How robust is a third family of compact stars against pasta phase effects?

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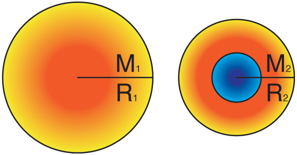
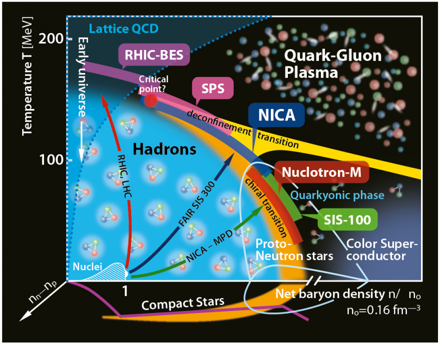
Motivation

What if we have twins





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

Neutron star mass and radius

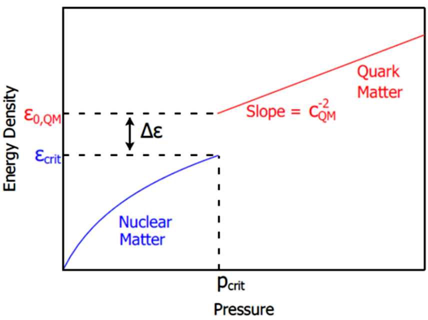
The structure and global properties of compact stars are obtained by solving the Tolman-Oppenheimer-Volkoff (TOV) equations[1,2,*]:

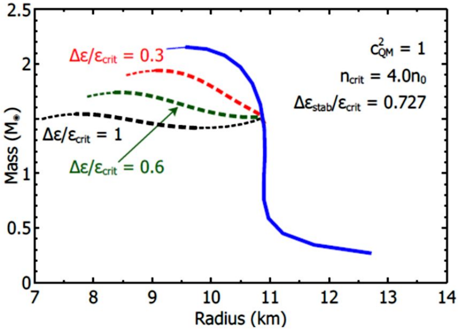
$$\begin{cases} \dfrac{dP(r)}{dr} = -\dfrac{GM(r)\varepsilon(r)}{r^2} \dfrac{\left(1+\dfrac{P(r)}{\varepsilon(r)}\right)\left(1+\dfrac{4\pi r^3 P(r)}{M(r)}\right)}{\left(1-\dfrac{2GM(r)}{r}\right)}; \\ \dfrac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r). \end{cases}$$

[1] R. C. Tolman, Phys. Rev. **55**, 364 (1939).
[2] J. R. Oppenheimer and G. M. Volkoff, Phys. Rev. **55**, 374 (1939).

[*] Valid for static neutron stars.

Neutron star mass-radius relation





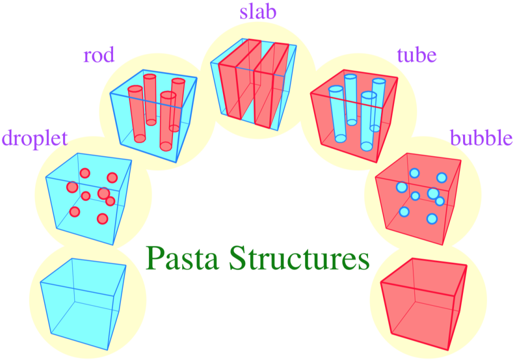
Credit: Mark G. Alford, Sophia Han, and Madappa Prakash. Phys. Rev. D 88, 083013 (2013)

Finite-size effects

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

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

Requires minimization of the surface

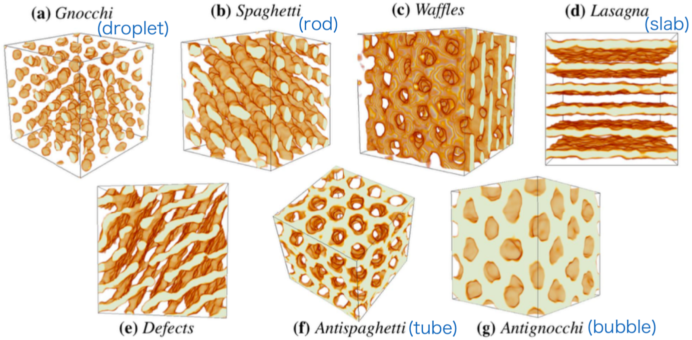


The surface tension σ is unknown and used as free parameter.

