# Report on collection of EoS to be used for injections

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## 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

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- 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.

## Nuclear matter Lagrangian:

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

- $B$-sum is over the baryonic octet
- Meson fields include $\sigma$ meson, $\boldsymbol{\rho}_\mu$-meson and $\omega_\mu$-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) | $a_i$ | $b_i$ | $c_i$ | $d_i$ | $g_{iN}$ |
|---|---|---|---|---|---|---|
| $\sigma$ | 550.1238 | 1.3881 | 1.0943 | 1.7057 | 0.4421 | 10.5396 |
| $\omega$ | 783 | 1.3892 | 0.9240 | 1.4620 | 0.4775 | 13.0189 |
| $\rho$ | 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)

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Current astrophysical constraints

Equation of state of dense matter

Phase transition to quark matter

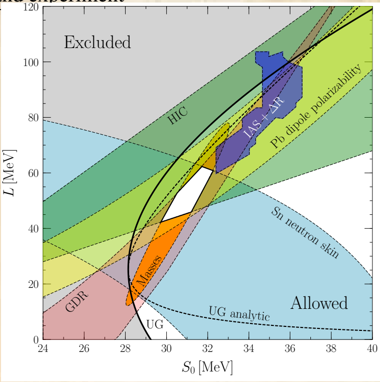
## Taylor expansion of nuclear energy

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

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

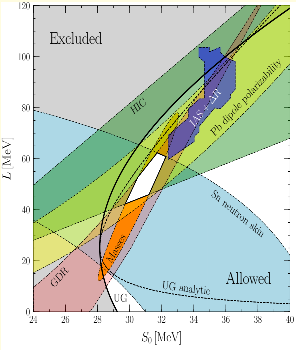
## Consistency between the density functional and experiment

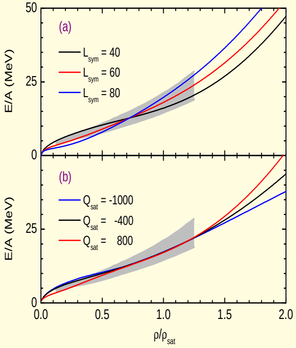
- saturation density $\rho_0 = 0.152\ \mathrm{fm}^{-3}$
- binding energy per nucleon $E/A = -16.14$ MeV,
- incompressibility $K_{sat} = 251.15$ MeV,
- skweness $Q_{sat} = 479$
- symmetry energy $E_{sym} = 32.30$ MeV,
- symmetry energy slope $L_{sym} = 51.27$ MeV,
- symmetry incompressibility $K_{sym}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



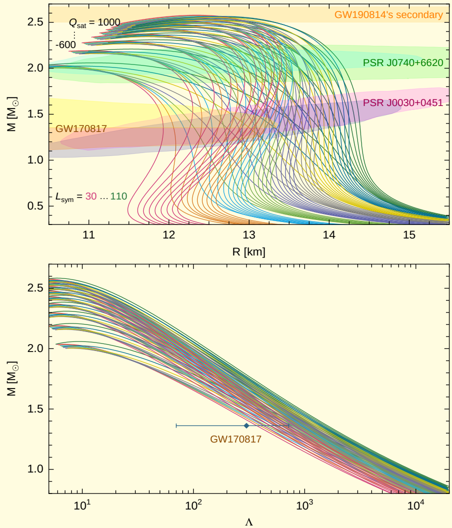

Credit: Tews, et al ApJ, 2017

## Consistency between the density functional with experiment and ab initio theory

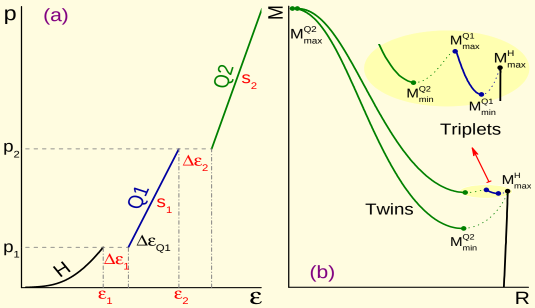



– Uncertainties will be quantified in terms of variation of higher-order characteristics around the central fit values.
– Low density physics depends strongly on the value of $L_{\rm sym}$ with strong correlation to the radius of the star and tidal deformability
– High-density physics strongly depends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



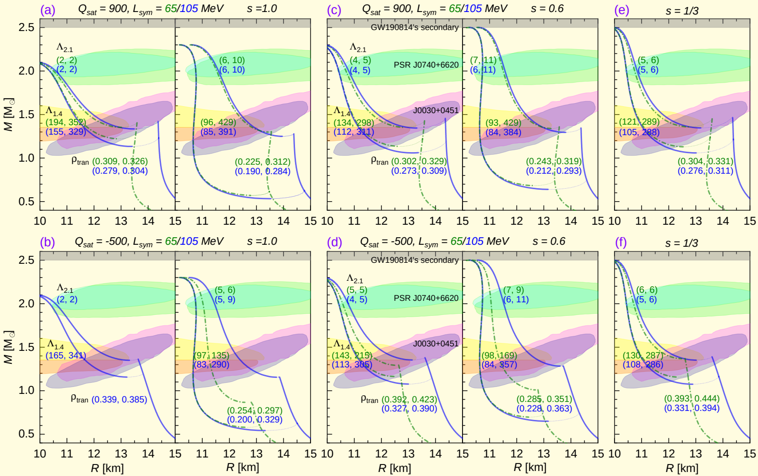

– Variation of $-600 \leq Q_{\rm sat} \leq 1000$ MeV and $30 \leq L \leq 110$
– Computed $9 \times 9 = 81$ matrix of EoS



