Dependence of Neutron Star Cooling on the Symmetry Energy

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In collabolation with

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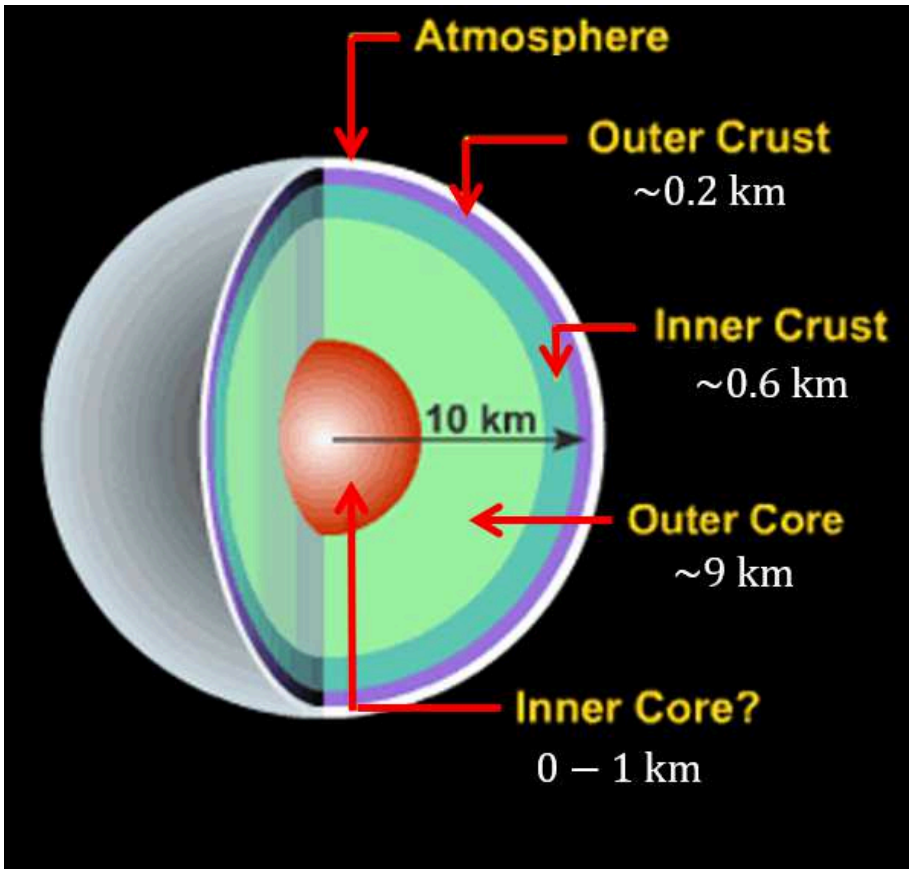
Basic Neutron Star (NS) Structure

- After supernova explosion, a hot NS (PNS) is born and cools rapidly with ~ 100 s.
- The cold NS with $T \ll 1$ MeV cools down by mainly neutrino loss with $t \lesssim 10^{4-5}$ yr while photon loss since this.
- Possible exotic particles in NS core.

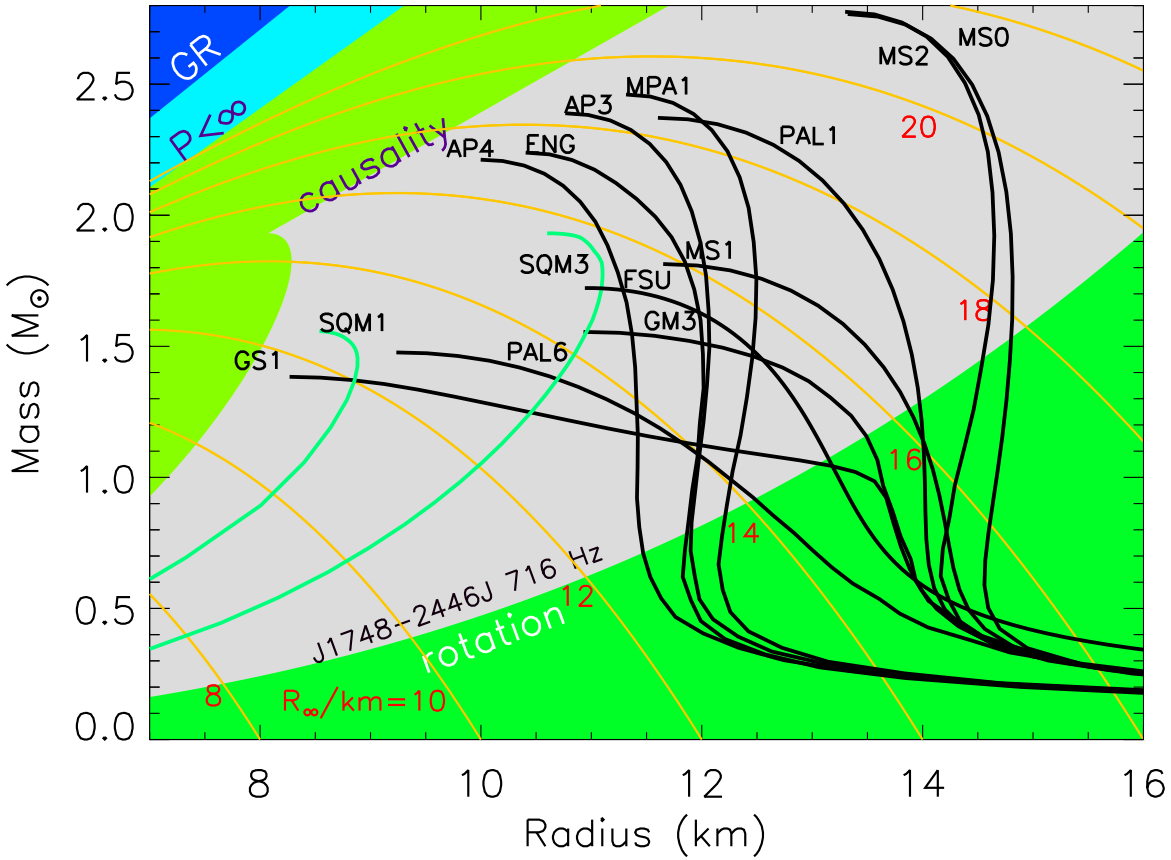
Typical value

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



Uncertainity of EoS

- EoS (P–ρ) determines the Mass–Radius relation through TOV equations.



(Lattimer 2012)

