From hadron resonance gas to quark-gluon plasma via Mott - dissociation of multiquark clusters

David Blaschke (IFT UWr, HZDR/CASUS)

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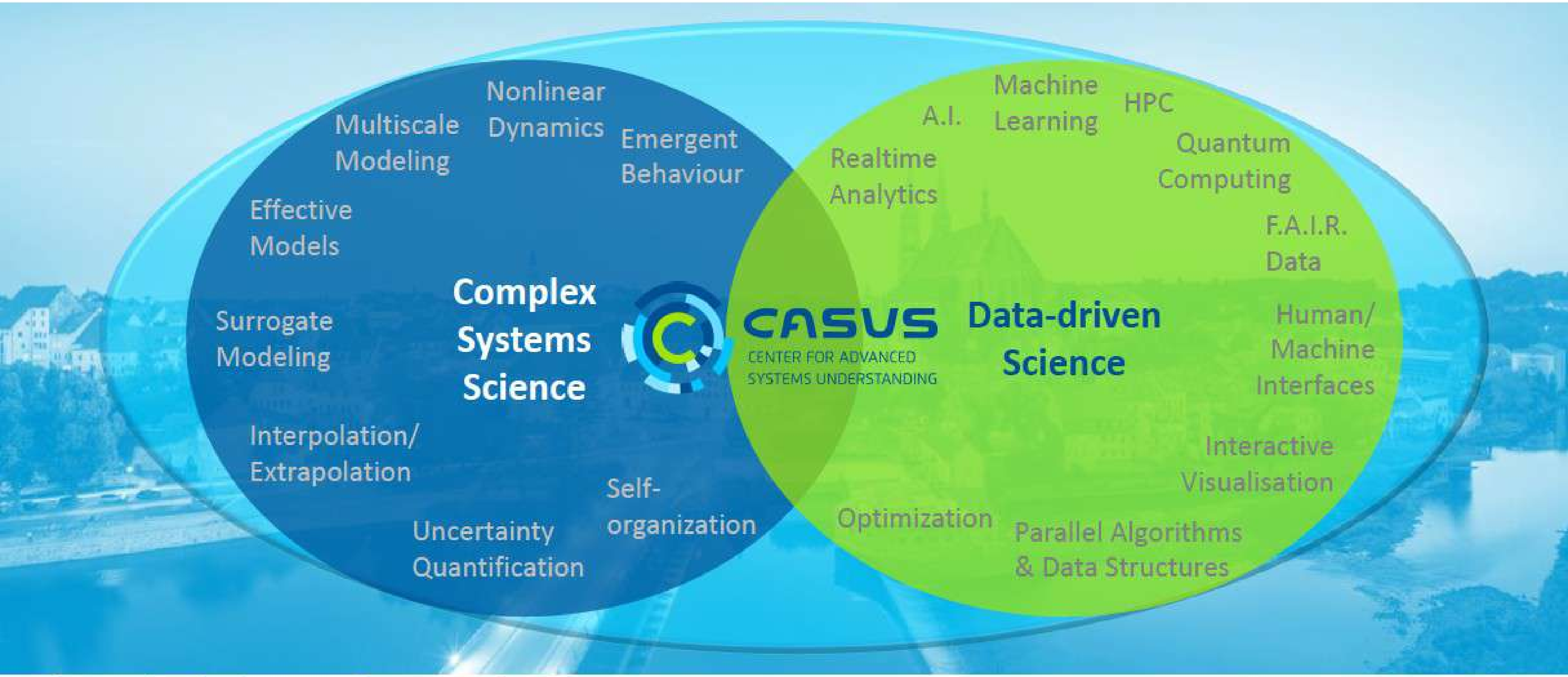

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Thanks to my collaborators:

Uniwersytet Wrocławski

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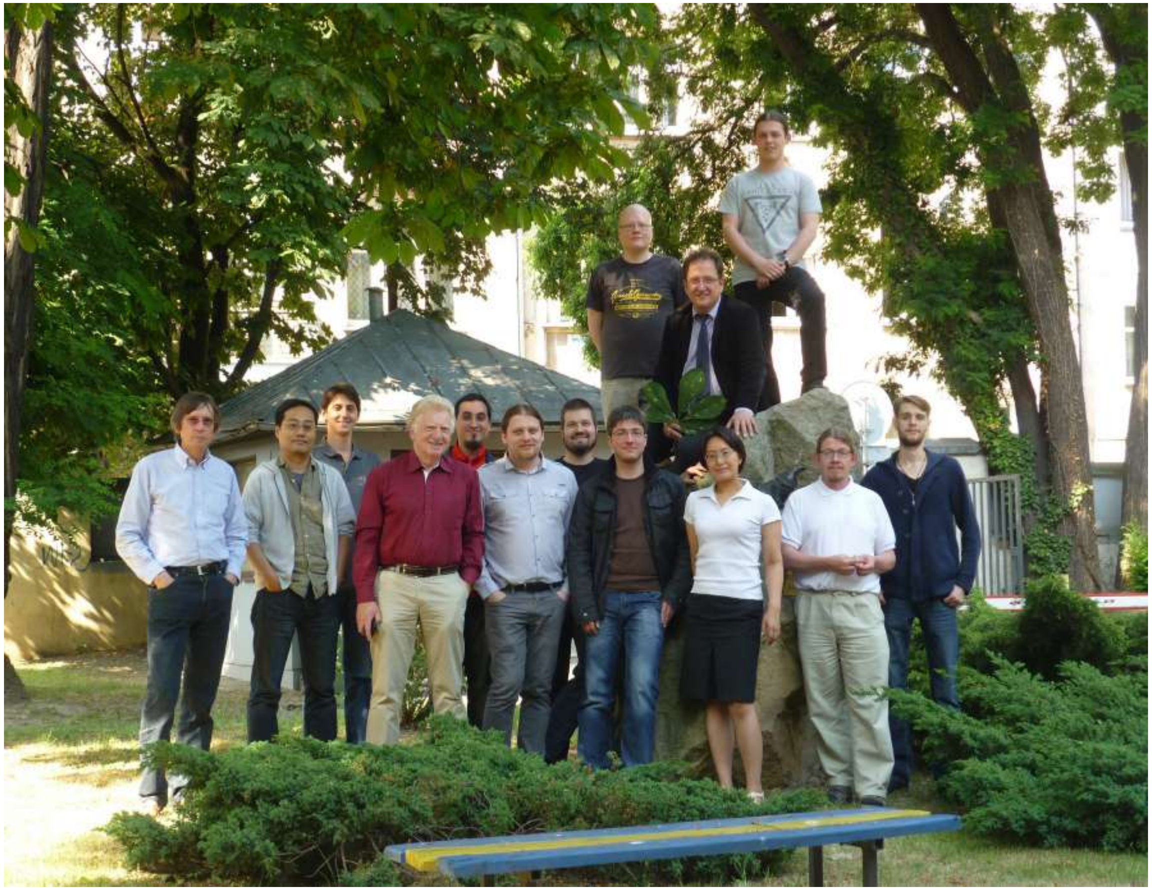

Wroclaw Group ...

