LATTICE 2022

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Chiral spin symmetry and the QCD phase diagram

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Based on: Glozman, O.P., Pisarski, arXiv:2204.05083
Lowdon, O.P., arXiv:2207.14718

CRC-TR 211 Strong-interaction matter under extreme conditions

ELEMENTS

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NIC

Chiral spin symmetry

Trafo:

Dirac: $\psi \to \psi' = \exp\left(i\frac{\varepsilon^n \Sigma^n}{2}\right)\psi$

Weyl: $\begin{pmatrix} R \\ L \end{pmatrix} \to \begin{pmatrix} R' \\ L' \end{pmatrix} = \exp\left(i\frac{\varepsilon^n \sigma^n}{2}\right)\begin{pmatrix} R \\ L \end{pmatrix}$

Generators:

$\Sigma^n = \{\gamma_k, -i\gamma_5\gamma_k, \gamma_5\} \qquad k = 1,2,3,4$

$[\Sigma^a, \Sigma^b] = 2\mathrm{i}\epsilon^{abc}\Sigma^c \qquad su(2)$

Obviously: $SU(2)_{CS} \supset U(1)_A$

Not so obvious $SU(2)_{CS} \otimes SU(2)_F : \quad \{(\vec{\tau} \otimes \mathbb{1}_D), (\mathbb{1}_F \otimes \vec{\Sigma}_k), (\vec{\tau} \otimes \vec{\Sigma}_k)\}$ 15 generators

$\downarrow$

$SU(4) \supset SU(2)_L \times SU(2)_R \times U(1)_A$

Emergent CS symmetry: where does it come from?

QCD quark action, chiral limit: $\bar{\psi}\gamma^{\mu}D_{\mu}\psi = \bar{\psi}\gamma^{0}D_{0}\psi + \bar{\psi}\gamma^{i}D_{i}\psi$

$[\Sigma^a, \gamma_0] = 0, [\Sigma^a, \gamma_i] \neq 0,$

CS invariant ($\bar{\psi}\gamma^{0}D_{0}\psi$) breaks CS ($\bar{\psi}\gamma^{i}D_{i}\psi$)

The classical QCD action in the chiral limit is not CS symmetric!

The free quark action in the chiral limit is not CS symmetric!

Quark gluon interactions:

colour-electric	colour-magnetic
$\bar{\psi}\gamma_0 T^a \psi\ A_0^a$	$\bar{\psi}\gamma_i T^a \psi\ A_i^a$
CS invariant	breaks CS

Necessary condition for approximate CS symmetry:

Quantum effective action Γ_k dominated by colour-electric interactions!

Spatial and temporal correlators at finite T

$$C_\Gamma(\tau, \boldsymbol{x}) = \langle O_\Gamma(\tau, \boldsymbol{x})\, O_\Gamma(0, \boldsymbol{0})\rangle$$

$$C_\Gamma(\tau, \boldsymbol{p}) = \int_0^\infty \frac{d\omega}{2\pi}\, K(\tau, \omega)\rho_\Gamma(\omega, \boldsymbol{p})\ ,$$

$$K(\tau, \omega) = \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}\ .$$

$$C^s_\Gamma(z) = \sum_{x,y,\tau} C_\Gamma(\tau, \boldsymbol{x})$$

$$C^\tau_\Gamma(\tau) = \sum_{x,y,z} C_\Gamma(\tau, \boldsymbol{x})$$

Spectral function: information about d. o. f.

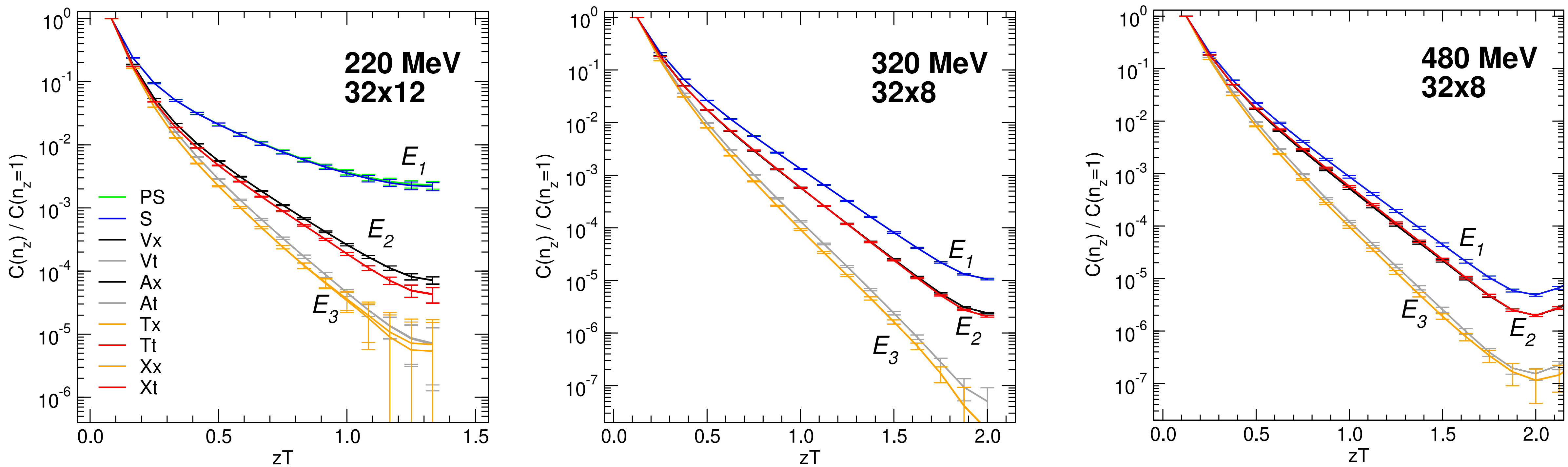
Inversion from discrete data ill-posed problem

