Effective models of QCD with infrared confinement

Ricardo L.S. Farias
Physics Department
Federal University of Santa Maria - Brazil

Confinement and symmetry from vacuum to QCD phase diagram

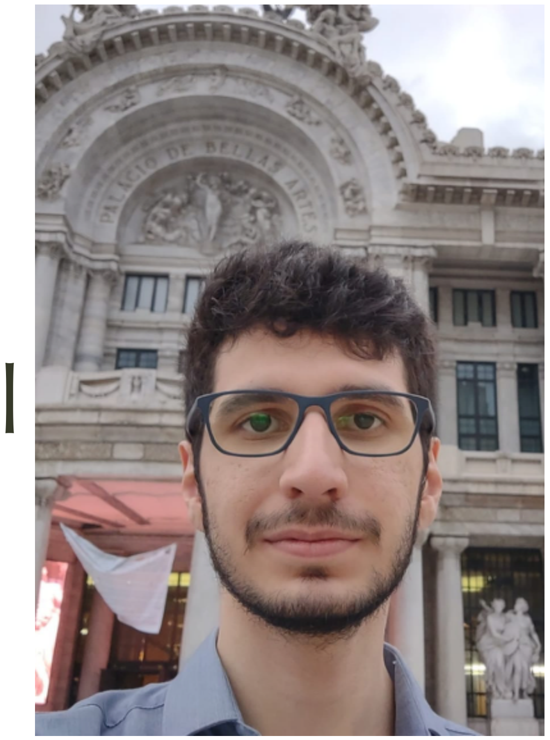
Conselho Nacional de Desenvolvimento Científico e Tecnológico

Benasque
February 14, 2025

FAPERGS

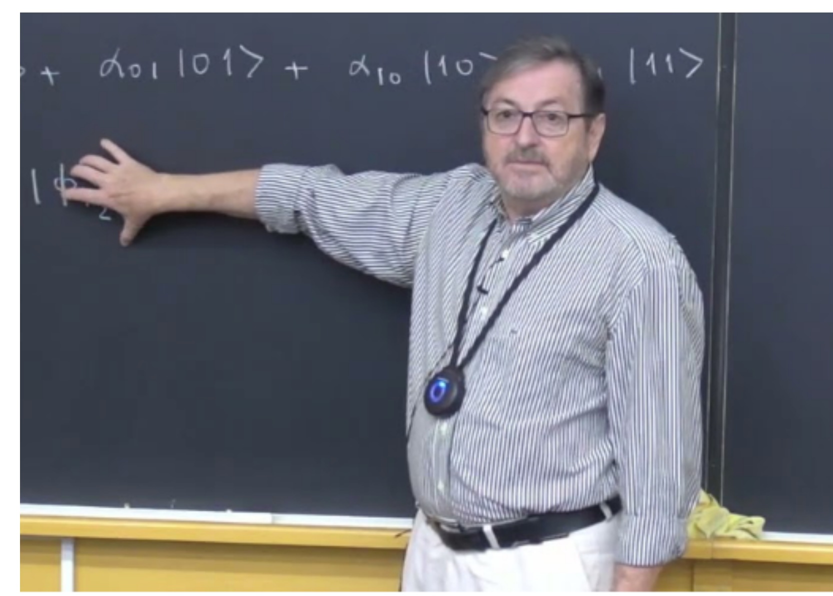
serrapilheira

In Collaboration with:



- Phd student Bruno Lopes - UFSM - Brazil

- Gastão I. Krein - IFT - Unesp - Brazil



Outline

- Motivation
- Confinement/deconfinement in dense QCD?
- IR confinement in effective models of QCD
- Warm-up at finite Temperature
- Perspectives

Approaches trying to understand confinement

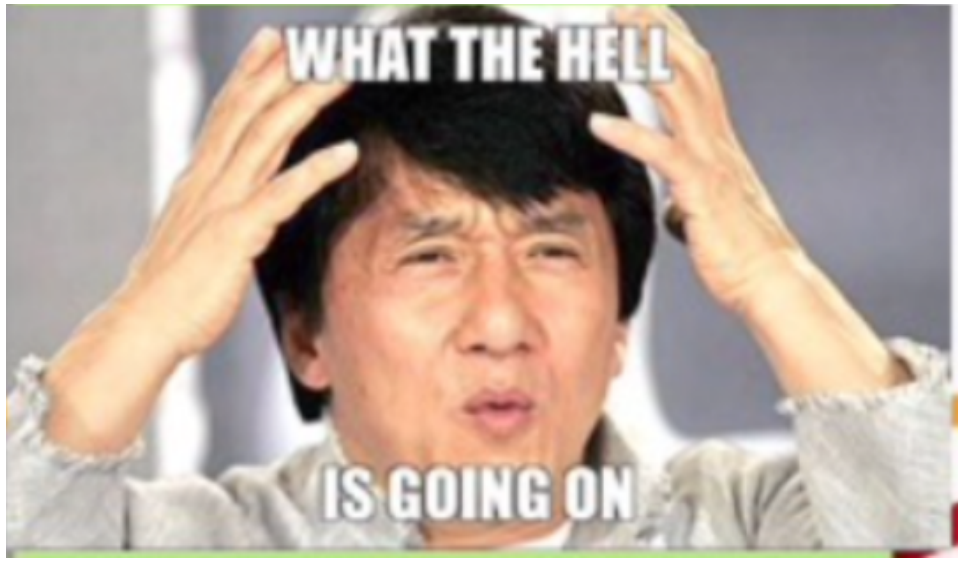
- Simple Models
- Gribov approach
- DSE/Functional approaches
- ADS/CFT duality
- Lattice QCD
- …

QCD

Color Confinement

- The underlying mechanism and the relationship between confinement and chiral symmetry breaking remain enduring mysteries in QCD

Long standing puzzle in QCD

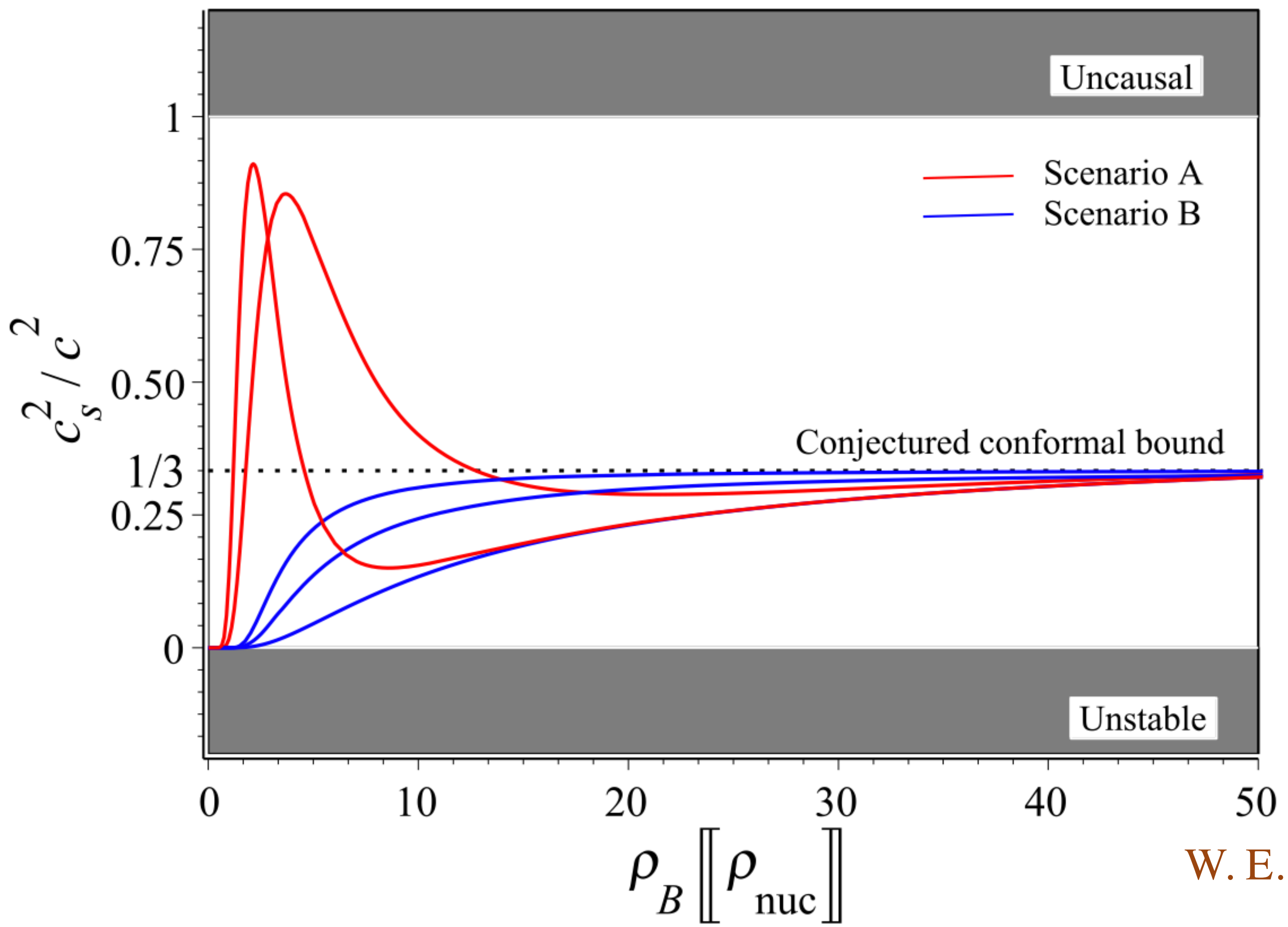


QCD

- Asymptotic freedom means that UV behavior of QCD is under control
- Dynamically generated masses for gluons and quarks means that QCD generates its own IR cutoffs

Confinement in effective models of QCD?

