# Rotating pulsar-like compact stars: the structure and implications

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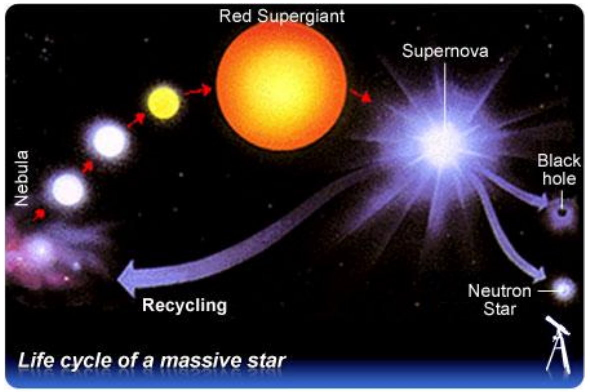
@DDF 2024 in Guiyang

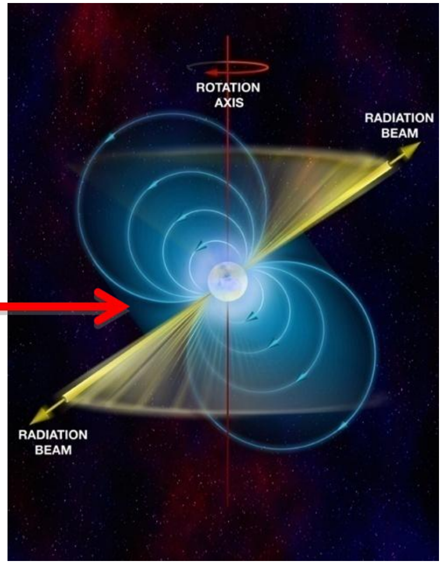
# Outline

- Introduction: strangeon stars
- EOS: massive and compact strangeon stars
- SSs as the remnants of BNS mergers: implications in short GRBs
- Summary

