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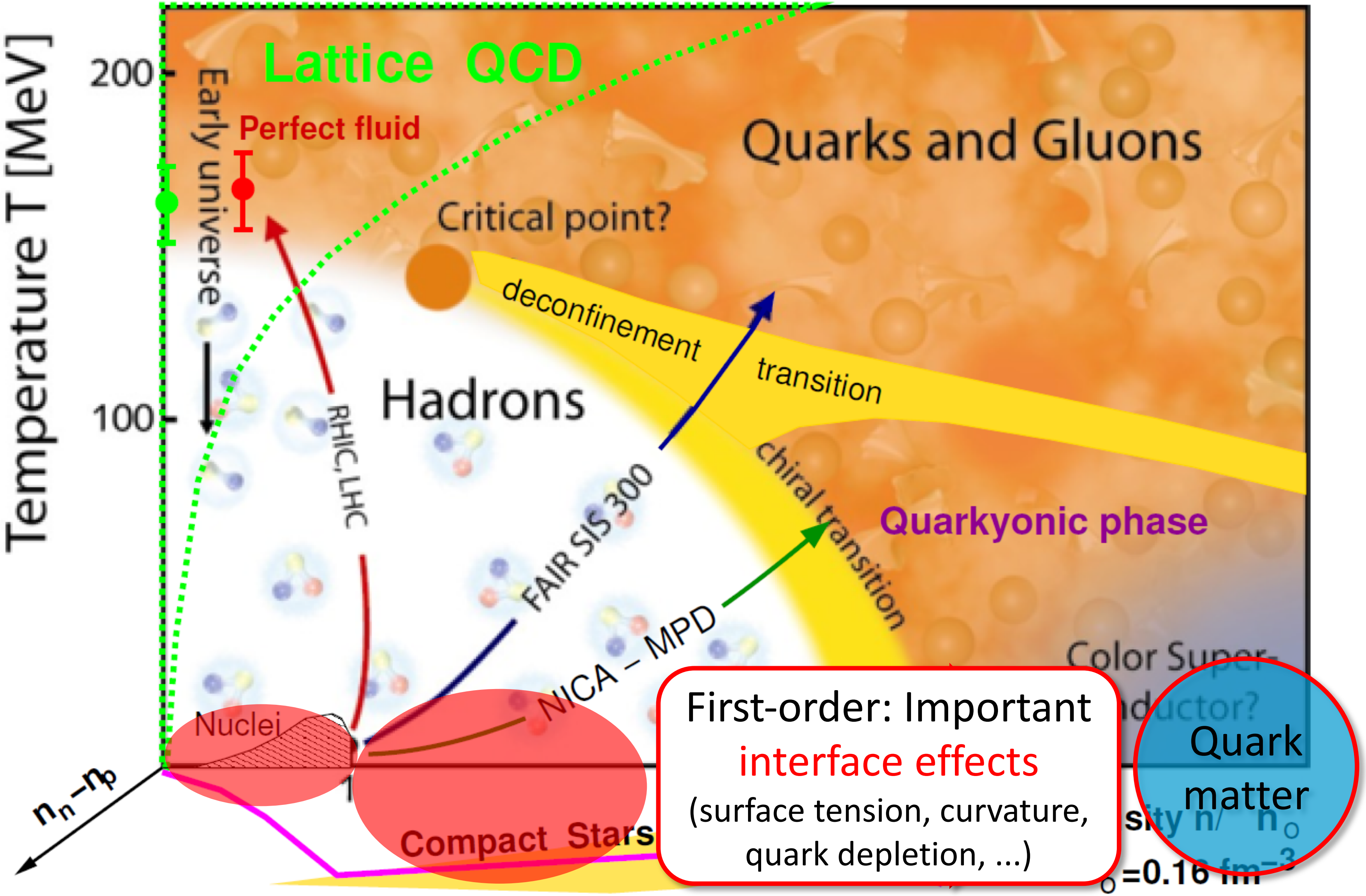
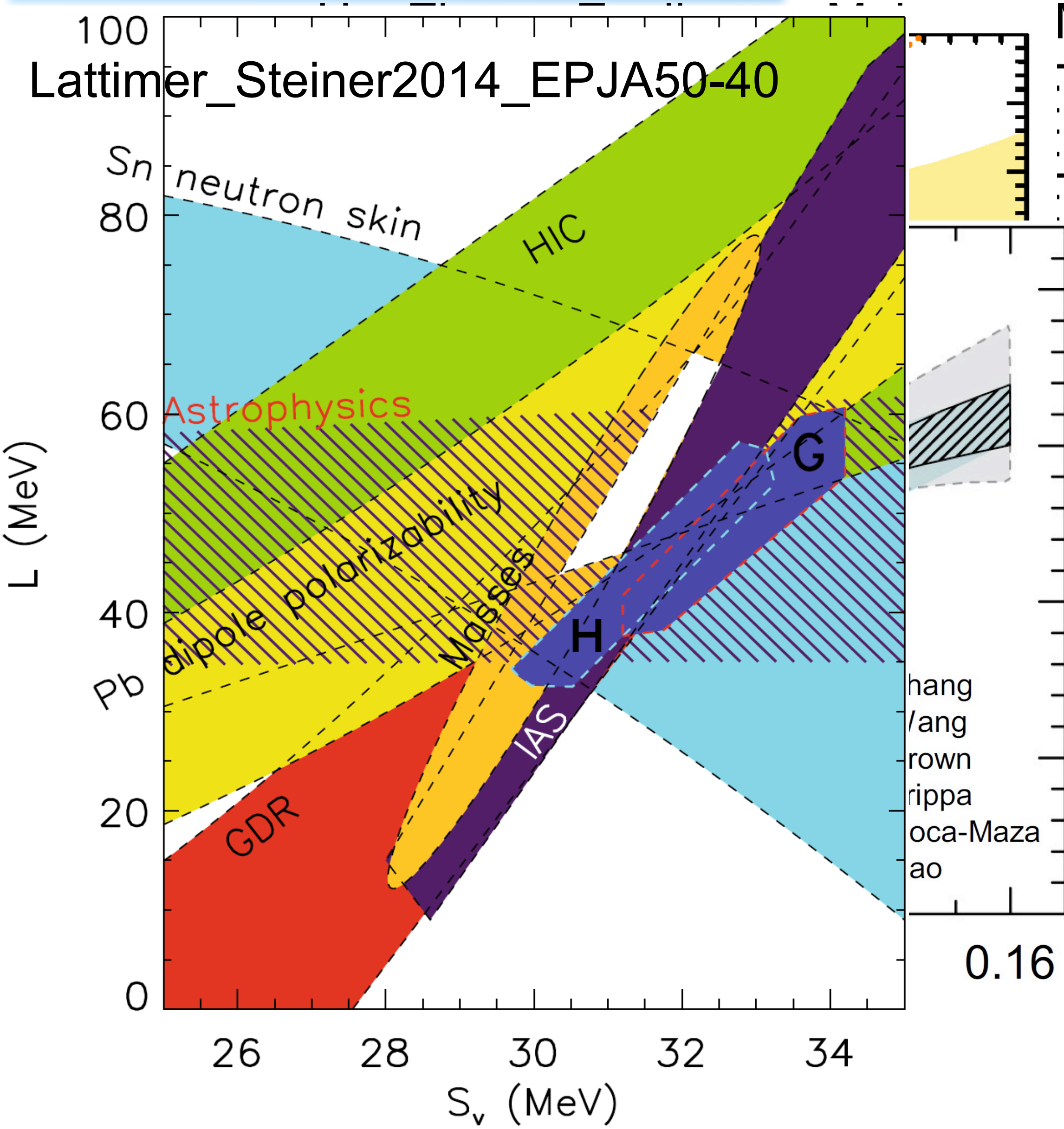
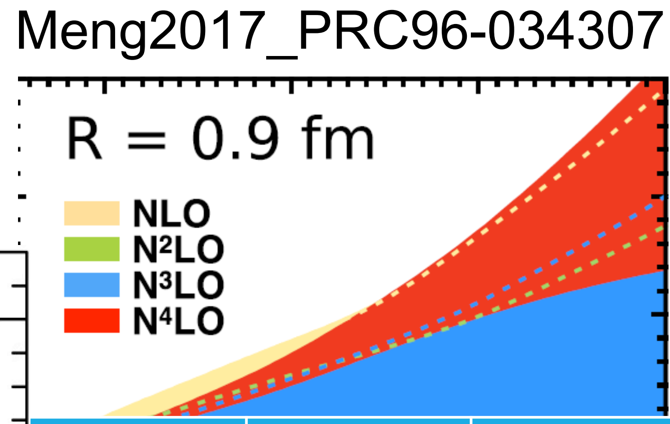
QCD Phase Diagram [McLerran2009_NPB195-275]



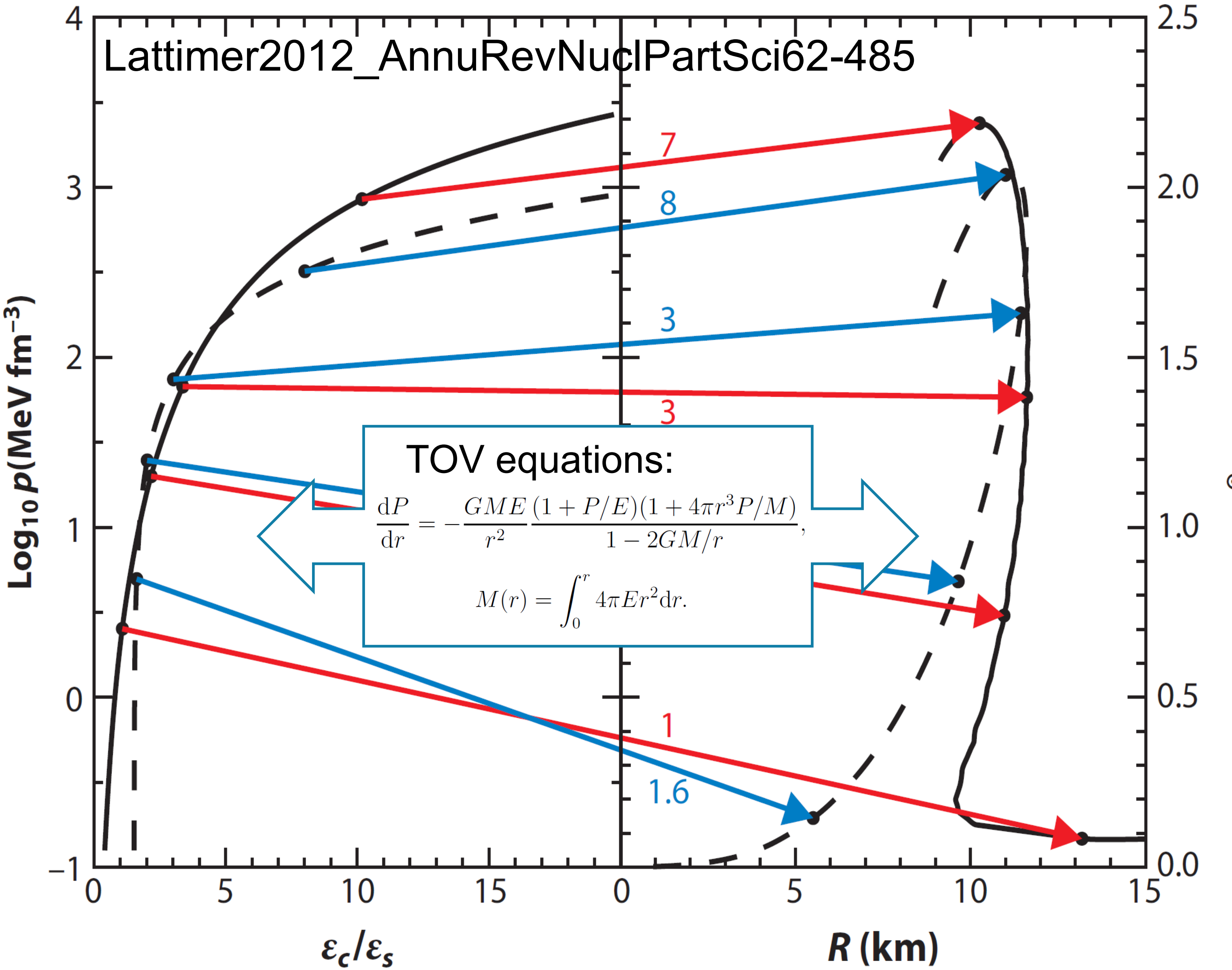
Nuclear matter constraints





	E_{sym} (MeV)	L (MeV)
NL3	37.35	118.33
TM1	36.84	110.61
PK1	37.64	115.88
PK1r	37.83	116.51
TW99	32.77	55.31
DDME2	32.32	51.30
PKDD	36.80	90.24

Compact star structures [Weber2005_PPNP54-193]

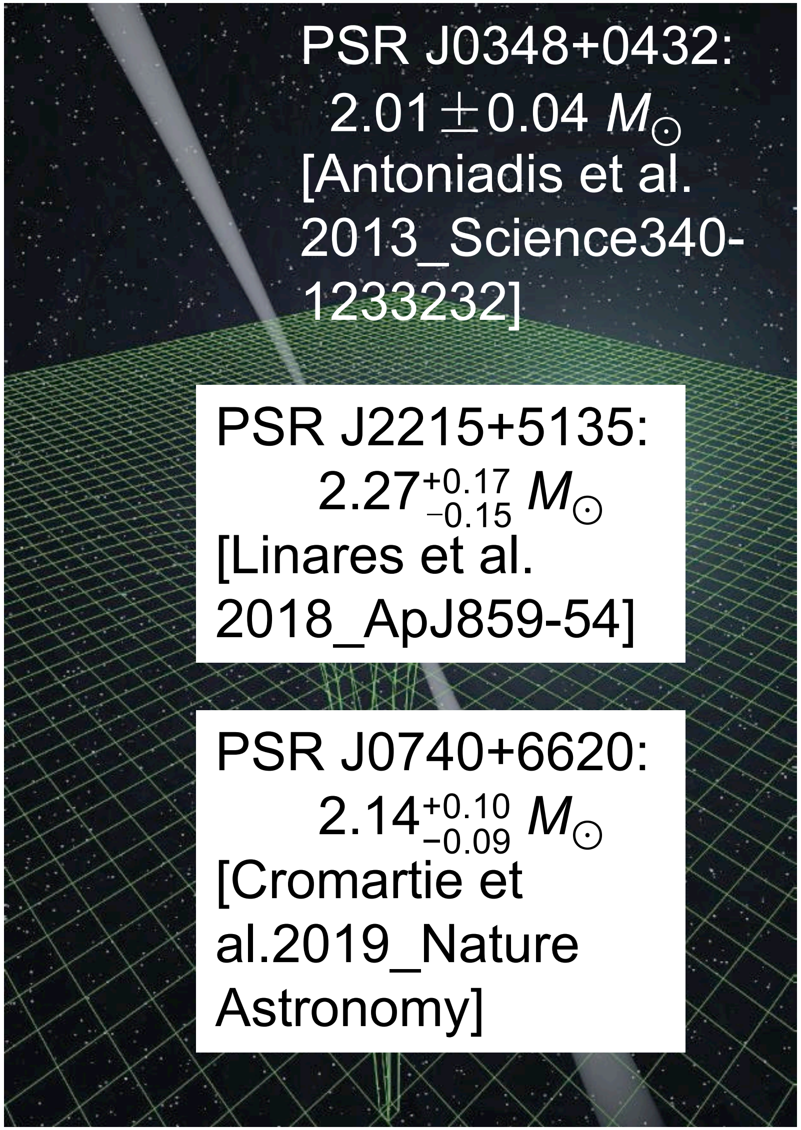


TOV equations:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GME}{r^2}\frac{(1+P/E)(1+4\pi r^3 P/M)}{1-2GM/r},$$

