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Southampton SO17 1BJ, United Kingdom

Dense QCD matter and neutron stars from holography

with C. Ecker, N. Kovensky, O. Papadopoulos, A. Poole

KS, JHEP 09, 112 (2020) (quarkyonic matter at T, μ_B)

KS, SciPost Phys. 11, 029 (2021)
(introduce isospin asymmetric baryonic matter)

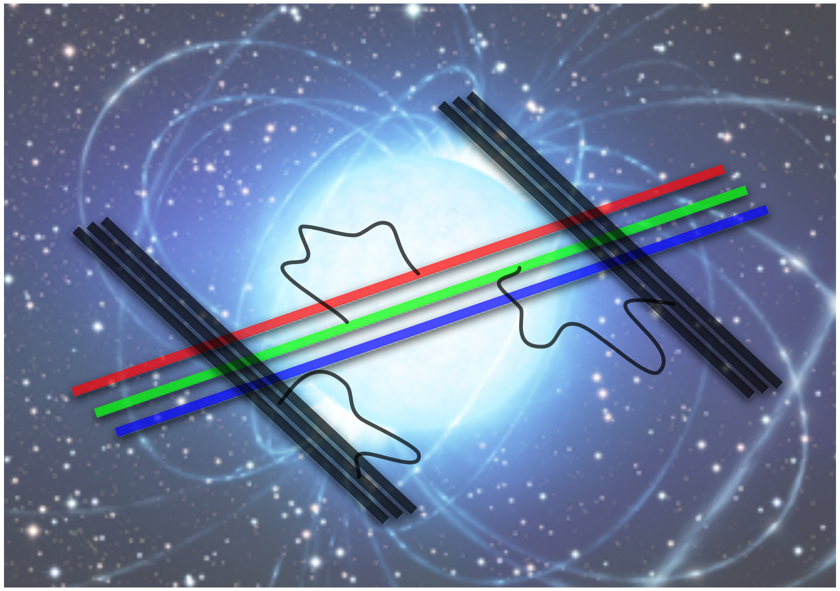
KPoS, PRD 105, 034022 (2022) (construct neutron star)

KPoS, SciPost Phys. Proc. 6, 019 (2022)
(predictions from holographic neutron star)

KPoS, SciPost Phys. 15, 162 (2023)
(baryons + meson condensates at μ_B, μ_I)

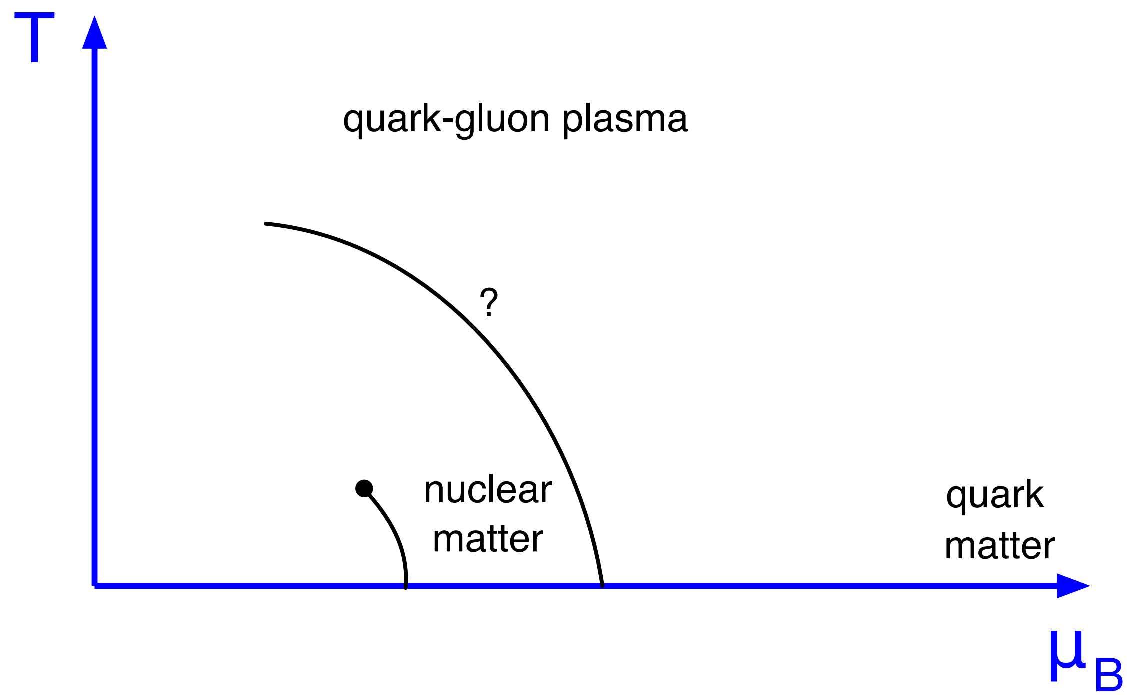
KS, JHEP 10, 133 (2024) (phases at T, μ_I)

EKPaS, arXiv:2509.02216 (softening nuclear matter)



A. Schmitt (foreground); ESO/L. Calçada (neutron star)

Motivation: Phases of QCD and neutron stars



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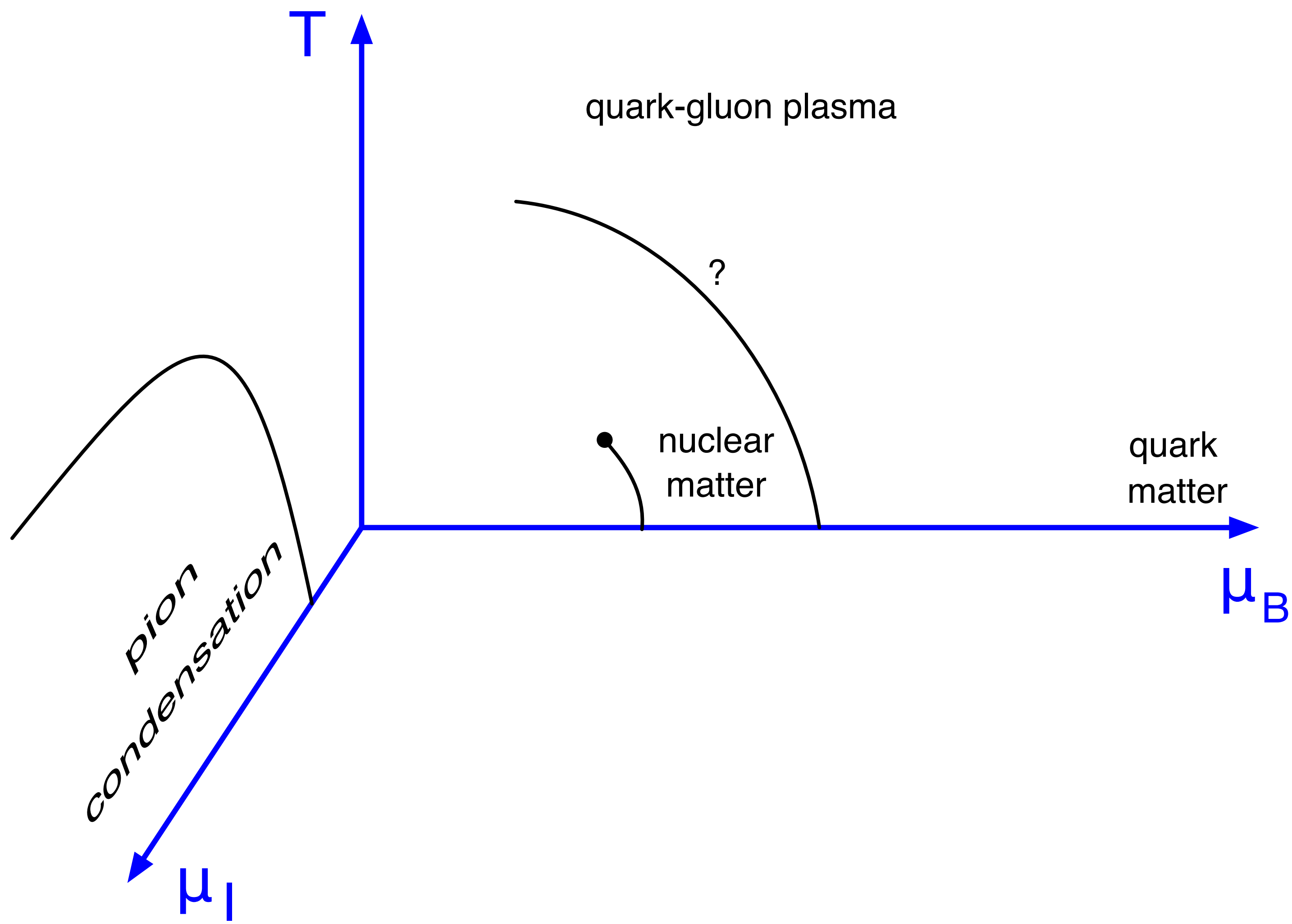