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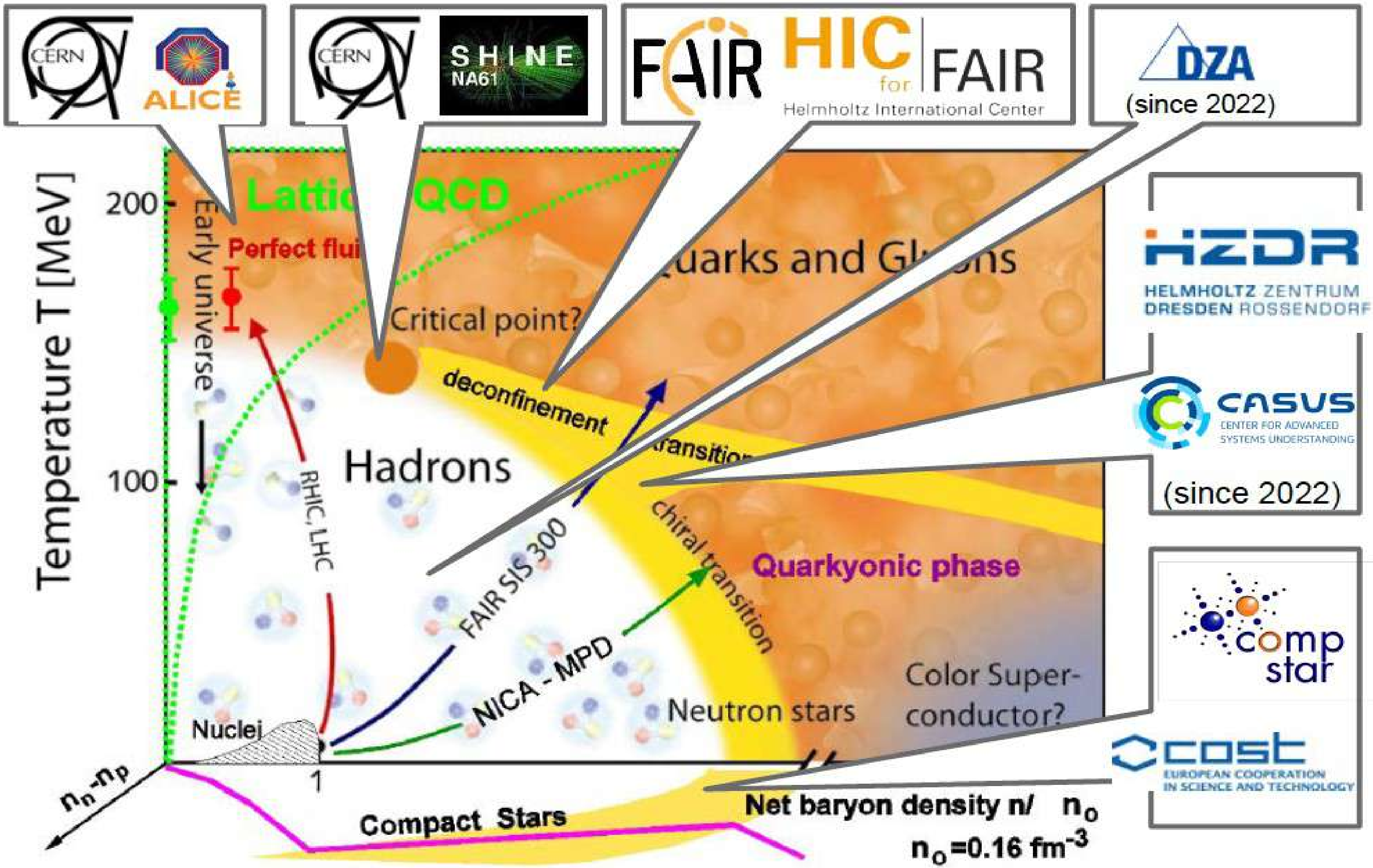
Division: Theory of Elementary Particles - Collaborations



QCD Phase Diagram

Landscape of our investigations

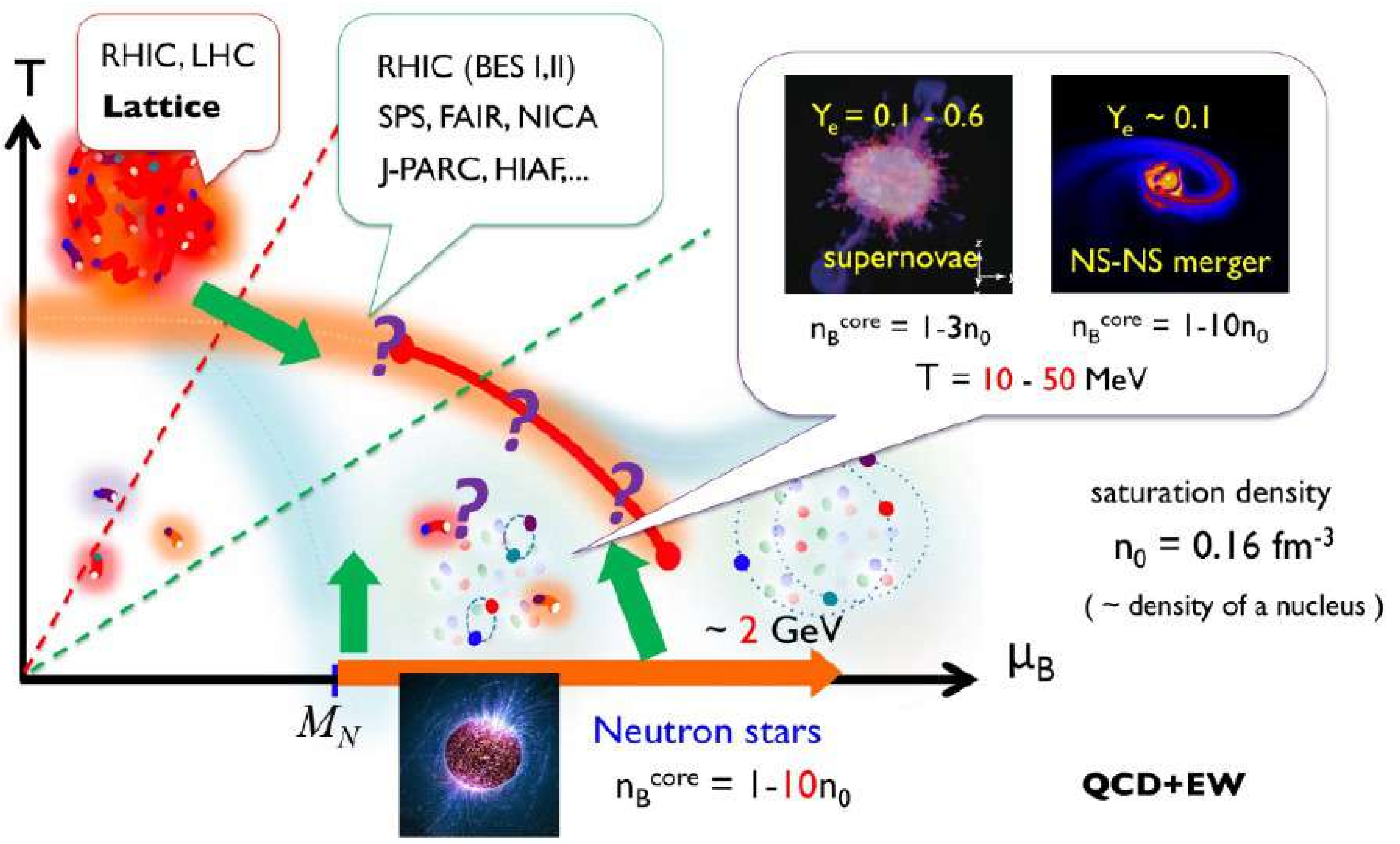
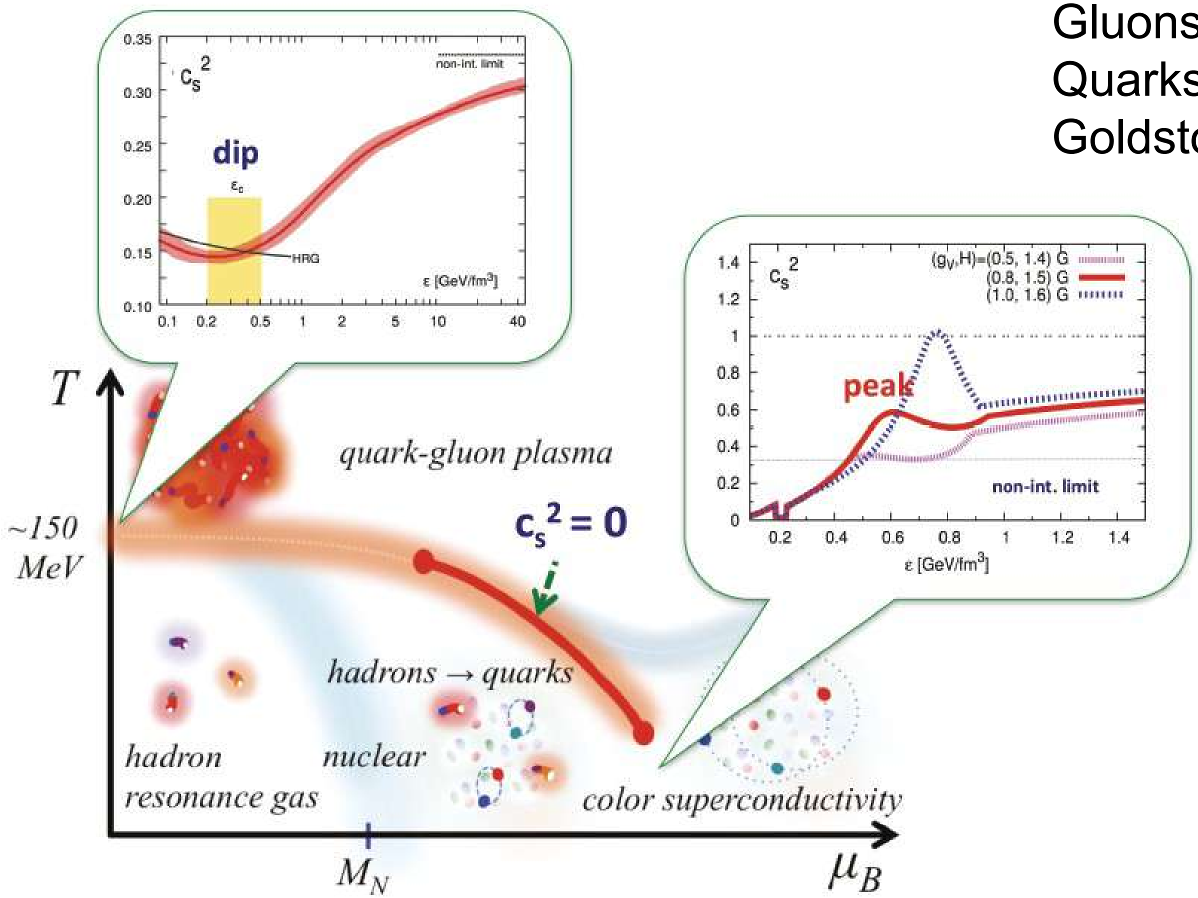


