Quark matter in compact stars: implication from recent observations

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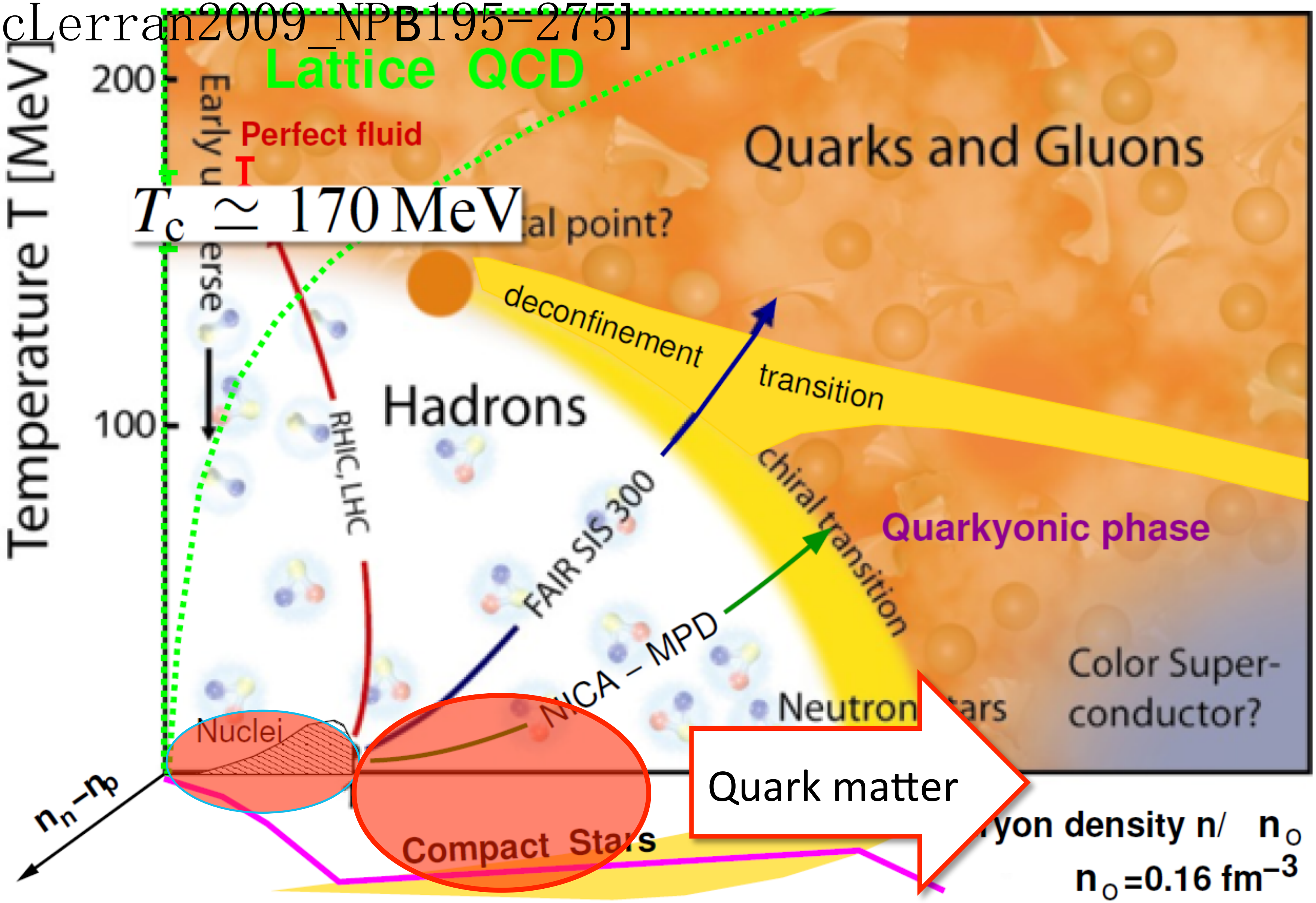
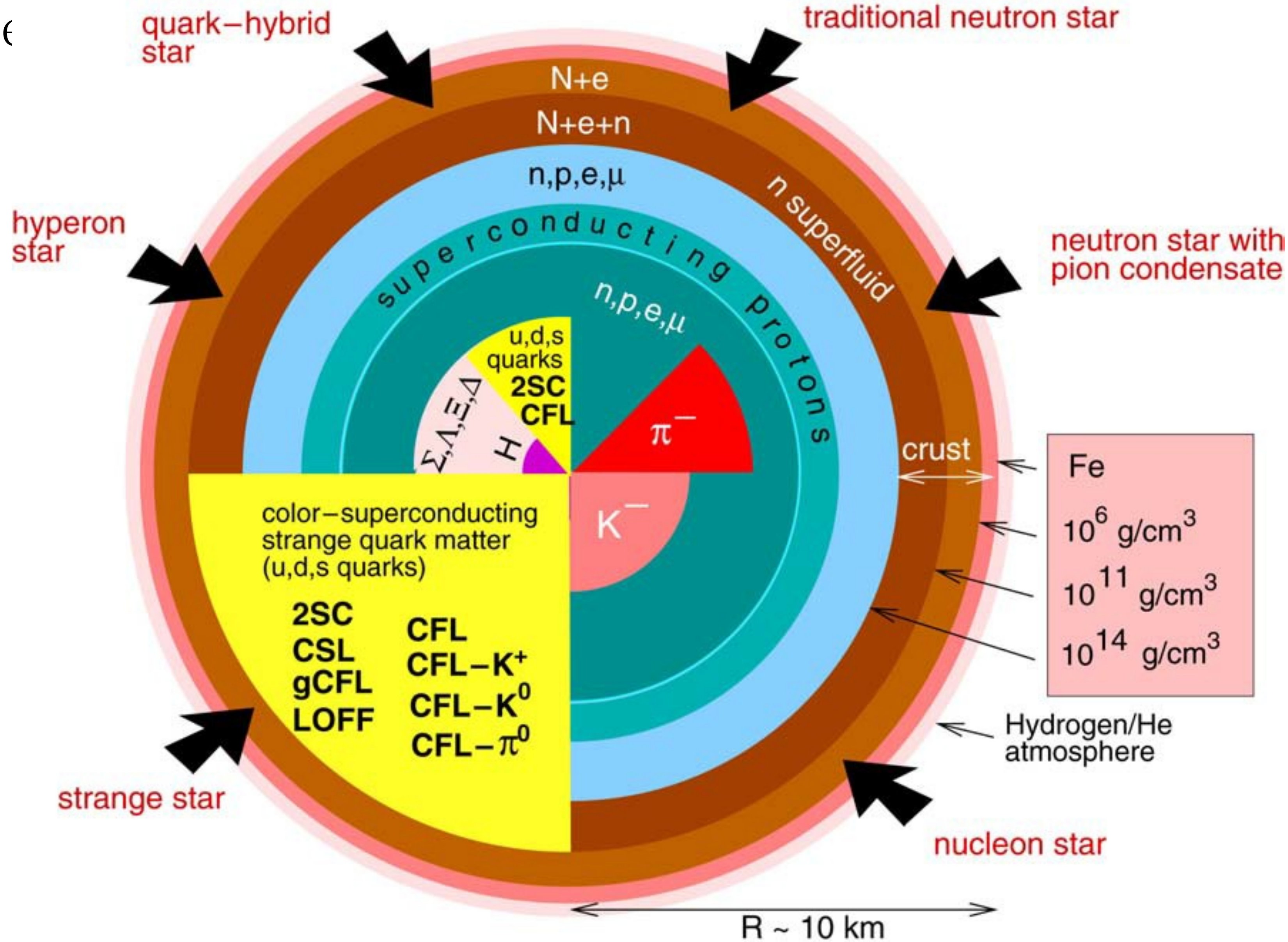
QCD Phase Diagram

