The QCD phase structure at finite density: Facts & Fiction

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Universität Heidelberg & ExtreMe Matter Institute

Wuhan, October 16th 2025

fqcd-collaboration.github.io

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STRUCTURES
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SFB1225

Experimental & Theoretical Landscape

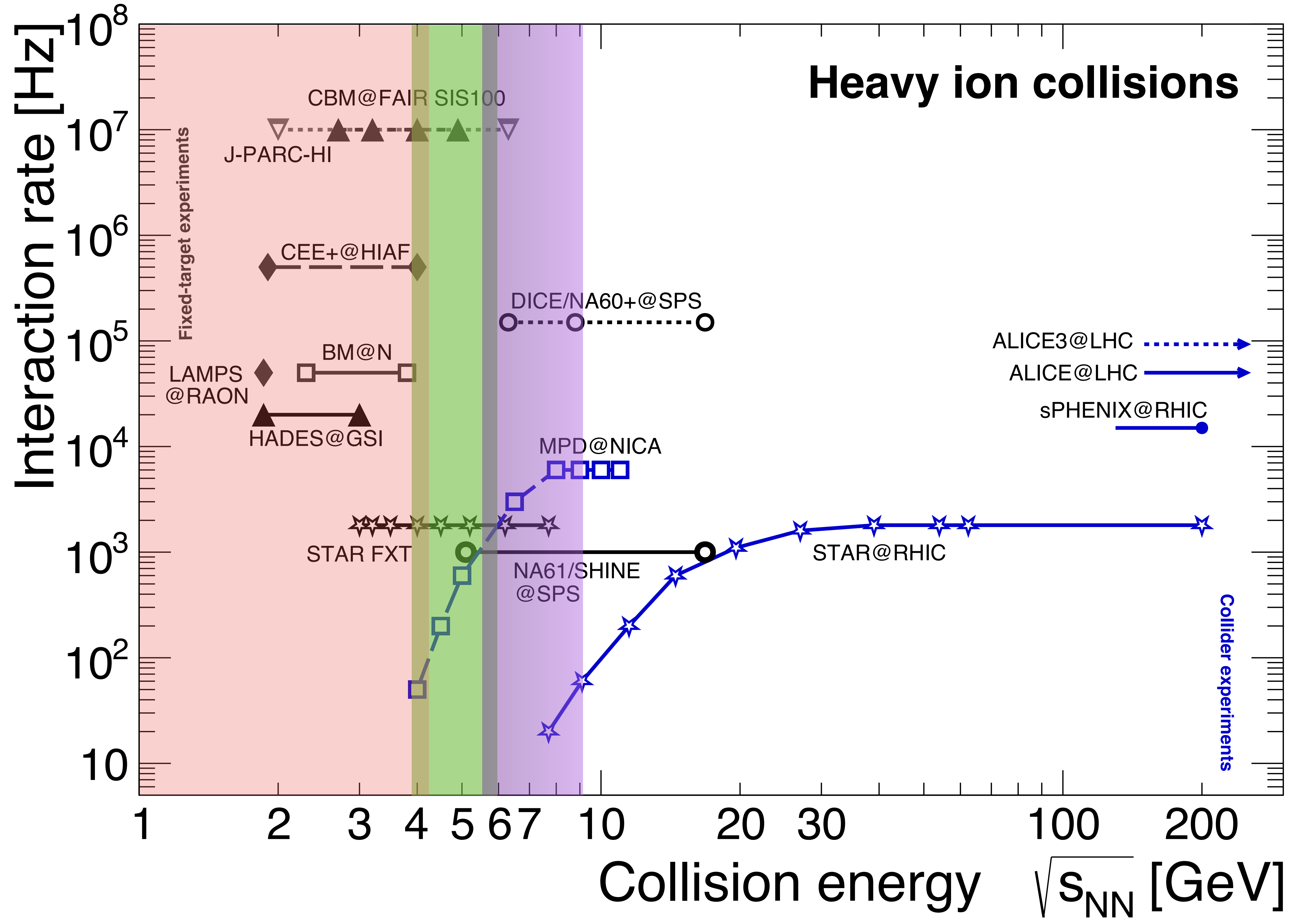
Experimental landscape

Theoretical landscape

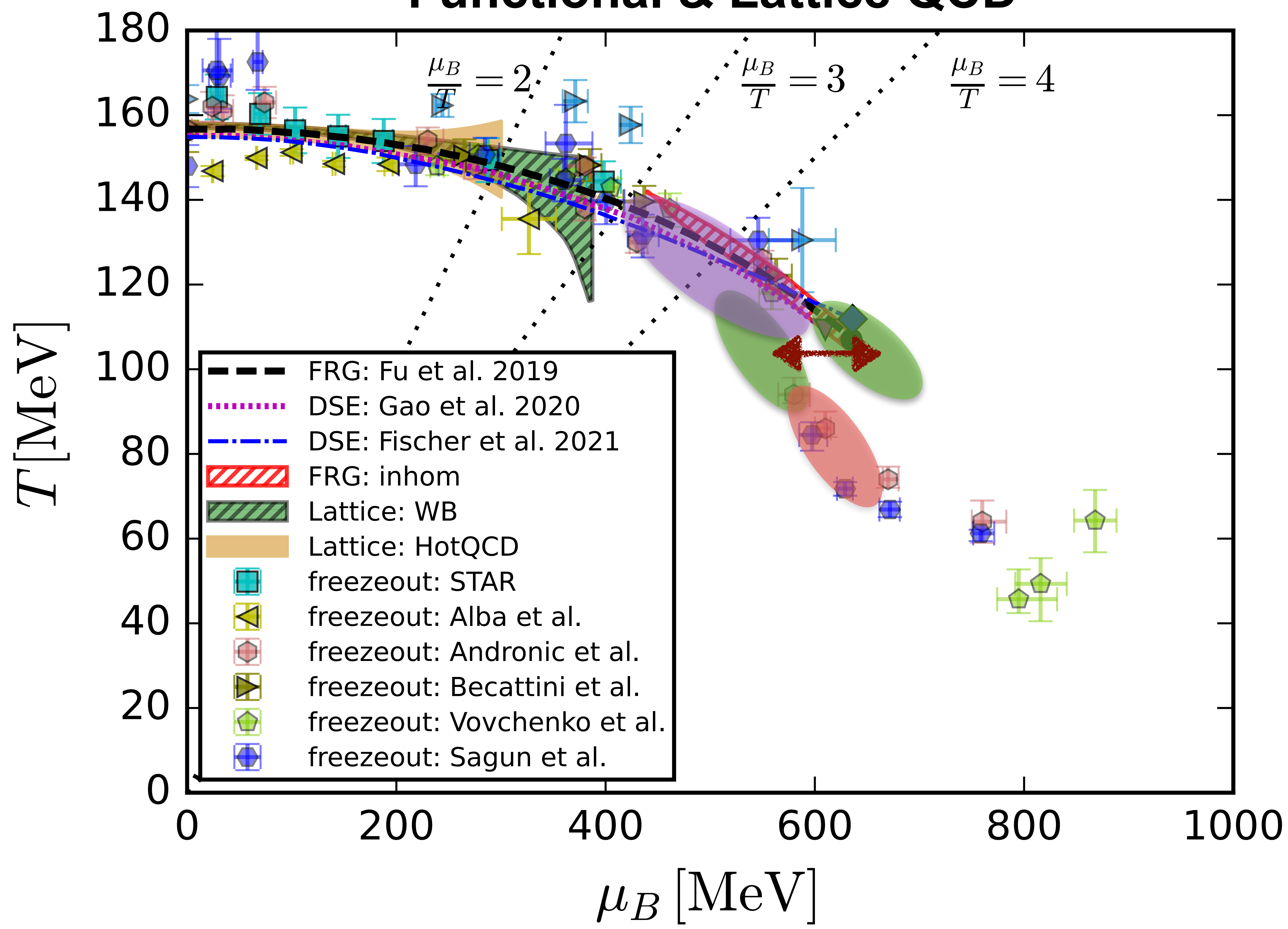
Onset of new phases on the chiral transition line (CEP)

New phases

Transition regime



Functional & Lattice QCD



Peak of kurtosis on the freeze-out line

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

fqcd-collaboration.github.io

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

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

QCD phase structure at finite density: Facts & Fiction

$\mu_B = 0$

Facts

- **Chiral crossover at about**

$$T_\chi \approx 155\,\mathrm{MeV}$$

- **Strongly correlated phase for temperatures**

$$T_\chi \lesssim T \lesssim 2\,T_\chi$$

Fiction

- **Physical QCD is in the chiral scaling regime**

Chiral scaling regimes are very small $m_\pi \lesssim 10\,\mathrm{MeV}$

Soft modes are commonplace

- **Confinement crossover is at XXX**

$$T_\chi \lesssim T_{\mathrm{conf}} \lesssim 2\,T_\chi$$

$\mu_B \neq 0$

Facts

- **No chiral critical end point for**

$$\mu_B \lesssim 600\,\mathrm{MeV}$$

- **No chiral crossover for**

$$\mu_B \gtrsim 700\,\mathrm{MeV}$$

Fiction

- **There is a CEP**

Onset of new phases $600\,\mathrm{MeV} \lesssim \mu_B^{\mathrm{onset}} \lesssim 700\,\mathrm{MeV}$

- **Scaling regime (Ising) of the CEP is humongous**

No, it is not! **Most likely: too small to be measured**

QCD phase structure at finite density: Facts & Fiction

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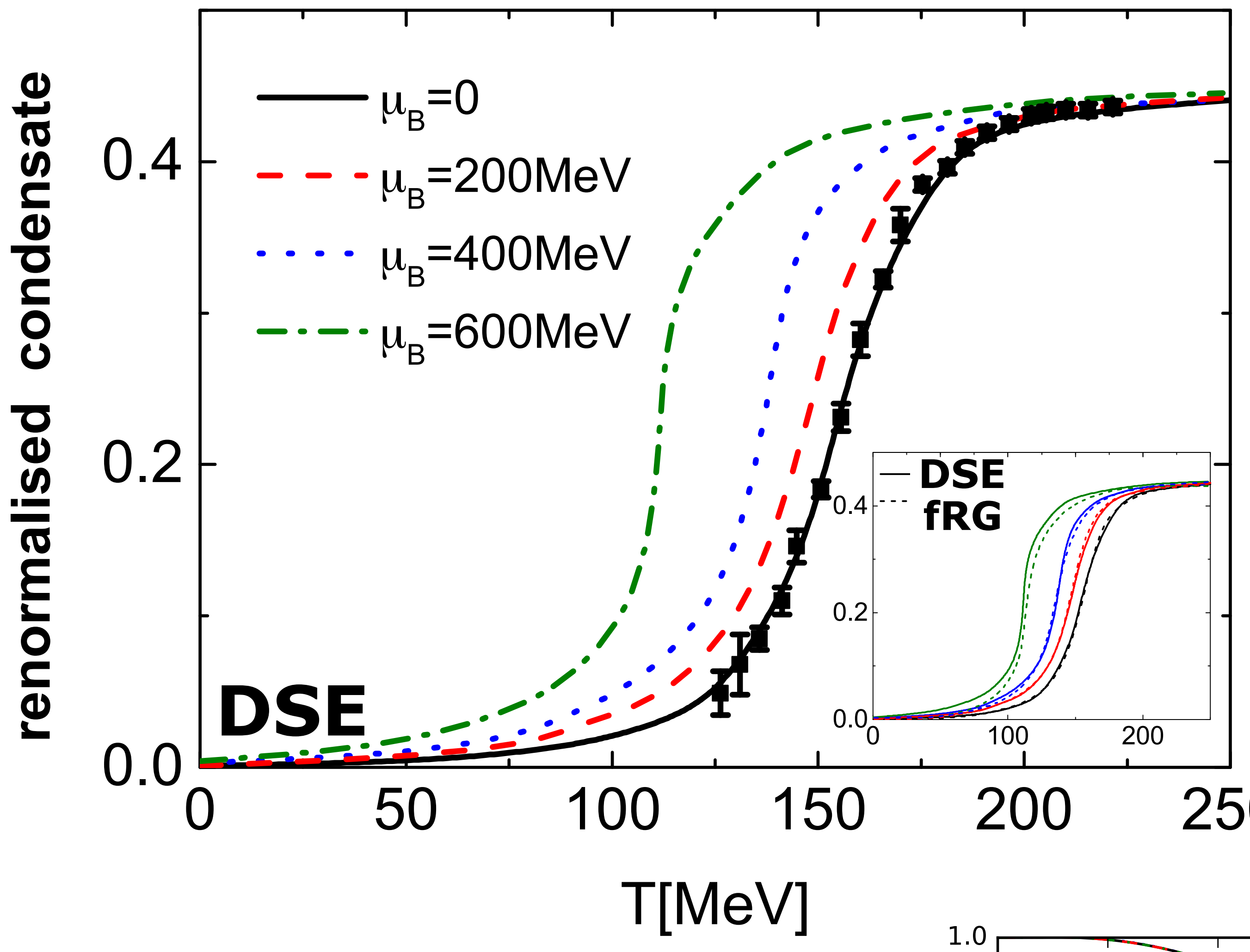
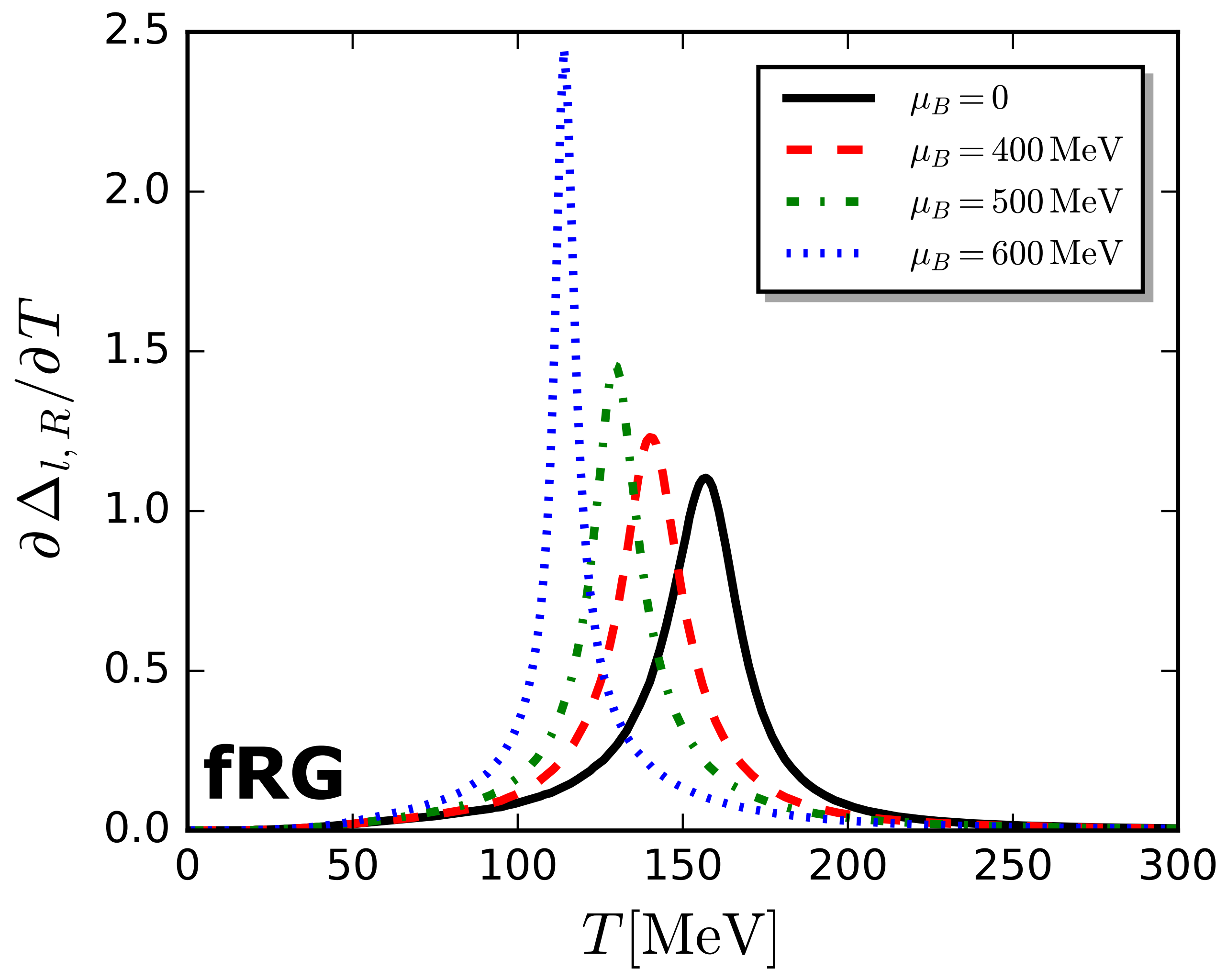
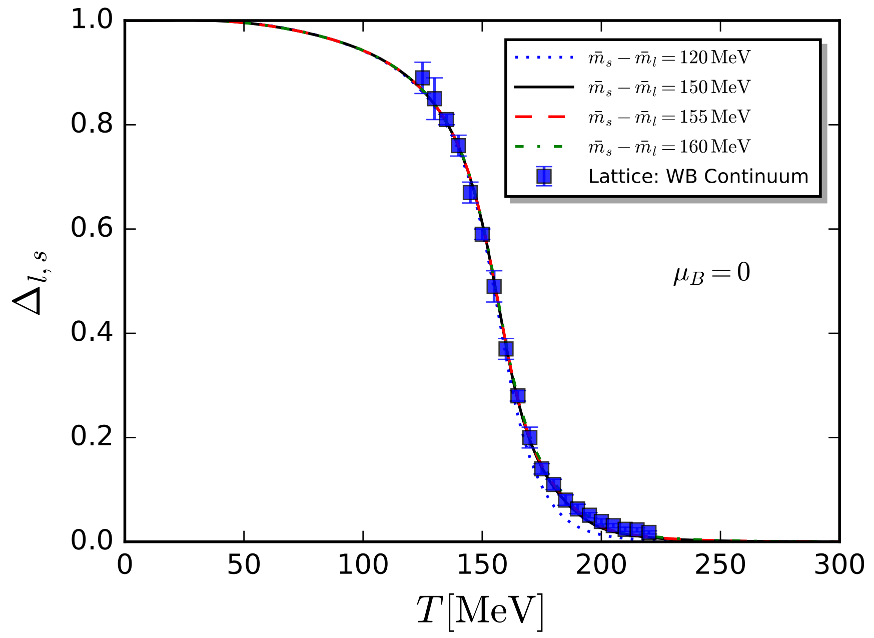
QCD phase structure at finite density: Facts & Fiction