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

QCD Phase Diagram

Landscape of our investigations



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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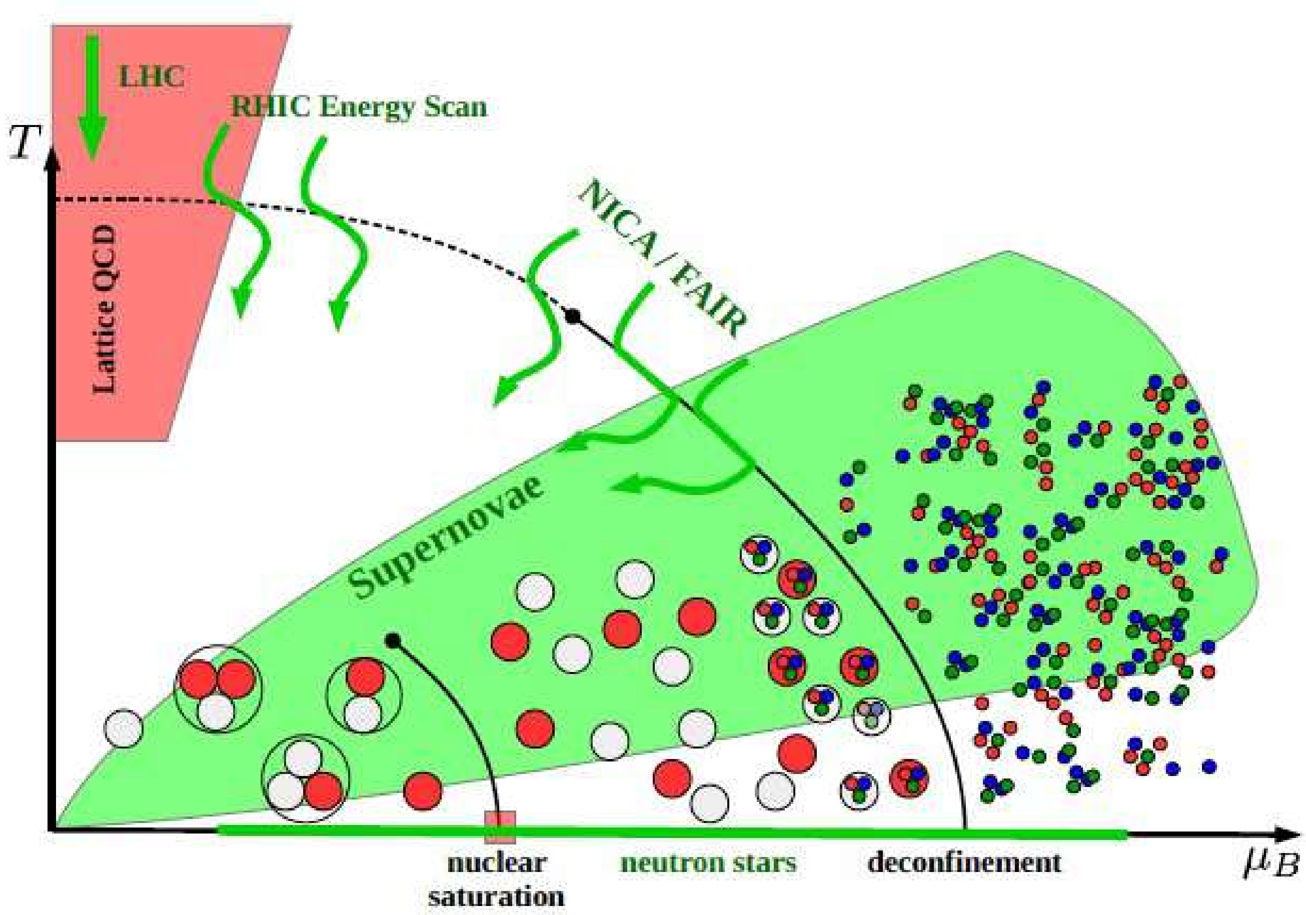
- Phase transition construction and hybrid neutron star properties

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

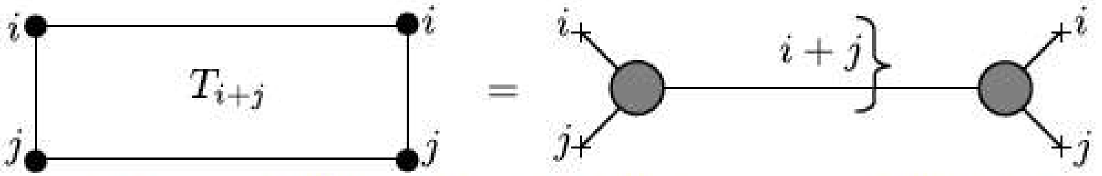
$$\frac{\delta \Omega}{\delta G_A(1 \ldots A, 1' \ldots A', z_A)} = 0 \; .$$

Cluster virial expansion follows for this Φ− functional

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

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

which in the separable approximation for the interaction potential,

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

leads to the closed expression for the T_A matrix

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

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

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

Unified approach to quark-nuclear matter

Useful relationships for many-particle functions

$$G_{i+j}^{(0)} = G_{i+j}^{(0)}(1,2,\ldots,i+j;\Omega_{i+j}) \quad = \quad \sum_{\Omega_i} G_i^{(0)}(1,2,\ldots,i;\Omega_i) G_j^{(0)}(i+1,i+2,\ldots,i+j;\Omega_j) \ .$$

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

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

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

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

which is straightforwardly proven by multiplying Equation for the $T_{i+j}-$ matrix with $G_{i+j}^{(0)}$ 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

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

Unified approach to quark-nuclear matter

Generalized Beth-Uhlenbeck EOS from Φ-deriv.

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

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

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

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

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

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

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

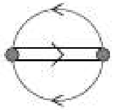
$$\Omega = -\mathrm{Tr}\,\{\ln(-G_1)\} - \mathrm{Tr}\{\Sigma_1 G_1\} + \mathrm{Tr}\,\{\ln(-G_2)\} + \mathrm{Tr}\{\Sigma_2 G_2\} + \Phi[G_1, G_2]\ ,$$

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

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



,

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

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

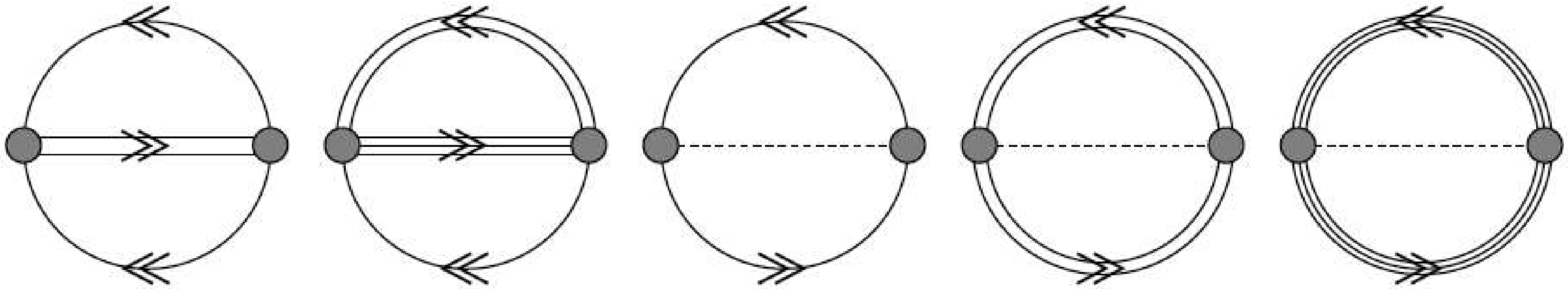
with the correlation density in the generalized Beth-Uhlenbeck form

