Neutron stars and holography

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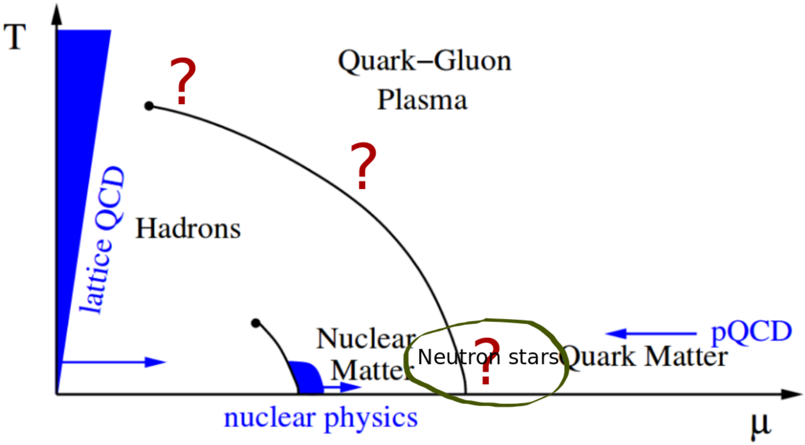
Réunion groupes de travail GdR Resanet et OG

w/ Matti Järvinen, Jere Remes 1809.07770

w/ Paul M. Chesler, Abraham Loeb, Aleksi Vuorinen (to appear)

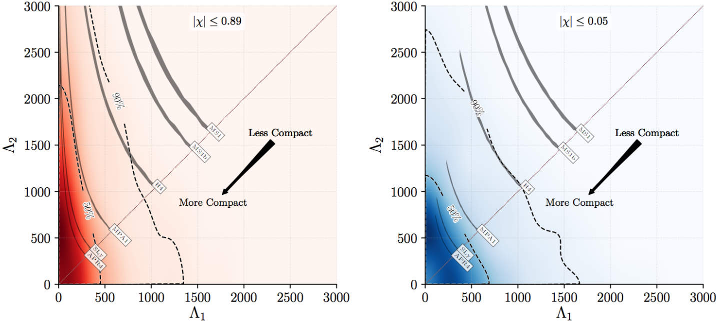
Motivation



- EoS restricted by CET, pQCD, observations & phenomenology, causality & thermodynamics [see also talk by Gulminelli]
- Can we restrict EoS more?

Astrophysical constraints

- Maximal mass $M > 1.97 M_\odot$ [Demorest el al.'10,Antoniadis et al.'13]
- Tidal deformabilities: $70 < \Lambda_{1.4 M_\odot} < 580$ with 90% credence [LIGO/Virgo'17'18'18] [see talk by Porter]
  - Even smaller values preferred by the signal
  - Essentially a bound for neutron star radius
  - Complementary to other radius measurements [see talk by Guillot]

