First-order phase transition from hypernuclear matter to deconfined quark matter obeying new constraints from compact star observations

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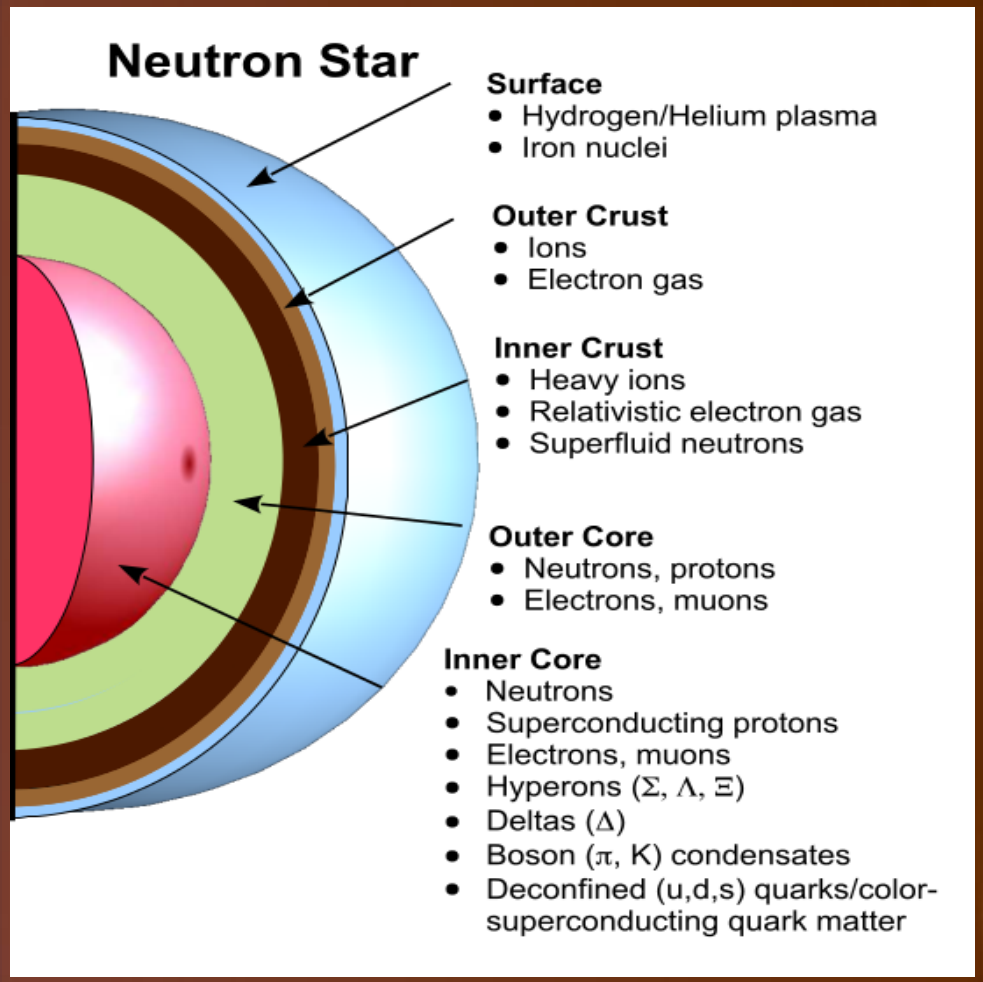
Nuclear Matter

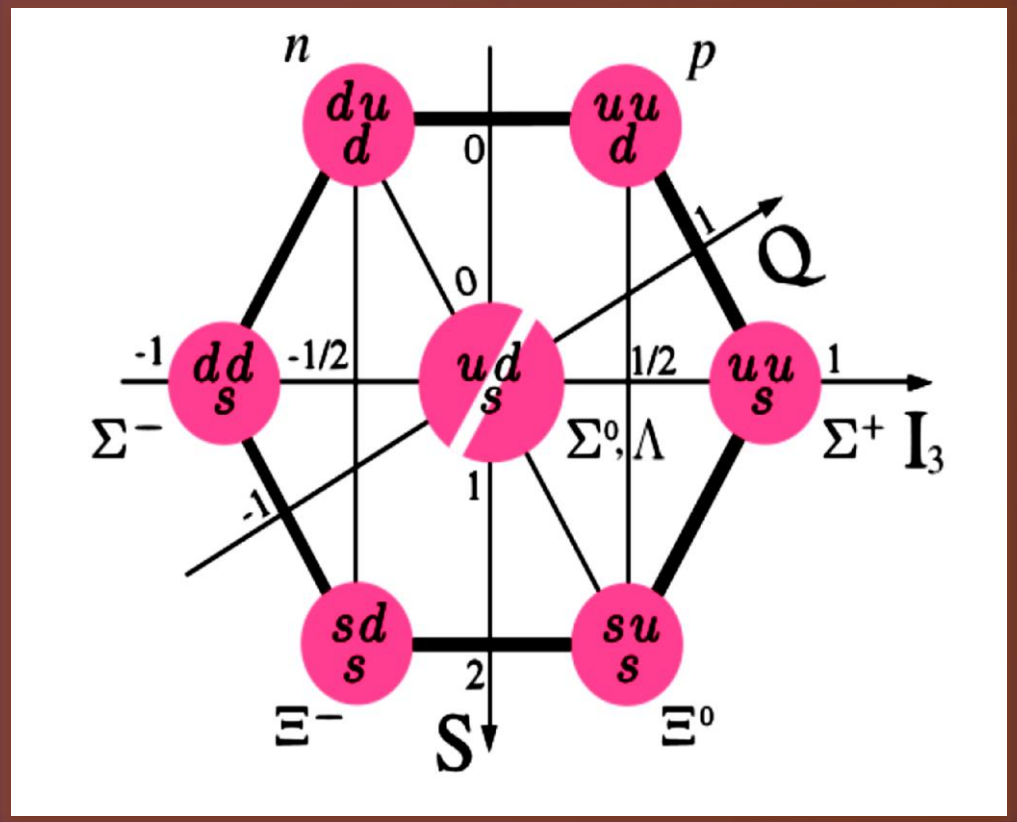
The number of nucleons is supposed to be infinite

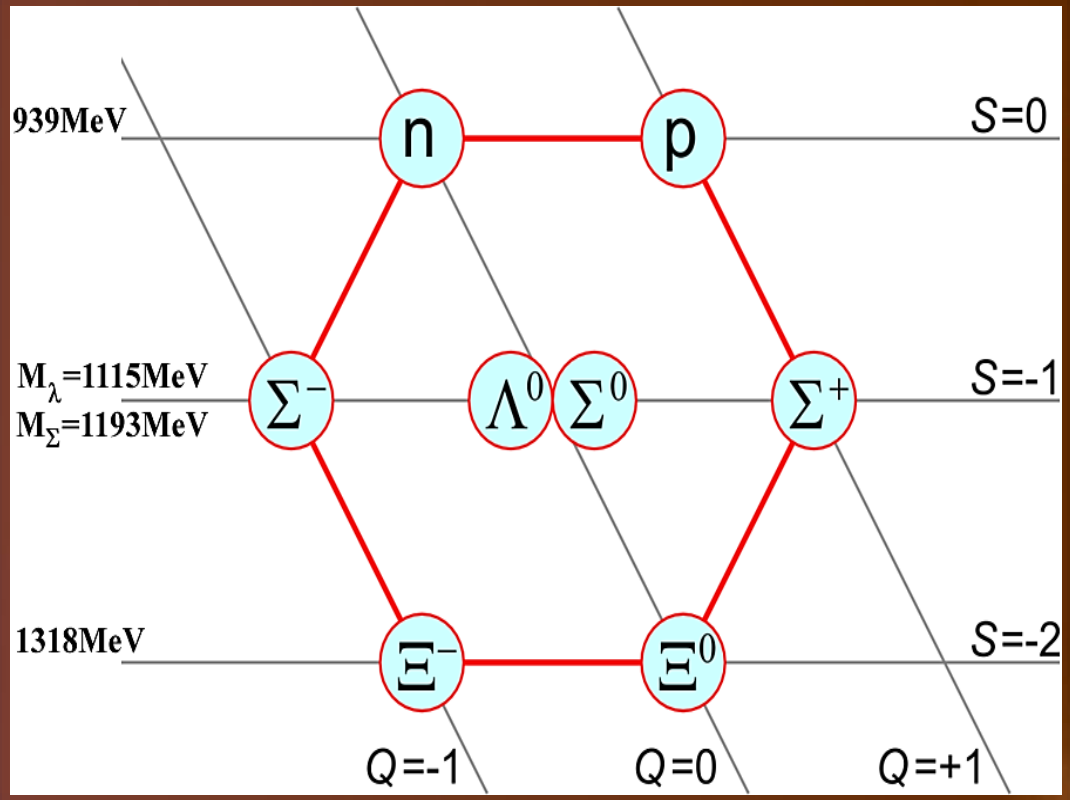
Coulomb interaction is disregarded because of the strong interaction between nucleons

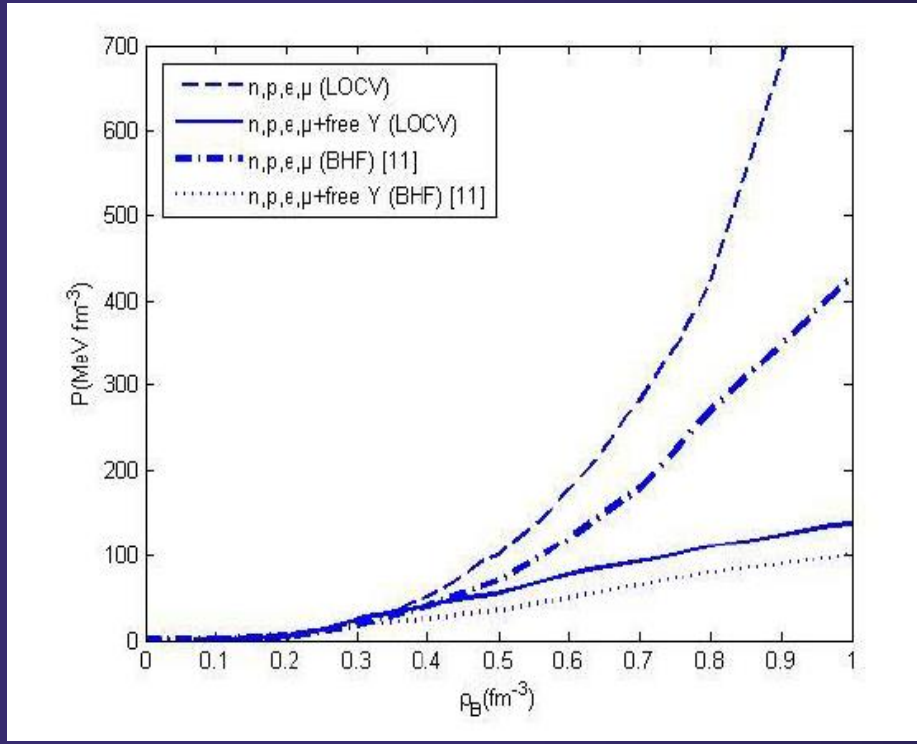
The density of nuclear matter is supposed to be finite

