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Heating and Cooling of Accreting Neutron Stars as a Probe of Neutron Star Interiors

Helei Liu (刘荷蕾)
School of Physical Science and Technology, Xinjiang University

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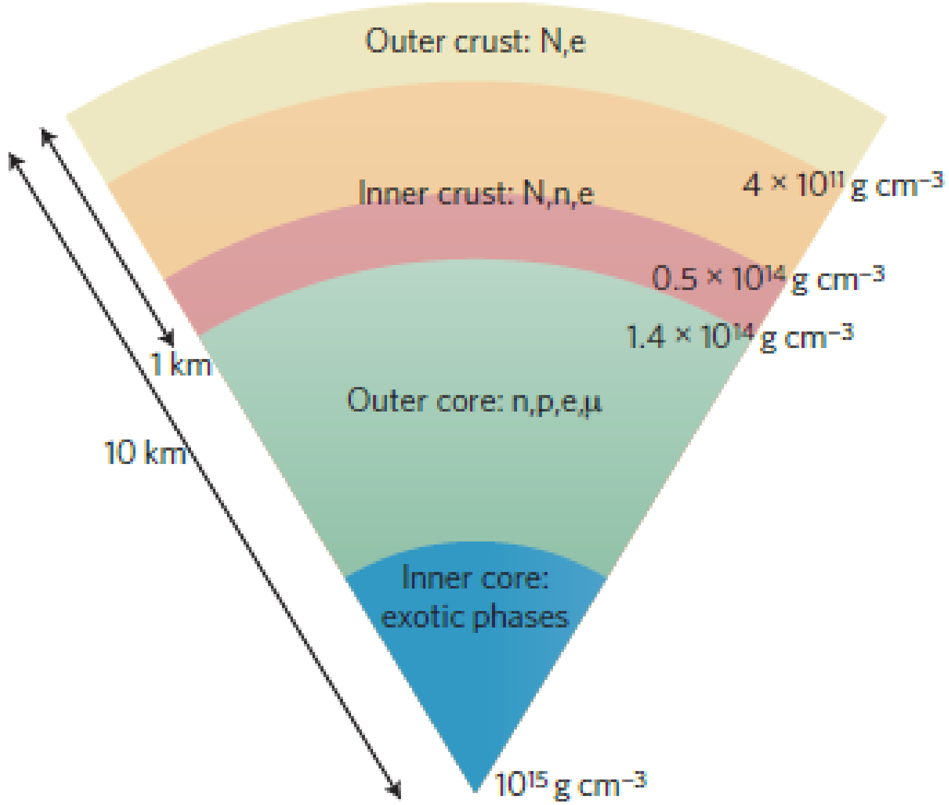
Today's Contents

- Background
  - Transiently accreting neutron stars
  - Heating and cooling of accreting neutron stars
- Elucidation of physics inside neutron stars from their cooling observations
  - EoS dependence of thermal evolution of accreting NS
  - Effect of neutrino heating on thermal evolution of accreting NS
- The mass and radius dependent of X-ray burst
- Conclusions & Future Perspective

Basic neutron star structure



Newton, 2013, Nat Phys

Typical value $M_{\mathrm{NS}}\sim 1.4 M_{\odot}, R_{\mathrm{NS}} \sim 10\ \mathrm{km}$

Core density >nuclear density

Possible exotic particles???

- No terrestrial experiments seem possible at such high densities and low temperature ($\ll 10^{10}$ K)
- Many equation of states (EoSs) for NS core matter have been developed

How to constrain EoS?

Many ways, but we consider heating and cooling of transiently accreting neutron stars and X-ray burst as the tools.

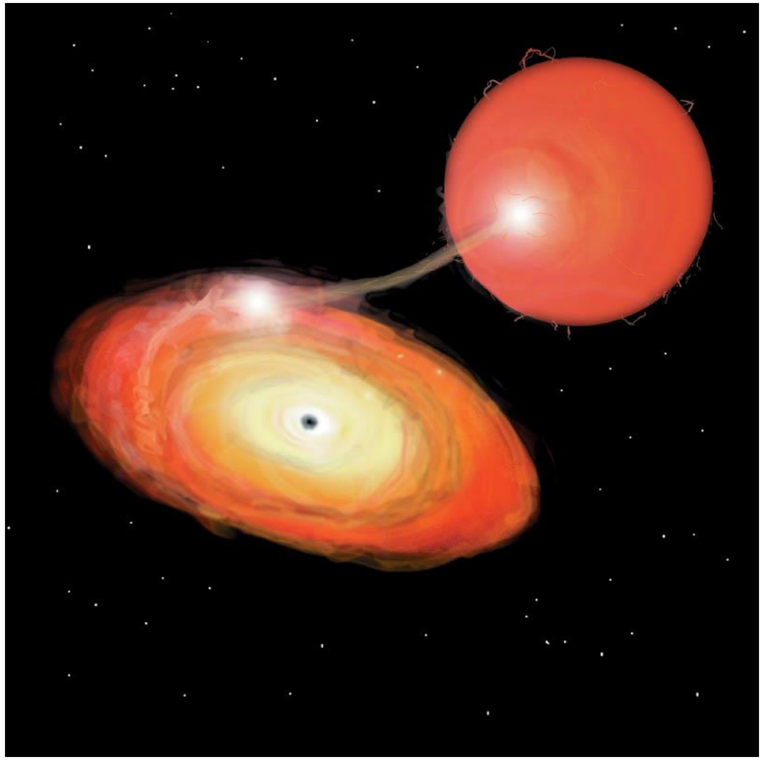
Transiently accreting neutron star

Low-mass x-ray binaries (LMXBs)

- $M_{\text{donar}} \lesssim 1 M_{\odot}$
- Orbital period: minites~days
- Old system (t$\gtrsim$ 1Gyr)
- Weak magnetic field ($B \sim 10^7$ to 10^9 G)
- Roche-Lobe Overflow

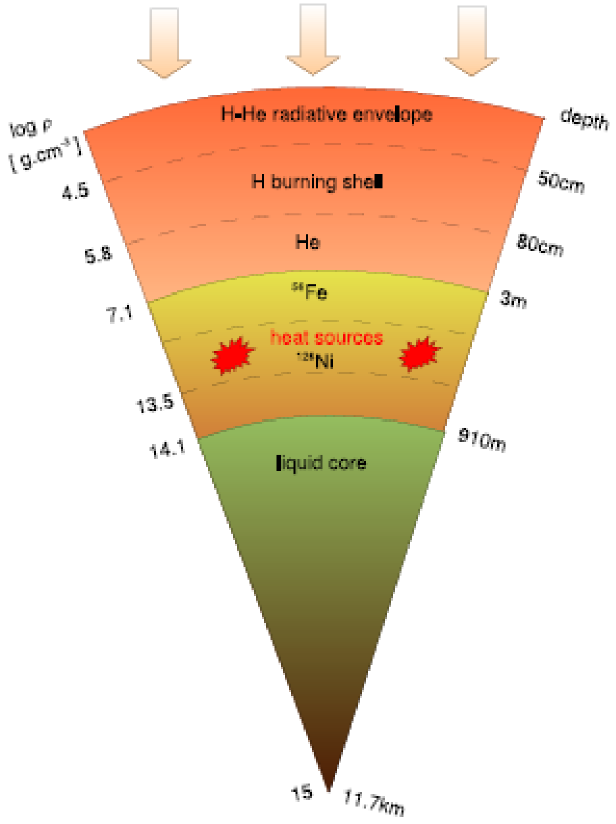
Soft x-ray transients (SXRTs)

- **Active phase**
  - accretion rate $\sim 10^{-10}$-10^{-8} $M_{\odot}$ yr^{-1}
  - Lx~$10^{36\text{-}39}$ erg/s
  - Weeks to months to years
- **Quiescent phase** (requires sensitive X-ray telescope)
  - little accretion
  - Lx~10^{34} erg/s



(NASA website)

