Current astrophysical constraints

Equation of state of dense matter

Integral parameters of compact stars

Phase transition to quark matter

Rapidly rotating hybrid stars and GW190814

Hypernuclear physics of compact stars constrained by gravitational-wave observations

Armen Sedrakian

Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar

FIAS Frankfurt Institute for Advanced Studies

Uniwersytet Wrocławski

DFG

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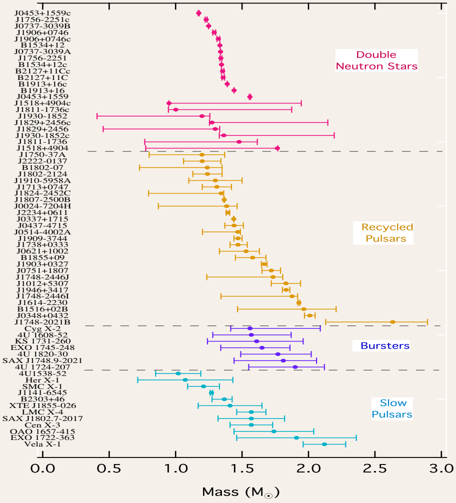
Measured masses and radii



The radii are less well determined, but NICER experiment predicts ~ 13 km for $1.4 M_{\odot}$.

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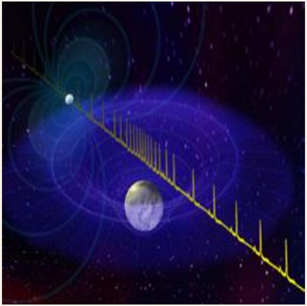
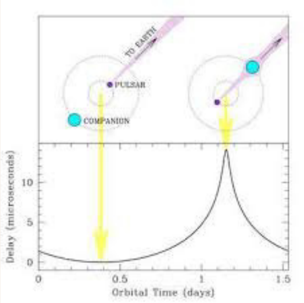
Three two-solar-mass neutron stars in binaries with WD





- 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.

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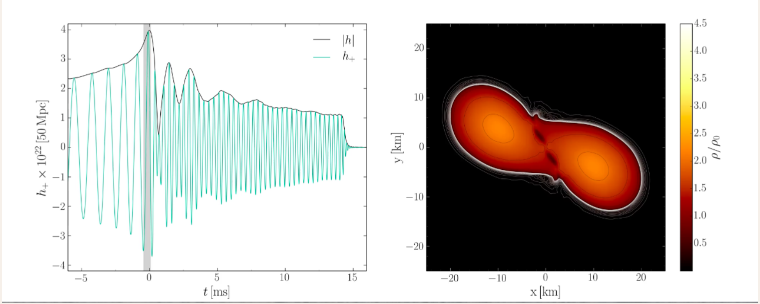
GW170817: First gravitational waves from a neutron star merger (Ligo-Virgo-Collaboration)



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

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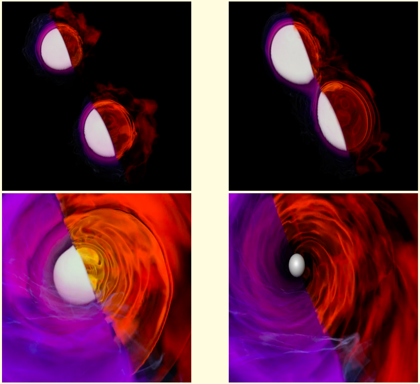


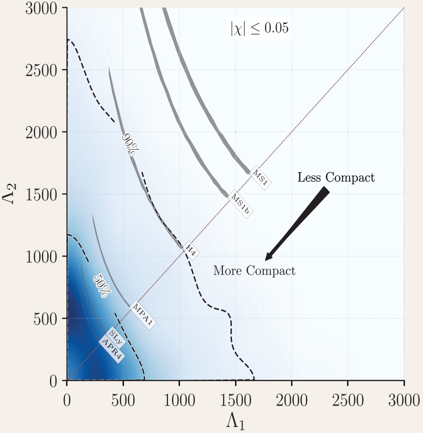
pictures courtesy: C. Breu, L. Rezzolla

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 $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
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 Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800	≤ 1400