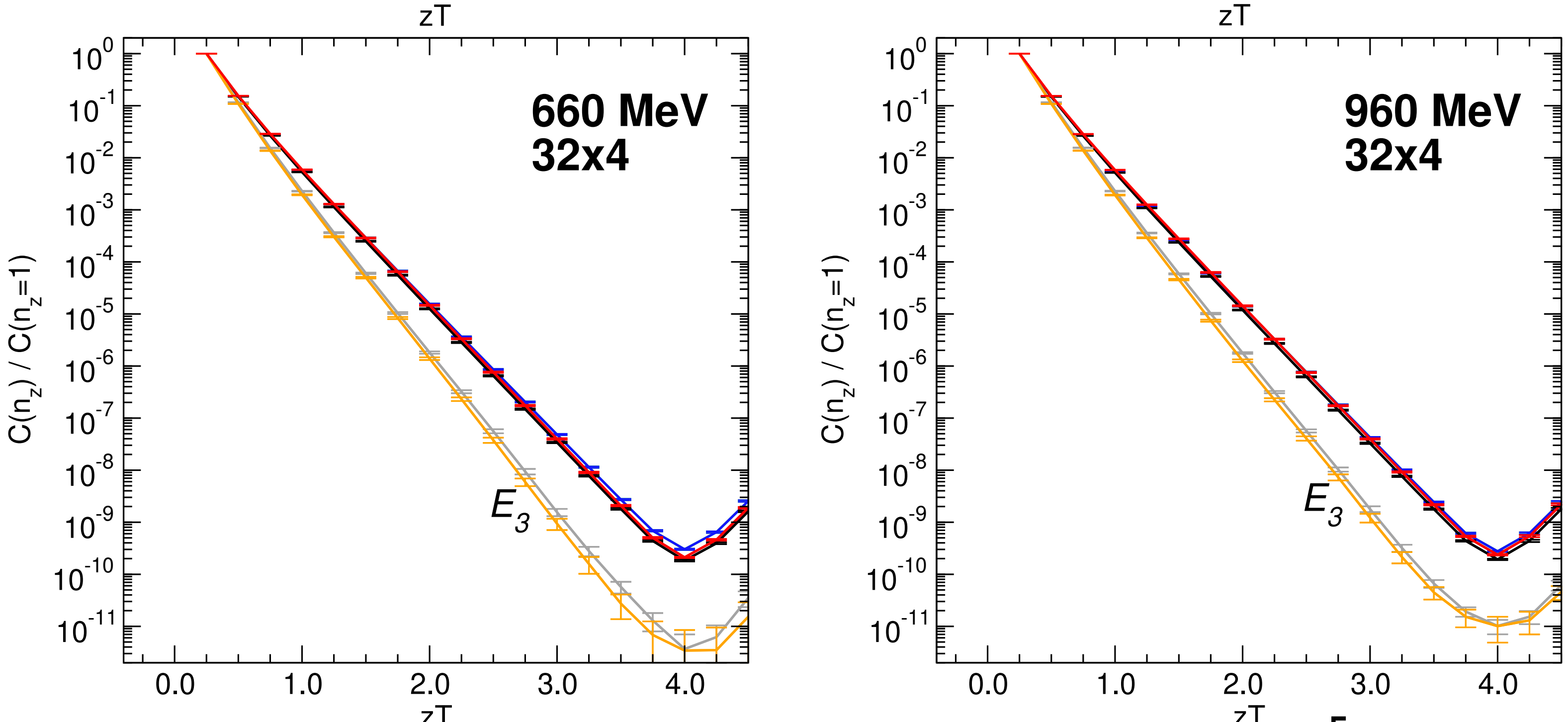
Finite T has preferred reference frame: colour-electric and colour magnetic distinguishable!

Spatial meson correlators at finite T

Multiplet structure

$$E_1: \quad PS \leftrightarrow S\,, \qquad U(1)_A$$
$$E_2: \quad V_x \leftrightarrow T_t \leftrightarrow X_t \leftrightarrow A_x\,, \qquad SU(4)$$
$$E_3: \quad V_t \leftrightarrow T_x \leftrightarrow X_x \leftrightarrow A_t\,. \qquad SU(2)_L \times SU(2)_R \times U(1)_A$$





