Modeling Hot and Dense QCD in Effective Theory

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Outline

1. Parity doubling of baryons
   - Chiral symmetry restoration vs. baryon masses
   - In-medium Hadron Resonance Gas
2. Resonance width: S-matrix approach
3. A model for cold and dense matter
   - “Confinement” w/o Polyakov loop
   - Implications for the structure of neutron stars

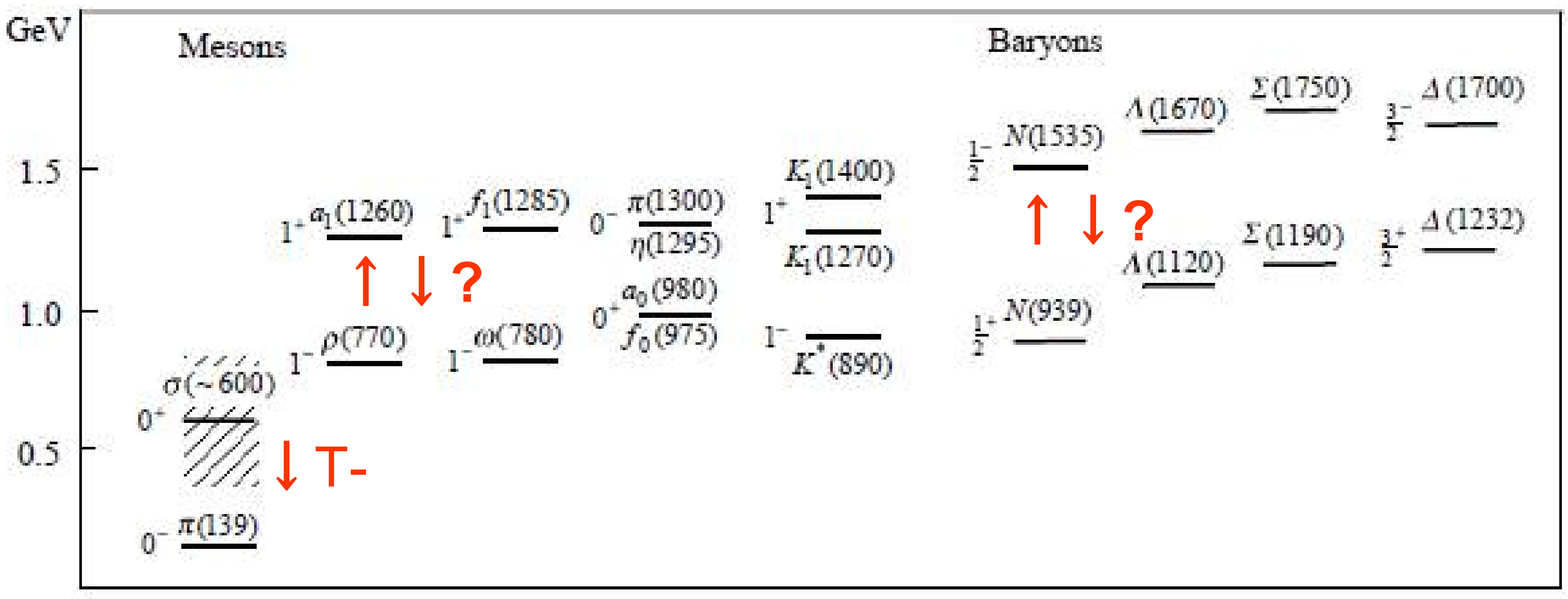
List of references

- Friman, Lo, Marczenko, Redlich and C.S., PRD 92 (2015).
- Huovinen, Lo, Marczenko, Morita, Redlich and C.S., PLB 769 (2017).
- C.S., NPA 970 (2018).
- Lo, Friman, Redlich and C.S., PLB 778 (2018).
- Marczenko and C.S., PRD 97 (2018).
- Morita, C.S., Lo and Redlich, EPJ Web Conf.17 (2018).
- Lo, Szymanski, Redlich and C.S., arXiv:1801.08040 [hep-ph].
- Marczenko, Blaschke, Redlich and C.S., arXiv:1805.06886 [nucl-th].

