Equation of state of neutron stars: Consistency with observation

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Contents

- Observables and current status
- Model: Skyrme force and RMF
- Cooling curve
- Summary

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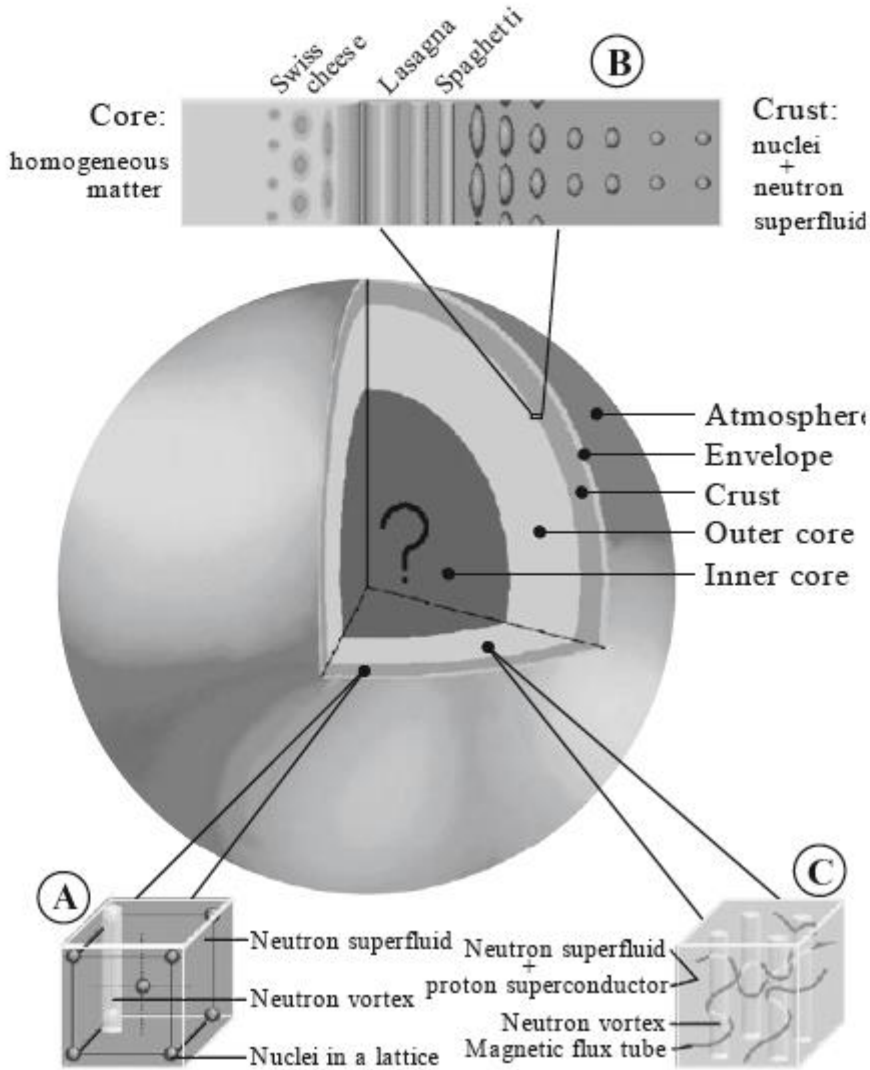


Fig. 11.1 A pictorial vision of the inside of a neutron star (drawing by the author, from [58])