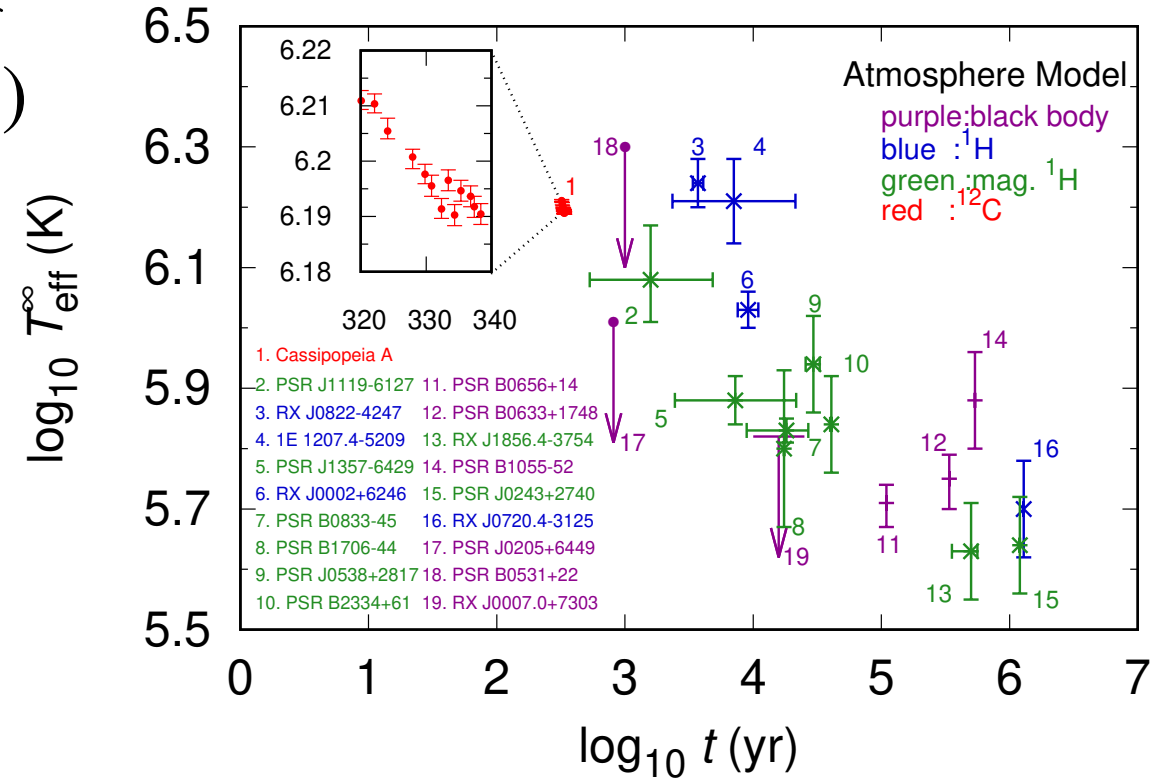
Temperature Observations of Isolated Neutron Stars (INS)

>>> Cold INS <<<

- Cassiopeia A (No.1)
- PSR B0833-4 (Vela, No.7)

** Only Upper $T_{\rm eff}^{\infty}$ **

- PSR J0205+6449 (3C58, No.17)
- RX J0007.0+7303 (CTA 1, No.19)



(Data: Lim *et al.* 2017)

How are cold INS explained ?

- Only Standard / Slow Cooling Processes
  $\Rightarrow$ Too hot to explain the cold INS
- Possible Non–Standard Cooling Processes to explain cold INSs:
  - Fast Cooling Processes (e.g., Nucleon Direct Urca Process (DU))
  - Nucleon Superfluidity (Pair Breaking Formation (PBF))

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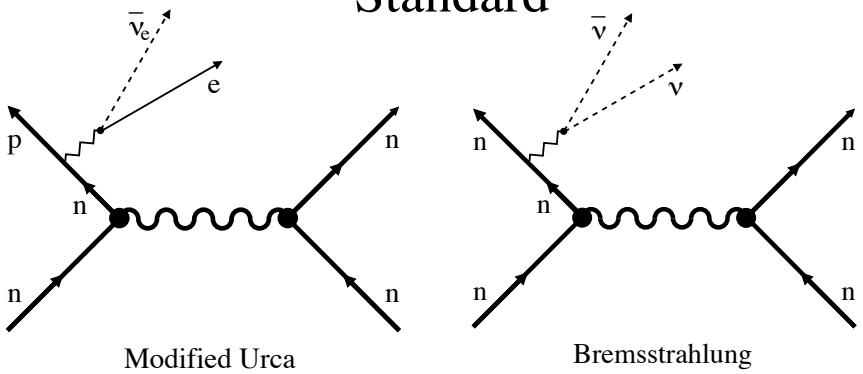
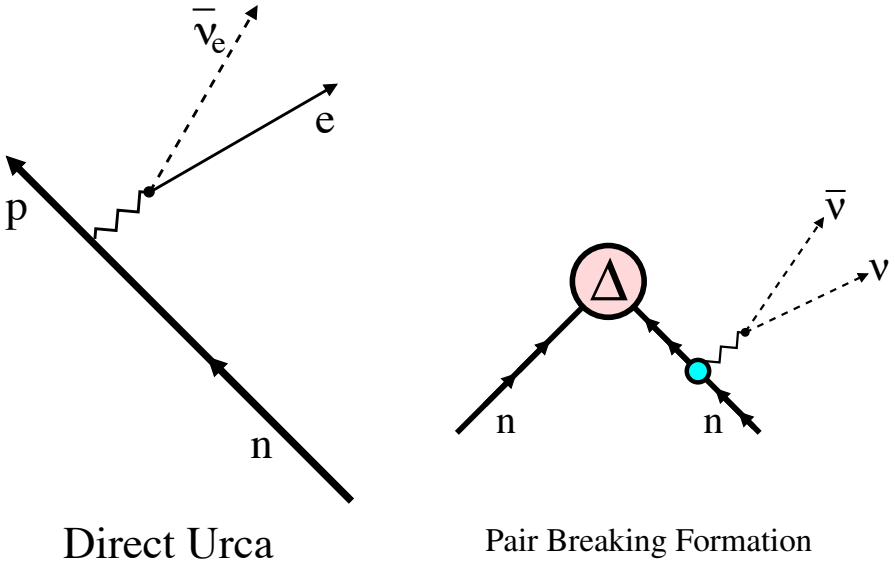
Standard



Non–Standard

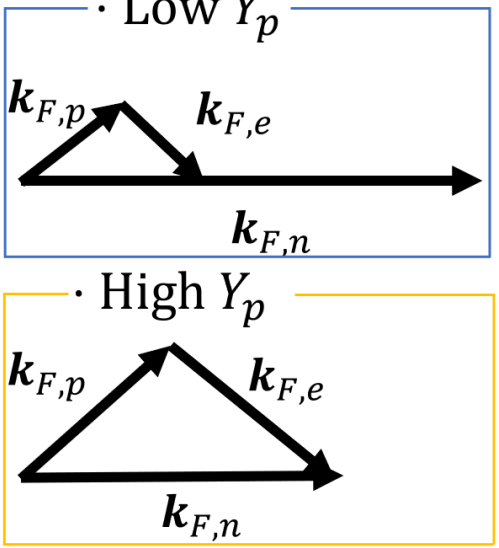


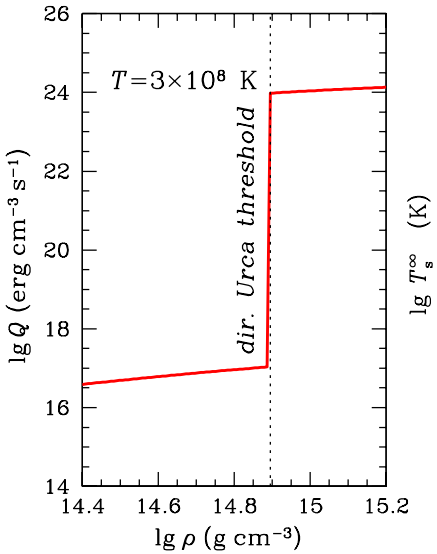
(Figures: Page *et al.* 2013)

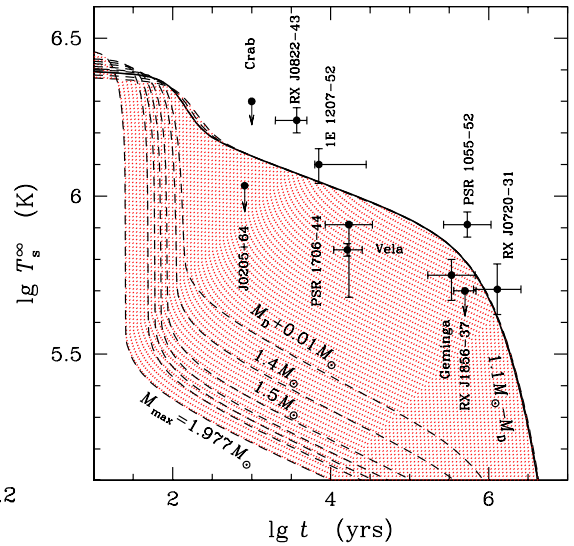
Direct Urca Process (DU) (Lattimer *et al.* 1991)

$$n \to p + l + \bar{\nu}_l \qquad p + l \to n + \nu_l$$

- High ϵ_ν enough to cool NS rapidly
- To keep momentum conversation among particles $\boldsymbol{k}_{\mathrm{F},n} = \boldsymbol{k}_{\mathrm{F},p} + \boldsymbol{k}_{\mathrm{F},l}$, DU occurs with $Y_p > Y_{p\mathrm{DU}} \simeq 0.14$