1. Parity doubling

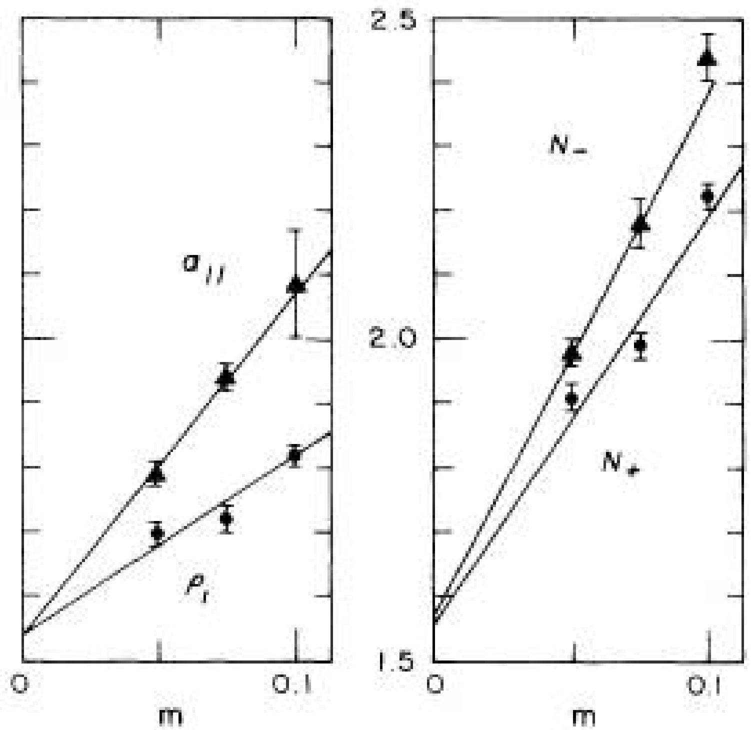
Spectra in a chirally restored world

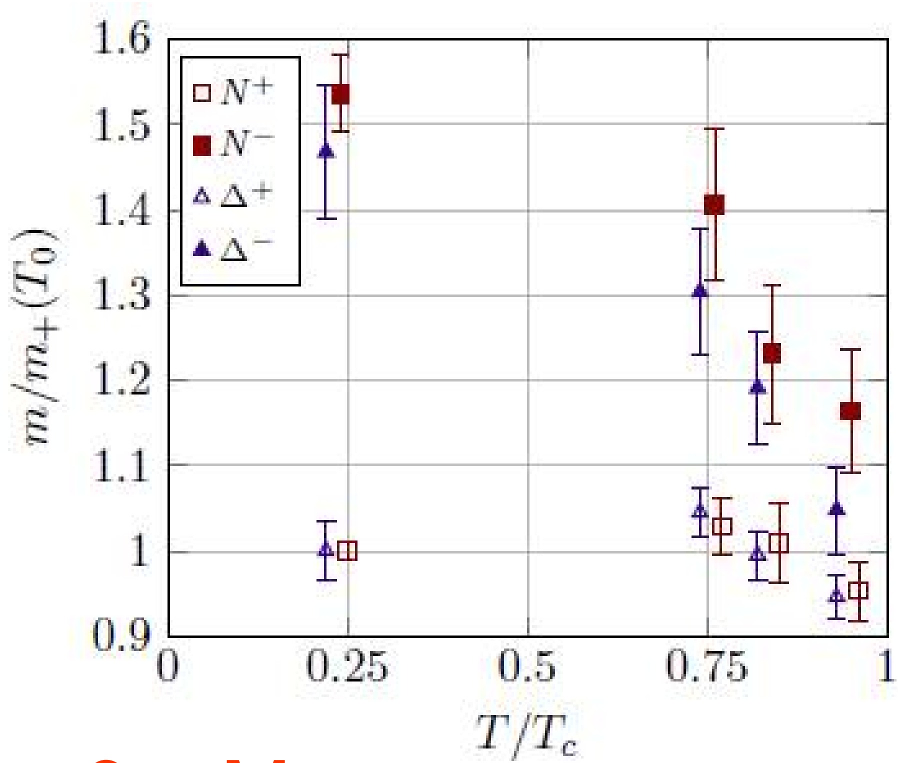
- ❑Lowest scalar meson → O(4) vector with pion
- ❑Parity partners degenerate → chiral partners
- ❑QCD ground-state particles: pions & nucleons



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

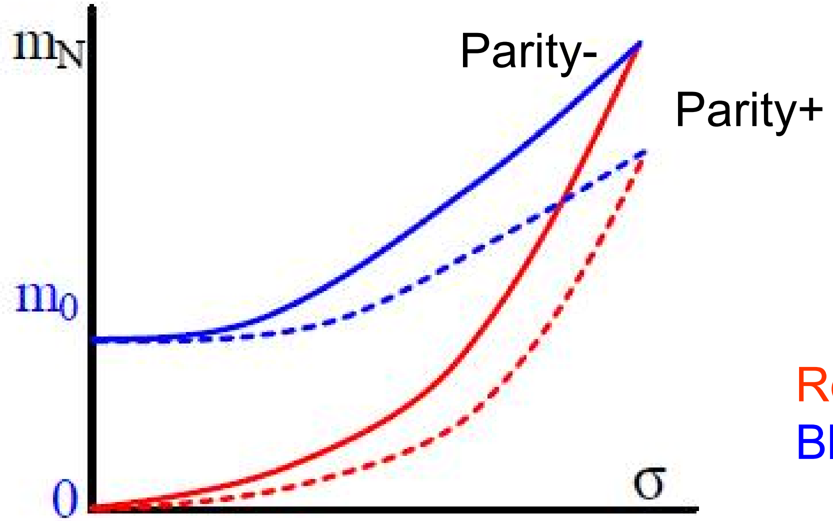
- SU(2) chiral transformation of 2 nucleons

  → how to assign 2 indep. rotation to them?

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

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

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



[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

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

  - ✓ Gell-Mann's equal spacing rule

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

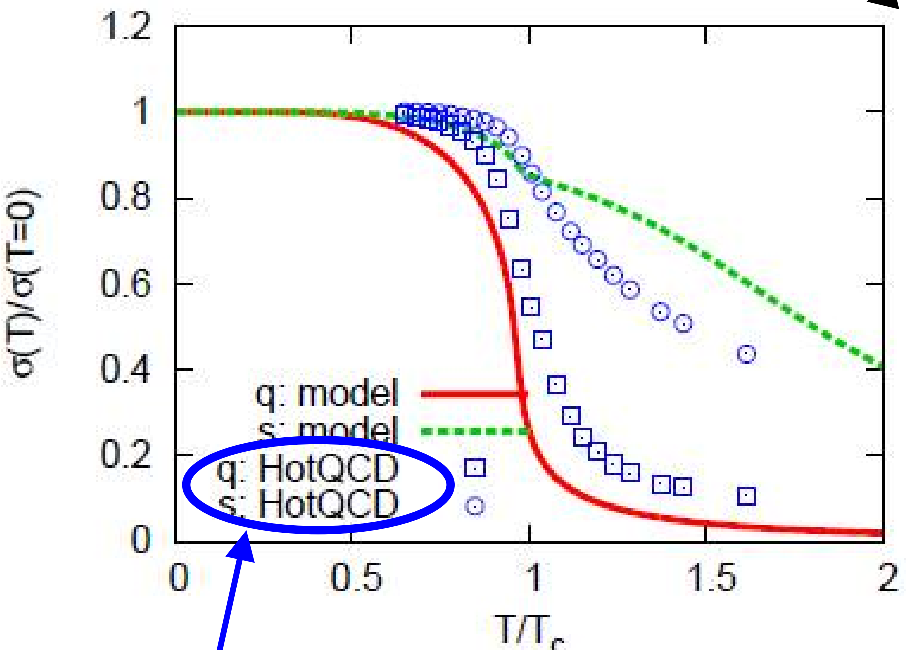
- Mass relations [CS, 2018)]

