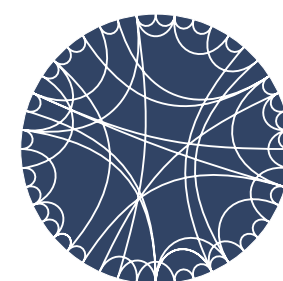
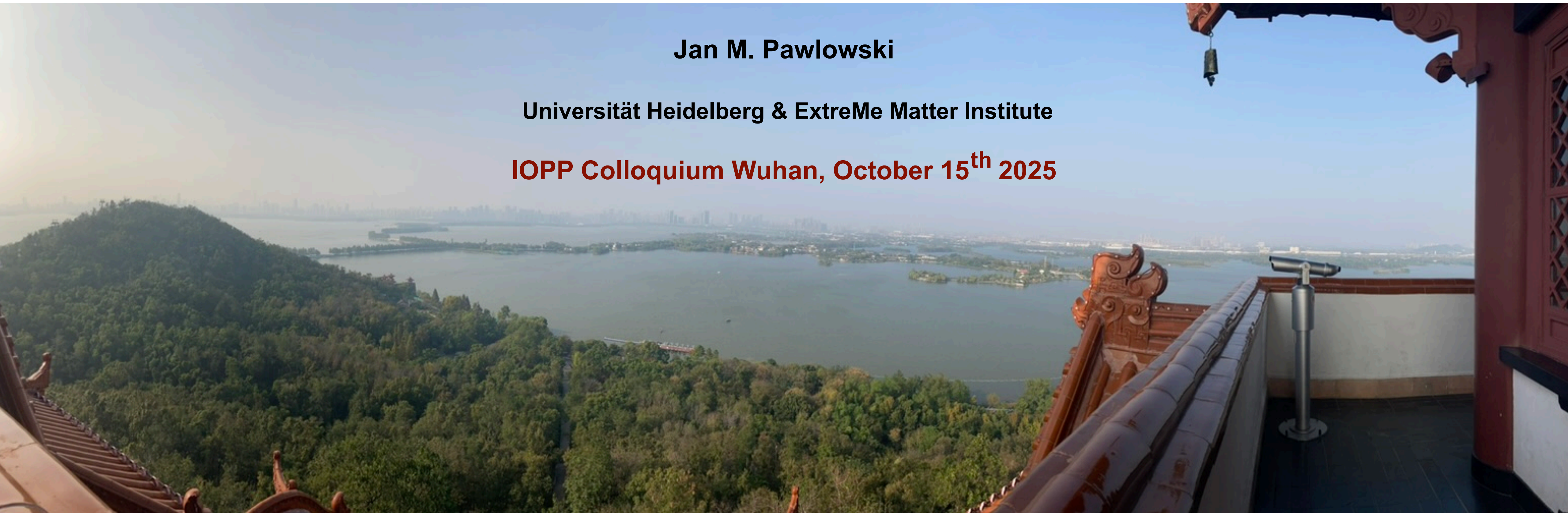


# QCD under extreme conditions

Jan M. Pawlowski

Universität Heidelberg & ExtreMe Matter Institute

IOPP Colloquium Wuhan, October 15<sup>th</sup> 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**



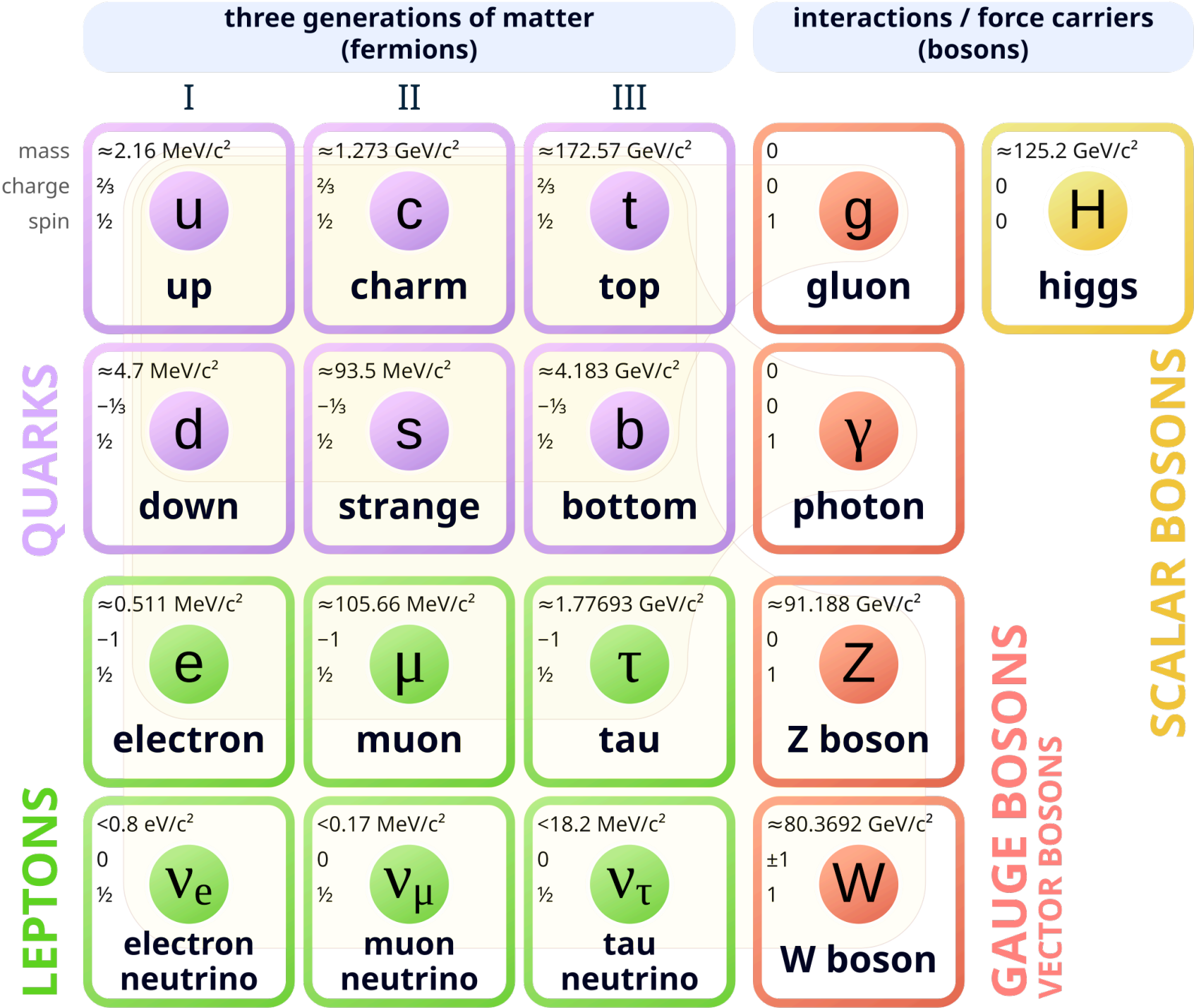
# QCD: why and how?

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

*Fermi*



Standard Model of Elementary Particles



QCD

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

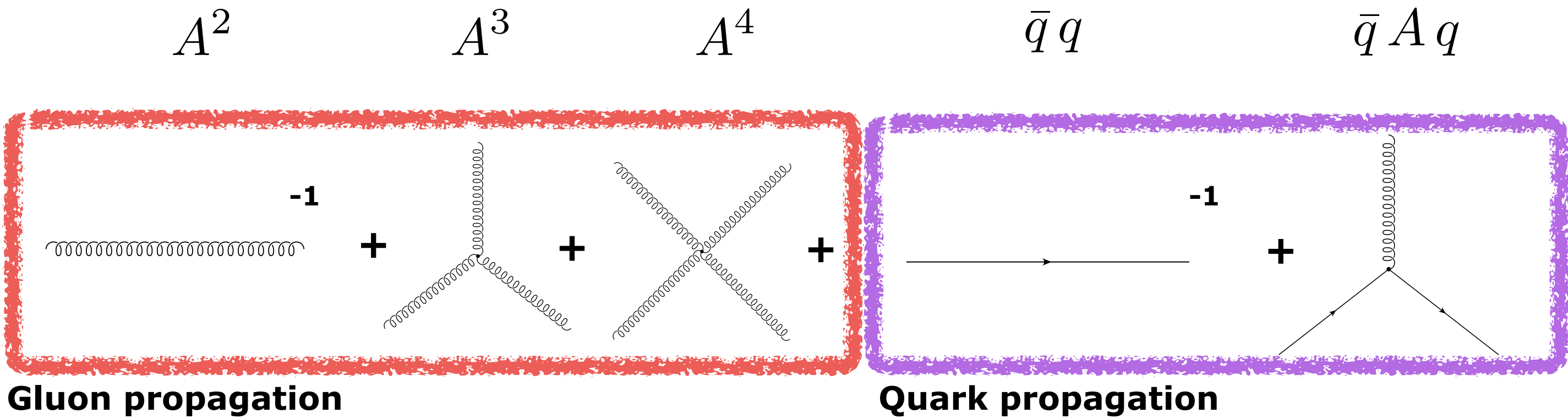
Standard Model of Elementary Particles

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



# QCD

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



Gluon self-interaction

Quark-gluon interaction

## Standard Model of Elementary Particles

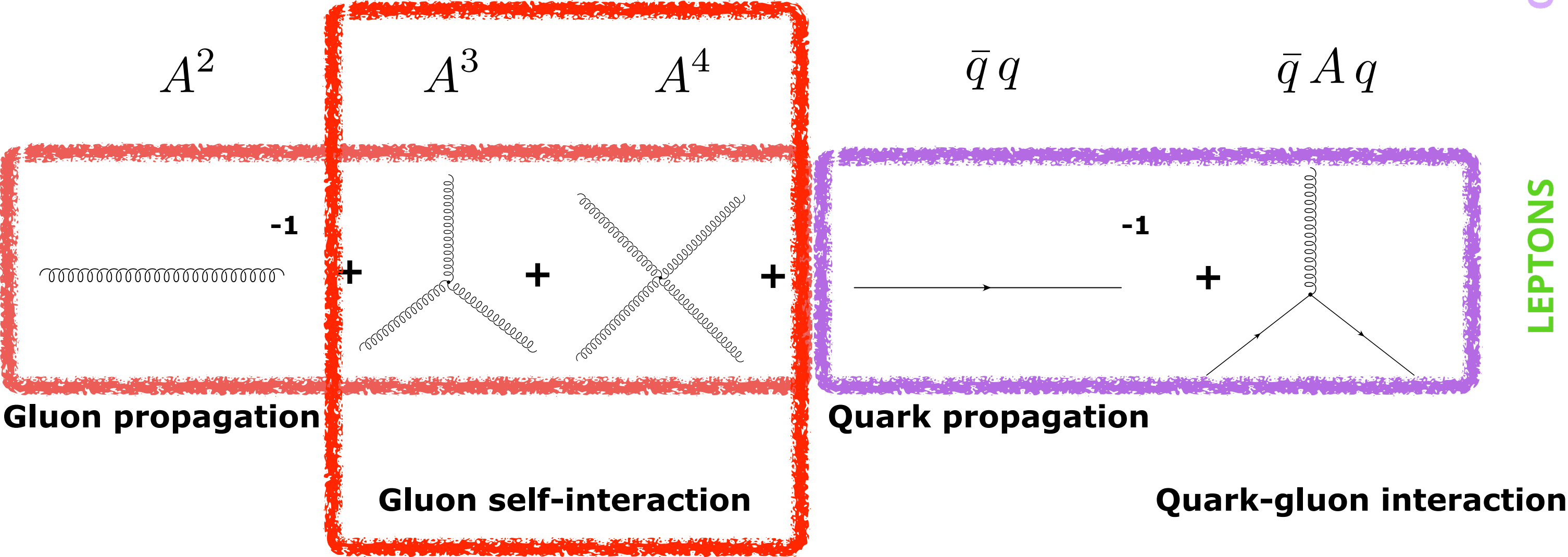
| three generations of matter (fermions) |                                                                  |                                                                   |                                                                    |     |  | interactions / force carriers (bosons) |    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

SCALAR BOSONS

GAUGE BOSONS  
VECTOR BOSONS

# QCD

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



Singles out QCD (no strong Higgs)

## Standard Model of Elementary Particles

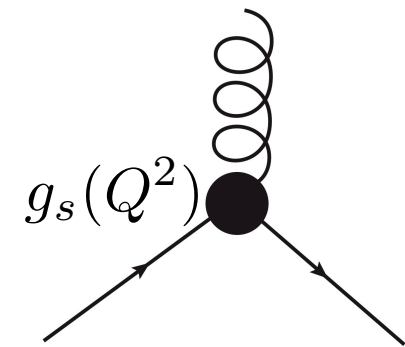
| three generations of matter (fermions)                                                                                                                                        |                                                                                                                                                            |                                                                                                                                                            | interactions / force carriers (bosons)                                                                                            |                                                                                                                           |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| I                                                                                                                                                                             | II                                                                                                                                                         | III                                                                                                                                                        |                                                                                                                                   |                                                                                                                           |
| <div>mass<br/>charge<br/>spin</div> <div><math>\approx 2.16 \text{ MeV}/c^2</math><br/><math>\frac{2}{3}</math><br/><math>\frac{1}{2}</math></div> <div><b>u</b><br/>up</div> | <div><math>\approx 1.273 \text{ GeV}/c^2</math><br/><math>\frac{2}{3}</math><br/><math>\frac{1}{2}</math></div> <div><b>c</b><br/>charm</div>              | <div><math>\approx 172.57 \text{ GeV}/c^2</math><br/><math>\frac{2}{3}</math><br/><math>\frac{1}{2}</math></div> <div><b>t</b><br/>top</div>               | <div><math>0</math><br/><math>0</math><br/><math>1</math></div> <div><b>g</b><br/>gluon</div>                                     | <div><math>\approx 125.2 \text{ GeV}/c^2</math><br/><math>0</math><br/><math>0</math></div> <div><b>H</b><br/>higgs</div> |
| <div><math>\approx 4.7 \text{ MeV}/c^2</math><br/><math>-\frac{1}{3}</math><br/><math>\frac{1}{2}</math></div> <div><b>d</b><br/>down</div>                                   | <div><math>\approx 93.5 \text{ MeV}/c^2</math><br/><math>-\frac{1}{3}</math><br/><math>\frac{1}{2}</math></div> <div><b>s</b><br/>strange</div>            | <div><math>\approx 4.183 \text{ GeV}/c^2</math><br/><math>-\frac{1}{3}</math><br/><math>\frac{1}{2}</math></div> <div><b>b</b><br/>bottom</div>            | <div><math>0</math><br/><math>0</math><br/><math>1</math></div> <div><b><math>\gamma</math></b><br/>photon</div>                  | <div>GAUGE BOSONS<br/>VECTOR BOSONS</div>                                                                                 |
| <div><math>\approx 0.511 \text{ MeV}/c^2</math><br/><math>-1</math><br/><math>\frac{1}{2}</math></div> <div><b>e</b><br/>electron</div>                                       | <div><math>\approx 105.66 \text{ MeV}/c^2</math><br/><math>-1</math><br/><math>\frac{1}{2}</math></div> <div><b><math>\mu</math></b><br/>muon</div>        | <div><math>\approx 1.77693 \text{ GeV}/c^2</math><br/><math>-1</math><br/><math>\frac{1}{2}</math></div> <div><b><math>\tau</math></b><br/>tau</div>       | <div><math>\approx 91.188 \text{ GeV}/c^2</math><br/><math>0</math><br/><math>1</math></div> <div><b>Z</b><br/>Z boson</div>      |                                                                                                                           |
| <div><math>&lt; 0.8 \text{ eV}/c^2</math><br/><math>0</math><br/><math>\frac{1}{2}</math></div> <div><b><math>\nu_e</math></b><br/>electron neutrino</div>                    | <div><math>&lt; 0.17 \text{ MeV}/c^2</math><br/><math>0</math><br/><math>\frac{1}{2}</math></div> <div><b><math>\nu_\mu</math></b><br/>muon neutrino</div> | <div><math>&lt; 18.2 \text{ MeV}/c^2</math><br/><math>0</math><br/><math>\frac{1}{2}</math></div> <div><b><math>\nu_\tau</math></b><br/>tau neutrino</div> | <div><math>\approx 80.3692 \text{ GeV}/c^2</math><br/><math>\pm 1</math><br/><math>1</math></div> <div><b>W</b><br/>W boson</div> |                                                                                                                           |

SCALAR BOSONS

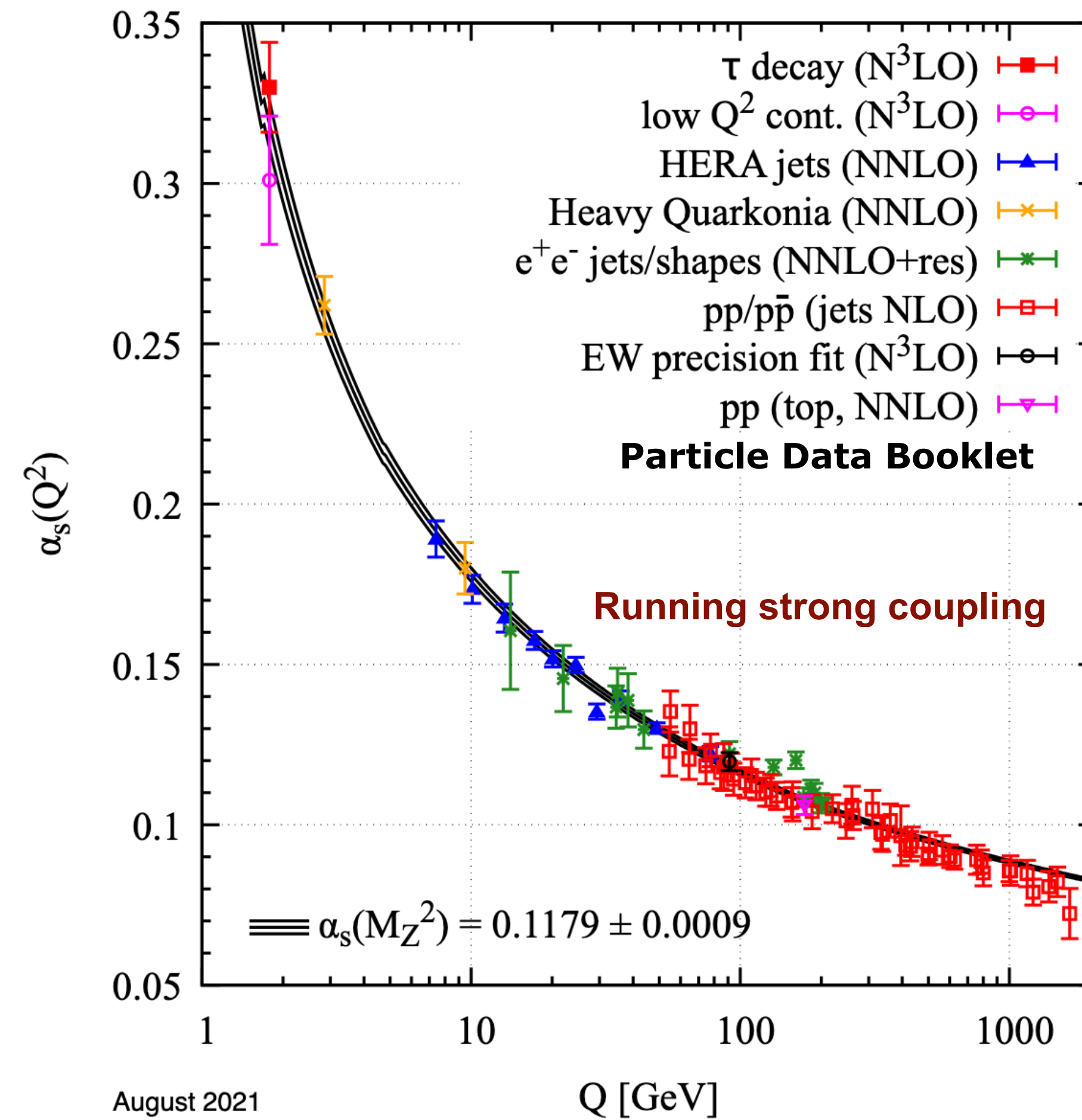
# What's hot in QCD?

Low Temperatures, densities

Large Temperatures, densities



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



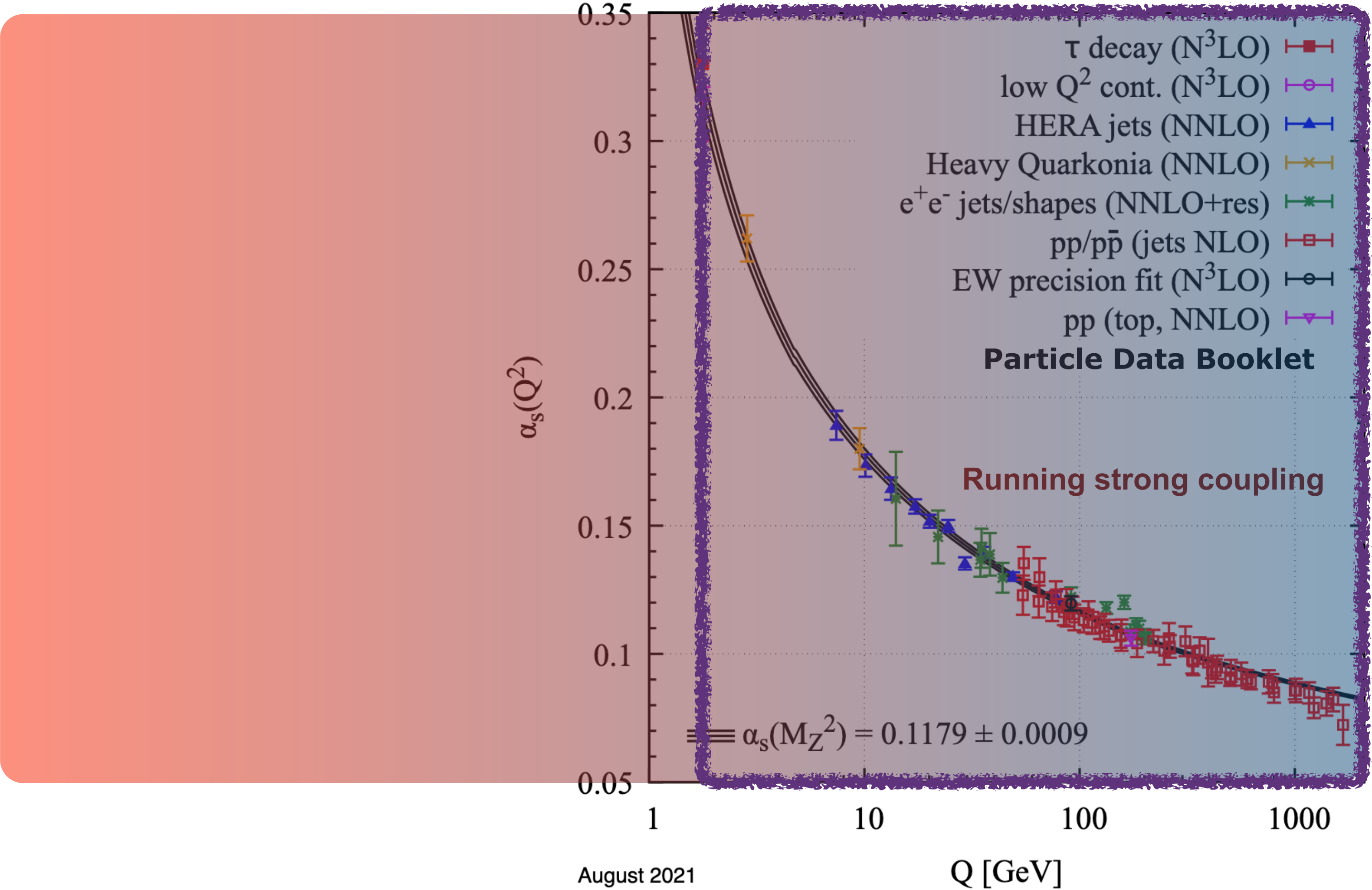
August 2021



# 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

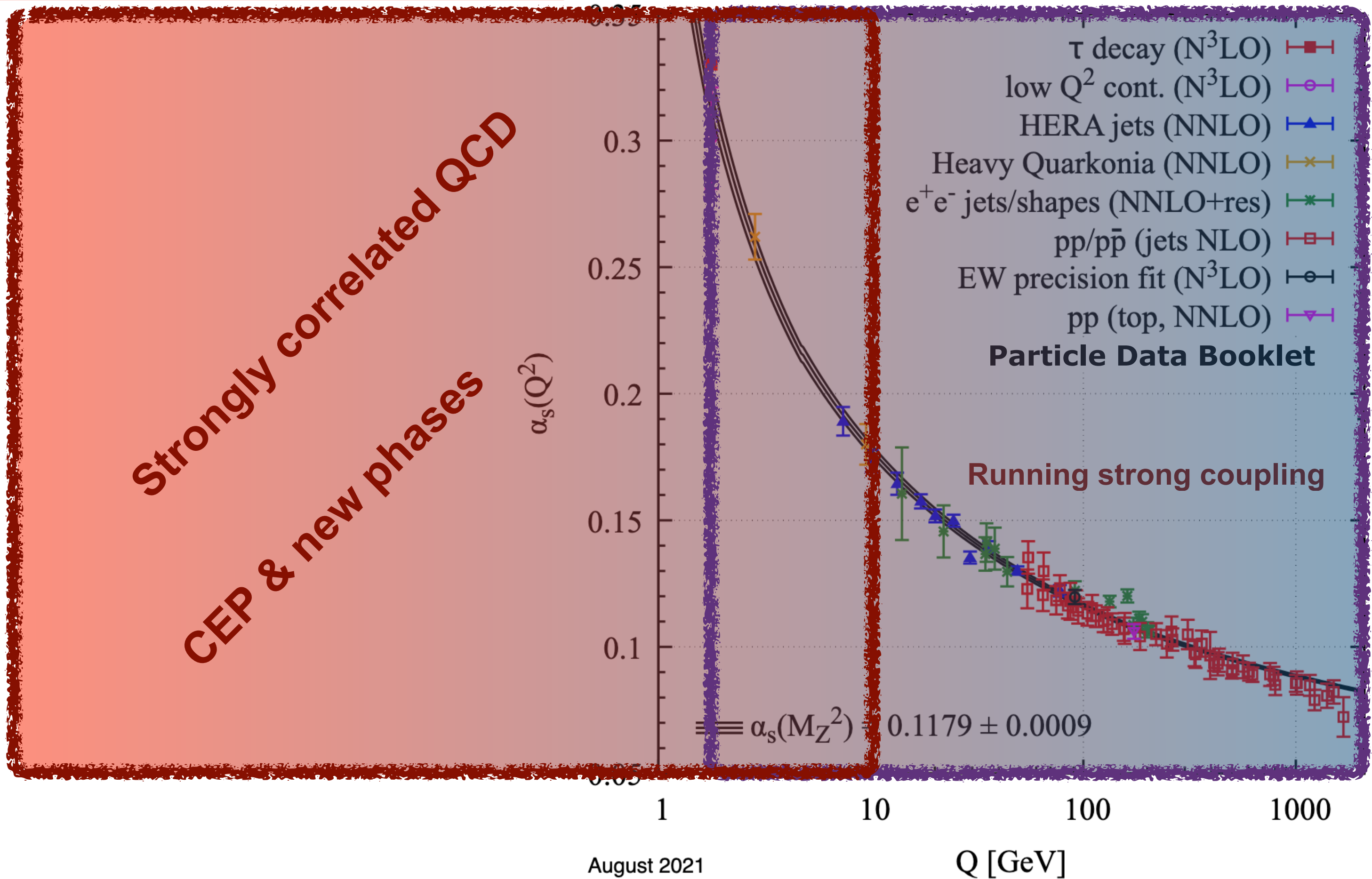
Asymptotic freedom  
Nobel Prize '04  
Gross, Politzer, Wilczek

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IR: confinement & chiral symmetry breaking



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⋮

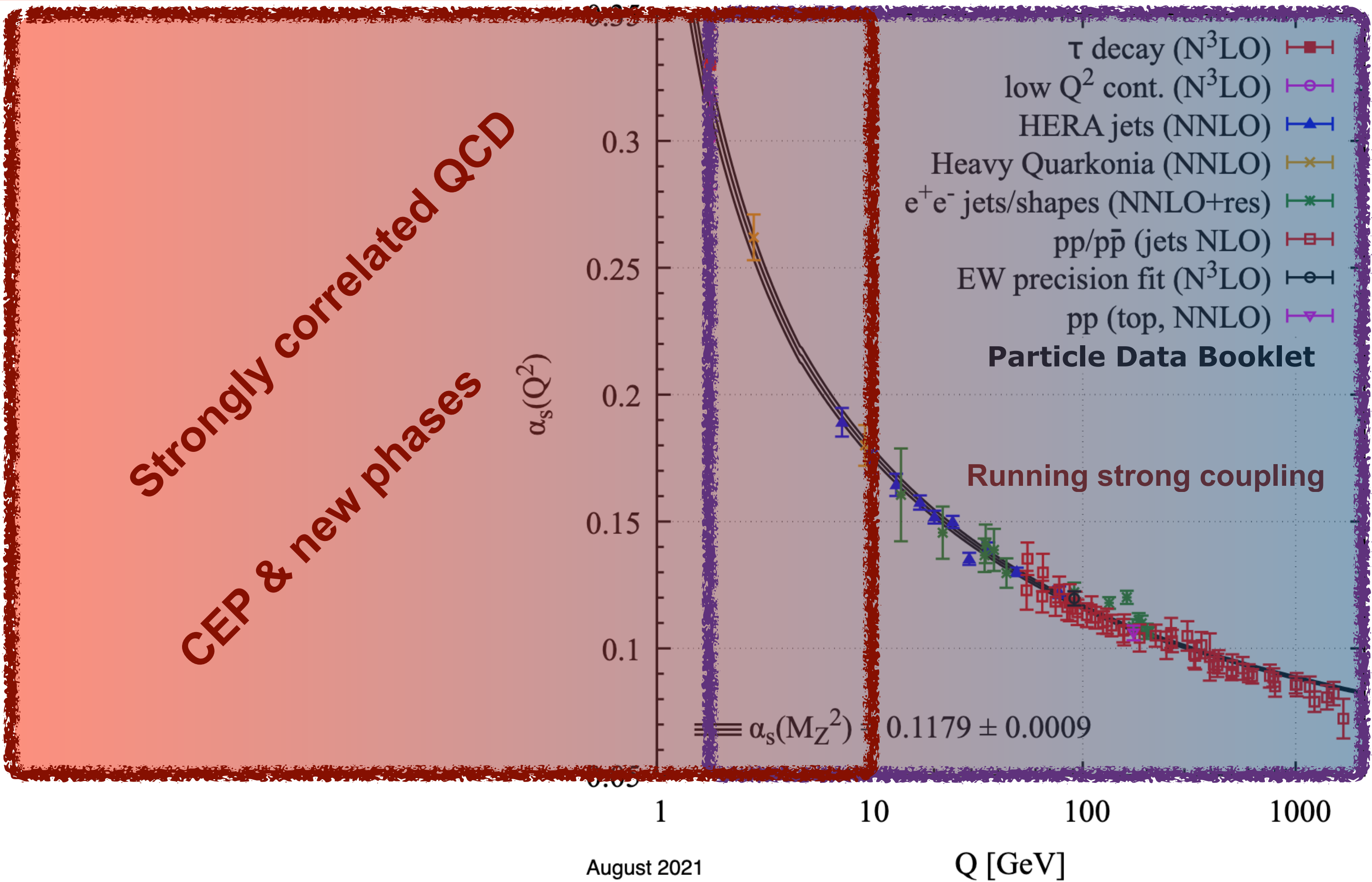
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deconvolution  
reconstruction

⋮

UV: weakly coupled quarks and gluons

Asymptotic freedom  
Nobel Prize '04  
Gross, Politzer, Wilczek



# 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....  
well, I have others

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



# Extrapolations & von Neumann's Elephant

Those are my interpretations,  
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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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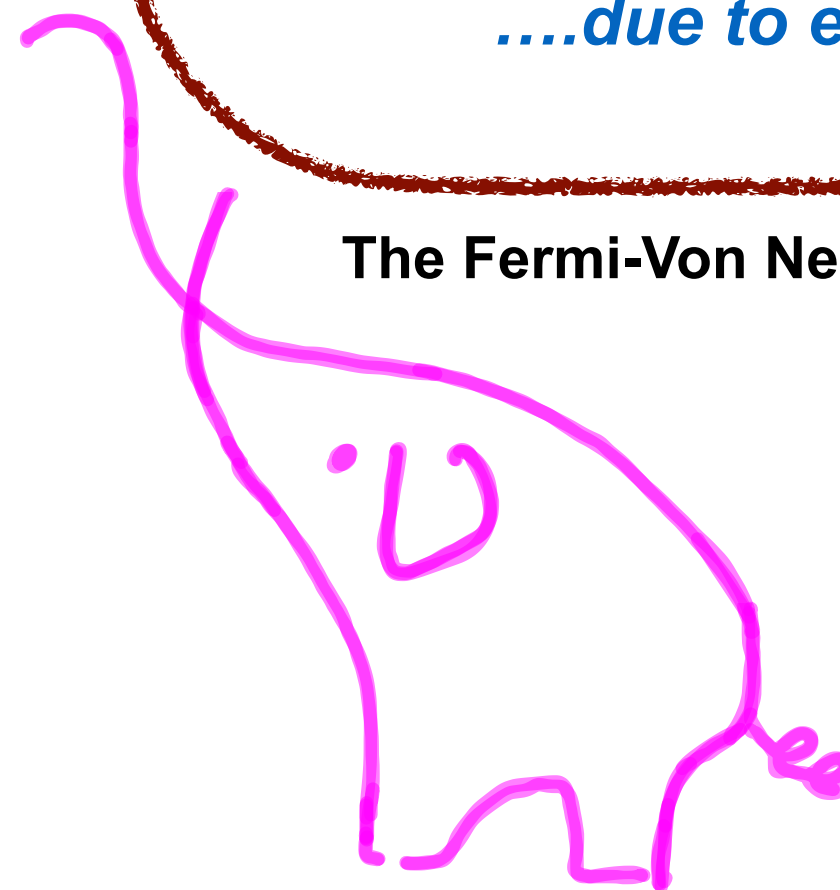
Von Neumann

*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





# Extrapolations & von Neumann's Elephant

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'... and now for something  
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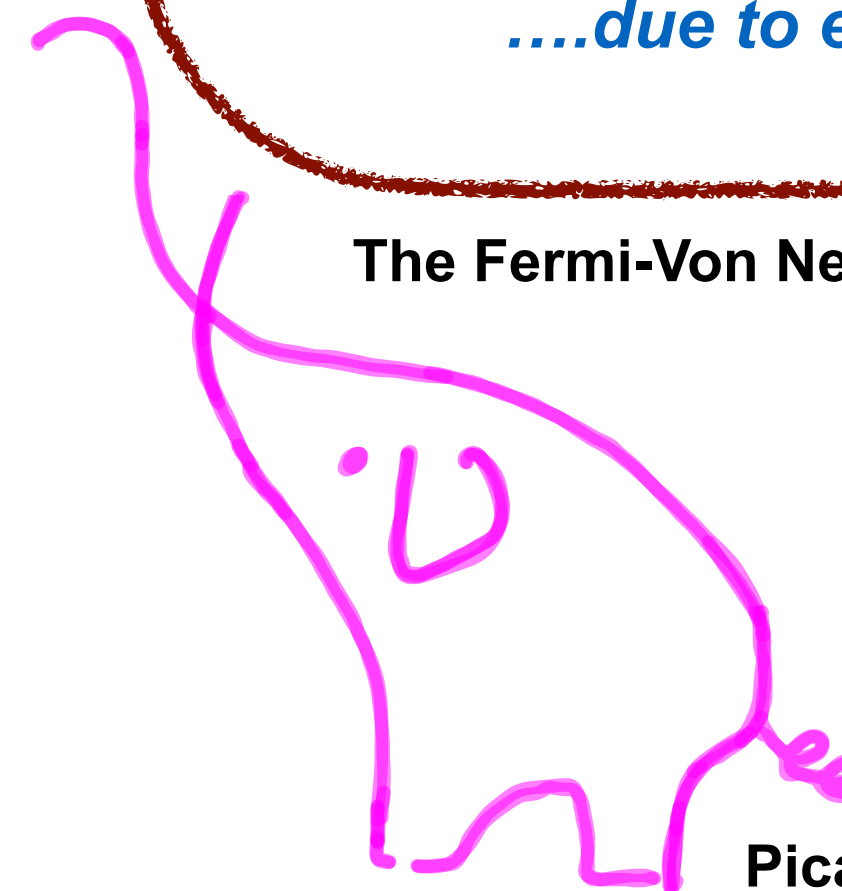
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Von Neumann

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 | $170\times 10^3$       |                |
| Quark      | u     | c         | t                      | $\frac{2}{3}$  |
| Quark      | d     | s         | b                      | $-\frac{1}{3}$ |
| Mass [MeV] | 4-8   | 80-130    | $(4.1-4.4)\times 10^3$ |                |



# Chiral symmetry breaking

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



up



down



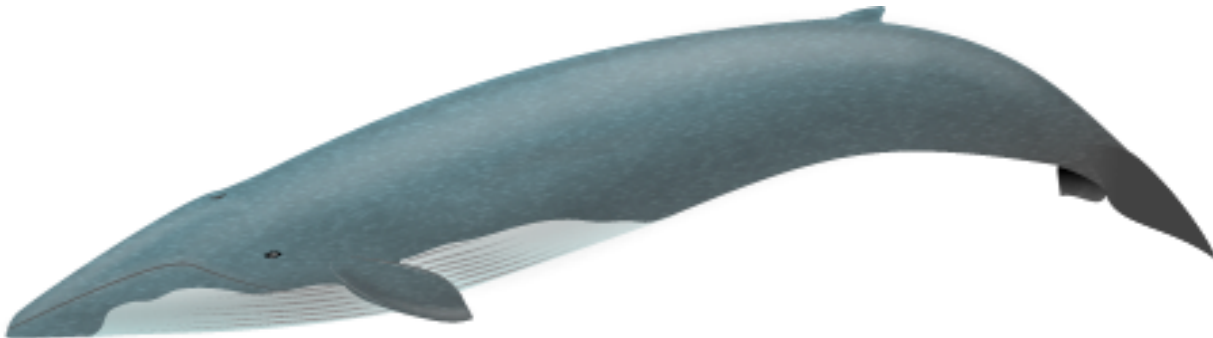
charm



strange



top



bottom



Current quark masses (Higgs)



