Constraining properties of dense, strongly interacting matter with compact stars

Armen Sedrakian
FIAS (Frankfurt) and IFT (Wroclaw University)

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FIAS Frankfurt Institute for Advanced Studies

Uniwersytet Wrocławski

In collaboration with:

Jia-Jie Li (Goethe-University $\rightarrow$ South Western University, China)

Arus Harutyunyan (Byurakan Astrophysical Observatory, Armenia)

Mark Alford (Washington University, St. Louis, USA)

Fridolin Weber (San Diego State University, USA)

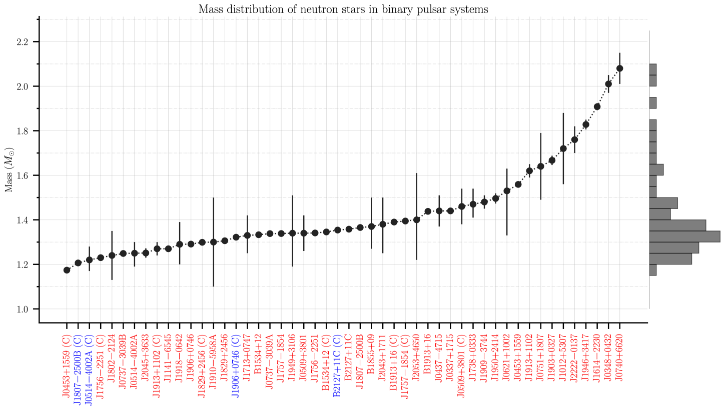
Micaela Oertel (Meudon Observatory, France)

Adriana Raduta (INPN, Romania)

Further DFT developments (not covered in this talk)

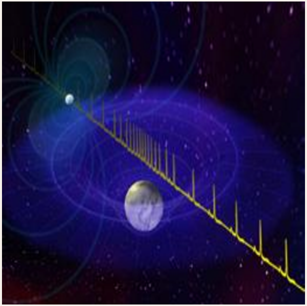
- Hypernuclear Δ-admixed stars with anti-kaon condensation
  V. B. Thapa, M. Sinha, J. J. Li, A. Sedrakian, Phys. Rev. D 103, 063004 (2021)
- Hypernuclear Δ-admixed stars in strong magnetic fields
  V. B. Thapa, M. Sinha, J. J. Li, A.n Sedrakian, Particles 3(4), 660-675 (2020)

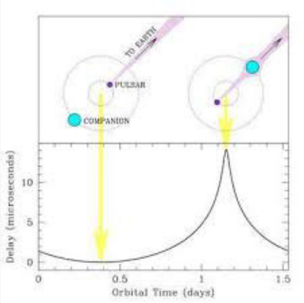
Pulsar mass measurements from radio observations



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

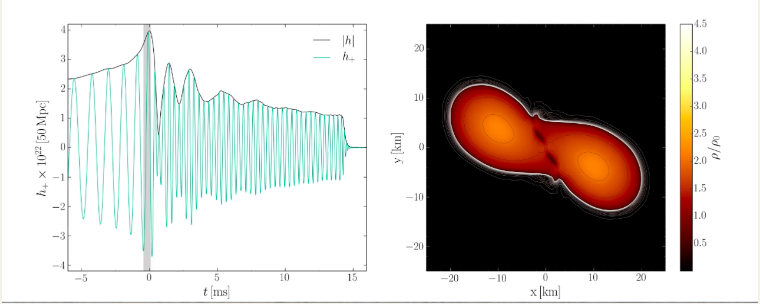
Three two-solar-mass neutron stars in binaries with WD





- The millisecond pulsar J1614-2230 in a binary with a white dwarf, $M = 1.97 \pm 0.04 M_\odot$ (Demorest et al. 2010), Relativistic Shapiro delay.
- The millisecond pulsar J0348+0432 in a binary with a white dwarf $M = 2.01 \pm 0.04 M_\odot$ (Antoniadis et al. 2013) [theor. assumptions about WD cooling.]
- The millisecond pulsar J0740+6620 $M = 2.14^{+0.10}_{-0.09} M_\odot$ (NANOGrav, Cromartie et al. 2019) Relativistic Shapiro delay.

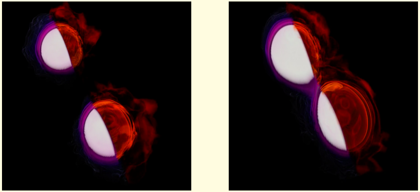
GW170817: First gravitational waves from a neutron star merger (Ligo-Virgo-Collaboration)



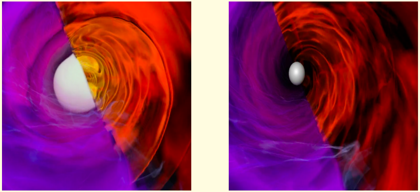
The associated EM events observed by over 70 observatories :

- + 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)

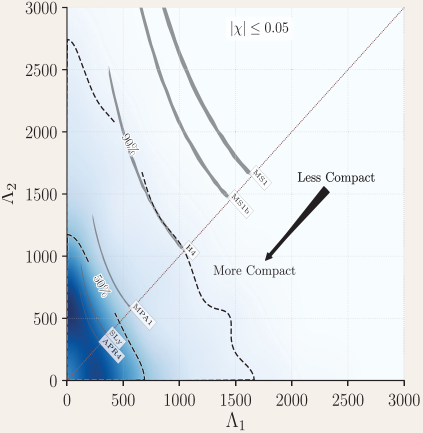


The gravitational wave signal allows for extraction of the tidal deformability of the two neutron stars Λ_1 and Λ_2.

