

QCD under extreme conditions

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Universität Heidelberg & ExtreMe Matter Institute

GSI Colloquium, November 11th 2025



STRUCTURES
CLUSTER OF
EXCELLENCE



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Outline

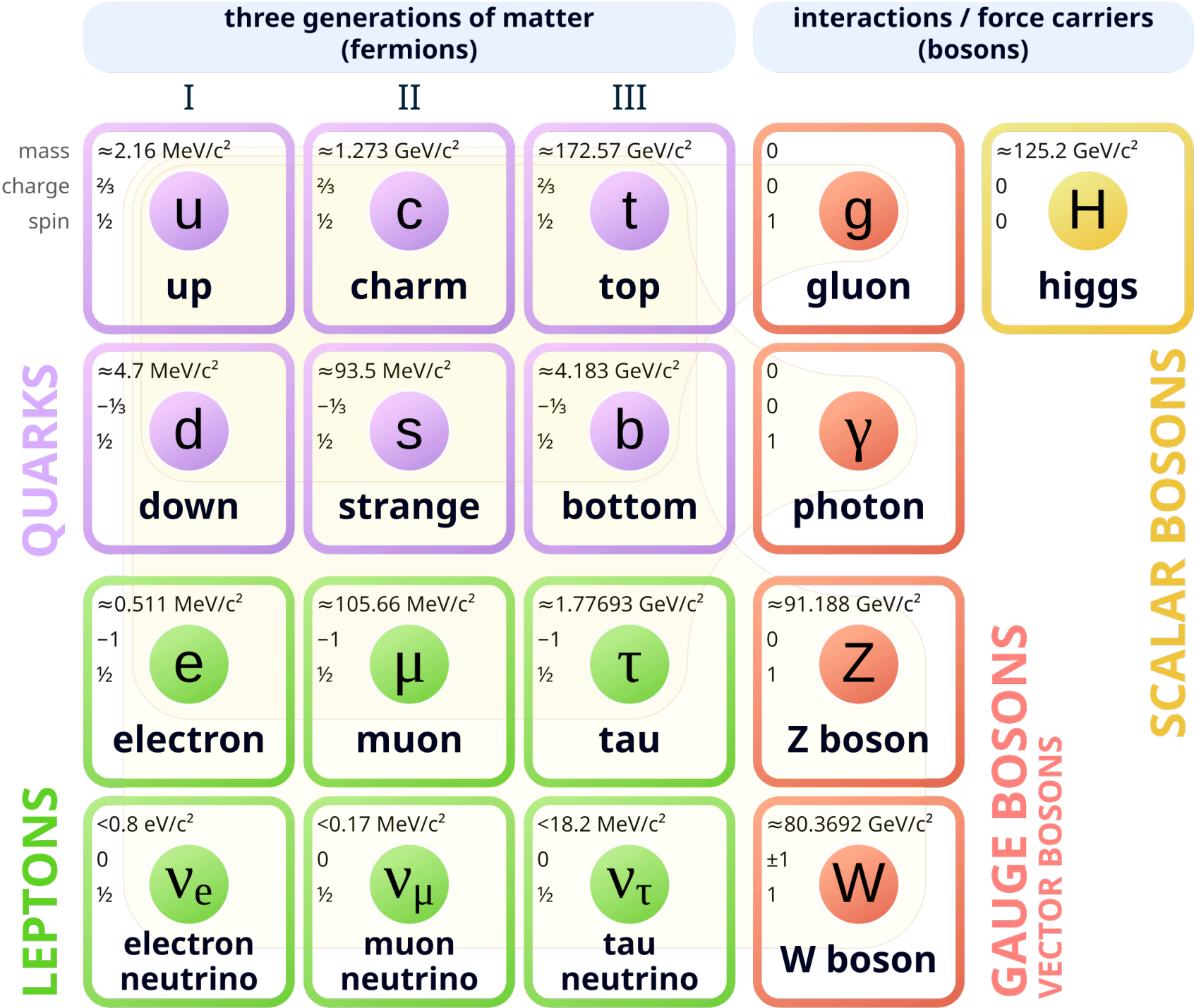
- **QCD: why and how?**
- **Chiral symmetry breaking & confinement: towards the QCD phase structure**
- **The physics of the QCD phase diagram & the experimental landscape**
- **Unfolding the QCD phase structure**
- **Outlook**

QCD: why and how?

Never underestimate the joy
people derive from hearing
something they already know

Fermi

Standard Model of Elementary Particles



QCD

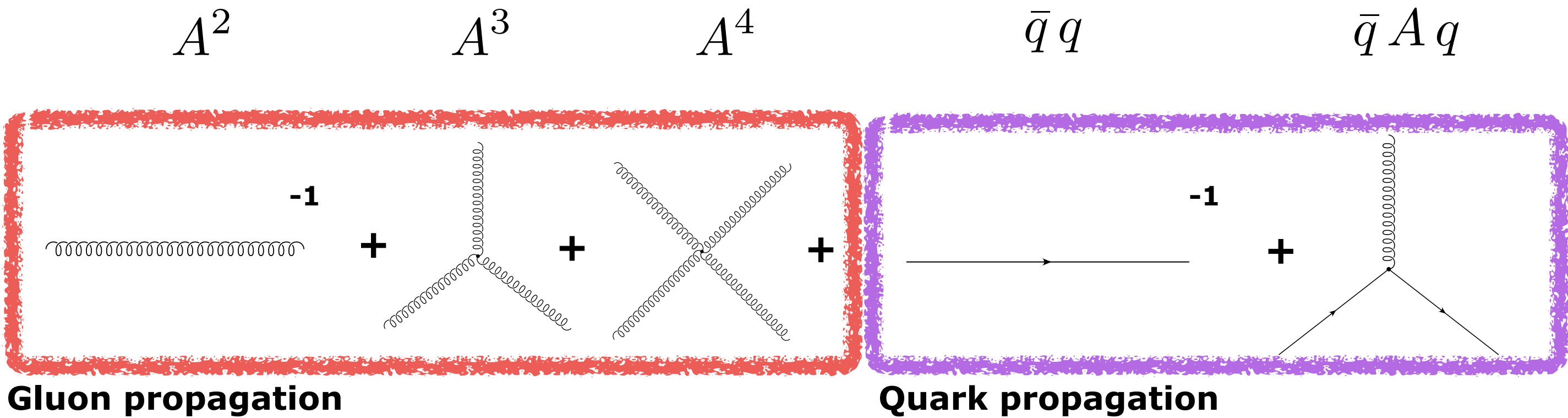
$$S_{\text{QCD}}[\Phi] = \frac{1}{4} \int_x F_{\mu\nu}^a F_{\mu\nu}^a + \int_x \bar{q} \left(i \not{D} + m_q - \gamma_0 \mu_q \right) q$$

Standard Model of Elementary Particles

three generations of matter (fermions)						interactions / force carriers (bosons)	
I		II		III			
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$		
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0		
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0		
QUARKS	 u up	 c charm	 t top	 g gluon	 H higgs		
	 d down	 s strange	 b bottom	 γ photon			
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	0 0 1			
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$  e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$  μ muon	$\approx 1.77693 \text{ GeV}/c^2$ -1 $\frac{1}{2}$  τ tau	$\approx 91.188 \text{ GeV}/c^2$ 0 -1 1  Z Z boson			
	$< 0.8 \text{ eV}/c^2$ 0 $\frac{1}{2}$  ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$  ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$  ν_τ tau neutrino	$\approx 80.3692 \text{ GeV}/c^2$ ± 1 1  W W boson			
					GAUGE BOSONS VECTOR BOSONS		
						SCALAR BOSONS	

QCD

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Gluon self-interaction

Quark-gluon interaction

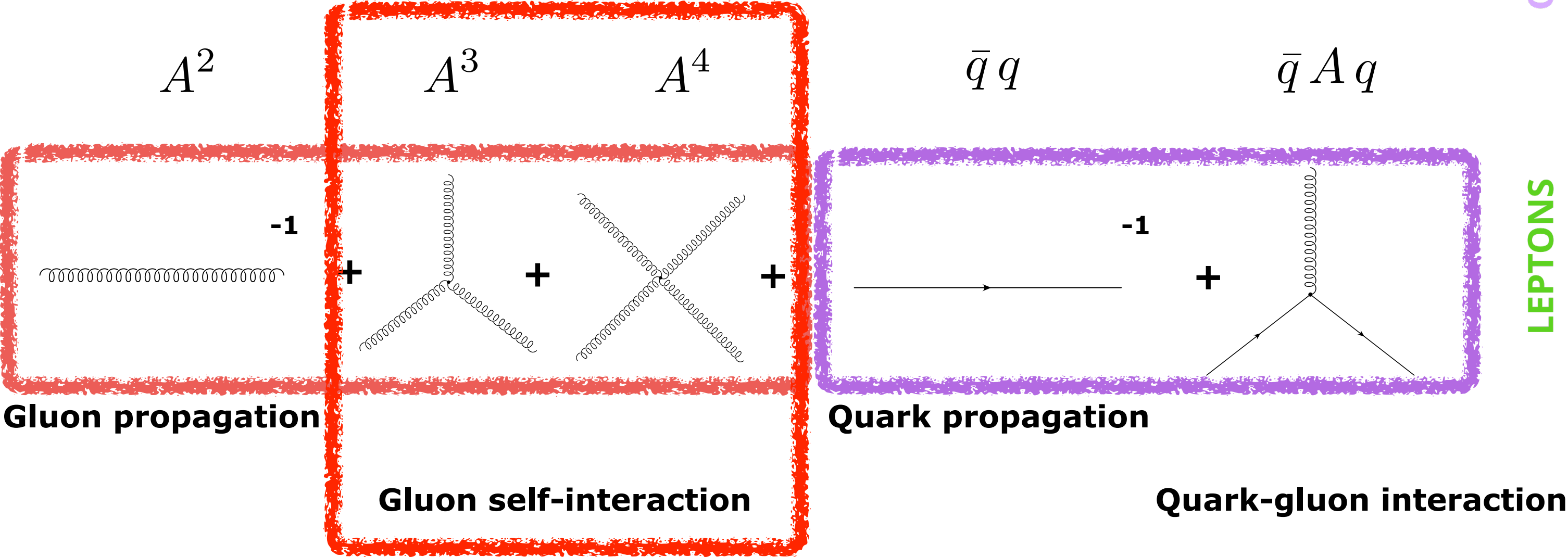
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Singles out QCD (no strong Higgs)

Standard Model of Elementary Particles

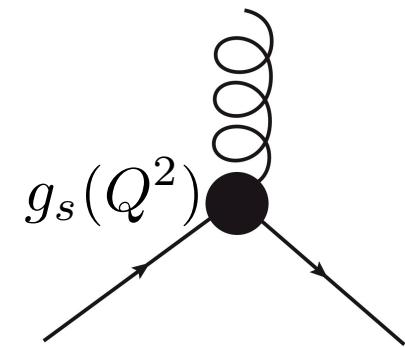
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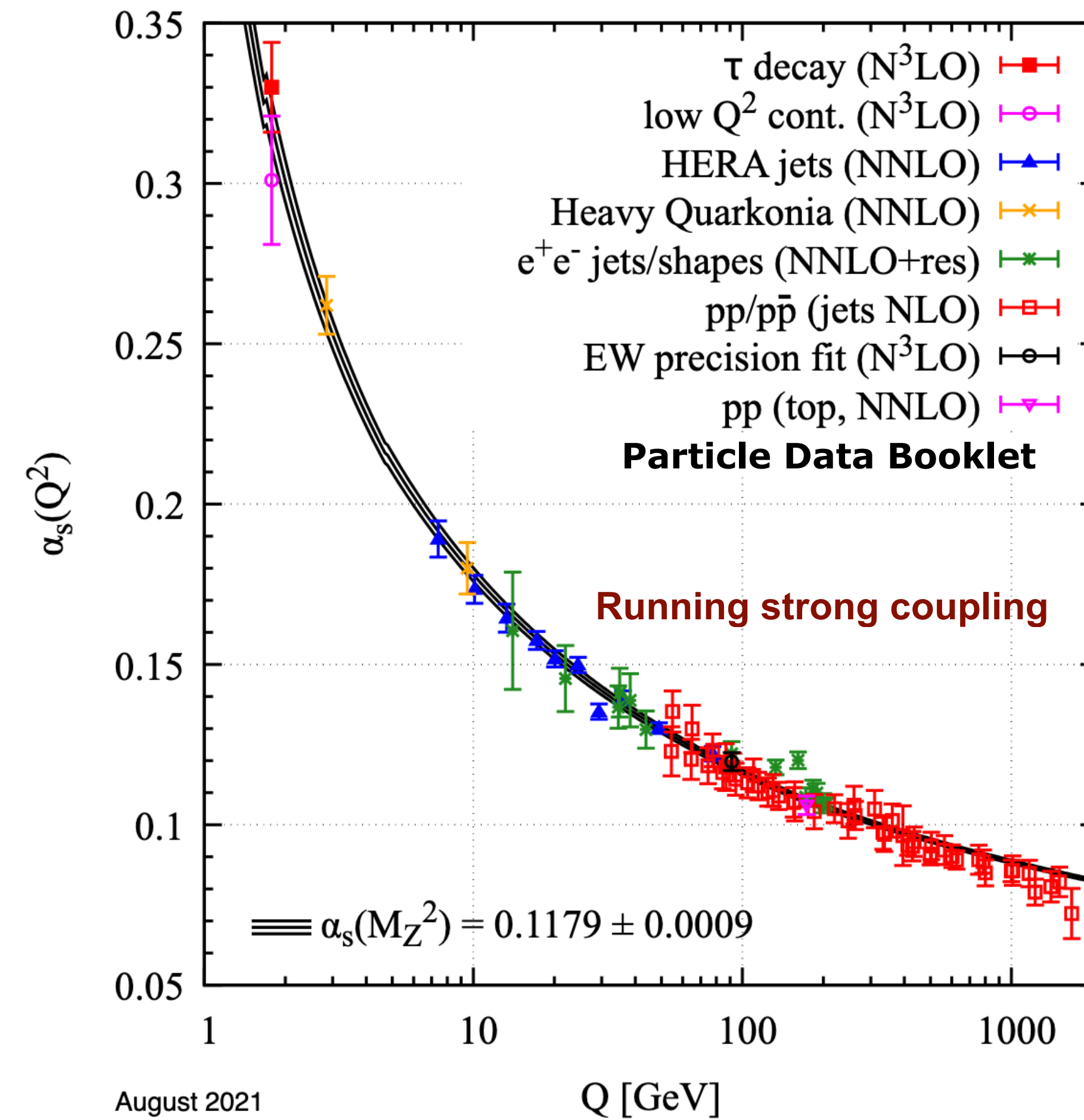
What's hot in QCD?

Low Temperatures, densities

Large Temperatures, densities



$$\alpha_s(Q^2) = \frac{g_s^2(Q^2)}{4\pi}$$

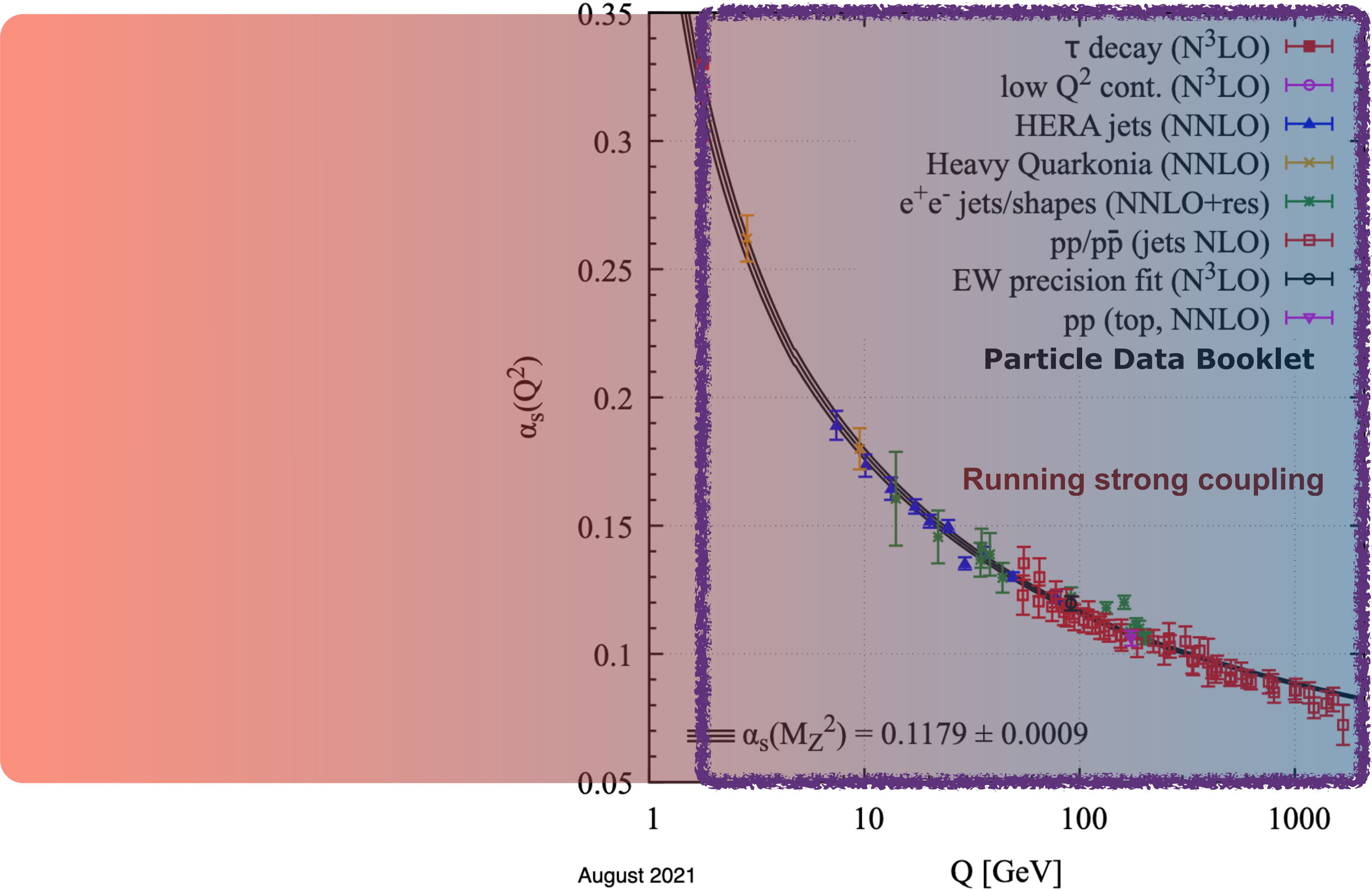


August 2021

What's hot in QCD?

Low Temperatures, densities

Large Temperatures, densities



QCD background
for
SM & BSM physics

crucial for 'unfolding'

deconvolution
reconstruction

⋮

UV: weakly coupled quarks and gluons

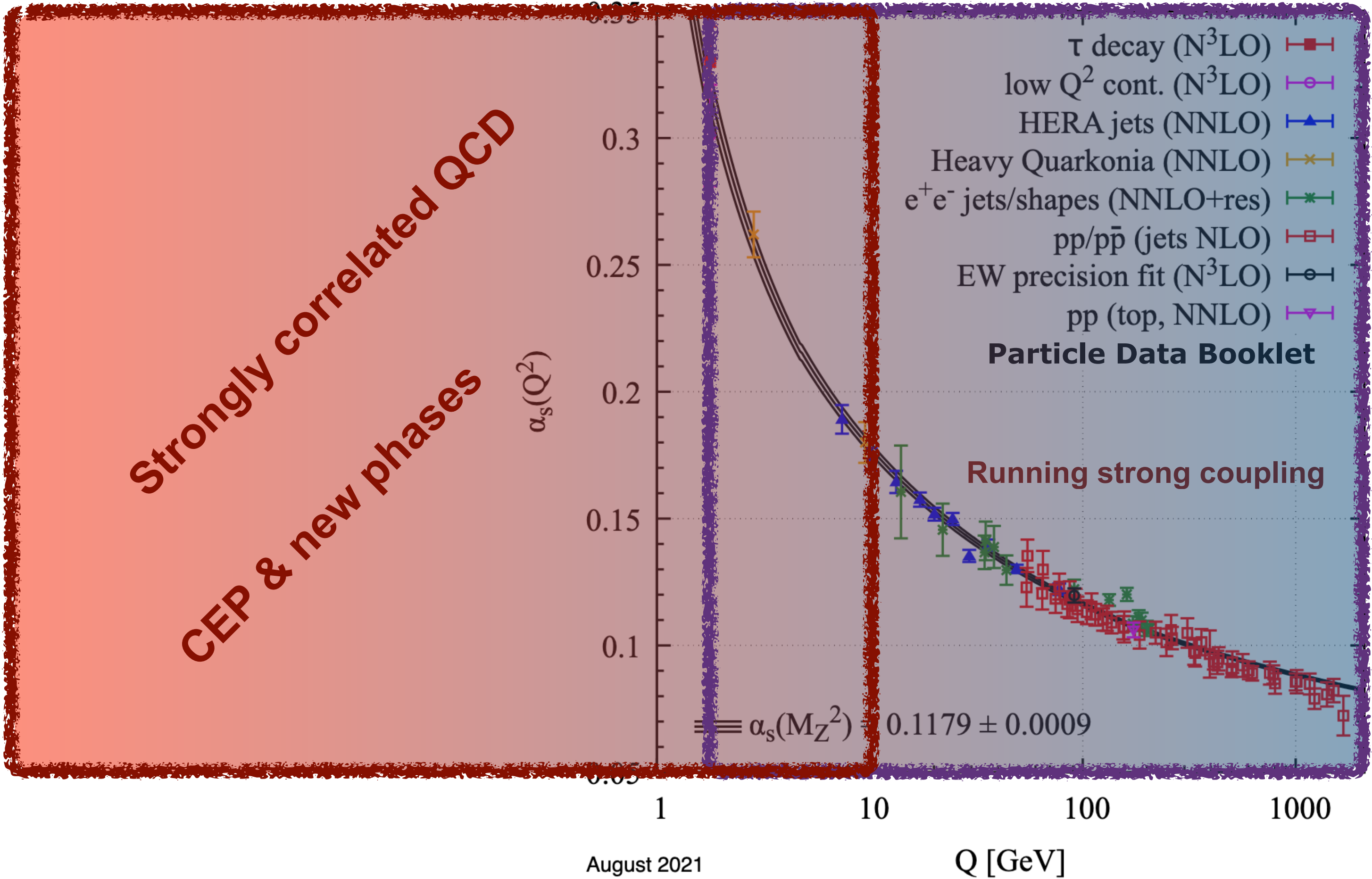
Asymptotic freedom
Nobel Prize '04
Gross, Politzer, Wilczek

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IR: confinement & chiral symmetry breaking



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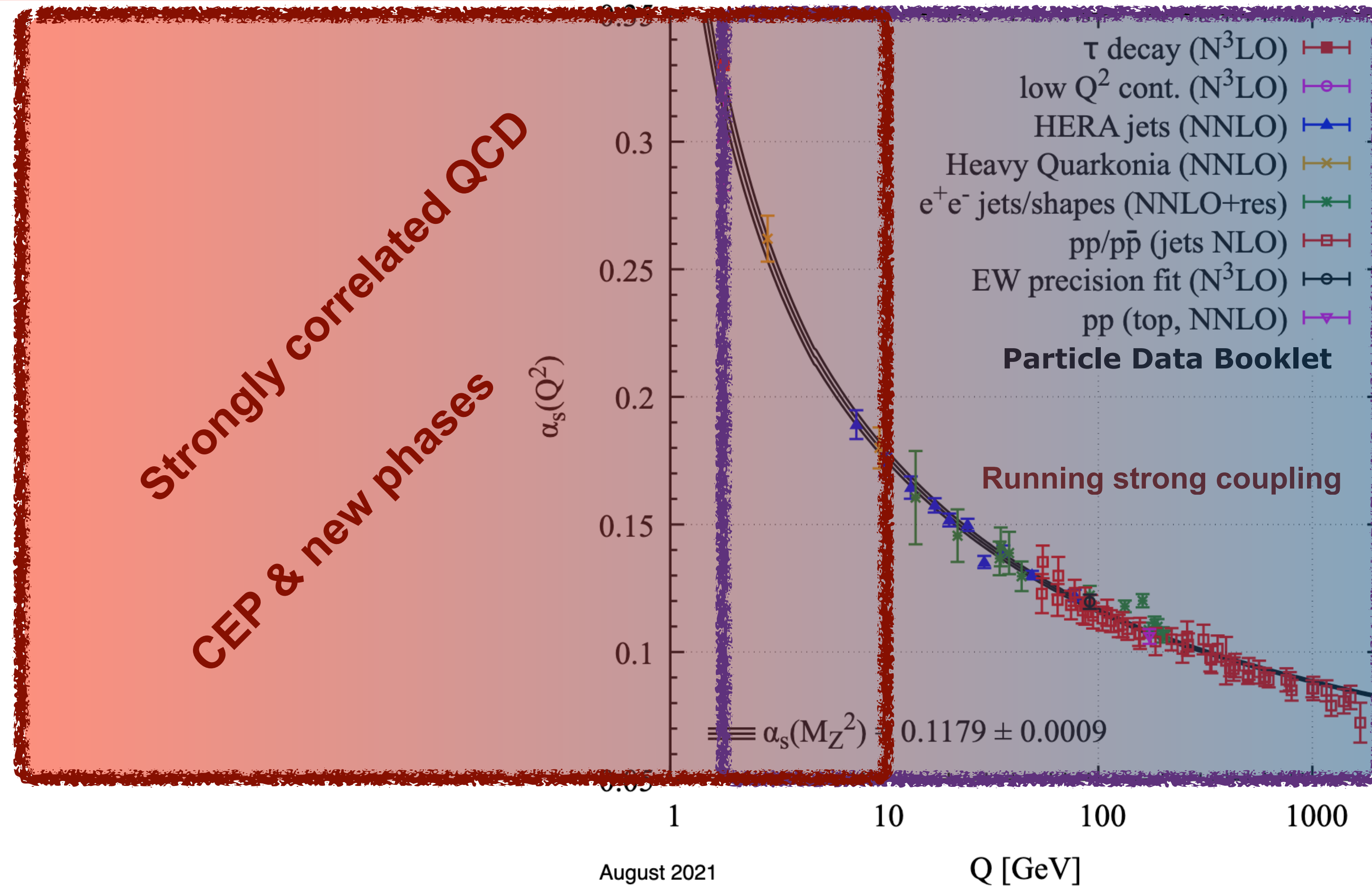
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Strongly correlated QCD: how to?

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

(1) Theory

Lattice QCD

Statistical QCD

QCD distribution $p_{\text{QCD}} \propto e^{-S_{\text{QCD}}}$

Importance sampling

Functional QCD

Diagrammatic QCD

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \left(\text{orange loop} - \text{dashed loop} - \text{solid loop} + \frac{1}{2} \text{blue loop} \right)$$

QCD free energy

Solution of large systems of integral-differential equation

Low energy effective theories

Controlled approximations /extrapolations of QCD



Extrapolations & von Neumann's Elephant

Extrapolations are ill-conditioned problems

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well, I have others

'... and now for something
completely different...'



Extrapolations & von Neumann's Elephant

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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,
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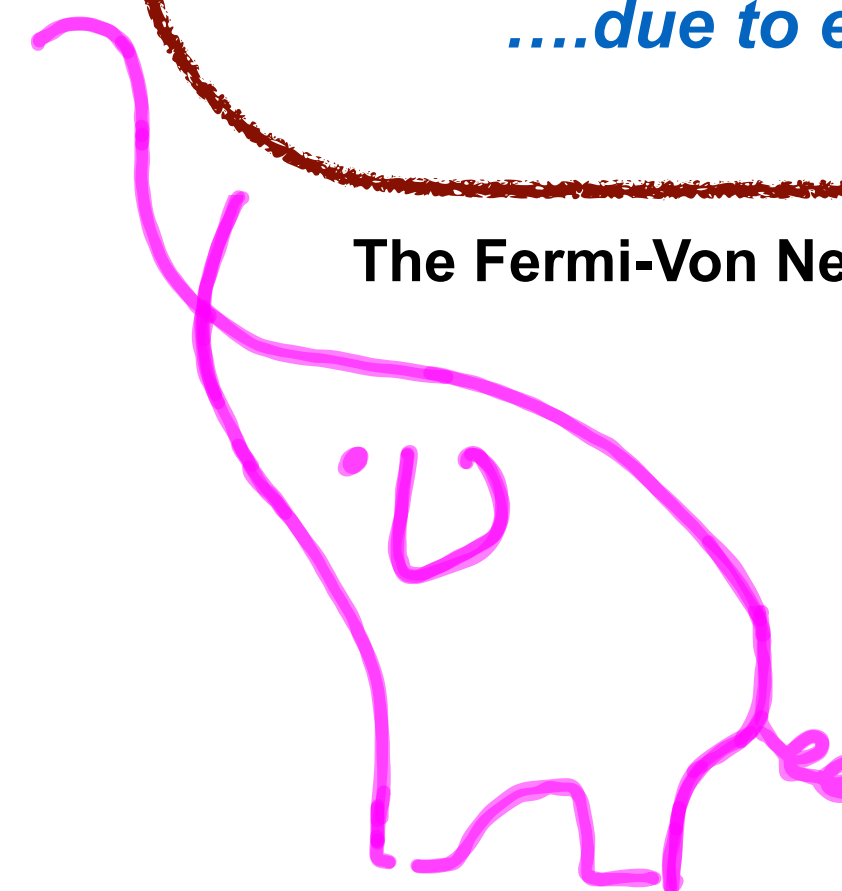
Von Neumann

*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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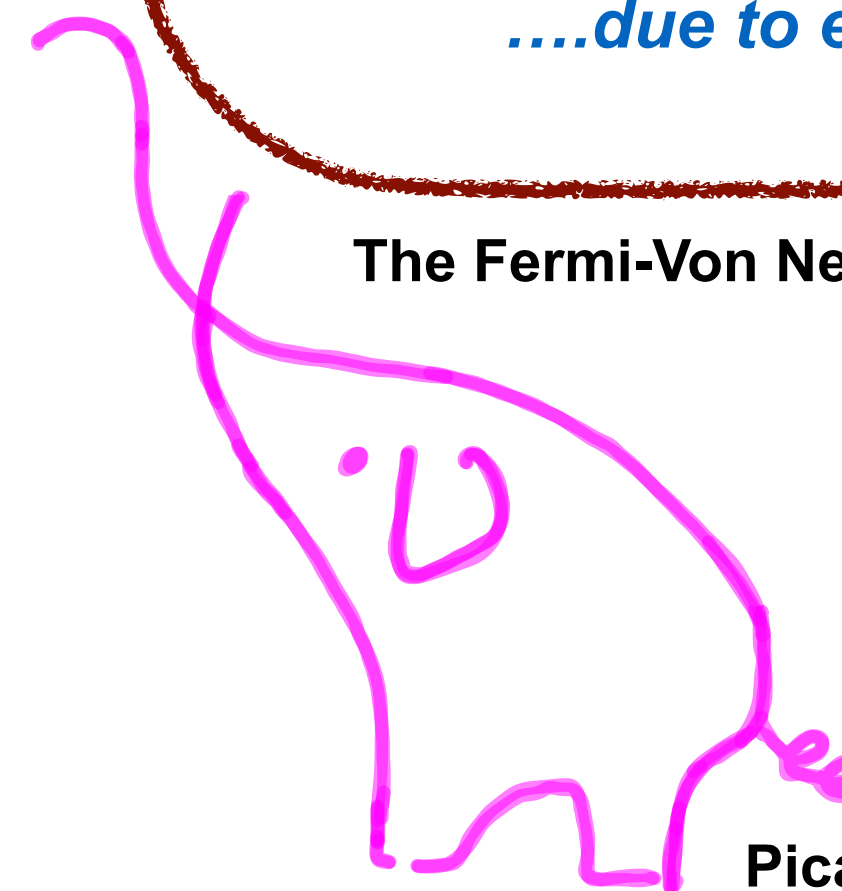
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Picasso-assisted Pawłowski elephant

Chiral symmetry breaking & confinement: towards the QCD phase structure

Chiral symmetry breaking

Dynamical chiral symmetry breaking (QCD) $\Delta m_{\chi\text{SB}} \approx 350\text{MeV}$

Current quark masses (Higgs)

Generation	first	second	third	Charge
Mass [MeV]	1.5-4	1150-1350	170×10^3	
Quark	u	c	t	$\frac{2}{3}$
Quark	d	s	b	$-\frac{1}{3}$
Mass [MeV]	4-8	80-130	$(4.1-4.4)\times 10^3$	

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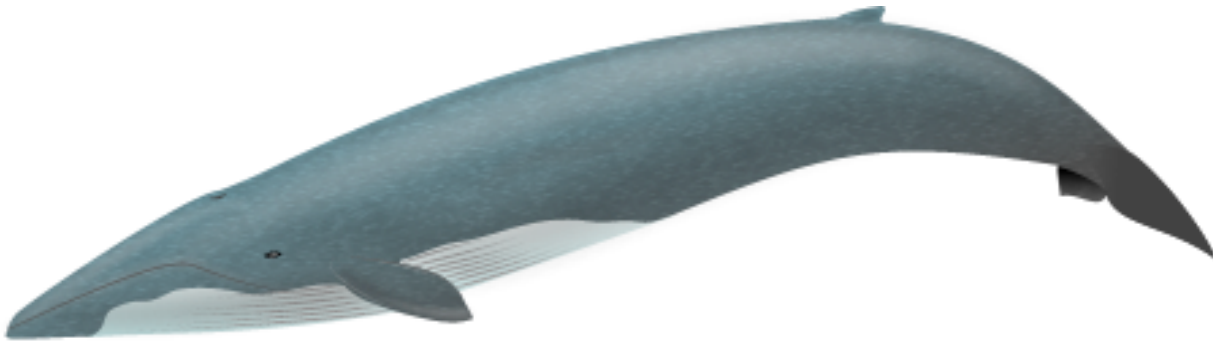
up



charm



top



down



strange



bottom



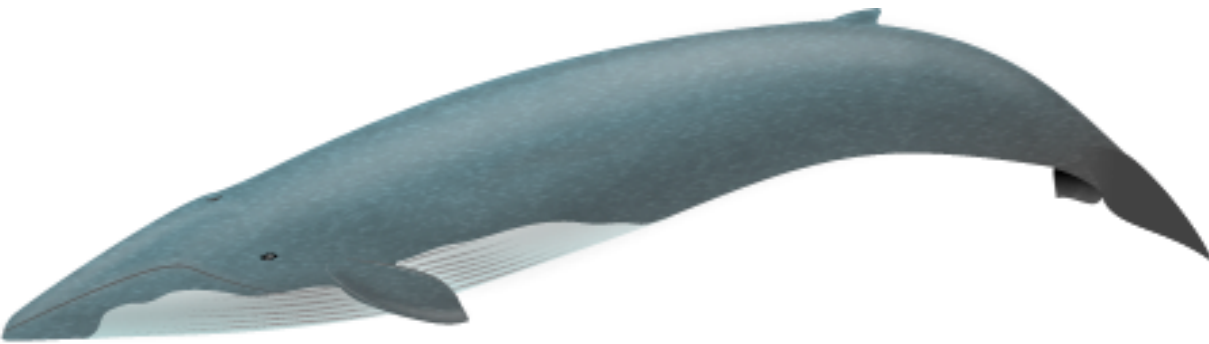
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top



bottom



charm



strange



up



down



Current quark masses (Higgs)

2 **light** flavours, one **heavy** flavour **2+1**

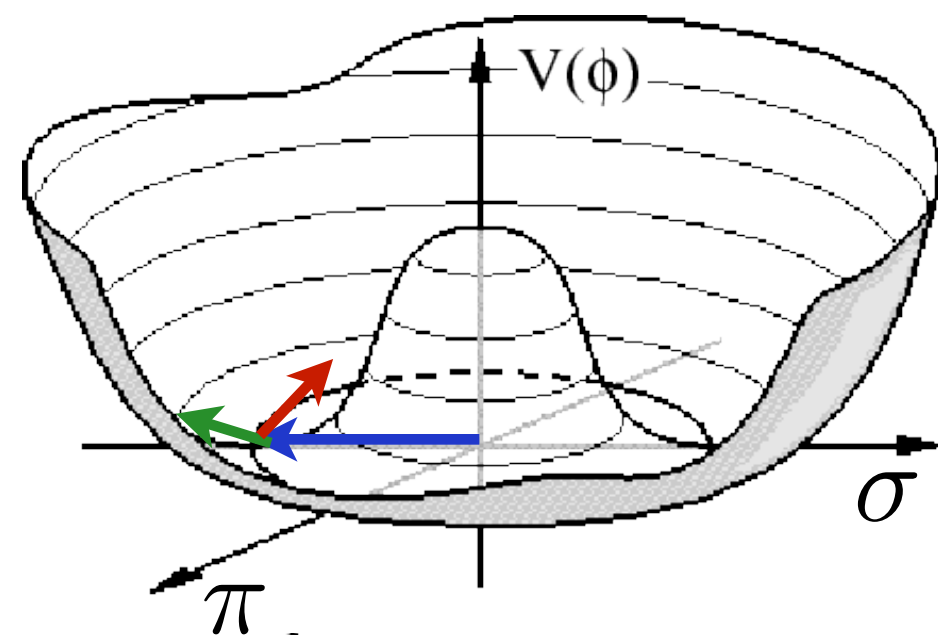
Dynamical chiral symmetry breaking

Order parameter

$$\sigma \propto \langle \bar{q}q \rangle = \langle q_L^\dagger q_R + q_R^\dagger q_L \rangle$$

chiral condensate

Meson potential



$$\vec{\pi} \simeq i \langle \bar{q} \vec{\sigma} \gamma_5 q \rangle$$

(Pseudo) Goldstones

- Chiral symmetry $\sigma = 0$
- Symmetry broken $\sigma \neq 0$

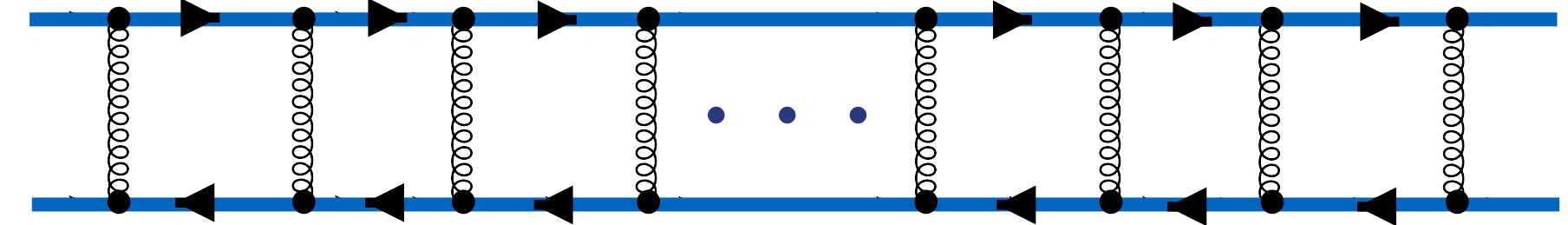
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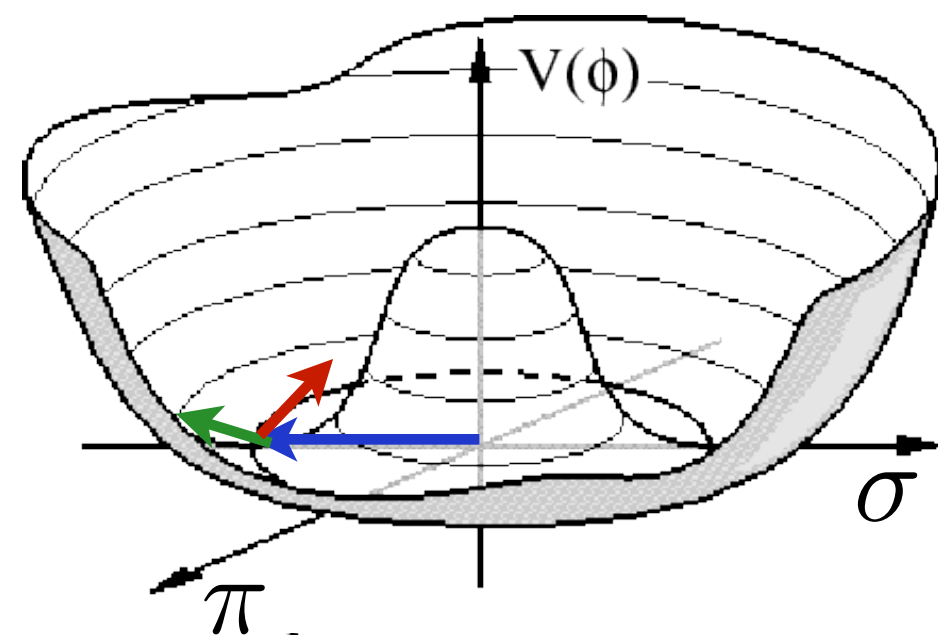
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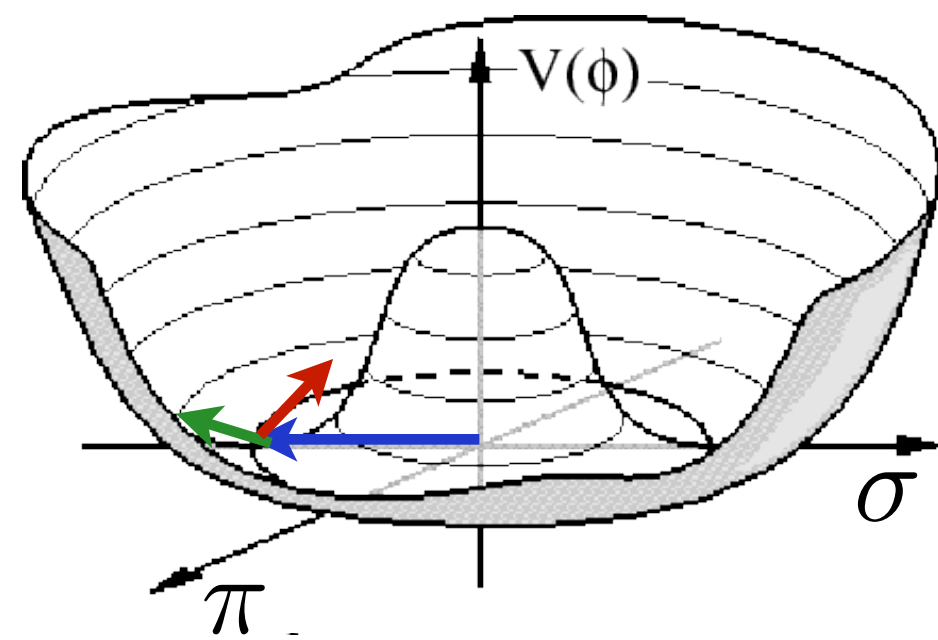
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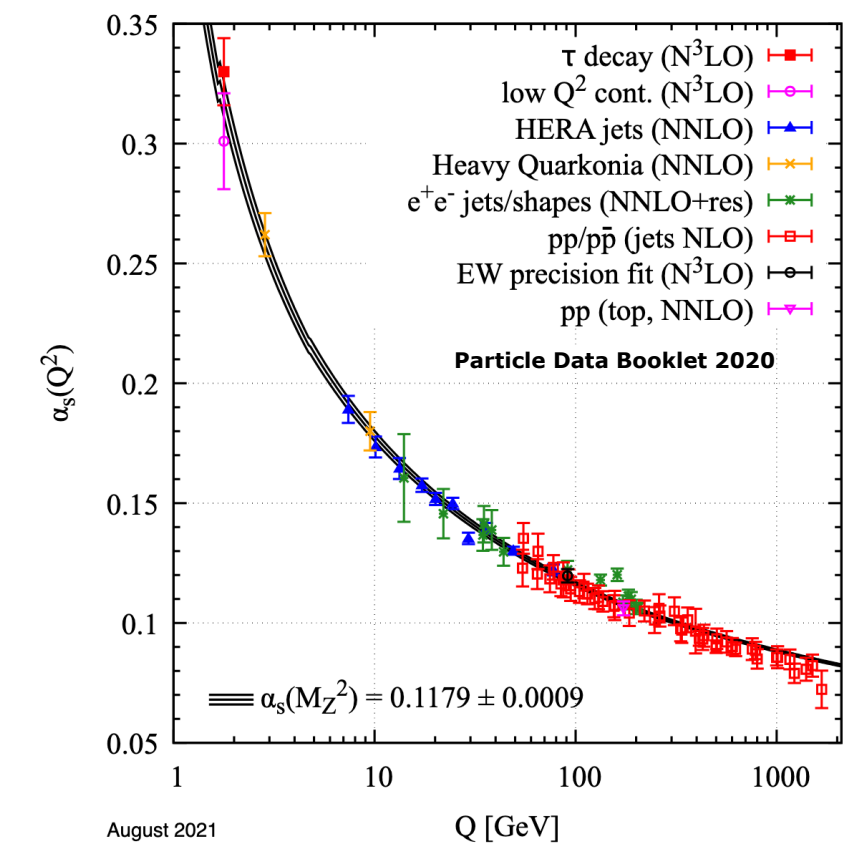
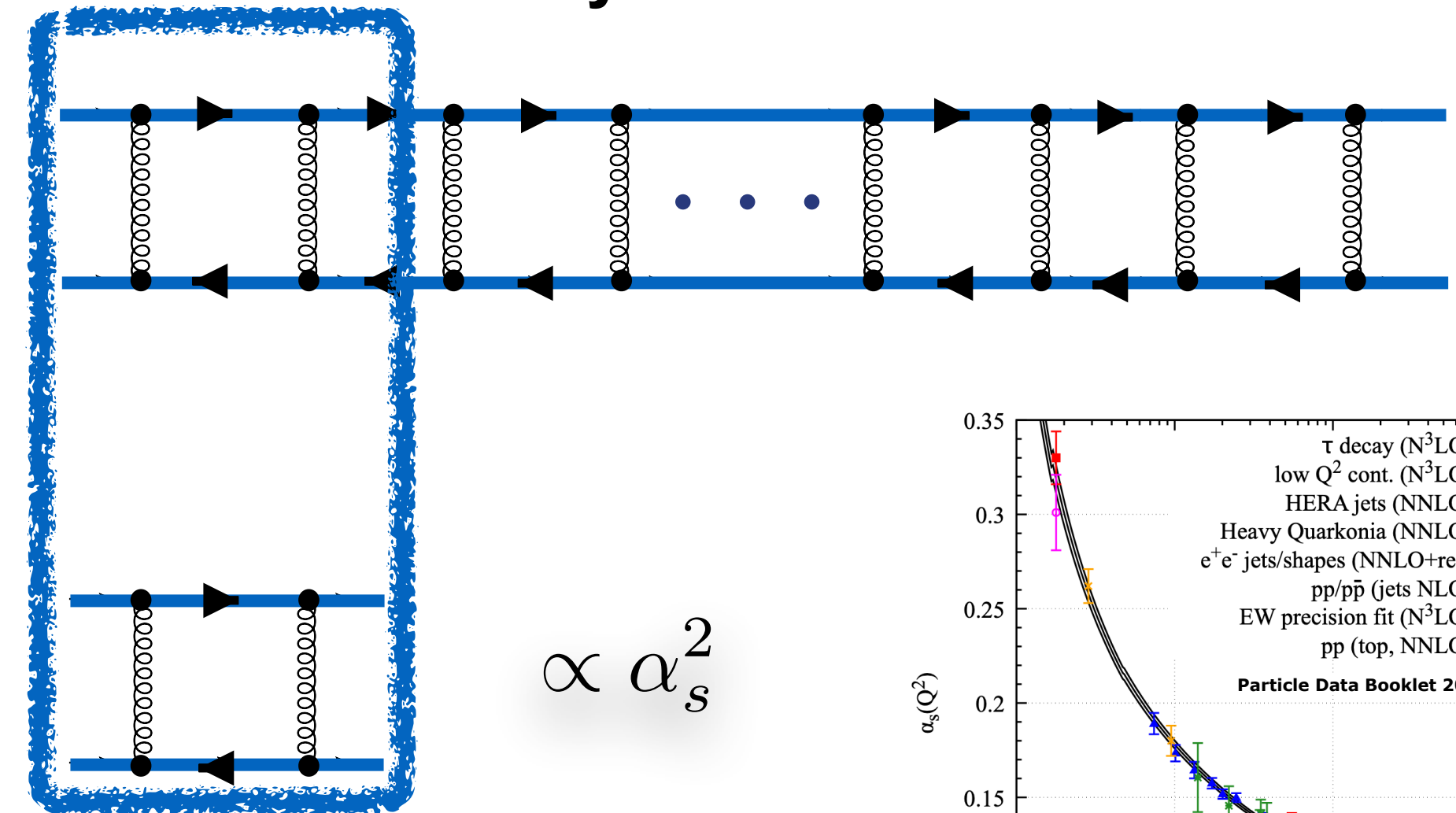


