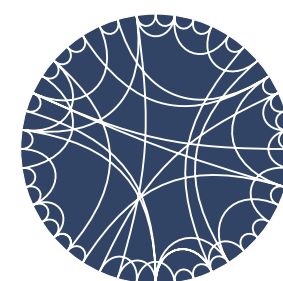
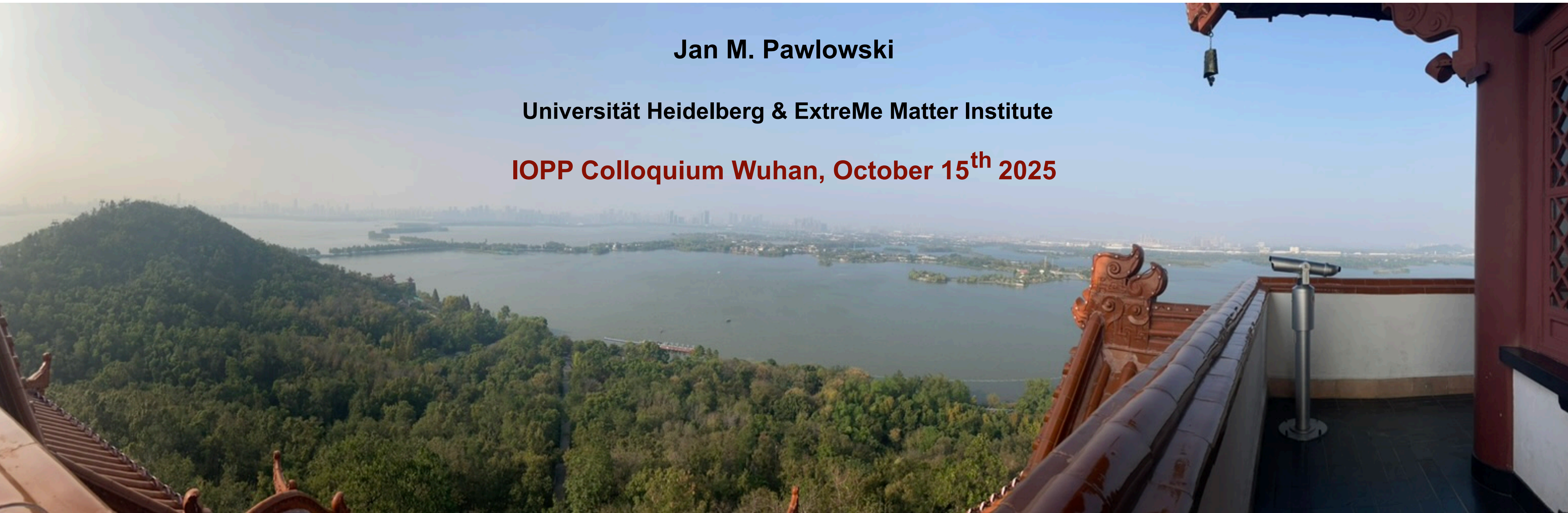


QCD under extreme conditions

Jan M. Pawlowski

Universität Heidelberg & ExtreMe Matter Institute

IOPP Colloquium Wuhan, October 15th 2025



STRUCTURES
CLUSTER OF
EXCELLENCE



**UNIVERSITÄT
HEIDELBERG**
ZUKUNFT
SEIT 1386



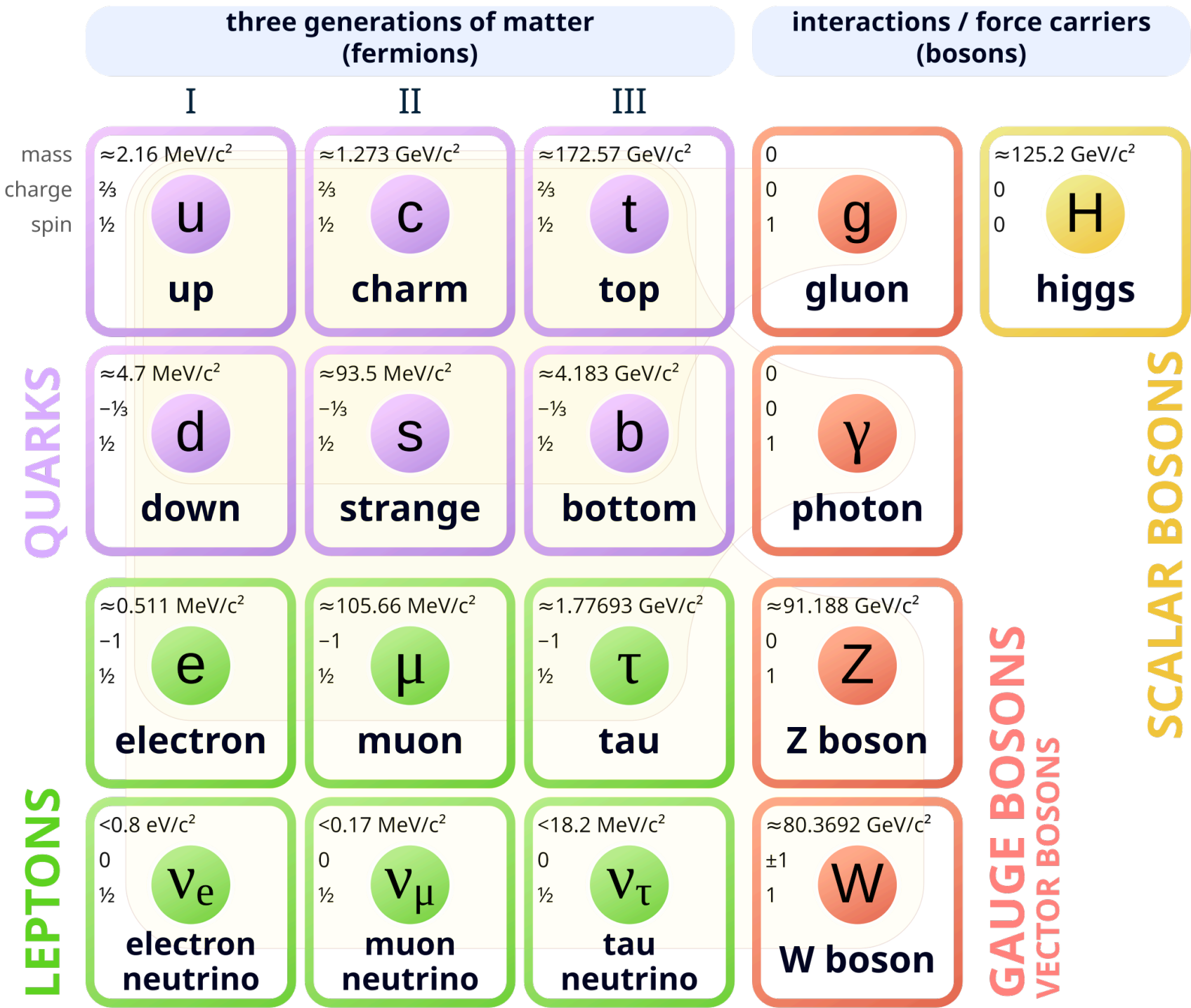
Outline

- **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

Standard Model of Elementary Particles



QCD

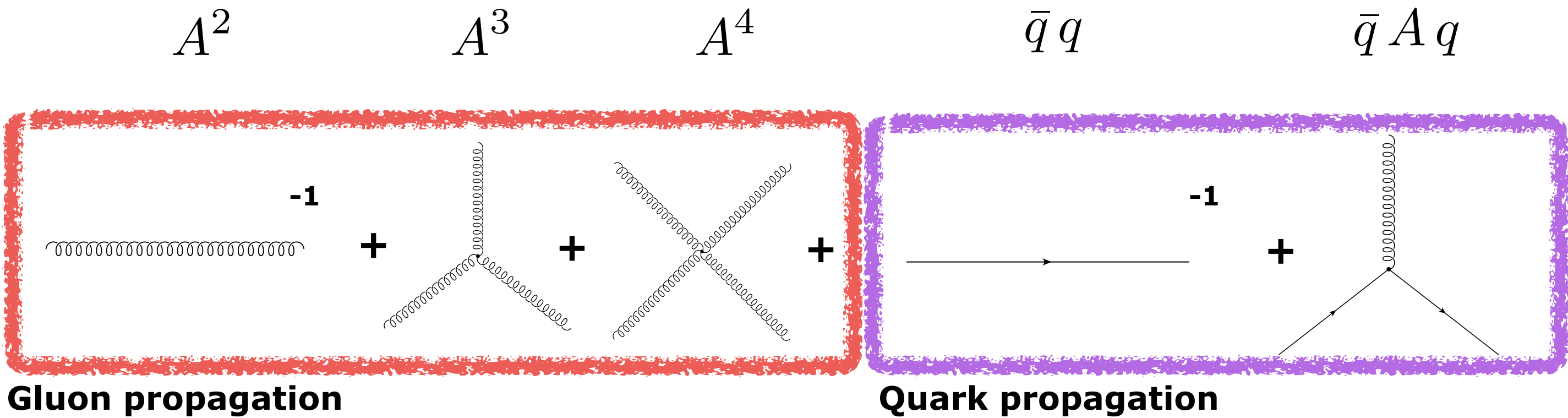
$$S_{\text{QCD}}[\Phi] = \frac{1}{4} \int_x F_{\mu\nu}^a F_{\mu\nu}^a + \int_x \bar{q} \left(i \not{D} + m_q - \gamma_0 \mu_q \right) q$$

Standard Model of Elementary Particles

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

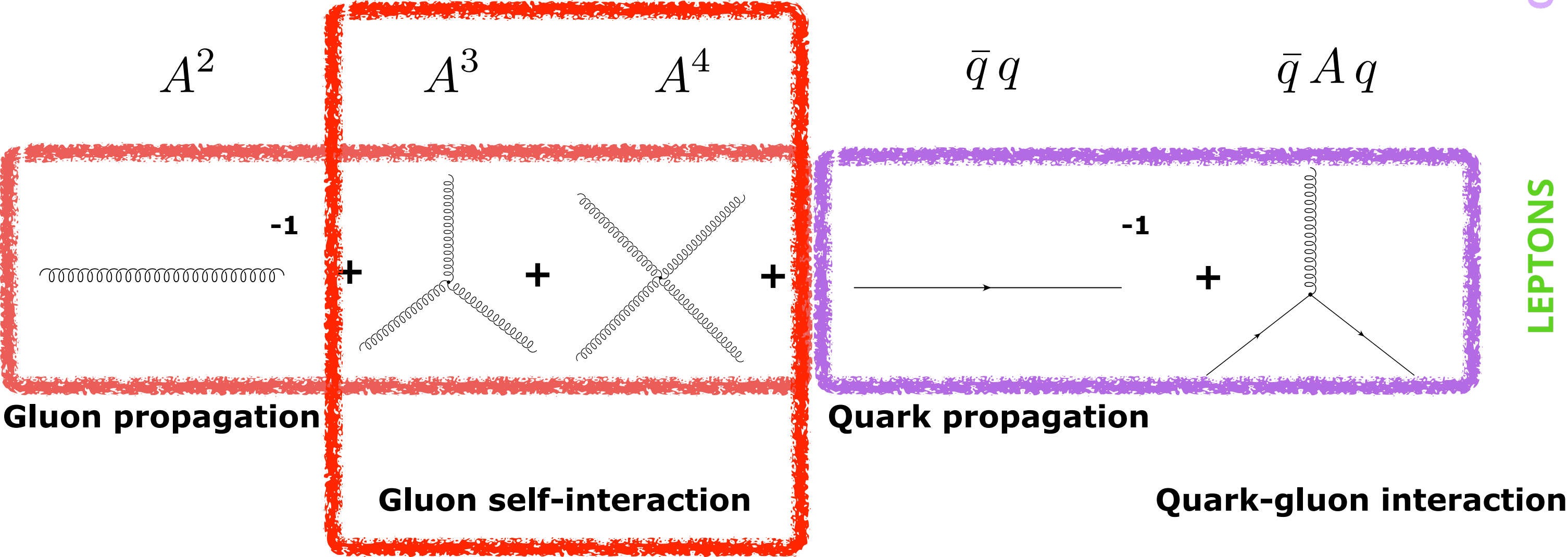
QCD

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Singles out QCD (no strong Higgs)

Standard Model of Elementary Particles

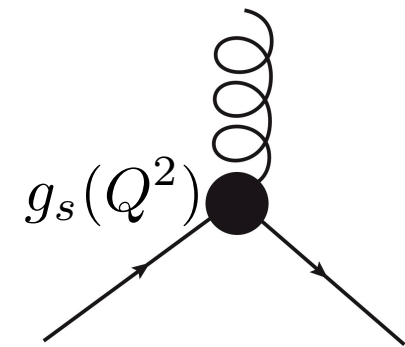
three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin $\approx 2.16 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.273 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 172.57 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon	$\approx 125.2 \text{ GeV}/c^2$ 0 0 H higgs
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon	GAUGE BOSONS VECTOR BOSONS
$\approx 0.511 \text{ MeV}/c^2$ -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 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	

SCALAR BOSONS

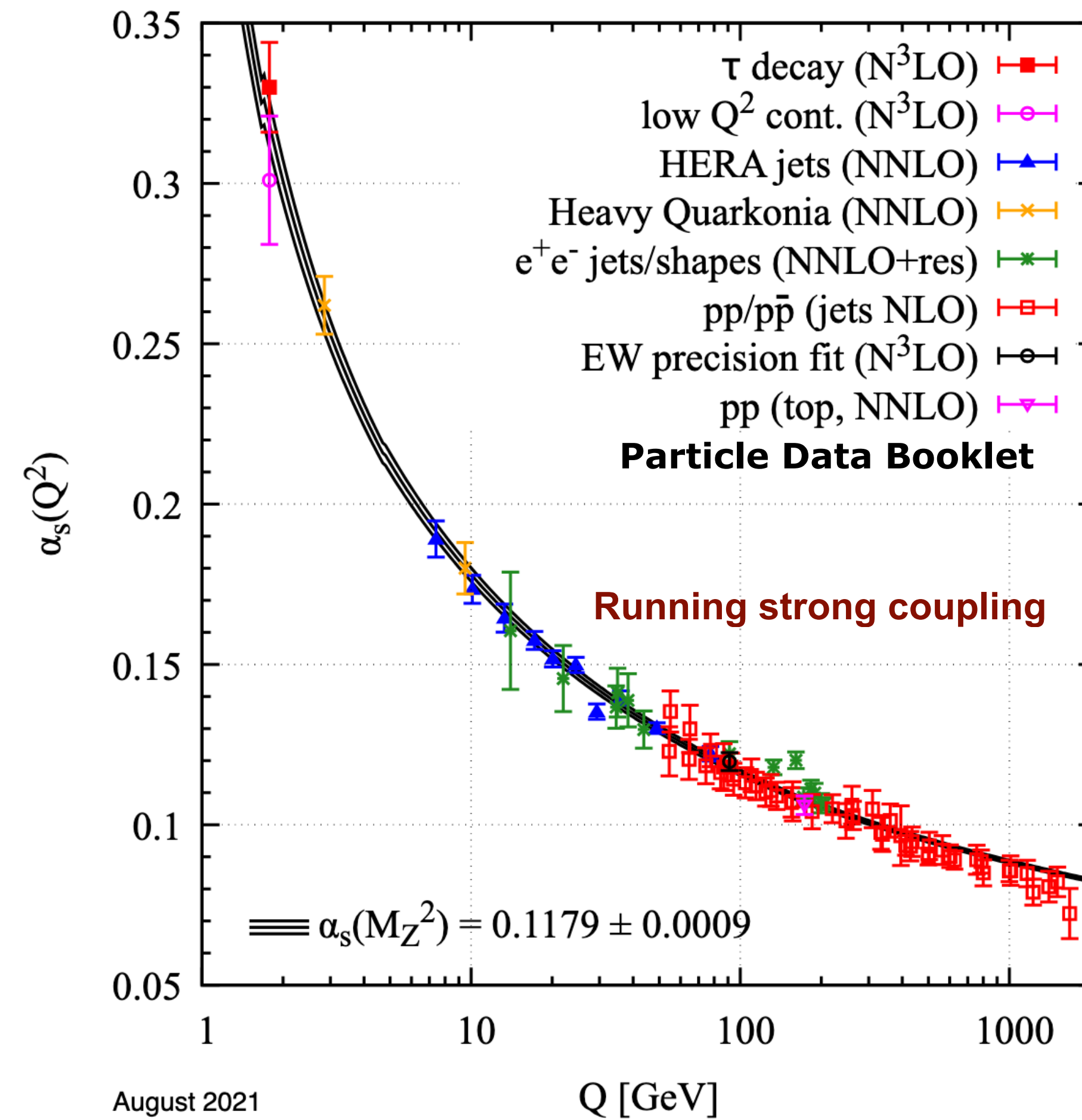
What's hot in QCD?

Low Temperatures, densities

Large Temperatures, densities



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

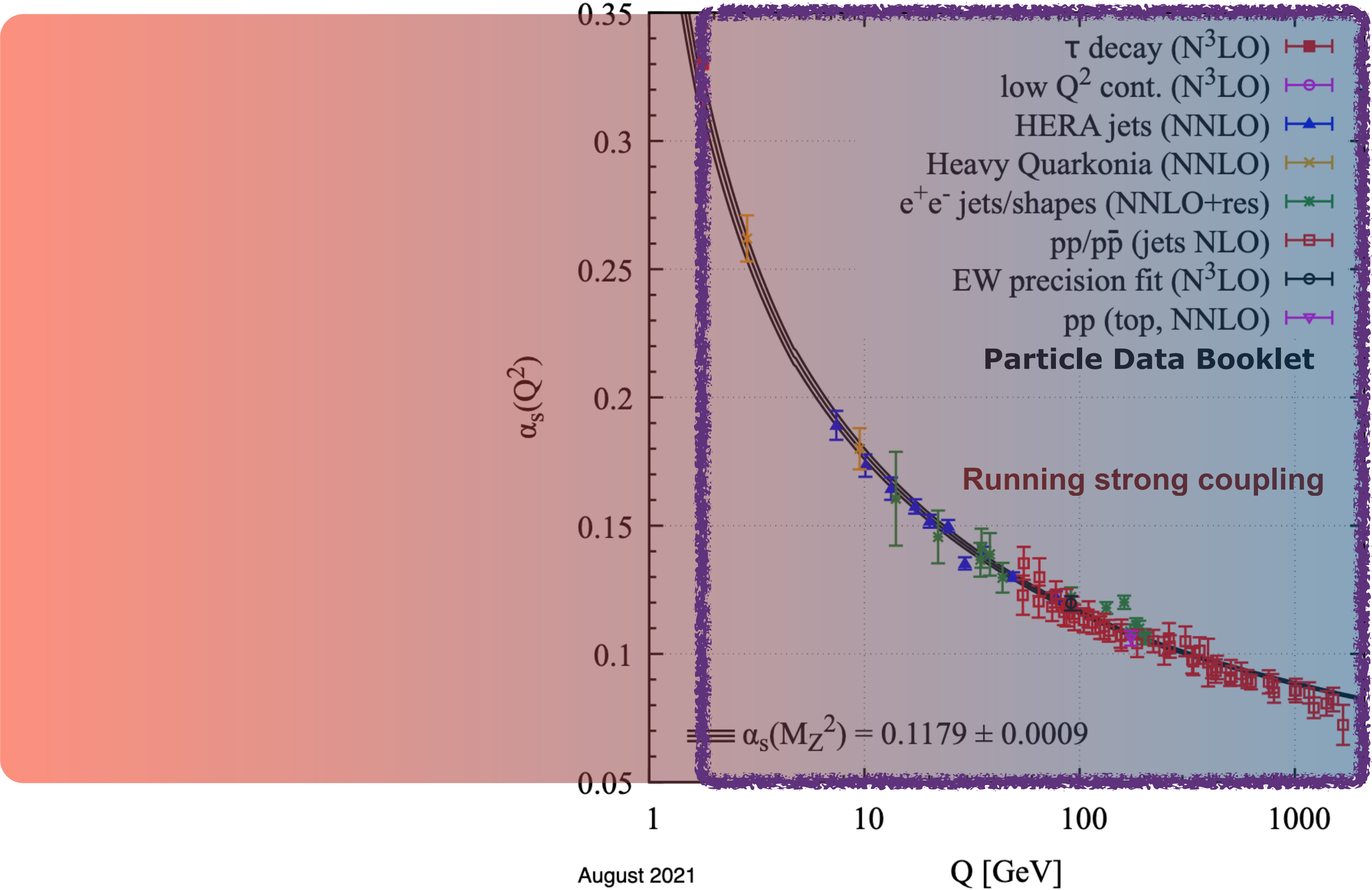


August 2021

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

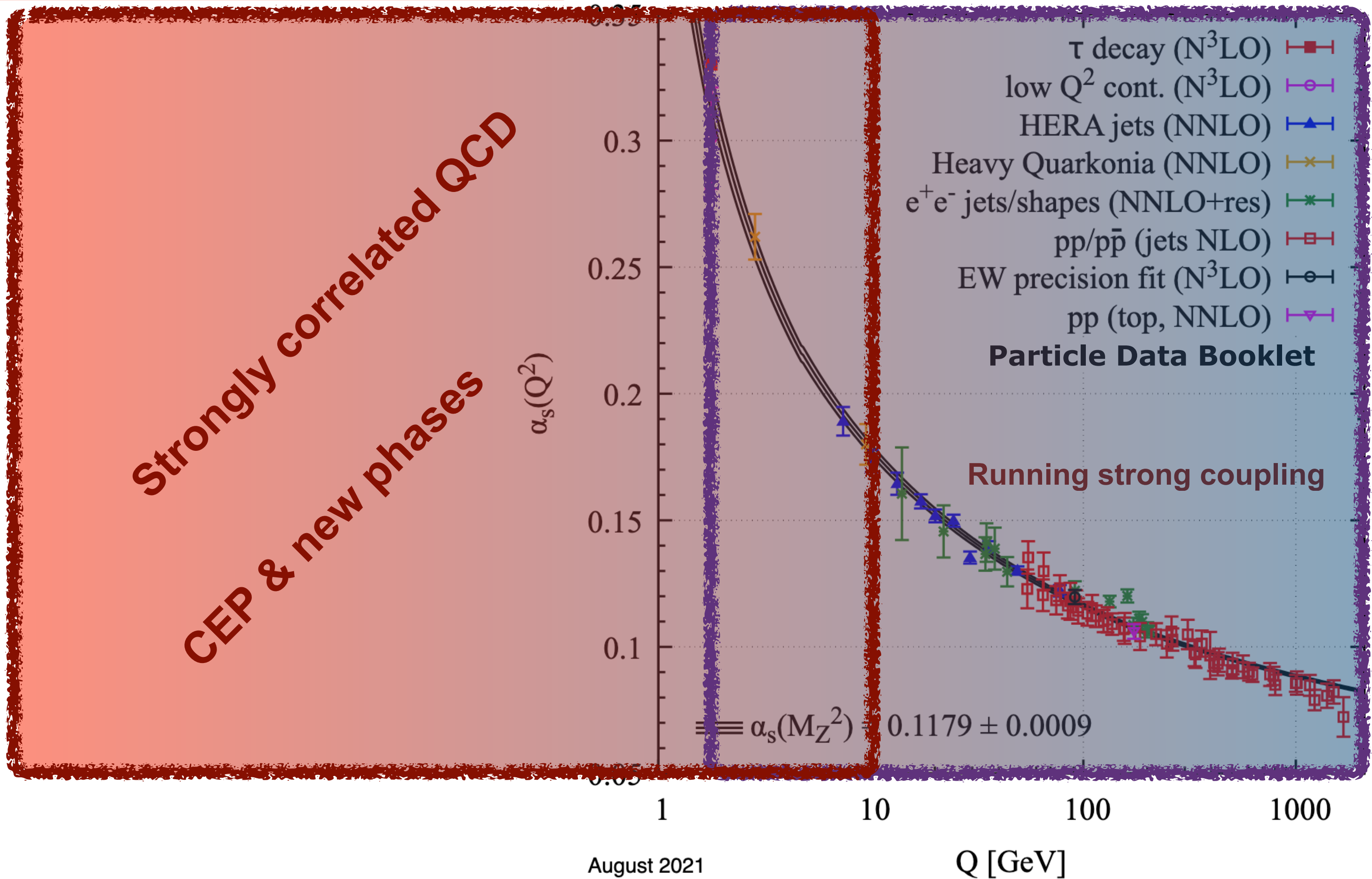
Asymptotic freedom
Nobel Prize '04
Gross, Politzer, Wilczek

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IR: confinement & chiral symmetry breaking



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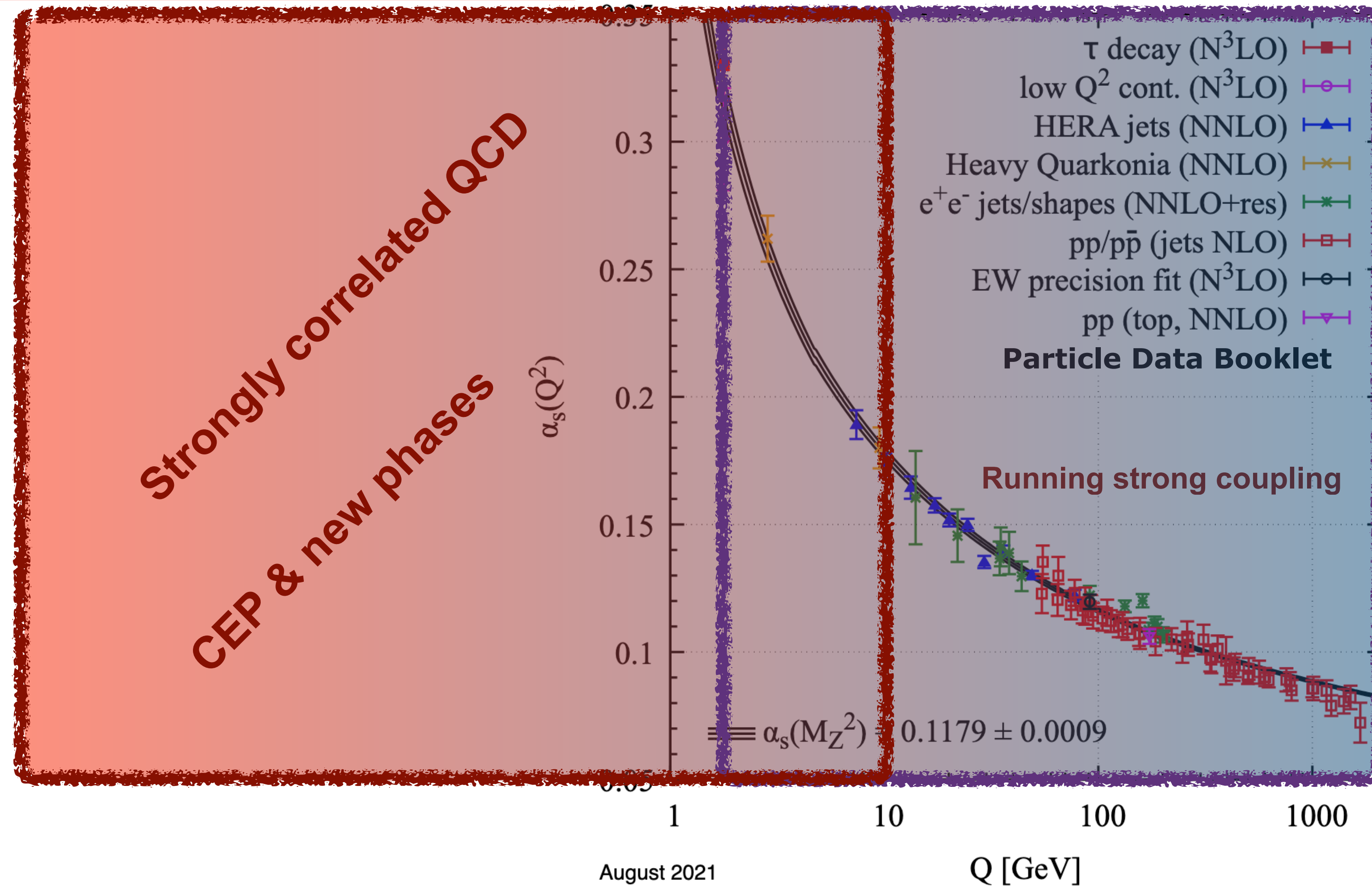
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UV: weakly coupled quarks and gluons

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

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

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

Those are my interpretations,
and if you don't like them....
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'... and now for something
completely different...'



Extrapolations & von Neumann's Elephant

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Extrapolations are ill-conditioned problems

‘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

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

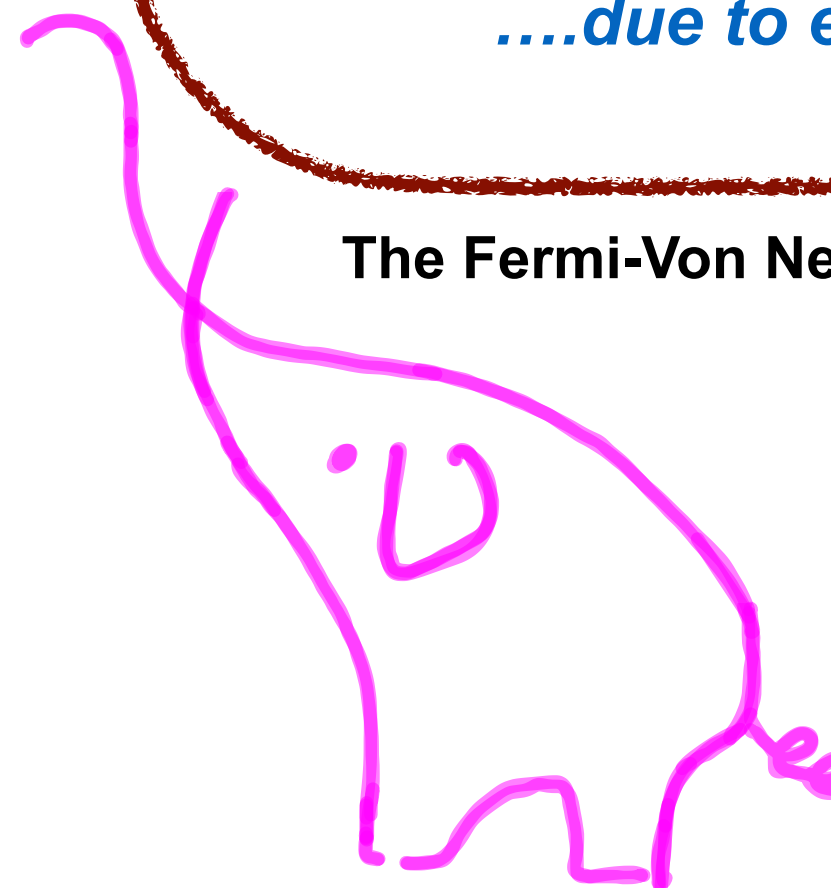
**In particular, extrapolations cannot predict the existence
and location of the CEP without external information**

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

*'With four parameters I can fit an elephant,
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Von Neumann

The Fermi-Von Neumann QCD phase structure elephant





Extrapolations & von Neumann's Elephant

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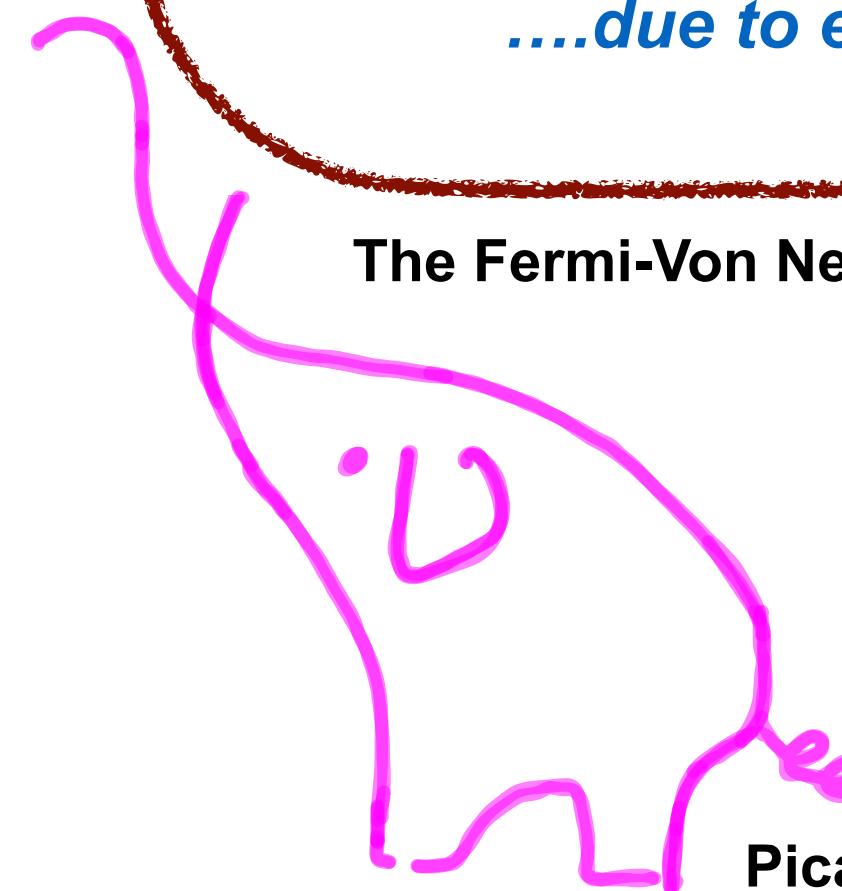
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The Fermi-Von Neumann QCD phase structure elephant



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	$(4.1-4.4)\times10^3$	

Chiral symmetry breaking

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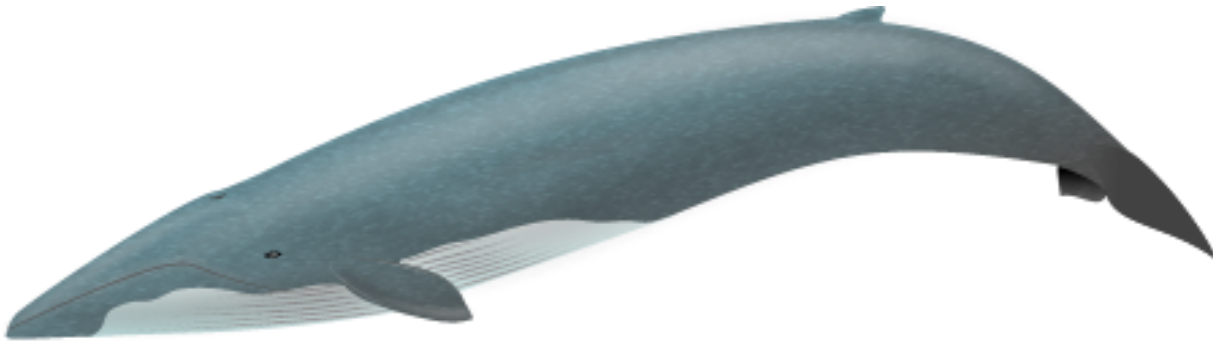
up



charm



top



down



strange



bottom



Current quark masses (Higgs)

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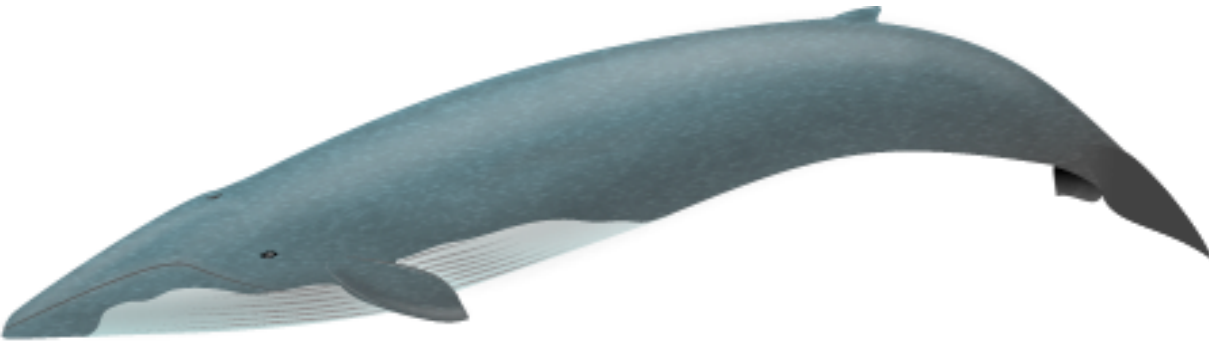
up



charm



top



down



strange



bottom



Current quark masses (Higgs)

