Neutron Stars Structure and Twins

Hovik Grigorian

Mescheryakov Laboratory of IT, JINR
A. Alikhanyan National Science Laboratory (AANL)
Yerevan State University

INFINUM Dubna Workshop on
“ *Infinite and Finite Nuclear Matter* ”
27 February- 3 March 2023, Dubna

Collaborators

- Alexander Ayriyan (LIT & AANL),
  David Blaschke (UW & JINR & MEPhI),
  Dmitry Voskresensky (MEPhI & JINR),
  Konstantin Maslov (MEPhI & JINR)
  David-Edwin Alvarez-Castillo (JINR),
  Nobutoshi Yasutake (Chiba Institute of Technology),
  Vahagn Abgaryan (JINR & AANL)

Star Structure analysis for extracting properties of the nuclear EoS models

- Outline

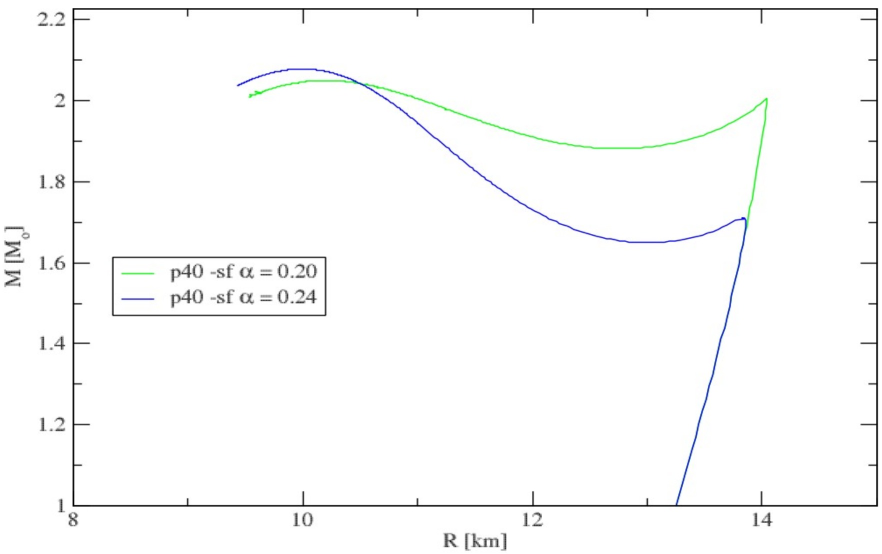
  I. Motivation

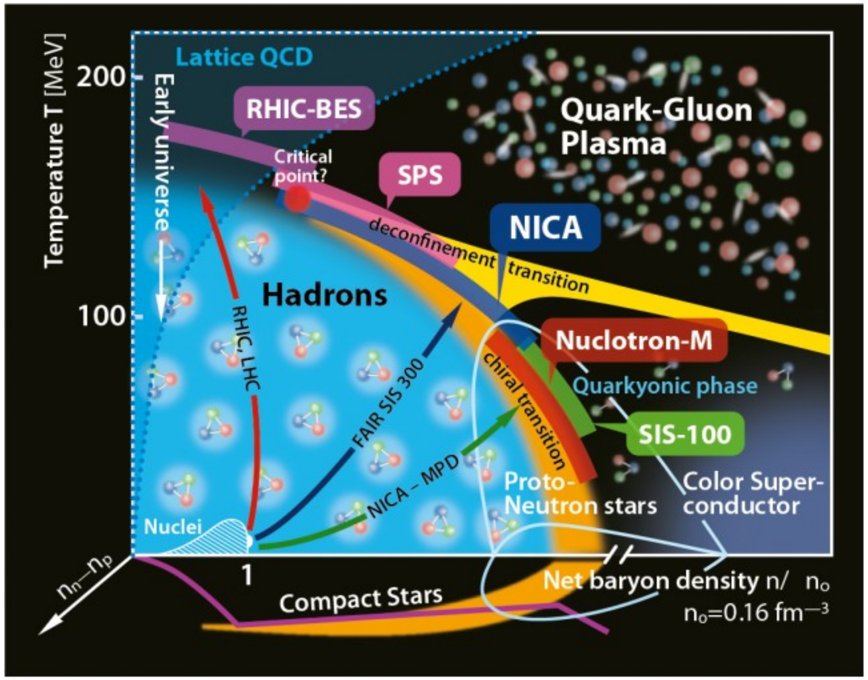
  II. Mixed phase construction for cold and dense nuclear matter

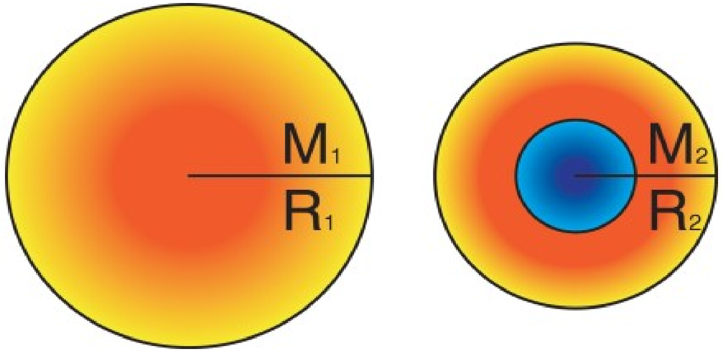
  III. Observational features of Neutron stars for extracting properties of the nuclear EoS

  IV. Conclusions

Motivation : What if we have twins ?

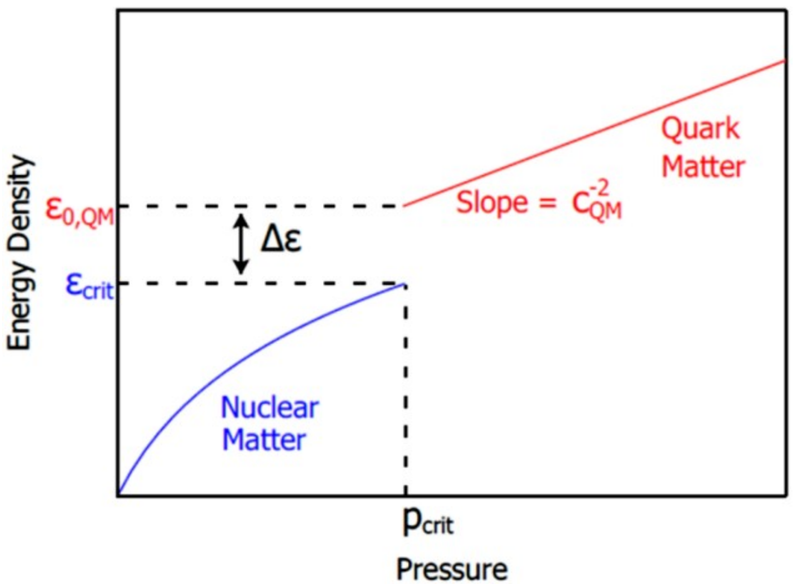


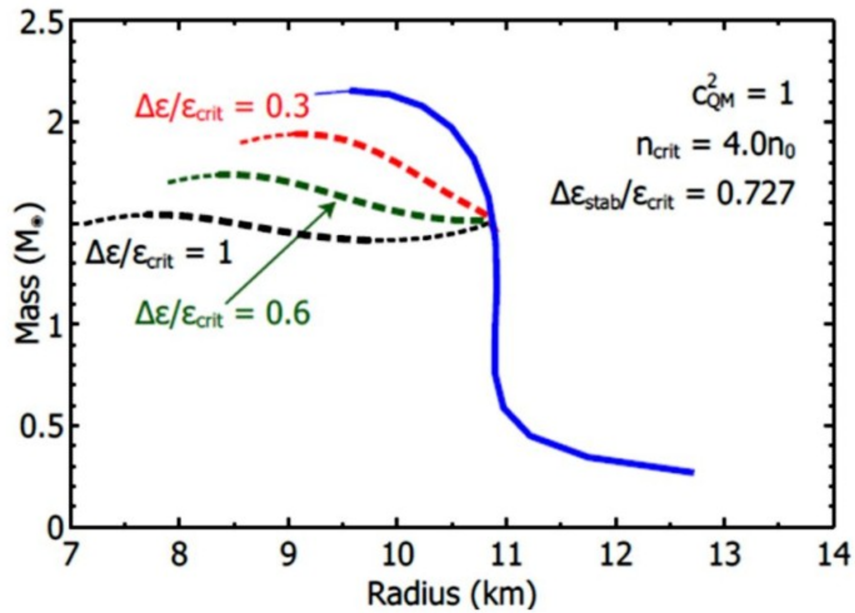




- Does hybrid neutron star exist?
- Does NS twin exist?
- Does CEP exist on QCD phase diagram?

Neutron star mass-radius relation





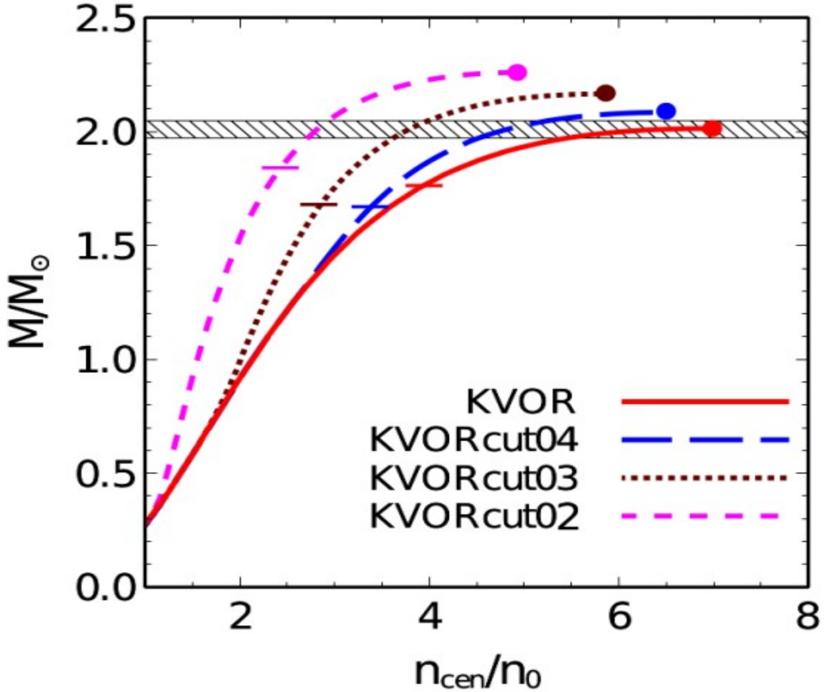
Seidov criterion for instability:

$$\frac{\Delta\varepsilon}{\varepsilon_{crit}} \geq \frac{1}{2} + \frac{3}{2}\frac{P_{crit}}{\varepsilon_{crit}}$$

Credit: Mark G. Alford, Sophia Han, and Madappa Prakash. Phys. Rev. D 88, 083013 (2013)

The realistic hadron and quark matter models

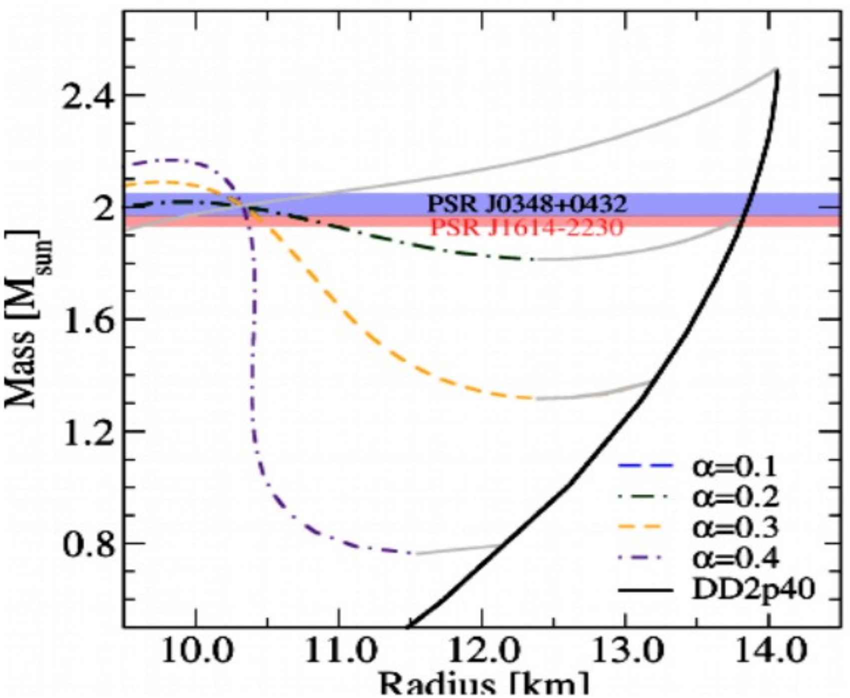
The hadron EoS model KVOR with modification of stiffness



Maslov, Kolomeitsev, Voskresensky, Nucl.Phys. A950 (2016)

Kolomeitsev & Voskresensky, Nuc. Phys. A 759 (2005)

The quark EoS model SFM with available volume fraction parameter



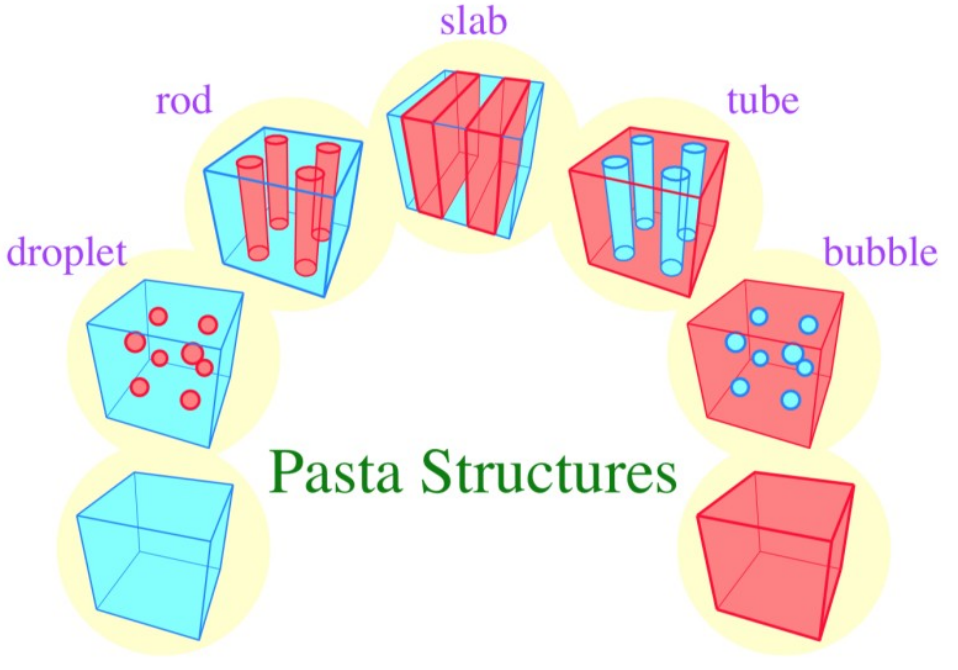
Kaltenborn, Bastian, Blaschke, Phys. Rev. D 96, 056024 (2017)

