Parity Doubling in QCD Thermodynamics

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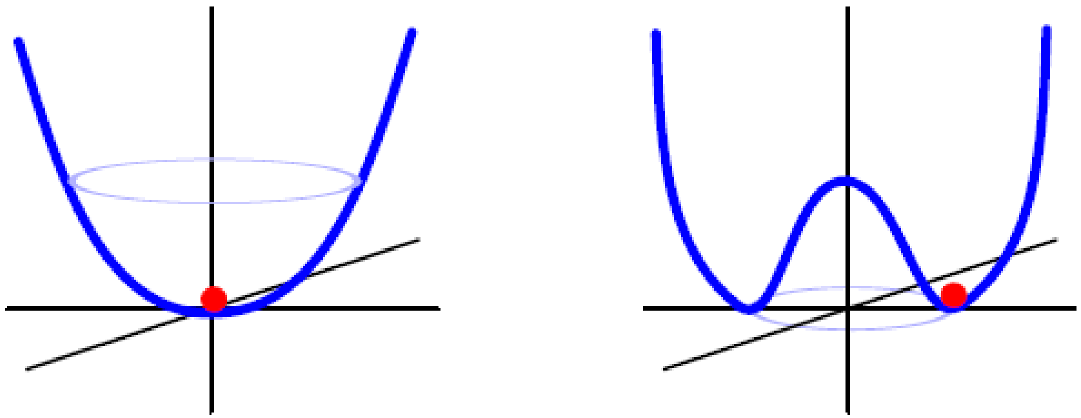
1. Parity doubling

Dynamical generation of mass

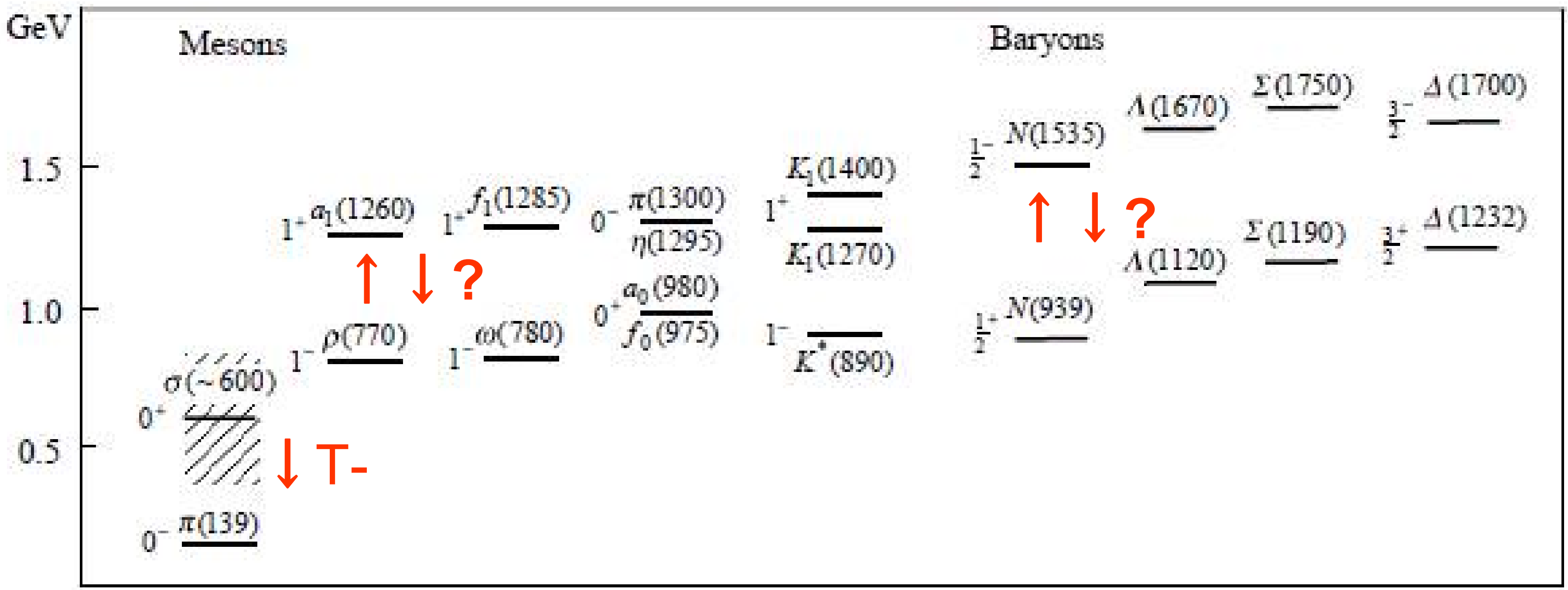
- EW mass and Higgs potential: <H>$\neq$0
- QCD/strong mass: $<\sigma>\neq 0$



- Higgs sector = linear sigma model
- Multiplet $\phi=(\vec{\pi},\sigma)$: O(4) symmetry → O(3)
- QCD phase tr. ≈ remnant of O(4) universality

