Phase structure and dynamics of QCD at high densities

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Universität Heidelberg & ExtreMe Matter Institute

Buenas Ideas on the QCD Phase Diagram, May 27th 2026

fqcd-collaboration.github.io

EMMI

STRUCTURES
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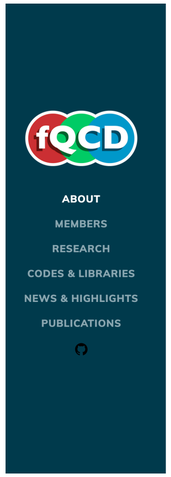
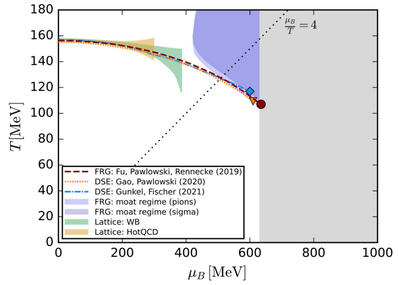
fQCD collaboration



fQCD COLLABORATION

We study the phase structure, thermodynamics and transport properties of strongly interacting matter. In order to access the notoriously difficult regimes of QCD, finite density and real time, we develop first-principles functional approaches with a focus on the functional renormalisation group and Dyson-Schwinger equations.

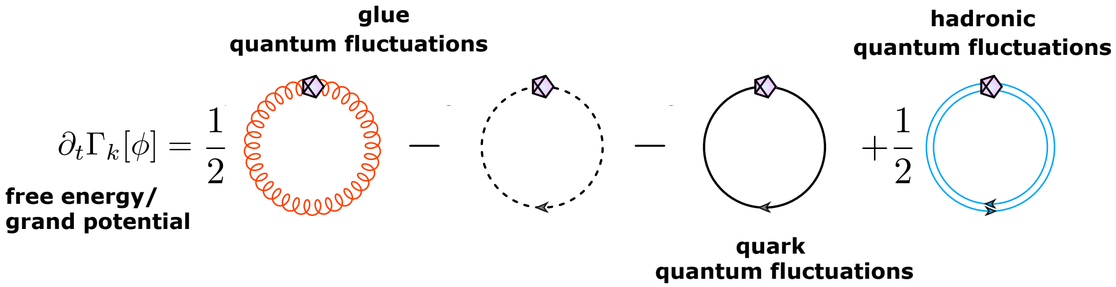


github

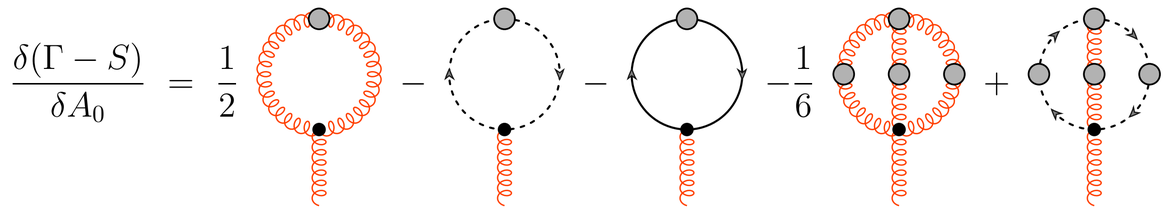
Dalian, Beijing, Darmstadt, Heidelberg, Gießen

Braun, Chen, Fu, Gao, Huang, Ihssen, Kockler, Lu, Pawlowski, Rennecke, Sattler, Stoll, Tan, Wang, Wen, Wessely, Yin, Zheng, Zorbach

Functional renormalisation group



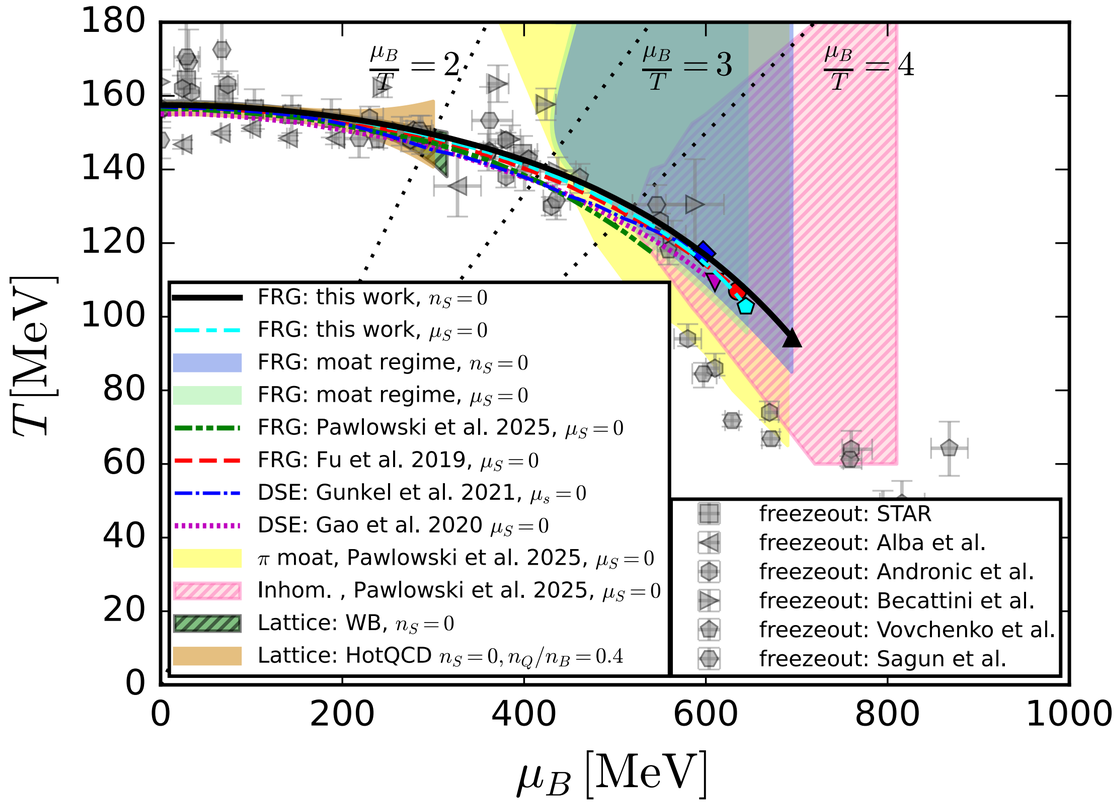
Dyson-Schwinger equations



Phase structure and dynamics of QCD at high densities

- **Critical end point and new phases: where do we stand?**
- **Strong correlations above the chiral crossover**
- **Ripples of the critical and point and new phases**
- **QCD moat and inhomogeneous phases**

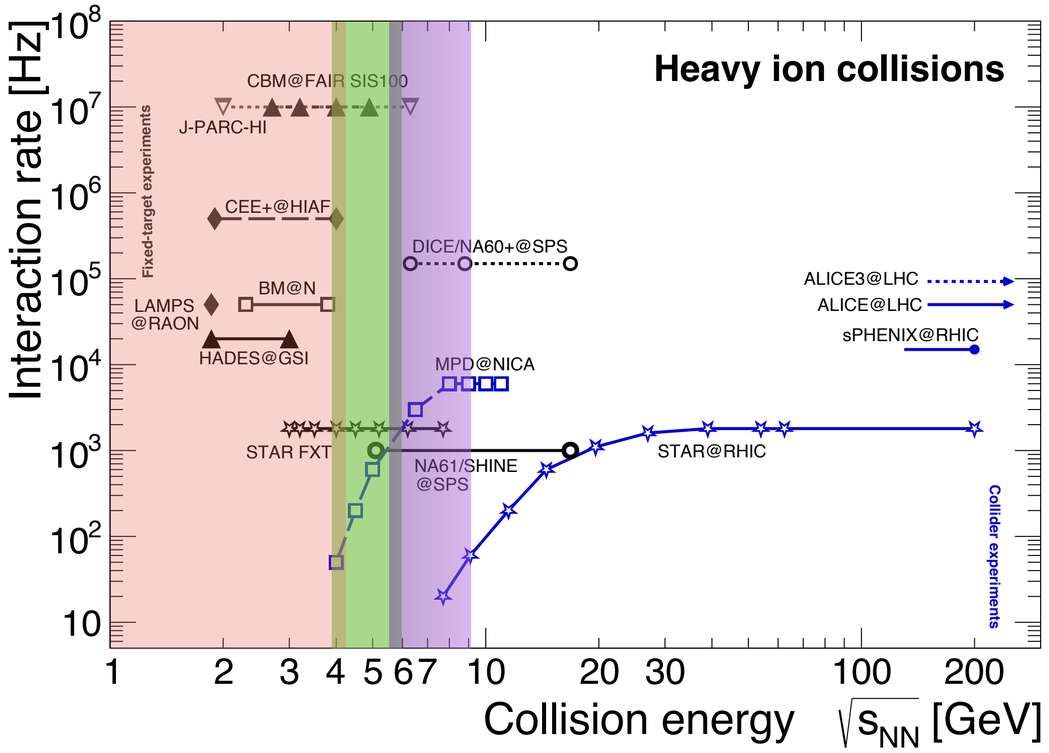
Critical end point and new phases: where do we stand?



Experimental & Theoretical Landscape

Experimental landscape

New phases



Peak of kurtosis on the freeze-out line

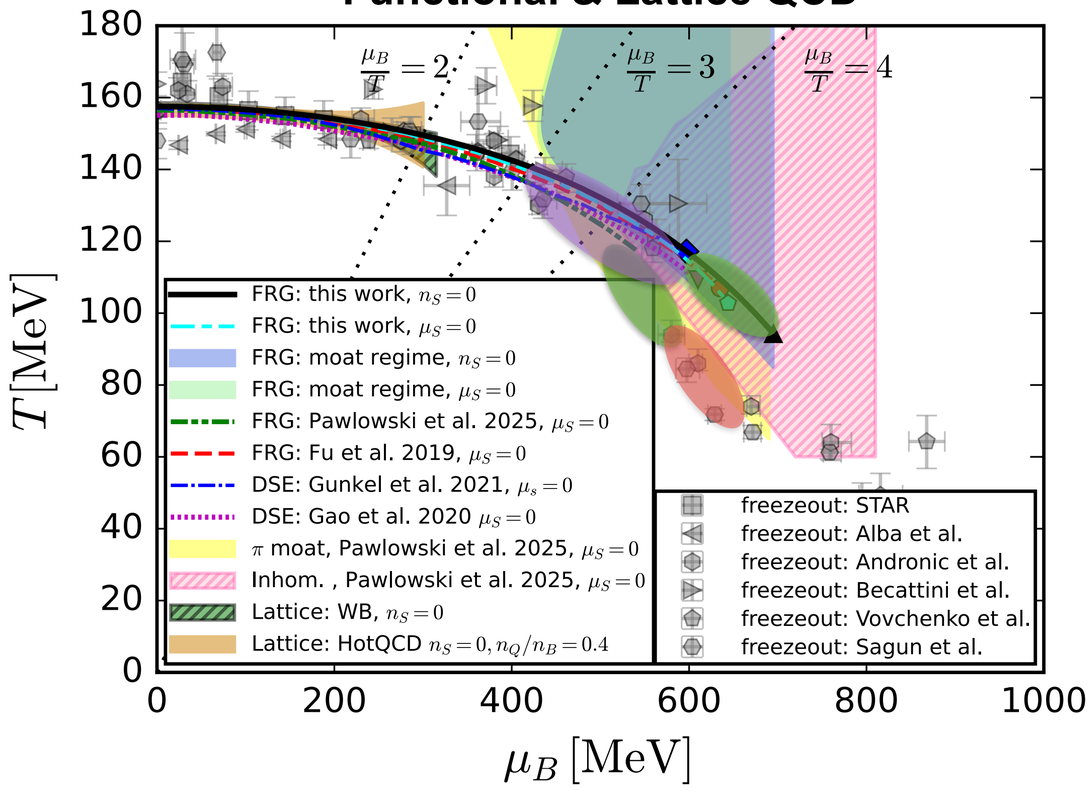
Galatyuk, A982 (2019) update 2025; CBM, EPJA 53 3 (2017) 60

Theoretical landscape

Onset of new phases on the chiral transition line (CEP)

Transition regime

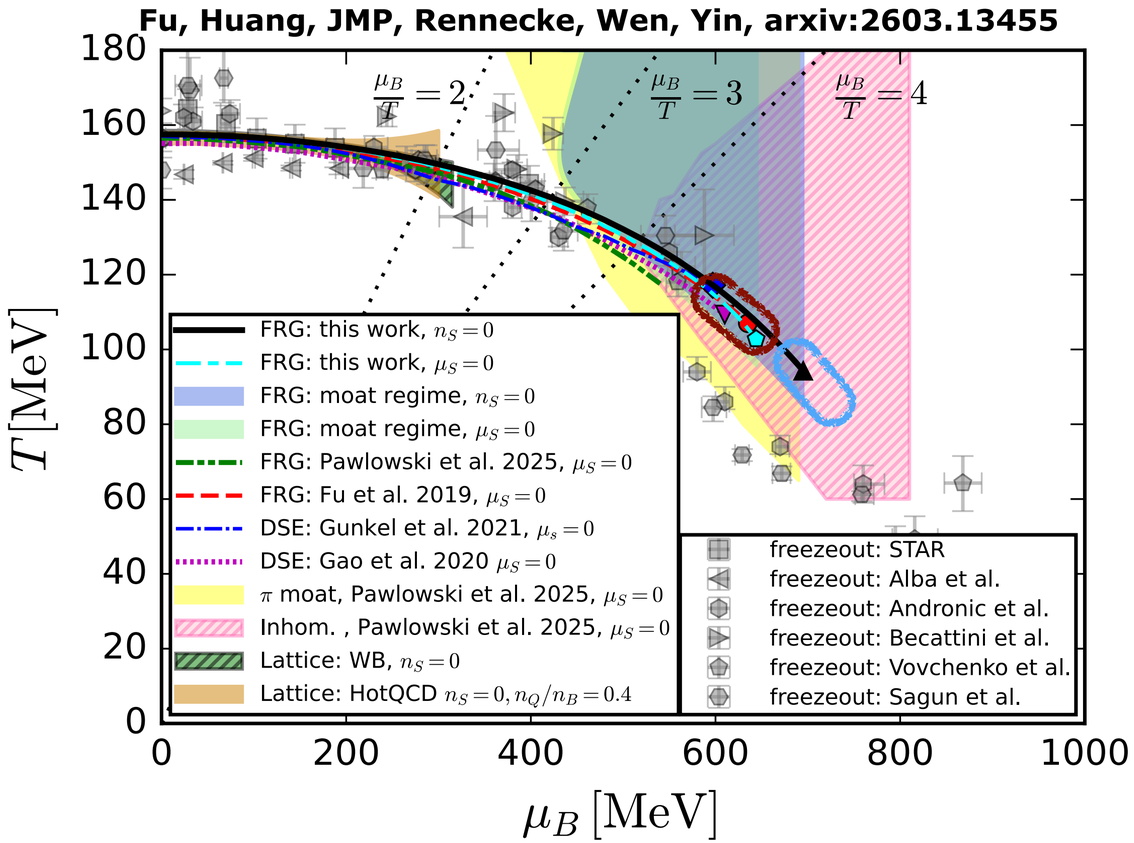
Functional & Lattice QCD



Fu, Huang, JMP, Rennecke, Wen, Yin, arxiv:2603.13455

Critical end point and new phases: where do we stand?

Quantitative functional QCD



$$\frac{\mu_B}{T} \lesssim 4.5$$

Functional QCD: CEP estimate

$$\mu_u = \mu_d = \mu_s$$

Fu, JMP, Rennecke, PRD 101 (2020) 054032 (fRG)

Gao, JMP, PLB 820 (2021) 136584 (DSE)

$$\mu_u = \mu_d \qquad \mu_s = 0$$

Gunkel, Fischer, PRD 104 (2021) 054022 (DSE)

$$(\mu_B\,,\,T)_{\mathrm{CEP}} \sim (105-115\,,\,600-650)\ \mathrm{MeV}$$

Strangeness neutrality

$$(\mu_B\,,\,T)_{\mathrm{CEP}} = (92\,,\,696)\ \mathrm{MeV}$$

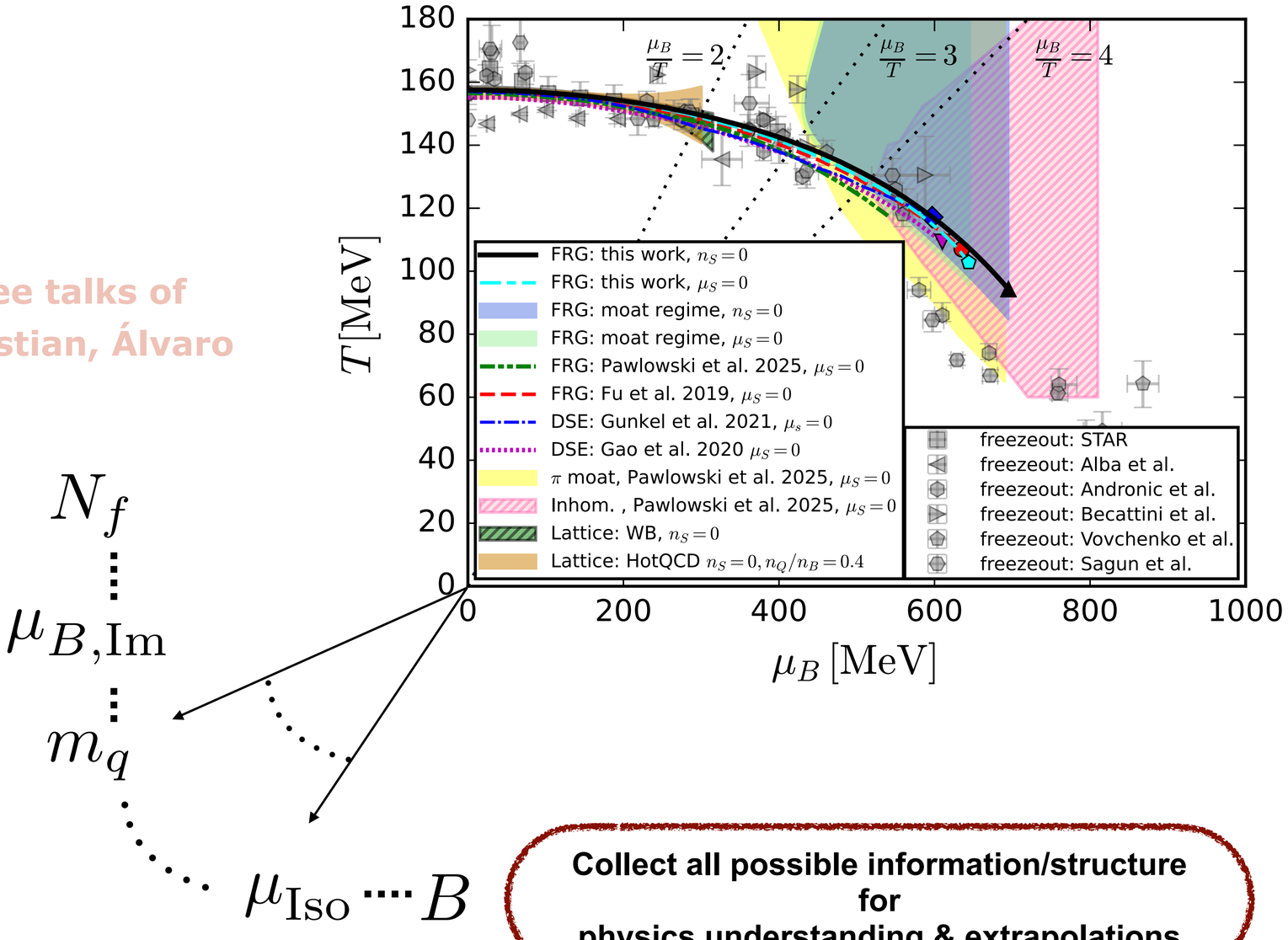
$$\frac{\kappa_{n_s=0}}{\kappa_{\mu_i=\mu_q}} = 0.897$$

Self-consistent Moat: JMP, Rennecke, Sattler, arxiv:2512.20510

Fu, Huang, JMP, Rennecke, Wen, Yin, arxiv:2603.13455

Critical end point and new phases: where do we stand?