Accreting NSs as nuclear physics laboratories

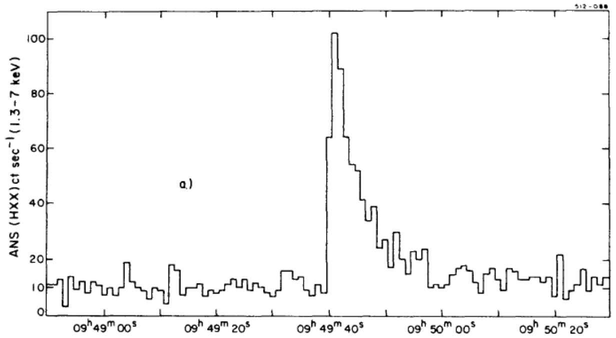


N Chamel, P Haensel . Living Rev. Relativity 2008

- **compression/heating of the envelope**

thermonuclear burning of light elements

Type I X-ray bursts and superbursts while accreting



Grindlay, 1976, ApJ

- **compression/heating of the crust**

e-captures, n-emission, pycnonuclear reactions

Cooling in quiescence

“Deep crustal heating”:
1~2 MeV/nuc

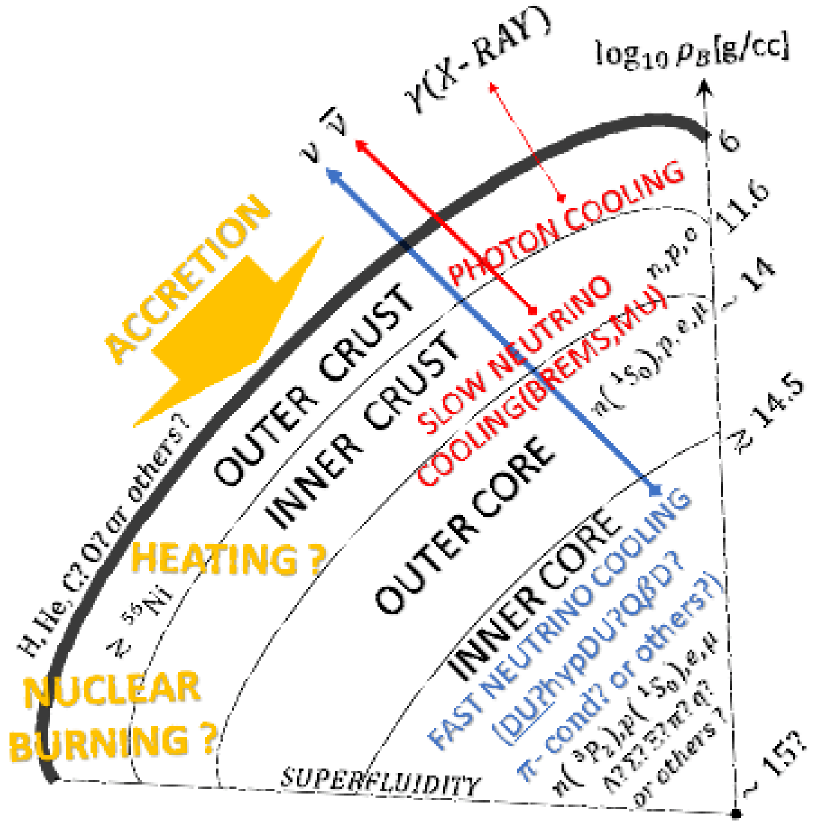
$$Q_i = 6.03\dot{M}_{-10}\,\frac{q_i}{\mathrm{MeV}}\,10^{33}\ \mathrm{erg\ s^{-1}}$$

P. Haensel et al, 1990,2003,2008

Energy Sources in Accreting NS

- Outer physics of NS
  - Release of gravitation
  - Nuclear burning

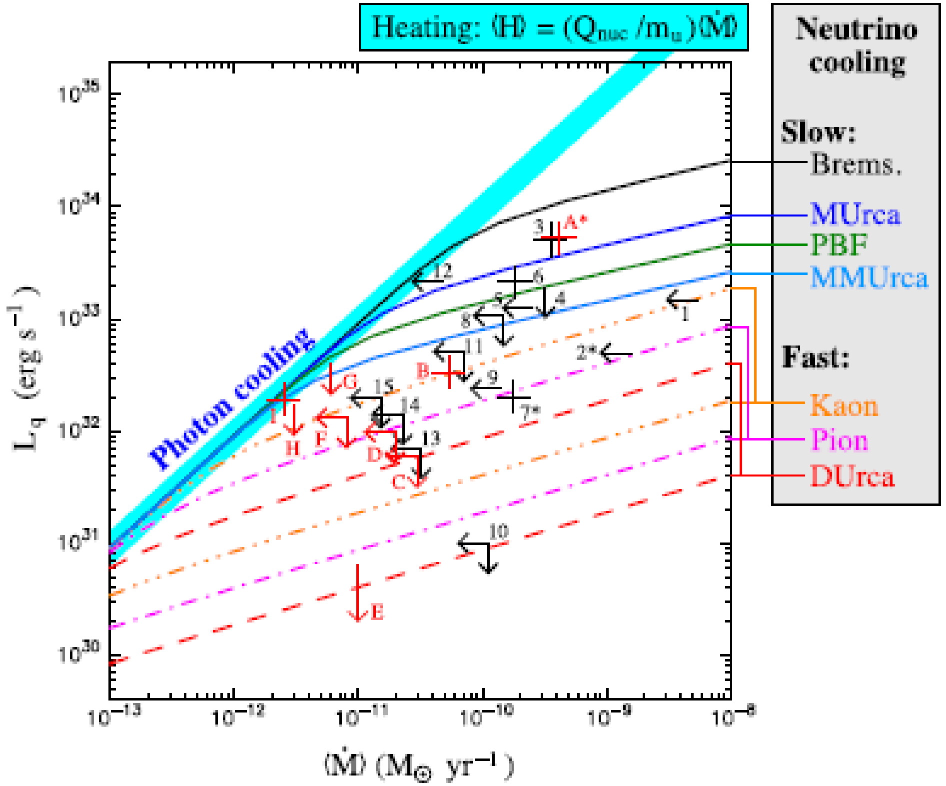
    3α reaction→HCNO cycle
    (Wallance & Woosley 1981)
    →αp process→rp process
    (Woosley & Weaver 1981,84)
    →SnSbTe cycle (Schatz+2001)
- Inner physics of NS
  - Crust heating (Haensel & Zdnick 90,03,08)
  - Shallow heating (Deibel, 2016)
  - ν emission (slow+Fast cooling)
  - EOS properties



⇒ Quiescent luminosity and burst phenomenon is related to not only outside but also inside physics of NS

Luminosity in quiescence of soft X-ray transients

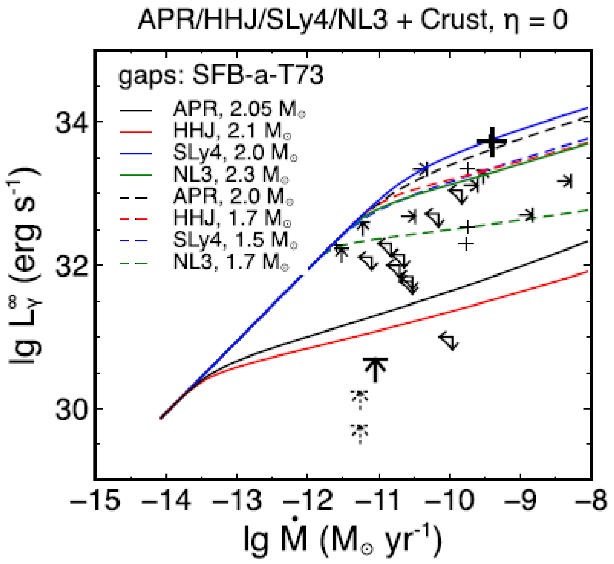
Steady state



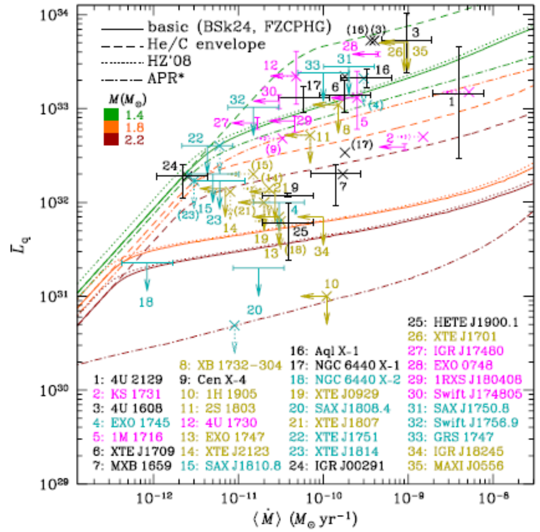
Wijnands et al, 2017

Depend on:

- the rate of neutrino cooling
- superfluidity
- Equation of state
- Surface composition



