Thermal Evolution of Isolated Neutron Star and the Influence of Equation of State

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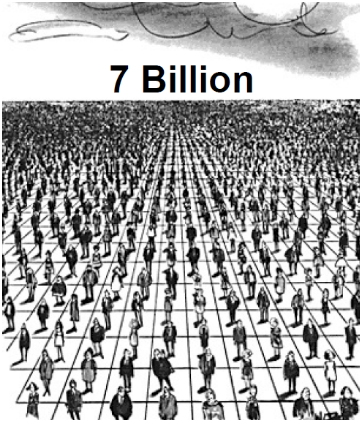
The Density of Neutron Star (NS)



$\Longrightarrow$

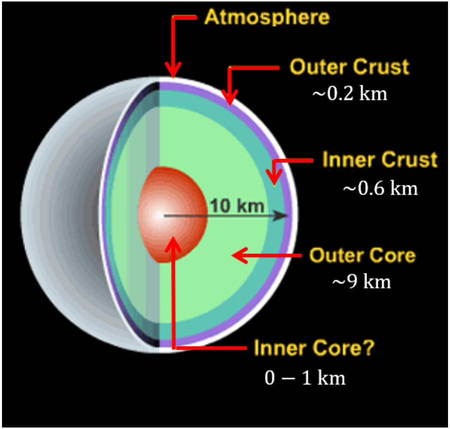
NS density is equivalent to the mass of the entire human population compressed to the size of a sugar cube.

Basic NS Size and Composition

- $\sim$ The size of Manhattan city
  $\Rightarrow$ Compact Object !!
- Supported by mainly nuclear pressure
- low temperature
  $T \lesssim 1$ MeV $\ll T_{\text{Fermi}}$
- At least neutrons, protons, electrons are degenerate.
- Possible exotic particles in NS core.

Typical values

$M \sim 1.4\ M_\odot$ & $R \sim 12$ km



Neutrino Transparency (Shapiro's text)

λ_i: mean free path of i particle

- $\nu_e - e$ Inelastic Scattering Off e (and μ)

$$\lambda_e = (\sigma_e n_e)^{-1} \sim \left(9 \times 10^7 \text{ km}\right) (\rho_0/\rho_{\rm B})^{4/3} (100 \text{ keV}/E_\nu)^3$$

- $n - \nu$ Elastic Scattering Off n

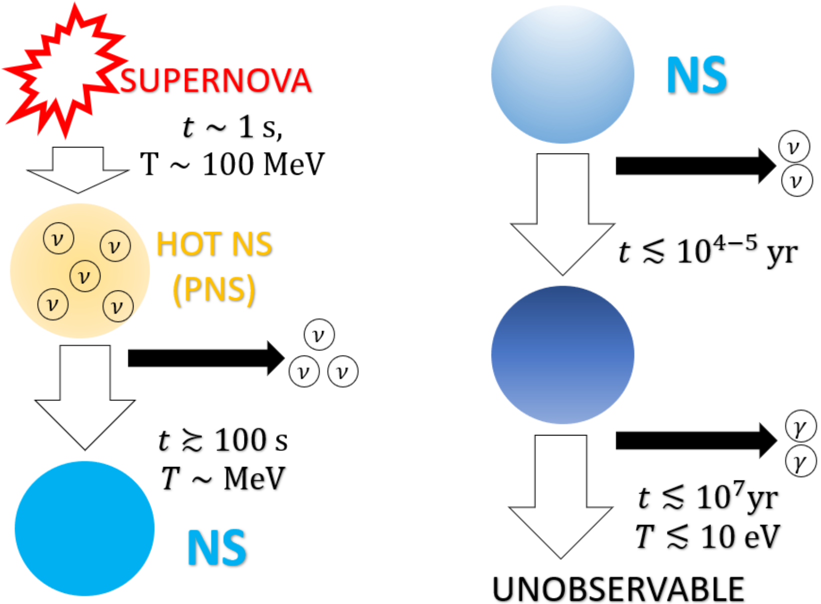
$$\lambda_n = (\sigma_n n_n)^{-1} \sim (300 \text{ km}) (\rho_0/\rho_{\rm B}) (100 \text{ keV}/E_\nu)^2$$

- The *effective* mean free path is

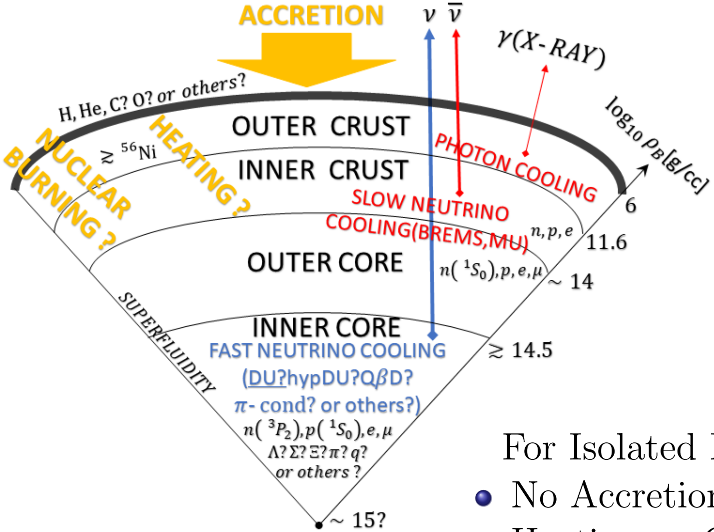
$$\lambda_{\rm eff} = \sqrt{\lambda_n \lambda_e} \sim \left(2 \times 10^5 \text{ km}\right) (\rho_0/\rho_{\rm B})^{7/6} (100 \text{ keV}/E_\nu)^{5/2}$$

$\Rightarrow$ Since $E_\nu \lesssim 100$ keV ($T \lesssim 10^9$ K),
$\lambda_{\rm eff} \gg R \sim 10$ km, and that is why
NS is transparent to neutrinos.

How is NS cooled ?



NS Structure and Cooling

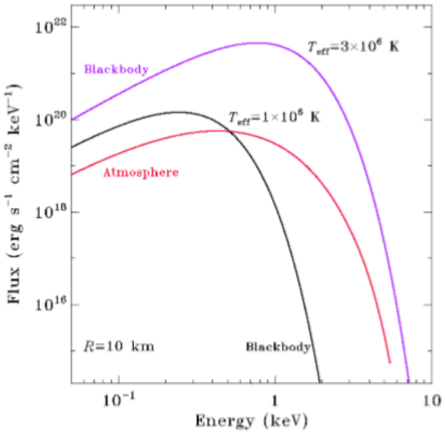


For Isolated NS (INS)

- No Accretion
- Heating ≪ Cooling

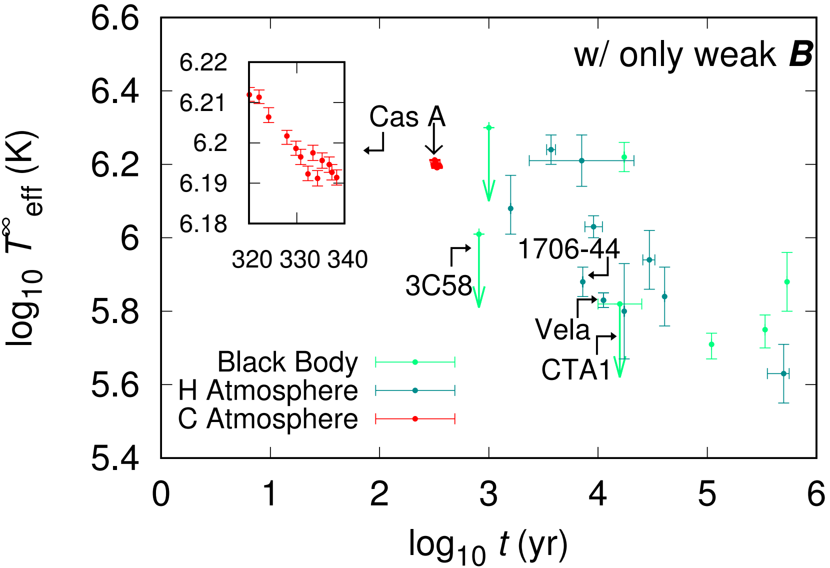
Surface Models of INS observations

- Cooling history can be compared with the observed Flux of INS.
  - Blackbody: unrealistic
  - Atmosphere: at higher T, lower $\boldsymbol{B}$
  - Solid/Liquid surface: at lower T, higher $\boldsymbol{B}$
- We consider INS with low $\boldsymbol{B}$, that is, blackbody/atmosphere surface models.



