

# Phases of QCD at Extremes

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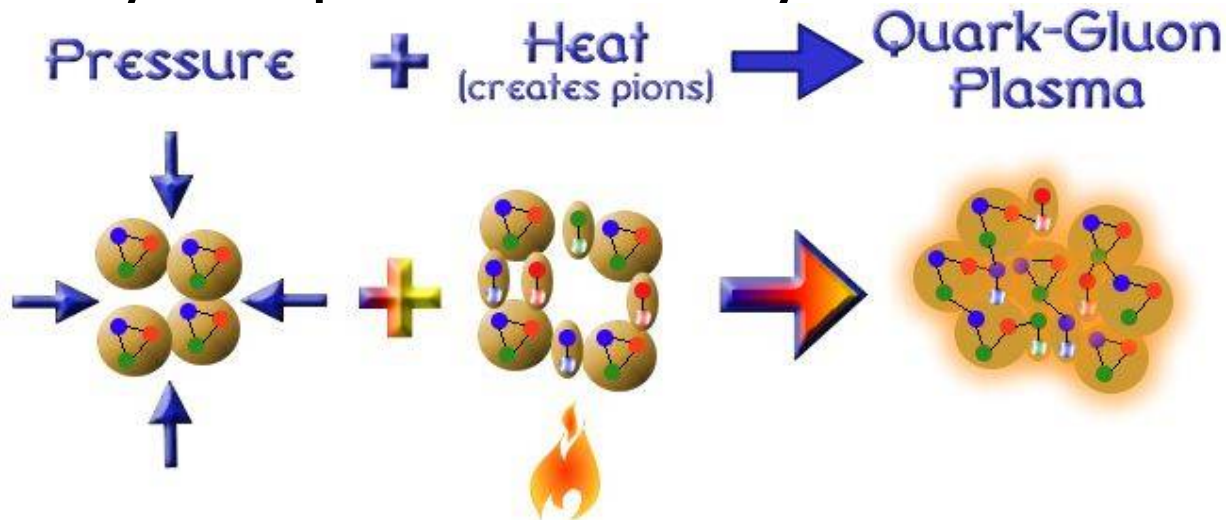
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# QCD at high temp./density

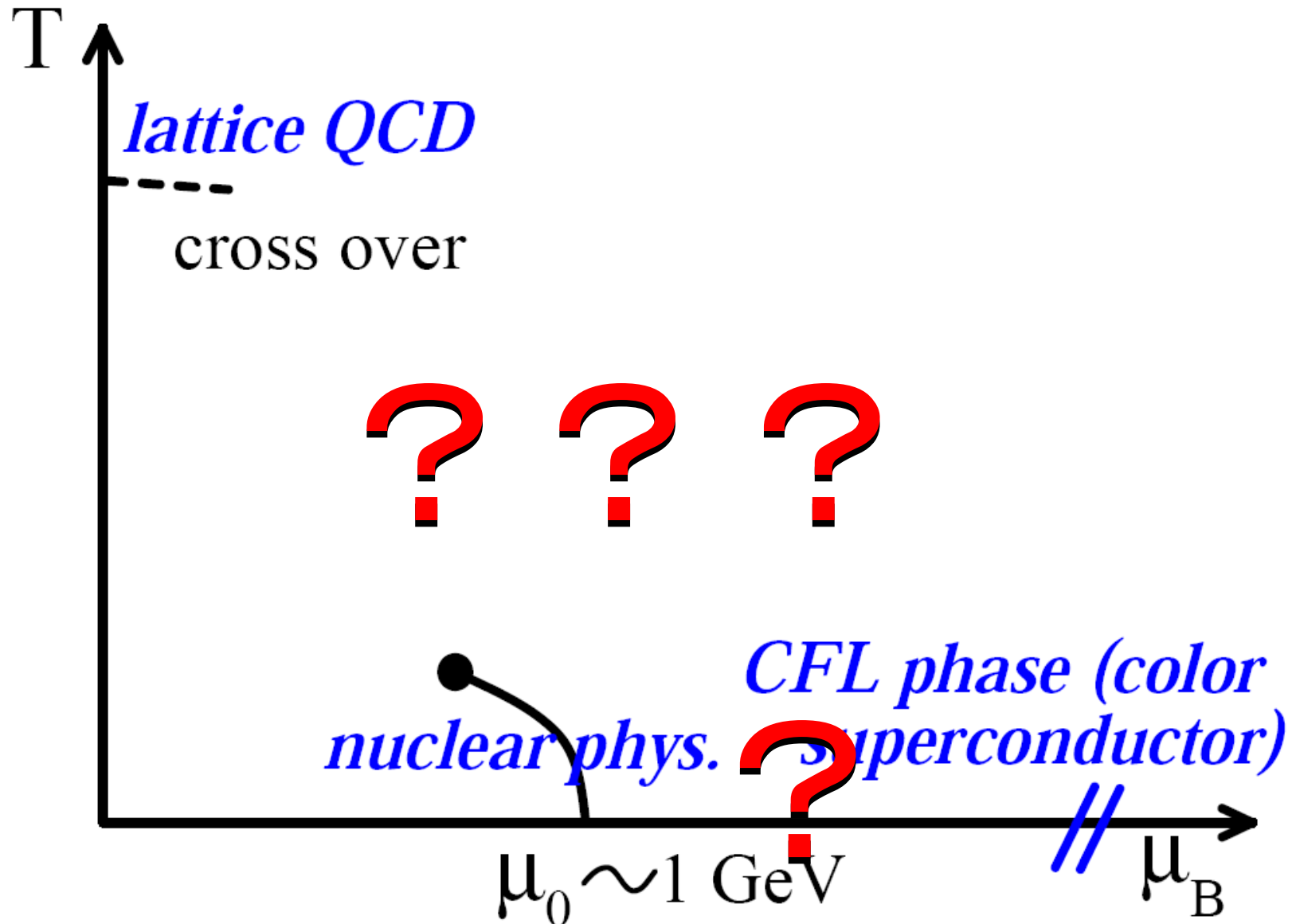
- Early Universe:  $T \approx 2 \times 10^{12} K$   
cf. the core of the Sun:  $T \approx 10^7 K$
- Neutron stars:  $\rho \approx (5 - 10)\rho_0$

- Let's heat/compress ordinary matter!