Chiral crossover at about $T_\chi \approx 155\,\mathrm{MeV}$

Functional QCD



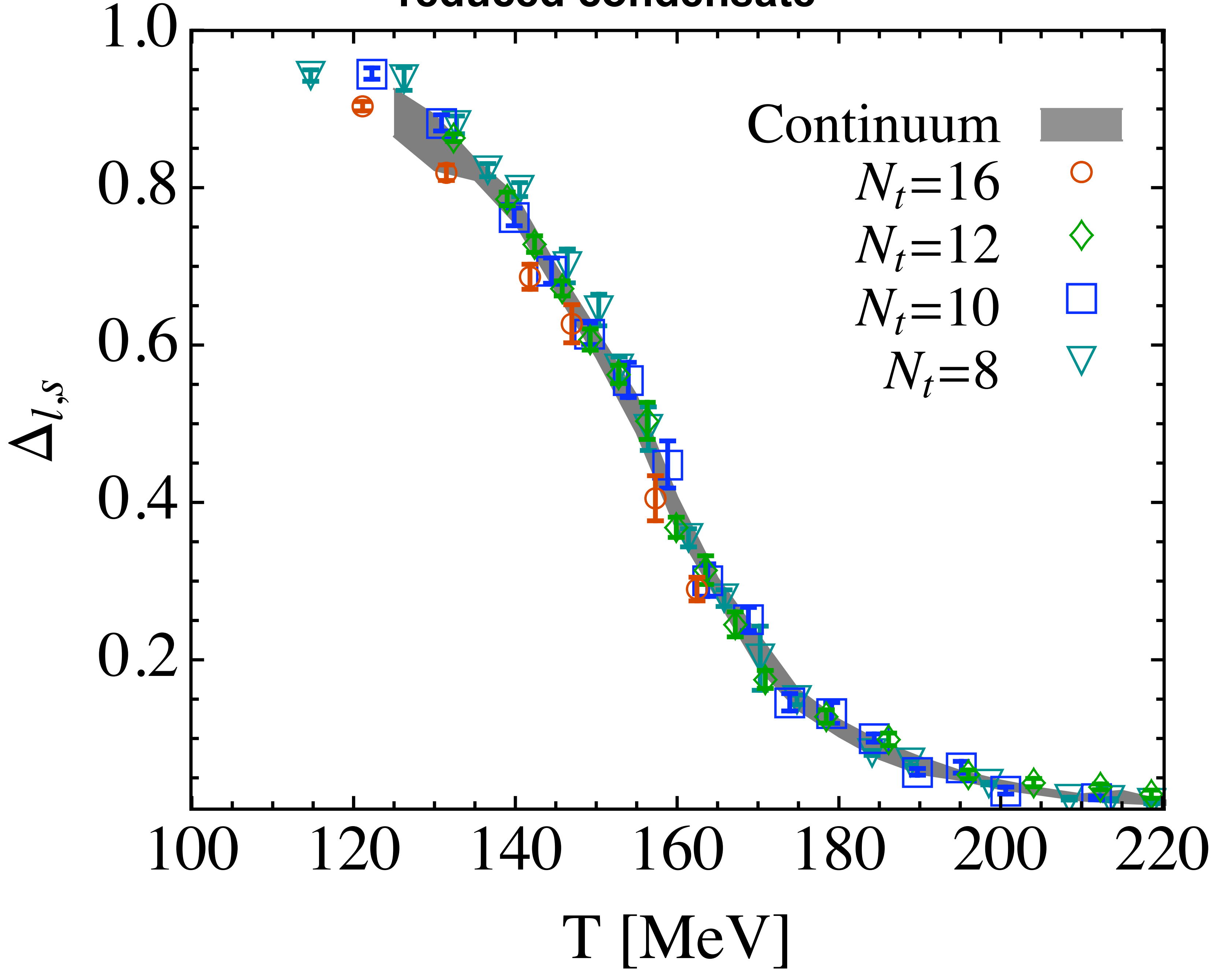




reduced condensate

Lattice QCD

reduced condensate



DSE: **Fischer, Luecker,Welzbacher, PRD 90 (2014) 034022**
Gao, JMP, PLB 820 (2021) 136584
Gunkel, Fischer, PRD 104 (2021) 054022

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

⋮

Borsányi, Fodor, Hoelbling, Katz, Krieg, Ratti, Szabo, JHEP 09, 073 (2010)

⋮

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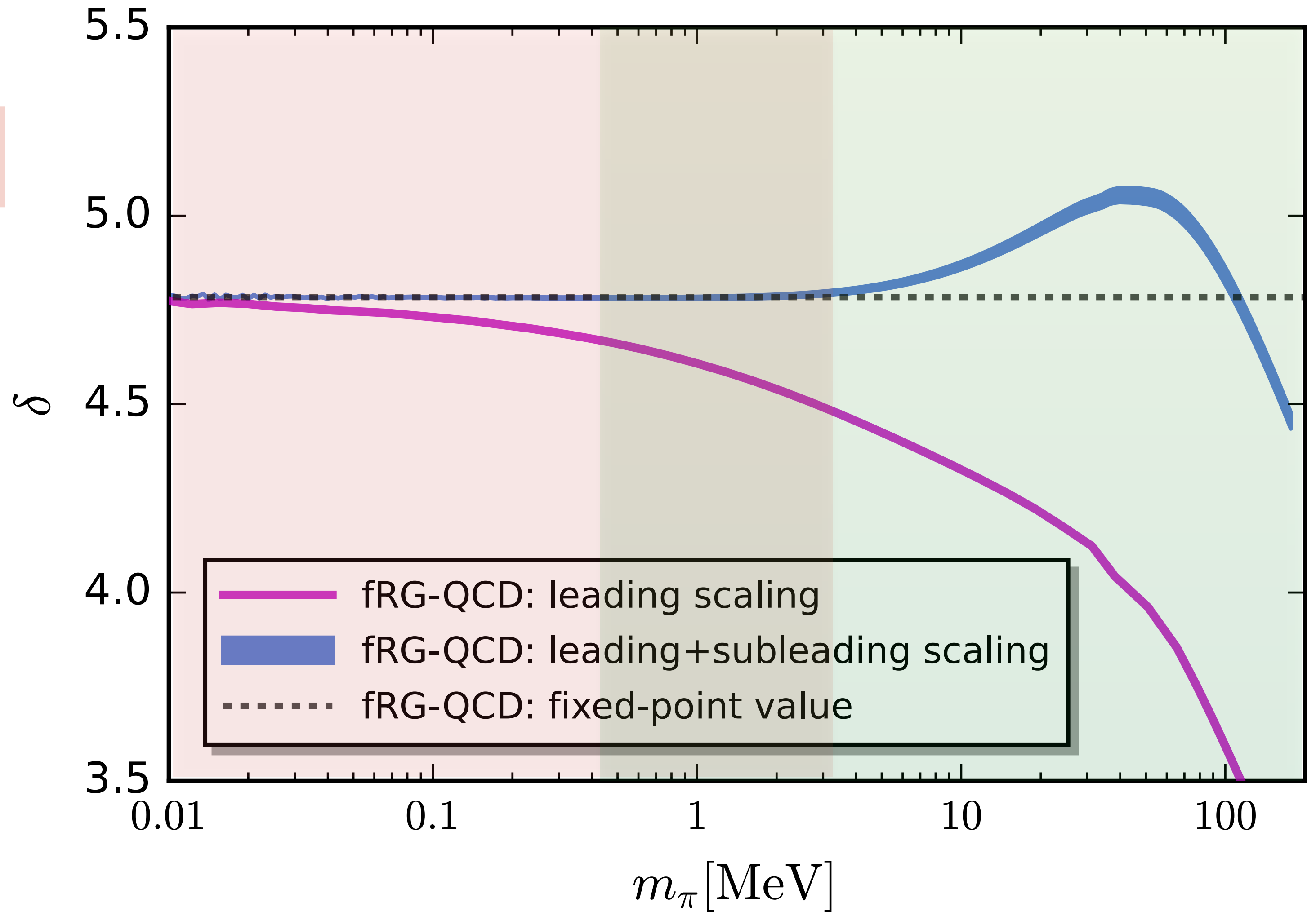
Chiral dynamics & quasi-massless modes in the chiral limit

Scaling coefficient as function of the pion mass



Critical O(4) scaling

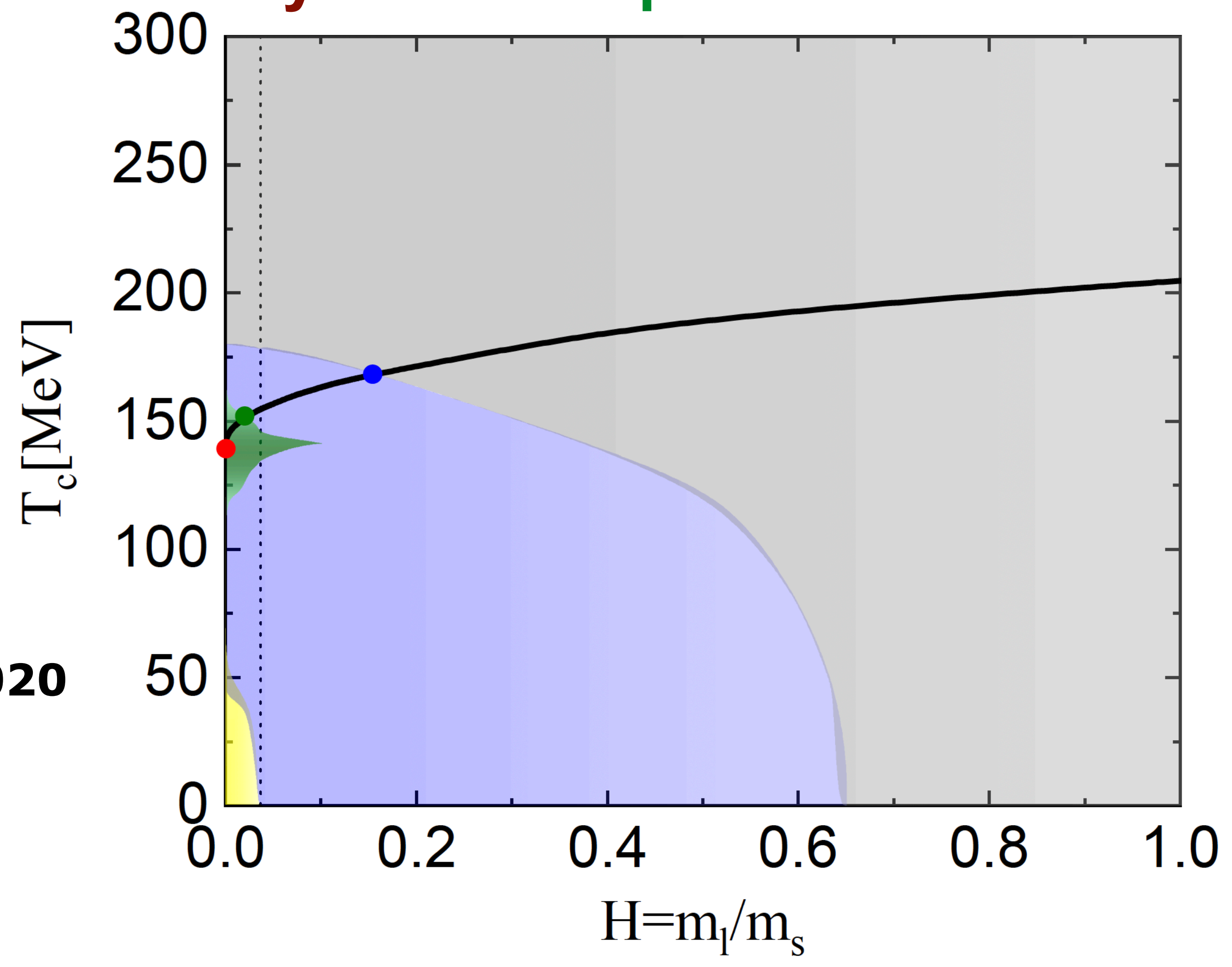
$$\Delta_l(m_\pi) \propto m_\pi^{2/\delta}\left[1 + a_m m_\pi^{2\theta_H} + \cdots\right]$$

'chiral scaling'

Trivial $\Delta_l^{1+\delta}$ scaling

Small chiral scaling regime

Chiral dynamics & quasi-massless modes



Critical scaling

Gao, JMP, PRD 105 (2022) 094020

'Non-critical chiral scaling'

Far away from the critical regime for $m_\pi \gtrsim 1\,\mathrm{MeV}$

$$\Delta_l(T,H) \approx \Delta_{l,\chi}(0)\Big(c_0 + c_{\frac{1}{5}} H^{\frac{1}{5}} + c_{\frac{1}{3}} H^{\frac{1}{3}} + c_1 H\Big)$$

$$V_\chi(\Delta_l) \propto \qquad \Delta_l^6 \qquad \Delta_l^4 \qquad \Delta_l^2$$

Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, PRD 111 (2025) 094010

Criticality & quasi-massless modes around the CEP

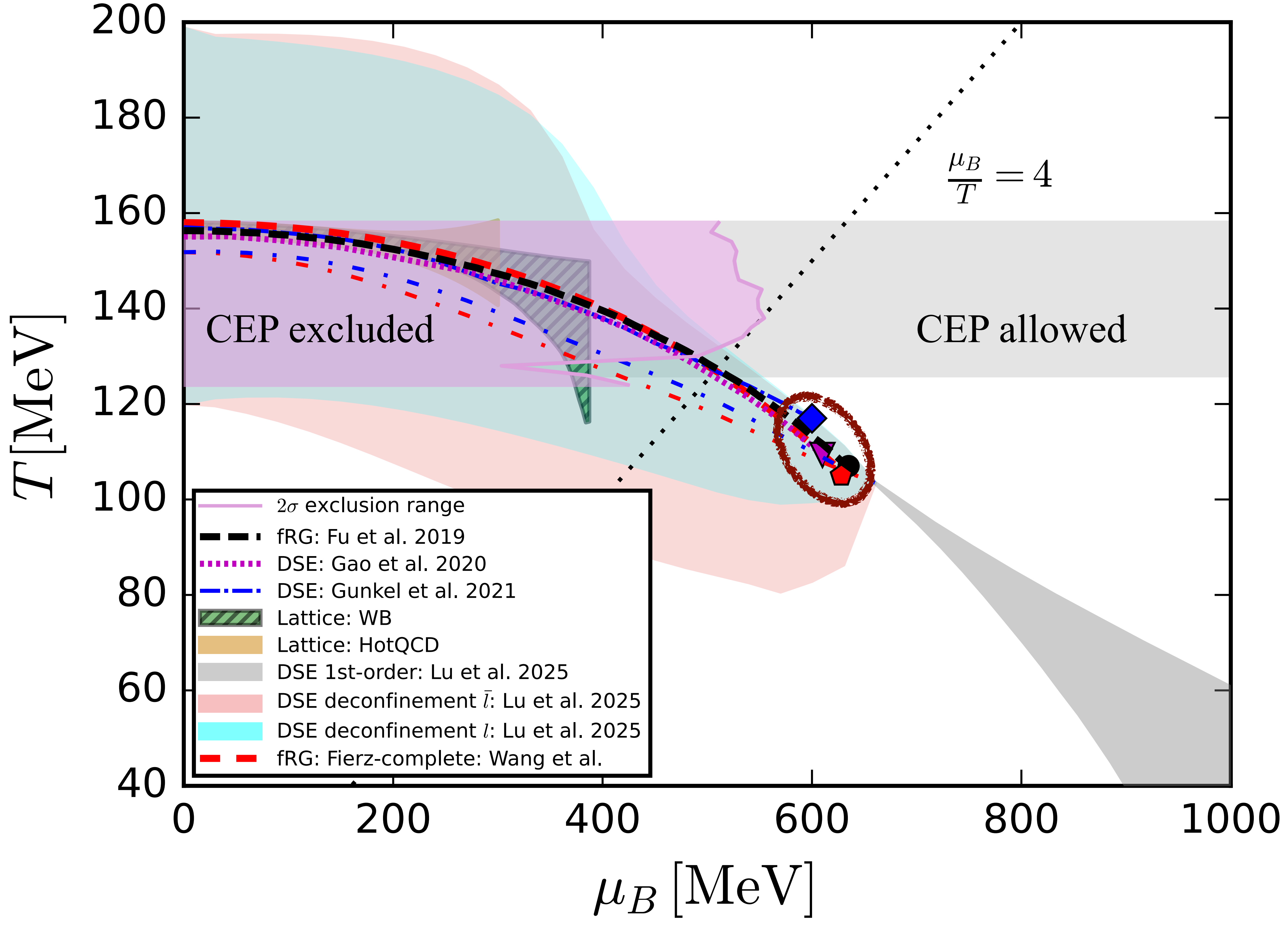
Fu, JMP, Rennecke, PRD 101 (2020) 054032

Wang, Zhou, Huang, Wen, Yin, Fu, in preparation

Small scaling regime around potential CEP

!!Great News!!

Location of CEP/New phase accessible via combination of precision measurements & computations



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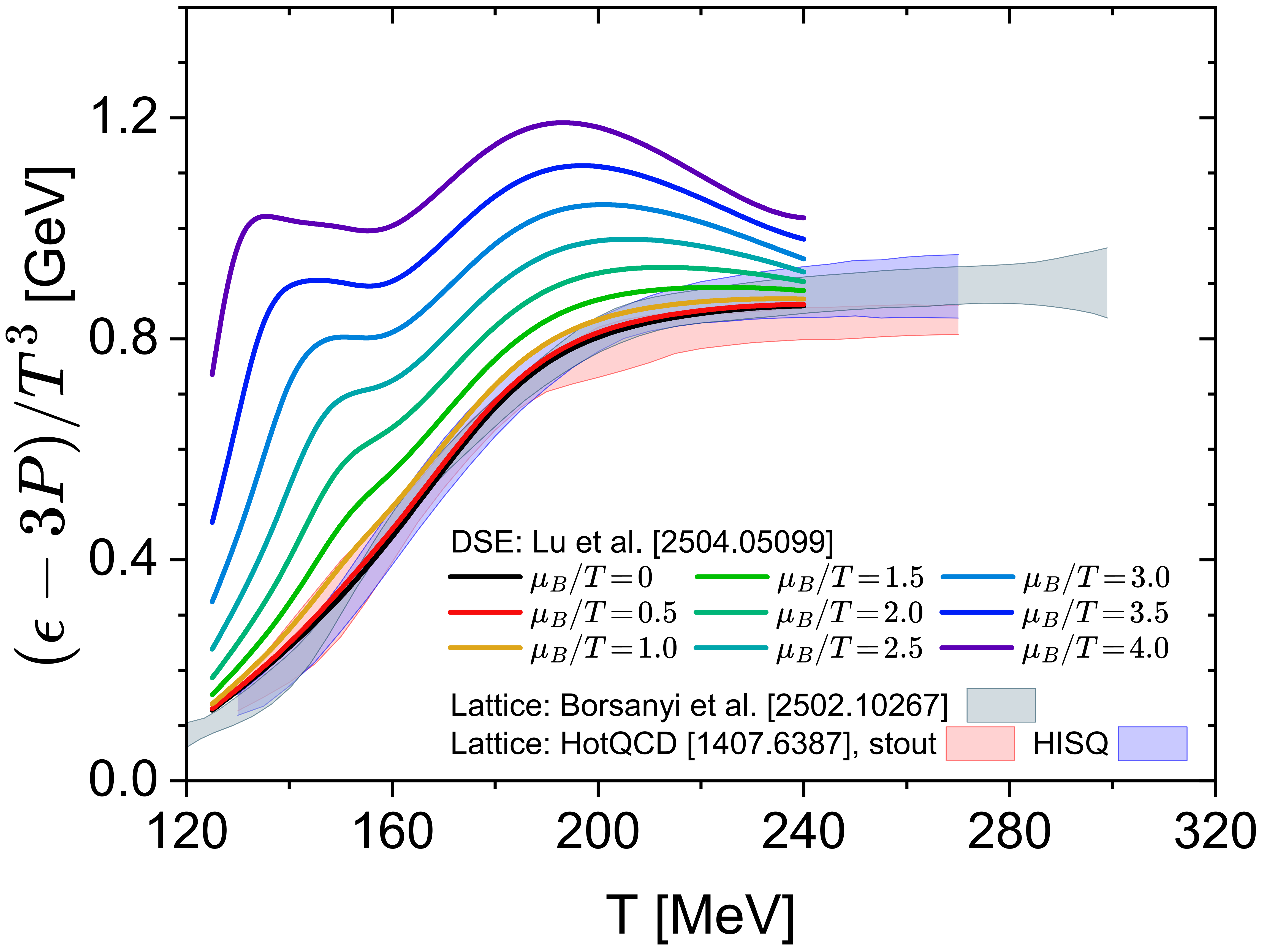
QCD phase structure at finite density: Facts & Fiction

