# Constraints of the maximum mass of quark stars based on post-merger evolutions

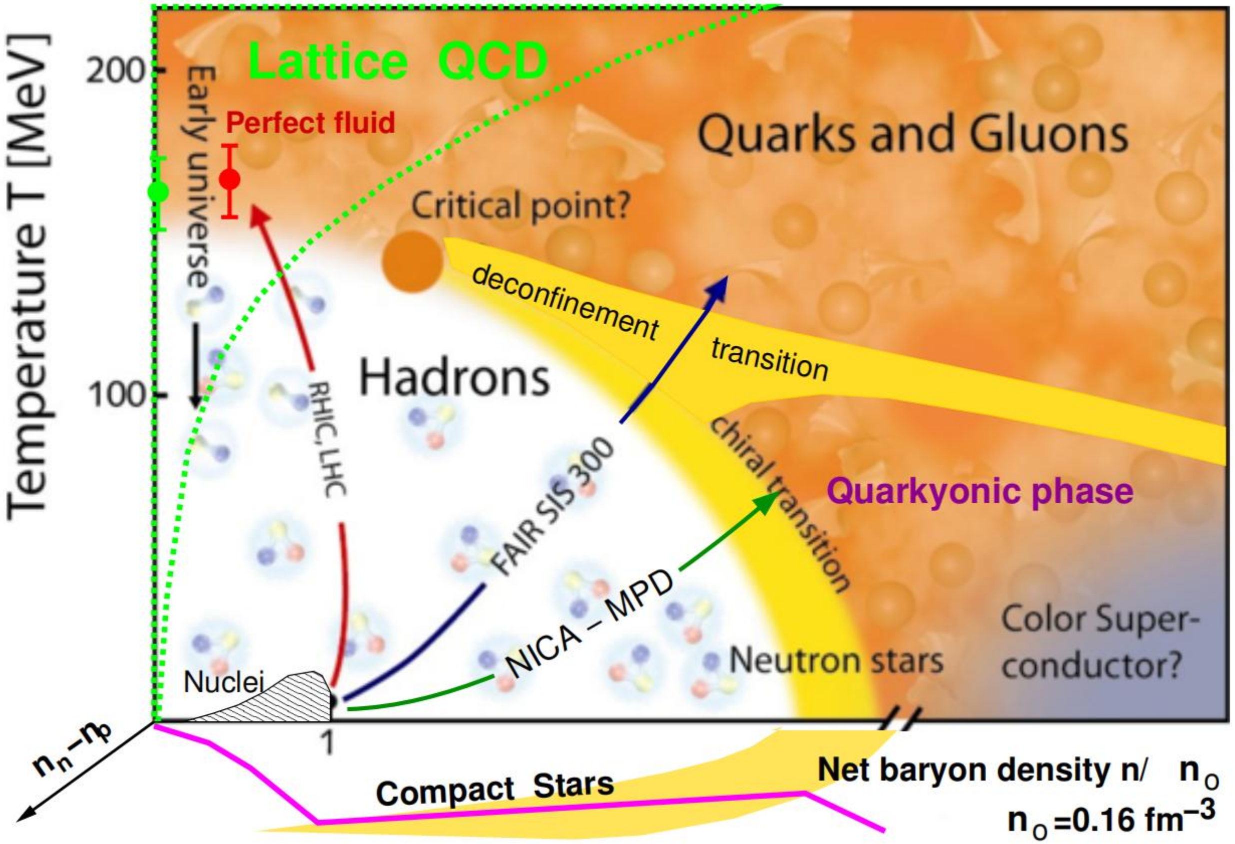
**Yurui Zhou (HUST)**

arXiv: 2407.08544

Collaborated with Chen Zhang, Junjie Zhao, Kenta Kiuchi, Sho Fujibayashi and
**Enping Zhou**

