Beth-Uhlenbeck Approach to Quark-Hadron Matter and Chemical Freeze-out in Heavy-Ion Collisions

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David Blaschke (HZDR/CASUS, IFT UWr)

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A NEW RESEARCH TRIANGLE

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QCD Phase Diagram

Landscape of our investigations

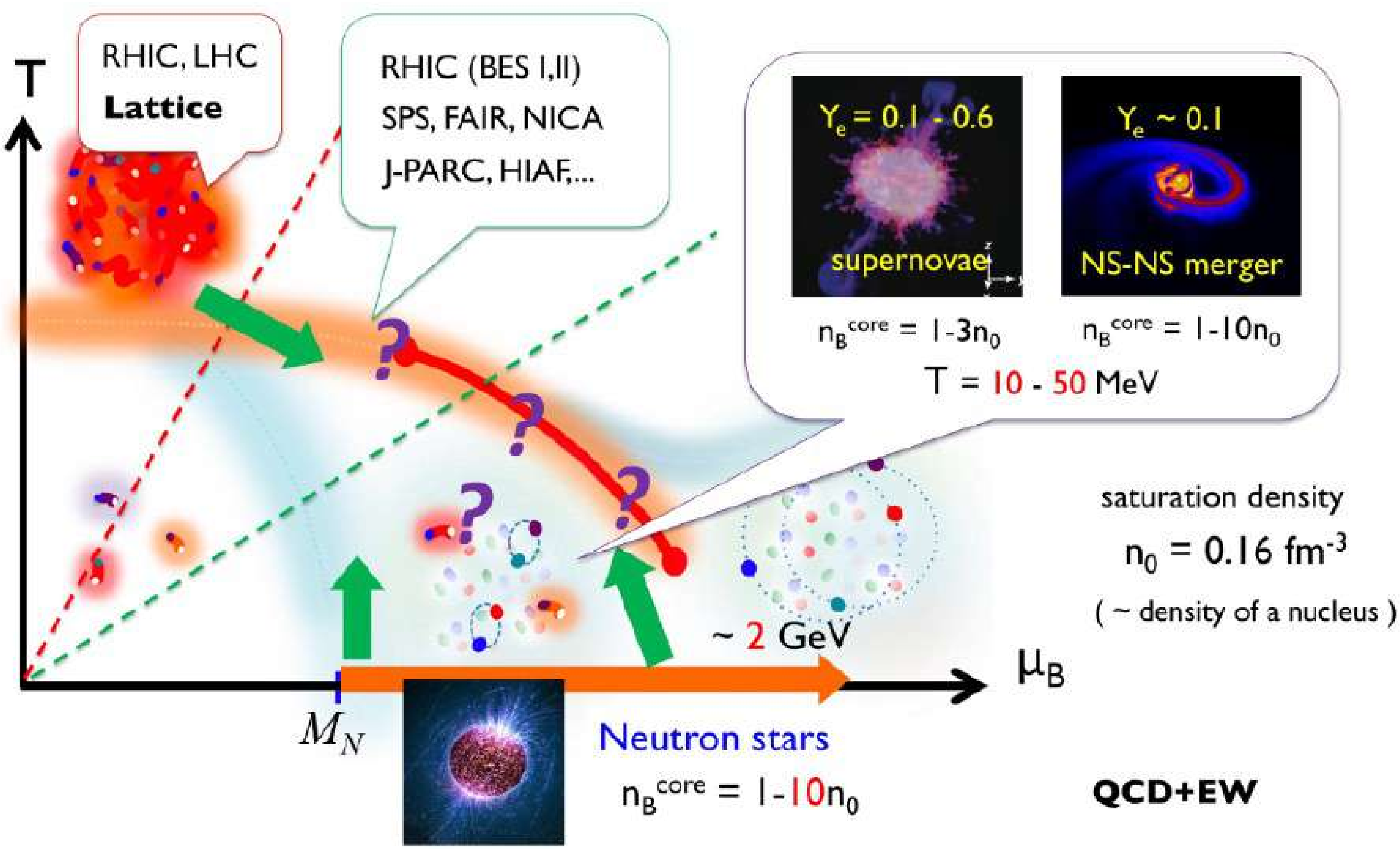

Figure from T. Kojo arXiv:1912.05326 [nucl-th]

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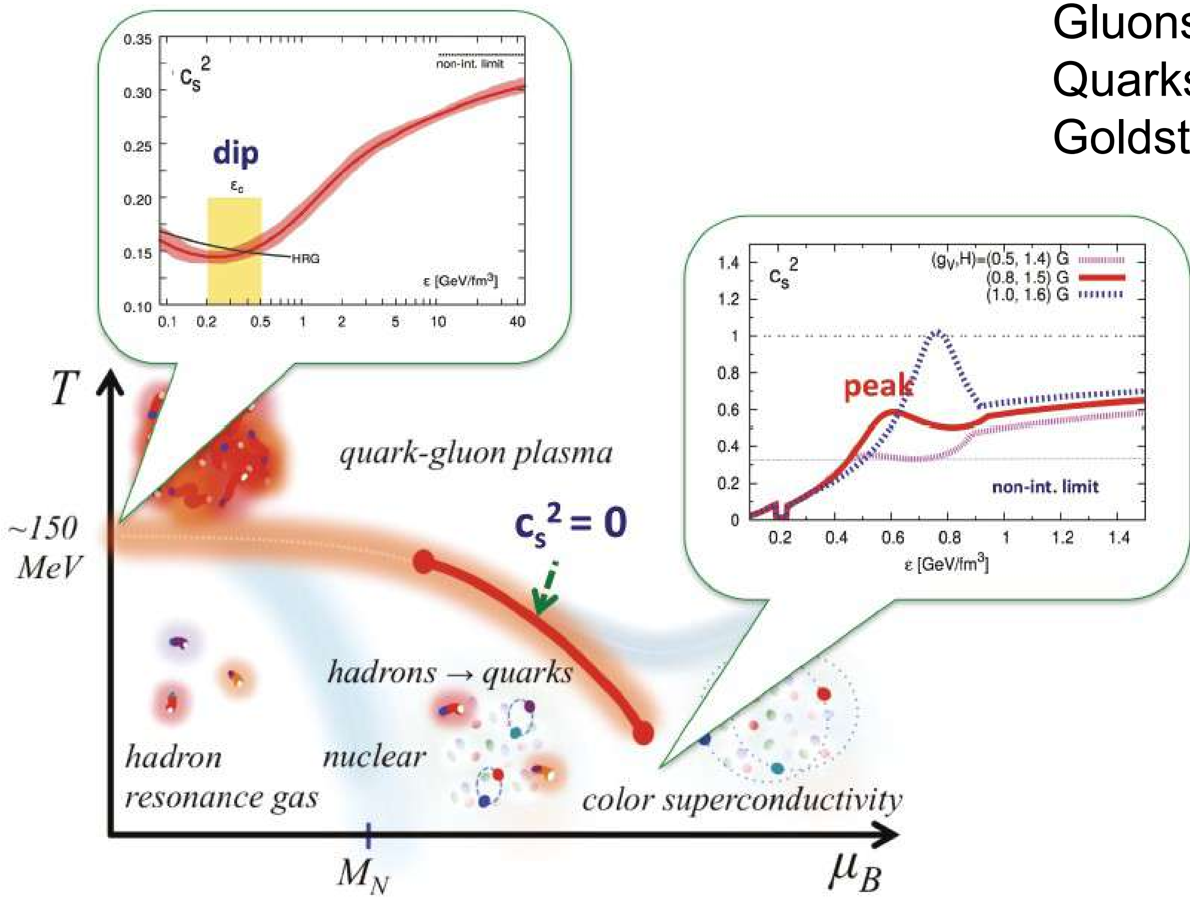

Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons

Quark-Hadron Duality?

Mutual influence of Order parameters for χSB and CSC

From: T. Kojo, "QCD equations of state in quark-hadron continuity", Universe 4 (2018) 42

T. Schaefer & F. Wilczek, Phys. Rev. Lett. 82 (1999) 3956
C. Wetterich, Phys. Lett. B 462 (1999) 164
T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym, Phys. Rev. Lett. 97 (2006) 122001

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- Chemical freeze-out as „inverse“ of the Mott effect for hadrons (χSB) and nuclear clusters (Pauli blocking)

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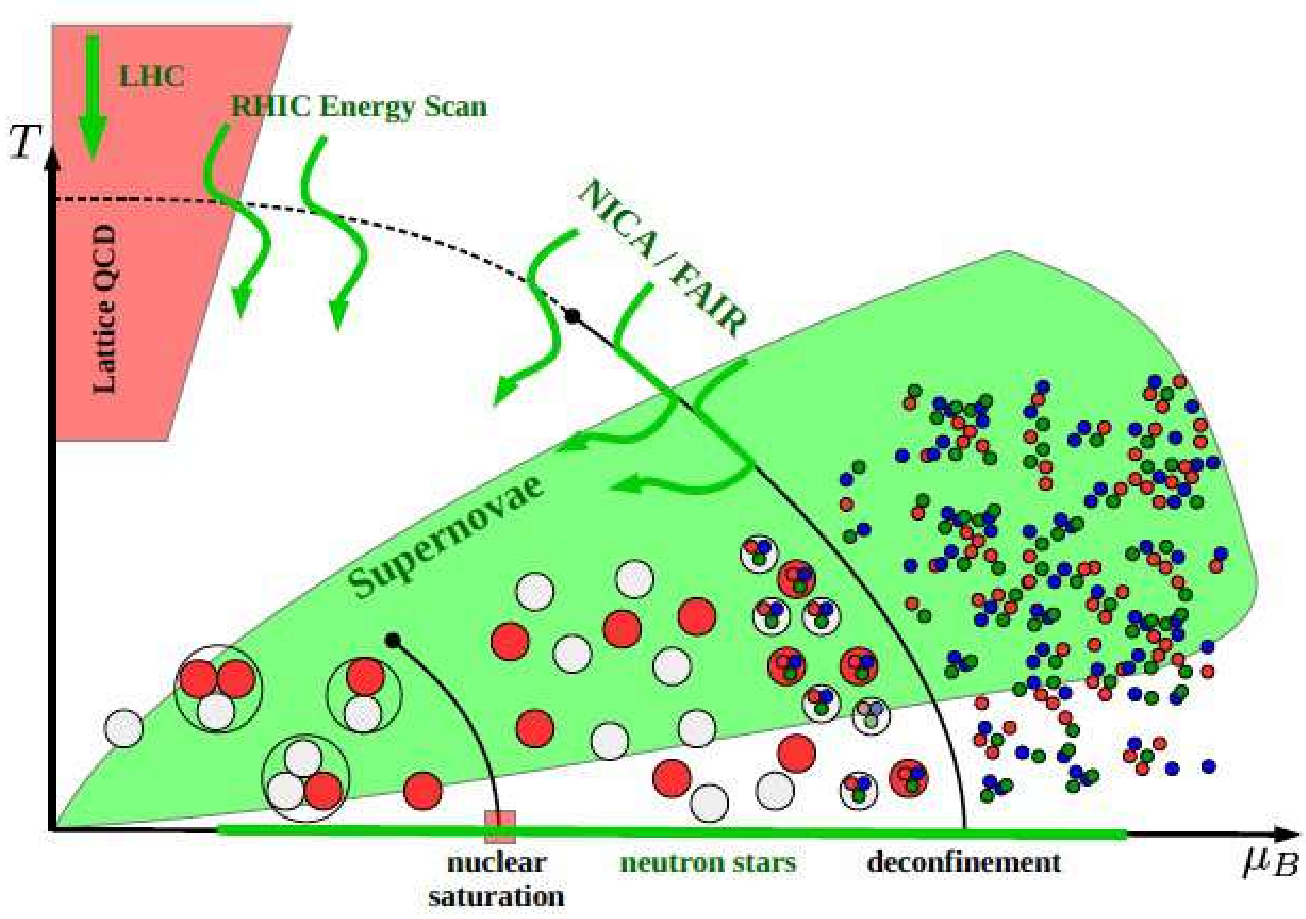
Unified EOS for quark-hadron matter

Cluster virial expansion & Beth-Uhlenbeck EoS

Unified approach to quark-nuclear matter

Clustering aspects in the QCD phase diagram



From: N.-U. Bastian, D.B., et al., Universe 4 (2018) 67; arxiv:1804.10178

Unified approach to quark-nuclear matter

Φ-derivable approach to cluster virial expansion

$$\Omega = \sum_{l=1}^{A} \Omega_l = \sum_{l=1}^{A} \left\{ c_l \left[\mathrm{Tr} \ln \left(-G_l^{-1} \right) + \mathrm{Tr} \left(\Sigma_l \; G_l \right) \right] + \sum_{\substack{i,j \\ i+j=l}} \Phi[G_i, G_j, G_{i+j}] \right\} \; ,$$

$$G_A^{-1} \;\; = \;\; {G_A^{(0)}}^{-1} - \Sigma_A \; , \; \Sigma_A(1 \ldots A, 1' \ldots A', z_A) = \frac{\delta \Phi}{\delta G_A(1 \ldots A, 1' \ldots A', z_A)}$$

Stationarity of the thermodynamical potential is implied

$$\frac{\delta \Omega}{\delta G_A(1 \ldots A, 1' \ldots A', z_A)} = 0 \; .$$

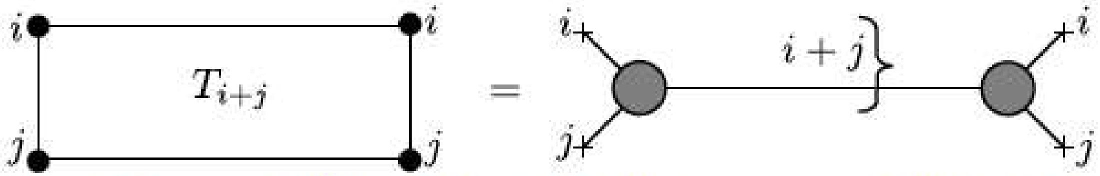
Cluster virial expansion follows for this $\Phi-$ functional

$\Phi =$ 

Figure: The Φ functional for $A-$particle correlations with bipartitions $A = i + j$.

Unified approach to quark-nuclear matter

Green's function and T-matrix, separable approx.



