# Dense QCD and compact stars

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Theoretical Physics Colloquium
Arizona State University
February 23, 2022

**Plan of the talk:**

1. Dense QCD: From NJL model EoS to synthetic parametrization
2. Mass-Radius diagram and astrophysical constraints
3. Tidal deformabilities and the GW170817 event
4. Universal relations and an example of application

**In collaboration with:**

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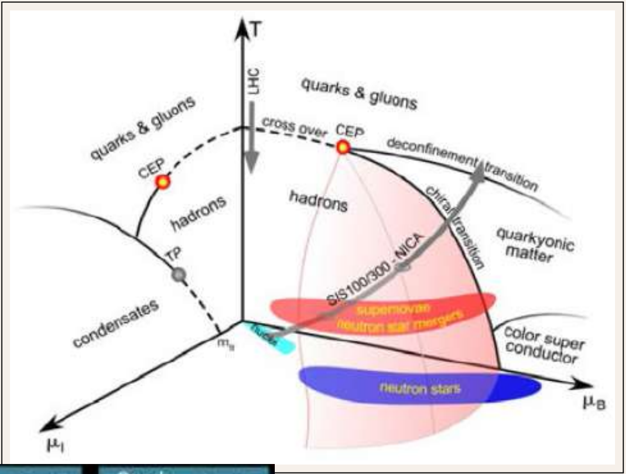
also for universalities: V. Paschalidis, K. Yagi, D. Blaschke, Alvarez-Castillo, Largani, Fischer, Raduta, Oertel, Khadkikar

# Dense QCD: From NJL model EoS to synthetic parametrization




**Leptons** spin = 1/2

| Flavor | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| $e$ electron | 0.000511 | −1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | −1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |

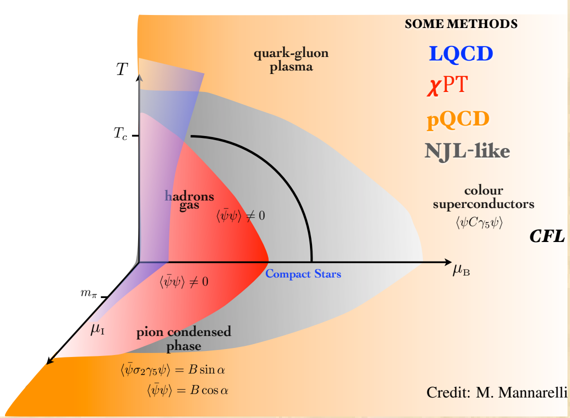
**Quarks** spin = 1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.003 | 2/3 |
| d down | 0.006 | −1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | −1/3 |
| t top | 175 | 2/3 |

The QCD Lagrangian is written for $\psi_q = (\psi_{qR}, \psi_{qG}, \psi_{qB})^T$ as

$$\mathcal{L}_{QCD} = \underbrace{\bar{\psi}^i_q (i\gamma^\mu)(D_\mu)_{ij}\psi^j_q - m_q \bar{\psi}^i_q \psi_{qi}}_{\text{quarks}} - \underbrace{\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}}_{\text{gluons(Yang-Mills)}} ,$$

where $\underbrace{(D_\mu)_{ij} = \delta_{ij}\partial_\mu - i g_s t^a_{ij} A^a_\mu}_{\text{covarinat derivative}}$ , and $\underbrace{F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu - 2q(A^\mu \times A^\nu)}_{\text{gluonic field (Yang-Mills) field tensor}}$



# NJL model description of quark matter

$$
\begin{aligned}
\mathcal{L}_{NJL} &= \underbrace{\bar\psi(i\gamma^\mu\partial_\mu - \hat m)\psi}_{\text{quarks}} + \underbrace{G_V(\bar\psi i\gamma^\mu\psi)^2}_{\text{vector}} + \underbrace{G_S\sum_{a=0}^{8}[(\bar\psi\lambda_a\psi)^2 + (\bar\psi i\gamma_5\lambda_a\psi)^2]}_{\text{scalar}-\text{pseudoscalar}} \\
&+ \underbrace{G_D\sum_{\gamma,c}[\bar\psi^a_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{abc}(\psi_C)^b_\beta][(\bar\psi_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^s_\sigma]}_{\text{pairing}} \\
&- \underbrace{K\left\{\det{}_f[\bar\psi(1+\gamma_5)\psi] + \det{}_f[\bar\psi(1-\gamma_5)\psi]\right\}}_{\text{t}'\text{Hooft interaction}},
\end{aligned}
$$

- quarks: $\psi^a_\alpha$, color $a = r, g, b$, flavor ($\alpha = u, d, s$); mass matrix: $\hat m = \mathrm{diag}_f(m_u, m_d, m_s)$;
- other notations: $\lambda_a$, $a = 1, ..., 8$, $\psi_C = C\bar\psi^T$ and $\bar\psi_C = \psi^T C$, $C = i\gamma^2\gamma^0$.