**@FPS 13 in Kunming**

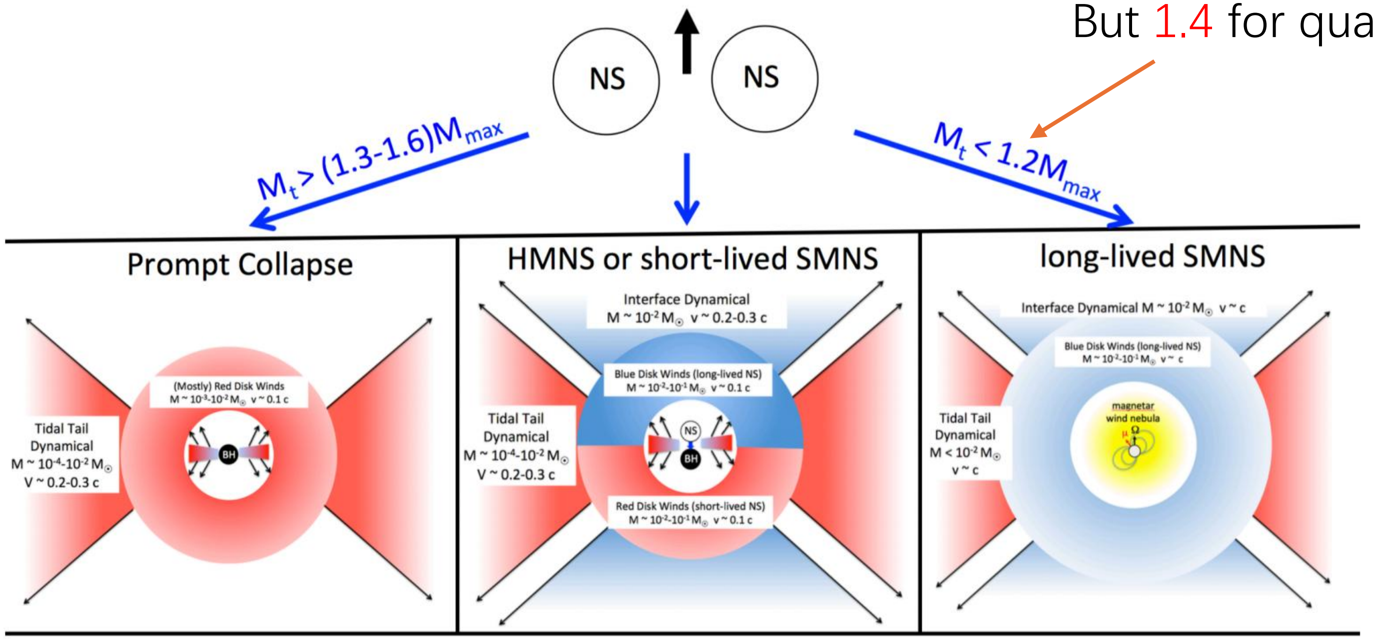
# QCD Phase Diagram




McLerran 2009

# Post-merger Pictures for Neutron/Quark Stars

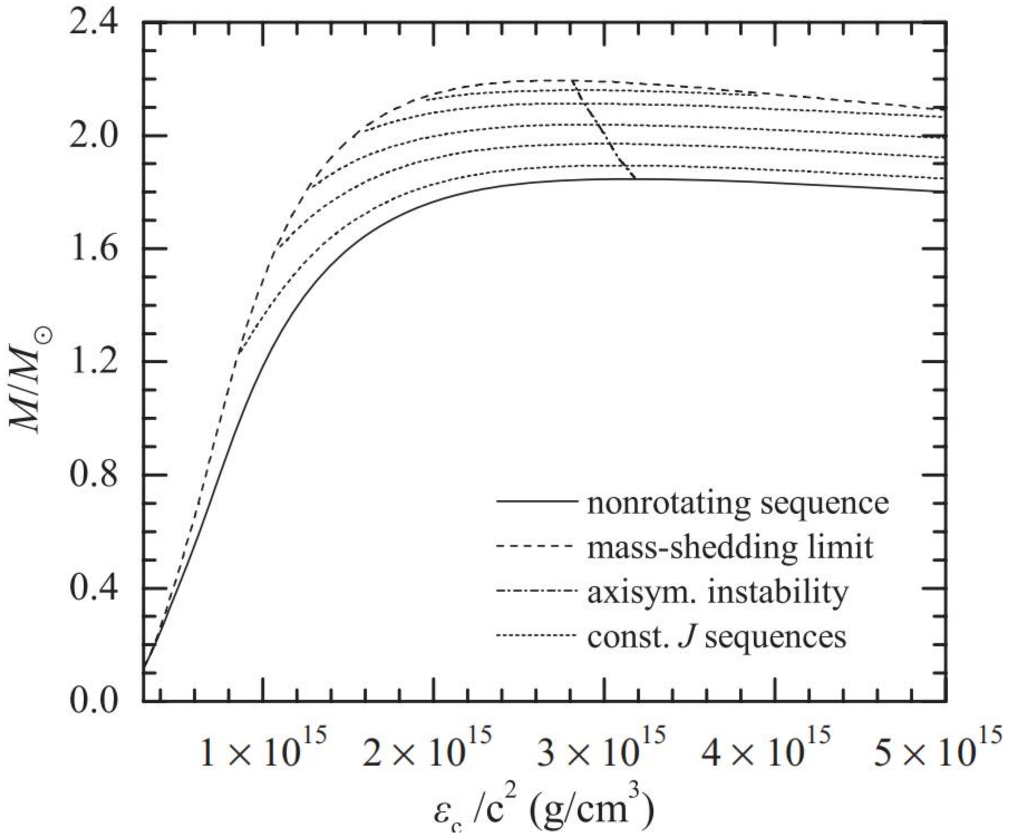
But 1.4 for quark stars



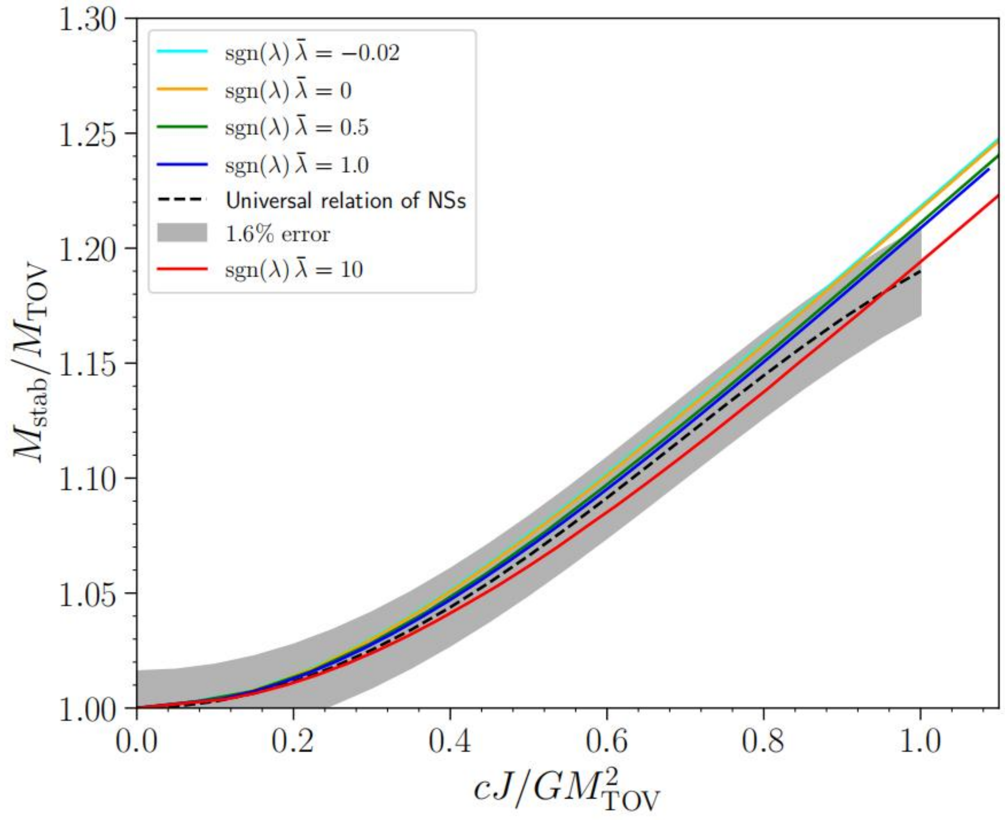

Margalit & Metzger 2017

The maximum mass for a supramassive remnant is about 1.2 $M_{\rm TOV}$ for neutron stars but 1.4 for quark stars. How does it affect the Post-merger pictures? Can a supramassive quark star collapse in a short timescale? Analysis for angular momentum dissipation is needed!

# Model the Remnant Rotating Quark Stars




Turning point criterion (Friedman, Ipser, and Sorkin 1988)




The relation is similar for neutron stars and quark stars

# Dissipation Mechanisms in the Inspiral Phase

**In this phase, Energy and angular momentum are mainly dissipated by gravitational waves.**

$$J_{\mathrm{merger}} = J_0 - J_{\mathrm{GW,i}}$$

$$M_{\mathrm{merger}} = M_0 - E_{\mathrm{GW,i}}$$