$$M(r) = \int_0^r 4\pi E r^2 \mathrm{d}r.$$

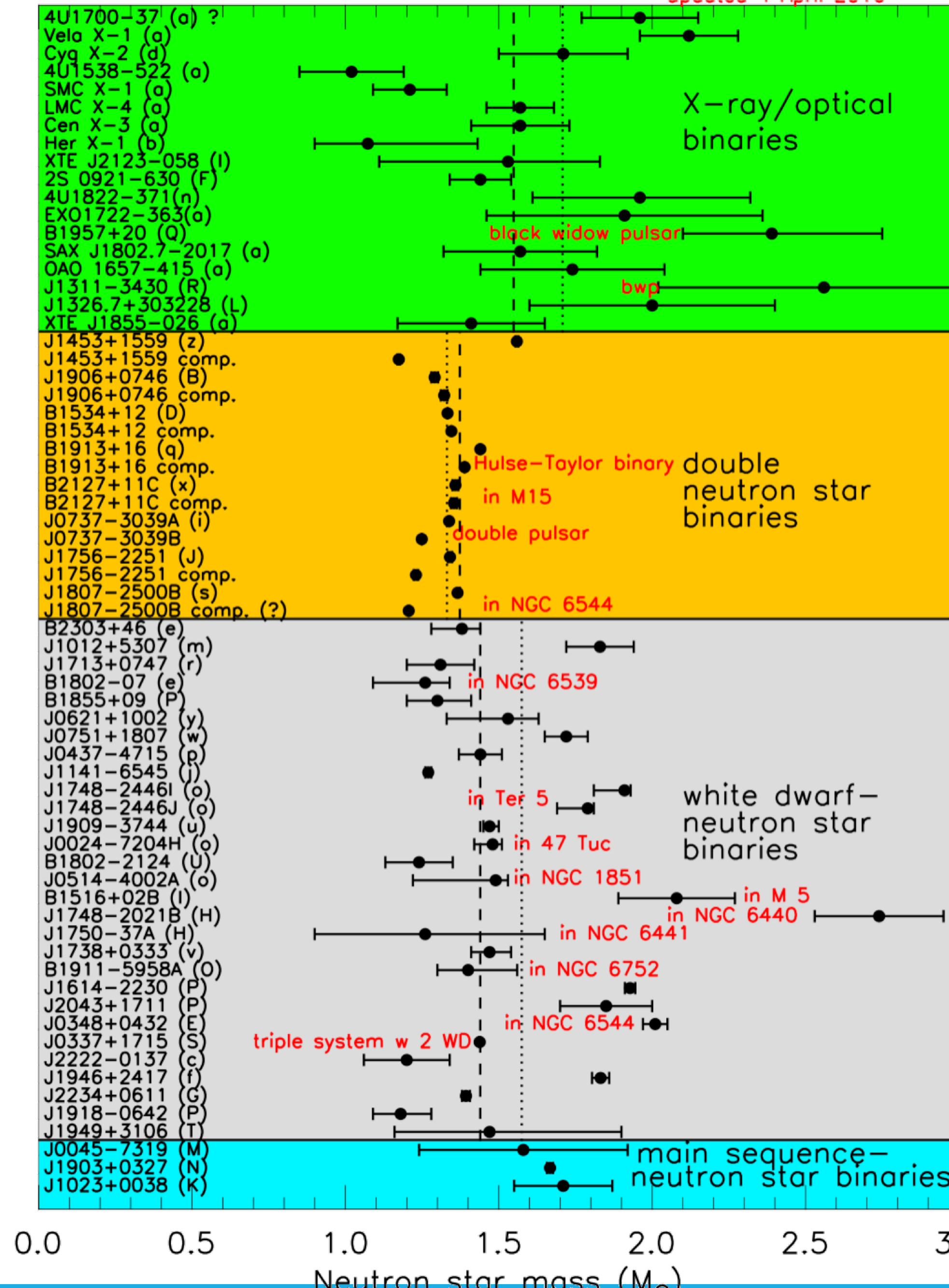
Mass measurements



PSR J0348+0432: $2.01 \pm 0.04\ M_{\odot}$ [Antoniadis et al. 2013_Science340-1233232]

PSR J2215+5135: $2.27^{+0.17}_{-0.15}\ M_{\odot}$ [Linares et al. 2018_ApJ859-54]

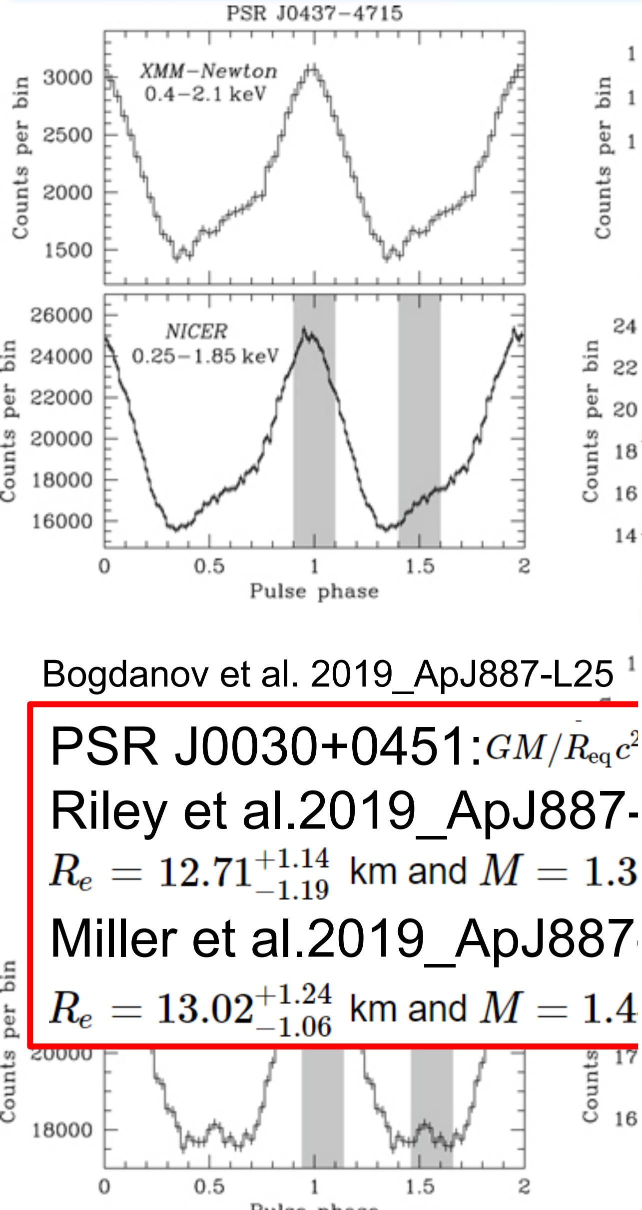
PSR J0740+6620: $2.14^{+0.10}_{-0.09}\ M_{\odot}$ [Cromartie et al.2019_Nature Astronomy]



From stellarcollapse.org/nsmasses

Radius measurements

PSR J0030+0451



Bogdanov et al. 2019_ApJ887-L25

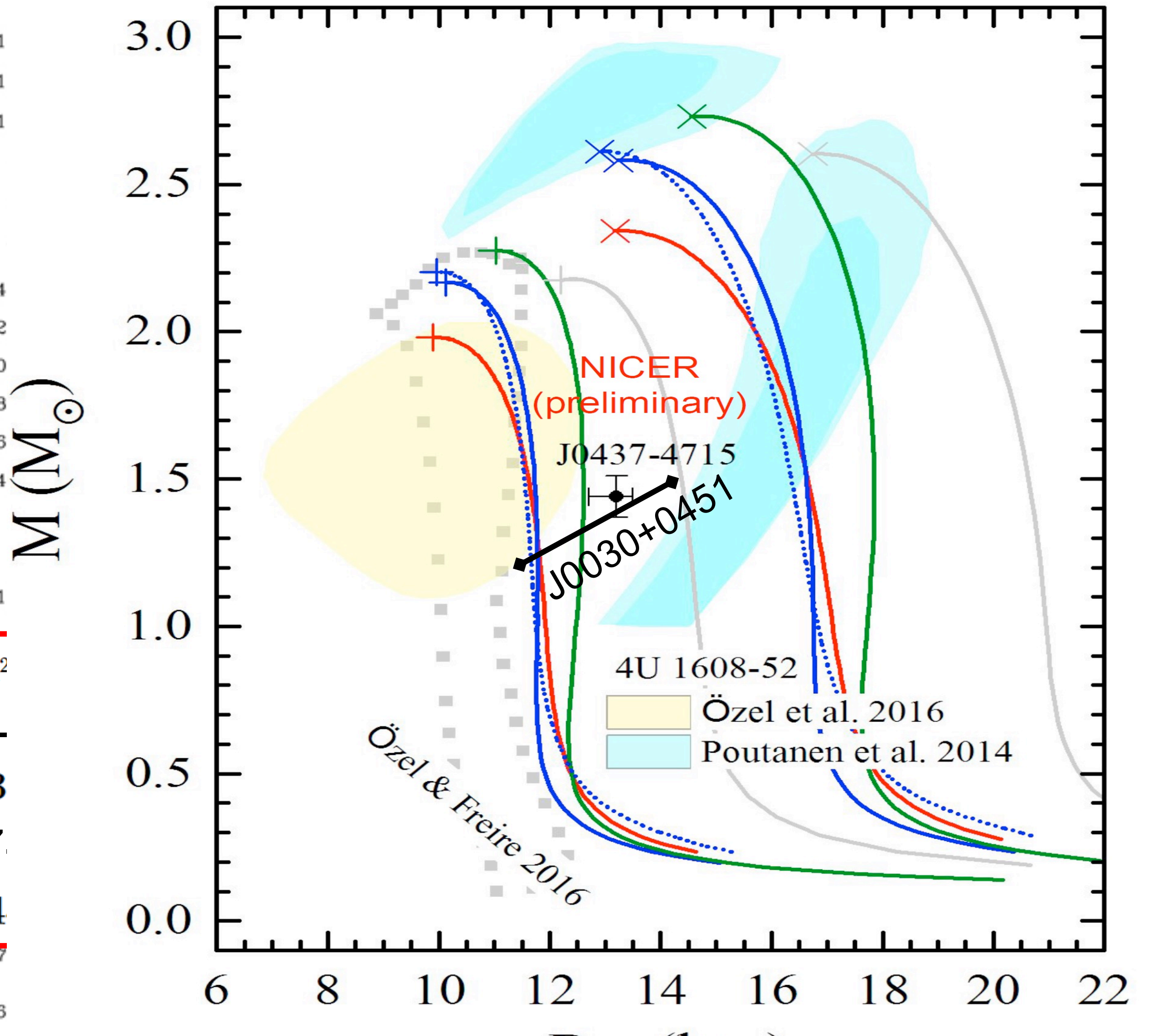
PSR J0030+0451: $GM/R_{eq}c^2$

Riley et al.2019_ApJ887-

$R_e = 12.71^{+1.14}_{-1.19}$ km and $M = 1.3$

Miller et al.2019_ApJ887

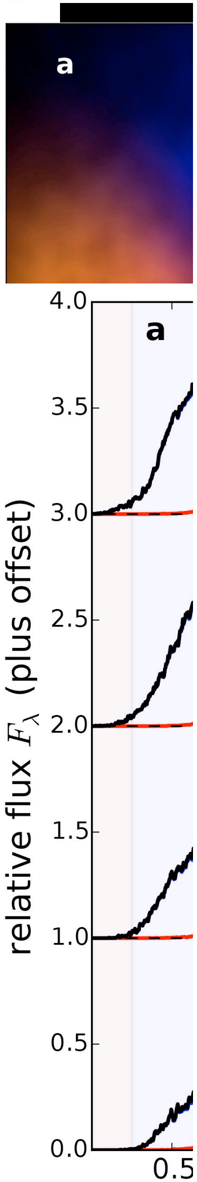
$R_e = 13.02^{+1.24}_{-1.06}$ km and $M = 1.4$