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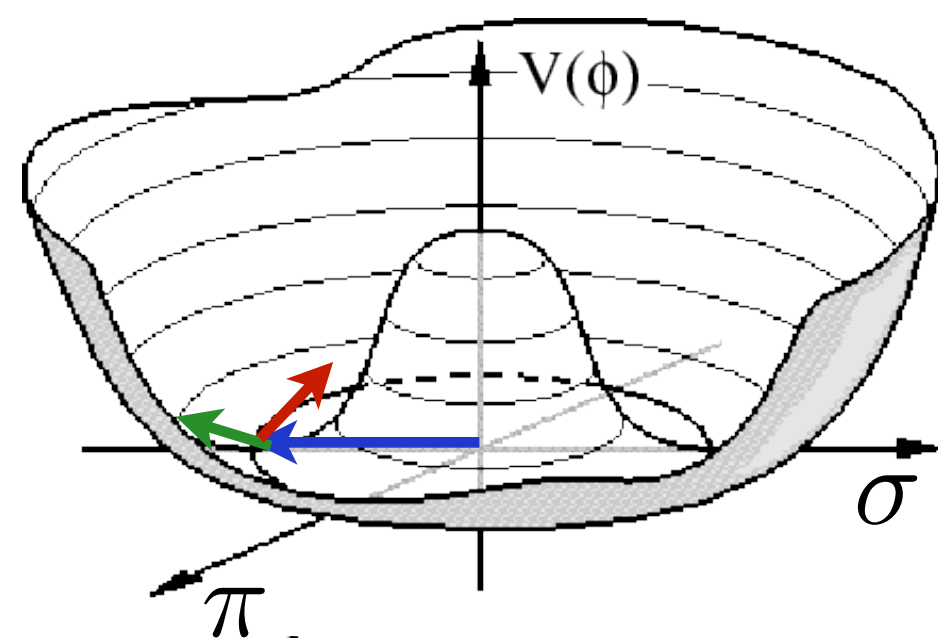
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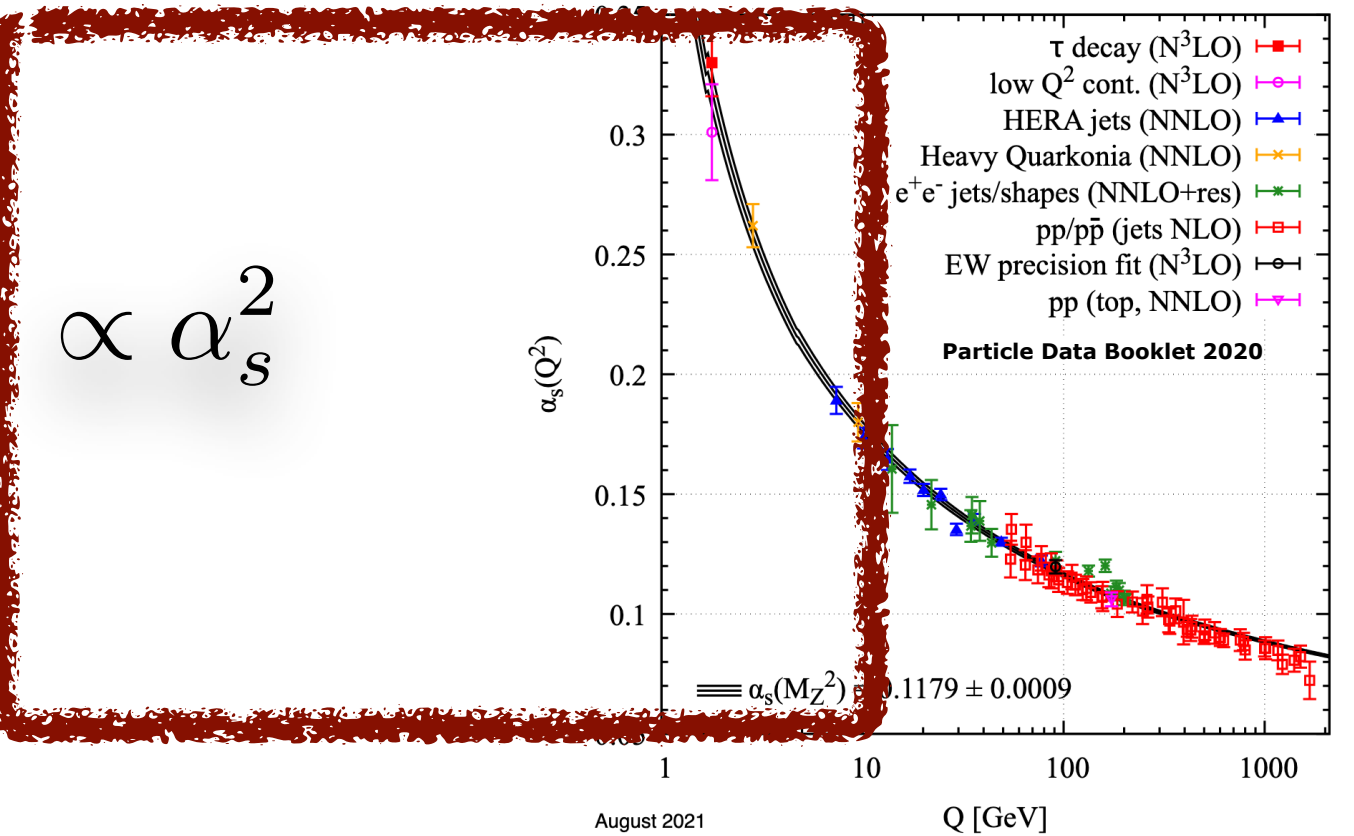
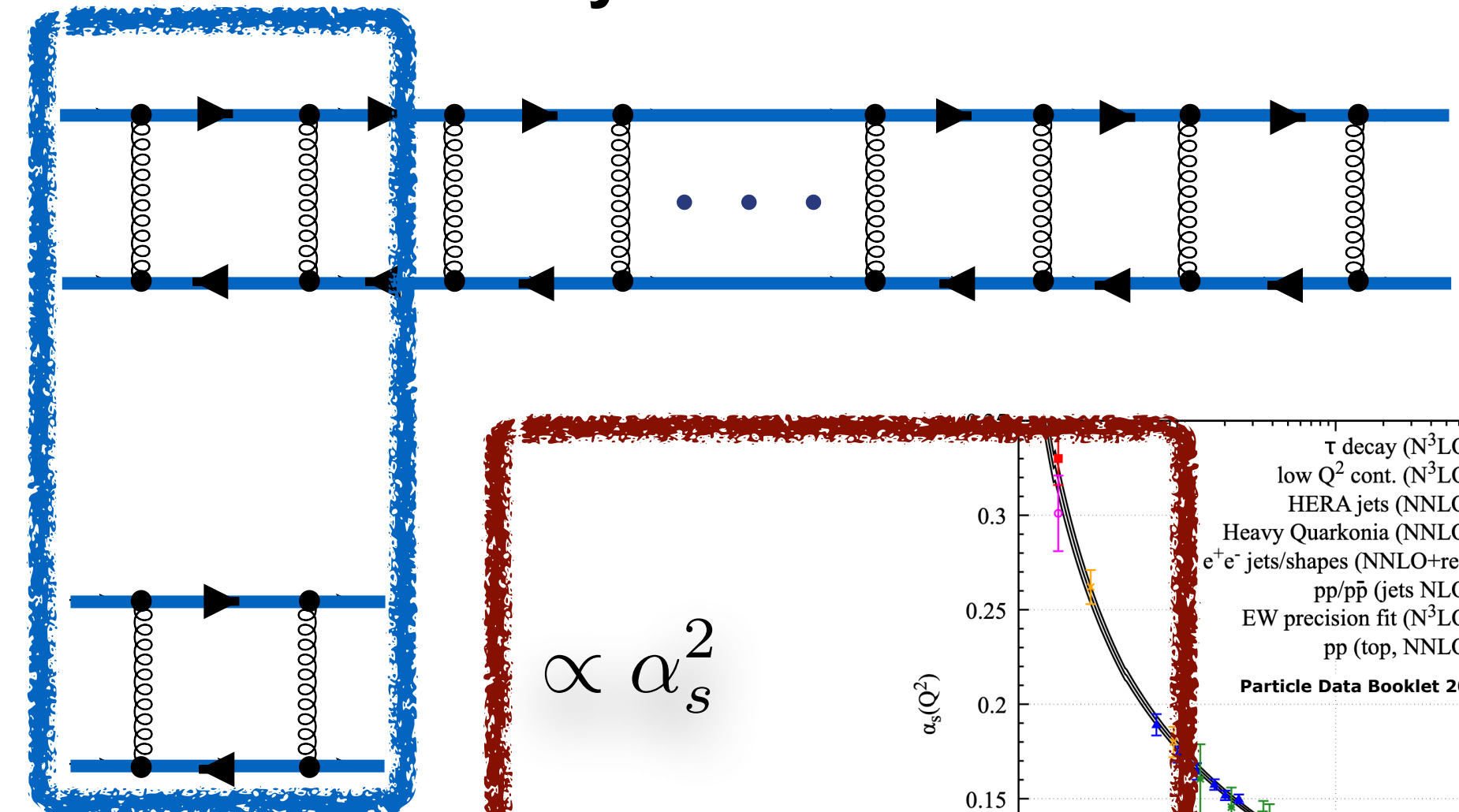


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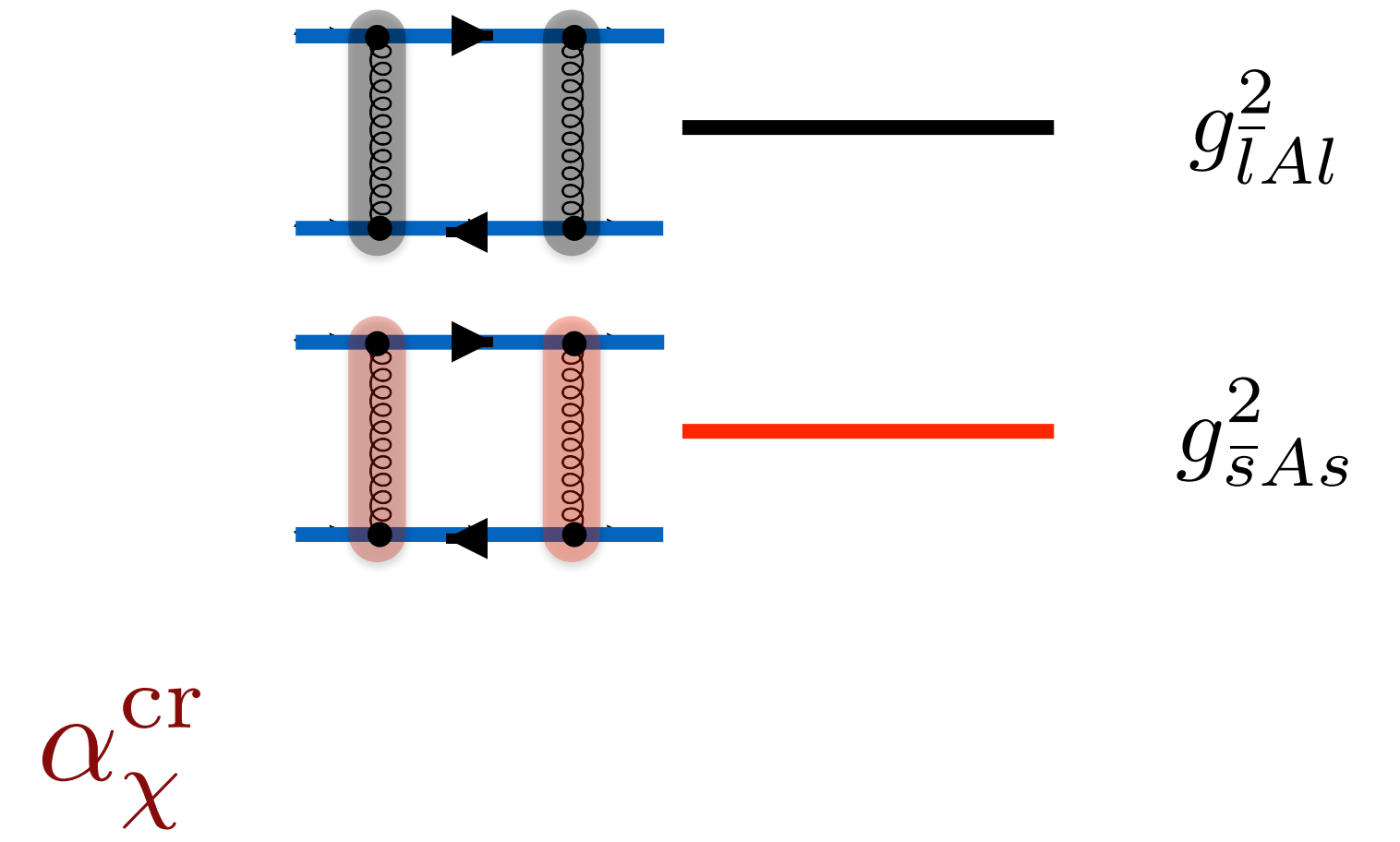
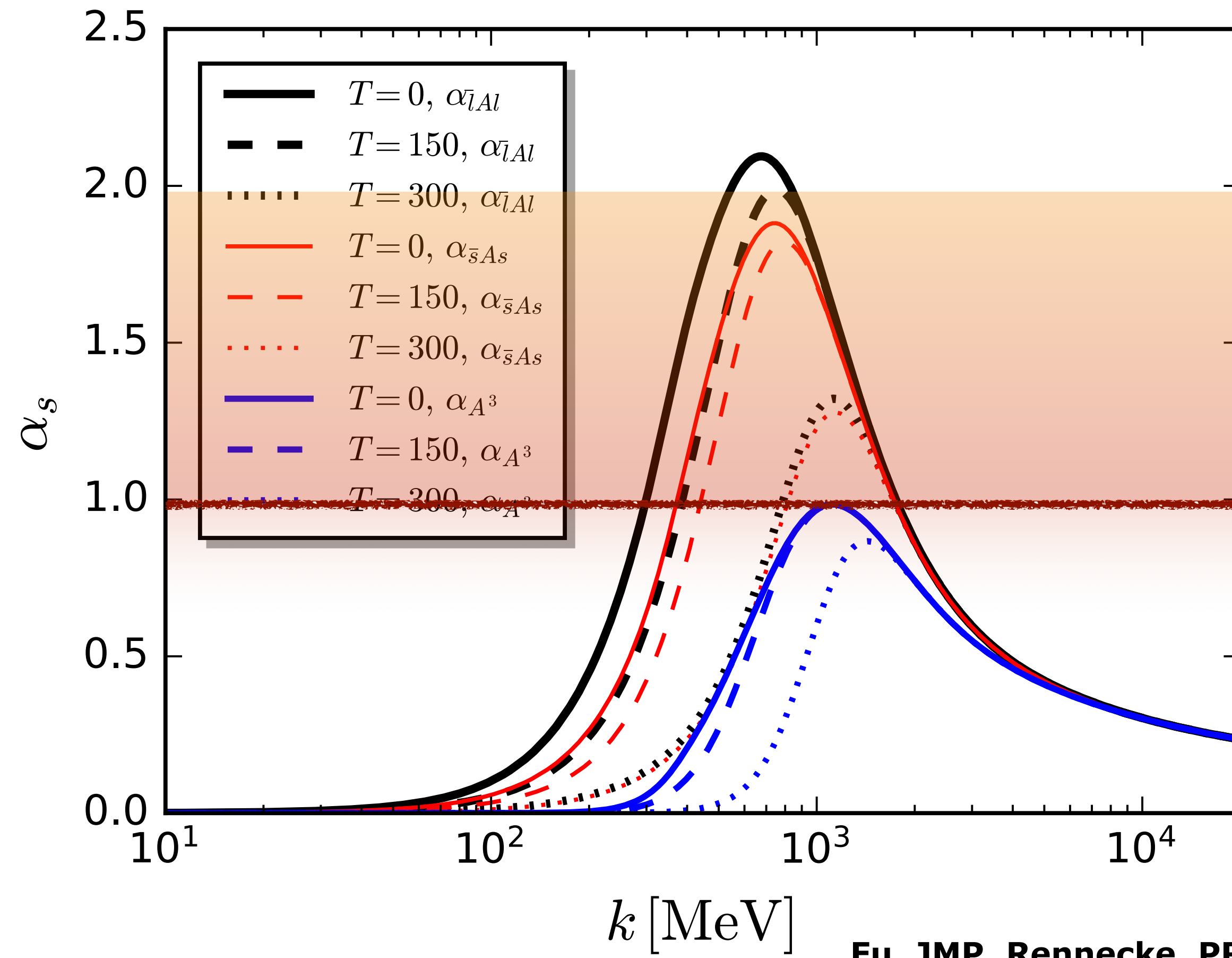
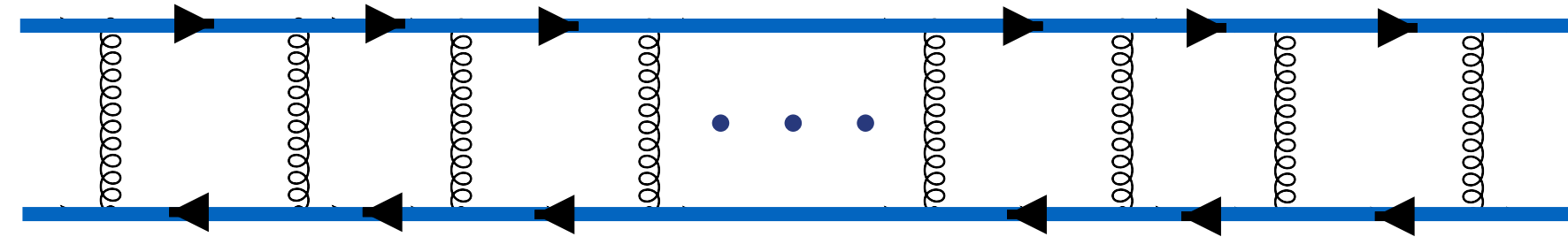
Dynamics



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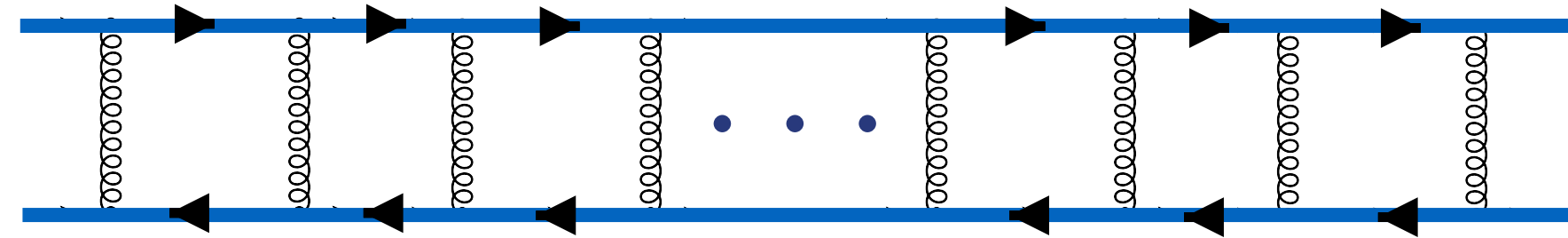
$$\alpha_s > \alpha_\chi^{\text{cr}} \approx 1$$

Thermal restoration of chiral symmetry

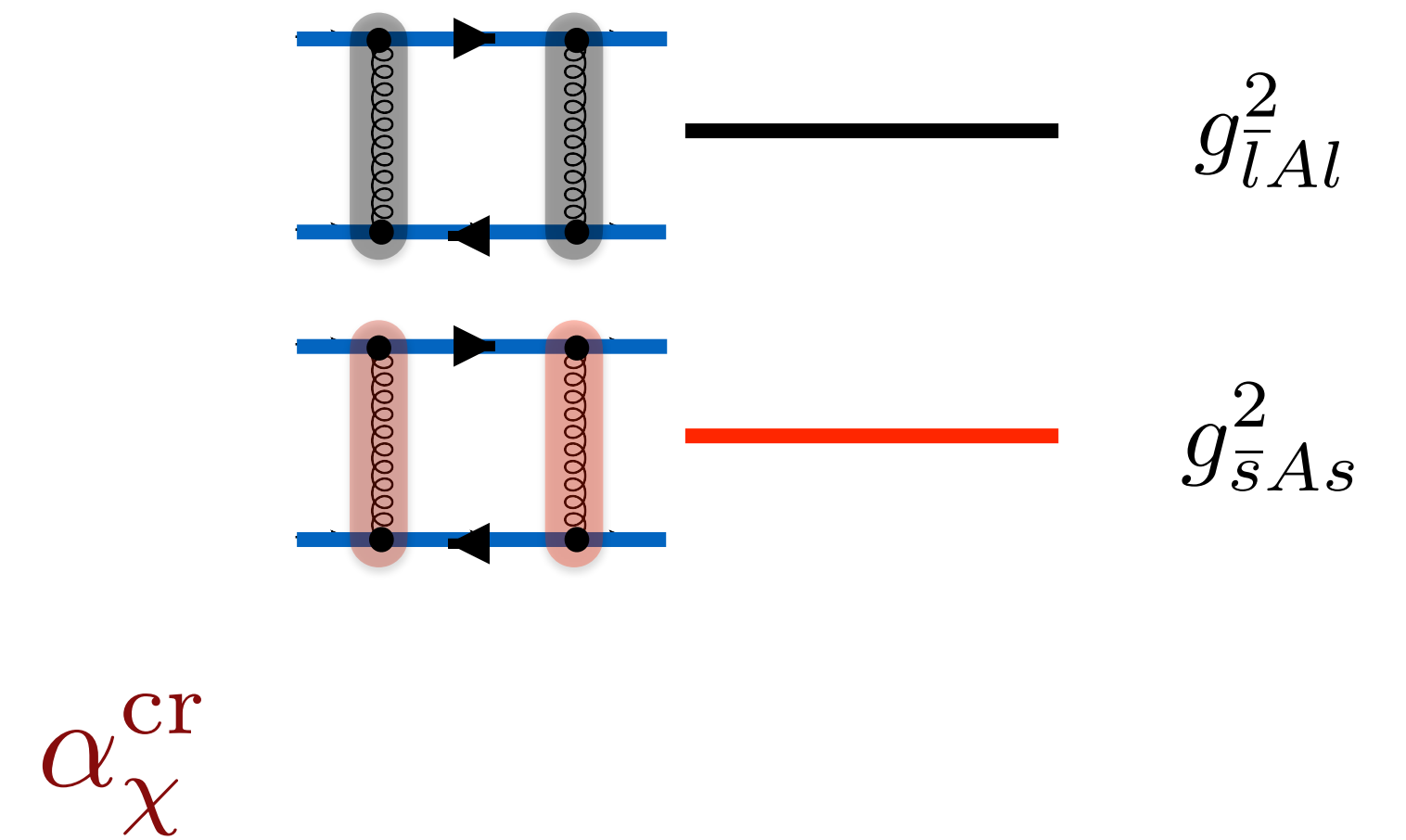
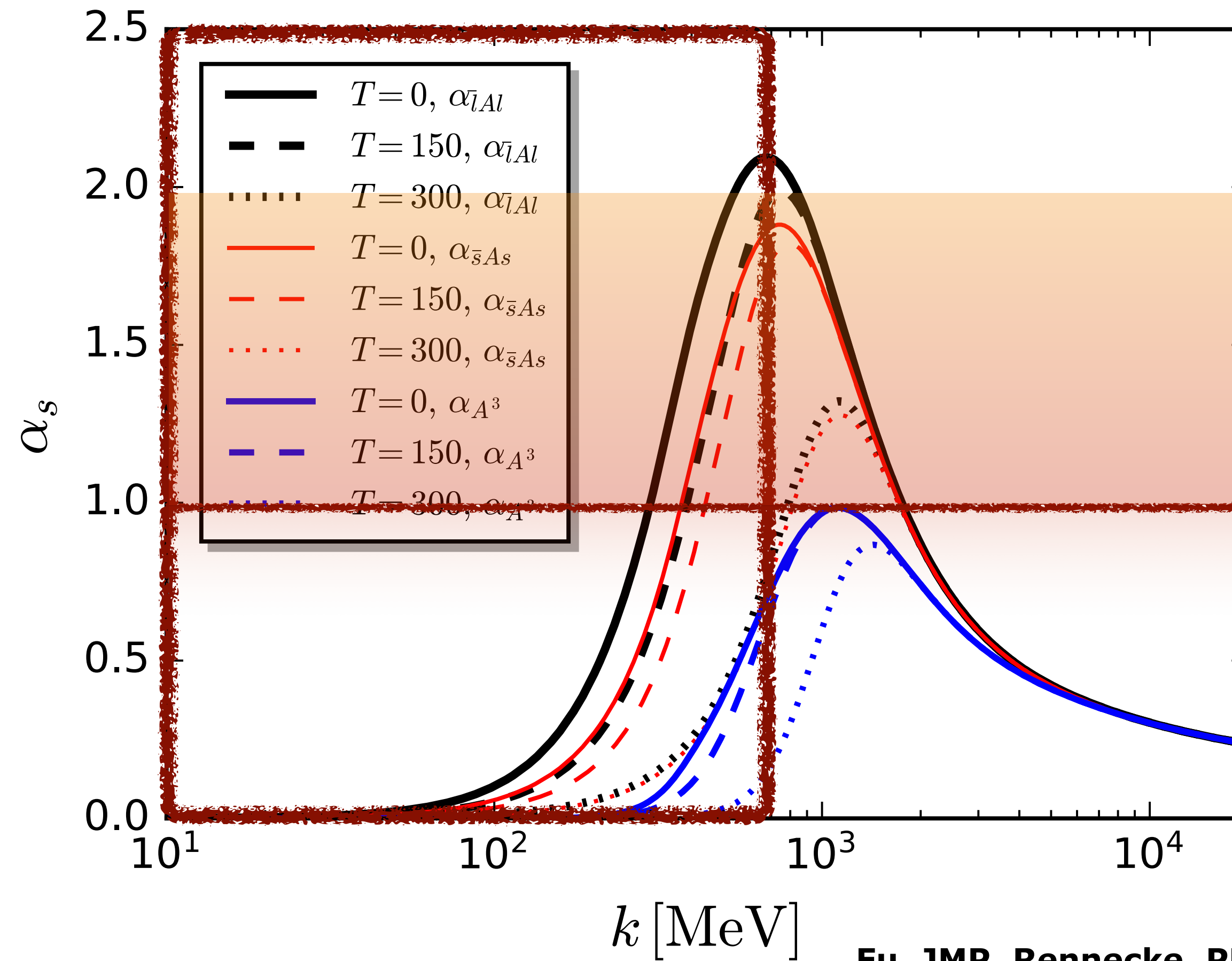


Fu, JMP, Rennecke, PRD 101 (2020) 054032

Thermal restoration of chiral symmetry



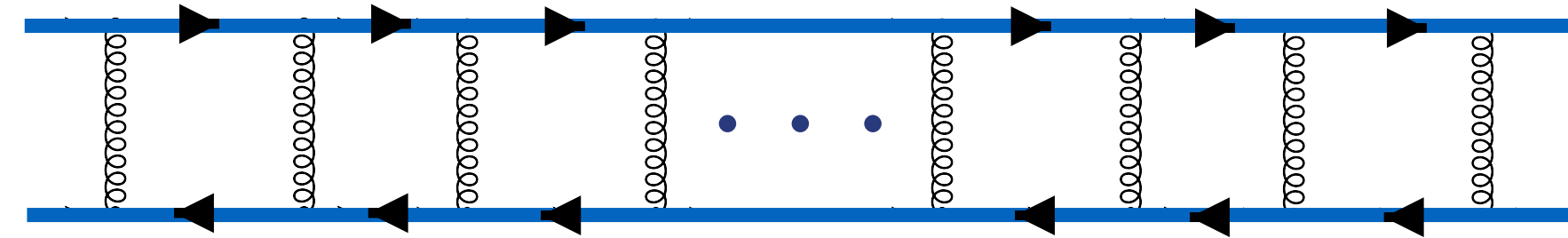
Effective couplings decays
due to
the gluon mass gap



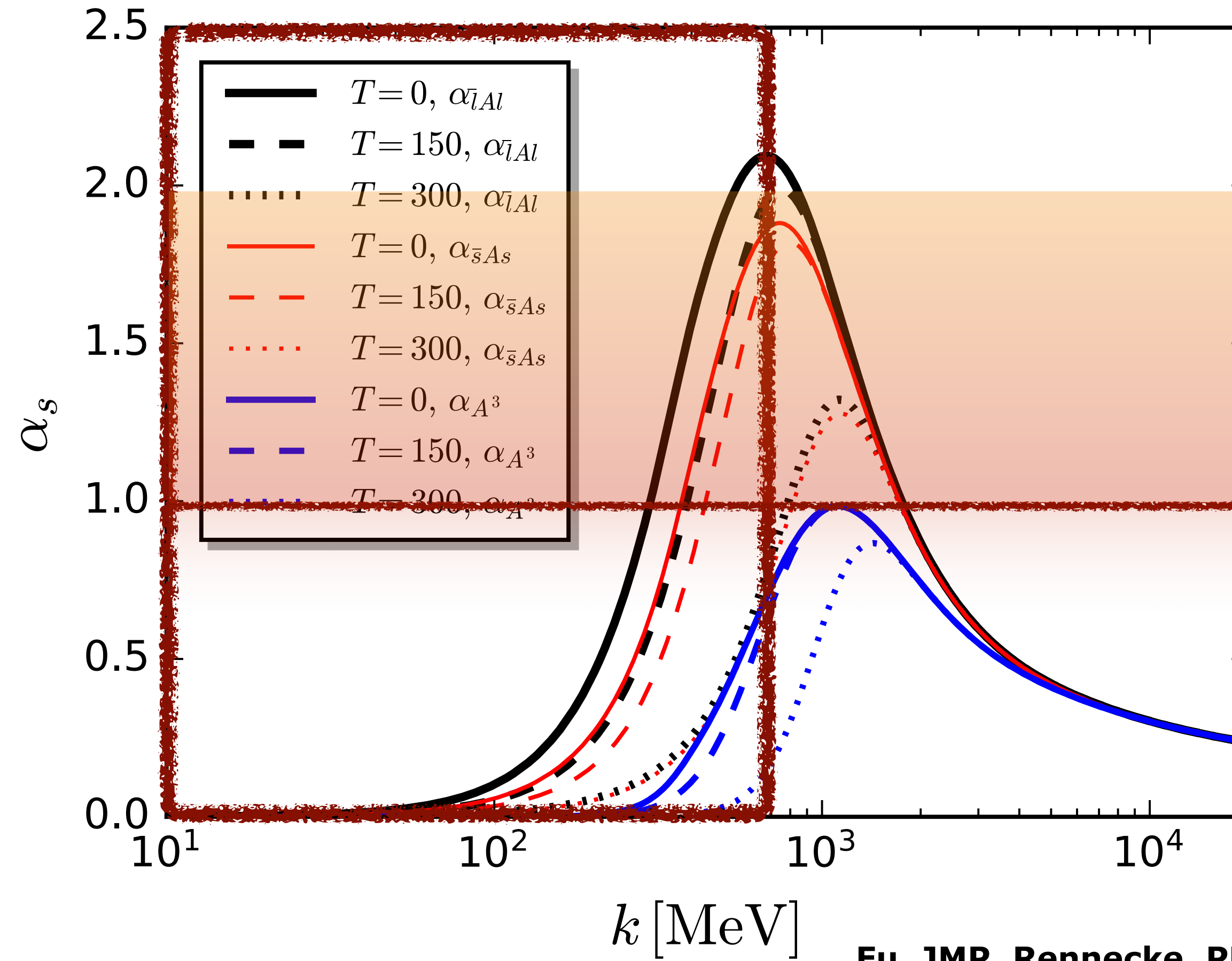
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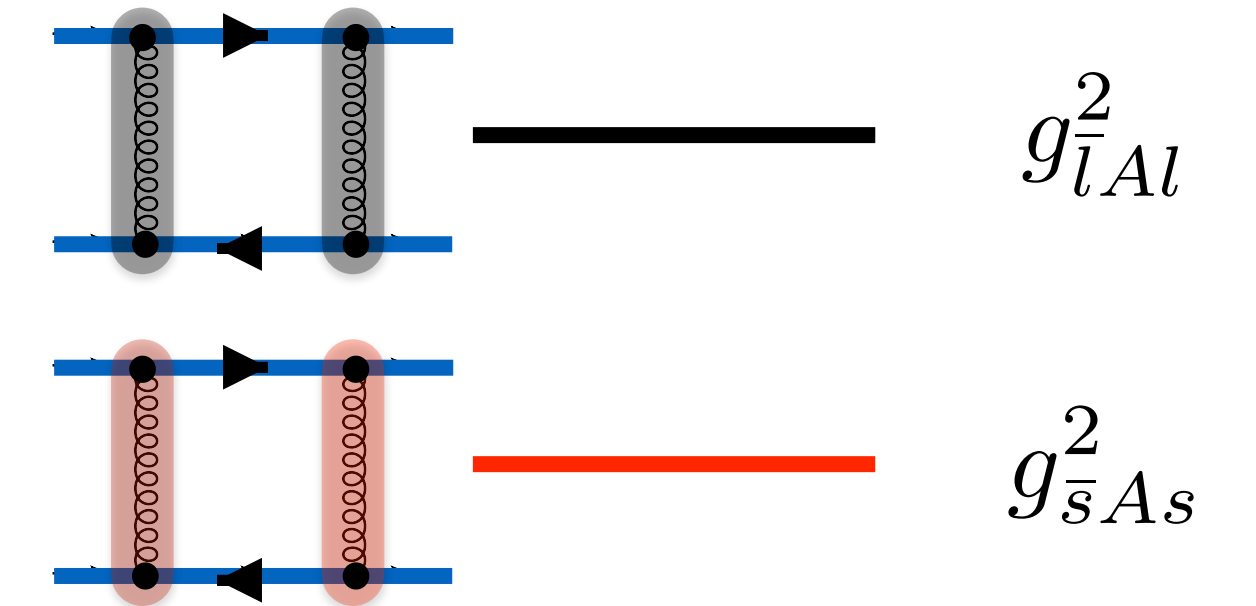
Thermal symmetry restauration
by melting down the coupling



Effective couplings decays
due to
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$\alpha_{\chi}^{\text{cr}}$



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

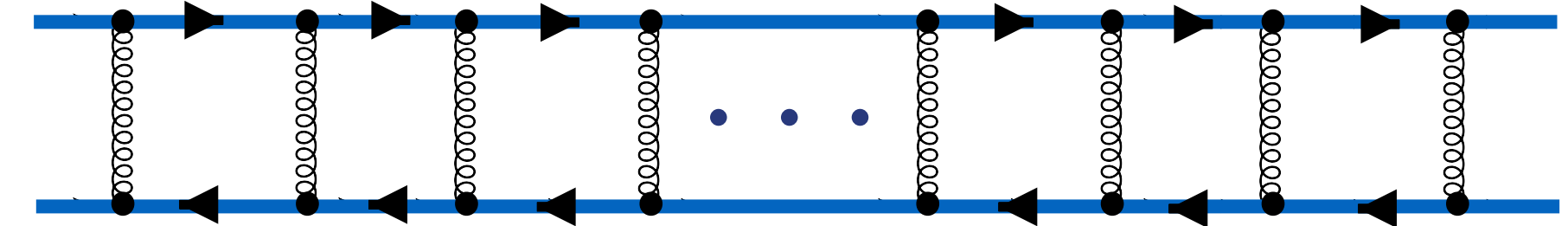
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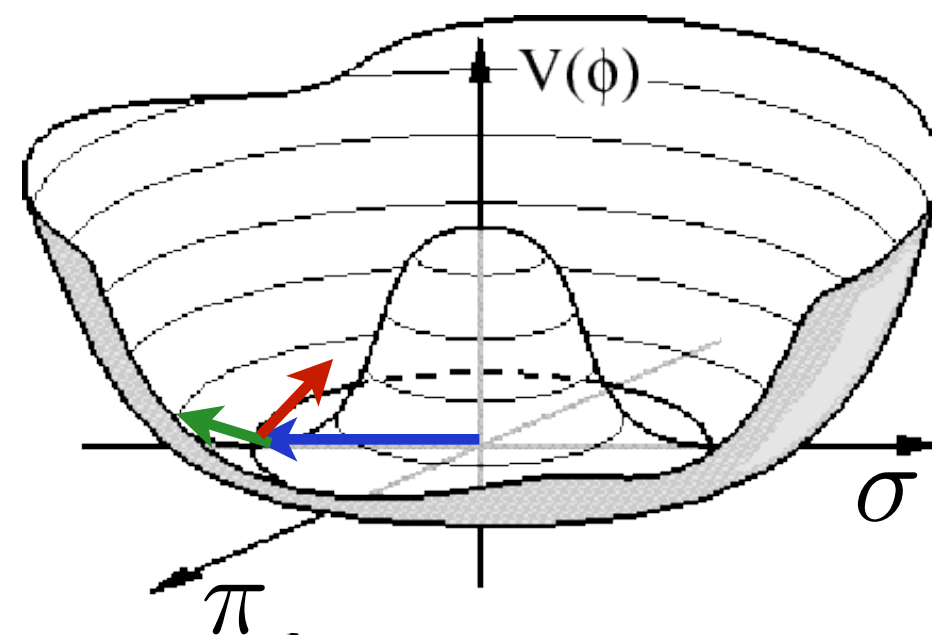
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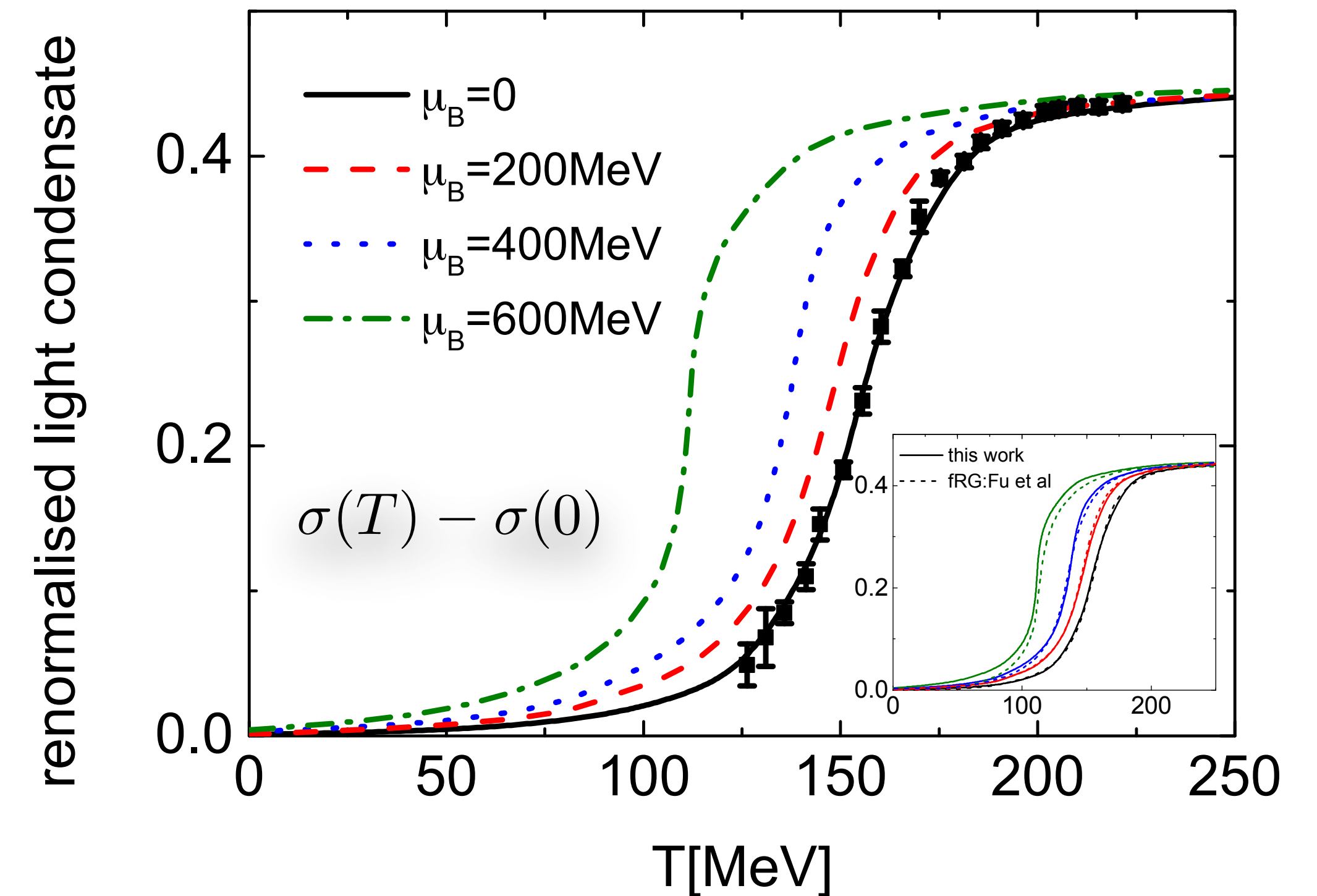


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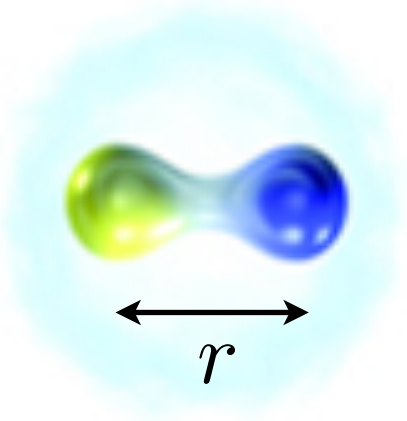
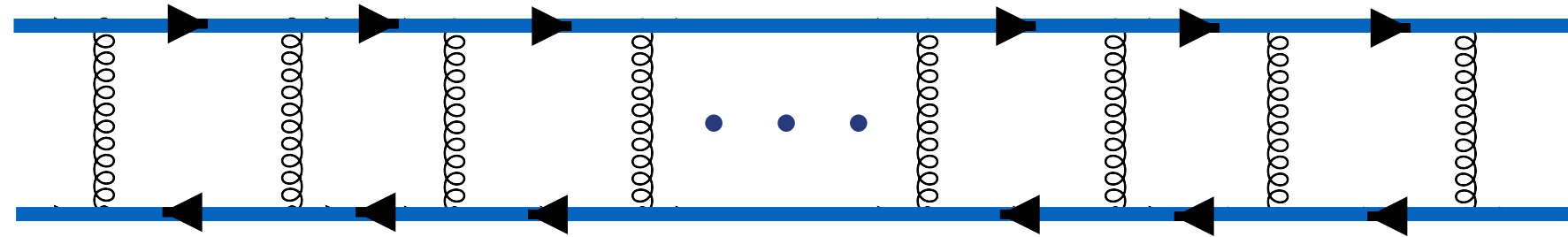
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QCD predictions from various approaches