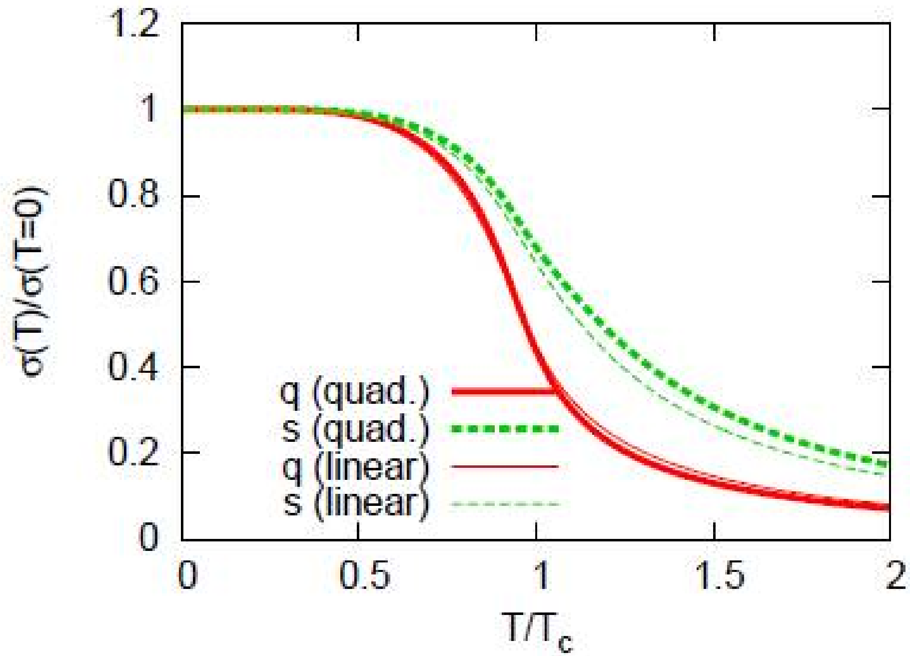
$$M_B(\sigma_q, \sigma_s; a, b, m_0)$$

Light-quark condensate Strange-quark condensate

Chiral condensates

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





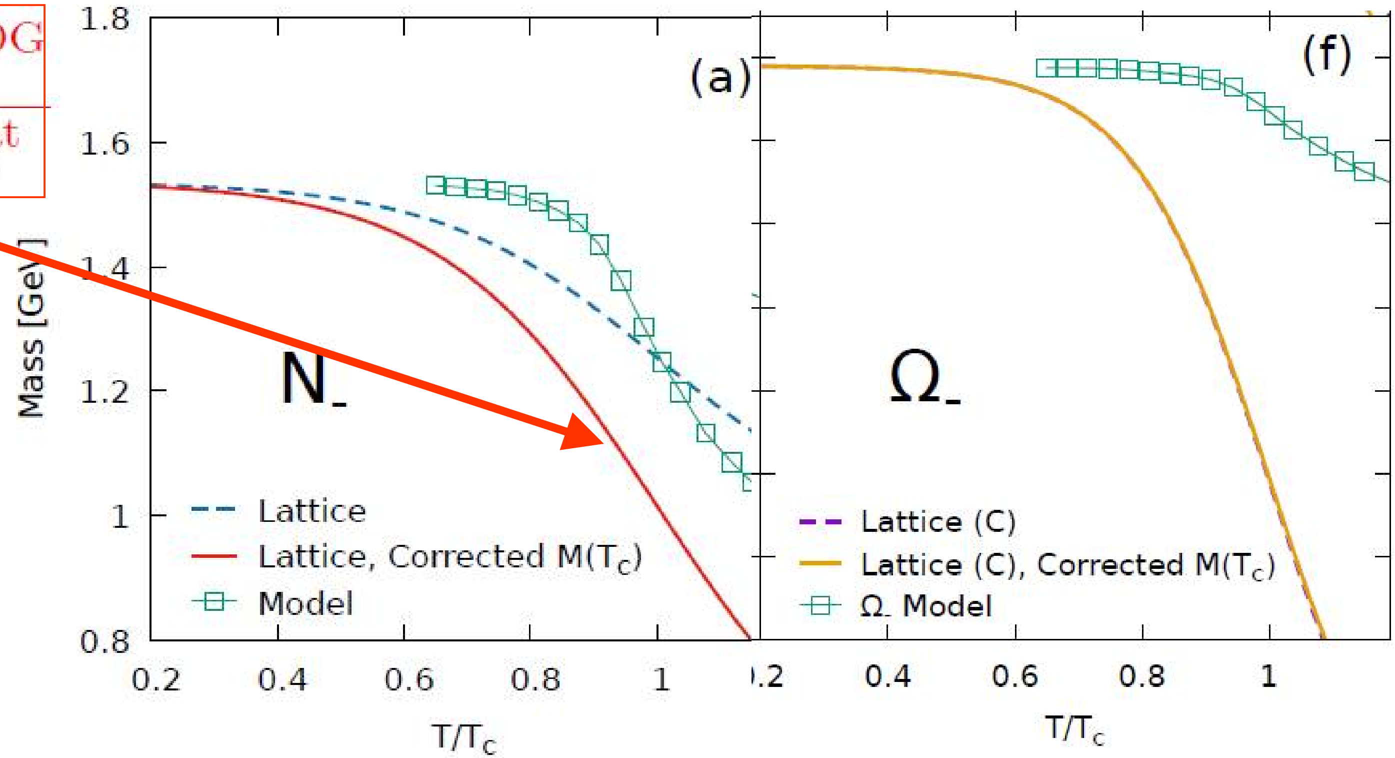
Lattice QCD w/ physical mpi

Chiral model vs. LQCD (FASTSUM)

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

$$M^{-}(T) = M^{-}(T=0)\omega(T,b) + M^{-}(T_c)(1-\omega(T,b))$$
$$\omega(T,b) = \tanh[(1-T/T_c)/b]/\tanh(1/b)$$