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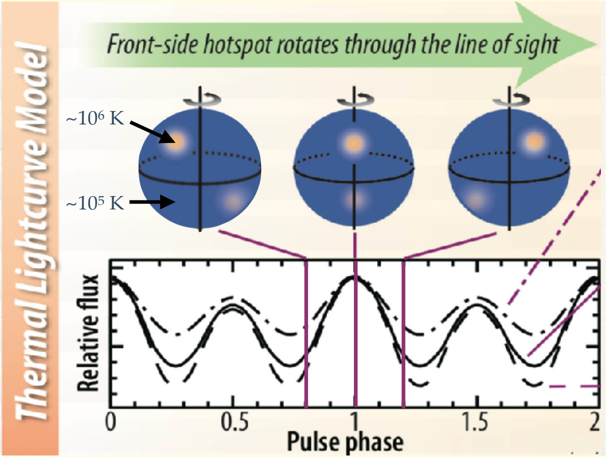

Pulse-profile modeling of the isolated 205.53 Hz millisecond pulsar PSR J0030+0451 observed in X-rays by NICER experiment:

- $1.44^{+0.15}_{-0.14} M_\odot$ –> $13.02^{+1.24}_{-1.06}$ km, Miller et al 2019.
- $1.34^{+0.15}_{-0.16} M_\odot$ –> $12.71^{+1.14}_{-1.19}$ km, Riley et al 2019.

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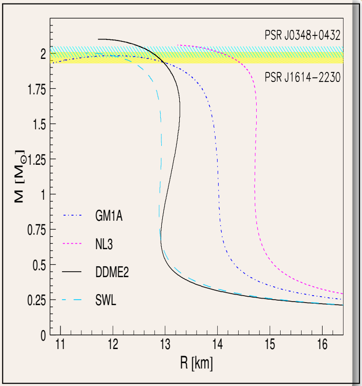
- Einstein's field equations:

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

- 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:

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

$$M(r) = 4\pi \int_0^r r^2 \epsilon(r) dr.$$

$$\boxed{P[\epsilon] \rightarrow M, R, I, Q, \ldots}$$

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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] (-)
- 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 (-)

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This talk

- Relativistic covariant DFT based on the DDME-2 parametrization and its variants
- Constraints from laboratory, astrophysics and *ab initio* calculations
- Examples of implementation in astrophysics of compact stars:

  (a) Equation of state, $M - R$ relation and deformability (GW170817)

  (b) First order phase transition to quark phase(s)

  (c) Rapid rotation and large masses (GW190814)

In collaboration with:

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

Fridolin Weber (San Diego State University, USA)

References:

- Equation of state: Eur. Phys. J. A 54, 133 (2018)
  Phys. Lett. B 783, 234, (2018)
  Phys. Rev. C 100, 015809 (2019)
- Deformabilities: Astrophys. J. Lett 874, L22 (2019)
- QCD-phase transition: Phys. Rev. D 101, 063022 (2020)
- Rapid rotation: Phys. Rev. D 102, 041301 (2020)
  Phys. Lett. B 810, 135812 (2020)

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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 $B \equiv p, n$
- 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.)

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Fixing the couplings: nucleonic sector

$$g_{iN}(\rho_B) = g_{iN}(\rho_0)h_i(x), \qquad h_i(x) = a_i\frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2} \quad i=\sigma,\omega,$$

$$g_{\rho N}(\rho_B) = g_{\rho N}(\rho_0)\exp[-a_\rho(x-1)], \quad i=\rho,(\pi-HF)$$

– DD-ME2 parametrization, Phys. Rev. C 71, 024312 (2005), Lalazissis, Vretrenar, Ring
– Similar to DD2 parametrizations (S. Typel)

	σ	ω	ρ
m_i [MeV]	550.1238	783.0000	763.0000
$g_{Ni}(\rho_0)$	10.5396	13.0189	3.6836
a_i	1.3881	1.3892	0.5647
b_i	1.0943	0.9240	—
c_i	1.7057	1.4620	—
d_i	0.4421	0.4775	—