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

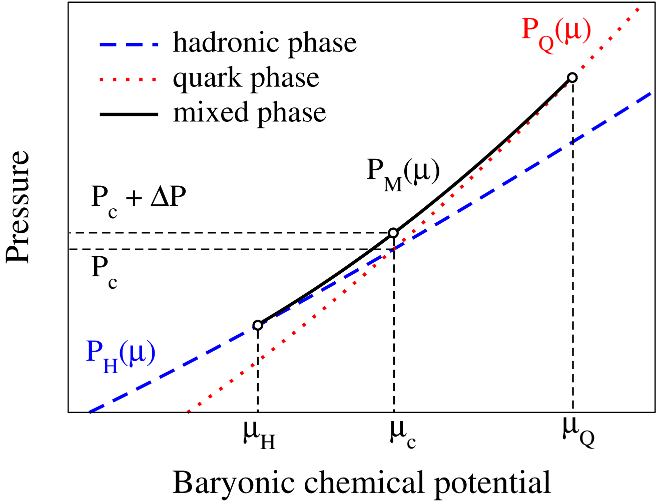
Finite-size effects

It looks like yummy Italian pasta



Credit: M. E. Caplan, C. J. Horowitz. Rev. Mod. Phys. 89(4), 041002 (2017)

Mimicking the Pasta phase. The idea



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 Replacement Interpolation Method (RIM)

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

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

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

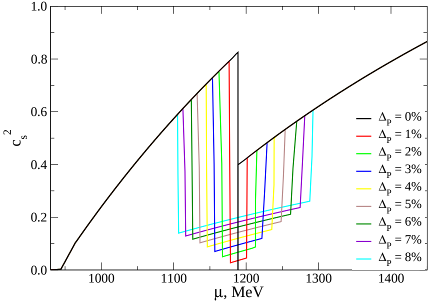
$$\frac{\partial^q}{\partial\mu^q} P_H(\mu_H) = \frac{\partial^q}{\partial\mu^q} P_M(\mu_H) \qquad \frac{\partial^q}{\partial\mu^q} P_Q(\mu_Q) = \frac{\partial^q}{\partial\mu^q} P_M(\mu_Q)$$

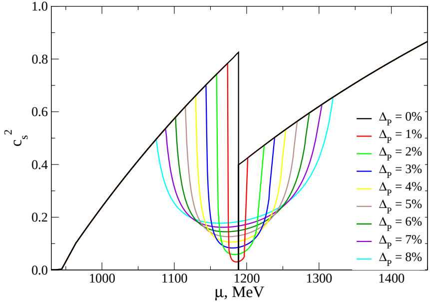
where $q = 1, 2, \ldots, k$. All $N + 2$ parameters (μ_H, μ_Q and α_q, for $q = 1, \ldots, N$) can be found by solving the above system of equations, leaving one parameter (ΔP) as a free one.

A. Ayriyan and H. Grigorian, *EPJ Web Conf.* **2018**, 173, 03003

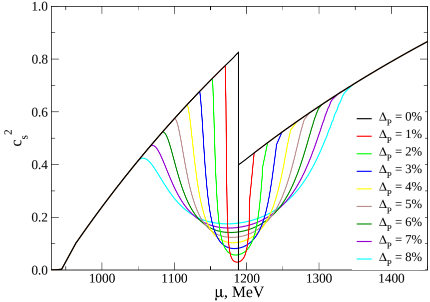
A. Ayriyan et al. *Phys. Rev. C* **2018**, 97(4), 045802

The Replacement Interpolation Method (RIM)



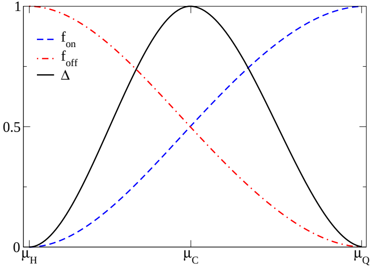


The squared speed vs chemical potential for the RIM construction with $k = 1$ (upper left) $k = 2$ (upper right) and $k = 3$ (right).