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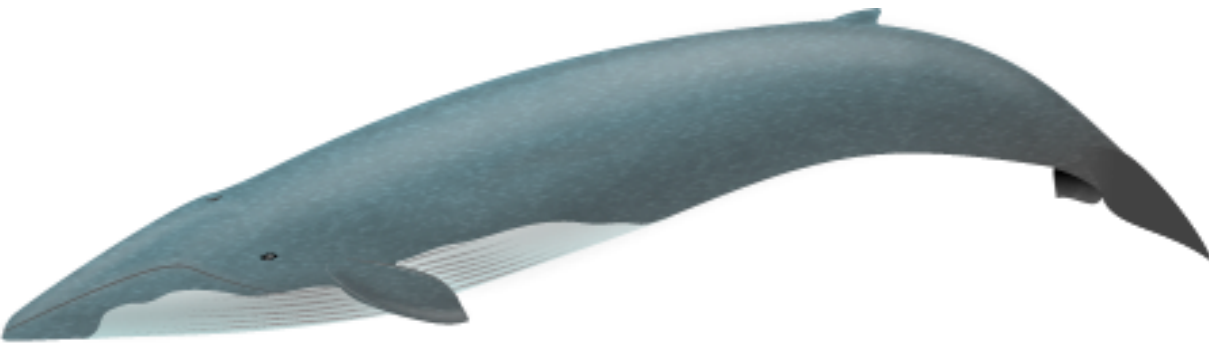
up



charm



top



down



strange



bottom



Current quark masses (Higgs)

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



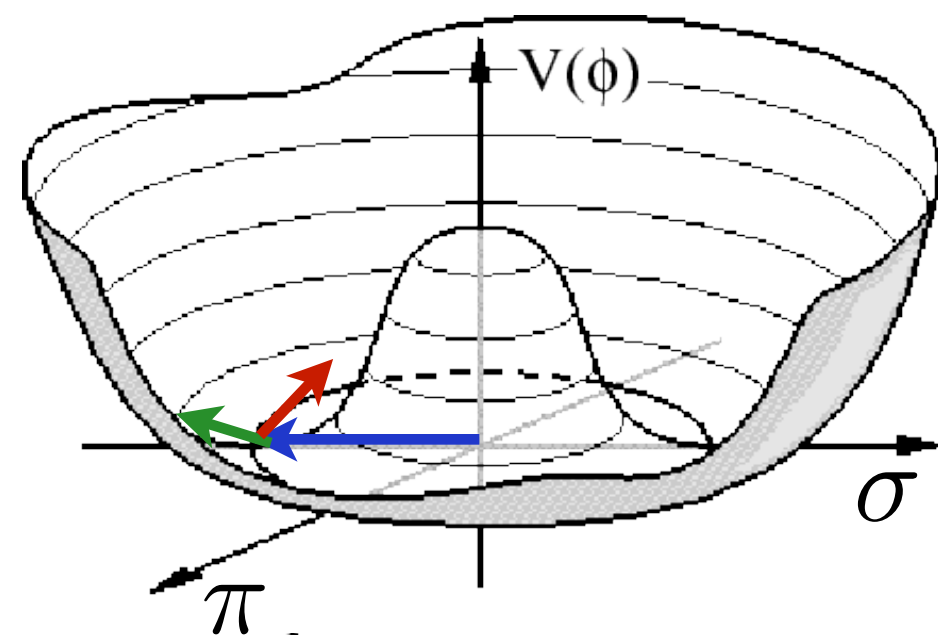
# Dynamical chiral symmetry breaking

## 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  $\sigma \neq 0$

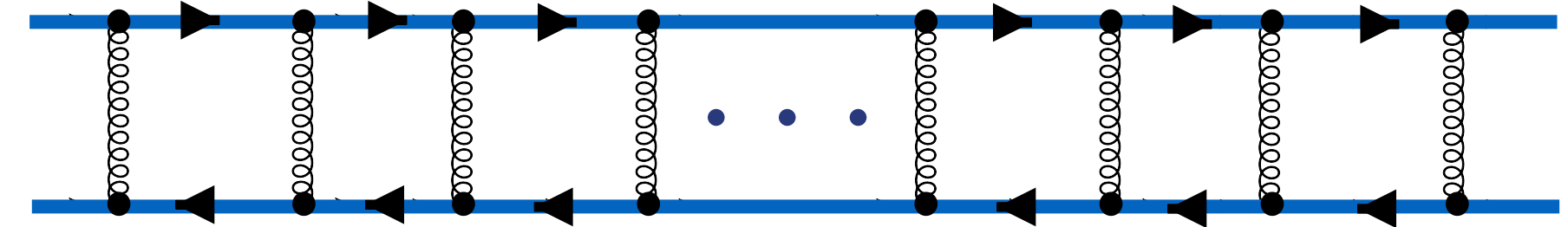
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## Order parameter

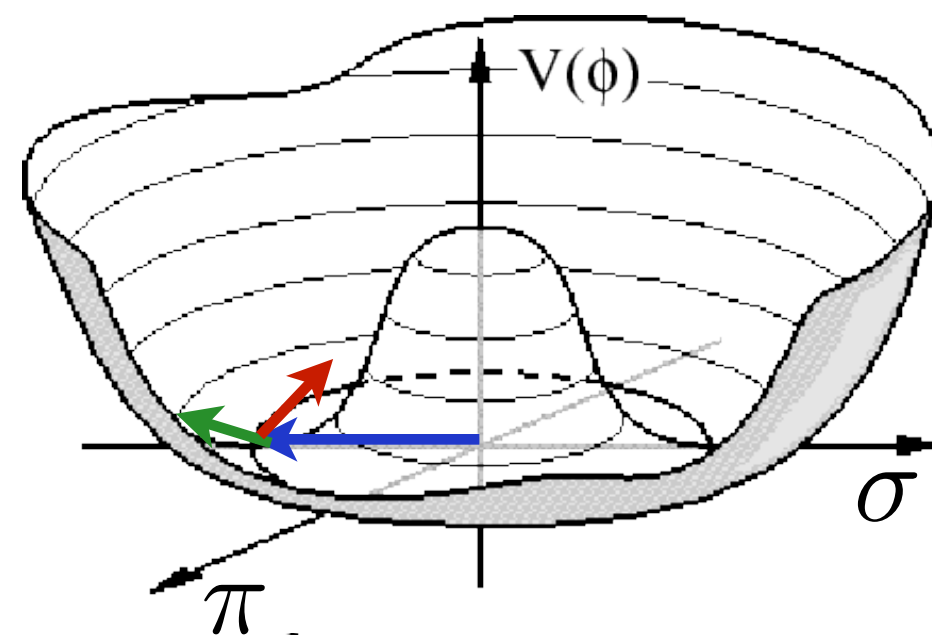
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## Dynamics



## Meson potential



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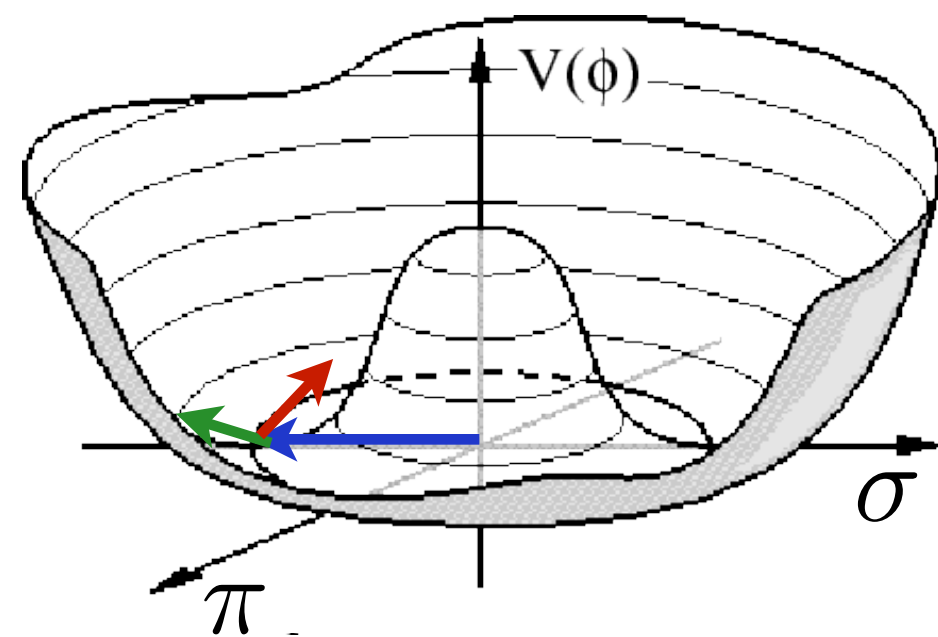
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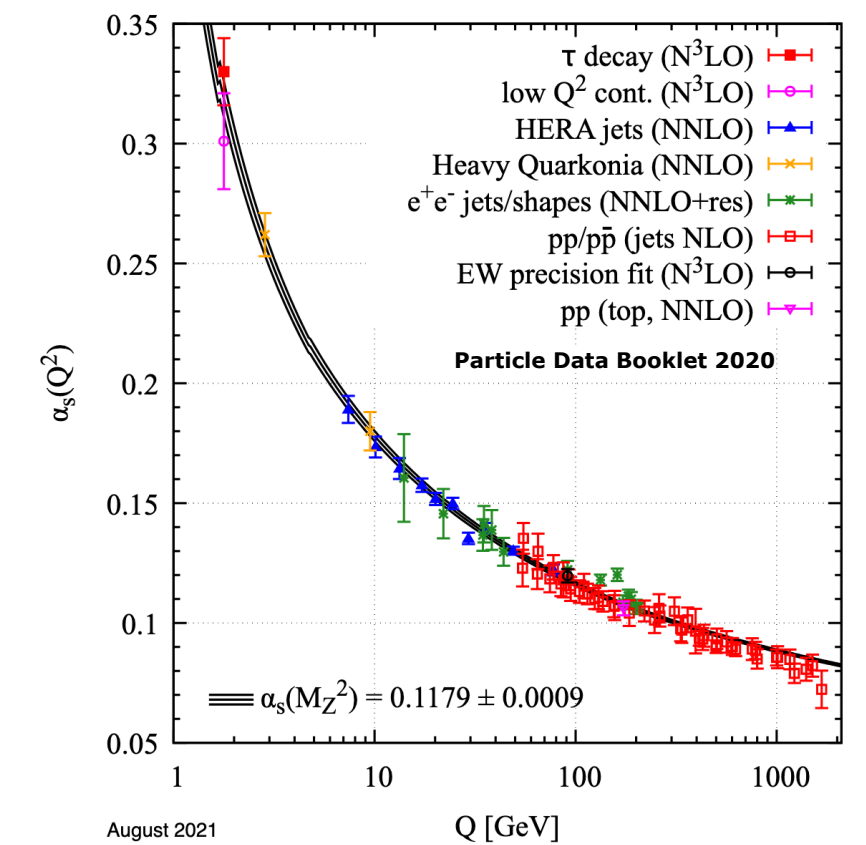
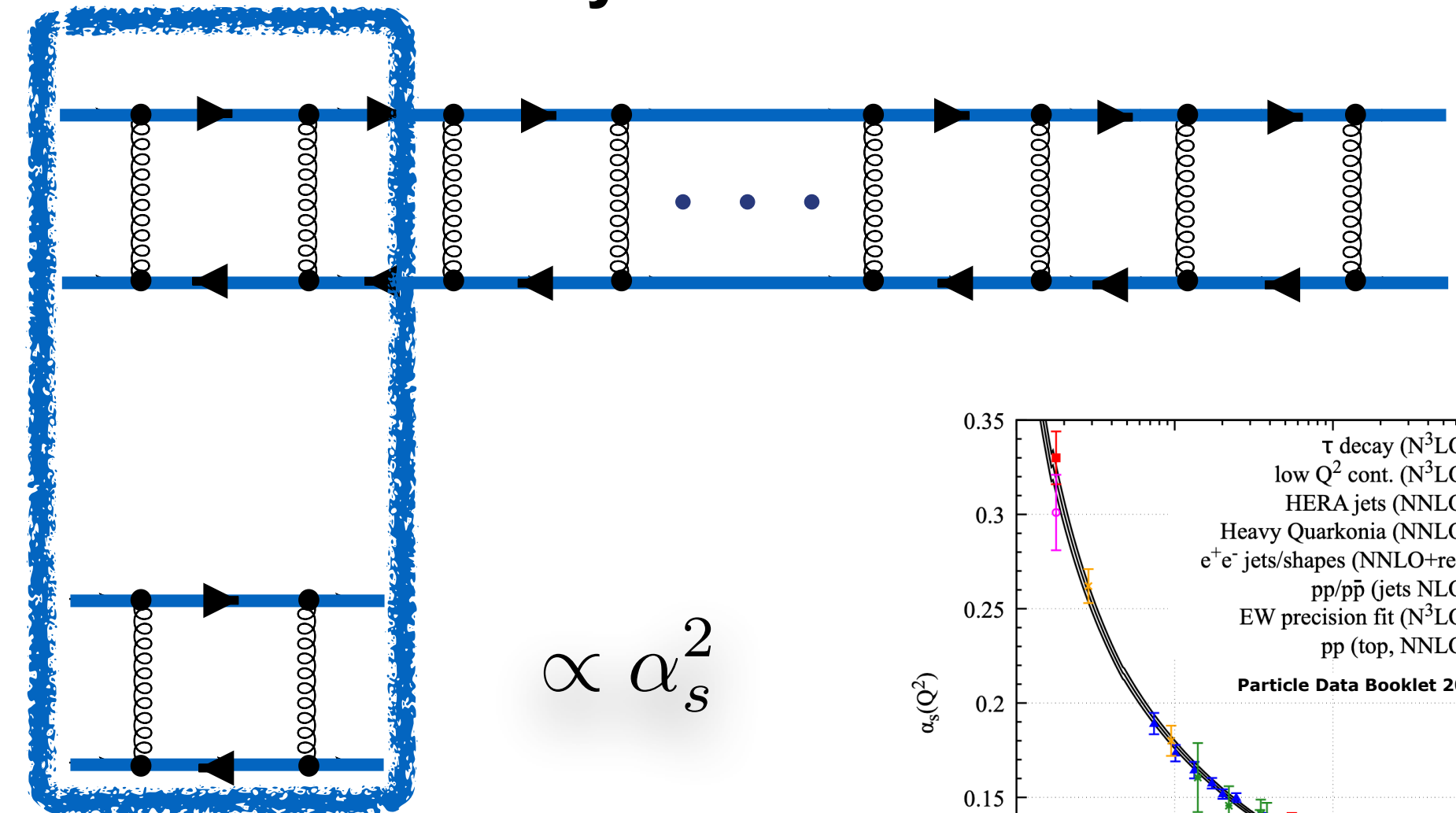


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## Dynamics



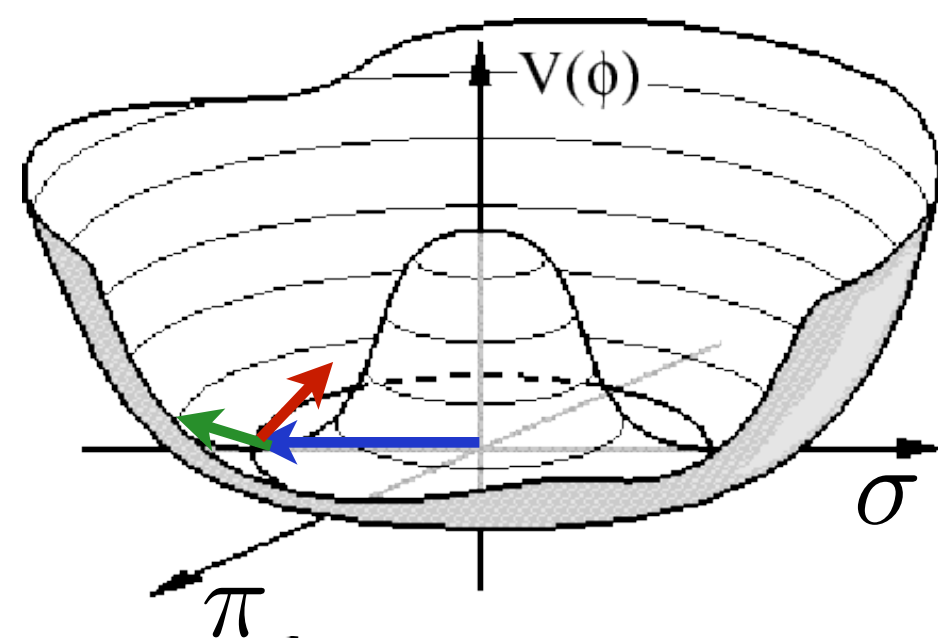
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chiral condensate

## Meson potential

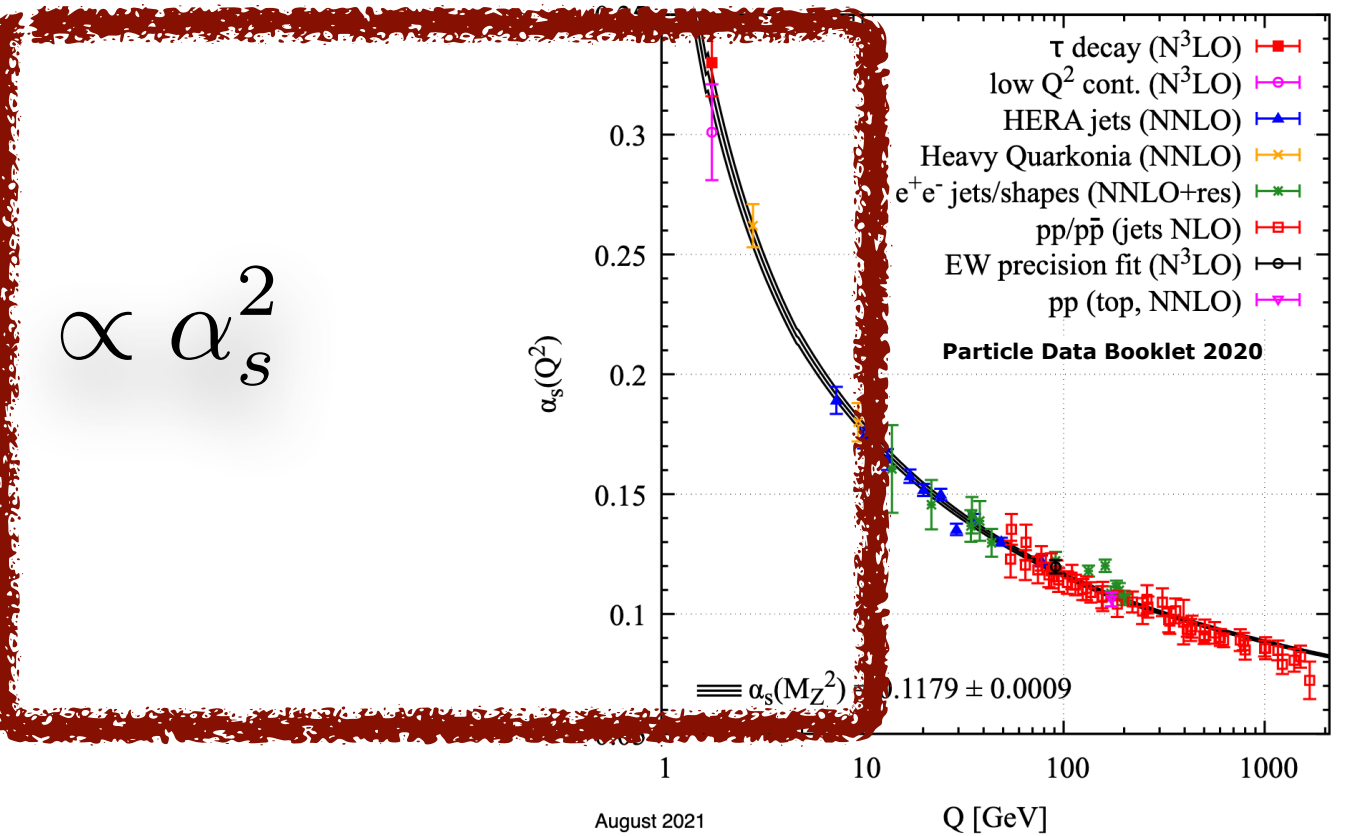
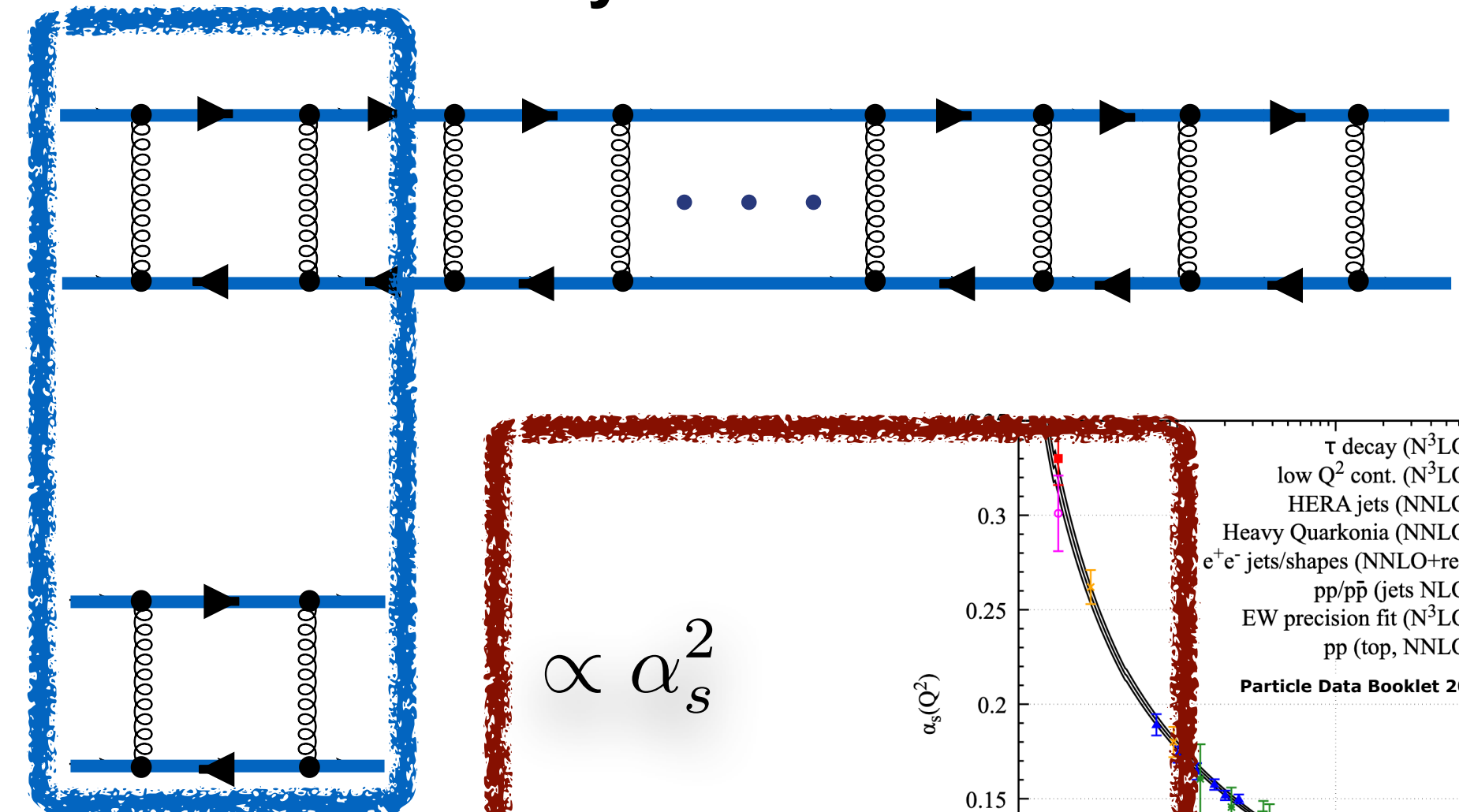


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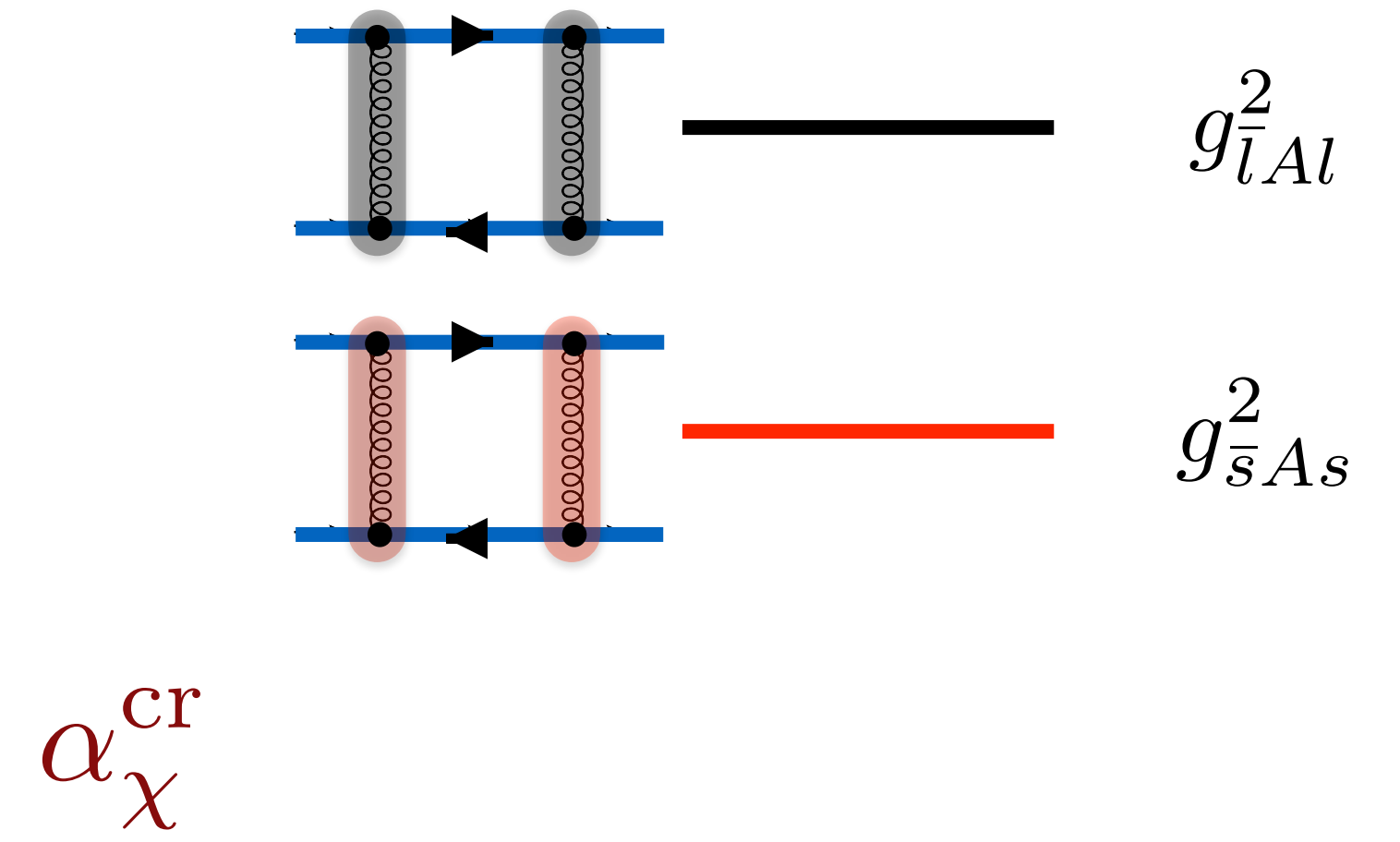
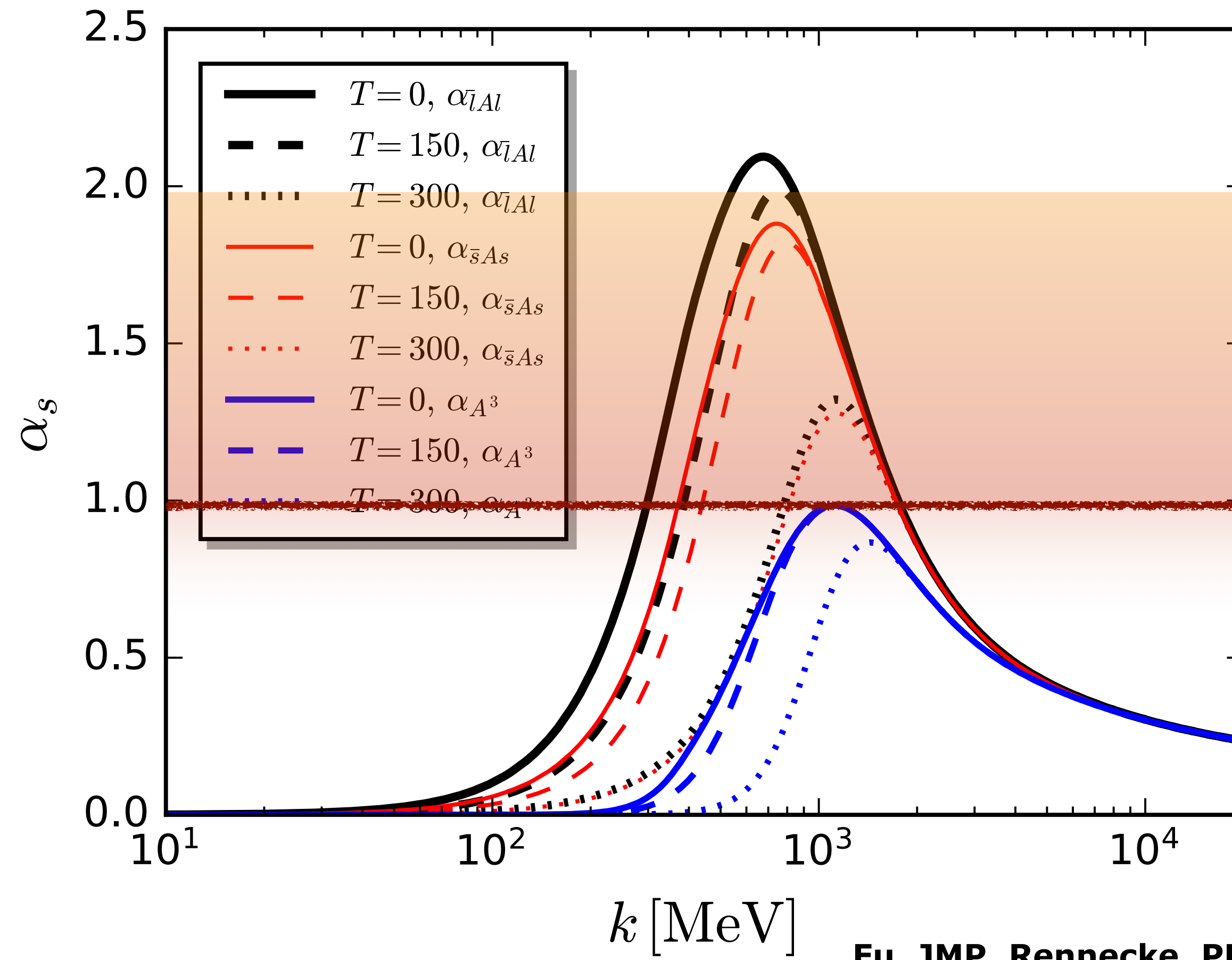
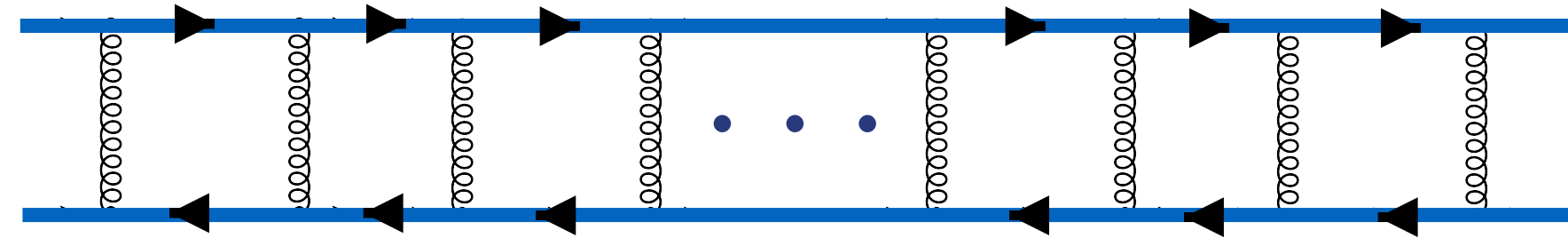
## Dynamics



Dynamical chiral symmetry breaking

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

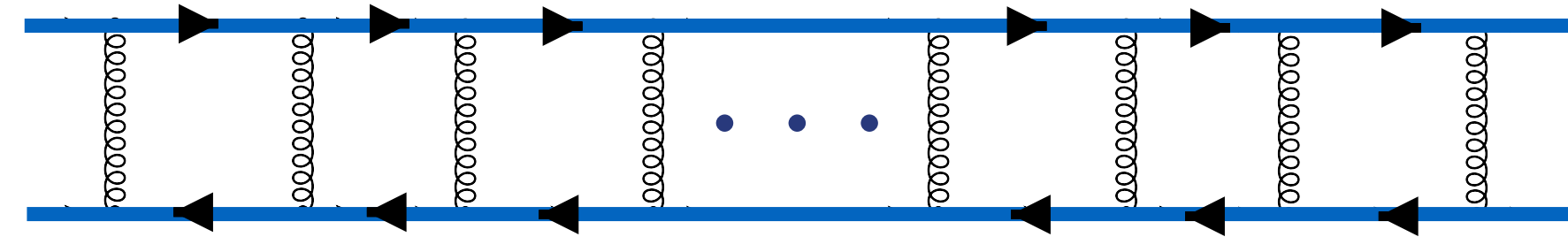
# Thermal restoration of chiral symmetry



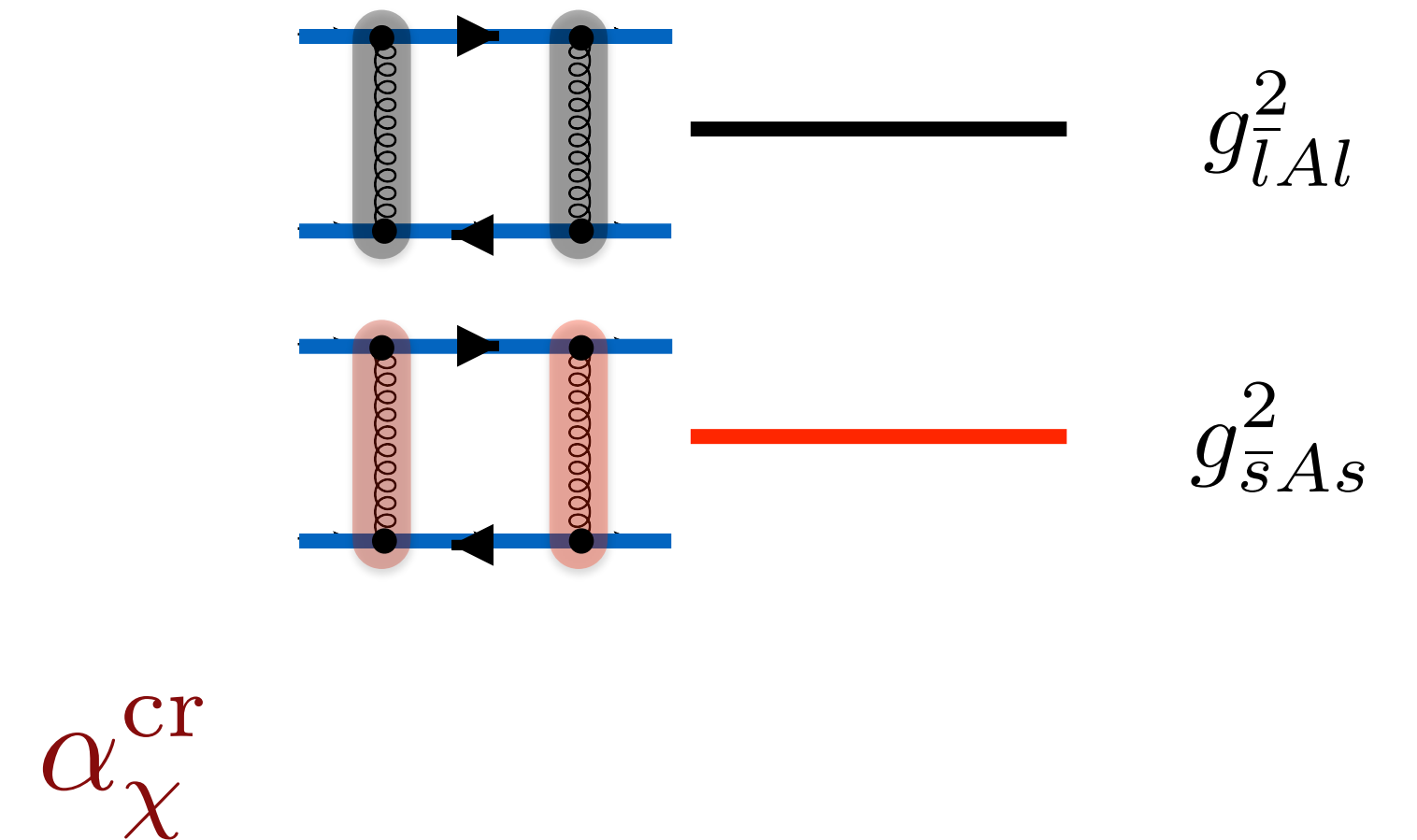
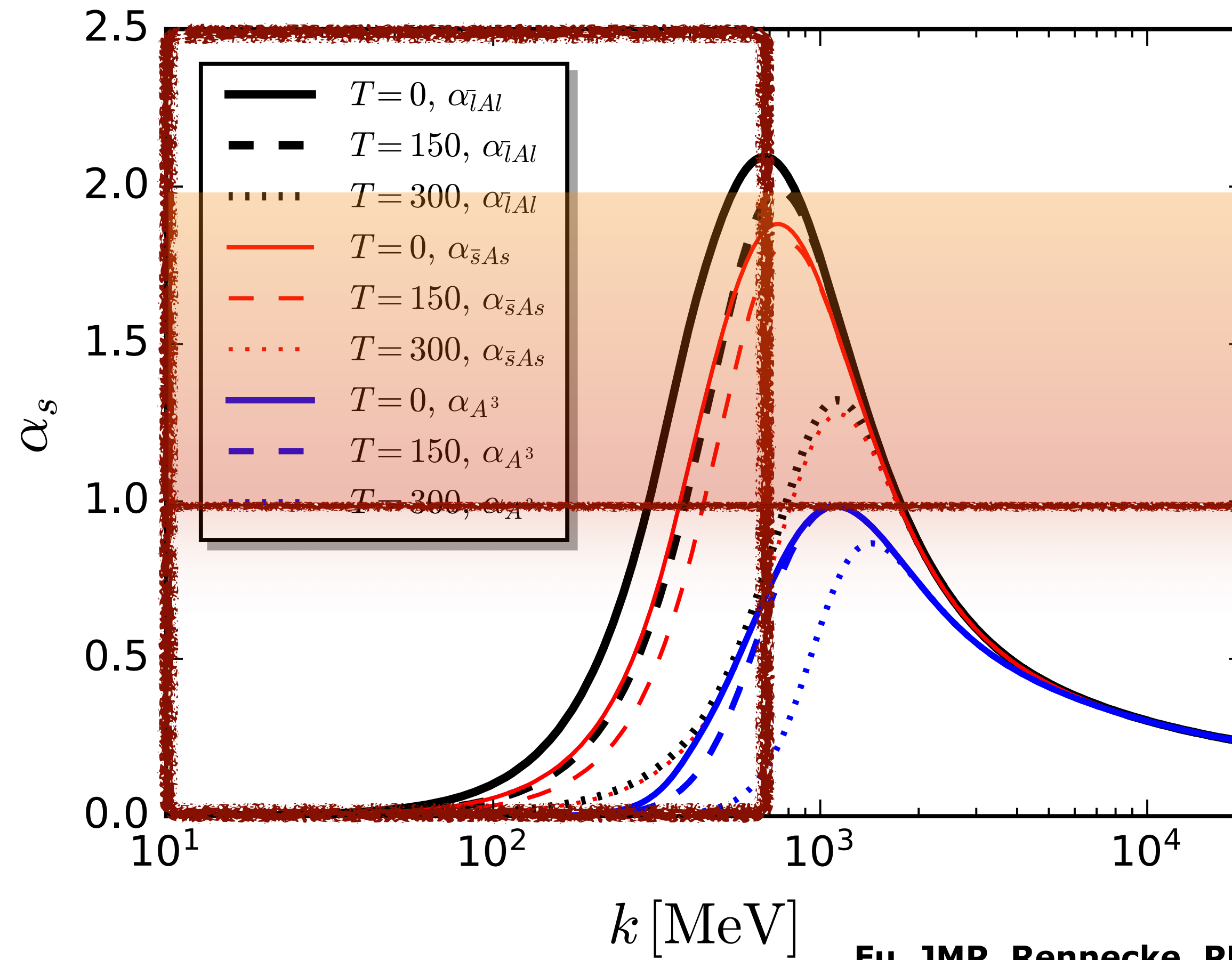
Fu, JMP, Rennecke, PRD 101 (2020) 054032



