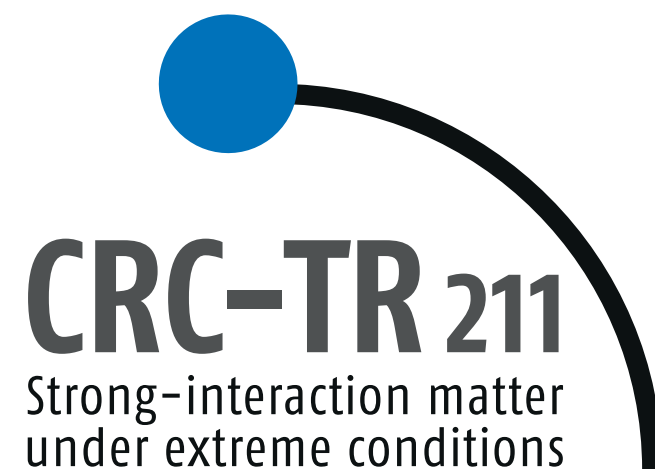


DENSE QCD AND THE MOAT REGIME

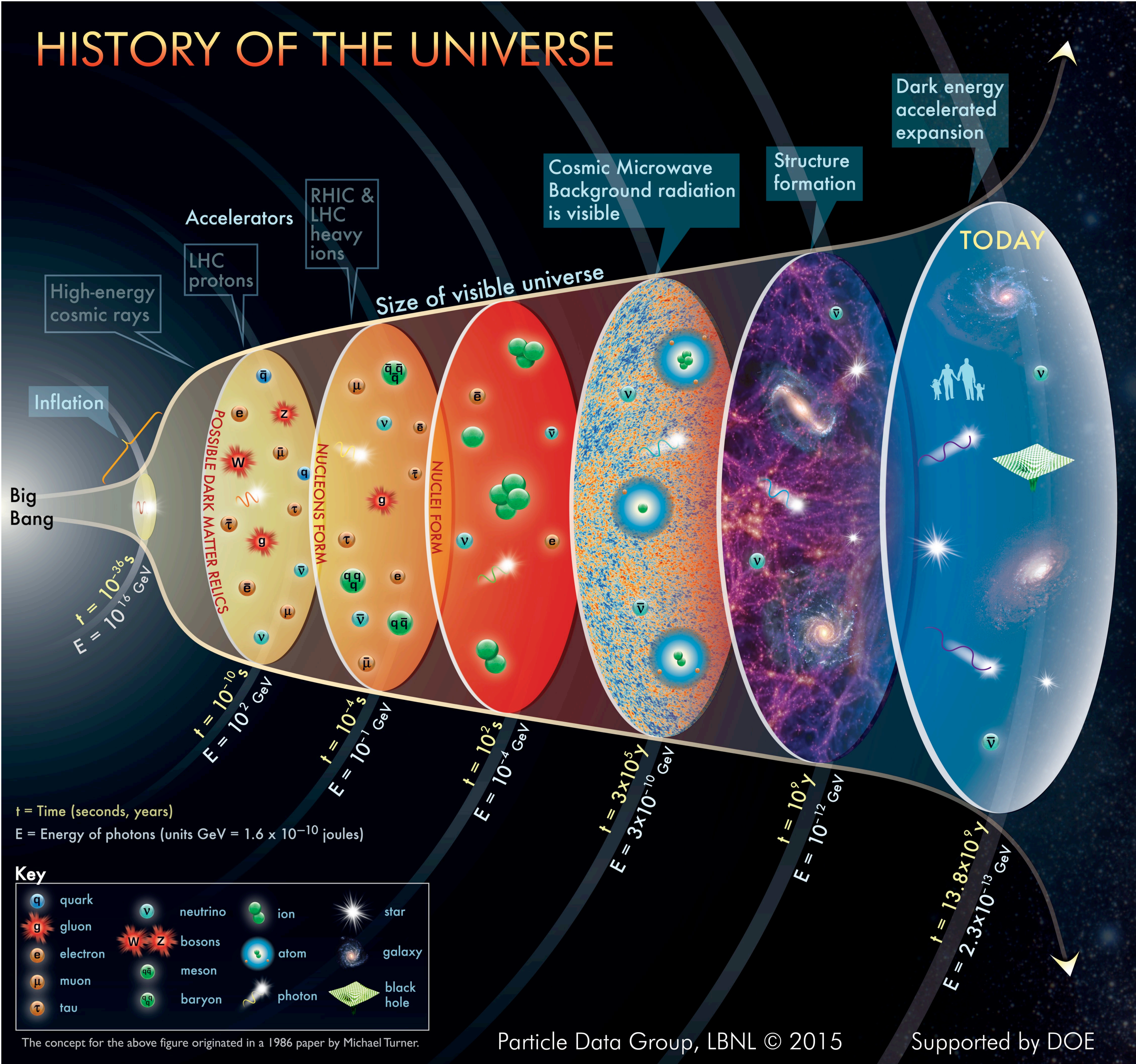
Fabian Rennecke



ERG 2026

UNIVERSITY OF SUSSEX - 02/09/2026

UNDERSTANDING MATTER IN EXTREME CONDITIONS



UNDERSTANDING MATTER IN EXTREME CONDITIONS



neutron stars can reach densities of several times the nuclear saturation density ($n \approx 5n_0$, $\mu_B \approx 1.5 \text{ GeV}$)



**study dense matter to understand
neutron stars & their mergers**

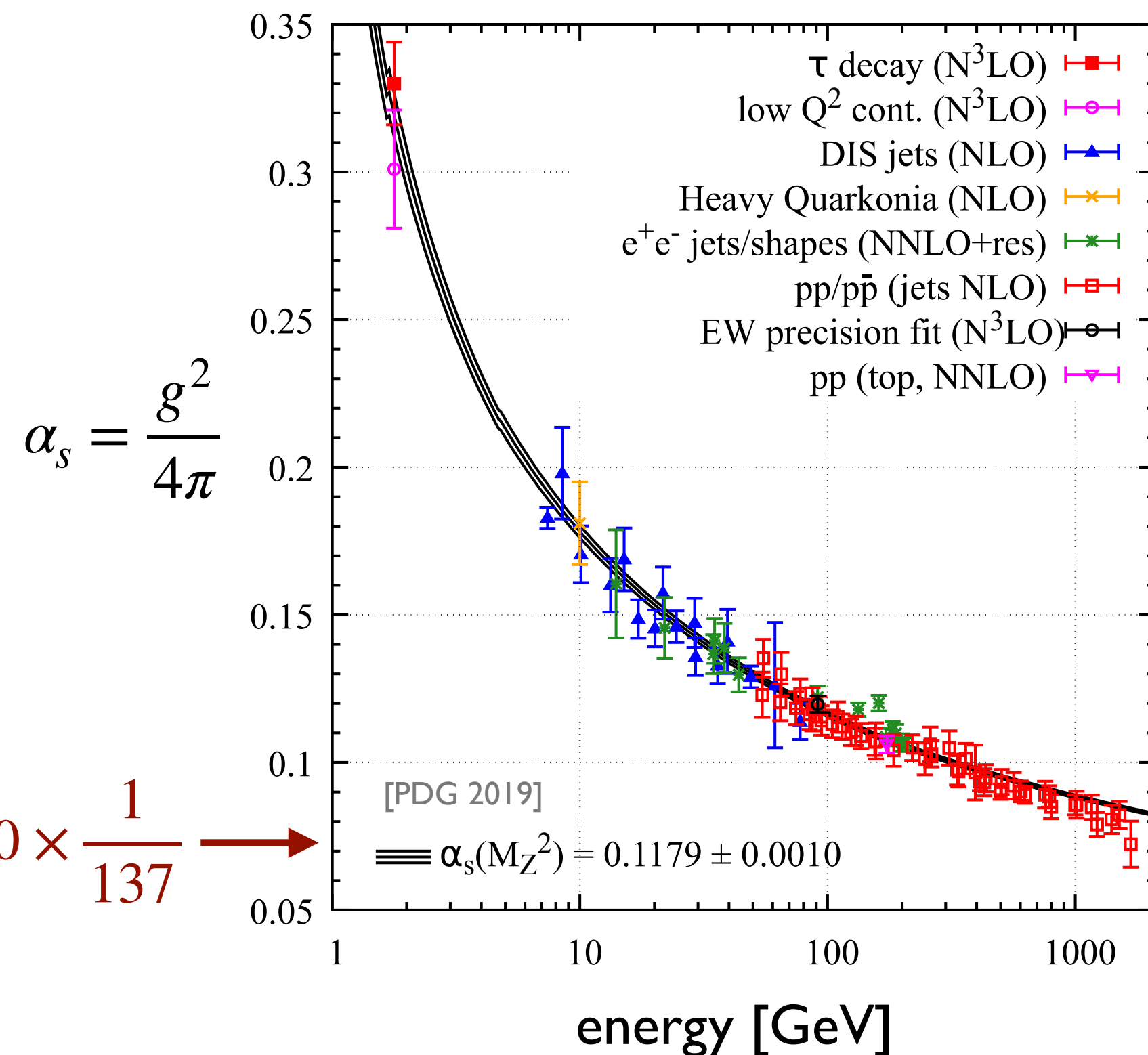
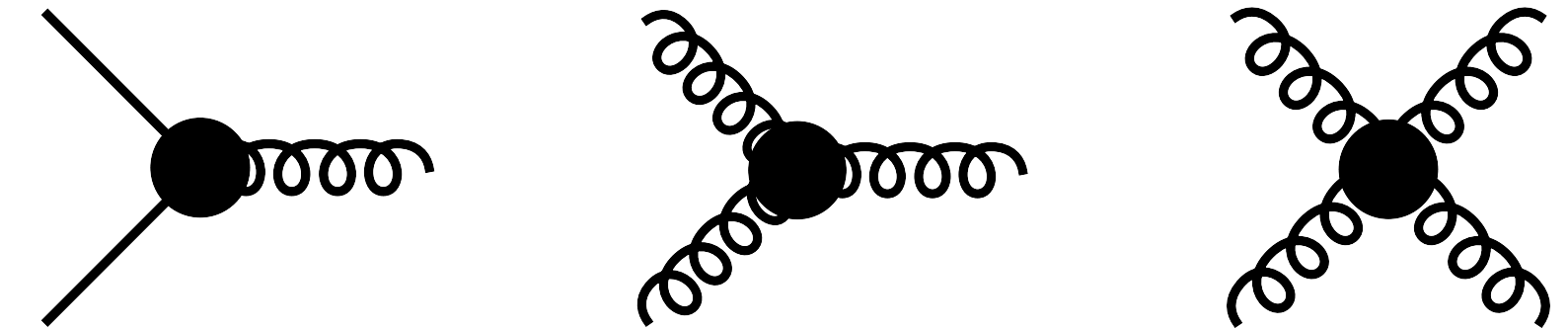
QCD

$SU(N_c = 3)$ gauge theory with $N_f = 6$ flavors of quarks

$$\mathcal{L}_{\text{QCD}} = \bar{q} (\gamma_\mu D_\mu - m_q) q - \frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a$$

- innocent looking, but still not understood to a large extent
- key feature: **asymptotic freedom**

microscopic interactions:



perturbative physics
quarks & gluons

UV

IR

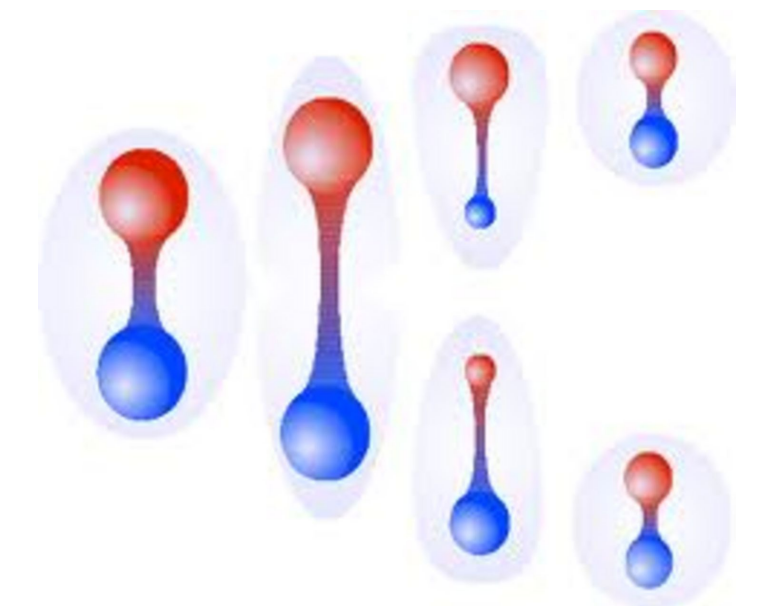
non-perturbative
many-body physics
bound states & condensates

- **confinement:**

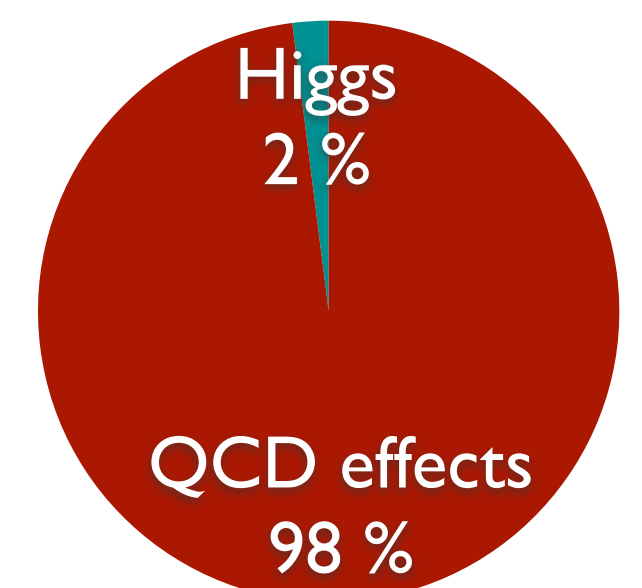
Millennium
Prize Problem



- origin of mass: **chiral symmetry breaking & scale anomaly**

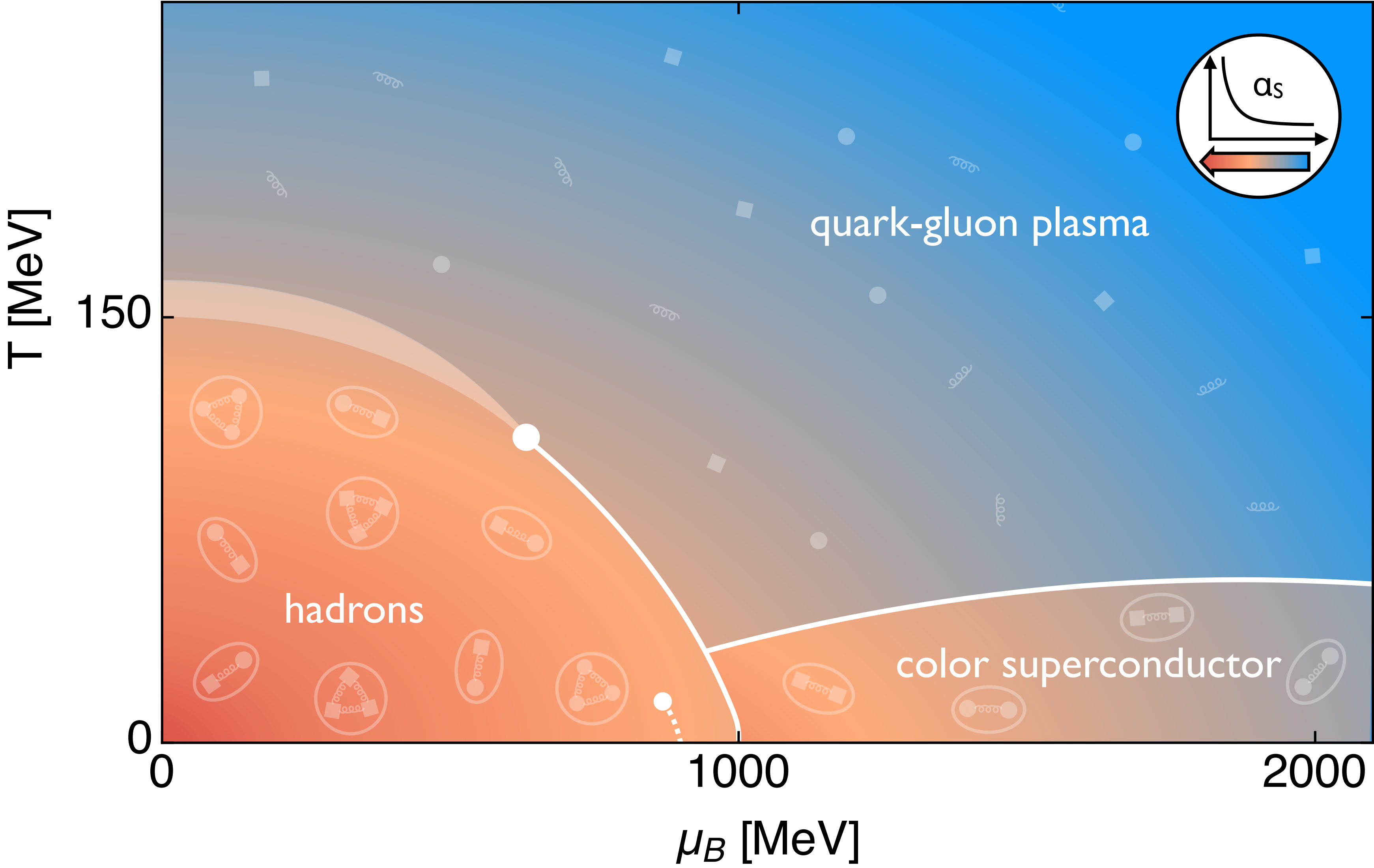


nucleon mass:



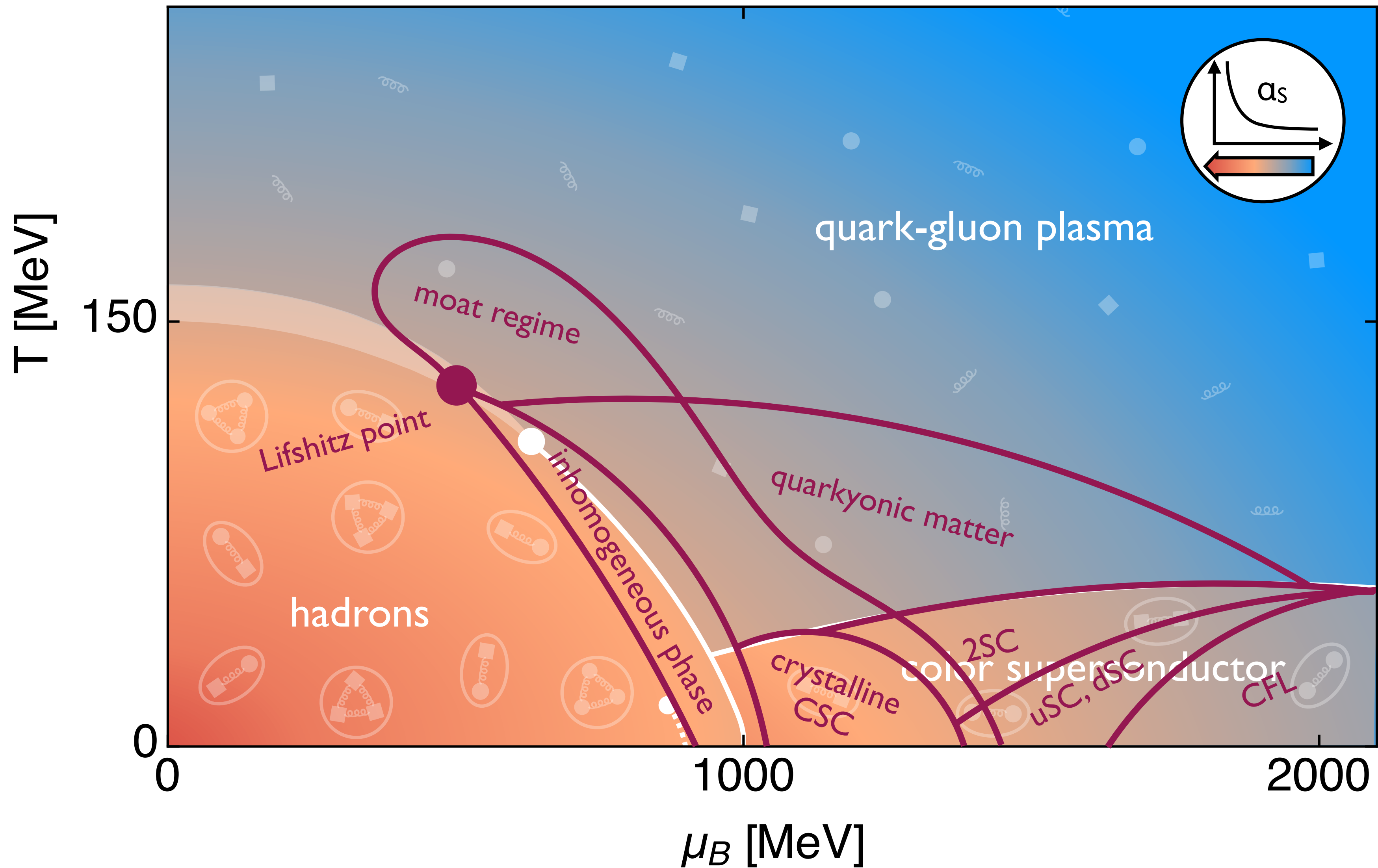
QCD PHASE DIAGRAM

Rough picture

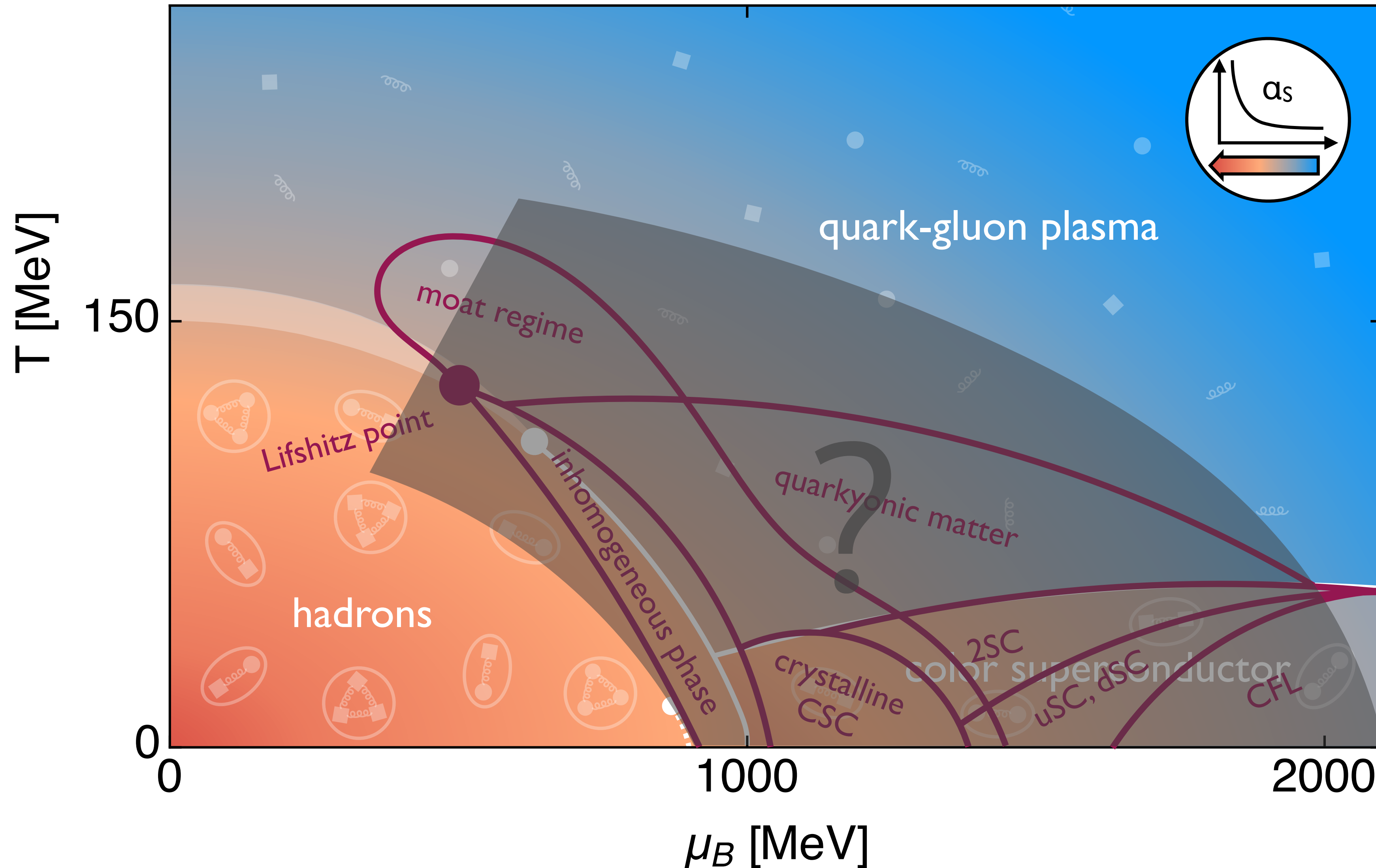


QCD PHASE DIAGRAM

Possibly many phases...



