Solving the Hyperon Puzzle – Then and Now

Celebrating Dr. Marcello Baldo's 80th Birthday

David Blaschke (HZDR/CASUS, IFT UWr)

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Stories to be told ...

Introduction to Hyperon Puzzle and Early Catania Solution

Terra Incognita: Agnostic Bayesian Analysis vs. Interpolation

Berlin Wall Constraint

Confining Density Functionals (CDF) for Quark Matter

Early Deconfinement in Supernova Explosions and Binary Mergers

Towards a Unified Approach: CDF or Brueckner Hartree Fock ?

Outlook: German Centre for Astrophysics (DZA)

Prehistory: From Berlin Wall to Catania

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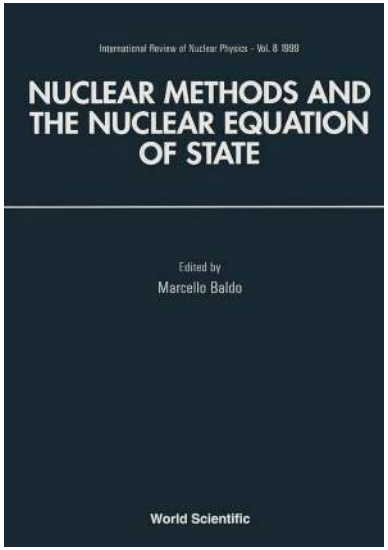
1989

– Sept: Castle Schwerin
– Oct: Univ. Heidelberg
– November: Berlin Wall (D.B., H. Schulz + wife, G. Röpke + daughter)

Prehistory: From Berlin Wall to Catania

1998: Catania - Siracusa



International Review of Nuclear Physics - Vol. 8 1999

NUCLEAR METHODS AND THE NUCLEAR EQUATION OF STATE

Edited by
Marcello Baldo

World Scientific

The Hyperon Puzzle and its Catania Solution:

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PHYSICAL REVIEW C **66**, 025802 (2002)

Hadron-quark phase transition in dense matter and neutron stars

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[1]*Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Corso Italia 57, I-95129 Catania, Italy*
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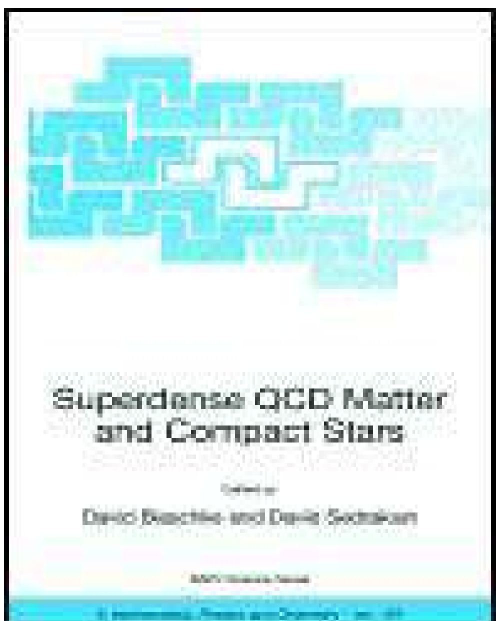
(Received 3 June 2002; published 26 August 2002)



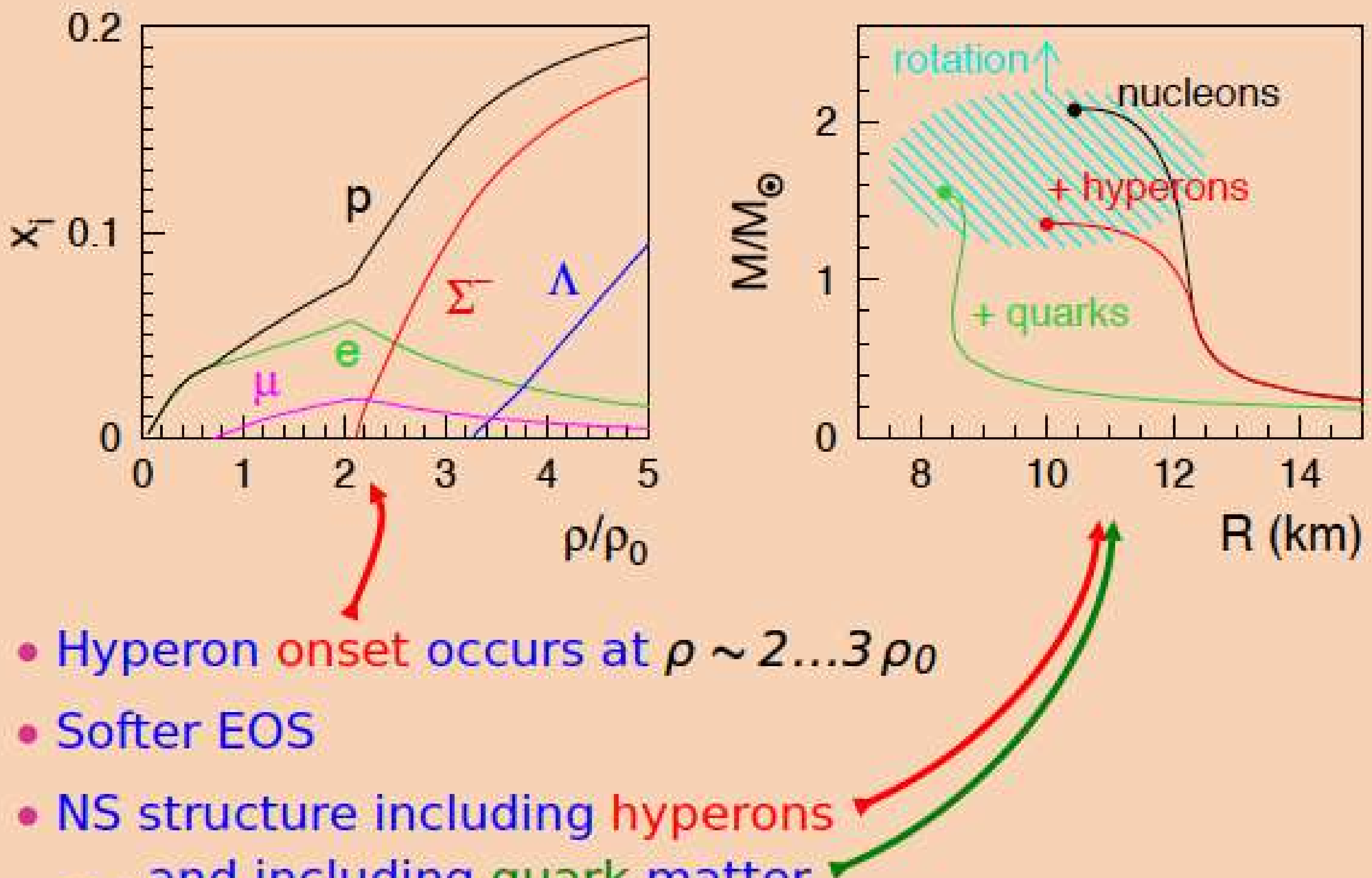
NEUTRON STAR STRUCTURE WITH HYPERONS AND QUARKS

M. Baldo, F. Burgio, H.-J. Schulze
INFN Sezione di Catania, Via S. Sofia 64, I-95123 Catania, Italy

Abstract We discuss the high-density nuclear equation of state within the Brueckner-Hartree-Fock approach. Particular attention is paid to the effects of nucleonic three-body forces, the presence of hyperons, and the joining with an eventual quark matter phase. The resulting properties of neutron stars, in particular the mass-radius relation, are determined. It turns out that stars heavier than 1.3 solar masses contain necessarily quark matter.

The Hyperon Puzzle and its Catania Solution:

- Generic implications for EOS and stellar structure:

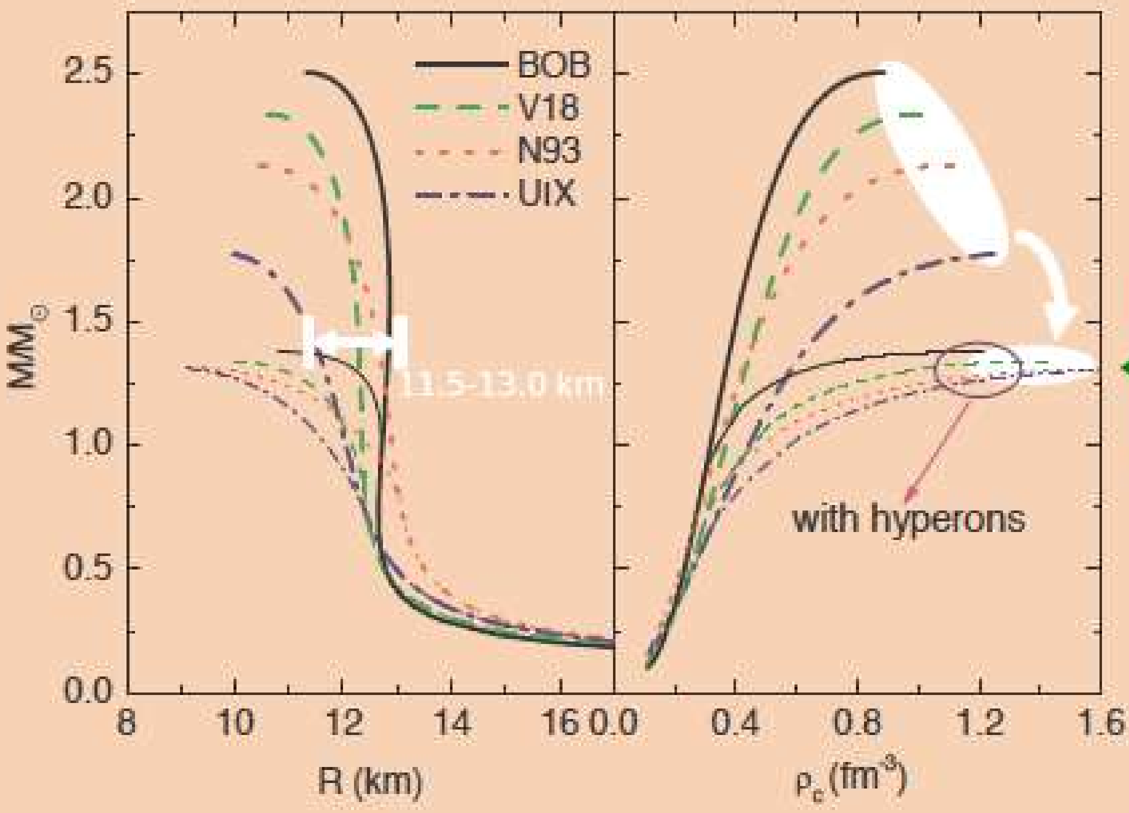


- Hyperon onset occurs at $\rho \sim 2 \ldots 3\,\rho_0$
- Softer EOS
- NS structure including hyperons
  . . . and including quark matter

Courtesy: Hans-Josef Schulze (2019)

The Hyperon Puzzle and its Catania Solution:

- Mass-radius relations with different nucleonic TBF:



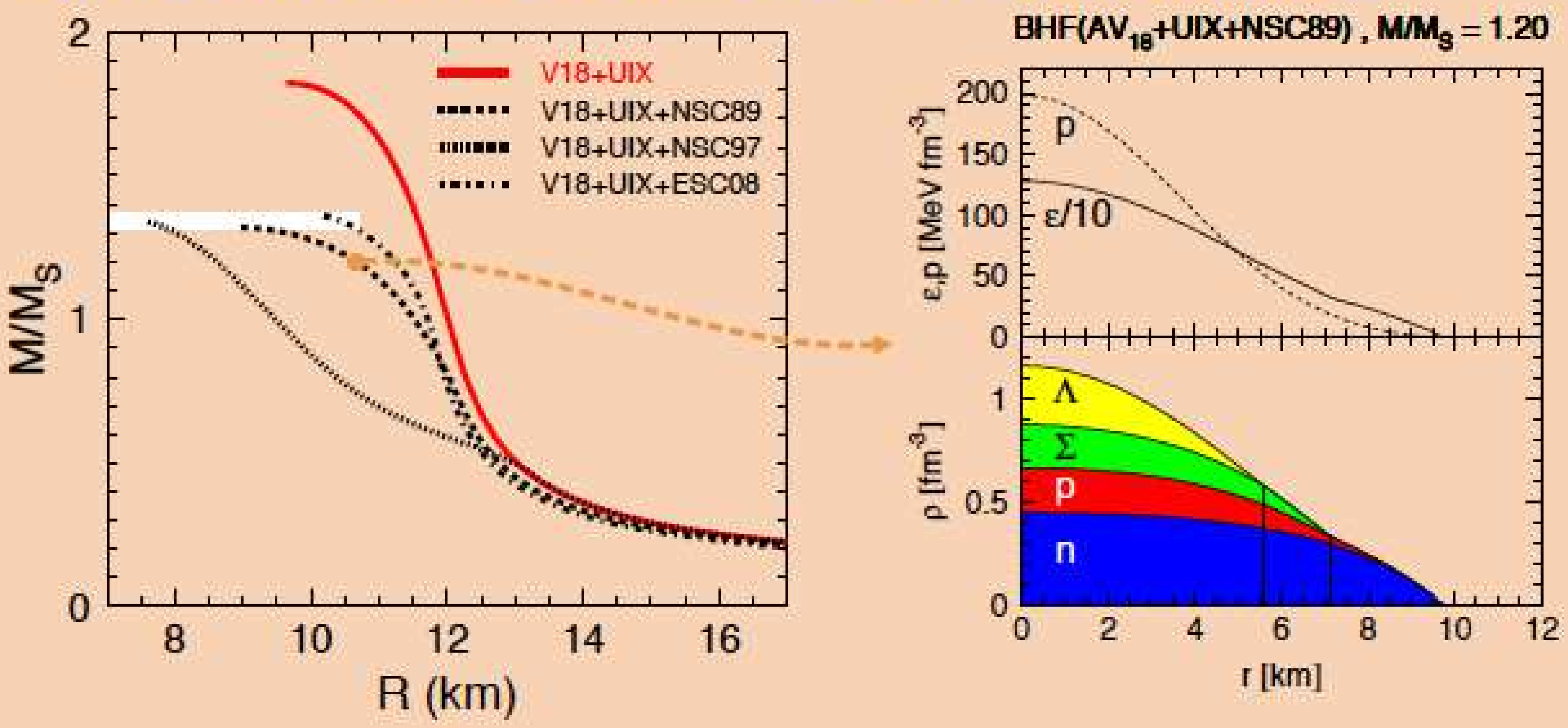
NSC89 *NY* potential
No *YY*
No hyperon TBF

➡ Large variation of M_{max} with nucleonic TBF
Self-regulating softening due to hyperon appearance
(stiffer nucleonic EOS → earlier hyperon onset)

Courtesy: Hans-Josef Schulze (2019)

The Hyperon Puzzle and its Catania Solution:

- Mass-radius relations using different *NY* potentials:



Maximum mass independent of potentials !

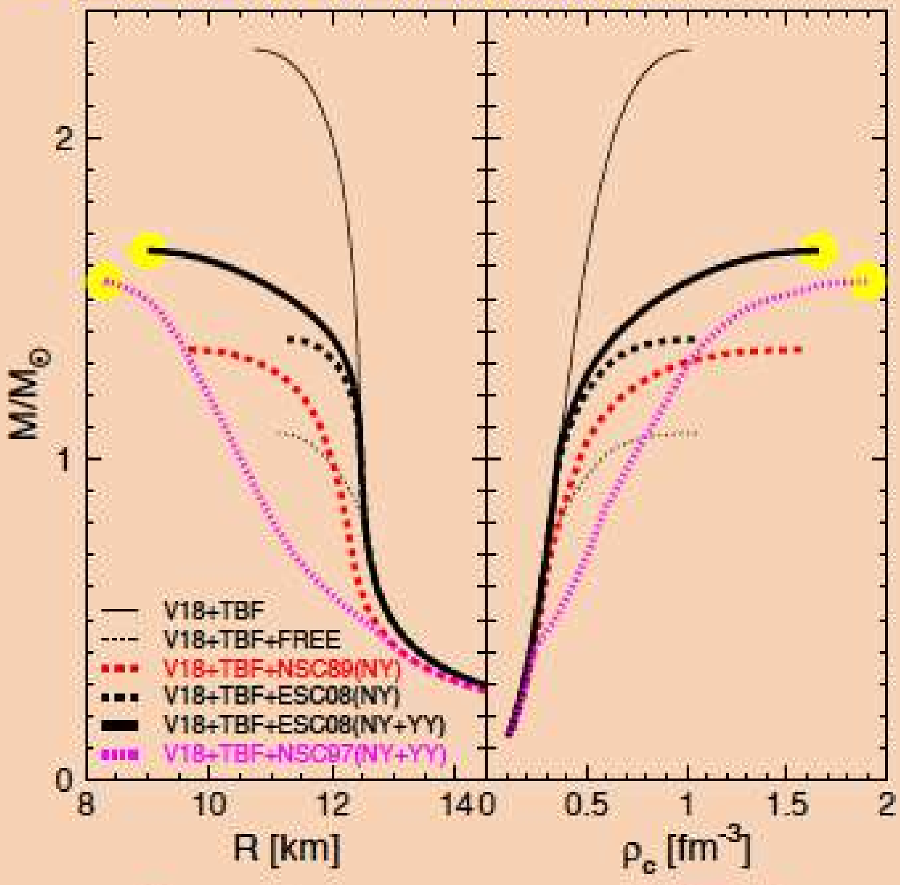
Maximum mass too low ($< 1.4 M_\odot$) !

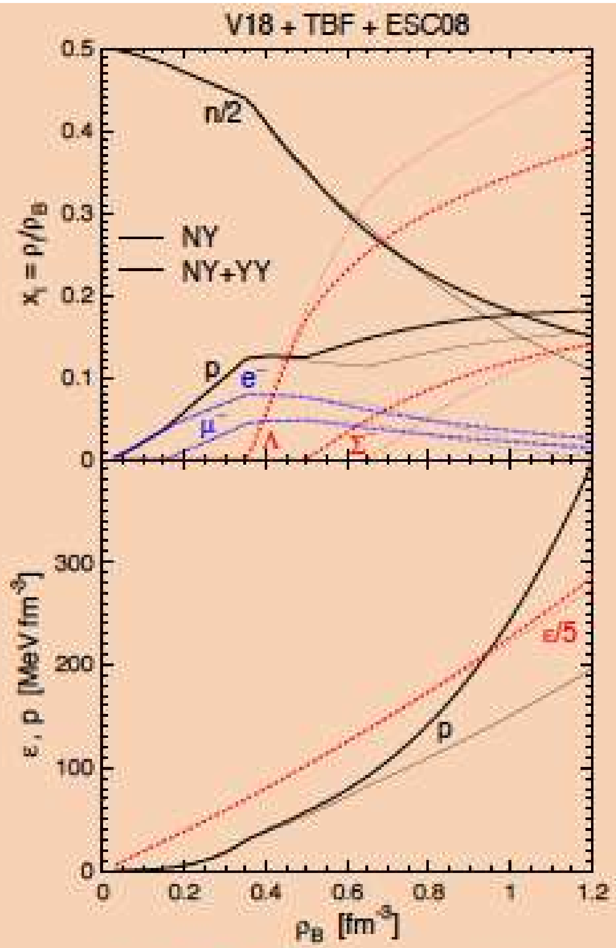
Proof for "quark" matter inside neutron stars ?

Courtesy: Hans-Josef Schulze (2019)

The Hyperon Puzzle and its Catania Solution:

- Effect of *YY* Interactions:





Mass increase to $\lesssim 1.7 M_\odot$

$\Lambda\Lambda$, $\Sigma^-\Sigma^-$ repulsive
$\Lambda\Sigma^-$ attractive !

- Hyperon TBF (*YNN*, *YYN*, *YYY*) unknown (exp. and theor.) !