[McLerran2009_NPB195-275]



Compact star structures

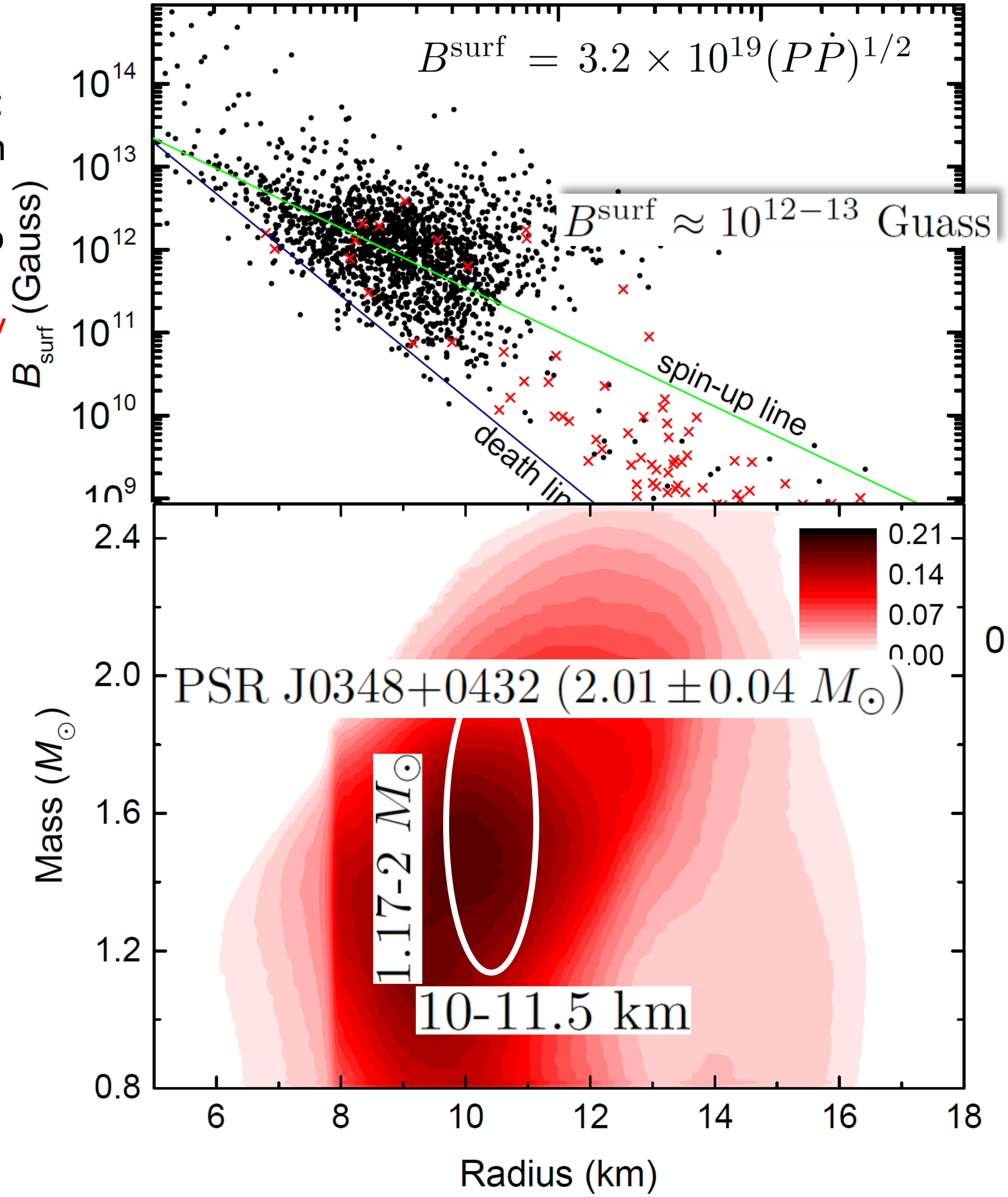
[Webe



Experimental constraint: Pulsars

Observables:

1. barycentric period P and its time derivative: spin-down driven by magnetic dipole radiation → surface magnetic field [Manchester_Hobbs_Teoh_Hobbs2005_AstronJ129-1993, …]
2. the cyclotron resonance features in the X-Ray spectrum of pulsars → surface magnetic field [Revnivtsev_Mereghetti2014_SpaceSciRev014-1]
3. photon spectrum of pulsars → surface temperature [Page2006_NPA777-497, Ho_Heinke 2009_Nature462-71] , mass-radius probability [Steiner_Lattimer _Brown2010_ApJ722-33, Guillot_Servillat _Webb_Rutledge2013_ApJ772-7, Ozel_Freire2016_AnnuRevAstro54-401…]
4. orbital motion of a binary system → precise mass measurement [Demorest et al. 2010_Nature467-1081, Antoniadis et al. 2013_Science340-6131, …]
5. gravitational waves emitted from the merger of binary compact stars → EoS [LIGO2009_RepProgPhys72-076901, Hotokezaka et al.2011_PRD83-124008…]



Baryonic matter

Shen EoS2&3: RMF model with the effective interaction TM1 and Λ-meson coupling determined by [Shen_Toki_Oyamatsu_Sumiyoshi2011_ApJ197-20]:

$$M_\Lambda = 1115.7 \text{ MeV}, g_\omega^\Lambda / g_\omega = 2/3, \text{and } g_\sigma^\Lambda / g_\sigma = 0.621.$$