(Pavlox *et al.* *2001*, His eConf. slide in 2004)

Age & Surface Temperature of INS



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TOV Equations

1. Mass Eq.

$$\frac{\partial M_{\rm tr}}{\partial r} = 4\pi r^2 \rho$$

2. Hydrostatic equilibrium Eq.

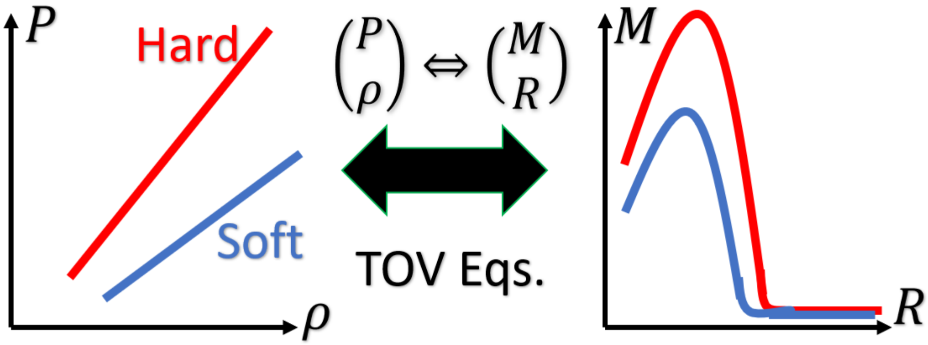
$$\frac{\partial P}{\partial r} = -\frac{G\rho}{r^2}\left(1 + \frac{P}{\rho c^2}\right)\left(M_{\rm tr} + \frac{4\pi r^3 P}{c^2}\right)\left(1 - \frac{2GM_{\rm tr}}{c^2 r}\right)^{-1}$$

under ideal fluid $T^{\mu\nu} = \mathrm{diag}(-\rho, P, P, P)$

$M_{\rm tr}$: total mass inside radius r, ρ: total mass energy density

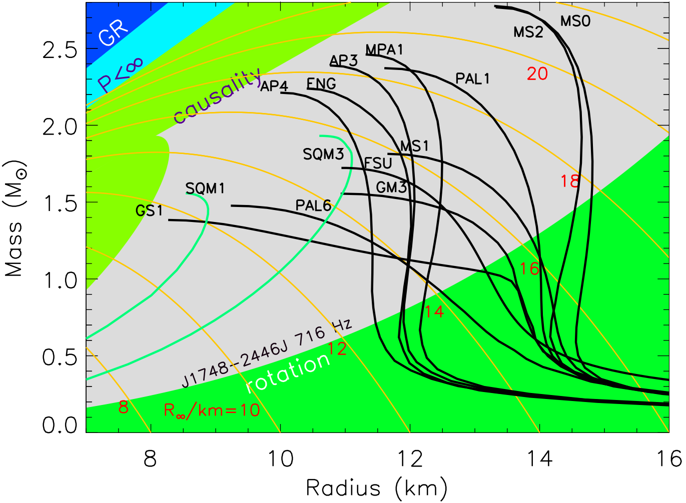
$\Rightarrow$ Since there are 3 variables $P(r), \rho(r), M_{\rm tr}(r)$ against inside a radius r, TOV Eqs. can be solved for given an EoS ($P = P(\rho)$).

Relation between (P, ρ) and (M, R)



- Soft EoS $\Leftrightarrow M \searrow$ Hard EoS $\Leftrightarrow M \nearrow$

Uncertainity of EoS: $P = P(\rho)$



(Lattimer 2013)

Symmetry Energy of Nuclear Matter

The energy of nuclear matter can be expressed as

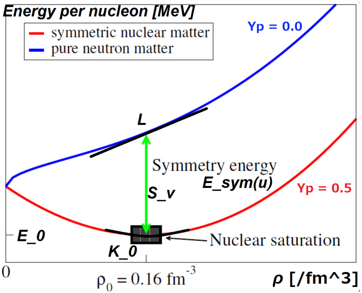
$$E_{\mathrm{nuc}}(u, Y_p) = E_0 + \frac{K_0}{18}(u-1)^2 + E_{\mathrm{sym}}(u)\,(1-2Y_p)^2$$

⇓ **symmetry energy** $(u \equiv \rho/\rho_0 = n_{\mathrm{B}}/n_0)$

$$E_{\mathrm{sym}}(u) = \left[S_v + \frac{L}{3}(u-1)\right] + \cdots$$

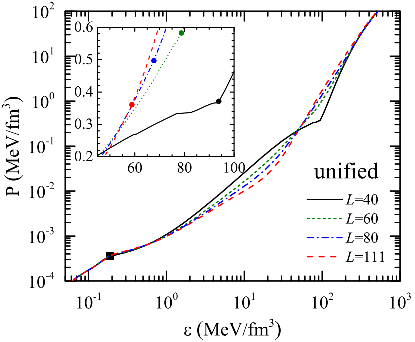
with saturation density ρ_0.

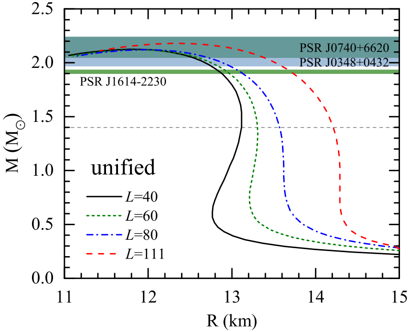
- $S_v \equiv E_{\mathrm{sym}}(u=1)$
- Slope parameter
  $$L \equiv 3\left(u\frac{\partial E_{\mathrm{sym}}(u)}{\partial u}\right)_{u=1}$$



(M. Thiel Bormio 2015)

L dependence on EoS and MR





(Ji, $\cdots$, Shen, 2019)

- ■ indicates the transition between core and crust.
- The smaller L is, the smaller R is.

Nuclear matter properties of the EoSs under finite temerature

Nuclear Interaction	n_0 (fm^{-3})	E_0 (MeV)	K_0 (MeV)	S_v (MeV)	L (MeV)	Type of int.
SKa	0.155	-16.0	263	32.9	74.6	Skyrme
LS180	0.155	-16.0	180	28.6	73.8	Skyrme
LS220	0.155	-16.0	220	28.6	73.8	Skyrme
LS375	0.155	-16.0	375	28.6	73.8	Skyrme
TM1(Shen)	0.145	-16.3	281	36.9	110.8	RMF
TMA	0.147	-16.0	318	30.7	90.1	RMF
NL3	0.148	-16.2	272	37.3	118.2	RMF
FSUgold	0.148	-16.3	230	32.6	60.5	RMF
FSUgold2.1	0.148	-16.3	230	32.6	60.5	RMF
IUFSU	0.155	-16.4	231	31.3	47.2	RMF
DD2	0.149	-16.0	243	31.7	55.0	RMF
SFHo	0.158	-16.2	245	31.6	47.1	RMF
SFHx	0.160	-16.2	239	28.7	23.2	RMF

(Oertel *et al.* 2017)

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Togashi	0.160	-16.1	241	30.0	35.0	Variational

Focus on Togashi EoS !!