Finite-size effects in mixed phase

Coulomb interaction **vs** **Surface tension**

Tends to break up the like-charged regions into smaller ones

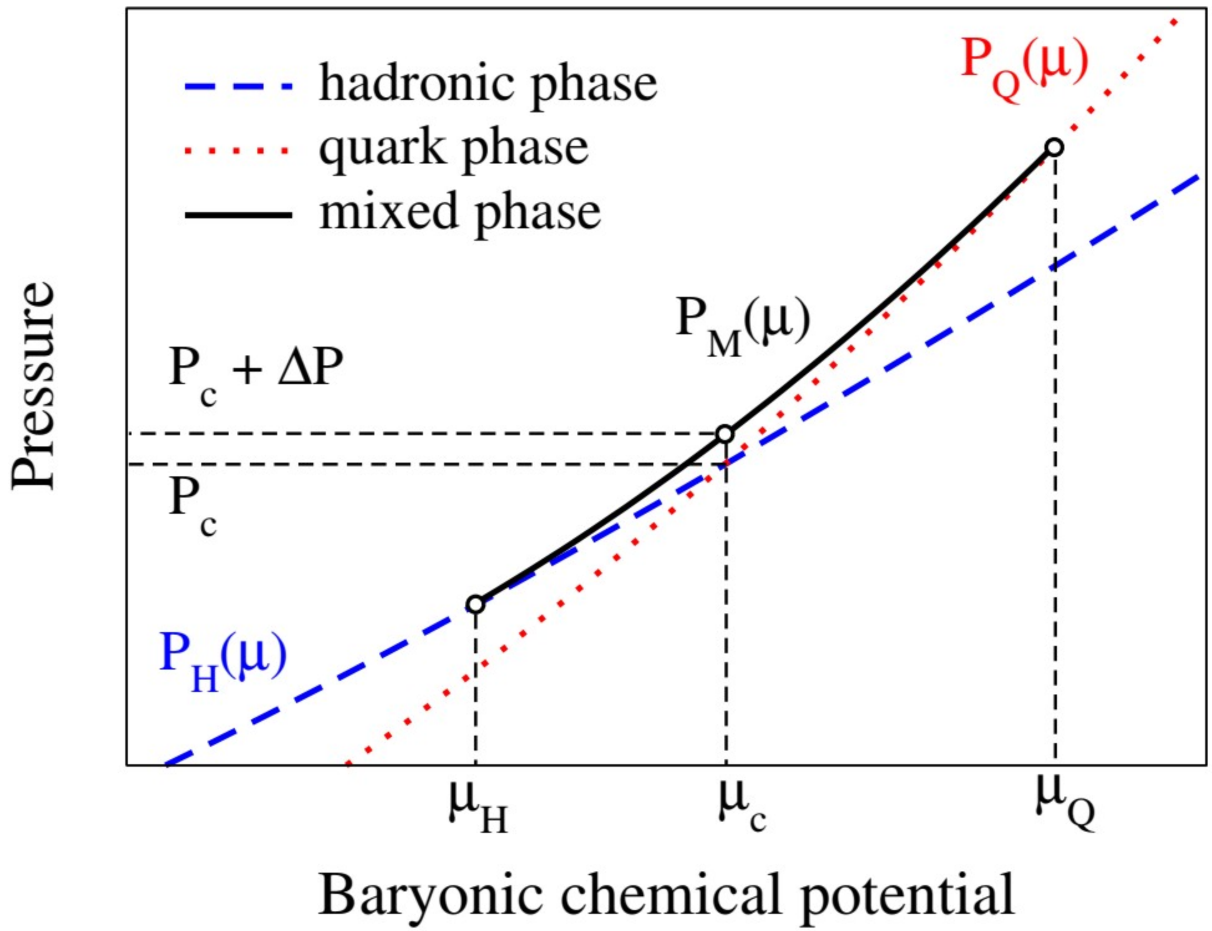
Requires minimization of the surface



The surface tension σ is unknown and used as free parameter.

Yasutake, Maruyama, Tatsumi, Phys. Rev. D80 (2009) 123009

Mimicking the Pasta phase.



Schematic representation of the interpolation function $P_M(\mu)$, it has to go though three points: $P_H(\mu_H)$, $P_c + \Delta P$ and $P_Q(\mu_Q)$.

The Interpolation Method

$$P_M(\mu) = \sum_{q=1}^{N} \alpha_q (\mu - \mu_c)^q + (1 + \Delta_P) P_c$$

where Δ_P is a free parameter representing additional pressure of the mixed phase at μ_c.

$$P_H(\mu_H) = P_M(\mu_H) \qquad P_Q(\mu_Q) = P_M(\mu_Q)$$

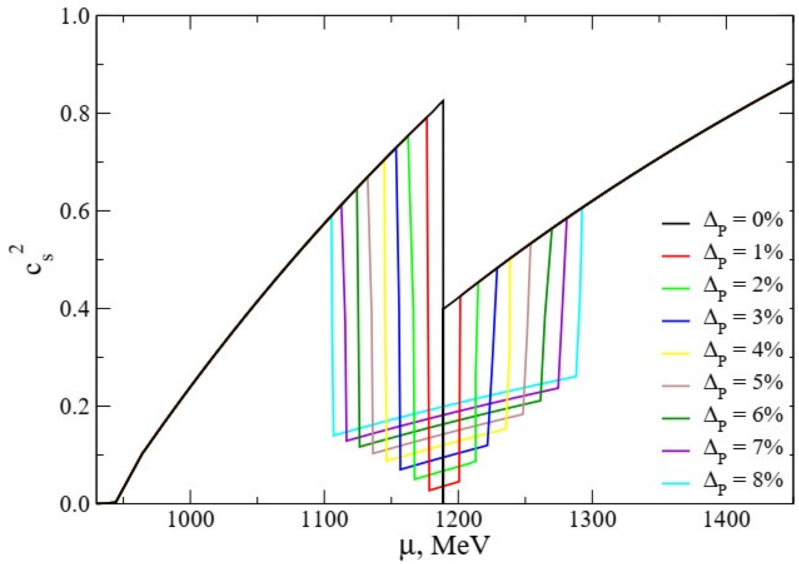
$$\frac{\partial^q}{\partial \mu^q} P_H(\mu_H) = \frac{\partial^q}{\partial \mu^q} P_M(\mu_H) \qquad \frac{\partial^q}{\partial \mu^q} P_Q(\mu_Q) = \frac{\partial^q}{\partial \mu^q} P_M(\mu_Q)$$

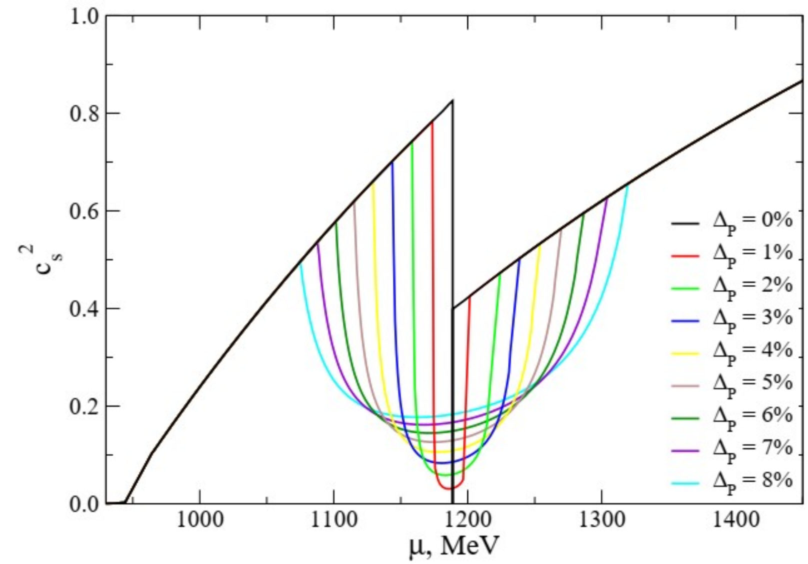
where $q = 1, 2, \ldots, k$. All $N + 2$ parameters (μ_H, μ_Q and α_q, for $q = 1, \ldots, N$) can be found by solving the above system of equations, leaving one parameter (ΔP) as a free one.

Ayriyan and Grigorian, *EPJ Web Conf.* **173**, 03003 (2018)

Abgaryan, Alvarez-Castillo, Ayriyan et al. *Universe* **4(9)**, 94 (2018)

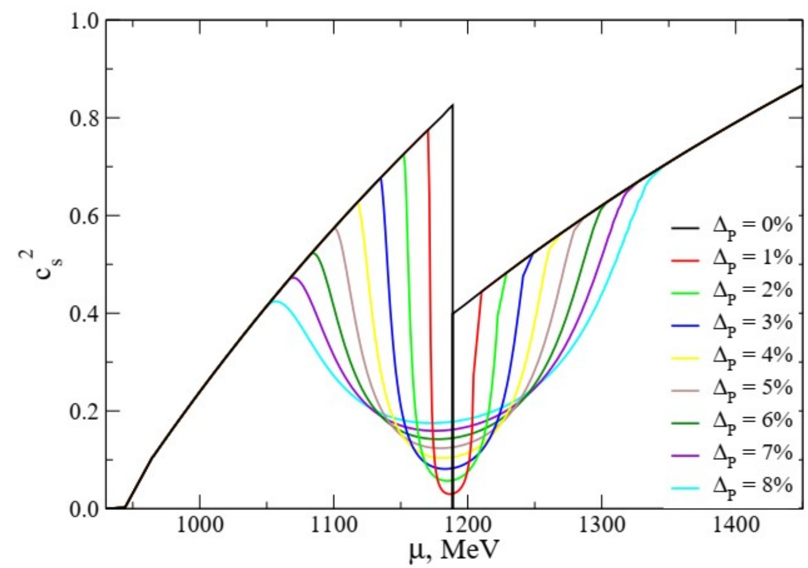
The Interpolation Method



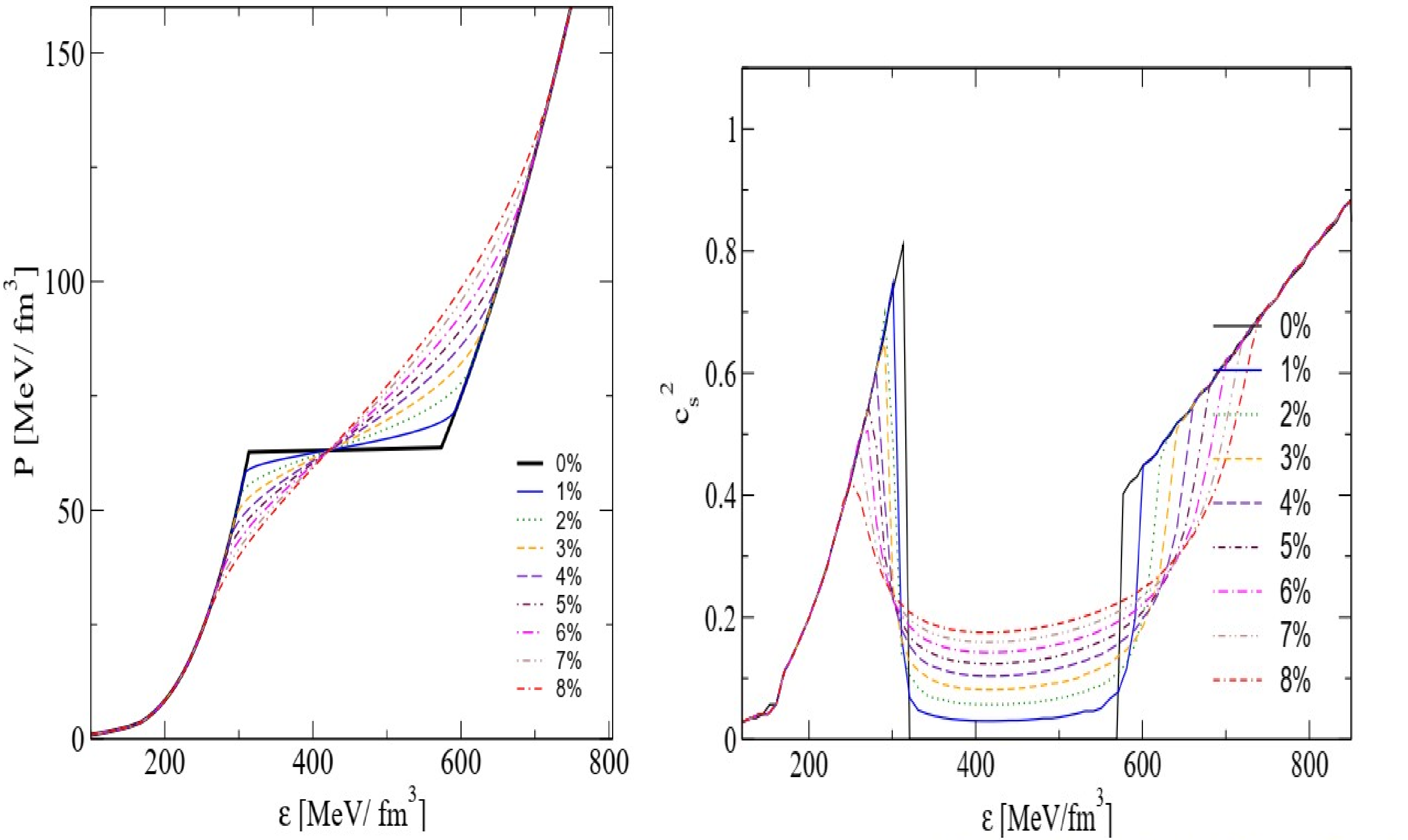


The squared speed vs chemical potential given by the interpolation with $k = 1$ (upper left) $k = 2$ (upper right) and $k = 3$ (right).