See talks of Christian, Álvaro



Collect all possible information/structure for physics understanding & extrapolations

$$\mu_u = \mu_d = \mu_s$$

$$\mu_u = \mu_d \quad \mu_s = 0$$

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Lattice

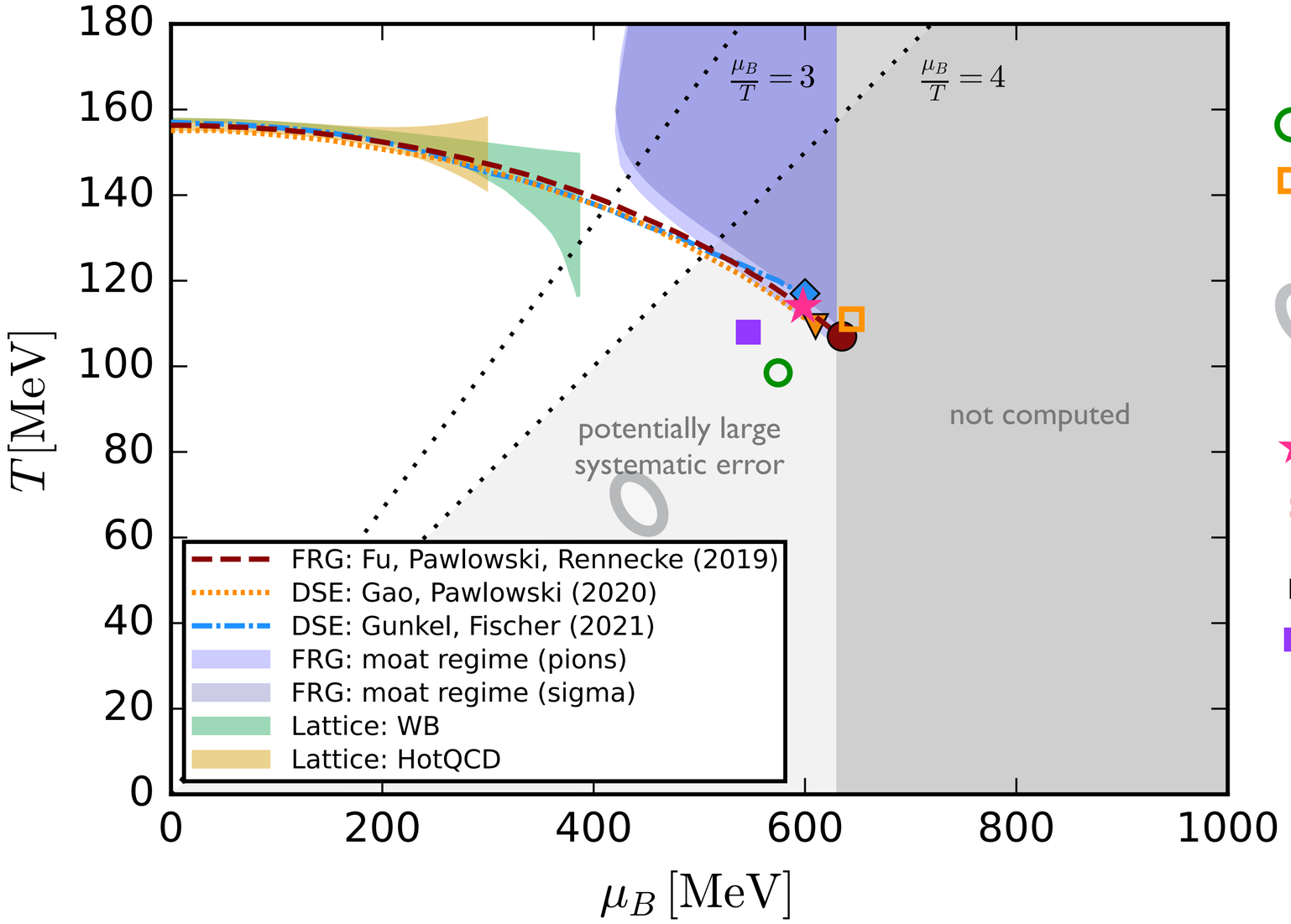
HotQCD:
Bazavov, Ding, Hegde, Kaczmarek, Karsch, Karthik, Laermann, Lahiri, Larsen, Li, Mukherjee, Ohno, Petreczky, Sandmeyer, Schmidt, Sharma, Steinbrecher,
PLB 795 (2019)

WB:
Borsányi, Fodor, Guenther, Kara, Katz, Parotto, Pasztor, Ratti, Szabo,
PRL 125 (2020) 052001

QCD PHASE DIAGRAM & THE CEP

Modified from Fabian Rennecke's plenary talk @ QM 2025

FRG & DSE results ? corroborated ? by subsequent "extrapolations" of lattice data



Fu, Luo, JMP, Rennecke, Yin, PRD 111, L031502

using Yang-Lee edge singularities:

- conformal Padé [Basar, 2312.06952]
- multi-point Padé [Clarke et al., 2405.10196]
  $N_\tau = 6, 8$ results + continuum estimate
  [Schmidt, 2504.00629]
- **very recent lattice extrapolation (16^3 x 8)**
  [Adam et al, 2507.13254]

using thermodynamics:

- ★ constant entropy density [Shah et al. 2410.16206]

See talk of Volodymyr [Shah et al. 2601.08823]

model-based extrapolation (tiny selection):

- ■ holography [Hippert et al., 2309.00579]
  (agrees with [Cai et al., 2201.02004])

CEP location well constrained by now. And it's **in FAIR range!**

$\sqrt{s_{NN}} \approx 3.6 - 4.1\,\mathrm{GeV}$

'… and now for something completely different…'

Extrapolations & von Neumann's Elephant

Those are my interpretations, and if you don't like them…. well, I have others

Extrapolations are ill-conditioned problems

'… and now for something completely different…'

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'There are two ways of doing calculations in theoretical physics.
One way is to have a clear physical picture of the process that you are calculating.
The other way is to have a precise and self-consistent mathematical formalism.
…You have neither'

Fermi to Dyson

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'*With four parameters I can fit an elephant,*
and with five I can make him wiggle his trunk'

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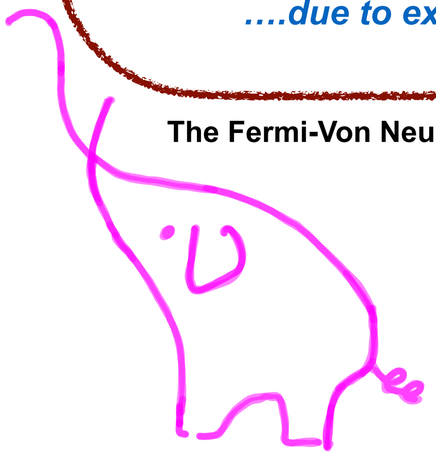
With four parameter models we can fit many data
but we cannot extrapolate without external information

In particular, extrapolations cannot predict the existence and location of the CEP without external information

The other way is to have a precise and self-consistent effective theory whose systematic error is under control ….due to external QCD information



The Fermi-Von Neumann QCD phase structure elephant

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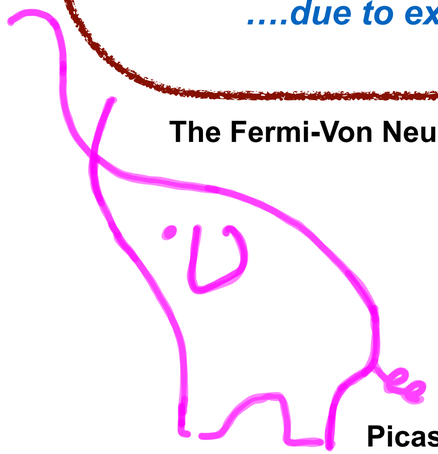

Picasso-assisted Pawlowski elephant

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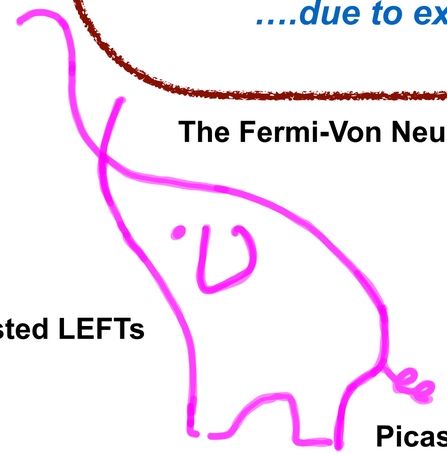

Proxy for QCD-assisted LEFTs

Picasso-assisted Pawlowski elephant

Direct computations and the minimal point of view

Those are my interpretations, and if you don't like them…. well, I have others

- **Self-consistent truncations to functional relations define analytic functions in μ_B , eg:**

$$\partial_t \Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B) = \mathrm{Loop}\left[\Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B),\ \Big\langle q(x)A_\mu(y)\bar{q}(z)\Big\rangle(\mu_B), \cdots;\ \mu_B\right]$$

Unique: QCD-based analytic continuations that satisfy the lattice benchmarks at small chemical potential.

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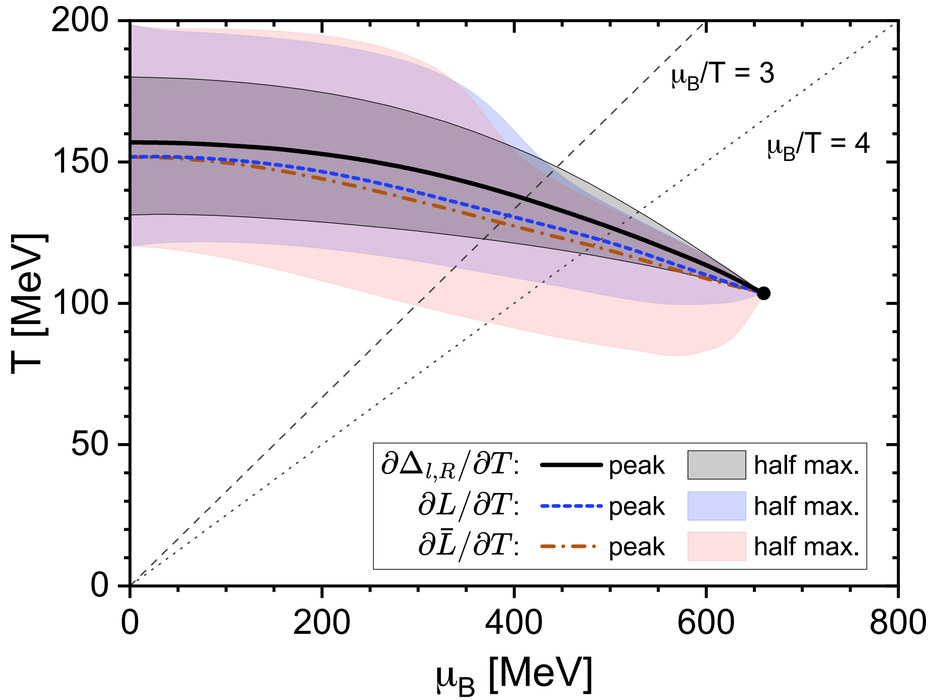
- **?Corroborated?**

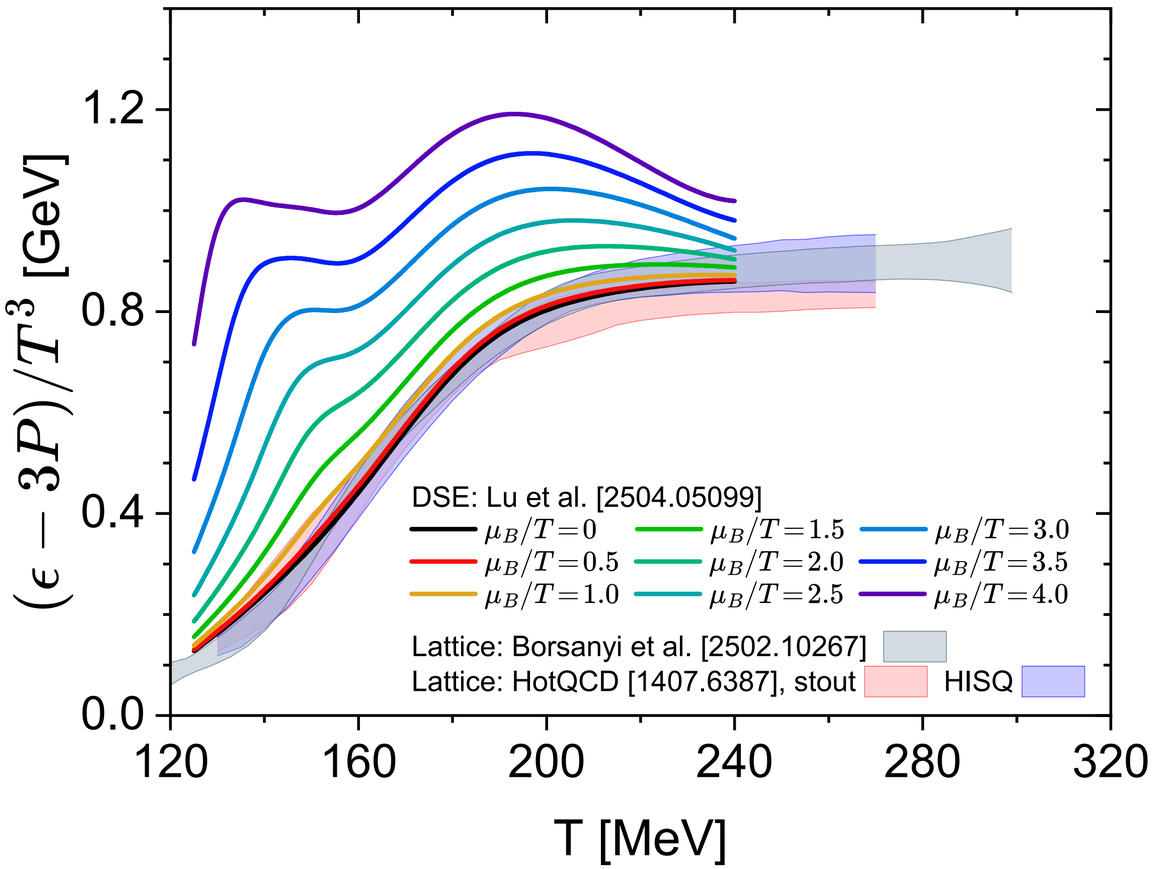
By definition, LEFTs (including extrapolations) cannot assess the existence or absence of emergent phenomena!

Strong correlations above the chiral crossover



Strongly correlated physics

Strongly correlated phase for temperatures $T_\chi \lesssim T \lesssim 2\,T_\chi$



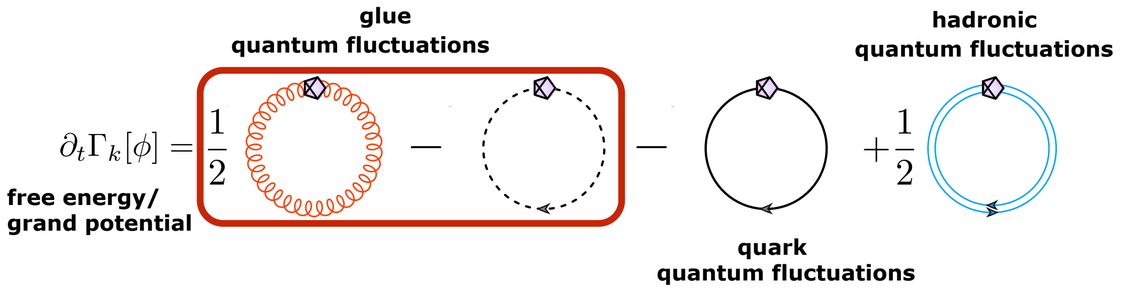
Lu, Gao, Liu, JMP, 113 (2026) 054019

Functional confinement & the dynamical gluonic background

FRG: Braun, Gies, JMP, PLB 684 (2010) 262

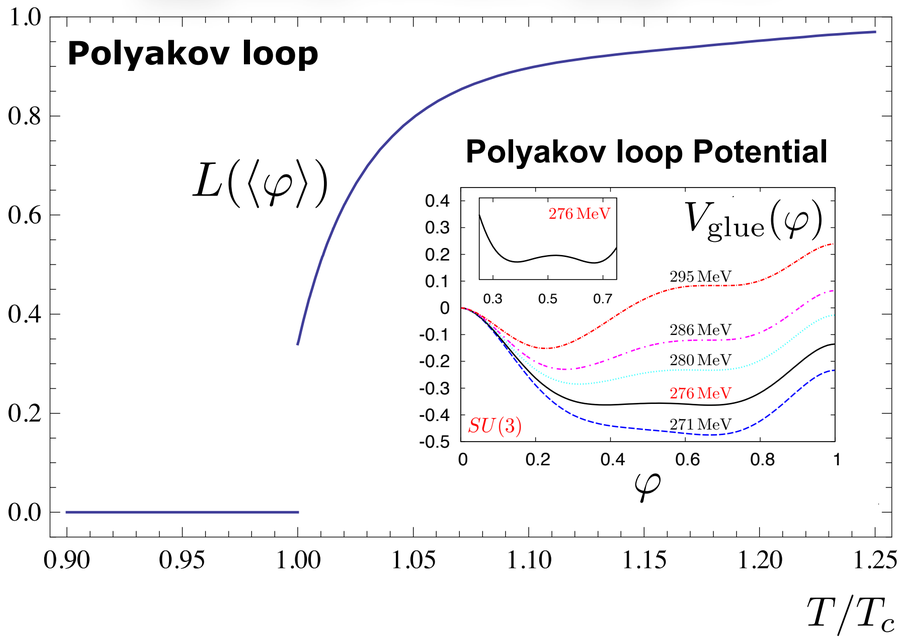
FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L(A_0) = \frac{1}{N_c}\mathrm{tr}\,\mathcal{P}e^{i\,g_s\int_0^\beta dt\,A_0(x)}$$



Polyakov loop Potential: $V_{\mathrm{glue}}(\varphi)$

$$\mathcal{P}e^{i\,g_s\int_0^\beta dt\,A_0(x)} = e^{2\pi i\,\varphi}$$



$$T_c/\sqrt{\sigma} = 0.658 \pm 0.023$$

$$\text{lattice}: T_c/\sqrt{\sigma} = 0.646$$

Functional confinement & the dynamical gluonic background

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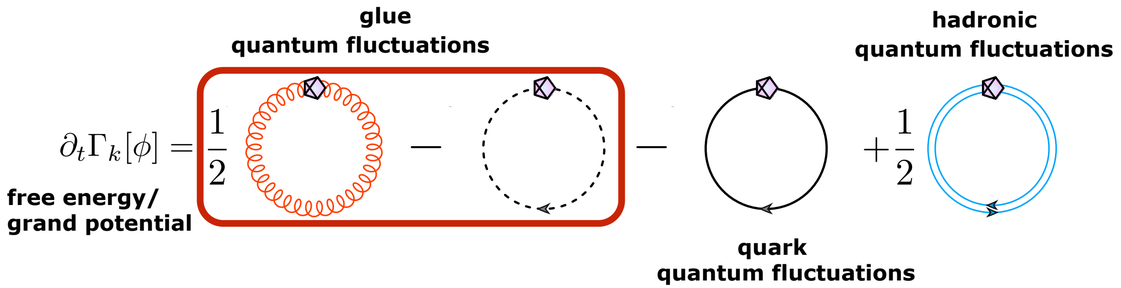