$$E_{\mathrm{GW,i}} = \frac{1}{16\pi} \sum_{(\ell,m)} \int_{t_0}^{t_{\mathrm{merger}}} dt' r^2 \dot{h}_{\ell m}(t') \dot{h}^*_{\ell m}(t')$$

$$J_{\mathrm{GW,i}} = \frac{1}{16\pi} \sum_{(l,m)} \int_{t_0}^{t_{\mathrm{merger}}} dt' m \Im[r^2 h_{lm}(t') \dot{h}^*_{lm}(t')]$$

| EOS, references | $M_1$ | $M_2$ | $J^{\mathrm{EOB}}_{\mathrm{merger}}$ | $J^{\mathrm{NR}}_{\mathrm{merger}}$ | $J^{\mathrm{empirical}}_{\mathrm{merger}}$ |
|---|---|---|---|---|---|
| DD2, [77, 78] | 1.4 | 1.2 | 5.904 | 5.996 | 5.944 |
| | 1.365 | 1.25 | 5.981 | 6.066 | 6.154 |
| | 1.35 | 1.35 | 6.33 | 6.379 | 6.633 |
| | 1.44 | 1.39 | 6.853 | 6.888 | 7.274 |
| SFHo, [79] | 1.4 | 1.2 | 5.699 | 5.726 | 5.807 |
| | 1.365 | 1.25 | 5.773 | 5.792 | 6.010 |
| | 1.35 | 1.35 | 6.101 | 6.109 | 6.478 |
| | 1.44 | 1.39 | 6.595 | 6.615 | 7.104 |

The relative error is reduced from **5%** to **1%**

The gravitational waveform can be calculated by accurate waveform models like SEOBNRv4T, TEOBResumS, NRTidalv3, etc.