Courtesy: Hans-Josef Schulze (2019)

The Hyperon Puzzle and its Catania Solution:

Quark Matter EOS of Dense Matter:

- Problem: No "exact" results from QCD:
  Large theoretical uncertainties, limited predictive power
- Current strategy:
  Use available eff. quark models (MIT, NJL, CDM, DSM, ...)
  in combination with the hadronic EOS
- An important constraint (from heavy ion collisions):
  In symmetric matter phase transition not below $\approx 3\rho_0$

→ E.g., the simplest (MIT) quark model requires
a density-dependent bag "constant":

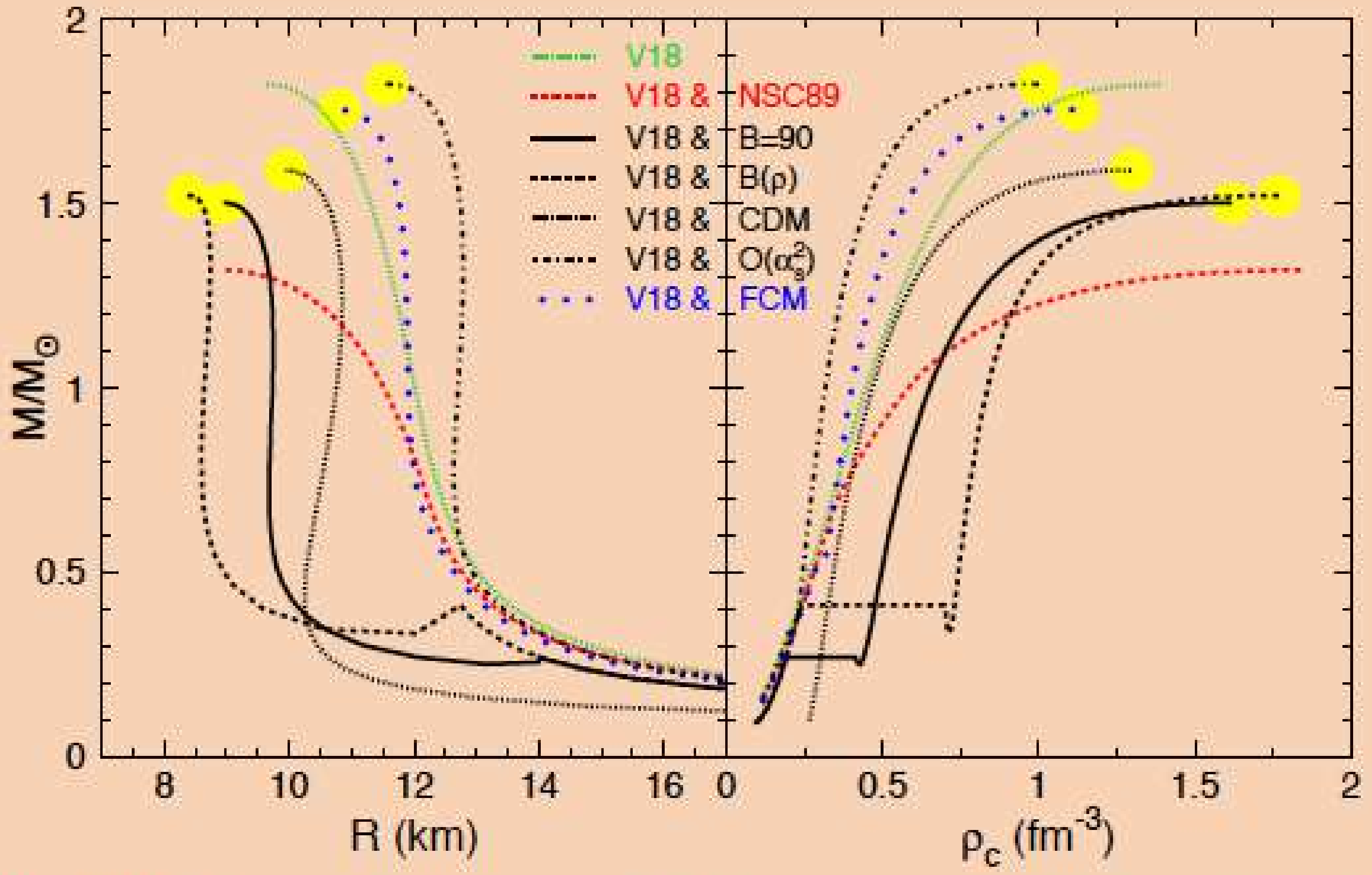
$$\epsilon_Q = B + \epsilon_{\mathrm{kin}} + \alpha_s \times \ldots$$

$$B(\rho) = B_\infty + (B_0 - B_\infty)\exp\left[-\beta\left(\rho/\rho_0\right)^2\right]$$

Courtesy: Hans-Josef Schulze (2019)

The Hyperon Puzzle and its Catania Solution:

- Different quark EOS's: bag models, color dielectric model:



NJL, FCM, Dyson-Schwinger models: hyperons prevent phase transition

➡ Maximum masses: 1.5...1.9 $M_\odot$, Radii are different !

Courtesy: Hans-Josef Schulze (2019)

The Hyperon Puzzle and its Catania Solution:

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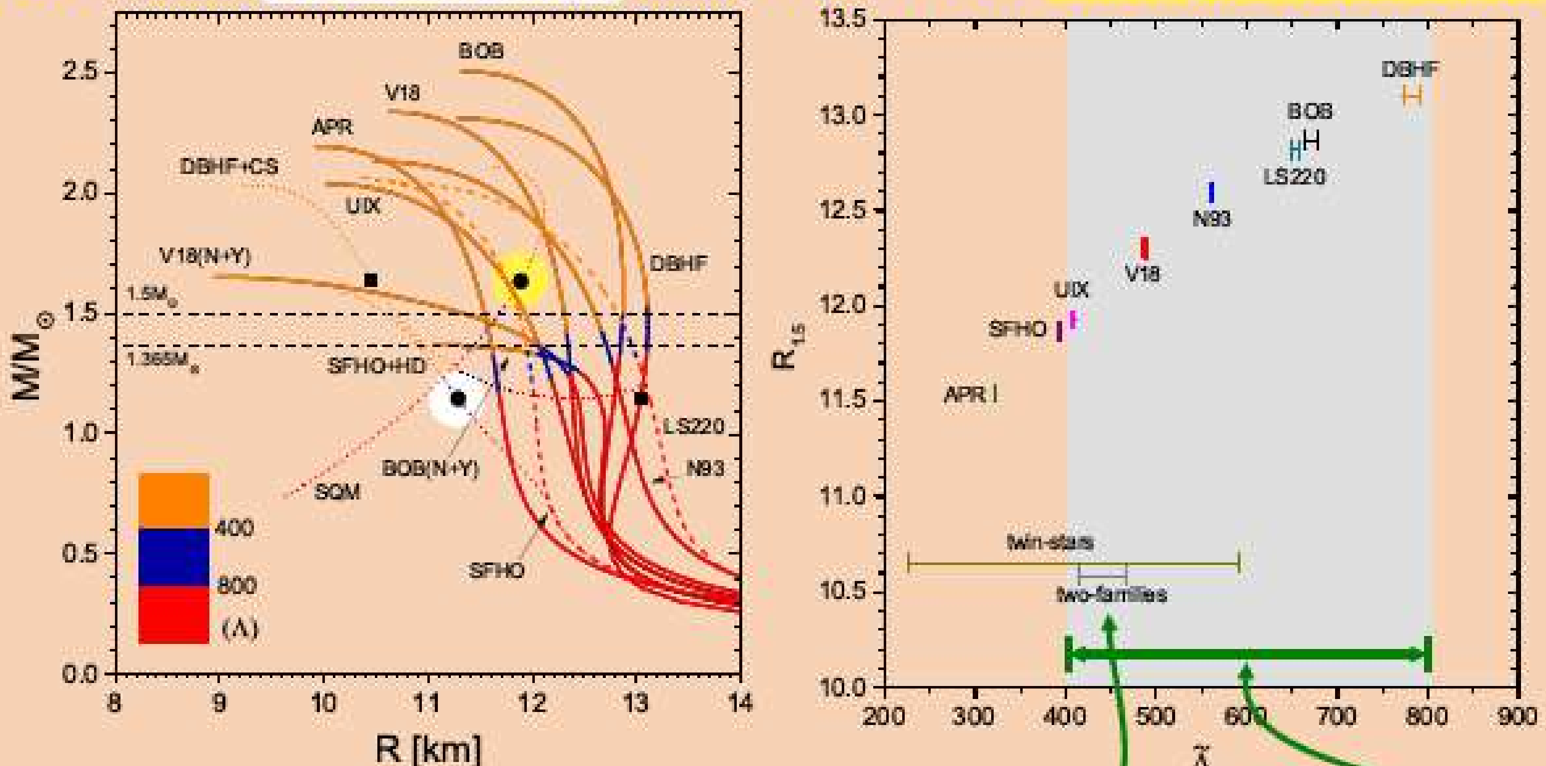
Some recent results with BHF (hyperonic) EOSs:

- In the *two-families* scenario could coexist low-mass hyperon stars and high-mass strange quark stars: APJ 860, 139 (2018)



Variation due to allowed mass asymmetry $q = M_2/M_1$

Constrained by GW170817 analyses

Courtesy: Hans-Josef Schulze (2019)

2000+ Town meetings of the SNNS community: Catania, Paris-Orsay, Darmstadt, ...

Town meeting in Orsay 2005, writing a proposal for „CompStar“ to ESF

2000+ Town meetings of the SNNS community: Catania, Paris-Orsay, Darmstadt, ...

EXOCT 2007 in Catania: Research Network „CompStar“ approved by ESF

QCD Phase Diagram

Landscape of our investigations

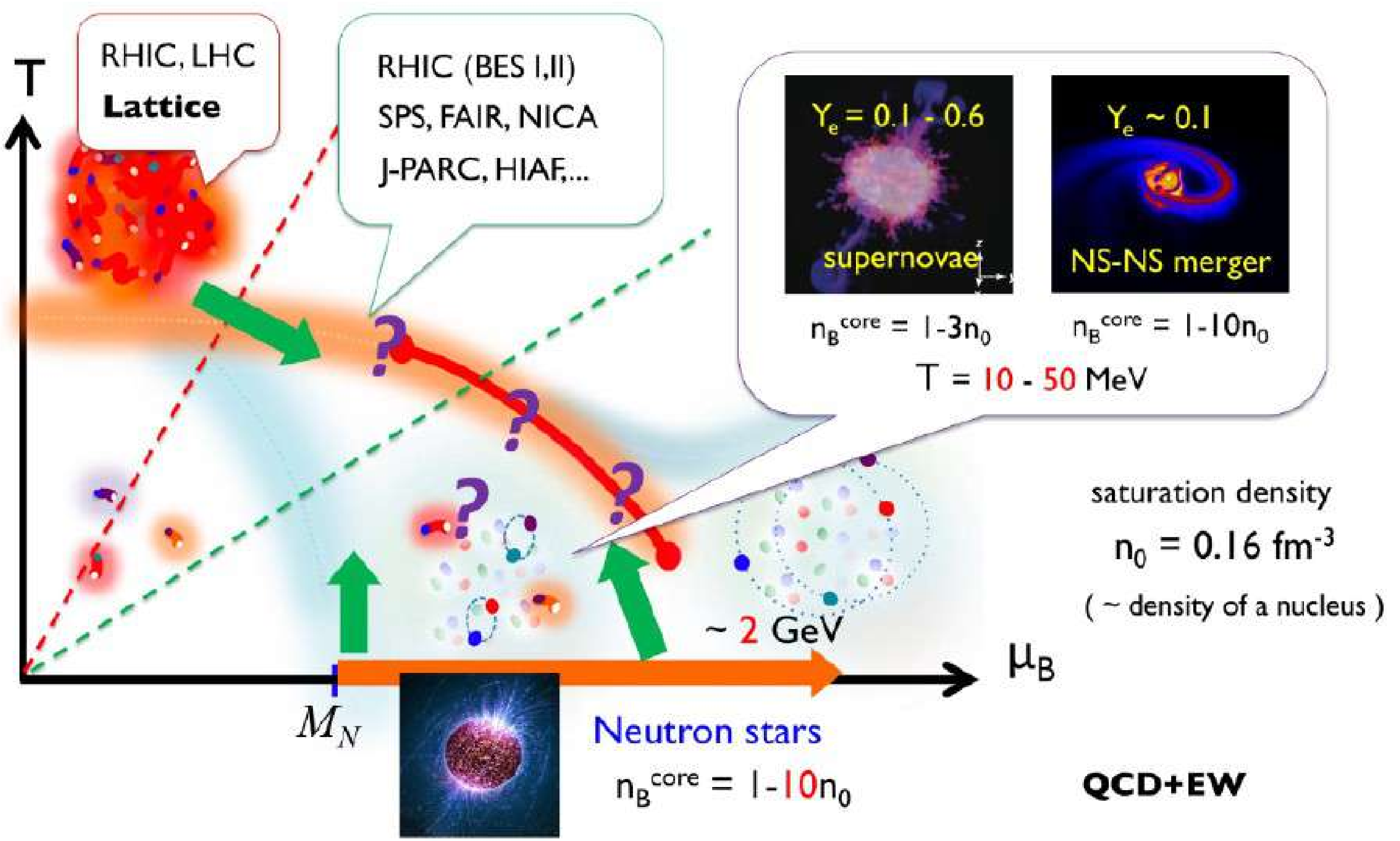
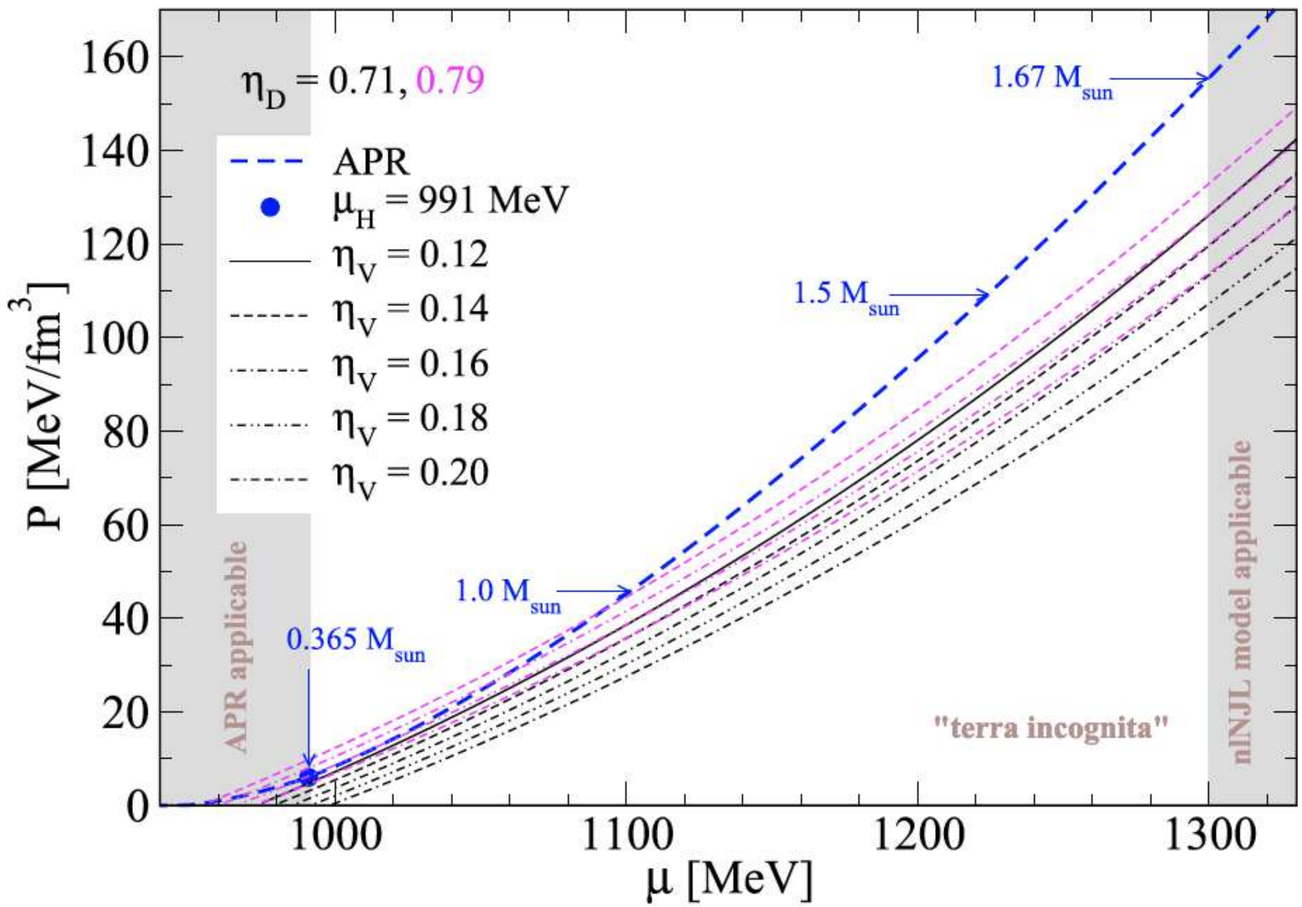


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

Pro and con quark matter in neutron stars

Where is deconfinement in “terra incognita” ?

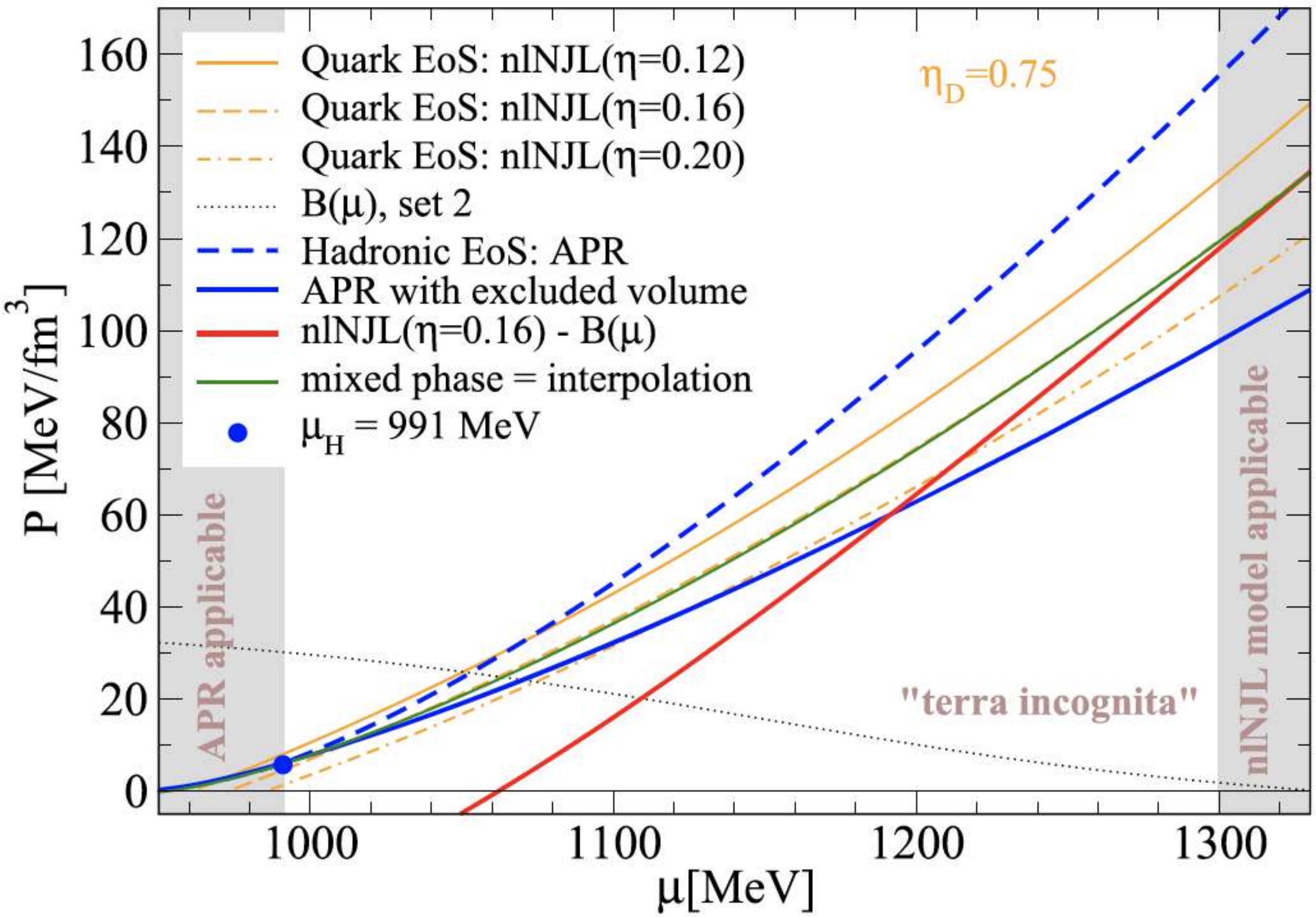


A. Ayriyan, D.B., A.G. Grunfeld, et al.

Eur. Phys. J. A (2021) 57:318
https://doi.org/10.1140/epja/s10050-021-00619-0

Pro and con quark matter in neutron stars

Strong 1st order PT masquerades as „crossover" via pasta phases



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Pro and con quark matter in neutron stars