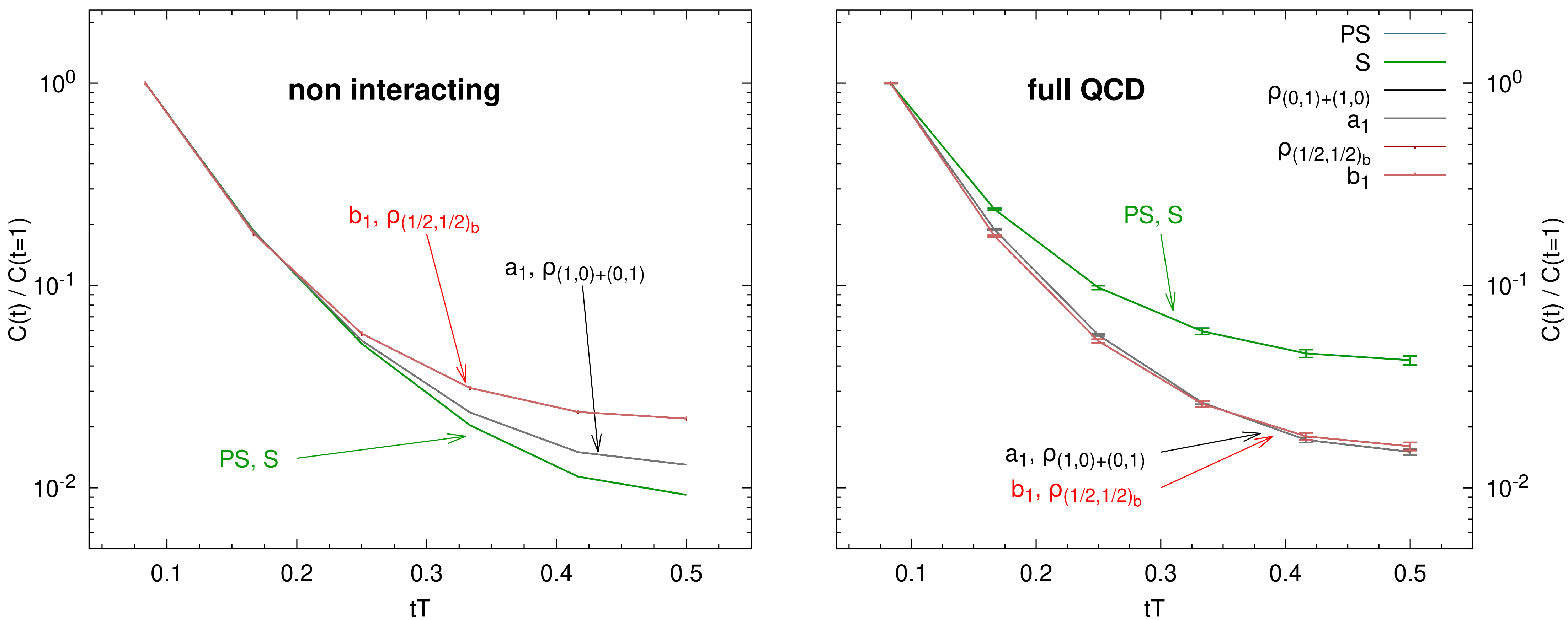
JLQCD domain wall fermions

Rohrhofer et al., Phys. Rev. D100 (2019)

Temporal correlators at finite T

JLQCD domain wall fermion configurations

Rohrhofer et al., Phys. Lett. B802 (2020)



$$48^3 \times 12 \qquad T = 220\text{MeV} \ (1.2T_c) \qquad (a = 0.075 \ \text{fm})$$

Three temperature regimes of QCD

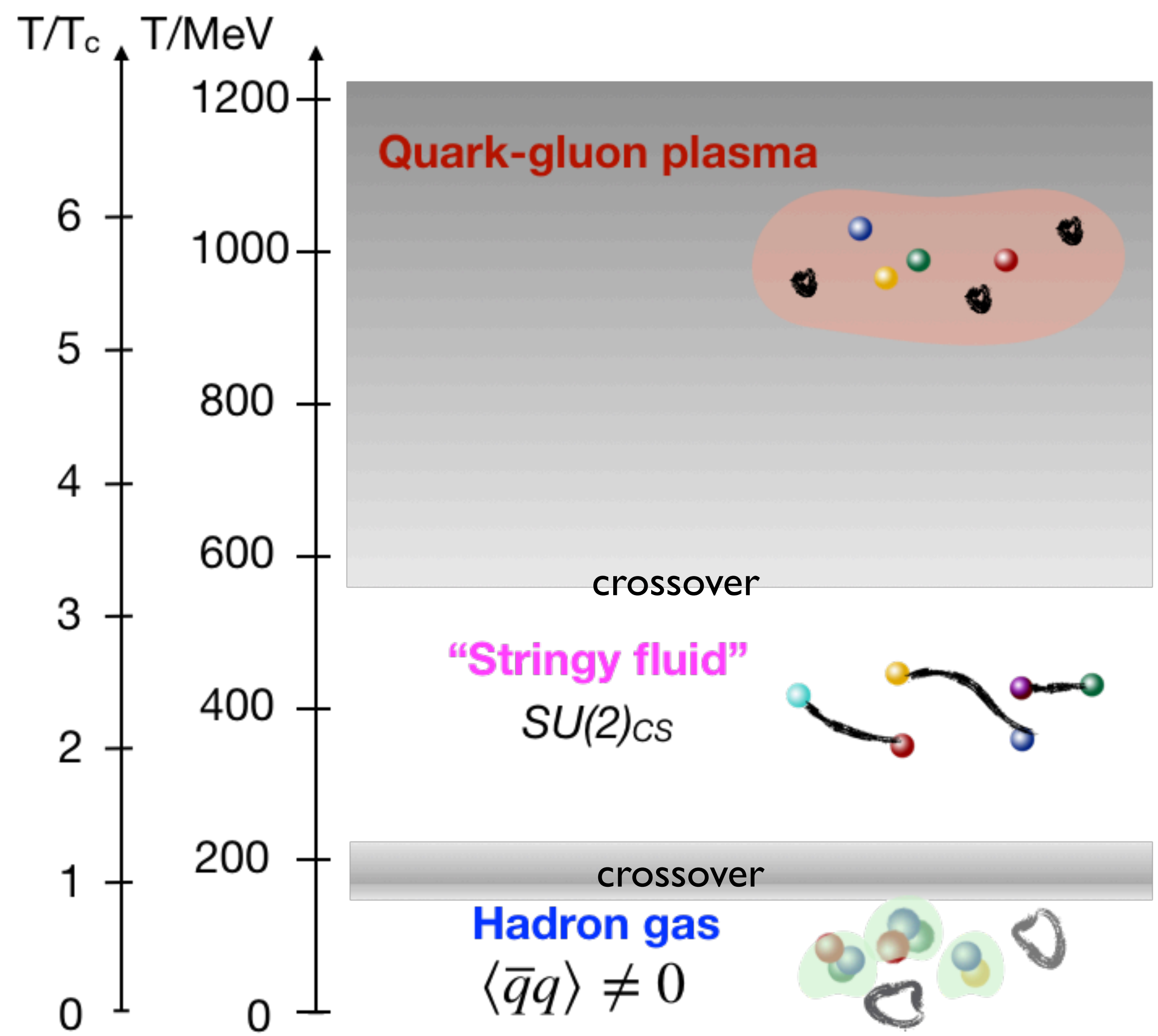
Symmetries (verified):

Degrees of freedom (to be verified):

Chiral symmetry (approximate)

Chiral spin symmetry (approximate)

Chiral symmetry broken



Rohrhofer et al., Phys. Rev. D100 (2019)

Check well-studied observables: screening masses

$$C^s_\Gamma(z) = \sum_{x,y,\tau} C_\Gamma(\tau, \boldsymbol{x}) \quad \stackrel{z\to\infty}{\longrightarrow} \text{const. } e^{-m_{scr}z}$$

Directly related to the partition function and equation of state

$$e^{pV/T} = Z = \mathrm{Tr}(e^{-aHN_\tau})$$
$$= \mathrm{Tr}(e^{-aH_zN_z}) = \sum_{n_z} e^{-E_{n_z}N_z}$$

