Phase structure and thermodynamics of strongly-interacting matter

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in collaboration with
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CPHT, École polytechnique; 28/09/2017

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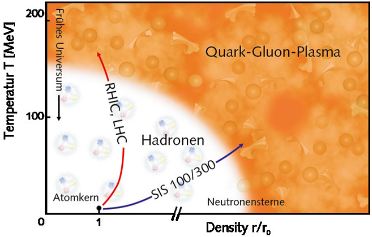
Sezione di Torino

Outline

Phase structure of the strong interaction

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



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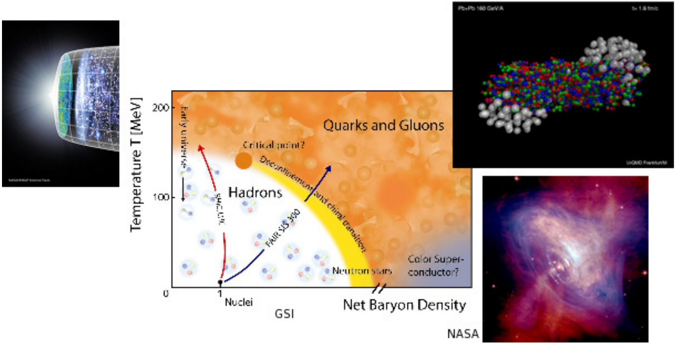
- low temperature & density: phase of confined, massive constituent quarks
- high temperature and/or density: phase of ‘massless’, deconfined quarks and gluons

Observations on the Phase Diagram of QCD



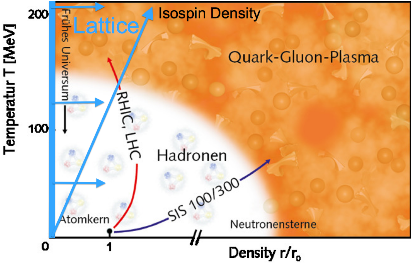
Probed in

- Early universe at small density and high temperature
- Compact star matter at small temperature and high density
- Relativistic heavy-ion collisions at LHC, RHIC, NICA, FAIR, . . .

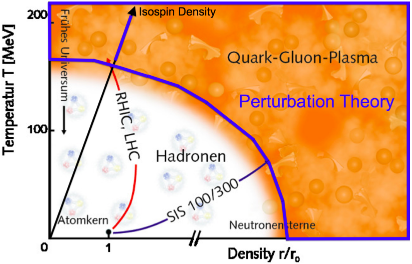
Theoretical Insights to the Phase Diagram of QCD

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

Lattice QCD



Perturbation theory



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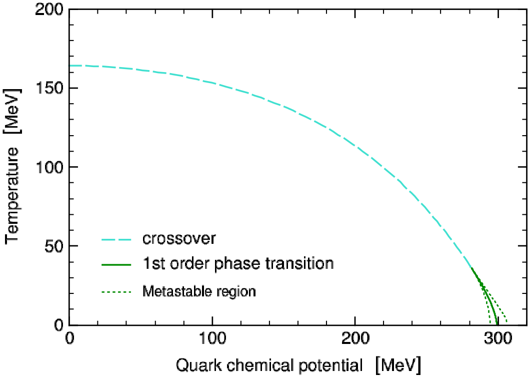
→ Effective model capturing the major properties

⇝ chiral and centre symmetry

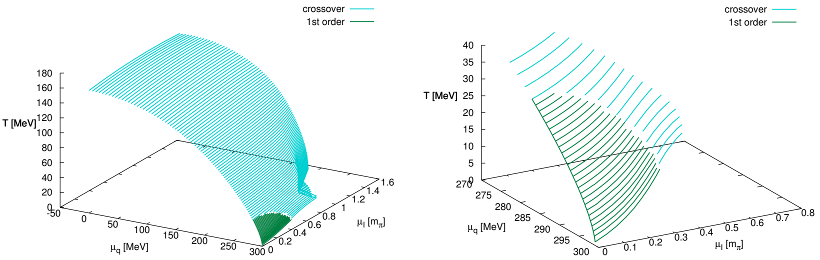
Phase diagram of the Polyakov-Quark-Meson model