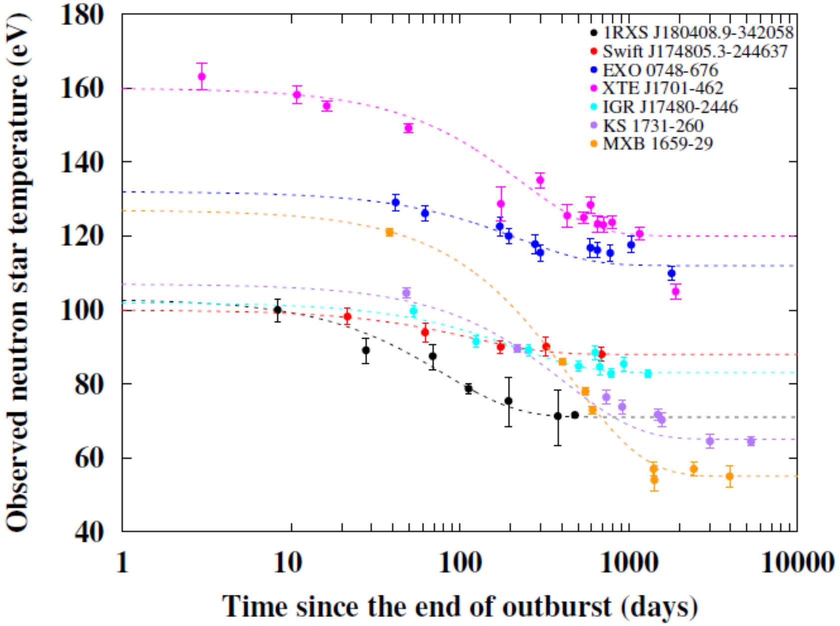
Han & steiner, 2017



Potekhin, et al, 2020

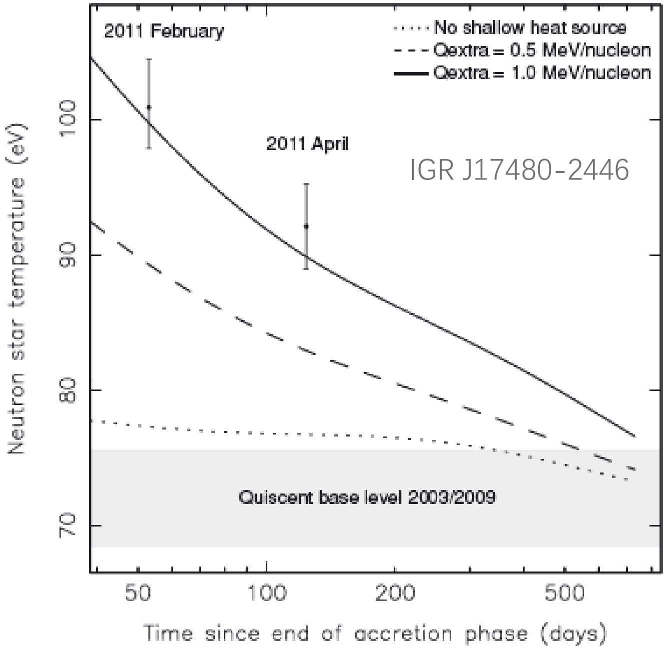
Luminosity in quiescence of soft X-ray transients

Crust cooling



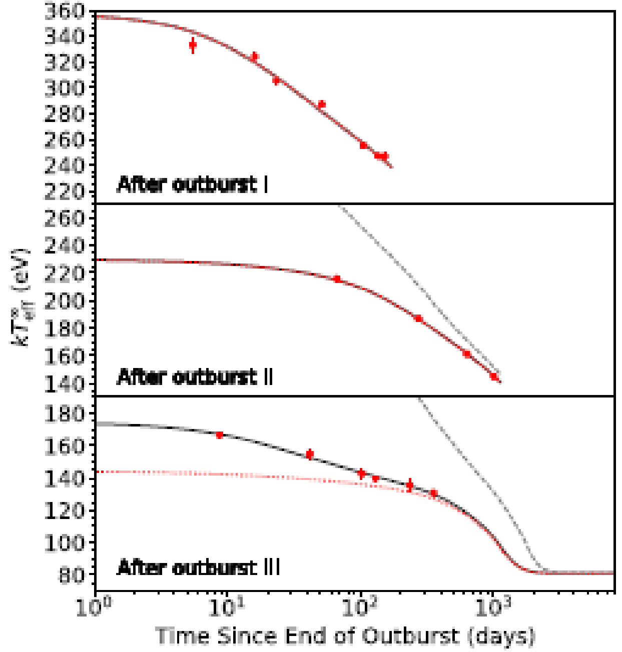
Wijnands et al, 2017

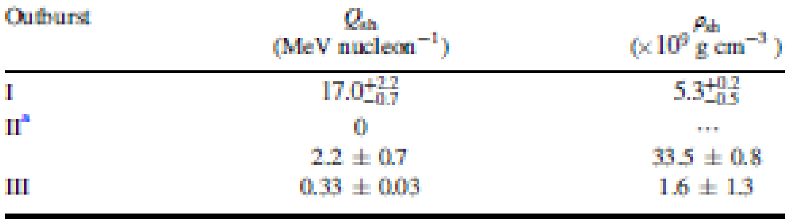
additional shallow heat source?



Degenaar et al, 2011

- Magnitude: 0-17 MeV/u
- Depth: 10^8-10^{10} g cm^{-2}
- Physics origin: unknown



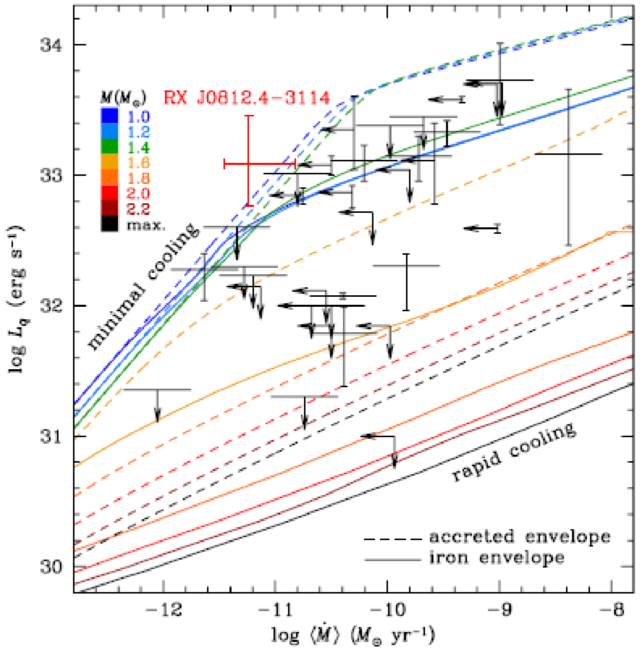


Outburst	$Q_{\rm sh}$ (MeV nucleon^{-1})	$\rho_{\rm sh}$ ($\times 10^9$ g cm^{-3})
I	$17.0^{+2.2}_{-0.7}$	$5.3^{+0.2}_{-0.3}$
II[a]	0	…
	2.2 ± 0.7	33.5 ± 0.8
III	0.33 ± 0.03	1.6 ± 1.3

Parikh, et al, 2017

Luminosity in quiescence of soft X-ray transients

RX J0812.4-3114



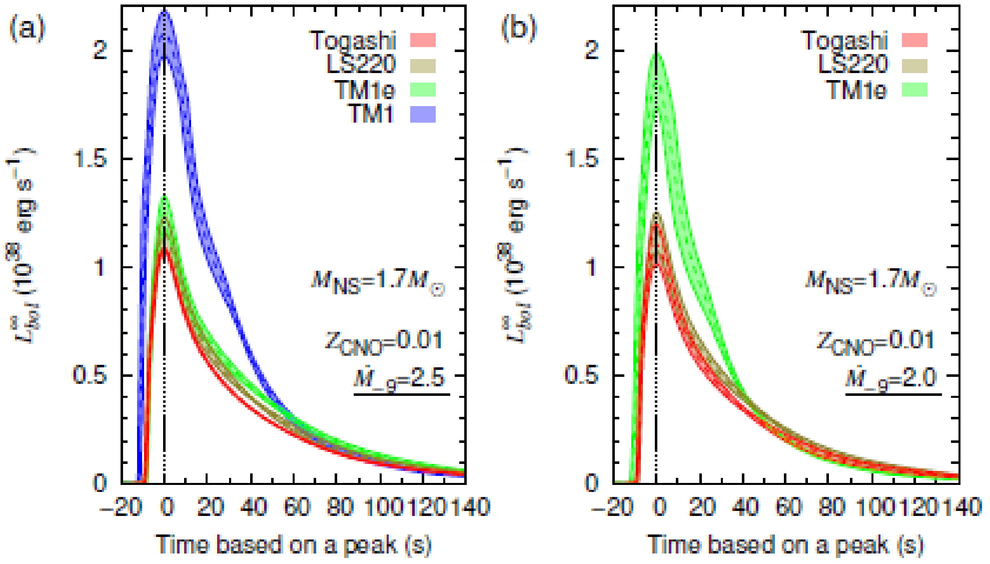
Zhao, et al, 2019

- Low accretion rate: $5.8 \times 10^{-12}\ M_{\odot}\ \mathrm{yr}^{-1}$
- High luminosity: $L_X \approx 1.6 \times 10^{33}\ \mathrm{erg\ s}^{-1}$

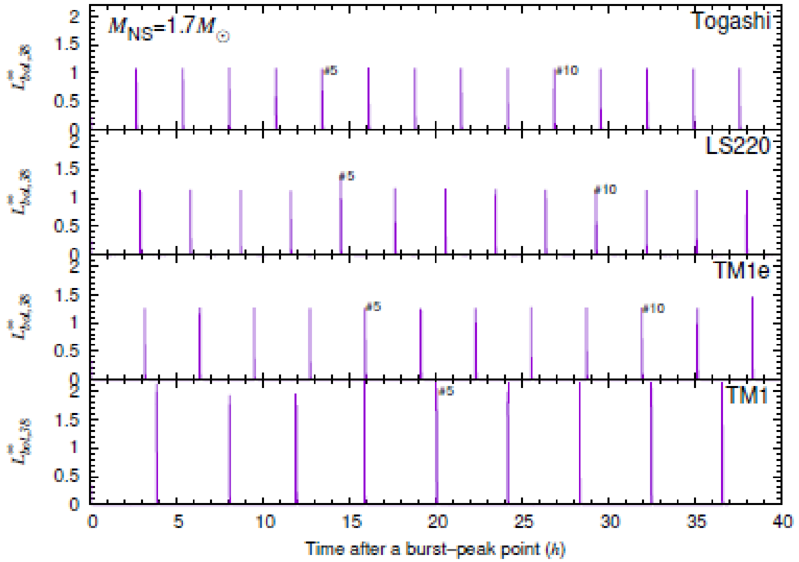
Possible explanation:

- RX J0812.4-3114 contains a relatively low-mass NS with minimum cooling
- The system may be young enough that the NS has not fully cooled from the supernova explosion
- Additional heating?