(Oertel *et al.* 2017)

Togashi EoS (Togashi *et al.* 2017)

- 1- & 2- body Hamiltonian as

$$H_{1,2} = -\sum_i \left[m_i c^2 + \frac{\hbar^2}{2m_i}\nabla_i^2 + \sum_{j<i} V_{ij} \right]$$

V_{ij}: Argonne V18 (AV18) (Wiringa *et al.* 1995)

- 3- body Hamiltonian as

$$H_3 = -\sum_{i<j<k} V_{ijk}$$

V_{ijk}: Ubrana IX (UIX)

(Carlson *et al.* 1983, Pudliner *et al.* 1995)

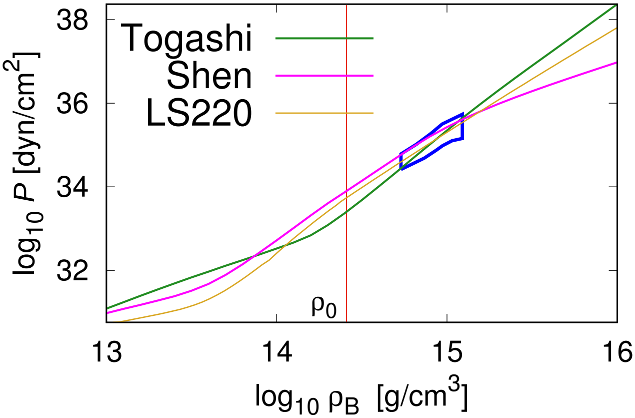
- Minimizing the free energy by using variation method of $H = H_{1,2} + H_3$, thermodynamic amounts $p, \epsilon, S, C_V, \cdots$ can be obtained.

EoS Models

Nuclear EoS	S_v (MeV)	L (MeV)	Type of Int.	References
LS220	28.6	73.8	Skyrme	Lattimer & Swesty 1991
Shen	36.9	110.8	RMF	Shen *et al.* 1998, 2011
Togashi	30.0	35.0	Variational	Togashi *et al.* 2017

- Togashi EoS is NEW EoS constructed on realistic nuclear potentials under finite temperature.
- Other EoSs are not based on realistic methods.
- We use above three EoSs in order to examine the consistency of INS cooling for Togashi EoS.

Pressure – Baryon Density Relation

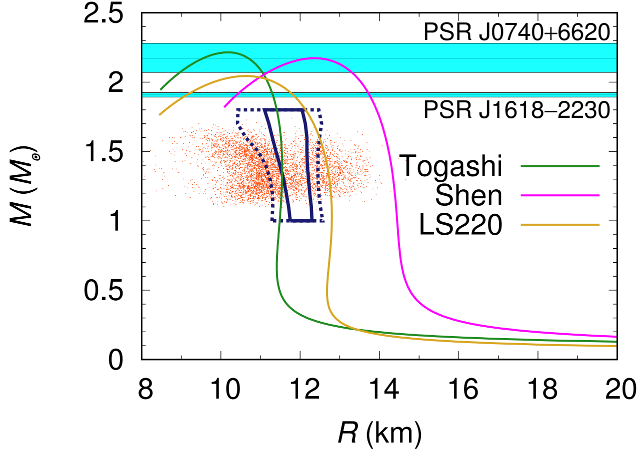


Togashi EoS is soft around $\rho_B \sim \rho_0$ while stiff $\rho_B \gg \rho_0$

The constraints on EoSs adopted in this work:

1. Experimental results by Heavy Ion Collision between Au–Au (Danielewicz *et al.* 2002)

Mass – Radius Relation

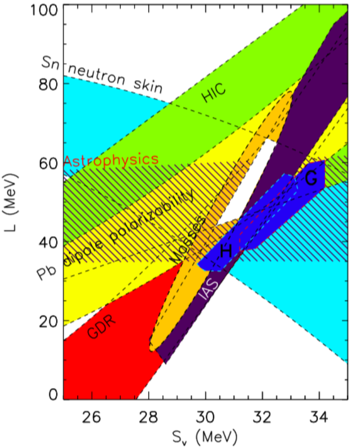


2. $M_{\max} \geqslant 2.17^{+0.11}_{-0.10}\ M_\odot$ (Cromartie *et al.* 2019)
3. $R \lesssim 13$ km by observations of GW and LMXB (Abbott *et al.* 2018, Steiner *et al.* 2010)

EoS stiffness and constraints

- $S_v L$ constraints
  (Lattimer & Steiner 2014)
  4. Neutron skin thickness
  5. ^{208}Pb dipole polarization
  6. Centroids of giant dipole resonances (GDR)
  7. Neutron matter studies (G and H)
  8. Nuclear masses
  9. Isobaric Analog State
- $S_v \lesssim 36$ MeV
- $L \lesssim 80$ MeV
  (ex. Beloin *et al.* 2019)

EoS	Togashi	Shen	LS220
S_v [MeV]	30.0	36.9	28.6
L [MeV]	35.0	111	73.8



Unitary Gas (UG) Criterion

10. UG bound
    (Tews *et al.* 2017)
    - Large Int. in NS
      $\Rightarrow$ UG approximation
    - Energy of n–rich nuclei is higher than UG energy E_{UG}:

$$E_{\mathrm{nuc}}(u,0) \geqslant E_{\mathrm{UG}} \approx 0.22 E_{\mathrm{F}}(u)$$

here, $E_{\mathrm{F}}(u)$ is *Fermi* energy

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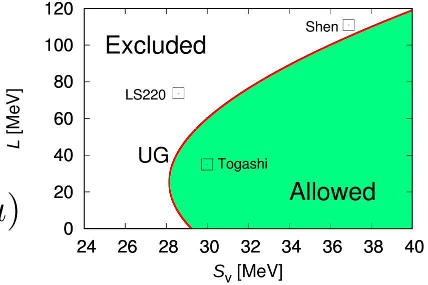

Unitary Gas (UG) Criterion

⑩ UG bound
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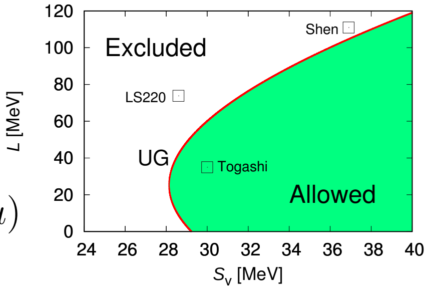

Togashi EoS is good in above conditions of ① ∼ ⑩ !!