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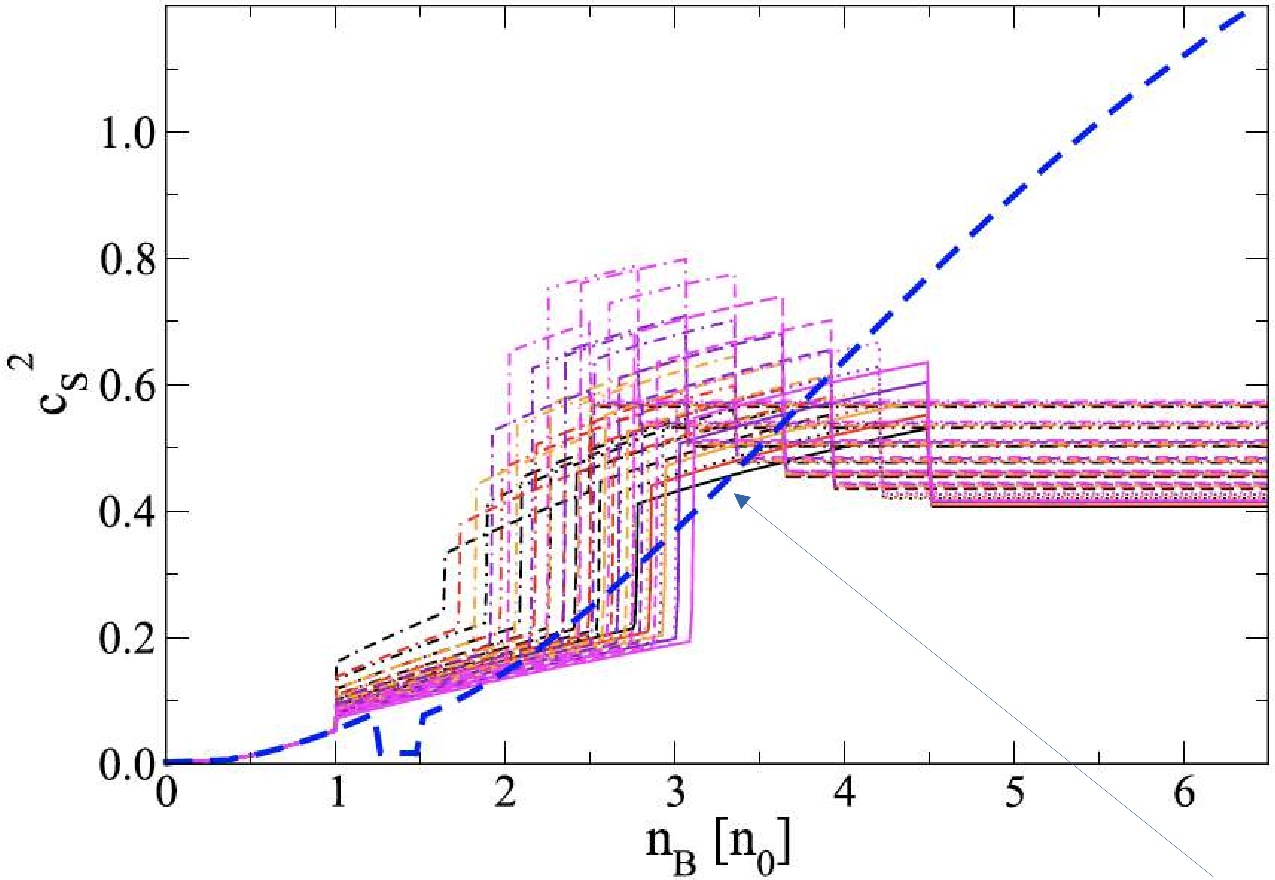


Two-zone interpolation scheme (TZIS) with crossover boundary condition → stiffening, analogous to "quarkyonic" matter behavior

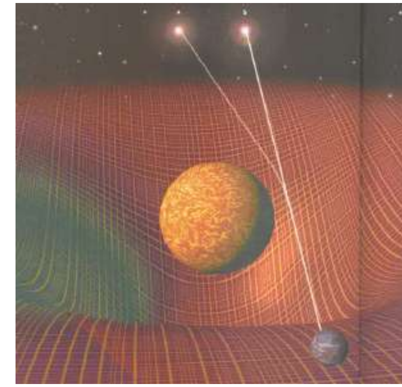
A. Ayriyan, D.B., A.G. Grunfeld, et al.

Eur. Phys. J. A (2021) 57:318
https://doi.org/10.1140/epja/s10050-021-00619-0

Neutron star phenomenology from TOV eqns.

There is a 1:1 correspondence EOS $\leftrightarrow$ M(R)

Tolman-Oppenheimer-Volkoff (TOV) equations

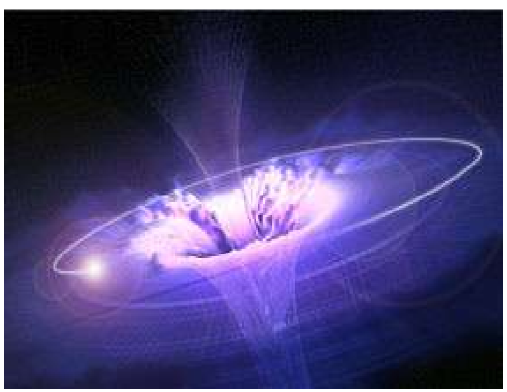


Einstein equations

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Non-rotating, spherical masses → Schwarzschild Metrics

$$ds^2 = -(1 - \frac{2M}{r})dt^2 + (1 - \frac{2M}{r})^{-1}dr^2 + r^2 d\Omega^2$$



Tolman-Oppenheimer-Volkoff eqs.*) for structure and stability of spherical compact stars

$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1 + \frac{P(r)}{\varepsilon(r)}\right)\left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right)\left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

Newtonian case GR corrections from EoS and metrics

*)R.C. Tolman, Phys. Rev. 55 (1939) 364; J.R. Oppenheimer, G.M. Volkoff, ibid., 374

Neutron star phenomenology from TOV eqns.

There is a 1:1 correspondence EOS $P(\varepsilon) \leftrightarrow M(R)$

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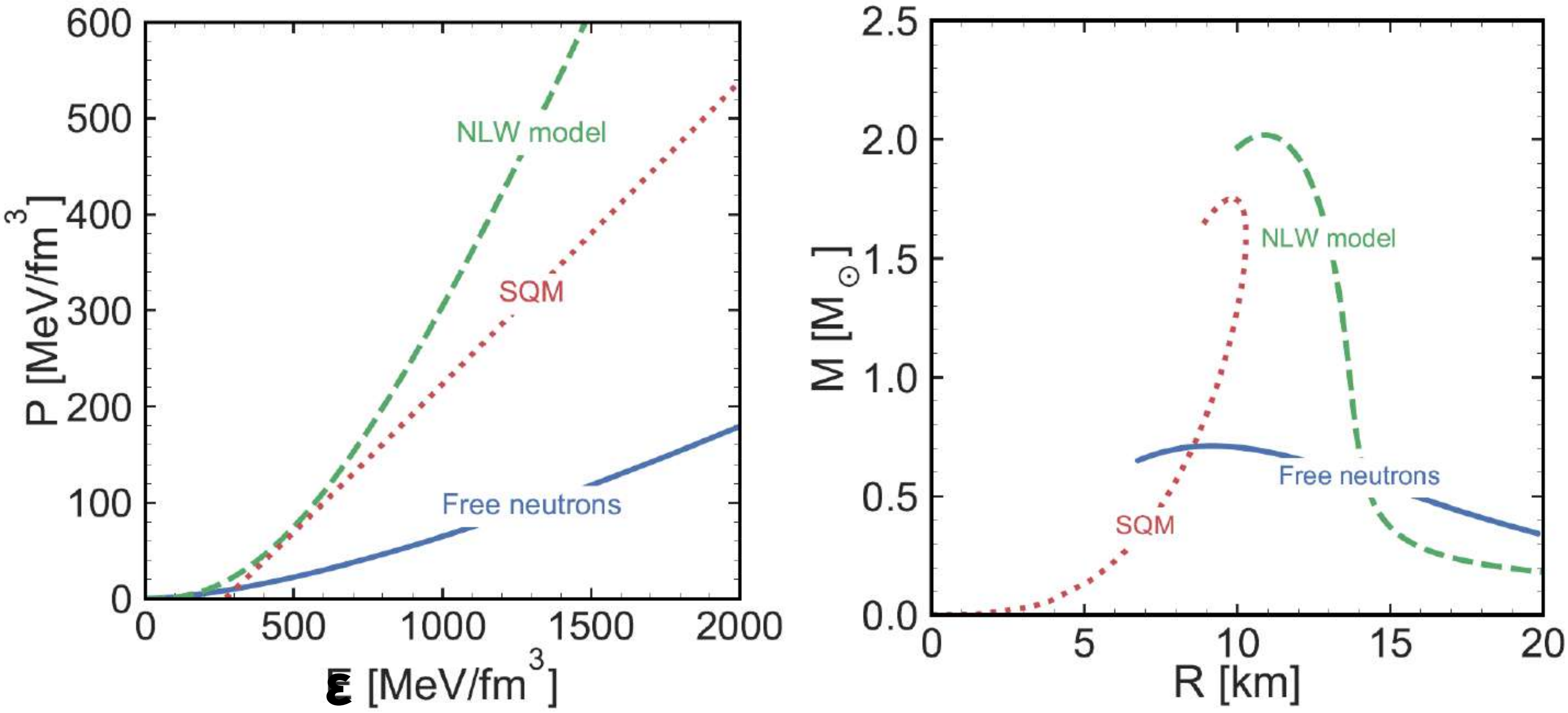
Tolman-Oppenheimer-Volkoff (TOV) equations - solutions



Stiffer equation of state → larger radius and larger maximum mass

"Berlin wall" constraint for neutron stars

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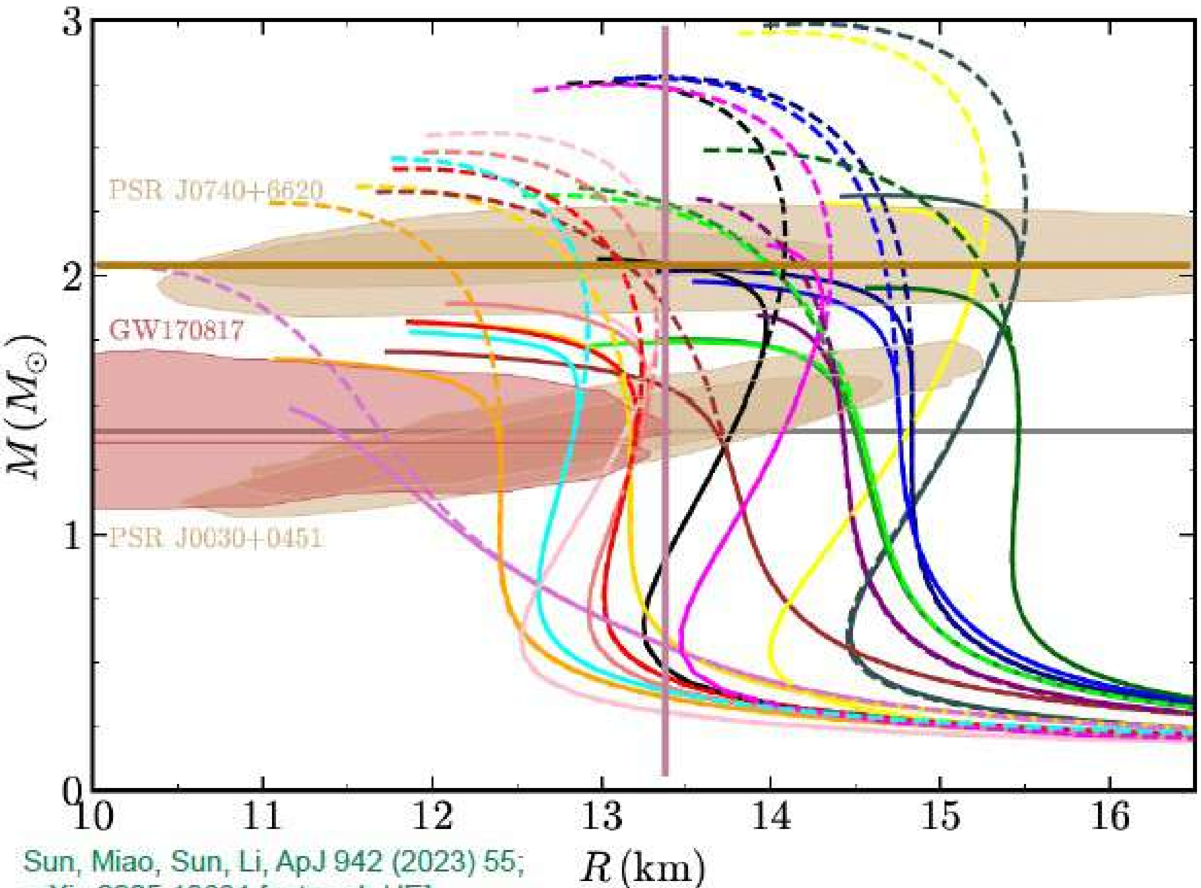
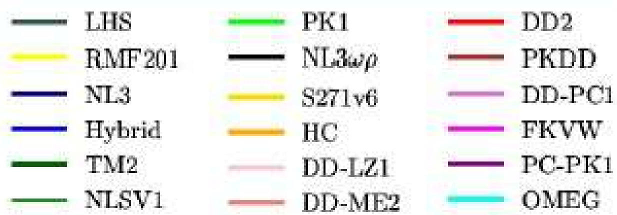
Realistic hadronic EOS (with strange baryons)

Tension with modern multi-messenger observations by LVC and NICER



Sun, Miao, Sun, Li, ApJ 942 (2023) 55; arXiv:2205.10631 [astro-ph.HE]

Examples for hadronic EoS without (dashed lines) and with (solid lines) strange baryons. EoS which fulfill the observational constraints should be left of the vertical line at 1.4 Msun and should cross the horizontal line for the minimal maximum mass at 2.01 Msun. There is no EoS of this sample which fulfills both constraints !!



From Tab. 2 select EoS which fulfill (w. Y) 70 < Λ_1.4 < 580 and check their M_max

EoS	M_max	EoS	M_max
NL3ωρ	1.974	DD2	1.935
DDLZ1	1.989	PKDD	1.781
DD-ME2	1.971	HC	1.828
OMEG	1.862		

“Berlin Wall” constraint for neutron stars?

Mass-radius diagram for purely hadronic EOS

Appearance of hyperons softens the EOS → Limitation for the maximum mass

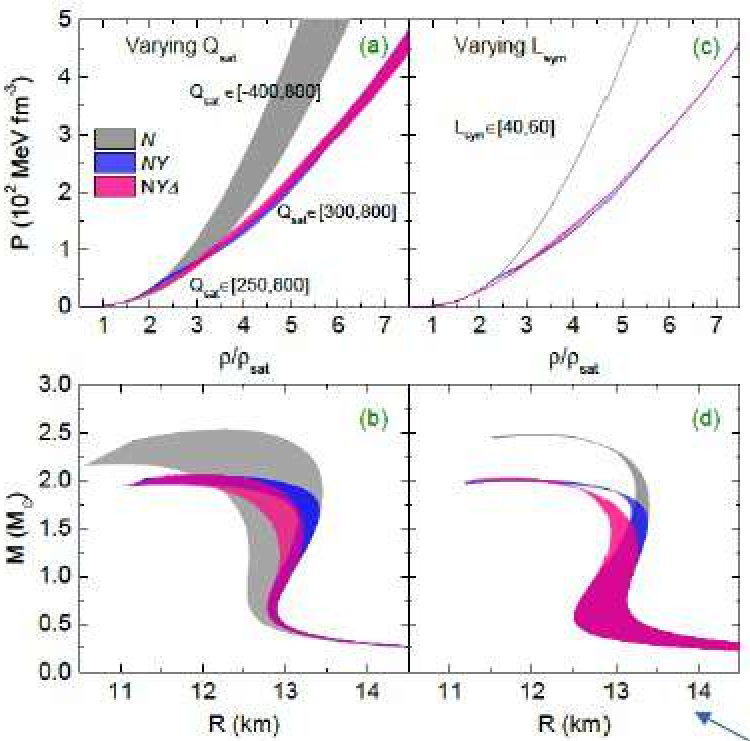


FIG. 4. EoS models and MR relations for N, NY, and $NY\Delta$ compositions of stellar matter. The bands are generated by varying the parameters Q_{sat} [MeV] (a, b) and L_{sym} [MeV] (c, d). The ranges of Q_{sat} and L_{sym} allowed by χEFT and maximum mass constraints are indicated in the figures.

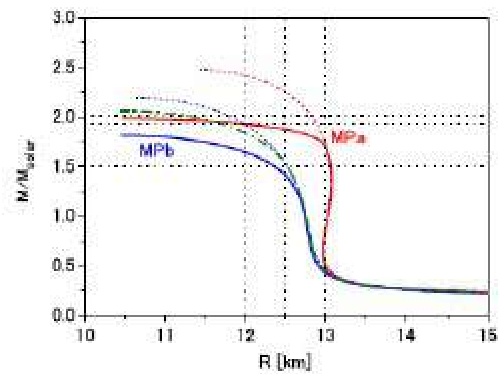


FIG. 7. Neutron-star masses as a function of the radius R. Solid (dashed) curves are with (without) hyperon (Λ and Σ^-) mixing for ESC+MPa and ESC+MPb. The dot-dashed curve for MPb is with Λ mixing only. Also see the caption of Fig. 3.

Yamamoto et al., Phys.Rev.C 96 (2017) 06580; arXiv:1708.06163 [nucl-th]

Yamamoto et al., Eur. Phys. J. A 52 (2016) 19; arXiv:1510.06099 [nucl-th]

Ji & Sedrakian, Phys. Rev. C 100 (2019) 015809; arXiv:1903.06057 [astro-ph.HE]

Examples for realistic hadronic EoS which suggest a Berlin Wall is inferior to the line M = 2.0 M_sun

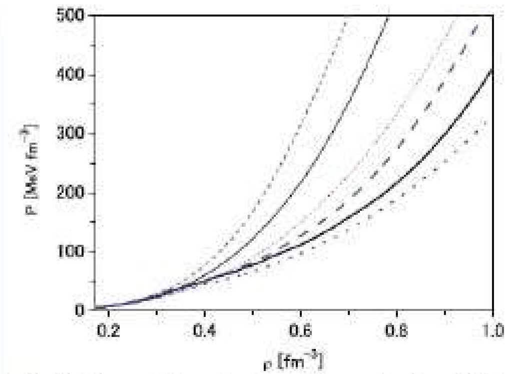


Fig. 8. Pressure P as a function of baryon density ρ. Thick (thin) curves are with (without) hyperon mixing. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb.