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

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Thermodynamics

Energy stress tensor for any generic field ϕ_i and its relevant components

$$T^{\mu\nu} = \frac{\partial \mathscr{L}}{\partial(\partial_\mu \phi_i)}\partial^\nu \phi_i - g^{\mu\nu}\mathscr{L}, \quad \rightarrow \quad \mathscr{E} \quad = \quad \langle T^{00}\rangle, \quad \mathscr{P} = \frac{1}{3}\sum_i \langle T^{ii}\rangle.$$

For the baryonic component

$$\mathscr{E}_B \quad = \quad \frac{\gamma_B}{2\pi^2}\int_0^{k_{F,B}} k^2 dk \left[T_B(k) + \frac{1}{2}V_B(k)\right],$$

$$T_B(k) \quad = \quad \hat{P}_B k_B + \hat{M}_B M_B, \quad V_B(k) = \hat{M}_B \Sigma_{S,B}(k) + \hat{P}_B \Sigma_{V,B}(k) - \Sigma_{0,B}(k),$$

with

$$\hat{P} = \vec{k}^*/E^* \quad \hat{M} = M^*/E^* \quad \vec{k}^* = \vec{k} + \hat{k}\Sigma_V \quad M^* = M + \Sigma_S.$$

Thermodynamic consistency requires:

$$\mathscr{P}_B = \rho_B^2 \frac{\partial \mathscr{E}_B}{\partial \rho_B}.$$

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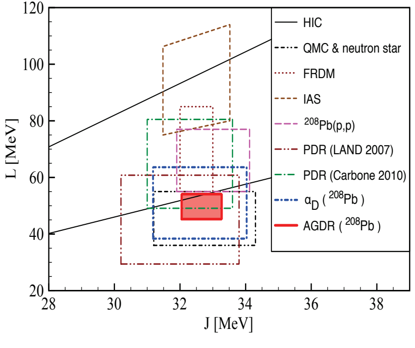
Taylor expansion of nuclear energy

$$\frac{E}{A}(\rho,\beta) = E_0 + E_{\rm sym}\beta^2 + L\beta^2\delta + \frac{1}{2!}(K_0 + K_{\rm sym}\beta^2)\delta^2 + \frac{1}{3!}Q_{\rm sat}\delta^3 + \mathcal{O}(\dots)$$

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

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 $K_0 = 250.90$ MeV,
- symmetry energy $E_{\rm sym} = 32.30$ MeV,
- symmetry energy slope $L = 51.24$ MeV,
- symmetry incompressibility $K_{\rm sym} = -87.19$ MeV
- higher order $Q_{\rm sat} = 479$ $Q_{\rm sym} = 777$ MeV



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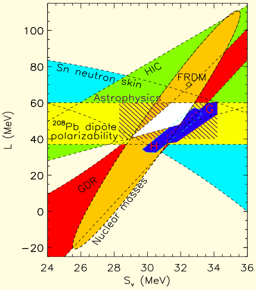
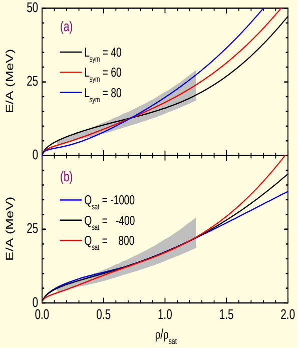
Consistency between the density functional with experiment and ab initio theory





Lagrangian parameters can be replaced by *physical parameters (characteristics)* at saturation (Margueron, et al. 2018):

$\rho_0 = 0.152\ \mathrm{fm}^{-3}$, $E/A = -16.14$ MeV, $K_0 = 250.90$ MeV, (leading order)
$E_{\mathrm{sym}} = 32.30$ MeV, $L = 51.24$ MeV, (next-to-leading order)
$K_{\mathrm{sym}} = -87.19$ MeV (3rd order)

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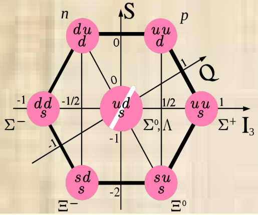
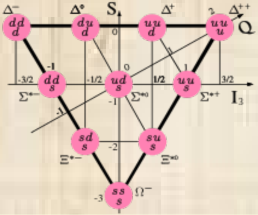
Beyond nucleons: Baryon octet $J^p = 1/2^+$ and baryon decuplet $J^p = 3/2^+$

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.