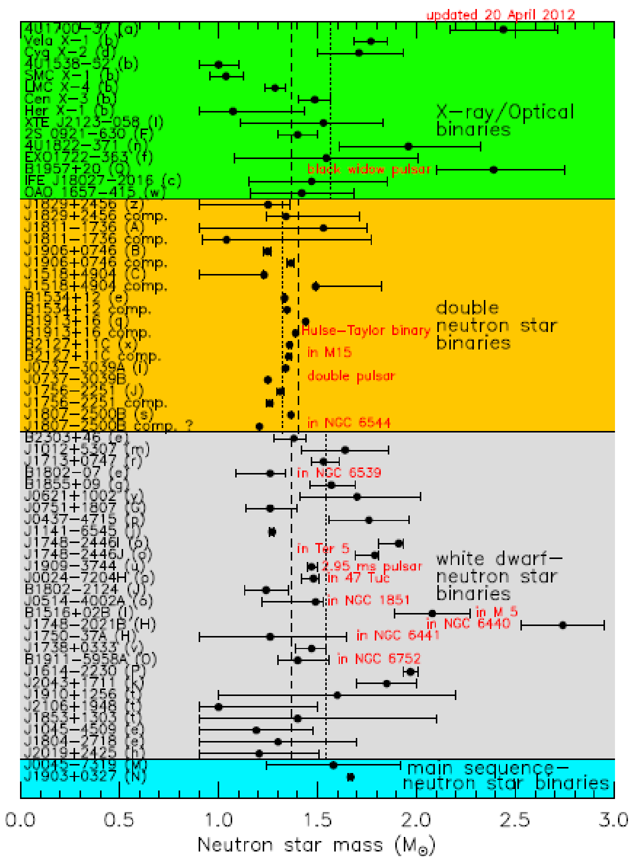
Observables and current status

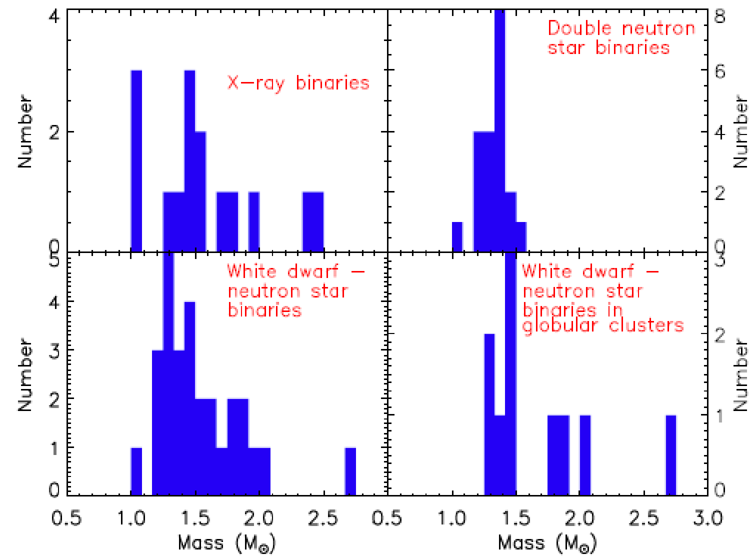
- Mass and radius: binary systems
  - X-ray/optical binaries
  - Double neutron stars
  - White dwarf/neutron stars
  - About 70 systems have been observed

- Temperature: isolated neutron stars
  - Cooling curve: temperature + age
  - About 20 objects have been measured

● Mass and radius

- Key ingredients: equation of state (EoS)
- Mass distribution (J. Lattimer, Ann. Rev. Nucl. Part., 2012)





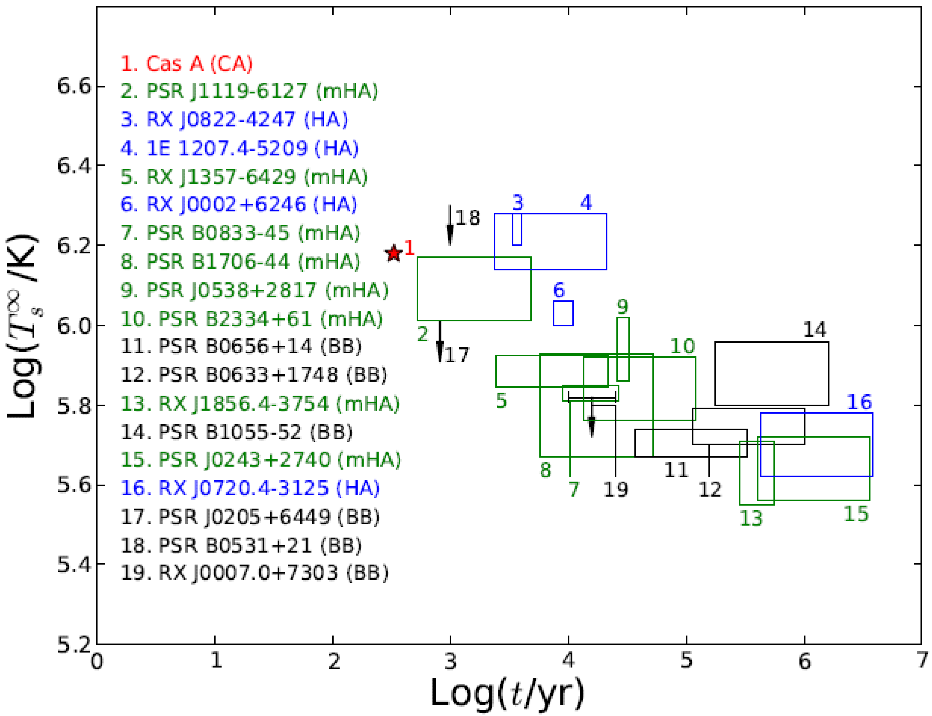
- PSR J1614-2230: $(1.97 \pm 0.04) M_\odot$
- PSR J0348+0432: $(2.01 \pm 0.04) M_\odot$

- Mass-radius (A. Steiner, J. Lattimer, E. Brown, ApJ, 2010): Determine EoS from data set of six neutron stars. Markov chain Monte Carlo algorithm within a Bayesian framework
- For M = 1.4 $M_\odot$, R = 11 – 12 km
- Maximum mass: (1.9 – 2.2)$M_\odot$

Table 9
Most Probable Values for Masses and Radii for Neutron Stars Constrained to Lie on One Mass Versus Radius Curve

Object	$M\ (M_\odot)$	R (km)	$M\ (M_\odot)$	R (km)
	$r_{ph} = R$		$r_{ph} \gg R$	
4U 1608–522	$1.52^{+0.22}_{-0.18}$	$11.04^{+0.53}_{-1.50}$	$1.64^{+0.34}_{-0.41}$	$11.82^{+0.42}_{-0.89}$
EXO 1745–248	$1.55^{+0.12}_{-0.36}$	$10.91^{+0.86}_{-0.65}$	$1.34^{+0.450}_{-0.28}$	$11.82^{+0.47}_{-0.72}$
4U 1820–30	$1.57^{+0.13}_{-0.15}$	$10.91^{+0.39}_{-0.92}$	$1.57^{+0.37}_{-0.31}$	$11.82^{+0.42}_{-0.82}$
M13	$1.48^{+0.21}_{-0.64}$	$11.04^{+1.00}_{-1.28}$	$0.901^{+0.28}_{-0.12}$	$12.21^{+0.18}_{-0.62}$
ω Cen	$1.43^{+0.26}_{-0.61}$	$11.18^{+1.14}_{-1.27}$	$0.994^{+0.51}_{-0.21}$	$12.09^{+0.27}_{-0.66}$
X7	$0.832^{+1.19}_{-0.051}$	$13.25^{+1.37}_{-3.50}$	$1.98^{+0.10}_{-0.36}$	$11.3^{+0.95}_{-1.03}$