RS and J. Schaffner-Bielich, Phys. Rev. D 93, 094014, 2016

→ There is a (small) region of a first order phase transition at large chemical potentials

Phase diagram of the Polyakov-Quark-Meson model



RS, E. S. Fraga and J. Schaffner-Bielich, arXiv:1307.2851v1 [hep-ph]

→ There is a (small) region of a first order phase transition at large chemical potentials . . . which shrinks with increasing isospin imbalance

Effective Model for QCD

Major properties of strongly interacting matter $\rightsquigarrow$ **symmetries**

- Dynamical mass-generation of constituent quarks: spontaneous chiral symmetry breaking
- Deconfinement: spontaneous centre symmetry breaking
  Order parameter: Polyakov loop Φ
  $\leftrightarrow$ Free energy of a test quark: $\Phi \sim \exp\left(-F_\mathrm{q}/T\right)$

$\rightarrow$ low temperature & density: chiral symmetry broken,
centre symmetric
high temperature and/or density: chiral symmetry restored,
centre symmetry broken

$\Rightarrow$ Polyakov-loop Quark-Meson model, PNJL model

Ingredients of the Polyakov–Quark-Meson model

$$\mathcal{L}_{\mathrm{PQM}} = \bar{q}\left[\mathrm{i}\,\gamma_\mu\left(\partial^\mu - \mathrm{i}A^\mu\delta_{\mu 0} + \mu_f\,\delta^{\mu 0}\right) - g\,\frac{\lambda_a}{2}\left(\sigma_a + \mathrm{i}\gamma_5\pi_a\right)\right]q + \frac{1}{2}\left(\partial_\mu\sigma_a\partial^\mu\sigma_a + \partial_\mu\pi_a\partial^\mu\pi_a\right) - U\left(\sigma_a, \pi_a\right) - \mathcal{U}\left(\Phi\left[A_0\right], \bar{\Phi}\left[A_0\right]; T\right)$$

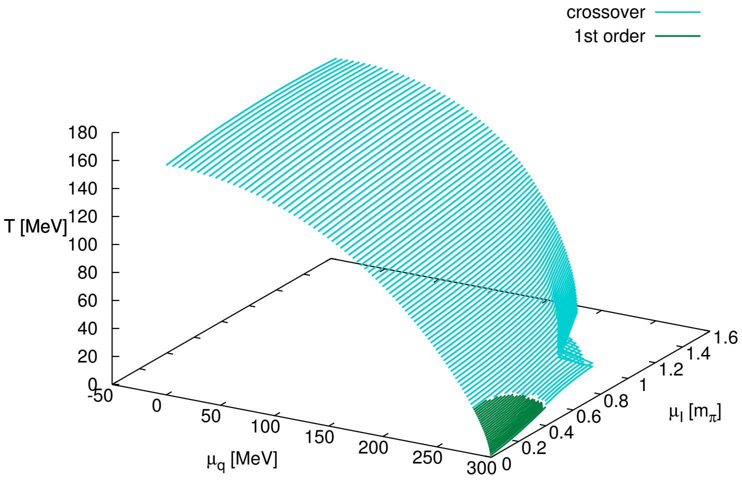
Ingredients:

- constituent quarks
- scalar and pseudoscalar mesons $\langle\bar{q}q\rangle$
  → generation of constituent quark masses by meson exchange
  (Yukawa coupling): $m_f = g\sigma_f$
  + vector mesons
- gauge fields ↔ Polyakov loop: $\Phi \sim \exp\left(\mathrm{i}\int_0^\beta \mathrm{d}\tau A_0\right)$
  → confinement (of quarks)