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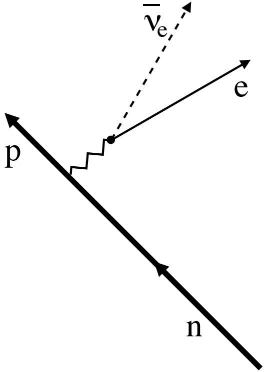
Direct Urca process (DU)



Direct Urca

- (Inverse) β decay as

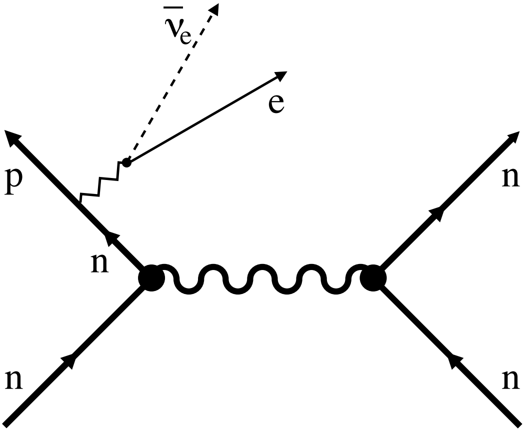
$$\begin{aligned} n &\rightarrow p + l + \bar{\nu}_l \\ p + l &\rightarrow n + \nu_l \end{aligned}$$

Direct Urca process (DU)

$$\begin{aligned} n &\rightarrow p + l + \bar{\nu}_l \\ p + l &\rightarrow n + \nu_l \end{aligned}$$

- $\epsilon_{\mathrm{DU}} \sim 10^{26-27} \ (n_{\mathrm{B}}/n_0)^{1/3} \ T_9^6 \ \mathrm{erg\ cm^{-3}\ s^{-1}}$
- When the momentum conversation $\boldsymbol{P}_{\mathbf{F}\boldsymbol{n}} < \boldsymbol{P}_{\mathbf{F}\boldsymbol{p}} + \boldsymbol{P}_{\mathbf{F}\boldsymbol{e}} \Leftrightarrow Y_p > 1/9$ without muons is satisfied, DU occurs.
- With muons, using $x_e = Y_e / \left(Y_e + Y_\mu\right)$, $Y_p > \left(1 + \left(1 + x_e^{1/3}\right)^3\right)^{-1} \gtrsim 0.1477$

Modified Urca (MU) Process



Modified Urca

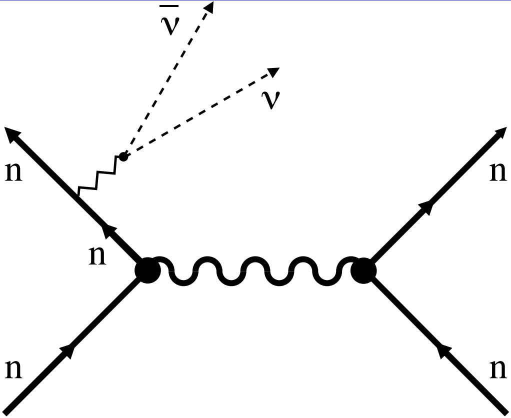
$$\begin{aligned} n + b &\rightarrow p + b + l + \bar{\nu}_l \\ p + b + l &\rightarrow n + l + b + \nu_l \end{aligned}$$

Modified Urca process (MU)

$$\begin{aligned} n + b &\rightarrow p + b + l + \bar{\nu}_l \\ p + b + l &\rightarrow n + l + b + \nu_l \end{aligned}$$

- $\epsilon_{\mathrm{MU}} \sim 10^{20-21} \ (n_{\mathrm{B}}/n_0)^{2/3} \ T_9^8$ erg cm^{-3} s^{-1}
- In case of $b = n$, since the momentum conversation $\boldsymbol{P_{\mathrm{F}p}} < 3\boldsymbol{P_{\mathrm{F}n}} + \boldsymbol{P_{\mathrm{F}e}}$ is satisfied, MU with $b = n$ always occurs
- In case of $b = p$, when the momentum conversation $\boldsymbol{P_{\mathrm{F}n}} < 3\boldsymbol{P_{\mathrm{F}p}} + \boldsymbol{P_{\mathrm{F}e}} \Leftrightarrow Y_p > 1/65$ is satisfied, MU with $b = p$ occurs.

Bremsstrahlung



Bremsstrahlung

- $b + b' \to b + b' + \nu + \bar{\nu}$
- $\epsilon_{\rm Brems} \sim 10^{18-20} \ \ (n_{\rm B}/n_0)^{2/3} \ \ T_9^8$ erg cm^{-3} s^{-1}
- Always occur

Neutrino Emissions in $npe\mu$

Classified with Fast, Slow, Medium Cooling Process

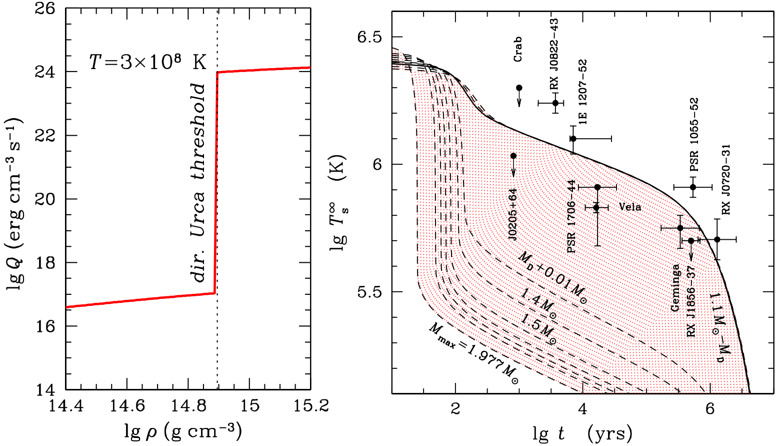
Direct Urca		$\epsilon_\nu \sim 10^{25-27}\,T_9^6$ erg cm^{-3} s^{-1}
$n \to p + l + \bar{\nu}_l$	$p + l \to n + \nu_l$	(Not always)
Modified Urca		$\epsilon_\nu \sim 10^{18-21}\,T_9^8$ erg cm^{-3} s^{-1}
$n + b \to p + b + l + \bar{\nu}_l$	$p + b + l \to n + l + b + \nu_l$	(Always)
Bremsstrahlung		$\epsilon_\nu \sim 10^{16-20}\,T_9^8$ erg cm^{-3} s^{-1}
$b + b' \to b + b' + \nu + \bar{\nu}$		(Always)
Pair Breaking Formation		$\epsilon_\nu \sim 10^{21-22}\,T_9^7$ erg cm^{-3} s^{-1}
$b + b \to [bb] + \nu + \bar{\nu}$		(Only $T \leq T_{\rm cr}$)

ϵ_ν: Neutrino emissivity of each process

T_9: temperature T in units of 10^9 K (~ 0.1 MeV)

$T_{\rm cr}$: Superfluid transition temperature

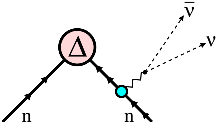
Cooling Effect of Neutrino Processes



M_D: Critical mass of Direct URCA (Yakovlev & Pethick. 2004)

Nucleon Superfluidity in NS

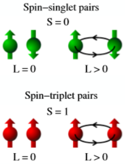
- Cooper paring occurs due to the attractive nuclear force:

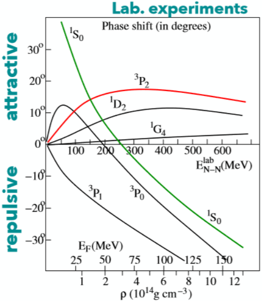


$$b + b \to [bb] + \nu + \bar{\nu}$$

at $T < T^b_{\rm cr} \sim 10^{8-9}$ K

- SF in NS core
  - p singlet pairing $(^1S_0)$
  - n triplet pairing $(^3P_2)$
- SF in NS crust
  - n singlet pairing $(^1S_0)$

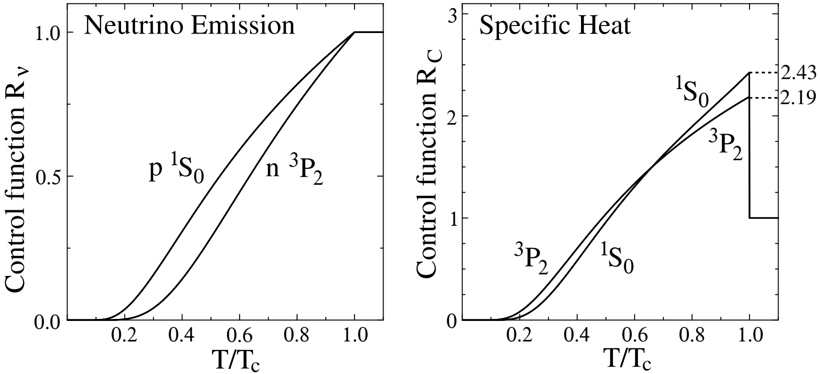




(Page *et al.* 2013)