# "Neutron stars": a general name of pulsar-like compact stars

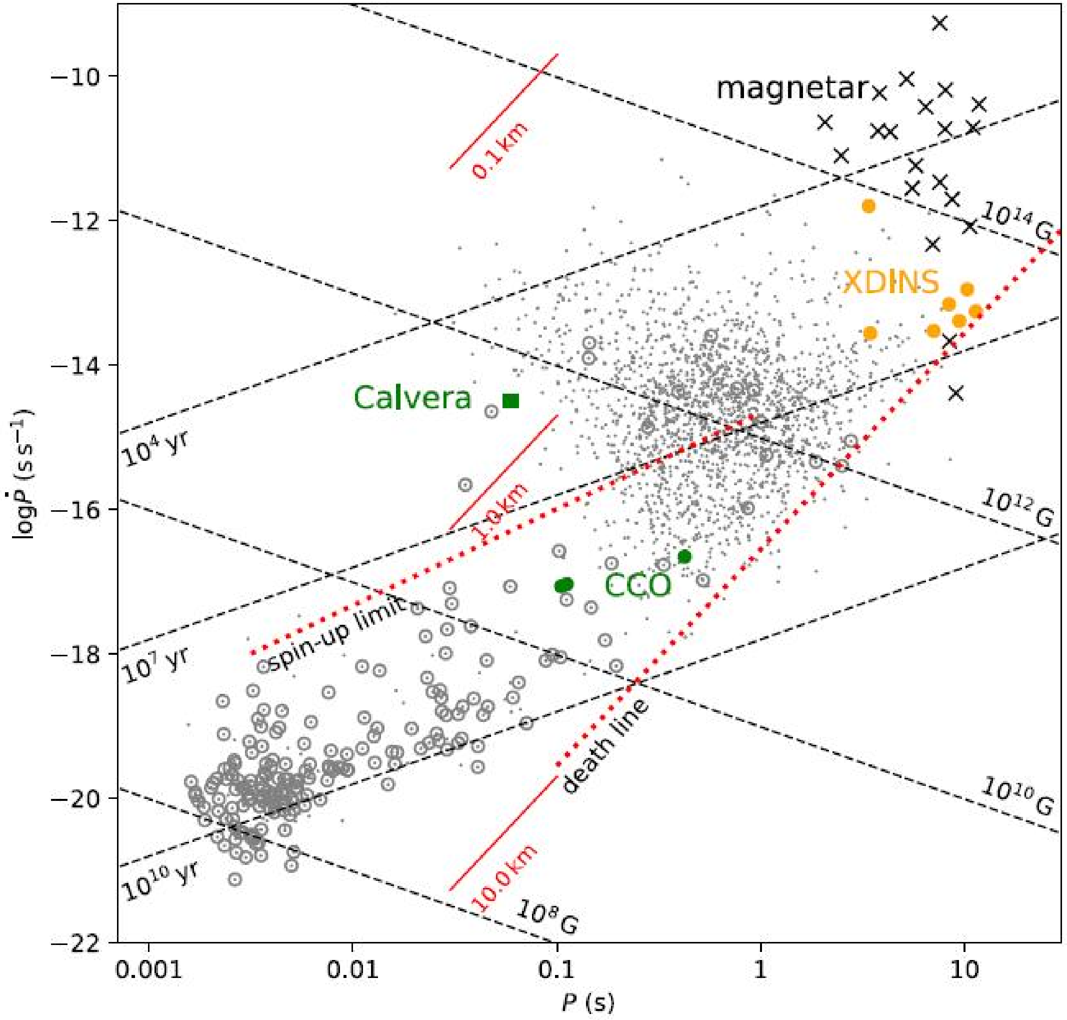



$M \sim 1.4\, M_{\odot}$ , $R \sim 10$ km




$$\bar{\rho} = \frac{M}{4\pi R^3/3} \simeq 2.4\rho_0$$

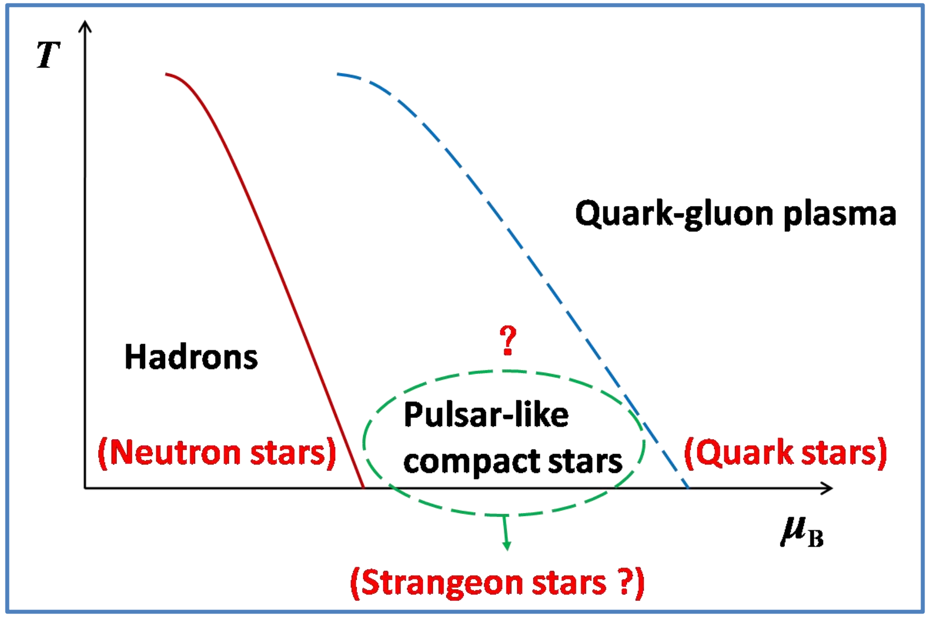
**( $\rho_0 \approx 2.8\times10^{14}$ g/cm³: saturated nuclear matter density)**

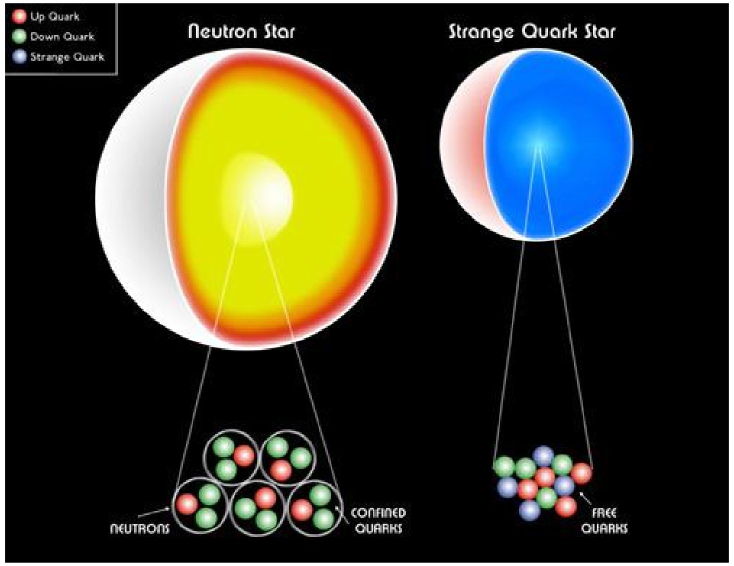


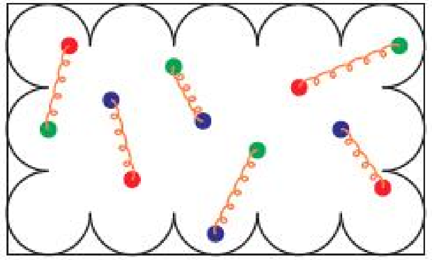

(Li et al. 2018)