# Dissipation Mechanisms in the Post-merger Phase

- **Three** main dissipation mechanisms: **mass outflows, neutrinos, and gravitational waves**.
- **Three** conservation equations: **energy, angular momentum, and baryon number**.
- Different mechanisms have different tendencies.

$$J_{\mathrm{GW,p}} \approx \frac{E_{\mathrm{GW,p}}}{\pi f_{\mathrm{peak}}} \approx 9.5 \times 10^{48}\,\mathrm{erg\,s} \left(\frac{E_{\mathrm{GW,p}}}{0.05\,M_{\odot}}\right) \left(\frac{f_{\mathrm{peak}}}{3.0\,\mathrm{kHz}}\right)^{-1}$$

$$J_{\mathrm{out}} \approx 5.8 \times 10^{48}\,\mathrm{erg\,s} \left(\frac{M_{\mathrm{out}}}{0.05\,M_{\odot}}\right) \left(\frac{R_{\mathrm{out}}}{100\,\mathrm{km}}\right)^{1/2} \times \left(\frac{M_{\mathrm{MQS}}}{2.6\,M_{\odot}}\right)^{1/2},$$

$$J_{\nu} \approx 3.0 \times 10^{48}\,\mathrm{erg\,s} \left(\frac{E_{\nu}}{0.1\,M_{\odot}c^2}\right) \left(\frac{R_{\mathrm{MQS}}}{15\,\mathrm{km}}\right)^{2} \times \left(\frac{\Omega}{10^4\,\mathrm{rad/s}}\right),$$