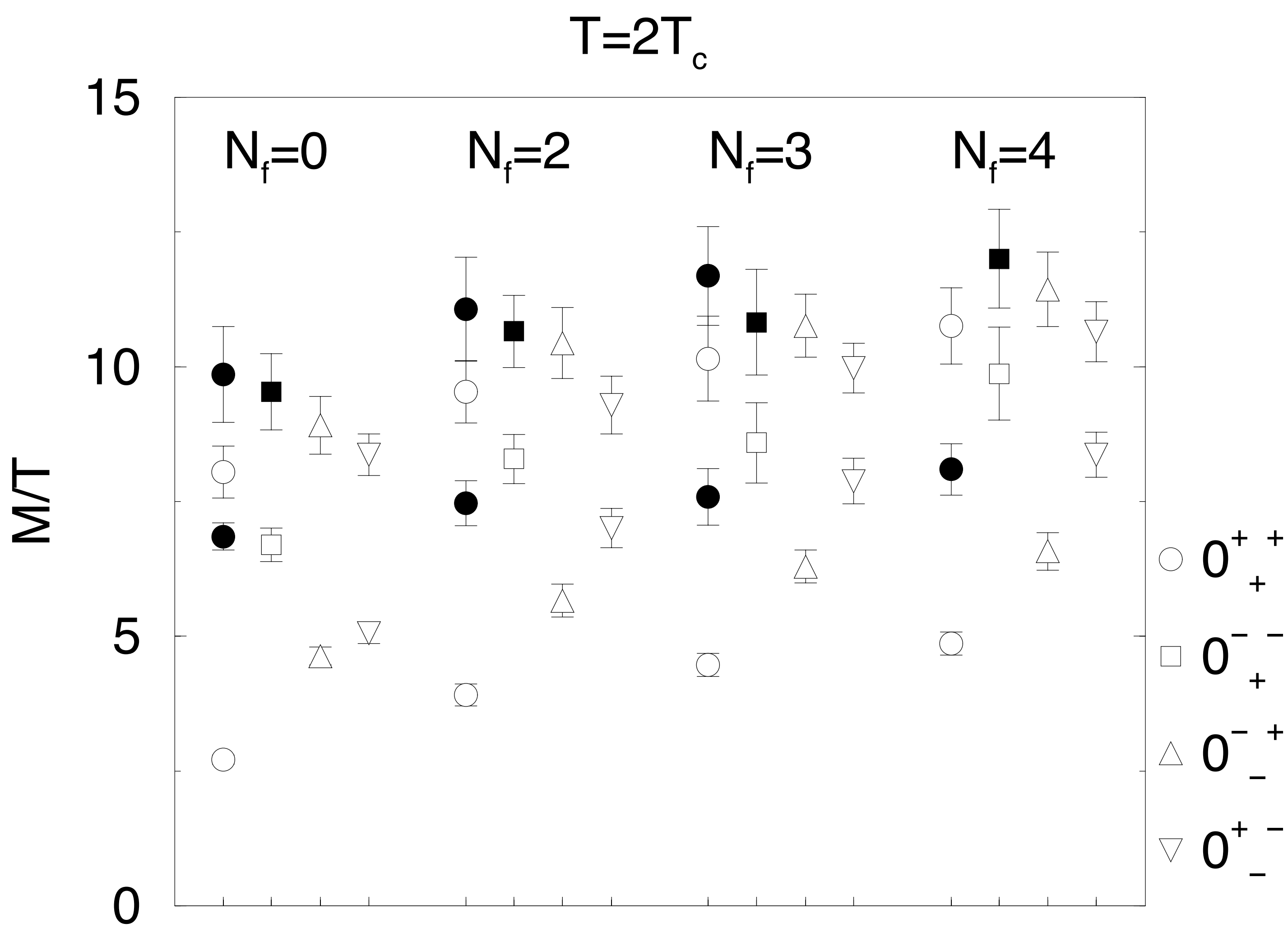
Screening masses: eigenvalues of H_z

For T=0 equivalent to eigenvalues of H, for $T \neq 0$ "finite size effect"

Colour-electric vs. colour magnetic fields

Scales at finite T:

$$\text{Matsubara} \sim \pi T, \quad \text{hard modes, fermions} \qquad \text{QCD}$$
$$\text{Debye/electric} \sim gT, \quad A_0 \qquad \text{EQCD}$$
$$\text{magnetic} \sim g^2T, \quad A_i \qquad \text{MQCD}$$



[Hart, Laine, O.P., NPB 00]

Screening masses in EQCD

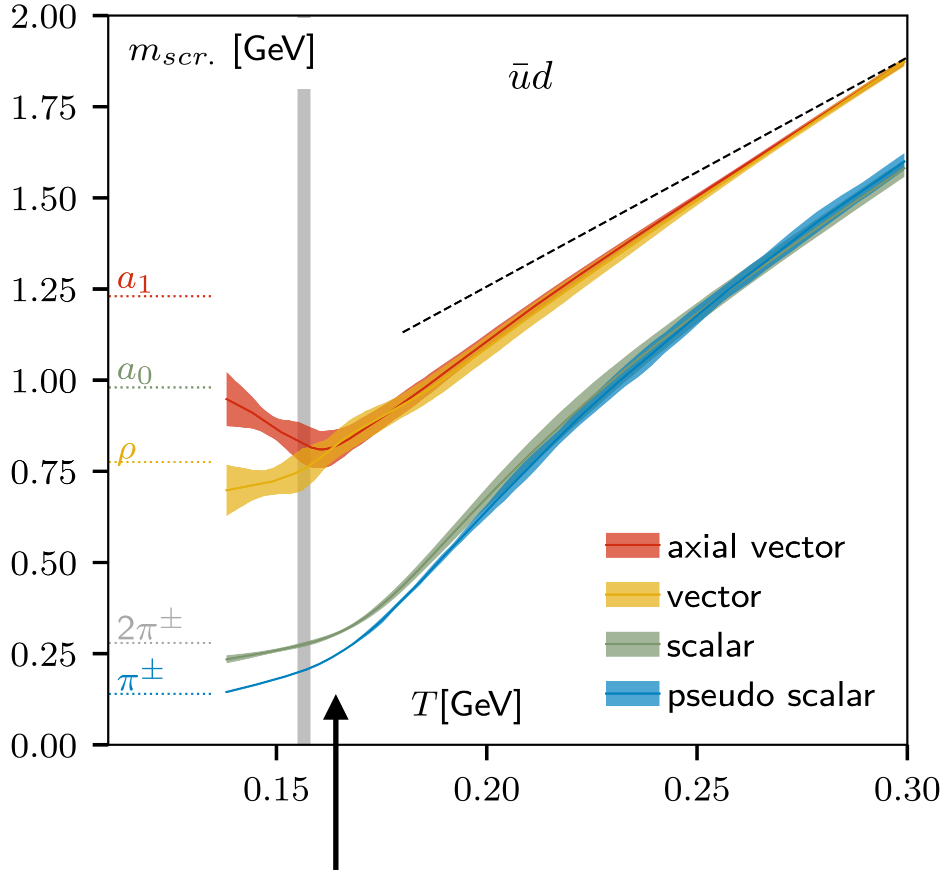
- ops. constructed only from A_i
- ops. containing also A_0