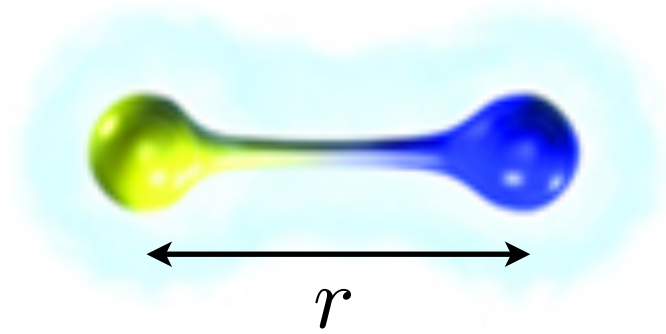


Confinement

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

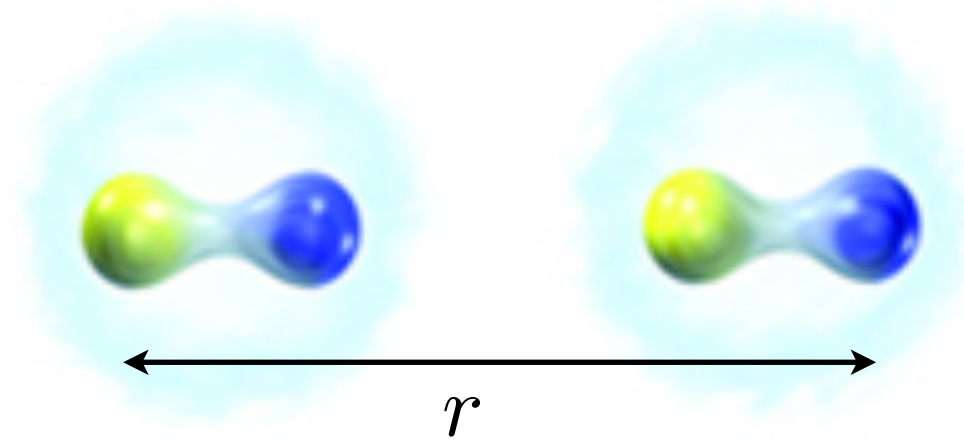
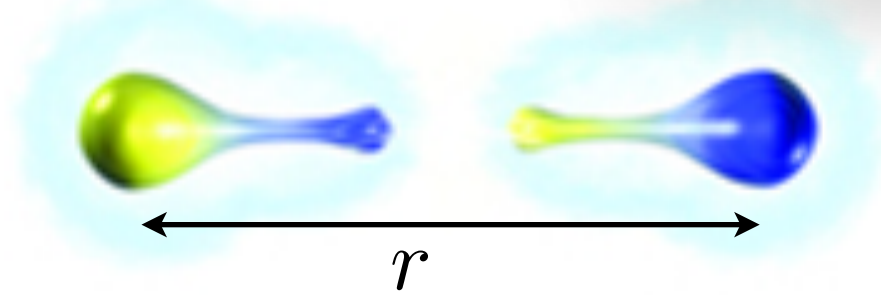


$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



$$F_{q\bar{q}} \simeq \sigma r$$

string breaking at $r \approx 1\text{fm}$

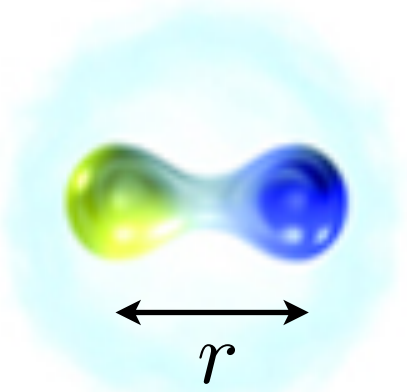
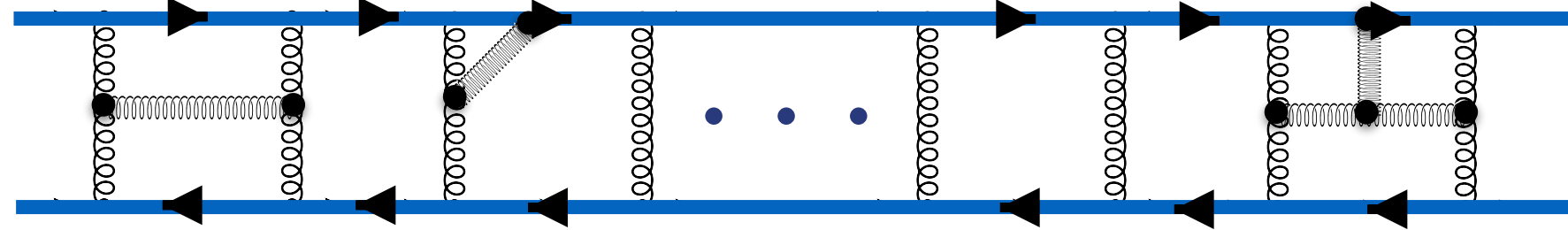


$$F_{q\bar{q}} \simeq \text{const.}$$

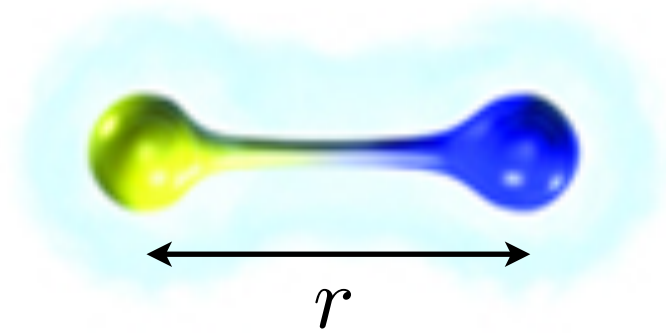
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Confinement: Gluon self-interaction

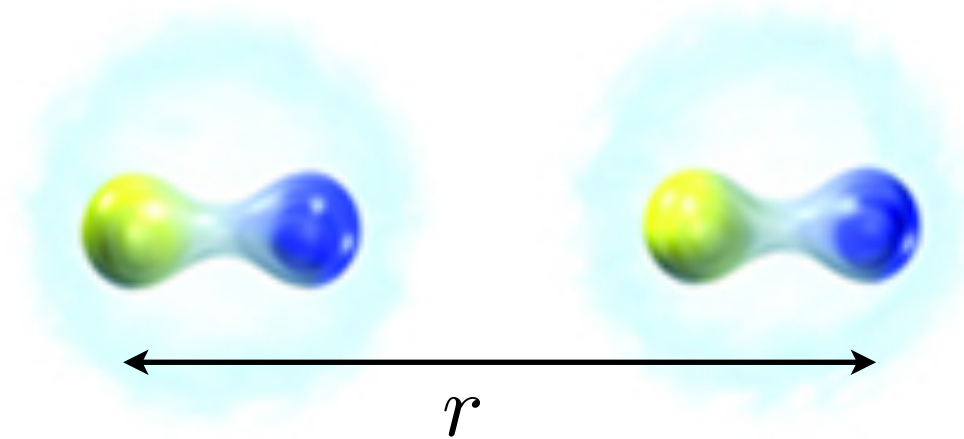
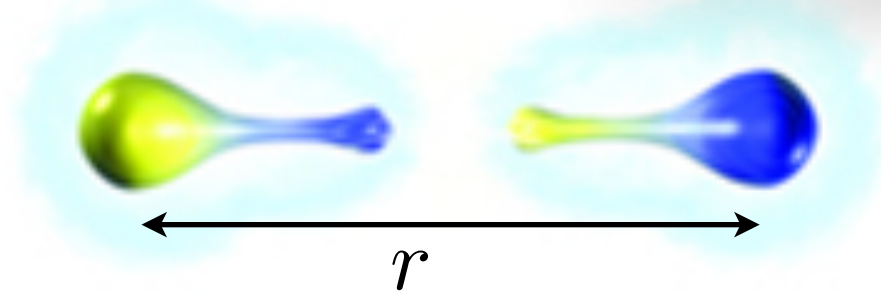


$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



$$F_{q\bar{q}} \simeq \sigma r$$

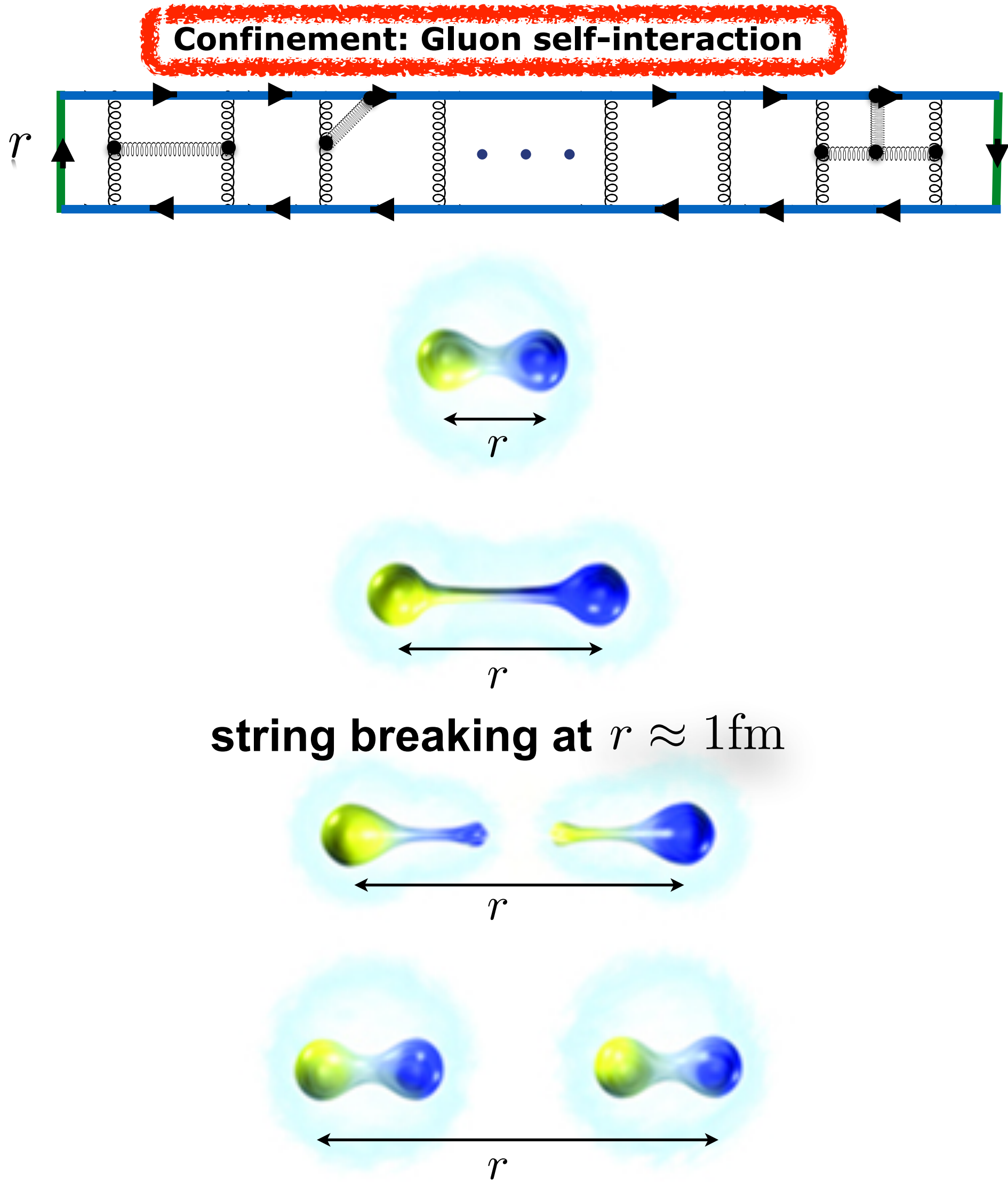
string breaking at $r \approx 1\text{fm}$



$$F_{q\bar{q}} \simeq \text{const.}$$

Confinement

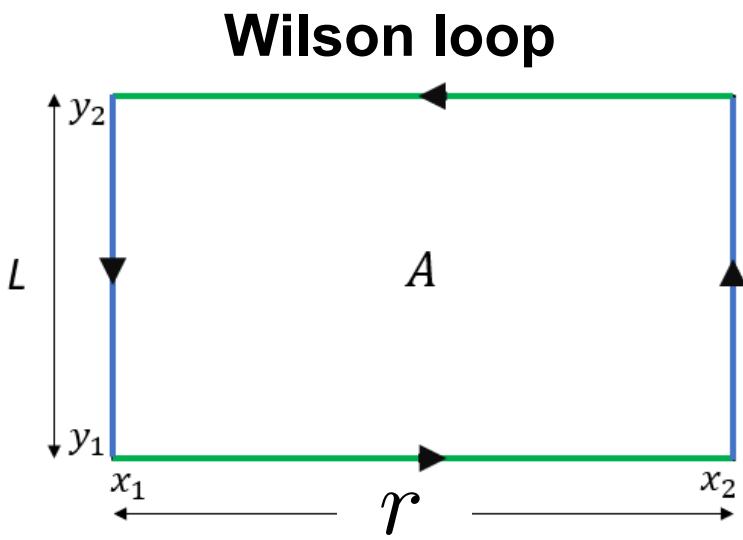
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



$$F_{q\bar{q}} \simeq -\frac{1}{r}$$

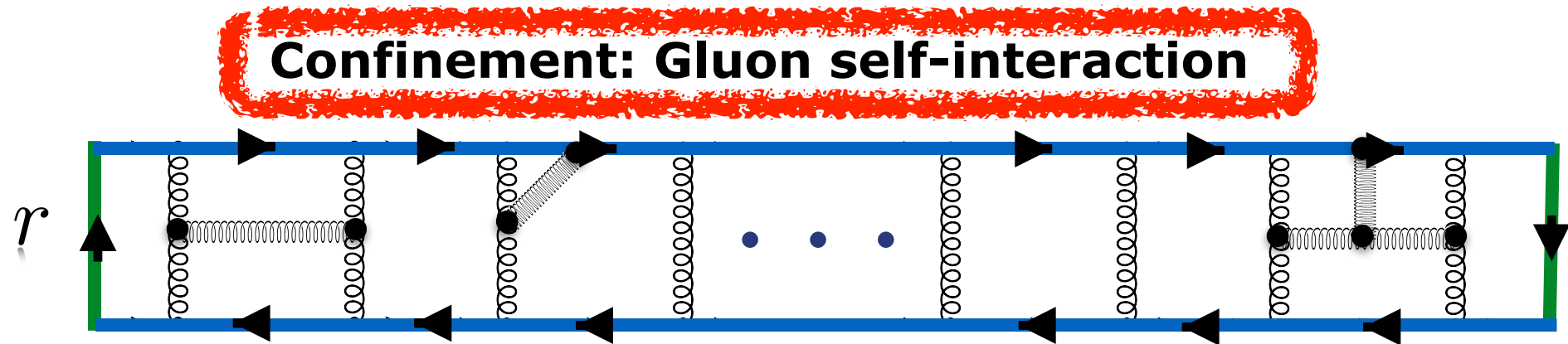
$$F_{q\bar{q}} \simeq \sigma r$$

$$F_{q\bar{q}} \simeq \text{const.}$$



Confinement

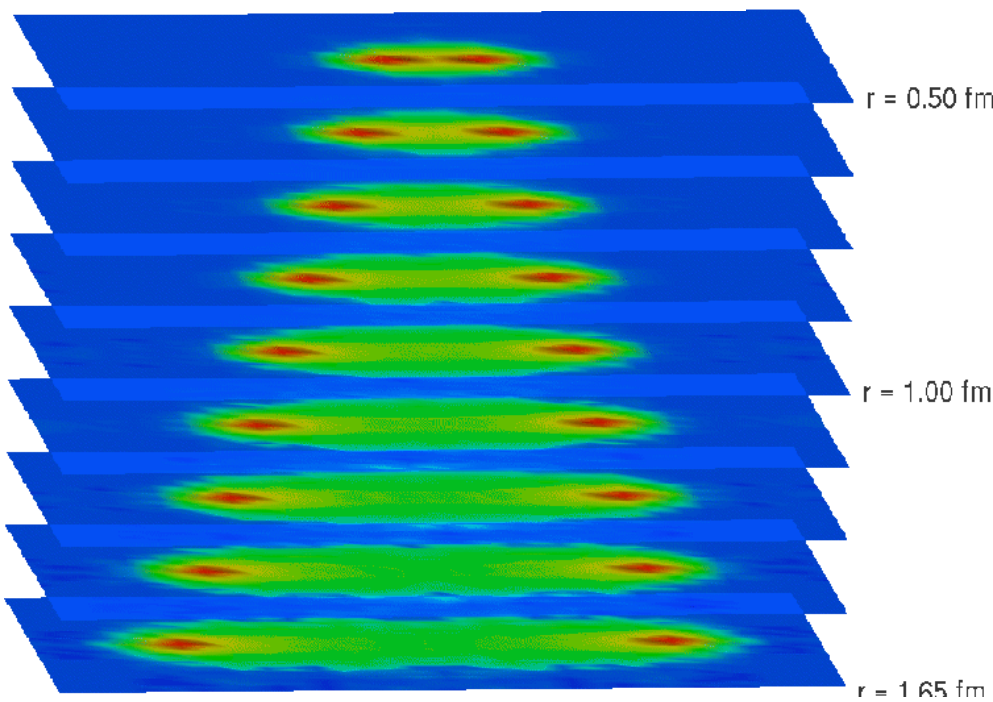
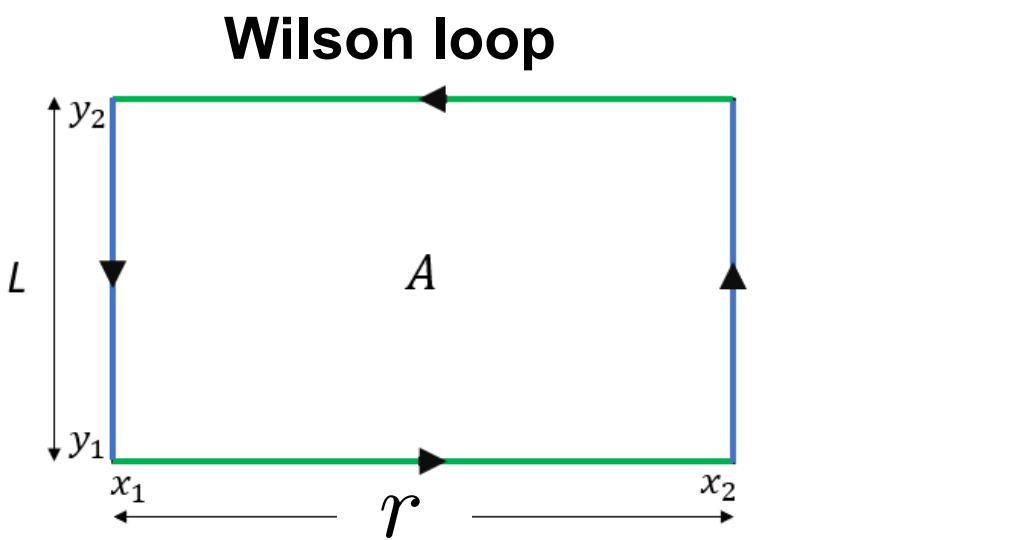
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



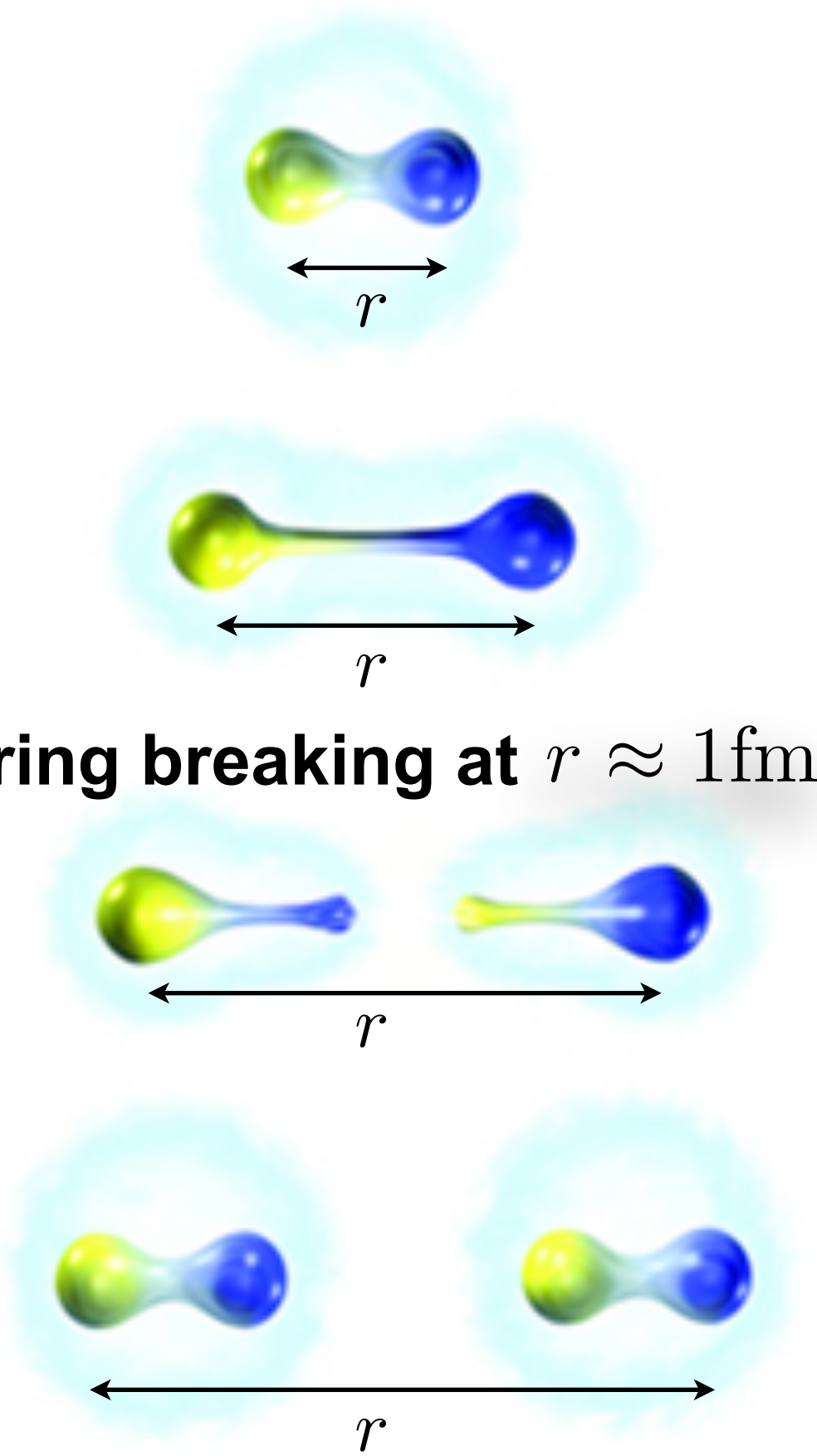
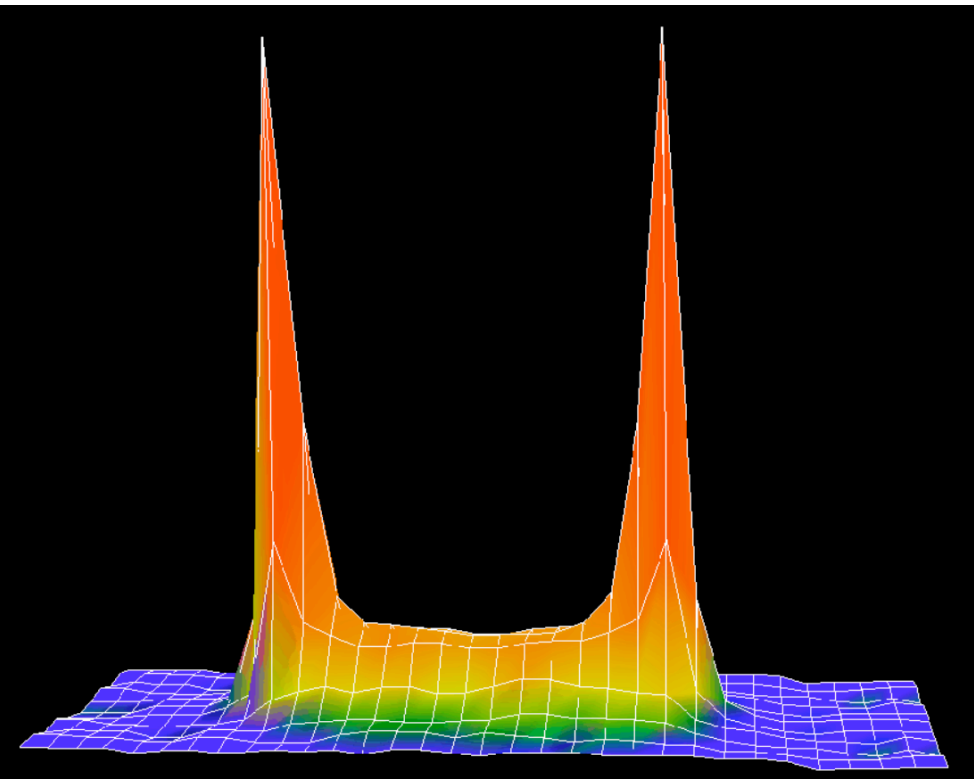
$$F_{q\bar{q}} \simeq -\frac{1}{r}$$

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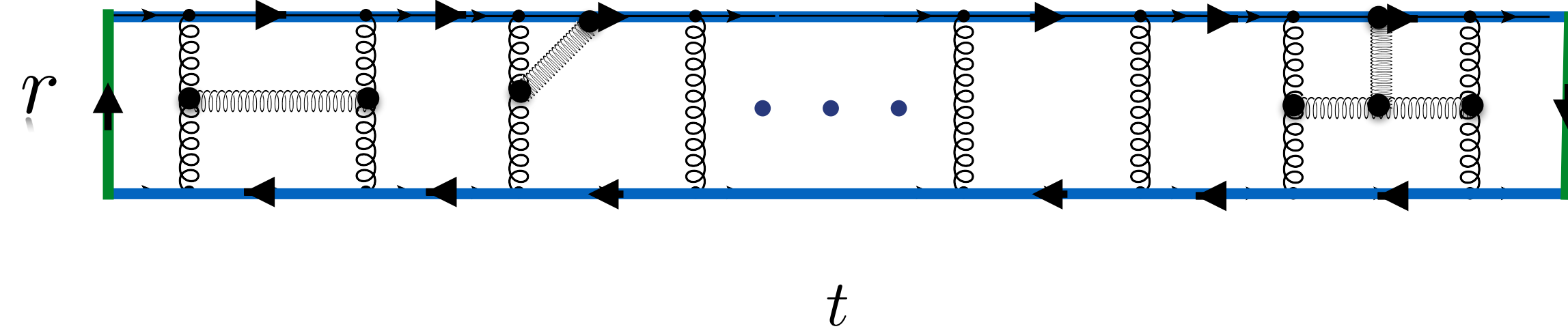
Energy density Bali et al. '94



string breaking at $r \approx 1\text{fm}$

Thermal confinement-deconfinement phase transition

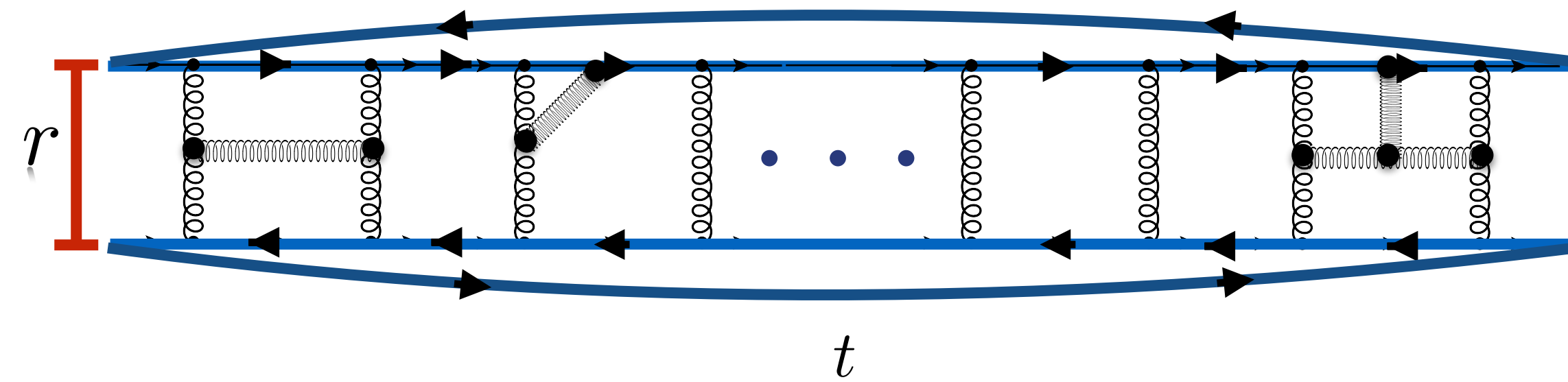
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



$$t < \frac{1}{T}$$

Thermal confinement-deconfinement phase transition

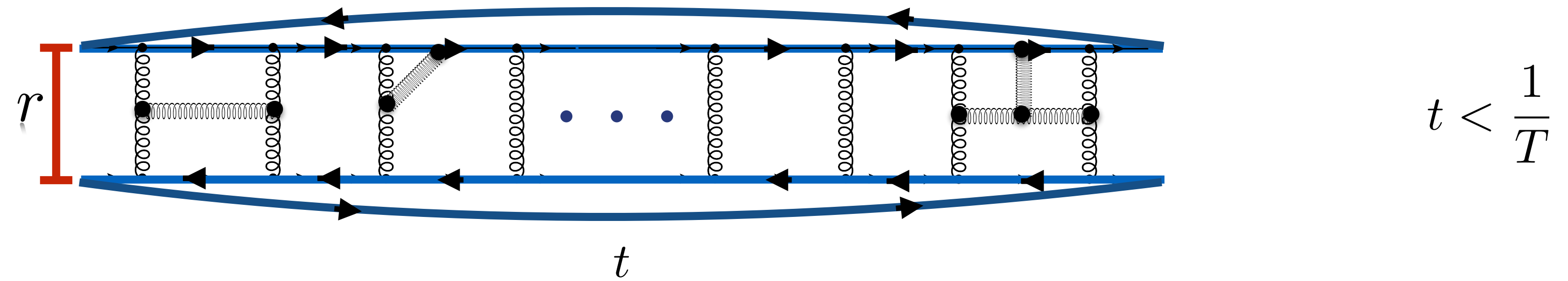
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



$$t < \frac{1}{T}$$

Thermal confinement-deconfinement phase transition

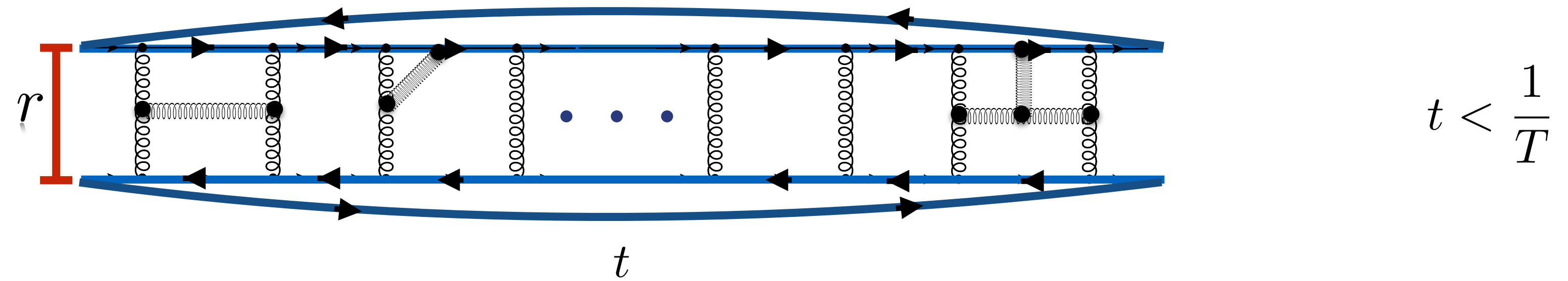
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



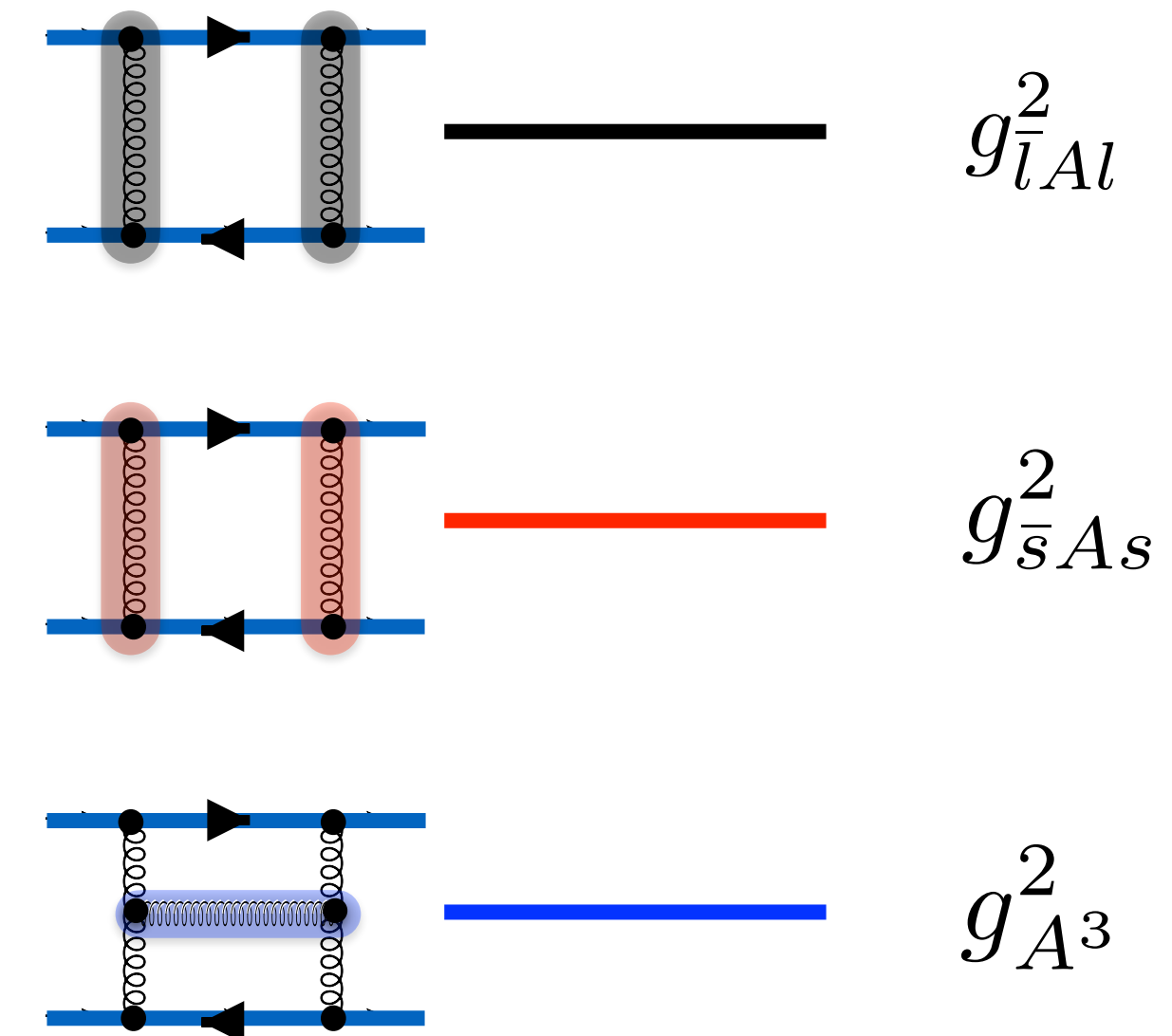
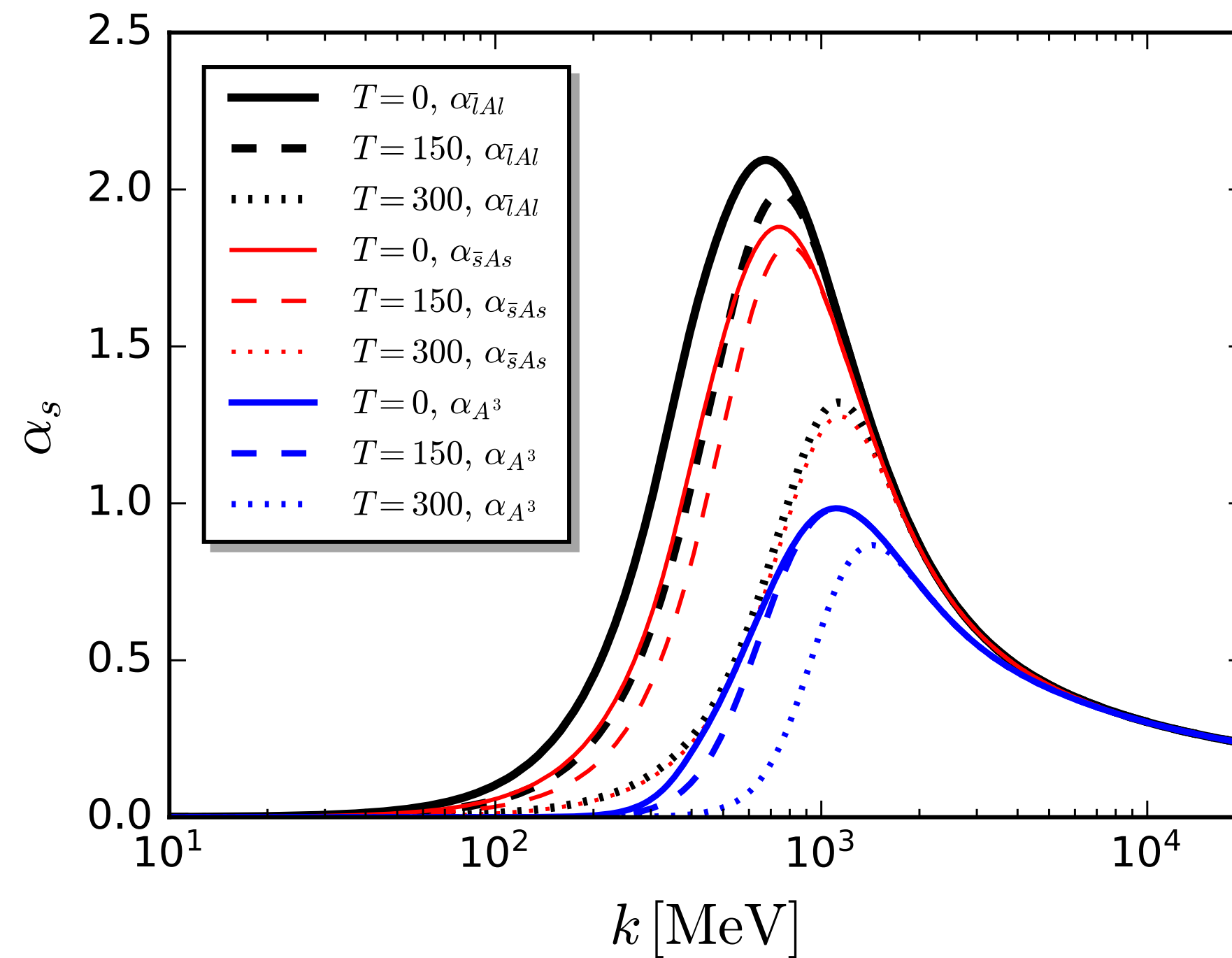
Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

Thermal confinement-deconfinement phase transition

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

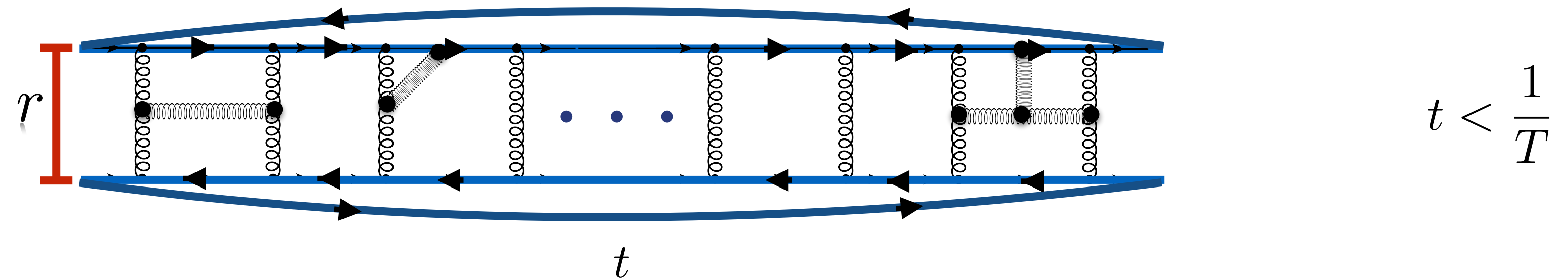


Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

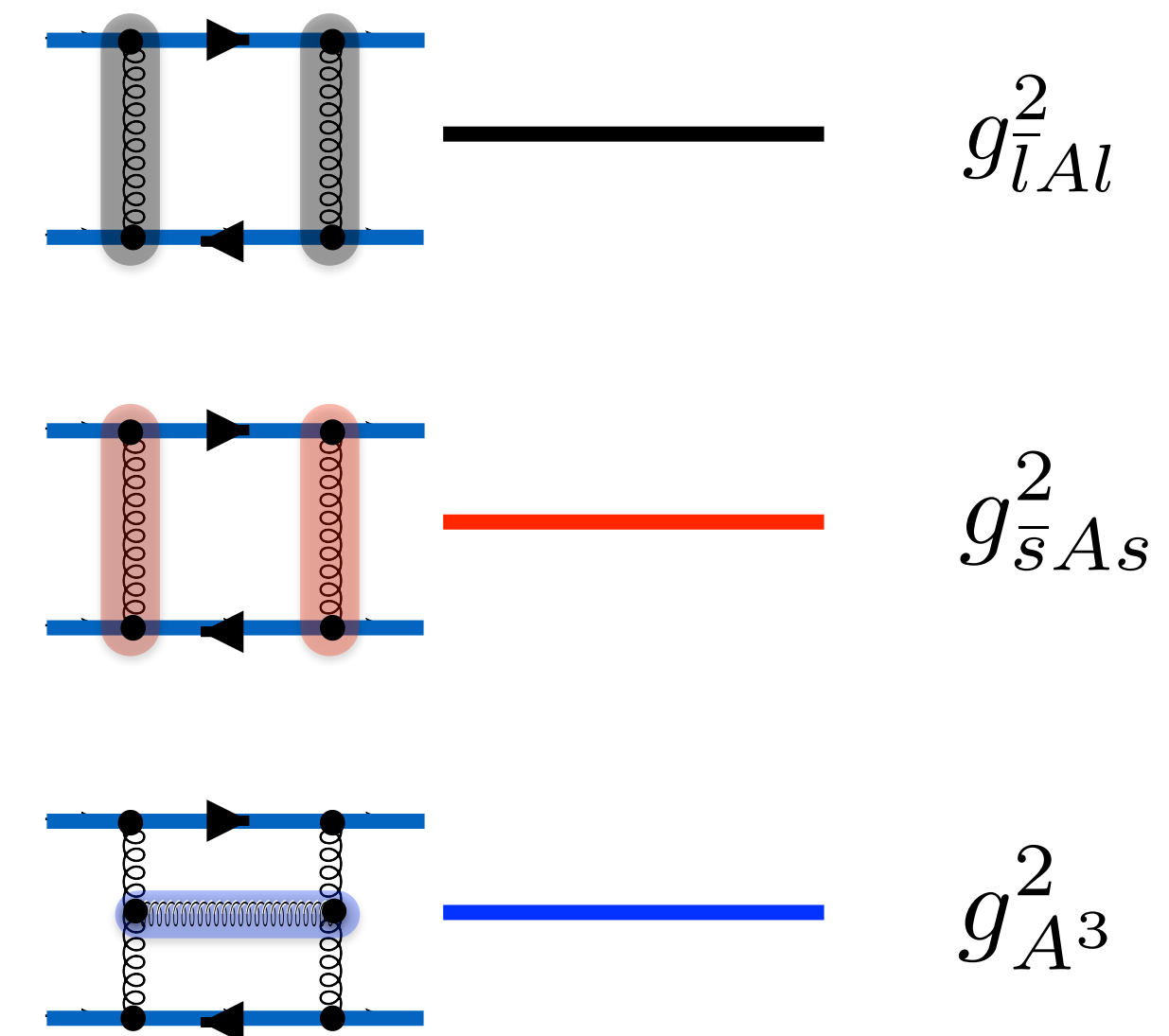
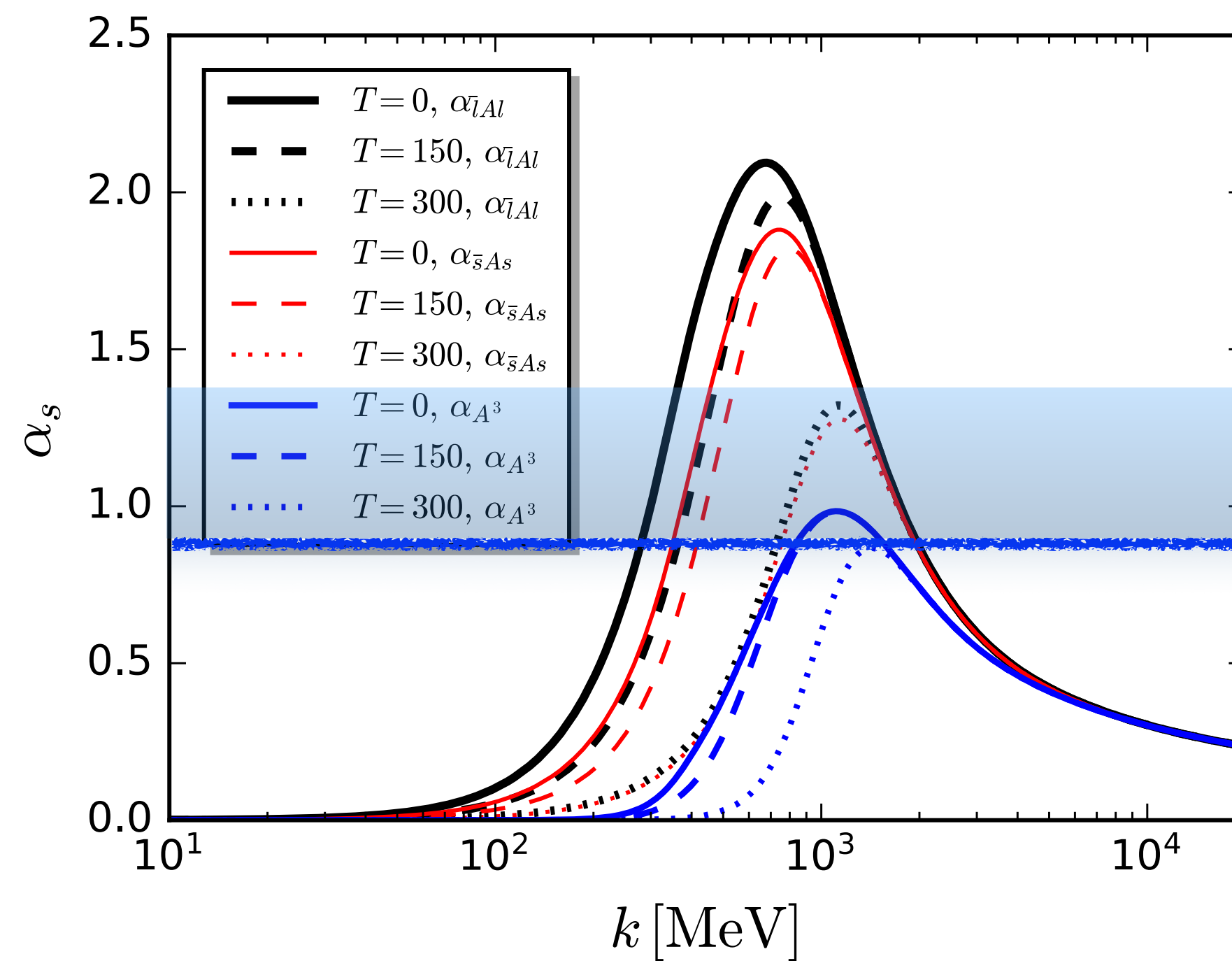