Speed of Sound X baryon density



W. E. Hanafy and A. Awad, The Astrophysical Journal, 951:144, 2023

Figure 1. Schematic plot to show two possible scenarios as suggested for the sound speed to evolve with baryon matter density, ρ_B, given in terms of the nuclear saturation density. In Scenario A, the speed of sound nonmonotonically evolves with density, reaching a maximum above the conjectured conformal upper bound, ${c_s}^2 = c^2/3$, at density $\simeq(3\text{–}5)\rho_{\rm nuc}$, and then decreases to approach the conformal bound from below at higher densities $\simeq 40\rho_{\rm nuc}$ where perturbative QCD is applied. In Scenario B, the speed of sound evolves monotonically with density, obeying the conjectured conformal upper bound at all densities. The shaded regions represent the excluded values of the sound speed as constrained by the stability and causality conditions.

Conformal Limit violation: First evidence

PHYSICAL REVIEW LETTERS

Editors' Suggestion

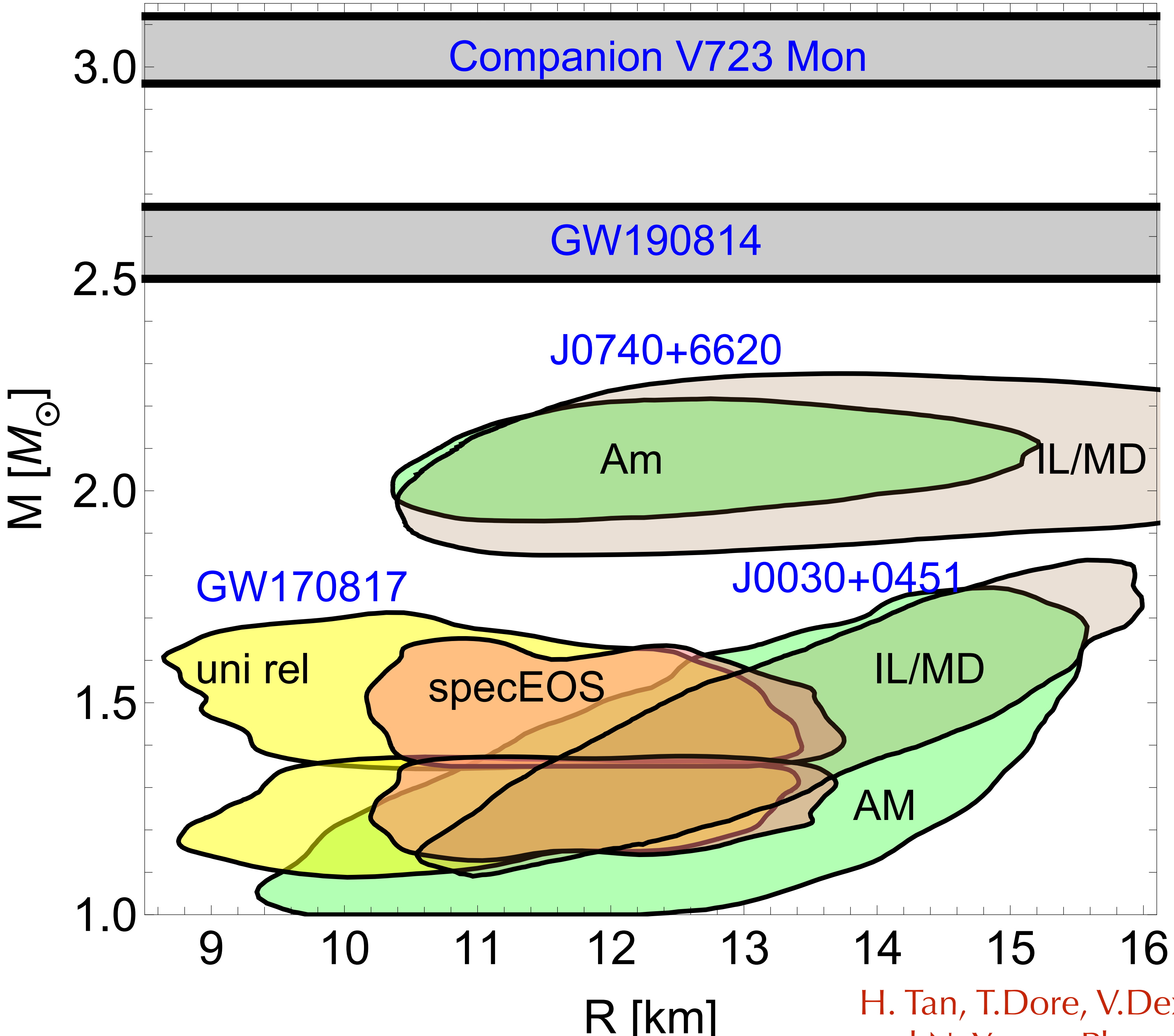
Sound Velocity Bound and Neutron Stars

Paulo Bedaque and Andrew W. Steiner
Phys. Rev. Lett. **114**, 031103 – Published 21 January 2015

If the bound on the speed of sound is actually violated – as it is strongly suggested by our results– the speed of sound, as a function of the energy density, has a peculiar shape. It raises from small values, reaches a maximum with $v_s^2 > 1/3$, lowers to a local minimum with $v_s^2 < 1/3$ and then raises again approaching $v_s^2 = 1/3$ from below at high densities. We find remarkable that such a conclusion can be derived from well established facts.

Finite baryon density

Observational constraints on the neutron star mass-radius plane from LIGO/Virgo and NICER data.



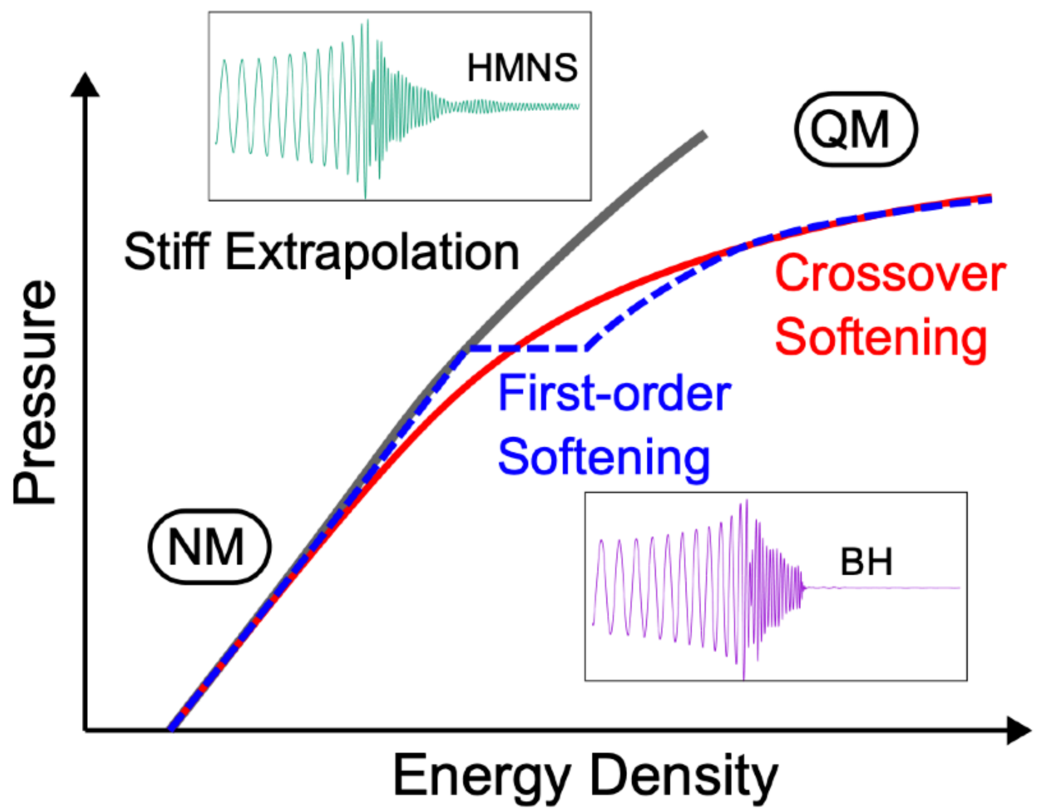
H. Tan, T.Dore, V.Dexheimer, J.Noronha-Hostler, and N. Yunes, Phys. Rev. D **105**, 023018 (2022).