M_{D}: Critical mass of DU (Yakovlev & Pethick 2004)

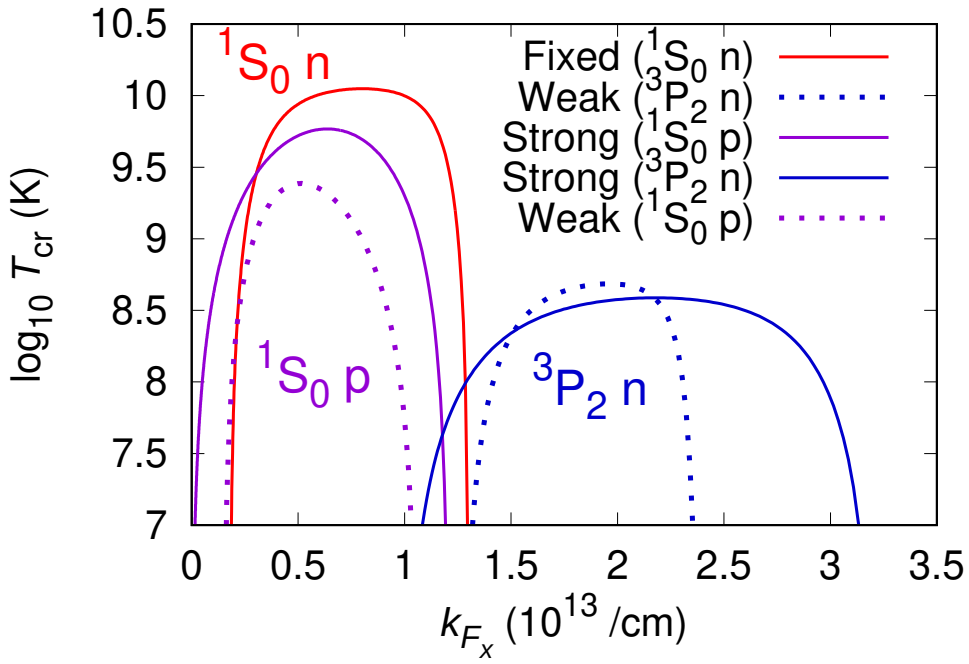
Nucleon Superfluid (SF) Effect

- $p : {}^1S_0$ $n : {}^1S_0, {}^3P_2$, $\cdots$ in low temperature

$$b + b \to [bb] + \nu + \bar{\nu}, \quad b = n, p, \cdots$$

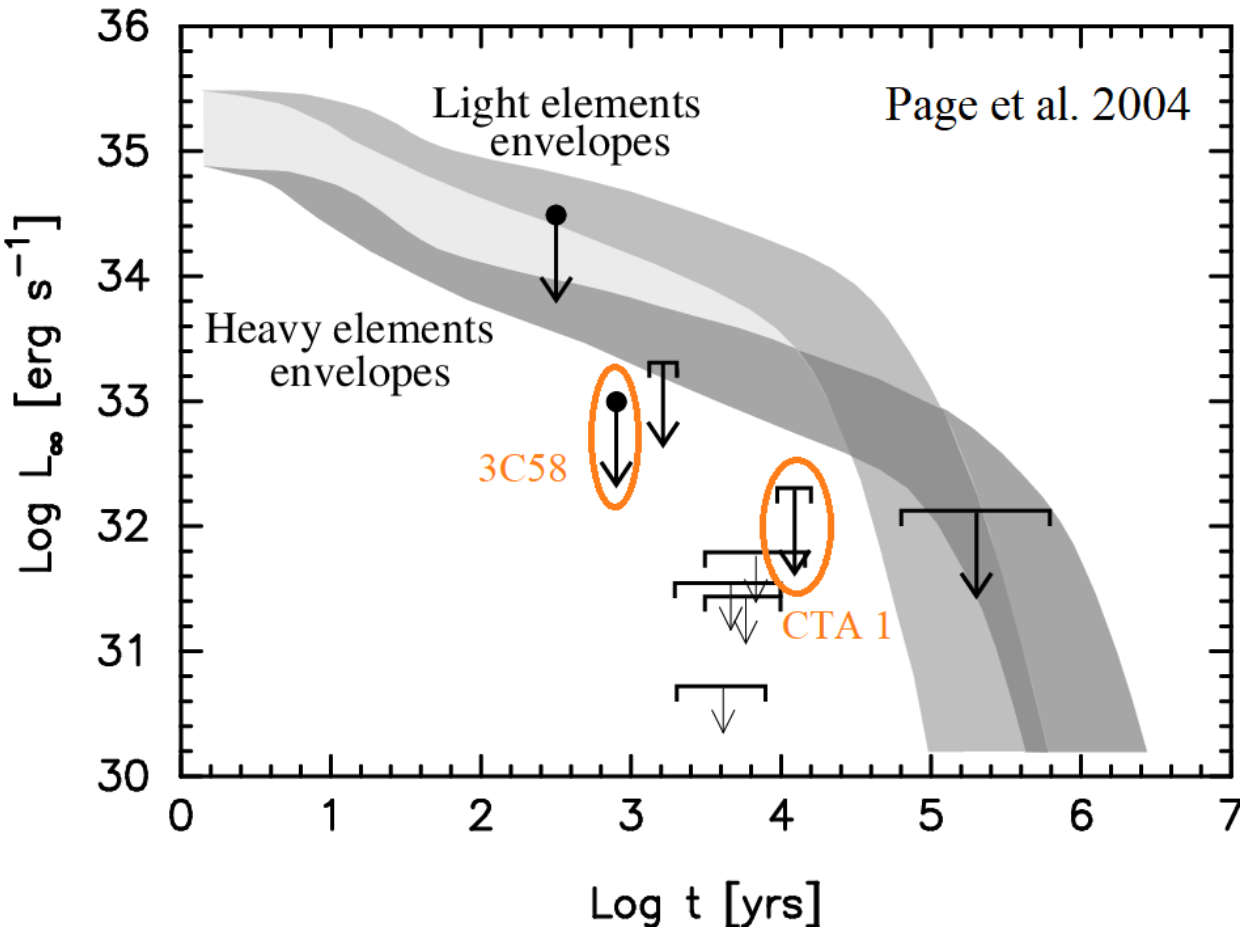
1. Cooling Suppression
   - $\epsilon_\nu \propto \exp\left(-T_{\rm cr}/T\right)$
   - Above all, $[n_{^3P_2} n_{^3P_2}]$ suppresses ν emission
2. PBF process
   - Medium Cooling

Density–Dependence of SF transition temperature $T_{\rm cr}$ is however uncertain...



(Our SF models in this work obtained by Ho *et al.* 2015)

Minimal Cooling Scenario



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

  A rapid cooling process is necessary.

