The Holographic Approach to Dense QCD Matter

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Introduction

Quantum ChormoDynamics (QCD) is the best undestood piece of the Standard Model, from the point of view of the fundamental degrees of freedom:

- It is $SU(3)$ Yang-Mills theory with six quark flavors in the fundamental representation, weakly coupled at high energies.
- However, the regime of interest for the matter found in neutron star (high, but not extremely high densities, low temperatures) is far from all reasonably simple approaches:
    - Far from perturbative regime
    - Beyond the well-studied nuclear matter density
    - Not suitable for lattice calculations (sign problem)
- Non-perturbative modeling + some degree of extrapolation is needed.

Introduction

In this talk I will describe how holographic models can provide a descriptions of many aspects of the non-perturbative physics and can be used to study strongly-interacting matter at

- High density
- Zero and finite temperature
- In and out of equilibrium
- Both in the dense quark matter and dense hadronic matter phases.

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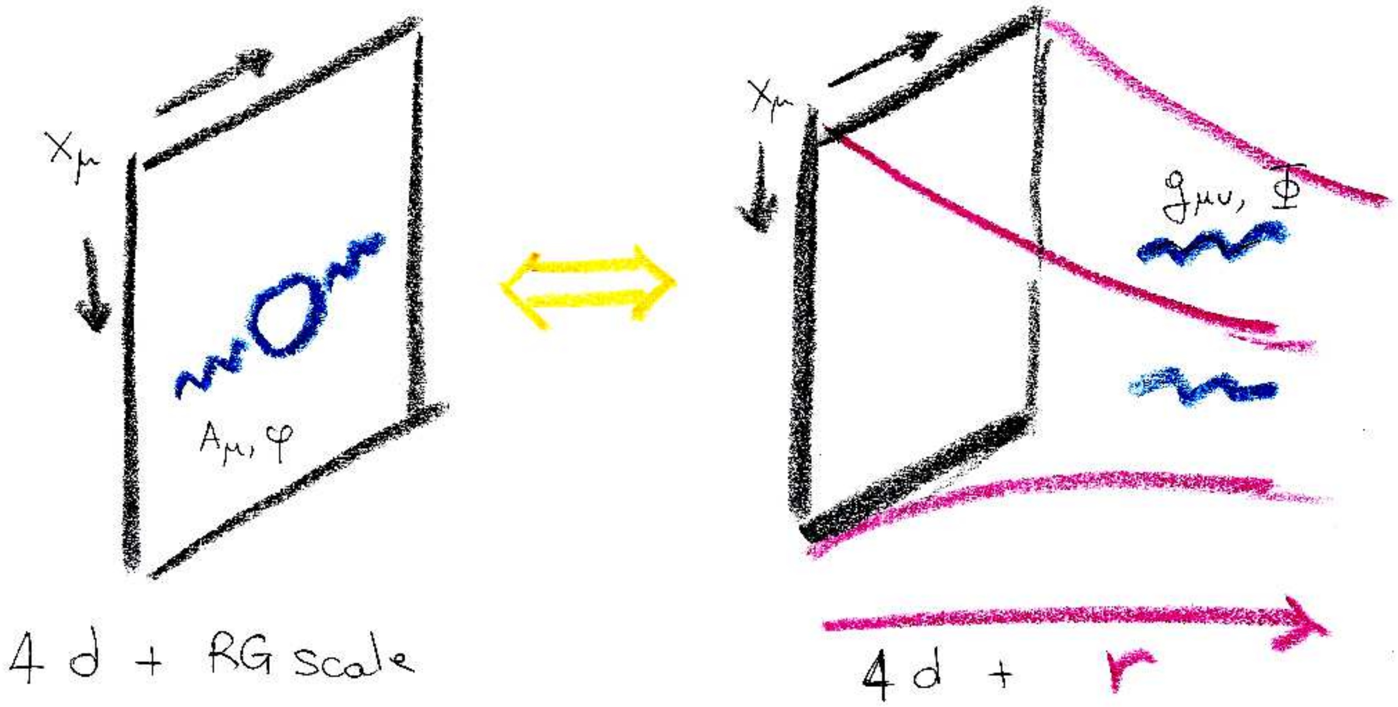
Outline

- Introduction to the holographic correspondence
- Holographic models for QCD
- Overview of applications to neutron star physics

AdS/CFT

The AdS/CFT duality: conjecture that certain quantum field theories are equivalent to theories of gravity in higher dimensions.



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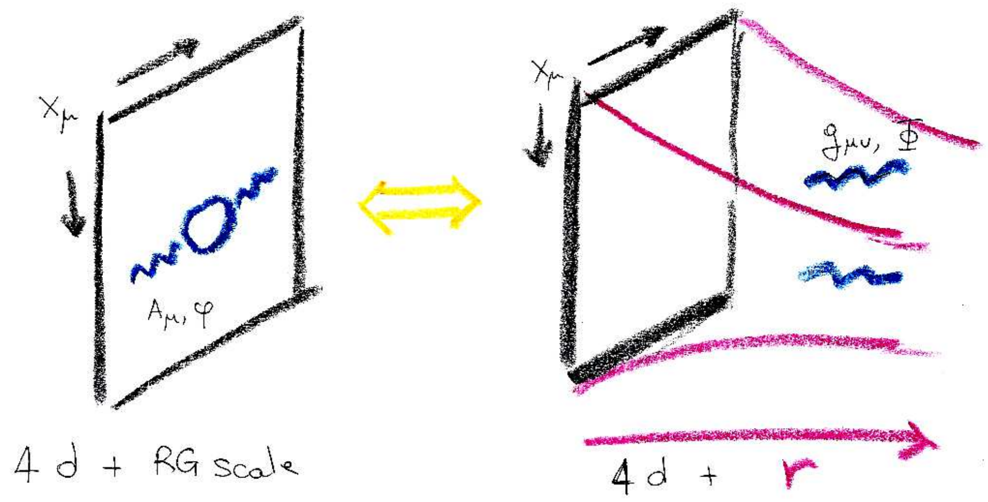

- Equivalent means that the two theories contain the same degrees of freedom, but arranged in differnt ways.
- Depending on the situation, one side or the other may be easier to handle.

