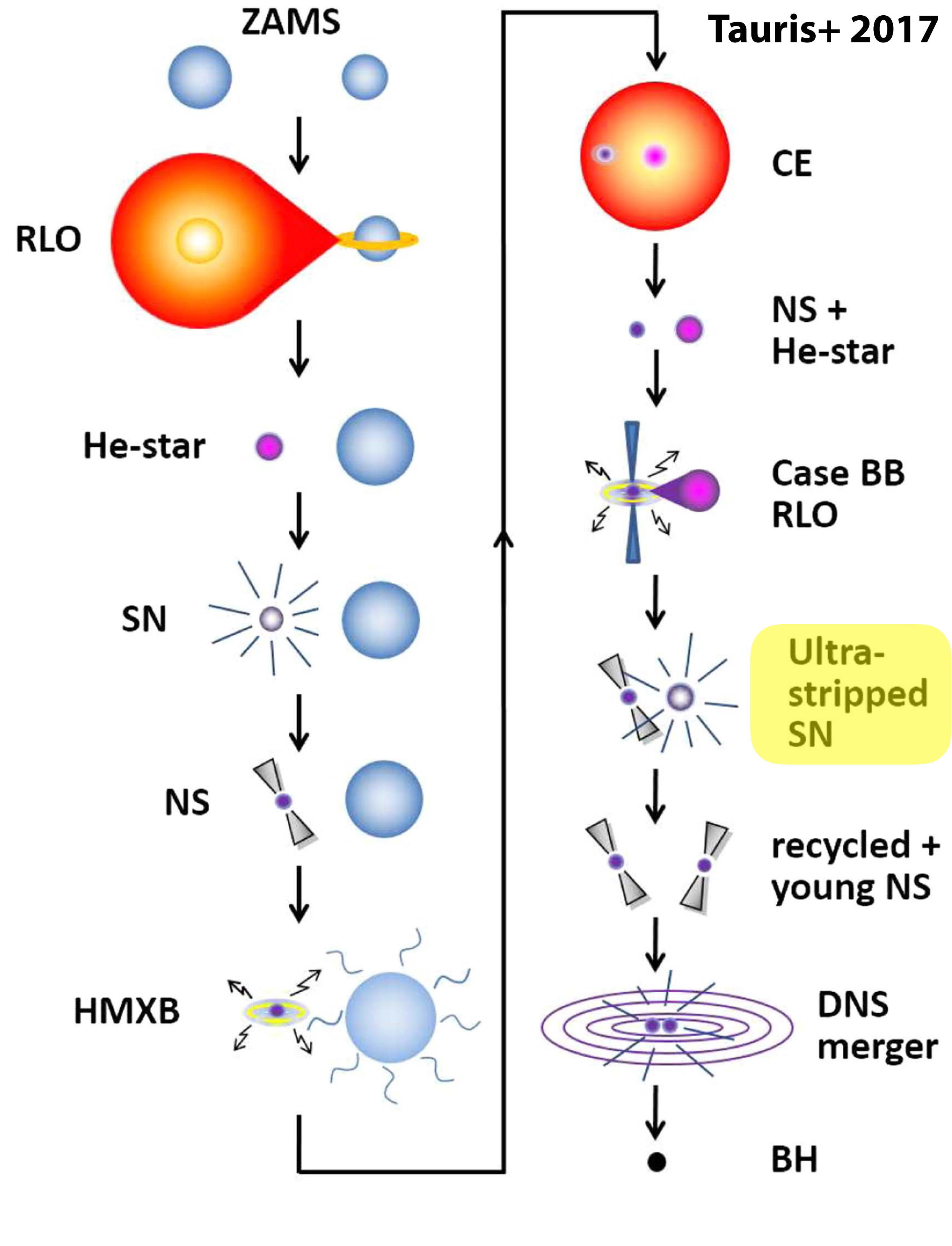
- **Implication on nuclear physics**
  - η=$(KL^2)^{1/3}$ determines NS radius [Sotani+ 2014]

