The moat regime in QCD

QuantFunc 2024

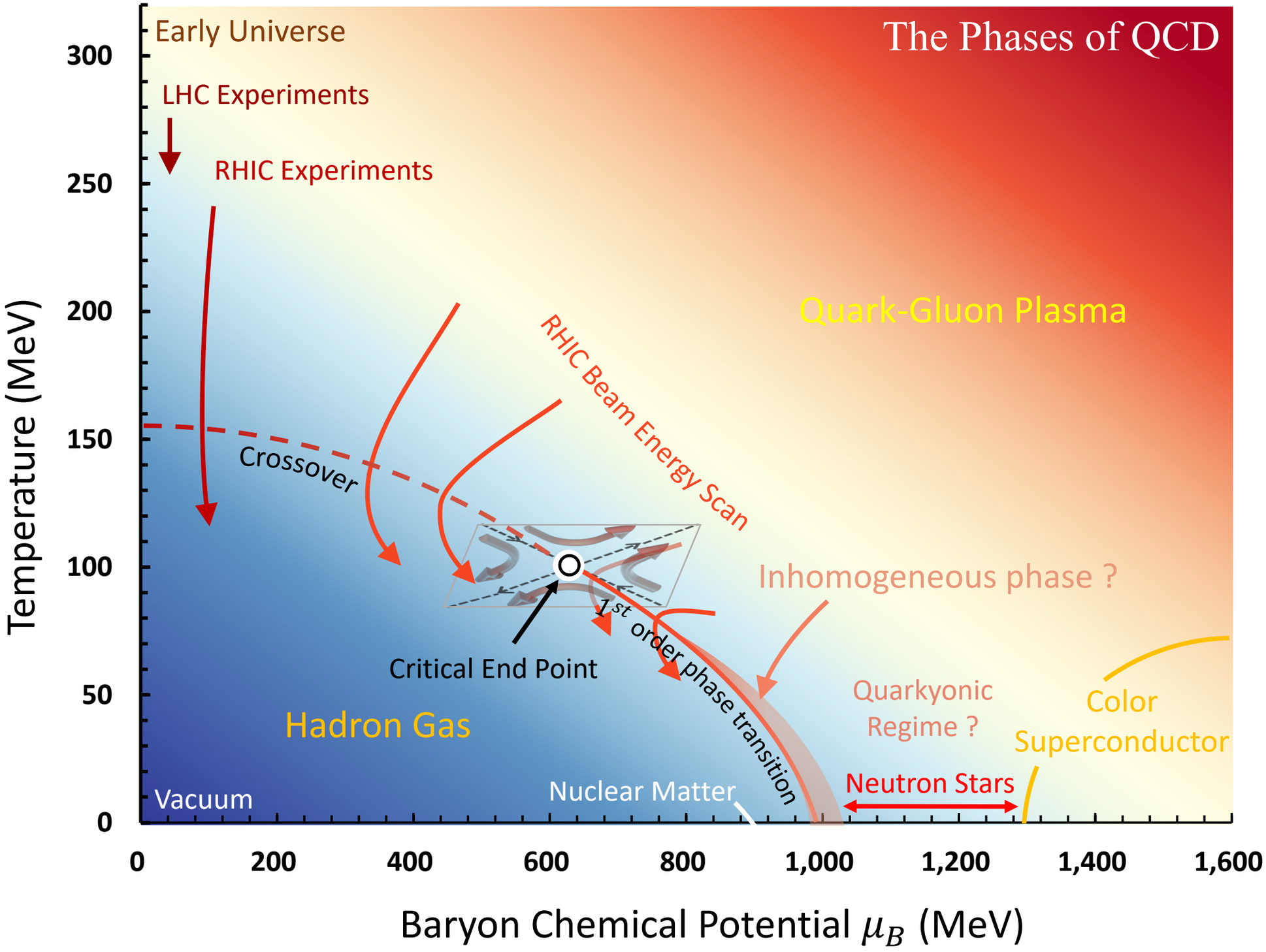
Shi Yin

Justus Liebig University Giessen

Outline

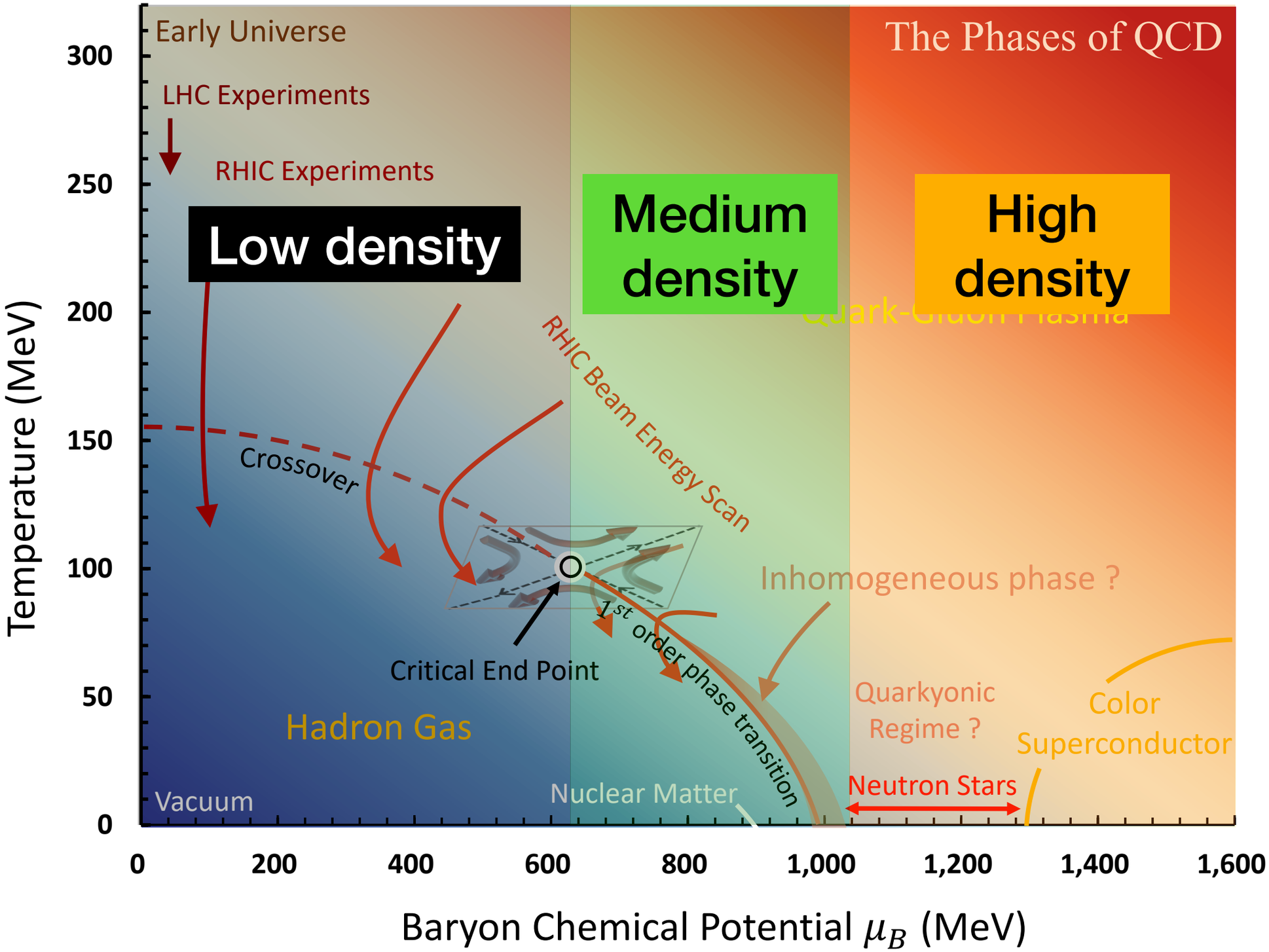
- QCD phase structure
- Moat regime in QCD
- Summary and outlook