Effects of equation of state on type-I x-ray burst



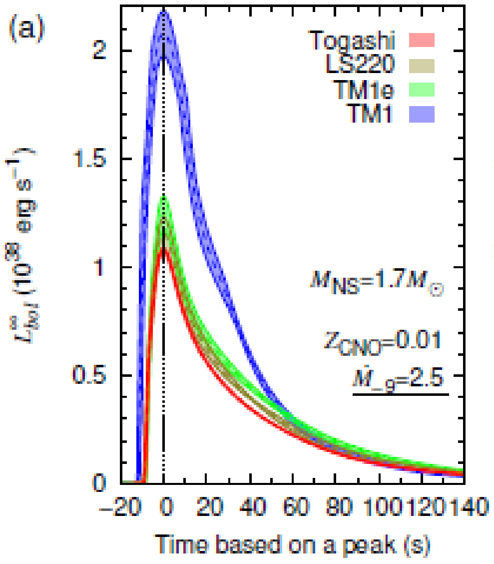
Dohi,2021,ApJ



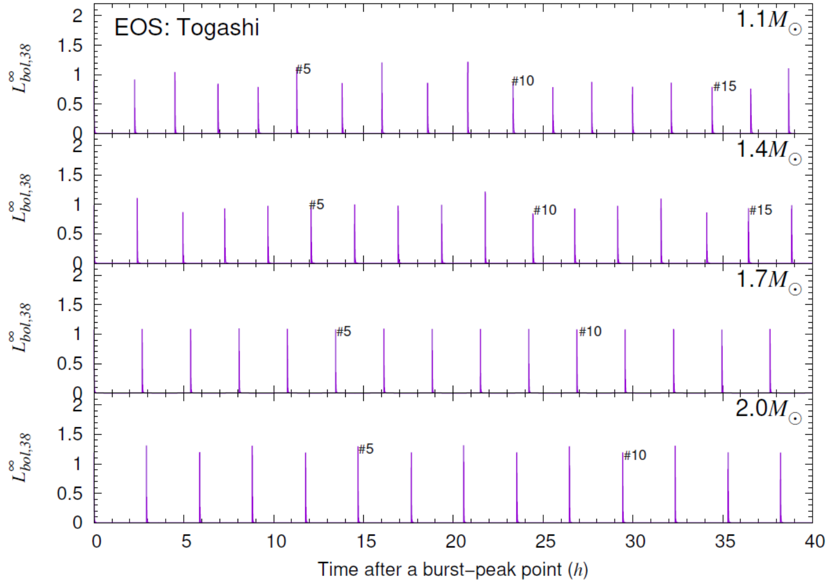
- Previous studies about multi-zone modeling cover with accreted layer, giving boundary conditions on NS crust, but don't consider some physics of interior NS

- Dohi, et al. studied X-ray bursts using a general relativistic stellar-evolution code with several EoSs

Effects of equation of state on type-I x-ray burst



Dohi,2021,ApJ



- Previous studies about multi-zone modeling cover with accreted layer, giving boundary conditions on NS crust, but don’t consider some physics of interior NS
- M increases, the time interval becomes larger, the peak luminosity becomes higher

Basic Equations

The general relativistic evolutionary equations:

$$
\begin{aligned}
\frac{\partial M_{tr}}{\partial r} &= 4\pi r^2 \rho \ , \\
\frac{\partial P}{\partial r} &= -\frac{G M_{tr} \rho}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{M_{tr} c^2}\right) V^2 \ , \\
\frac{\partial (L_r e^{2\phi/c^2})}{\partial M_r} &= e^{2\phi/c^2}\left(\varepsilon_{\rm n} - \varepsilon_{\nu} + \varepsilon_{\rm g}\right) \ , \\
\frac{\partial \ln T}{\partial \ln P} &= \nabla_{\rm rad} \ , \\
\frac{\partial \phi}{\partial M_{tr}} &= \frac{G(M_{tr} + 4\pi r^3 P/c^2)}{4\pi r^4 \rho} V^2 \ ,
\end{aligned}
$$

where

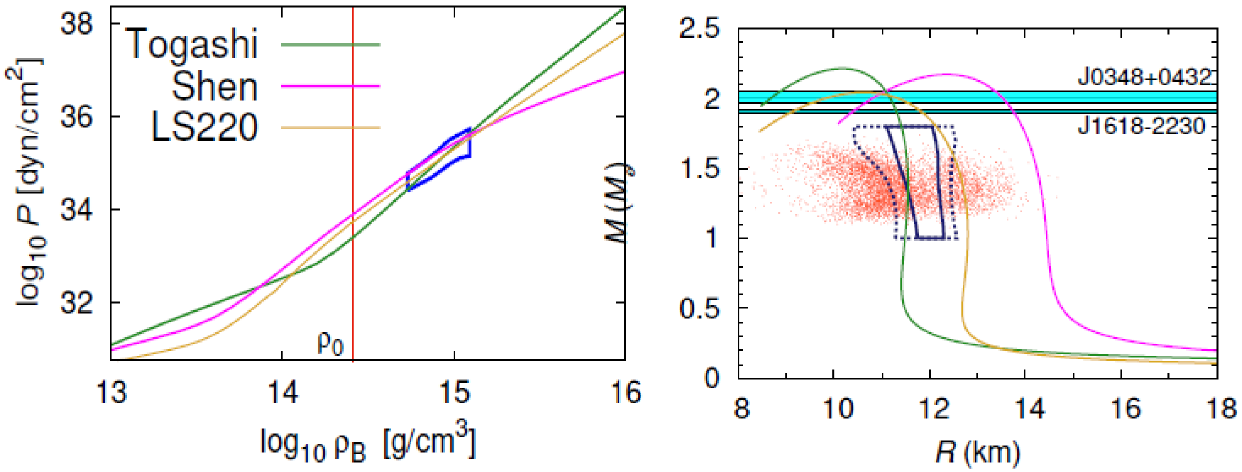
$$
\frac{\partial M_{tr}}{\partial M_r} = \frac{\rho}{\rho_0} V^{-1}, \ \ V \equiv \left(1 - \frac{2 G M_{tr}}{c^2 r}\right)^{-1/2} .
$$

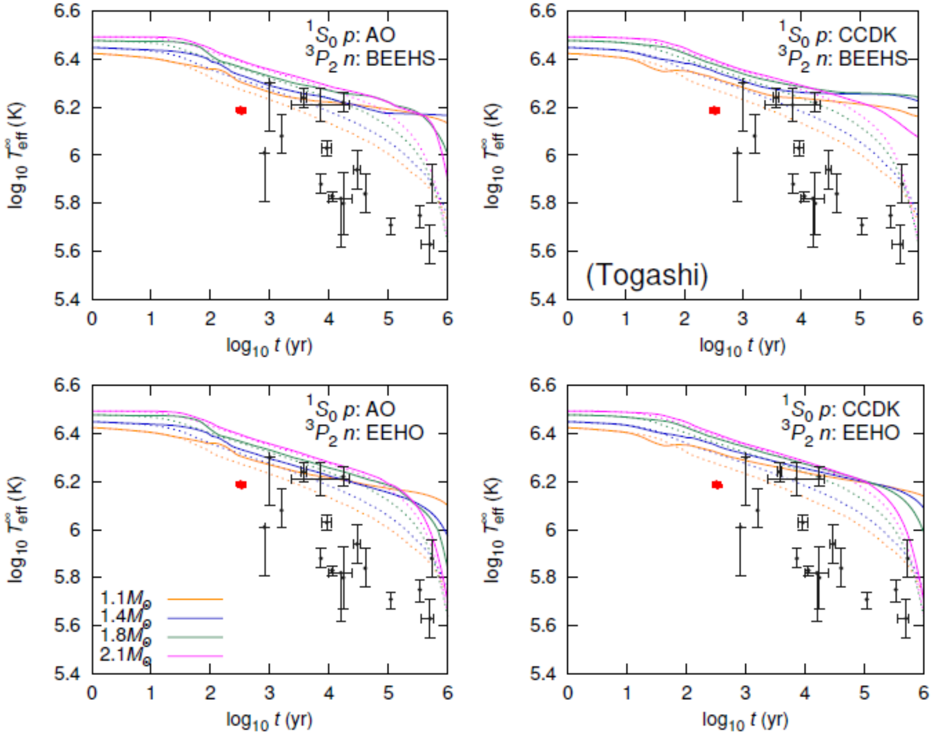
Fujimoto et al, 1984; Thorne et al, 1977;

