Signals for Chiral Symmetry Restoration

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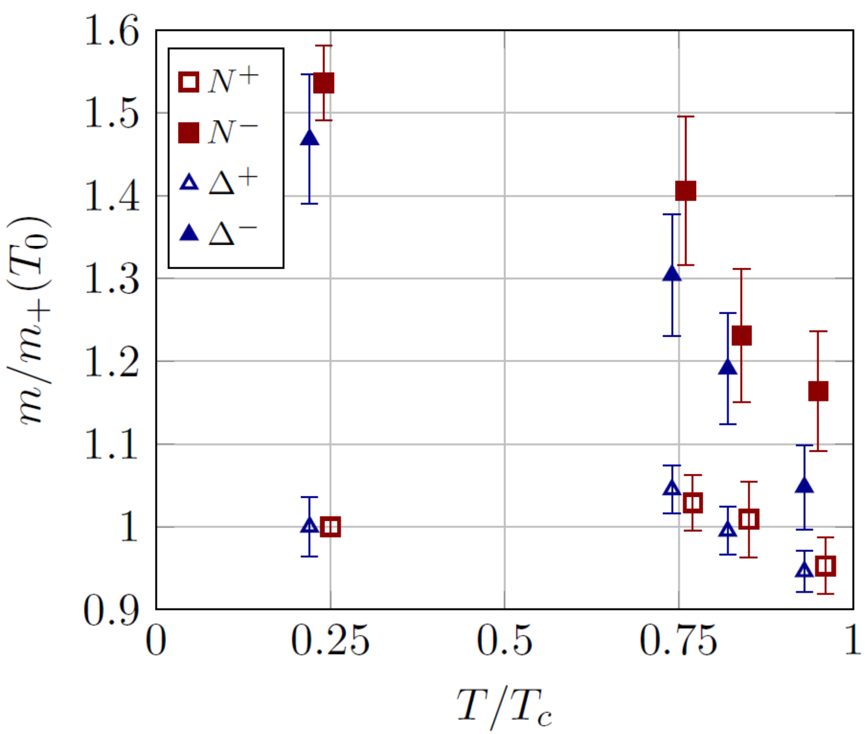
Fate of hadrons in matter

Unbroken chiral symmetry → **parity doubling**

- ❑In reality, the mass different is huge.
- ❑Degenerate parity partners at high T/ρ_B as signatures of chiral symmetry restoration!



Temporal masses from LQCD at zero density, FASTSUM Collab. (Aarts et al.), 2017-19

Refs. Marczenko, Redlich, CS, Phys.Rev.D (2023); Koch, Marczenko, Redlich, CS, arXiv:2308.15794

BARYON NUMBER FLUCTUATIONS

Net proton vs. baryon number fluct.

χ_2^B sensitive to the QCD phase transition

→Net proton fluctuations as a good proxy for net baryon fluctuations: folklore

✓Nucleon parity doublet: N(939) & N*(1535)

- Mean: $\langle N_B \rangle \equiv \kappa_1^B = \kappa_1^+ + \kappa_1^-$
- Variance: $\langle \delta N_B \delta N_B \rangle \equiv \kappa_2^B = \kappa_2^{++} + \kappa_2^{--} + 2\kappa_2^{+-}$
- Cumulants → susceptibilities:

$$\kappa_n^B = VT^3 \chi_n^B \qquad \chi_2^B = \chi_2^{++} + \chi_2^{--} + 2\chi_2^{+-}$$

- Sign and strength of χ_2^{+-}?

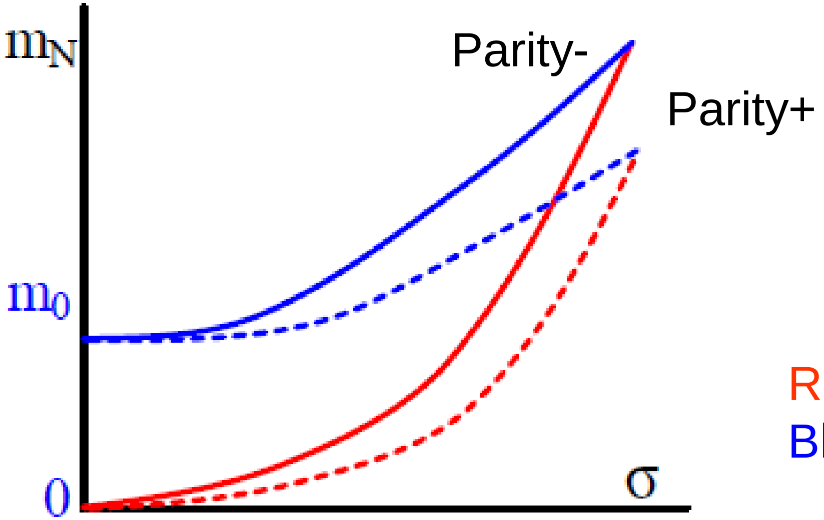
DeTar-Kunihiro/Parity doublet model

- SU(2) chiral transformation of 2 nucleons

  → how to assign 2 indep. rotation to them?