2 light flavours, one heavy flavour 2+1

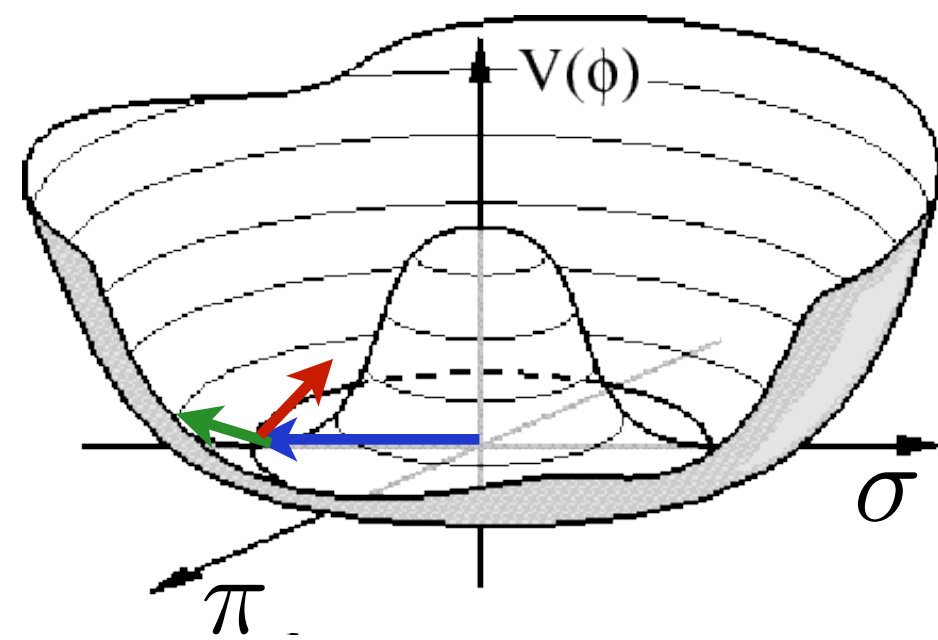
Dynamical chiral symmetry breaking

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 $\sigma \neq 0$

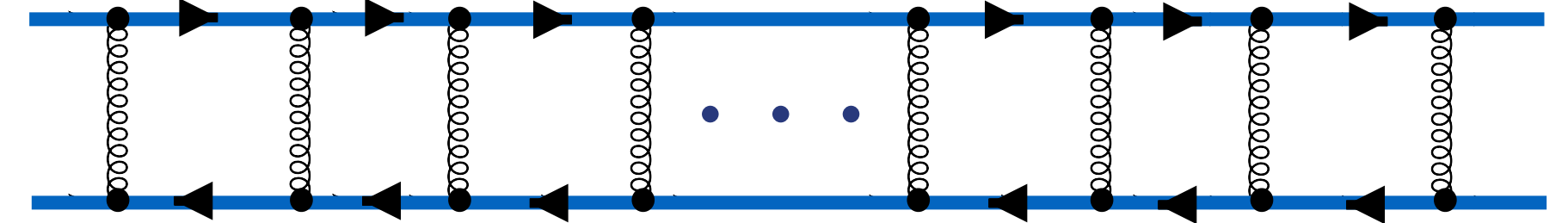
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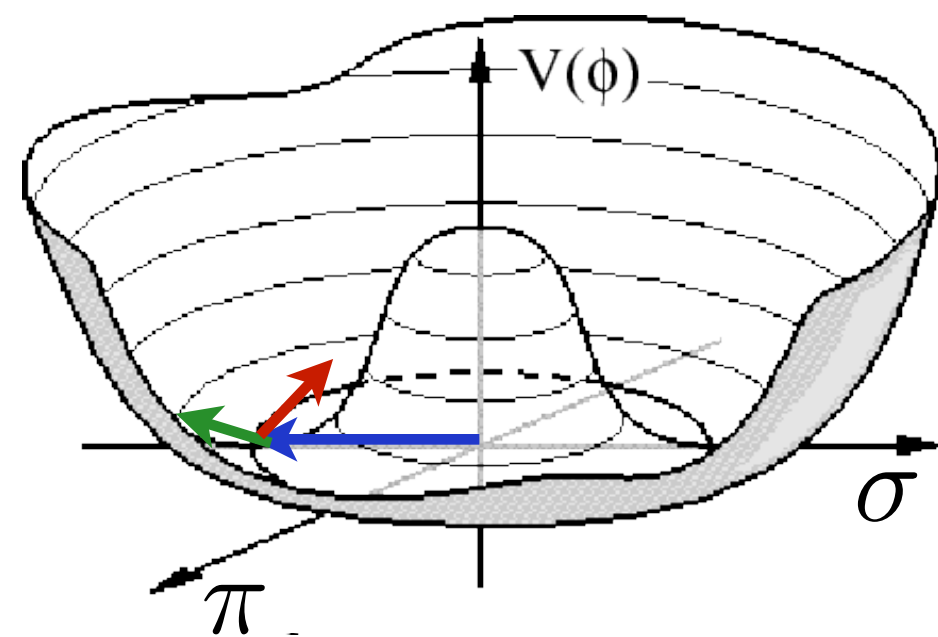
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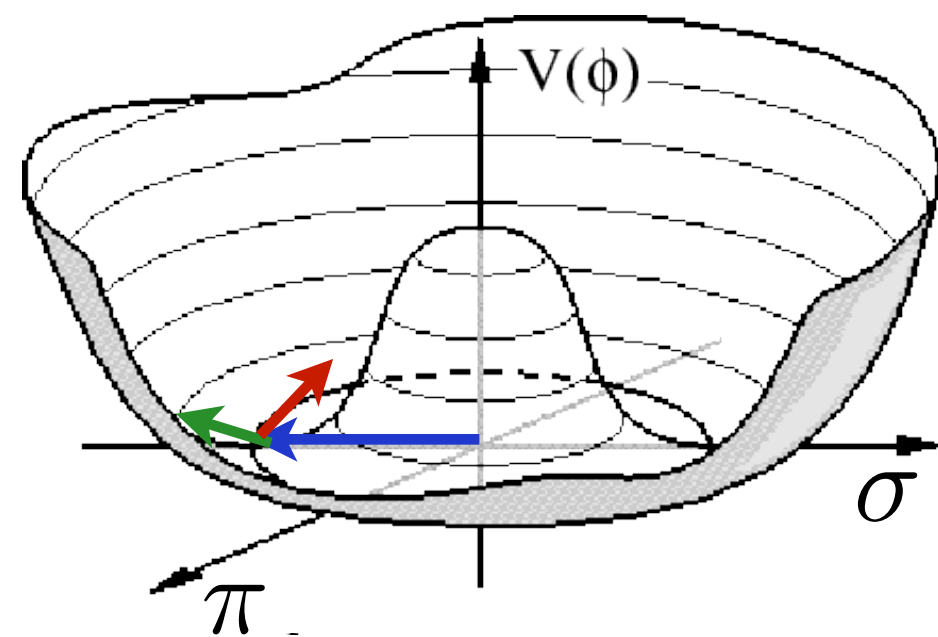
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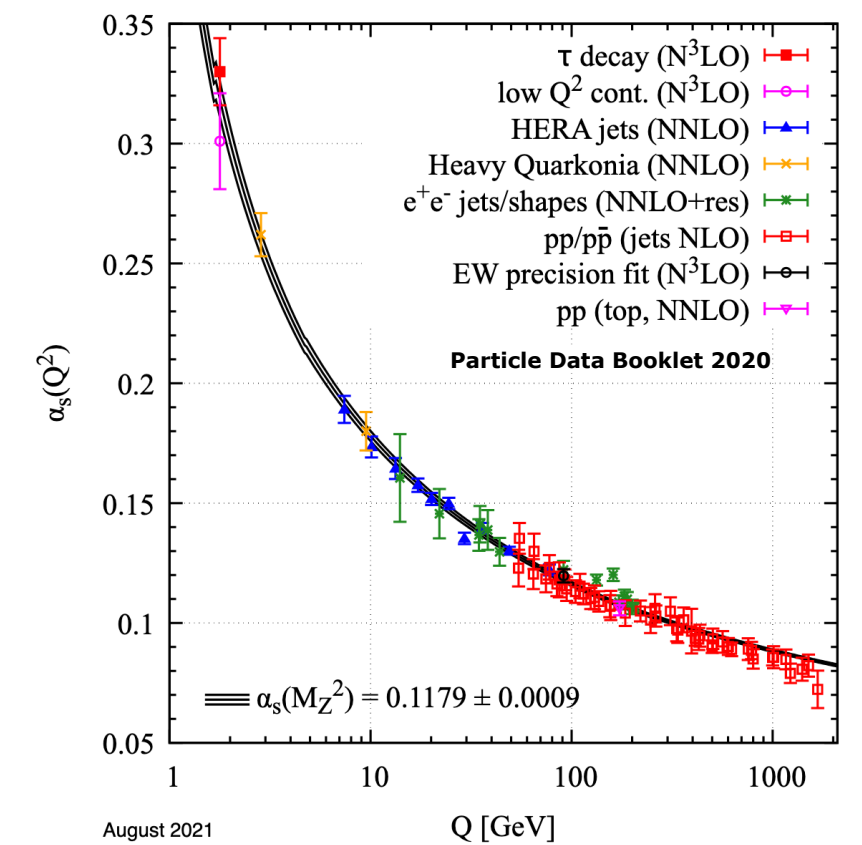
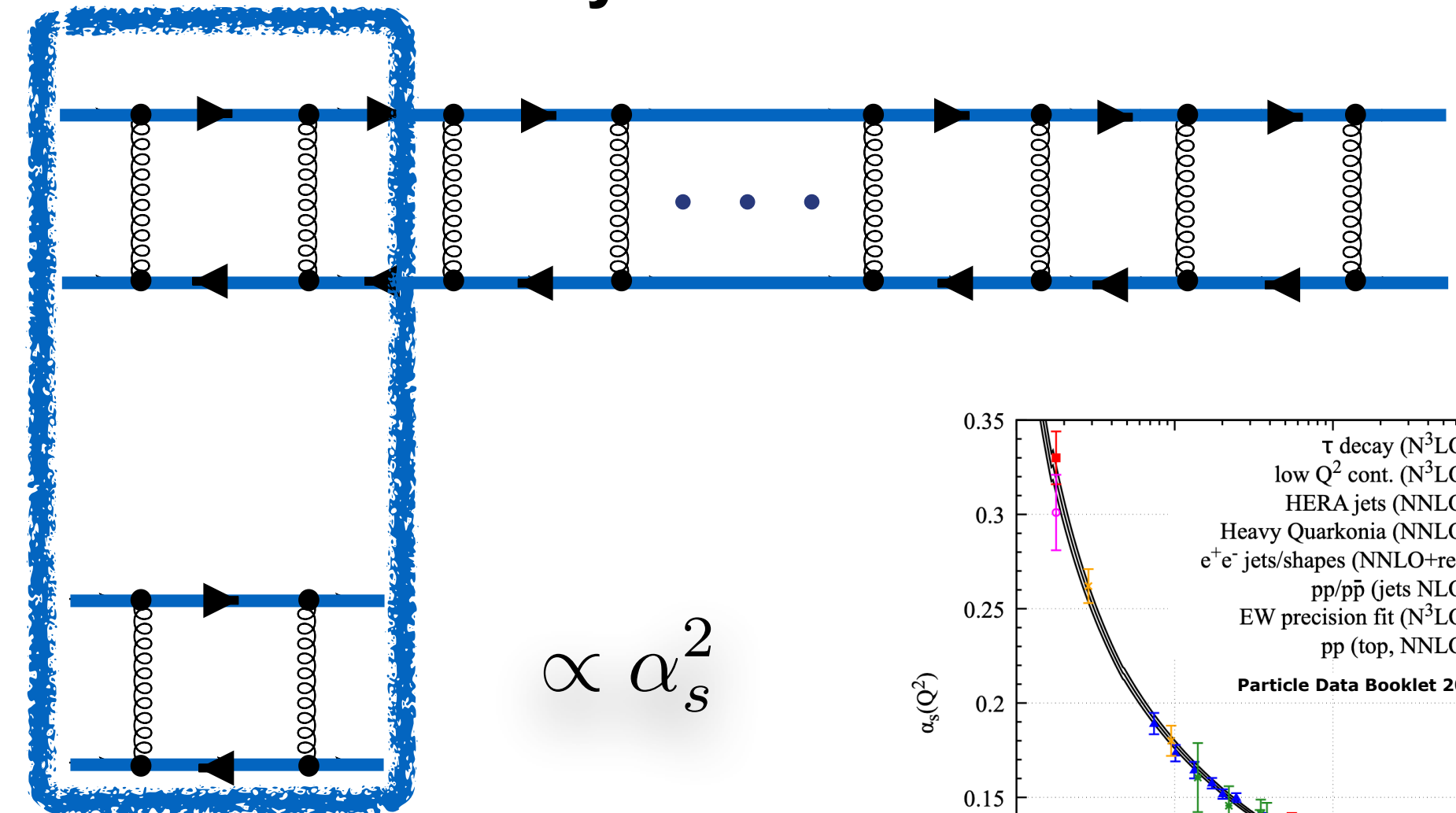


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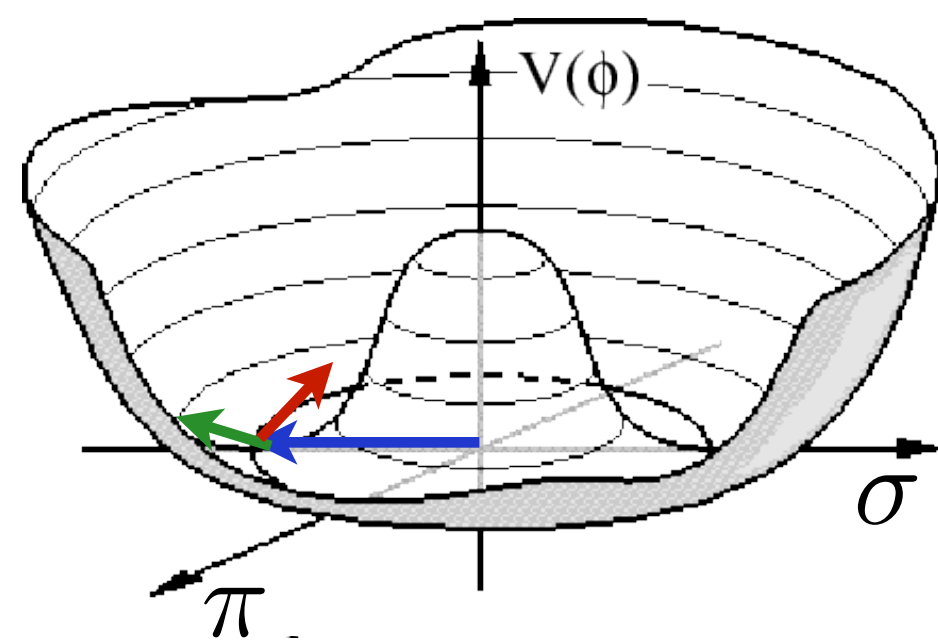
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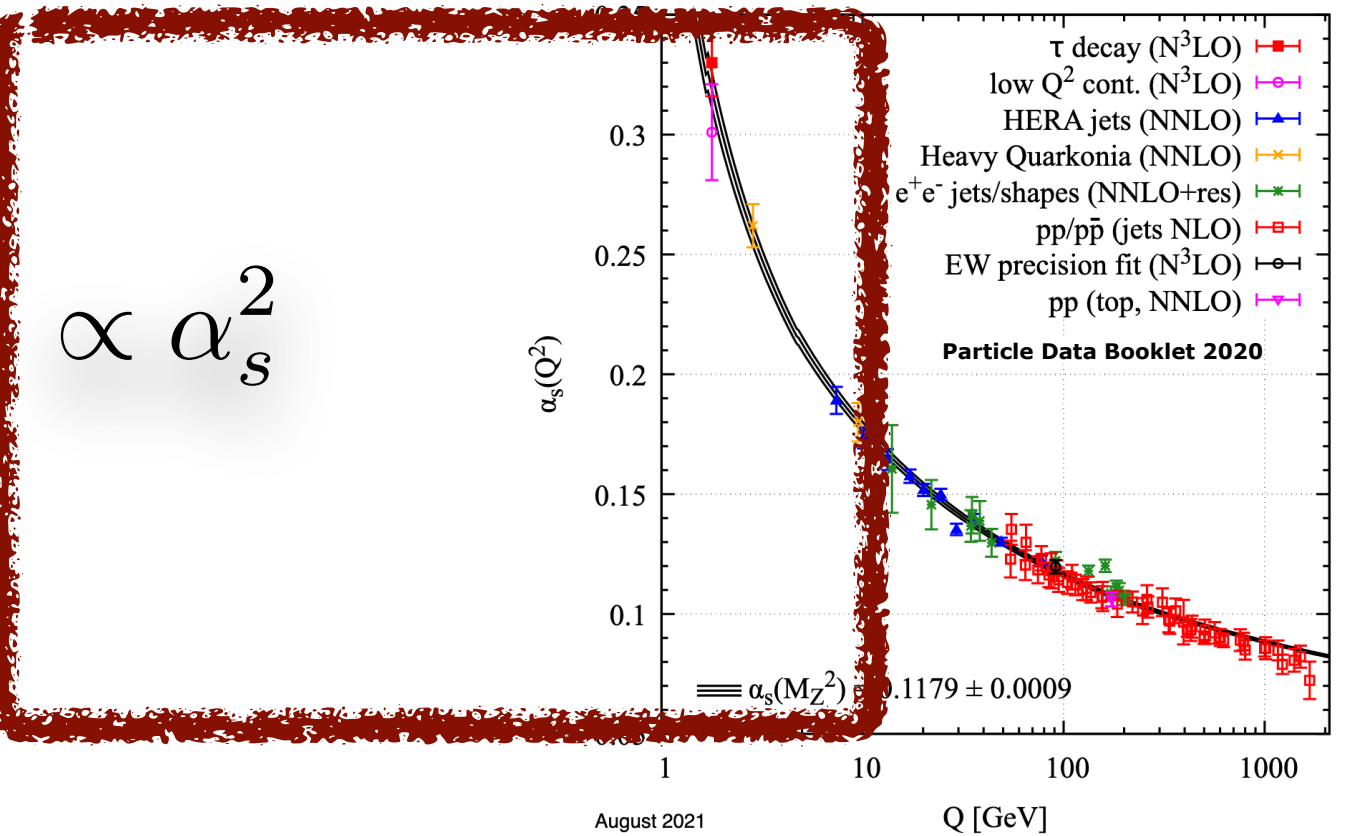
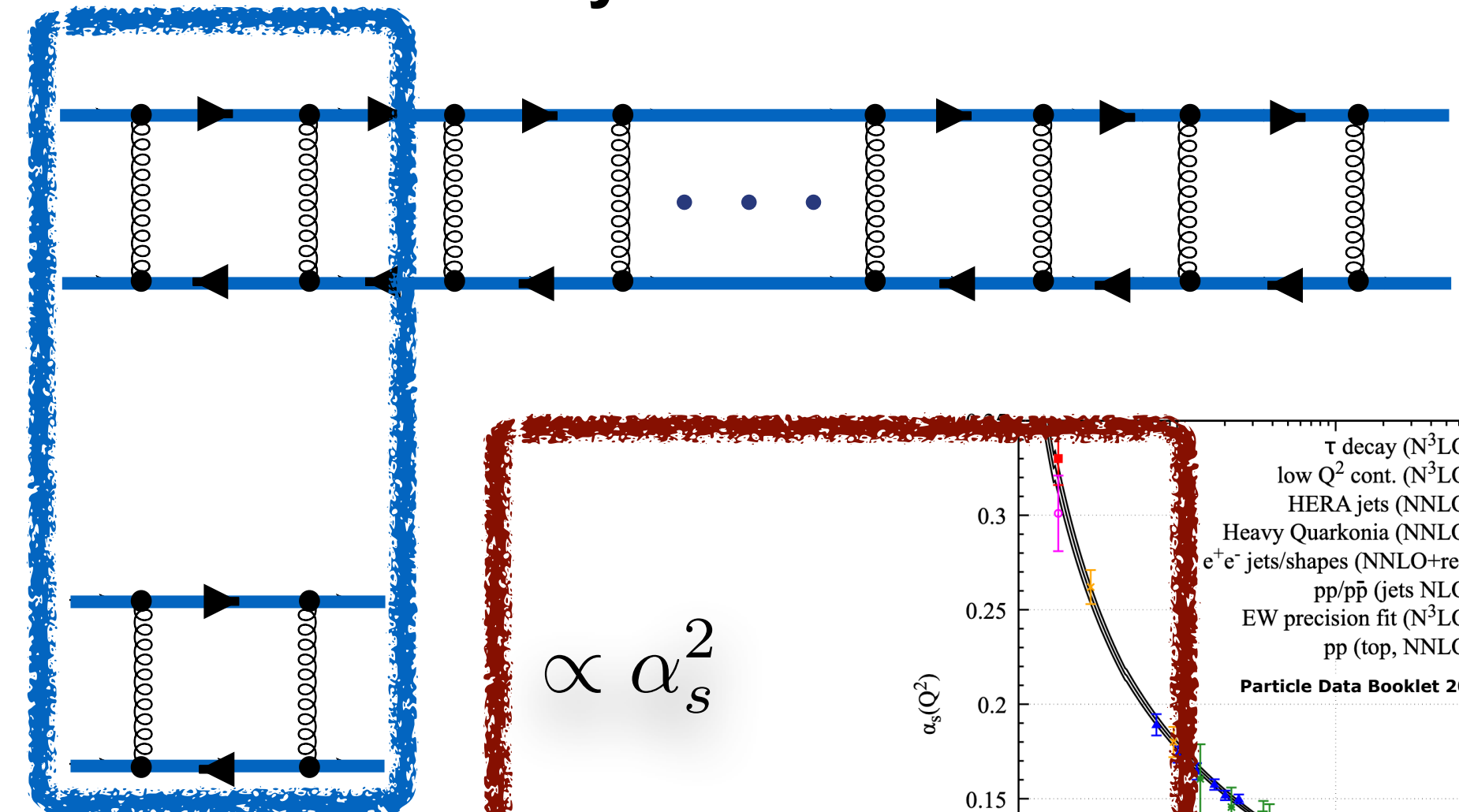


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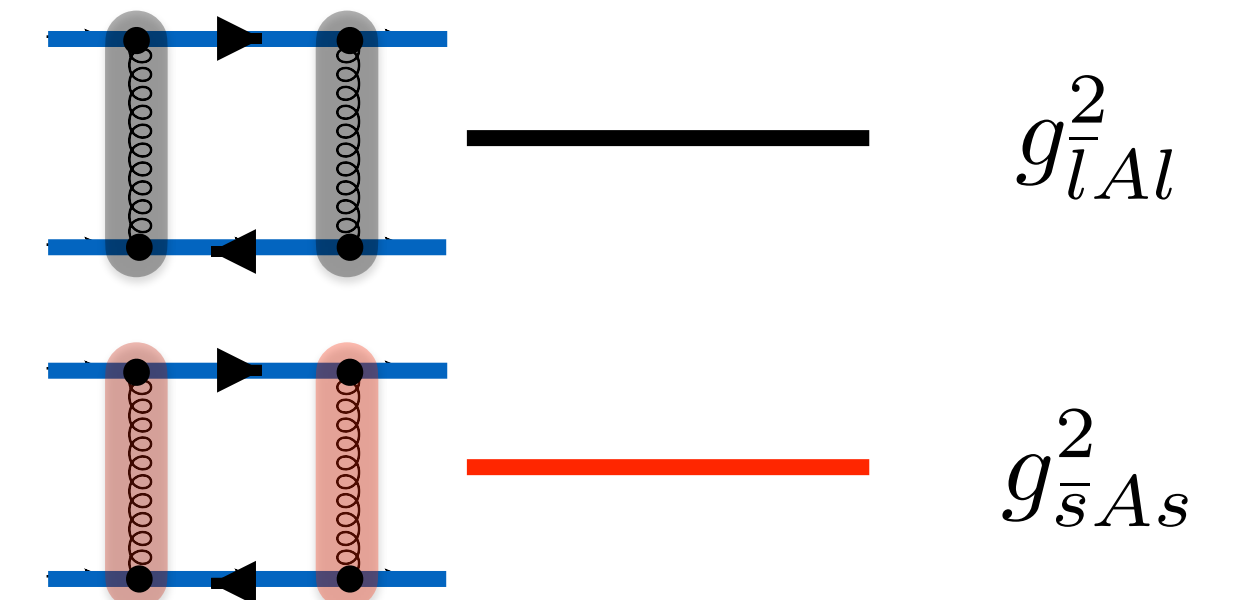
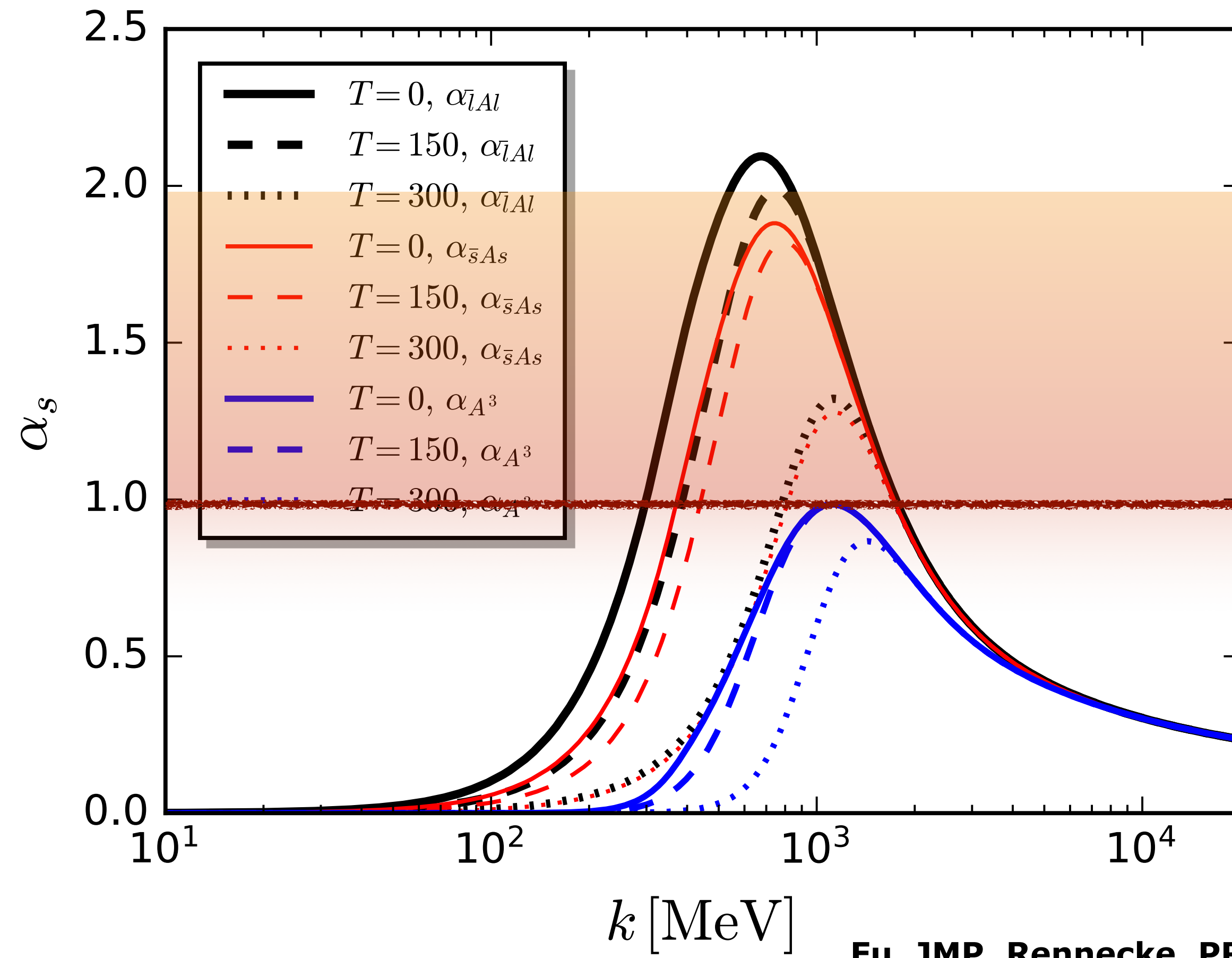
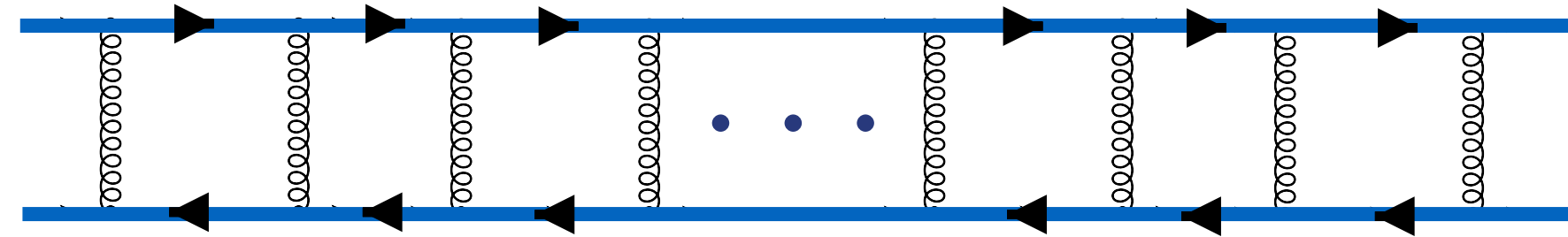
Dynamics



Dynamical chiral symmetry breaking

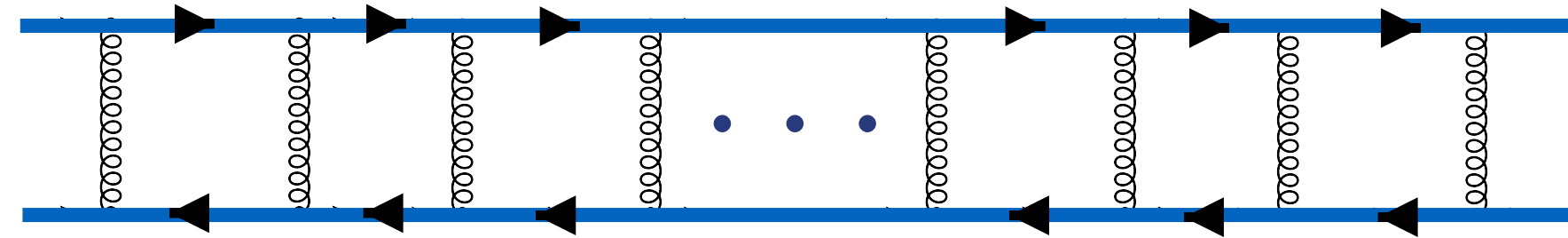
$$\alpha_s > \alpha_\chi^{\text{cr}} \approx 1$$

Thermal restoration of chiral symmetry

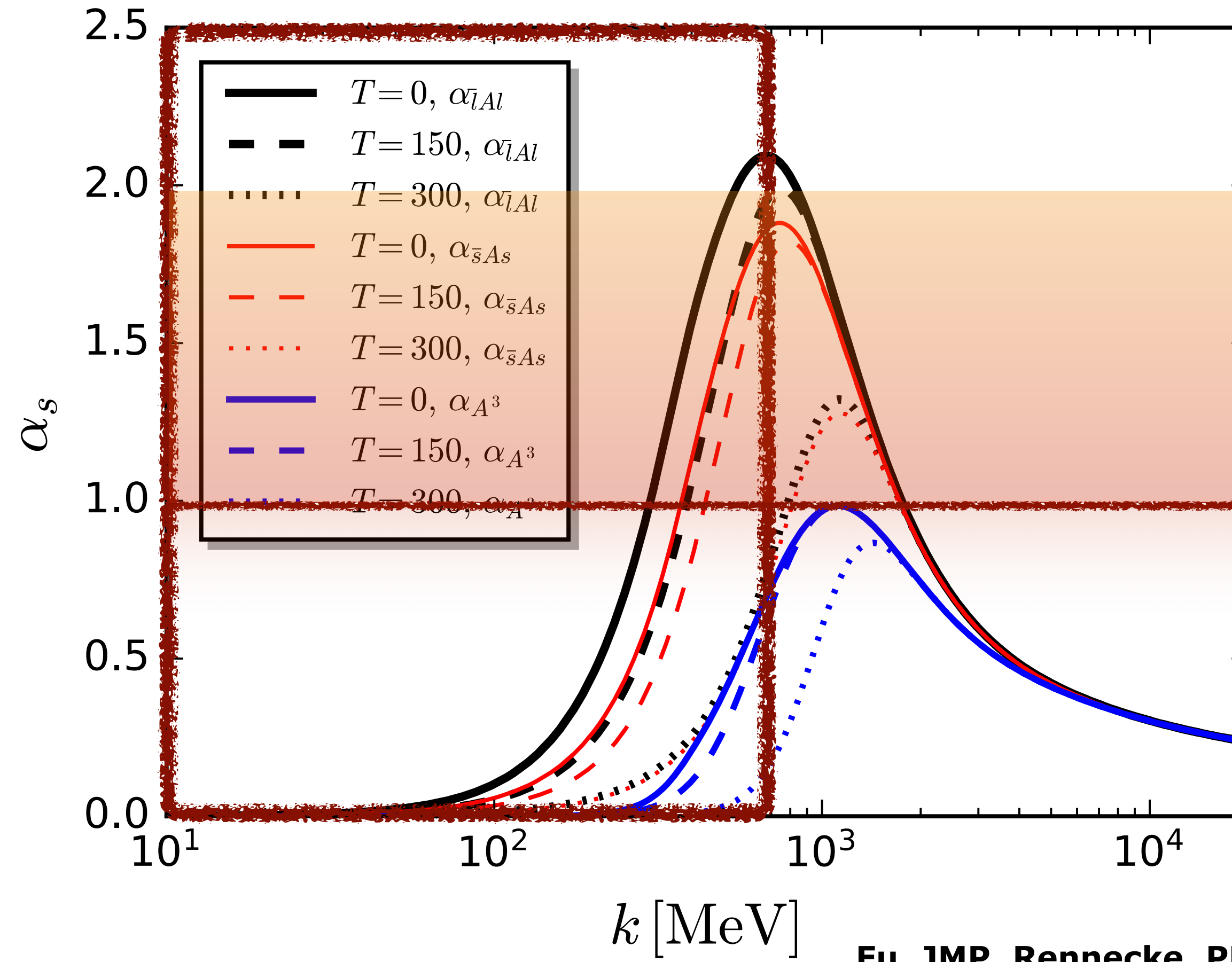


Fu, JMP, Rennecke, PRD 101 (2020) 054032

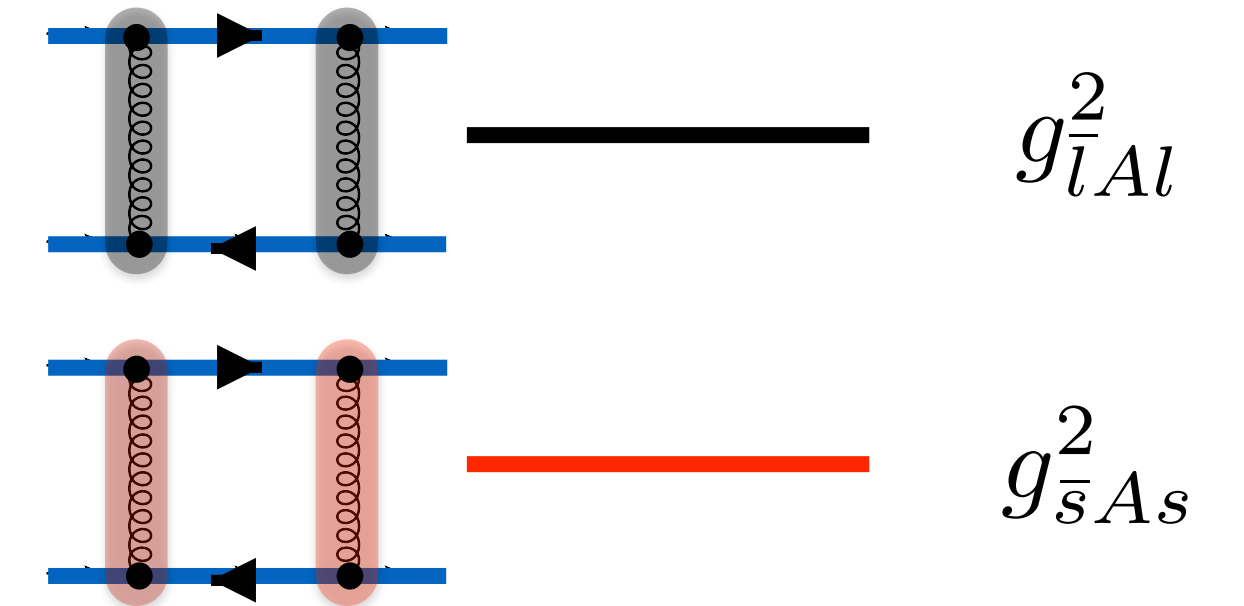
Thermal restoration of chiral symmetry



Effective couplings decays
due to
the gluon mass gap



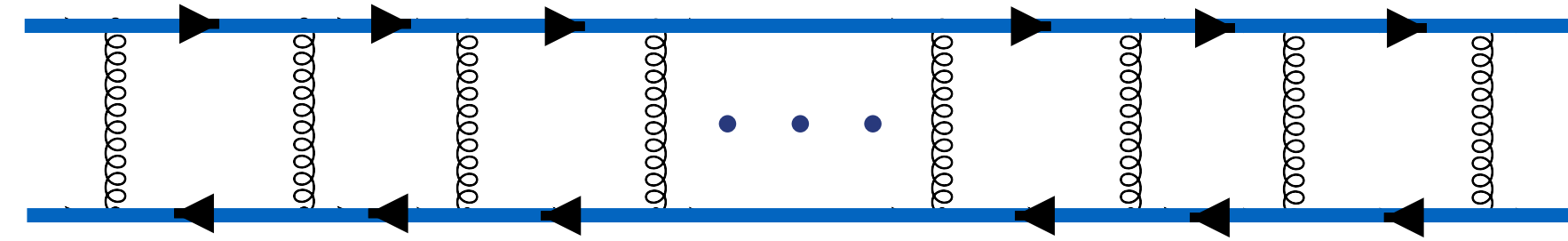
$\alpha_{\chi}^{\text{cr}}$



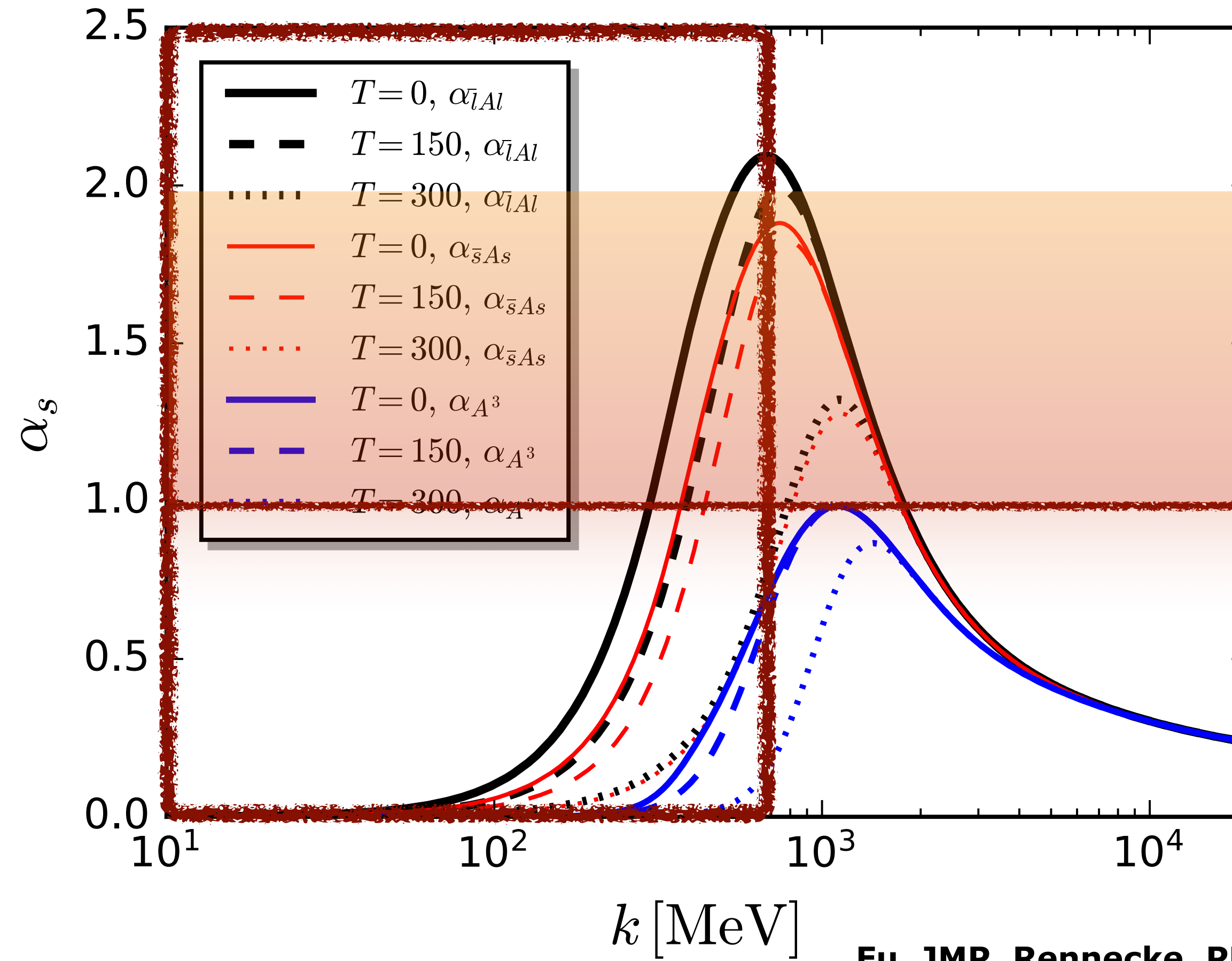
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Thermal restoration of chiral symmetry