The T_A matrix fulfills the Bethe-Salpeter equation in ladder approximation

$$T_{i+j}(1,2,\dots,A;1',2',\dots A';z) = V_{i+j} + V_{i+j}G^{(0)}_{i+j}T_{i+j} \ ,$$

which in the separable approximation for the interaction potential,

$$V_{i+j} = \Gamma_{i+j}(1,2,\dots,i;i+1,i+2,\dots,i+j)\Gamma_{i+j}(1',2',\dots,i';(i+1)',(i+2)',\dots,(i+j)') \ ,$$

leads to the closed expression for the T_A matrix

$$T_{i+j}(1,2,\dots,i+j;1',2',\dots(i+j)';z) = V_{i+j}\left\{1-\Pi_{i+j}\right\}^{-1} \ ,$$

with the generalized polarization function

$$\Pi_{i+j} = \mathrm{Tr}\left\{\Gamma_{i+j}G^{(0)}_i\Gamma_{i+j}G^{(0)}_j\right\}$$

The one-frequency free $i-$particle Green's function is defined by the $(i-1)$-fold Matsubara sum

$$\begin{aligned} G^{(0)}_i(1,2,\dots,i;\Omega_i) &= \sum\nolimits_{\omega_1\dots\omega_{i-1}} \frac{1}{\omega_1-E(1)}\,\frac{1}{\omega_2-E(2)}\cdots\frac{1}{\Omega_i-(\omega_1+\dots\omega_{i-1})-E(i)} \\ &= \frac{(1-f_1)(1-f_2)\dots(1-f_i)-(-)^i f_1 f_2\dots f_i}{\Omega_i-E(1)-E(2)-\dots E(i)} \ . \end{aligned}$$

Unified approach to quark-nuclear matter

Useful relationships for many-particle functions

$$G^{(0)}_{i+j} = G^{(0)}_{i+j}(1,2,\ldots,i+j;\Omega_{i+j}) \quad = \quad \sum_{\Omega_i} G^{(0)}_i(1,2,\ldots,i;\Omega_i) G^{(0)}_j(i+1,i+2,\ldots,i+j;\Omega_j) \ .$$

Another set of useful relationships follows from the fact that in the ladder approximation both, the full two-cluster ($i+j$ particle) T matrix and the corresponding Greens' function

$$G_{i+j} = G^{(0)}_{i+j}\left\{1 - \Pi_{i+j}\right\}^{-1} \qquad (1)$$

have similar analytic properties determined by the $i+j$ cluster polarization loop integral and are related by the identity

$$T_{i+j} G^{(0)}_{i+j} = V_{i+j} G_{i+j} \ . \qquad (2)$$

which is straightforwardly proven by multiplying Equation for the $T_{i+j}-$ matrix with $G^{(0)}_{i+j}$ and using Equation (1). Since these two equivalent expressions in Equation (2) are at the same time equivalent to the two-cluster irreducible Φ functional these functional relations follow

$$T_{i+j} = \delta\Phi/\delta G^{(0)}_{i+j} \ ,$$
$$V_{i+j} = \delta\Phi/\delta G_{i+j} \ .$$

Unified approach to quark-nuclear matter

Generalized Beth-Uhlenbeck EOS from Φ-deriv.

Consider the partial density of the $A-$particle state defined as

$$n_A(T,\mu) = -\frac{\partial \Omega_A}{\partial \mu} = -\frac{\partial}{\partial \mu} d_A \int \frac{d^3q}{(2\pi)^3} \int \frac{d\omega}{2\pi} \left[\ln\left(-G_A^{-1}\right) + \mathrm{Tr}\left(\Sigma_A\ G_A\right)\right] + \sum_{\substack{i,j\\ i+j=A}} \Phi[G_i, G_j, G_{i+j}] \, .$$

Using spectral representation for $F(\omega)$ and Matsubara summation

$$F(iz_n) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{\mathrm{Im}F(\omega)}{\omega - iz_n}\, , \quad \sum_{z_n} \frac{c_A}{\omega - iz_n} = f_A(\omega) = \frac{1}{\exp[(\omega-\mu)/T] - (-1)^A}$$

with the relation $\partial f_A(\omega)/\partial\mu = -\partial f_A(\omega)/\partial\omega$ we get for Equation (3) now

$$n_A(T,\mu) = -d_A \int \frac{d^3q}{(2\pi)^3} \int \frac{d\omega}{2\pi} f_A(\omega) \frac{\partial}{\partial\omega} \left[\mathrm{Im}\ln\left(-G_A^{-1}\right) + \mathrm{Im}\left(\Sigma_A\ G_A\right)\right] + \sum_{\substack{i,j\\ i+j=A}} \frac{\partial \Phi[G_i, G_j, G_A]}{\partial \mu}\, ,$$

where a partial integration over ω has been performed For two-loop diagrams of the sunset type holds a cancellation[3] which generalize here for cluster states

$$d_A \int \frac{d^3q}{(2\pi)^3} \int \frac{d\omega}{2\pi} f_A(\omega) \frac{\partial}{\partial\omega} \left(\mathrm{Re}\Sigma_A\ \mathrm{Im}G_A\right) - \sum_{\substack{i,j\\ i+j=A}} \frac{\partial\Phi[G_i, G_j, G_A]}{\partial\mu} = 0\, .$$

Using generalized optical theorems we can show that ($G_A = |G_A| \exp(i\delta_A)$)

$$\frac{\partial}{\partial\omega}\left[\mathrm{Im}\ln\left(-G_A^{-1}\right) + \mathrm{Im}\Sigma_A\ \mathrm{Re}G_A\right] = 2\mathrm{Im}\left[G_A\ \mathrm{Im}\Sigma_A \frac{\partial}{\partial\omega} G_A^*\ \mathrm{Im}\Sigma_A\right] = -2\sin^2\delta_A \frac{\partial\delta_A}{\partial\omega}\, .$$

The density in the form of a generalized Beth-Uhlenbeck EoS follows

$$n(T,\mu) = \sum_{i=1}^{A} n_i(T,\mu) = \sum_{i=1}^{A} d_i \int \frac{d^3q}{(2\pi)^3} \int \frac{d\omega}{2\pi} f_i(\omega) 2\sin^2\delta_i \frac{\partial\delta_i}{\partial\omega}\, .$$

[3] B. Vanderheyden & G. Baym, J. Stat. Phys. (1998), J.-P. Blaizot et al., PRD (2001)

Unified approach to quark-nuclear matter

Example: deuterons in nuclear matter

The $\Phi-$derivable thermodynamical potential for the nucleon-deuteron system reads

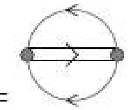
$$\Omega = -\mathrm{Tr}\left\{\ln(-G_1)\right\} - \mathrm{Tr}\{\Sigma_1 G_1\} + \mathrm{Tr}\left\{\ln(-G_2)\right\} + \mathrm{Tr}\{\Sigma_2 G_2\} + \Phi[G_1, G_2] \ ,$$

where the full propagators obey the Dyson-Schwinger equations

$$G_1^{-1}(1,z) = z - E_1(p_1) - \Sigma_1(1,z);\ \ G_2^{-1}(12,1'2',z) = z - E_1(p_1) - E_2(p_2) - \Sigma_2(12,1'2',z),$$

with selfenergies and Φ functional

$$\Sigma_1(1,1') \quad = \quad \frac{\delta\Phi}{\delta G_1(1,1')}\ ;\ \ \Sigma_2(12,1'2',z) = \frac{\delta\Phi}{\delta G_2(12,1'2',z)}\ , \Phi =$$



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fulfilling stationarity of the thermodynamic potential $\partial\Omega/\partial G_1 = \partial\Omega/\partial G_2 = 0$.
For the density we obtain the cluster virial expansion

$$n = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu} = n_{\mathrm{qu}}(\mu, T) + 2n_{\mathrm{corr}}(\mu, T)\ ,$$

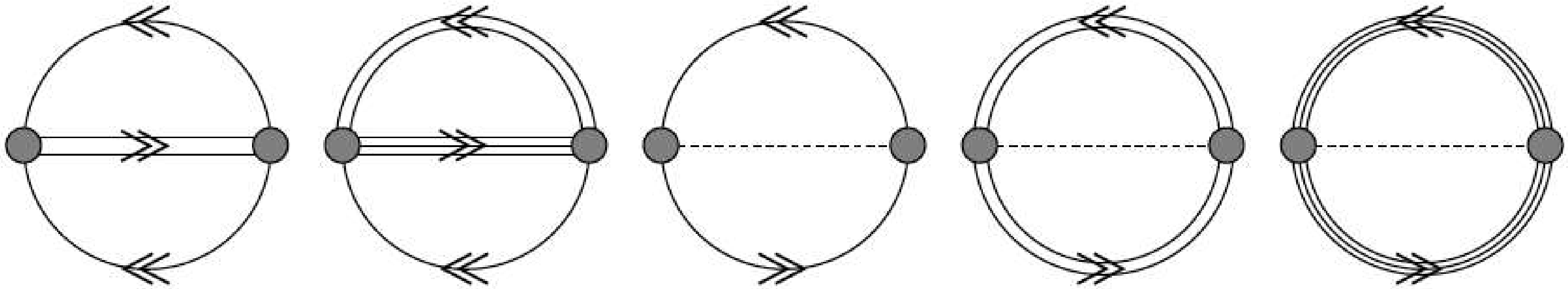
with the correlation density in the generalized Beth-Uhlenbeck form

$$n_{\mathrm{corr}} = \int \frac{dE}{2\pi} g(E) 2\sin^2\delta(E)\frac{d\delta(E)}{dE}\ .$$

Unified approach to quark-nuclear matter

Cluster virial expansion for quark-hadron matter

$$\Omega = \sum_{i=Q,M,D,B} c_i \left[\mathrm{Tr} \ln \left(-G_i^{-1}\right) + \mathrm{Tr}\left(\Sigma_i \, G_i\right)\right] + \Phi\left[G_Q, G_M, G_D, G_B\right] ,$$



When Φ functional for the system is given by 2-loop diagrams holds

$$n = -\frac{\partial \Omega}{\partial \mu} = \sum_a a \, n_a(T, \mu)$$

$$= \sum_a a \, d_a \int \frac{d\omega}{\pi} \int \frac{d^3q}{(2\pi)^3} \left\{ f_\phi^{(a),+} - \left[f_\phi^{(a),-} \right]^* \right\} 2 \sin^2 \delta_a(\omega, q) \frac{\partial \delta_a(\omega, q)}{\partial \omega} ,$$

Analogous for the entropy density $s = -\partial \Omega / \partial T$.

Unified approach to quark-nuclear matter

Cluster virial expansion for quark-hadron matter

The cluster decomposition of the thermodynamic potential is given as

$$\Omega_{\mathrm{total}}(T,\mu,\phi,\bar{\phi}) = \Omega_{PNJL}(T,\mu,\phi,\bar{\phi}) + \Omega_{\mathrm{pert}}(T,\mu,\phi,\bar{\phi}) + \Omega_{MHRG}(T,\mu,\phi,\bar{\phi}),$$

where the first two terms describe the quark and gluon degrees of freedom via the mean–field thermodynamic potential for quark matter in a gluon background field $\mathcal{U}$

$$\Omega_{PNJL}(T,\mu,\phi,\bar{\phi}) = \Omega_Q(T,\mu,\phi,\bar{\phi}) + \mathcal{U}(T,\phi,\bar{\phi})$$

with a perturbative correction $\Omega_{\mathrm{pert}}(T,\mu,\phi,\bar{\phi})$.
The Mott-Hadron-Resonance-Gas (MHRG) part for the multi-quark clusters is

$$\Omega_{MHRG}(T,\mu,\phi,\bar{\phi}) = \sum_{i=M,B,\dots} \Omega_i(T,\mu,\phi,\bar{\phi}),$$

where the multi–quark states are described by the GBU formula:

$$\begin{aligned} n &= -\frac{\partial\Omega}{\partial\mu} = \sum_a a\, n_a(T,\mu) \\ &= \sum_a a\, d_a \int \frac{d\omega}{\pi} \int \frac{d^3q}{(2\pi)^3} \left\{ f_\phi^{(a),+} - \left[f_\phi^{(a),-}\right]^* \right\} 2\sin^2\delta_a(\omega,q) \frac{\partial\delta_a(\omega,q)}{\partial\omega} \,, \end{aligned}$$

where d_i is the degeneracy factor, a is the number of valence quarks in the cluster an $f_\phi^{(a),+}$, $\left[f_\phi^{(a),-}\right]^*$ are the Polyakov-loop modified distribution functions.
Analogous for the entropy density $s = -\partial\Omega/\partial T$.

Unified approach to quark-nuclear matter

Polyakov-loop modified distribution functions

For multiquark clusters with net number a of valence quarks holds

$$f_\phi^{(a),\pm} \overset{(a\ \mathrm{even})}{=} \frac{(\phi - 2\bar{\phi} y_a^\pm) y_a^\pm + y_a^{\pm 3}}{1 - 3(\phi - \bar{\phi} y_a^\pm) y_a^\pm - y_a^{\pm 3}} ,$$

$$f_\phi^{(a),\pm} \overset{(a\ \mathrm{odd})}{=} \frac{(\bar{\phi} + 2\phi y_a^\pm) y_a^\pm + y_a^{\pm 3}}{1 + 3(\bar{\phi} + \phi y_a^\pm) y_a^\pm + y_a^{\pm 3}} ,$$

where $y_a^\pm = e^{-(E_p \mp a\mu)/T}$ and $E_p = \sqrt{\vec{p}^2 + M^2}$.
It is instructive to consider the two limits $\phi = \bar{\phi} = 1$ (deconfinement)