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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

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

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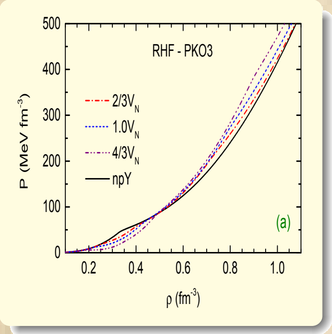
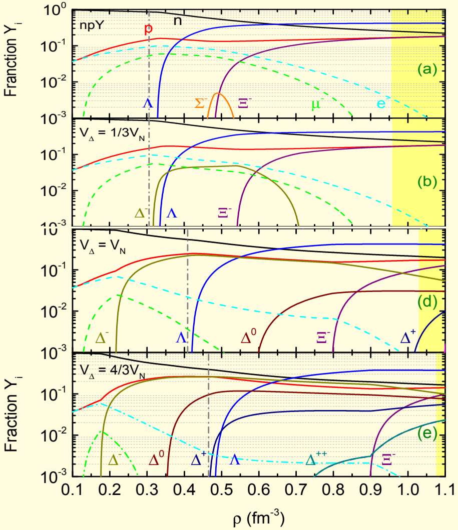


EoS and MR-relations for hyperonic and Δ-admixed models. Inclusion of Δ-resonances with different potential depths: strong reduction of the radius.



Large population ($\sim 20\%$) of heavy baryons. Λ population dominates at asymptotically large densities.

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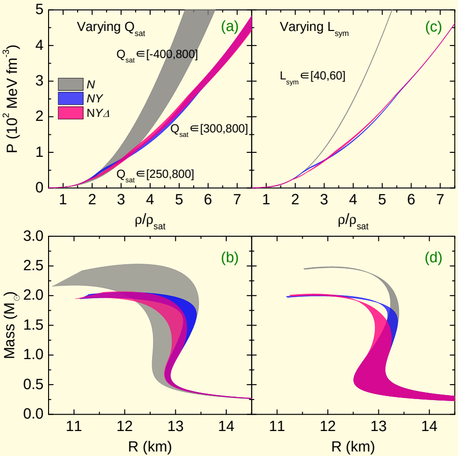

EoS models and MR relations for N, NY, and $NY\Delta$ compositions of stellar matter with the DDME2 parametrization. The bands are generated by varying the parameters $Q_{\rm sat}$ [MeV] (a, b) and $L_{\rm sym}$ [MeV] (c, d). The ranges of $Q_{\rm sat}$ and $L_{\rm sym}$ allowed by χEFT and maximum mass constraints are indicated in the figures.

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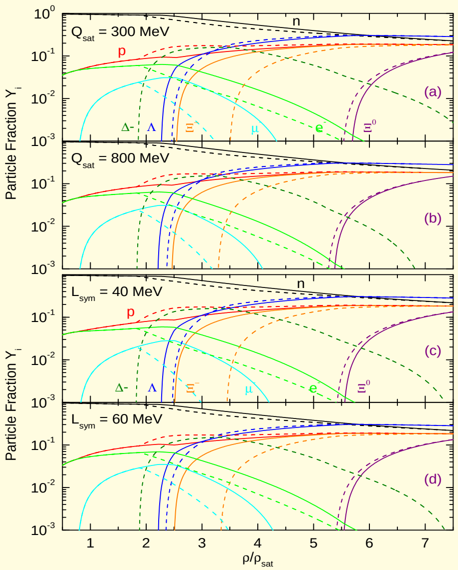
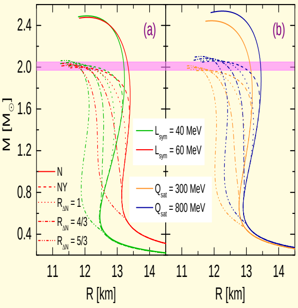
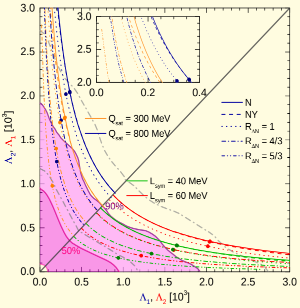


Dependence of particle abundances on characteristics $L_{\rm sym}$ and $Q_{\rm sat}$.