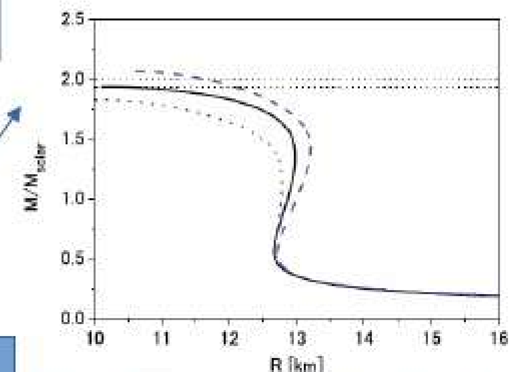
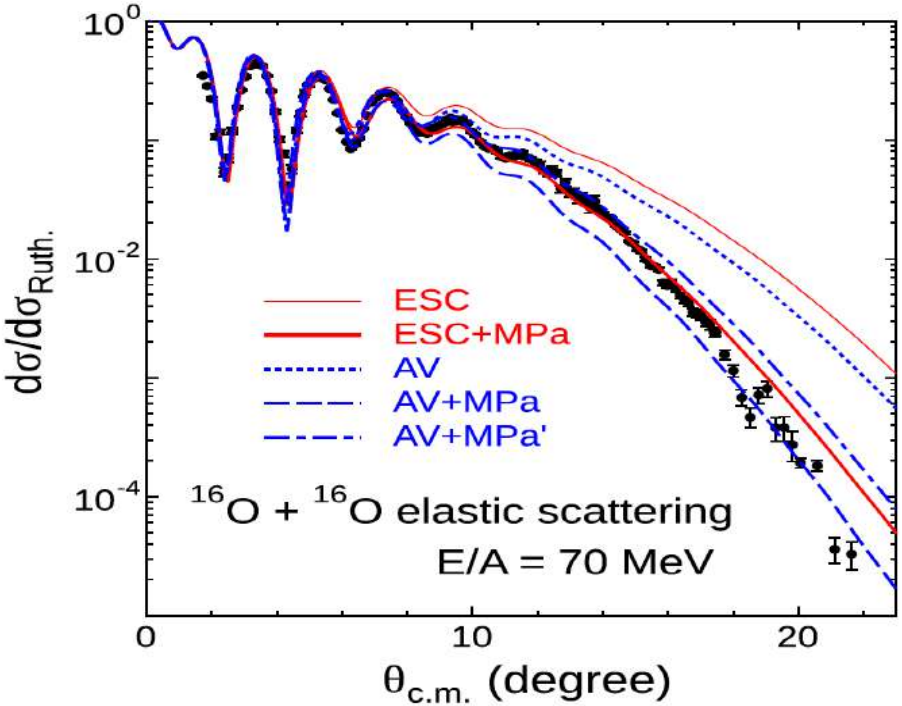


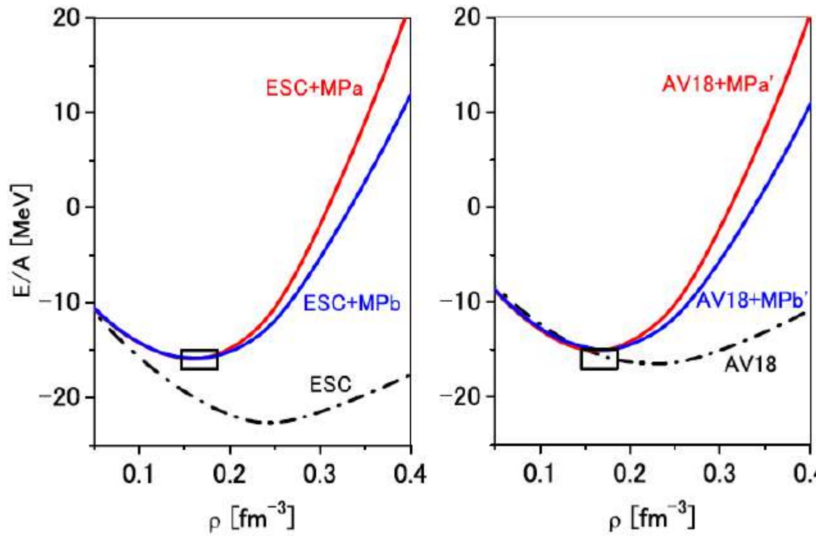
Fig. 9. Neutron-star masses as a function of the radius R. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb. Two dotted lines show the observed mass $(1.97 \pm 0.04)M_\odot$ of J1614-2230.

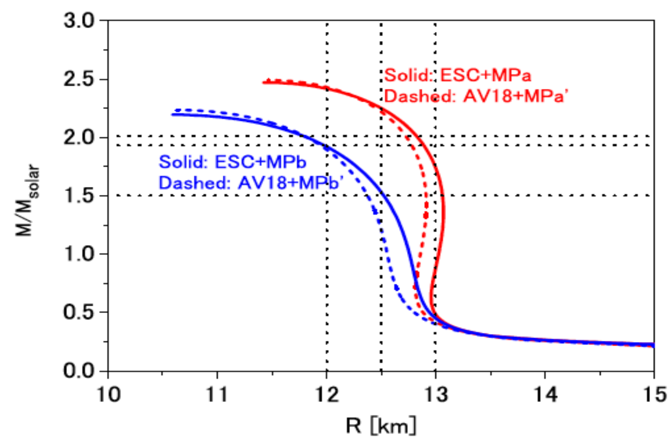
“Berlin wall” constraint for neutron stars

Realistic hadronic EOS (with strange baryons)

Y. Yamamoto, H. Togashi, T. Tamagawa, T. Furumoto, N. Yasutake, T. Rijken, PRC 96 (2017)



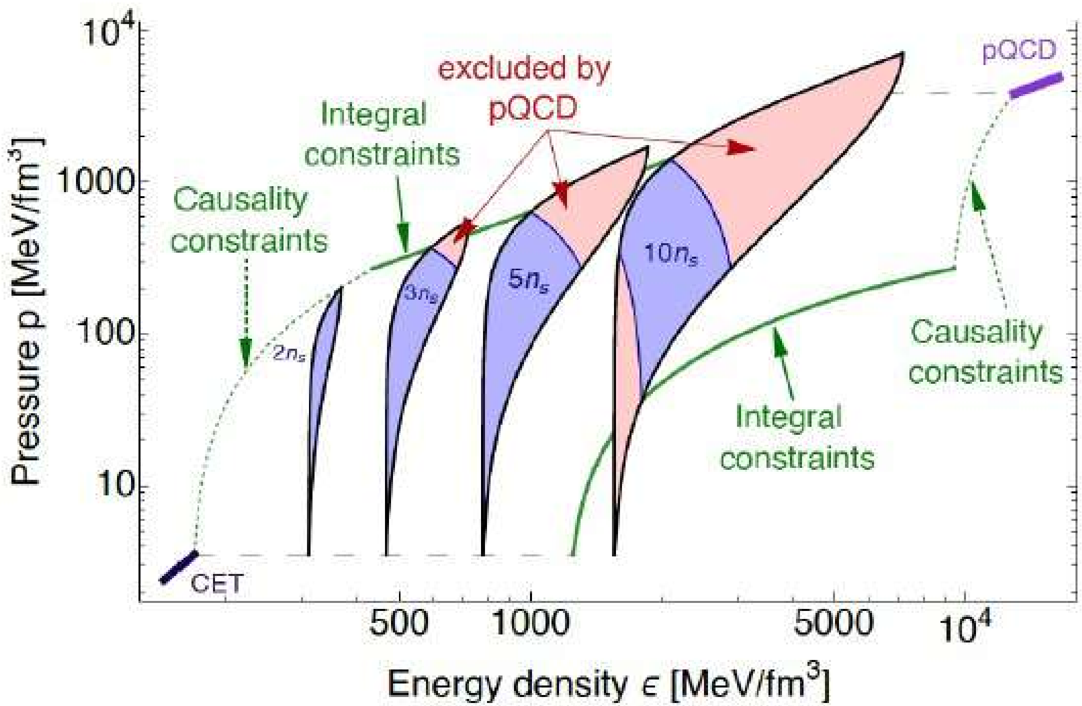




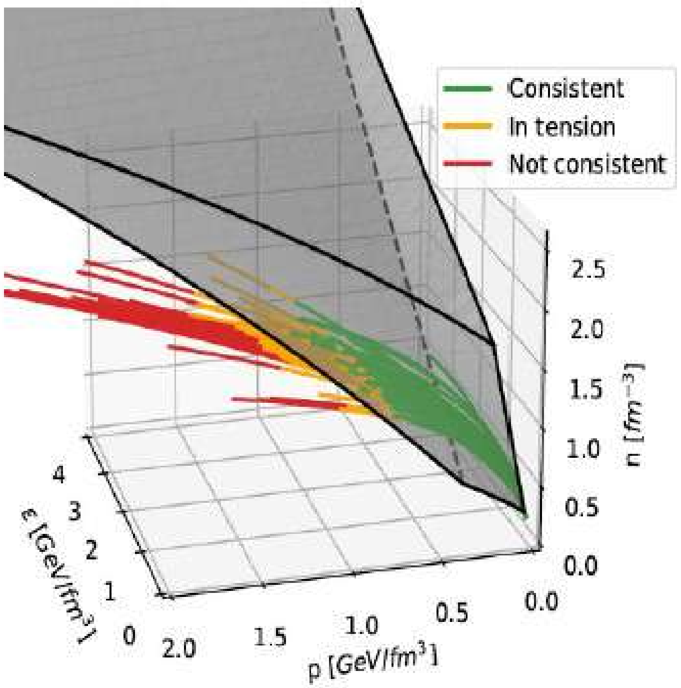
Short-range multi-pomeron exchange potential (MPP) added to AV18 potential gives significant improvement of large-angle scattering cross section (s.a.) and the Nuclear saturation properties, when compared to APR.
→ Neutron star radii R(M< 2 M_sun) > 12 km !!

Pro and con quark matter in neutron stars

Neutron star EoS constraint from pQCD



Consistency check for neutron star EoS from the CompOSE library

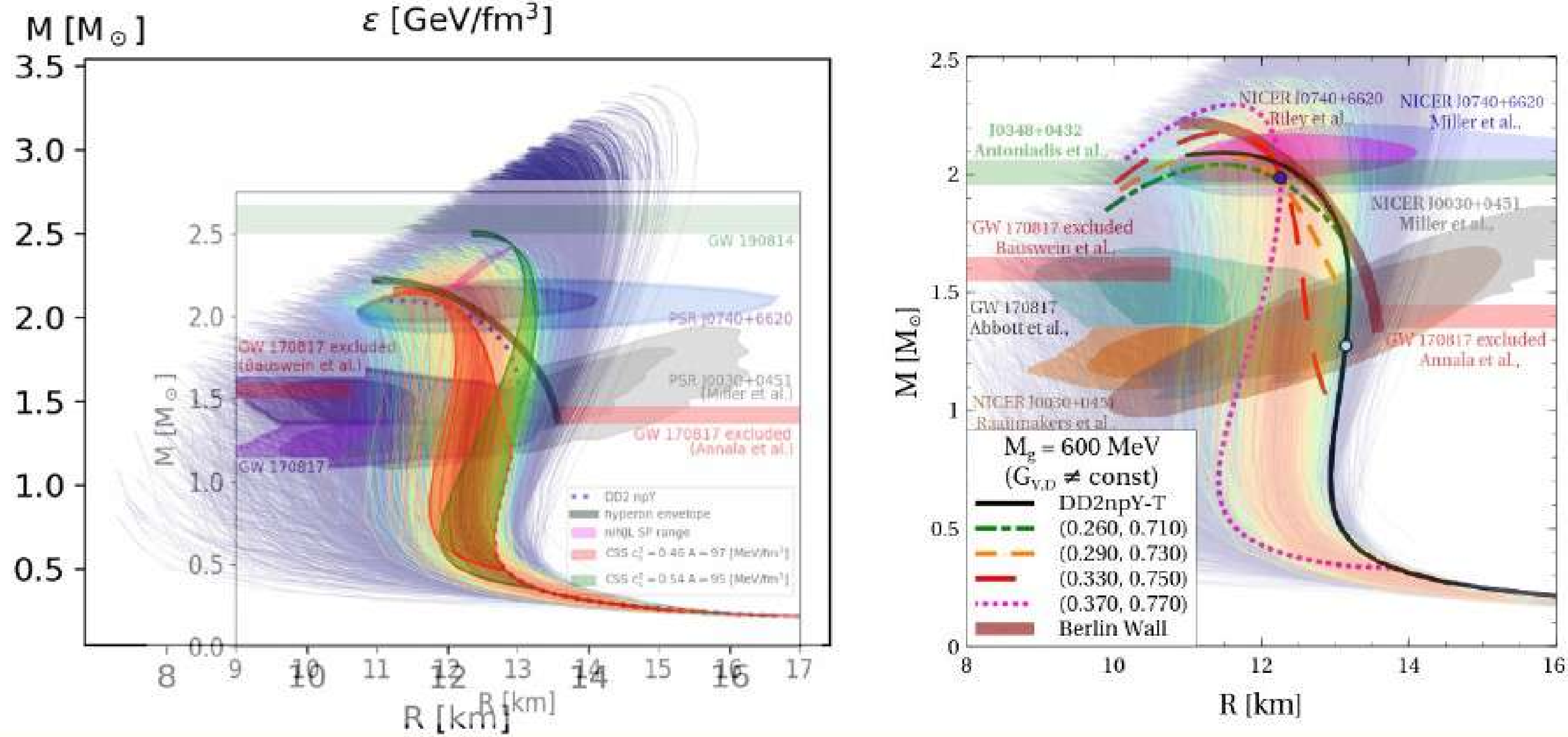


O. Komoltsev and A. Kurkela, Phys. Rev. D 128 (2022) 202701

Breaking the “Berlin wall” constraint

With Bayesian analyses and hybrid EOS

M(R) curves generated by causality, thermodynamic stability and pQCD limit



The conjectured “Berlin Wall” overlaid to the Fig. 2 from Gorda, Komoltsev & Kurkela [2204.11877 [nucl-th]] and hybrid EoS with quark matter described by a CSS model (left) and a confining relativistic density functional (right).

CompStar in Catania 2011

Relativistic density functionals for QCD

String-flip model for quark matter confinement

Röpke, Blaschke, Schulz, PRD34 (1986) 3499

$$\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{ \int_0^\beta d\tau \int_V d^3x \left[\mathcal{L}_{\rm eff} + \bar{q}\gamma_0\hat{\mu}q\right] \right\}, \quad q = \begin{pmatrix} q_u \\ q_d \end{pmatrix}, \quad \hat{\mu} = {\rm diag}(\mu_u, \mu_d)$$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm free} - \boxed{U(\bar{q}q, \bar{q}\gamma_0 q)}, \quad \mathcal{L}_{\rm free} = \bar{q}\left(-\gamma_0\frac{\partial}{\partial\tau} + i\vec{\gamma}\cdot\vec{\nabla} - \hat{m}\right)q\,, \quad \hat{m} = {\rm diag}(m_u, m_d)$$

General nonlinear functional of quark density bilinears: scalar, vector, isovector, diquark ...
Expansion around the expectation values:

$$U(\bar{q}q,\, \bar{q}\gamma_0 q) = U(n_{\rm s}, n_{\rm v}) + (\bar{q}q - n_{\rm s})\Sigma_{\rm s} + (\bar{q}\gamma_0 q - n_{\rm v})\Sigma_{\rm v} + \dots\,,$$

$$\langle\bar{q}q\rangle = n_{\rm s} = \sum_{f=u,d} n_{{\rm s},f} = -\sum_{f=u,d}\frac{T}{V}\frac{\partial}{\partial m_f}\ln\mathcal{Z}\,, \quad \Sigma_{\rm s} = \left.\frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial(\bar{q}q)}\right|_{\bar{q}q=n_{\rm s}} = \frac{\partial U(n_{\rm s}, n_{\rm v})}{\partial n_{\rm s}}\,,$$

$$\langle\bar{q}\gamma_0 q\rangle = n_{\rm v} = \sum_{f=u,d} n_{{\rm v},f} = \sum_{f=u,d}\frac{T}{V}\frac{\partial}{\partial\mu_f}\ln\mathcal{Z}\,, \quad \Sigma_{\rm v} = \left.\frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial(\bar{q}\gamma_0 q)}\right|_{\bar{q}\gamma_0 q=n_{\rm v}} = \frac{\partial U(n_{\rm s}, n_{\rm v})}{\partial n_{\rm v}}$$

$$\boxed{\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\mathcal{S}_{\rm quasi}[\bar{q}, q] - \beta V\,\Theta[n_{\rm s}, n_{\rm v}]\right\}, \quad \Theta[n_{\rm s}, n_{\rm v}] = U(n_{\rm s}, n_{\rm v}) - \Sigma_{\rm s} n_{\rm s} - \Sigma_{\rm v} n_{\rm v}}$$

$$\mathcal{S}_{\rm quasi}[\bar{q}, q] = \beta\sum_n\sum_{\vec{p}}\bar{q}\,G^{-1}(\omega_n, \vec{p})\,q\,, \quad G^{-1}(\omega_n, \vec{p}) = \gamma_0(-i\omega_n + \hat{\mu}^*) - \vec{\gamma}\cdot\vec{p} - \hat{m}^*$$

Relativistic density functionals for QCD

$$\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\{\mathcal{S}_{\rm quasi}[\bar{q},q] - \beta V \Theta[n_{\rm s},n_{\rm v}]\}\ , \quad \Theta[n_{\rm s},n_{\rm v}] = U(n_{\rm s},n_{\rm v}) - \Sigma_{\rm s} n_{\rm s} - \Sigma_{\rm v} n_{\rm v}$$

$$\mathcal{Z}_{\rm quasi} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\{\mathcal{S}_{\rm quasi}[\bar{q},q]\} = \det[\beta G^{-1}]\ , \qquad \ln\det A = {\rm Tr}\ln A$$

$$P_{\rm quasi} = \frac{T}{V}\ln \mathcal{Z}_{\rm quasi} = \frac{T}{V}{\rm Tr}\ln[\beta G^{-1}]$$

"no sea" approximation ...

$$= 2N_c \sum_{f=u,d} \int \frac{d^3p}{(2\pi)^3}\left\{T\ln\left[1+{\rm e}^{-\beta(E_f^*-\mu_f^*)}\right] + T\ln\left[1+{\rm e}^{-\beta(E_f^*+\mu_f^*)}\right]\right\}$$

$$P_{\rm quasi} = \sum_{f=u,d}\int \frac{dp}{\pi^2}\frac{p^4}{E_f^*}\left[f(E_f^*-\mu_f^*) + f(E_f^*+\mu_f^*)\right]$$

$$E_f^* = \sqrt{p^2 + {m_f^*}^2}$$

$$f(E) = 1/[1+\exp(\beta E)]$$

$$P = \sum_{f=u,d}\int_0^{p_{{\rm F},f}} \frac{dp}{\pi^2}\frac{p^4}{E_f^*} - \Theta[n_{\rm s},n_{\rm v}]\ , \quad p_{{\rm F},f} = \sqrt{{\mu_f^*}^2 - {m_f^*}^2}$$

$$\hat{m}^* = \hat{m} + \Sigma_{\rm s}$$
$$\hat{\mu}^* = \hat{\mu} - \Sigma_{\rm v}$$

Selfconsistent densities

$$n_{\rm s} = -\sum_{f=u,d}\frac{\partial P}{\partial m_f} = \frac{3}{\pi^2}\sum_{f=u,d}\int_0^{p_{{\rm F},f}} dp p^2 \frac{m_f^*}{E_f^*}\ , \quad n_{\rm v} = \sum_{f=u,d}\frac{\partial P}{\partial \mu_f} = \frac{3}{\pi^2}\sum_{f=u,d}\int_0^{p_{{\rm F},f}} dp p^2 = \frac{p_{{\rm F},u}^3 + p_{{\rm F},d}^3}{\pi^2}\ .$$