QCD PHASE DIAGRAM

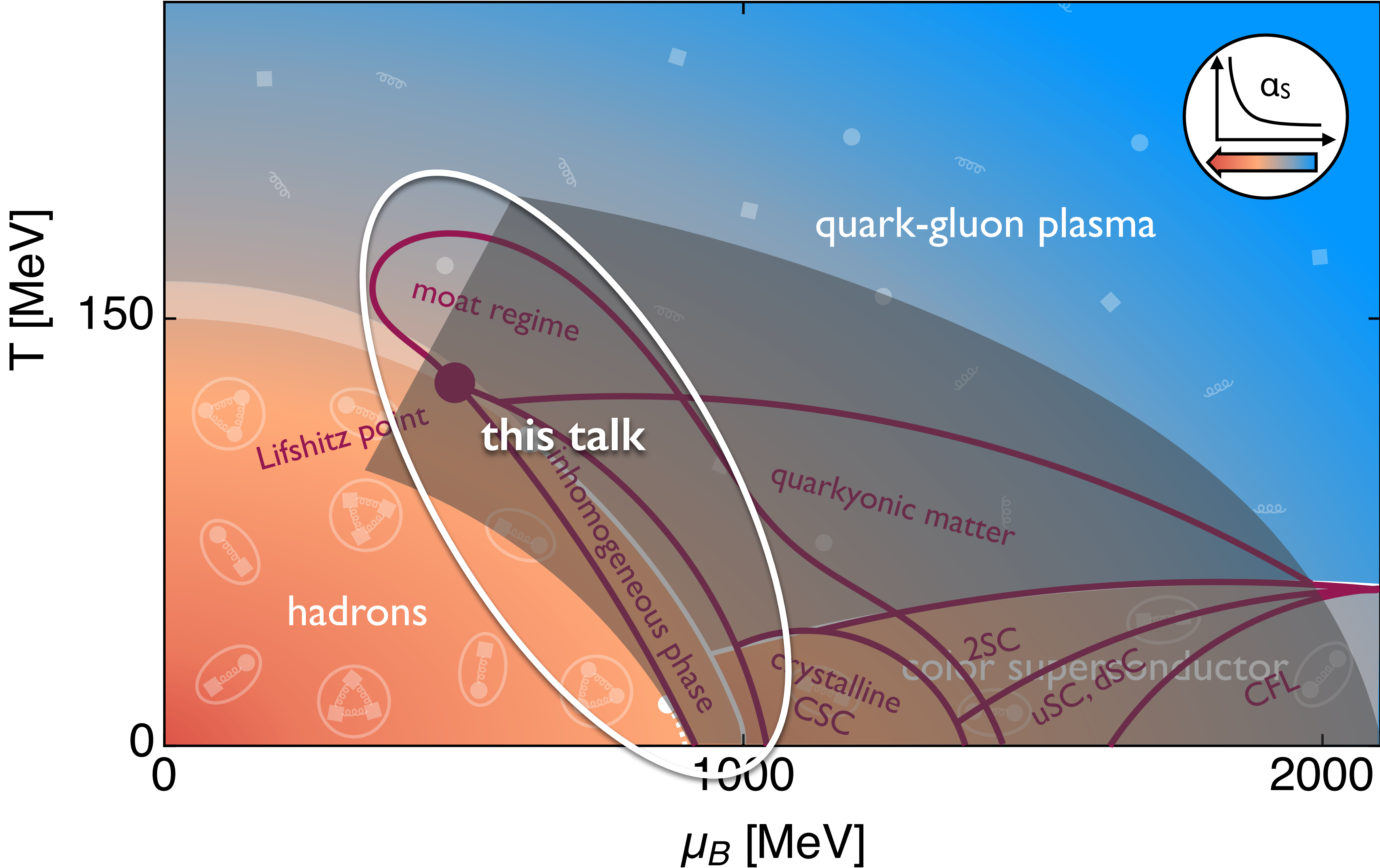


theoretical challenges:

- strong coupling: **non-perturbative**
- sign problem at finite density: **lattice QCD of limited use**
- different degrees of freedom in different phases: **EFTs of limited use**

↓
FRG

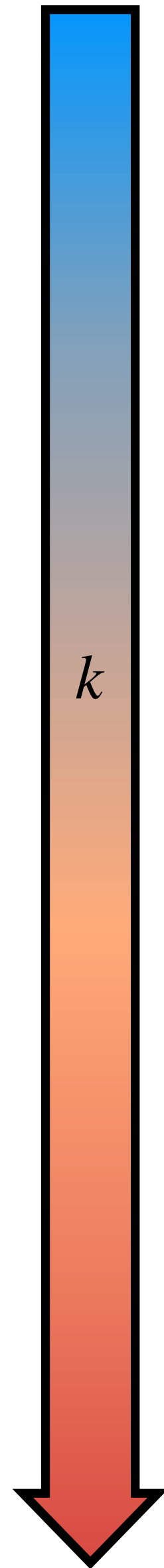
QCD PHASE DIAGRAM



- outline
- scale evolution of QCD
 - moats in QCD
 - moat phenomenology

(RG) SCALE EVOLUTION OF QCD

SCALE EVOLUTION OF QCD



k

integrate-out fluctuations from UV to IR

SCALE EVOLUTION OF QCD

$\Lambda \gg 1 \text{ GeV}$

- initial action: gauge fixed QCD at weak coupling
- $N_f = 3$ relevant quark flavors with approx. **chiral symmetry**:

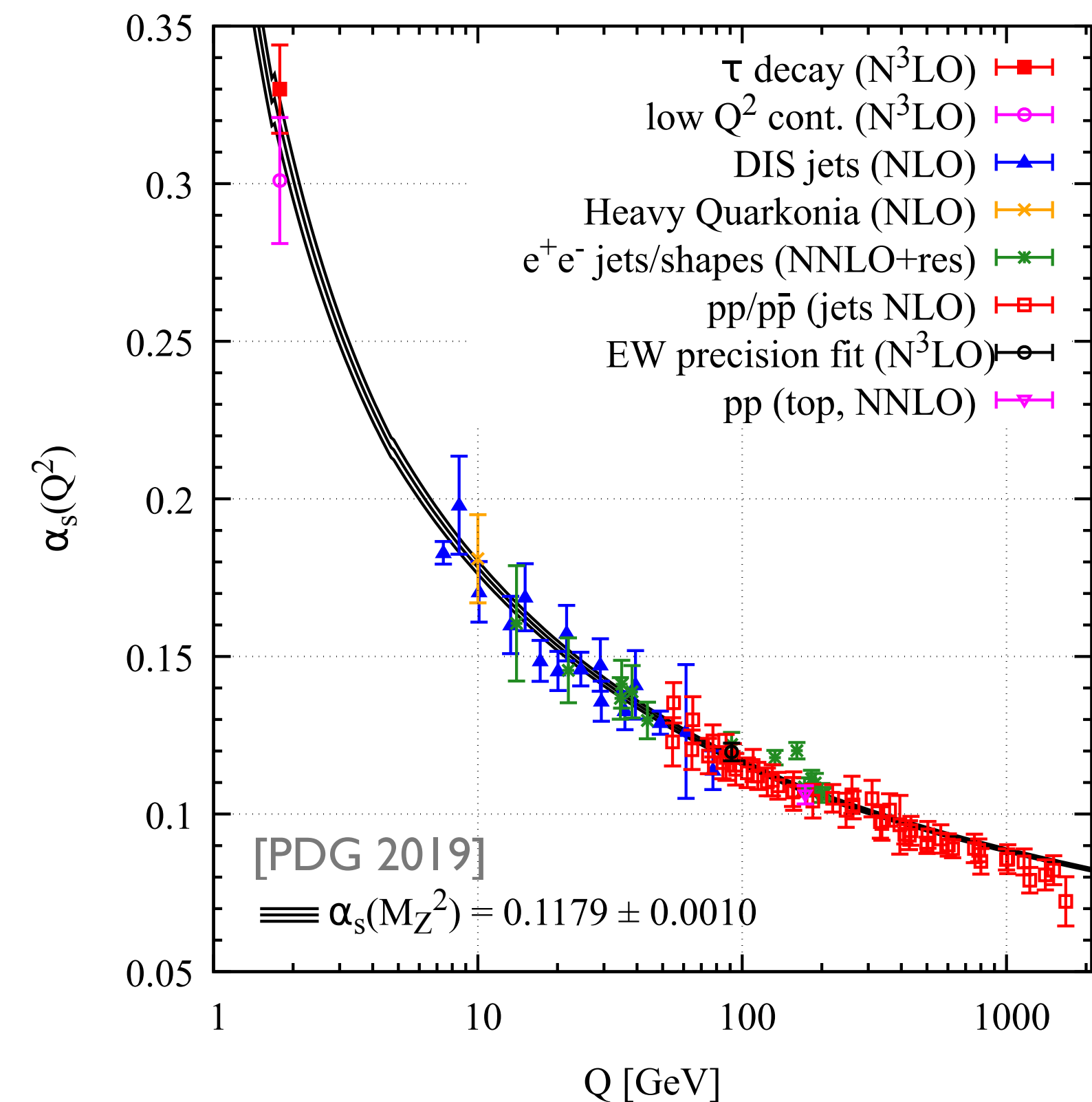
$$SU(3)_L \times SU(3)_R \times U(1)_V \times \mathbb{Z}_3^A$$

axial anomaly

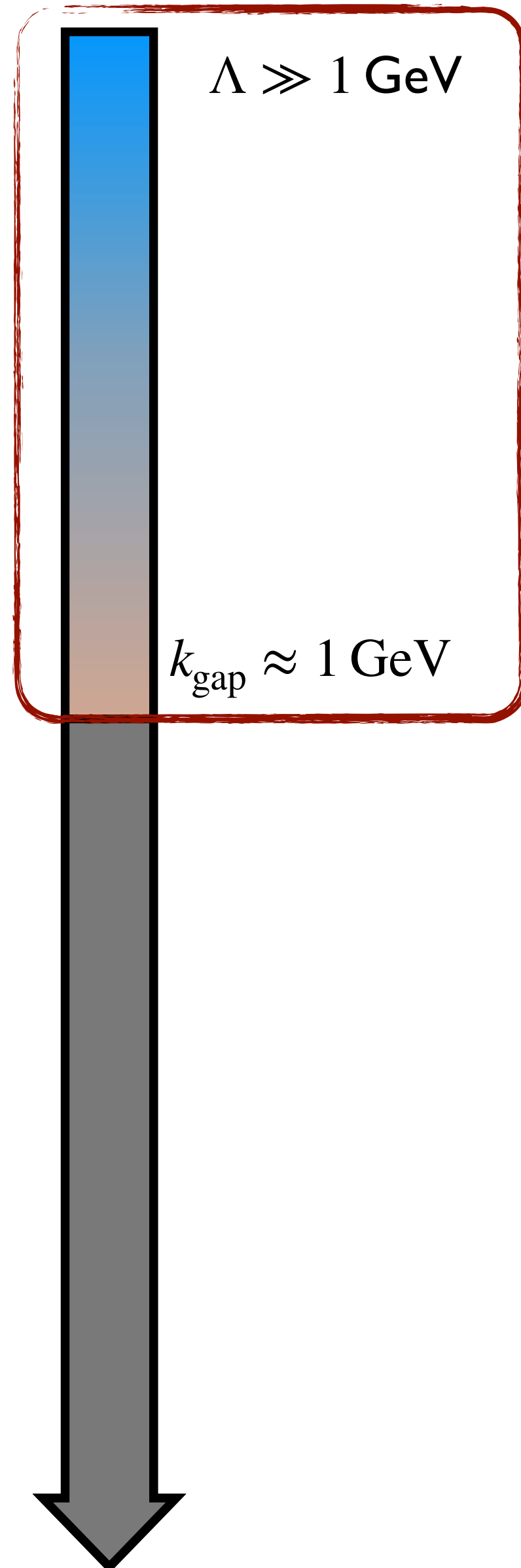
- **asymptotic freedom**: fluctuations increase strong coupling



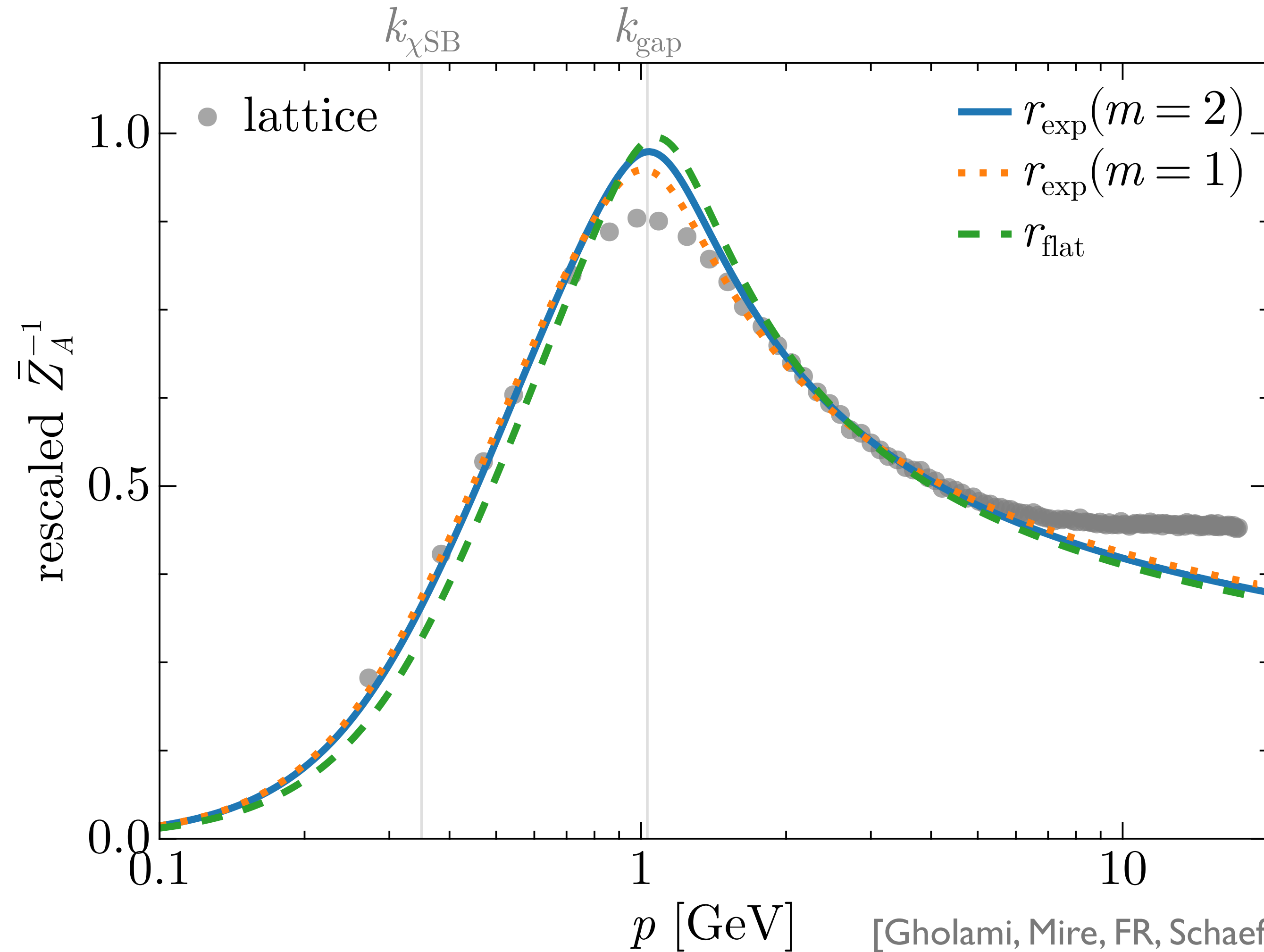
strong correlations



SCALE EVOLUTION OF QCD



- gluon mass gap is generated: **confinement**



[Gholami, Mire, FR, Schaefer, Yin, 2606.23772]

CONFINEMENT IN PRACTICE

- regulator breaks gauge invariance

$$\Delta S_k \sim \int_q A(q) R_k(q) A(-q) \longrightarrow \text{introduce "counter term"} \sim m_{\text{gap},k}^2 A^2$$

- flow $\partial_t m_{\text{gap},k}$ related to modified Slavnov-Taylor identity [Ellwanger, PLB 335 (1994)]

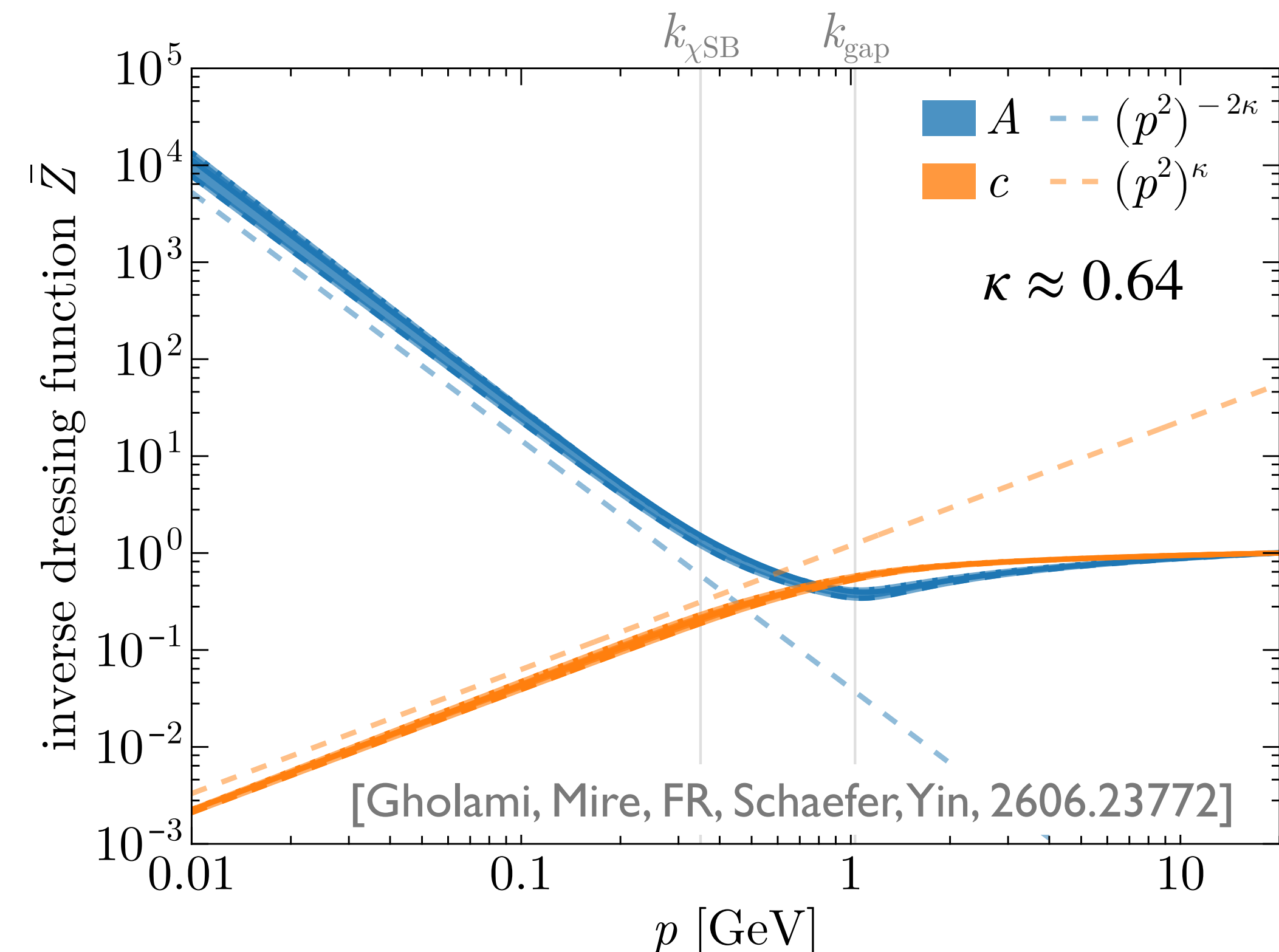
- bootstrap**: get $\partial_t m_{\text{gap},k}$ from gluon 2pt function and tune UV value so system runs into confining **IR scaling solution**

$$\begin{aligned} G_A(p) &\xrightarrow{p \rightarrow 0} \frac{1}{(p^2)^{1-2\kappa}} \\ G_c(p) &\xrightarrow{p \rightarrow 0} \frac{1}{(p^2)^{1+\kappa}} \end{aligned} \longrightarrow \text{mass gap for } \kappa > 1/2$$

more details: talk by

Ugo Mire

Wed. 15:00



[Kugo, Ojima, PTP Suppl. (1979)]

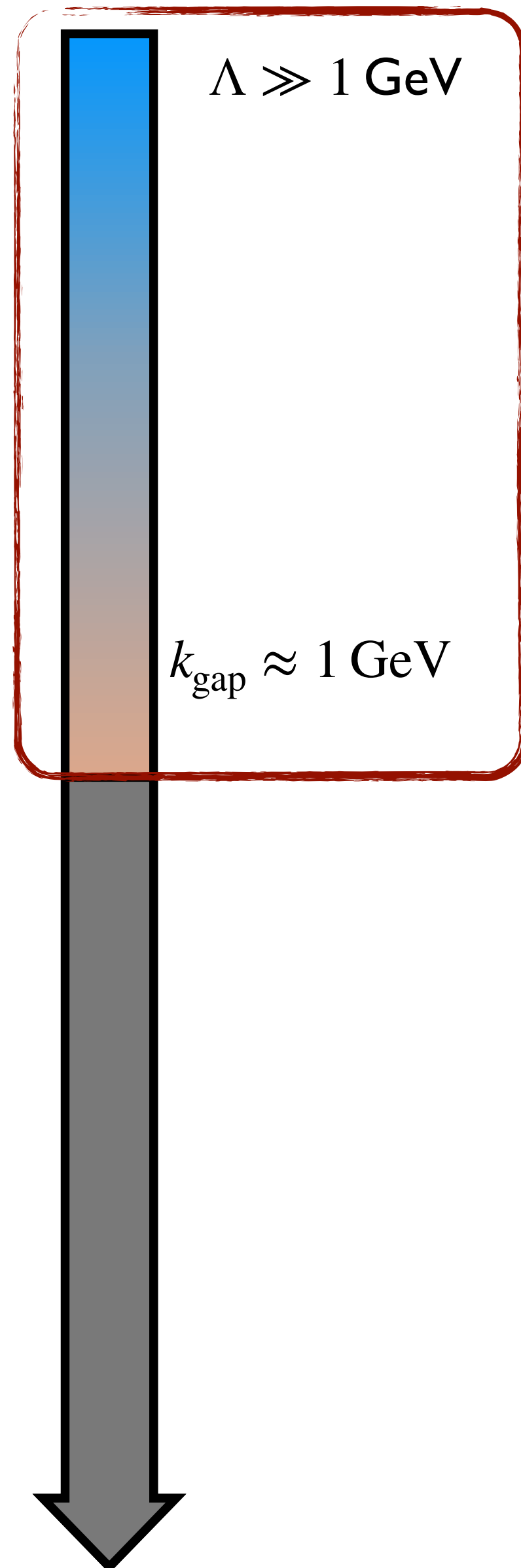
[von Smekal, Hauck, Alkofer, PRL 79 (1997)]

[Fischer, Maas, Pawłowski, Ann. Phys. 324 (2009)]

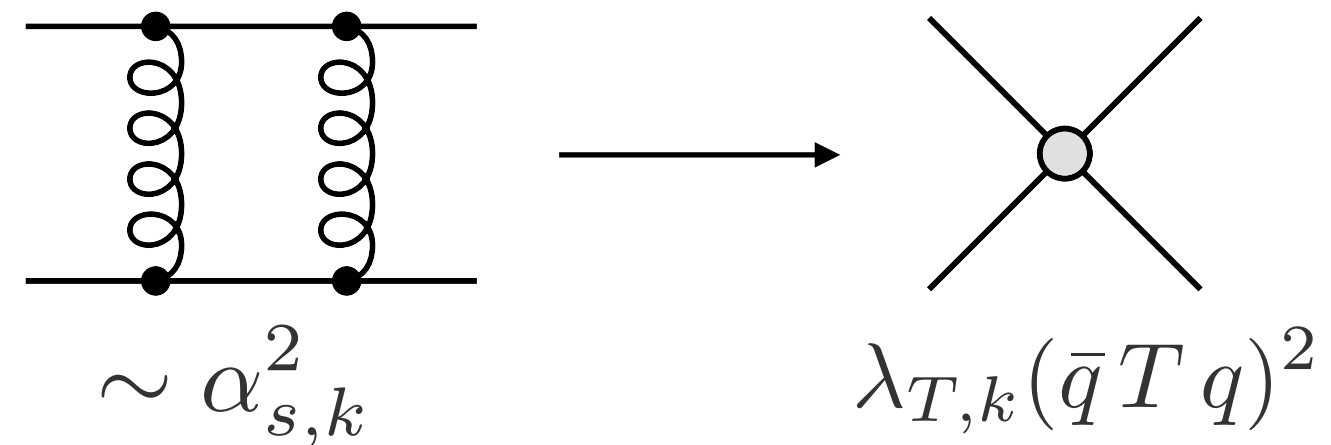
[Cyrol et al., PRD 94 (2016)]

[Goertz, Pastor-Gutierrez, Pawłowski, PRD 112 (2024)]