Physics input:

- Equation of state
- Neutrino emission
  - Standard cooling
    - Modified URCA
    - Bremsstrahlung process
  - fast cooling
    - Direct URCA
    - Pion condensation process
    - …
  - PBF
- heating
  - deep crustal heating
  - shallow heating …

EoS dependence of the cooling curves





Dohi, Hashimoto, 2019

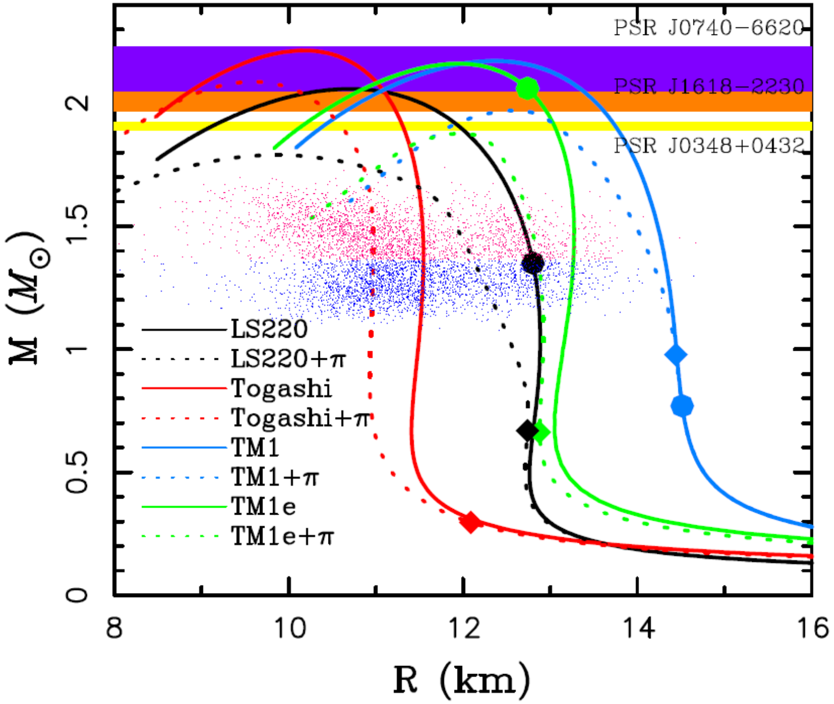
- $2M_\odot$ NS observation
- GW170817
- Low mass X-ray binary observations

DU process of Togashi EoS is prohibited

Any other fast cooling processes work in NS? (exotic particles such as hyperons, pions, kaons, and quarks)

EoS+pion condensation

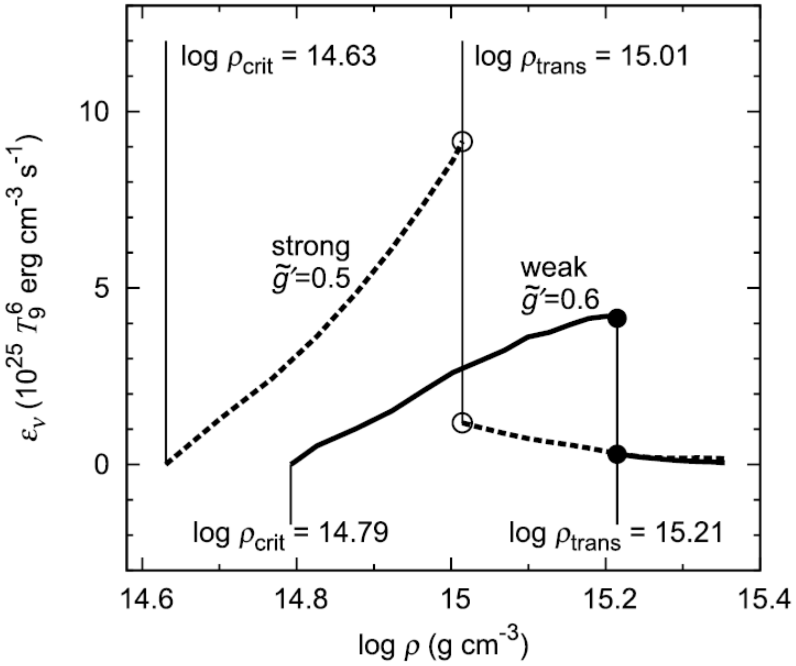
Liu & Dohi, PRD, 2021



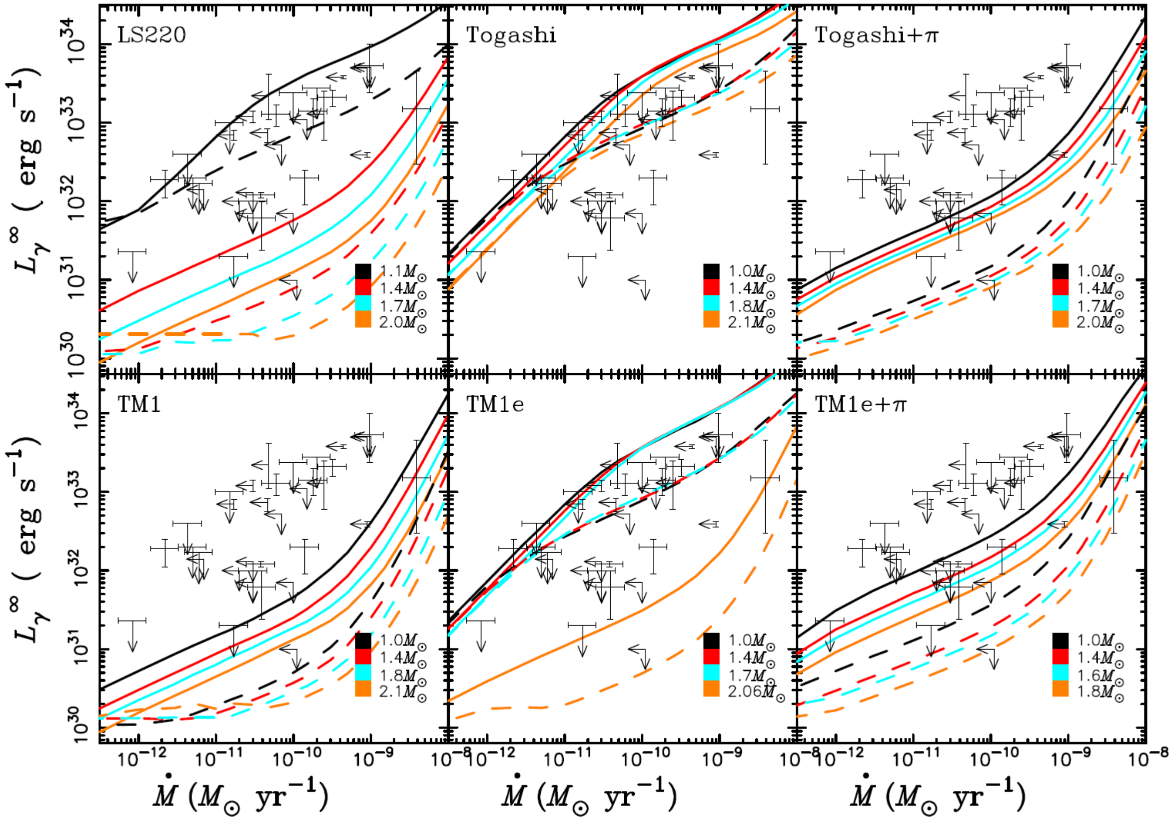
EoS	Togashi	Togashi+π
$M_{\max}(M_\odot)$	2.21	2.09