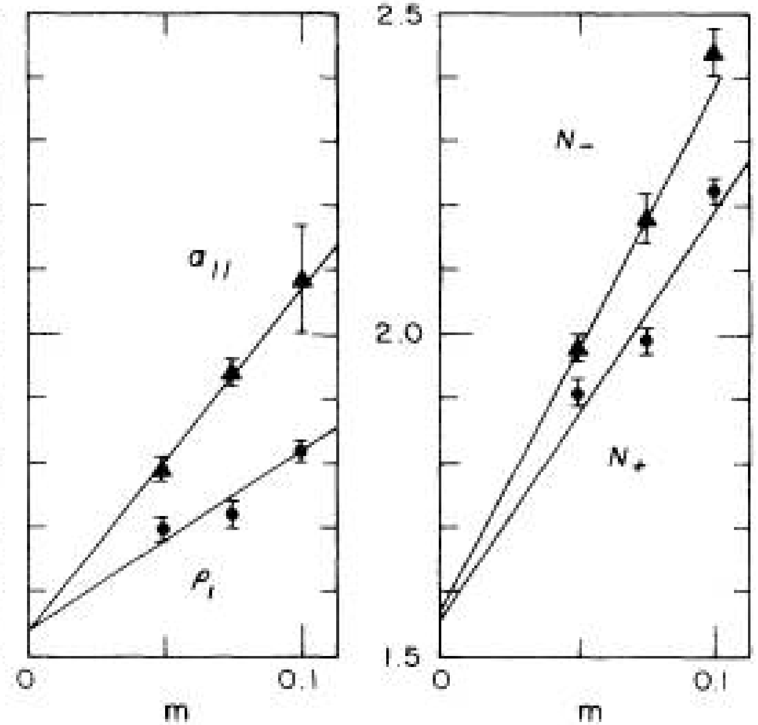
Spectra in a chirally restored world

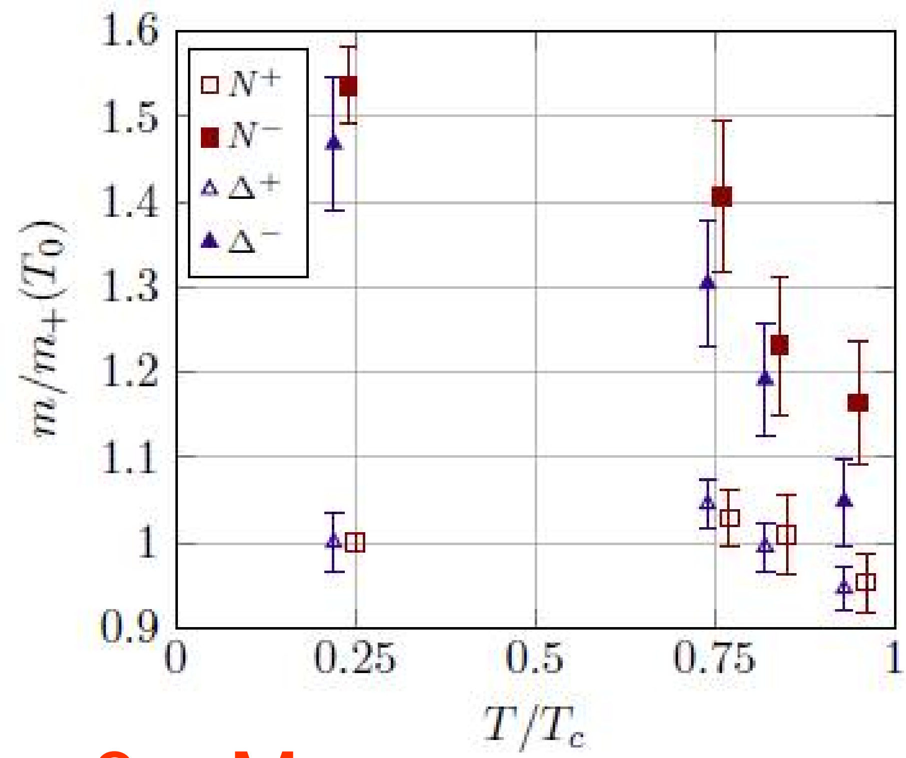
- ❑ Lowest scalar meson → O(4) vector with pion
- ❑ Parity partners degenerate → chiral partners
- ❑ QCD ground-state particles: pions & nucleons



Lattice QCD tells us …

- ❑Spatial correlations [DeTar-Kogut, 1987]
- ❑Temporal correlations [FASTSUM Coll., 2015-17: mpi≈400 MeV, mk≈500 MeV, Wilson fermions, Tch=185 MeV]





vs. Mn ≈ 3 x Mq

Non-SCB mass of nucleons

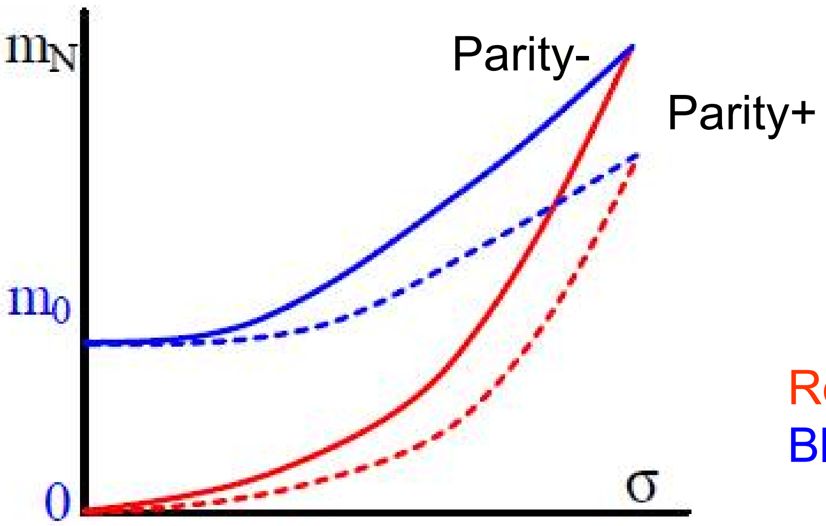
- SU(2) chiral transformation of 2 nucleons

  → how to assign 2 indep. rotation to them?

$$\psi_{1L} \to g_l\, \psi_{1L}\,, \quad \psi_{1R} \to g_r\, \psi_{1R} \;\sim\; \psi_{1L} : (1/2, 0) \quad \psi_{1R} : (0, 1/2)$$

$$\psi_{2L} \to g_r\, \psi_{2L}\,, \quad \psi_{2R} \to g_l\, \psi_{2R} \;\sim\; \psi_{2L} : (0, 1/2) \quad \psi_{2R} : (1/2, 0)$$

$$\mathcal{L}_m = m_0 \left(\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2\right) \;\Rightarrow\; m_{N_\pm} = \frac{1}{2}\left[\sqrt{c_1\sigma^2 + 4m_0^2} \mp c_2\sigma\right]$$



[DeTar-Kunihiro, 1989]

Red: Standard
Blue: Mirror

Origin of the survival mass?

- ❑ Emergence of a scale in QCD → trace anomaly

$$\partial_\mu J^\mu = T^\mu_\mu \propto \langle H | G^2 | H \rangle$$

  - in hot matter: reduced by 50% at Tc [Miller, 2007: lattice EoS]
  - in nuclear matter: reduced by 5% at normal ρ [Cohen et al. 1995: Feynman-Hellmann theorem & low-density approx.]

- ❑ How large is m0? --- not conclusive!
  - Models: 300-800 MeV
  - Lattice (FASTSUM): 800-900 MeV

✓ m0≈ a few Λ qcd, mass diff.≈ weaker m0 dep.

Parity doubling of baryons

- ❑Baryon octet and decuplet with finite m0
- ❑Consistent with established phenomenology:
  - ✓Gell-Mann-Okubo mass formula

$$\frac{3}{4}m_\Lambda + \frac{1}{4}m_\Sigma - \frac{1}{2}\left(m_N + m_\Xi\right) = 0$$

  - ✓Gell-Mann's equal spacing rule

$$m_{\Sigma^*} - m_\Delta = m_{\Xi^*} - m_{\Sigma^*} = m_\Omega - m_{\Xi^*}$$

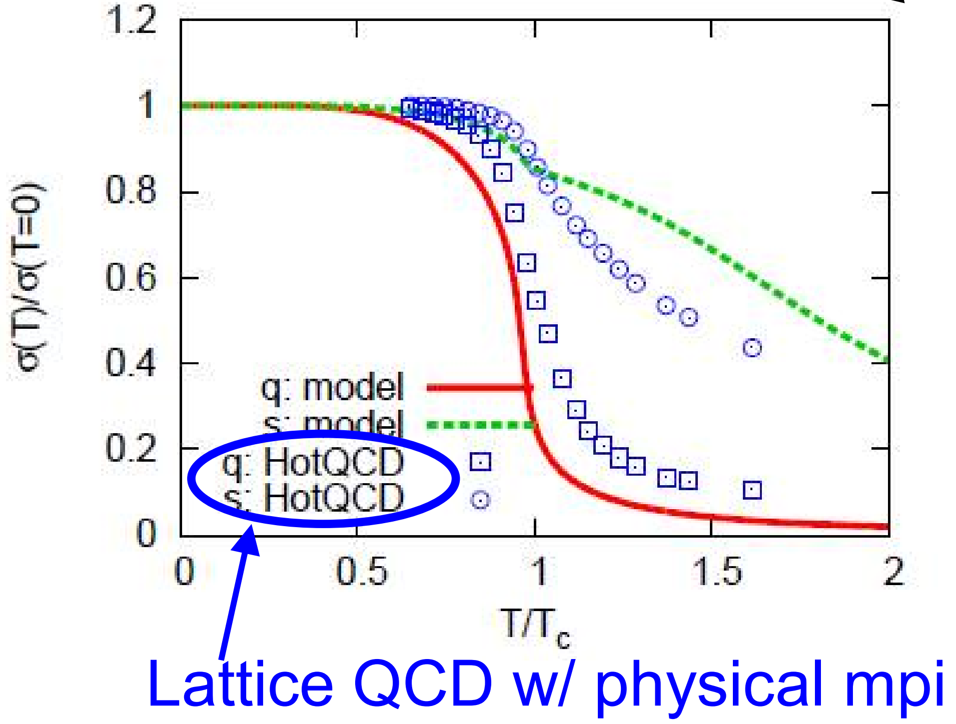
- ❑Mass relations [CS, 2018)]