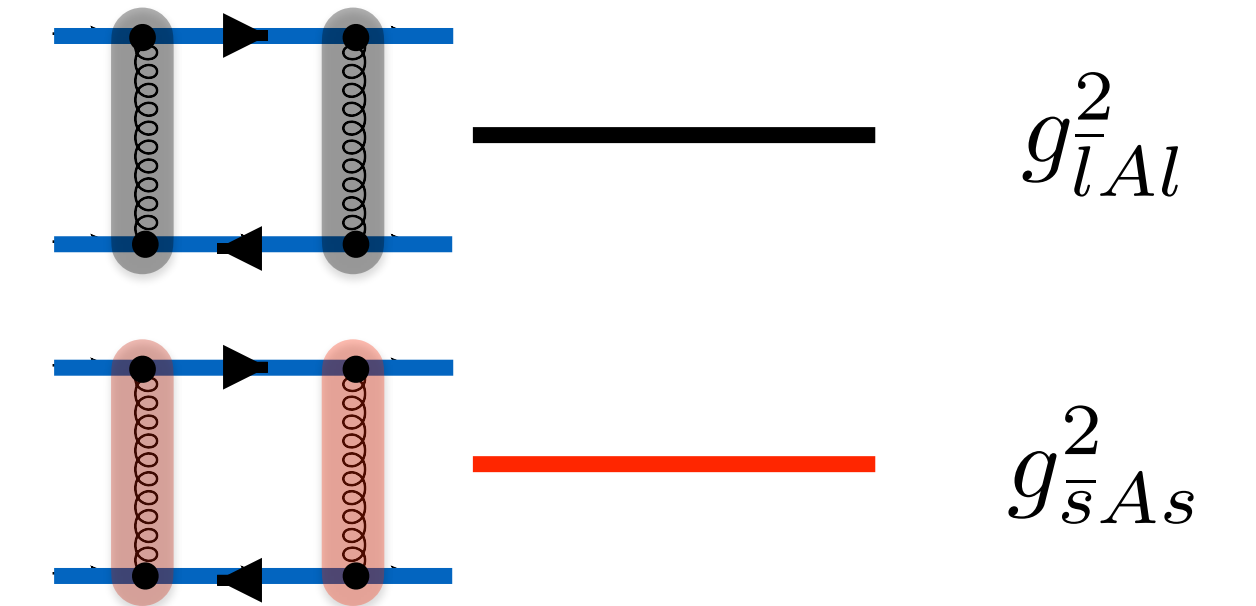
Thermal symmetry restauration
by melting down the coupling



Effective couplings decays
due to
the gluon mass gap



$\alpha_{\chi}^{\text{cr}}$



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

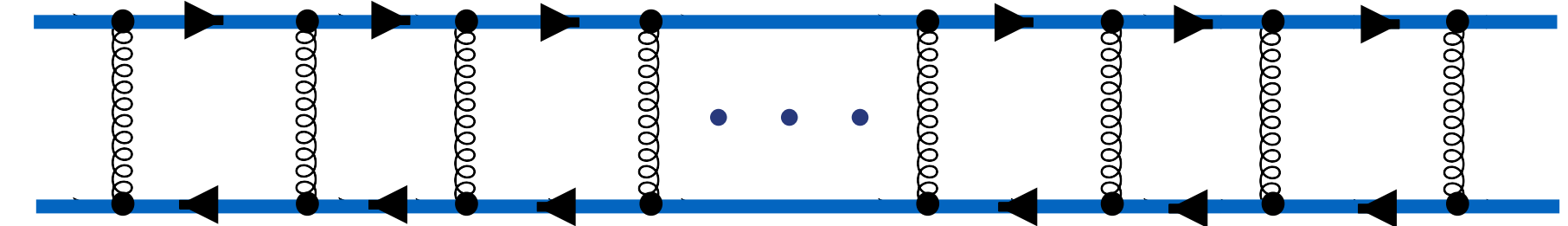
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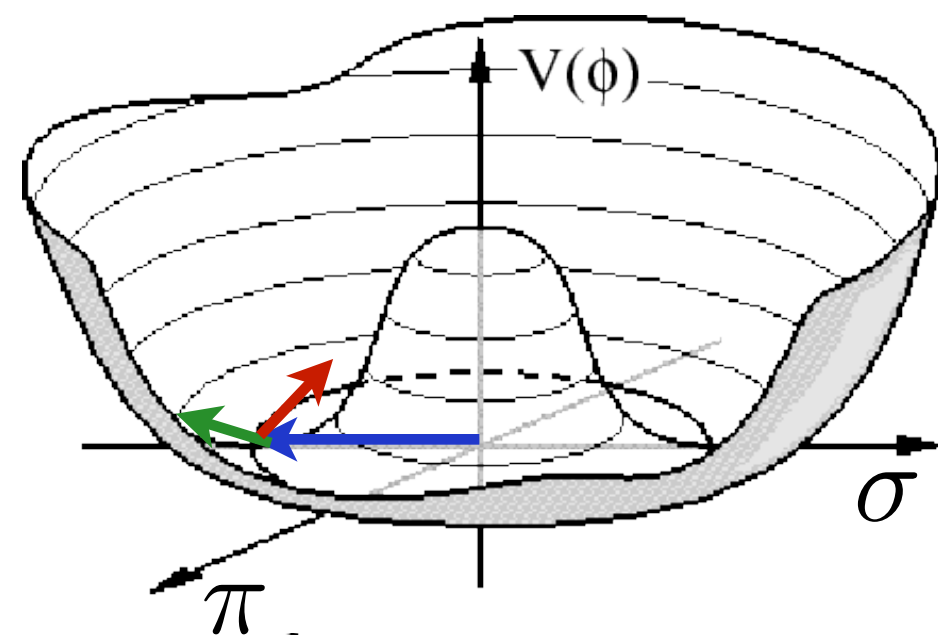
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Dynamics



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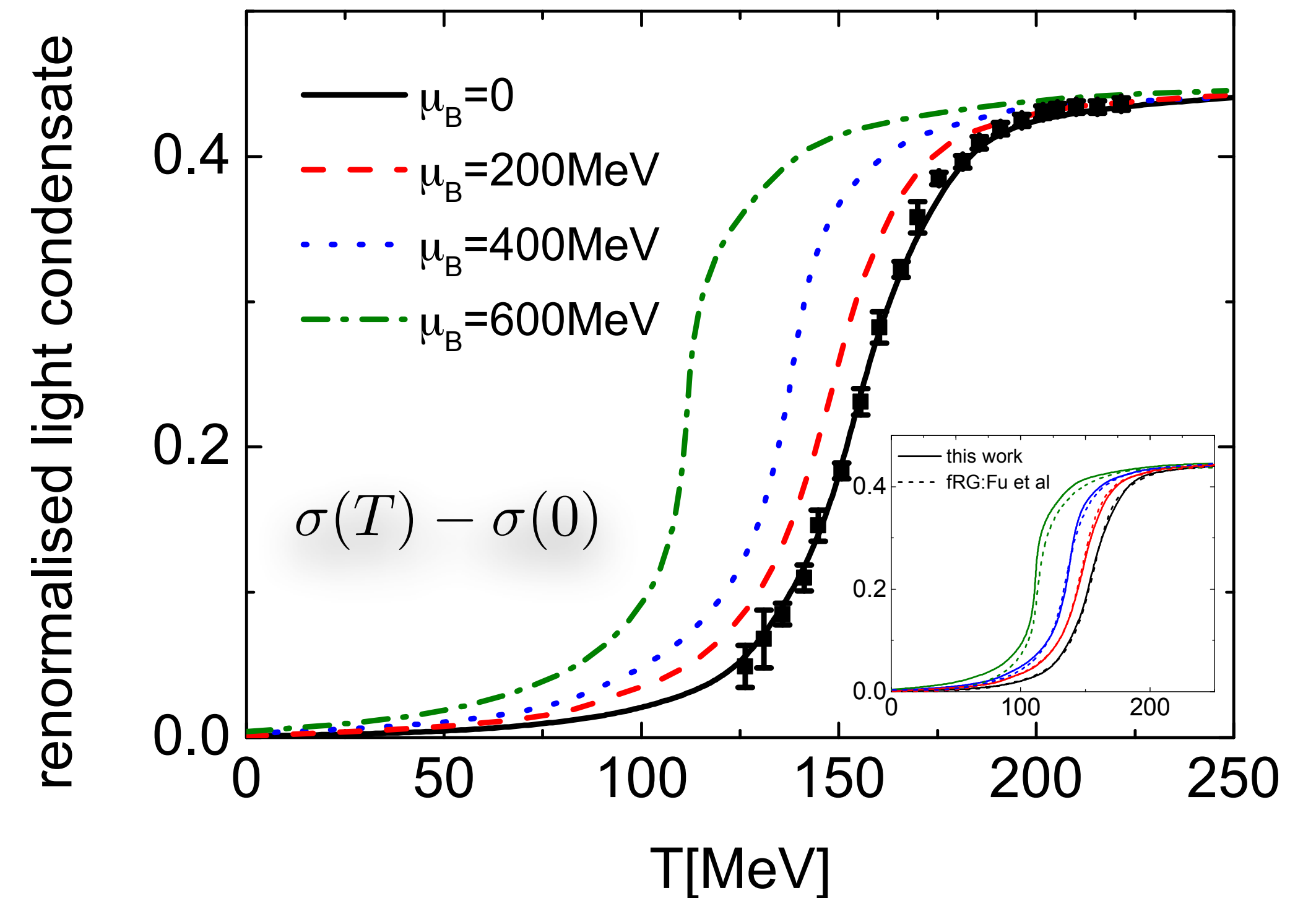


$$\vec{\pi} \simeq i \langle \bar{q} \vec{\sigma} \gamma_5 q \rangle$$

(Pseudo) Goldstones

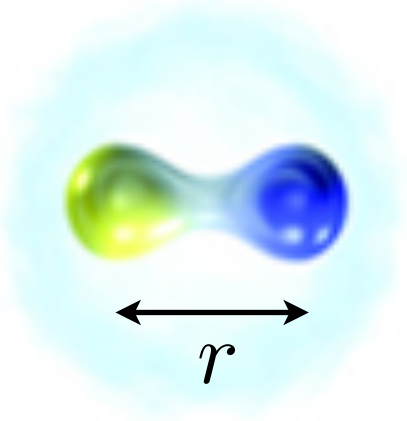
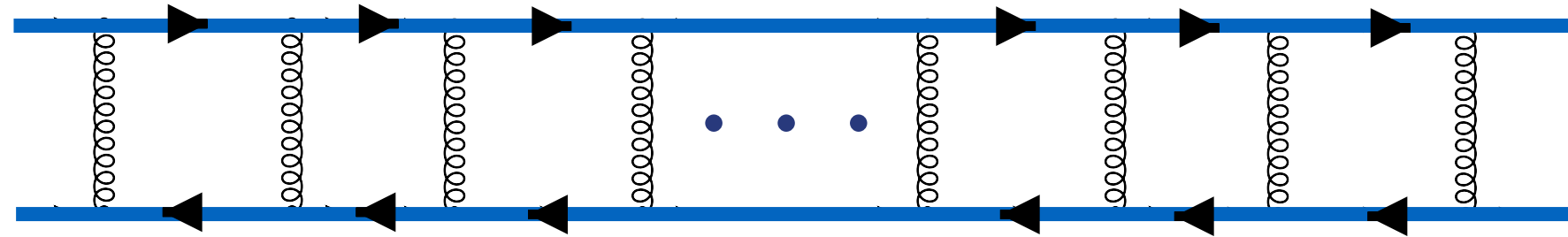
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QCD predictions from various approaches

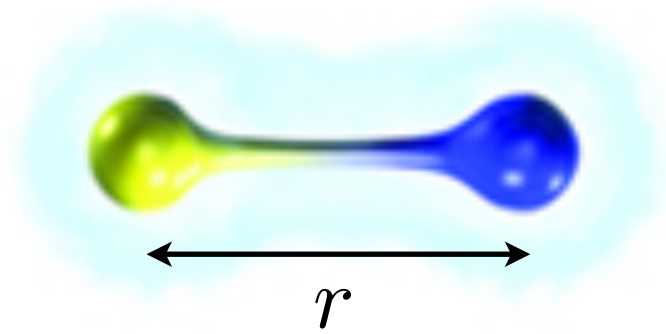


Confinement

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

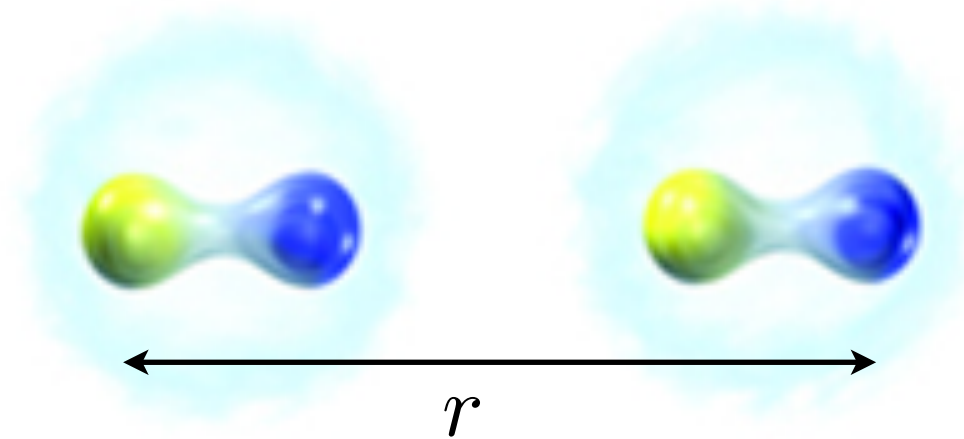
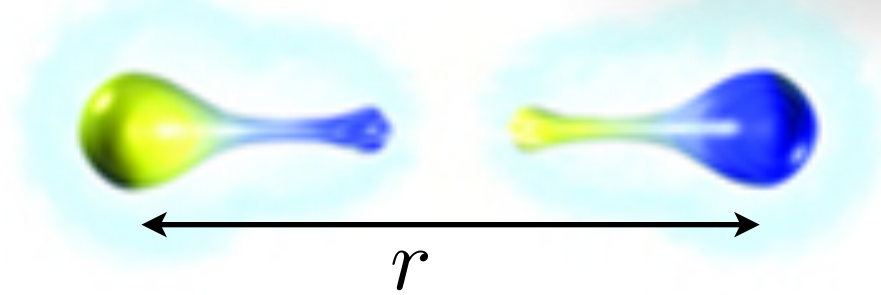


$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



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

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

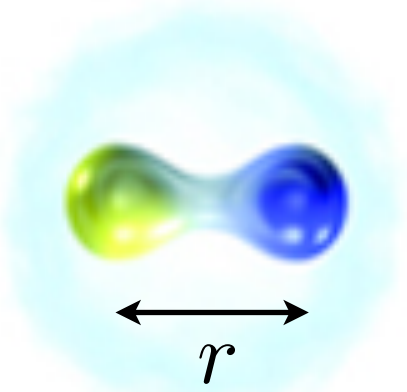
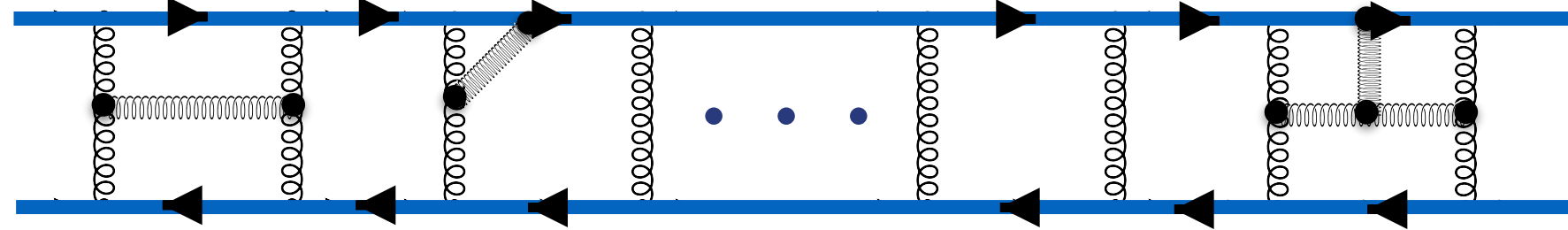


$$F_{q\bar{q}} \simeq \text{const.}$$

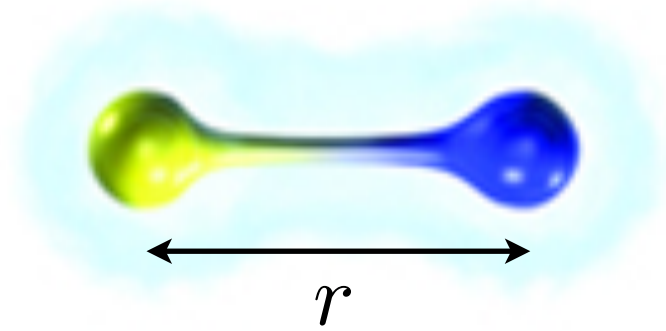
Confinement

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

Confinement: Gluon self-interaction

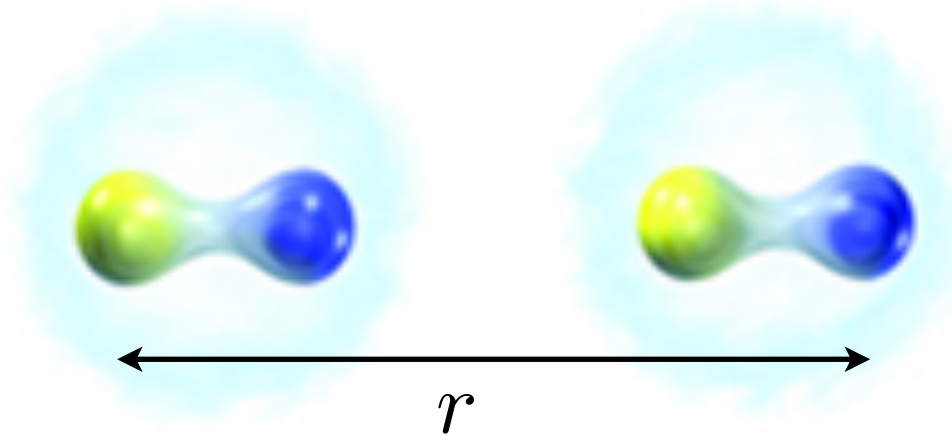
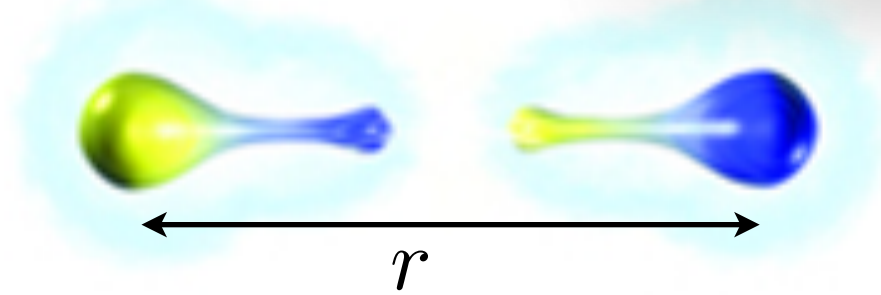


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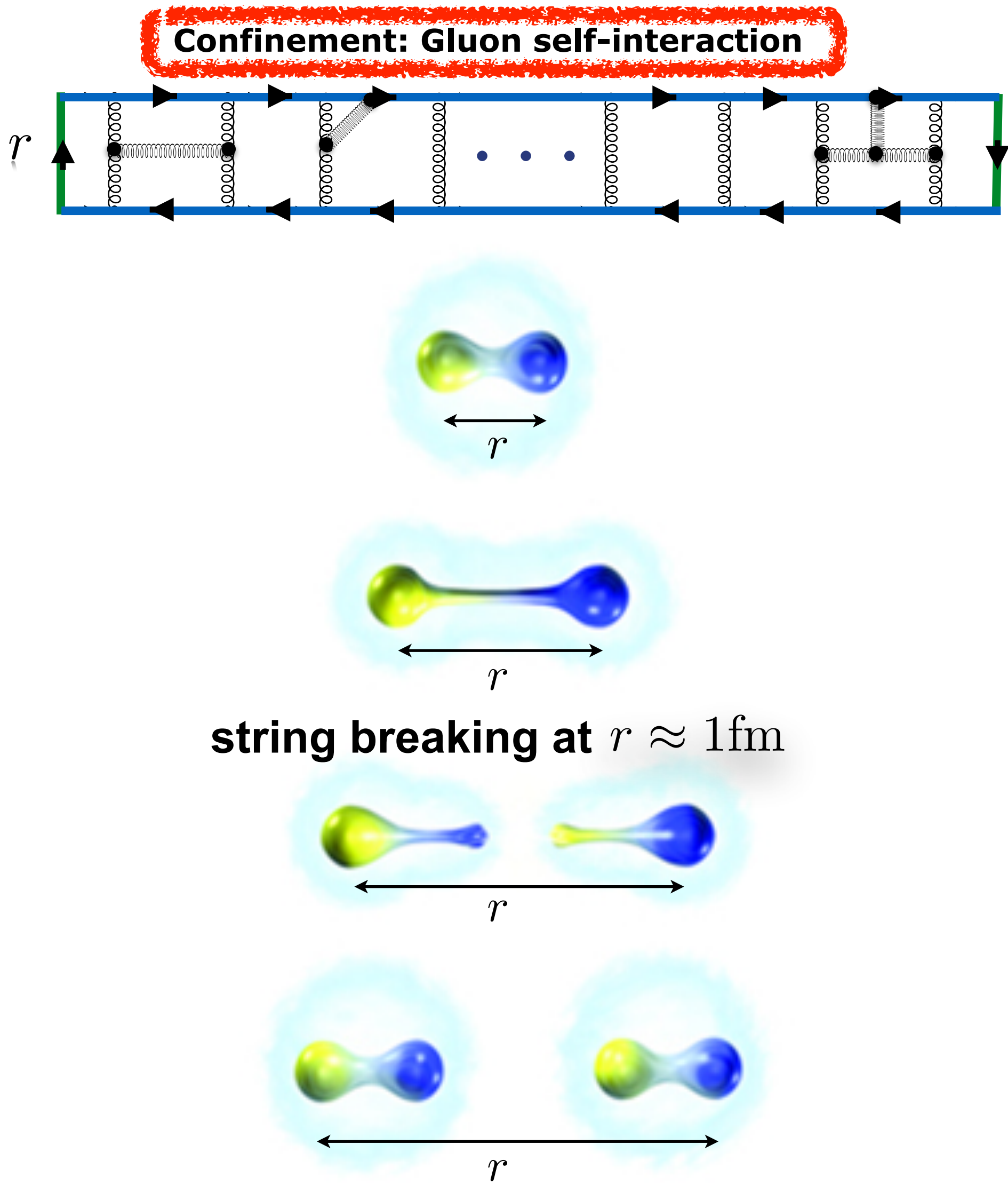
string breaking at $r \approx 1\text{fm}$



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Confinement

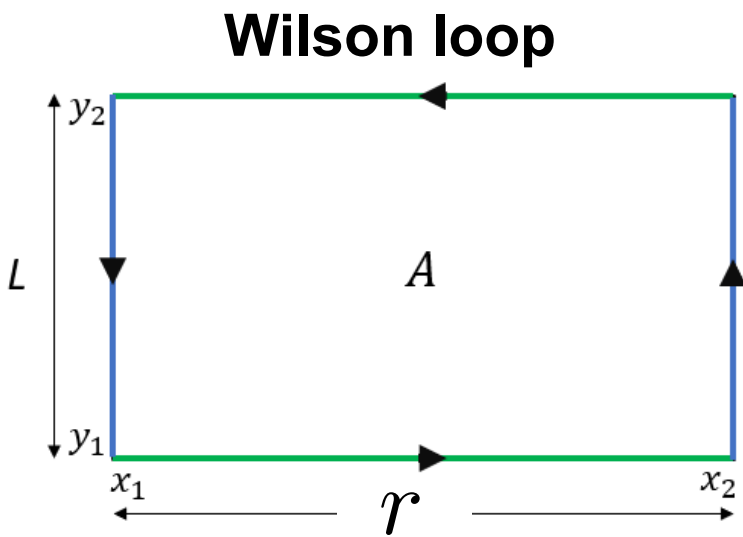
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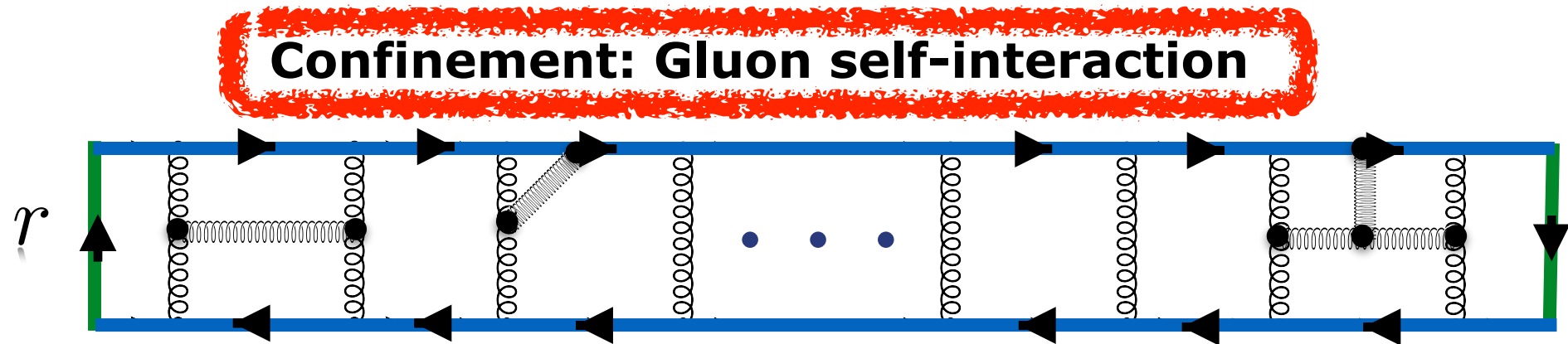
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$$F_{q\bar{q}} \simeq \text{const.}$$



Confinement

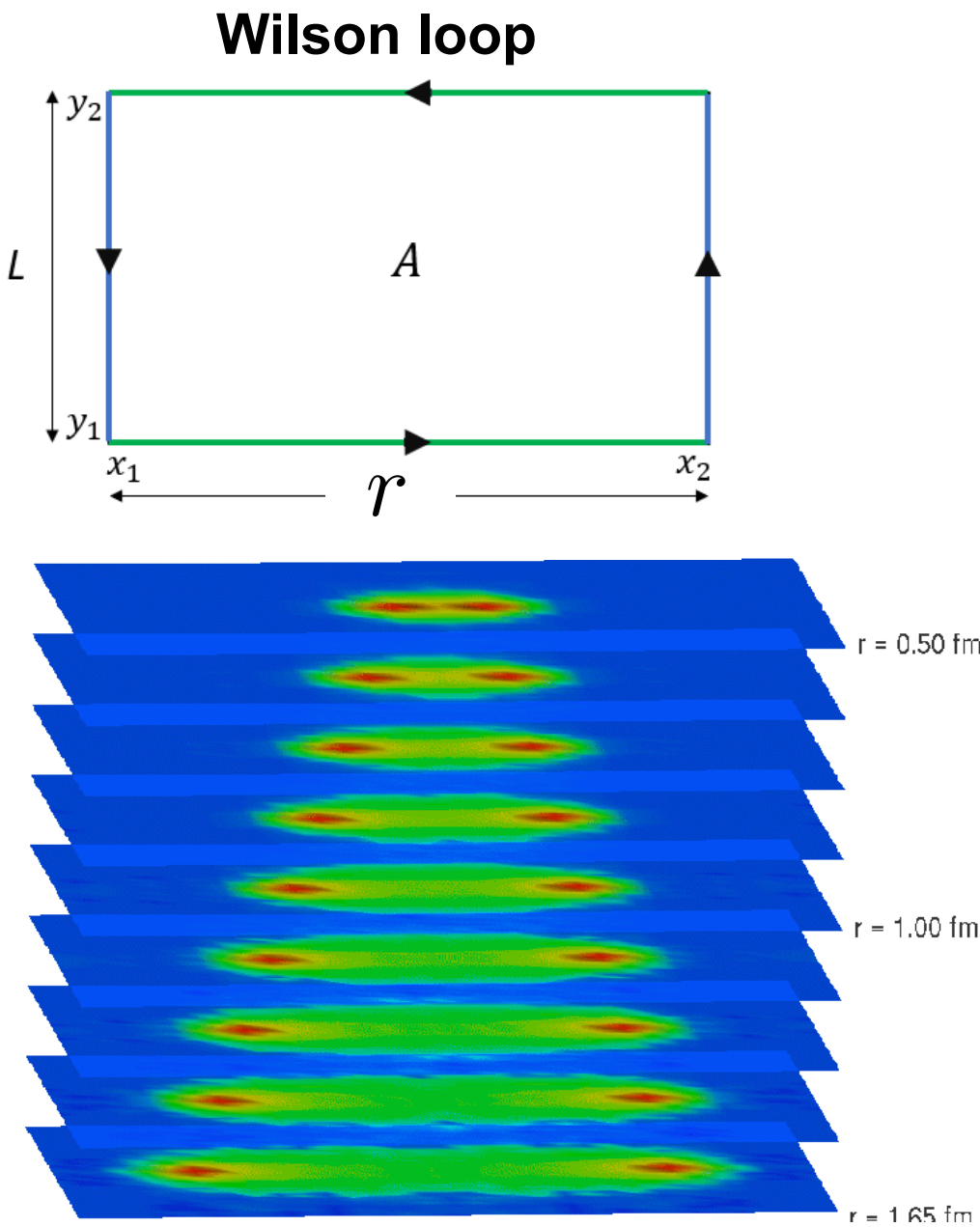
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



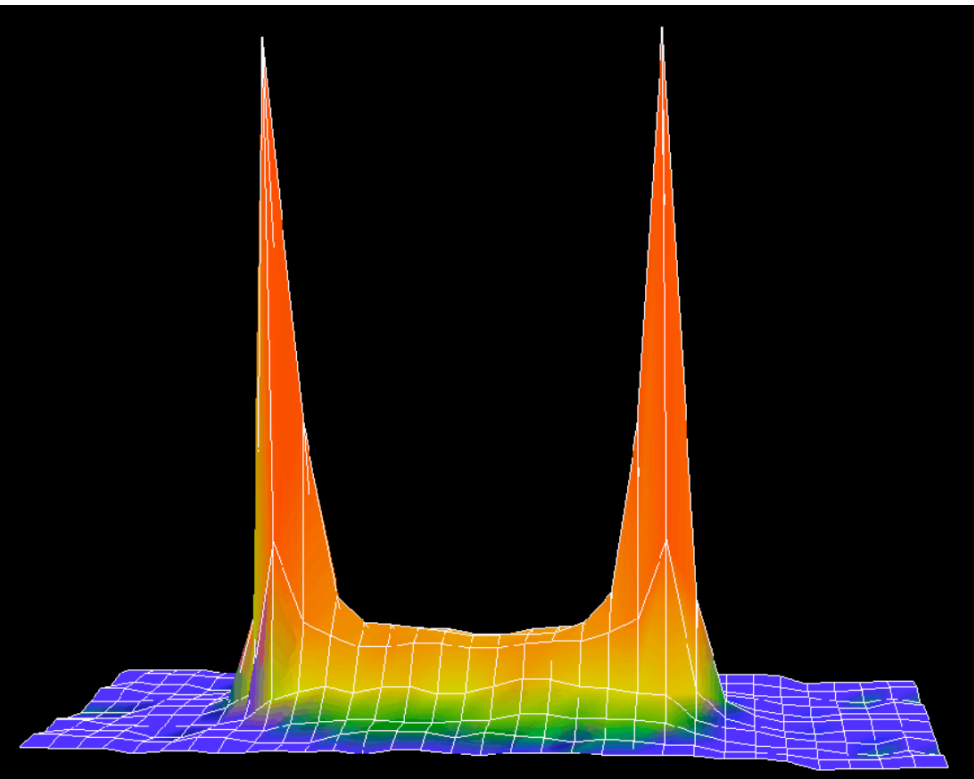
$$F_{q\bar{q}} \simeq -\frac{1}{r}$$

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

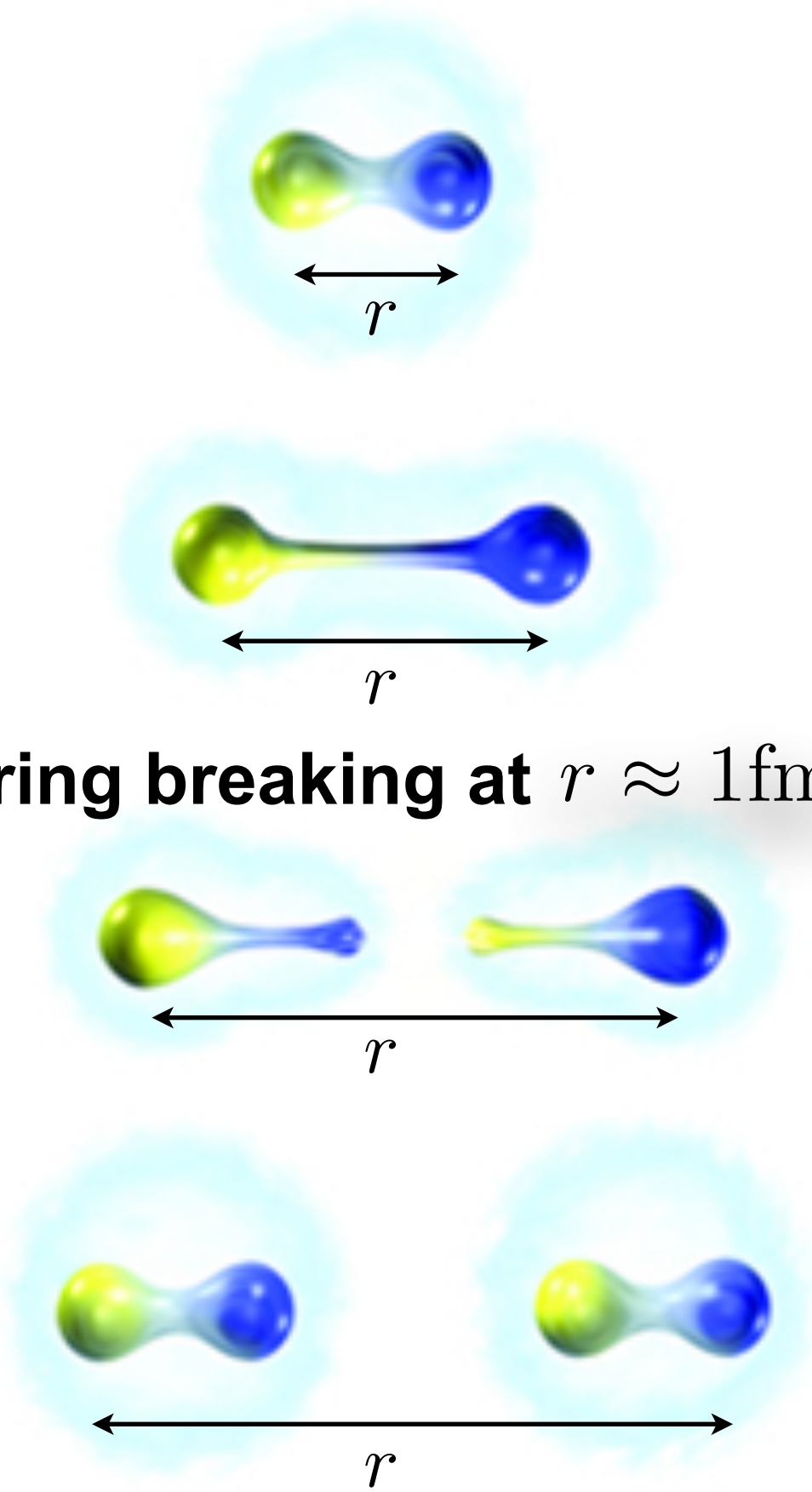
$$F_{q\bar{q}} \simeq \text{const.}$$



Energy density Bali et al. '94

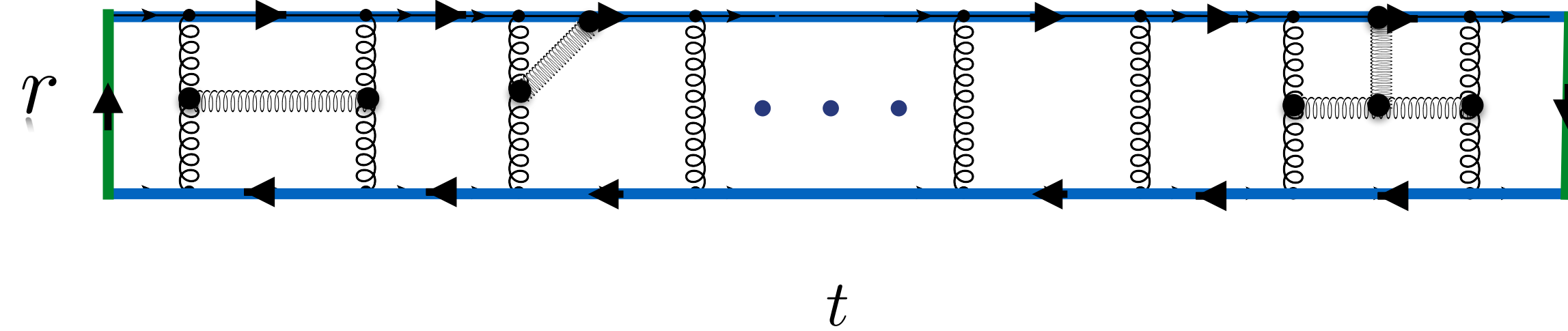


string breaking at $r \approx 1\text{fm}$



Thermal confinement-deconfinement phase transition

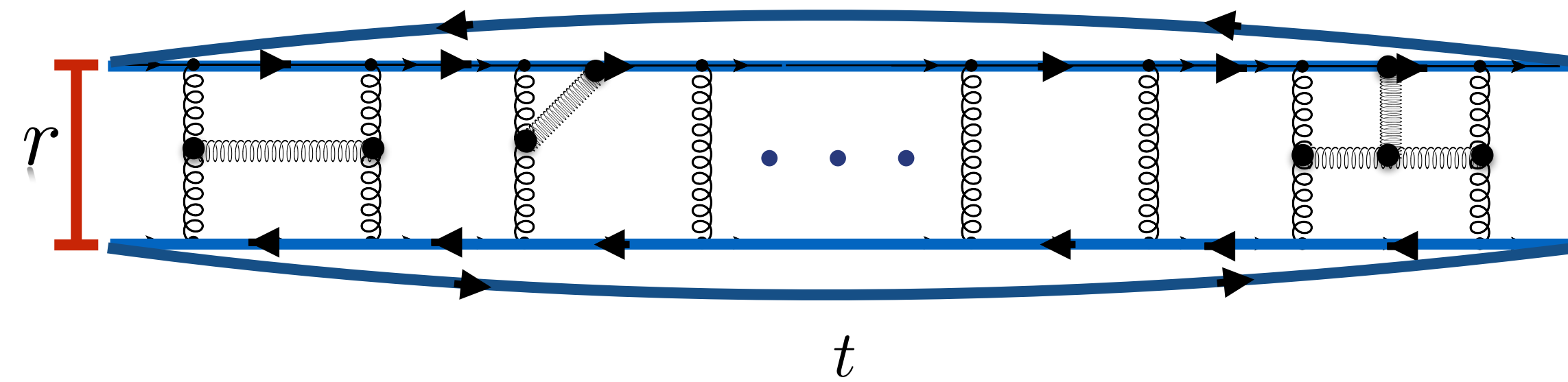
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