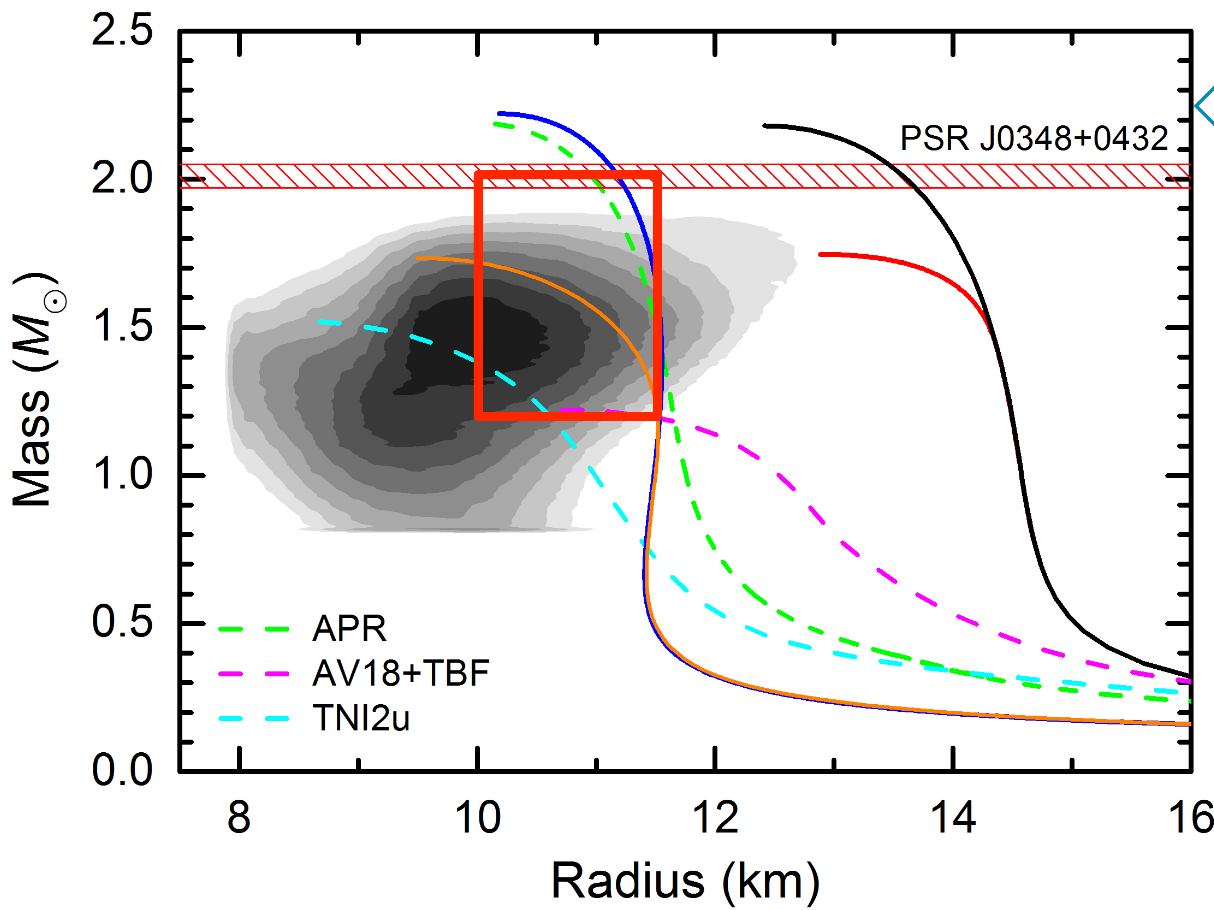
Sugahara_Toki1994_NPA579-557

1. the saturation density	ρ_0 (fm^{-3})	0.145
2. the energy:	E/A (MeV)	−16.3
3. the incompressibility	k (MeV)	281
4. the symmetry energy:	a_{sym} (MeV)	36.9

VM EoS: Cluster variational method with the potential AV18 + UIX [Togashi_Hiyama_Yamamoto_Takano2016_PRC93-035808, 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

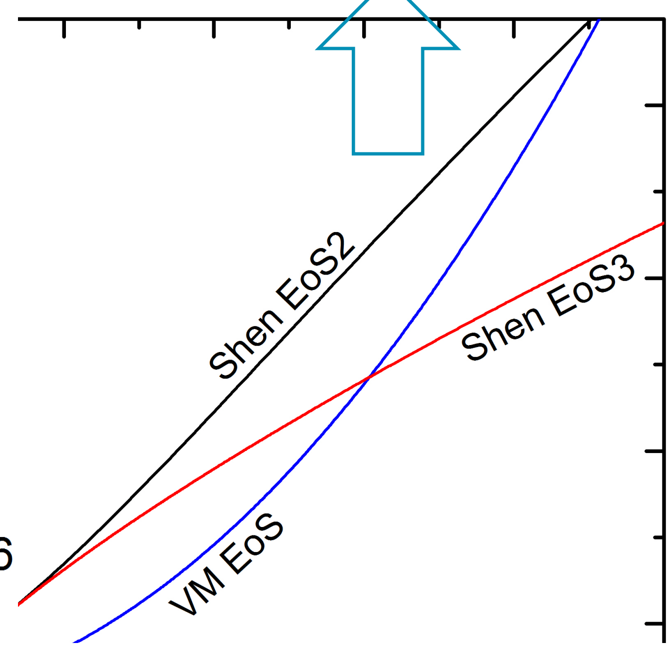
Baryon Stars



TOV equations:

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

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



Dashed curves: The EoSs of nuclear matter are obtained based on the non-relativistic G-matrix approach.

APR: without hyperons [Akmal_Pandharipande_Ravenhall1998_PRC58-1804];

AV18+TBF: obtained with the realistic nucleon-nucleon interaction AV18, the Urbana three nucleon interaction and the Nijmegen softcore nucleon-hyperon potential [Baldo_Burgio_Schulze2000_PRC61-055801];

TNI2u: considering three hyperon interaction [Takatsuka_Nishizaki_Yamamoto_Tamagaki2006_PTP115-355];

Quark matter

[Fraga_Romatschke2005_PRD71-105014]

Perturbation model: Expand the thermodynamic potential density up to the order of α_s in the MS scheme:

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

with
$$\omega_i^0 = -\frac{g_i m_i^4}{24\pi^2}\left[u_i v_i \left(u_i^2 - \frac{5}{2}\right) + \frac{3}{2}\ln(u_i + v_i)\right],$$
$$\omega_i^1 = \frac{g_i m_i^4}{12\pi^3}\left\{\left[6\ln\left(\frac{\bar\Lambda}{m_i}\right) + 4\right]\left[u_i v_i - \ln(u_i + v_i)\right] + 3\left[u_i v_i - \ln(u_i + v_i)\right]^2 - 2v_i^4\right\}.$$

Here we have defined $u_i = \mu_i/m_i$ and $v_i = \sqrt{u_i^2 - 1}$.

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

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

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

$\Lambda_{\overline{\mathrm{MS}}} = 376.9$ MeV, $\hat m_u = 3.8$ MeV, $\hat m_d = 8$ MeV, and $\hat m_s = 158$ MeV.