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

The Mixing Interpolation Method (MIM)



$$f_{>,L} = \alpha_L \left(\frac{\mu - \mu_H}{\mu_Q - \mu_H} \right)^2 + \beta_L \left(\frac{\mu - \mu_H}{\mu_Q - \mu_H} \right)^3$$

$$f_{<,R} = \alpha_R \left(\frac{\mu_Q - \mu}{\mu_Q - \mu_H} \right)^2 + \beta_R \left(\frac{\mu_Q - \mu}{\mu_Q - \mu_H} \right)^3$$

D. Alvarez-Castillo and D. Blaschke, EPJA (submitted), arXiv:1807.03258

V. Abgaryan, D. Alvarez-Castillo, A. Ayriyan, D. Blaschke, H. Grigorian, Universe (submitted), arXiv:1807.08034

The Mixing Interpolation Method (MIM)

$$\Delta(\mu) = \begin{cases} 0 & \mu < \mu_H \\ g_L(\mu) & \mu_H \leq \mu \leq \mu_C \\ g_R(\mu) & \mu_C \leq \mu \leq \mu_Q \\ 0 & \mu > \mu_Q \end{cases}$$

$$g_L = \delta_L \left(\frac{\mu - \mu_H}{\mu_C - \mu_H}\right)^2 + \gamma_L \left(\frac{\mu - \mu_H}{\mu_C - \mu_H}\right)^3$$

$$g_R = \delta_R \left(\frac{\mu_Q - \mu}{\mu_Q - \mu_C}\right)^2 + \gamma_R \left(\frac{\mu_Q - \mu}{\mu_Q - \mu_C}\right)^3$$

D. Alvarez-Castillo and D. Blaschke, EPJA (submitted), arXiv:1807.03258

V. Abgaryan, D. Alvarez-Castillo, A. Ayriyan, D. Blaschke, H. Grigorian, Universe (submitted), arXiv:1807.08034

The Mixing Interpolation Method (MIM)

$$f_{\lesseqgtr,L}(\mu)\Big|_{\mu=\mu_c} = f_{\lesseqgtr,R}(\mu)\Big|_{\mu=\mu_c} = 1/2$$

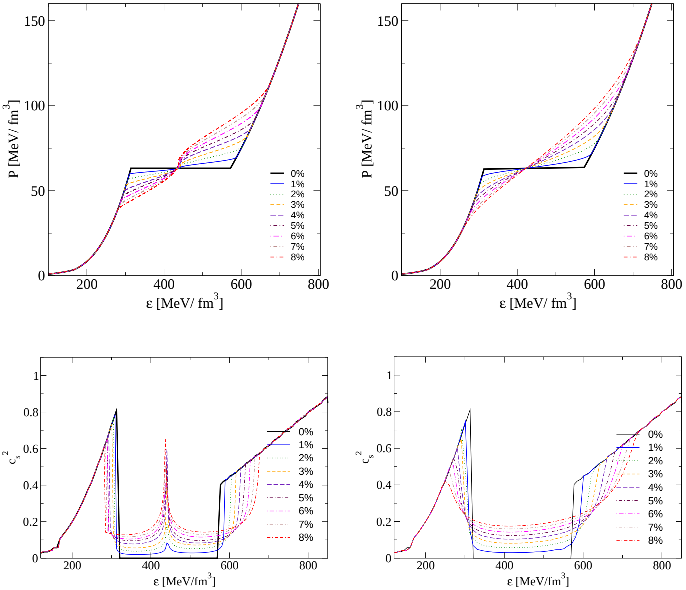
$$\frac{\partial f_{\lesseqgtr,L}(\mu)}{\partial \mu}\Big|_{\mu=\mu_c} = \frac{\partial f_{\lesseqgtr,R(\mu)}}{\partial \mu}\Big|_{\mu=\mu_c}$$

$$\frac{\partial^2 f_{\lesseqgtr,L}(\mu)}{\partial \mu^2}\Big|_{\mu=\mu_c} = \frac{\partial^2 f_{\lesseqgtr,R(\mu)}}{\partial \mu^2}\Big|_{\mu=\mu_c}$$

