Strangeness
in neutron star equation of state and cooling

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in collaboration with Yeunhwan Lim, Kyujin Kwak & Chang Ho Hyun

PRC 89, 055804 (2014)
IJPME 24, 1550100 (2015)
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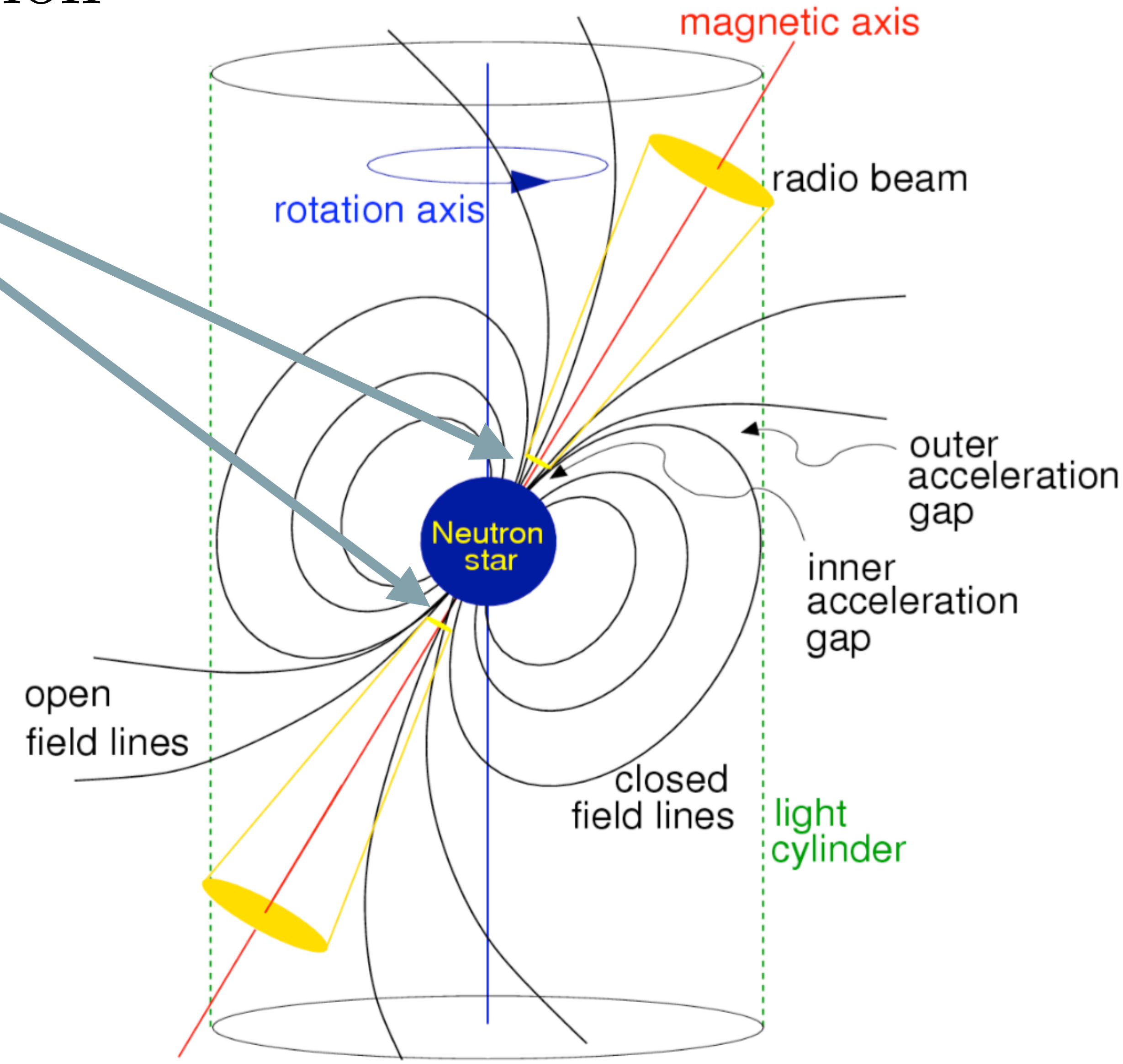
Properties of Neutron Star