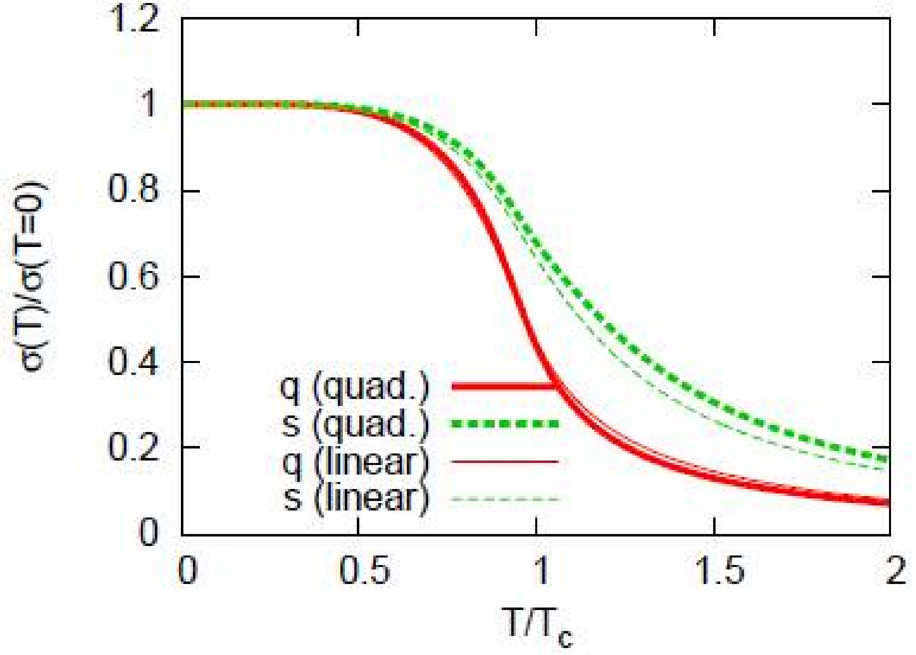
$$M_B(\sigma_q, \sigma_s; a, b, m_0)$$

Light-quark condensate   Strange-quark condensate

Chiral condensates

- Quark condensates from a model vs. LQCD
- Pion mass dependence: mpi = 140, 400 MeV





Chiral model vs. LQCD (FASTSUM)

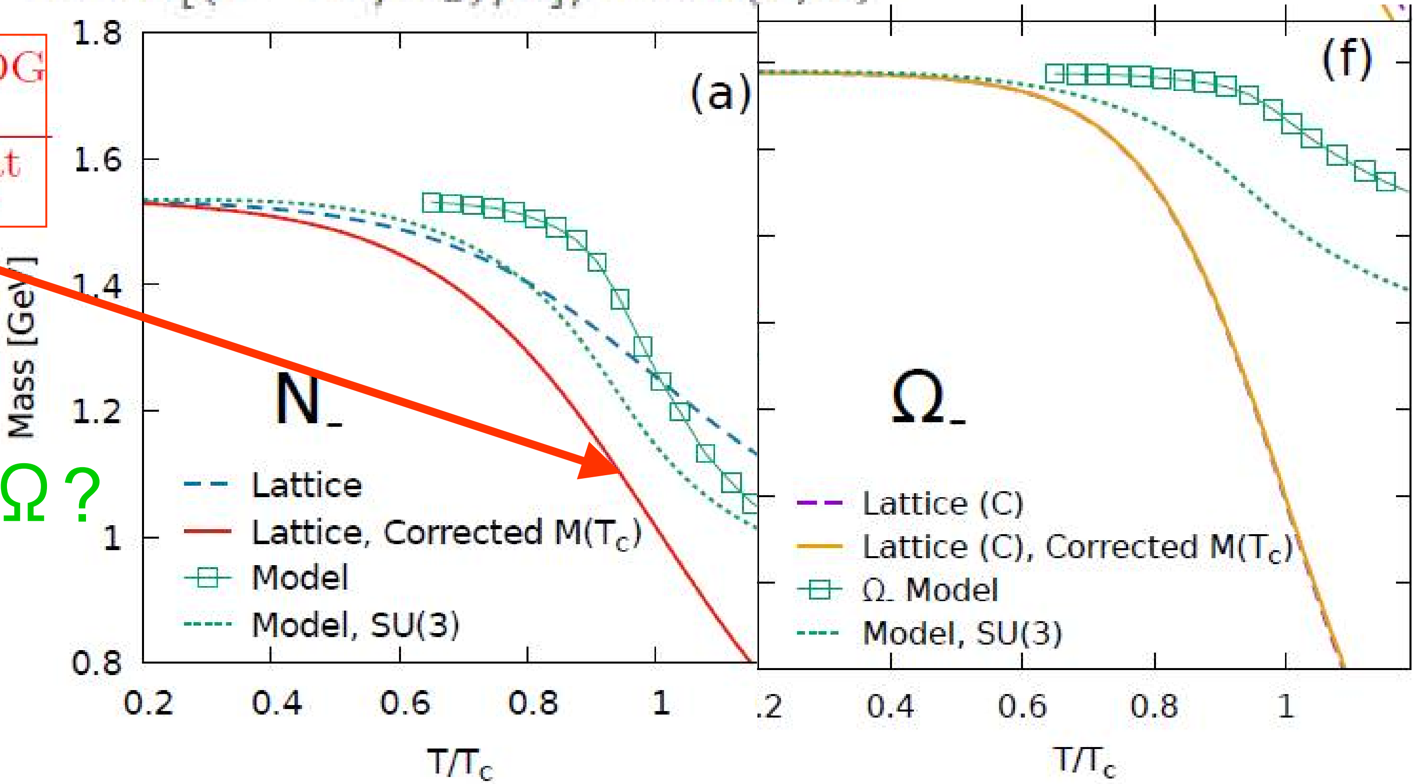
- ❑Strong mpi dependence; SU(2+1) vs. SU(3)
- ❑Fitting the LQCD masses [Aarts et al., 2017]

$$M^-(T) = M^-(T=0)\omega(T,b) + M^-(T_c)(1-\omega(T,b))$$

$$\omega(T,b) = \tanh[(1-T/T_c)/b]/\tanh(1/b)$$

$$M_-^{\rm lat}(T_c) \times \frac{M_+^{\rm PDG}}{M_+^{\rm lat}}$$

SU(3) limit vs. Ω ?