# EoS of pulsars?

- **Components: hardons? quarks? others?**
- **Interactions: non-perturbative QCD!**

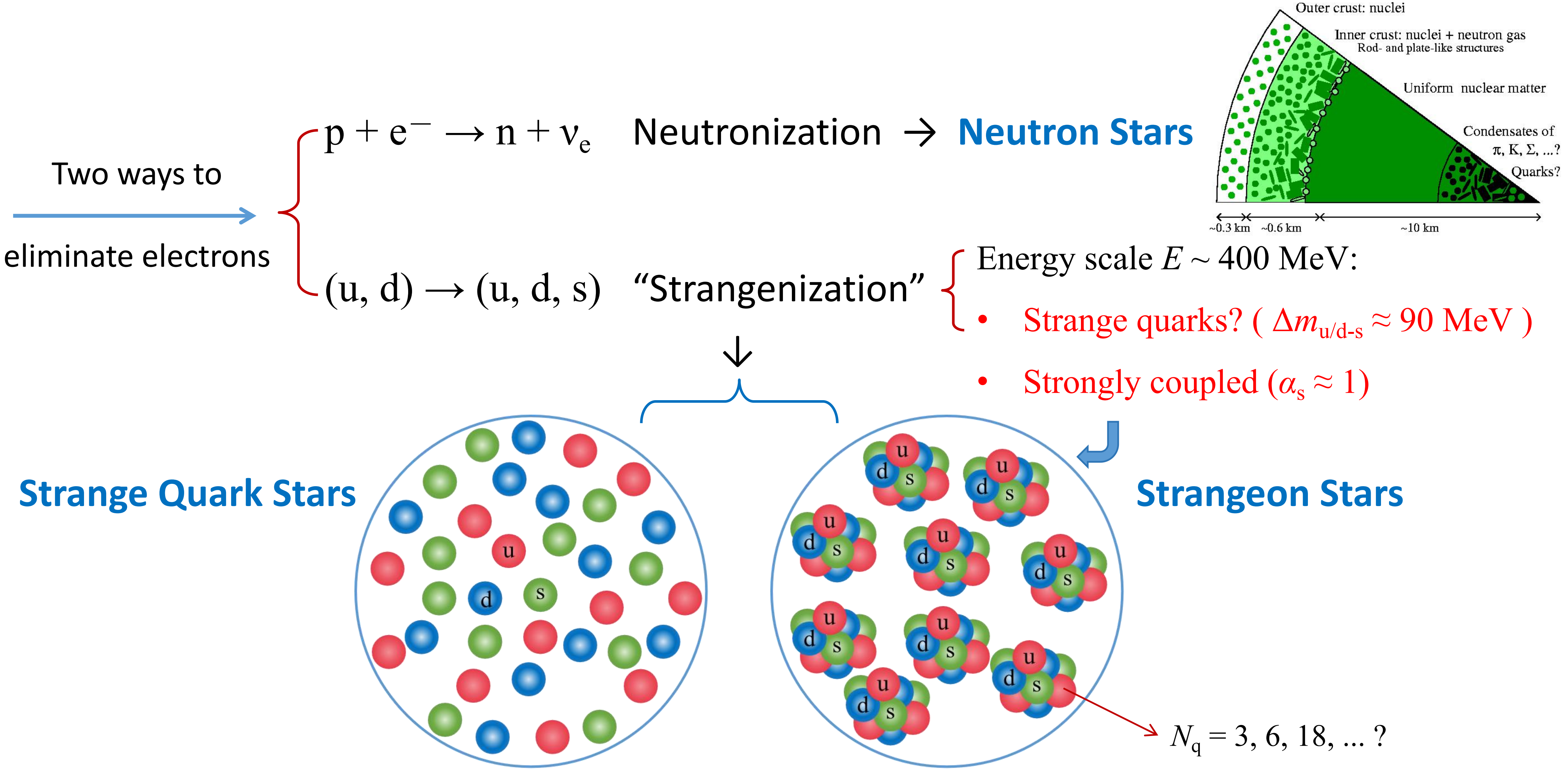


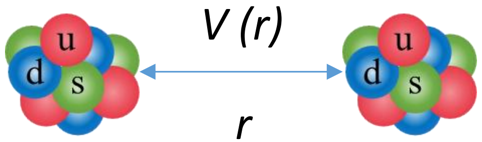
$$\alpha_S(q^2) \simeq \frac{4\pi}{9\ln(q^2/\Lambda^2)} \sim 1$$

$$\bar{\rho} = \frac{M}{4\pi R^3/3} \simeq 2.4\rho_0$$ **: Energy scale ~ 400 MeV > $m_{\text{strange quark}}c^2$**