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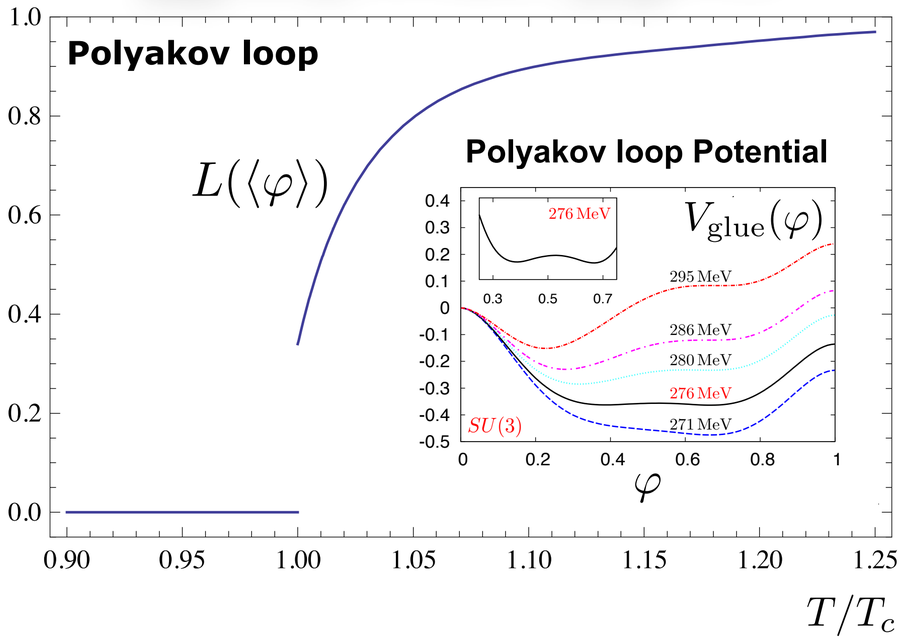
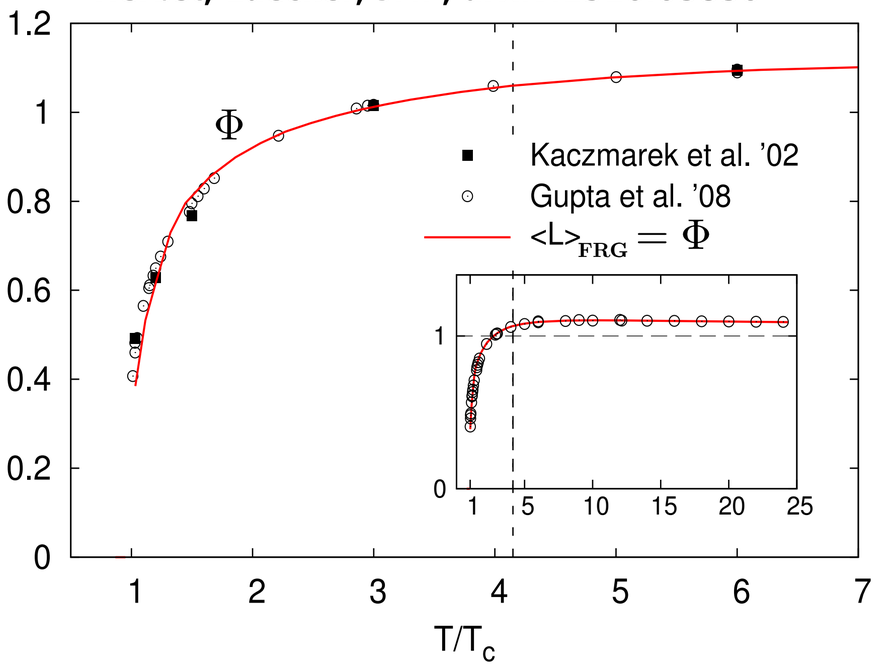
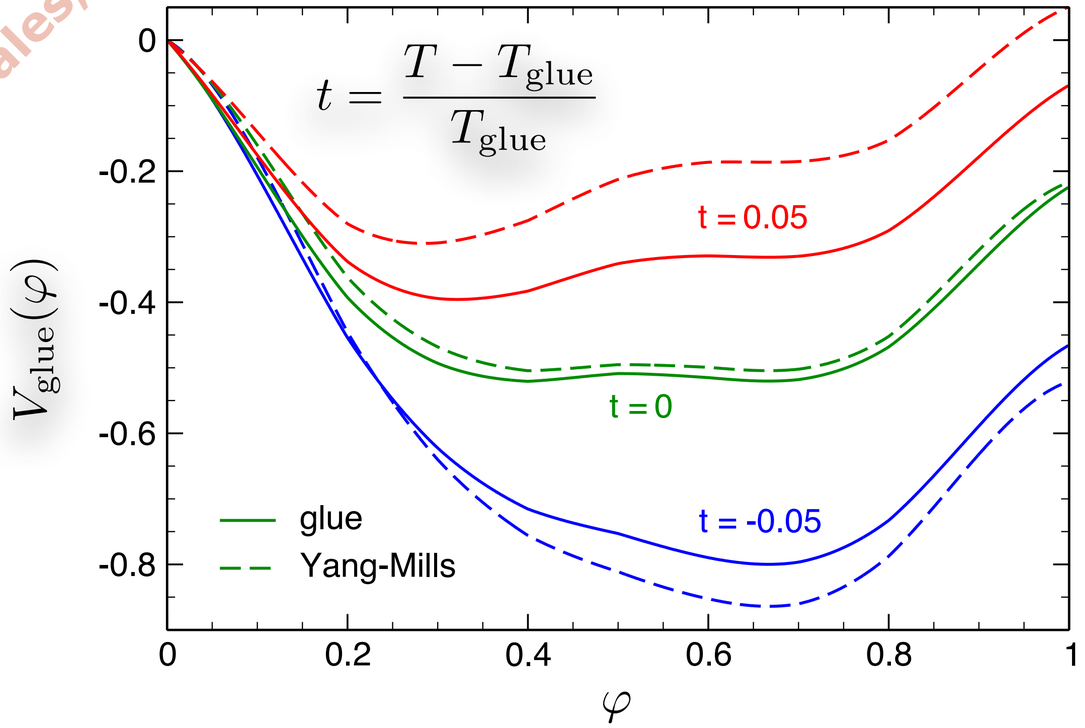


Herbst, Luecker, JMP, arXiv:1510.03830

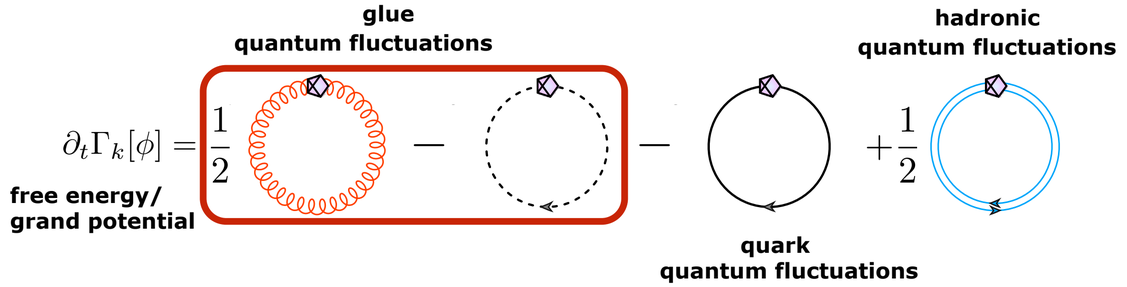


Functional confinement & the dynamical gluonic background

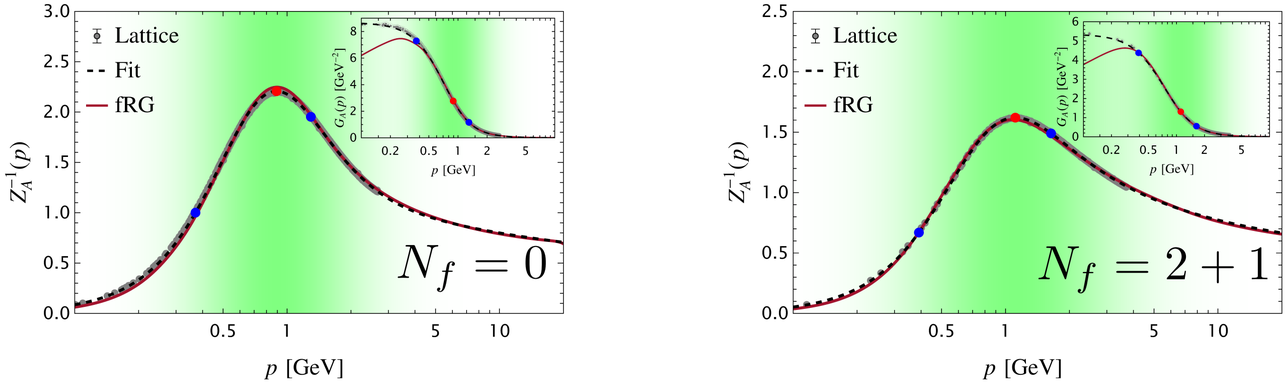
Yang-Mills vs two-flavour glue potential



Haas, Stiele, Braun, JMP, Schaffner-Bielich, PRD 87 (2013) 076004



gluon propagators in YM & QCD

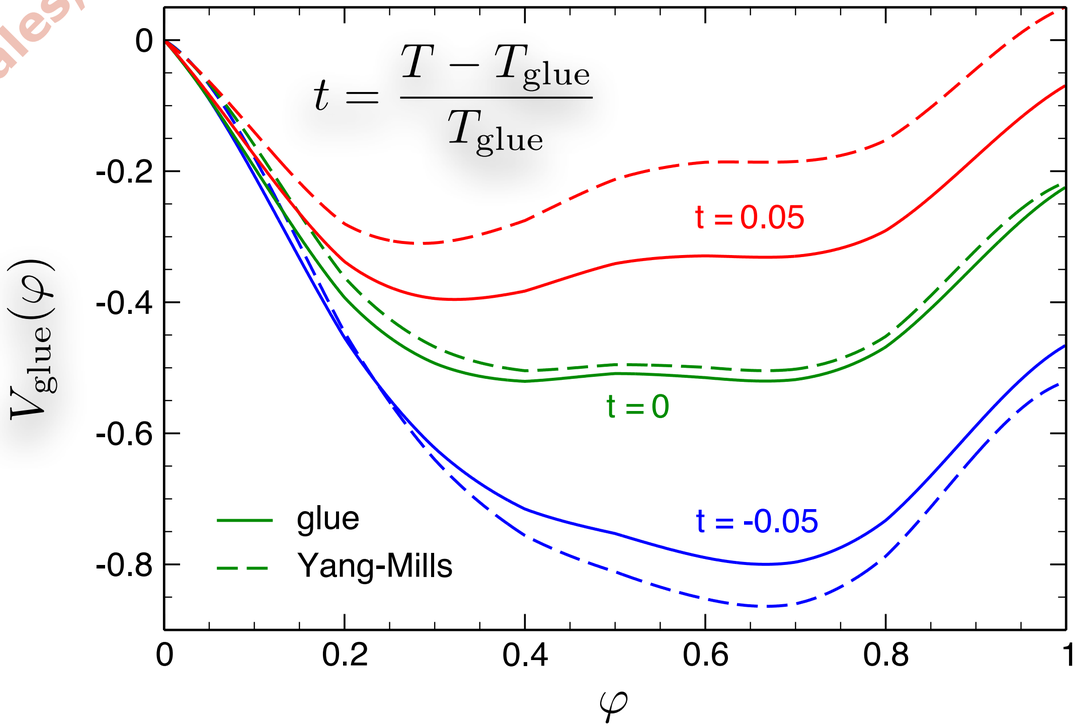


Fereirra, Papavassiliou, JMP, EPJC 85 (2025) 11, 1339

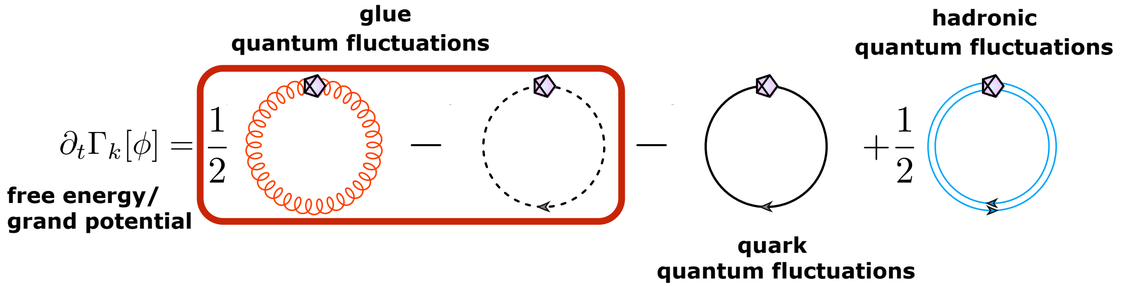
$$T_{\rm glue}^{(\rm QCD)} \approx 200\,\text{MeV}$$

Functional confinement & the dynamical gluonic background

Yang-Mills vs two-flavour glue potential



Haas, Stiele, Braun, JMP, Schaffner-Bielich, PRD 87 (2013) 076004



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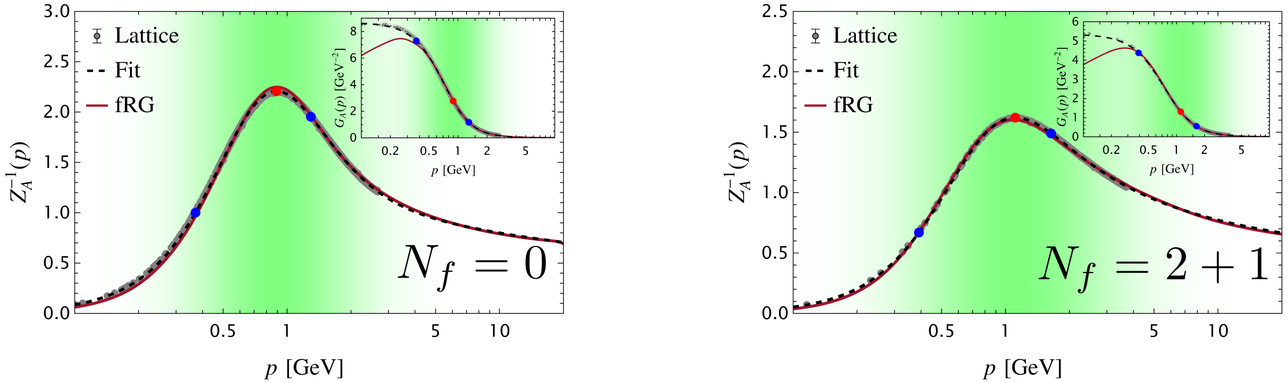


Fereirra, Papavassiliou, JMP, EPJC 85 (2025) 11, 1339

Direct applications to the QCD phase structure

Braun, Haas, Marhauser, JMP, PRL 106 (2011) 022002

Fischer, Fister, Lücker, JMP, PLB 732 (2014) 273

Fischer, Lücker, Welzbacher, PRD 90 (2014) 034022

fRG & DSE

Fischer, Lücker, JMP, PRD 91 (2015) 014024

Lu, Gao, Liu, JMP, 113 (2026) 054019

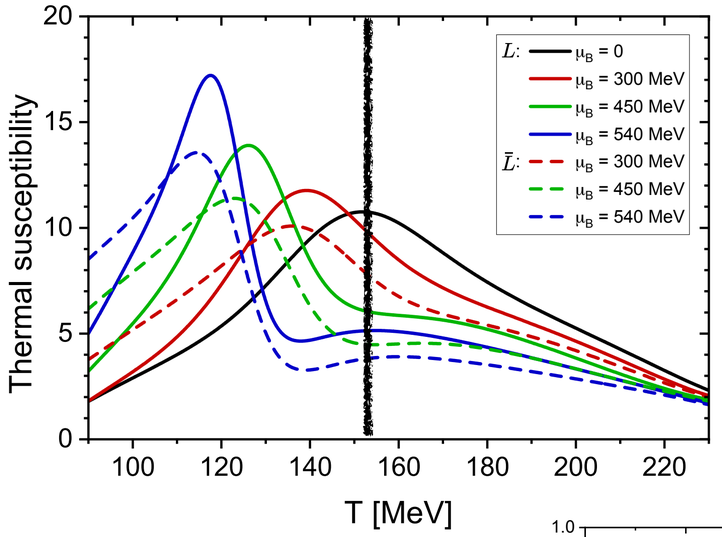
Lu, Fischer, Gao, Liu, JMP, arXiv:2603.09336

Relation to chiral spin symmetry?

Strongly correlated physics

‘Confinement’ related ‘crossovers’ at $T_\chi \lesssim T_{\rm conf} \lesssim 2\,T_\chi$

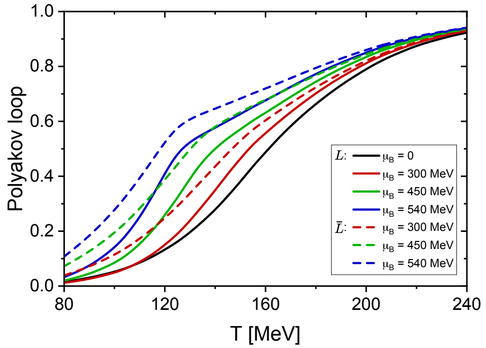
Functional QCD



Variants of the traced Polyakov loop

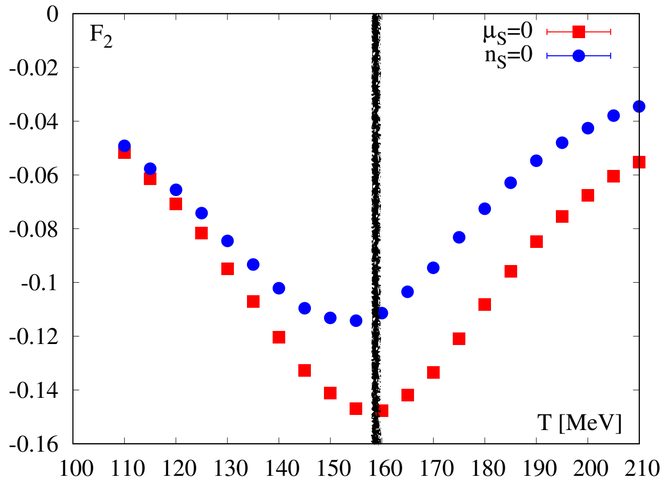
$$P = \frac{1}{N_c}\,\mathrm{tr}\, e^{2\pi i \varphi}$$

$$\propto P\big(\langle \mathrm{ev}(\varphi)\rangle\big)$$



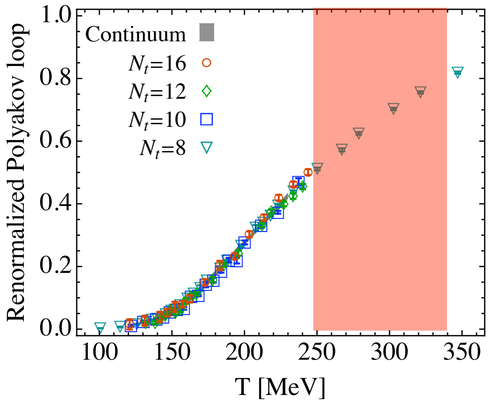
Lu, Gao, Liu, JMP, 113 (2026) 054019

Lattice QCD



$$\propto T\frac{\partial^2 \log|\langle P\rangle|}{(\partial \mu_B/T)^2}$$

$$\propto \langle P\rangle$$



⋮

Bazavov, Brambilla, Ding, Petreczky, Schadler, Vairo, Weber, PRD 93 (2016) 11, 114502

⋮

Borsányi, Fodor, Guenther, Kara, Paolo Parotto, Pásztor, Pirelli, Wong, PRD 110 (2024) 114507

Strongly correlated physics

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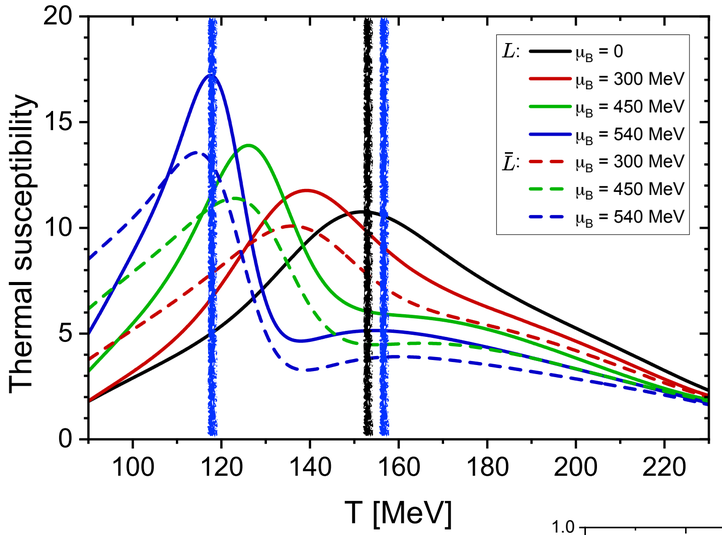

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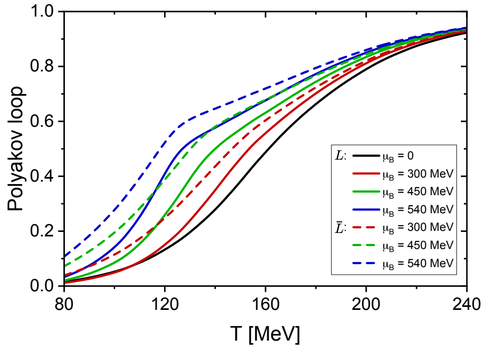
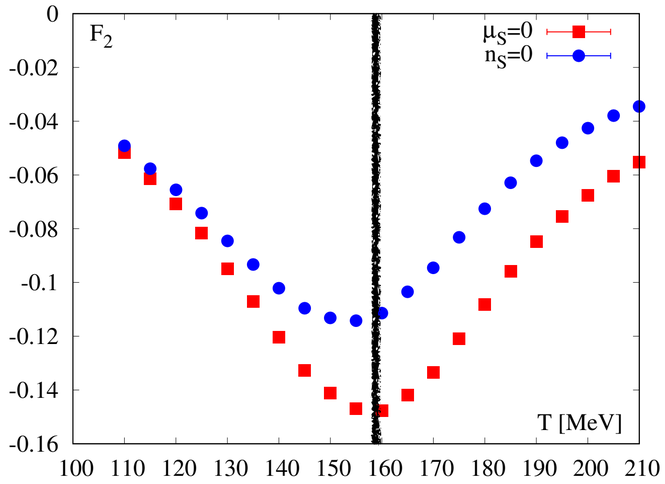