Symmetry Energy of Nuclear Matter

The energy of nuclear matter can be expressed as

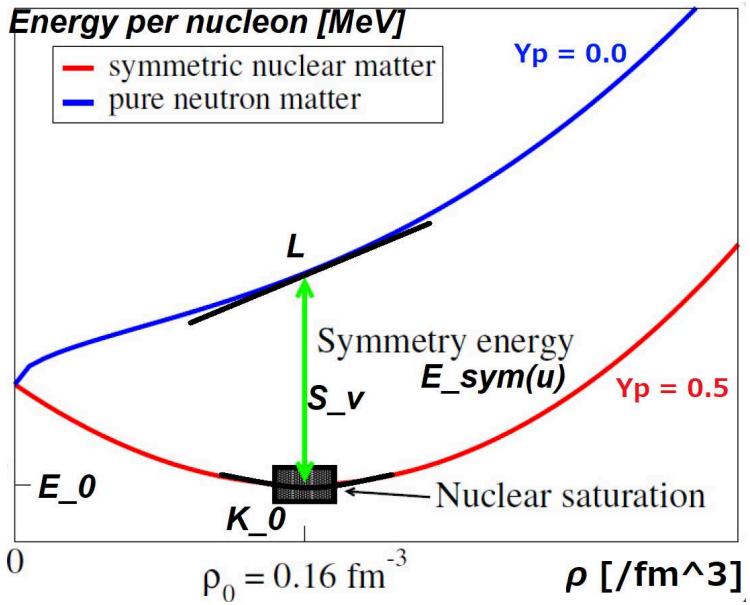
$$E_{\rm nuc}(u, Y_p) = E_0 + \frac{K_0}{18}(u-1)^2 + E_{\rm sym}(u)(1-2Y_p)^2$$

$$\Downarrow \textbf{symmetry energy} \qquad (u \equiv \rho/\rho_0 = n_{\rm B}/n_0)$$

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

with saturation density ρ_0.

- Slope parameter
  $L \equiv 3\left(u\frac{\partial E_{\rm sym}(u)}{\partial u}\right)_{u=1}$
  $\Rightarrow$Connector between EoS softness and INS cooling (DU)



(M. Thiel Bormio 2015)

EoS adopted in this work

Nuclear EoS	L (MeV)	$R_{1.4M_\odot}$ (km)	$M_{\rm max}$ ($M_\odot$)	Interaction	Refs
LS220	73.8	12.7	2.04	Skyrme	Lattimer & Swesty 1991
Shen	110.8	14.3	2.17	RMF	Shen *et al.* 1998, 2011
Togashi	35.0	11.6	2.21	Variational	Togashi *et al.* 2017

- We examine the cooling curves with above EoSs which L is different.

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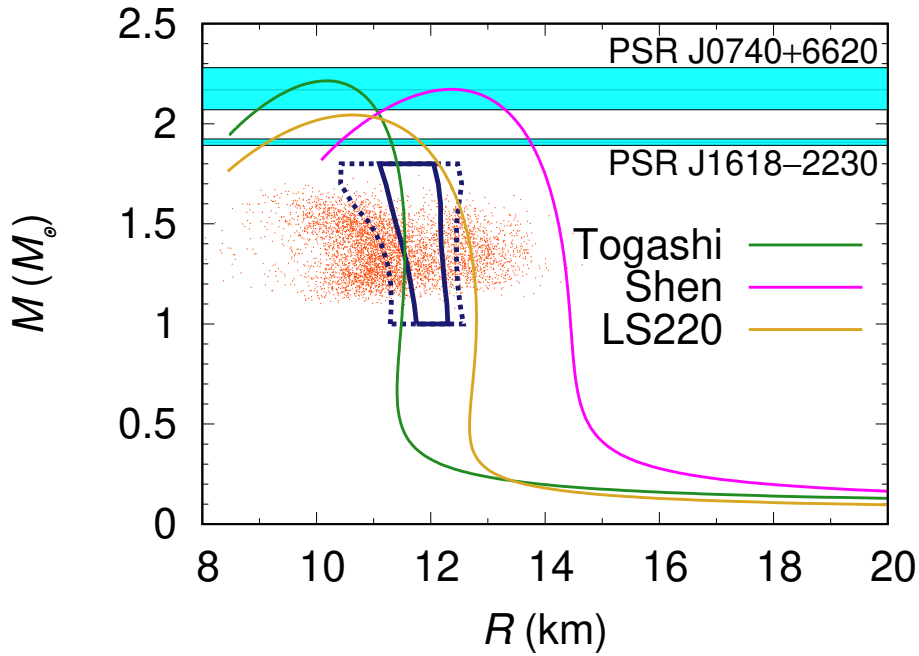
- We examine the cooling curves with above EoSs which L is different.
- Radius Constraint :
  - $R_{1.4M_\odot} \lesssim 13$ km (e.g. Abbott *et al.* 2018)

$\Rightarrow$ Small–L value is observationally preferred



Basic Equations of 1D Spherical INS thermal evolution (Thorne 1977)

1. TOV equations
2. Thermal Transport Equations

$$\frac{\partial \ln T}{\partial \ln P} = \nabla_{\rm rad} \ ,$$

Here, $\nabla_{\rm rad}$ is the radiation gradient, which depends on the thermal conductivity

3. Energy Balance without heating source

$$\frac{\partial (L_r e^{2\phi_{00}/c^2})}{\partial M_r} = -e^{2\phi_{00}/c^2} \left(\varepsilon_\nu + e^{-\phi_{00}/c^2} C_V \frac{\partial T}{\partial t} \right) \ .$$

with Henyey method

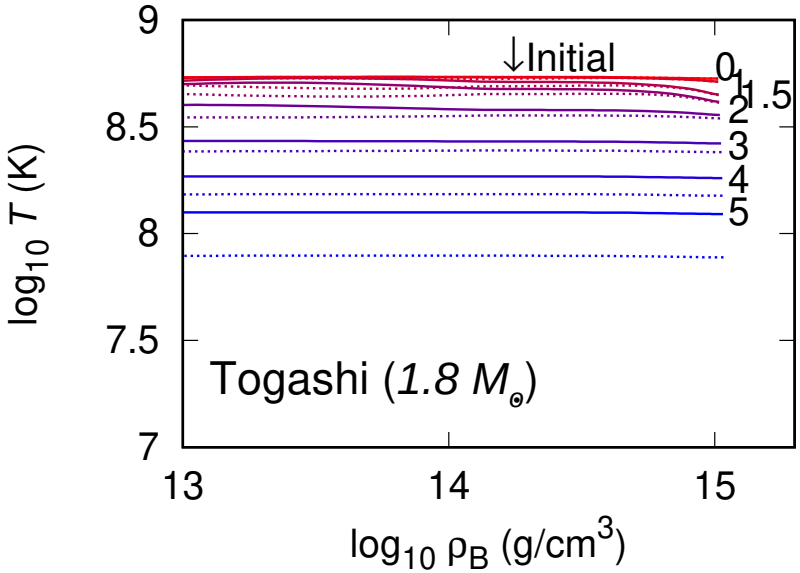
Uncertain Physics of INS cooling

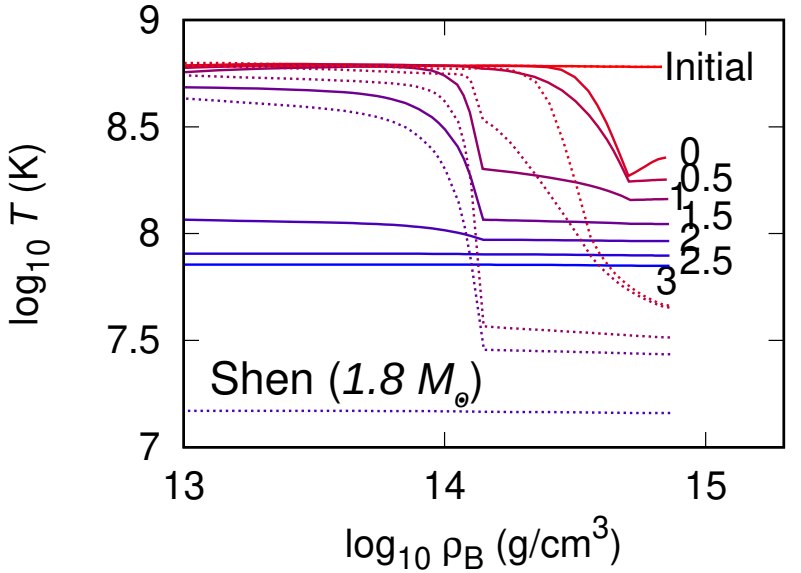
Table: The list of several unknown parameters or INS cooling