Thermal confinement-deconfinement phase transition

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

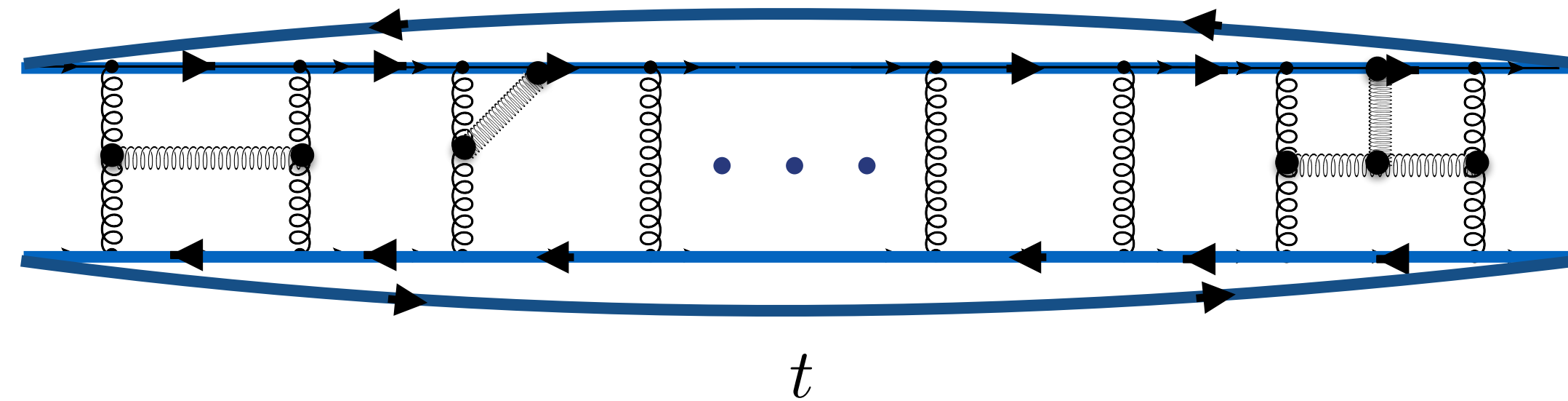


Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

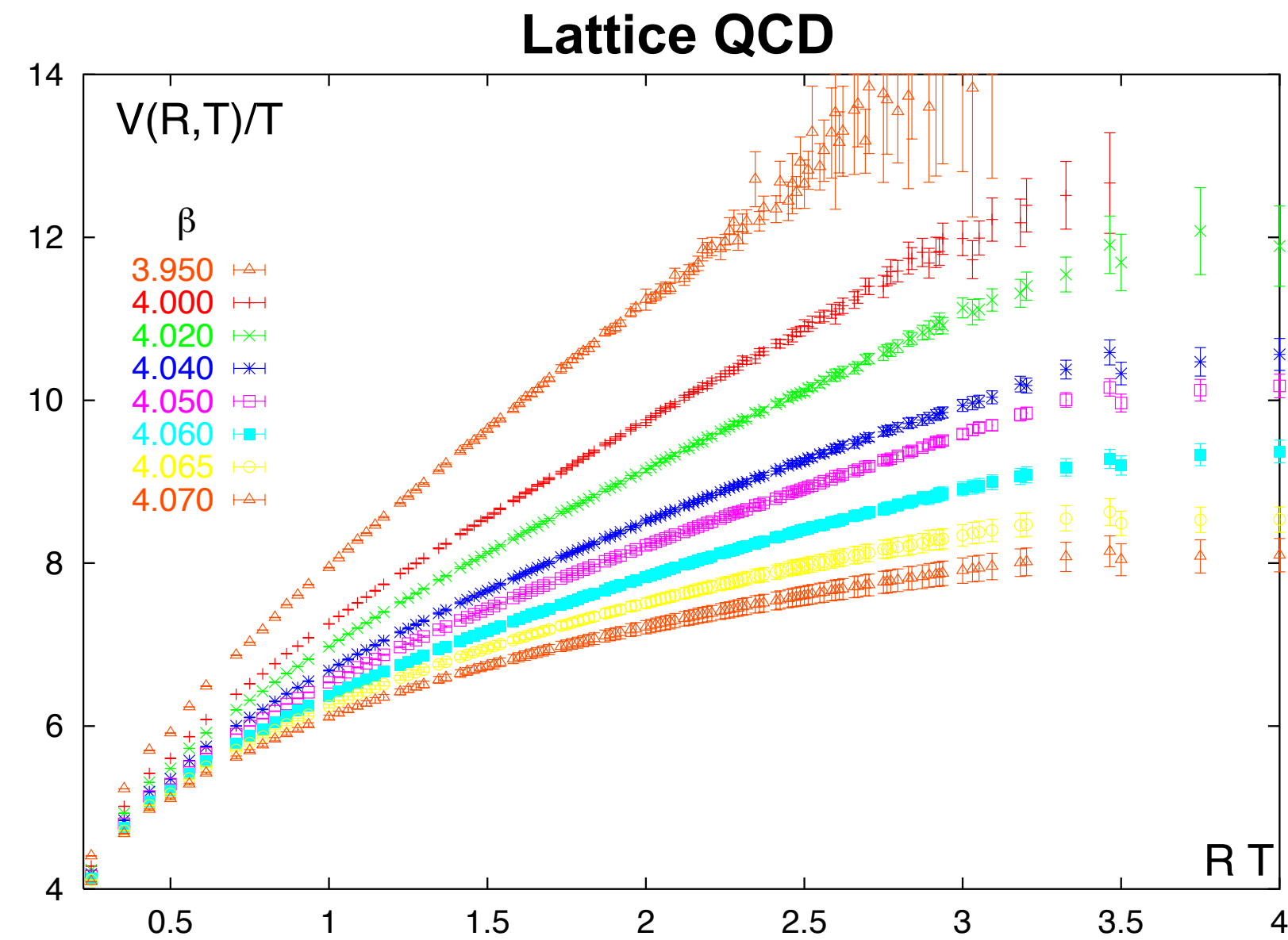


Thermal confinement-deconfinement phase transition

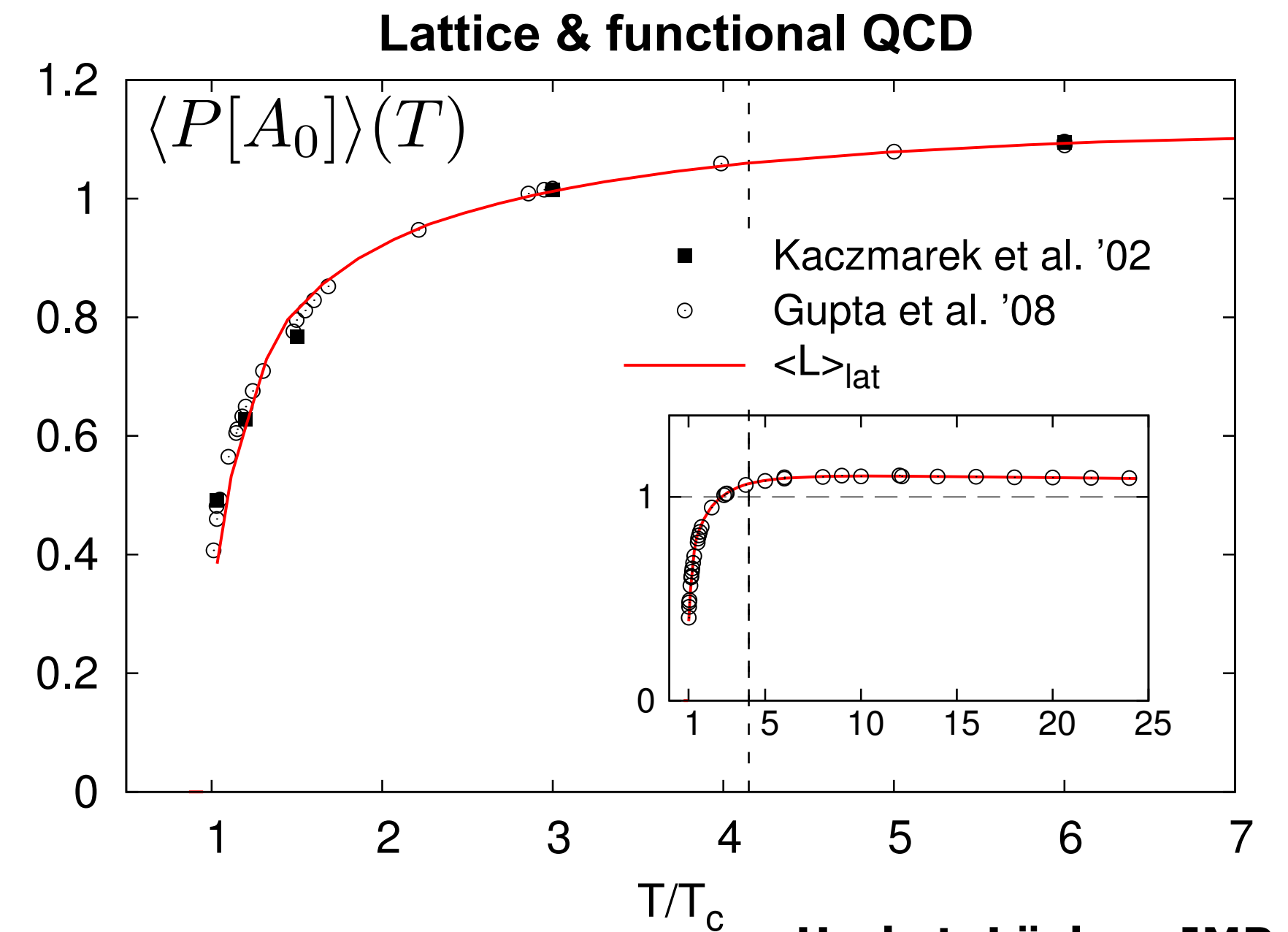
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$



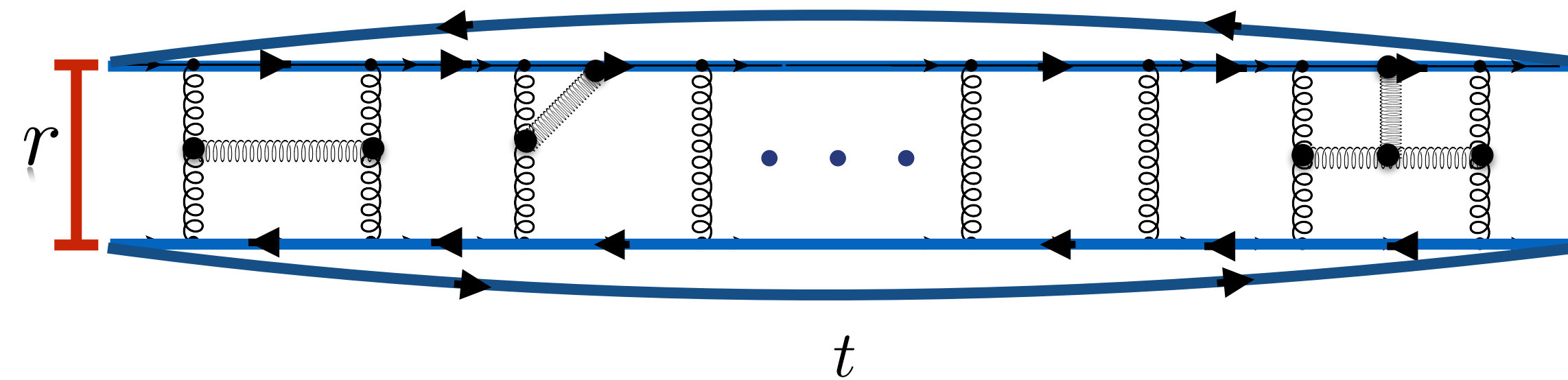
Kaczmarek et al '99



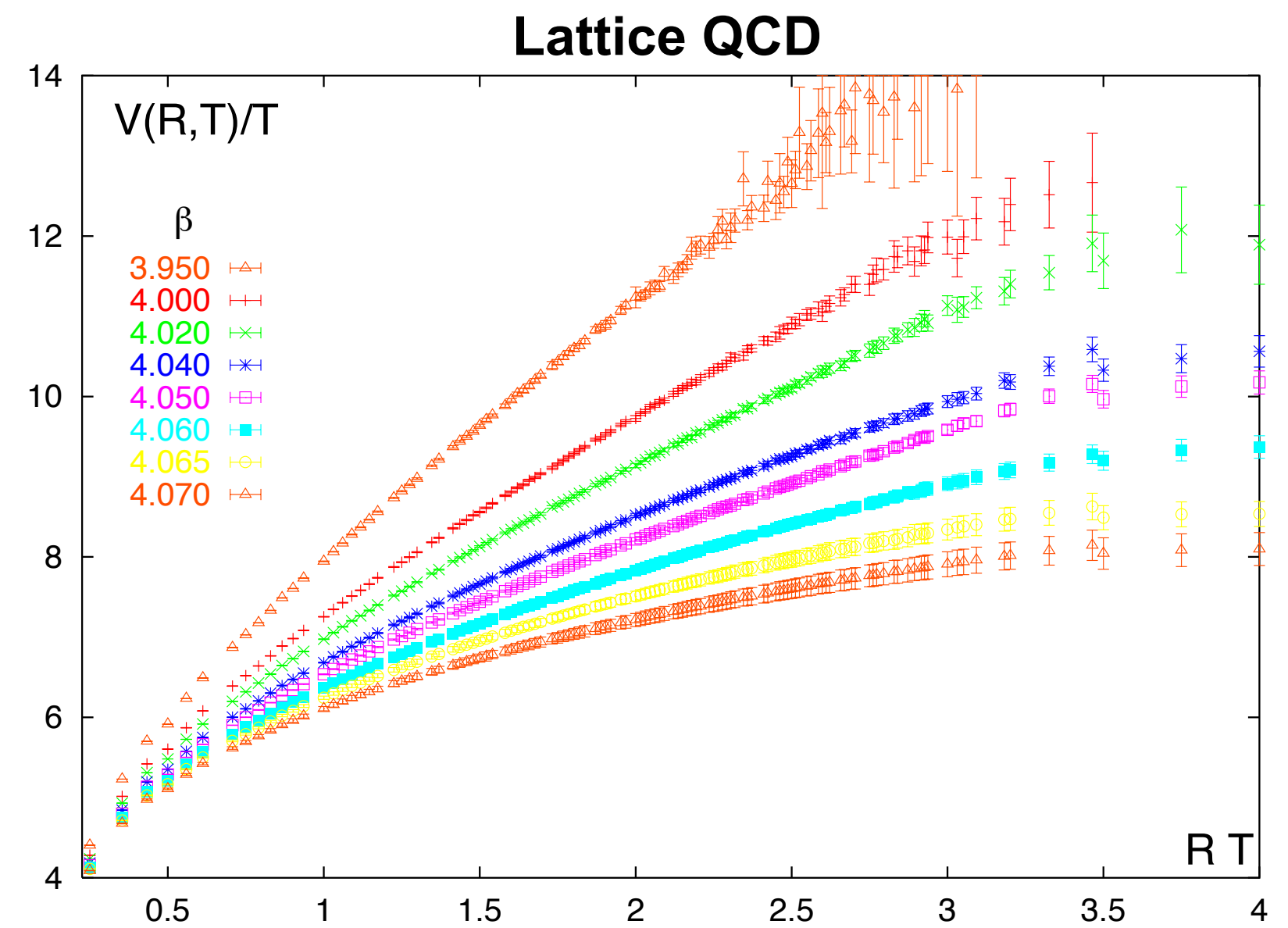
Herbst, Lücker, JMP, 2015

Thermal confinement-deconfinement phase transition

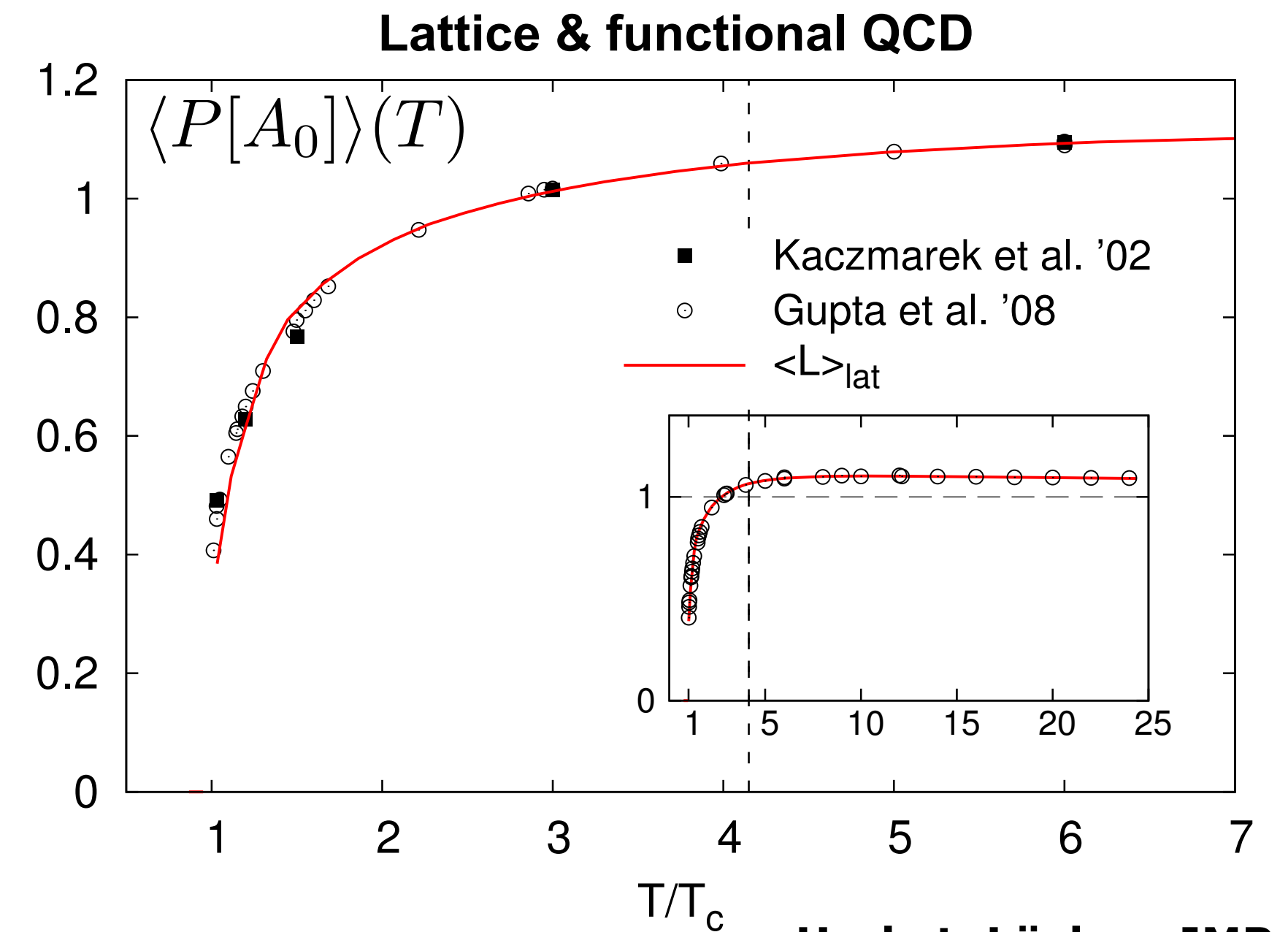
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$



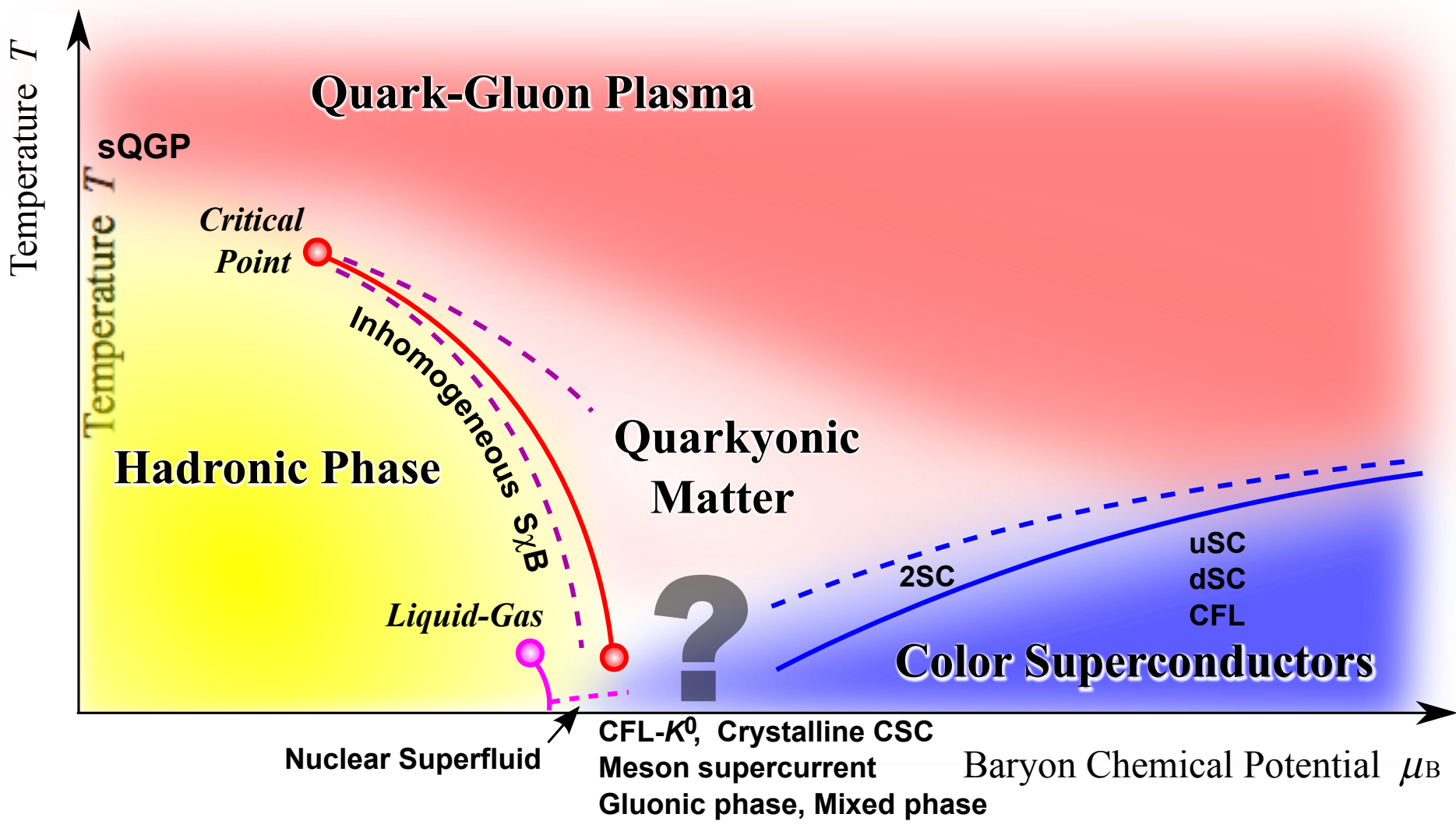
Kaczmarek et al '99



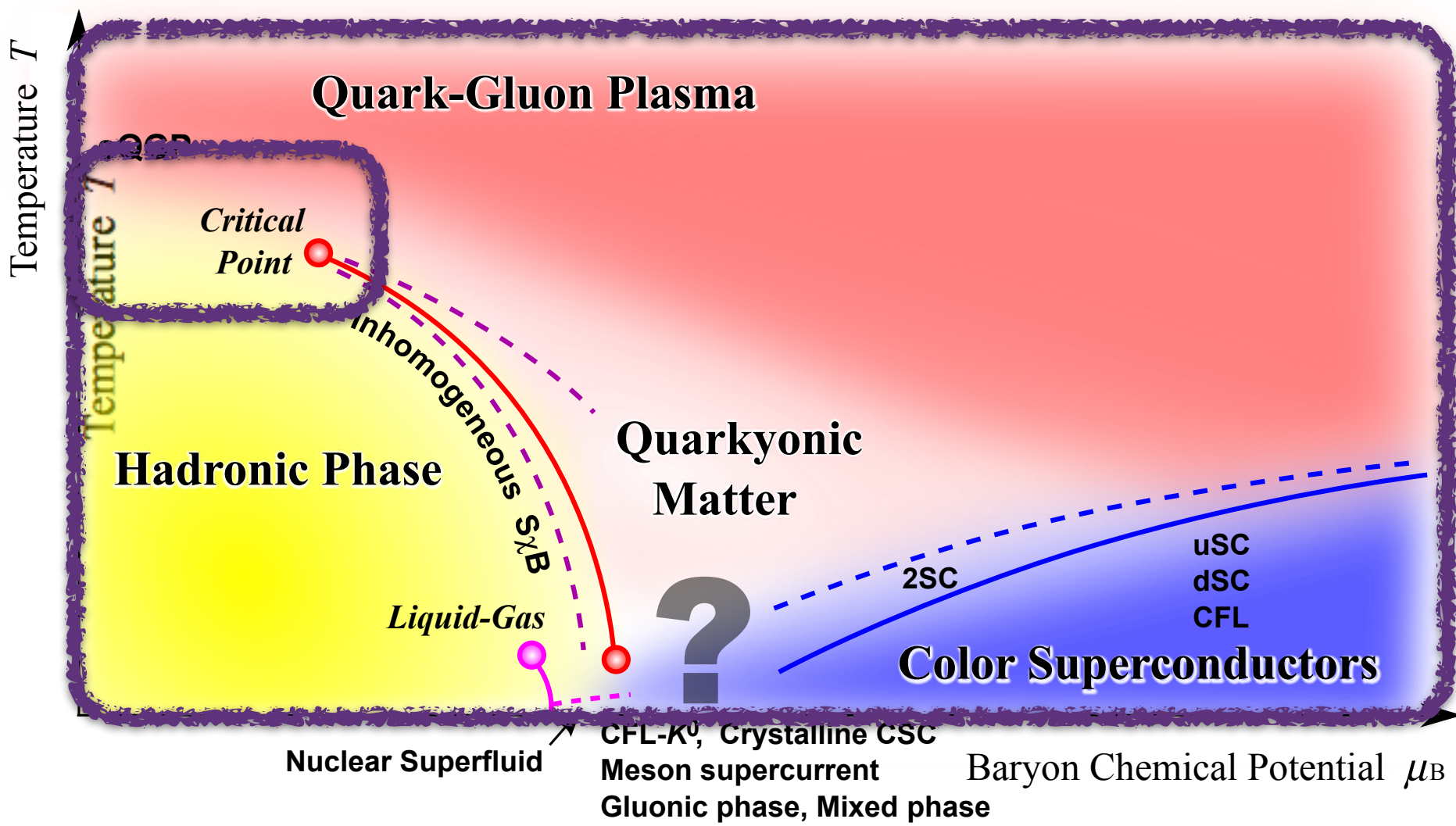
Herbst, Lücker, JMP, 2015

The physics of the QCD phase diagram & the experimental landscape

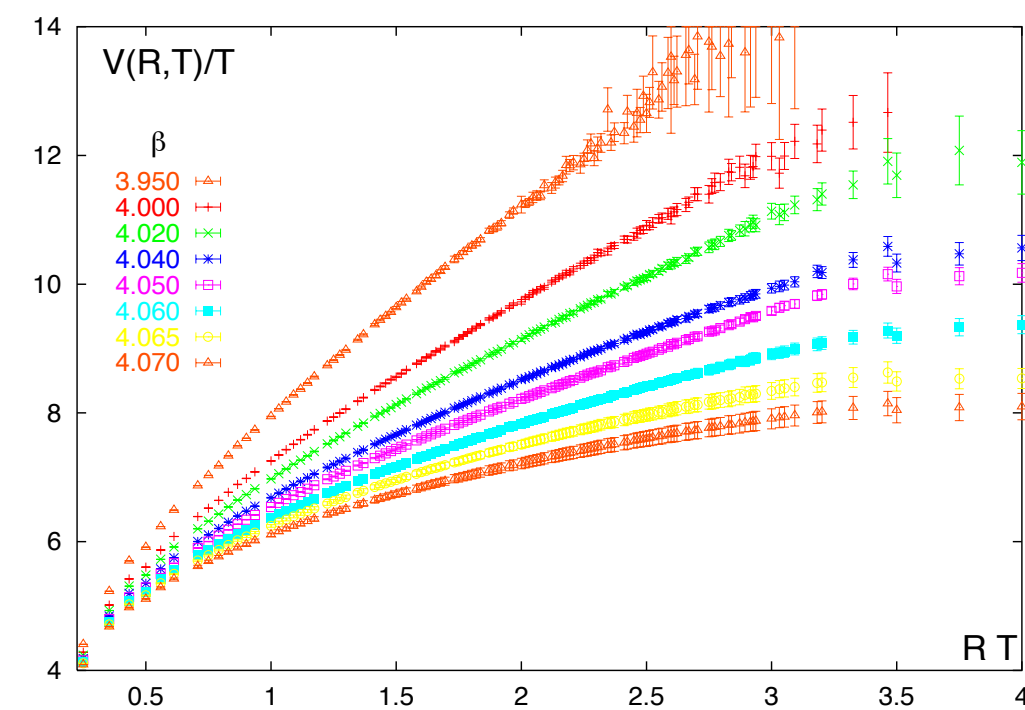
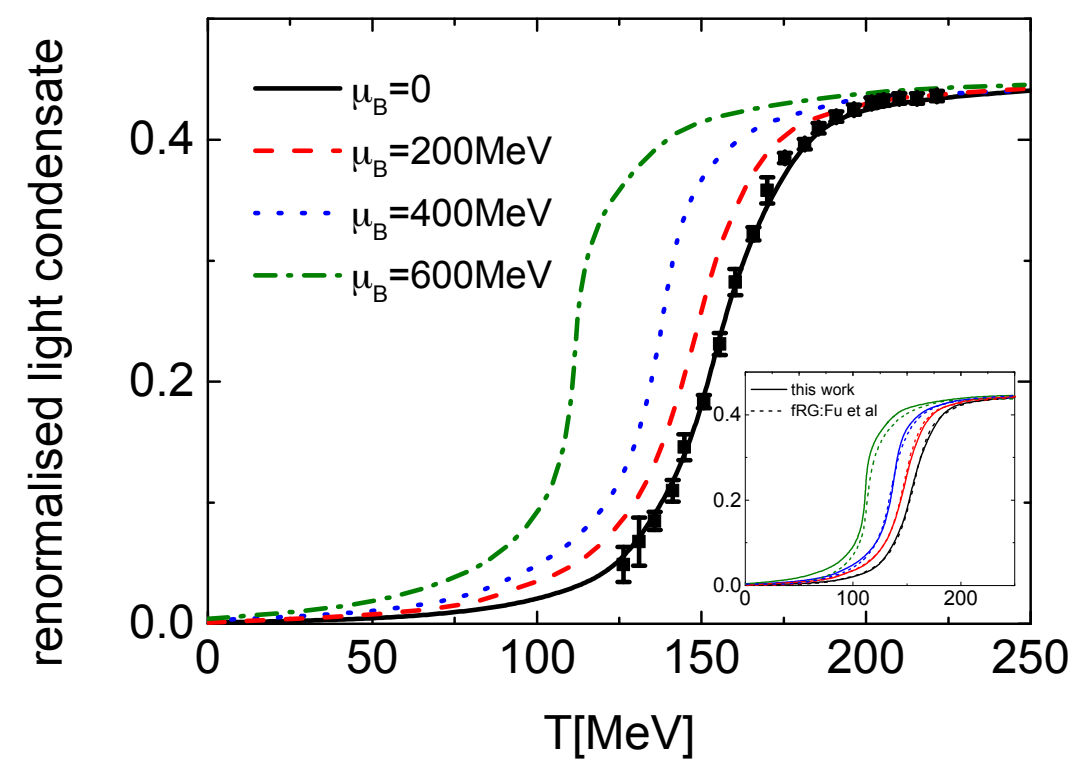
QCD phase structure



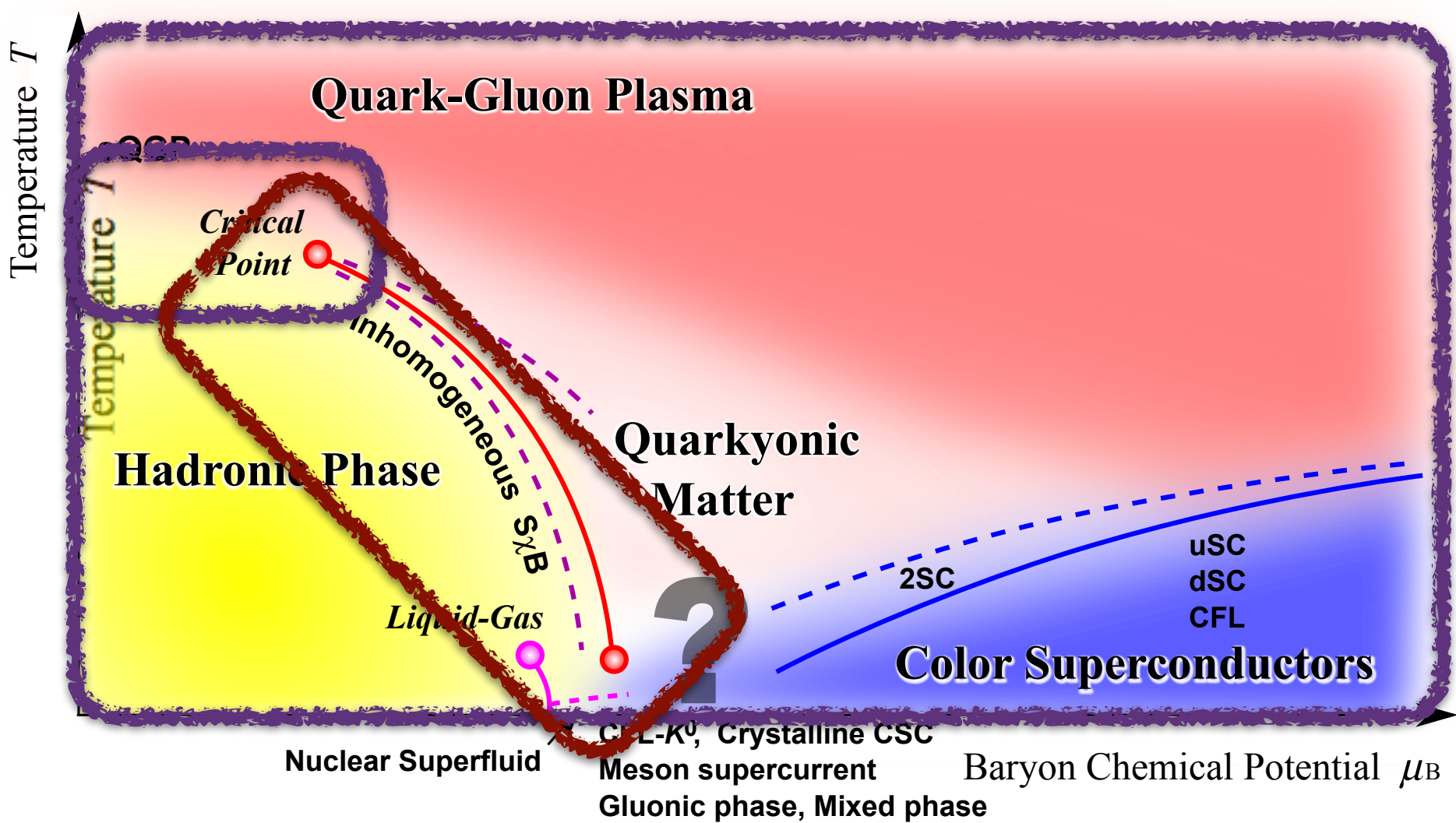
QCD phase structure



Chiral symmetry breaking & Confinement: the search for the CEP



QCD phase structure

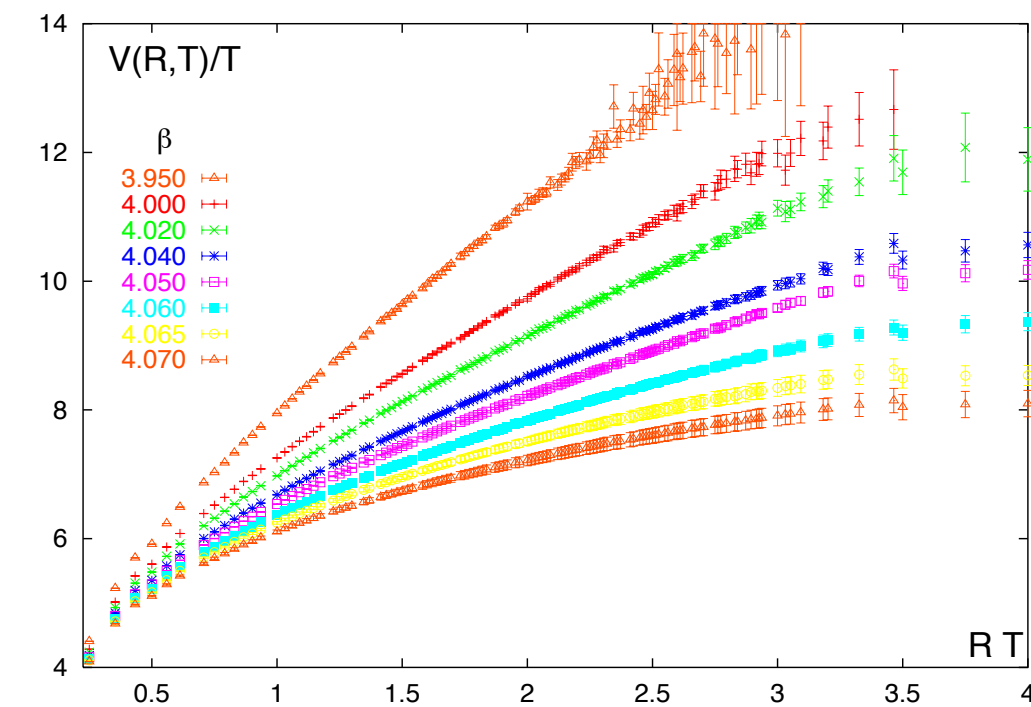
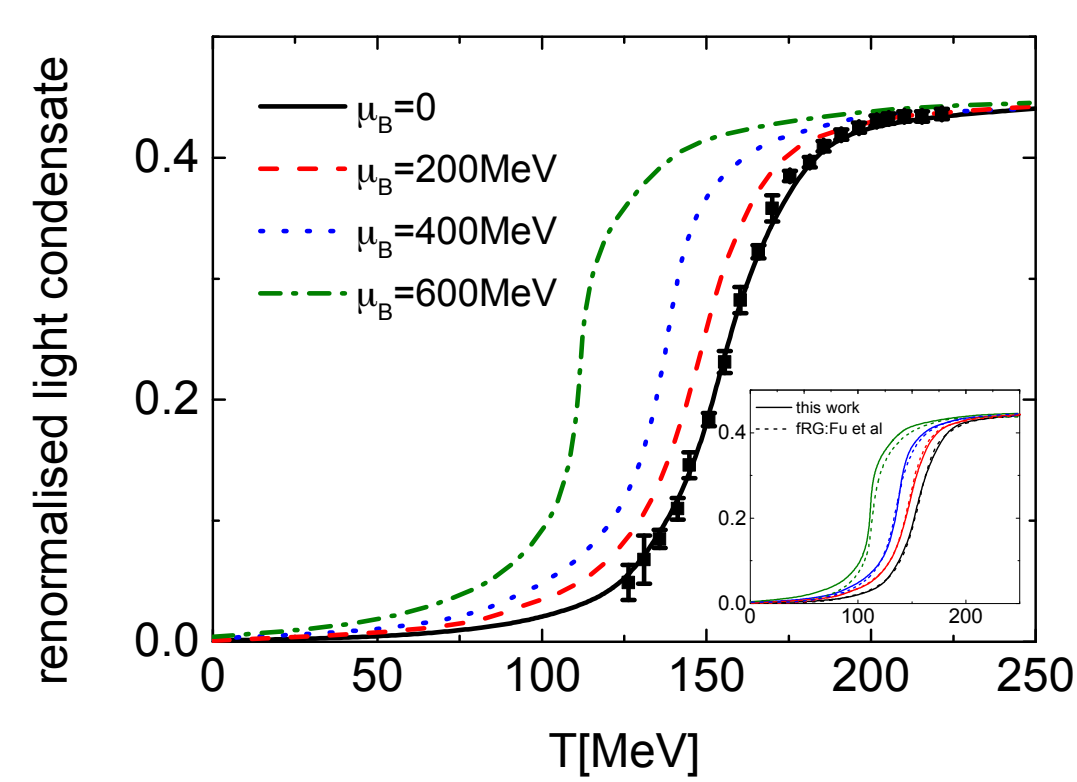


Moat regime & inhomogeneous phases: CEP & beyond

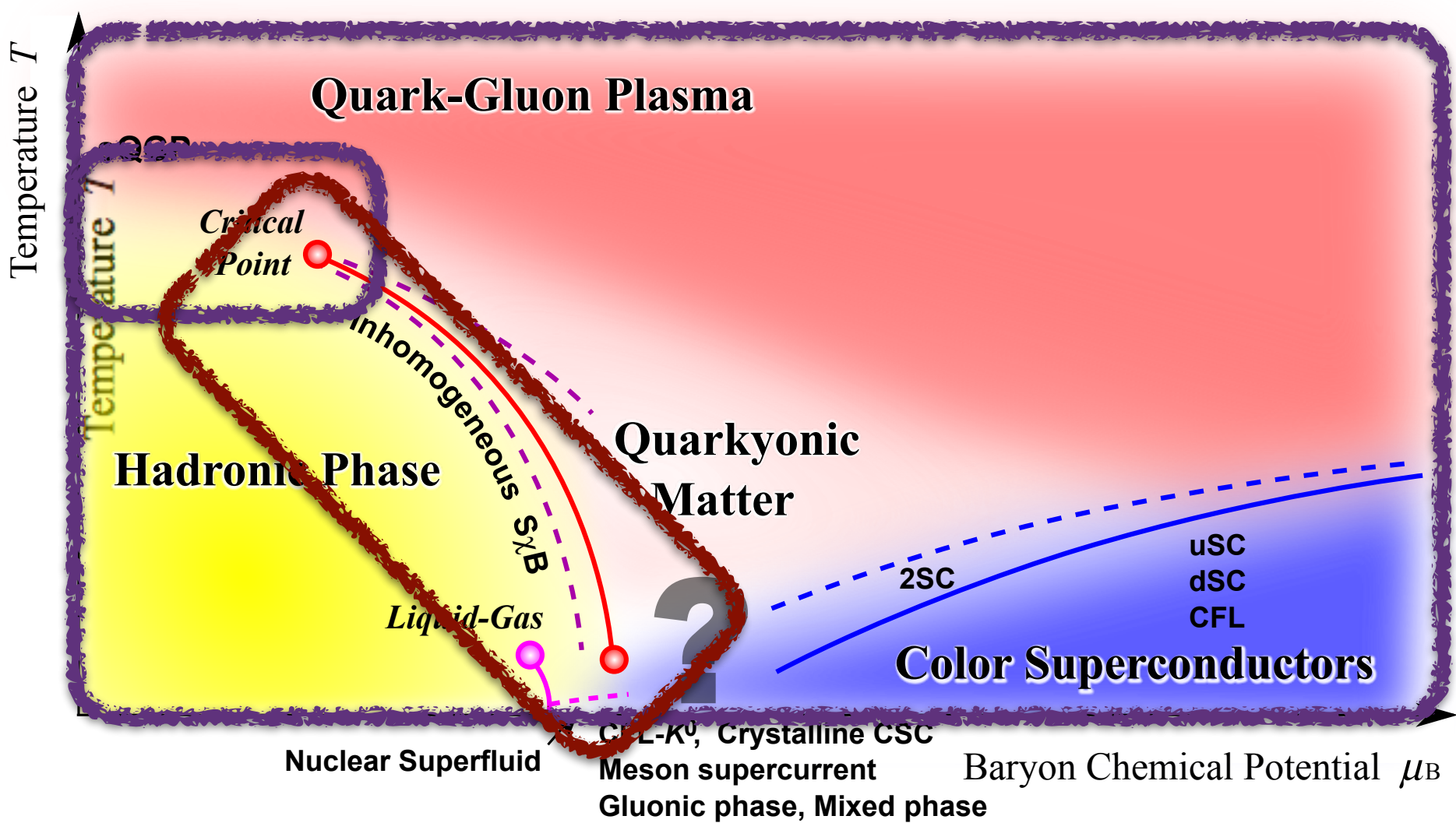
Signatures of the QCD Moat: Fu, JMP, Rennecke, PRD 101 (2020) 054032