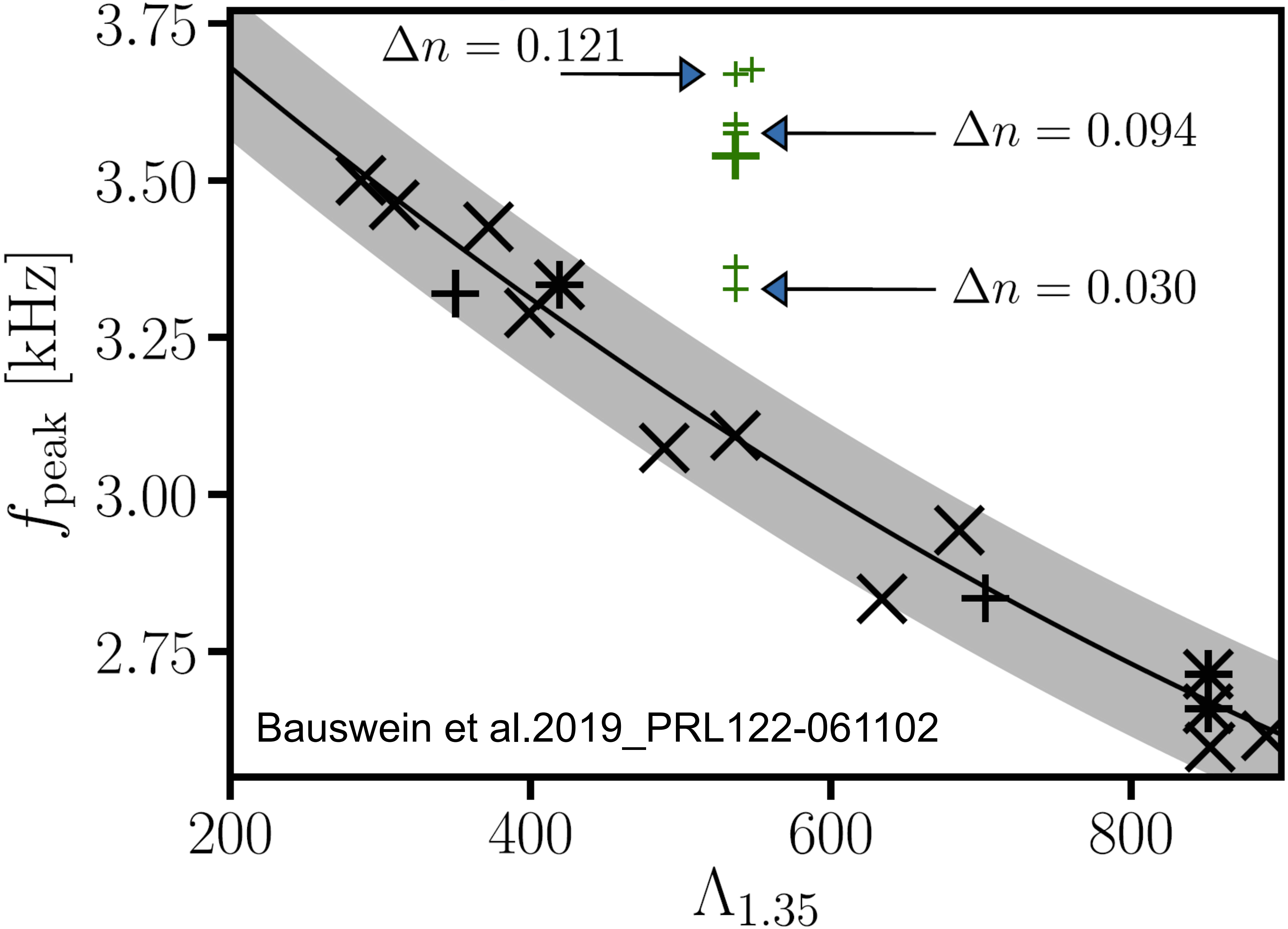


From Ang Li's talk

Binary neutron star merger

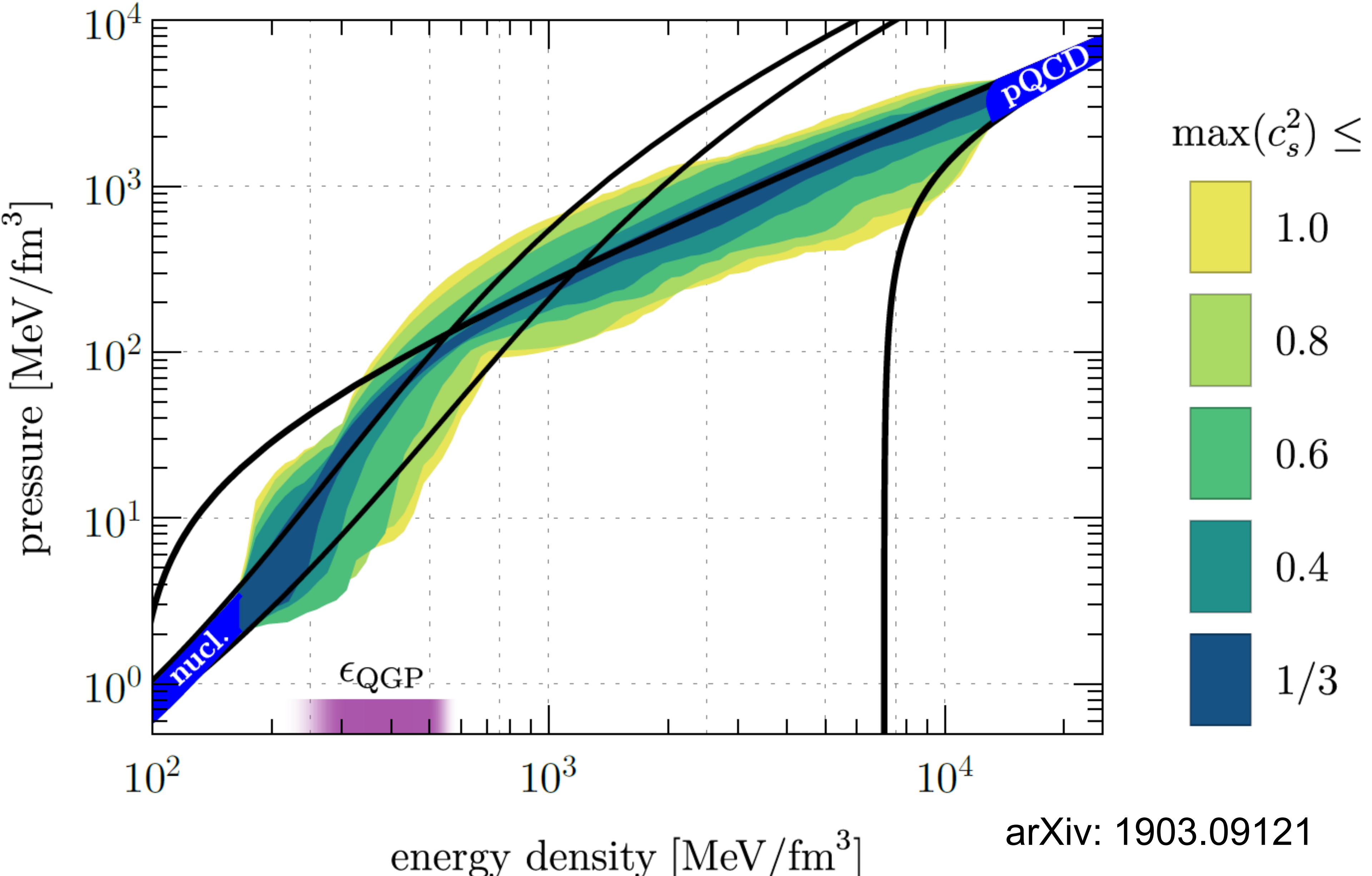
Gravitational waves: GW170817





Bauswein et al.2019_PRL122-061102

Constraint on EoSs



arXiv: 1903.09121

Hadronic matter (RMFT)

Lagrangian density for infinite nuclear matter

$$\mathcal{L}_{\rm NM} = \sum_{i=n,p} \bar{\Psi}_i \left[i\gamma^\mu \partial_\mu - m^* - \gamma^0 \left(g_\omega \omega + g_\rho \tau_{i,3} \rho_3 \right) \right] \Psi_i$$
$$-\frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} m_\omega^2 \omega^2 + \frac{1}{2} m_\rho^2 \rho_3^2 + U(\sigma, \omega)$$

TM1 (Shen EoS2): $U(\sigma, \omega) = -\frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 + \frac{1}{4} c_3 \omega^4$

S = 36.89 MeV; *L* = 110.79 MeV

TM1e (Shen EoS4) [arXiv:2001.10143]: $\mathcal{L}_{\omega\rho} = \Lambda_{\rm v} g_\omega^2 g_\rho^2 \omega^2 \rho^2$

S = 31.38 MeV; *L* = 40 MeV

TM1Λ: $\mathcal{L}_Y = \bar{\psi}_\Lambda \left[i\gamma^\mu \partial_\mu - m_\Lambda^* - \gamma^0 \alpha_{\omega\Lambda} g_\omega \omega \right] \psi_\Lambda$

Typel-Wolter ansatz: $g_{\sigma,\omega}(n) = g_{\sigma,\omega}(n_0) a_{\sigma,\omega} \frac{1 + b_{\sigma,\omega}(n/n_0 + d_{\sigma,\omega})^2}{1 + c_{\sigma,\omega}(n/n_0 + e_{\sigma,\omega})^2}$

PKDD, TW99, DDME2, DD2

$$g_\rho(n) = g_\rho(n_0) \exp\left[-a_\rho (n/n_0 - 1) \right]$$

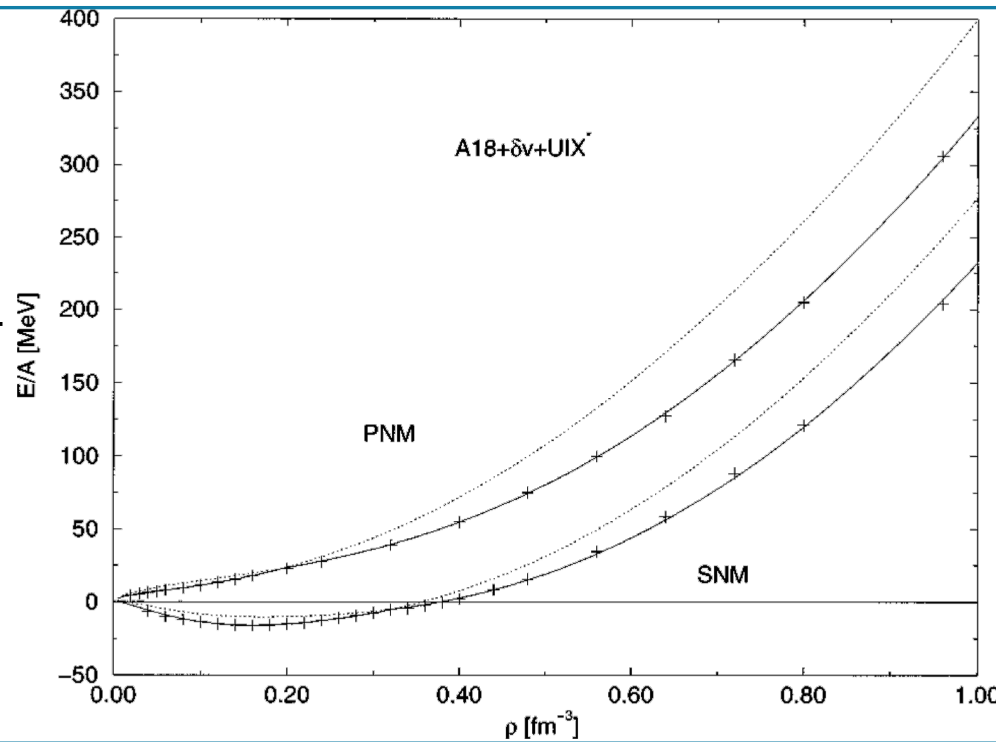
Hadronic matter (Variational methods)

VM EoS: adopting the realistic nucleon interactions AV18 + UIX [Togashi_ Nakazato_Takehara_Yamamuro_Suzuki_Takano2017_NPA961-78]:

1. the saturation density: ρ_0 (fm^{-3}) **0.160**
2. the energy: E/A (MeV) **-16.1**
3. the incompressibility: k (MeV) **245**
4. the symmetry energy: a_{sym} (MeV) **30.0**

VMΛ: Togashi_Hiyama_Yamamoto_Takano2016_PRC93-035808

APR: AV18 +δv+ UIX* [Akmal_Pandharipande_ Ravenhall1998_PRC58-1804]:



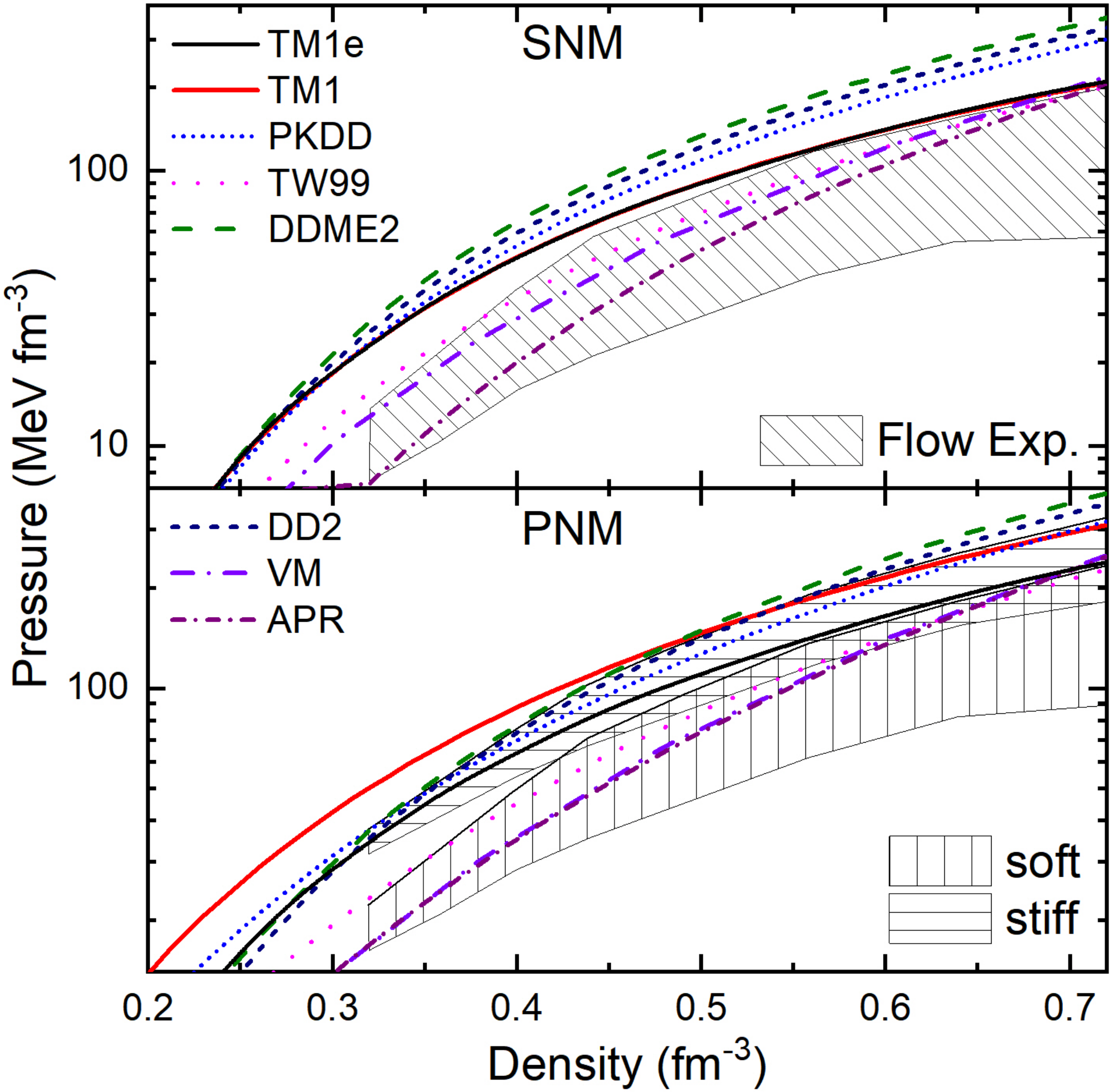
Hadronic matter properties

	n_0	B	
	fm^{-3}	MeV	M
TM1e	0.145	16.26	2
TM1	0.145	16.26	2
PKDD	0.150	16.27	2
TW99	0.153	16.25	2
DDME2	0.152	16.14	2
DD2	0.149	16.02	2
VM	0.160	16.09	
APR	0.160	**15.08**	

Li_Han2013_PLB727-276:

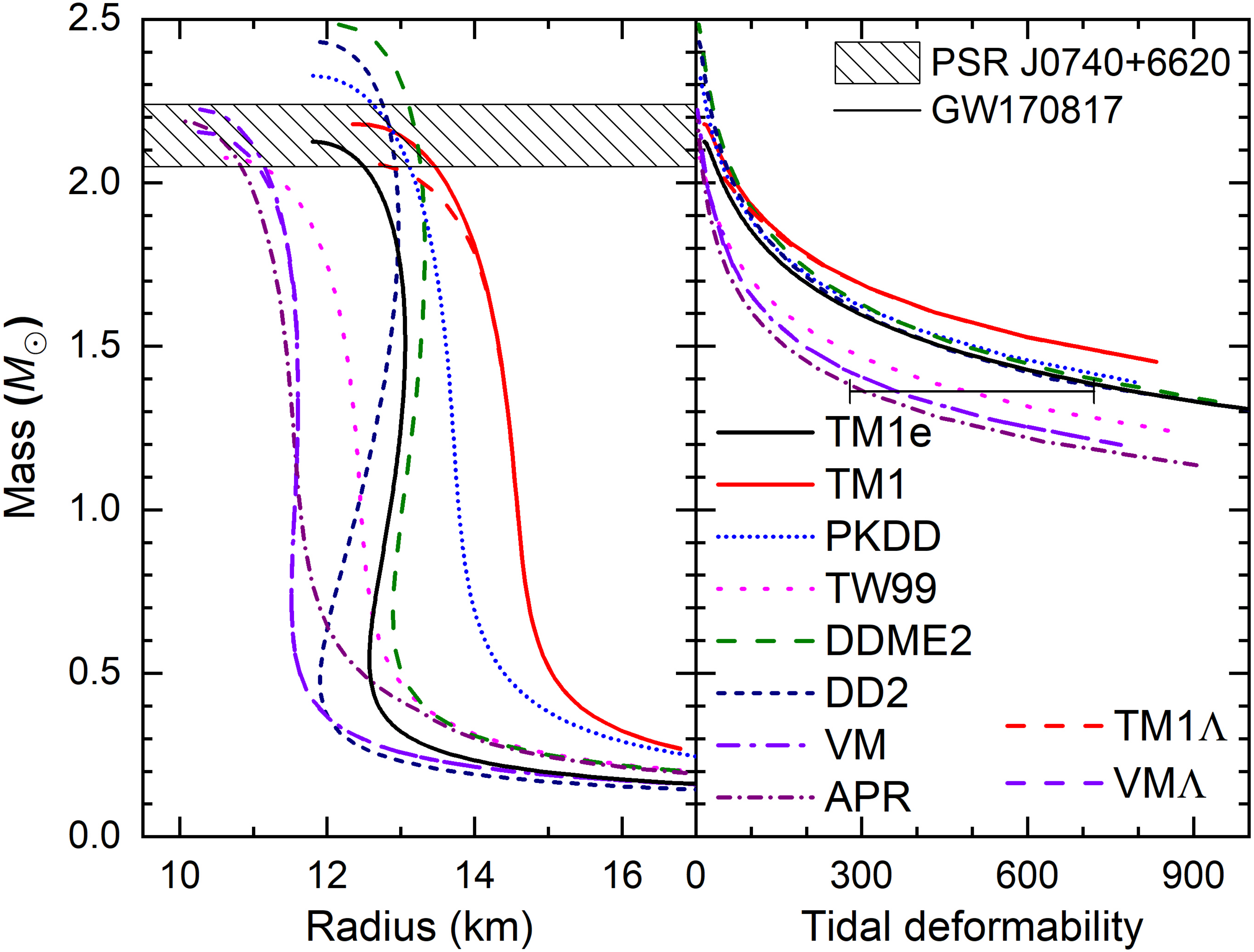
$E_{\mathrm{sym}}(\rho_0) = 31.6 \pm 2.66\mathrm{MeV}$