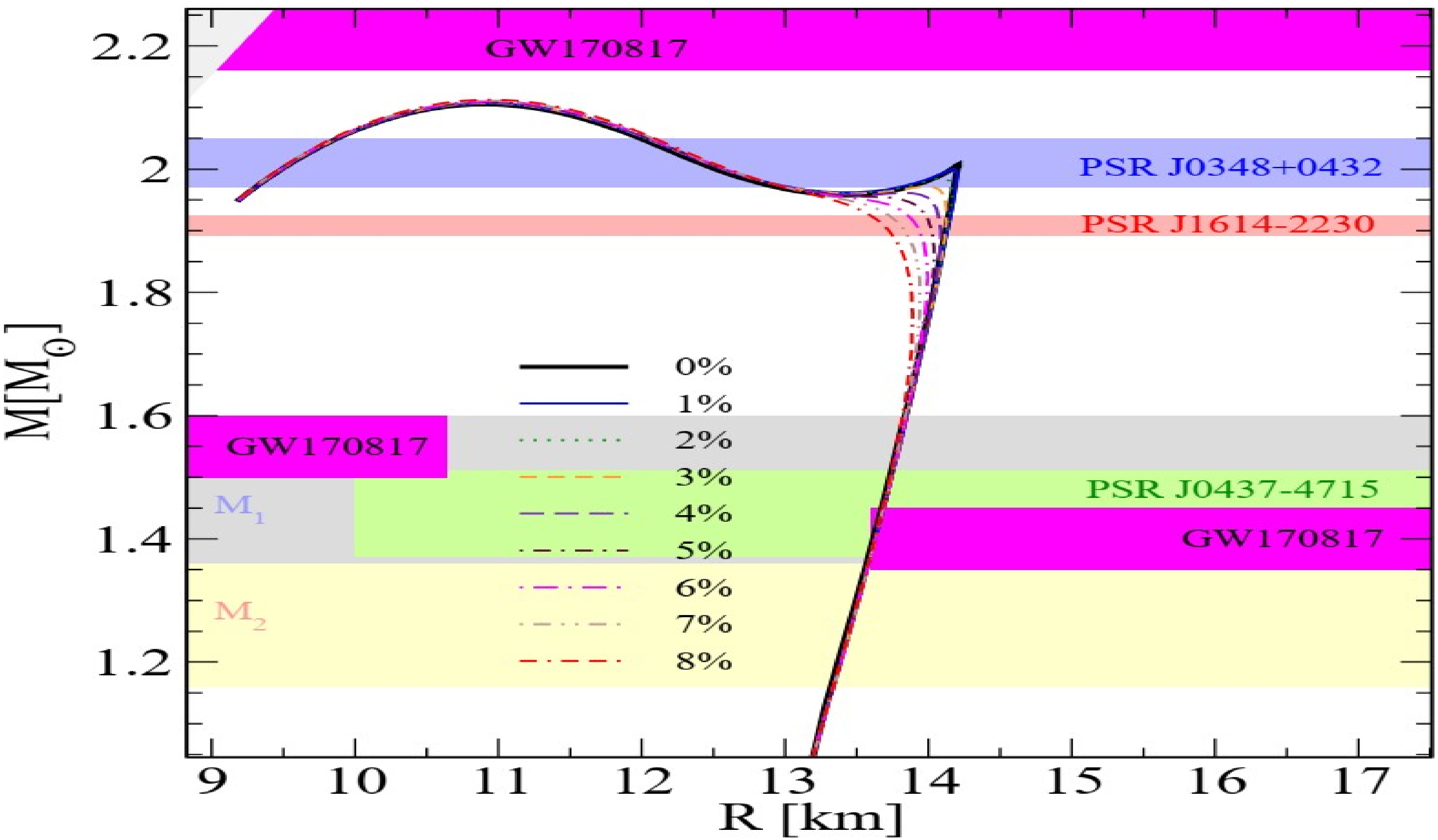
Abgaryan, Alvarez-Castillo, Ayriyan, Blaschke and Grigorian. Universe 4(9) (2018), 94



The results of pasta mimicking



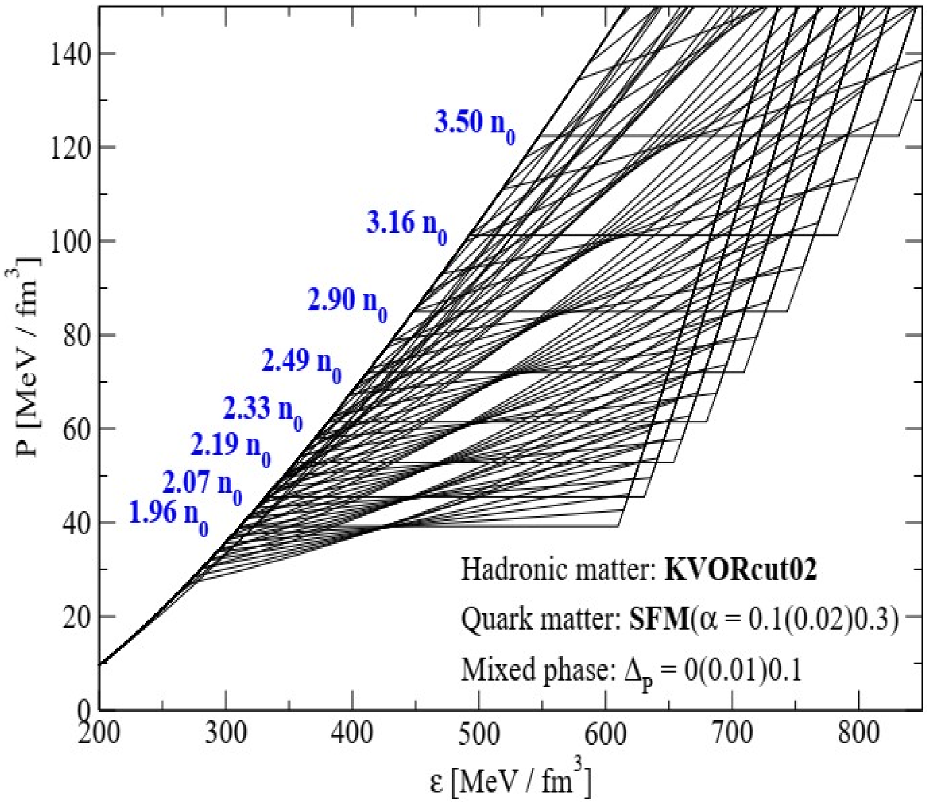
The results of pasta effects

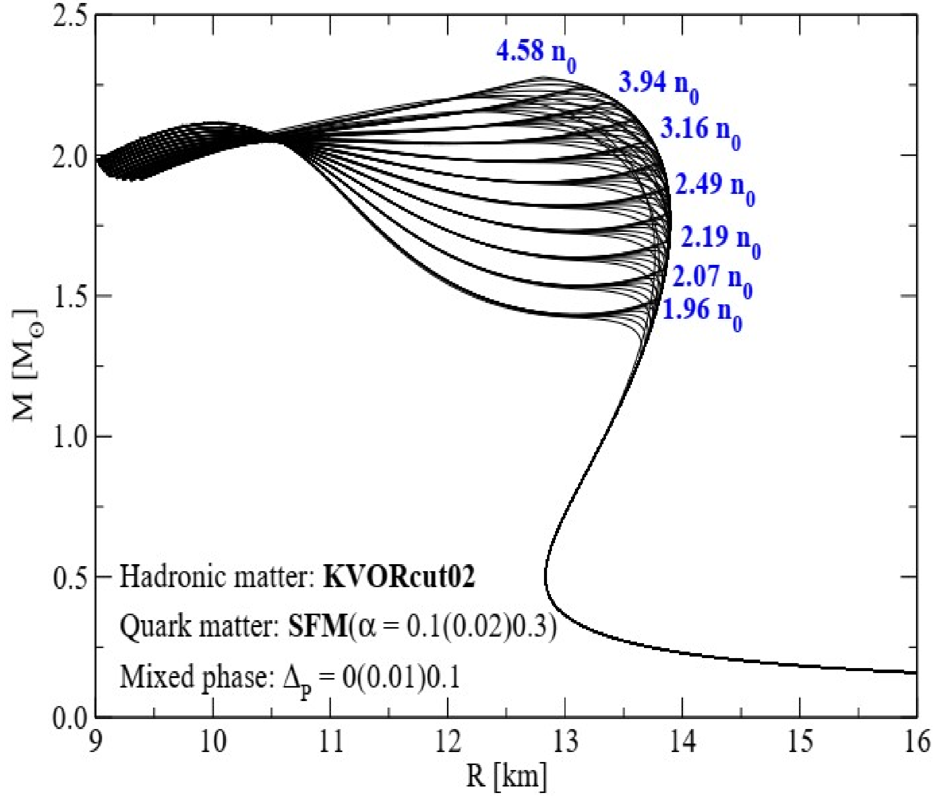


Third family robust against Δ_P up to around 5%!

Abgaryan, Alvarez-Castillo, Ayriyan et al. Universe 4(9), 94 (2018)

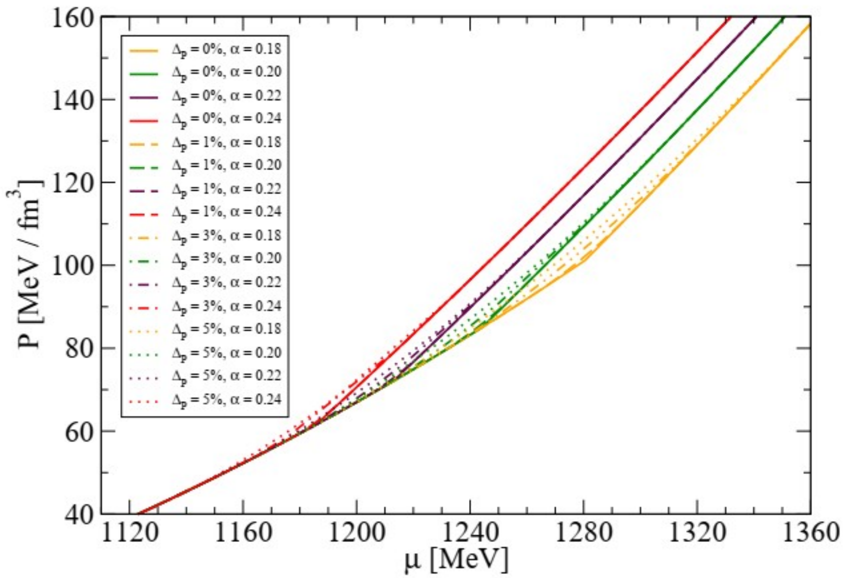
Robustness of third family solutions

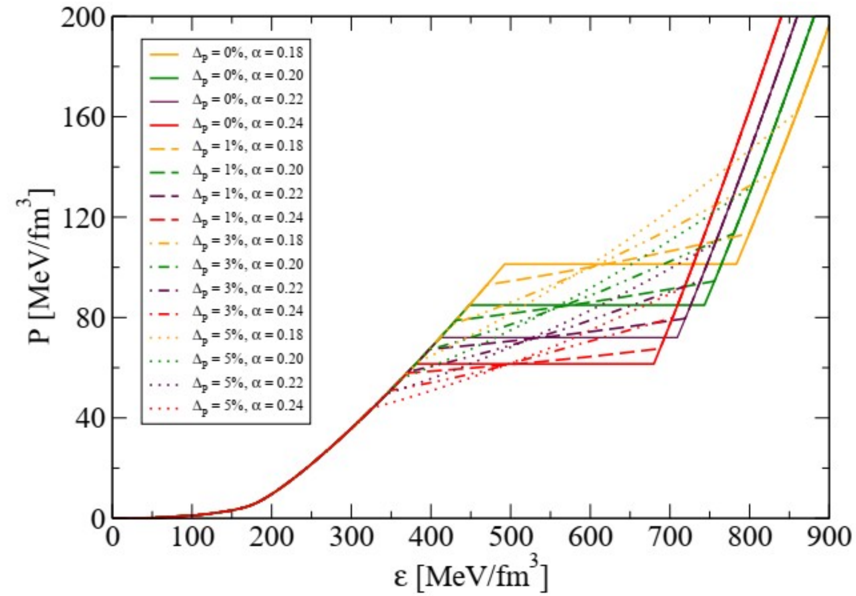


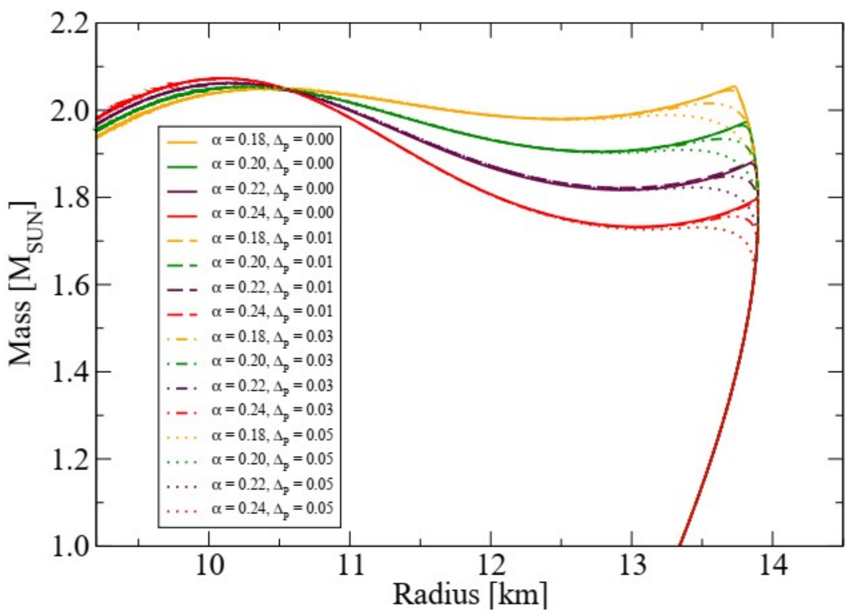


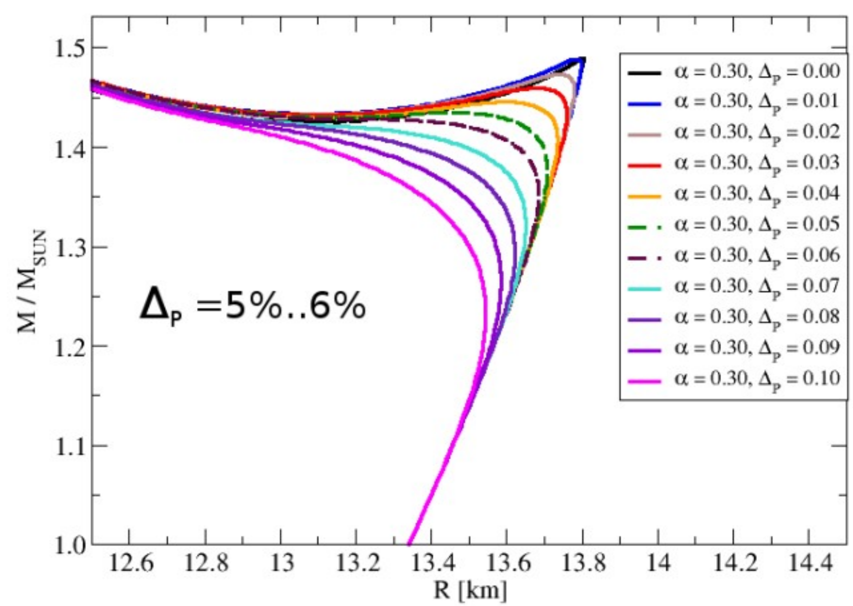
Ayriyan, Bastian, Blaschke, Grigorian, Maslov, Voskresensky. PRC 97, 045802 (2018)