Non-perturbative corrections

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

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

The QCD sum-rule result predicts [Shuryak1978_PLB79-135]:

$$B = -\frac{1}{4}\langle T^{\mu}_{\mu}\rangle = \frac{11 - \frac{2}{3}N_f}{32}\frac{\alpha_s}{\pi}\langle G^{\mu\nu}_{a} G_{a\mu\nu}\rangle - \frac{1}{4}\sum_f m_f \langle \bar{q}_f q_f\rangle$$

$$\approx 455\,\mathrm{MeV}/\mathrm{fm}^3$$

Equating the pressures of QGP ($-B + 37\frac{\pi^2}{90}T^4$) and pion gas ($\frac{\pi^2}{30}T^4$) at $\mu = 0$ and $T = T_c$ (~170 MeV), one have:

$$B \simeq 400\,\mathrm{MeV}/\mathrm{fm}^3$$

On the other hand, fits to light hadron spectra suggest:

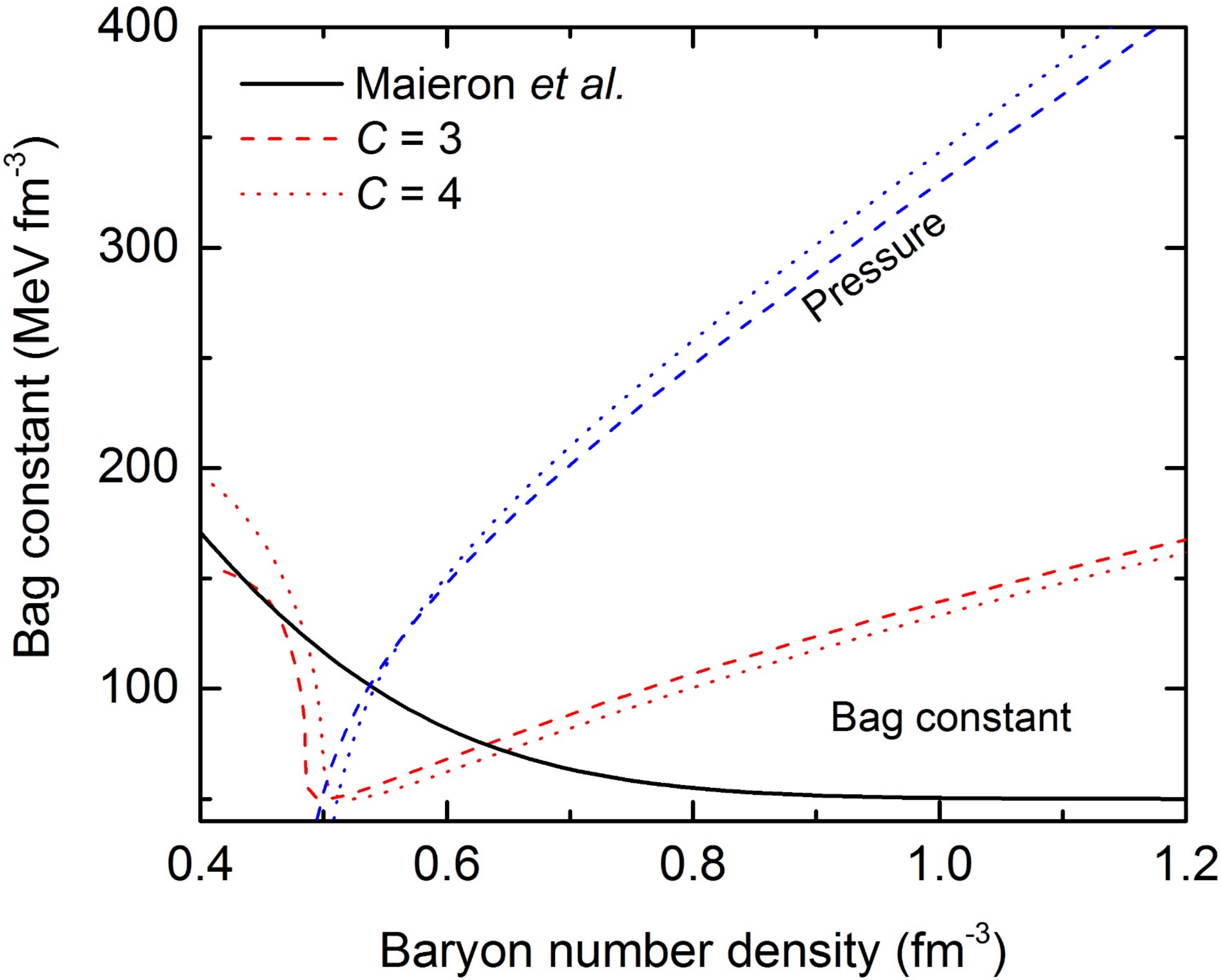
$$B \simeq 50\,\mathrm{MeV}/\mathrm{fm}^3$$

Gaussian parametrization for the bag constant B:

$$B = B_{\mathrm{QCD}} + (B_0 - B_{\mathrm{QCD}})\exp\left[-\left(\frac{\sum_i \mu_i - m_\Lambda}{2\Lambda_{\overline{\mathrm{MS}}}}\right)^2\right],$$