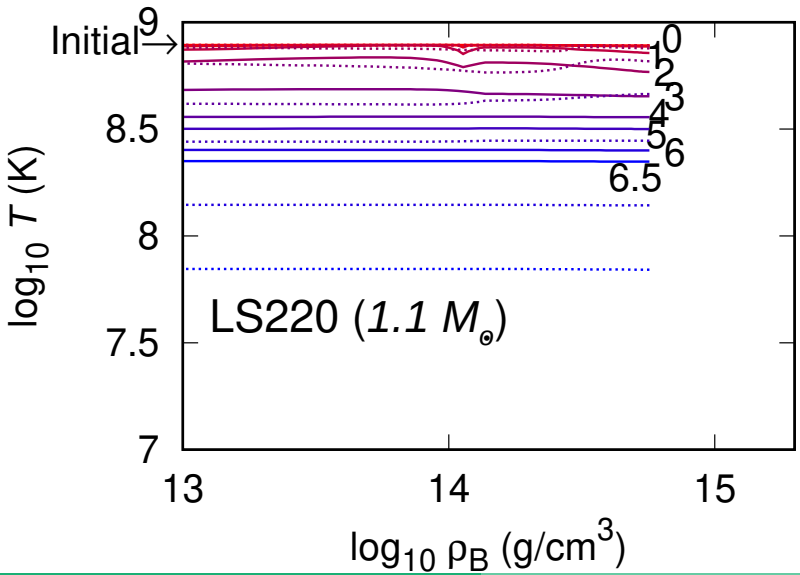
Uncertain Parameters for given M or central density	Affected amounts of Basic Equations
1. Equation of State (EoS)	
$\Rightarrow P - \rho_{\rm B}$ or $M - R$ relations	ν Loss Energy
$\Rightarrow$How many particles in NS core ?	
2. Nucleon Superfluidity (SF)	ν Loss Energy
$\Rightarrow \rho_{\rm B} - T_{\rm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

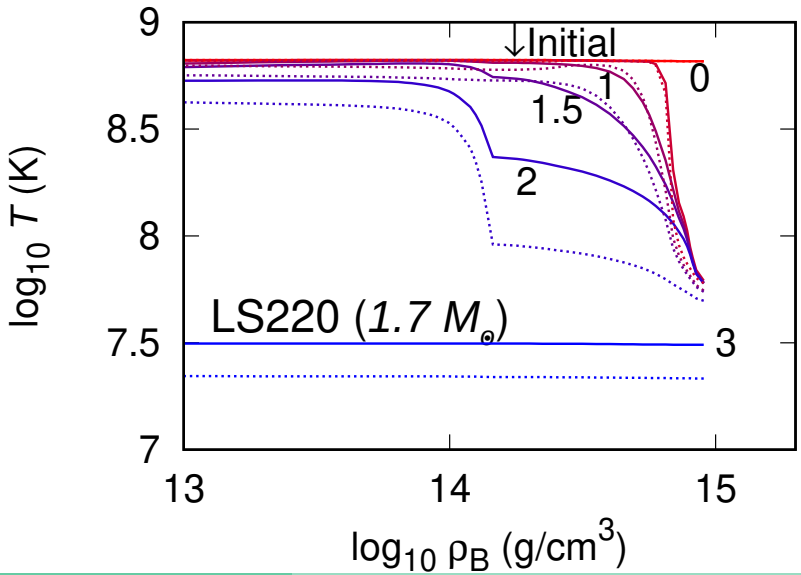
$T_{\rm cr}$: SF Transition Temperature $T_{\rm b}$: Temperature outside NS Crust as $\rho \sim 10^{8-10}{\rm g/cc}$