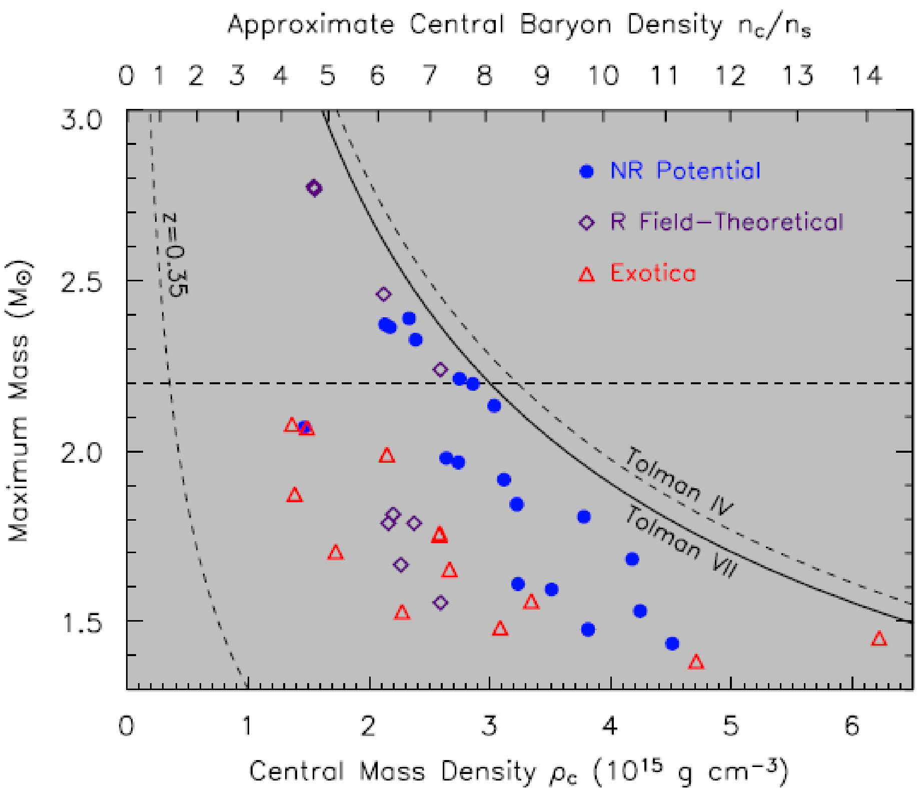
- Temperature
  - Key ingredients: EoS (particle fraction), Elements in the envelop, Nuclear superfluidity



- Cas A: Observed about 300 yrs ago
- Age group
- young: less than 10^4 yrs
- middle: $10^4 – 10^5$ yrs
- old: more than 10^5 yrs
- Slow-quick-slow cooling

Model

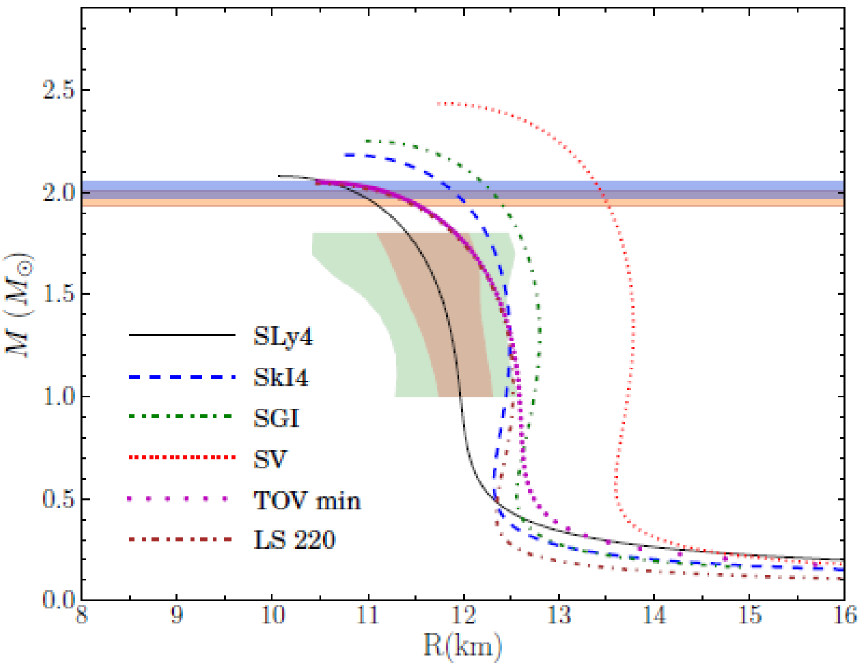
- Theories



- **Skyrme force**
  - General form

$$\hat{v}_{\rm SF}(\mathbf{r}_i,\mathbf{r}_j) = t_0(1+x_0\hat{P}_\sigma)\delta(\mathbf{r}_i-\mathbf{r}_j)+\frac{t_1}{2}(1+x_1\hat{P}_\sigma)\Big[\delta(\mathbf{r}_i-\mathbf{r}_j)\hat{\mathbf{k}}^2+\hat{\mathbf{k}}^{\dagger 2}\delta(\mathbf{r}_i-\mathbf{r}_j)\Big]$$
$$+t_2(1+x_2\hat{P}_\sigma)\hat{\mathbf{k}}^\dagger\cdot\delta(\mathbf{r}_i-\mathbf{r}_j)\hat{\mathbf{k}}+\frac{1}{6}t_3(1+x_3\hat{P}_\sigma)n^\alpha\delta(\mathbf{r}_i-\mathbf{r}_j)$$
$$+iW_0\hat{\mathbf{k}}^\dagger\delta(\mathbf{r}_i-\mathbf{r}_j)\times\hat{\mathbf{k}}\cdot(\hat{\boldsymbol{\sigma}}_i+\hat{\boldsymbol{\sigma}}_j)\,,$$