# Thermal restoration of chiral symmetry



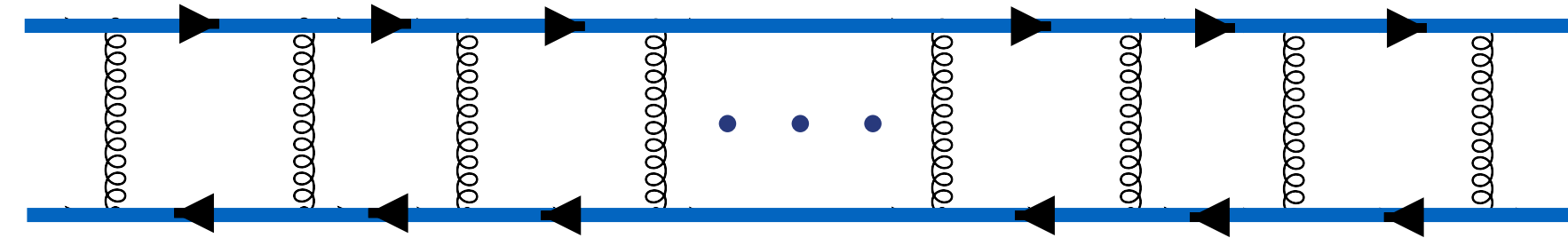
Effective couplings decays  
due to  
the gluon mass gap



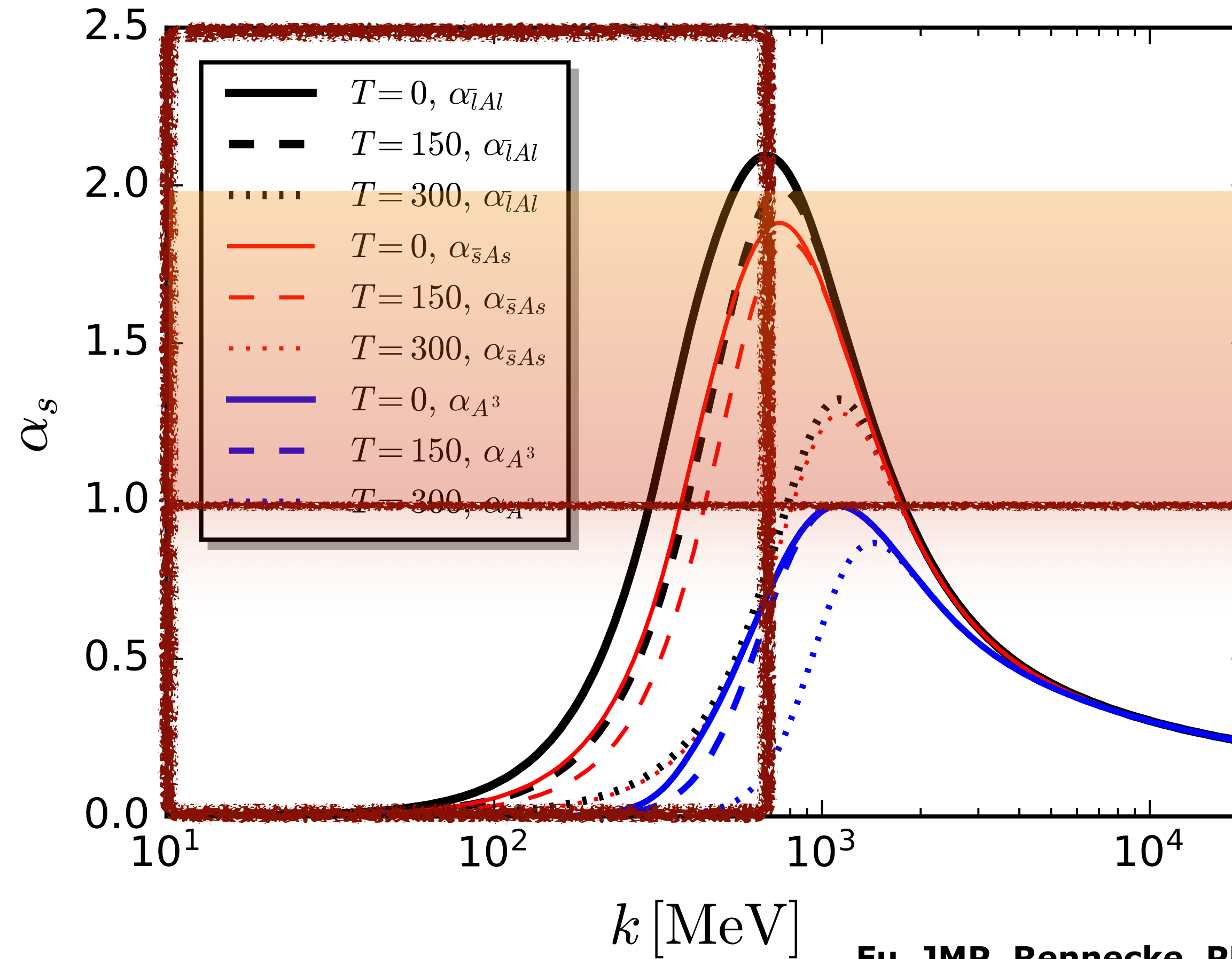
Fu, JMP, Rennecke, PRD 101 (2020) 054032

# Thermal restoration of chiral symmetry

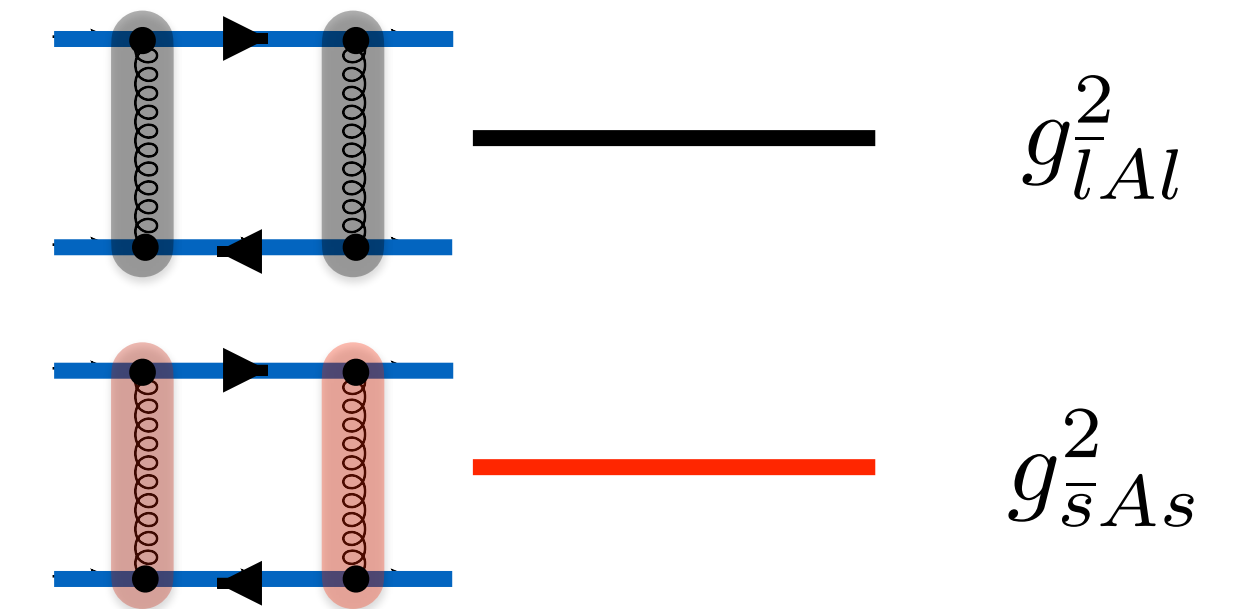
Thermal symmetry restauration  
by melting down the coupling



Effective couplings decays  
due to  
the gluon mass gap



$\alpha_\chi^{cr}$



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

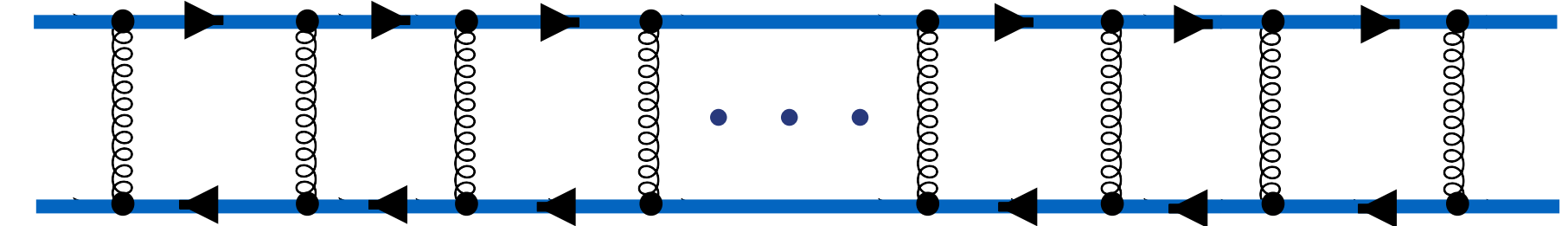
# Thermal restoration of chiral symmetry

## Order parameter

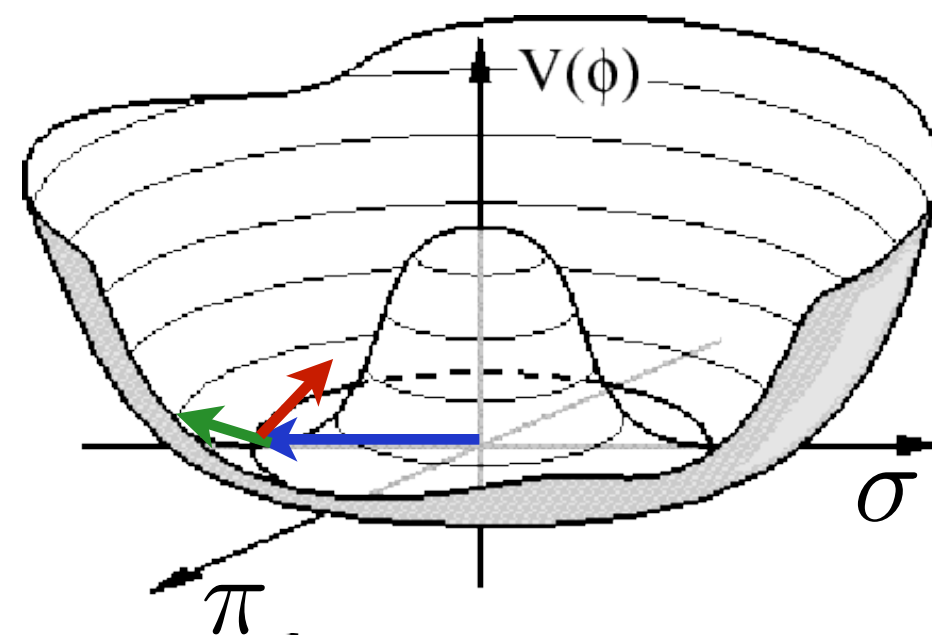
$$\sigma \propto \langle \bar{q}q \rangle = \langle q_L^\dagger q_R + q_R^\dagger q_L \rangle$$

chiral condensate

## Dynamics



## Meson potential

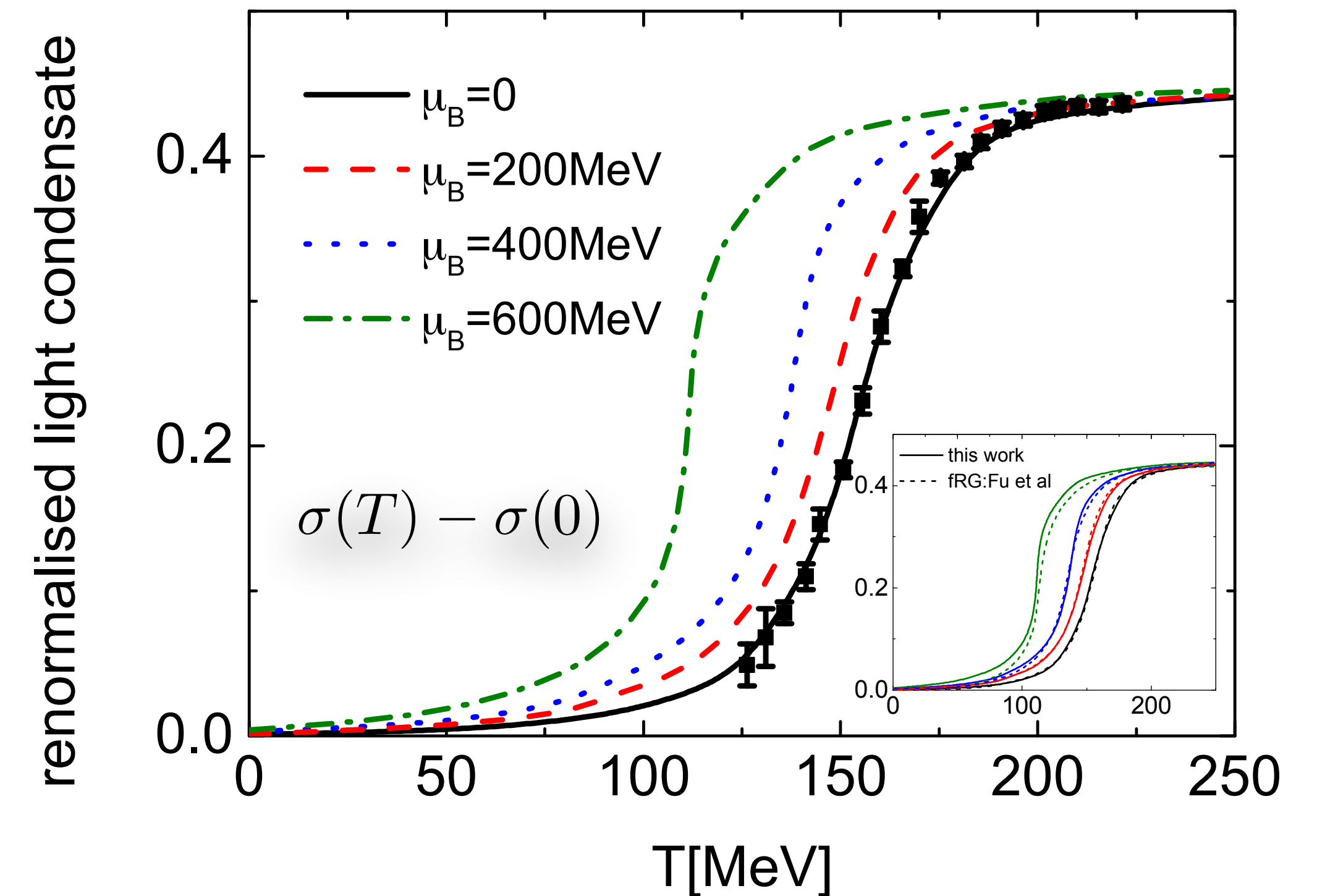


$$\vec{\pi} \simeq i \langle \bar{q} \vec{\sigma} \gamma_5 q \rangle$$

(Pseudo) Goldstones

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

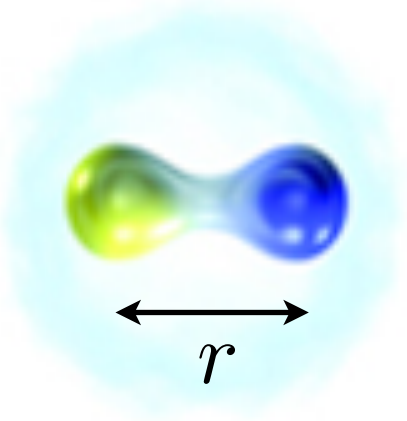
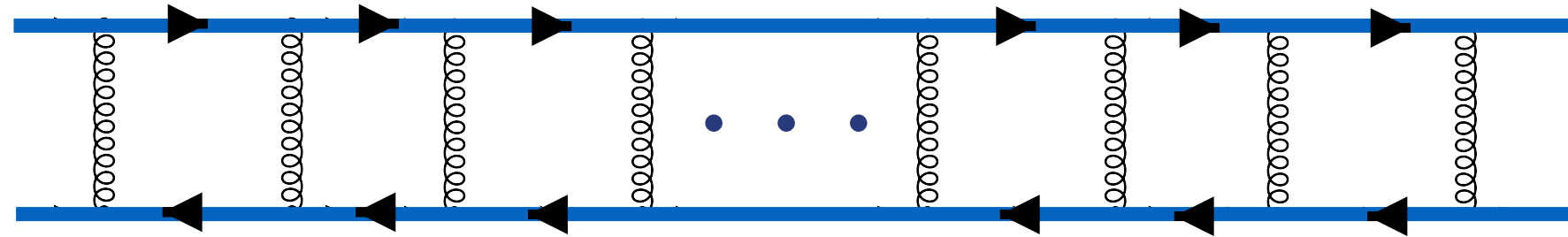
## QCD predictions from various approaches



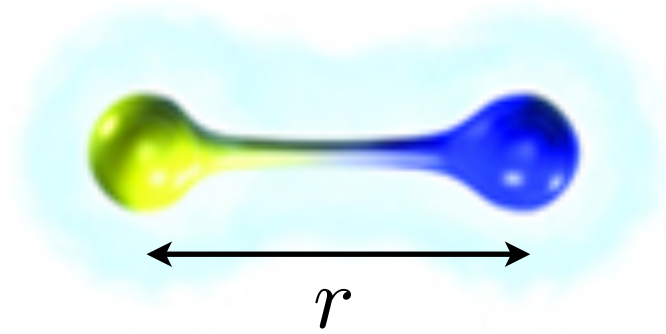


# Confinement

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

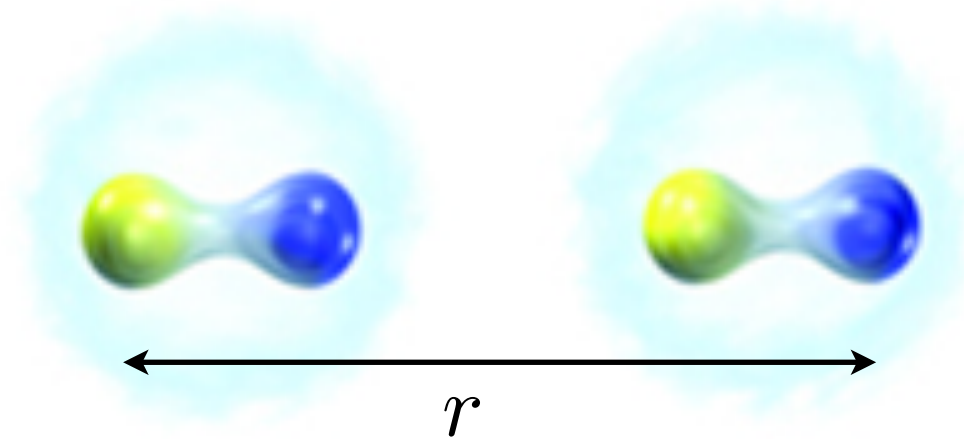
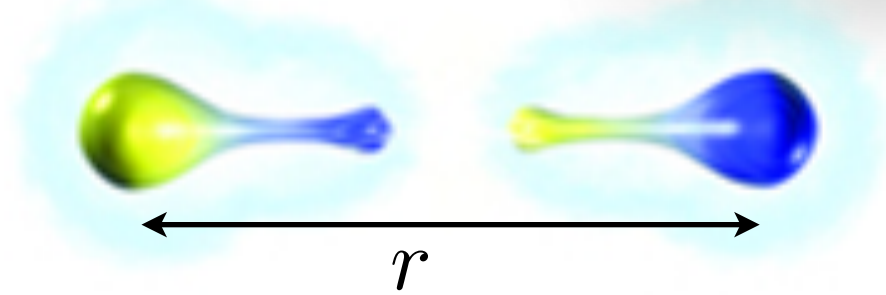


$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



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

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

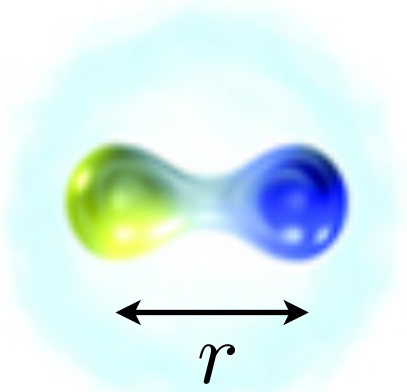
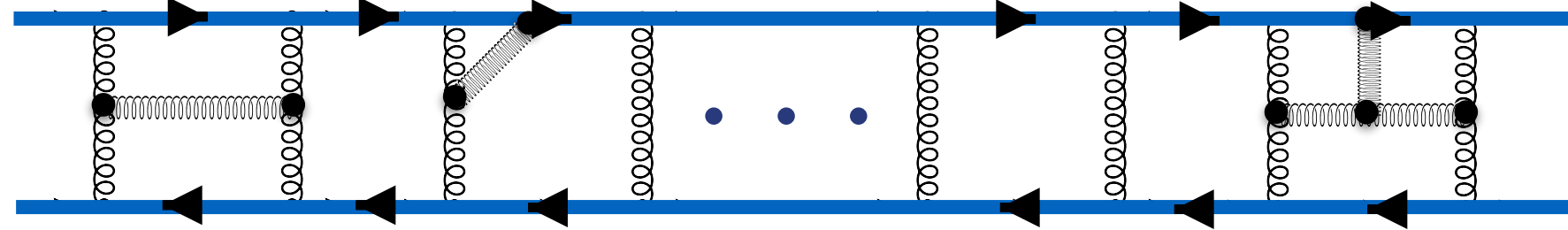


$$F_{q\bar{q}} \simeq \text{const.}$$

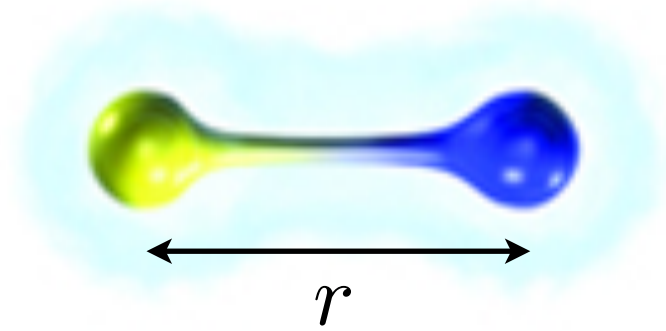
# Confinement

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

Confinement: Gluon self-interaction

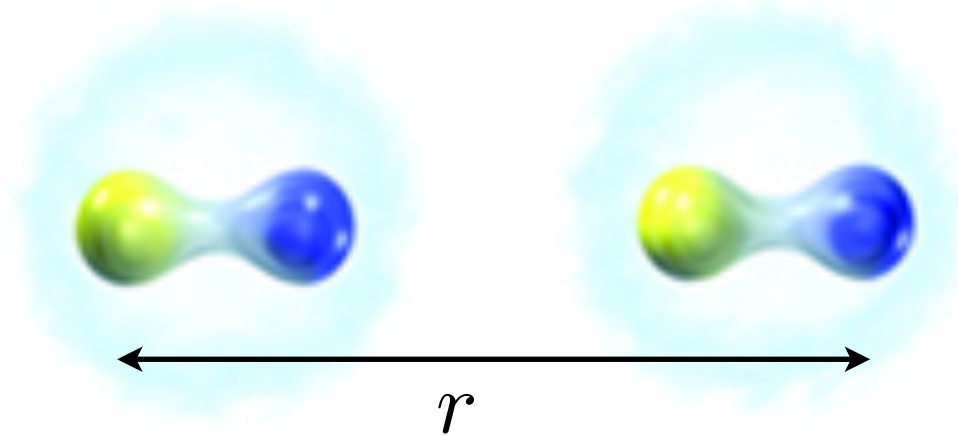
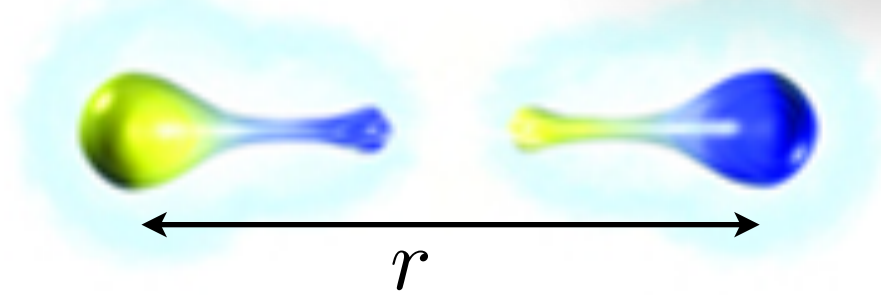


$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



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

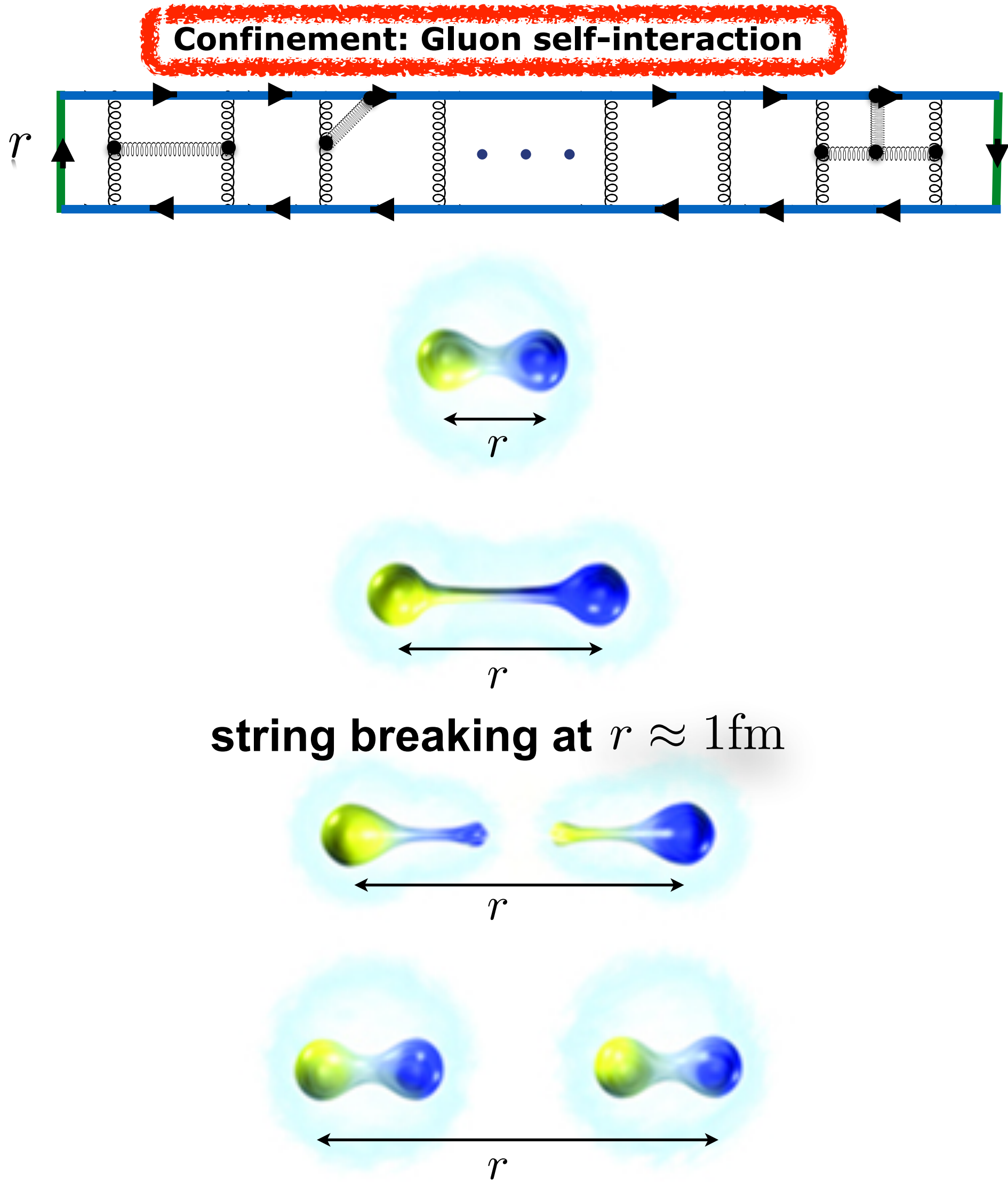
string breaking at  $r \approx 1\text{fm}$



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

# Confinement

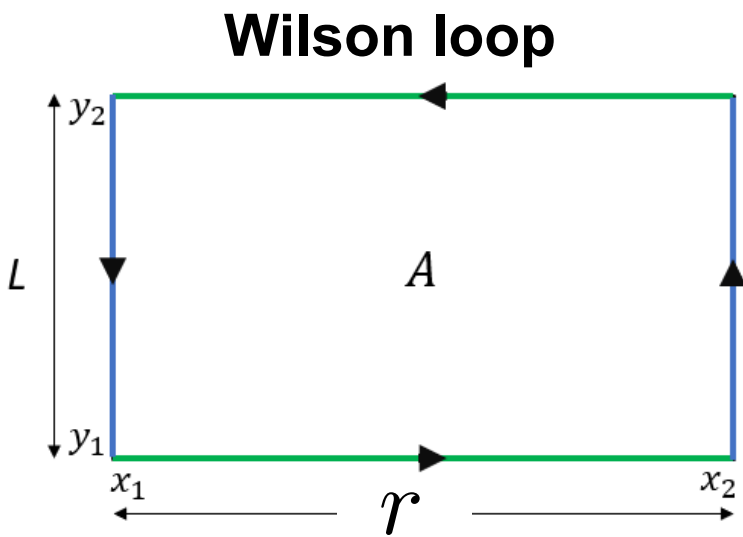
Free energy  $F_{q\bar{q}}$  of a quark - antiquark pair



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

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

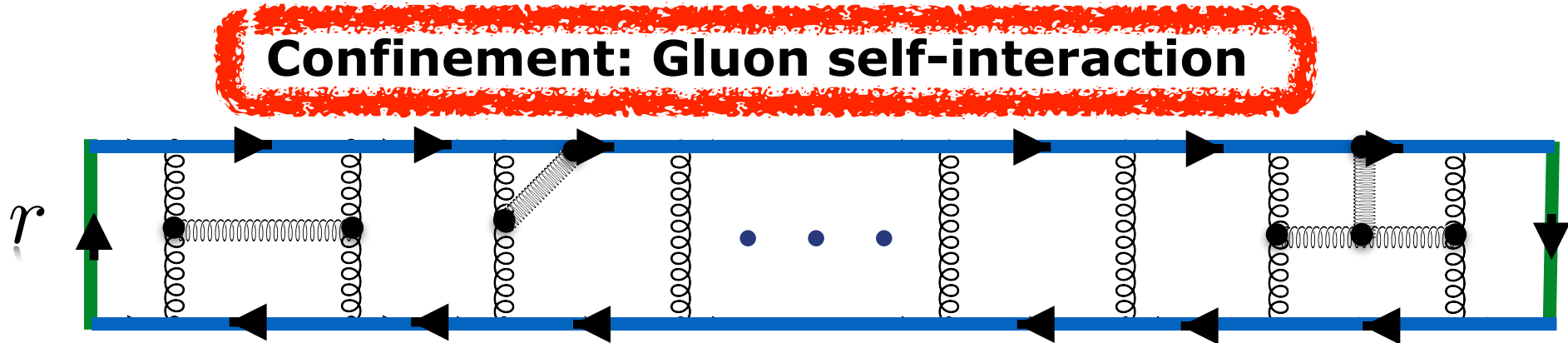
$$F_{q\bar{q}} \simeq \text{const.}$$





# Confinement

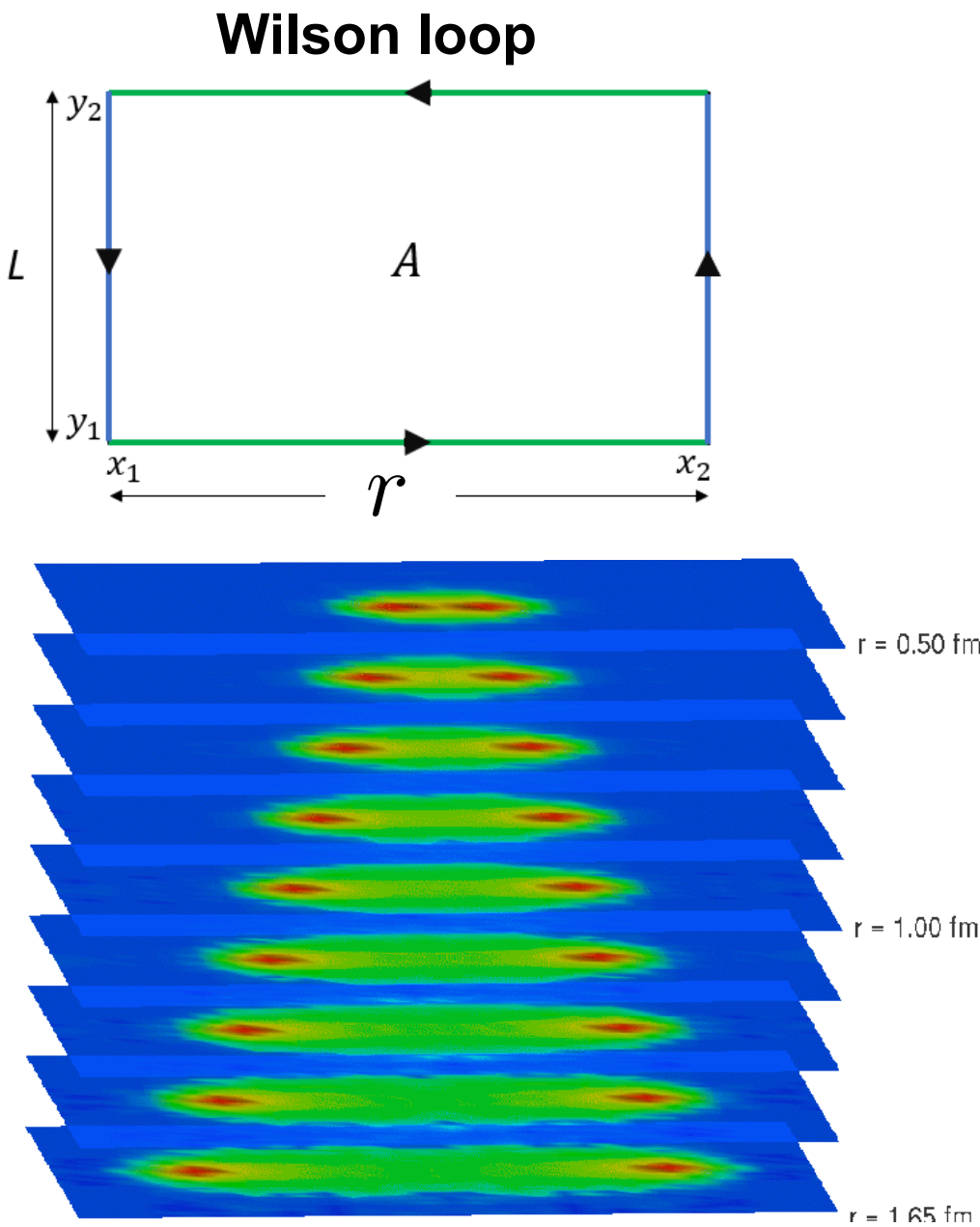
Free energy  $F_{q\bar{q}}$  of a quark - antiquark pair