e^+e^- pair creation

Pulsar



$$M = 1.5 \sim 2.0 M_\odot$$

$$R = 10 \sim 15 \text{ km}$$

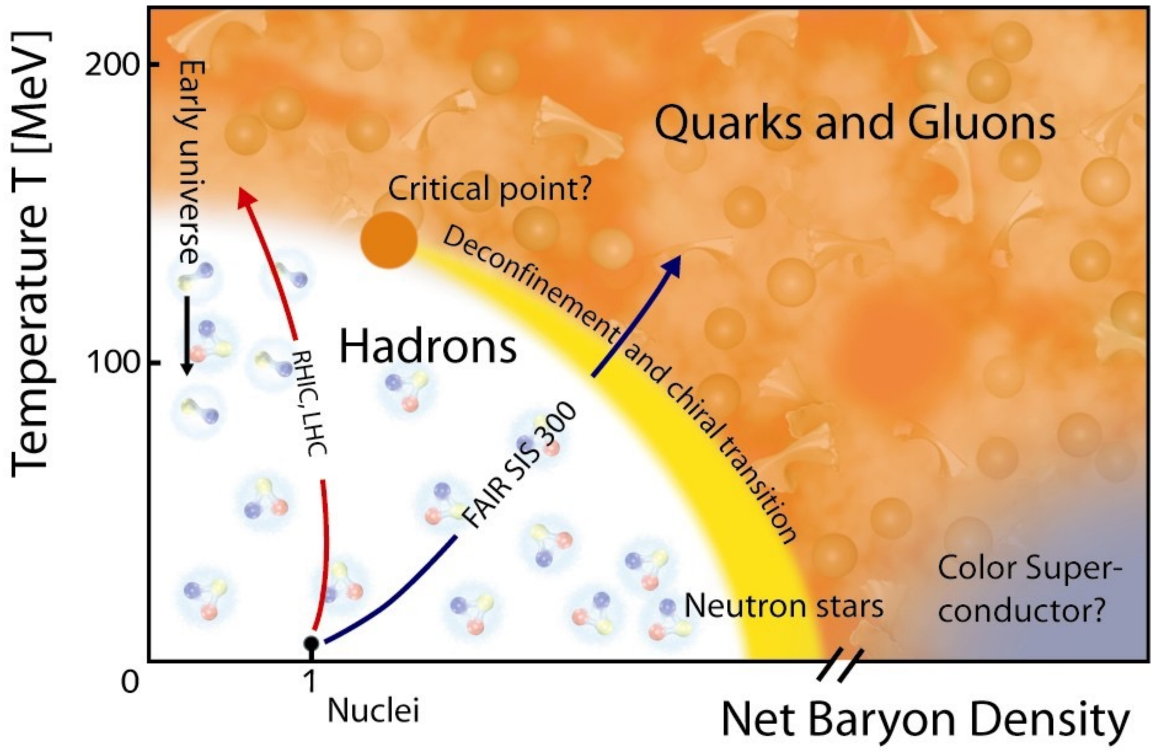
$$A \sim 10^{57} \text{ nucleons}$$

Infinite nuclear matter / mean field approaches

Physics of Dense Matter

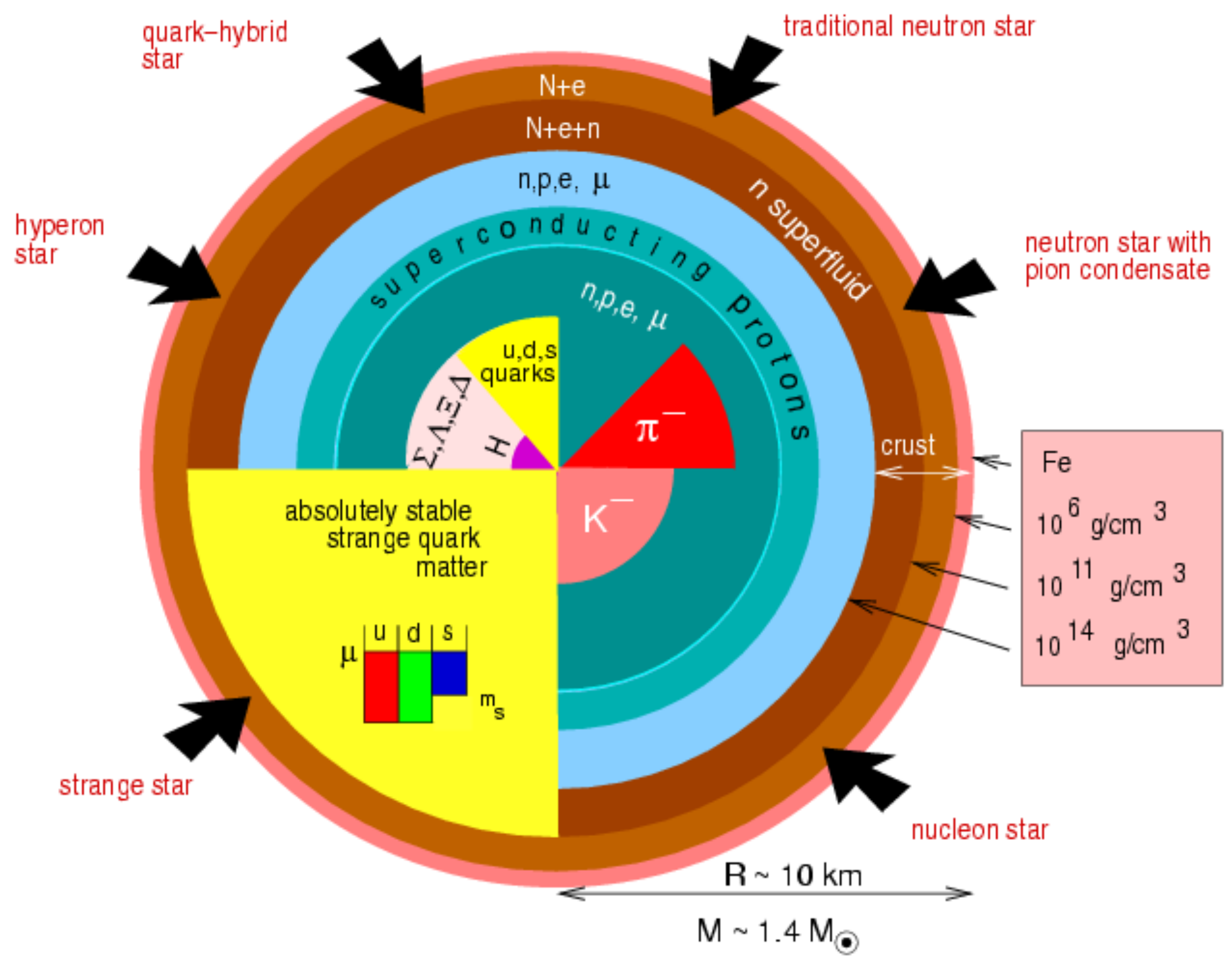
Strong interactions mediated by gluons with color charges

- Chiral perturbation theory
- QCD effective models
- Color superconductivity
- Color-flavor locking
- AdS/QCD