QCD Moat: Pisarski, Rennecke, PRL 127 (2021) 152302

Chiral symmetry breaking & Confinement: the search for the CEP



QCD phase structure



Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



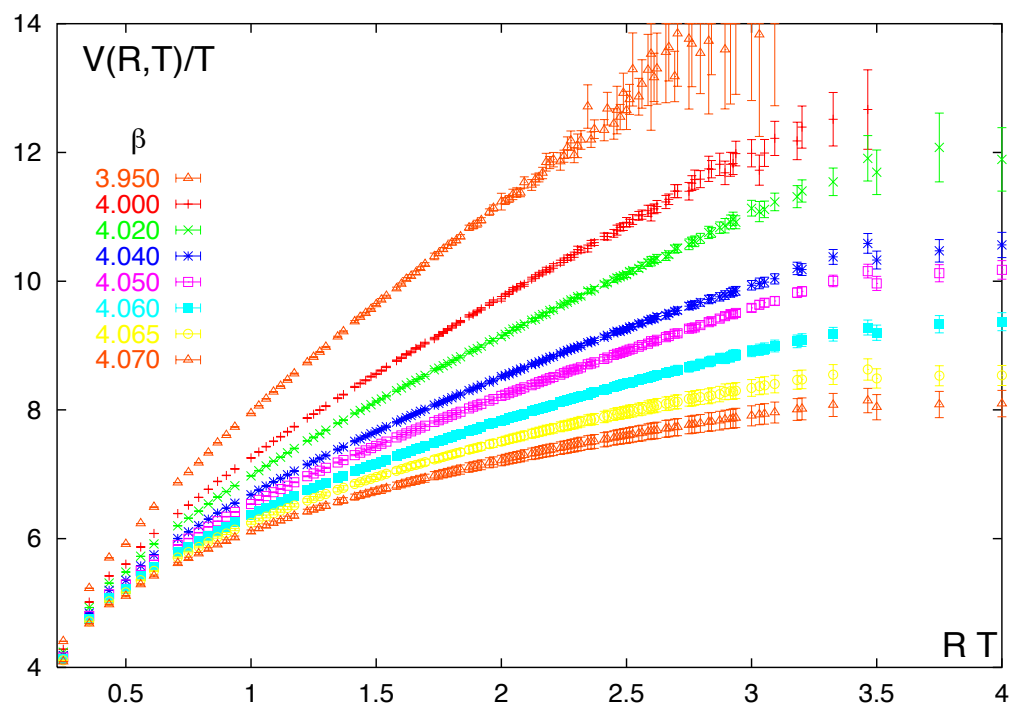
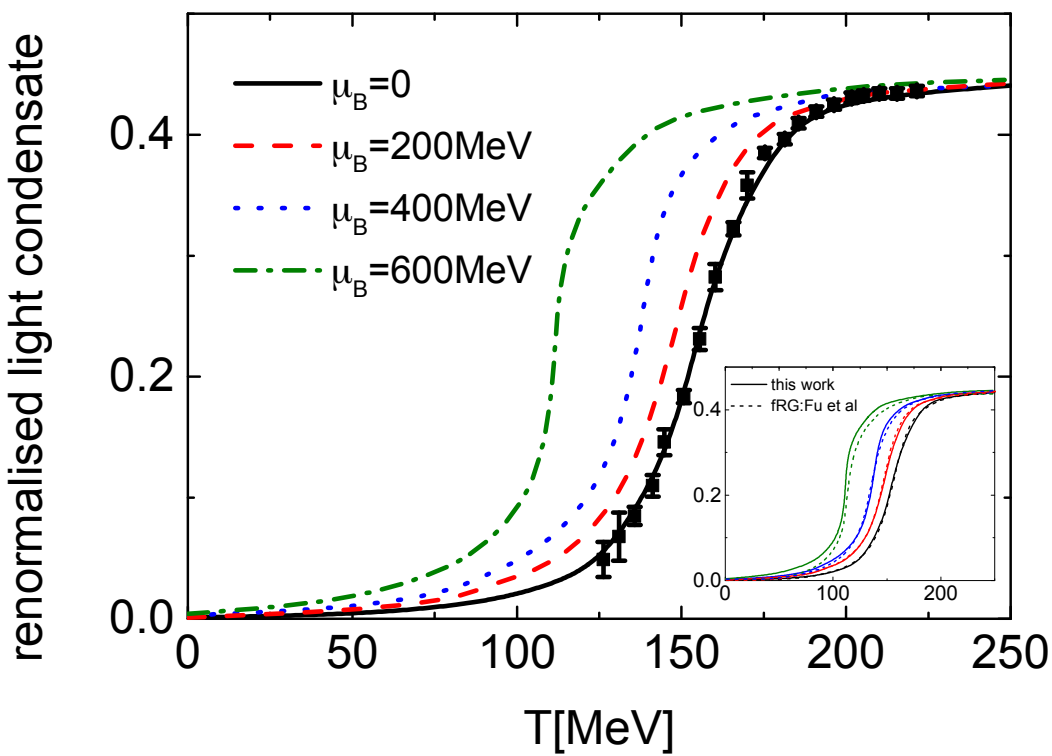
Wikimedia commons:
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US Moat

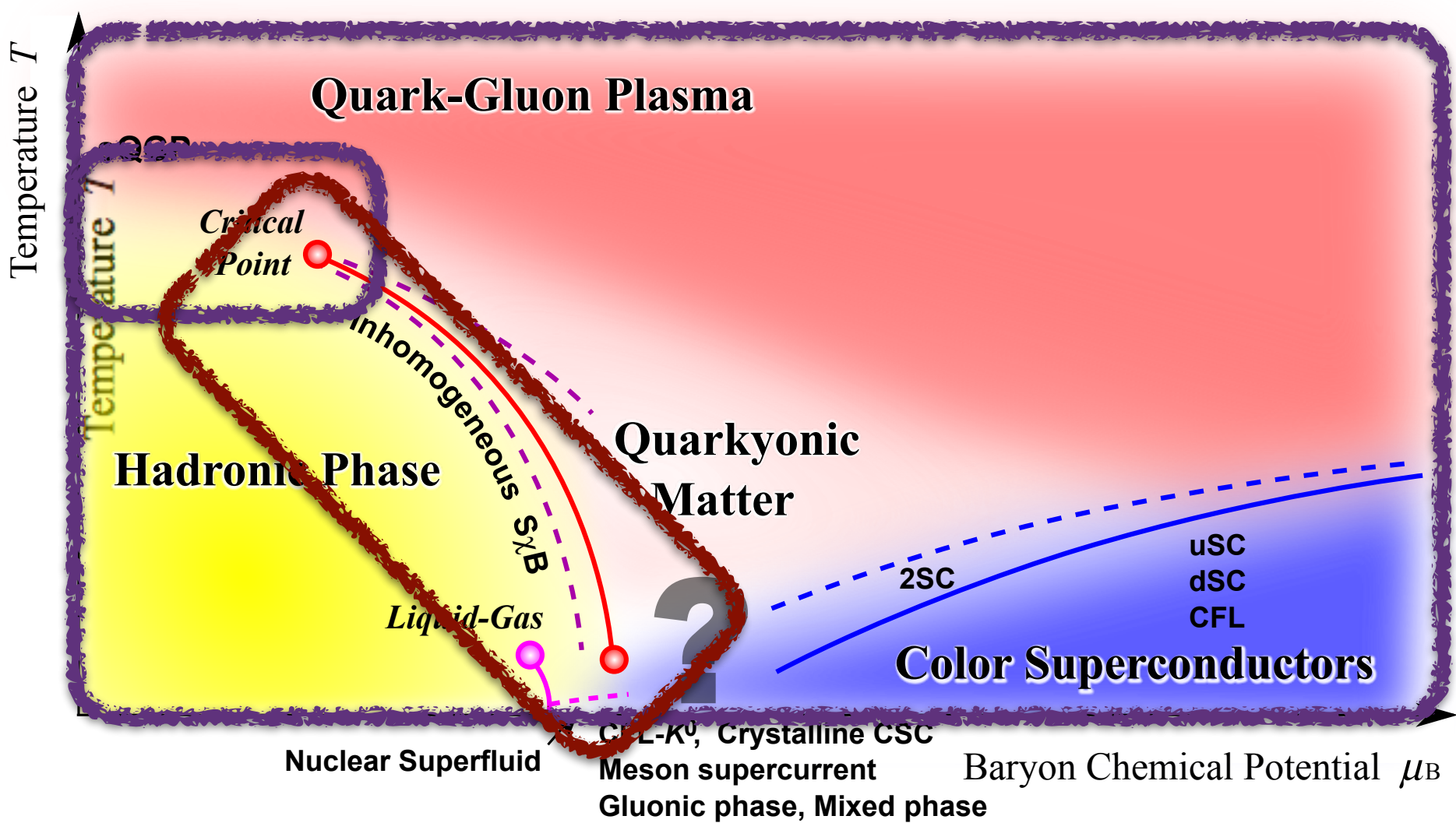


Wikipedia

Chiral symmetry breaking & Confinement: the search for the CEP



QCD phase structure



Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



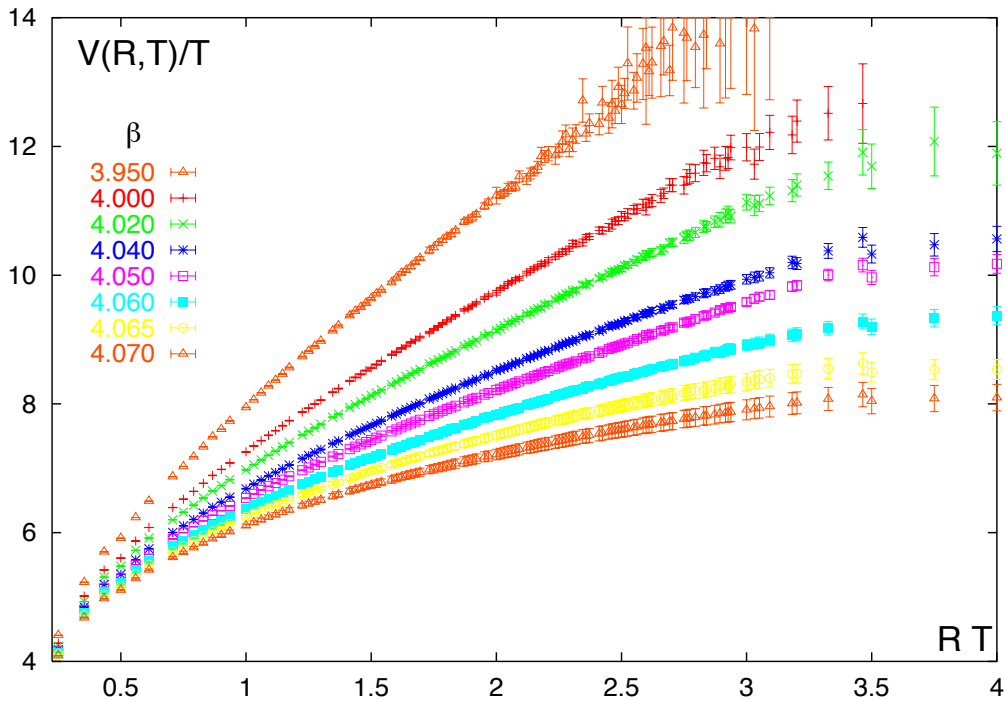
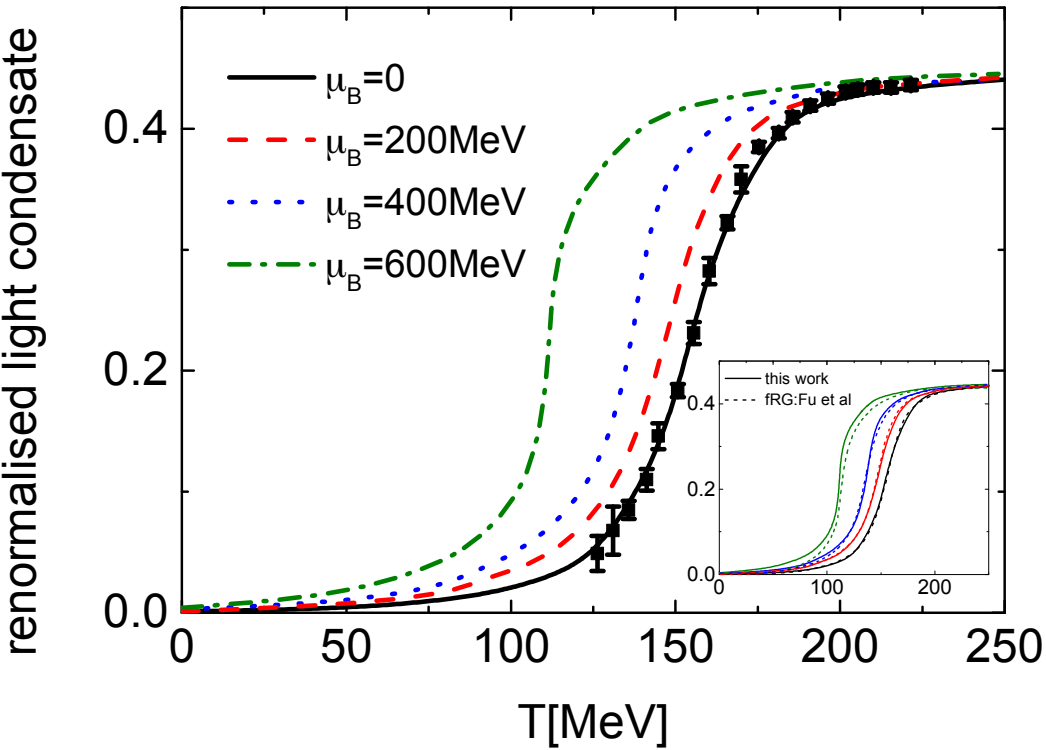
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US Moat

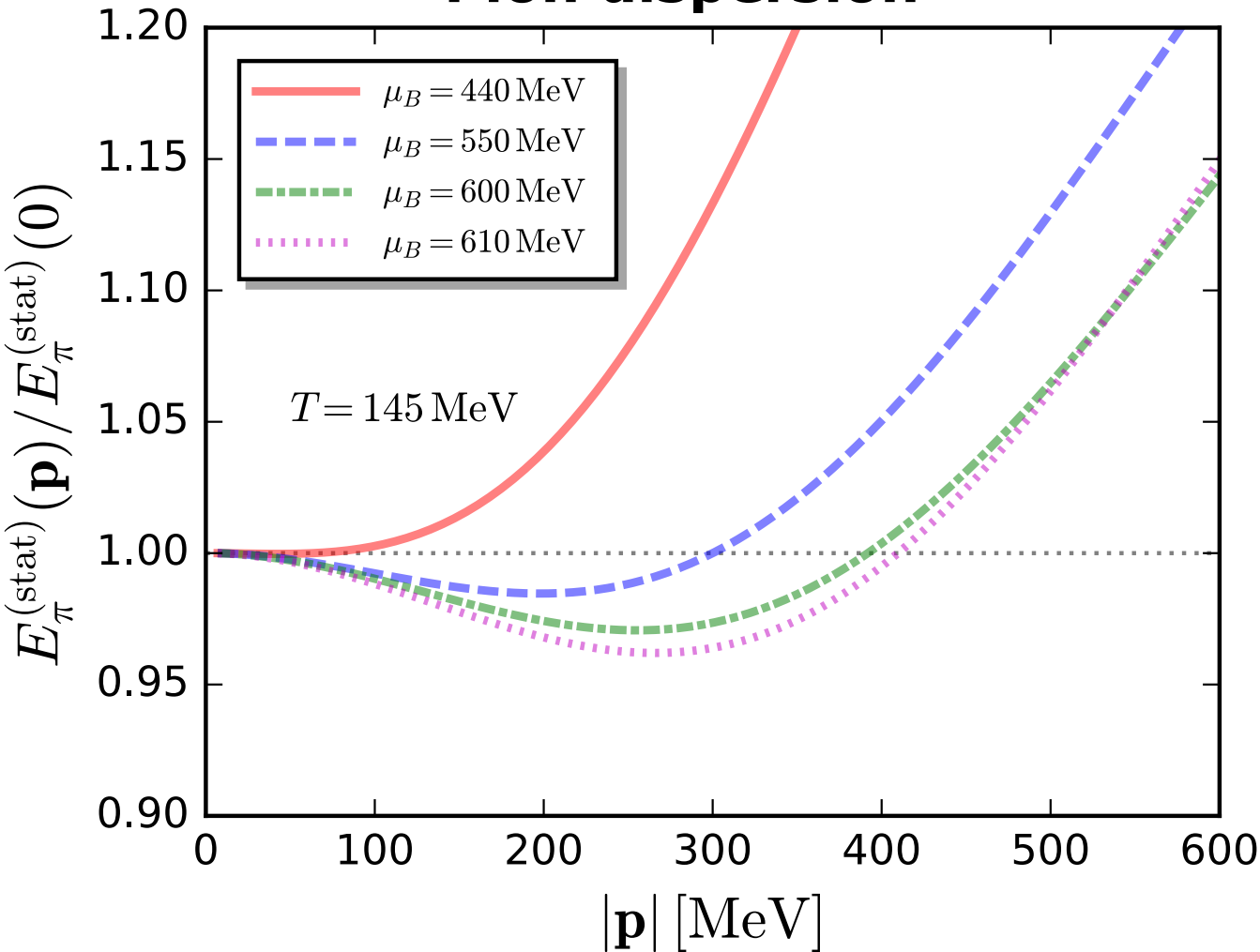


Wikipedia

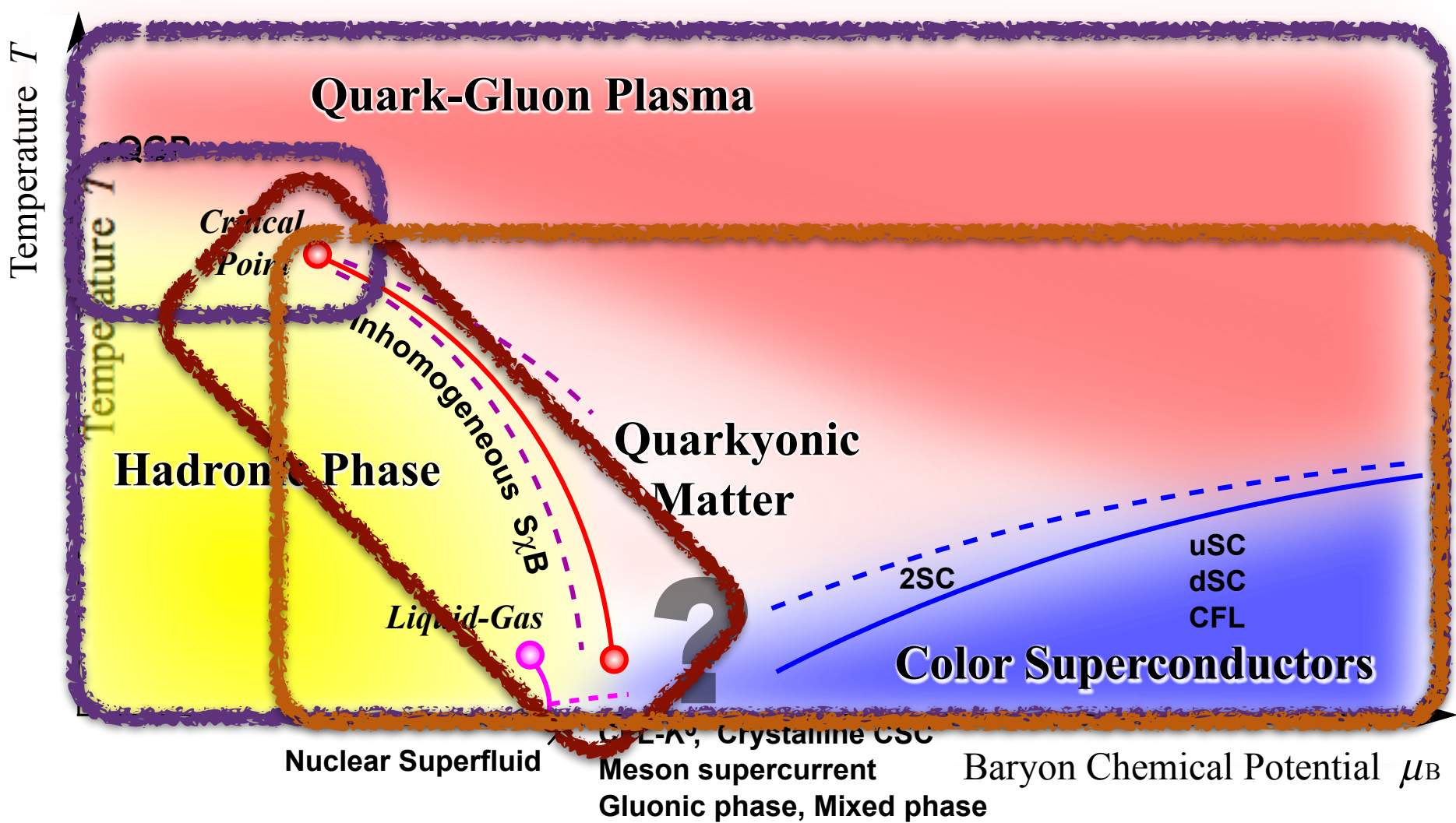
Chiral symmetry breaking & Confinement: the search for the CEP



Pion dispersion



QCD phase structure



Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



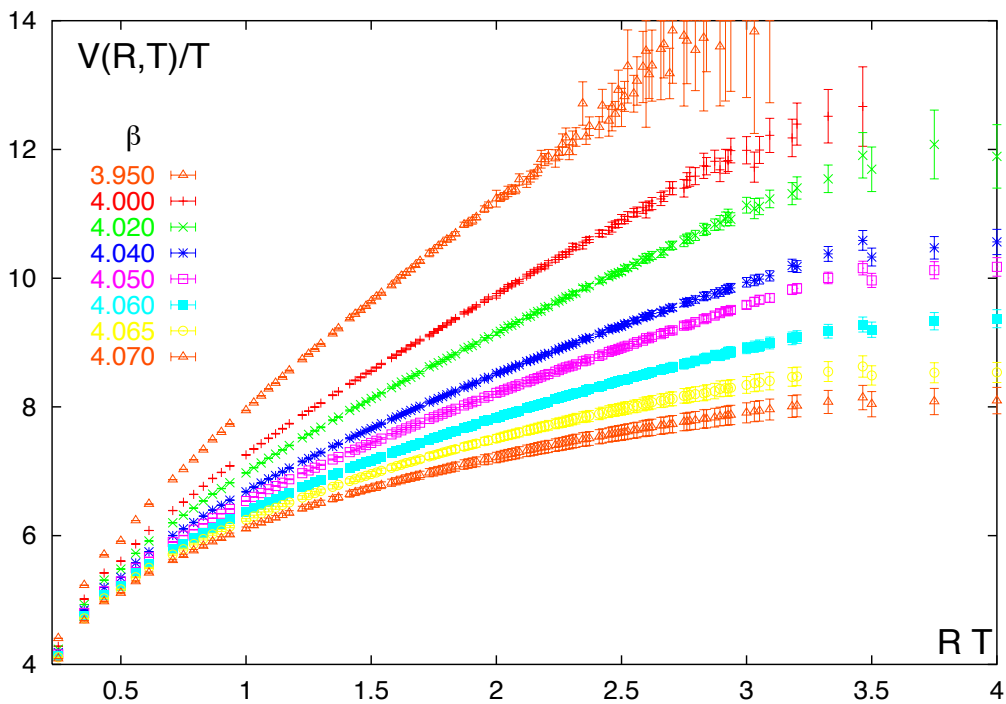
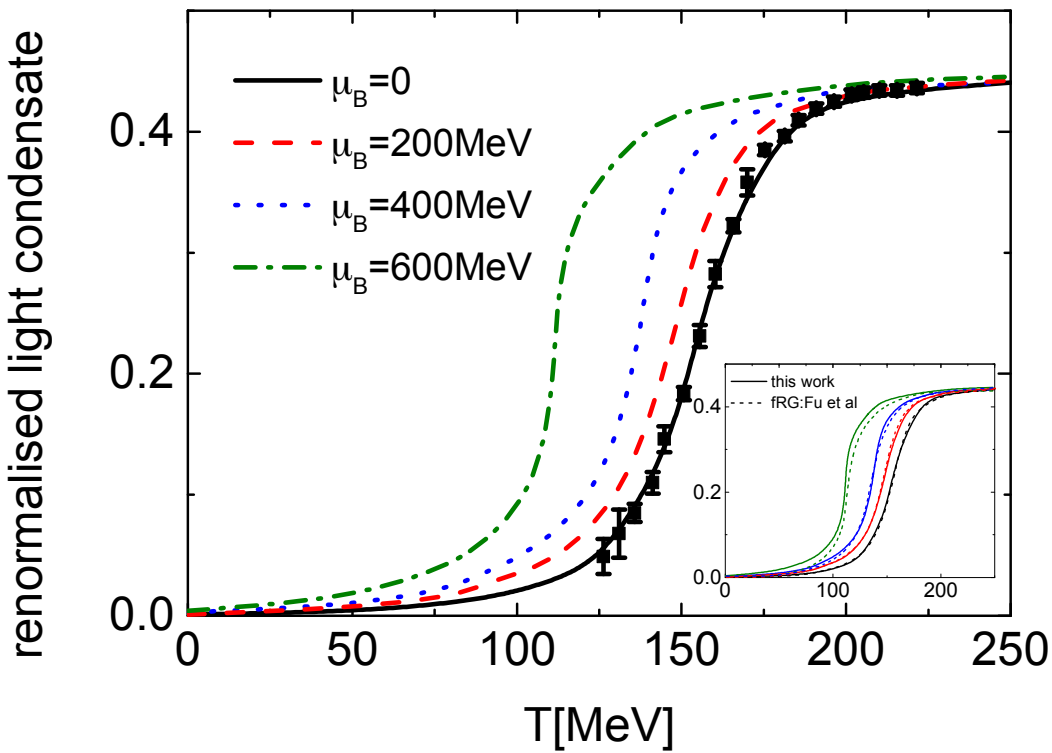
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US Moat



Wikipedia

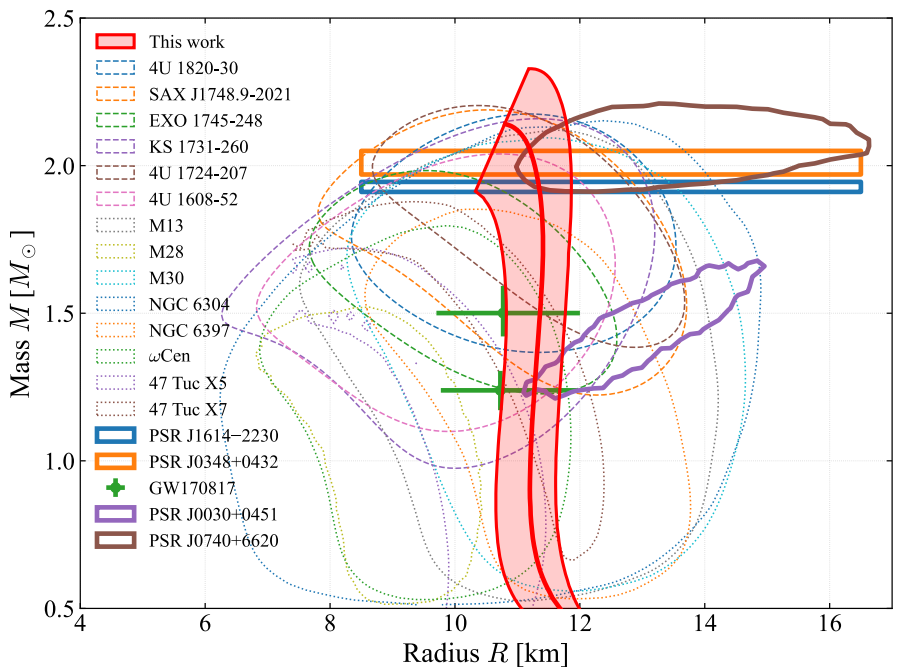
Chiral symmetry breaking & Confinement: the search for the CEP



Condensed matter QCD

Data Analysis

Fujimoto-Fukushima-Kamata-Murase (2018-2024)



Color superconductivity

Competing orders

Nuclear EoS

■
■
■

QCD phase structure

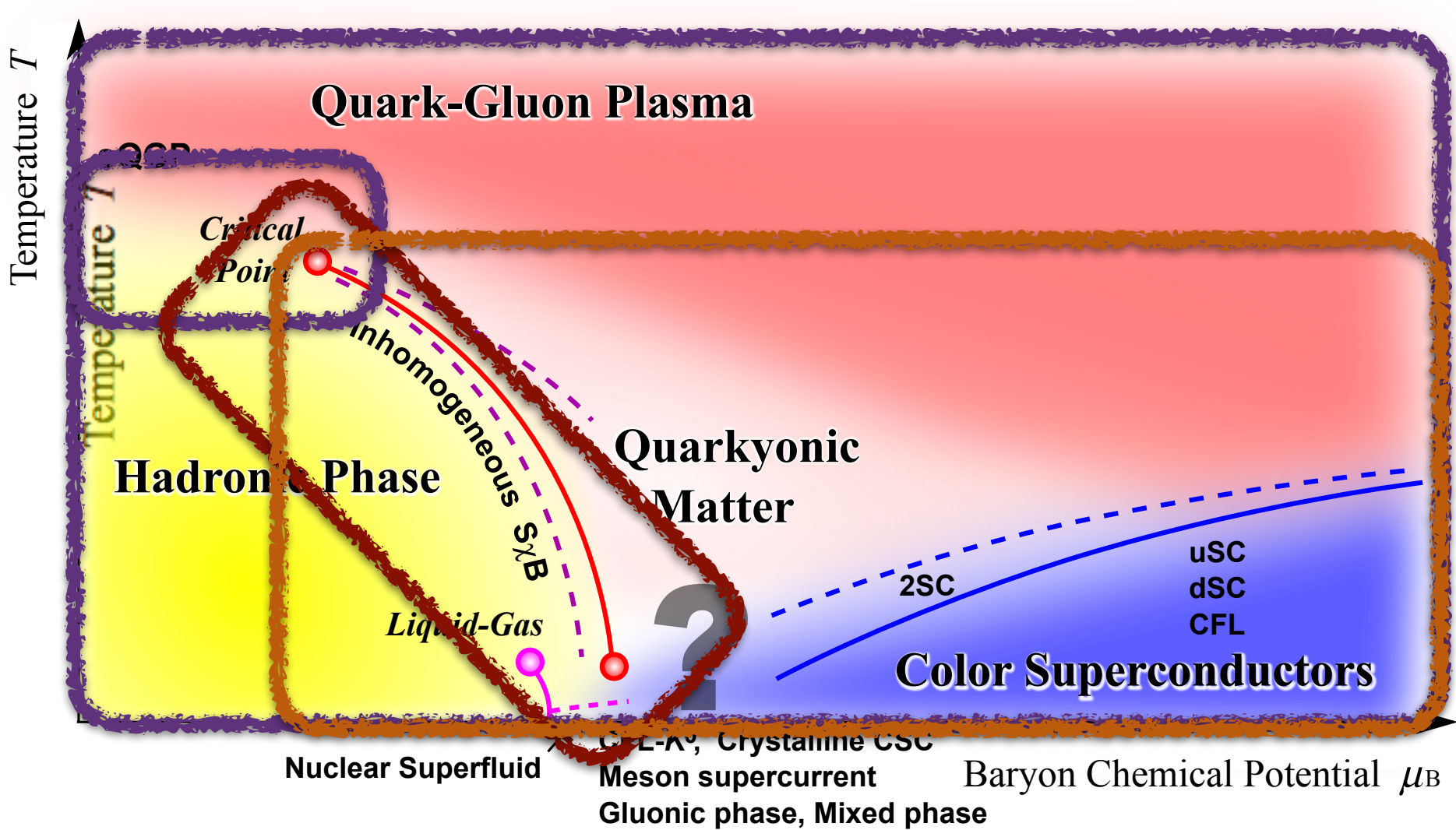
early universe, HIC, nuclear astrophysics

Experiments

HIC, nuclear astrophysics

HIC, nuclear astrophysics

Moat regime & inhomogeneous phases: CEP & beyond



Chinese Moat



Wikipedia

German Moat



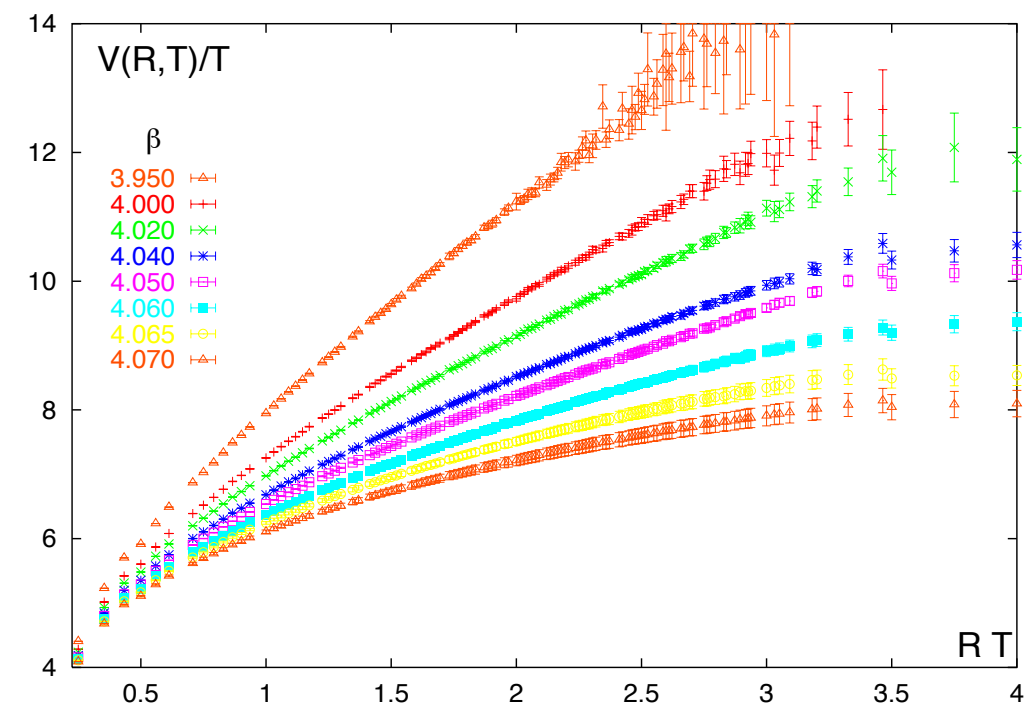
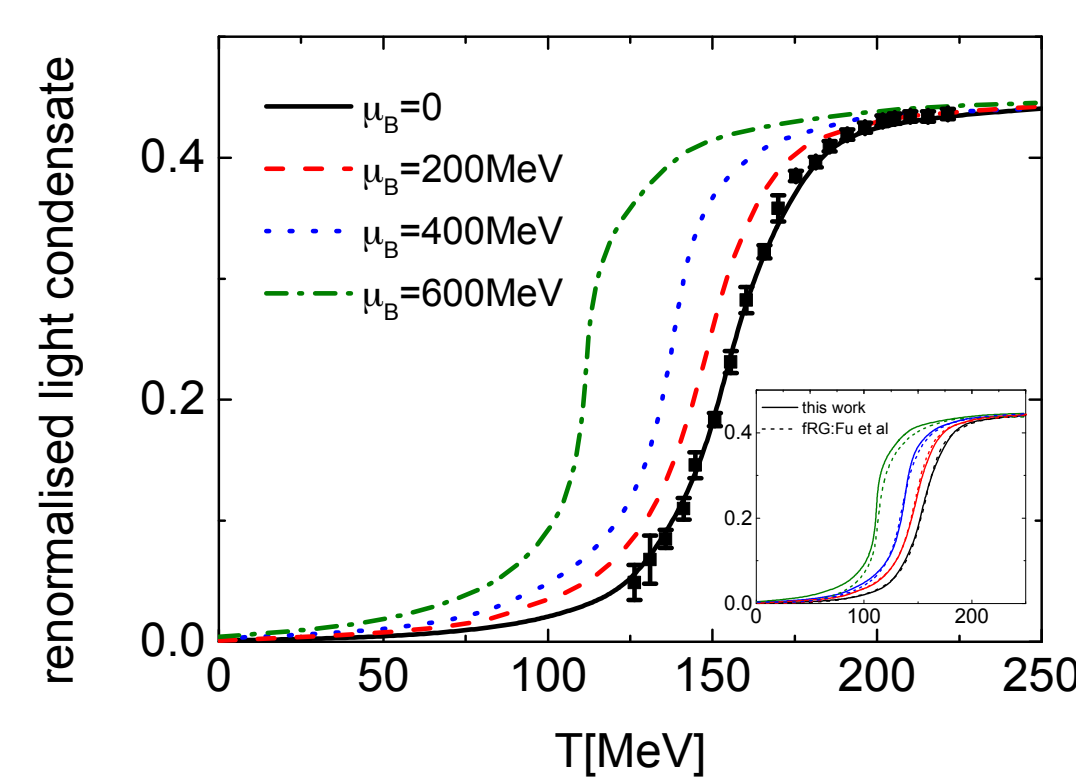
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US Moat



Wikipedia

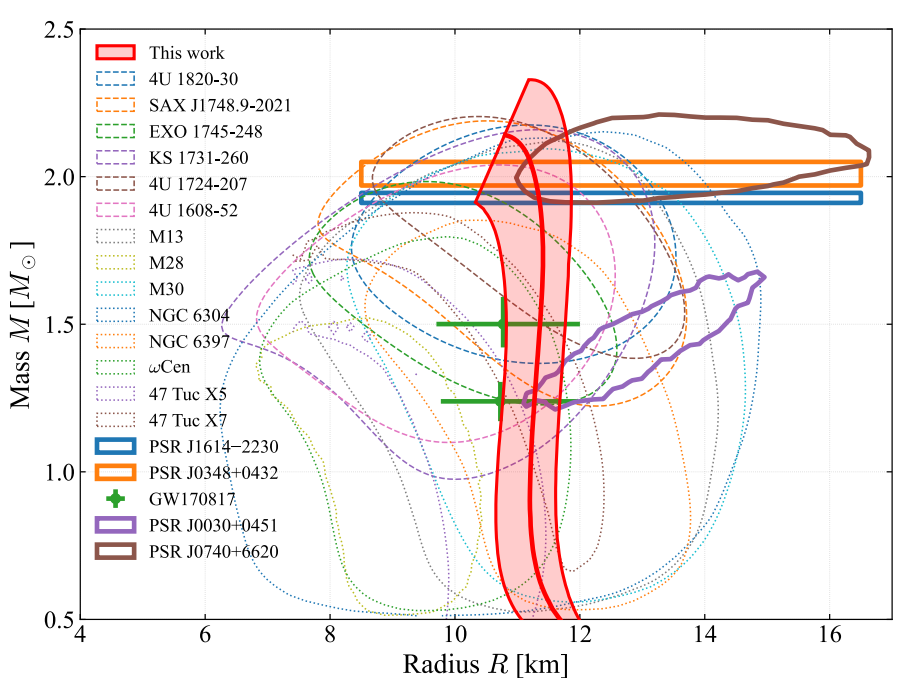
Chiral symmetry breaking & Confinement: the search for the CEP



Condensed matter QCD

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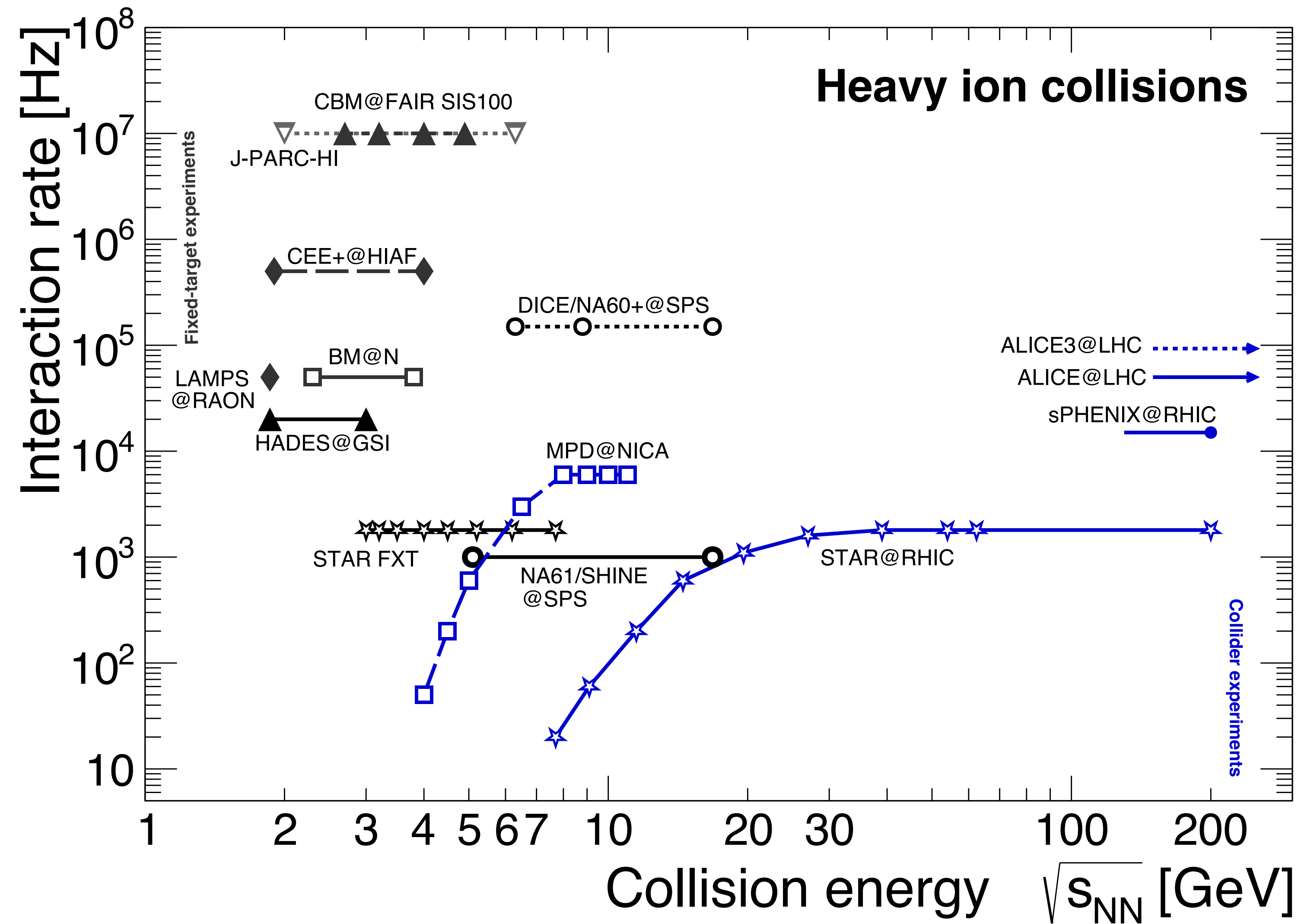
Competing orders

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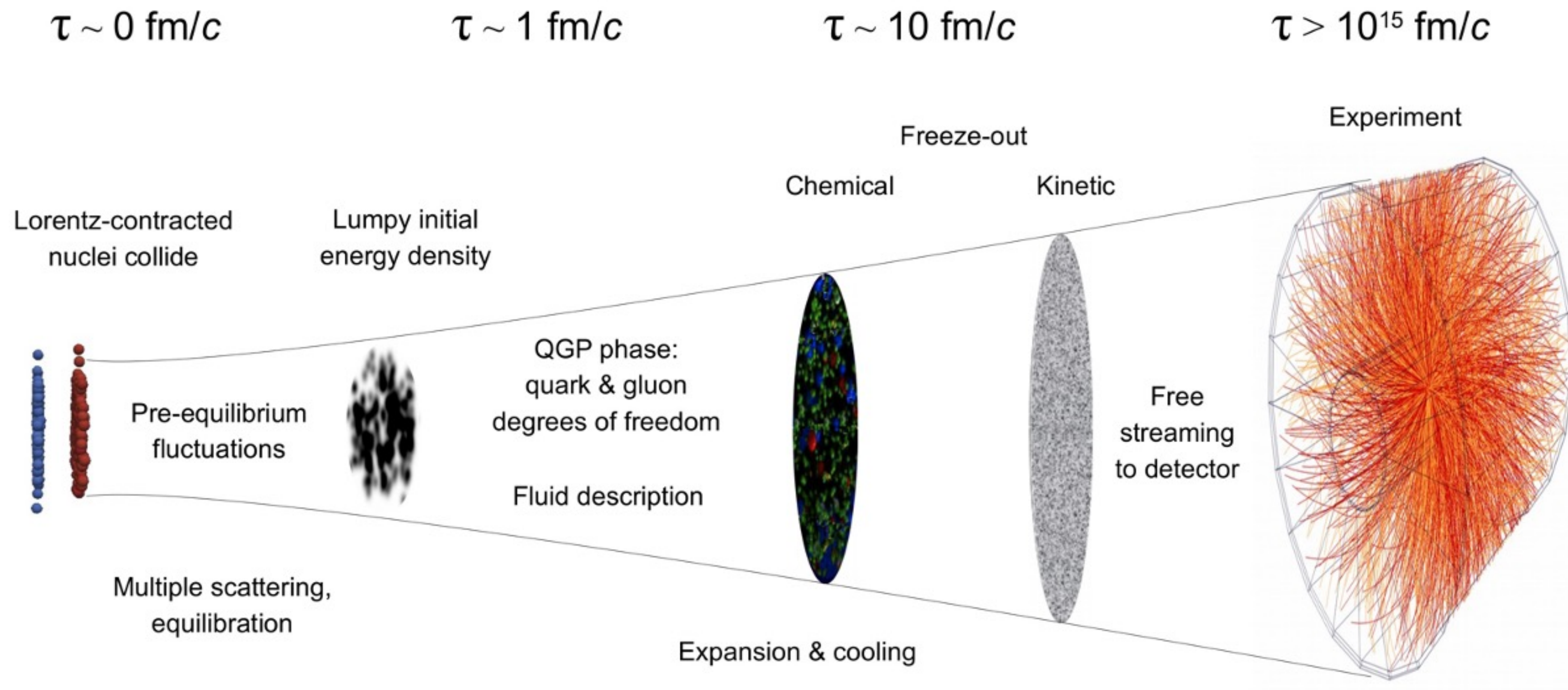
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Strongly correlated QCD: how to?