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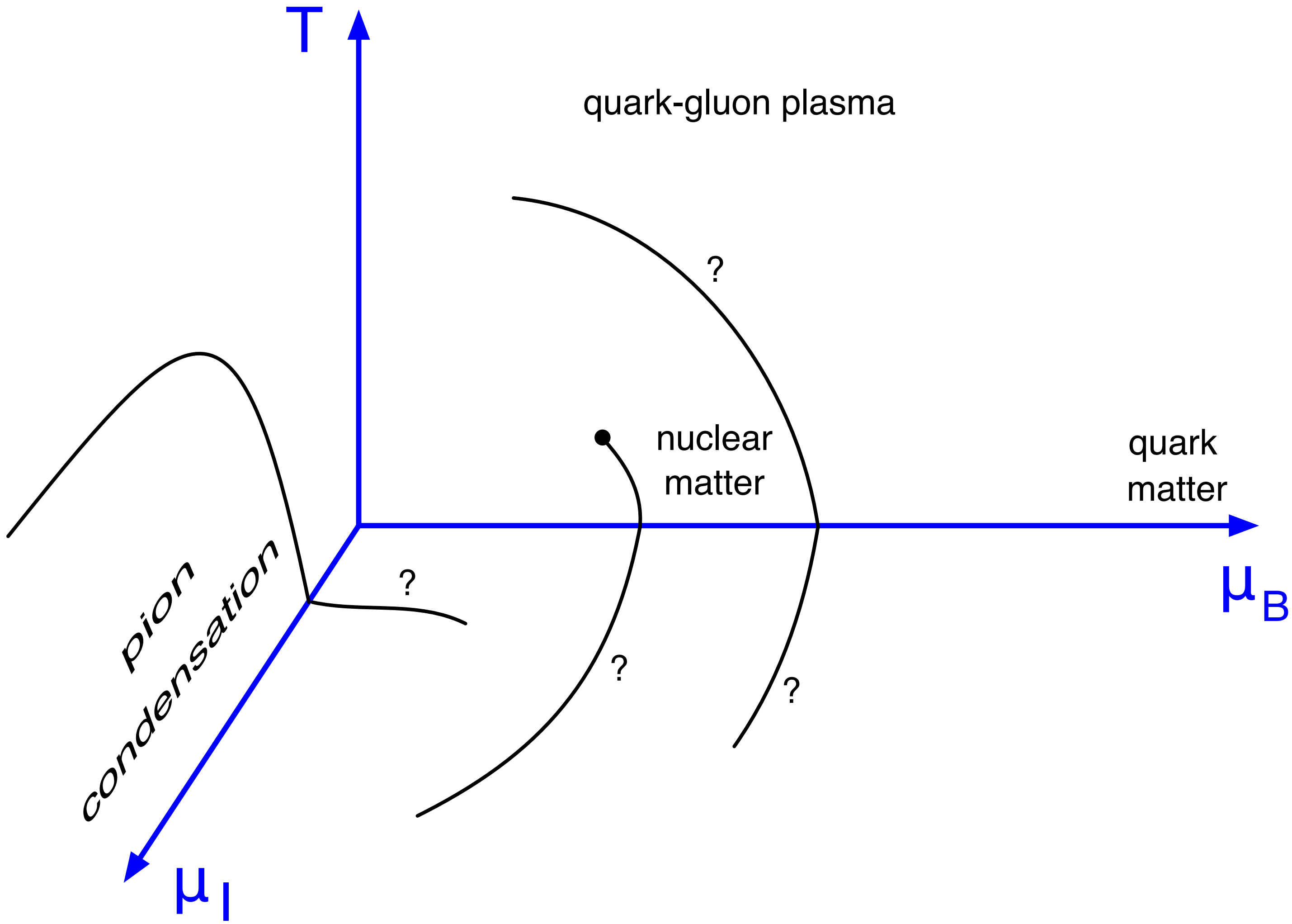

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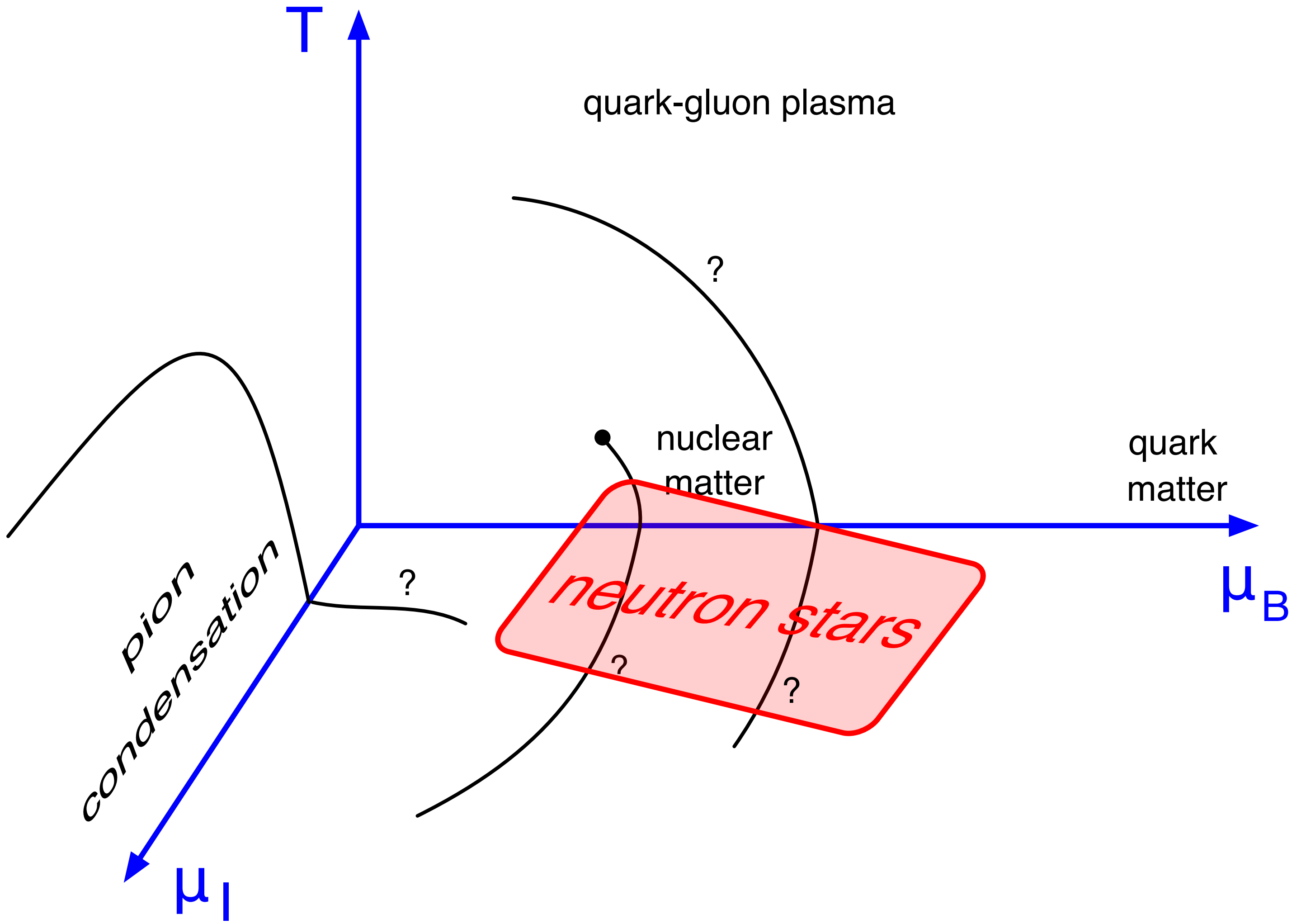

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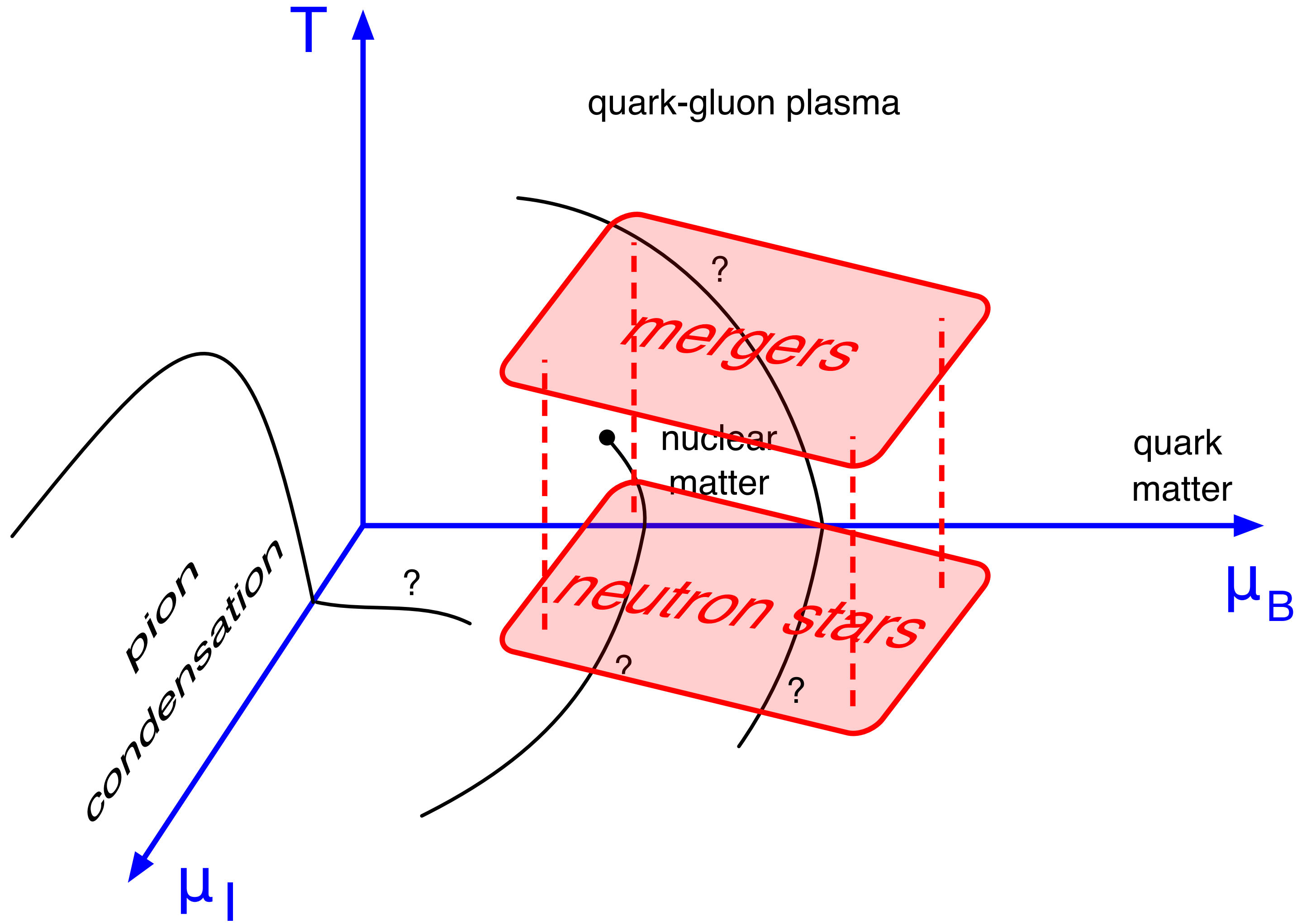
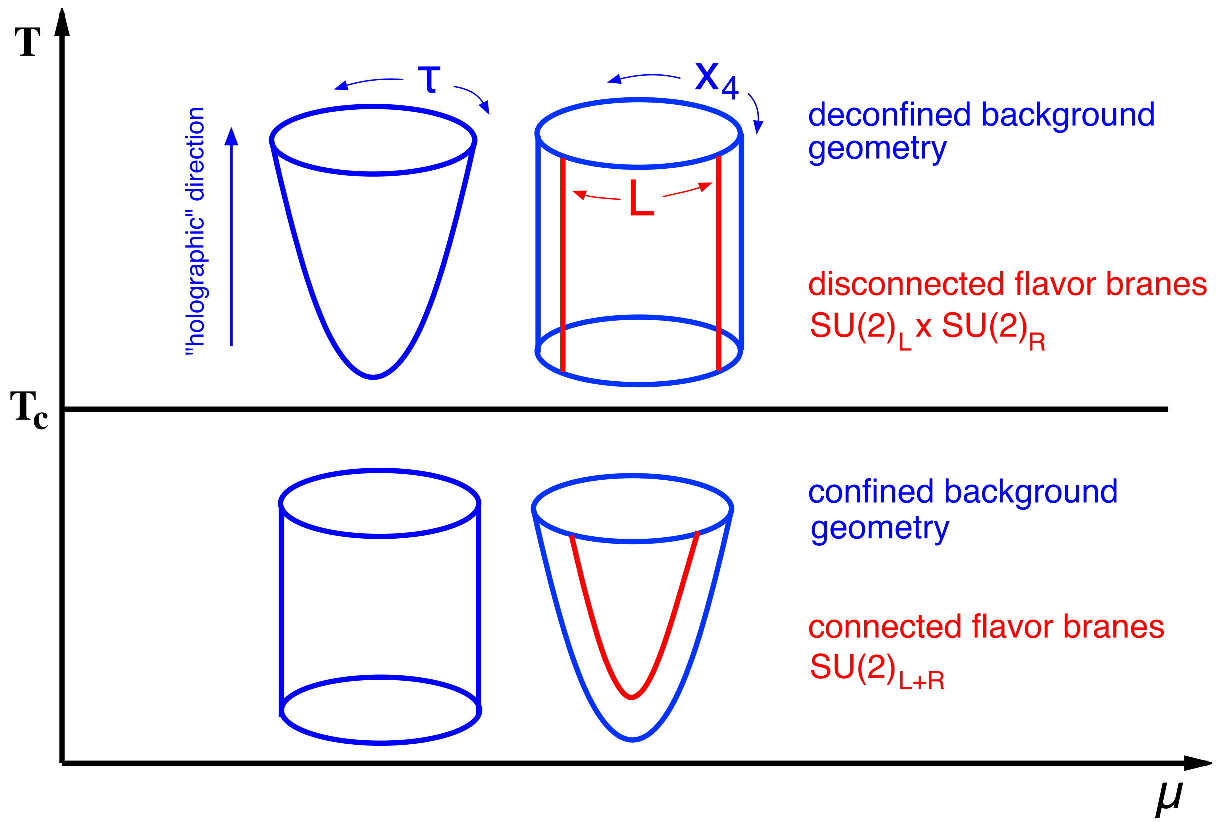