Relativistic density functionals for QCD

String-flip model for quark matter

Density functional for the SFM

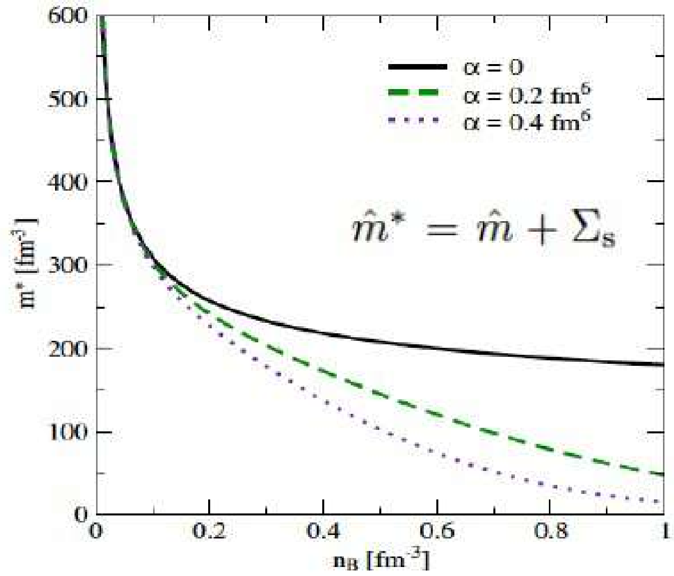
$$U(n_s, n_v) = D(n_v) n_s^{2/3} + a n_v^2 + \frac{b n_v^4}{1 + c n_v^2} ,$$

Quark selfenergies

$$\Sigma_s = \frac{2}{3} D(n_v) n_s^{-1/3} ,$$

Quark "confinement"

$$\Sigma_v = 2 a n_v + \frac{4 b n_v^3}{1 + c n_v^2} - \frac{2 b c n_v^5}{(1 + c n_v^2)^2} + \frac{\partial D(n_v)}{\partial n_v} n_s^{2/3}$$

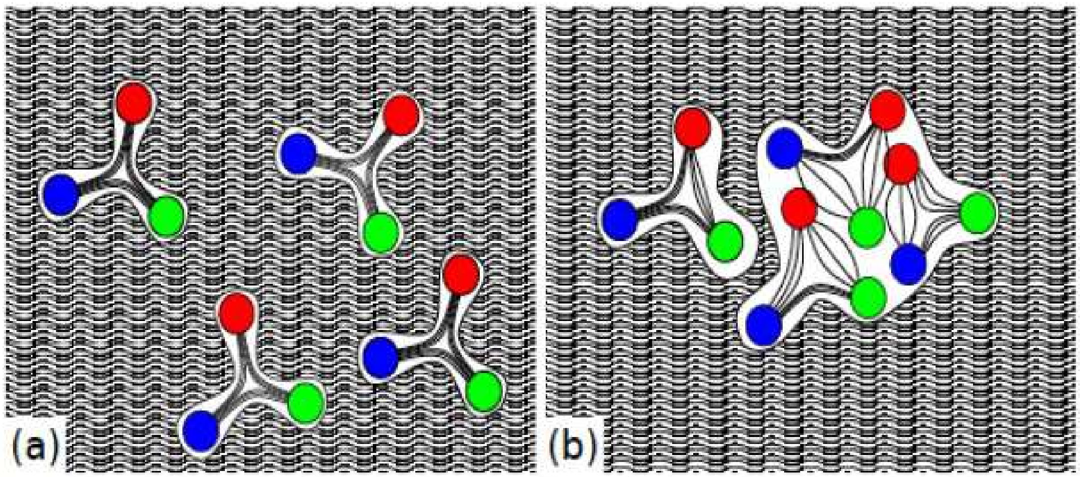


String tension & confinement due to dual Meissner effect (dual superconductor model)

$$D(n_v) = D_0 \Phi(n_v)$$

Effective screening of the string tension in dense matter by a reduction of the available volume $\alpha = v|v|/2$

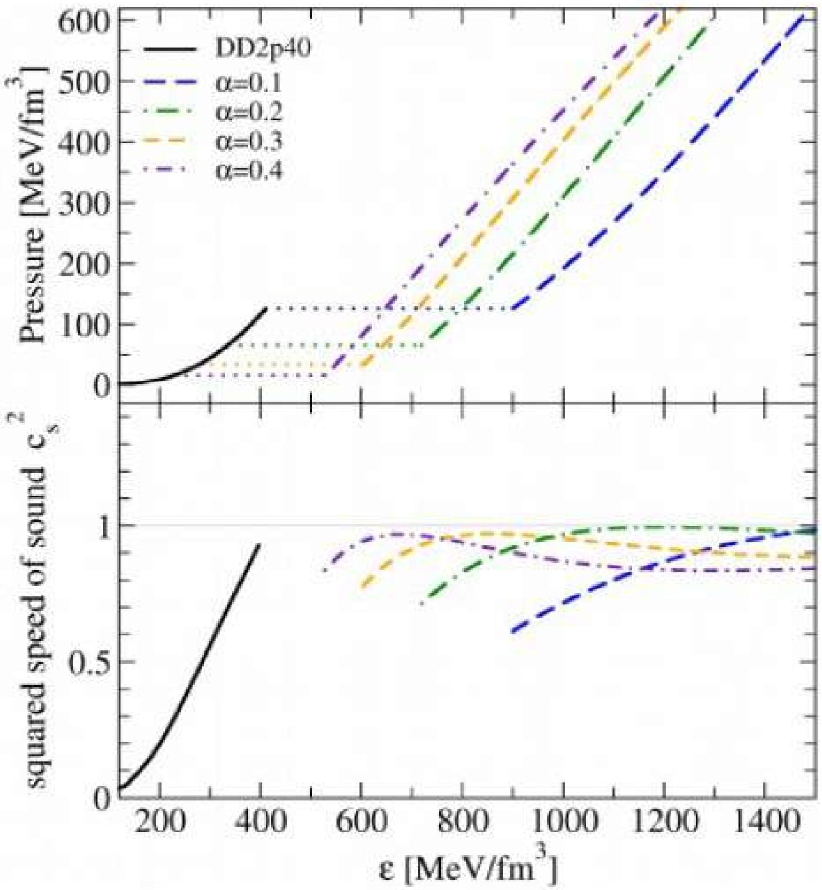
$$\Phi(n_B) = \begin{cases} 1, & \text{if } n_B < n_0 \\ e^{-\alpha(n_B - n_0)^2}, & \text{if } n_B > n_0 \end{cases}$$

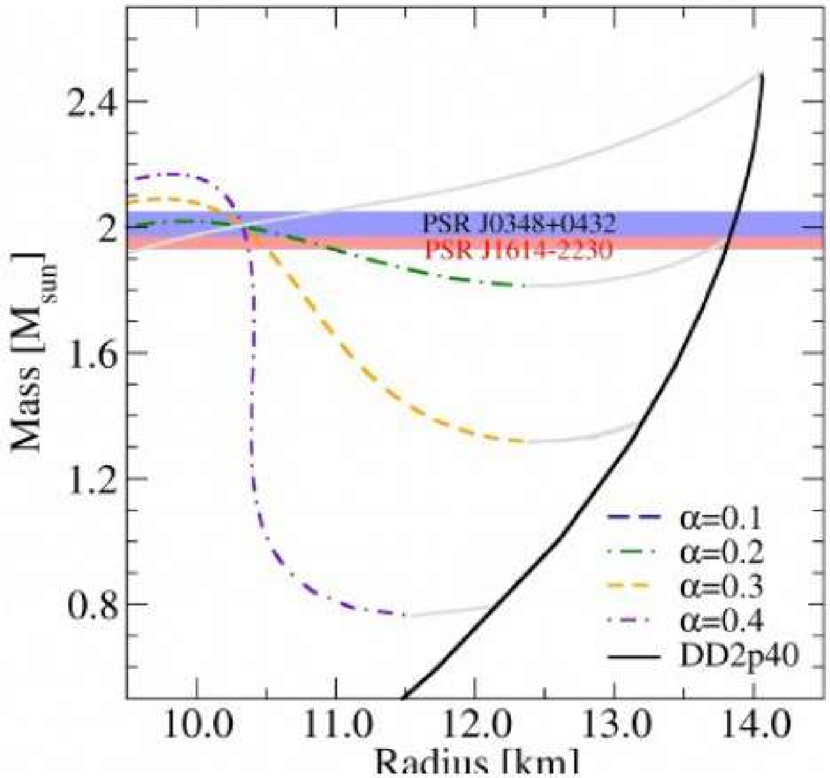


Relativistic density functionals for QCD

String-flip model for quark matter

Results for 1st order phase transition by Maxwell construction with DD2p40





Kaltenborn, Bastian, Blaschke, arXiv:1701.04400 ⟶ Phys. Rev. D 96, 056024 (2017)

Nonlocal chiral quark model - generalized

$$S_E = \int d^4x \left\{ \bar\psi(x)\left(-i\partial\!\!\!/ + m_c\right)\psi(x) - \frac{G_S}{2} j_S^f(x) j_S^f(x) - \frac{H}{2}\left[j_D^a(x)\right]^\dagger j_D^a(x) - \frac{G_V}{2} j_V^\mu(x)\, j_V^\mu(x) \right\}$$

$$j_S^f(x) = \int d^4z\; g(z)\; \bar\psi(x+\frac{z}{2})\;\Gamma_f\,\psi(x-\frac{z}{2}),$$

$$j_D^a(x) = \int d^4z\; g(z)\; \bar\psi_C(x+\frac{z}{2})\;\Gamma_D\;\psi(x-\frac{z}{2})$$

$$j_V^\mu(x) = \int d^4z\; g(z)\; \bar\psi(x+\frac{z}{2})\; i\gamma^\mu\;\psi(x-\frac{z}{2}).$$

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

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

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

D.B., D. Gomez-Dumm, A.G. Grunfeld, T. Klaehn, N.N. Scoccola, “Hybrid stars within a covariant, nonlocal chiral quark model”, Phys. Rev. C 75, 065804 (2007)

Interpolating between quark phase parametr.

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<u>Twofold interpolation method:</u>

1. to model the unknown density dependence of the confining mechanism by interpolating a bag pressure contribution between zero and a finite value B at low densities in the vicinity of the hadron-to-quark matter transition, and
2. to model a density dependent stiffening of the quark matter EoS at high density by interpolating between EoS for two values of the vector coupling strength, $\eta_<$ and $\eta_>$.

$$P(\mu) = [f_<(\mu)(P(\mu;\eta_<) - B) + f_>(\mu)P(\mu;\eta_<)]f_\ll(\mu) + f_\gg(\mu)P(\mu;\eta_>)$$

$$f_<(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu - \mu_<}{\Gamma_<}\right)\right], \quad f_\ll(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu - \mu_\ll}{\Gamma_\ll}\right)\right],$$

$$f_>(\mu) = 1 - f_<(\mu)\ , \quad f_\gg(\mu) = 1 - f_\ll(\mu).$$

D.E. Alvarez-Castillo, D.B., A.G. Grunfeld, V.P. Pagura, Phys. Rev. D99, 063010 (2019); [arxiv:1805.04105v3]

Interpolation vs. momentum dependent coeff.

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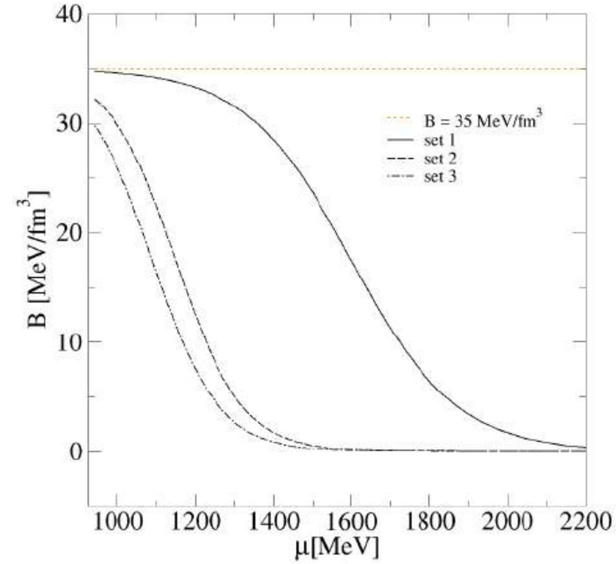
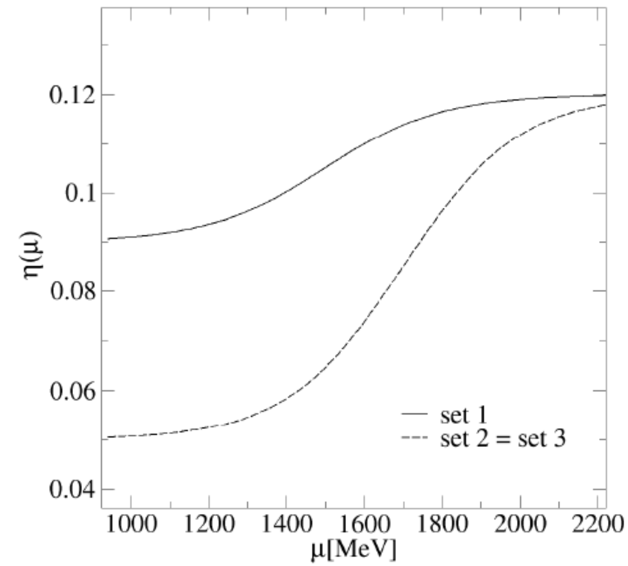
$$\begin{aligned} P(\mu) &= P(\mu;\eta,B)f_<(\mu) + P(\mu;\eta,0)f_>(\mu) \\ &= P(\mu;\eta,0)[f_<(\mu)+f_>(\mu)] - Bf_<(\mu) \\ &= P(\mu;\eta,B(\mu)), \end{aligned}$$

$B(\mu) = Bf_<(\mu)$ is the μ−dependent bag pressure

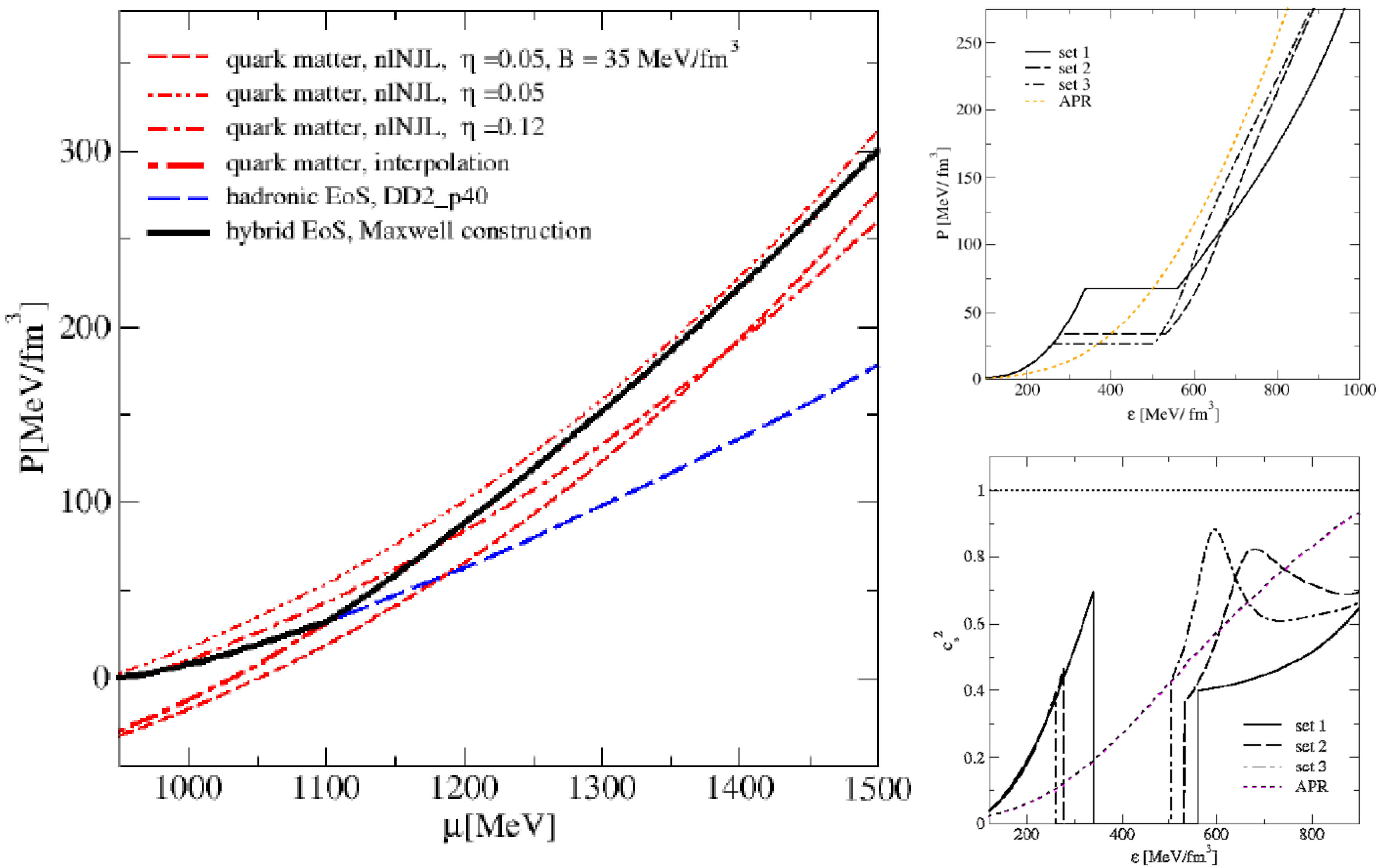
$$\begin{aligned} P(\mu) &= P(\mu;\eta_<,B)f_\ll(\mu) + P(\mu;\eta_>,B)f_\gg(\mu) \\ &= P(\mu;\eta_<,B)[f_\ll(\mu)+f_\gg(\mu)] \\ &\quad +(\eta_> - \eta_<)f_\gg(\mu)\frac{dP(\mu;\eta,B)}{d\eta}\bigg|_{\eta=\eta_<} \\ &= P(\mu;\eta_<,B) \\ &\quad +[\eta_> f_\gg(\mu) + \eta_< f_\ll(\mu) - \eta_<]\frac{dP(\mu;\eta,B)}{d\eta}\bigg|_{\eta=} \\ &= P(\mu;\eta(\mu),B)\ , \end{aligned}$$

$\eta(\mu) = \eta_> f_\gg(\mu) + \eta_< f_\ll(\mu)$ is the medium-dependent vector meson coupling