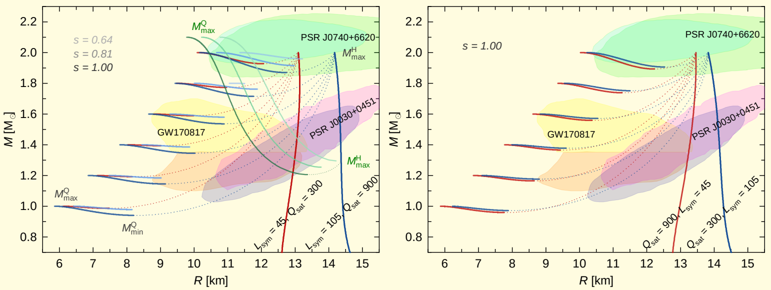

*Left:* EoS with two sequential phase transitions. *Right:* Mass-radius relationships, emergences of minima in the function $M(R)$.

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).

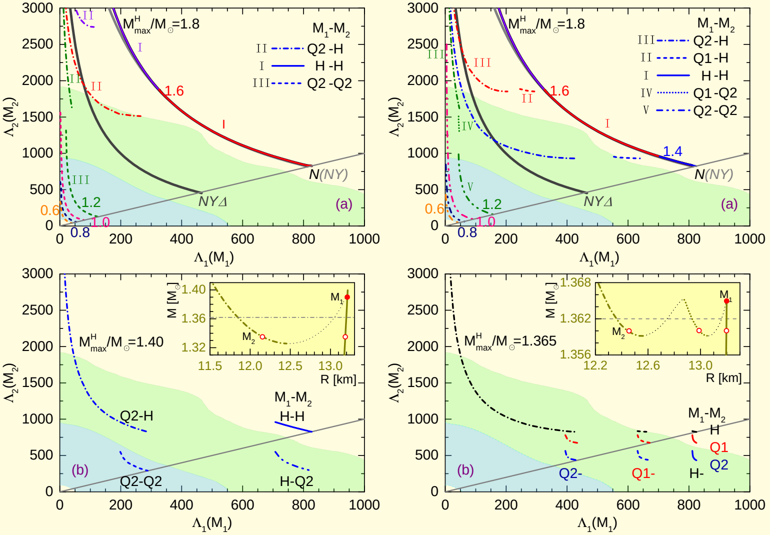
$$p(\varepsilon) = \begin{cases} p_1, & \varepsilon_1 < \varepsilon < \varepsilon_1 + \Delta\varepsilon_1 \\ p_1 + s_1\left[\varepsilon - (\varepsilon_1 + \Delta\varepsilon_1)\right], & \varepsilon_1 + \Delta\varepsilon_1 < \varepsilon < \varepsilon_2 \\ p_2, & \varepsilon_2 < \varepsilon < \varepsilon_2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



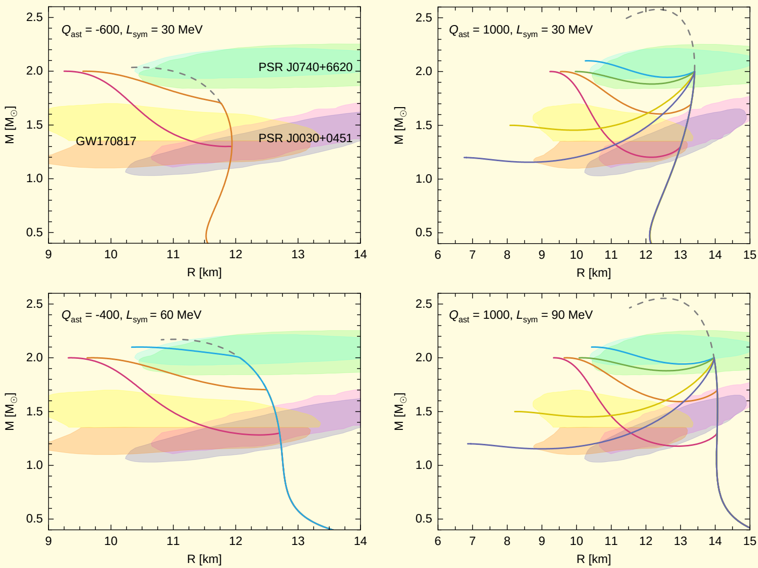

Low-density quark-hadron phase transition case.




High-density phase transition case.




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




Models available in the injection format.