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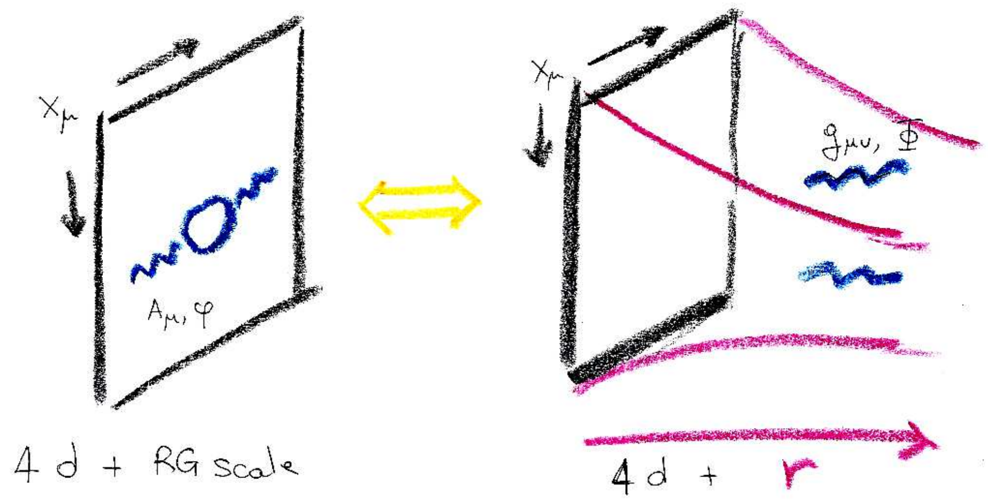
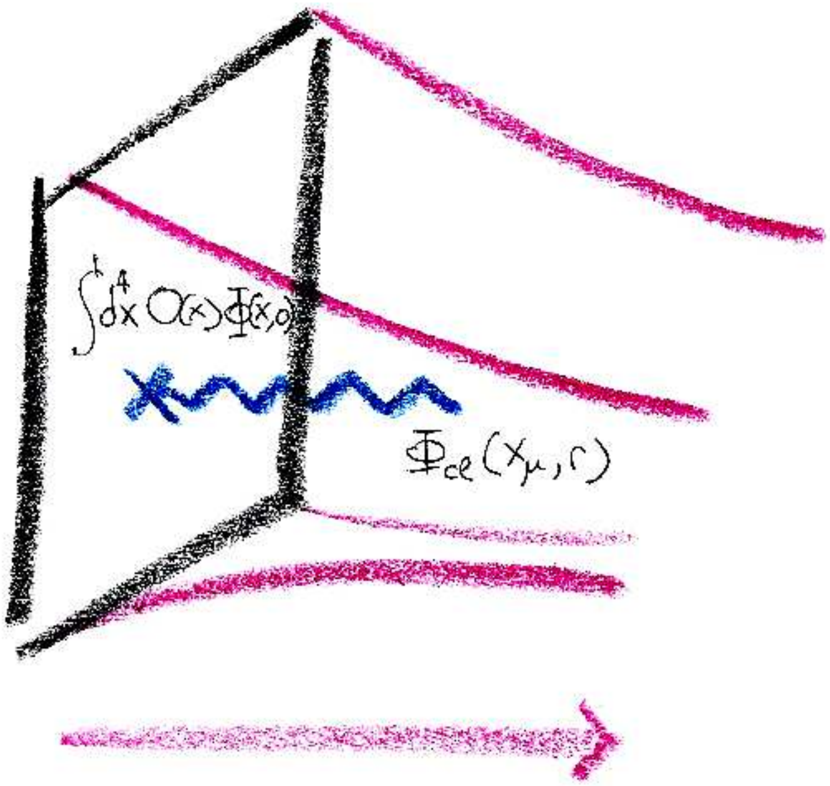


- $\mathcal{N} = 4$ SYM theory in 4D $\Leftrightarrow$ IIB String theory on $AdS_5 \times S^5$
- large N, large λ: Gravity side becomes classical and non-stringy.
- Conformal invariance $\Leftrightarrow$ AdS spacetime $ds^2 = r^{-2}(dr^2 + dx_\mu^2)$, Scaling isometry $r \to \lambda r$, $x_\mu \to \lambda x_\mu$.
- RG scale $\Leftrightarrow$ radial coordinate r; UV $\Leftrightarrow$ AdS boundary $r = 0$.

Field/Operator correspondence

- QFT operator $O(x) \Leftrightarrow$ Bulk field $\Phi(x, r)$.
- $\Phi_0(x) = \Phi(x, 0)$ is a source for $O(x)$ in the QFT:



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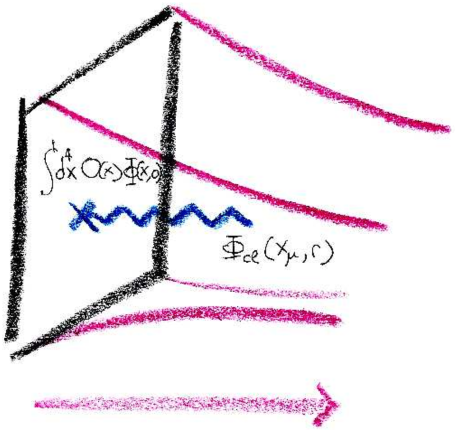

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$m^2 = \Delta(\Delta - d)$.

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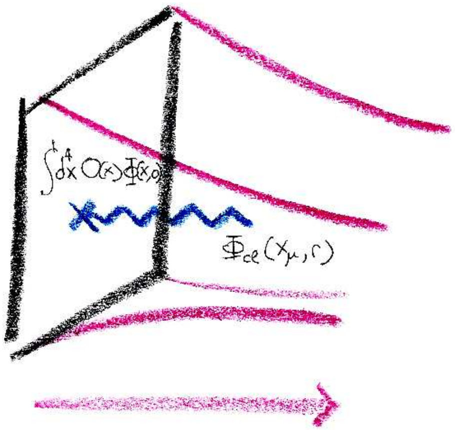

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$$\mathcal{Z}_{QFT}[\Phi_0(x)] = \exp i S_{cl}[\Phi_0(x)]$$

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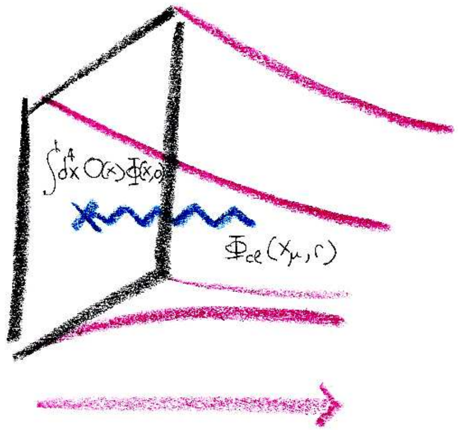

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$$\langle O(x_1) \dots O(x_n) \rangle = \frac{\delta}{\delta \Phi_0(x_1)} \dots \frac{\delta}{\delta \Phi_0(x_n)} S_{cl}[\Phi_0]$$

Phenomenological holography

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Top-down Construct string theory backgrounds which break susy/conformal invarariance.