$L(\rho_0) = 58.9 \pm 16.0\mathrm{MeV}$

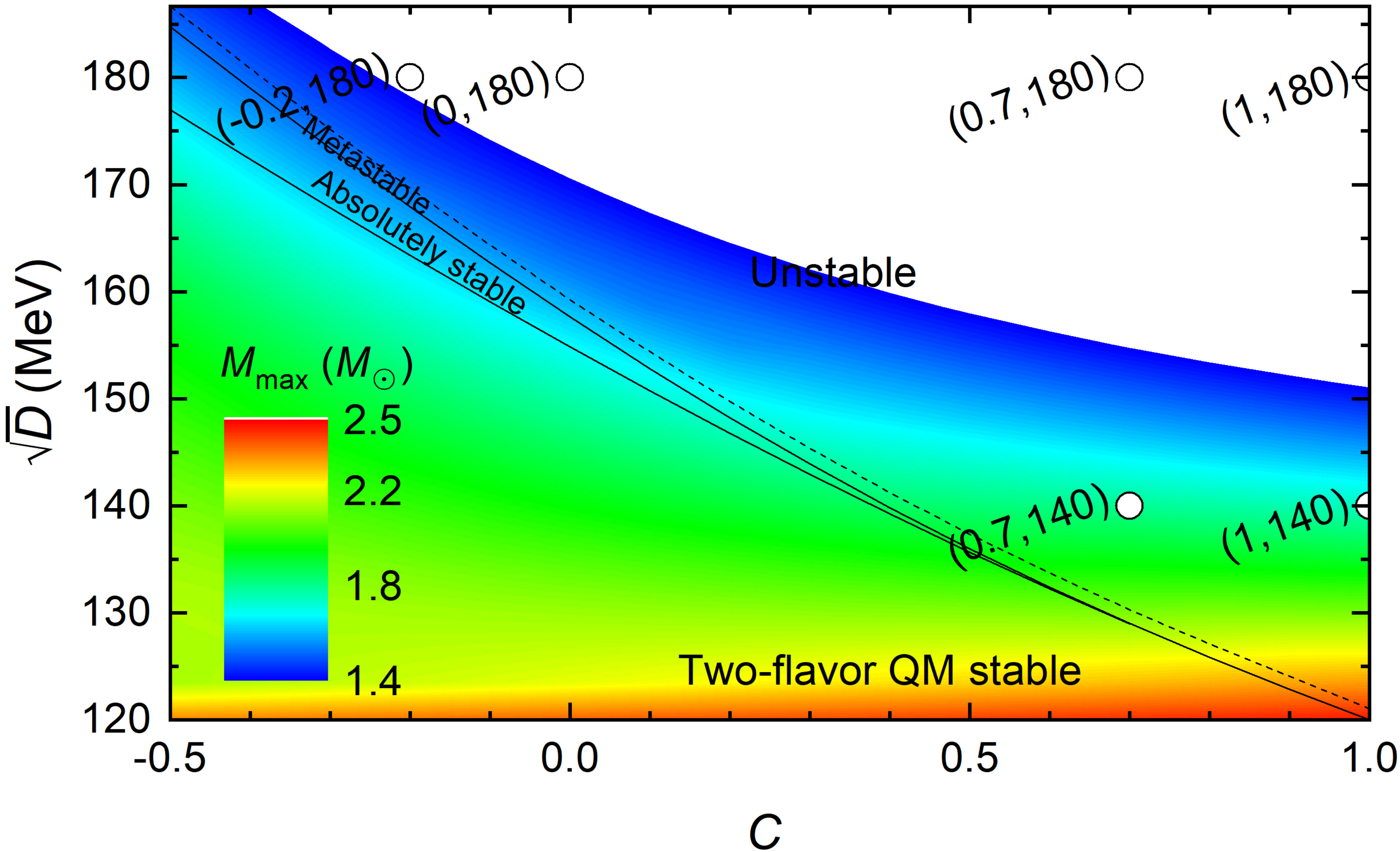


Danielewicz_Lacey_Lynch2002_Science298-1592

Neutron stars



Quark matter (Equivparticle model)



$m_I = \frac{D}{n^{1/3}} - \tau_i \delta D_I n^{\alpha} e^{-\beta n}$; (Chu_Chen2014_ApJ780-135)

Quark matter (Perturbation model)

Expand the thermodynamic potential density up to the order of α_s in the MS scheme [Fraga_Romatschke2005_PRD71-105014]:

$$\Omega^{\rm pt} = \sum_i^{N_f} \left(\omega_i^0 + \omega_i^1 \alpha_s\right)$$

$$\alpha_s(\bar\Lambda) = \frac{1}{\beta_0 L}\left(1 - \frac{\beta_1 \ln L}{\beta_0^2 L}\right),$$

$$m_i(\bar\Lambda) = \hat m_i \alpha_s^{\frac{\gamma_0}{\beta_0}}\left[1 + \left(\frac{\gamma_1}{\beta_0} - \frac{\beta_1\gamma_0}{\beta_0^2}\right)\alpha_s\right],$$

where $L = 2\ln\left(\frac{\bar\Lambda}{\Lambda_{\overline{\rm MS}}}\right)$ and $\Lambda_{\overline{\rm MS}}$ is the $\overline{\rm MS}$ renormalization point.

The renormalization scale $\bar\Lambda = \frac{C_1}{3}\sum_{i=u,d,s}\mu_i$ with C_1 = 1~4.

We introduce an extra bag constant B to take into account the energy difference between the physical and perturbative vacua:

$$\Omega = \Omega^{\rm pt} + B$$

$$B = B_{\rm QCD} + (B_0 - B_{\rm QCD})\exp\left[-\left(\frac{\sum_i \mu_i - 930}{\Delta\mu}\right)^4\right]$$

where $B_0 = 50$ MeV fm^{-3} and $B_{\rm QCD} = 400$ MeV fm^{-3}.

Quark matter (NJL model)

The Lagrangian density of a SU(3) NJL model:

$$L_{\rm NJL} = \sum_{i=u,d,s} \bar{\psi}_i \left[i\gamma^\mu \partial_\mu - M_i - 4G_V\gamma^0 n_i\right]\psi_i$$
$$+2\sum_{i=u,d,s}\left(G_V n_i^2 - G_S\sigma_i^2\right) + 4K\sigma_u\sigma_d\sigma_s$$

The thermodynamic potential density can then be obtained with

$$\Omega_{\rm QM} = \sum_{i=u,d,s}\left[\omega_i^0(\mu_i^*, M_i) - E_i^0(\Lambda, M_i) + 2G_S\sigma_i^2 - 2G_V n_i^2\right] - 4K\sigma_u\sigma_d\sigma_s - E_0$$

Parameters

HK [Hatsuda_Kunihiro1994_PR247-221]:

Λ = 631.4 MeV, m_{s0} = 135.7 MeV, G_S = 1.835/Λ^2 , K = 9.29/Λ^5

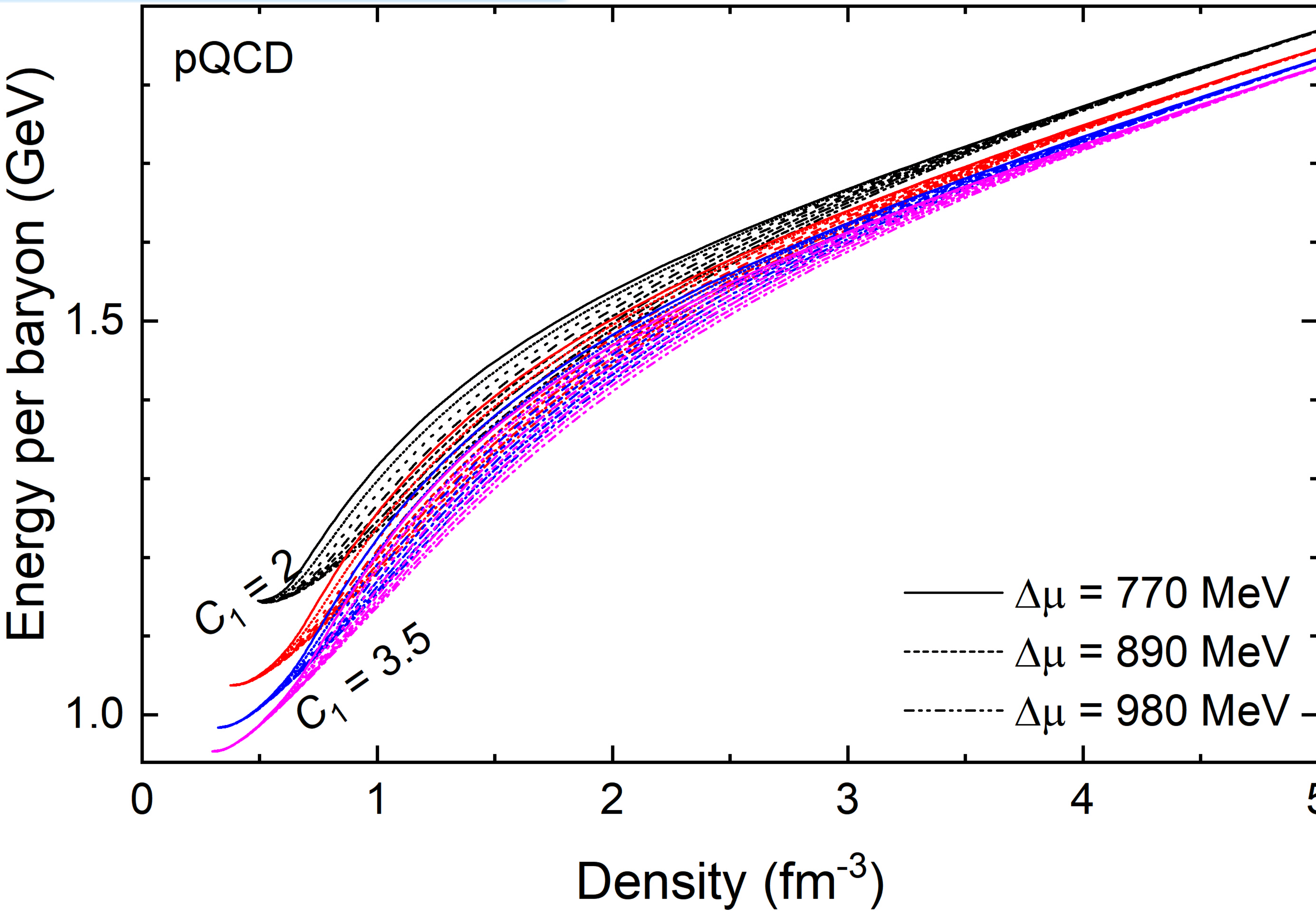
RKH [Rehberg_Klevansky_Hüfner1996_PRC53-410]:

Λ = 602.3 MeV, m_{s0} = 140.7 MeV, G_S = 1.835/Λ^2 , K = 12.36/Λ^5

m_{u0} = m_{d0} = 5.5 MeV

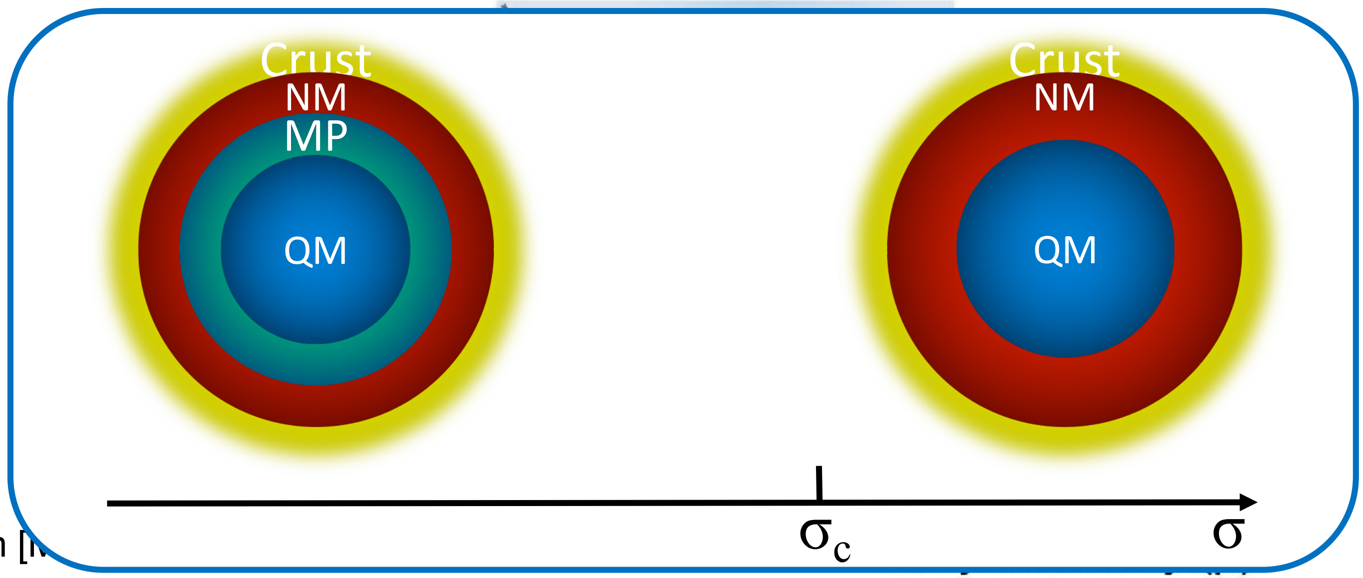
G_V = 0, 0.5 G_S, G_S, and 1.5 G_S

Quark matter properties



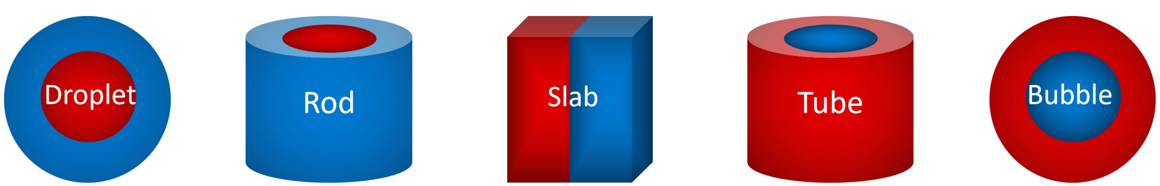
Hadron-quark mixed phase inside compact stars

First-order phase transition



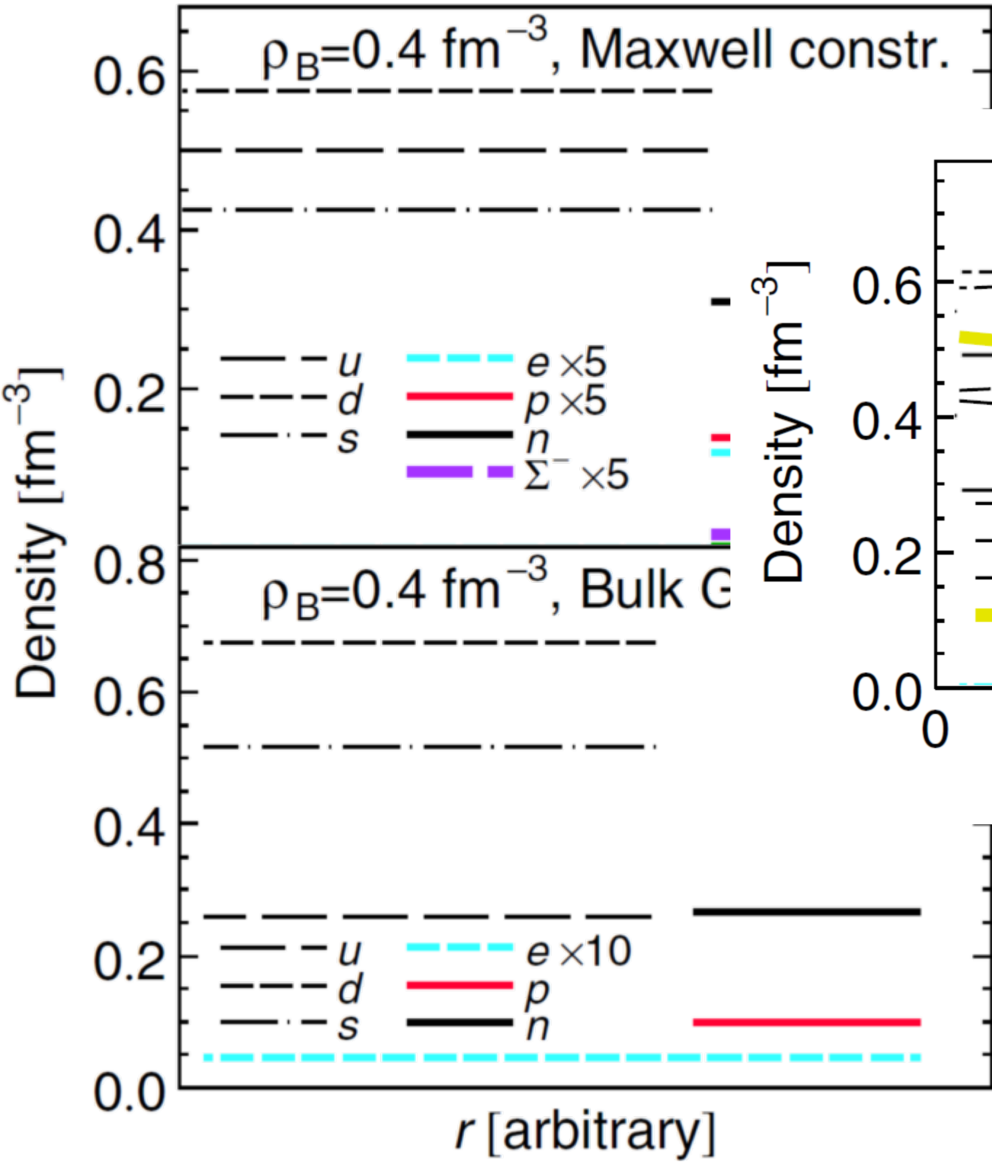
Taken from [

- $\sigma = 0$: point-like hadronic matter (HM) and quark matter (QM), i.e., Gibbs construction.
- Moderate σ : geometrical structures [Chiba, Endo, Heiselberg, Maruyama, Tatsumi, Voskresensky, Yasuhira, Yasutake, ...]