QCD phase structure



SY, Y.-y. Tan and W.-j. Fu, Nucl.Tech. 46 (2023) 04, 040002

QCD phase structure

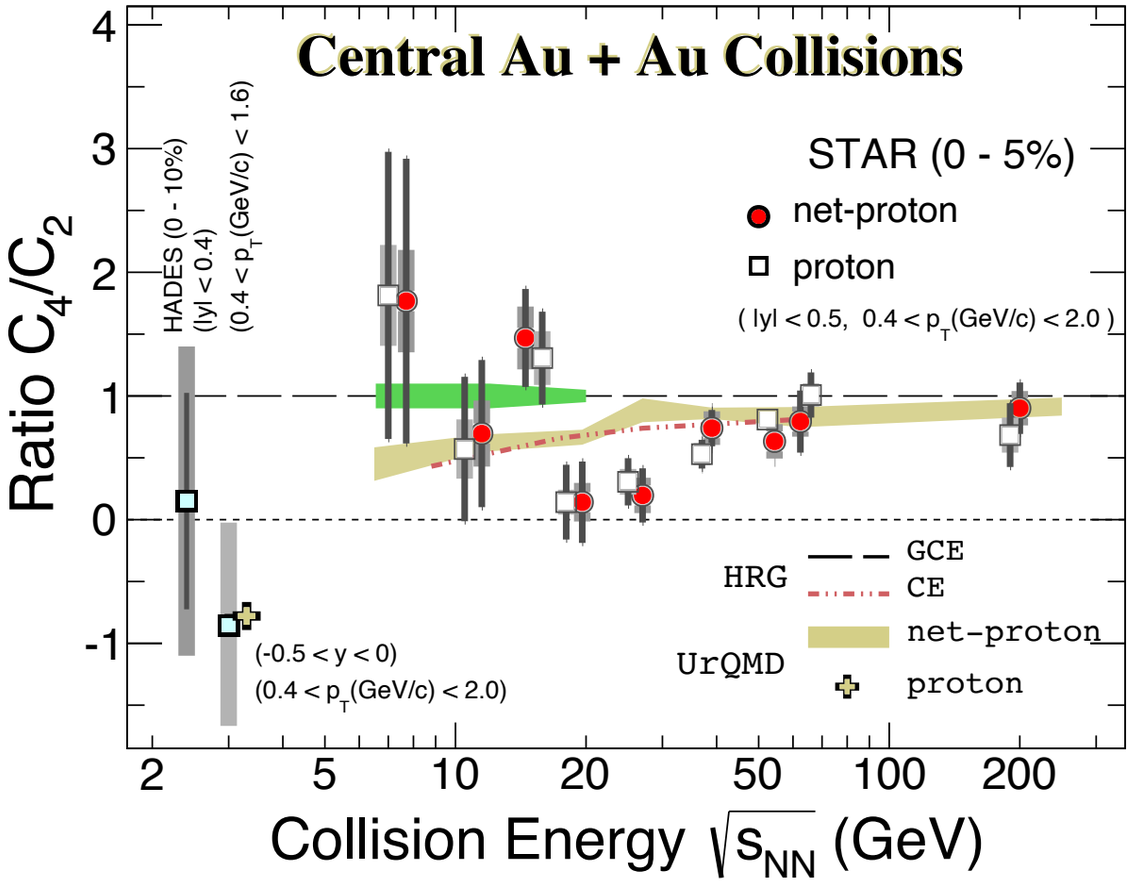


SY, Y.-y. Tan and W.-j. Fu, Nucl.Tech. 46 (2023) 04, 040002

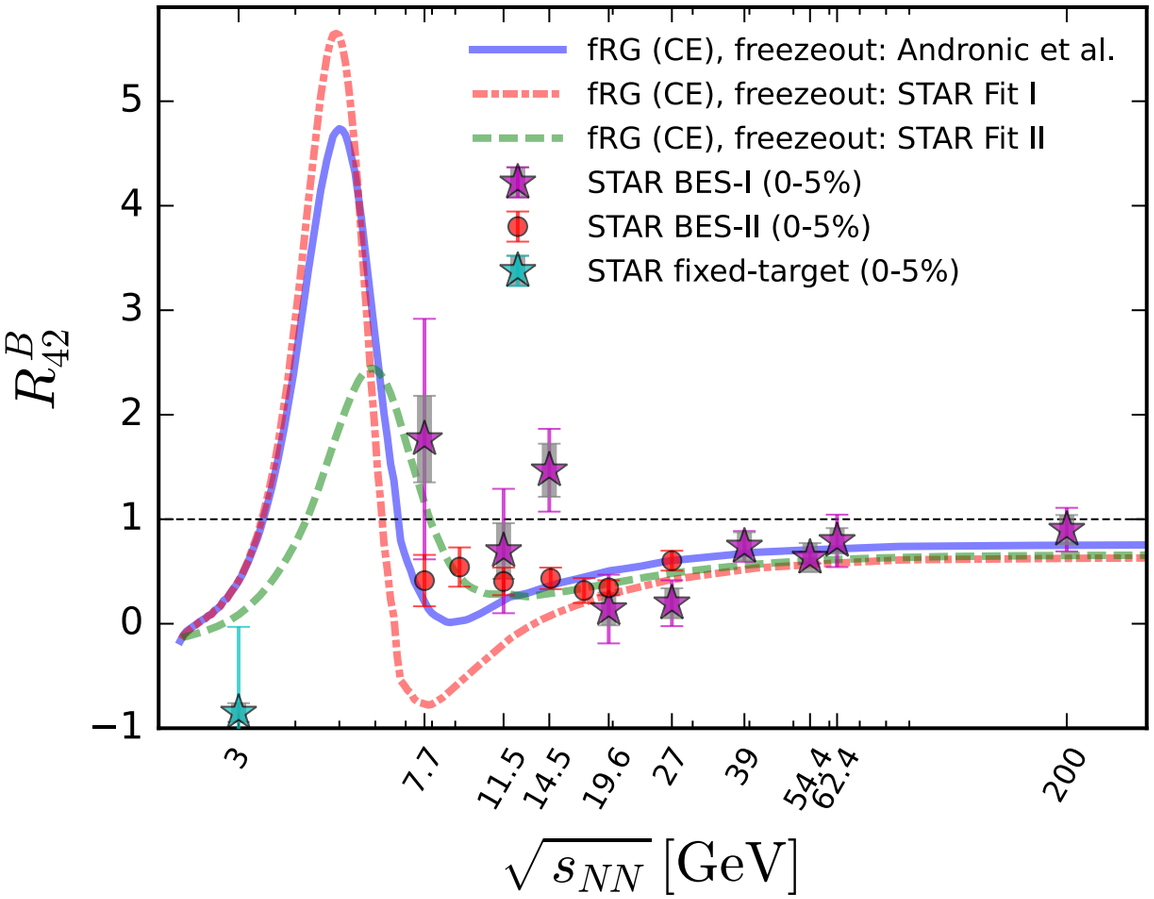
Looking for CEP

From low density to medium density

Proton number fluctuations

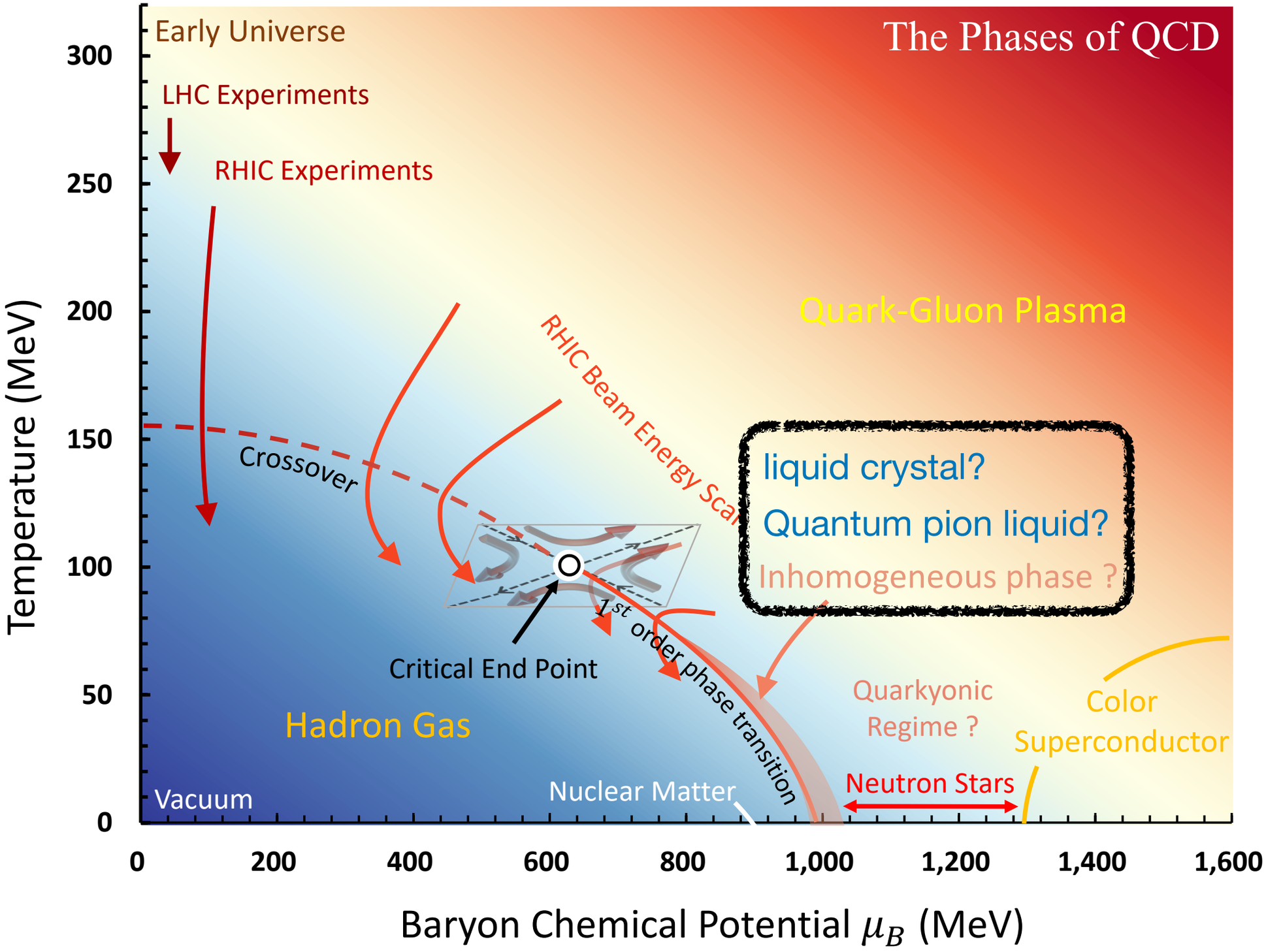


M. S. Abdallah et. al., *Phys.Rev.Lett.* 128 (2022) 20, 202303



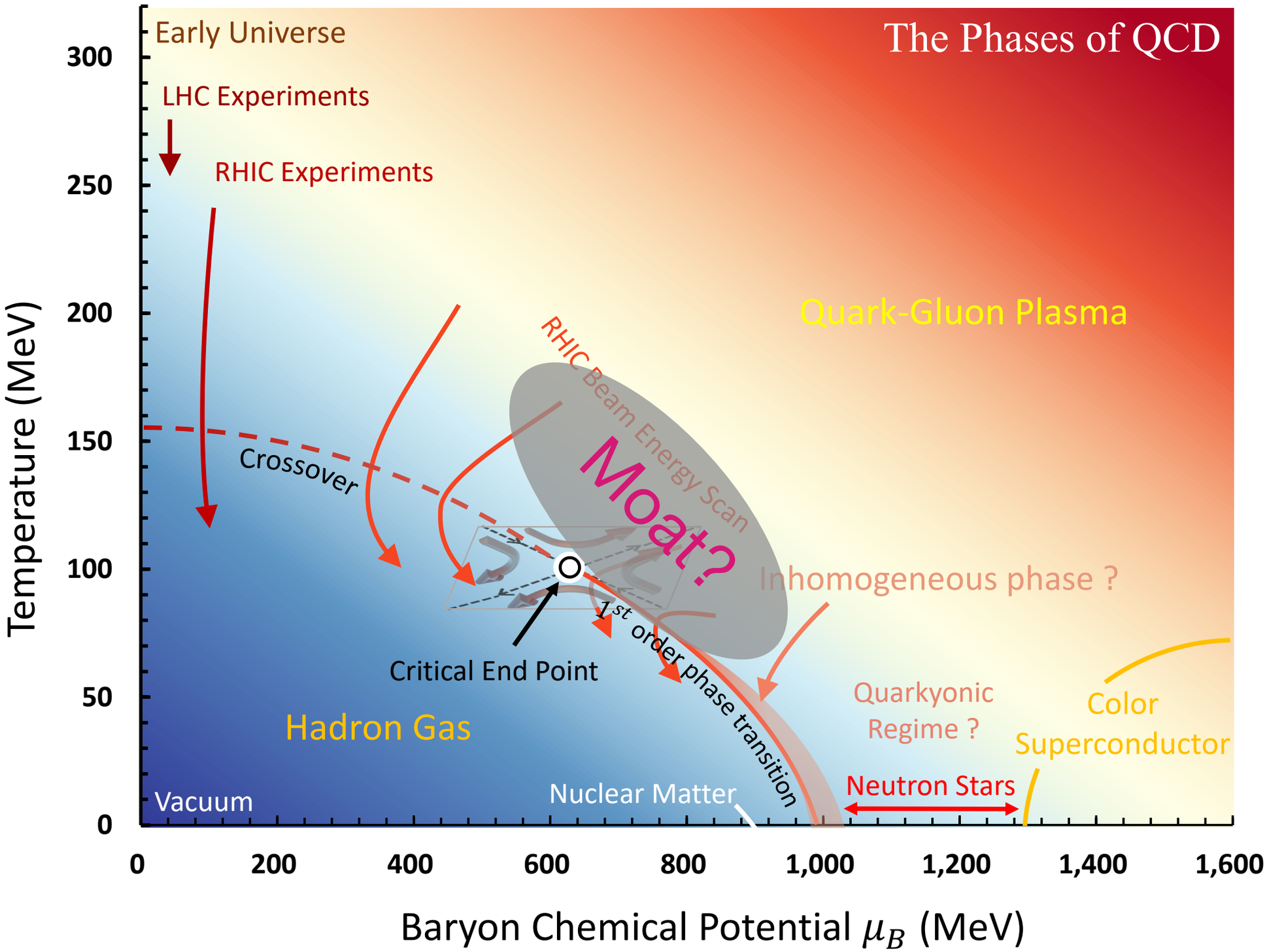
W.-j. Fu, XF Luo, J. M. Pawlowski, F. Rennecke and SY, arXiv:2308.15508

QCD phase structure



SY, Y.-y. Tan and W.-j. Fu, Nucl.Tech. 46 (2023) 04, 040002

Moat regime



SY, Y.-y. Tan and W.-j. Fu, Nucl.Tech. 46 (2023) 04, 040002

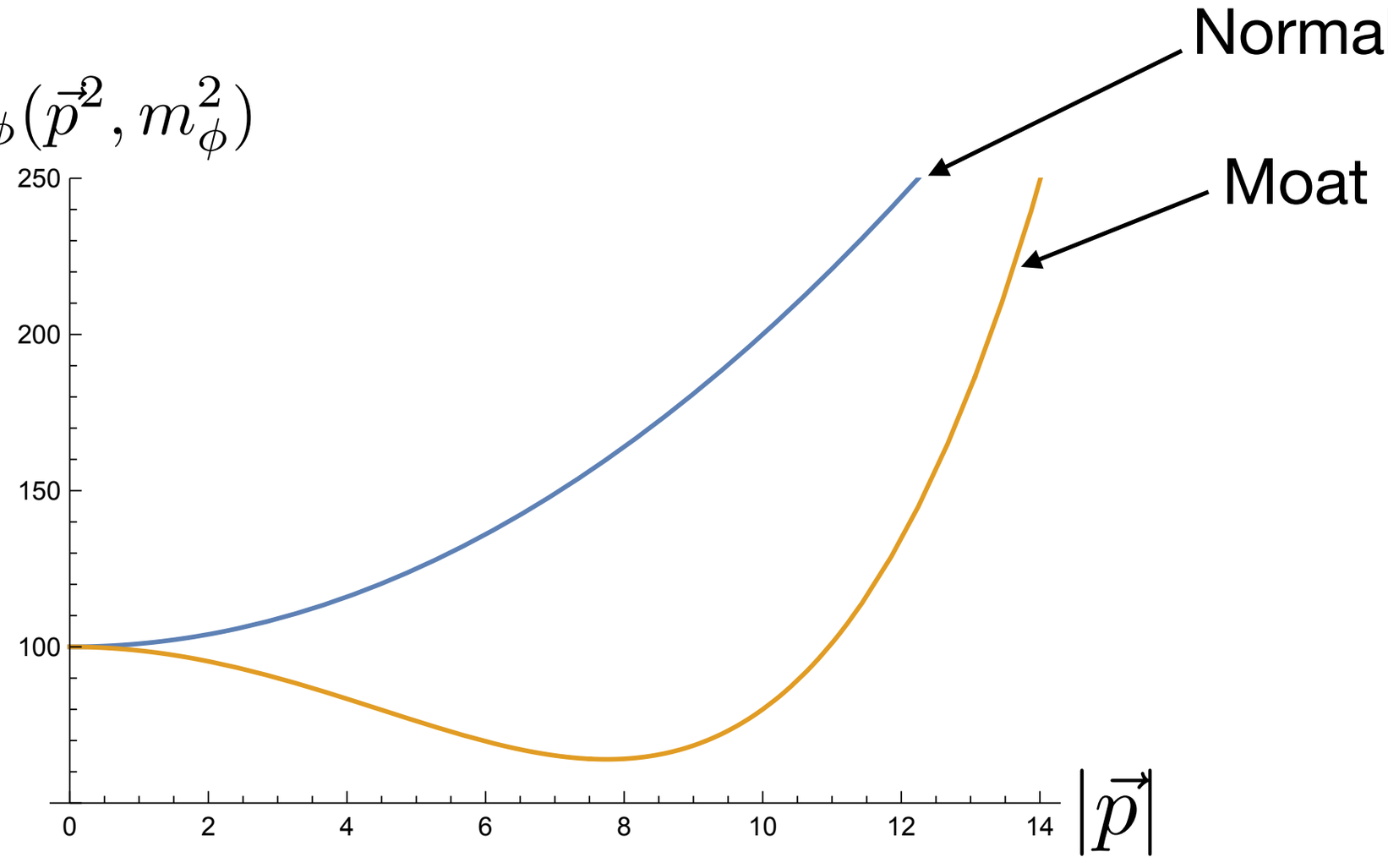
Moat behavior

Dispersion relation

$$E_\phi(\vec{p}^2, m_\phi^2) = \sqrt{\vec{p}^2 + m_\phi^2 + \Pi_{1-\text{loop}}(\vec{p}^2, m_\phi^2)}$$

$$= \sqrt{Z_\phi(\vec{p}^2)\,\vec{p}^2 + m_\phi^2}$$

Finite temperature and density !!!

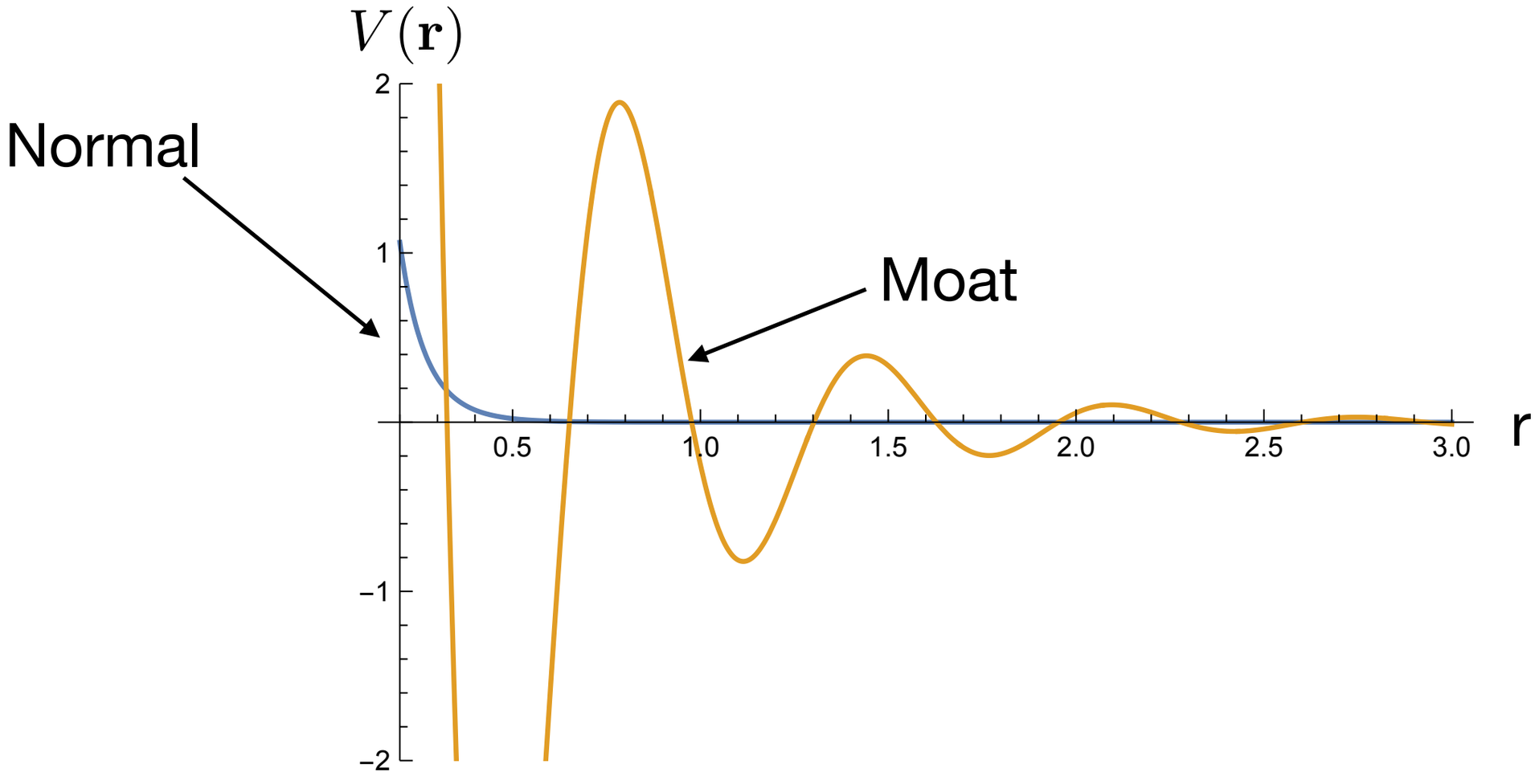


Friedel Oscillations

Analogy to condensed matter:

$$V(\mathbf{r}) = Q_1 Q_2 \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{r}} \frac{1}{\mathbf{k}^2 + m^2 + \Pi(0,\mathbf{k})}$$

J. Kapusta and T. Toimela, *Phys.Rev.D* 37 (1988) 3731



Fabian Rennecke, SY, in preparation

Observables in moat

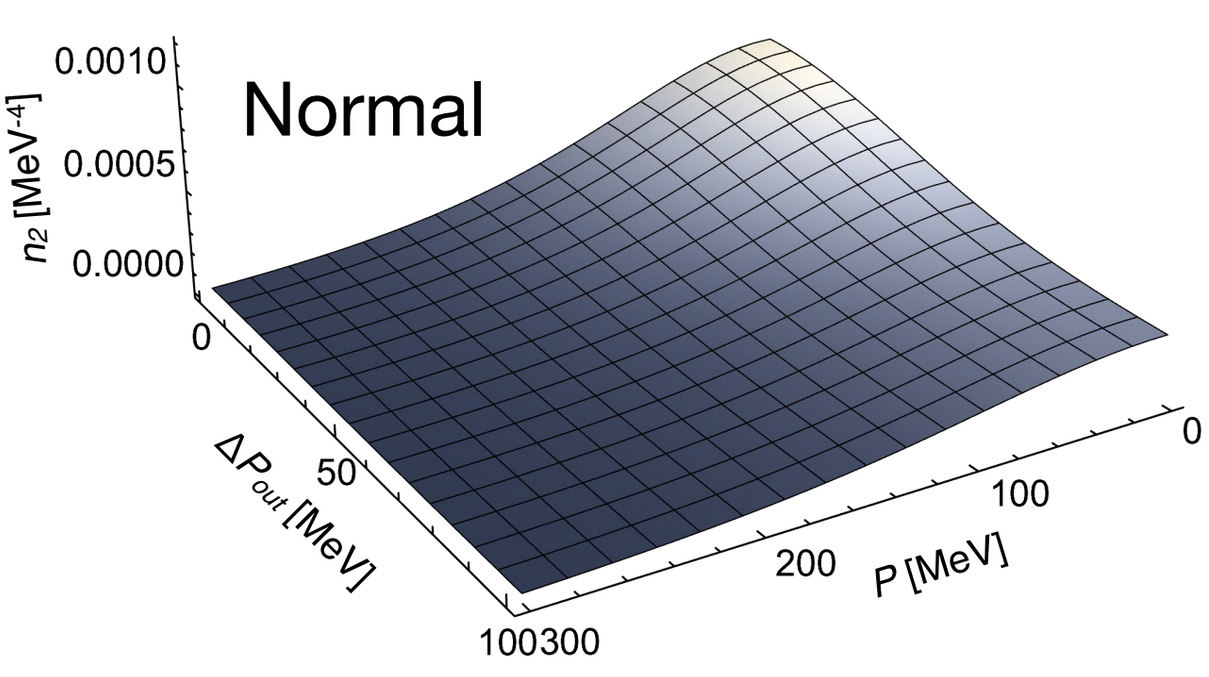
First look on what might be happening in the moat:

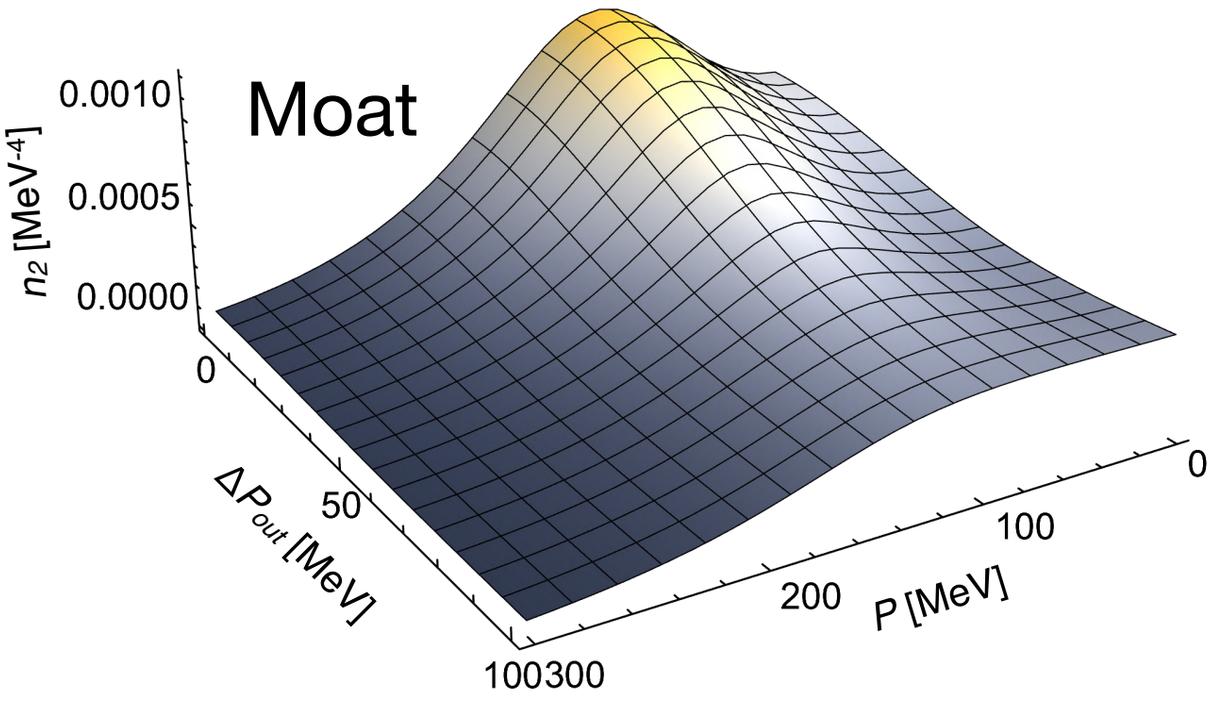
R. D. Pisarski, F. Rennecke, *PRL* 127 (2021), 152302

R. D. Pisarski, F. Rennecke, D. H. Rischke, PRD 107 (2023) 11, 116011

$$C(\mathbf{P}, \Delta\mathbf{P}) = \int_X e^{-i\Delta P \cdot X} f(X, \mathbf{P}) \rho(X, \mathbf{P})$$

Spectral function at finite temperature and density !!!





Outline

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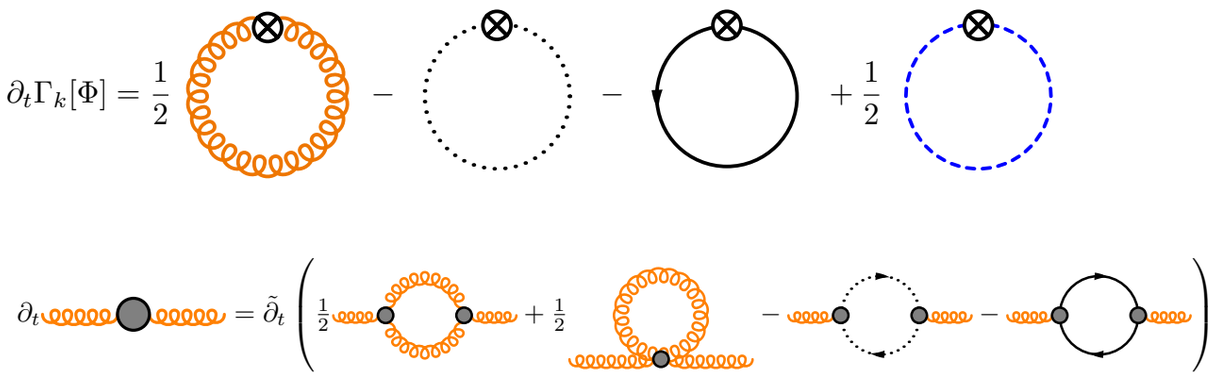
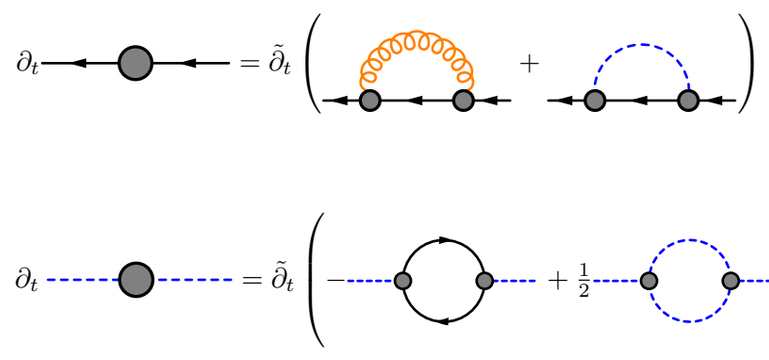
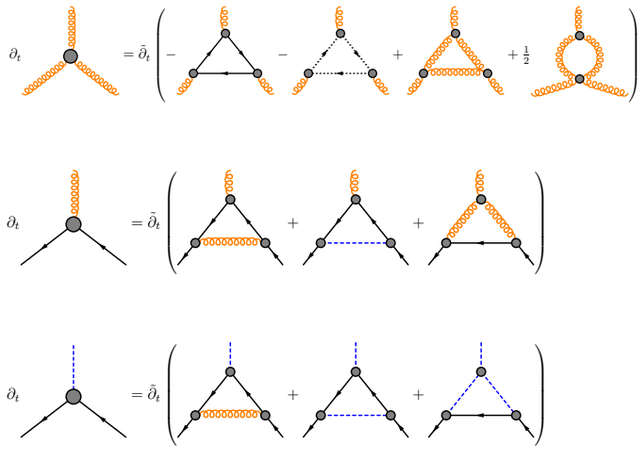
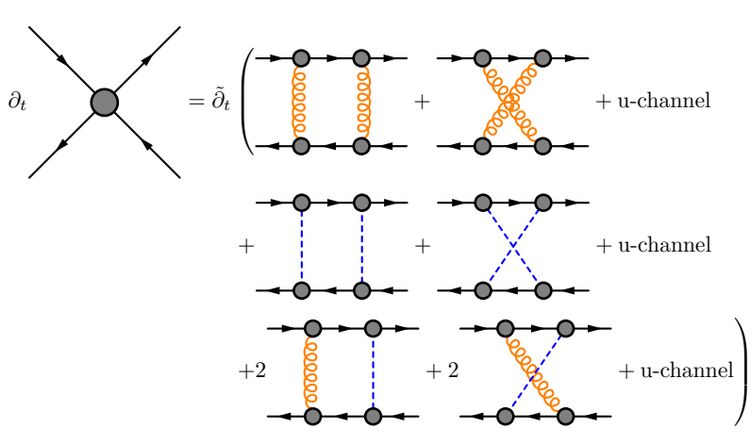
QCD within functional renormalization group

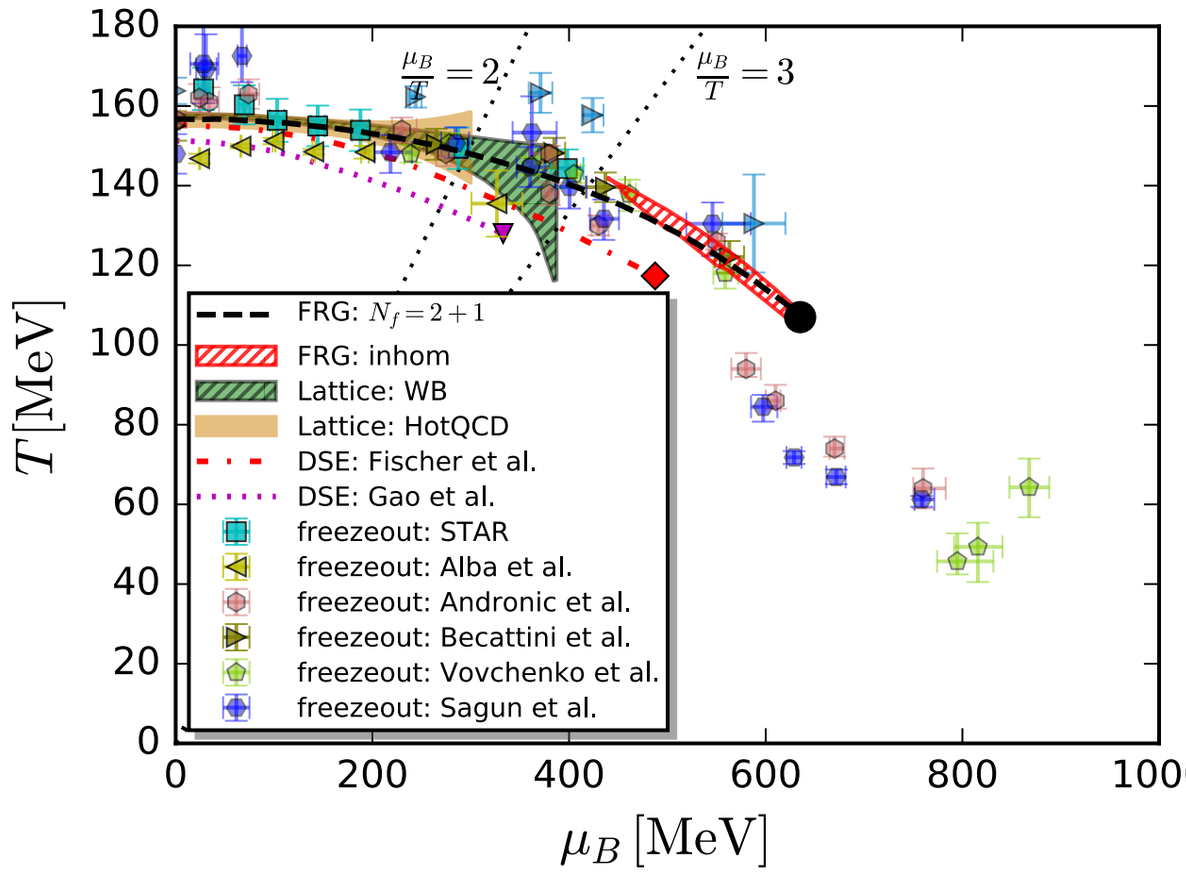
Flow equations of QCD











Critical endpoint

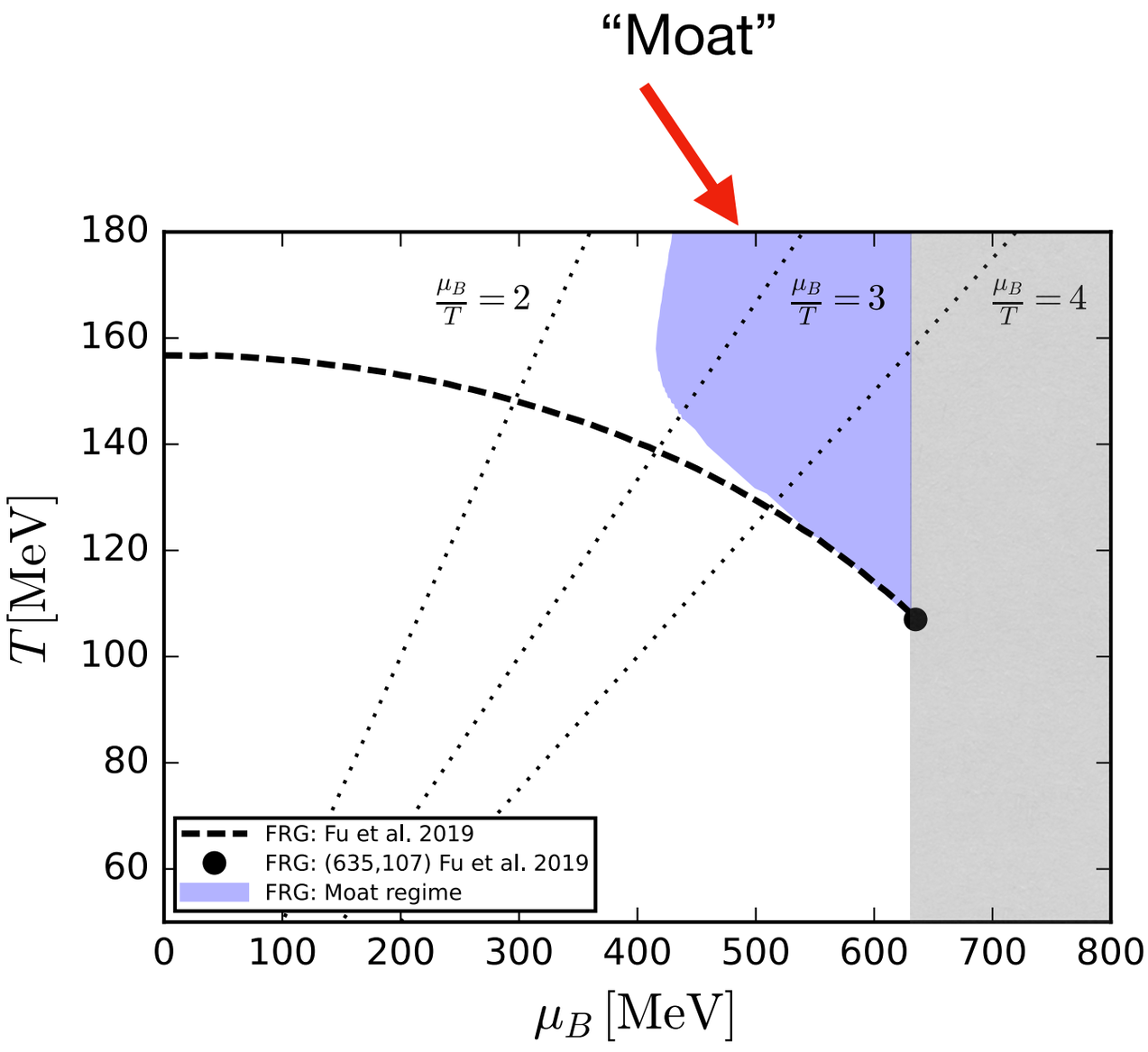
$$(T_{CEP}, \mu_{B_{CEP}}) = (107, 635)\,\mathrm{MeV}$$

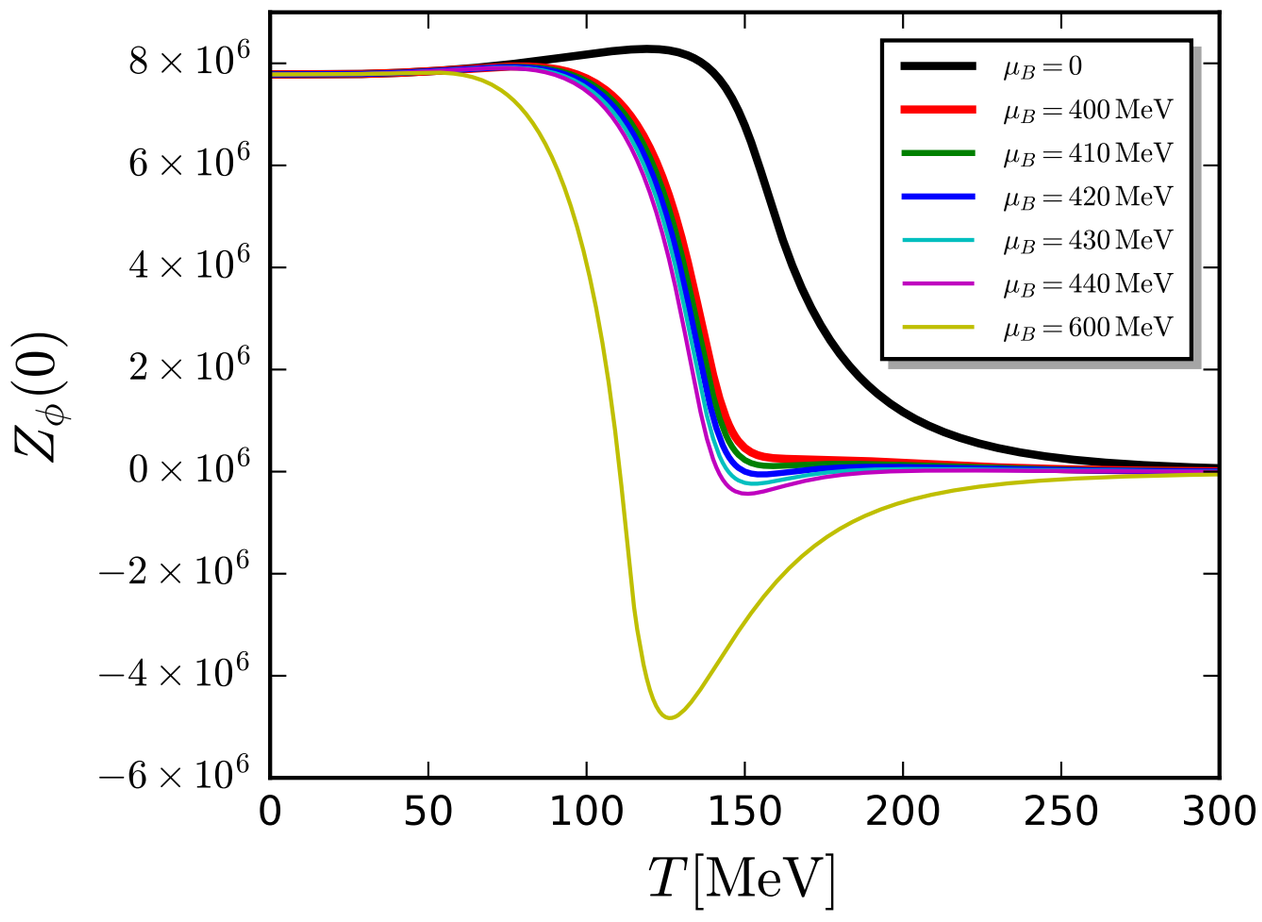
Quantitative improvement on the way !!!