- Quarks and gluons emerge – Quark Gluon Plasma
- via QGP formation, “dressed”  $\rightarrow$  “undressed” quark

# Phase diagram



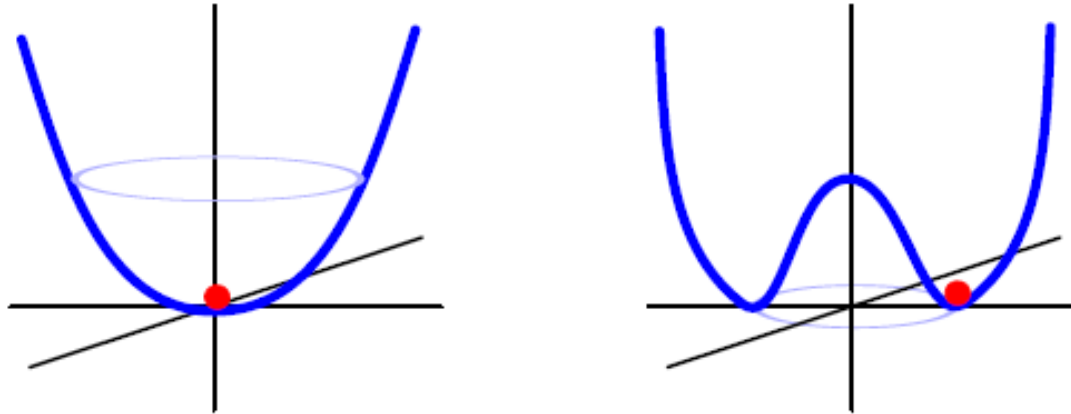
# Outline

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

# **1. Parity doubling**

# Dynamical generation of mass

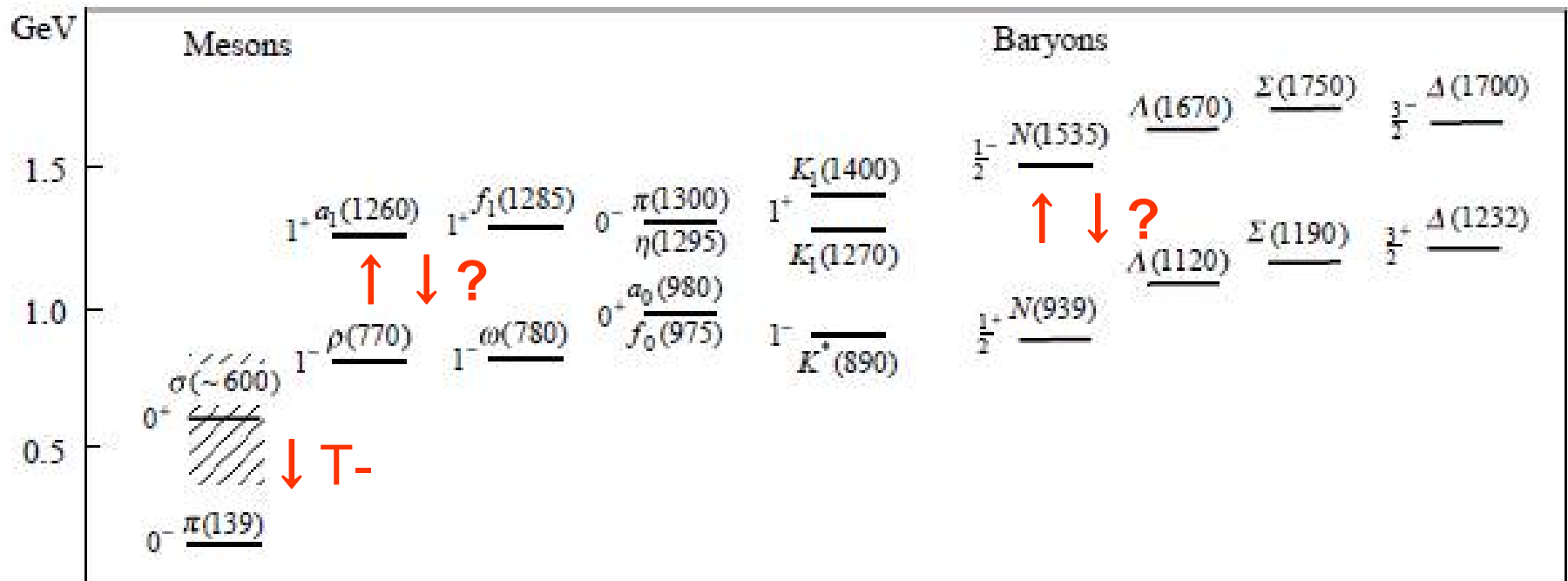
- EW mass and Higgs potential:  $\langle H \rangle \neq 0$
- QCD/strong mass:  $\langle \sigma \rangle \neq 0$



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

# Spectra in a chirally restored world

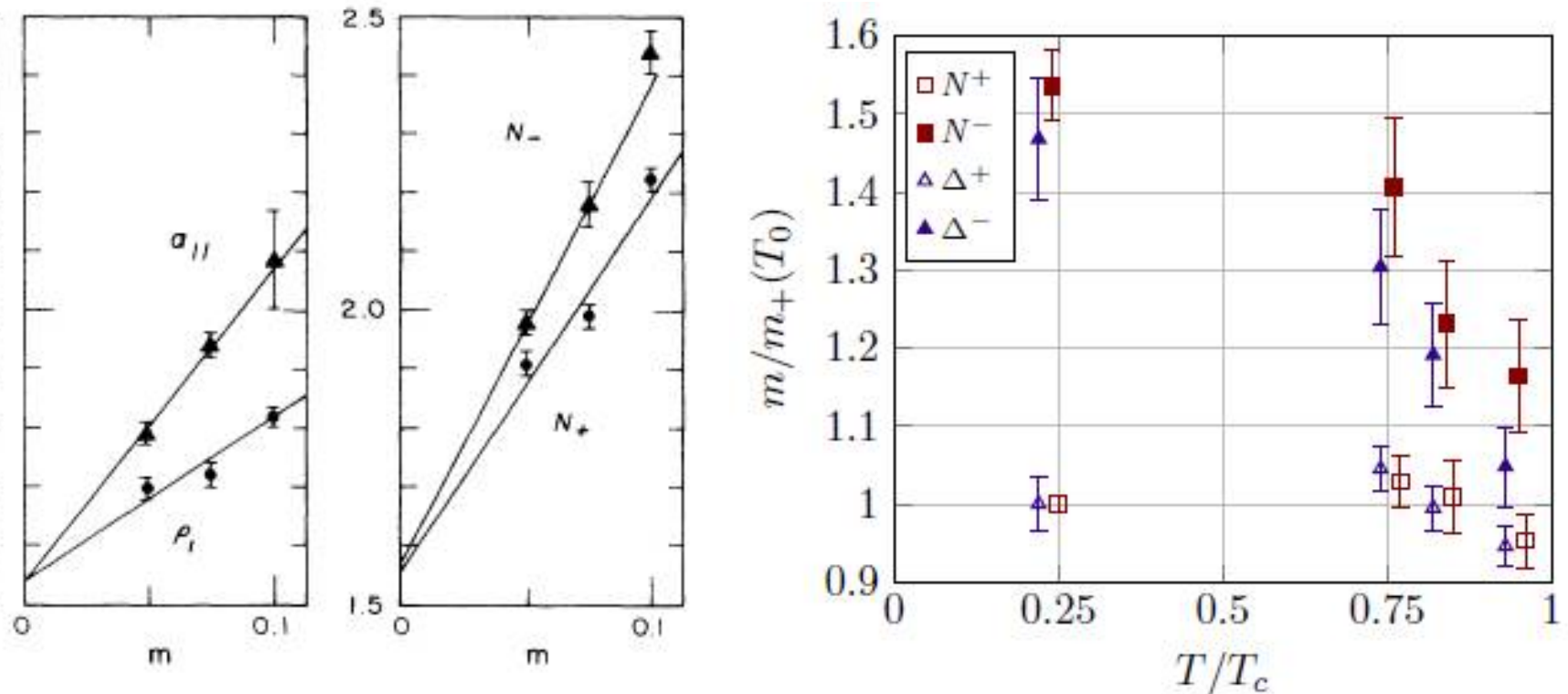
- Lowest scalar meson  $\rightarrow$  O(4) vector with pion
- Parity partners degenerate  $\rightarrow$  chiral partners
- QCD ground-state particles: pions & nucleons