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

Thermal confinement-deconfinement phase transition

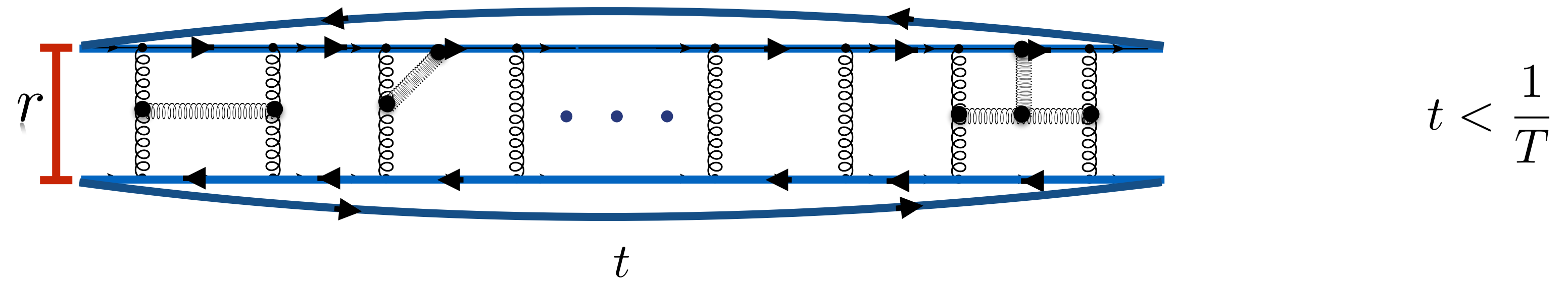
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



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

Thermal confinement-deconfinement phase transition

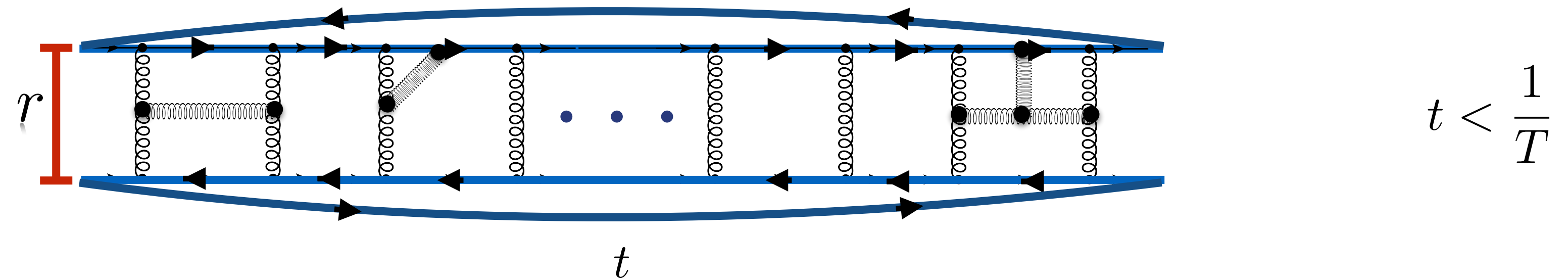
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



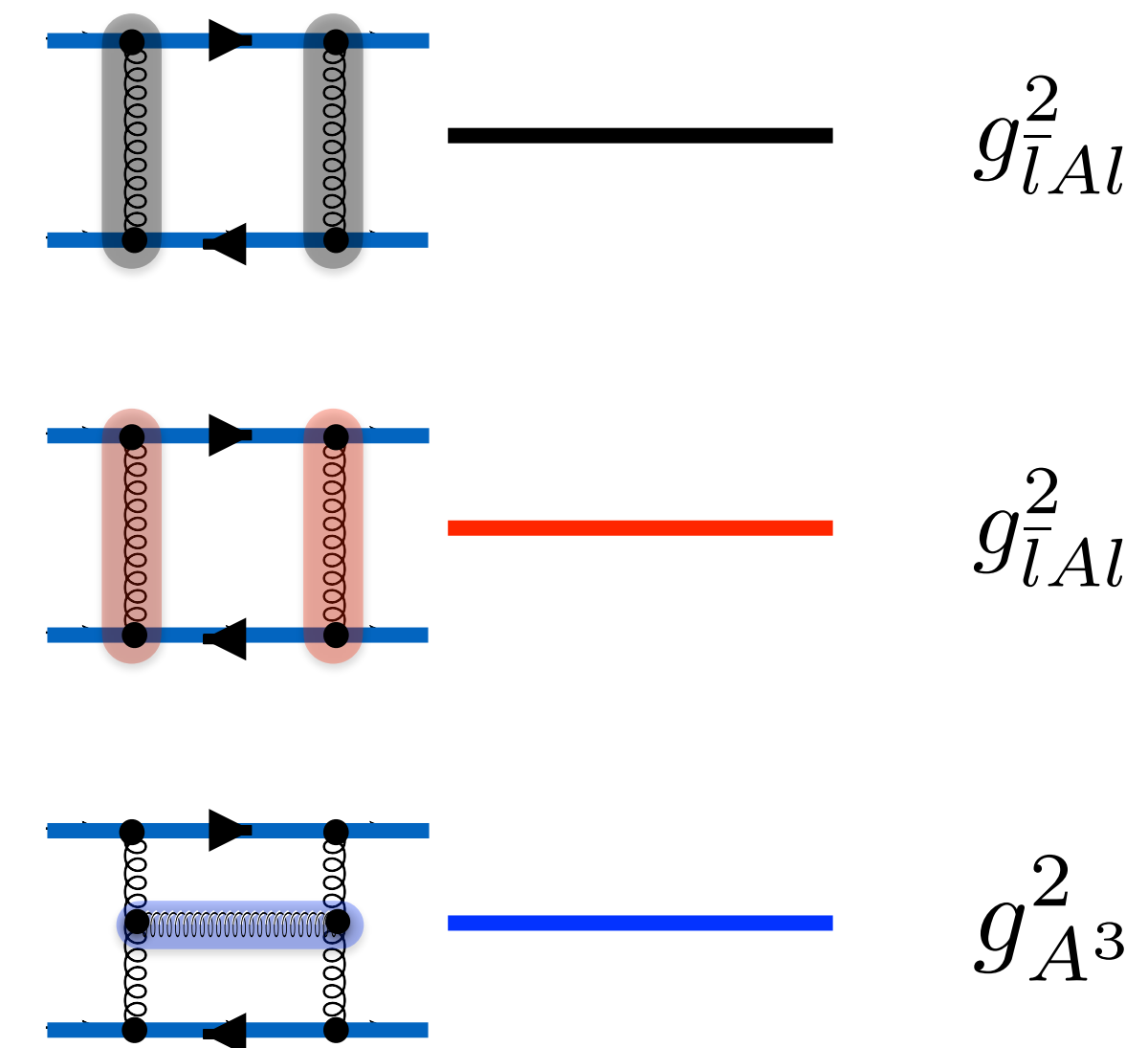
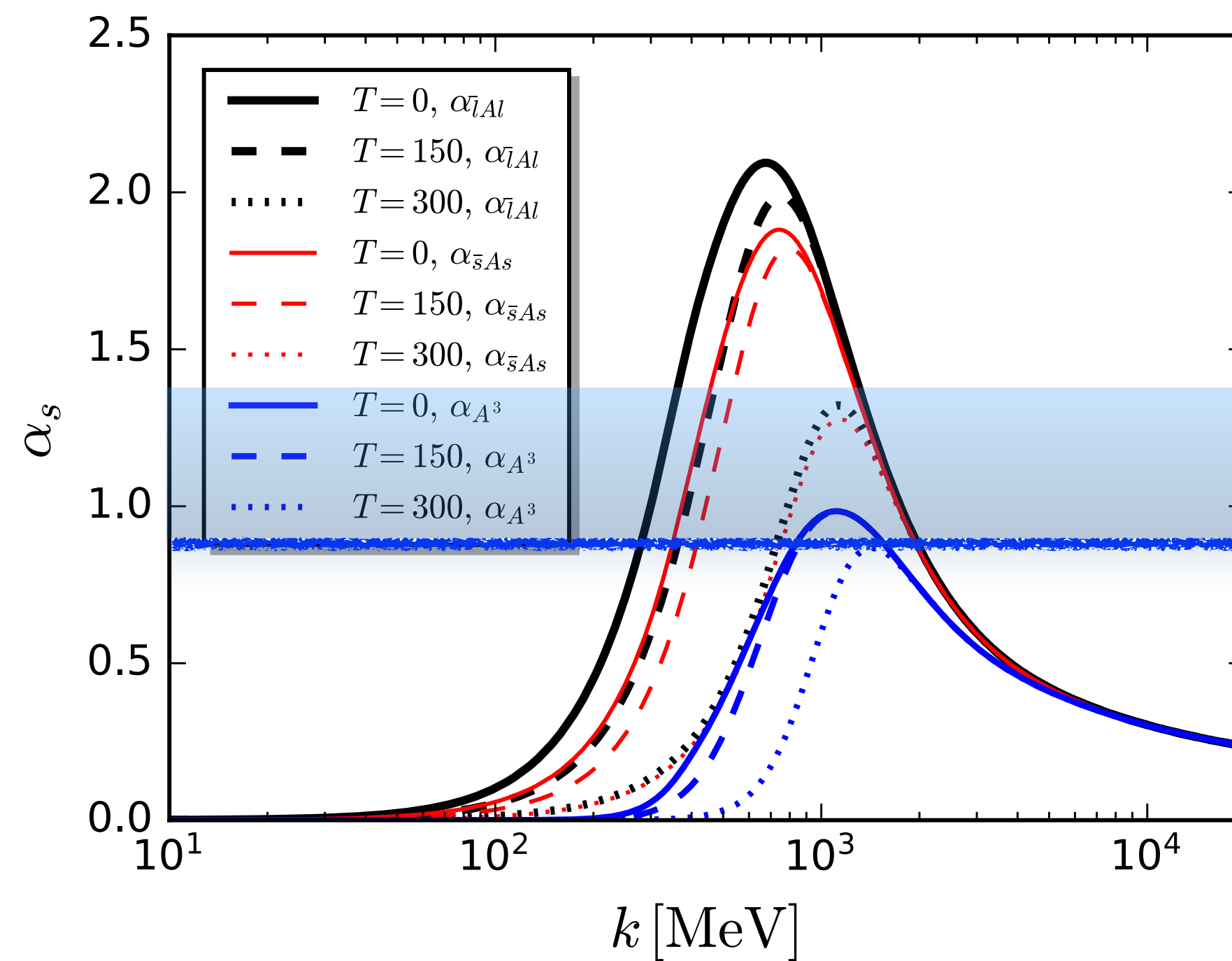
Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

Thermal confinement-deconfinement phase transition

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

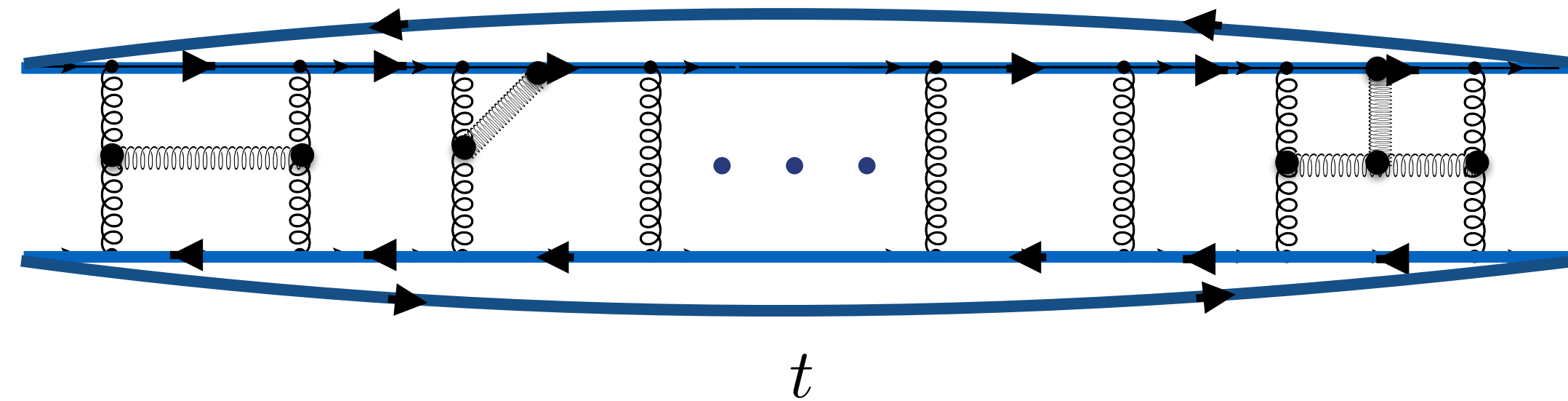


Polyakov loop correlation $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

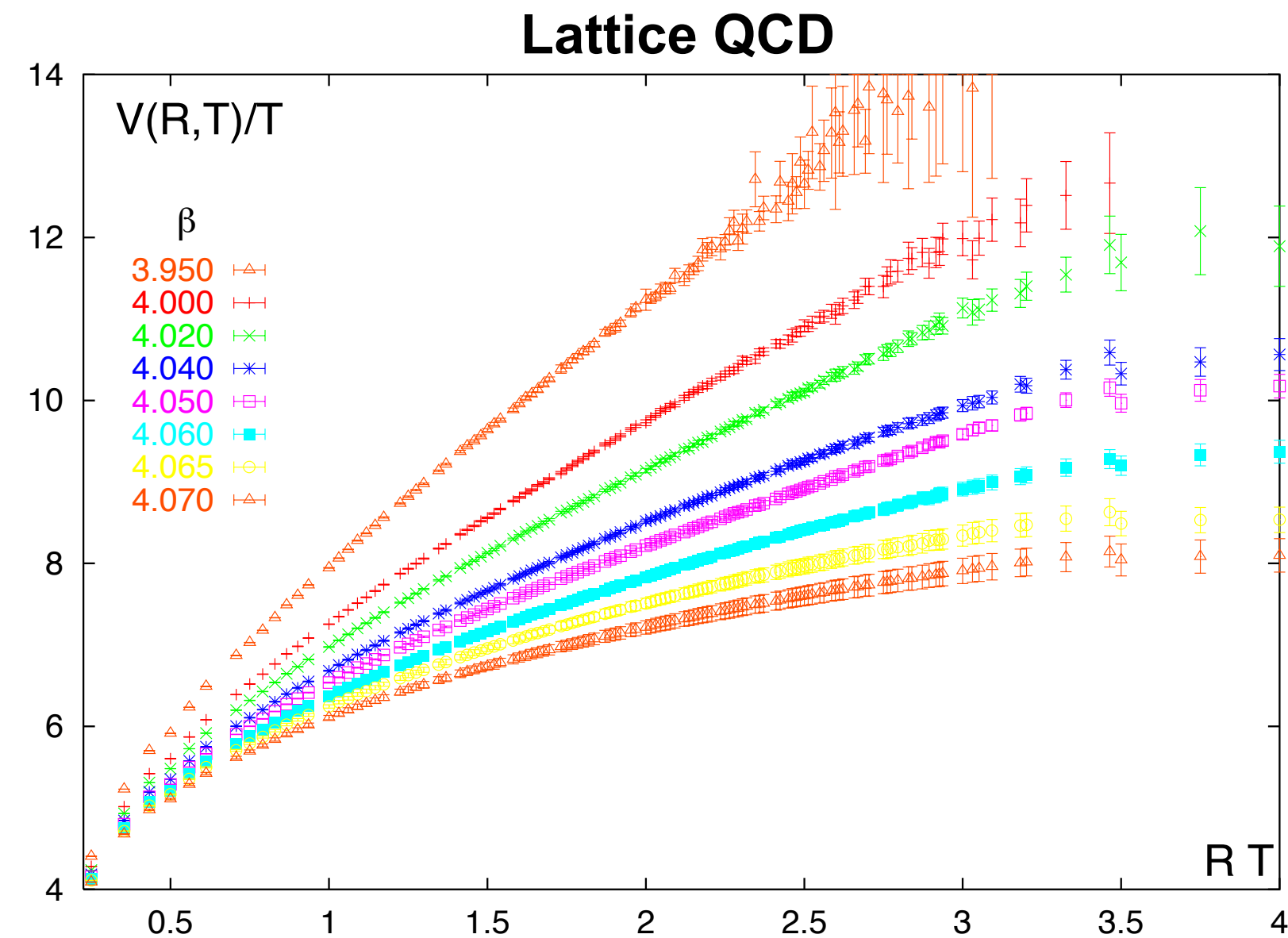


Thermal confinement-deconfinement phase transition

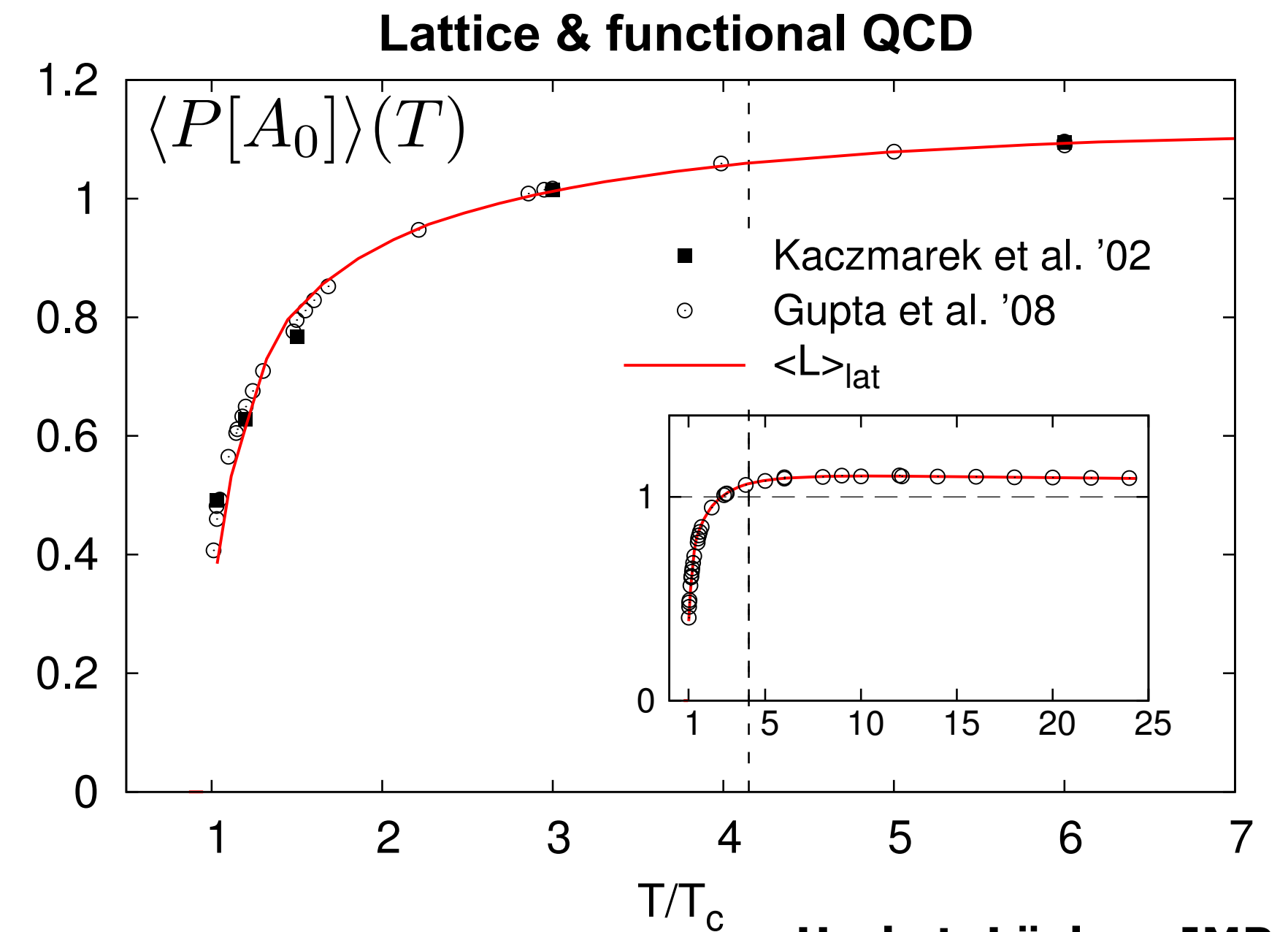
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



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



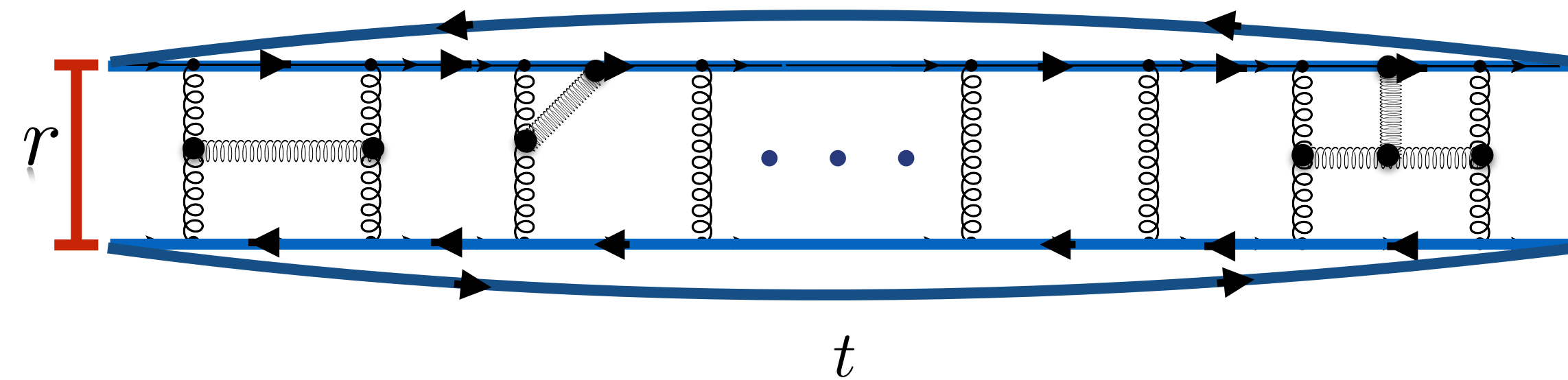
Kaczmarek et al '99



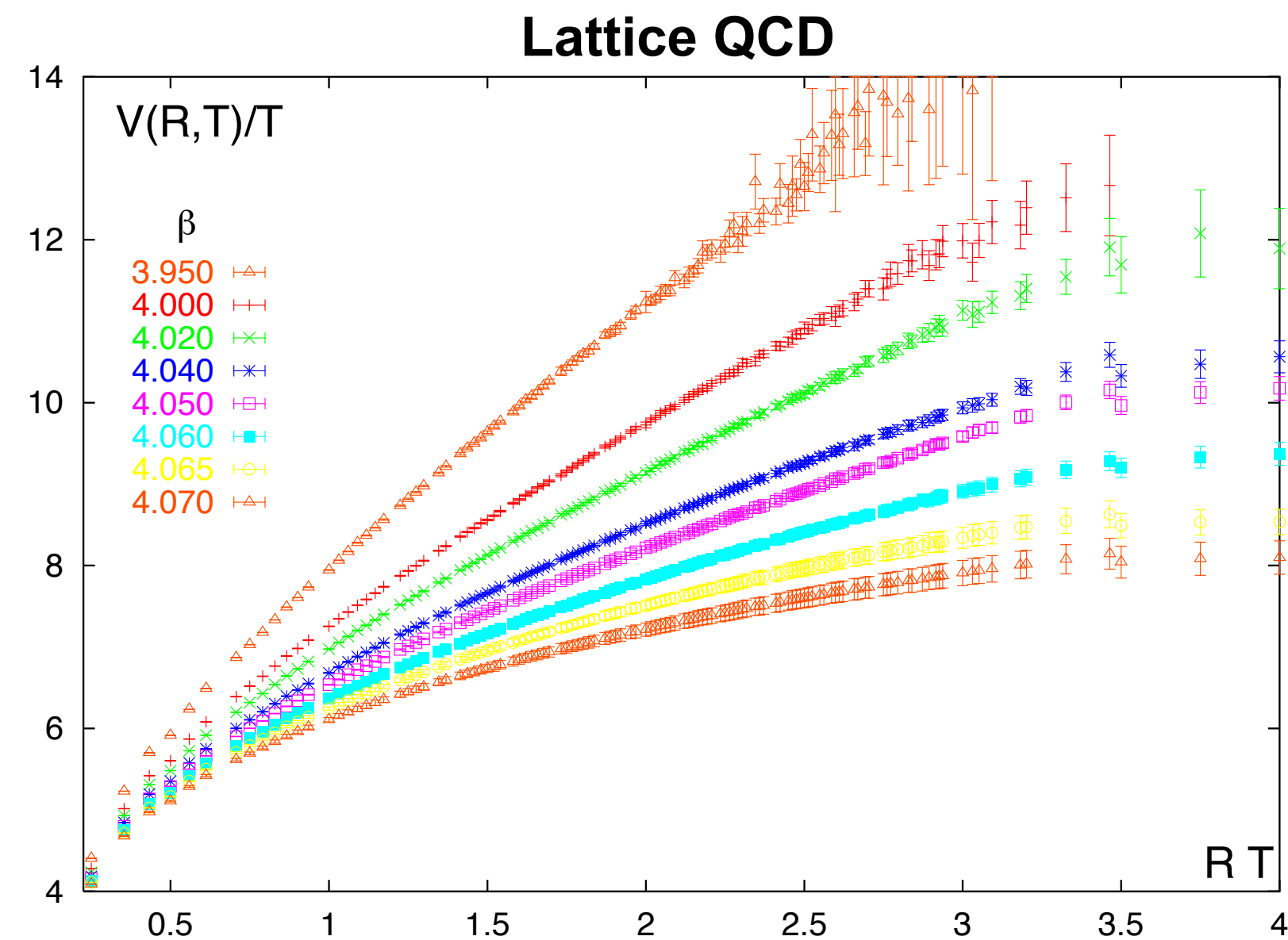
Herbst, Lücker, JMP, 2015

Thermal confinement-deconfinement phase transition

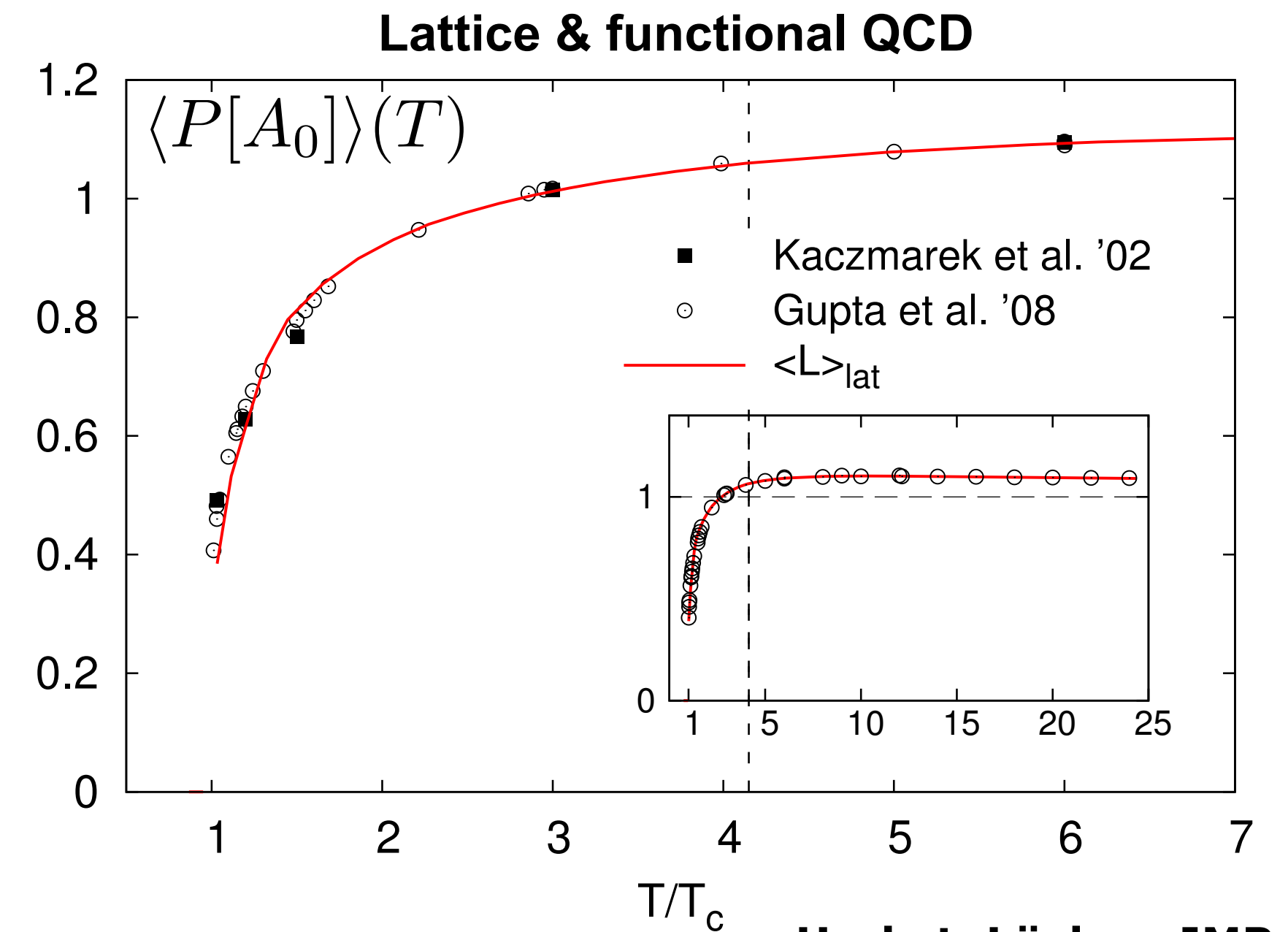
Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