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

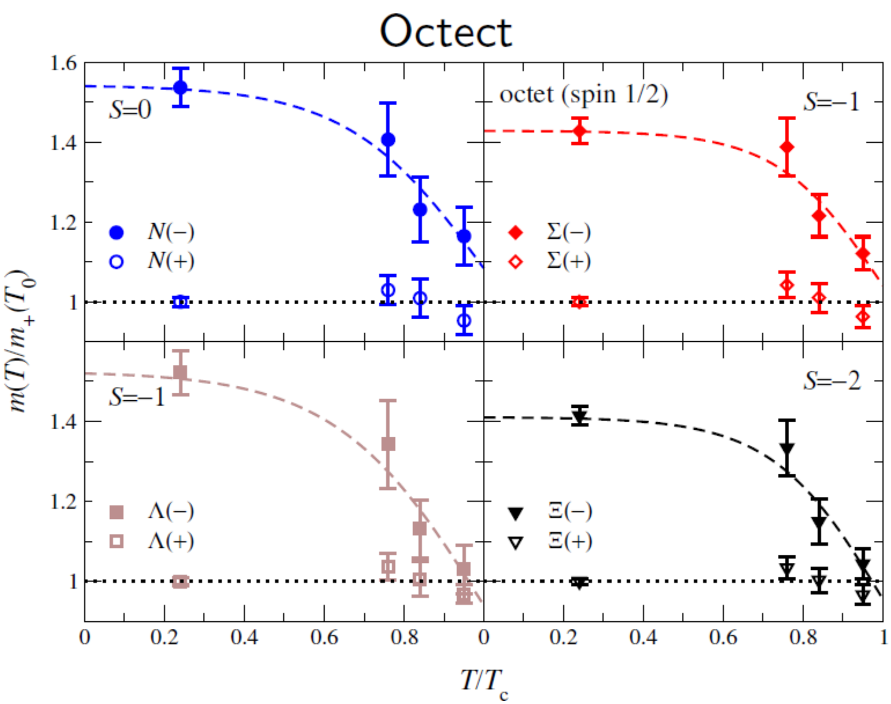
$$\mathcal{L}_m = m_0 \left(\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2 \right) \;\Rightarrow\; m_{N_\pm} = \frac{1}{2} \left[\sqrt{c_1 \sigma^2 + 4 m_0^2} \mp c_2 \sigma \right]$$

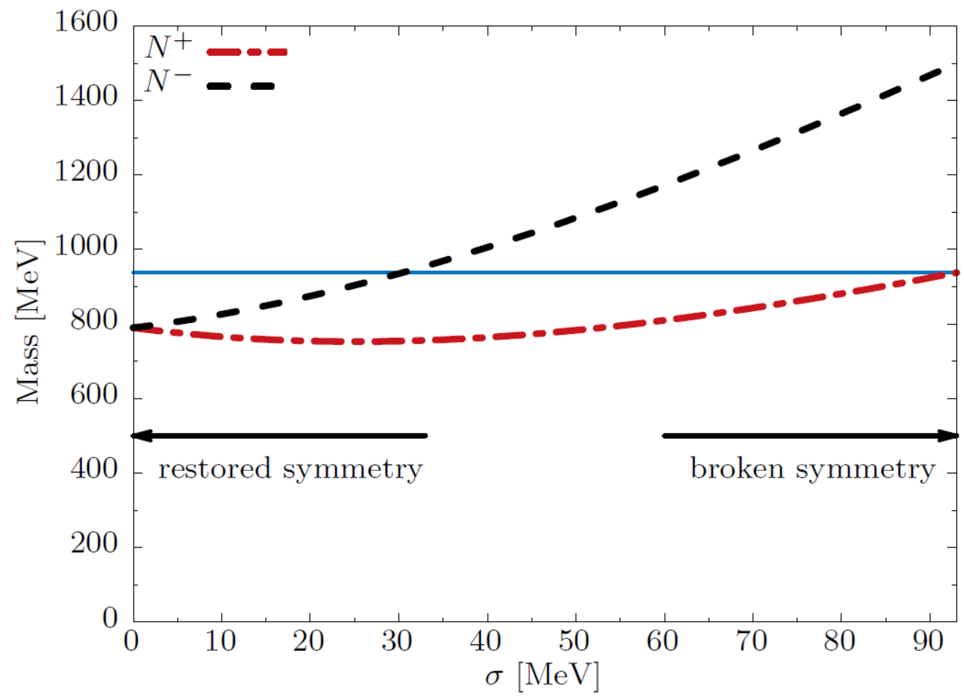


[DeTar-Kunihiro, 1989]

Red: standard
Blue: Mirror

Parity doubling of baryons





- ❑Lattice QCD at zero μ [Aarts et al., 2016]
- ❑Survival mass $m_N \approx m_0 \neq 0$ [DeTar, Kunihiro, 1989]

$$M_\pm = \sqrt{m_0^2 + c_1^2\sigma^2} \mp c_2\sigma \xrightarrow{\sigma \to 0} m_0$$

Thermodynamics of parity doubler

Linear sigma model for (σ,π), ω, (N,N*) & MF

- New chemical potentials $\mu_{+,-}$ for N,N*
- Set at the end $\mu_{\pm} = \mu_N = \mu_B - g_\omega \omega$
- Susceptibilities from thermodynamics pot.