⇝ scalar fields: order parameters for chiral symmetry breaking

⇝ Polyakov-loop: order parameter for confinement

Constraining the Phase diagram of the PQM model

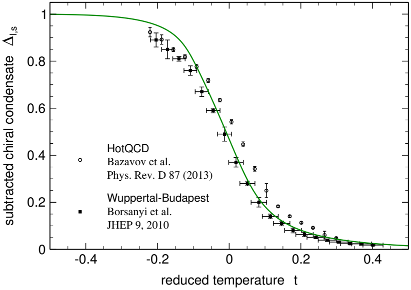


RS, E. S. Fraga and J. Schaffner-Bielich, arXiv:1307.2851v1 [hep-ph]

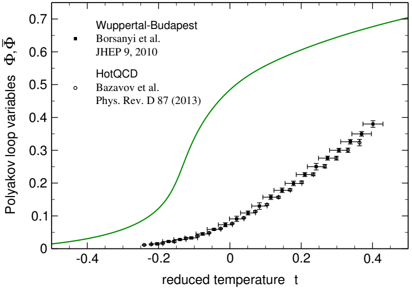
Constraints from the lattice @ $\mu = 0$

Order parameters ...

Chiral symmetry



Centre symmetry



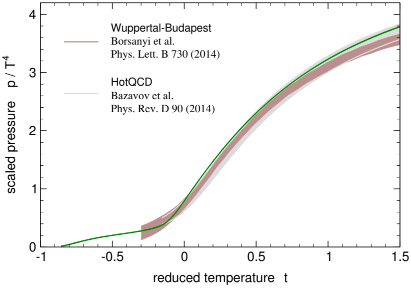
L. Haas, RS, J. Braun, J. Pawlowski and J. Schaffner-Bielich, Phys. Rev. D 87, 076004, 2013
T. K. Herbst, M. Mitter, J. Pawlowski, B.-J. Schaefer and RS, Phys. Lett. B 731, 248-256, 2014

- Quantitative agreement in the chiral sector
- Polyakov loop of effective model $\Phi[\langle A_0\rangle]$ upper limit of lattice $\langle\Phi\rangle$: $\Phi\left[\langle A_0\rangle\right] \geq \langle\Phi[A_0]\rangle$
  J. Braun, H. Gies and J. Pawlowski, Phys. Lett. B 684, 262-267, 2010

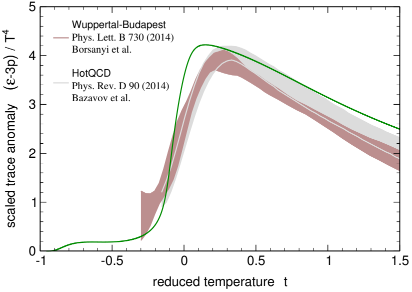
Constraints from the lattice @ $\mu = 0$

...and thermodynamics

Pressure



Trace anomaly: $\epsilon - 3p = T\frac{\partial p}{\partial T} - 4p$



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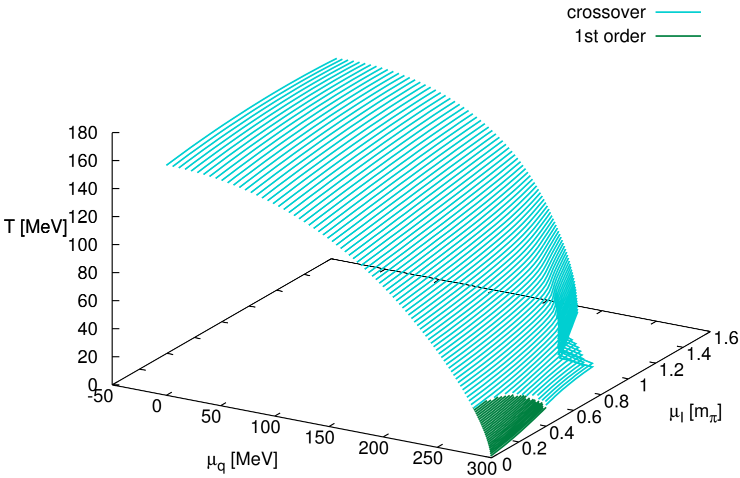
- Quantitative agreement or at least within the trend of lattice data