Wei-jie Fu, Jan M. Pawlowski, Fabian Rennecke, *Phys.Rev.D* 101 (2020), 054032

Moat regime in QCD

Negative meson wave function renormalisation



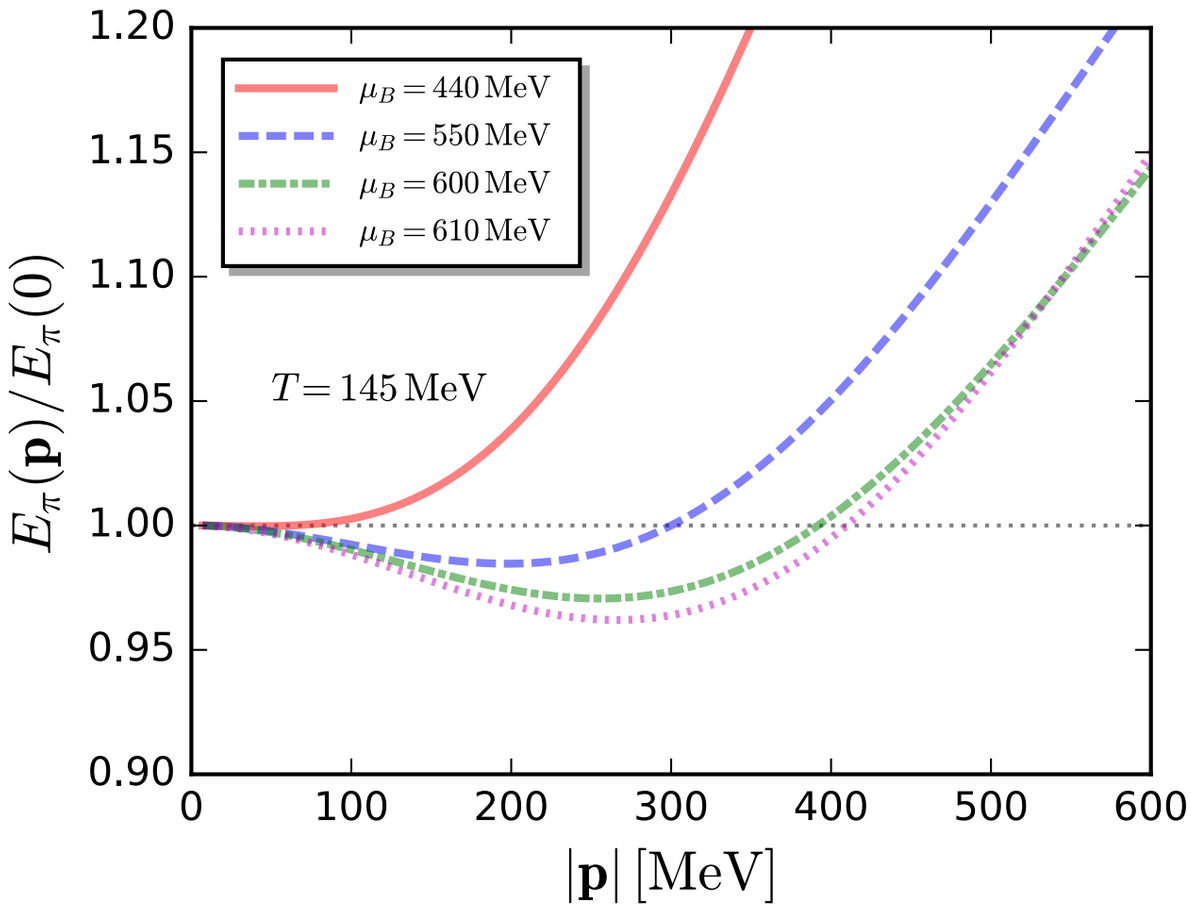


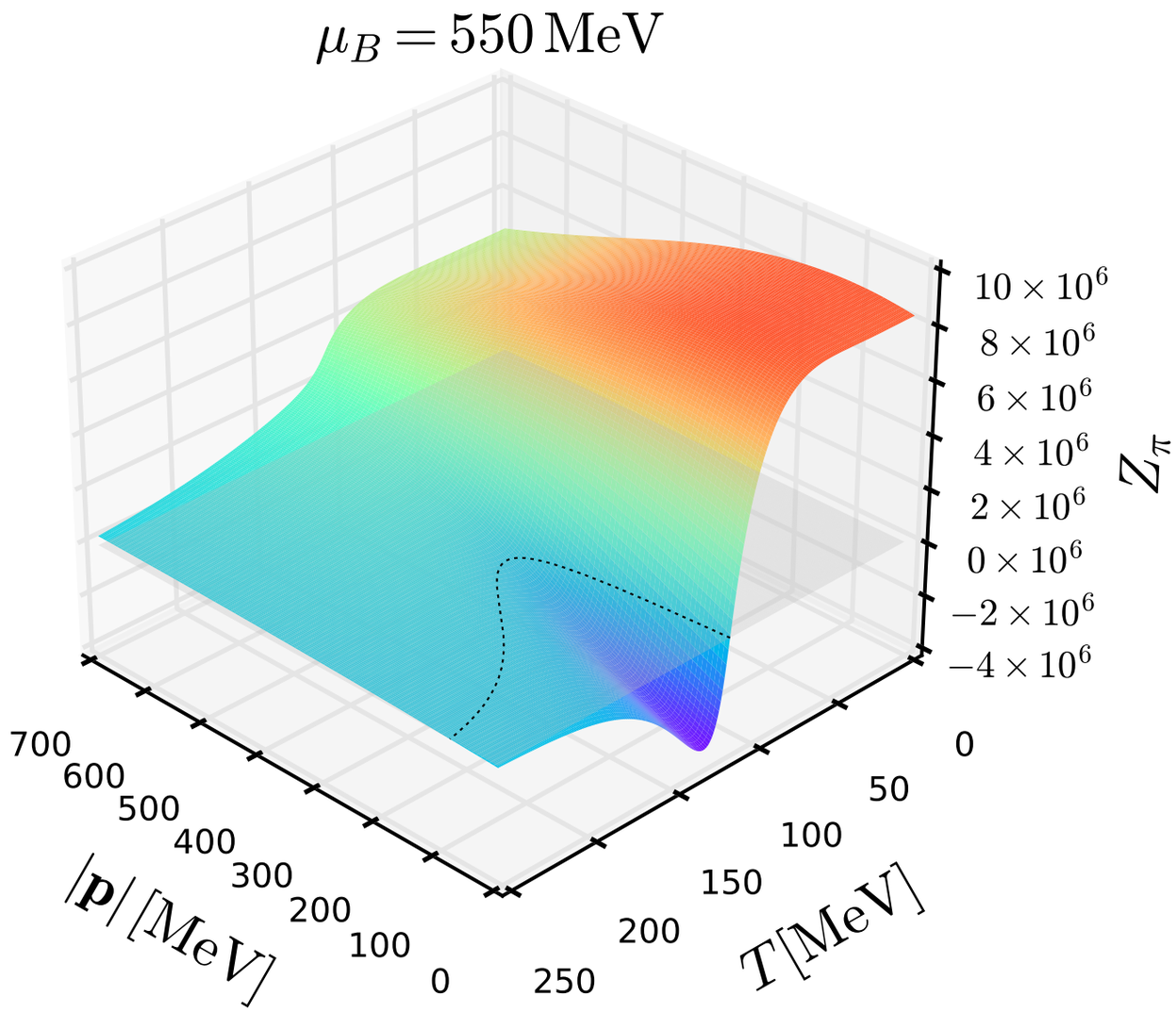
Wei-jie Fu, Jan M. Pawlowski, Fabian Rennecke, *Phys.Rev.D* 101 (2020), 054032

Moat regime in QCD

Dispersion relation

$$E_\pi(\vec{p}) = \sqrt{Z_\pi^\perp(\vec{p})\,\vec{p}^2 + m_\pi^2}$$

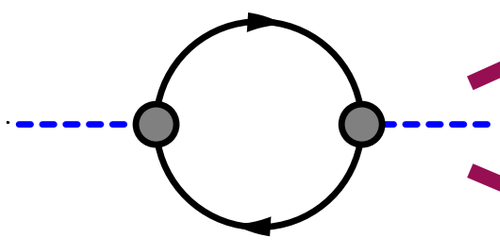




Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

Generation of moat behavior

Quark loop



particle creation and annihilation (C.A.)

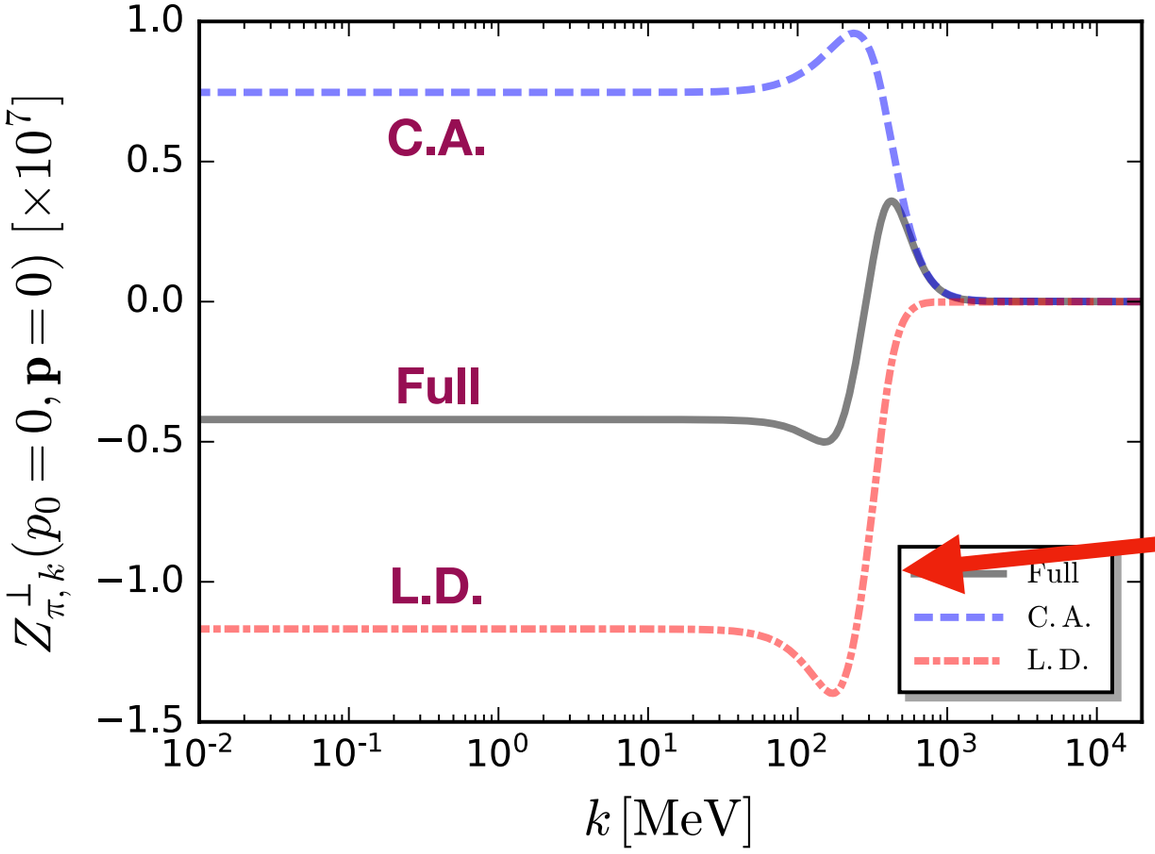
$$\mathcal{FF}^{\mathrm{CA}}_{(1,1)}(p) = \frac{k^3}{4E(|\vec{q}|)E(|\vec{q}-\vec{p}|)}\left\{\frac{1}{ip_0 - E(|\vec{q}|) - E(|\vec{q}-\vec{p}|)}\left[-1 + n_F\big(E(|\vec{q}|);T,\mu\big) + n_F\big(E(|\vec{q}-\vec{p}|);T,-\mu\big)\right]\right.$$

$$\left. + \frac{1}{ip_0 + E(|\vec{q}|) + E(|\vec{q}-\vec{p}|)}\left[1 - n_F(E(|\vec{q}|);T,\mu) - n_F(E(|\vec{q}-\vec{p}|);T,-\mu)\right]\right\}.$$

$$\mathcal{FF}^{\mathrm{LD}}_{(1,1)}(p) = \frac{k^3}{4E(|\vec{q}|)E(|\vec{q}-\vec{p}|)}\left\{\frac{1}{ip_0 - E(|\vec{q}|) + E(|\vec{q}-\vec{p}|)}\left[-n_F\big(E(|\vec{q}|);T,-\mu\big) + n_F\big(E(|\vec{q}-\vec{p}|);T,-\mu\big)\right]\right.$$

$$\left. + \frac{1}{ip_0 + E(|\vec{q}|) - E(|\vec{q}-\vec{p}|)}\left[n_F\big(E(|\vec{q}|);T,\mu\big) - n_F\big(E(|\vec{q}-\vec{p}|);T,\mu\big)\right]\right\}.$$

Landau damping (L.D.)