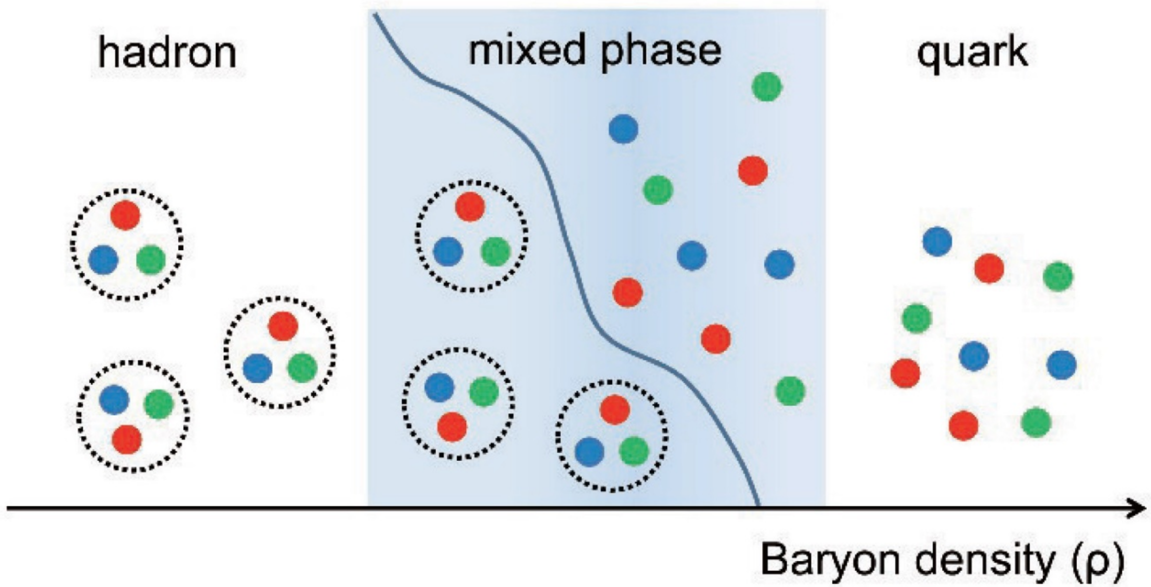
where $B_0 = 50$ MeV fm^{-3}, $B_{\mathrm{QCD}} = 400$ MeV fm^{-3}.

Bag constant [Maieron et al.2004_PRD70-043010]



Hadron-quark mixed phase inside compact stars

First-order phase transition [Masuda_Hatsuda_Takatsuka2016_EPJA52-65]



- σ = 0: point-like hadronic matter (HM) and strange quark matter (SQM), i.e., Gibbs construction.
- Moderate σ : geometrical structures [Chiba, Endo, Heiselberg, Maruyama, Tatsumi, Voskresensky, Yasuhira, Yasutake, ...]
  From Guo-yun Shao's talk:

- Large σ: the quark-hadron interface becomes planar, i.e., Maxwell construction.

Construct the mixed phase

The total volume occupied by the mixed phase is V, where the volume occupied by the quark phase is V_q. Then we can define the quark fraction:

$$\chi = V_q / V.$$

The thermodynamic quantities for the mixed phase:

Baryon number density $n_{\mathrm{t}} = (1-\chi) n_B + \chi n_q,$

Energy density $E_{\mathrm{t}} = (1-\chi)(E_B + E_l^B) + \chi (E_q + E_l^q).$

By minimizing the total energy density E_{t}, we obtain the phase equilibrium conditions:

$$\mu_n = \mu_u + 2\mu_d, \quad P_B = P_q.$$

Maxwell

Local charge neutrality

$$Q_B = n_l^B \text{ and } Q_q = n_l^q.$$

Gibbs

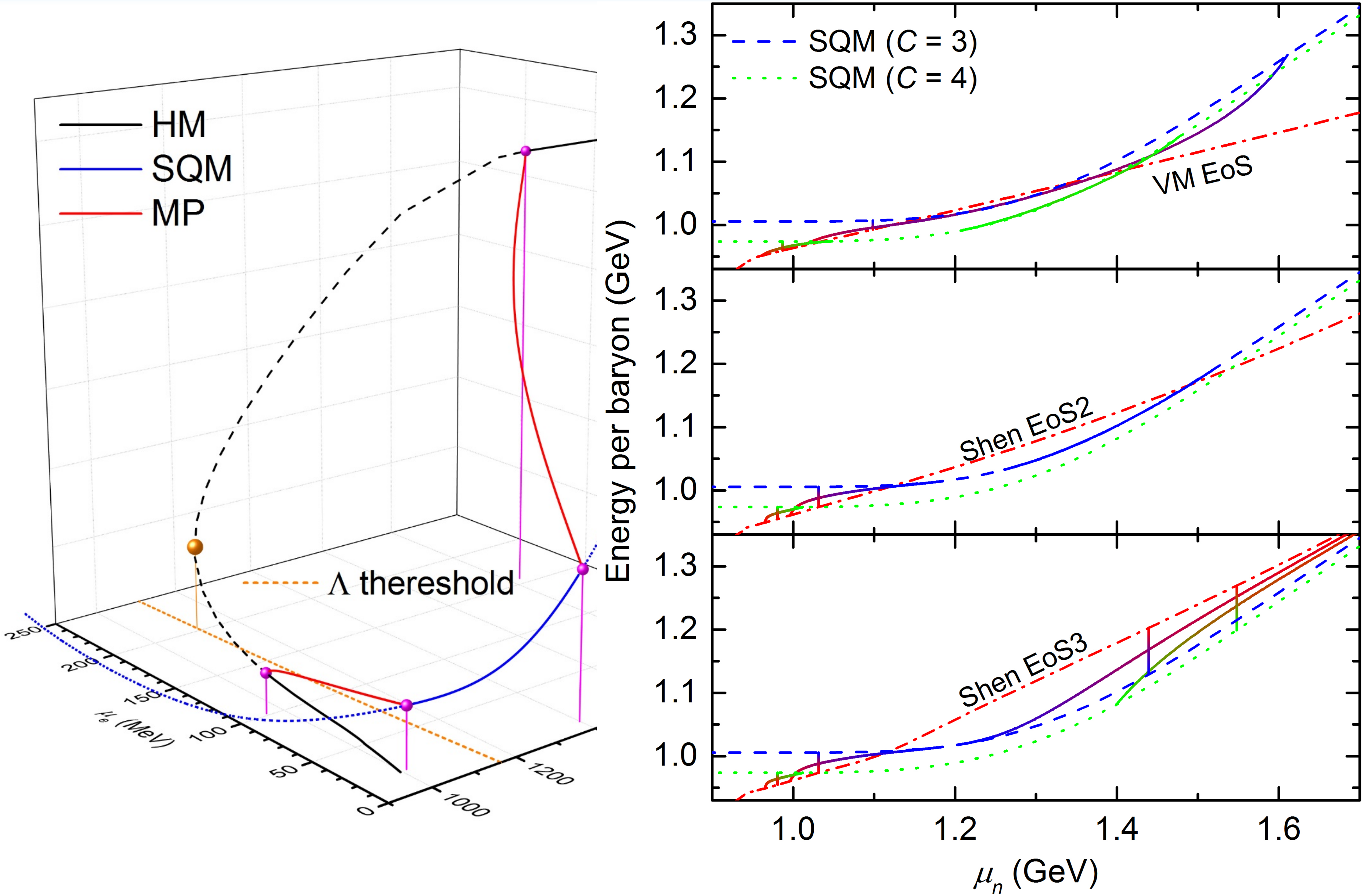