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

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

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

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 $\Omega_{\rm pert}(T,\mu,\phi,\bar\phi)$.
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

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

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

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)

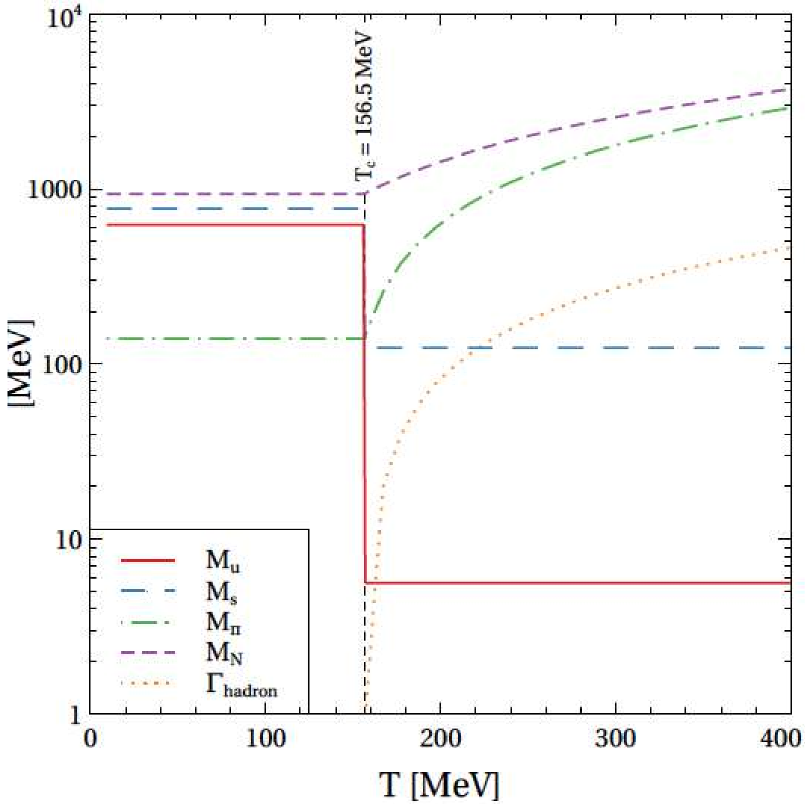
$$f_{\phi=1}^{(a=0,2,4,\dots),\pm} = \frac{y_a^\pm}{1 - y_a^\pm}, \quad f_{\phi=1}^{(a=1,3,5,\dots),\pm} = \frac{y_a^\pm}{1 + y_a^\pm},$$

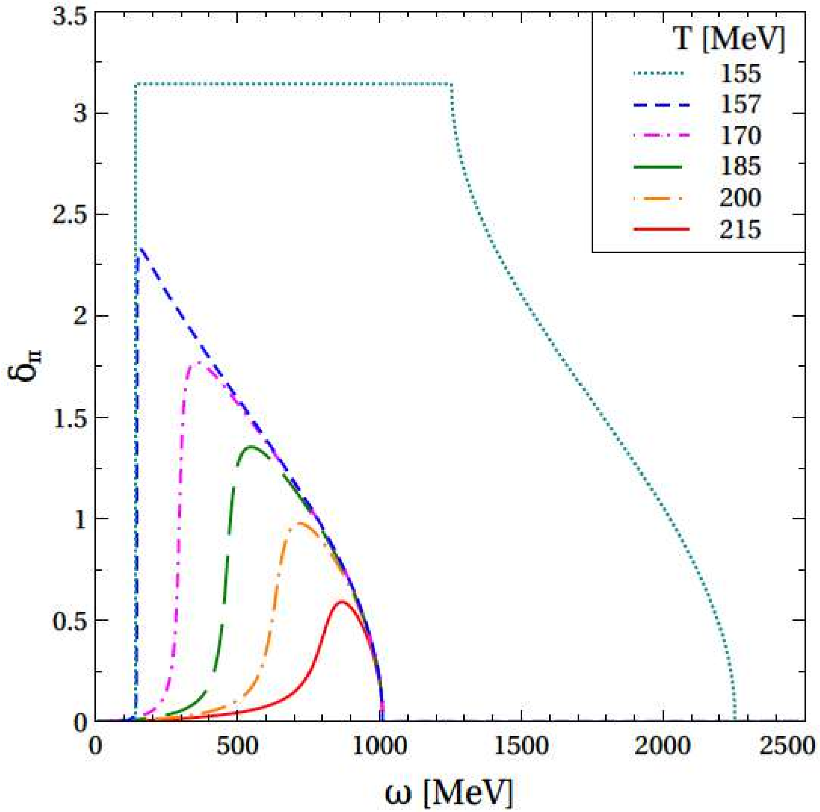
and $\phi = \bar{\phi} = 0$ (confinement),

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

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

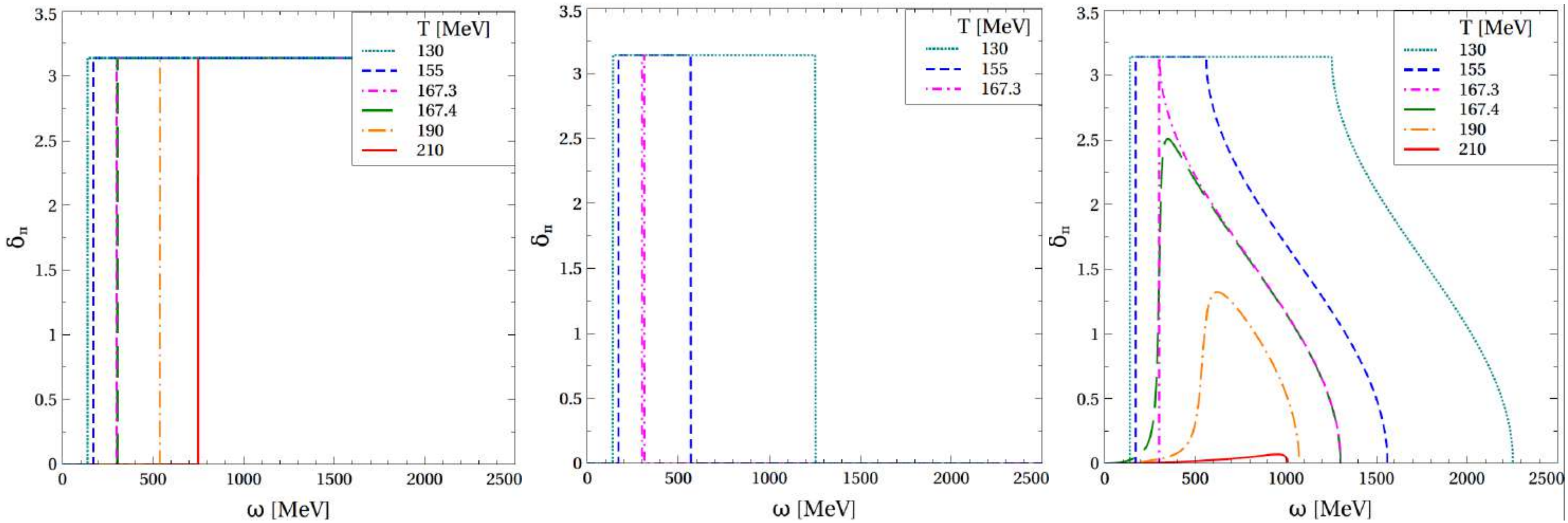
PDG baryons	d_i	$M_{\rm PDG}$ [MeV]	M_i [MeV]	$M^<_{{\rm th},i}$ [MeV]	$M^>_{{\rm th},i}$ [MeV]
n/p	4	939	939	1881	16.8
Λ	2	1116	1082	2024	135.2
Σ	6	1193	1082	2024	135.2
Δ	16	1232	1251**)	3135	28
Ξ^0	2	1315	1225	2167	253.6
Ξ^-	2	1322	1225	2167	253.6
$\Sigma(1385)$	6	1385	1394**)	3278	146.4
$\Lambda(1405)$	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 Step-up-continuum model → Mott Hadron Resonance Gas (MHRG)