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



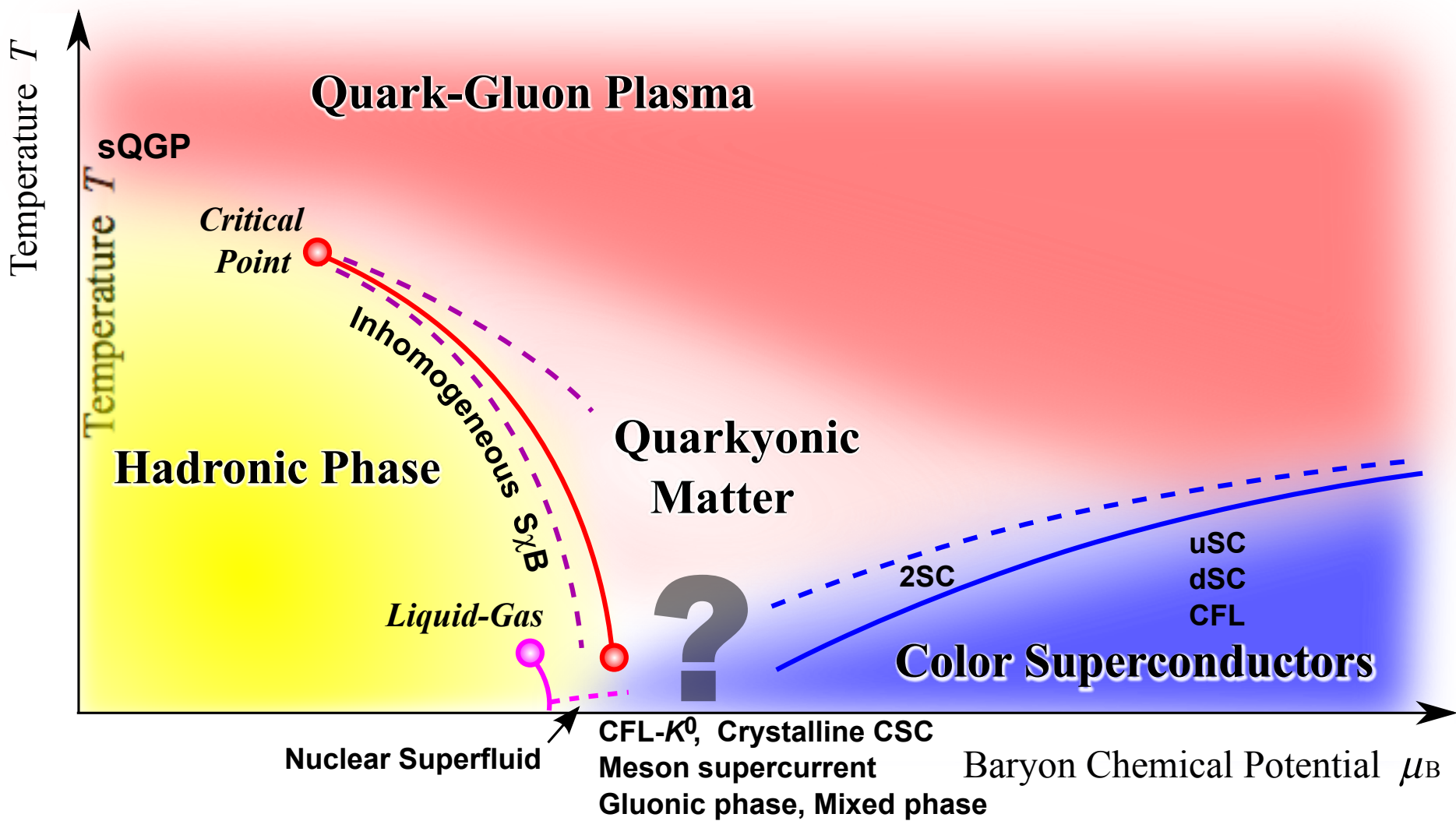
Kaczmarek et al '99



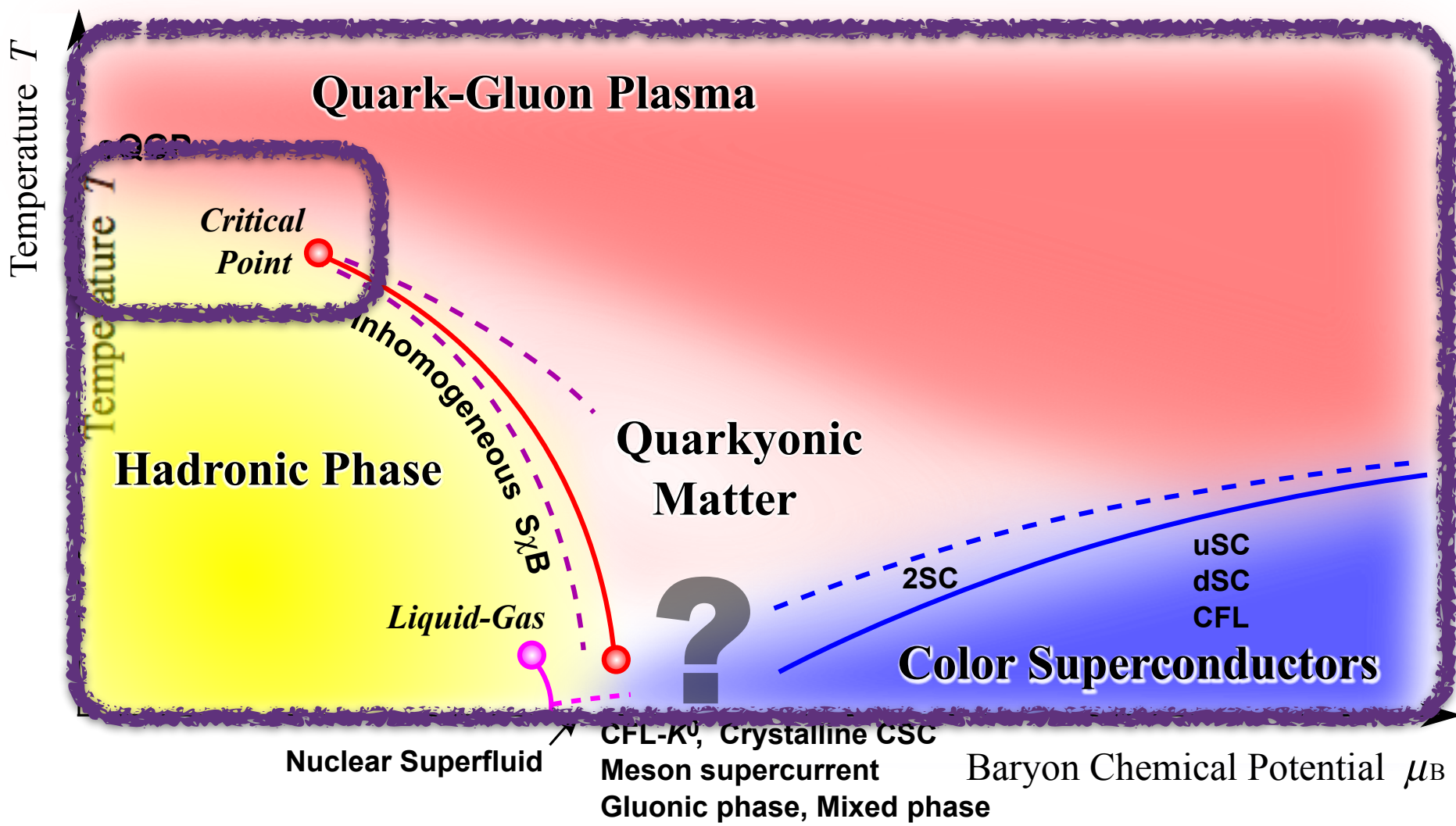
Herbst, Lücker, JMP, 2015

The physics of the QCD phase diagram & the experimental landscape

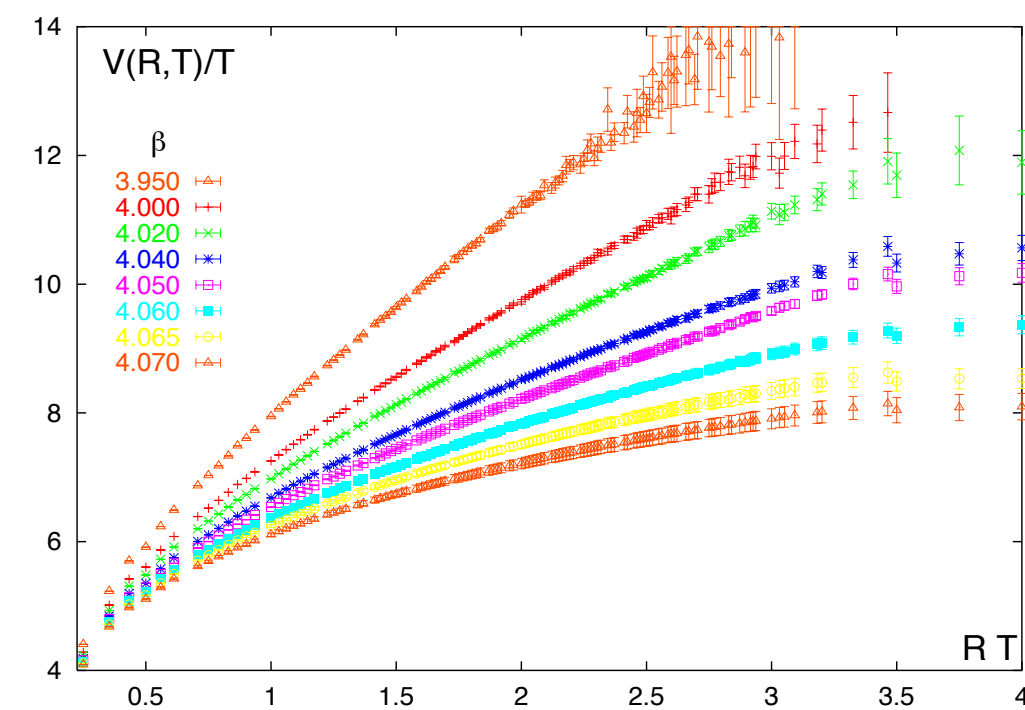
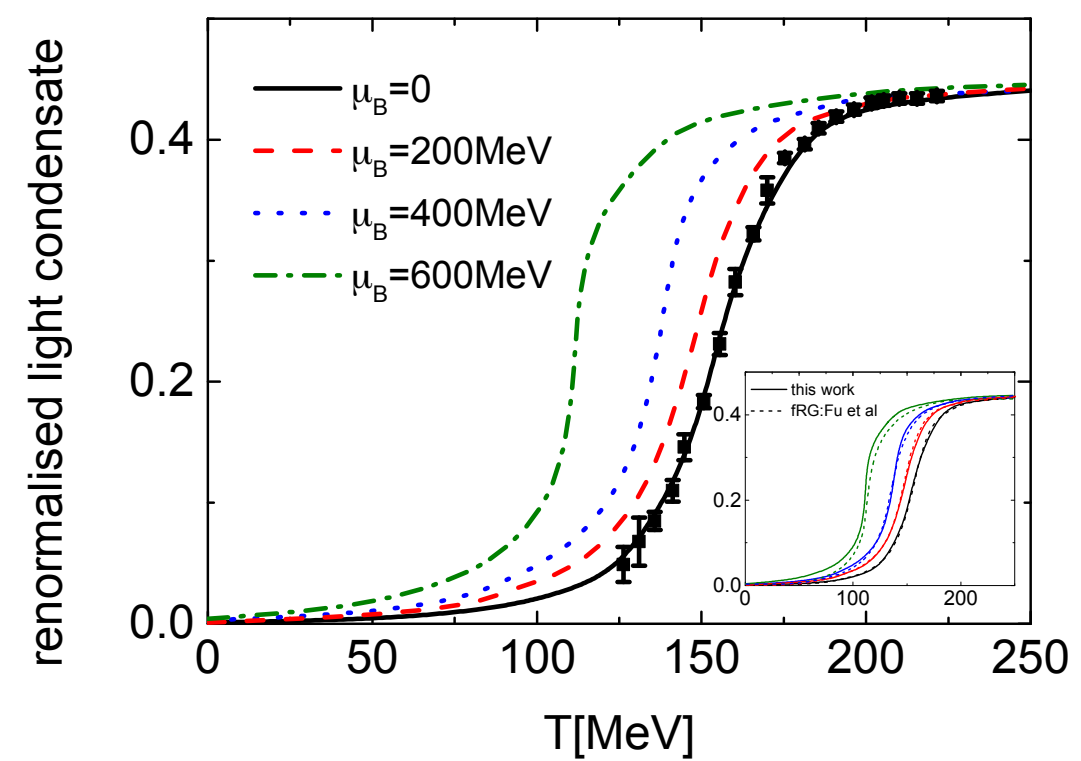
QCD phase structure



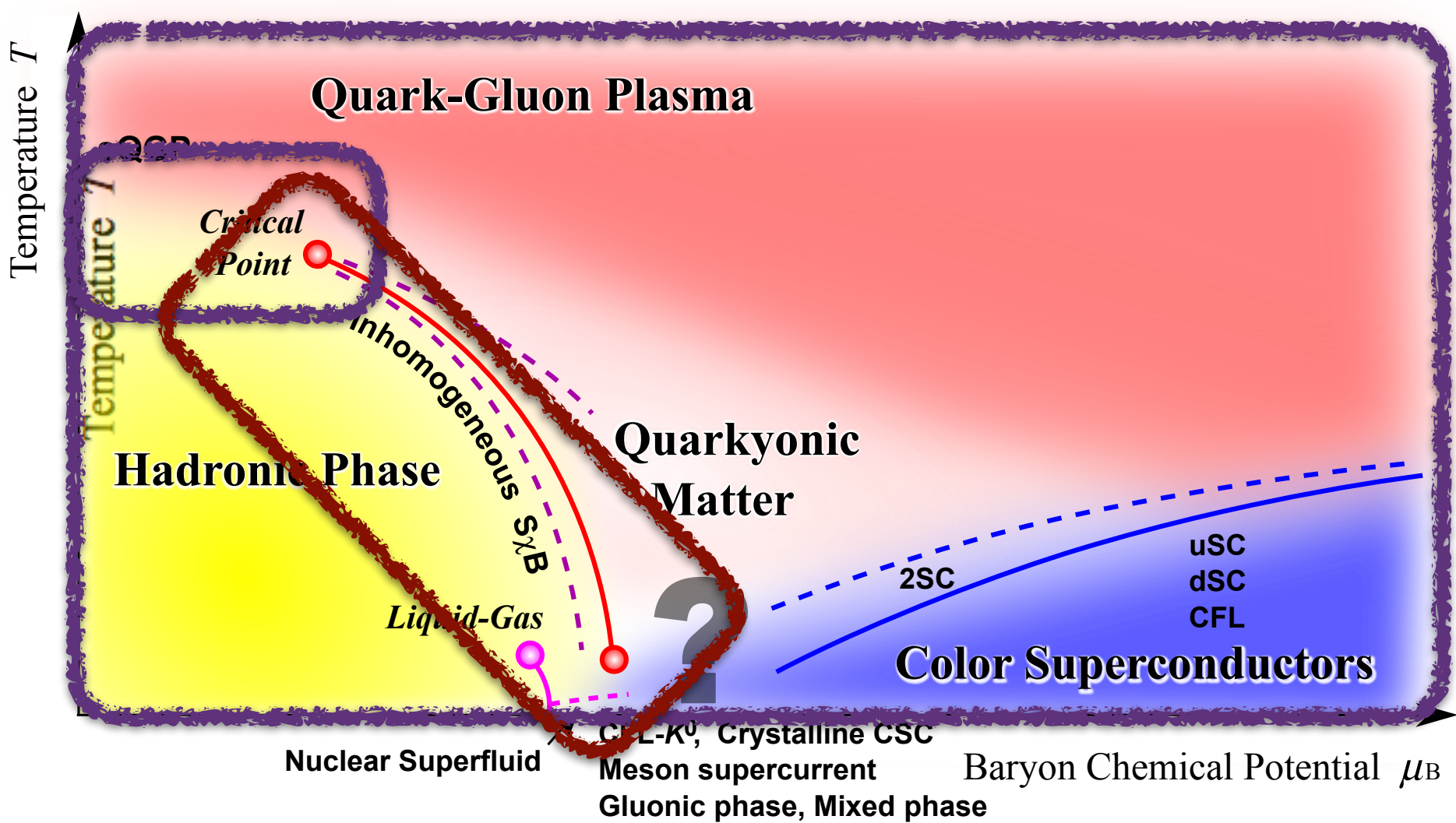
QCD phase structure



Chiral symmetry breaking & Confinement: the search for the CEP



QCD phase structure

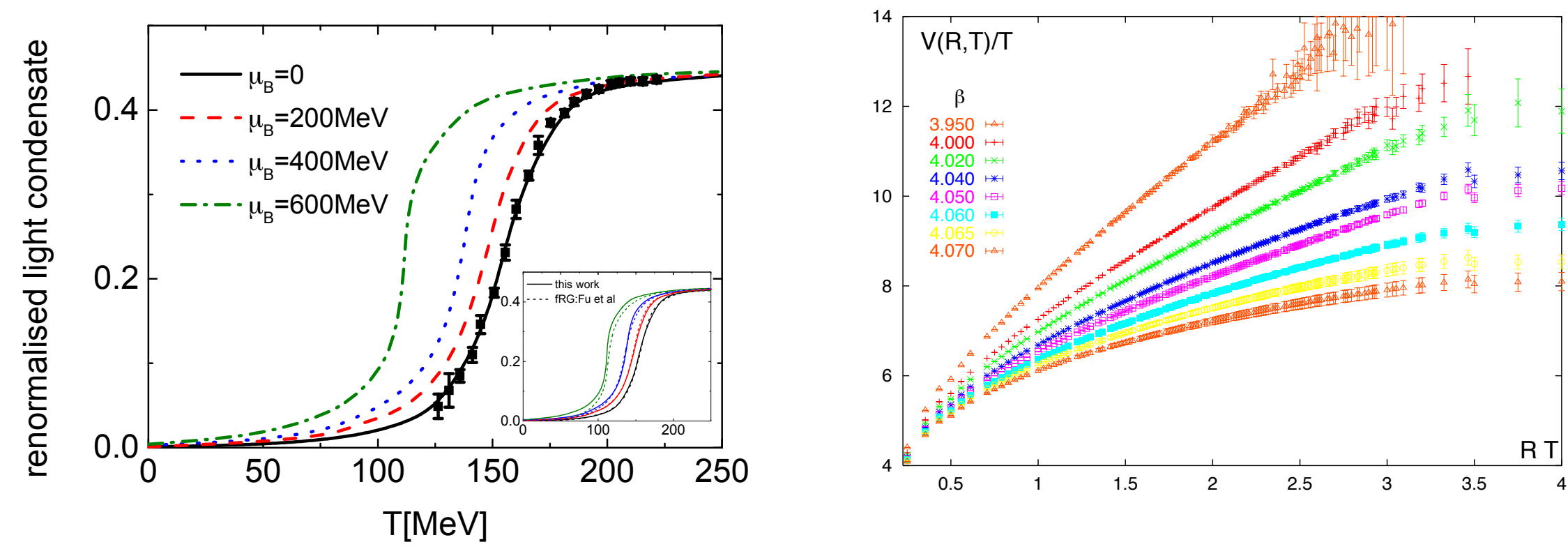


Moat regime & inhomogeneous phases: CEP & beyond

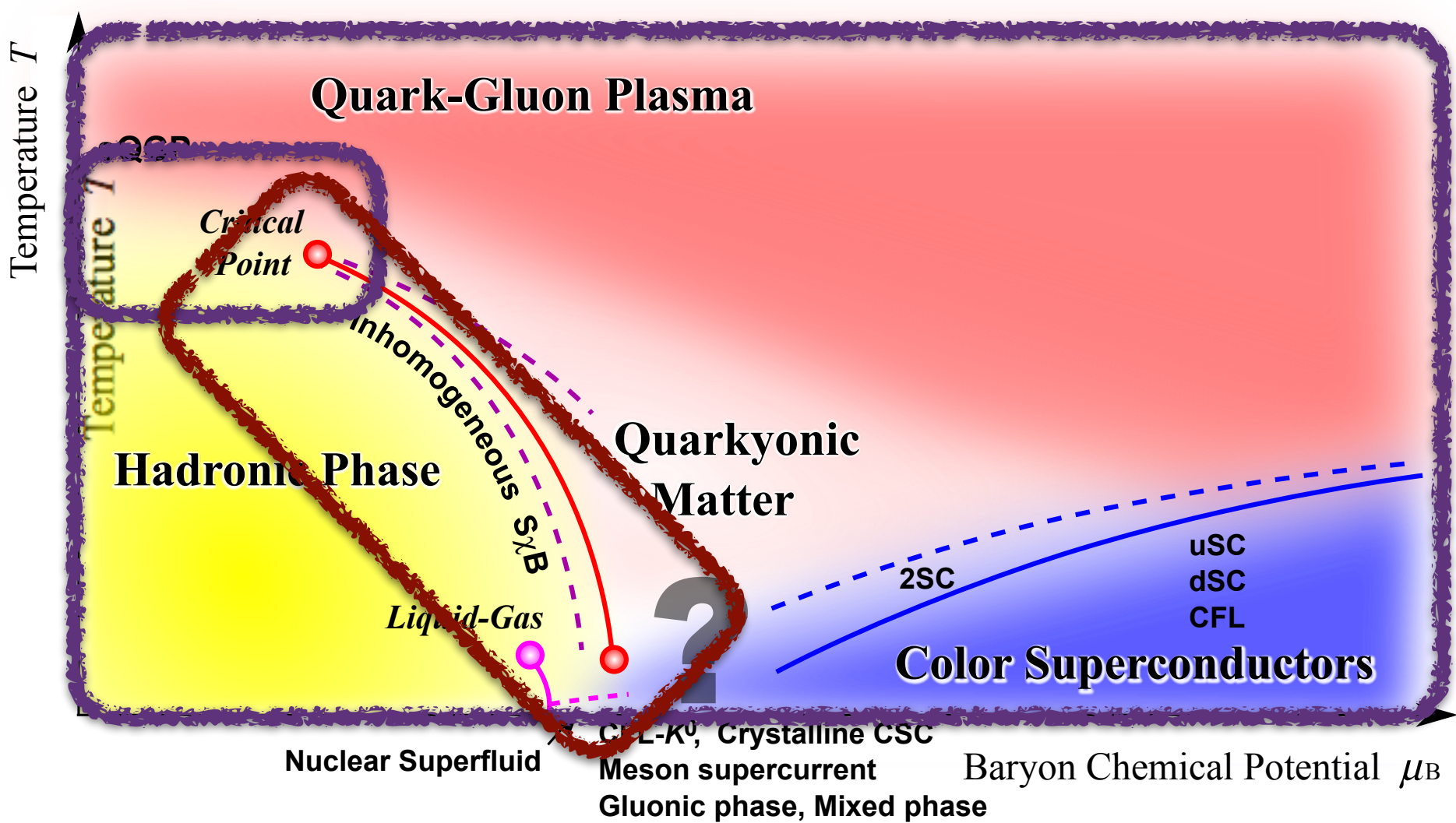
Signatures of the QCD Moat: Fu, JMP, Rennecke, PRD 101 (2020) 054032

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



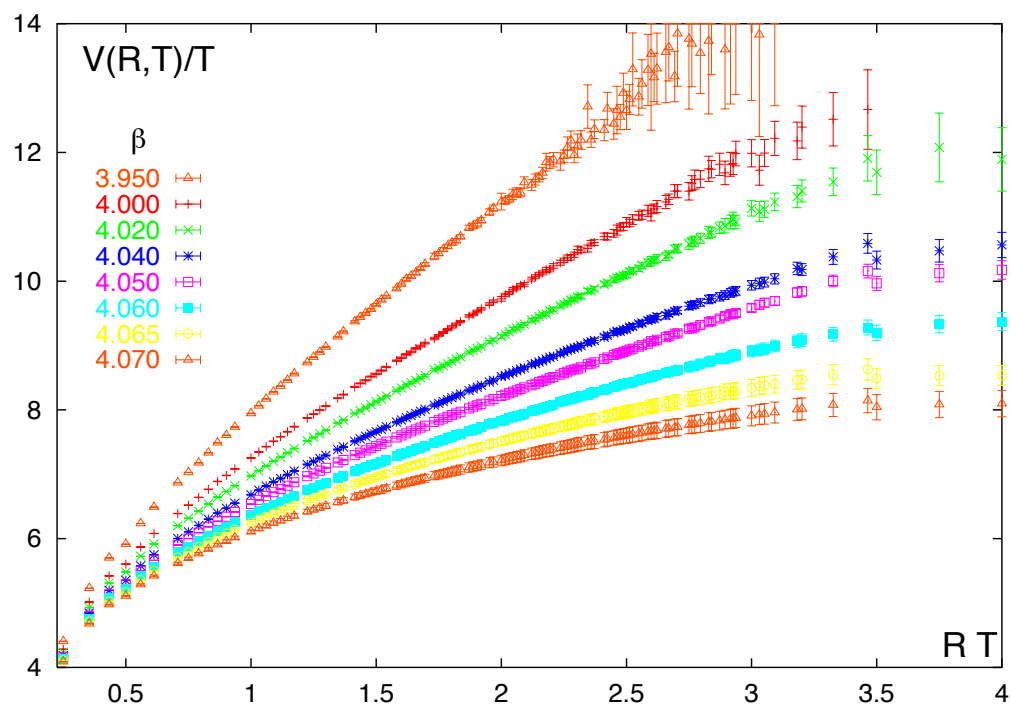
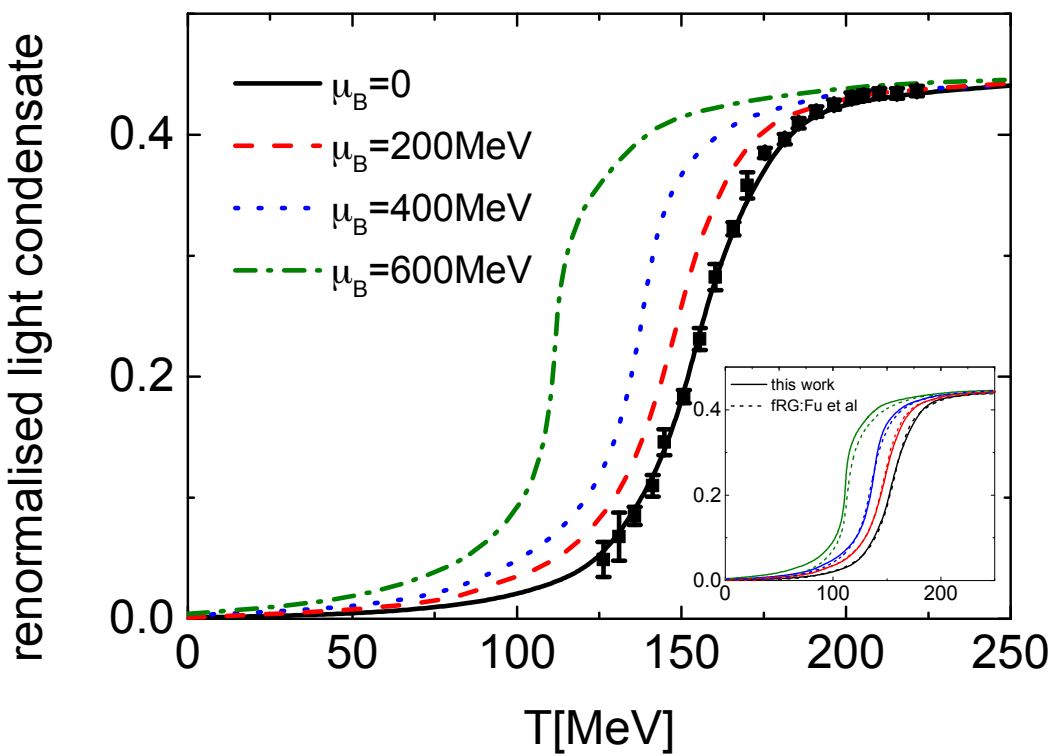
Wikimedia commons:
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US Moat

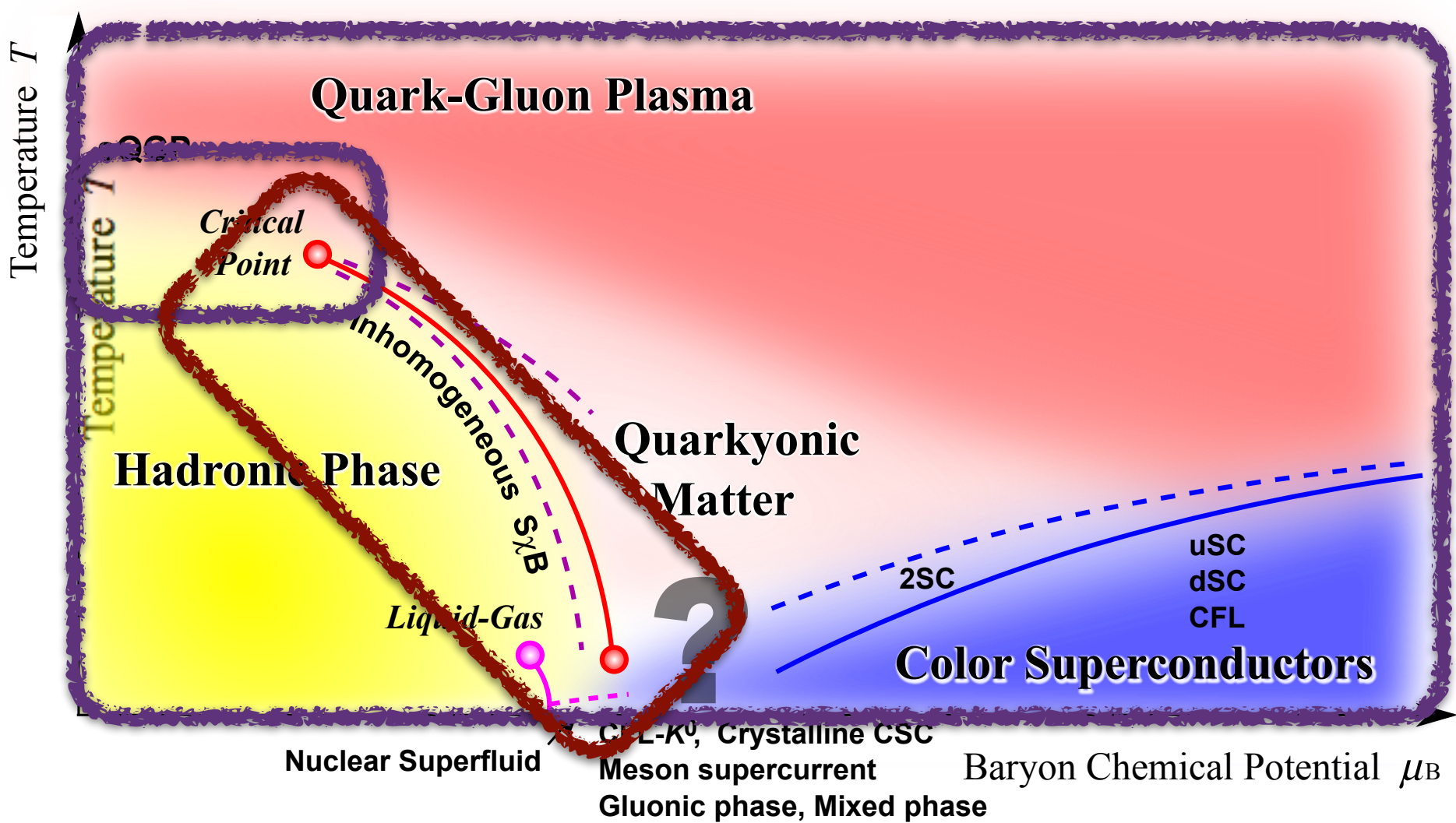


Wikipedia

Chiral symmetry breaking & Confinement: the search for the CEP



QCD phase structure



Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



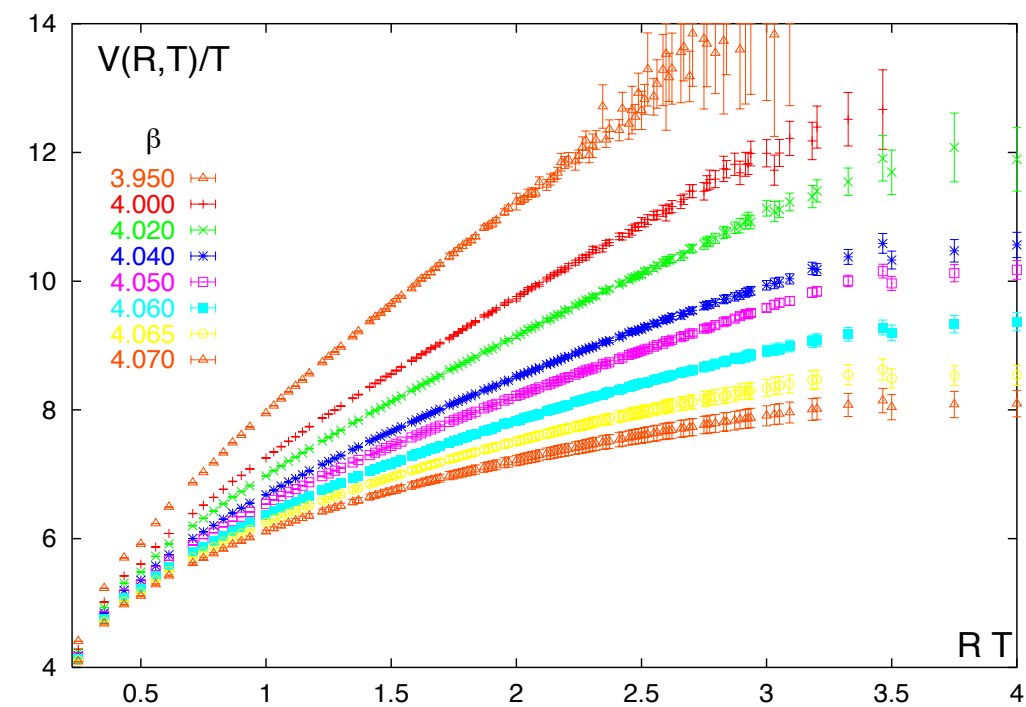
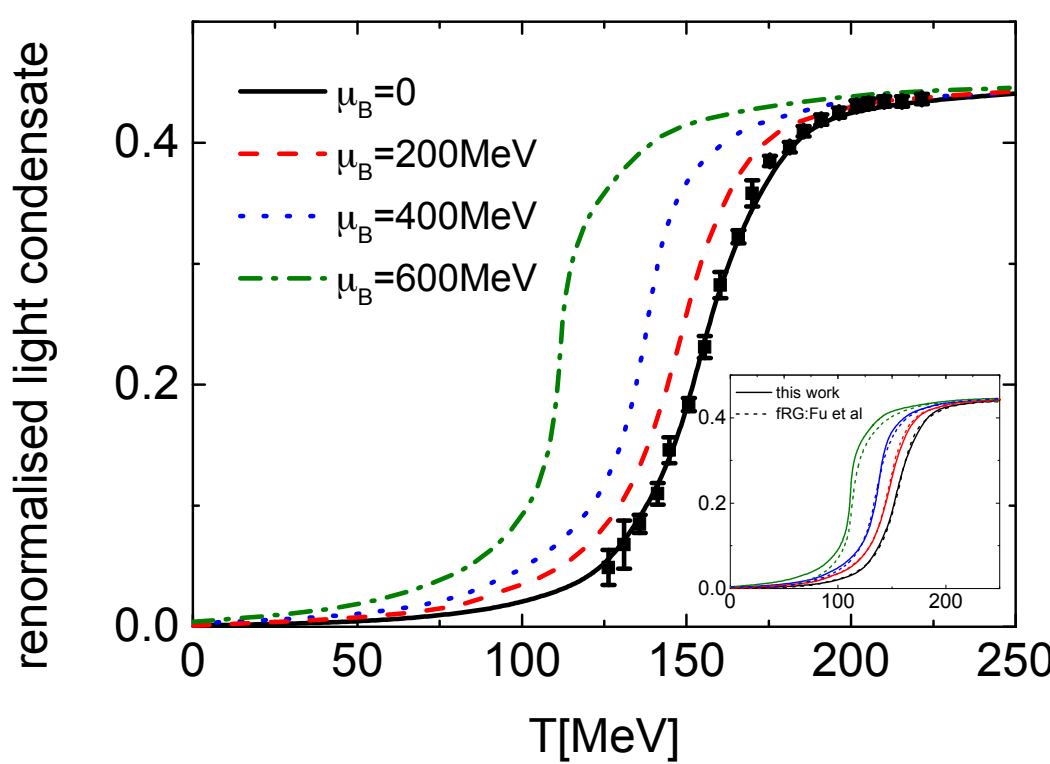
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US Moat

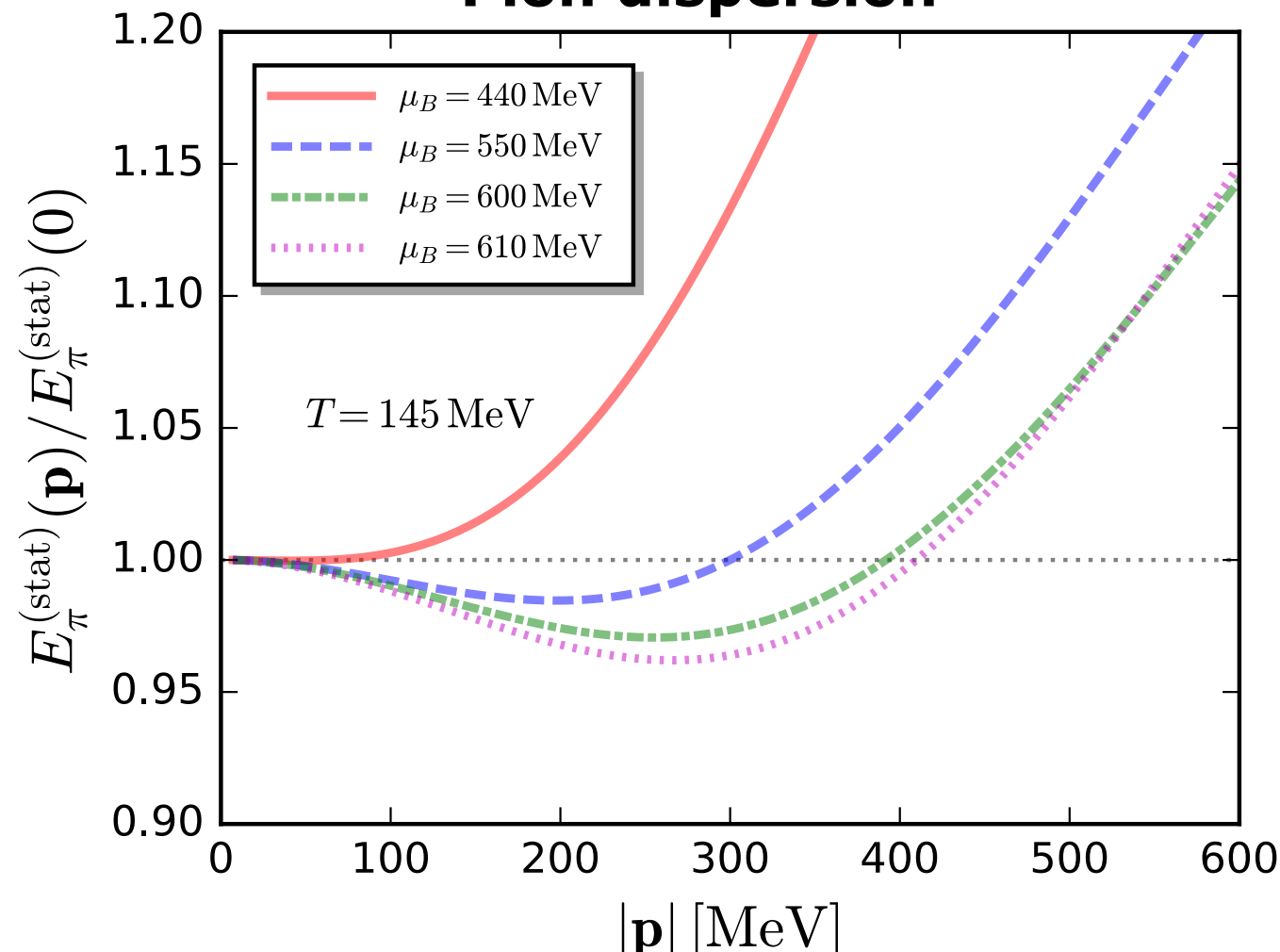


Wikipedia

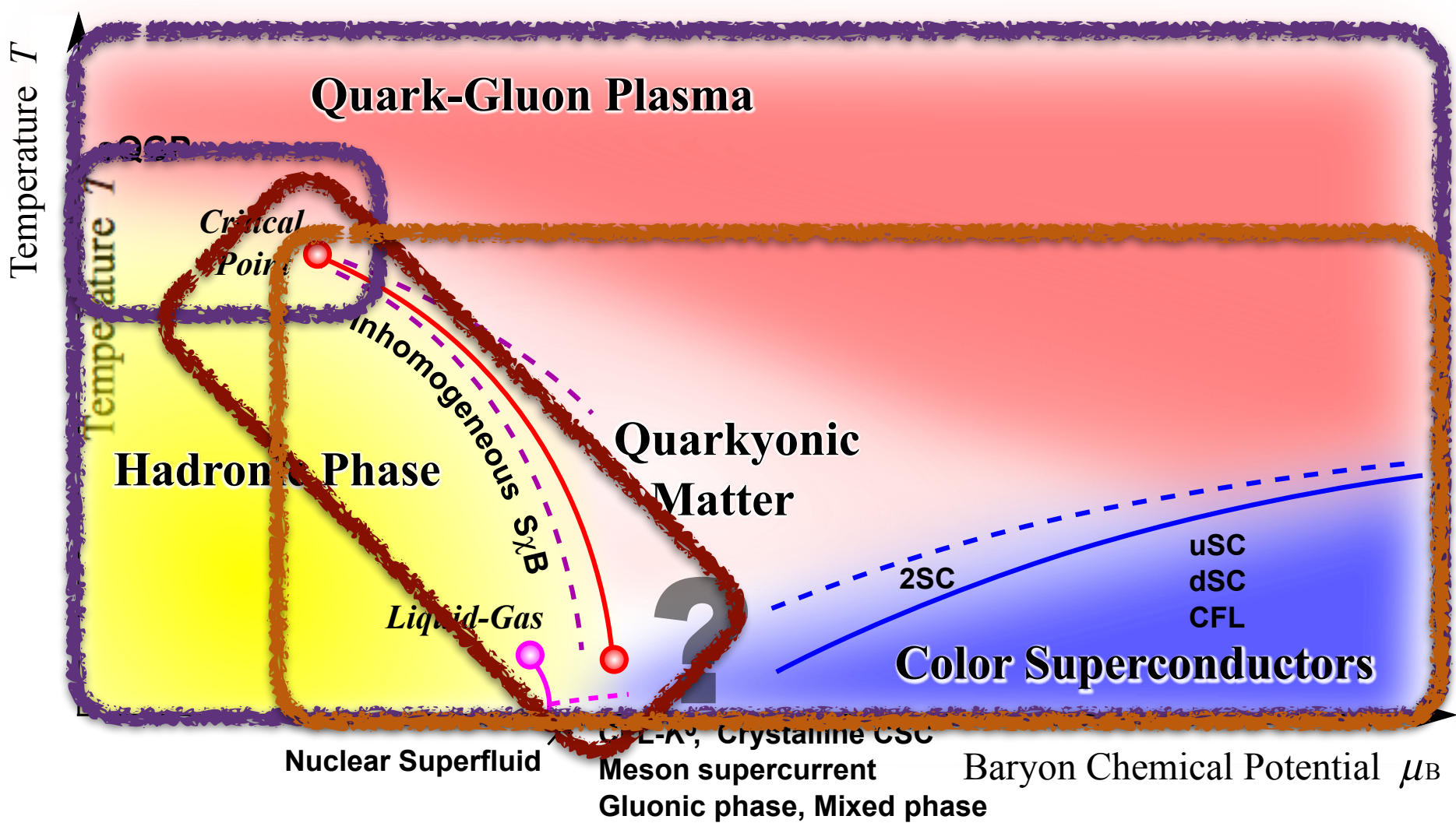
Chiral symmetry breaking & Confinement: the search for the CEP