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

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





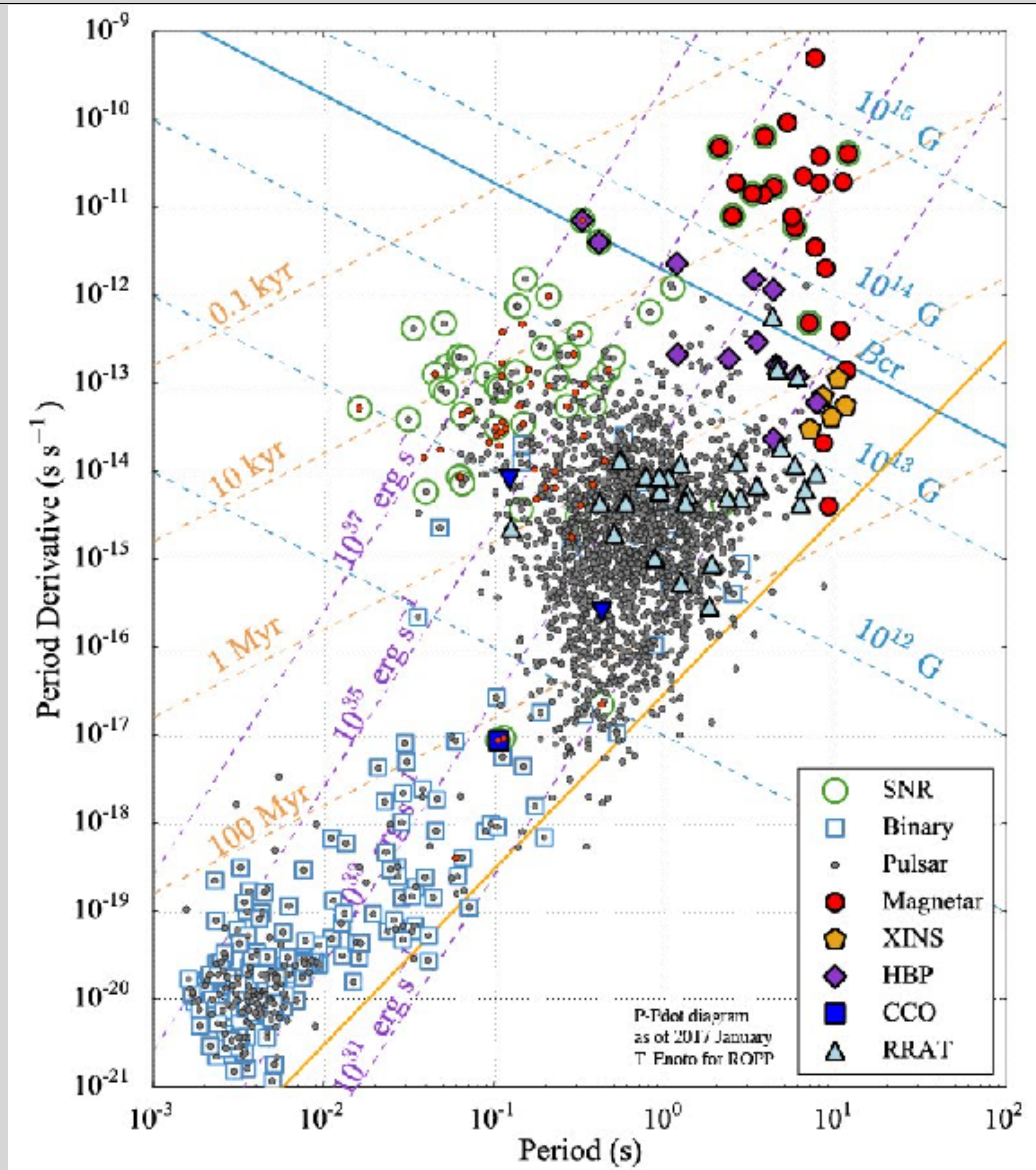


Summary of NS mass

- **NS mass would be determined by the interface of Si/Si-O layers**
  - shock is launched from this mass
  - Stellar evolution is important

- **Low-mass NS is interesting**
  - Might be originated from close-binary interactions
  - Might be related to ultra-stripped SNe
  - More statistics w/ GW observations