  - Mass-radius relation

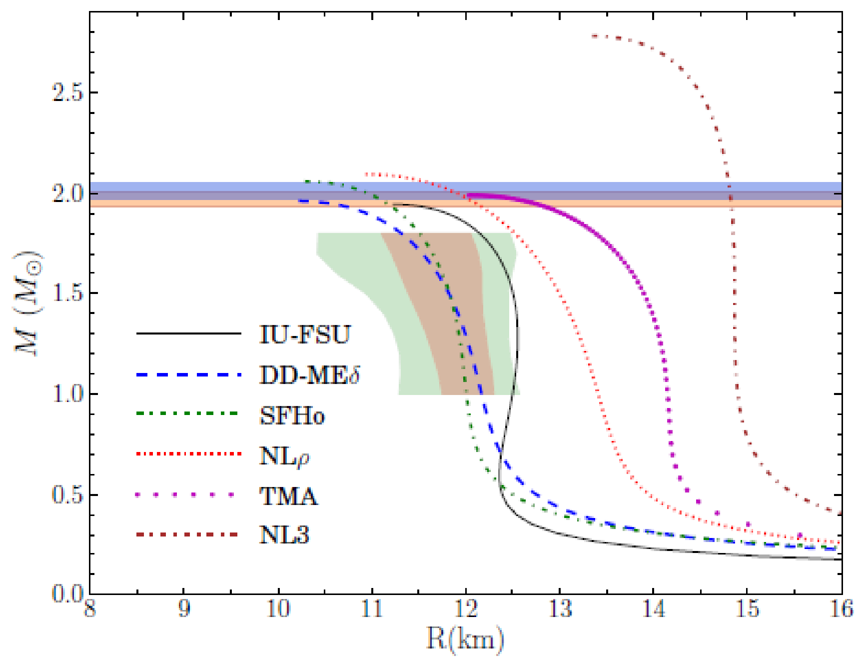


- RMF

  - General form

$$\mathcal{L} = \bar{\psi}\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \frac{1}{2}g_\rho \vec{\tau}\cdot\vec{b\!\!\!/} + g_\delta \vec{\delta}\cdot\vec{\tau} - m_N + g_\sigma\sigma - \frac{1}{2}e(1+\tau_3)A\!\!\!/\right]\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{b}^\mu\cdot\vec{b}_\mu$$
$$+\frac{1}{2}\partial_\mu\vec{\delta}\cdot\partial^\mu\vec{\delta} - \frac{1}{2}m_\delta^2\vec{\delta}^2 - V_{\text{eff}}(\sigma,\omega^\mu\omega_\mu,\vec{b}^\mu\cdot\vec{b}_\mu),$$

  - Mass-radius relation



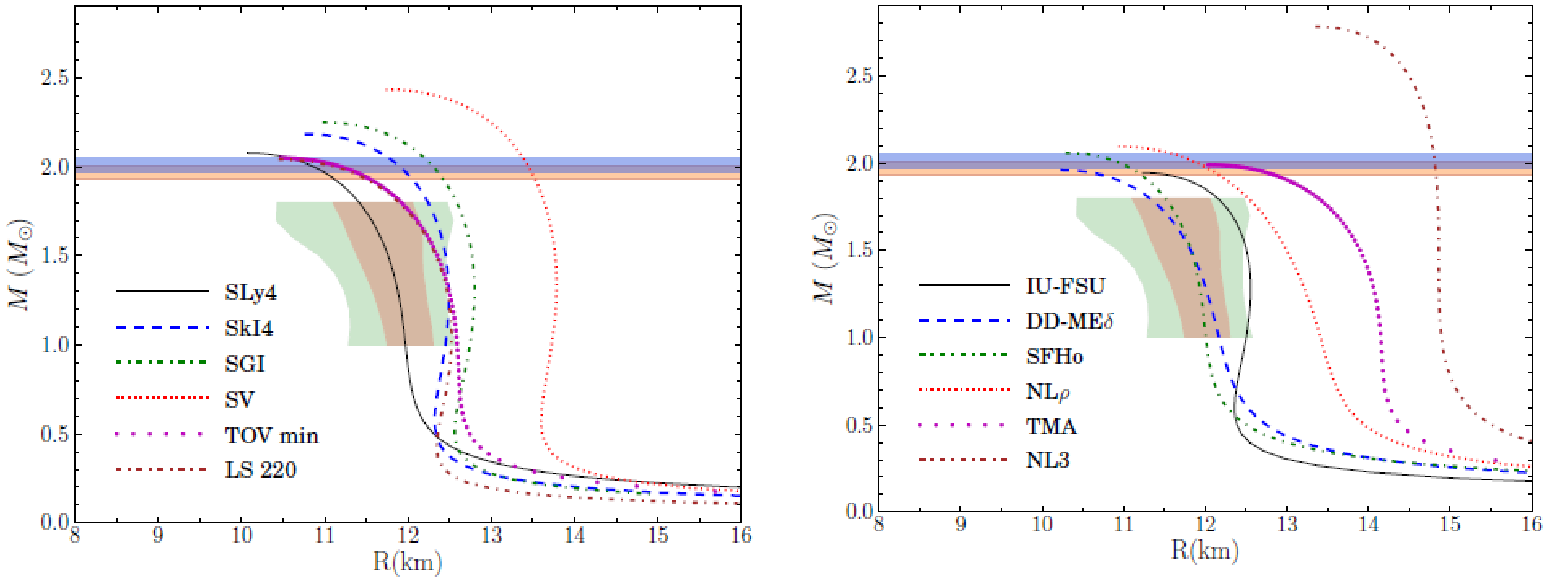
Cooling curve

- Cooling mechanism
  - Photon emission: mostly on the surface
  - Neutrino emission: entire region, major energy loss