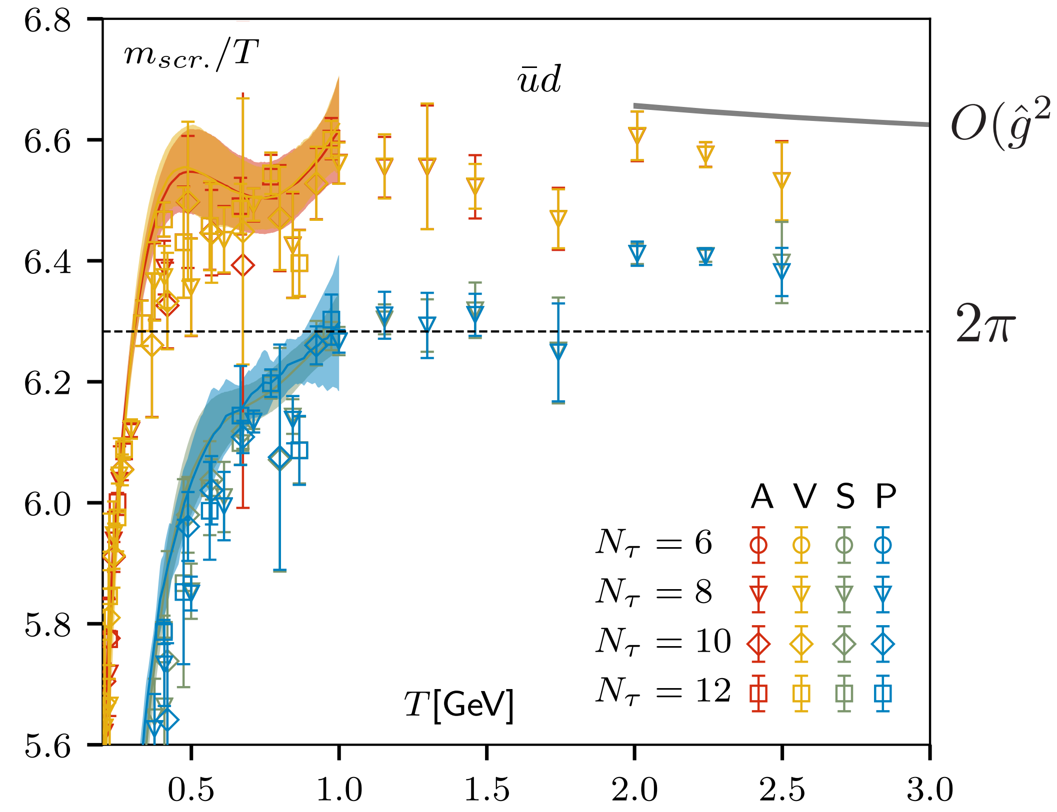
Colour-electric fields dynamically dominant, perturbative ordering reversed!

Meson screening masses

HotQCD, Phys. Rev. D100 (2019)

HISQ, physical point, continuum extrapolated





Chiral symmetry restoration

Heavy chiral partners "come down"
in all flavour combinations

→ pressure increases

Drastic change: "vertical" - "horizontal"

Resummed pert. theory:

$$\frac{m_{PS}}{2\pi T} = 1 + p_2\, \hat{g}^2(T) + p_3\, \hat{g}^3(T) + p_4\, \hat{g}^4(T)\ ,$$

$$\frac{m_V}{2\pi T} = \frac{m_{PS}}{2\pi T} + s_4\, \hat{g}^4(T)\ ,$$

[Laine, Vepsäläinen., JHEP 04]
[Dalla Brida et al., JHEP 22]

Cannot describe the "bend"

Change of dynamics at $T \approx 0.5$ GeV in 12 lightest meson channels! CS symmetry!

Effective degrees of freedom…? ➡ Spectral functions

Based on micro-causality of scalar, local quantum fields at finite T:

[Bros, Buchholz., NPB 94, Ann. Inst. Poincare Phys. Theor. 96]

$$\rho_{\rm PS}(p_0,\vec{p}) = \int_0^\infty ds \int \frac{d^3\vec{u}}{(2\pi)^2}\; \epsilon(p_0)\,\delta\big(p_0^2-(\vec{p}-\vec{u})^2-s\big)\,\widetilde{D}_\beta(\vec{u},s)$$

Exact, goes to Källen-Lehmann representation for $T \to 0$

For stable massive particle with gap to continuum states (QCD pions):

$$\widetilde{D}_\beta(\vec{u},s) = \widetilde{D}_{m,\beta}(\vec{u})\,\delta(s-m^2) + \widetilde{D}_{c,\beta}(\vec{u},s)$$