$$\Omega = \Omega_+ + \Omega_- + V_\sigma + V_\omega$$

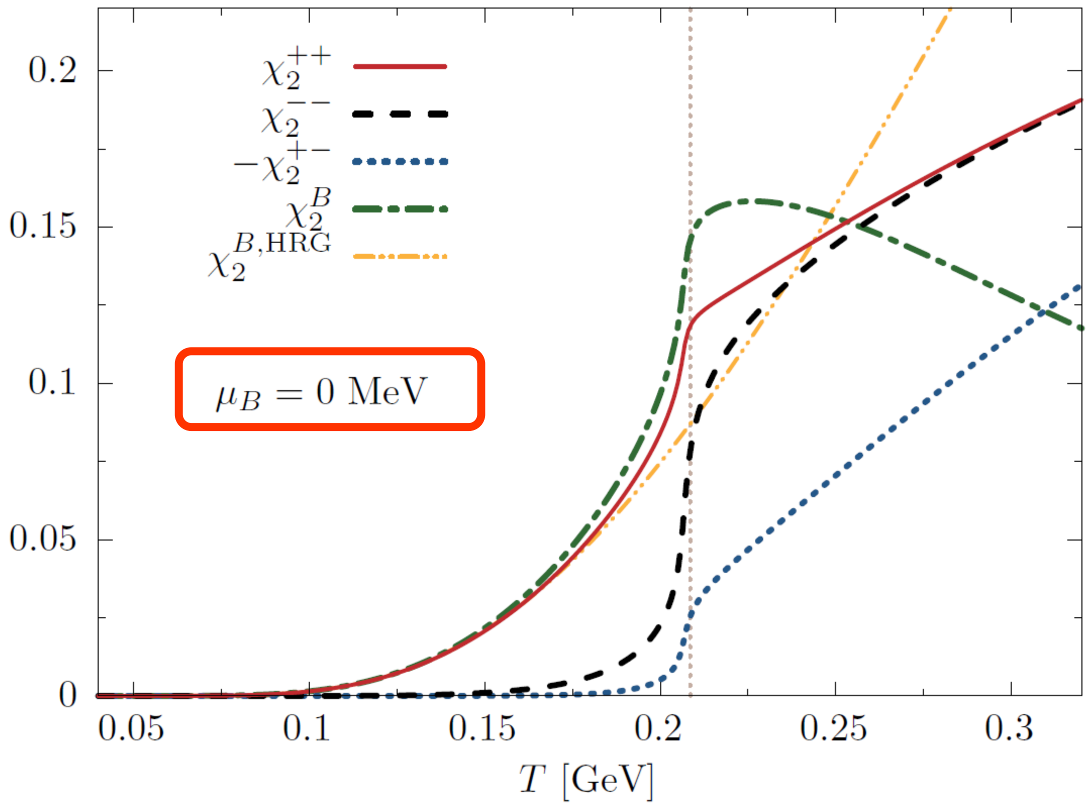
$$0 = \frac{\partial \Omega}{\partial \sigma}$$

$$0 = \frac{\partial \Omega}{\partial \omega}$$

$$\chi_2^{\alpha\beta} = \frac{1}{VT^3}\kappa_2^{\alpha\beta} = -\left.\frac{\mathrm{d}^2\hat{\Omega}}{\mathrm{d}\hat{\mu}_\alpha \mathrm{d}\hat{\mu}_\beta}\right|_{T,\mu_\alpha=\mu_\beta=\mu_N}$$