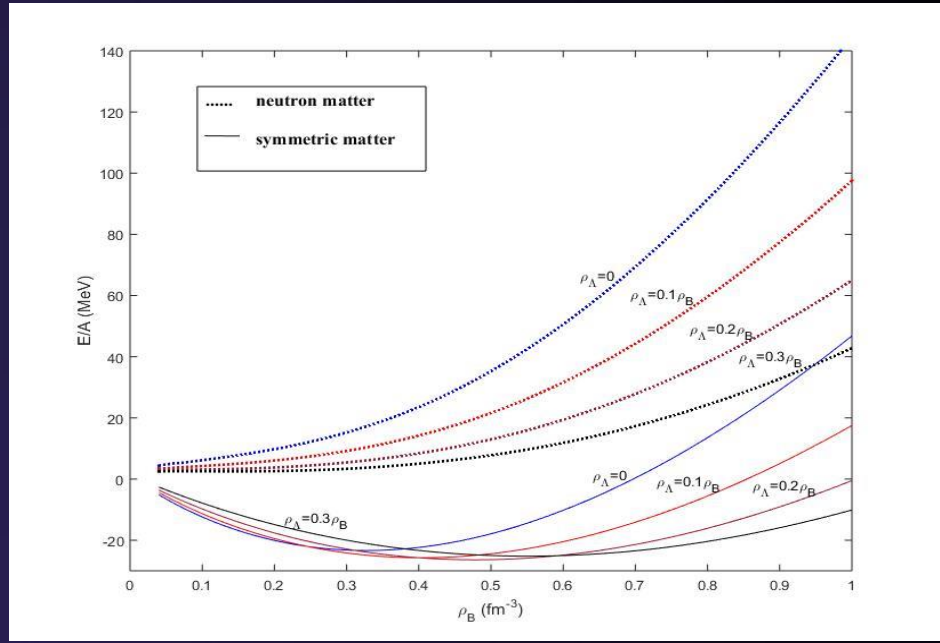
$$\rho = \lim_{N,V\to\infty} \frac{N}{V}$$




n
p
du d
uu d
0
0
1
Q
-1
dd s
-1/2
ud s
1/2
uu s
1
Σ⁻
Σ⁰,Λ
Σ⁺
I3
-1
1
sd s
su s
2
Ξ⁻
S
Ξ⁰

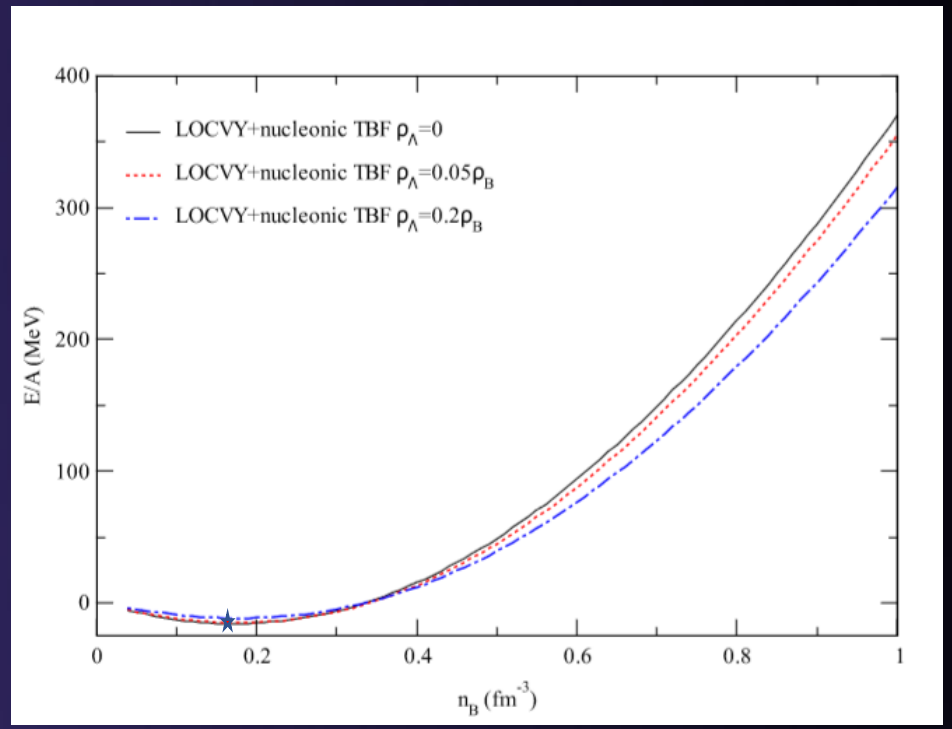

939MeV
n
p
S=0
Mλ=1115MeV
MΣ=1193MeV
Σ⁻
Λ⁰
Σ⁰
Σ⁺
S=-1
1318MeV
Ξ⁻
Ξ⁰
S=-2
Q=-1
Q=0
Q=+1



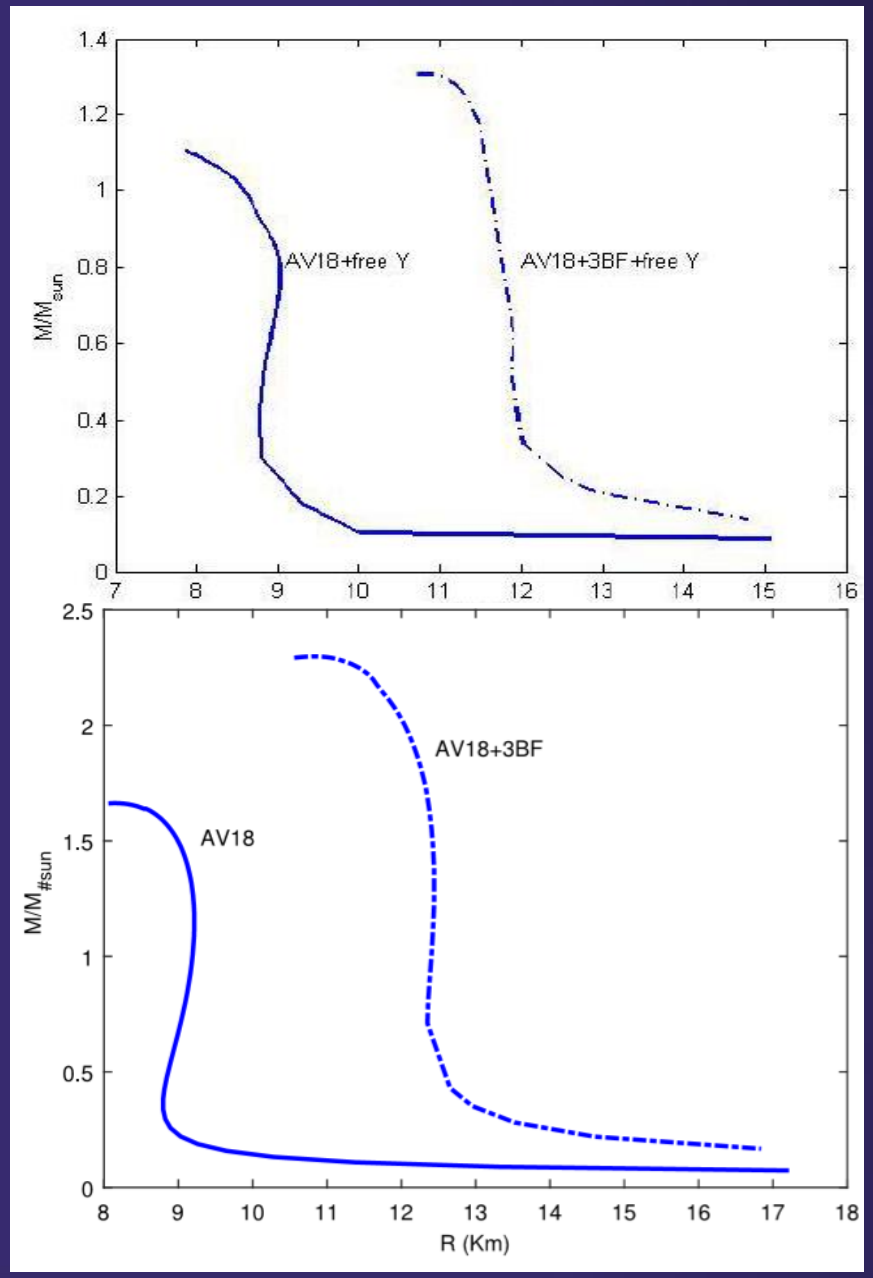


M. Baldo, G. F. Burgio, and H. J. Schulze, Physical Review C 61, 055801 (2000)

$\rho_0(fm^{-3})$	0.1748
$E_0/_A(MeV)$	-15.58
$E_{sym}(MeV)$	39.9
K_0	295.77



Mass-Radius Relation



For PSRJ0740+6620

$Mmax = 2.17^{+0.11}_{-0.10} M\odot$

for the binary neutron star merger GW170817

R($1.6M\odot$) > 10.7 km

&

R($1.4M\odot$) < 13.6 km

Hyperon Puzzle

Phase Transition From Hyper Nuclear Matter to Deconfined Quark Matter as a Solution to the Hyperon Puzzle

Initiation of a new collaboration that joins different domains of state-of-the-art expertise

LOCV
For hadronic phase

nl-NJL
For quark phase

LOCV method

Lowest Order Constrained Variational method

$$Hamiltonian\ of\ nuclear\ matter : H = \sum_i \frac{{P_i}^2}{2m_i} + \sum_{i \neq j} V(ij)$$

Trial wave function : $\boldsymbol{\Psi(1 \ldots A) = F(1 \ldots A)\Phi(1 \ldots A)}$

$$\boldsymbol{E = \langle H \rangle = \frac{1}{N} \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = E_1 + E_{MB} \cong E_1 + E_2}$$

Characteristics

- A pure variational method in configuration space
- Generalized to finite temperature
- Calculation of correlation functions
- Using both central and tensor correlation functions
- Energy per baryon and correlation functions are state-dependent
- Using normalization condition as the only constraint