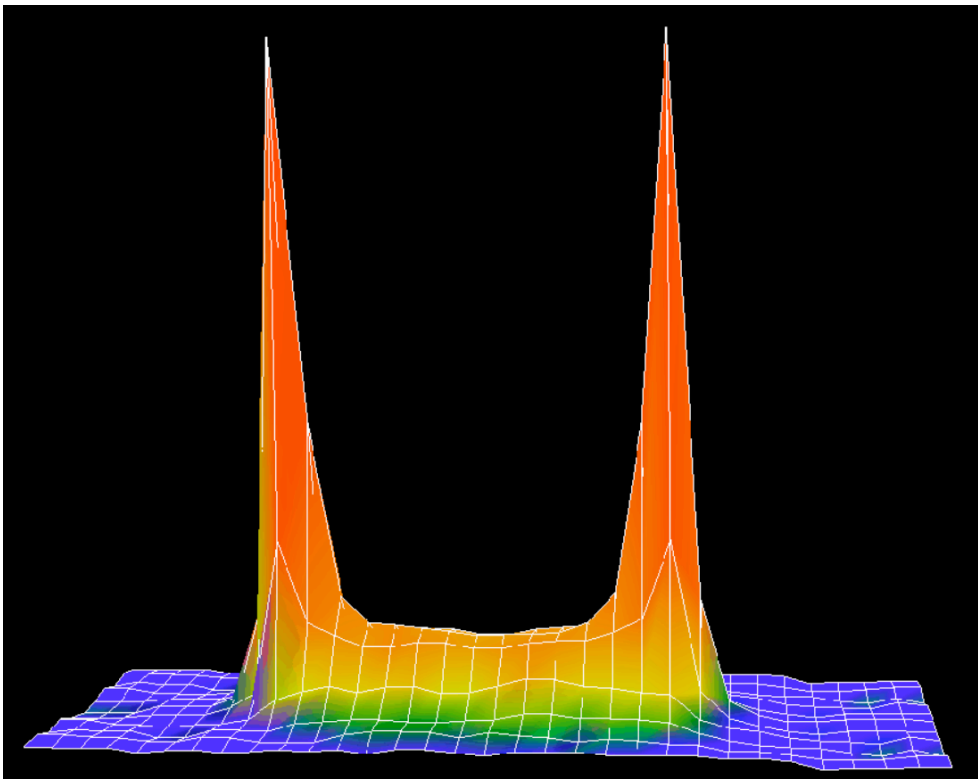
$$F_{q\bar{q}} \simeq -\frac{1}{r}$$

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

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

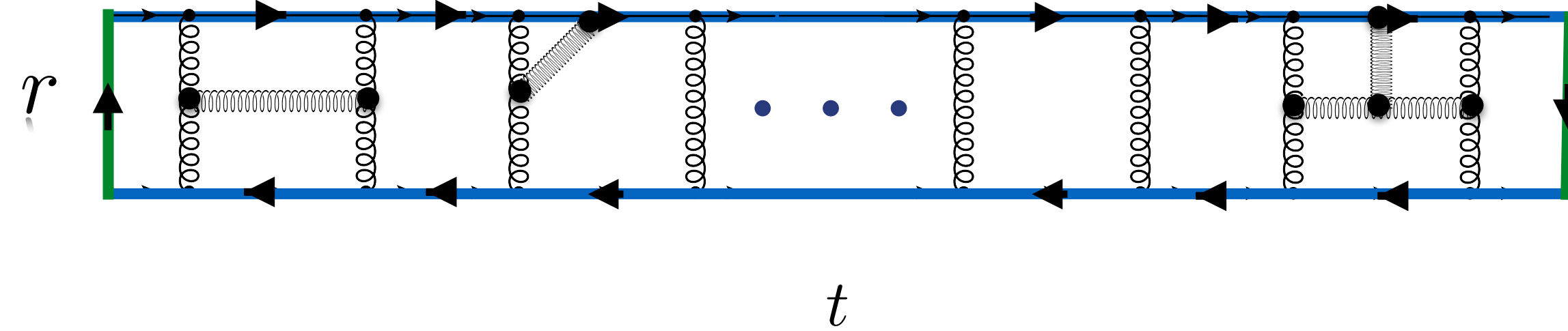


Energy density      Bali et al. '94



# Thermal confinement-deconfinement phase transition

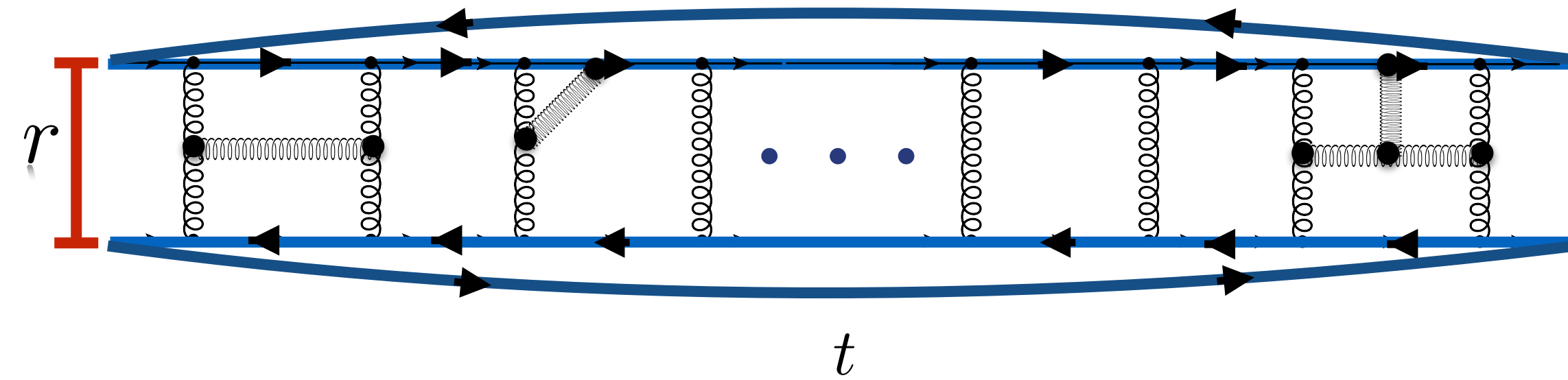
Free energy  $F_{q\bar{q}}$  of a quark - antiquark pair



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

# Thermal confinement-deconfinement phase transition

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

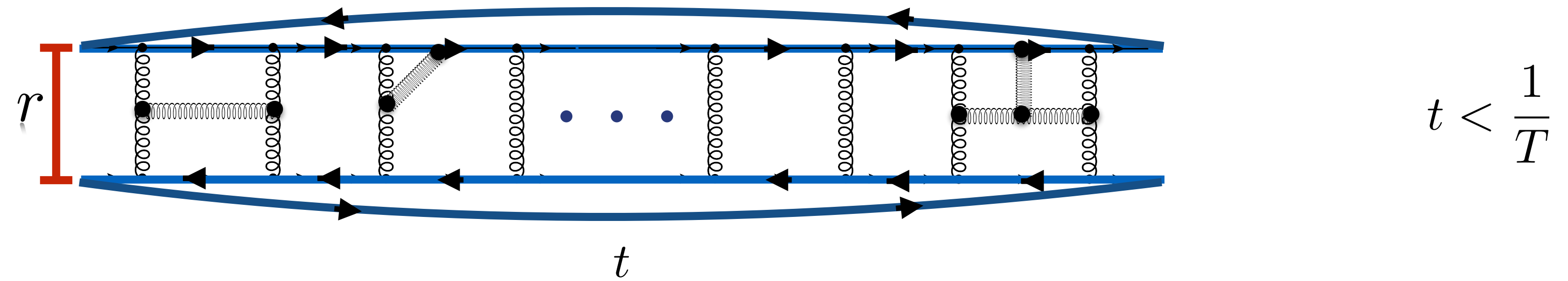


$$t < \frac{1}{T}$$



# Thermal confinement-deconfinement phase transition

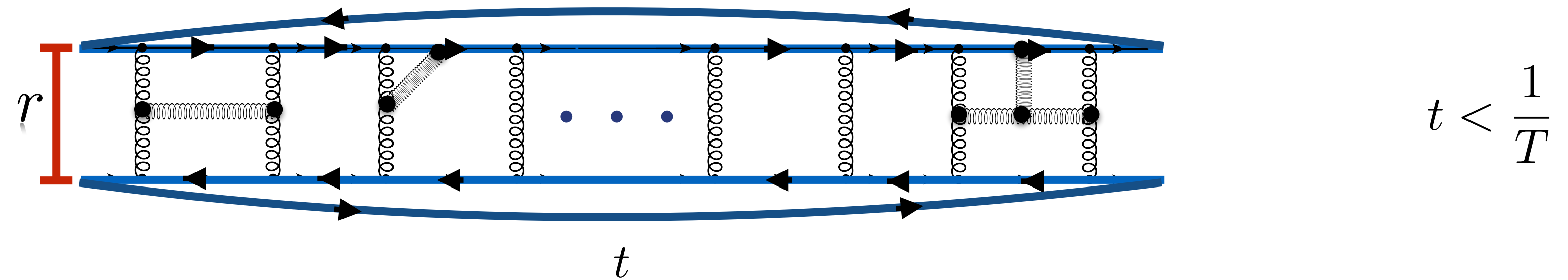
Free energy  $F_{q\bar{q}}$  of a quark - antiquark pair



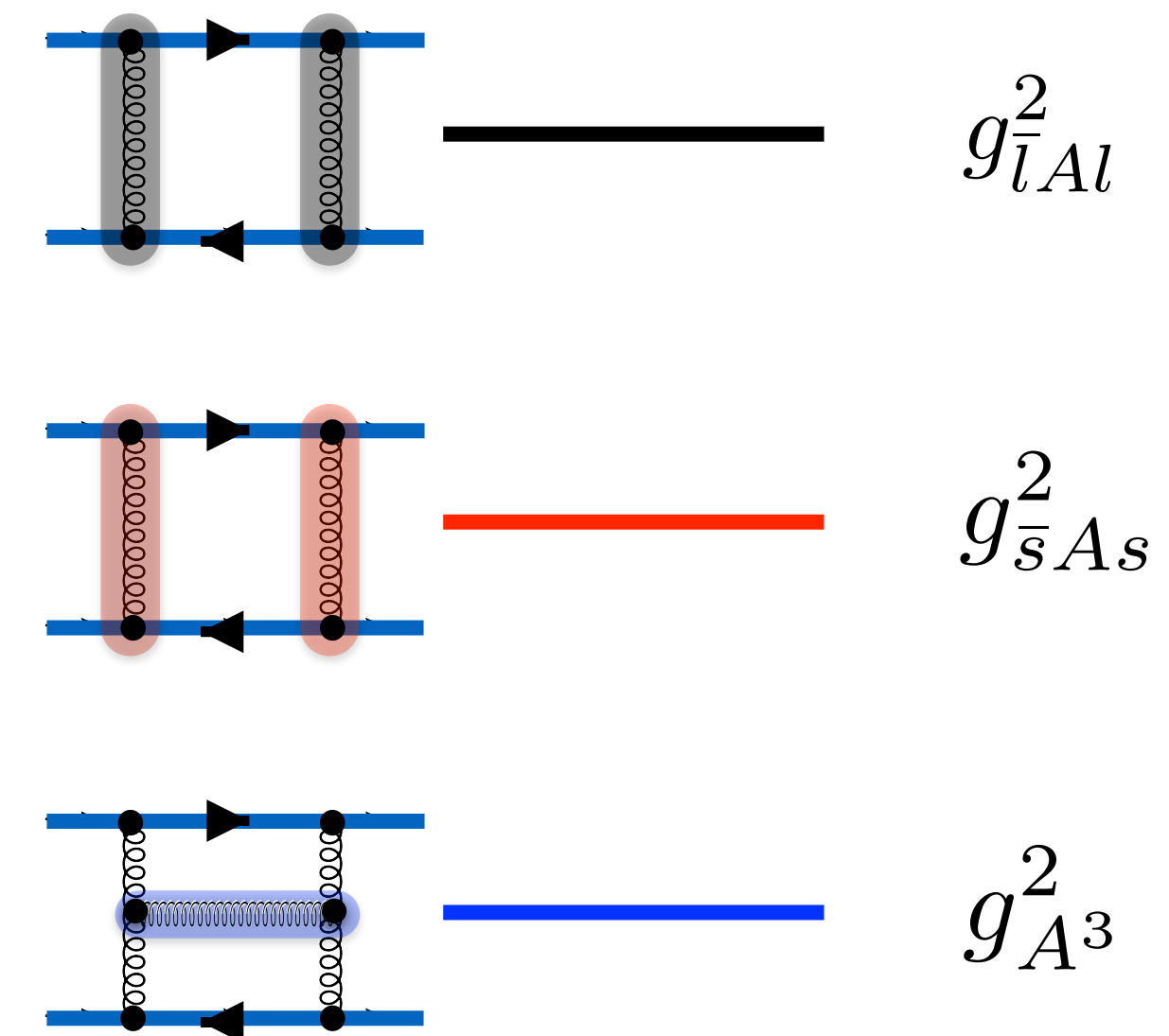
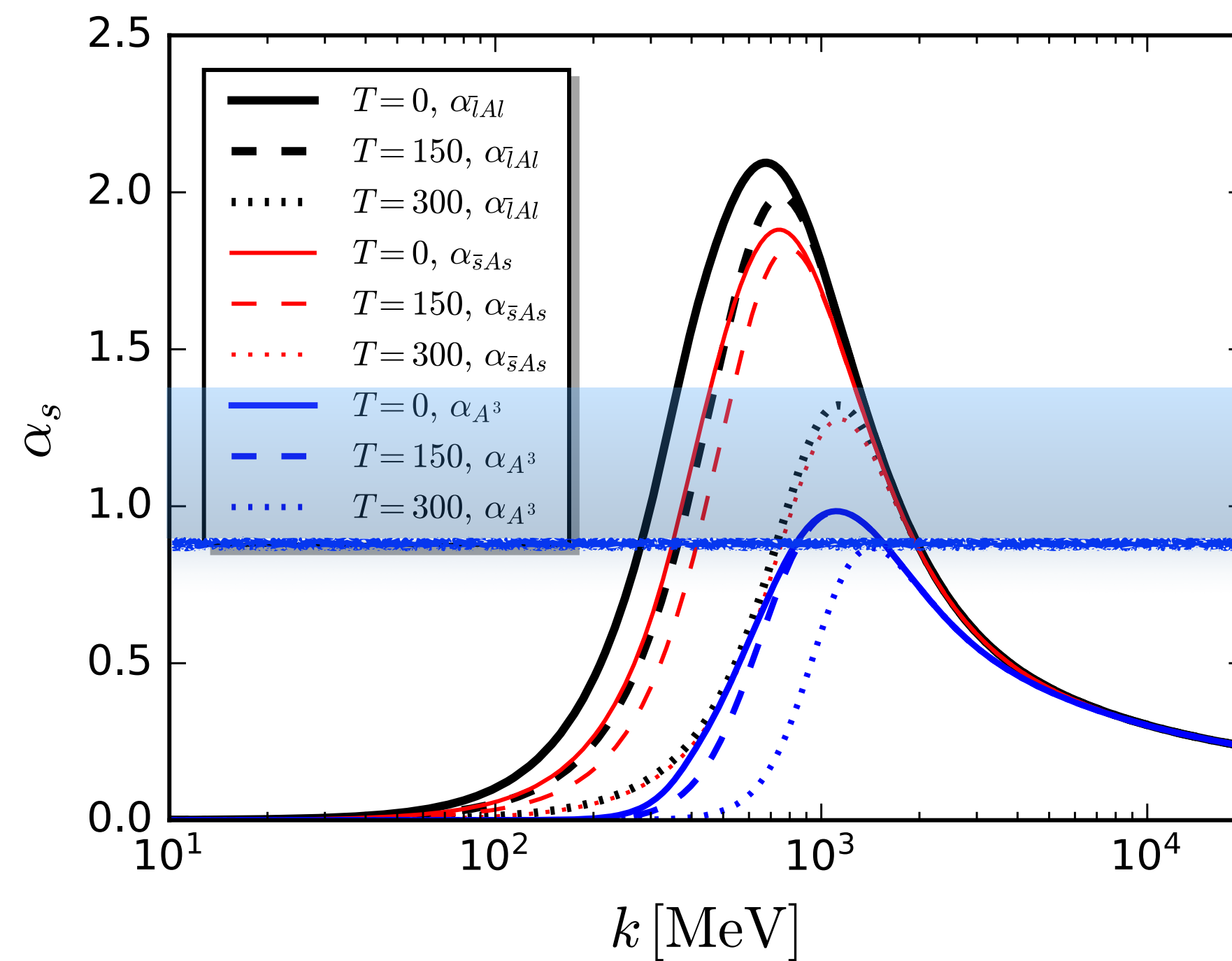
**Polyakov loop correlation**  $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

# Thermal confinement-deconfinement phase transition

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

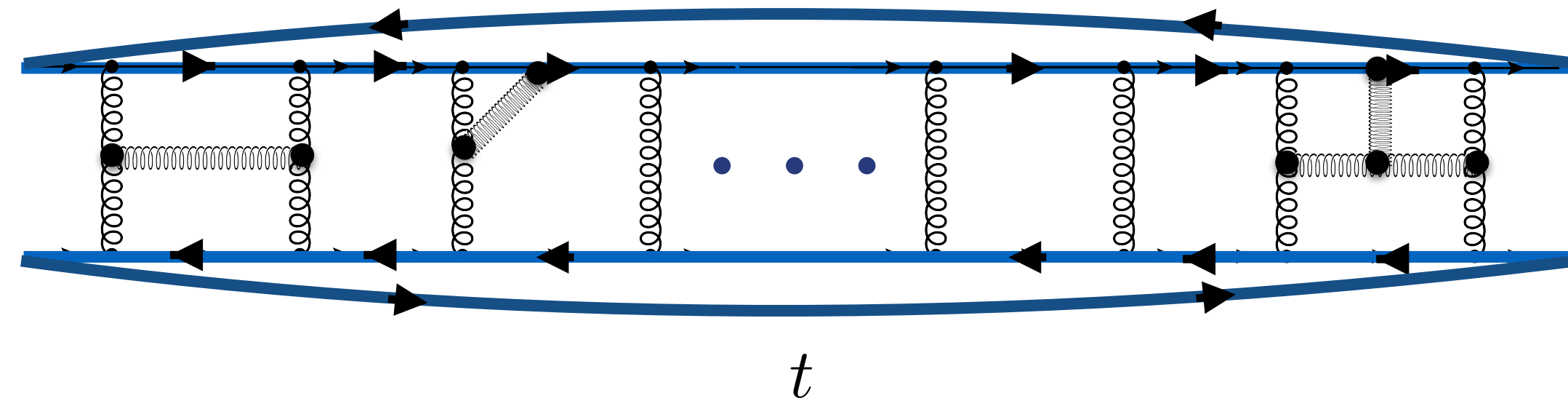


Polyakov loop correlation  $\langle P(0)P^\dagger(r) \rangle \sim V(r, T)/T$

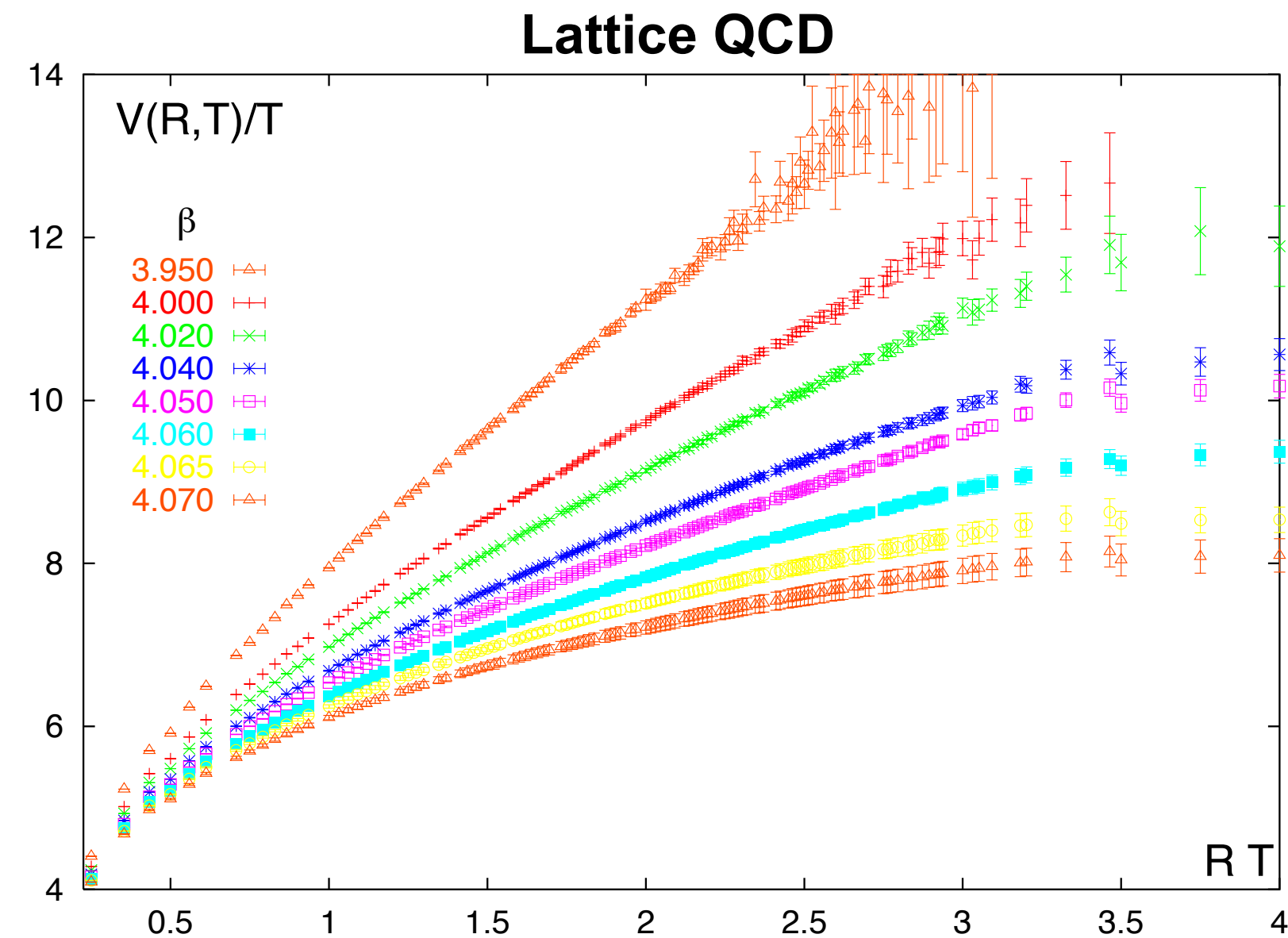


# Thermal confinement-deconfinement phase transition

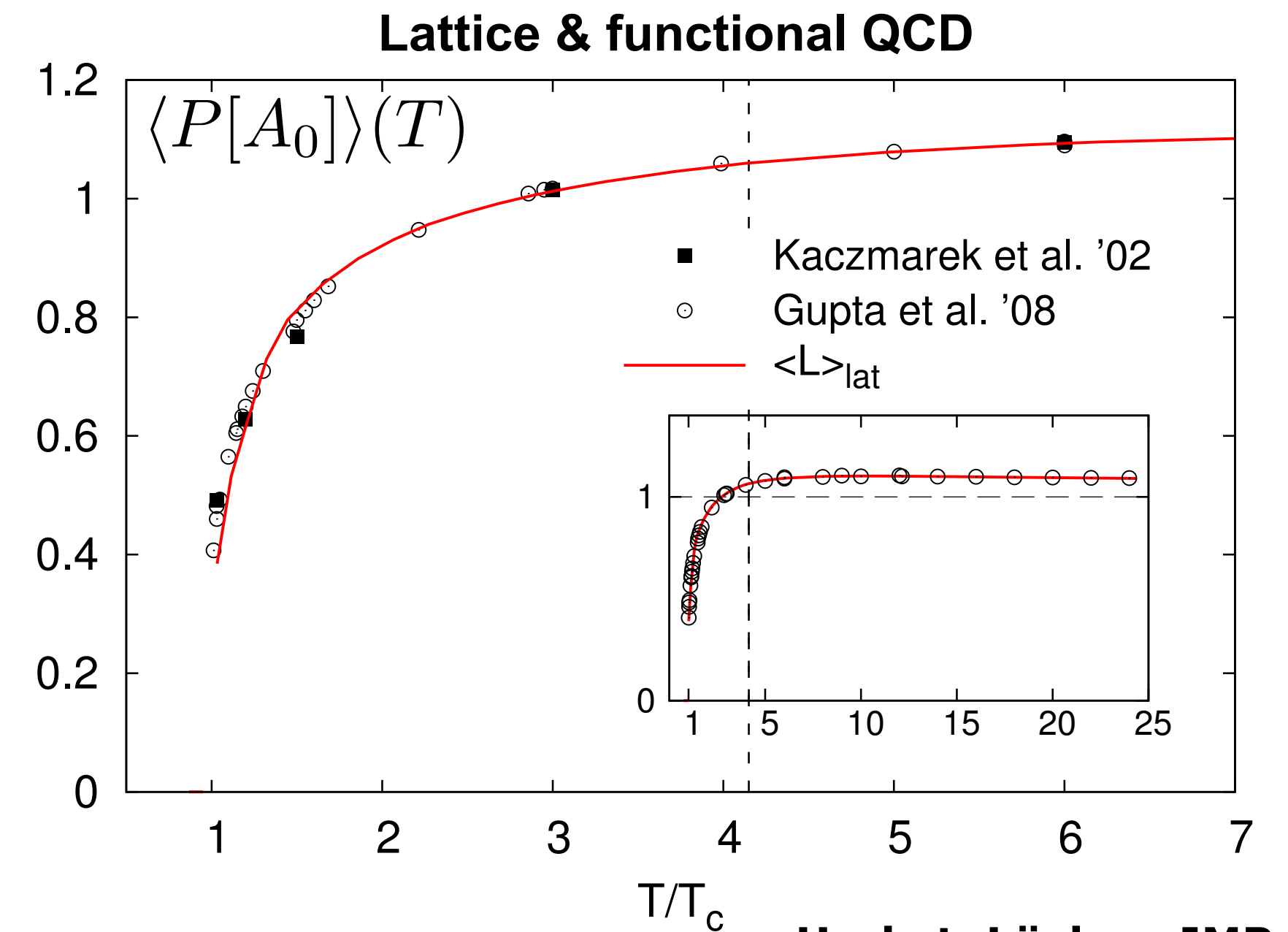
Free energy  $F_{q\bar{q}}$  of a quark - antiquark pair



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



Kaczmarek et al '99

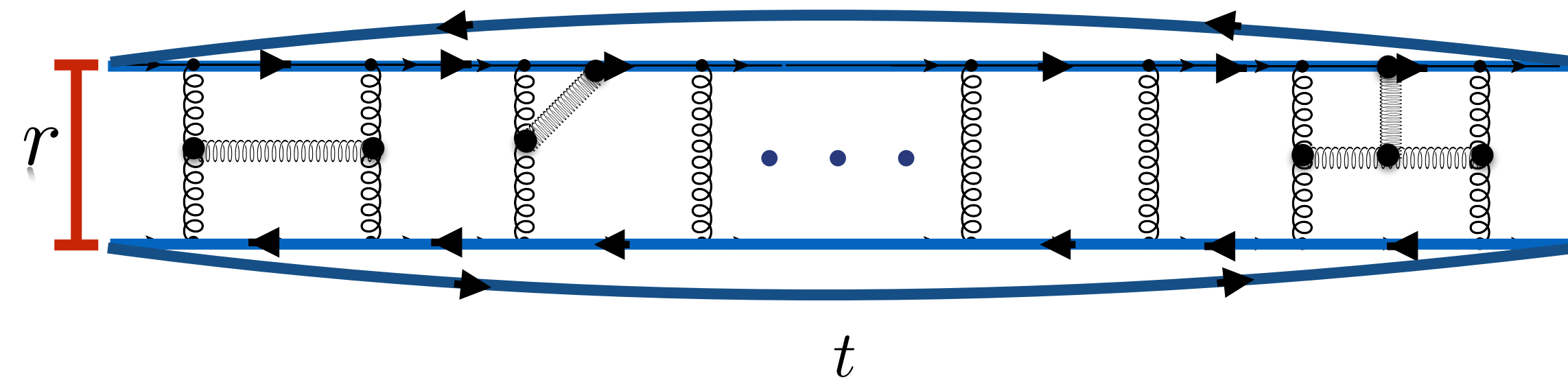


Herbst, Lücker, JMP, 2015

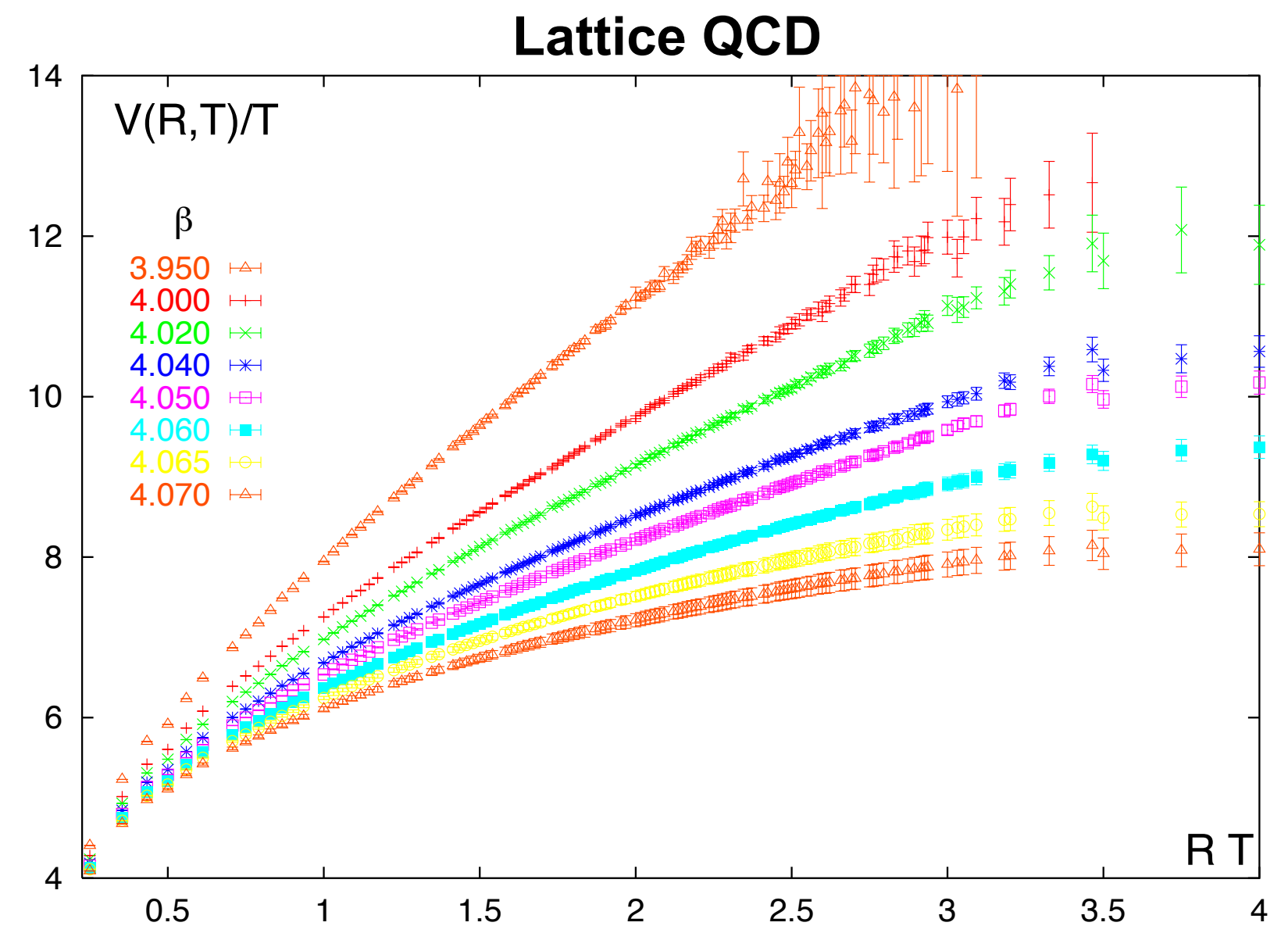


# Thermal confinement-deconfinement phase transition

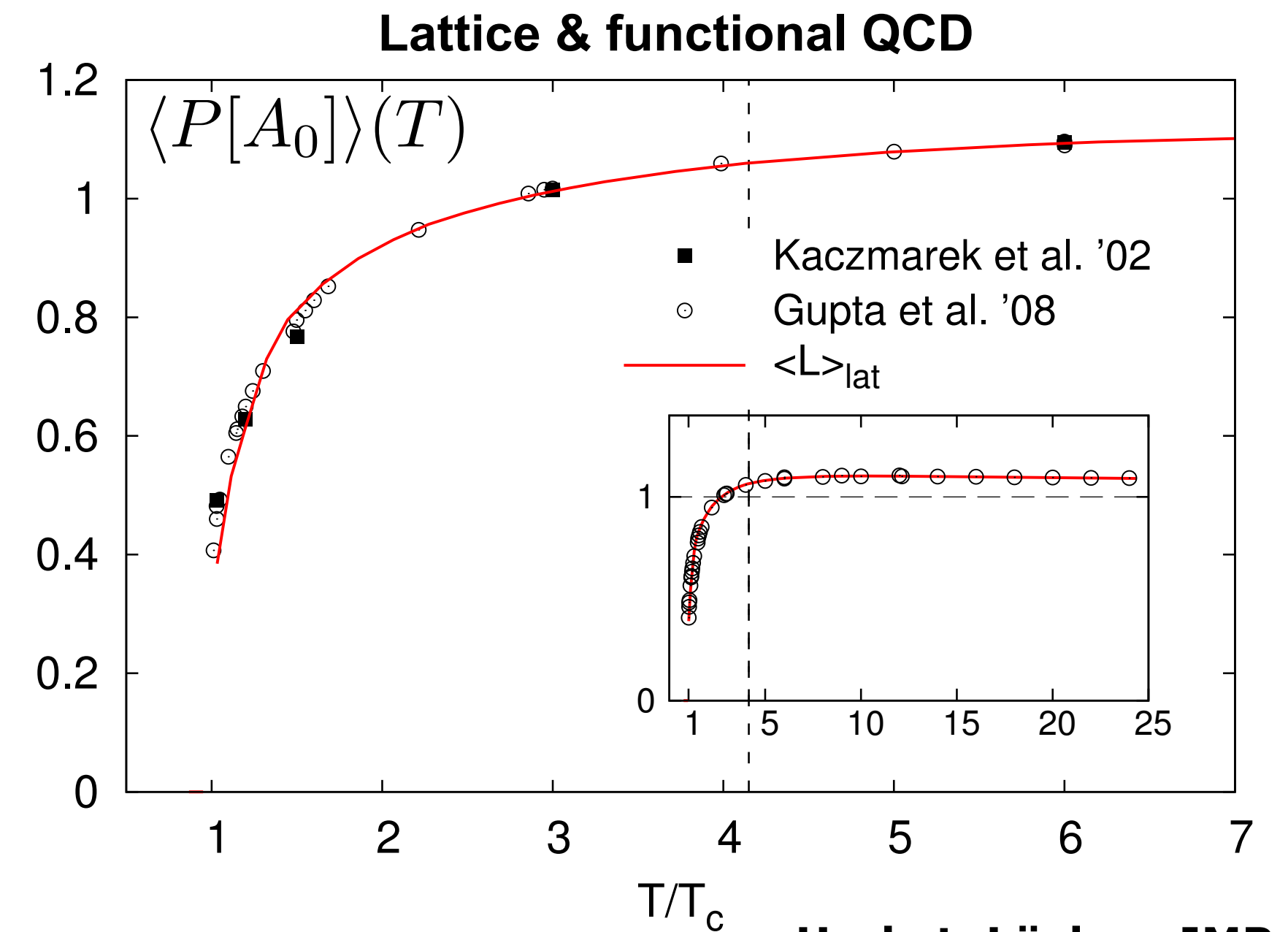
Free energy  $F_{q\bar{q}}$  of a quark - antiquark pair