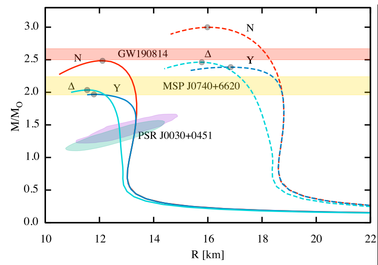
$$Q_{ij} = -\lambda \mathcal{E}_{ij}, \quad \Lambda = \frac{\lambda}{M^5},$$

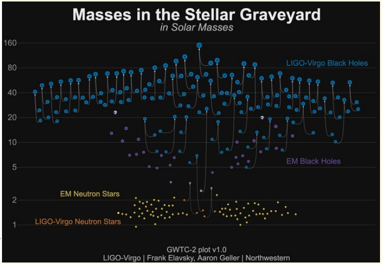
where Q_{ij} is the induced quadrupole moment, $\mathcal{E}_{ij}$ is the tidal field of the partner.

	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_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

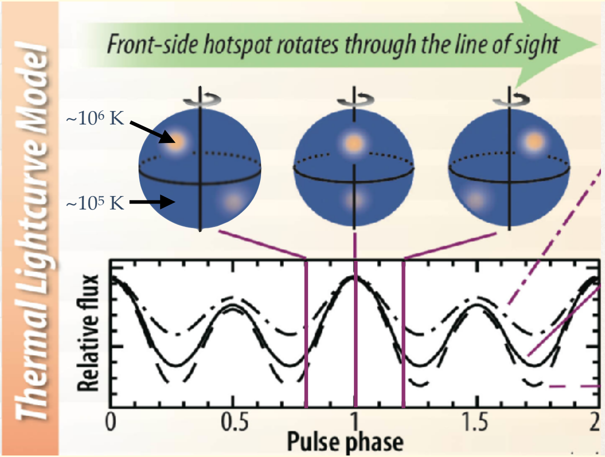


– GW190814 event: extreme mass asymmetric ratio created by a $22.2 - 24.3\, M_\odot$ black hole and a $2.50 - 2.67\, M_\odot$ compact object (no em counterpart).
– Light object's nature is enigmatic as it is in the mass gap $2.5\, M_\odot \lesssim M \lesssim 5\, M_\odot$ where no compact object had ever been observed before.





Solid curves – static solutions; dashed curves - maximally rotating (Keplerian) solutions.



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.

CDF based equations of states

- Using EoS in a form of density functional: the pressure of dense zero-temperature matter is a functional of energy-density: $P(\varepsilon(r))$.
- The parameters of the functional are adjusted to the available data (astrophysics, laboratory and ab initio calculations)
- DFT has been extended to baryon octet and includes hyperons and Delta-resonances
- Fast in implementation to generate quickly families of EoS

- Relativistic models of nuclear matter as DFT:
  (a) relativistic covariance, causality is fulfilled (+)

  (b) The Lorentz structure of interactions is maintained explicitly (+)

  (c) straightforward extension to the strange sector and resonances (+)

  (d) fast implementation (+)

  (e) not a QFT in the QED/QCD sense (-)
- Extended to finite-temperature and iso-entropic case
  The models are studied at S =Const. and Y_e =Const. (early stages of evolution, no significant entropy gradients in the core)
- Mapping of CDF onto the Taylor expansion of energy of nuclear matter
  A family of models are generated with varying symmetry energy, its slope, etc.

Goals:

- Construct an EoS in a form of density functional: the pressure of dense zero-temperature matter is a functional of energy-density: $P(\varepsilon(r))$
- The parameters of the functional are adjusted to the available data; in our case astrophysics and laboratory data.
- *Ab initio* calculations are data $\rightarrow$ check compatibility and adjust if required.
- DFT must be versatile enough to accommodate the baryon spin-1/2 octet and spin-3/2 decouplet.
- Fast in implementation to generate quickly families of EoS

DFT's :

- Relativistic mean-field models of nuclear matter reinterpreted as DFT:
  (a) relativistic covariance, causality is fulfilled automatically (+)
  (b) The Lorentz structure of interactions is maintained explicitly (+)
  (c) straightforward extension to the strange sector and resonances (+)
  (d) fast implementation (+)
  (e) the microscopic counterpart is unknown [not a QFT in the QED/QCD sense] (-)
  (f) uncertainties can be quantified in terms of Taylor expansion coefficients
- Non-relativistic DFTs (e.g. Skyrme or Gogny classes):
  (a) high accuracy at low-densities (+)
  (b) extensive tests on laboratory nuclei (+)
  (c) relativistic covariance is lost and high-density extrapolation is not obvious (-)
  (d) extensions to heavy baryons not straightforward (-)