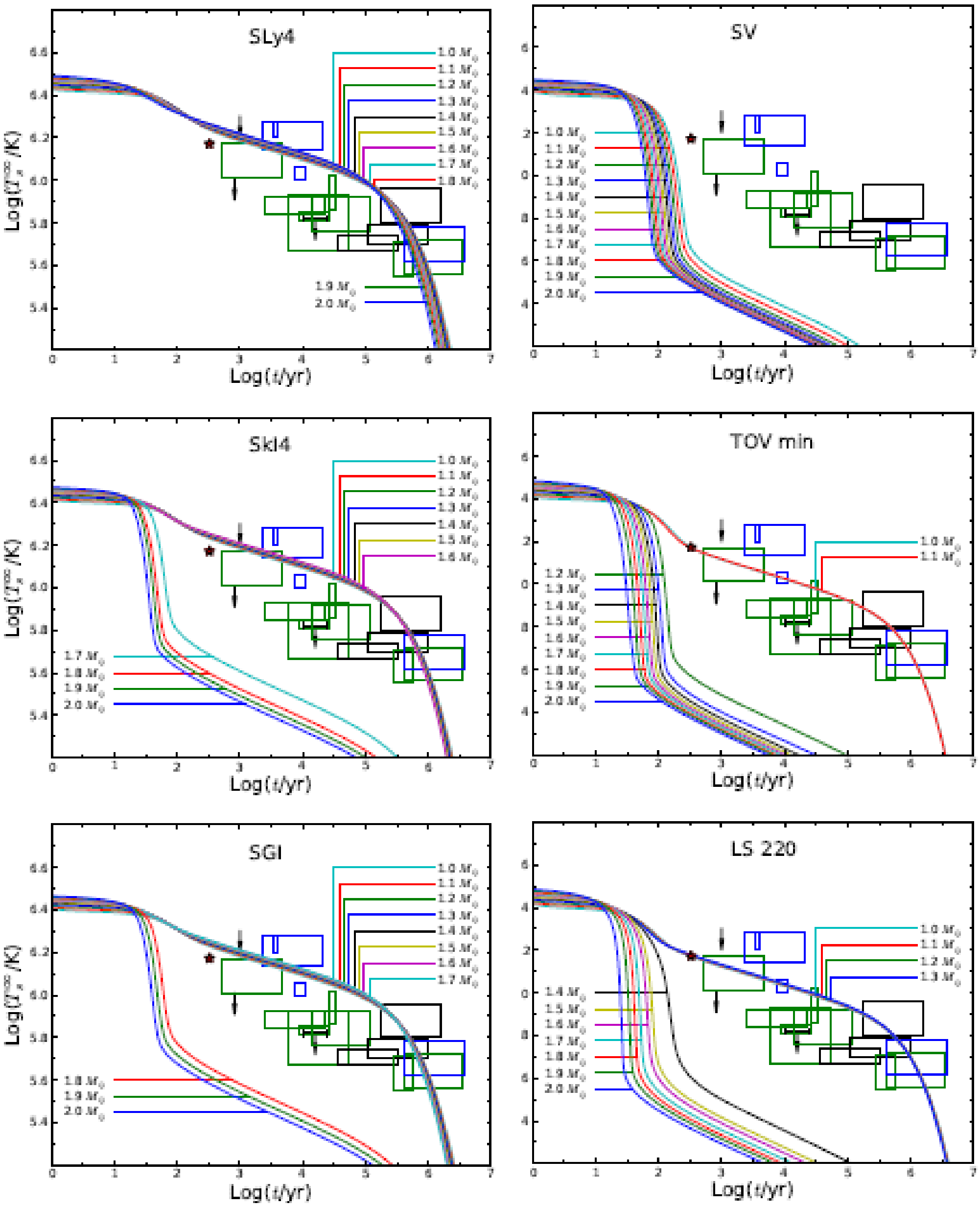
Name	Process	Emissivity[b] (erg cm^{-3} s^{-1})	
Modified Urca (neutron branch)	$n+n \rightarrow n+p+e^- + \bar{\nu}_e$ $n+p+e^- \rightarrow n+n+\nu_e$	$\sim 2\times 10^{21}\,\mathcal{R}\,T_9^8$	Slow
Modified Urca (proton branch)	$p+n \rightarrow p+p+e^- + \bar{\nu}_e$ $p+p+e^- \rightarrow p+n+\nu_e$	$\sim 10^{21}\,\mathcal{R}\,T_9^8$	Slow
Bremsstrahlung	$n+n \rightarrow n+n+\nu\bar{\nu}$ $n+p \rightarrow n+p+\nu\bar{\nu}$ $p+p \rightarrow p+p+\nu\bar{\nu}$	$\sim 10^{19}\,\mathcal{R}\,T_9^8$	Slow
Cooper pair formations	$n+n \rightarrow [nn]+\nu\bar{\nu}$ $p+p \rightarrow [pp]+\nu\bar{\nu}$	$\sim 5\times 10^{21}\,\mathcal{R}\,T_9^7$ $\sim 5\times 10^{19}\,\mathcal{R}\,T_9^7$	
Direct Urca	$n \rightarrow p+e^- + \bar{\nu}_e$ $p+e^- \rightarrow n+\nu_e$	$\sim 10^{27}\,\mathcal{R}\,T_9^6$	Fast
π^- condensate	$n+ <\pi^-> \rightarrow n+e^- + \bar{\nu}_e$	$\sim 10^{26}\,\mathcal{R}\,T_9^6$	Fast
K^- condensate	$n+ <K^-> \rightarrow n+e^- + \bar{\nu}_e$	$\sim 10^{25}\,\mathcal{R}\,T_9^6$	Fast

● Standard cooling

- Direct Urca, Modified Urca, Pair bremsstrahlung
- We do not know the mass of observed stars
- Probably mass of the stars lie in the canonical range (1.2 – 1.6)$M_\odot$