Nucleon Superfluid (SF) Effect

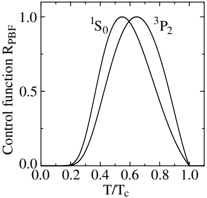
1. Cooling Suppression



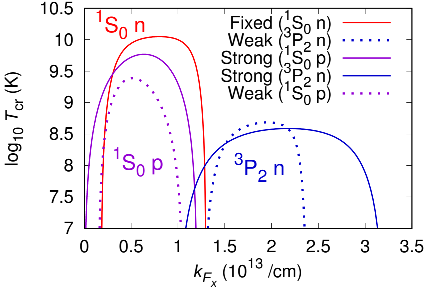
- $\epsilon_\nu^{\mathrm{SF}} = R_\nu \epsilon_\nu^{\mathrm{NONSF}}, \quad C_b^{\mathrm{SF}} = R_C C_b^{\mathrm{NONSF}}$
- Above all, $[n_{^3P_2} n_{^3P_2}]$ suppresses ν emission

Nucleon SF Effect

2. Pair Breaking Formation (PBF)
   - Release of Latent Heat
   - $\epsilon_\nu \sim 10^{22}\, T_9^7\ R_{\mathrm{PBF}}\left(\frac{T}{T_{\mathrm{cr}}}\right)$ erg cm^{-3} s^{-1}
   - Medium Cooling (> MU, Brems)



- T_{cr} can be obtained from gap equations, but is unknown due to uncertain nuclear force.
- In this work, we adopt the right SF models (Ho *et al.* 2015)



Photon Emission

- Dominant for $t \gtrsim 10^{4-5}$ yr
- Blackbody γ emission, we have

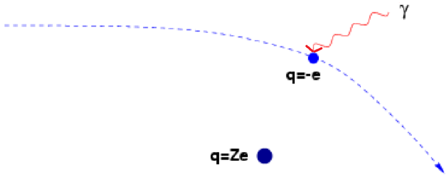
$$
\begin{aligned}
L_\gamma &= 4\pi R^2 a T_{\rm eff}^4 \\
&= 7 \times 10^{36}\ \mathrm{erg\ s^{-1}} \left(\frac{R}{10\ \mathrm{km}}\right) a T_{\rm eff,7}^4
\end{aligned}
$$

a: *Stefan-Boltzmann* constant
$T_{\rm eff}$: Effective temperature in units of 10^7 K

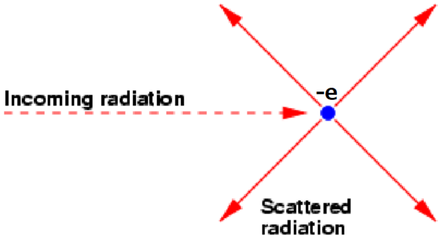
- With atomosphere as INS envelop, L_γ becomes higher due to the opacity κ.
  $\Leftarrow$ Generally, the lighter the surface composition is, the higher L_γ is.

Radiative Opacity κ_{rad}

- free-free absorption
  (Schatz 1999)
  $\kappa_{ff} \propto \rho T^{-7/2}$



- Scattering
  (Paczynski 1983)
  $\kappa_{es} = \sigma_{\text{Th}} \frac{(1+X)}{2m_p}$



- $\kappa_{\text{rad}} = \kappa_{ff} + \kappa_{es}$

m_p: proton mass
X: hydrogen mass fraction
σ_{Th}: Thomoson scattering cross section

Thermal Conductive Opacity $\kappa_{\rm cond}$

$$\kappa_{\rm cond} = \left(\sum_{i=n,p,e^-,\mu^-} \kappa_i^{-1} \right)^{-1} = \left(\sum_{i=n,p,e^-,\mu^-} \left(\frac{\pi^2 T n_B Y_i}{3 m_i^* \nu_c} \right)^{-1} \right)^{-1}$$

ν_c: i-particle collision frequency m_i^*: i-particle effective mass

Regions	Outer Crust	Inner Crust	Core
Dominant particles for $\kappa_{\rm cond}$	e^-	n	e^-, μ^- and n

- We calculate the conductive opacities considering only electrons (Potekhin *et al.* 2015) and neutrons (Baiko *et al.* 2001).
- Total opacity κ is given by

$$\kappa = \left(\kappa_{\rm rad}^{-1} + \kappa_{\rm cond}^{-1} \right)^{-1}$$

$T_\mathrm{s} - T_\mathrm{b}$ relation

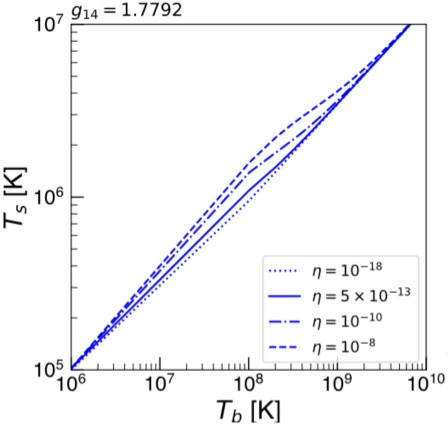
Since observed value is the surface temperature T_s, we have to connect T_s with interior temperature T_b

- Parameter for the amount of light elements ΔM:

$$\eta = \frac{g}{10^{14}\ \mathrm{cm\ s^{-2}}} \frac{\Delta M}{M}$$

with surface gravity g.

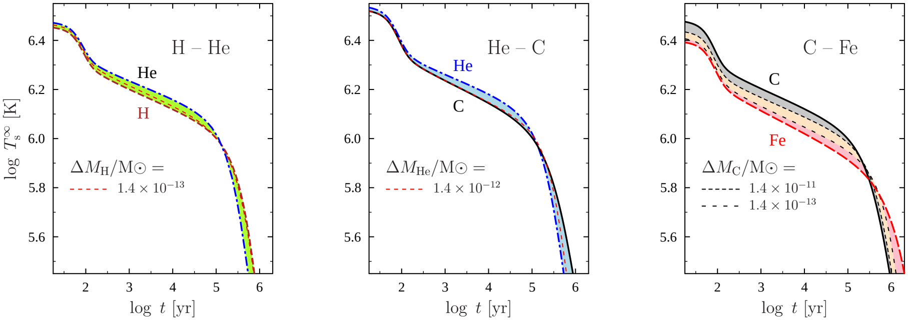
- The higher η is, the higher T_s is.



(Hamaguchi *et al.* 2018)

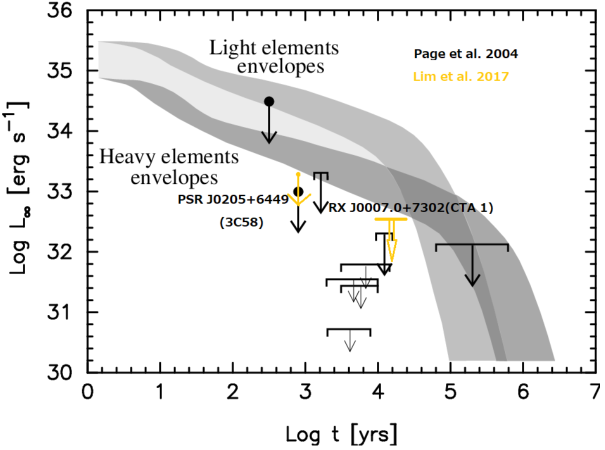
Surface composition of INS envelop

- $T_{\rm eff}$: He>H>C> $\cdots$ >Fe(Ni) on INS envelop
- In this slides, we adopt Ni 100%, and H 73%, He 25%, and Ni 2% with $\Delta M = 5 \times 10^{-13} M_{\odot}$.