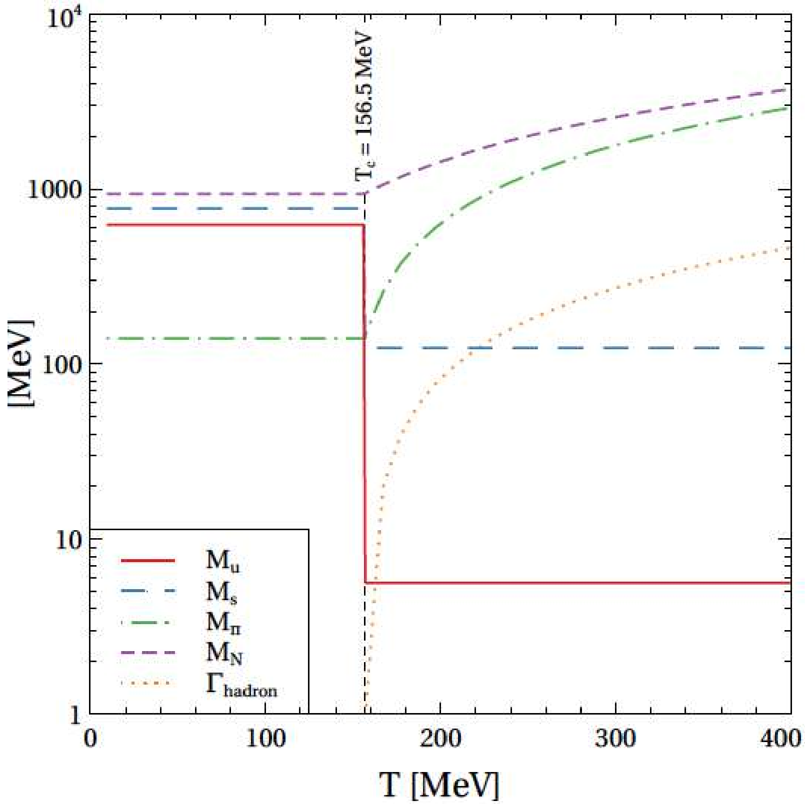
$$f_{\phi=1}^{(a=0,2,4,\dots),\pm} = \frac{y_a^\pm}{1 - y_a^\pm} , \quad f_{\phi=1}^{(a=1,3,5,\dots),\pm} = \frac{y_a^\pm}{1 + y_a^\pm} ,$$

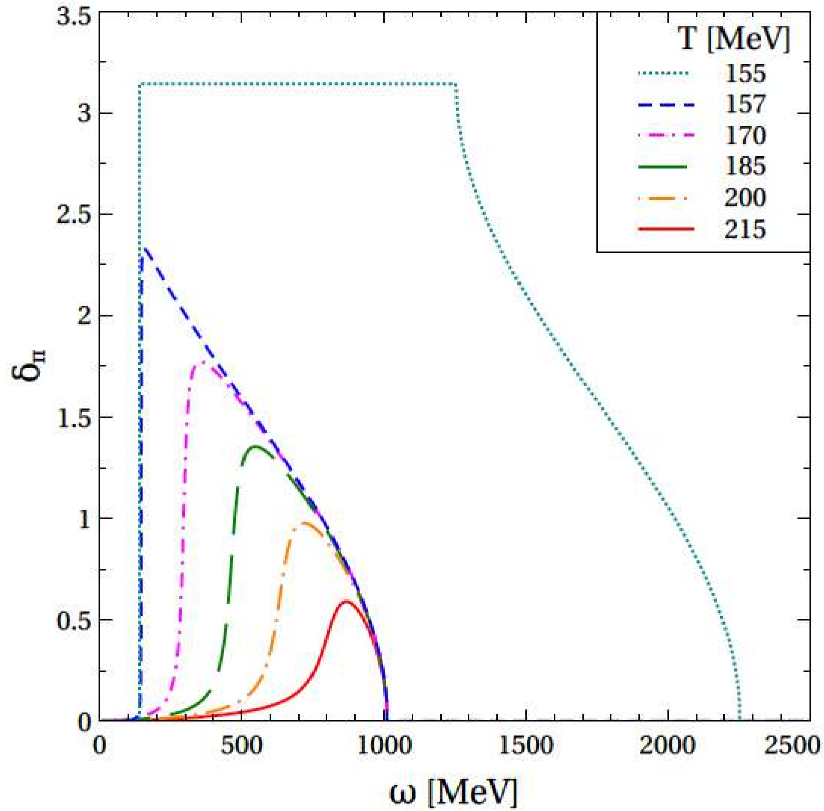
and $\phi = \bar{\phi} = 0$ (confinement),

$$f_{\phi=0}^{(a=0,2,4,\dots),\pm} = \frac{y_a^{\pm 3}}{1 - y_a^{\pm 3}} , \quad f_{\phi=0}^{(a=1,3,5,\dots),\pm} = \frac{y_a^{\pm 3}}{1 + y_a^{\pm 3}} .$$

Unified approach to quark-hadron matter

Inputs: mass spectrum & phase shifts (models)





D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

Unified approach to quark-hadron matter

Inputs: mass spectrum (Particle Data Tables)

Mesons

PDG mesons	d_i	$M_{\rm PDG}$ [MeV]	M_i [MeV]	$M^{<}_{{\rm th},i}$ [MeV]	$M^{>}_{{\rm th},i}$ [MeV]
π^+/π^0	3	140	140	1254	11.2
K^+/K^0	4	494	494	1397	129.6
η	1	548	878	1349	90.1
ρ^+/ρ^0	9	775	783	1254	11.2
ω	9	783	783	1254	11.2
K^{*+}/K^{*0}	12	895	$806^{*)}$	2651	140.8
η'	1	960	878	1349	90.1
a_0	3	980	$1095^{*)}$	2508	22.4
f_0	1	980	$1095^{*)}$	2508	22.4
ϕ	3	1020	1069	1540	248
..					
$\pi_2(1880)$	15	1895	$1095^{*)}$	2508	22.4
$f_2(1950)$	5	1944	$1095^{*)}$	2508	22.4
$a_4(2040)$	27	1996	$1095^{*)}$	2508	22.4
$f_2(2010)$	5	2011	$1095^{*)}$	2508	22.4
$f_4(2050)$	9	2018	$1095^{*)}$	2508	22.4
$K_4^*(2045)$	36	2045	$1238^{*)}$	2651	140.8
$\phi(2170)$	3	2175	$1381^{*)}$	2794	259.2
$f_2(2300)$	5	2297	$1095^{*)}$	2508	22.4
$f_2(2340)$	5	2339	$1095^{*)}$	2508	22.4

Baryons

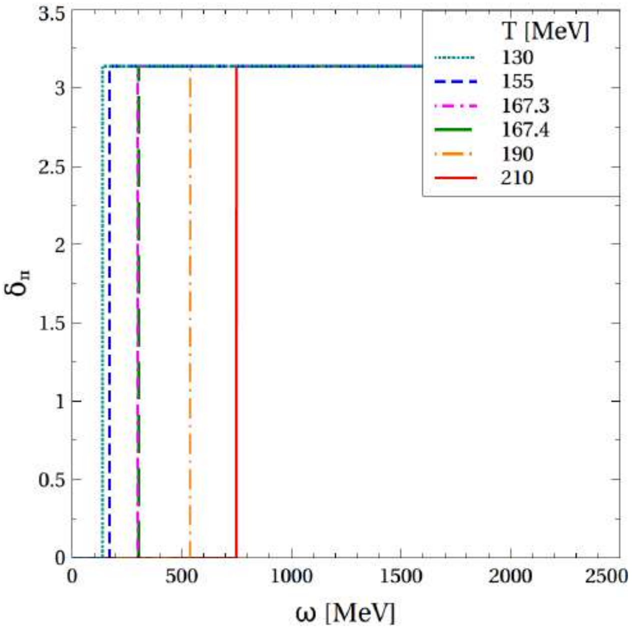
PDG baryons	d_i	$M_{\rm PDG}$ [MeV]	M_i [MeV]	$M^{<}_{{\rm th},i}$ [MeV]	$M^{>}_{{\rm th},i}$ [MeV]
n/p	4	939	939	1881	16.8
Λ	2	1116	1082	2024	135.2
Σ	6	1193	1082	2024	135.2
Δ	16	1232	$1251^{**)}$	3135	28
Ξ^0	2	1315	1225	2167	253.6
Ξ^-	2	1322	1225	2167	253.6
$\Sigma(1385)$	6	1385	$1394^{**)}$	3278	146.4
$\Lambda(1405)$	2	1405	$1394^{**)}$	3278	146.4
$N(1440)$	4	1440	$1251^{**)}$	3135	28
..					
$N(2195)$	36	2220	$1251^{**)}$	3135	28
$\Sigma(2250)$	6	2250	$1394^{**)}$	3278	146.4
$\Omega^-(2250)$	2	2252	$1680^{**)}$	3564	383.2
$N(2250)$	20	2275	$1251^{**)}$	3135	28
$\Lambda(2350)$	10	2350	$1394^{**)}$	3278	146.4
$\Delta(2420)$	48	2420	$1251^{**)}$	3135	28
$N(2600)$	24	2600	$1251^{**)}$	3135	28

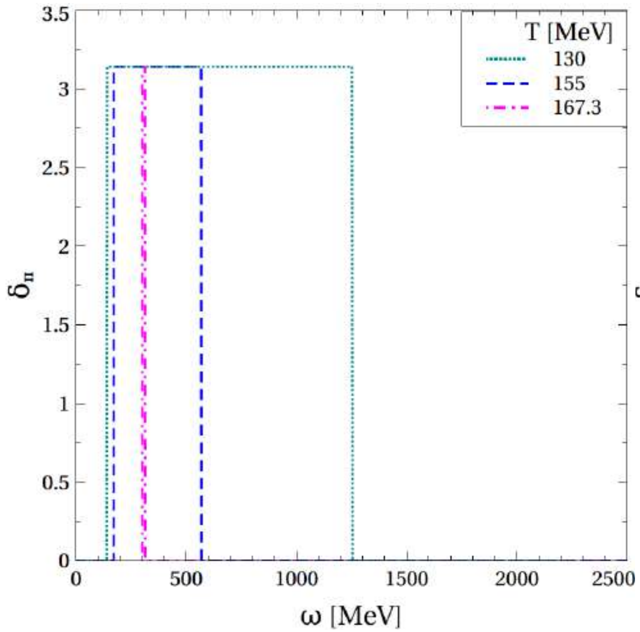
… and colored clusters (model) !

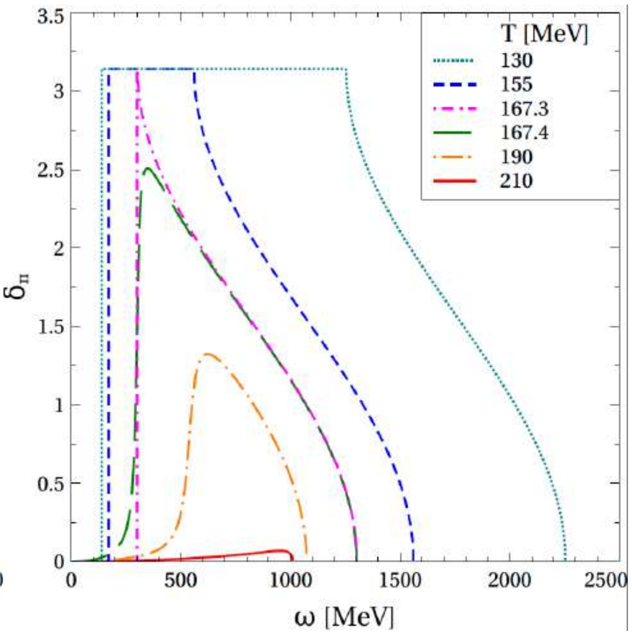
D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

Unified approach to quark-hadron matter

Inputs for the phase shifts (models)







Step-up (SU) model → Hadron Resonance Gas

Step-up-step-down model → Mott Hadron Resonance Gas (MHRG)

Step-up-continuum model

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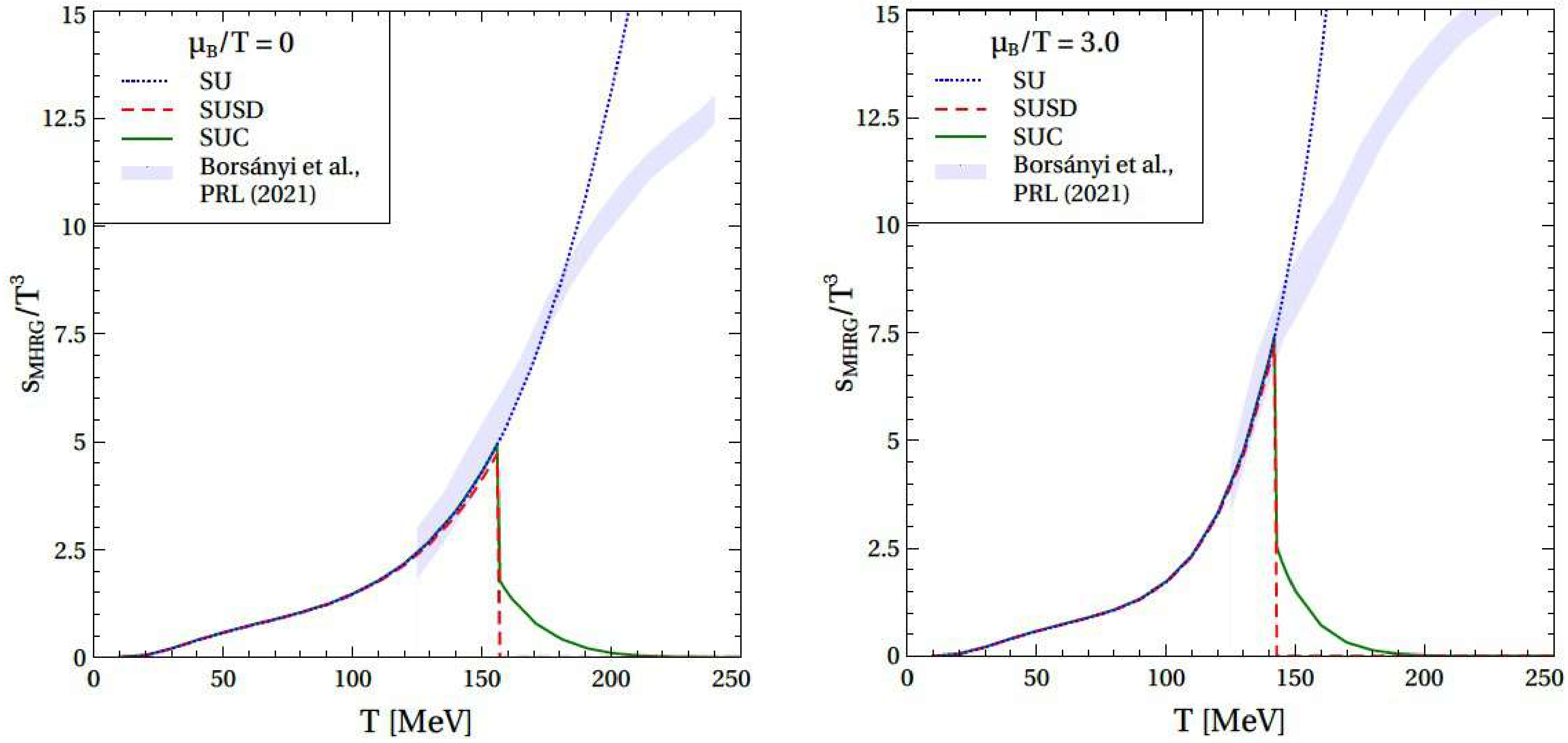
Unified approach to quark-hadron matter