Evolution of Temperature Structure

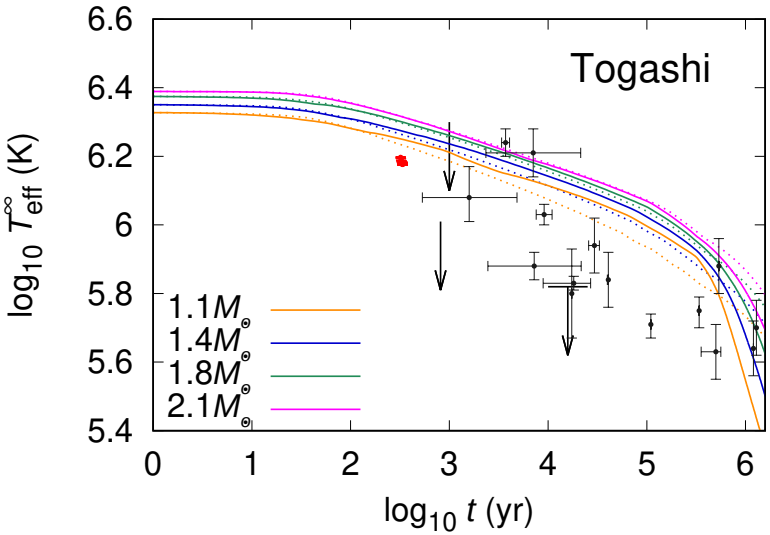


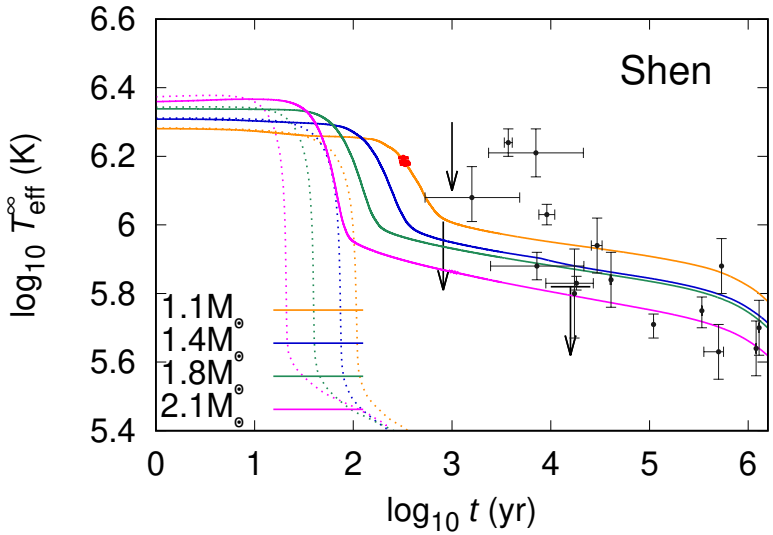


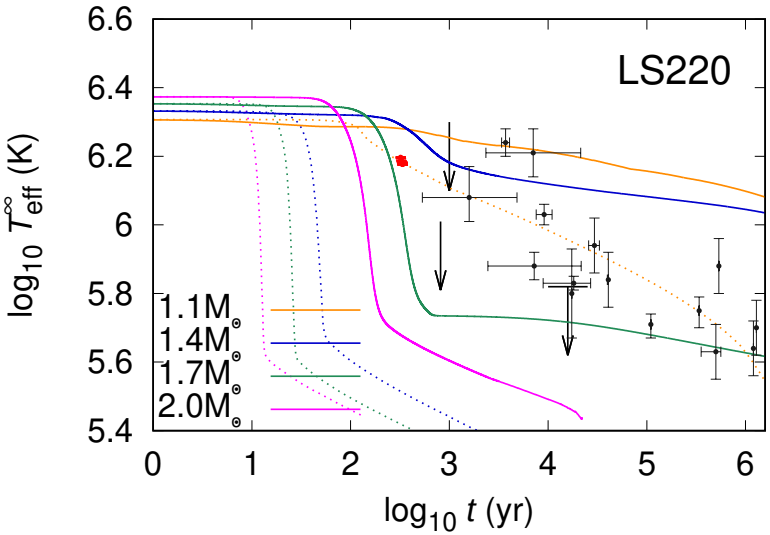




EoS dependence on cooling curves



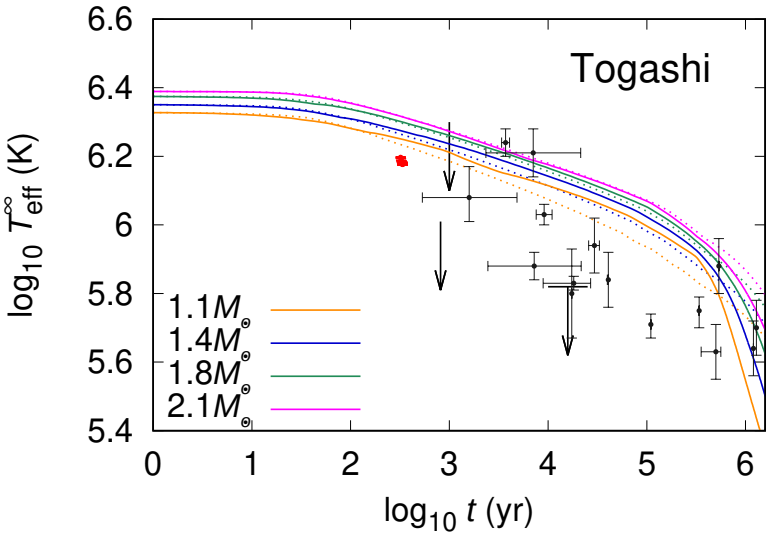


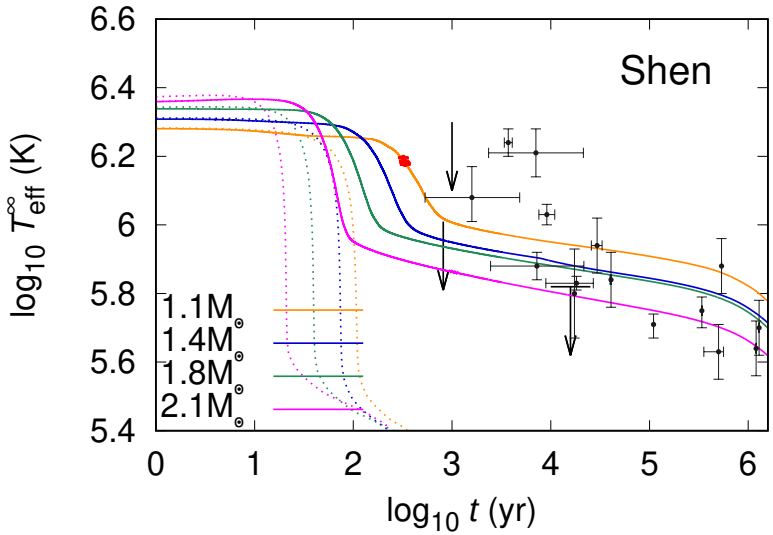


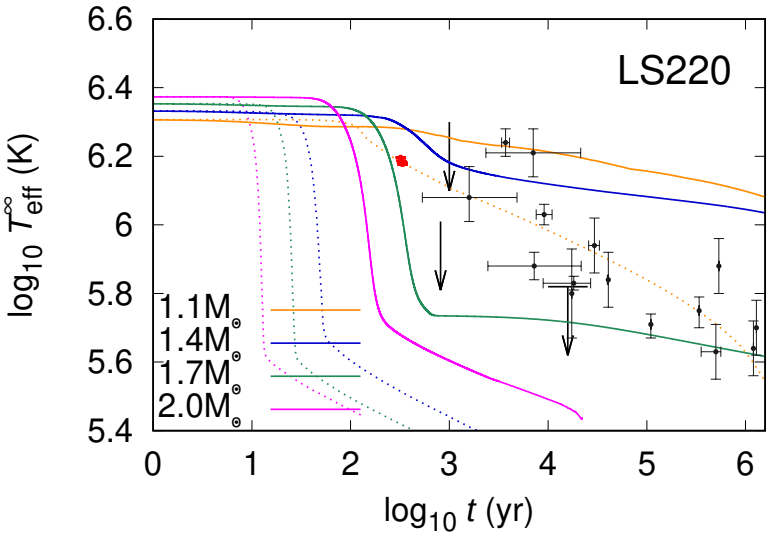
· · · · · · : w/o SF model

——— : w SF model

EoS dependence on cooling curves





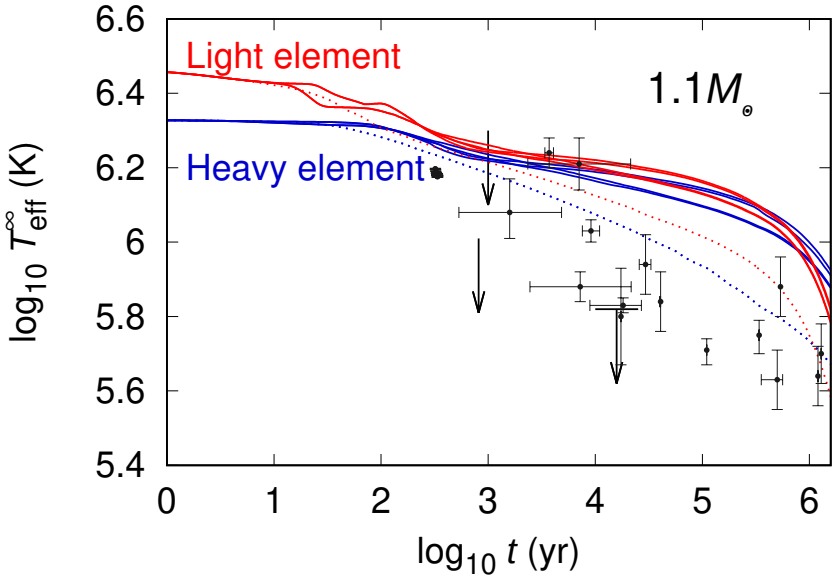


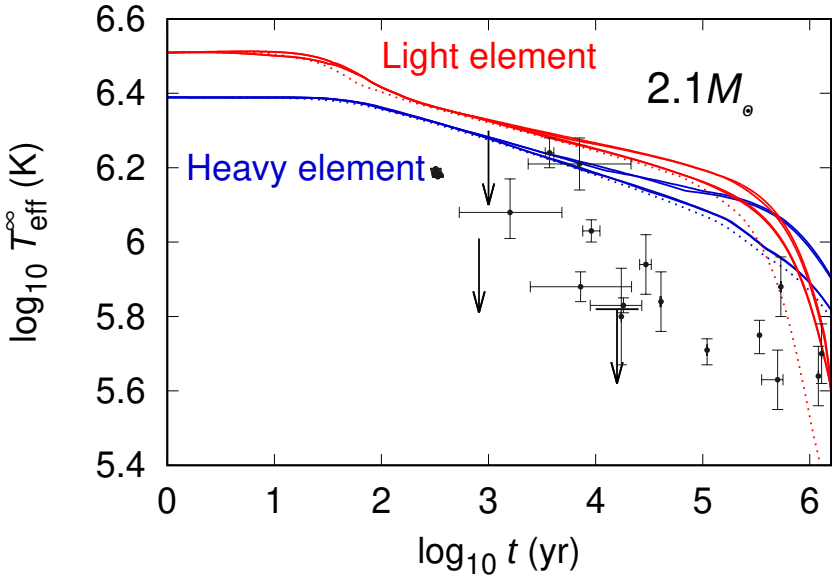
· · · · · · : w/o SF model

——— : w SF model

- DU is prohibited with the Togashi EoS.