Robustness of third family solutions

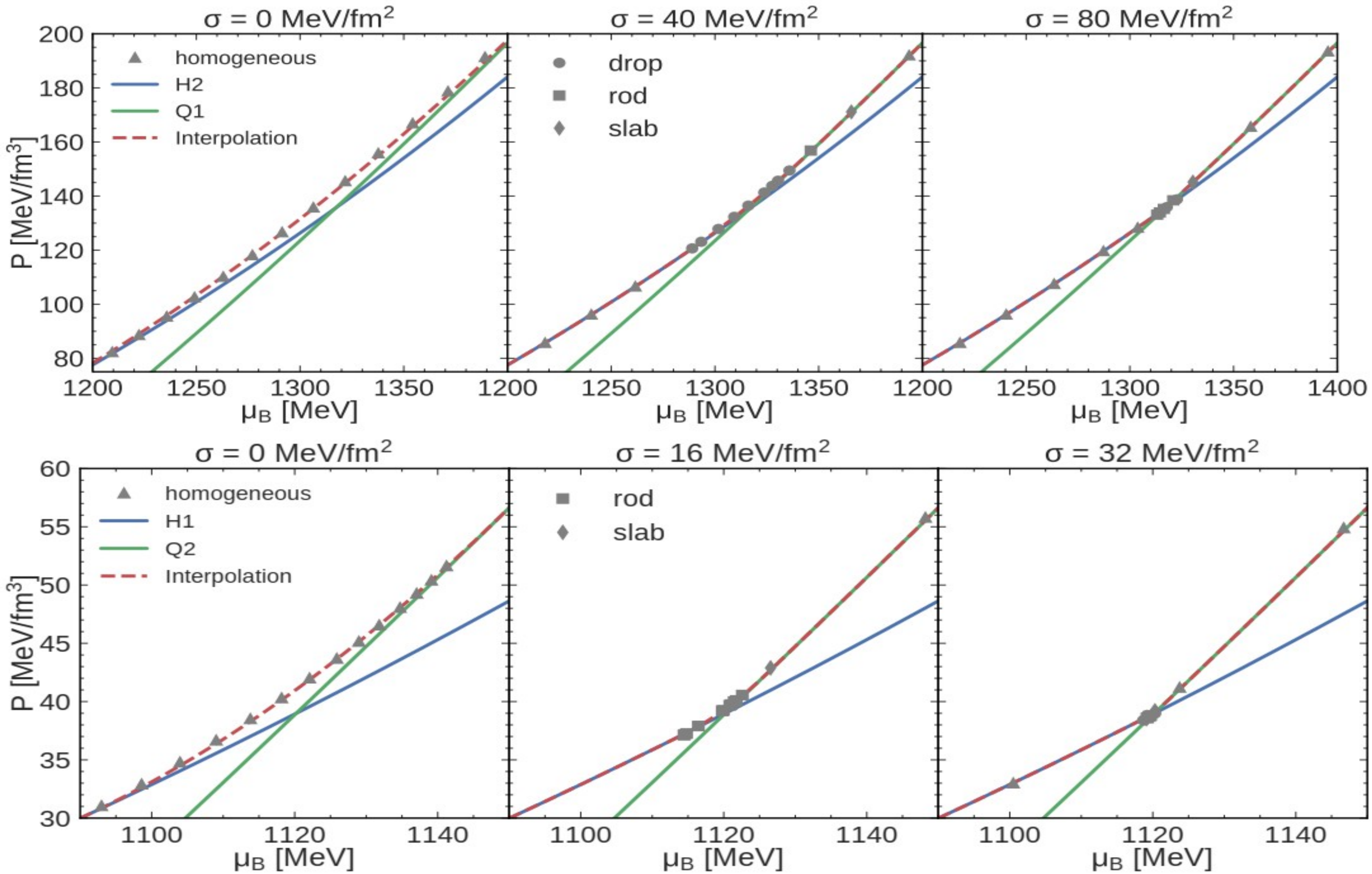




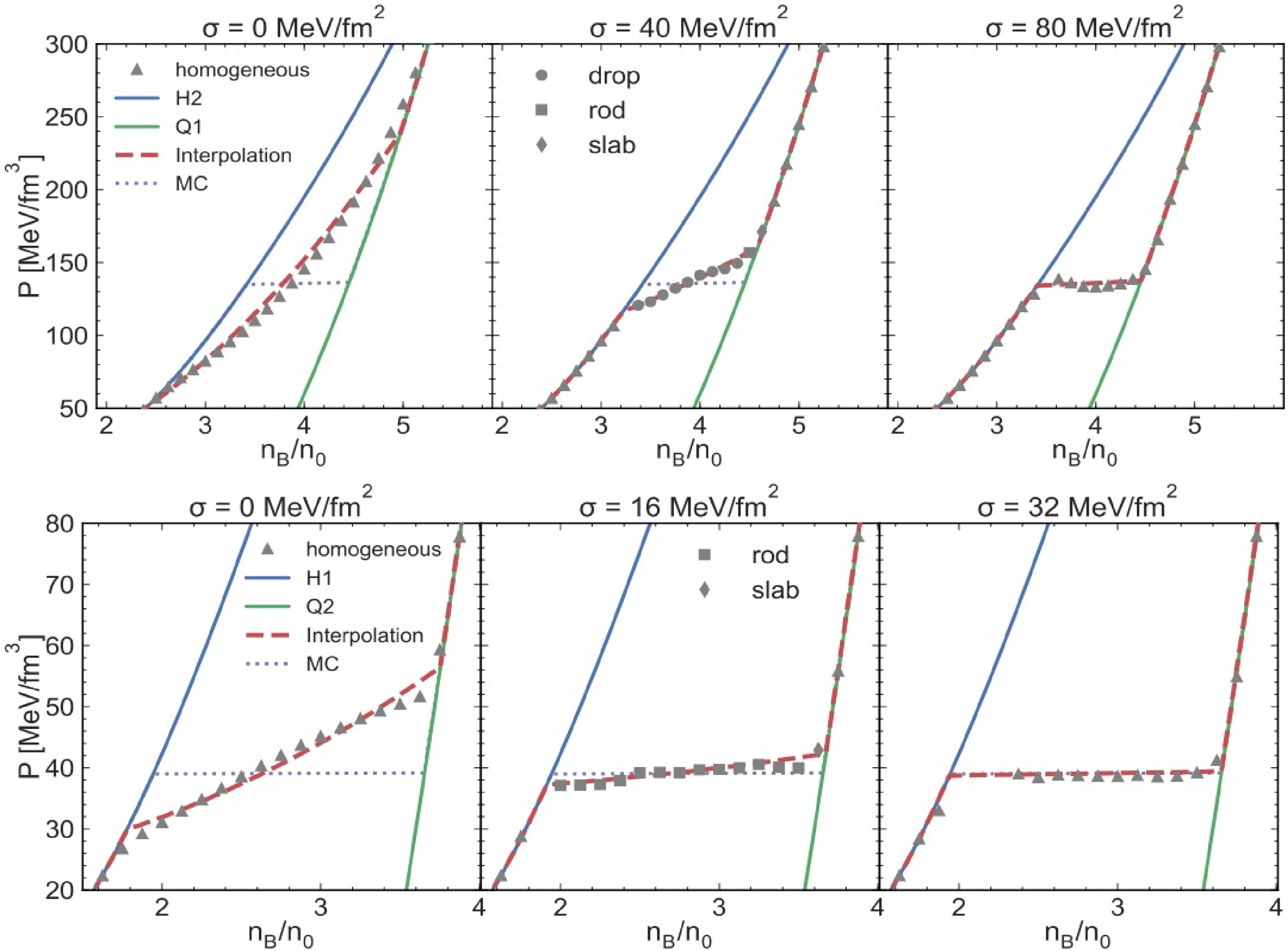




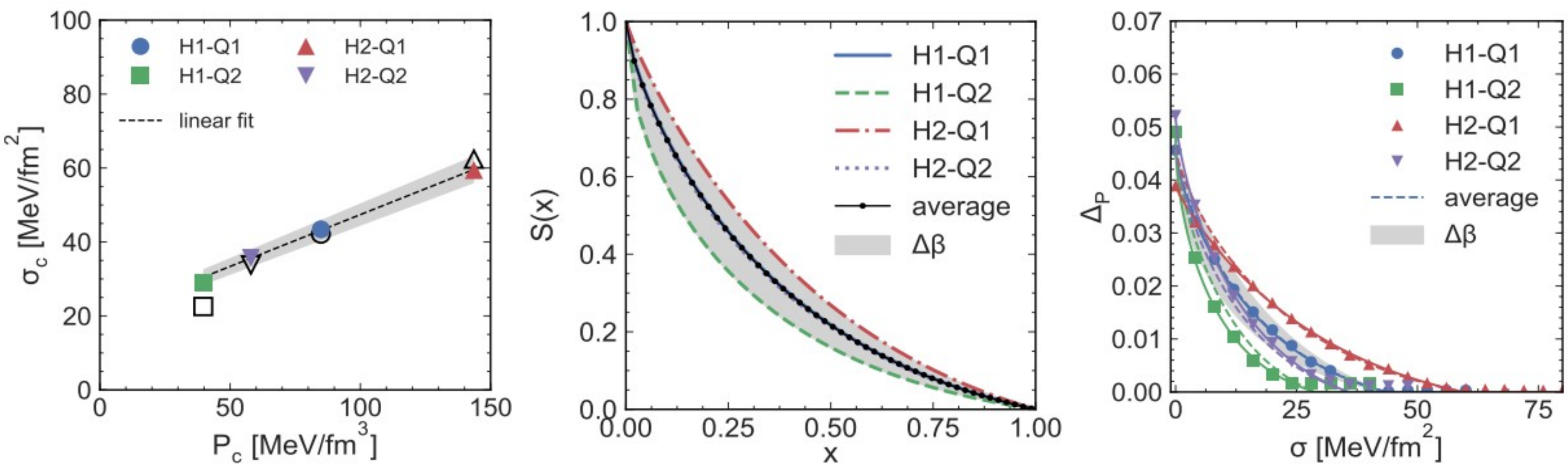
Dependence on surface tension



Dependence on surface tension



Dependence on surface tension



$$\sigma_c = d\,(P_c - P_0) + \sigma_0 :$$

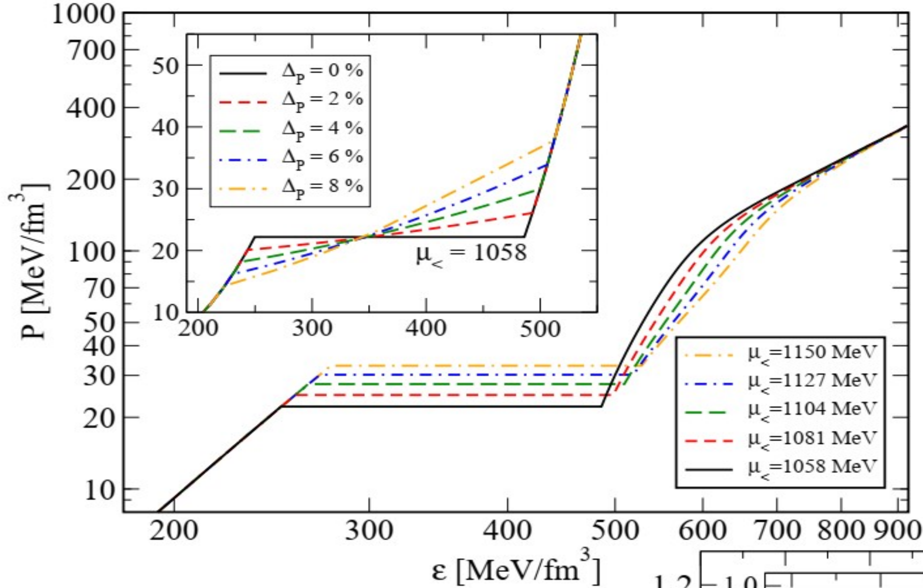
$d = 0.45 \pm 0.02$ fm,
$P_0 = 40$ MeV/fm^3,
and $\sigma_0 = 31.6 \pm 1.19$ MeV/fm^2

$$\Delta_P(\sigma) = \Delta_P(0) S(\sigma/\sigma_c; \beta) : \quad \overline{\beta} = 0.64$$

$$S(x;\beta) = e^{-x}(1 - x^{\beta})\theta(1-x)$$

Maslov, Yasutake, Blaschke, Ayriyan, Grigorian, Maruyama, Tatsumi, Voskresensky. PRC100, 025802 (2019)

Model EoS for Hybrid NS

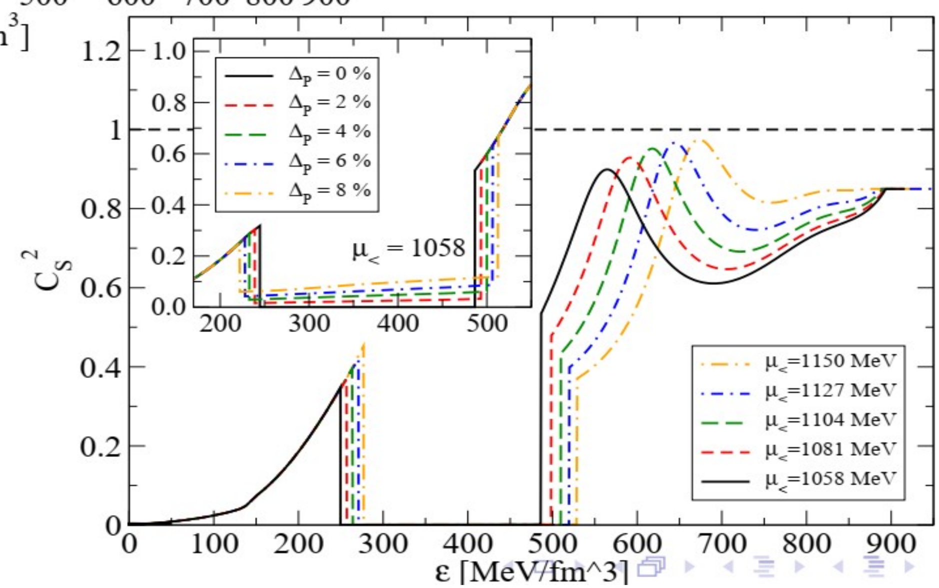


DD2 with excluded volume plus color superconducting two-flavor quark matter, described within a nonlocal covariant chiral quark model.

$$P(\mu) = P(\mu; \eta(\mu), B(\mu)) = -\Omega^{MFA}(\eta(\mu)) - B(\mu)$$

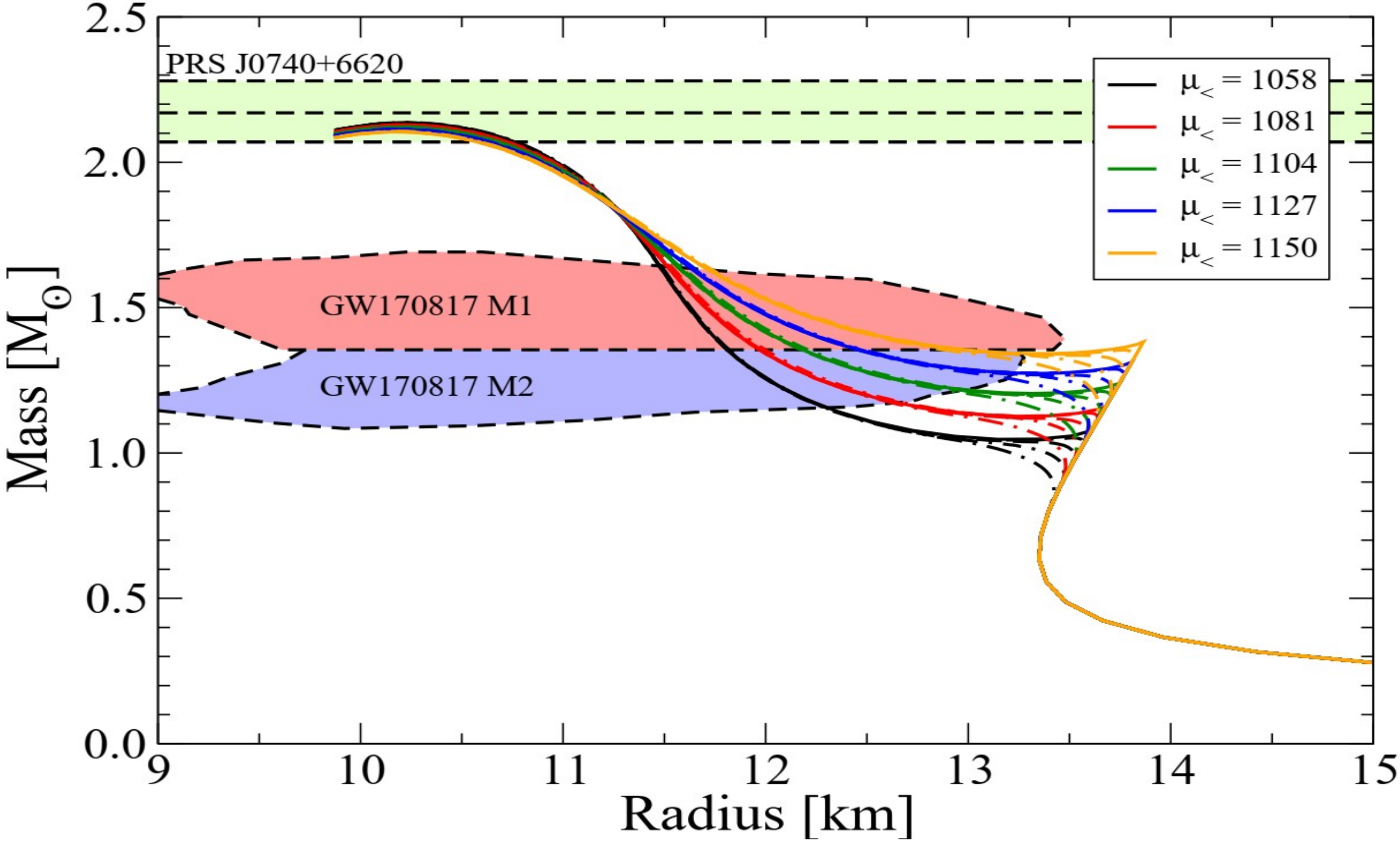
$$\Omega^{MFA} = \frac{\bar{\sigma}^2}{2G_S} + \frac{\bar{\Delta}^2}{2H} - \frac{\bar{\omega}^2}{2G_V} - \frac{1}{2}\int \frac{d^4p}{(2\pi)^4} \ln\det\left[\, S^{-1}(\bar{\sigma}, \bar{\Delta}, \bar{\omega}, \mu_{fc})\right]$$

$$\frac{d\Omega^{MFA}}{d\bar{\Delta}} = 0\,, \quad \frac{d\Omega^{MFA}}{d\bar{\sigma}} = 0\,, \quad \frac{d\Omega^{MFA}}{d\bar{\omega}} = 0\,.$$