Astrophysical implications to QCD phase diagram

- Gravitational wave detection - opened a new window on the universe

- Ligo-Virgo-Kagra colaboration

- Nicer



$$c_s^2 = \frac{\partial P}{\partial \epsilon}$$

Peak in the sound velocity

Kenji Fukushima, https://arxiv.org/pdf/2501.01907

Polyakov Loop

- Finite T, **INFINITE** quark mass -> quench dynamical quarks
- Confinement/deconfinement of gluons - center symmetry
- Dynamical quarks break center symmetry - Polyakov loop is an **APROXIMATE** measure of confinement!

$$\begin{aligned}\mathcal{L}_{\mathrm{PNJL}} &= \bar{q}(i\gamma_\mu D^\mu - \hat{m})q - \mathcal{U}(\Phi, \Phi^*, T) \\ &+ \frac{G_s}{2}\sum_{a=0}^{8}[(\bar{q}\lambda_a q)^2 - (\bar{q}\gamma_5\lambda_a q)^2] \\ &- \frac{G_V}{2}\sum_{a=0}^{8}[(\bar{q}\gamma_\mu\lambda_a q)^2 + (\bar{q}\gamma_\mu\gamma_5\lambda_a q)^2] \\ &+ K[\det_f(\bar{q}(1-\gamma_5)q) + \det_f(\bar{q}(1+\gamma_5)q)],\end{aligned}$$

PNJL model

But we have a problem:

Polyakov loop zero at T=0

How important is
confinement /deconfinement
phase transition(crossover)
at high density?

Alternatives:

- Polyakov loop potential as a function of chemical potentials, magnetic Fields, …

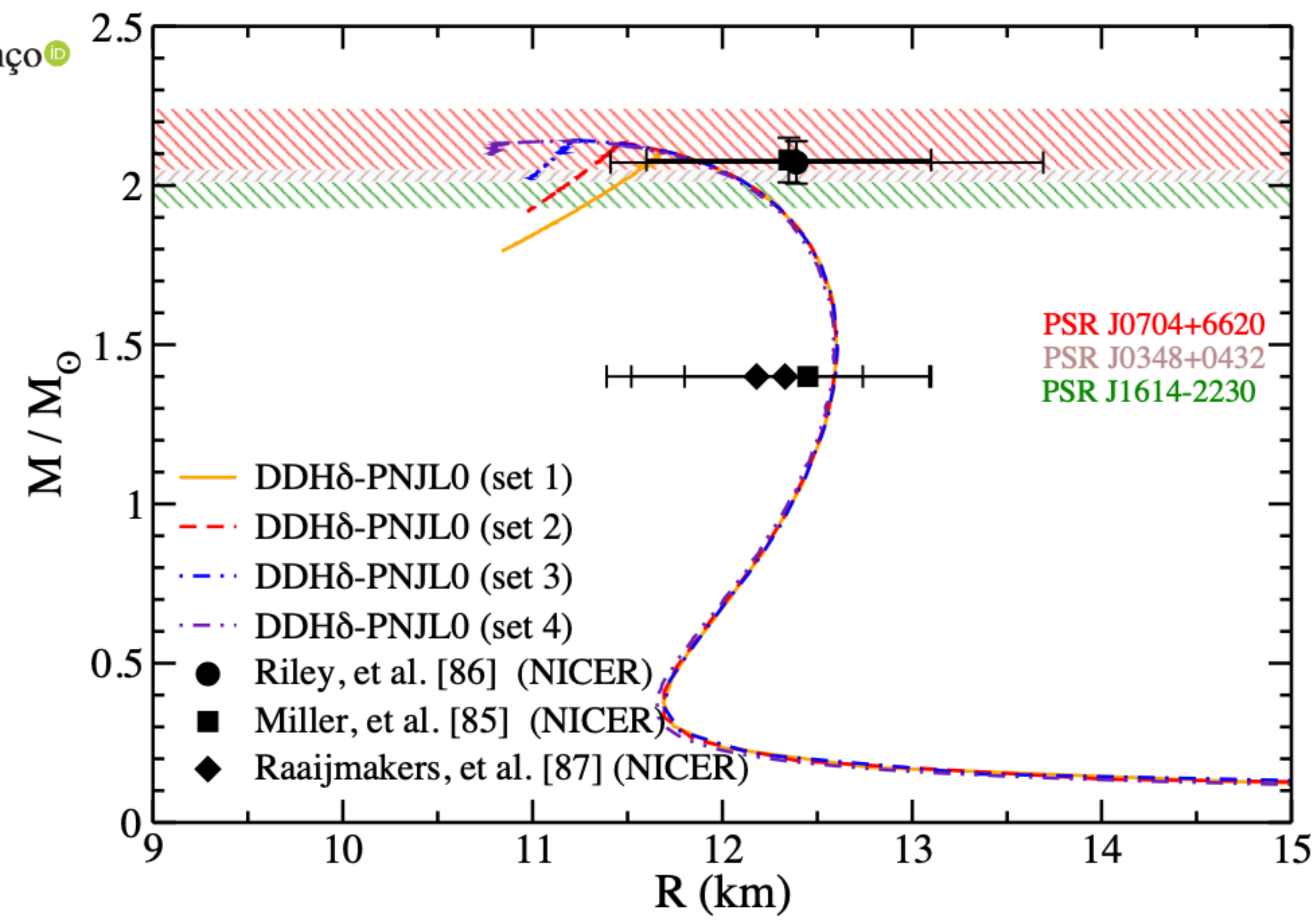
PHYSICAL REVIEW D **104,** 116001 (2021)

PNJL model at zero temperature: The three-flavor case

O. A. Mattos, T. Frederico, C. H. Lenzi, M. Dutra, and O. Lourenço
Departamento de Física, Instituto Tecnológico de Aeronáutica,
DCTA, 12228-900 São José dos Campos, SP, Brazil

$$G_s \rightarrow \mathcal{G}_s(G_s, \Phi) = G_s(1 - \Phi^2),$$

$$G_V \rightarrow \mathcal{G}_V(G_V, \Phi) = G_V(1 - \Phi^2),$$



Infrared confinement - Old propose

Main quantity is the quark propagator: $$S(k)^{-1} = \not{k} - M + i\varepsilon.$$

- Confinement -> propagator of a colored state should have no singularities on the real, positive p^2 axis

- No singularities on the negative (spacelike) p^2 axis would imply tachyonic behavior (forbidden by causality).

- Quark propagator - quarks have no mass-pole and cannot go on mass shell.

- **The phenomenon o quark confinement is considered!**

Infrared confinement

If colored free states do not exist then it is reasonable to expect that the corresponding propagators for this colored particles and bound states have no mass-poles.

Infrared confinement - Old propose

Ground-state $q\bar{q}$ mass spectrum in quantum chromodynamics

H. J. Munczek and A. M. Nemirovsky

Show more

Phys. Rev. D **28**, 181 – **Published 1 July, 1983**

DOI: https://doi.org/10.1103/PhysRevD.28.181

SUPERCOMPUTER COMPUTATIONS RESEARCH INSTITUTE

ON THE IMPLICATIONS OF CONFINEMENT

by

G. Krein, C.D. Roberts and A.G. Williams

FSU-SCRI-90-168

October 26, 1990

THE FLORIDA STATE UNIVERSITY
TALLAHASSEE, FLORIDA

ELSEVIER

Physics Letters B

Volume 388, Issue 1, 7 November 1996, Pages 154-160

Extended NJL model for light and heavy mesons without q-q thresholds

Dietmar Ebert [a 1], Thorsten Feldmann [a 1] ✉, Hugo Reinhardt [b 2]

SU(2) Nambu—Jona-Lasinio model (NJL)

$$\mathcal{L}_{\mathrm{NJL}} = \bar{\psi}(i\partial\!\!\!/ - \hat{m})\psi + G\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\boldsymbol{\tau}\psi)^2\right]$$

good **chiral** physics, pions,…
BUT no confinement and no AF

G, Λ and m_c → m_π, f_π and $\langle\bar{\psi}\psi\rangle$

$$\Omega(T,\mu_q) = \frac{(M-m_0)}{4G} - 2N_cN_f\int_\Lambda \frac{d^3k}{(2\pi)^3}\omega(k) - 4N_cN_fT\int \frac{d^3k}{(2\pi)^3}\left[\log\left(1+e^{-(\omega(k)+\mu_q)/T}\right) + \log\left(1+e^{-(\omega(k)-\mu_q)/T}\right)\right]$$