Global charge neutrality

$$n_l = (1-\chi) Q_B + \chi Q_q.$$

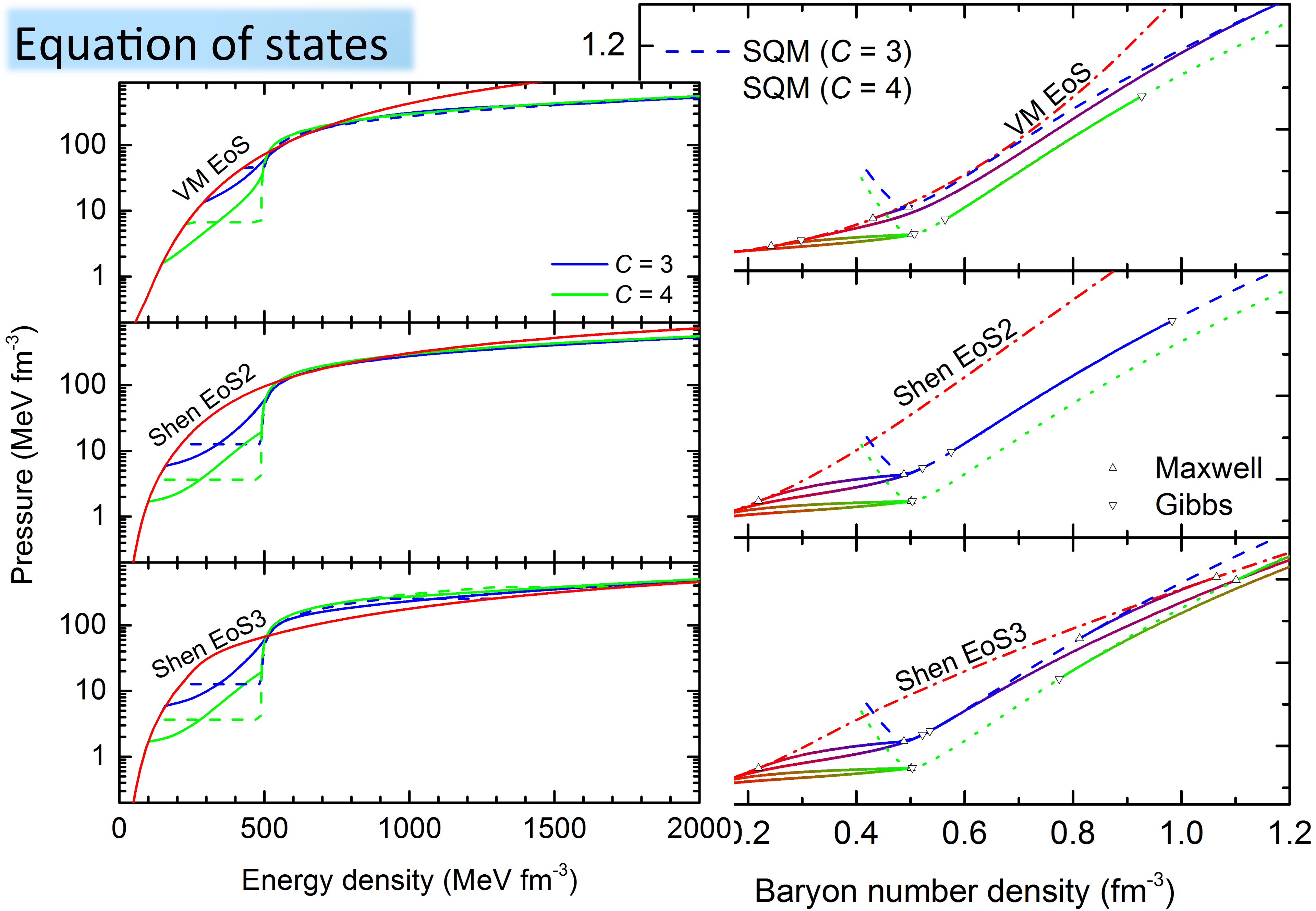
$$\mu_e^B = \mu_e^q$$

Note: the β-equilibrium condition is fulfilled.