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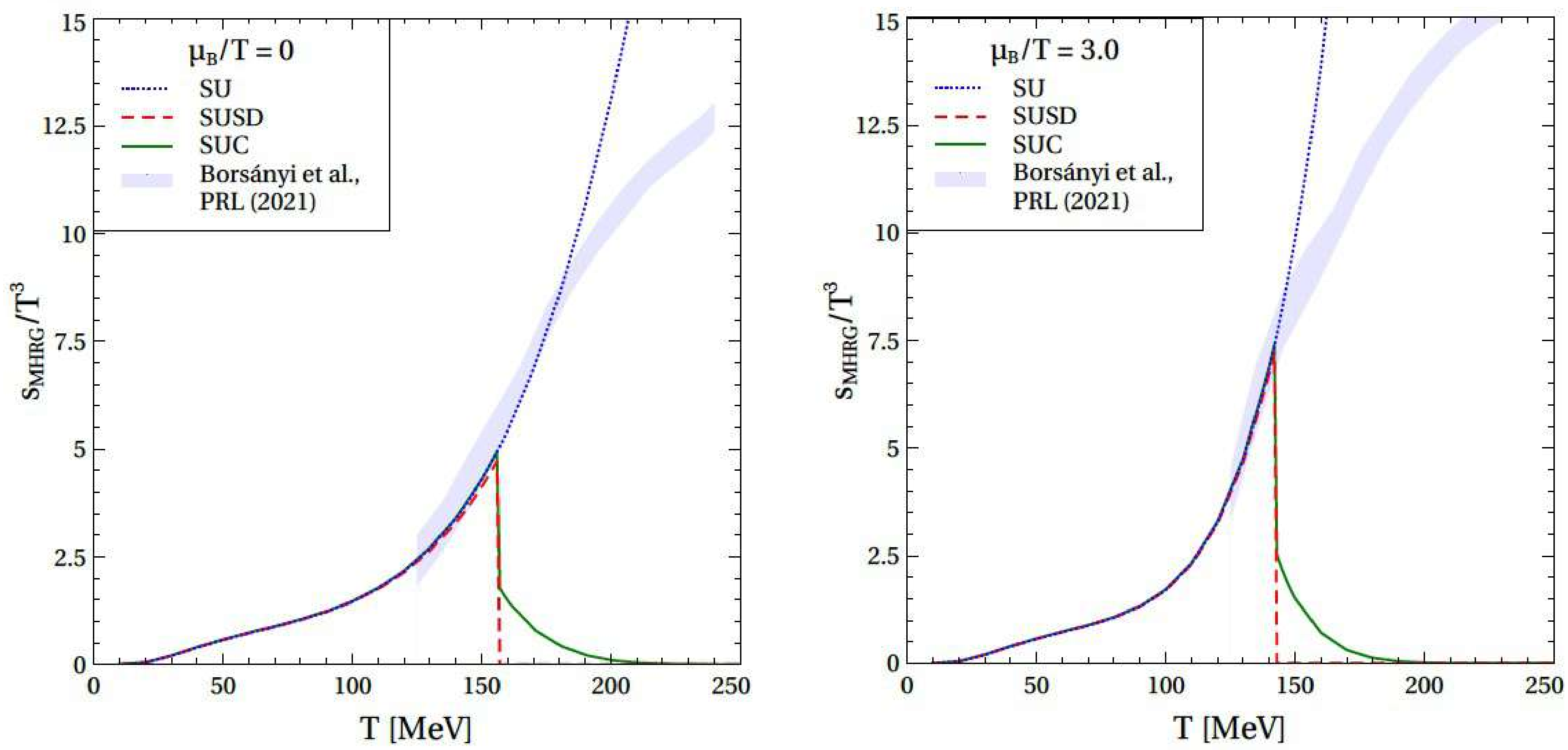
Unified approach to quark-hadron matter

Results for Mott-Hadron Resonance Gas (MHRG)



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

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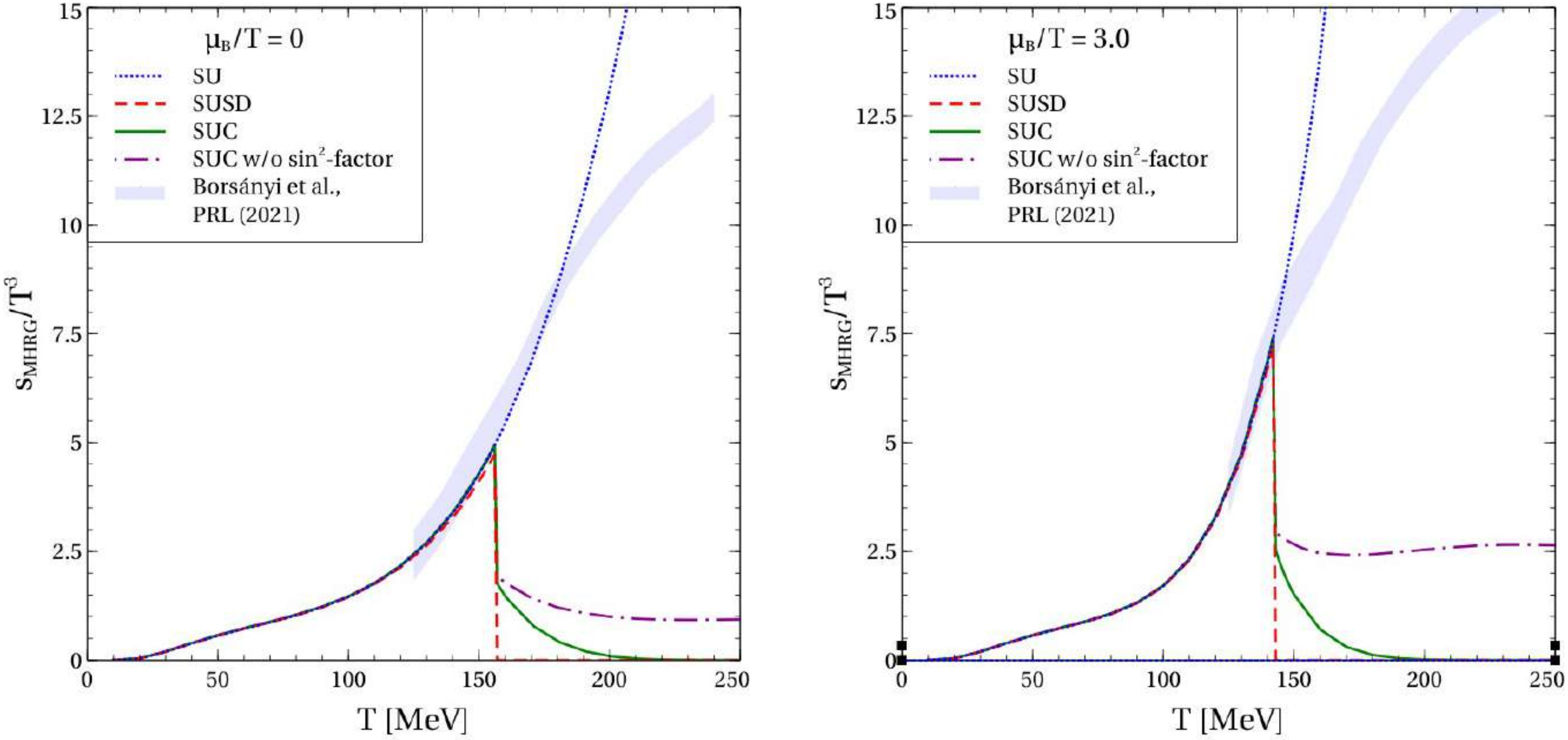
Entropy for MHRG: role of the $\sin^2$-term