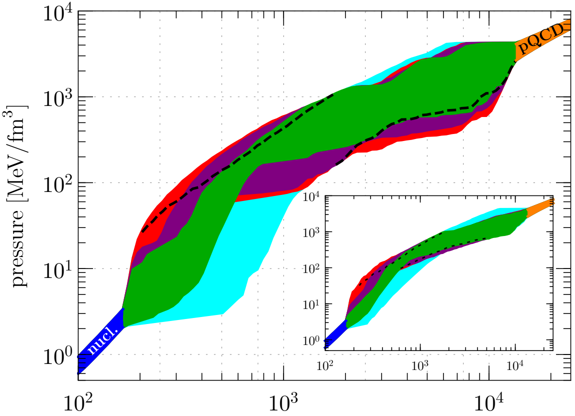


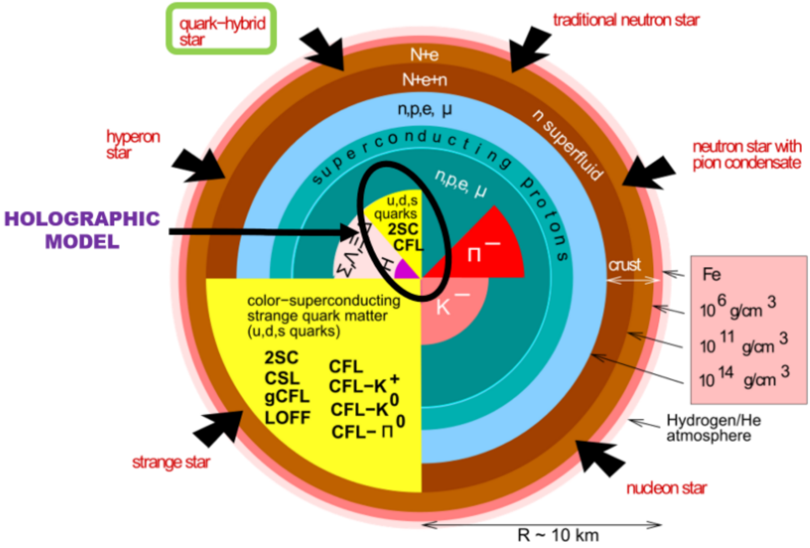
Interpolated equations of state

State of the art for QCD EoS at $T = 0$: interpolations between nuclear EoS and pQCD, constrained by

[Annala-Gorda-Kurkela-Vuorinen'17]

- Speed of sound $< c$
- Highest observed neutron star mass $\approx 2.0\, M_\odot$ (cyan area)
- LIGO observation of neutron star merger GW170817: upper bound on tidal deformability ($\Lambda_{1.4M_\odot} < 800$: red area)





quark–hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
HOLOGRAPHIC MODEL
N+e
N+e+n
n,p,e, μ
n superfluid
superconducting protons
n,p,e, μ
u,d,s quarks
2SC
CFL
Λ
Σ
Ξ
Δ
H
π⁻
K⁻
crust
color−superconducting strange quark matter (u,d,s quarks)
2SC
CSL
gCFL
LOFF
CFL
CFL−K+
CFL−K0
CFL−π0
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
Hydrogen/He atmosphere
strange star
nucleon star
R ~ 10 km

Model building

Top-down phenomenology

- Find a solvable theory (as similar as possible)
- Extrapolate to QCD
- Compare with experiments/observations
- Goal: qualitative features

gives feedback to

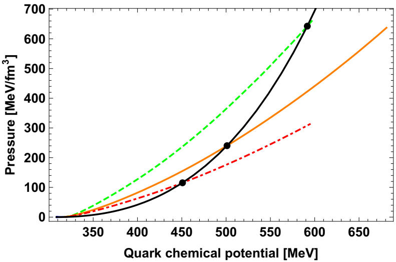
Bottom-up phenomenology

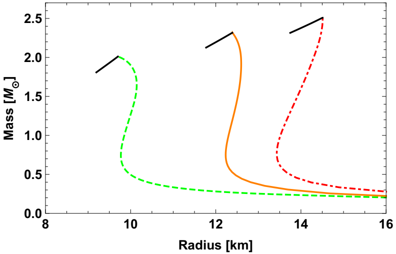
- Construct a model (capturing right degrees of freedom)
- Fit parameters to experiments/observations
- Extrapolate to regime of interest
- Goal: quantitative results

Proof of concept: $\mathcal{N} = 4$ with quenched quarks

- Works really well w/ heavy ion pheno
- Equation of state from D3-D7 top down model:
  $\epsilon = 3p + \frac{\sqrt{3}m^2}{2\pi}\sqrt{p}$

  [Hoyos-NJ-Rodriguez-Vuorinen'16]
- Matched with stiff, intermediate, and soft nuclear EoSs
  [Hebeler-Lattimer-Pethick-Schwenk'13]