2. NS spin from SN



Stability argument and limitation of rotation

- **For a rotating body, there are some criteria to be stable**
  - **T**(rotation energy) **~ $MR^2\Omega^2$**
  - **W**(gravitational binding energy) **~ GM^2R^{-1}**
- **Instability criteria;**
  - **$T/|W| \gtrsim 0.26$: dynamical instability**
  - **$T/|W| \gtrsim 0.14$: secular instability**
  - **$T/|W| \gtrsim O(0.01)$: low-T/W instability**
- **For the fastest rotating pulsar** (PSR J1748-2446ad; Ω=4.5x10^3 s^{-1}), **$T/|W|$~0.036** (assuming a rigid body, $M=1.4M_\odot$, R=10km)
  - BTW, $T/|W|$~7x10^{-6} for Sun (w/ rigid body assumption). If it collapses to a NS, $T/|W|$=0.49! (faster than break-up)

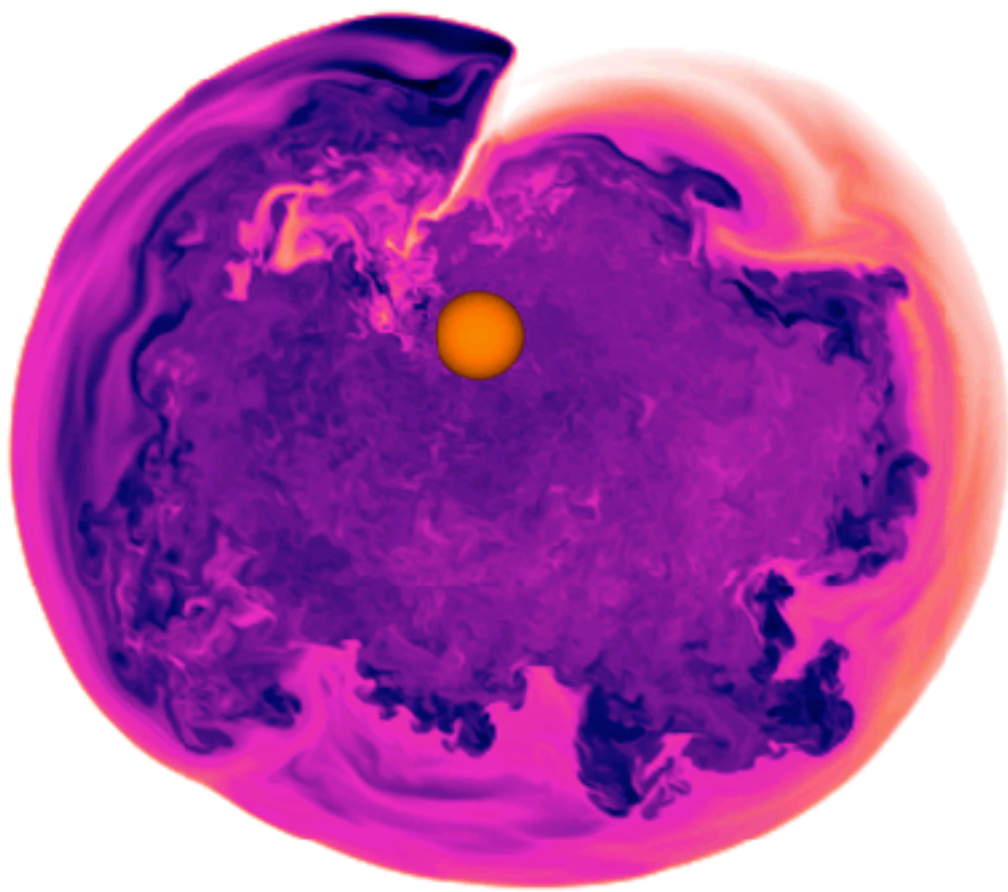
Angular momentum conservation

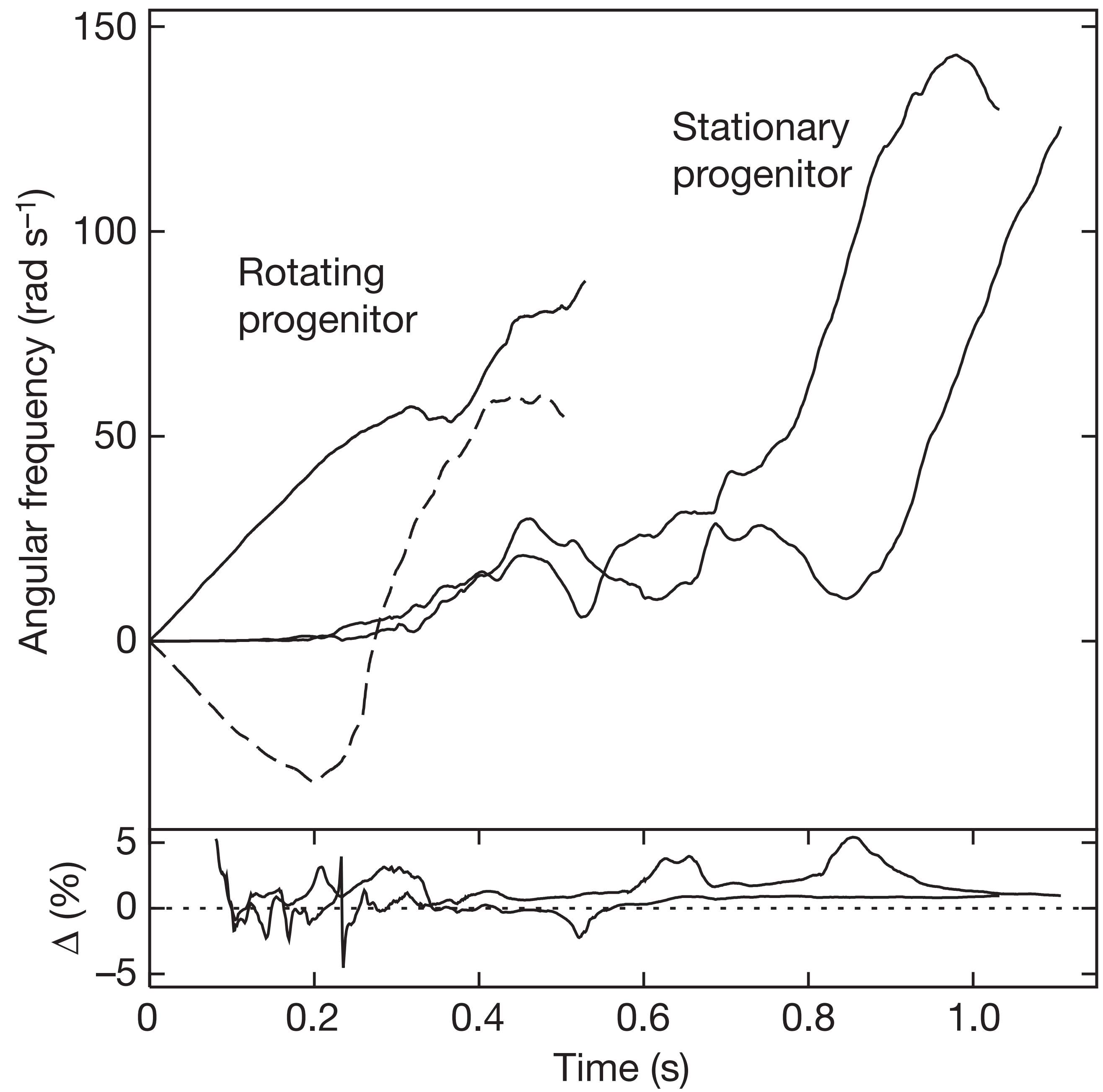
- **Angular momentum conservation: $\Omega \propto R^{-2}$**
  $\Omega_{NS}=10^4 x \Omega_{core}(R_{NS}/10km)^{-2}(R_{core}/1000km)^2$

- **What is typical rotation rate of core?**
  - **Depends on the treatment of magnetic fields, e.g.,**
    - **Ω=0.37 rad/s** [Heger+ 00] **w/o B => P_{NS}=1.7ms**
    - **Ω=0.05 rad/s** [Heger+ 05] **w/B => P_{NS}=12ms**
  - **NB) large uncertainty is remaining**