Nuclear matter Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{NM} &= \underbrace{\sum_B \bar{\psi}_B \left[\gamma^\mu \left(i\partial_\mu - g_{\omega BB}\omega_\mu - \frac{1}{2} g_{\rho BB} \boldsymbol{\tau} \cdot \boldsymbol{\rho}_\mu\right) - (m_B - g_{\sigma BB}\sigma)\right]\psi_B}_{\text{baryons}} \\
&+ \underbrace{\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu}_{\text{mesons}} \\
&- \underbrace{\frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^\mu \cdot \boldsymbol{\rho}_\mu}_{\text{mesons}} + \underbrace{\sum_\lambda \bar{\psi}_\lambda (i\gamma^\mu\partial_\mu - m_\lambda)\psi_\lambda}_{\text{leptons}} - \underbrace{\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{electromagnetism}},
\end{aligned}
$$

- B-sum is over the baryonic octet
- Meson fields include σ meson, $\boldsymbol{\rho}_\mu$-meson and ω_μ-meson
- Leptons include electrons, muons and neutrinos for $T \neq 0$

Two types of relativistic density functionals based on relativistic Lagrangians

- linear mesonic fields, density-dependent couplings (DDME2, DD2, etc.)
- non-linear mesonic fields; coupling constant are just numbers (NL3, GM1-3, etc.)

Fixing the couplings: nucleonic sector

$$g_{iN}(\rho_B) = g_{iN}(\rho_0)h_i(x), \qquad h_i(x) = a_i\frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2} \quad i=\sigma,\omega,$$
$$g_{\rho N}(\rho_B) = g_{\rho N}(\rho_0)\exp[-a_\rho(x-1)], \quad i=\rho,(\pi-HF)$$

Meson (i)	m_i (MeV)	a_i	b_i	c_i	d_i	g_{iN}
σ	550.1238	1.3881	1.0943	1.7057	0.4421	10.5396
ω	783	1.3892	0.9240	1.4620	0.4775	13.0189
ρ	763	0.5647				7.3672

$h_i(1)=1$, $h_i''(0)=0$ and $h_\sigma''(1)=h_\omega''(1)$, which reduce the number of free parameters to three in this sector.

– DD-ME2 parametrization, G. Lalazissis, et al., Phys. Rev. **C71**, 024312 (2005)
– DD2 parametrizations, S. Typel, Eur. Phys. J. **A52**, 16 (2016)
– DD-ME2+LQ parametrizations, J. J. Li, Sedrakian, Phys. Rev. **C100**, 015809 (2019)

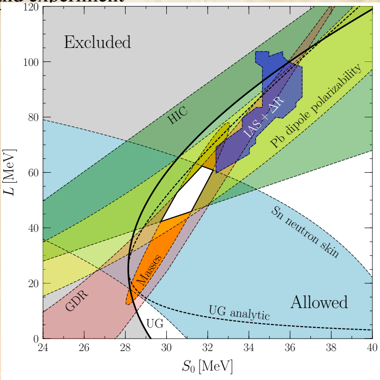
Taylor expansion of nuclear energy

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

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

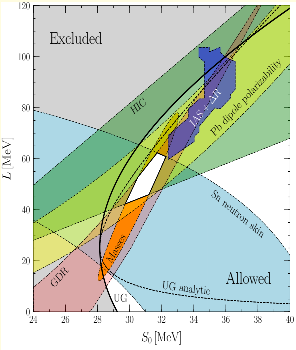
Consistency between the density functional and experiment

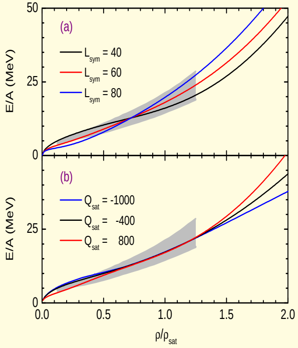
- saturation density $\rho_0 = 0.152\ \mathrm{fm}^{-3}$
- binding energy per nucleon $E/A = -16.14$ MeV,
- incompressibility $K_{\rm sat} = 251.15$ MeV,
- skweness $Q_{\rm sat} = 479$
- symmetry energy $E_{\rm sym} = 32.30$ MeV,
- symmetry energy slope $L_{\rm sym} = 51.27$ MeV,
- symmetry incompressibility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



Credit: Tews, et al ApJ, 2017

Consistency between the density functional with experiment and ab initio theory

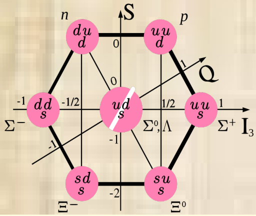


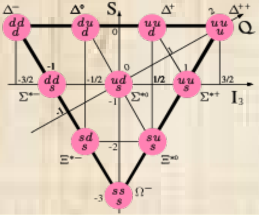


– Uncertainties will be quantified in terms of variation of higher-order characteristics around the central fit values.
– Low density physics depends strongly on the value of $L_{\rm sym}$ with strong correlation to the radius of the star and tidal deformability
– High-density physics strongly depends on the value of $Q_{\rm sym}$ with strong correlations to the mass of the star.