Analytic structure inherited from vacuum, in absence of phase transition

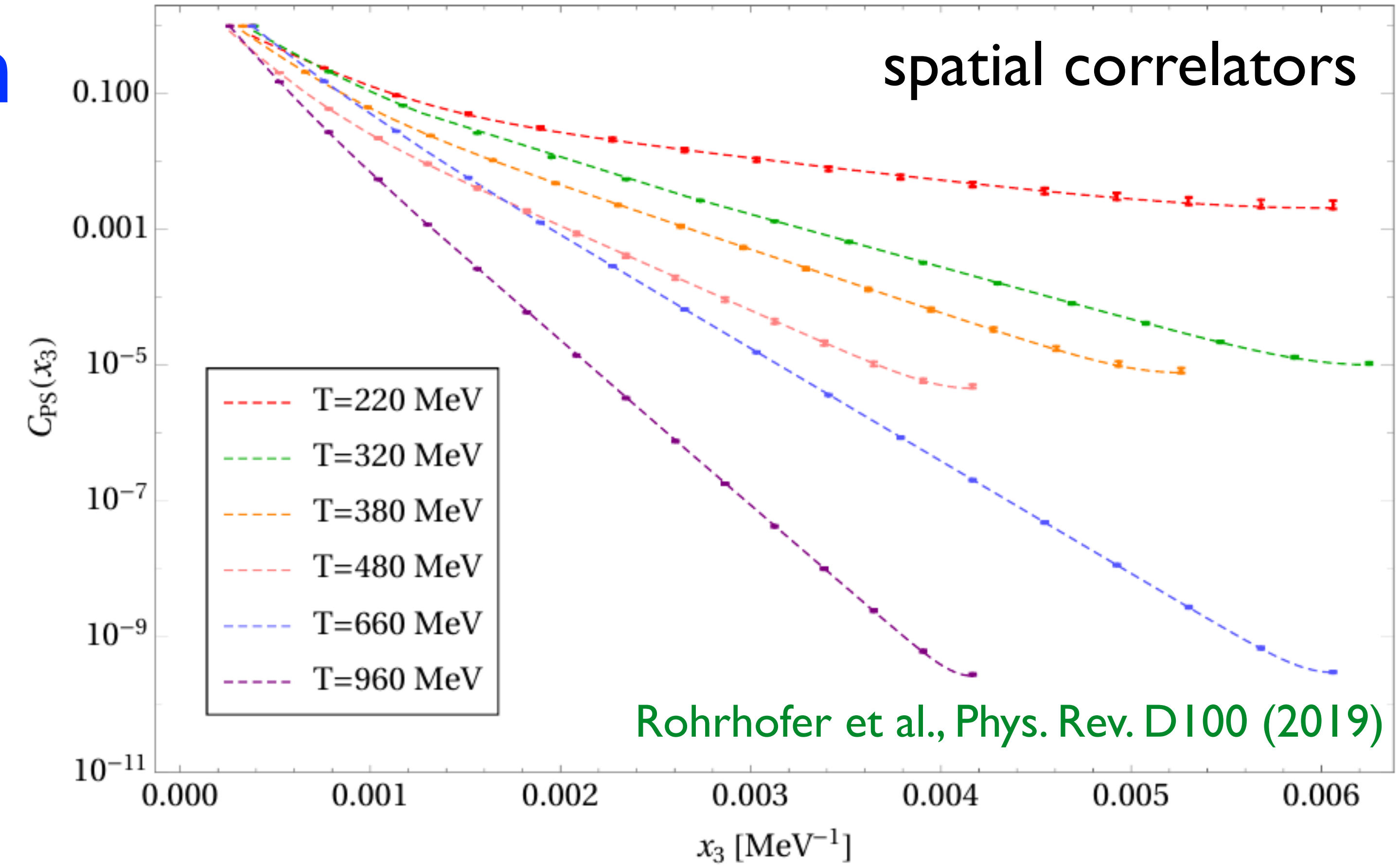
➡ low energy behaviour influenced (at low T dominated) by vacuum particle states

The pion spectral function

[Lowdon, O.P., arXiv:2207.14718]