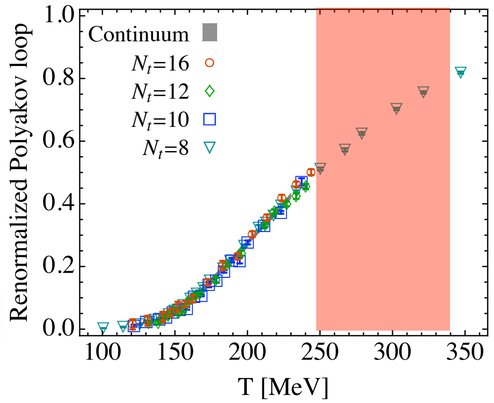
Lu, Gao, Liu, JMP, 113 (2026) 054019

Lattice QCD



$$\propto T\frac{\partial^2 \log|\langle P\rangle|}{(\partial \mu_B/T)^2}$$

$$\propto \langle P\rangle$$



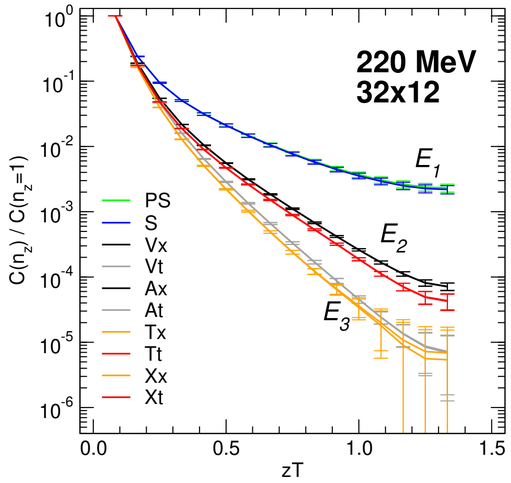
Bazavov, Brambilla, Ding, Petreczky, Schadler, Vairo, Weber, PRD 93 (2016) 11, 114502

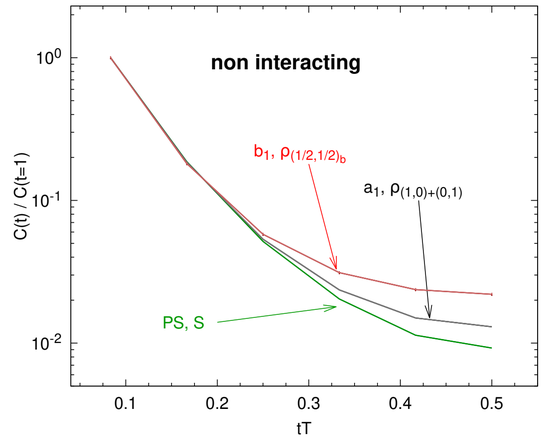
Borsányi, Fodor, Guenther, Kara, Paolo Parotto, Pásztor, Pirelli, Wong, PRD 110 (2024) 114507

Strongly correlated physics

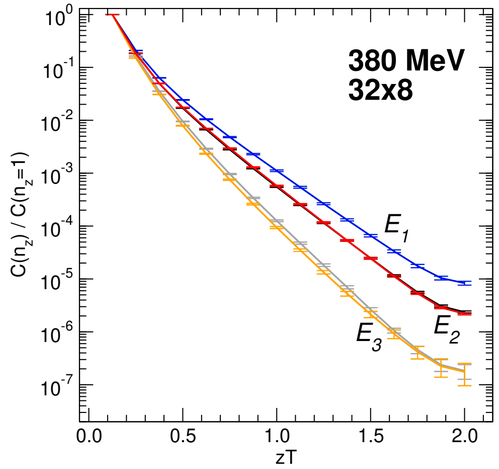
See talk of Leonid

Spin symmetry for $T_\chi \lesssim T \lesssim 2T_\chi$

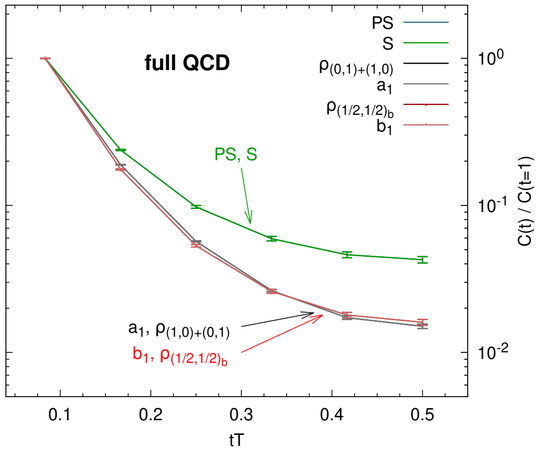




Rohrhofer, Aoki, Cossu, Fukaya, Glozman, Hashimoto, Lang, Prelovsek, PRD 96 (2017) 094501



Rohrhofer, Aoki, Glozman, Hashimoto, PLB 802 (2020) 135245

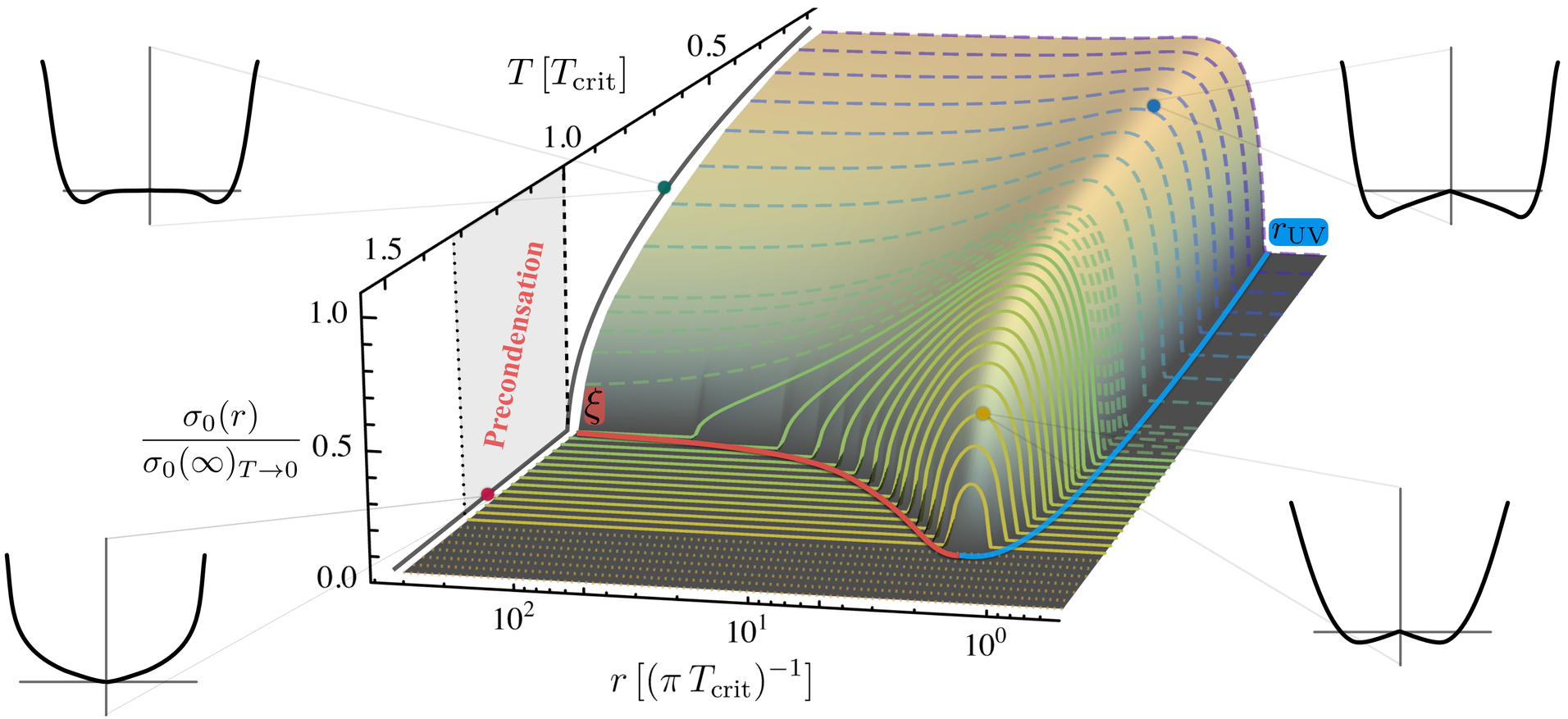


Relation?

Strongly correlated physics

See talk of Álvaro

Precondensation in chiral QCD

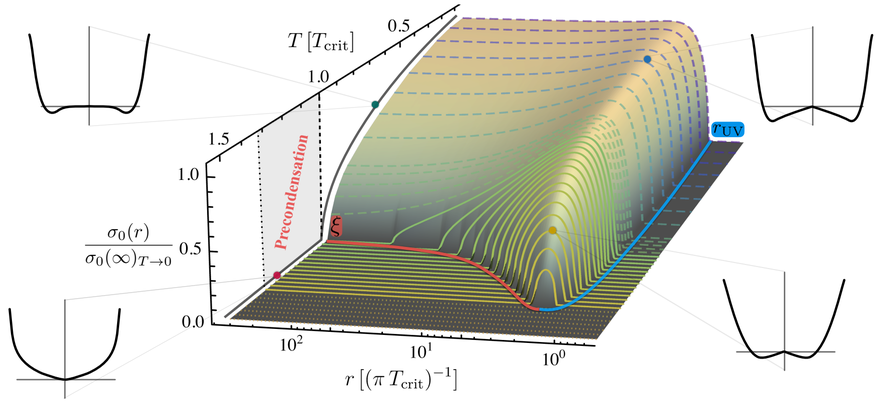


Strongly correlated physics

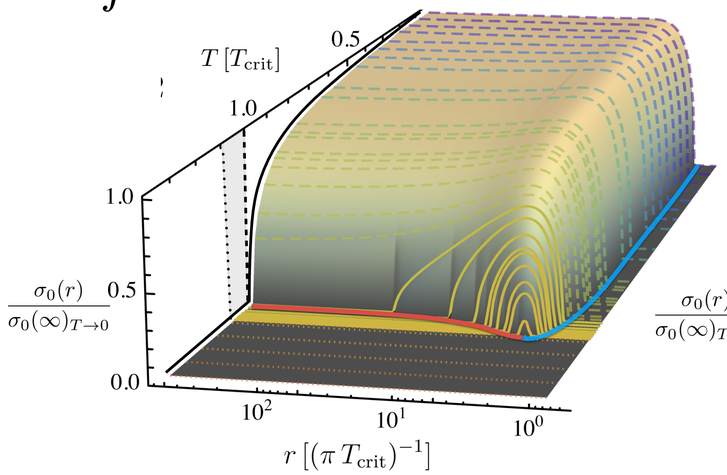
See talk of Álvaro

Precondensation for different flavours

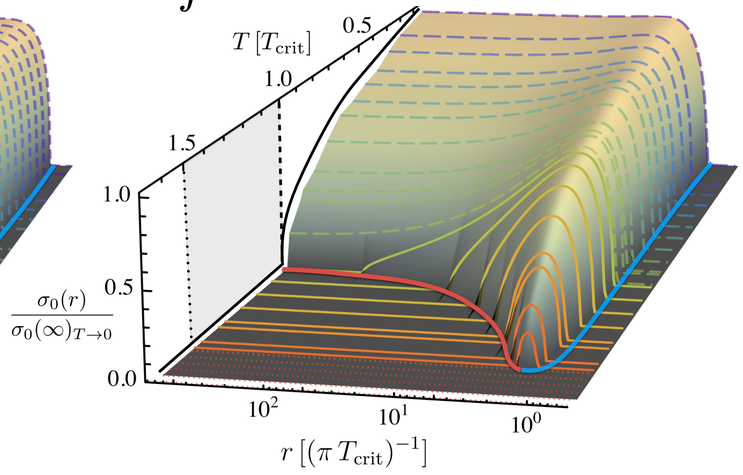
$N_f = 3$



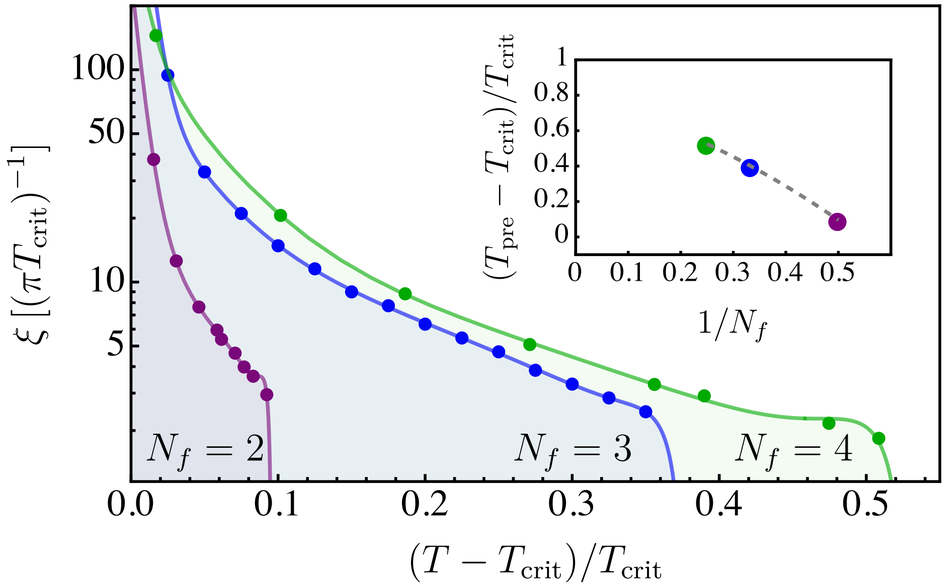
$N_f = 2$

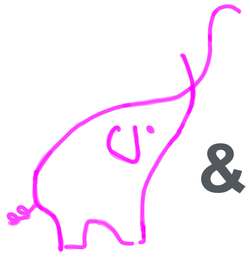


$N_f = 4$



Correlation length of 'domains'





& functional QCD

Ripples of the CEP

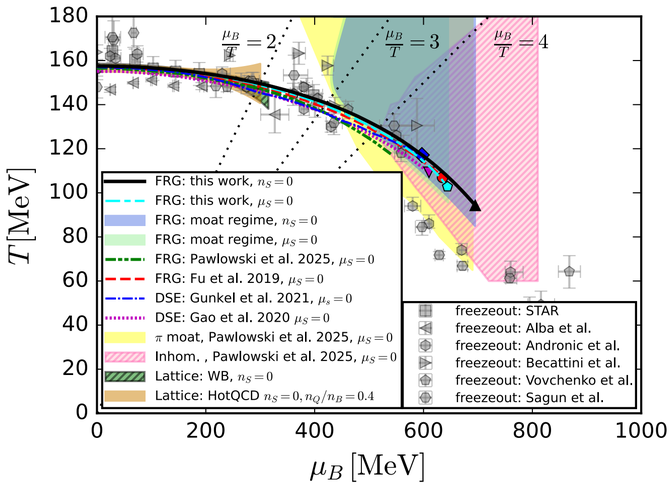
aka

(Strong) signals of the ONP

QCD-assisted low energy effective theory

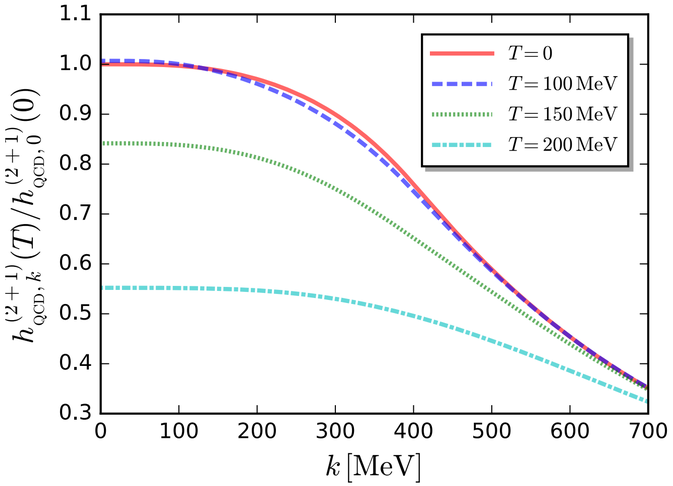
Direct QCD input

chiral phase structure



+

quark-antiquark — meson scattering



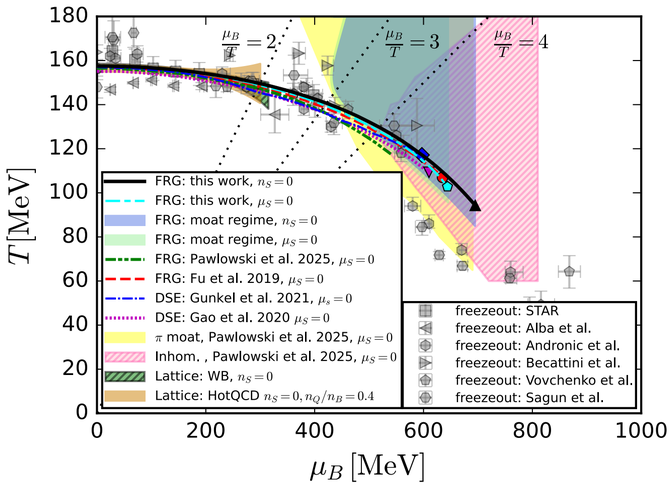
Fu, JMP, Rennecke, PRD 101 (2020) 054032

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

QCD-assisted low energy effective theory

Direct QCD input

chiral phase structure



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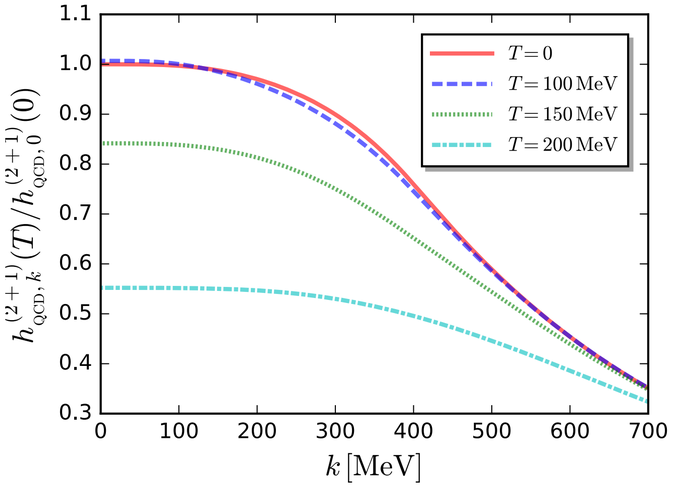


Fu, JMP, Rennecke, PRD 101 (2020) 054032

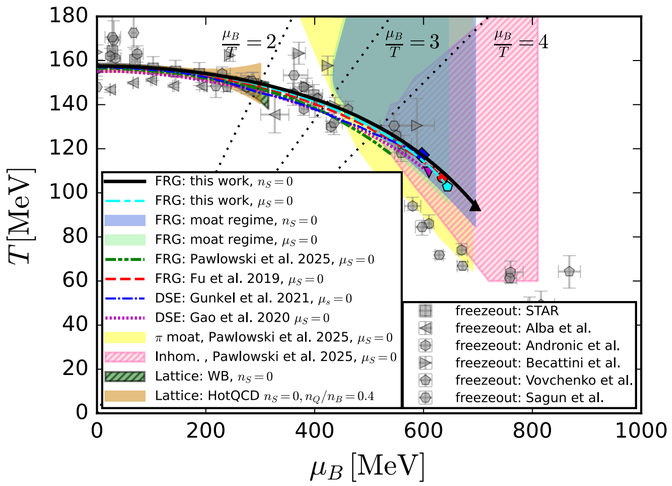
low energy quantum, thermal & density fluctuations via fRG (QCD-assisted PQM model)

