On the phase structure and equation of state of strongly-interacting matter

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in collaboration with
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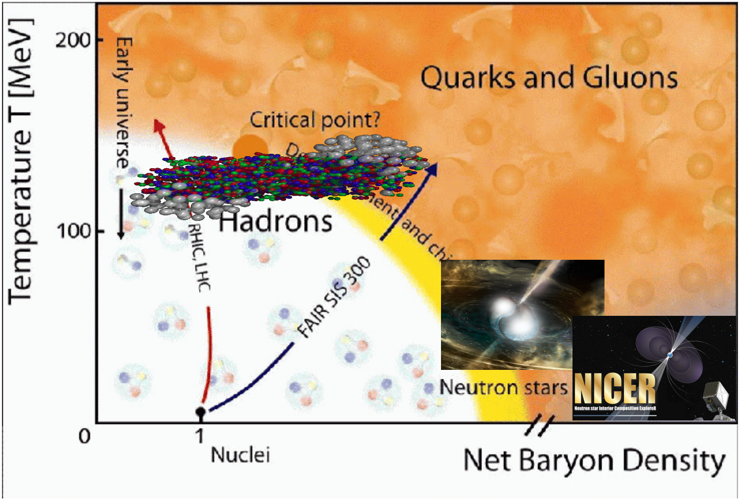
Sezione di Torino

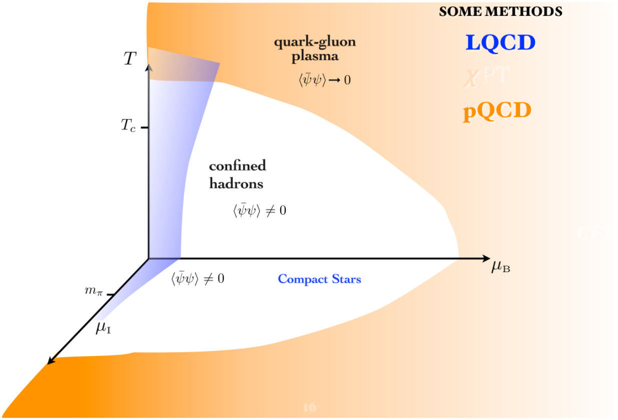
Observations on the Phase Diagram of QCD



GSI/FAIR; UrQMD; LIGO; NICER

Phase structure of the strong interaction

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left[\,\mathrm{i}\,\gamma_\mu\,(\partial^\mu - \mathrm{i}\,gA^\mu) - m + \gamma_0\,\mu_f\,\right]q - \frac{1}{4}\,G^a_{\mu\nu}\,G^{\mu\nu}_a$$



after Massimo Mannarelli, `Mannarelli-IAPS-2016.pdf`

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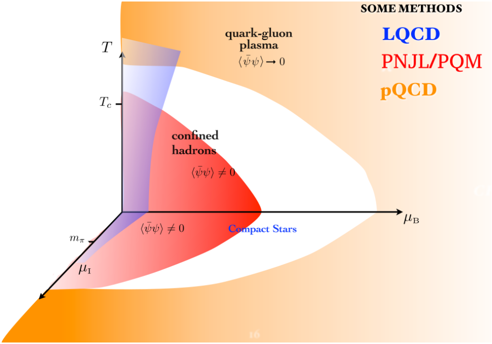

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$\mathcal{L}_{\mathrm{PNJL/PQM}}$

Outline

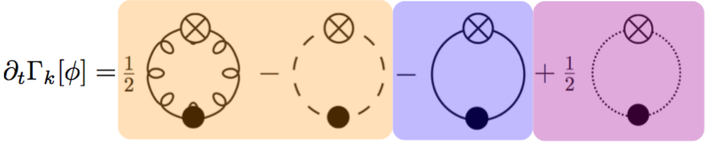
1. **Introduction: Different ways to describe the generation of constituent quark masses**
2. **Results: Nambu–Jona-Lasinio model vs. Quark-Meson model**
3. **Results: Comparison to lattice results**
4. **Conclusions**

From QCD to the PNJL and PQM model

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left[\,\mathrm{i}\,\gamma_\mu\left(\partial^\mu - \mathrm{i}\,g A^\mu\right) - m + \gamma_0\,\mu_f\right] q - \frac{1}{4}\,G^a_{\mu\nu}\,G^{\mu\nu}_a$$

glue quantum fluctuations

hadronic quantum fluctuations



free energy

quark quantum fluctuations

RG-scale k: $t = \ln k$

NJL-model QM-model PNJL-model PQM-model

$\mathcal{L}_{\mathrm{NJL}}$ $\mathcal{L}_{\mathrm{QM}}$ $\mathcal{L}_{\mathrm{PNJL}}$ $\mathcal{L}_{\mathrm{PQM}}$