Use holography: Witten-Sakai-Sugimoto model

background from N_c D4-branes and compact x_4: E. Witten, Adv. Theor. Math. Phys. 2, 505 (1998)

add N_f D8-$\overline{\text{D8}}$ branes: T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)

- top-down approach with only 2 (or 3) parameters: λ, M_{KK} (and L)
- supersymmetry and conformal symmetry broken
- successfully applied to meson, baryon, glueball spectra



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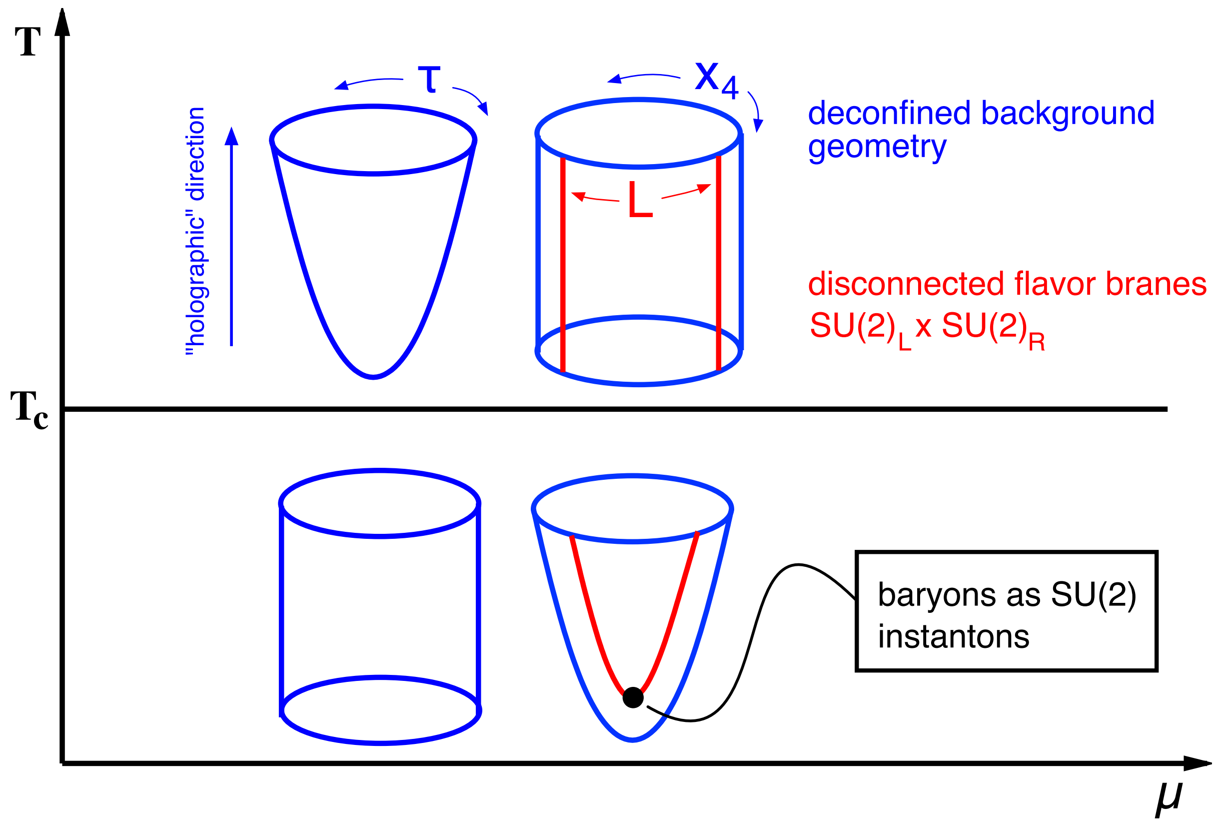

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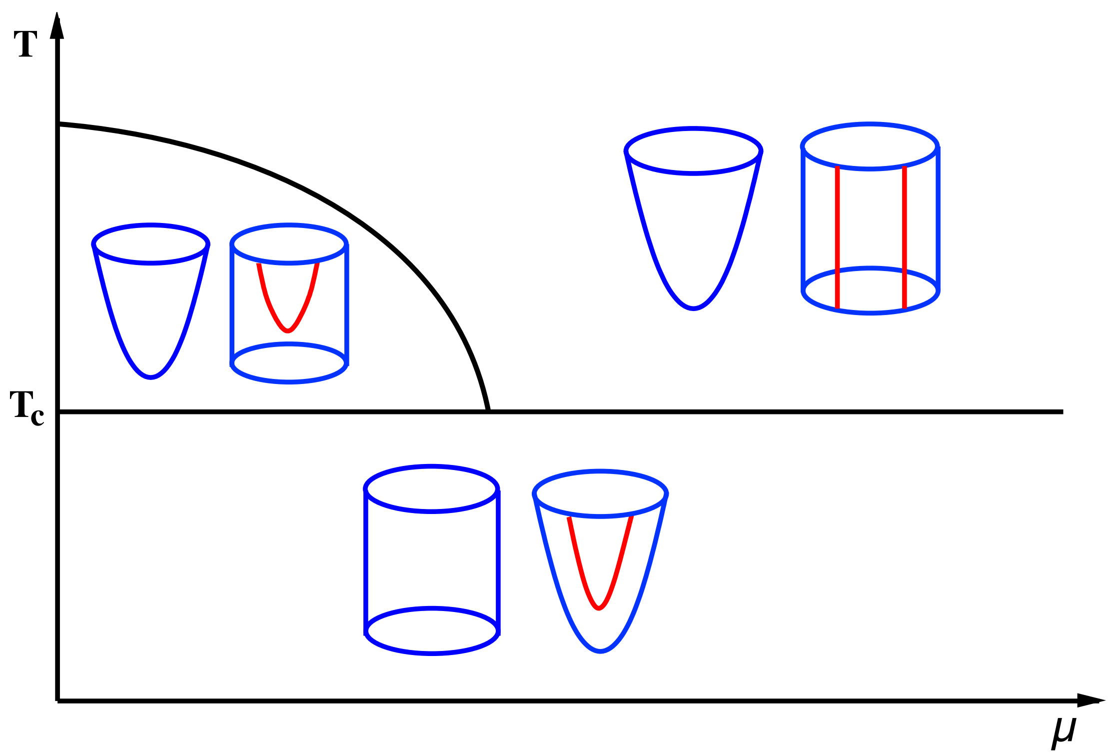

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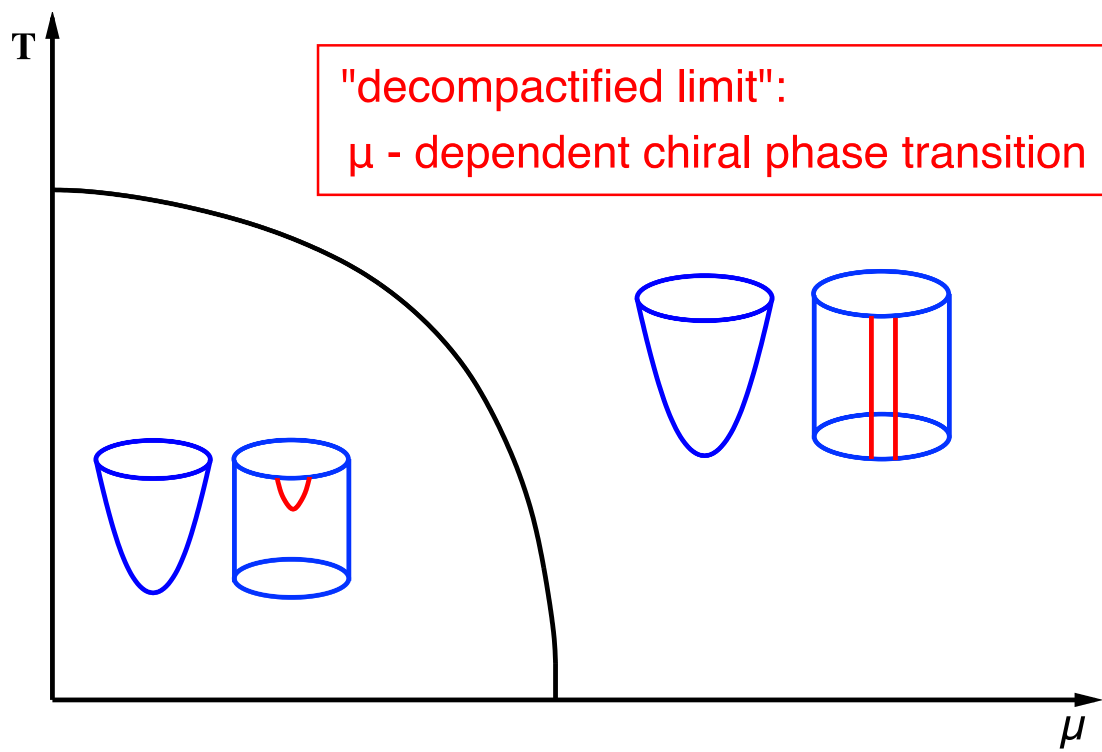
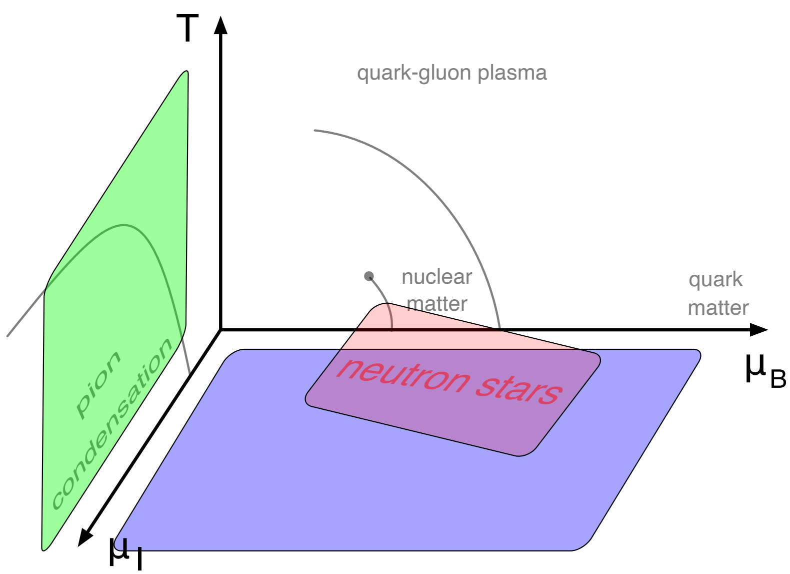