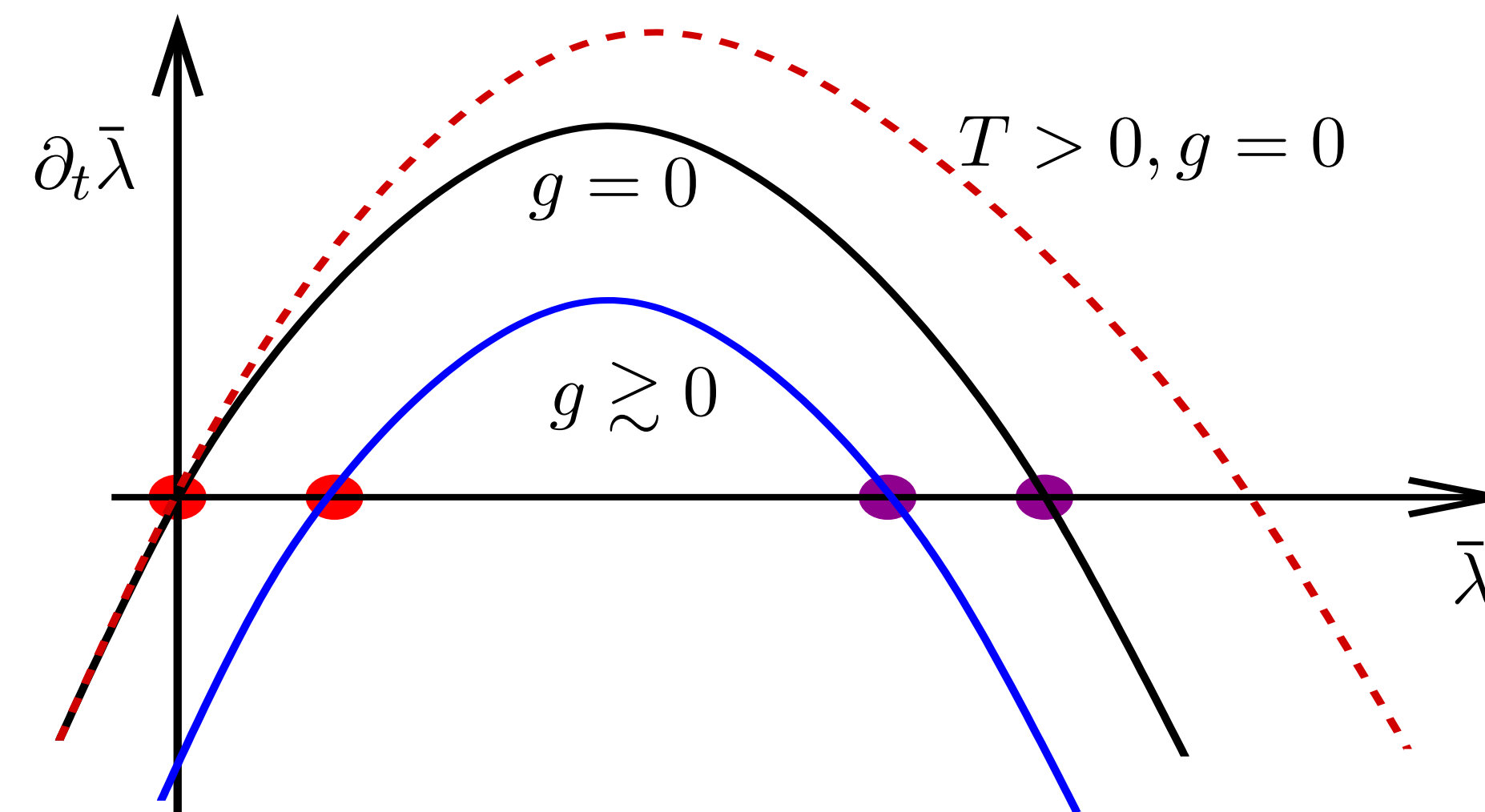
SCALE EVOLUTION OF QCD



- effective four-quark interactions are generated

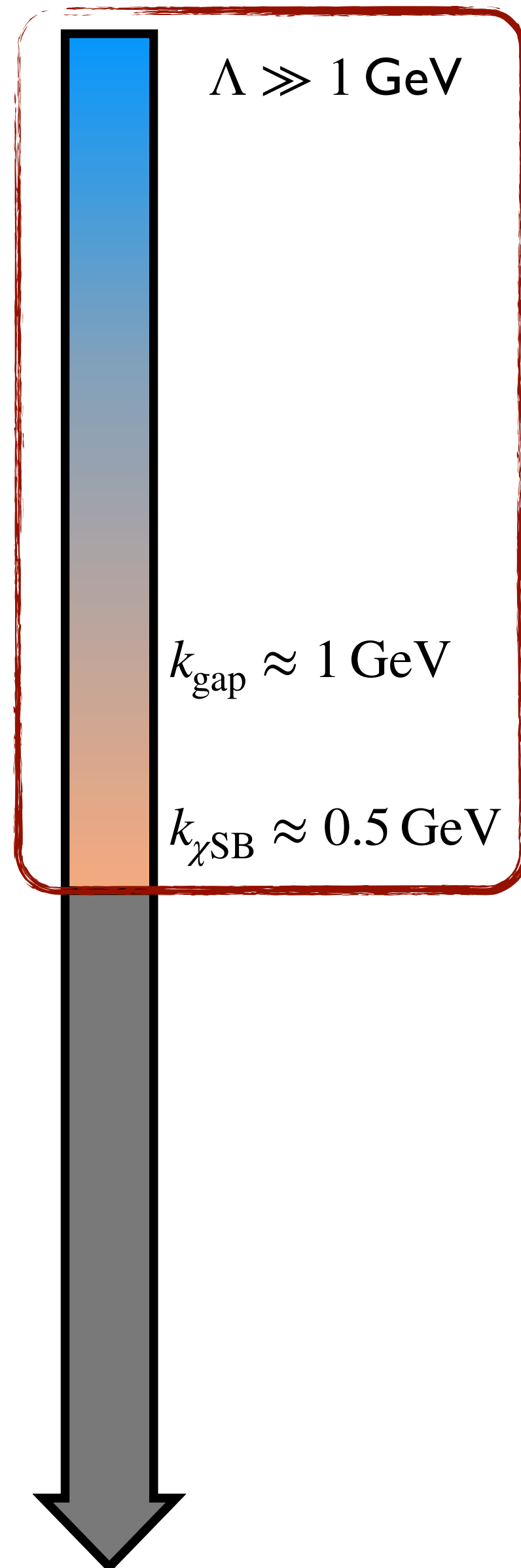


- running controlled by IR-attractive fixed point for small g

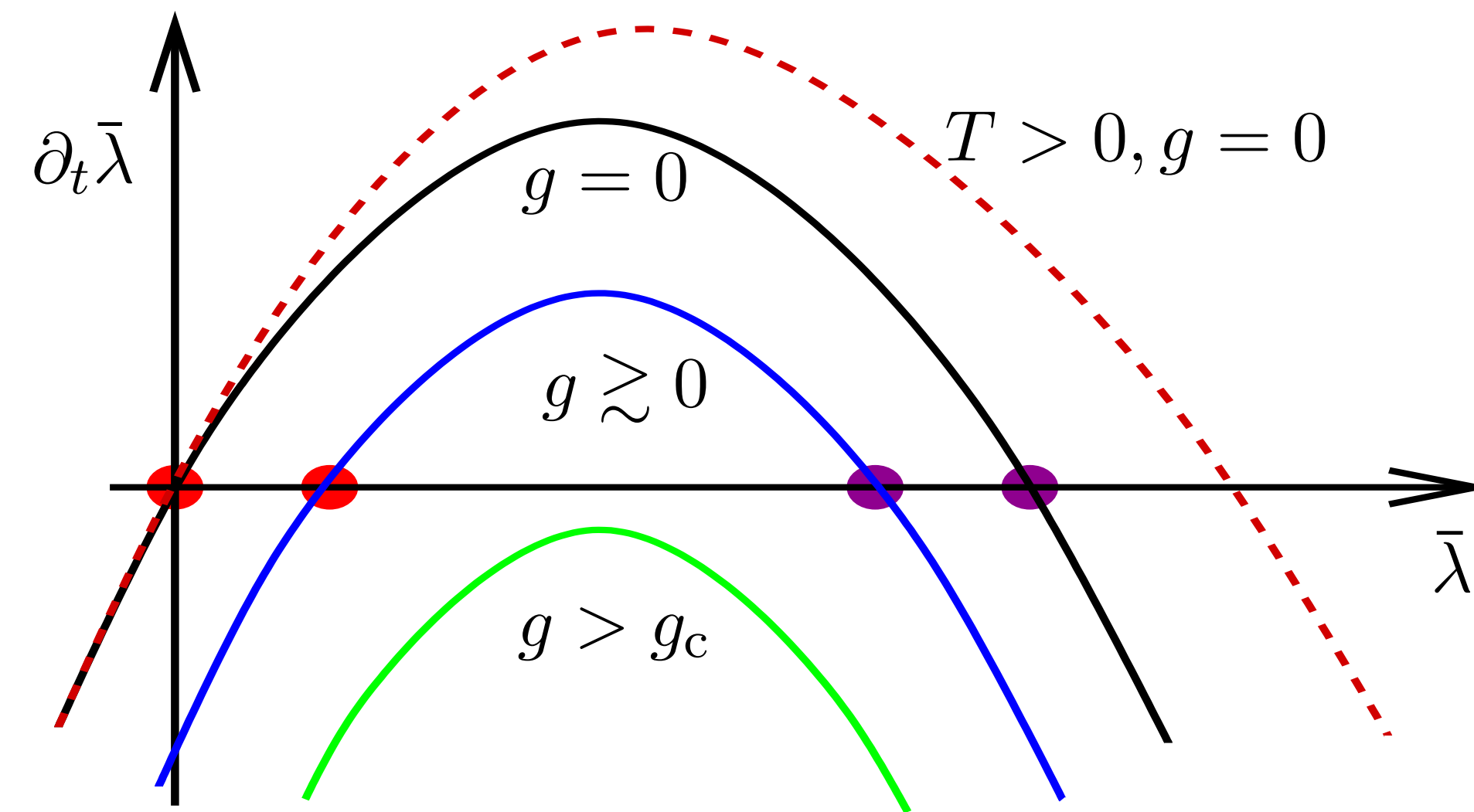


[Gies, Wetterich, PRD 96 (2003), Braun Gies, PLB 645 (2007)]

SCALE EVOLUTION OF QCD



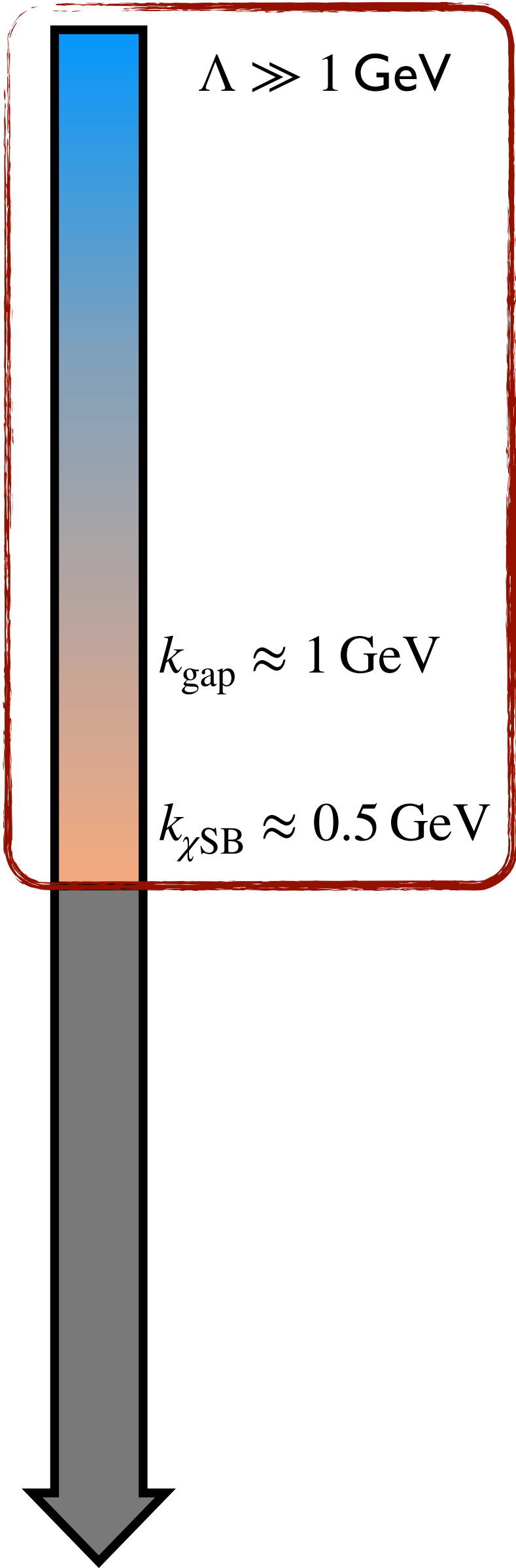
- strong coupling exceeds critical value: fixed points vanish



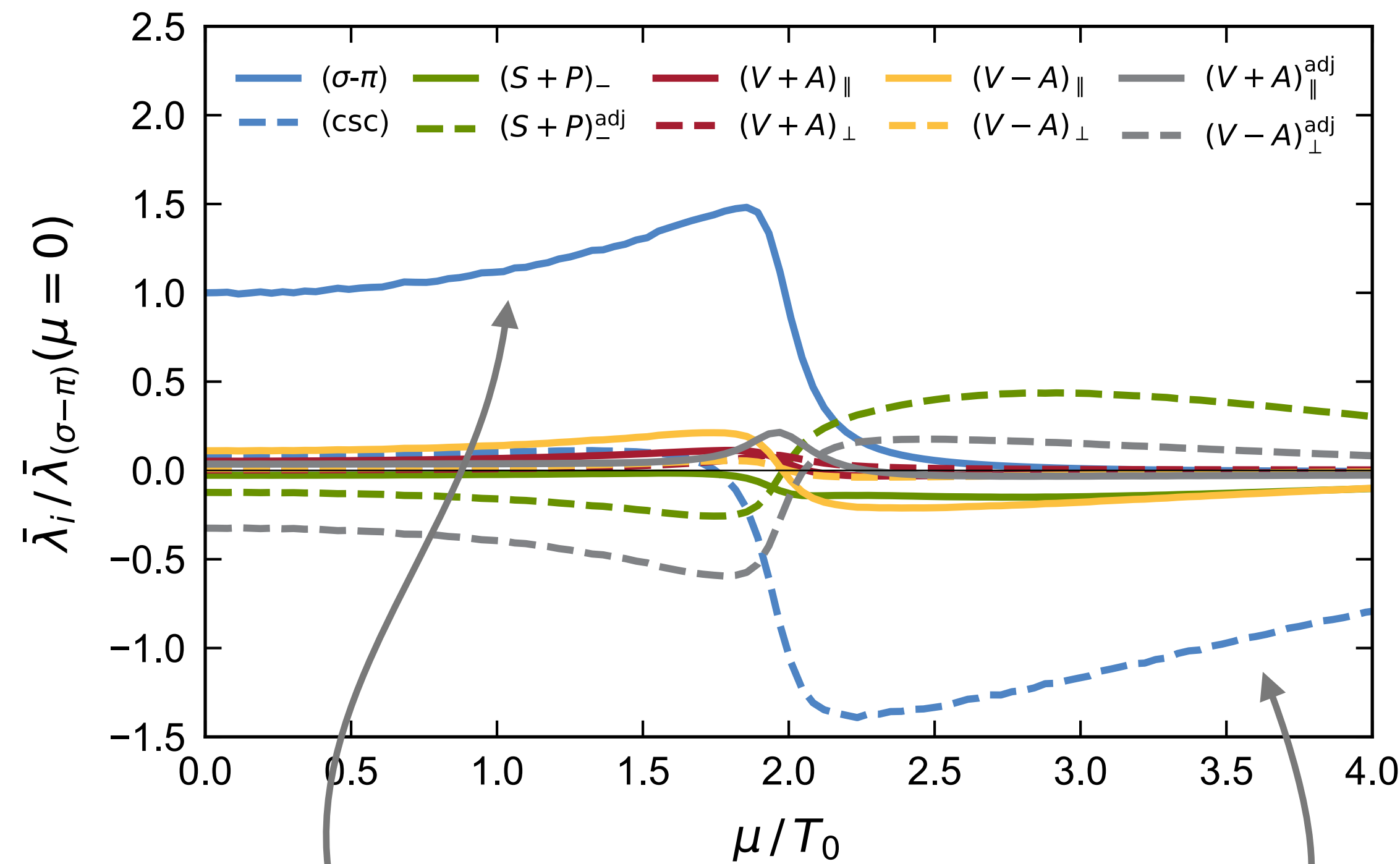
[Gies, Wetterich, PRD 96 (2003), Braun Gies, PLB 645 (2007)]

→ $\lambda_{T,k}$ becomes resonant: **spontaneous symmetry breaking**

EMERGENT ORDER



- resonances in different channels indicate different phases:



construct Fierz-complete
set of interaction channels

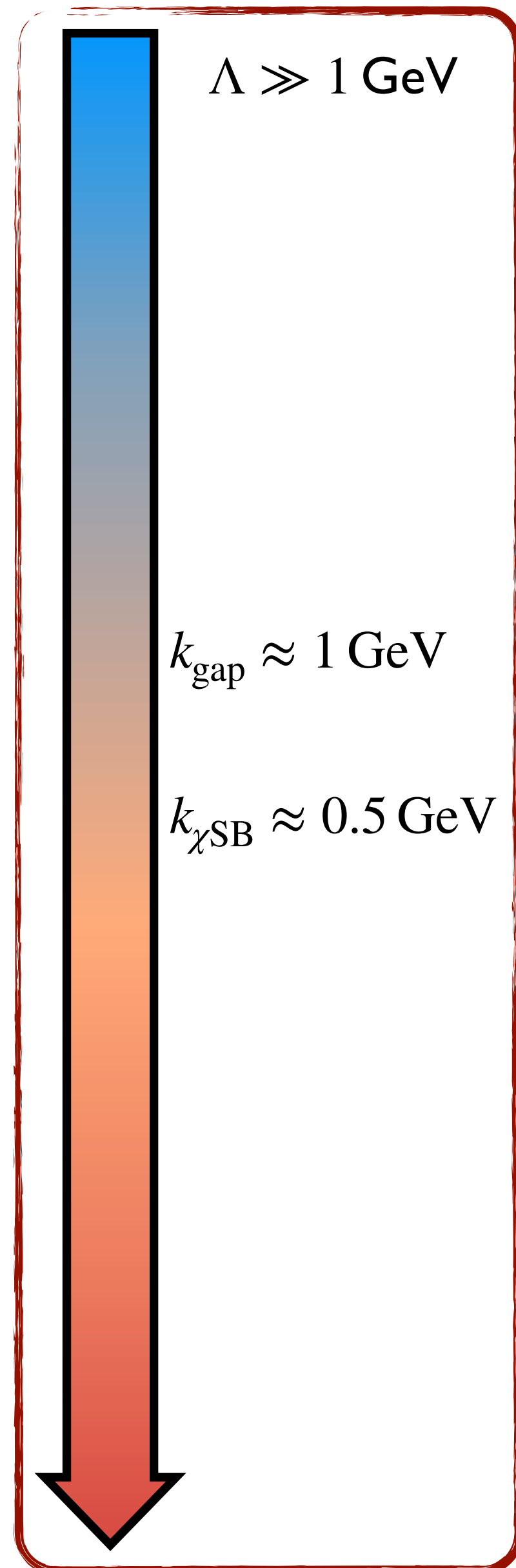
$N_f = 2:$
[Braun, Leonhardt, Pospiech, PRD 101 (2020)]

chiral condensate $\sim \langle \bar{q}q \rangle$:
hadronic phase

quark Cooper-pair $\sim \langle qq \rangle$:
color-superconductor

→ unbiased, dynamical decision about favored ground state

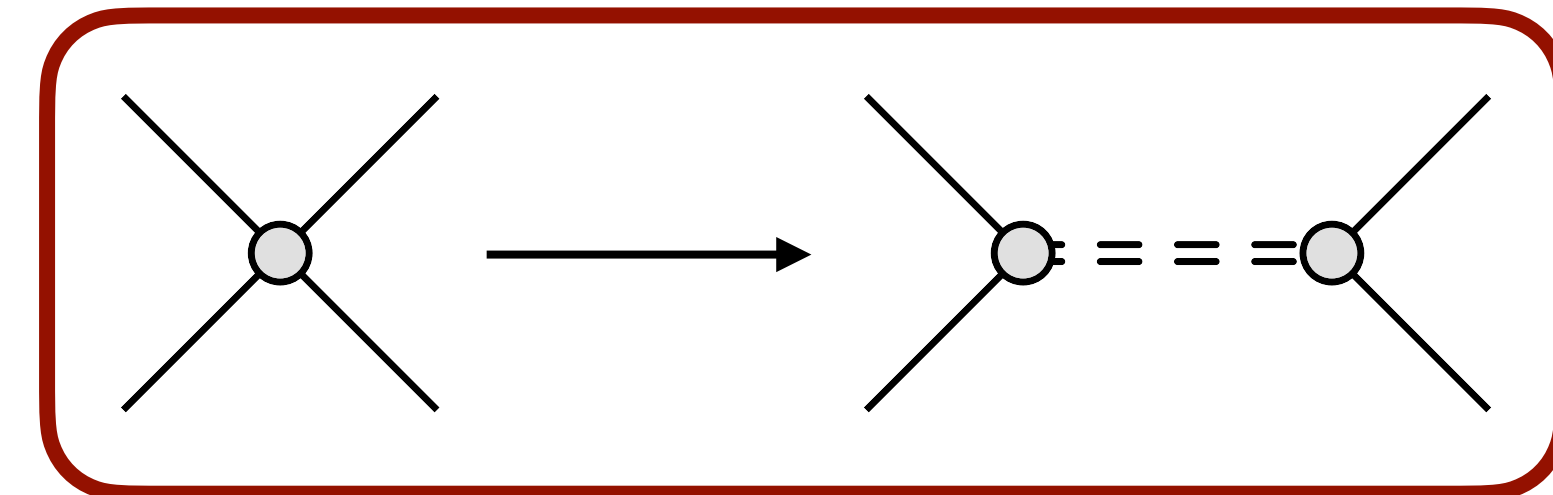
SCALE EVOLUTION OF QCD



Low-energy regime of QCD

- express resonant 4-quark channels in terms of meson/diquark-exchange (similar: baryons from 6-quark interactions)

$$\lambda_{T,k}(p) \sim \frac{h_{T,k}^2(p)}{p^2 + m_{\phi,k}^2}$$



- flow equations for fundamental fields and emergent bound states (still exact!)

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \text{gluons} - \text{ghosts} - \text{quarks} + \frac{1}{2} \text{bound states}$$

gluons

ghosts

quarks

bound states

→ capture the dynamical transition from fundamental fields to low-energy degrees of freedom

DYNAMICAL "HADRON"IZATION

- bosonize 4-quark interaction at each RG-step $\longrightarrow$ scale-dep. composite fields $\hat{\phi} \rightarrow \hat{\phi}_k$
- introduce $\hat{\phi}_k$ to generating functional via additional source term $\longrightarrow$ generalized flow

$$\partial_t \Gamma_k = \frac{1}{2} G_k^{ab} \dot{R}_{ab,k} - \dot{\Phi}_k^a \left(\frac{\delta \Gamma_k}{\delta \Phi^a} + c \delta_{a\sigma} \right) + G_k^{ab} \frac{\delta \dot{\Phi}_k^c}{\delta \Phi^a} R_{cb,k}$$

$$\Phi = \{q, \bar{q}, A, c, \bar{c}, \phi, \dots\}$$

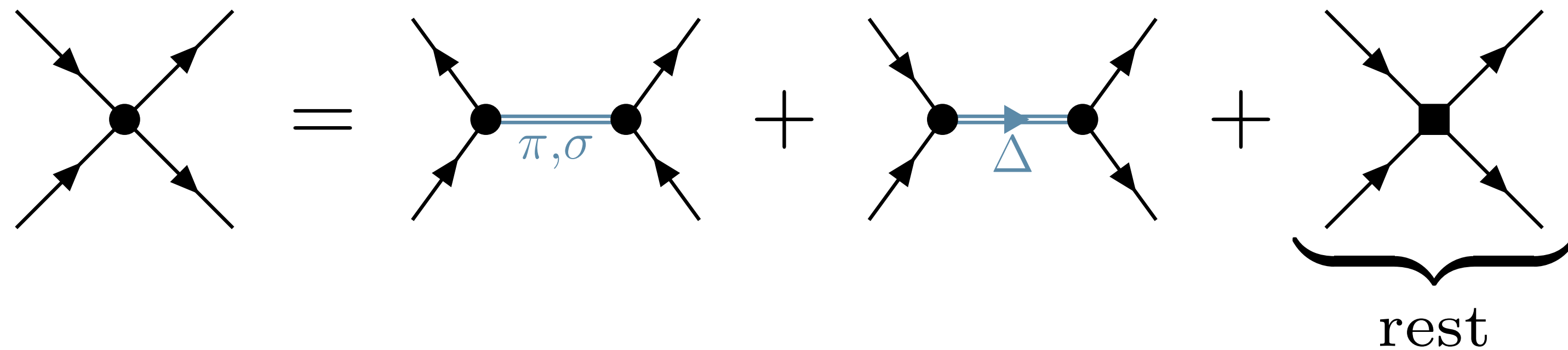
$$\dot{\Phi}_k = \langle \partial_t \hat{\Phi}_k \rangle - \frac{1}{2} \eta_{\Phi,k} \Phi$$

[Gies, Wetterich, PRD 65, 69 (2001, 02)]
[Pawlowski, Ann. Phys. 332 (2005)]

- choose $\langle \partial_t \hat{\Phi}_k \rangle$ to "absorb" flow of desired 4-quark channel

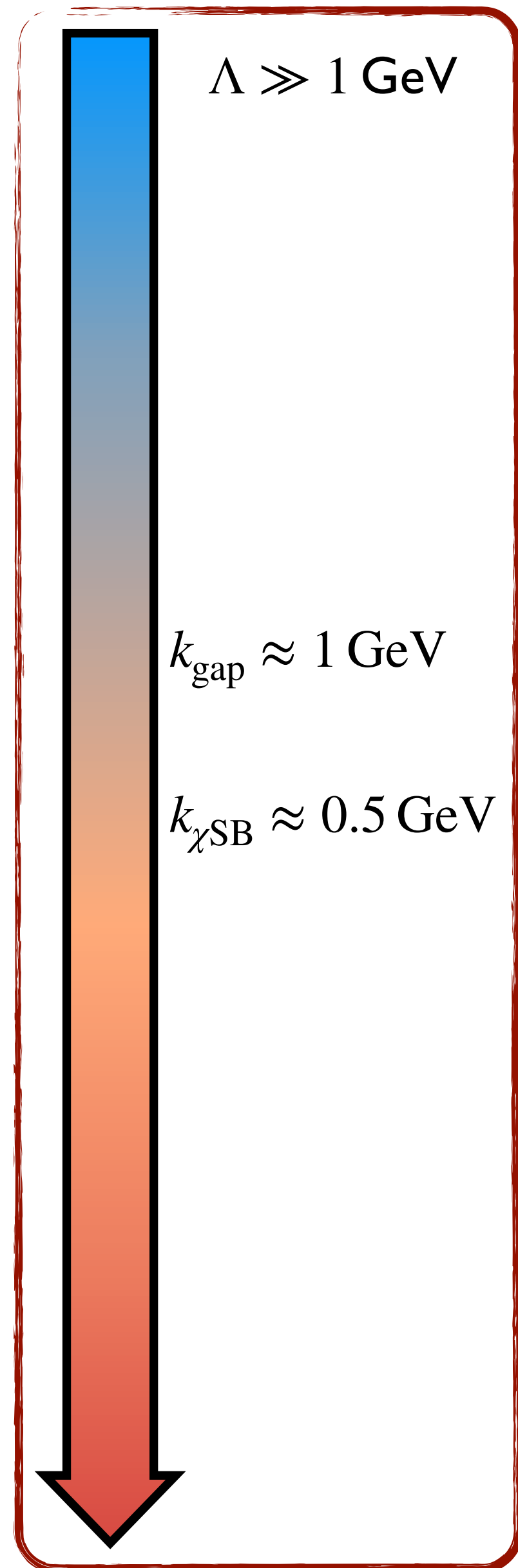
example: mesons & diquarks [Gholami, Mire, FR, Schaefer, Yin, 2606.23772]

$$\langle \partial_t \hat{\Phi}_k \rangle \sim \frac{\dot{\lambda}_{T,k}}{h_{T,k}} (\bar{q} T q)$$



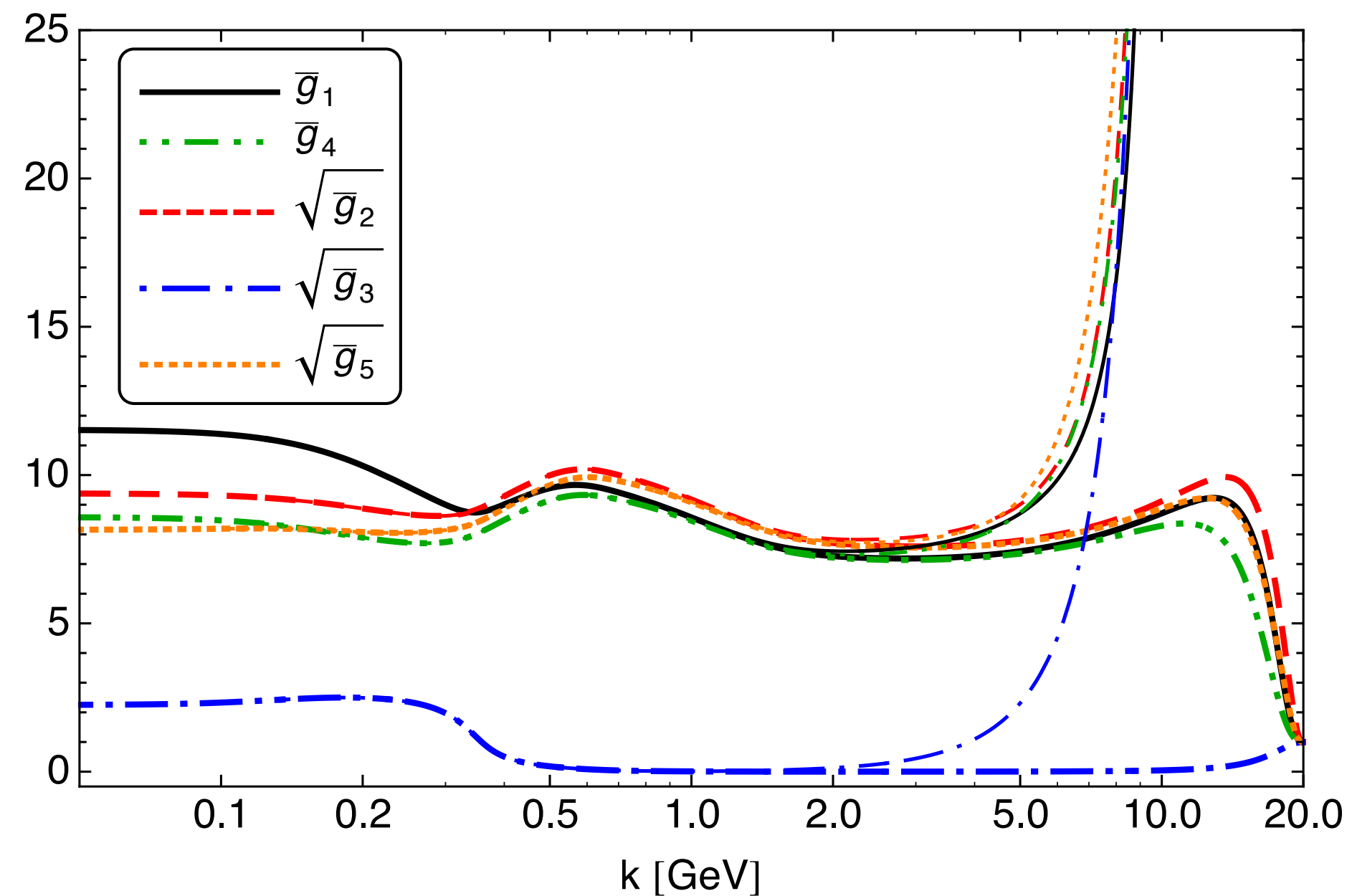
$\longrightarrow$ unified description of constituents (quarks & gluons) and composites