Parameters of the model:

- $G_S$ the scalar coupling and cut-off $\Lambda$ are fixed from vacuum physics
- $G_D$ is the di-quark coupling $\simeq 0.75 G_S$ (via Fierz) but free to change
- $G_V$ and $\rho_{\rm tr}$ are treated as free parameters

# QCD interactions pairing interactions and gaps

- Symmetric in space wave function (isotropic interaction) $\langle 0|\psi^a_{\alpha\sigma}\psi^b_{\beta\tau}|0\rangle$
- Antisymmetry in colors $a, b$ for attraction
- Antisymmetry in spins $\sigma, \tau$ (Cooper pairs as spin-0 objects)
- Antisymmetry in flavors $\alpha, \beta$

2SC phase:

Low densities, large $m_s$ (strange quark decoupled)

$$\Delta(2SCs) \propto \Delta\epsilon^{ab3}\epsilon_{\alpha\beta} \qquad \delta\mu \ll \Delta,$$

Crystalline or gapless phases:

Intermediate densities, large $m_s$ (strange quark decoupled)

$$\Delta(\text{cryst.}) \propto \epsilon_{\alpha\beta}\Delta_0\, e^{i\vec{Q}\cdot\vec{r}} \qquad \delta\mu \geq \Delta,$$

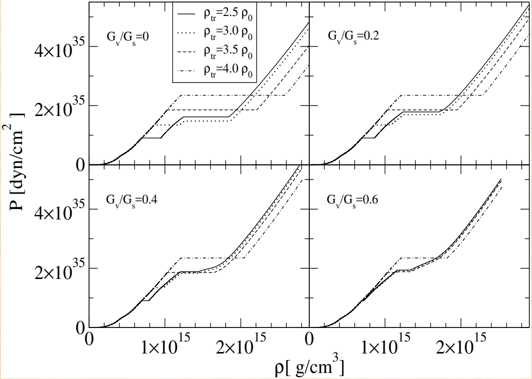
CFL phase:

High densities nearly massless $u, d, s$ quarks

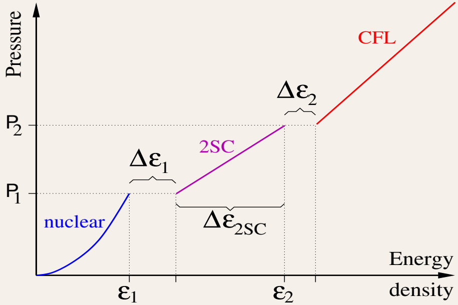
$$\Delta(CFL) \propto \langle 0|\psi^a_{\alpha L}\psi^b_{\beta L}|0\rangle = -\langle 0|\psi^a_{\alpha R}\psi^b_{\beta R}|0\rangle = \Delta\epsilon^{abC}\Delta\epsilon_{\alpha\beta C}.$$

# EOS hadronic matter + Q1 (2SC) and Q2 (CFL) phases of matter

- Maxwell: large surface tension –> sharp jump: $P_N(\mu_B) = P_Q(\mu_B)$
- Glendenning: low surface –> smooth transition



# Synthetic equations of state with constant speed of sound




Parameters of the models:

$$(\epsilon_1, P_1) \quad \Delta\varepsilon_1, \quad \Delta\varepsilon_{2SC} \quad (\varepsilon_2, P_2) \quad \Delta\varepsilon_2$$

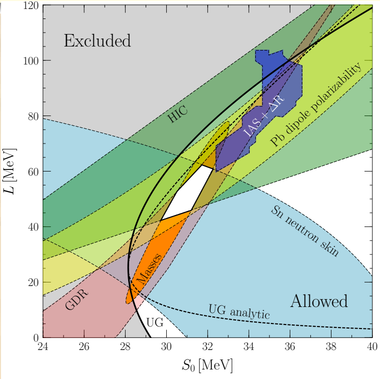
Note that there are five independent parameters.

## Taylor expansion of nuclear energy

$$E(\chi,\delta) \simeq E_0 + \frac{1}{2!}K_0\chi^2 + \frac{1}{3!}Q_{\rm sym}\chi^3 + E_{\rm sym}\delta^2 + L\delta^2\chi + \mathcal{O}(\chi^4,\chi^2\delta^2), \qquad (1)$$

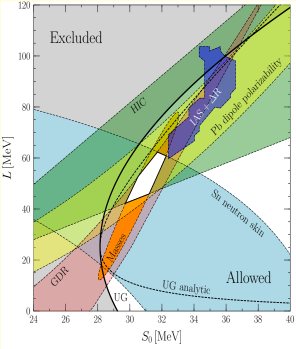
where $\delta = (n_n - n_p)/(n_n + n_p)$ and $\chi = (\rho - \rho_0)/3\rho_0$.

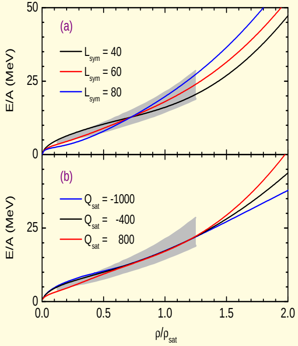
- saturation density $\rho_0 = 0.152\ \mathrm{fm}^{-3}$
- binding energy per nucleon $E/A = -16.14$ MeV,
- incompressibility $K_{\rm sat} = 251.15$ MeV,
- skweness $Q_{\rm sat} = 479$
- symmetry energy $E_{\rm sym} = 32.30$ MeV,
- symmetry energy slope $L_{\rm sym} = 51.27$ MeV,
- symmetry incompressibility $K_{\rm sym} = -87.19$ MeV




Credit: Lattimer et al 2017

# Consistency between the density functional and experiment




– Uncertainties will be quantified in terms of variation of higher-order characteristics around the central fit values.

– Low density physics depends strongly on the value of $L_{\rm sym}$ with strong correlation to the radius of the star and tidal deformability

– High-density physics strongly depends on the value of $Q_{\rm sym}$ with strong correlations to the mass of the star.