Nuclear matter is not an ideal gas

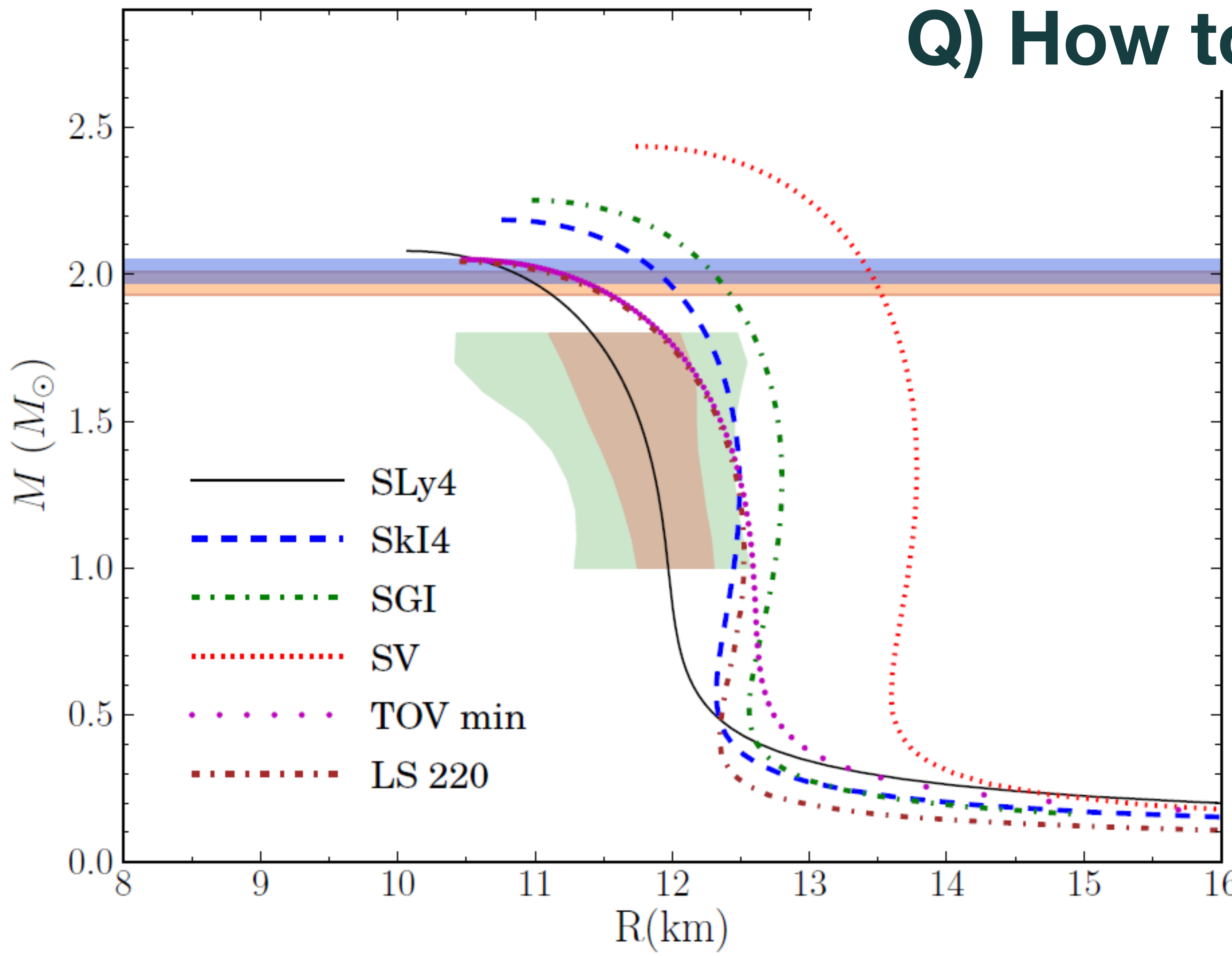
F. Weber 2005



- **still uncertain due to the nature of strong interactions**
- **introduction of 3 body forces**
- **exotic states with strangeness**
- **… …**

Maximum Mass of Neutron Stars

Q) How to understand ?



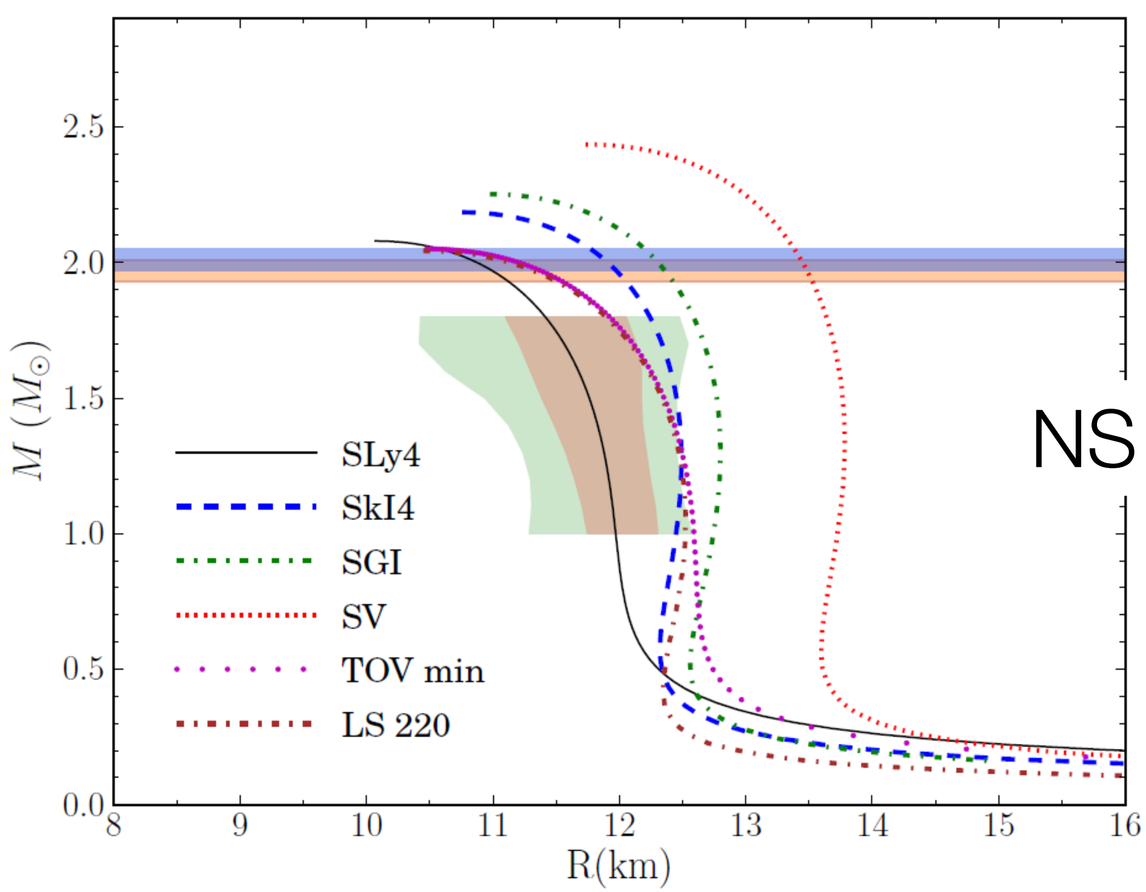
Neutron Star-White Dwarf Binaries

1.97 solar mass NS : Nature 467 (2010) 1081

2.01 solar mass NS : Science 340 (2013) 6131

Role of strangeness

- dense matter with u & d quarks: p(uud) + n(udd)
- **s-quark can reduce pressure of dense matter via neutrino emission**
- **reduce maximum mass of neutron stars**