Bottom-up: Construct phenomenological gravity models such that, using holography rules, we can match the properties of the QFT.

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Bottom-up: Construct phenomenological gravity models such that, using holography rules, we can match the properties of the QFT.

- Not a controlled approximation of a more fundamental theory;
- Free parameters can be used to fit data from other techniques and have a quantitative match.

Minimal holographic YM

- The bulk theory is five-dimensional (x^μ + RG coordinate r)
- Include only lowest dimension YM operators ($\Delta = 4$)

4D Operator		Bulk field	Coupling
TrF^2	$\Leftrightarrow$	Φ	$N \int e^{-\Phi}\, TrF^2$
$T_{\mu\nu}$	$\Leftrightarrow$	$g_{\mu\nu}$	$\int g_{\mu\nu} T^{\mu\nu}$

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- Breaking of conformal symmetry, mass gap, confinement, and all non-perturbative dynamics driven by the dilaton dynamics (aka the Yang-Mills coupling).
- (Eventually: add axion field $a \Rightarrow TrF\tilde{F}$)

5-D Eistein-Dilaton Theory

Gursoy, Kiritsis, Mazzanti, Nitti, 2007-2012

Bulk dynamics described by a 2-derivative action:

$$S_E = -M_p^3 N_c^2 \int d^5x \sqrt{-g} \left[R - \frac{4}{3} (\partial \Phi)^2 - V(\Phi) \right]$$

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- Effective Planck scale $\sim N_c^2$ is large.
- Features: asymptotic freedom, confinement, discrete linear glueball spectrum, correct thermodynamics and phase diagram

Five dimensional setup

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- $\lambda(r) \propto$ running 't Hooft coupling
- $A(r), \lambda(r)$ determined by solving bulk Einstein's equations.

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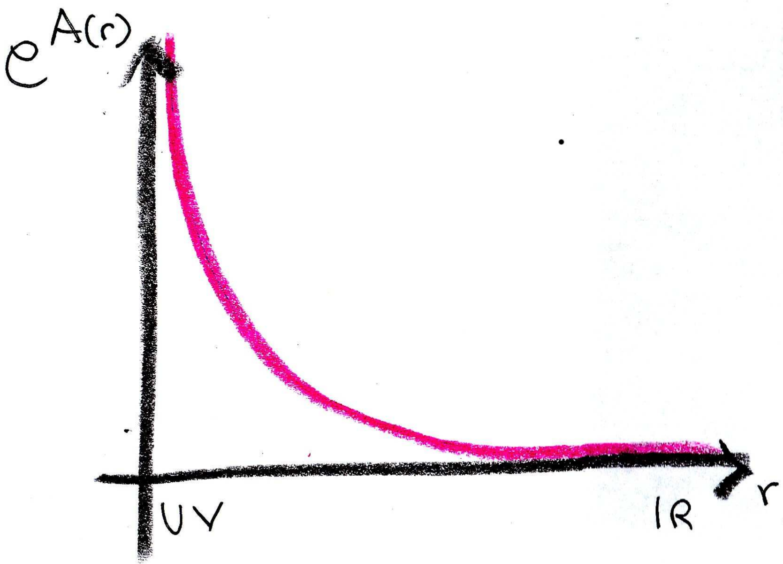

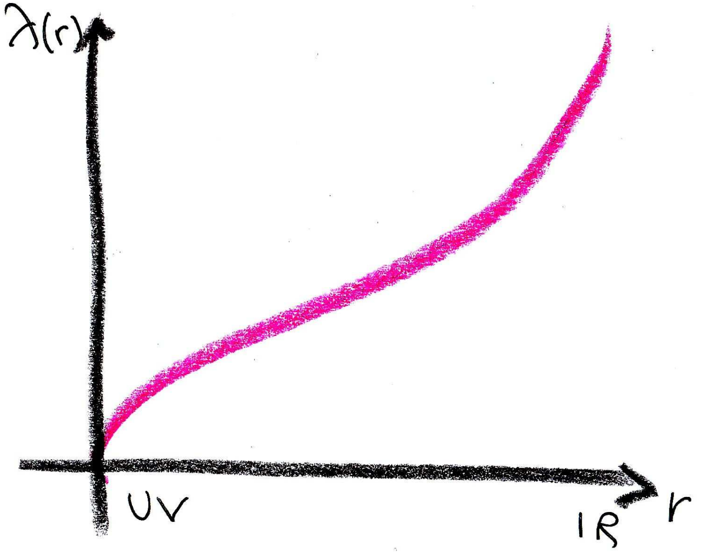

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- Phase transition happens at T_c where $\mathcal{F}_1(T_c) = \mathcal{F}_2(T_c)$

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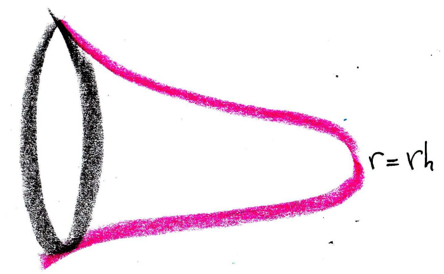

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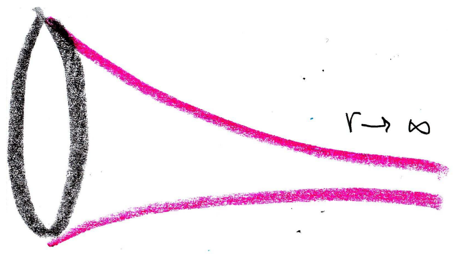