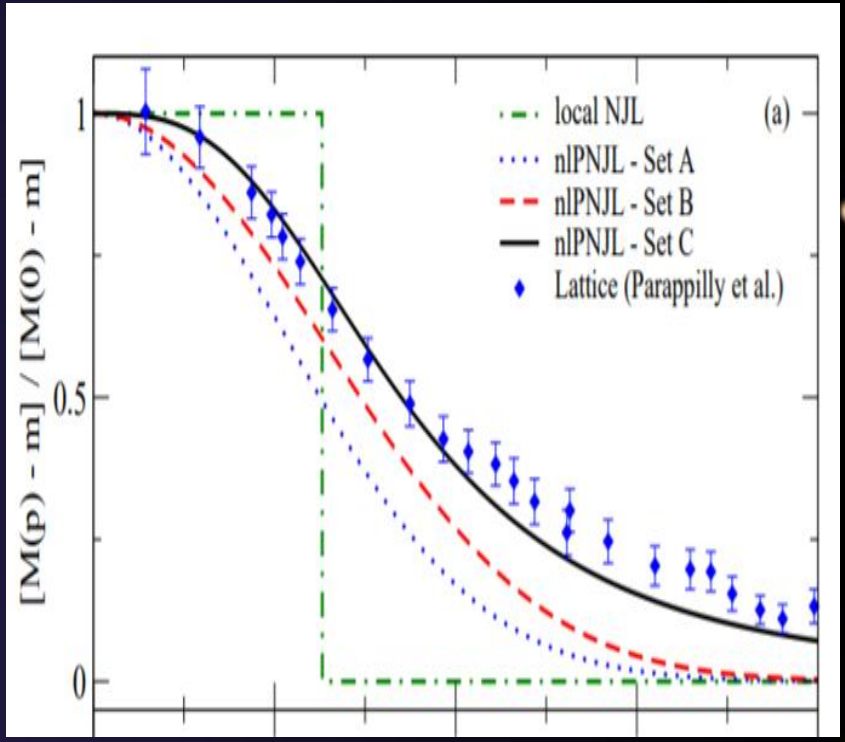
nl-NJL model
Nonlocal Nambu–Jona-Lasinio model

Characteristics

- nonlocal covariant extension of the NJL model
- quark fields interact via nonlocal (momentum dependent) vertices
- Nonlocal interactions regularize the model in such a way there is not need to introduce sharp cutoffs

nl-NJL model

- Constant coefficients (model A)
- density-dependent coefficients (model B)



G.A. Contrera, A. G. Grunfeld and D. Blaschke, EPJ A 52 (2016)

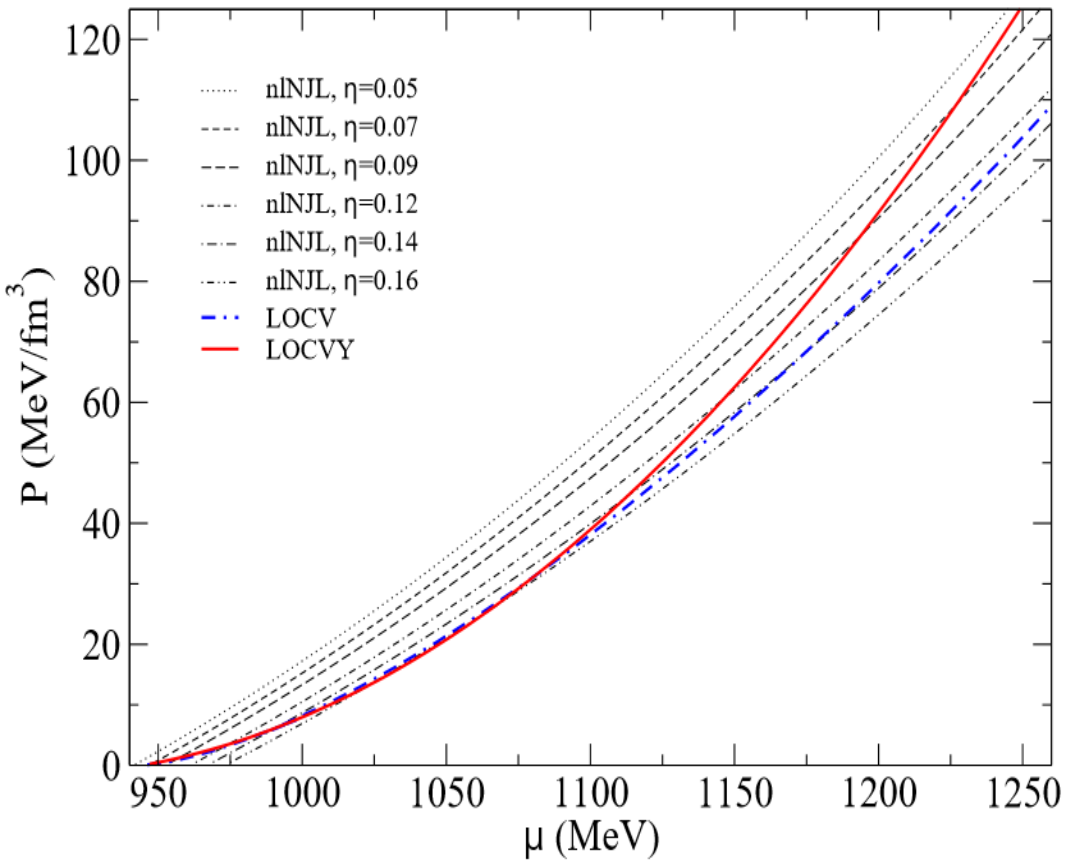
First Order Phase Transition (PT) by a Maxwell construction