EMERGENT LOW-ENERGY PHYSICS

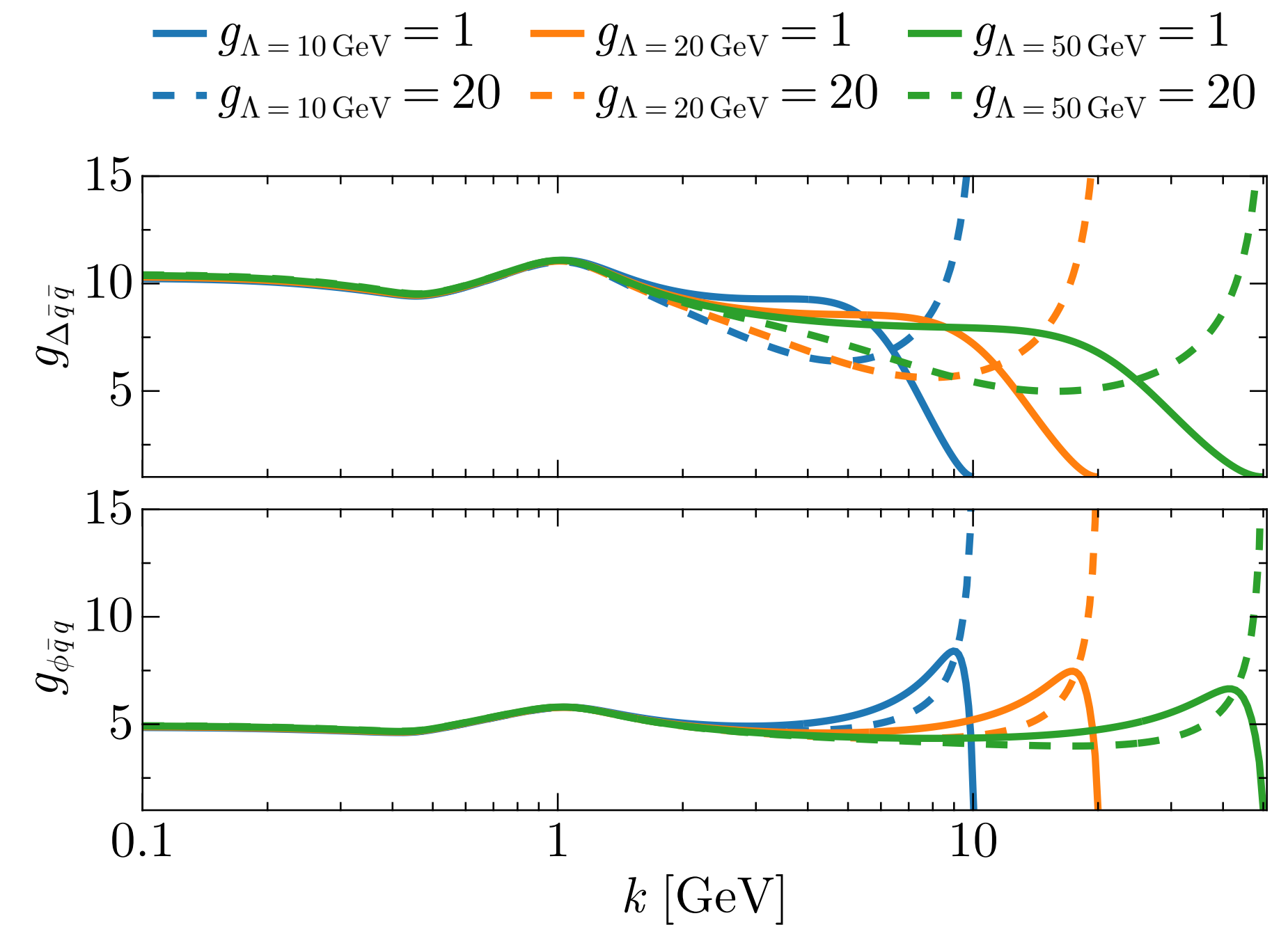


- parameters of composite sector uniquely determined by fixed point at small g

vector meson interactions
[FR, PRD 92 (2015)]

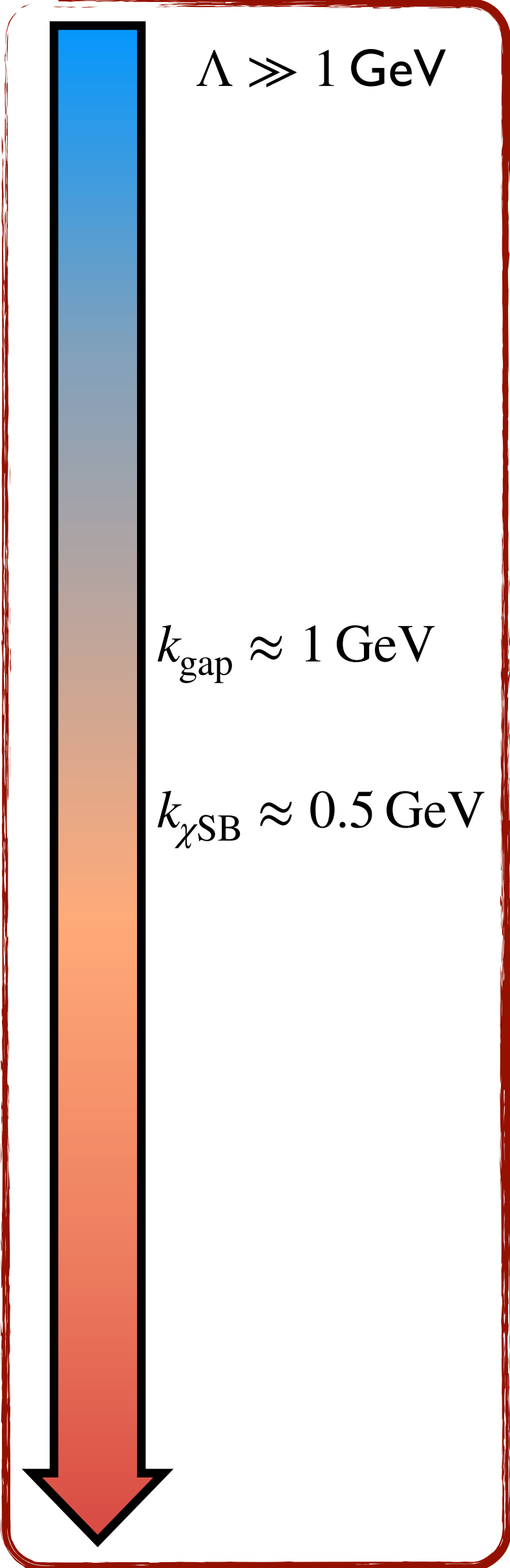


quark-meson/diquark interactions
[Gholami, Mire, FR, Schaefer, Yin, 2606.23772]



→ low-energy sector emerges dynamically, no free model parameters

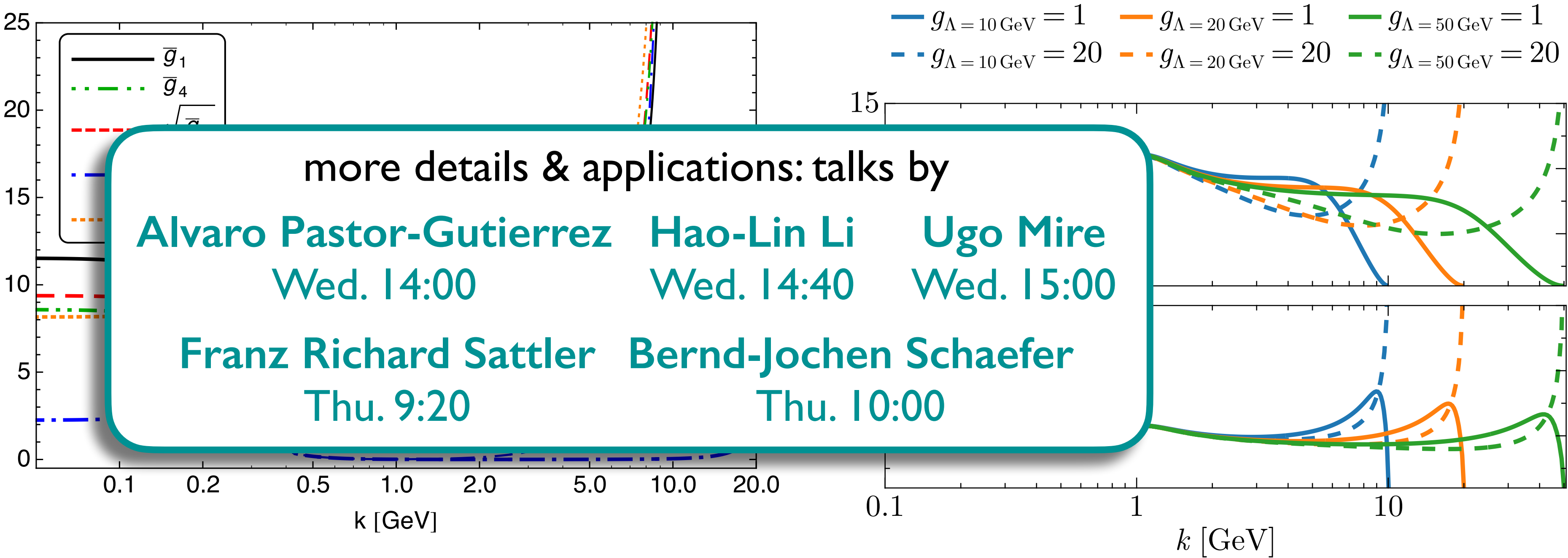
EMERGENT LOW-ENERGY PHYSICS



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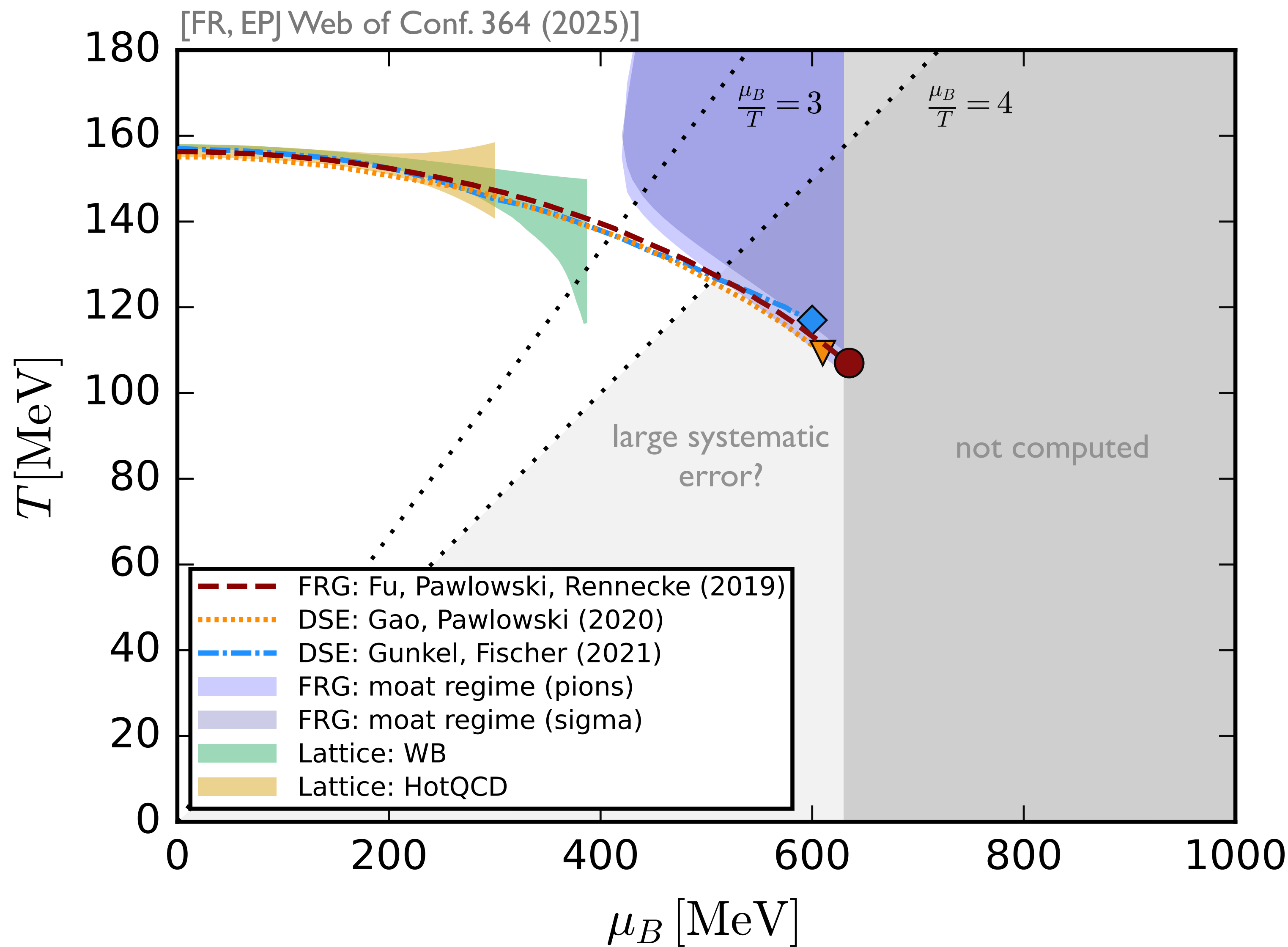
quark-meson/diquark interactions
[Gholami, Mire, FR, Schaefer, Yin, 2606.23772]



→ low-energy sector emerges dynamically, no free model parameters

QCD PHASE DIAGRAM & THE CRITICAL ENDPOINT

First results for the chiral transition from direct computations in QCD (assuming homogeneous phases)



CEP at $(T, \mu_B) \approx (110, 630)$ MeV

[Fu, Pawlowski, FR; PRD 101 (2019)]

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

● confirmed by different methods and improved approximations

direct calculations in QCD:

[Gao, Pawlowski, PLB 820 (2020)]

[Gunkel, Fischer, PRD 104 (2021)]

[Lu et al., PRD 113 (2025)]

[Fu, Huang, Pawlowski, FR, Wen, Yin, 2603.13455]

[Wang et al., 2607.07354]

extrapolations from lattice data:

[Basar, PRC 110 (2023)]

[Clarke et al., PRD 112 (2024)]

[Shah et al., PRC 113 (2024)]

● new feature: the moat regime

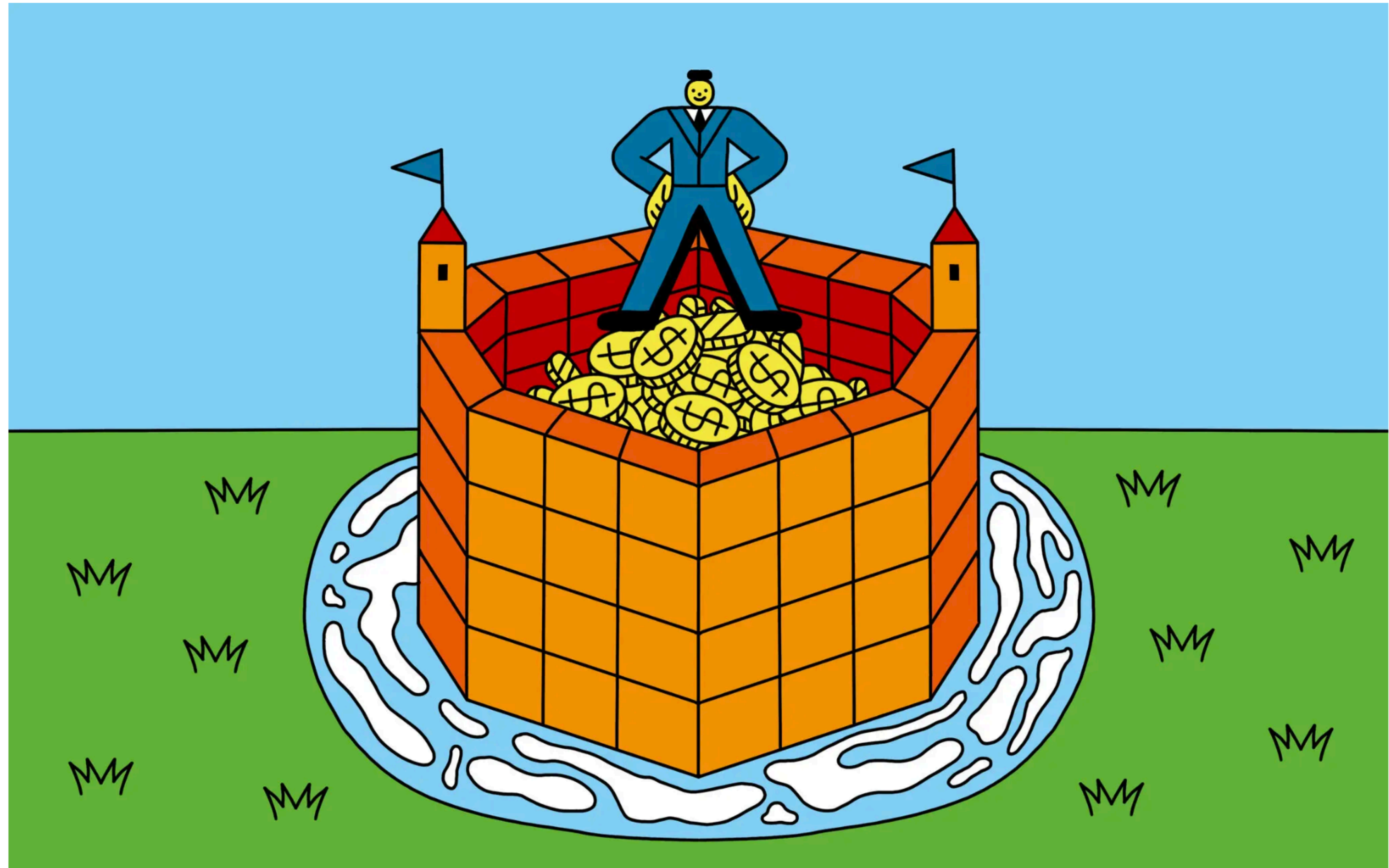
MOATS IN QCD

THE MOAT

/ mōt /

A word used by corporate executives, often as a brag, to describe a competitive edge that boosts profits and market share.

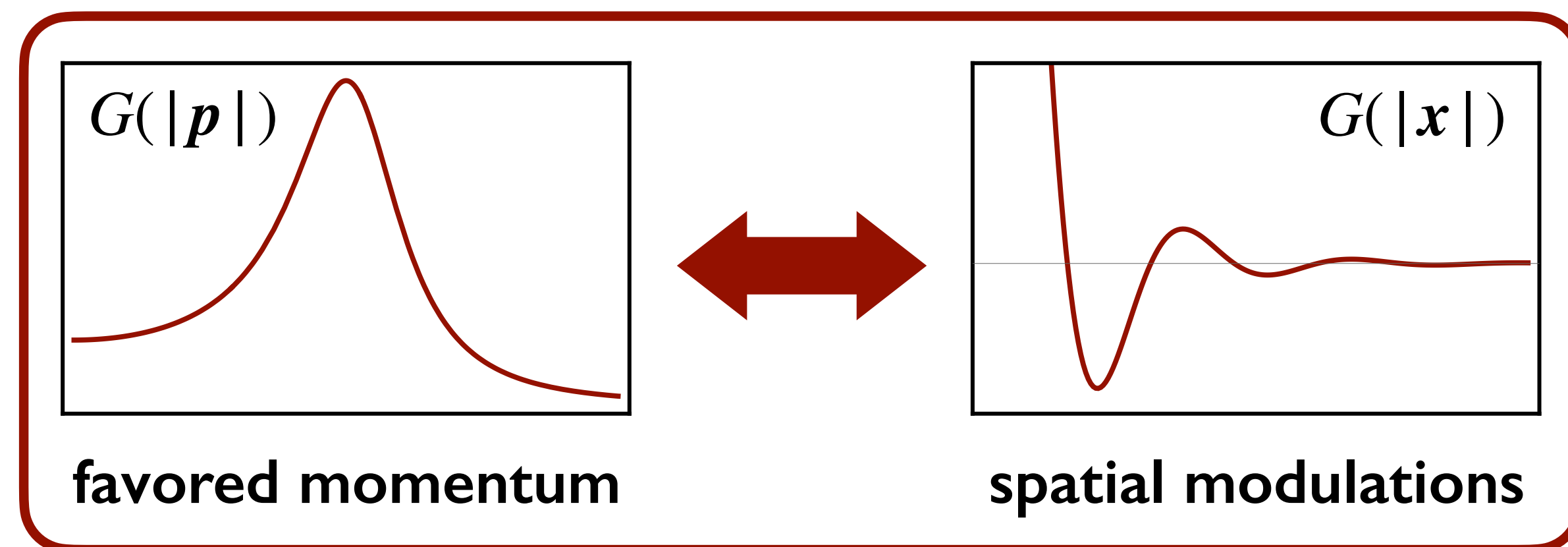
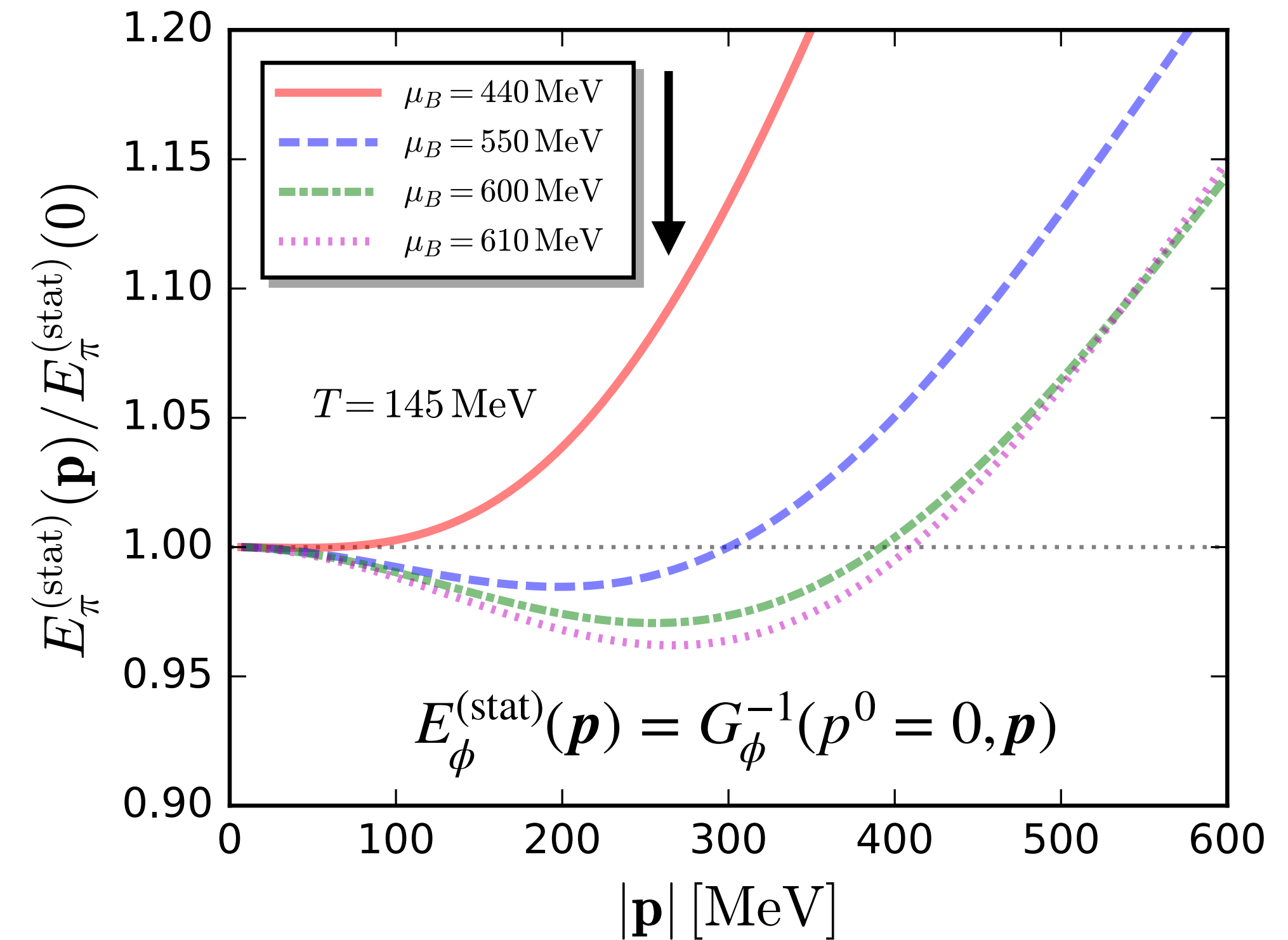
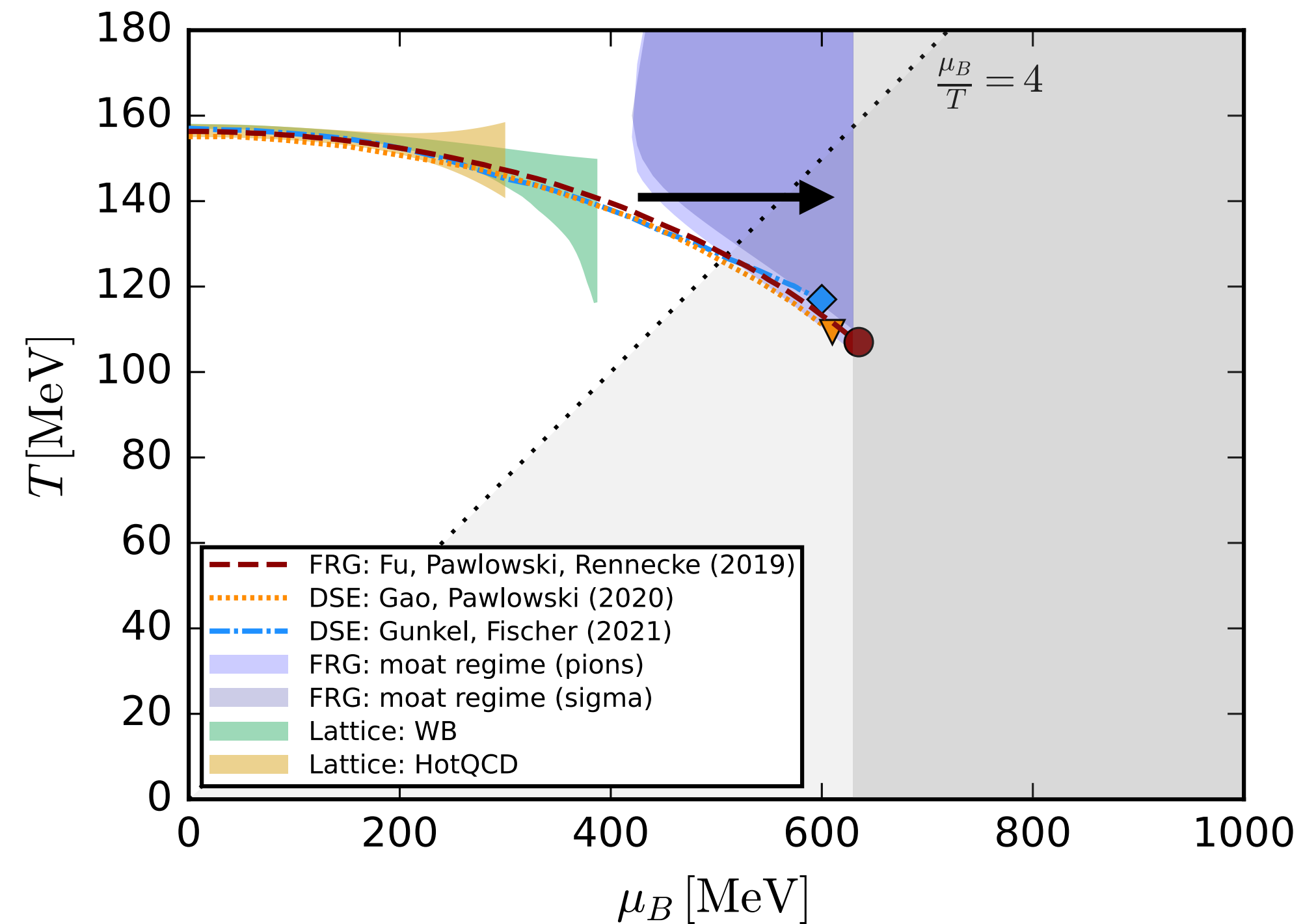
[T.J. Smith, NY Times]