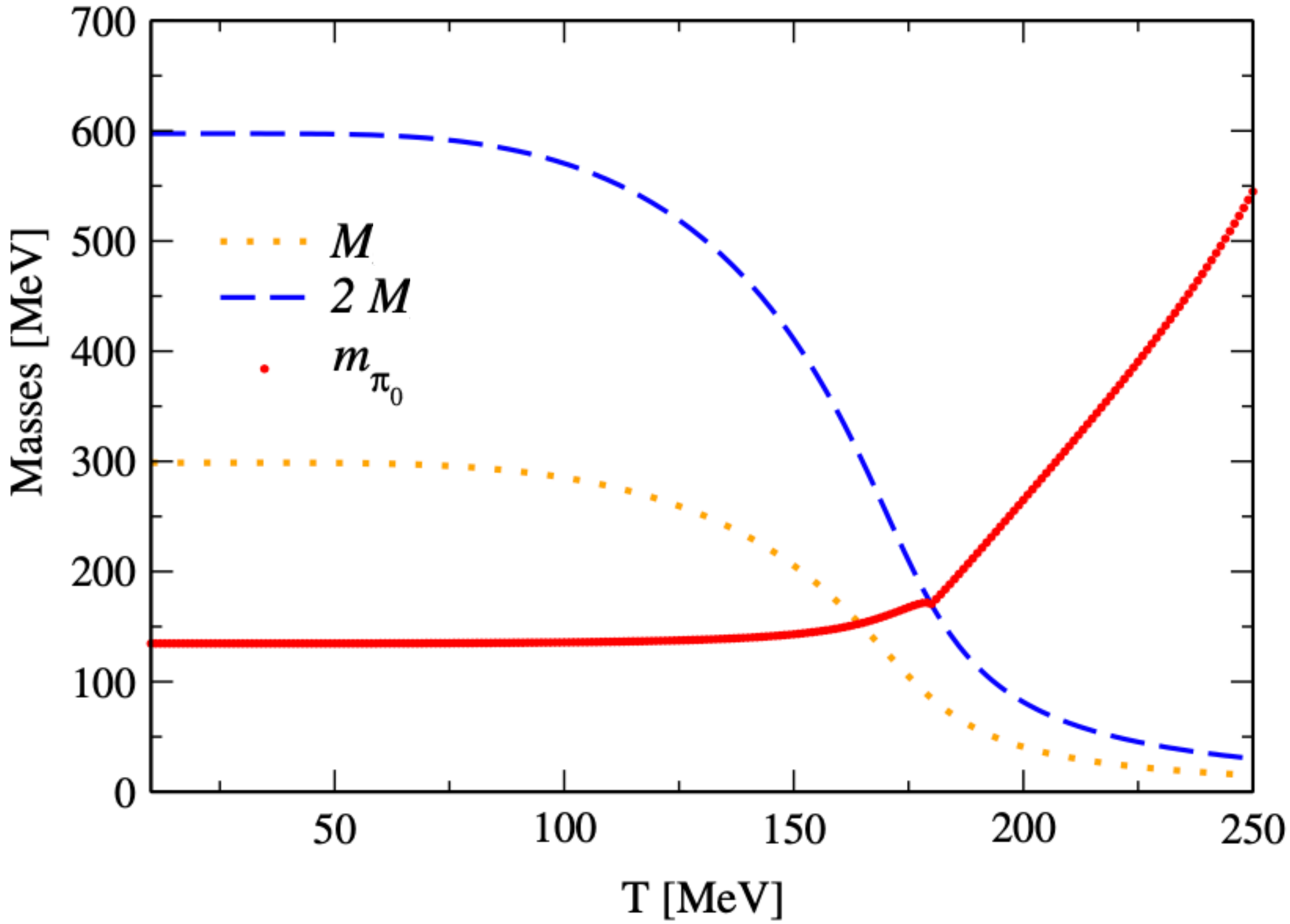
UV divergent! Needs regularization!

$$M = m_0 + 4N_cN_fG\int_\Lambda \frac{d^3k}{(2\pi)^3}\frac{M}{\omega(k)} - 4N_cN_fG\int \frac{d^3k}{(2\pi)^3}\frac{M}{\omega(k)}[(n_-(k)+n_+(k)]$$

Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961)

Unphysical thresholds in the NJL model

The NJL model does not prevent hadrons from decaying into free quarks, which makes the realistic description of hadron properties on their mass shell questionable properties on their mass shell.



SU(2) Nambu—Jona-Lasinio model (NJL)

- Unphysical thresholds are due to the lack of confinement in NJL model

- These thresholds can be removed by a IR cutoff in Proper-Time formalism!

ELSEVIER

Physics Letters B

Volume 388, Issue 1, 7 November 1996, Pages 154-160

Extended NJL model for light and heavy mesons without q-q thresholds

Dietmar Ebert [a 1], Thorsten Feldmann [a 1], Hugo Reinhardt [b 2]

Infrared confinement

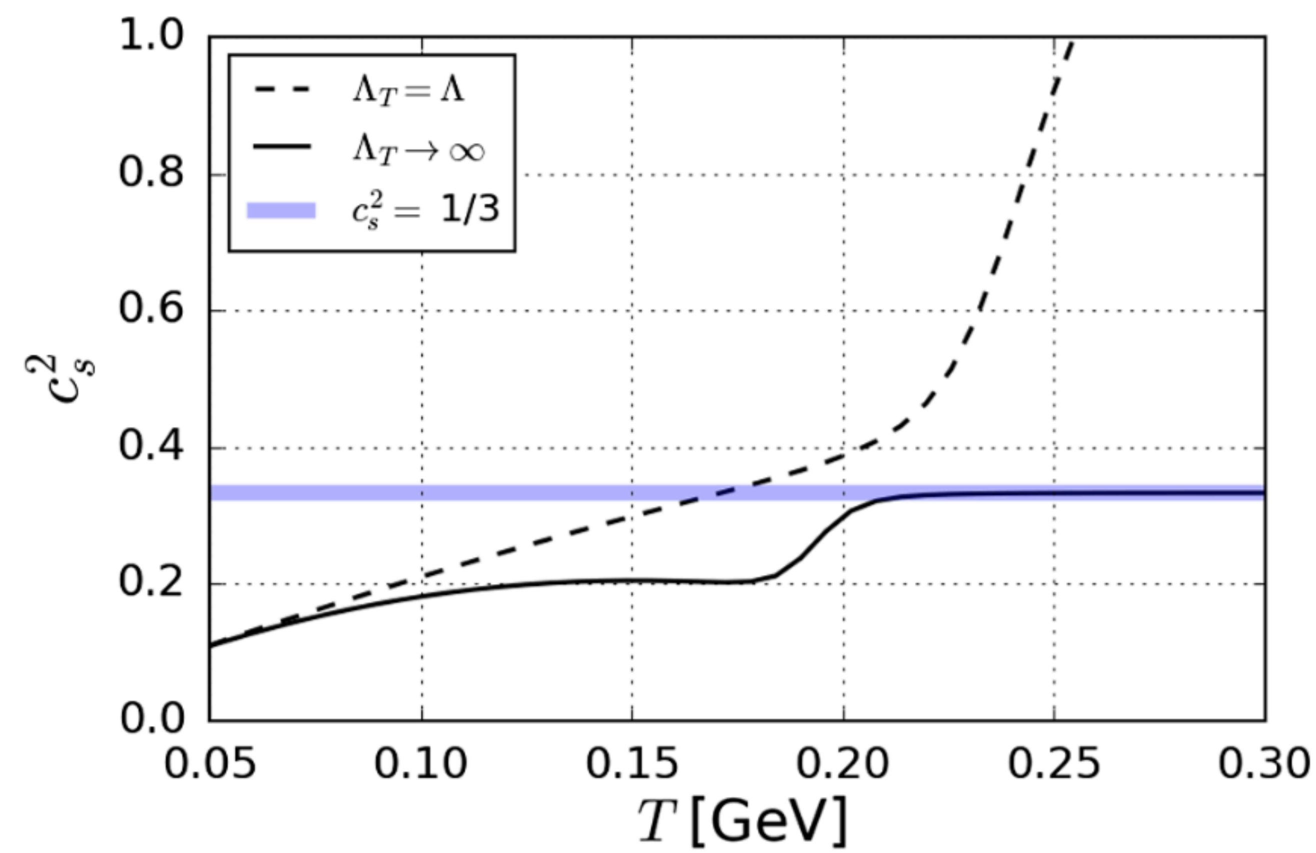
$$\frac{1}{A^n} \to \frac{1}{\Gamma[n]} \int_{1/\Lambda_{\rm UV}^2}^{1/\Lambda_{\rm IR}^2} d\tau\, \tau^{n-1} e^{-A\tau}$$

$$\int_{1/\Lambda_{UV}^2}^{1/\Lambda_{IR}^2} ds \exp\left[-s\left(k^2+m^2\right)\right] = \frac{\exp^{-\frac{k^2+m^2}{\Lambda_{IR}^2}} - \exp^{-\frac{k^2+m^2}{\Lambda_{UV}^2}}}{k^2+m^2}$$

After some manipulation with Jacobi Theta functions:

$$\Omega^{PT} = \frac{(m-m_0)^2}{4G} + \frac{3}{4\pi^2}\int_{1/\Lambda_{\rm UV}^2}^{1/\Lambda_{\rm IR}^2} d\tau\, \frac{e^{-m^2\tau}}{\tau^3} +$$

$$\frac{3}{2\pi^2}\int_0^{1/\Lambda_{\rm IR}^2} d\tau\, \frac{e^{-m^2\tau}}{\tau^3} \sum_{n=1}^{+\infty} \cos(n\pi)\exp\left(\frac{-n^2}{4\tau T^2}\right)$$