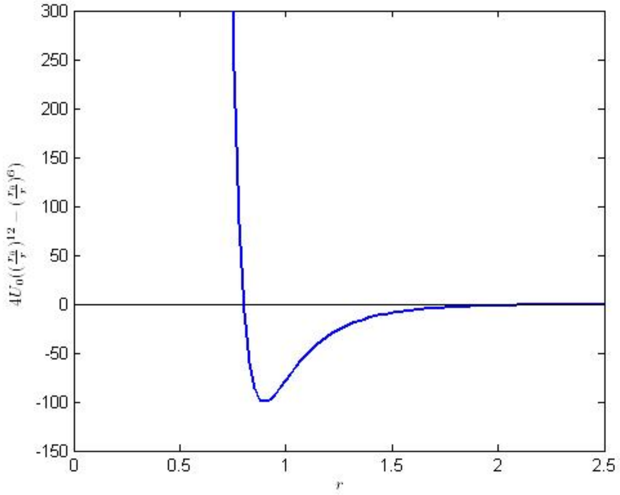
Two ways to
eliminate electrons
$p + e^- \rightarrow n + \nu_e$
Neutronization → Neutron Stars
Outer crust: nuclei
Inner crust: nuclei + neutron gas
Rod- and plate-like structures
Uniform nuclear matter
Condensates of
π, K, Σ, ...?
Quarks?
~0.3 km
~0.6 km
~10 km
$(u, d) \rightarrow (u, d, s)$
"Strangenization"
Energy scale $E \sim 400$ MeV:
Strange quarks? ( $\Delta m_{u/d\text{-}s} \approx 90$ MeV )
Strongly coupled ($\alpha_s \approx 1$)
Strange Quark Stars
u
d
s
Strangeon Stars
$N_q = 3, 6, 18, \ldots$ ?

# Strangeon-strangeon potential



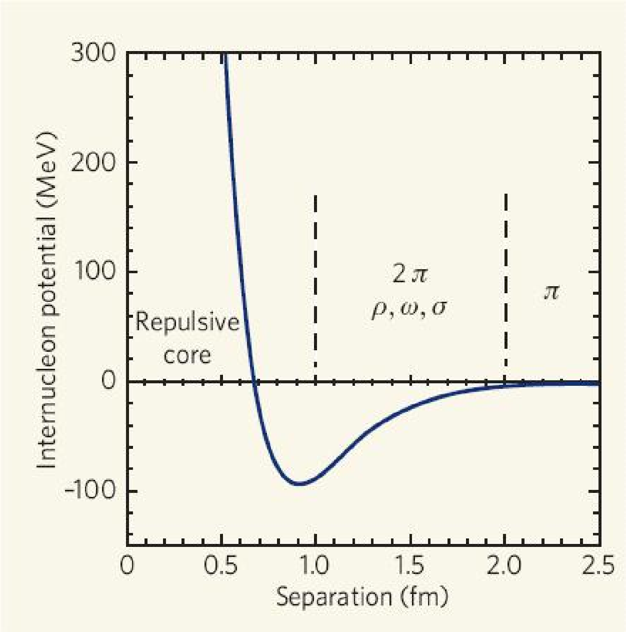

- Lennard-Jones model

$$V(r) = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6]$$ (Lai & Xu, 2009)




- Yukawa potential with meson coupling

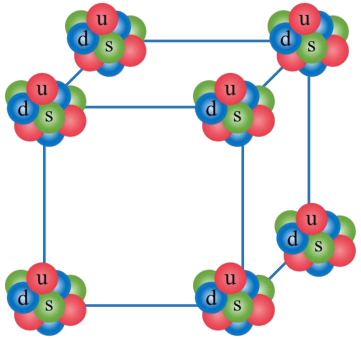
$$V(r) = \frac{g_{\omega H}^2}{4\pi}\frac{e^{-m_\omega r}}{r} - \frac{g_{\sigma H}^2}{4\pi}\frac{e^{-m_\sigma r}}{r}$$ (Lai, Gao & Xu, 2013)




Empirical form of nucleon-nucleon potential (Wilczek, 2007)

# EoS

$$V(r) \to \epsilon = \epsilon(n) \to P = P(n)$$



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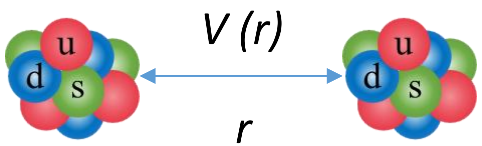


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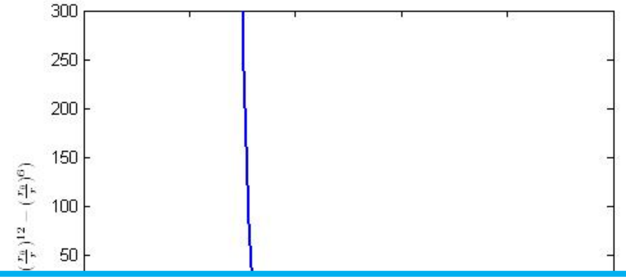