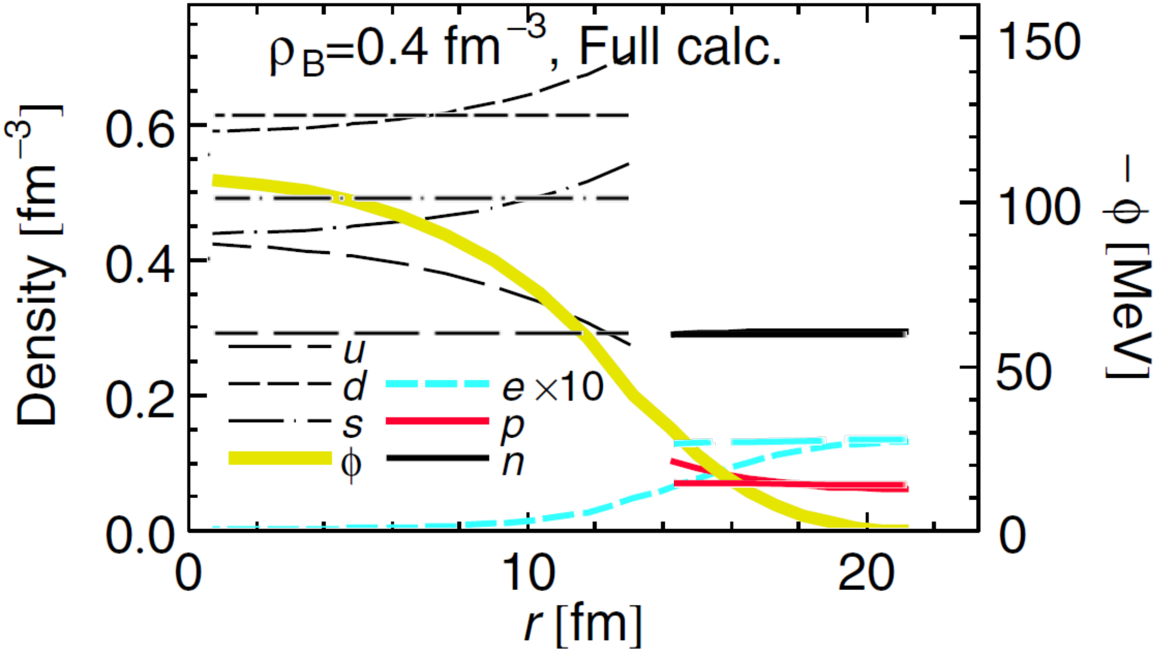


- $\sigma > \sigma_c$: bulk separation of HM and QM, i.e., Maxwell construction.

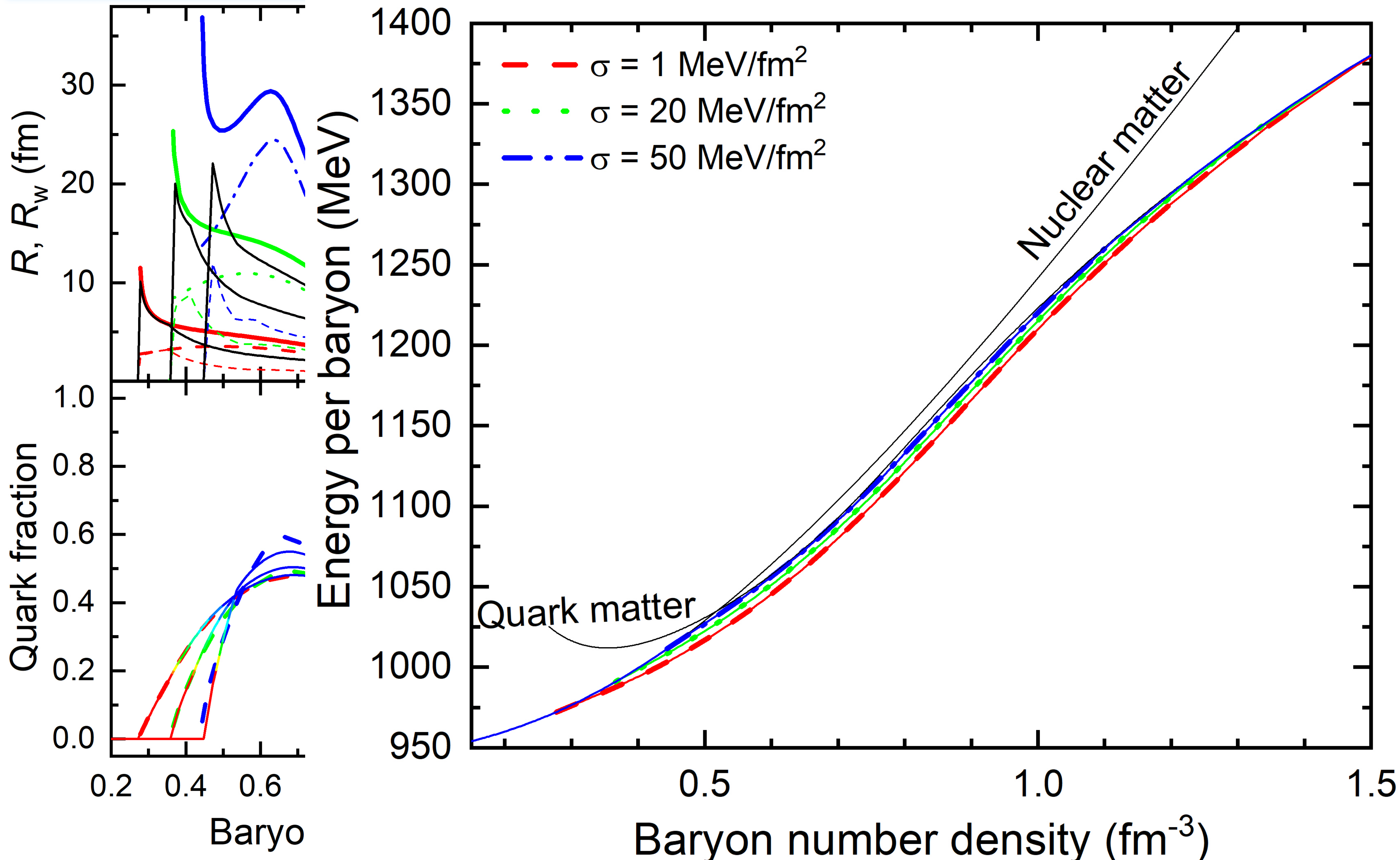
Mixed phase [Maruyama et al.2007_PRD76-123015]



Minimize energy per baryon at fixed density



Mixed phase with continuous dimensionality [Ravenhall_Pethick_Wilson1983_PRL50-2066]



Estimations of surface tension

Lattice QCD: Huang, Potvin, Rebbi, Sanie[illegible] de Forcrand, Lucini, Vettorazzo, et al.

For vanishing chemical potentials!

Effective models:

MIT bag model [Oertel_Urban2008_PRD77-074015], Linear sigma model [Palhares_Fraga2010_PRD82-125018, Pinto_Koch_Randrup2012_PRC86-025203, Kroff_Fraga2015_PRD91-025017], NJL model [Garcia_Pinto2013_PRC88-025207, Ke_Liu2014_PRD89-074041], 3f Polyakov-quark-meson model [Mintz_Stiele_Ramos_Schaffner-Bielich2013_PRD87-036004], Dyson-Schwinger equation approach [Gao_Liu2016_PRD94-094030], Equivparticle model [Xia_Peng_Sun_Guo_Lu_Jaikumar2018_PRD98-034031], and Nucleon-meson model [Fraga_Hippert_Schmitt2019_PRD99-014046]

$$\sigma < 30\ \mathrm{MeV/fm^2}$$

Quasiparticle model [Wen_Li_Liang_Peng2010_PRC82-025809]

$$\sigma = 30\sim70\ \mathrm{MeV/fm^2}$$

NJL model adopting the MRE method [Lugones_Grunfeld_Ajmi2013_PRC88-045803]

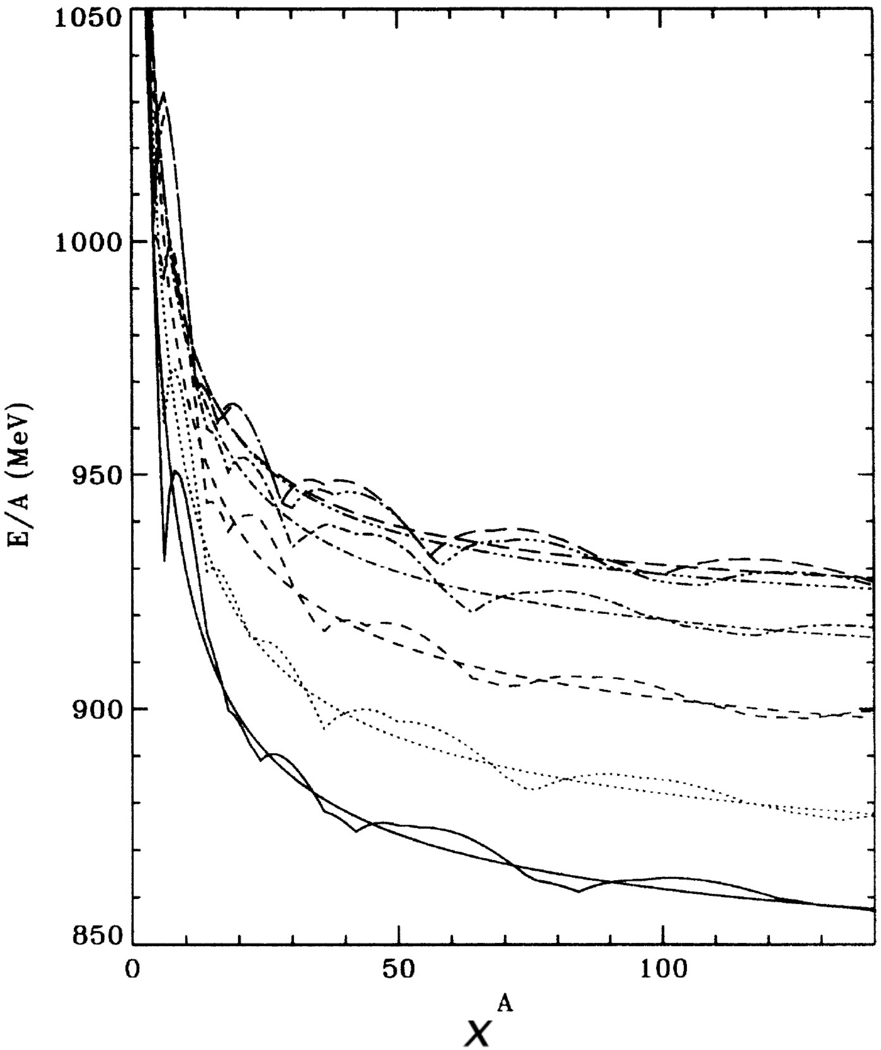
$$\sigma = 145\sim165\ \mathrm{MeV/fm^2}$$

For color-flavor locked SQM, dimensional analysis suggests: [Alford_Rajagopal_Reddy_Wilczek2001_PRD64-074017]

$$\sigma \approx 300\ \mathrm{MeV/fm^2}$$

For magnetized SQM, σ has a different value in the parallel and transverse directions with respect to the magnetic field [Lugones_Grunfeld2017_PRC95-015804, Lugones_Grunfeld2019_PRC99-035804]

Multiple Reflection Expansion (MRE) method



MRE method [Berger_Jaffe1987_PRC35-213, Madsen1994_PRD50-3328, . . .]