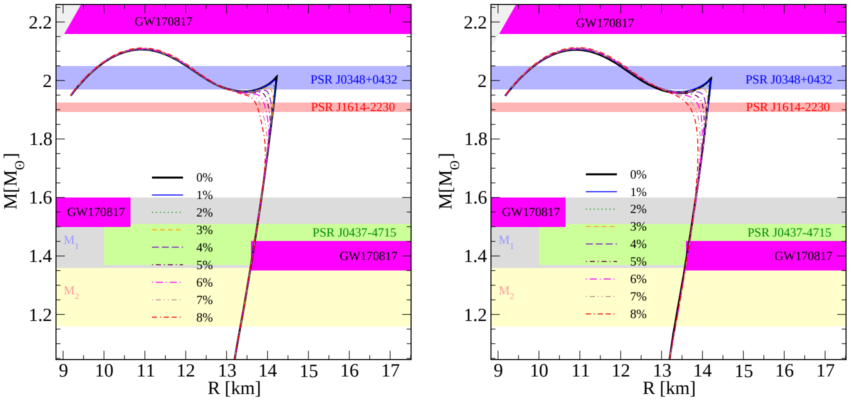
$$\begin{aligned}
g_L(\mu)\Big|_{\mu=\mu_C} &= g_R(\mu)\Big|_{\mu=\mu_C} &= 1 \\
\frac{\partial g_L(\mu)}{\partial \mu}\Big|_{\mu=\mu_C} &= \frac{\partial g_R(\mu)}{\partial \mu}\Big|_{\mu=\mu_C} &= 0 \ .
\end{aligned}$$

$$\begin{aligned}
\frac{\partial^2 P}{\partial \mu^2}\Big|_{\mu=\mu_H} &= \frac{\partial^2 P_H}{\partial \mu^2}\Big|_{\mu=\mu_H} \\
\frac{\partial^2 P}{\partial \mu^2}\Big|_{\mu=\mu_Q} &= \frac{\partial^2 P_Q}{\partial \mu^2}\Big|_{\mu=\mu_Q} \ .
\end{aligned}$$

The results of pasta mimicking



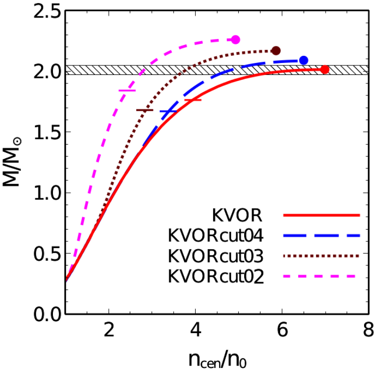
The results of pasta effects



Third family robust against additional pressure up to around $\Delta_P = 5\%$!

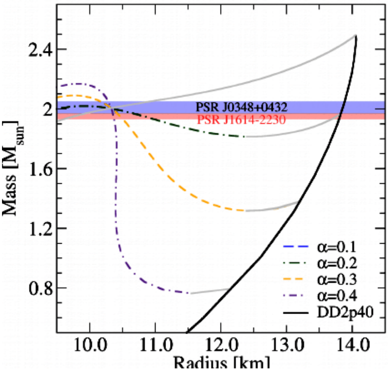
The realistic hadron and quark matter models

The hadron EoS model KVOR with modification of stiffness



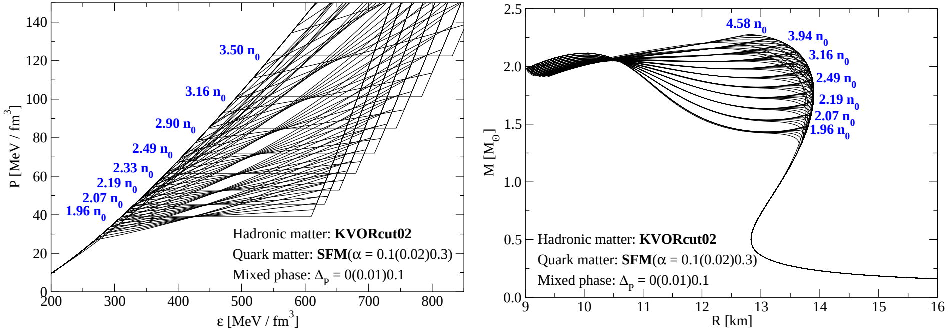
Maslov, Kolomeitsev, Voskresensky, Nucl.Phys. A950 (2016)
Kolomeitsev & Voskresensky, Nuc. Phys. A 759 (2005)