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

Functional QCD **Lattice QCD**



Lu, Gao, Liu, JMP, arXiv:2504.05099

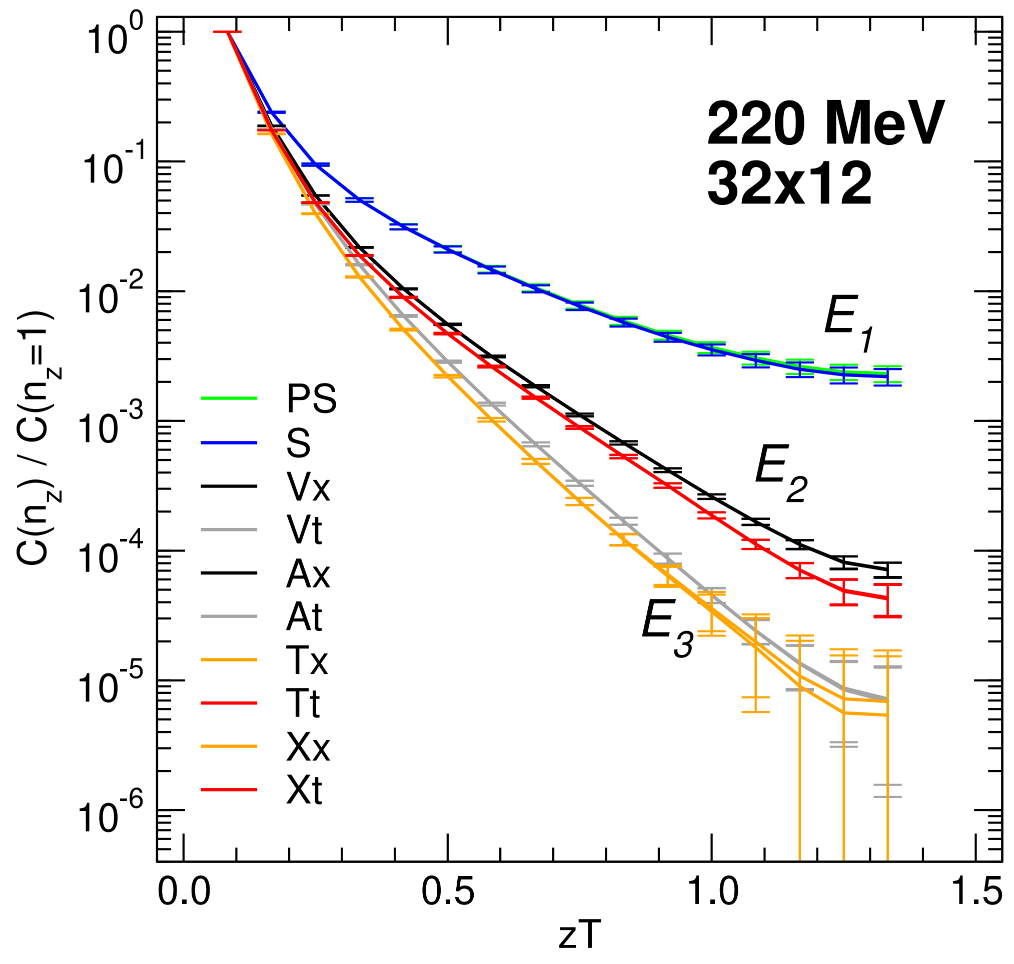
QCD phase structure at finite density: Facts & Fiction

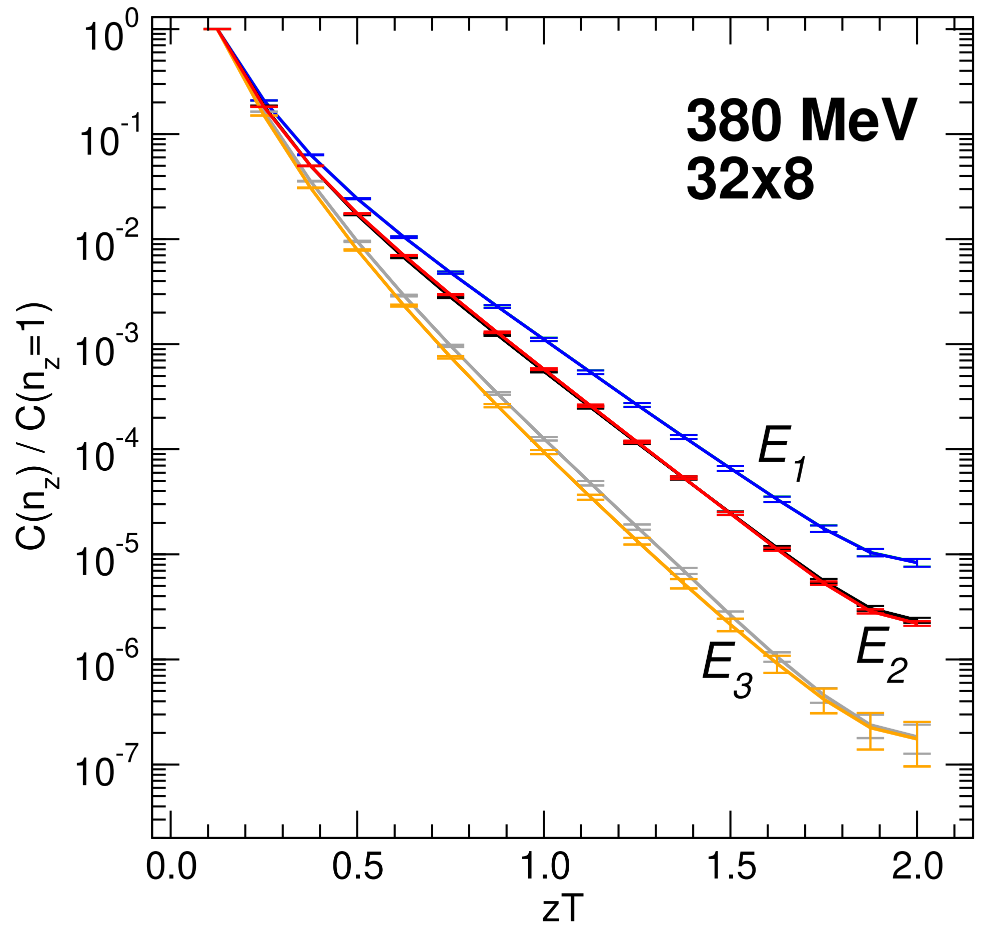
Chiral spin symmetry for $T_\chi \lesssim T \lesssim 2\,T_\chi$

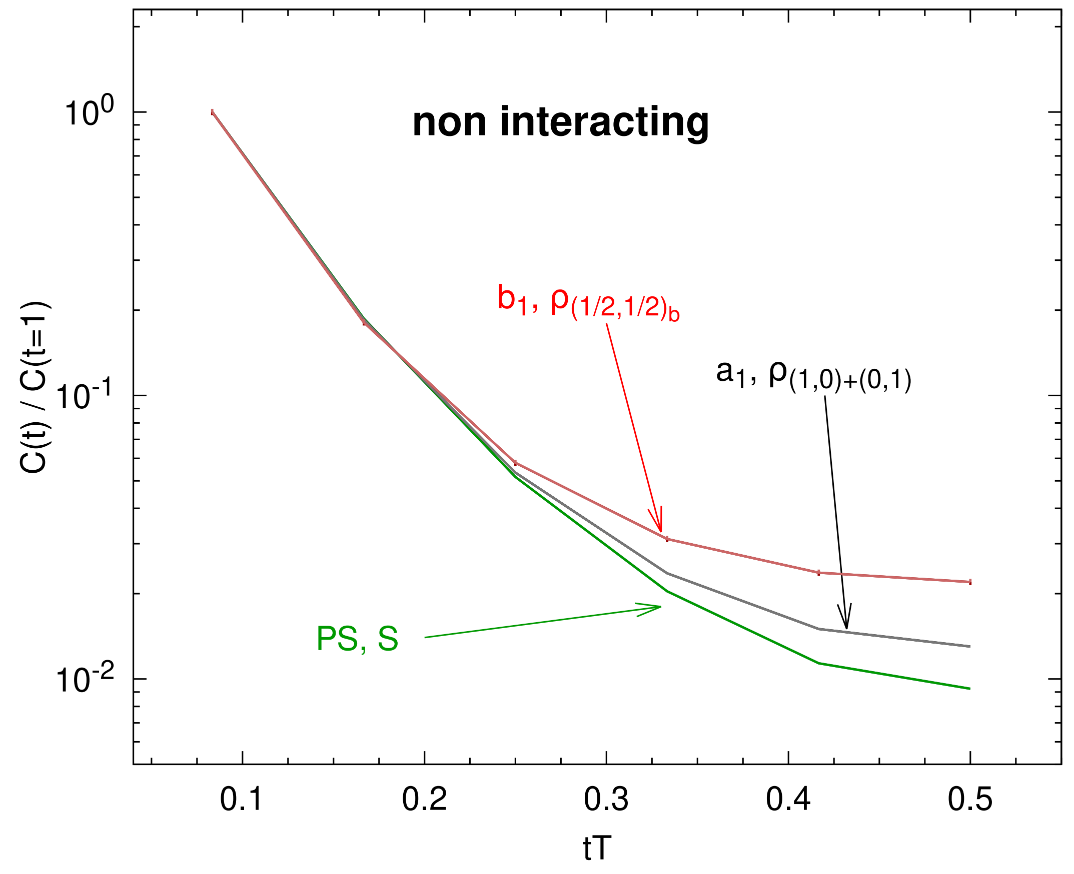
Functional QCD

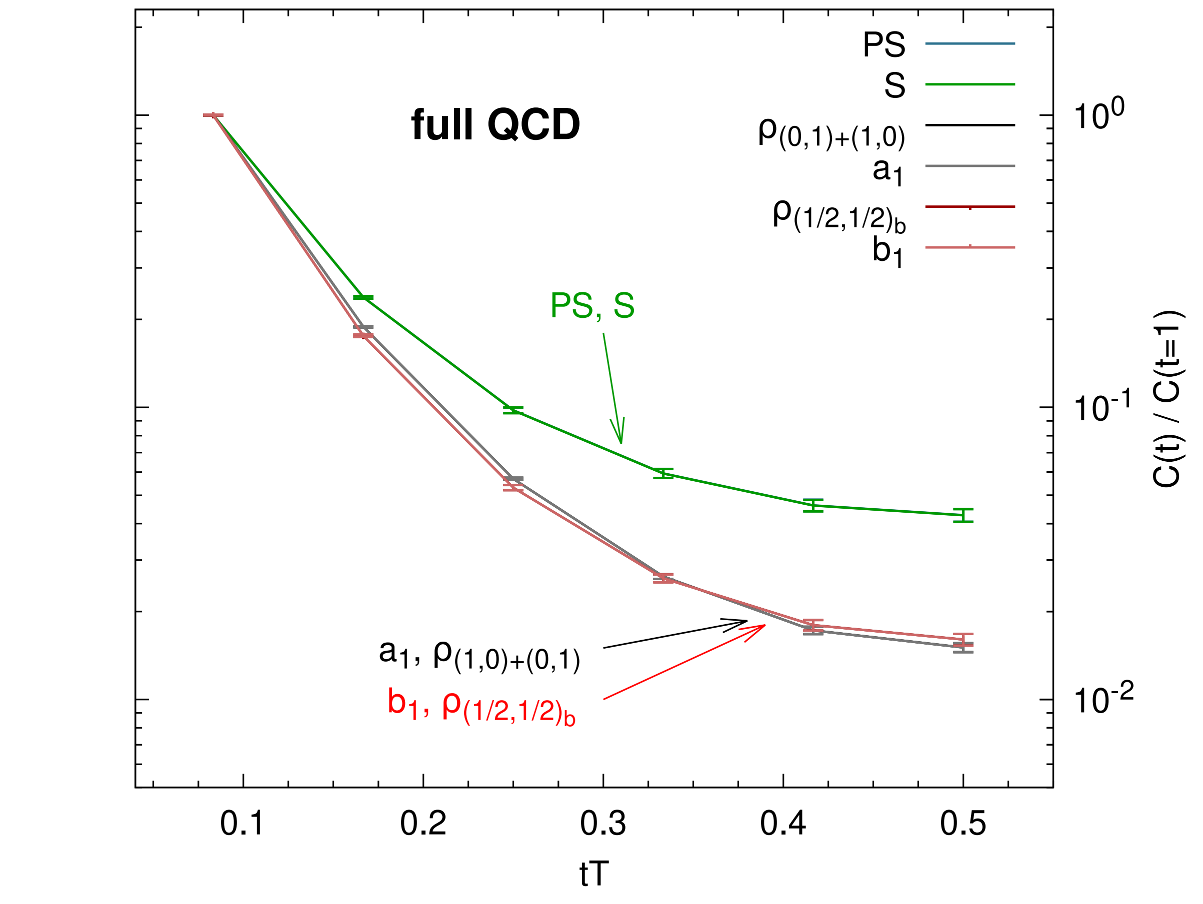
not yet

Lattice QCD









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

⋮

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

⋮

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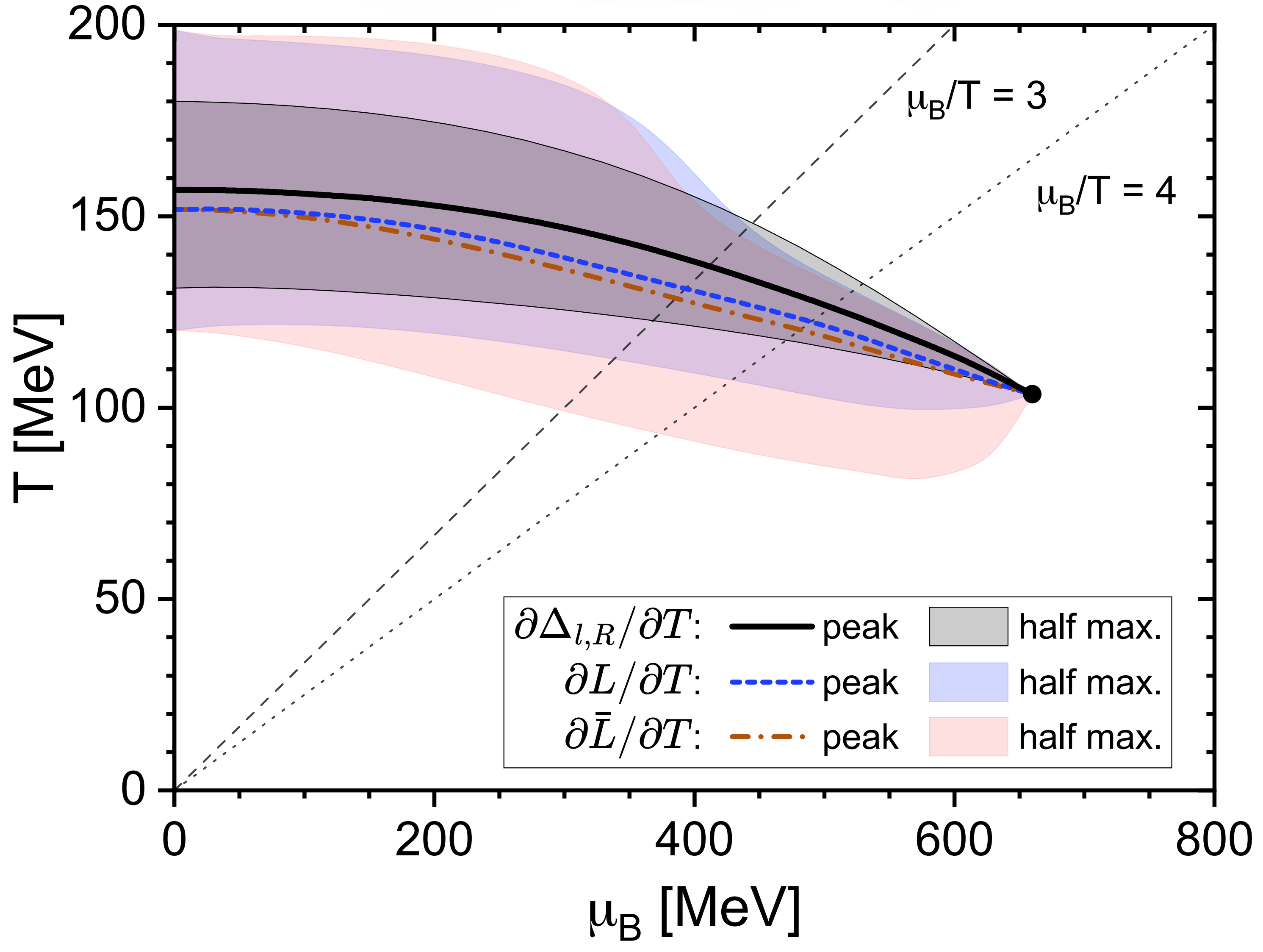
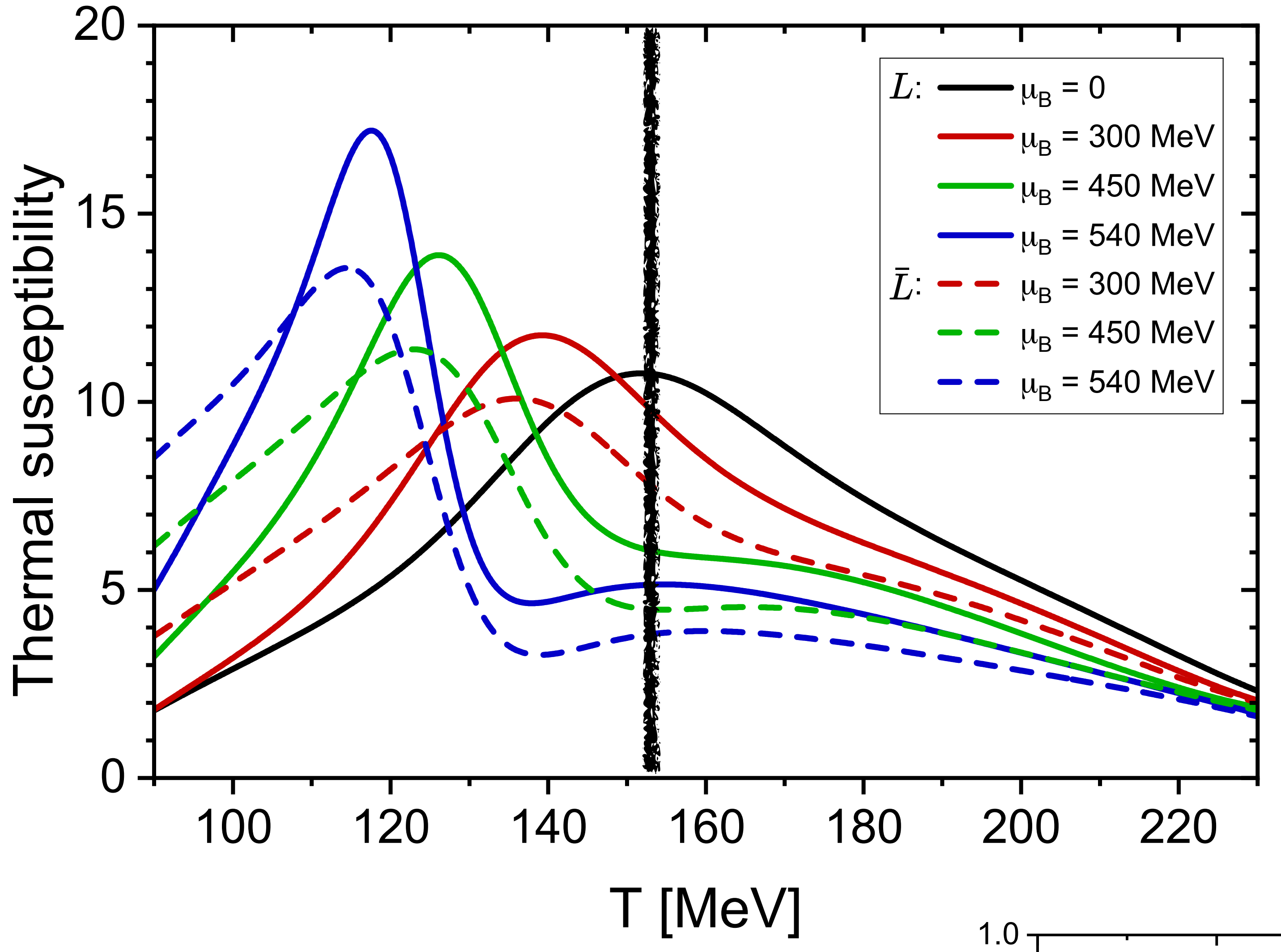