Maxwell construction between Q and H phases



Maxwell construction between Q and H phases

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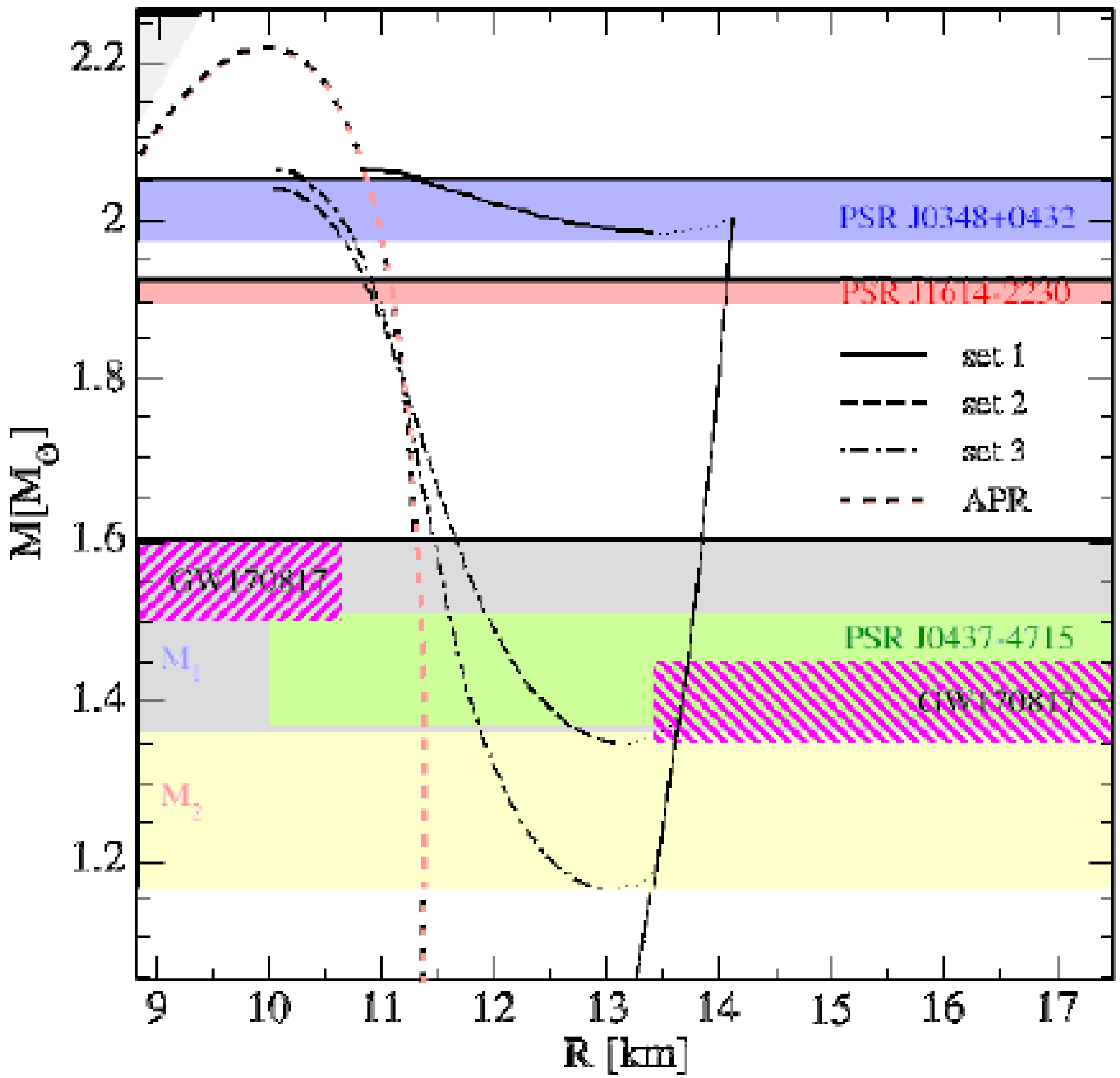
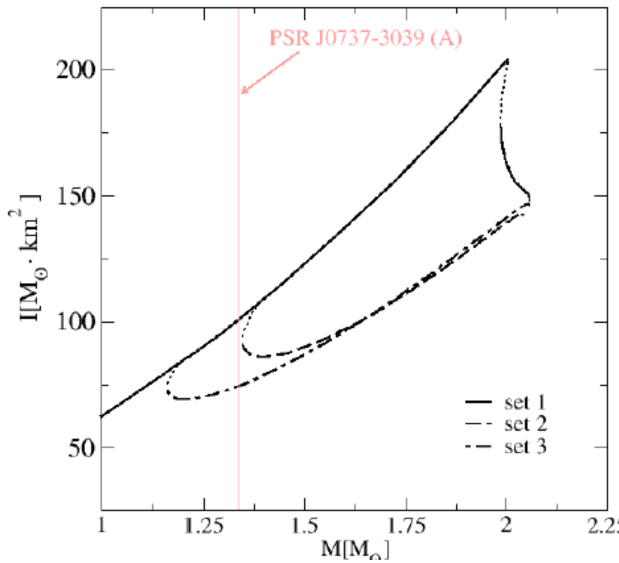
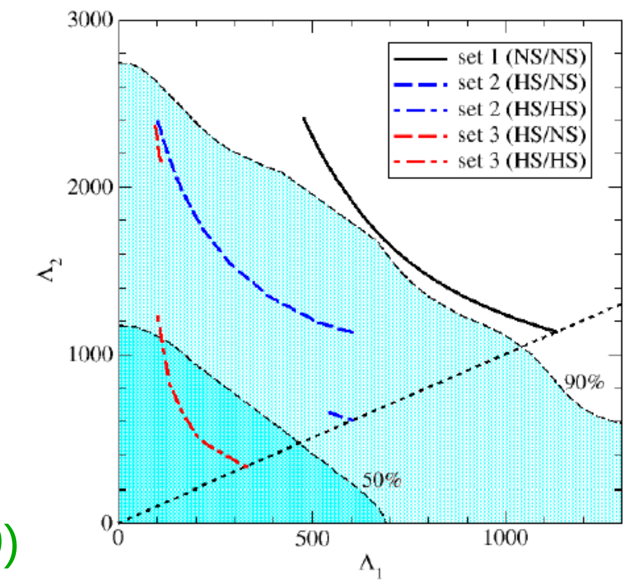






D.E. Alvarez-Castillo et al., Phys. Rev. D99, 063010 (2019)

NewCompStar Conference in Warsaw

Dinner table with Pawel Haensel and Pierre Pizzochero

Hyperon puzzle: Update due to 2M⊙ constraint

New hadronic EoS: Lowest order constraint variational (LOCV) approach with hyperons (analogous to the well-known APR EoS):
Impose normalization condition by demanding vanishing of the control parameter χ ,

$$\chi = \langle \Psi | \Psi \rangle - 1 = \frac{1}{A} \sum_{ij} \langle ij | F_p^2 - f^2 | ij - ji \rangle = 0, \quad (1)$$

where F_p is the Pauli function. For asymmetric nuclear matter, it is defined by

$$F_p(r) = \begin{cases} [1 - \frac{9}{2}(\frac{J_1(k_{f_i} r)}{k_{f_i} r})^2]^{-\frac{1}{2}} & \text{indistinguishable particles,} \\ 1 & \text{distinguishable particles,} \end{cases}$$

where $J_1(k_{f_i} r)$ denotes the spherical Bessel function of order 1 and k_{f_i} is the Fermi momentum of each particle. The wave function of the system then reads

$$\Psi(1...A) = F(1...A)\Phi(1...A), \quad (2)$$

where $\Phi(1...A)$ is the uncorrelated Fermi system wave function (Slater determinant of plane waves) and $F(1...A)$ is the many-body correlation function. In (2), $f(ij)$ denotes to the two-body state-dependent correlation functions. In the Jastrow formalism, the two-body correlation functions $f(ij)$ are defined as

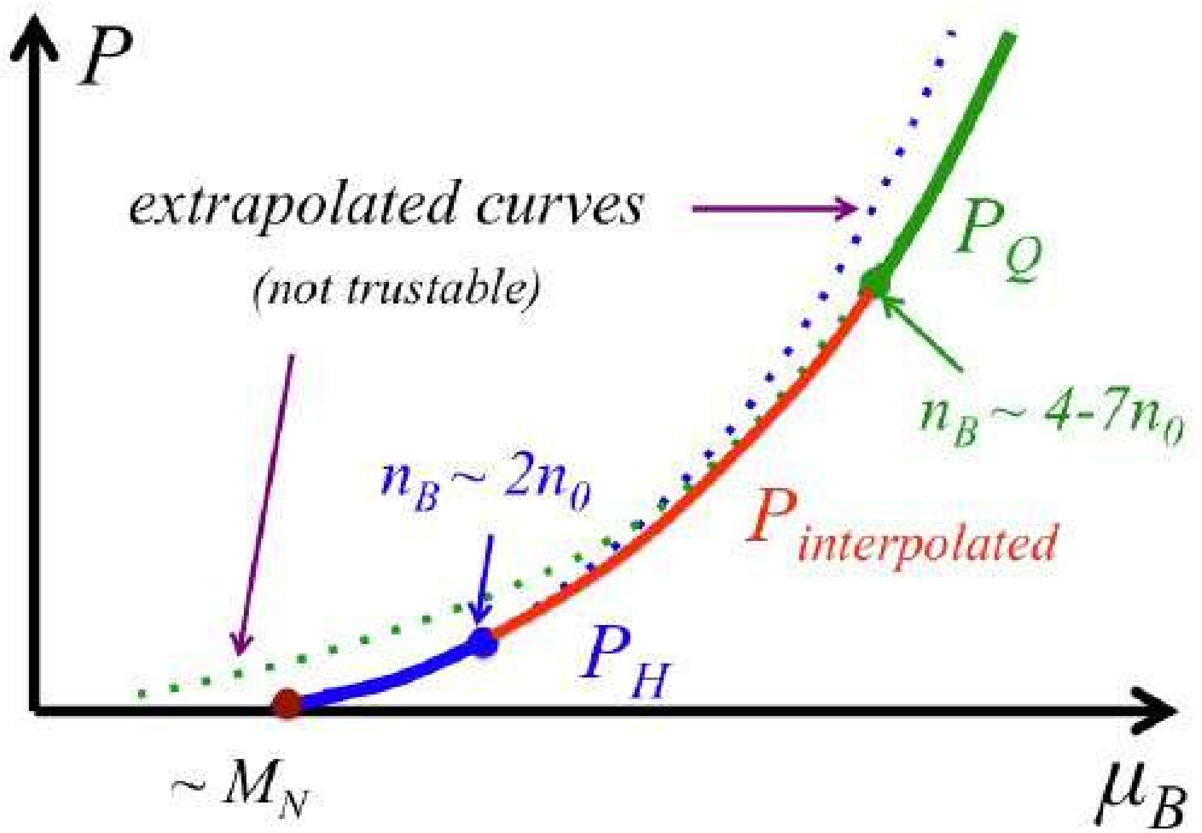
$$f(ij) = \sum_{\alpha,p=1}^{3} f_\alpha^p(ij) O_\alpha^p(ij), \quad (3)$$

where O_α^p is the projection operator which projects on to the α channels, i.e., α =

For details and inclusion of hyperons, see: S. Goudarzi, H.R. Moshfegh, PRC 91 (2015) 054320

Hyperon puzzle: Update due to 2M⊙ constraint

Interpolating between Q and H phases



Note:

Here, a usual Maxwell construction Makes no sense!

Replaced by "Kojo interpolation"

From: T. Kojo, P.D. Powell, Y. Song and G. Baym, PRD 91, 045003 (2015)
See also discussion in: D.B. and N. Chamel, arxiv:1803.01836

Hyperon puzzle: Update due to 2M$_\odot$ constraint

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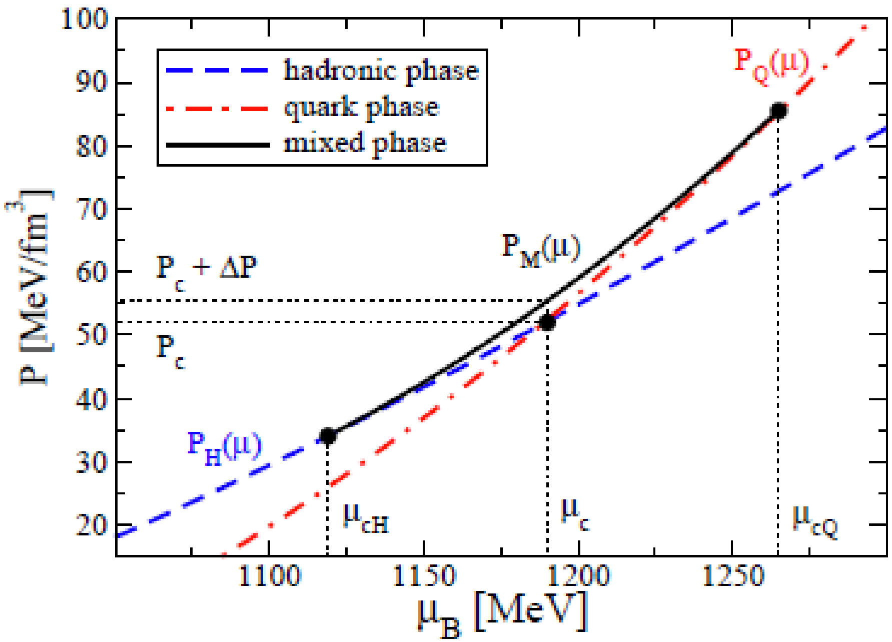
PHYSICAL REVIEW C 97, 045802 (2018)

Robustness of third family solutions for hybrid stars against mixed phase effects

A. Ayriyan,[1,*] N.-U. Bastian,[2,†] D. Blaschke,[2,3,4,‡] H. Grigorian,[1,§] K. Maslov,[3,4,‖] and D. N. Voskresensky[3,4,¶]
[1]Laboratory for Information Technologies, Joint Institute for Nuclear Research, Joliot-Curie Street 6, 141980 Dubna, Russia
[2]Institute of Theoretical Physics, University of Wroclaw, Max Born Place 9, 50-204 Wroclaw, Poland
[3]Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Joliot-Curie Street 6, 141980 Dubna, Russia
[4]National Research Nuclear University (MEPhI), Kashirskoe Shosse 31, 115409 Moscow, Russia



Strong 1st order transition (large density jump)
→ surface tension large → structures (pasta phases)

Simple interpolation ansatz (Ayriyan et al.(2017)):

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

Continuity of pressure: $P_M(\mu_{cH}) = P_H(\mu_{cH}) = P_H$

$$P_M(\mu_{cQ}) = P_Q(\mu_{cQ}) = P_Q,$$

and density: $n_M(\mu_{cH}) = n_H(\mu_{cH})$

$$n_M(\mu_{cQ}) = n_Q(\mu_{cQ})$$

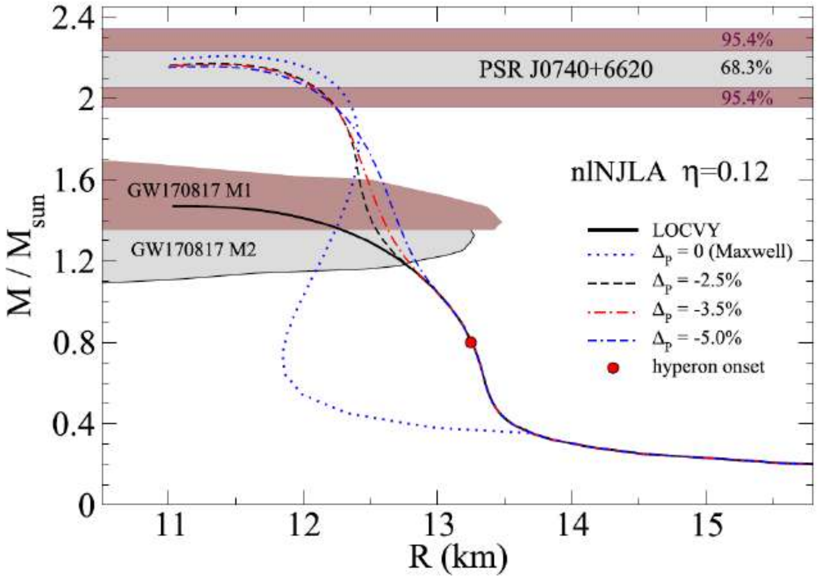
Hyperon puzzle: Update due to 2M⊙ constraint

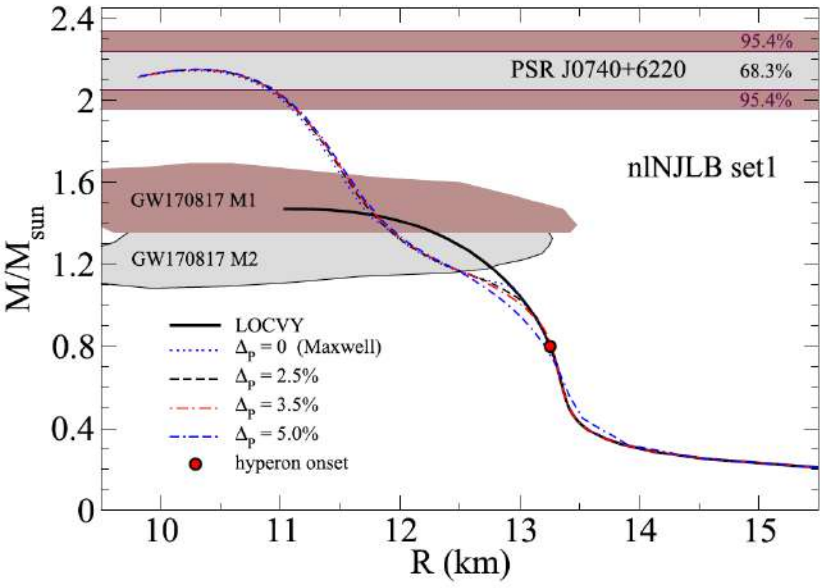
Interpolating between Q and H phases

Direct comparison of the two interpolation schemes
(two alternatives to solve the reconfinement problem)

Model A: $\Delta_p < 0$, $|\Delta_p| > \min(|\Delta_p|)$
The case of unphysical Maxwell construction – Kojo interpolation,
$|\Delta_p| \to 0$ violates stability

Model B: $\Delta_p > 0$
The case of mimicking pasta phases – Grigorian interpolation,
$\Delta_p \to 0$: Maxwell construction





M. Shahrbaf, D.B., S. Khanmohamadi, J. Phys. G 47, 115201 (2020)

ECT* Trento: The first BNS merger GW170817

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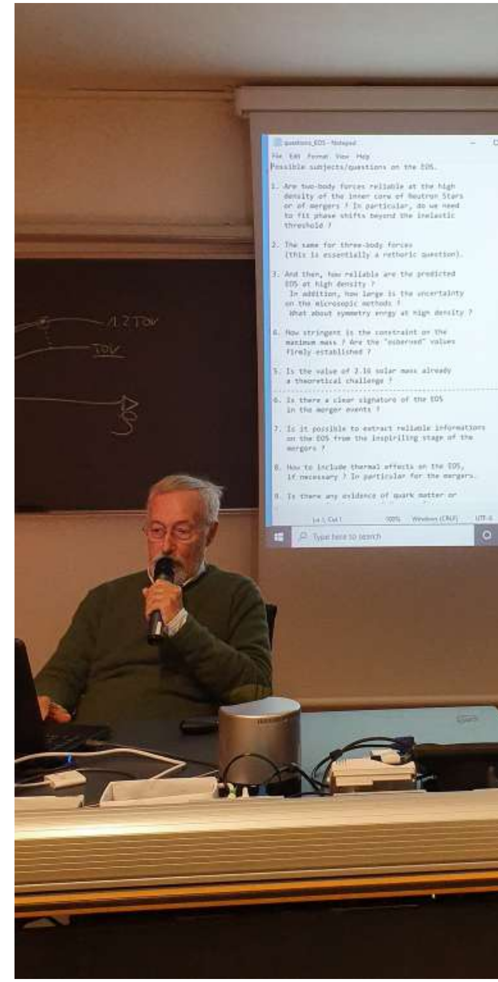
Villa Tambosi, October 2019

ECT* Trento: The first BNS merger GW170817



Villa Tambosi, October 2019

Relativistic density functional for quark matter

What is new?