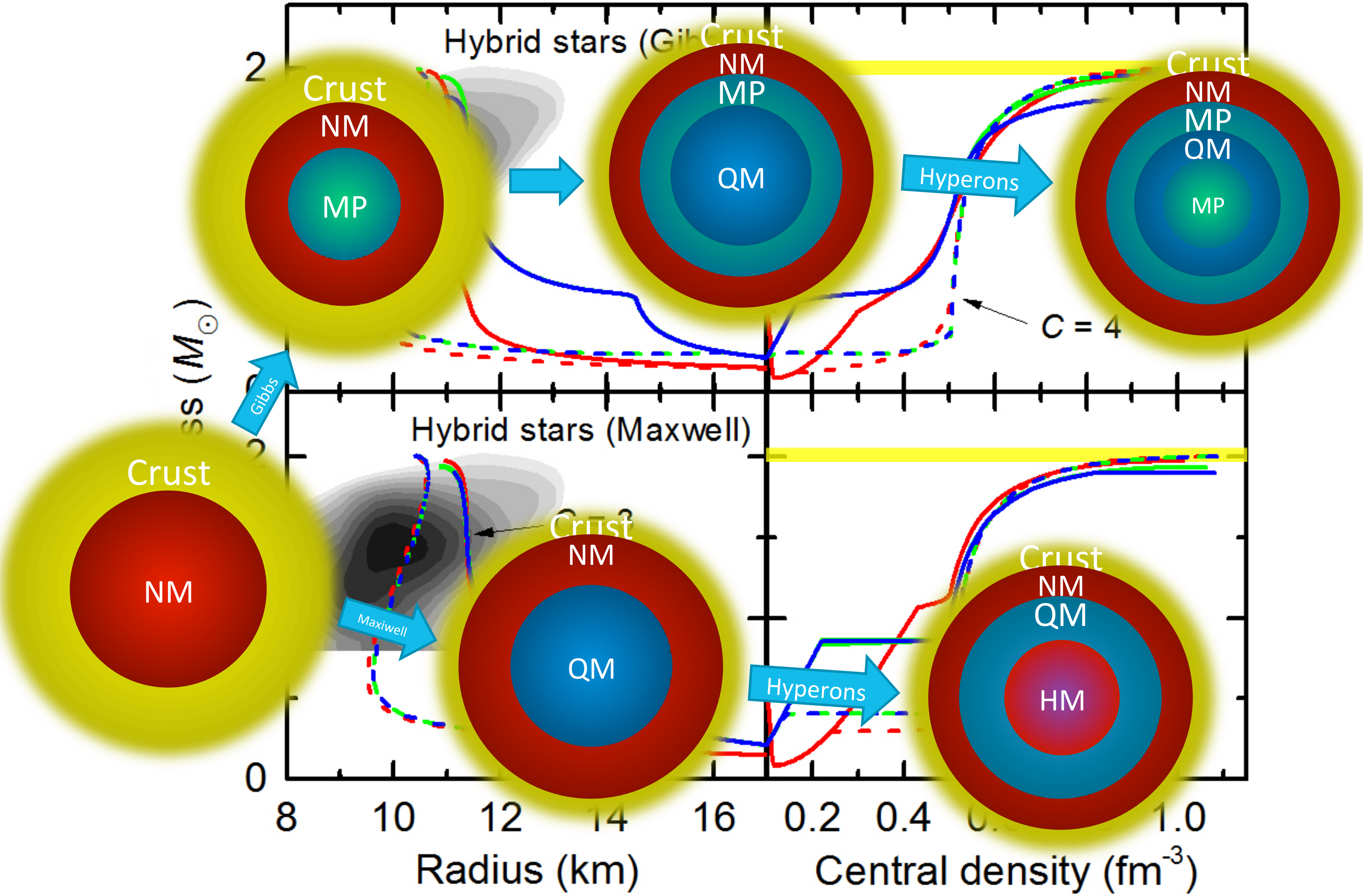
The phase transition in compact stars



Equation of states



Mass, radius, and central density



Summary

The compact stars with possible existence of hyperonic matter and quark matter were investigated. It was found that:

① The first-order deconfinement phase transition does not always reduce the maximum mass of compact stars;

② Massive neutron stars may consist of multilayers baryonic matter, quark matter and their mixed phases;

③ The existence of quark matter in compact stars reduces their radii, which are more consistent with the recent observations [R = 10-11.5 km at $M \approx$ 1.17-2 $M_{\odot}$, Ozel_Freire2016_AnnuRevAstro54-401];

Thank you!!!