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

QCD-assisted low energy effective theory

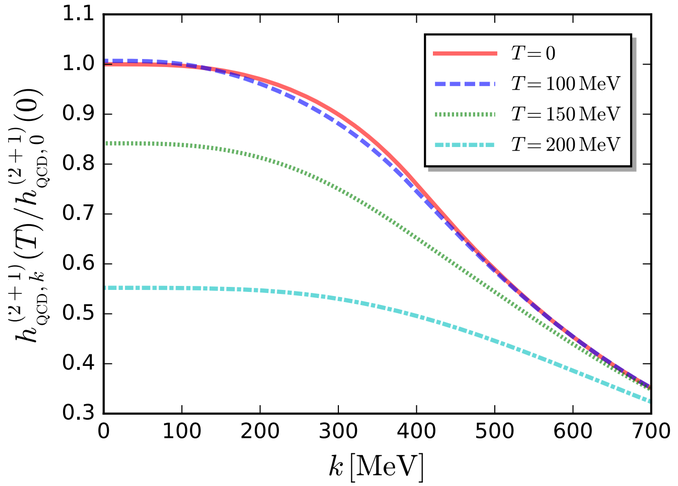
Direct QCD input

chiral phase structure



+

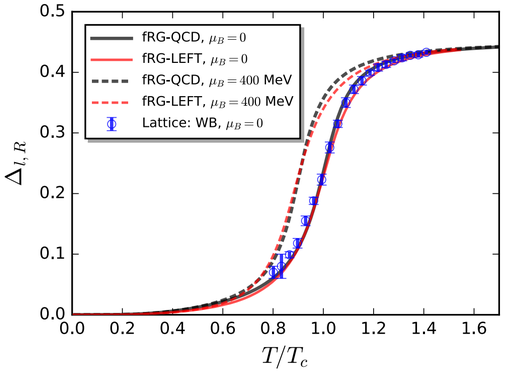
quark-antiquark — meson scattering



Fu, JMP, Rennecke, PRD 101 (2020) 054032

low energy quantum, thermal & density fluctuations via fRG (QCD-assisted PQM model)

renormalised chiral condensate

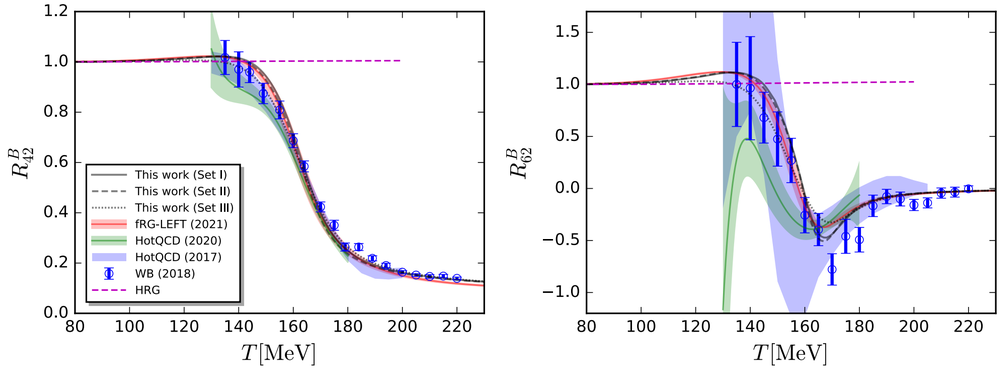


Benchmarks with lattice and fQCD

at

vanishing density and fQCD at finite density

baryon number fluctuations



Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

Ripples of the critical point at chemical freeze-out

Canonical corrections via subensemble acceptance

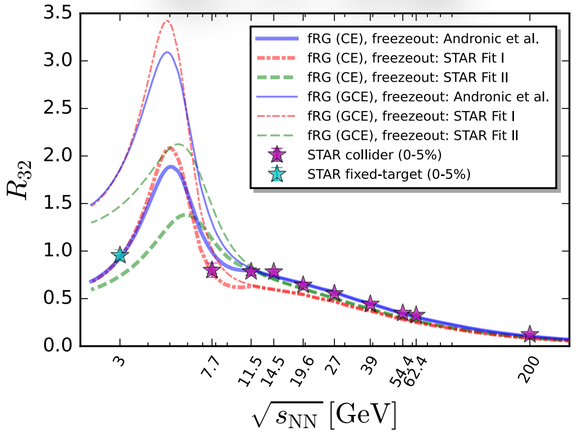
Vovchenko, Savchuk, Poberezhnyuk, Gorenstein, Koch, PLB 811, 135868 (2020)

fixing the subensemble volume

subensemble volume **system volume**

$$V_1 = \alpha V$$

$$\bar{R}^B_{32} = (1-2\alpha) R^B_{32}$$



qualitative adjustment

$$\alpha(\bar{s}) = a\left(1-\sqrt{\bar{s}}\right)\theta\left(1-\bar{s}\right)$$

$$a = 0.33 \qquad \sqrt{\bar{s}} = \frac{\sqrt{s_{\rm NN}}}{11.9\,\text{GeV}}$$

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

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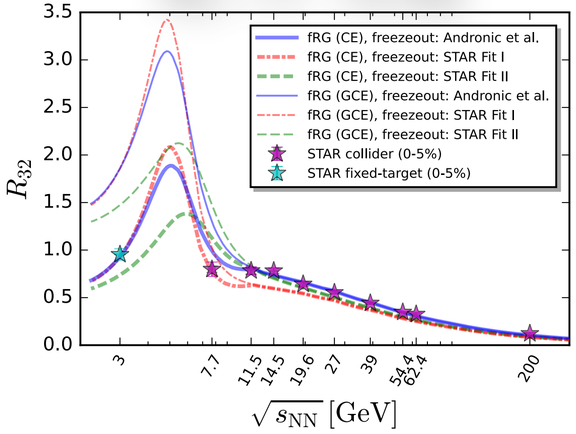

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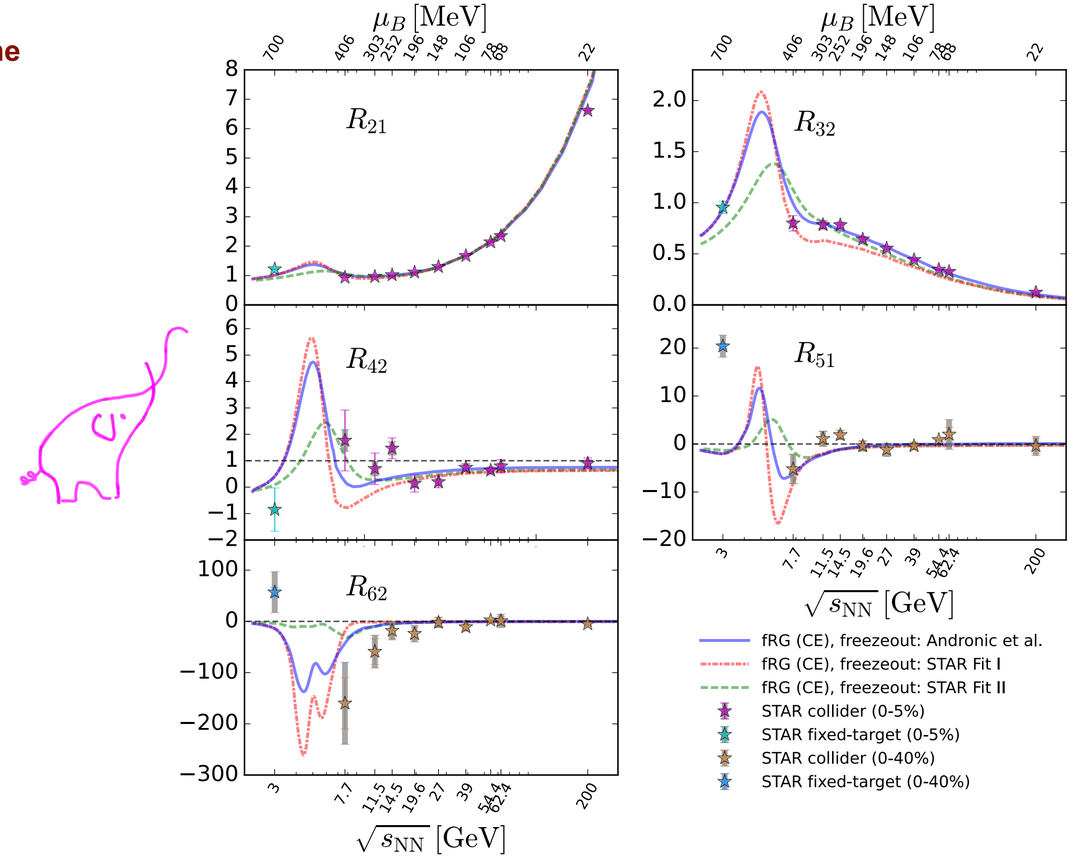
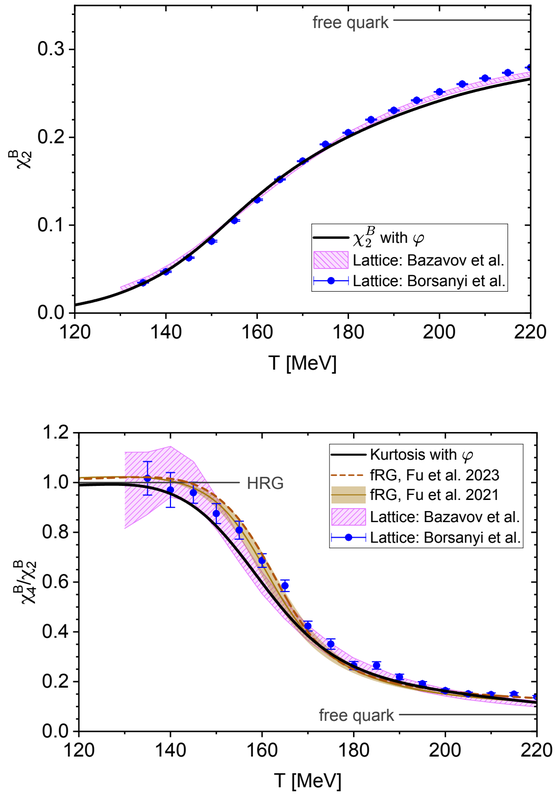
$$a = 0.33 \qquad \sqrt{\bar{s}} = \frac{\sqrt{s_{\rm NN}}}{11.9\,\text{GeV}}$$

baryon & proton number fluctuations



baryon fluctuations with functional QCD

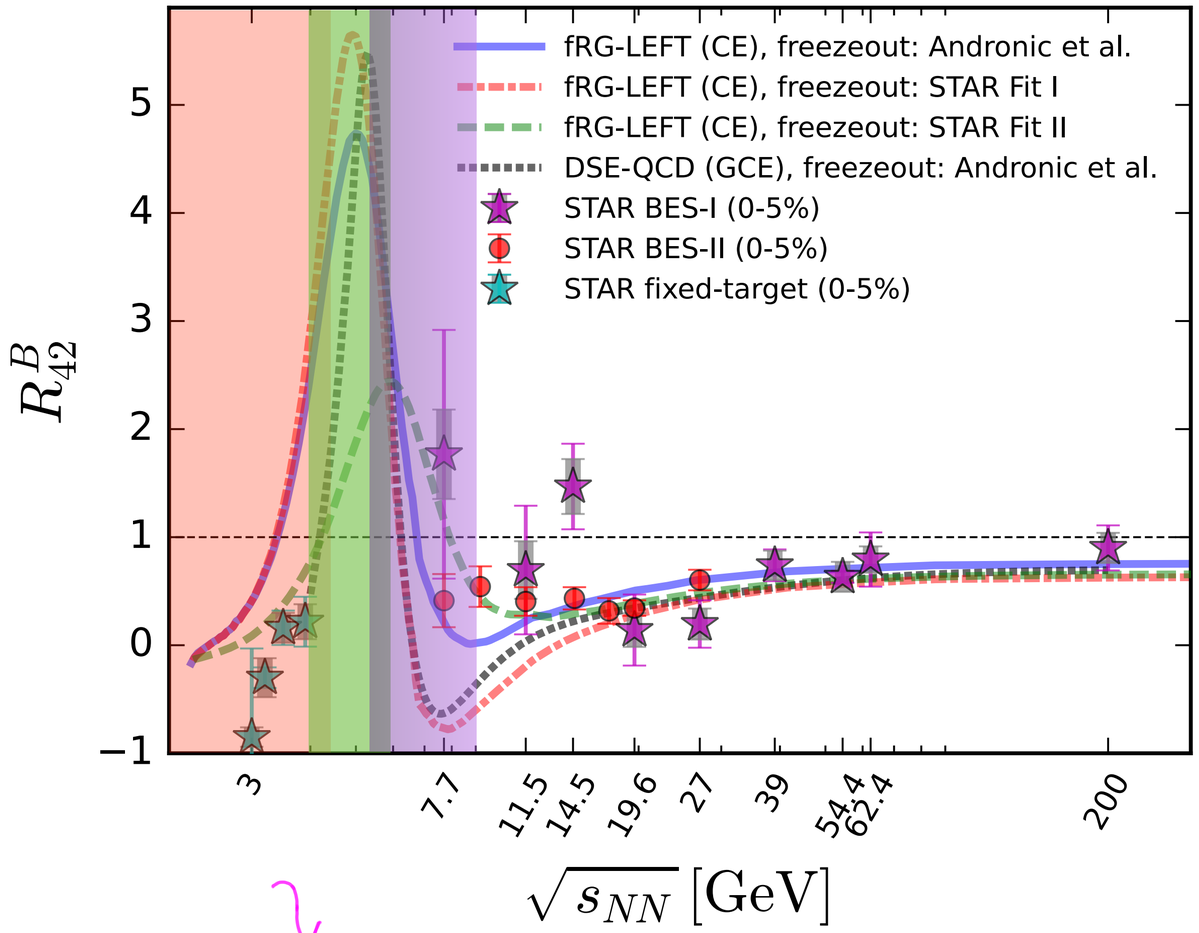


Gao, Liu, Lu, JMP, PRD 113 (2026) 054019

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

Ripples of the critical point at chemical freeze-out

net-baryon fluctuations in QCD vs net-proton fluctuations at STAR



Dominated by non-critical soft modes

Results:
1st principles functional QCD computations
& low energy effective theories/extrapolations

& functional QCD

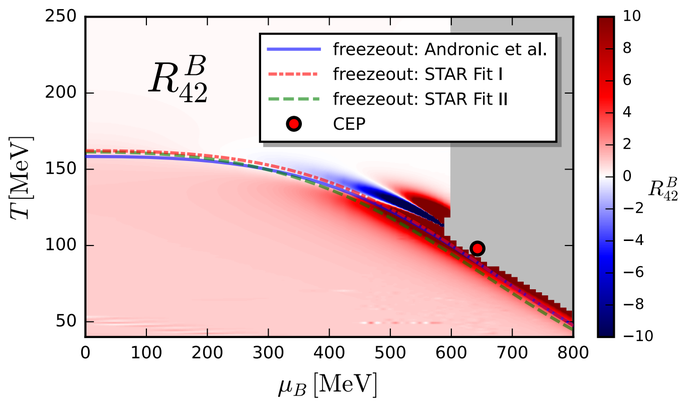
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

Fu, Luo, JMP, Rennecke, Yin, PRD 111, L031502

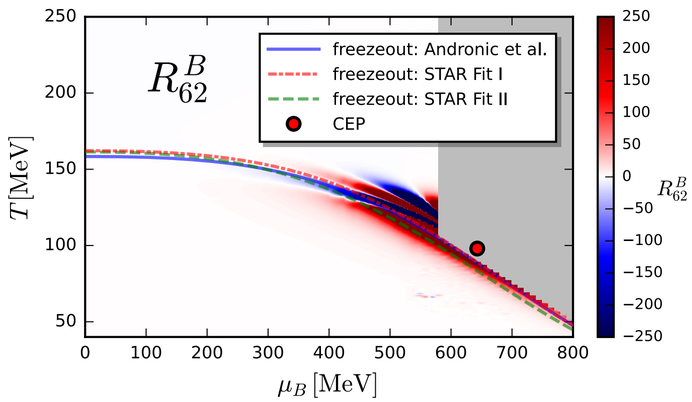
Functional QCD: Lu, Gao, Liu, JMP, 113 (2026) 054019

Ripples of the critical point

baryon number fluctuations in the phase structure

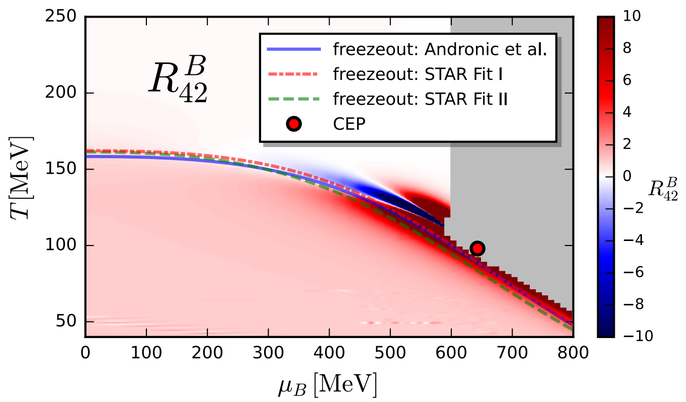


$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (98, 643)\,\mathrm{MeV}$$



Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

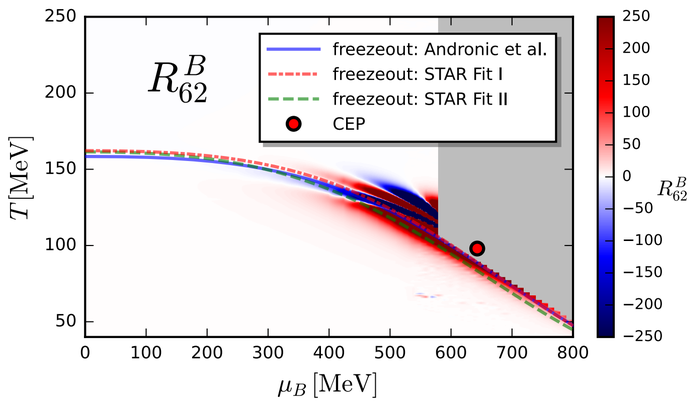
Ripples of the critical point



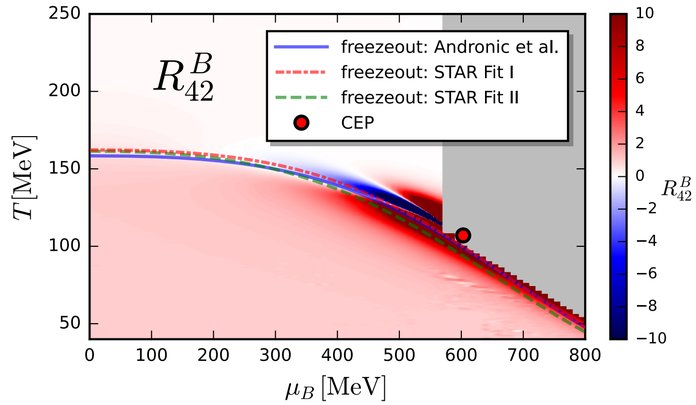
baryon number fluctuations in the phase structure

$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (98, 643)\,\mathrm{MeV}$$

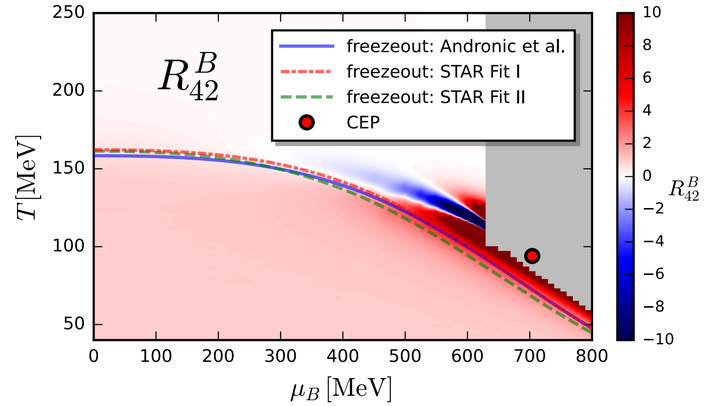
Ride the



Variations of the CEP in the allowed estimate regime



$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (108, 604)\,\mathrm{MeV}$$

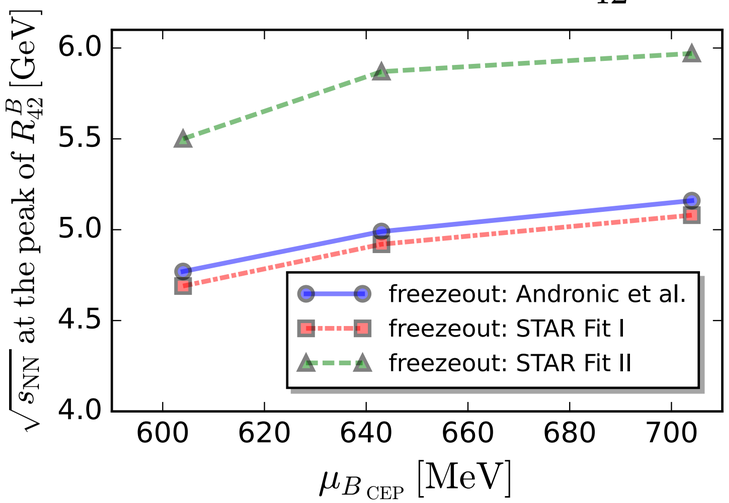


$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (94, 704)\,\mathrm{MeV}$$

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

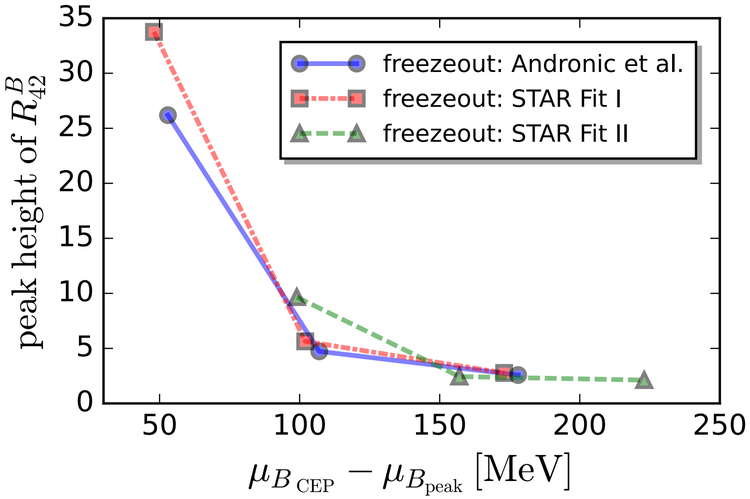
Ripples of the critical point at chemical freeze-out