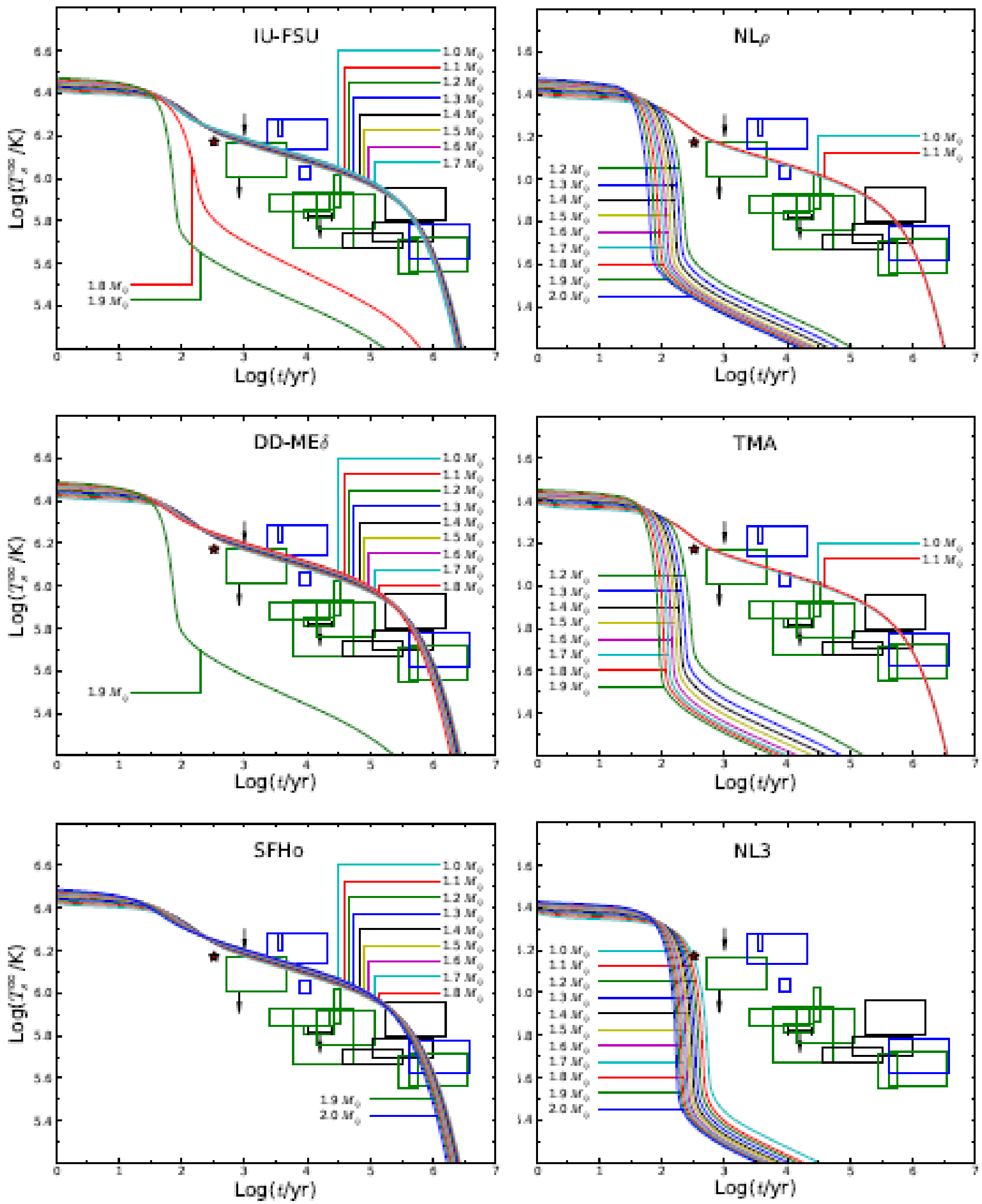


- Skyrme force



- Mass in the range of $(1.0 - 2.0)M_{\odot}$
- Abrupt drop: ingnition of direct Urca
- SLy4: do direct Urca
- Stiffer EoS allows early direct Urca
- No model can explain middle-age data
- Good: SLy4, SkI4, SGI
- TOV-min: fitted to neutron star mass, but does not satisfy cooling