$$\chi_2^B = \chi_2^{++} + \chi_2^{--} + 2\chi_2^{+-}$$

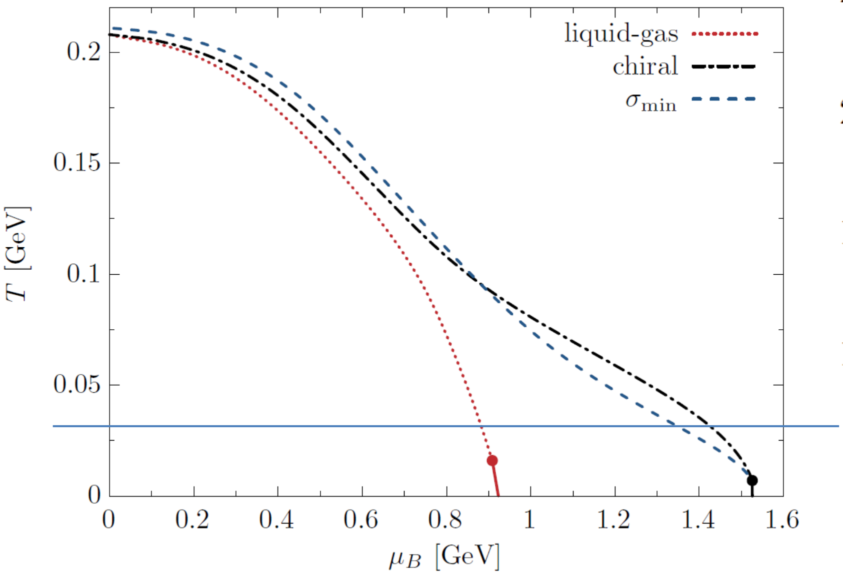
Correlations between N & N*

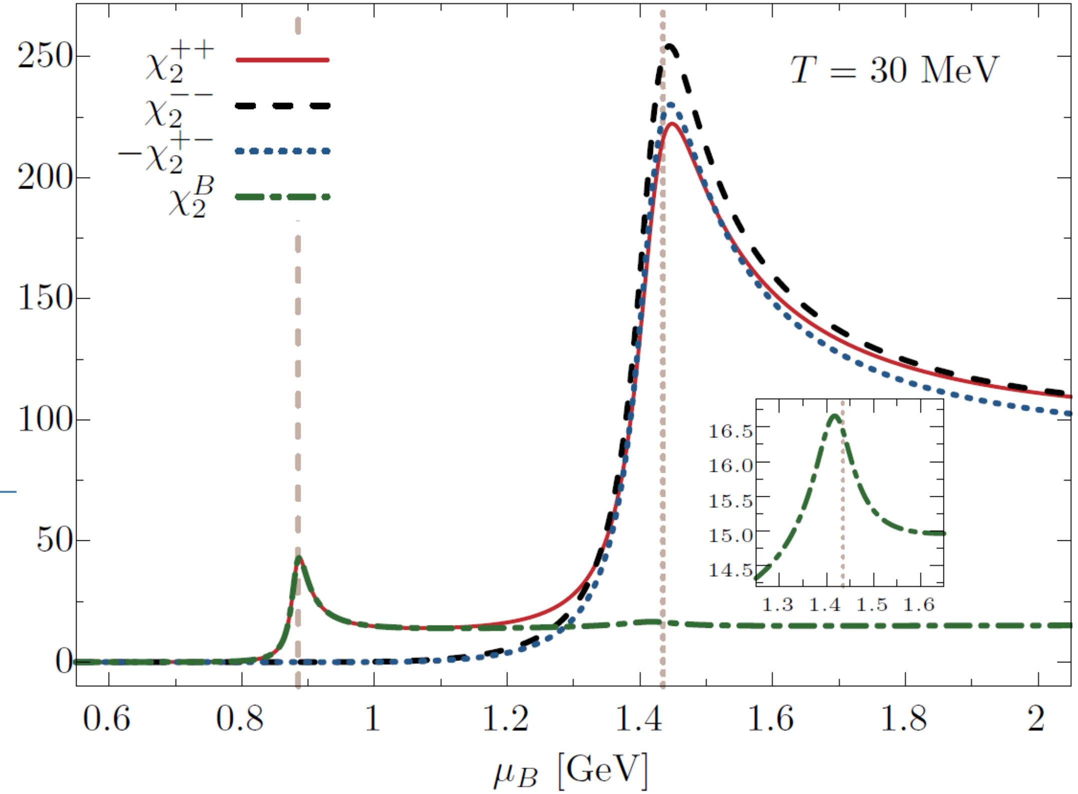


- χ_2^B dominated by positive-parity fluct.
- N* being relevant only near Tc
- χ_2^{+-} sets in only near Tc, and it's **negative**.
- χ_2^{+-} becomes more negative with repulsive int.

Linear sigma model & nucleon parity doubler

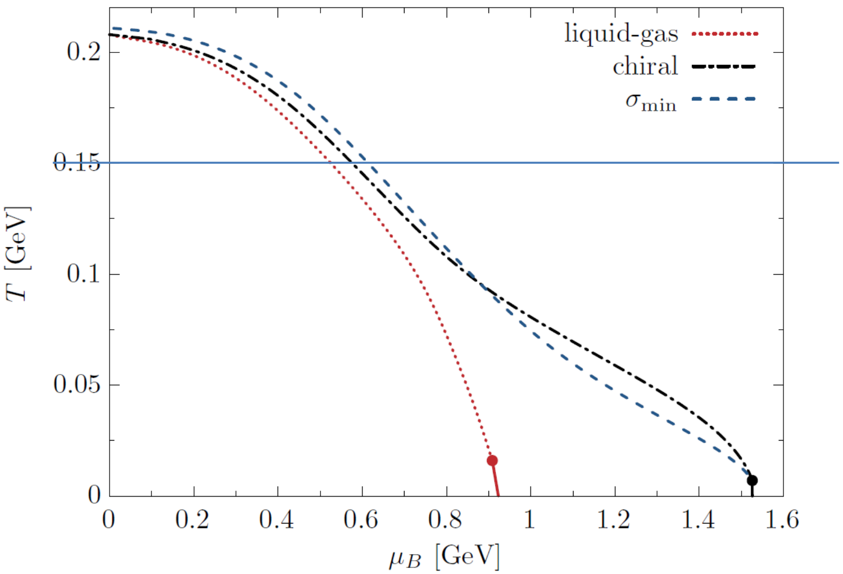
Liquid-gas vs. chiral

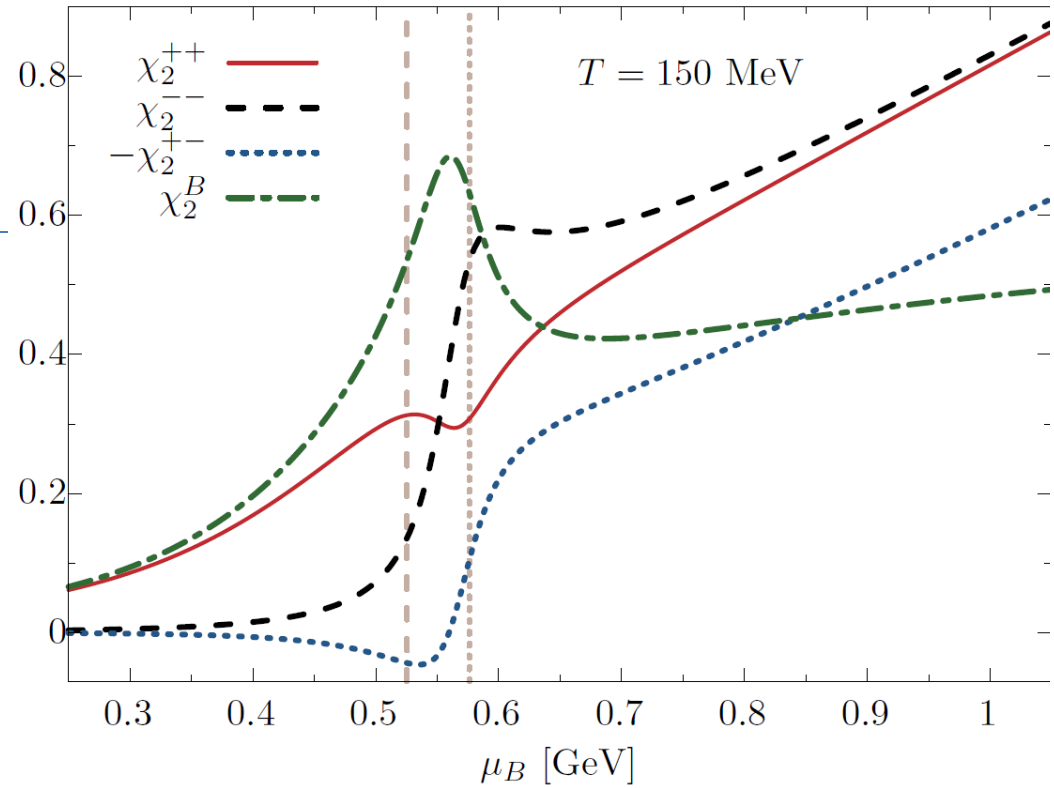




- LG dominated by χ_2^{++}
- Chiral dominated by both, but $\chi_2^{--} > \chi_2^{++}$
- Peaks diminished by χ_2^{+-} ➔ weak signal in χ_2^{B}