Cooling Curves with Togashi EoS





- Compared without superfluidity, the cooling curves with SF models become in higher– temperature regions due to the ν suppression.
- Some low–temperature observations seem to be difficult to be explained with Togashi EoS.

DU threshold of Symmetry Energy

The β–equlibrium condition can be expressed as

$$\mu_n - \mu_p = -\frac{\partial w(u, Y_p)}{\partial Y_p} = 4E_{\rm sym}(u)\,(1 - 2Y_p) = \mu_e$$

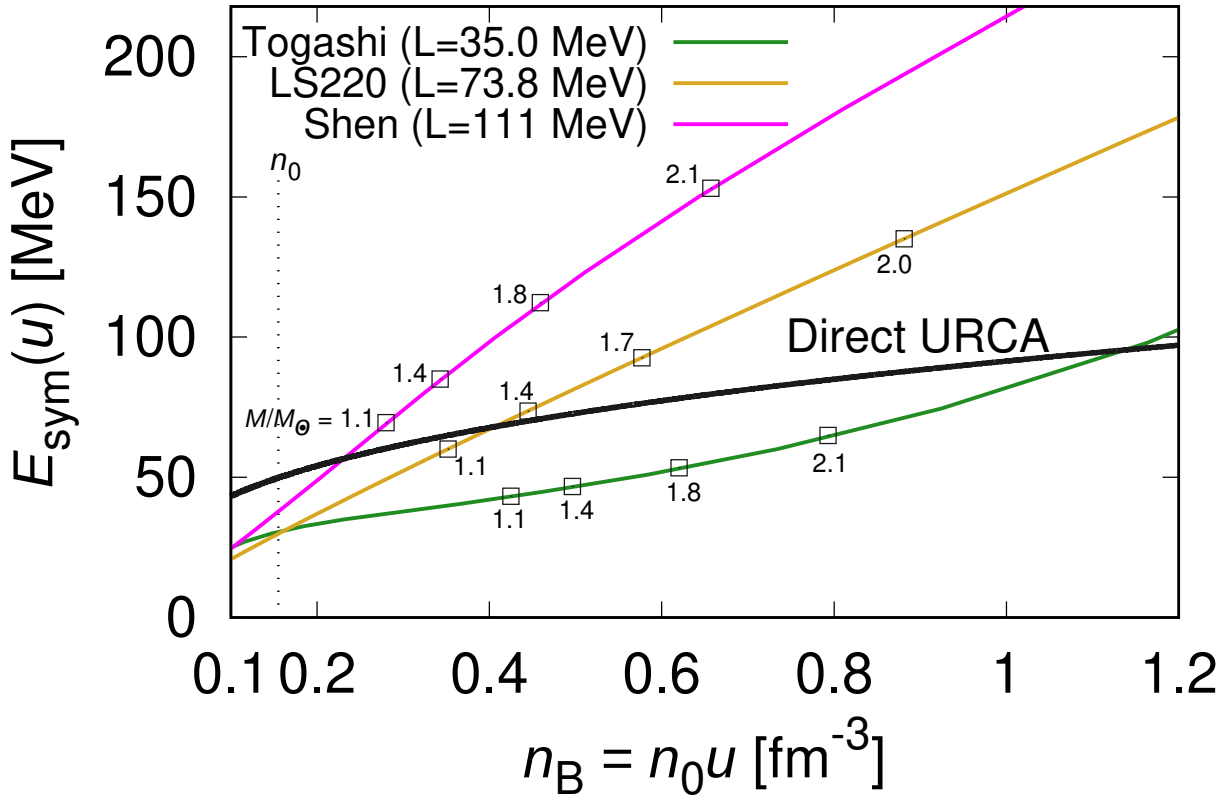
(e.g., Tews et al. 2017)

$\Rightarrow$ The condition to cause DU about $E_{\rm sym}(u)$ is given by

$$\frac{E_{\rm sym}(u)}{u^{1/3}} \geq \frac{\hbar c}{4}\frac{Y_{p\rm DU}}{1 - 2Y_{p\rm DU}}\left(\frac{\pi^2 n_0}{3}\right)^{\frac{1}{3}} \simeq 51\ {\rm MeV}\ ({\rm w/o\ muon})$$

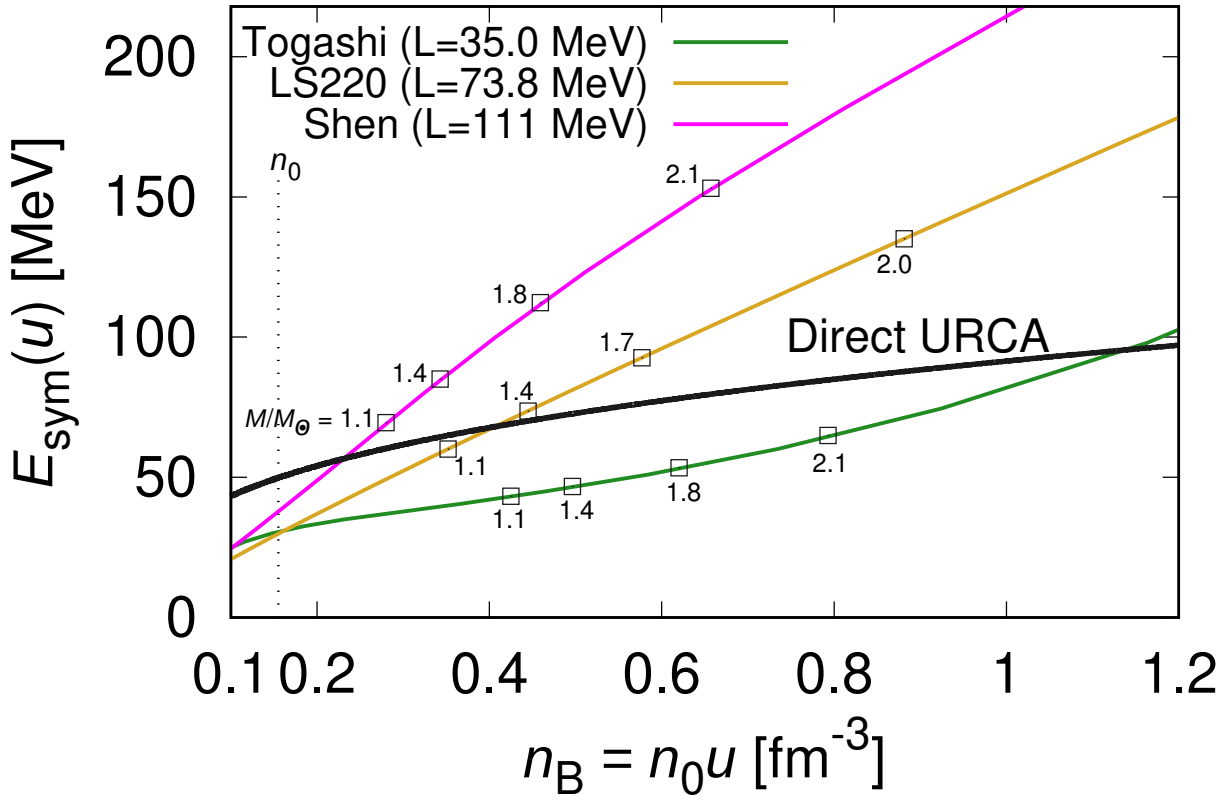
with $n_0 = 0.155\ {\rm fm}^{-3}$. Compared with the $E_{\rm sym}(u)$ value of EoS, whether DU occurs can be judged !