Pion dispersion



QCD phase structure



Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



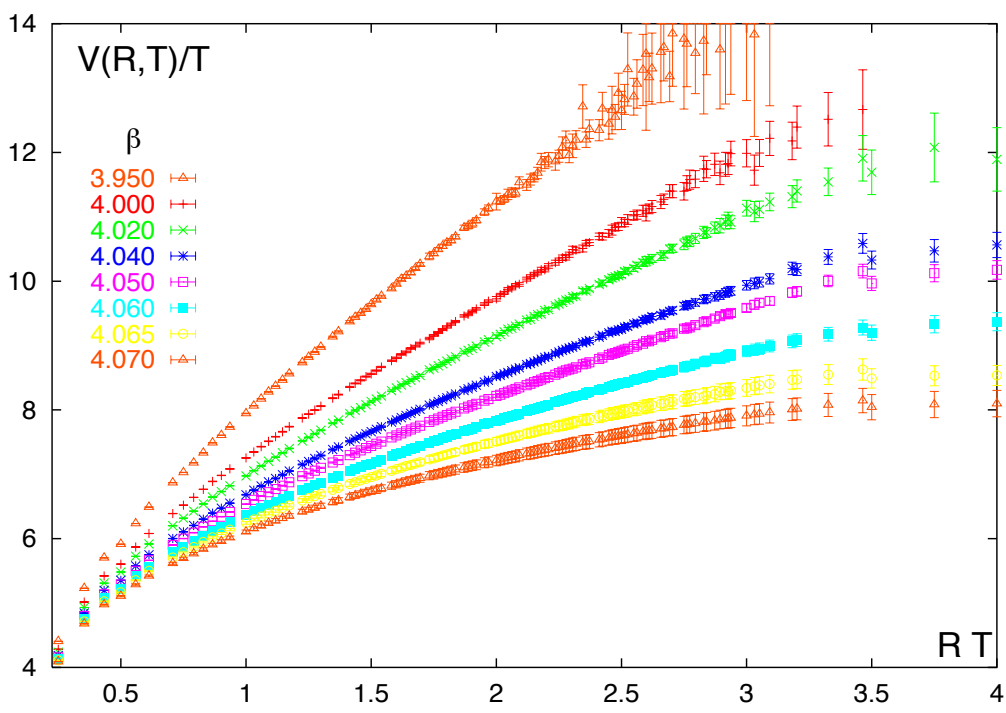
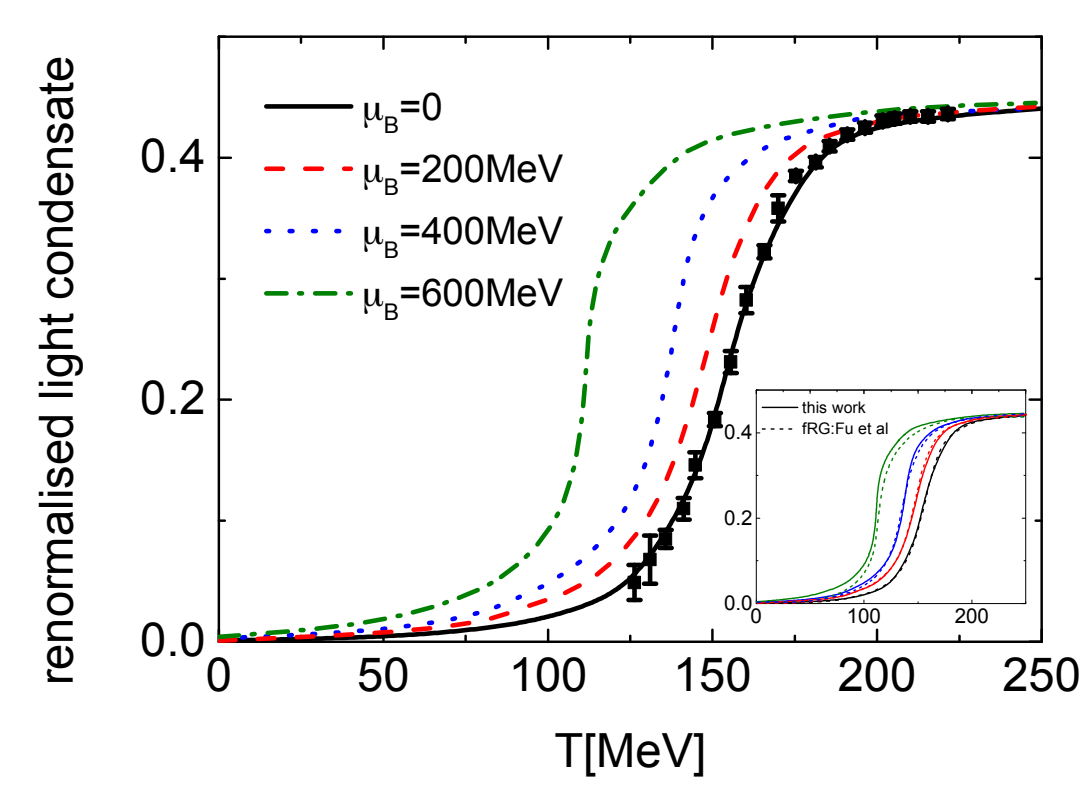
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US Moat



Wikipedia

Chiral symmetry breaking & Confinement: the search for the CEP



Condensed matter QCD

Color superconductivity

Competing orders

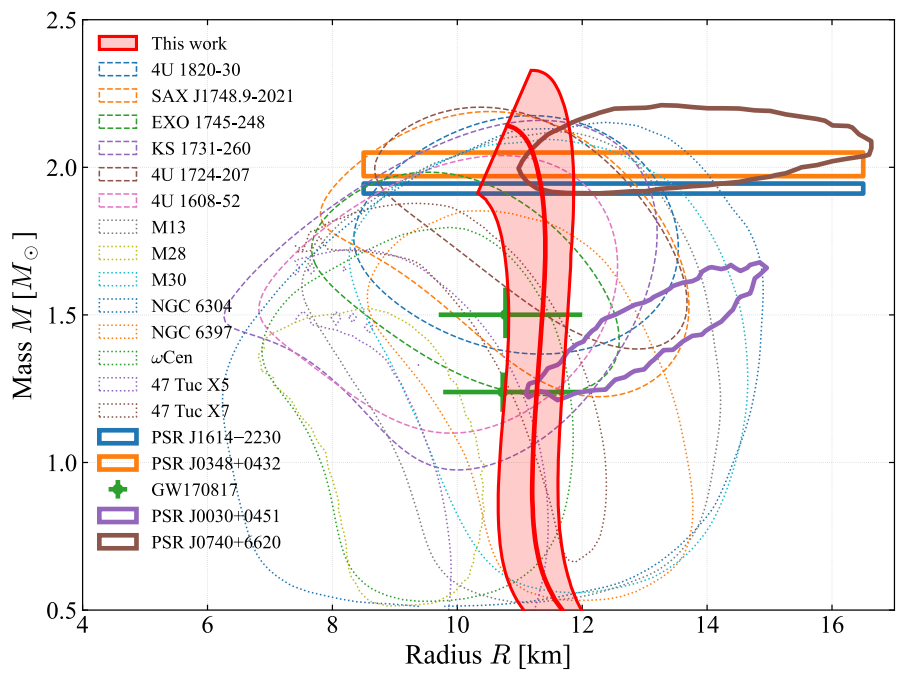
Nuclear EoS

■
■
■

Data Analysis



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



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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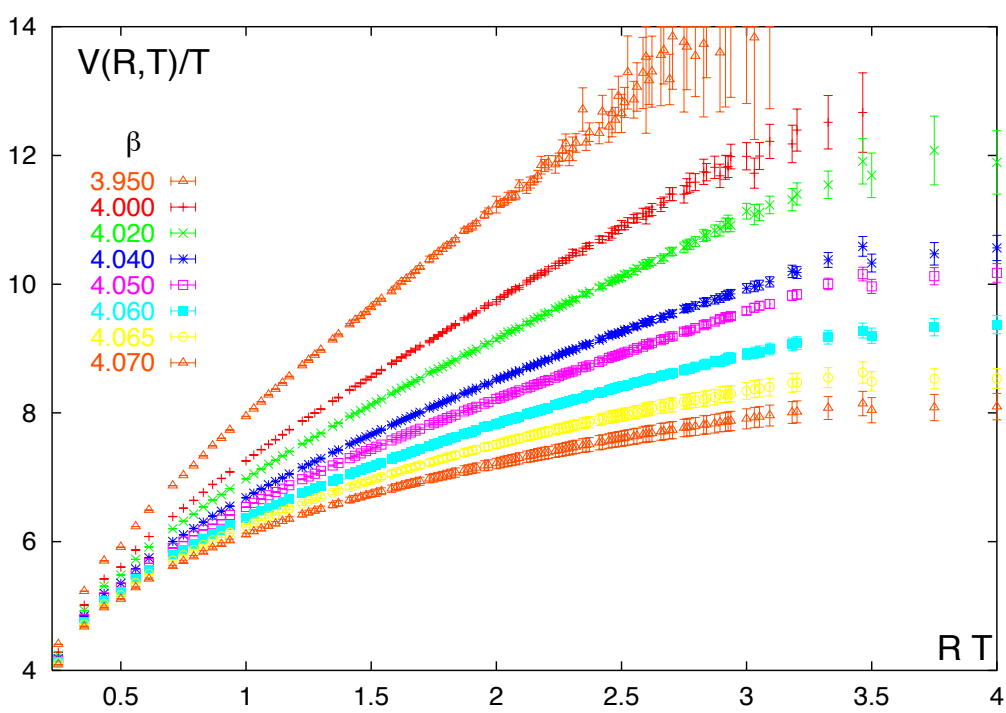
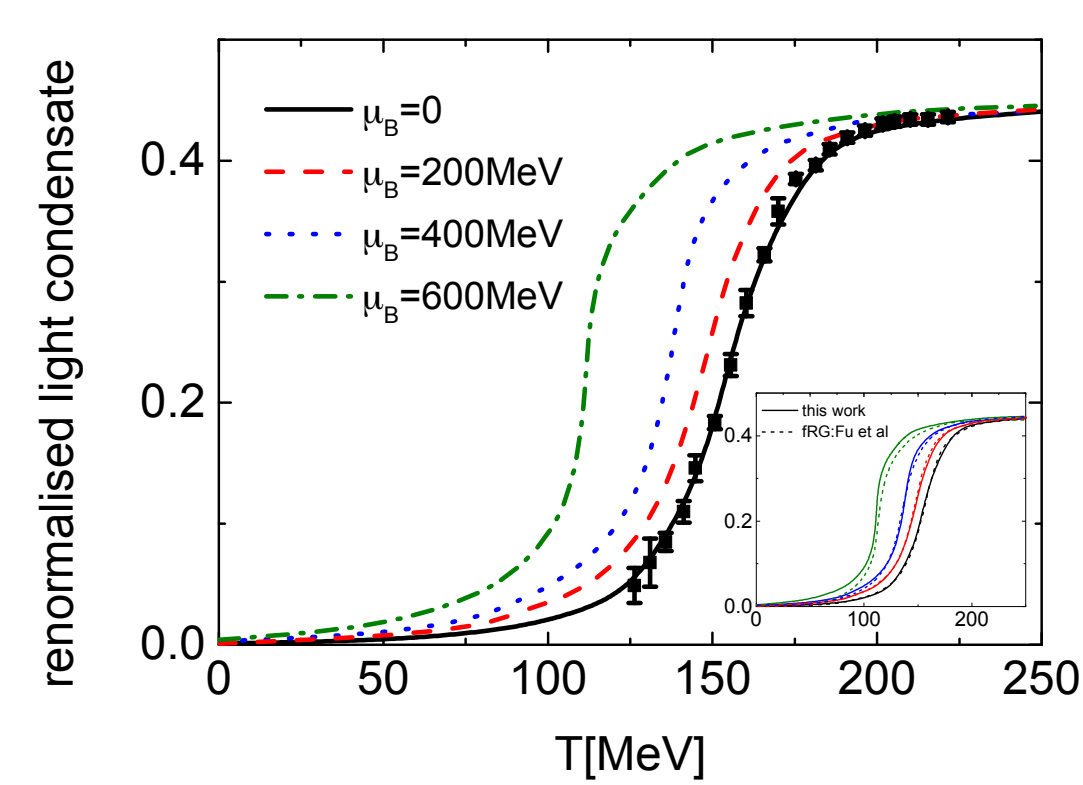
US Moat



Wikipedia

Chiral symmetry breaking & Confinement: the search for the CEP

Condensed matter QCD



Color superconductivity

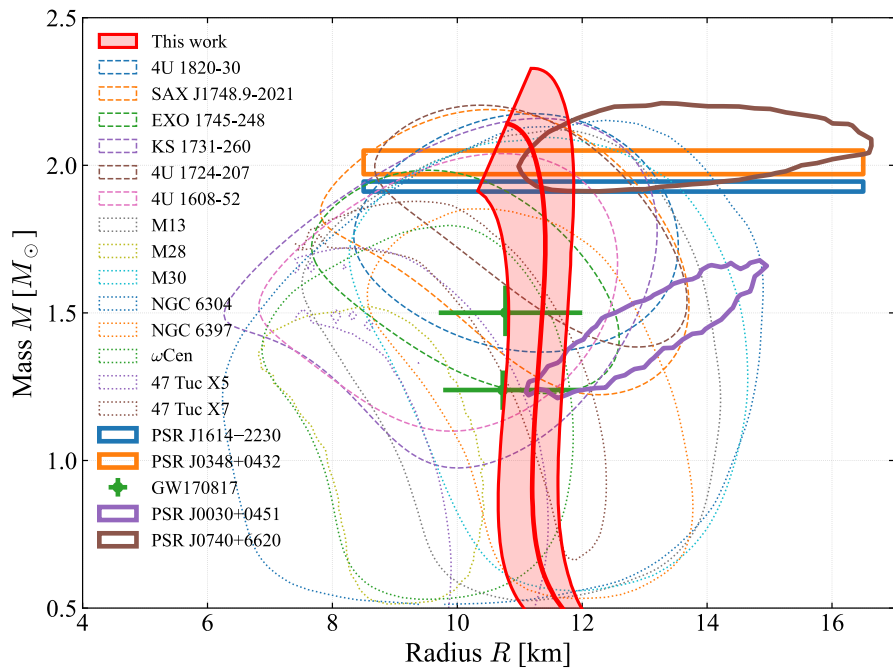
Competing orders

Nuclear EoS

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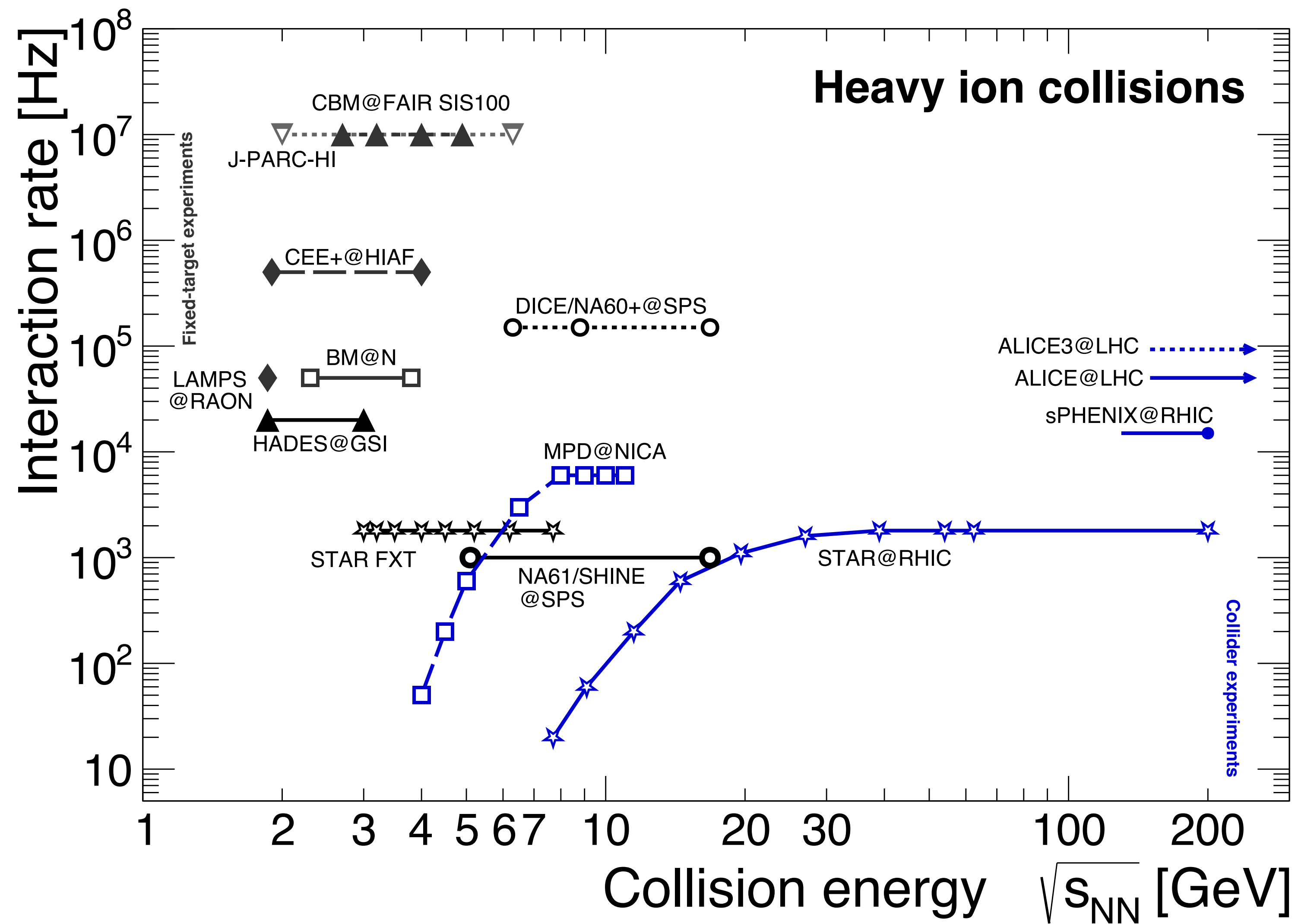
Data Analysis

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

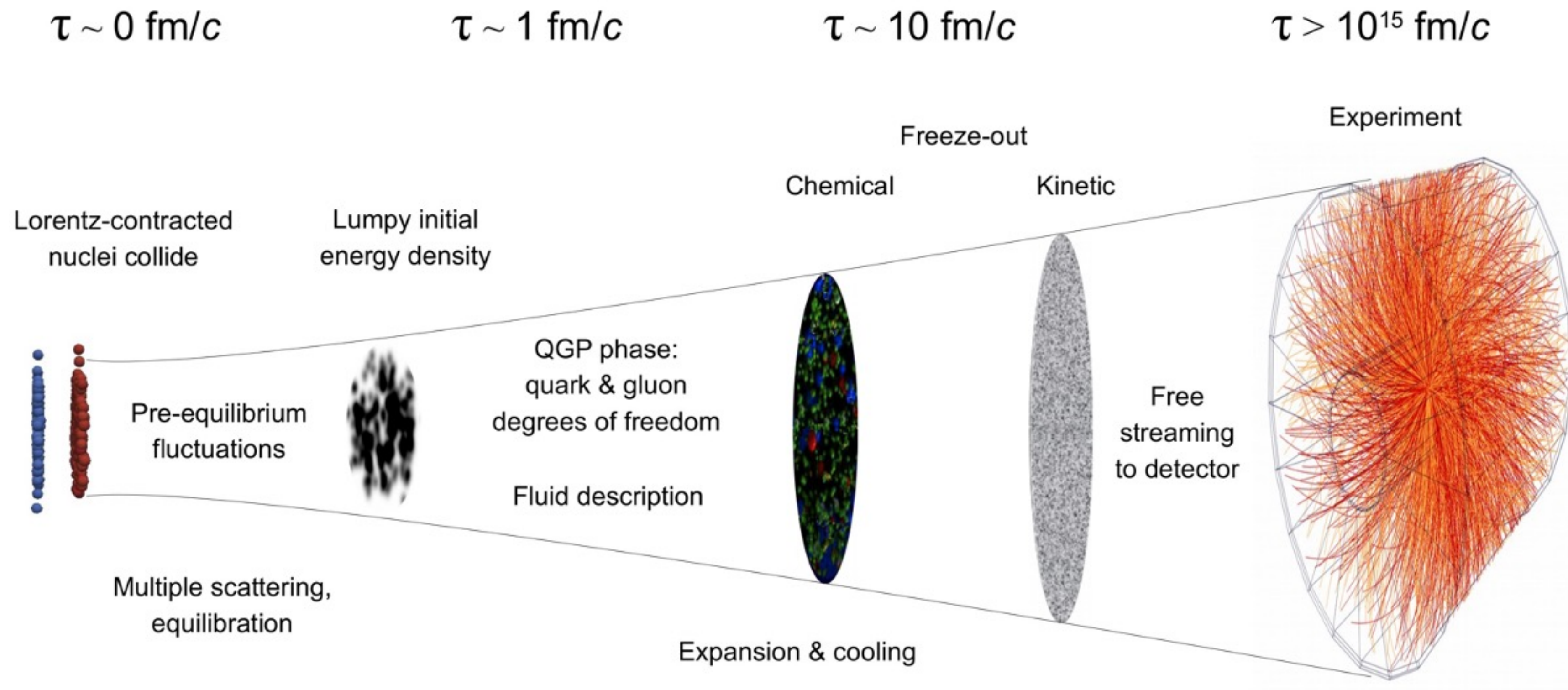


Strongly correlated QCD: how to?

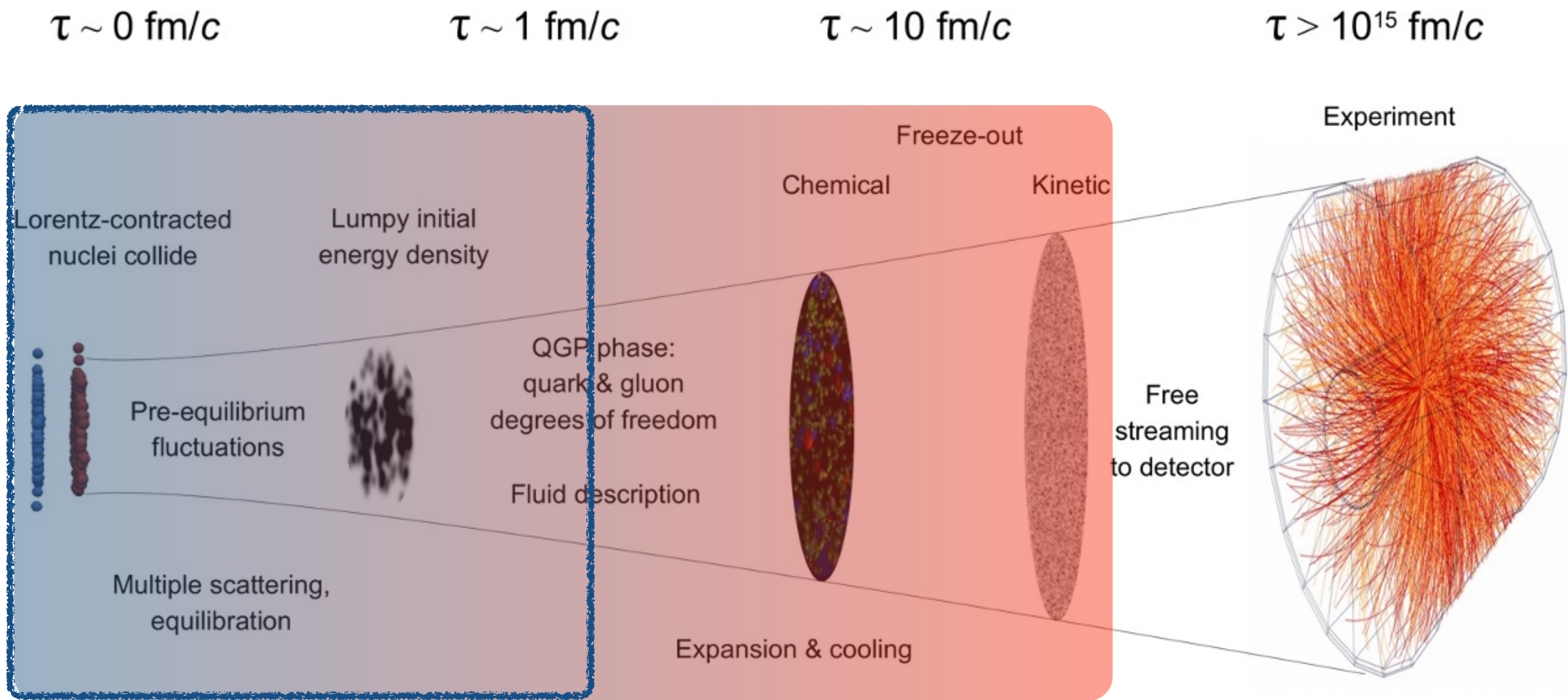
(2) Experiments (extreme QCD)



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



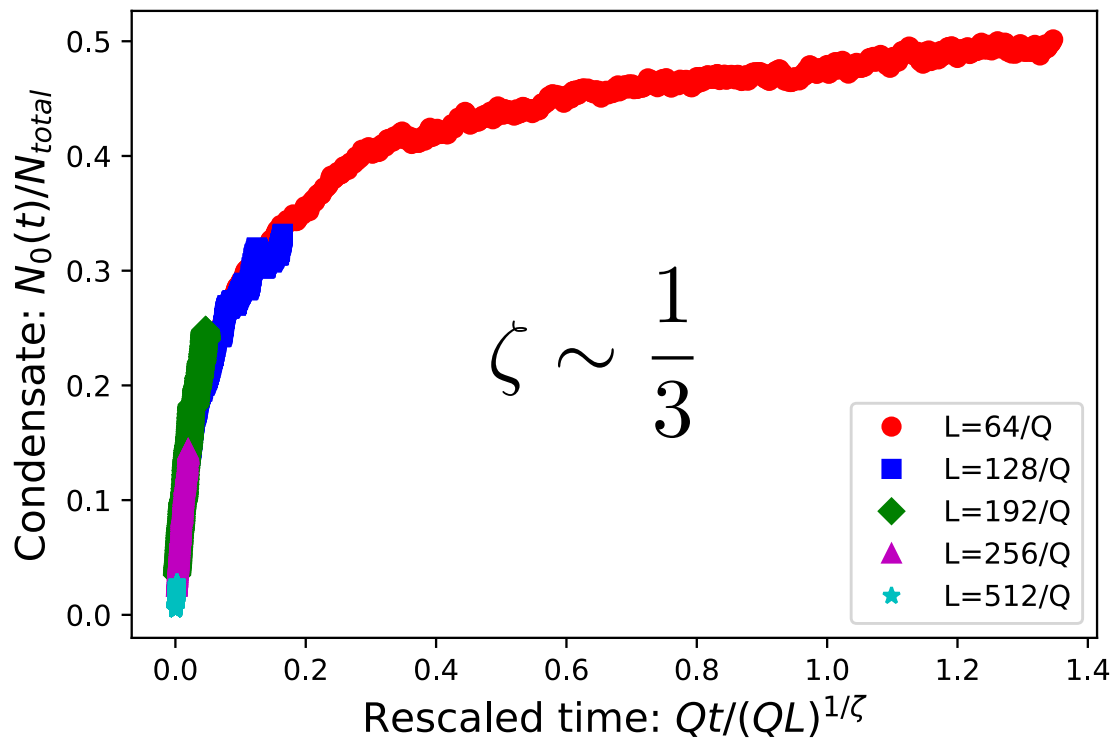
Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)