Deconfinement $\Lambda_{IR} \to 0$

Traditional approach uses arbitrary parametrizations for the temperature dependence of the infrared cutoff

$$\Lambda_{IR} \to \Lambda_{IR}(T)$$

$$\Lambda_{IR} \to \Lambda_{IR} \frac{M(T)}{M(T=0)}$$

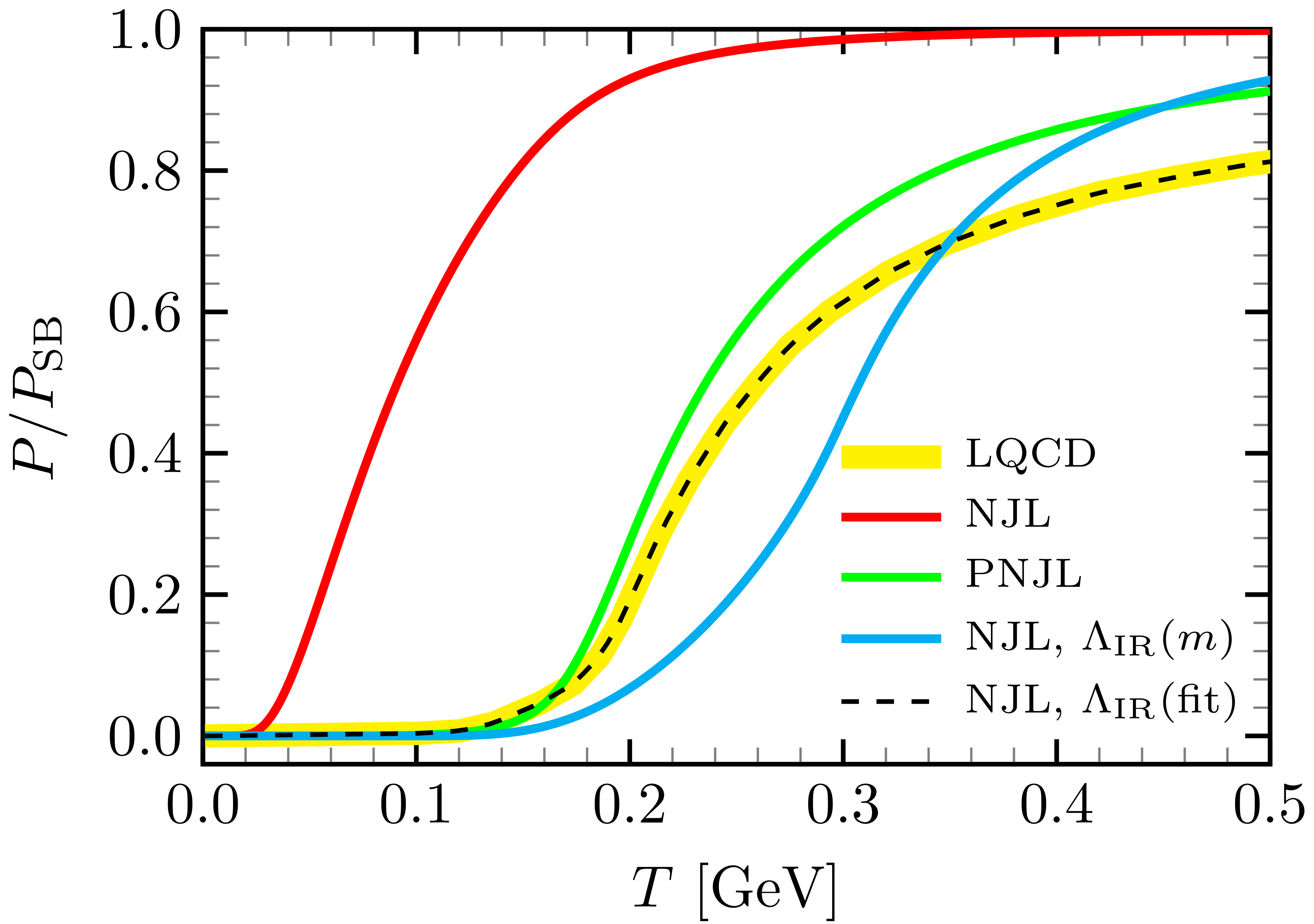
Contact Interaction models

Chiral symmetry restoration and deconfinement coincide!