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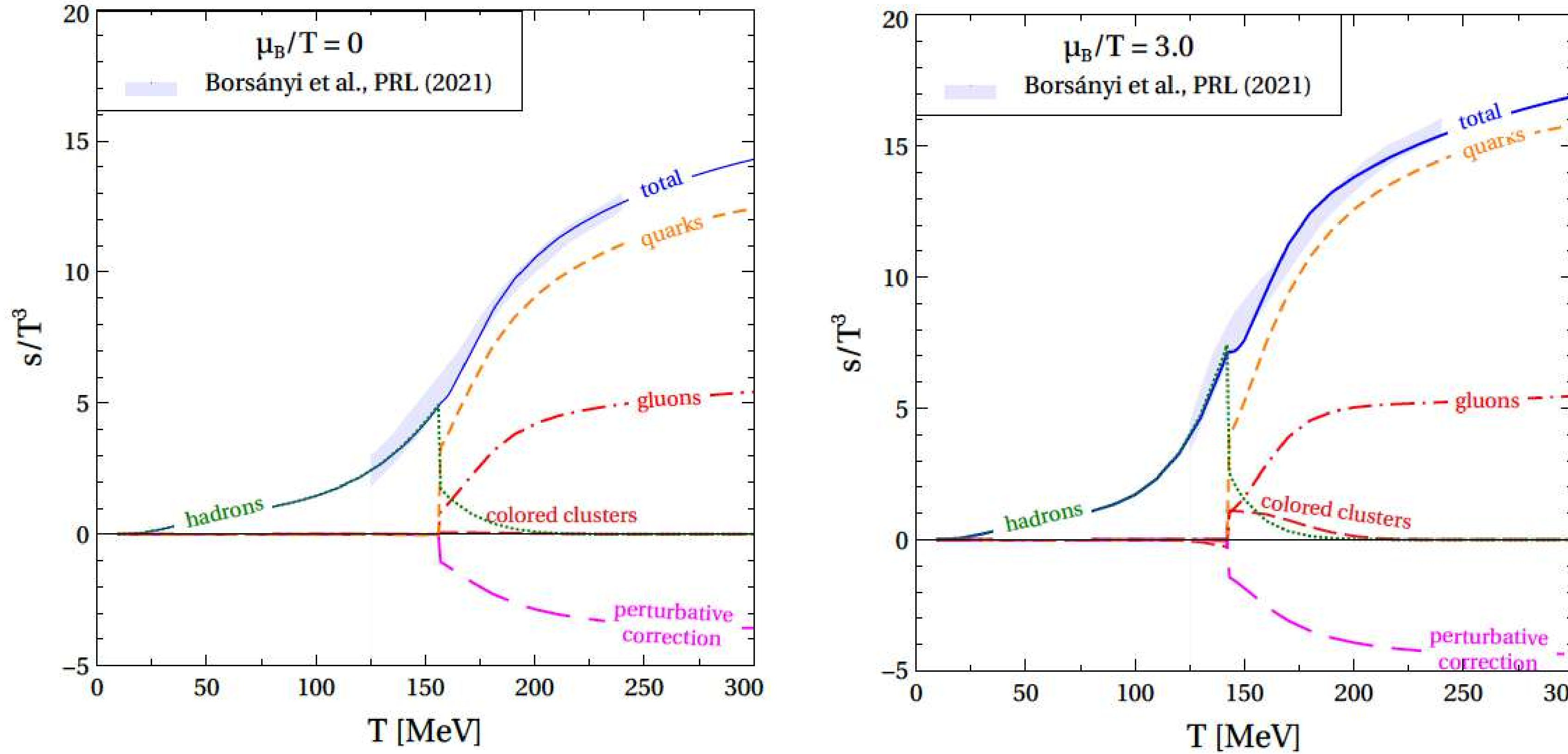
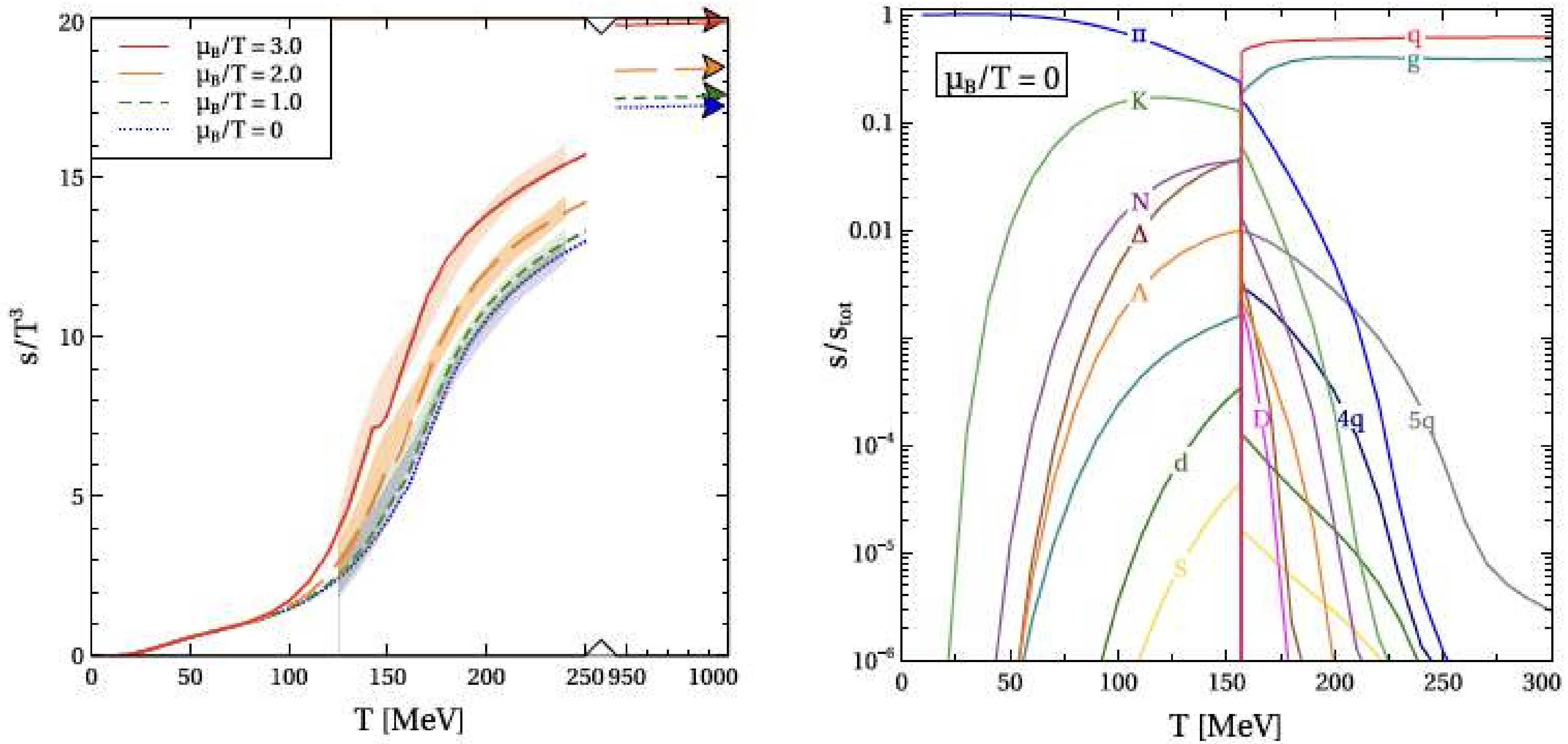
Results for the entropy density



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

Unified approach to quark-hadron matter

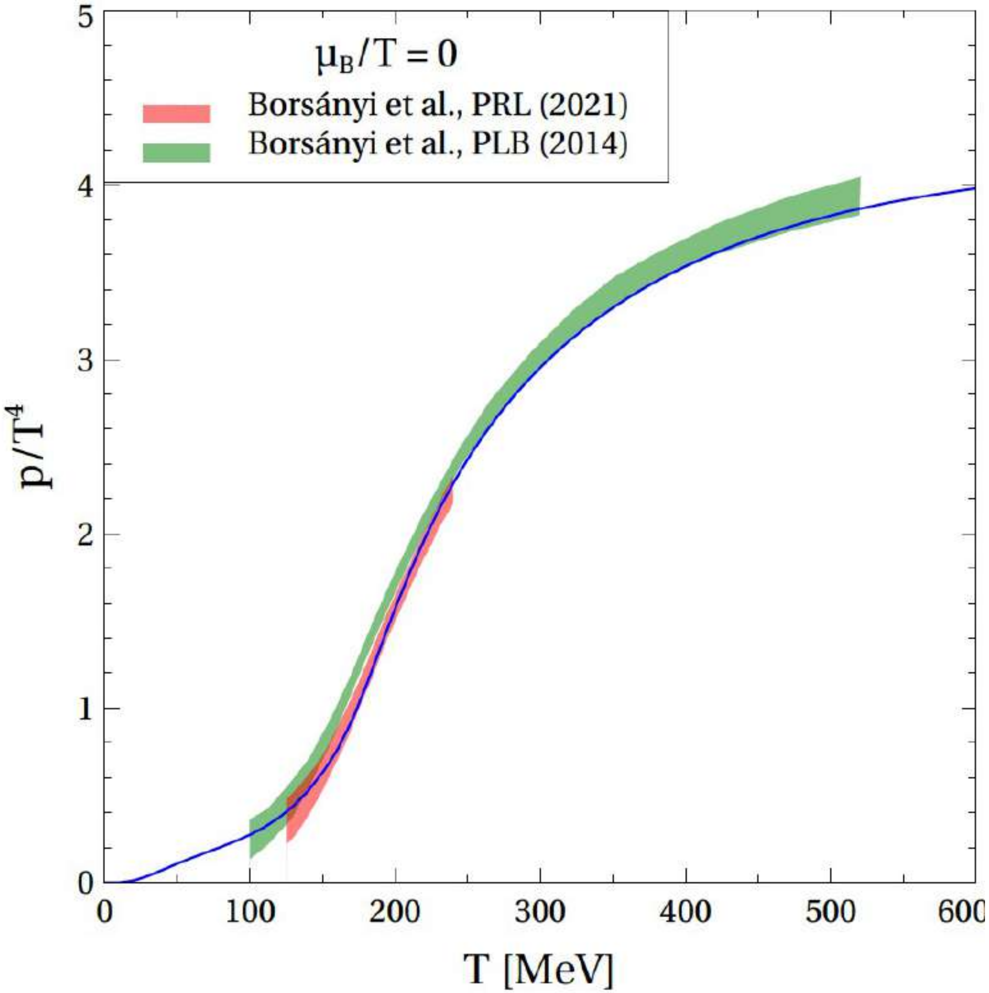
Results for the entropy density & composition