(Beznogov *et al.* 2016)

Minimal Cooling Scenario



- Slow Cooling + Superfluidity (Page *et al.* 2004)
- Inconsistent with stars in SNR 3C58 and CTA 1

Rapid cooling processes are necessary !!

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Uncertain Physics of INS cooling

Table: The list of several unknown parameters or INS cooling

Uncertain Parameters for given M or central density	Affected amounts of Basic Equation
1. Equation of State (EoS)	
$\Rightarrow P - \rho_B$ or $M - R$ relations	ν Loss Energy
$\Rightarrow$How many particles in NS core ?	
2. Nucleon Superfluidity (SF)	ν Loss Energy
$\Rightarrow \rho_B Y_{\rm baryon} - T_{\rm cr}$ relations	
3. Surface Composition	$T_{\rm eff} - T_{\rm b}$ Relation
$\Rightarrow$Is NS envelop light or heavy ?	γ Loss Energy

$T_{\rm cr}$: SF Transition Temperature $T_{\rm b}$: Temperature outside NS Crust as $\rho \sim 10^{8-10}$g/cc

Relativistic Heat Diffusion (Maarten Kater's M thesis 2011)

- The action of heat to describe diffusion of a scalar ϕ field with a sink term Q is

$$S_{\text{diffuse}} = \int dx^4 \frac{\sqrt{-g}}{2} \left(\phi \left(C_V n^\mu \partial_\mu - \frac{\kappa}{\sqrt{-g}} \partial_\mu \gamma^{\mu\nu} \partial_\nu \right) \phi + Q\phi \right)$$

$$\approx \int dx^4 \frac{\sqrt{-g}}{2C_V} \left| \left(C_V n^\mu \partial_\mu - \frac{\kappa}{\sqrt{-g}} \partial_\mu \gamma^{\mu\nu} \partial_\nu \right) \phi + Q\phi \right|^2$$

where g is determinant of $g^{\mu\nu} = n^\mu n^\nu + \gamma^{\mu\nu}$

$n^\mu = (\exp(-\phi), 0, 0, 0)$, $\gamma^{\mu\nu}$: spacial part

- Equation of motion of scalar field ϕ

$$\left(C_V n^\mu \partial_\mu - \frac{\kappa}{\sqrt{-g}} \partial_\mu \gamma^{\mu\nu} \partial_\nu \right) \phi + Q = 0$$

Cooling Transport Equation

Solving Einstein Eq. with ideal fluid, we obtain

$$\frac{\partial(L_r e^{2\phi/c^2})}{\partial M_r} = -e^{2\phi/c^2}\left(\varepsilon_\nu + \varepsilon_\gamma + e^{-\phi/c^2} C_V \frac{\partial T}{\partial t}\right) \,,$$
$$\frac{\partial(T_r e^{\phi/c^2})}{\partial r} = \frac{L_r}{4\pi r^2 \kappa}$$

This is enhanced version of classical *Heat Equation* as

$$\nabla \cdot \boldsymbol{J} = -C_V \frac{dT}{dt} - q$$
$$\kappa \nabla T = -\boldsymbol{J}$$

$\boldsymbol{J}$: Heat Current, q: nonrelativistic loss of particles

Basic Equations (Thorne 1977)

- Henyey method (Henyey *et al.* 1964)

1. TOV equations
2. Energy Transport

$$\frac{\partial \ln T}{\partial \ln P} = \frac{3}{4}\frac{\kappa L_r P}{acT^4}\left(\frac{\partial P}{\partial M_{\rm r}}\right)^{-1} + \left(1 - \left(1 + \frac{P}{\rho c^2}\right)^{-1}\right) ,$$

3. Energy conversation

$$\frac{\partial (L_r e^{2\phi/c^2})}{\partial M_r} = -e^{2\phi/c^2}\left(\varepsilon_\nu + \varepsilon_\gamma + e^{-\phi/c^2} C_V \frac{\partial T}{\partial t}\right) .$$

ϕ: gravitational potential, L_r: luminosity inside radius r,
$\epsilon_\nu, \epsilon_\gamma$: neutrino and photon emissivities, respectively,
C_V: Capacity of NS, κ: opacity,
ρ_0, ρ: rest and total mass density inside radius r, respectively,
$M_r, M_{\rm tr}$:rest and total mass inside radius r, respectively, which obeys a relation as

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

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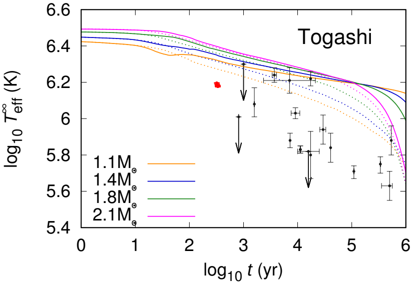
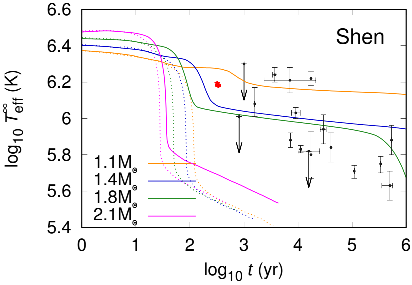
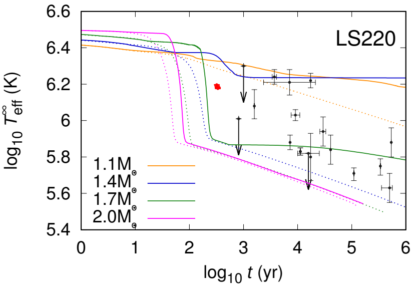
EoS dependence on cooling curves