Beyond nucleons: Baryon octet $J^p = 1/2^+$ and baryon decuplet $J^p = 3/2^+$

Strangeness carrying baryons + resonances (nucleon excitations)





$R_{\alpha Y} = g_{\alpha Y}/g_{\alpha N}$ and $\kappa_{\alpha Y} = f_{\alpha Y}/g_{\alpha Y}$ for hyperons in SU(6) spin-flavor model

$R \backslash Y$	Λ	Σ	Ξ
$R_{\sigma Y}$	2/3	2/3	1/3
$R_{\sigma^* Y}$	$-\sqrt{2}/3$	$-\sqrt{2}/3$	$-2\sqrt{2}/3$
$R_{\omega Y}$	2/3	2/3	1/3
$\kappa_{\omega Y}$	-1	$1 + 2\kappa_{\omega N}$	$-2 - \kappa_{\omega N}$
$R_{\phi Y}$	$-\sqrt{2}/3$	$-\sqrt{2}/3$	$-2\sqrt{2}/3$
$\kappa_{\phi Y}$	$2 + 3\kappa_{\omega N}$	$-2 - \kappa_{\omega N}$	$1 + 2\kappa_{\omega N}$
$R_{\rho Y}$	0	2	1
$\kappa_{\rho Y}$	0	$-3/5 + (2/5)\kappa_{\rho N}$	$-6/5 - (1/5)\kappa_{\rho N}$
$f_{\pi Y}$	0	$2\alpha_{ps}$	$-(1/2)\alpha_{ps}$

$\alpha_{ps} = 0.40$. κ is the ratio of the tensor to vector couplings of the vector mesons.

The depth of hyperonic potentials in symmetric nuclear matter are used as a guide the range of hyperonic couplings:

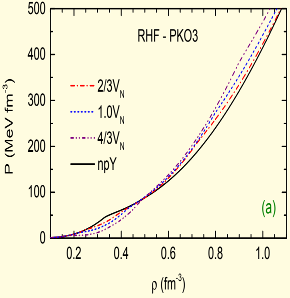
- Λ particle: $V_{\Lambda}^{(N)}(\rho_0) \simeq -30$ MeV
- Ξ particle: $V_{\Xi}^{(N)}(\rho_0) \simeq -14$ MeV
- Σ particle: $V_{\Xi}^{(N)}(\rho_0) \simeq +30$ MeV

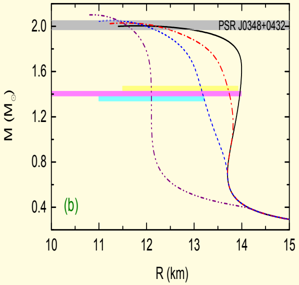
These ranges capture the most interesting regions of the parameter space of masses and radii.

The depth of Δ-potentials in symmetric nuclear matter are used as a guide the range the couplings:

- Electron and pion scattering: $-30\text{ MeV} + V_{\Delta}^{(N)}(\rho_0) \leq V_{\Delta}(\rho_0) \leq V_N(\rho_0)$
- Use instead $R_{m\Delta} = g_{m\Delta}/g_{mN}$ for which the typical range used is

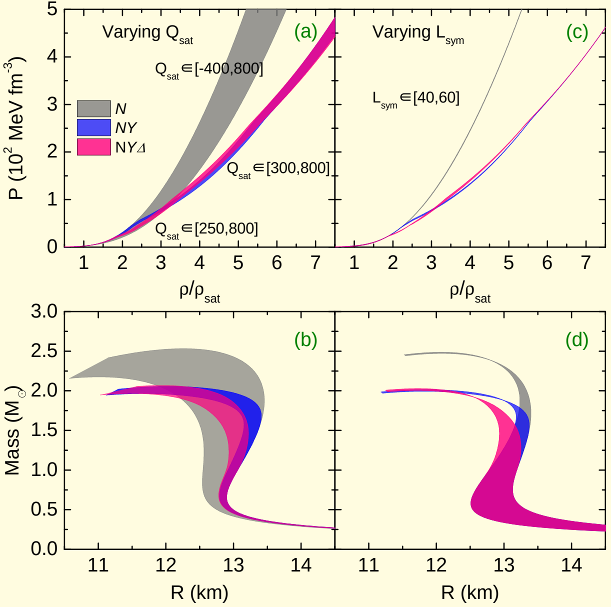
$$R_{\rho\Delta} = 1, \quad 0.8 \leq R_{\omega\Delta} \leq 1.6, \quad R_{\sigma\Delta} = R_{\omega\Delta} \pm 0.2.$$