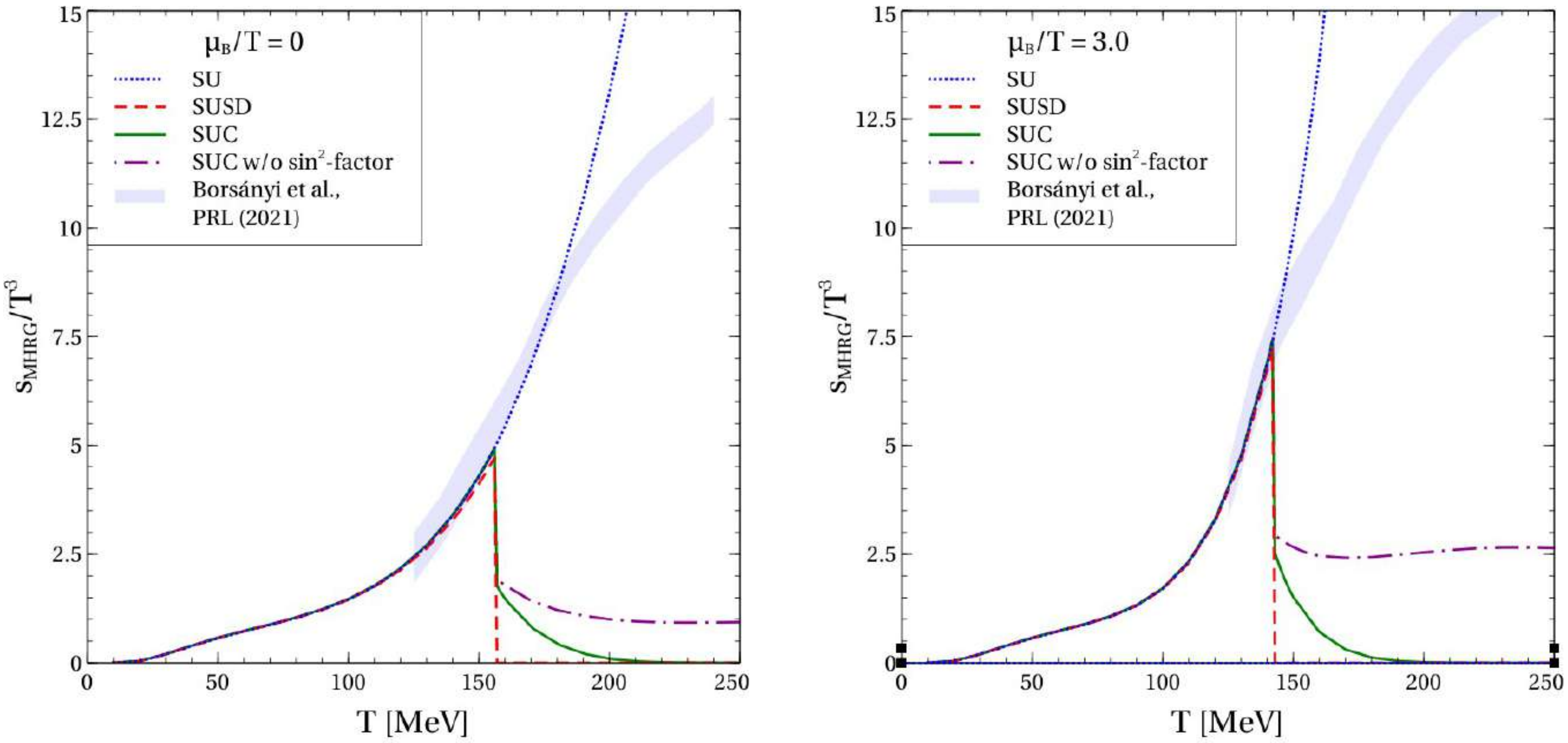
Results for Mott-Hadron Resonance Gas (MHRG)



D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

Unified approach to quark-hadron matter

Entropy for MHRG: role of the $\sin^2$-term



D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

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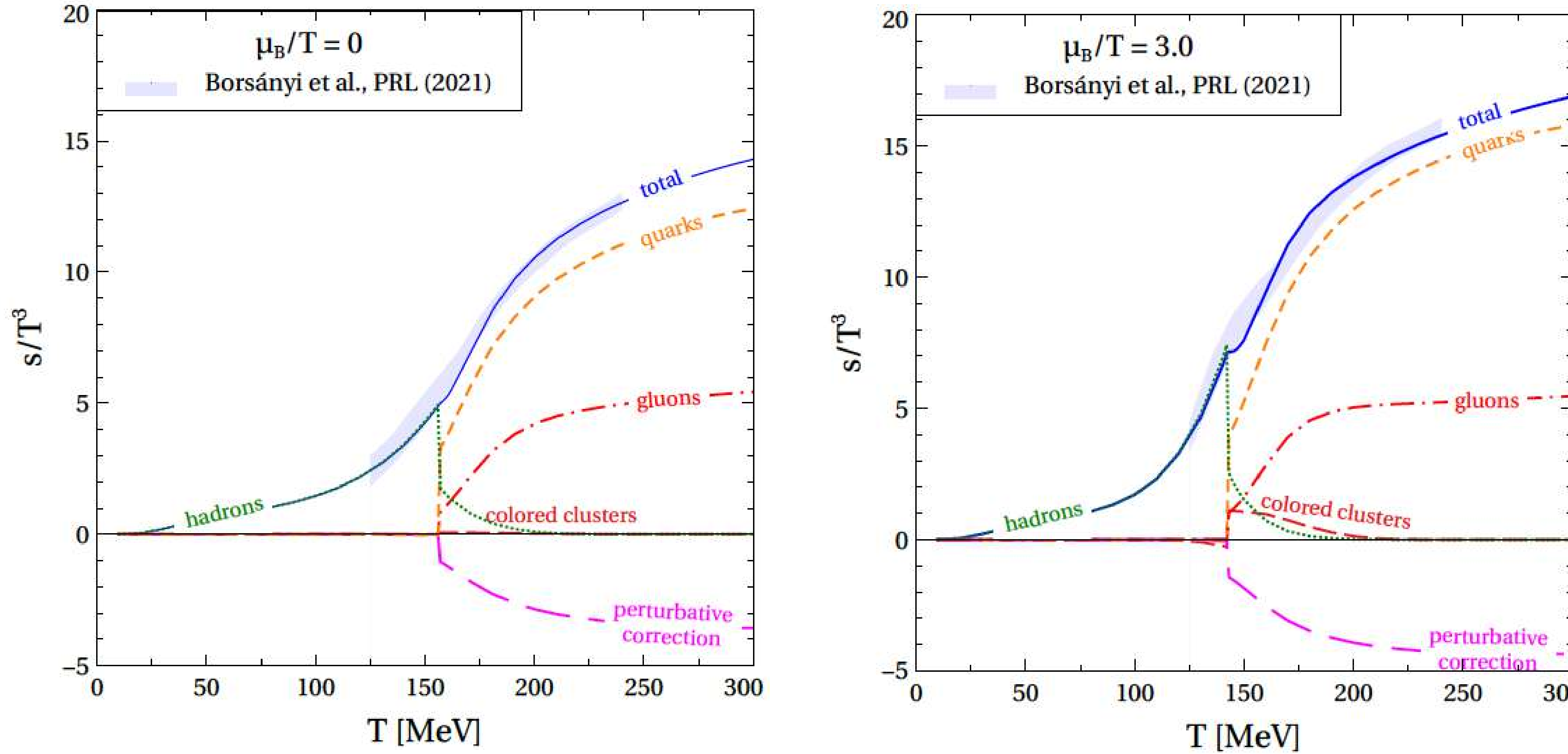
Results for the entropy density



D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

Unified approach to quark-hadron matter

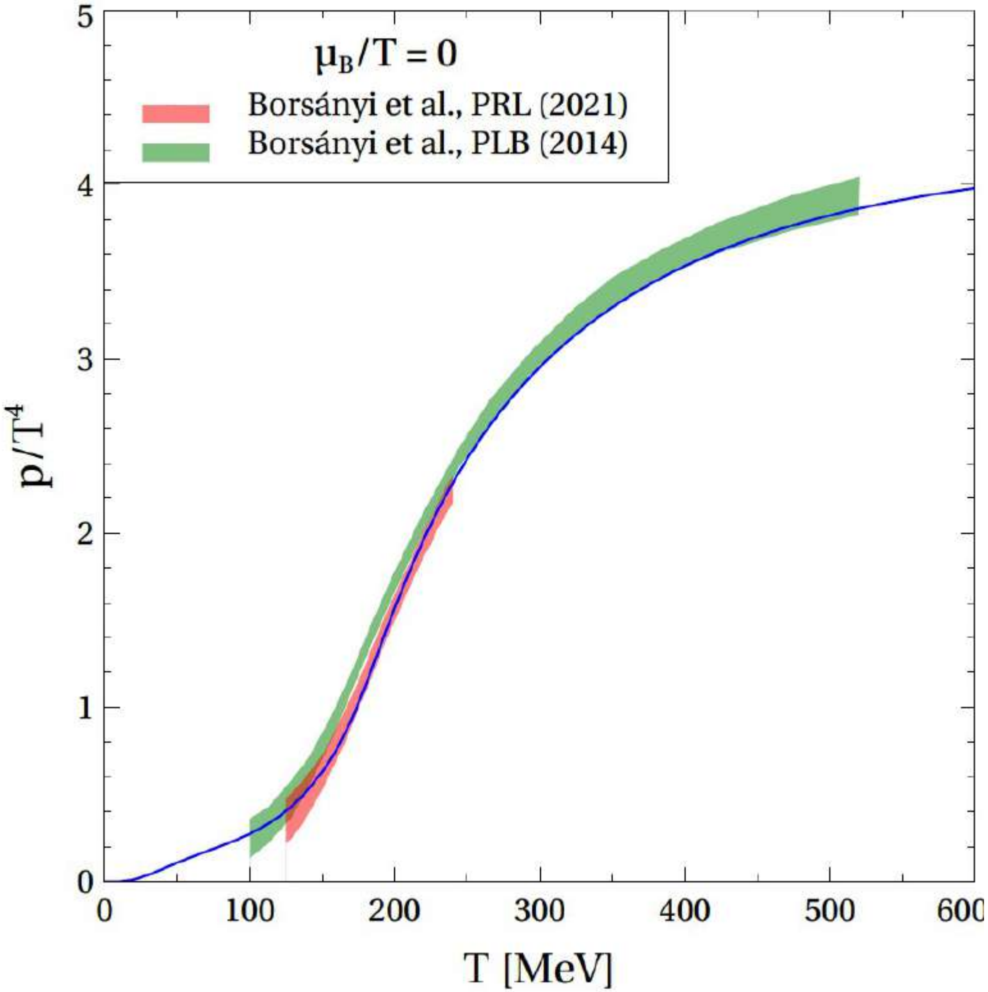
Results for pressure=thermodynamic potential

The pressure is obtained by integrating the entropy density over temperature

$s(T) = dp(T) / dT$

$\rightarrow p(T) = \int dT' \, s(T')$

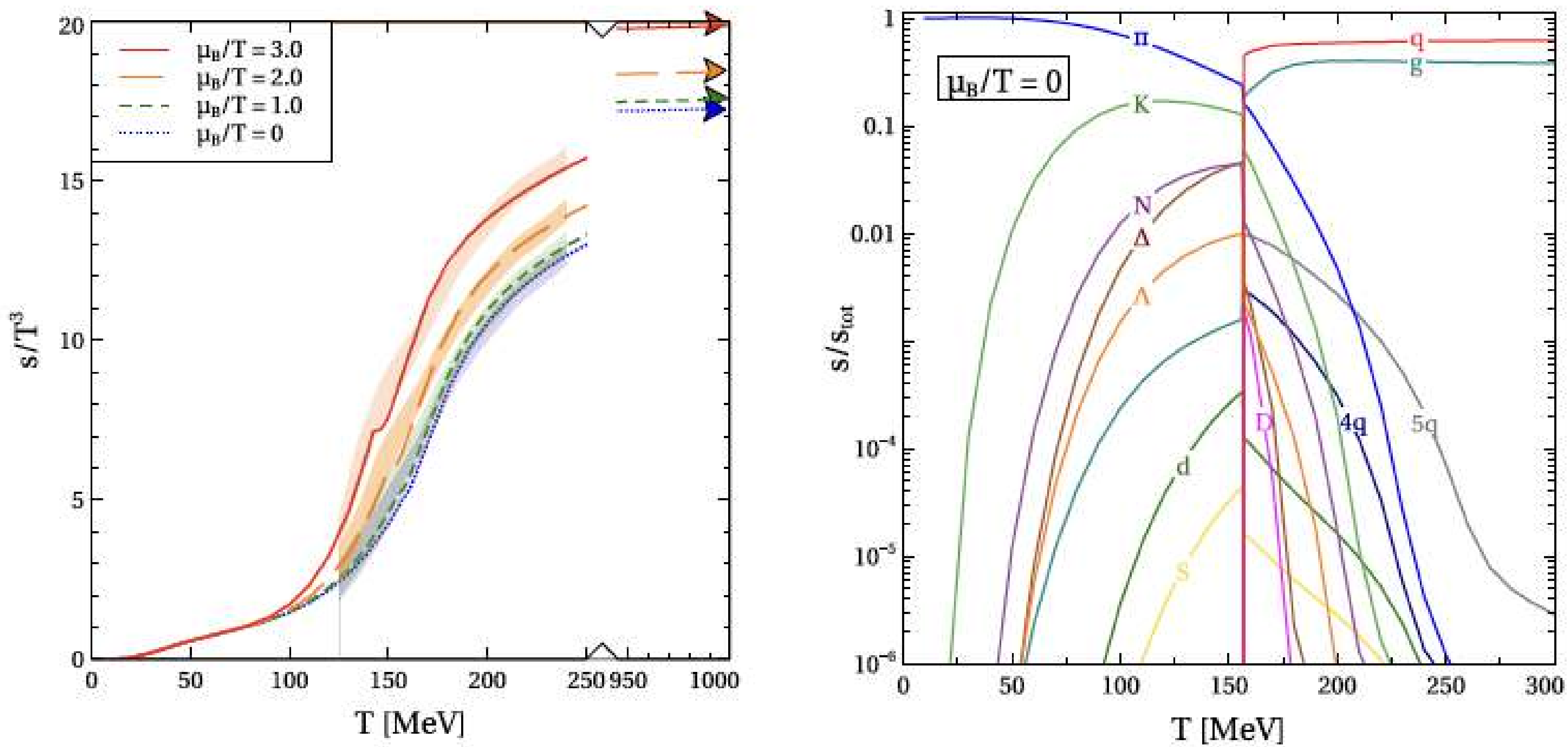
Excellent agreement with Lattice QCD thermodynamics !