# Mass-Radius diagram

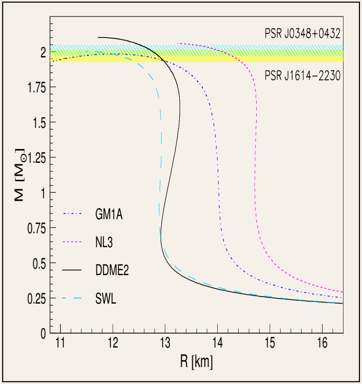
# Stationary compact stars

- Einstein's field equations:

$$\boxed{G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = -8\pi T_{\mu\nu},}$$

- Energy-momentum tensor:

$$T_{\mu\nu} = -P(r) g_{\mu\nu} + [P(r) + \epsilon(r)]\, u_\mu u_\nu$$

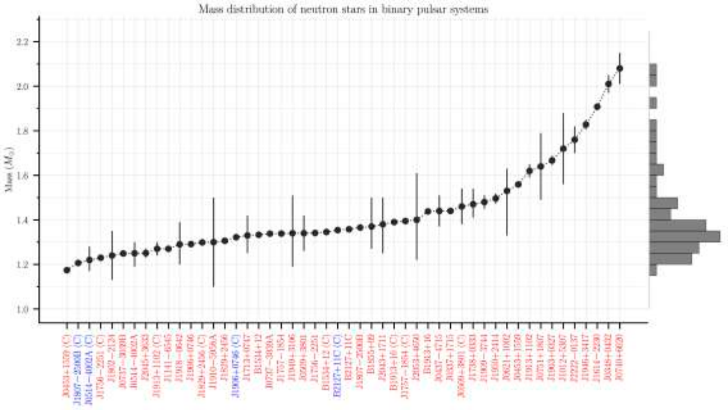



TOV equations, static spherically symmetrical stars:

$$\frac{dP(r)}{dr} = -\frac{G\epsilon(r)M(r)}{c^2 r^2}\left(1+\frac{P(r)}{\epsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2 r}\right)^{-1}.$$

$$M(r) = 4\pi \int_0^r r^2 \epsilon(r) dr. \qquad \boxed{P[\epsilon] \quad \to \quad M, R, I, Q, \ldots}$$

## Pulsar mass measurements from radio observations




Credits: P. Freire, V. V. Krishnan, (MPIFR, Bonn).

# Quarks and new equilibria of compact objects

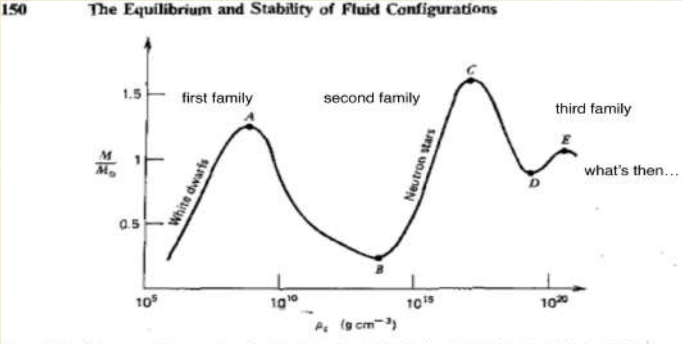
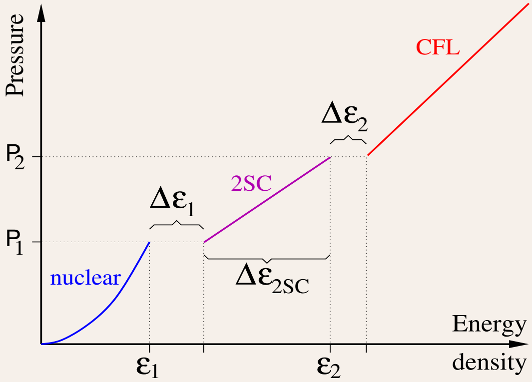



Figure 6.2 Schematic diagram showing the turning points in the mass versus central density diagram for equilibrium configurations of cold matter.

S. Shapiro, S. Teukolsky, "Black holes, White dwarfs and Neutron Stars"

-*White dwarfs* -first family, $M \leq 1.5M_{\odot}$, [S. Chandrasekhar, L. Landau (1930-32)]
-*Neutron Stars* - second family, $M \leq 2M_{\odot}$, [Oppenhimer-Volkoff (1939)]
-*Hybrid Stars* - third family, $M \leq 2M_{\odot}$, [Gerlach (1968), Glendenning-Kettner (2000)]
- *Fourth Family* - see Phys. Rev. Lett. 119, 161104 (2017).

# EoS with sequential phase transitions




Need to specify:

The scheme extends the EoS with constant speed of sound (CSS) of M. G. Alford, S. Han, M. Prakash, Phys. Rev. D 88, 083013 (2013) to double phase transitions: Phys. Rev. Lett. 119, 161104 (2017).