# Lattice QCD tells us ...

❑ Spatial correlations [DeTar-Kogut, 1987]

❑ Temporal correlations [FASTSUM Coll., 2015-17:  
mpi $\approx$ 400 MeV, mk $\approx$ 500 MeV, Wilson fermions, Tch=185 MeV]



vs.  $M_n \approx 3 \times M_q$



# Non-SCB mass of nucleons

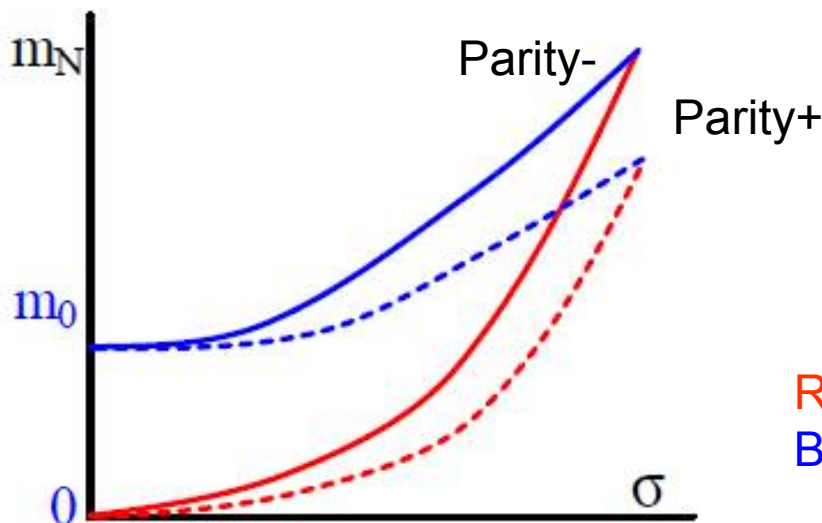
□ SU(2) chiral transformation of 2 nucleons

→ how to assign 2 indep. rotation to them?

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

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

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



[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  $T_c$  [Miller, 2007: lattice EoS]
- in nuclear matter: reduced by 5% at normal  $\rho$  [Cohen et al. 1995: Feynman-Hellmann theorem & low-density approx.]

□ How large is  $m_0$ ? --- not conclusive!

- Models: 300-800 MeV
- Lattice (FASTSUM): 800-900 MeV

✓  $m_0 \approx$  a few  $\Lambda_{\text{qcd}}$ , mass diff.  $\approx$  weaker  $m_0$  dep.

# Parity doubling of baryons

- ❑ Baryon octet and decuplet with finite  $m_0$
- ❑ 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

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

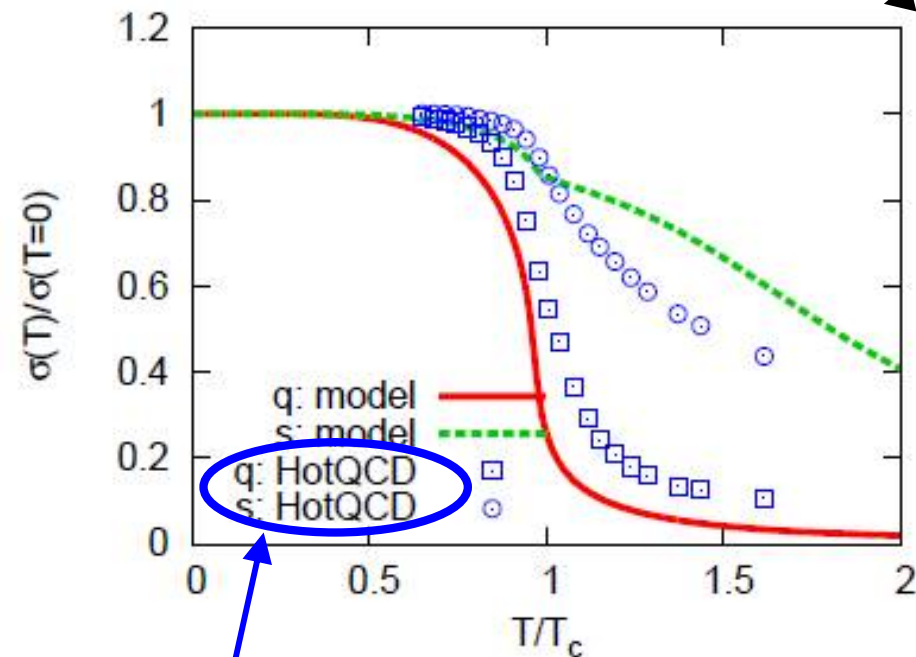
- ❑ Mass relations [CS, 2018)]

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

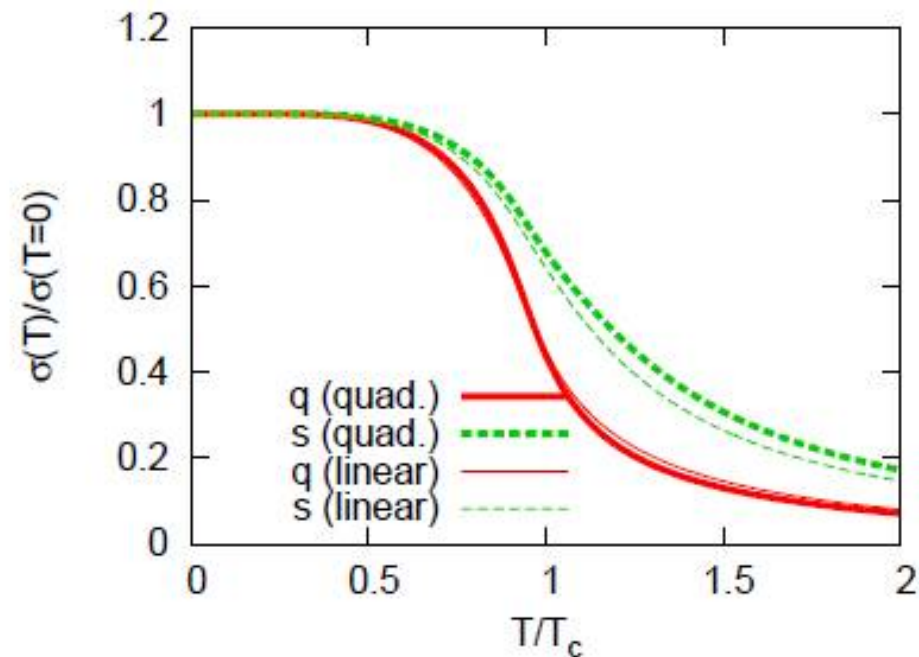
Light-quark condensate    Strange-quark condensate

# Chiral condensates

- ❑ Quark condensates from a model vs. LQCD
- ❑ Pion mass dependence:  $m_{\pi} = 140, 400 \text{ MeV}$