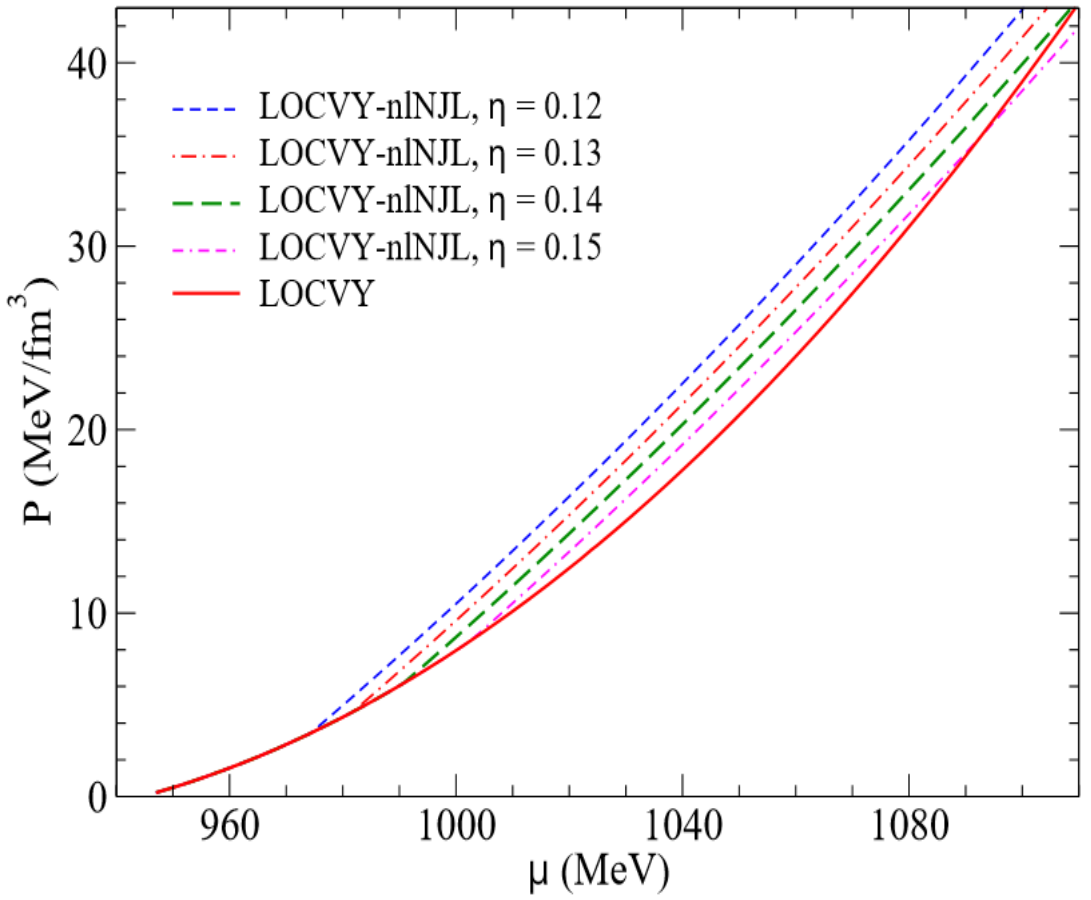
$$\mu_H = \mu_Q = \mu_c$$

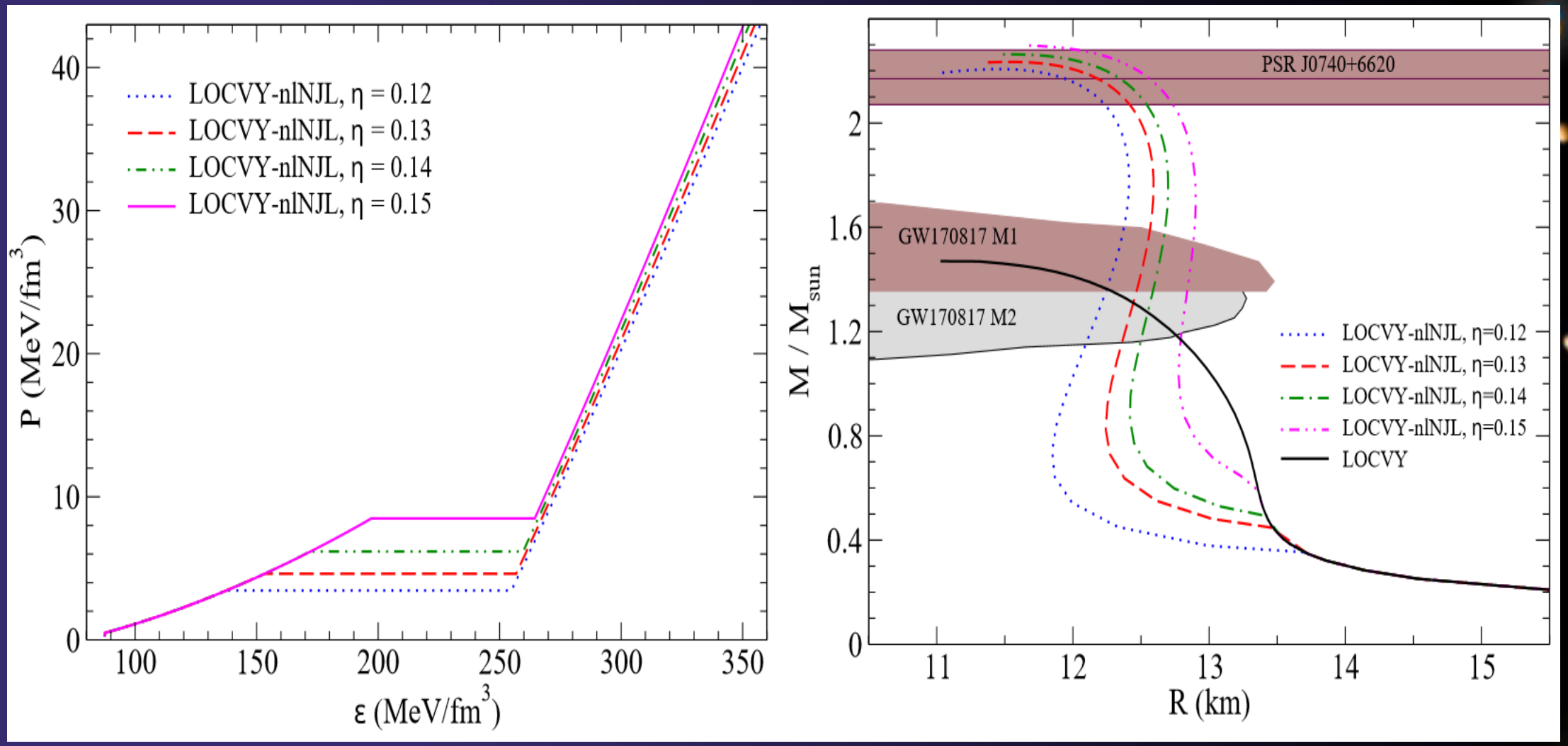
$$T_H = T_Q = T_c$$

$$P_H(\mu_B, \mu_e) = P_Q(\mu_B, \mu_e) = p_c$$

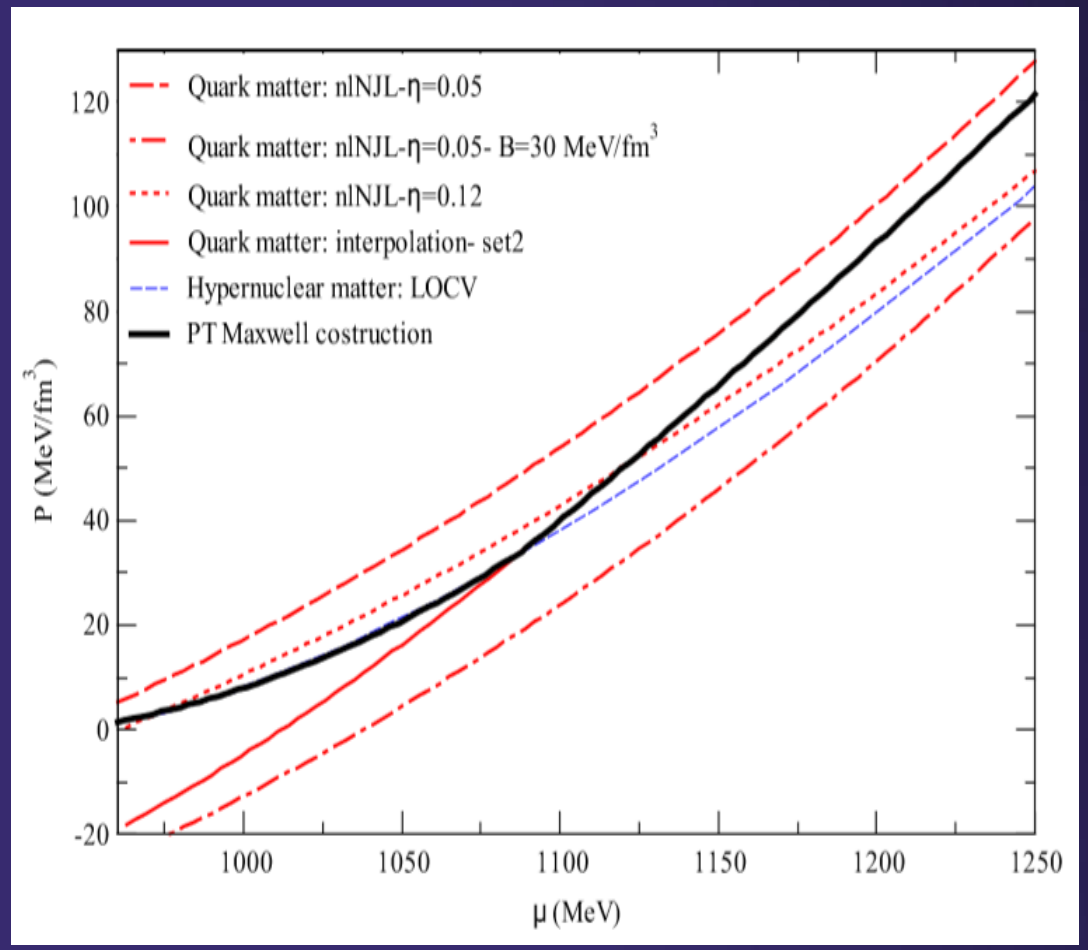
Model A

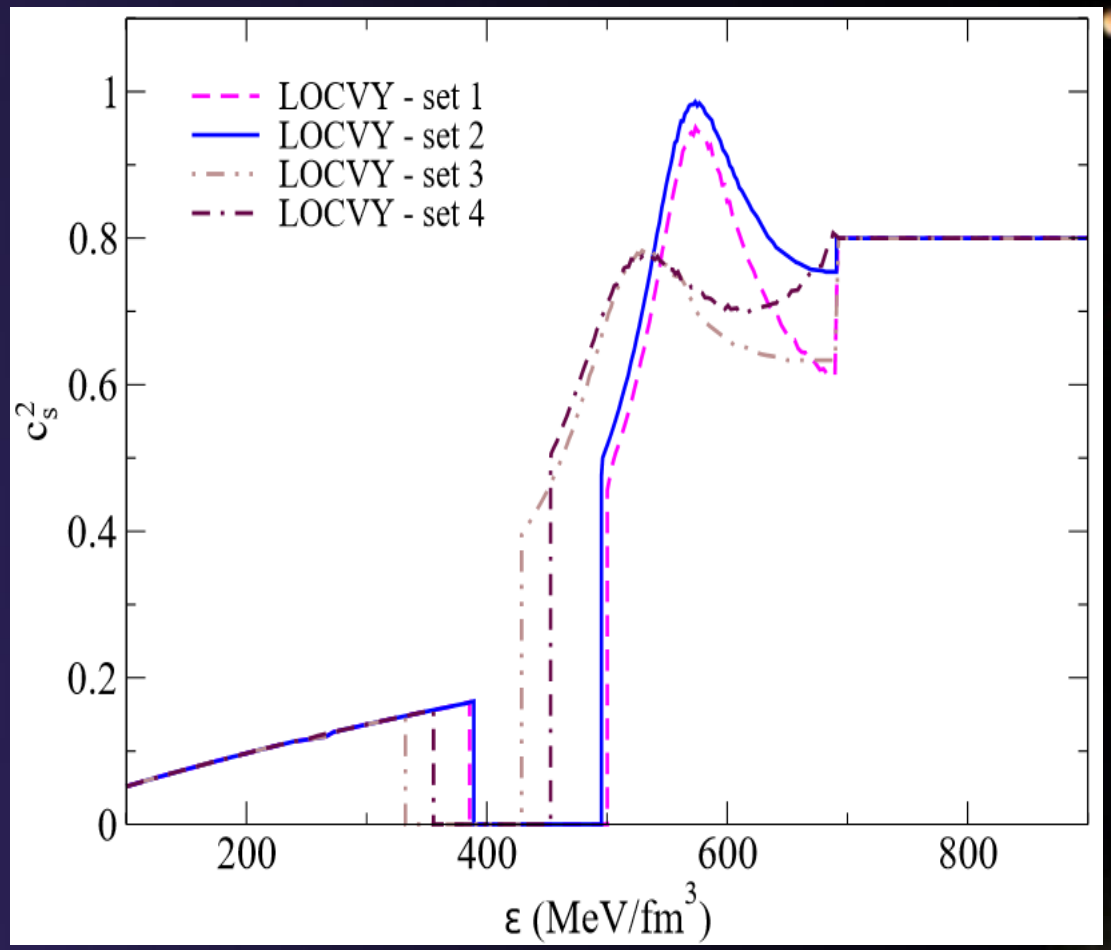

nlNJL, η=0.05
nlNJL, η=0.07
nlNJL, η=0.09
nlNJL, η=0.12
nlNJL, η=0.14
nlNJL, η=0.16
LOCV
LOCVY
P (MeV/fm^3)
μ (MeV)
0
20
40
60
80
100
120
950
1000
1050
1100
1150
1200
1250