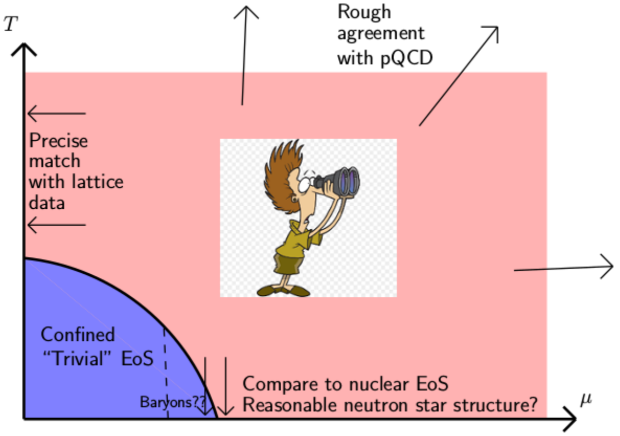
- Neutron stars with "holographic" quark matter core (black curves) are unstable

This talk: what are the results for a more realistic holographic model?

Modeling QCD in bottom-up holography

Idea: constrain holographic model using available data

- In particular, extrapolate lattice data to finite μ
- Complementary to the top-down approach



Goal: a good model of the (deconfined) QCD EoS for all T and μ

Holographic V-QCD: the fusion

A specific model with dynamical quarks, obtained by fusing together:

1. IHQCD: model for glue inspired by string theory (dilaton gravity)

   [Gürsoy-Kiritsis-Nitti,Gubser-Nellore]
2. Add flavor and chiral symmetry breaking via tachyon brane actions

   [Klebanov-Maldacena,Bigazzi-Casero-Cotrone-Kiritsis-Paredes; Gürsoy-Kiritsis-Nitti,Iatrakis-Kiritsis-Paredes]

Consider 1. + 2. in the Veneziano limit with full backreaction:
$N_c \to \infty$ and $N_f \to \infty$ with $x \equiv N_f/N_c$ fixed
$\Rightarrow$ V-QCD models

[Järvinen-Kiritsis'11]

- A very good overall model for physics of QCD over most of the parameter space (N_f/N_c, m_q, T, μ, B, θ ...)

Fix freedom

In the UV ($\lambda \to 0$) match with pQCD:

- Match with perturbative QCD beta function at two loops
- Asymptotic freedom
- Logarithmic flow of the coupling and mass

[Gürsoy-Kiritsis'07,Järvinen-Kiritsis'11]

In the IR ($\lambda \to \infty$): various qualitative constraints

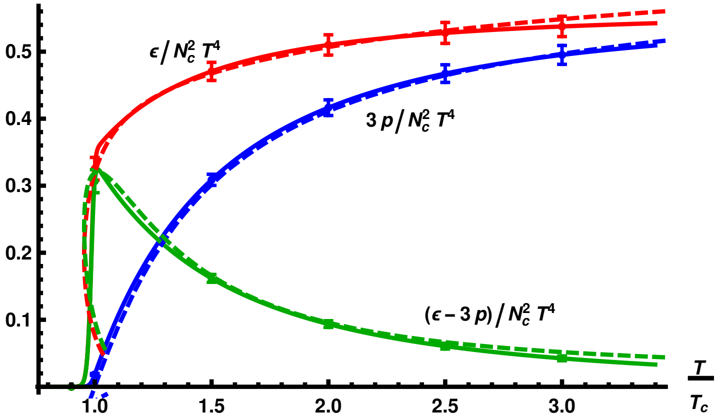
- Linear confinement
- Discrete glueball & meson spectrum
- Linear radial Regge trajectories
- Correct behavior at large quark masses

[Gürsoy-Kiritsis-Nitti'07,Järvinen-Kiritsis'11,Arean-Iatrakis-Järvinen-Kiritsis'13&'16,Järvinen'15]

Final task: determine the potentials in the middle, $\lambda = \mathcal{O}(1)$

- Qualitative comparison to experimental data
- Quantitative fit to lattice QCD (this talk)