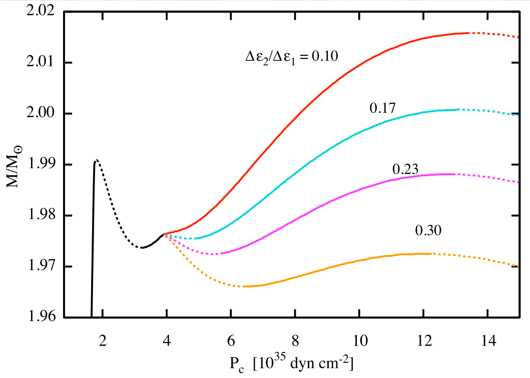
# EoS in analytical form

$$P(\varepsilon) = \begin{cases} P_1, & \varepsilon_1 < \varepsilon < \varepsilon_1 + \Delta\varepsilon_1 \\ P_1 + s_1\left[\varepsilon - (\varepsilon_1 + \Delta\varepsilon_1)\right], & \varepsilon_1 + \Delta\varepsilon_1 < \varepsilon < \varepsilon_2 \\ P_2, & \varepsilon_2 < \varepsilon < \varepsilon_2 + \Delta\varepsilon_2 \\ P_2 + s_2\left[\varepsilon - (\varepsilon_2 + \Delta\varepsilon_2)\right], & \varepsilon > \varepsilon_2 + \Delta\varepsilon_2 \,. \end{cases}$$

Need to specify:

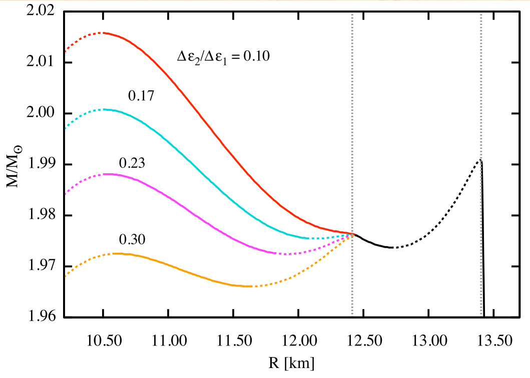
- the two speeds of sounds: $s_1$ and $s_2$
- the point of transition from NM to QM $\varepsilon_1, P_1$
- the magnitude of the first jump $\Delta\varepsilon_1$
- the size of the 2SC phase, i.e, the second transition point $\varepsilon_2, P_2$
- the size of the second jump $\Delta\varepsilon_2$

# Mass-central pressure relation



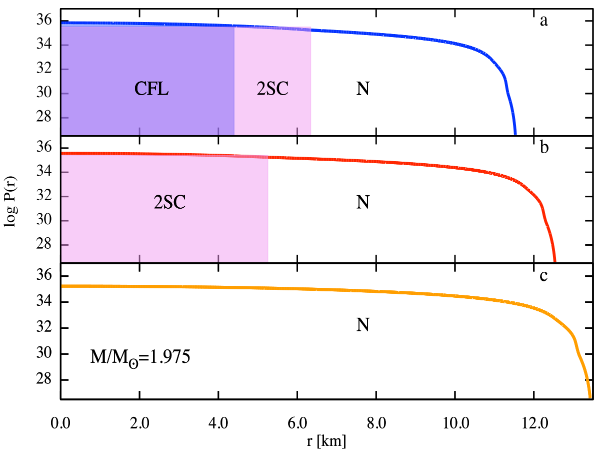

- Phase Q1: $P_1 = 1.7 \times 10^{35}\,\mathrm{dyn\,cm}^{-2}$, $\Delta\varepsilon_{2SC}/\varepsilon_1 = 0.27$, $\Delta\varepsilon_1/\varepsilon_1 = 0.6$. Phase Q2: 4 different values of $\Delta\varepsilon_2$.
- Speeds of sound $s_1 = 0.7$ and $s_2 = 1$.
- Stable branches –> solid lines, unstable branches –> dashed lines.
- Triplets emerge for $\Delta\varepsilon_2 = 0.23$

# Mass-radius relation




Same as previous slide but the $M - R$ relation.
Emergence of twins and triplets –> strong first order phase transition in quark matter.

# Internal structure of triplet stars




- Internal profiles of triplets with $M = 1.975$ M$_\odot$ and $\Delta\varepsilon_2/\Delta\varepsilon_1 = 0.23$.
- "$N$" –> nuclear only, 2SC —> single phase, CFL,2SC –> two phases.

# Stability "matrix" for different magnitudes of jumps

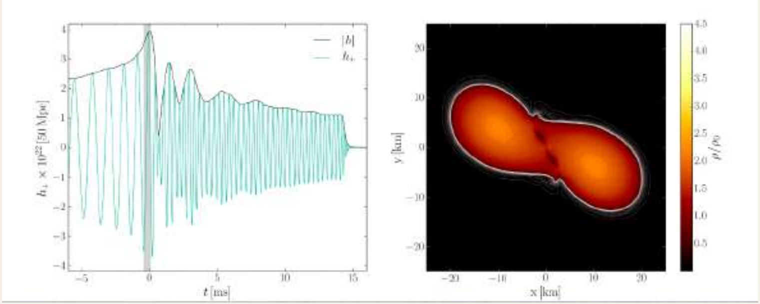
| | $\Delta\varepsilon_1/\varepsilon_1$ | | | |
|---|---|---|---|---|
| $\Delta\varepsilon_2/\Delta\varepsilon_1$ | 0.4 | 0.5 | 0.6 | 0.7 |
| 0.1 | $s, s$ | $s, s$ | $\underbrace{us, s}_{\text{N-2SC}}$ | $\underbrace{u, us}_{\text{N-CFL}}$ |
| 0.2 | $s, s$ | $s, s$ | $\underbrace{us, us}_{\text{triplet}}$ | $\underbrace{u, us}_{\text{N-CFL}}$ |
| 0.3 | $s, s$ | $s, s$ | $\underbrace{us, us}_{\text{N-2SC;N-CFL}}$ | $\underbrace{u, us}_{\text{N-CFL}}$ |
| 0.4 | $s, s$ | $\underbrace{s, us}_{\text{2SC-CFL}}$ | $\underbrace{us, u}_{\text{N-2SC}}$ | $u, u$ |
| 0.5 | $s, s$ | $\underbrace{s, us}_{\text{2SC-CFL}}$ | $\underbrace{us, u}_{\text{N-2SC}}$ | $u, u$ |