large occupancies

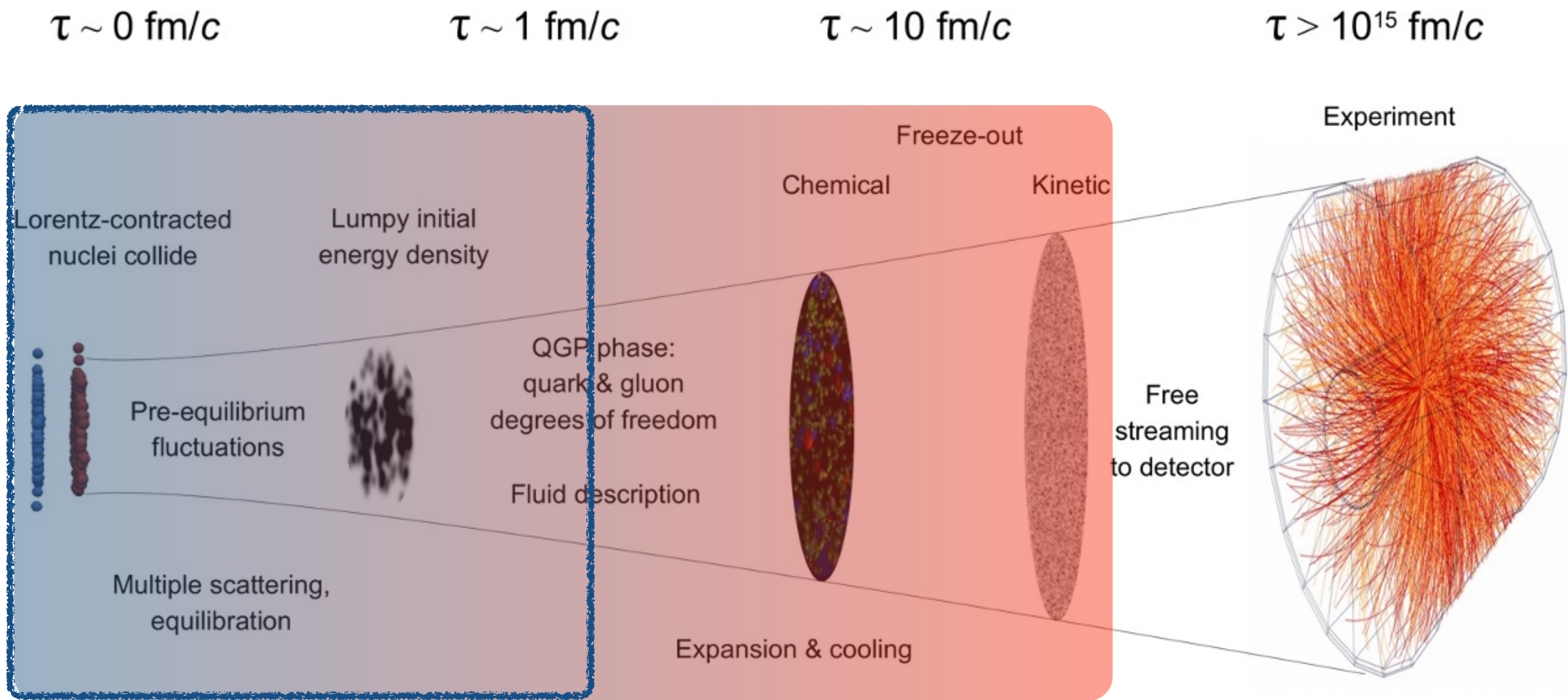
non-thermal fixed point

Classical-statistical



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

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



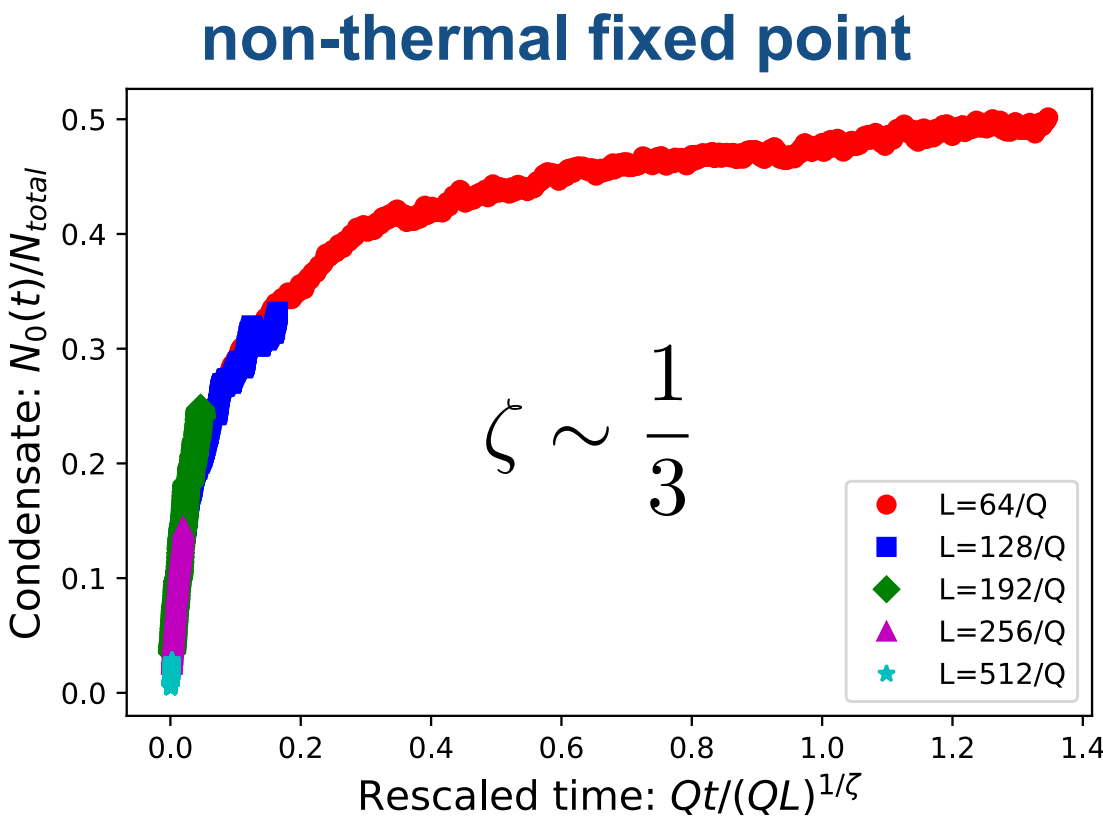
large occupancies

statistics + collective behaviour

&

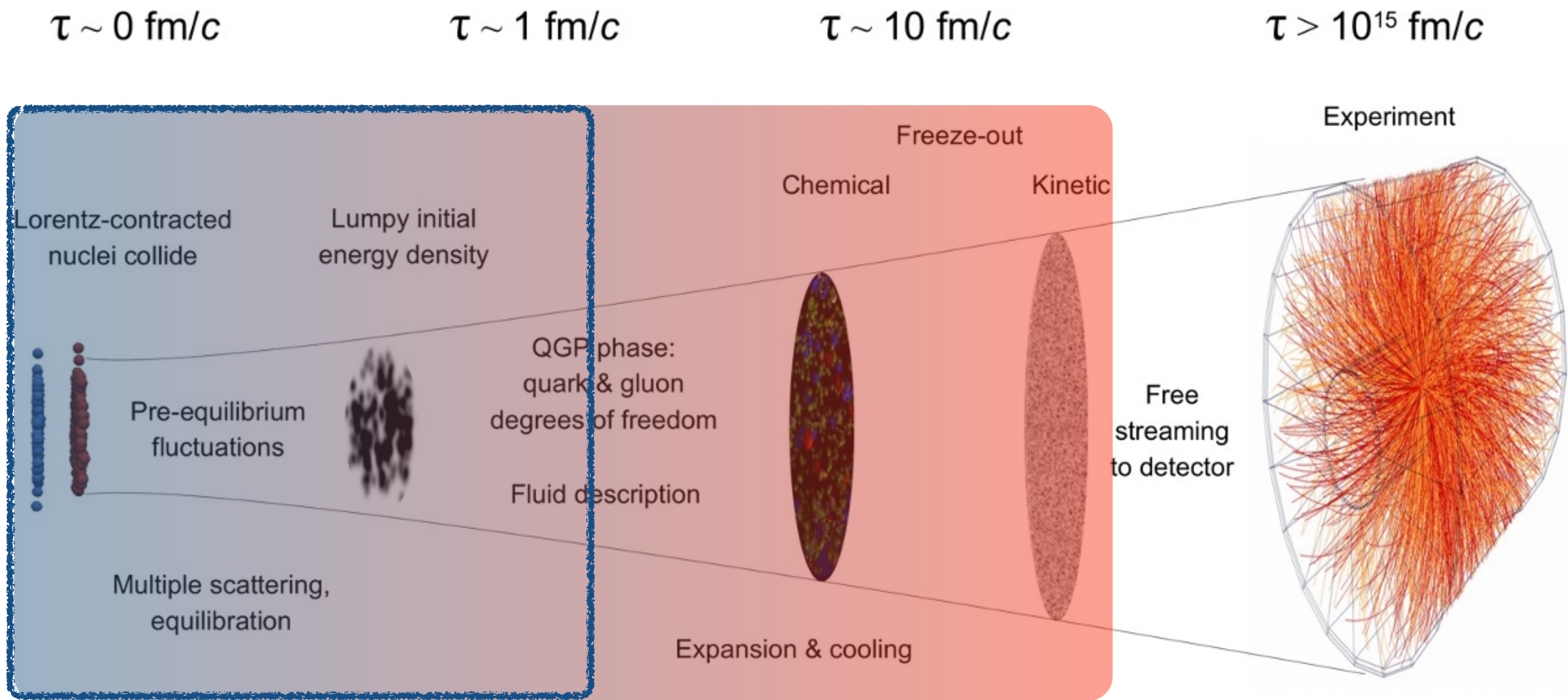
strongly correlated quantum dynamics

Classical-statistical



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

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



large occupancies

statistics + collective behaviour

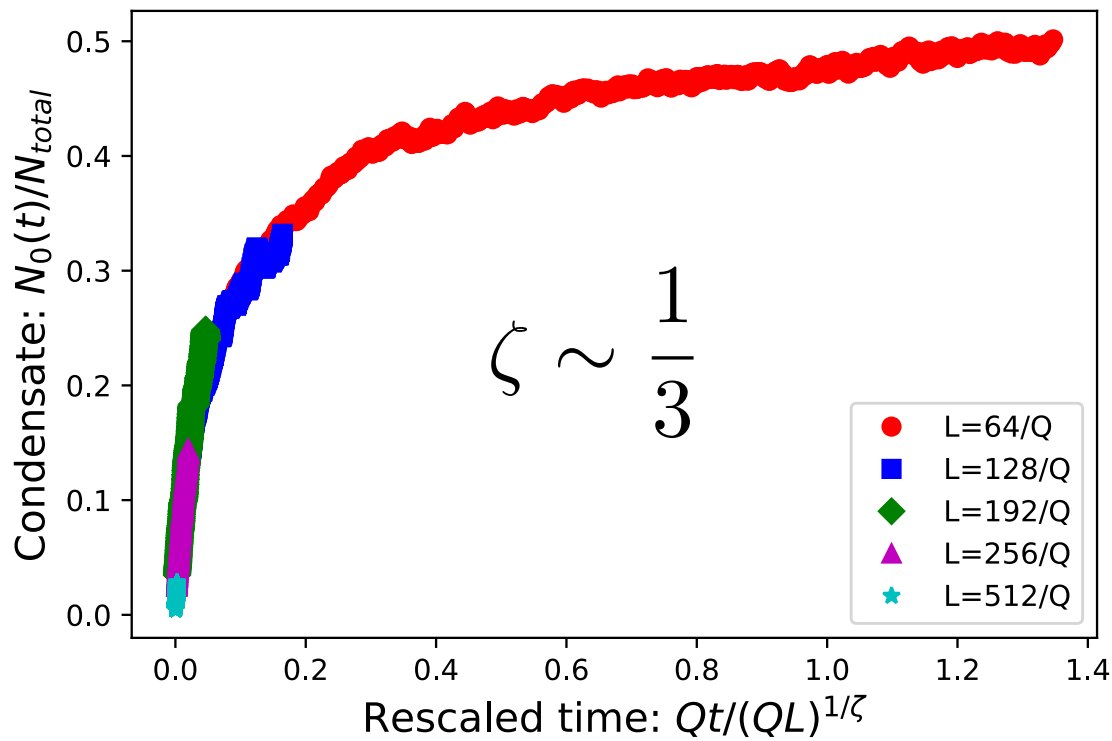
Background

&

strongly correlated quantum dynamics

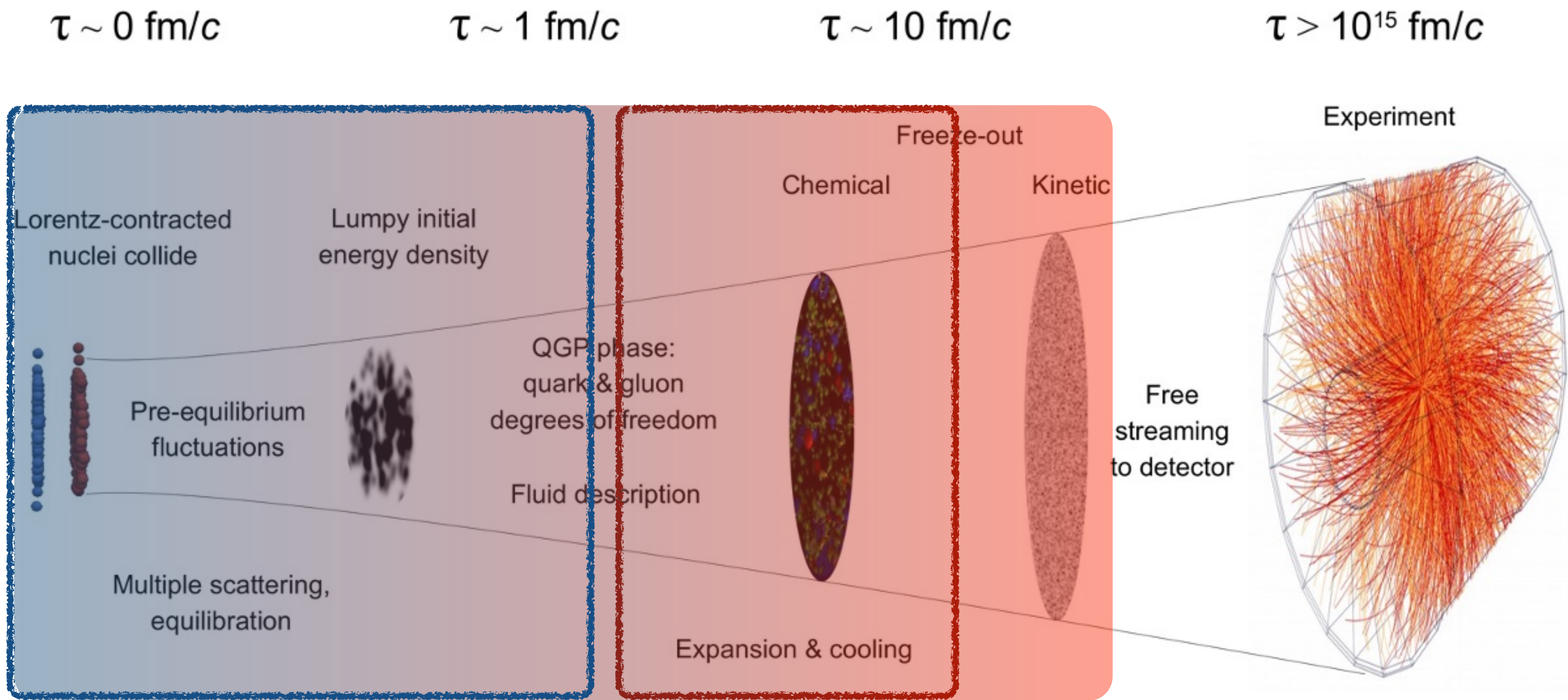
Classical-statistical

non-thermal fixed point



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

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



large occupancies

statistics + collective behaviour

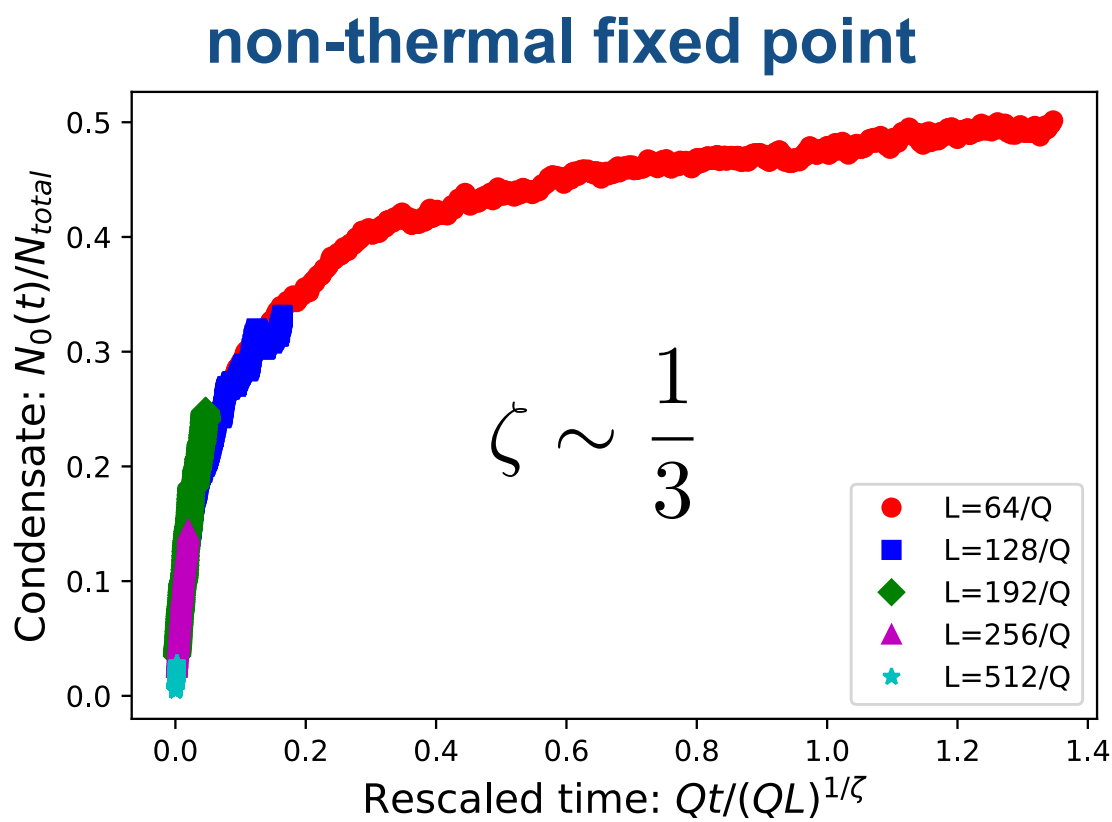
Background

&

strongly correlated quantum dynamics

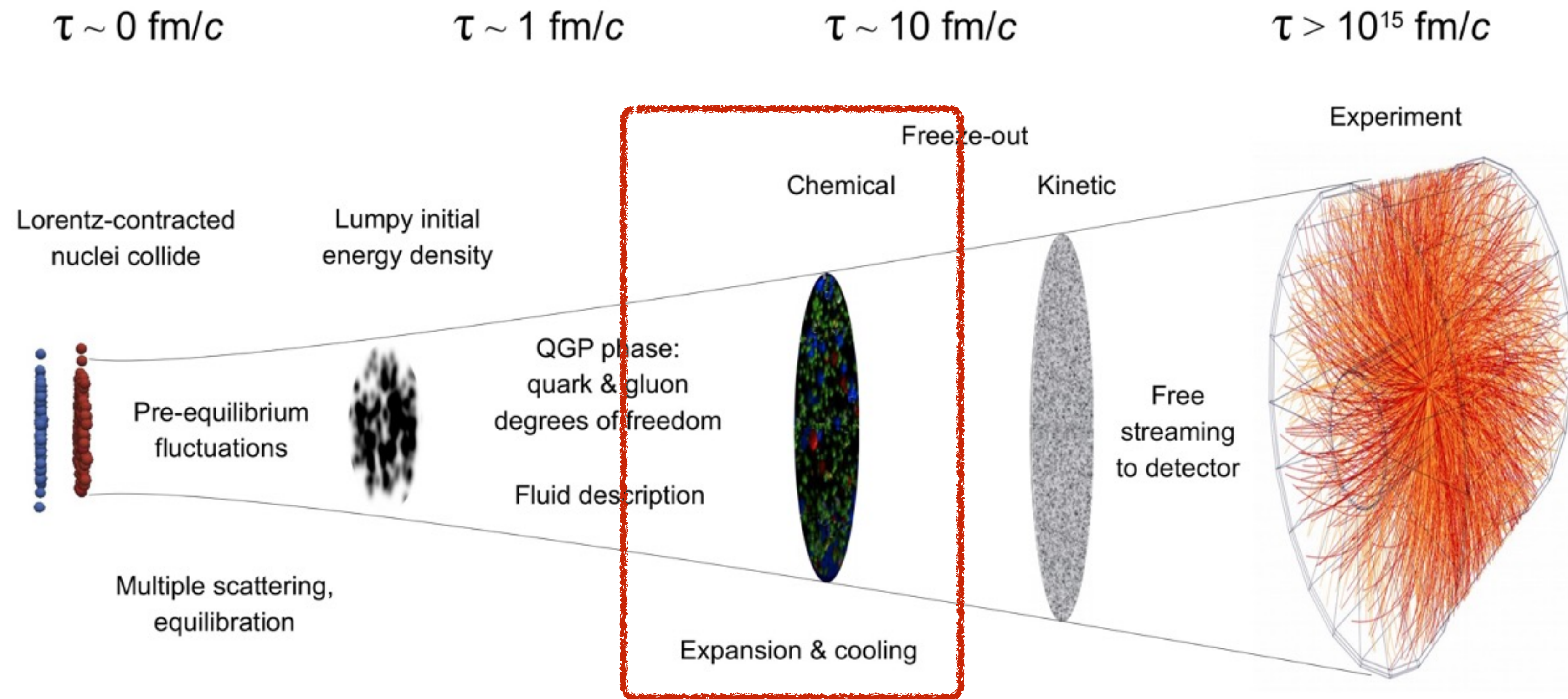
The cool stuff!

Classical-statistical



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

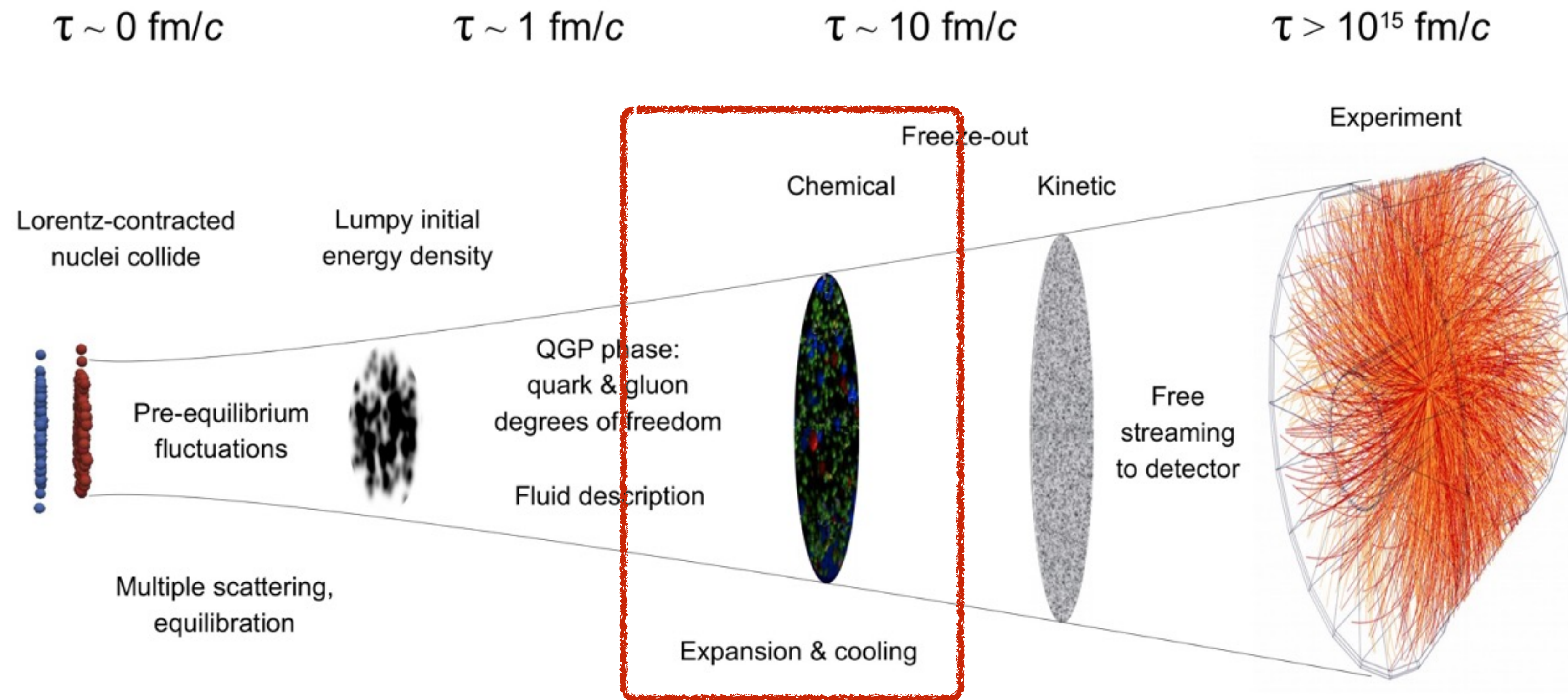
Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)



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

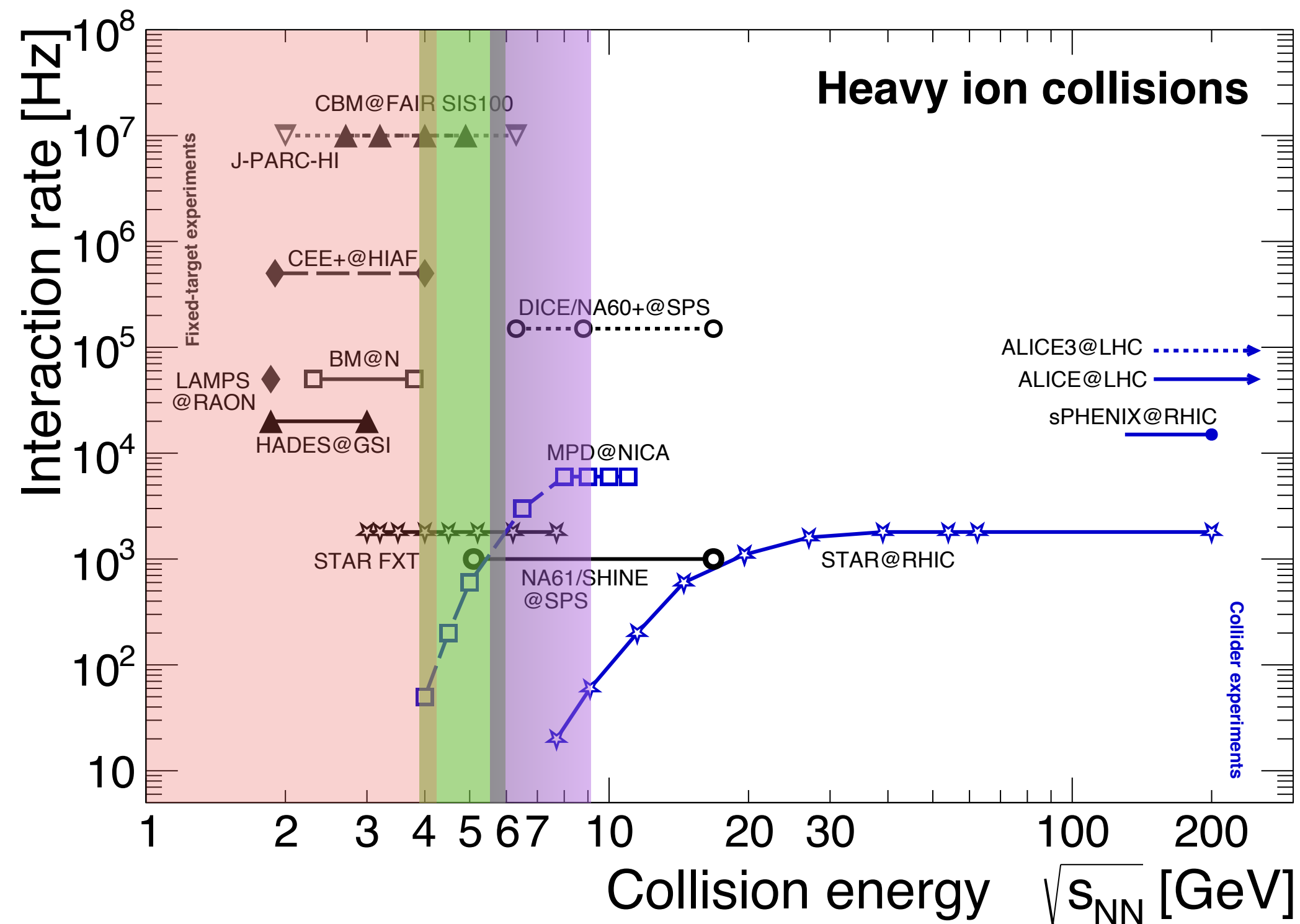
Experimental landscape

Theoretical landscape

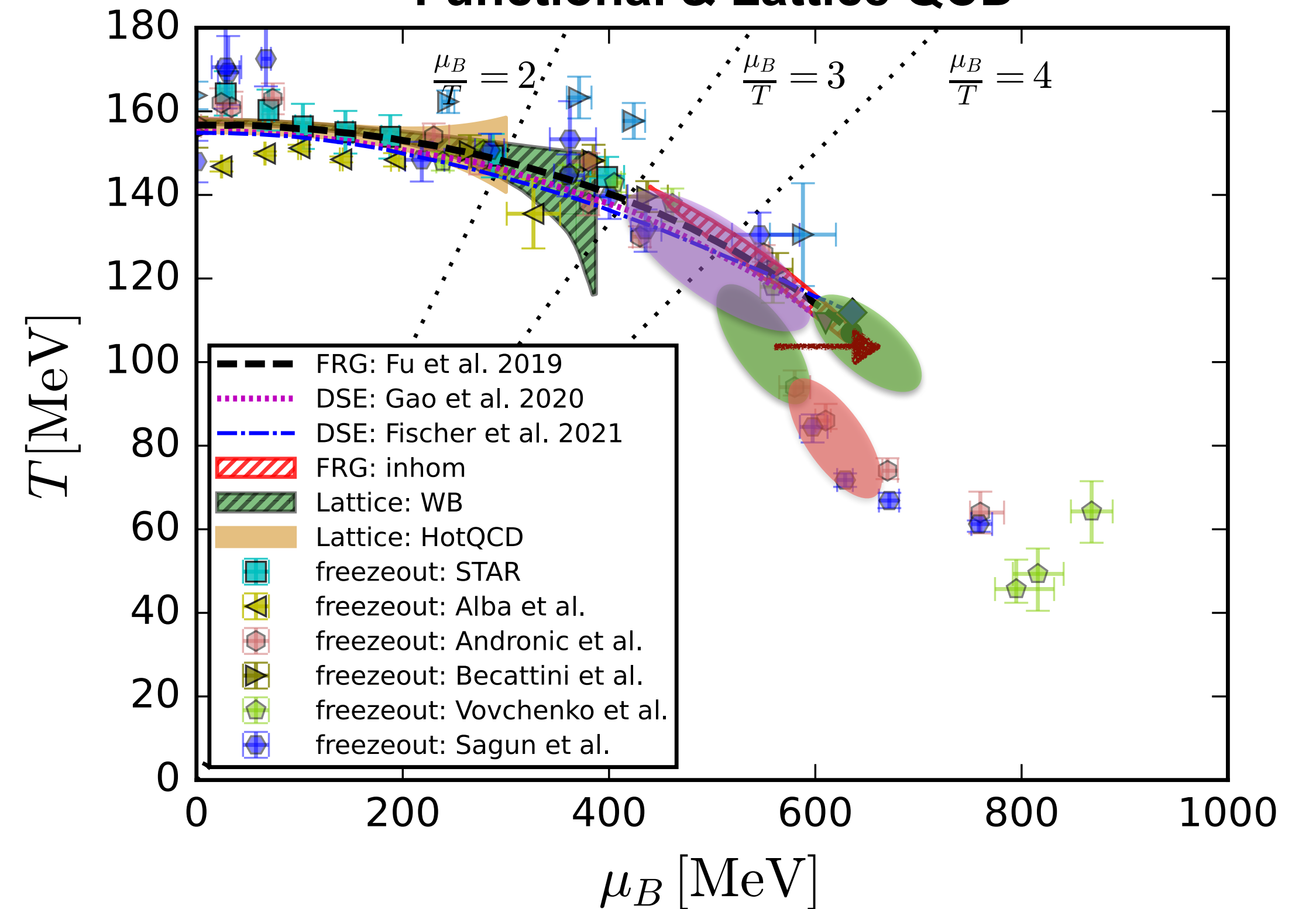
Onset of new phases on the chiral transition line (CEP)

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



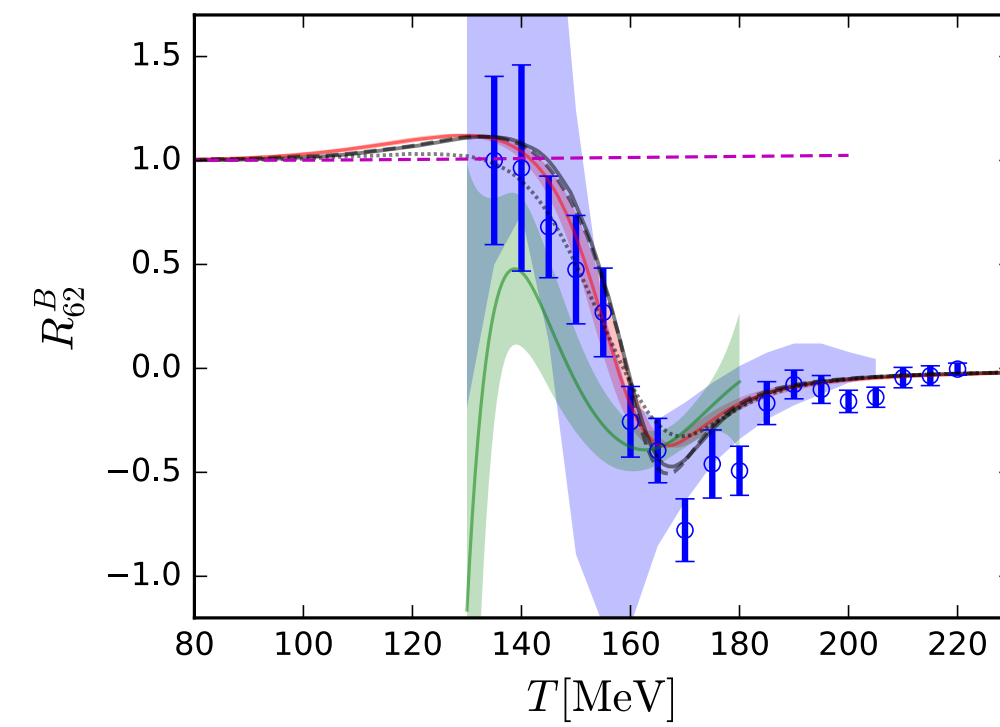
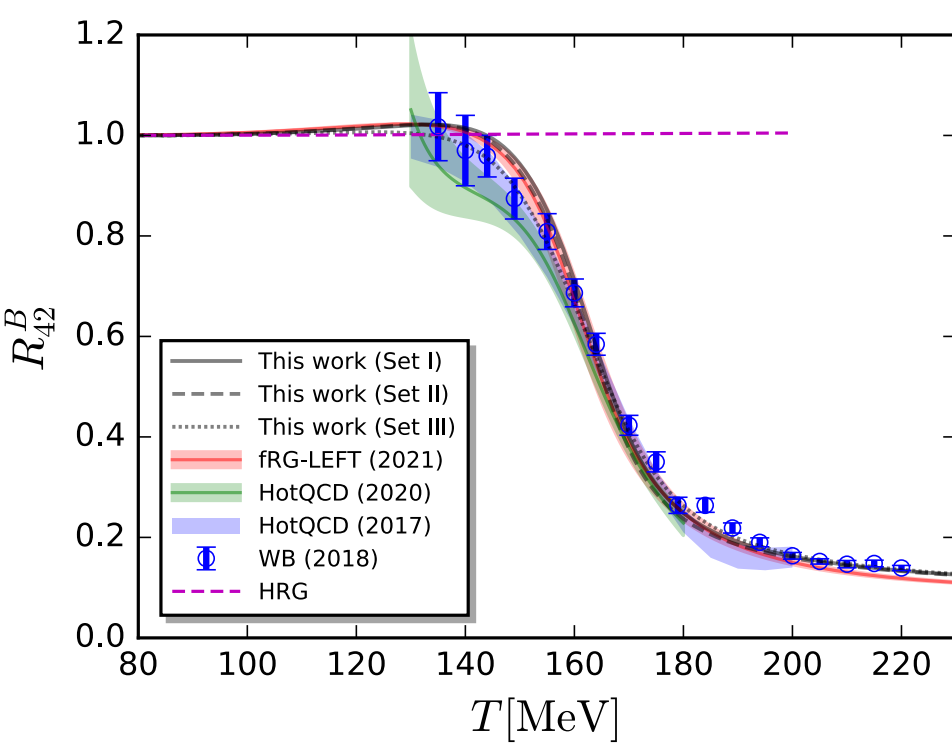
fqcd-collaboration.github.io

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

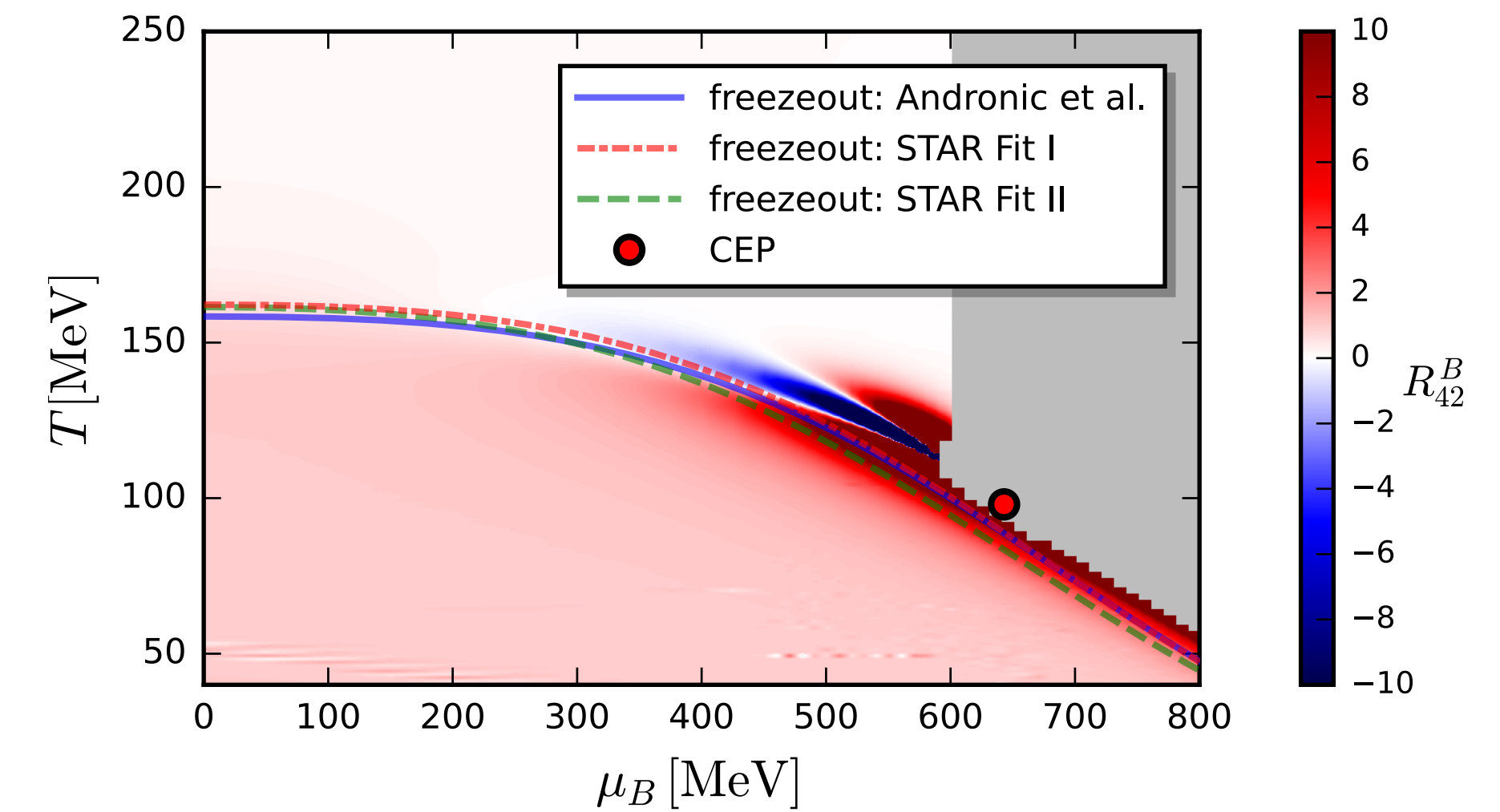
Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

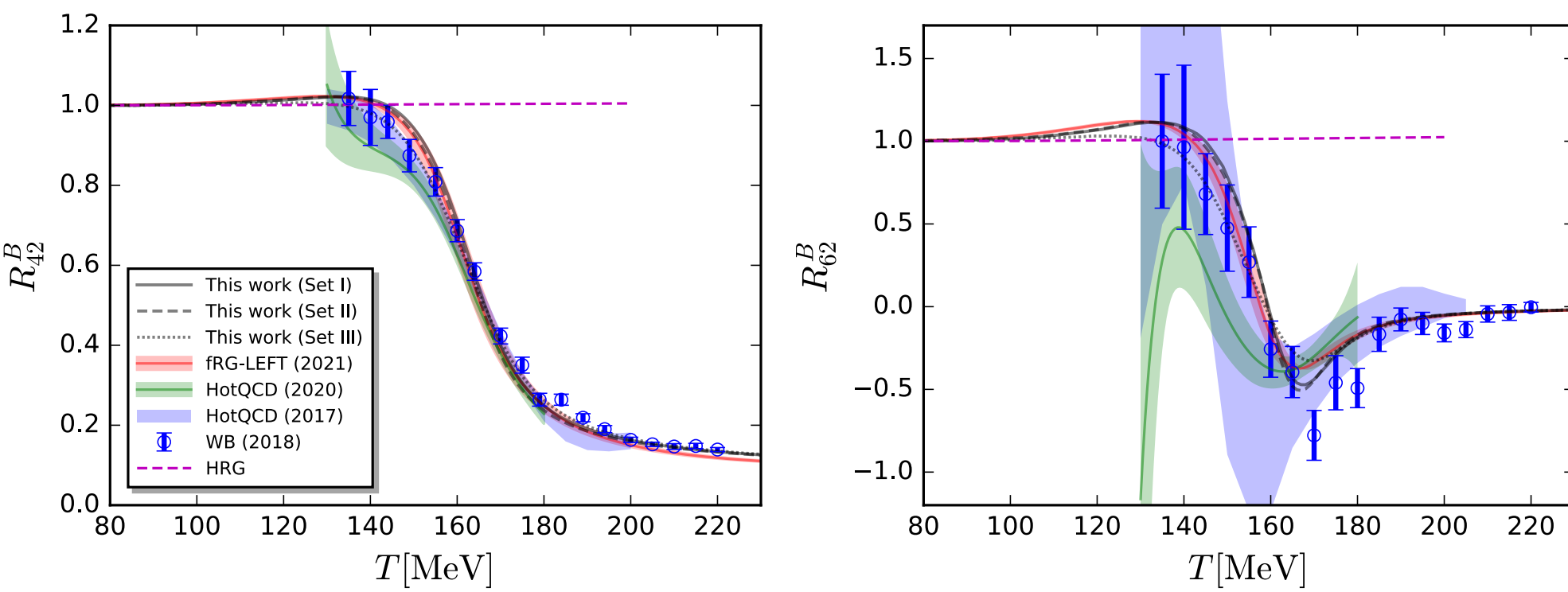
Ripples of the critical point from fluctuations of conserved charges



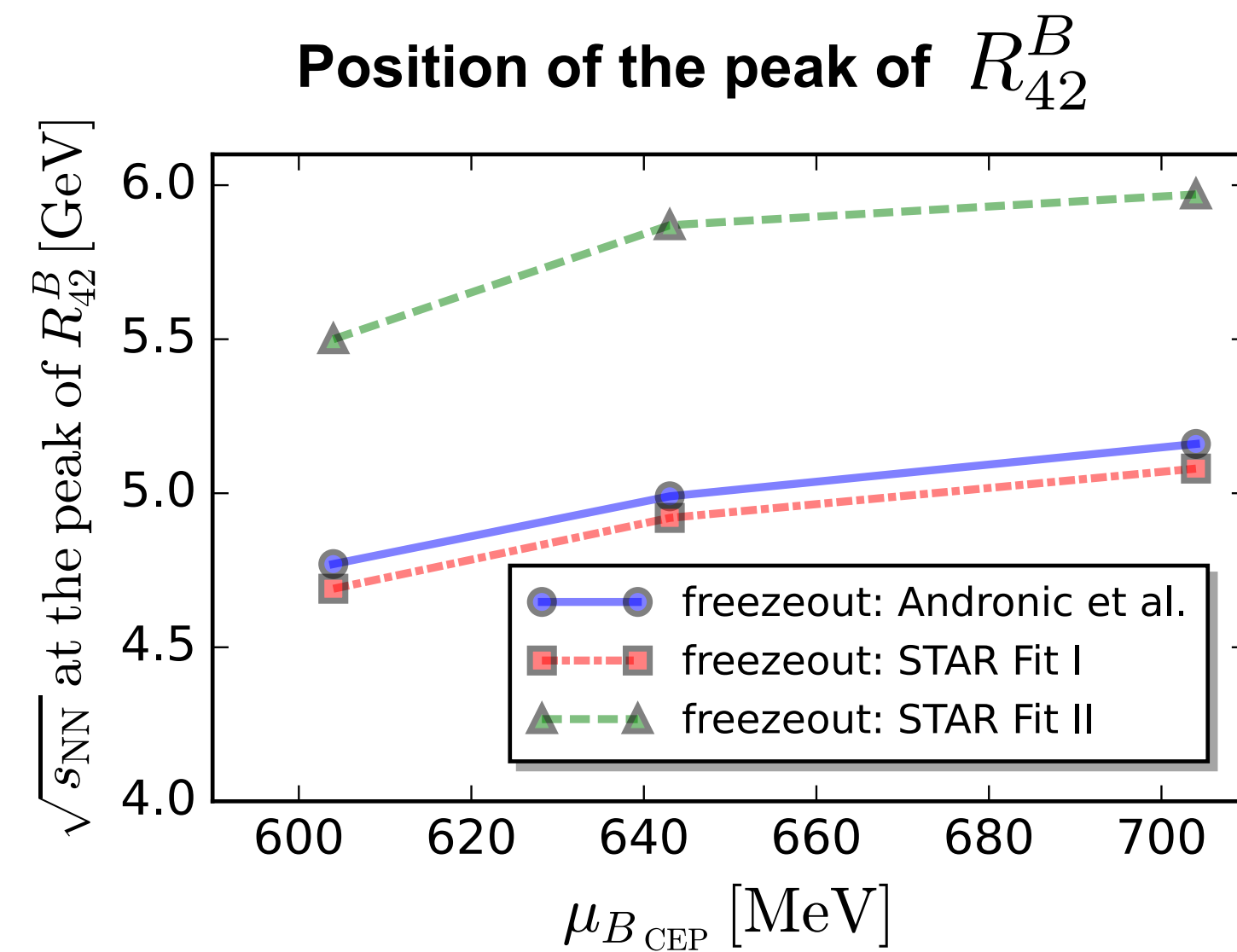
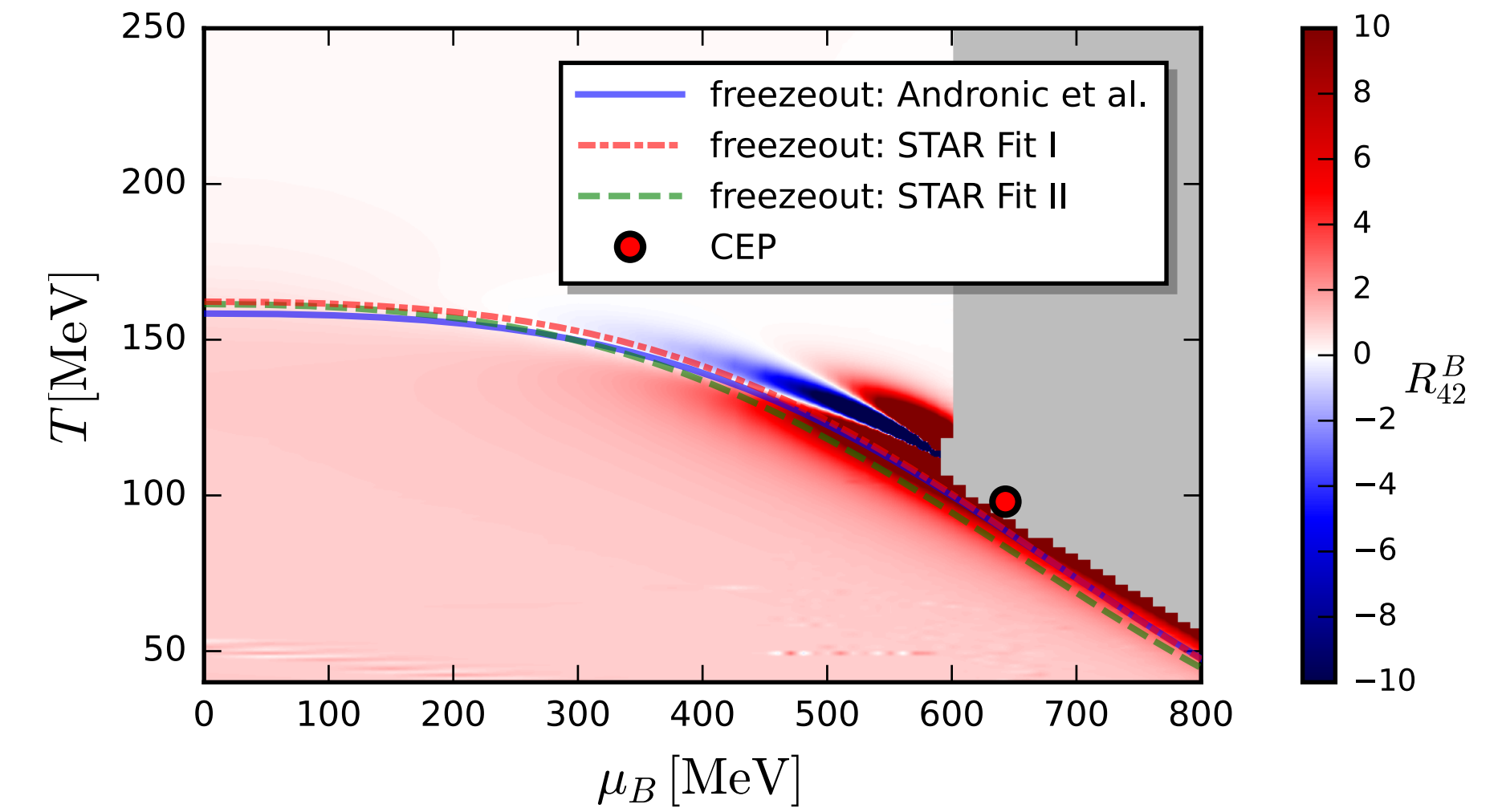
baryon number fluctuations