Lattice QCD w/ physical  $m_{\pi}$



# Chiral model vs. LQCD (FASTSUM)

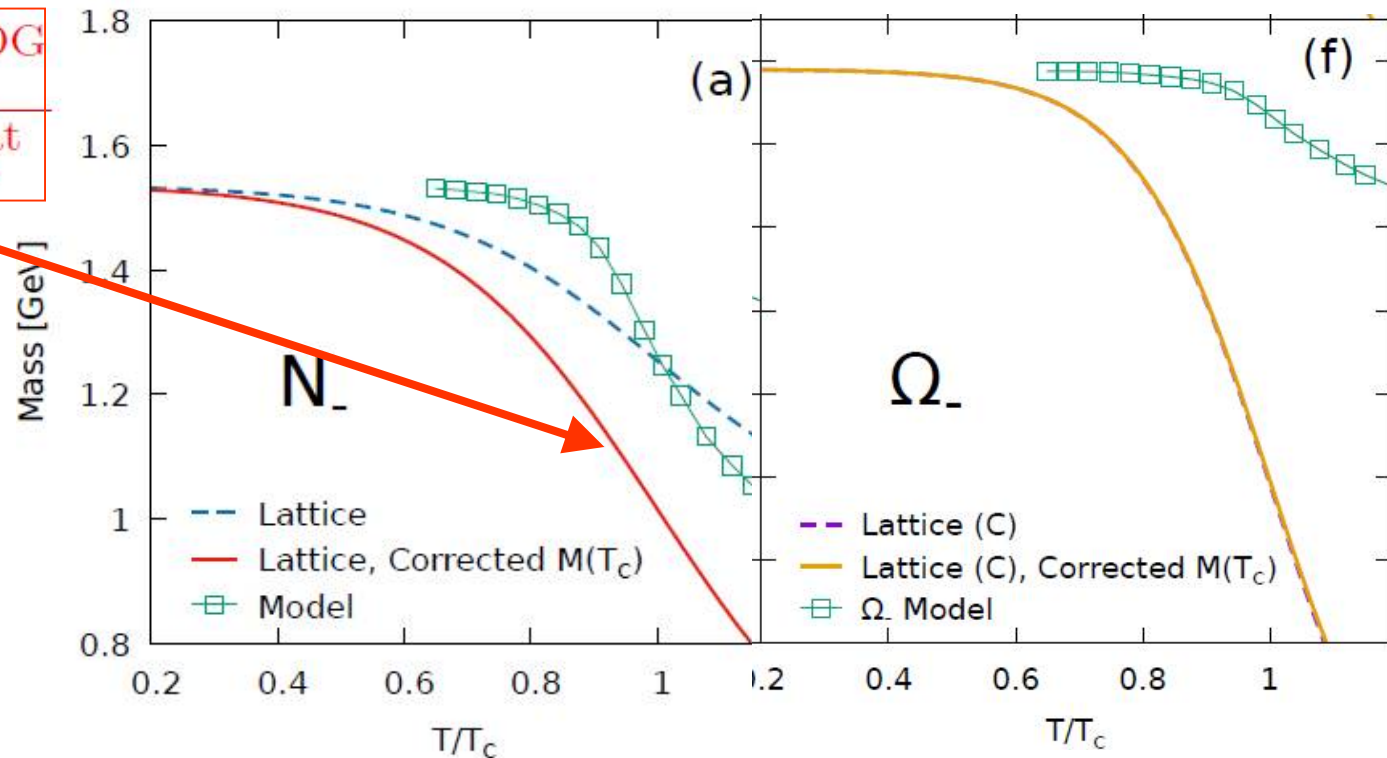
❑ Strong mpi dependence; SU(2+1) vs. SU(3)

❑ Fitting the LQCD masses [Aarts et al., 2017]

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

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

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



**Any imprint in EoS?**

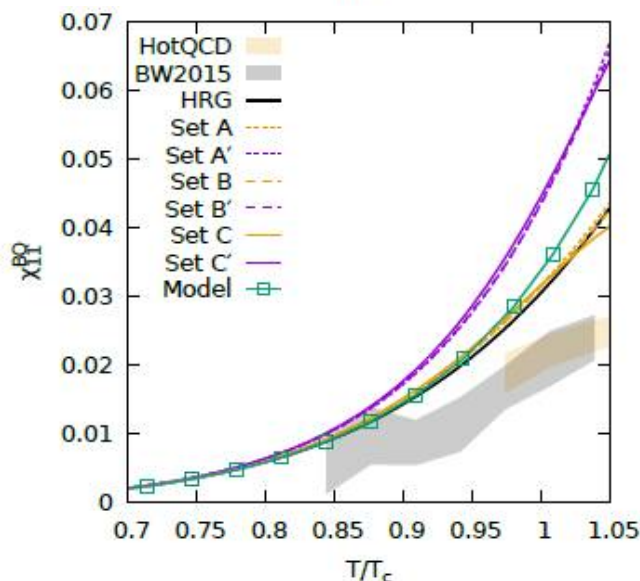
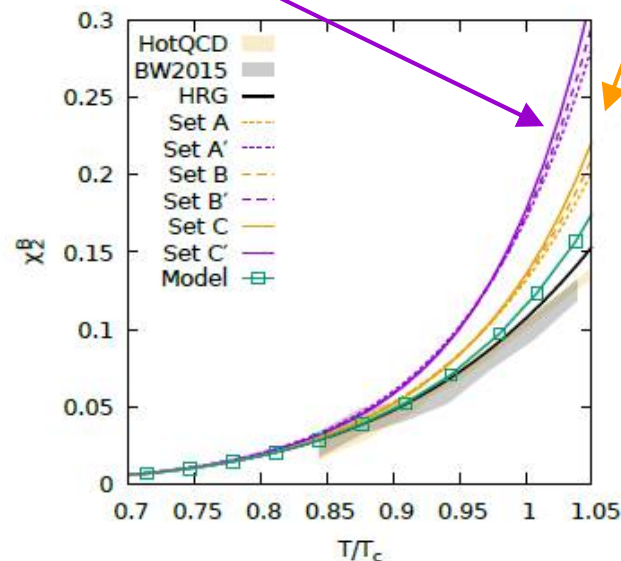
# Signal of chiral symmetry restoration

- ❑ Lattice QCD shows clearly  $\langle q\bar{q} \rangle$  dropping!
- ❑ More deviation from HRG in higher-order fluctuations  $\rightarrow$  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?  $\rightarrow$  baryon number fluctuations.