NS spin up by SASI

Blondin & Mezzacappa, Nature (2007)





see also; Fernandez (2010), Foglizzo+ (2012), Wongwathanarat+ (2013), Guilet & Fernandez (2014), Kazaroni+ (2016), and others

NS spin down mechanisms

- **Early time (from seconds to days after explosion)**
  - **propeller effect w/ fallback** [Illarionov & Suynaev 75]
  - **magnetically driven wind w/ strong-B** [Thompson+ 04]
  - **anisotropic neutrino emission** [Suwa & Enoto 14]

- **Late time**
  - **r-mode and GW emission** [Lindblom+ 98, but see also Arras+ 03]
  - **GW emission by deformed NS w/ strong-B** [Stella 05]
  - **magnetic braking by dipole radiation** [many textbooks]

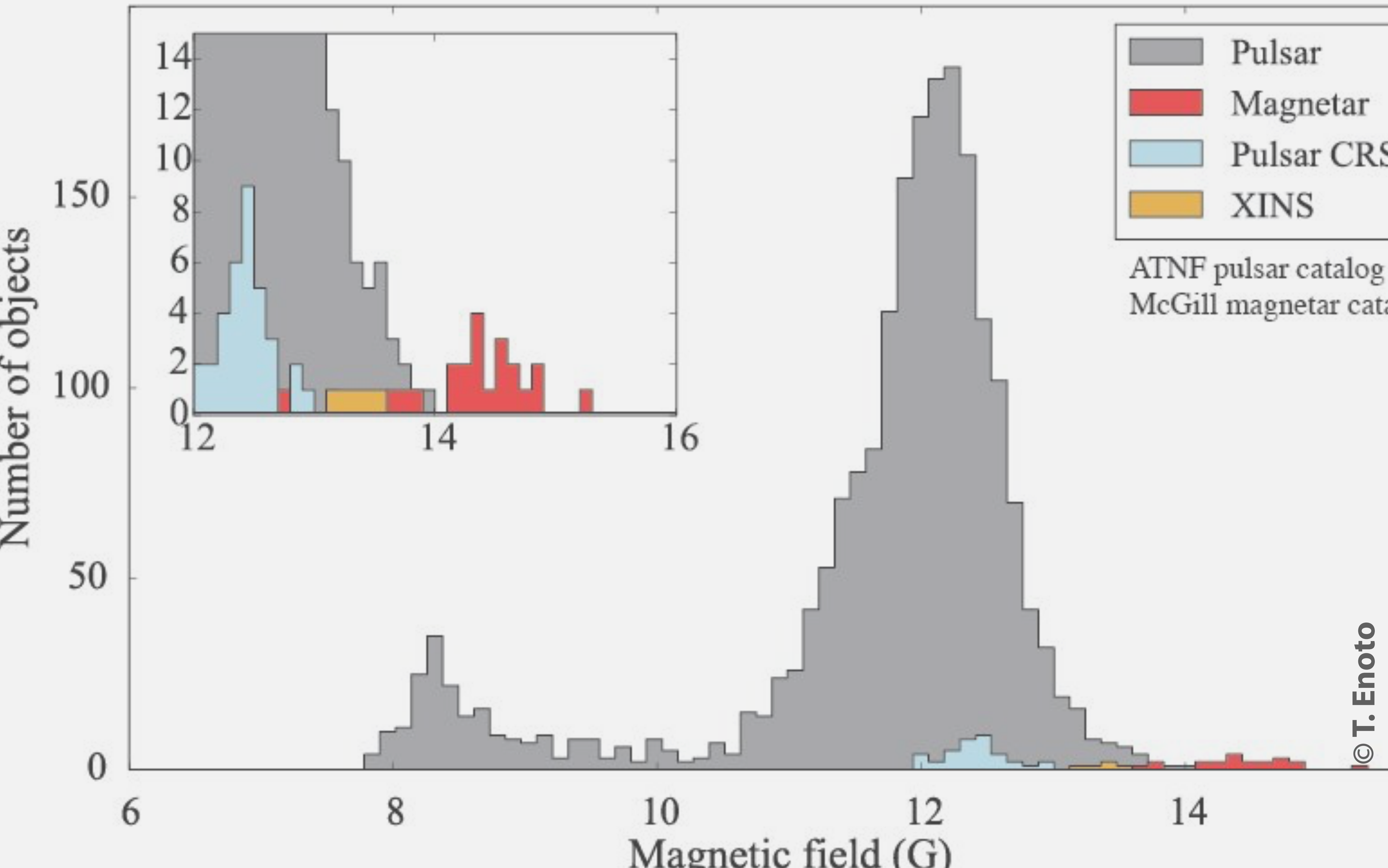
Summary of NS spin

* **NS spin at birth is determined by precollapse**
  * stellar evolution is important

* **NS spin-up**
  * angular momentum conservation
  * SASI

* **NS spin-down**
  * propeller effect, wind, r-mode w/ GW, dipole radiation, etc…