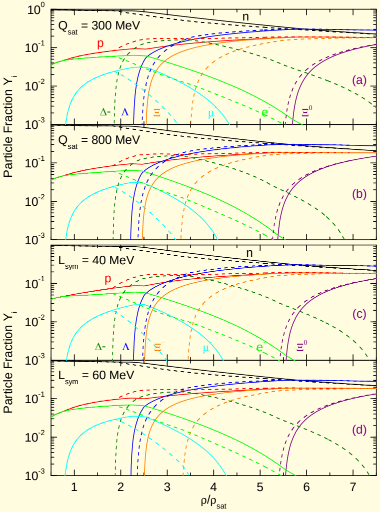


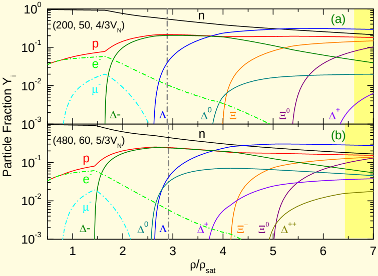


EoS and MR-relations for hyperonic and Δ-admixed models for different potential depths

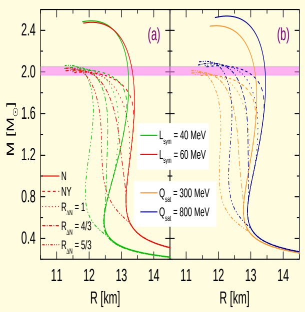
- Δ-resonances lead to softening at low and stiffening at high densities
- The radii are reduced for Δ-admixed stars (1-2 km depending on potential depth)
- The masses remain almost unchanged for Δ-admixed stars

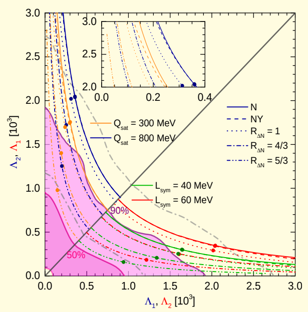

Varying Q_{sat}
(a)
$Q_{sat} \in [-400,800]$
N
NY
NYΔ
$Q_{sat} \in [300,800]$
$Q_{sat} \in [250,800]$
P (10^2 MeV fm^{-3})
ρ/ρ_{sat}
Varying L_{sym}
(c)
$L_{sym} \in [40,60]$
ρ/ρ_{sat}
(b)
Mass ($M_\odot$)
R (km)
(d)
R (km)





Left: Particle fraction for varying fractions of Q (upper two panels) and L (lower two panels). Right: Particles fractions for different Δ-potential depth V_Δ.



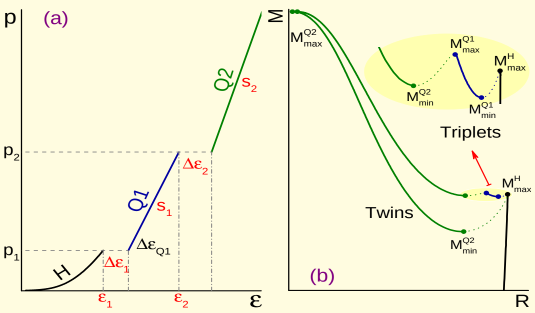


Tidal deformabilities

$$\Lambda = \frac{\lambda}{M^5} = \frac{2}{3}\frac{k_2}{C^5}, \qquad \lambda = \frac{2}{3}k_2R^5,$$

k_2 is tidal Love number, R star's radius, $C = M/R$ compactness for $NY\Delta$ matter and GW170817 constraints.

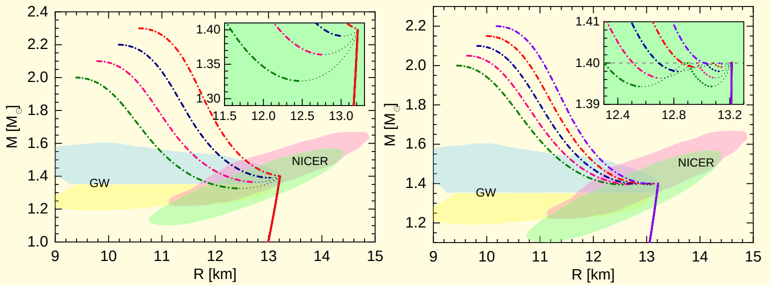
Consistency is achieved for low $L_{\rm sym}$ and $Q_{\rm sat}$ values and for heavy baryon compositions.



Left: EoS with two sequential phase transitions. *Right:* Mass-radius relationships, emergences of minima in the function $M(R)$.