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

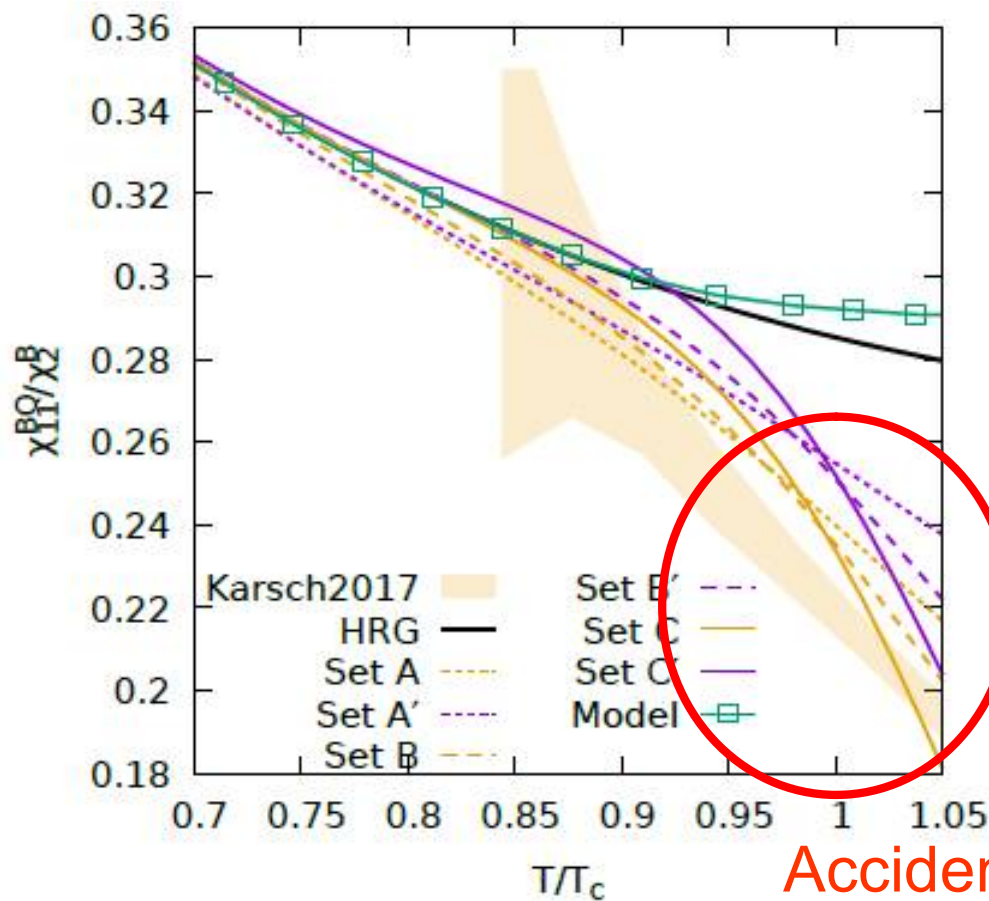
uncorrected

# 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

$$\Omega = \Omega_0 + \Omega_{\text{int}}$$
$$\Delta \ln Z = \int dE e^{-\beta E} \frac{1}{4\pi i} \text{tr} \left[ S^{-1} \overleftrightarrow{\frac{\partial}{\partial E}} S \right]_c$$

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

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

Dynamical information

# What is missing? --- finite width

□  $K^0^*/\kappa(800)$  meson: chiral partner of kaon

NOTE: omitted from PDG summary table

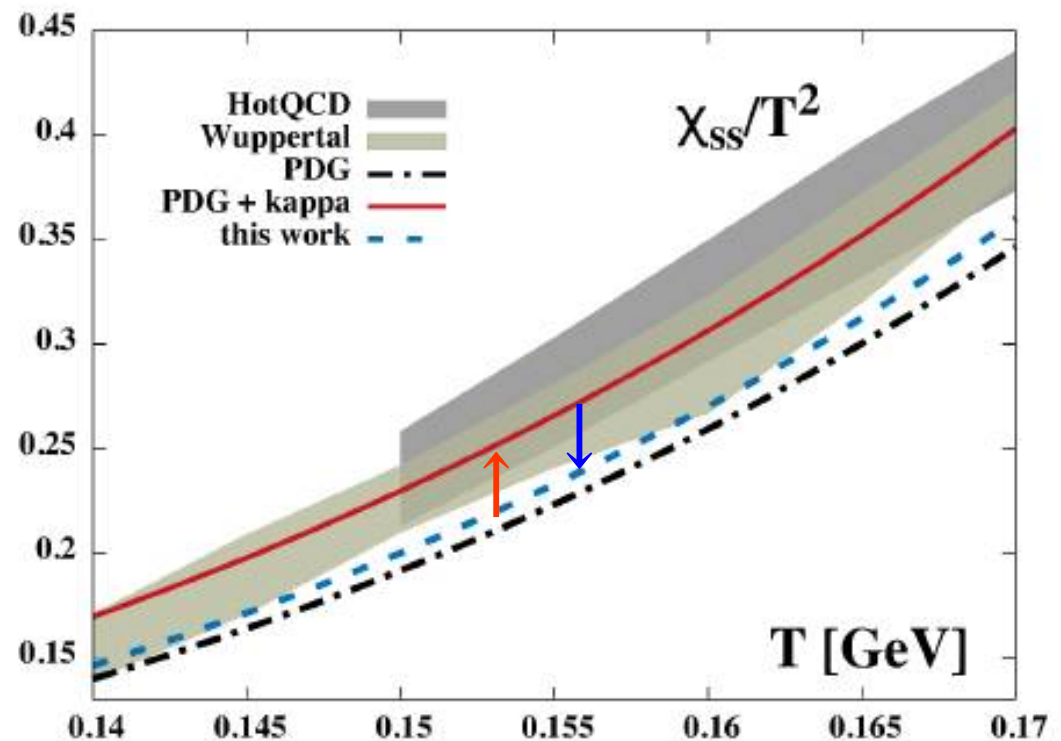
□ S matrix approach [Friman et al. 2015]

✓ Empirical  $\pi$ -K phase shift from experiment

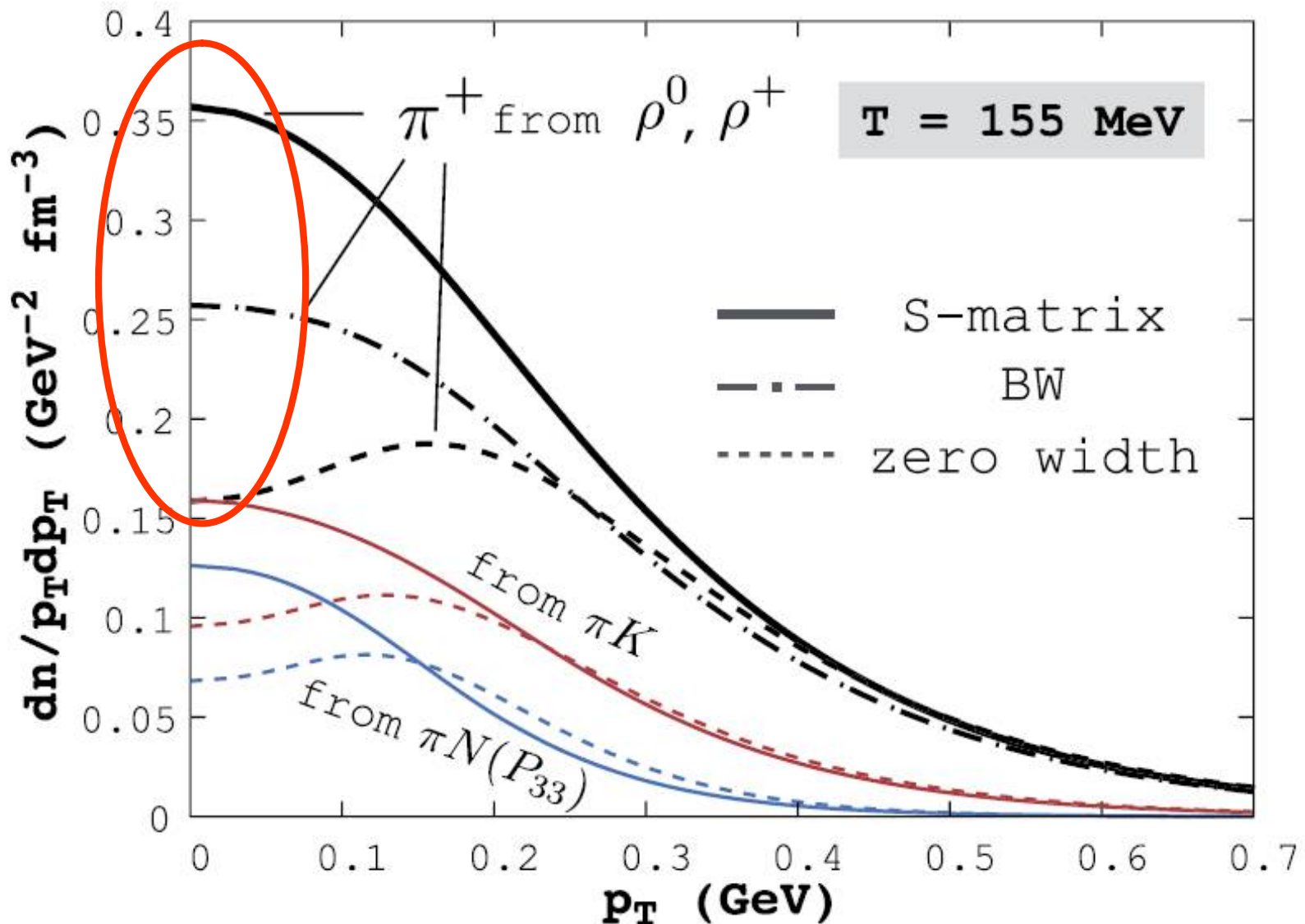
$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\text{int}}$$