NS EOS without strangeness

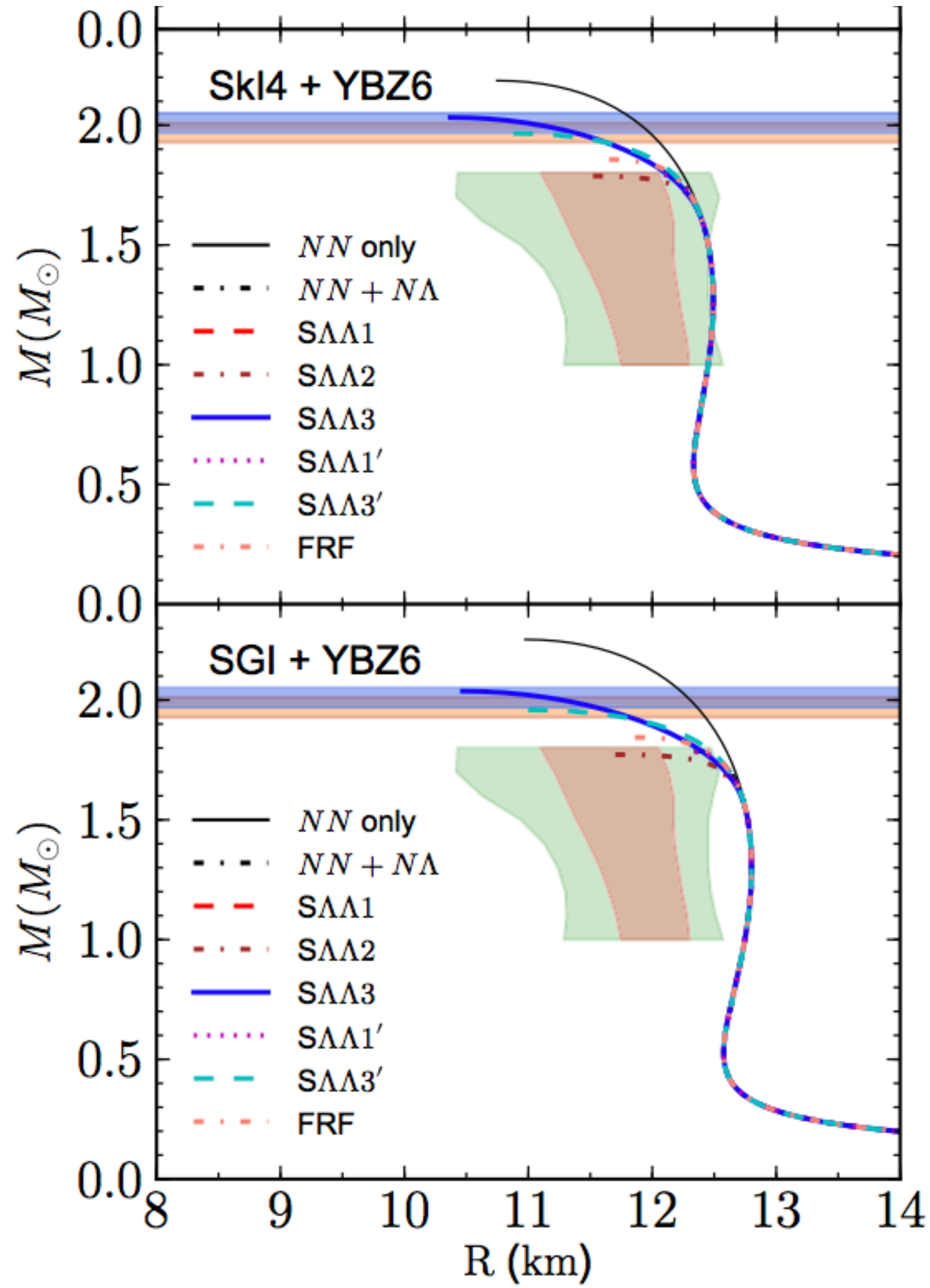
There are possibilities of NS EOS with strangeness