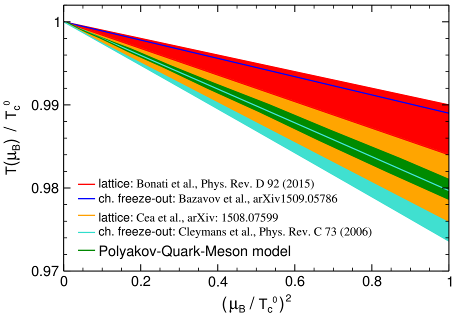
Seems to capture the important physics

Constraining the Phase diagram of the PQM model



RS, E. S. Fraga and J. Schaffner-Bielich, arXiv:1307.2851v1 [hep-ph]

Constraints from the lattice @ $\mu \lesssim T_c$



RS, J. Schaffner-Bielich, Phys. Rev. D 93, 094014 (2016)

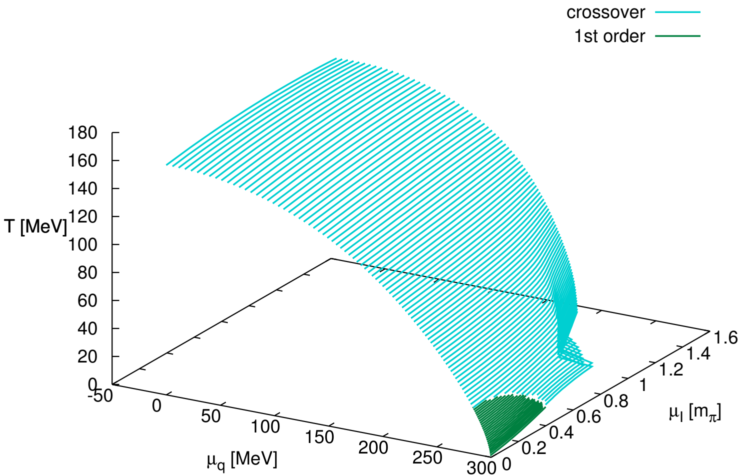
Curvature of the phase transition line:
$T_c\,(\mu) \propto \mu^2$ for $\mu \lesssim T_c$

Comparison to chemical freeze-out of hadrons in relativistic HICs

$\Rightarrow$ Within the lattice uncertainty,
and consistent with experimental results (?)

$\rightarrow$ Impact on curvature: coupling strength of vector mesons

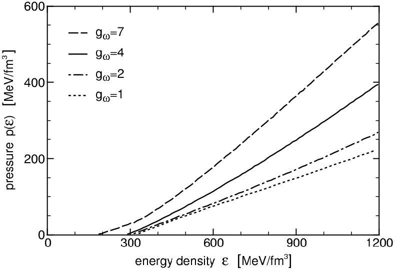
Constraining the Phase diagram of the PQM model

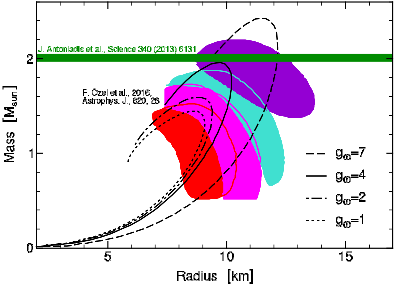


RS, E. S. Fraga and J. Schaffner-Bielich, arXiv:1307.2851v1 [hep-ph]

Constraints from Compact Star Masses and Radii

Calculate the equation of state within the model
and solve the GR equations to gain the mass-radius relation.