cf. HRG

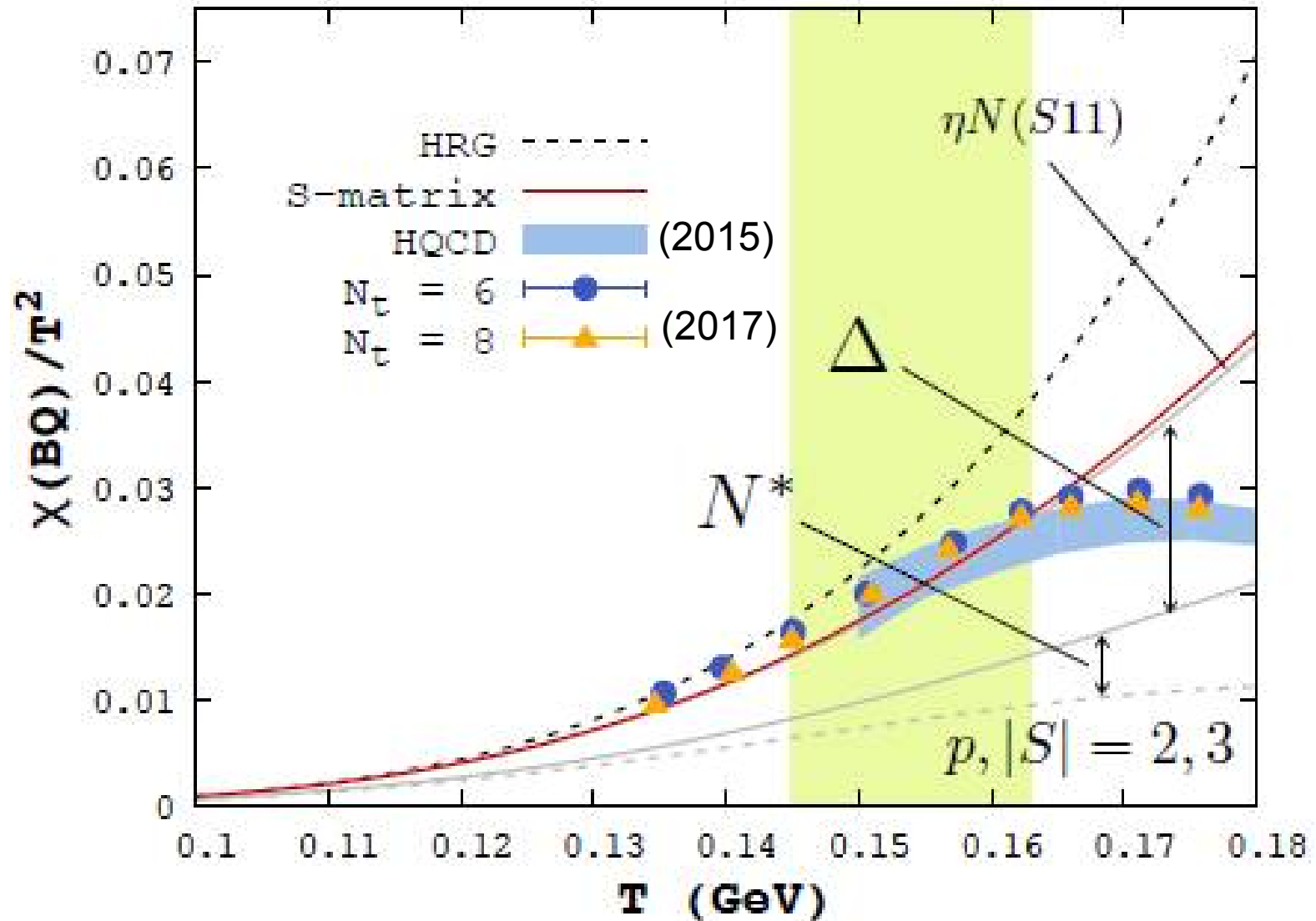
$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\text{res}}$$



# $\rho$ -meson width vs. pion pt-dist.



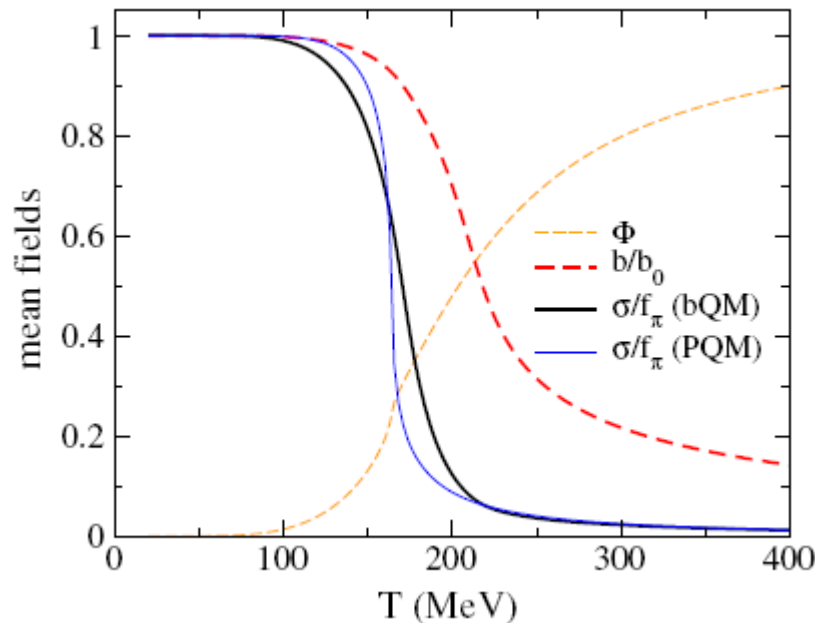
# Pi-Nucleon system [Lo et al., 2018]