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



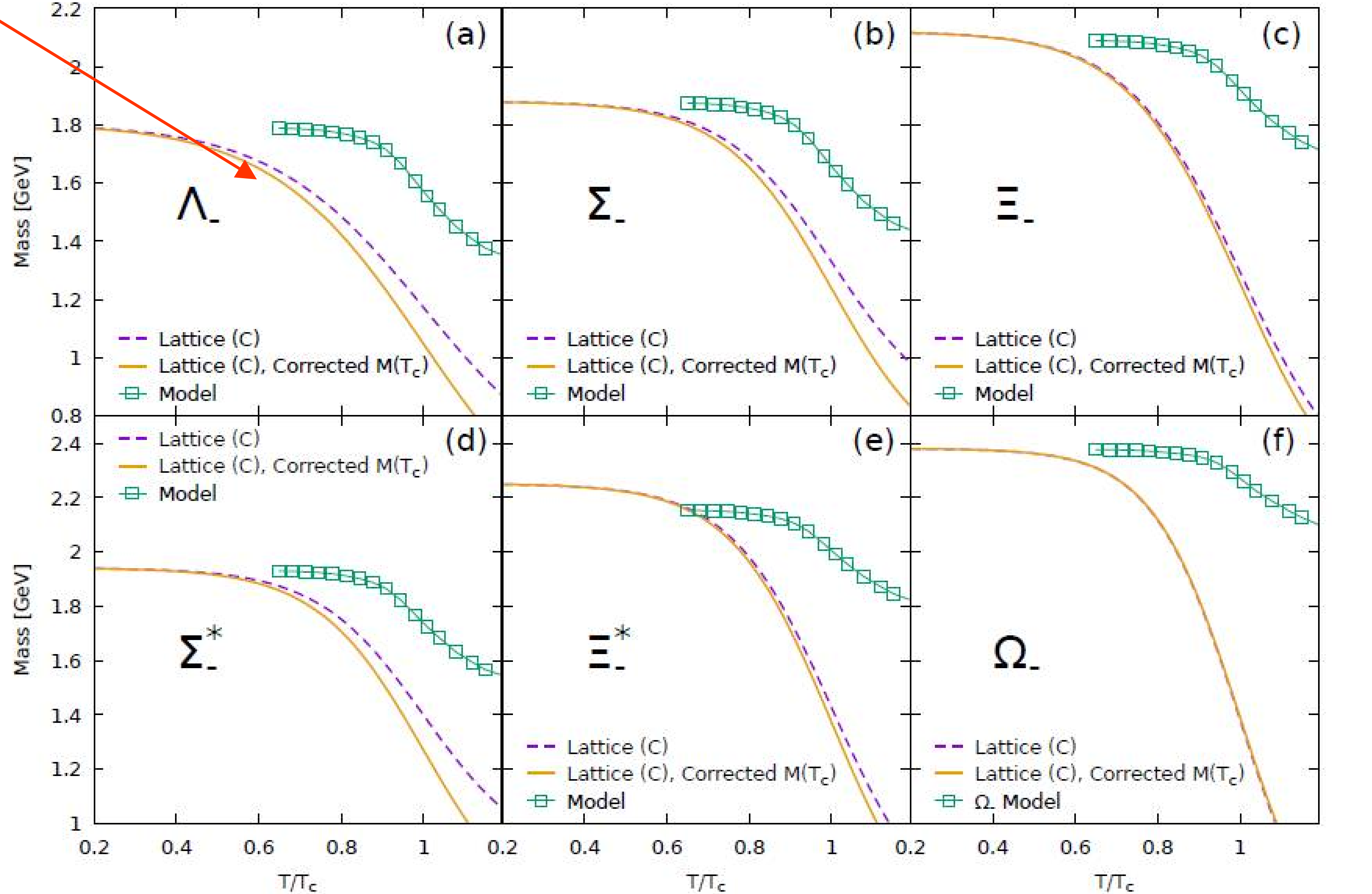
Any imprint in EoS?

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.

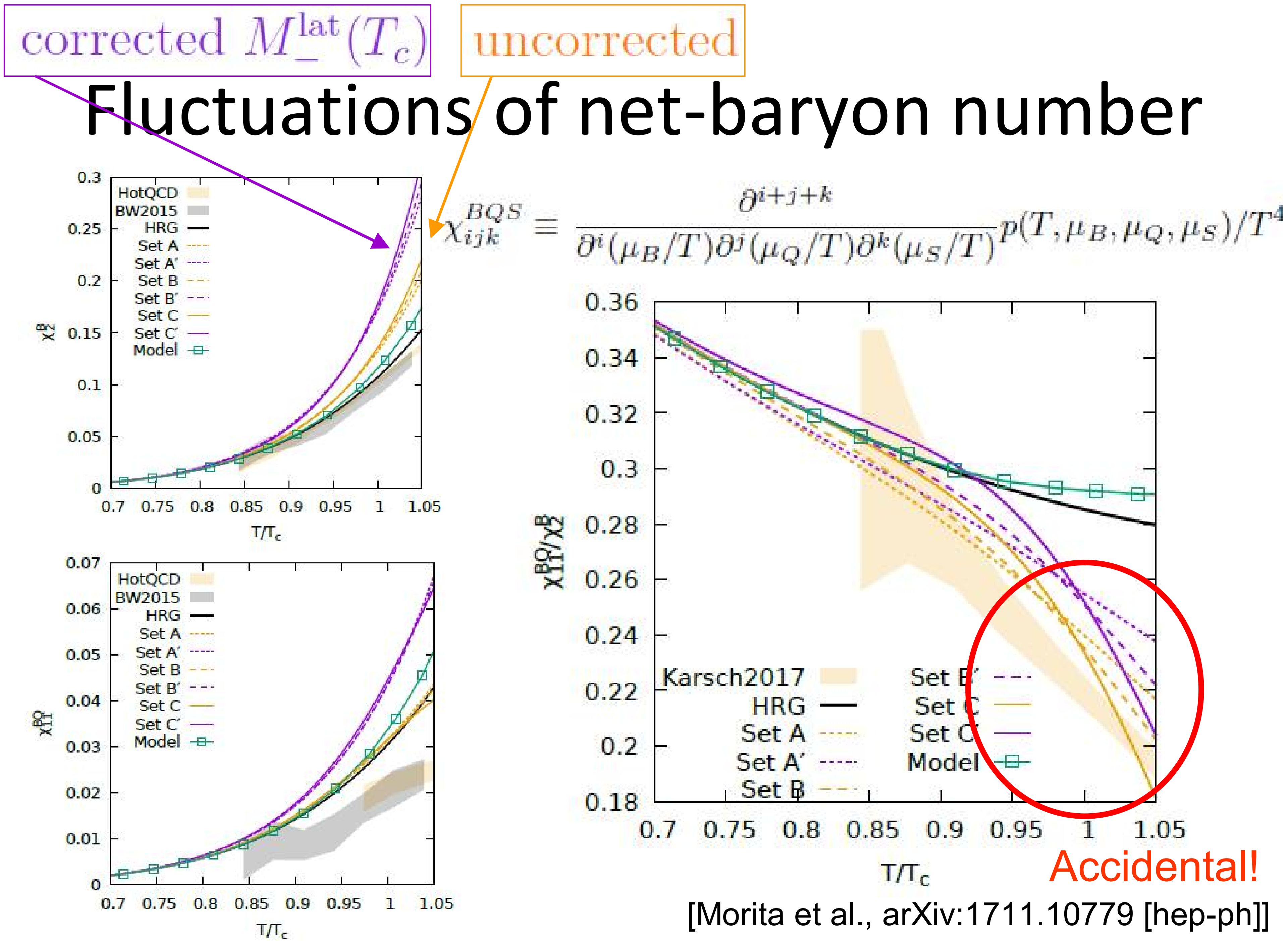
$$M_-^{\mathrm{lat}}(T_c) \times \frac{M_+^{\mathrm{PDG}}}{M_+^{\mathrm{lat}}}$$