Any imprint in EoS?

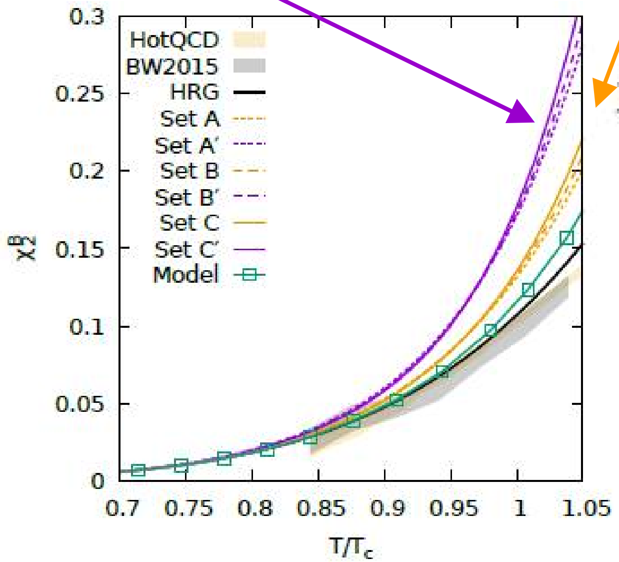
Signal of chiral symmetry restoration

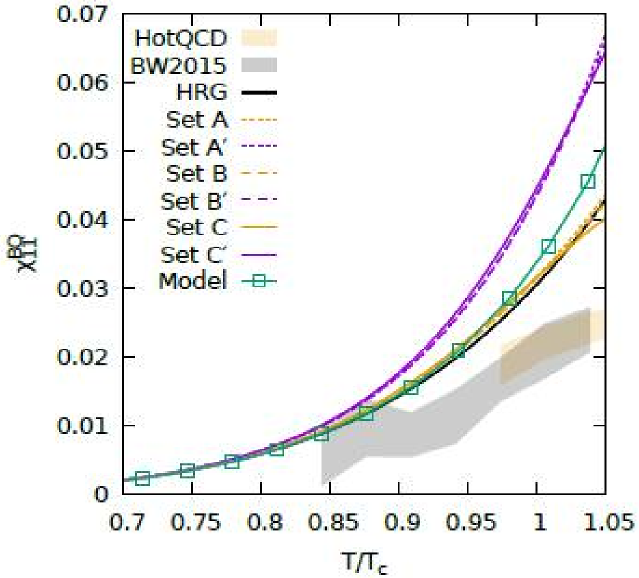
- Lattice QCD shows clearly <qqbar> dropping!
- More deviation from HRG in higher-order fluctuations → Missing states? Interactions? and/or in-medium effects?
- In-medium HRG [Aarts et al., 2017]
  - T-dep. masses motivated by Lattice findings
  - Constant masses for positive-parity states
  - Its verification? → baryon number fluctuations.

corrected $M_{-}^{\rm lat}(T_c)$

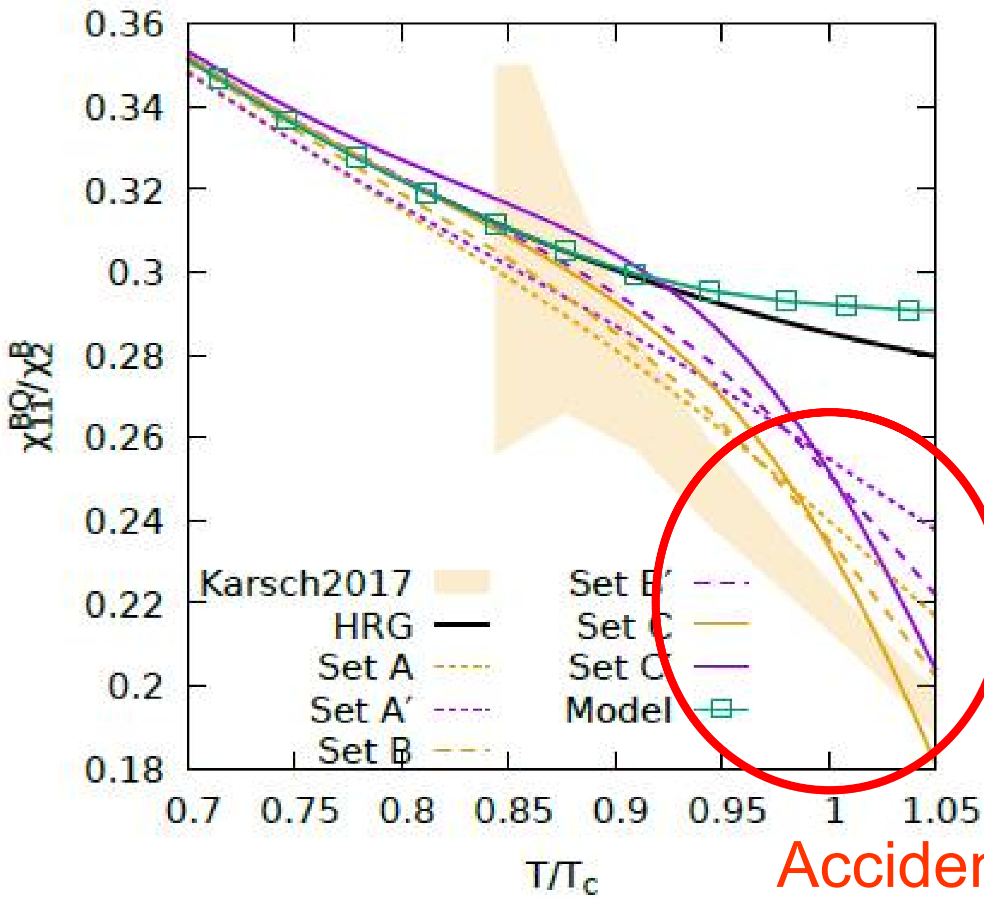
uncorrected

Fluctuations of net-baryon number





$$\chi_{ijk}^{BQS} \equiv \frac{\partial^{i+j+k}}{\partial^i(\mu_B/T)\partial^j(\mu_Q/T)\partial^k(\mu_S/T)} p(T,\mu_B,\mu_Q,\mu_S)/T^4$$



Accidental!