Liquid-gas vs. chiral



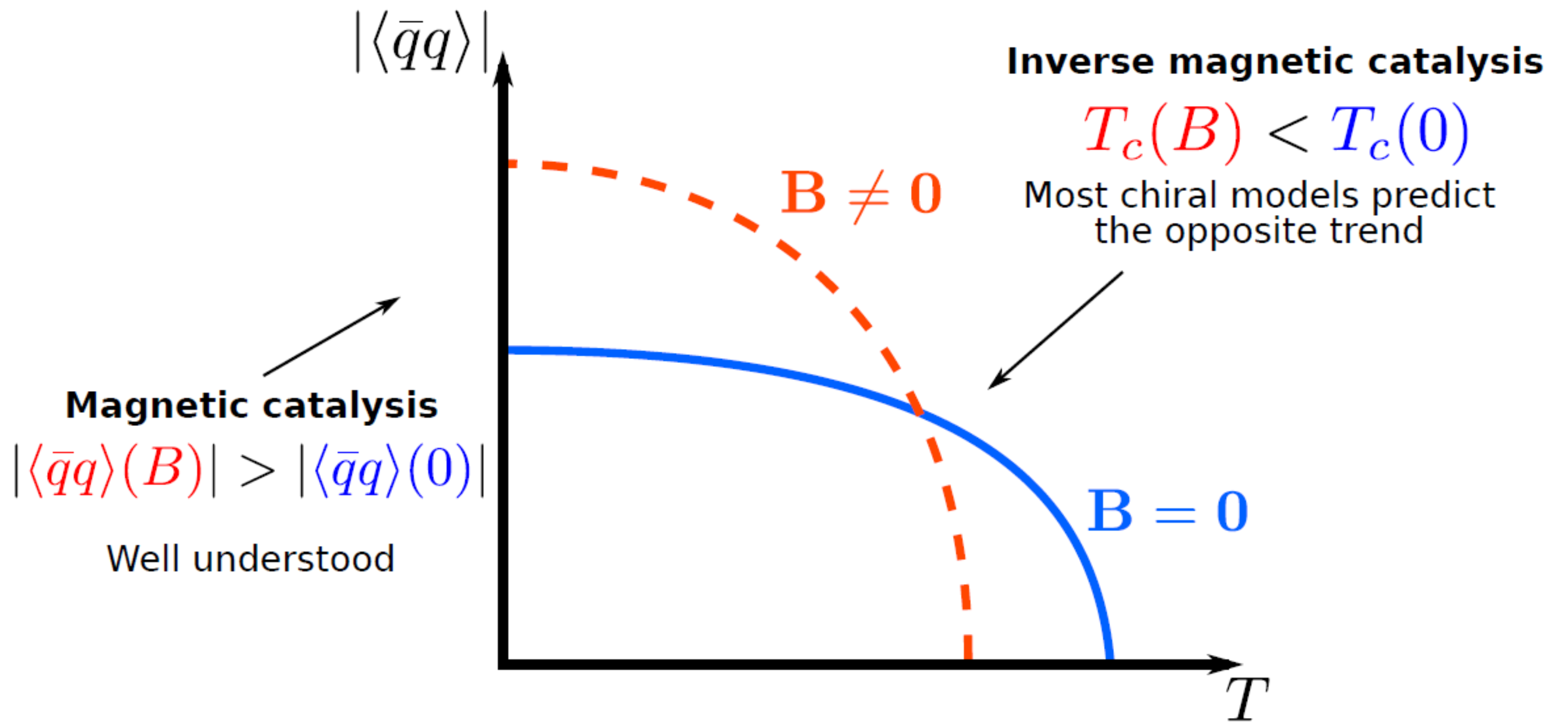


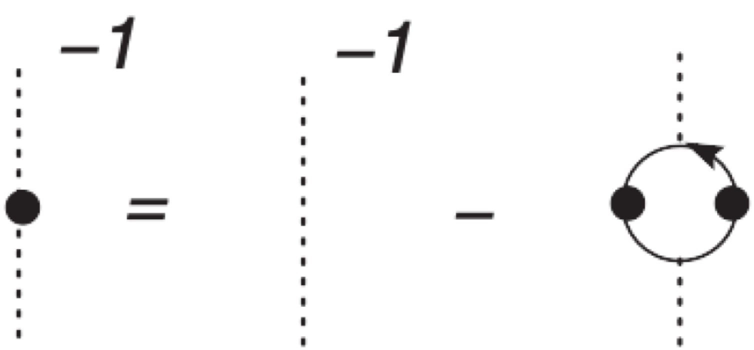
- ❑ Increasing T ➔ 2 peaks getting closer
- ❑ Qualitative difference of χ_2^{++} from χ_2^{--}
- ❑ Stronger signal left in χ_2^{B}

Refs. Lo, Szymanski, Redlich, CS, EPJA (2022); Szymanski, Lo, Redlich, CS, arXiv:2309.03124.