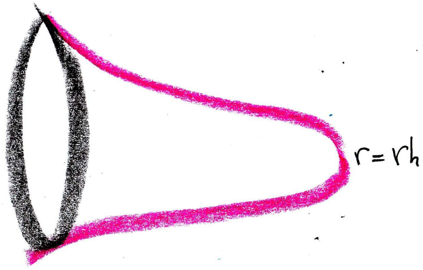

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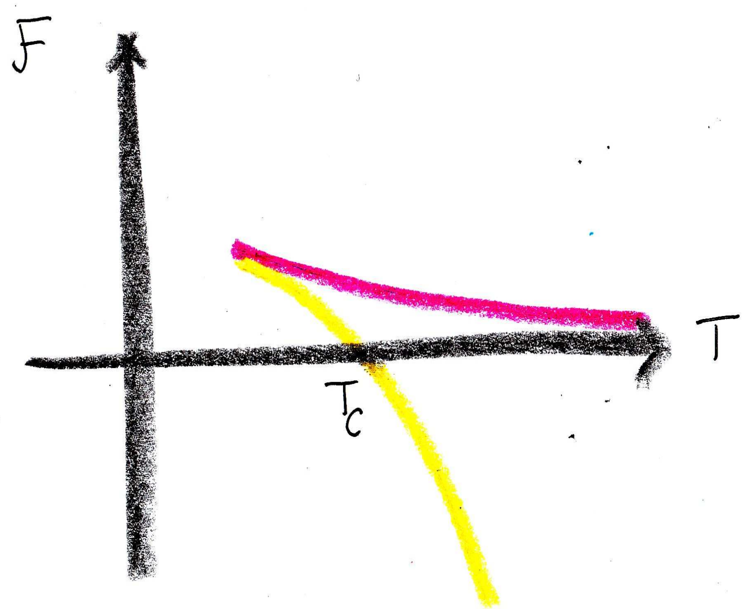
- the black hole always corresponds to a deconfined phase

Phase diagram



First order transition to a black hole phase for $T > T_c$, dual to deconfinement phase transition

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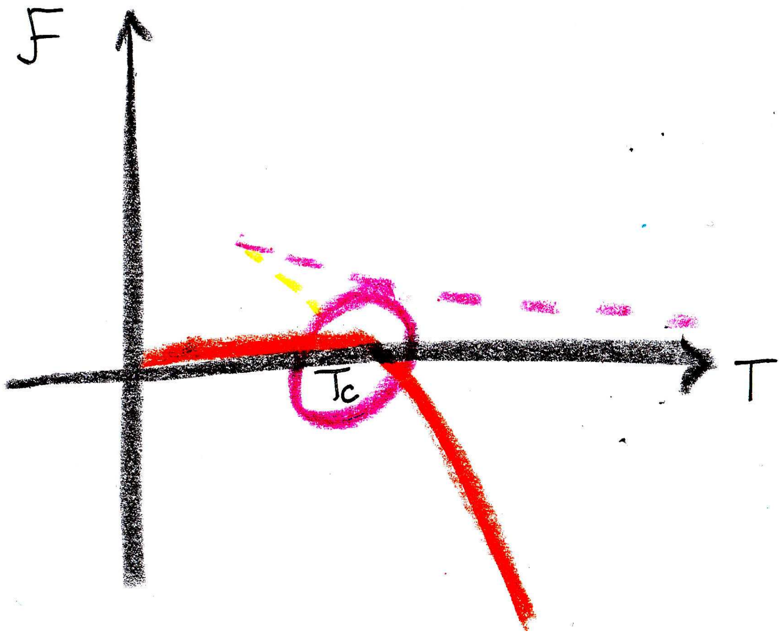

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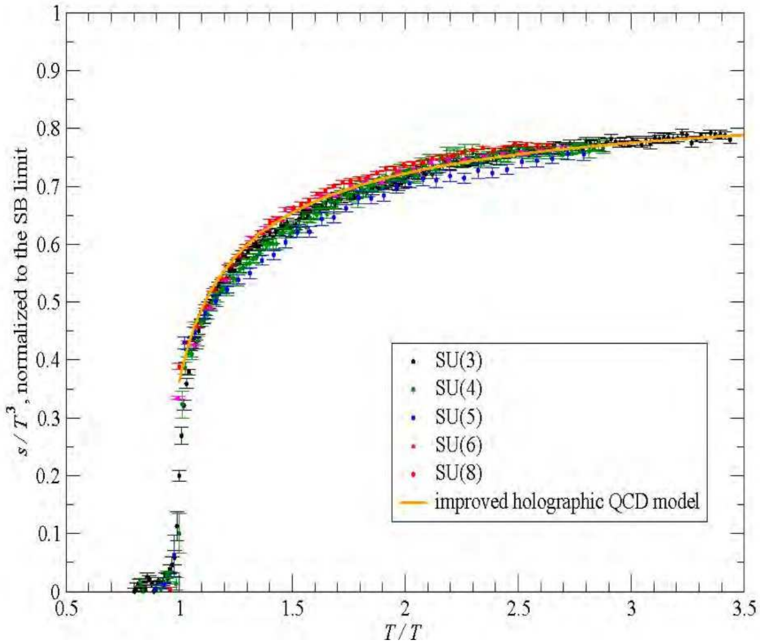

$s(T)/T^3$ lattice data: Panero, hep-lat/0106019

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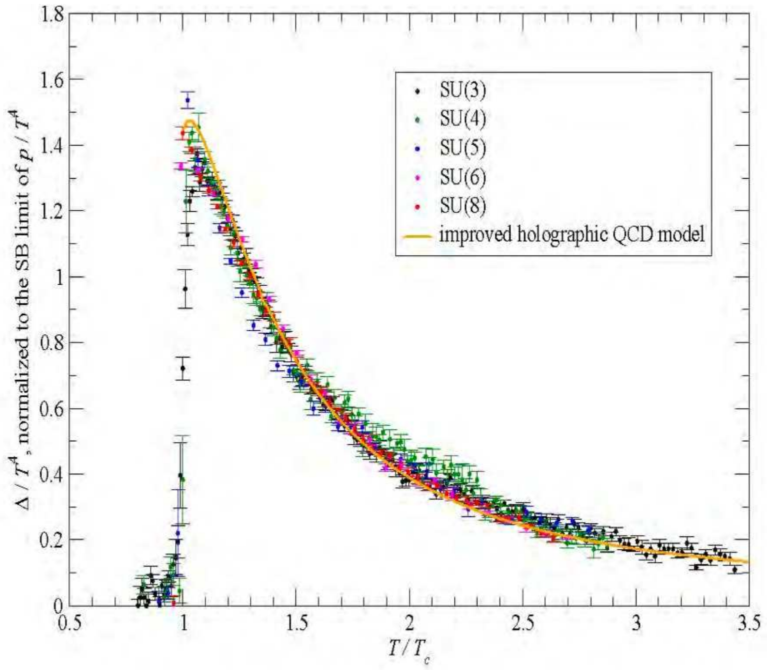

$(\epsilon - 3p)/T^4$ lattice data: Panero, hep-lat/0106019

Adding Flavor: V-QCD

Casero, Gursoy, Iatrakis, Jarvinen, Kiritsis, Mazzanti, Nitti, Paredes, 2007-...