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



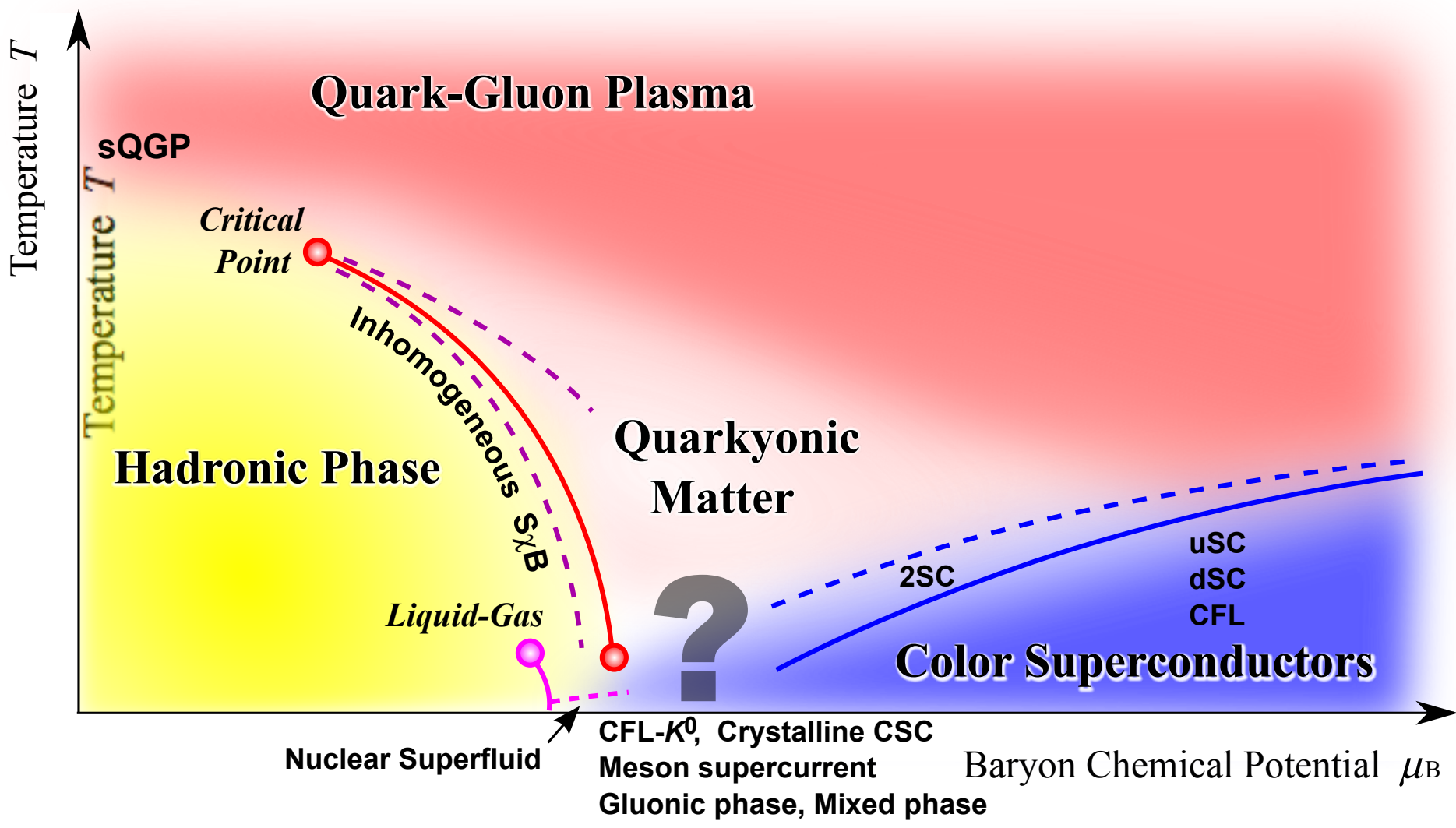
Kaczmarek et al '99



Herbst, Lücker, JMP, 2015

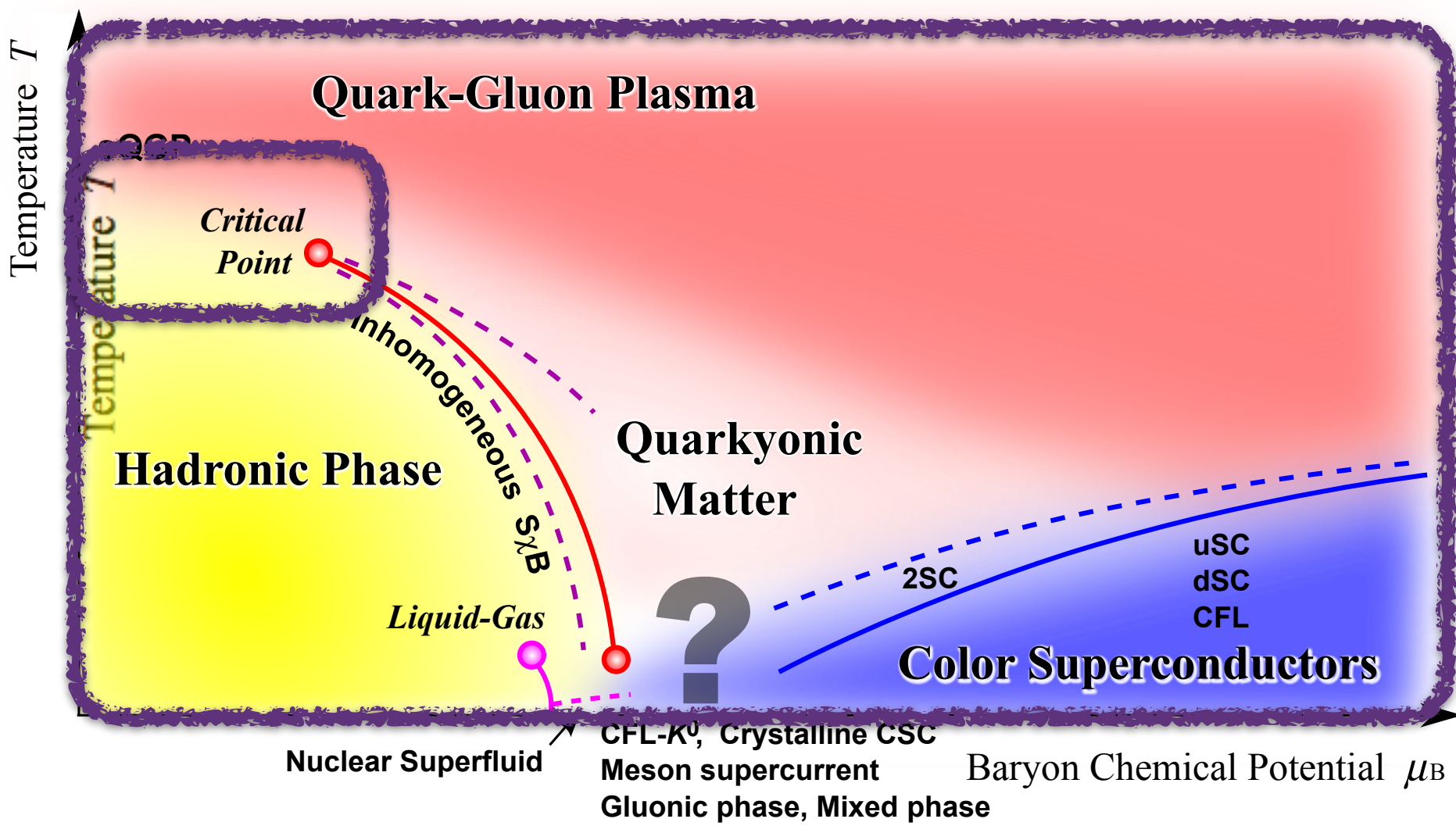
# **The physics of the QCD phase diagram & the experimental landscape**

# QCD phase structure

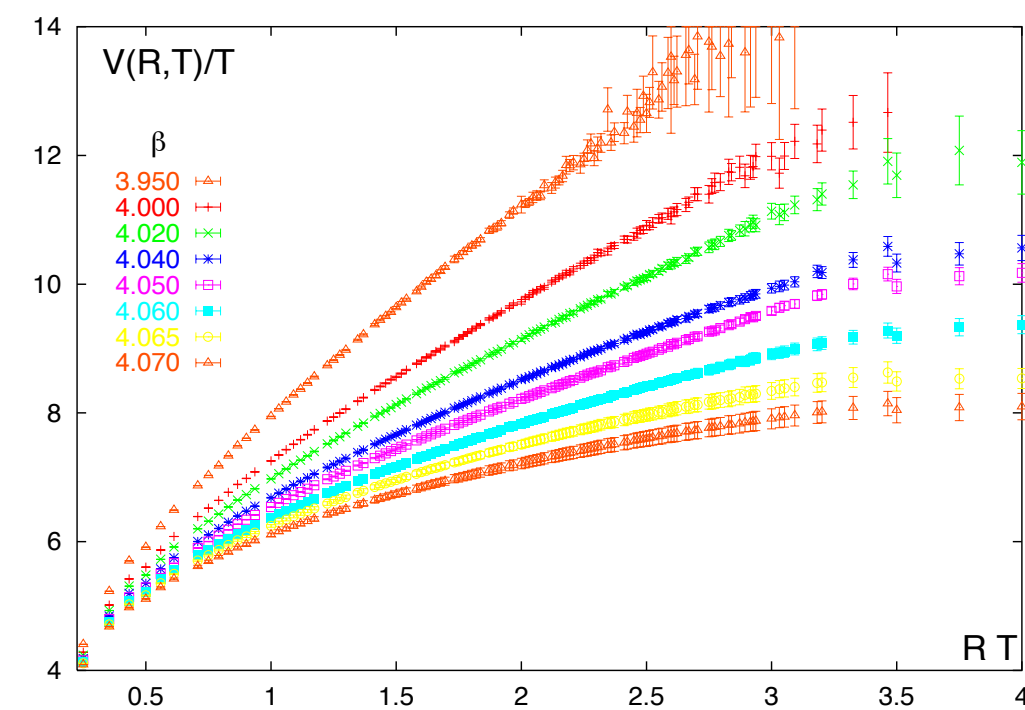
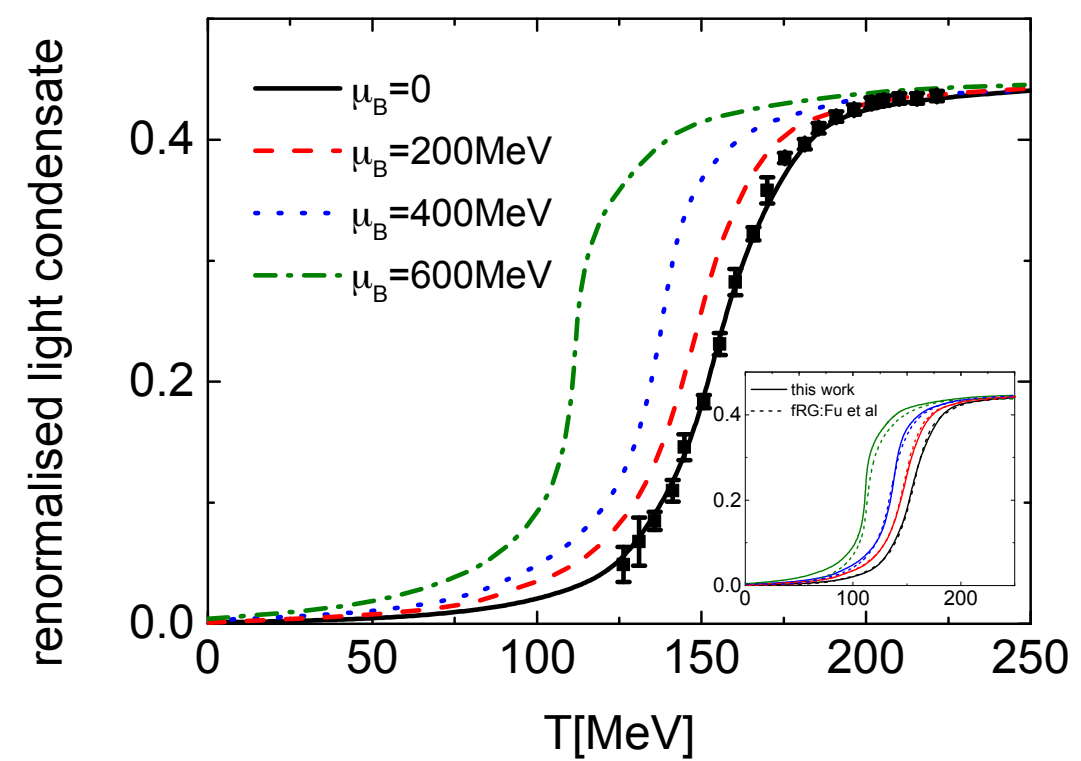




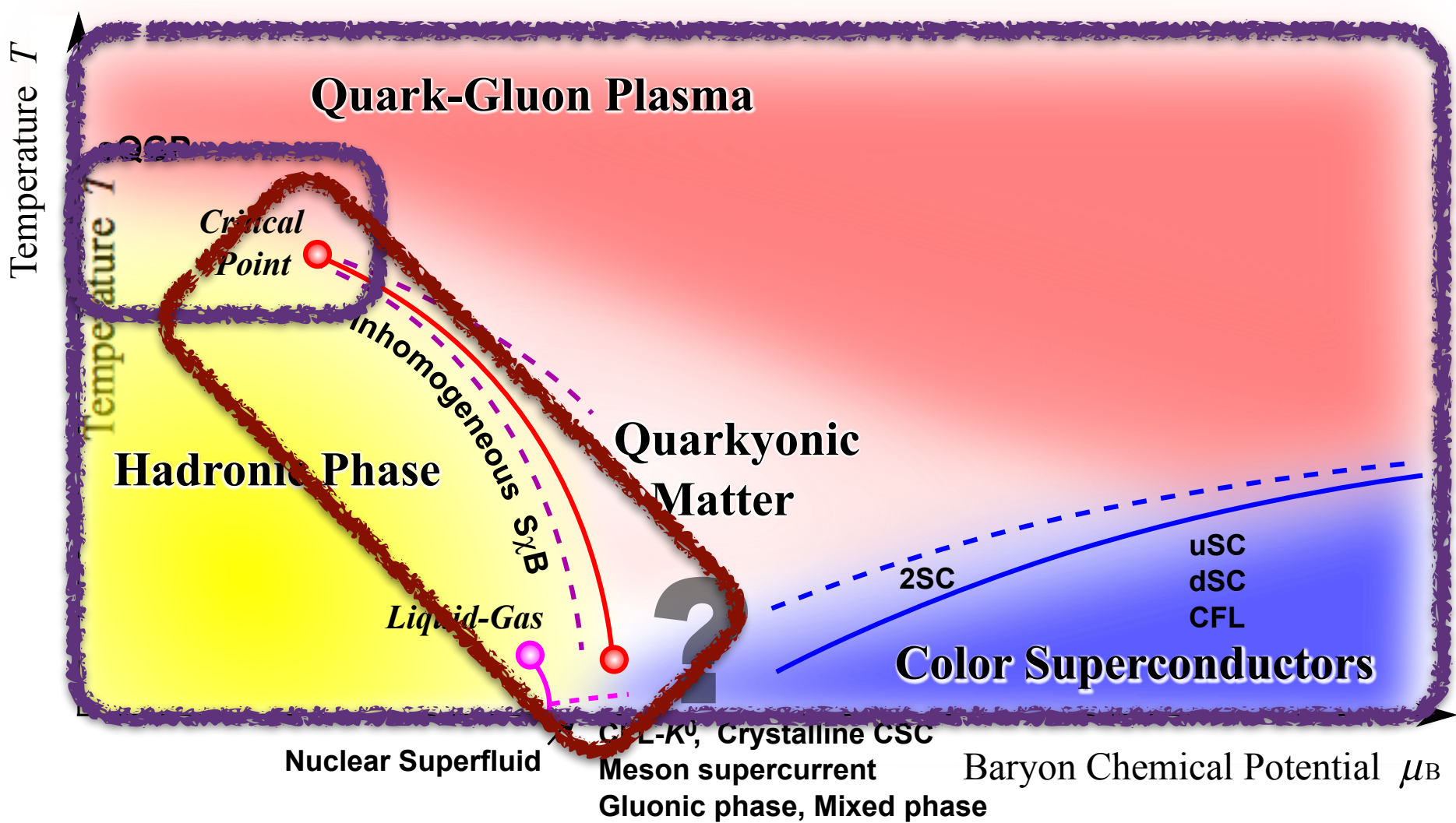
# QCD phase structure



## Chiral symmetry breaking & Confinement: the search for the CEP



# QCD phase structure

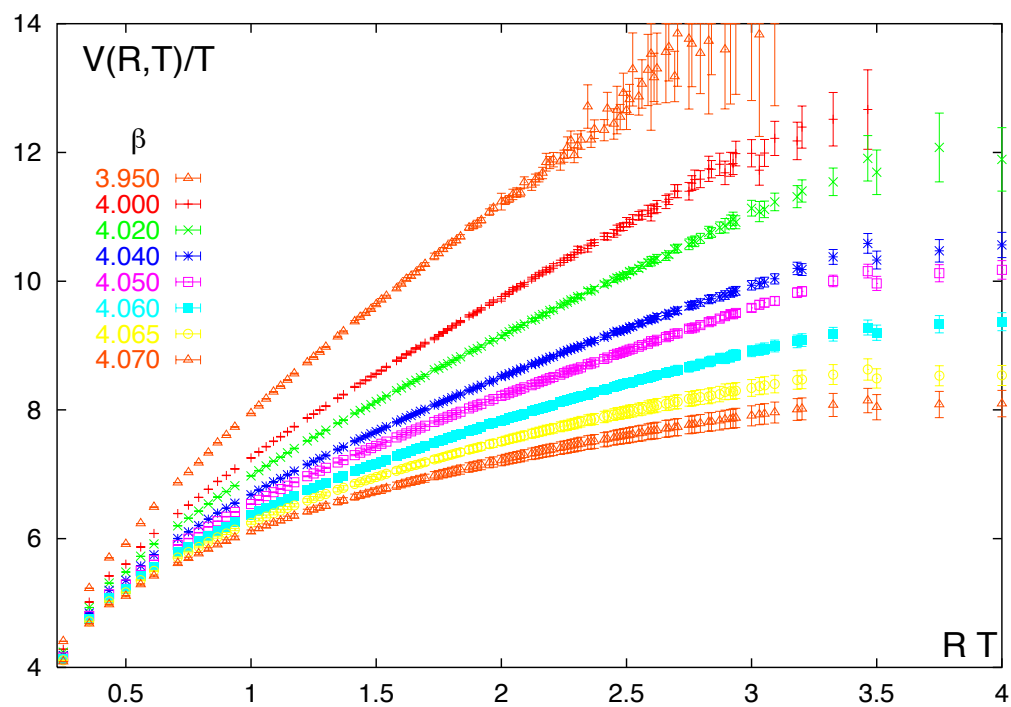
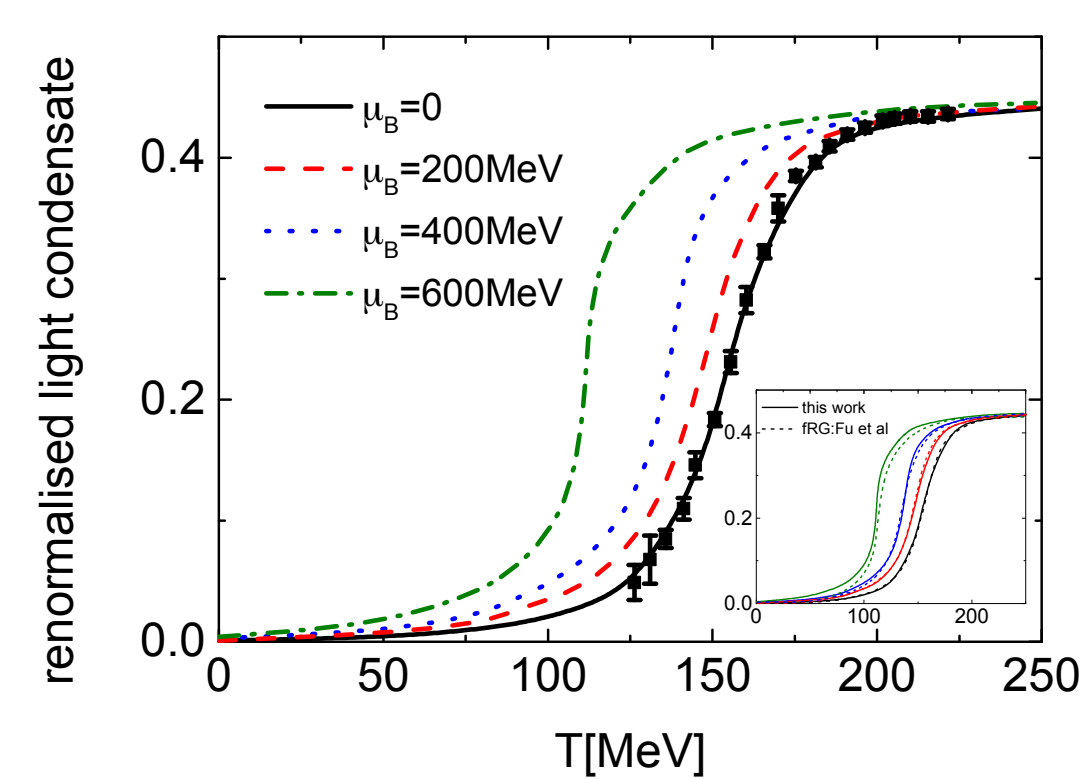


## Moat regime & inhomogeneous phases: CEP & beyond

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

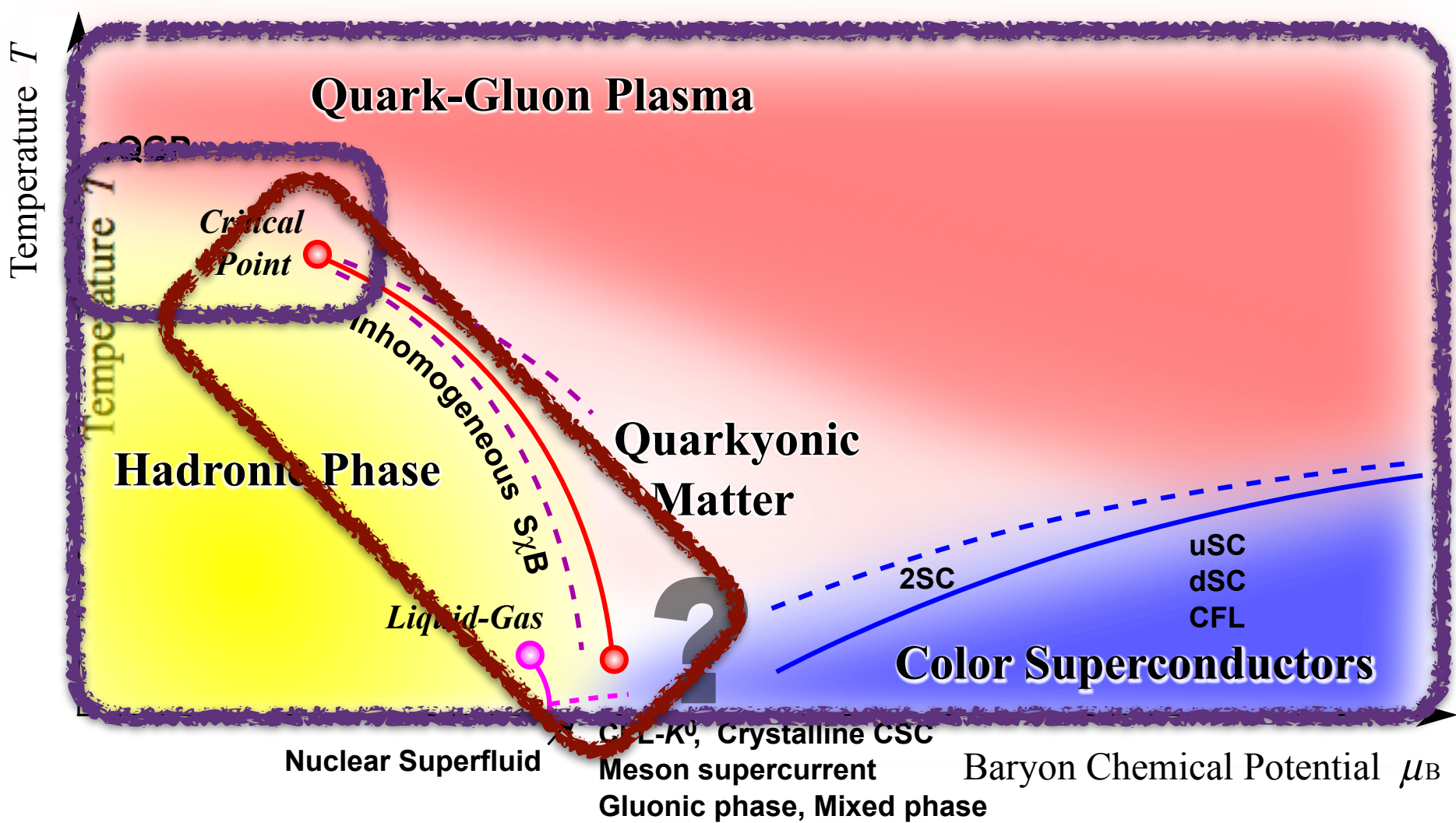
QCD Moat: Pisarski, Rennecke, PRL 127 (2021) 152302

## Chiral symmetry breaking & Confinement: the search for the CEP





# QCD phase structure



## Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



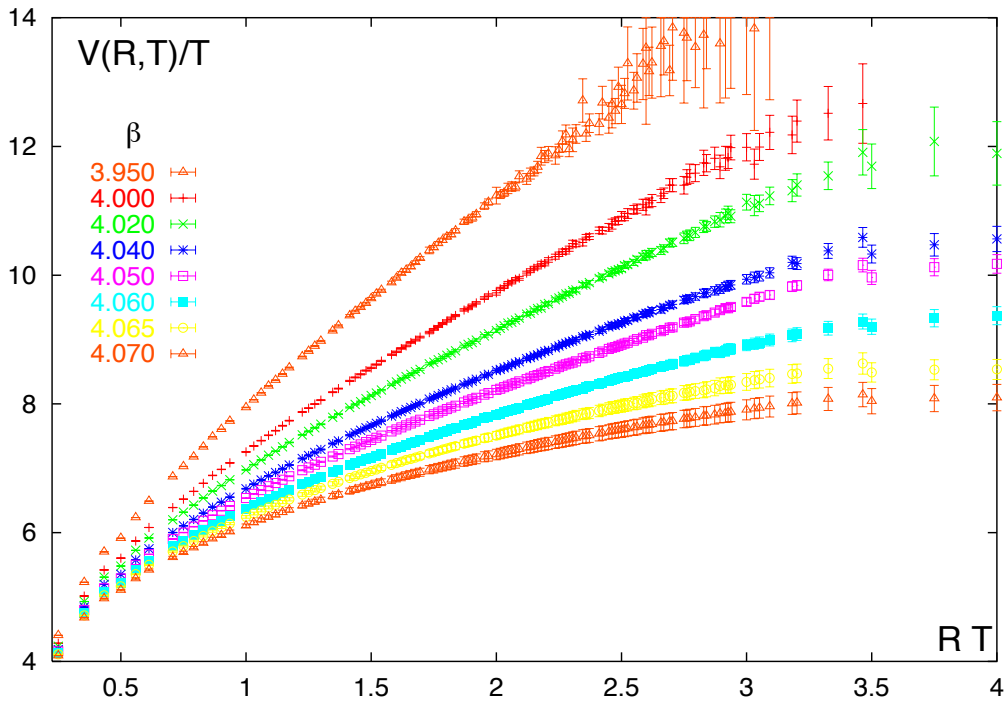
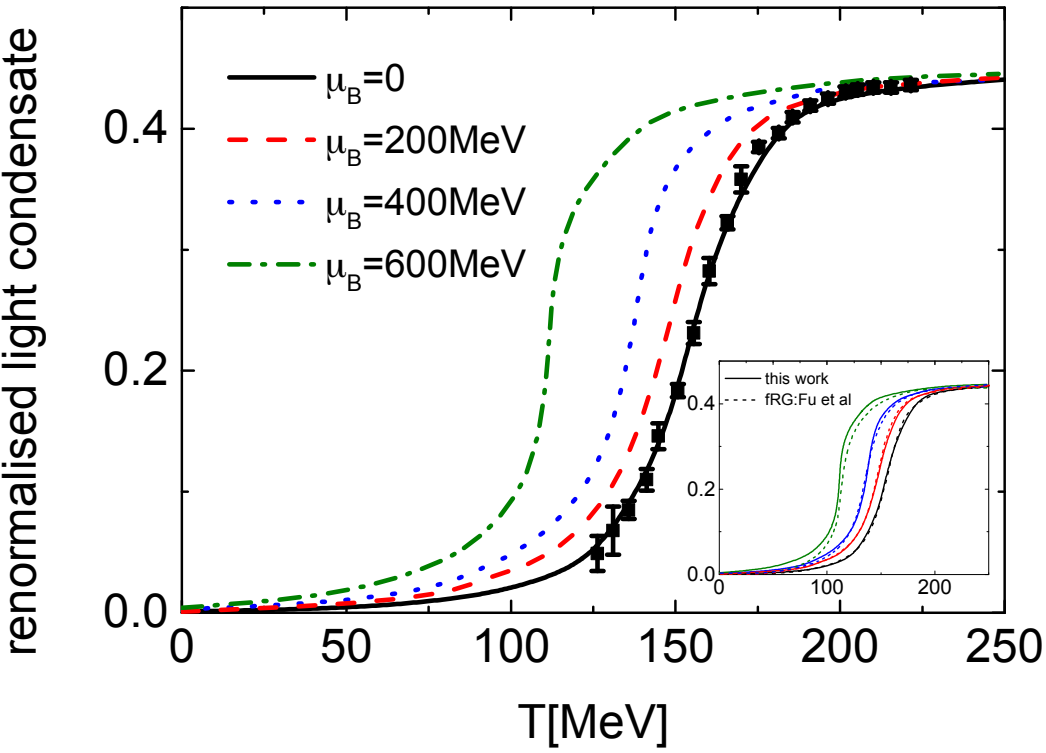
Wikimedia commons:  
© Günter Seggebäing, CC BY-SA 3.0

US Moat



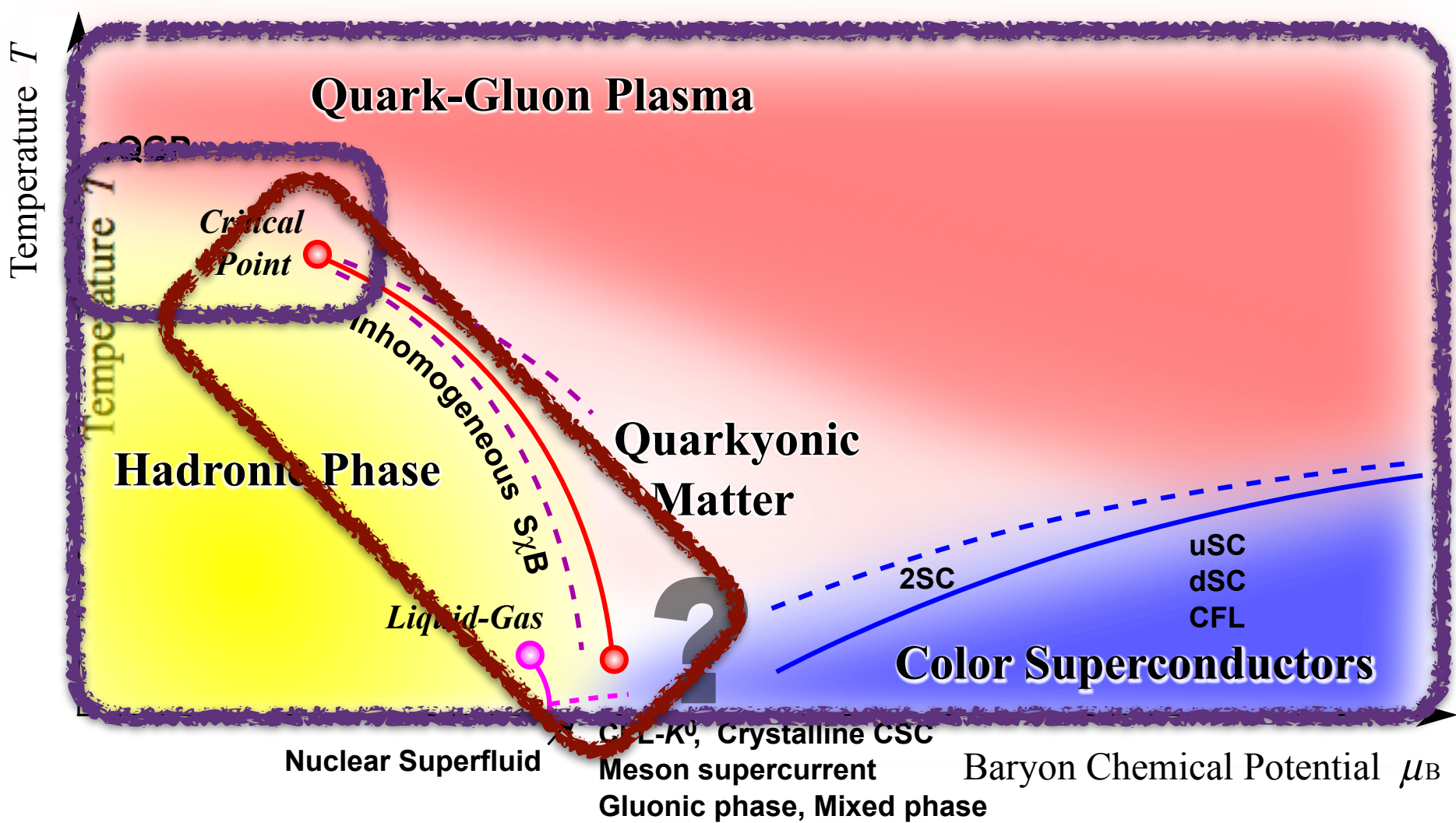
Wikipedia

## Chiral symmetry breaking & Confinement: the search for the CEP





# QCD phase structure



## Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



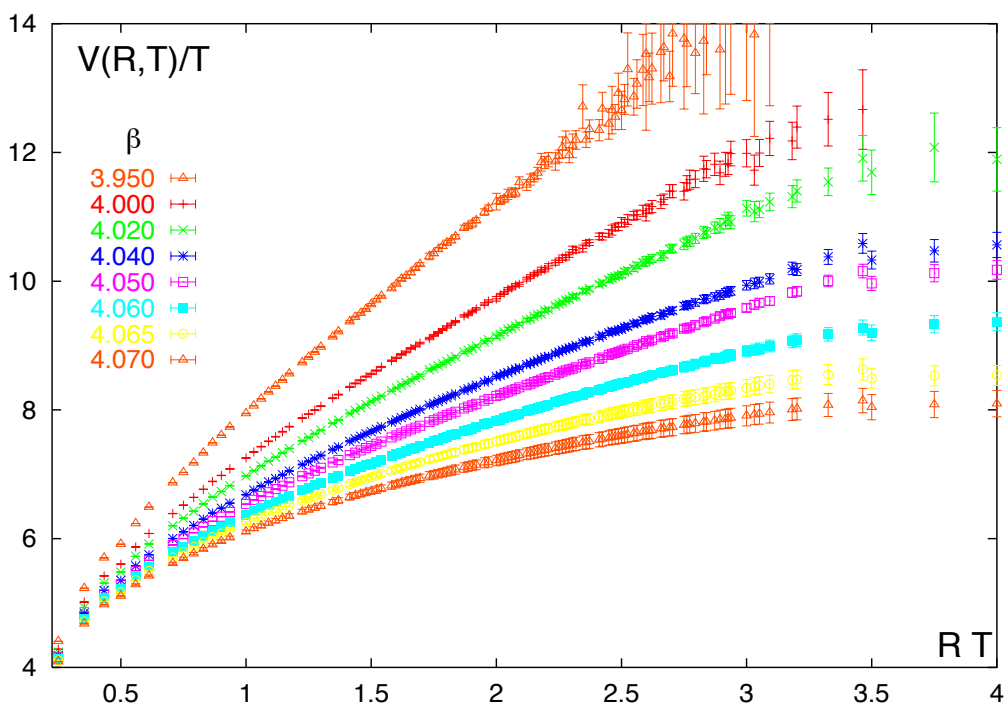
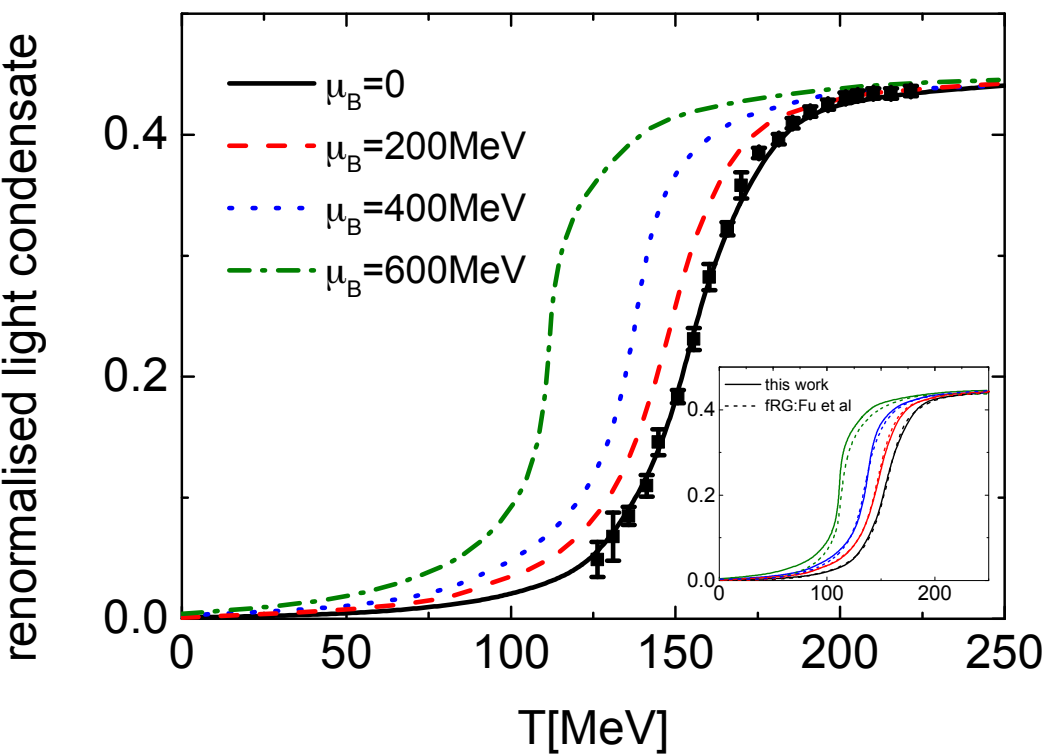
Wikimedia commons:  
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US Moat