Effects of pion condensation

- ➢ Soften the EoSs
- ➢ Strong pion neutrino emission

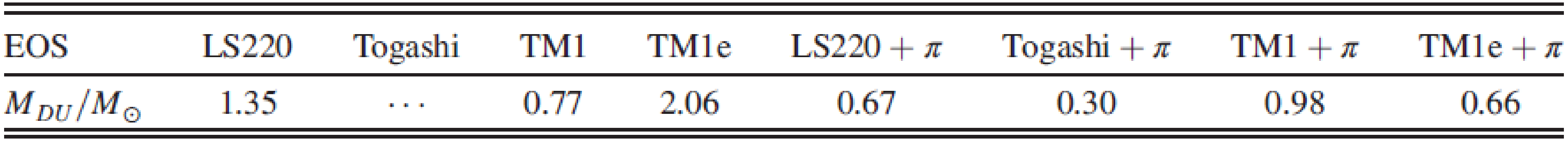


Quiescent Luminosity of accreting NS



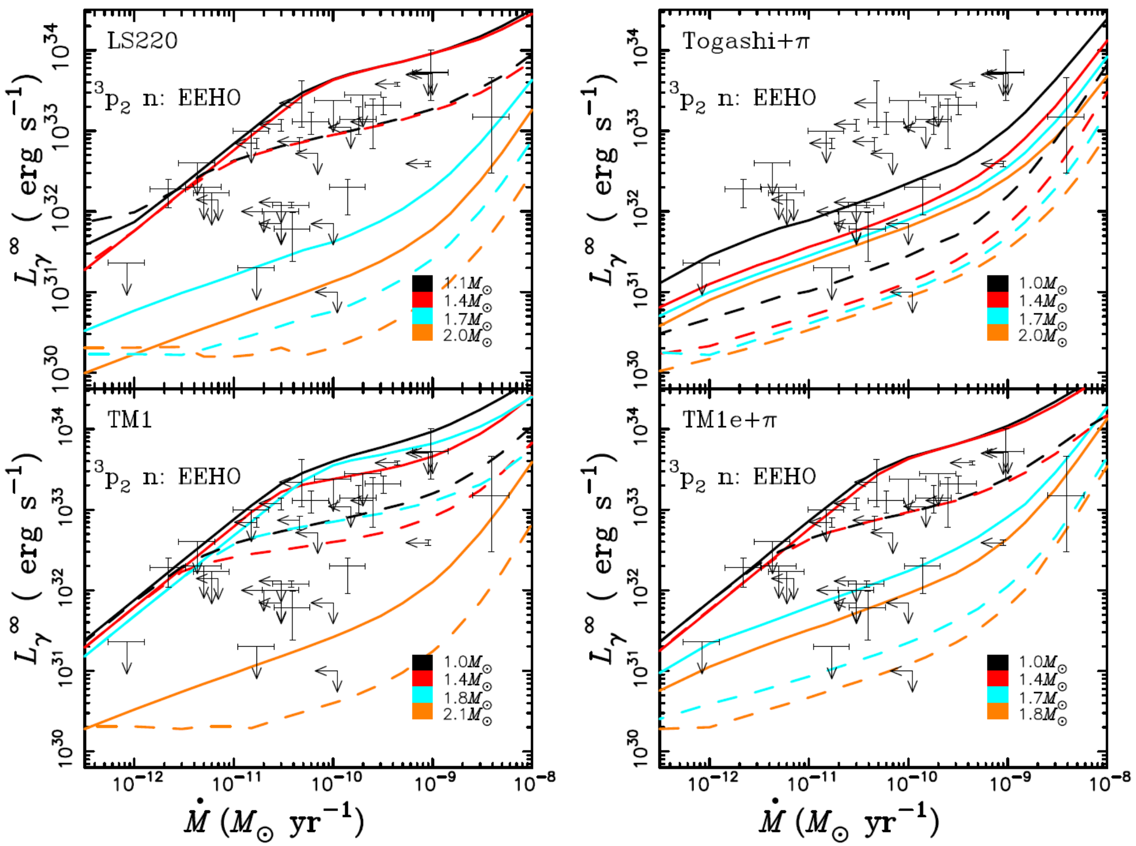
Liu & Dohi, PRD, 2021

Heating curves with TM1,Togashi+π, TM1e+π located too low, superfluidity is needed



EOS	LS220	Togashi	TM1	TM1e	LS220 + π	Togashi + π	TM1 + π	TM1e + π
$M_{DU}/M_\odot$	1.35	⋯	0.77	2.06	0.67	0.30	0.98	0.66

Quiescent Luminosity of accreting NS

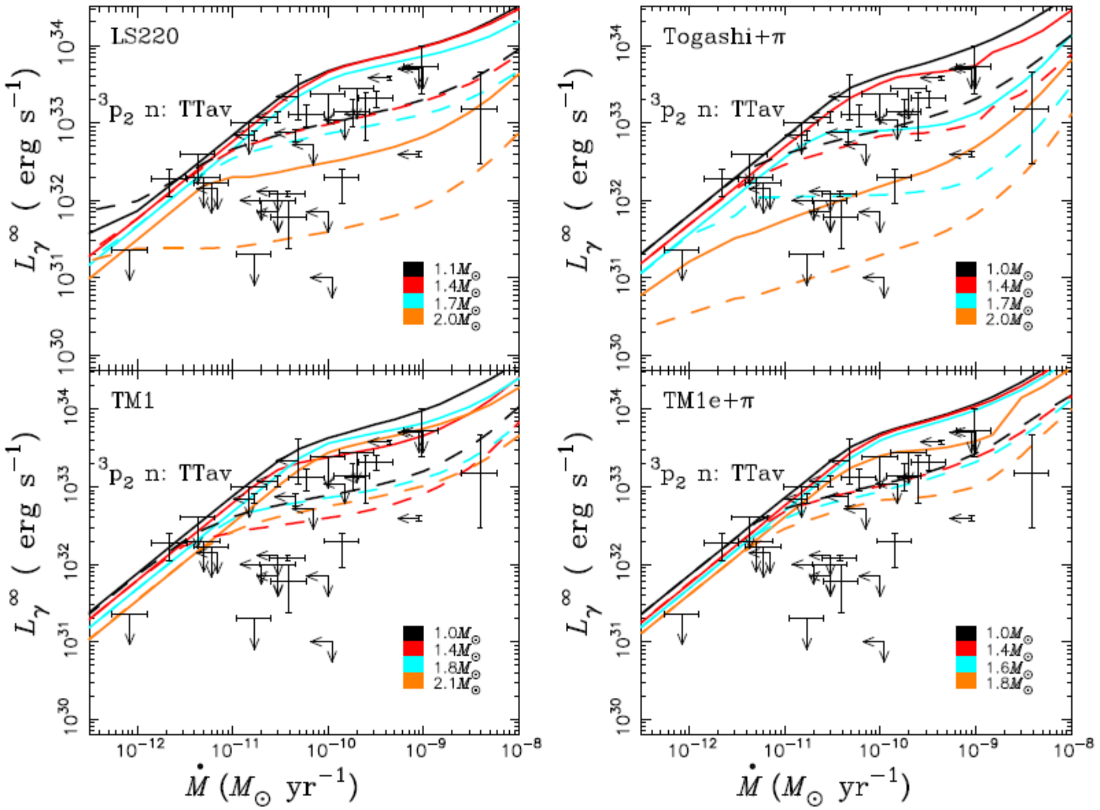


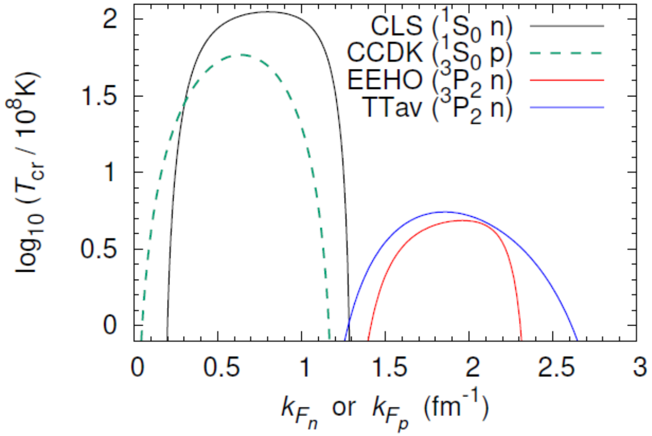
Liu & Dohi, PRD, 2021

Neutron $^1S_0$: CLS
Proton $^1S_0$: CCDK

EEHO for Neutron $^3P_2$ is too weak to explain some hot observations

Quiescent Luminosity of accreting NS





Strong neutron $^3P_2$ superfluidity TTav can fit cooling observations

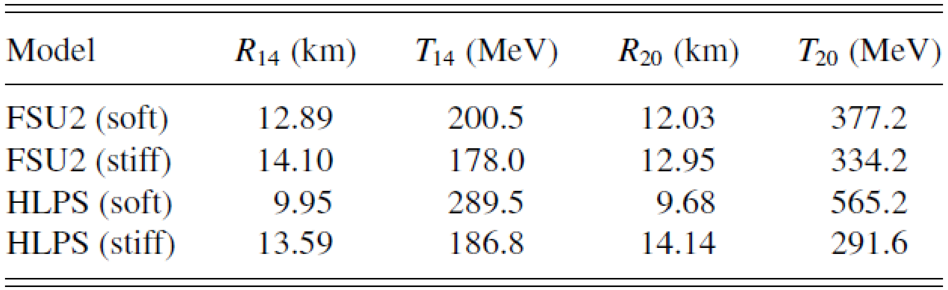
Crustal heating by neutrinos from the surface of accreting neutron stars

Charged Pion Production from infalling matter

Kinetic energy:

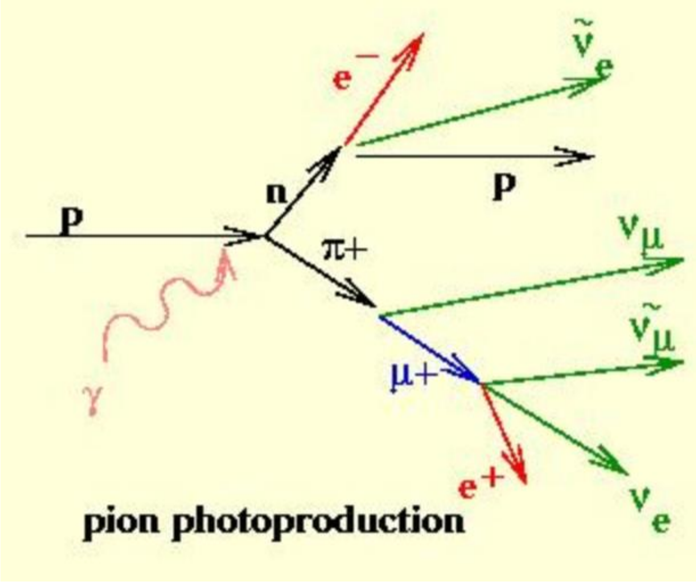
$$T = m_0 c^2 \left(\frac{1}{\sqrt{1 - R_S/R}} - 1 \right)$$

Bildsten, et al., 1992



Model	R_{14} (km)	T_{14} (MeV)	R_{20} (km)	T_{20} (MeV)
FSU2 (soft)	12.89	200.5	12.03	377.2
FSU2 (stiff)	14.10	178.0	12.95	334.2
HLPS (soft)	9.95	289.5	9.68	565.2
HLPS (stiff)	13.59	186.8	14.14	291.6

Fattoyev, et al, 2018



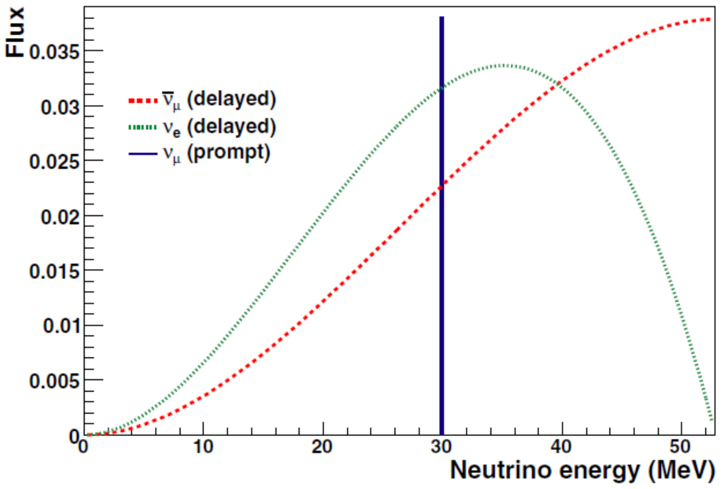
If $T_{\text{kin}} \gtrsim 290$ MeV (pion production threshold), it could occur near the surface due to free-fall material

Crustal heating by neutrinos from the surface of accreting neutron stars

- After pion production
  - $\pi^0 \to \gamma + \gamma$
  - $\pi^+ \to \mu^+ + \nu_\mu, \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$
  - $\pi^- \to \mu^- + \bar{\nu}_\mu, \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

$E_{\nu_\mu} = 29.8$ MeV, $E_{\nu_e} = 33.3$ MeV, $E_{\bar{\nu}_\mu} = 37.7$ MeV from neutrino energy spectrum

Scholberg, 2006



- Then, assuming the probability 50% that neutrinos move into the crust , the total carrying energy is:

$$q_\nu \approx 0.5\left(E_{\nu_\mu} + E_{\nu_e} + E_{\bar{\nu}_\mu}\right) N_{\pi^+}$$

$=50.4 \text{ MeV} N_{\pi^+}$

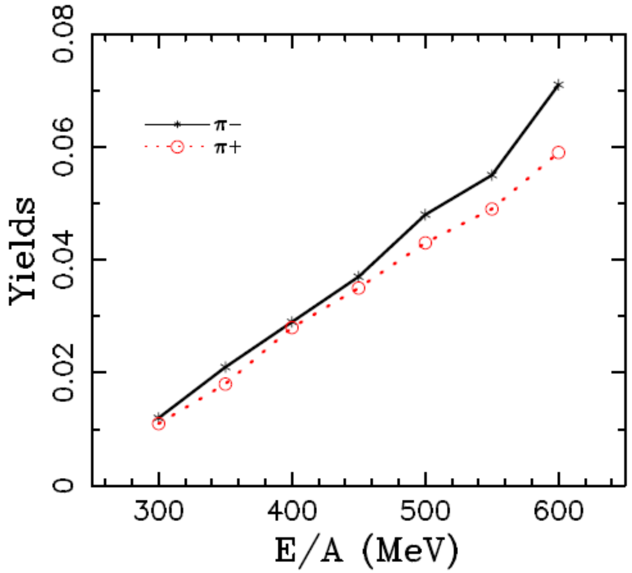
- For neutrino transport, all neutrinos are assumed to eventually deposit in the crust

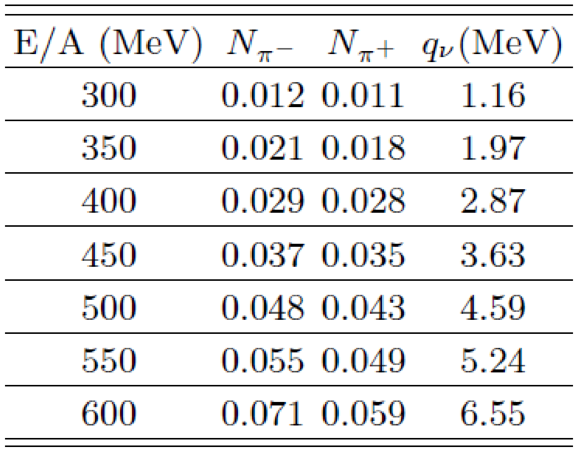
Does the pion production affect quiescent luminosity of transiently accreting neutron stars?

Estimation of q_ν

- The pion production obtained from the IBUU transport model
- We consider α-Fe collision

$$q_\nu \approx 0.5\left(E_{\nu_\mu} + E_{\nu_e} + E_{\bar{\nu}_\mu}\right)(N_{\pi^+} + N_{\pi^-})$$
$$= 50.4 \text{ MeV } (N_{\pi^+} + N_{\pi^-})$$





E/A (MeV)	N_{π^-}	N_{π^+}	q_ν(MeV)
300	0.012	0.011	1.16
350	0.021	0.018	1.97
400	0.029	0.028	2.87
450	0.037	0.035	3.63
500	0.048	0.043	4.59
550	0.055	0.049	5.24
600	0.071	0.059	6.55

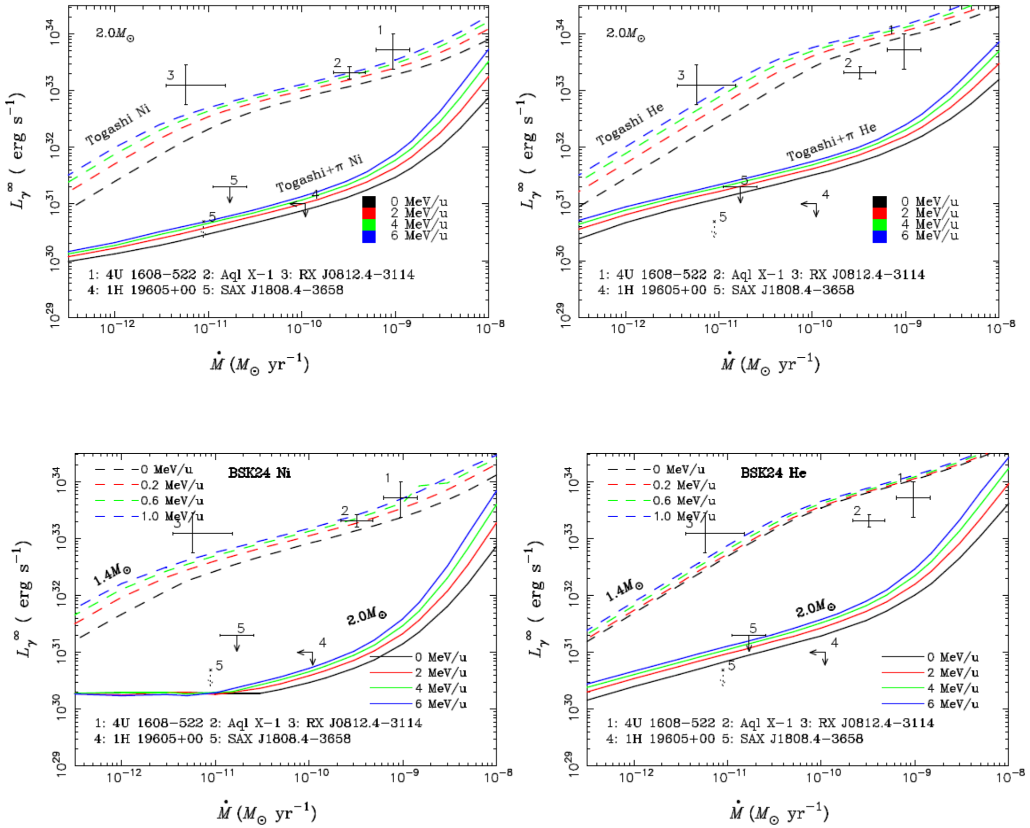
- ➢ Decelerated by radiative pressure
- ➢ free-fall condition
- ➢ Electromagnetic acceleration