D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

Unified approach to quark-hadron matter

Results for the entropy density & composition



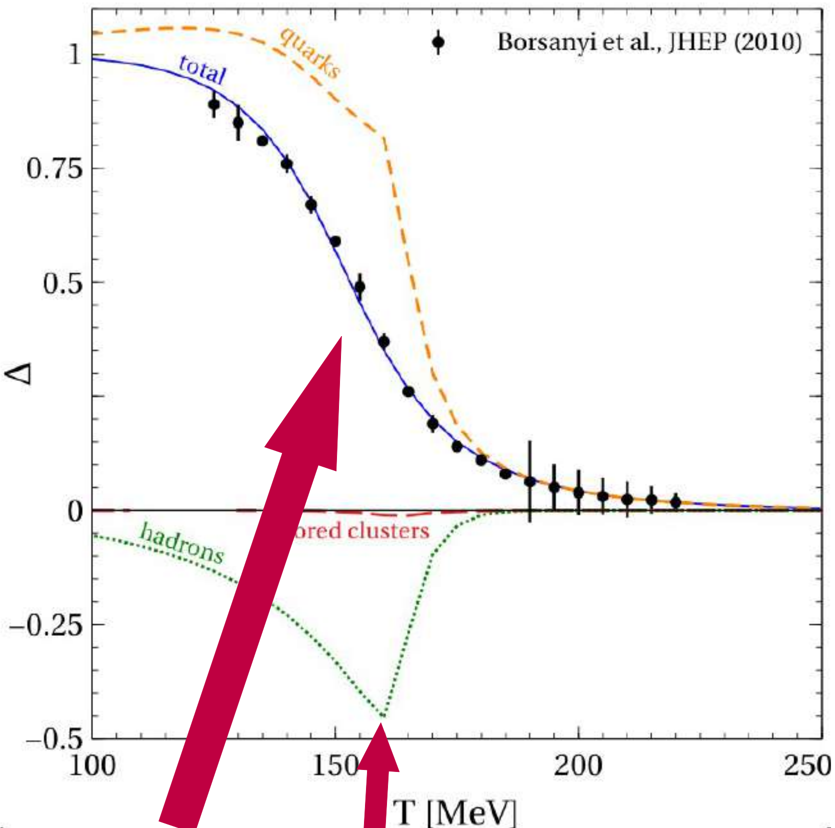
Abrupt hadronisation (change in the composition) at the chiral crossover transition with Tc=156 MeV

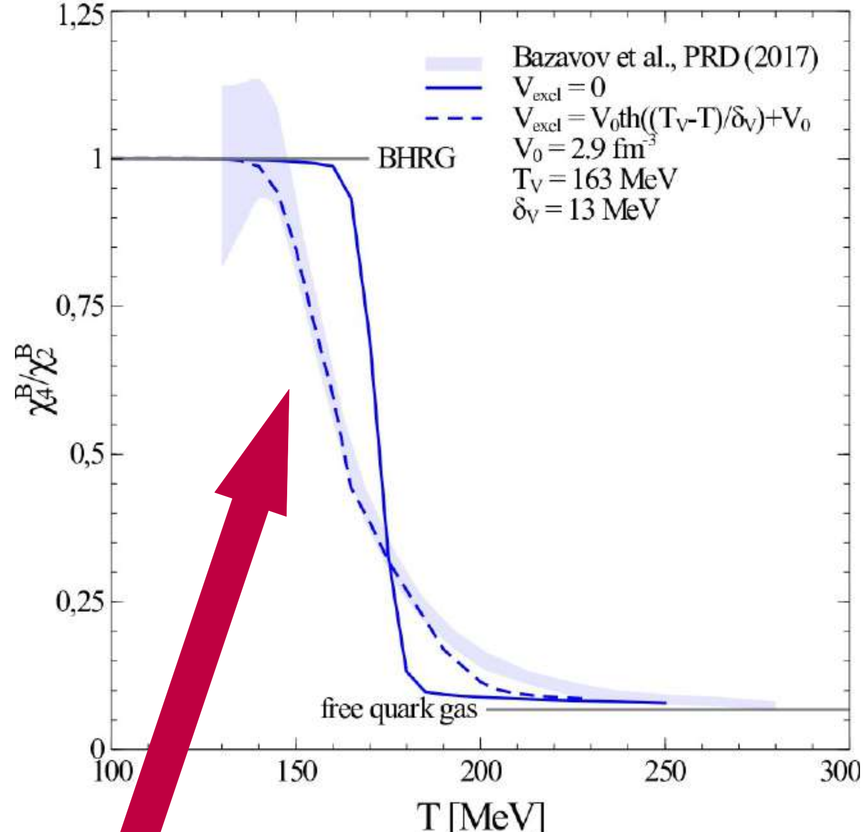
→ important for understanding chemical freeze-out in ultrarelativistic heavy-ion collisions.

D.B., M. Ciernak, O. Ivanytskyi and G. Röpke, arXiv:2308.07950; EPJA 60 (2024) 14

Unified approach to quark-hadron matter

Chiral condensate & baryon susceptibilities





Smooth crossover for the chiral condensate,
Despite abrupt change in the composition!

D.B., O. Ivanytskyi & G. Röpke, in preparation (2024)

Ratio of baryon susceptibilities shows:
Importance of (repulsive) virial corrections among baryons, modeled, e.g., by excluded volume ...

Unified approach to quark-hadron matter

Applications to cool hybrid neutron star matter

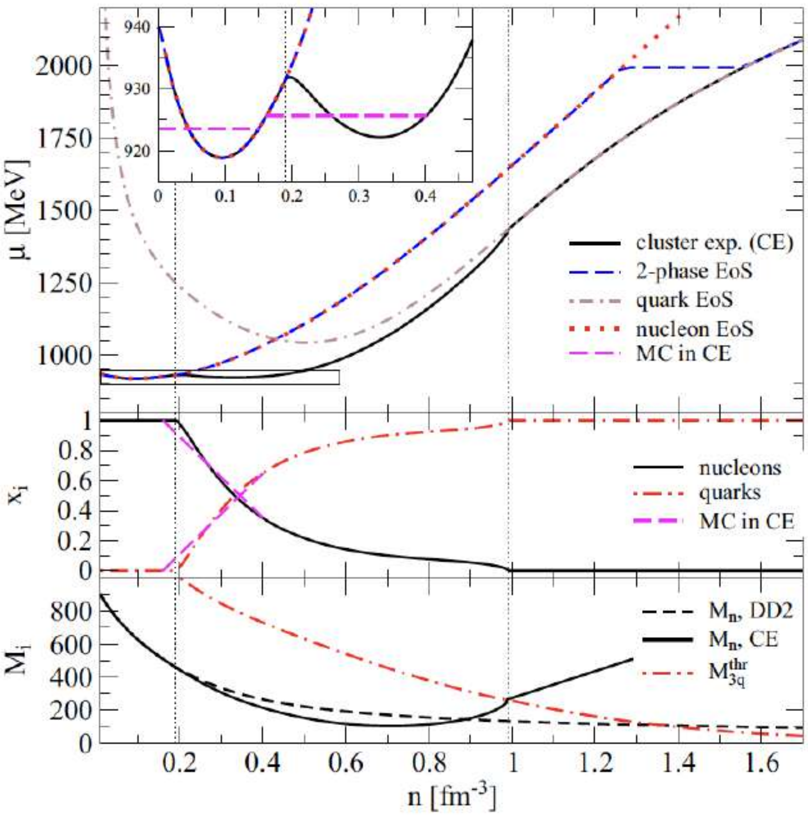
$$\delta_{i=n}(M) = \pi\,\Theta(M - M_i)\,\Theta(M_i^{\rm thr} - M)\,,$$

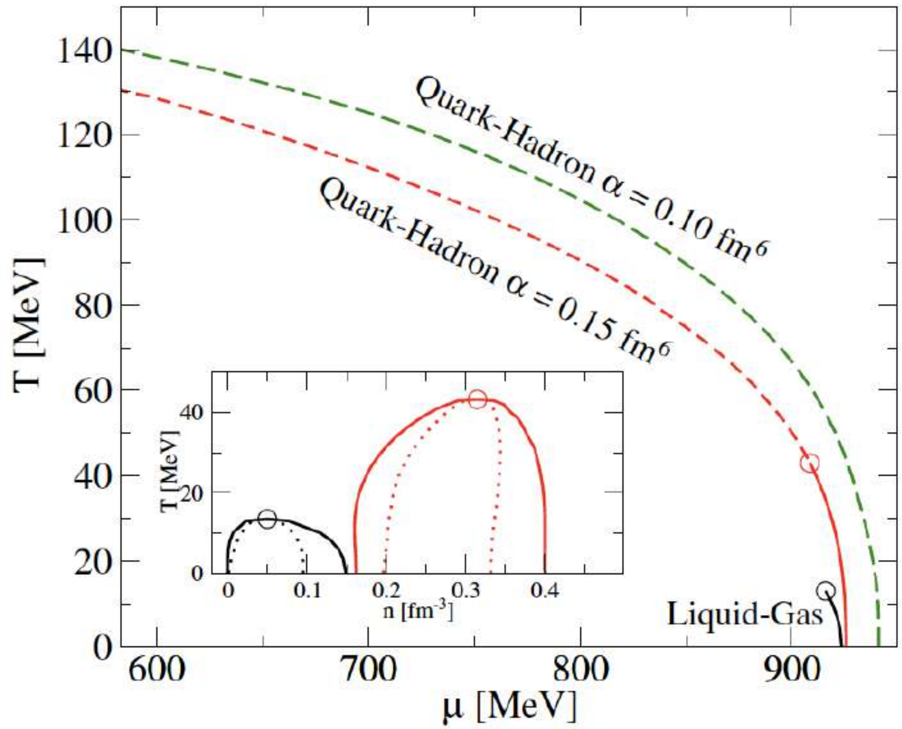
Step-up-step-down phase shift model for N

$$\delta_{i=q}(M) = \pi\,\Theta(M - M_i)\,,$$

$$U^{\rm SFM} = D(n_{\rm v})n_{\rm q,s}^{2/3} + a n_{\rm q,v}^2$$

Confining density functional model for q





N. Bastian and D.B., EPJA 57 (2021) 35

QCD phase diagram with crossover & low-T CEP;

Possibly „crossover all over“, or two CEP’s

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

Chemical freeze-out in heavy-ion collisions

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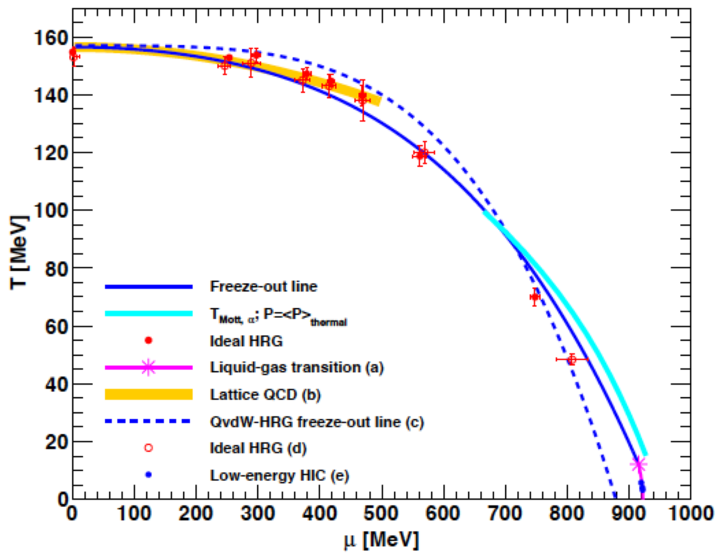
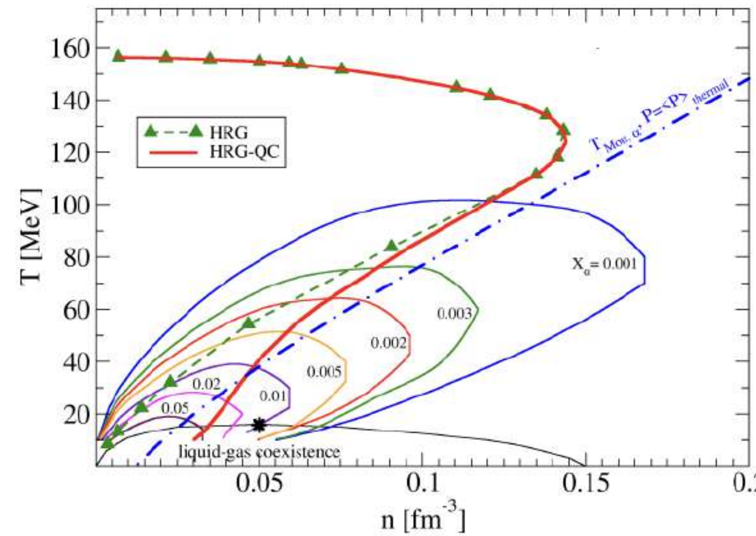
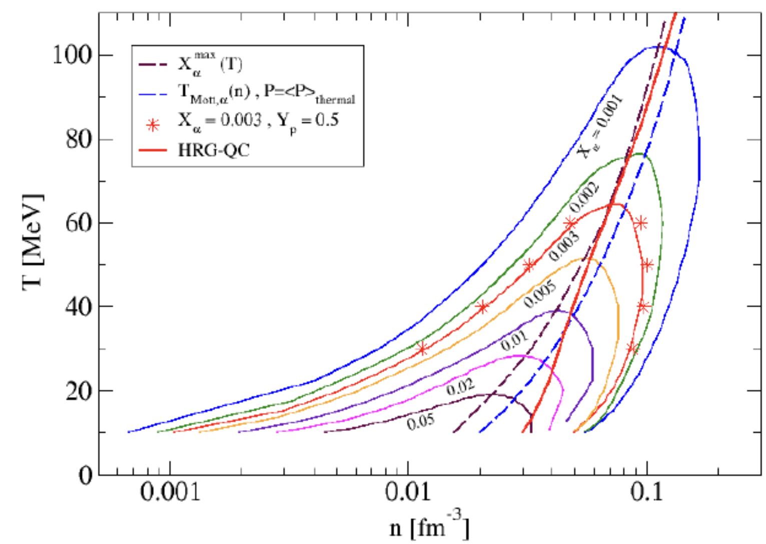
„inverse“ of Mott dissociation by χSR or Pauli blocking