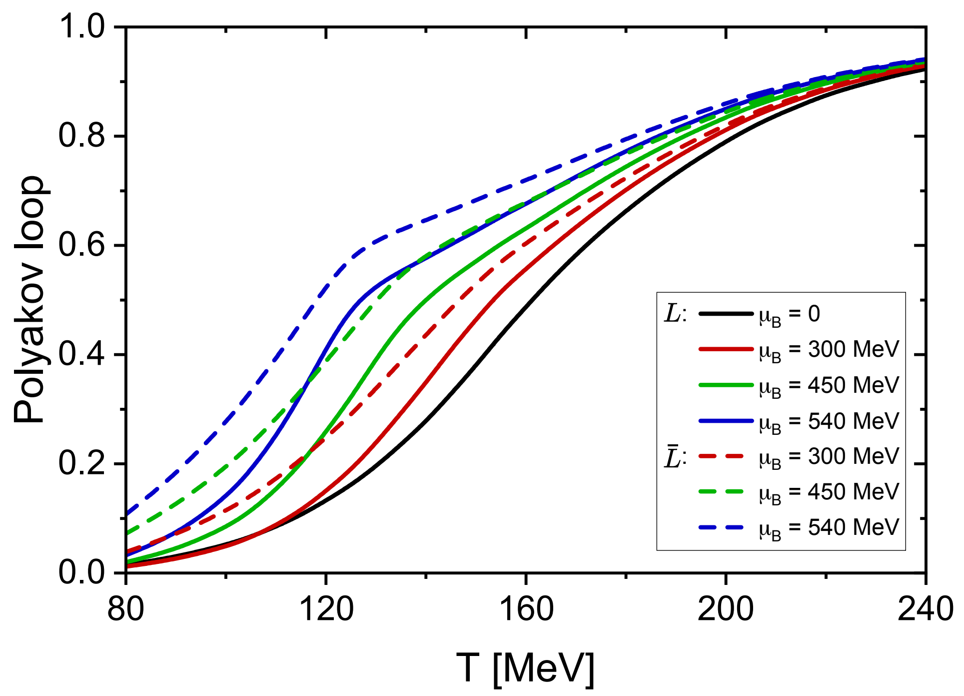
Strongly correlated physics

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

Functional QCD



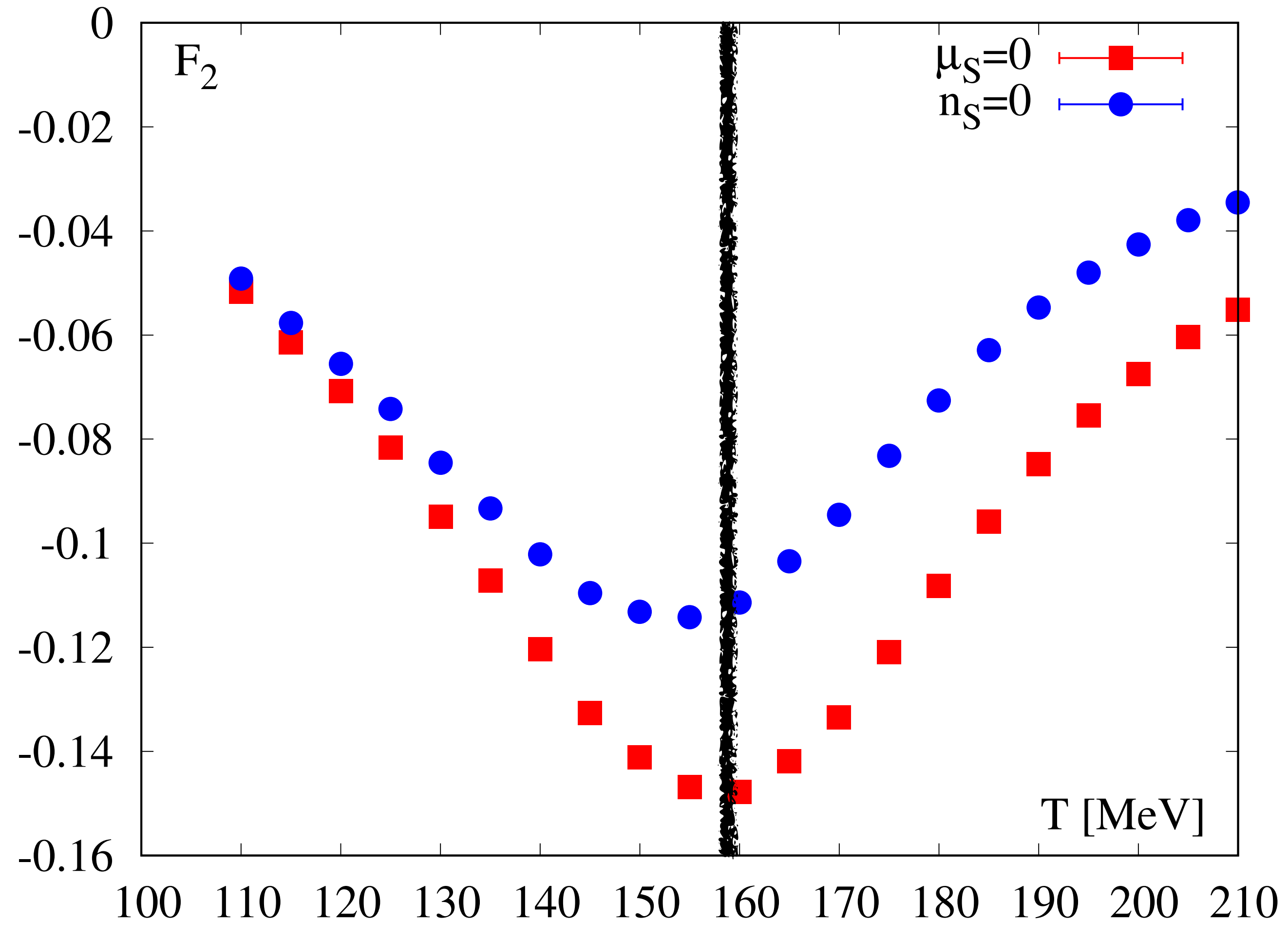
$\propto P\big(\langle \mathrm{ev}(\varphi)\rangle\big)$



Variants of the traced Polyakov loop

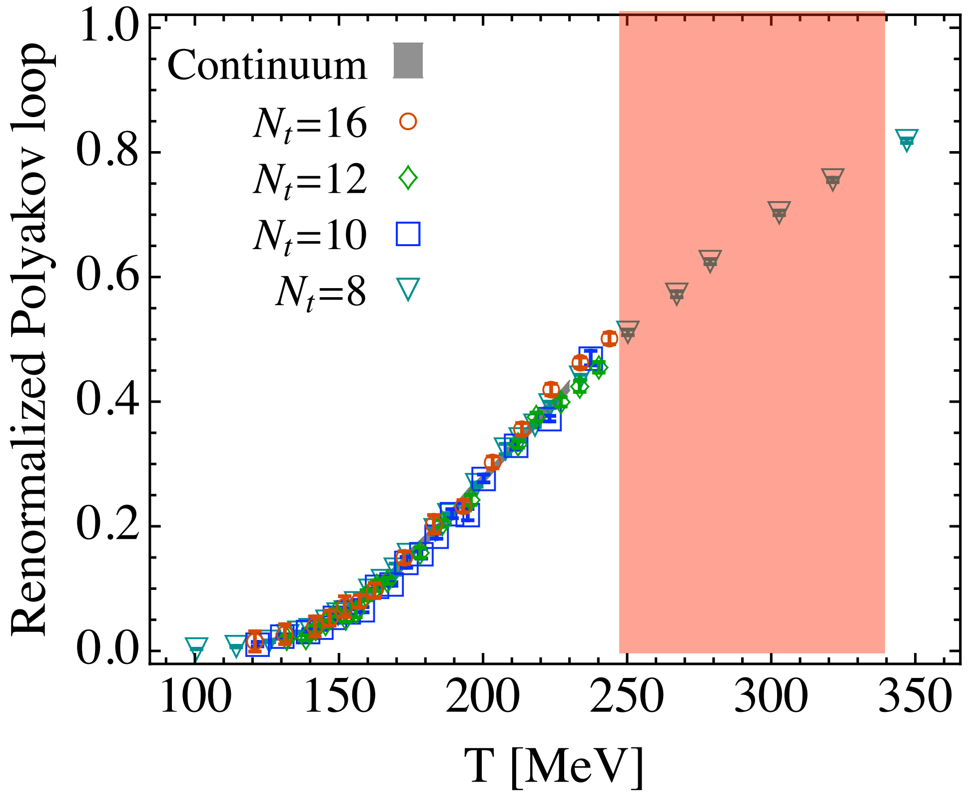
$$P = \frac{1}{N_c}\mathrm{tr}\, e^{2\pi i\varphi}$$

Lattice QCD



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

$\propto \langle P\rangle$



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Braun, Gies, JMP, PLB 684 (2010) 262-267

⋮

Lu, Gao, Liu, JMP, arxiv:2504.05099

Borsanyi, Fodor, Hoelbling, Katz, Krieg, Ratti, Szabo, JHEP 09, 073 (2010)

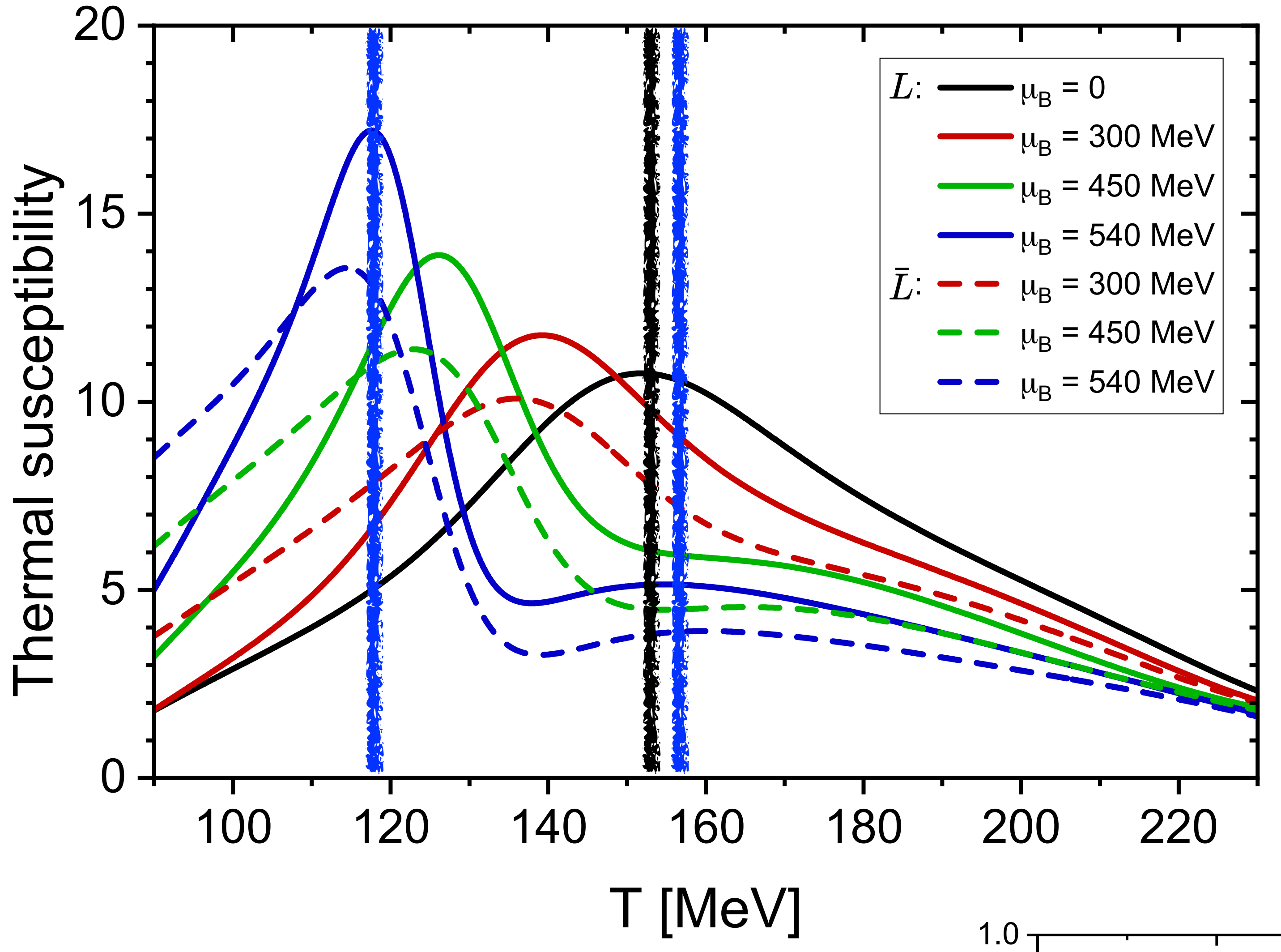
⋮

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

Strongly correlated physics

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

Functional QCD



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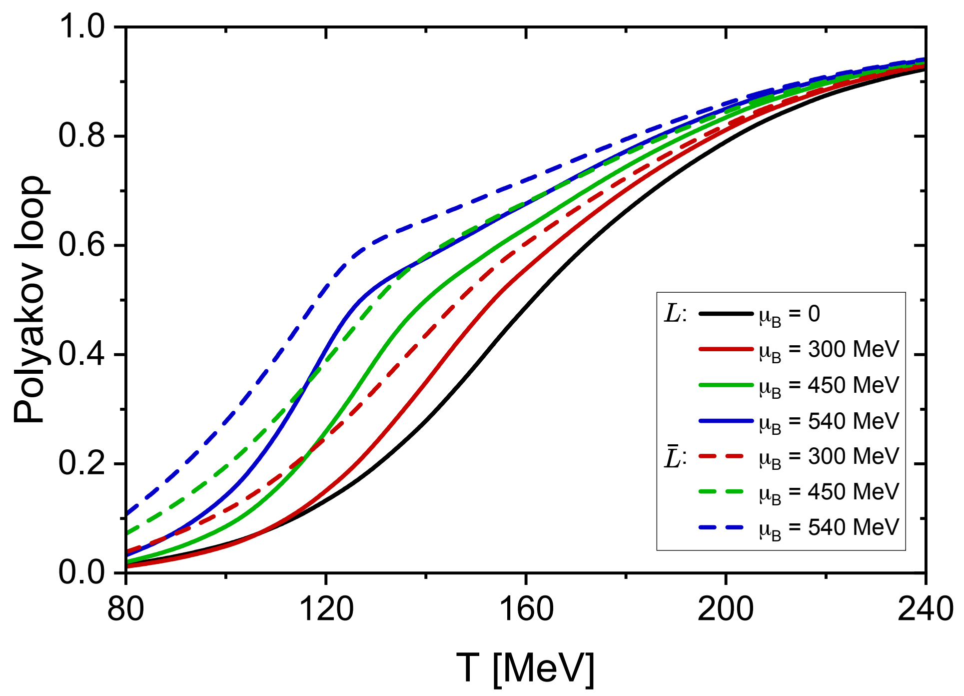

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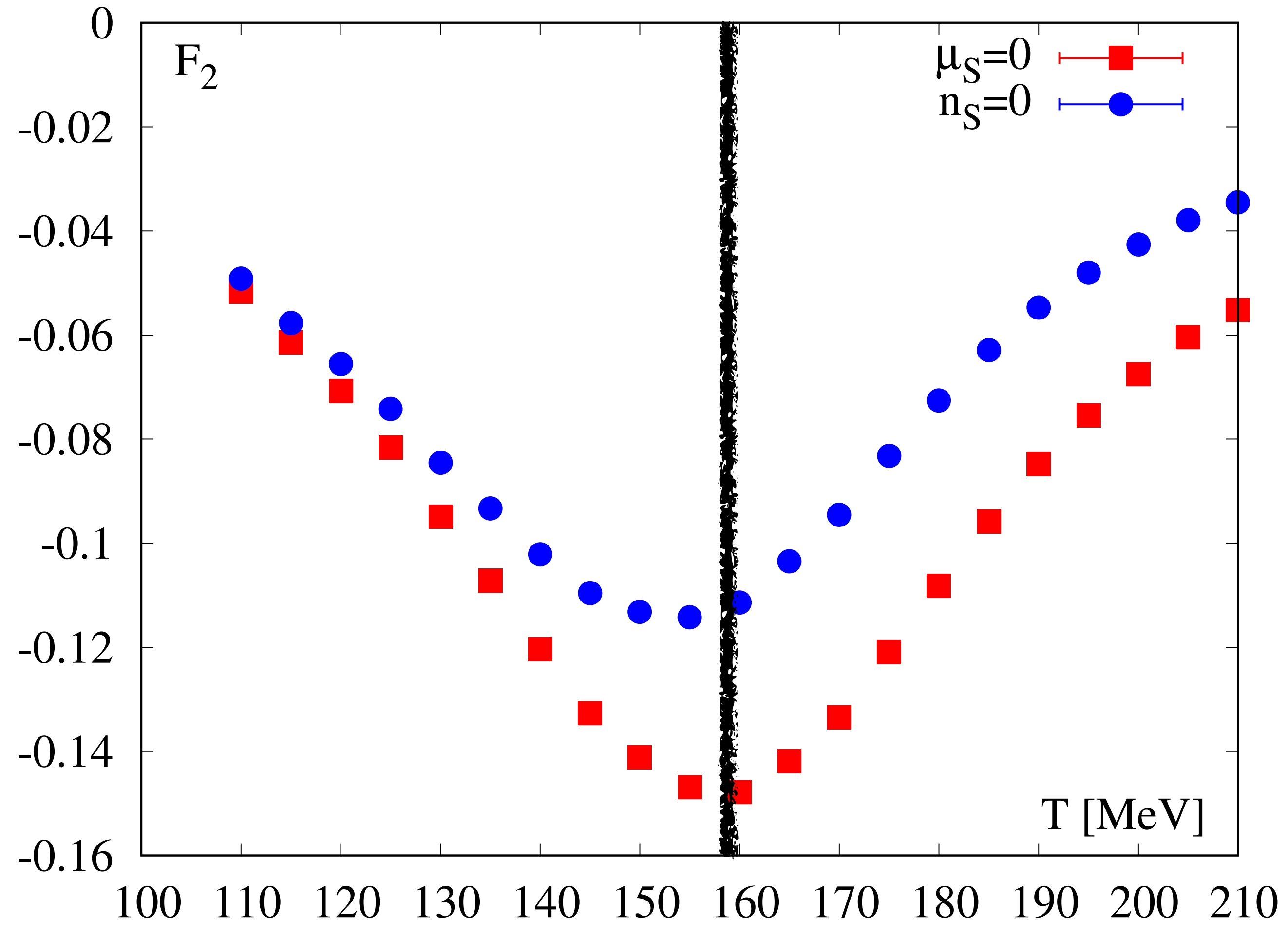

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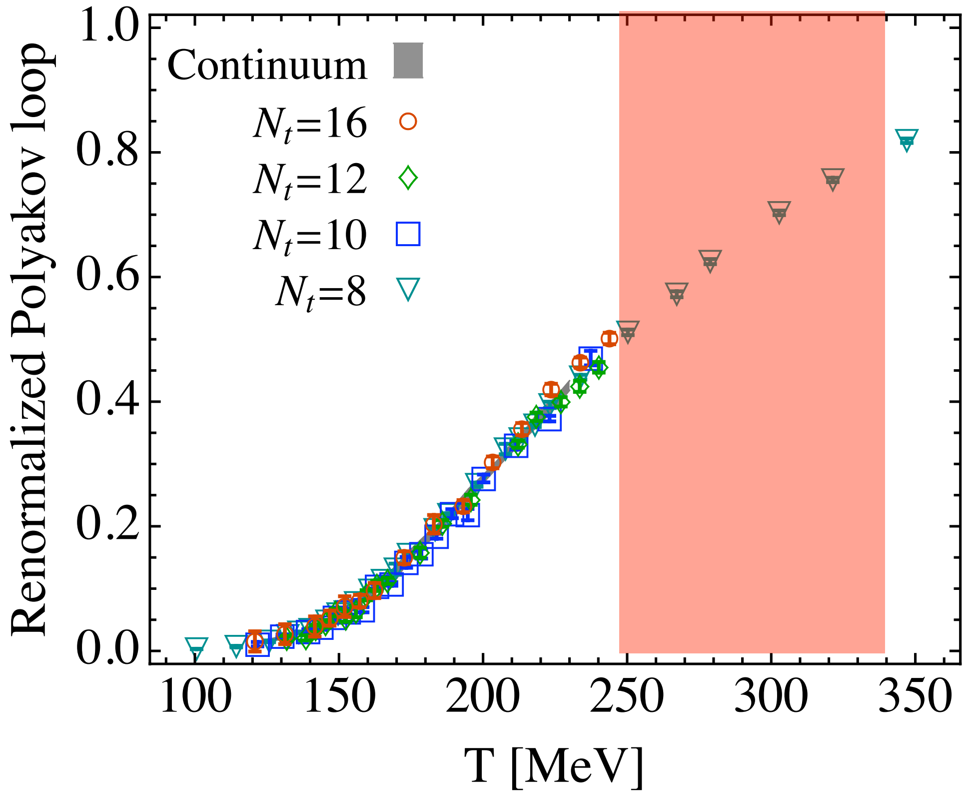

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QCD phase structure at finite density: Facts & Fiction

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$$\mu_B \lesssim 600\,\mathrm{MeV}$$