Results

1. thermal pion condensation (decompactified limit), compare to lattice QCD
   N. Kovensky and A. Schmitt, JHEP 10, 133 (2024)

2. baryons, pions and rho mesons (confined geometry)
   N. Kovensky, A. Poole, A. Schmitt, SciPost Phys. 15, 162 (2023)

3. neutron stars (confined geometry)
   N. Kovensky, A. Poole, A. Schmitt, Phys. Rev. D 105, 034022 (2022)



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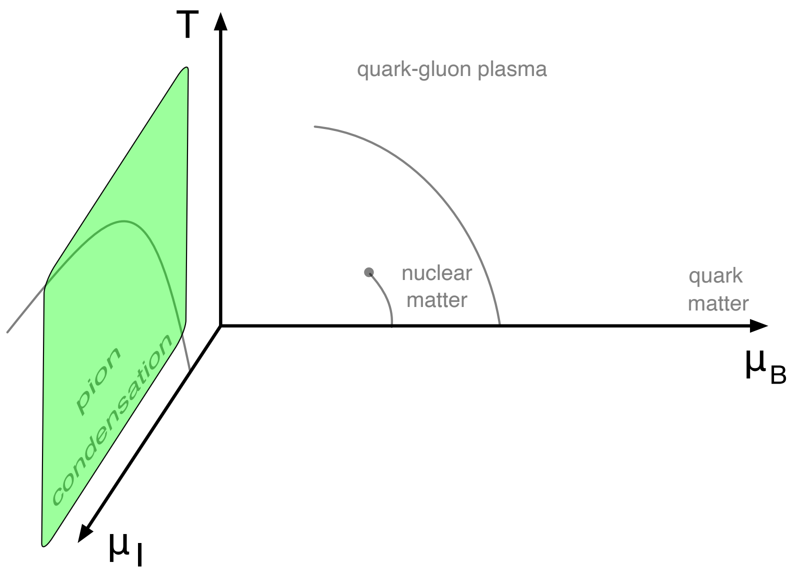


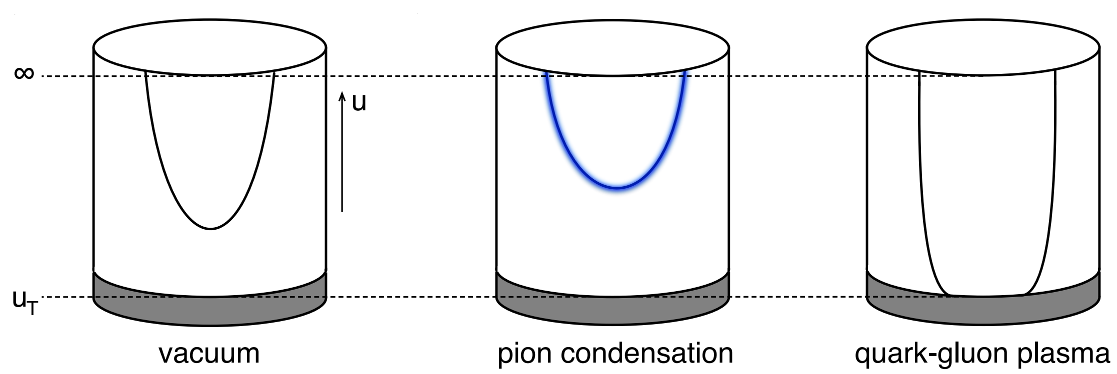
Thermal pion condensation: setup

N. Kovensky and A. Schmitt, JHEP 10, 133 (2024)

- DBI action on D8-branes for $U(2)$ gauge fields, $F_{\mu\nu} = \hat{F}_{\mu\nu} + F^a_{\mu\nu}\sigma_a$
- T-dependent metric
- add effective mass term for m_π
- include pion condensate θ in holonomy of A_z
  $\rightarrow$ boundary conditions via global rotation
- chemical potentials in boundary

$$\begin{aligned} \hat{A}_0(\pm\infty) &= \mu_B \\ A^1_0(\pm\infty) &= \mp\mu_I \sin\theta \\ A^2_0(\pm\infty) &= \pm\mu_I \sin\theta \\ A^3_0(\pm\infty) &= \mu_I \cos\theta \end{aligned}$$

- for given μ_B, μ_I, T solve classical EOMs for $\hat{A}_0$, A^a_0, and embedding x_4, and minimize free energy with respect to θ
- compare free energies (on-shell action) of different phases

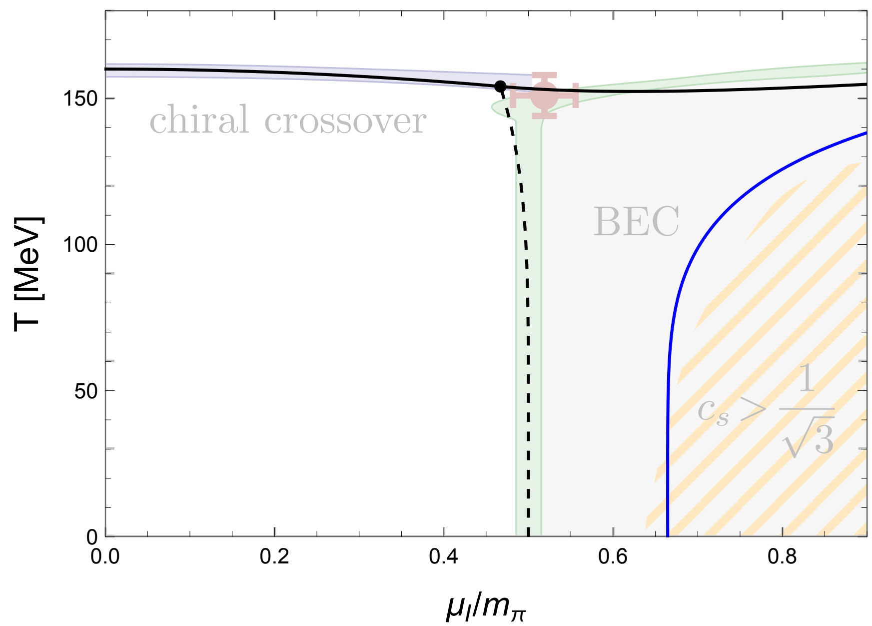


Thermal pion condensation

N. Kovensky and A. Schmitt, JHEP 10, 133 (2024)

comparison to lattice QCD: B. B. Brandt, F. Cuteri and G. Endrődi, JHEP 07, 055 (2023)

parameters L, $\lambda/(M_{\rm KK}L)$ fitted to f_π, $T_c(\mu_I = 0)$
(and physical pion mass m_π)



1st order chiral phase transition, 2nd order onset of pion condensation

speed of sound $c_s^2 > 1/3$ for large μ_I

Thermal pion condensation

N. Kovensky and A. Schmitt, JHEP 10, 133 (2024)

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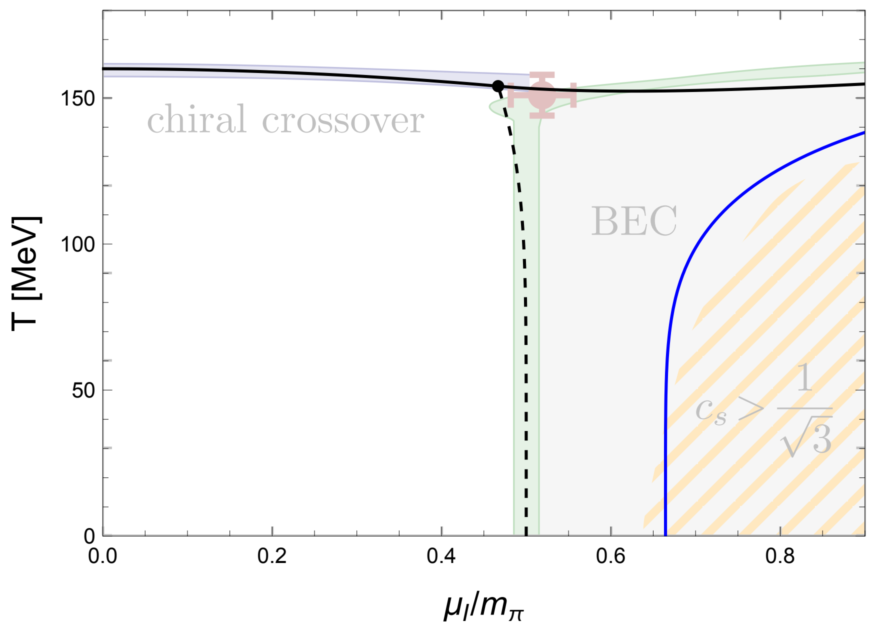