The average effects due to quark depletion are treated with a modification to the density of states, i.e.,

$$\frac{\mathrm{d}N_i^{\mathrm{MRE}}}{\mathrm{d}p_i} = -\frac{g_i p_i}{4\pi^2}\arctan\left(\frac{m_i}{p_i}\right) S$$

with the contributions to the total energy

$$\bar{E}_i^{\mathrm{MRE}} = \int_0^{\nu_i(R)} \sqrt{p_i^2 + m_i^2}\,\frac{\mathrm{d}N_i^{\mathrm{MRE}}}{\mathrm{d}p_i}\,dp_i$$

and pressure

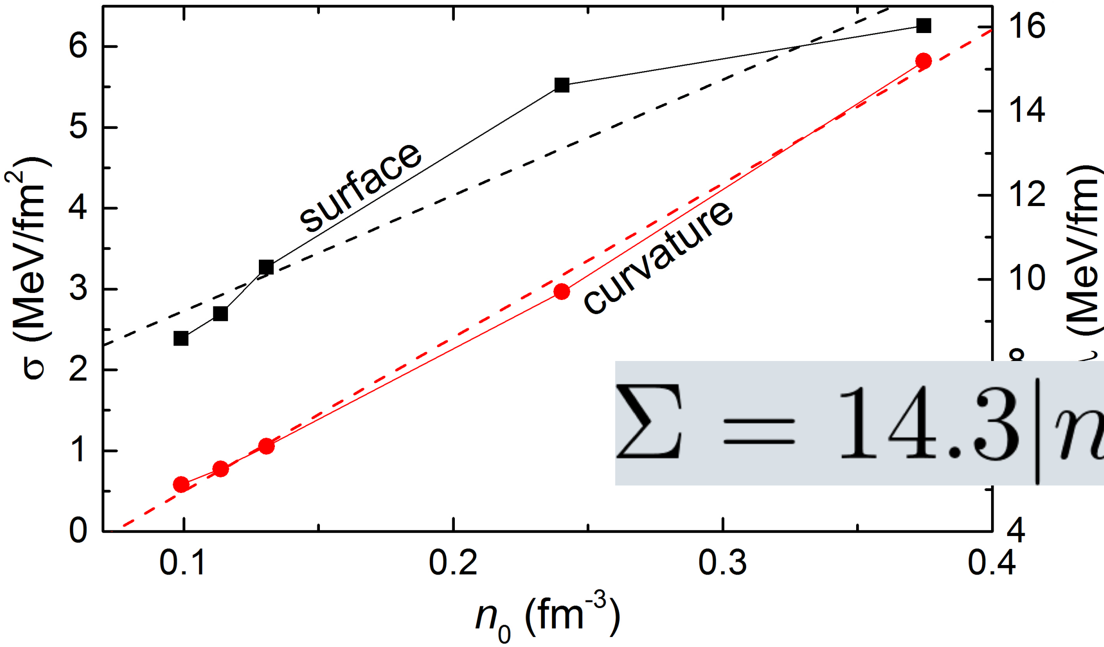
$$P^{\mathrm{MRE}} = -\sum_i \left.\frac{\mathrm{d}\bar{E}_i^{\mathrm{MRE}}}{\mathrm{d}V}\right|_{N_i^{\mathrm{MRE}}}.$$

Surface tension estimation:

$$P_i^{\mathrm{MRE}} = -\Sigma_i^{\mathrm{MRE}}\frac{\mathrm{d}S}{\mathrm{d}V}$$

$$\Rightarrow \Sigma^{\mathrm{MRE}} = \sum_{i=u,d,s} \Sigma_i^{\mathrm{MRE}}$$

Equivparticle model predictions



Liquid-drop type formula

$$\frac{M}{A} = \frac{E_0}{n_0} + \frac{\alpha_S}{A^{1/3}} + \frac{\alpha_C}{A^{2/3}}$$

$$\sigma = \alpha_S \left(\frac{n_0^2}{36\pi}\right)^{1/3},$$

$$\Sigma = 14.3\left|n^Q - n^H\right| + 1.3$$

Oertel_Urban2008_PRD77-074015

Parameters		Bulk properties					Interface effects			
C	$\sqrt{D}$ MeV	n_0 fm^{-3}	n_{u0} fm^{-3}	n_{d0} fm^{-3}	n_{s0} fm^{-3}	E_0/n_0 MeV	α_S MeV	α_C MeV	σ MeV/fm^2	λ MeV/fm
-0.5	180	0.37	0.37	0.49	0.26	900.04	58	328	6.3	15.2
0	156	0.24	0.24	0.36	0.12	911.87	69	243	5.5	9.70
0.4	129	0.11	0.11	0.20	0.023	850.91	56	177	2.7	5.49
0.7	129	0.099	0.099	0.19	0.0055	918.94	54	172	2.4	5.12
0.7	140	0.13	0.13	0.24	0.018	995.77	61	185	3.3	6.03

Numerical recipe

Hadronic matter (TM1e, TM1, PKDD, TW99, DDME2, DD2, VM, APR, TM1Λ, and VMΛ)

	n_0	B	K	S	L	$M_{\max}$	$R_{1.4}$
	fm^{-3}	MeV	MeV	MeV	MeV	$M_\odot$	km
TM1e	0.145	16.26	281.16	31.38	40	2.13	13.1
TM1	0.145	16.26	281.16	36.89	110.79	2.18	14.3
PKDD	0.150	16.27	262.19	36.79	90.21	2.33	13.6
TW99	0.153	16.25	240.27	32.77	55.31	2.08	12.3
DDME2	0.152	16.14	250.92	32.30	51.25	2.49	13.2
DD2	0.149	16.02	242.72	31.67	55.04	2.43	12.8
VM	0.160	16.09	245	30.0	**35.22**	2.22	11.6
APR	0.160	**15.08**	**266**	**34.6**	**58.47**	2.19	11.4

Surface tension Σ

- $\Sigma = 5,\ 20,\ 50\ \mathrm{MeV/fm^2}$;
- $\Sigma = 0.5\Sigma_\mathrm{c}$;
- $\Sigma = \sum_{i=u,d,s} \Sigma_i^\mathrm{MRE}$;
- $\Sigma = 0.3\sum_{i=u,d,s} \Sigma_i^\mathrm{MRE}$;
- $\Sigma = 14.3|n^Q - n^H| + 1.3$.

Critical surface tension

$$\Sigma_\mathrm{c} = \frac{\left(\mu_{e0}^H - \mu_{e0}^Q\right)^2}{8\pi\alpha\left(\lambda_D^Q + \lambda_D^H\right)}$$

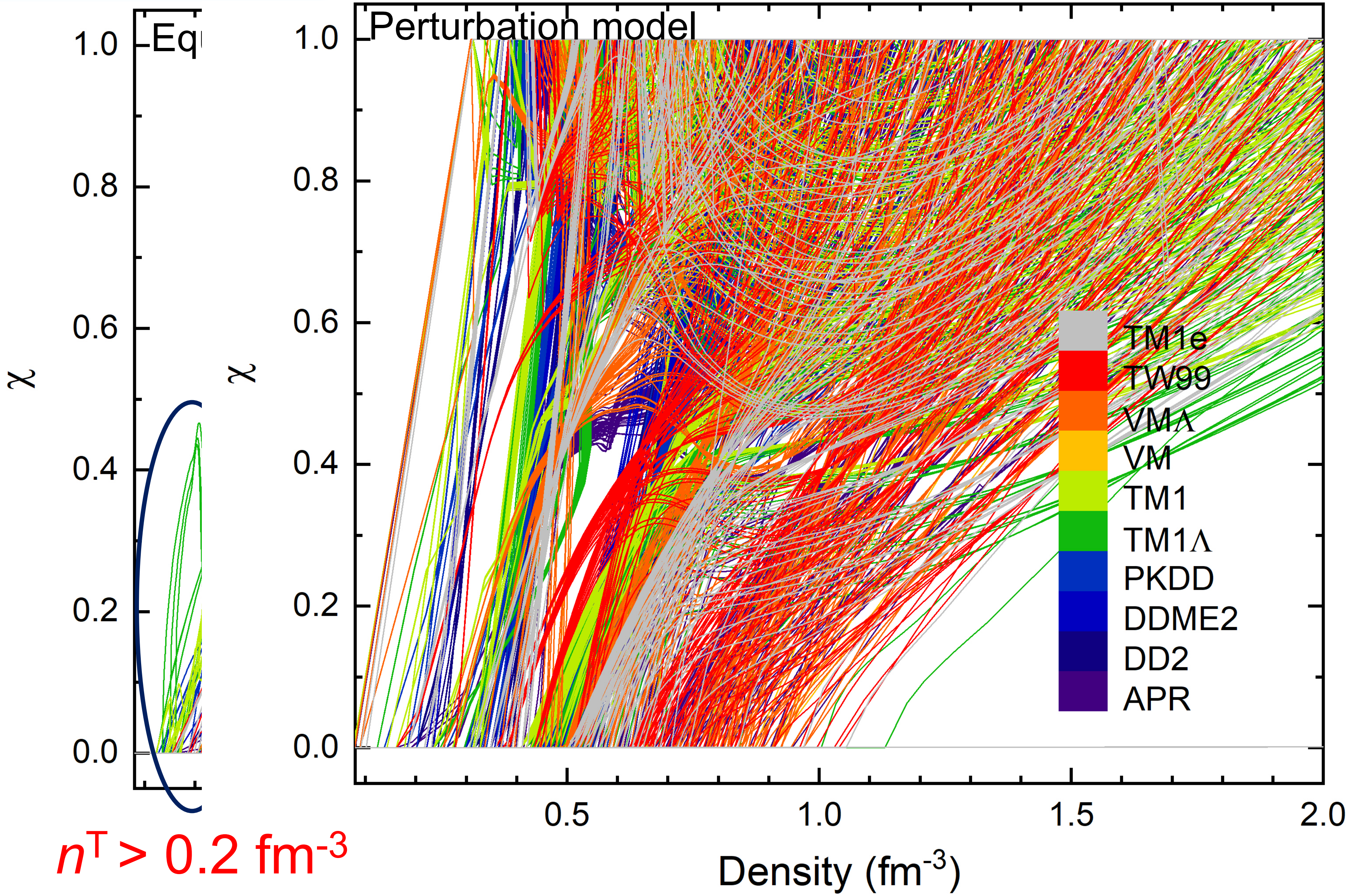
Quark matter

Equivparticle model with (C, $\sqrt{D}$ in MeV): (-0.2, 180), (0, 180), (0.7, 140), (0.7, 180), (1, 140), and (1, 180).

Perturbation model with C_1 = 2, 2.5, 3, 3.5 and Δμ = 770, 800, 830, 860, 890, 920, 950, 980 MeV

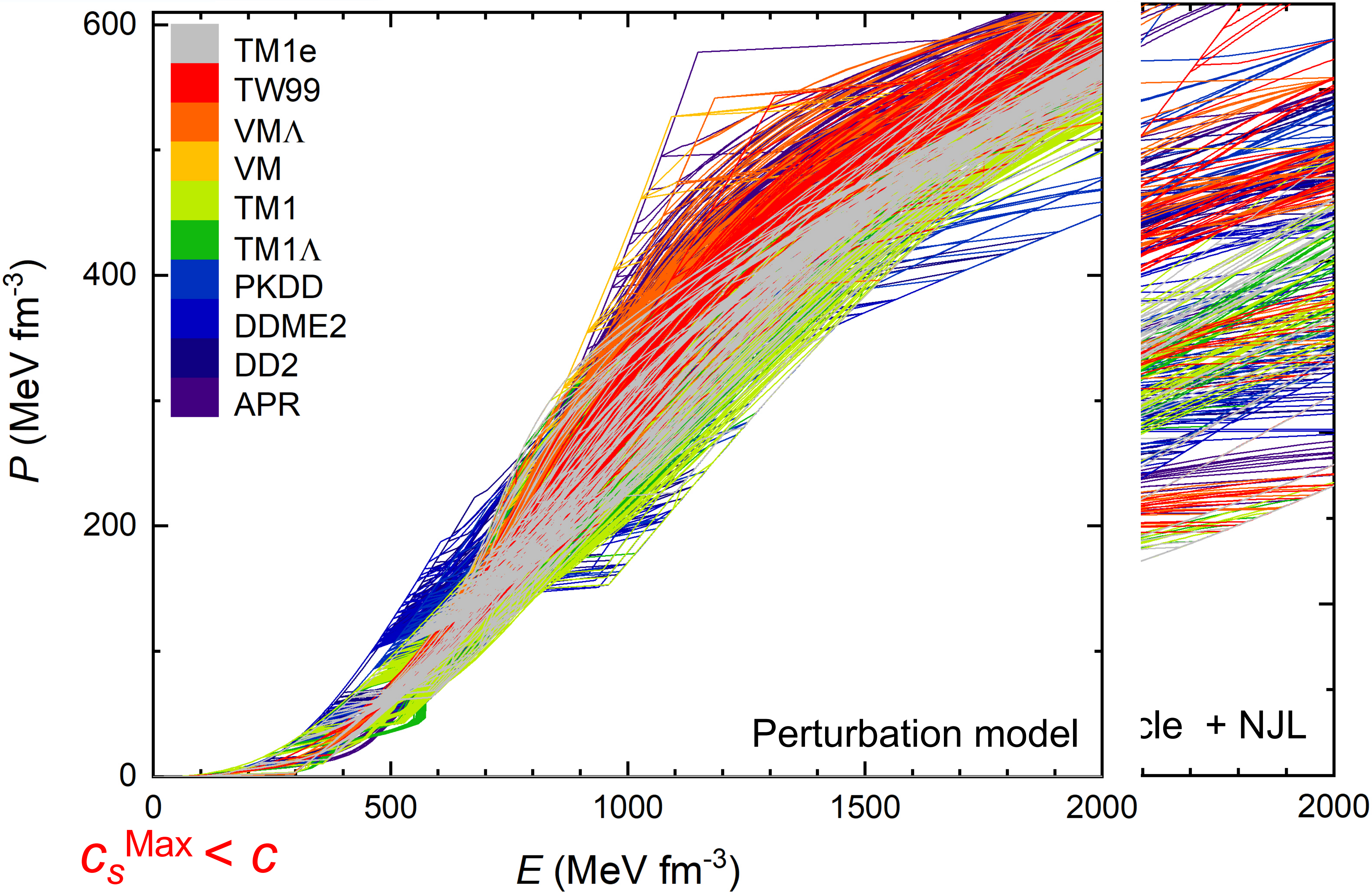
NJL model with parameter sets HK and RKH (G_V = 0, 0.5 G_S, G_S, and 1.5 G_S)