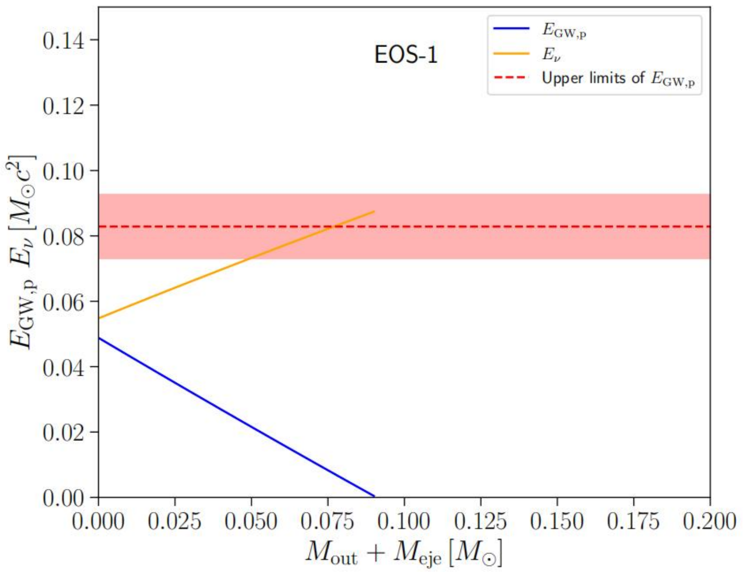
Therefore, in principle, we can determine the amount of dissipation of the three dissipation mechanisms via the three conservation equations, equivalent to solving a linear system with three unknowns.

# Main Results

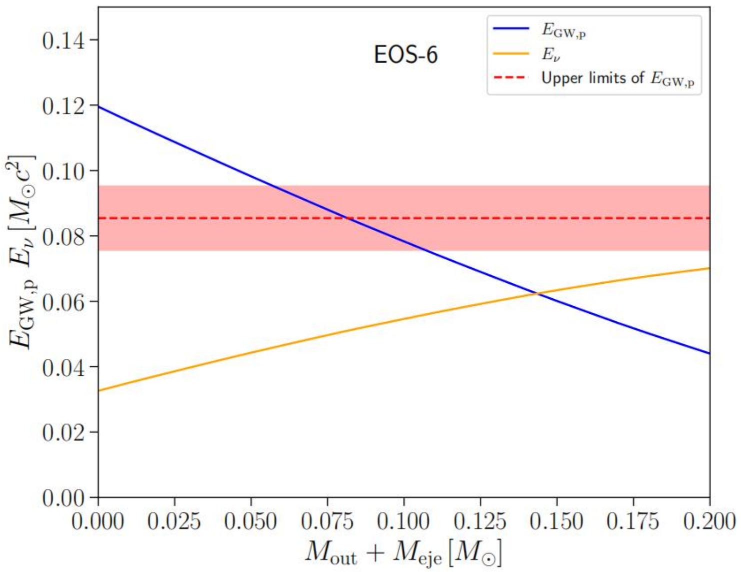
Upper bound for gravitational waves （Zappa et al. 2018）

$$E_{\rm GW} := E_{\rm GW,i} + E_{\rm GW,p} \lesssim 0.13 \pm 0.01\, M_\odot c^2 \left(\frac{M}{2.8\, M_\odot}\right).$$