The negative meson wave function renormalisation is caused by Landau damping

Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

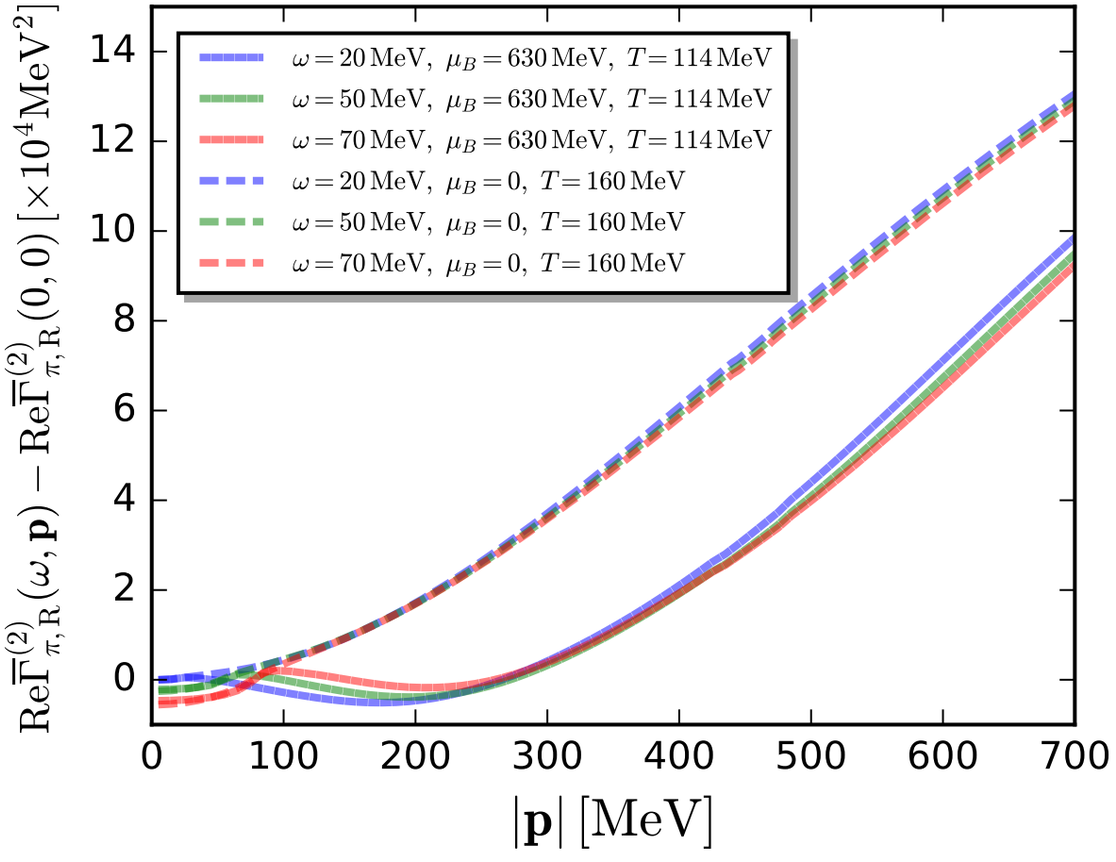
Pion spectral function

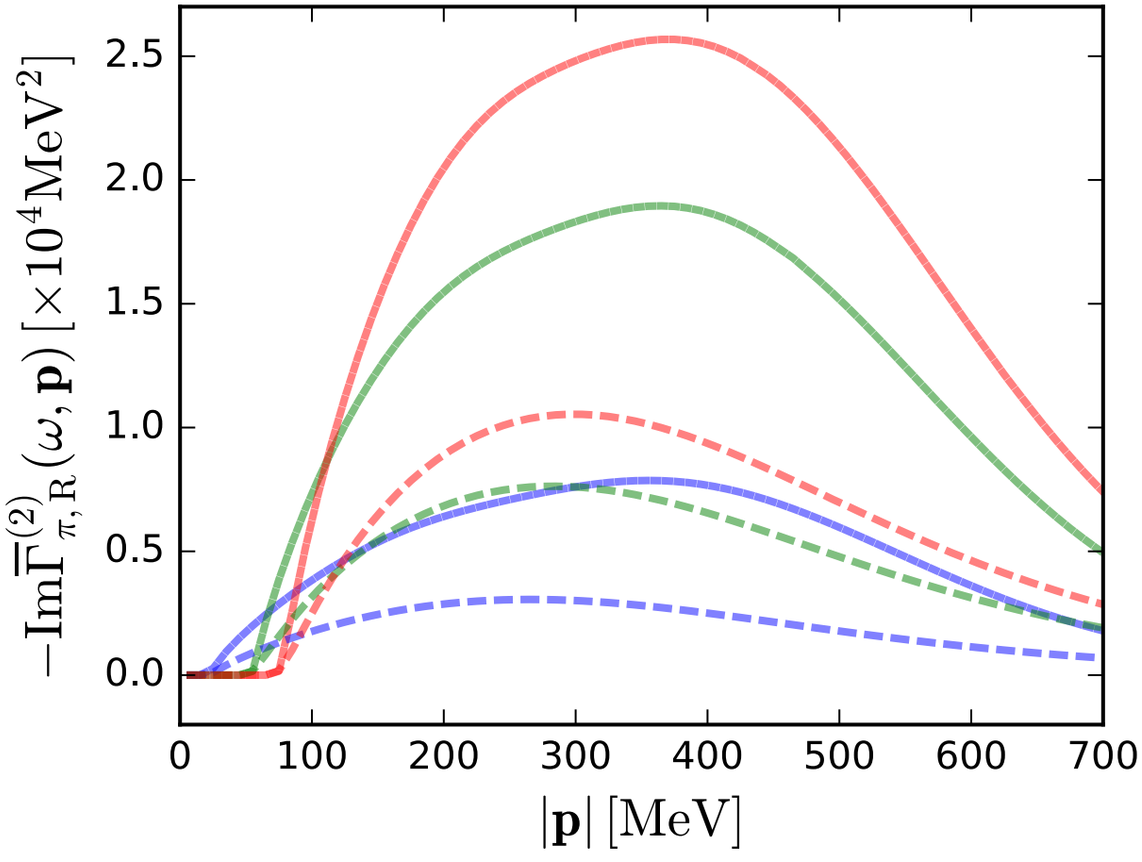
Analytical continuation $p_0 \to -i(\omega + i\epsilon)$ $\quad \Gamma^{(2)}_{\phi\phi,\mathrm{R}}(\omega,\vec{p}) = \lim_{\epsilon\to 0^+} \Gamma^{(2)}_{\phi\phi}\big(-\mathrm{i}(\omega+\mathrm{i}\epsilon),\vec{p}\big)$

$$\mathrm{Re}\Gamma^{(2)}_{\pi}(\omega,\mathbf{p}) = \mathrm{Re}\big(-Z^{\parallel}_{\pi}(\omega,\mathbf{p})\omega^2 + Z^{\perp}_{\pi}(\omega,\mathbf{p})\mathbf{p}^2\big) + m^2_{\pi}$$

$$\mathrm{Im}\Gamma^{(2)}_{\pi}(\omega,\mathbf{p}) = \mathrm{Im}\big(-Z^{\parallel}_{\pi}(\omega,\mathbf{p})\omega^2 + Z^{\perp}_{\pi}(\omega,\mathbf{p})\mathbf{p}^2\big)$$

$$\rho_{\phi}(\omega,\boldsymbol{p}) = -\frac{1}{\pi}\frac{\mathrm{Im}\Gamma^{(2)}_{\phi\phi,\mathrm{R}}(\omega,\boldsymbol{p})}{\big(\mathrm{Re}\Gamma^{(2)}_{\phi\phi,\mathrm{R}}(\omega,\boldsymbol{p})\big)^2 + \big(\mathrm{Im}\Gamma^{(2)}_{\phi\phi,\mathrm{R}}(\omega,\boldsymbol{p})\big)^2}$$

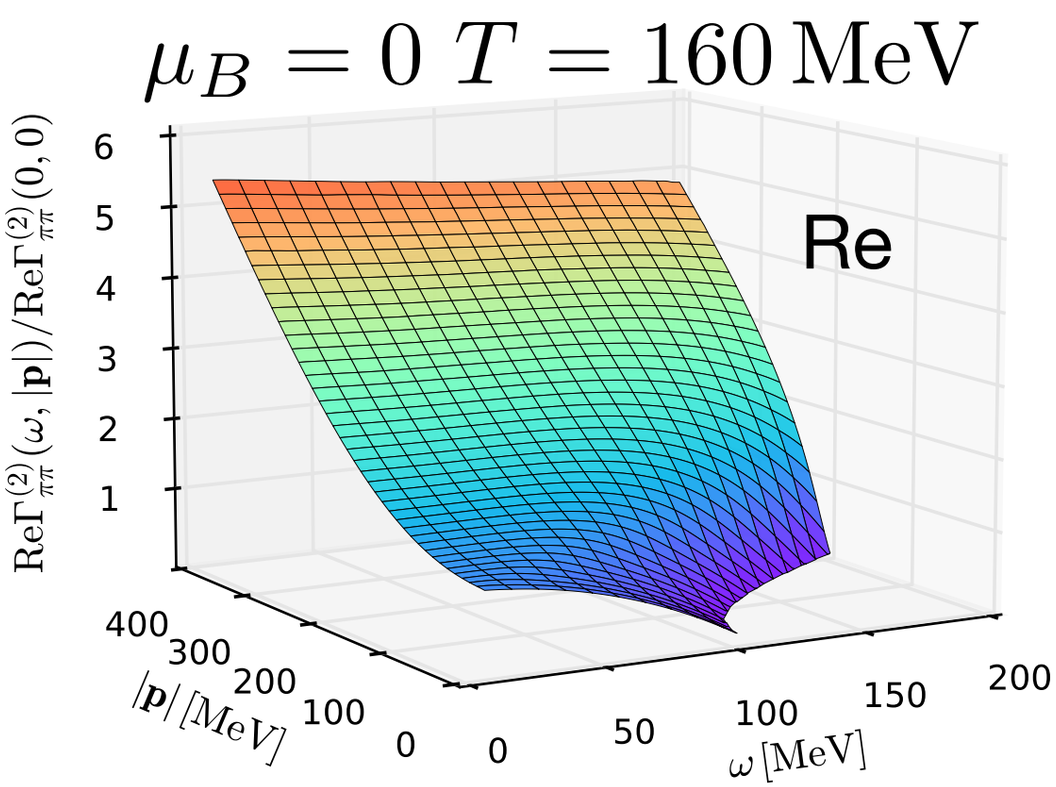


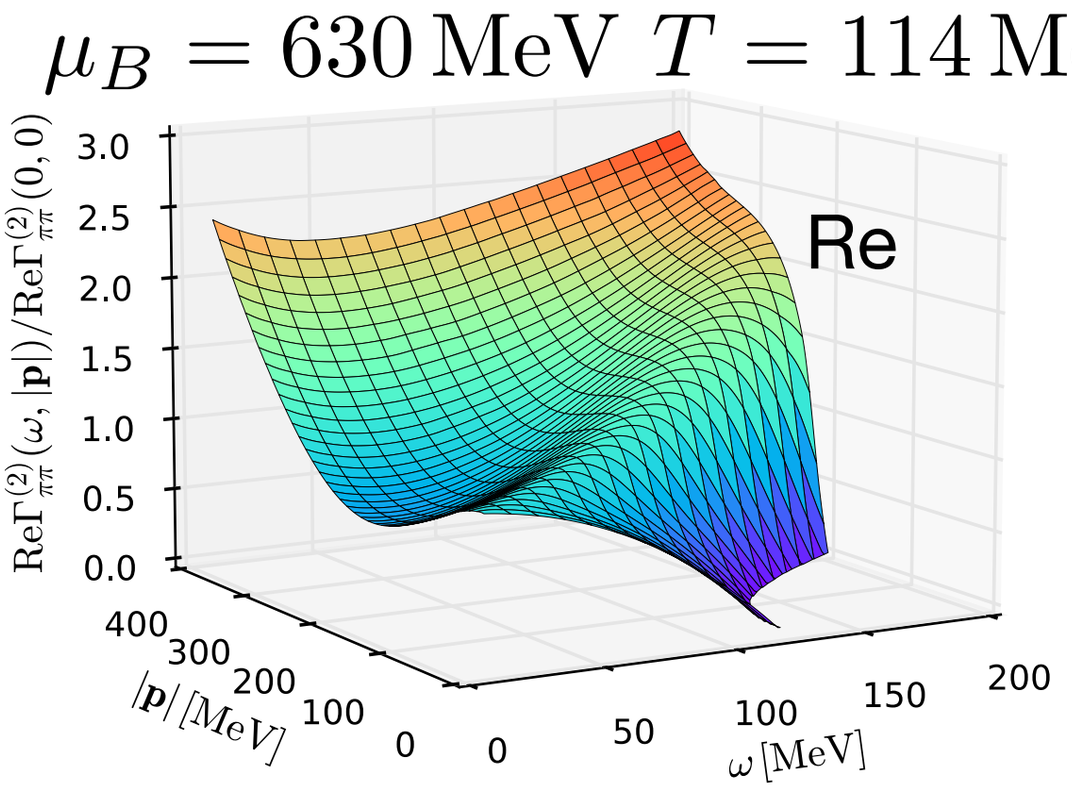


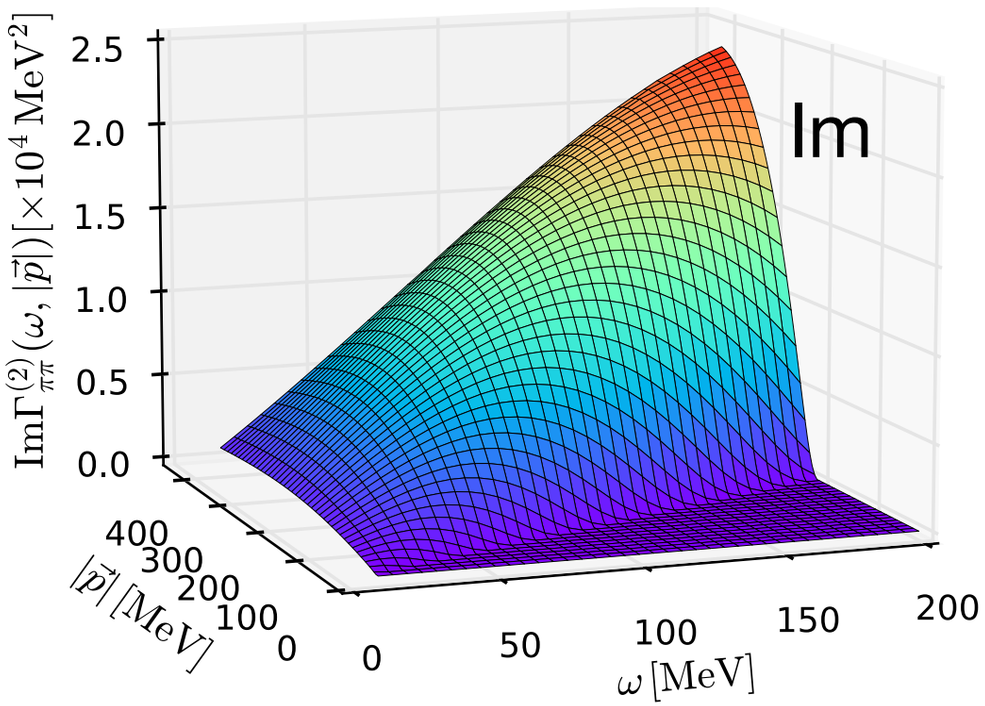
Moat effect is in the space-like regime

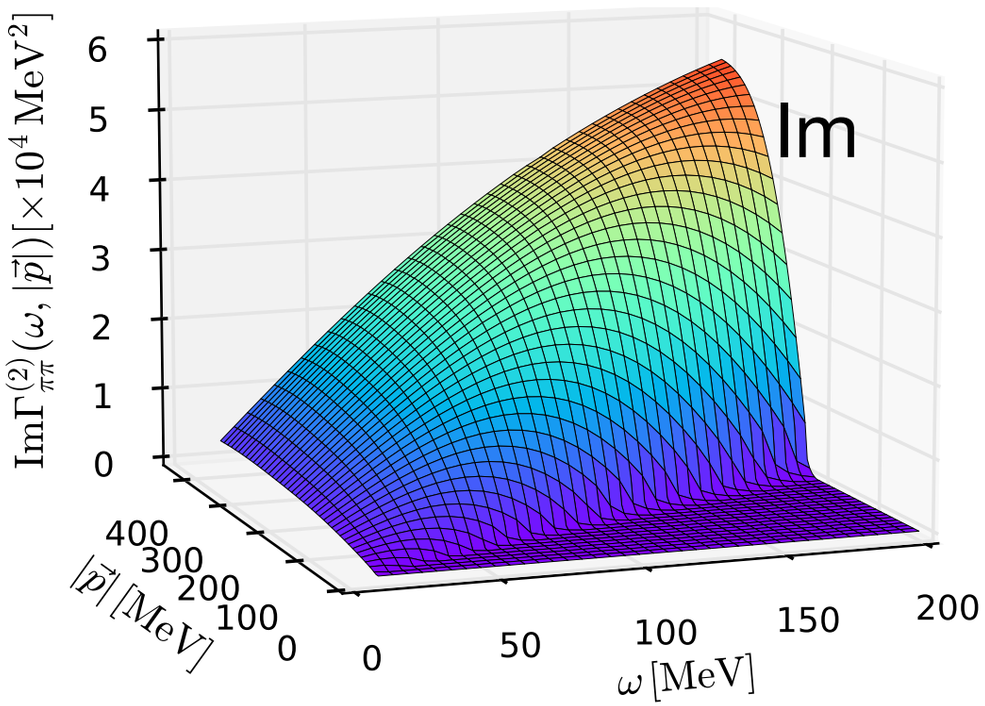
Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