Tidal deformabilities

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

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.

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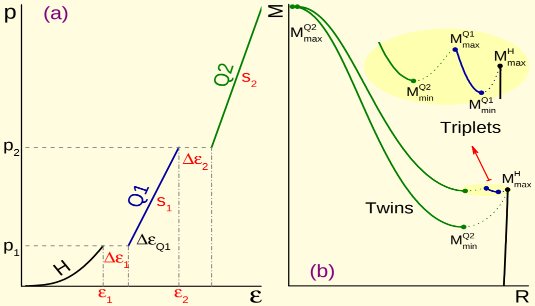

Left: EoS with two sequential phase transitions. *Right:* Mass-radius relationships, emergences of minima in the function $M(R)$.

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).

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

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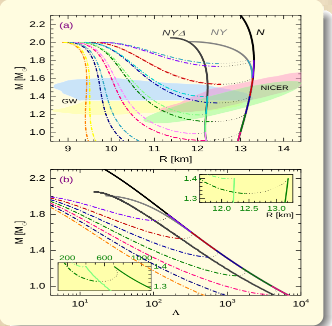
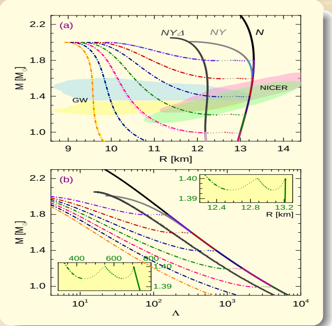
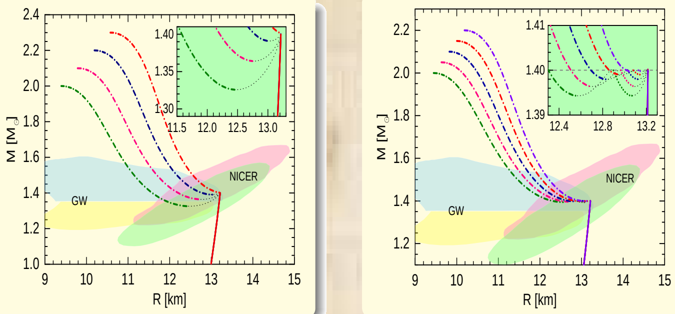


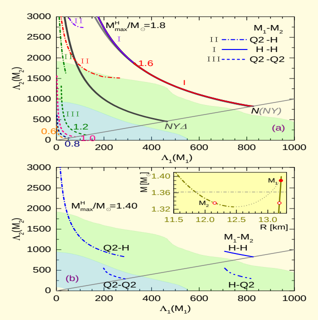


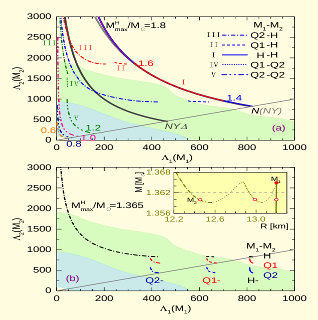
(a) Mass-radius relation for hybrid stars with a single (left) and double (right) phase transition(s), with three different hadronic envelopes: nucleonic (N), hyperonic (NY) and Δ-resonance–hyperon admixed ($NY\Delta$).
Each hybrid star branch bifurcates from a hadronic sequence at $M^{\rm H}_{\rm max}/M_\odot = 0.60$-$1.80$. (hyperons appear in the two cases: $M^{\rm H}_{\rm max}/M_\odot = 1.60$ and 1.80). In each case the maximum mass of the hybrid branch is fixed at $M^{\rm Q2}_{\rm max}/M_\odot = 2.00$.