A. Zacchi, RS, J. Schaffner-Bielich; Phys. Rev. D 92 (2015) 4, 045022

- Precise mass measurements
- Currently large uncertainties on radius constraints, high precision with future x-ray and gravitational wave measurements

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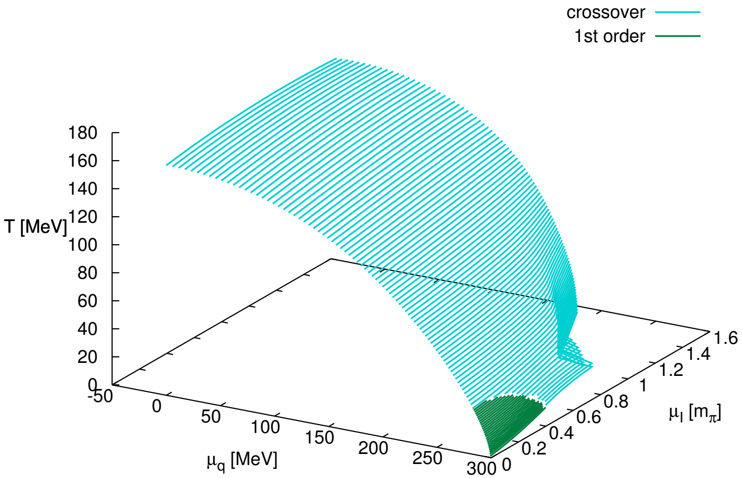
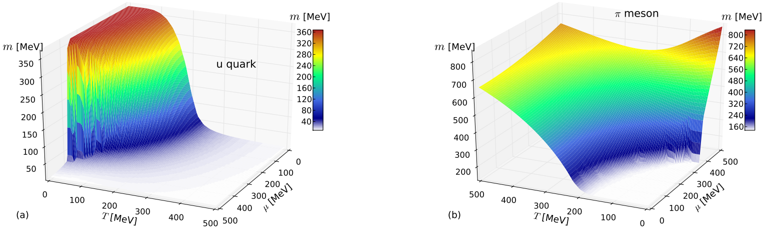


RS, E. S. Fraga and J. Schaffner-Bielich, arXiv:1307.2851v1 [hep-ph]

Input to HIC phenomenology

- Medium dependence of quark and meson masses



R. Marty, E. Bratkovskaya, W. Cassing and J. Aichelin, Phys. Rev. C 92, 015201 (2015),
R. Marty and J. Aichelin, Phys. Rev. C 87, 034912 (2013)

→ elastic scattering and hadronisation cross-sections
→ input to transport calculation

- transverse momentum and rapidity distributions
- elliptic flow as function of transverse momentum and rapidity

→ transport coefficients:
shear & bulk viscosity, thermal conductivity

A. Abhishek, H. Mishra, S. Ghosh, arXiv:1709.08013 [hep-ph]

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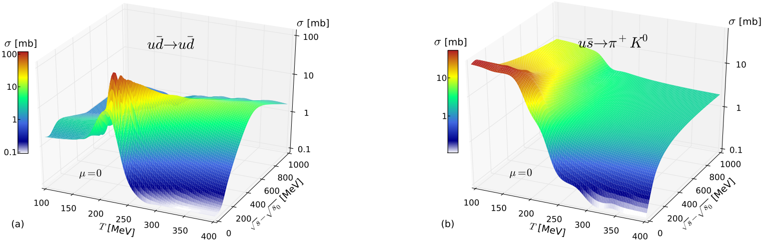

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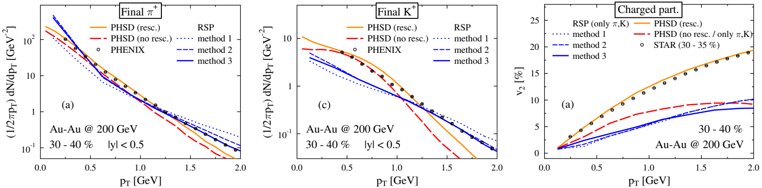