O. Ivanytskyi & D.B., Phys. Rev. D 105 (2022) 114042

Interaction $\mathcal{U} = D_0 \left[(1+\alpha)\langle\overline{q}q\rangle_0^2 - (\overline{q}q)^2 - (\overline{q}i\vec{\tau}\gamma_5 q)^2\right]^{\varkappa}$

- **Parameters**

  D_0 - dimensionfull coupling, controls interaction strength

  α - dimensionless constant, controls vacuum quark mass

  $\langle\overline{q}q\rangle_0$ - χ-condensate in vacuum (introduced for the sake of convenience)

  $\varkappa = 1/3$ $\Downarrow$ motivated by String Flip model

  $\varkappa = 1$ $\Downarrow$ Nambu–Jona-Lasinio model

  $$\mathcal{U}_{SFM} \propto \langle q^+q\rangle^{2/3}$$

  $$\Sigma_{SFM} = \frac{\partial \mathcal{U}_{SFM}}{\partial\langle q^+q\rangle} \propto \langle q^+q\rangle^{-1/3} \propto separation$$

- **Dimensionality**

  $$[\mathcal{U}] = energy^4, \quad [\overline{q}q] = energy^3 \quad \Rightarrow \quad [D_0]_{\varkappa=1/3} = energy^2 = [string\ \ tension]$$

self energy = string tension × separation $\Rightarrow$ **confinement**

Relativistic density functional for quark matter

Expansion around mean fields

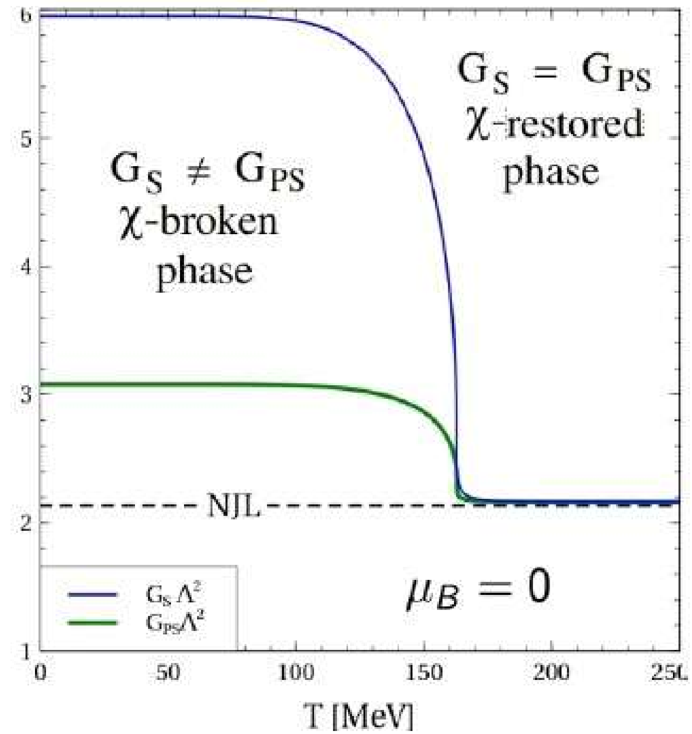
$$\mathcal{U} = \underbrace{\mathcal{U}_{MF}}_{0^{\text{th}}\ \text{order}} + \underbrace{(\overline{q}q - \langle\overline{q}q\rangle)\,\Sigma_S}_{1^{\text{st}}\ \text{order}} - \underbrace{G_S\,(\overline{q}q - \langle\overline{q}q\rangle)^2 - G_{PS}\,(\overline{q}i\vec{\tau}\gamma_5 q)^2}_{2^{\text{nd}}\ \text{order}} + \ldots$$

- **Mean-field scalar self-energy**

$$\Sigma_S = \frac{\partial\mathcal{U}_{MF}}{\partial\langle\overline{q}q\rangle}$$

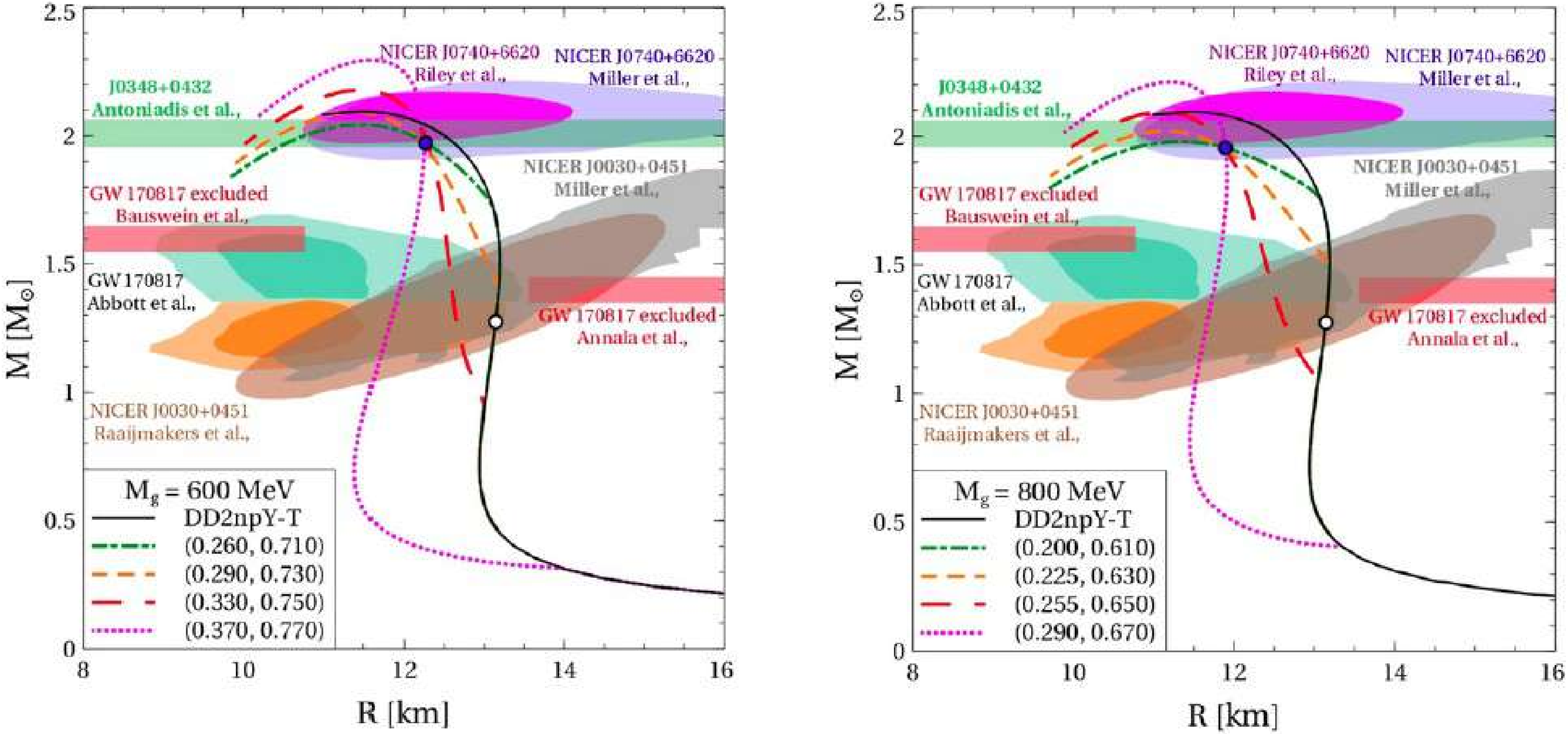
- **Effective medium dependent couplings**

$$G_S = -\frac{1}{2}\frac{\partial^2\mathcal{U}_{MF}}{\partial\langle\overline{q}q\rangle^2}, \quad G_{PS} = -\frac{1}{6}\frac{\partial^2\mathcal{U}_{MF}}{\partial\langle\overline{q}i\vec{\tau}\gamma_5 q\rangle^2}$$



Relativistic density functional for quark matter

Mass-radius diagram for hybrid neutron stars



Observational data prefer early deconfinement?

Relativistic density functional for quark matter

Phase diagram with two-zone interpolation

O. Ivanytskyi & D.B., EPJA 58, 152 (2022)

- **Normal quark matter**

  2 spin × 2 flavor × 3 color =12

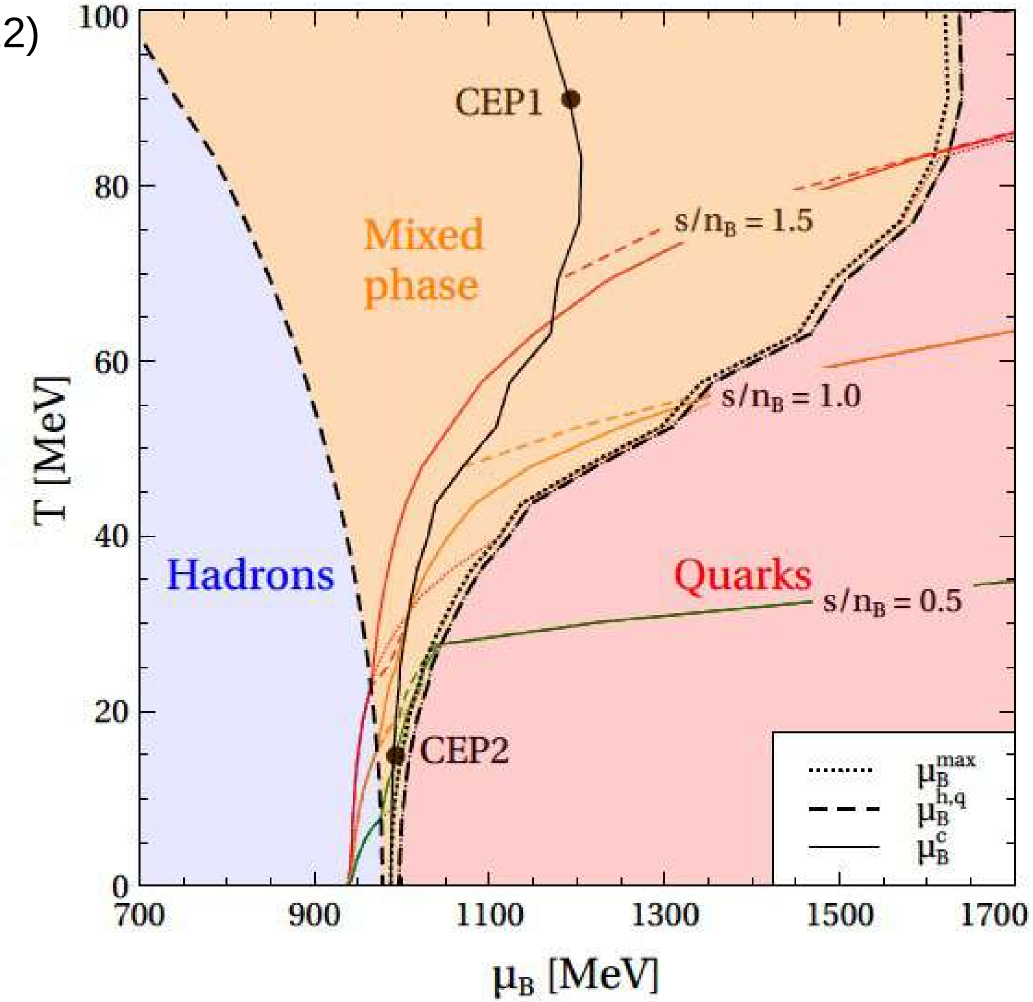
- **2SC quark matter**

  2 spin × 2 flavor × 1 color+1=5

Quark pairing reduces number of quark states

⇓

requires higher T along adiabat



→ **EOS tables are prepared for simulation of supernovae and NS mergers**

QCD Phase Diagram

Landscape of our investigations

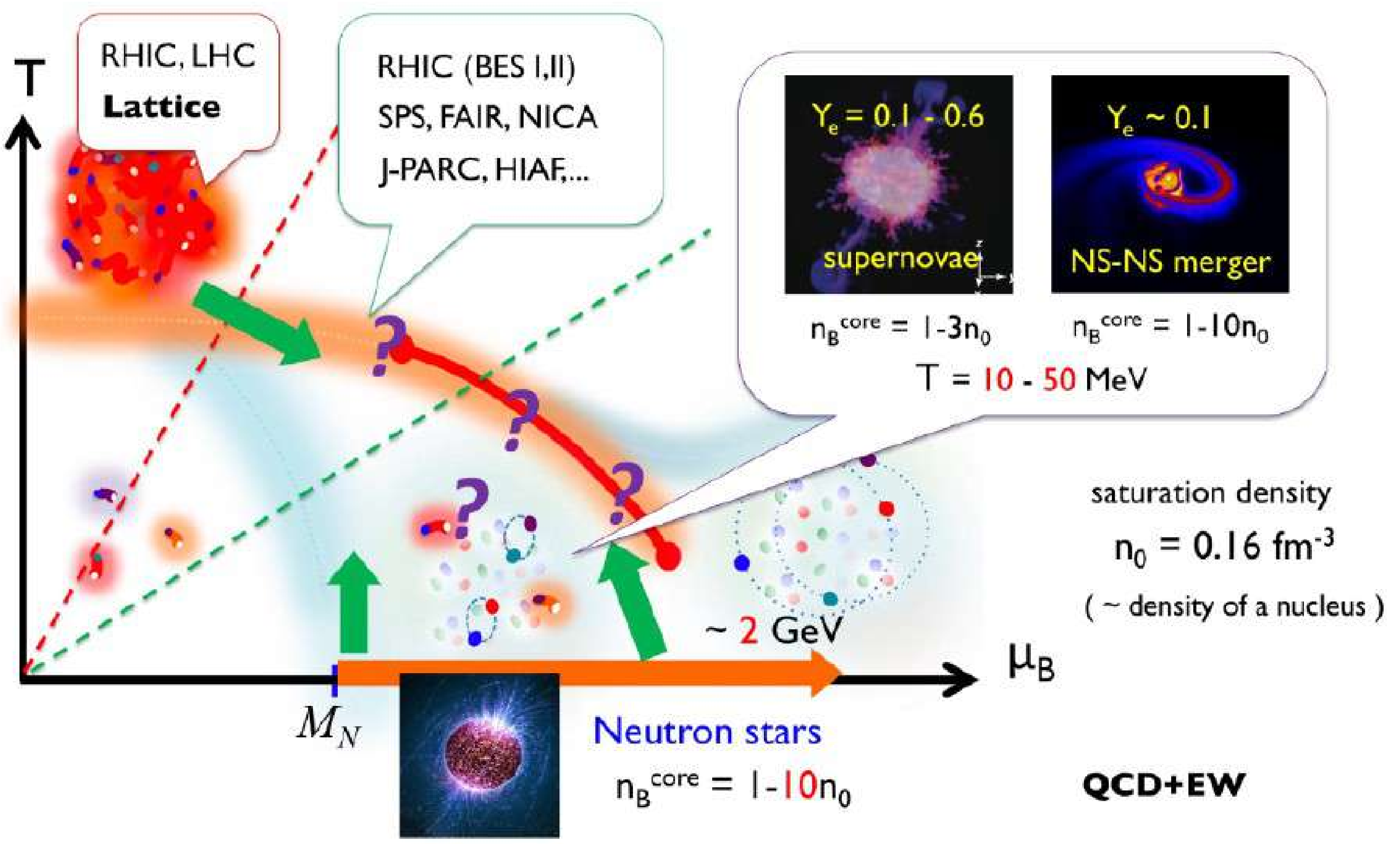
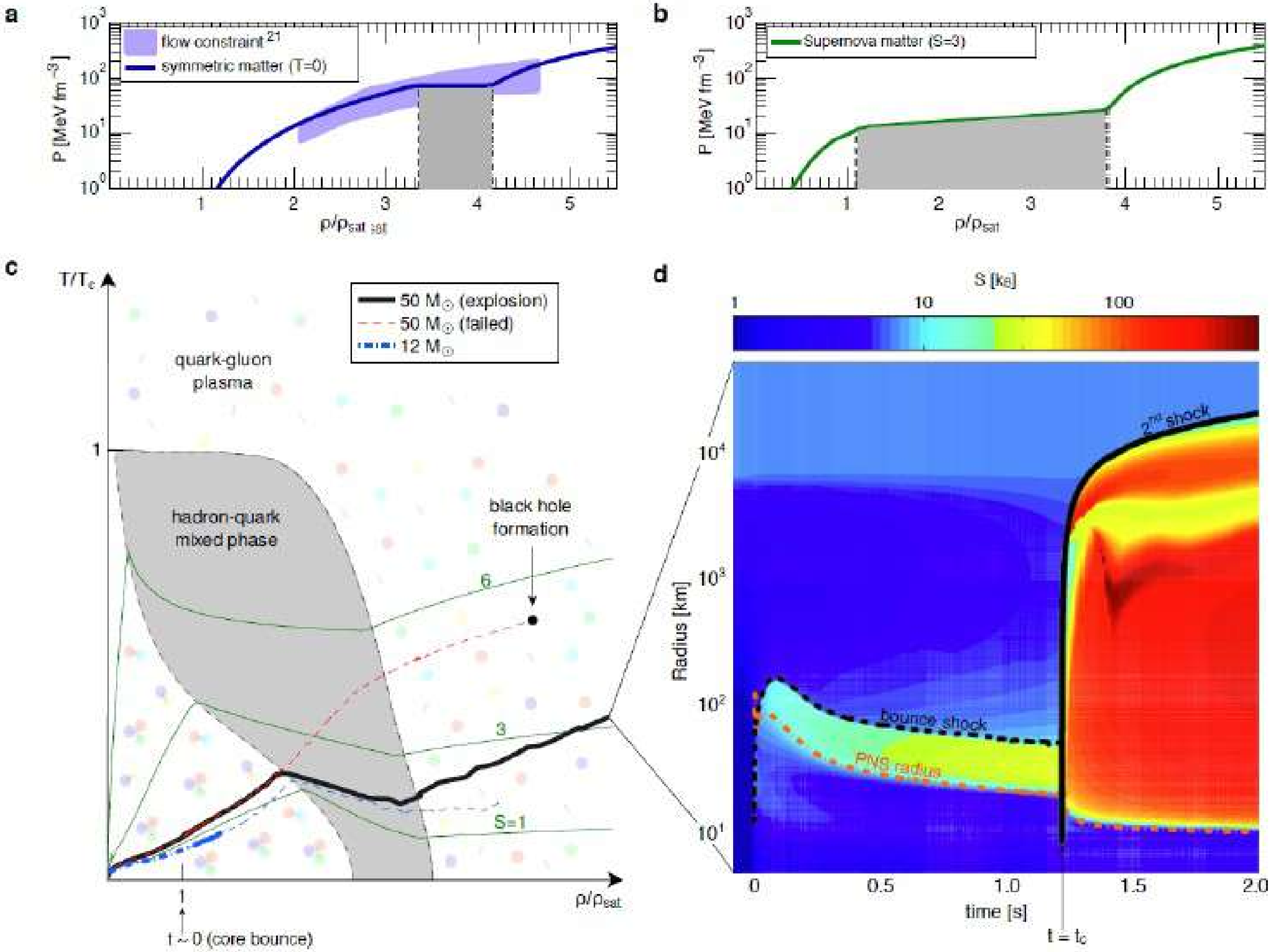


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

Deconfinement as supernova engine

Of massive blue supergiant star explosions



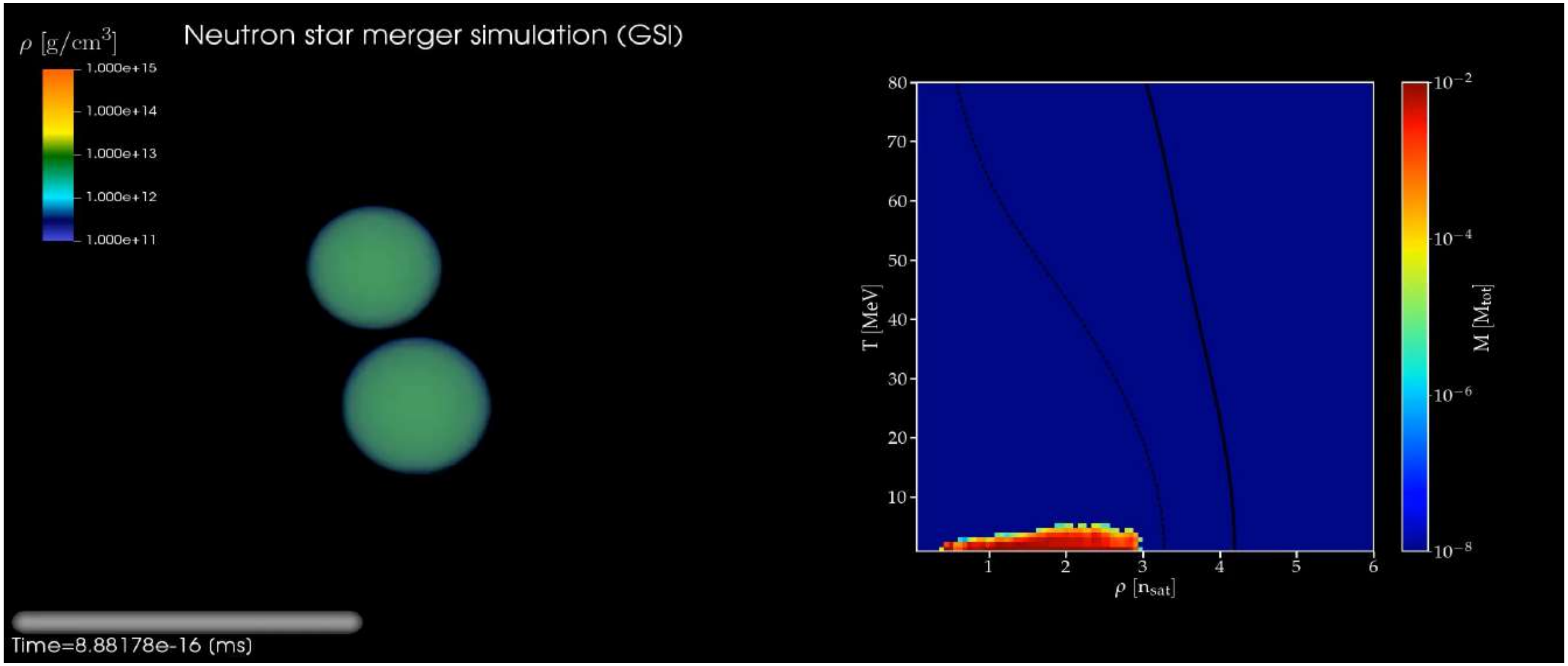
Progenitor:
M = 50 M_O

T. Fischer et al., Nature Astronomy 2, 960 (2018)

Ultra-heavy Nucleus-Nucleus Collisions !