High temperature, low baryon density:

→ χSB entails confinement of hadrons and clusters

→ chem. Freeze-out coincides with LQCD crossover

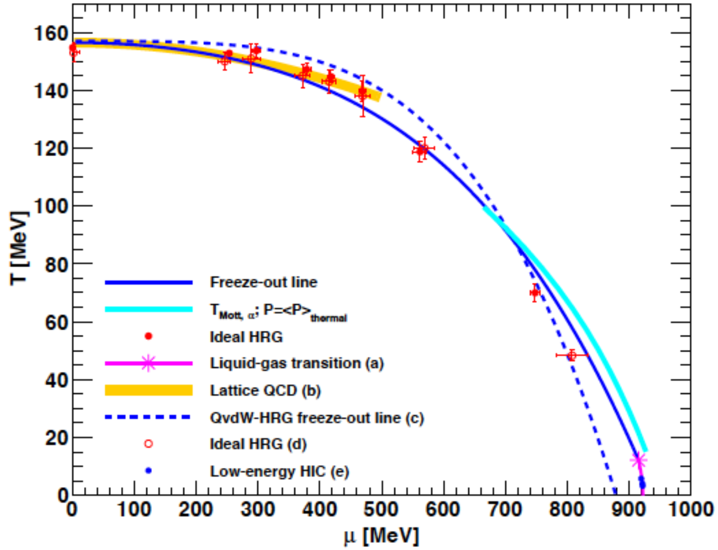
Intermediate temperature (30-100 MeV), high density:

→ Pauli blocking destroys nuclear clusters
→ Mott dissociation line for clusters (α) = freeze-out line

D.B., S. Liebing, G. Röpke, B. Dönigus, arXiv:2408.01399

Chemical freeze-out in heavy-ion collisions

„inverse“ of Mott dissociation by χSR or Pauli blocking

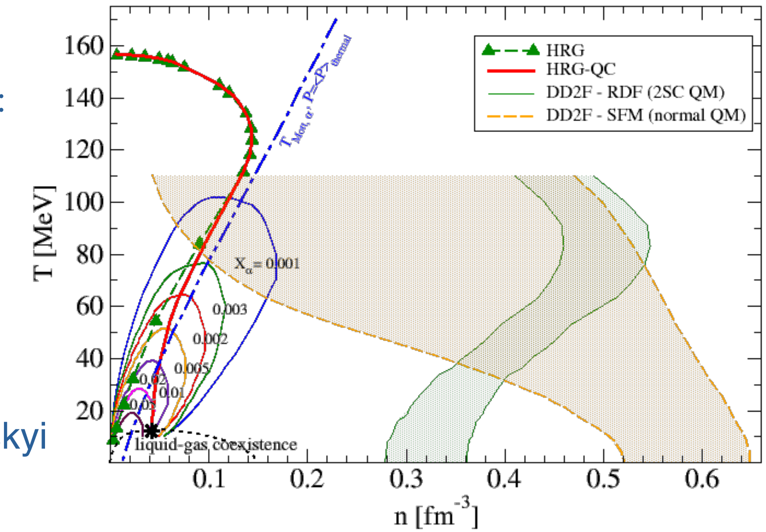


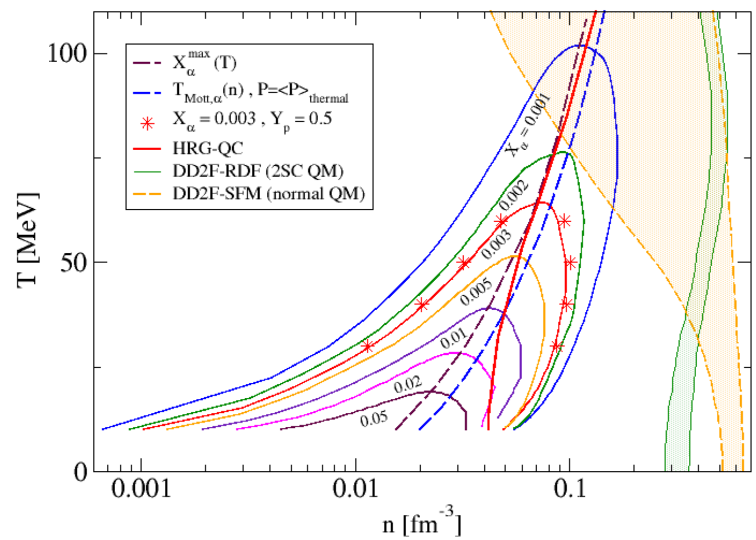
With quark deconfinement:

- 2SC QM
- normal QM

Thanks to:

Oleksii Ivanytskyi





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D.B., S. Liebing, G. Röpke, B. Dönigus, arXiv:2408.01399

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**

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

self energy = string tension × separation $\Rightarrow$ $\boxed{\textbf{confinement}}$

Relativistic density functional for quark matter

Expansion around mean fields

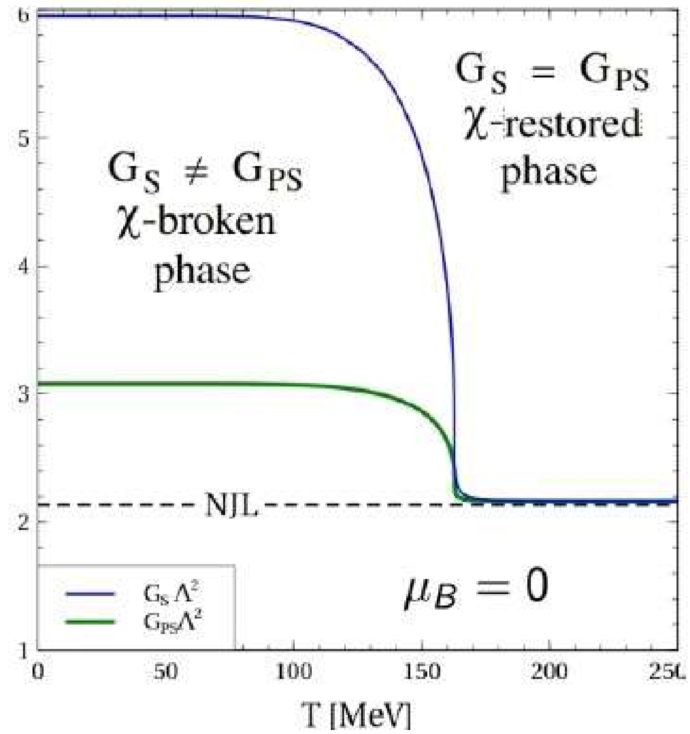
$$\mathcal{U} = \underbrace{\mathcal{U}_{MF}}_{0^{\text{th}}\ \text{order}} + \underbrace{\left(\bar{q}q - \langle\bar{q}q\rangle\right)\Sigma_S}_{1^{\text{st}}\ \text{order}} - \underbrace{G_S\left(\bar{q}q - \langle\bar{q}q\rangle\right)^2 - G_{PS}\left(\bar{q}i\vec{\tau}\gamma_5 q\right)^2}_{2^{\text{nd}}\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

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

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

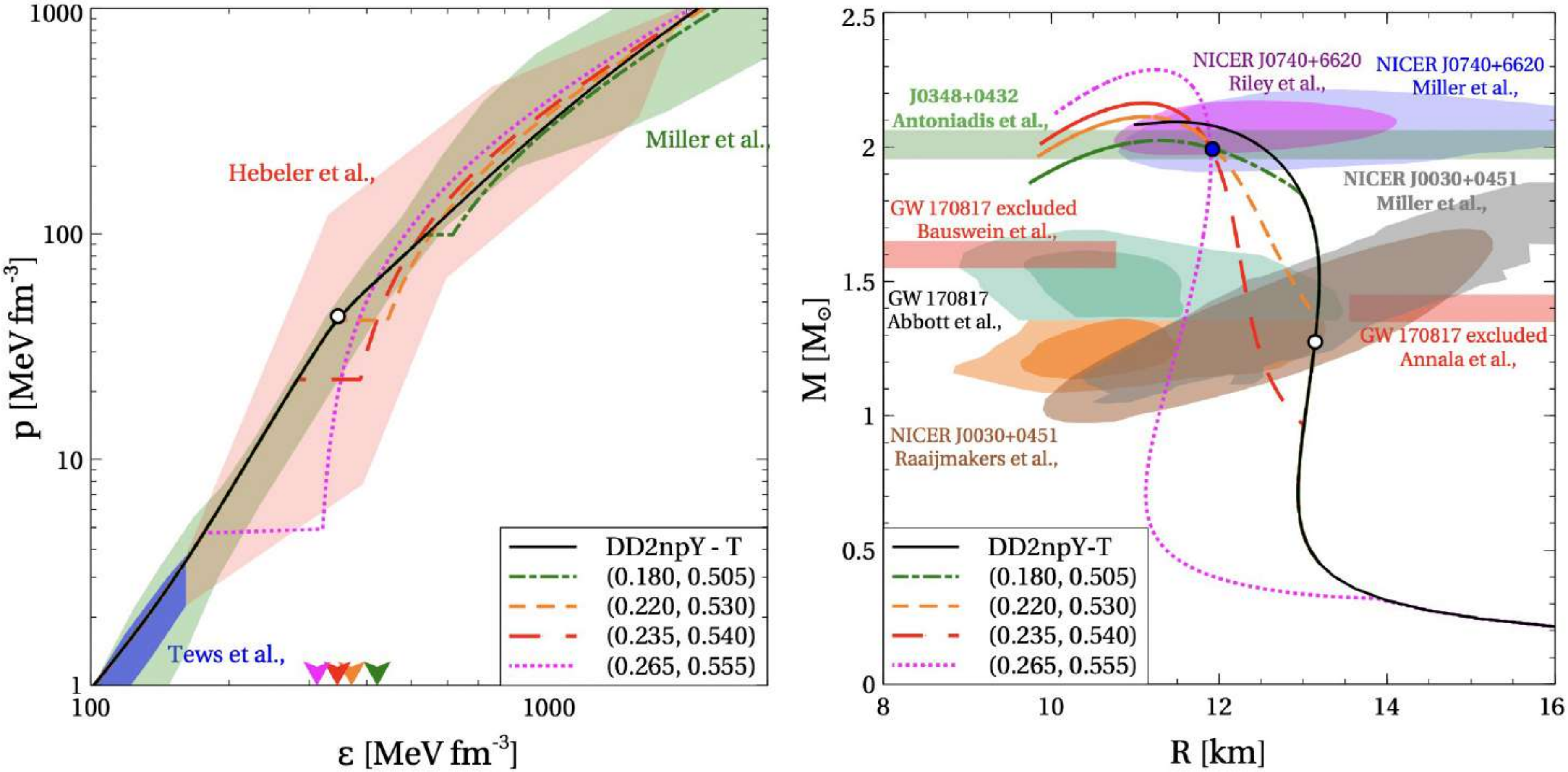
- **Effective medium dependent couplings**

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



Relativistic density functional for quark matter

EOS and Mass-radius diagram for hybrid neutron stars



Observational constraints prefer early onset of deconfinement

Thanks to my collaborators:

Uniwersytet Wrocławski

T. Fischer, G. Röpke, A. Bauswein, O. Ivanytskyi, O. Vitiuk, N. Bastian, M. Cierniak, U. Shukla, S. Liebing, K. Maslov,

A. Ayriyan,

H. Grigorian,

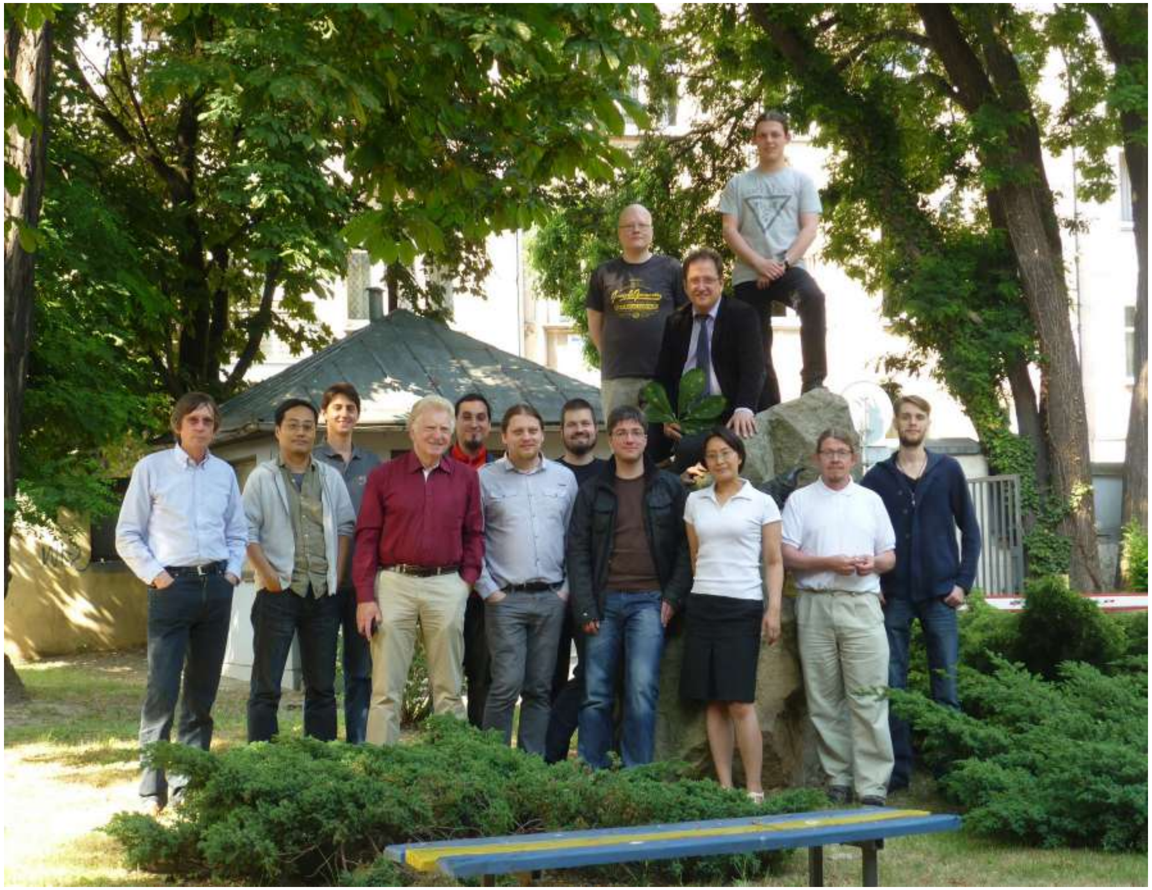
D.N. Voskresensky,

M. Kaltenborn,

G. Grunfeld,

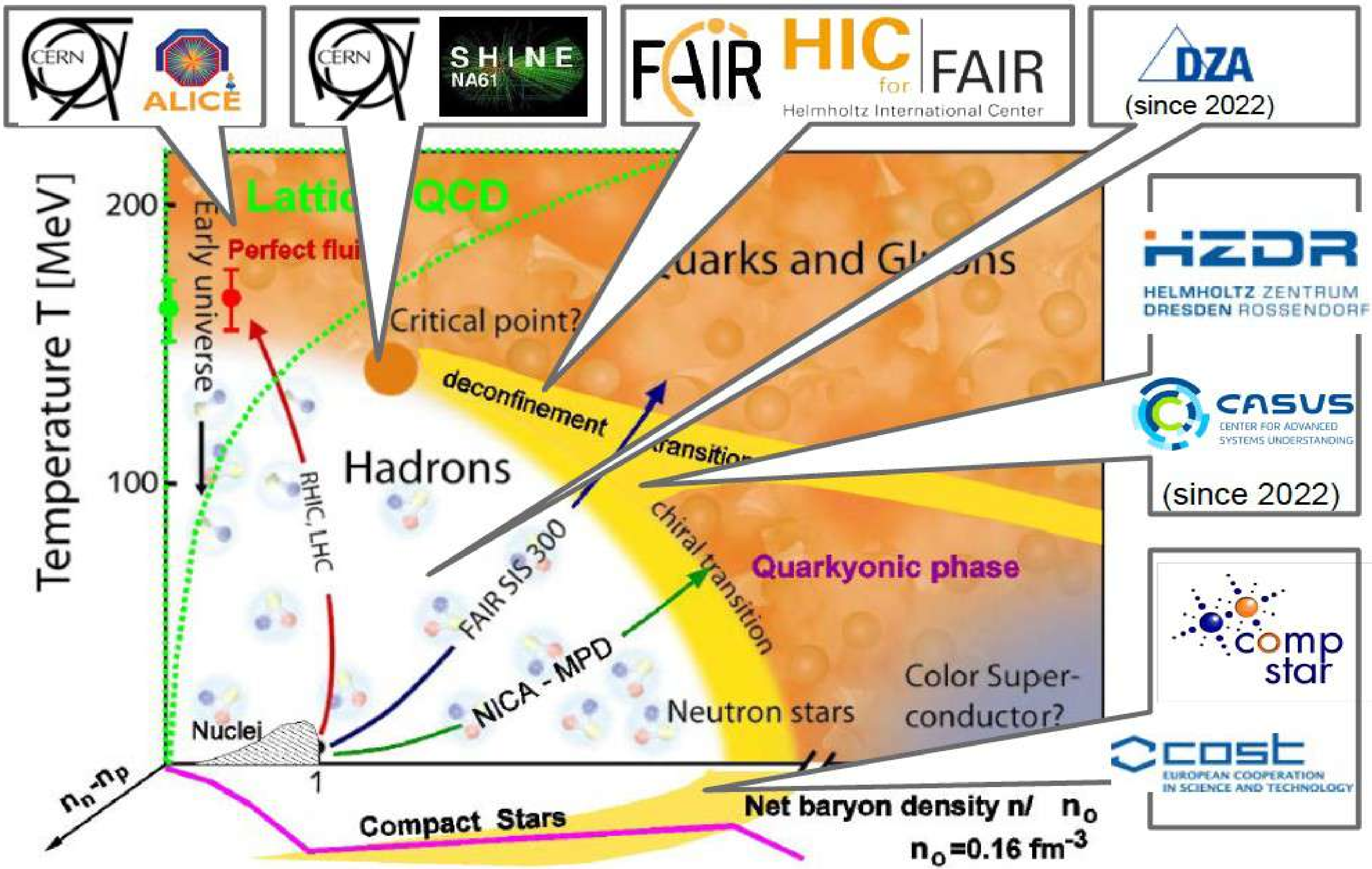
D. Alvarez-Castillo,

B. Dönigus, ...

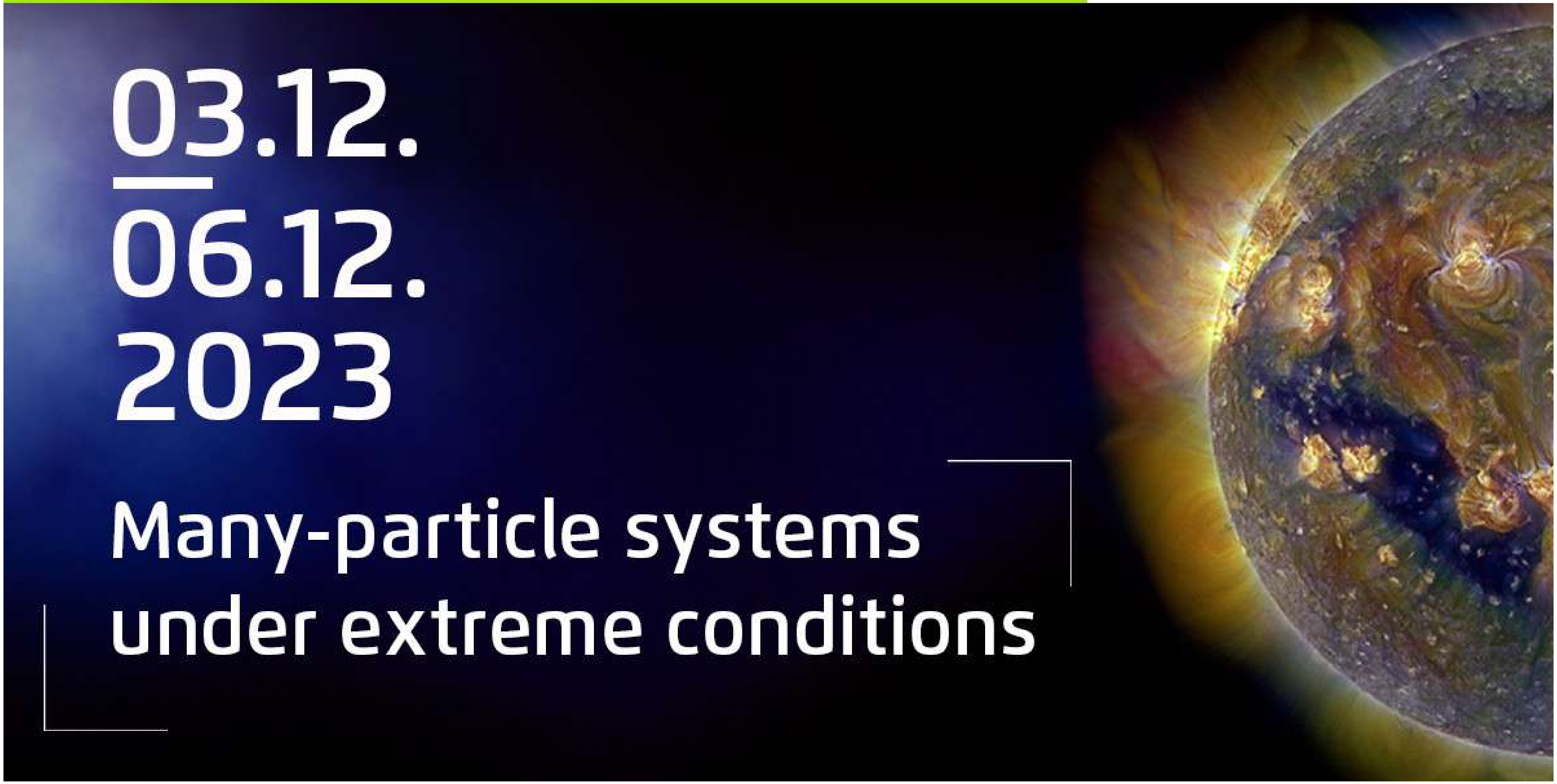


Wroclaw Group ...

Division: Theory of Elementary Particles - Collaborations



Polish-German WE-Heraeus Seminar & Max Born Symposium:



https://events.hifis.net/event/1076

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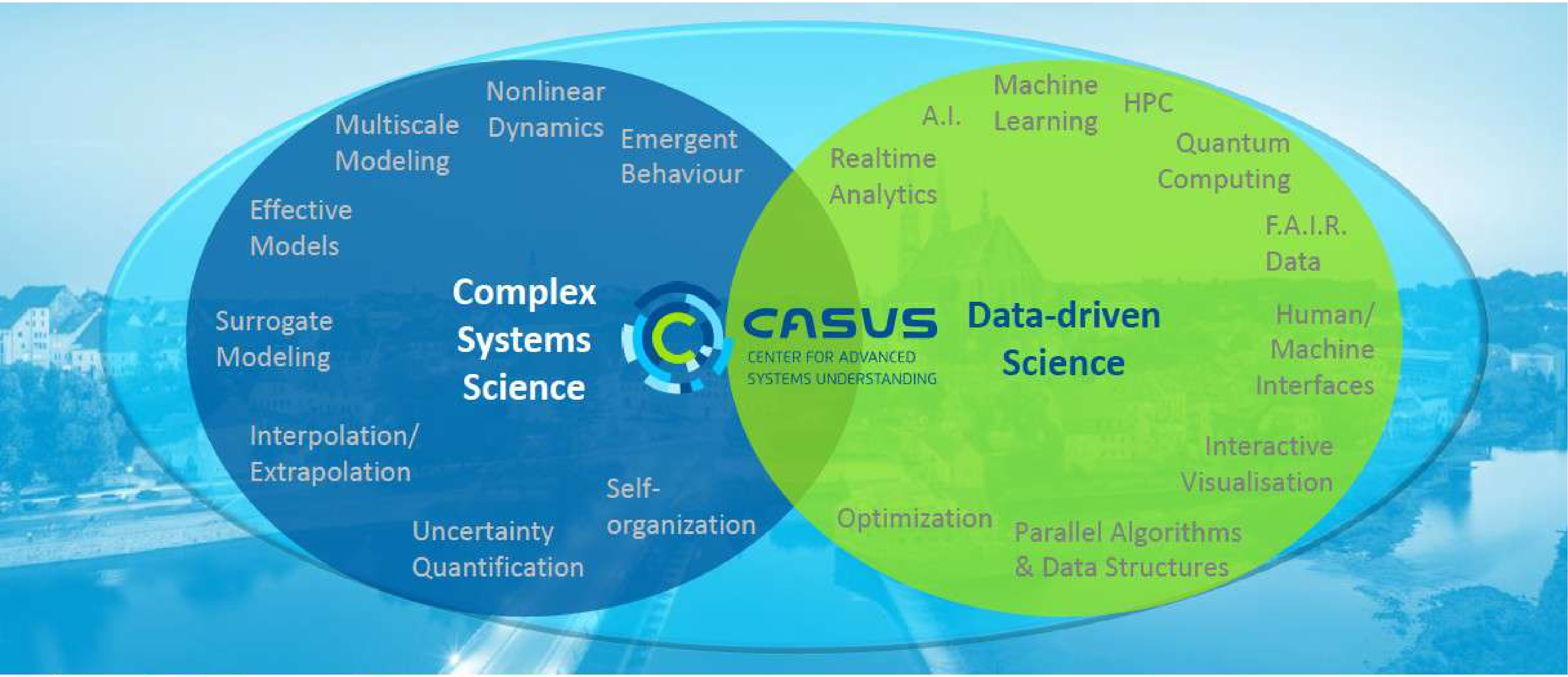
Understanding complex systems with data

CASUS pushes the frontier of data-driven complex systems science



70 people, 20 countries, the brightest minds

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Prof. Dr. Justin Calabrese
Ecological Data Science

Smithsonian

Dr. Attila Cangi
Matter under Extreme Conditions

Sandia National Laboratories

Dr. Artur Yakimovich
Machine Learning for Infection and Disease

Roche UCL

Dr. Ricardo Martinez-Garcia
Dynamics of Complex Living Systems

PRINCETON UNIVERSITY

Dr. Michael Hecht
Mathematical Foundations of Complex System Science

MAX PLANCK INSTITUTE OF MOLECULAR CELL BIOLOGY AND GENETICS

Dr. Weronika Schlechte-Welnicz
SCULTETUS Center

CRTD Center for Regenerative Therapies TU Dresden

Excellence recognized

ERC Starting Grant
Dr. Tobias Dornheim

CASUS/UWr joint Professor
Prof. Dr. David Blaschke

Professor University of Arizona (Faculty)
Dr. Jesse Alston

COLLEGE OF AGRICULTURE & LIFE SCIENCES
Natural Resources & the Environment

Fullbright scholarship
Dr. Debanjan Konar

FULBRIGHT

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New: The German Centre for Astrophysics (DZA)

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Research
Technology
Digitization

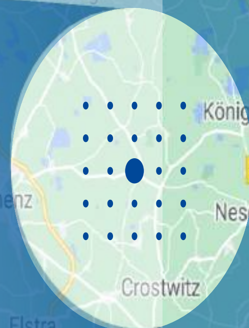
„Science Creating Prospects for the Region!"