THE MOAT REGIME IN QCD

[Pisarski, FR, PRL 127 (2021)]

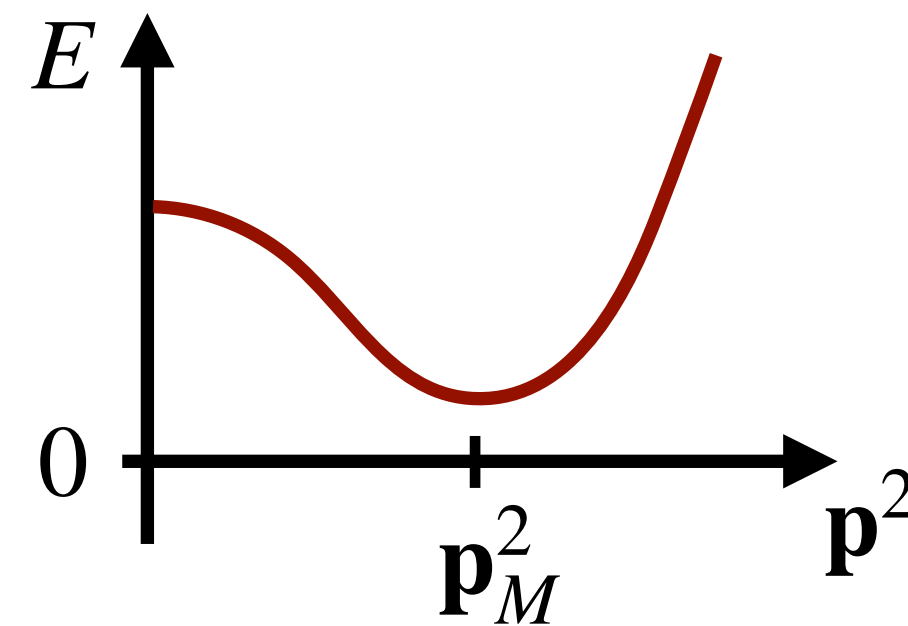
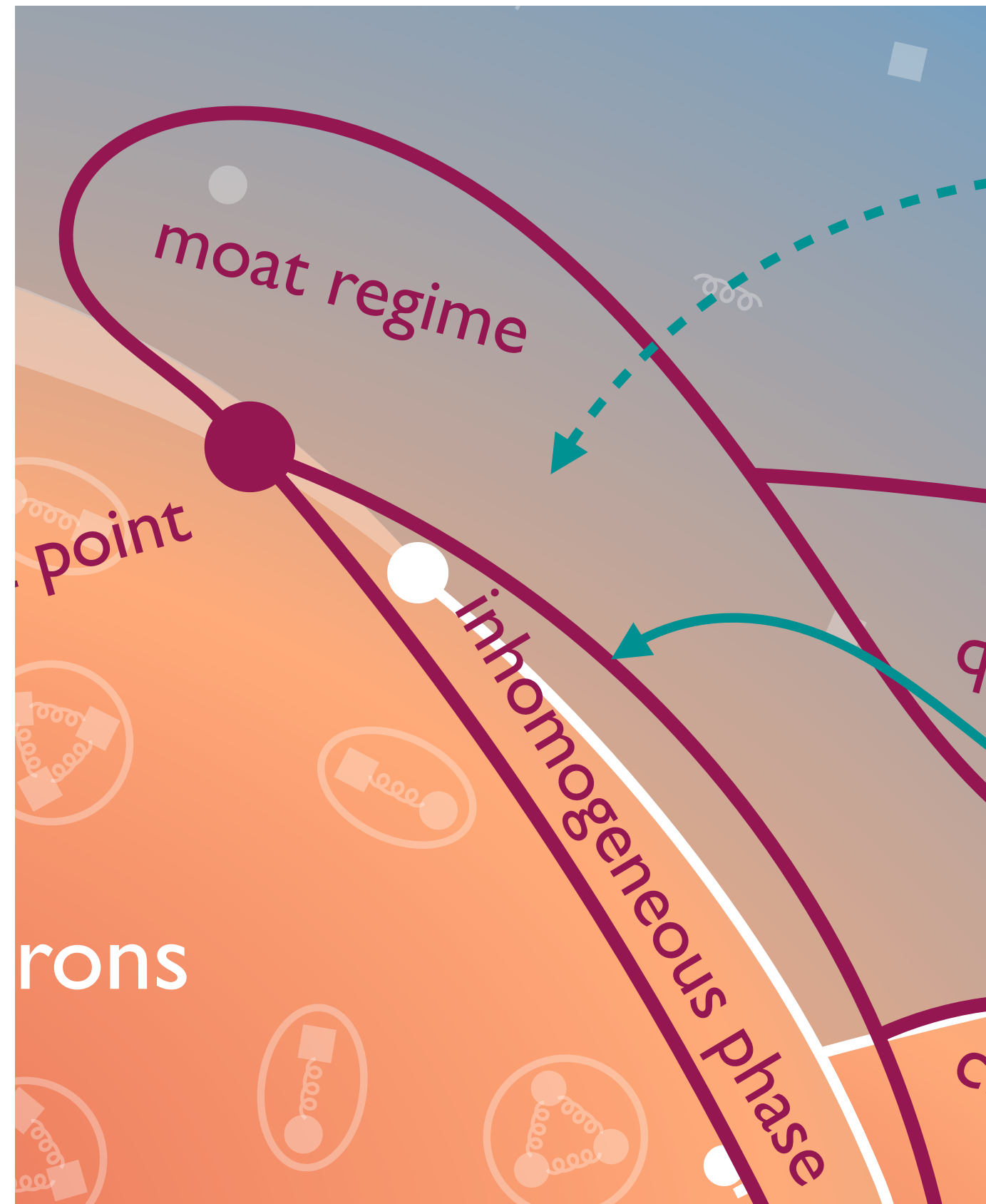
(static) mesonic energy is minimal at nonzero momentum ($\leftrightarrow$ negative spatial wave function renormalization $Z^\perp(\nabla\phi)^2$)



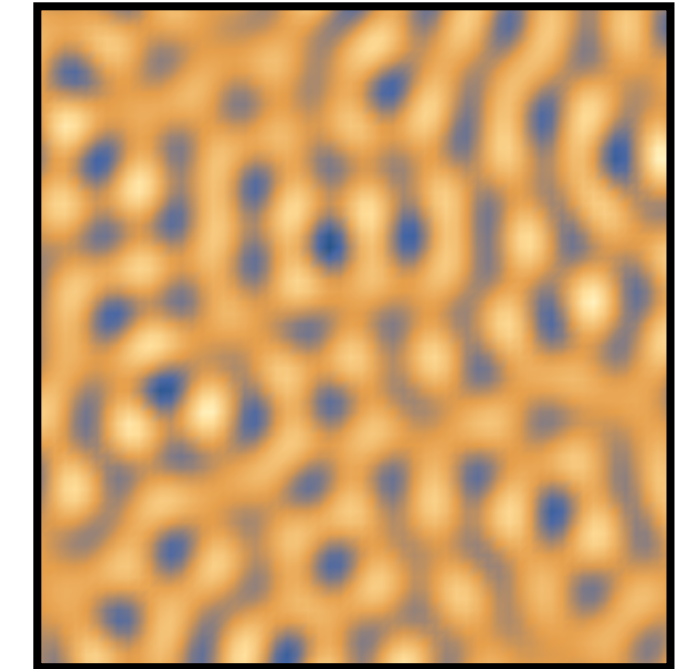
moat is overarching feature for spatially modulated phases

[Nussinov et al. PRL 135 (2024)]

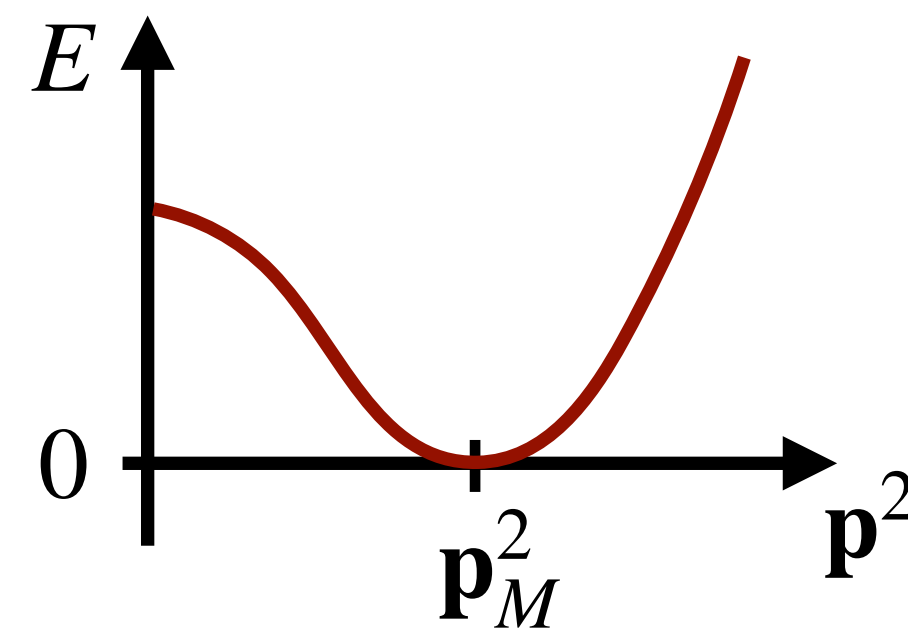
FROM MOATS TO INHOMOGENEOUS PHASES



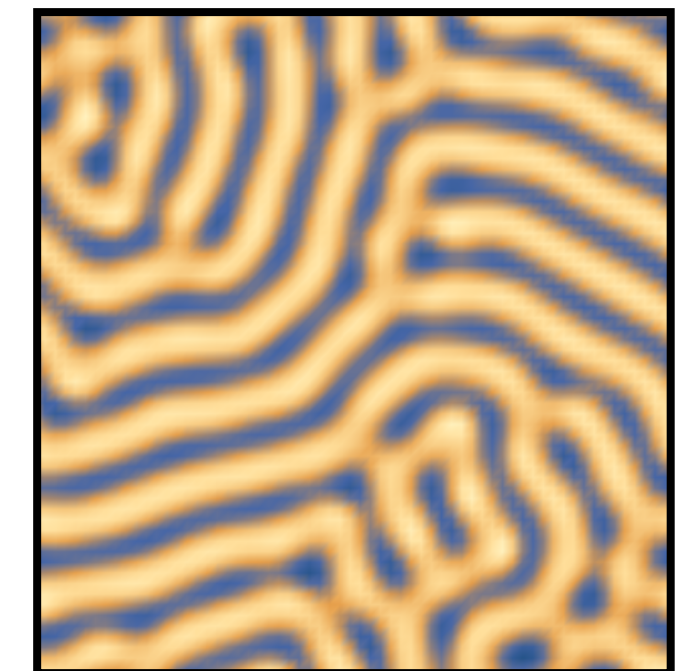
$E > 0$ for all p^2



(possible) spatial field configurations



$E = 0$ at $p^2 > 0$:

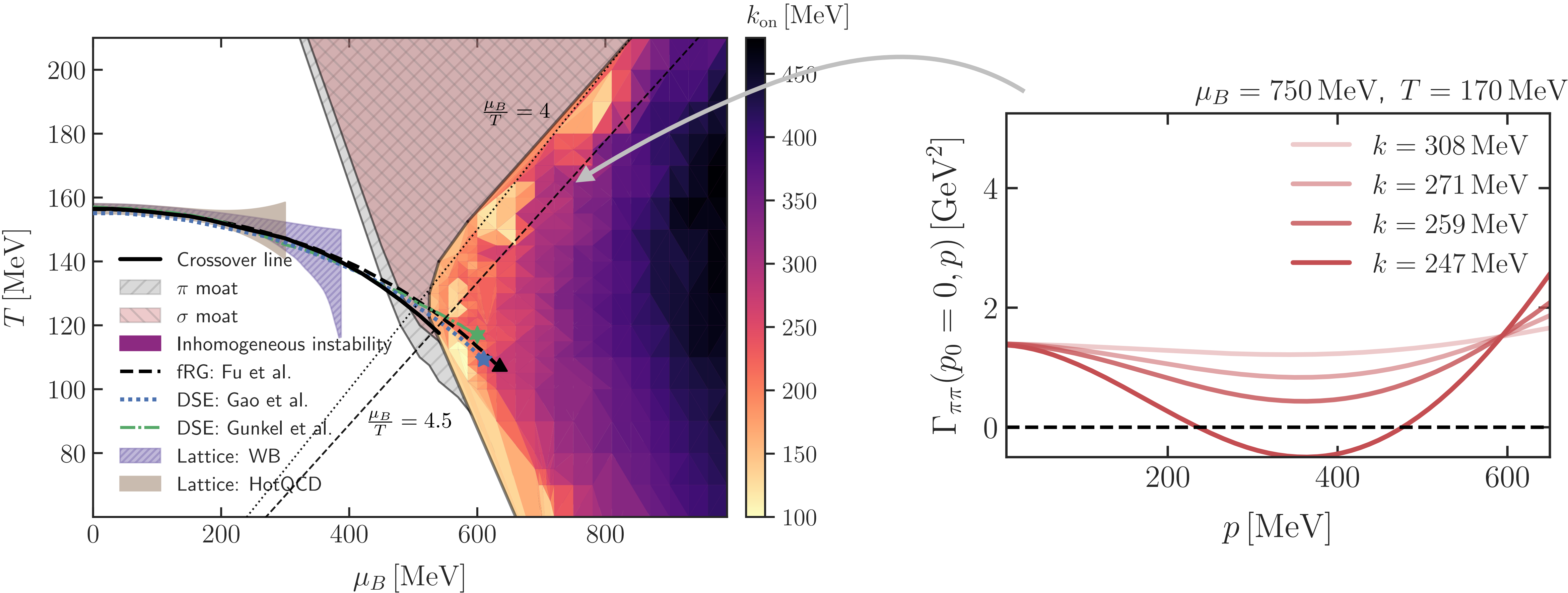


$E(p_M > 0) = 0$: zero energy cost to condense particles with nonzero momentum

→ instability towards inhomogeneous/crystalline phase

INHOMOGENEOUS INSTABILITY IN QCD

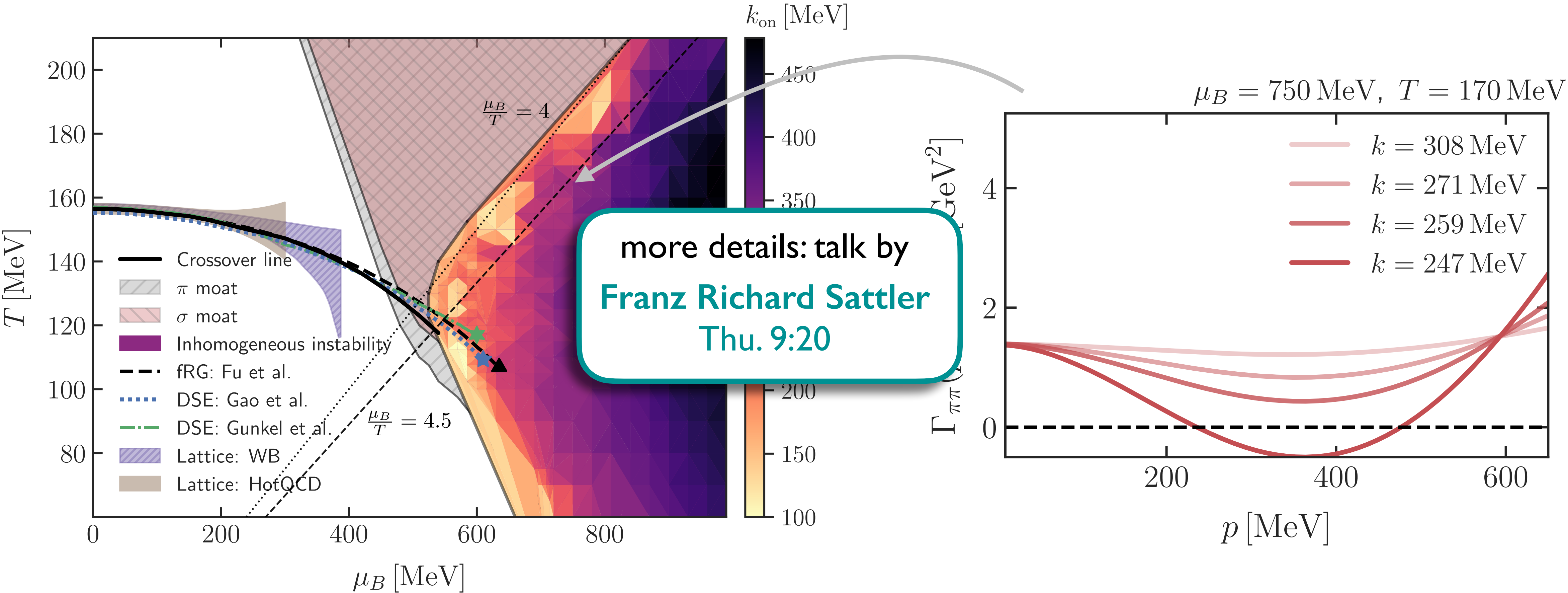
- moat regime established in QCD by now [Fu, Pawłowski, FR, PRD 101 (2019)]
[Fu, Pawłowski, Pisarski, FR, Wen, Yin, PRD 111 (2024)]
[Fu, Huang, Pawłowski, FR, Wen, Yin, 2603.13455]
- self-consistent resolution of momentum dependence: instabilities [Pawłowski, FR, Sattler; EPJ Spec.Top. (2025)]



→ inhomogeneous instability at intermediate scale $k > 0$

INHOMOGENEOUS INSTABILITY IN QCD

- moat regime established in QCD by now [Fu, Pawłowski, FR, PRD 101 (2019)]
[Fu, Pawłowski, Pisarski, FR, Wen, Yin, PRD 111 (2024)]
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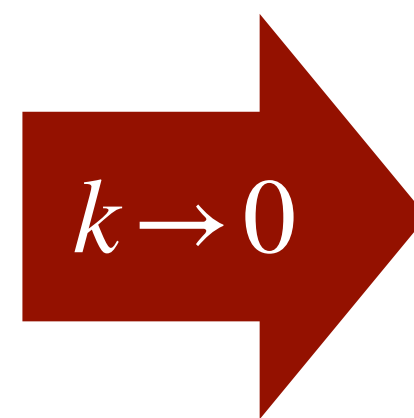
➔ inhomogeneous instability at intermediate scale $k > 0$

INTERMEDIATE-SCALE INSTABILITIES?

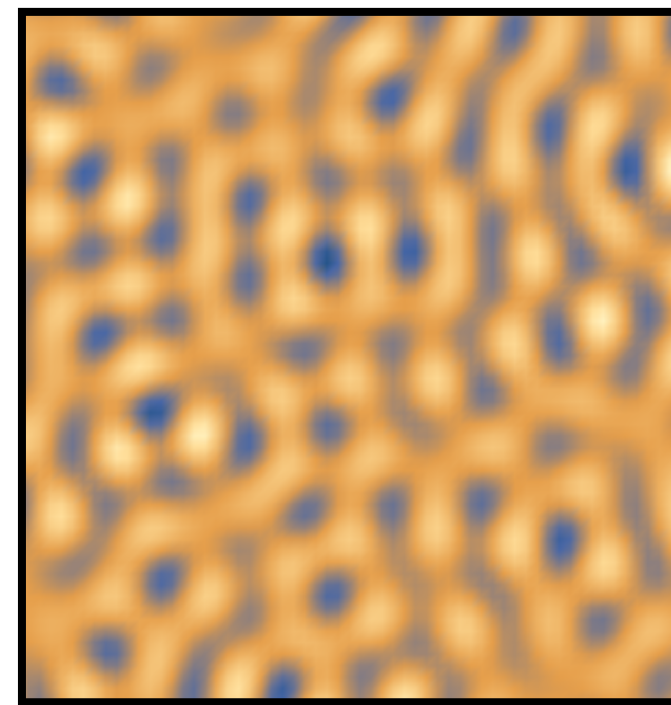
[Pawlowski, FR, Sattler; EPJ Spec.Top. (2025)]

what can happen at macroscopic scales $k = 0$?

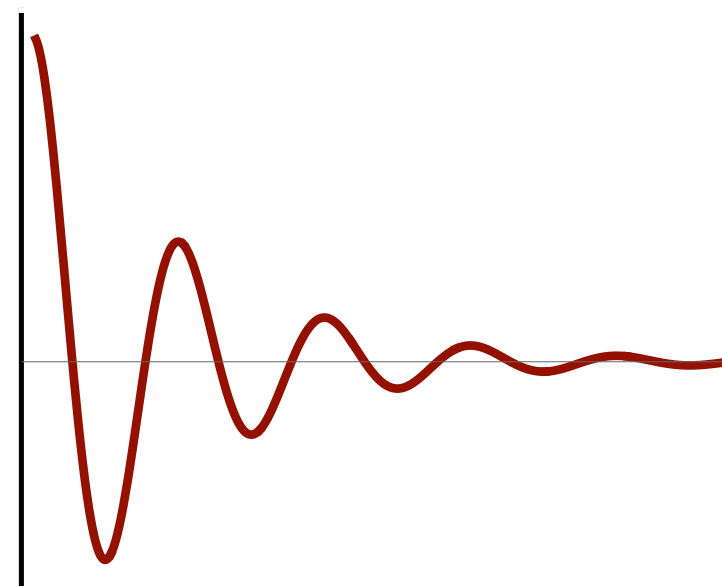
what we have:
inhomogeneous structures
at intermediate scales:



no instab. at $k=0$
isotropic moat

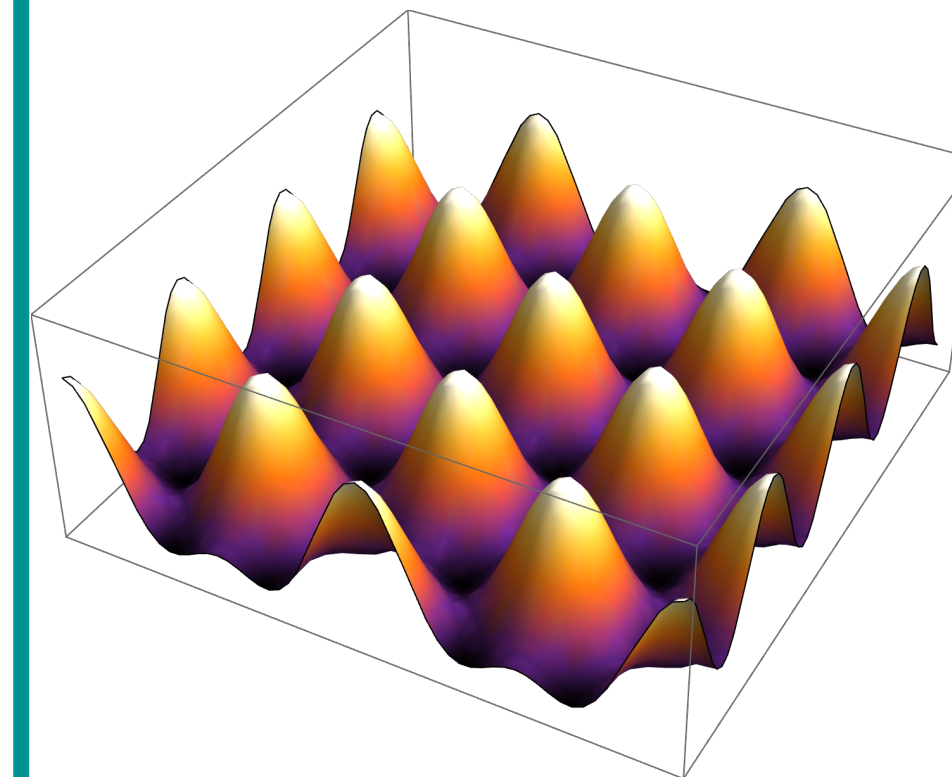


$$\langle \phi(r)\phi(0) \rangle \sim \sin(p_M r) e^{-mr}$$

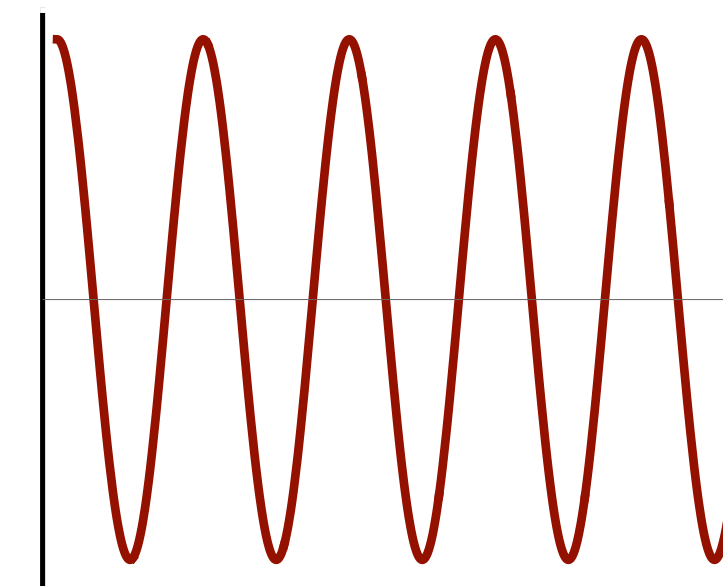


e.g., quantum pion liquid
[Pisarski, Tsvetlik, Valgushev, PRD 102 (2020)]

instab. at $k=0$
inhom. phase



$$\langle \phi(r)\phi(0) \rangle \sim \sin(p_M r)$$

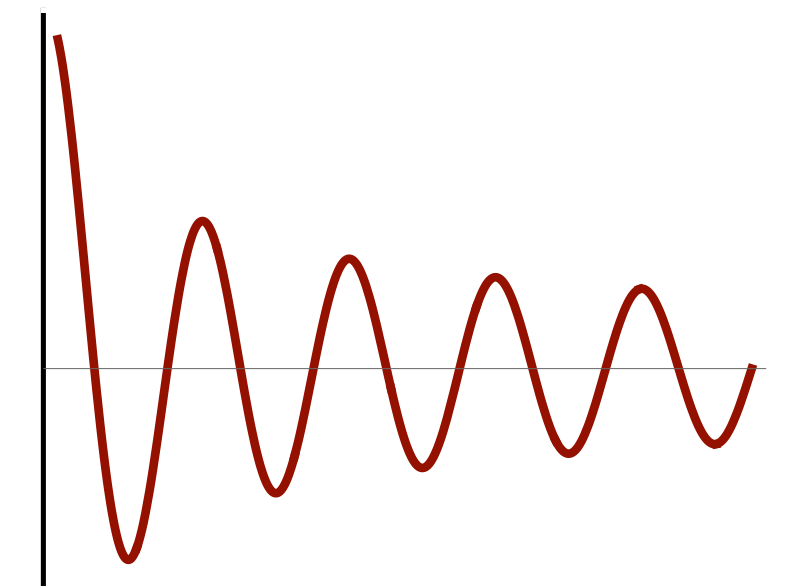


reviews:
[Fukushima, Hatsuda, RPP 74 (2010)]
[Buballa, Carignano, PPNP 81 (2014)]

"washed out" instab.
liquid crystal



$$\langle \phi(r)\phi(0) \rangle \sim \sin(p_M r) r^{-\alpha}$$



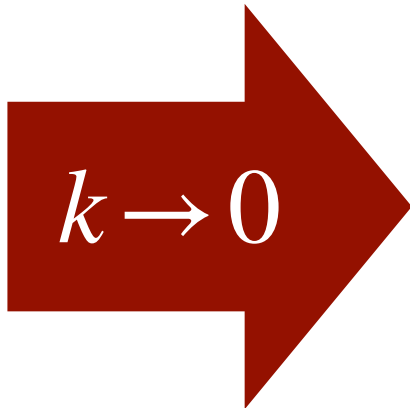
[Lee et al., PRD 92 (2015)]
[Hidaka et al., PRD 92 (2015)]

INTERMEDIATE-SCALE INSTABILITIES?