(b) Mass-deformability relation for the configurations shown in (a) (only We NY or $NY\Delta$ envelopes). The inset has $M^{\rm H}_{\rm max}/M_\odot = 1.40$. The smaller radius (deformability) curve corresponds to $NY\Delta$ envelope stars, whereas the larger ones - to N-NY envelope stars.



Mass-radius relation for hybrid EoS with single (left) and double (right) phase transitions and nucleonic envelope. The EoS are identified by the maximum mass $M^{\rm Q2}_{\rm max}/M_\odot = 2.00\text{-}2.20$, and the maximum mass of the hadronic star which is fixed at $M^{\rm H}_{\rm max}/M_\odot = 1.40$. The emergence of twin configurations is shown in the inset.





(a) Tidal deformabilities of compact objects with a single (left) and double (right) phase transition(s) for a fixed value of binary chirp mass $\mathcal{M} = 1.186M_\odot$. The are three types of pairs on the left and six pairs on the right (labelled by numerals I-VI). (b) The same as in (a) but for fixed$M^{\rm H}_{\rm max} = 1.40M_\odot$. The shaded regions correspond to the 50% and 90% credibility regions taken from the analysis of GW170817 within PhenomPNRT model. The inset shows the mass-radius relation around the phase transition region. The open circles (labeled M_2) are the masses of two possible companions for the star of mass M_1 (full circle) for a fixed value of binary chirp mass $\mathcal{M} = 1.186M_\odot$.

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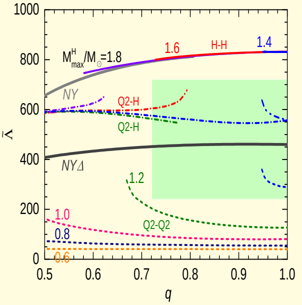

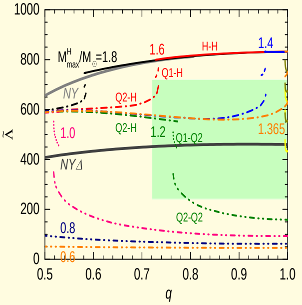

Mass weighted deformability vs. mass asymmetry for a binary system with fixed chirp mass $\mathcal{M} = 1.186 M_\odot$ predicted by a range of hybrid EoS with single phase transition and various values of $M^{\rm H}_{\rm max}$. The error shading indicates the constraints estimated from the GW170817 event and the electromagnetic transient AT2017gfo.

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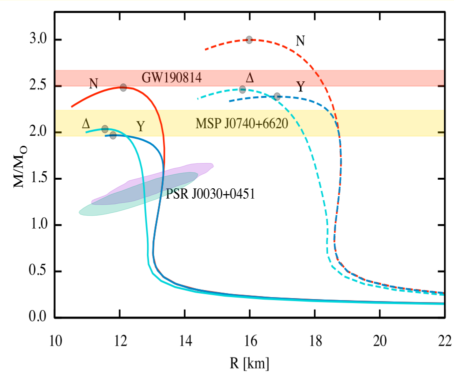
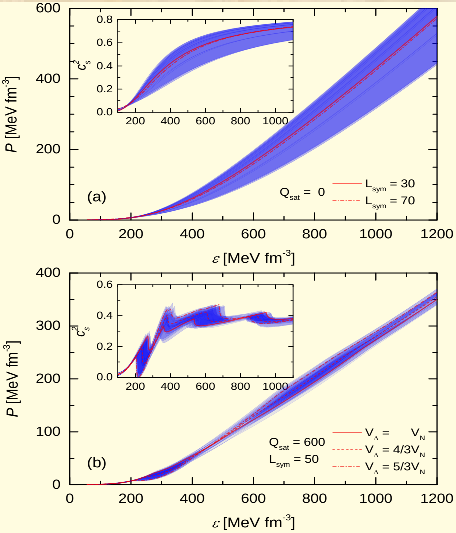
– GW190814 event: extreme mass asymmetric ratio created by a $22.2 - 24.3\,M_\odot$ black hole and a $2.50 - 2.67\,M_\odot$ compact object (no em counterpart).