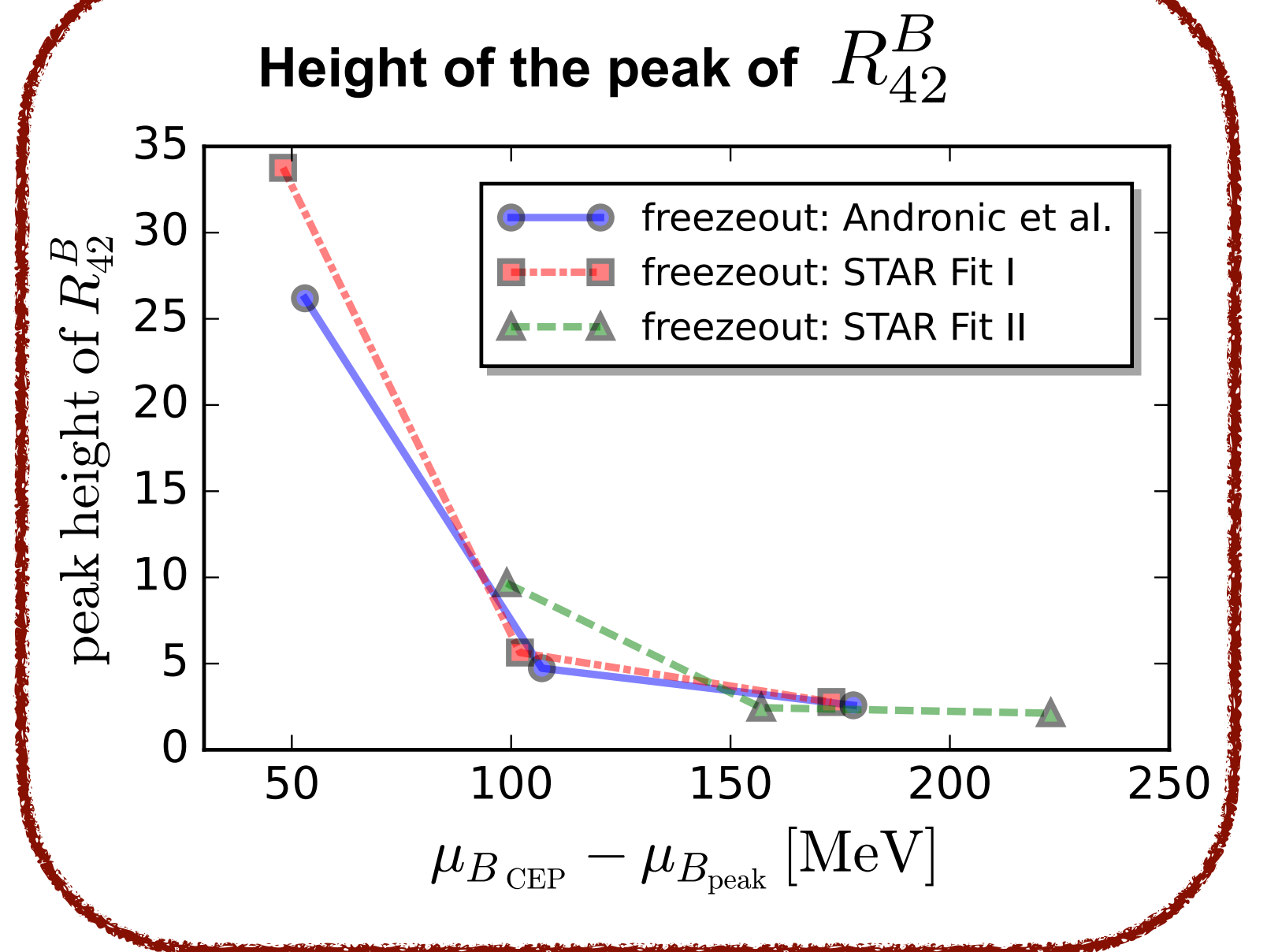
Ripples of the critical point from fluctuations of conserved charges



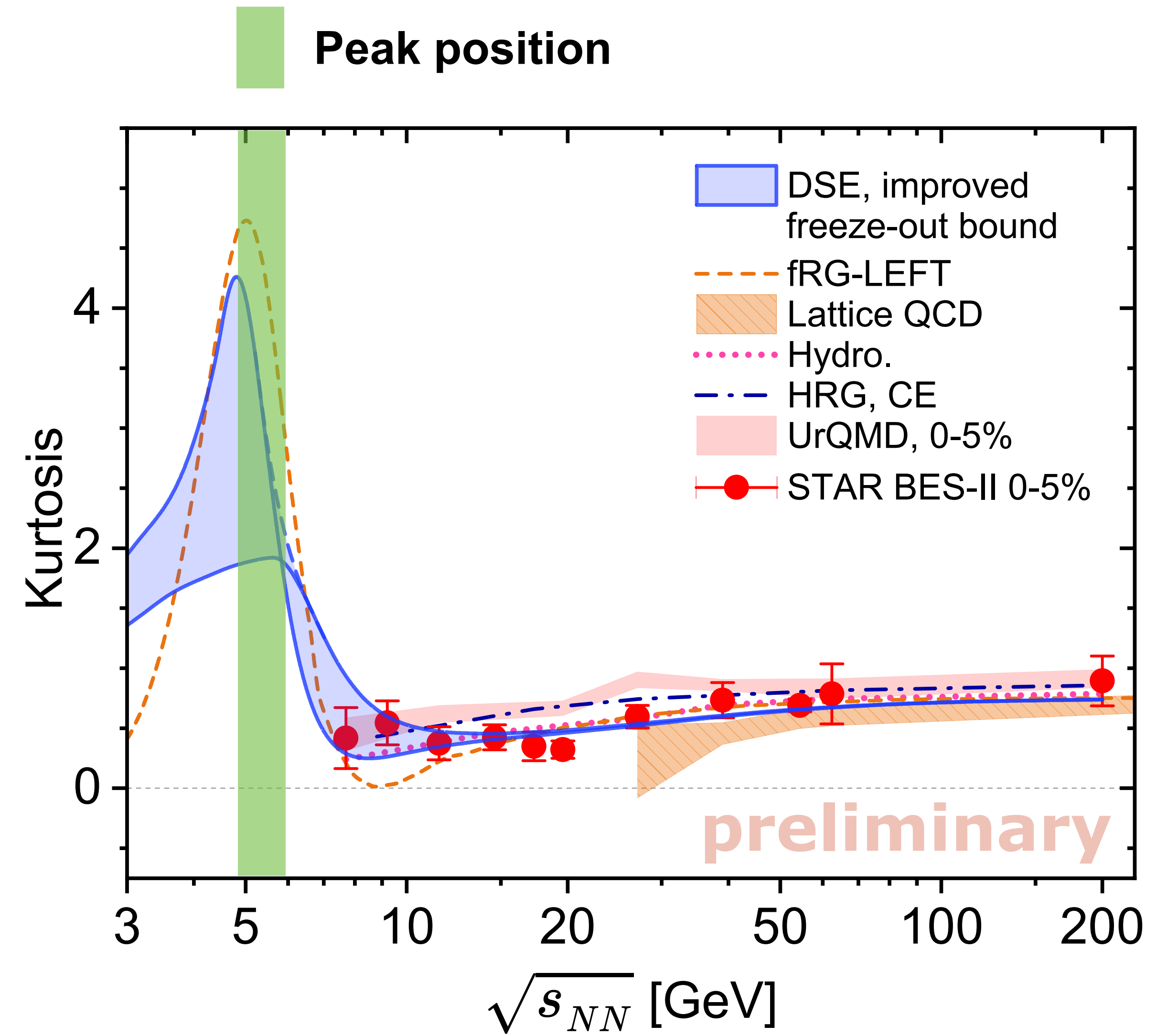
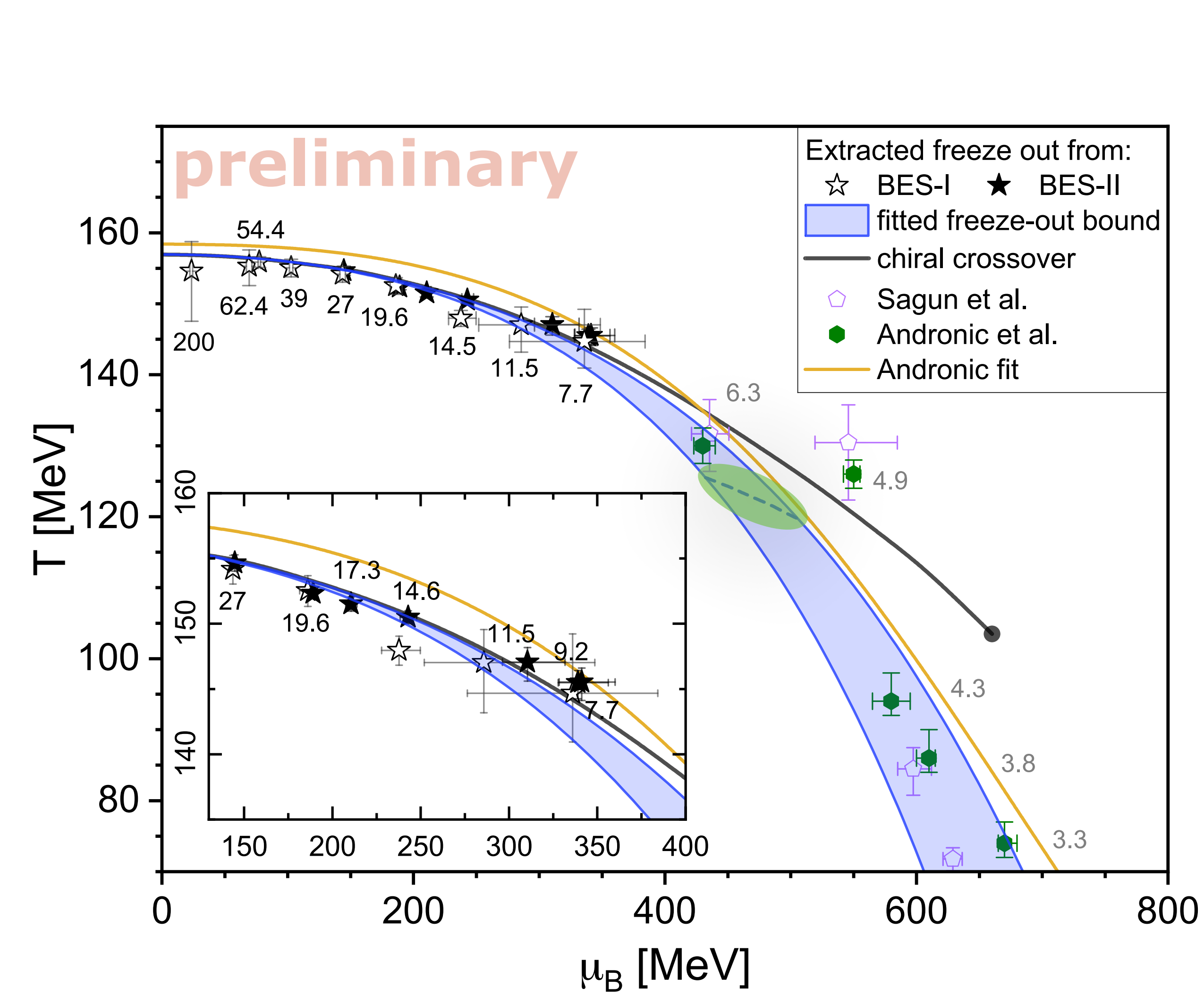
baryon number fluctuations



Reconstructing the CEP



Ripples of the critical point at chemical freeze-out



Outlook

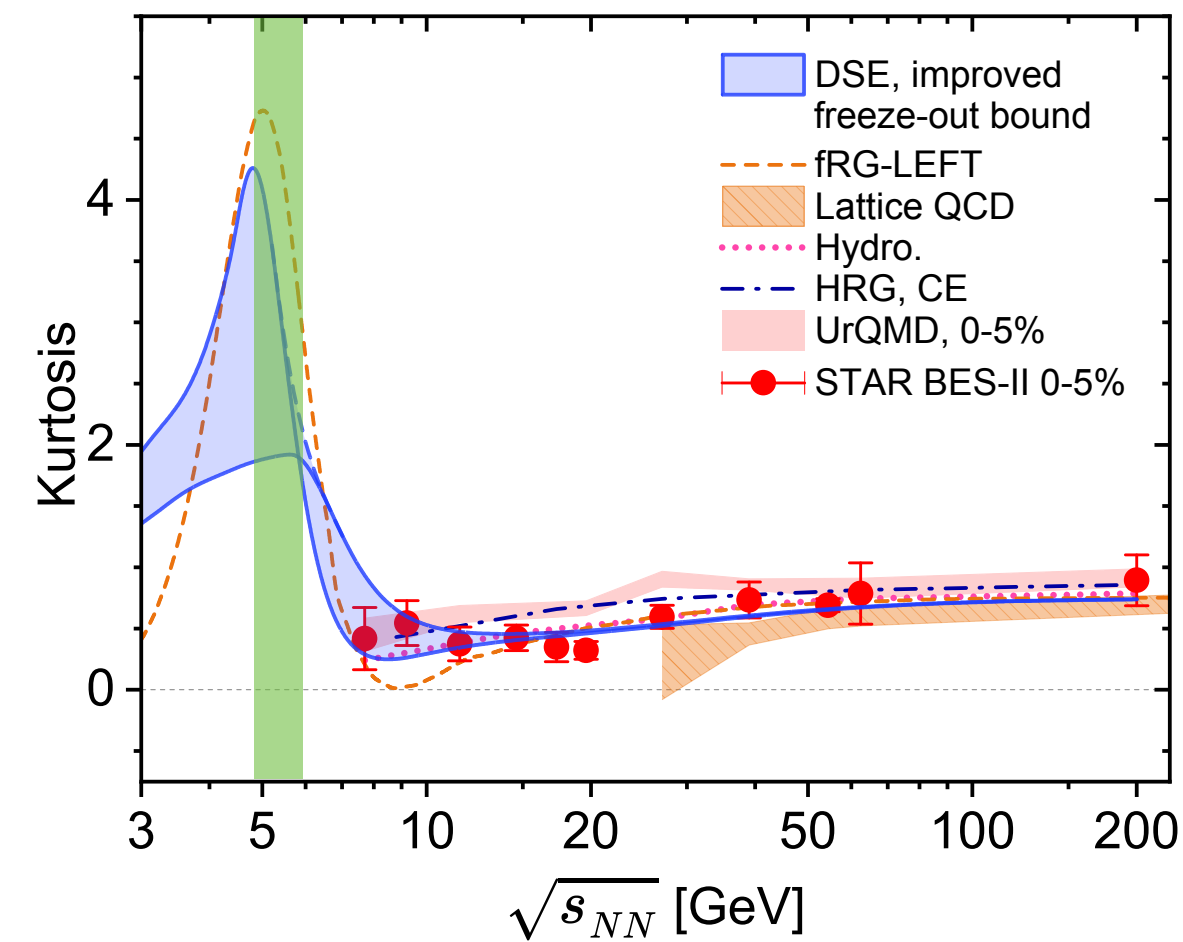
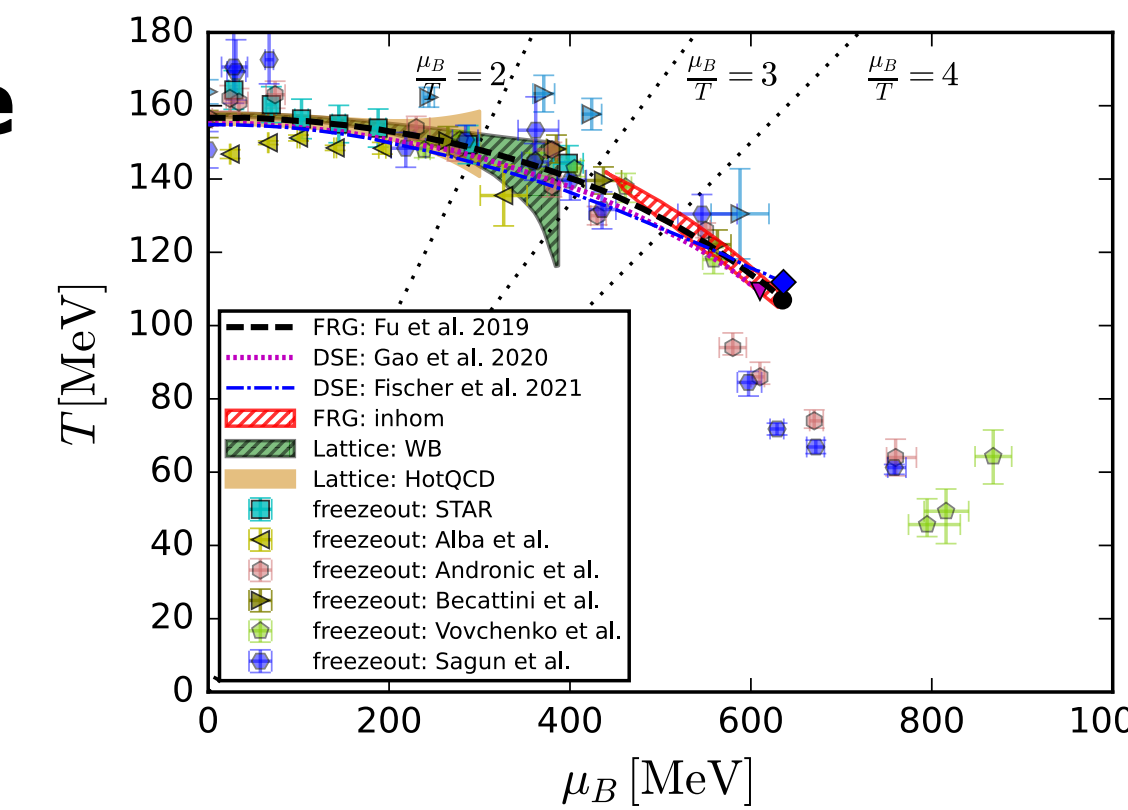
Unfolding the phase structure with QCD and freeze-out data



Fu, Lu, Gao, JMP, Rennecke, Wen, Xu, in progress

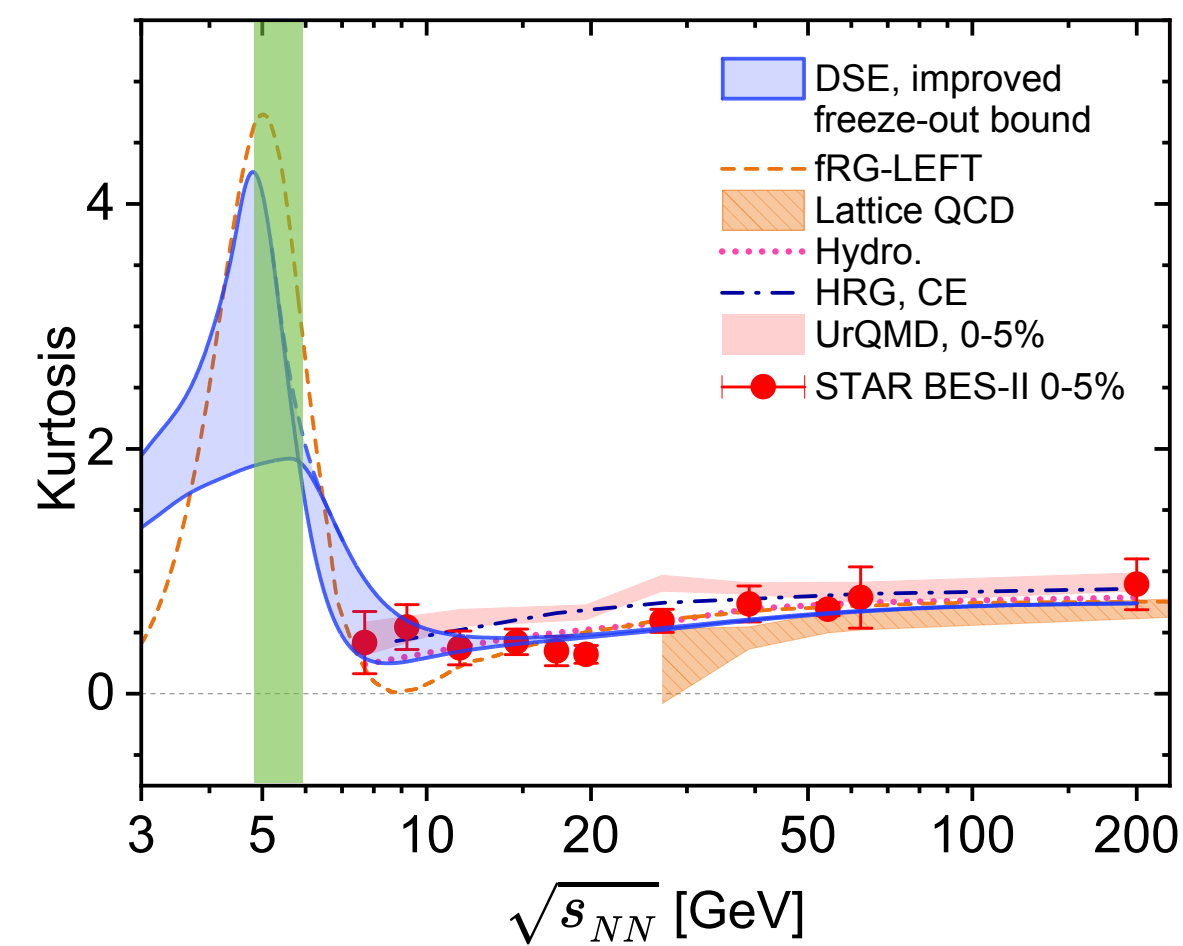
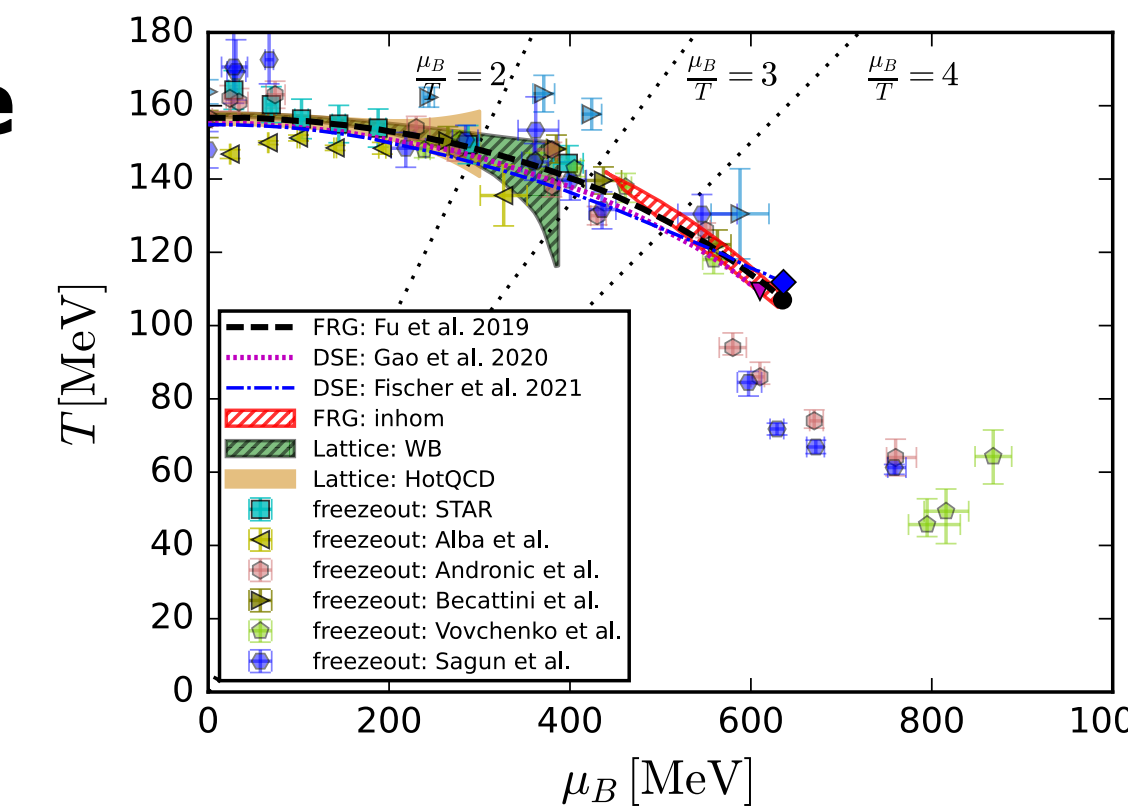
Outlook

- 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



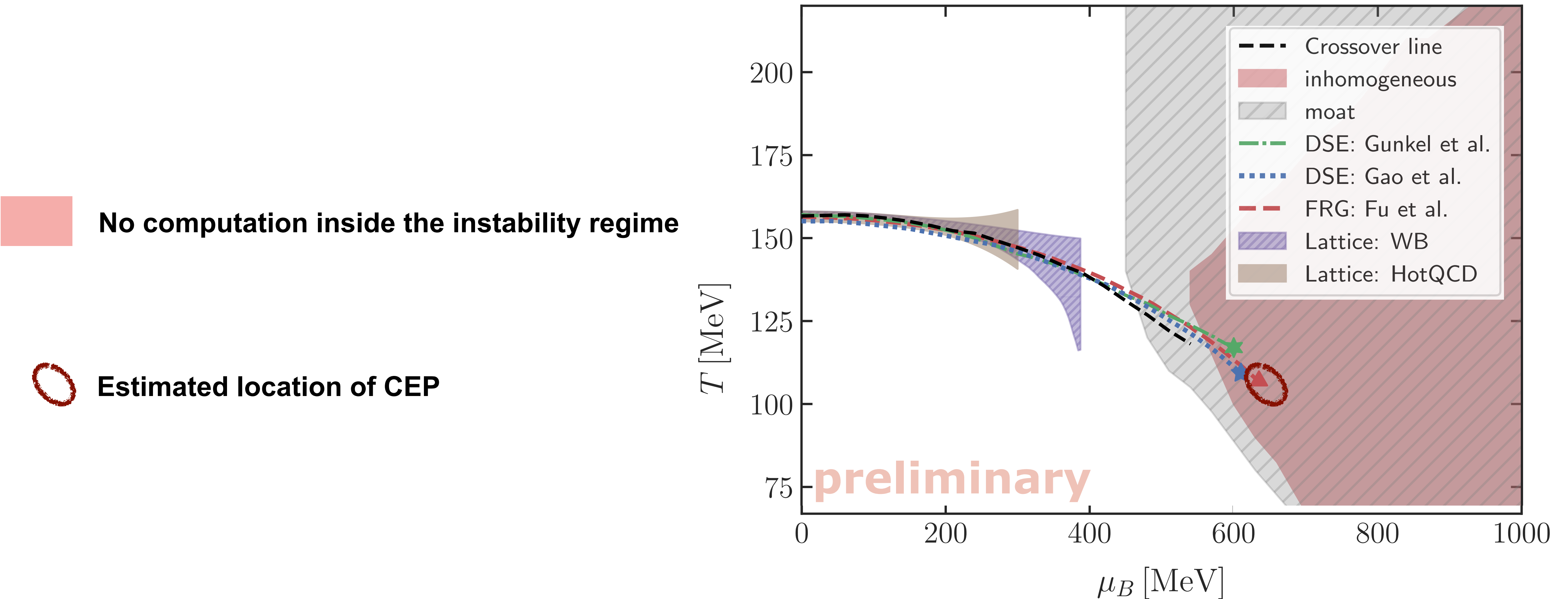
Outlook

- QCD: why and how? **The cool stuff!**
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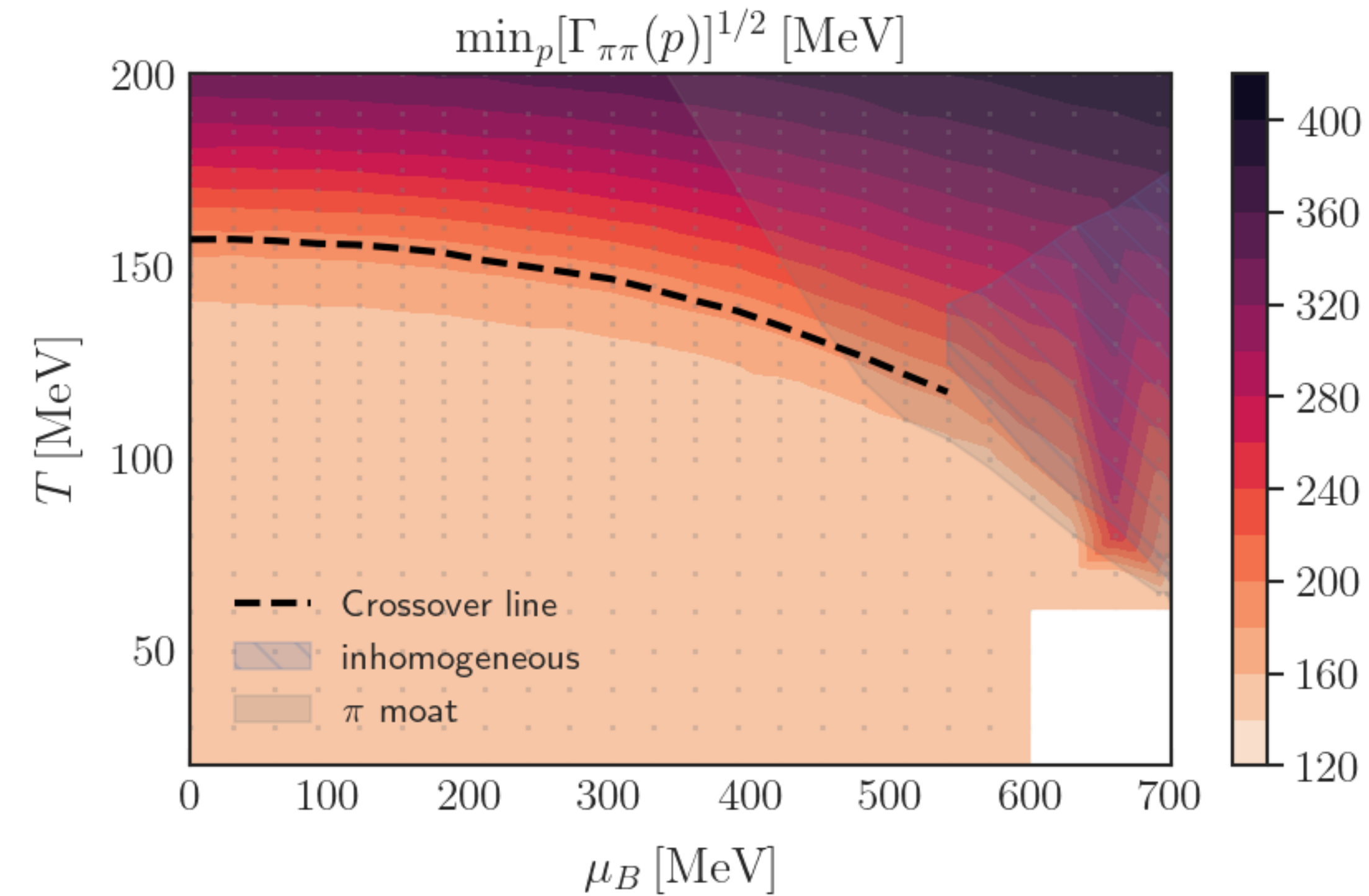
The QCD Moat reloaded

resolution of the moat regime

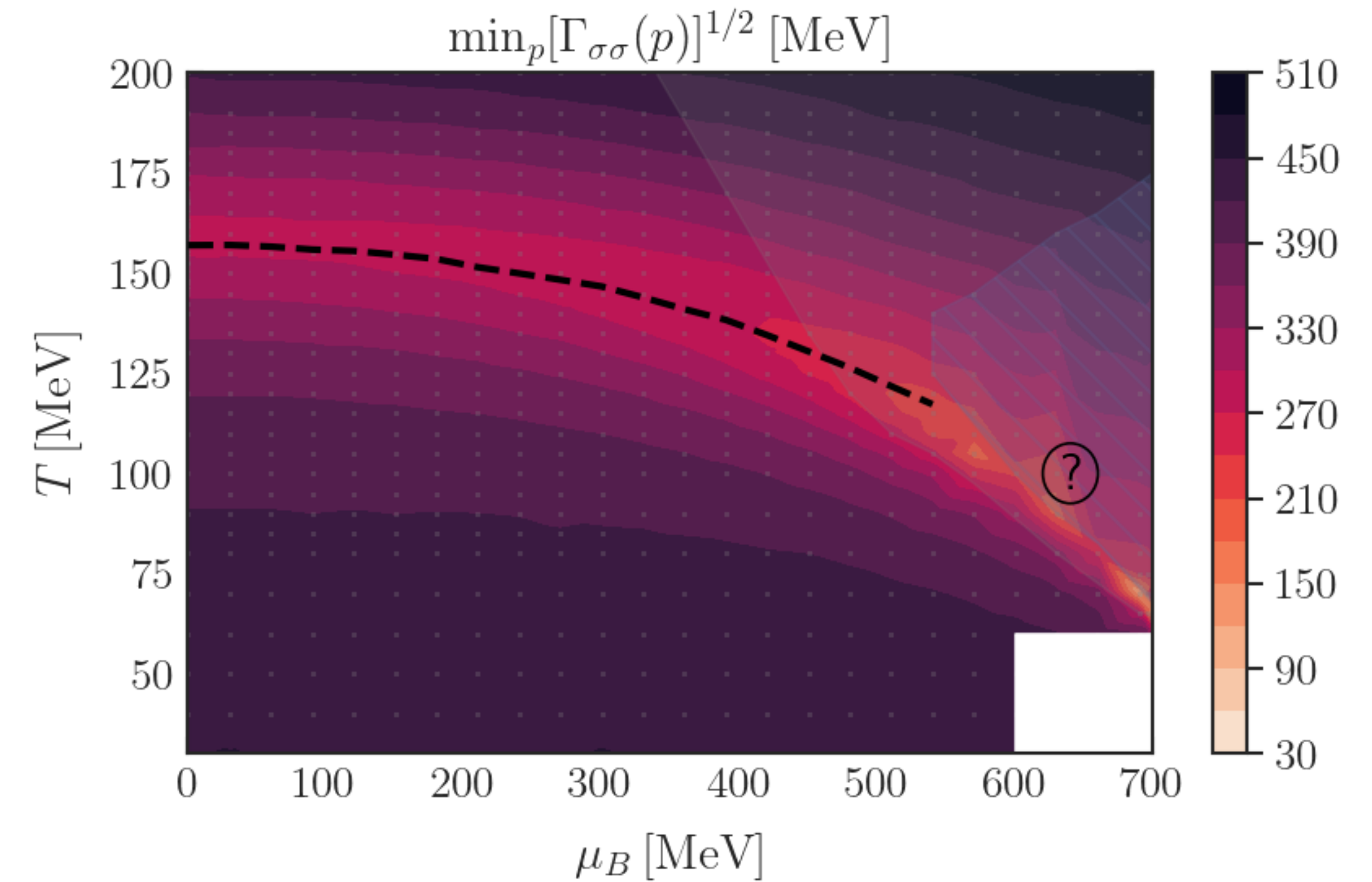


The QCD Moat

Pion ‘minimum’ mass



Scalar mode ‘minimum’ mass



preliminary