[Morita et al., arXiv:1711.10779 [hep-ph]]

2. Resonance widths

What is missing? --- finite width

❑Thermodynamics of broad resonances

→S matrix approach [Dashen, Ma and Bernstein, 1969]

- Grand canonical potential

$$\Omega = \Omega_0 + \Omega_{\text{int}}$$

$$\Delta \ln Z = \int dE\, e^{-\beta E} \frac{1}{4\pi i} \text{tr} \left[S^{-1} \frac{\overleftrightarrow{\partial}}{\partial E} S \right]_c$$

- Leading contribution: 2-body [Beth-Uhlenbech, 1937]

$$\Delta \ln Z = \int dE\, e^{-\beta E} \times \frac{1}{\pi} \frac{\partial}{\partial E} \text{tr}\, (\delta_E)$$

Phase shift

Dynamical information

What is missing? --- finite width

- ❑K0*/ κ (800) meson: chiral partner of kaon

  NOTE: omitted from PDG summary table

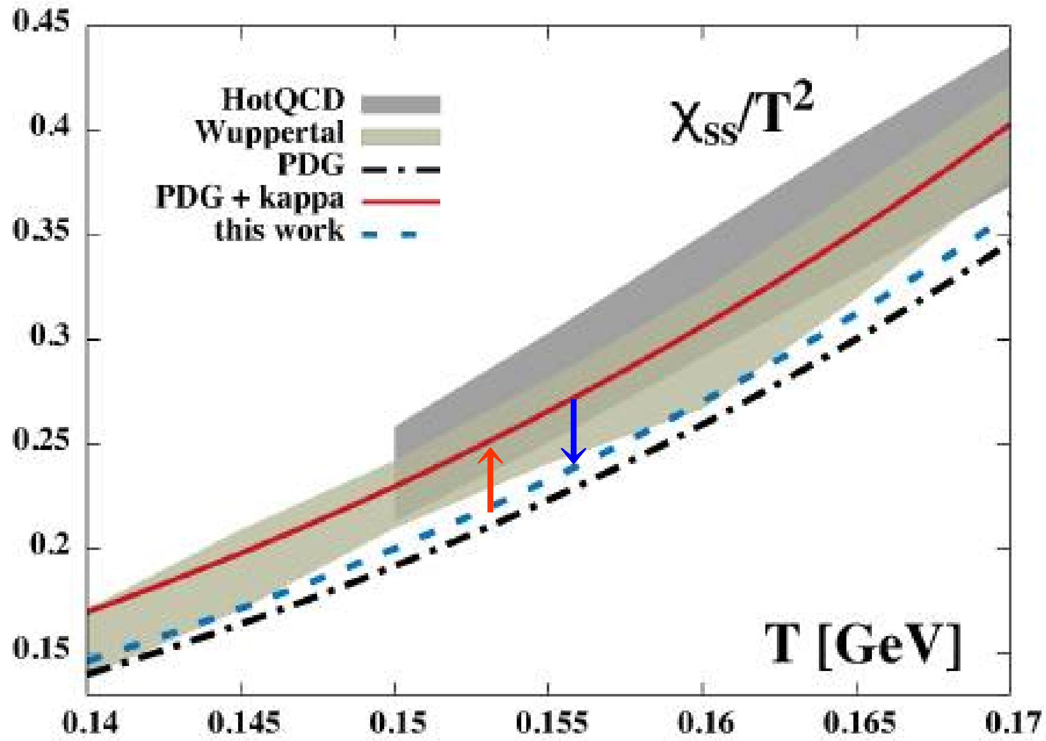
- ❑S matrix approach [Friman et al. 2015]