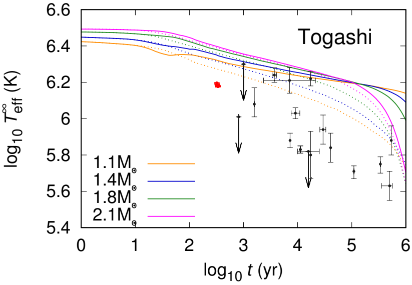


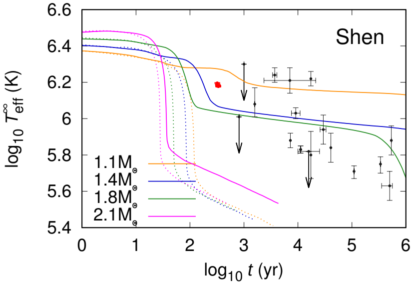


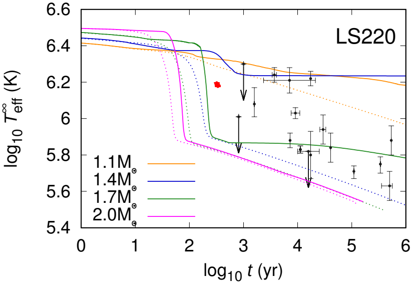
······ : w/o SF model

——— : w/ SF model

EoS dependence on cooling curves





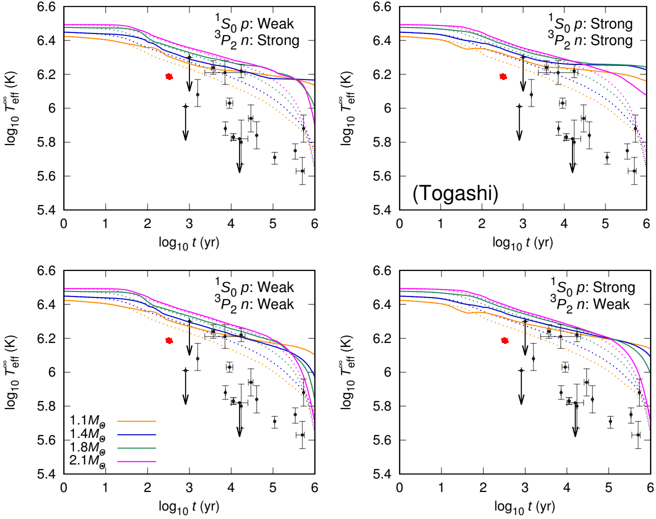


······ : w/o SF model

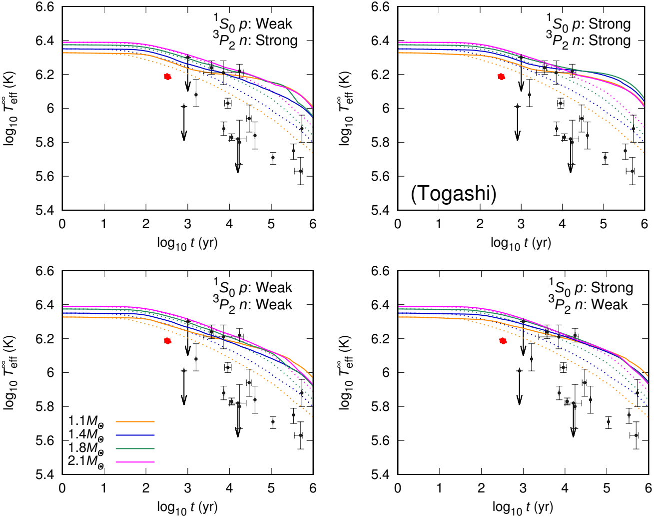
——— : w/ SF model

- Even with 2.1 $M_\odot$, Direct URCA is prohibited with the Togashi EoS !!

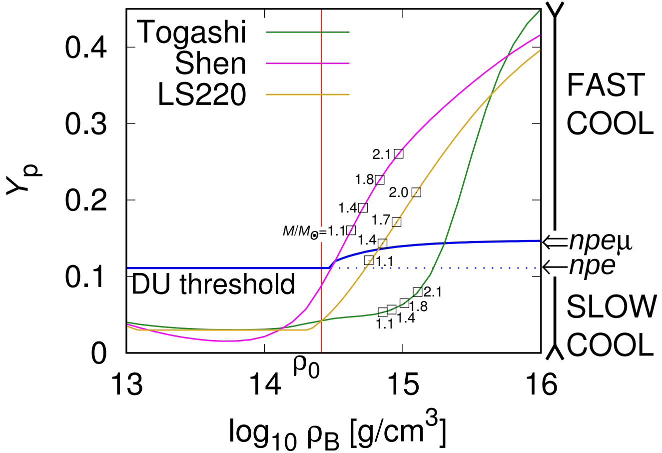
SF-model dependence with Togashi EoS (with light compositions)



SF-model dependence with Togashi EoS (with heavy compositions)

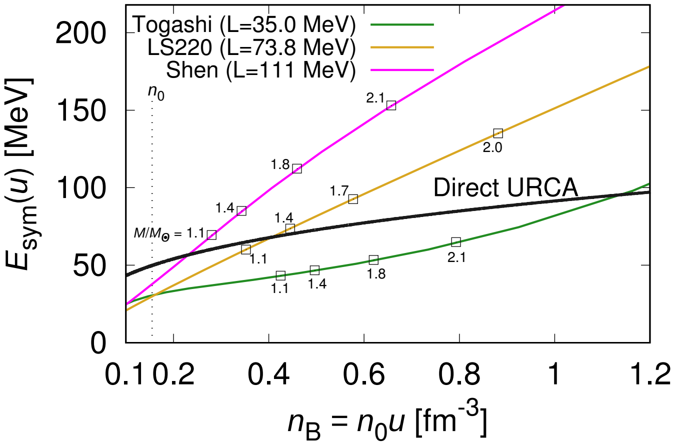


Density dependence of Y_p



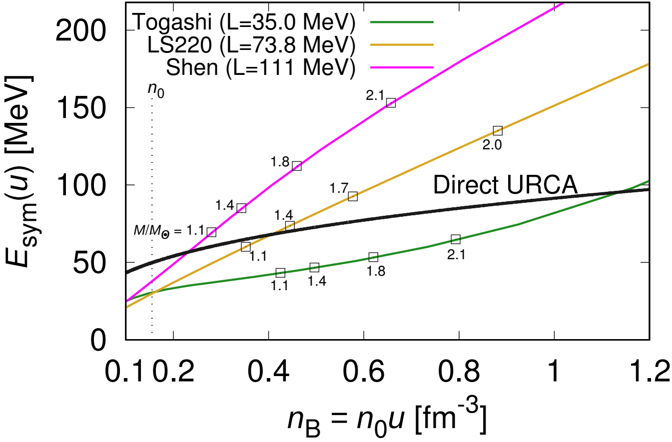
- The Togashi EoS has low value of Y_p and is inconsistent with INS observations.

Symmetry Energy and Rapid Cooling



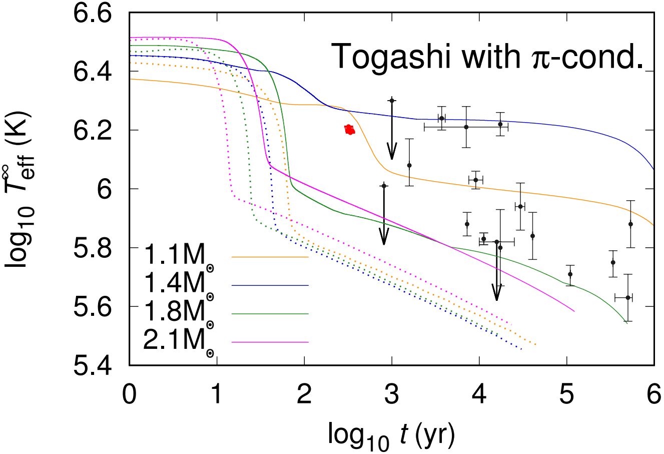
- Direct URCA is hard to occur for the model with small $E_{\rm sym}(u)$ or L, that is, small R values

Symmetry Energy and Rapid Cooling

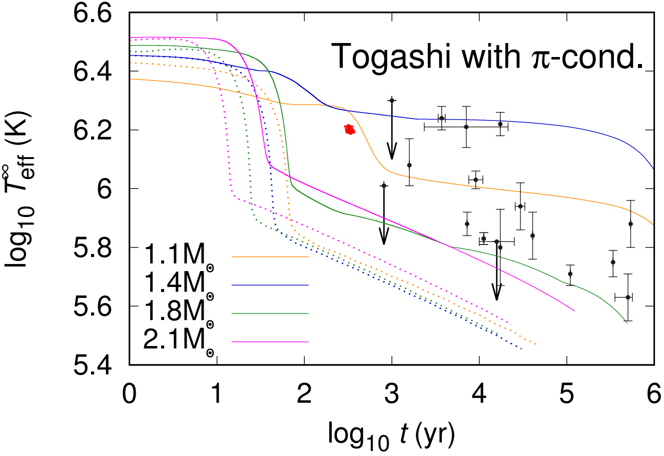


- Direct URCA is hard to occur for the model with small $E_{\mathrm{sym}}(u)$ or L, that is, small R values
  $\Rightarrow$ Another strong cooling process is needed !!

Cooling curves with pion condensation process adopted by Muto *et al.* 1993



Cooling curves with pion condensation process adopted by Muto *et al.* 1993



⇒ Togashi EoS with pion condensation is consistent !!