BARYON NUMBER FLUCTUATIONS IN A FINITE MAGNETIC FIELD

The model

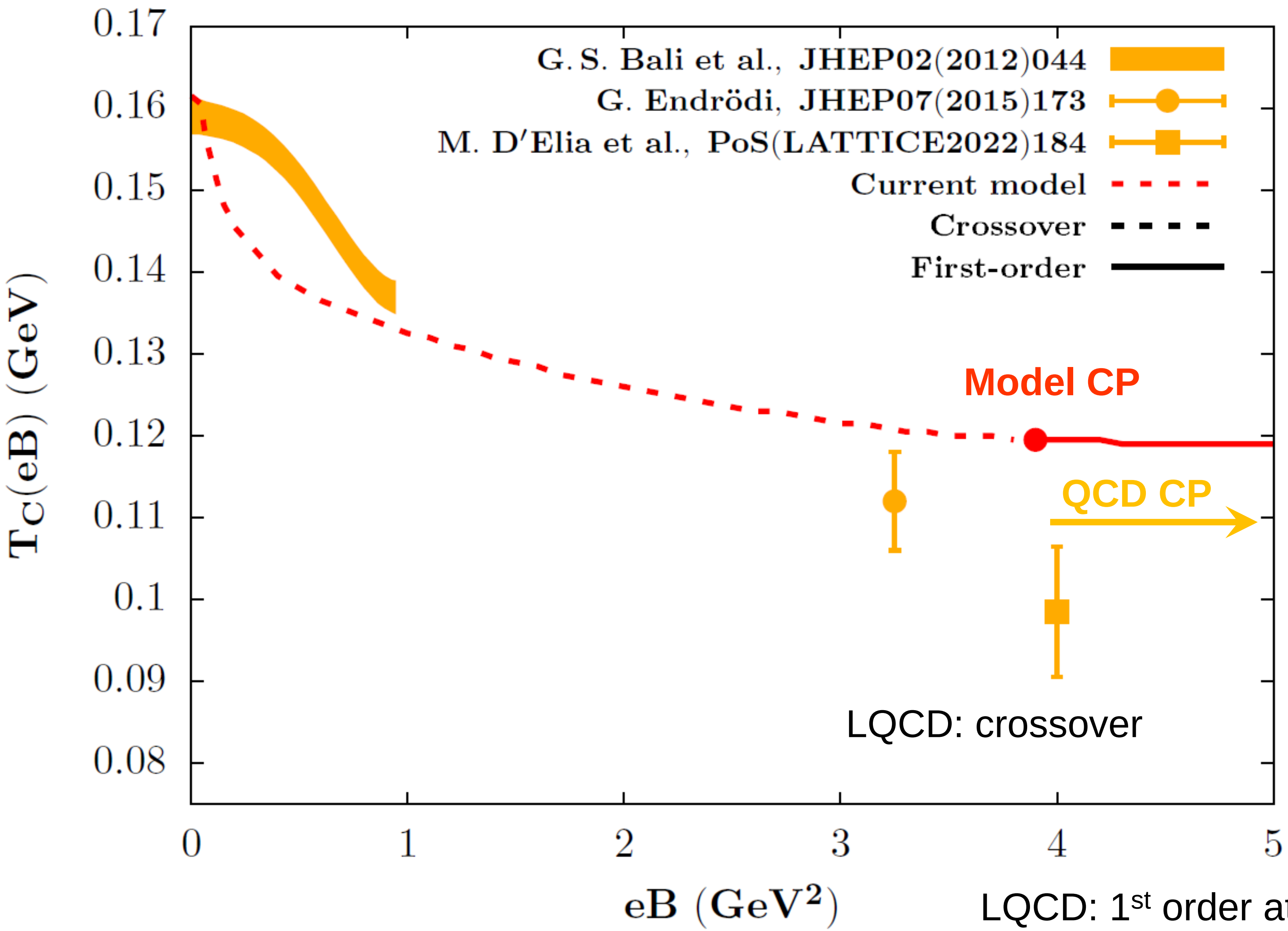




- ❑ Screening of 4-fermi interaction; G → G(T,B)
- ❑ Can capture both MC and inverse-MC.

[Szymanski et al., to appear on arXiv]