N_f quark flavors: more bulk fields.

- Bi-fundamental scalars Scalars

$$T^i_j \Leftrightarrow \bar{q}^i q_j$$

- $U(N_f)_L \times U(N_f)_R$ gauge fields

$$A_B^{a;L}, A_B^{a;R} \quad \Leftrightarrow \quad J_\mu^{a;L,R} \equiv \bar{q}^i \gamma_\mu \, (\tau^a)_i^j \, (1 \pm \gamma_5) q_j \quad a = 1 \ldots N_f^2, \; i, j = 1 \ldots$$

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$$S_{flavor} = \int d^5x \, V_0(\lambda) e^{-T^2} \sqrt{-\det(g_{AB} + \kappa(\lambda)\partial_A T \partial_B T + w(\lambda) F_{AB})}$$

- χSB : $T \to \infty$ in the IR.

Finite temperature and density

- To describe a finite baryon density state: turn on a mon-trivial $U(1)$ gauge field in the bulk:

$$A_0 = a(r)\delta^i_j, \qquad T^i_j = \tau(r)\delta^i_j$$

- Near the boundary:

$$a(r) \sim \mu + \rho r^3 + \ldots, \quad \tau(r) \sim mr + \sigma r^3 + \ldots \qquad r \to 0$$

- Deconfined state at finite temperature and chemical potential: charged black hole solution.
- Equation of state of the black hole provides the equation of state of a uniform distribution of deconfined matter at finite temperature and chemical potential

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Chemical potential (μ), Charge density (ρ), Quark mass (m), Chiral condensate (σ)

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Phase diagrams

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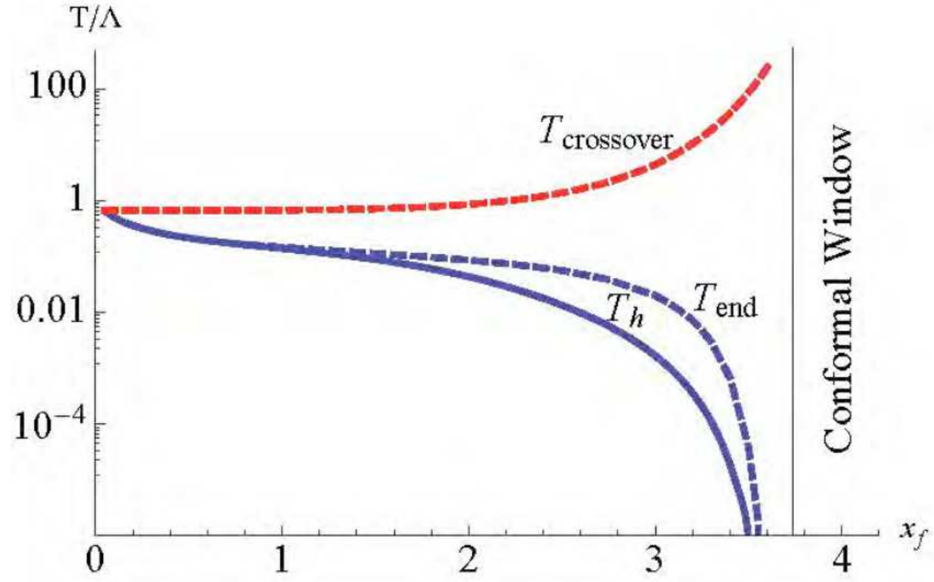
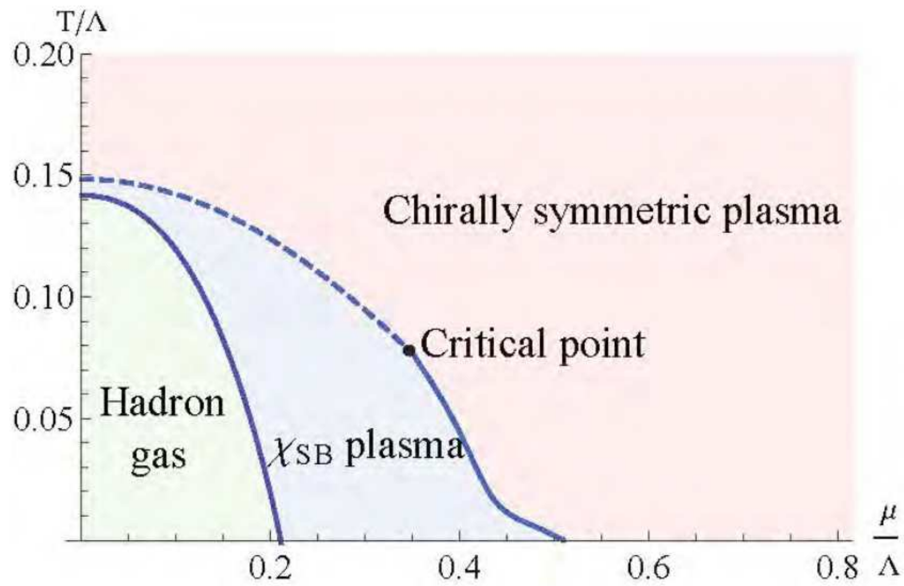


Finite Temperature and Density



Out-of-equilibrium physics

- Charged black hole solutions describe a homogeneous and static state.
- In the long-wavelength limit the dynamics is described by the transport of conserved charges the stress tensor and the flavor currents

$$T_{\mu}, J_{\mu}^{L,R}$$

- Holography computes real-time response functions associated to these currents, e.g.

$$\langle J_{\mu}^{a} J_{\nu}^{b} \rangle, \qquad \langle T_{ij} T_{kl} \rangle \quad (\sim \eta)$$

- More general, far from equilibrium hydrodynamics can be studied numerically (e.g. similar studies exist for QGP)

Holography applied to neutron stars

- N = 4 models
- V-QCD
- Dense hadronic matter
- Future developements

(partial) list of contributors: P. Chesler, C. Ecker, C. Hoyos, T. Ishii, M. Jarvinen, N. Jokela, A. Loeb, G. Nijs, J. Remes, D. Rodríguez Fernández, W. van der Schee, A. Vourinen...