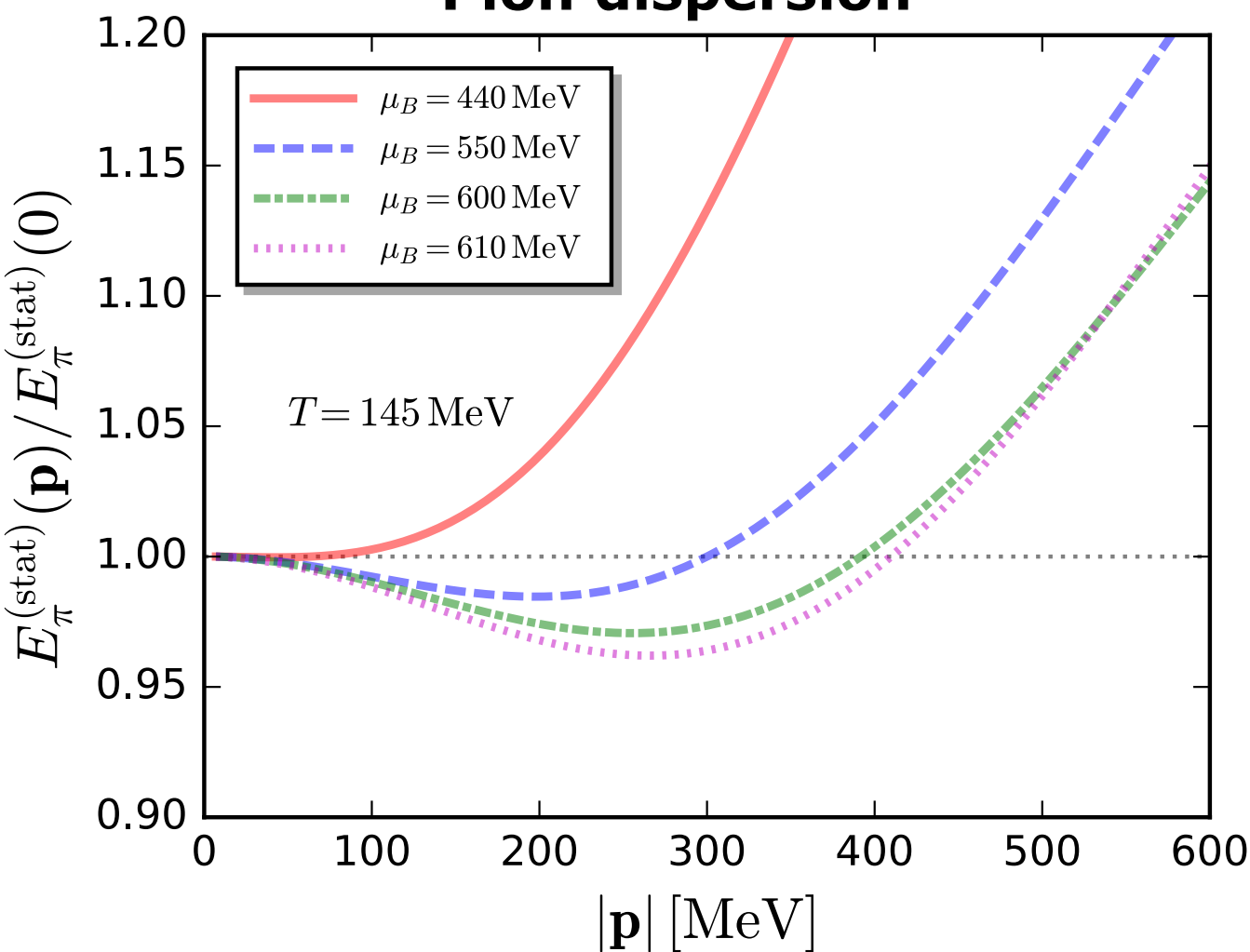


Wikipedia

## Chiral symmetry breaking & Confinement: the search for the CEP

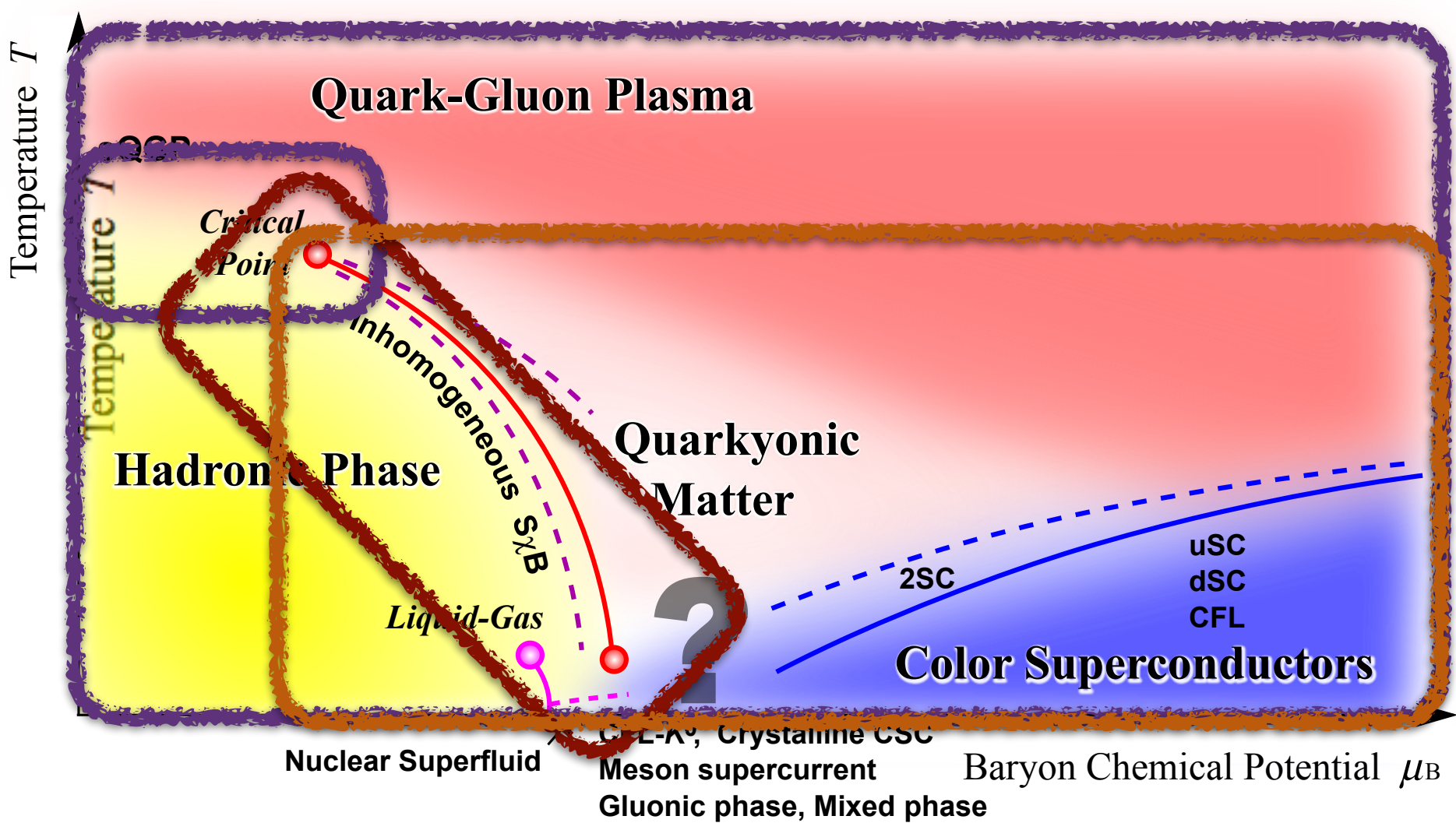


Pion dispersion





# QCD phase structure



## Moat regime & inhomogeneous phases: CEP & beyond

Chinese Moat



Wikipedia

German Moat



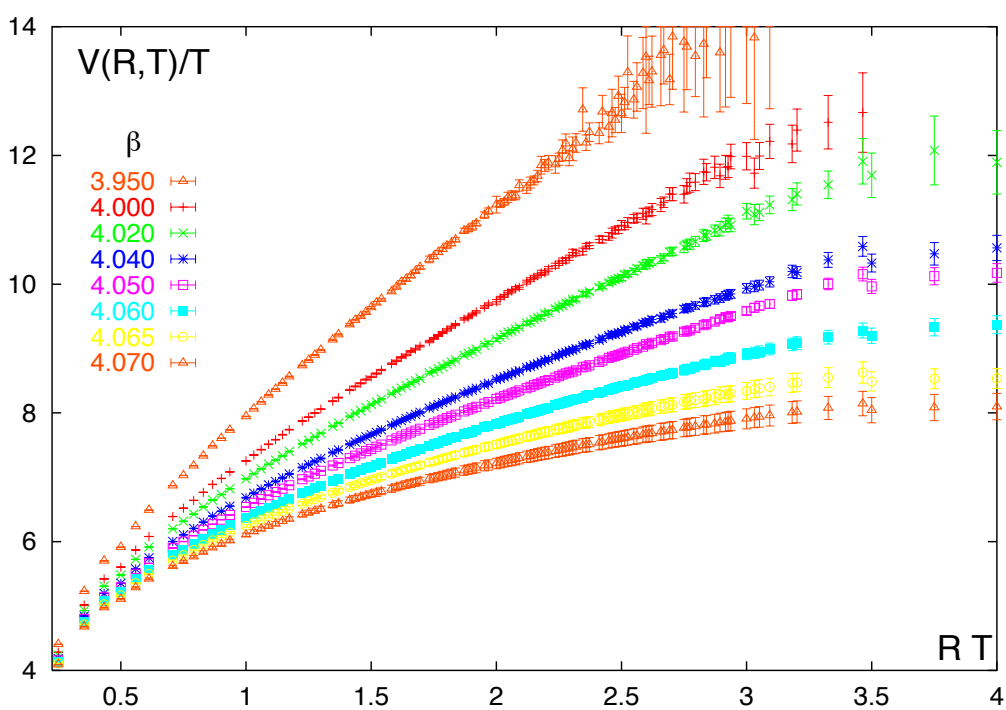
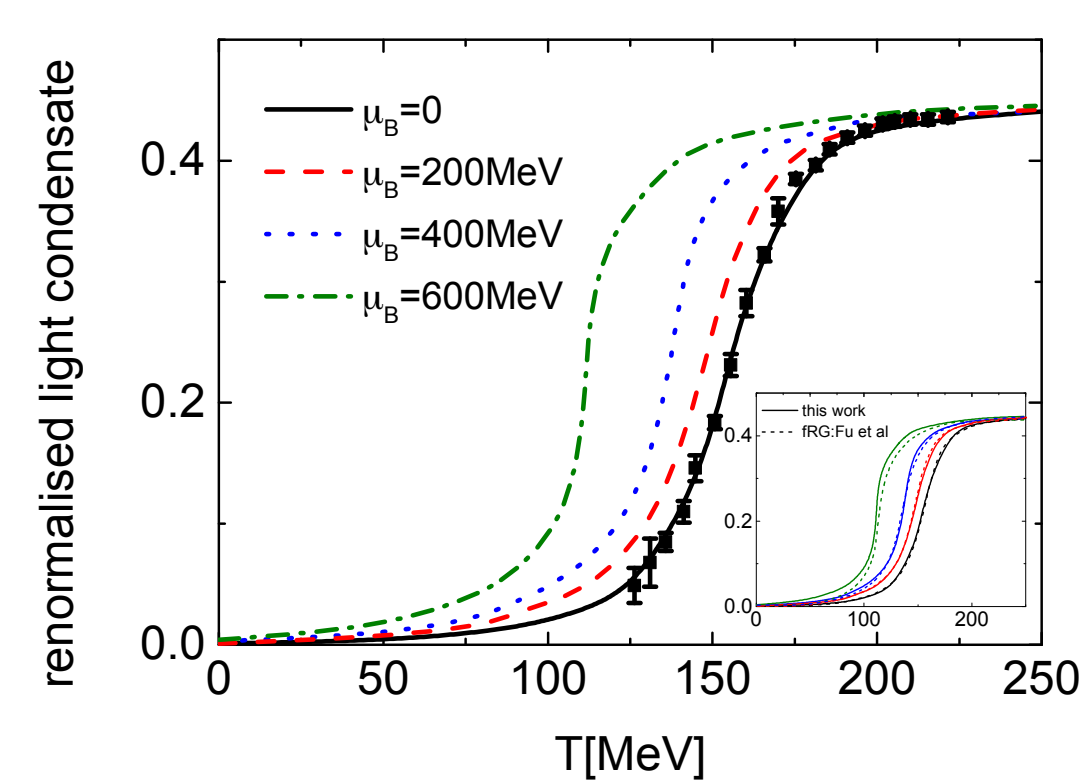
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US Moat



Wikipedia

## Chiral symmetry breaking & Confinement: the search for the CEP



## Condensed matter QCD

Color superconductivity

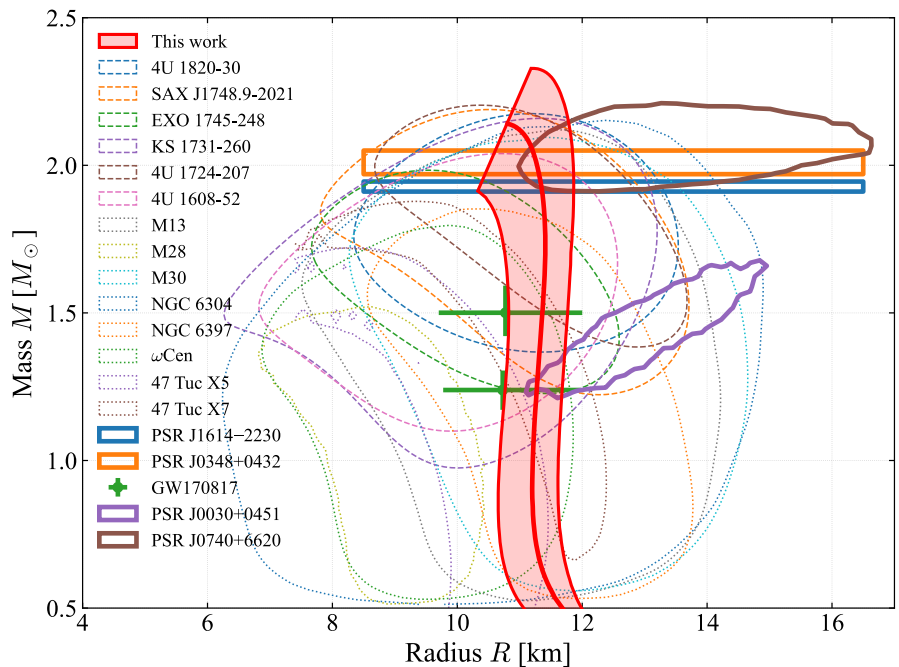
Competing orders

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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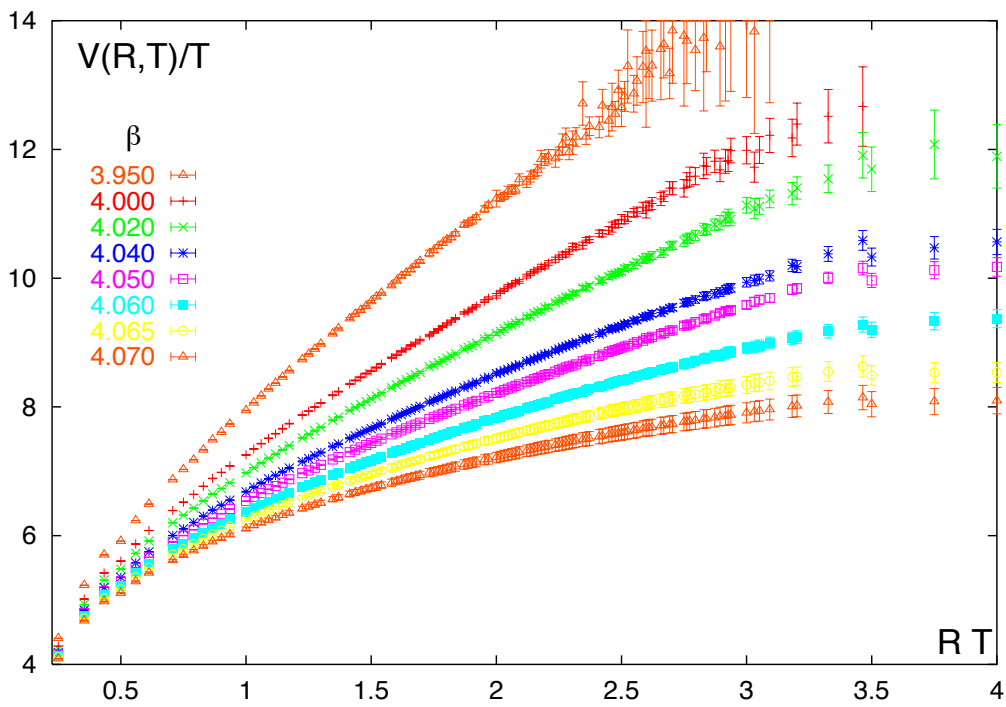
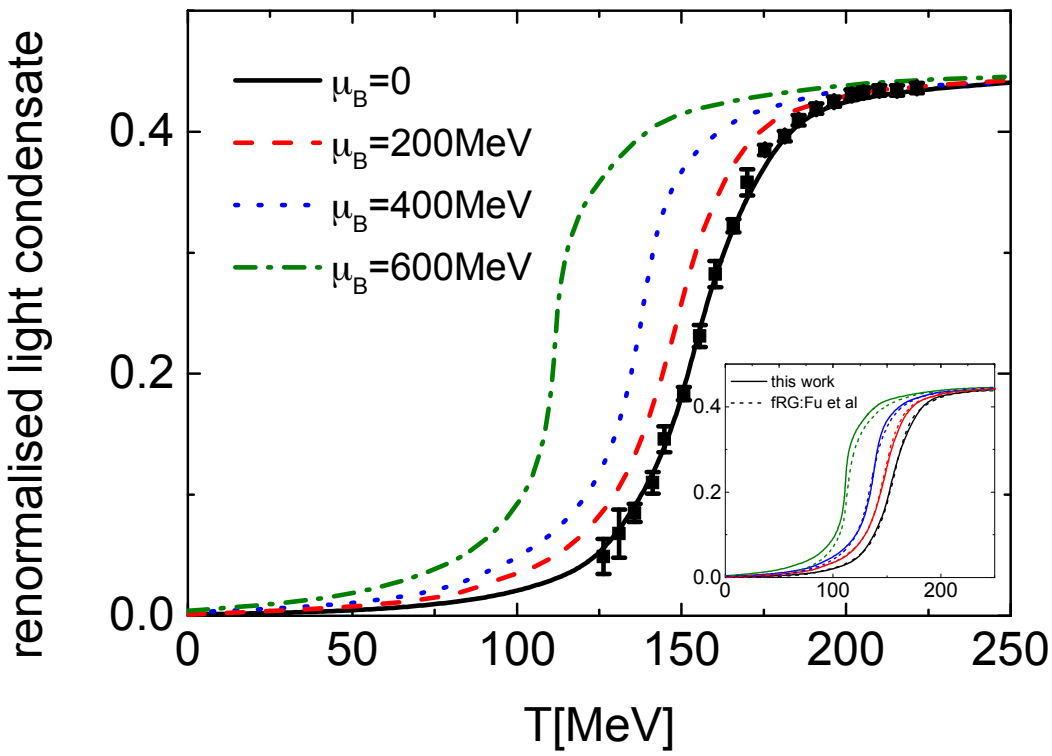
US Moat



Wikipedia

## Chiral symmetry breaking & Confinement: the search for the CEP

## Condensed matter QCD



## Color superconductivity

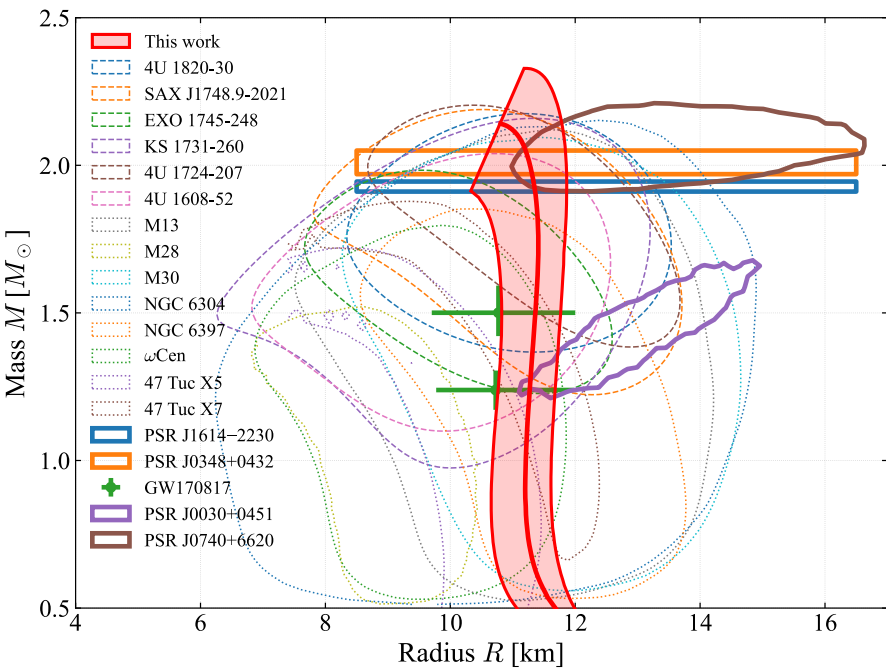
## Competing orders

## Nuclear EoS

- 
- 
- 

## Data Analysis

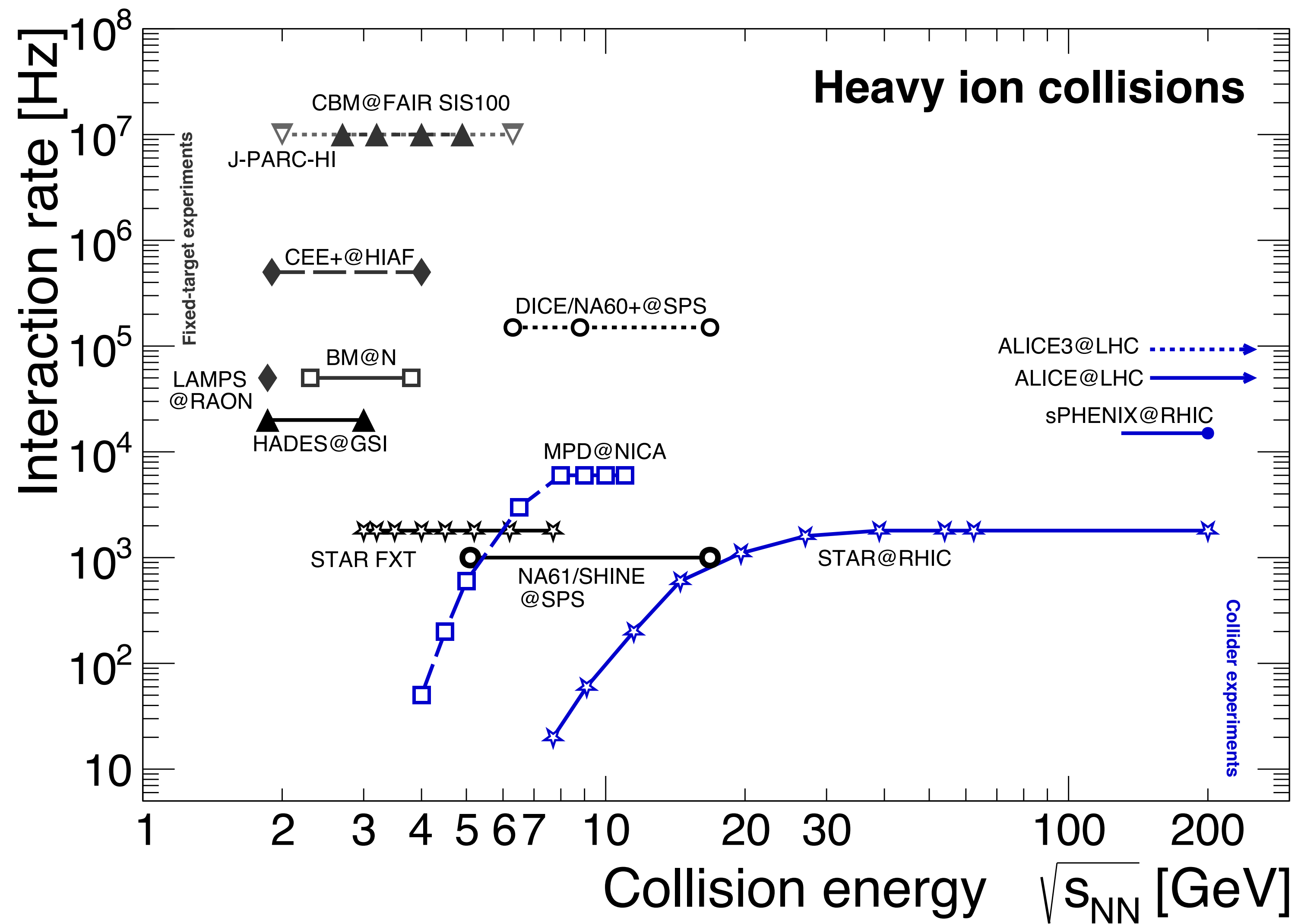
Fujimoto-Fukushima-Kamata-Murase (2018-2024)



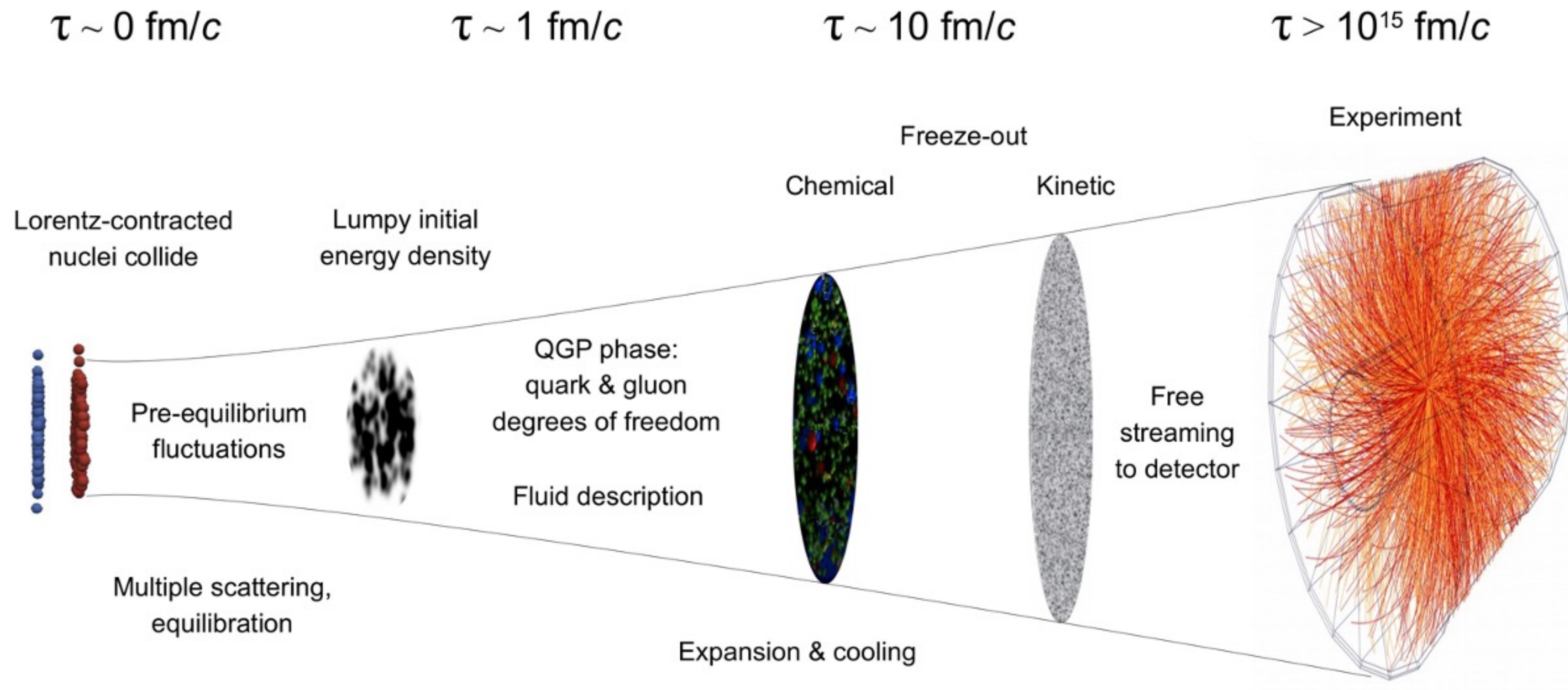


# Strongly correlated QCD: how to?

## (2) Experiments (extreme QCD)

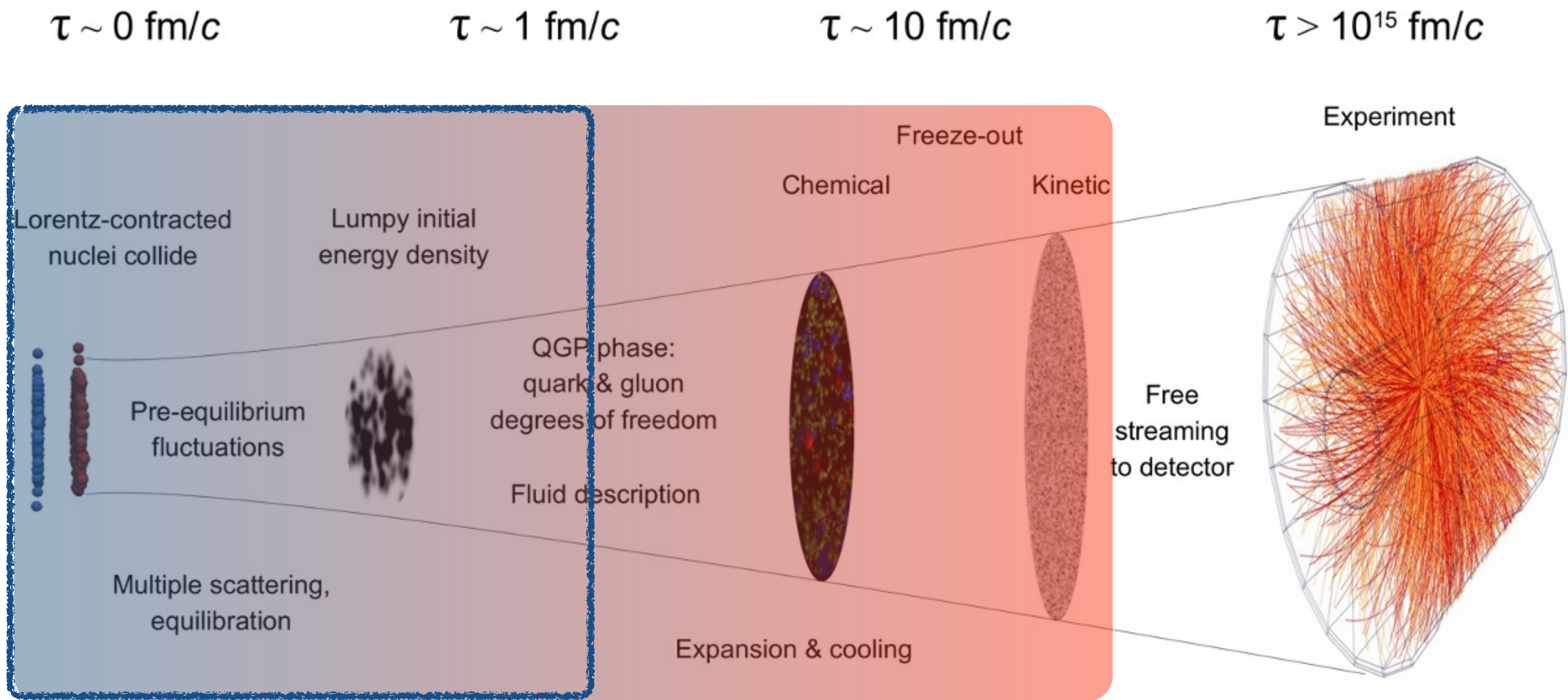


# Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)





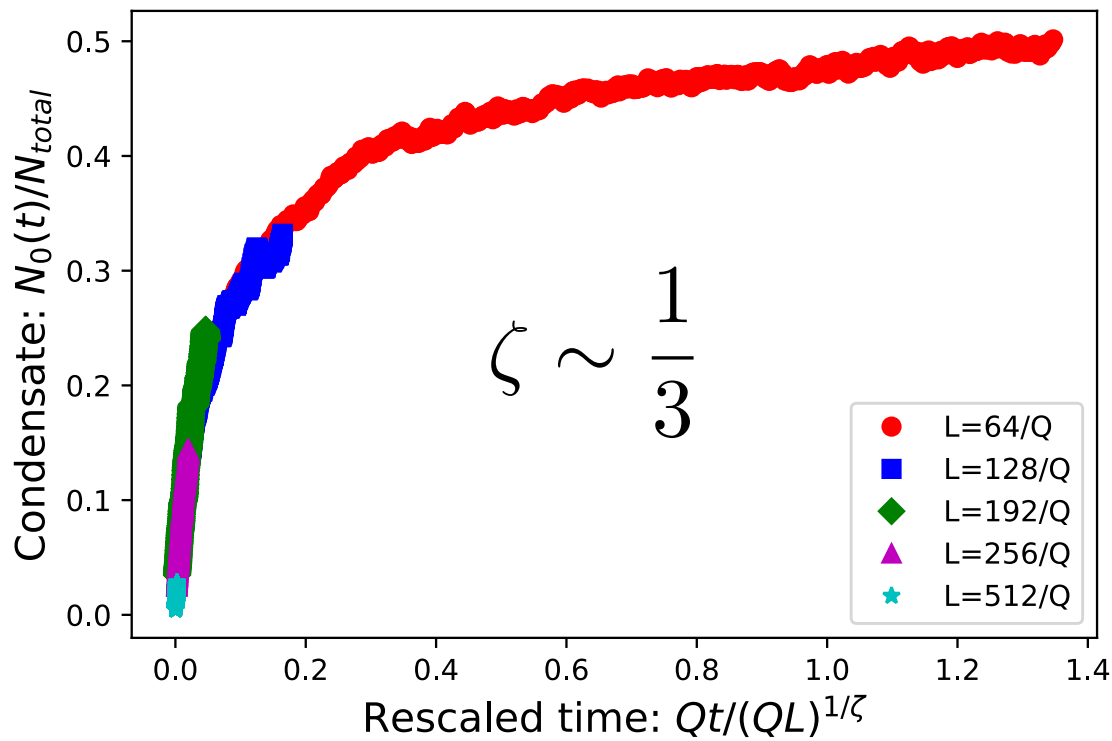
# Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)