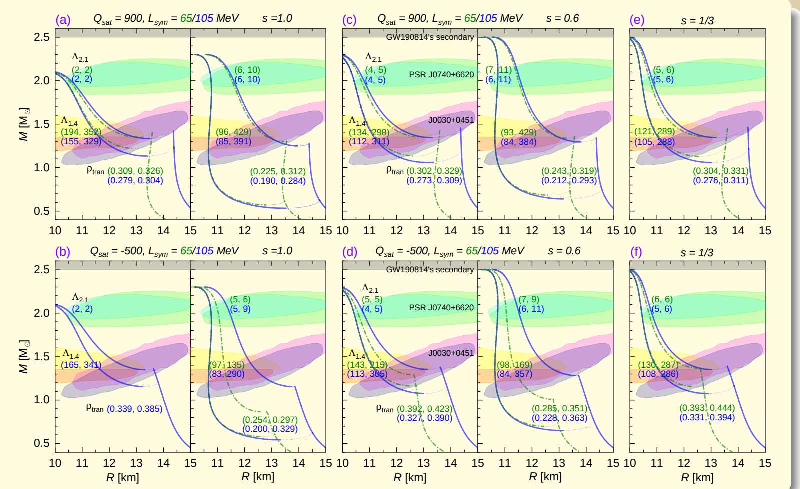
Case when $NY\Delta$-matter makes a first order phase *sequential* transitions to various *generic new phases* (we had in mind phases of color superconducting phases).

$$p(\varepsilon) = \begin{cases} p_1, & \varepsilon_1 < \varepsilon < \varepsilon_1 + \Delta\varepsilon_1 \\ p_1 + s_1\left[\varepsilon - (\varepsilon_1 + \Delta\varepsilon_1)\right], & \varepsilon_1 + \Delta\varepsilon_1 < \varepsilon < \varepsilon_2 \\ p_2, & \varepsilon_2 < \varepsilon < \varepsilon_2 + \Delta\varepsilon_2 \\ p_2 + s_2\left[\varepsilon - (\varepsilon_2 + \Delta\varepsilon_2)\right], & \varepsilon > \varepsilon_2 + \Delta\varepsilon_2. \end{cases}$$

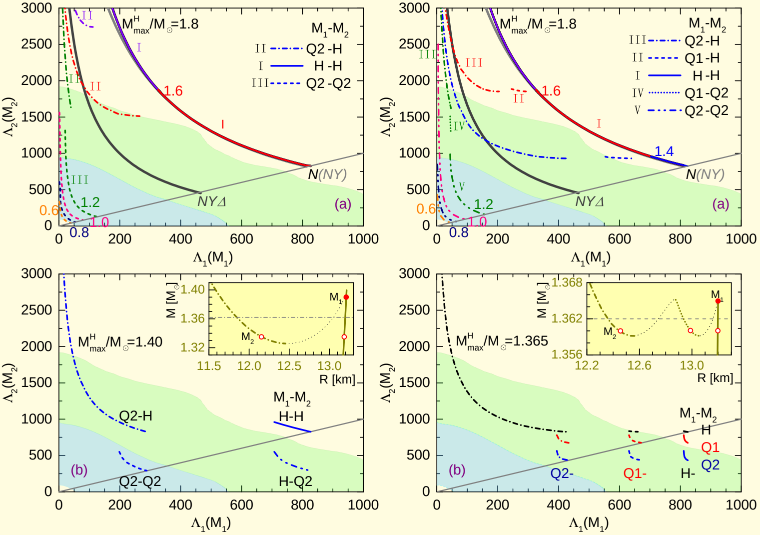


Mass-radius relation for hybrid EoS with single (left) and double (right) phase transitions and nucleonic envelope.

– Parameters are chosen to lead to twin (left) and triplet (right) configurations
– The choice is not constrained by the J0740 radius (see next slide)
– Delta-resonances (reduction of the radius) narrows down the range where triplets can appear

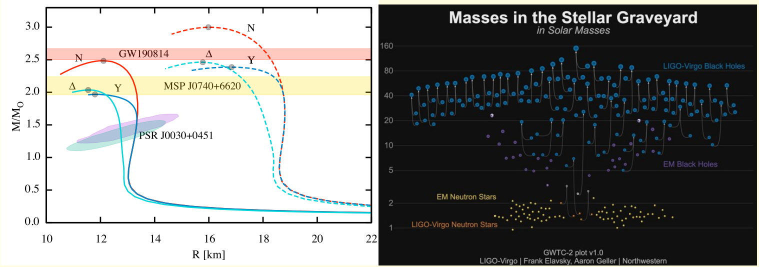


Constraints on the $M - R$ relation of CSs featuring twin configurations for different speeds of sound, L and Q. Model implies *early phase transition to quark phase.*

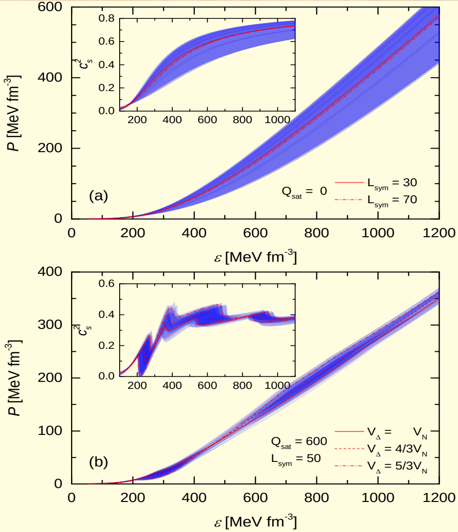


Tidal deformabilities of compact objects with a single (left) and double (right) phase transition(s) for a fixed value of binary chirp mass $\mathcal{M} = 1.186 M_\odot$.