### **3. Model for Cold Dense Matter**

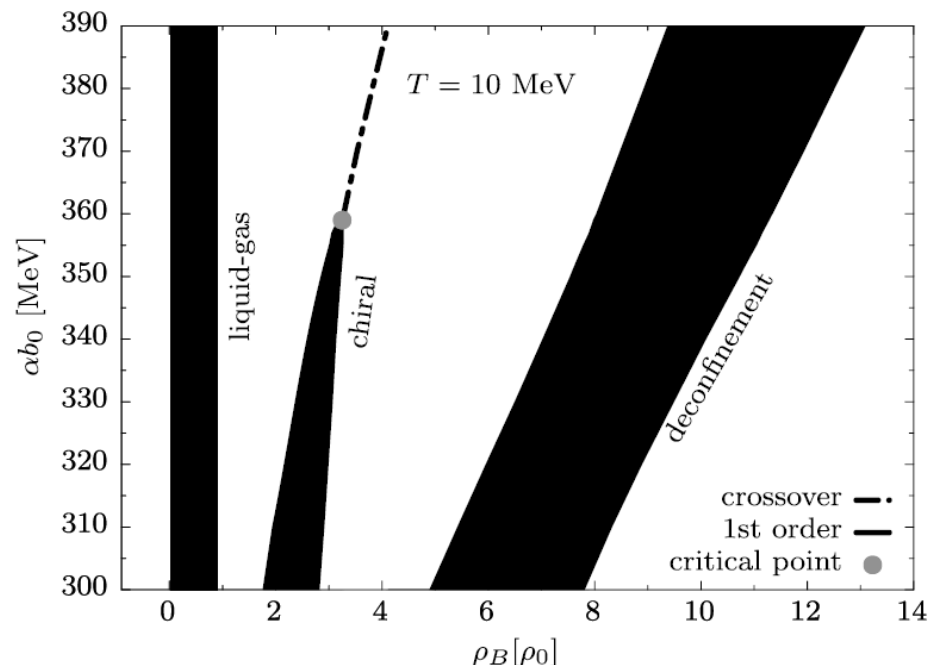
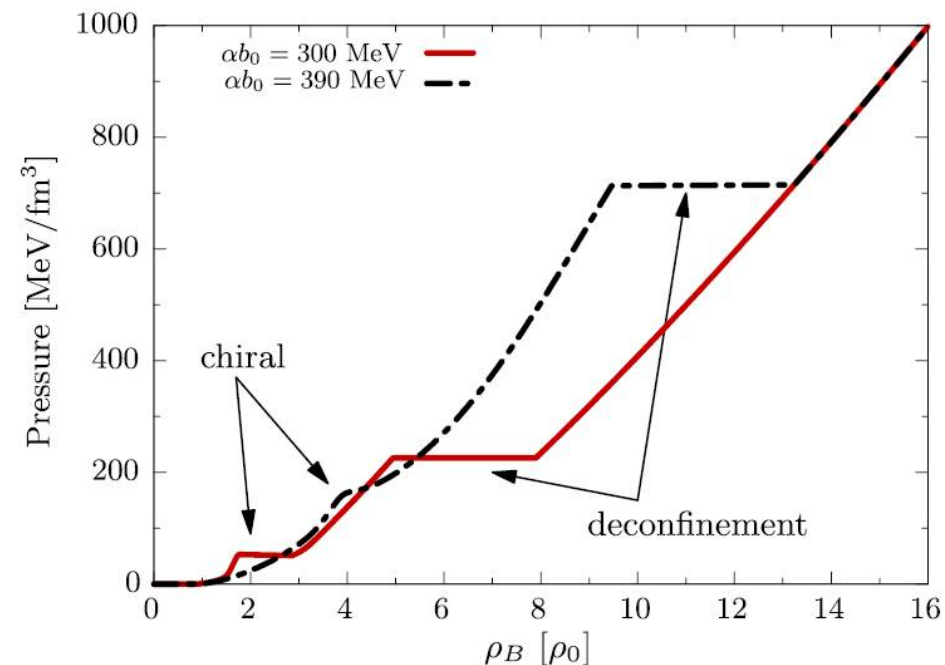
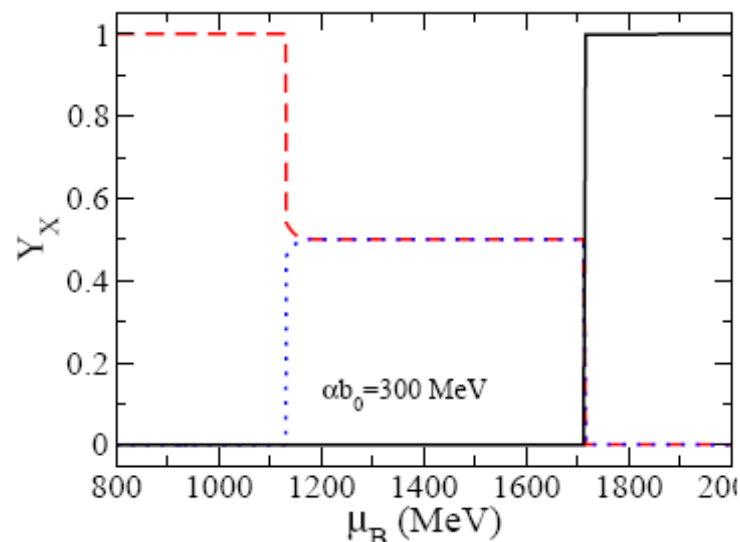
# Quark-nucleon hybrid model

- ❑ 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
- ❑  $T \neq 0$ ,  $\mu = 0$  thermodynamics vs. PQM