$M_{\rm TOV} \approx 2.011\, M_\odot$

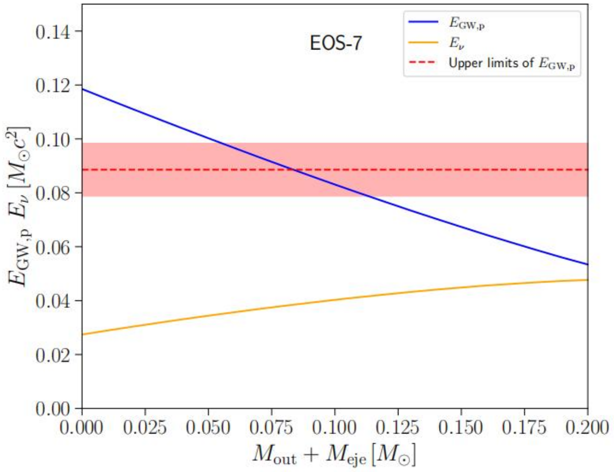



$M_{\rm TOV} \approx 2.254\, M_\odot$

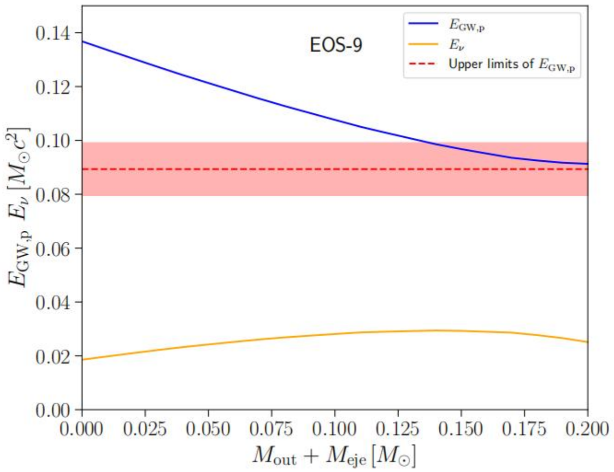


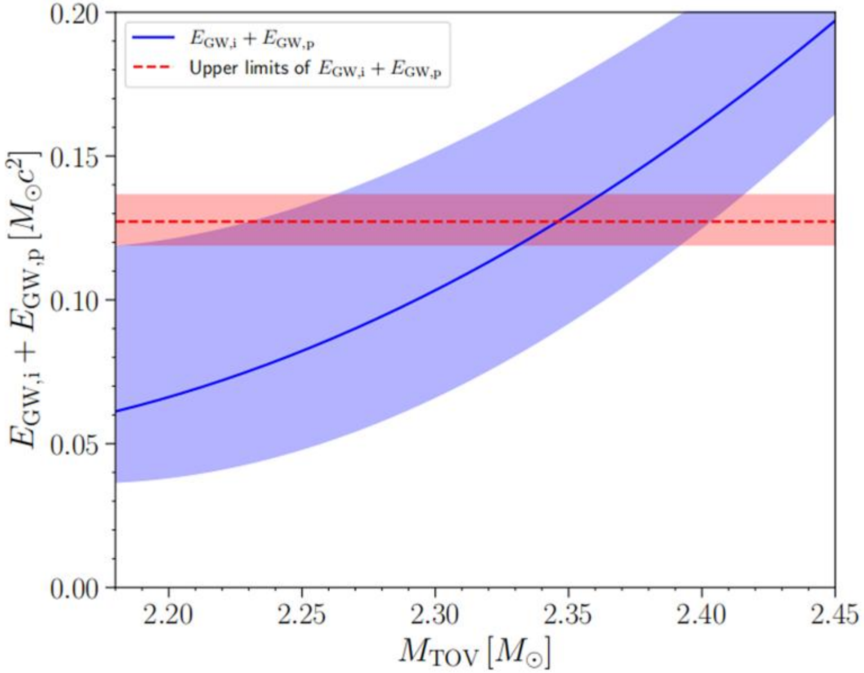
# Main Results

$$M_{\mathrm{TOV}} \approx 2.284\, M_{\odot}$$




$$M_{\mathrm{TOV}} \approx 2.350\, M_{\odot}$$

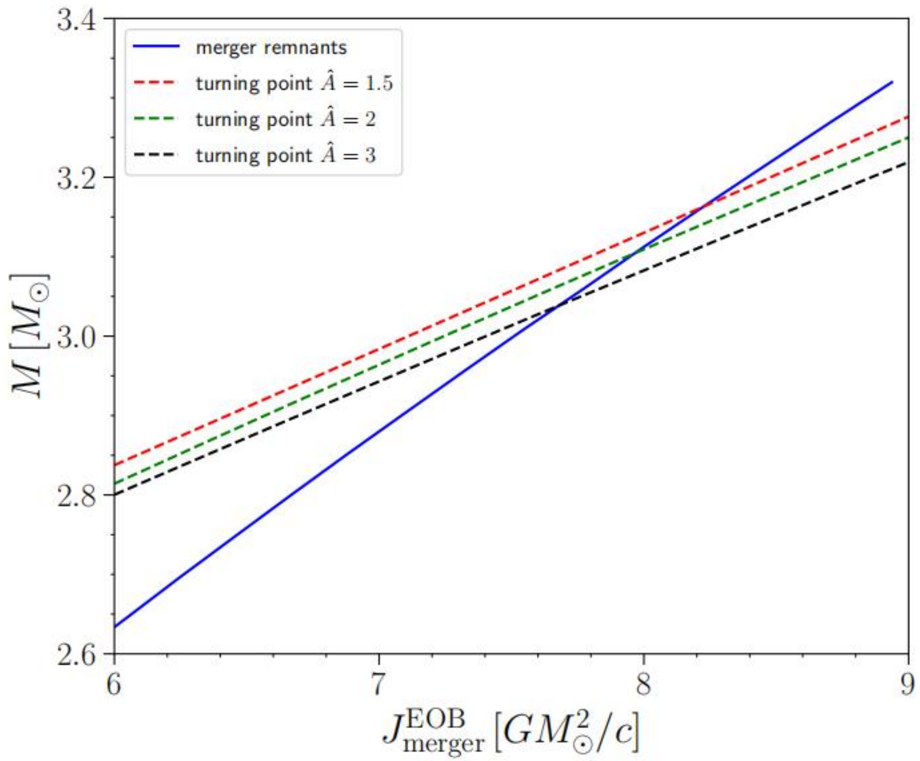



Considering the main uncertainties in our analysis, the constraint can be set as:

$$M_{\mathrm{TOV}} \lesssim 2.35^{+0.07}_{-0.17}\, M_{\odot}$$

# Threshold Mass for Prompt Collapse




$M_{\rm thres} \approx 3.10^{+0.06}_{-0.06}\, M_\odot$ about 2% differ from NR simulations $M_{\rm thres} \approx 3.075^{+0.025}_{-0.025}\, M_\odot$