Top-down Flavored $N = 4$ models

- Model the high-density phase with $N = 4$ SUSY Yang-Mills + $N = 2$ SUSY flavor d.o.f.
- Holographic dual: 10-dimensional $AdS_5 \times S^5$ black hole with "flavor D3-D7 branes" : can compute EoS exactly:

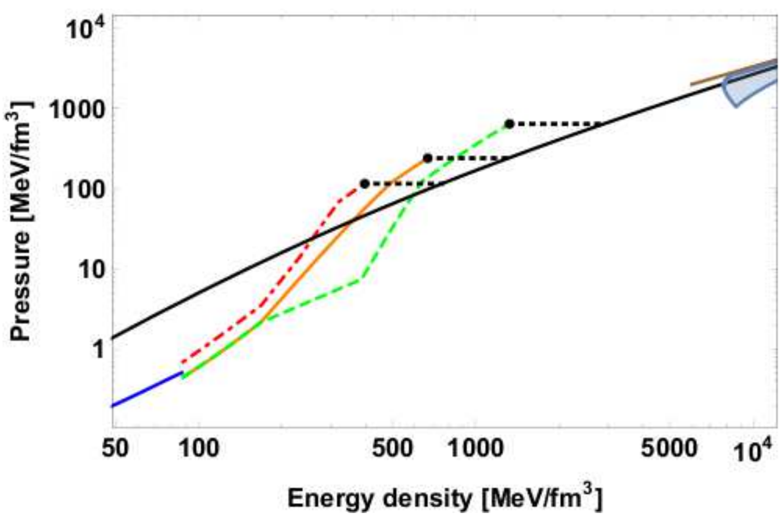
$$\epsilon = 3p + \alpha\sqrt{p}$$

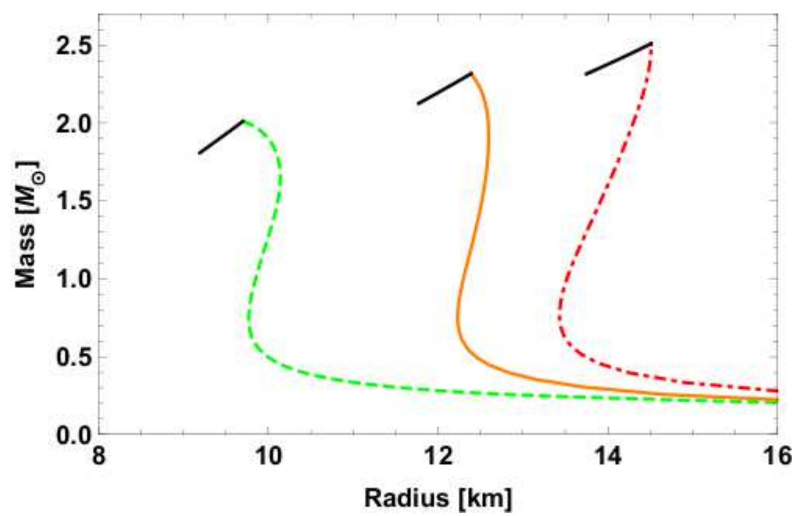
- Fix parameter α by matching with low-density EoS from nuclear theory and with perturbative limit at high density.
- Use standard TOV equations to obtain Mass-Radius curves.

Top-down Flavored $N = 4$ models

Results:

- Strong first order transition between nuclear matter and quark matter
- Quark matter stars unstable; Mass-radius curve effectively ends at phase transition.





Hoyos, Jokela, D. Rodríguez Fernández, A. Vourinen, 1603.02943

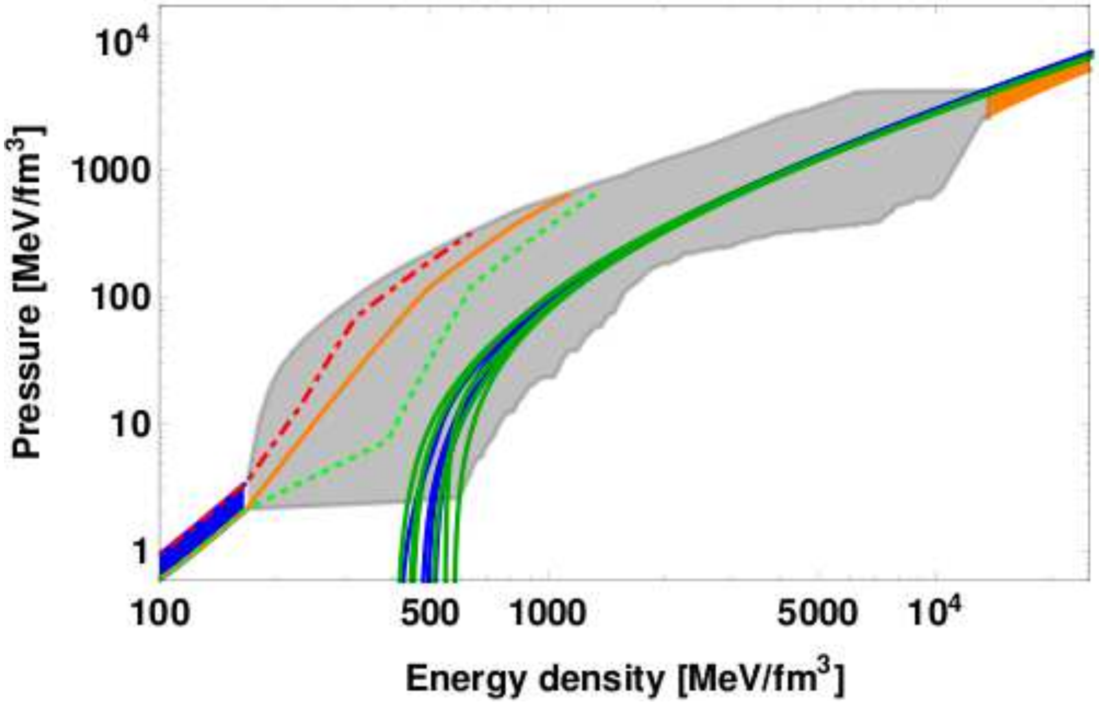
V-QCD

Similar analysis on phenomenological 5d models of V-QCD:
explore parameter that the EoS

- has consistent thermodynamics (continous p and μ);
- speed of sound < 1
- matches pQCD at high μ and Chiral Effective Theory at low μ
- Use these constraints to model low-μ phase with a polytropic fluid and high-μ phase with V-QCD (using fits to lattice results at zero density and finite temperature to fix some of the parameters).