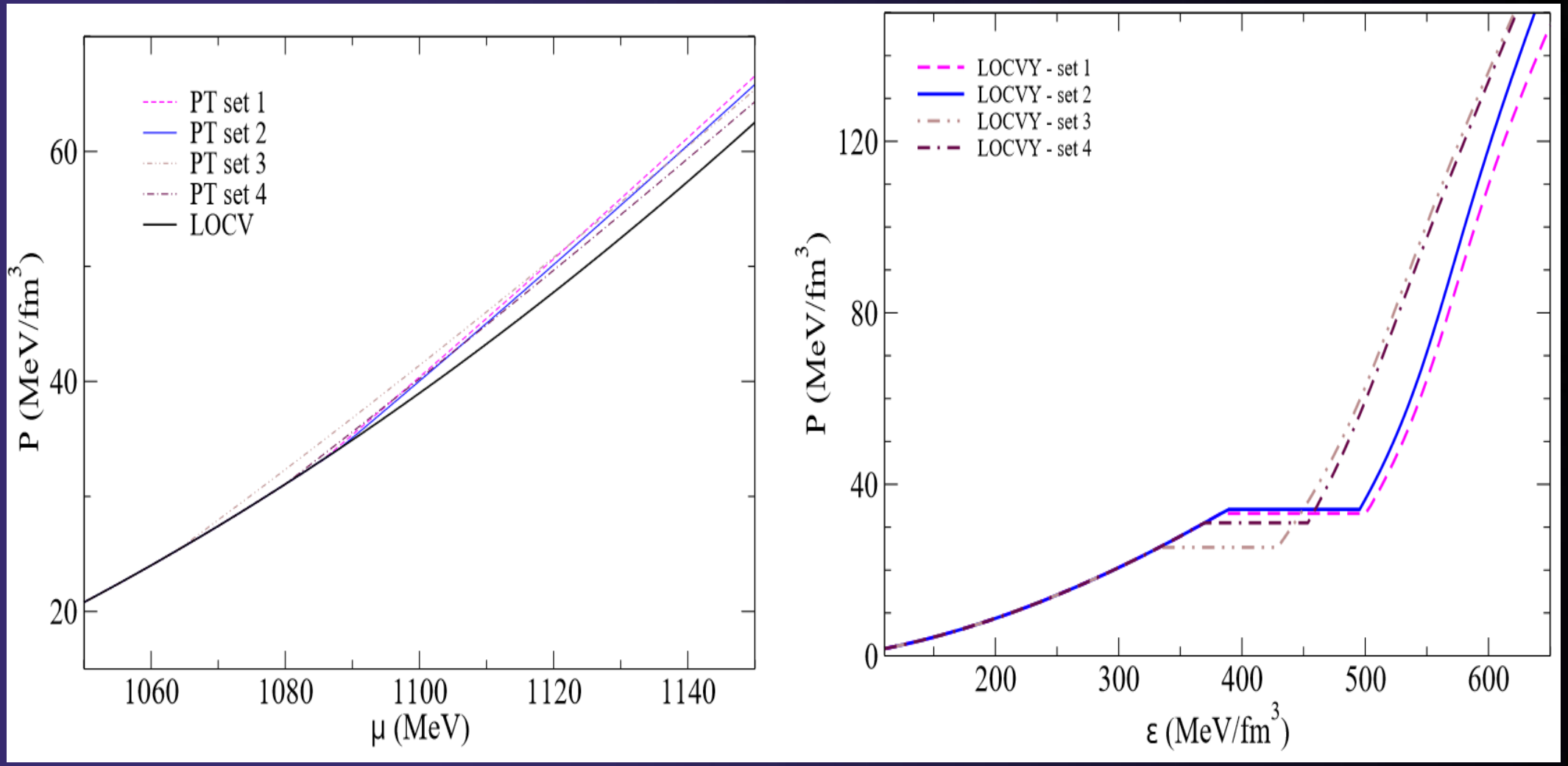

LOCVY-nlNJL, η = 0.12
LOCVY-nlNJL, η = 0.13
LOCVY-nlNJL, η = 0.14
LOCVY-nlNJL, η = 0.15
LOCVY
P (MeV/fm^3)
μ (MeV)
0
10
20
30
40
960
1000
1040
1080

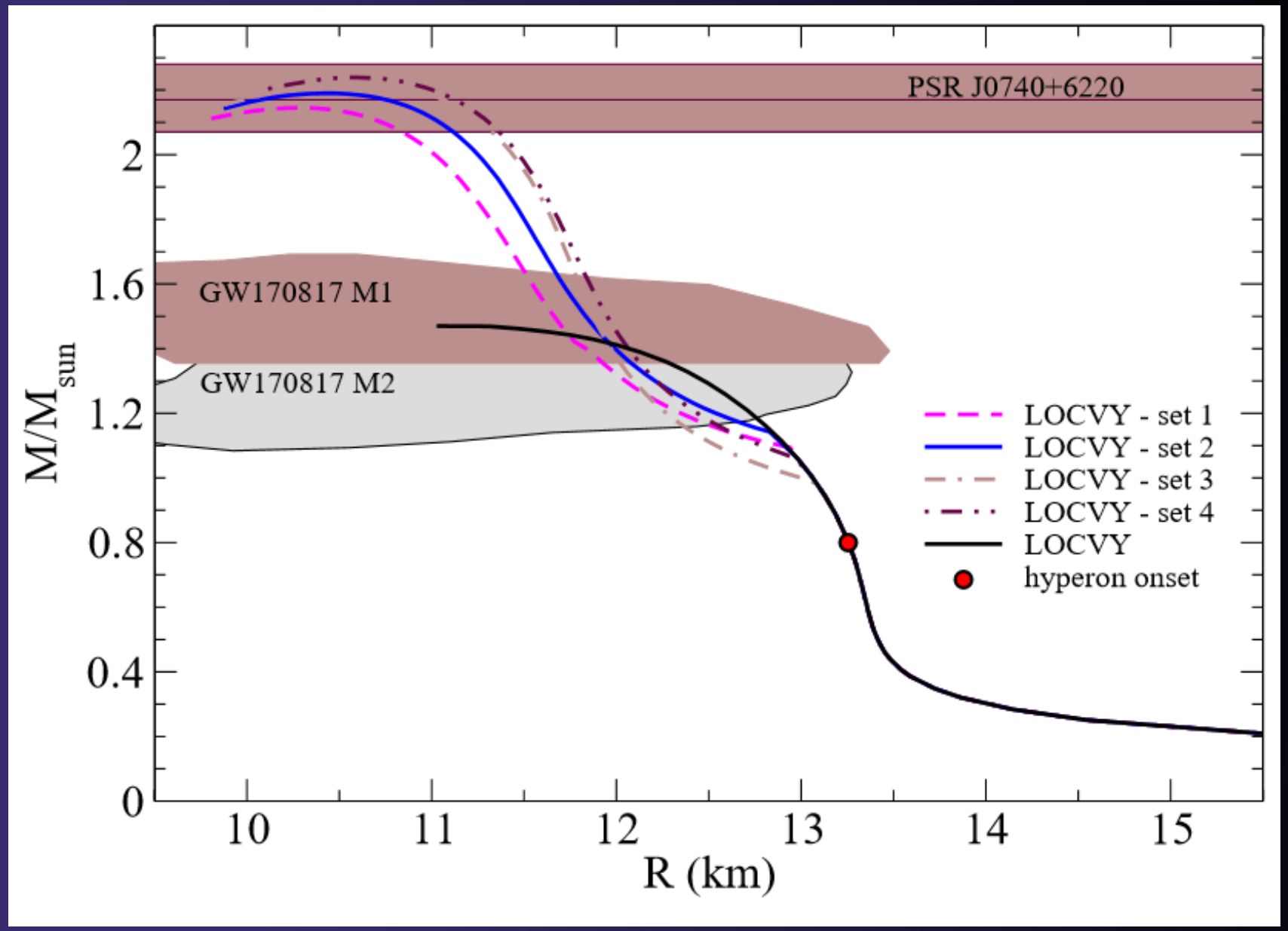

LOCVY-nlNJL, η = 0.12
LOCVY-nlNJL, η = 0.13
LOCVY-nlNJL, η = 0.14
LOCVY-nlNJL, η = 0.15
P (MeV/fm^3)
ε (MeV/fm^3)
0
10
20
30
40
100
150
200
250
300
350
PSR J0740+6620
GW170817 M1
GW170817 M2
M / M$_{sun}$
R (km)
0
0.4
0.8
1.2
1.6
2
11
12
13
14
15
LOCVY-nlNJL, η=0.12
LOCVY-nlNJL, η=0.13
LOCVY-nlNJL, η=0.14
LOCVY-nlNJL, η=0.15
LOCVY

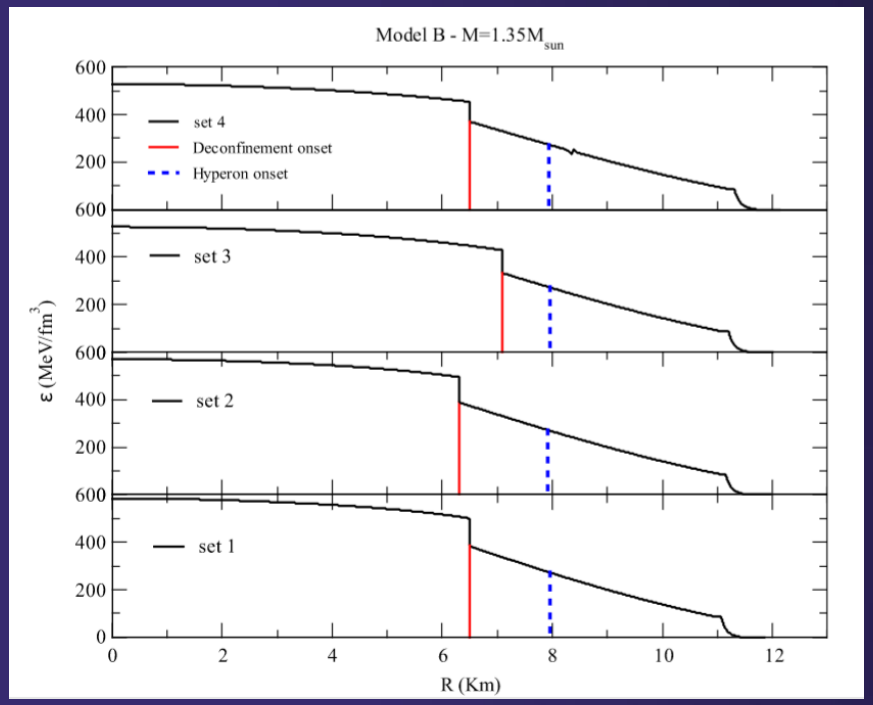
Model B

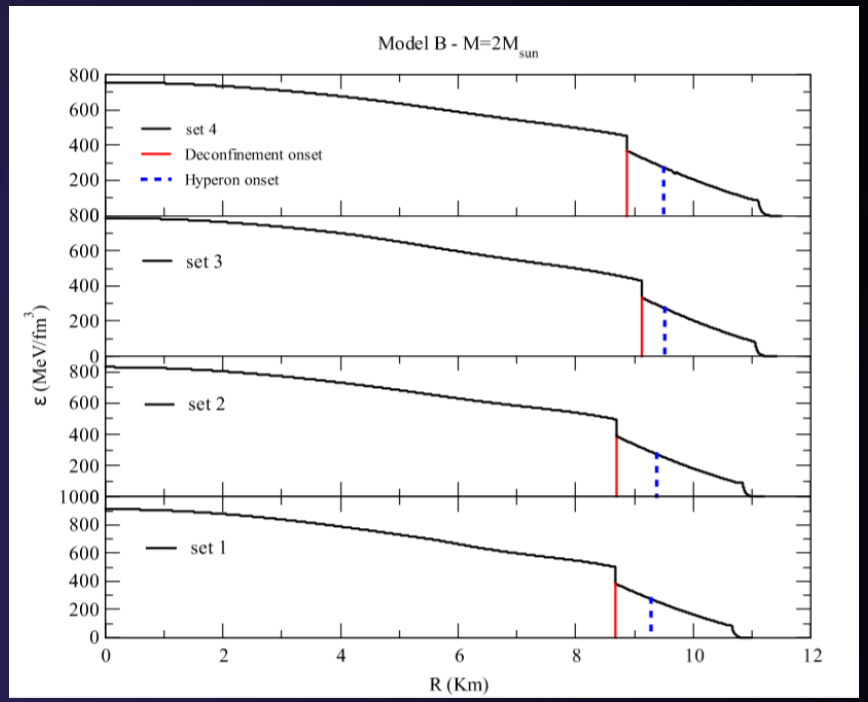

Quark matter: nlNJL-η=0.05
Quark matter: nlNJL-η=0.05- B=30 MeV/fm3
Quark matter: nlNJL-η=0.12
Quark matter: interpolation- set2
Hypernuclear matter: LOCV
PT Maxwell costruction
P (MeV/fm3)
μ (MeV)
120
100
80
60
40
20
0
-20
1000
1050
1100
1150
1200
1250