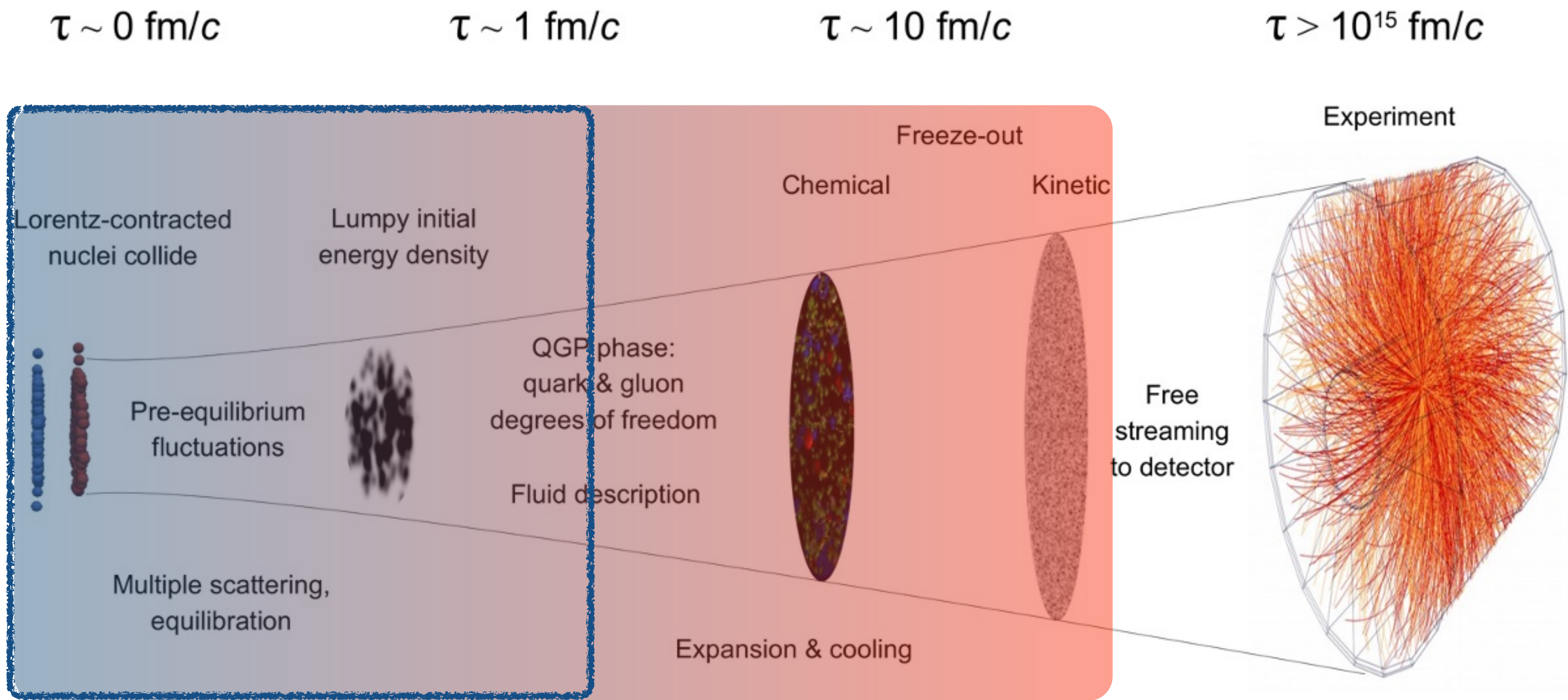
(2) Experiments (extreme QCD)



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



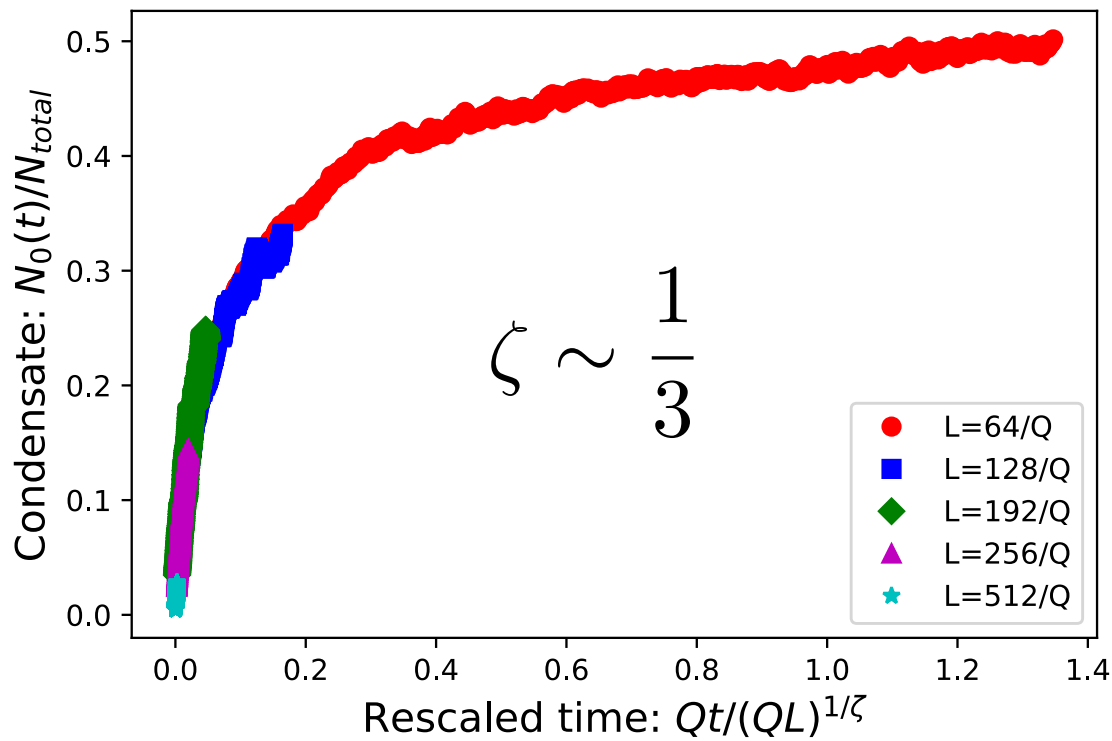
Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)



large occupancies

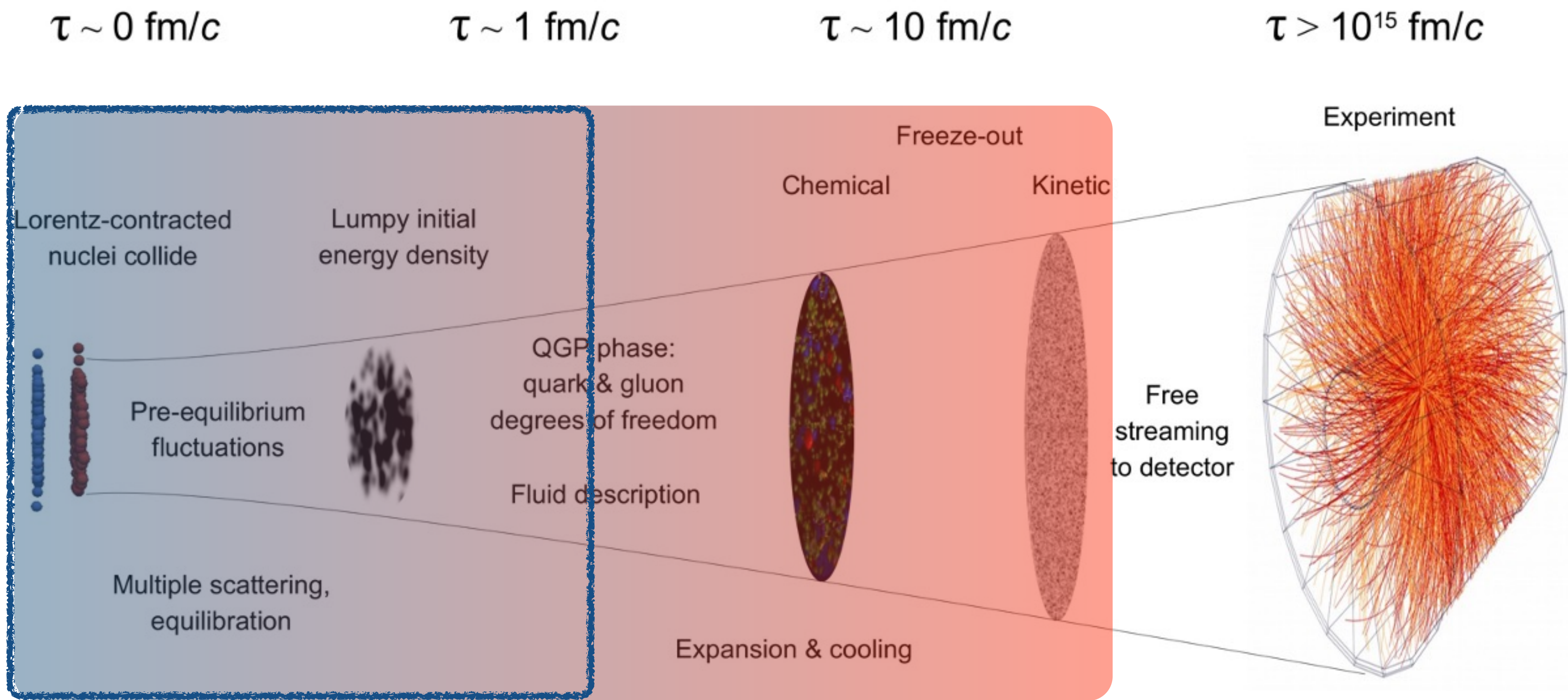
non-thermal fixed point

Classical-statistical



$$\sim \int_{\text{vol}} \langle P(0)P^\dagger(r) \rangle$$

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



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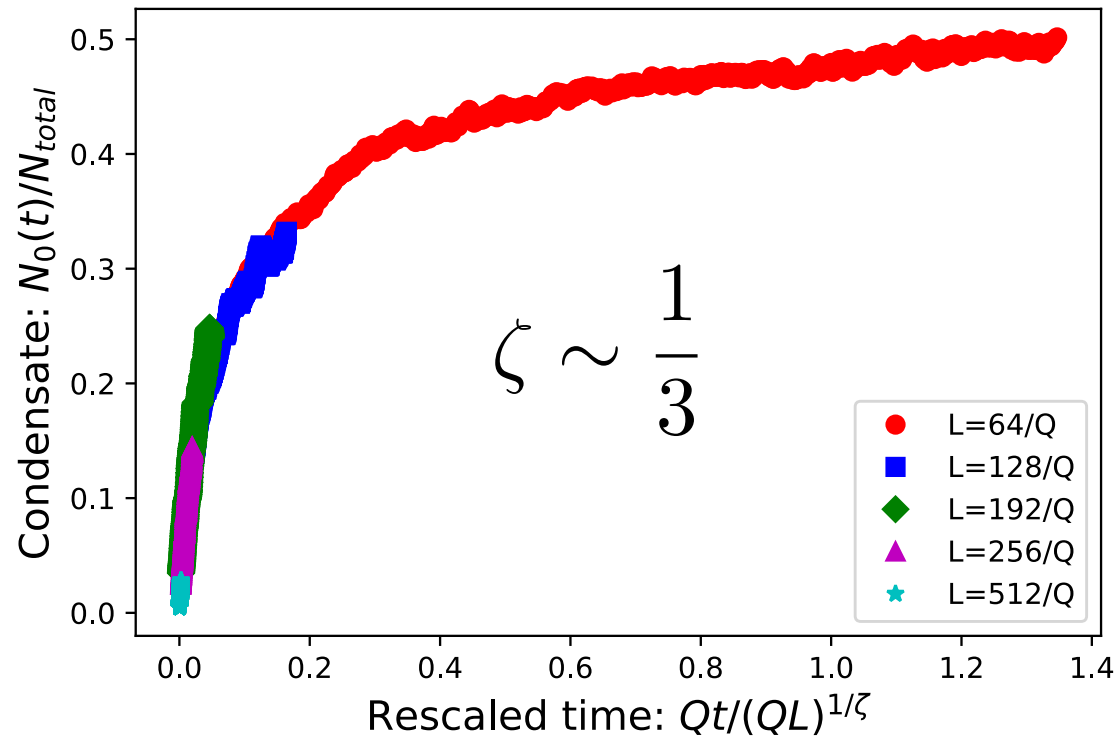
statistics + collective behaviour

&

strongly correlated quantum dynamics

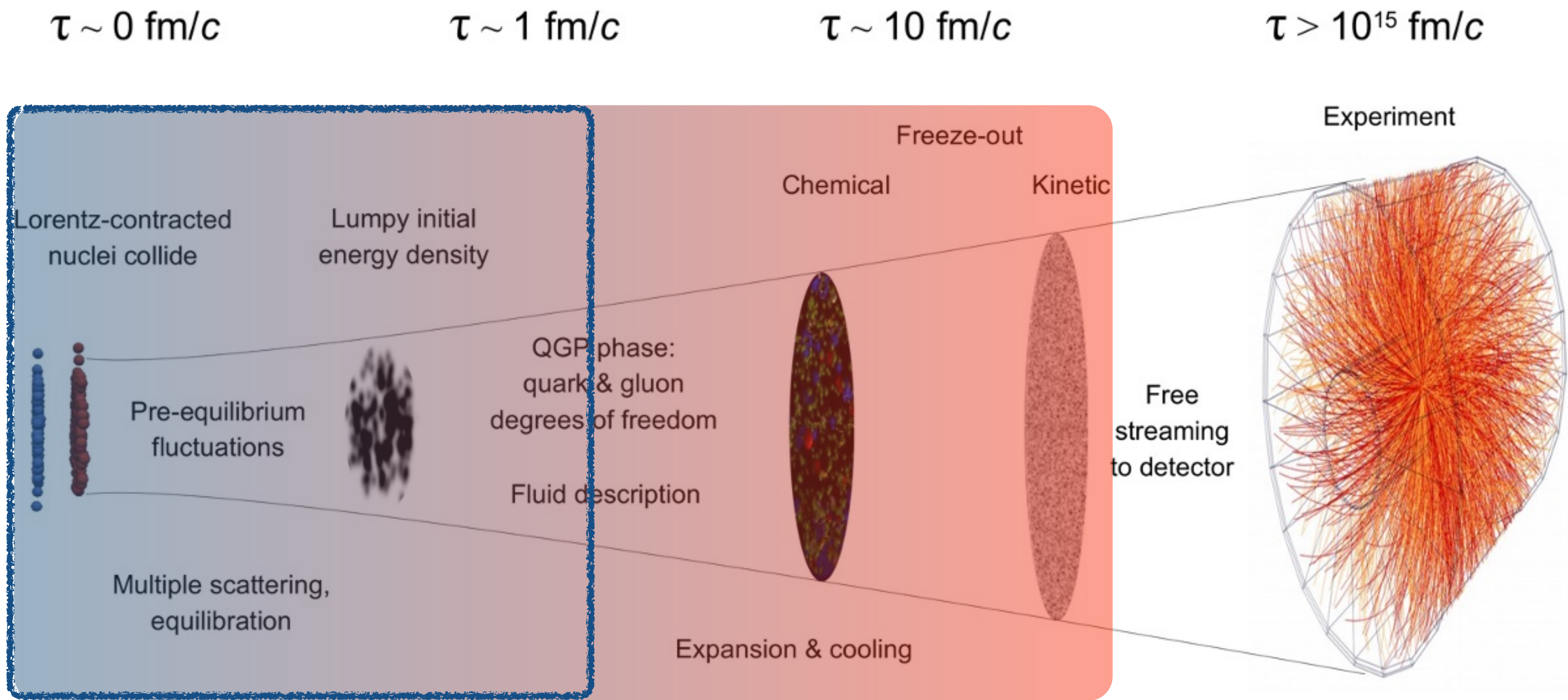
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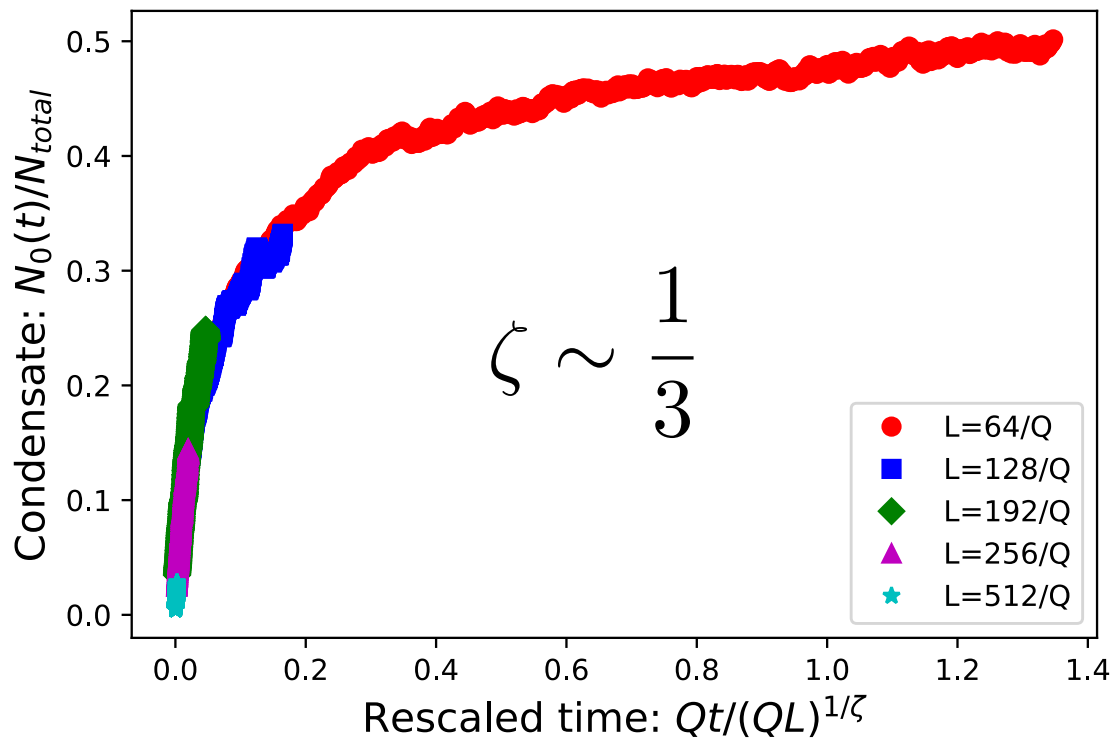
Background

&

strongly correlated quantum dynamics

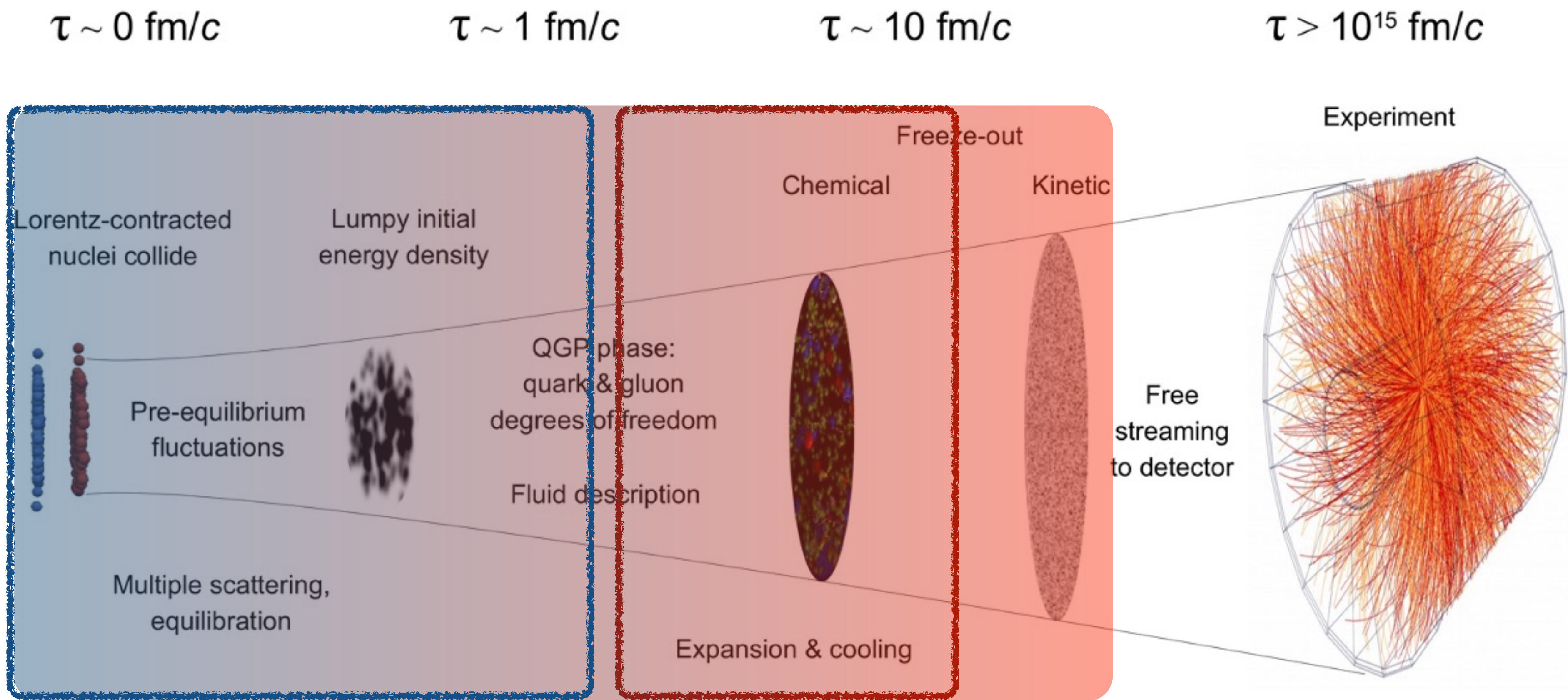
Classical-statistical

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



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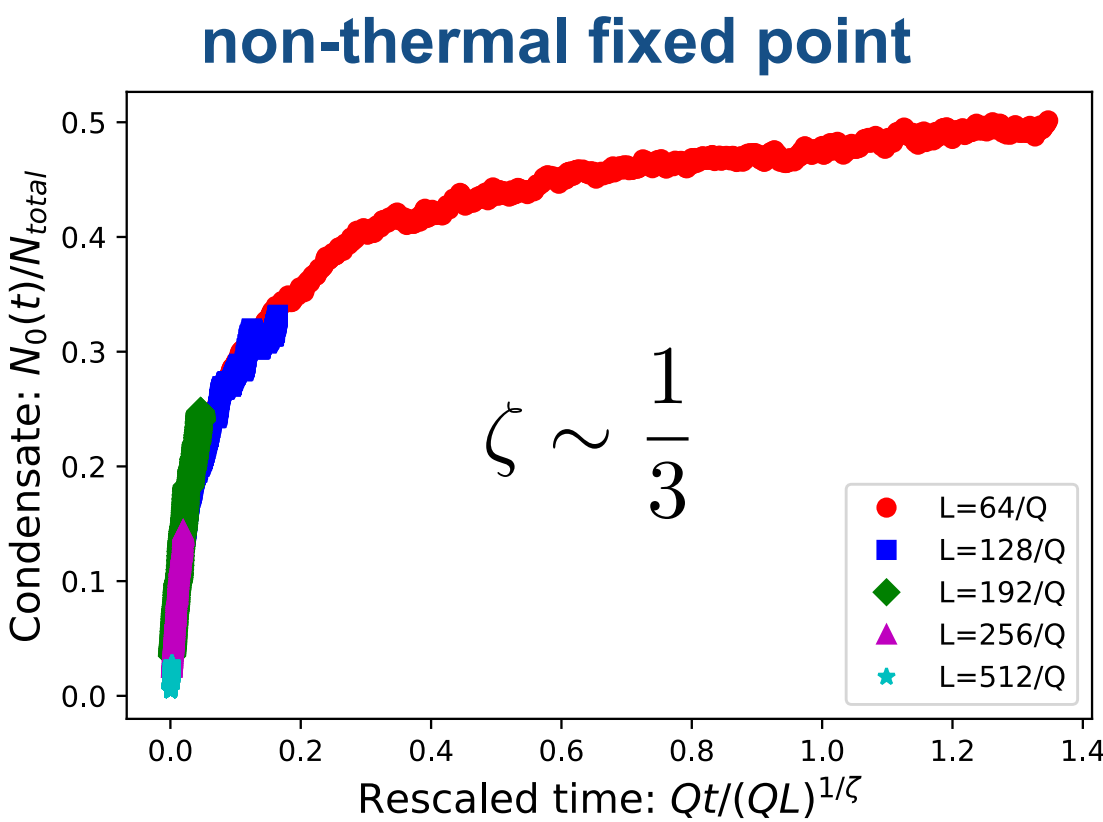
Background

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strongly correlated quantum dynamics

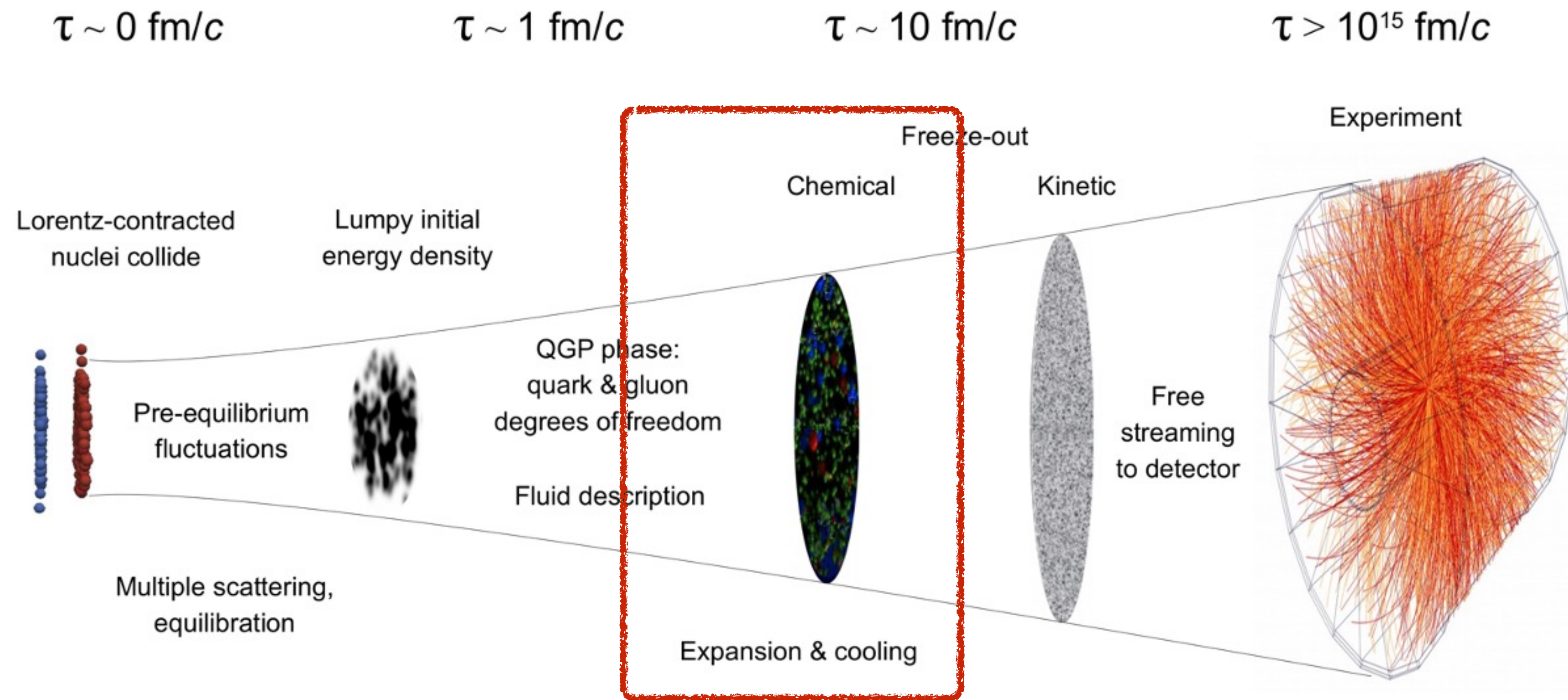
The cool stuff!

Classical-statistical



$$\sim \int_{\text{vol}} \langle P(0)P^\dagger(r) \rangle$$

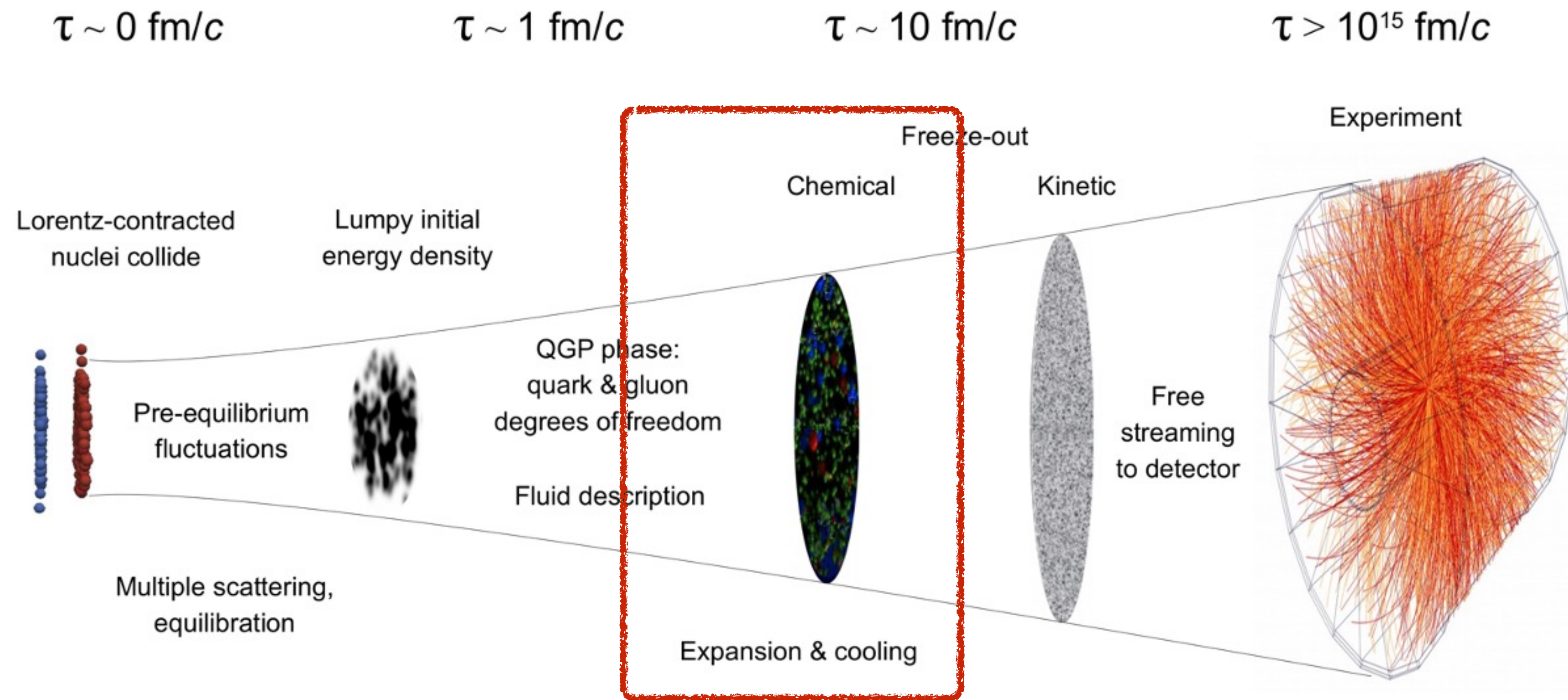
Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)



← How to unfold: inverse problem!

strongly correlated quantum dynamics

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



How to unfold: inverse problem!

strongly correlated quantum dynamics

Unfolding the phase structure of QCD

Experimental & Theoretical Landscape

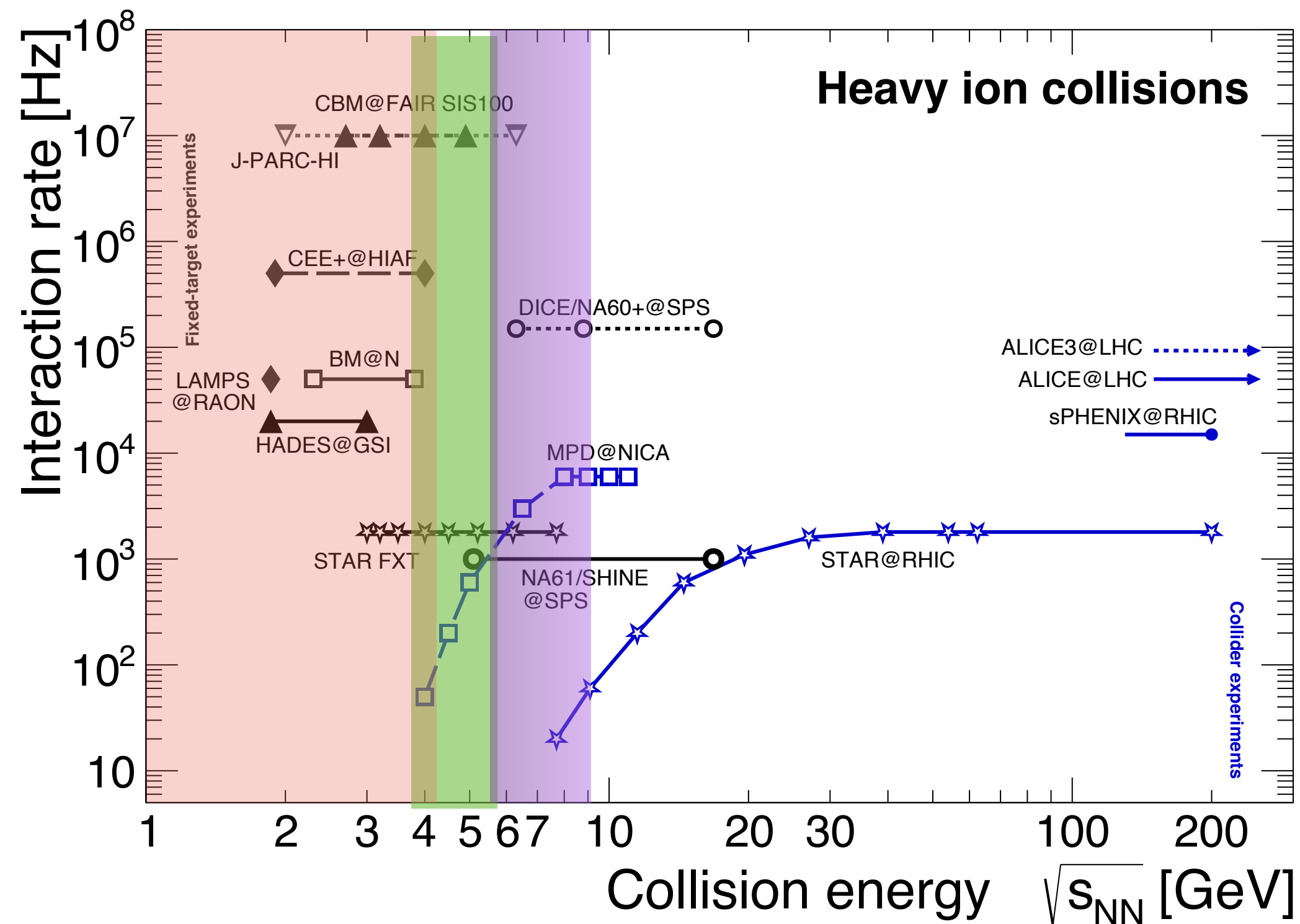
Experimental landscape

Theoretical landscape

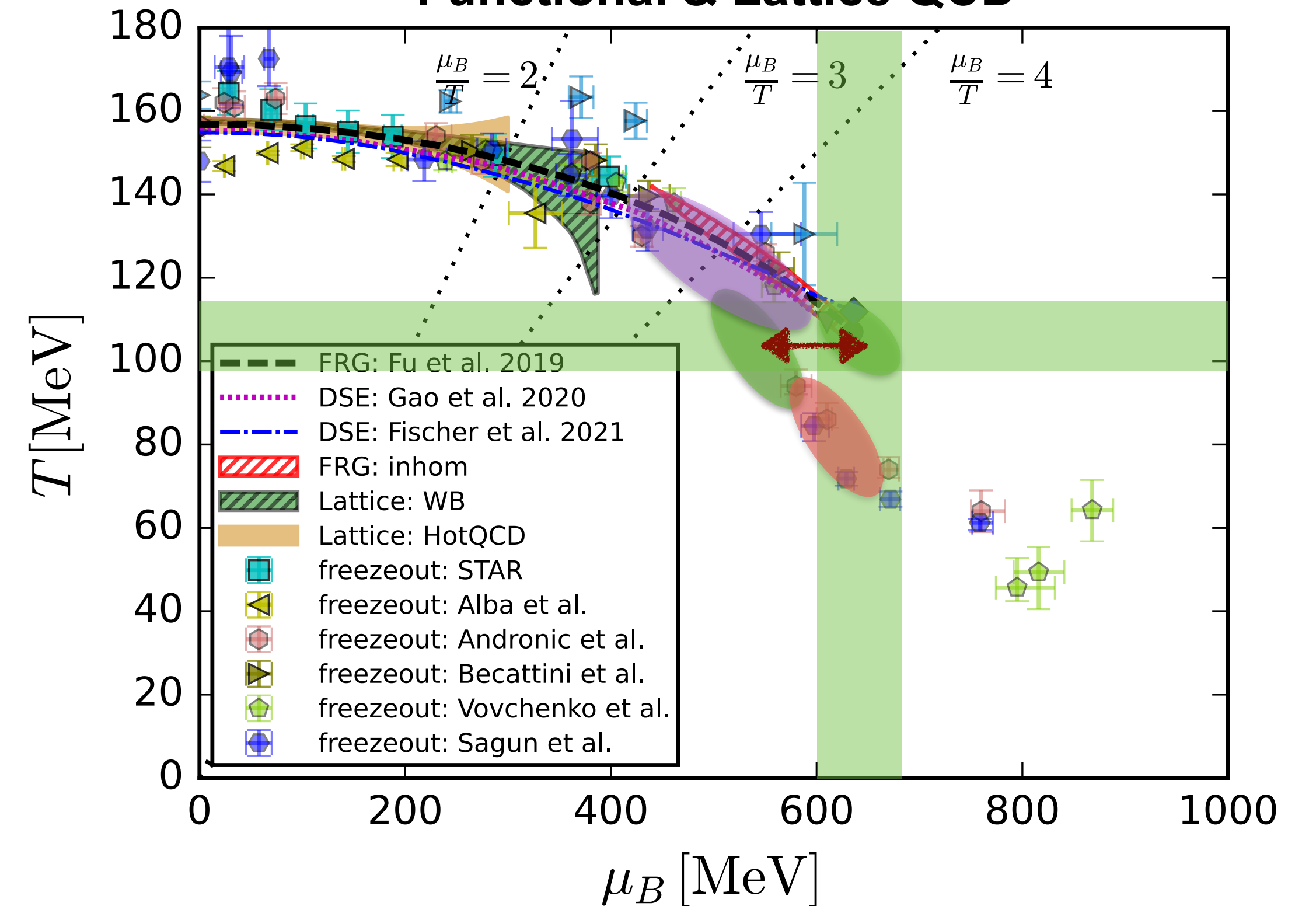
Onset of new phases on the chiral transition line (CEP)

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

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

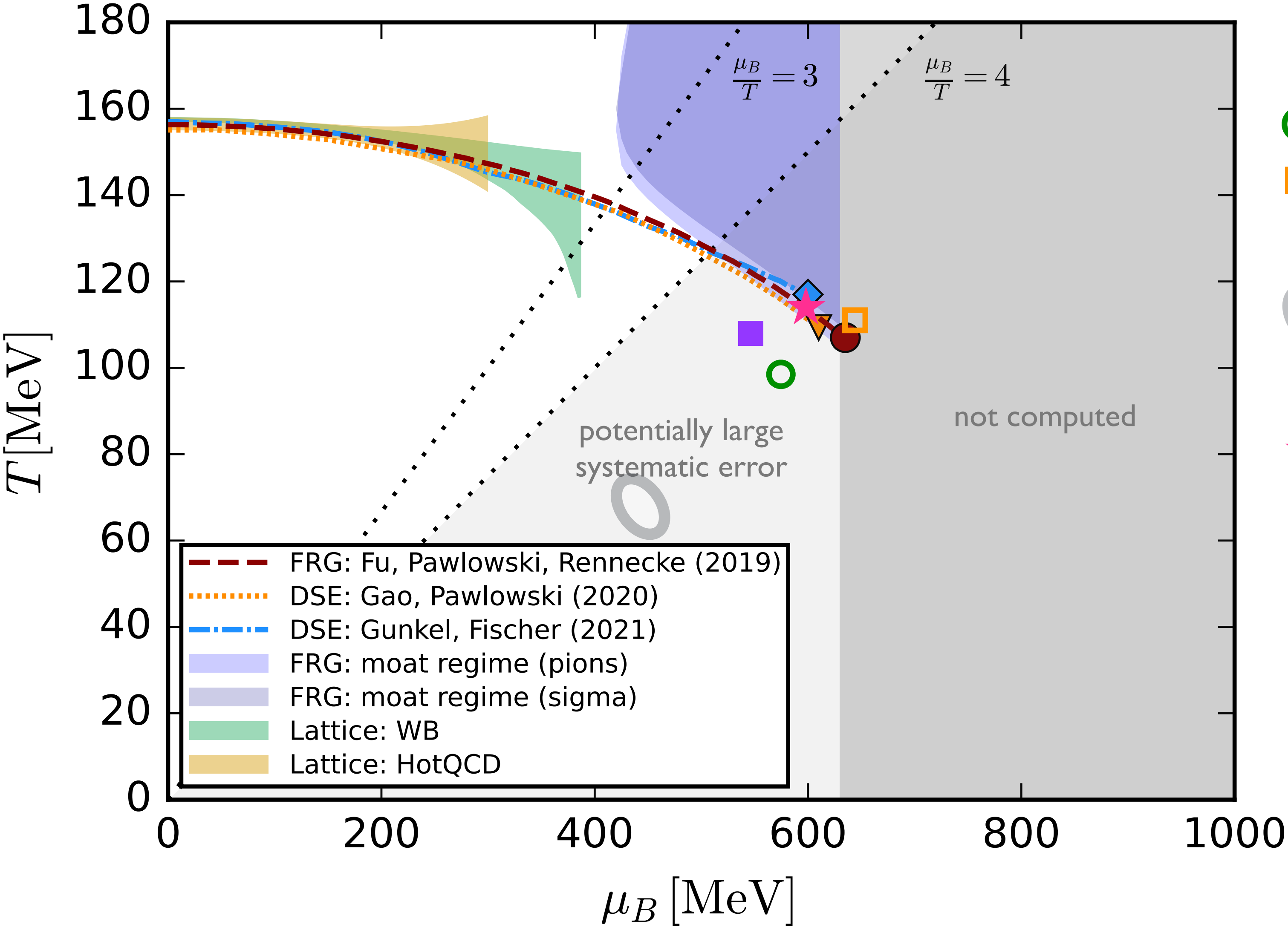
Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

QCD PHASE DIAGRAM & THE CEP

Modified from Fabian Rennecke's
plenary talk @ QM 2025

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



using Yang-Lee edge singularities:

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

using thermodynamics:

- constant entropy density [Shah et al. 2410.16206] (pink star)

model-based extrapolation (tiny selection):