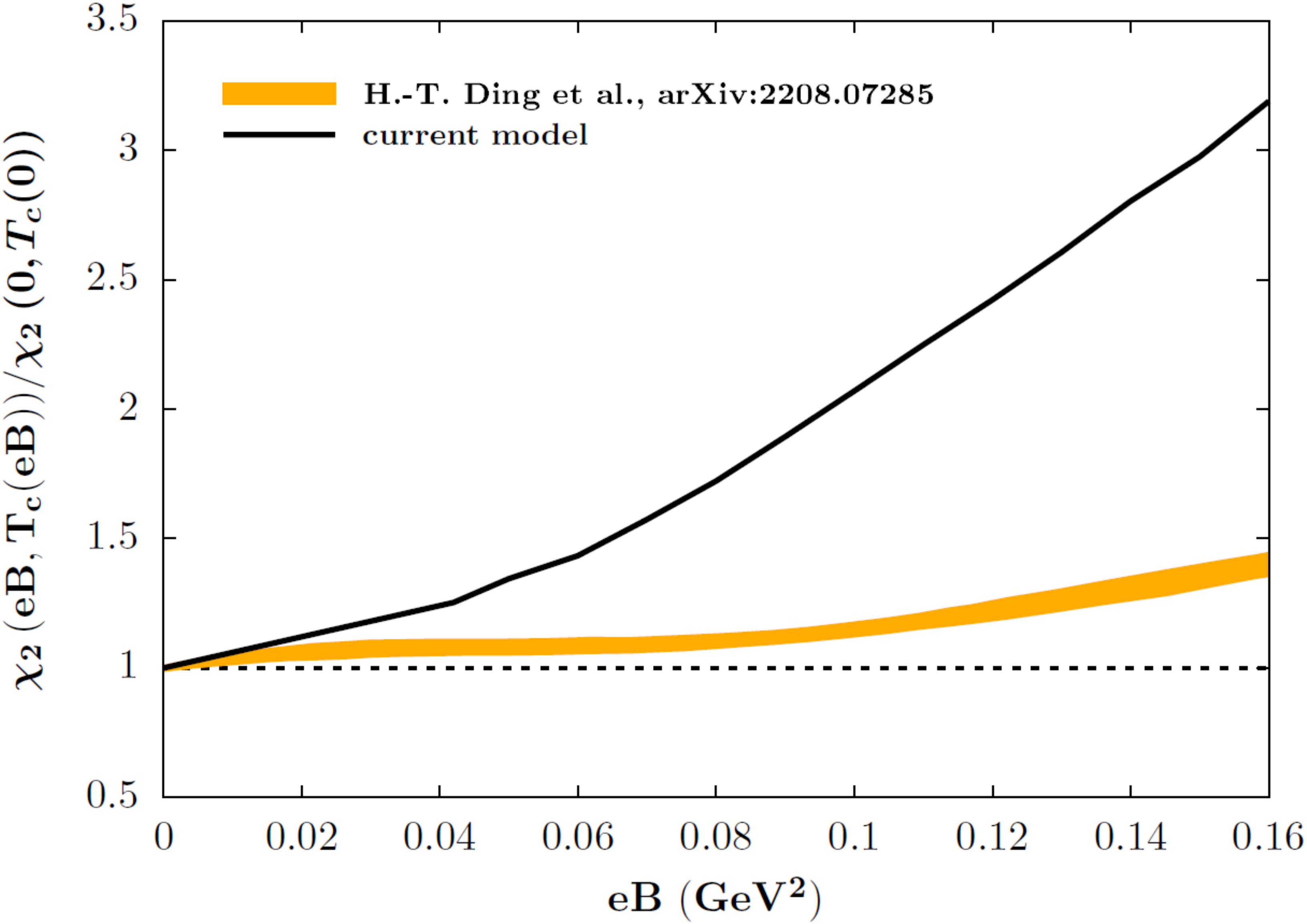
Chiral crossover → CP



LQCD: 1st order at 9 GeV2

[Szymanski et al., to appear on arXiv]

Net-baryon number susceptibility



Ref. Marczenko, Redlich, CS, to appear on arXiv

BARYON NUMBER FLUCTUATIONS IN NEUTRON STARS

Speed of sound

Method: the piecewise-linear parametrization of the speed of sound [Annala et al., Nature, 2020]

$$c_s^2(\mu) = \frac{(\mu_{i+1} - \mu)\, c_{s,i}^2 + (\mu - \mu_i)\, c_{s,i+1}^2}{\mu_{i+1} - \mu_i}$$

- ❑ Construct an ensemble of EoSs in agreement with χEFT and pQCD.
- ❑ Related also to net-baryon number sus. via

$$c_s^2 \equiv \frac{\mathrm{d}p}{\mathrm{d}\epsilon} = \frac{n}{\mu}\frac{1}{\chi}$$

[Marczenko et al., to appear on arXiv]

Curvature of the energy per particle

Trace anomaly, max. in c_s^2 [Fujimoto et al., 2022]

$$\Delta \equiv \frac{\epsilon - 3p}{3\epsilon} = \frac{1}{3} - \frac{p}{\epsilon} \qquad c_s^2 = \frac{1}{3} - \Delta - \epsilon \frac{\mathrm{d}\Delta}{\mathrm{d}\epsilon}$$

- New decomposition

$$c_s^2 = \frac{1}{\mu}\frac{\mathrm{d}p}{\mathrm{d}n} = 2\underbrace{\frac{n}{\mu}\frac{\mathrm{d}\epsilon/n}{\mathrm{d}n}}_{\text{Slope}} + \underbrace{\frac{n^2}{\mu}\frac{\mathrm{d}^2\epsilon/n}{\mathrm{d}n^2}}_{\text{Curvature of energy per particle}} = \alpha + \beta$$

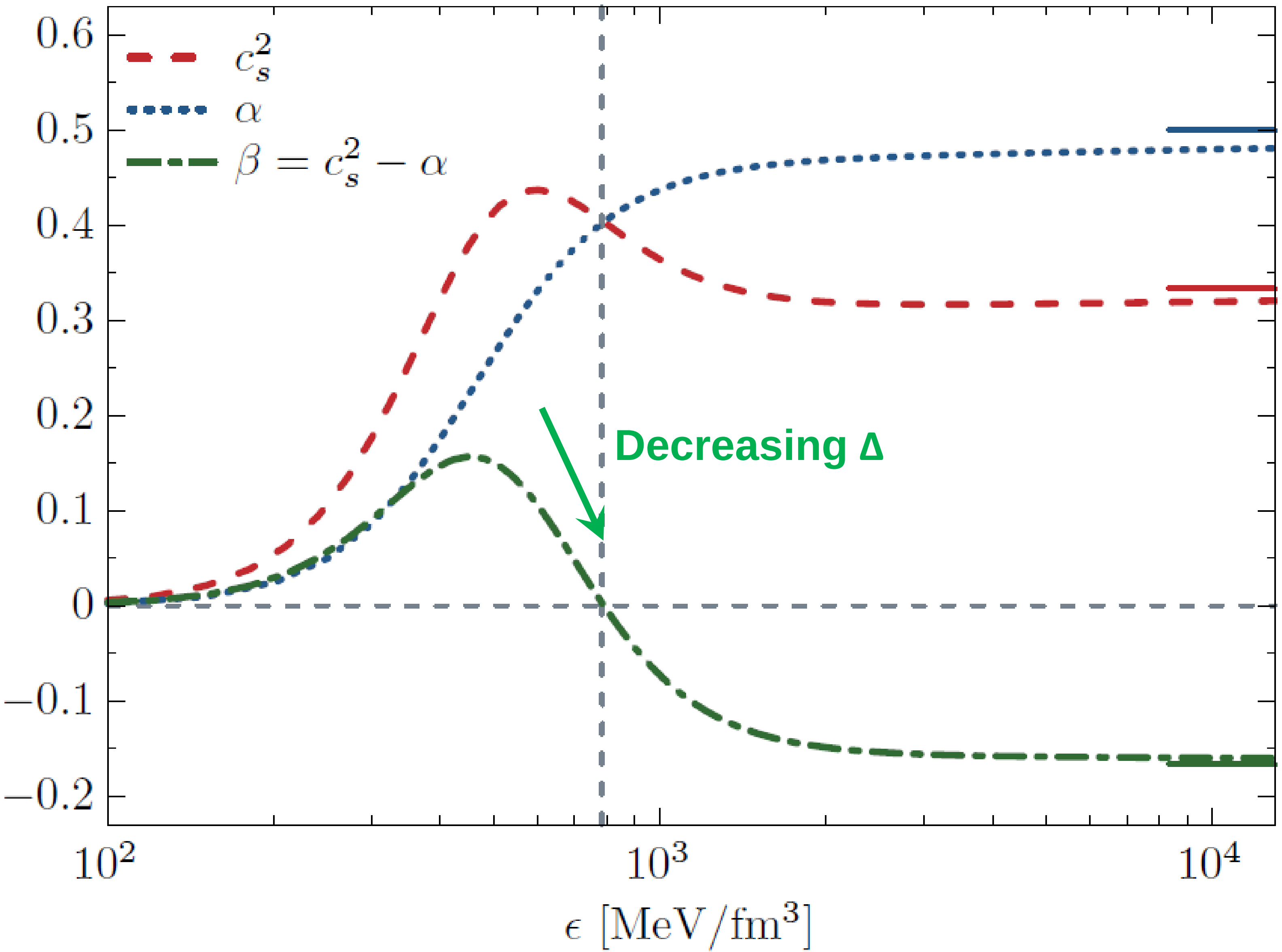
Slope **Curvature of energy per particle**