Neutron Star EOS with Strangeness

$$\Lambda^0(uds) \ : \ 1116 \text{ MeV}$$

$$K^-(\bar{u}s) \ : \ 495 \text{ MeV}$$

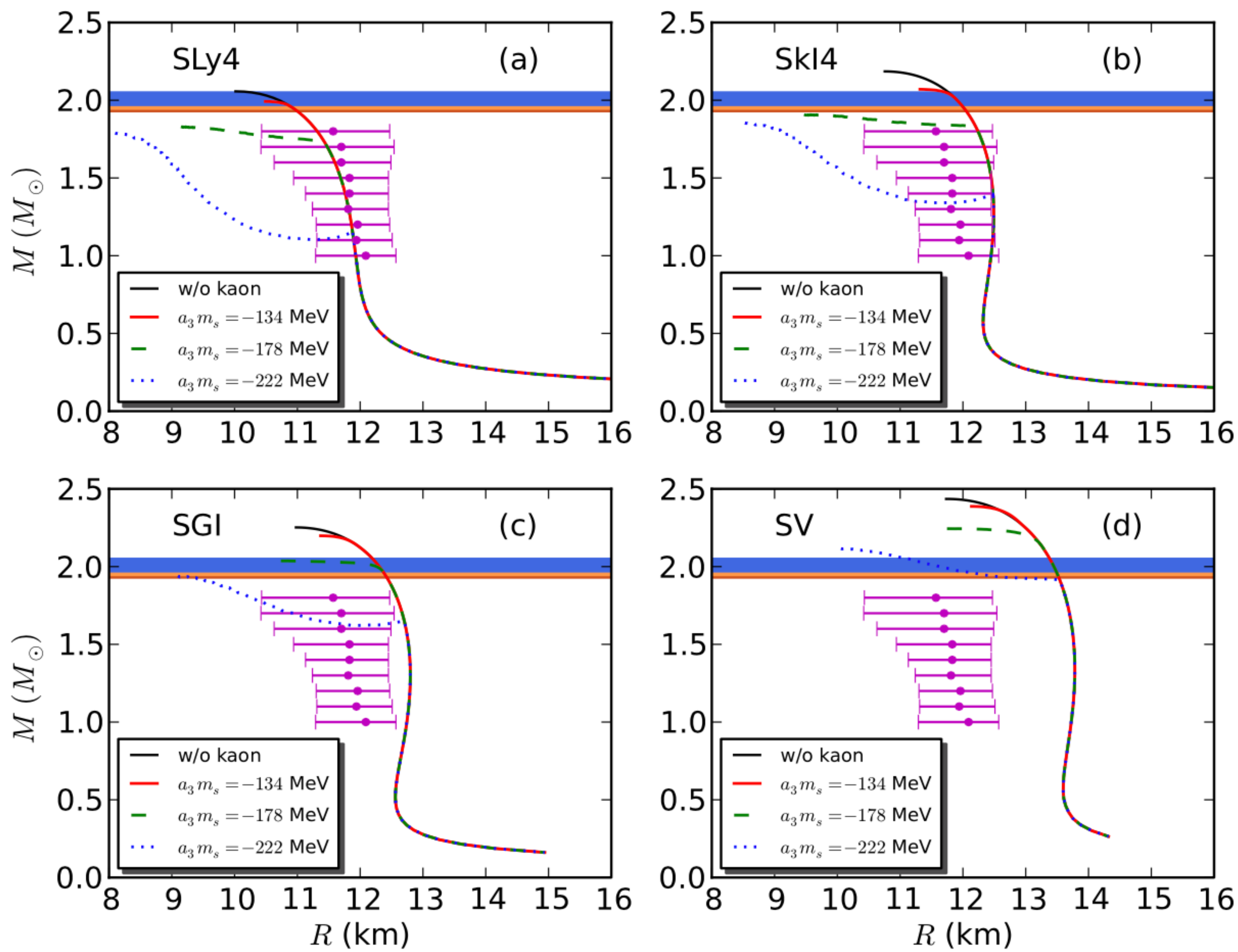
Maximum NS mass



Possibilities with Repulsive Lambda-Lambda interactions

NS mass with kaons

Data: Steiner et al. ApJ 722, 33 (2010)



prefer smaller Sigma_KN (larger chemical potential)

NS mass with strangeness

- In general, strangeness reduces maximum NS mass
- But, there still remain possibilities for the strangeness with repulsive Lambda-Lambda interaction or smaller Sigma_KN

With Lambda hyperons

SLy4	SkI4	SGI
$1.15 \sim 1.85$	$1.47 \sim 1.97$	$1.44 \sim 2.04$

With kaon condensation

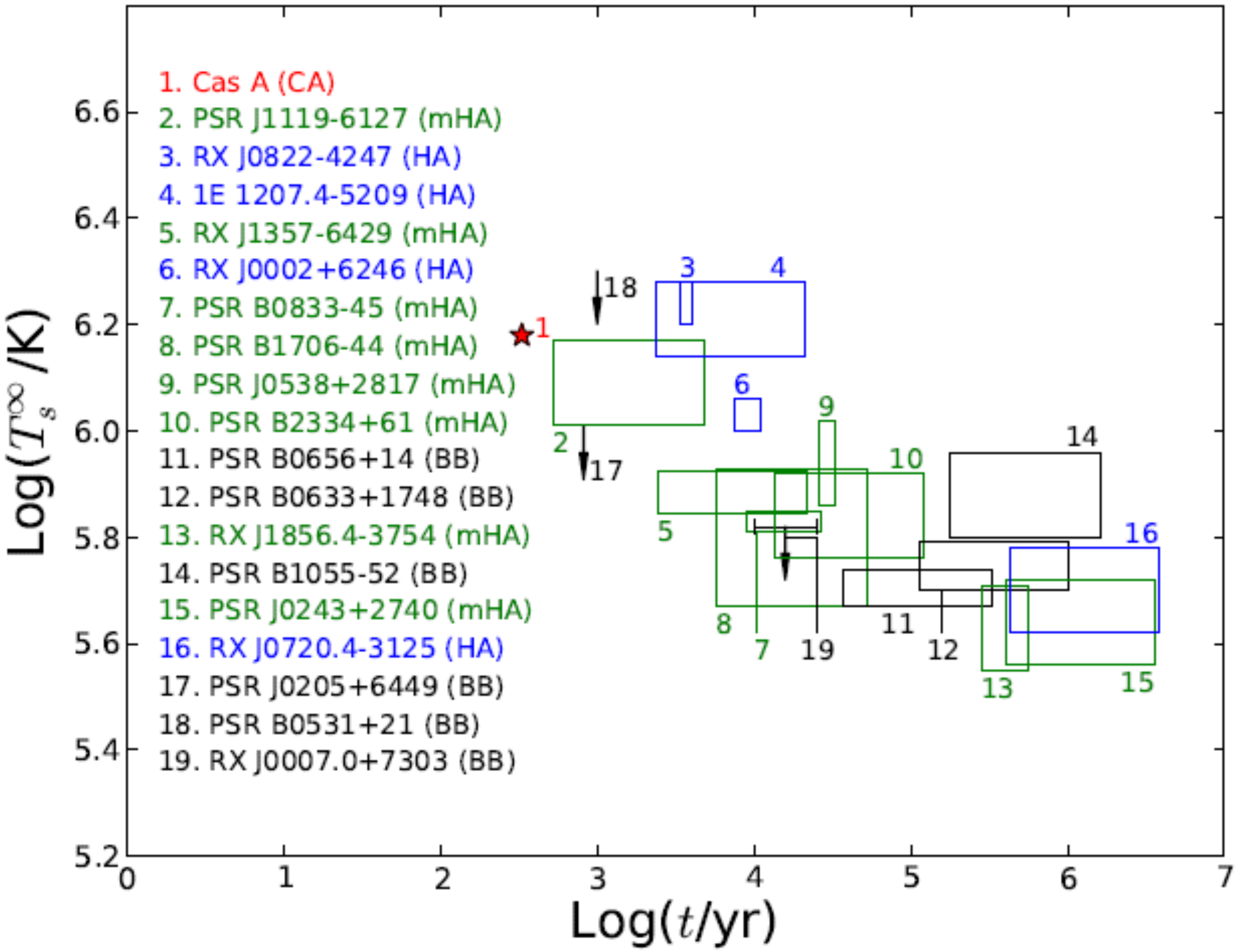
consistent with 2 Msun NS

$a_3 m_s$	SLy4	SkI4	SGI
-134	$1.94 \sim 1.99$	$2.00 \sim 2.06$	$2.12 \sim 2.19$
-178	$1.74 \sim 1.83$	$1.84 \sim 1.90$	$1.95 \sim 2.03$
-222	$1.49 \sim 1.79$	$1.64 \sim 1.85$	$1.75 \sim 1.93$

NS cooling with Strangeness

Q) Can **NS EOS with strangeness** be consistent with
both **NS maximum mass & NS cooling**?