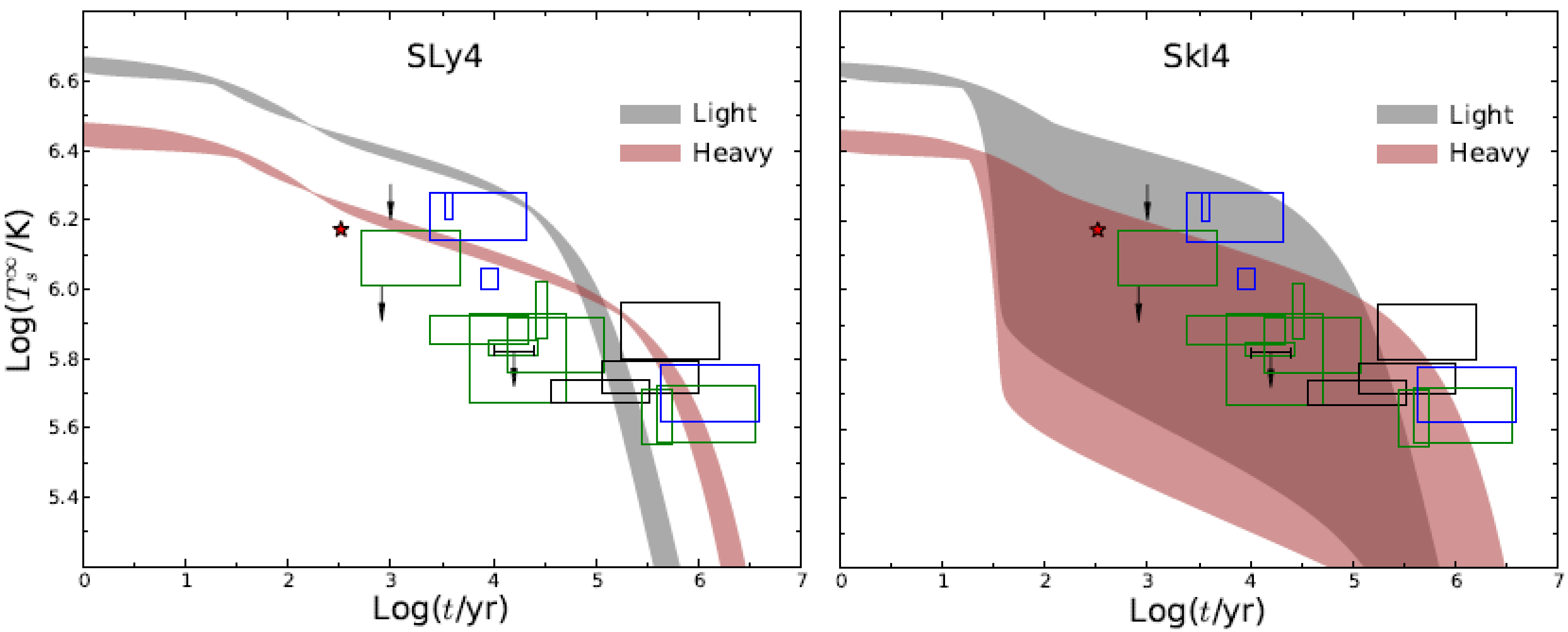
- RMF



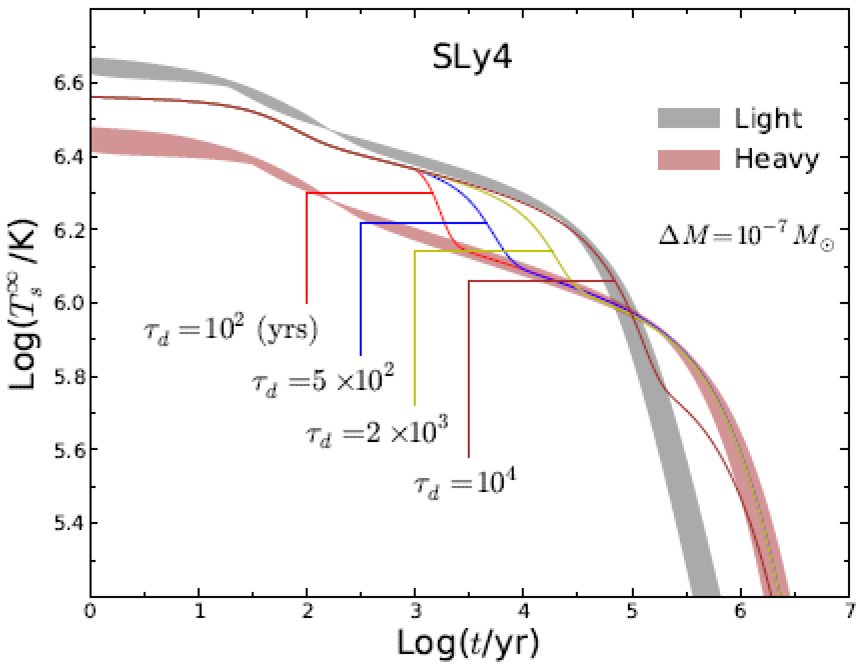
- Mass in the range of (1.0 – 2.0)$M_\odot$
- Abrupt drop: ingnition of direct Urca
- SFHo: do direct Urca
- No model can explain middle-age data
- Good: IU-FSU, DD-Meδ, SFHo