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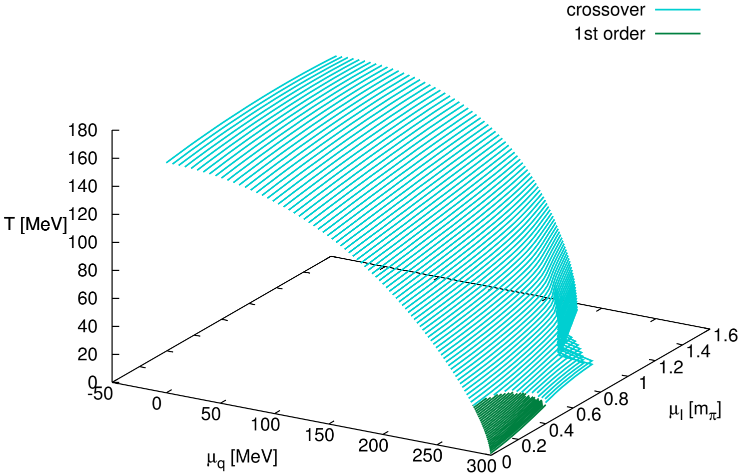


RS, E. S. Fraga and J. Schaffner-Bielich, arXiv:1307.2851v1 [hep-ph]

A closer look to the Polyakov-loop potential

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

$$\begin{aligned}\mathcal{L}_{\mathrm{PQM}} &= \bar{q}\left[\mathrm{i}\,\gamma_\mu\left(\partial^\mu - \mathrm{i}\,A^\mu\,\delta_{\mu 0} + \mu_f\,\delta^{\mu 0}\right) - g\,\frac{\lambda_a}{2}\,(\sigma_a + \mathrm{i}\gamma_5\pi_a)\right]q \\ &\quad + \frac{1}{2}\,(\partial_\mu\sigma_a\partial^\mu\sigma_a + \partial_\mu\pi_a\partial^\mu\pi_a) - \;U\,(\sigma_a,\pi_a) - \mathcal{U}\left(\Phi[A_0]\,,\bar{\Phi}[A_0]\,;T\right)\end{aligned}$$

$\mathcal{U}\left(\Phi,\bar{\Phi};T\right) \leftrightarrow G_{\mu\nu}\,G^{\mu\nu}$: gluon interaction

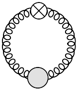
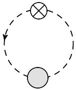
Parametrised Polyakov-loop potential fitted to pure gauge / Yang-Mills simulations

$\Rightarrow \mathcal{U}_{\mathrm{YM}}$: pure gauge / Yang-Mills / quenched Polyakov-loop potential !

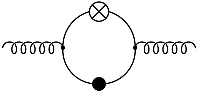
$\rightarrow$ How does it change in the presence of dynamical quarks?

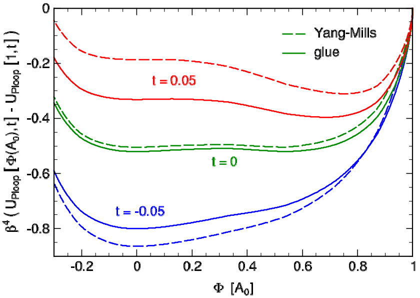
Unquenching the Polyakov-loop potential

Yang-Mills and QCD glue potential
in the Functional Renormalisation Group

$$\partial_t \Gamma_k[\bar{A};\phi] = \frac{1}{2}$$  $$-$$ 

Pure gauge theory . . .
. . . or gauge part of full QCD
including matter back-reaction

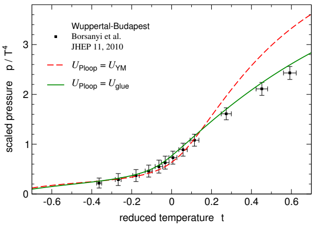
$$\partial_t \Pi^{\mathrm{ferm}}_{A,k} \simeq$$ 