Thermal masses



Fluctuations of net-baryon number

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



[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

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

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

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

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

Phase shift

Dynamical information

What is missing? --- finite width

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

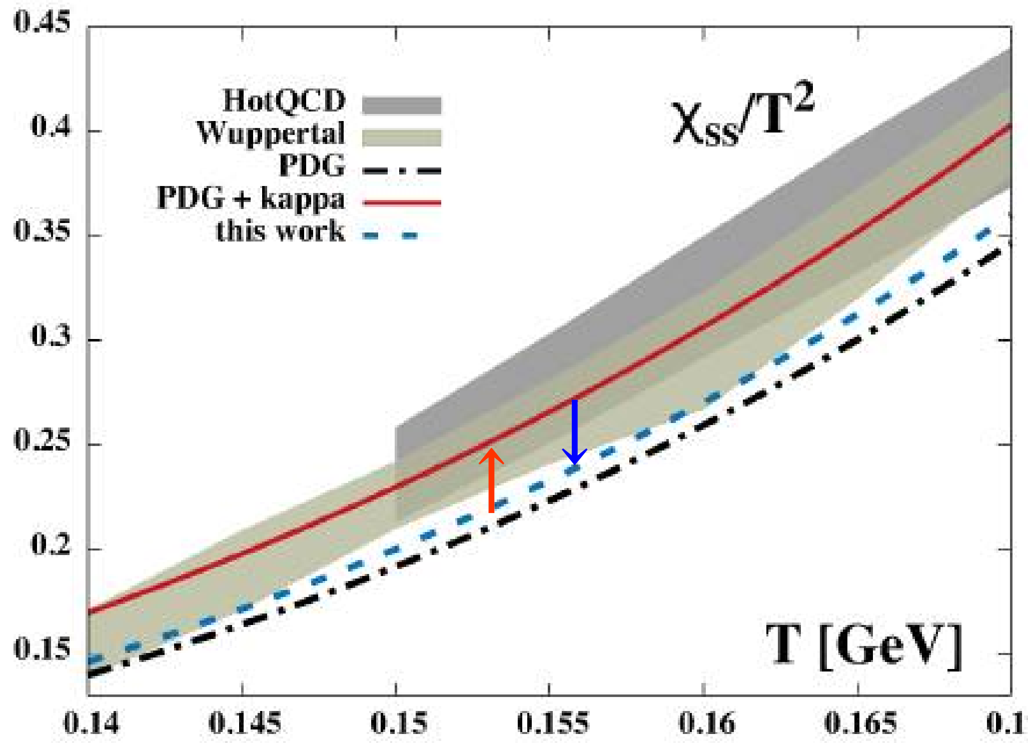
  NOTE: omitted from PDG summary table

- ❑S matrix approach [Friman et al. 2015]
  - ✓Empirical π -K phase shift from experiment