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

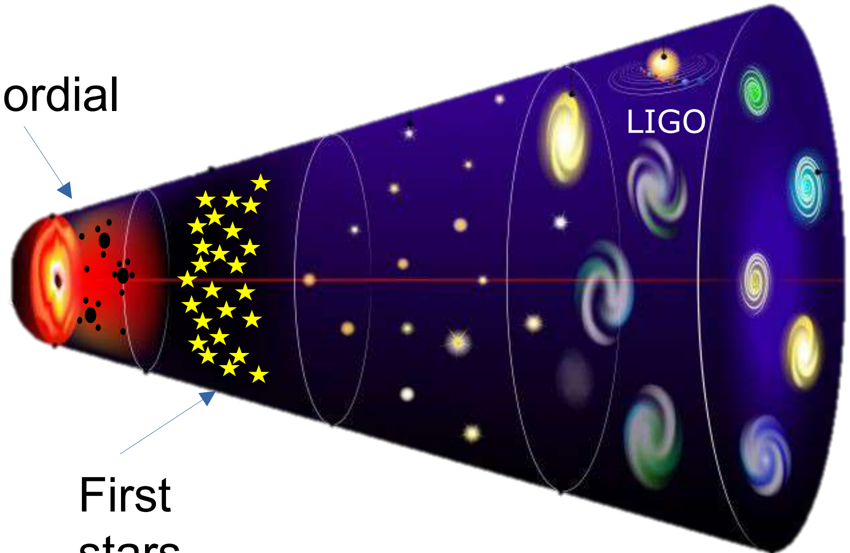
Unified approach to quark-hadron matter

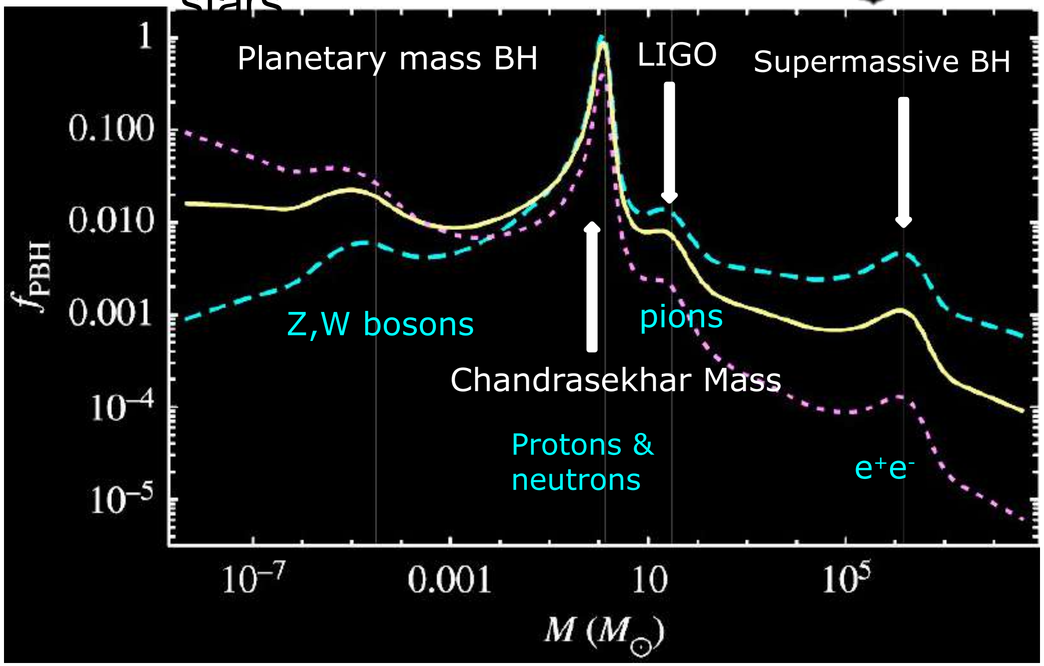
Results for pressure=thermodynamic potential



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

JWST results – primordial black holes !





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

DZA

Key role plays the QCD hadronization transition !

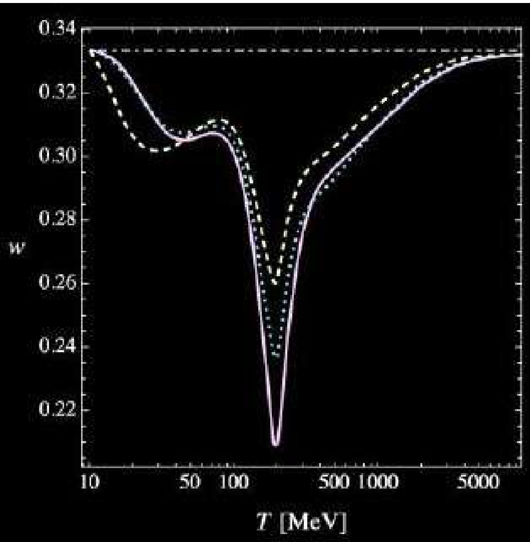
Different peaks correspond to different particles created at the early universe phase transitions and the corresponding reduction in the sound velocity.

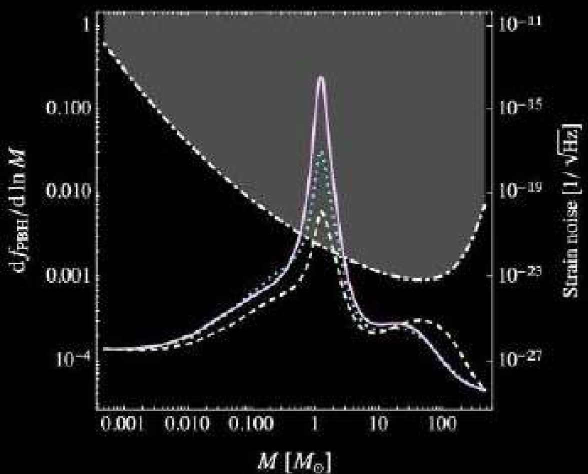
BH mass corresponds to the horizon size at each time.

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 !