3. NS magnetic-field from SN



Possible origin of B-field

* **fossil field hypothesis (flux conservation)**
* fields generated internally in the progenitor
* **fields amplified during core collapse**
* **fields amplified by dynamo processes in proto-NS**

Fossil fields hypothesis

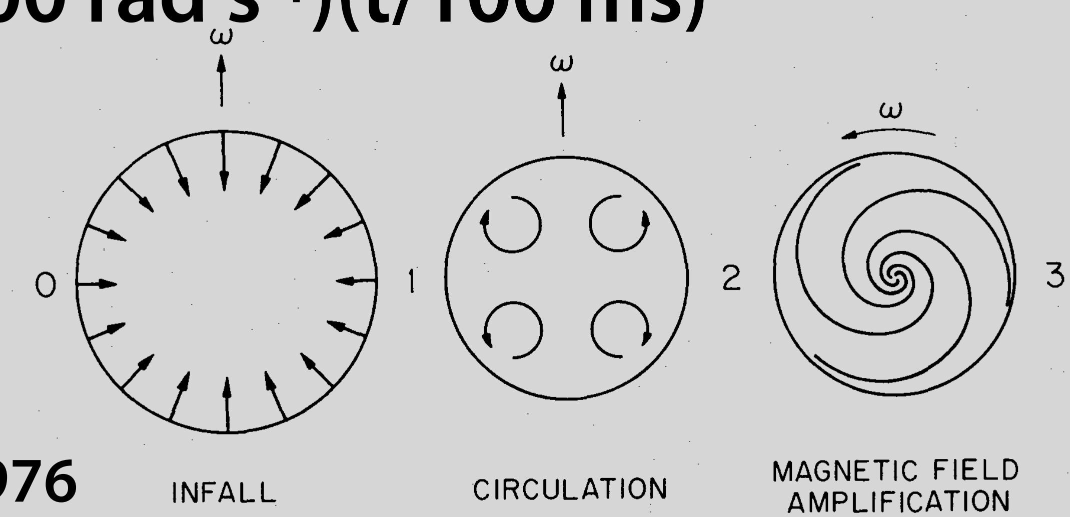
* **Flux conservation indicates $B \propto R^{-2}$**
* **$E_{mag}/E_{gra} = B^2R^3/(GM^2/R) = B^2R^4/(GM^2)$**

	B (G)	R (cm)	M ($M_\odot$)	BR^2 (G cm^2)	E_{mag}/E_{grav}
OBA-type	1-10^4	10^{12}	10	10^{24}-10^{28}	10^{-14}-10^{-6}
WD	10^4-10^9	10^9	1	10^{22}-10^{27}	10^{-16}-10^{-6}
young NS	10^8-10^{15}	10^6	1	10^{20}-10^{27}	10^{-20}-10^{-6}

Amplification during core collapse

- **Flux conservation**
  - $B_{NS}=10^4 \times B_{core}(R_{NS}/10\mathrm{km})^{-2}(R_{core}/1000\mathrm{km})^2$
  - For magnetar, $B_{core}=10^{11}$G, which is unlikely
  - Normal pulsar is possible ($B_{core}=10^8$G; stellar convection)