Our approach: LQCD input: Pressure to fix $\Lambda_{IR}(T)$

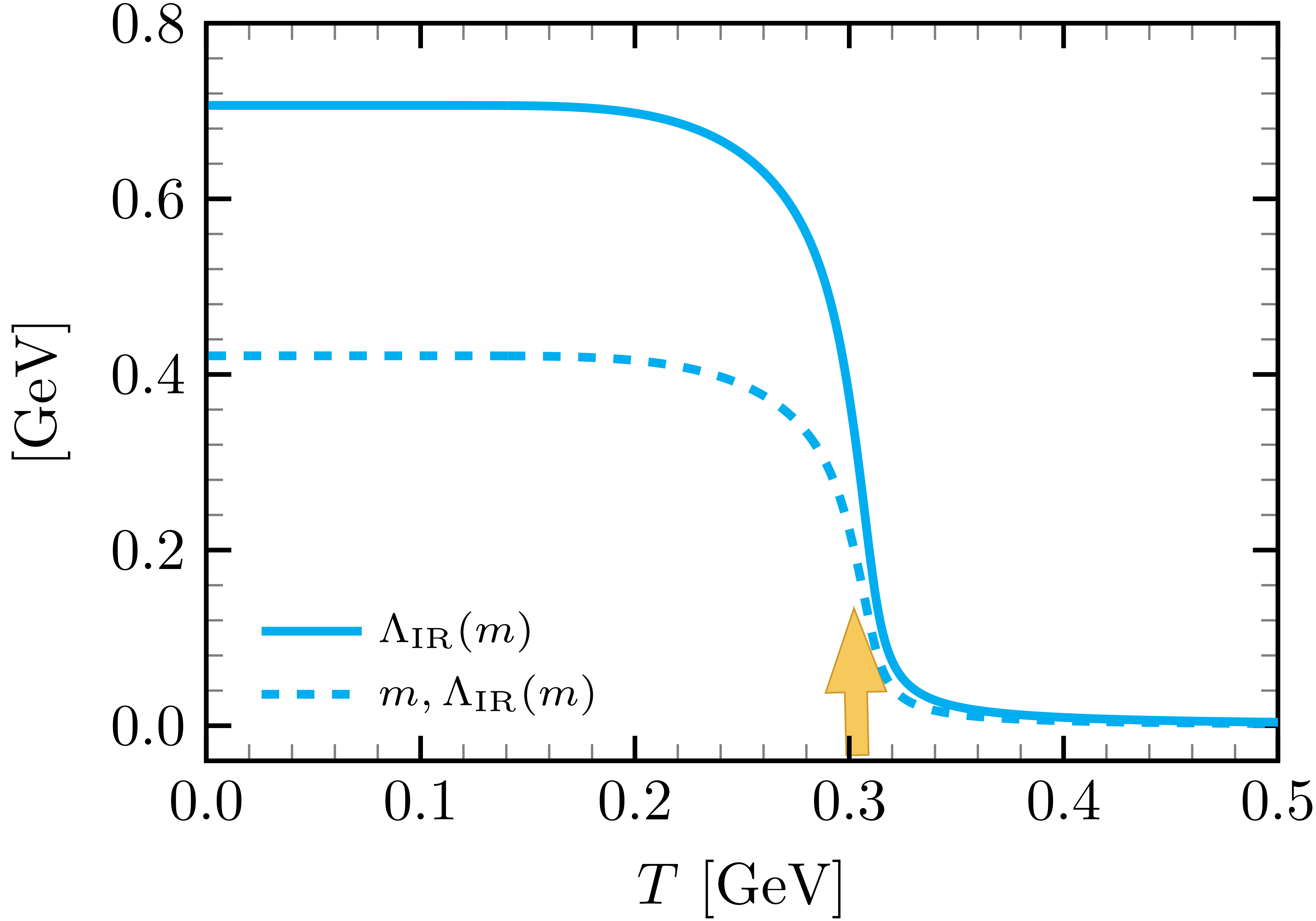
Lattice input - Pressure X T

Lattice input: Pressure to fix $\Lambda_{IR}(T)$

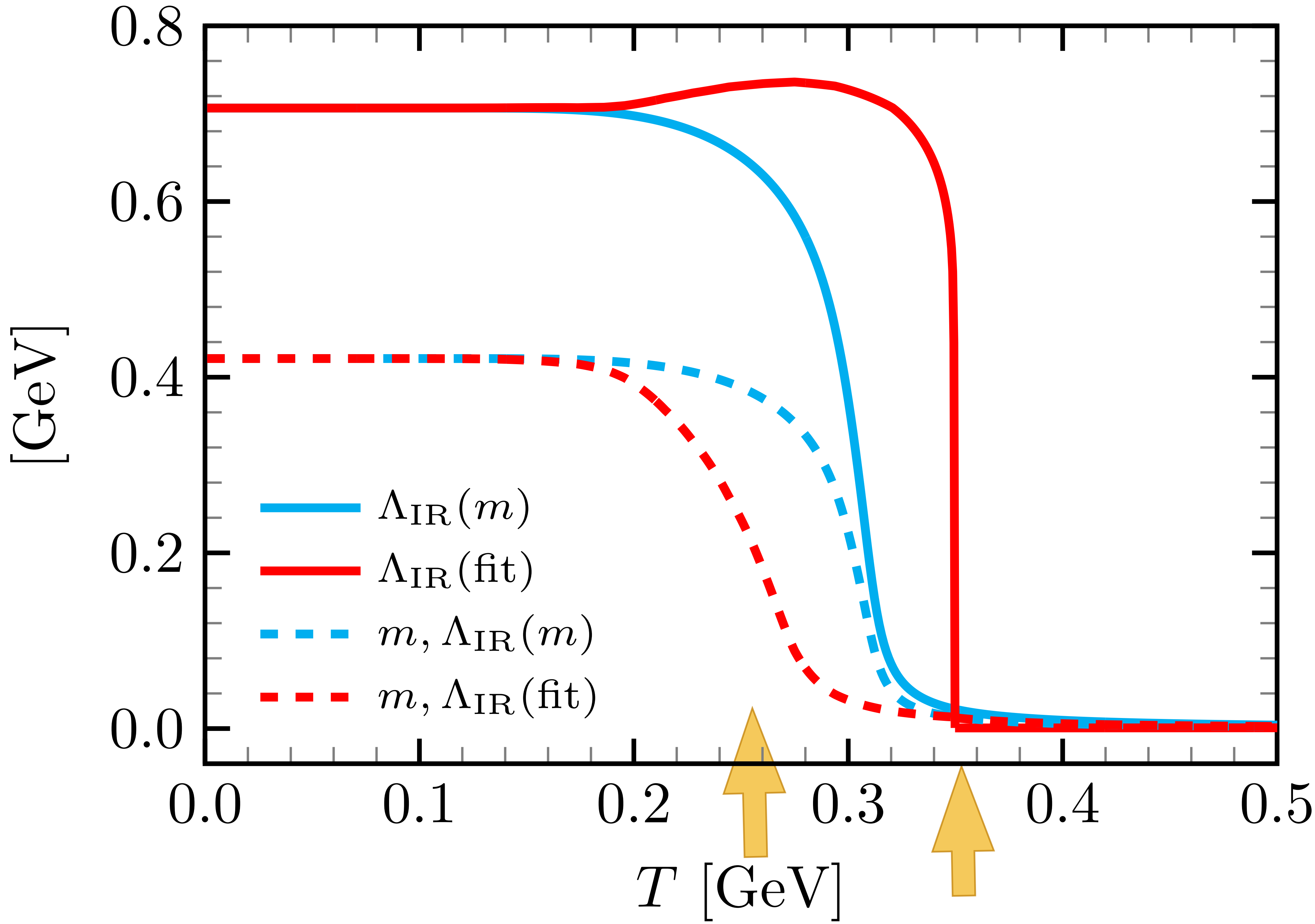


A. Bazavov, T. Bhattacharya, M. Cheng, N.H. Christ, C. DeTar, *Phys. Rev. D* 80 (2009) 014504

Numerical results NJL



Numerical results NJL



NJL model is nonrenormalizable

- Does not have confinement
- Does not have asymptotic freedom,
- Needs regularization,
- too much freedom…

Why Contact Interaction Models?

IR confinement in renormalizable model

LSMq

QMM

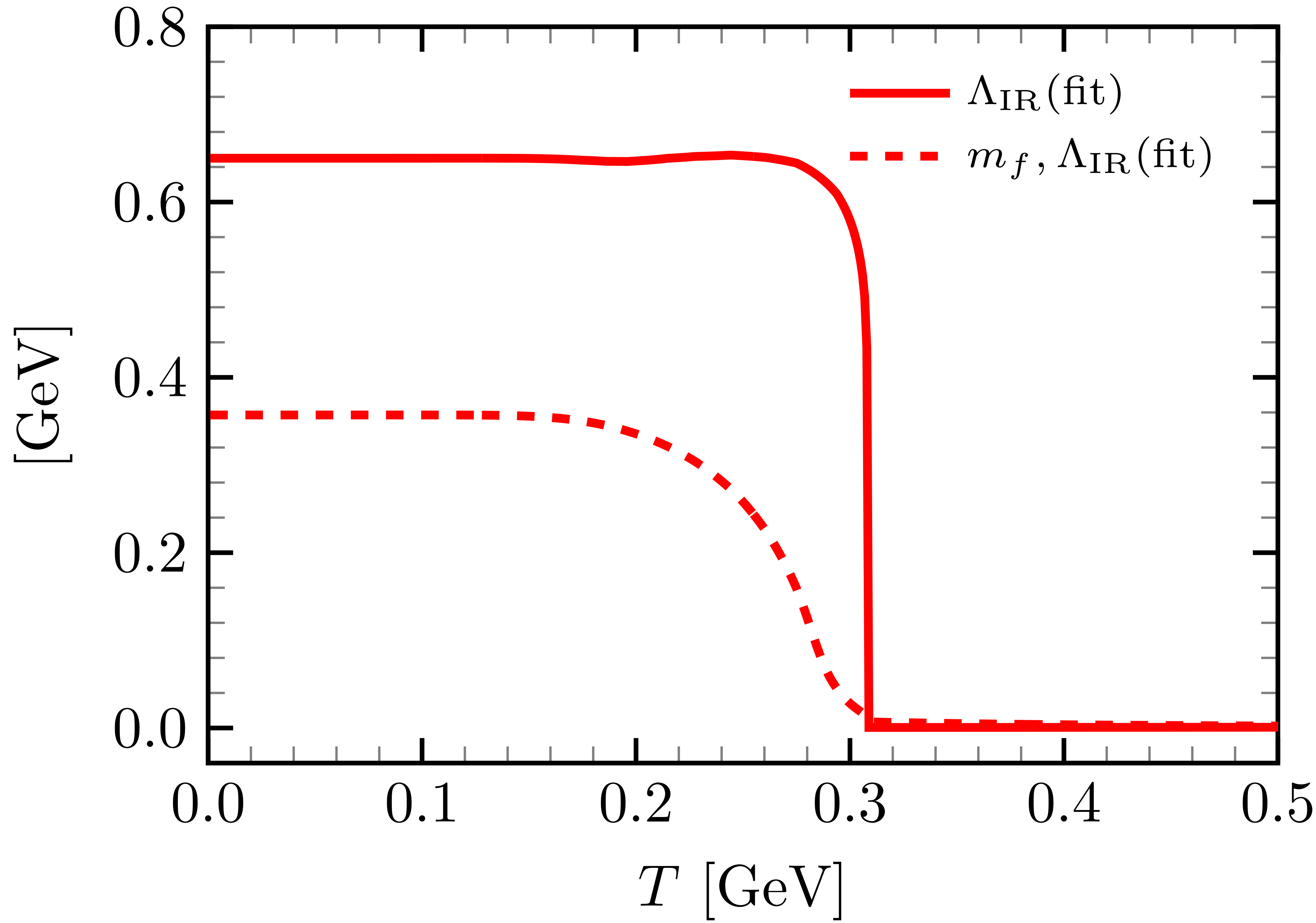
$$\mathcal{L} = \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + \frac{a^2}{2}(\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 + \bar{\psi}\left[i\gamma^\mu\partial_\mu - g\sigma - ig\gamma^5\vec{\tau}\cdot\vec{\pi}\right]\psi\,.$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + \frac{a^2}{2}(\sigma^2 + 2\sigma v + v^2 + \vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2 + 2\sigma v + v^2 + \vec{\pi}^2)^2 + hv + \bar{\psi}\left[i\gamma^\mu\partial_\mu - g\sigma - gv - ig\gamma^5\vec{\tau}\cdot\vec{\pi}\right]\psi\,.$$

$$V_{\text{tree}} = -\frac{1}{2}a^2v^2 + \frac{1}{4}\lambda v^4 - hv$$

$$V_f = \frac{N_c N_f}{8\pi^2}\int_{1/\Lambda_{UV}^2}^{1/\Lambda_{IR}^2} d\tau\, \frac{e^{-\tau m_f^2}}{\tau^3} + \frac{N_c N_f}{4\pi^2}\int_0^{1/\Lambda_{IR}^2} d\tau\, \frac{e^{-\tau m_f^2}}{\tau^3}\sum_{n=1}^{+\infty}\cos(n\pi)e^{-n^2/4T^2\tau}$$

Numerical results: LSMq



Conclusions

- Possible split between chiral symmetry restoration and deconfinement at finite temperature
- Including a LQCD input we show that the IR cutoff decrease with T, simulating deconfinement!
- Interesting way to investigate confinement/deconfinement at finite density within effective models of QCD

Perspectives

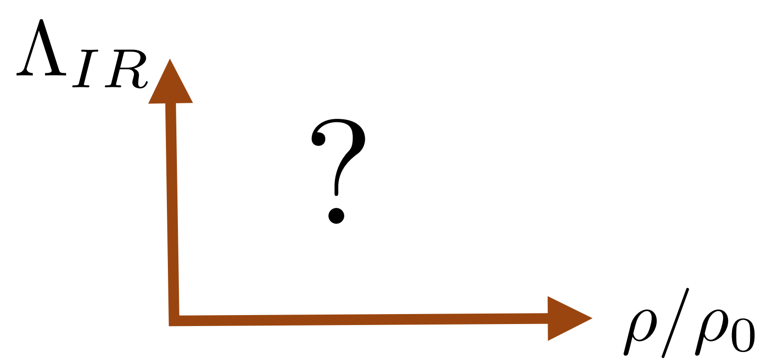
nature physics
LETTERS
https://doi.org/10.1038/s41567-020-0914-9
Check for updates

OPEN

Evidence for quark-matter cores in massive neutron stars

Eemeli Annala[1], Tyler Gorda[2], Aleksi Kurkela[3,4], Joonas Nättilä[5,6,7] and Aleksi Vuorinen[1]