Fitting glue sector



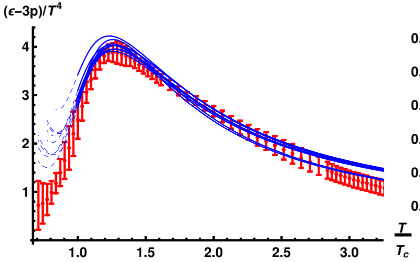
- Revisited the fits by [Gürsoy-Kiritsis-Mazzanti-Nitti'09]
- Fit to large N_c YM lattice data

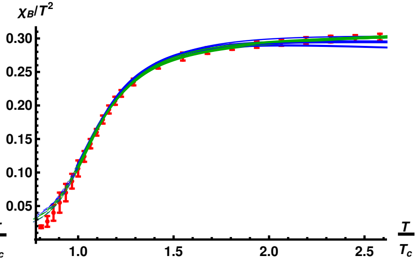
[Panero'09]

Fitting flavor sector

Precision fit of QCD EoS at finite μ and T:

- Fit to lattice data at $\mu = 0$ as well as possible + require agreement with pQCD at large μ and T
  [Borsanyi et al.'11'13]
- Predict the EoS elsewhere
- Well constrained description even at $\mu = \mathcal{O}(\Lambda_{QCD})$



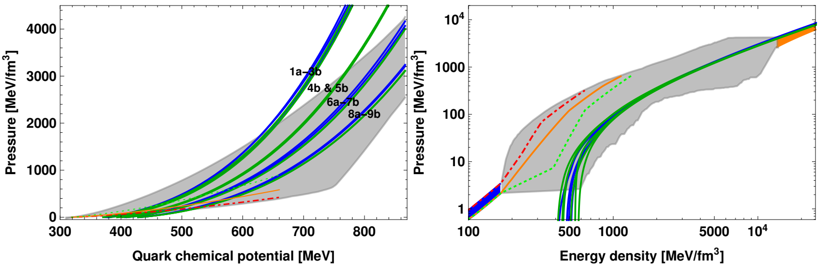


Extrapolated EoSs of cold QCD

After fit to lattice data the V-QCD result compared to

- EoSs interpolated between chiral effective theory and pQCD (gray band)
- Stiff, intermediate, and soft nuclear EoSs

[Hebeler-Lattimer-Pethick-Schwenk'13]



Basic idea & constraints

We use

1. Interpolated EoSs between chiral effective theory at low densities and pQCD to model the baryonic phase
2. V-QCD EoSs, with various parameter choices, to model the deconfined phase

- Essentially all possible EoSs consistent with the holographic model and known physics
- $\mathcal{O}(10^5)$ interpolated EoSs $\times$ $\mathcal{O}(10)$ holographic EoSs

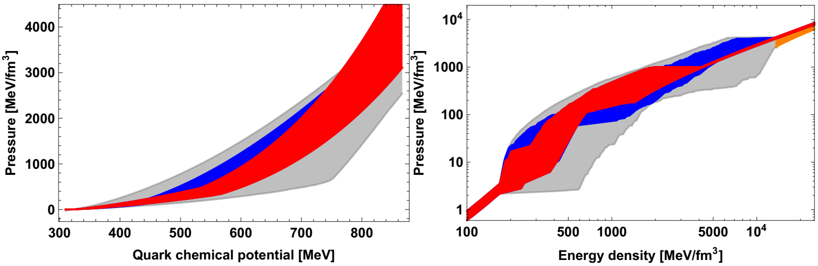
We apply astrophysical constraints:

1. Maximal neutron star mass $> 1.97 M_\odot$
2. LIGO: tidal deformability $70 \leq \Lambda \leq 580$

Results: $T = 0$

All constructed EoSs and those passing astrophysical constraints and for $n_B/n_s \lesssim 10$