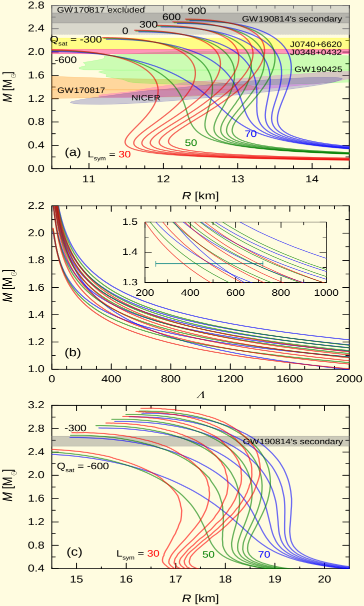
– GW190814 event: extreme mass asymmetric ratio created by a $22.2 - 24.3\,M_\odot$ black hole and a $2.50 - 2.67\,M_\odot$ compact object (no em counterpart).
– Light object's nature is enigmatic as it is in the mass gap $2.5\,M_\odot \lesssim M \lesssim 5\,M_\odot$ where no compact object had ever been observed before.



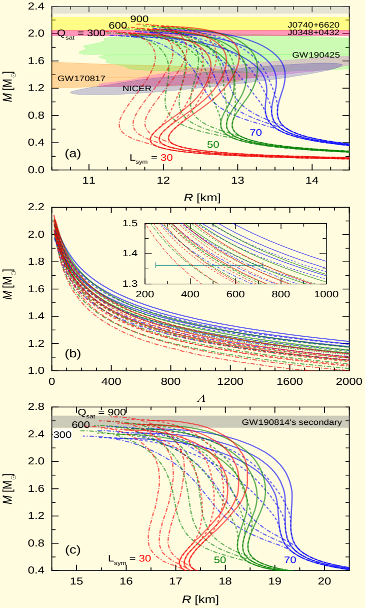
Solid curves – static solutions; dashed curves - maximally rotating (Keplerian) solutions.



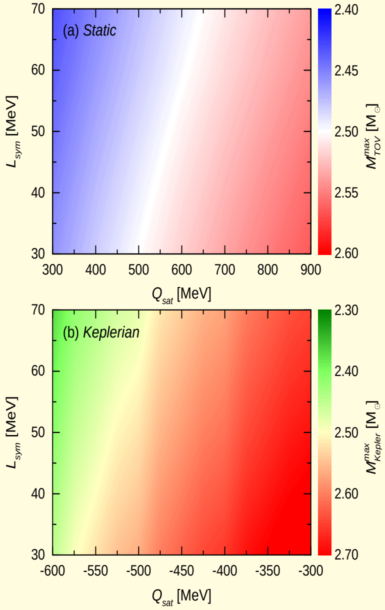
EoS and the corresponding speed-of-sound squared for (a) N and (b) $NY\Delta$ matter. In (a) $Q \in [-600, 900]$ and $L_{\rm sym} \in [30, 70]$. EoS with $Q = 0$, $L_{\rm sym} = 30$ and 70 are shown by solid and dash-dotted lines for illustration. In (b) $Q \in [300, 900]$, $L_{\rm sym} \in [30, 70]$ $V_D/V_N = 1, 4/3$ and $5/3$ EoSs with $Q = 600$, $L_{\rm sym} = 50$ and three indicated values of V_D are shown for illustration.



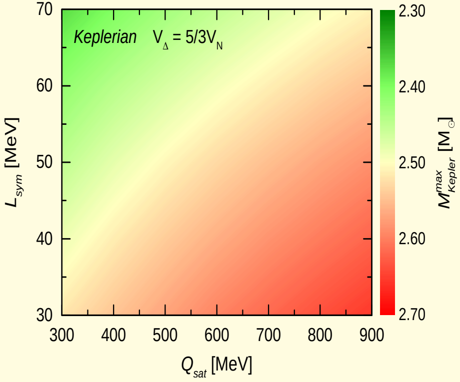
Mass-radius (a) mass-tidal deformability (b) for static N-stars. (c) Mass-radius for maximally rotating (Keplerian) sequences.



Mass-radius (a) mass-tidal deformability (b) for static $NY\Delta$-stars. (c) Mass-radius for maximally rotating (Keplerian) sequences.



Maximum masses of (a) static and (b) Keplerian *N*-stars.



Maximum masses for Keplerian $NY\Delta$-stars. The Δ potential $V_\Delta = 5/3V_N$, the maximal value studied.