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

DZA

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

Location for the Low Seismic Lab

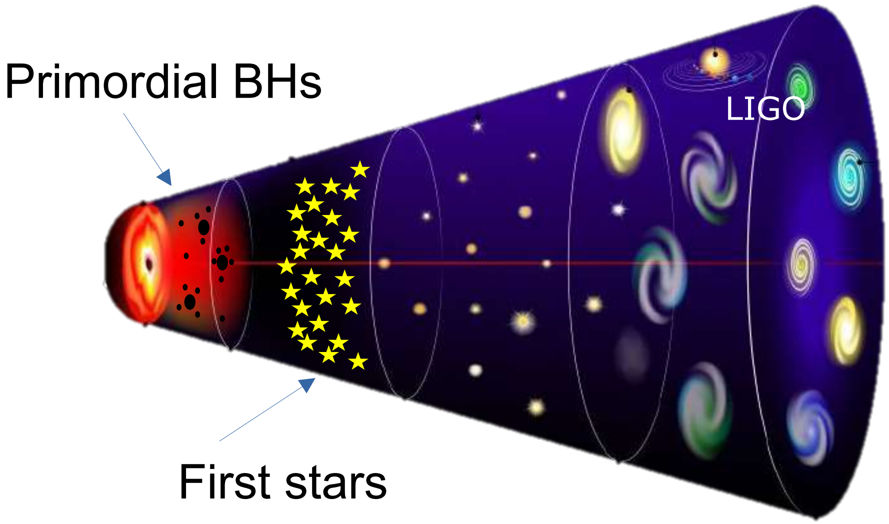


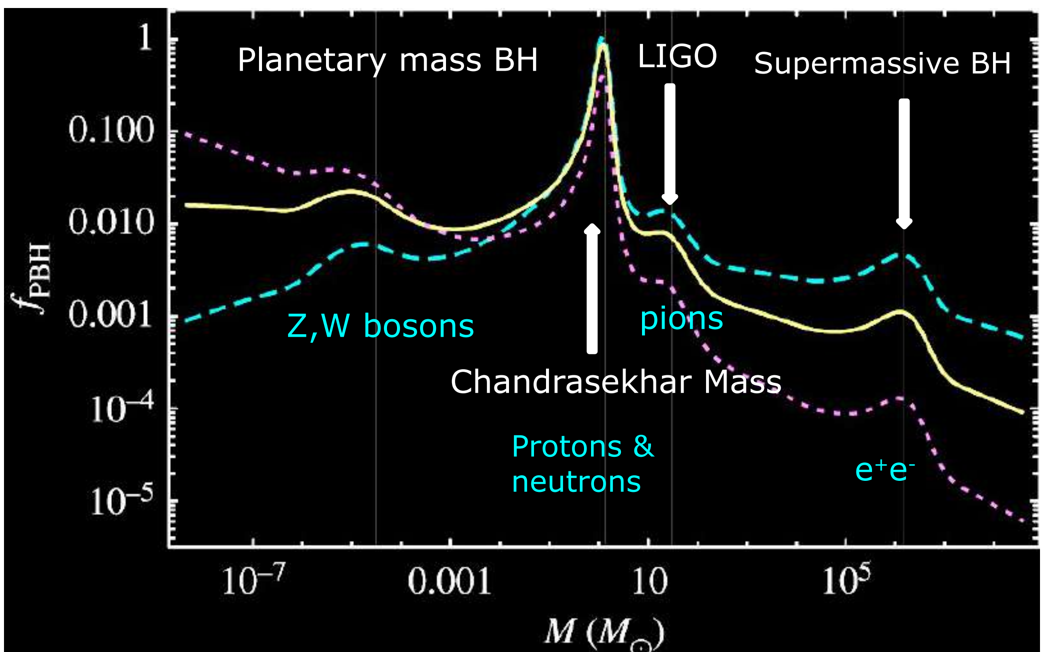
TECHNISCHE UNIVERSITÄT DRESDEN

DZA

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

JWST results – primordial black holes !





Talk at University of Wroclaw by Günther Hasinger, Founding director of the German Centre for Astrophysics In Görlitz:

Key role plays the QCD hadronization transition !

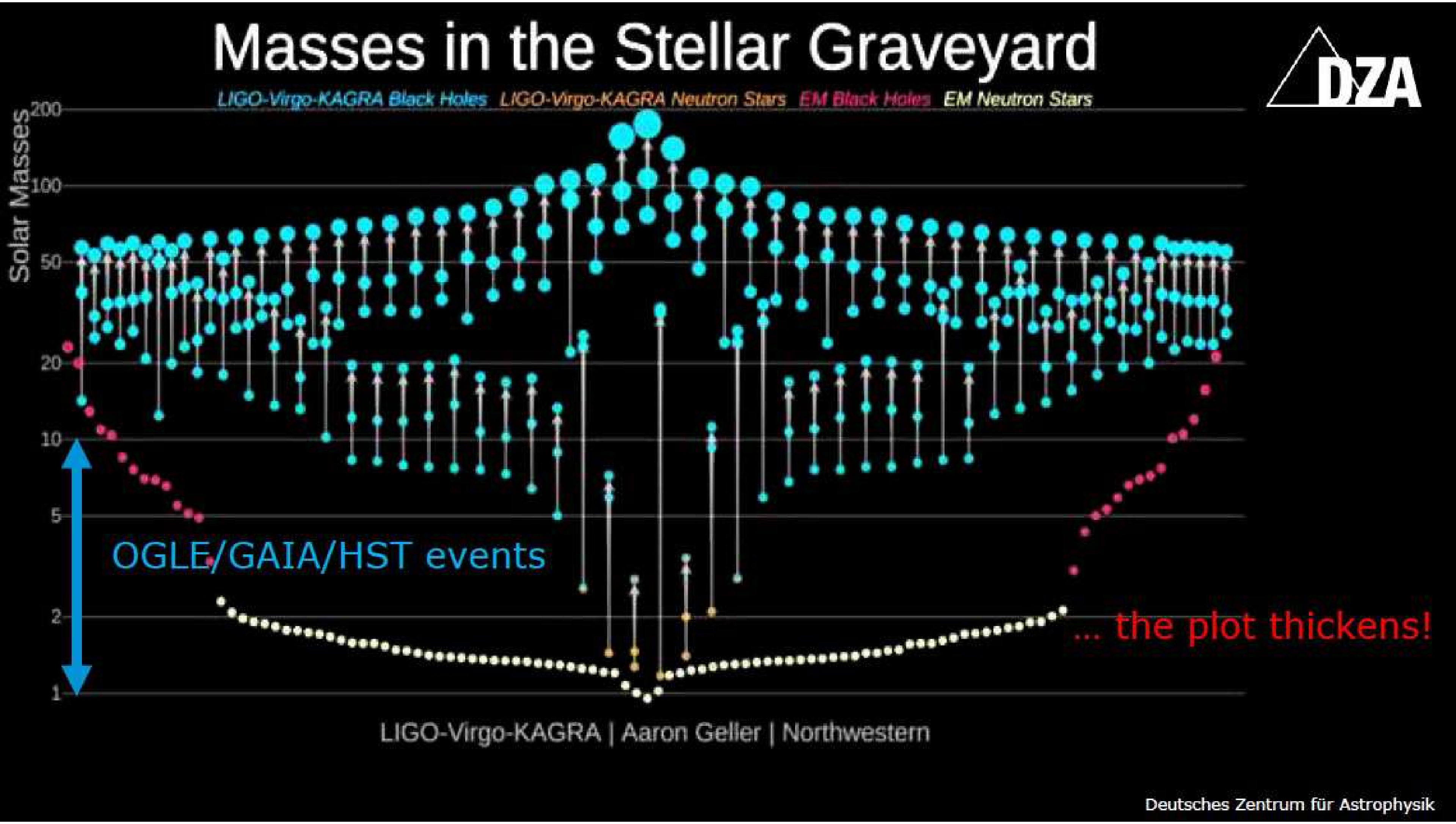
Different peaks correspond to different particles created at the early universe phase transitions and the corresponding reduction in the sound velocity.

BH mass corresponds to the horizon size at each time.

Only requirement is enough fluctuation power in a volume fraction of 10^{-9} of the early Universe.

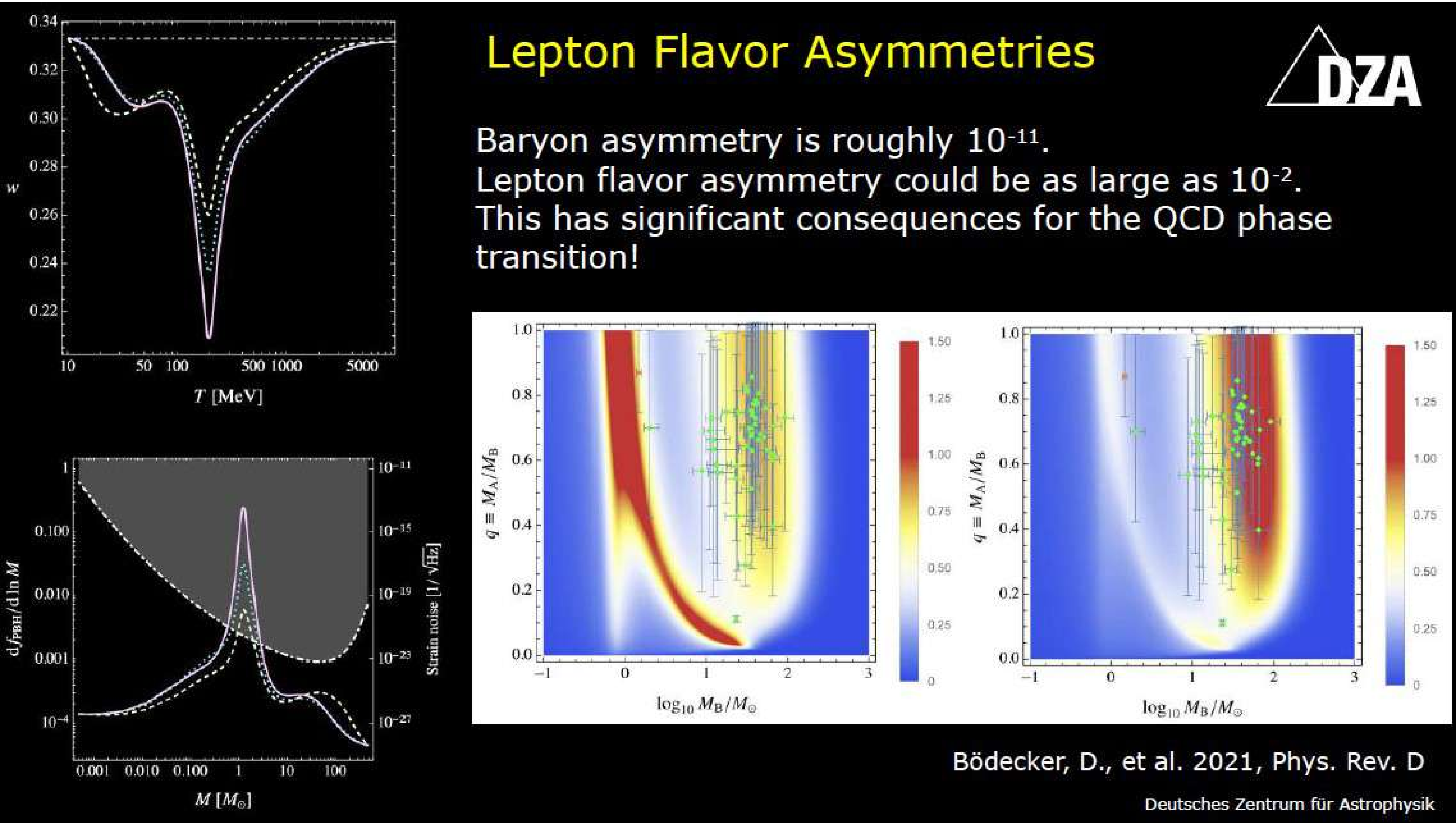
Carr, Clesse, García-Bellido 2019

JWST results – primordial black holes !



Courtesy: Günther Hasinger (Karpacz 2024)

JWST results – primordial black holes !



Courtesy: Günther Hasinger (Karpacz 2024)

JWST results – primordial black holes !

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New constraints on PBH mass function

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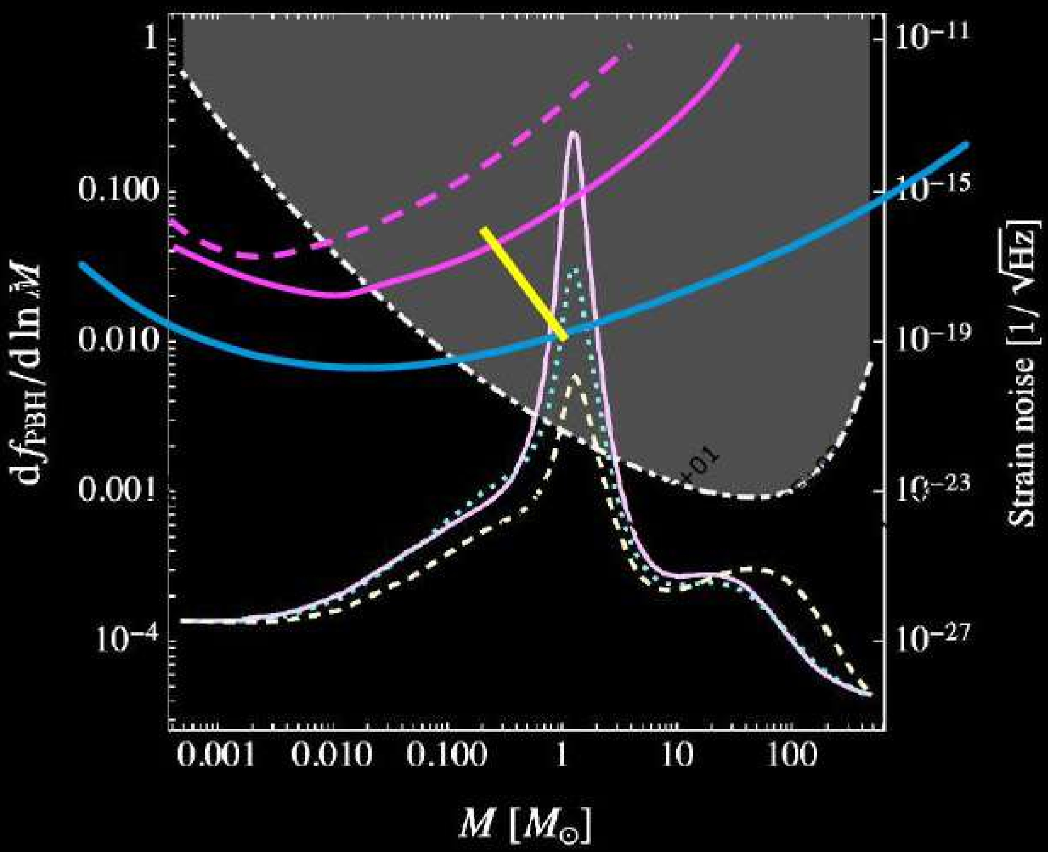

Original MACHO & OGLE microlensing constraints (Wyrzykowski, L., et al. 2011, solid). Reanalysis of the MACHO constraints on PBH in the light of the new Gaia MW rotation curve (Garcia-Bellido, J. & Hawkins, M., 2024, dashed)
New 20-yr OGLE microlensing constraints (Mroz, P. et al., arXiv 2403.02386).
Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run.

➔ Just about fits!

Deutsches Zentrum für Astrophysik

Courtesy: Günther Hasinger (Karpacz 2024)