Position of the peak of R^B_{42}



Reconstructing the CEP

Height of the peak of R^B_{42}



Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

Ripples of the critical point at chemical freeze-out

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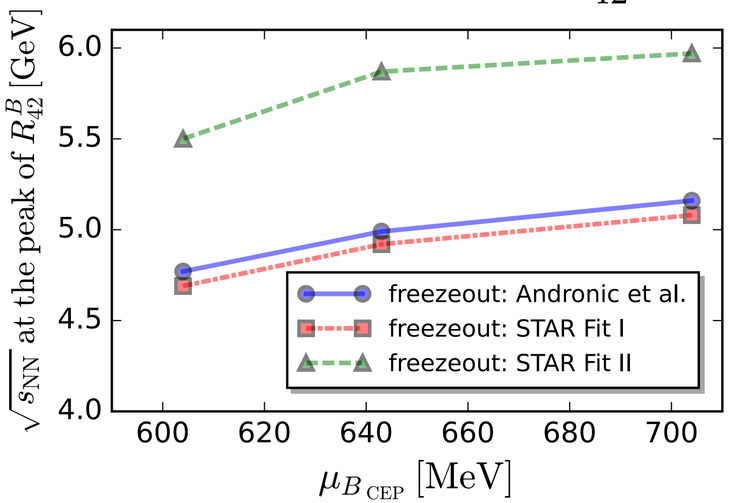

Reconstructing the CEP

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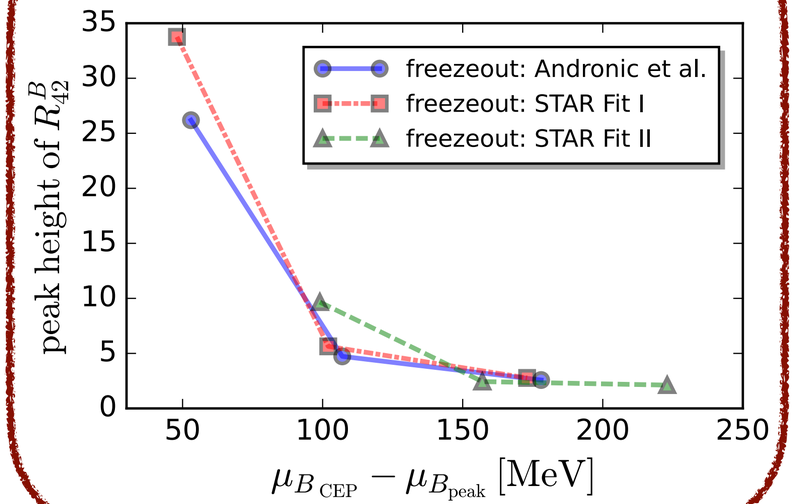
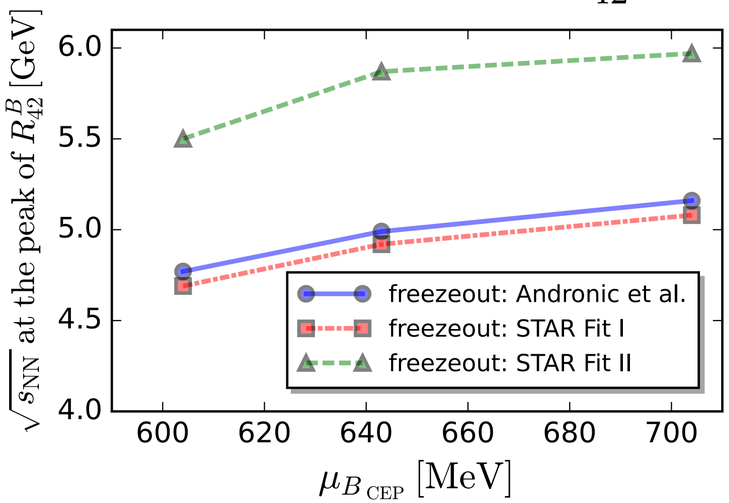


Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

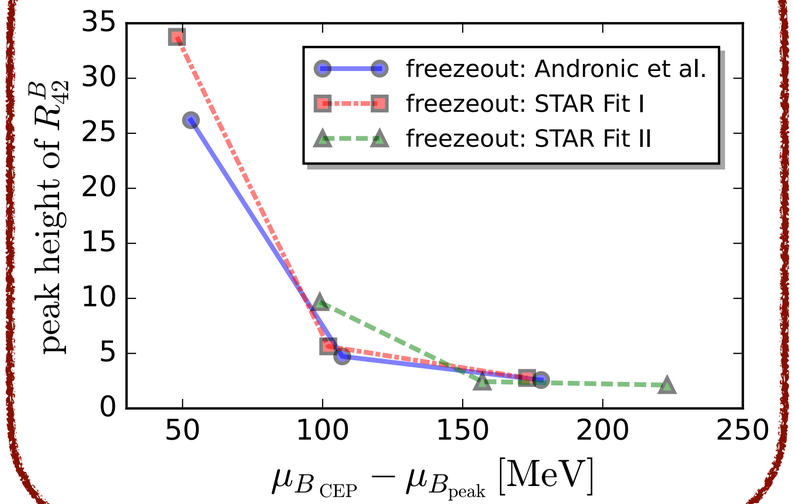
Ripples of the critical point at chemical freeze-out

Position of the peak of R^B_{42}



Reconstructing the CEP

Height of the peak of R^B_{42}



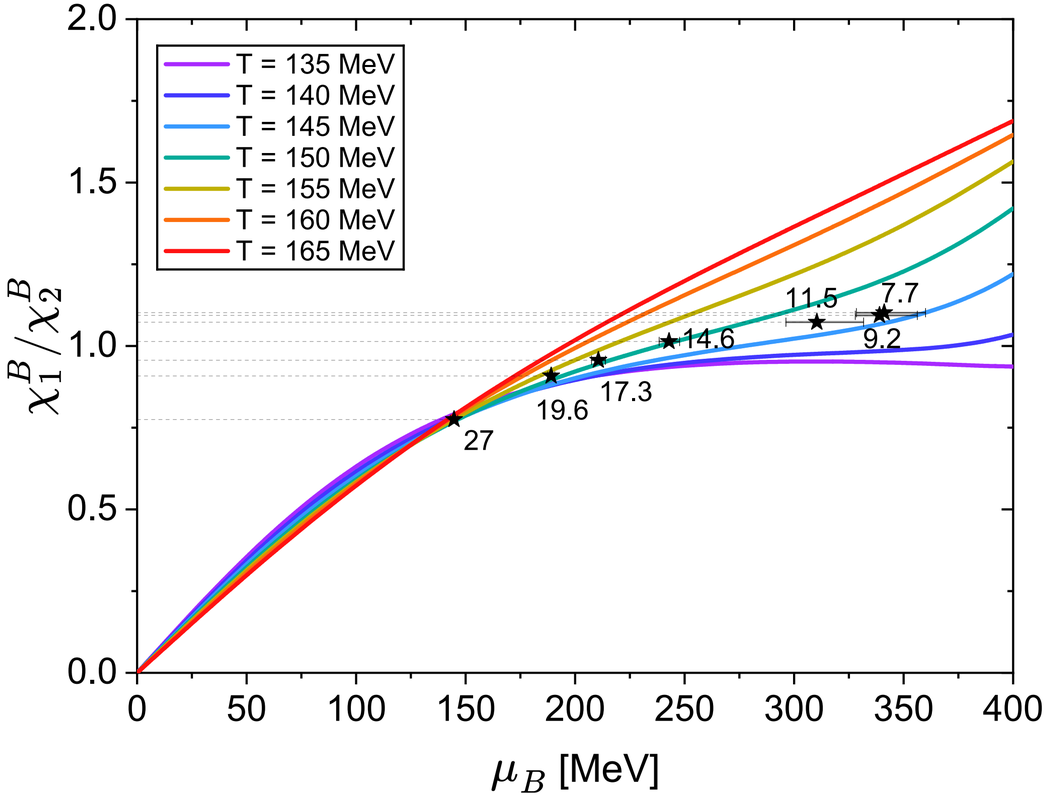
Unfolding the high density regime with new phases & physics

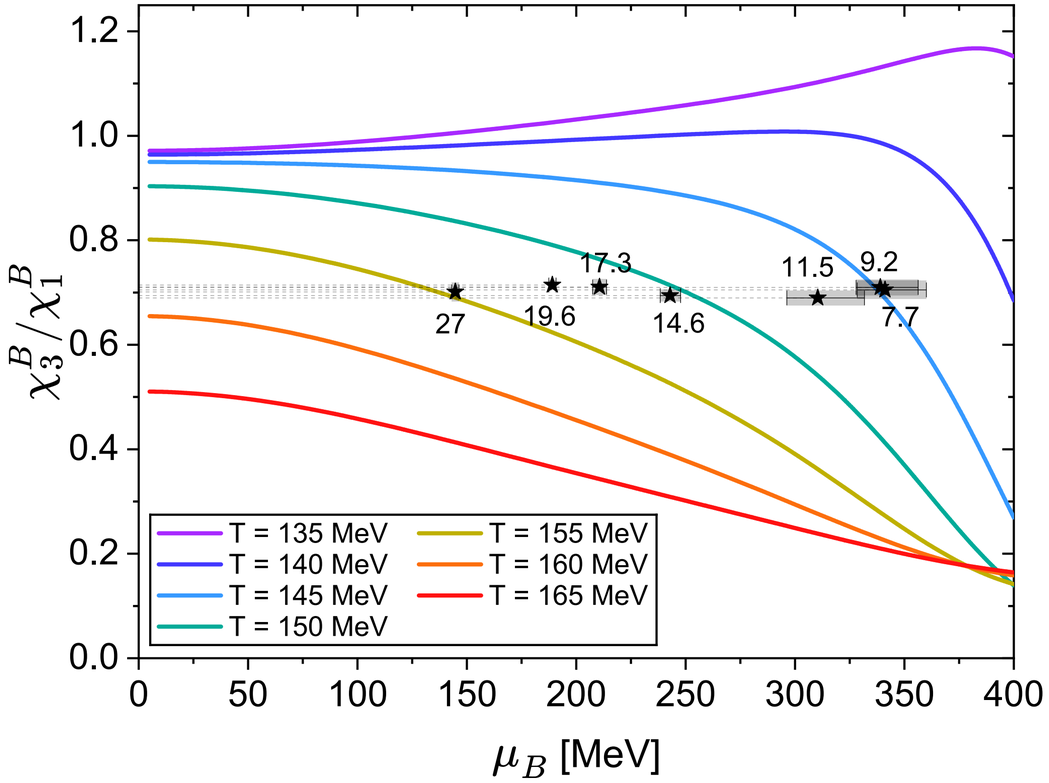
Great opportunity for a combined high precision analysis of high density QCD (Exp. data + lattice QCD + functional QCD)

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

Functional Freeze-out

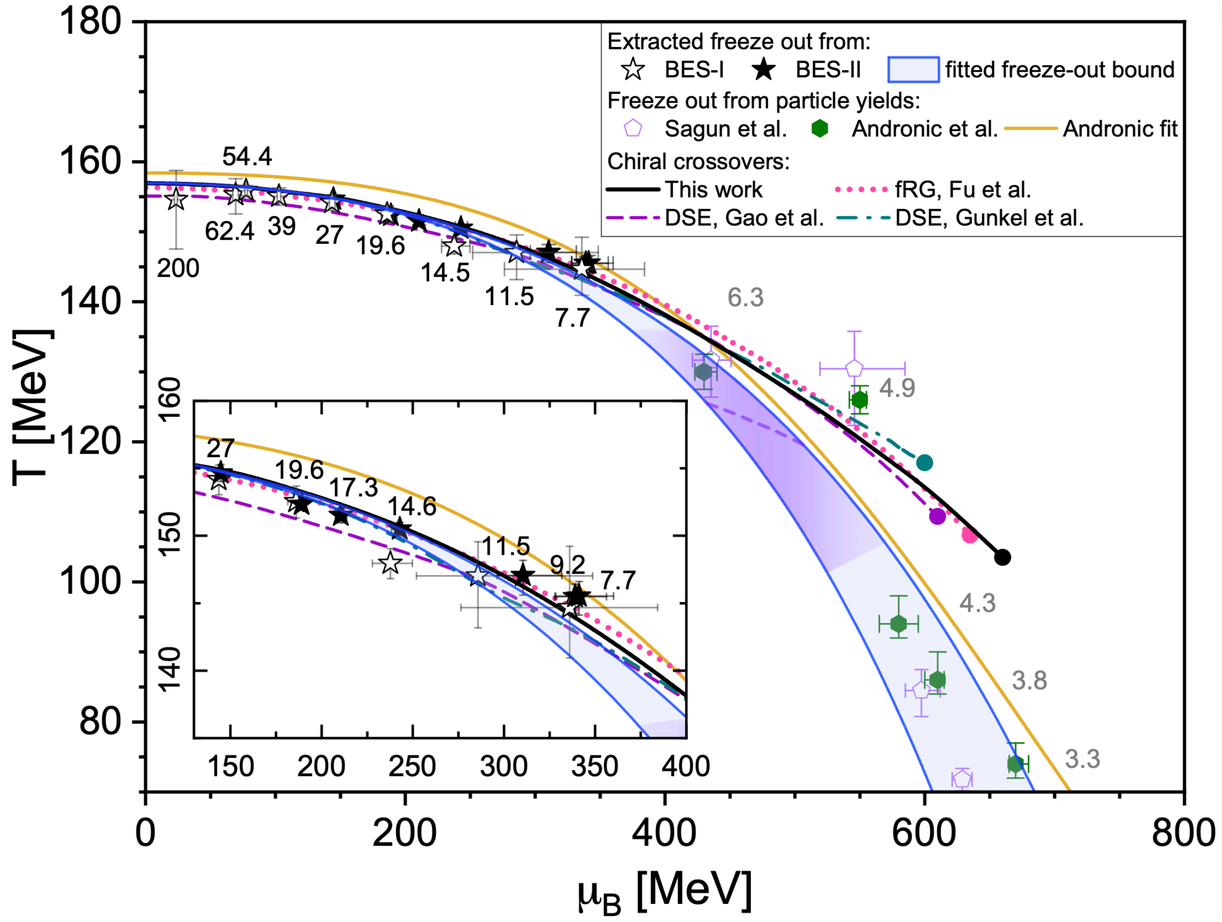
$$(T_f\ ,\ \mu_{B\,f}) \longleftrightarrow \sqrt{s}$$