Real part and Imaginary part









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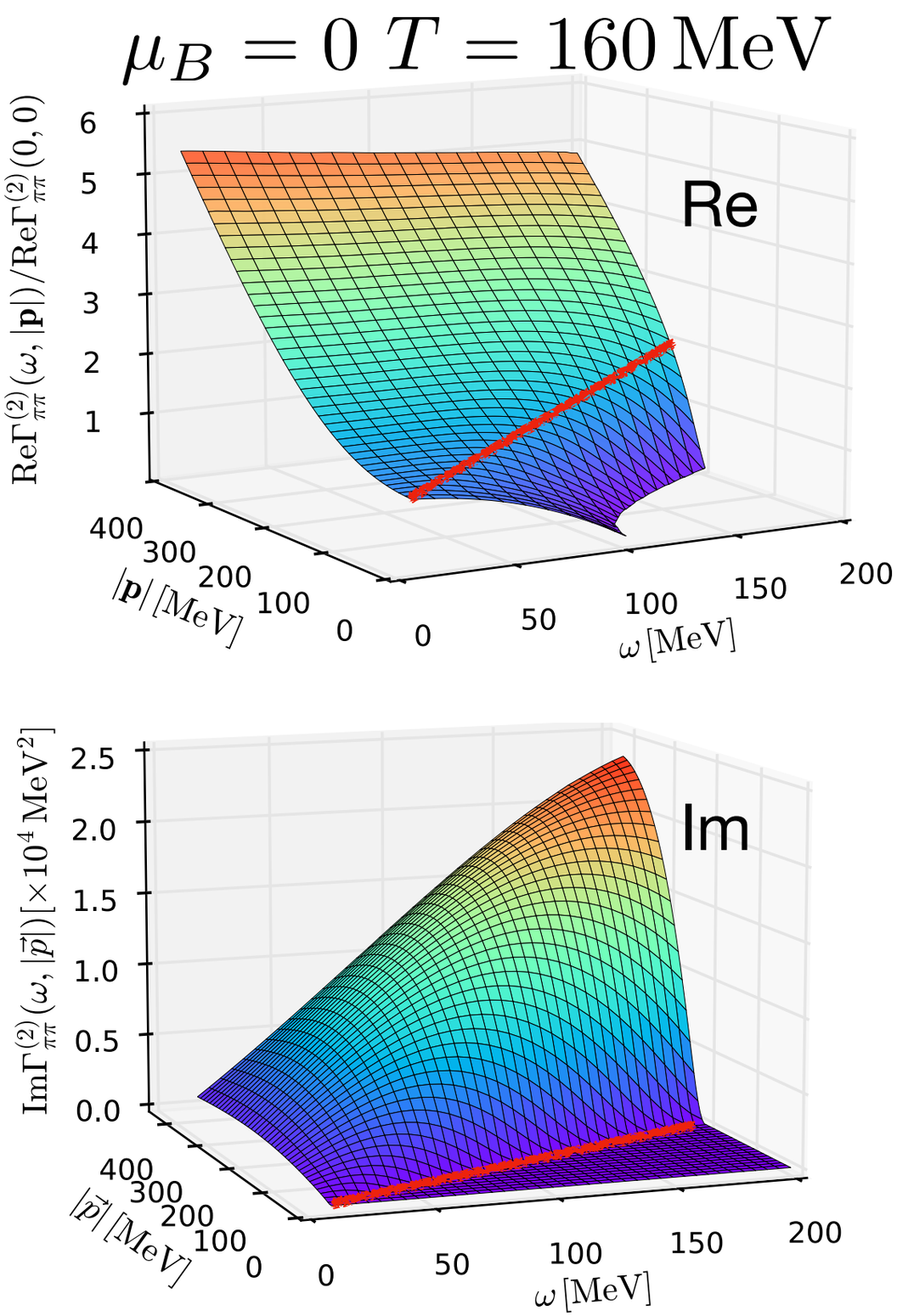
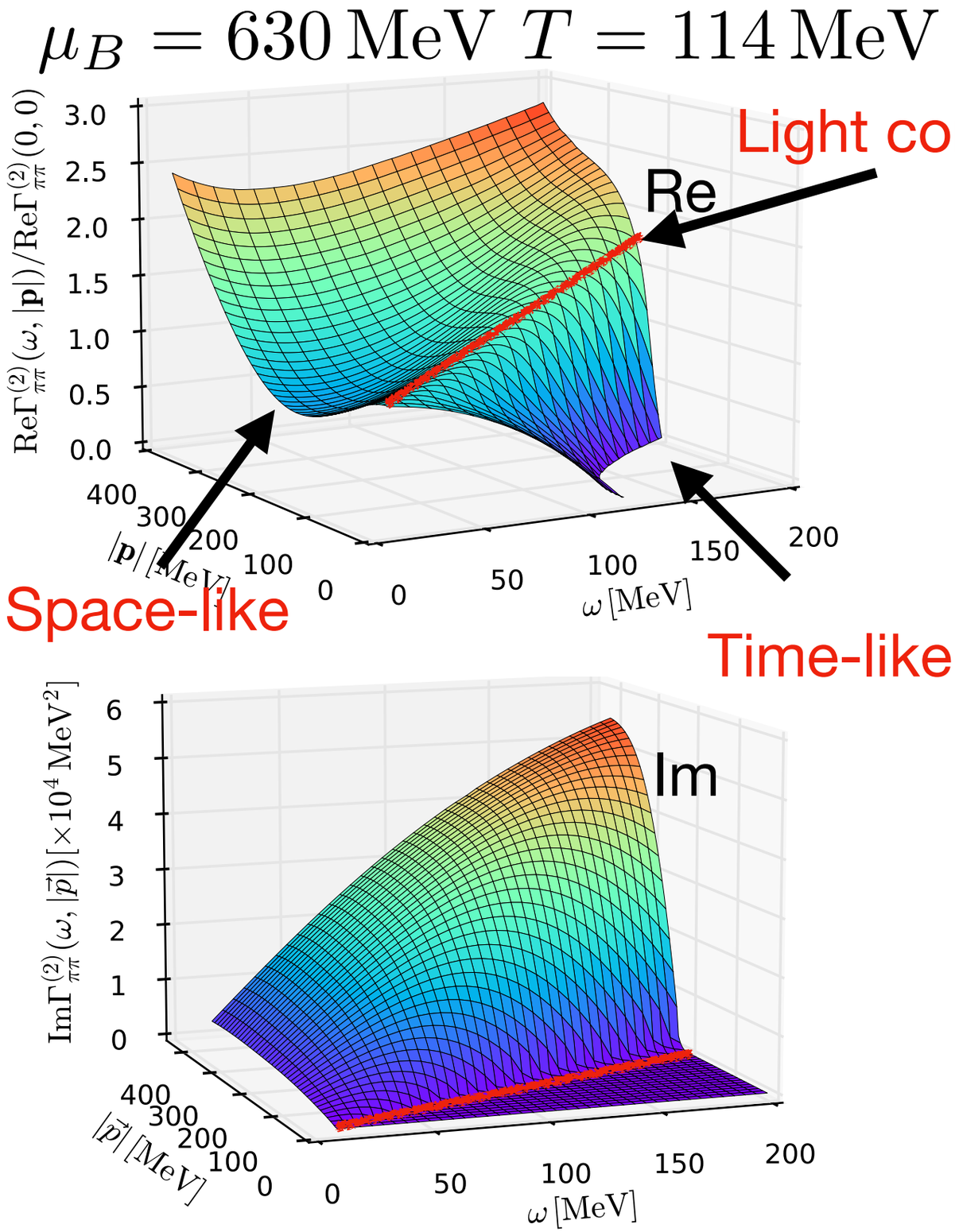
Real part and Imaginary part

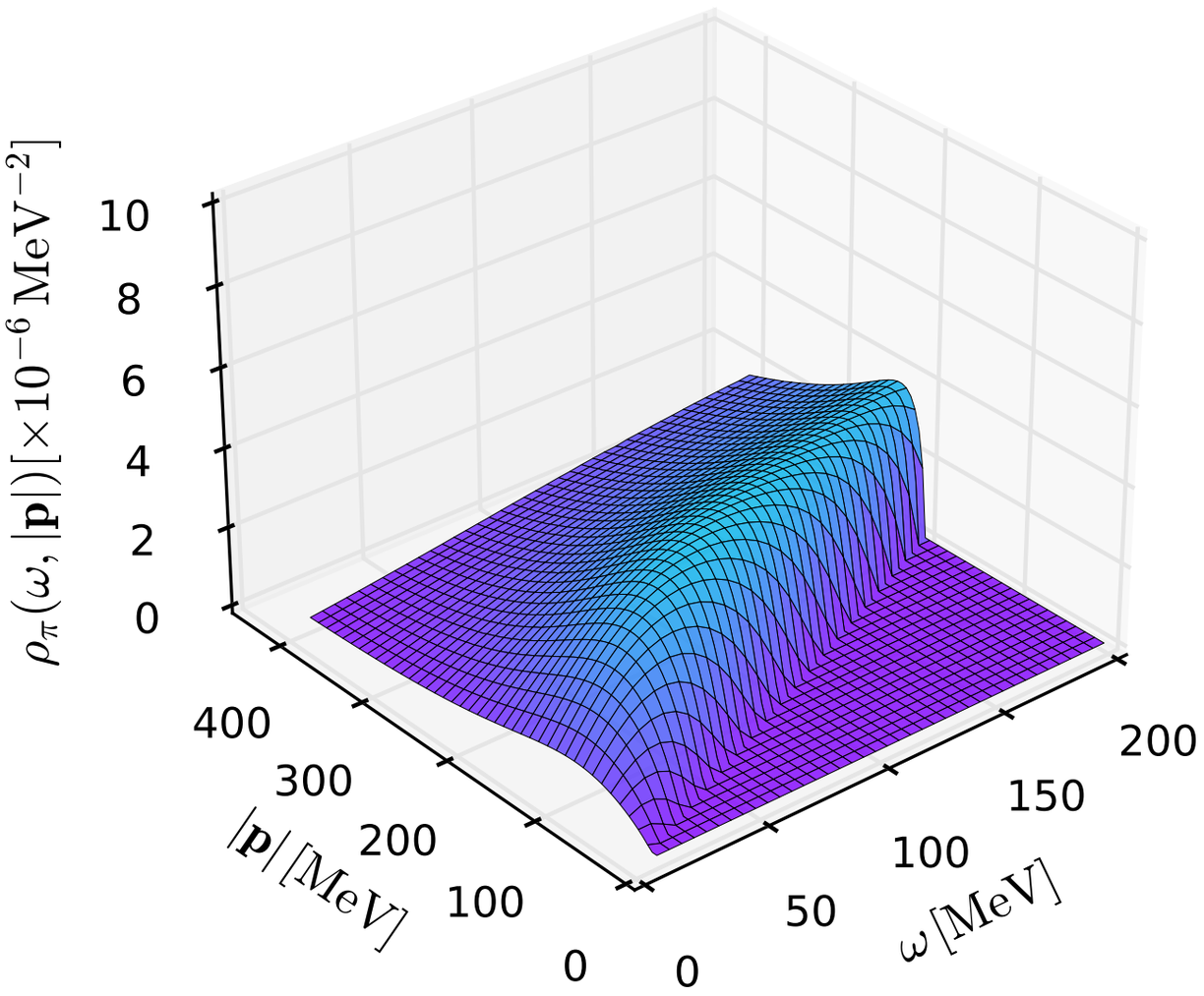




Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

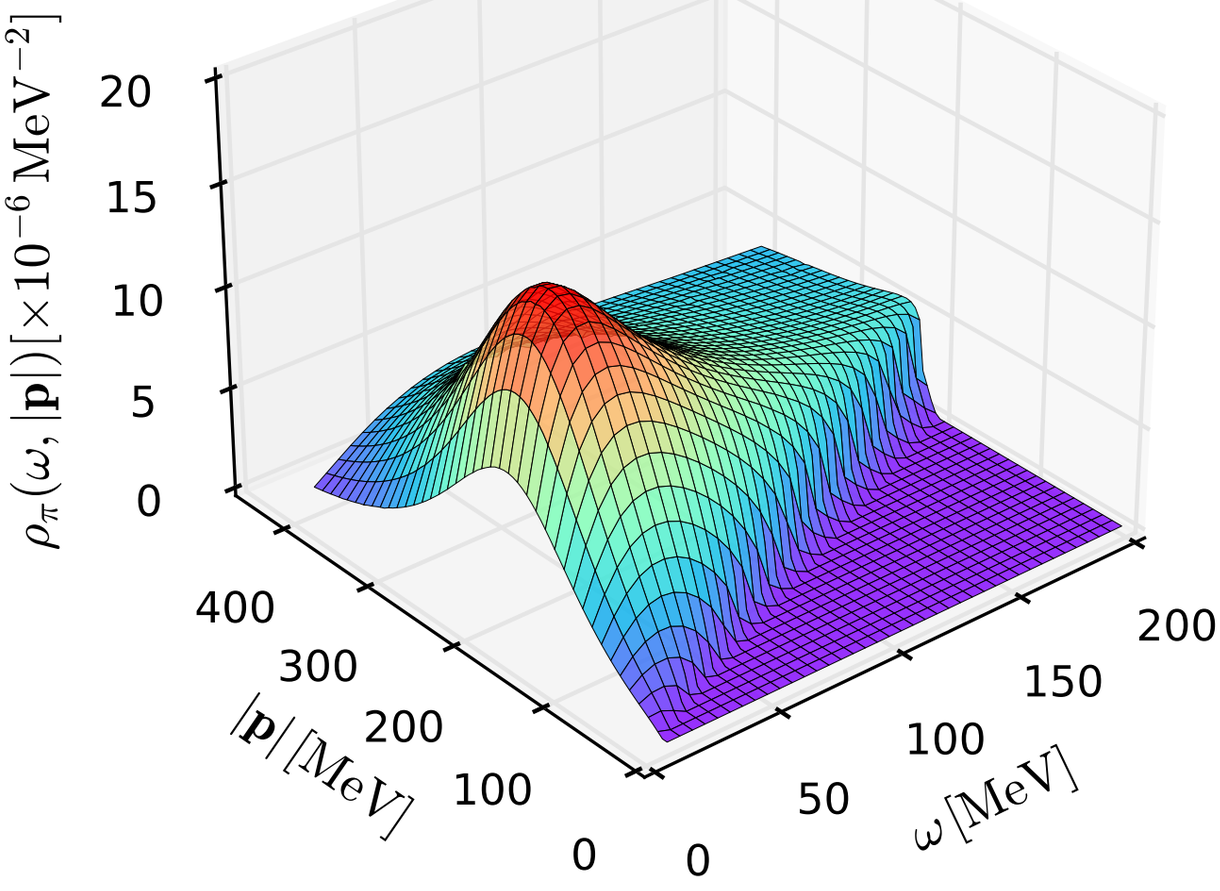
Pion spectral function

$\mu_B = 0\ T = 160\,\mathrm{MeV}$



Competition between real-part and Imaginary part

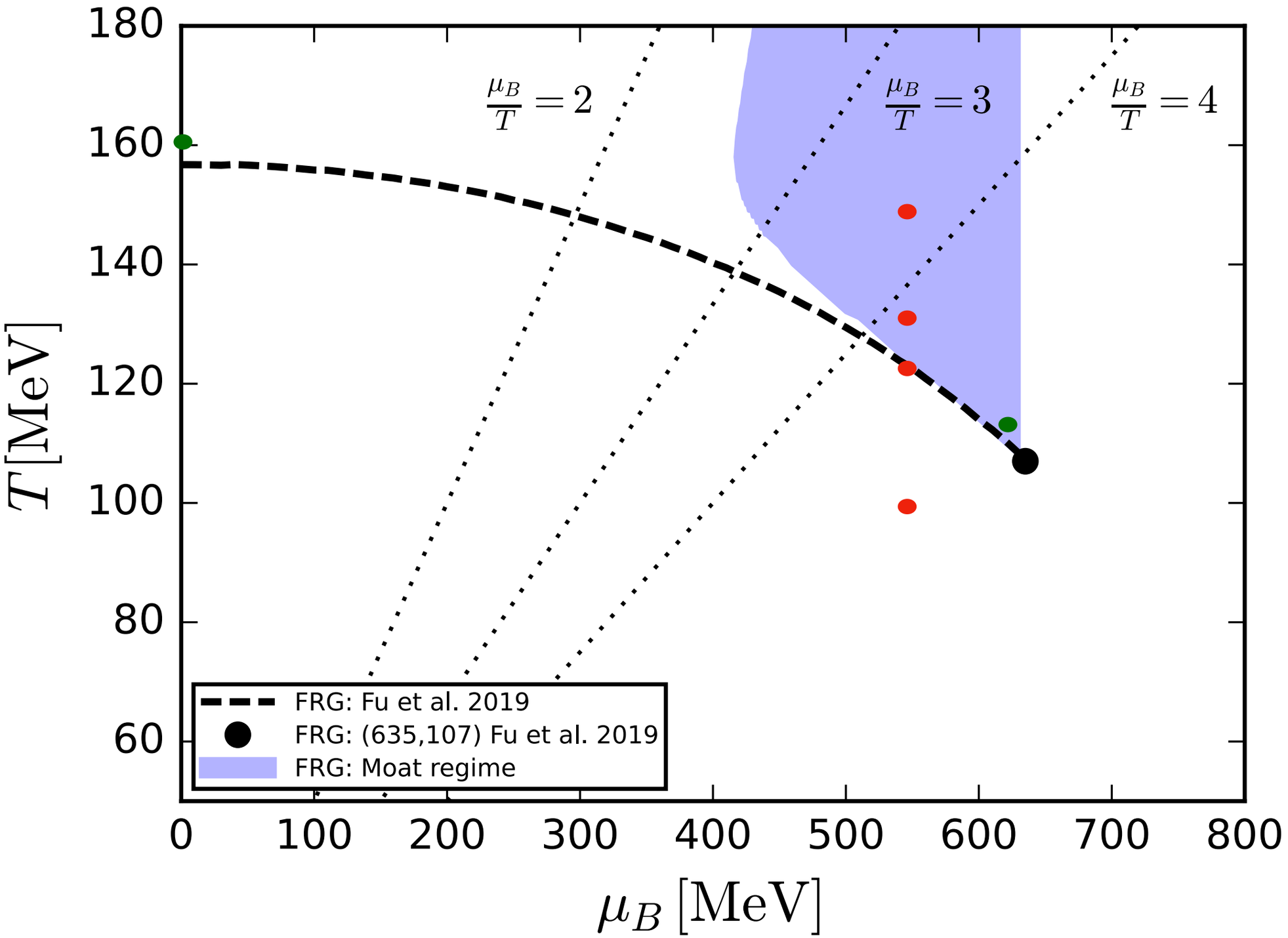
$\mu_B = 630\,\mathrm{MeV}\ T = 114\,\mathrm{MeV}$