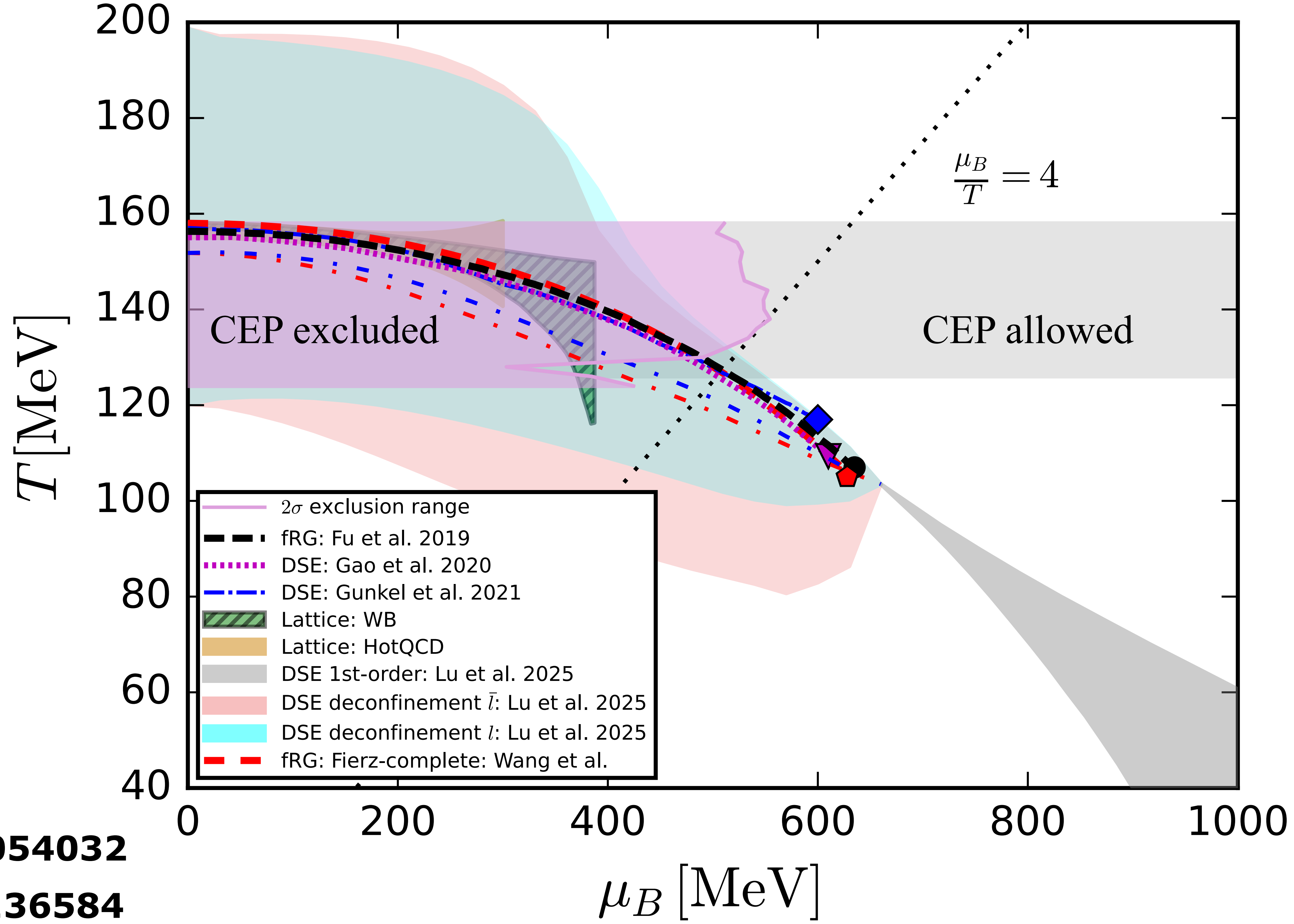
chiral: driven by scalar-pseudo scalar fluctuations

QCD phase structure at finite density: Facts & Fiction

No chiral critical end point for $\mu_B \lesssim 600\,\mathrm{MeV}$

Functional QCD

Functional QCD CEP+ lattice QCD exclusion plot



Lattice QCD

$\mu_B \lesssim 450\,\mathrm{MeV}$

Fu, JMP, Rennecke, PRD 101 (2020) 054032
Gao, JMP, PLB 820 (2021) 136584
Gunkel, Fischer, PRD 104 (2021) 054022

Lu, Gao, Liu, JMP, arXiv:2504.05099
Lu, Gao, Liu, arXiv:2509.02974
Wang et al, in preparation

Borsanyi, Fodor, Guenther, Parotto, Pasztor, Ratti, Vovchenko, Wong, arxiv: 2502.10267

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- No chiral critical end point for

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- Onset of new phases and their physics

Onset of new phases $600\,\mathrm{MeV} \lesssim \mu_B^{\mathrm{onset}} \lesssim 700\,\mathrm{MeV}$

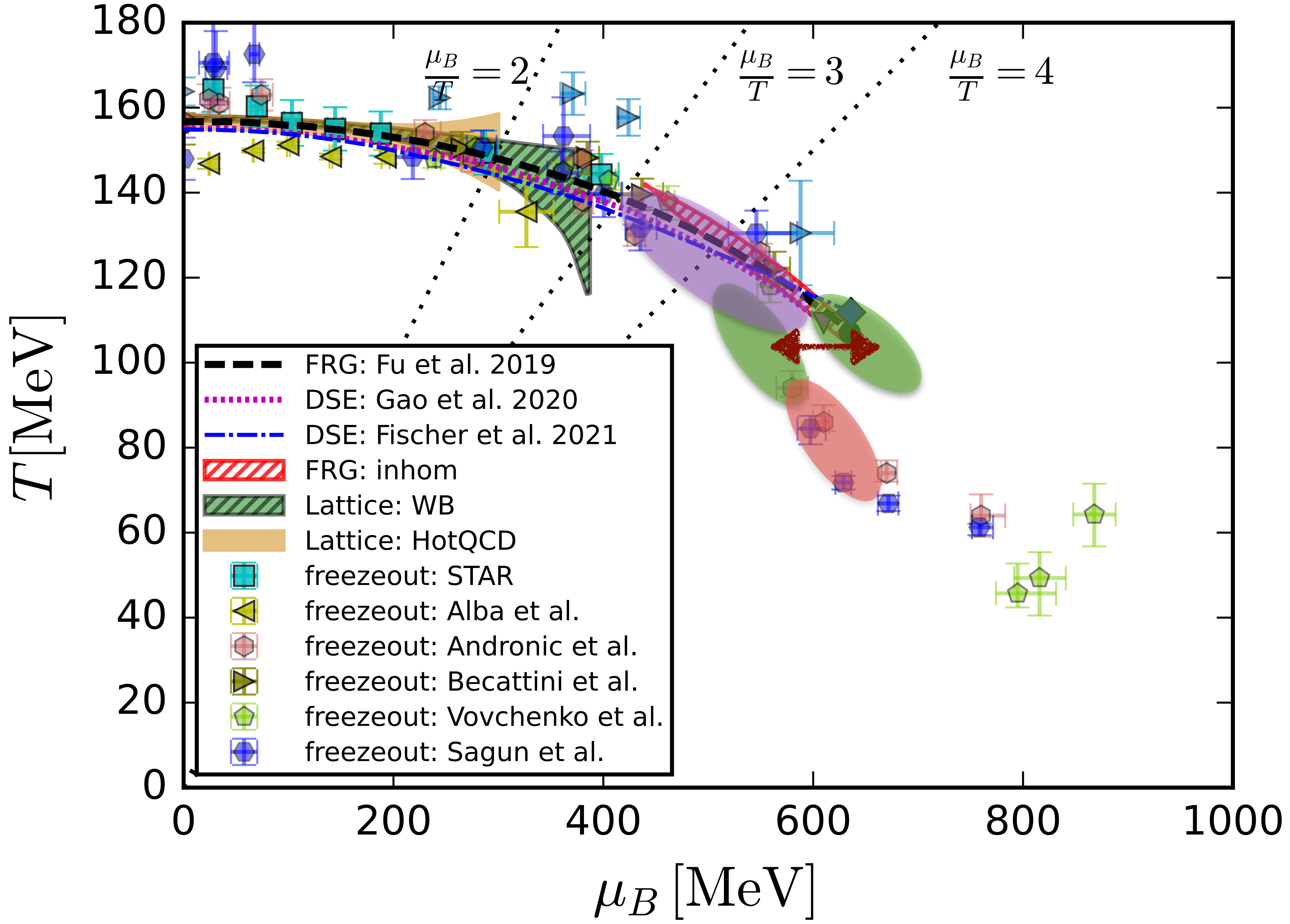
QCD phase structure at finite density: Facts & Fiction

Onset of new phases at $600\,\mathrm{MeV} \lesssim \mu_B^{\mathrm{onset}} \lesssim 700\,\mathrm{MeV}$

Functional QCD

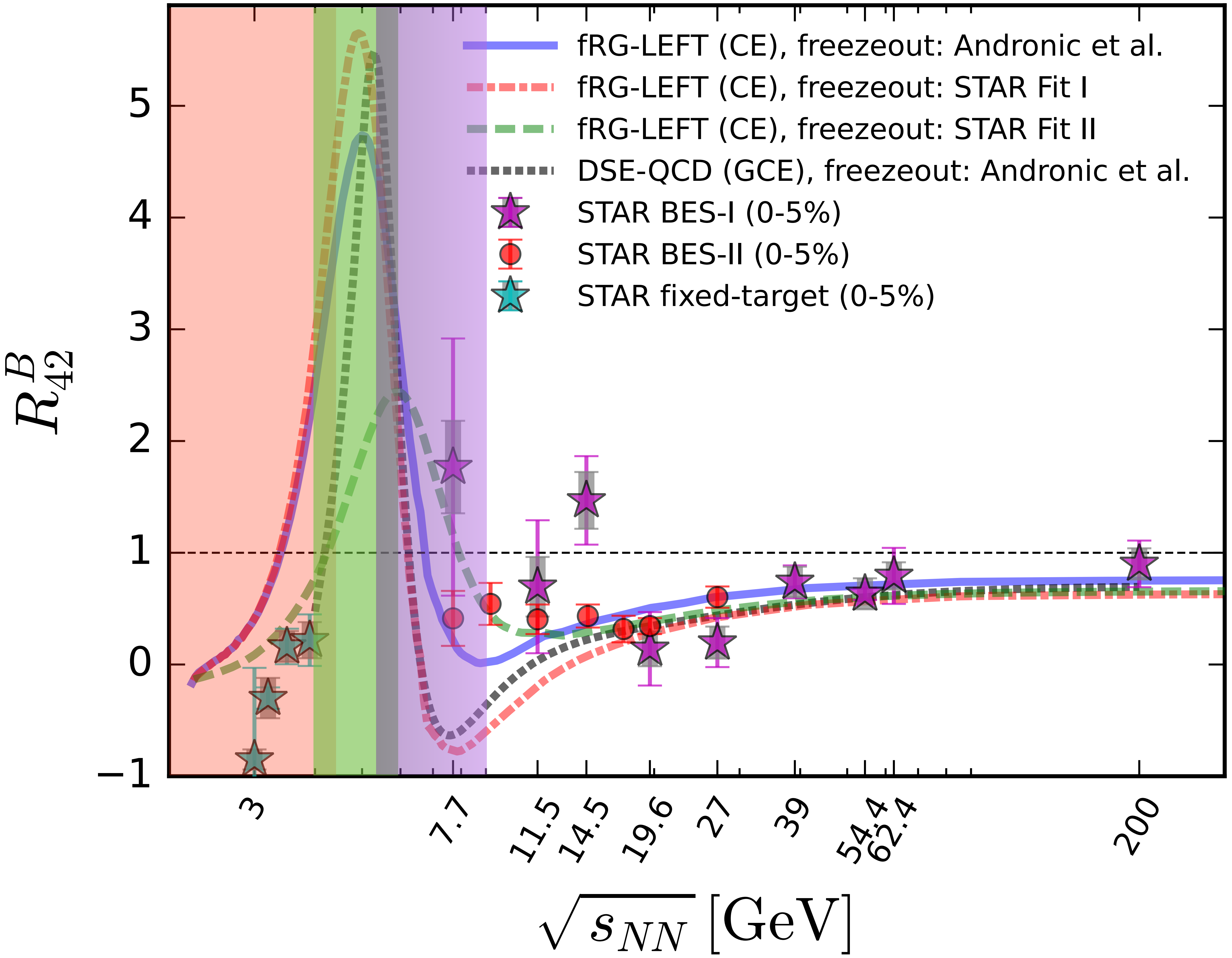
Lattice QCD

High density phase structure from functional QCD



Ripples of the critical point

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

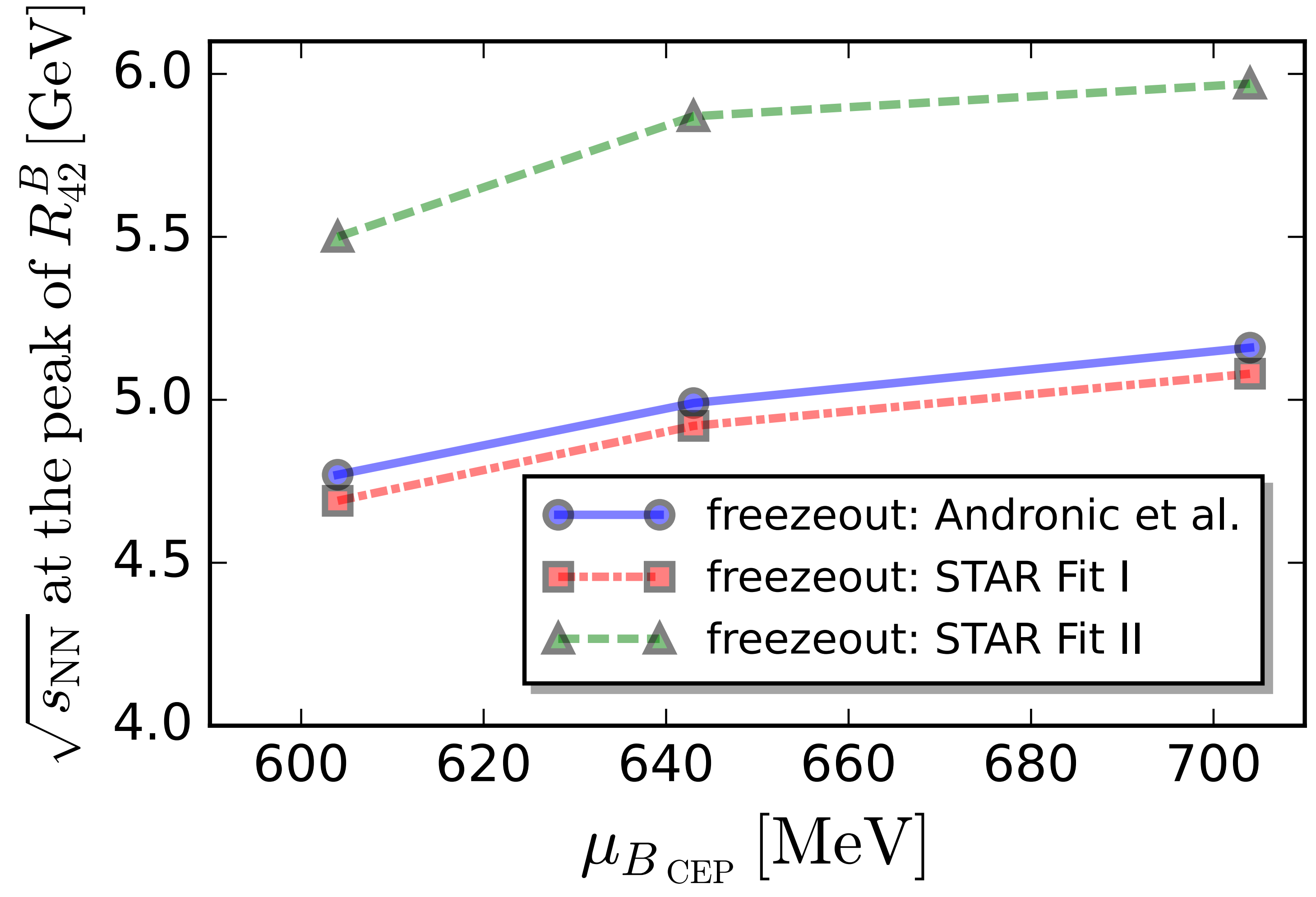
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