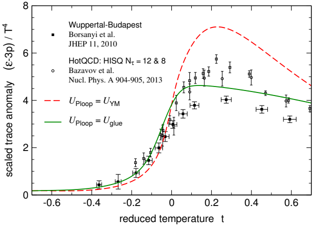


$$\Rightarrow \quad \mathcal{U}_{\mathrm{glue}}(t,\Phi) = \mathcal{U}_{\mathrm{YM}}\left(t_{\mathrm{YM}}(t),\Phi\right), \quad t_{\mathrm{YM}}\left(t_{\mathrm{glue}}\right) \simeq 0.57\, t_{\mathrm{glue}}$$

L. Haas, RS, J. Braun, J. Pawlowski and J. Schaffner-Bielich, Phys. Rev. D 87, 076004, 2013

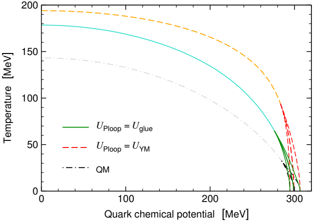
Impact of unquenching: $\mathcal{U}_{\mathrm{YM}} \to \mathcal{U}_{\mathrm{glue}}$

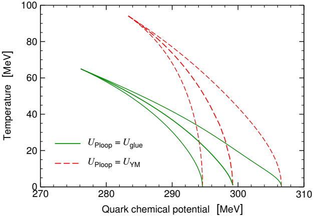




L. Haas, RS, J. Braun, J. Pawlowski and J. Schaffner-Bielich, Phys. Rev. D 87, 076004, 2013
T. K. Herbst, M. Mitter, J. Pawlowski, B.-J. Schaefer and RS, Phys. Lett. B 731, 248-256, 2014

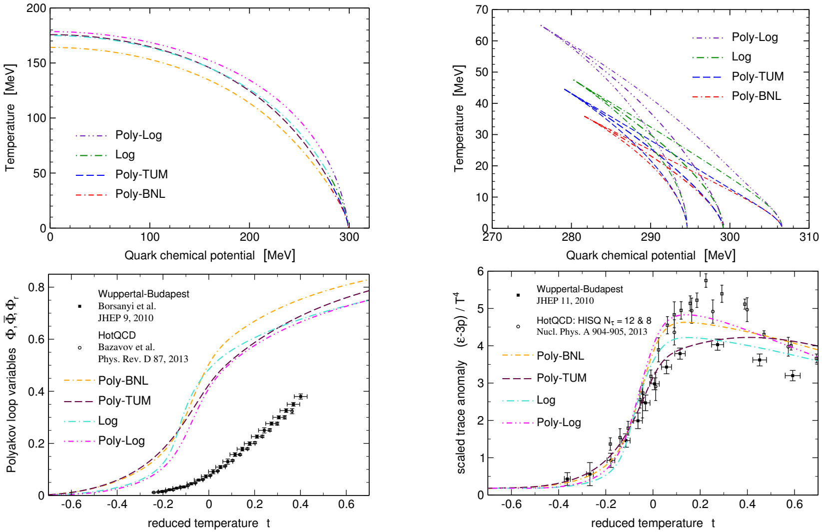
→ smoothens the transition





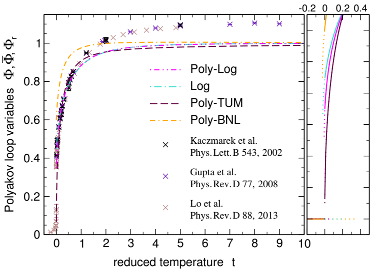
RS and J. Schaffner-Bielich, Phys. Rev. D 93, 094014, 2016