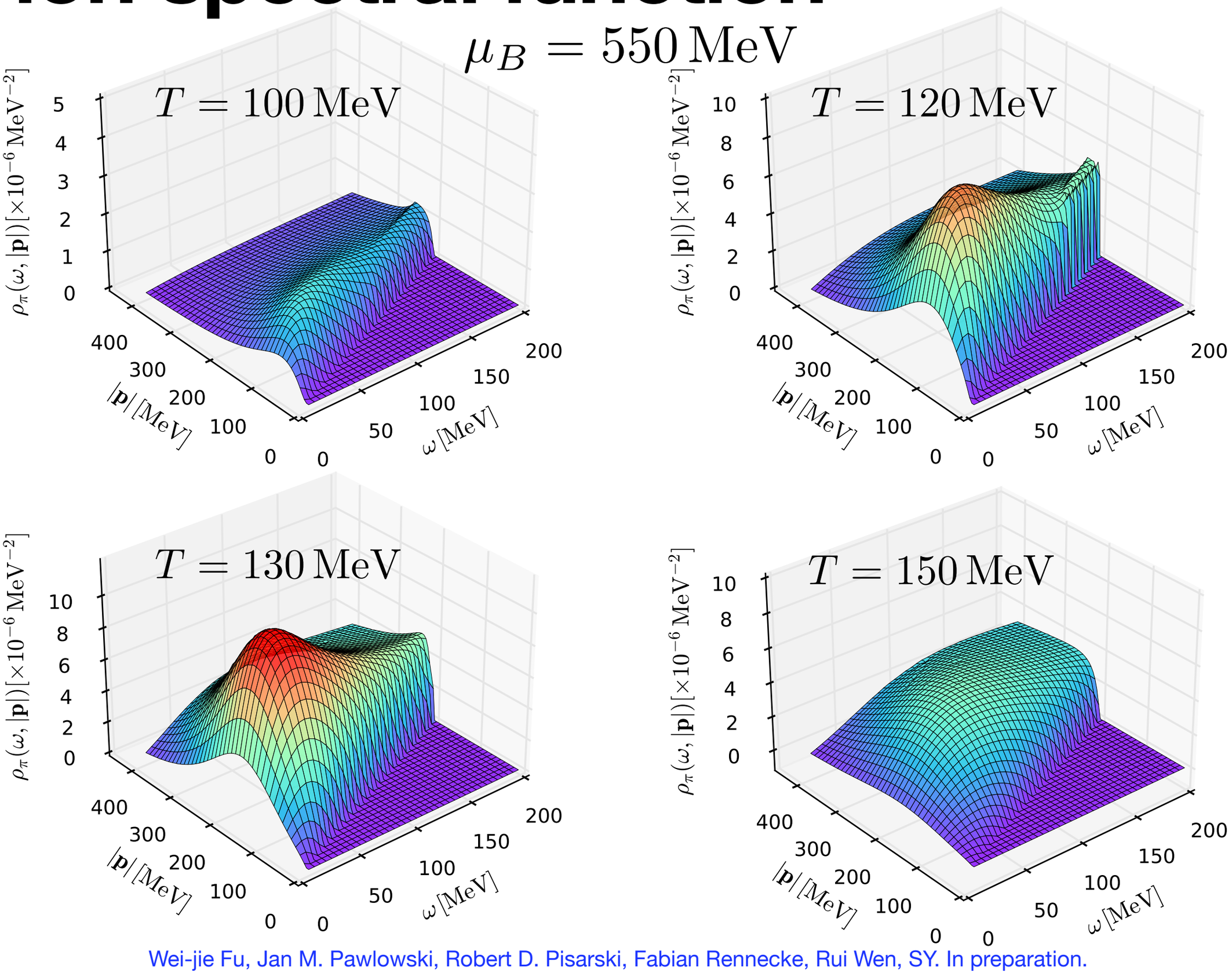
Moat peak

Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

Moat regime


$\frac{\mu_B}{T} = 2$
$\frac{\mu_B}{T} = 3$
$\frac{\mu_B}{T} = 4$
FRG: Fu et al. 2019
FRG: (635,107) Fu et al. 2019
FRG: Moat regime
$T\,[\mathrm{MeV}]$
$\mu_B\,[\mathrm{MeV}]$
180
160
140
120
100
80
60
0
100
200
300
400
500
600
700
800

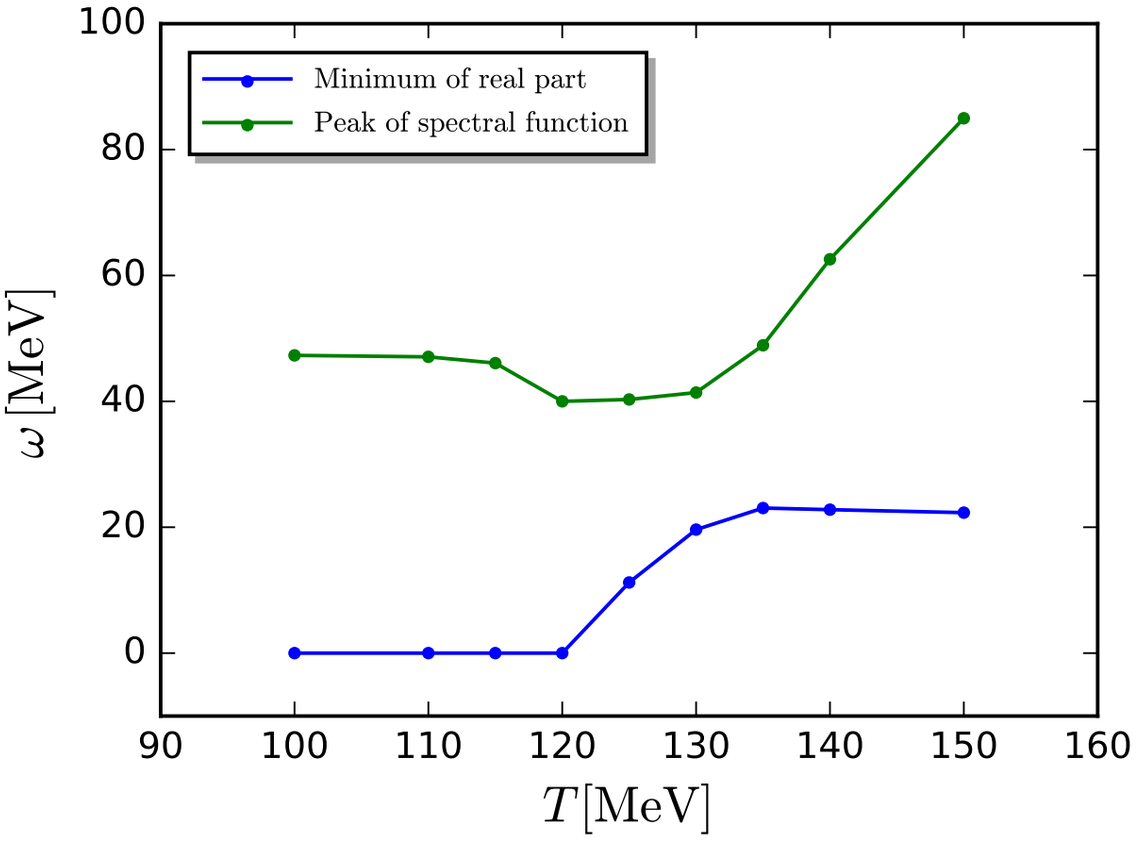
Pion spectral function

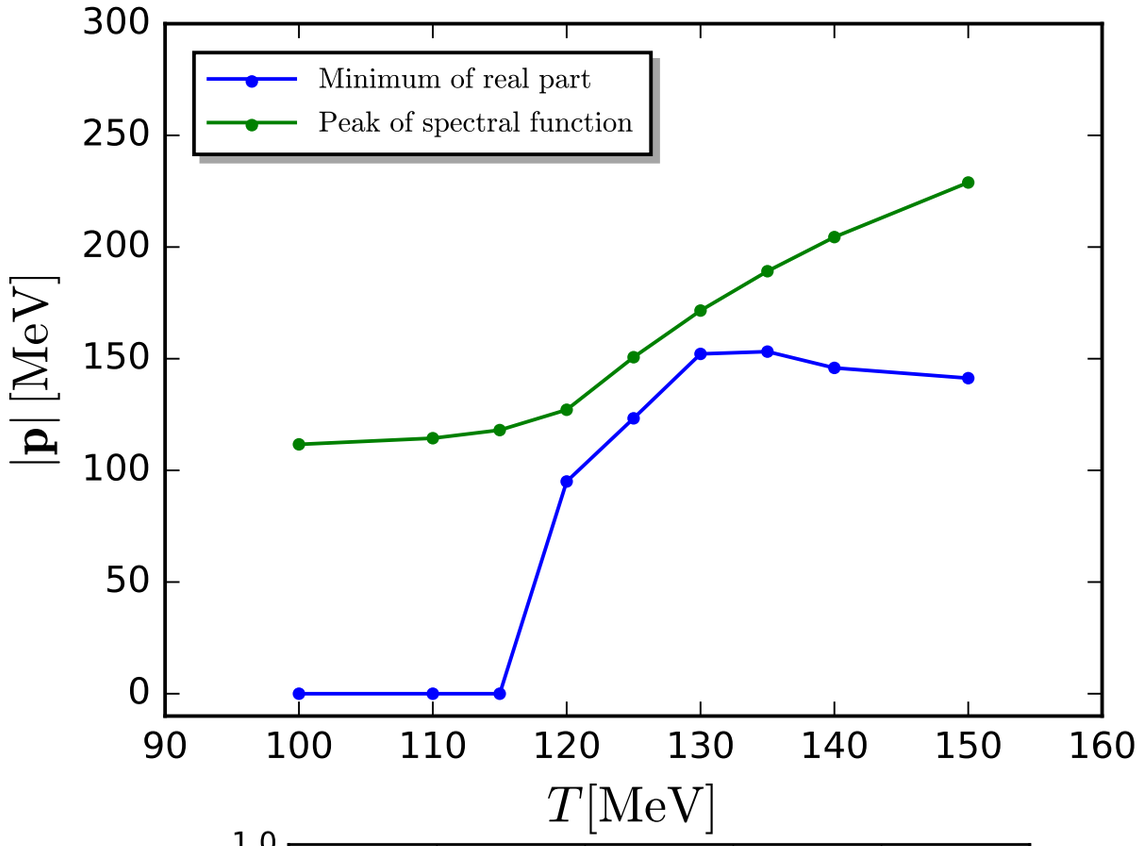


Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

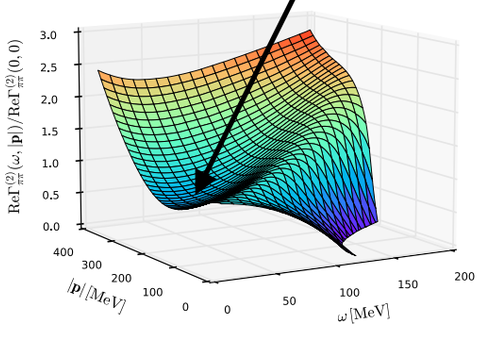
Minimum of Real-part and peak of spectral function