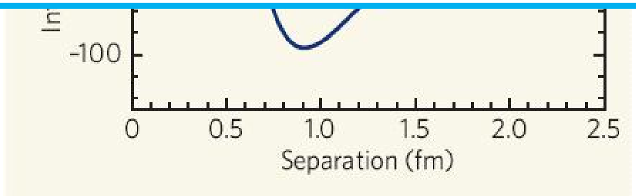


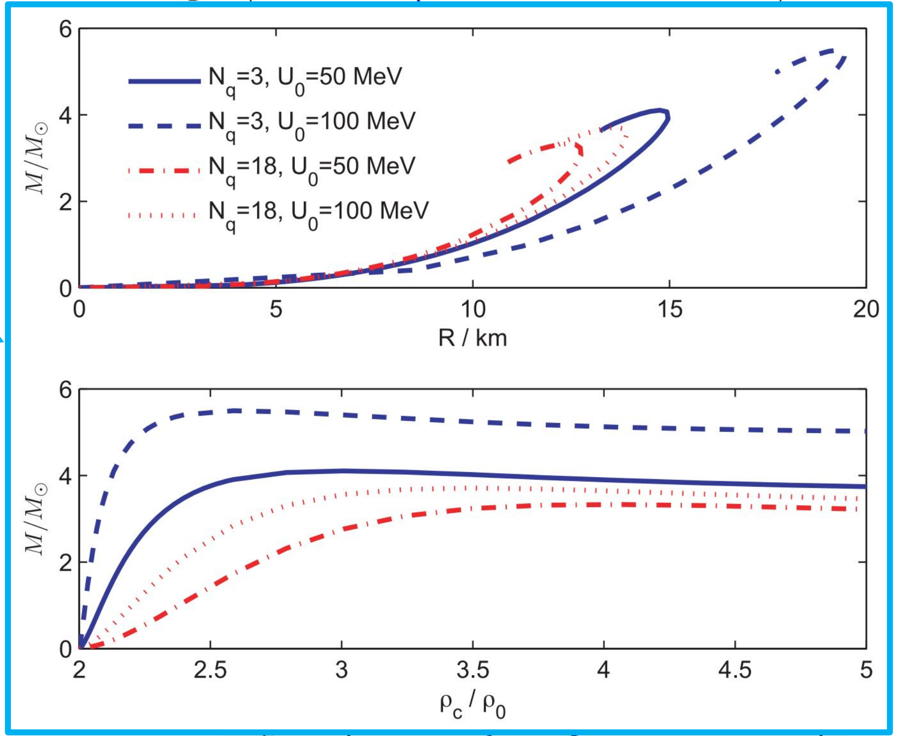


# EoS

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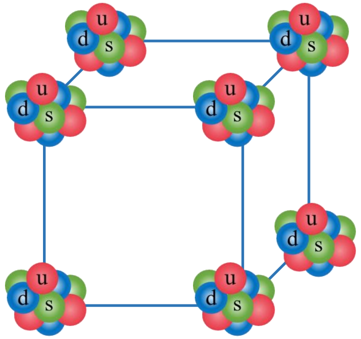
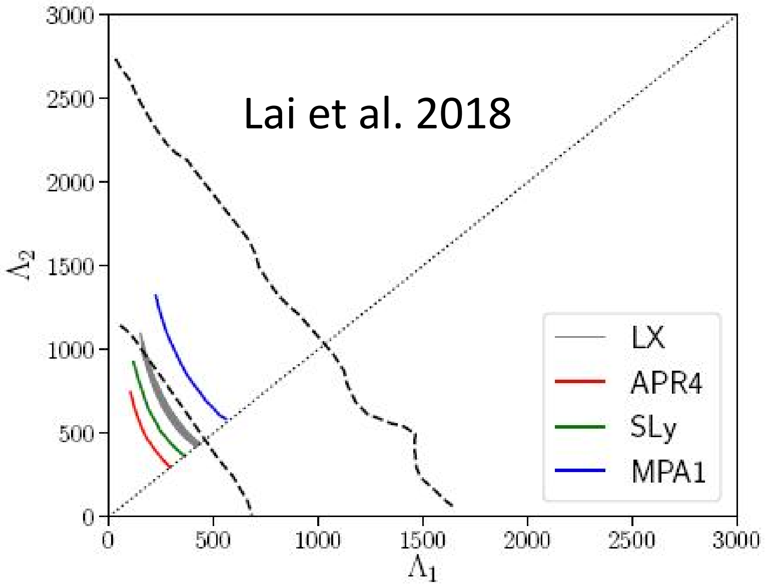