  ✓Empirical π -K phase shift from experiment

$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\rm int}$$

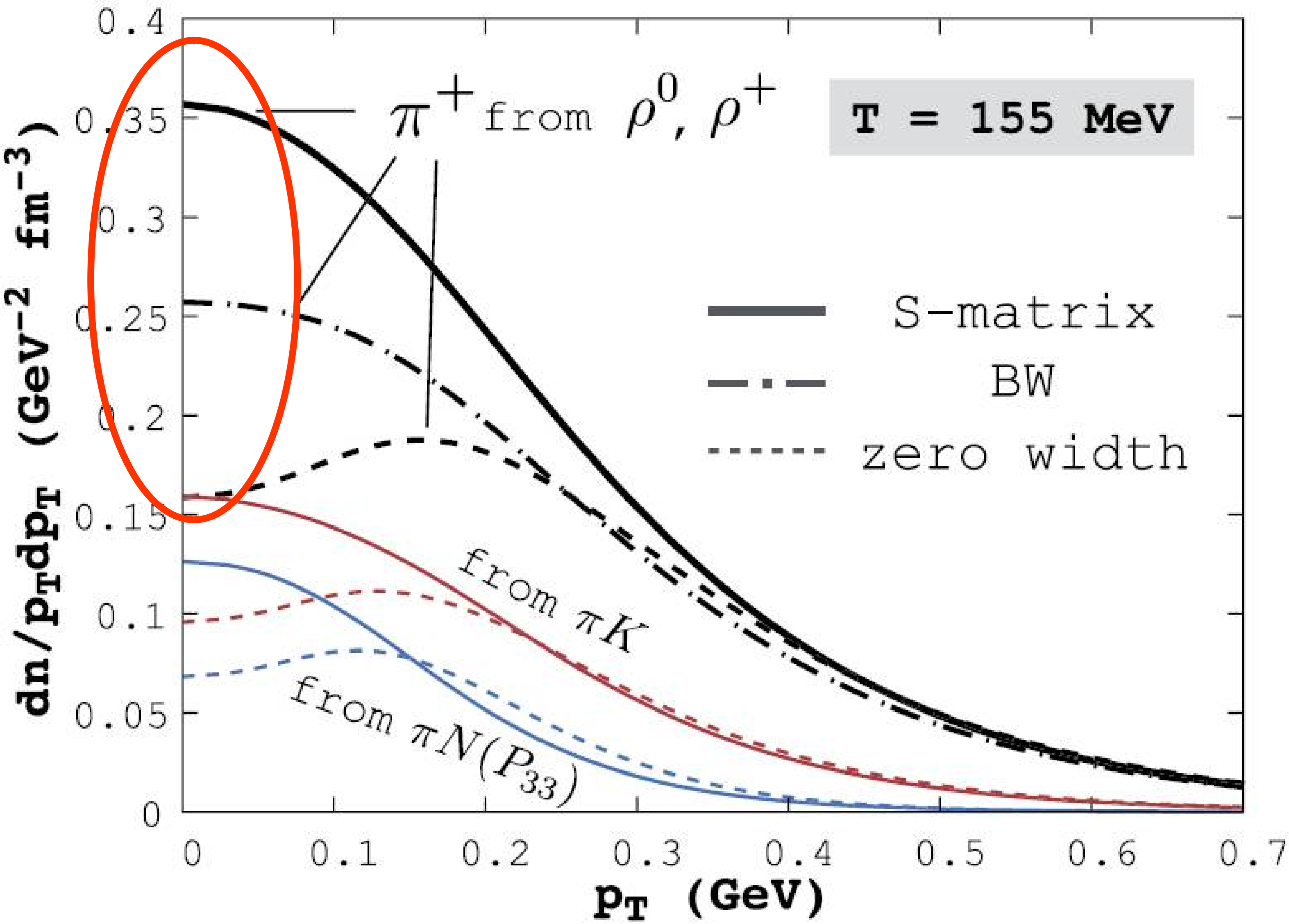
cf. HRG

$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\rm res}$$



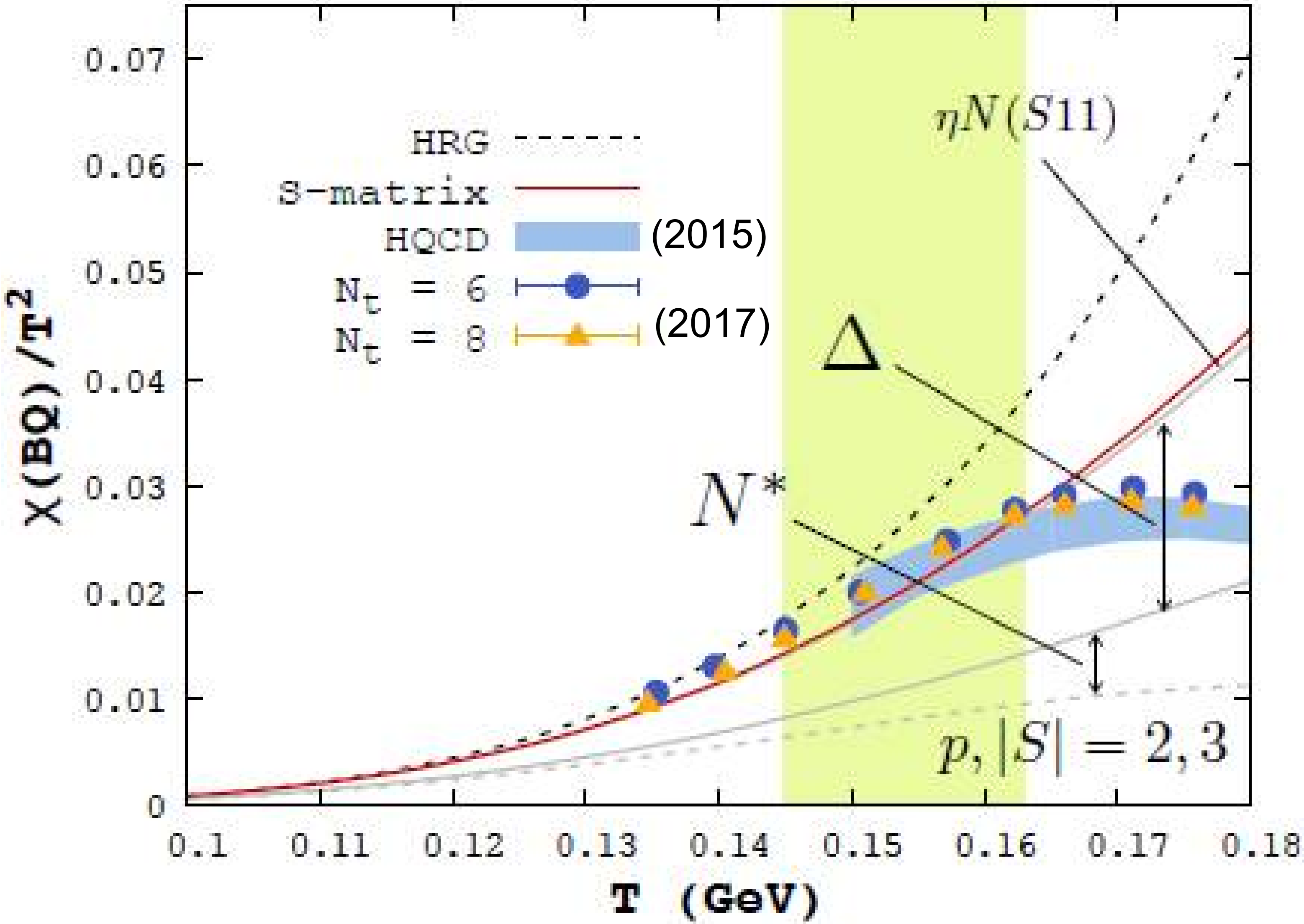
[Huovinen, Lo et al., 2017]

ρ -meson width vs. pion pt-dist.



Talk by K. Redlich (next session)

Pi-Nucleon system [Lo et al., 2018]

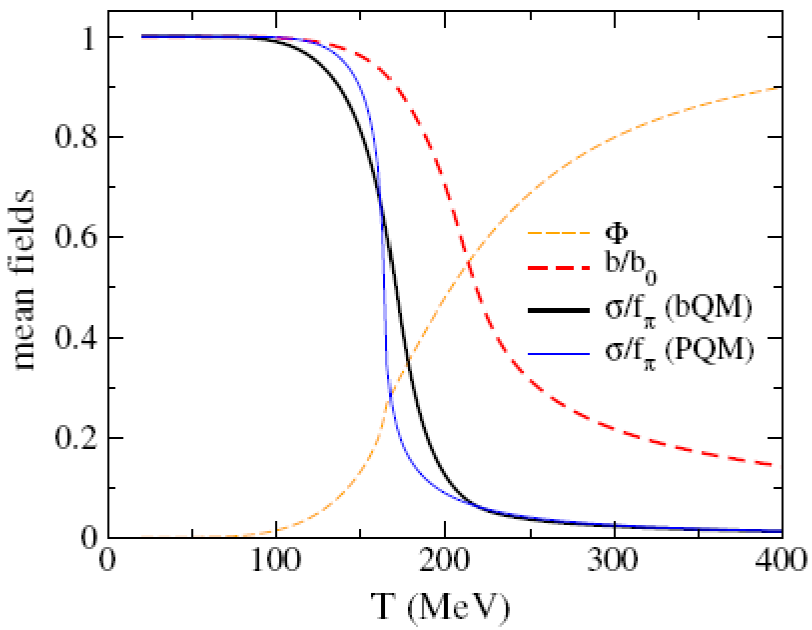


3. Model for Cold Dense Matter

[Benic et al. 2015]

Quark-nucleon hybrid model

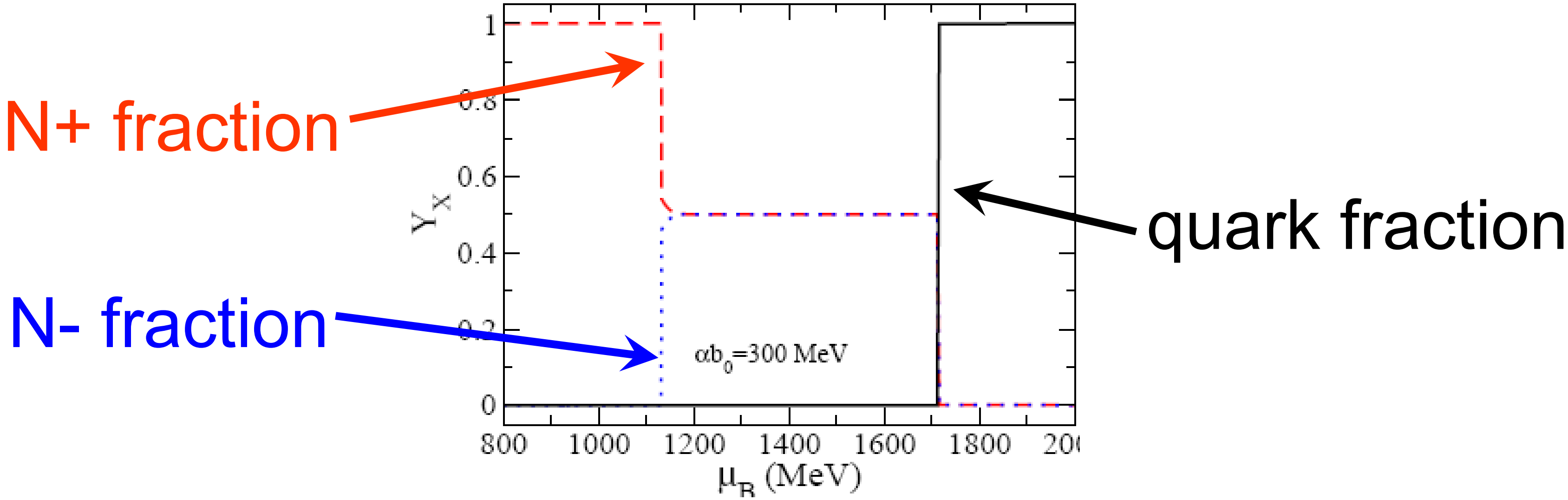
- How to suppress quarks at low density?
  - IR/UV cutoff "b" in Fermi dist. functions
  - from const. "b" to a VEV of a scalar field b
- Chiral & deconf. p.t. in a single framework
- T≠0, μ =0 thermodynamics vs. PQM