J.-M. Pawlowski, `Talk_Pawlowski_ERG2012.pdf`

Polyakov-loop extended NJL and QM model

$$\mathcal{L}_{\mathrm{PNJL/PQM}} = \mathcal{L}_{\mathrm{chiral}} + \mathcal{L}_{\mathrm{Polyakov-loop}} + \mathcal{L}_{\mathrm{kinetic,interaction}}$$

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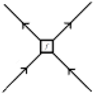

$$\mathcal{L}^{\mathrm{NJL}}_{\mathrm{chiral}} = G\left[(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2\right] - m_0\,(\bar{q}q)$$

A. Cabo Montes de Oca, *Eur. Phys. J. C (2018) 78*

Polyakov-loop extended NJL and QM model

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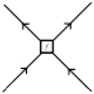
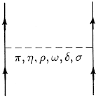


$$\mathcal{L}_{\mathrm{chiral}}^{\mathrm{NJL}} = G\left[(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2\right] - m_0\,(\bar{q}q)$$

$$\mathcal{L}_{\mathrm{chiral}}^{\mathrm{QM}} = \bar{q}\left[g\left(\sigma + i\gamma_5\vec{\tau}\vec{\pi}\right)\right]q - h\sigma + \frac{\lambda^2}{4}\left(\sigma^2 + \pi^2 - v^2\right)^2$$



A. Cabo Montes de Oca, *Eur. Phys. J. C (2018) 78*; P. Veselý, `NN_potential.pdf`

Polyakov-loop extended NJL and QM model

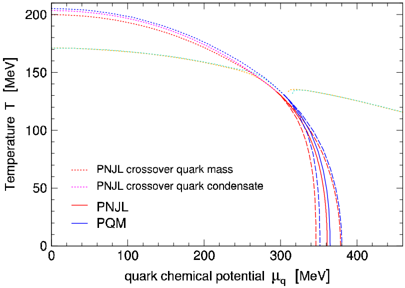
$$
\begin{aligned}
\Omega_{\mathrm{PNJL/PQM}}\left(m_q, \Phi, \bar{\Phi}, T, \mu\right) &= U_{\mathrm{chiral}}\left(m_q\right) + \\
&+ \mathcal{U}_{\mathrm{Polyakov-loop}}\left(\Phi, \bar{\Phi}, T(, \mu)\right) + \\
&+ \Omega_{\bar{q}q}\left(m_q, \Phi, \bar{\Phi}, T, \mu\right)
\end{aligned}
$$

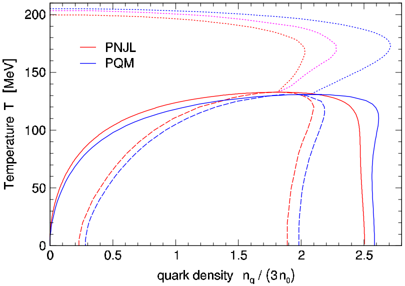
$$
\begin{aligned}
U^{\mathrm{NJL}}_{\mathrm{chiral}} &= \frac{\left(m_q - m_0\right)}{4G} \\
U^{\mathrm{QM}}_{\mathrm{chiral}} &= \frac{\lambda^2}{4}\left(\sigma^2 - v^2\right)^2 - h\sigma \,; \quad m_q = g\sigma
\end{aligned}
$$

Comaprison of PNJL and PQM model results

- Comparing results of both models using the same vacuum phenomenlology *(which wasn't done so far!)*

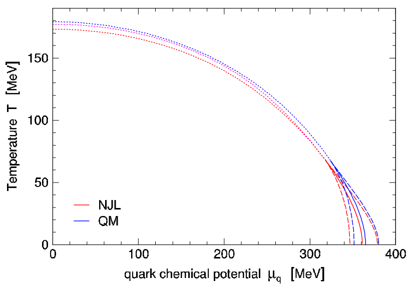
Constant	f_π	m_π	m_K	m_η	$m_{\eta'}$	m_σ	m_ℓ	m_s	Λ
Value [MeV]	92.4	135	497.7	514.8	957.8	728.9	367.7	549.5	602.3