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

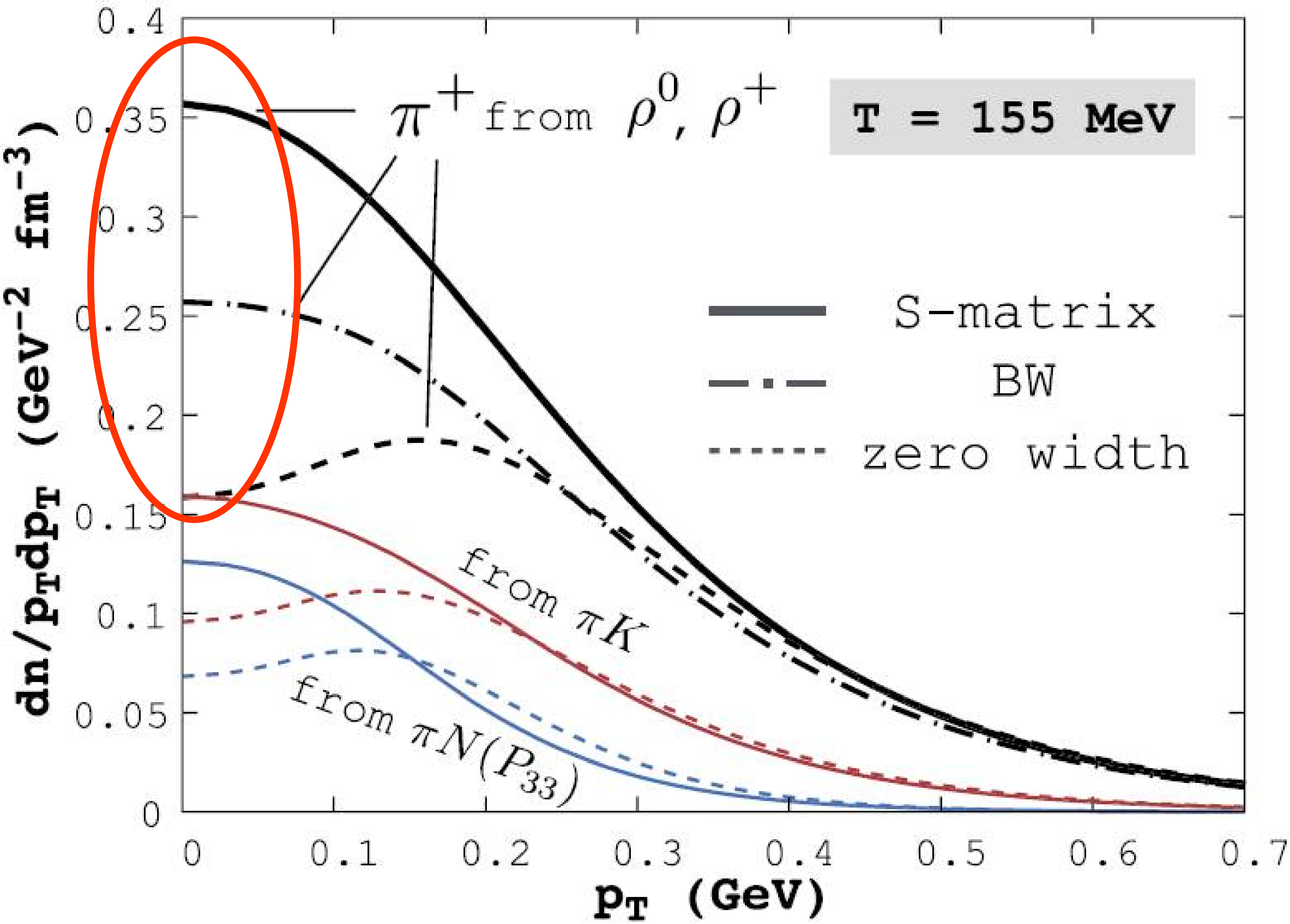
cf. HRG

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

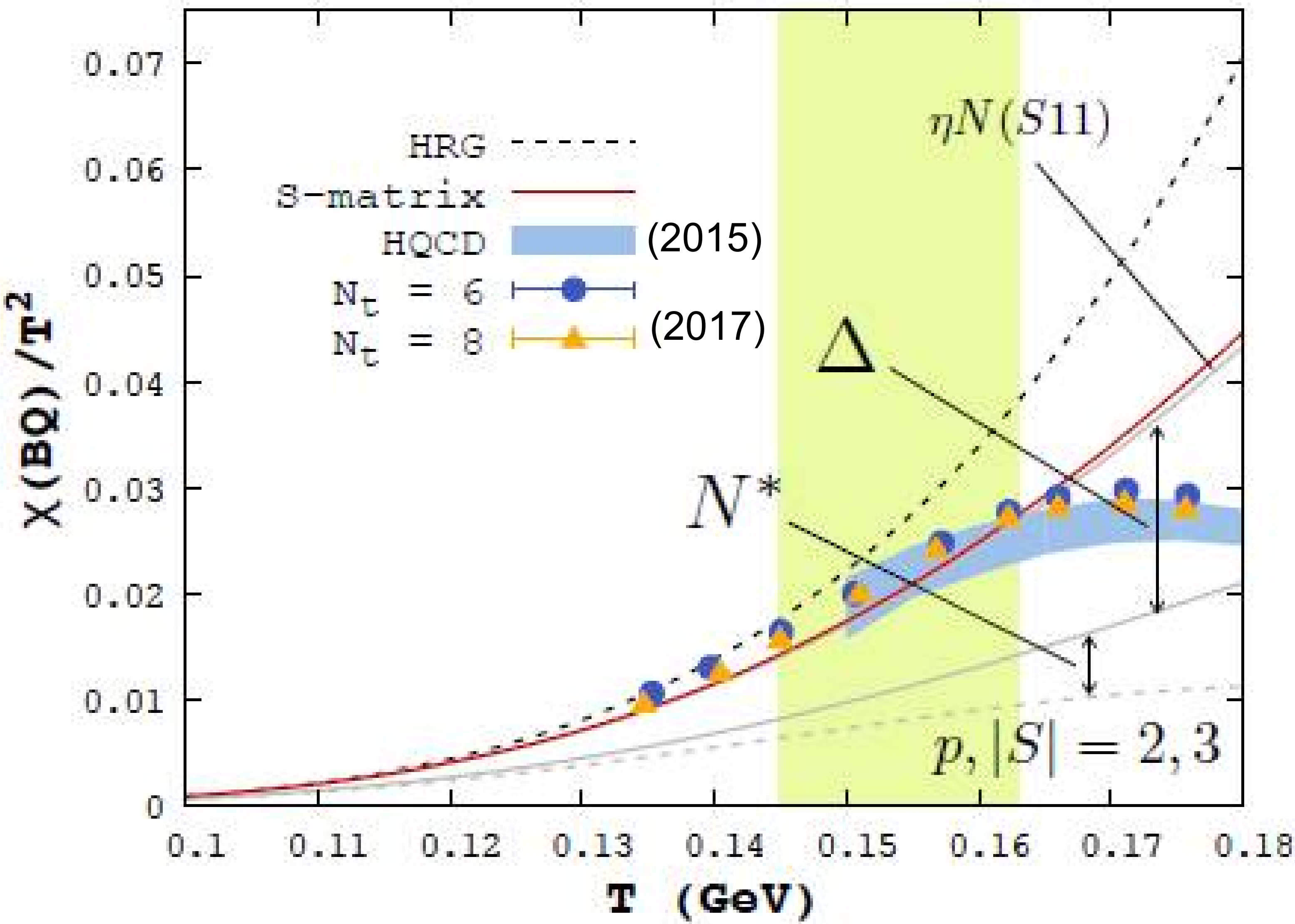


[Huovinen, Lo et al., 2017]

ρ -meson width vs. pion pt-dist.



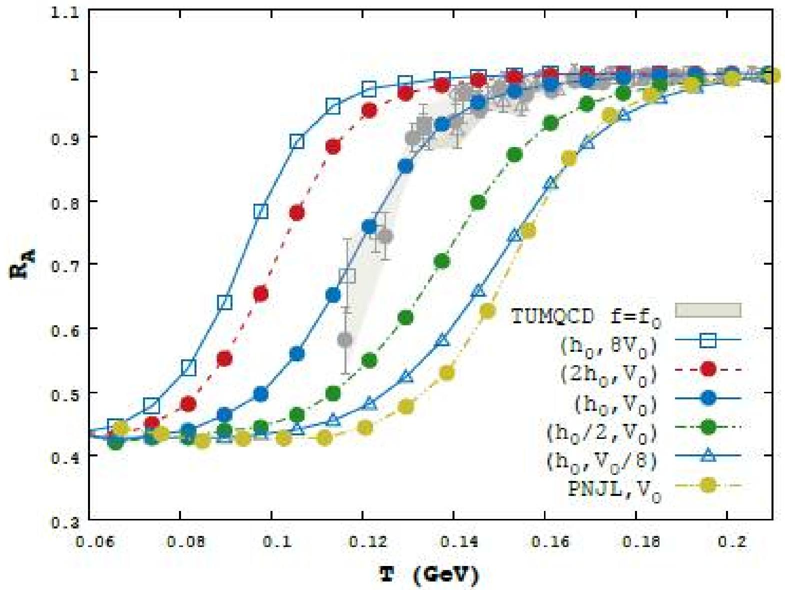
Pi-Nucleon system [Lo et al., 2018]