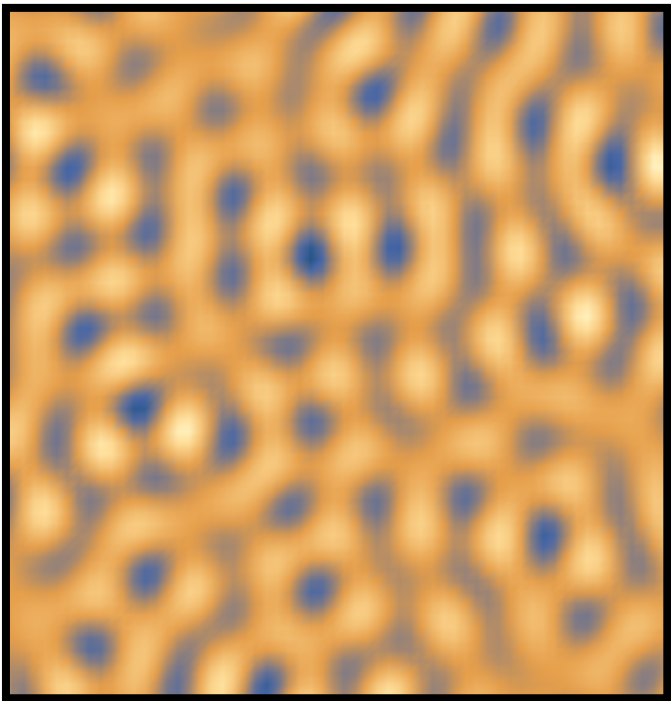
[Pawlowski, FR, Sattler; EPJ Spec.Top. (2025)]

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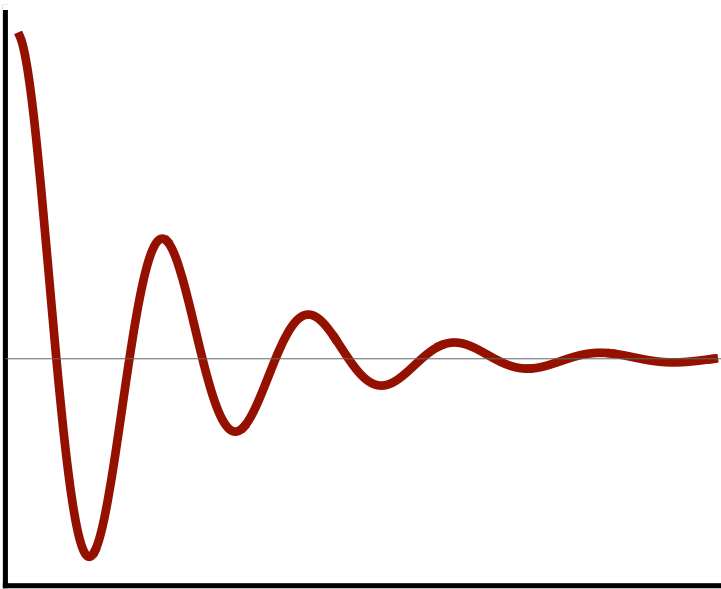
what we have:
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no instab. at $k = 0$
isotropic moat

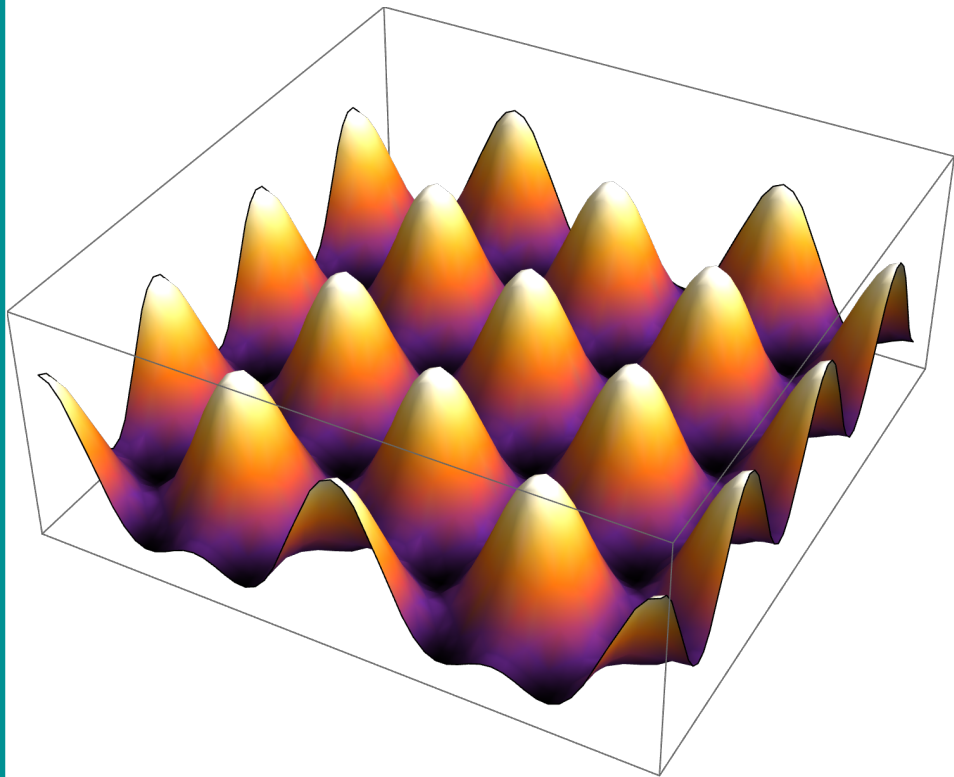


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inhom. phase



$$\langle \phi(r) \phi(0) \rangle \sim \sin(p_M r)$$



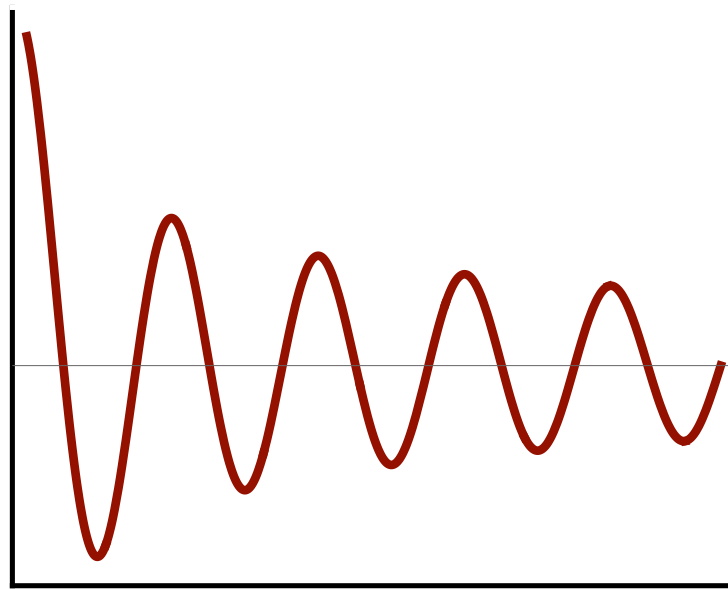
poster by
Ana Garcia-Page

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"washed out" instab.
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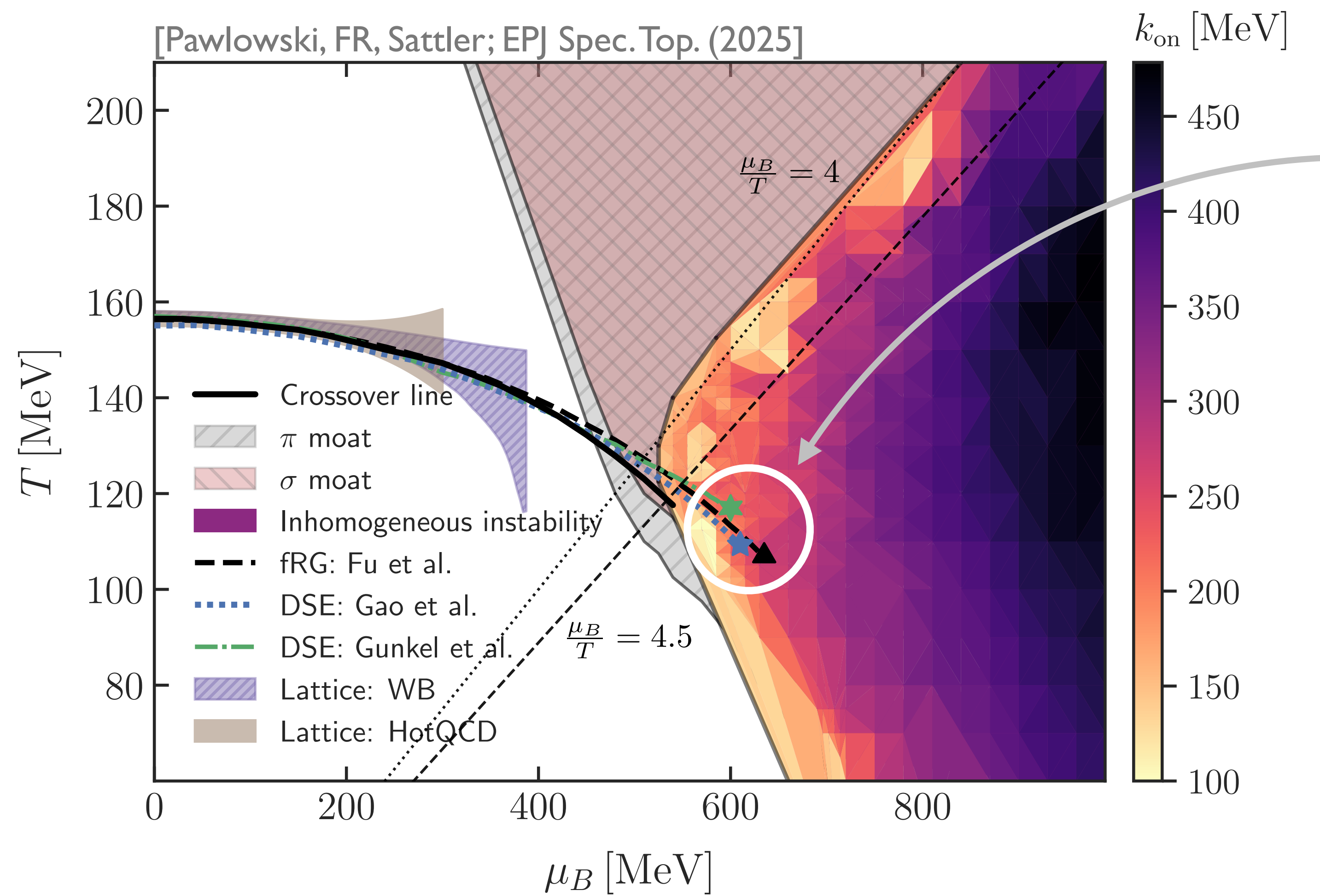


$$\langle \phi(r) \phi(0) \rangle \sim \sin(p_M r) r^{-\alpha}$$



[Lee et al., PRD 92 (2015)]
[Hidaka et al., PRD 92 (2015)]

IMPLICATIONS FOR THE CEP?



CEP within unstable region!

If instabilities persist and also affect critical mode, **fate of ordinary CEP unclear:**

[Haensch, FR, von Smekal, PRD 110 (2023)]

- Lifshitz point instead of CEP (different univ. class!)
- Lifshitz point and CEP
- Lifshitz region
- none of the above ...

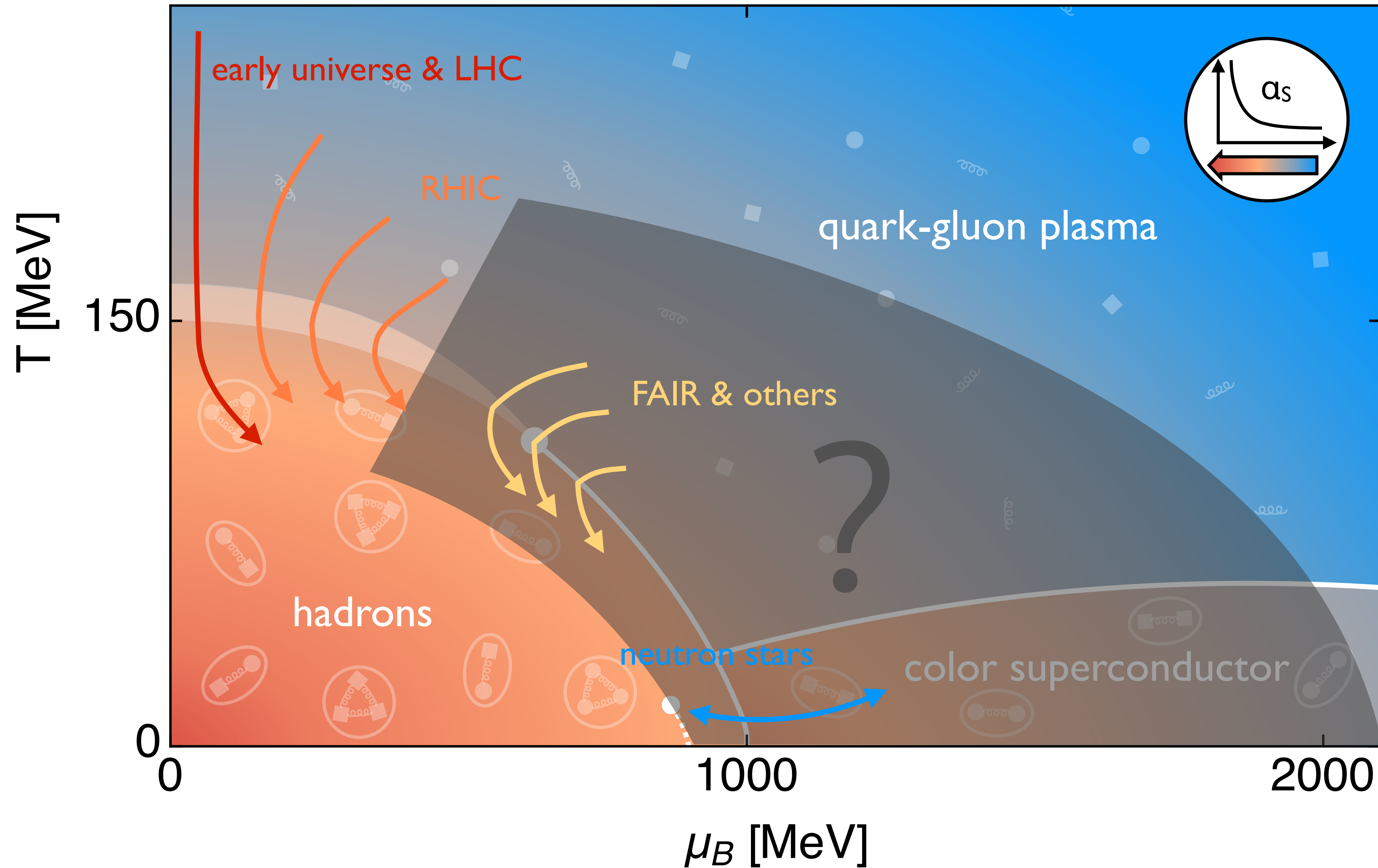
[Buballa, Carignano 1406.1367]

[Pisarski, Skokov, Tsvetlik, 1801.08156]

➡ need to think about alternatives to conventional CEP scenario

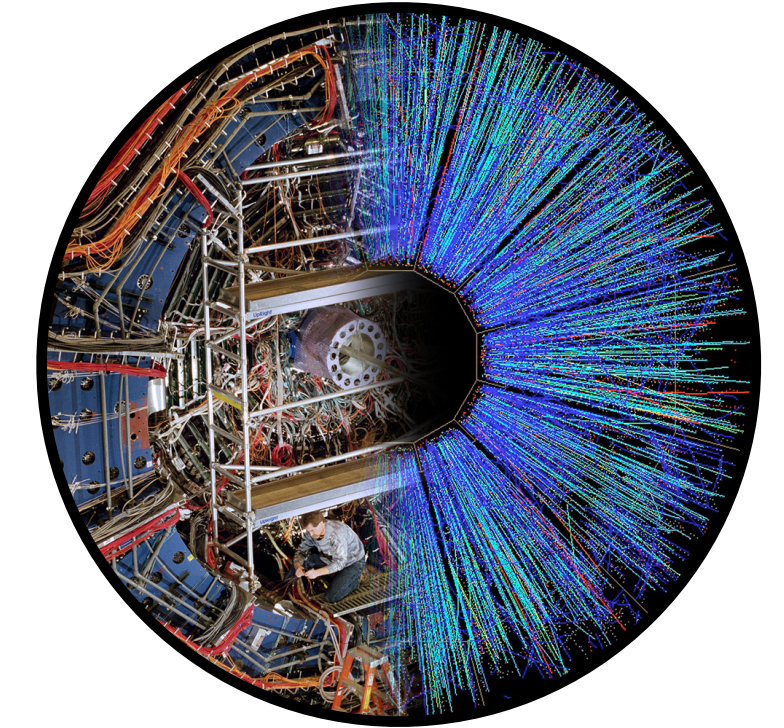
MOAT PHENOMENOLOGY

QCD PHASE DIAGRAM IN EXPERIMENTS

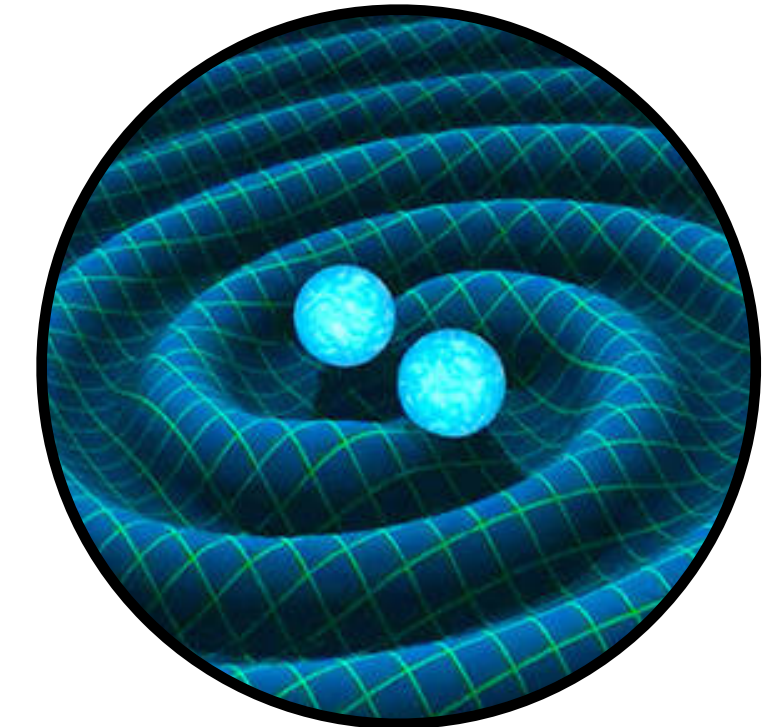


Experiments:

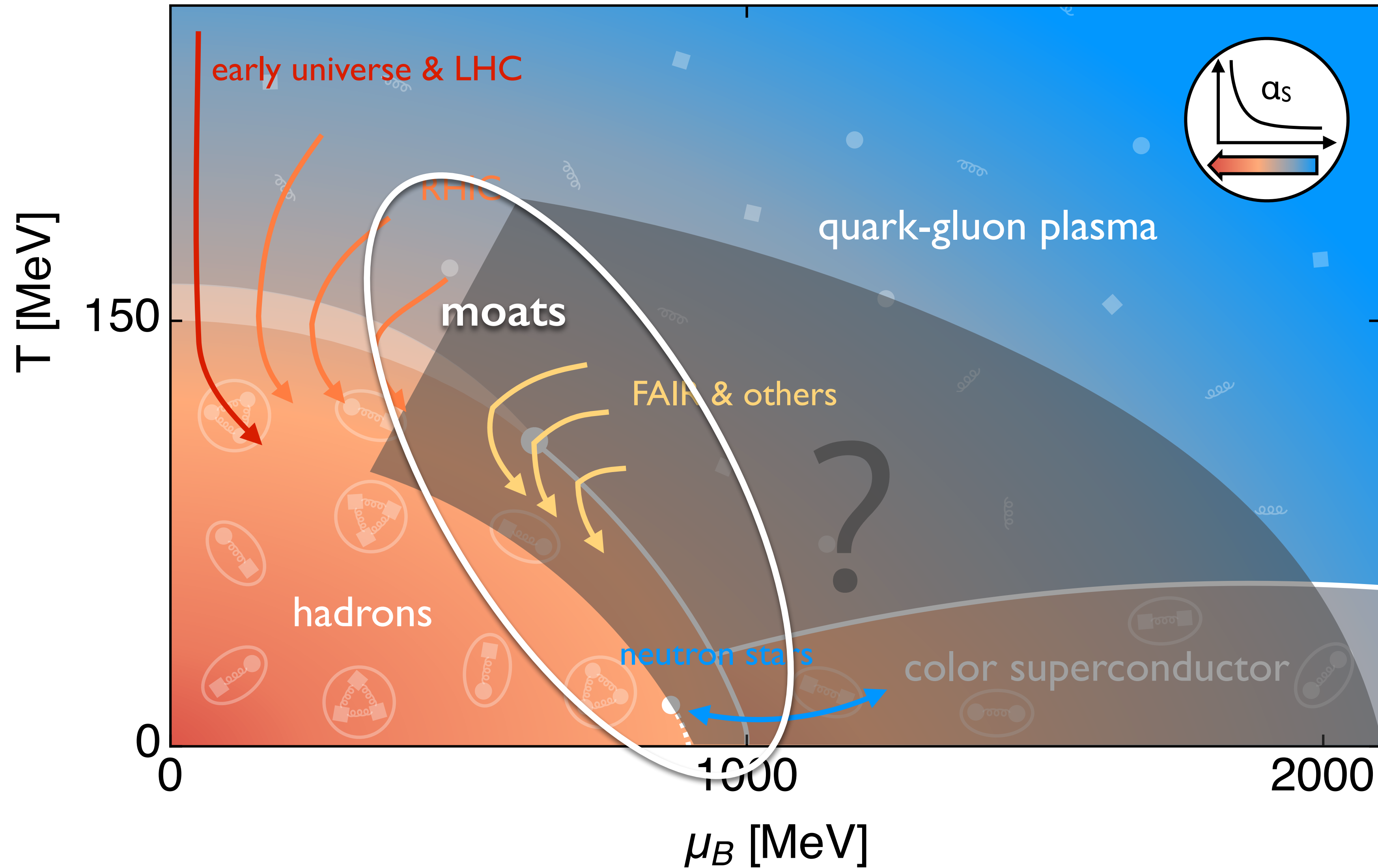
heavy-ion collisions



multi-messenger astronomy

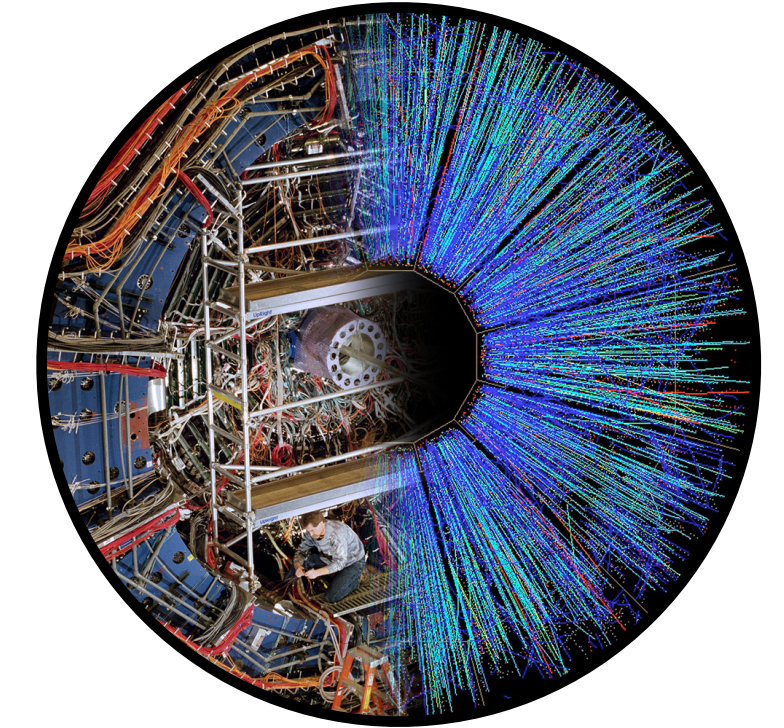


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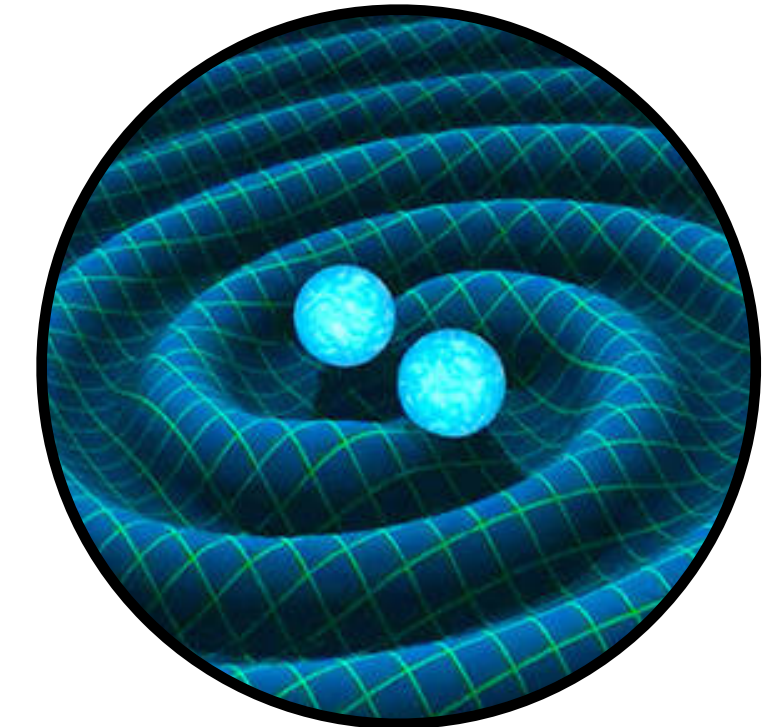