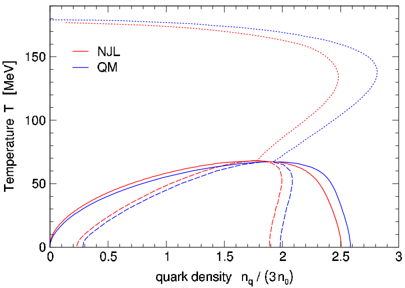




W. Alberico, A. Beraudo, R. C. Pereira, P. Costa, H. Hansen, M. Motta and RS, *in preparation*

Comparison of NJL and QM model results





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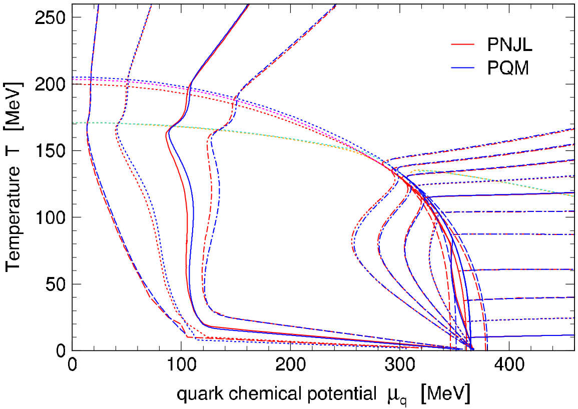
⇒ results for NJL vs QM show that differences come from the chiral part, as to be expected

Comaprison of PNJL and PQM model results

Lines of constant entropy per baryon $S/N = s/n$



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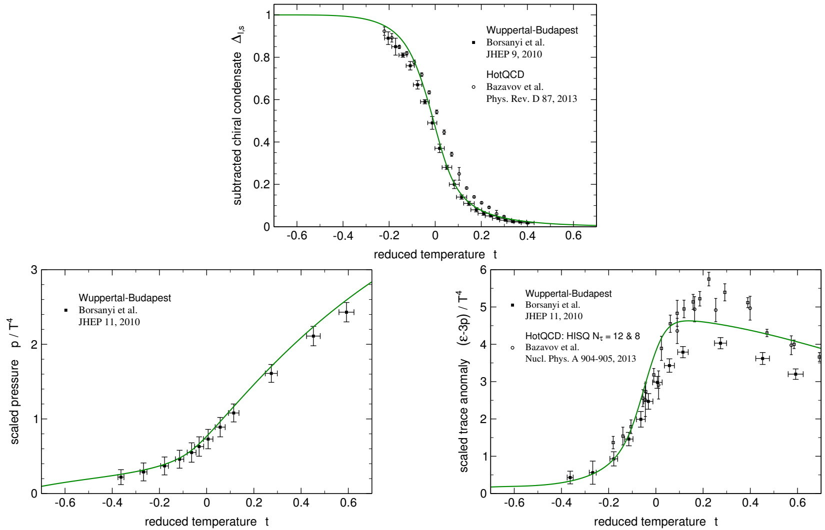
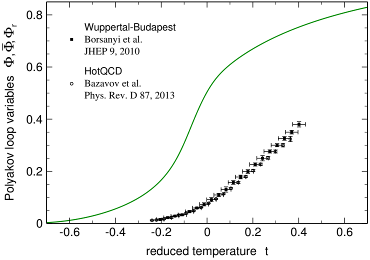
Such a model vs. lattice



Such a model vs. lattice

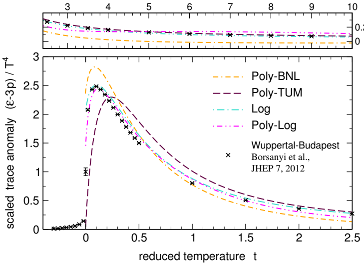
- Chiral transition and thermodynamics compare well ...but

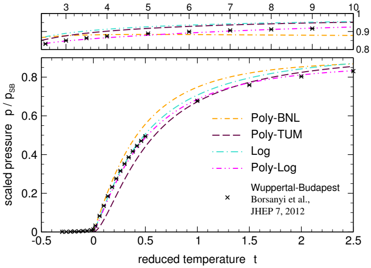


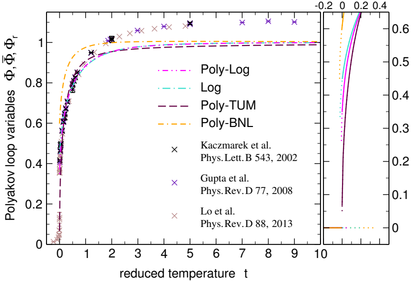
- The Polyakov-loop (~ order parameter of confinement) rises faster...

$\Rightarrow$ How is the situation in pure gauge theory (gluons only) ?