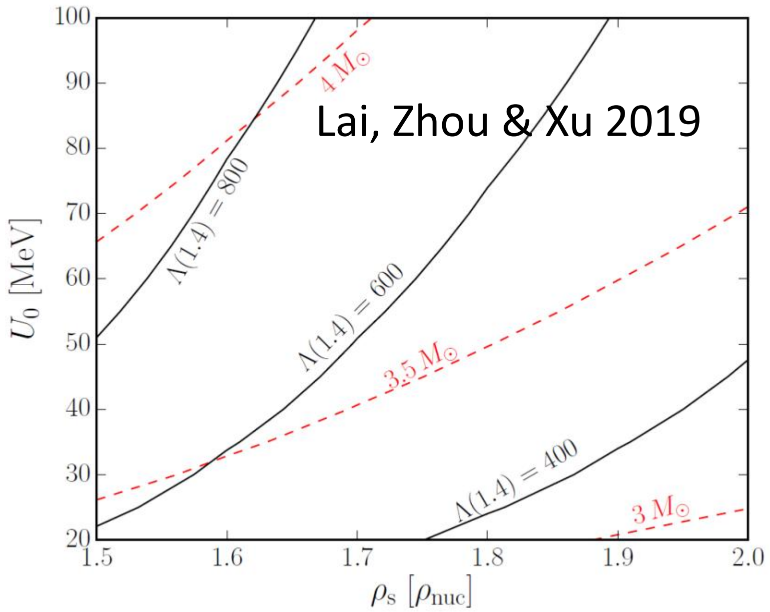

Empirical form of nucleon-nucleon potential (Wilczek, 2007)

# Tidal deformability of SSs

Strangeon star model passes ***dynamical*** test of $\Lambda$

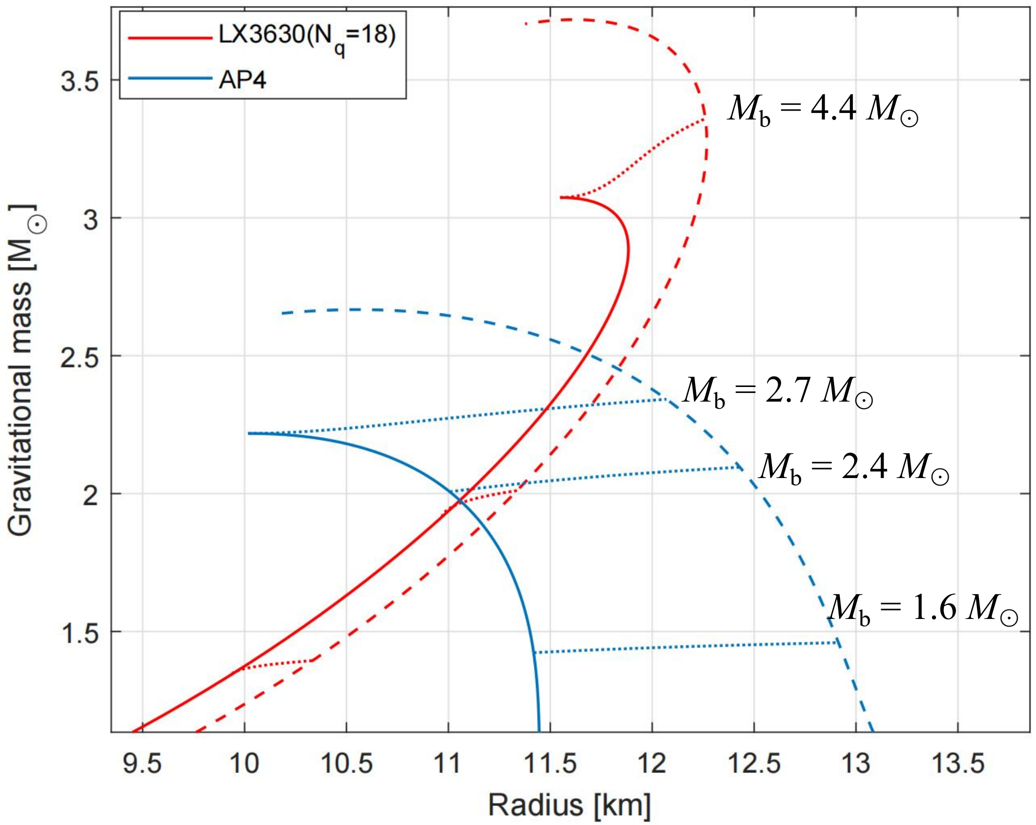
- Most of EoS parameters satisfy the constraint of GW170817
- The minimal Λ(1.4) is ~ 280 with $M_{\rm TOV}$ ~ 2.9$M_\odot$
- High-mass strangeon stars could still pass the test of GWs



# NS/SS under rigid rotation (*in the slow-rotation approximation*)

- Along the constant baryonic mass lines, the increases of $M_{max}$ for SSs are more pronounced than that for NSs.
- The shrinkage of an NS/SS during spin-down can lead to the release of gravitational energy.