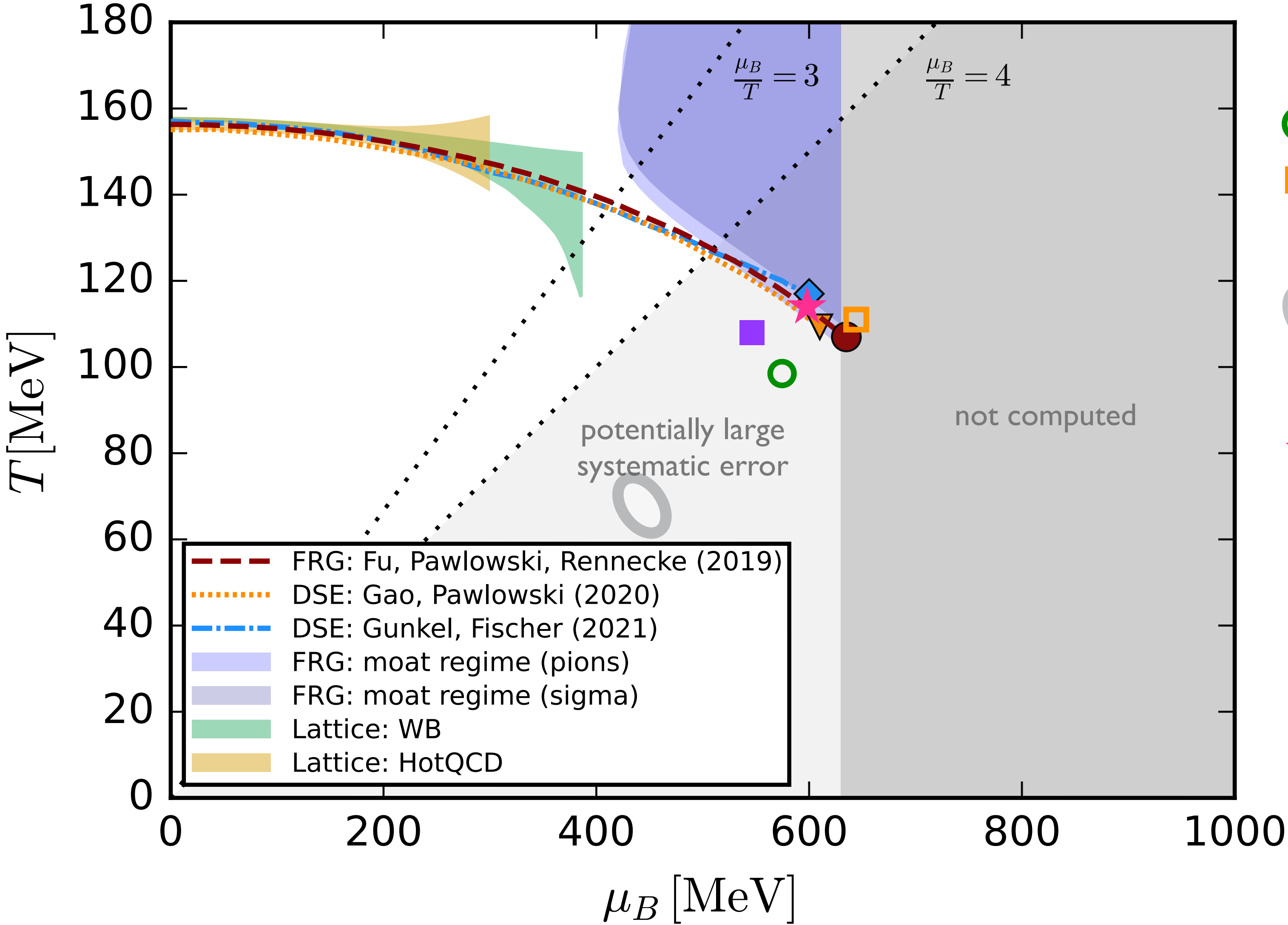
- holography [Hippert et al., 2309.00579] (purple square)
(agrees with [Cai et al., 2201.02004])

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

QCD PHASE DIAGRAM & THE CEP

Modified from Fabian Rennecke's
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Fu, Luo, JMP, Rennecke, Yin, PRD 111, L031502

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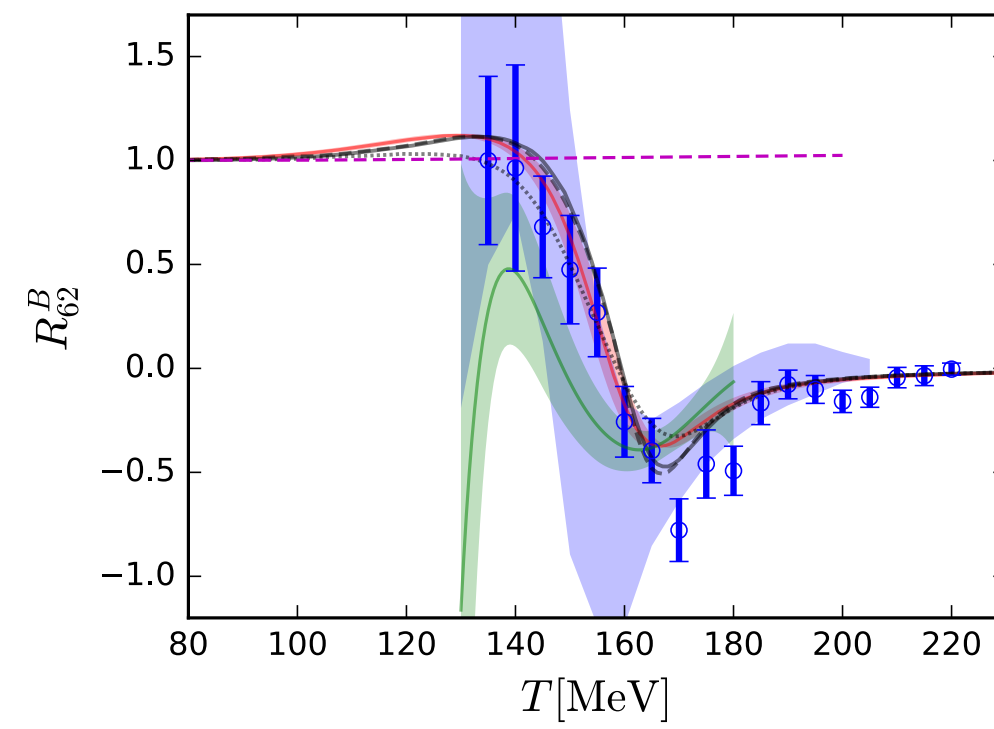
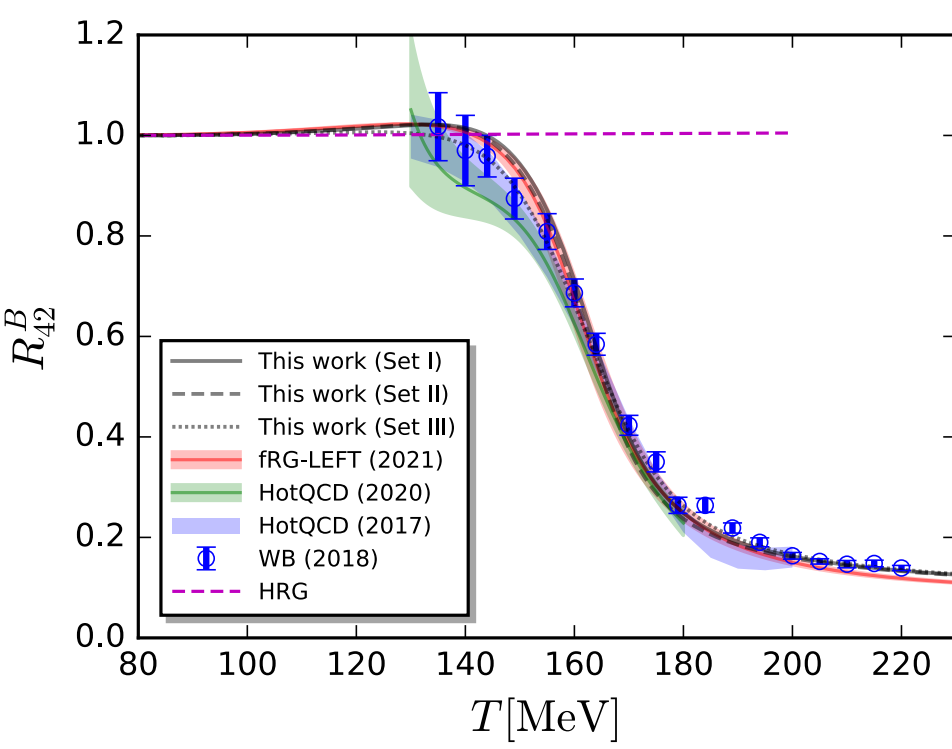
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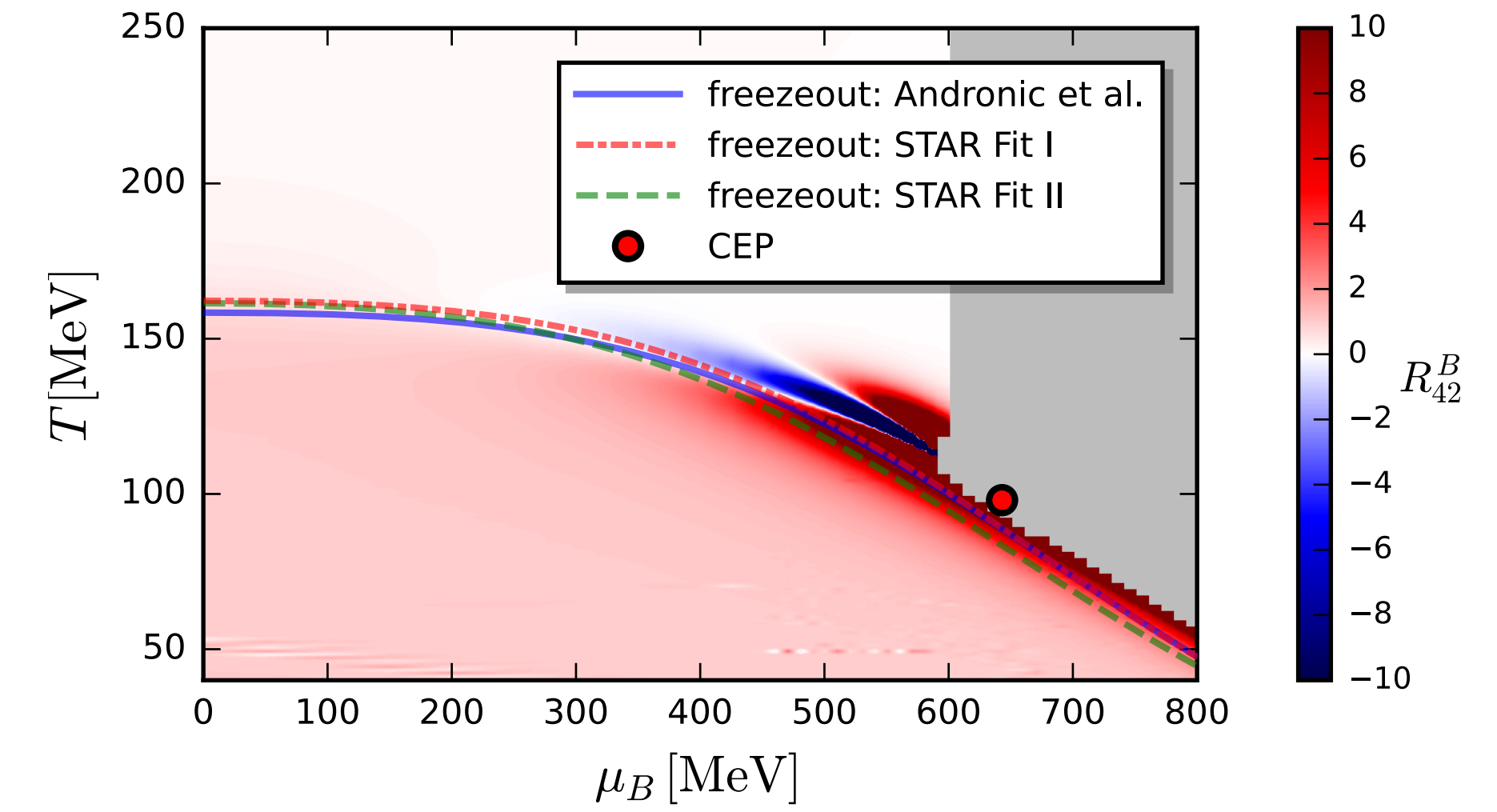
CEP location well constrained
by now. And it's in **FAIR** range!

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

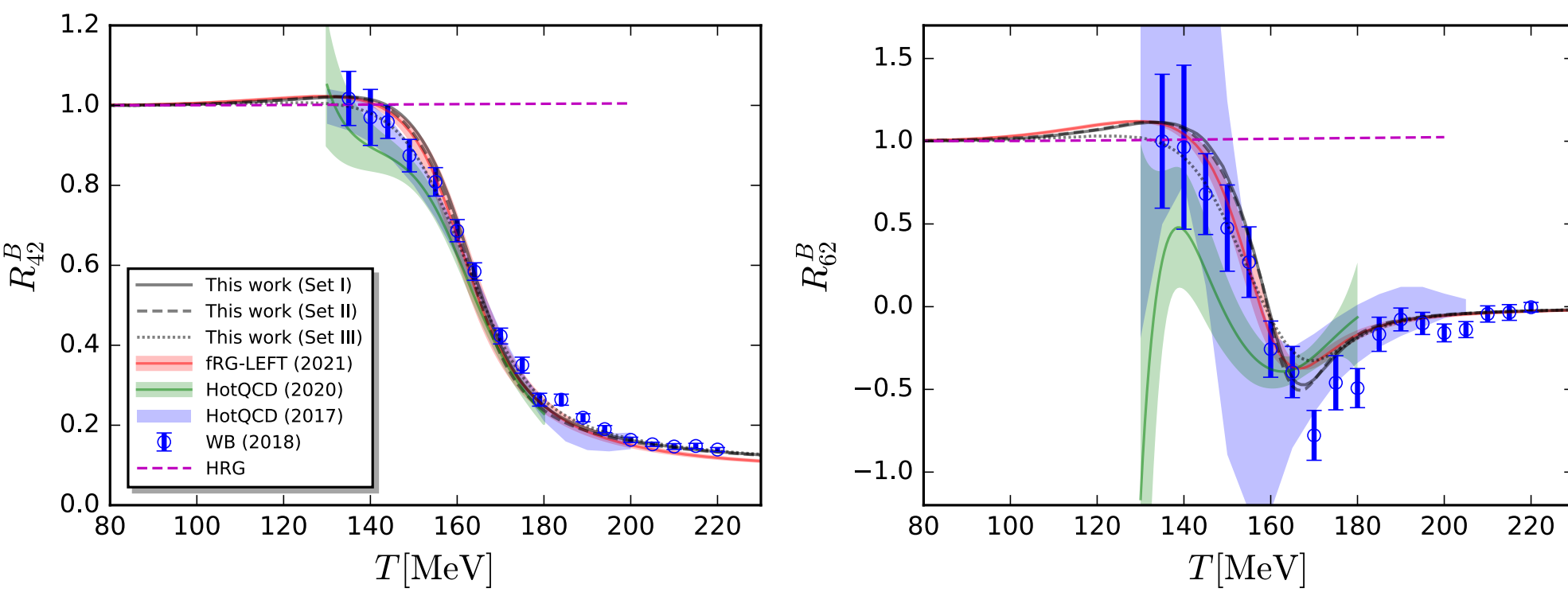
Ripples of the critical point



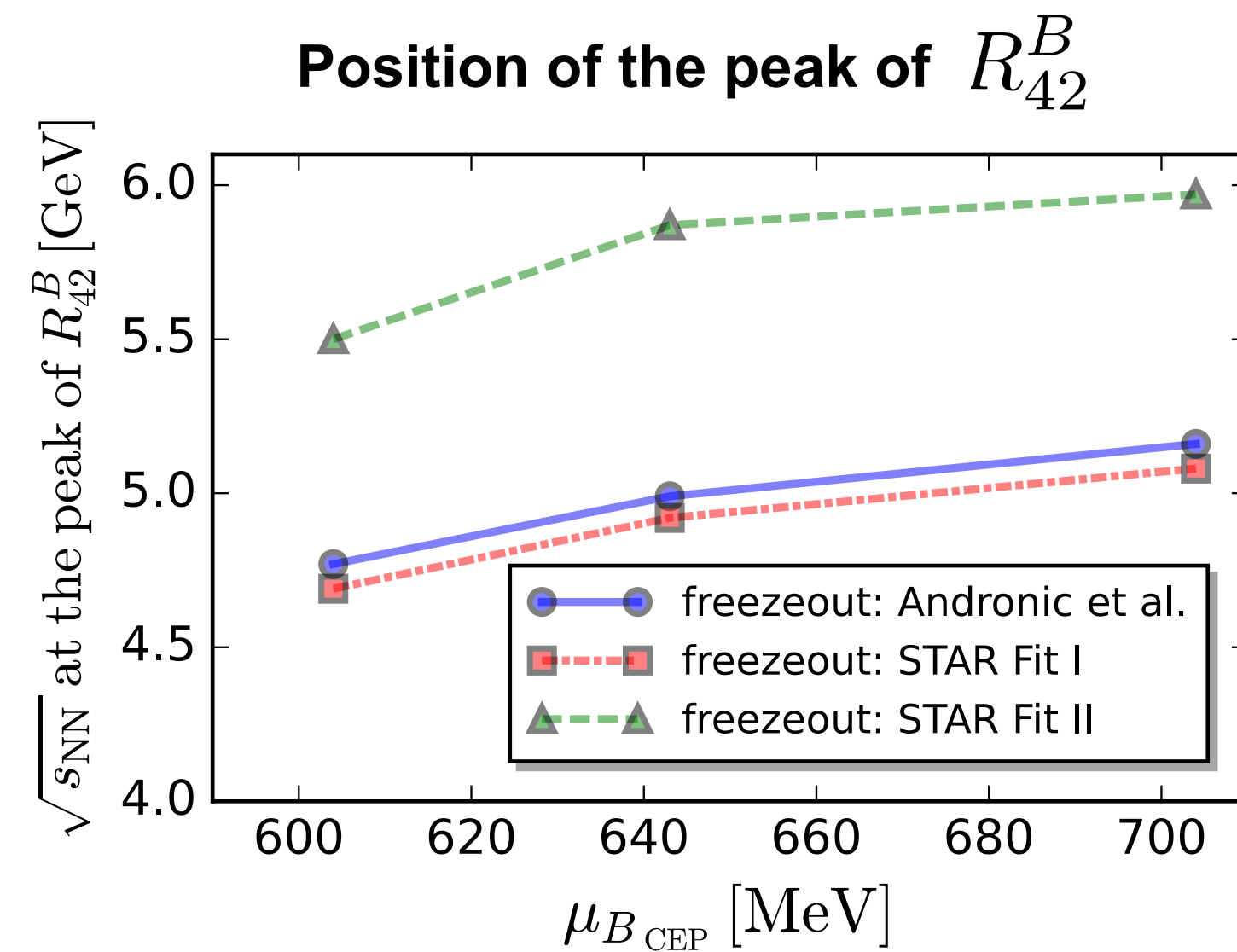
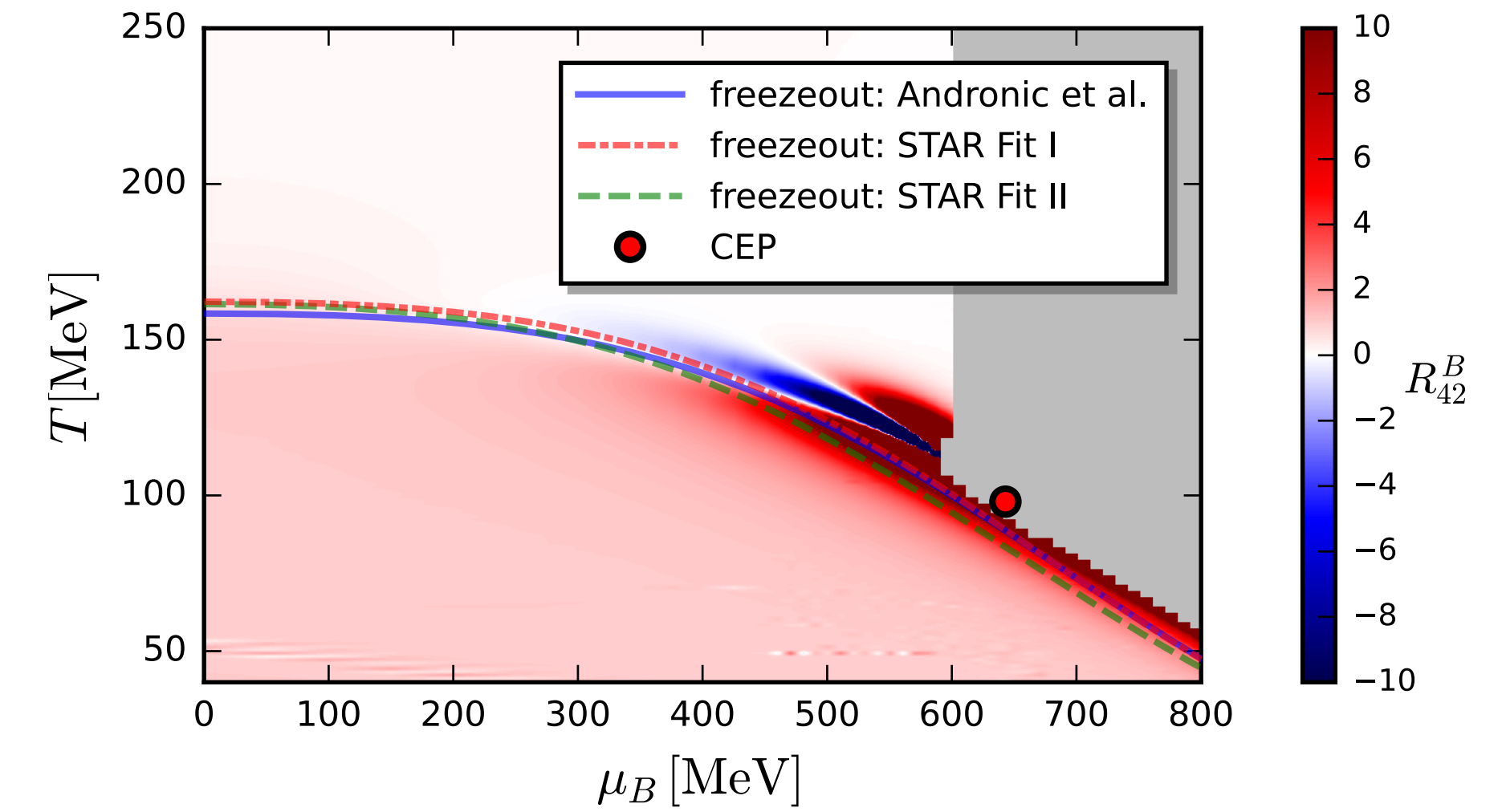
baryon number fluctuations



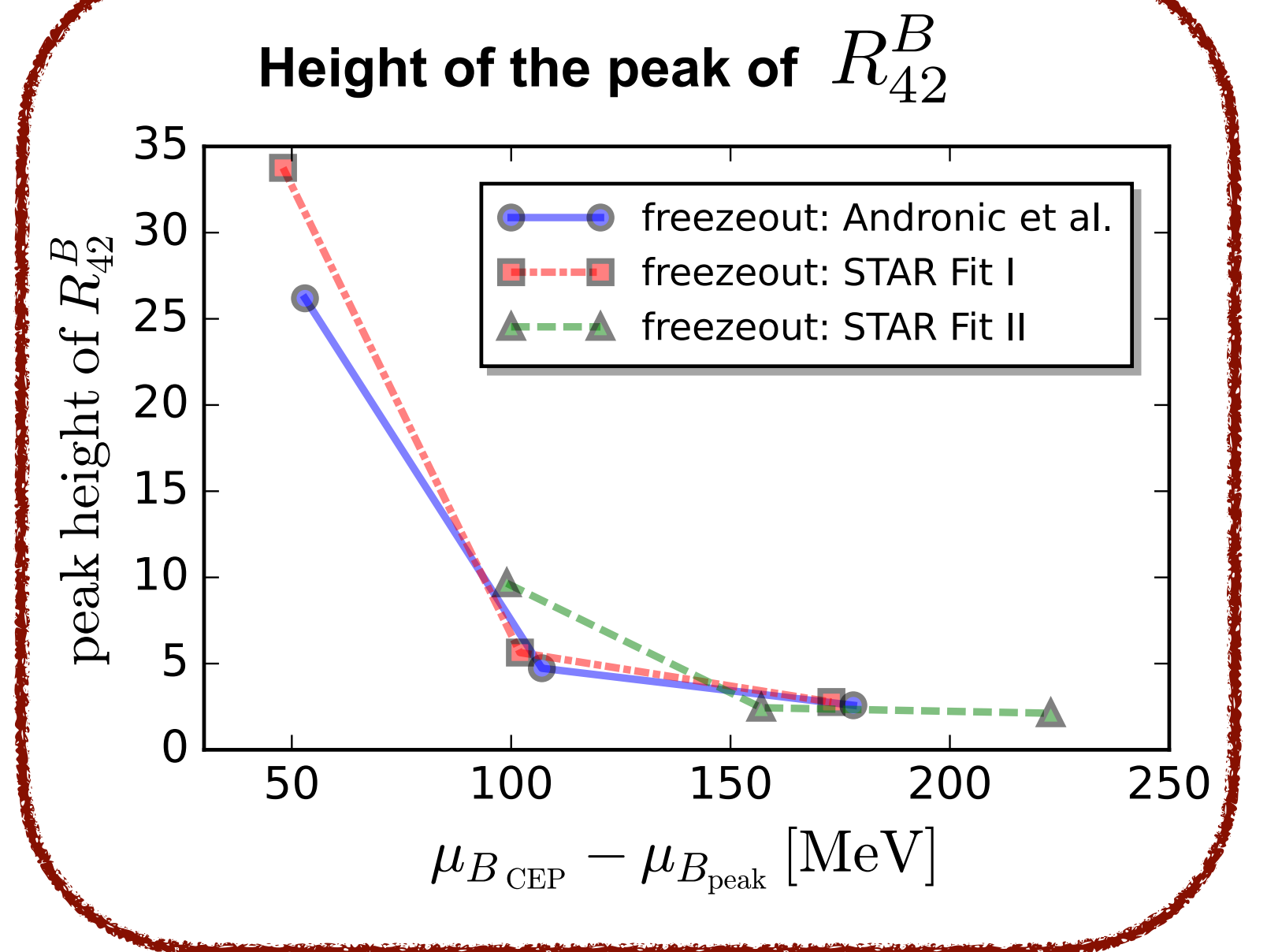
Ripples of the critical point



baryon number fluctuations

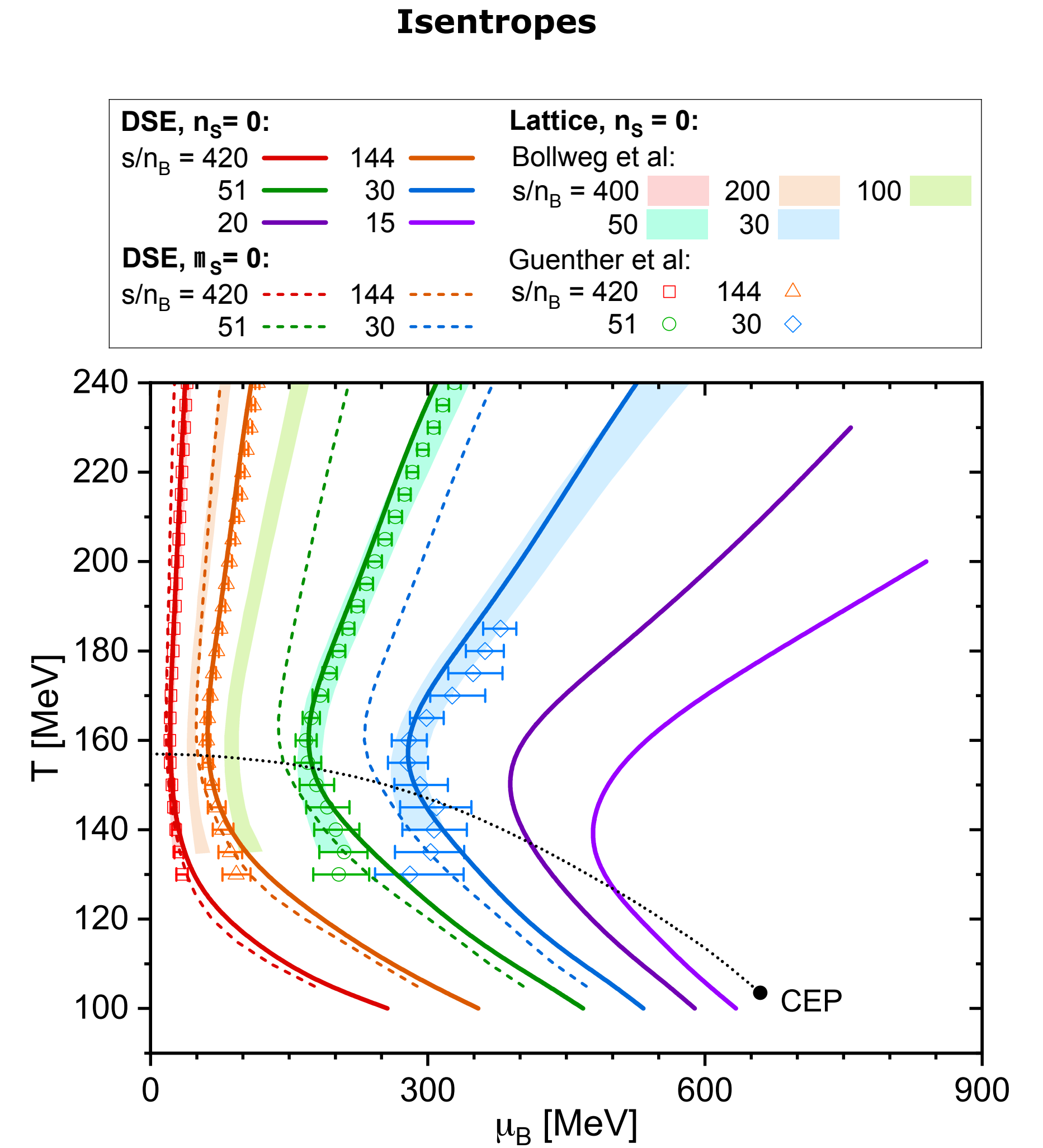
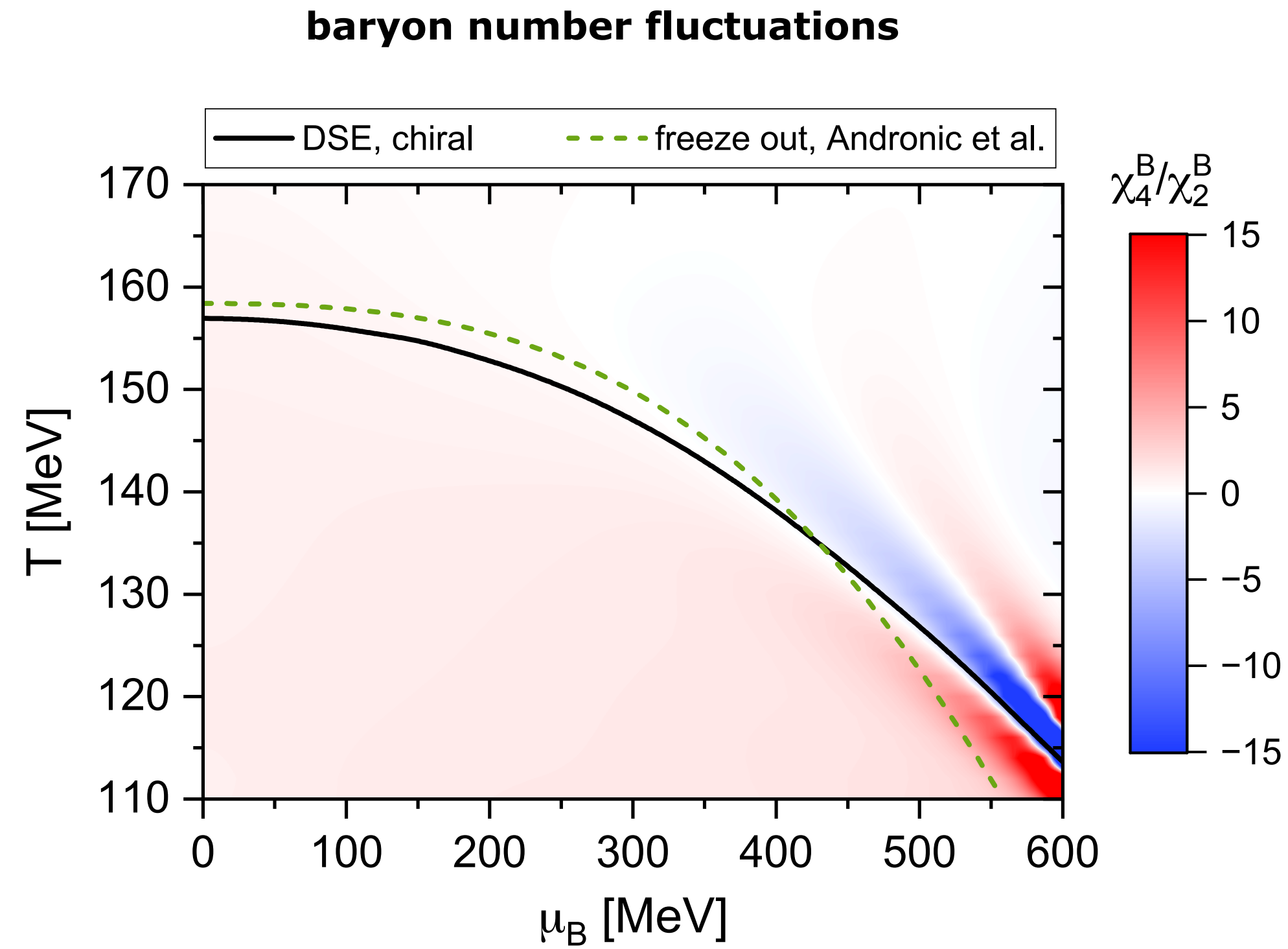


Reconstructing the CEP



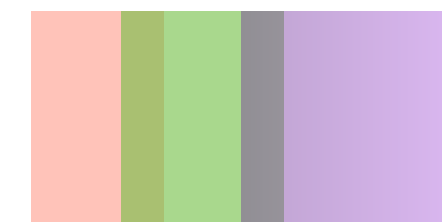
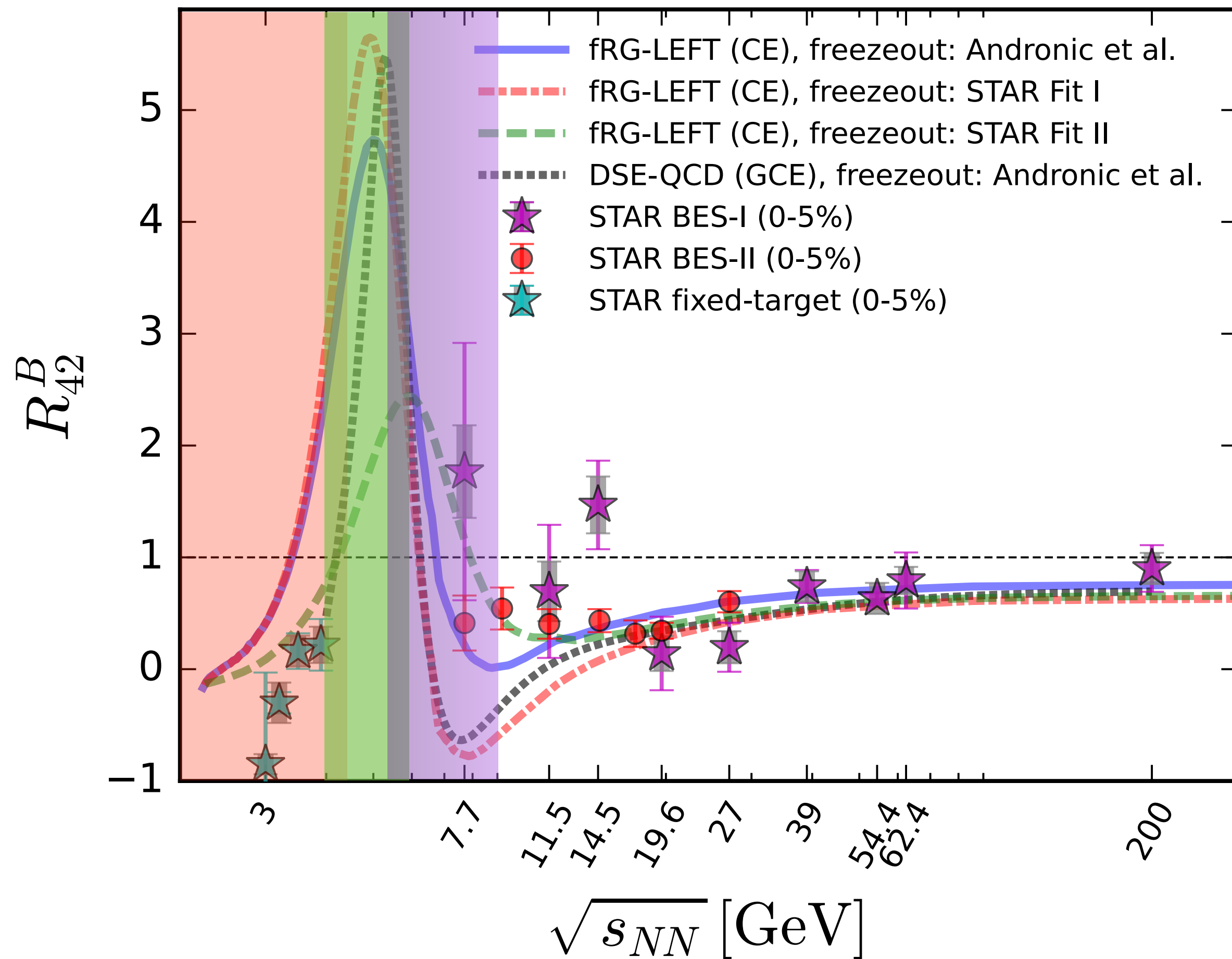
Ripples of the critical point

Functional QCD: DSE



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

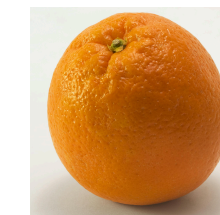
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

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

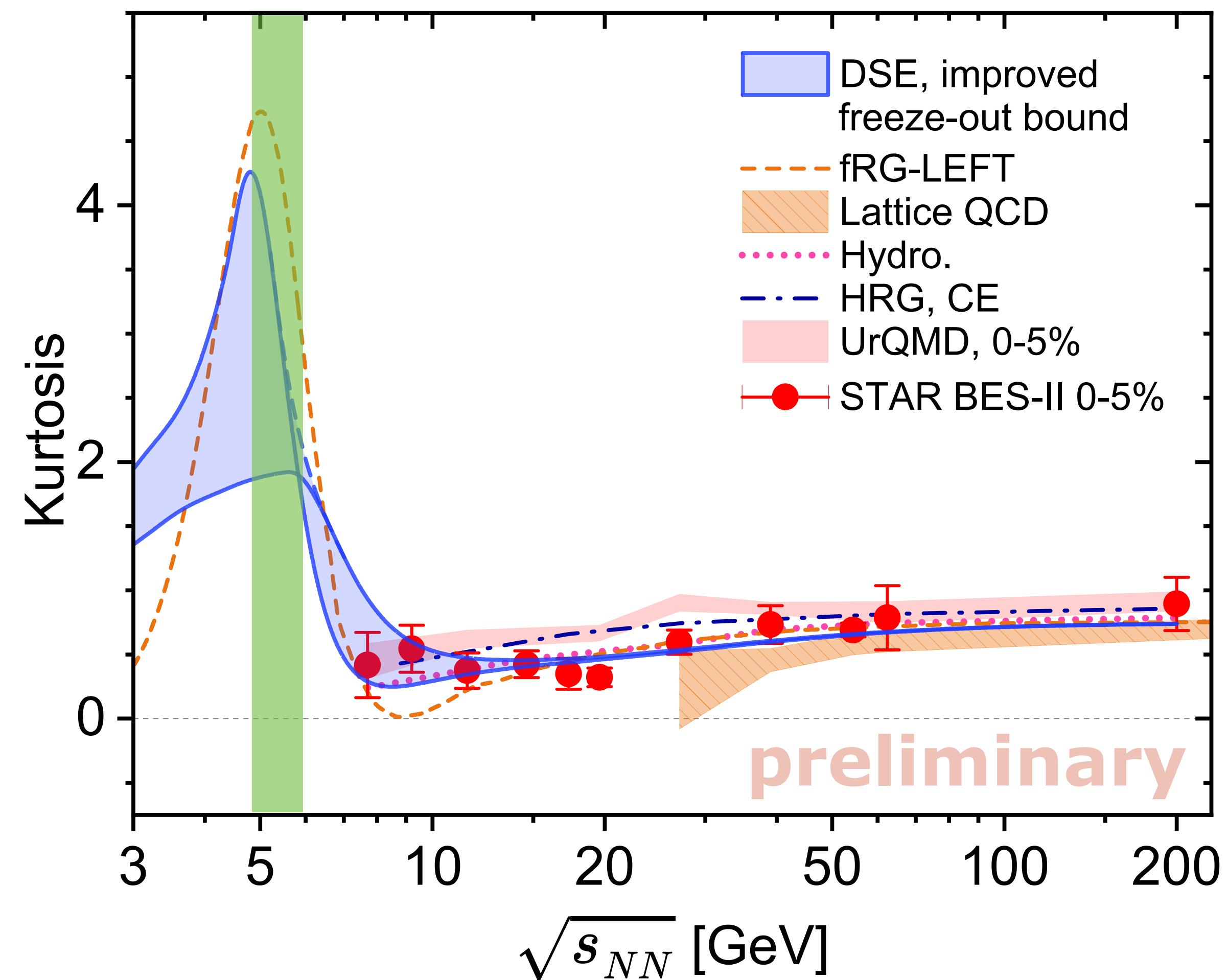
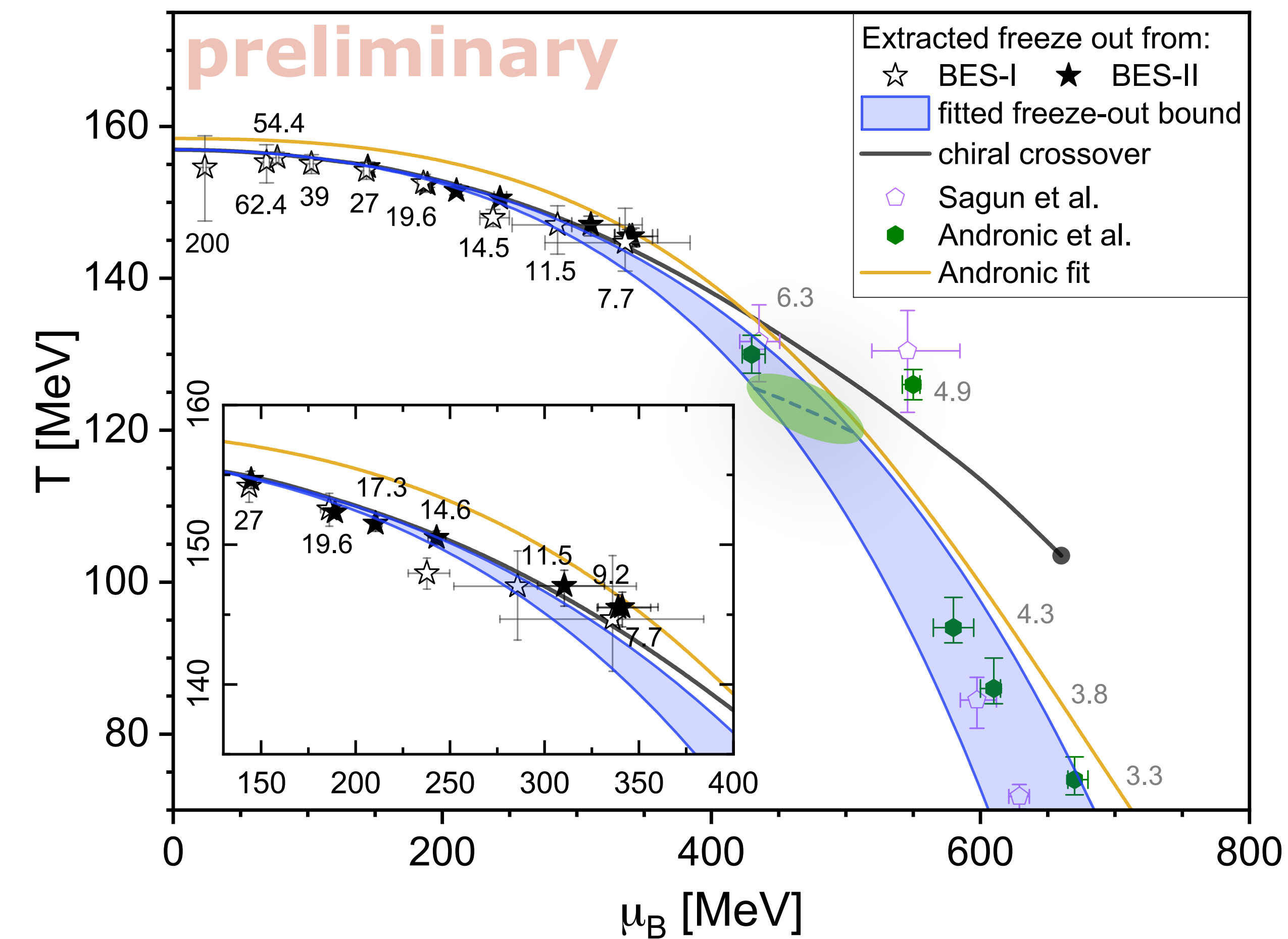
Lu, Gao, Liu, JMP, arXiv:2504.05099