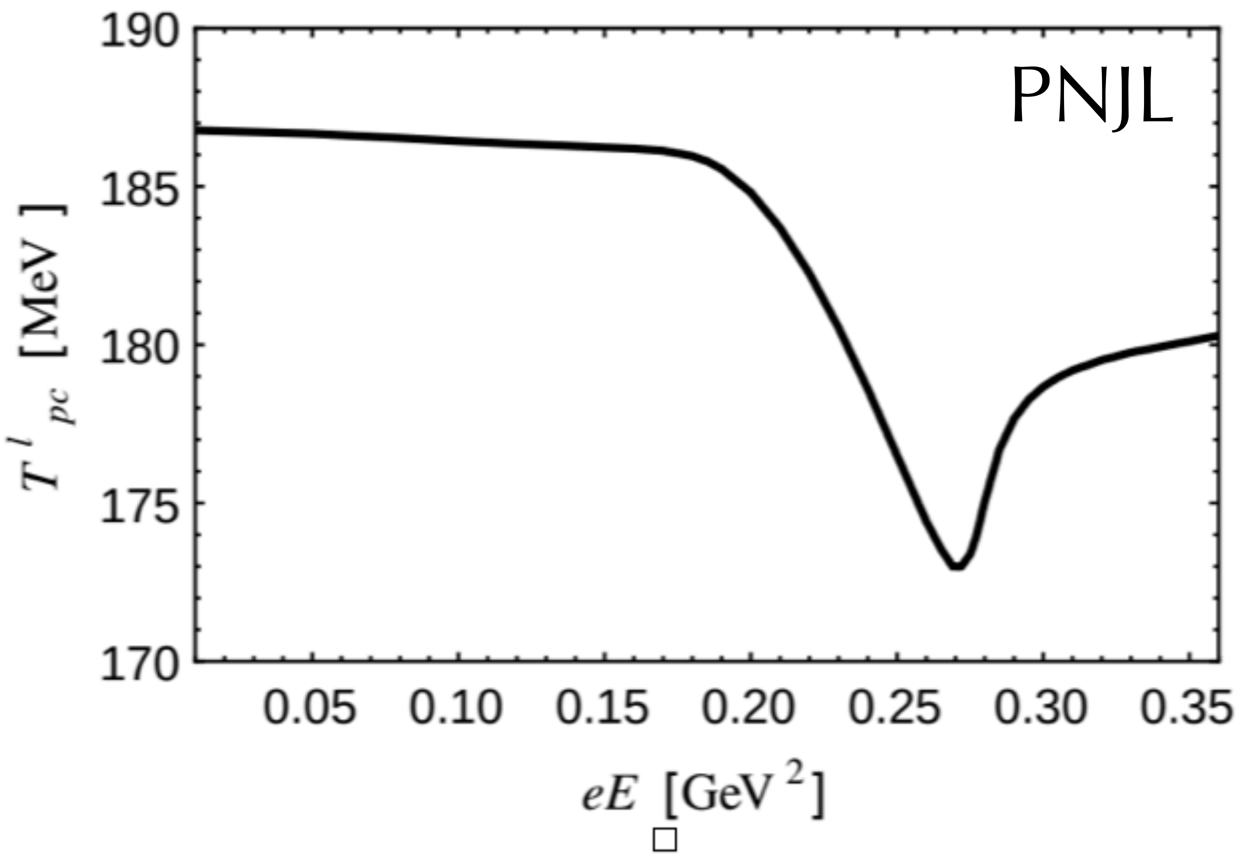
$$\Lambda_{IR} = \Lambda_{IR}(\rho)$$



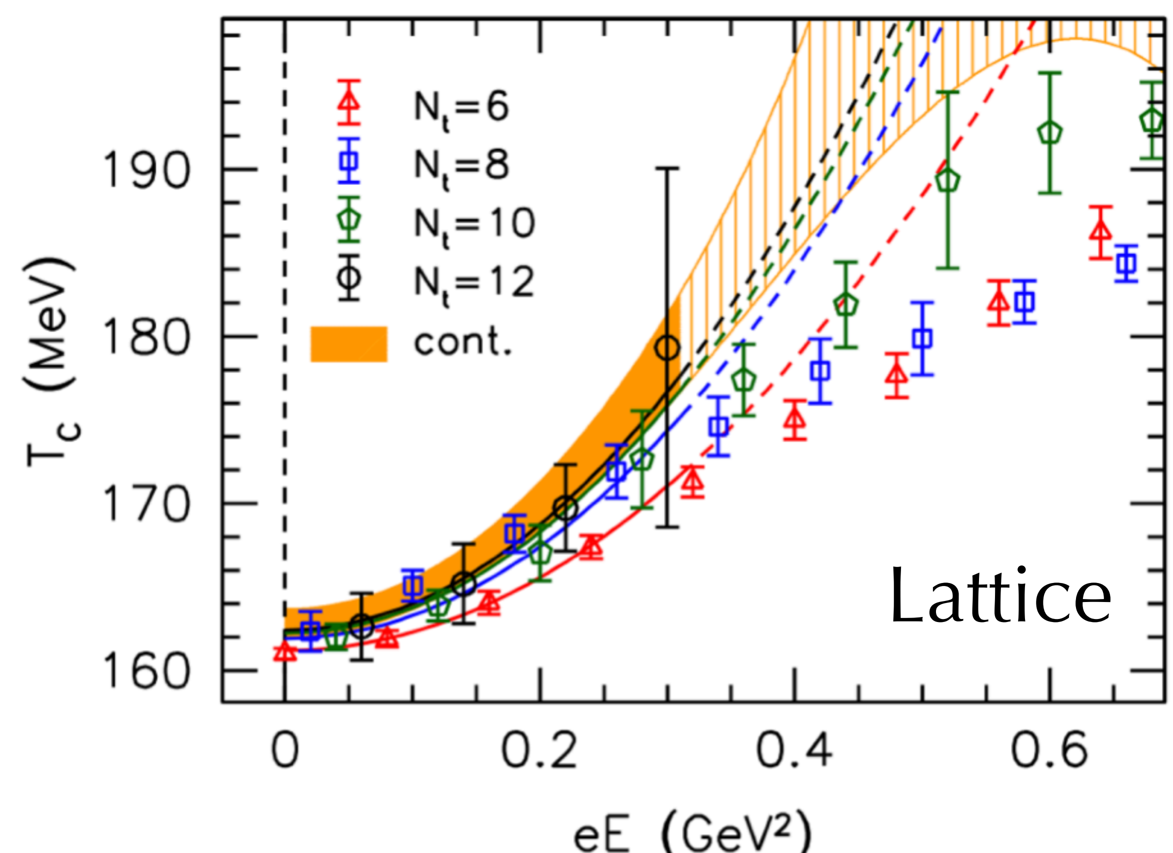
- IR confinement + Astrophysical constraints: from observation data to the theory

Perspectives

- Mesons masses in LSMq and SU(3) NJL
- IR confinement in diquarks, pion condensation, BEC phase, …
- Behavior of sound velocity at high density
- T X eE