Neutron Star Cooling



depends on

- particle fraction
- elements in the envelope
- nuclear superfluidity
- … …

arXiv:1501.04397

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)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times10^{21}\, \mathcal{R}\, T_9^8$	Slow
Modified Urca (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, \mathcal{R}\, T_9^8$	Slow
Bremsstrahlung	$n+n \to n+n+\nu\bar{\nu}$ $n+p \to n+p+\nu\bar{\nu}$ $p+p \to p+p+\nu\bar{\nu}$	$\sim 10^{19}\, \mathcal{R}\, T_9^8$	Slow
Cooper pair formations	$n+n \to [nn]+\nu\bar{\nu}$ $p+p \to [pp]+\nu\bar{\nu}$	$\sim 5\times10^{21}\, \mathcal{R}\, T_9^7$ $\sim 5\times10^{19}\, \mathcal{R}\, T_9^7$	
Direct Urca	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\, \mathcal{R}\, T_9^6$	Fast
π^- condensate	$n+ < \pi^- > \to n+e^- + \bar{\nu}_e$	$\sim 10^{26}\, \mathcal{R}\, T_9^6$	Fast
K^- condensate	$n+ < K^- > \to n+e^- + \bar{\nu}_e$	$\sim 10^{25}\, \mathcal{R}\, T_9^6$	Fast

Cooling with strangeness

arXiv:1608.02078

$$\Lambda \to p + l + \bar{\nu}_l$$
$$p + l \to \Lambda + \nu_l \,,$$

$$Q_\Lambda = 4.0 \times 10^{27} \frac{m_\Lambda^* m_p^*}{m_\Lambda m_p} \left(\frac{n_e}{n_0}\right)^{1/3} R\, T_9^6 \times \Theta_t \,\mathrm{erg\,cm^{-3}\,s^{-1}}\,,$$

$$n + \langle K^- \rangle \to n + l + \bar{\nu}_l$$

$$Q_K = 2.5 \times 10^{26} \frac{m_n^{*2}}{m_n^2} \left(\frac{n_e}{n_0}\right)^{1/3} T_9^6\, \theta_K^2 \times \tan^2\theta_C \,\mathrm{erg\,cm^{-3}\,s^{-1}}\,,$$

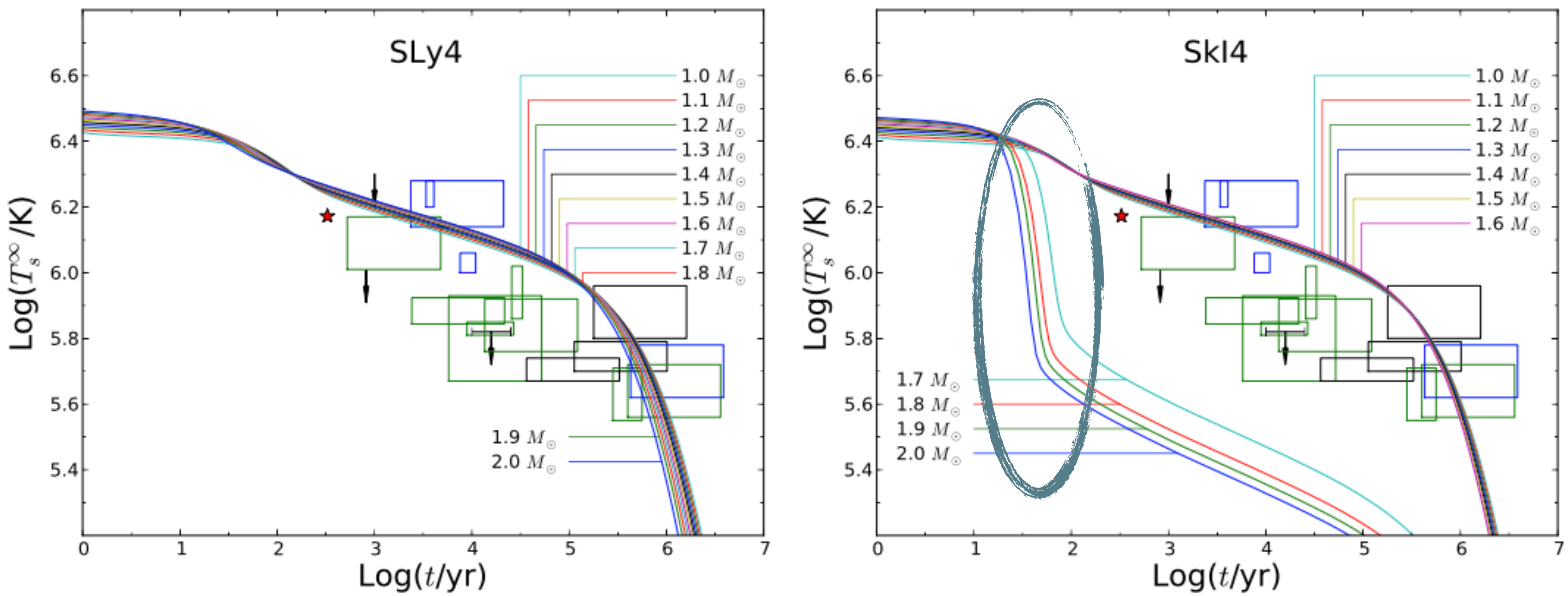
Role of nucleon direct Urca (without strangeness)