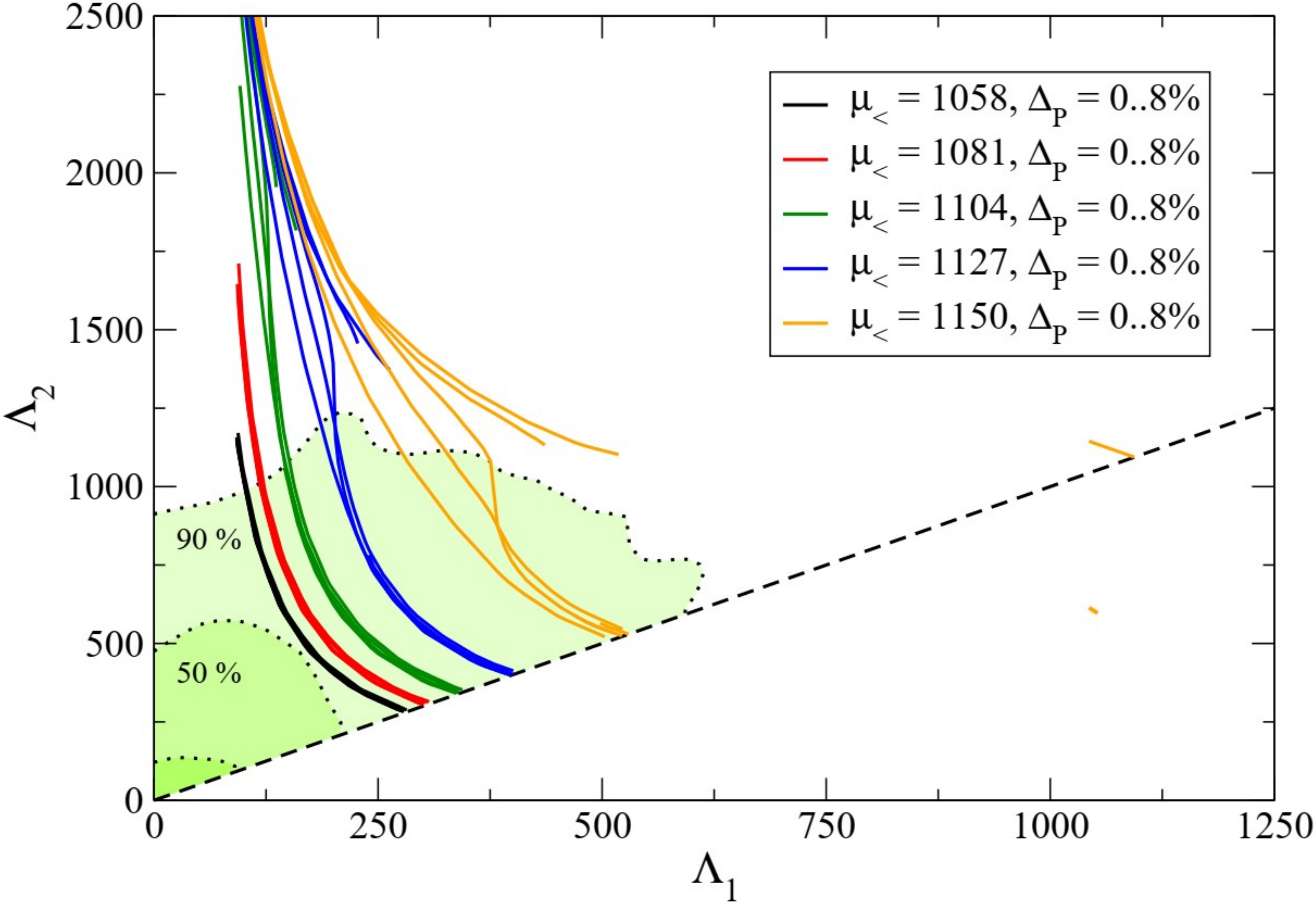


Alvarez-Castillo, Blaschke, Grunfeld, and Pagura, PRD99, 063010 (2019)

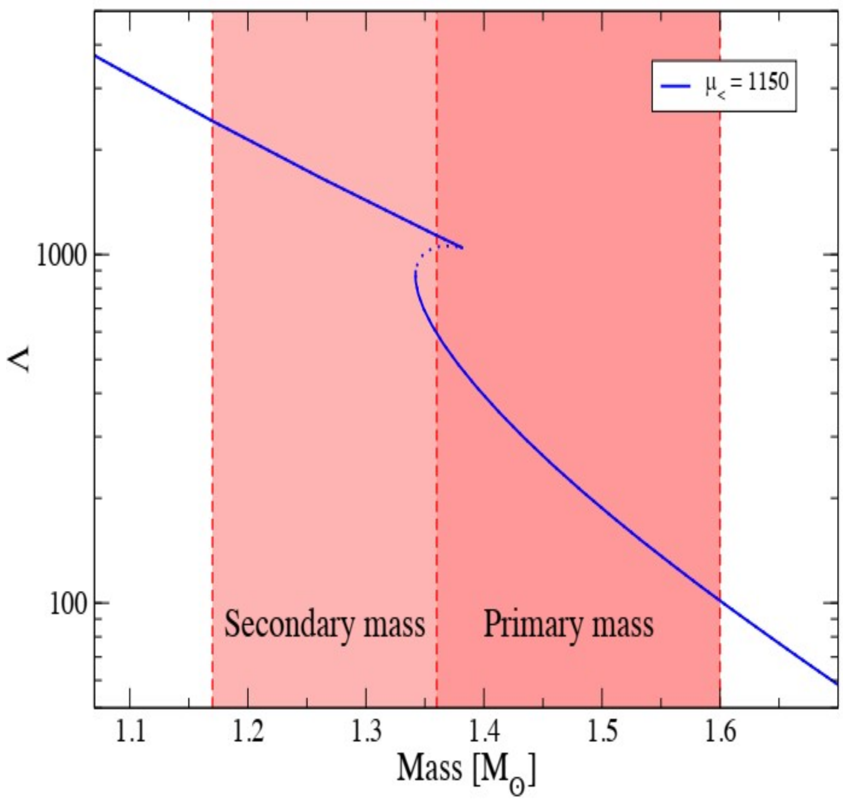
M-R relation for Hybrid NS

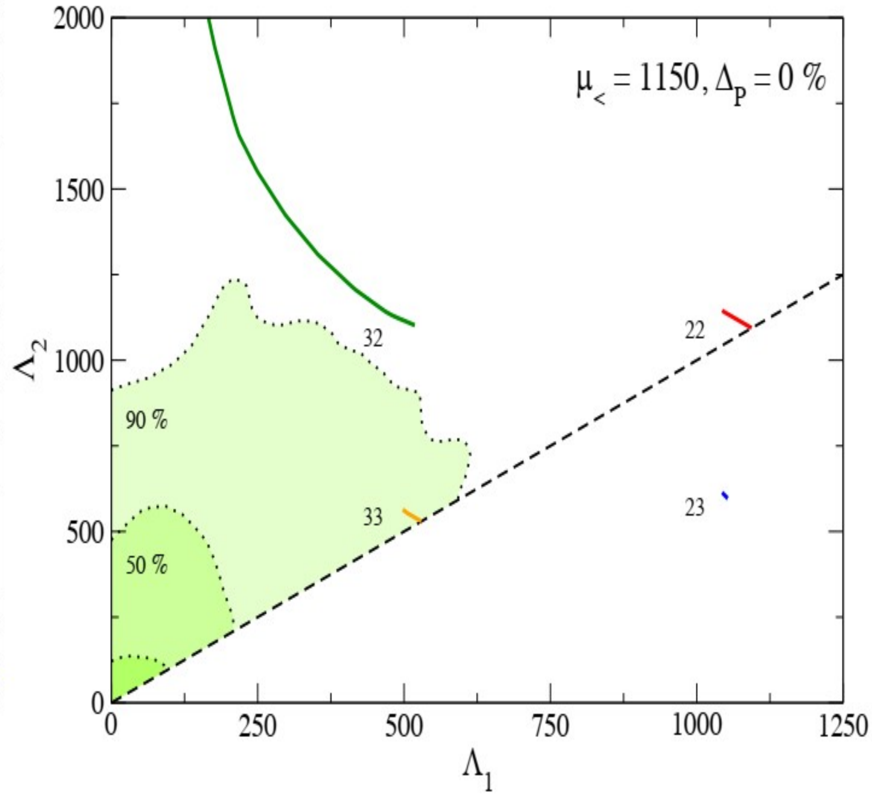


Λ_1- Λ_2 diagram and observational constraints

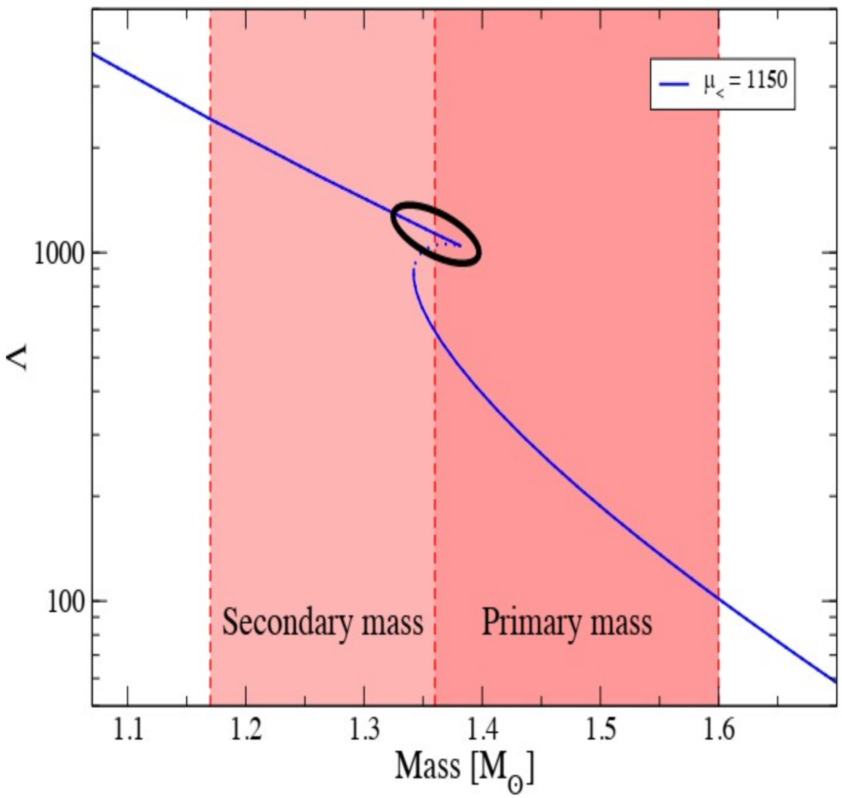


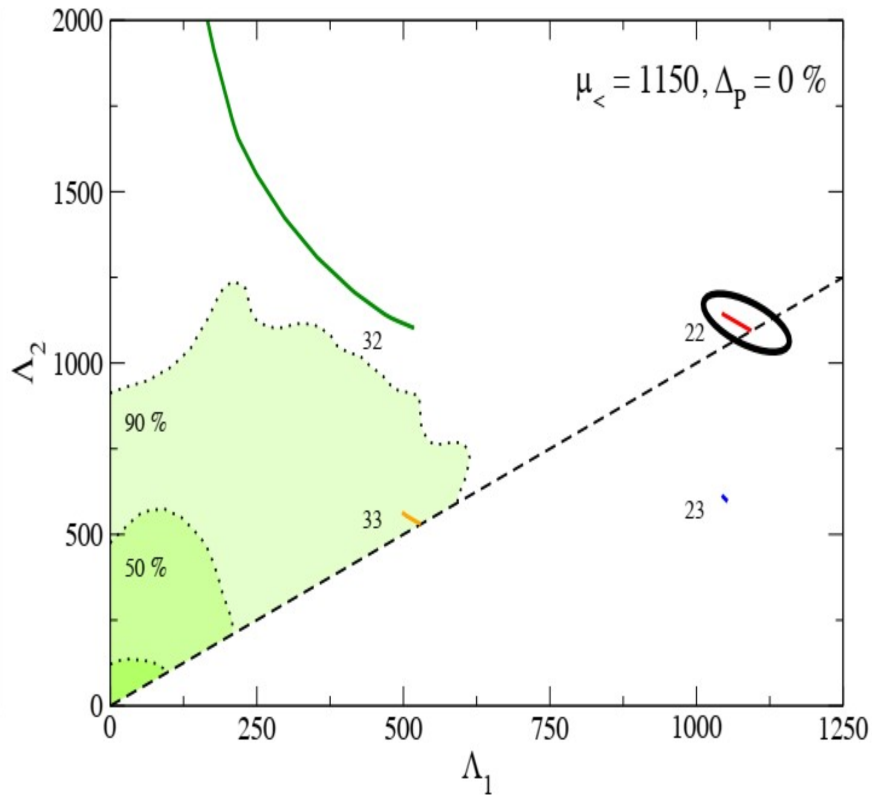
Lambda-Lambda diagram: Hybrid EoS NS – NS merging