$$\alpha = 2\frac{\frac{1}{3} - \Delta}{\frac{4}{3} - \Delta}, \qquad \beta = c_s^2 - \alpha$$

$$\alpha \in [0,1] \text{ and } \beta \in [-1,1]$$

[Marczenko et al., to appear on arXiv]

A new criterion of conformality



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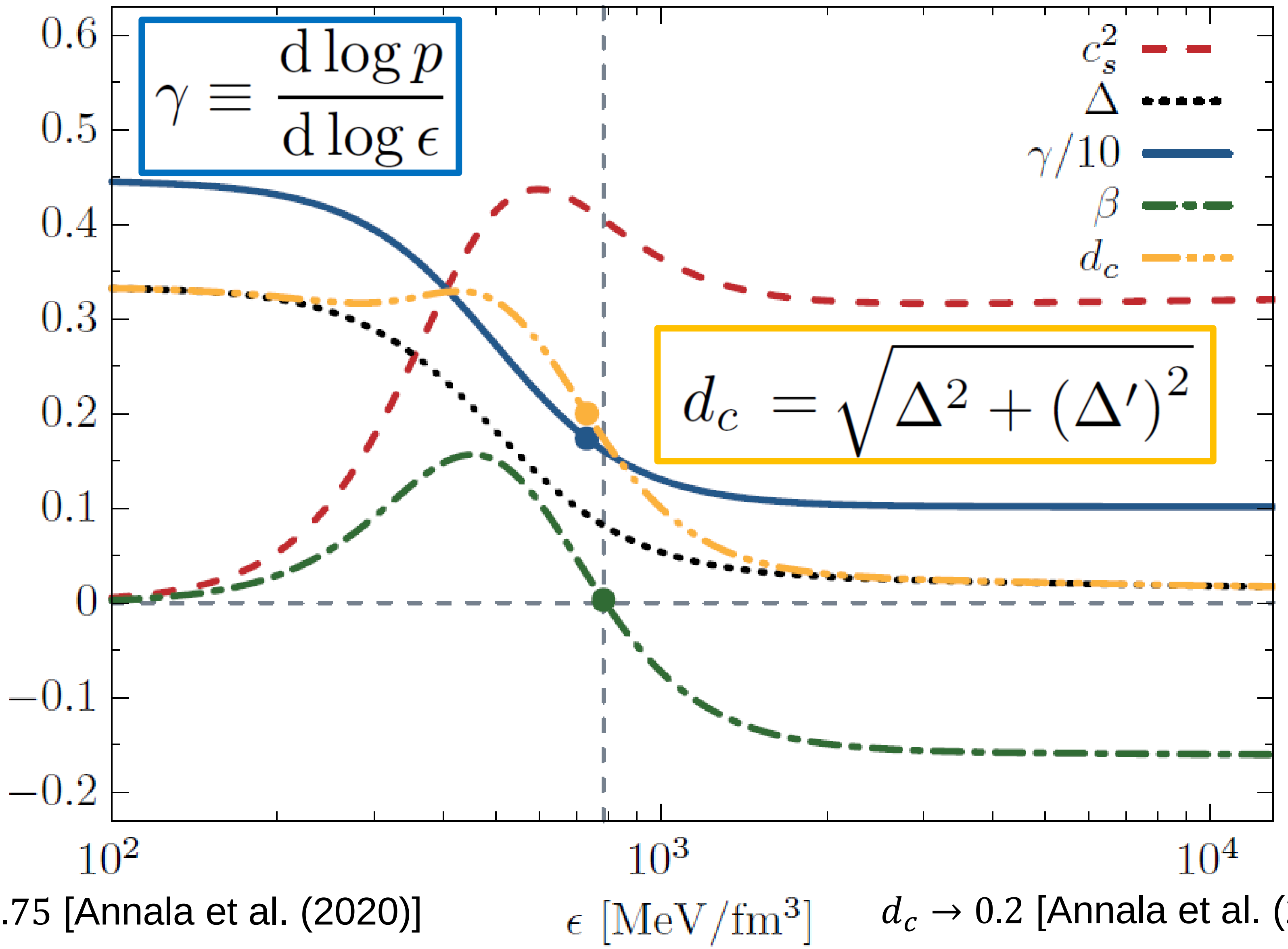

$\gamma \to 1.75$ [Annala et al. (2020)]

$d_c \to 0.2$ [Annala et al. (2023)]

SUMMARY

Concluding remarks

- Negative correlation between N and N*
  - $\chi_2^{++ \approx \mathrm{proton}}$ may not reflect χ_2^B.
  - χ_2^{proton} is able to identify the QCD CP.
  - Proposition: $\chi_2^{++,--,+-}$ in Lattice QCD and other approaches.
- 4-Fermi interaction dressed by quark loops
  - MC & inverse MC, Tc (B), χ_2 (B)
- Curvature of energy per particle in NSs