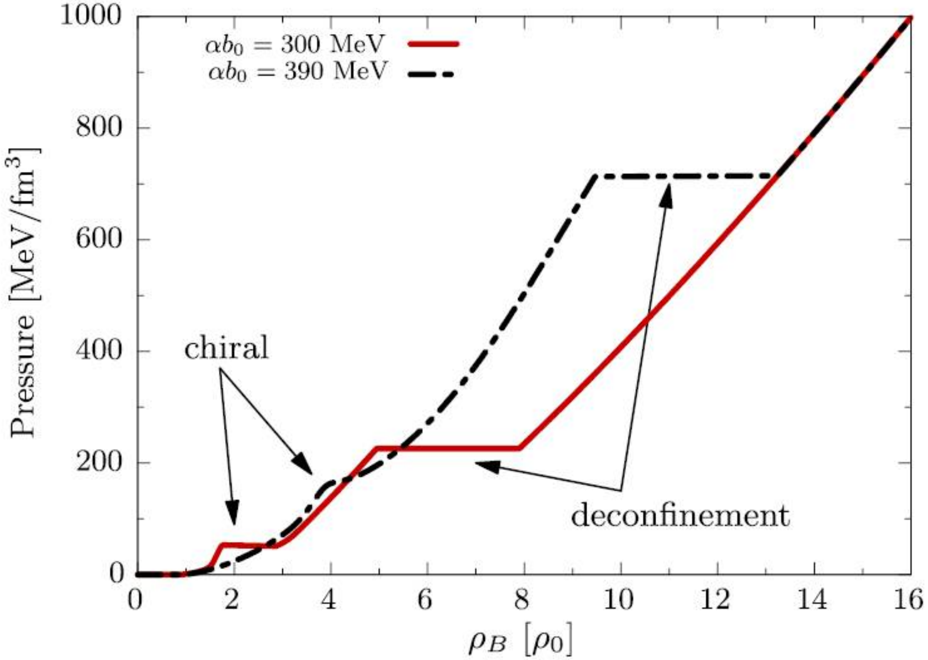


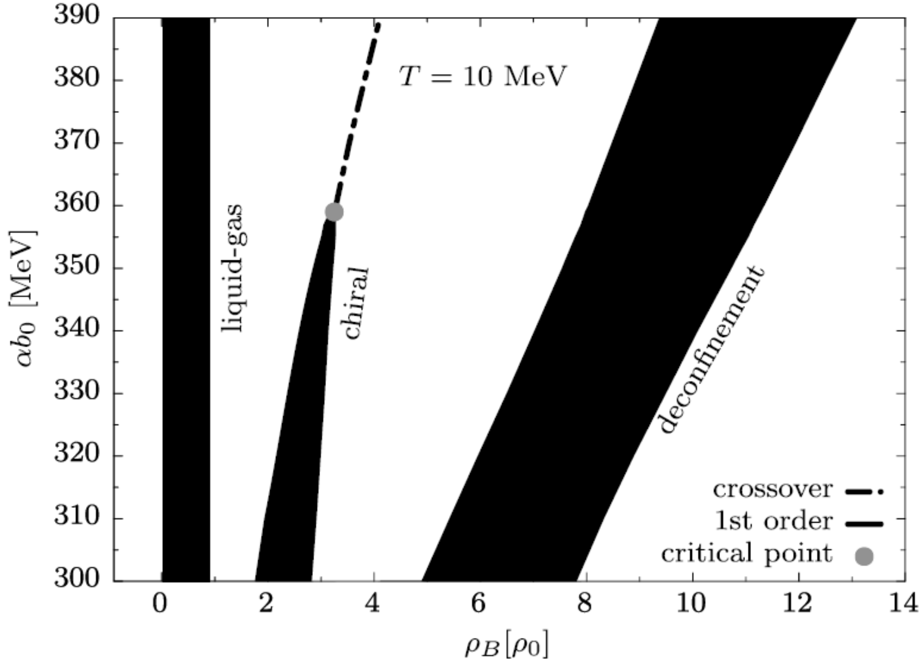
$$\langle \Phi \rangle \approx 1 - \langle b \rangle / \langle b_0 \rangle$$

[Marczenko, CS, 2017]