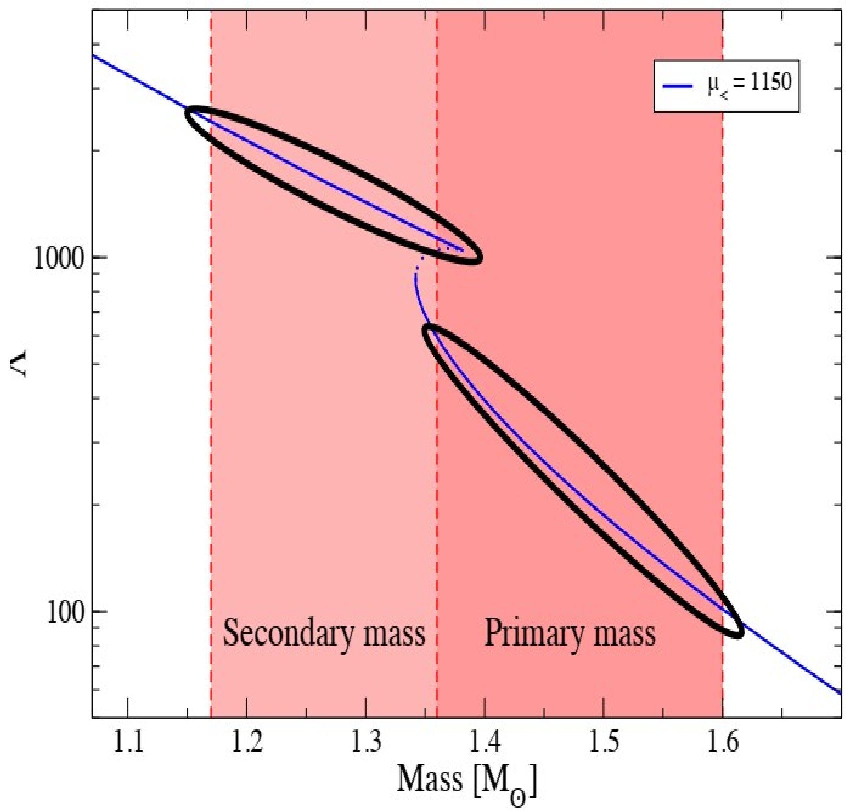


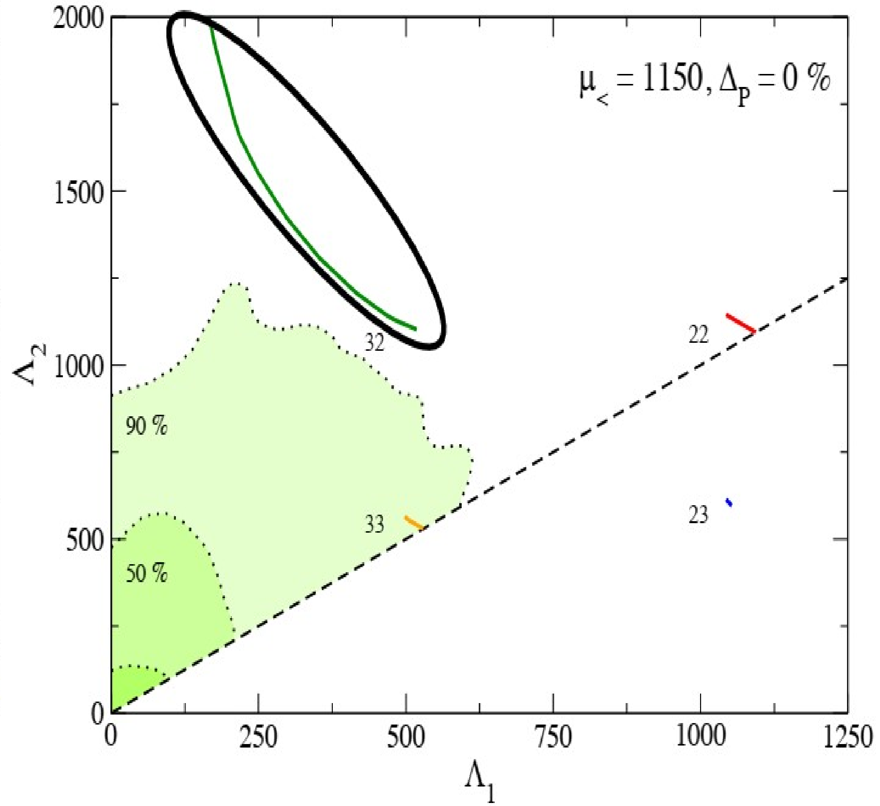
Hadron - Hadron



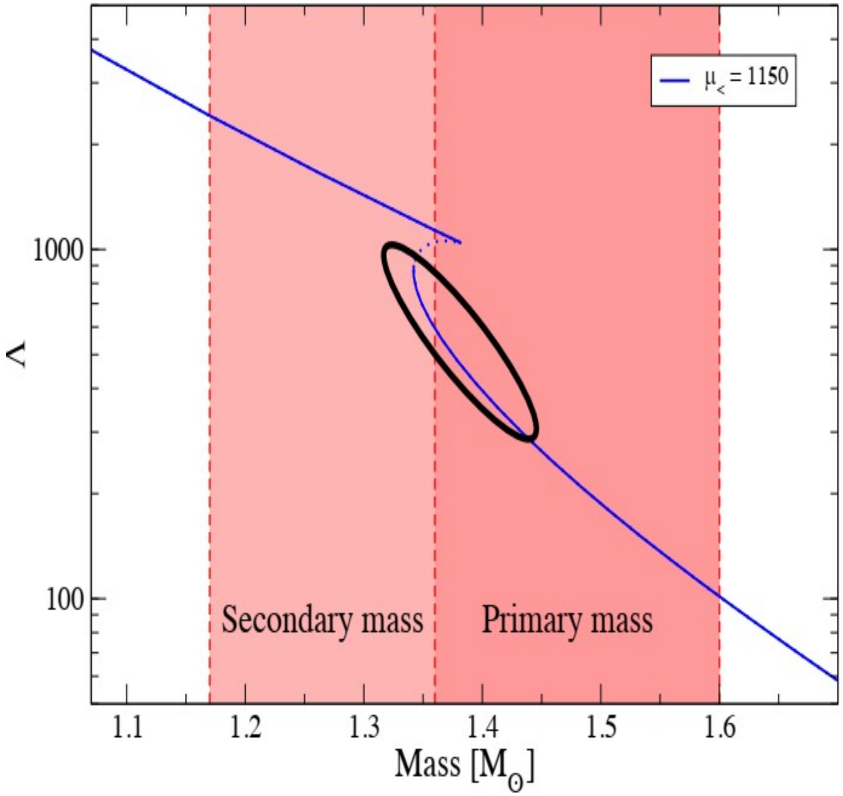


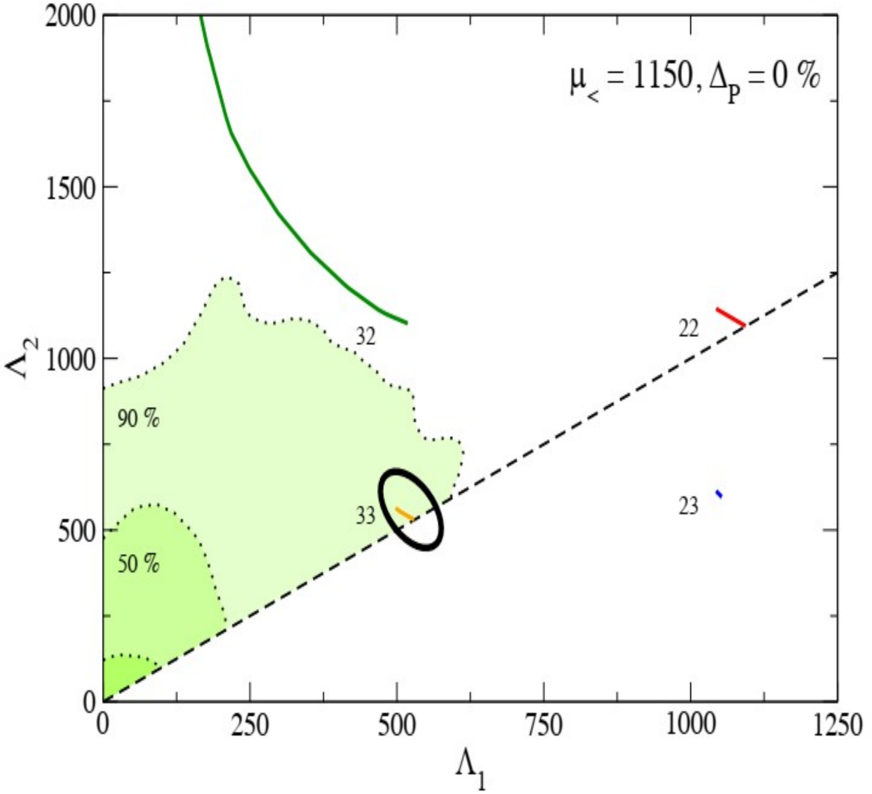
Hadron - Hybrid



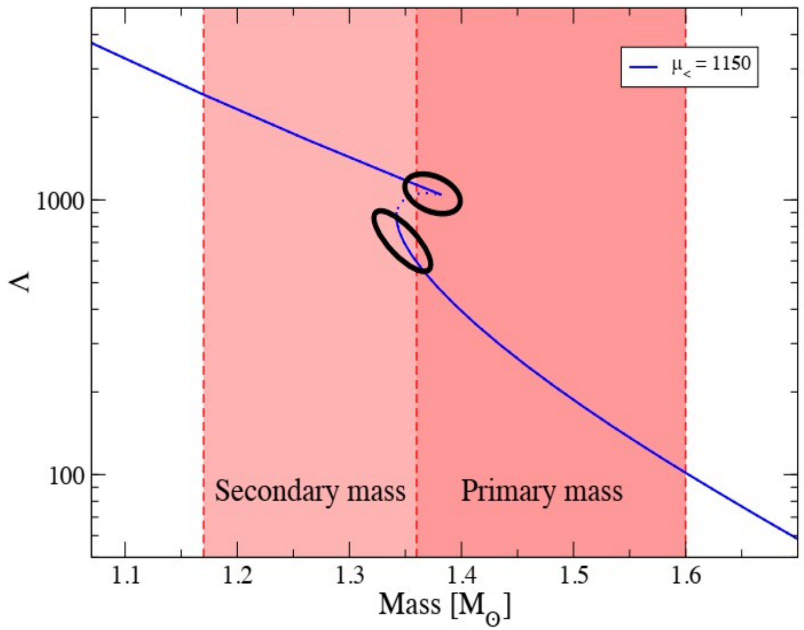


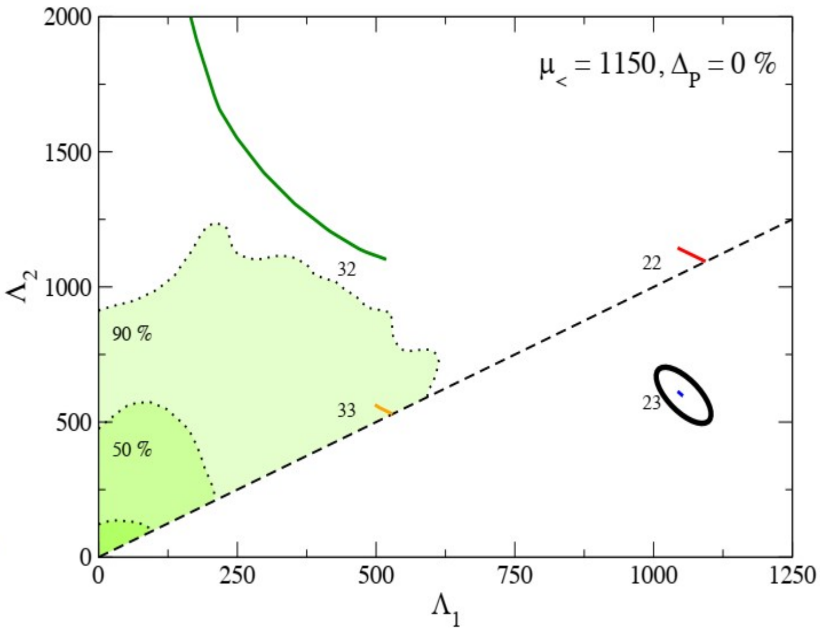
Hybrid - Hybrid





Hybrid - Hadron



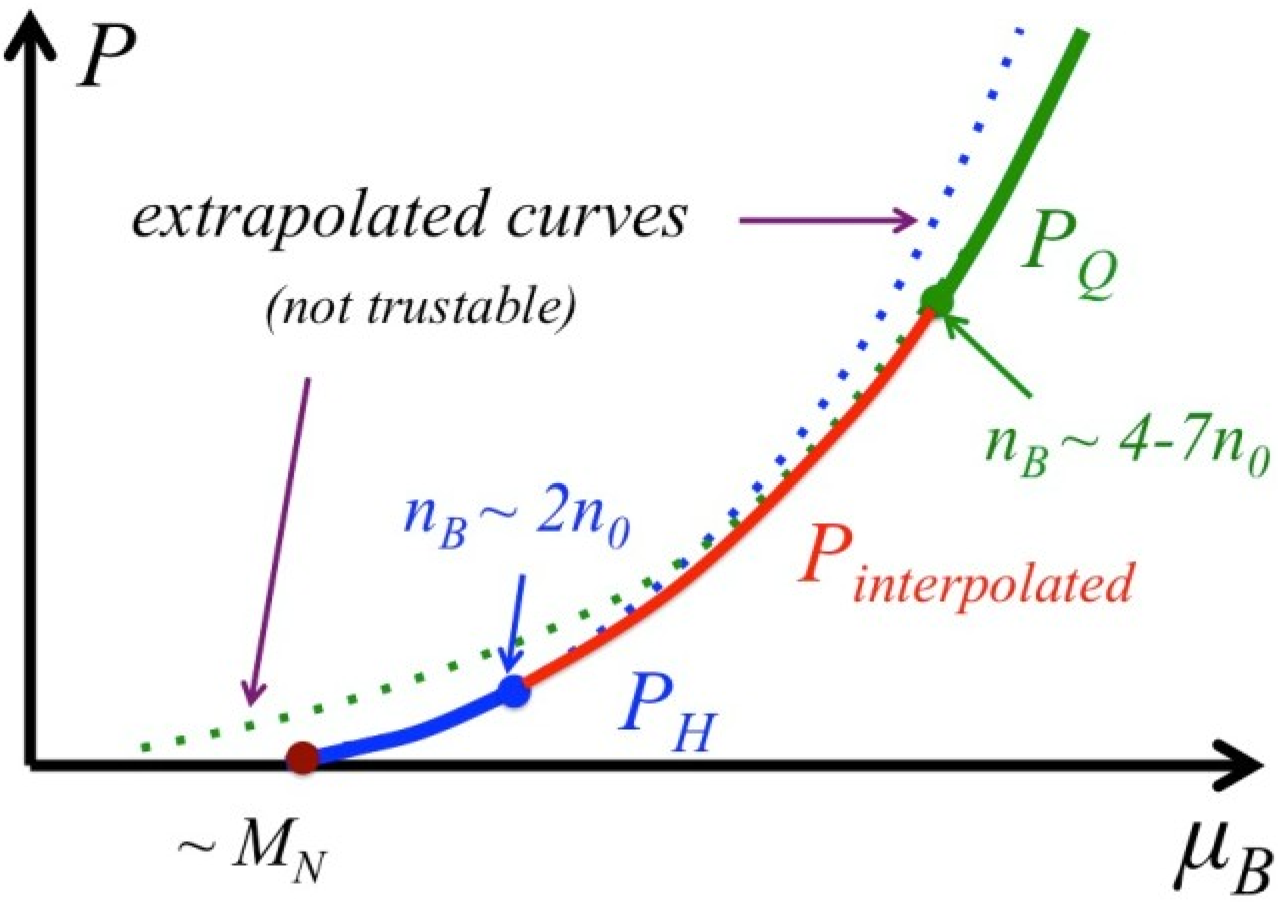


The same phenomena were found in Montana, Tolos, Hanauske, Rezzolla. PRD99, 103009 (2019) for politropic models

More interesting results have been achieved by Prof. Armen Sedrakian for triplet of compact stars produced by the forth family.