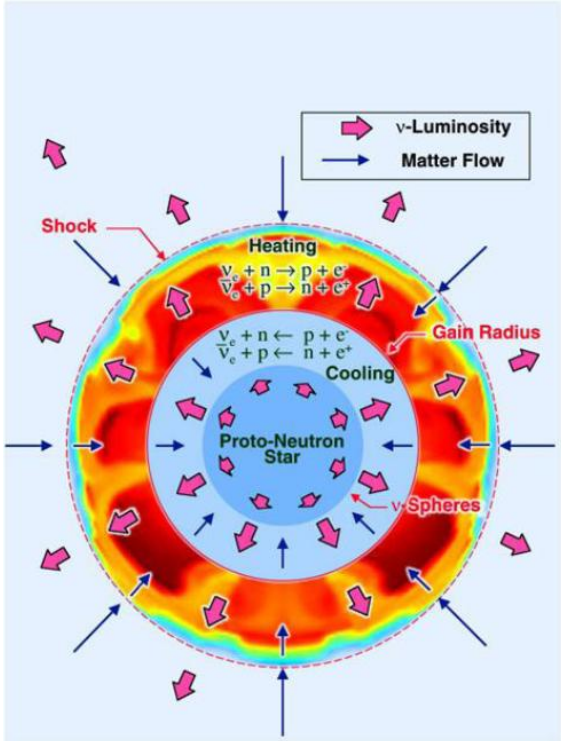

(Yang et al. 2024)

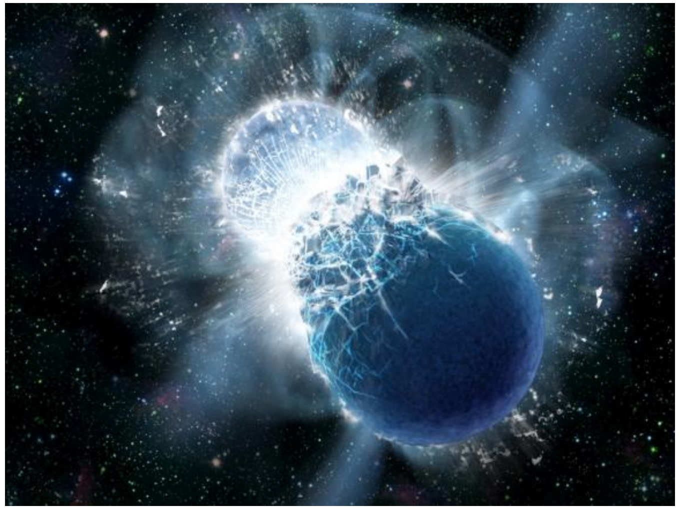
# SSs as the remnants of BNS mergers

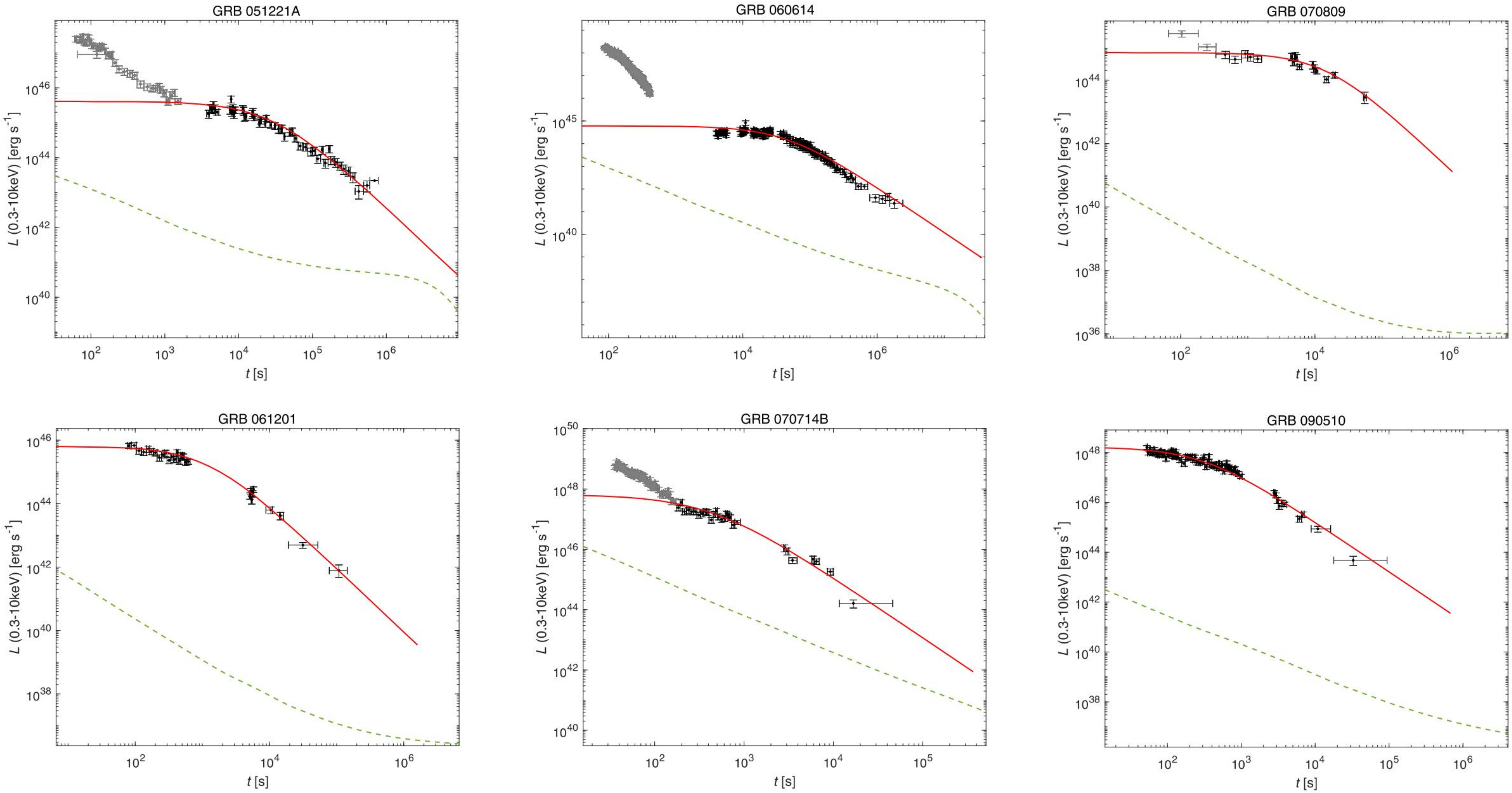
- Because $M_{\mathrm{TOV}}$ values are high for SSs, the remnants of the BNS mergers would probably be even long-lived.
- During spin-down after merger, the decrease of radius of the remnant will lead to the release of gravitational energy.
- Can the released gravitational energy provide the energy source for the X-ray plateau in the afterglow of short GRBs ?