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

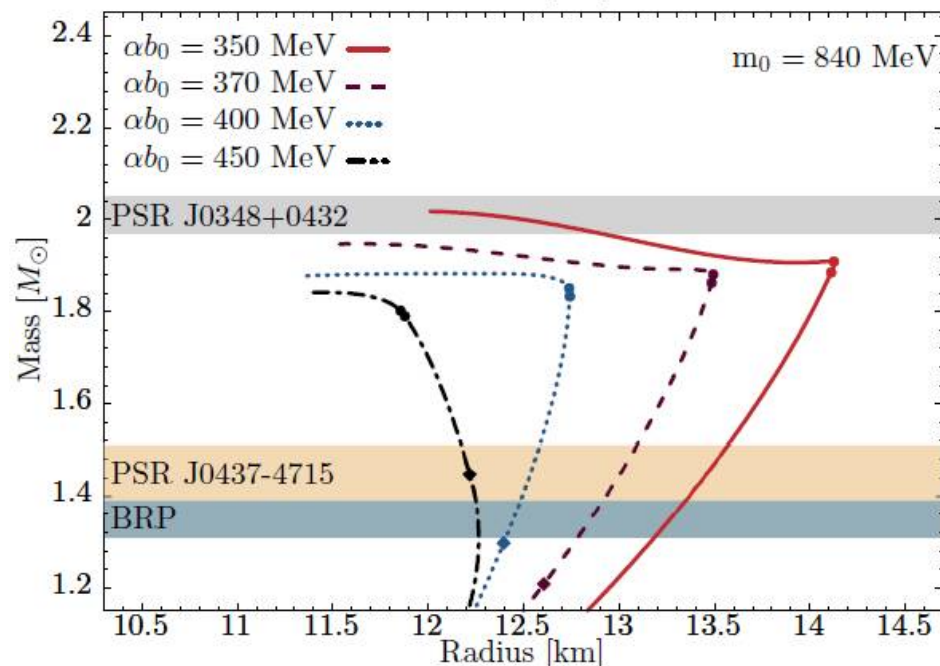
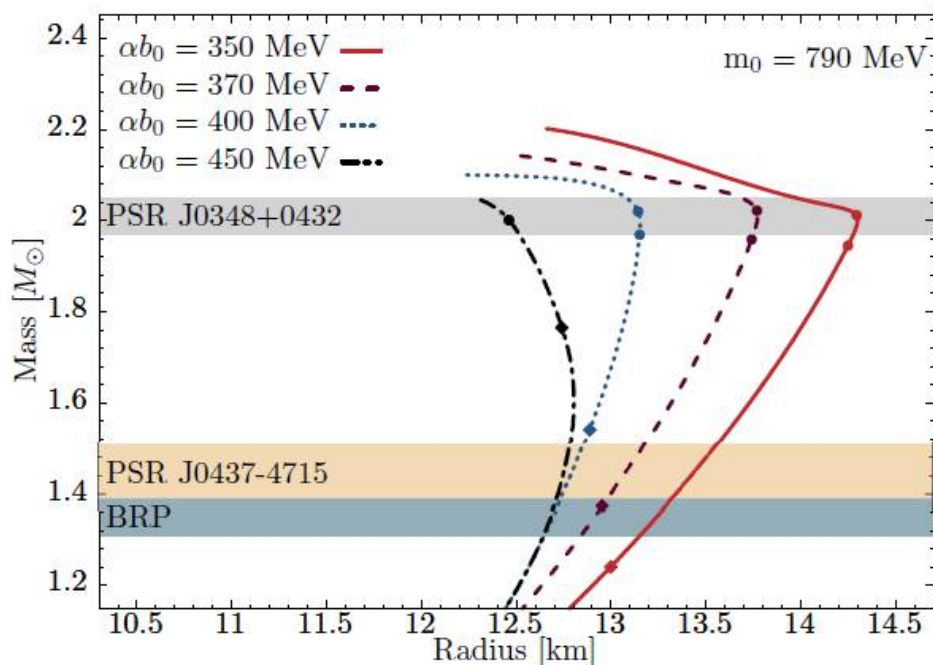
# Onset of different fermions





# Neutron stars

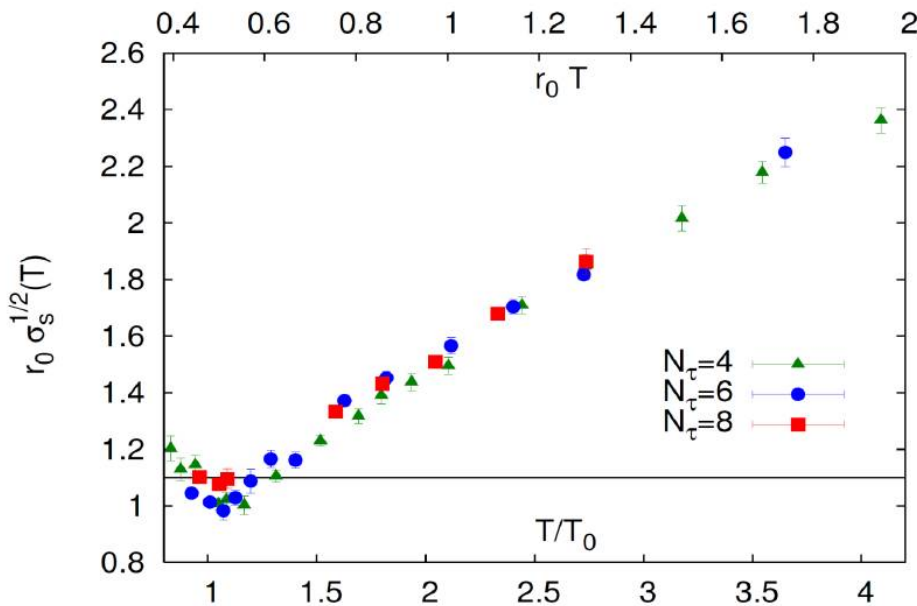
- $\beta$ -equilibrium and charge neutrality
- Constraints on the mass and compactness of a star  $\rightarrow$  **hadronic scenario w/o deconf. quarks**



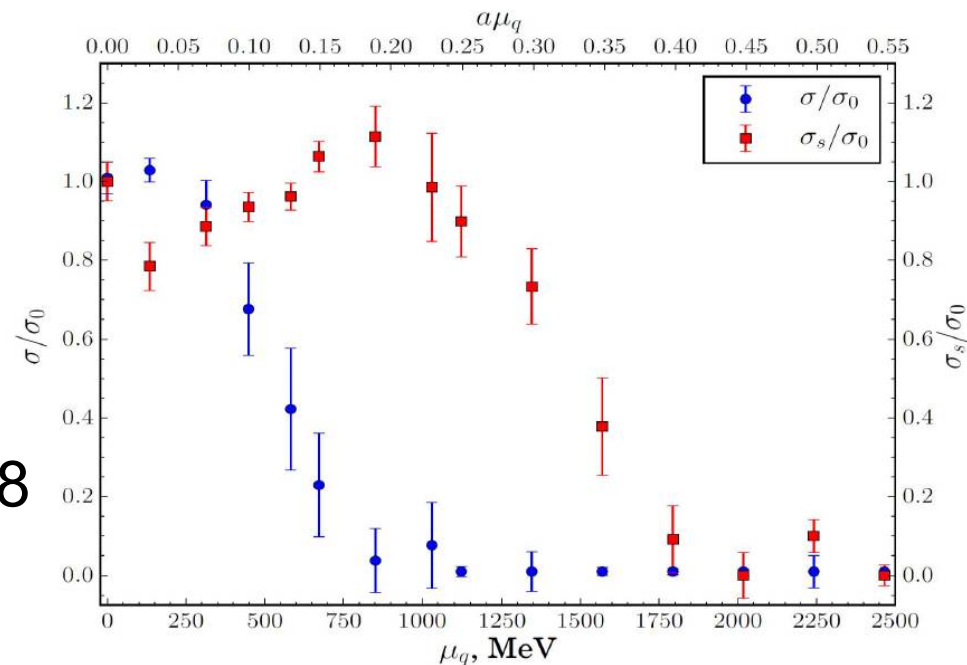
# Fate of confinement: hot vs. dense

□ Non-pert. color-mag. sector  $\rightarrow$  perturbative!

$\leftarrow$  SU(3)<sub>c</sub>,  $T > 0$ ,  $\mu = 0$ ;  
Cheng et al., PRD 2008  
[mpi = 220 MeV].



$\rightarrow$  SU(2)<sub>c</sub>,  $T = 0$ ,  $\mu > 0$ ;  
Bornyakov et al., JHEP 2018  
[mpi = 740 MeV].



# 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  $\approx$  chromo-magnetic sector  
Cf.  $SU(2) : \sigma \rightarrow 0$  at large  $\mu$
- ◆ Interplay between CSB and confinement
- ◆ Higher-lying states ... vs. Holographic QCD?
- ◆ Toward more realistic description of QCD