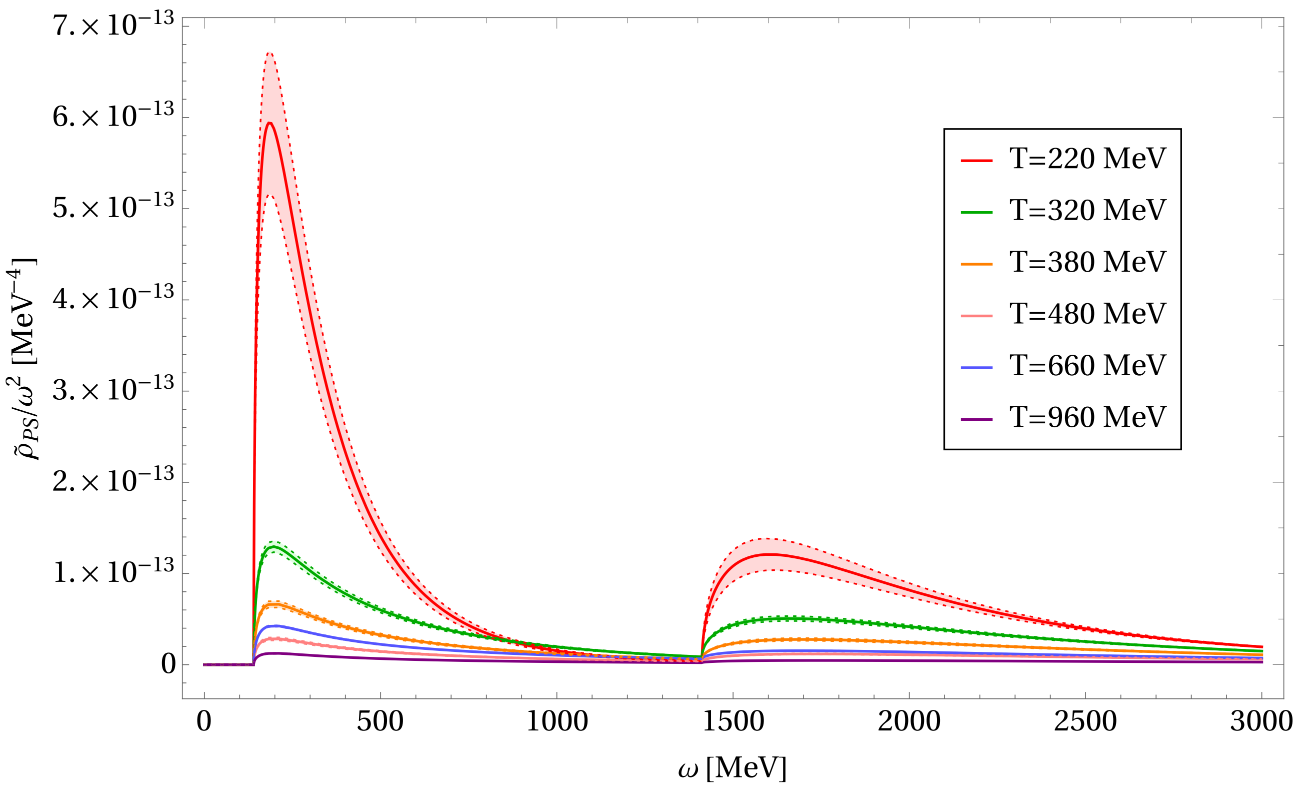
2-state fits π, π^*

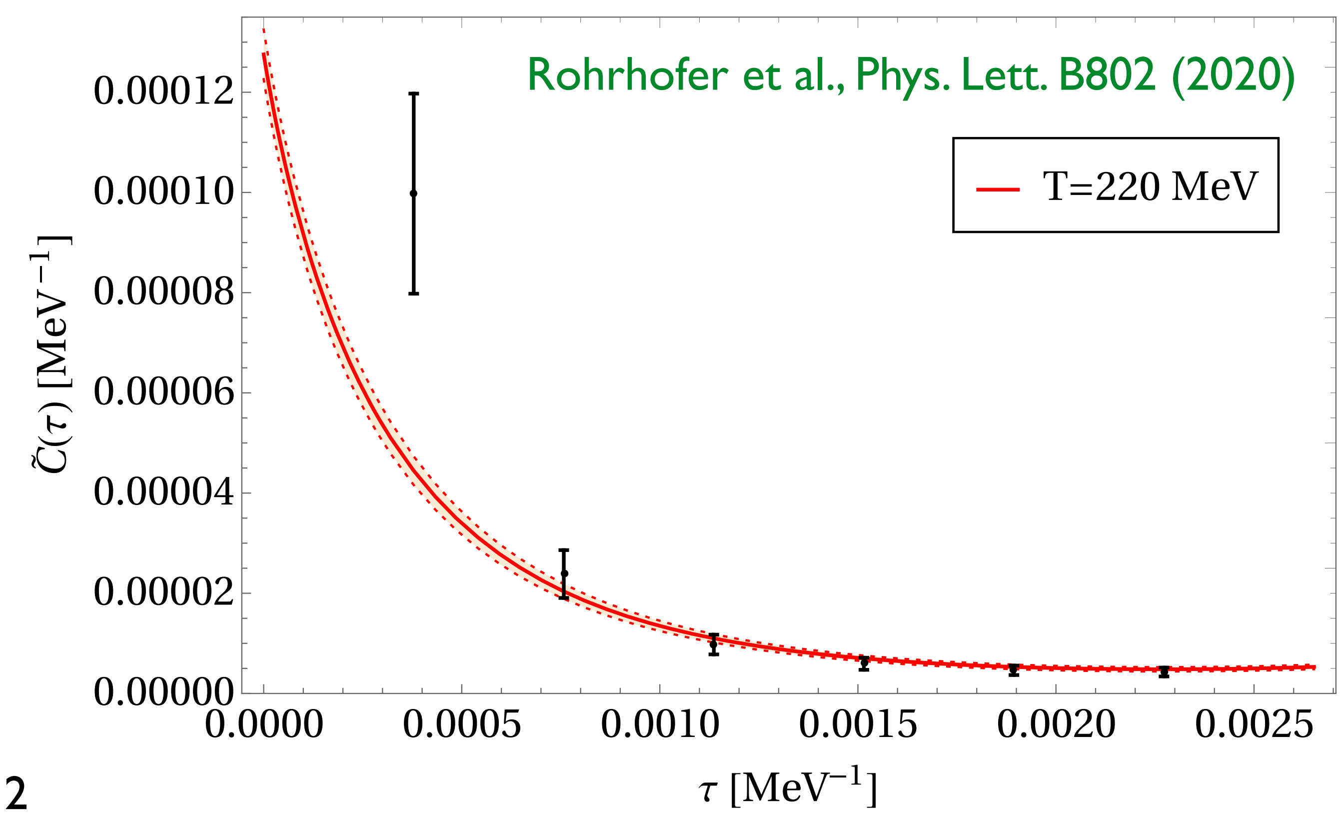
$D_{m,\beta}$ ⟵



Rohrhofer et al., Phys. Rev. D100 (2019)

spectral functions ⟶ predict temporal correlators, compare with data





Rohrhofer et al., Phys. Lett. B802 (2020)

Finite density

- Finite density: $\mu\bar{\psi}\gamma_0\psi$ is CS invariant; regime must continue to finite density

- Upper "boundary" CS band: vector screening mass "bend" (one possible def.)

$$r_V^{-1} \equiv m_V(\mu_B = 0, T_\mathrm{s}) = C_0 T_\mathrm{s} \quad \Rightarrow \quad \begin{array}{ll} T < T_\mathrm{s} & \text{unscreened} \\ T > T_\mathrm{s} & \text{screened} \end{array}$$

- For small μ_B

$$\frac{m_V(\mu_B)}{T} = C_0 + C_2 \left(\frac{\mu_B}{T}\right)^2 + \ldots \quad \Rightarrow \quad \frac{dT_\mathrm{s}}{d\mu_B} = -\frac{2C_2}{C_0}\frac{\mu_B}{T} - \frac{2C_2^2}{C_0^2}\left(\frac{\mu_B}{T}\right)^3 + \ldots$$