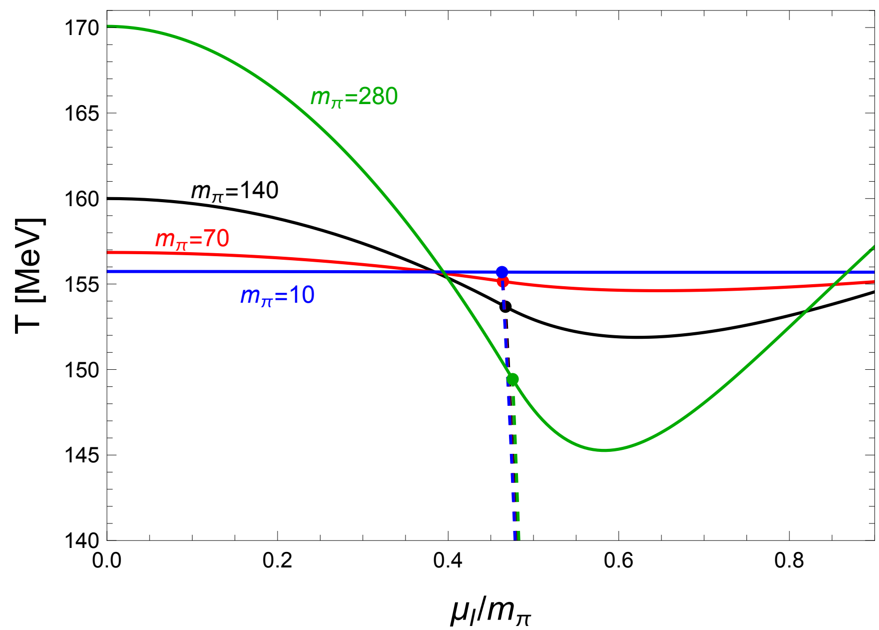

variation of m_π

Thermal pion condensation

N. Kovensky and A. Schmitt, JHEP 10, 133 (2024)

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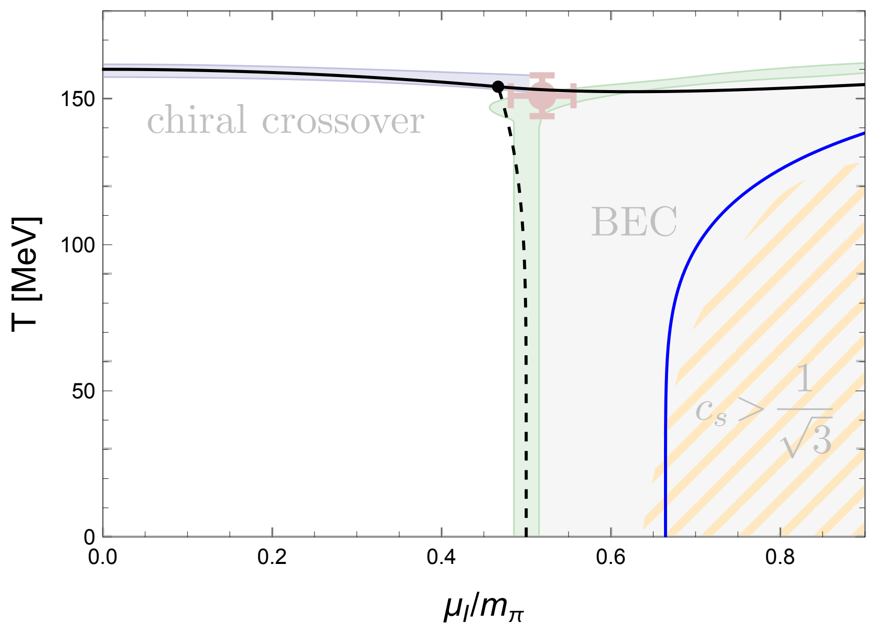
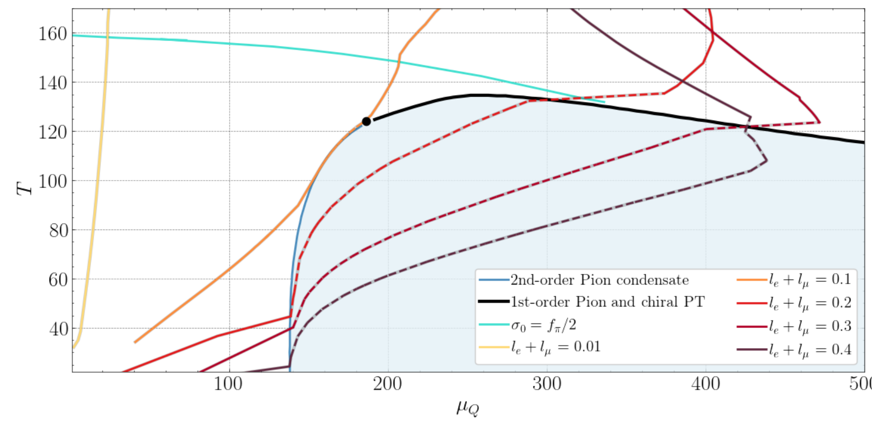


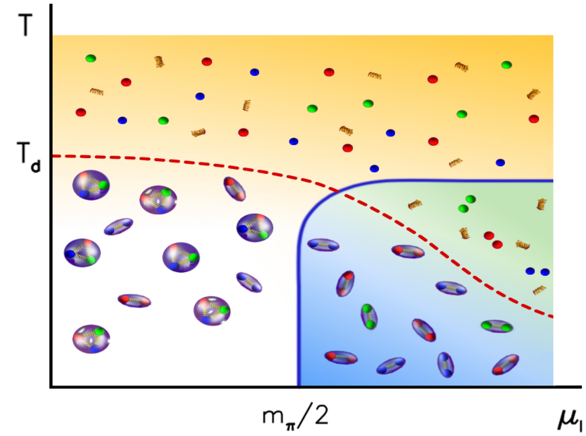


O. Ferreira *et al.*, arXiv:2507.06518 [hep-ph]

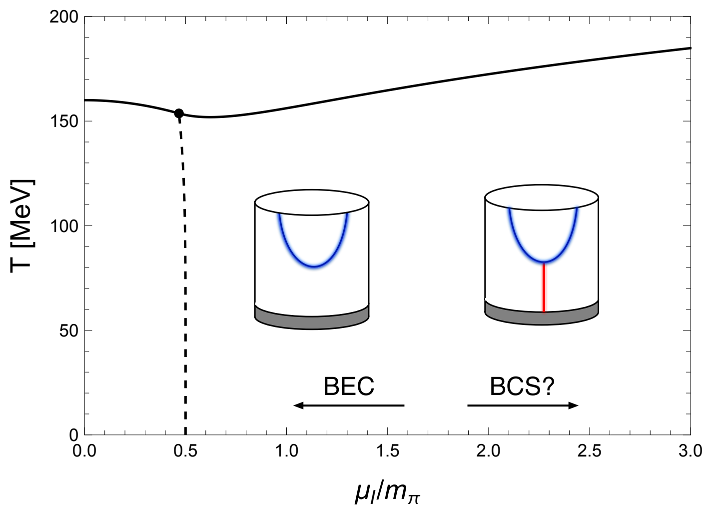
1st-order transition?

Thermal pion condensation: BEC-BCS crossover?

QCD conjecture: Crossover from condensed pions (BEC) to weakly coupled $\langle \bar{u}\gamma^5 d\rangle$ Cooper pairs (BCS)?
D.T. Son, M.A. Stephanov, PRL 86, 592 (2001)



B. B. Brandt *et al.*,PRD 97, 054514 (2018)

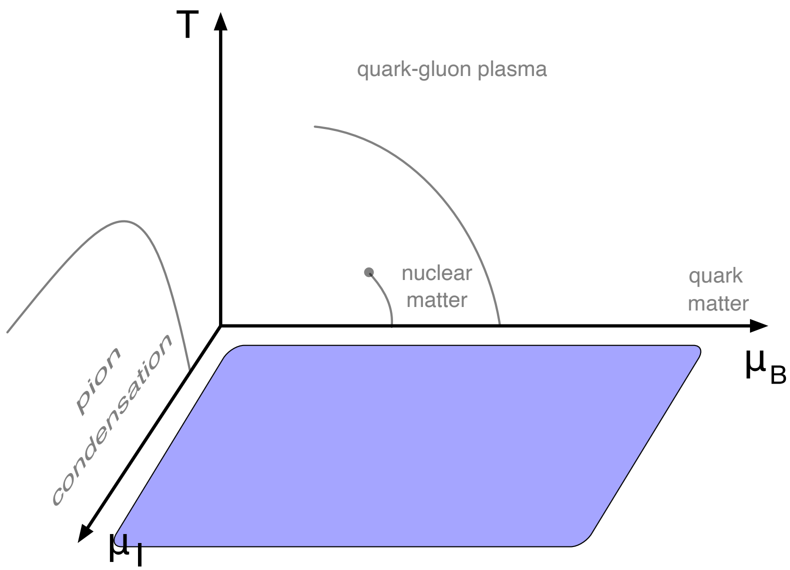


Add string sources
→ coexistence of quarks (infrared) and pion condensate
→ analogous to quarkyonic matter
N. Kovensky, A. Schmitt, JHEP 09 (2020), 112

→ solutions exist, but do not seem to be energetically favored
N. Kovensky and A. Schmitt, work in progress

Results

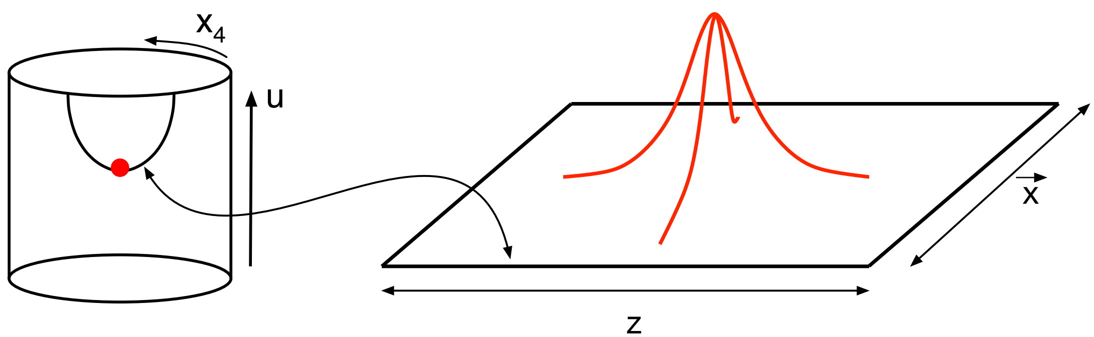
2. baryons, pions and rho mesons (confined geometry)
N. Kovensky, A. Poole, A. Schmitt, SciPost Phys. 15, 162 (2023)



Adding baryons

baryons in AdS/CFT: wrapped D-branes with N_c string endpoints
E. Witten, JHEP 9807, 006 (1998); D. J. Gross, H. Ooguri, PRD 58, 106002 (1998)