$$n \to p + e^- + \bar{\nu}_e$$

$$p + e^- \to n + \nu_e$$

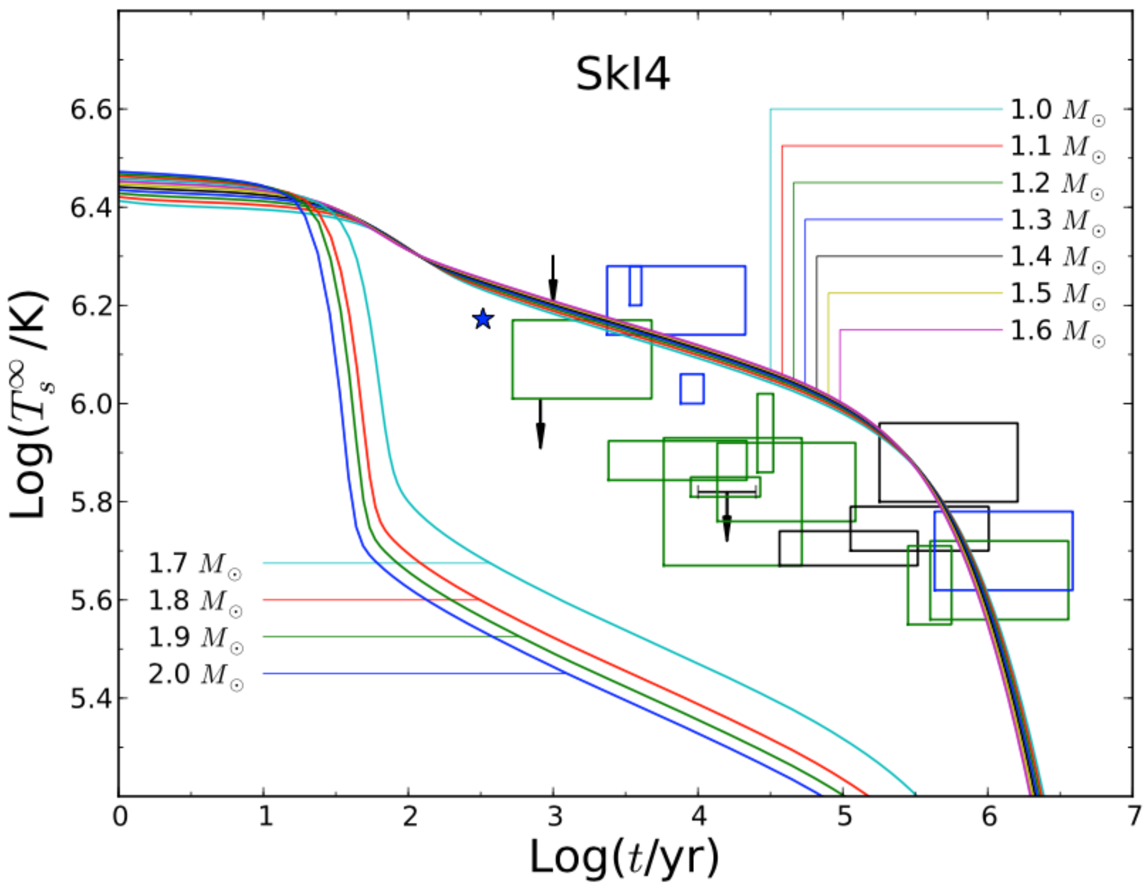
	SLy4	SkI4
$M_{\rm max}$	2.07 (-)	2.19 (1.63)

maximum mass without strangeness (critical mass for nucleon direct Urca)

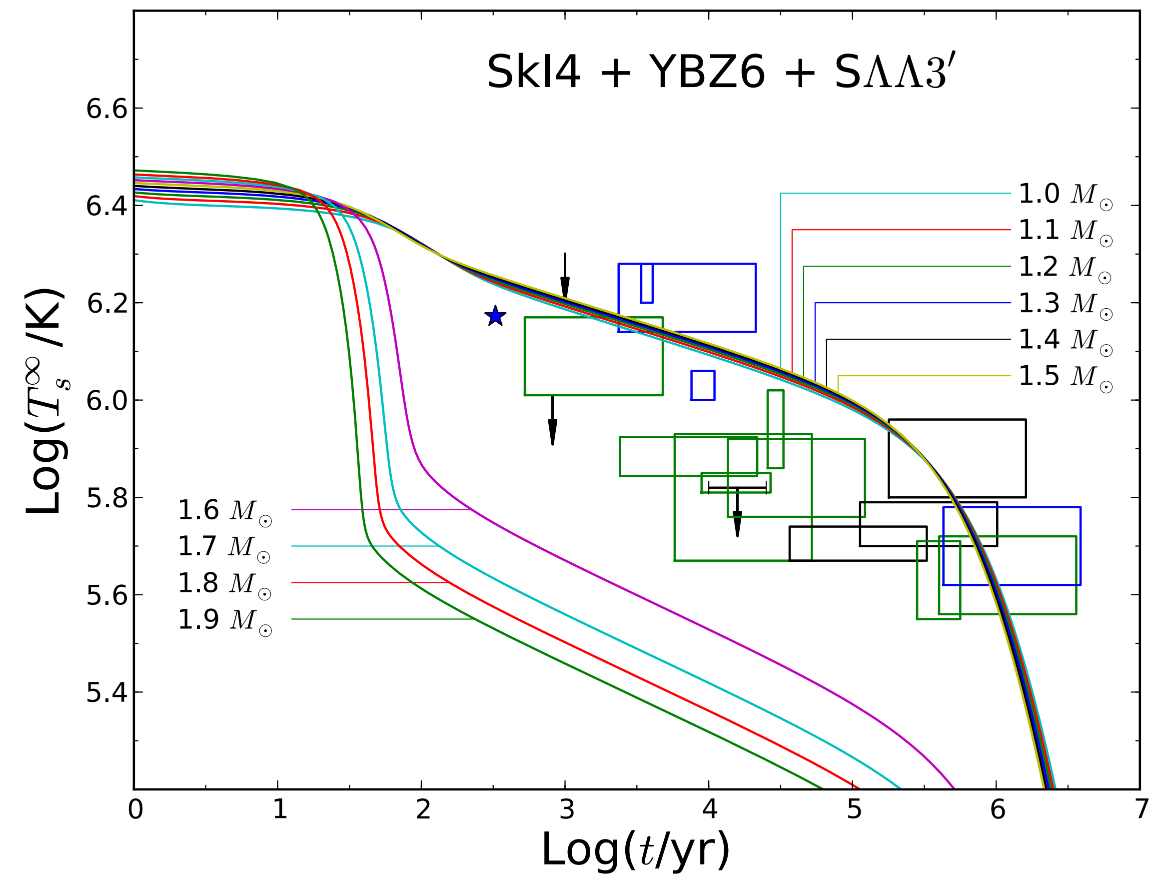


Without direct Urca **With direct Urca**

Cooling with hyperons (Skyrme force model **SkI4**)



without hyperons
(sudden drop between 1.6~1.7)



with hyperons
(sudden drop between 1.5~1.6)