- Stable/unstable branches are referred by $s/u$, the Q1 and Q2 phases.
- Increasing the jumps –> instability

# Tidal deformabilities and radii of compact stars

# The GW170817 event

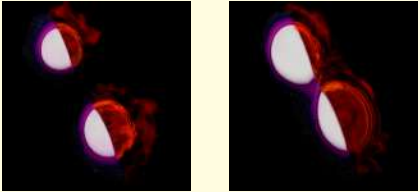
## GW170817: First gravitational waves from a neutron star merger (Ligo-Virgo-Collaboration)



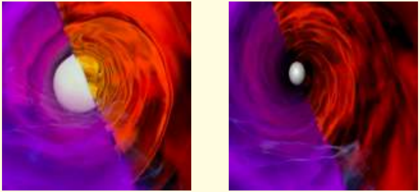

The associated EM events observed by over 70 observatories :

- + 2sec gamma ray burst is detected
- +10 h 52 min bright source in optical
- +11 h 36 min infrared emission; +15 h ultraviolet
- +9 days X-rays; +16 days radio

Pre-merger signal



Post-merger not observed (yet)

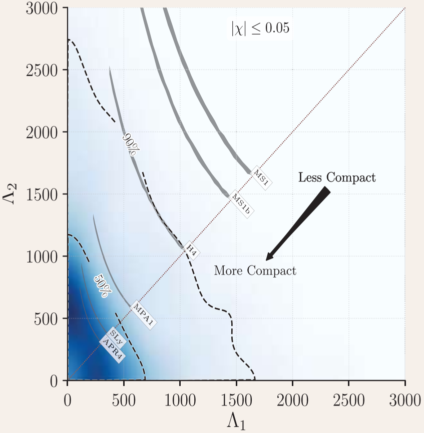


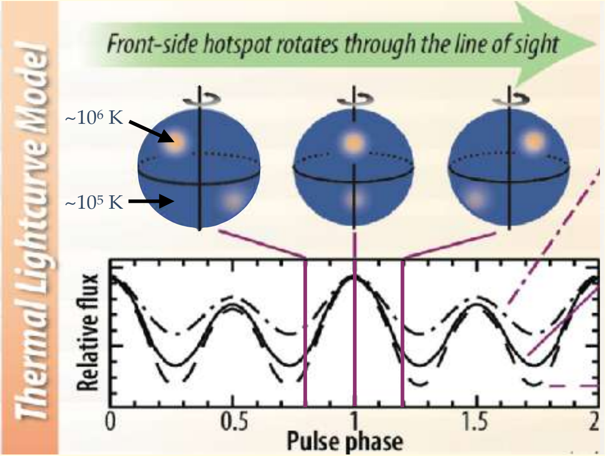
The gravitational wave signal allows for extraction of the tidal deformability of the two neutron stars $\Lambda_1$ and $\Lambda_2$.

$$Q_{ij} = -\lambda \mathcal{E}_{ij}, \quad \Lambda = \frac{\lambda}{M^5},$$

where $Q_{ij}$ is the induced quadrupole moment, $\mathcal{E}_{ij}$ is the tidal field of the partner.

| | Low-spin priors ($\lvert\chi\rvert \leq 0.05$) | High-spin priors ($\lvert\chi\rvert \leq 0.89$) |
|---|---|---|
| Primary mass $m_1$ | 1.36–1.60 $M_\odot$ | 1.36–2.26 $M_\odot$ |
| Secondary mass $m_2$ | 1.17–1.36 $M_\odot$ | 0.86–1.36 $M_\odot$ |
| Chirp mass $\mathcal{M}$ | $1.188^{+0.004}_{-0.002} M_\odot$ | $1.188^{+0.004}_{-0.002} M_\odot$ |
| Mass ratio $m_2/m_1$ | 0.7–1.0 | 0.4–1.0 |
| Total mass $m_{\rm tot}$ | $2.74^{+0.04}_{-0.01} M_\odot$ | $2.82^{+0.47}_{-0.09} M_\odot$ |
| Radiated energy $E_{\rm rad}$ | $> 0.025 M_\odot c^2$ | $> 0.025 M_\odot c^2$ |
| Luminosity distance $D_{\rm L}$ | $40^{+8}_{-14}$ Mpc | $40^{+8}_{-14}$ Mpc |
| Viewing angle $\Theta$ | $\lesssim 55°$ | $\lesssim 56°$ |
| Using NGC 4993 location | $\lesssim 28°$ | $\lesssim 28°$ |
| Combined dimensionless tidal deformability $\tilde{\Lambda}$ | $\leq 800$ | $\leq 700$ |
| Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$ | $\leq 800$ | $\leq 1400$ |

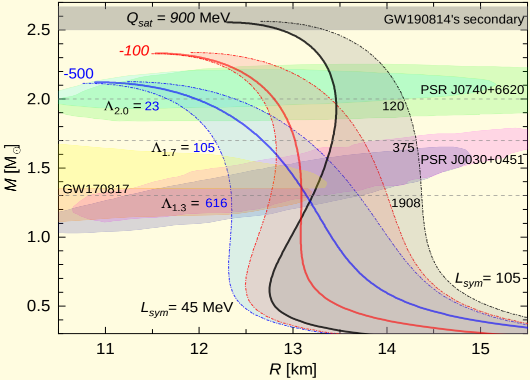





Pulse-profile modeling of PSR J0030+0451 and PSR J0740+6620 [Riley et al 2019,2021), Miller et al 2019,2021]