$$\mu_B = 550\,\mathrm{MeV}$$

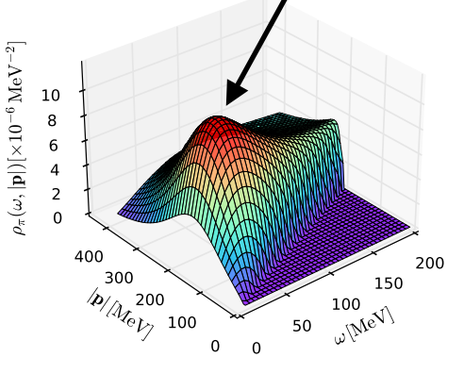


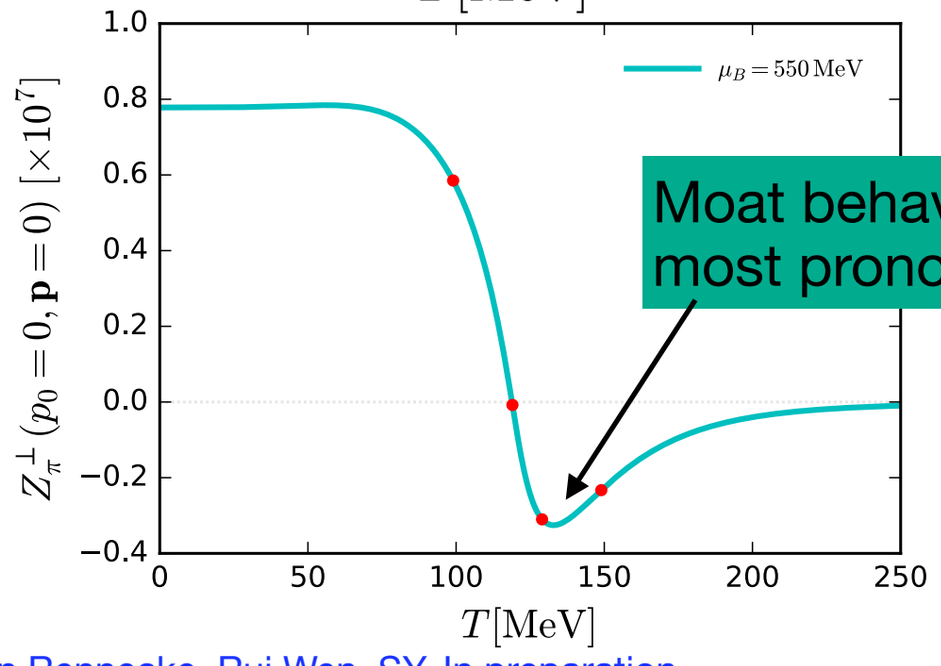


Minimum point



Peak



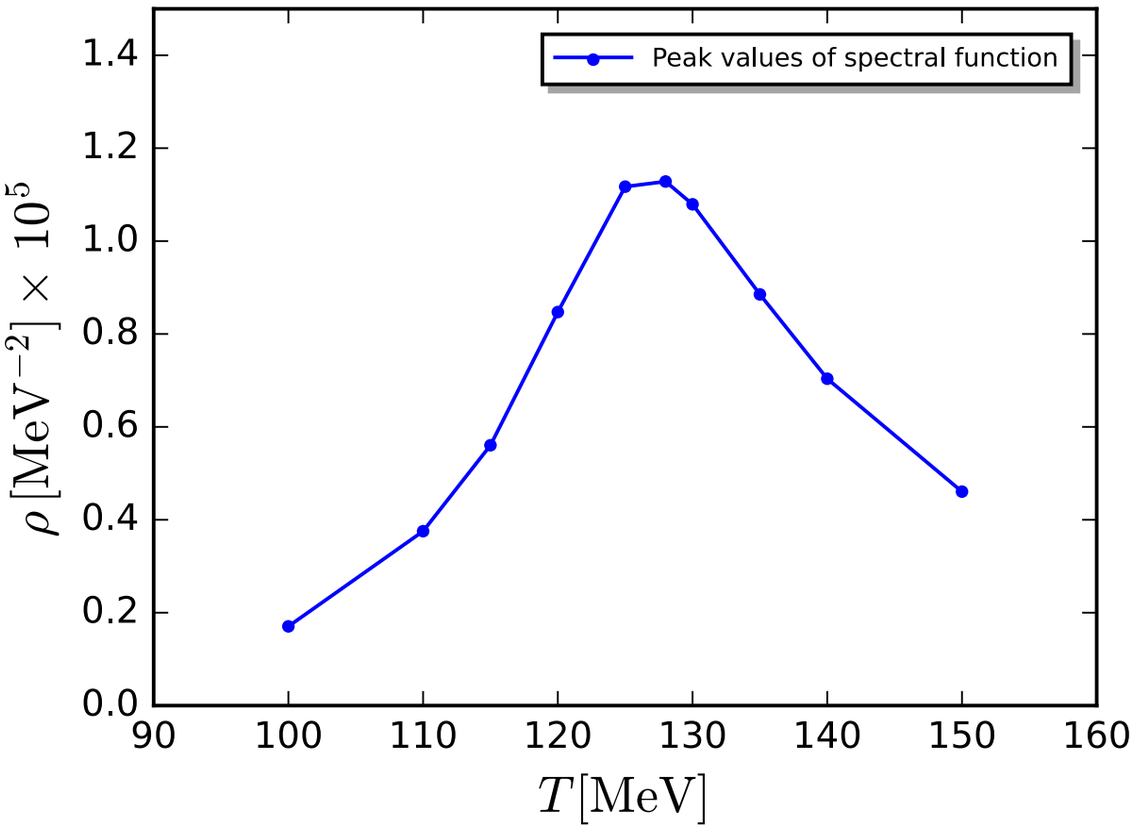


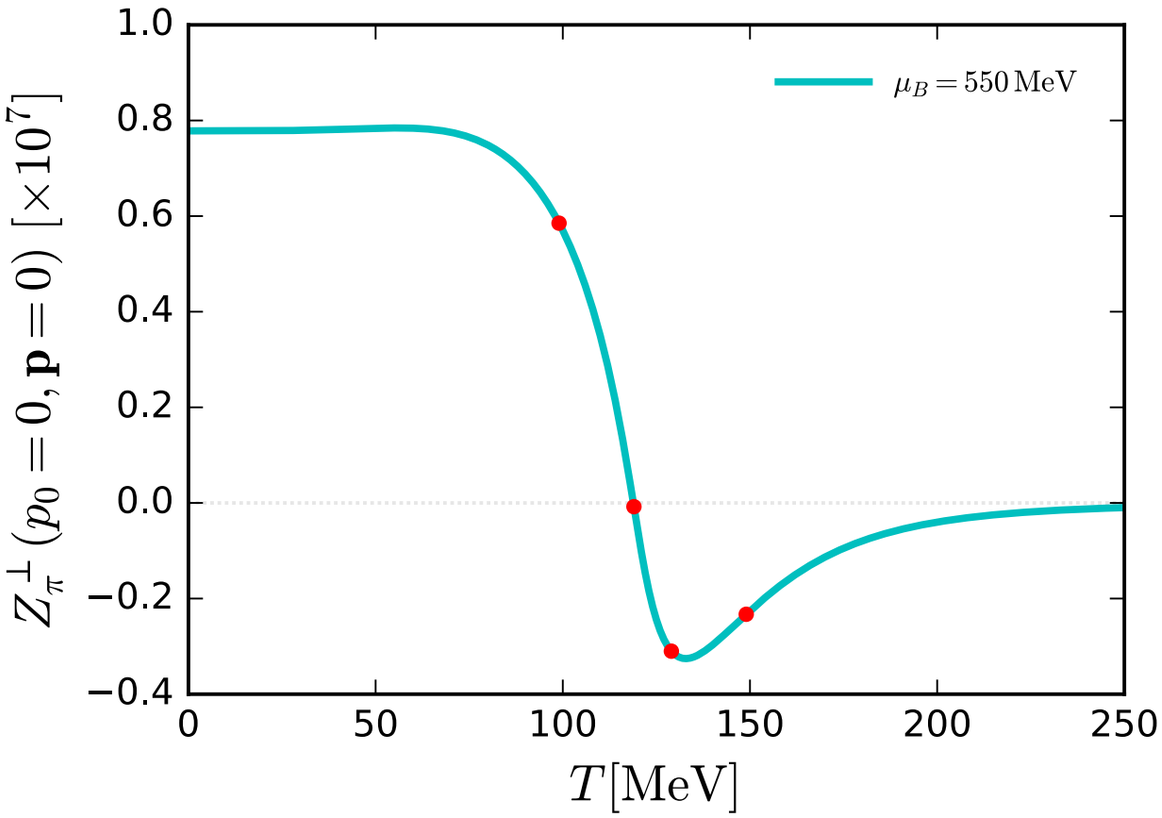
Moat behavior is most pronounced

Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

Peak height of spectral function

$$\mu_B = 550\,\mathrm{MeV}$$





Wei-jie Fu, Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, SY. In preparation.

Outline

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- Moat regime in QCD
- Summary and outlook

Summary and outlook

- Moat behavior is found in medium density area.
- Moat is generated by Landau damping in quark loop.
- Moat exists in the space-like region of the spectral function.
- Moat will enhance the peak of the spectral function in the space-like region.

- Study the influence of moat on experimental observables.

Summary and outlook

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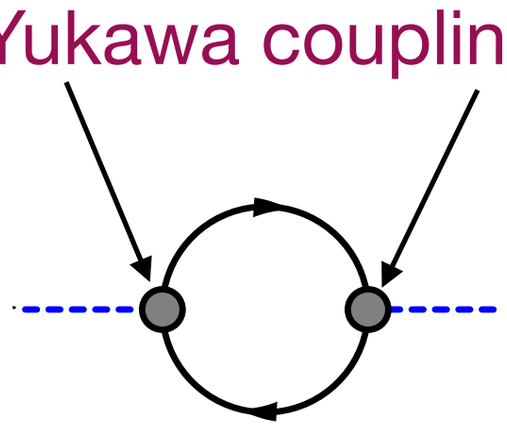
- Moat is generated by Landau damping in quark loop.
- Moat exists in the space-like region of the spectral function.
- Moat will enhance the peak of the spectral function in the space-like region.

- Study the influence of moat on experimental observables.

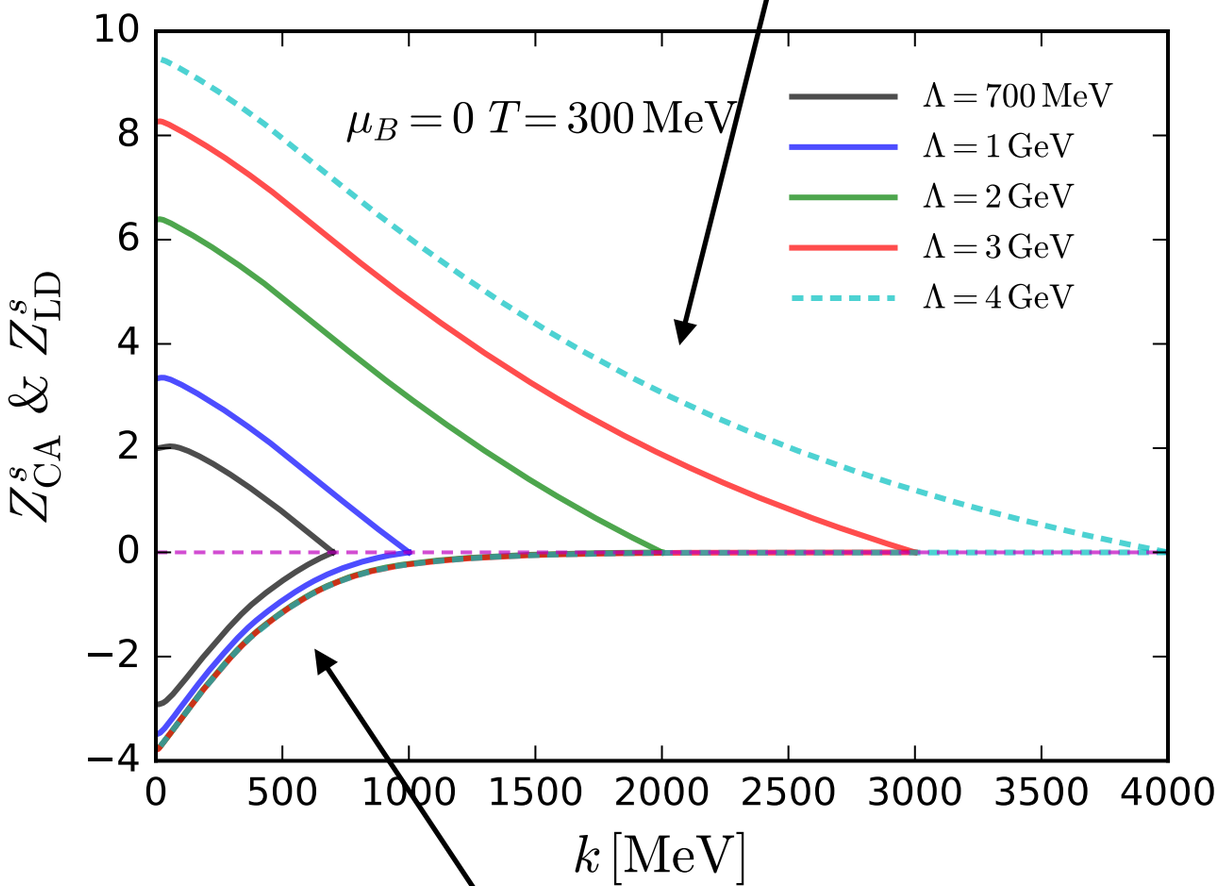
Thank you !!!

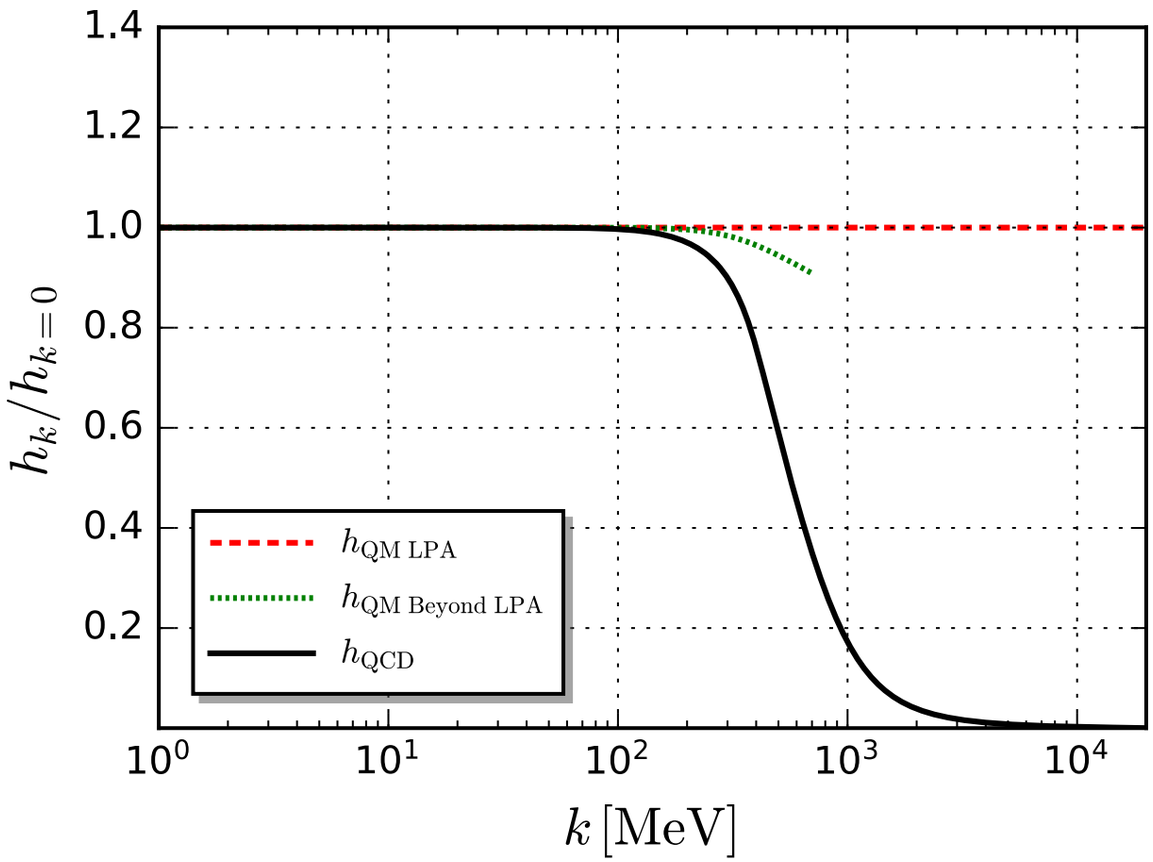
Back up

Yukawa coupling



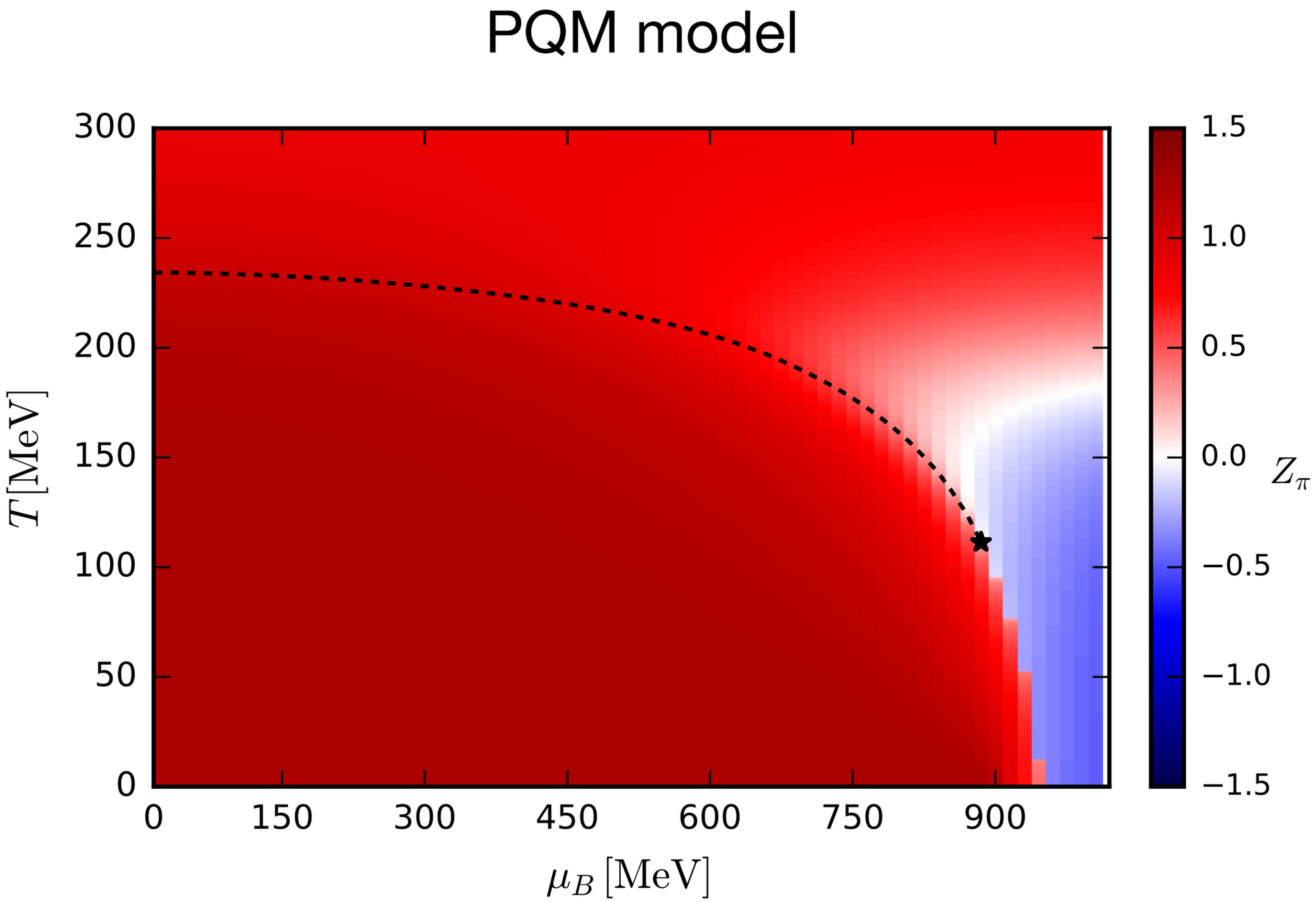
particle creation and annihilation (C.A.)





Landau damping (L.D.)

Back up


PQM model
300
250
200
150
100
50
0
T[MeV]
0
150
300
450
600
750
900
μ_B [MeV]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Z_π