Ripples of the critical point at chemical freeze-out

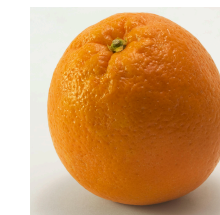


Peak position

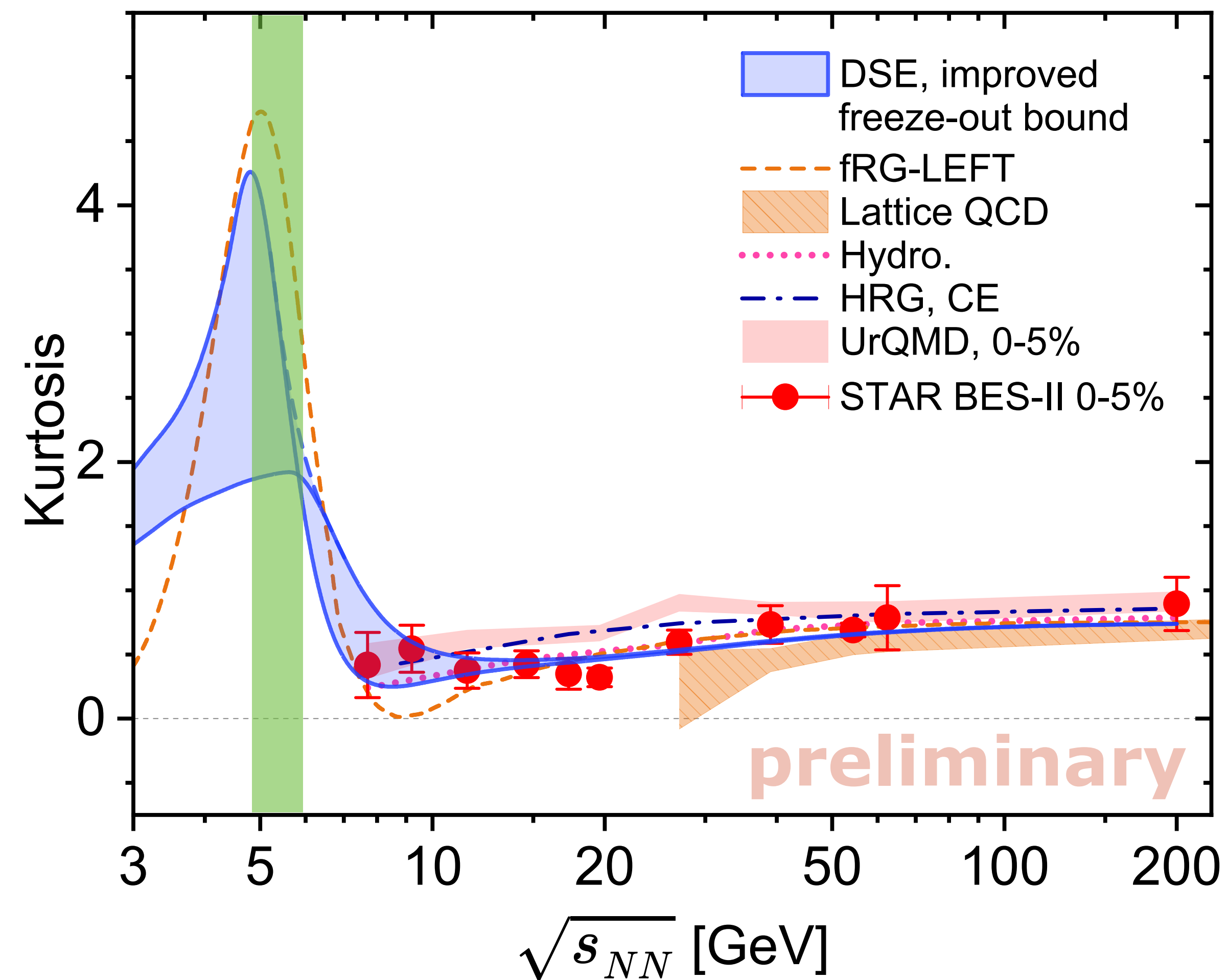
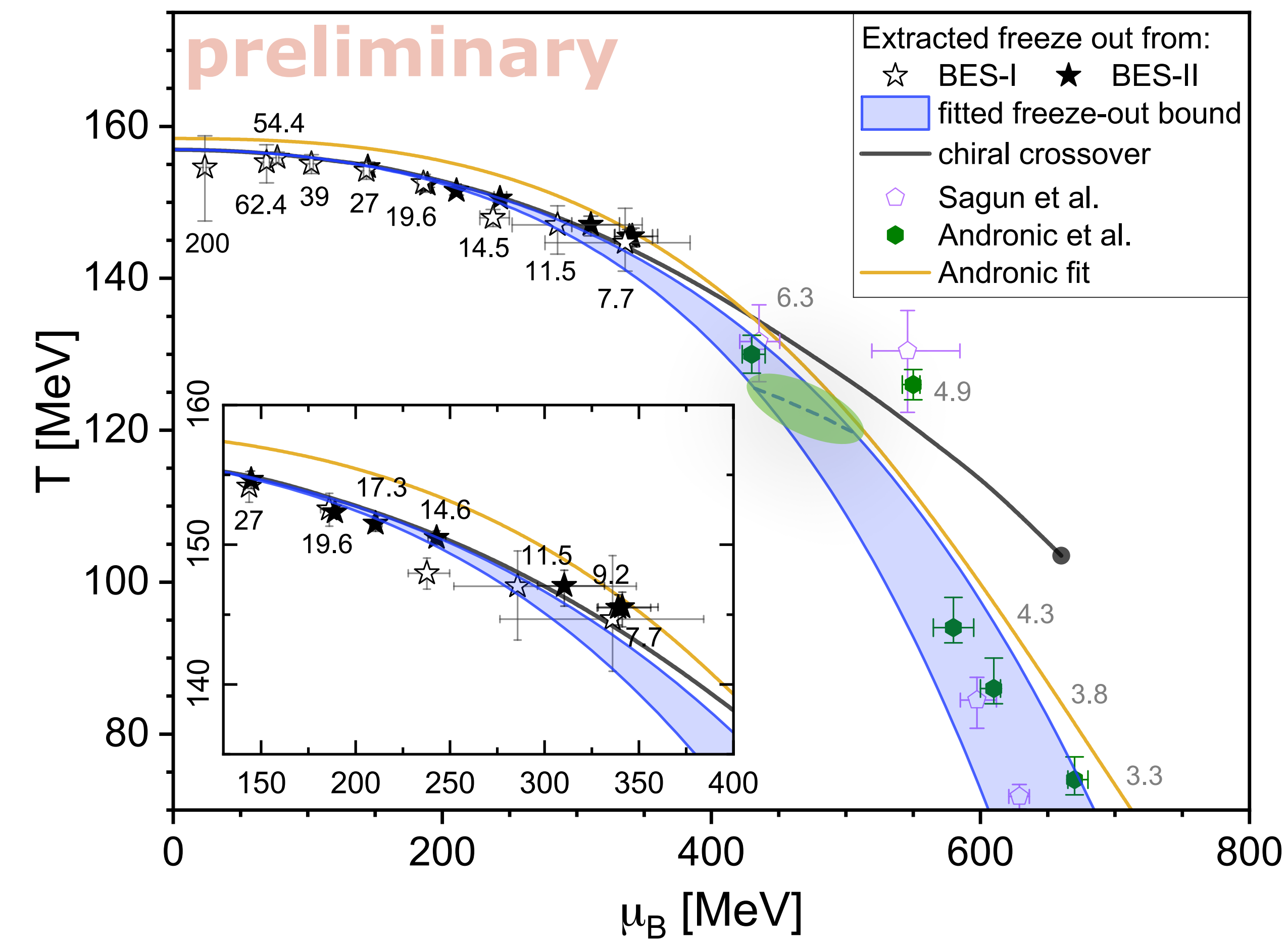




Ripples of the critical point at chemical freeze-out



Peak position



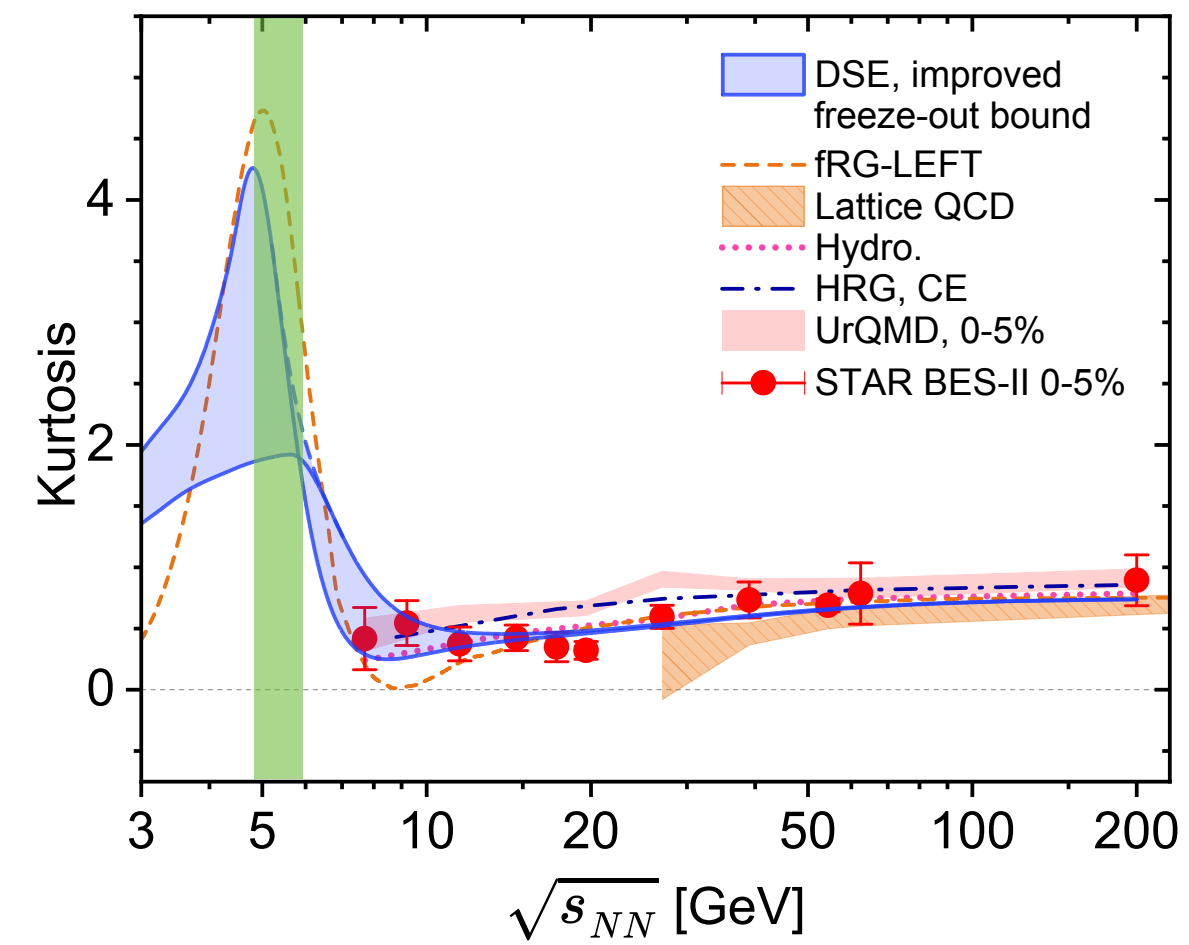
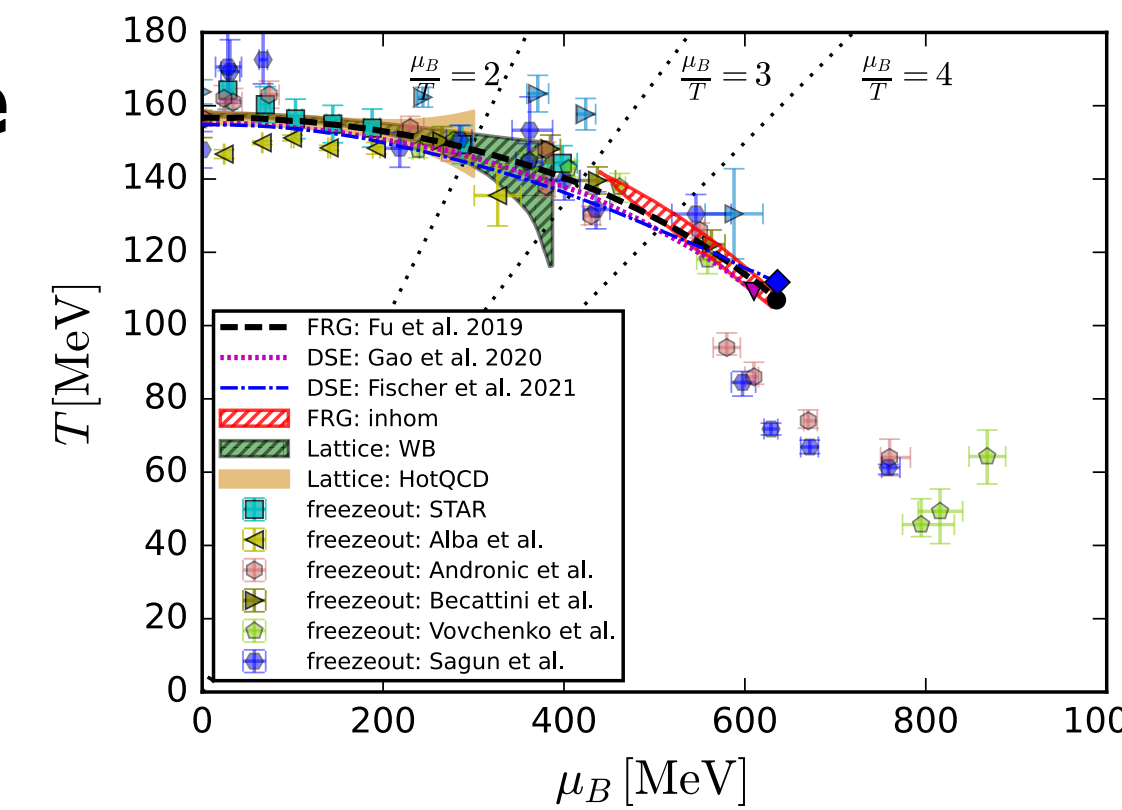
Demand: build in dynamics

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

Outlook

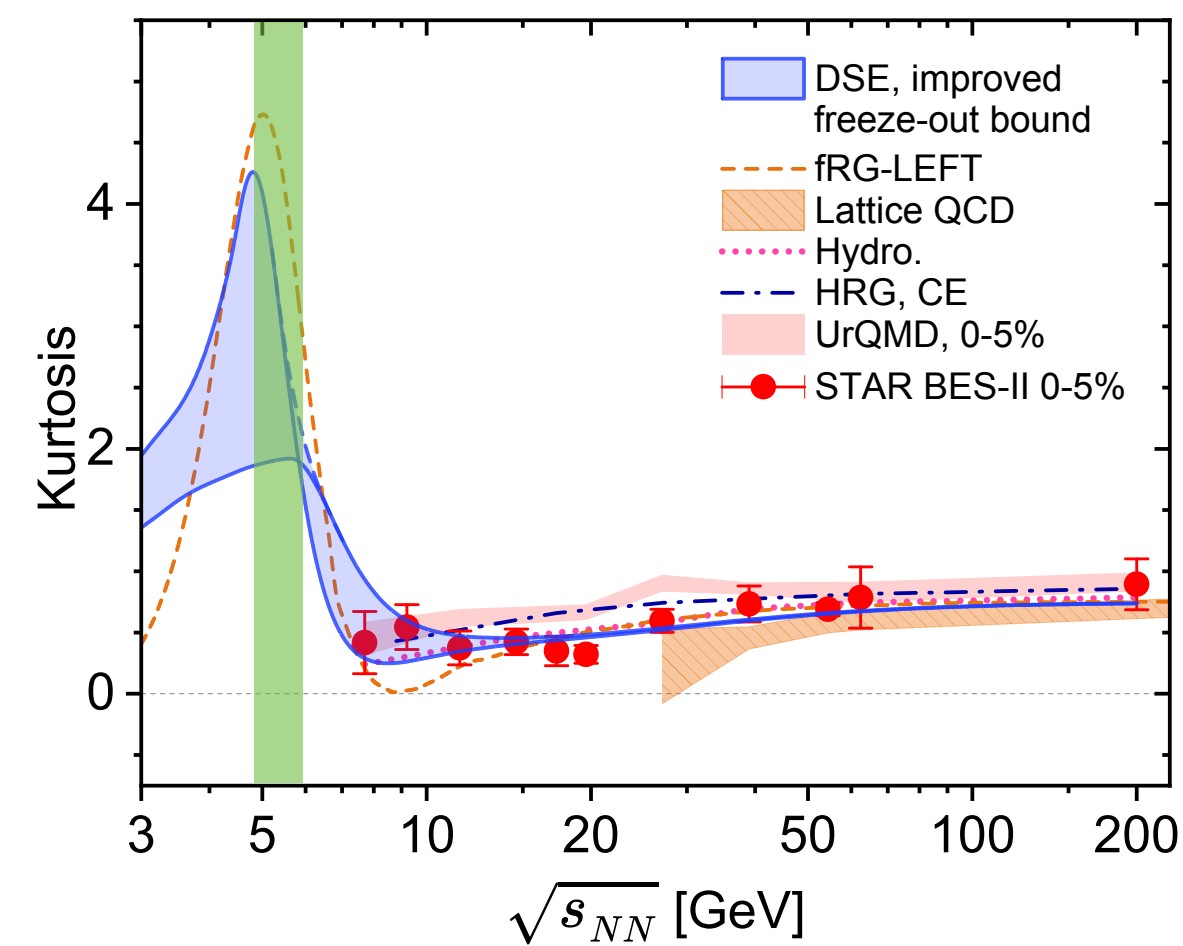
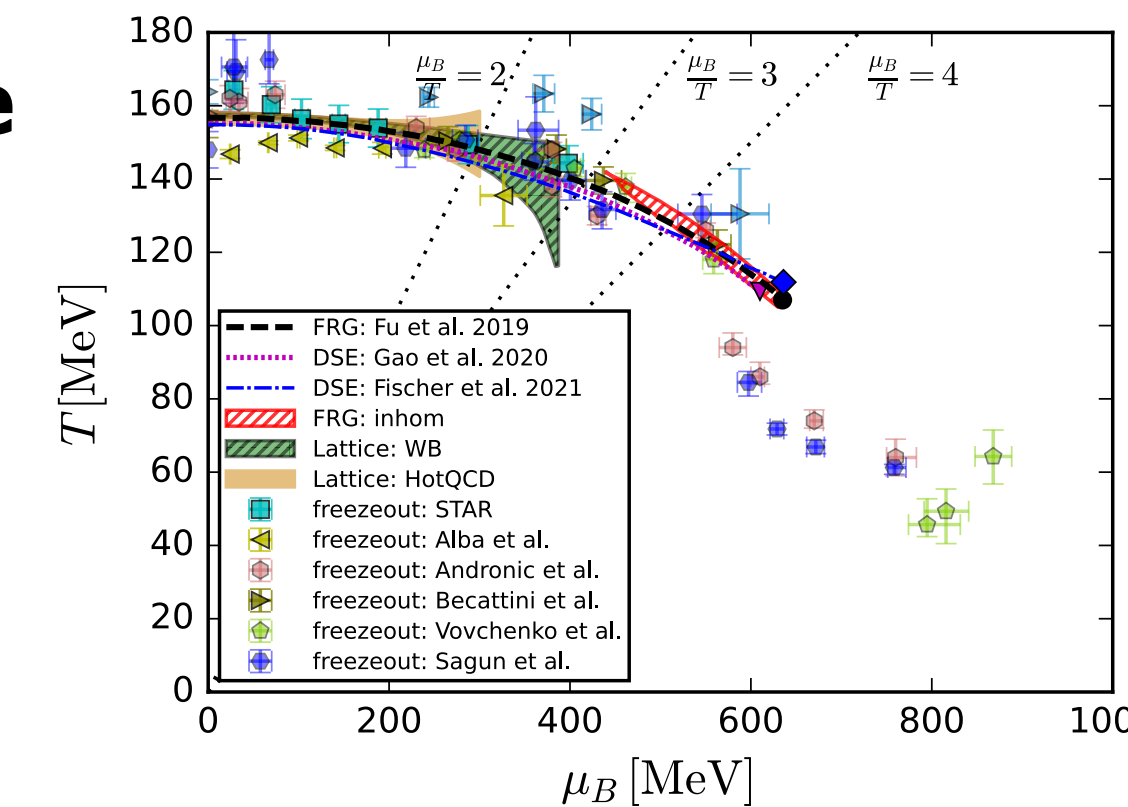
Outlook

- QCD: why and how?
- Chiral symmetry breaking & confinement: towards the QCD phase structure
- The physics of the QCD phase diagram & the experimental landscape
- Unfolding the QCD phase structure



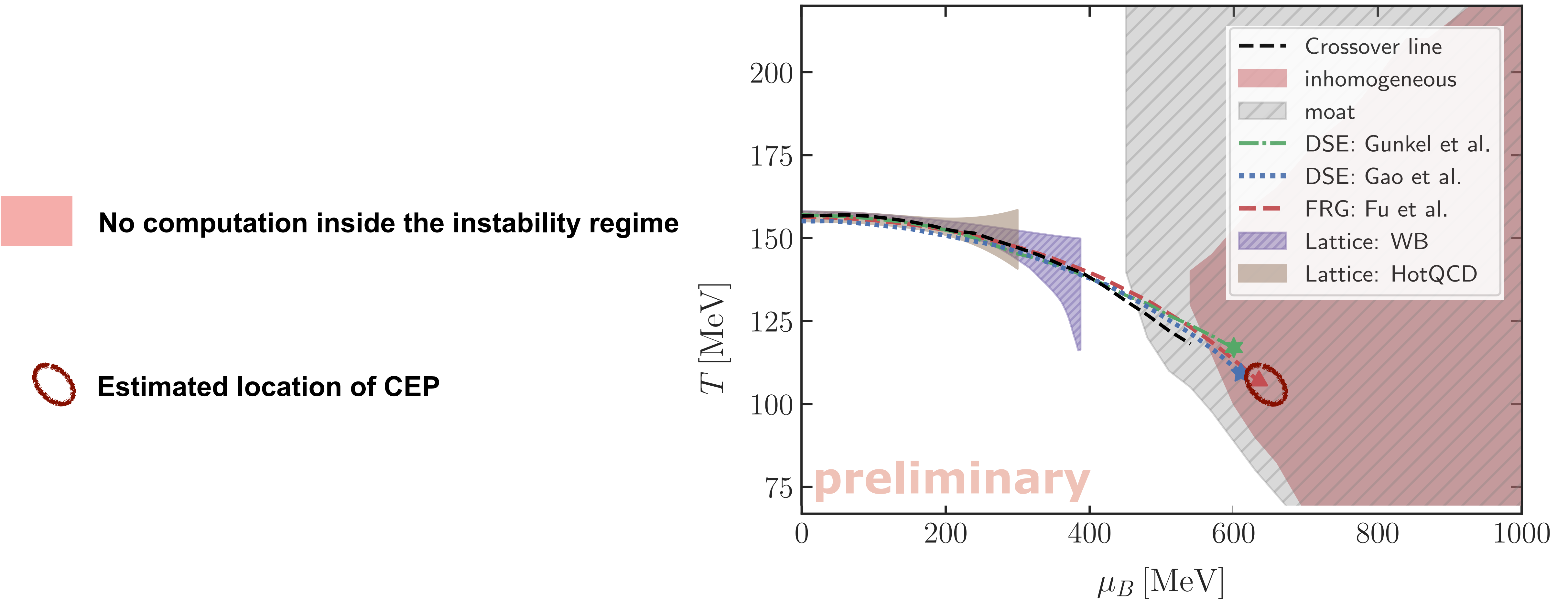
Outlook

- QCD: why and how? **The cool stuff!**
- Chiral symmetry breaking & confinement: towards the QCD phase structure
- The physics of the QCD phase diagram & the experimental landscape
- Unfolding the QCD phase structure



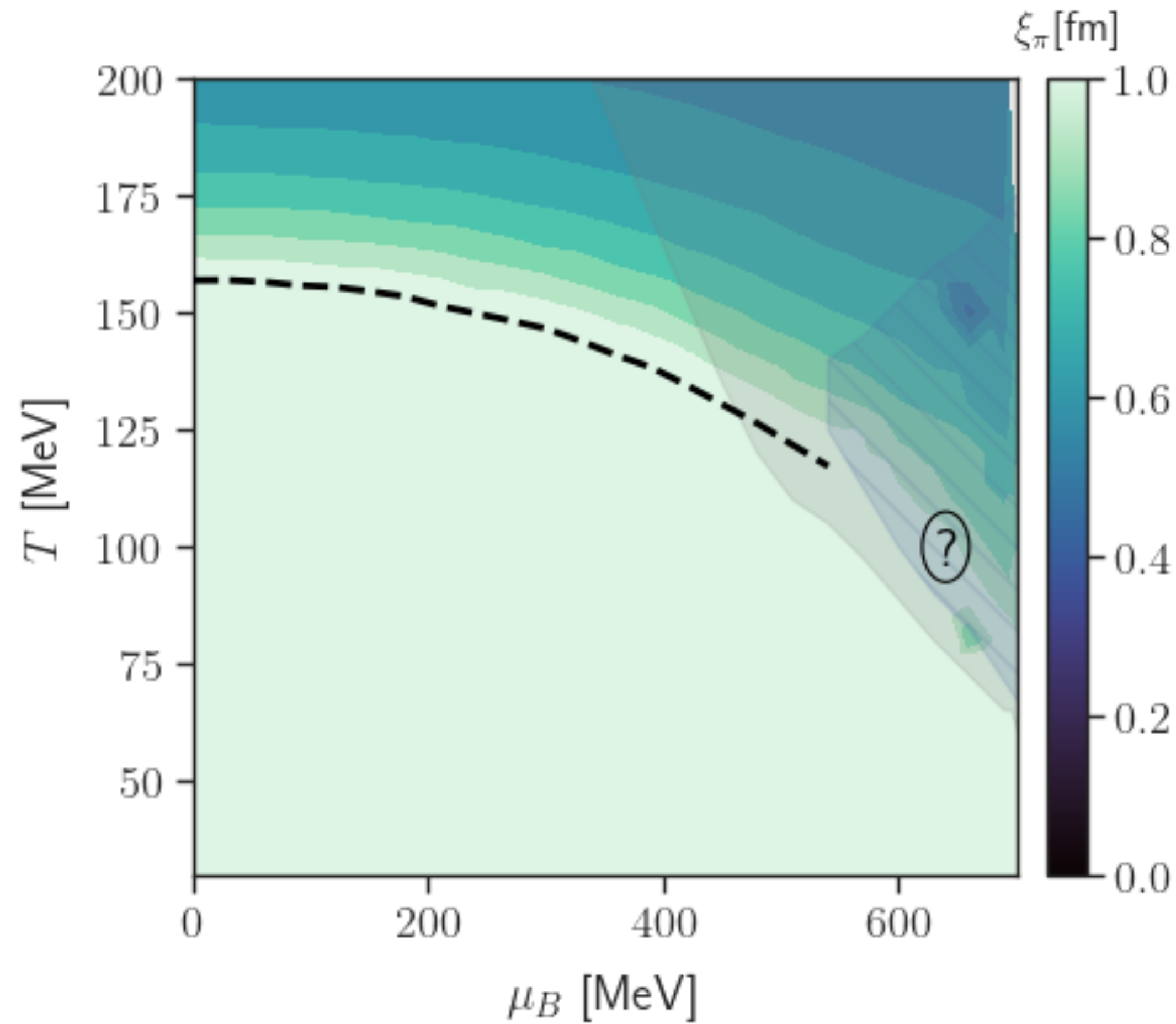
The QCD Moat reloaded

resolution of the moat regime

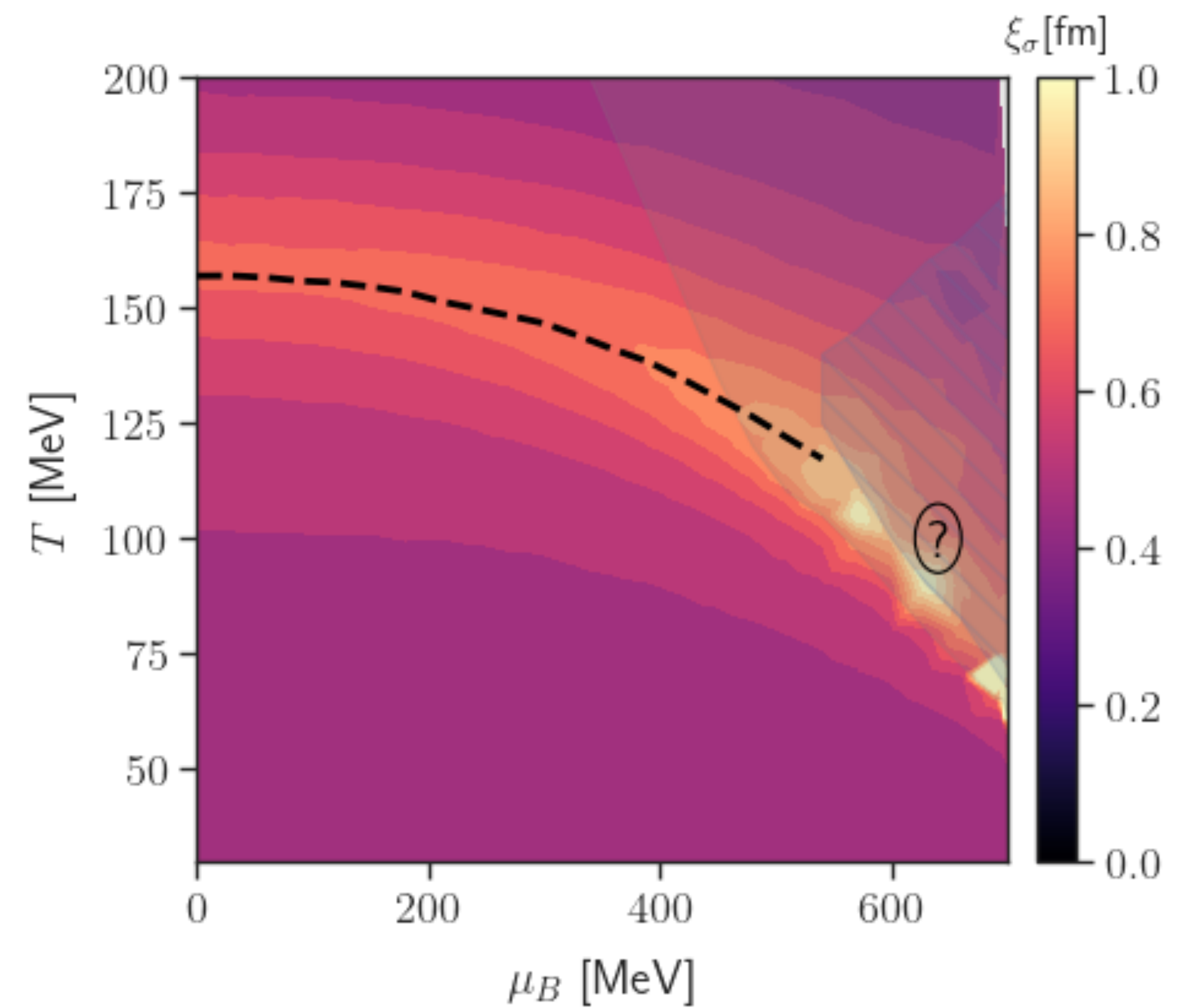


The QCD Moat

Correlation length



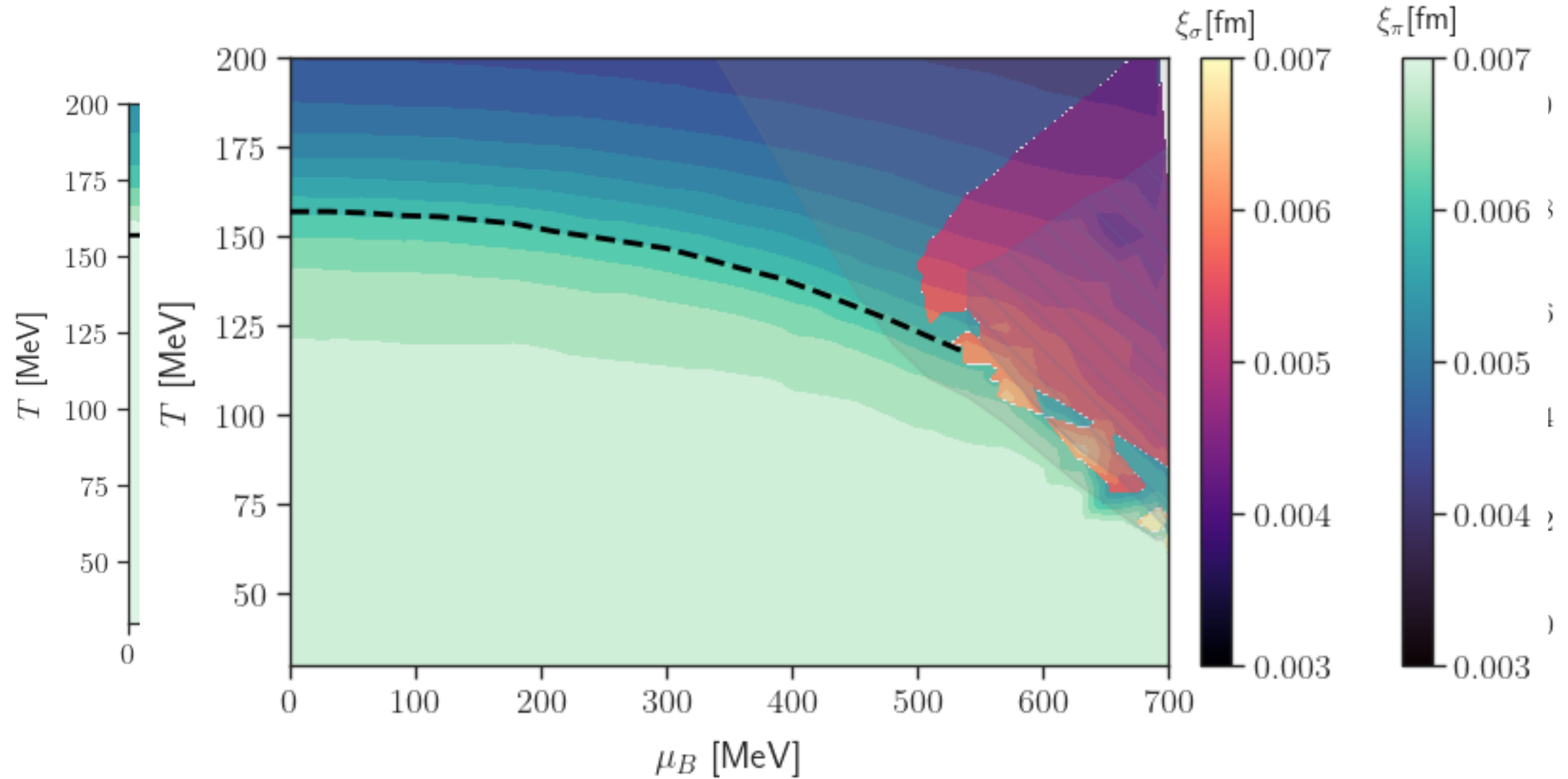
Pion correlation length

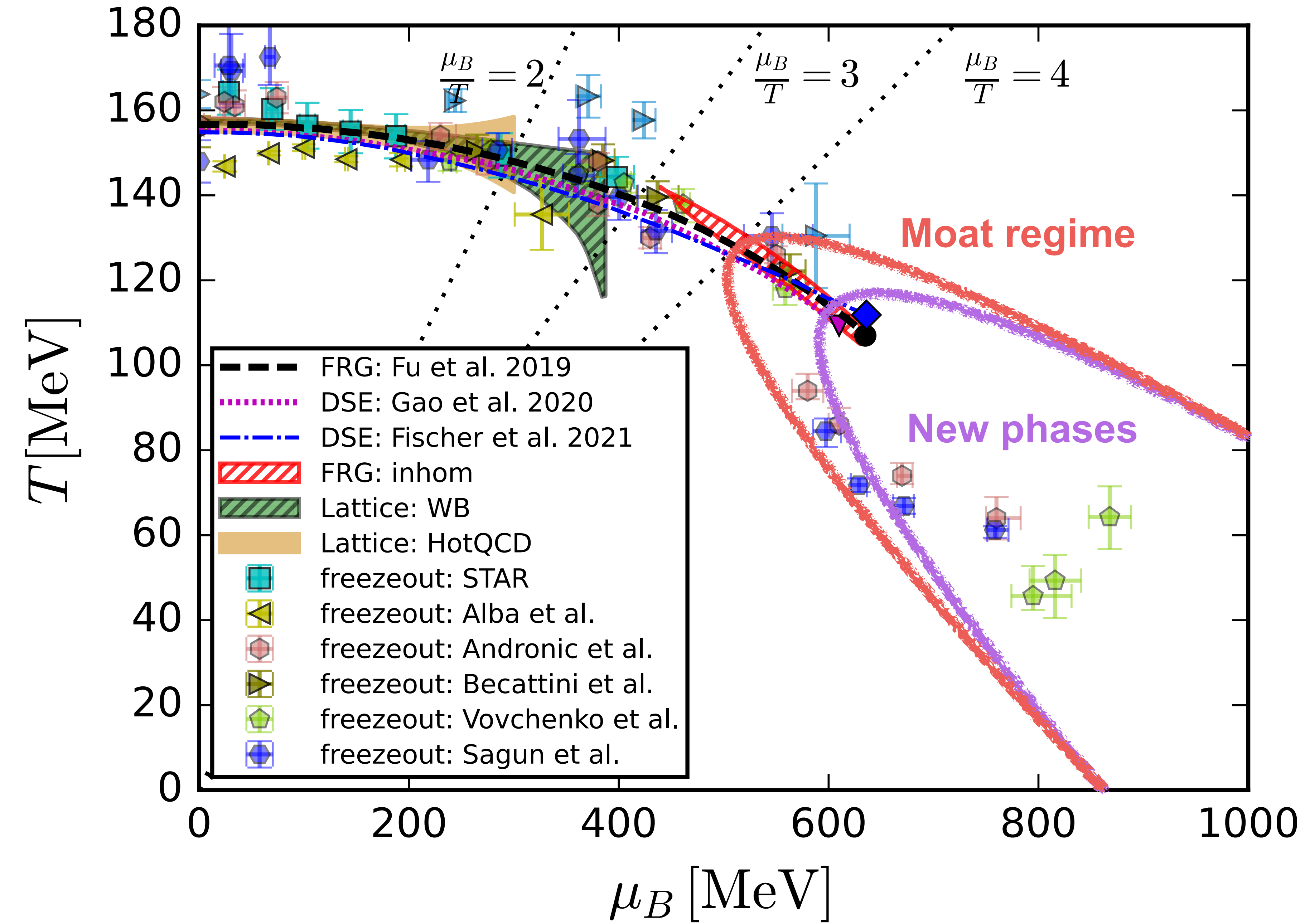


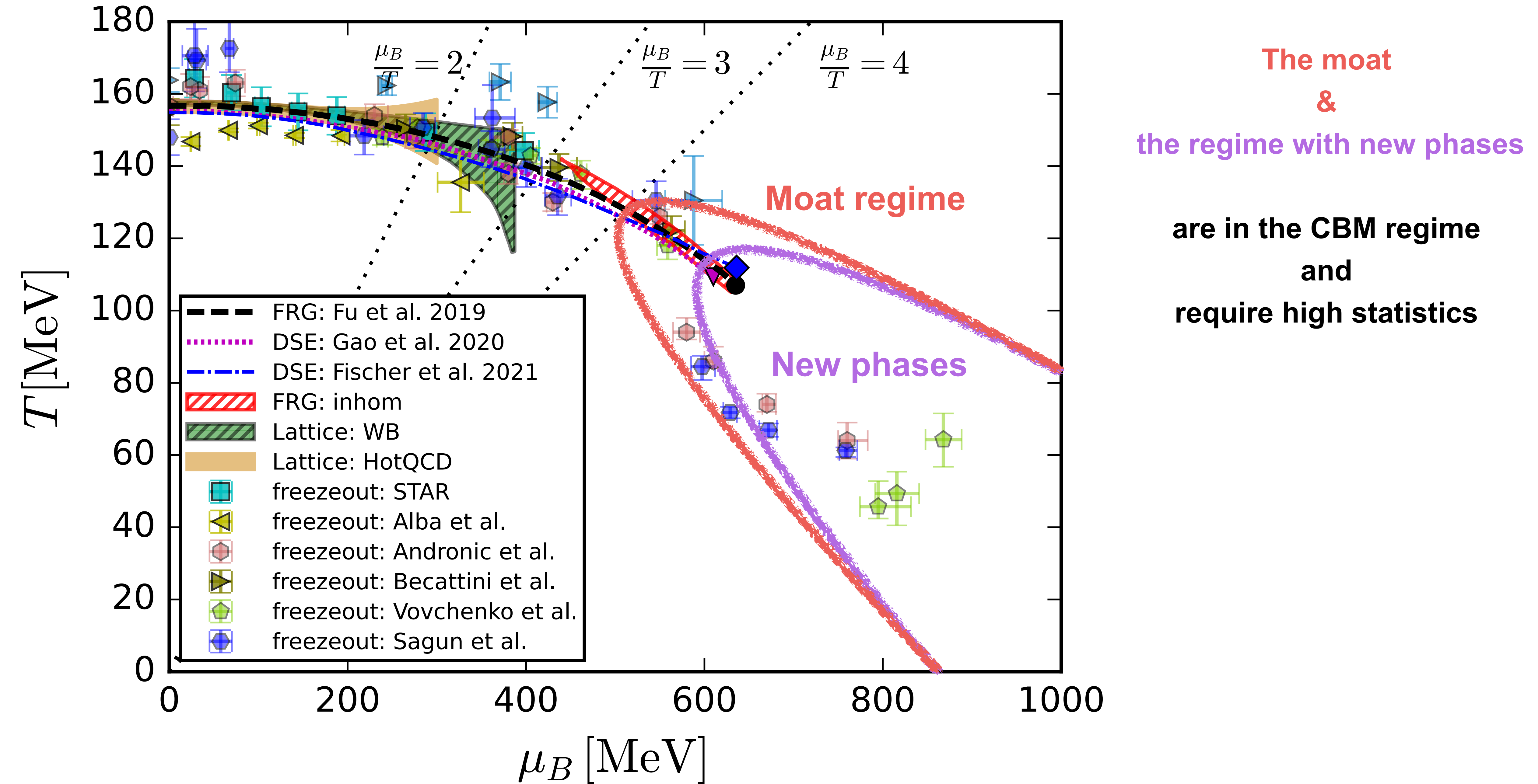
Scalar mode correlation length

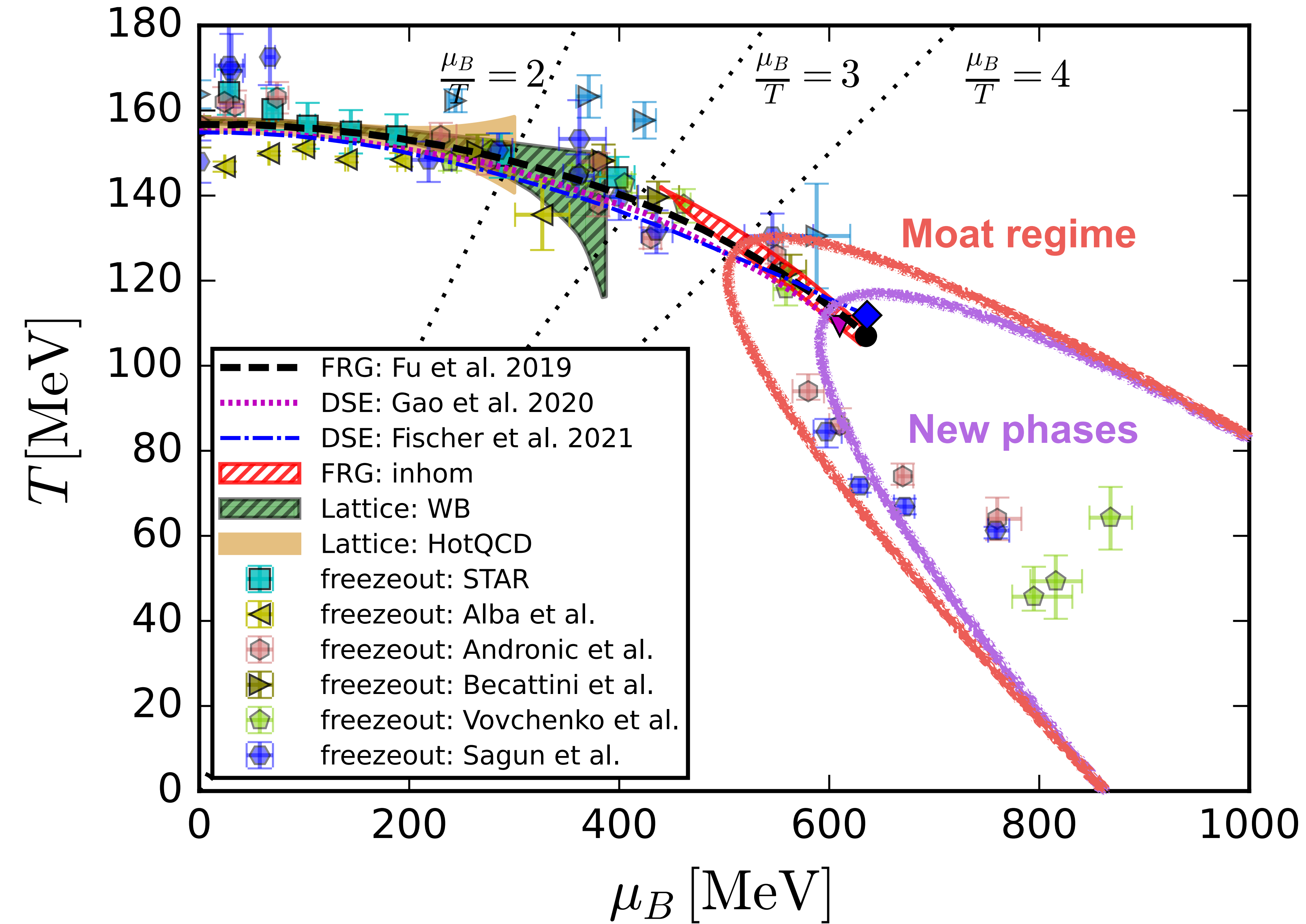
The QCD Moat

Correlation length









**The moat
&
the regime with new phases**

**are in the CBM regime
and
require high statistics**



!Go for it!