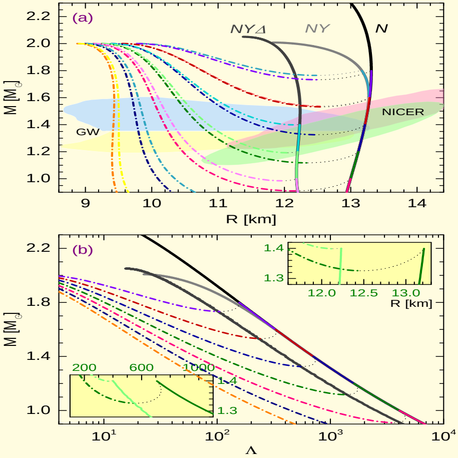
- $1.34^{+0.15}_{-0.16} M_\odot$ –> $12.71^{+1.14}_{-1.19}$ km, $1.44^{+0.15}_{-0.14} M_\odot$ –> $13.02^{+1.24}_{-1.06}$ km,
- $2.08^{+0.09}_{-0.09} M_\odot$ –> $12.39^{+1.30}_{-0.98}$ km, $2.07^{+0.07}_{-0.07} M_\odot$ –> $13.71^{+2.61}_{-1.50}$ km.

# Mass-radius relation for hadronic stars



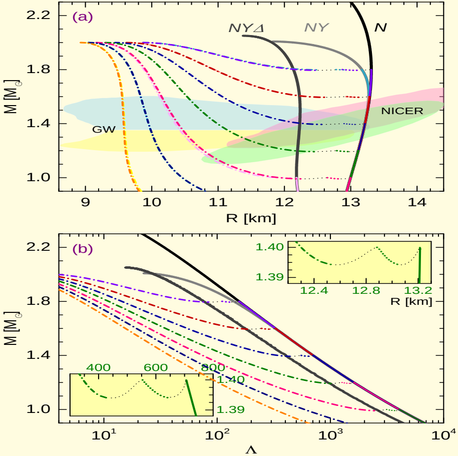

- The range of $L_{\rm sym}$ corresponds to the lower inference and mean value found from PREX-II analysis.
- The maximum mass increases monotonically with $Q_{\rm sat}$.
- Low $L_{\rm sym}$ values allow for GW170817 to be explained by hadronic stars for all the values of $Q_{\rm sat}$, but are in tension with the PREX-II analysis of Indiana group.

# $M - R$ and $M - \Lambda$ for twin stars



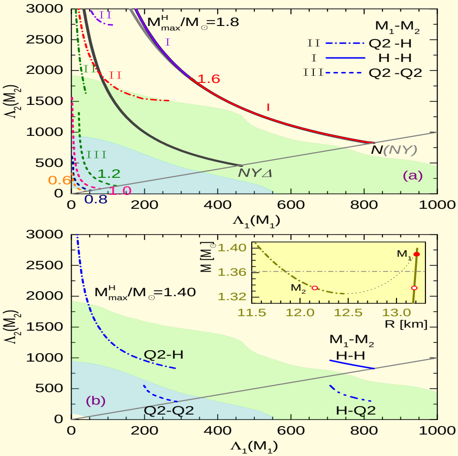

(a) Mass-radius relation for hybrid stars with a single QCD phase translation, with different hadronic envelopes. (b) Mass-deformability relation for stars featuring nucleonic envelopes. The inset shows the results for the case $M^{\rm H}_{\rm max}/M_\odot = 1.20$.

# $M - R$ and $M - \Lambda$ for triplet stars



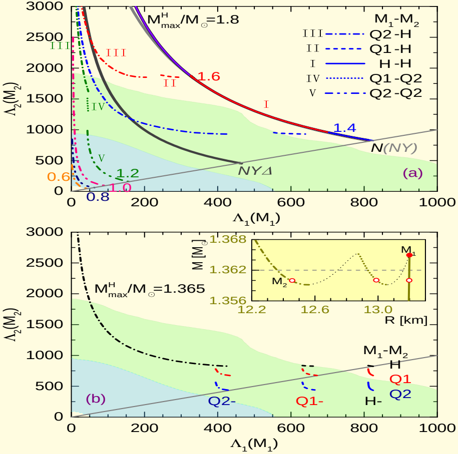

(a) Mass-radius relation for hybrid stars with a single QCD phase translation, with different hadronic envelopes. (b) Mass-deformability relation for stars featuring nucleonic envelopes. The inset shows the results for the case $M^{\mathrm{H}}_{\mathrm{max}}/M_\odot = 1.20$.

# Λ-Λ for twin stars




a) Tidal deformabilities of compact objects in the binary with chirp mass $\mathcal{M} = 1.186 M_\odot$ (b) Prediction by an EoS with maximal hadronic mass $M^{\rm H}_{\rm max} = 1.365 M_\odot$. The inset shows the mass-radius relation around the phase transition region. The circles $M_2$ are two possible companions for circle $M_1$, generating two points in the $\Lambda_1$-$\Lambda_2$ curves while one point is located below the diagonal line.