- **Rotation**
  - Differential rotation is naturally generated during collapse
  - Winding-up by differential rotation;
    $B_\varphi \sim B_p \Delta\Omega\, t \sim 10^{14}\mathrm{G}(B_p/10^{12}\mathrm{G})(\Delta\Omega/1000\ \mathrm{rad\ s^{-1}})(t/100\ \mathrm{ms})$



Meier+ 1976

Amplification in proto-NS

- **Rotation & winding-up**

- **Fast amplification processes**
  - **small scale dynamo (if $P>t_{conv}$), up to 10^{16}G (E_{mag}~E_{conv})**
  - **α-Ω dynamo (if $P<t_{conv}$), up to 10^{15}G**
  - **Magneto-rotational instability (if $\Omega_{core}>\Omega_{env}$), up to ?**
  - **Tayler-Spruit dynamo (if unstable B configuration), up to ?**

Relaxation time scales

- **Turbulent B-fields would be relaxed to some equilibrium configuration** (Braithwaite & Cantiello 2013)
  - $t_{equil} \sim t_{Alfven}^2/P \sim 10$ s $(B_{equil}/10^{15}G)^{-2}(P/1ms)^{-1}$

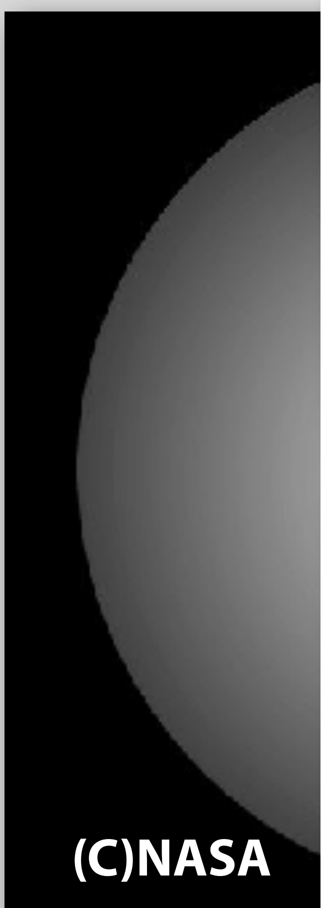
	B (G)	P (ms)	t_{equil}
magnetar	10^{15}	10^3	0.01 s
ms-magnetar	10^{15}	1	10 s
pulsar	10^{12}	30	3 days
CCO	10^{10}	300	1000 years