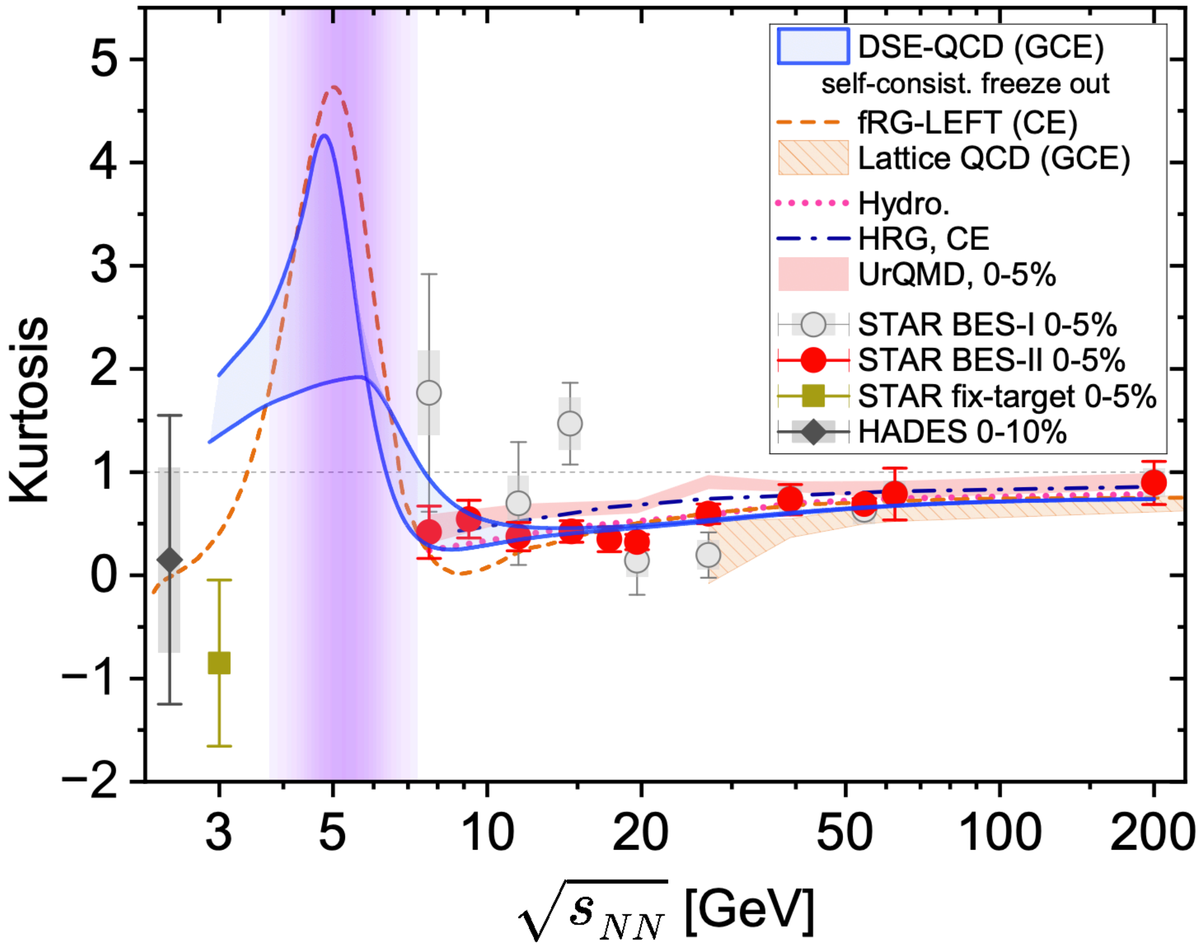




Lu, Fischer, Gao, Liu, JMP, arXiv:2603.09336

Ripples of the critical point at chemical freeze-out





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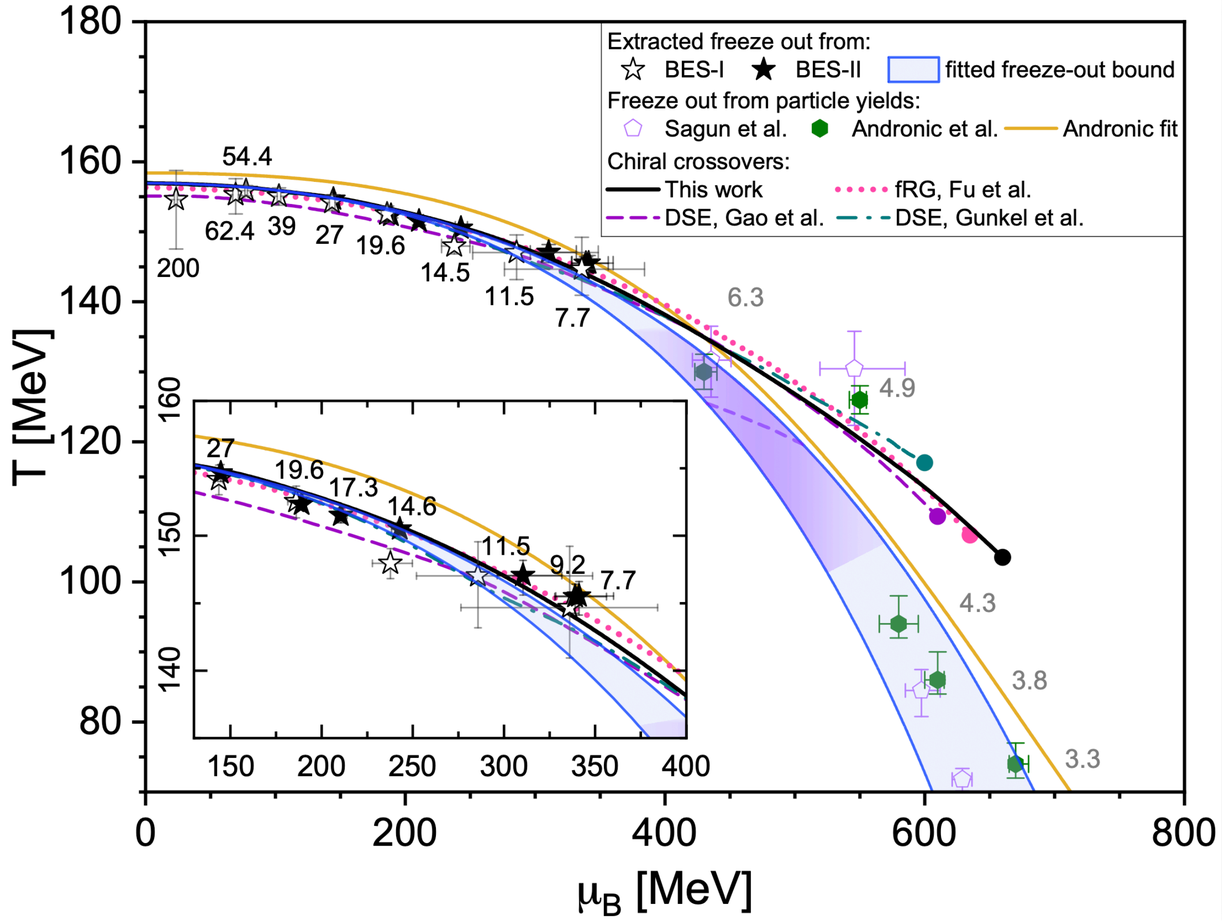
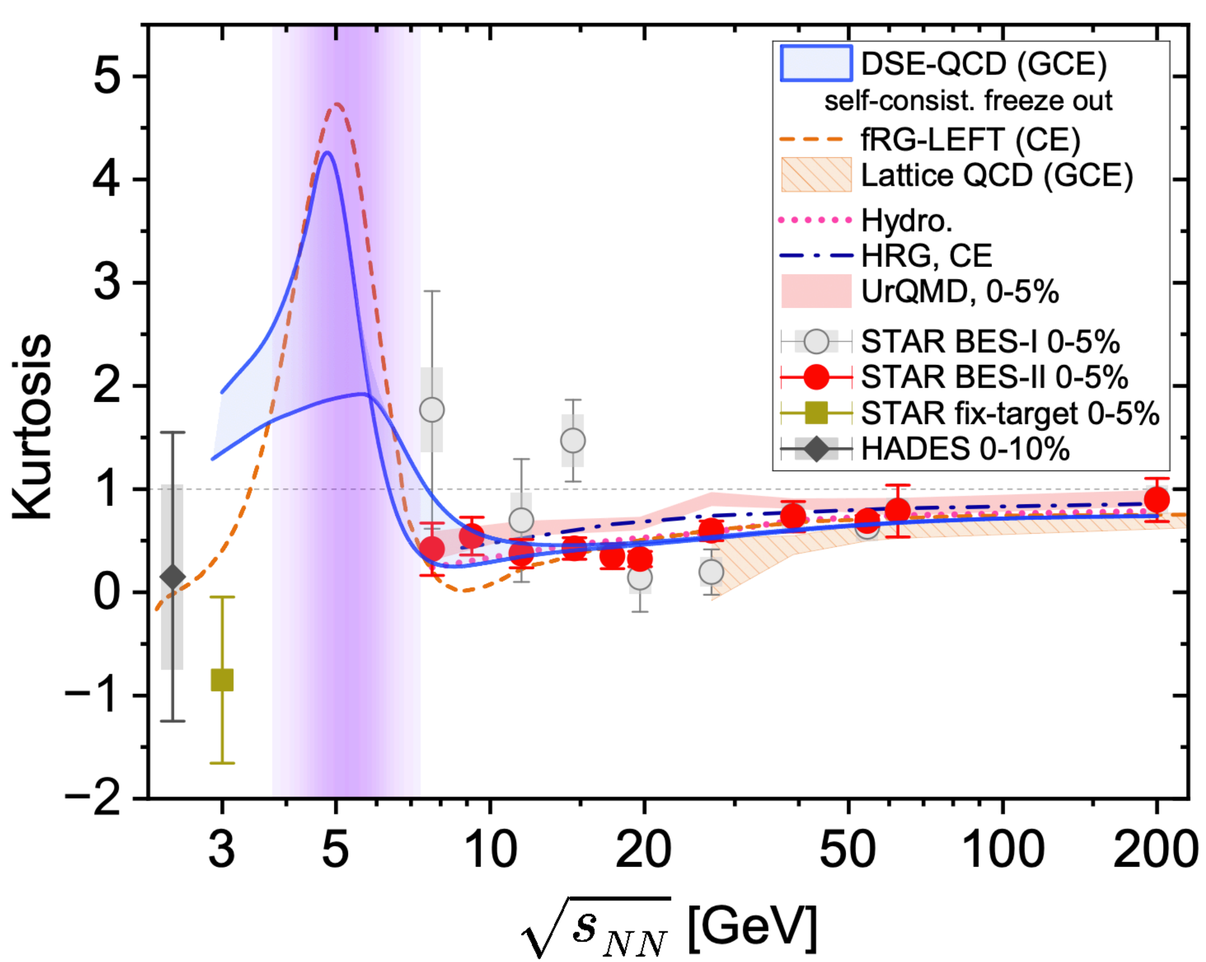


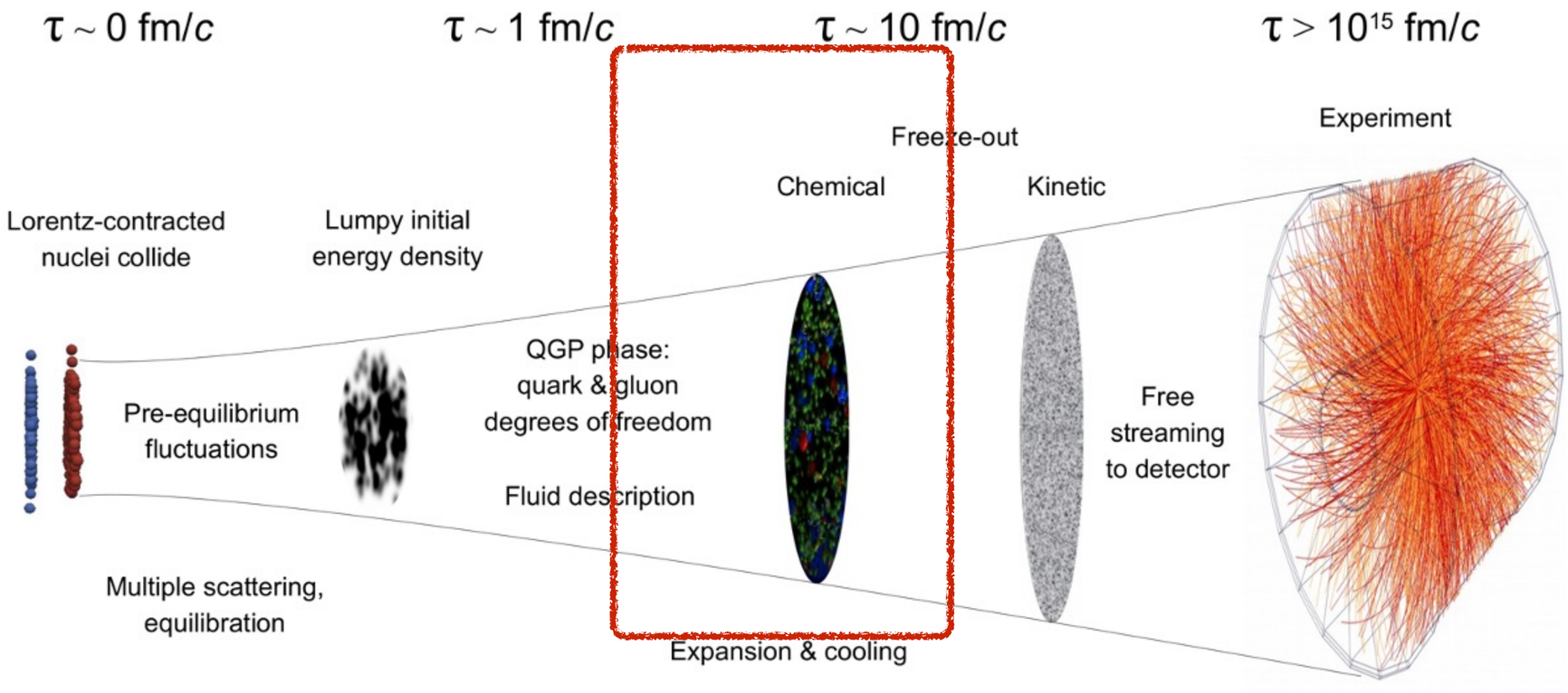


Demand: build in dynamics

EMMI workshop: Collective phenomena and the EoS of dense baryonic matter

Lu, Fischer, Gao, Liu, JMP, arXiv:2603.09336

Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)

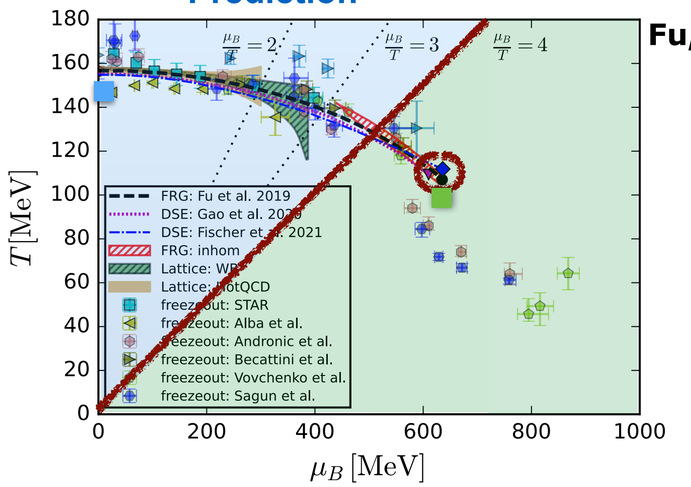


How to unfold: inverse problem!

Demand: unfolding HICs

The QCD moat and inhomogeneous phases

Prediction



Fu, JMP, Rennecke, PRD 101 (2020) 054032

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

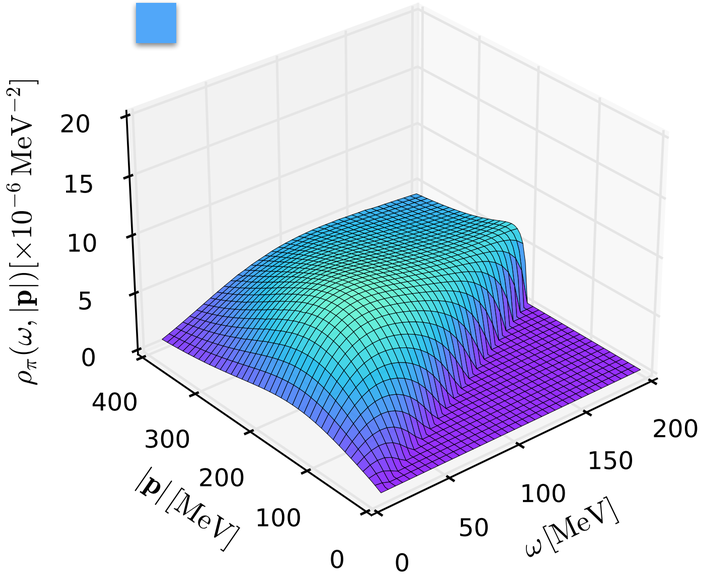
Regime of quantitative reliability of current best truncation

T=160 MeV & μ_B =0 MeV

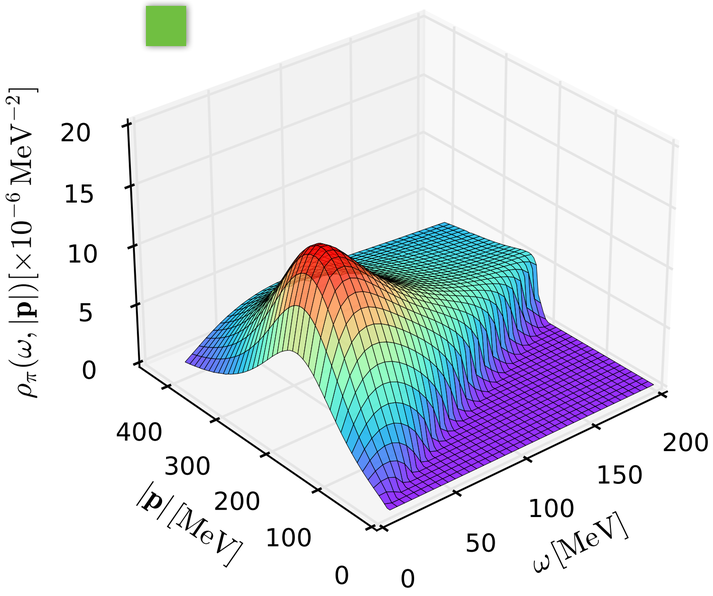
T=114 MeV & μ_B =630 MeV

Estimate

Moat regime was not captured quantitatively



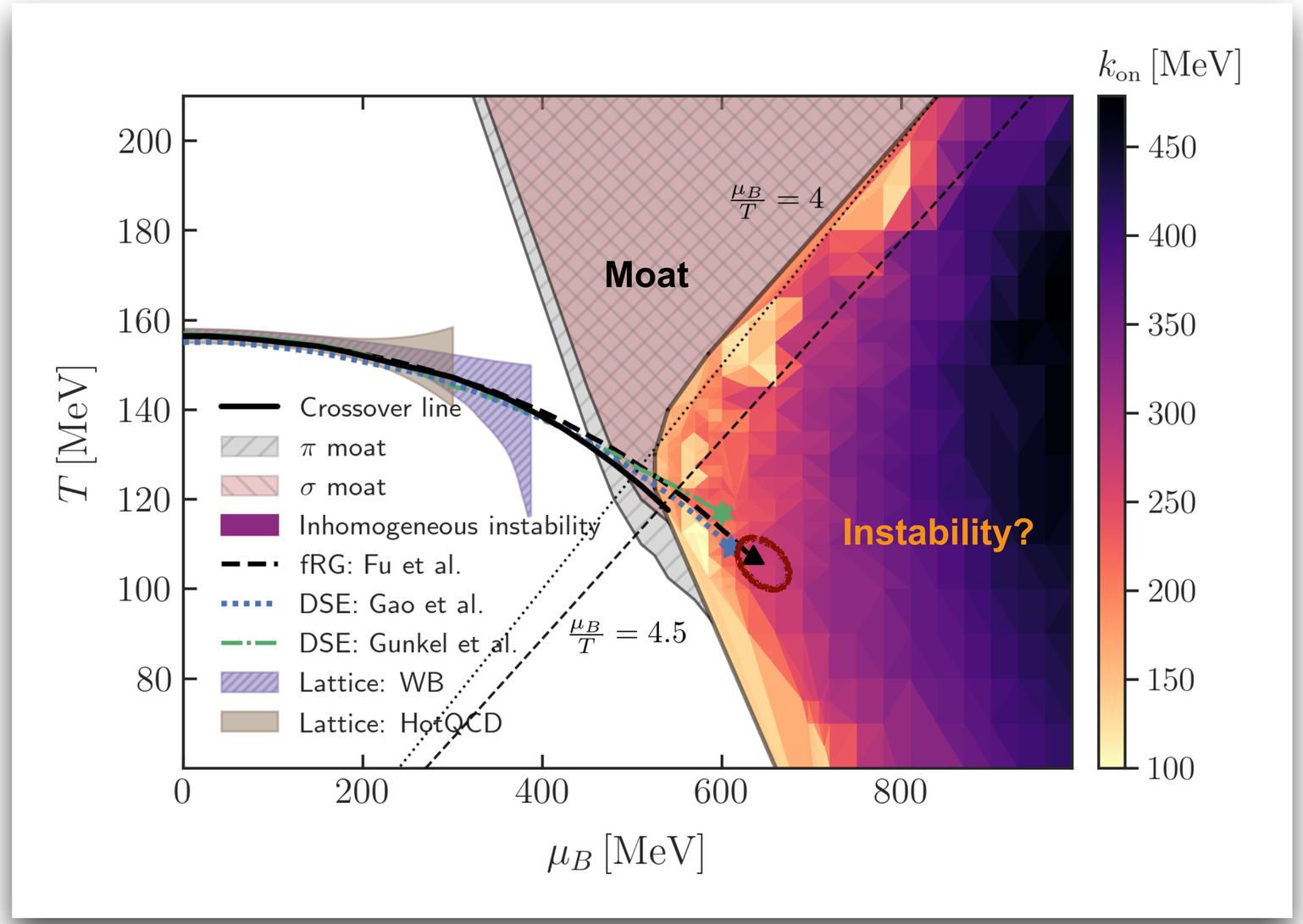
Pion spectral functions



Fu, JMP, Pisarski, Rennecke, Wen, Yin, PRD 111 (2025) 094026

The QCD Moat reloaded

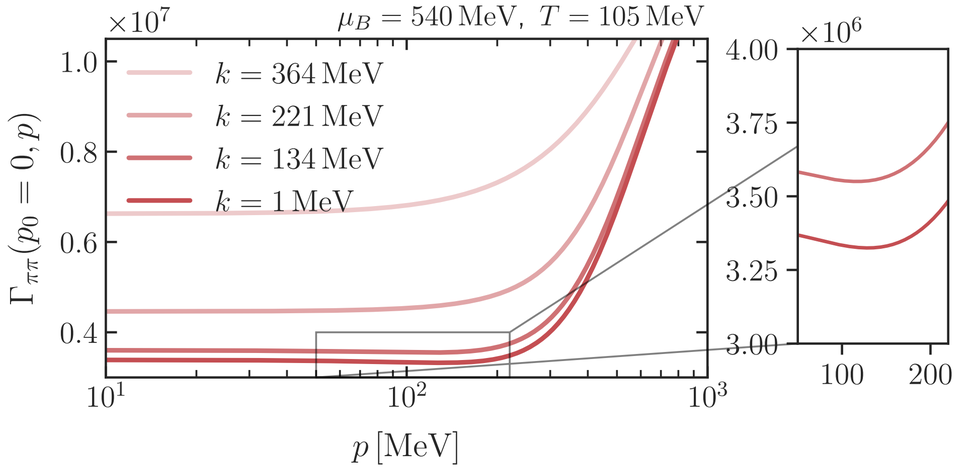
Estimated location of CEP

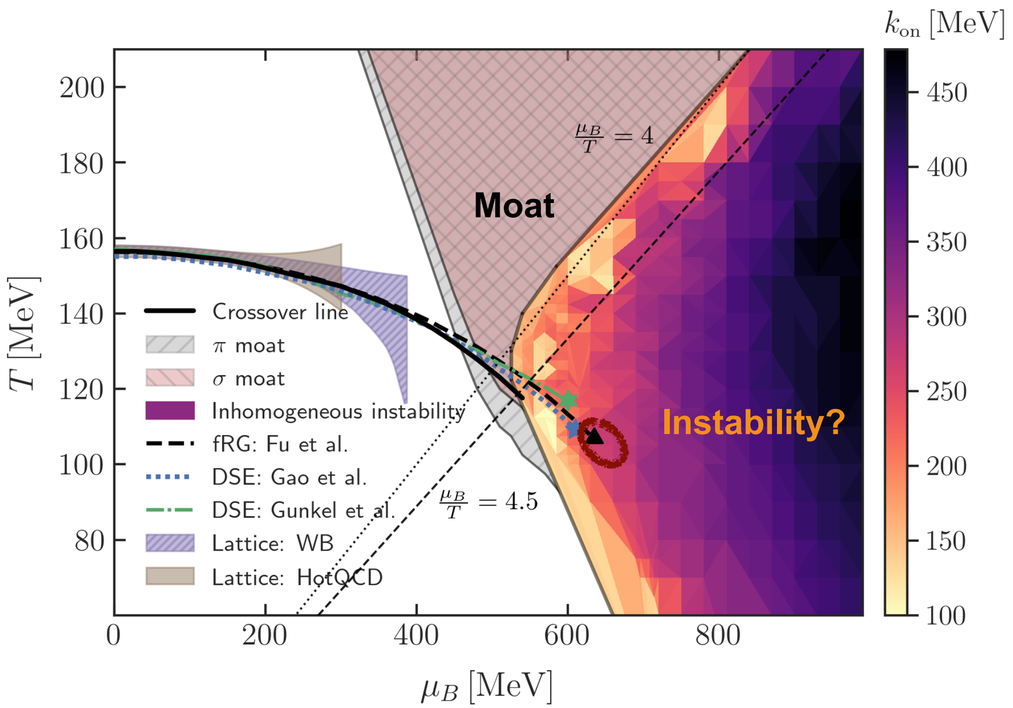


Pawlowski, Sattler, Rennecke, arxiv:2512.20510

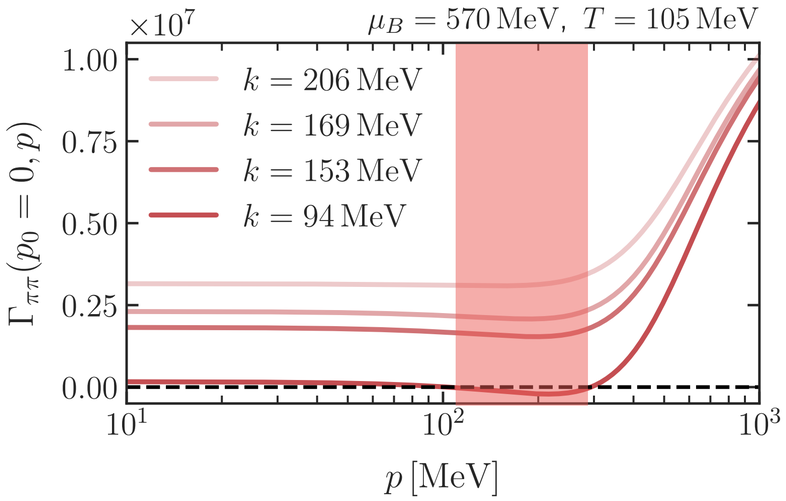
The QCD Moat reloaded

Moat





Instability



No full computation deep inside the instability regime

Estimated location of CEP

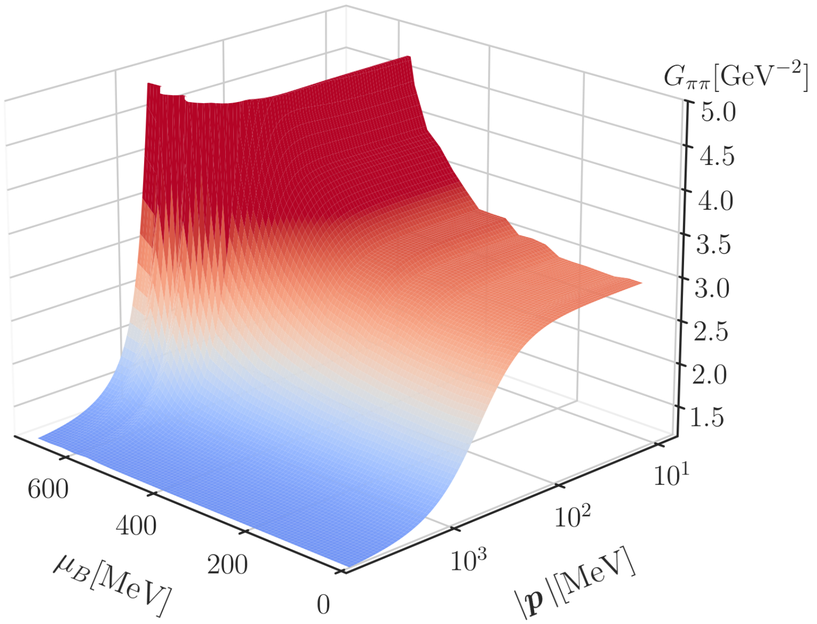
Pawlowski, Sattler, Rennecke, arxiv:2512.20510