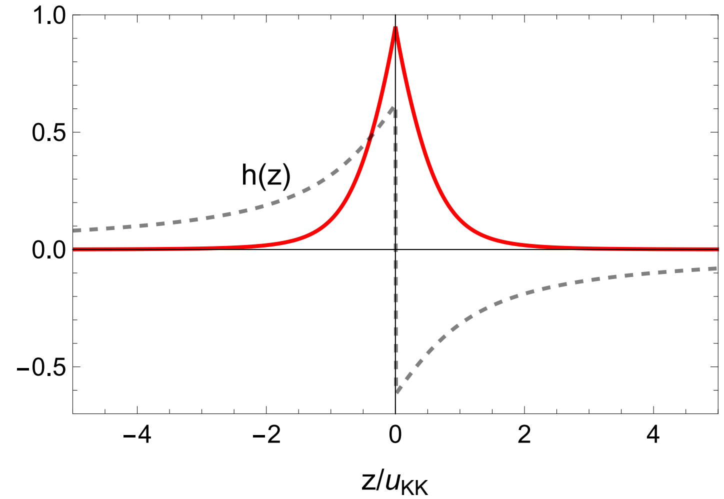
baryons in Sakai-Sugimoto: D4-branes wrapped on S^4
equivalently: instantons on D8-branes ($\to$ baryon number from Chern-Simons term)
T. Sakai, S. Sugimoto, Prog. Theor. Phys. 113, 843-882 (2005)
H. Hata, T. Sakai, S. Sugimoto, S. Yamato, Prog. Theor. Phys. 117, 1157 (2007)



here: dense many-baryon system
$\to$ homogeneous ansatz
M. Rozali, *et al.*, J. Wu, JHEP 0801, 053 (2008)

$$A_i^a(\vec{x}, z) = h_i(z)\delta_i^a$$

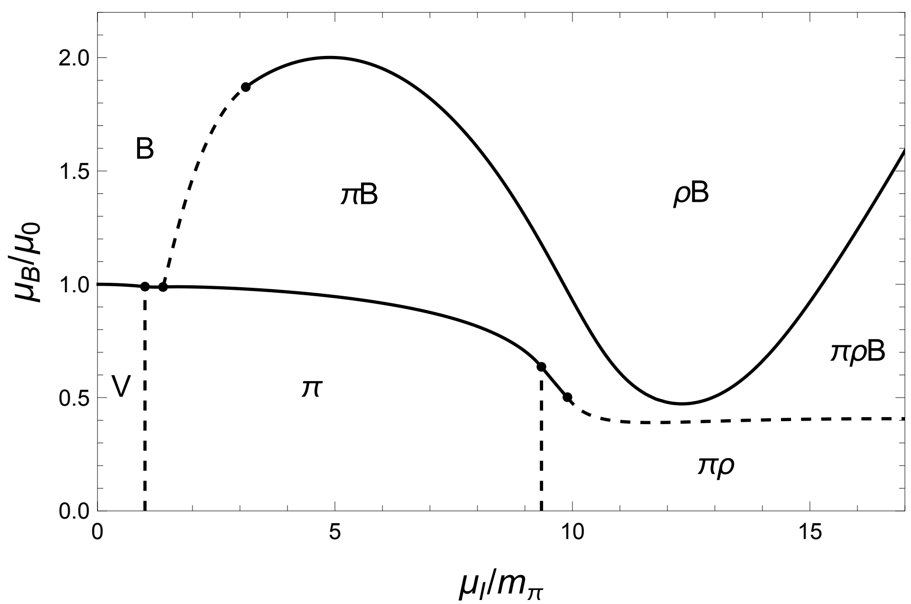
requires discontinuity in $h_i(z)$
different h_i's $\to$ isospin asymmetry



Isospin-asymmetric (baryonic) matter: phase diagram

N. Kovensky, A. Poole, A. Schmitt, SciPost Phys. 15, 162 (2023)

parameters fitted to reproduce m_π, m_ρ, f_π



no baryons at low μ_B

O. Aharony, K. Peeters, J. Sonnenschein and M. Zamaklar, JHEP 02, 071 (2008)

D. T. Son and M. A. Stephanov, PRL 86, 592-595 (2001)

effective pion mass increases in baryonic medium

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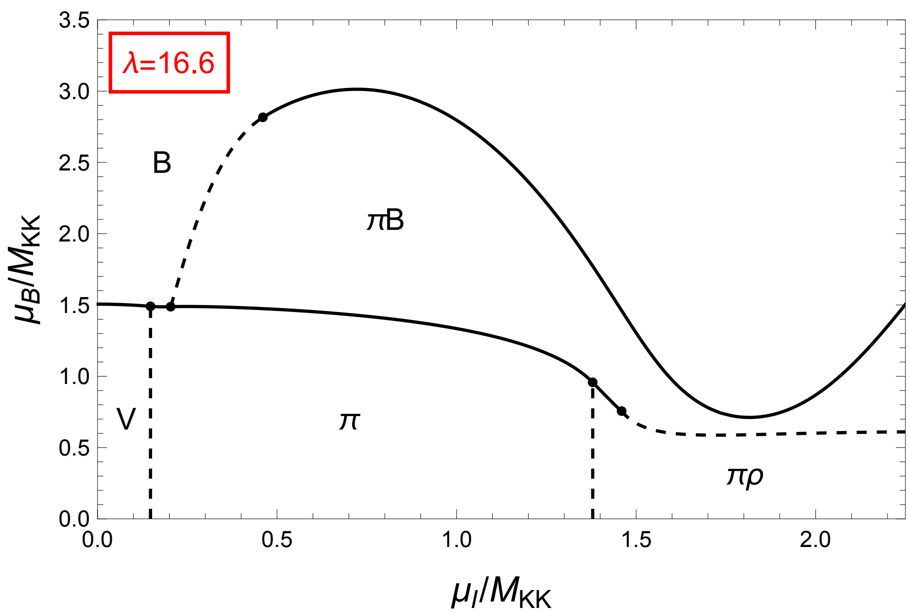

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πB phase disfavored for large couplings (keeping m_π/m_ρ fixed)

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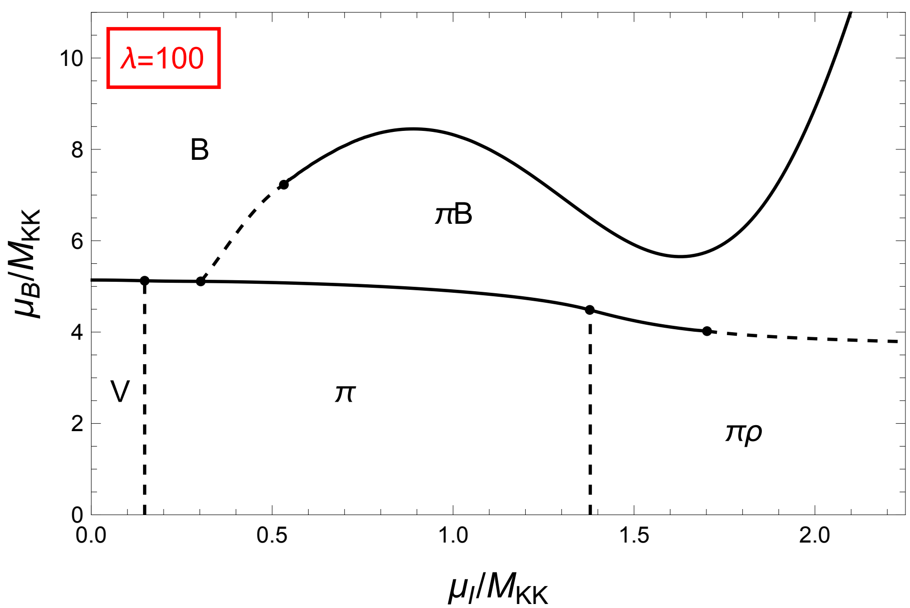

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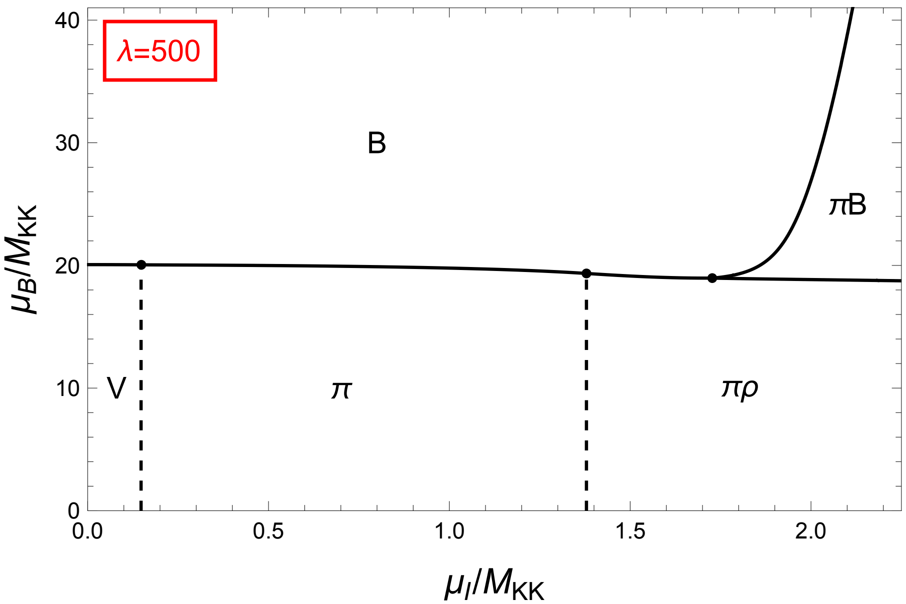

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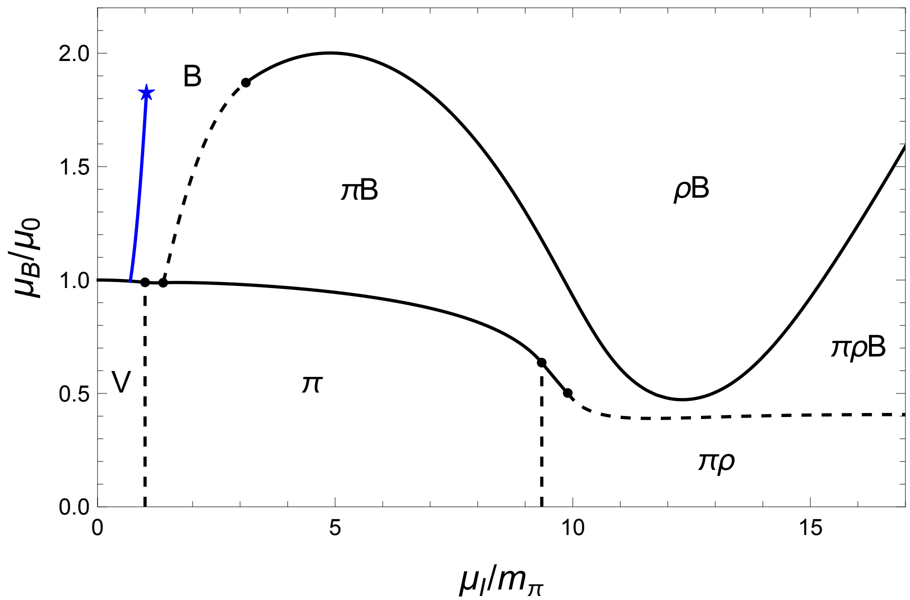