large occupancies

non-thermal fixed point

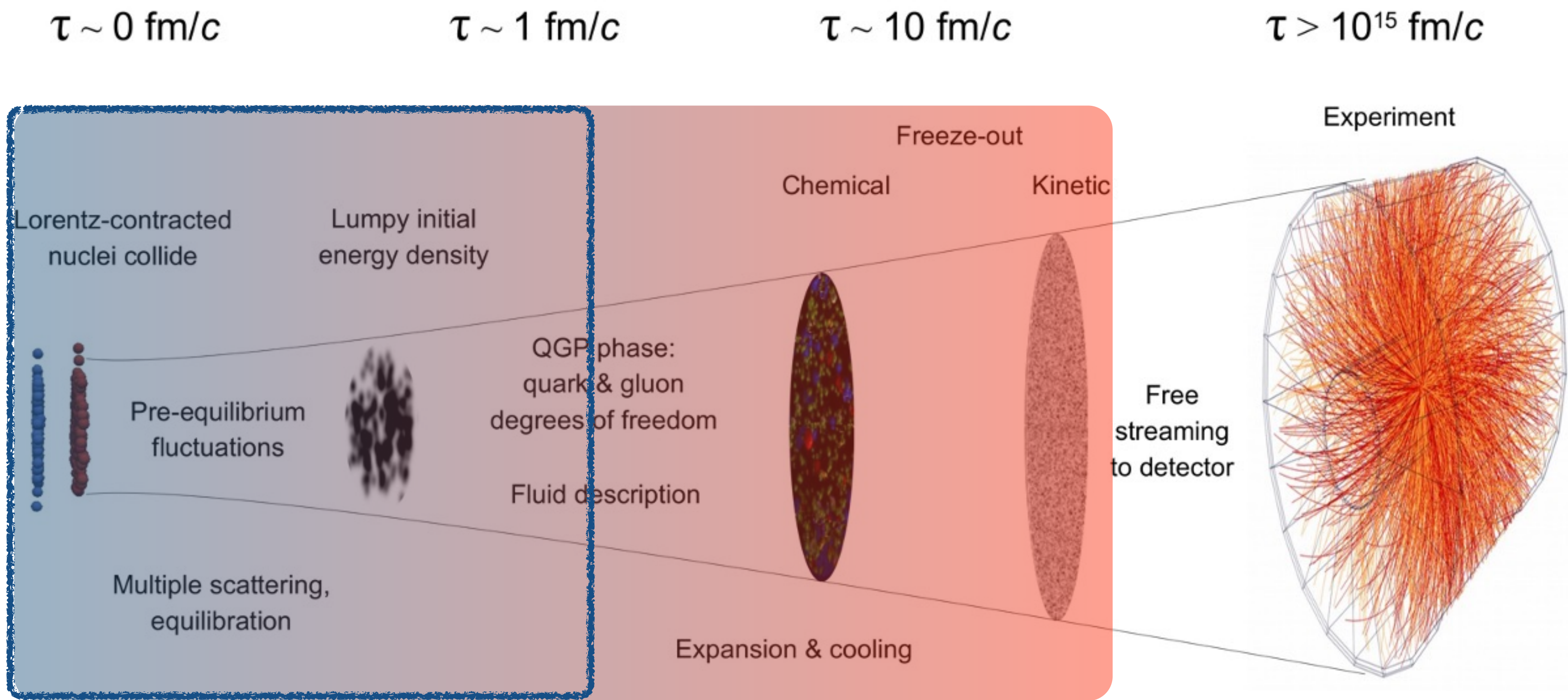
Classical-statistical



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



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



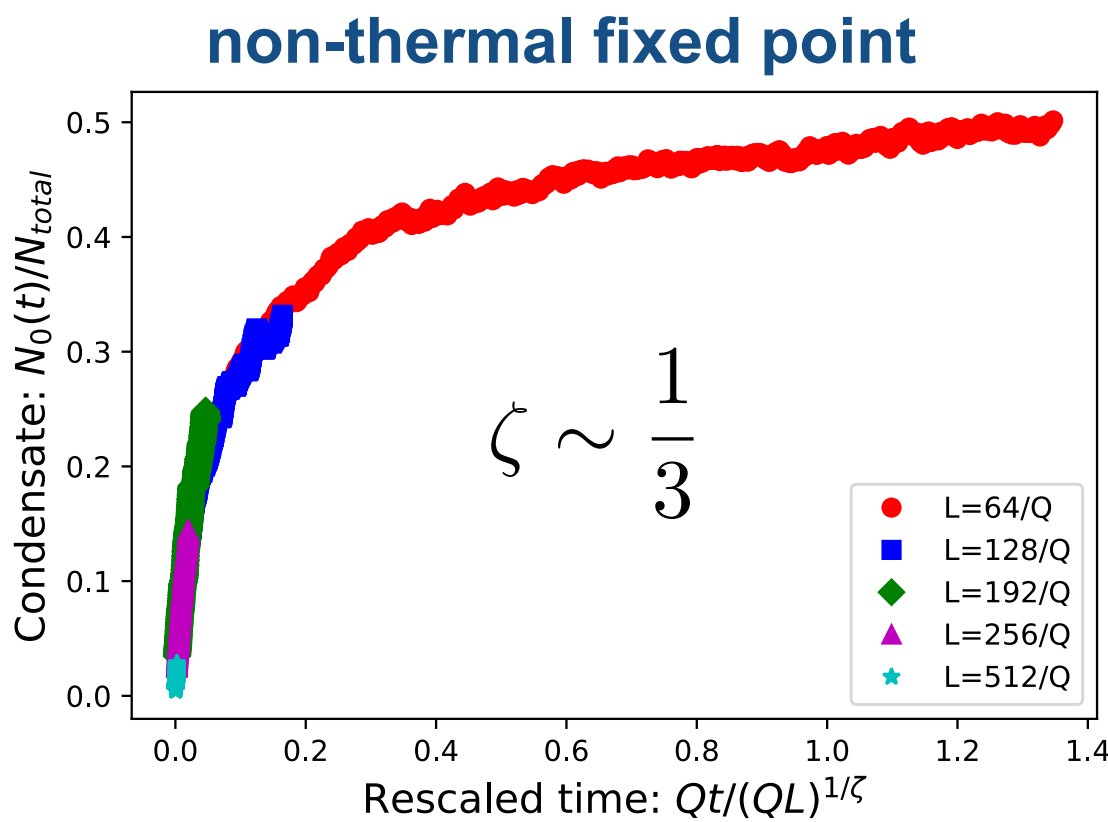
large occupancies

statistics + collective behaviour

&

strongly correlated quantum dynamics

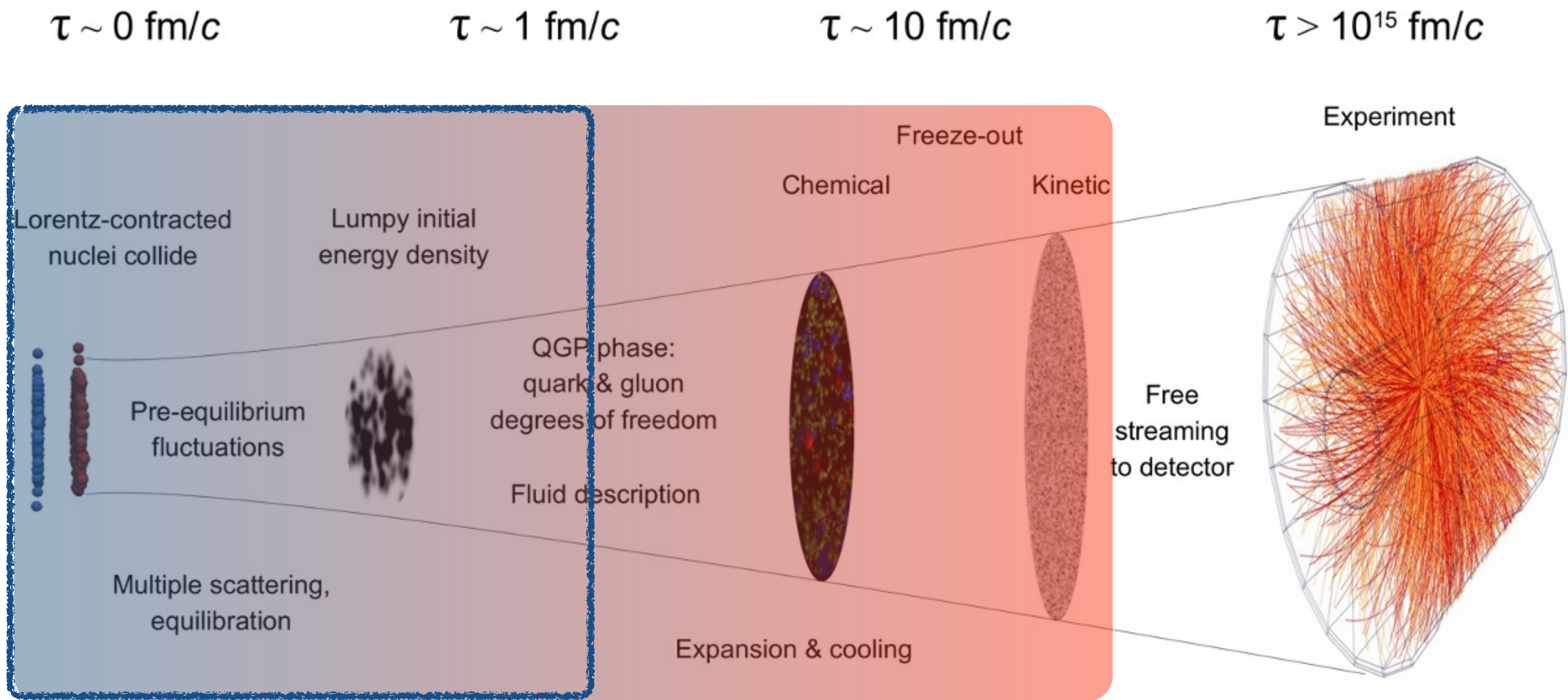
Classical-statistical



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



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



large occupancies

statistics + collective behaviour

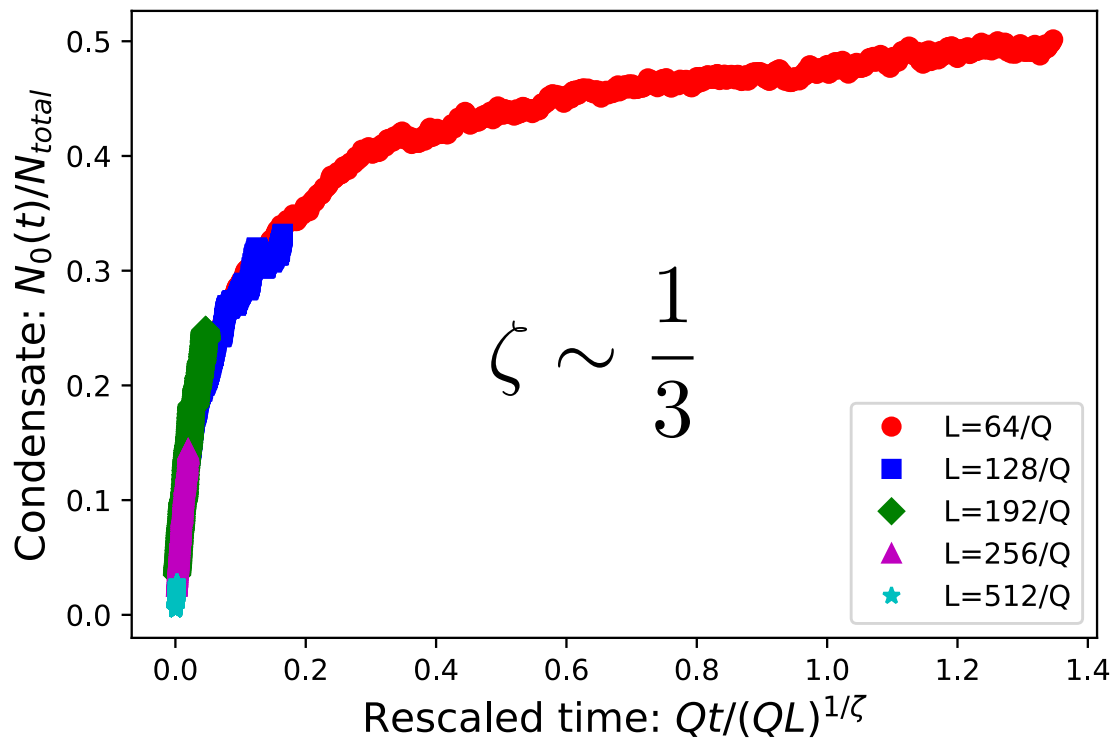
Background

&

strongly correlated quantum dynamics

Classical-statistical

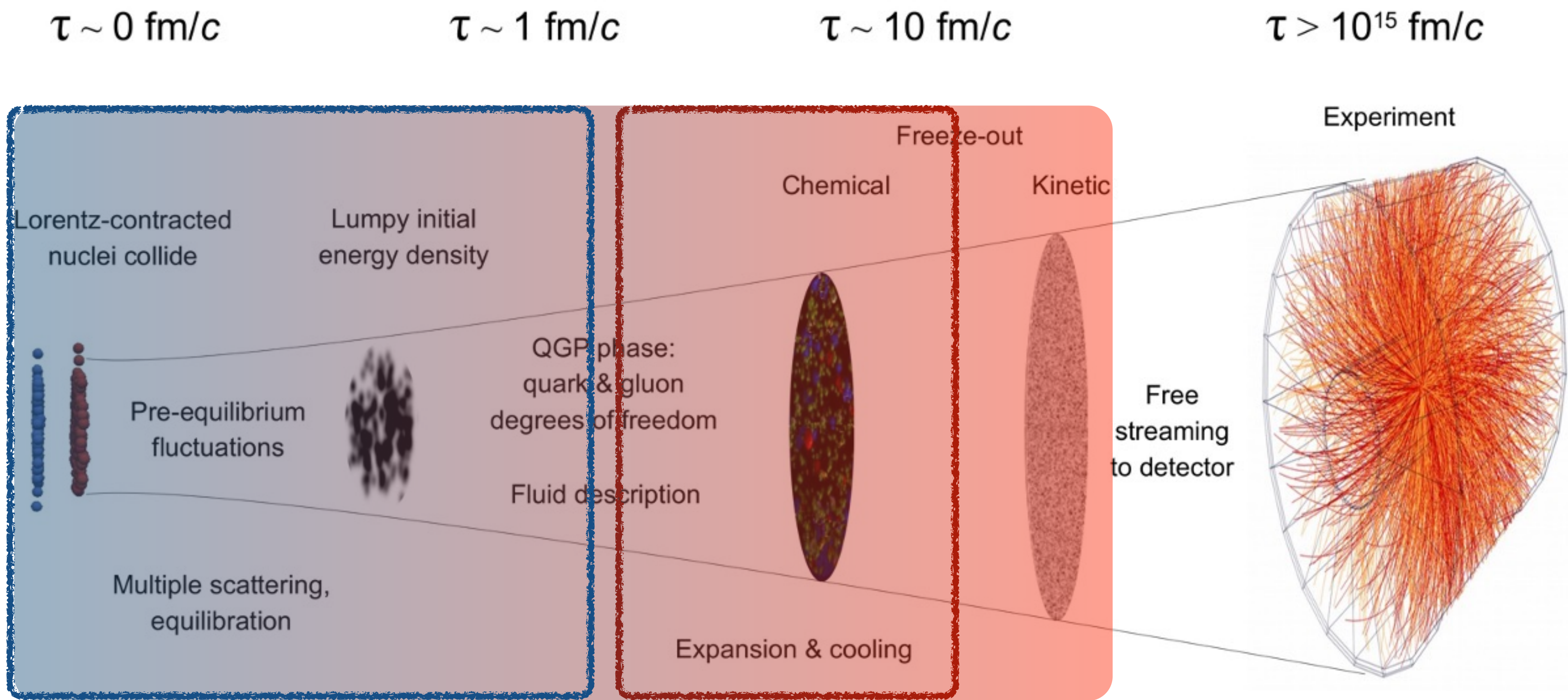
non-thermal fixed point



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



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



large occupancies

statistics + collective behaviour

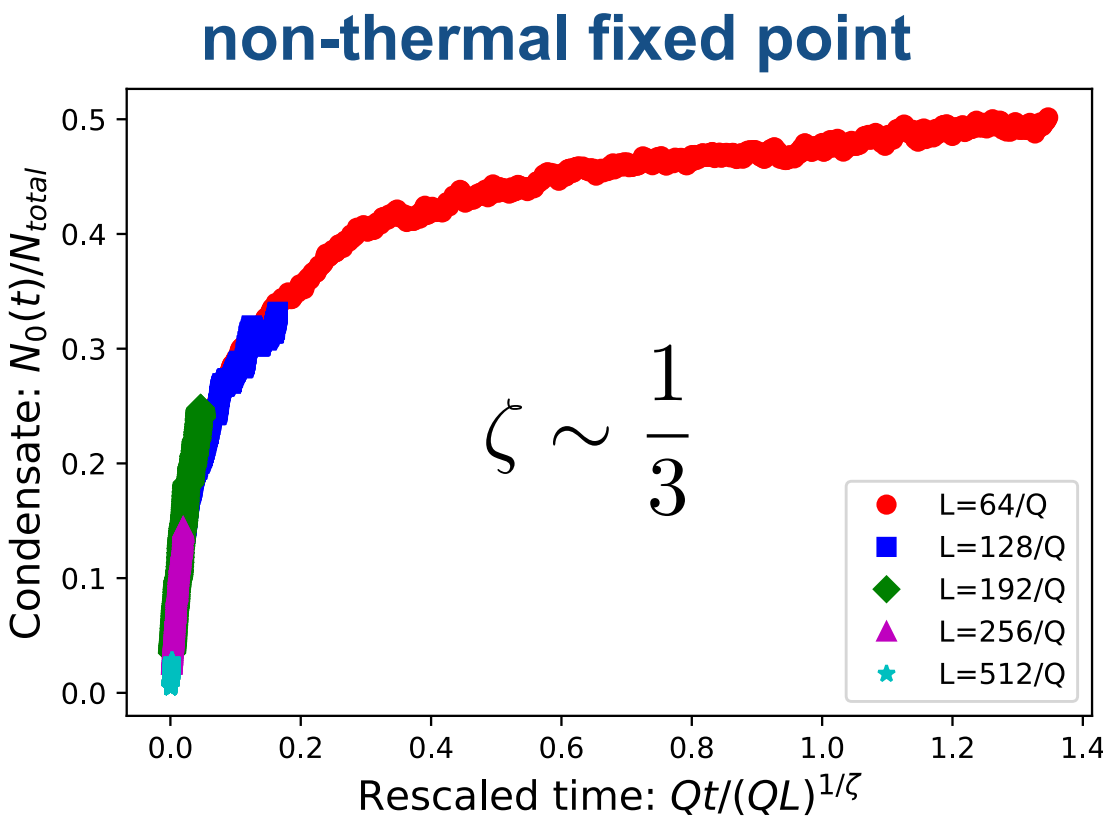
Background

&

strongly correlated quantum dynamics

The cool stuff!

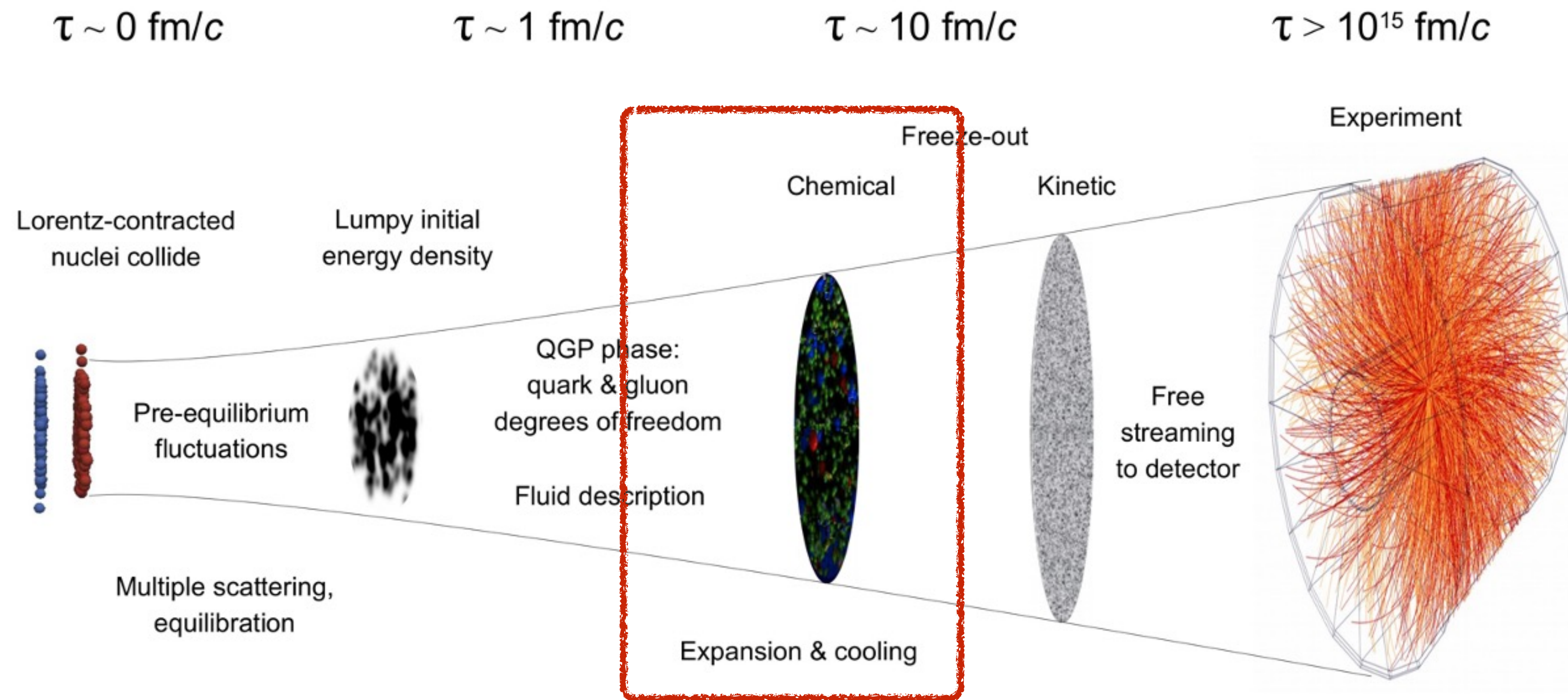
Classical-statistical



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



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

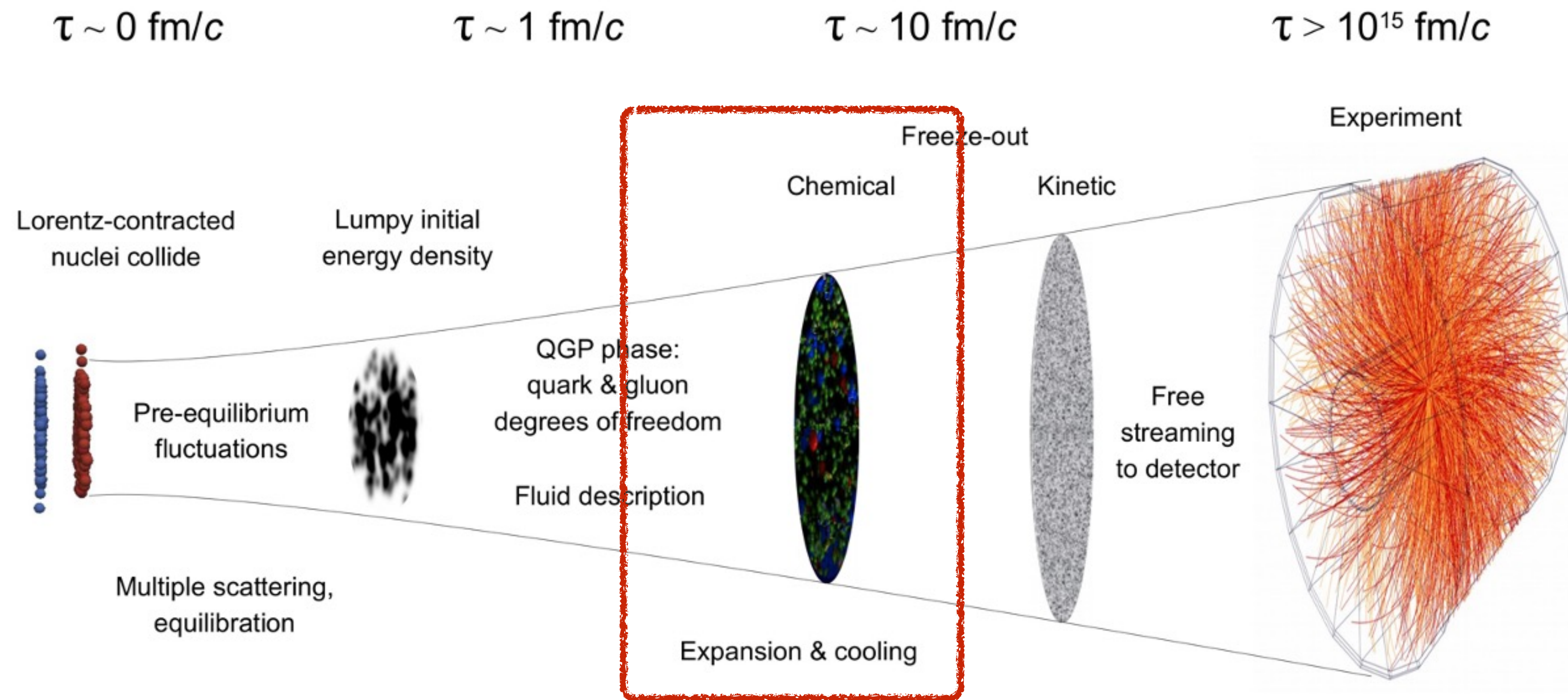


How to unfold: inverse problem!

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

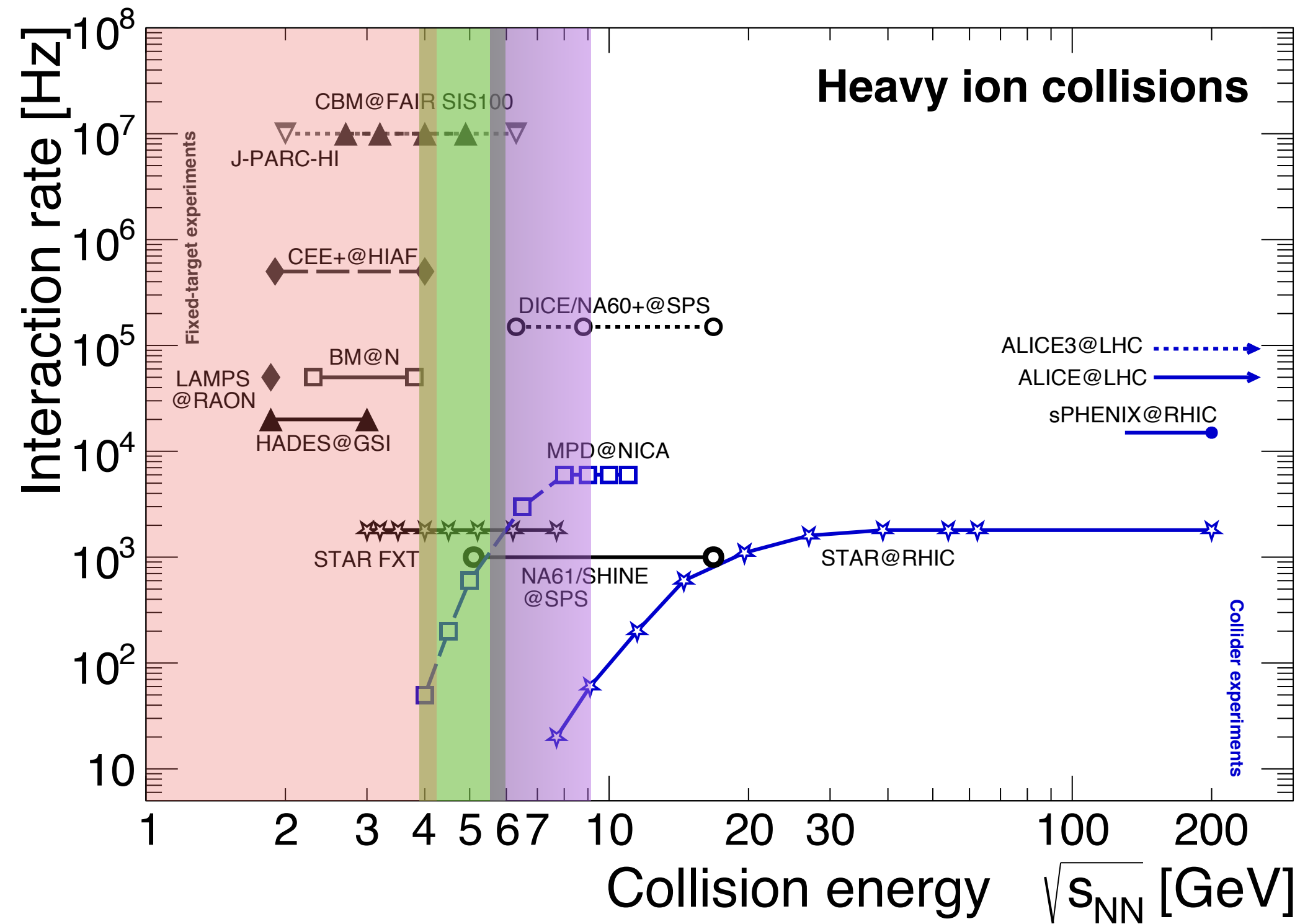
## Experimental landscape

## Theoretical landscape

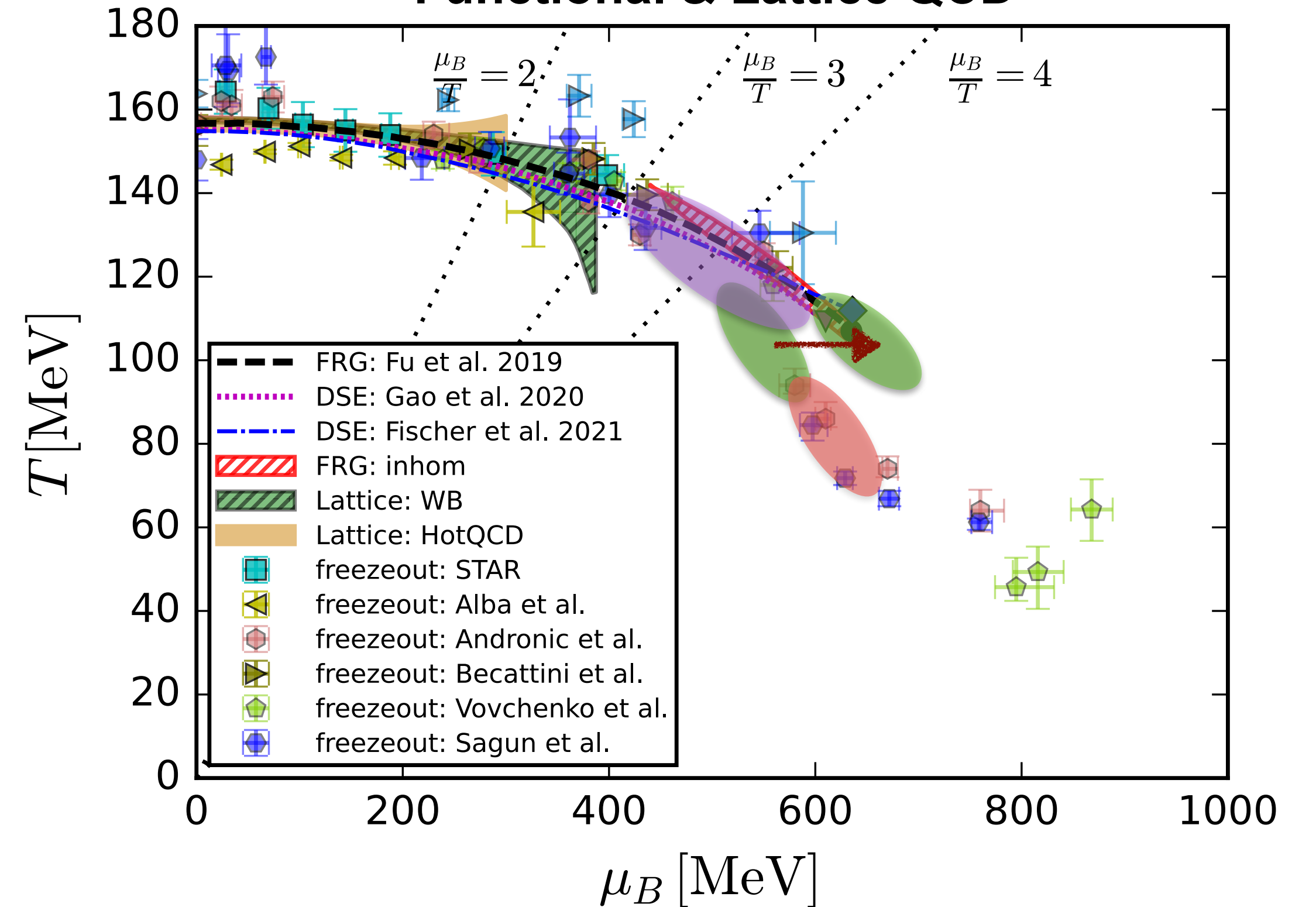
Onset of new phases on the chiral transition line (CEP)

### 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

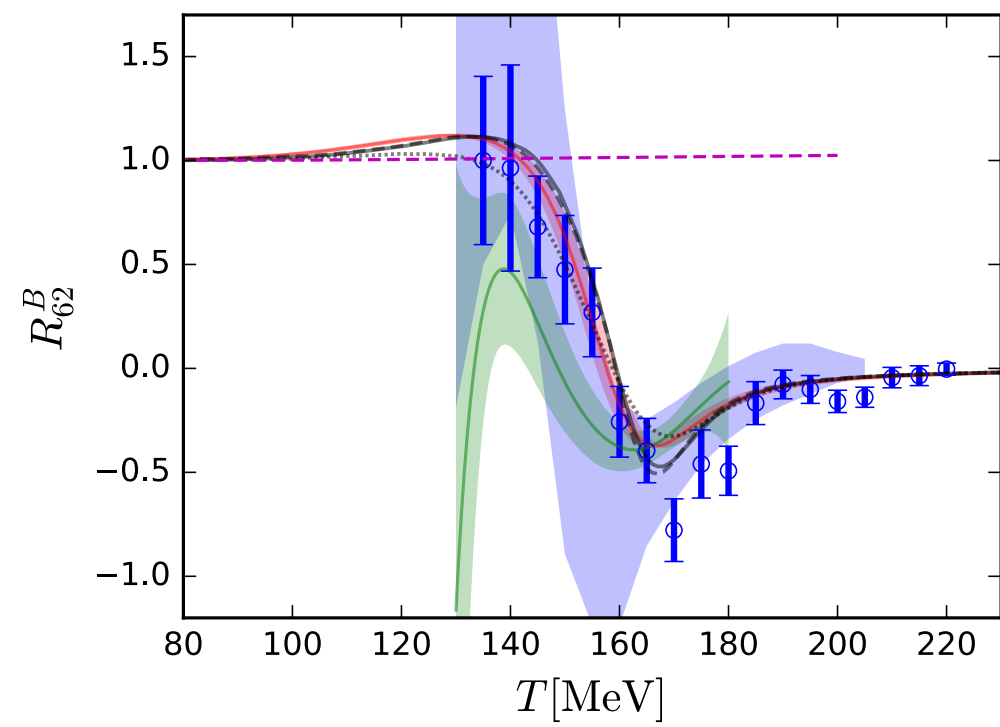
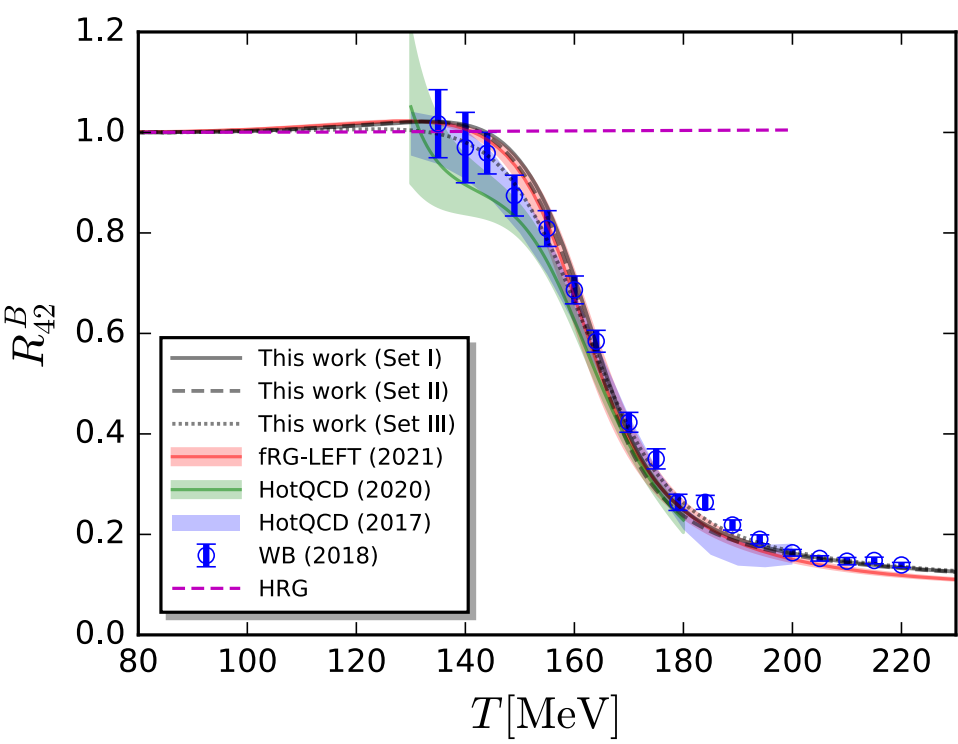
Fu, JMP, Rennecke, PRD 101 (2020) 054032

Gao, JMP, PLB 820 (2021) 136584

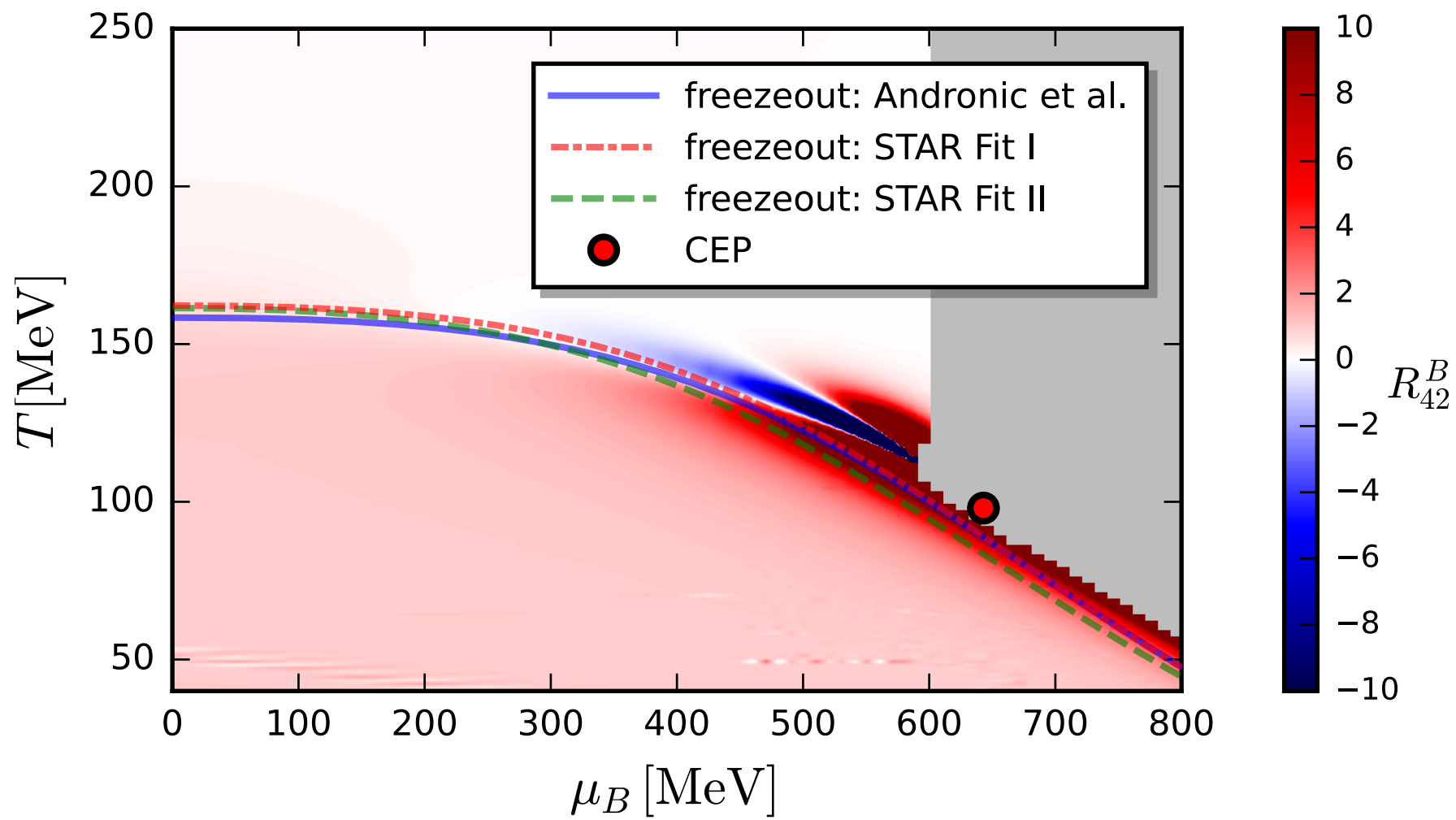
Gunkel, Fischer, PRD 104 (2021) 054022



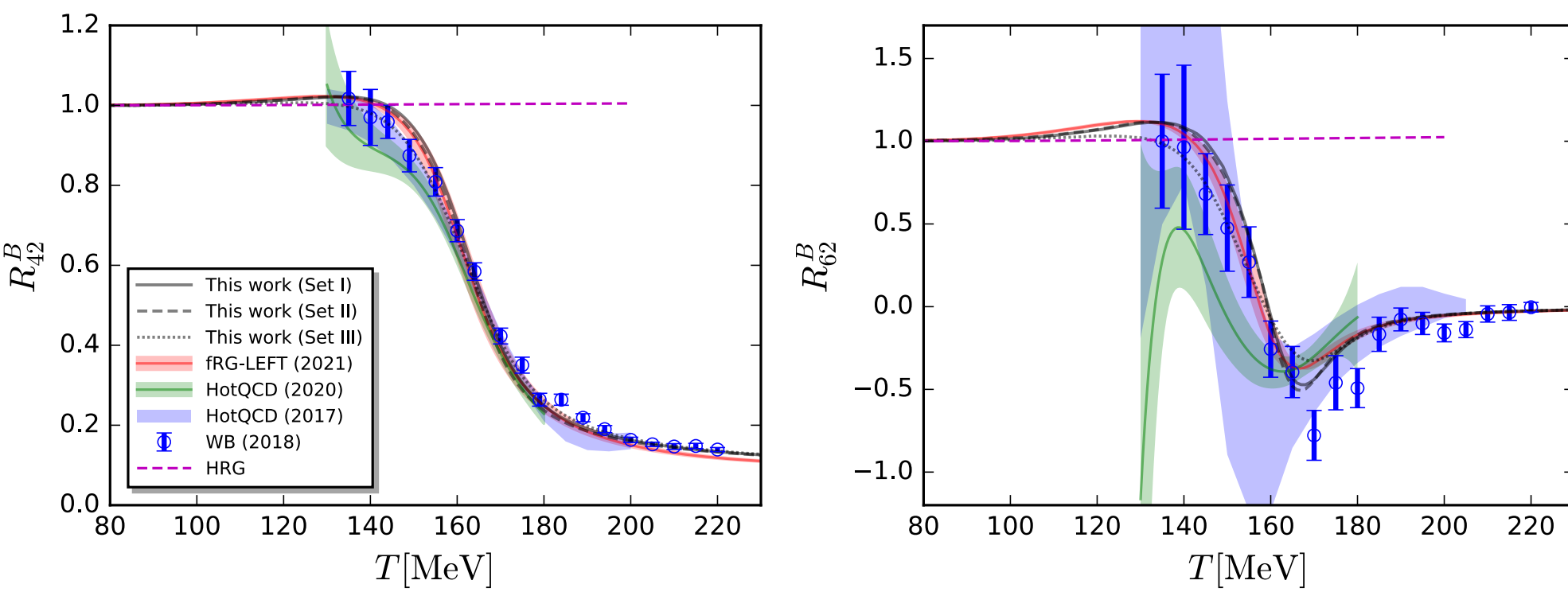
# Ripples of the critical point from fluctuations of conserved charges