The quark EoS model SFM with available volume fraction parameter

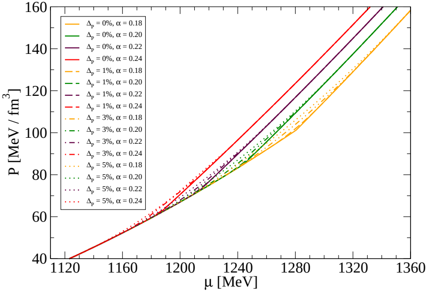


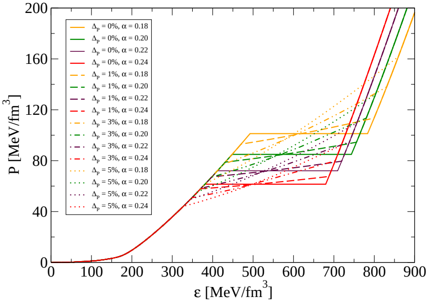
Kaltenborn, Bastian, Blaschke, Phys. Rev. D 96, 056024 (2017)

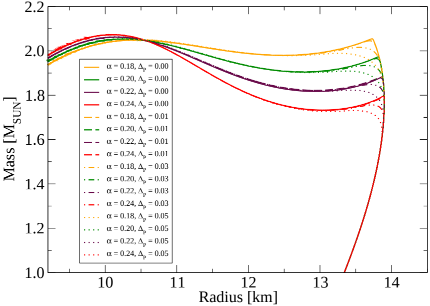
Results of mimicking pasta phase

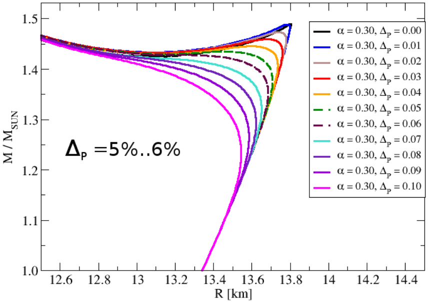


Results of mimicking pasta phase

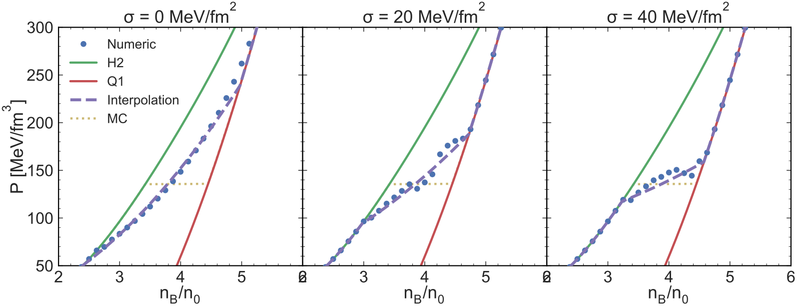




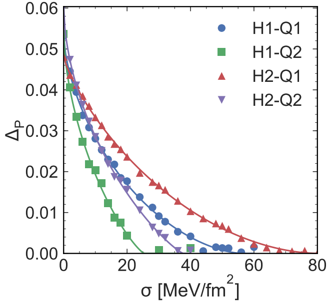




Comparison with the real pasta



Mixed phase model
supports third family!



Maslov, Yasutake, Ayriyan et al.
In preparation (2018)

Thank you for your attention!

K. Maslov, N. Yasutake, A. Ayriyan, D. Blaschke, H. Grigorian, T. Maruyama, T. Tatsumi, D. N. Voskresensky. *Hybrid equation of state with pasta phases and third family of compact stars I: Pasta phases and effective mixed phase model*. **In preparation** (2018)

V. Abgaryan, D. Alvarez-Castillo, A. Ayriyan, D. Blaschke and H. Grigorian. *Two Novel Approaches to the Hadron-Quark Mixed Phase in Compact Stars*. **Universe** 4(9) (2018), 94
doi 10.3390/universe4090094

A. Ayriyan, N.-U. Bastian, D. Blaschke, H. Grigorian, K. Maslov, and D. N. Vosk- resensky. Robustness of third family solutions for hybrid stars against mixed phase effects. **Physical Review C** 97 (2018), 045802
doi 10.1103/PhysRevC.97.045802 doi 10.1103/PhysRevC.97.045802

A. Ayriyan and H. Grigorian. *Model of the Phase Transition Mimicking the Pasta Phase in Cold and Dense Quark-Hadron Matter*. **European Physical Journal WoC** (2018), vol. 173, 03003
doi 10.1051/epjconf/201817303003