Binary neutron star merger simulation: S. Blacker, A. Bauswein

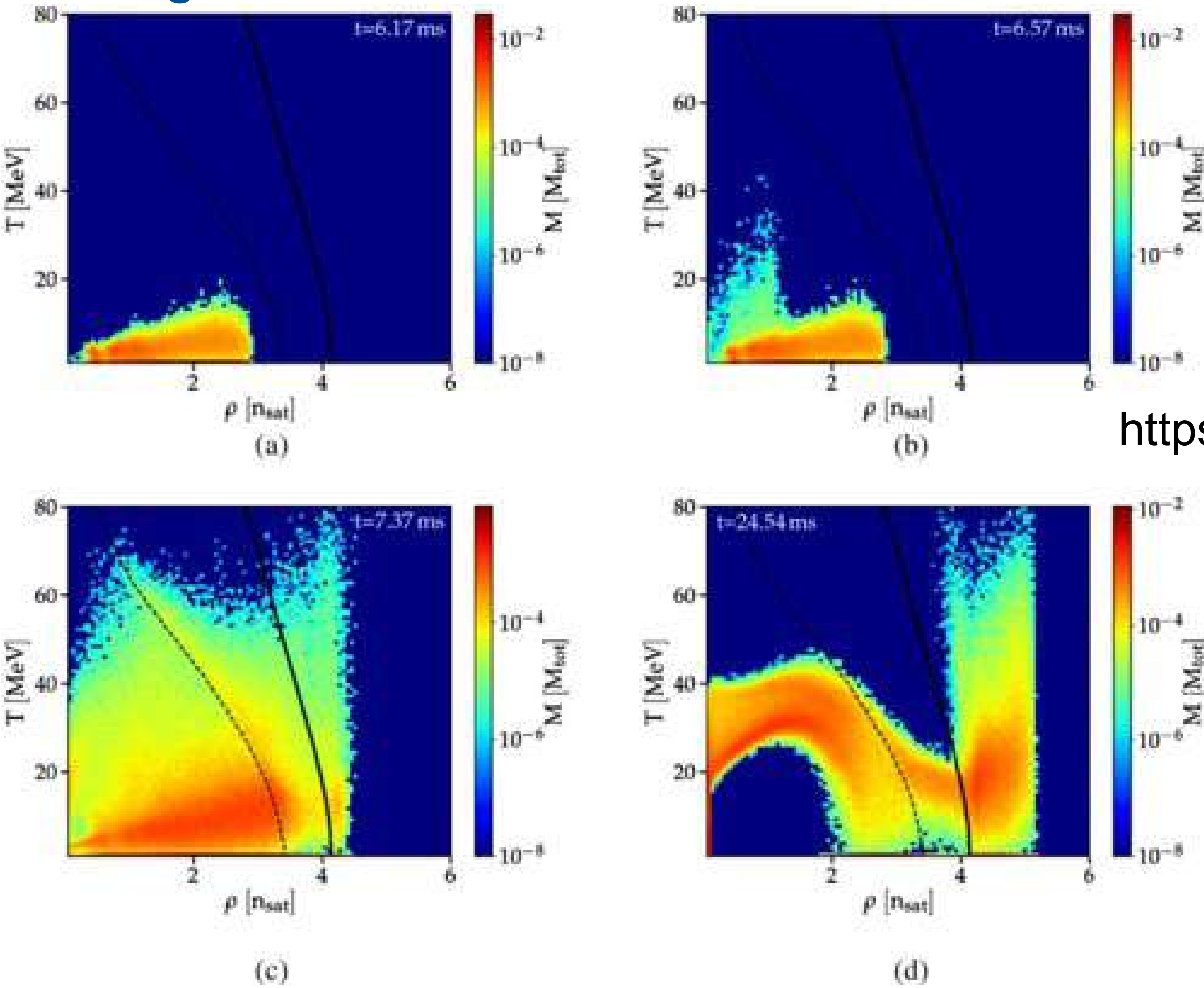
Population of the QCD phase diagram with mixed phase; time = 6 … 25 ms



S. Blacker, A. Bauswein et al., Phys. Rev. D 102 (2020) 123023

Ultra-heavy Nucleus-Nucleus Collisions !

Population of the QCD phase diagram in a merger



1.35 M_sun + 1.35 M_sun

EoS for supernova and merger simulations:

CompOSE

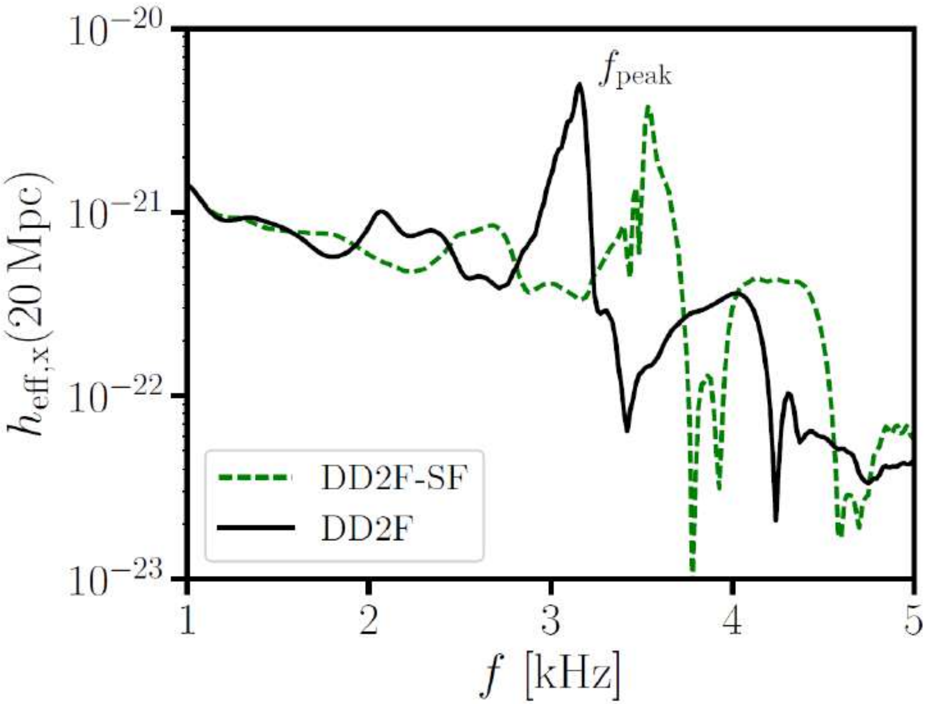
With deconfinement:

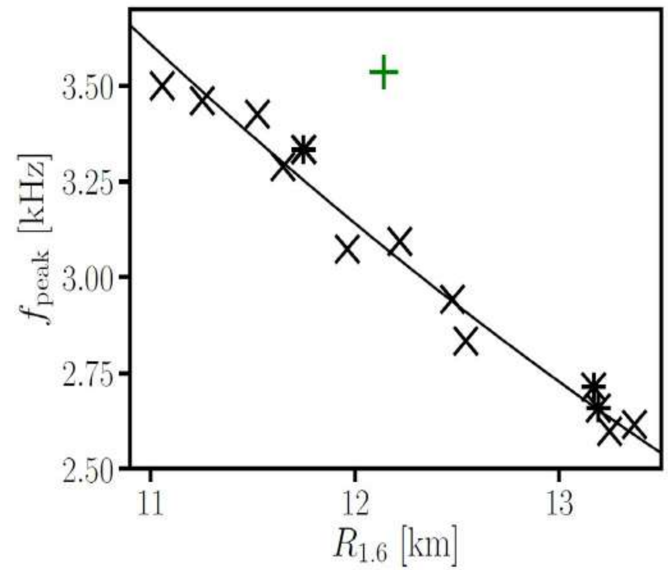
https://compose.obspm.fr/eos/166

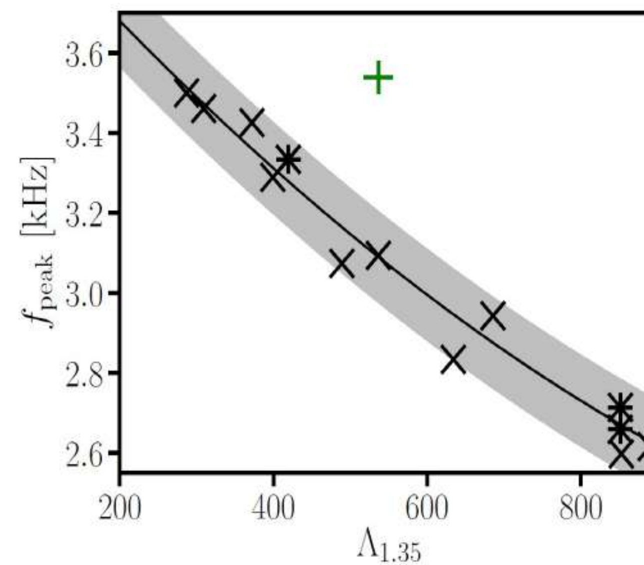
S. Blacker, A. Bauswein, et al., Phys. Rev. D 102 (2020) 123023

Ultra-heavy Nucleus-Nucleus Collisions !

Signal of a deconfinement transition







Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**
Complementarity of **f_{peak}** from postmerger with tidal deformability **$\Lambda_{1.35}$** from inspiral phase.

A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]

Towards a unified approach to Q-H matter

One route: Quantum Many-Body Theory with potential models

Nuclear matter equation of state from a quark-model nucleon-nucleon interaction

K. Fukukawa,[1,2] M. Baldo,[1] G. F. Burgio,[1] L. Lo Monaco,[3] and H.-J. Schulze[1]
[1] *INFN Sezione di Catania, Dip. di Fisica, Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy*
[2] *Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Osaka 567-0047, Japan and*
[3] *Dipartimento di Fisica, Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy*
(Dated: September 12, 2018)

Quark model for the NN interaction → BBG approach for the EOS → PRC(2015)

Quark-quark interaction and quark matter in neutron stars

Y. Yamamoto[1],* N. Yasutake[2], and Th.A. Rijken[31]
[1] *RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[2] *Department of Physics, Chiba Institute of Technology, 2-1-1 Shibazono Narashino, Chiba 275-0023, Japan*
[3] *IMAPP, Radboud University, Nijmegen, The Netherlands* → PRC(2022)

BBG approach for the EOS with the same multipomeron repulsion on nucleonic and quark level. Effective, density-dependent quark mass (bag pressure?) is Essential for a reaasonable Q-H phase transition in the model.

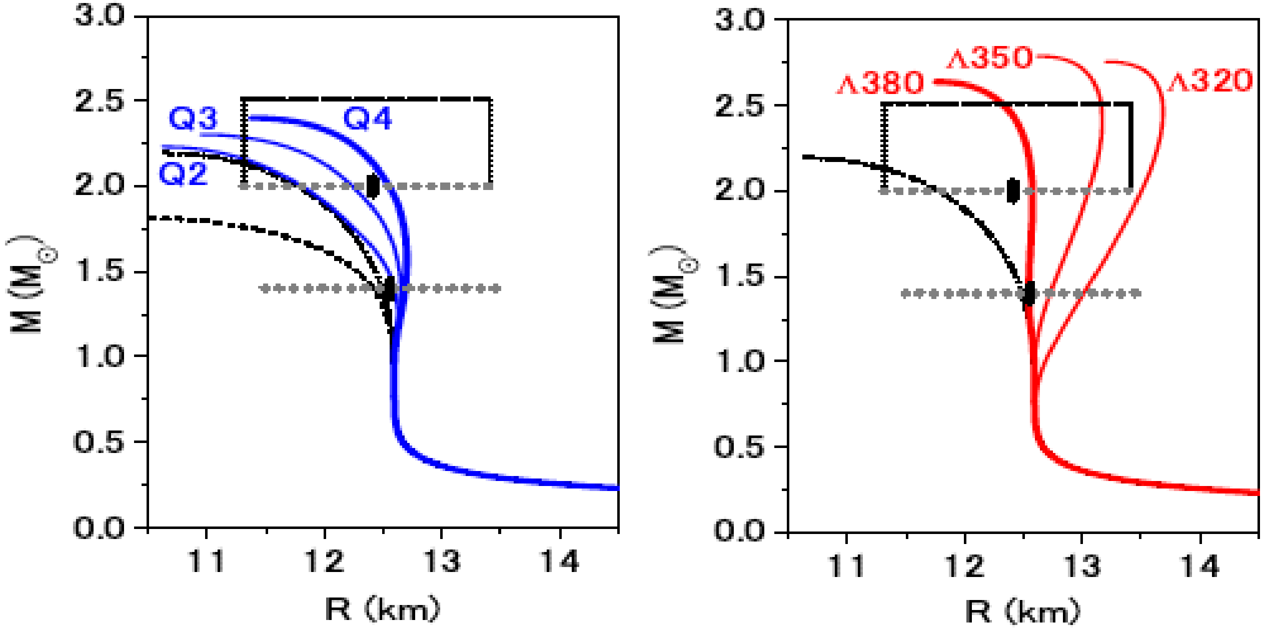
Towards a unified approach to Q-H matter

One route: Quantum Many-Body Theory with potential models

Quark phases in neutron stars consistent with implications of NICER

Y. Yamamoto[1,*] N. Yasutake[2], and Th.A. Rijken[3,1]

→ PRC(2023)



BBG approach to EOS with same multipomeron repulsion on nucleonic and quark level.

Phase transition by Maxwell construction (left) or quarkyonic matter construction (right).

Outlook: The German Centre for Astrophysics (DZA)

Research Technology Digitization

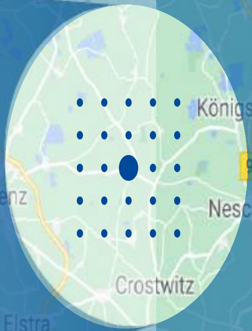
„Science Creating Prospects for the Region!"

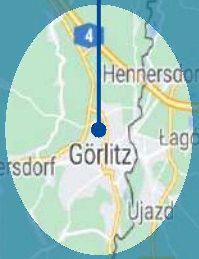
Scientific Commission: 13. July 2022
Structural and Transfer-Commission: 30. August 2022
Final decision (Approval): 29. September 2022

Fascination and inspiration of astrophysics

Why in Saxony? Lusatia is a unique region for Astrophysics, Technology and Digitization

Location for the Low Seismic Lab





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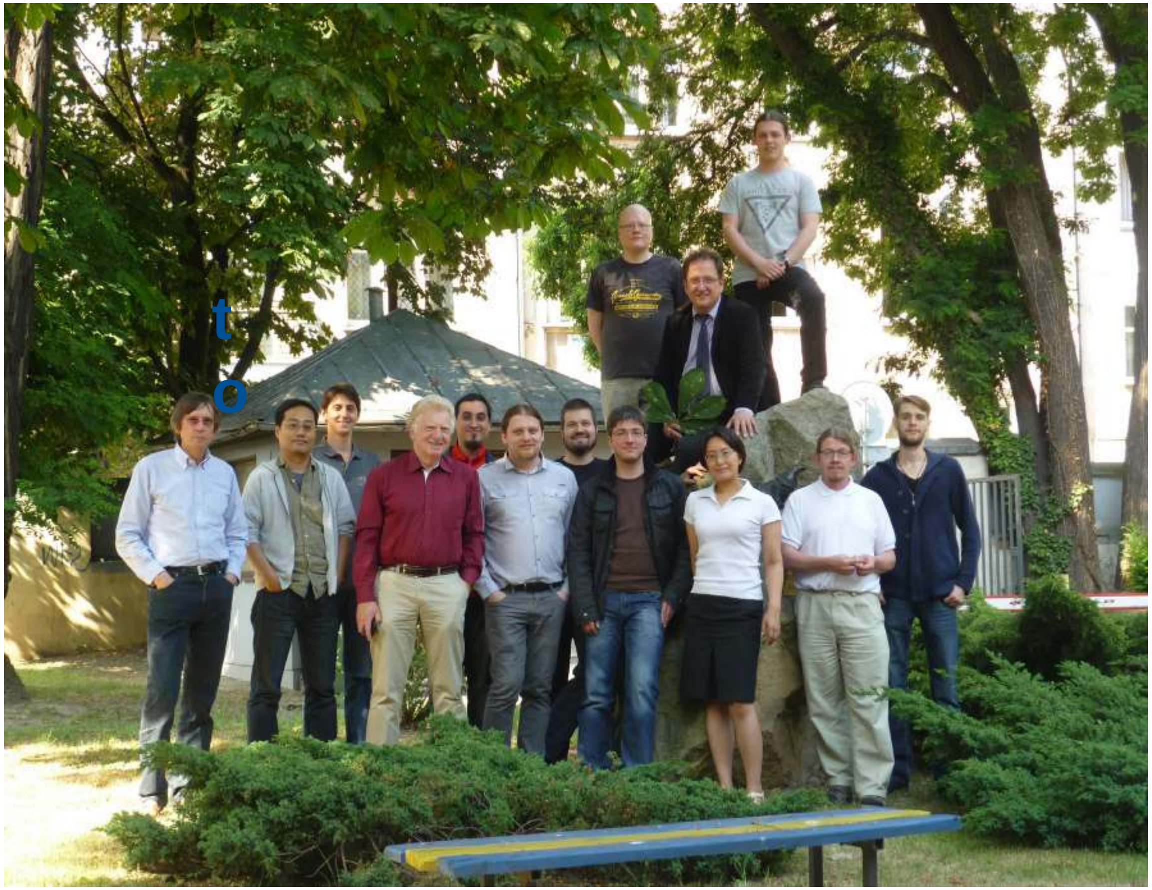
DZA

A center for astrophysics with advanced data intensive computing and technology development.

Thanks to my collaborators:

T. Fischer, G. Röpke, A. Bauswein, O. Ivanytskyi, N. Bastian, M. Cierniak, U. Shukla, S. Liebing, K. Maslov, A. Ayriyan, H. Grigorian, D.N. Voskresensky, M. Kaltenborn, G. Grunfeld, D. Alvarez-Castillo, B. Dönigus, D. Ohse, S. Chanlaridis, J. Antoniadis ...



Wroclaw Group ...

Thanks to Marcello and the Catania group ...

… for their contributions to the physics and their hospitality !

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Uniwersytet Wrocławski
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Freistaat SACHSEN

Pro and con quark matter in neutron stars

The early days: 1973 – asymptotic freedom of QCD

VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

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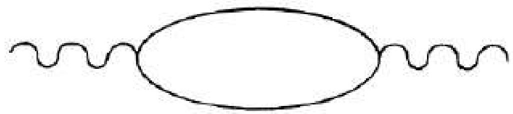
$$B/V = \tfrac{1}{3}N/V = \tfrac{1}{18}d\sum_i p_{Fi}^3/\pi^2, \quad (8)$$

$$P = \tfrac{1}{24}d\sum_i p_{Fi}^4/\pi^2, \quad (9)$$

$$\rho = E/V = \tfrac{1}{8}d\sum_i p_{Fi}^4/\pi^2, \quad (10)$$



$$E/N = BV/N + D(N/V)^{1/3},$$

with $D \equiv \frac{3}{4}\pi^2(1 + g_c^2/6\pi^2)\,\Sigma_i f_i^{4/3}$.

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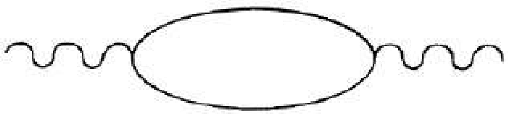

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CAN A NEUTRON STAR BE A GIANT MIT BAG?*

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Received 30 March 1976

We show, on the basis of the M.I.T. bag model of hadrons, that a neutron matter-quark matter phase transition is energetically favorable at densities around ten to twenty times nuclear matter density. It is unlikely, however, that quark matter can be found within stable neutron stars, or that it may form a third family of dense stellar objects.

Con