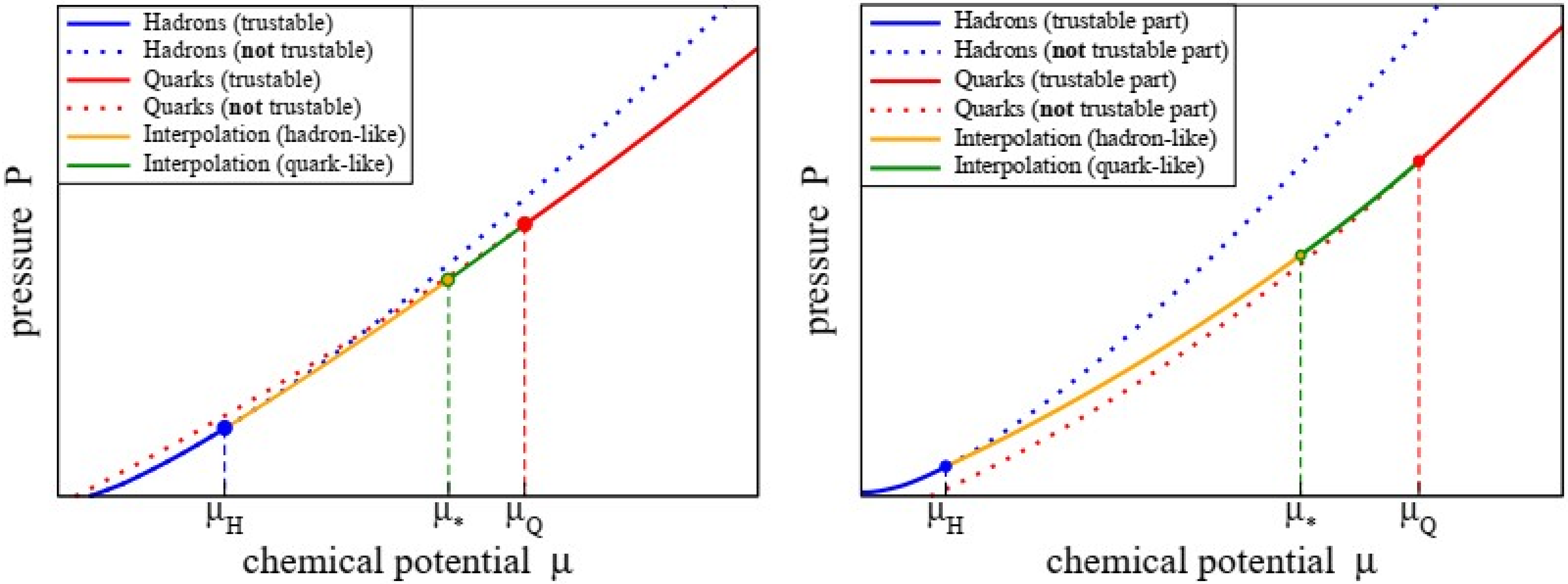
The region $\Lambda_2 < \Lambda_1$ was called unphysical at Abbott *et al.* PRL121 (2018).

Two-zone interpolation



Credit: Gordon Baym et al 2018 Rep. Prog. Phys. 81, 056902 (2018)

Two-zone interpolation

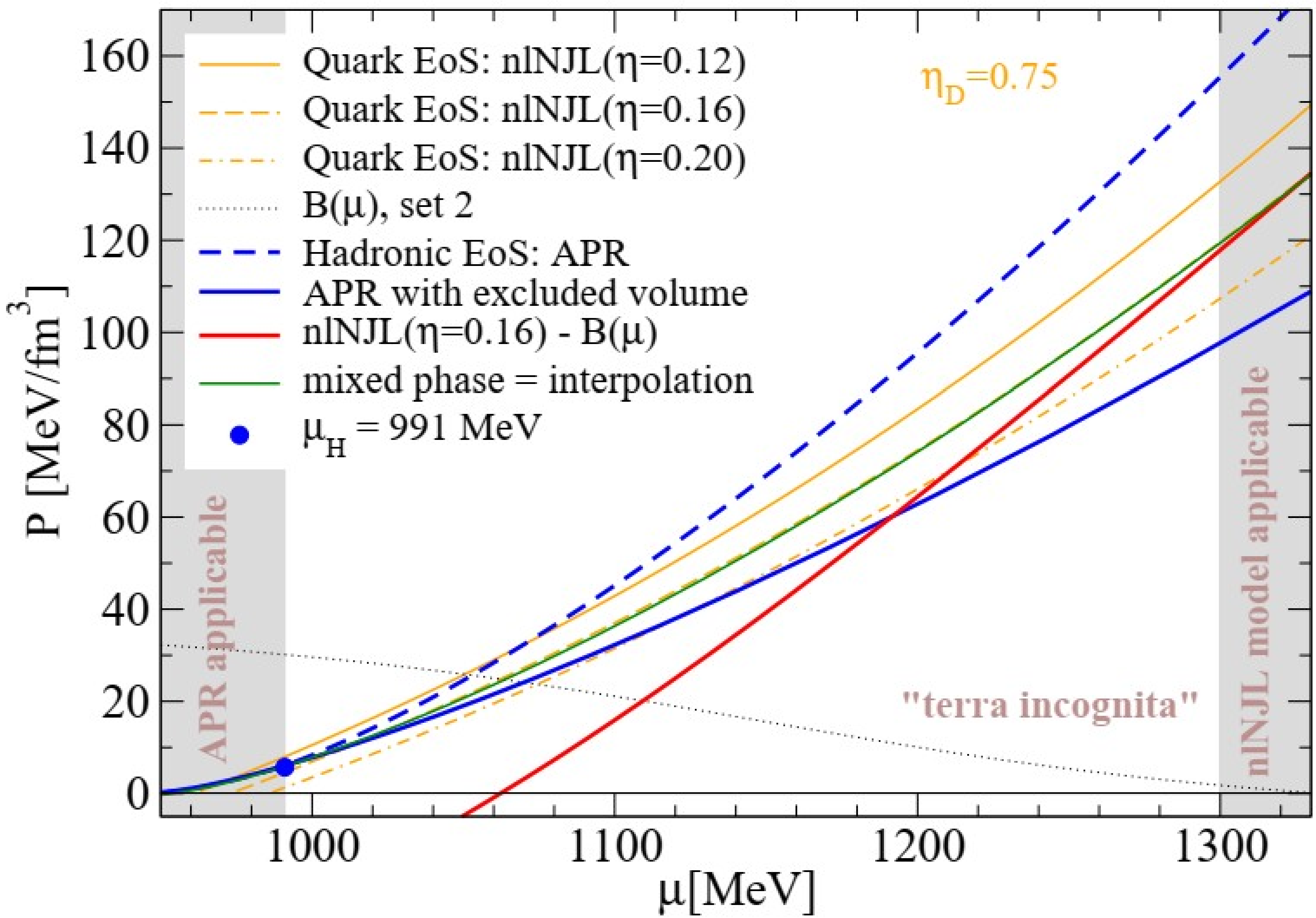


Well known APR (blue dots) and nonlocal NJL (red dots).
The idea of interpolation is between n_h and n_q is to use two parabolic functions:

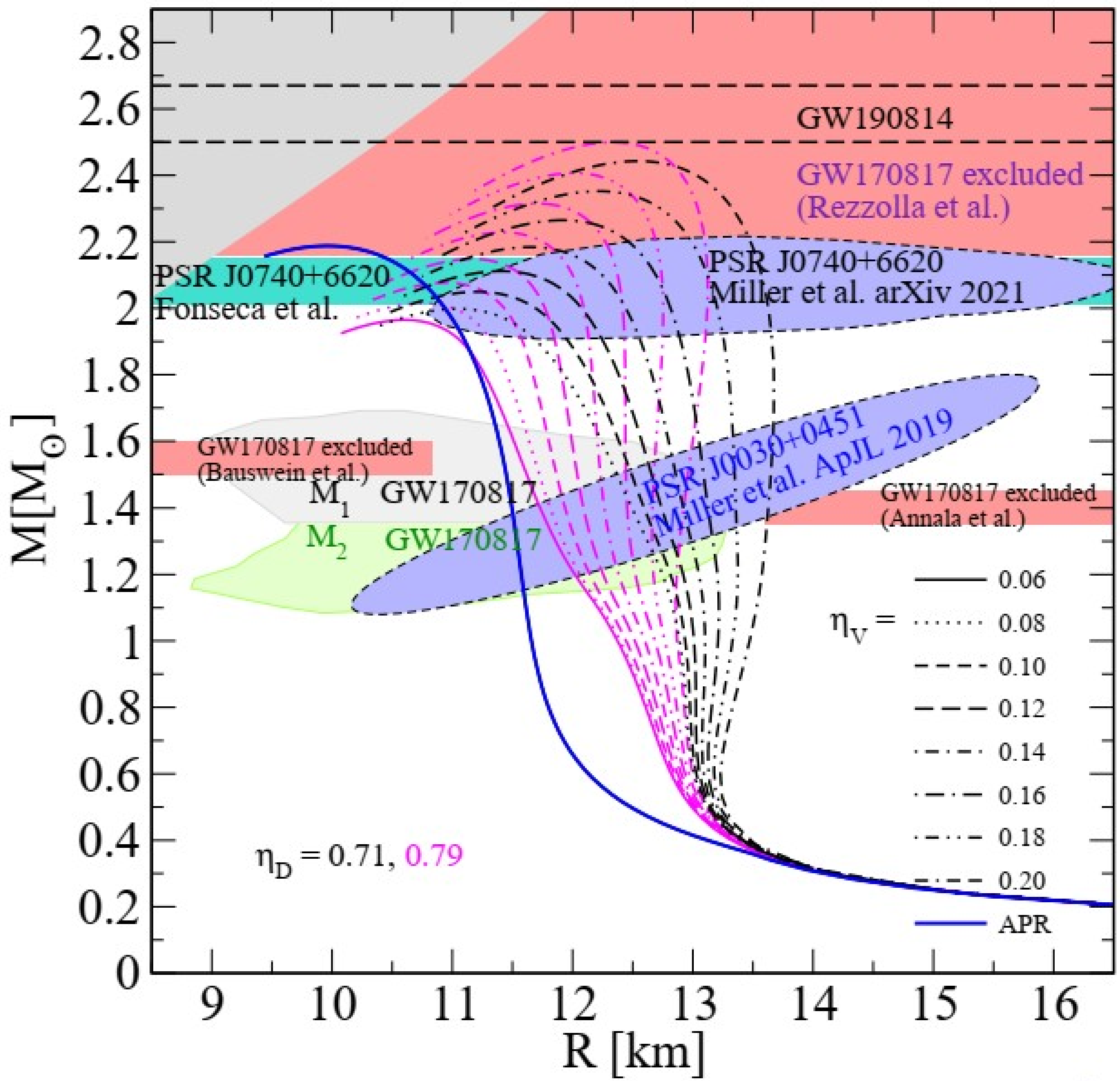
$$\begin{cases} P_\eta(\mu) &= a_\eta(\mu-\mu_H)^2 + b_\eta(\mu-\mu_H) + c_\eta \quad \mu \le \mu_c \\ P_\rho(\mu) &= a_\rho(\mu-\mu_Q)^2 + b_\rho(\mu-\mu_Q) + c_\rho \quad \mu \ge \mu_c \end{cases}$$

where μ_H and μ_Q correspond to n_H and n_Q respectively, and μ_c is free parameter taking value between them: $\mu_H < \mu_c < \mu_Q$.