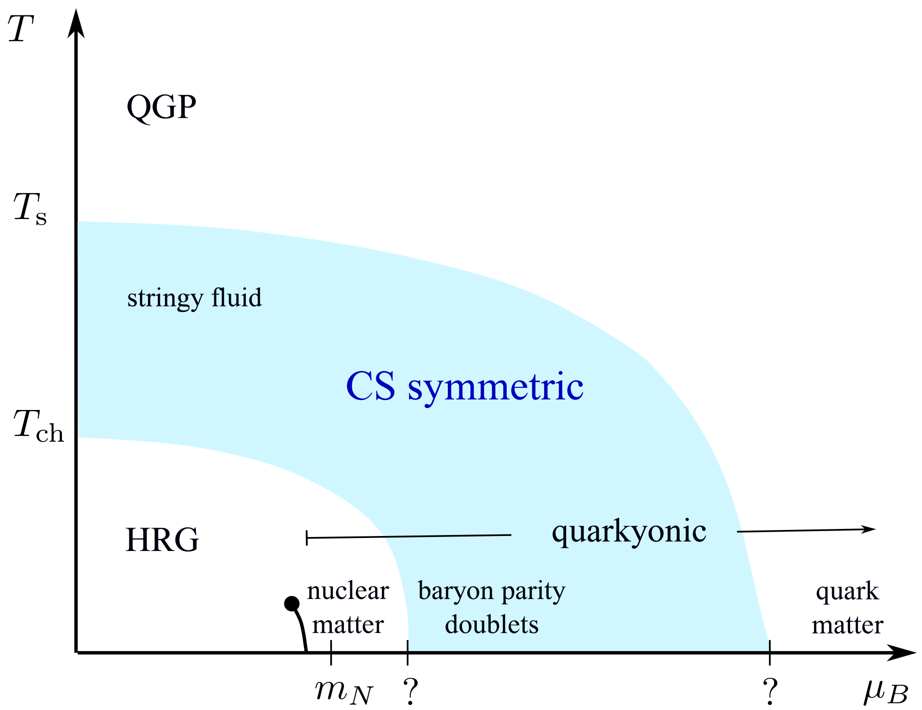
$C_2 > 0$ [Hart et al., PLB 01; Pushkina et al., PLB 05]]

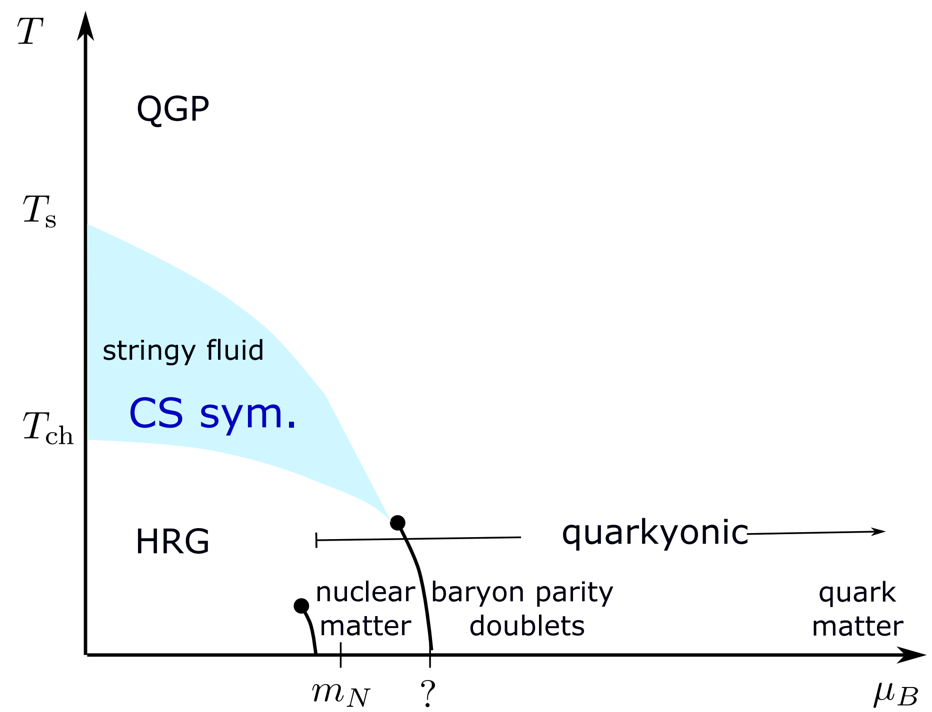
- Lower "boundary" CS band: restoration of full chiral symmetry

$$\frac{T_\mathrm{pc}(\mu_B)}{T_\mathrm{pc}(0)} = 1 - 0.016(5)\left(\frac{\mu_B}{T_\mathrm{pc}(0)}\right)^2 + \ldots \quad \approx \frac{T_\mathrm{ch}(\mu_B)}{T_\mathrm{ch}(0)}$$

- Can we find separate order parameters for $SU(2)_A, U(1)_A, SU(4)$?

The QCD phase diagram

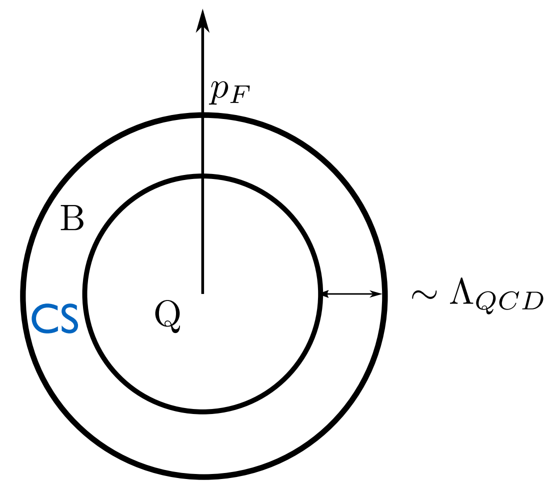




...

- Cold and dense candidate: baryon parity doublet models, CS symmetric [Glozman, Catillo PRD 18]
- Quarkyonic matter [McLerran, Pisarski, NPA 07; O.P., Scheunert JHEP 19]

  -contains chirally symmetric baryon matter
  -consistent with intermediate CS regime



- CS consistent with or without chiral phase transition

Conclusions

- QCD has an emergent approximate Chiral Spin symmetry in an intermediate temperature and density range
- Screening masses entirely non-perturbative in that window
- New spectral representation based on old locality principles: spectral functions from spatial lattice correlators
- Effective degrees of freedom in CS-regime consistent with hadron-like states
- CS-regime extends as a band into QCD phase diagram; natural connection to quarkyonic matter, investigate imag. chem. pot.