Quark fraction



$n^{T} > 0.2\ \mathrm{fm}^{-3}$

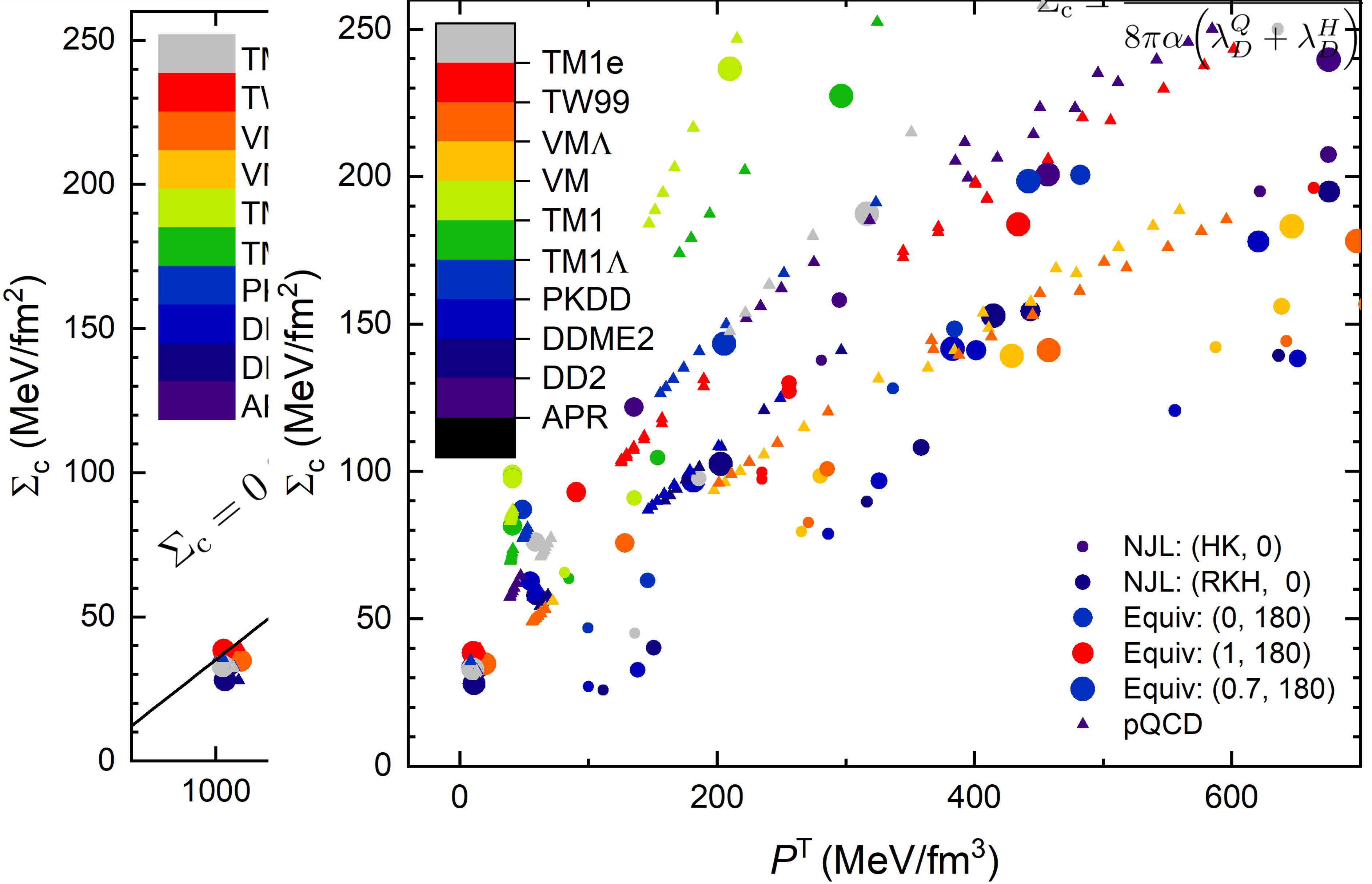
Equation of State



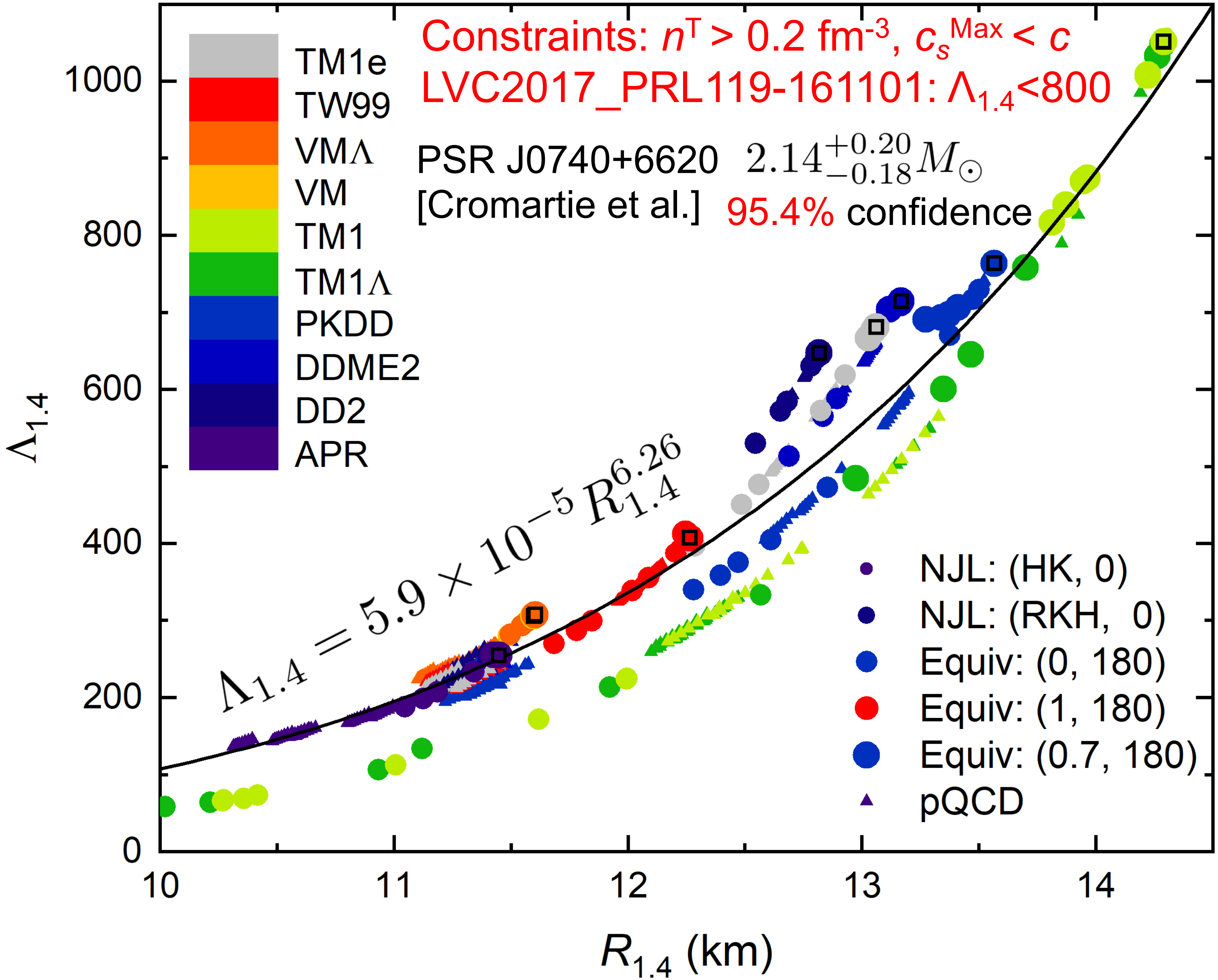
$c_s^{Max} < c$

Critical surface tension

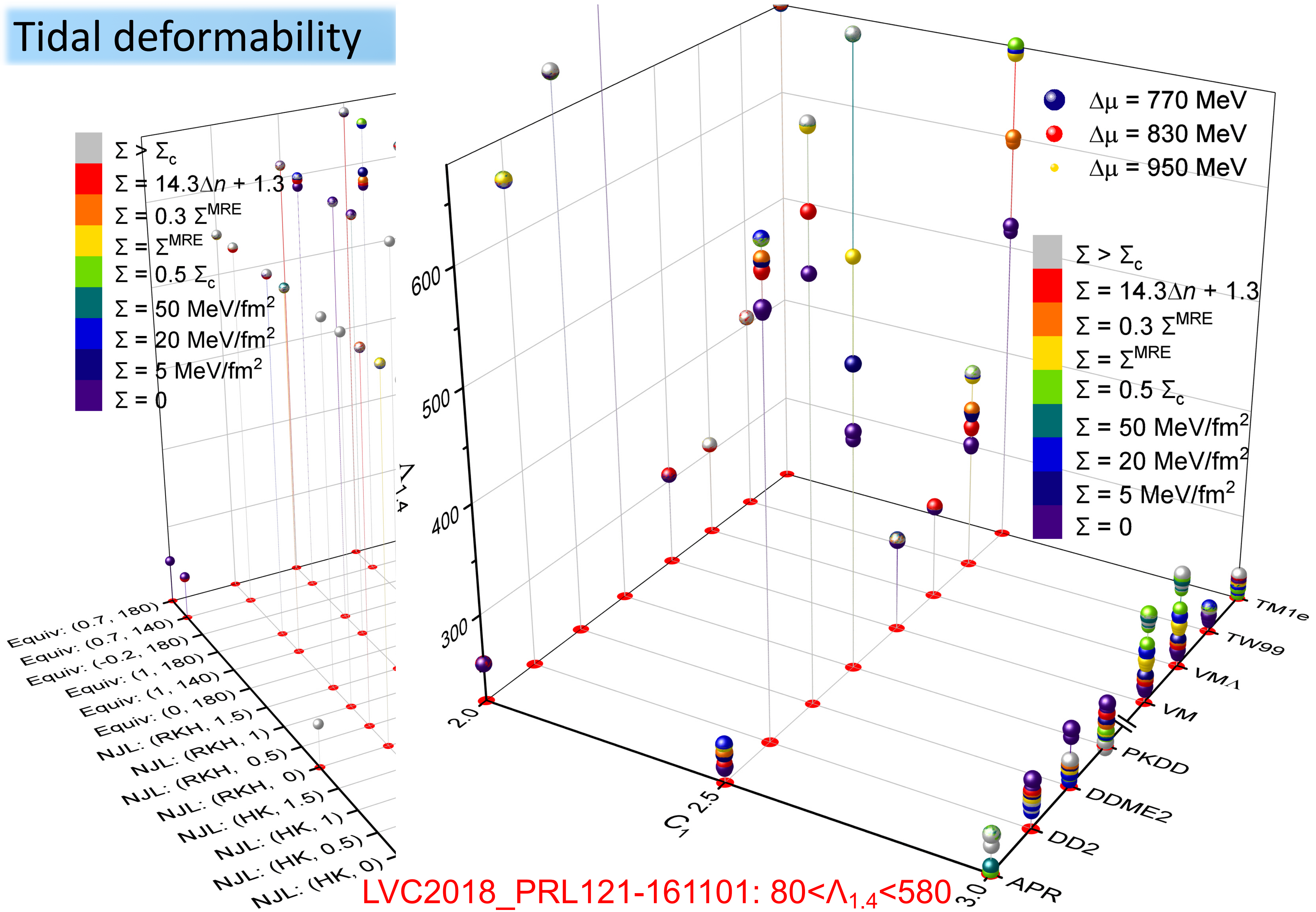
$$\Sigma_c = \frac{\left(\mu_{e0}^H - \mu_{e0}^Q\right)^2}{8\pi\alpha\left(\lambda_D^Q + \lambda_D^H\right)}$$



Radius tidal deformability correlation



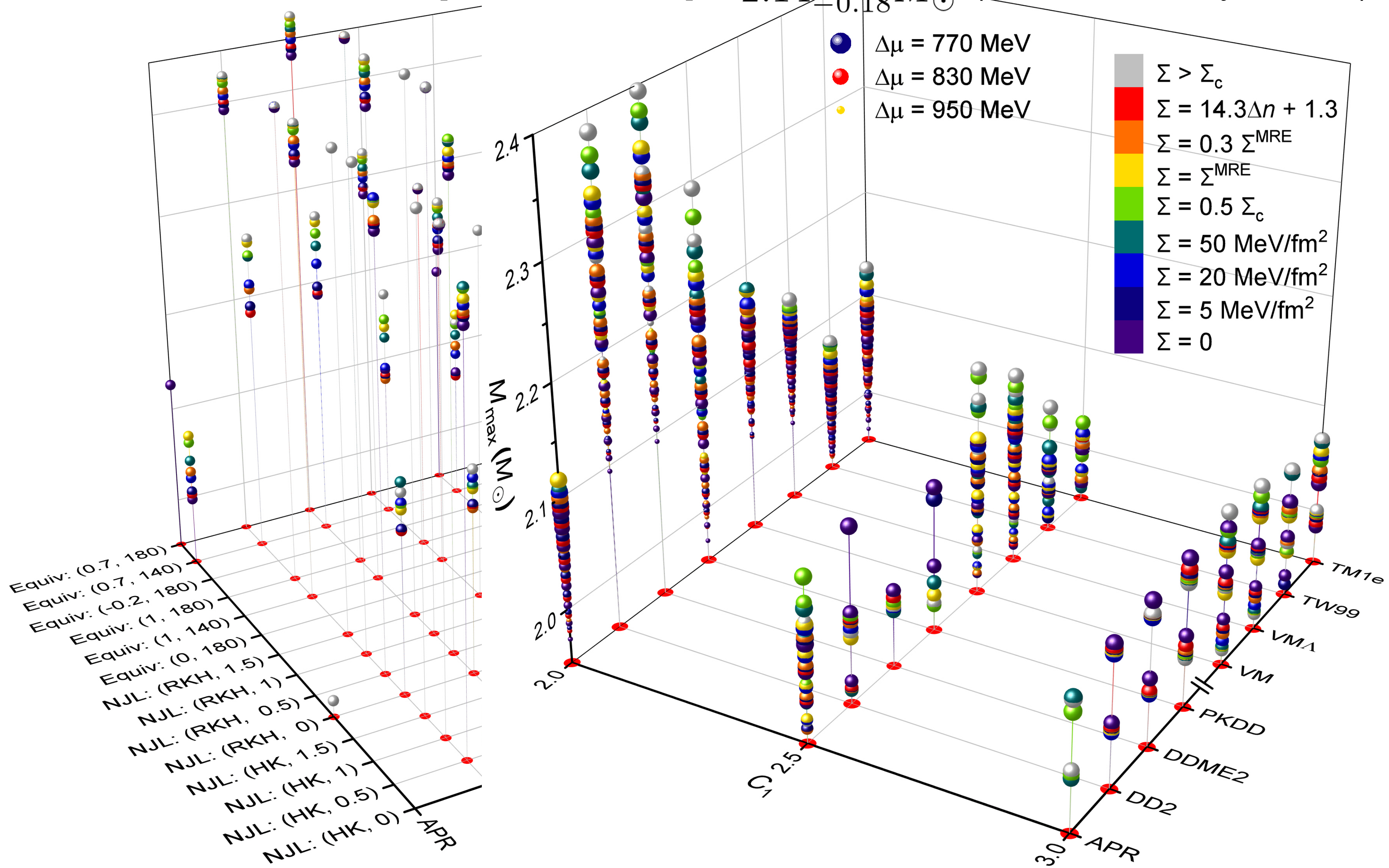
Tidal deformability



LVC2018_PRL121-161101: $80<\Lambda_{1.4}<580$

Maximum mass

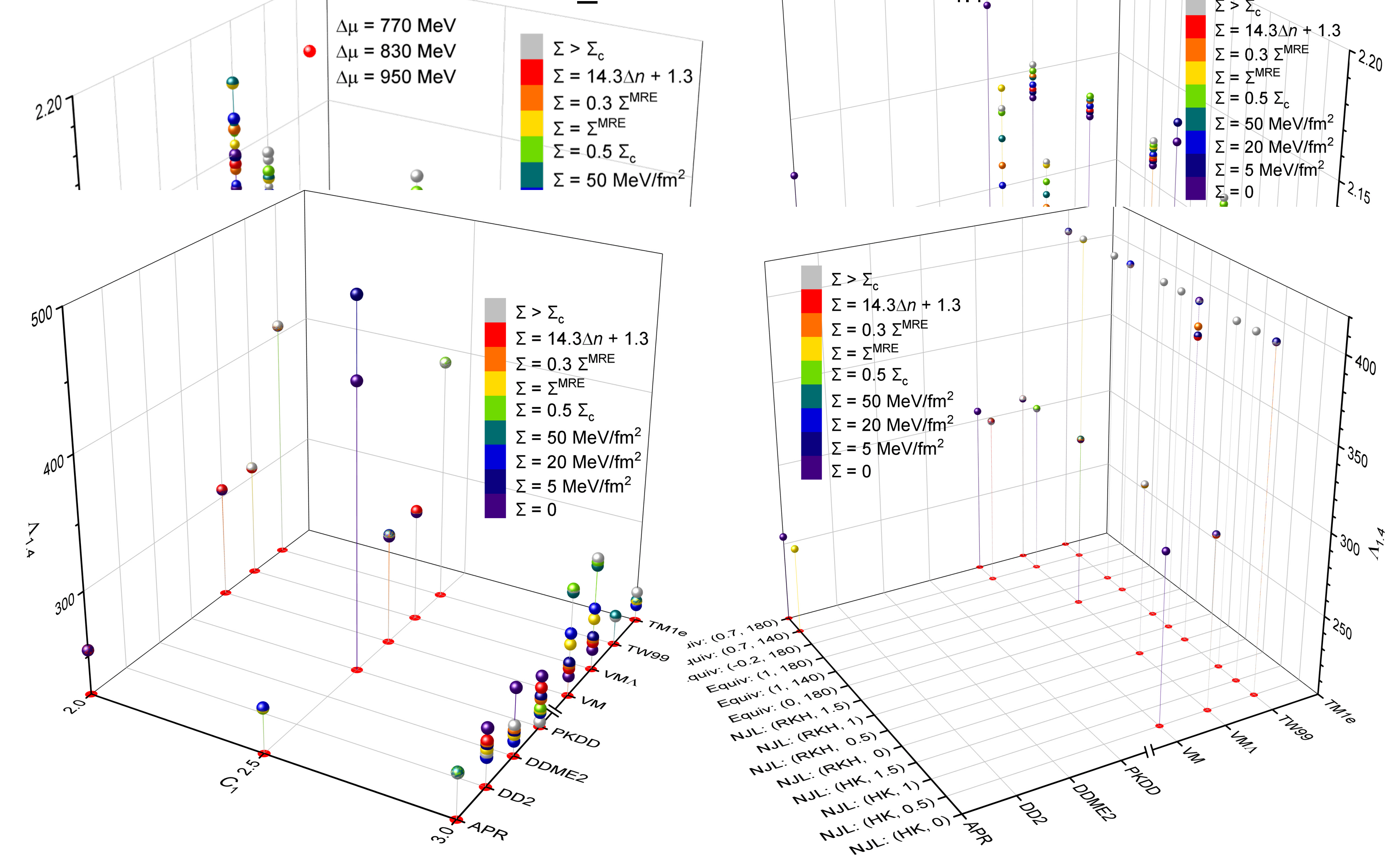
PSR J0740+6620 [Cromartie et al.] $2.14^{+0.10}_{-0.09} M_\odot$ (68.3% credibility interval)
$2.14^{+0.20}_{-0.18} M_\odot$ (95.4% credibility interval)