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

Lu, Gao, Liu, JMP, arXiv:2504.05099

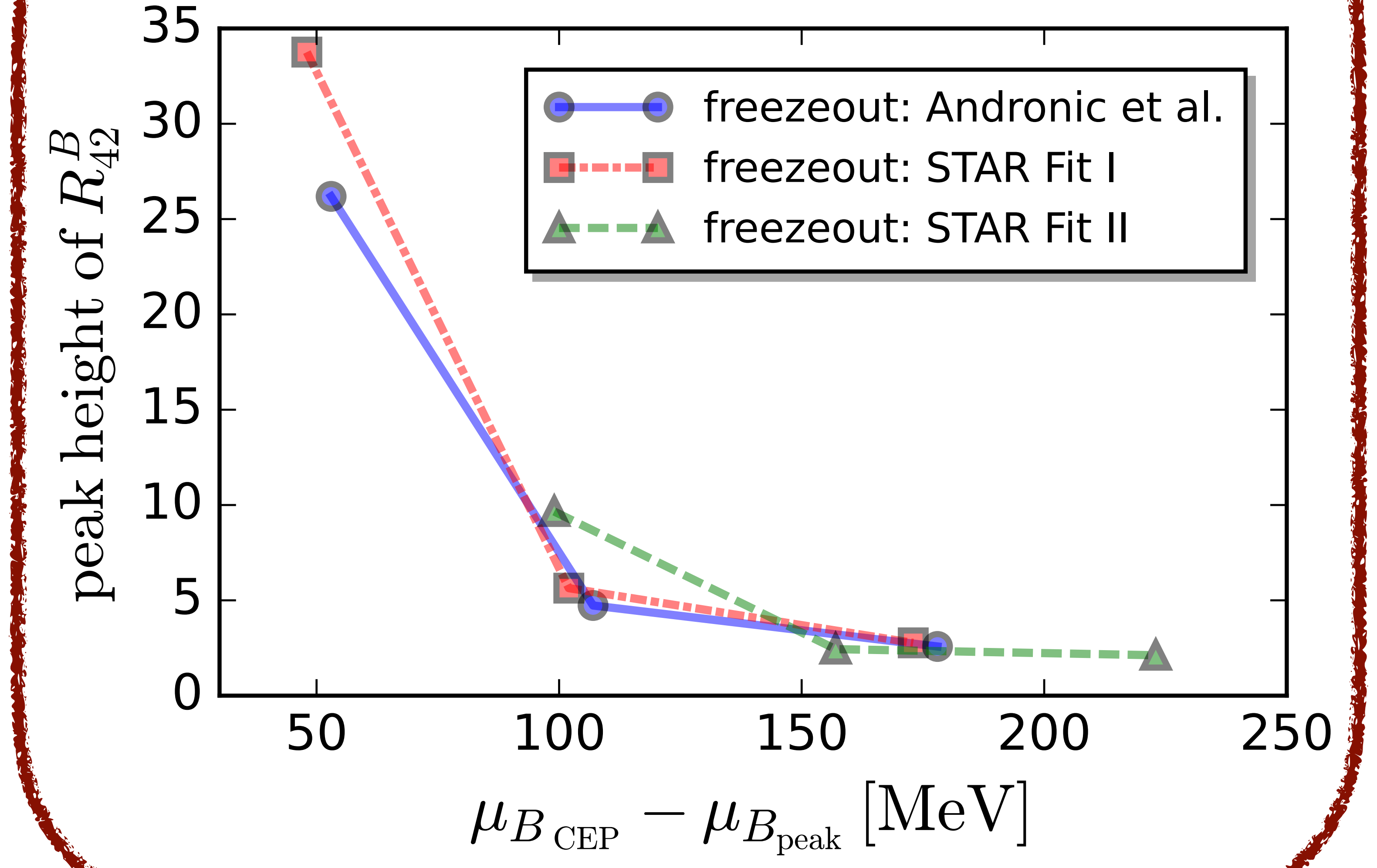
Ripples of the critical point

Position of the peak of R_{42}^B



Reconstructing the CEP

Height of the peak of R_{42}^B

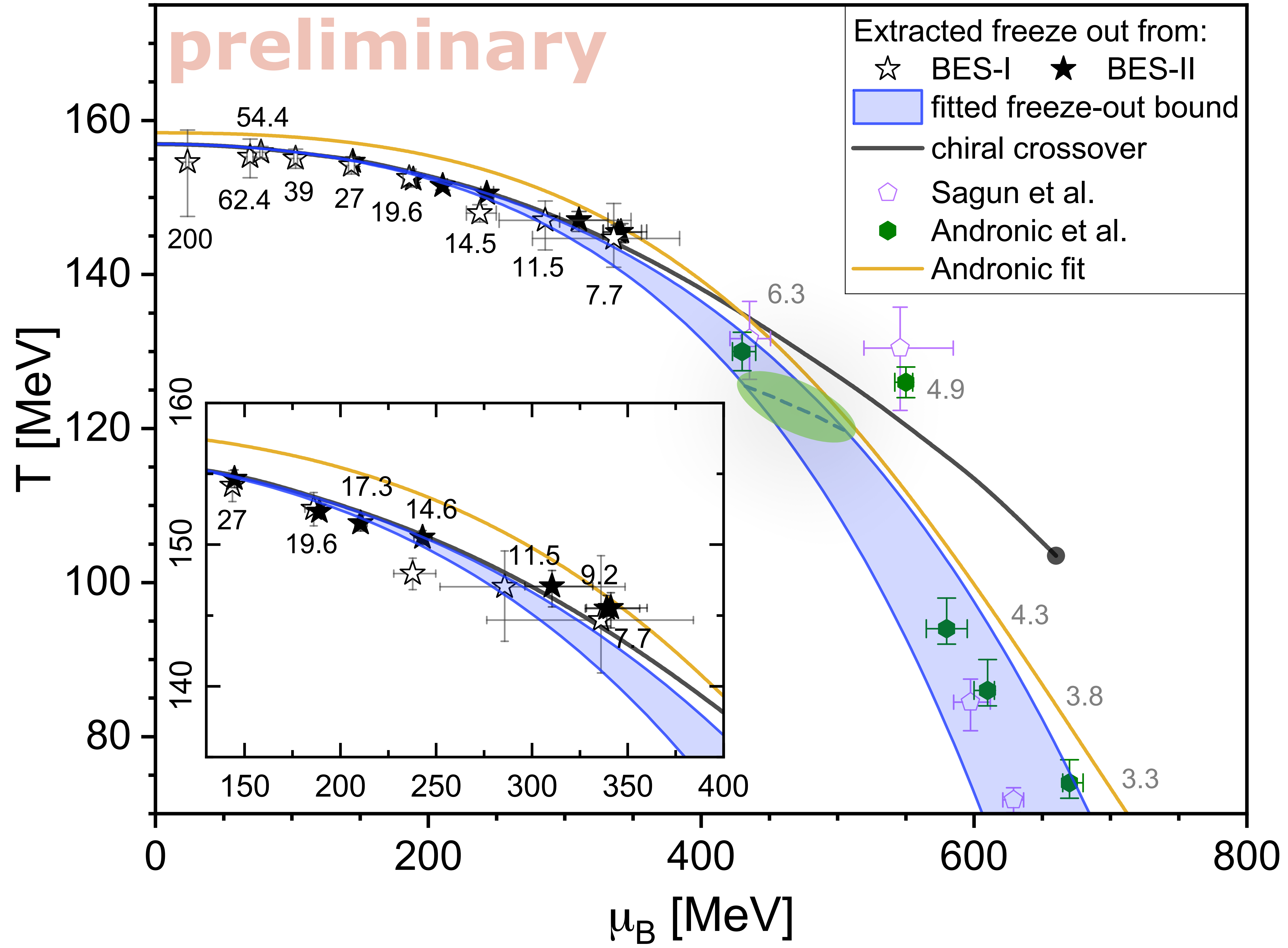


Dominated by non-critical soft modes

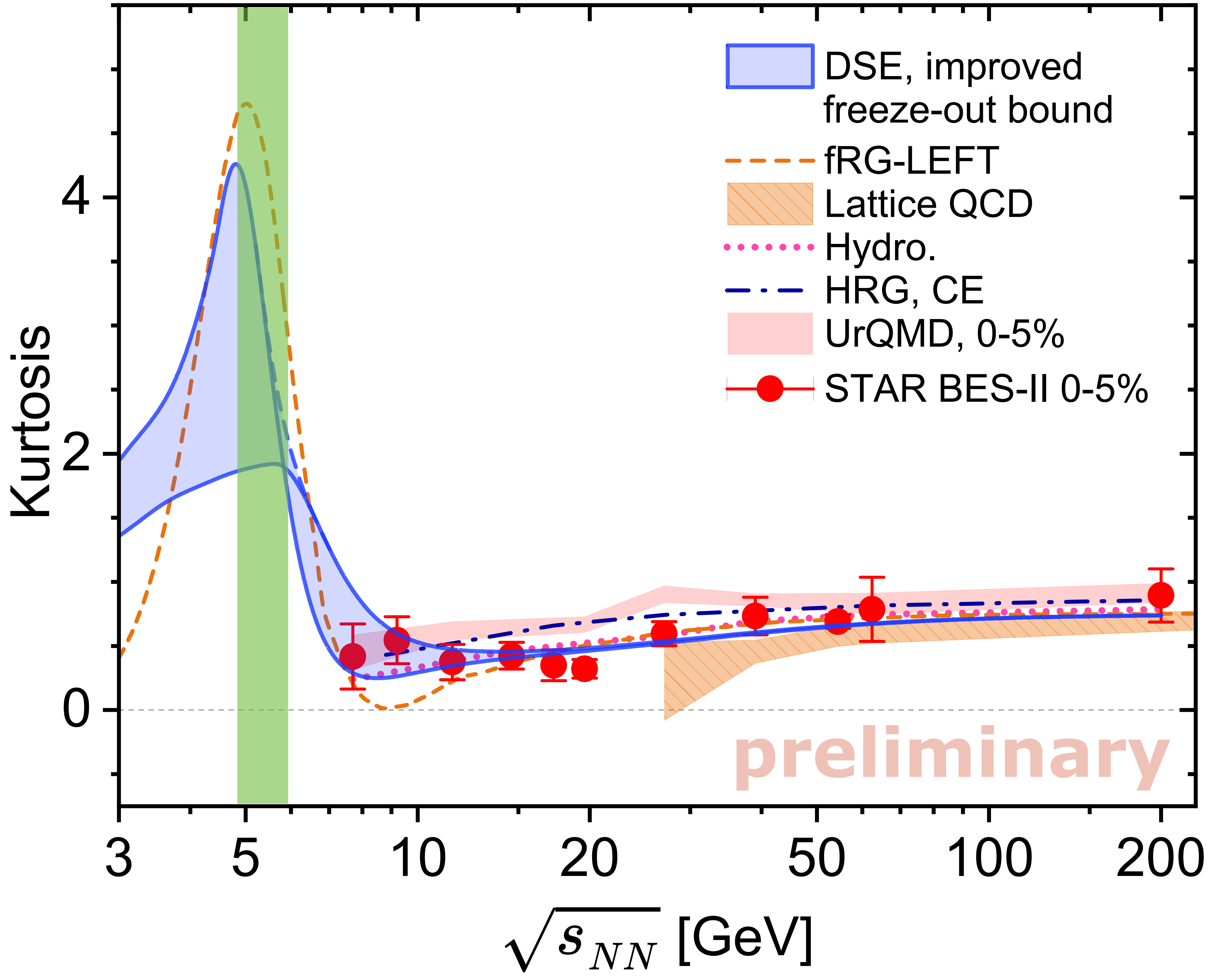
Demand: Precise freeze-out line at high density

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

Functional Freeze-out



Peak position



Demand: build in dynamics

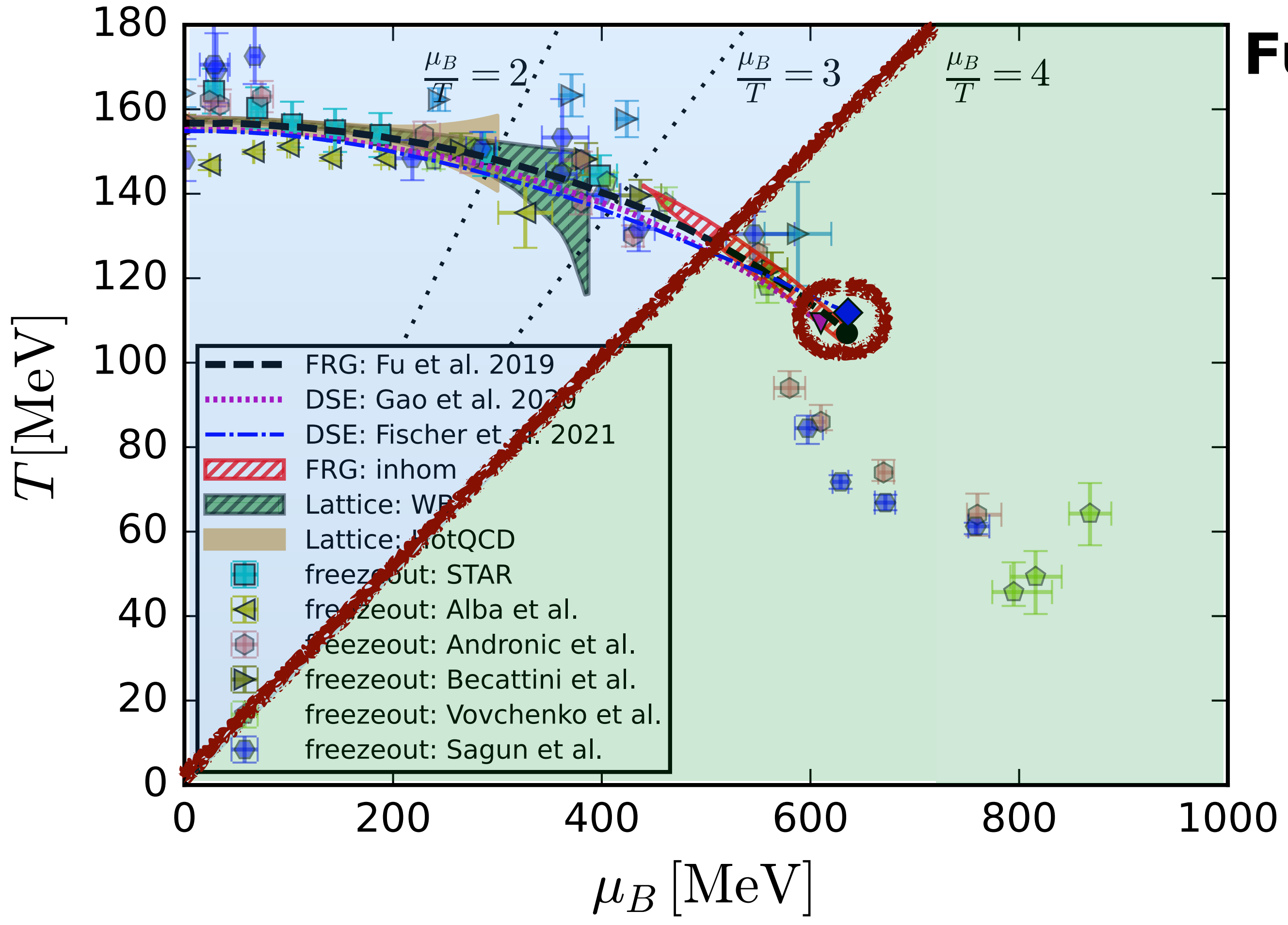
Fischer, Lu, Gao, Liu, JMP, in preparation

The QCD Moat

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

Prediction

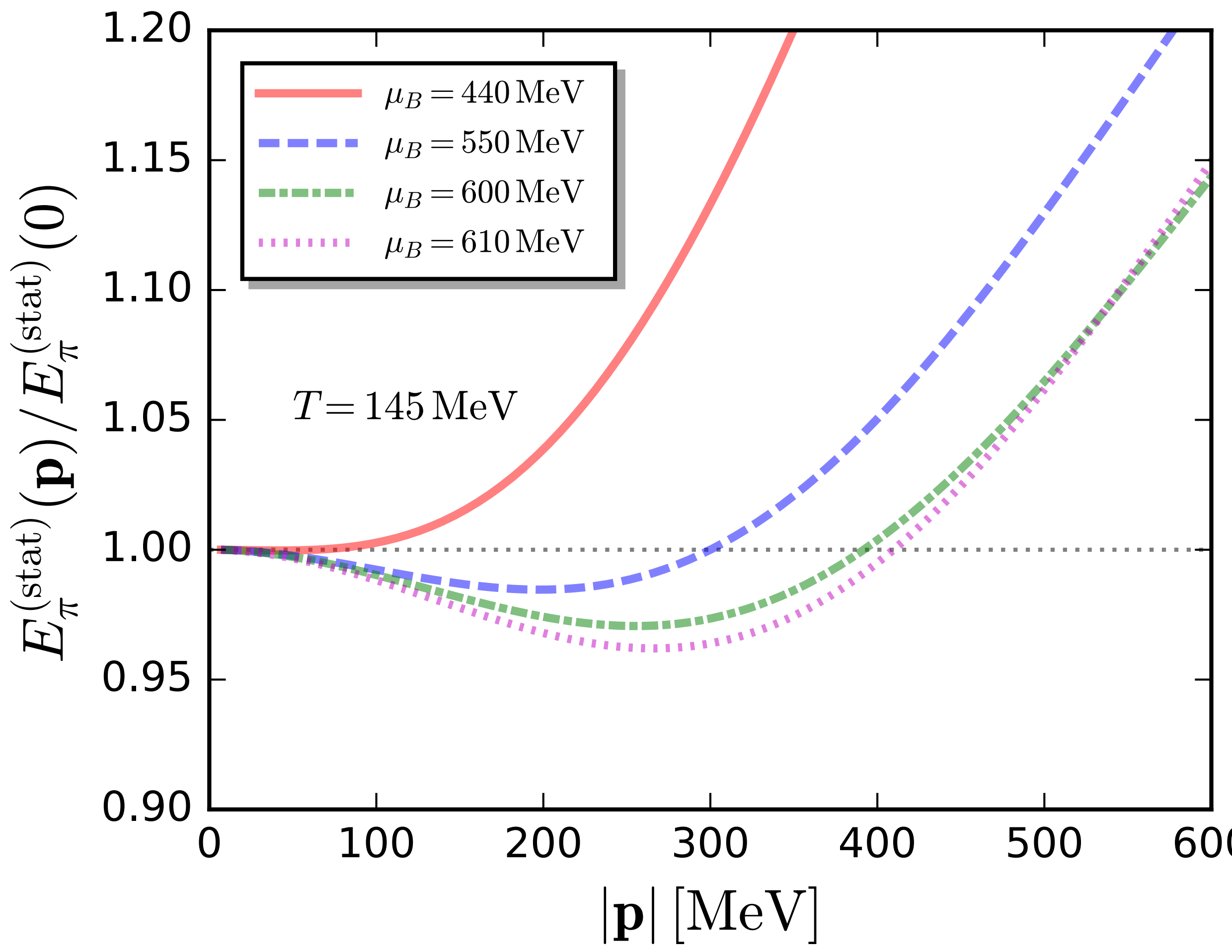


Fu, JMP, Rennecke, PRD 101 (2020) 054032

Regime of quantitative reliability of current best truncation

Estimate

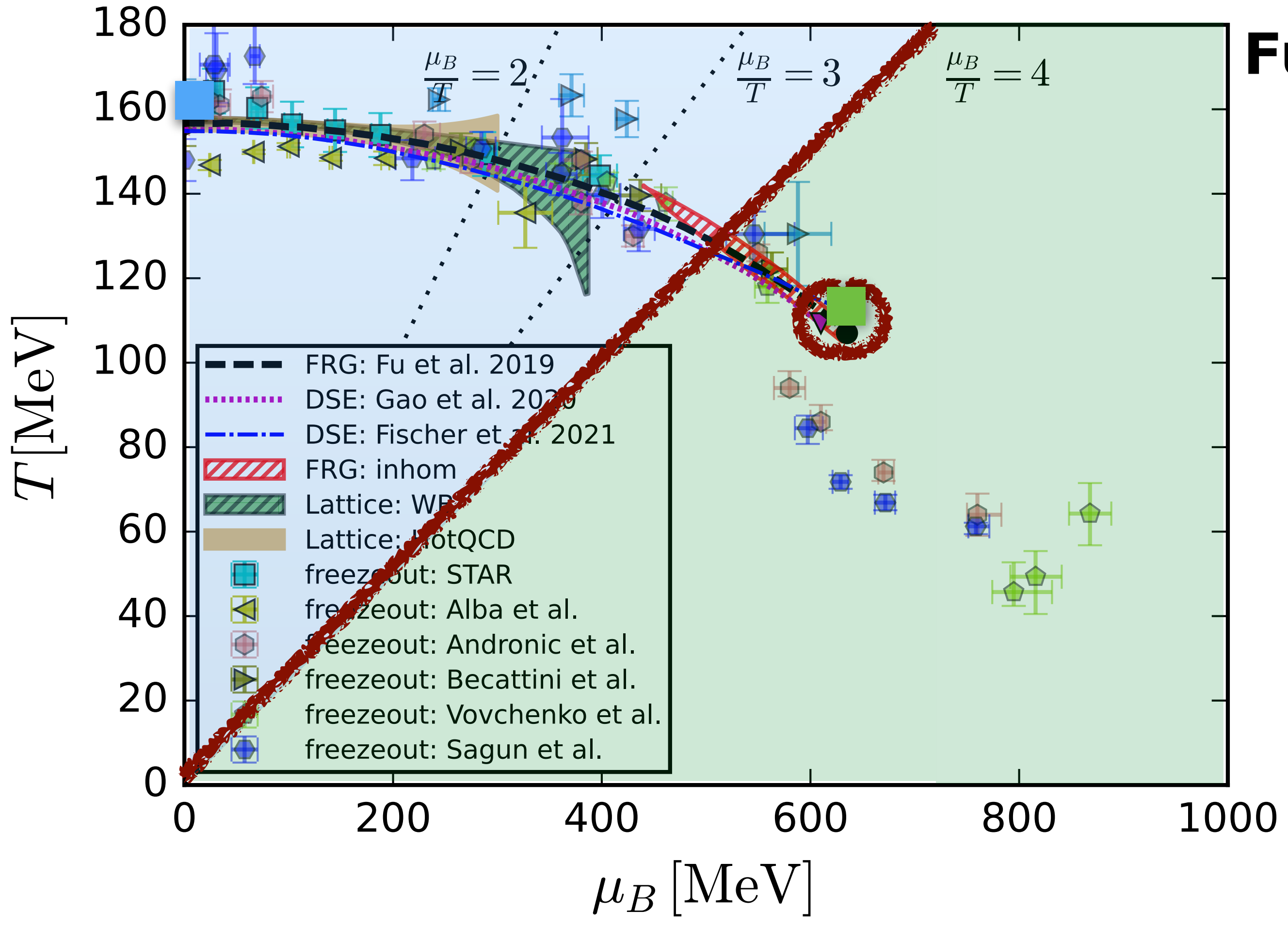
Moat regime is not yet captured quantitatively



Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

The QCD Moat

Prediction



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

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

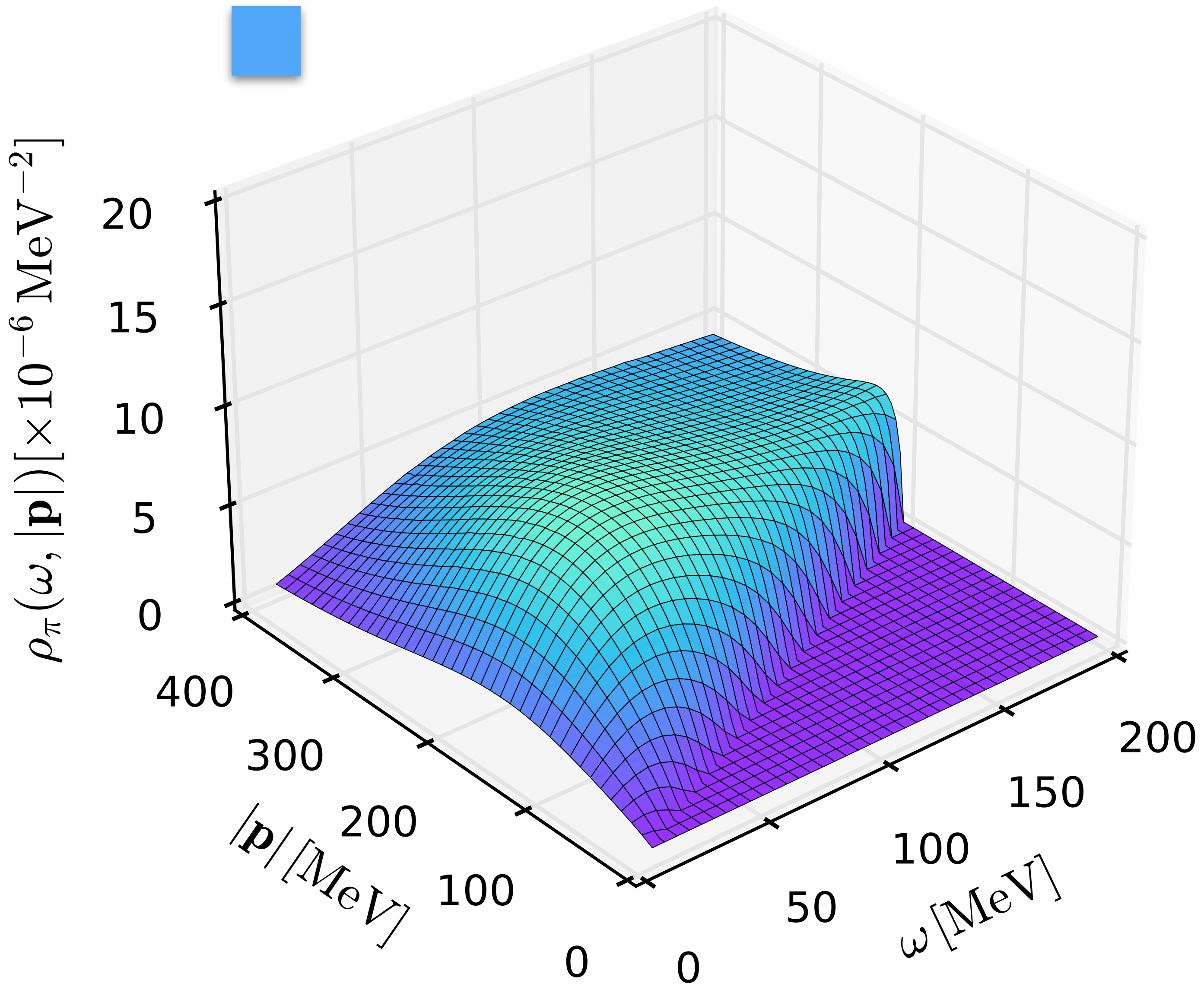
Regime of quantitative reliability of current best truncation