# Joint Constraints on the Parameter Space

**Reparametrization (Zhang & Mann 2021):**

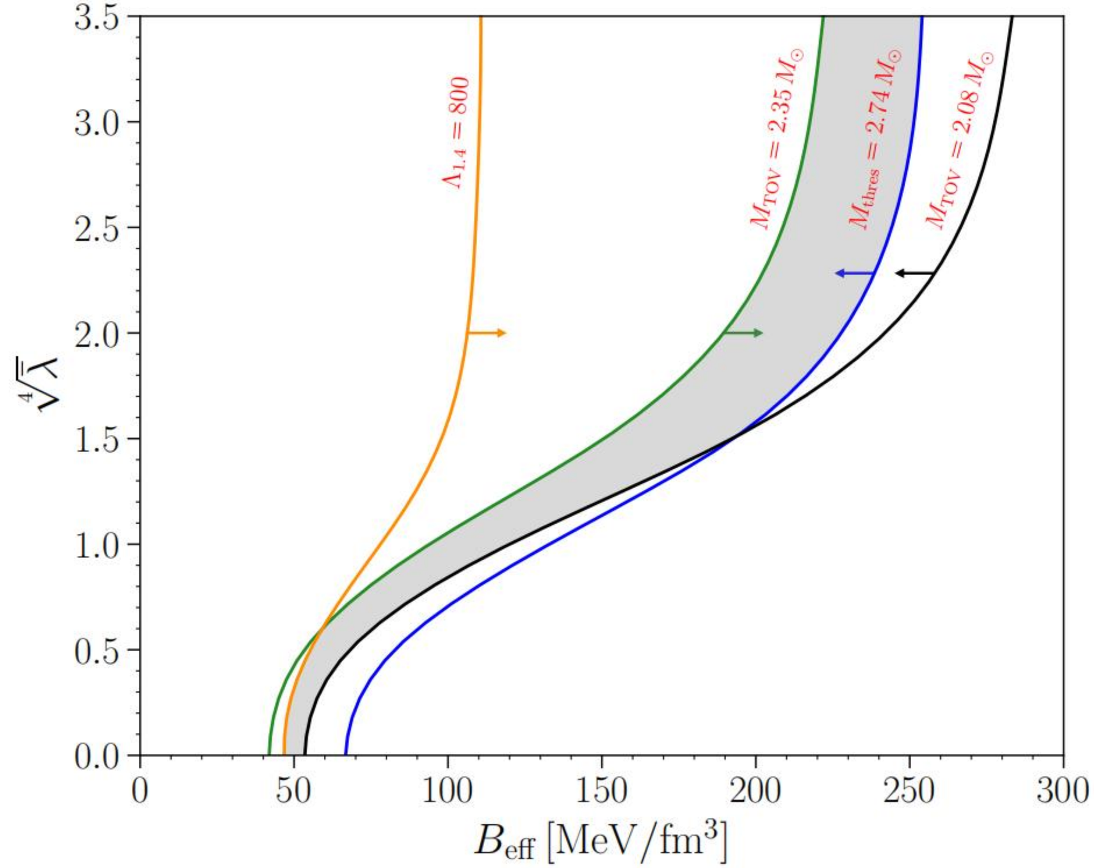
$$\lambda = \frac{\xi_{2a}\Delta^2 - \xi_{2b} m_s^2}{\sqrt{\xi_4 a_4}} \qquad (\xi_4, \xi_{2a}, \xi_{2b}) = \begin{cases} (((\frac{1}{3})^{\frac{4}{3}} + (\frac{2}{3})^{\frac{4}{3}})^{-3}, 1, 0) & \text{2SC phase} \\ (3, 1, 3/4) & \text{2SC+s phase} \\ (3, 3, 3/4) & \text{CFL phase} \end{cases}$$

$$p = \frac{1}{3}(\rho - 4B_{\rm eff}) + \frac{4\lambda^2}{9\pi^2}\left(-1 + \text{sgn}(\lambda)\sqrt{1 + 3\pi^2\frac{(\rho - B_{\rm eff})}{\lambda^2}}\right)$$

**Rescaling:**

$$\bar{\lambda} = \frac{\lambda^2}{4B_{\rm eff}} = \frac{(\xi_{2a}\Delta^2 - \xi_{2b} m_s^2)^2}{4\, B_{\rm eff}\,\xi_4 a_4} \qquad \bar{\rho} = \frac{\rho}{4\, B_{\rm eff}},\ \bar{p} = \frac{p}{4\, B_{\rm eff}}$$

$$\bar{p} = \frac{1}{3}(\bar{\rho} - 1) + \frac{4}{9\pi^2}\bar{\lambda}\left(-1 + \text{sgn}(\lambda)\sqrt{1 + \frac{3\pi^2}{\bar{\lambda}}(\bar{\rho} - \frac{1}{4})}\right)$$




**EOS can be completely governed by** $(\text{sgn}(\lambda)\,\bar{\lambda}, B_{\rm eff})$

# Summary

- A supramassive quark star can collapse to a black hole in a short timescale because the angular momentum left in it is not large enough to reach the mass shedding limit.
- The mass-gap object can not be consistently explained by quark stars after considering the constraint from the electromagnetic counterparts of GW170817.
- Our analysis can connect the multi-messenger observations and with the future observations of neutrinos and post-merger gravitational waves constraints for EOSs can be better imposed.

**Thanks!**