⇒ Some exotic particles may be in neutron stars !?

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How to dissolve the gap between INS observations and EoS with small L value?

An EoS with small L can account for radius constraint but cannot INS observations.
$\Rightarrow$ How to dissolve ?

1. Considering exotic particles
   - Some enhanced cooling processes by exotic particles
   - However, EoS becomes softer and NS may not support $2M_\odot$ (ex. *Hyperon puzzle*).
2. Changing the NS structure
   - Changing the TOV equations by introducing a modified gravity

We introduce the modified gravity as Second Scalar-Tensor (ST) theory.

Action of Gravity

- Einstein-Hilbert Action (GR)

$$S_G = \frac{M_{pl}^2}{2} \int dx^4 \sqrt{-g}\ R$$

- Action of ST theory with massless Brans-Dicke model:

$$S_G = \int dx^4 \sqrt{-g} \left[\frac{M_{pl}^2}{2} F(\phi) R - \left(1 - 6Q^2\right) F(\phi) X \right]$$

R: Ricci scalar $\quad M_{pl} = (8\pi G)^{-1/2}$: Reduced Planck Mass
g: the determinant of metric tensor $g_{\mu\nu}$
Q: parameter to characterize the coupling between the field ϕ and the gravity sector. (GR if $Q \to 0$)

$X = -g^{\mu\nu}\partial_\mu \phi \partial_\nu \phi / 2, \quad F(\phi) = \exp\left(-2Q\phi/M_{pl}\right)$

(we adopt natural units $c = \hbar = 1$)

TOV Equations

1. Mass Eq.

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

2. Hydrostatic equilibrium Eq.

$$\frac{\partial P}{\partial r} = -\frac{G}{r^2}(\rho + P)\left(M + 4\pi r^3 P\right)\left(1 - \frac{2GM}{r}\right)^{-1}$$

- 3 Variables as $P(r), \rho(r), M(r)$
- Boundary condition: $\rho(r = 0) = \rho_{\rm c}$

Eq. of Motions (Kase & Tsujikawa. 2019)

1. Mass Eq.

$$M' = -4\pi F^{-1} r^2 \left[\left(1-2Q^2\right)\rho + 6Q^2 P\right] + \phi' \frac{2QM_{pl}M + 8QM_{pl}\pi r^3 F^{-1} P + r\phi'\left(4\pi r M_{pl}^2 - M\right)\left(1+2Q^2\right)}{2M_{pl}\left(M_{pl} - Qr\phi'\right)}$$

2. Hydrostatic equilibrium Eq.

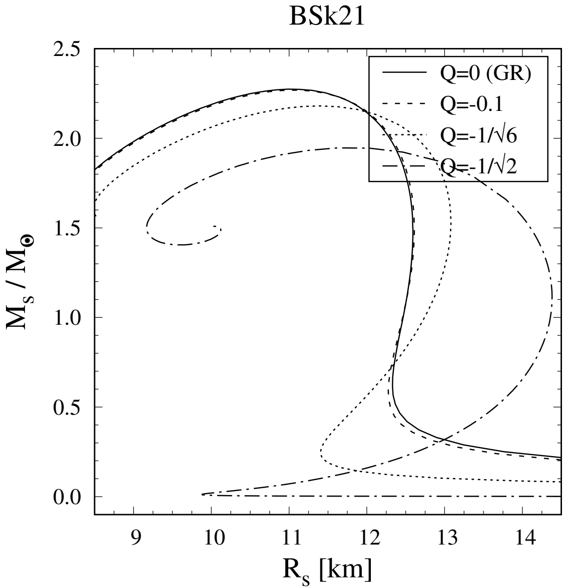
$$-\frac{2P'}{\rho+P} = \frac{2M_{pl}^2(h-1) - 2F^{-1}r^2 P + hr\phi'\left[\left(6Q^2-1\right)r\phi' - 8QM_{pl}\right]}{2hrM_{pl}\left(M_{pl} - Qr\phi'\right)}$$

3. Euler-Lagrange Eq. of ϕ

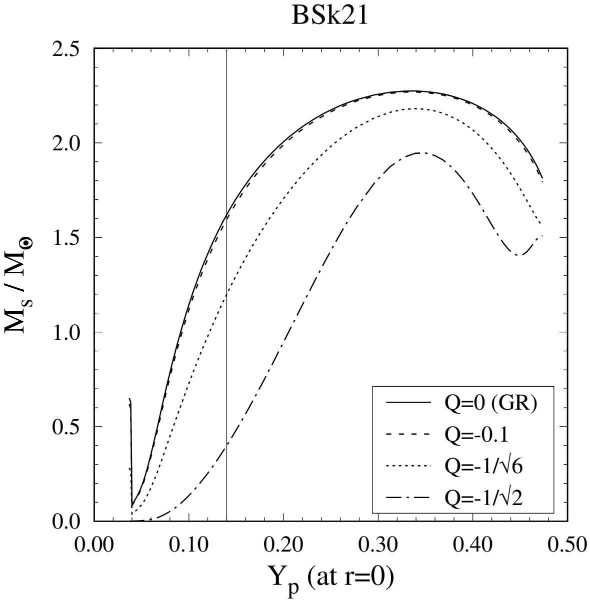
$$\phi'' = -\frac{\phi'}{2M_{pl}^2 rh}\left[2(h+1)M_{pl}^2 + r^2 F^{-1}\left(P - \rho + 2(\rho - 3P)Q^2\right)\right] + \frac{Q(\rho - 3P)}{M_{pl} h F}$$

- 4 Variables: $P(r), \rho(r), M(r), \phi(r)$, due to $h(r) = 1 - 2M/r$
- Boundary conditions:
  $\rho(0) = \rho_c,\ \phi(0) = \phi'(0) = 0,\ \phi(\infty) \to \phi_\infty,\ \phi'(\infty) \to 0$

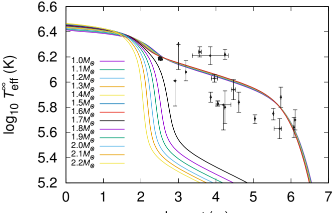
MR relation (Calculated by R. Kase)



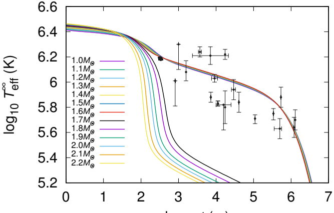
Y_p distribution



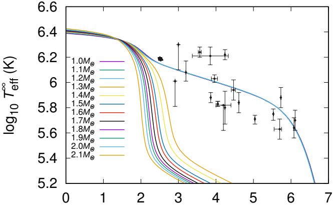
Cooling Curves with modified gravity



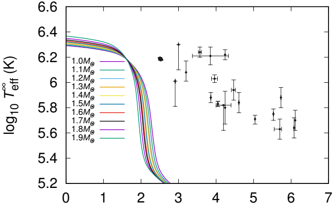
BSK21 with GR



BSK21 with Q = -0.10



BSK21 with Q = -1/√6



BSK21 with Q = -1/√2

The smaller Q is, DU occurs with smaller mass.

⇒ Can modified gravity can dissolve the problem between EoS constraint and INS observation ?

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Summary & Future Work

- For Togashi EoS, mass and radius constraints are satisfied, but the cooling curves cannot account for the thermal data.
- However with some strong coolings, such a EoS becomes "consistent" model !!
  $\Rightarrow$ Exotic particles may be in the neutron star !!
  $\Rightarrow$ Or possibility of modified gravity ?

IN FUTURE WORK

- The cooling simulation for the Togashi EoS with other exotic particle（above all Λ, mesons）
- Cooling Calculations with massive Brans-Dicke (but Pessimistic due to *Chameleon Mechanism*)