Quiescent luminosities of SXTs with neutrino heating

Model	R_{14} (km)	T_{14} (MeV)	R_{20} (km)	T_{20} (MeV)
Togashi	11.55	232.1	11.17	427.2
Togashi + π	10.97	249.7	10.33	493.8
BSK24	12.54	207.2	12.27	363.5

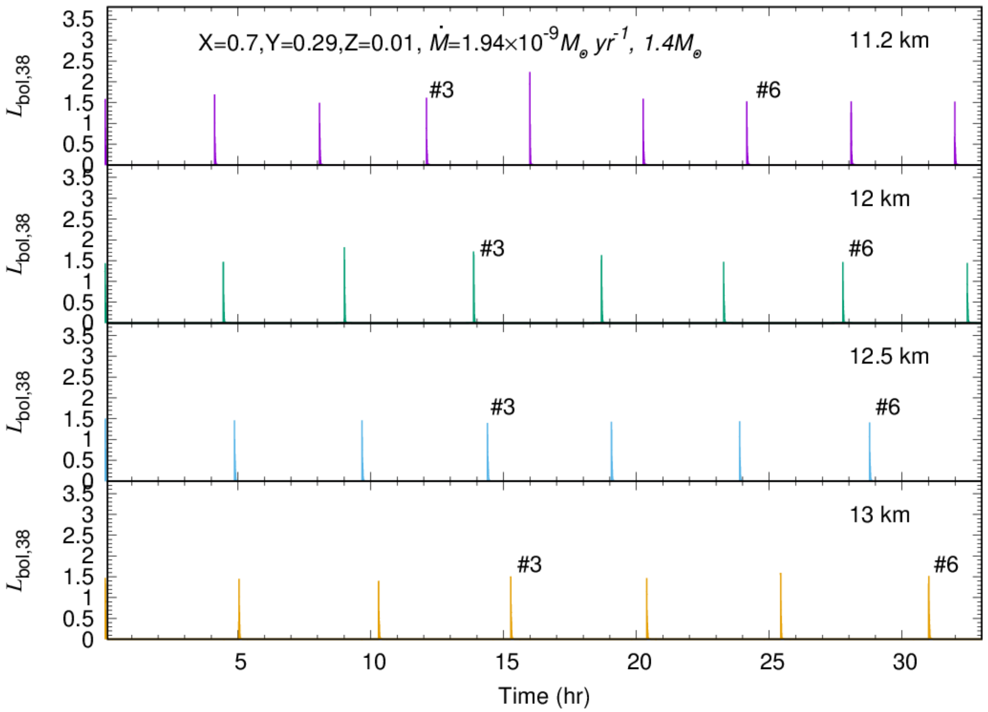
- $q_\nu = 0 - 1$ MeV/u for $1.4M_\odot$
- $q_\nu = 0 - 6$ MeV/u for $2.0M_\odot$

- SAX J1808.4-3658 (low accretion rate, high luminosity)can be explained with a $2M_\odot$ neutron star
- The observation on cold sources can still be explained with neutrino heating

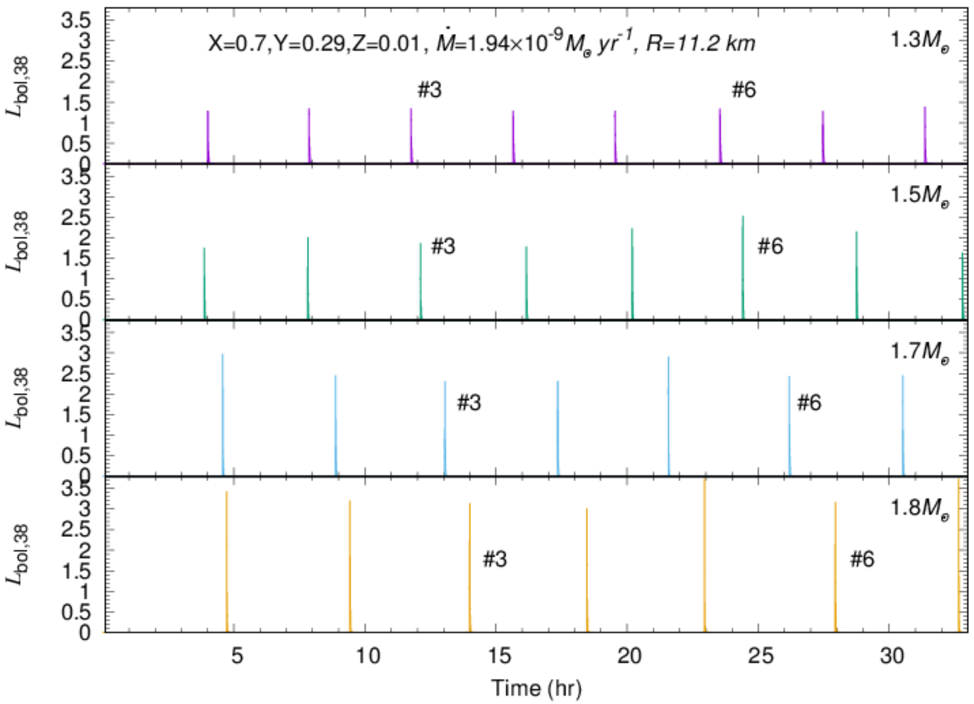


Liu, et al, 2021, PRD

Mass and radius dependence of Type I x-ray burst

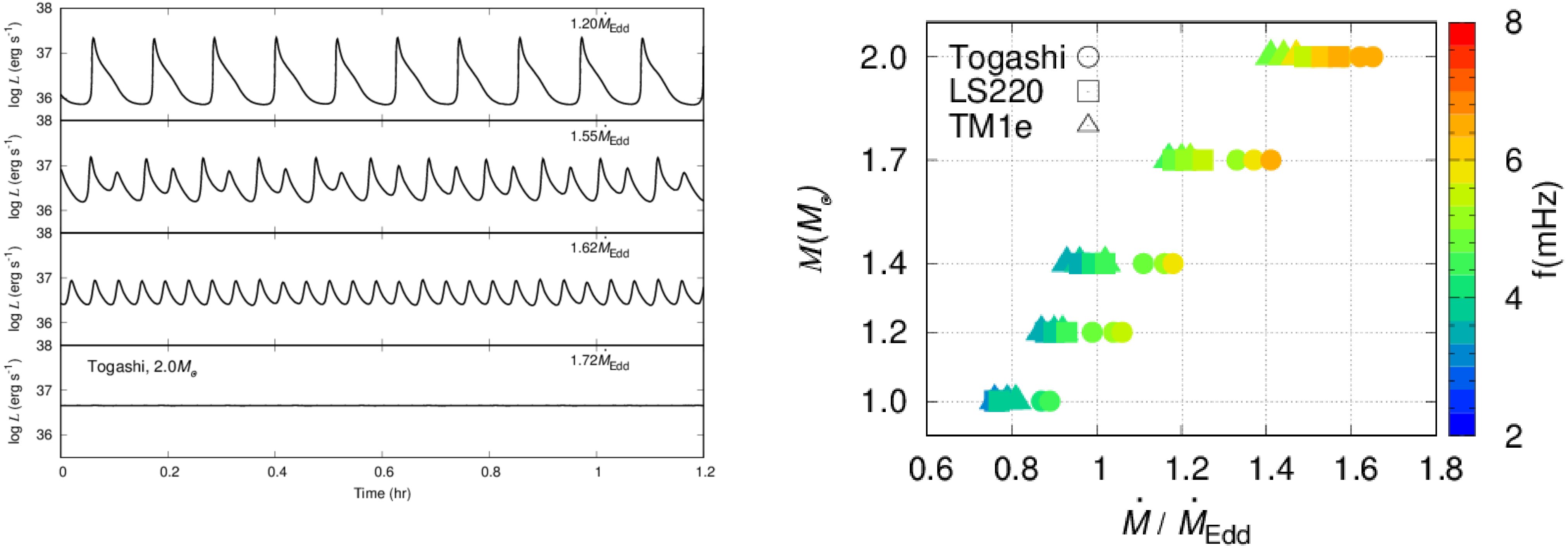


Large radius models get higher luminosity



Higher mass models get higher luminosity

EoS dependence of mHz Qpo



Summary & future work plan

- ✓ Studying the cooling and heating of accreting neutron stars in quiescence
  - EoSs dependence
    - Direct URCA threshold
    - superfluid
  - Effect of neutrino heating
    - The observation on hot source such as SAX J1808.4-3658can be explained with a $2M_\odot$ neutron star under the condition that neutrino heating is considered
- ✓ Studying the mass and radius dependence of type I x-ray burst

Future work plan:

- Studying the possible heating mechanism in the crust of accreting neutron stars
- Studying the EoS dependence of crust cooling
- Studying the EoS dependence of type I x-ray burst and mHz QPO

THANKS!