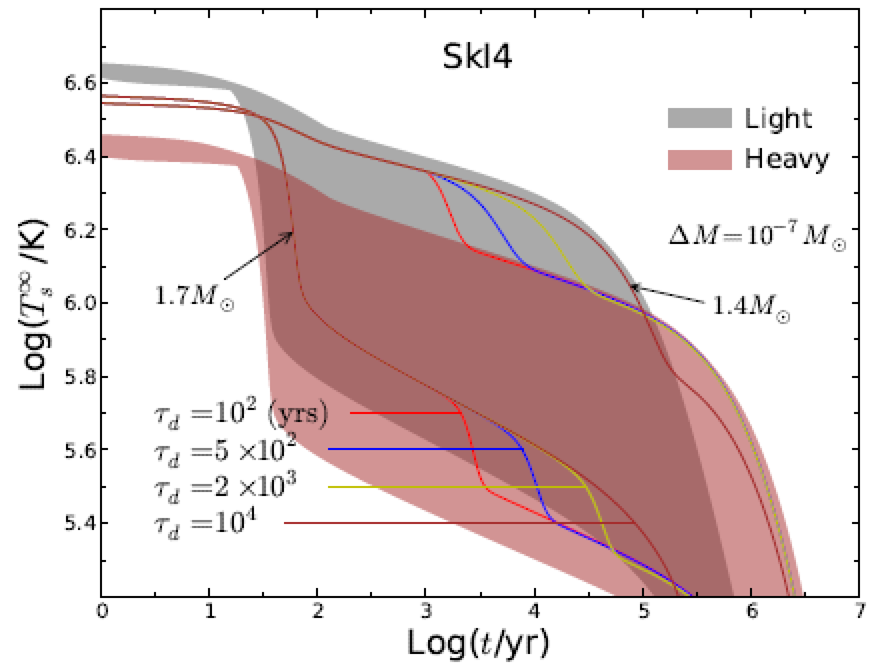
● Effect of envelop element

- Mass range: $(1.2 - 2.0)M_{\odot}$
- Heavy dependence on model

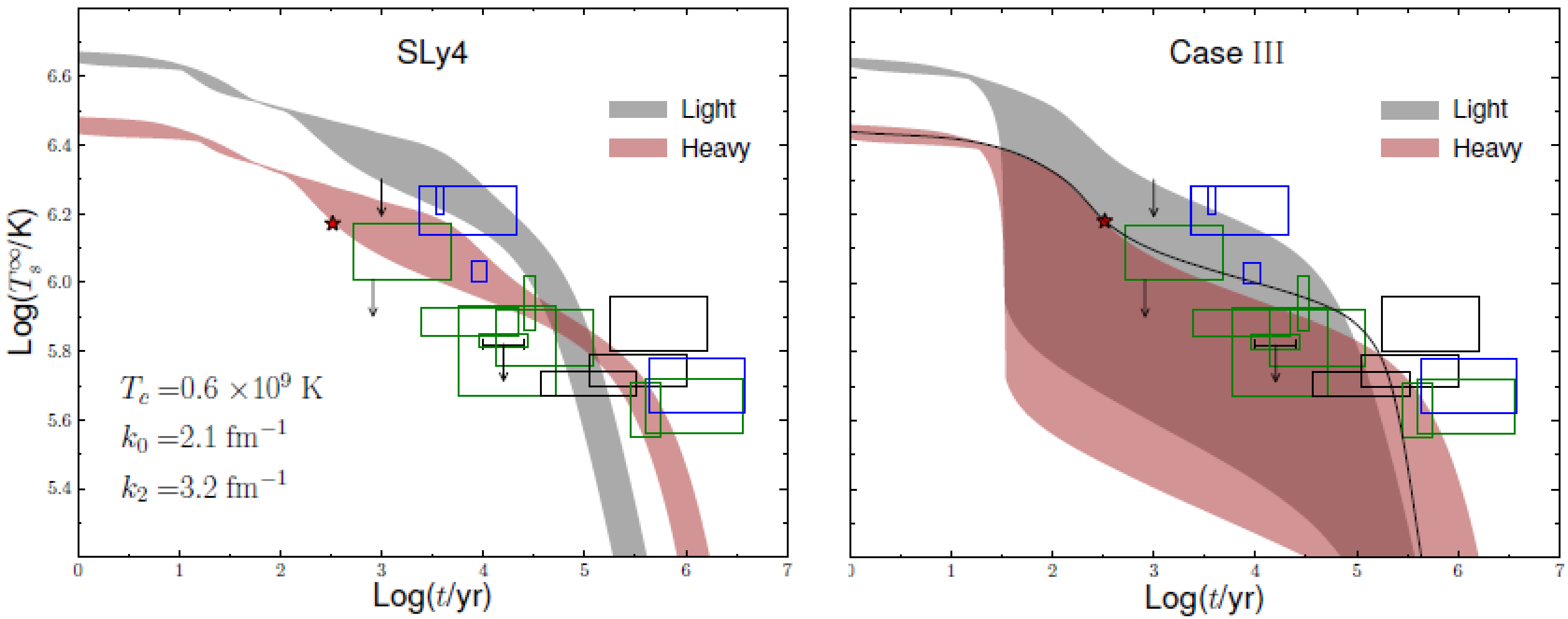


- Dependence on the light element life time





- Effect of nuclear superfluidity



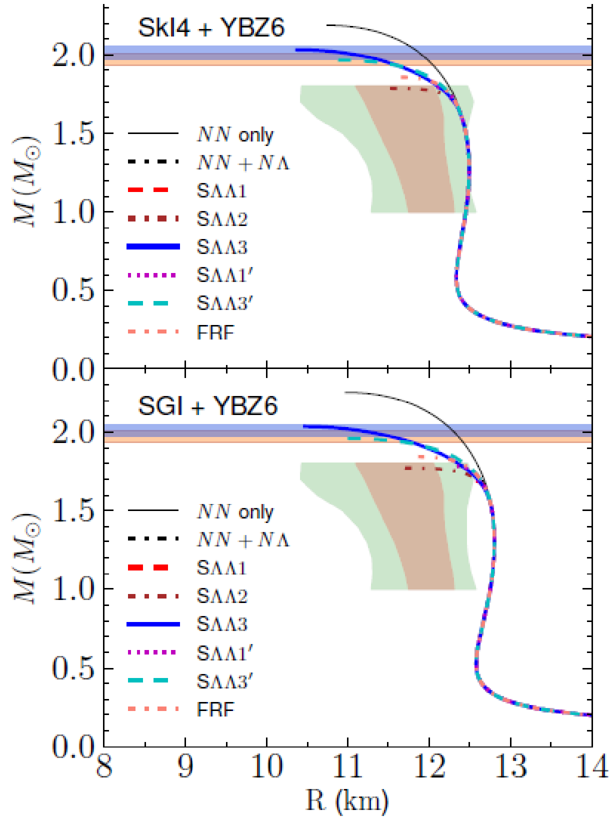
Summary

- Mass-radius and temperature data: experimental constraints
- Nuclear models: Skyrme force, RMF
- Could distinguish better models: Good for mass-radius is also good for temperature evolution
- Proper combination of envelop elements and nuclear superfluidity: prediction within the data
- More to consider

▪ Strangeness

- hyperon puzzle

- kaon condensation (Y. Lim, K. Kwak, CHH, C.-H. Lee, PRC, 2014)



- Y. Lim, CHH, K. Kwak, C.-H. Lee, arXiv: 1412.5722, submitted to NPA

- Cooling curve with strangeness: in progress
- Improve models: systematic way to determine the EoS at high densities

- 새로운 현상 발견
- 새로운 핵모형 개발
- 핵력의 체계적 이해
- 계산 기술의 발전

- 별의 진화와 원소의 생성 원리 이해, 초신성 폭발의 원인 규명, 고밀도 핵물질의 상태방정식 이해

- RIA를 가동 또는 건설 중인 나라: 미국, 캐나다, 독일, 프랑스, 러시아, 중국, 일본, 한국 등
- RAON: 한국 최초의 핵물리 연구용 가속기
- 우리의 배를 타고 미지의 세계를 탐험할 수 있는 멋있는 여행