Strong constraints

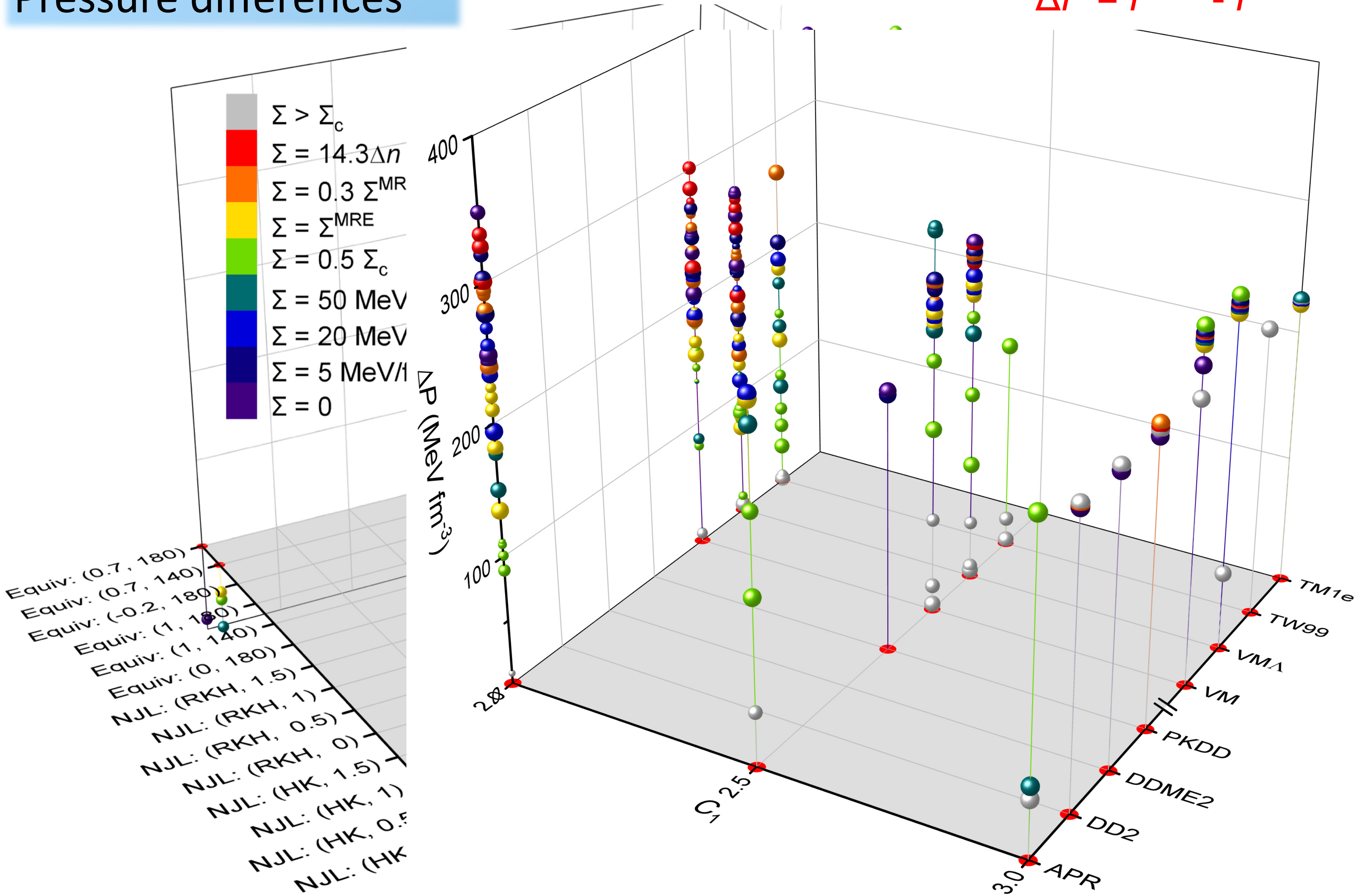
PSR J0740+6620 [Cromartie et al.] $2.14^{+0.10}_{-0.09} M_\odot$

LVC2018_PRL121-161101: $80<\Lambda_{1.4}<580$

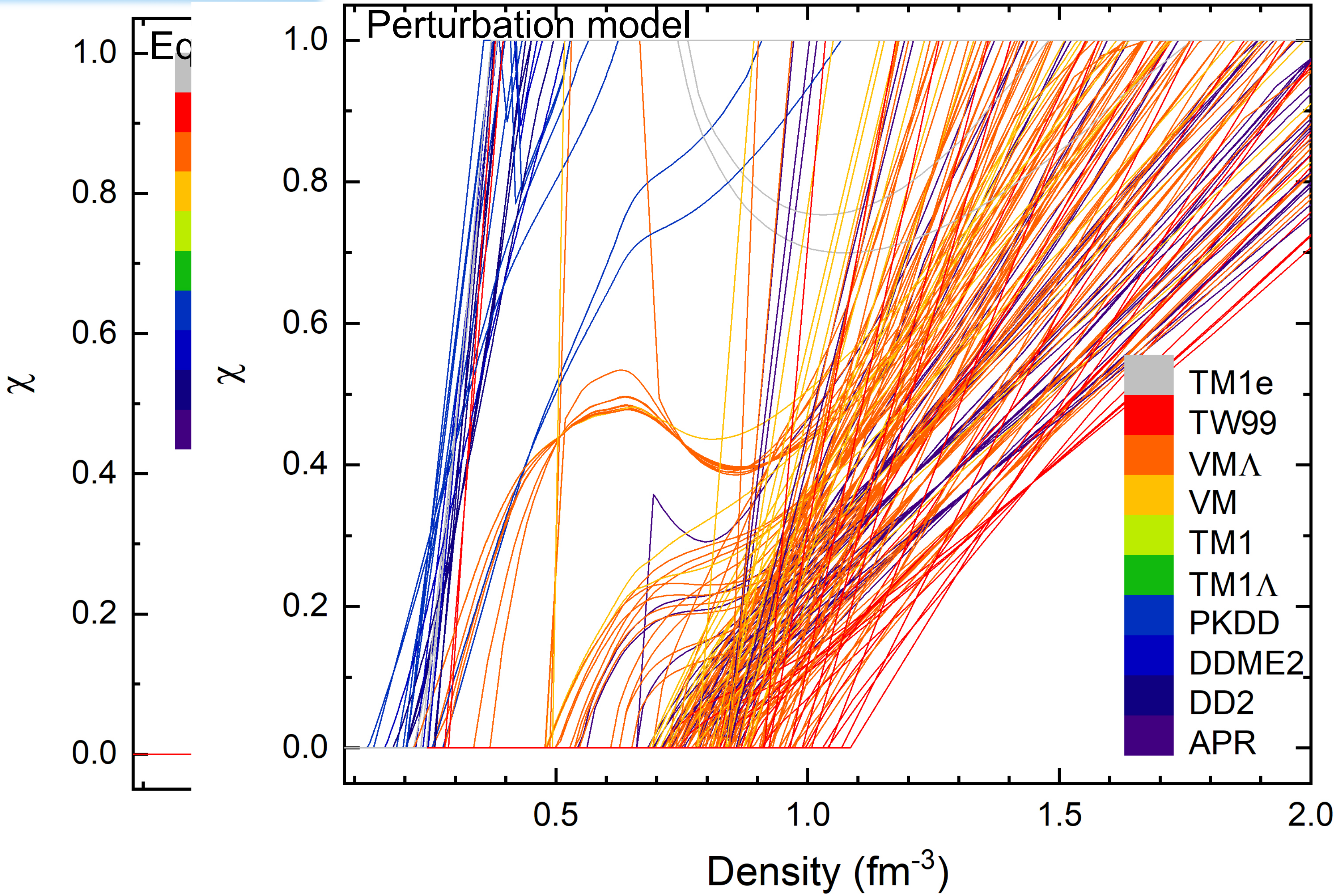


Pressure differences

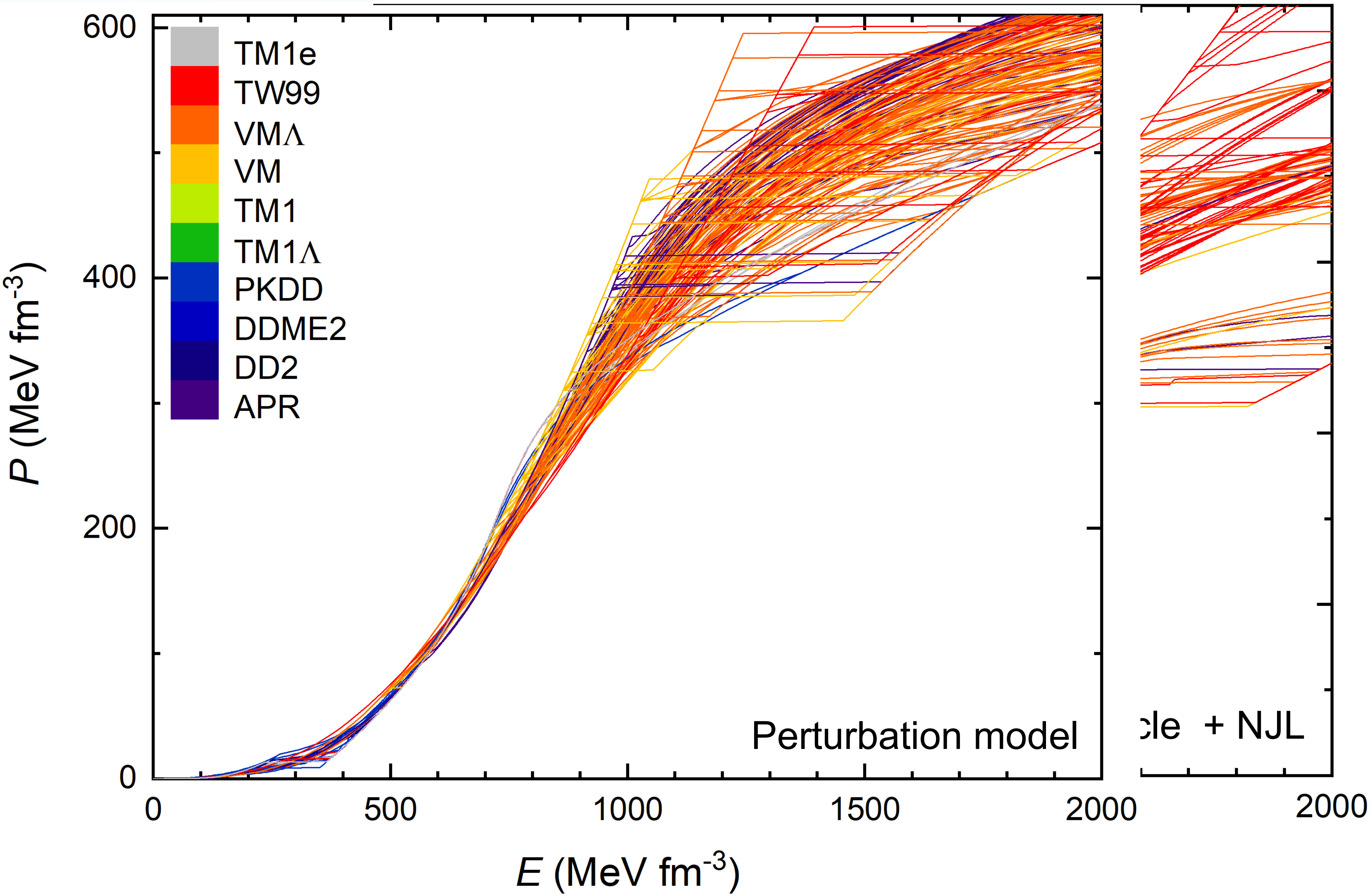
$\Delta P = P^{Max} - P^{onset}$



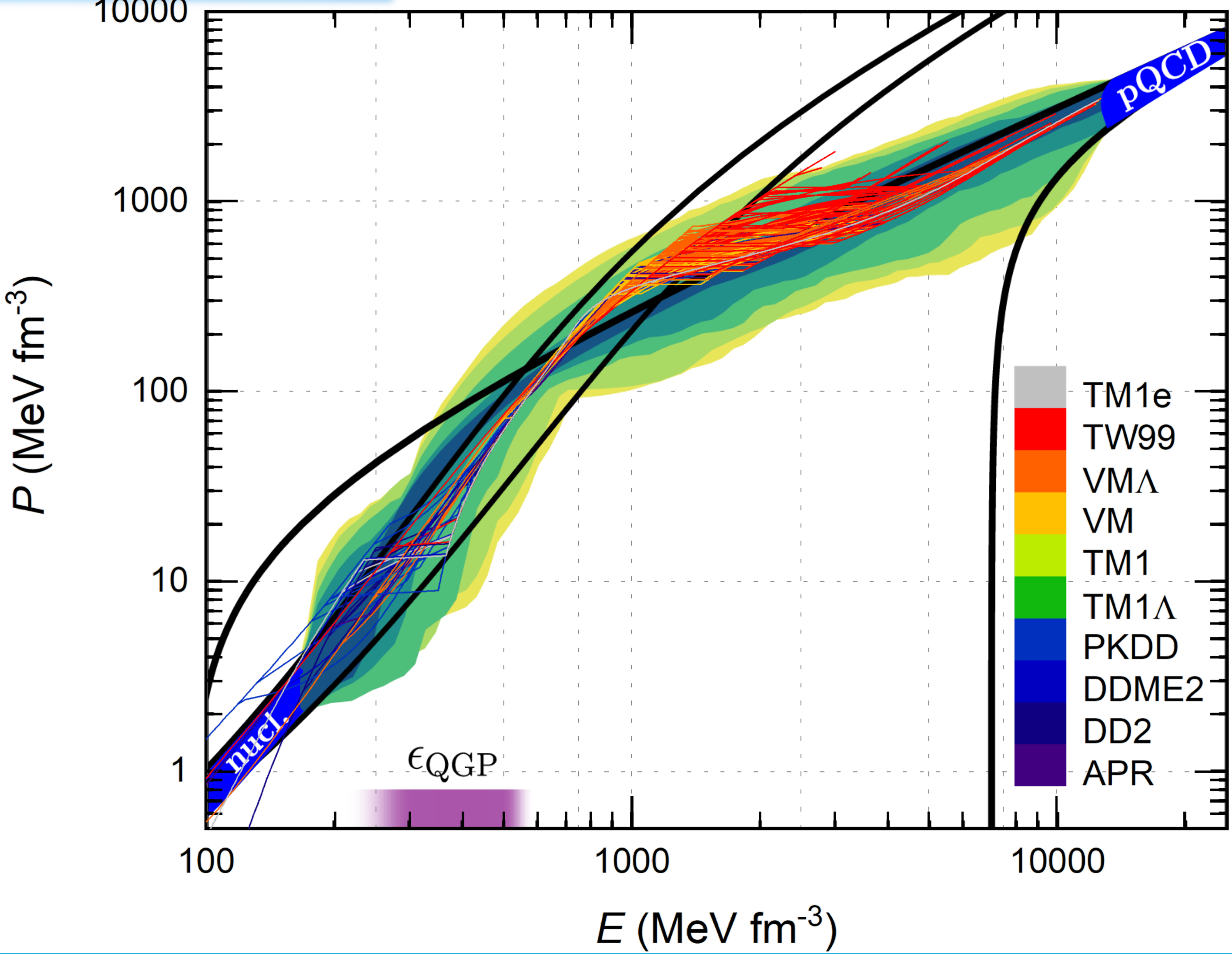
Quark fraction



Equation of State



Equation of State



Summary

The possible hadron-quark deconfinement phase transition in dense stellar matter were investigated. It was found that:

① A linear correlation is observed for the critical surface tension with baryon chemical potential, where the slope and intercept are connected to the adopted EoSs for hadronic matter and quark matter;

② The correlation between radius and tidal deformability preserve in hybrid stars;

③ The quark-hadron interface has sizable effects on compact star structures once quark matter emerge;

④ The astrophysical constrains indicate a deconfinement phase transition in most massive compact stars (perturbation model and most cases in Equivparticle and NJL models);

⑤ A crossing of the constrained EoSs at $E \approx 700$ MeV/fm^3 is observed.

Thank you!!!