Model ingredient vs. lattice in pure gauge

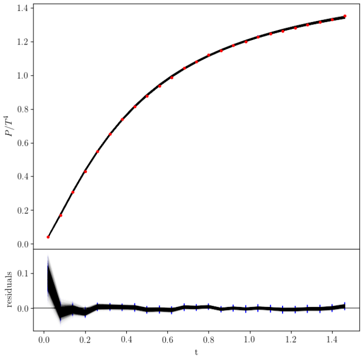


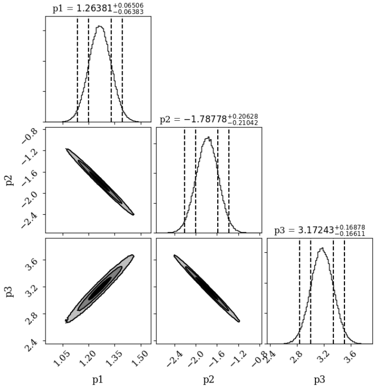




⇒ quite some scatter between lattice and model

New fit to pure gauge lattice data

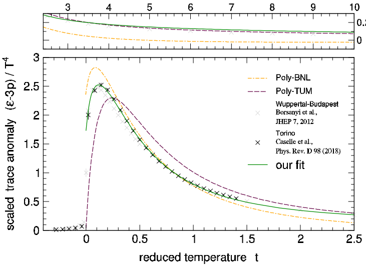


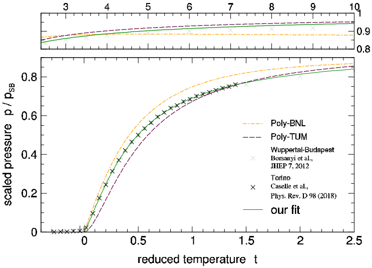


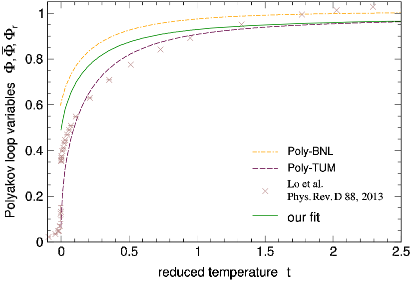
N. Baillot, H. Hansen, RS, *in preparation*
data from *M. Caselle, A. Nada, and M. Panero, Phys. Rev. D 98 (2018)*

Perform a new fit of the parameters of the Polyakov-loop potential to today's lattice data in pure gauge theory

Model ingredient vs. lattice in pure gauge



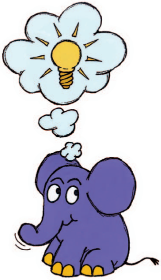




$\Rightarrow$ comparable situation as in QCD:
thermodynamics fits well,
but order parameter for deconfinement overshooted

Conclusions

- To describe the region of the phase diagram that is not accessible with ab-initio methods chose a framework that describes fundamental properties: constituent quark masses and deconfinement.
- Quark interaction can be described by point-like interaction or due to meson exchange.
- If both models are adjusted to the same vacuum physics both descriptions give compatible results.
- Ab-initio results can be ~reproduced at zero/small density.
- Deviations for the ‘order parameter’ for deconfinement already in pure gauge theory.



Thank You for your attention!

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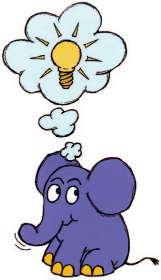

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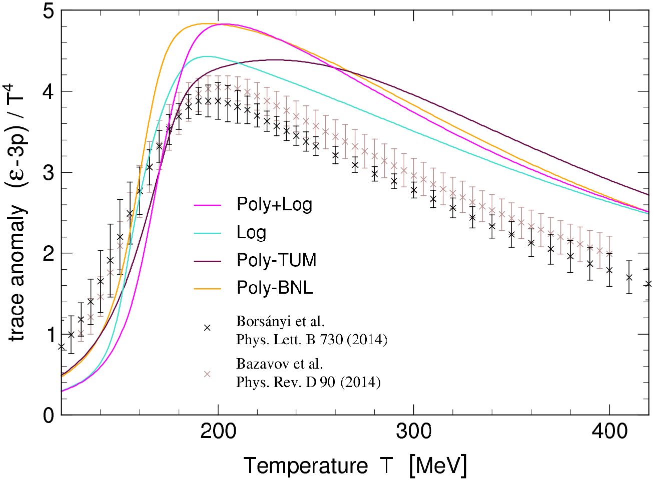

Densities at phase transition