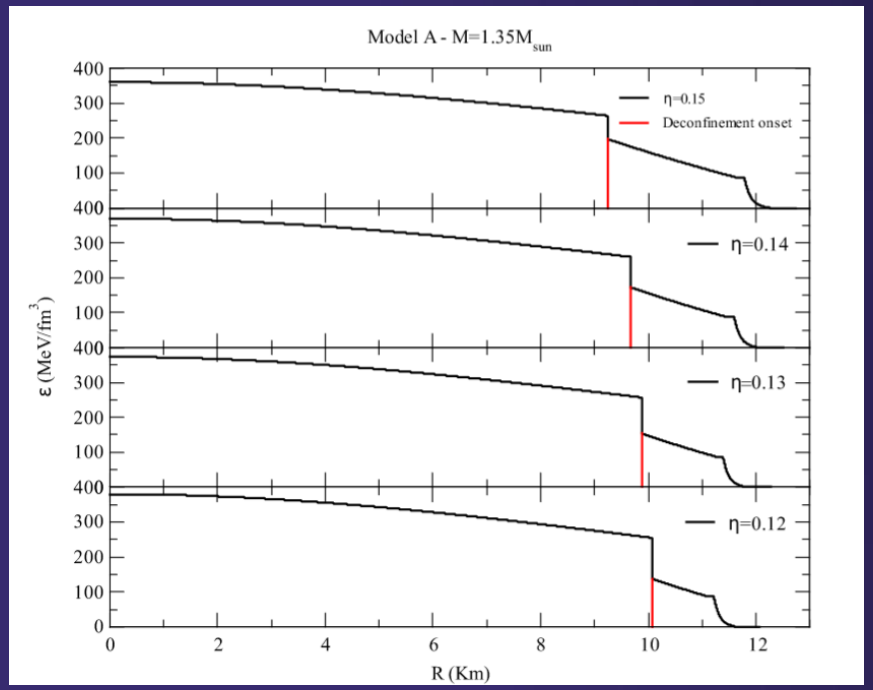

LOCVY - set 1
LOCVY - set 2
LOCVY - set 3
LOCVY - set 4
c2s
ε (MeV/fm3)
1
0.8
0.6
0.4
0.2
0
200
400
600
800

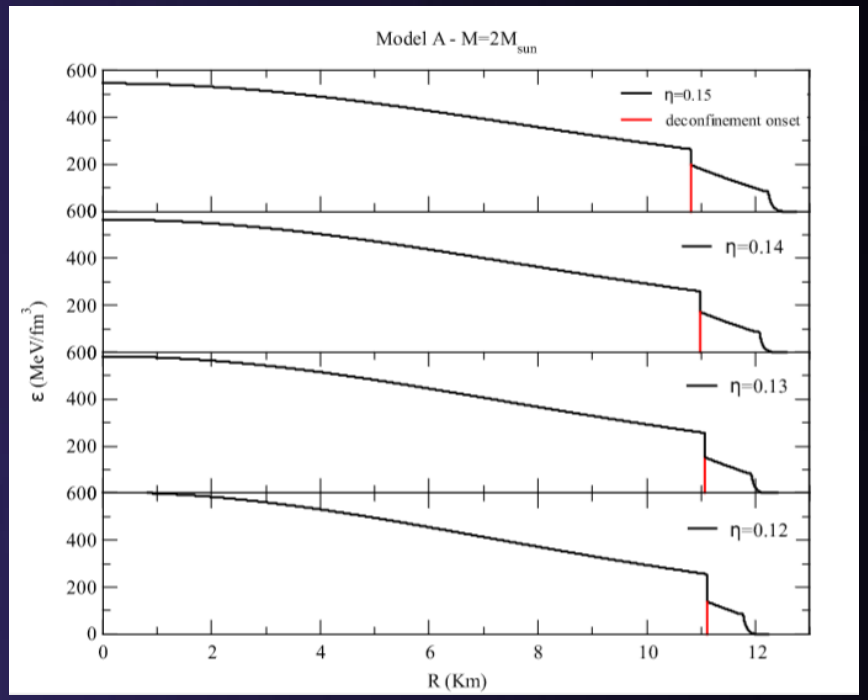

PT set 1
PT set 2
PT set 3
PT set 4
LOCV
P (MeV/fm^3)
μ (MeV)
20
40
60
1060
1080
1100
1120
1140
LOCVY - set 1
LOCVY - set 2
LOCVY - set 3
LOCVY - set 4
P (MeV/fm^3)
ε (MeV/fm^3)
0
40
80
120
200
300
400
500
600

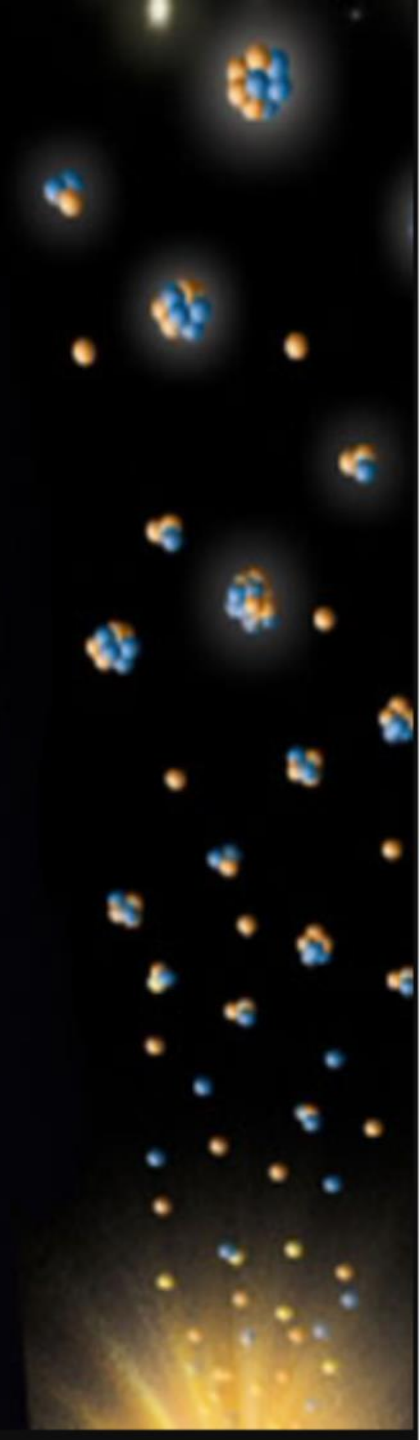

PSR J0740+6220
GW170817 M1
GW170817 M2
LOCVY - set 1
LOCVY - set 2
LOCVY - set 3
LOCVY - set 4
LOCVY
hyperon onset
M/M_sun
R (km)
0
0.4
0.8
1.2
1.6
2
10
11
12
13
14
15


Model B - M=1.35M$_{sun}$
set 4
Deconfinement onset
Hyperon onset
set 3
set 2
set 1
ε (MeV/fm^3)
R (Km)

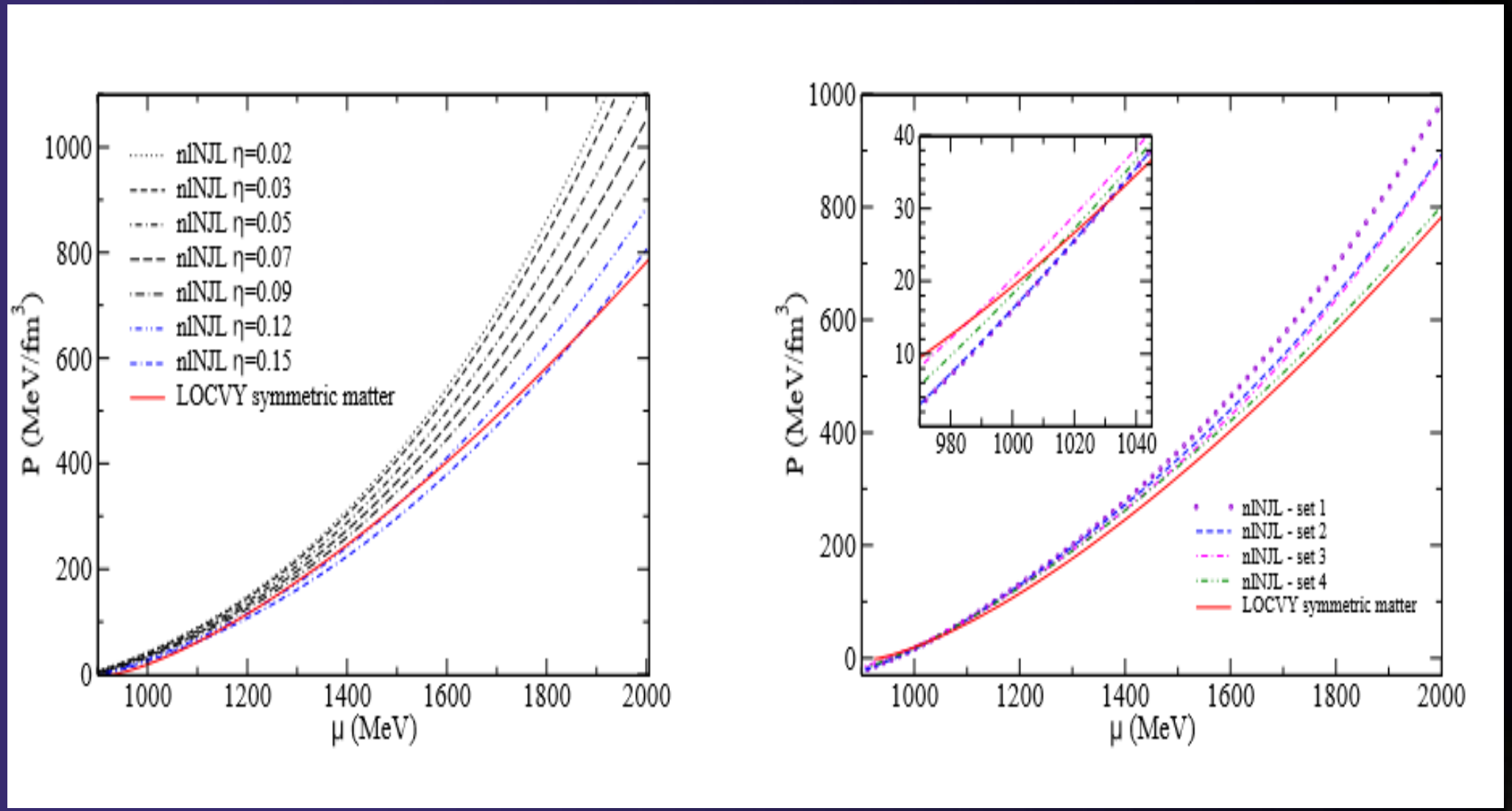

Model B - M=2M$_{sun}$
set 4
Deconfinement onset
Hyperon onset
set 3
set 2
set 1
ε (MeV/fm^3)
R (Km)