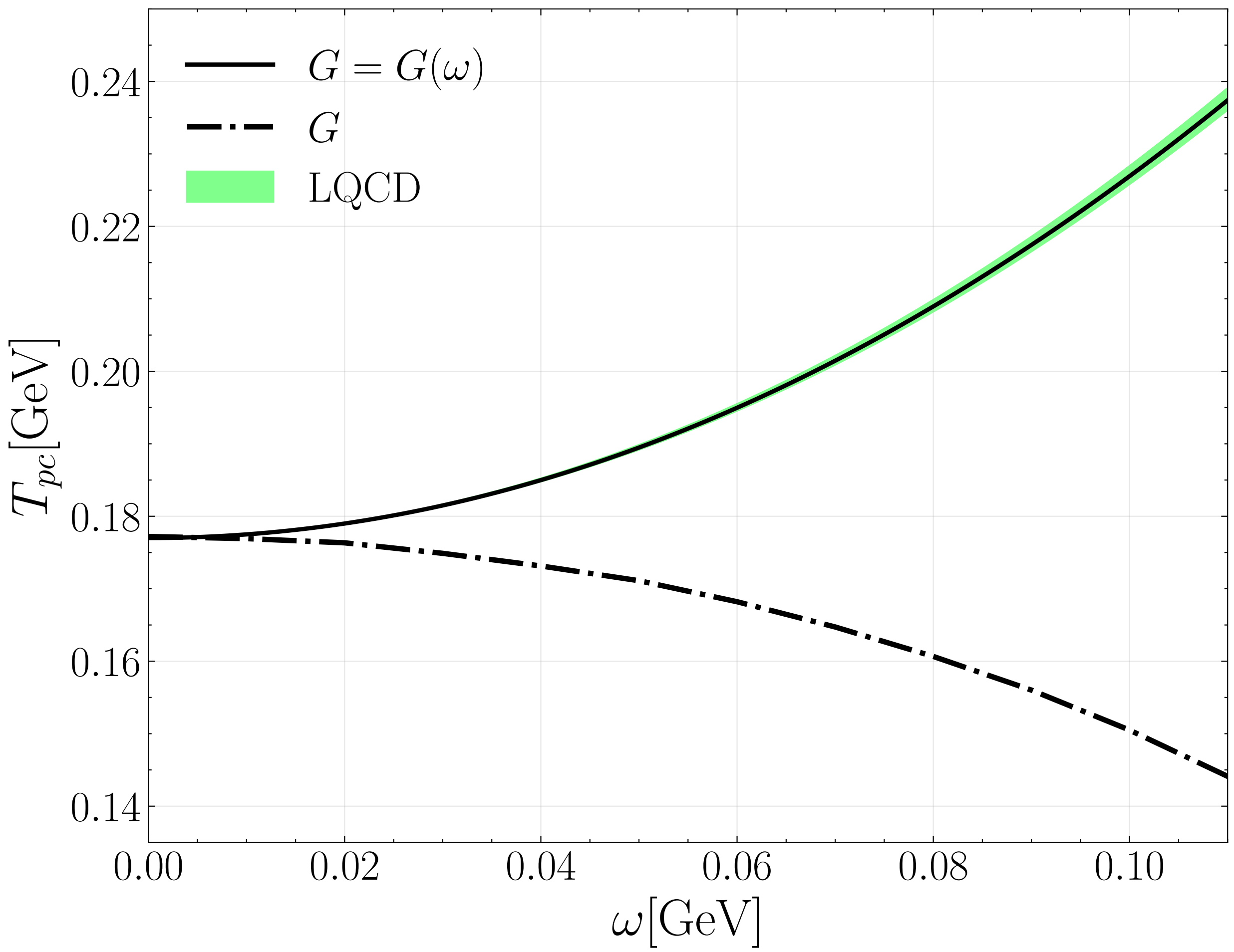


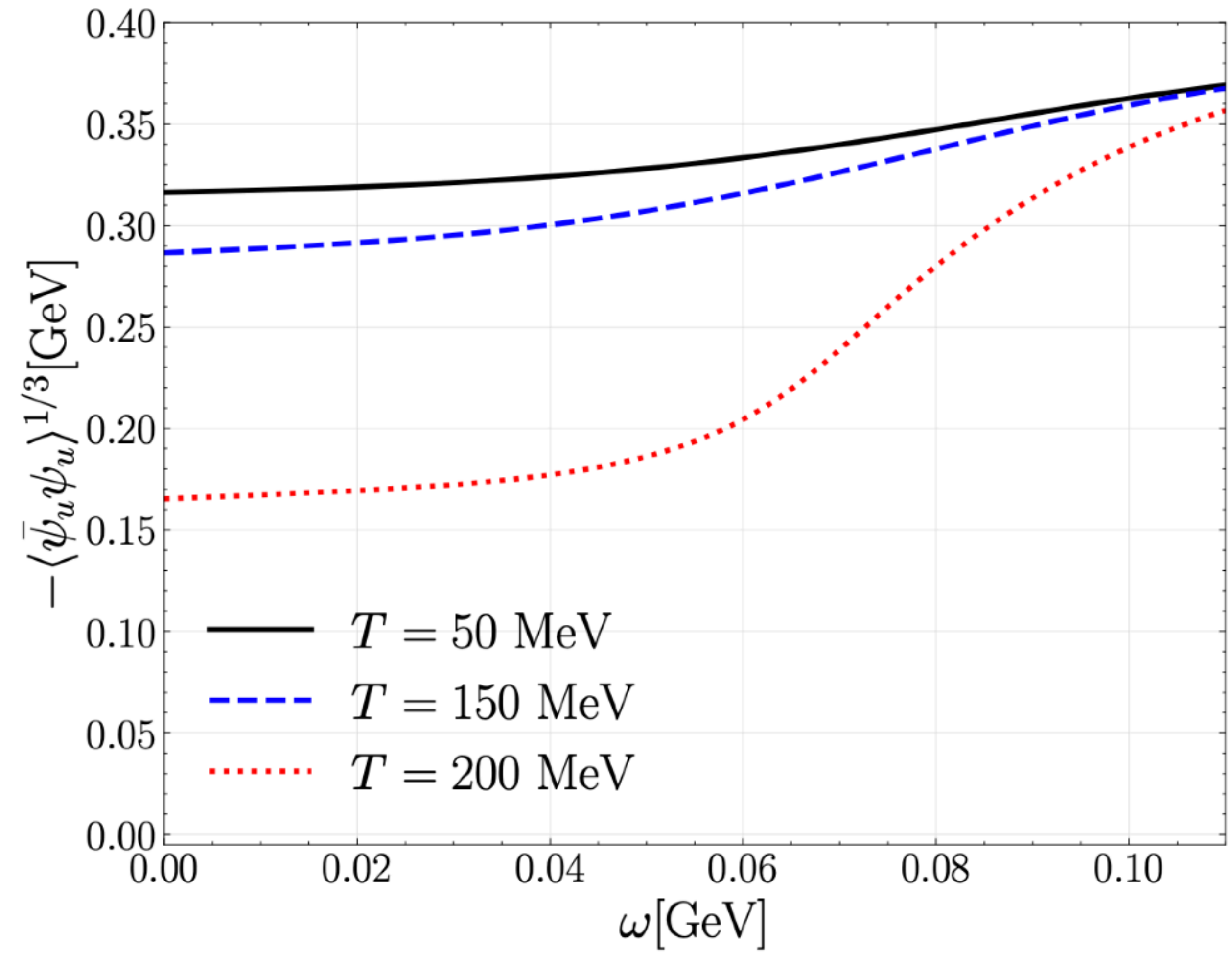
Tavares, W.R., Farias, R.L.S., Avancini, S.S. Phys.Rev.D 101 (2020) 1, 016017



G. Endrodi and G. Markó, PRD 109, 034506 (2024)

Perspectives





Chiral vortical catalysis constrained by LQCD simulations

Rodrigo M. Nunes (Santa Maria U., Brazil), Ricardo L.S. Farias (Santa Maria U., Brazil), William R. Tavares (Rio de Janeiro State U.), Varese S. Timóteo (Campinas State U.) (Dec 19, 2024)

e-Print: 2412.14541 [hep-ph]

V. V. Braguta, A. Kotov, A. Roenko, and D. Sychev, PoS **LATTICE2022**, 190 (2023), 2212.03224.

Conferences in Brazil

XXII Jorge André Swieca Summer school of Nuclear Theoretical Physics

April 28 to May 2 (2025), Niterói, RJ, Brazil

CA1: A modern description of dense matter
Palestrante: Veronica Dexheimer (Kent State University, EUA)

CA2: Hot and dense QCD in colliders
Palestrante: Carlos Alberto Salgado (Universidade de Santiago de Compostela, Espanha)

CA3: Effective Field Theories
Palestrante: Laura Tolos (Institute of Space Sciences, Espanha)

CA4: Nuclear reactions
Palestrante: Chloe Hebborn (Michigan State Uni - EUA)

Conferences in Brazil

ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research
INSTITUTO PRINCIPIA

9TH CONFERENCE ON CHIRALITY, VORTICITY AND MAGNETIC FIELDS IN QUANTUM MATTER

July 7 – 11, 2025
at Principia Institute, São Paulo, Brazil

SPEAKERS

Alejandro Ayala (UNAM, Mexico)
Francesco Becattini (Florence, Italy)
Maxim Chernodub (Université de Tours, France)
Ricardo Farias (UFSM, Brazil)
Eduardo Fraga (UFRJ, Brazil)
Kenji Fukushima (University of Tokyo, Japan)
Luis Hernandez (UAM, Mexico)
Huan Zhong Huang (UCLA, USA, and Fudan, China)
Mei Huang* (UCAS, Beijing, China)
Dmitri Kharzeev* (Stony Brook Uni. and BNL, USA)
Gastão Krein (UNESP, Brazil)
Jinfeng Liao (Indiana University, USA)
Michael Lisa (Ohio State University, USA)
Marcelo Loewe (Universidad San Sebastian, Chile)
Enrique Muñoz (PUC, Chile)
Fernando Navarra (USP, Brazil)
Alfredo Raya (UMSNH, Mexico)
Norberto Scoccola (UNSAM, Argentina)
Igor Shovkovy (Arizona State University, USA)
Aihong Tang (BNL, USA)
Maria Elena Tejeda (UniCol, Mexico)
Cristian Villavicencio (UBB, Chile)
Sergei Voloshin (Wayne State, USA)

*To be confirmed

This event is the 9th conference in the series on Chirality, Vorticity, and Magnetic Field in Heavy-Ion Collisions, which has extended in 2024 to include other domains of Quantum Matter.

This one-week conference brings together researchers from different domains of physics, both from theoretical and experimental communities, to discuss new avenues in exploring chiral and vortical phenomena and associated electromagnetic effects in strongly interacting matter, heavy-ion collisions, superconductors, (magneto-)hydrodynamical systems and astrophysical objects.

Registration deadline:
May 17, 2025

Online registration and more information:
ictp-saifr.org/ccvmfqm2025

ICTP SAIFR · FAPESP · ICTP · unesp · IFT-UNESP · INSTITUTO PRINCIPIA

ORGANIZERS
Ana Mizher (IFT-UNESP/USP, Brazil)
Giorgio Torrieri (UNICAMP, Brazil)
Dirk Rischke (Goethe Universitat, Germany)

Organizers:

- **Ana Mizher** (IFT-UNESP/USP, Brazil)
- **Giorgio Torrieri** (UNICAMP, Brazil)
- **Dirk Rischke** (Goethe Universitat, Germany)

Thank you for your attention!