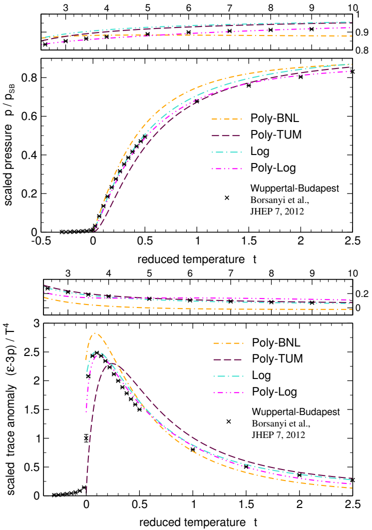
Results with different parameterisations . . . differ



RS and J. Schaffner-Bielich, Phys. Rev. D 93, 094014, 2016

Different parameterisations . . . differ already in YM



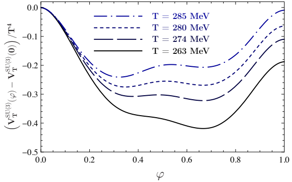


L. Haas, RS, J. Braun, J. Pawlowski and J. Schaffner-Bielich, Phys. Rev. D 87, 076004, 2013

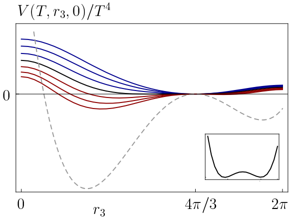
RS et al., in preparation

Input to construct consistent P.-loop potentials

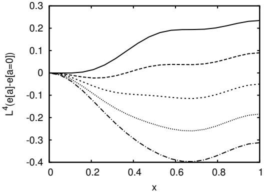
Polyakov-loop potential in continuum calculations



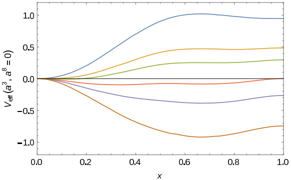
L. Fister and J. M. Pawlowski, Phys. Rev. D 88 (2013) 045010



U. Reinosa, J. Serreau, M. Tissier and N. Wschebor, Phys. Rev. D 93 (2016) 105002

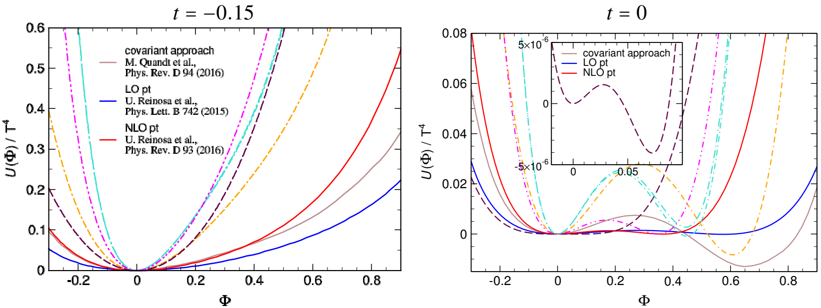


H. Reinhardt and J. Heffner, Phys. Rev. D 88 (2013) 045024



M. Quandt and H. Reinhardt, Phys. Rev. D 94 (2016) 065015

Compare parameterisations and calculations



RS et al., in preparation

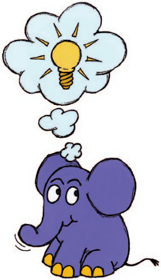
→ Calculated potentials flatter at $t < 0$

⇒ Effect in PQM/PNJL qualitatively as unquenching

→ Small height of barrier at phase transition

Conclusions

- PQM/PNJL: Effective model to describe chiral symmetry breaking and confinement aspects
- Constrain framework and test improvements
  - against lattice data at vanishing density, small density and nonzero isospin density
  - astrophysics observations at large density, zero temperature
- Make predictions on the existence and location of a CEP
- Can serve as input to HIC phenomenology
- Gauge sector requires revision: use input of ab-initio continuum calculations



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Thank You for your attention!

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