– 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 $\in [300, 900]$, $_{\rm sym} \in [30, 70]$ $V_D/V_N = 1, 4/3$ and $5/3$ EoSs with $Q = 600$, $L_{\rm sym} = 50$ and three indicated values of V_D are shown for illustration.

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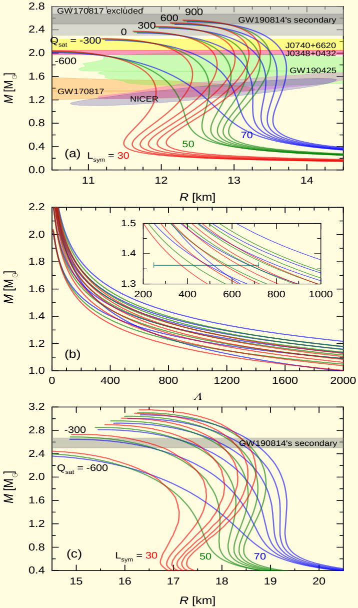

Mass-radius (a) mass-tidal deformability (b) for static *N*-stars. (c) Mass-radius for maximally rotating (Keplerian) sequences.

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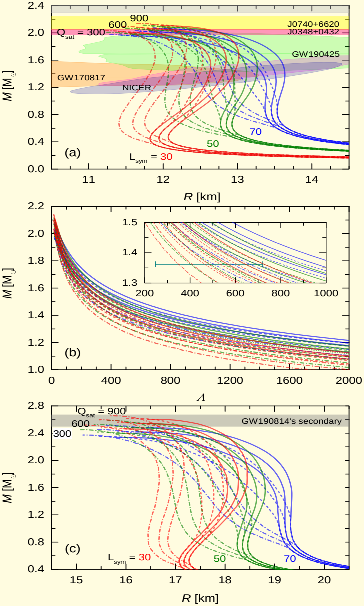
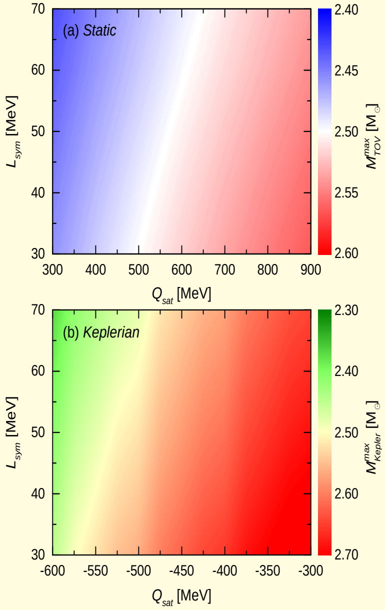
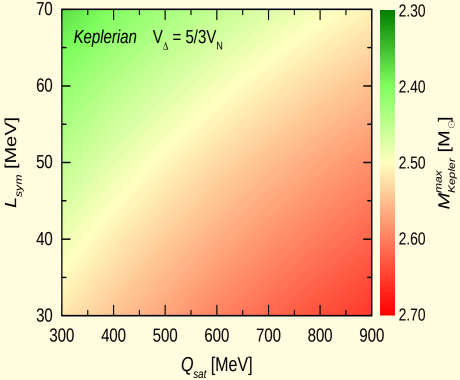


Mass-radius (a) mass-tidal deformability (b) for static $NY\Delta$-stars. (c) Mass-radius for maximally rotating (Keplerian) sequences.



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



Maximum masses of (a) static and (b) Keplerian $NY\Delta$-stars. The Δ potential $V_\Delta = 5/3V_N$, the maximal value studied.

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Further DFT developments (not covered in this talk)

- Hot compact stars, universal relations, limits on the maximum mass, S. Khadkikar, A. R. Raduta, M. Oertel, A. Sedrakian, arXiv:2102.00988, arXiv:2008.00213
- Hypernuclear Δ-admixed stars with anti-kaon condensation: V. B. Thapa, M. Sinha, J. J. Li, A. Sedrakian, arXiv:2102.08787
- Hypernuclear Δ-admixed stars in strong magnetic fields: V. B. Thapa, M. Sinha, J. J. Li, A. Sedrakian, arXiv:2010.00981