Model A - M=1.35M$_{sun}$
η=0.15
Deconfinement onset
η=0.14
η=0.13
η=0.12
ε (MeV/fm^3)
R (Km)

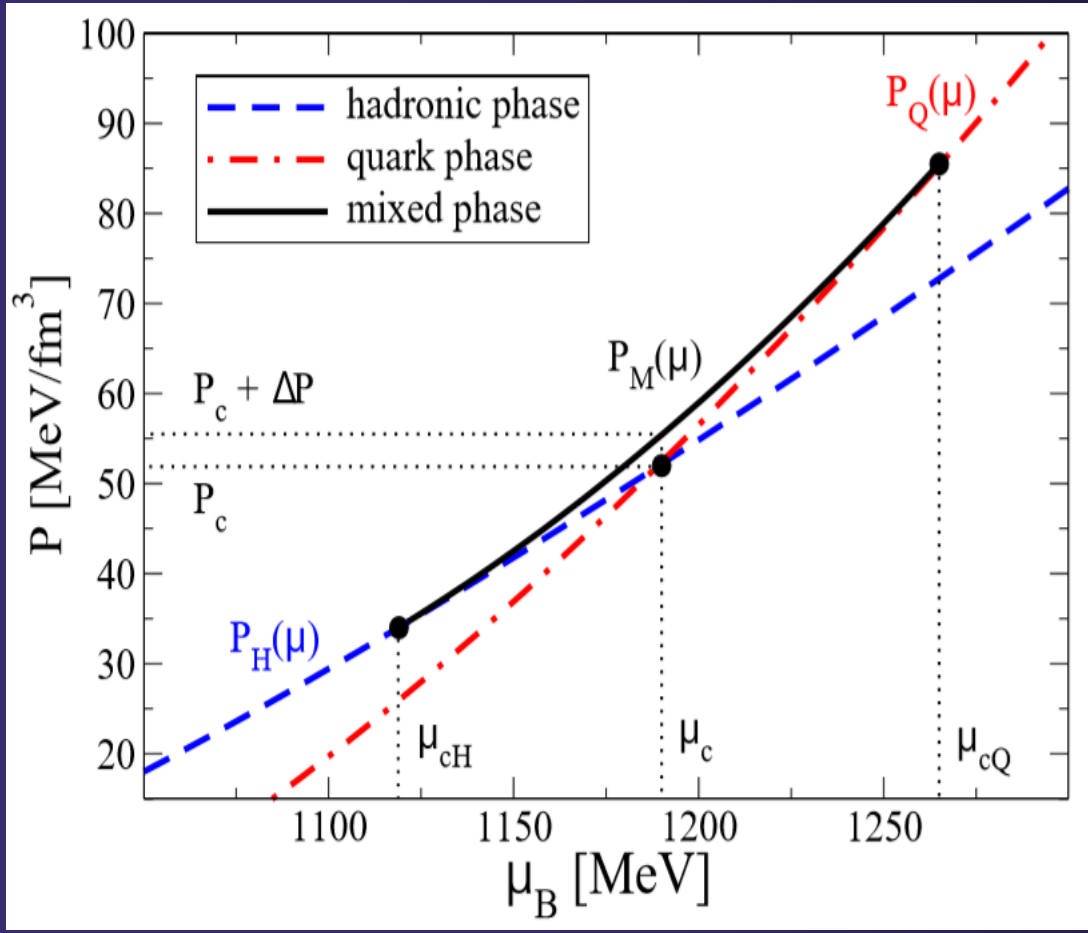

Model A - M=2M$_{sun}$
η=0.15
deconfinement onset
η=0.14
η=0.13
η=0.12
ε (MeV/fm^3)
R (Km)



Symmetric Matter



Replacement Interpolation Method (RIM)
A Mixed Phase Approach

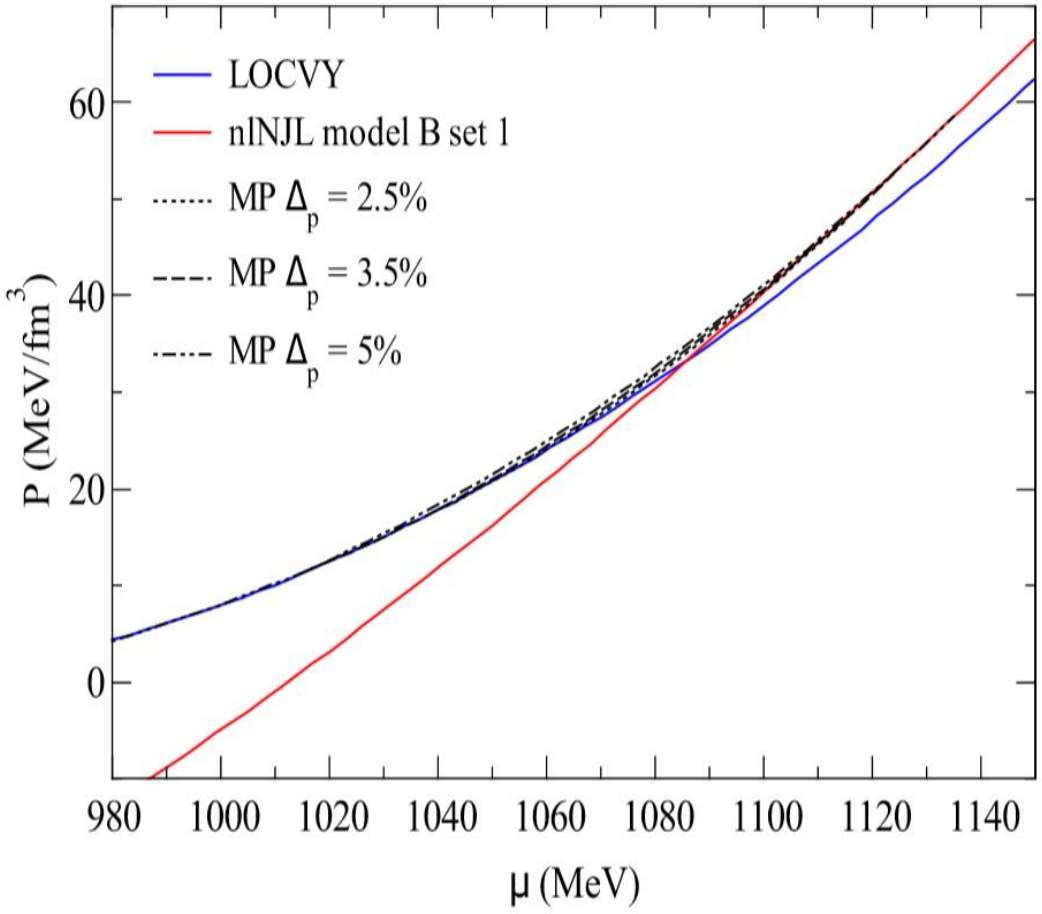


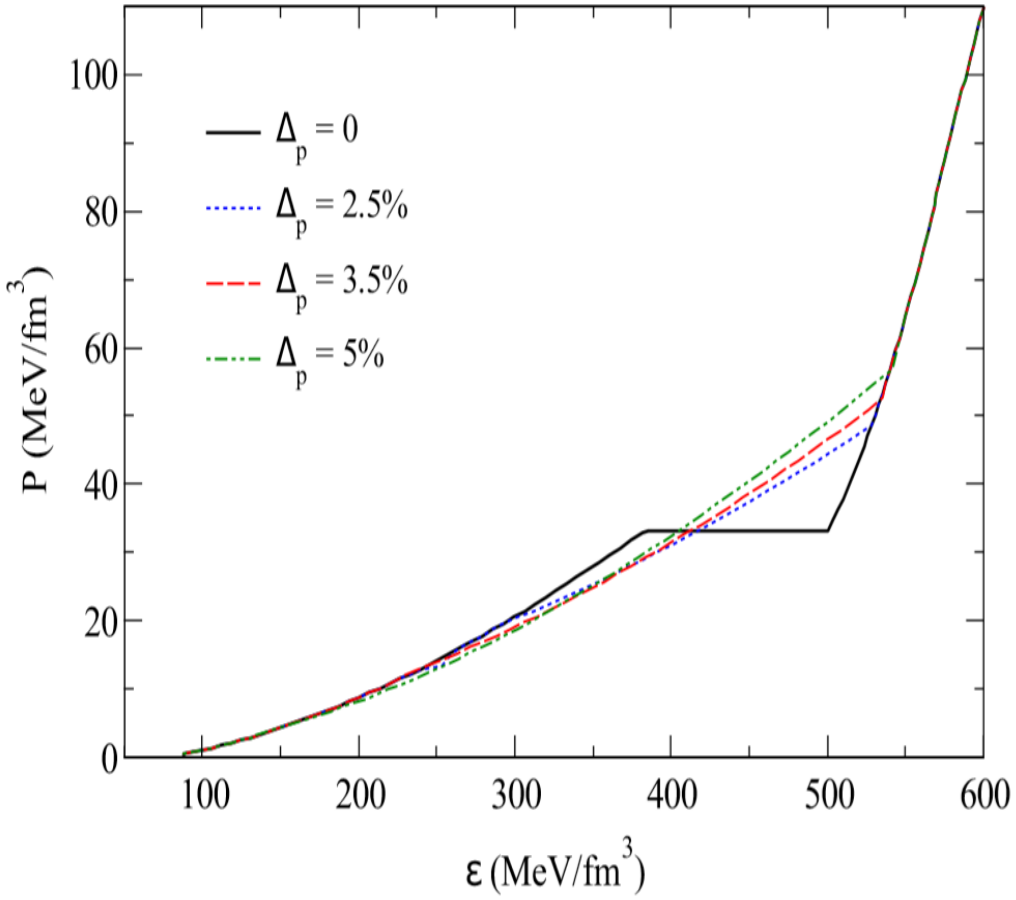
$$P_M(\mu) = a(\mu - \mu_c)^2 + b(\mu - \mu_c) + P_c + \Delta P.$$