# Λ-Λ for triplet stars



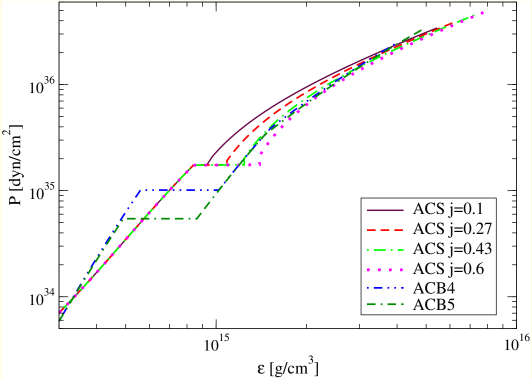

The case of double phase transition a) Tidal deformabilities of compact objects in the binary with chirp mass $\mathcal{M} = 1.186 M_\odot$ (b) Prediction by an EoS with maximal hadronic mass $M^{\rm H}_{\rm max} = 1.365 M_\odot$. The inset shows the mass-radius relation around the phase transition region. The circles $M_2$ are two possible companions for circle $M_1$, generating two points in the $\Lambda_1$-$\Lambda_2$ curves while one point is located below the diagonal line.

# Universal relations

## Universalities of TOV solutions:

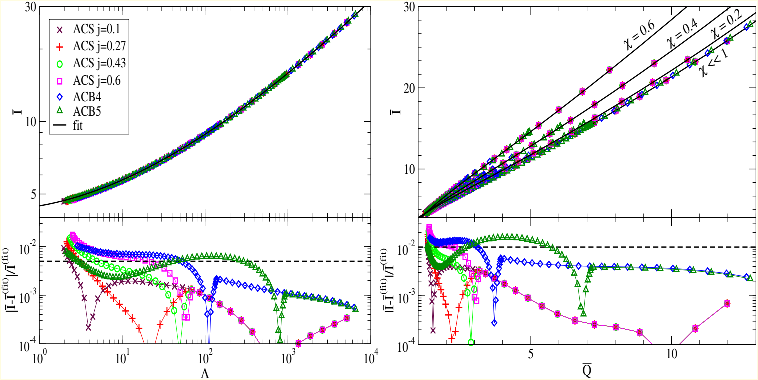
- Universal (independent of the underlying EoS) relations among the global properties of compact stars - $I-L-Q$ relations. (Yagi and Yunes 2013a; Maselli et al. 2013; Breu and Rezzolla 2016; Yagi and Yunes 2017)
  Well established for:
  (a) zero temperature slowly rotating stars
  (b) rapidly rotating cold star
  (c) magnetized cold star
- Finite temperature stars (proto-neutron stars, BNS remnants) - universalities, $I-L-Q$ relations and $I(C)$ are broken (Martinon et al. 2014; Marques et al. 2017; Lenka et al. 2019). Both $S$ =Const and $S$-gradients
- But if one considers fixed values of $(S/A, Y_{L,e})$ universal relations hold - accuracy comparable to cold compact stars (A. Raduta, M. Oertel, A. S., arXiv:2008.00213)
- Universalities also hold for rapidly rotating hot stars for fixed values of $(S/A, Y_{L,e})$ (S. Khadkikar, A. Raduta, M. Oertel, A. S. arXiv:2102.00988)
- Universalities also hold for cold (arXiv:1712.00451) and hot (arXiv:2112.10439) rapidly rotating hybrid stars (Paschalidis et al, Largani et al.)
- Universality can be used to extract the maximum mass of hot static compact stars from GW170817 arXiv:2102.00988

# Input EoS to test universalities



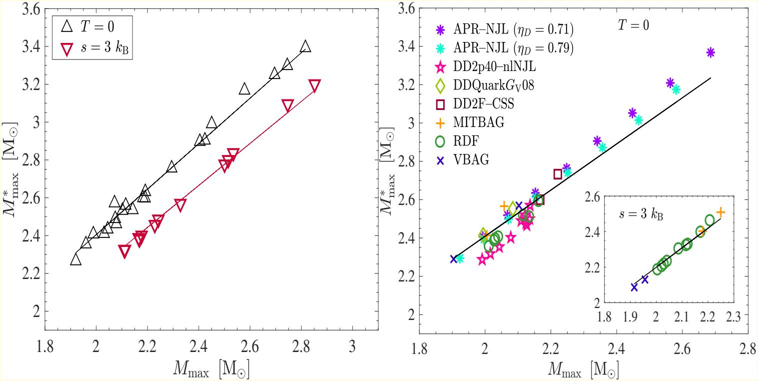

- Hybrid star EoS with single phase transition first used to test the universalities for such objects

# Examples of universalities



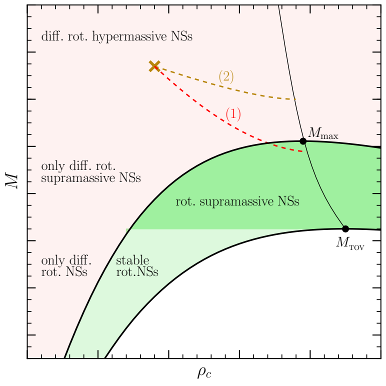

- Moment of inertia vs tidal deformability and moment of inertia vs quadrupole moment

# Examples of universalities




- Maximum masses of Keplerian vs static hadronic (left) and hybrid (right) stars.