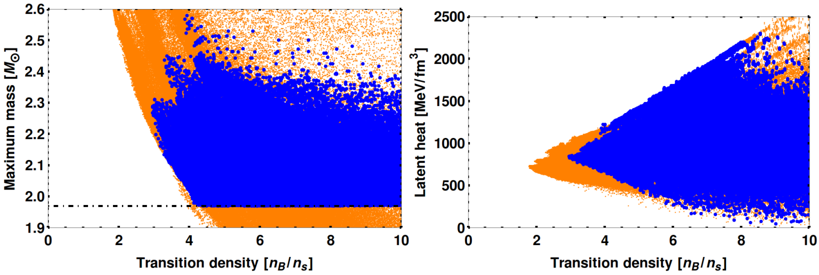
- Holographic band is really narrow
- $p - e$ band cut from below ($> 1.97 M_\odot$) and above ($\Lambda_{1.4 M_\odot} < 580$)
- Allowed EoS are really constrained



Results: $T = 0$

All constructed EoSs and those passing astrophysical constraints

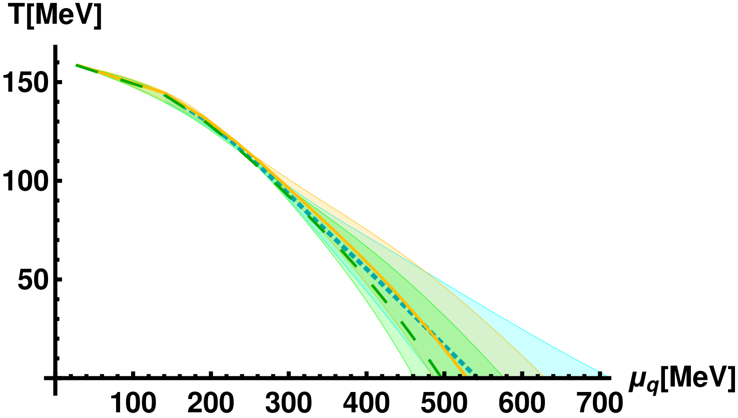
- Only strong first order transitions between the two phases (assuming reasonable transition densities)
- Consequently, no neutron stars with quark matter cores
- Constraint on the latent heat at the transition



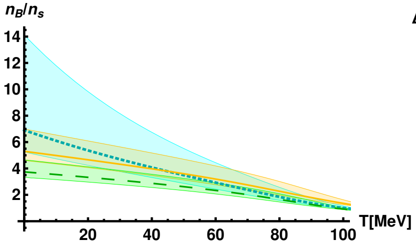
Results: $T \neq 0$

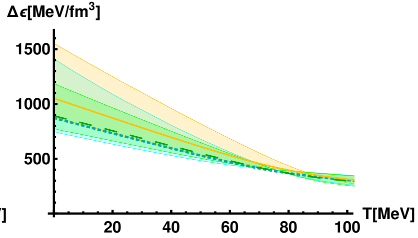
- Only $T \neq 0$ ones which $\sim$pass astrophysical constraints

$M_{\max}/M_\odot$	Pot. **5b**	Pot. **7a**	Pot. **8b**	Pure NM
DD2	2.05	2.20	2.38	2.42
IUF	1.91	1.95	1.95	1.95
SFHx	1.95	2.05	2.13	2.13



- Transition density not too high
- Latent heat decreases with T, making it below 1 GeV/fm^3
- Quark matter core should be observable in merger [Most-Papenfort-Dexheimer-Hanauske-Schramm-Störmer-Rezzolla'18,Bauswein-Bastian-Blaschke-Chatziioannou-Clark-Fischer-Oertel'18]





Conclusions

- Main results:
  - V-QCD fits very nicely lattice data at $\mu = 0$ and
  - gives reasonable looking predictions at low T and intermediate μ
  - Cold neutron stars with stable "holographic" quark matter cores look unlikely
  - Nontrivial constraints: latent heat at transition
  - Quark matter core possible to be formed in a merger
- Several possible extensions
  - Finite B and CP-odd physics can be "turned on"
  - Transport, emissivities
  - Out-of-equilibrium properties
  - Holographic confined phase
  - Effects of flavor dependent quark masses