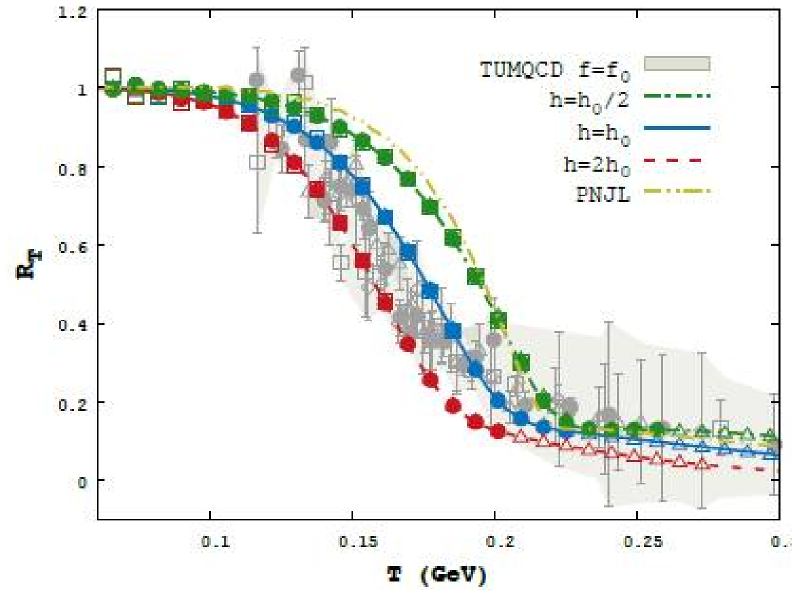


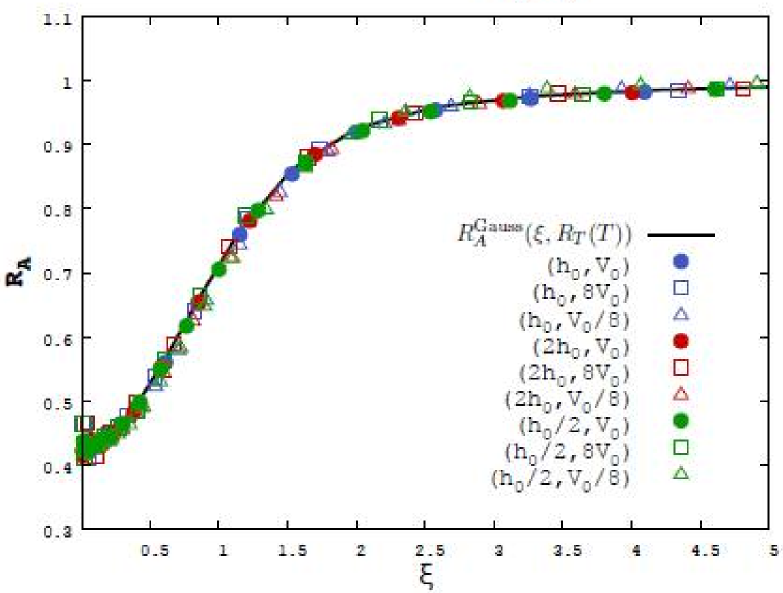
3. Model for Cold Dense Matter

[Lo, Szymanski et al., 2018]

Hot QCD: Polyakov loop fluct.







$$R_A = \chi_A/\chi_R,\ R_T = \chi_I/\chi_R$$

✓Renormalization

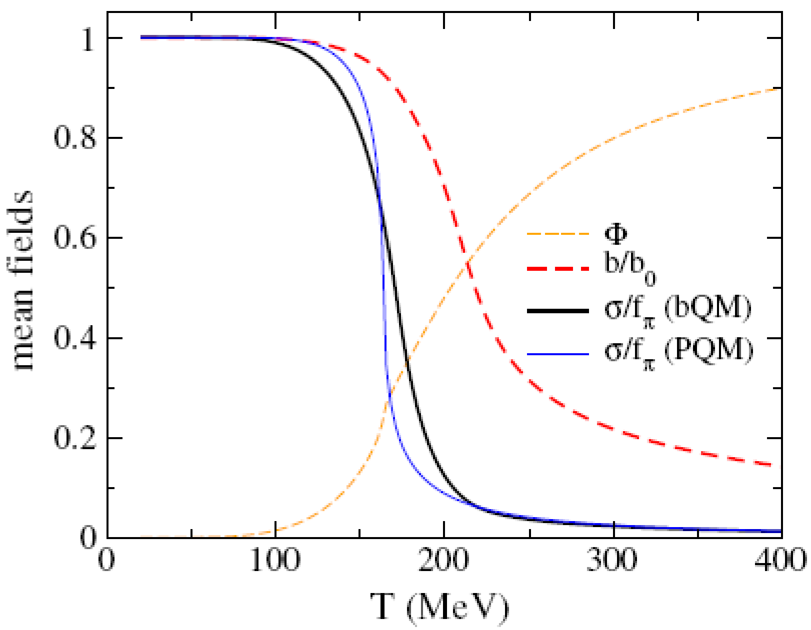
✓Scaling: $R_A(\xi, R_T)$

$$\xi = \tilde{h} \times \frac{\sqrt{VT^3}}{2\sqrt{\alpha_1}}$$

[Benic et al. 2015]

Quark-nucleon hybrid model

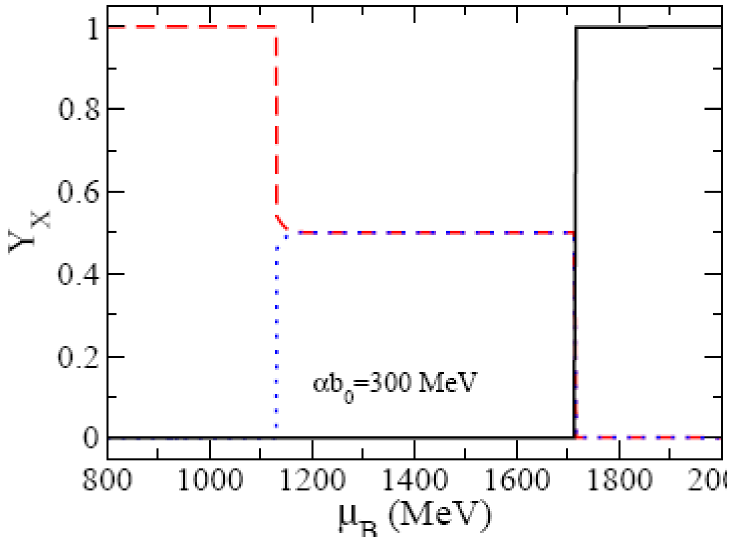
- How to suppress quarks at low density?
  - IR/UV cutoff “b” in Fermi dist. functions
  - from const. “b” to a VEV of a scalar field b
- Chiral & deconf. p.t. in a single framework
- T≠0, μ =0 thermodynamics vs. PQM