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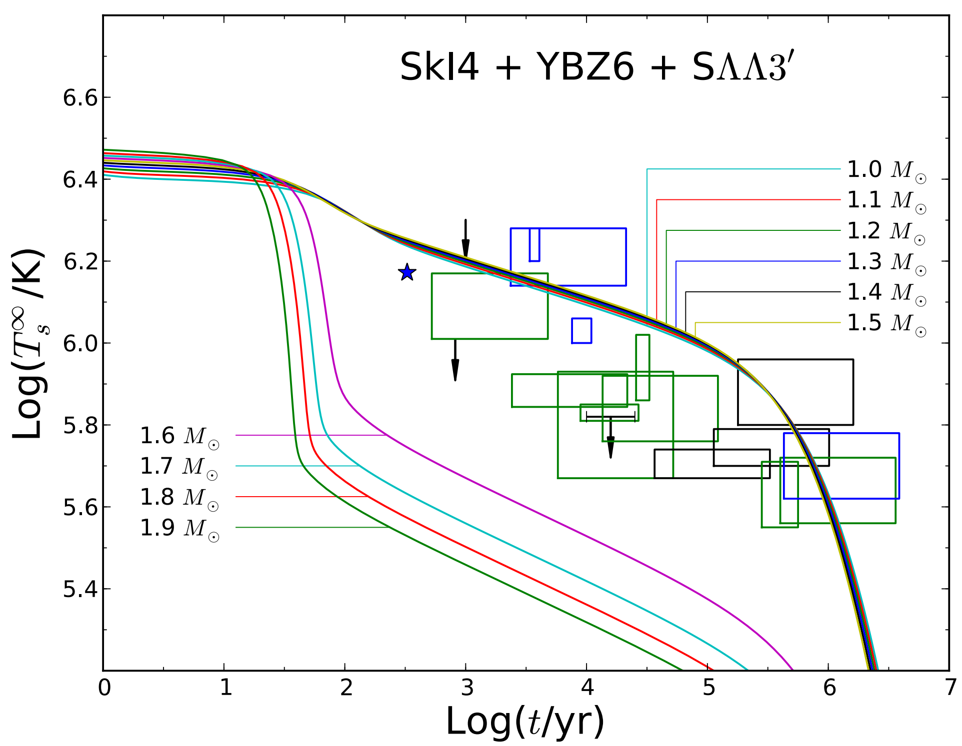
Cooling with hyperons



NS mass : 1.0 – 2.0 $M_\odot$

- abrupt drop: ingnition of direct URCA
- stiffer EoS allows early direct Urca
- no calculated-curve can explain middle-age data
- require real fine-tuning to explain the data

Sudden drop between 1.5~1.6

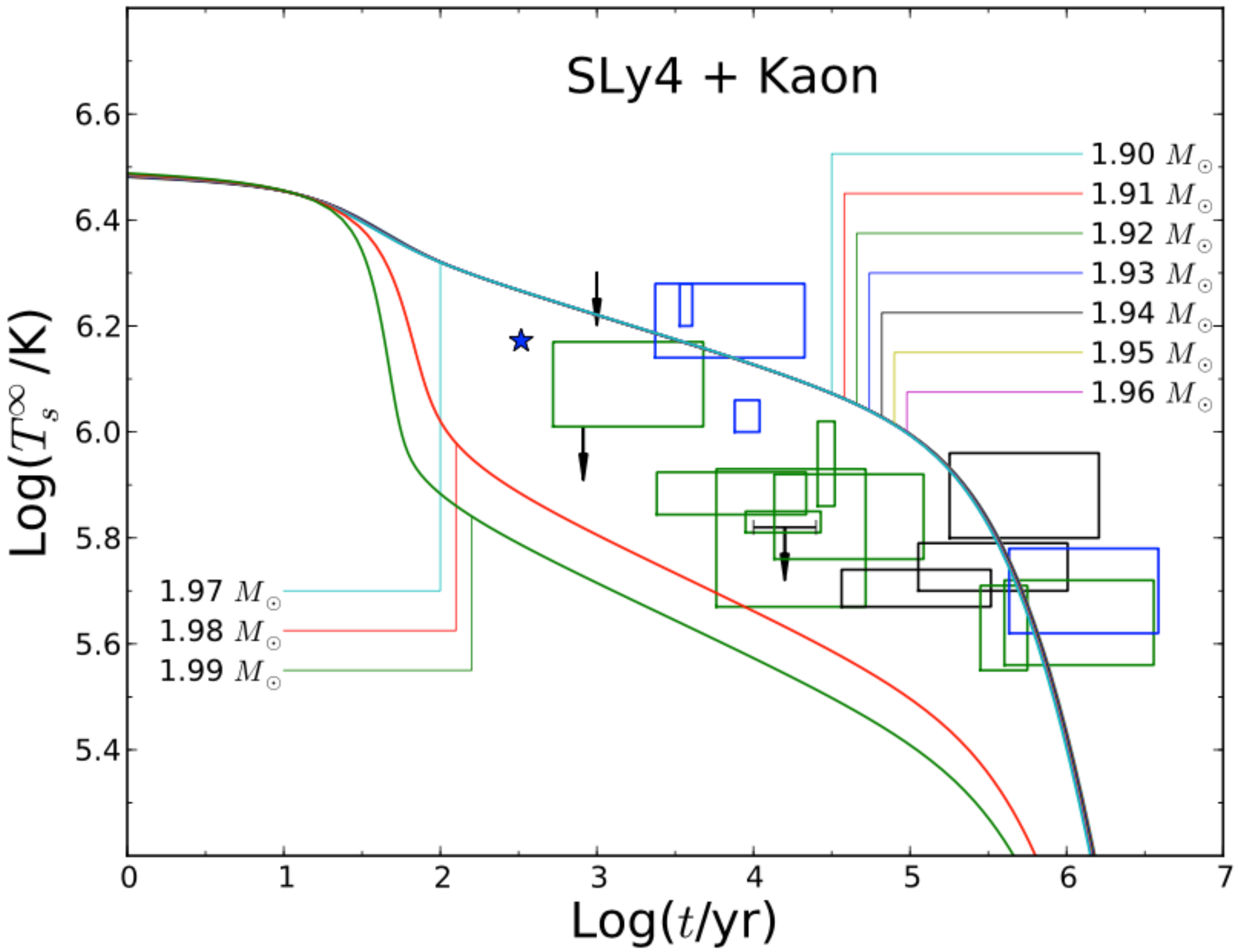
Q) Whether masses of all neutron stars with temperature estimation lie in such a narrow mass range?

with Yeunhwan Lim, Chang Ho Hyun

Negligible contribution with kaons

density for nucleon direct Urca < density for kaon condensation

Nucleon direct Urca is the dominant neutrino emission process



Discussion

- Strangeness in NS seems to be still alive.
- Cooling requires real fine tuning of the parameters in the theory.
- New observations (X-ray, GW, ..) & experiments (RAON in Korea, …) will be able to provide important clues for NS EOS.