T=160 MeV & μ_B =0 MeV

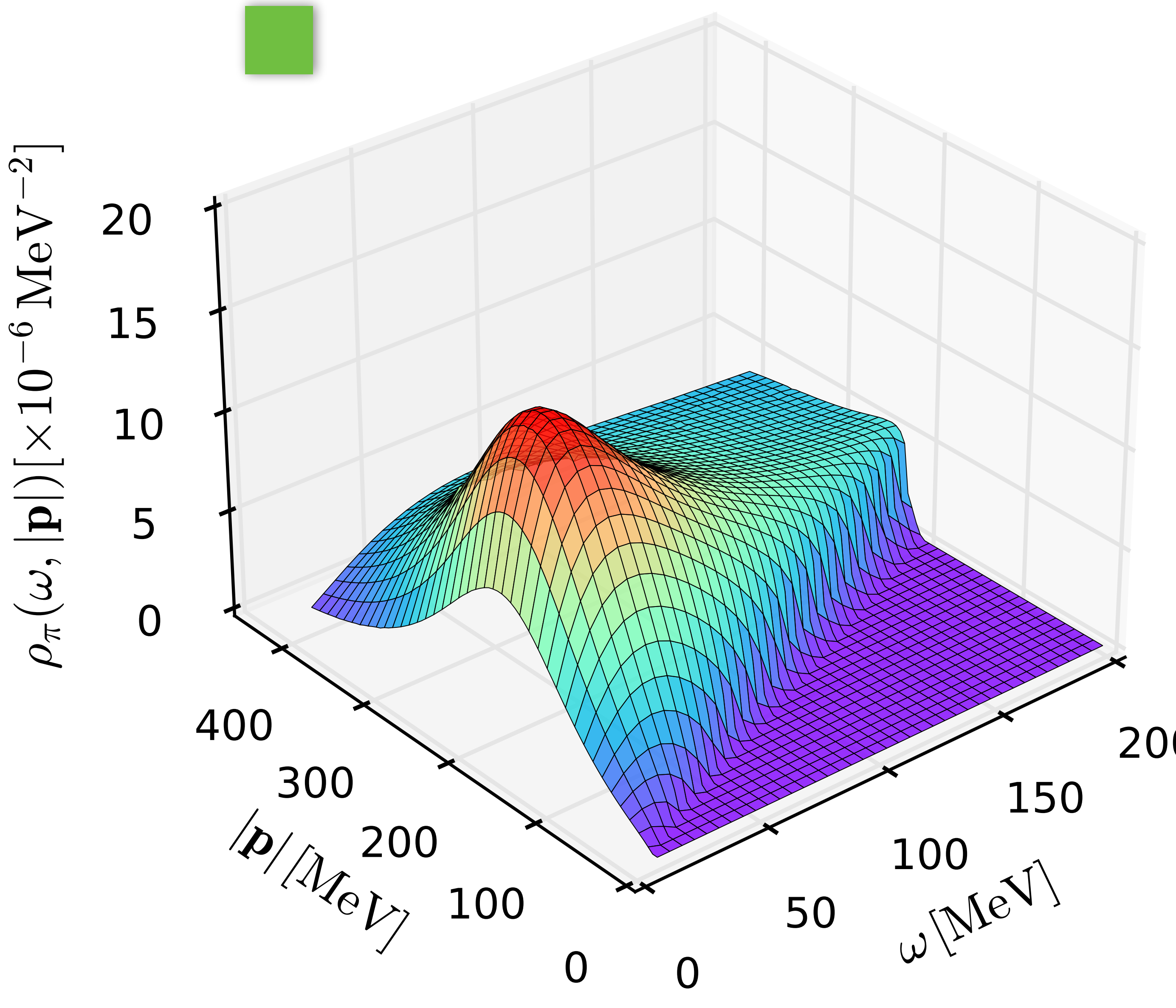
T=114 MeV & μ_B =630 MeV

Estimate

Moat regime is not yet captured quantitatively



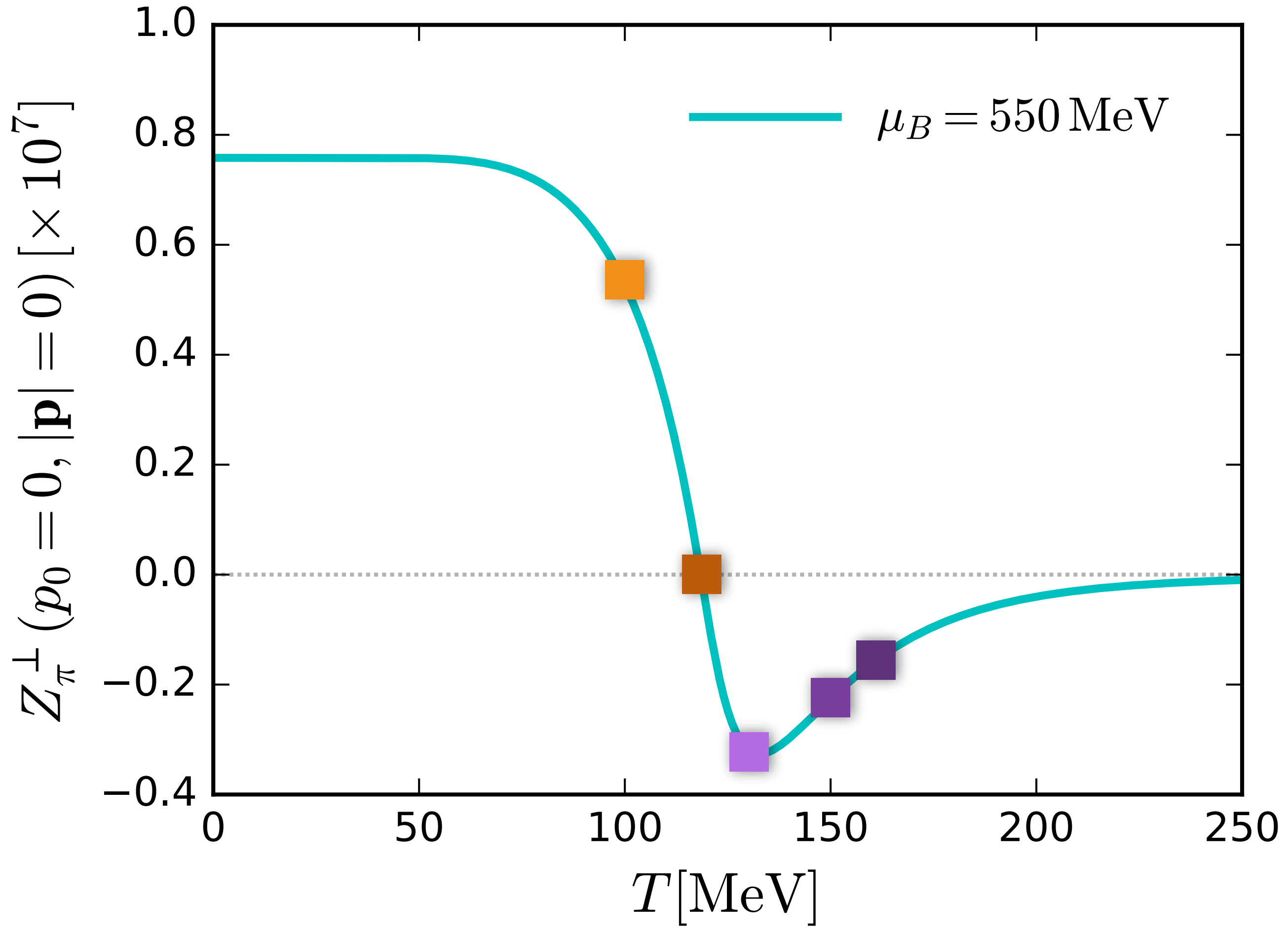
Pion spectral functions

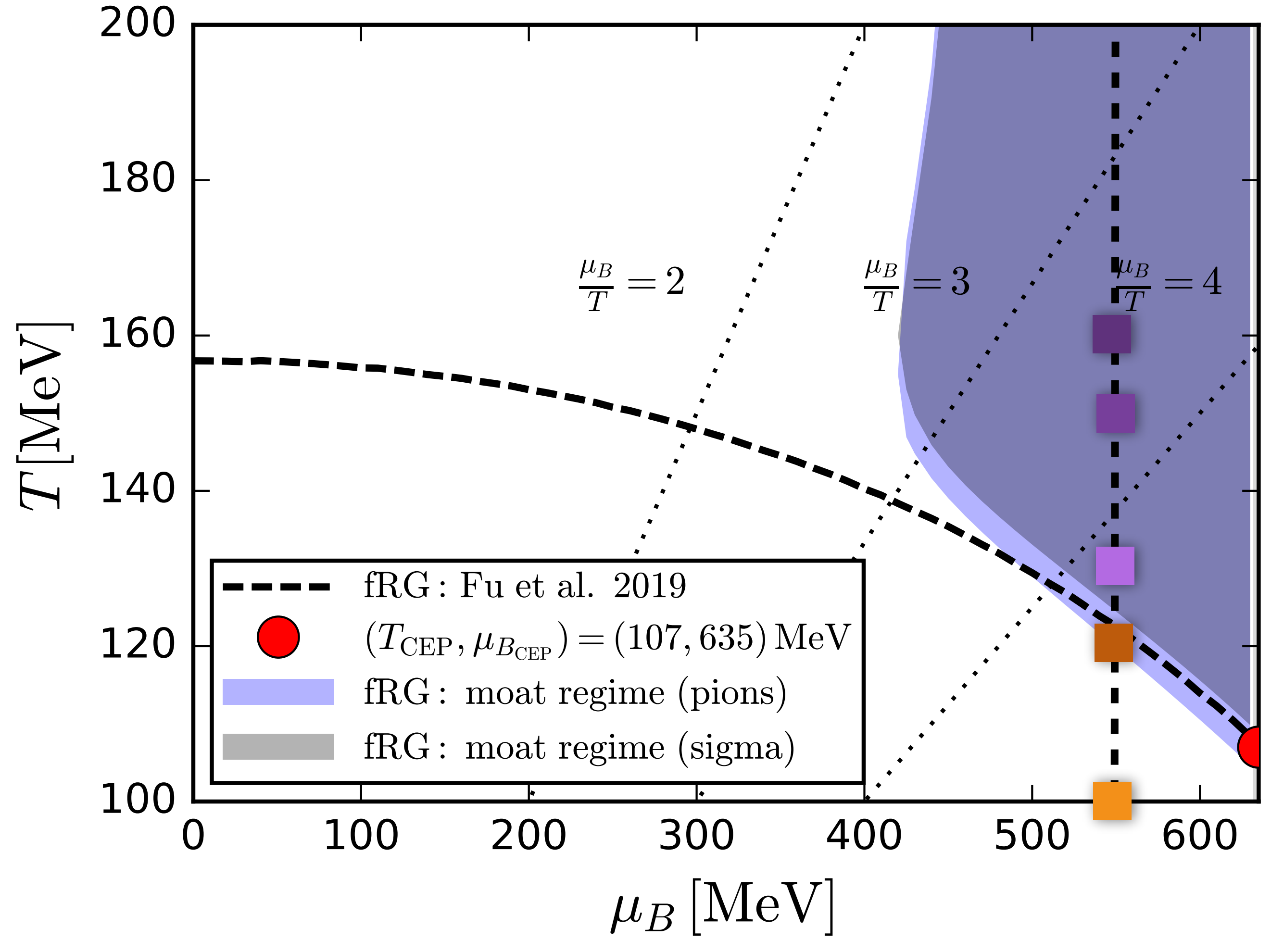


Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

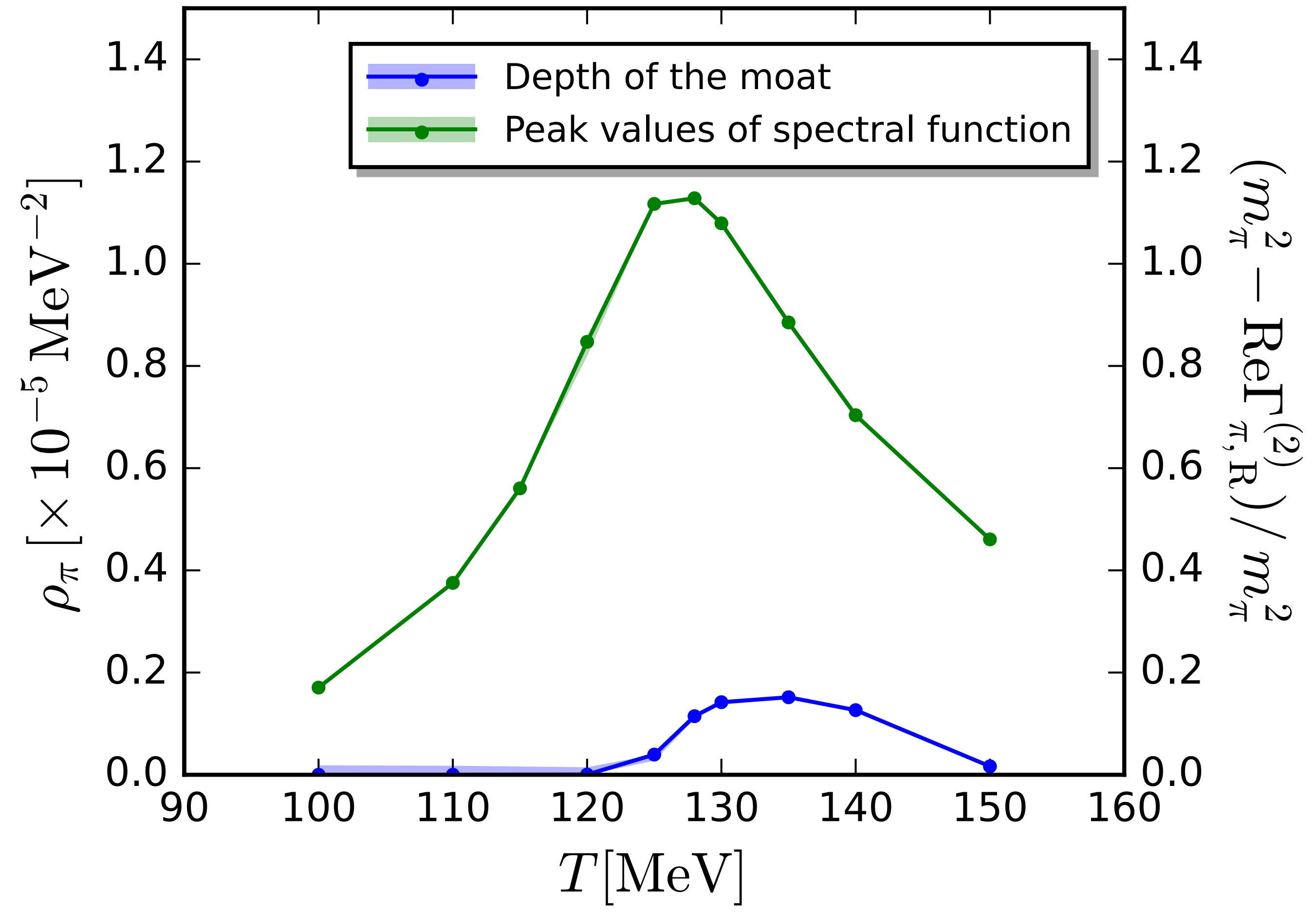
The QCD Moat

Spatial wave function of the pion at p=0





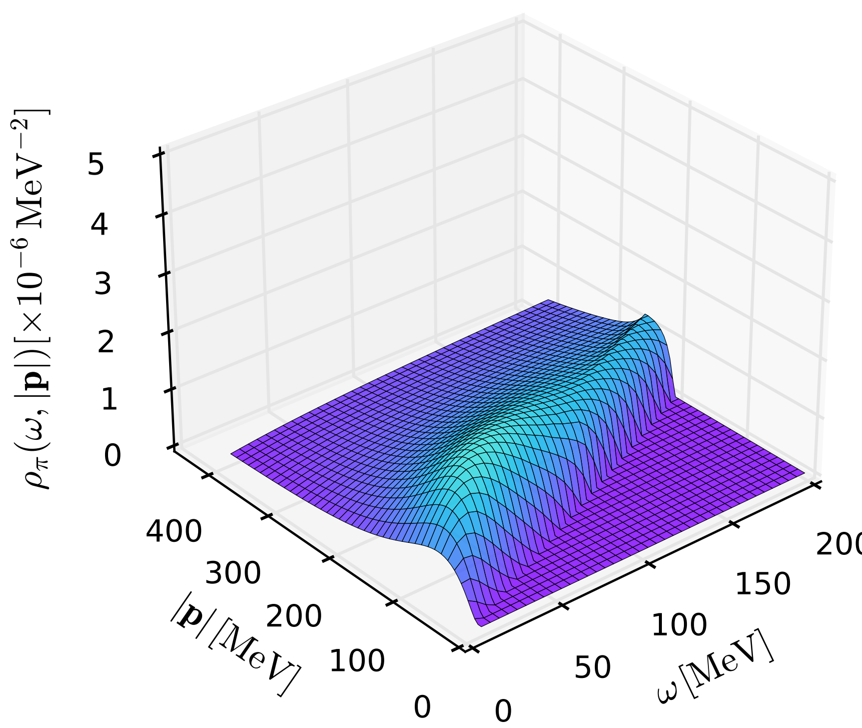
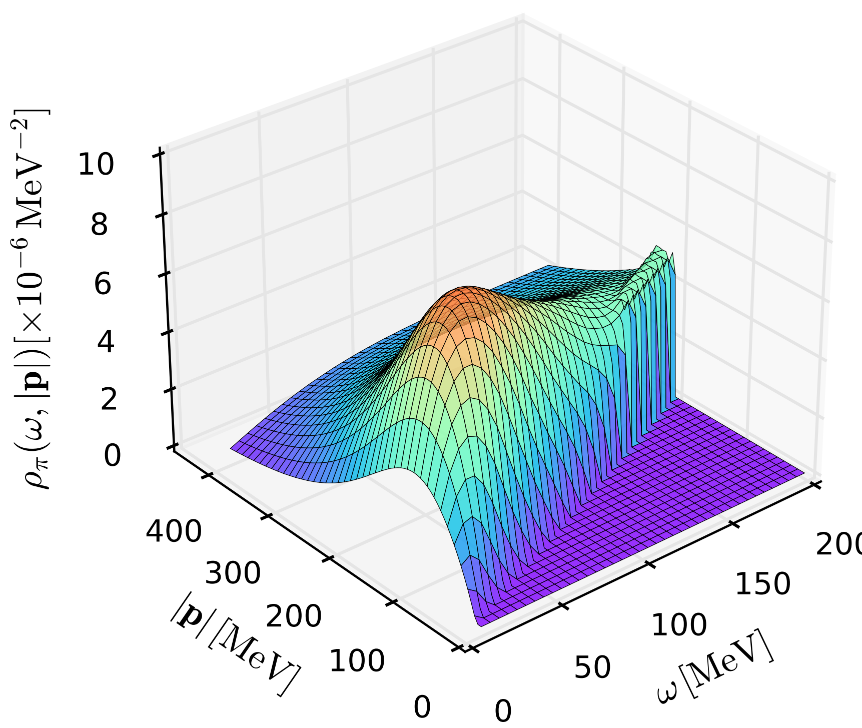
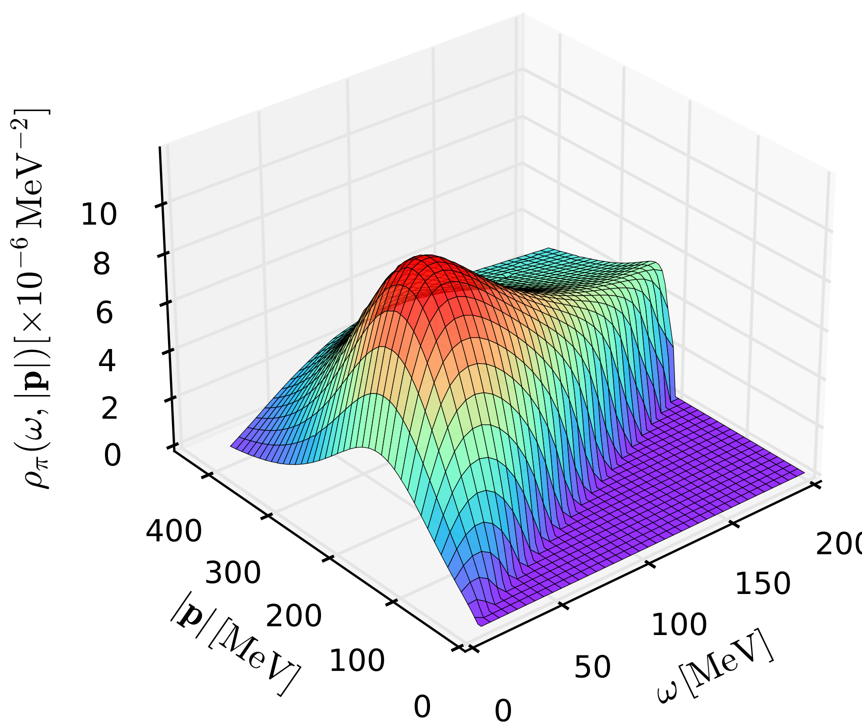
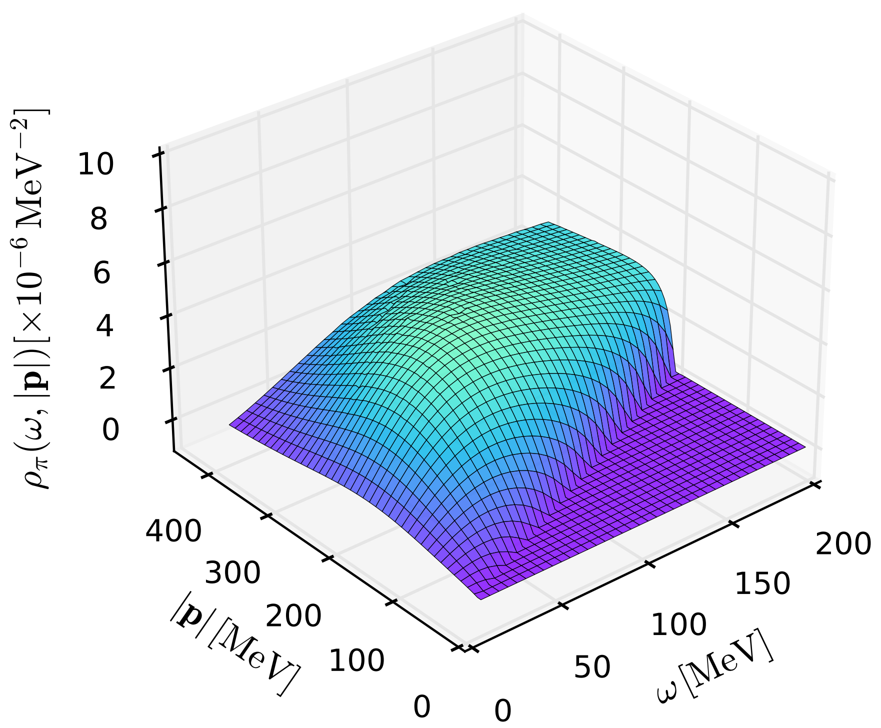
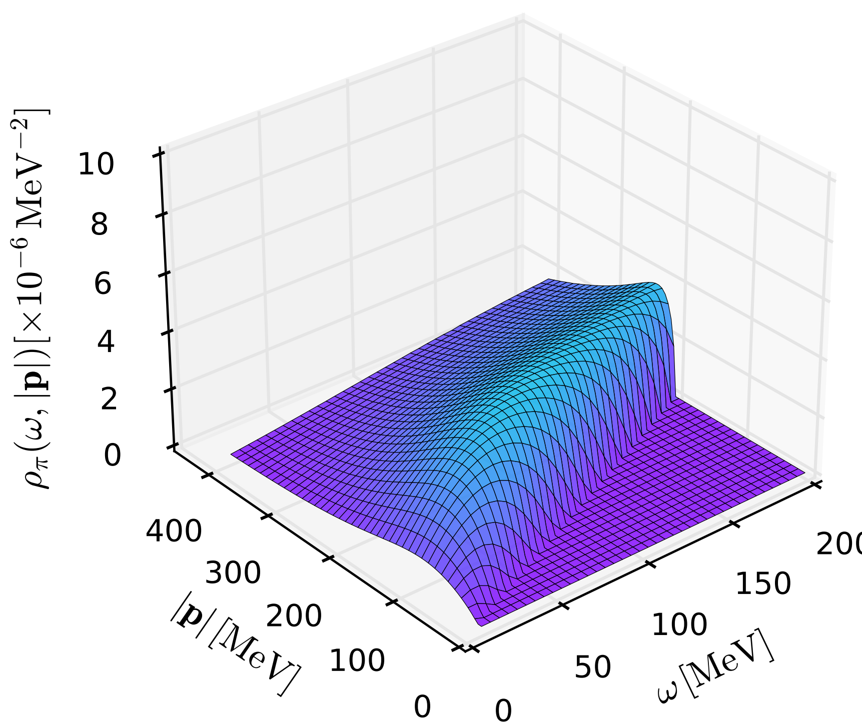
Depth of the moat & spectral peak of the pion



Dissecting the moat & the moaton

μ_B = 650 MeV

T=100 MeV **T=120 MeV** **T=130 MeV** **T=150 MeV** **T=160 MeV**

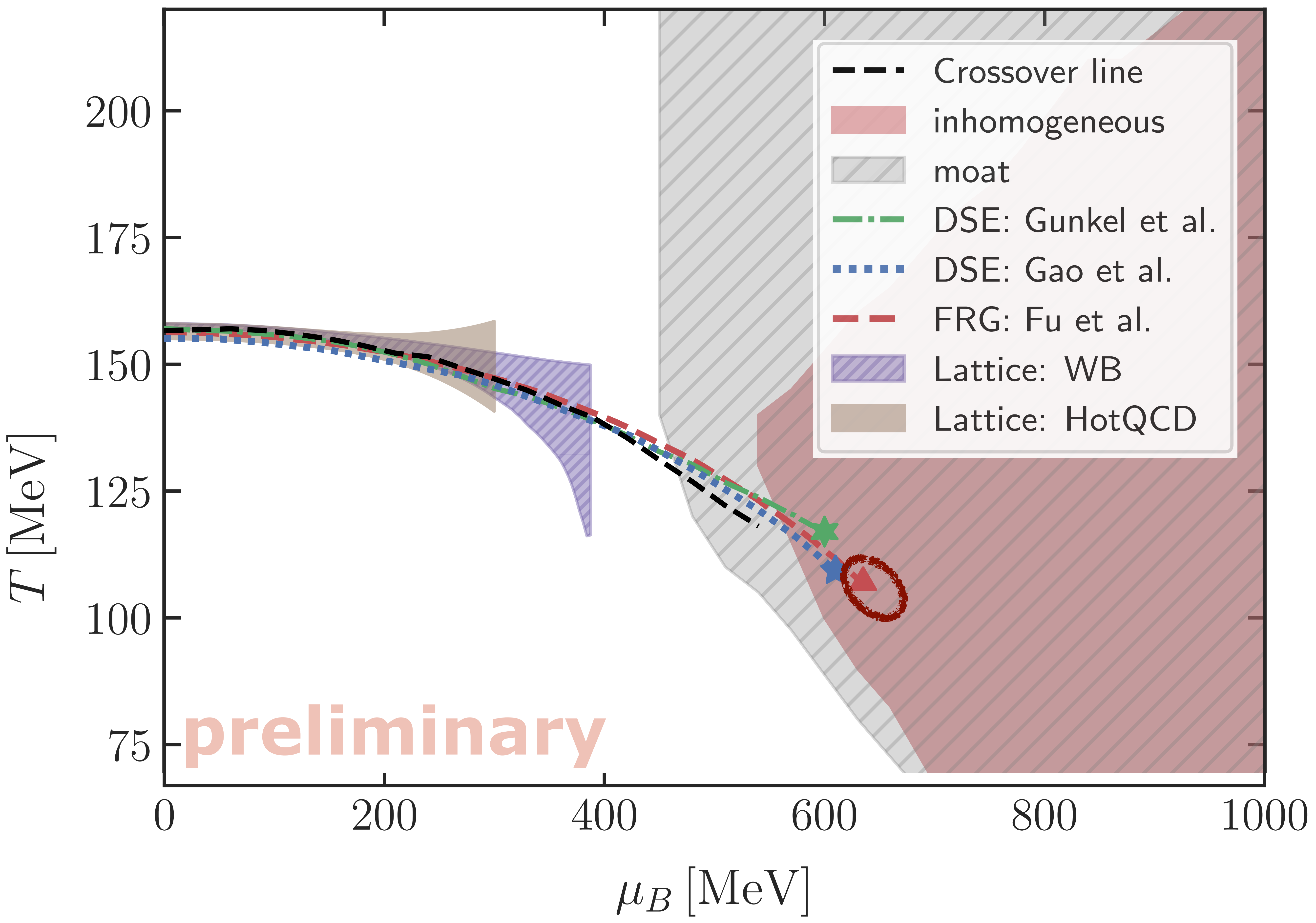
Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, 2412.15949

The QCD Moat

resolution of the moat regime

No computation inside the instability regime

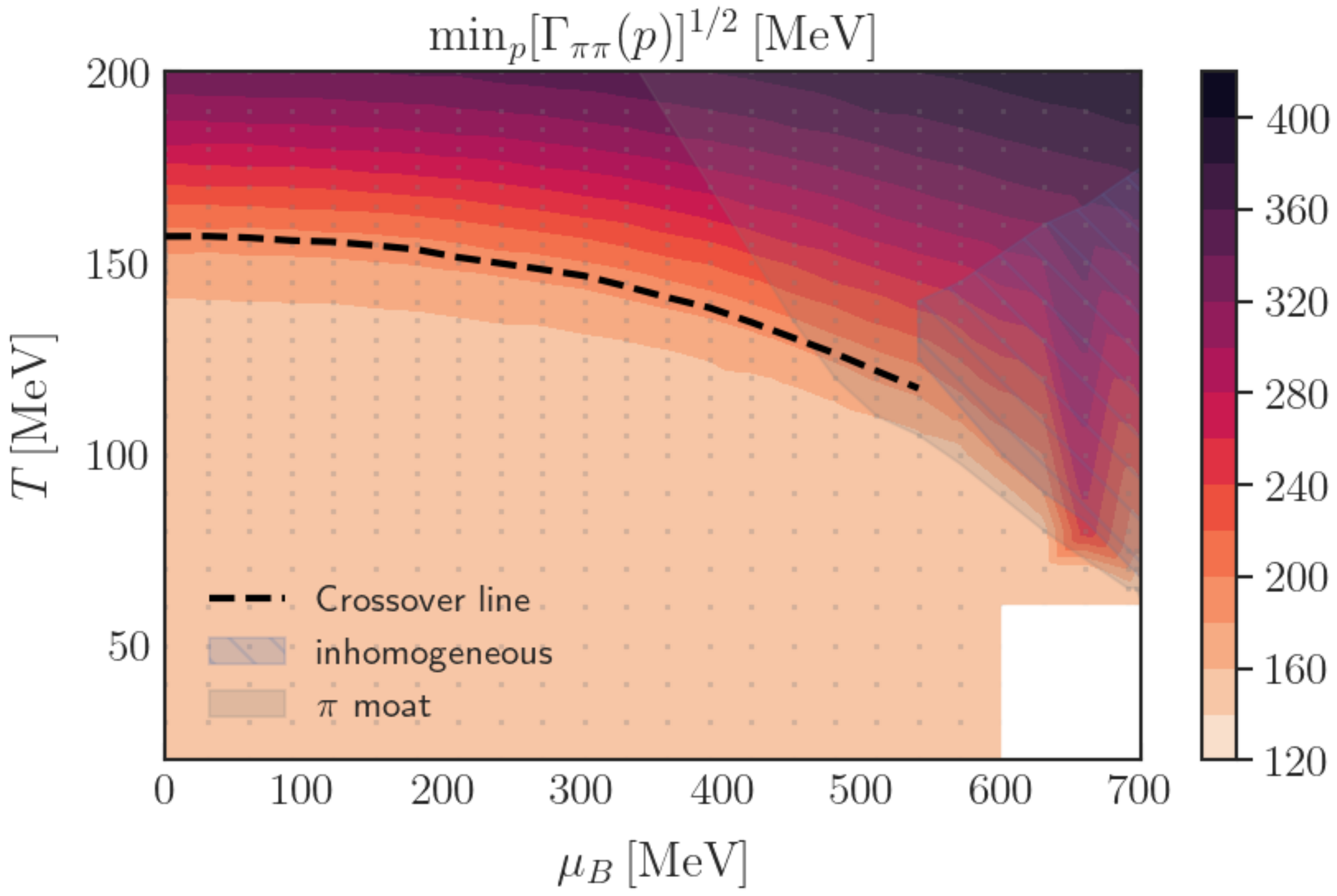
Estimated location of CEP



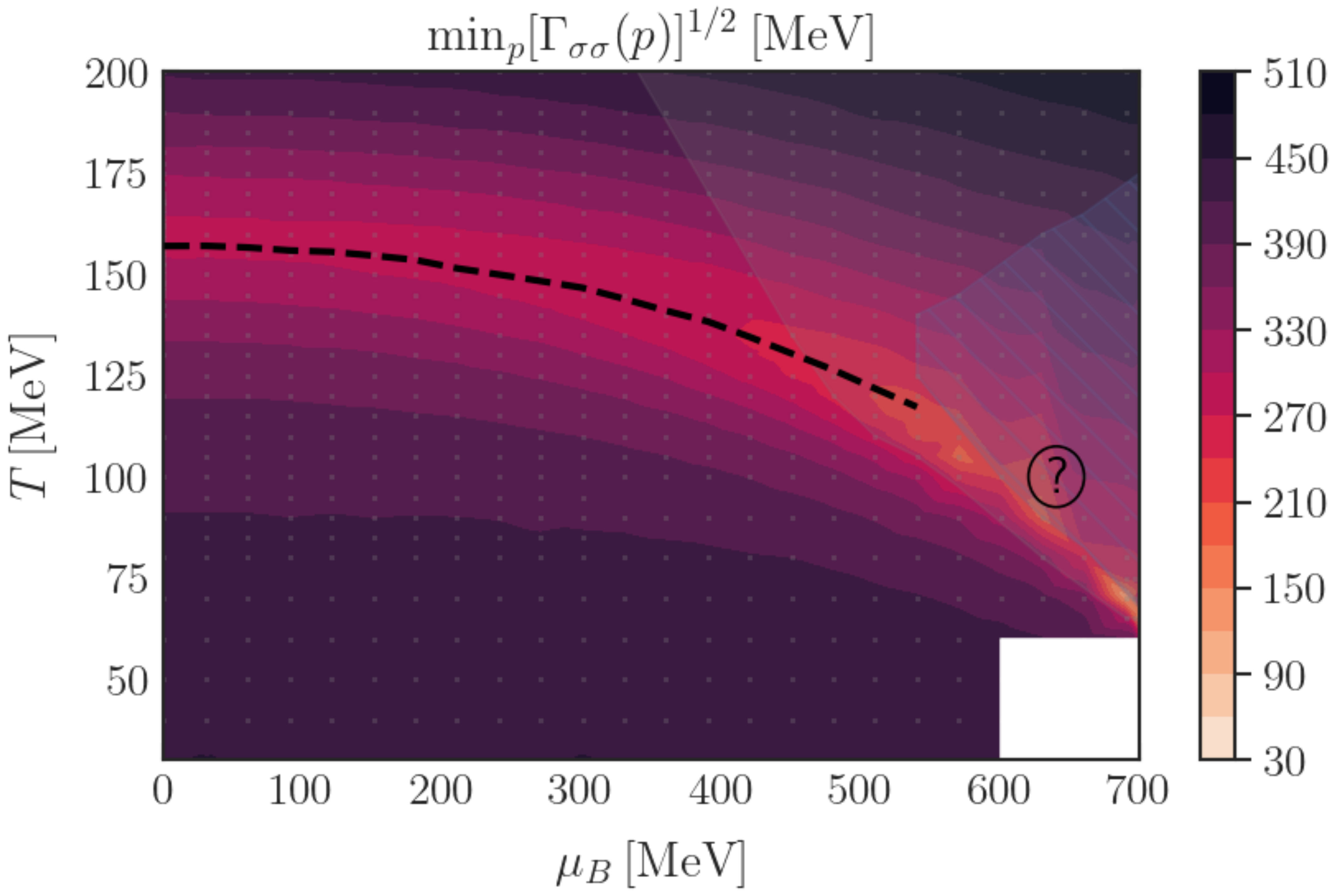
JMP, Rennecke, Sattler, in preparation

The QCD Moat

Pion 'minimum' mass



Scalar mode 'minimum' mass



preliminary

JMP, Rennecke, Sattler, in preparation

QCD phase structure at finite density: Facts & Fiction

Facts

Fiction

$\mu_B = 0$

- Chiral crossover at about

$$T_\chi \approx 155\,\mathrm{MeV}$$

- Strongly correlated phase for temperatures

$$T_\chi \lesssim T \lesssim 2\,T_\chi$$

- Physical QCD is in the chiral scaling regime

Chiral scaling regimes are very small $m_\pi \lesssim 10\,\mathrm{MeV}$

Soft modes are commonplace

- Confinement crossover is at XXX

$$T_\chi \lesssim T_{\mathrm{conf}} \lesssim 2\,T_\chi$$

$\mu_B \neq 0$

- No chiral critical end point for

$$\mu_B \lesssim 600\,\mathrm{MeV}$$

- No chiral crossover for

$$\mu_B \gtrsim 700\,\mathrm{MeV}$$

- Onset of new phases and their physics

Onset of new phases $600\,\mathrm{MeV} \lesssim \mu_B^{\mathrm{onset}} \lesssim 700\,\mathrm{MeV}$

- Scaling regime (Ising) of the CEP is humongous

No, it is not! Most likely: too small to be measured