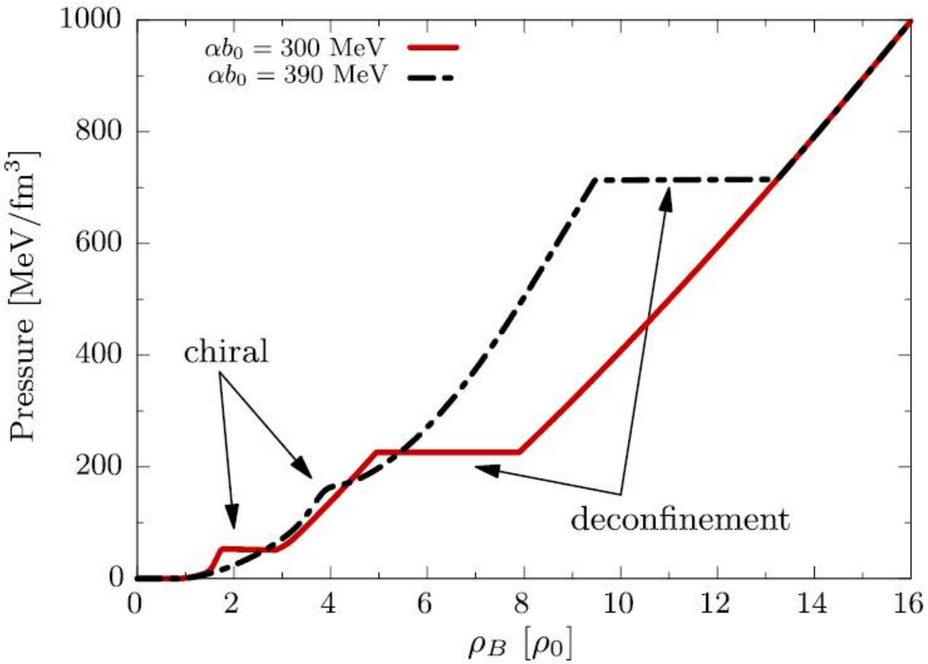


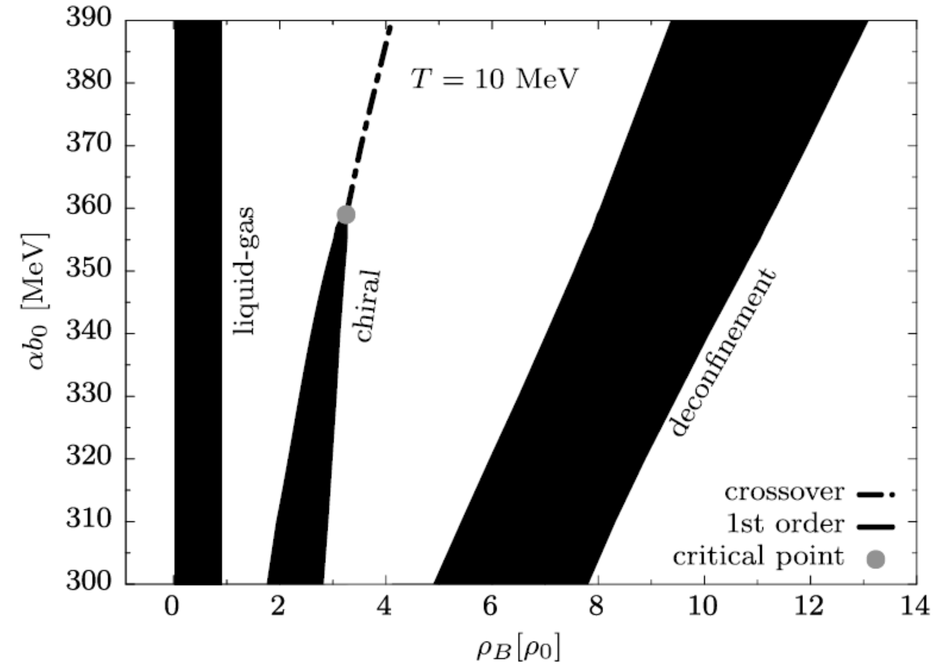
$$\langle \Phi \rangle \approx 1 - \langle b \rangle / \langle b_0 \rangle$$

[Marczenko, CS, 2017]

Onset of different fermions



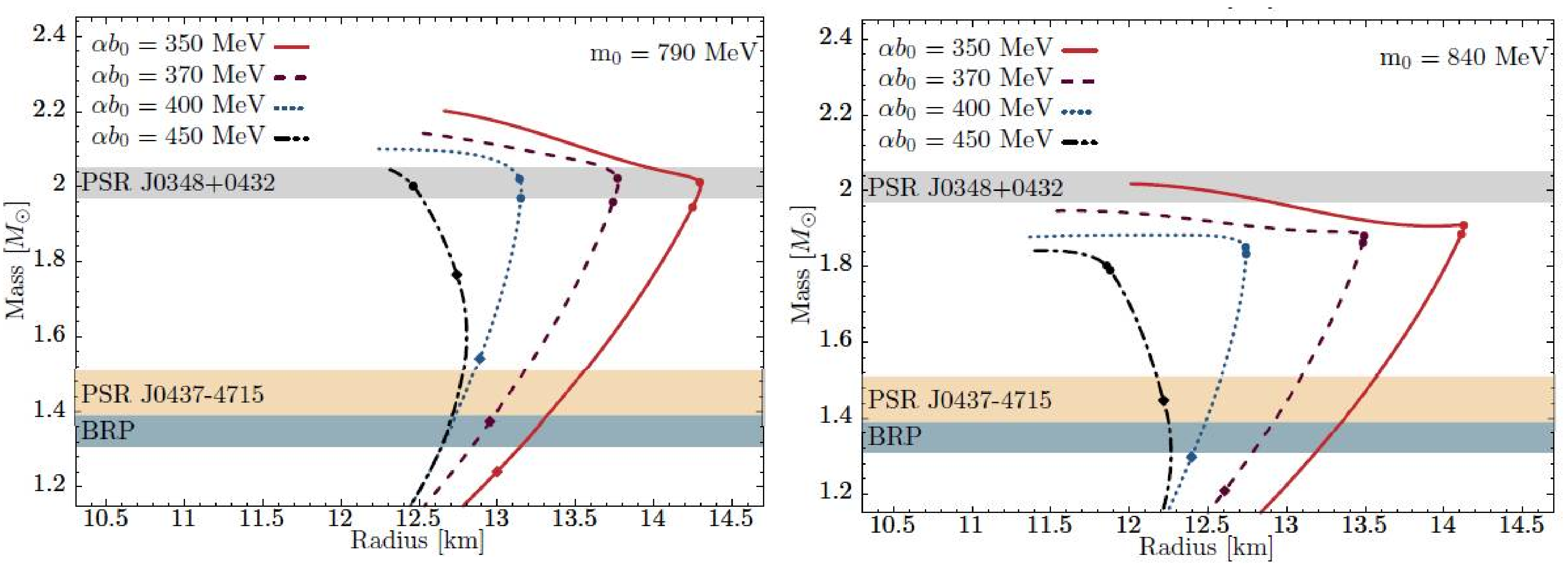




[Marczenko, Blaschke, Redlich, CS, arXiv:1805.06886 [nucl-th]]

Neutron stars

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



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

  Cf. SU(2) : σ s→ 0 at large mu
- Interplay between CSB and confinement

- Higher-lying states near QCD p.t.
- Toward more realistic description of QCD