V-QCD

Jokela, Jarvinen, Remes, 1809.07770



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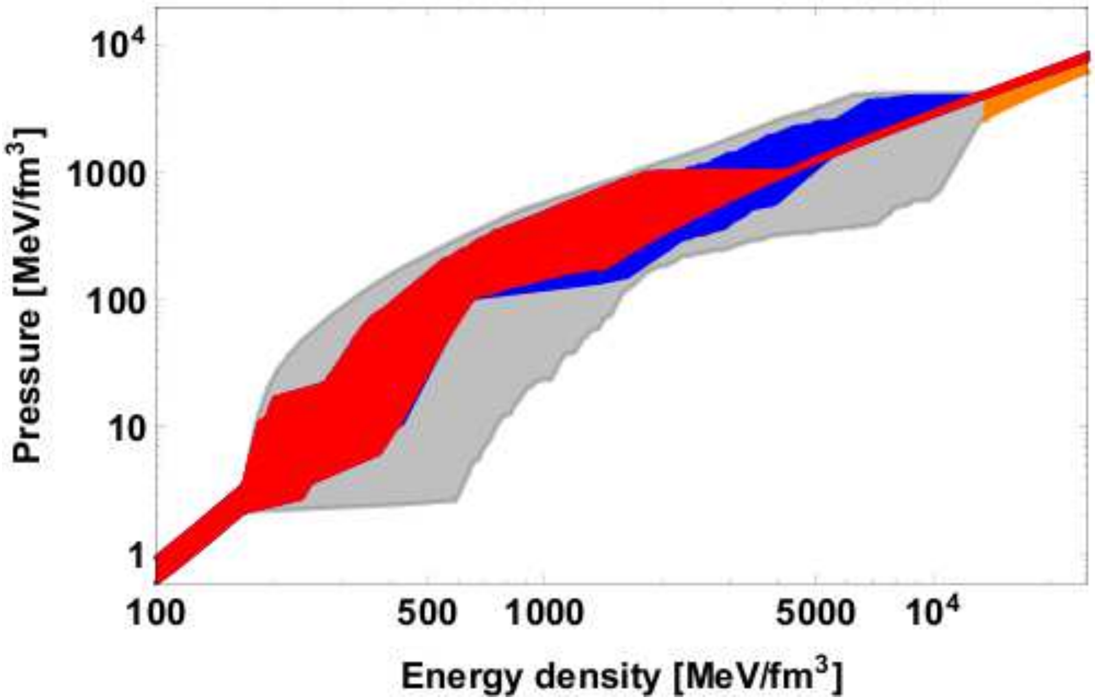

- Space of acceptable EoS (requiring at most one phase transition) and compatible with astrophysical observations (Maximal mass + tidal deformability from GW170817).

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More challenging: model the hadronic phase also using holography.

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- Baryons in holography are solitonic solutions of the non-abelian gauge fields dual to the flavor currents.
- Soliton localized in holographic direction r and in space $\vec{x}$
- Homogeneous ansatz:

$$A^i = a(r)\sigma^i$$

equivalent to "smearing" the baryon uniformly over space Ishii, Jarvinen, Nijs, 1903.06169

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- Stiff equation of state ($c_s^2 > 1/3$)
- First beginning-to-end holographic neutron-star collisions with gravitational wave emission Ecker, Jarvinen, Nijs, van der Schee 1908.03213

Uniefied Weak/Strong approach

Improved weak/strong coupling matching: use hybrid low-density model to match V-QCD in the dense baryonic phase

Jokela, Jarvinen, Nijs, Remes 2006.01141.

- No polytropes at low densities, use collection of theory-motivated EoS instead.

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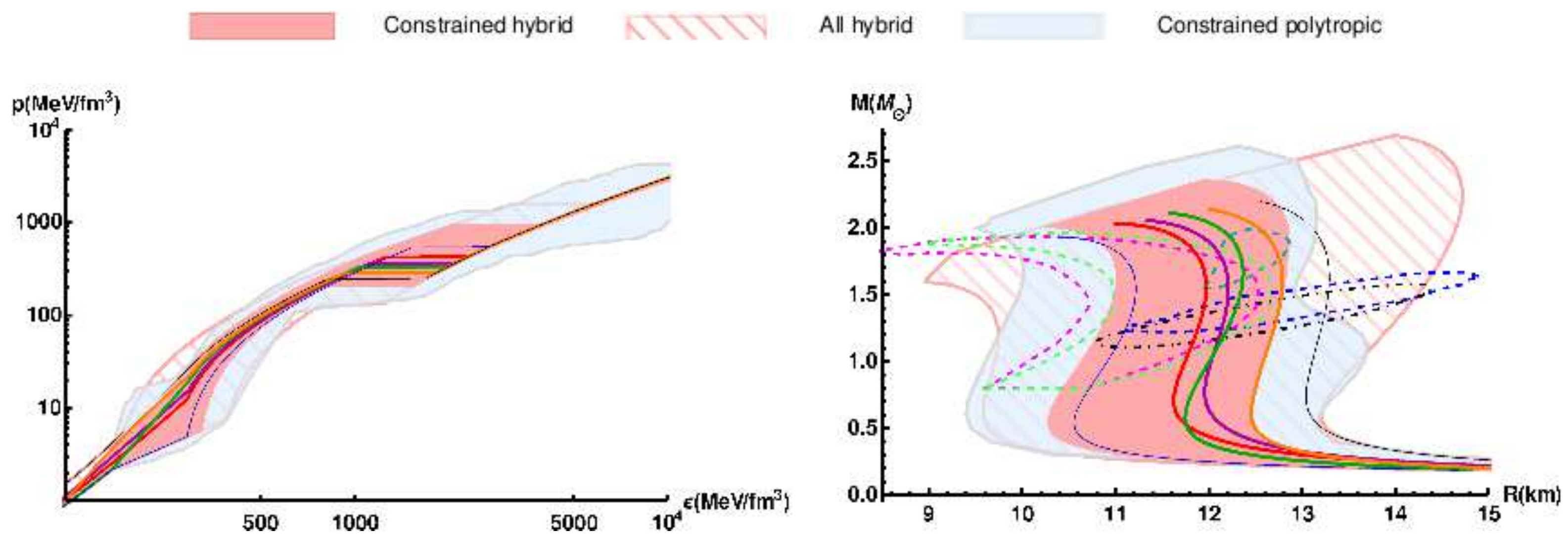
Jokela, Jarvinen, Nijs, Remes 2006.01141.