# Why we consider short GRBs?

- A CCSN has a hot and dense envelope surrounding the newborn NS/SS, which would make it difficult for the gravitational energy to be taken out.
- A BNS remnant would have a cleaner environment, so gravitational energy would have chance to be taken away.
- The mass of the remnant $M \sim 2.36\ M_{\odot}$ .






(Yang et al. 2024)

- The magnetic dipole field strength $B_\mathrm{p}$ of the remnants in our scenario can be much smaller than that in the magnetar scenario (when the plateau emission is powered only by spin-down luminosity of magnetars).

The efficiency of converting the $L_{\mathrm{grav}}$ to the observed $L_{\mathrm{X}}$

| SGRB | $B_p$ ($10^{15}$ G) | $P_0$ (ms) | $\eta_{\mathrm{g}}$ | $\chi^2$/d. o. f. | $B_p$ ($10^{15}$ G) | $\chi^2$/d. o. f. |
|---|---|---|---|---|---|---|
| 051221A | $1.69^{+0.19}_{-0.34}$ | $5.29^{+0.63}_{-1.06}$ | $0.69^{+0.18}_{-0.25}$ | 1.1017 | $10.4 \pm 0.9$ | 1.3213 |
| 060614 | $0.88^{+0.13}_{-0.13}$ | $3.33^{+0.51}_{-0.50}$ | $0.11^{+0.04}_{-0.03}$ | 1.9674 | $15.6 \pm 0.5$ | 1.0821 |
| 061201 | $4.17^{+0.54}_{-0.90}$ | $2.60^{+0.34}_{-0.54}$ | $0.14^{+0.04}_{-0.05}$ | 1.2937 | $20.6 \pm 1.5$ | 1.2417 |
| 070714B | $8.73^{+1.31}_{-2.04}$ | $3.23^{+0.50}_{-0.75}$ | $0.58^{+0.19}_{-0.24}$ | 2.1809 | $36.9 \pm 4.0$ | 1.9500 |
| 070809 | $4.98^{+0.80}_{-1.20}$ | $10.94^{+1.53}_{-2.58}$ | $0.63^{+0.21}_{-0.26}$ | 1.1828 | $5.8 \pm 1.1$ | 1.2615 |
| 090510 | $6.40^{+0.86}_{-1.52}$ | $2.05^{+0.28}_{-0.48}$ | $0.25^{+0.07}_{-0.11}$ | 1.9234 | $11.6 \pm 0.5$ | 1.1914 |

(Yang et al. 2024) (Stratta et al. 2018)

# Summary

- Pulsar-like compact stars could be strangeon stars.
- Most of EoS parameters satisfy the constraint of GW170817.
- Strangeon stars as the remnants of the BNS mergers would be even long-lived, and the released gravitational energy could provide an alternative energy source for the X-ray plateau in the afterglow of short GRBs.

***Thank you !***