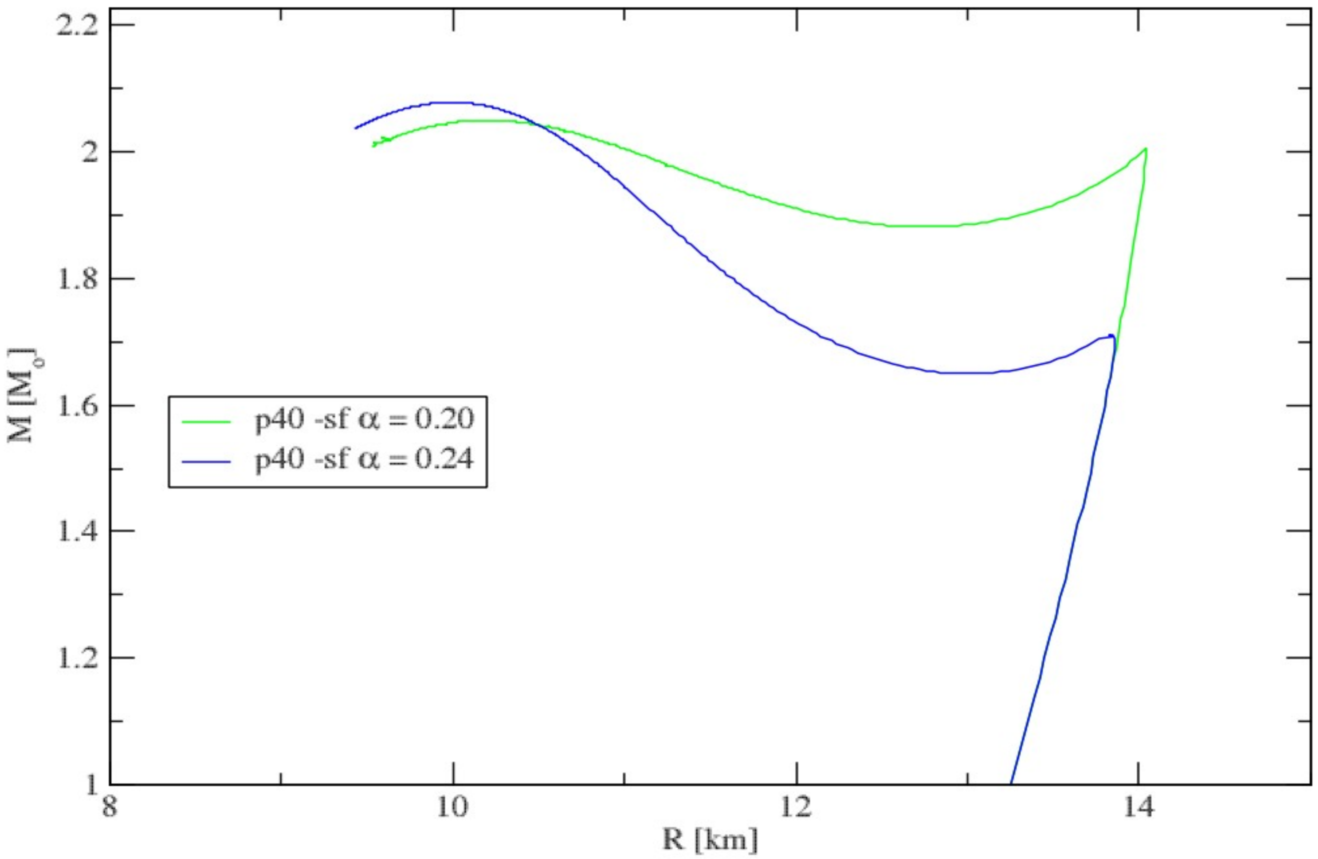
Two-zone interpolation



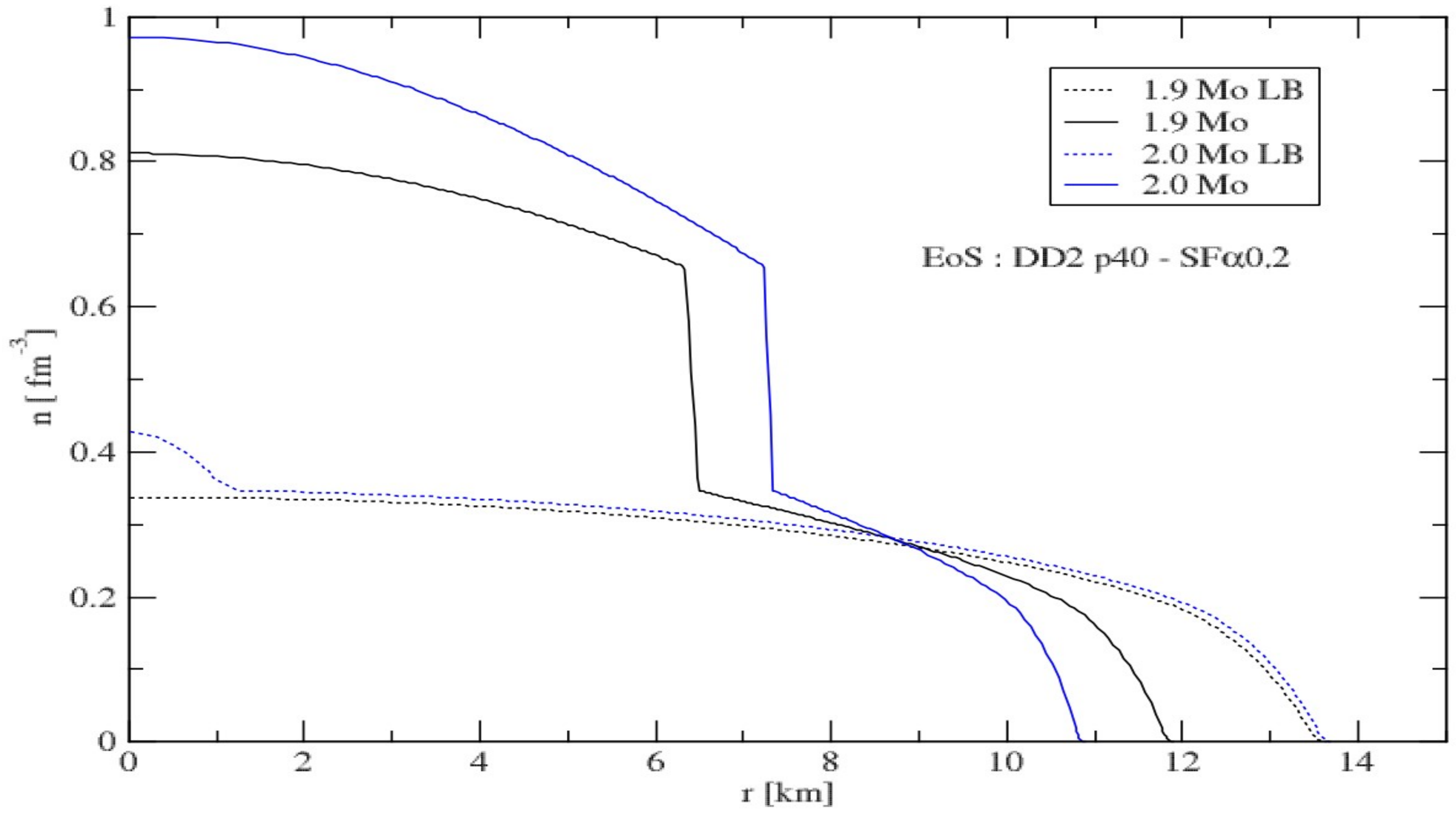
Two-zone interpolation



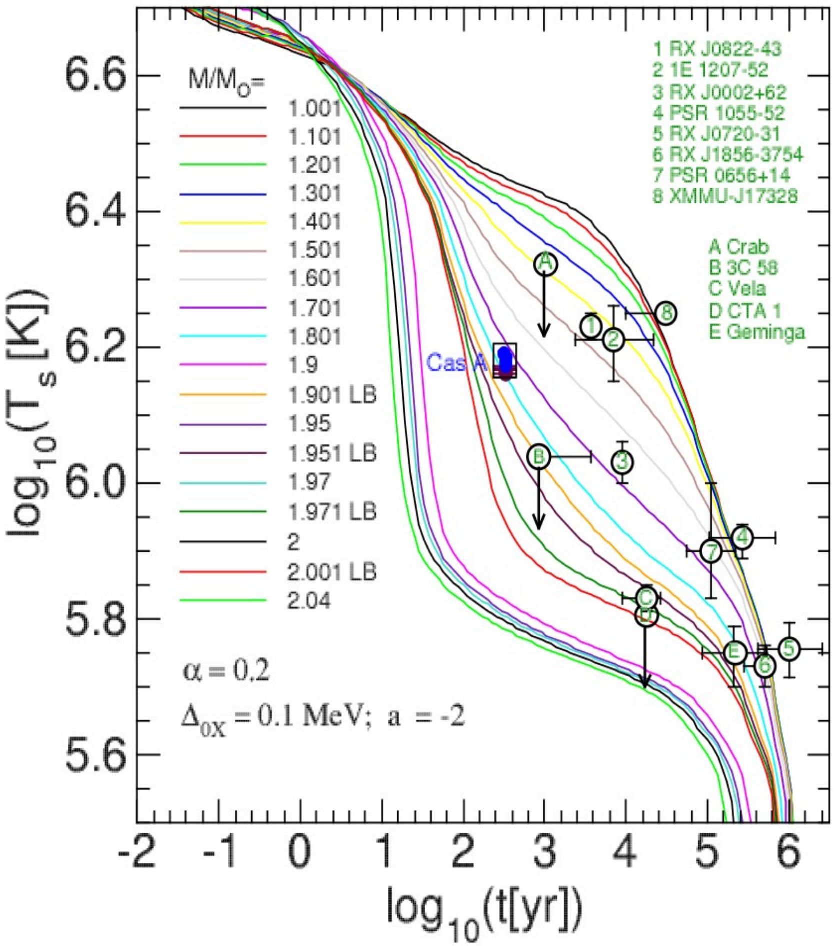
High Mass Twin CS

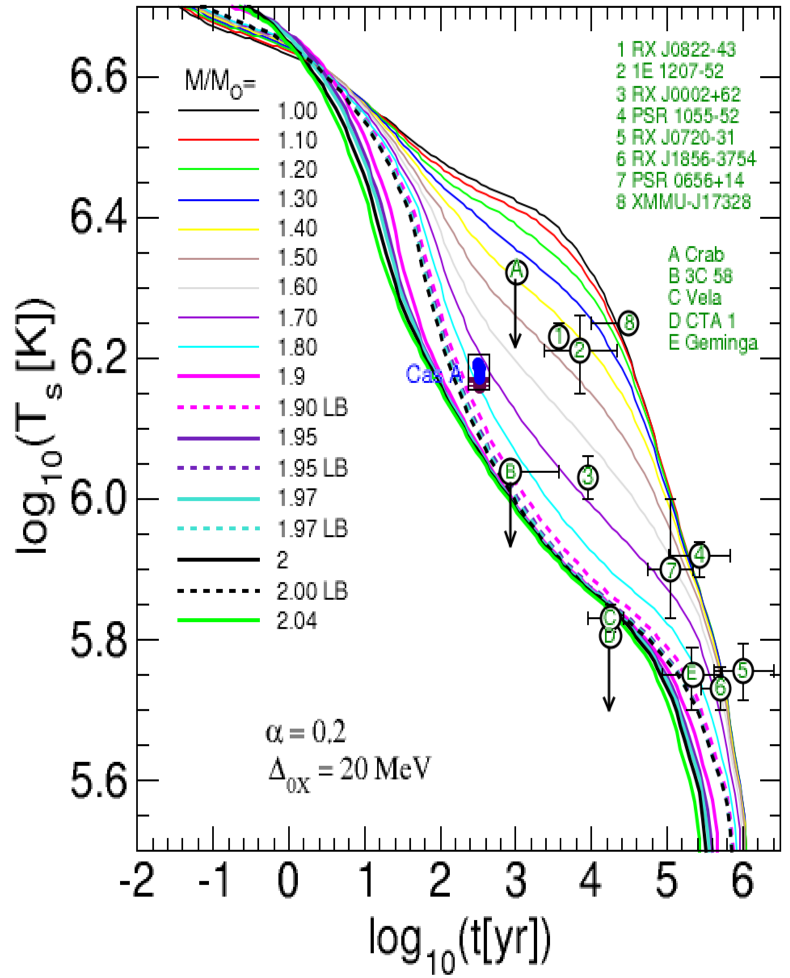


Different Configurations with the same NS mass

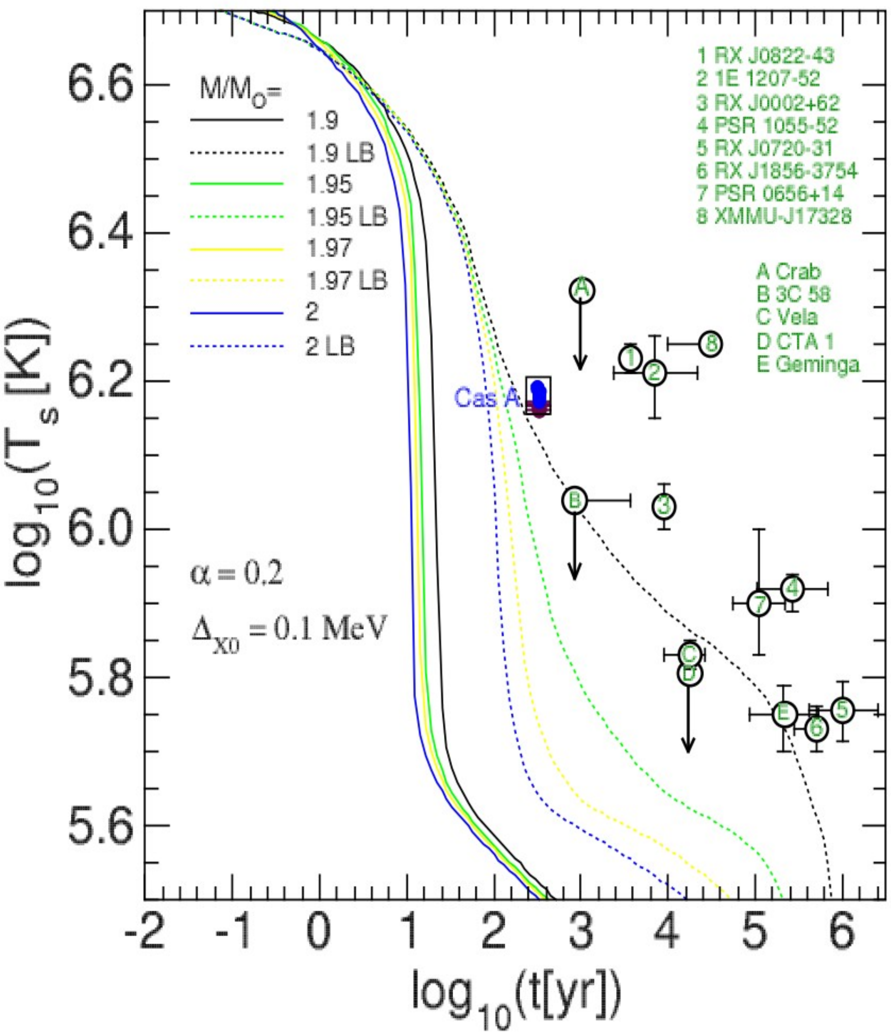


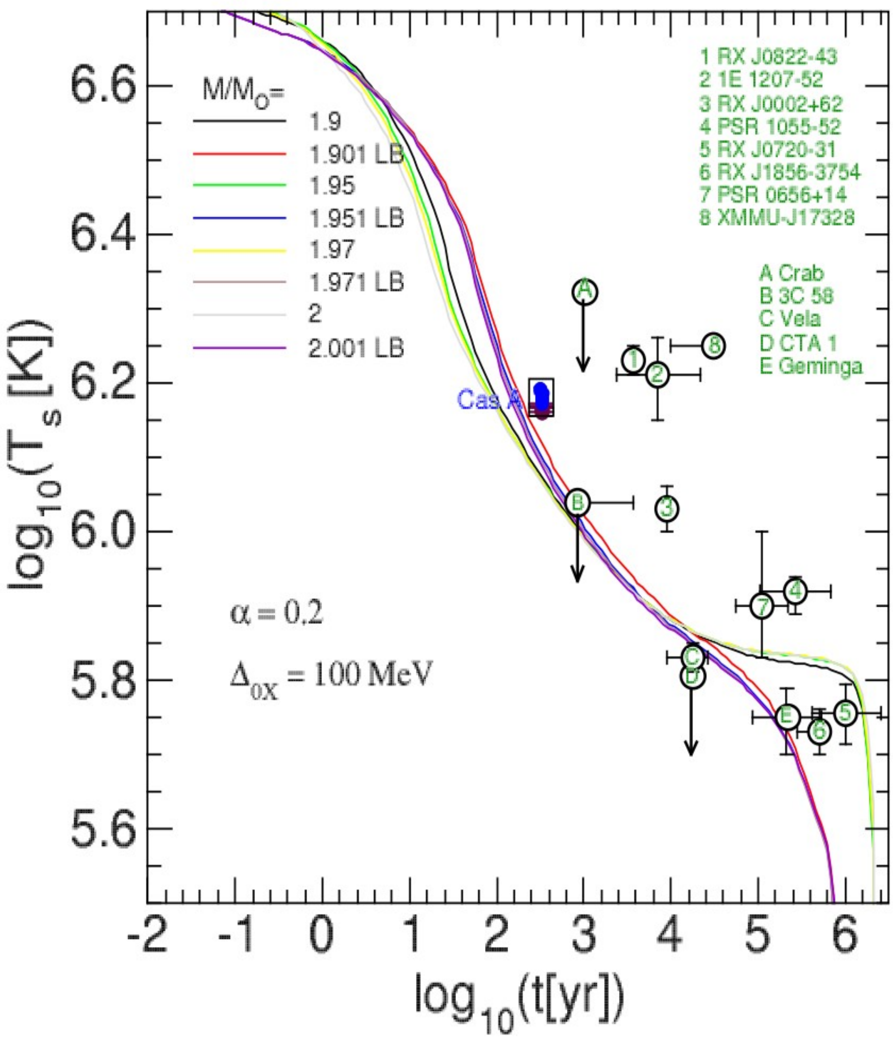
Cooling of Twin CS





Highmass Twins: QM SC Effect





Conclusions

The mixed phase interpolation method is very simple and well describes quark-hadron pasta phase for any give possible surface tension value.

The third family survives against pasta phase for the considered EoS models.

$\Lambda_1 - \Lambda_2$ relation from GW170817 favours softer EoS and hybrid stars with strong phase order transitions (even with no third family due to the mixed phase).

The region $\Lambda_2 < \Lambda_1$ has physical meaning in case of low-mass twins, when heavier companion belongs to the second family and the lighter one to the third family.

If NICER will approve the "fictitious radius measurement" it will support the low-mass twin stars around 1.4 $M_\odot$ for considered models.