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
- Universality can be used to extract the maximum mass of hot static compact stars from GW170817. arXiv:2102.00988

Relating the static and Keplerian properties of hot stars

- Maximum mass

$$M_K^\star(S/A, Y_e) = C_M^\star(S/A, Y_e) M_S^\star(S/A, Y_e) \ ,$$

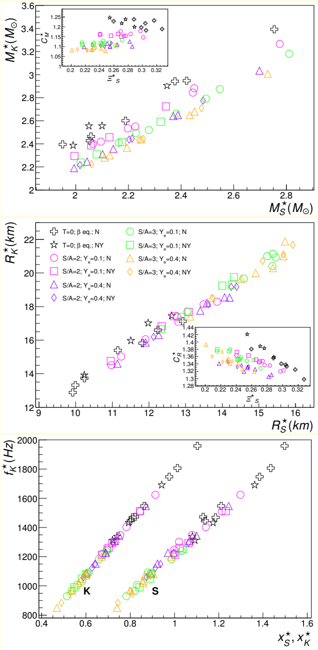
- Radius of maximum mass star

$$R_K^\star(S/A, Y_e) = C_R^\star(S/A, Y_e) R_S^\star(S/A, Y_e) \ ,$$

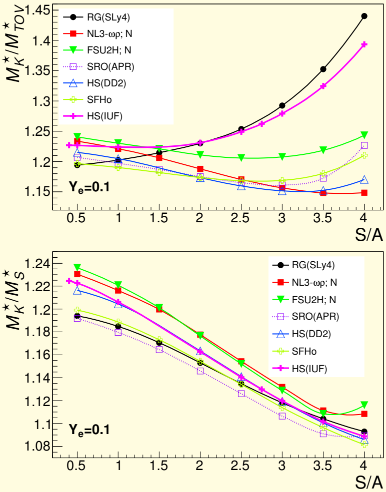
- Rotation frequency of maximum mass star

$$f_K^\star(S/A, Y_e) = C_f^\star(S/A, Y_e) x_S^\star(S/A, Y_e) \ ,$$

- And not only for the maximum of a sequence, but for arbitrary mass configurations, see S. Khadkikar, A. Raduta, M. Oertel, A. S. arXiv:2102.00988



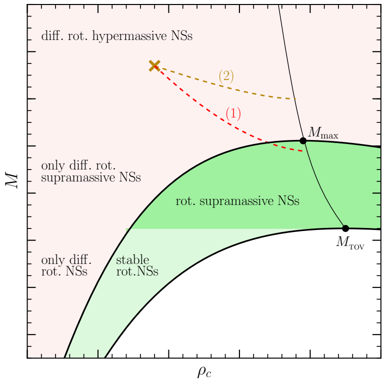
Universality for maximum mass objects.



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.

Maximum TOV mass from GW170817

Scenario supported by observations and numerical simulations (Margalit-Metzger 2017, Rezzolla et al 2018, Ruiz et al (2018), Shibata et al (2019a).]



- 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

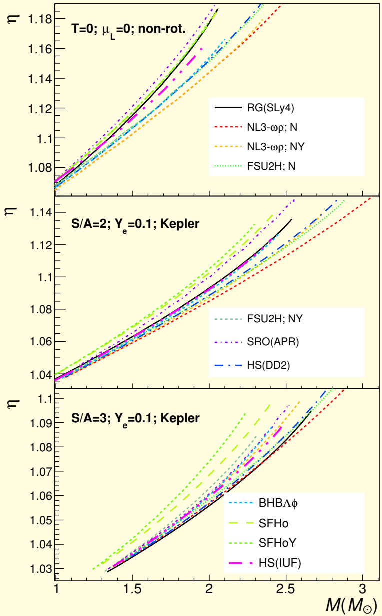
- The extraction of the upper limit circumvents the full dynamical study and uses the *baryon mass* conservation at *at merger* $t = 0$ *and collapse* $t = t_c$

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

- 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).



Dependence of the η parameter on the gravitational mass.

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 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 $1.35 \leq M/M_\odot \leq 1.6$
- 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 ± 0.036 and 0.091 ± 0.037 for $S/A = 2$ and 3 and $Y_e = 0.1$,
- Substituting the numerical values 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,

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

(2σ 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 $C_M^\star$.

In collaboration with:

Jia-Jie Li (Goethe-University → South Western University, China)

Arus Harutyunyan (Byurakan Astrophysical Observatory, Armenia)

Mark Alford (Washington University, St. Louis, USA)

Fridolin Weber (San Diego State University, USA)

Micaela Oertel (Meudon Observatory, France)

Adriana Raduta (INPN, Romania)

Further DFT developments (not covered in this talk)

- Hypernuclear Δ-admixed stars with anti-kaon condensation
  V. B. Thapa, M. Sinha, J. J. Li, A. Sedrakian, Phys. Rev. D 103, 063004 (2021)
- Hypernuclear Δ-admixed stars in strong magnetic fields
  V. B. Thapa, M. Sinha, J. J. Li, A.n Sedrakian, Particles 3(4), 660-675 (2020)

THANK YOU FOR THE ATTENTION