$$P_M(\mu_c) = P_c + \Delta P = P_M.$$

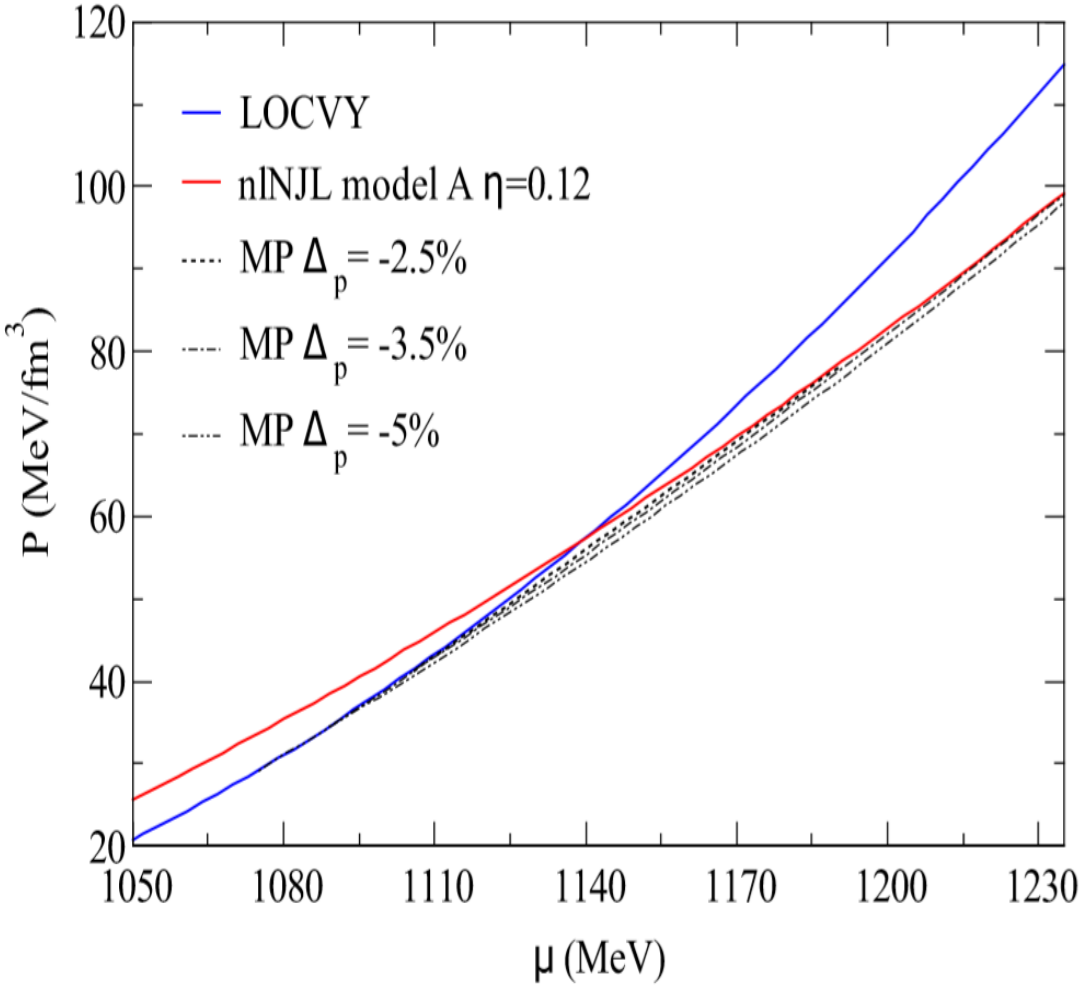
$$\begin{aligned} P_M(\mu_{cH}) &= P_H(\mu_{cH}) = P_H, \\ P_M(\mu_{cQ}) &= P_Q(\mu_{cQ}) = P_Q, \\ n_M(\mu_{cH}) &= n_H(\mu_{cH}), \\ n_M(\mu_{cQ}) &= n_Q(\mu_{cQ}). \end{aligned}$$

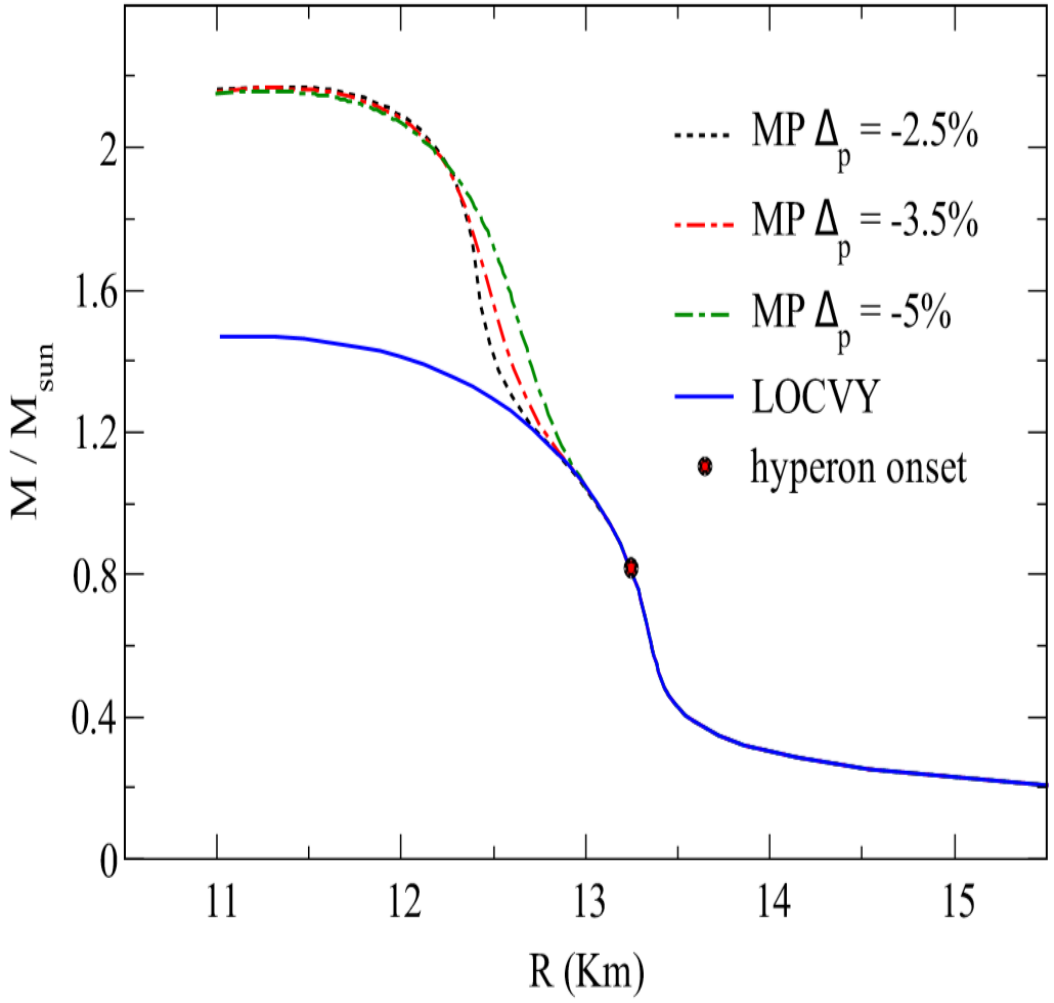
RIM for Model B





RIM for Model A





Main Results

1. model B with density dependent parameters allows for an intermediate hypernuclear matter phase in the hybrid star, between the nuclear and color superconducting quark matter phase, while in model A such a phase cannot be realized because the phase transition onset is at low densities, before the hyperon threshold density is passed.

2. for model A the cases with a sufficiently strong repulsive vector mean field ($\eta > 0.12$) which produce reasonable hybrid star EoS have also a phase transition under isospin-symmetric conditions. For $\eta = 0.12$ the critical density is $n_c = 0.79\ fm^{-3}$ and for $\eta = 0.15$ it is $n_c = 0.98\ fm^{-3}$. For the less repulsive vector mean fields ($\eta \leq 0.11$) there is no deconfinement transition in symmetric matter!

3. For model B in which a density-dependent bag pressure serves as a confining mechanism at low densities, a deconfinement phase transition under isospin-symmetric conditions is predicted for all considered parametrizations (set 1 - set 4) at densities between 2.2 n_0 and 2.7 n_0.

4. Using the RIM, for model A the low density problem (no confinement) is cured and model B is now more realistic with a mixed phase.


Thank you

LOCV Method:Lowest Order Constrained Variational Method

$$f(ij) = \sum_{\alpha.p=1}^{3} f_{\alpha}^{p}(ij) O_{\alpha}^{p}(ij)$$

$$\alpha = \{J, L, S, T, T_z\}$$

p=1 for s=0

s=1 $with$ L=J

p=2,3 for s=1 $with$ J=L±1

$$O_{\alpha}^{p}(ij) = 1,\ \frac{1}{6}(S_{12} + 4P_t),\ \frac{1}{6}(2P_t - S_{12})$$

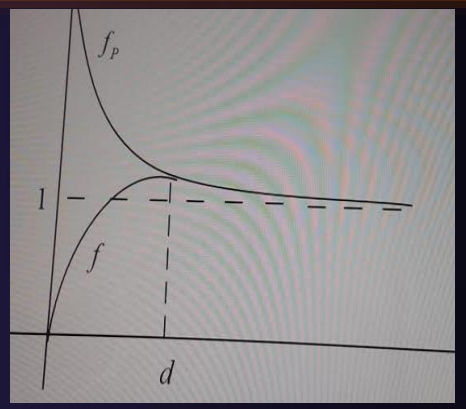
$$S_{12} = 3(\boldsymbol{\sigma}_1.\hat{r})(\boldsymbol{\sigma}_2.\hat{r}) - \boldsymbol{\sigma}_1.\boldsymbol{\sigma}_2$$

$$\left|ij\right\rangle = \left|k_1, {}^1/_2, m_{\sigma_1}, \tfrac{1}{2}, m_{\tau_1}, k_2, {}^1/_2, m_{\sigma_2}, \tfrac{1}{2}, m_{\tau_2}\right\rangle$$

The only constraint in LOCV method is renormalization condition of wave functions

$$\langle \Psi | \Psi \rangle = 1 - \sum_{ij} \langle ij | F_p^2 - F^2 | ij - ji \rangle \quad : \quad \chi = \frac{1}{N} \sum_{ij} \langle ij | F_p^2 - F^2 | ij - ji \rangle = 0$$

$$F_P = \begin{cases} \left(1 - \frac{9}{2}\left(\frac{J_l(K_f r)}{K_f r}\right)^2\right)^{-\frac{1}{2}} & T_z = \pm 1 \\ 1 & T_z = 0 \end{cases}$$



$$E_2 = \int dr \left[G\left(f'^2(r)\right) + S\left(f(r)\right) - \lambda\left(f(r)\right)\right] = \int dr\, L\left(f'(r), f(r)\right), \delta E_2 = 0$$

$$\frac{\partial \mathcal{L}}{\partial f} - \frac{\partial}{\partial r}\frac{\partial \mathcal{L}}{\partial f'} = 0$$

H. Moshfegh and M. Modarres, Journal of Physics G: Nuclear and Particle Physics **24**, 821 (1998)