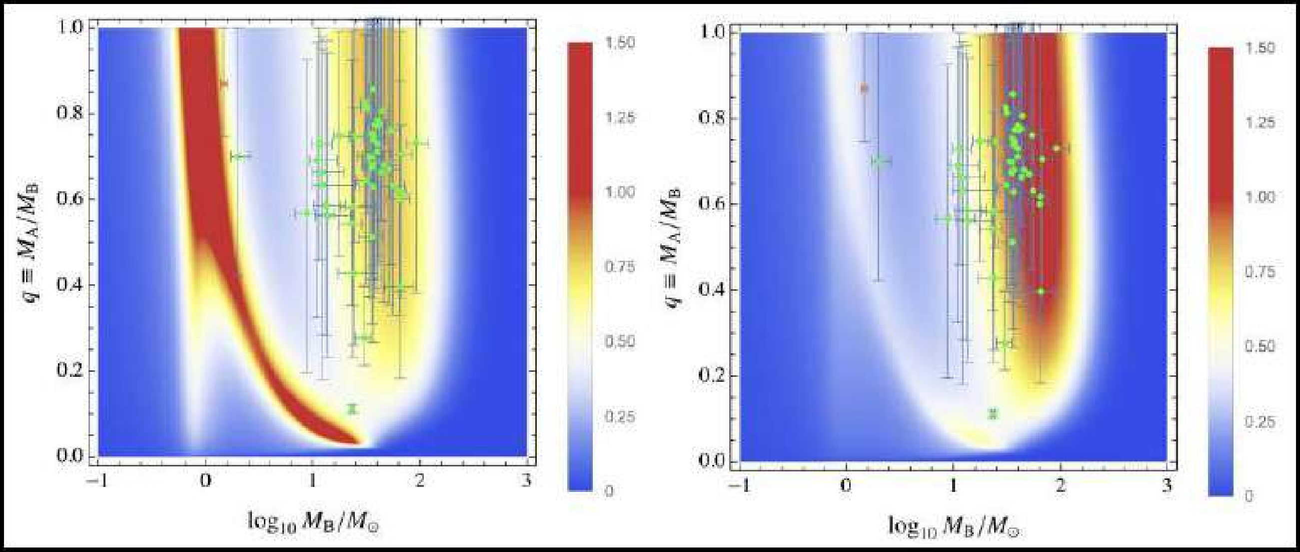




Lepton Flavor Asymmetries

DZA

Baryon asymmetry is roughly 10^{-11}.
Lepton flavor asymmetry could be as large as 10^{-2}.
This has significant consequences for the QCD phase transition!



Bödecker, D., et al. 2021, Phys. Rev. D

Deutsches Zentrum für Astrophysik

Courtesy: Günther Hasinger (Karpacz 2024)

JWST results – primordial black holes !

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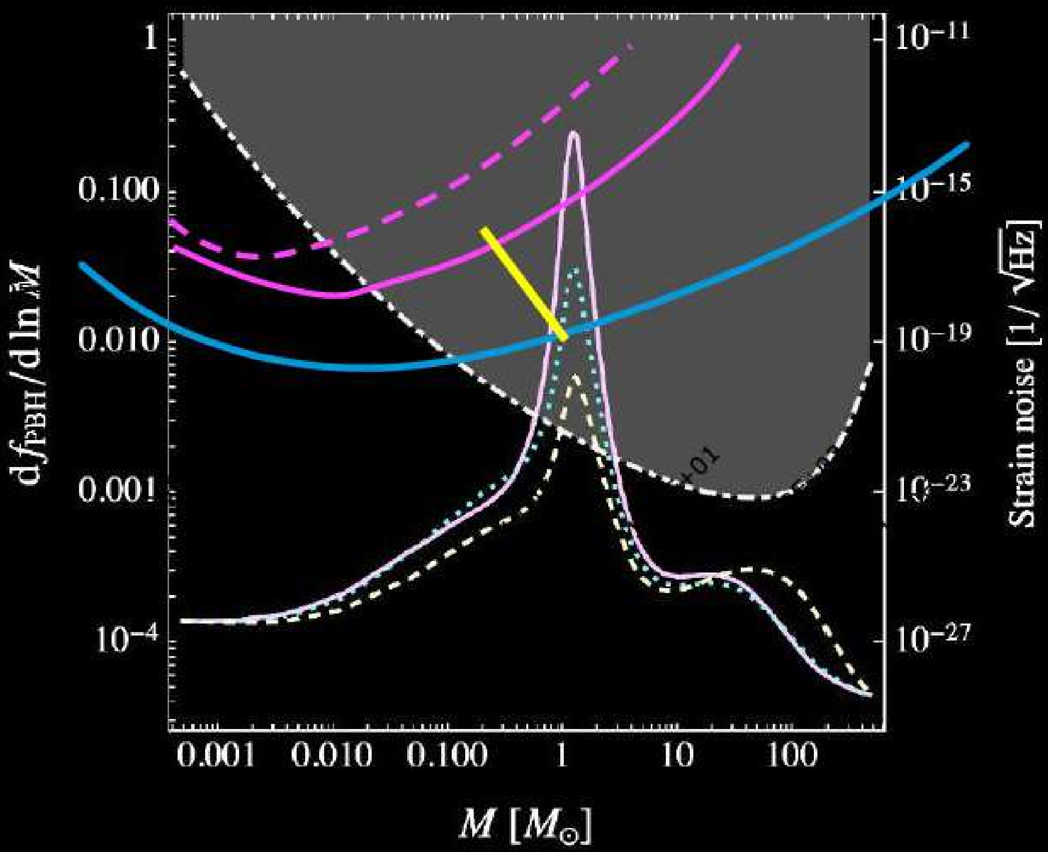
SYSTEMS UNDERSTANDING

New constraints on PBH mass function

DZA



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).

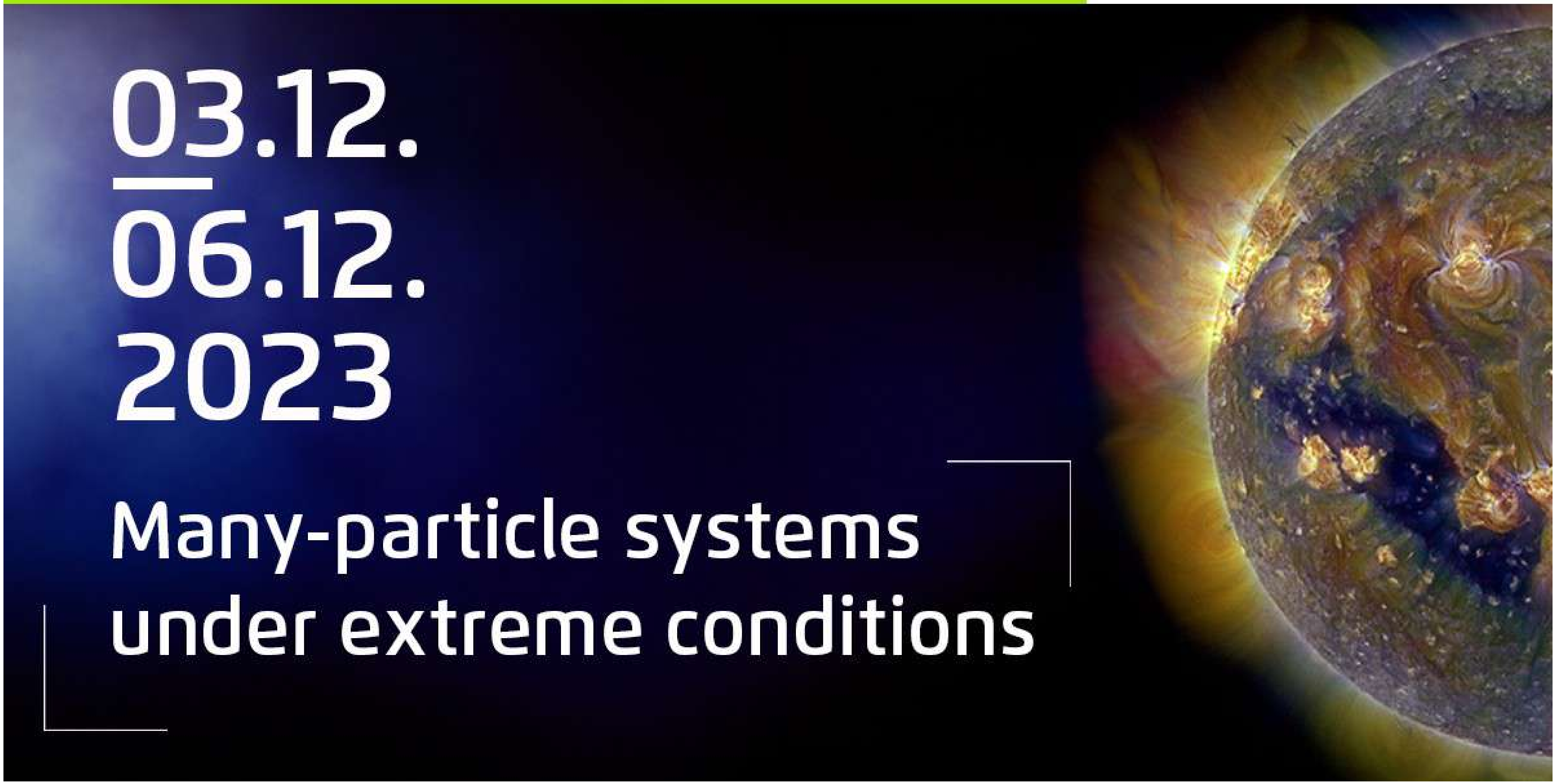
Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run.

➔ Just about fits!

Deutsches Zentrum für Astrophysik

Courtesy: Günther Hasinger (Karpacz 2024)

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



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