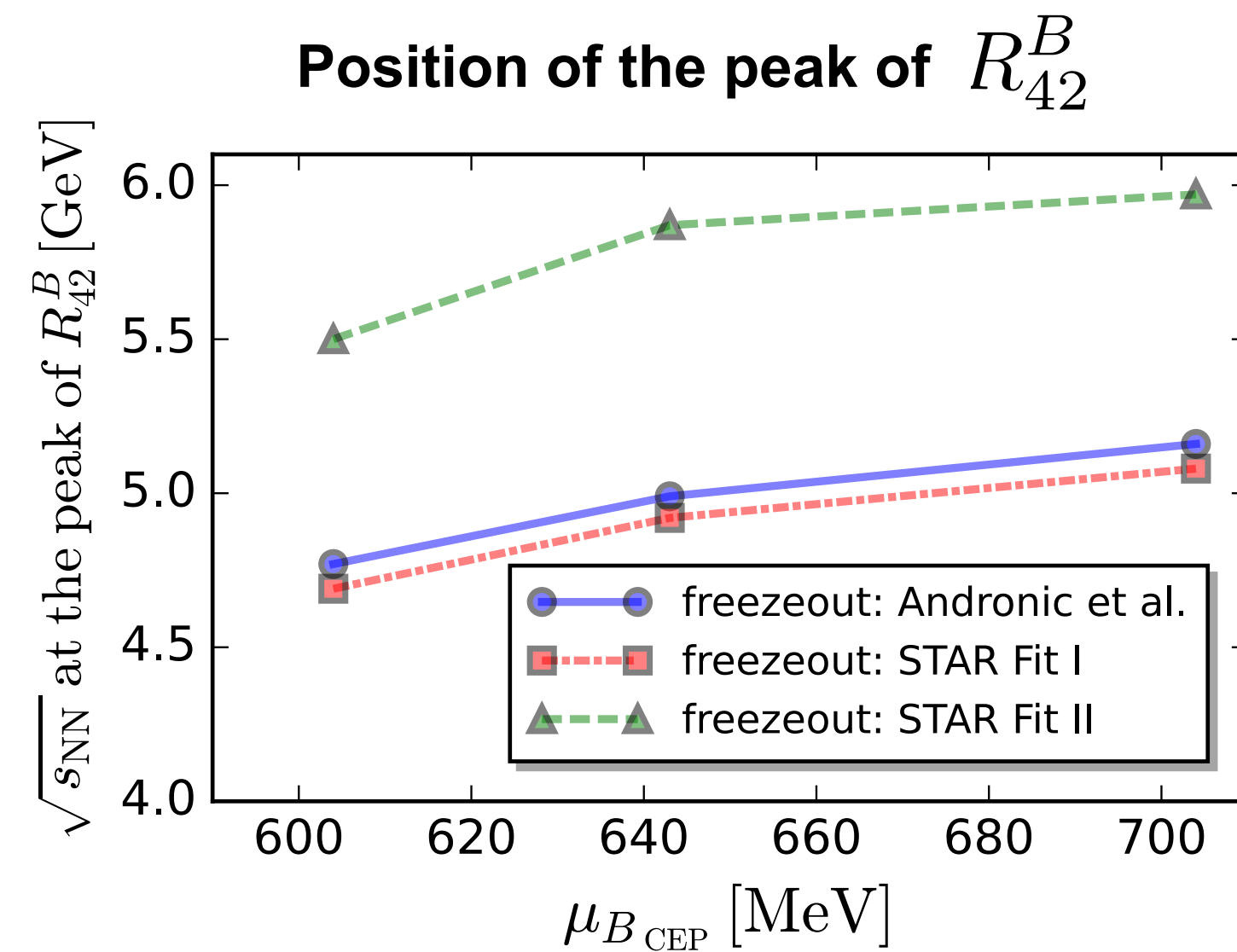
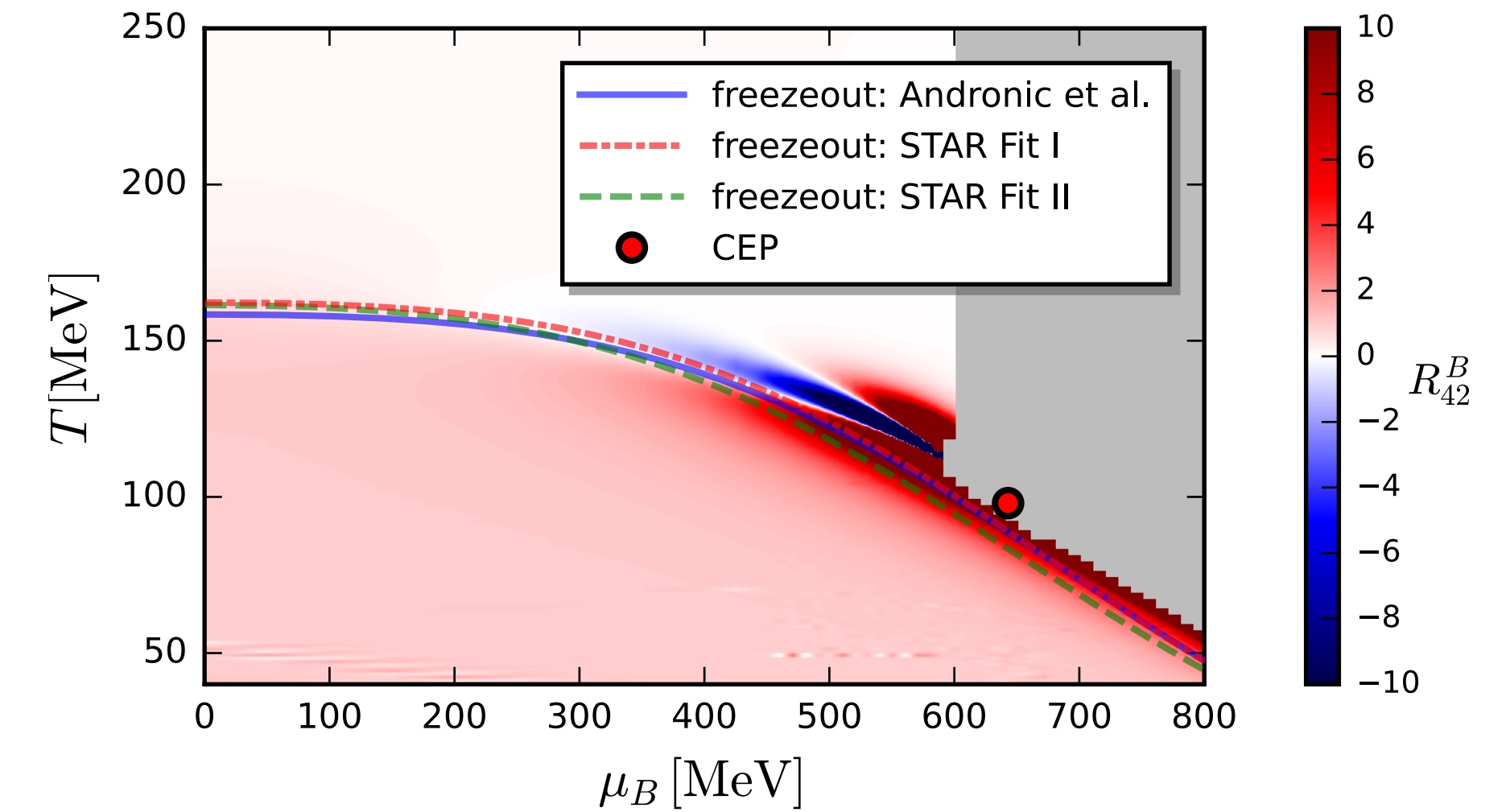
**baryon number fluctuations**



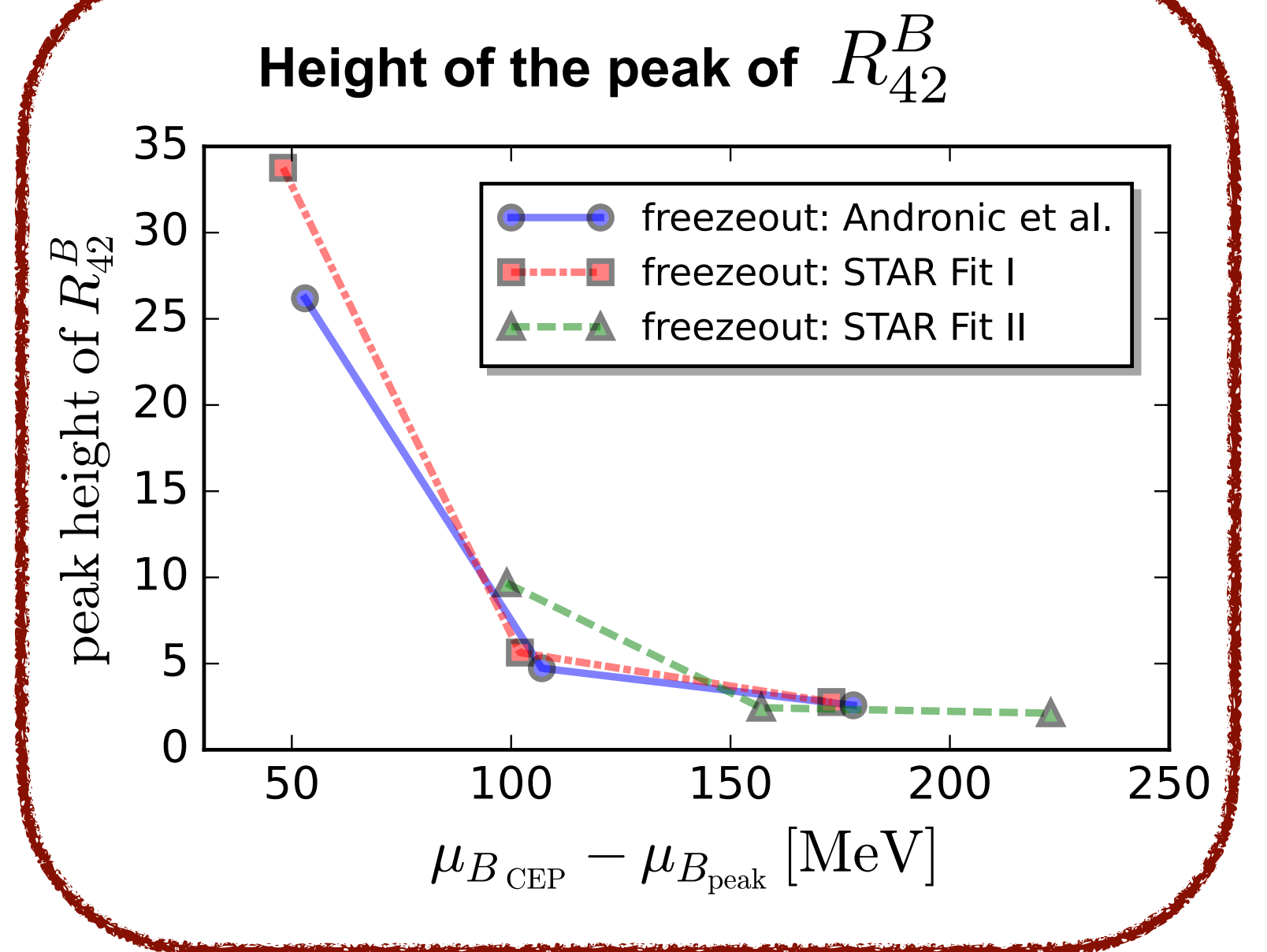
# Ripples of the critical point from fluctuations of conserved charges



baryon number fluctuations

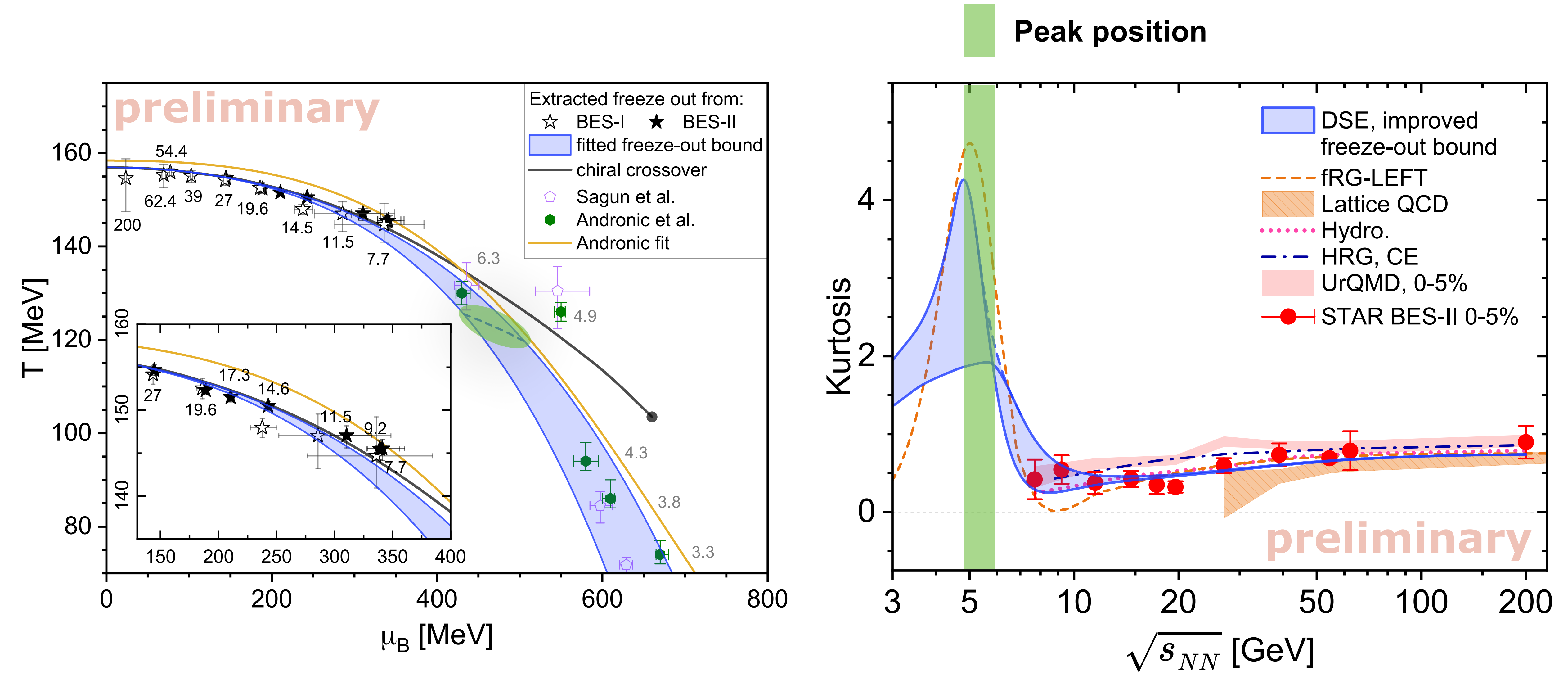


Reconstructing the CEP





# Ripples of the critical point at chemical freeze-out



# Outlook



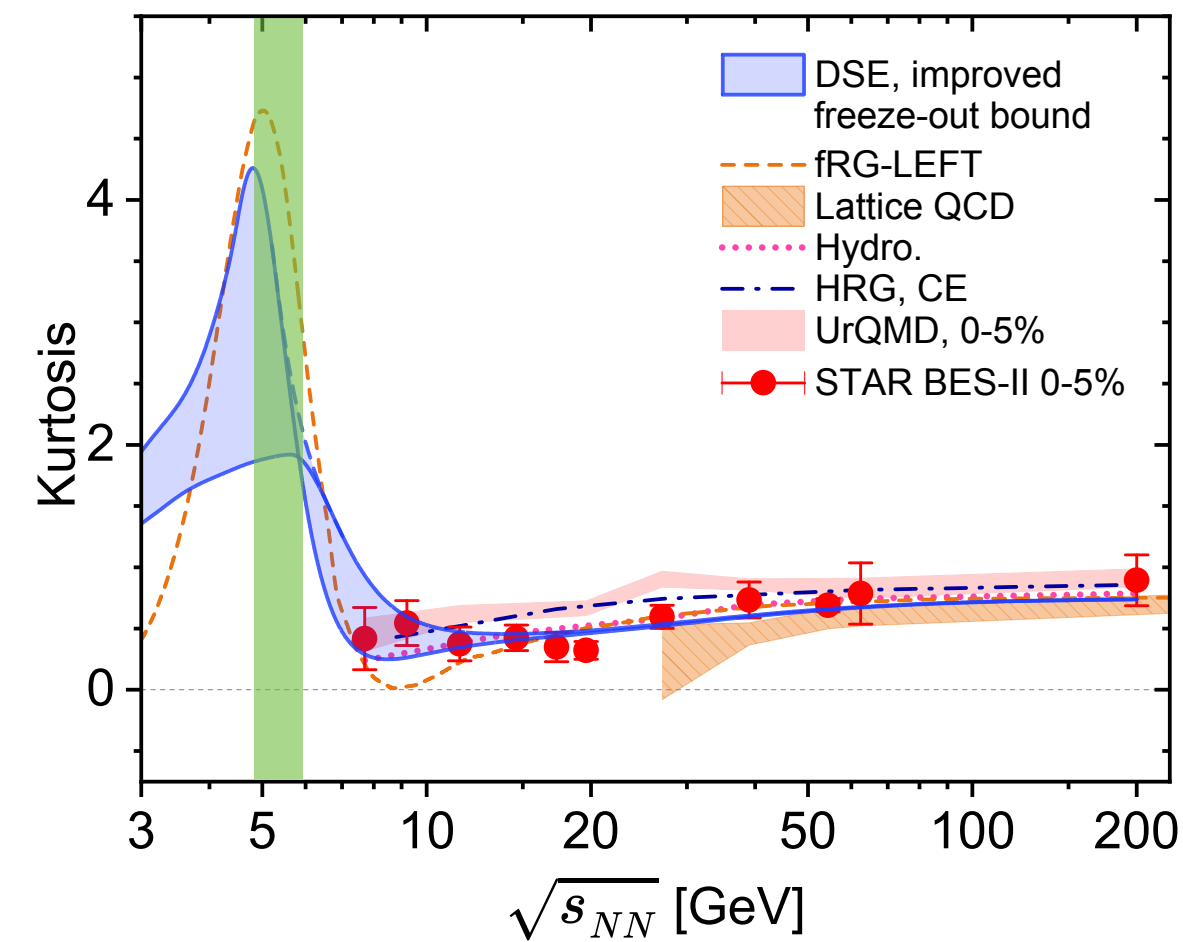
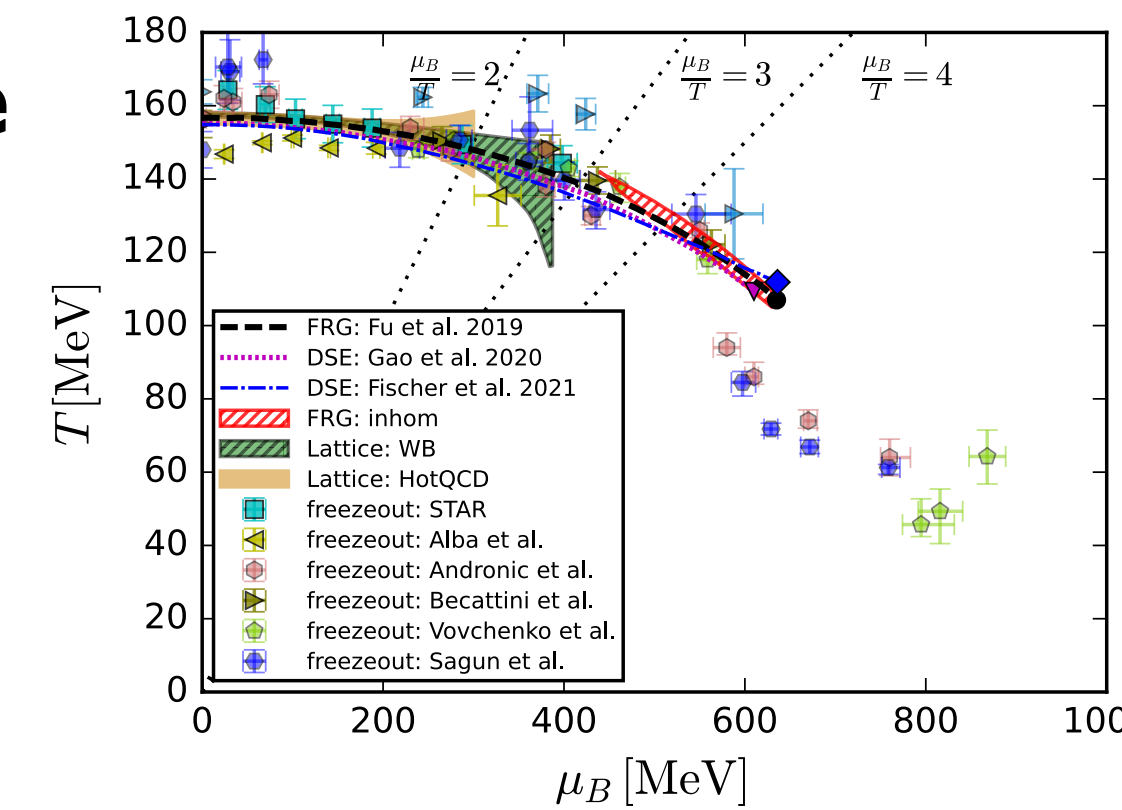
# Unfolding the phase structure with QCD and freeze-out data



**Fu, Lu, Luo, Gao, JMP, Rennecke, Wen, Xu, .... in progress**

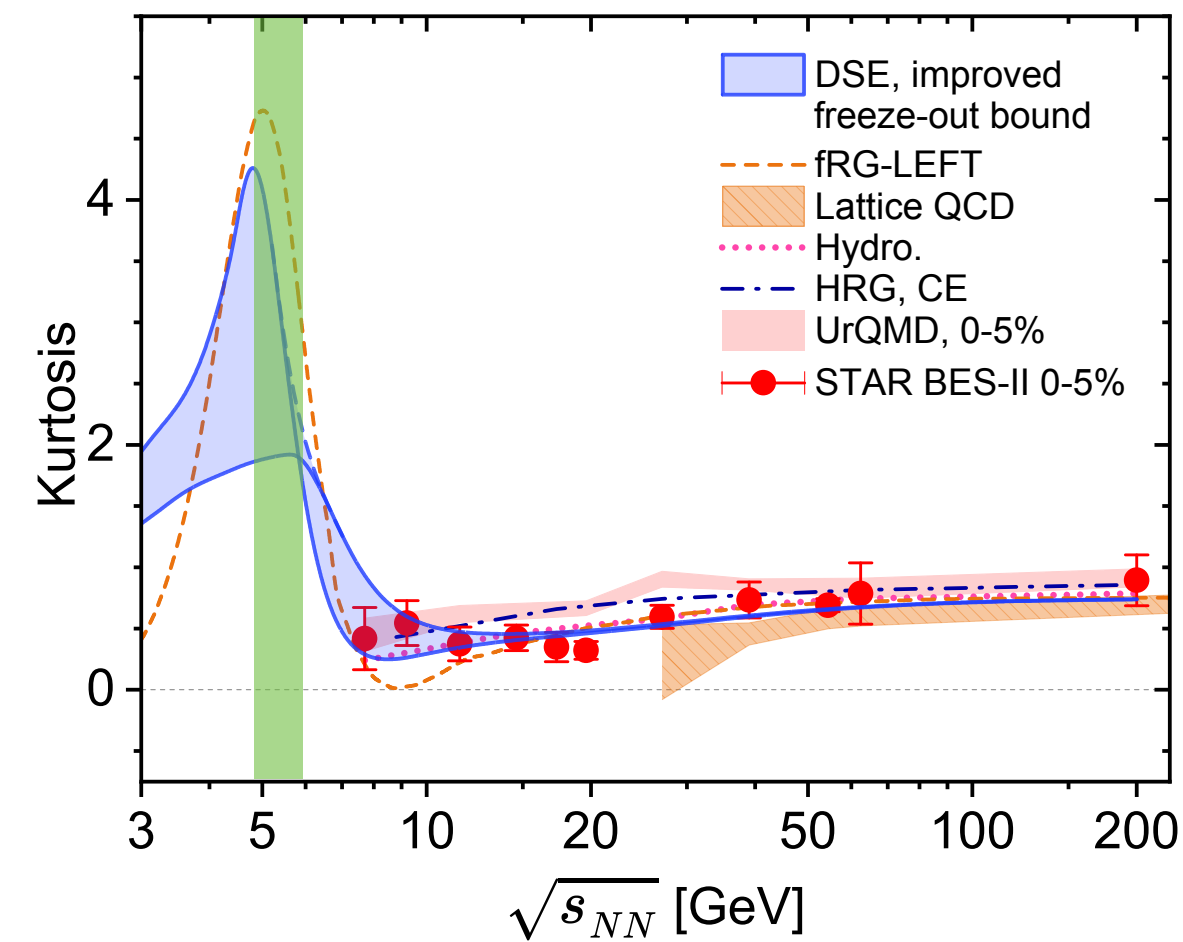
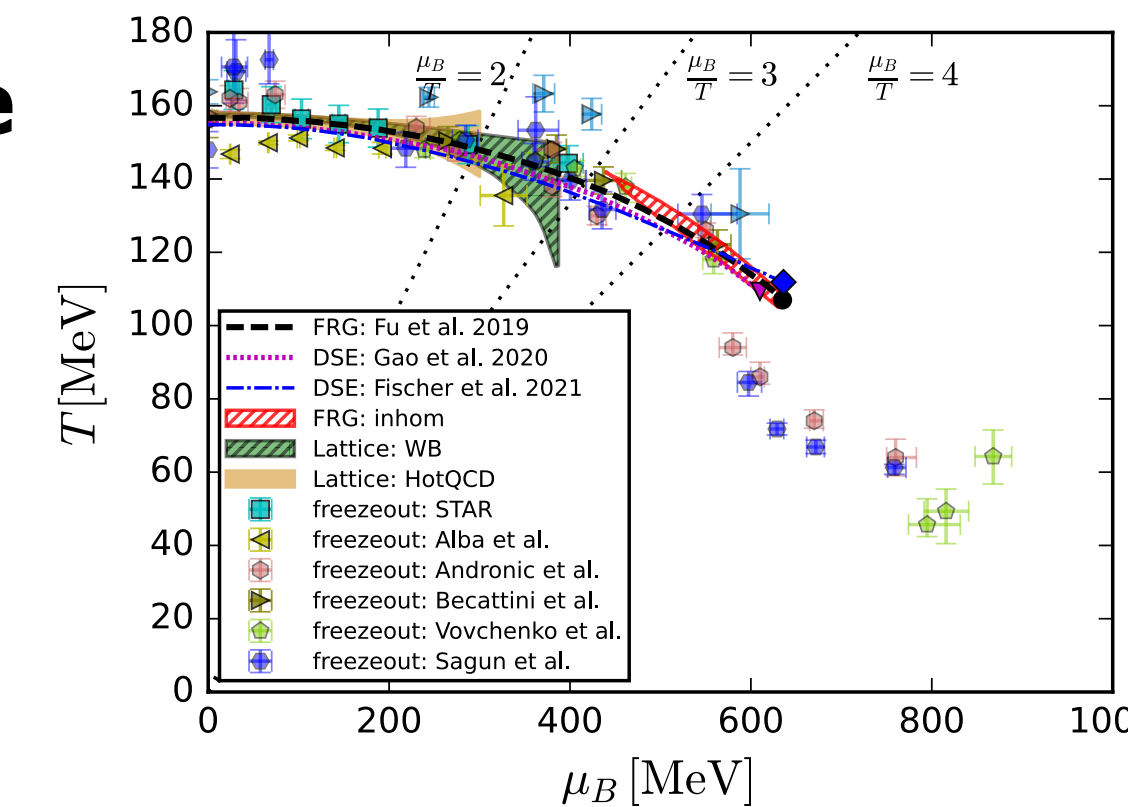
# Outlook

- 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

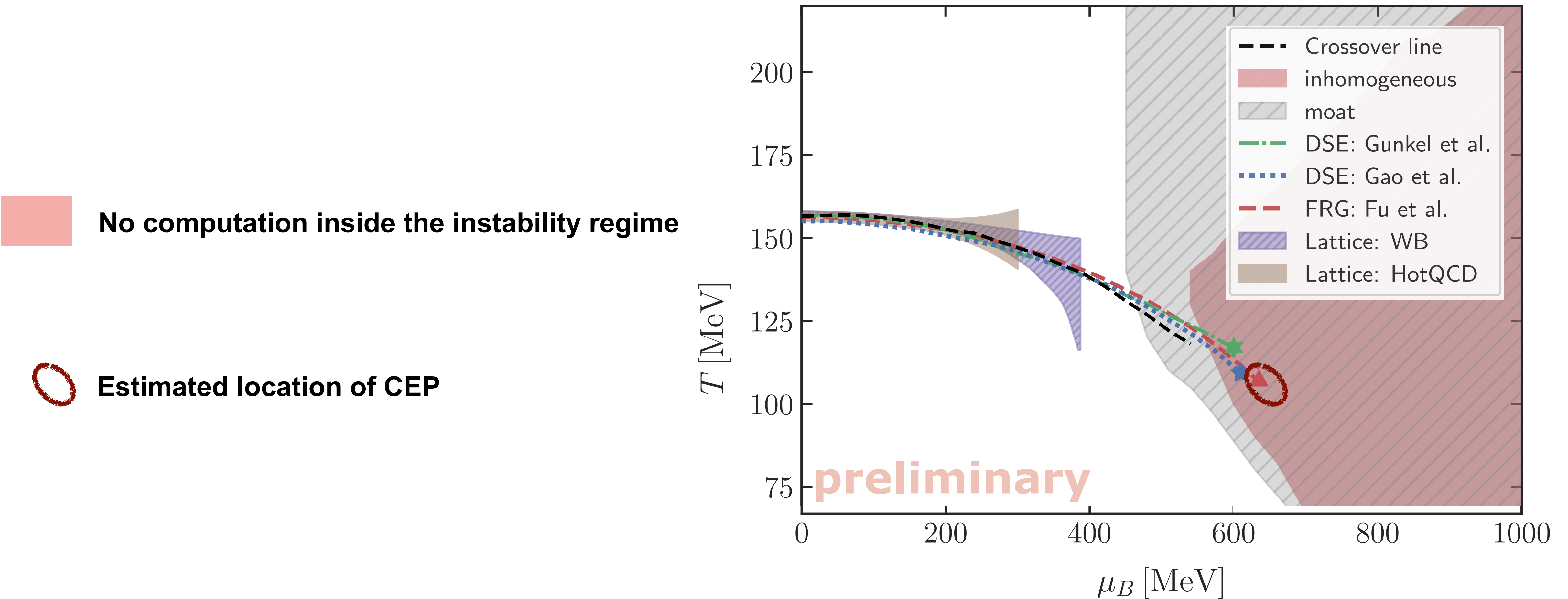
- QCD: why and how? **The cool stuff!**
- Chiral symmetry breaking & confinement: towards the QCD phase structure
- The physics of the QCD phase diagram & the experimental landscape
- Unfolding the QCD phase structure





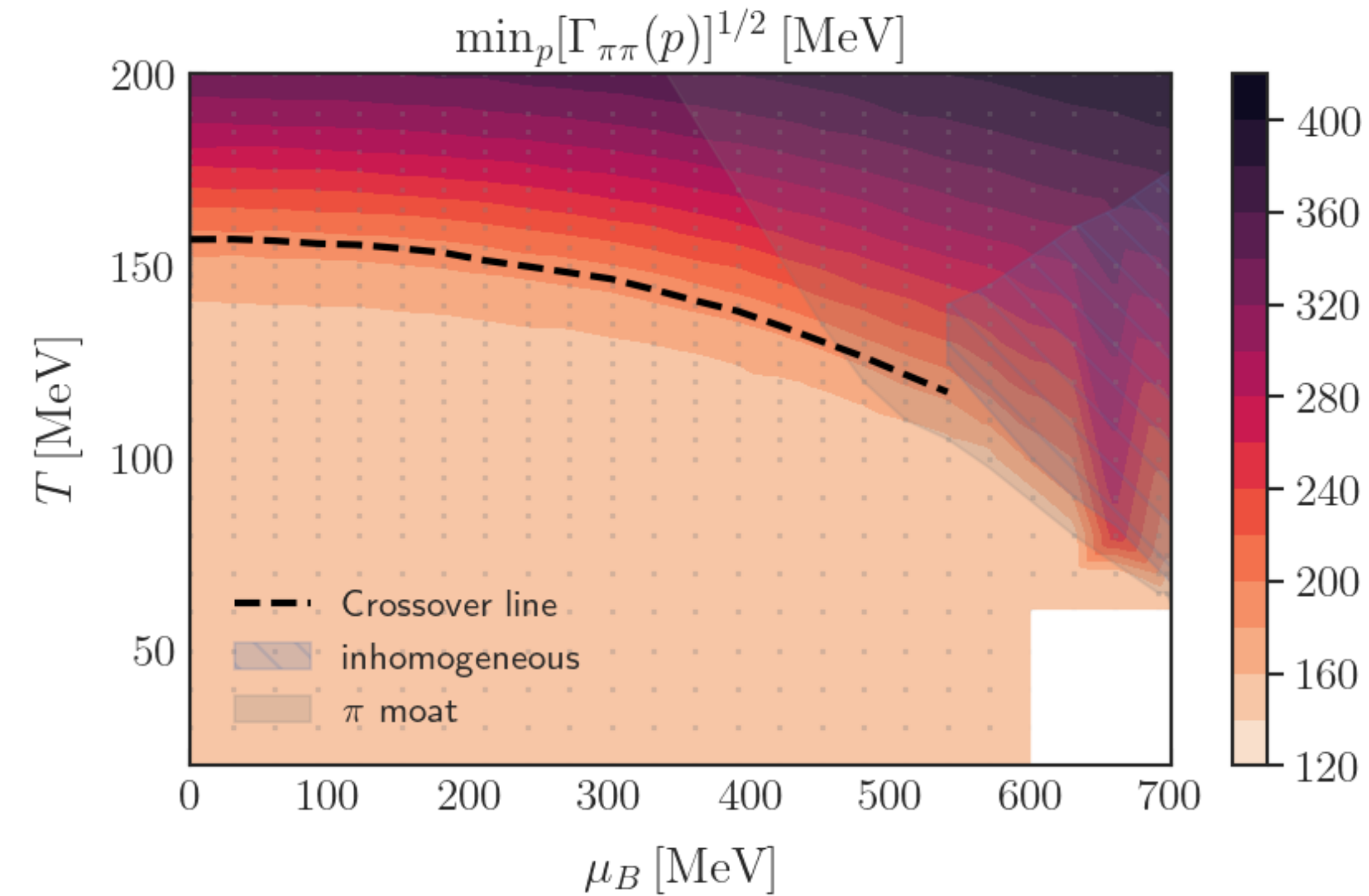
# The QCD Moat reloaded

## resolution of the moat regime

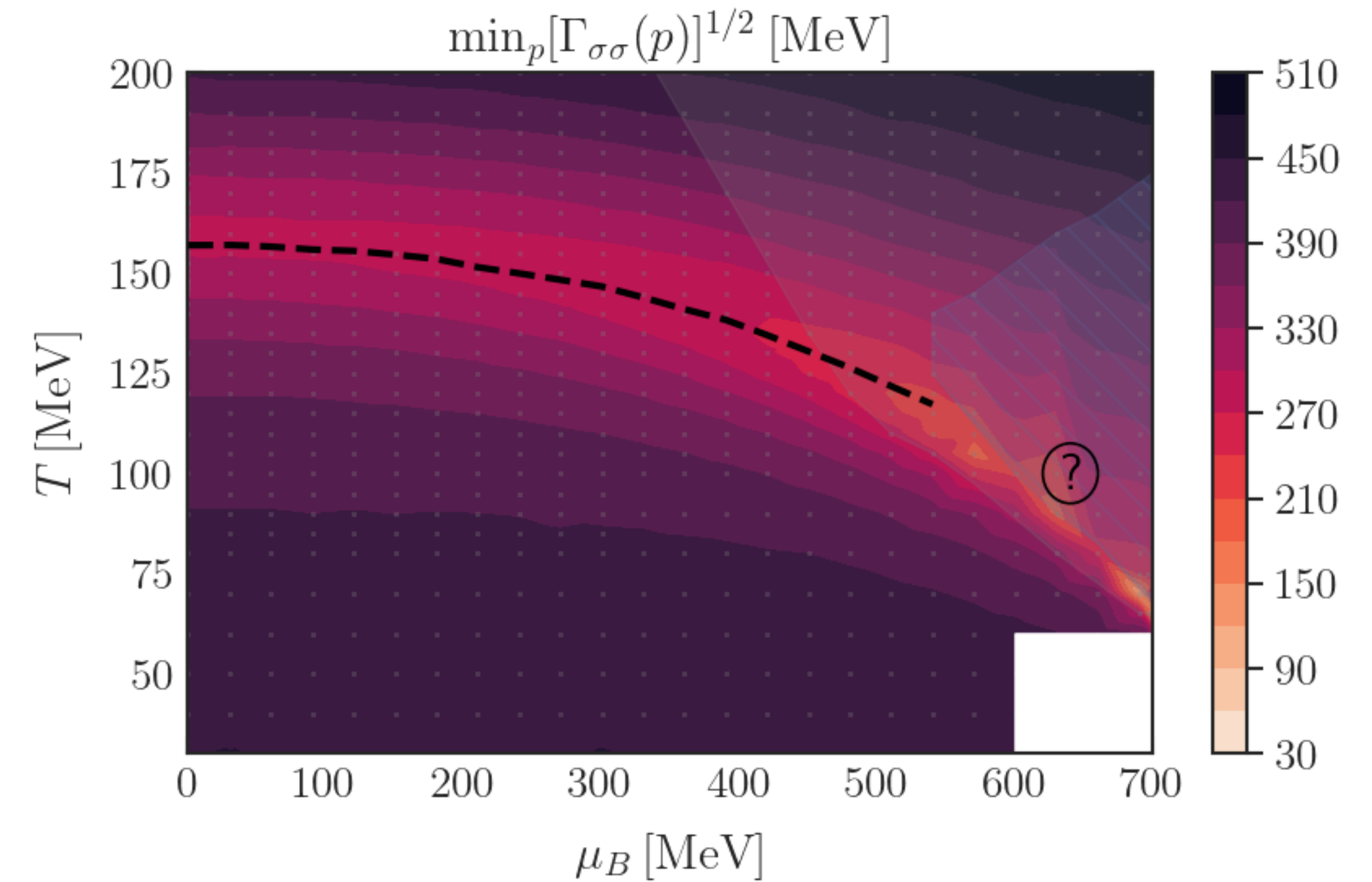


# The QCD Moat

## Pion ‘minimum’ mass



## Scalar mode ‘minimum’ mass



preliminary