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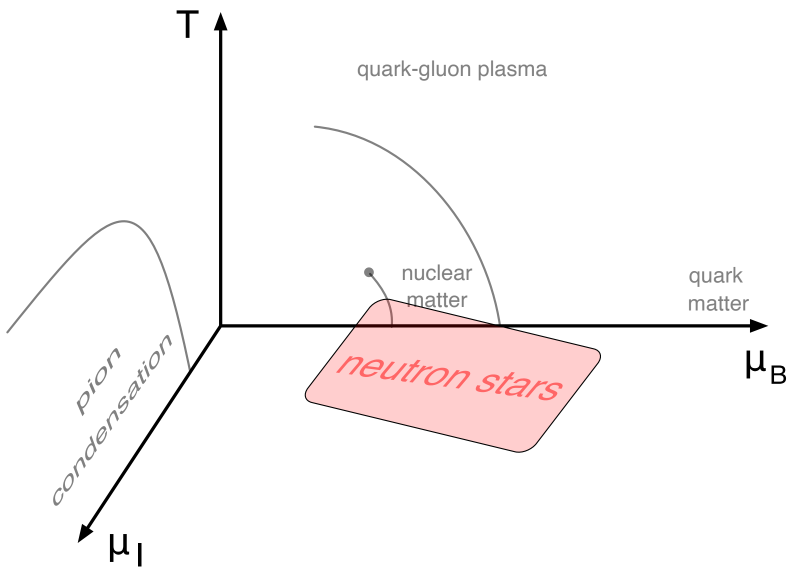
D. T. Son and M. A. Stephanov, PRL 86, 592-595 (2001)

β-equilibrium + charge neutrality

$\rightarrow$ no pion condensation in neutron stars

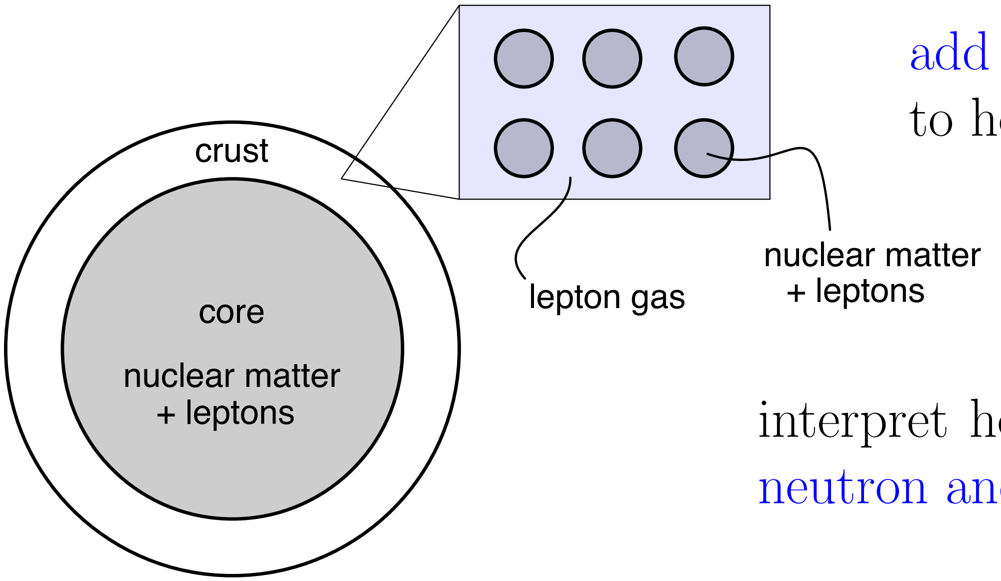
Results

3. neutron stars (confined geometry)
N. Kovensky, A. Poole, A. Schmitt, Phys. Rev. D 105, 034022 (2022)



Building a neutron star from holography (page 1/4)

N. Kovensky, A. Poole, A. Schmitt, Phys. Rev. D 105, 034022 (2022)



add leptons (electrons + muons) to holographic nuclear matter

interpret holographic isospin components as neutron and proton

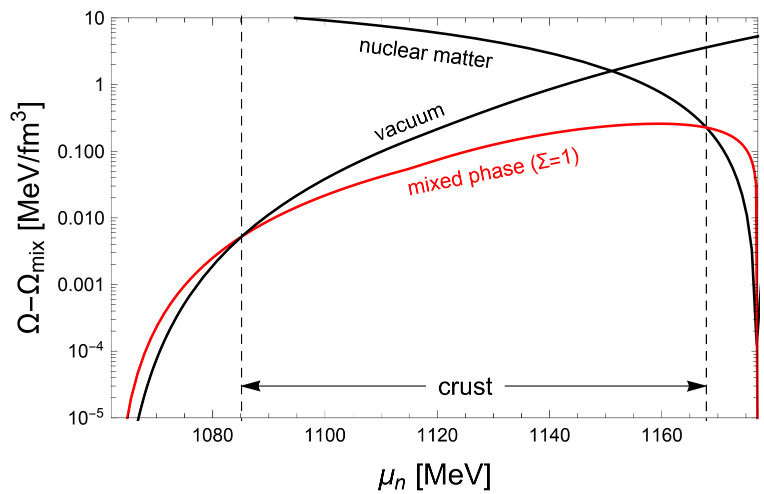
construct uniform (locally neutral) and mixed (globally neutral) phases in β-equilibrium $\mu_n = \mu_p + \mu_e$

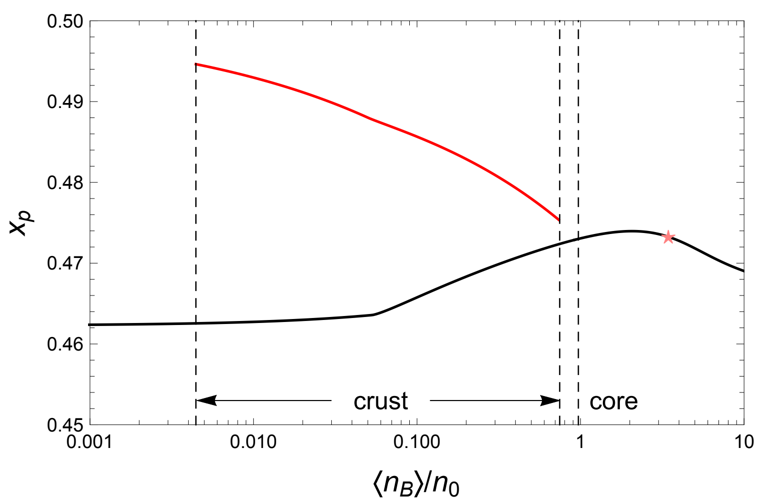
use Wigner-Seitz approximation and step-like interfaces (surface tension Σ as input)

dynamic calculation of clusters and crust-core transition

Building a neutron star from holography (page 2/4)

mixed phase energetically preferred for small μ_n





large-N_c artifact:
continuous isospin spectrum
→ large proton fraction
→ muons in inner crust

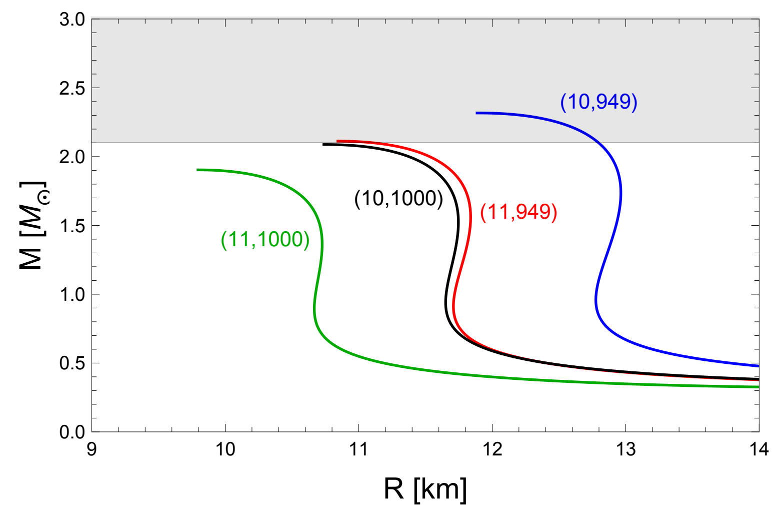
possible improvement: different N_c scaling of μ_I

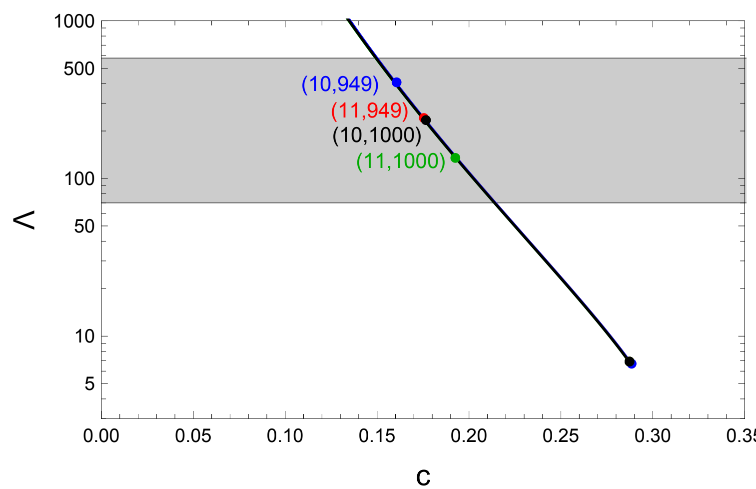
L. Bartolini, S. B. Gudnason, SPP 16, 156 (2024)

Building a neutron star from holography (page 3/4)

couple to gravity ("TOV equations") → mass-radius curves
for different parameter pairs $(\lambda, M_{\mathrm{KK}})$ with $\Sigma = 1\,\mathrm{MeV/fm}^2$