See also talk of Fabian

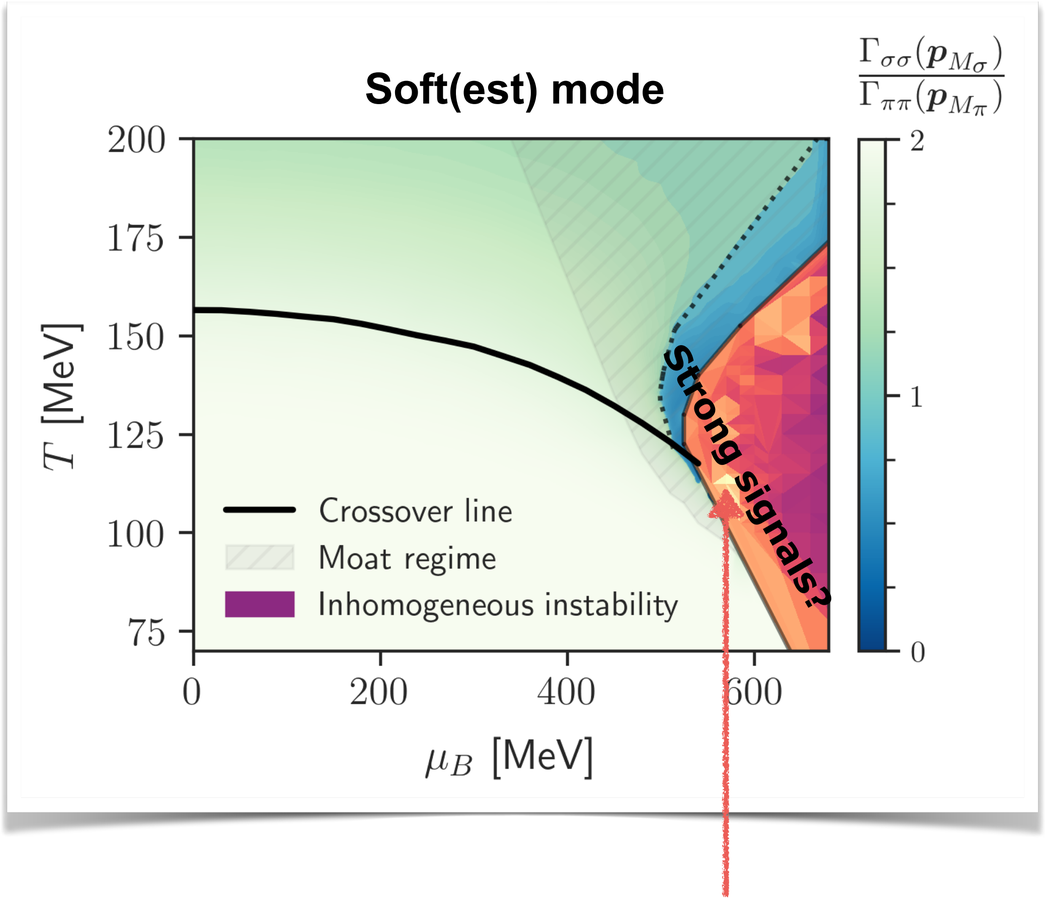
The QCD Moat reloaded

Soft mode

Pion propagator



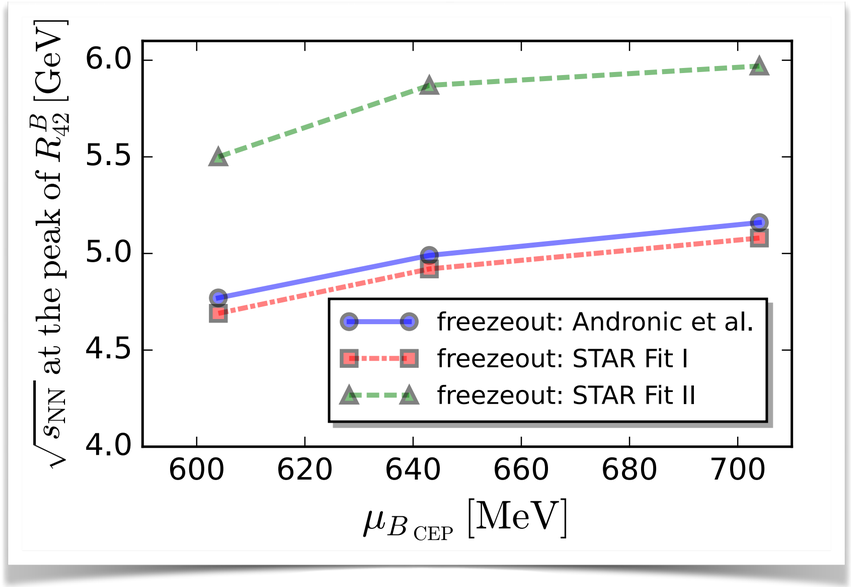
Soft(est) mode

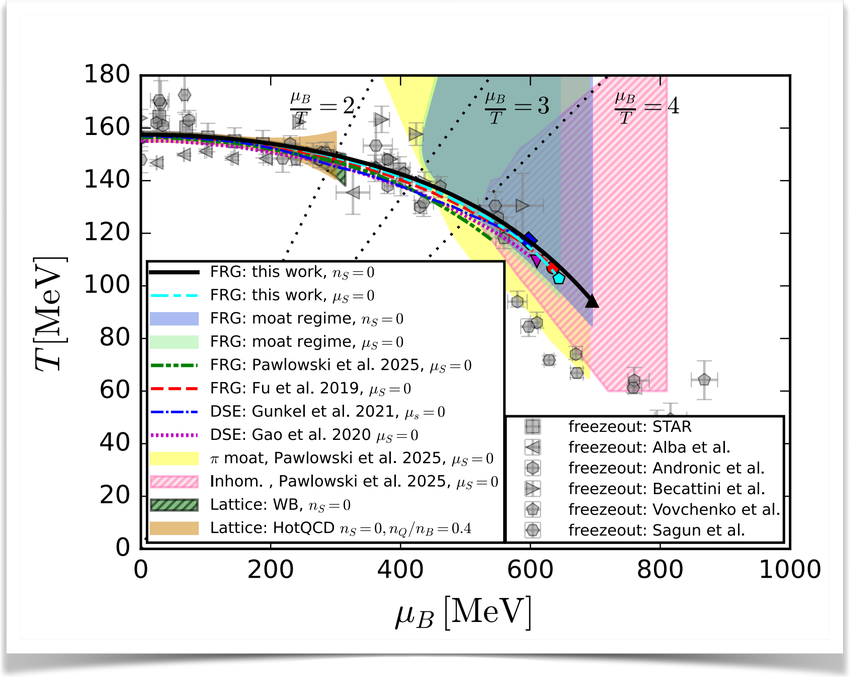


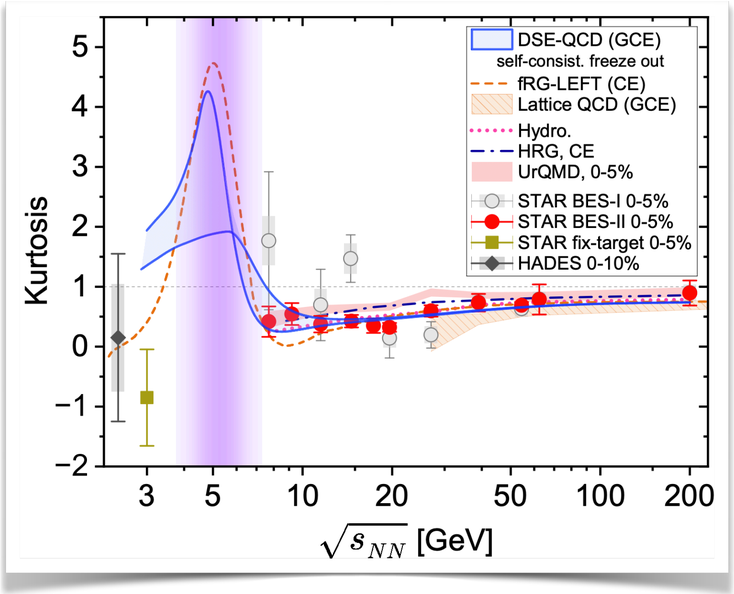
$k_{\mathrm{on}} \lesssim 100\,\mathrm{MeV}$

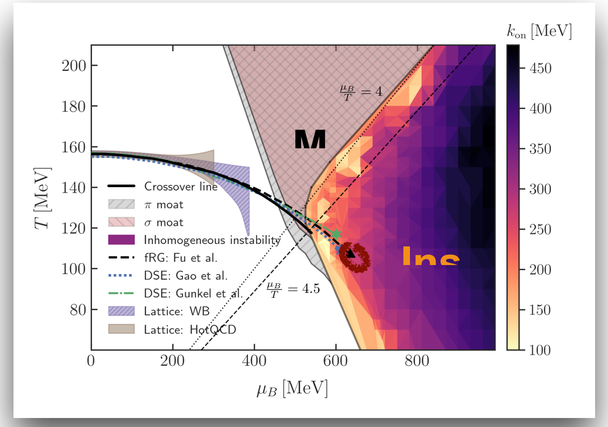
Pawlowski, Sattler, Rennecke, arxiv:2512.20510

First functional shot on the experimental location of the peak



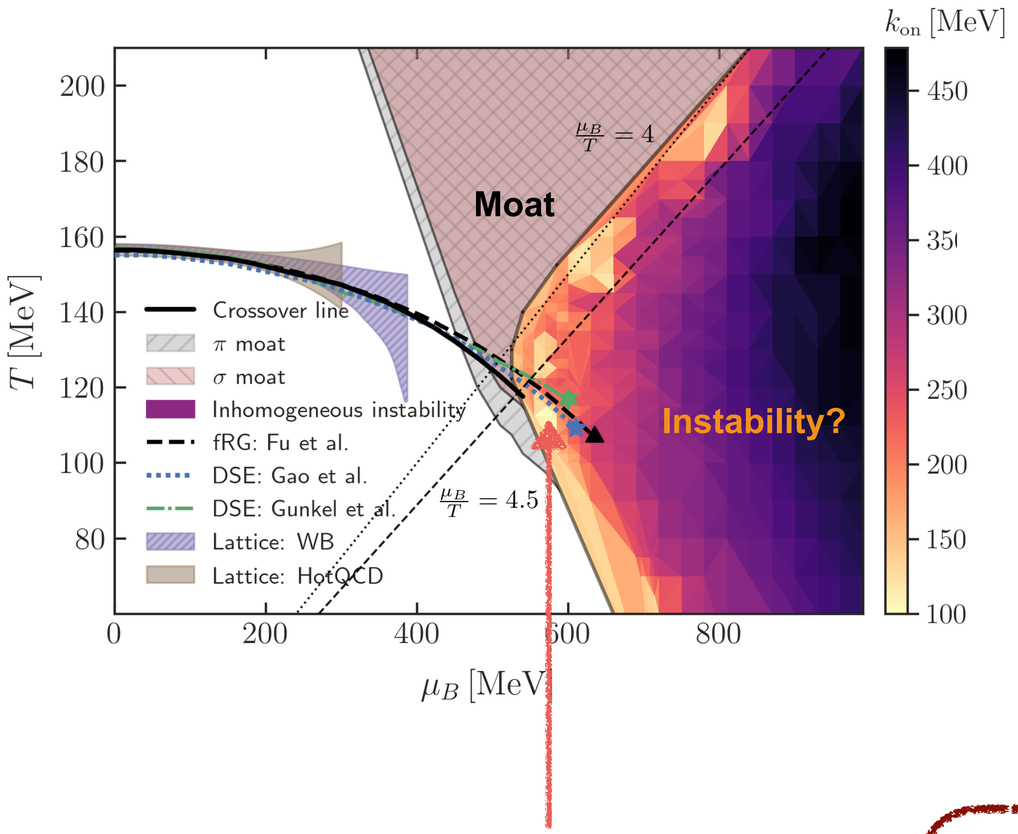






$$\sqrt{s_{\rm peak}} \approx 5$$

Experimental signatures for the onset of new phases



$k_{\rm on} \lesssim 100\,{\rm MeV}$

The moat

&

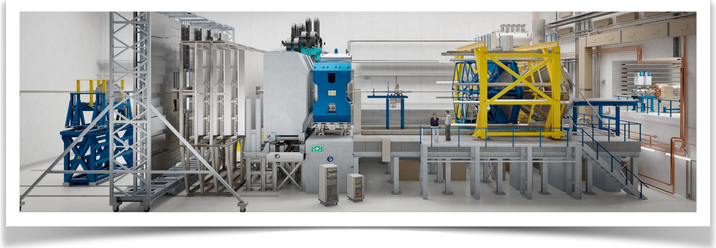
the regime with new phases

are in the CBM regime

and

require high statistics

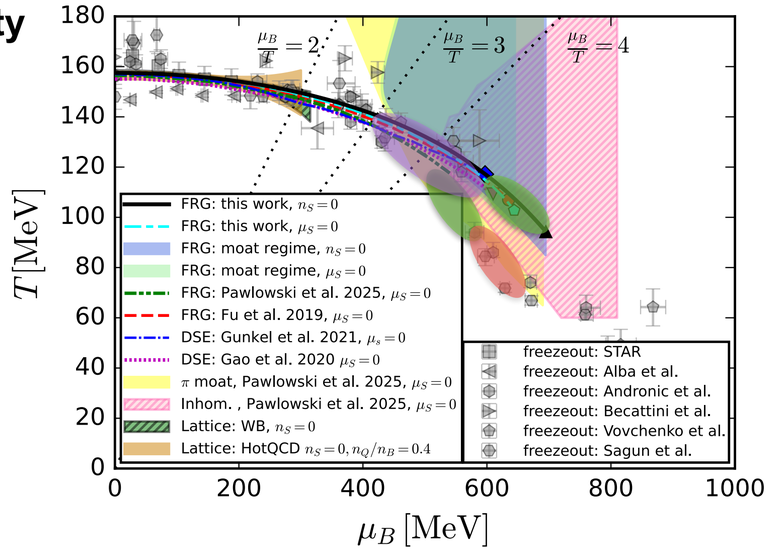
$$\sqrt{s_{\rm peak}} \approx 5$$

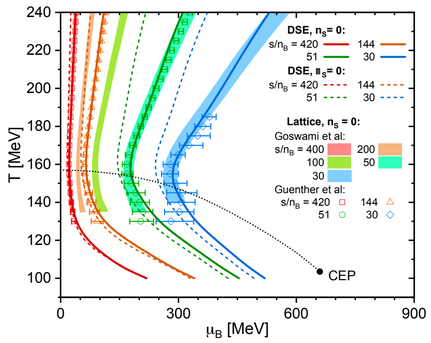


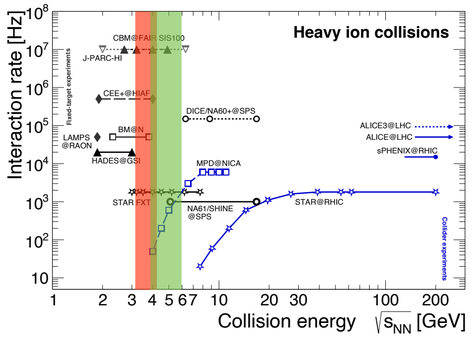
!Go for it!

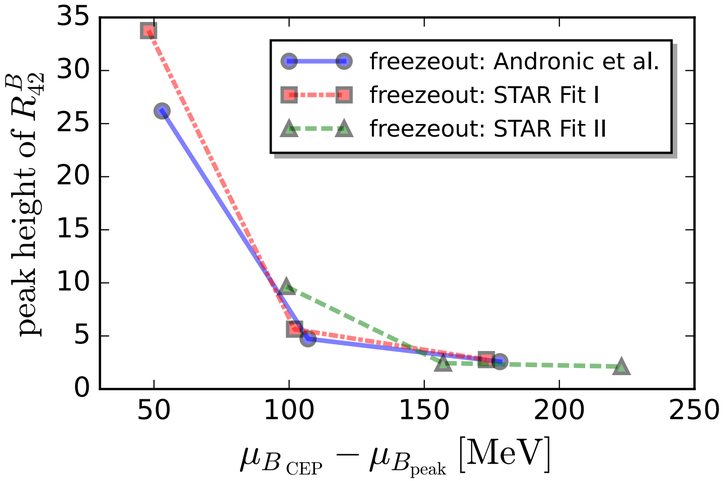
Summary

- **Functional QCD provides direct 1st principle results for the phase structure at finite density**
  - **Predictions:** $\frac{\mu_B}{T} \lesssim 4.5$
  - **Estimates:** $4.5 \lesssim \frac{\mu_B}{T} \lesssim 8$
- **Soft modes are commonplace, critical regimes are small**
- **Ripples of new phases aka of the critical end point**
  - **Explanation for the convergence of CEP locations of extrapolation approaches**
  - **Results & observables: EoS, fluctuations of conserved charges, tiny critical regime & onset of new phases; moat regime, ….**
  - **Peak height of kurtosis carries the location of the CEP**



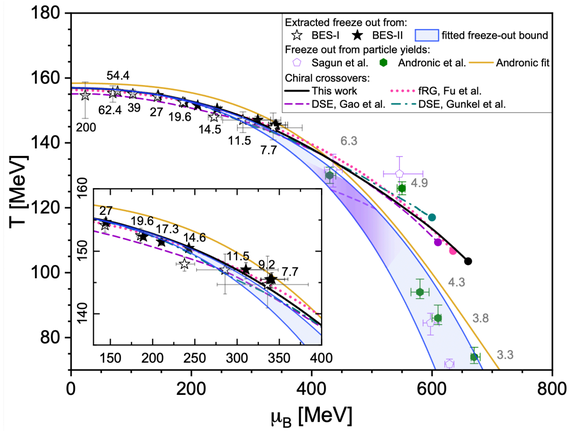


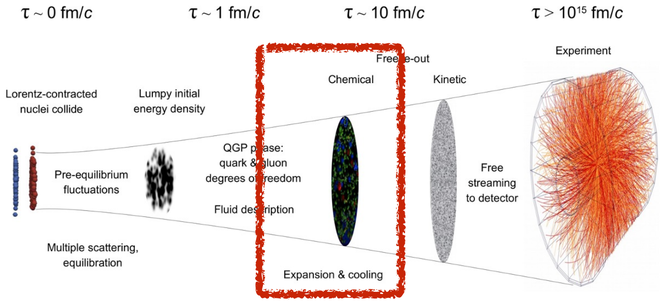




Summary

- **Functional freeze out & towards real time dynamics**





'Combined unfolding'

- **First steps in the QCD moat and inhomogeneous phases**

$$\sqrt{s_{\mathrm{peak}}} \approx 5$$