Symmetry Energy and Rapid Cooling



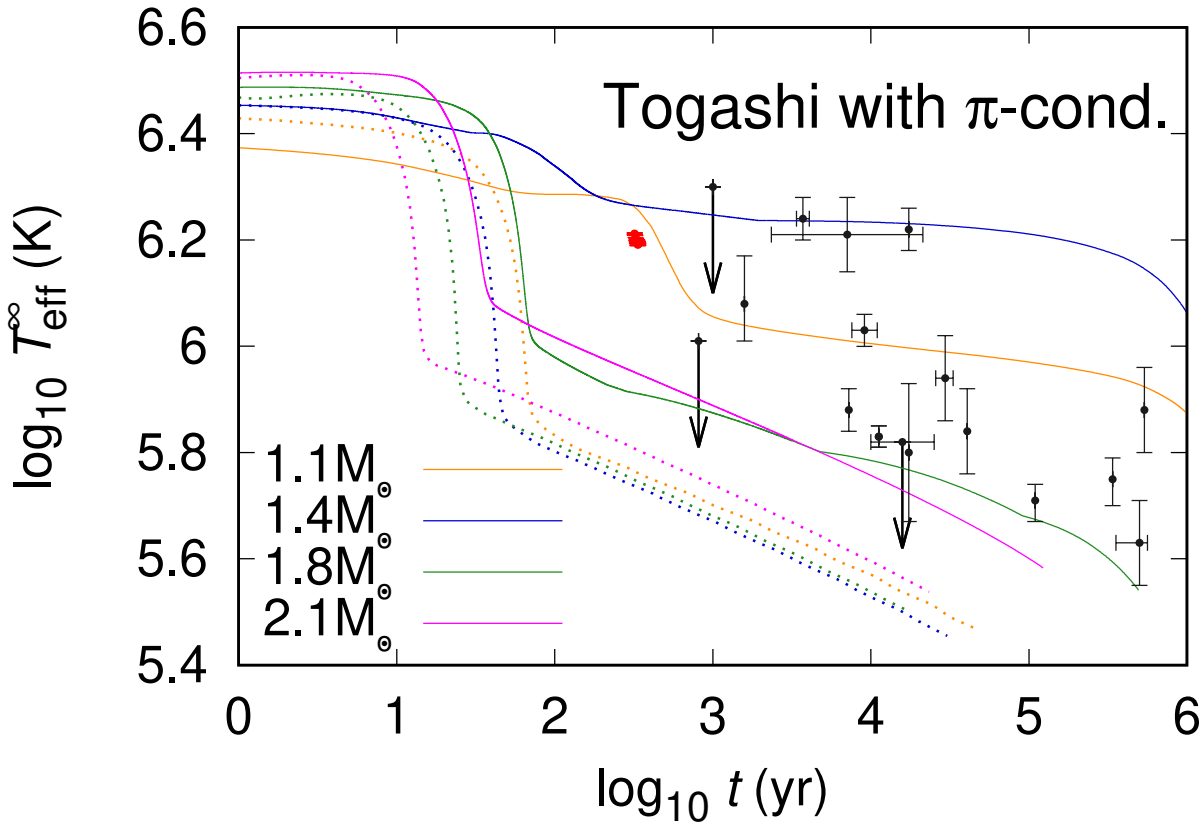
- DU is hard to occur for the model with small $E_{\rm sym}(u)$ or L, that is, small R values

Symmetry Energy and Rapid Cooling



- DU is hard to occur for the model with small $E_{\rm sym}(u)$ or L, that is, small R values
  $\Rightarrow$ Is another strong cooling process needed !?

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



Togashi EoS with pion condensation is consistent.

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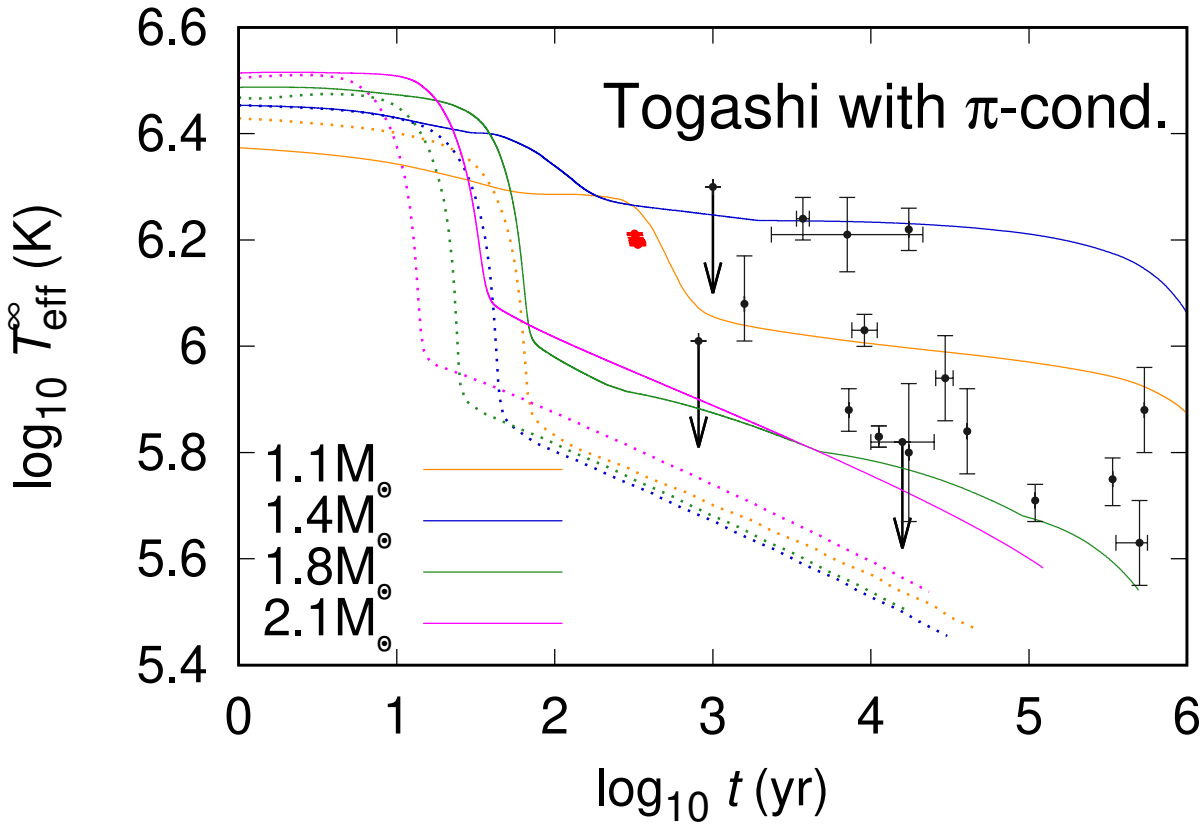

Togashi EoS with pion condensation is consistent.

⇒ Possible exotic particles in NS with small–L model

Conclusion

- For the Togashi EoS, radius constraint is satisfied, but the cooling curves cannot account for the low–temperature observation.
- But with some strong coolings, such a EoS may become ”consistent” model.
  $\Rightarrow$ Possible exotic particles with small–L model !?

FUTURE WORK

- Cooling Calculations with different L models
- Considering exotic particles with fast cooling process and EoS（above all Λ, mesons)
- Or Modified Gravity !? (Dohi *et al.*, 2020, *in prep.*)