Experiments:

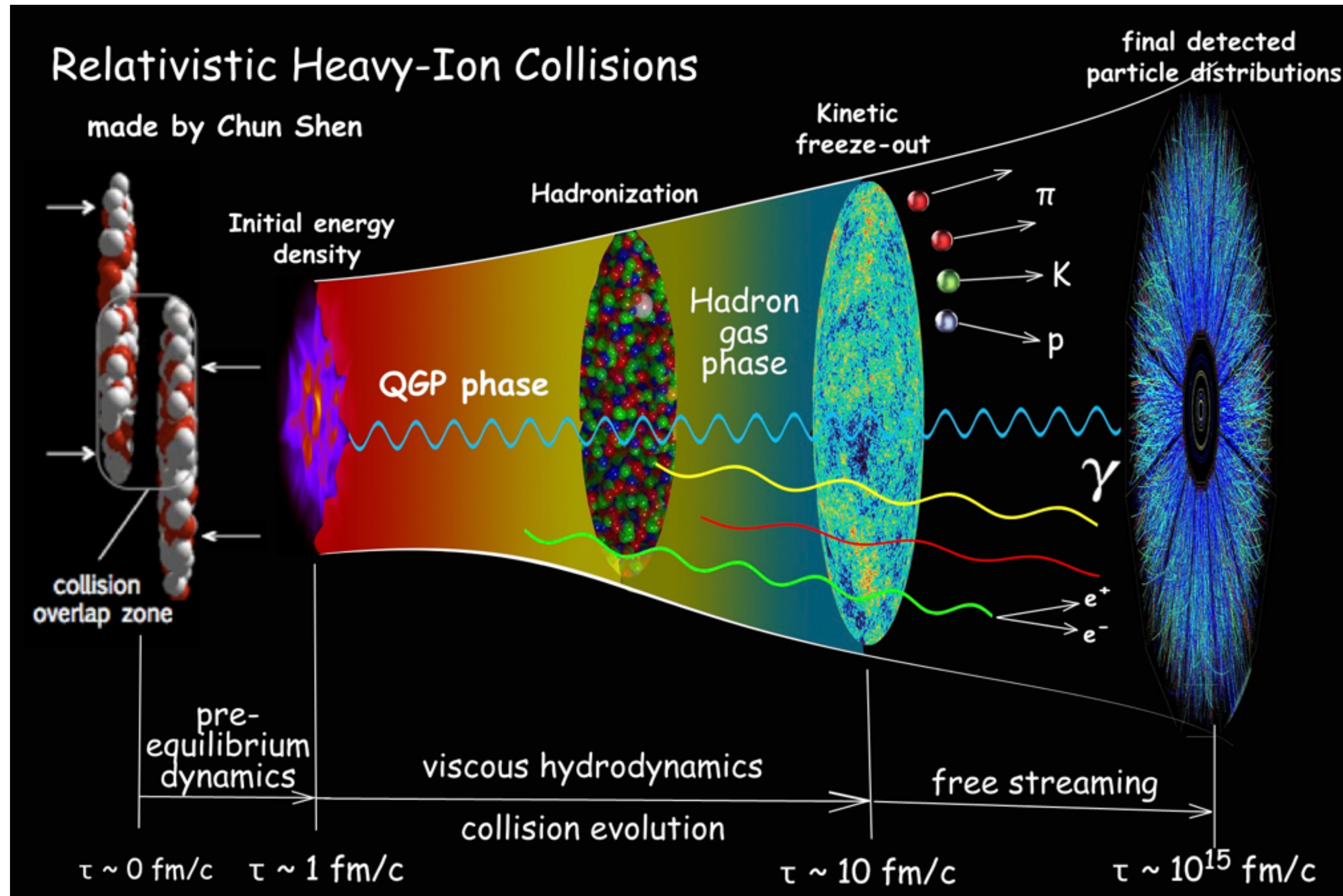
heavy-ion collisions



multi-messenger astronomy



HEAVY-ION COLLISIONS



[D. Fehrenz, GSI/FAIR (as of April 2024)]

SEARCH FOR MOATS IN HICS

intuitive idea [Pisarski, FR, PRL 127 (2021)]

Characteristic feature: particle modes with minimal energy at nonzero momentum

⇒ **modified particle correlations at nonzero momentum**

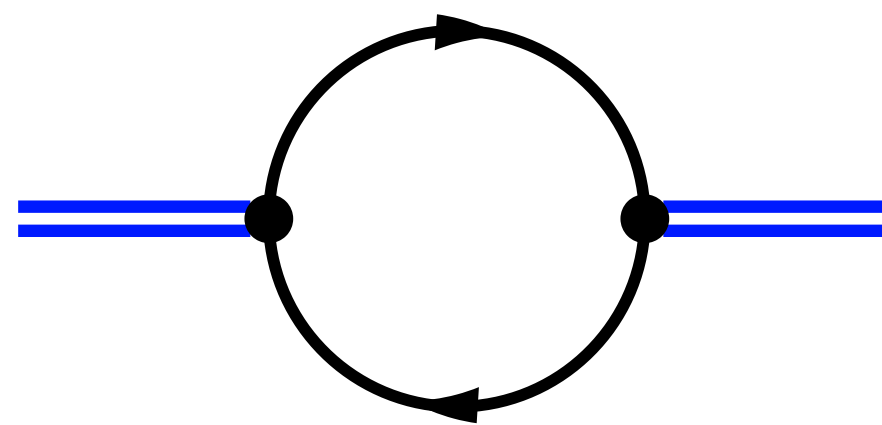
SEARCH FOR MOATS IN HICS

intuitive idea [Pisarski, FR, PRL 127 (2021)]

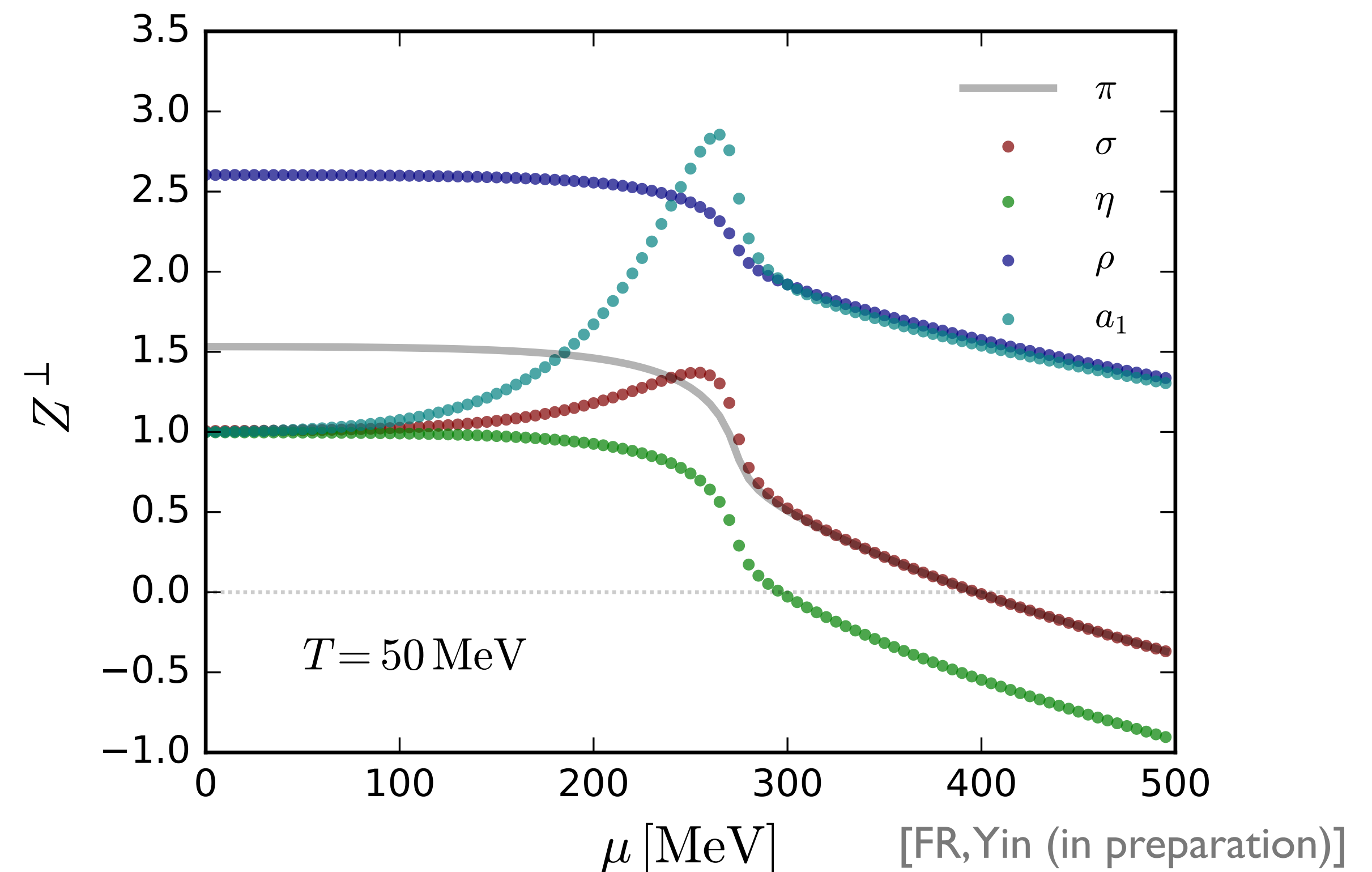
Characteristic feature: particle modes with minimal energy at nonzero momentum
 $\Rightarrow$ **modified particle correlations at nonzero momentum**

where to look for moats?

- first found in QCD in π and σ meson channels
- models: they can appear in all sorts of mesons:
 - kaons: [Cao; PRD 112 (2025)]
 - η, ρ, a_1 : [FR, Yin (in preparation)]



not surprising: moat generated
by particle-hole fluctuations
around Fermi surface
[FR, Yin, PRD 113 (2025)]

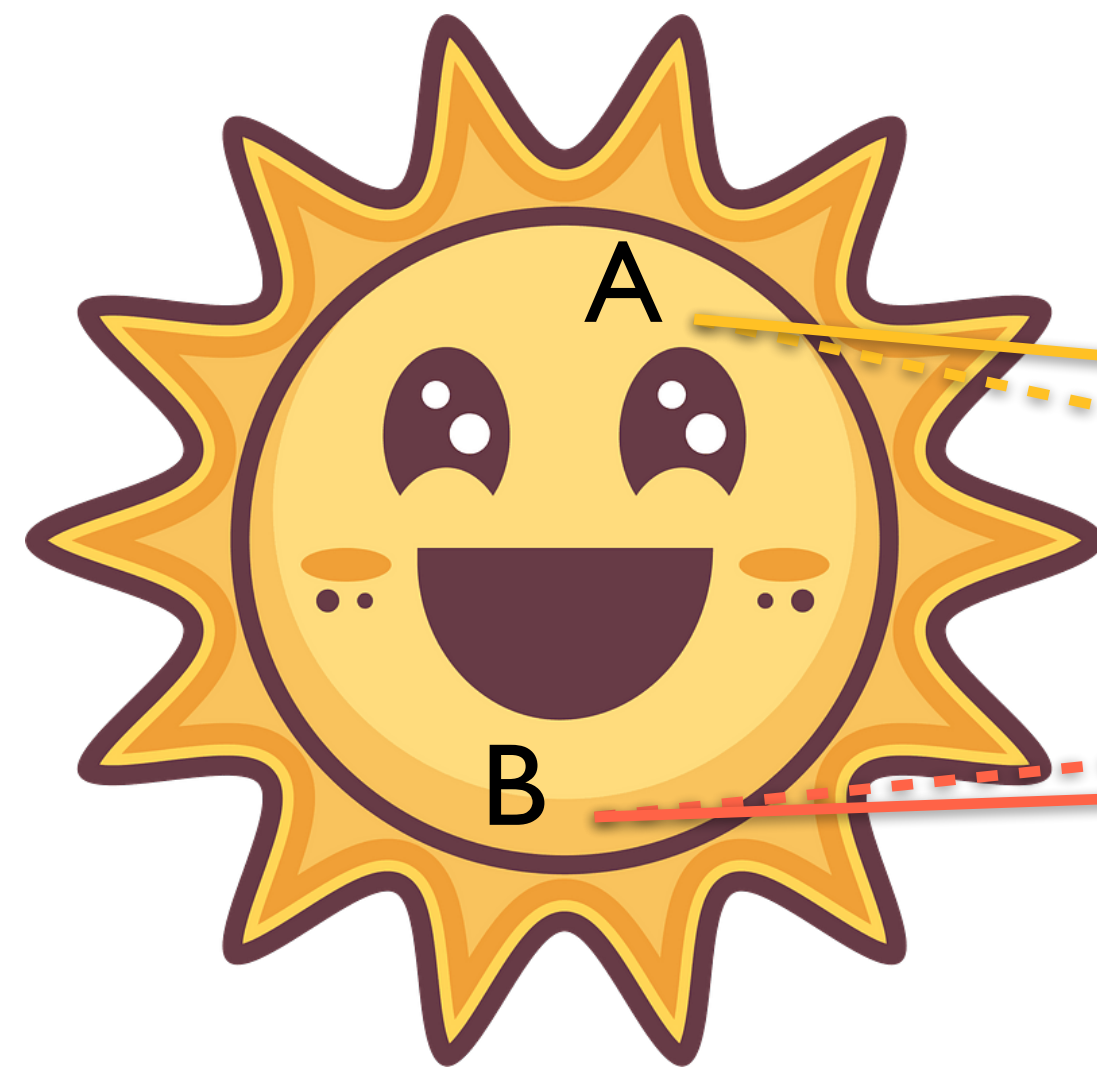


$\longrightarrow$ look for signatures related to the **momentum dependence of meson correlations**

HANBURY-BROWN-TWISS CORRELATIONS

Borrow idea from astronomy to measure size of stars: **HBT interferometry**

[Hanbury Brown, Twiss (1954)]



original experiment in Narrabri, Australia

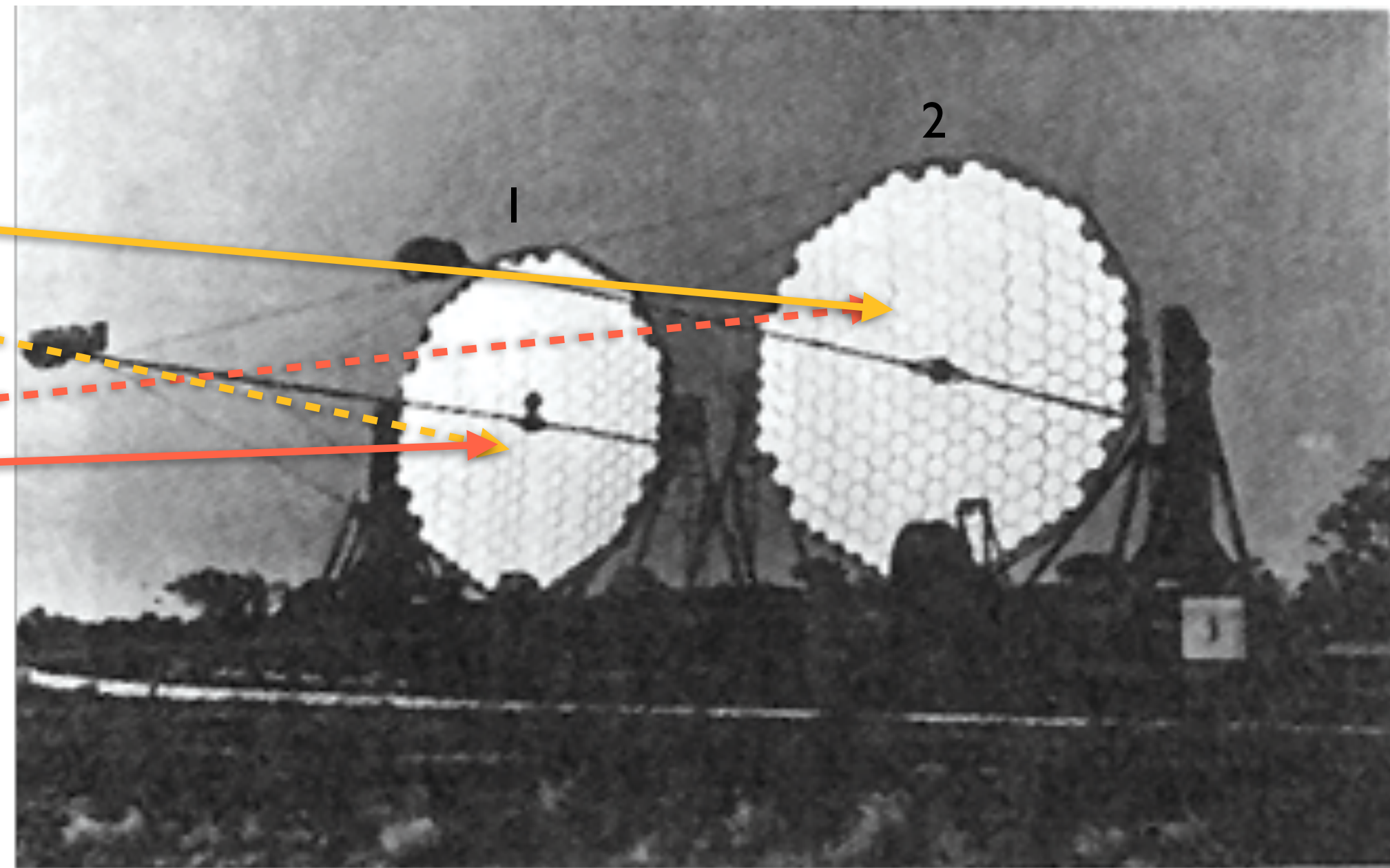


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

[Goldhaber (1991)]

Adapted in HICs, e.g., to estimate size of fireball (emission source) from pion-pion correlations and study strong interactions among hadrons

[Lisa et al., Ann.Rev.Nucl.Part.Sci. 55 (2005)]

[Fabbietti, Sarti, Doce, Ann.Rev.Nucl.Part.Sci. 71 (2021)]

HANBURY-BROWN-TWISS CORRELATIONS

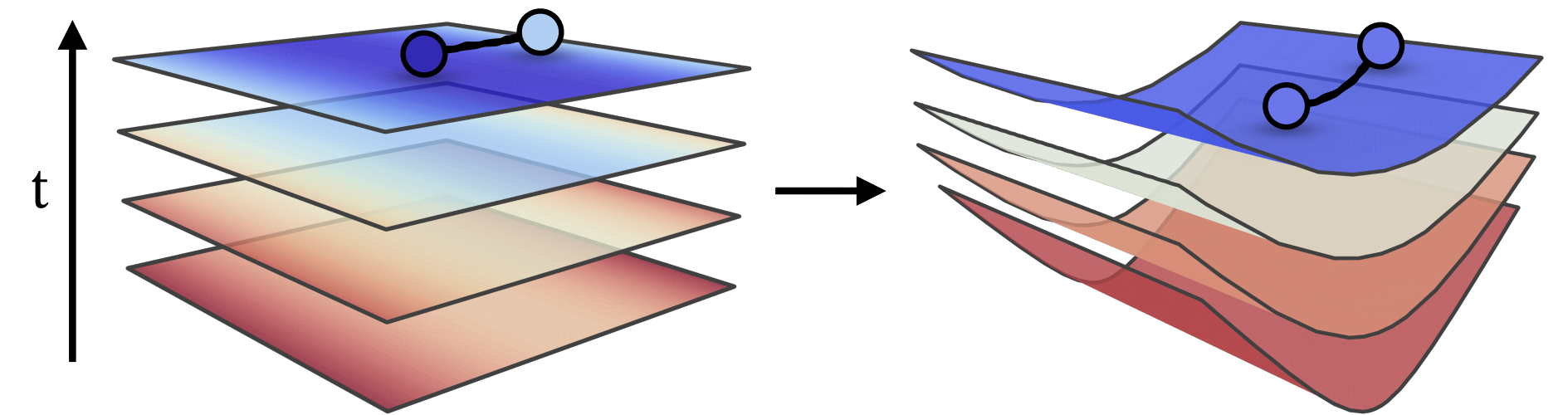
[FR, Pisarski, Rischke, PRD 107 (2023)]

Two-pion correlations from interference

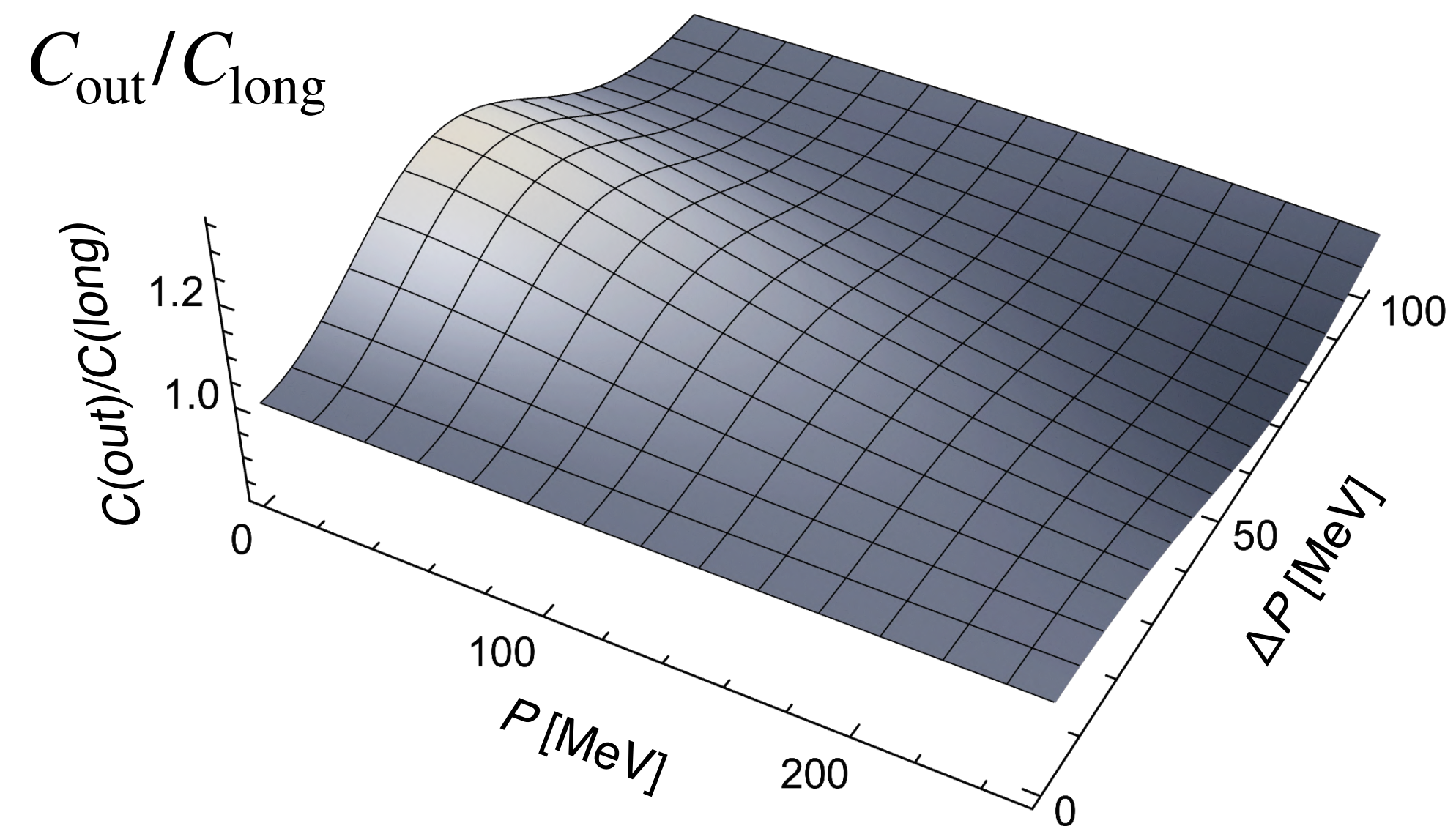
$$\langle \hat{N}_\pi \hat{N}_\pi \rangle \sim C(\mathbf{P}, \Delta\mathbf{P}) \sim \int d\Sigma_X DP_\parallel e^{-i\overline{\Delta\mathbf{P}} \cdot \mathbf{X}} f(X, P) \rho(X, P)$$