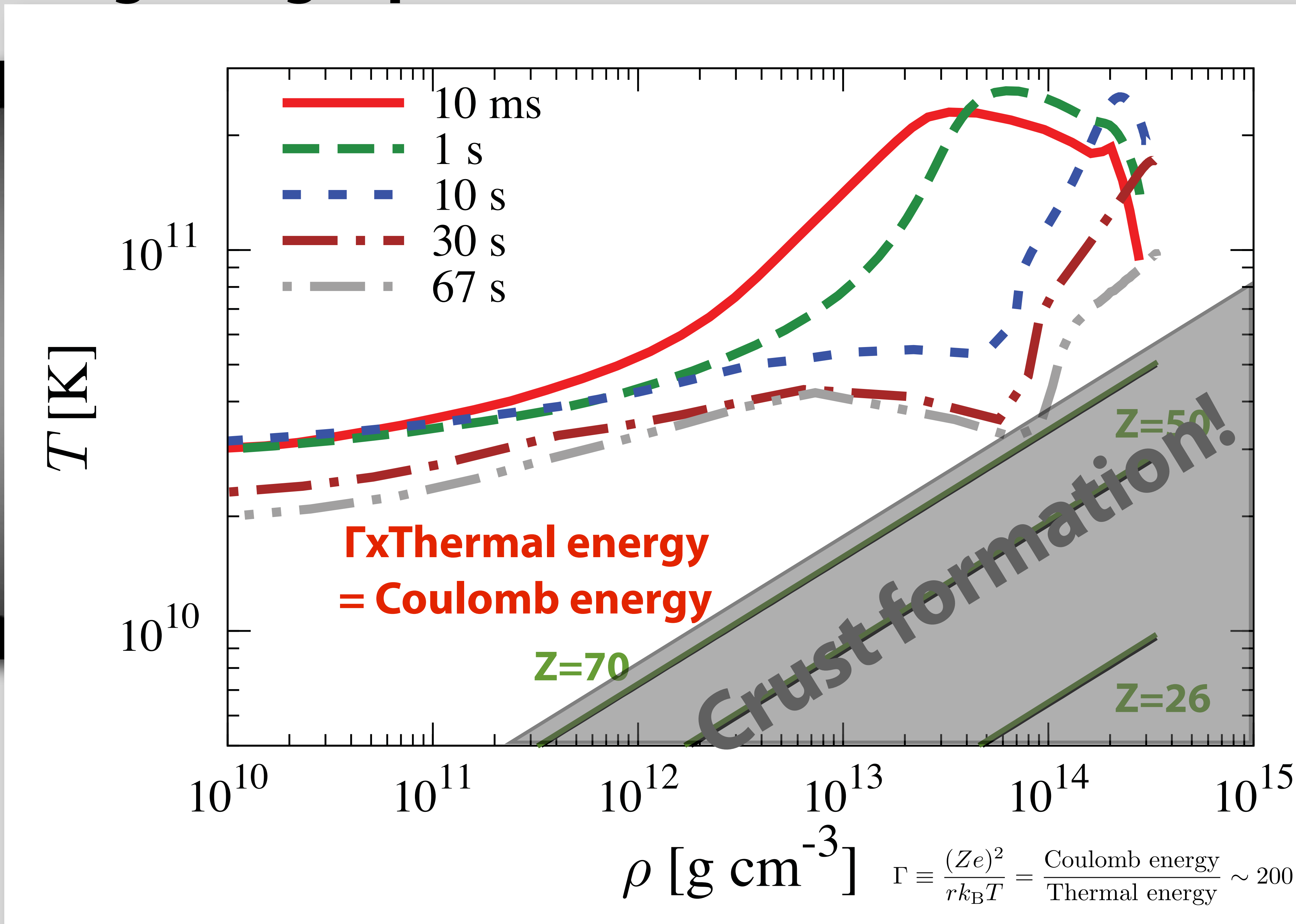
see talk by Fujisawa-san

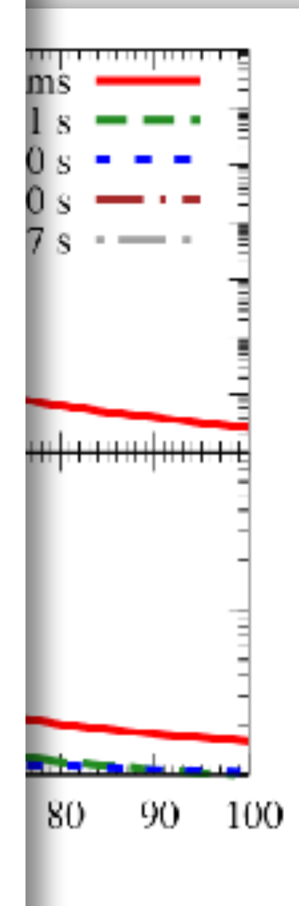
Crust formation

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

- **If crust forms earlier than t_{equil}, B-fields will be anchored before getting equilibrium state**







y Nakazato-san

Summary of NS B-fields

- **Regulation process is not clear yet**
  - fossil? amplified in progenitor? during core collapse? after proto-NS formation?

- **Crust formation**
  - *after* equilibrium is achieved for magnetars
  - *before* equilibrium is achieved for other NSs

Agenda

Observable of NS:

1. **mass**
2. **spin**
3. **magnetic fields**

Can we calculate them w/ supernova simulations?

Summary

Can we calculate them w/ supernova simulations?

1. **mass**
   - *yes w/ stellar evolution*
   - Si/Si-O interface at collapse is important
2. **spin**
   - *probably yes w/ stellar evolution*
   - post-explosion evolution is important
3. **magnetic fields**
   - *no, origin is highly uncertain*
   - crust formation might be important