Onset of different fermions



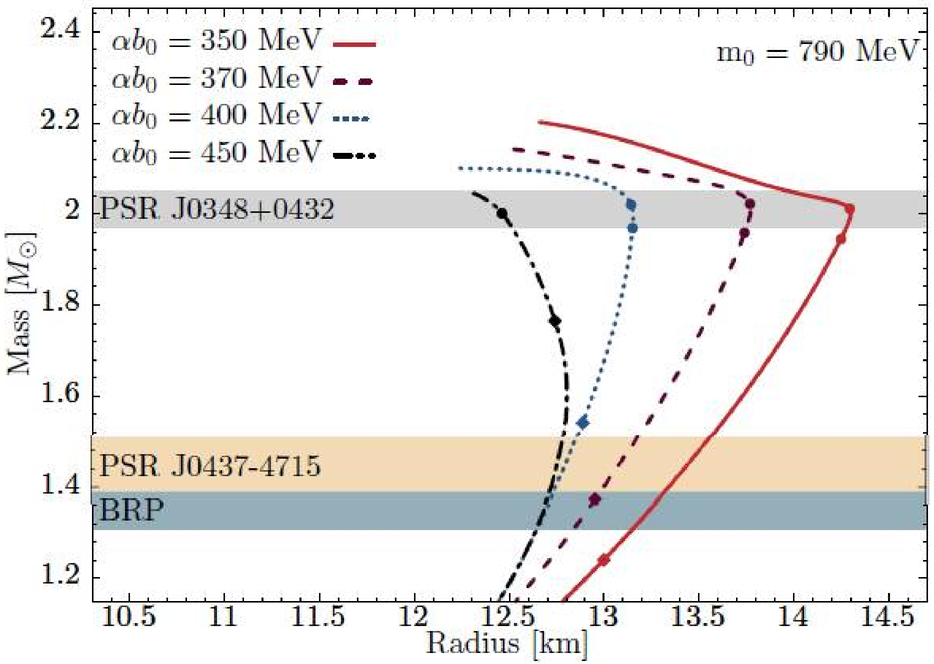


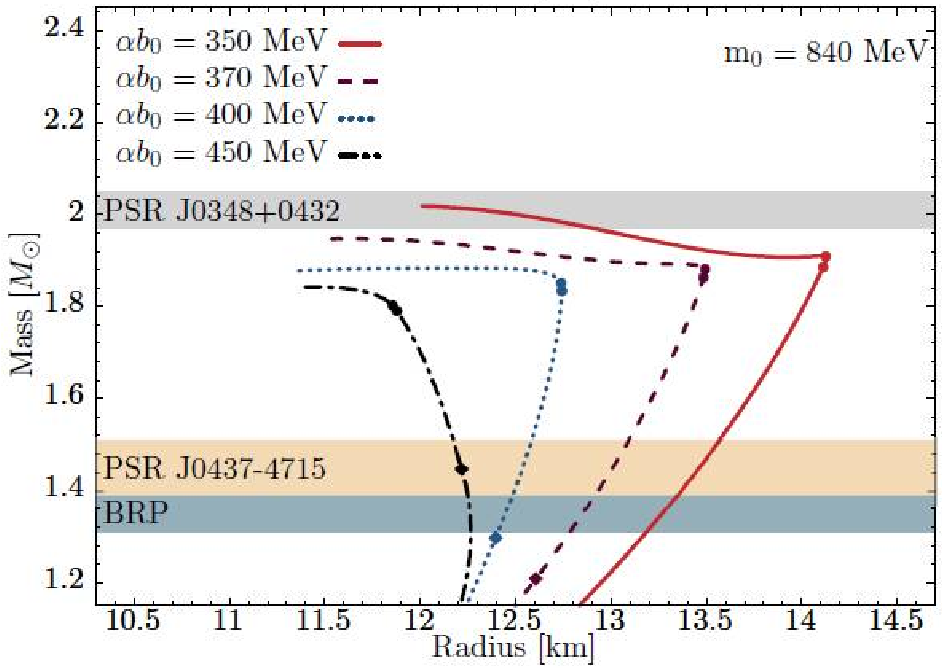


[Marczenko, Blaschke, Redlich, CS, arXiv:1805.06886 [nucl-th]]

Neutron stars

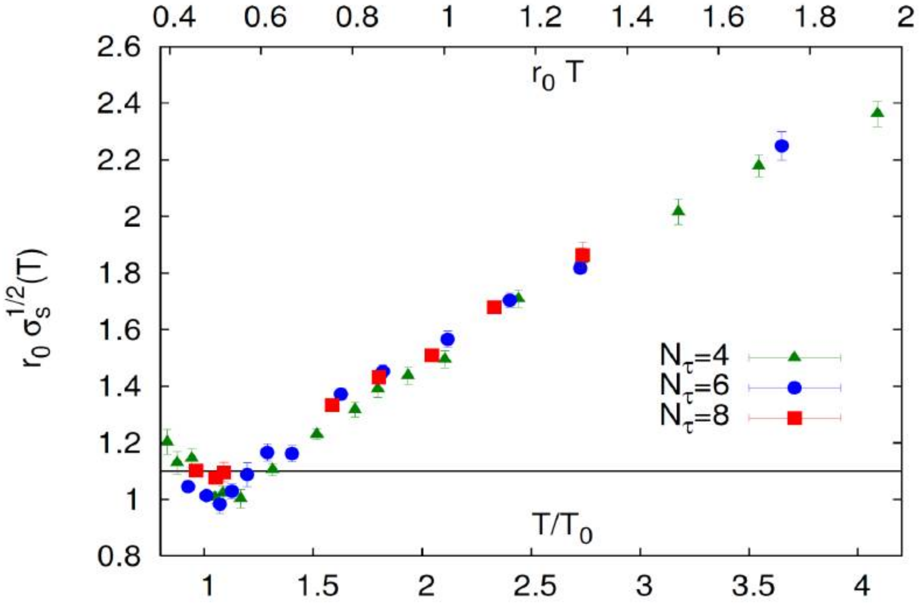
- ❑ β -equilibrium and charge neutrality
- ❑ Constraints on the mass and compactness of a star → hadronic scenario w/o deconf.quarks





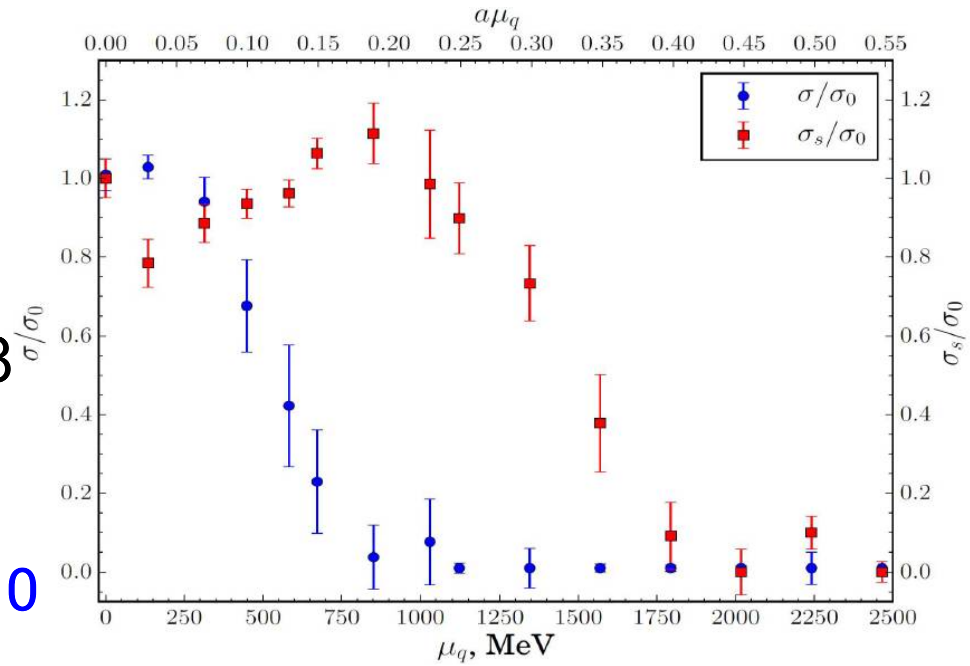
Fate of confinement: hot vs. dense

❑Non-pert. color-mag. sector → perturbative!



← SU(3)c, T >0, μ = 0;
Cheng et al., PRD 2008
[mpi = 220 MeV].

→ SU(2)c, T = 0, μ > 0;
Bornyakov et al., JHEP 2018
[mpi = 740 MeV].



✓m0(μ =0) vs. m0($\mu \neq$0)

✓Color-mag.monopoles at $\mu \neq$0

Summary

- Emergent parity-doubling structure as a manifestation of restored chiral symmetry

Lessons:

- Naive “in-medium HRG” does not work.
- Effect of resonance widths – beyond HRG
- Survival mass ≈ chromo-magnetic sector
- Interplay between CSB and confinement

- Higher-lying states … vs. Holographic QCD?
- Toward more realistic description of QCD