↑
spectral function

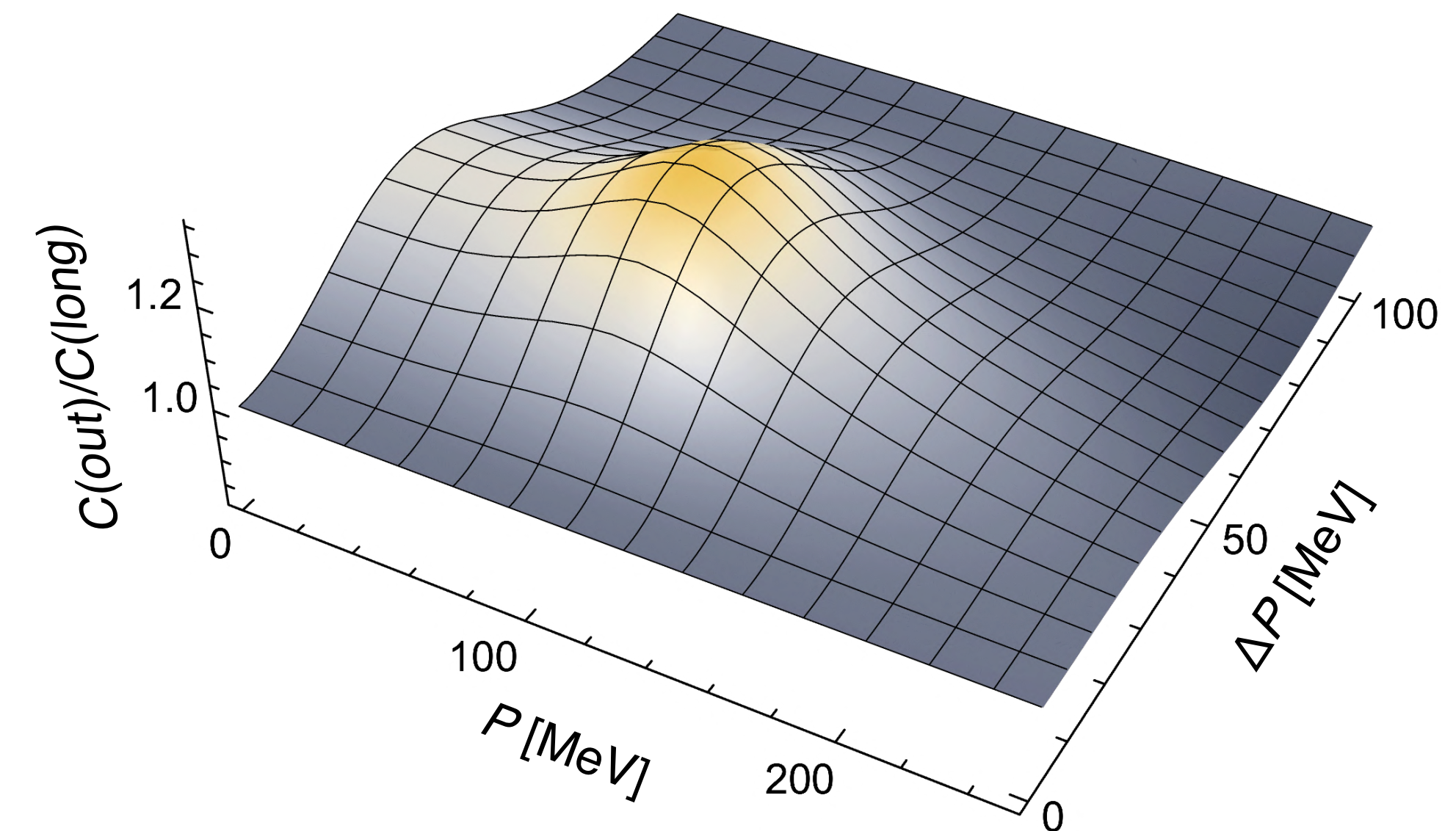
correlations on hypersurface with fixed T and μ_B



normal:



moat:



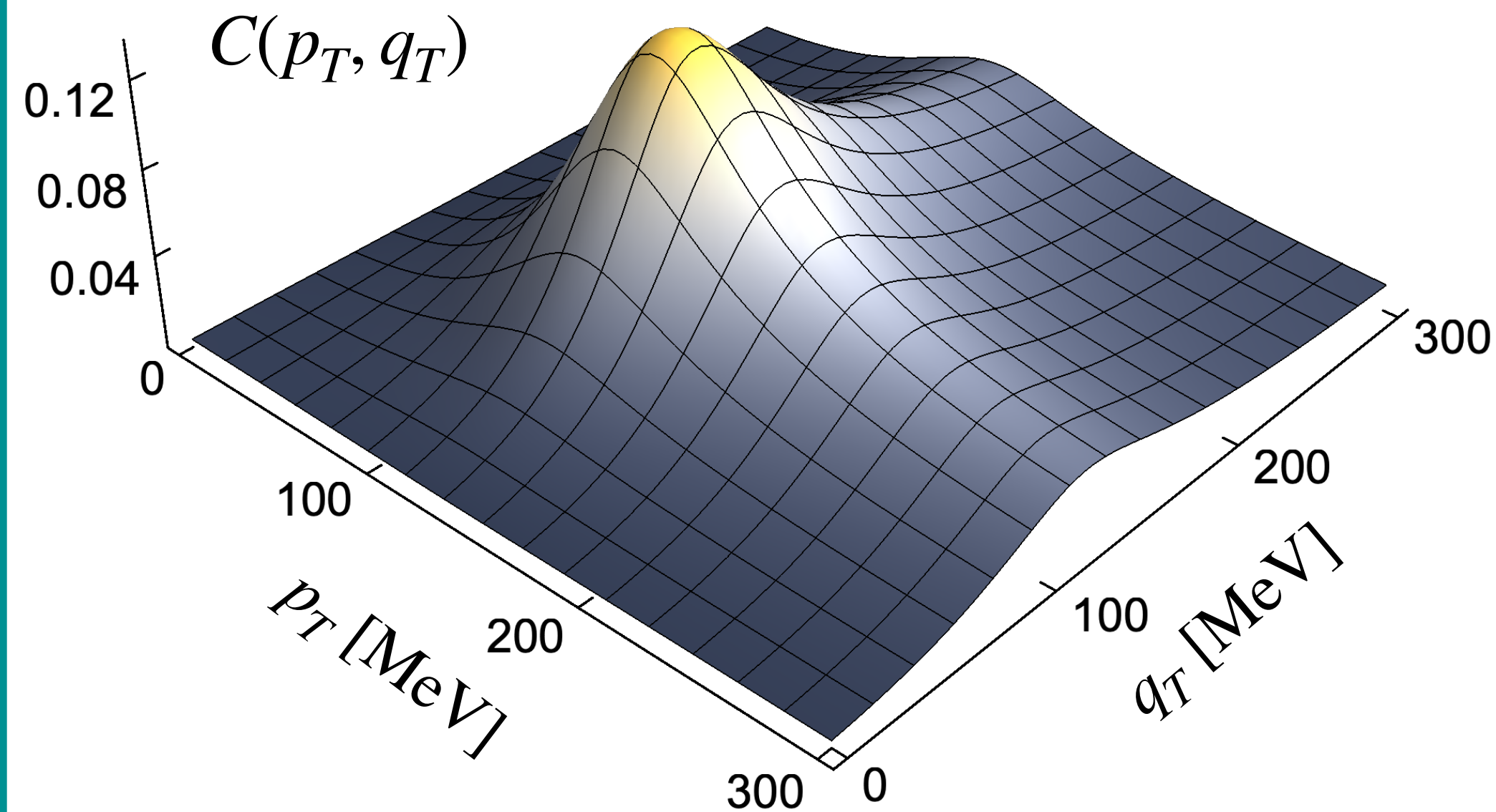
→ characteristic peak at nonzero average pair momentum

MORE TWO-PARTICLE CORRELATIONS

qualitative result appears to be generic

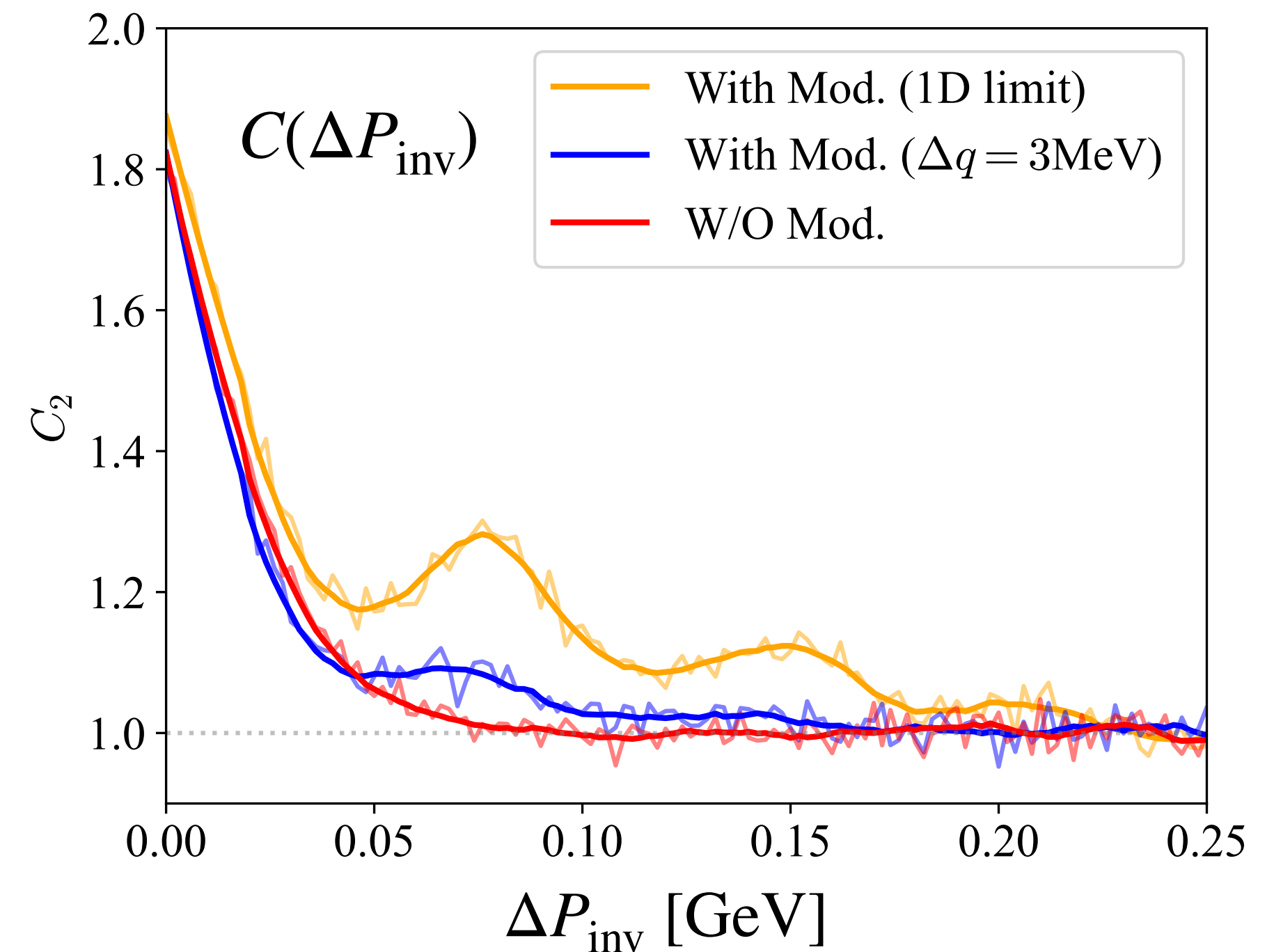
thermodynamic fluctuations in a moat regime

[Pisarski, FR; PRL 127 (2021)]



interference from primordial inhomogeneity (with AMPT transport)

[Fukushima et al.; PRC 109 (2023)]

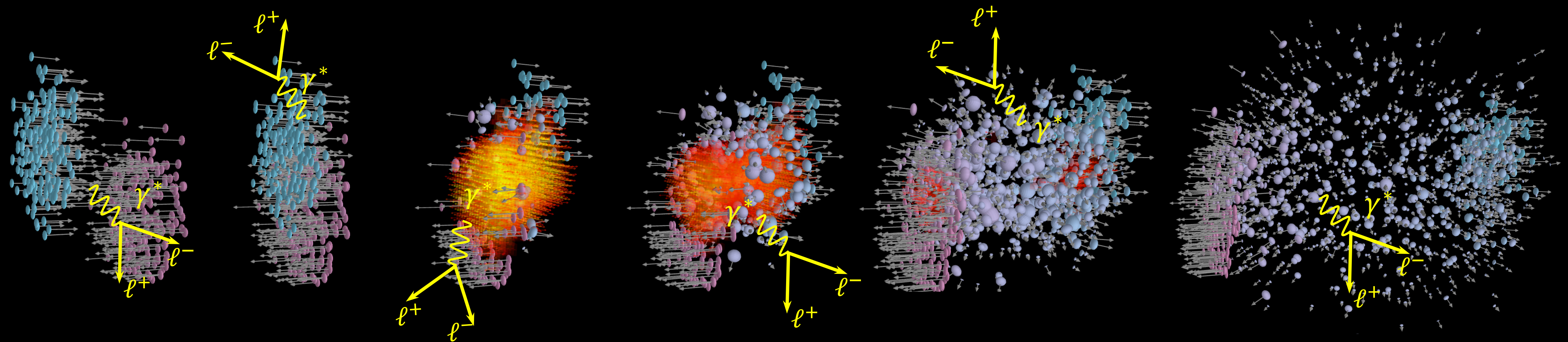


→ peak position related to wavenumber of underlying spatial modulation

DILEPTON PRODUCTION

ELECTROMAGNETIC RADIATION FROM QCD FIREBALL

credit: Tetyana Galatyuk



Electromagnetic radiation (γ, γ^*)

Reflect the whole history of a collision

No strong final state interaction
 $\leadsto$ leave reaction volume undisturbed

Encodes information on matter properties
enabling unique measurements:

- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- restoration of chiral symmetry
- transport properties

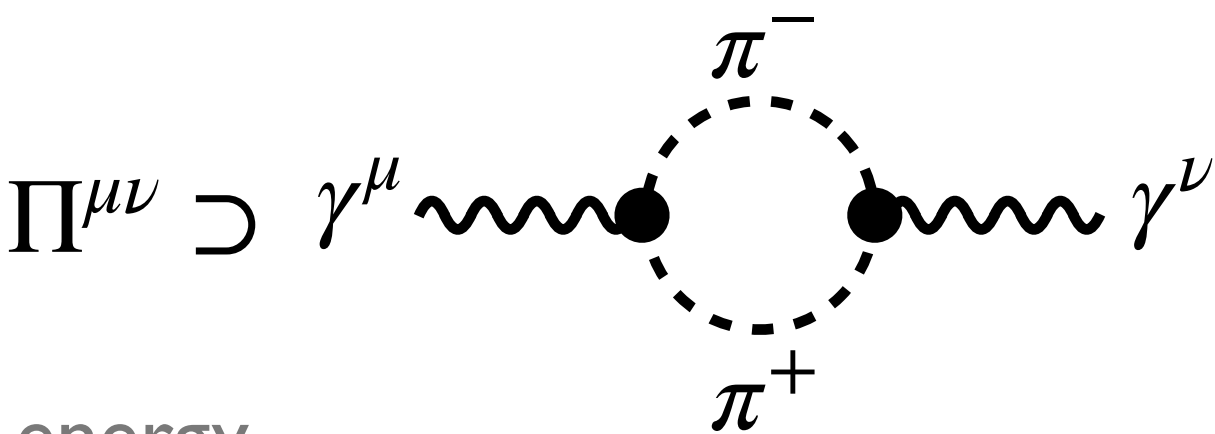
DILEPTON PRODUCTION

[Nussinov, Ogilvie, Pannullo, Pisarski, FR, Schindler, Winstel; PRL 135 (2024)]

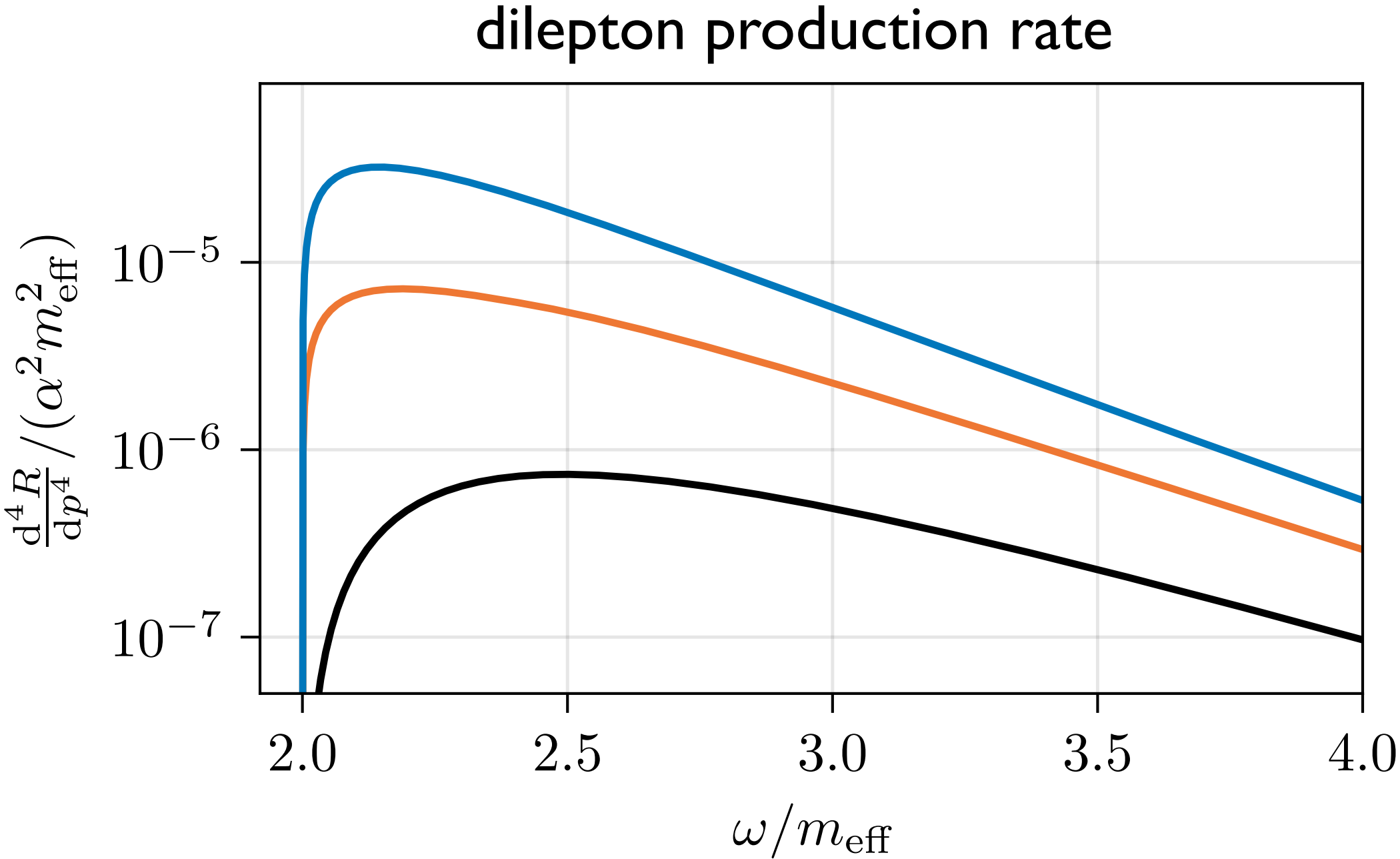
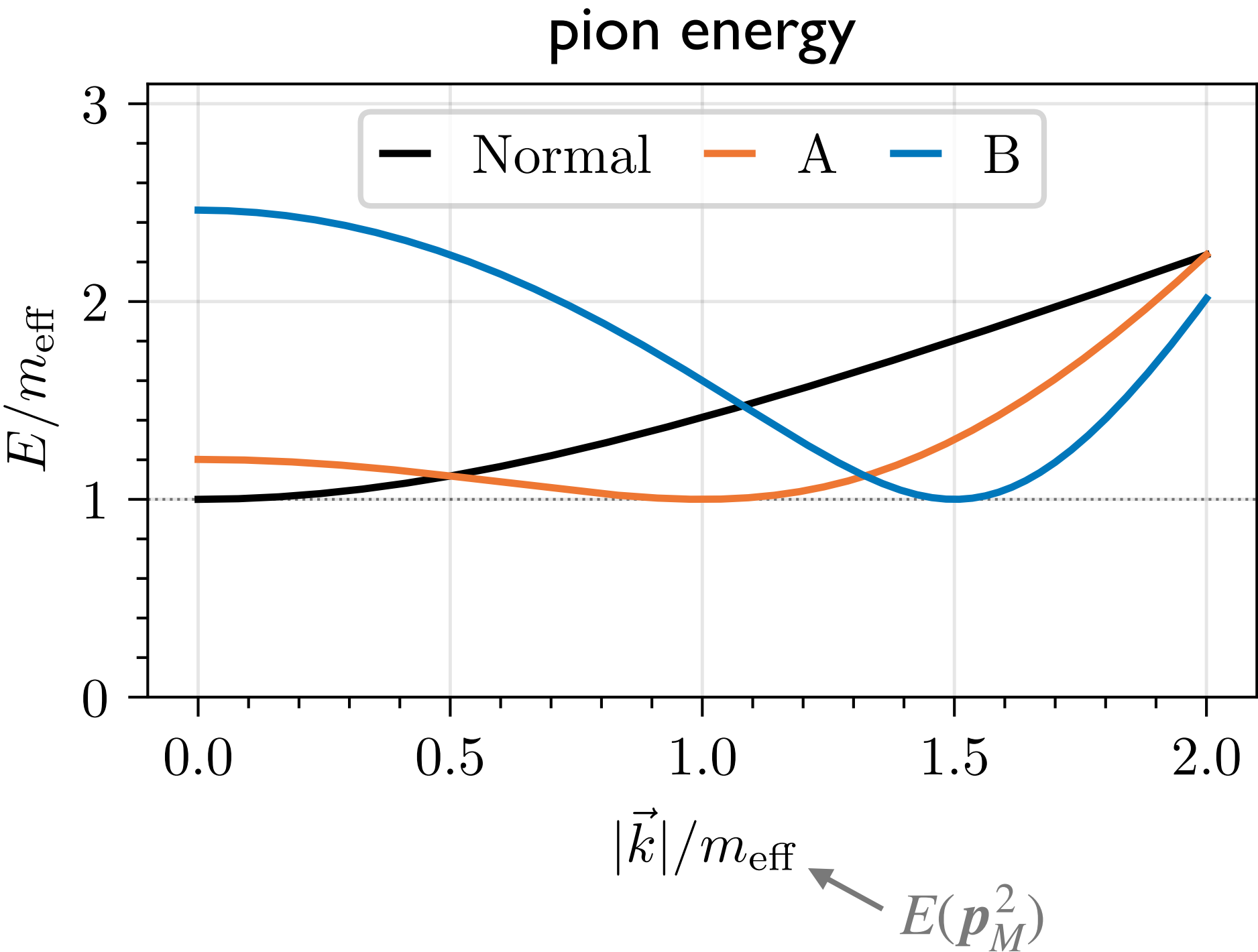
Contribution to the dilepton rate through pions/moatons:

$$\frac{d^4R}{dp^4} \sim \text{Im} \Pi^{\mu\nu}(p)$$

photon self-energy



For back-to-back dileptons ($p = 0$)

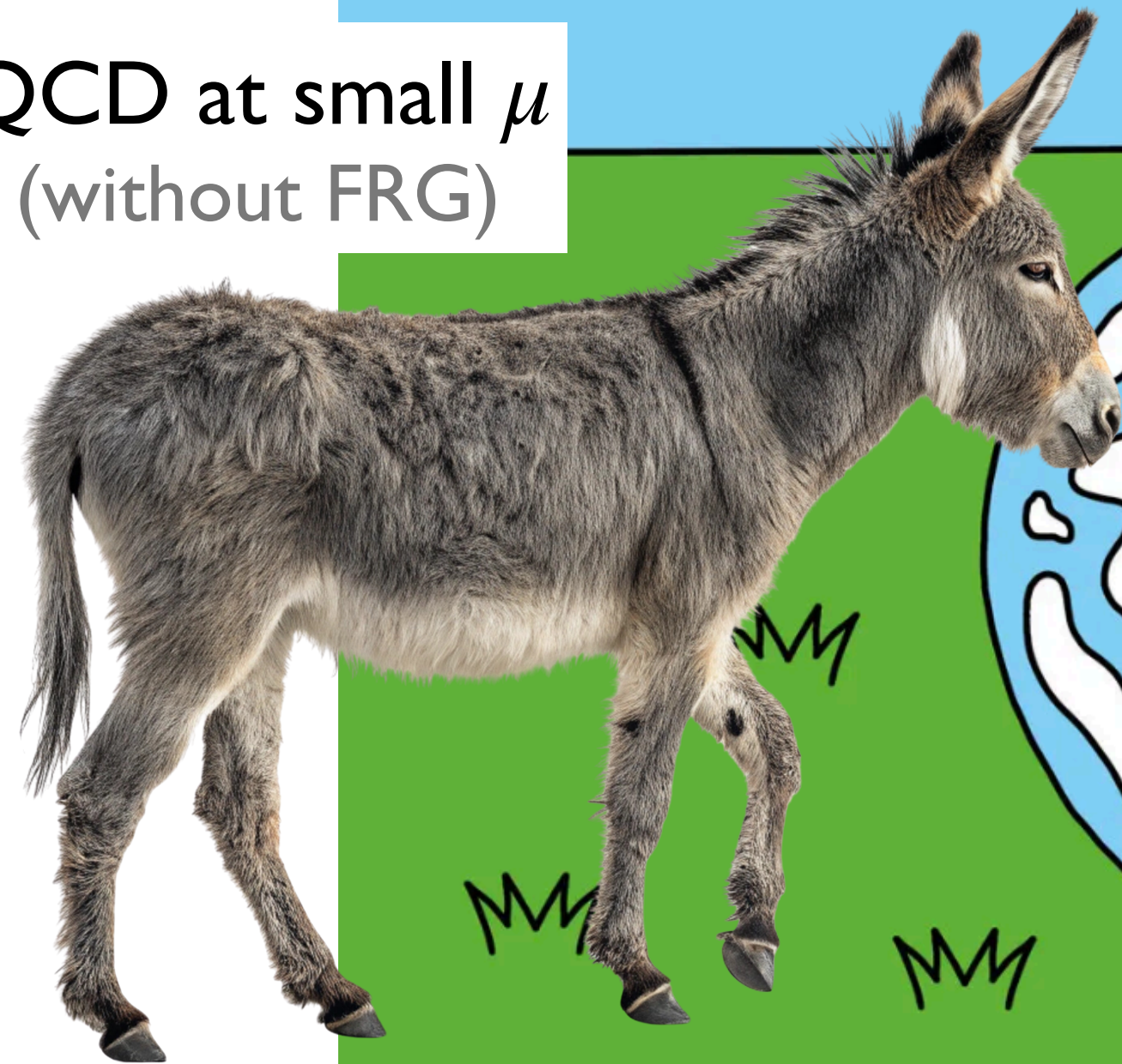


→ enhanced dilepton rate at two-pion threshold

CONCLUSIONS

Opportunity to discover new phases,
facilitated by FRG

QCD at small μ
(without FRG)



QCD at large μ
(with FRG)