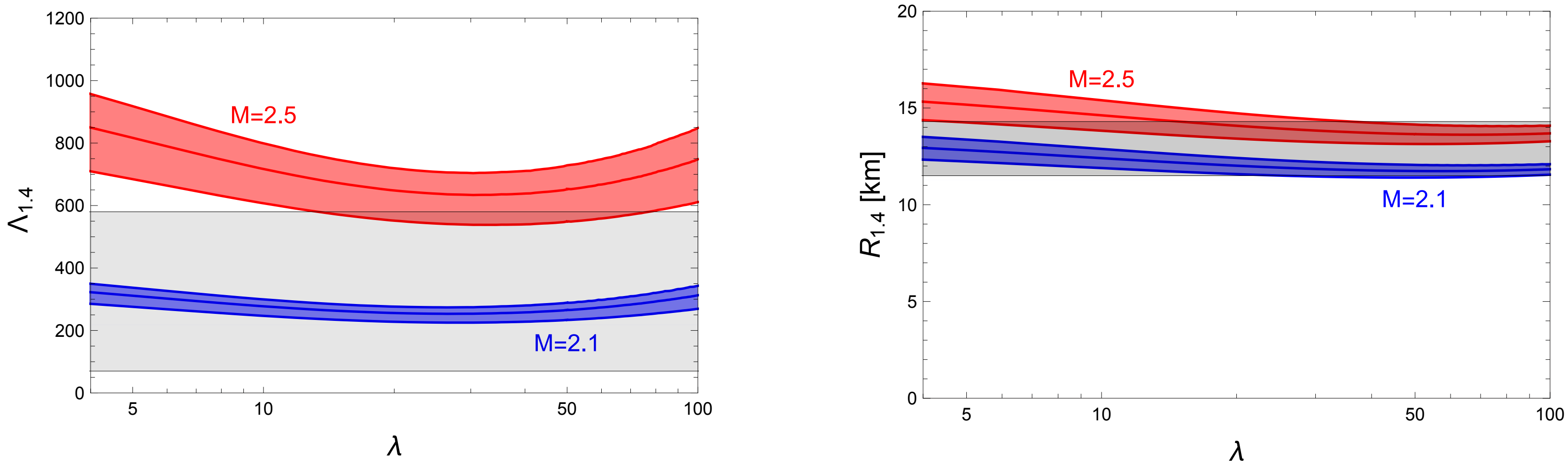
fit to	λ	M_{KK}
f_π, m_ρ	16.63	949 MeV
σ, m_ρ	12.55	949 MeV
n_0, E_B	7.09	1000 MeV





realistic maximal masses and
1.4-solar-mass deformabilities

Building a neutron star from holography (page 4/4)



astrophysical constraints from GW170817 + NICER

2.5-solar-mass stars barely possible

parameter-independent prediction for
lower bounds on $\Lambda_{1.4}$ and radius $R_{1.4}$

extract constraints systematically: N. Kovensky, A. Poole, A. Schmitt, SPP Proc. 6, 019 (2022)

other holographic approaches to compact stars (combined with "traditional" methods), see reviews
M. Järvinen, EPJC 82, 282 (2022)
C. Hoyos, N. Jokela and A. Vuorinen, Prog. Part. Nucl. Phys. 126, 103972 (2022)

Softening holographic nuclear matter (page 1/2)

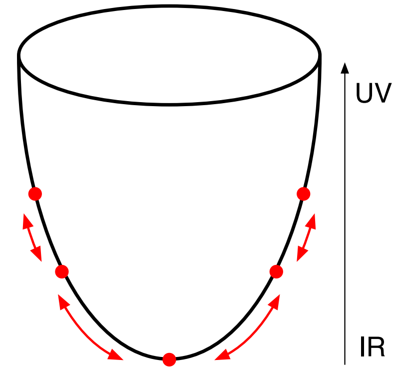
dynamical location(s) of discontinuitie(s)

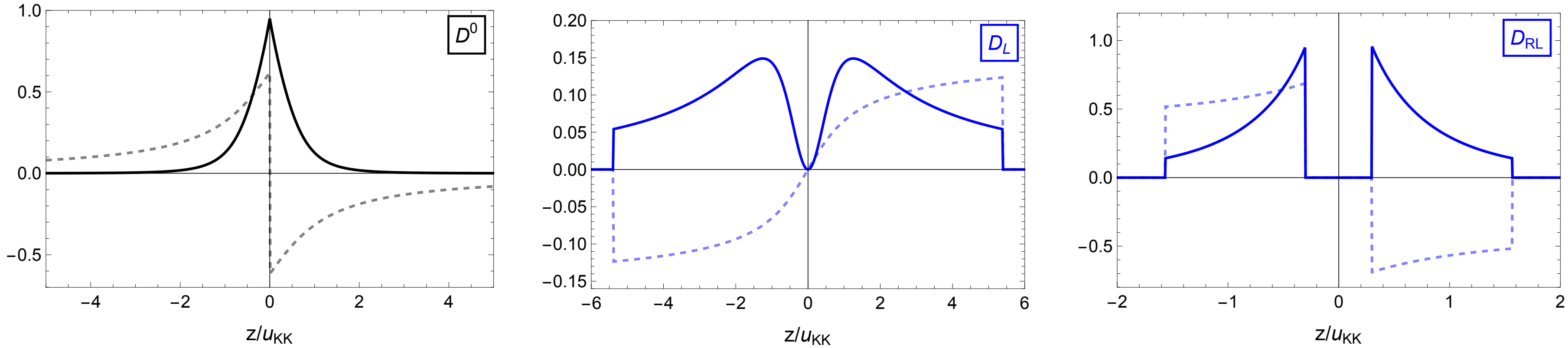
M. Rozali, H. H. Shieh, M. Van Raamsdonk, J. Wu, JHEP 01, 053 (2008)

F. Preis and A. Schmitt, JHEP 07, 001 (2016) (instanton approach)

M. Elliot-Ripley, P. Sutcliffe and M. Zamaklar, JHEP 10, 088 (2016)

J. Cruz Rojas, T. Demircik and M. Järvinen, Symmetry 15, 331 (2023)



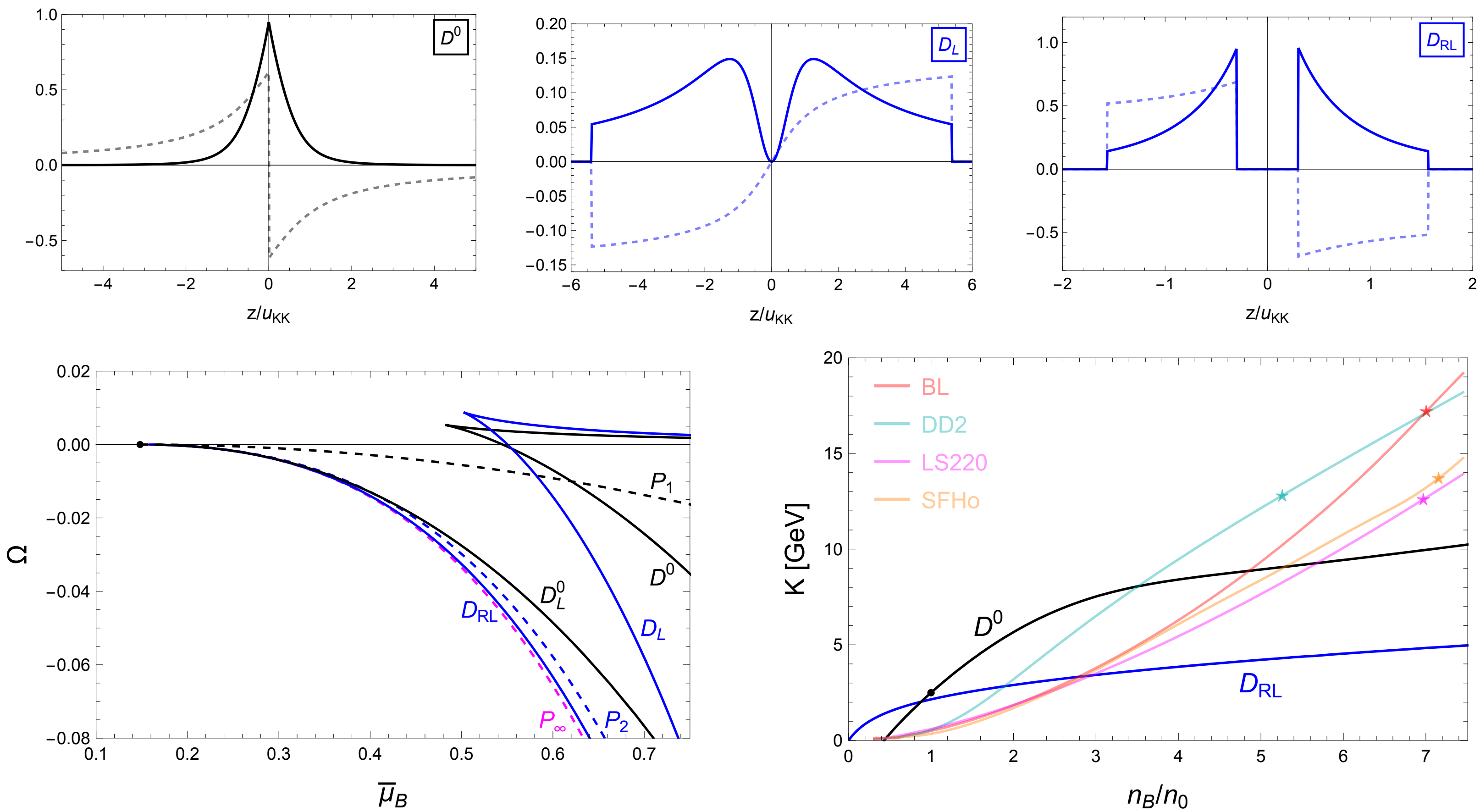


systematic study of all solutions with ≤ 4 discontinuities ($\mu_I = 0$)

C. Ecker, N. Kovensky, O. Papadopoulos, A. Schmitt, arXiv:2509.02216

Softening holographic nuclear matter (page 2/2)

C. Ecker, N. Kovensky, O. Papadopoulos, A. Schmitt, arXiv:2509.02216



configuration D^0 used for neutron stars not favored and too stiff at saturation

block-like structure D_{RL} preferred, becomes pointlike for $n_B \to 0$

second layer softens nuclear matter

Summary

- holographic Witten-Sakai-Sugimoto model gives a "QCD-like" theory with all necessary ingredients (chiral transition, baryons, pion condensation, ...)

- introducing isospin-asymmetric (baryonic) matter allows us to
  - study phase structure for finite μ_B, μ_I, T
  - construct neutron stars from a single model

Outlook

- improve holographic crust (pasta structures, inner crust)
- include magnetic field
  pointlike baryons: F. Preis, A. Rebhan and A. Schmitt, JPG 39, 054006 (2012)
- compute surface tension dynamically
- include strangeness (kaon condensation, hyperons)
- compute transport properties
  C. Ecker, N. Kovensky, O. Papadopoulos, A. Schmitt, work in progress
  D3-D7 and VQCD: C. Hoyos *et al.*, PRD 105, 066014 (2022)
- use improved (block-like) nuclear matter for quarkyonic phase
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- finite temperature equation of state (→ neutron star merger)