# Maximum TOV mass from GW170817




- the merger leaves behind a hypermassive neutron star (HMNS)
- the internal dissipation leads to vanishing internal shears and uniform rotation.
- the star enters the region of stability of supramassive neutron stars close to the maximum mass
- the star crosses the stability line beyond which it is unstable to collapse

## Maximum TOV mass from GW170817

- The extraction of the upper limit circumvents the full dynamical study and uses the *baryon mass* conservation at *at merger* $t = 0$ *and collapse* $t = t_c$

$$M_B(t_c, S/A, Y_e) = M_B(0) - M_{\rm out} - M_{\rm ej},$$

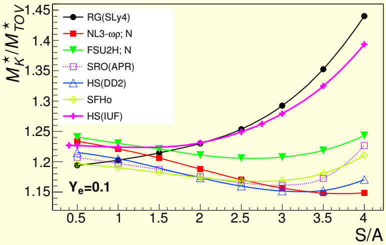
- Transform from the baryonic to the gravitational mass

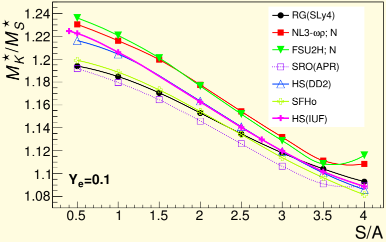
$$M_B(t_c, S/A, Y_e) = \eta(S/A, Y_e)M(t_c, S/A, Y_e) = \eta(S/A, Y_e)M_K^\star(S/A, Y_e),$$

  The last step assumes that the star is Keplerian (Shibata et al 2019 relax this assumption).

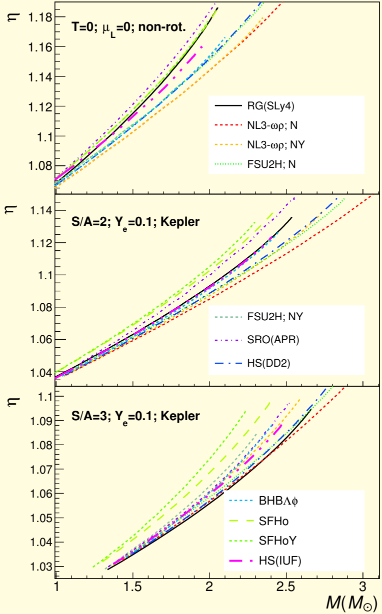
- Solve the mass conservation for hot Keplerian mass

$$M_K^\star(S/A, Y_e) = \frac{1}{\eta(S/A, Y_e)}\left[\eta(0)M(0) - M_{\rm out} - M_{\rm ej}\right].$$




The different normalizations (cold vs hot) show that the universality is broken when normalized to the cold TOV mass and is maintained if normalized by static hot star.




Dependence of the $\eta$ parameter on the gravitational mass.

Dense QCD and compact stars

A Sedrakian

Dense QCD

Mass-Radius diagram

Tidal deformabilities and radii of compact stars

Universalities relations

The analysis of GW170817 gives us the values:

- $M(0) = 2.73M_\odot \,{}^{+0.04}_{-0.01}$
- $M_{\rm ej} = 0.04 \pm 0.01M_\odot \to M_{\rm out} + M_{\rm ej} = 0.1 \pm 0.041$
- In GW170817 the primary/secondary masses lie in the range $1.35 \le M/M_\odot \le 1.6$
- for cold compact stars based on our collection of EoS we have $\eta(0) \simeq 1.120 \pm 0.002$ for $M = 1.6M_\odot$ and $\eta(0) \simeq 1.085 \pm 0.001$ for $M = 1.2M_\odot$
- For our estimates we adopt the value $\eta(0) \simeq 1.1004^{+0.0014}_{-0.0003}$ leading to $M_B(0) = 3.00^{+0.05}_{-0.01}M_\odot$.
- Assuming that the star is rotating at the Keplerian frequency we then find that $\eta(2, 0.1) \simeq 1.139 \pm 0.004$ and $\eta(3, 0.1) \simeq 1.099 \pm 0.003$. For the quantity $(M_{\rm out} + M_{\rm ej})/\eta(S/A, Y_e)$ we obtain $0.087 \pm 0.036$ and $0.091 \pm 0.037$ for $S/A = 2$ and 3 and $Y_e = 0.1$,
- Substituting the numerical values in

$$M_K^\star(S/A, Y_e) = \frac{1}{\eta(S/A, Y_e)}\left[\eta(0)M(0) - M_{\rm out} - M_{\rm ej}\right].$$

we find

$$\boxed{M_K^\star(2, 0.1) = 2.55^{+0.06}_{-0.04}, \quad M_K^\star(3, 0.1) = 2.64^{+0.06}_{-0.04}.}$$

Next step gives us *maximum mass of non-rotating hot compact stars*, using *universality*

$$M_S^\star(2,0.1) = 2.19^{+0.05}_{-0.03}, \quad M_S^\star(3,0.1) = 2.36^{+0.05}_{-0.04}.$$

The universality is broken, but we can deduce an upper limit on *the maximum mass of cold compact stars*. The average values $C_M^\star = 1.19 \pm 0.04$ for $S = 2$ and $C_M^\star = 1.18 \pm 0.11$ for $S = 3$ can now be used to obtain, respectively,

$$\boxed{M_{\rm TOV}^\star = 2.15^{+0.09+0.16}_{-0.07-0.16}, \qquad M_{\rm TOV}^\star = 2.24^{+0.10+0.44}_{-0.07-0.44}.}$$

($2\sigma$ standard deviation)

- Constant entropy per baryon and constant electron fraction star (?)
- $S/A = 2$ and 3 – average values for the inner part of the merger remnant.
- more precise result would require a profile for $S$

*Conclusion: Accounting for the finite temperature of the merger remnant relaxes the derived constraints on the maximum mass of the cold, static compact star, obtained in by Margalit-Metzger 2017, Rezzolla et al 2018, Ruiz et al (2018), Shibata et al (2019a).*

*Universality is lost and the final upper limit becomes EoS dependent due to the EoS dependence of* $C_M^\star$.