- No polytropes at low densities, use collection of theory-motivated EoS instead.
- Improved constraints on EoS



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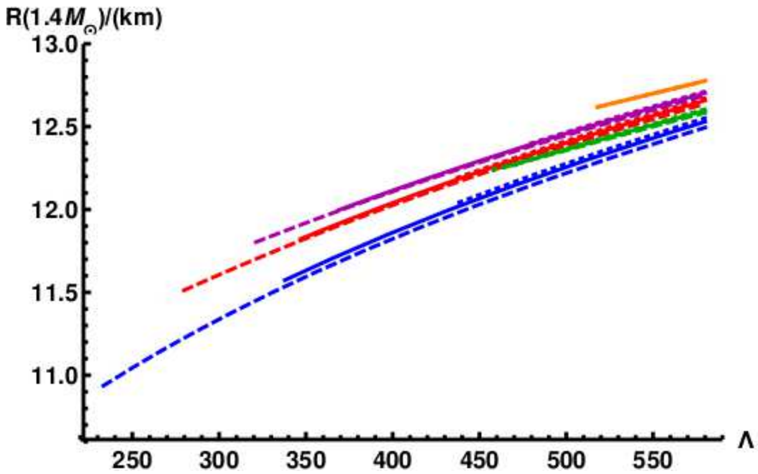

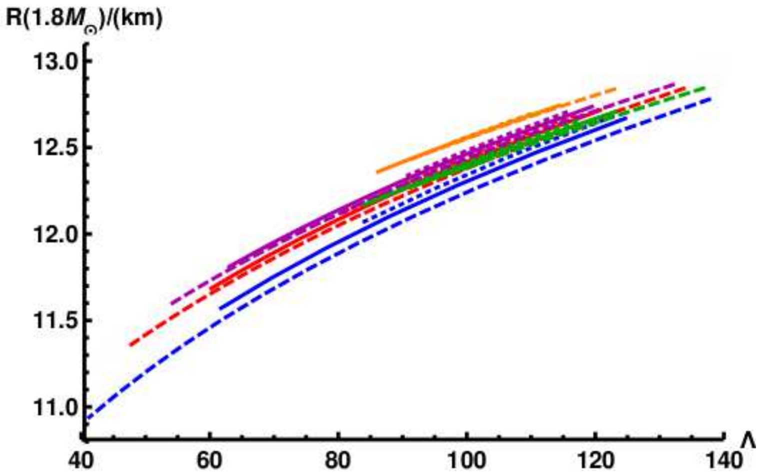

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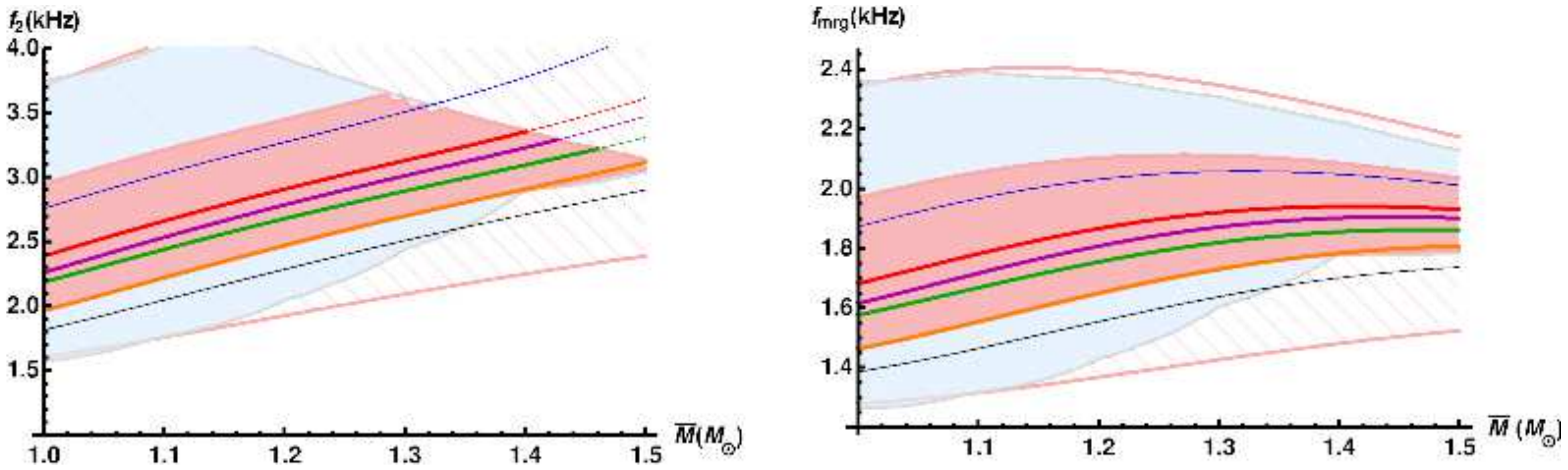
- Constraints on peak frequencies of post-merger GWs (inferred from static properties + numerical simulations)



The Future

- Finite temperature equations of state have been constructed using the same methods (V-QCD + matching low-density nuclear theory). Relevant for post-merger transient states. Chesler, Jokela, Loeb, Vuorinen 1906.08440

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- Baryons. Construct more precise description of hardronic matter: study properties of single baryon then construct a holographic fluid of baryons given a bulk equation of state.
- Use holographic correlation functions to compute quantities related to weak interactions.

Electroweak interactions: neutrino opacities

Oertel, Pascal, Mancini, Novak 2003.02152

- In-medium neutrino-nucleon and neutrino-neutrino interactions important for post-merger phase (cooling, ejecta composition, shockwave dynamics). E.g.

$$p + e^- \leftrightarrow n + \nu_e, \qquad p \leftrightarrow n + e^+ + \nu_e$$

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This are exactly the things that Holography can compute !

Self-energies

Schematically:

$$Z = \int \mathcal{D}_{EW} \int \mathcal{D}_{QCD} e^{iS_{EW}[\nu,W,Z\ldots]} e^{iS_{QCD}+e^{iS_{int}}} \qquad S_{int} = \int d^4x W_\mu J^\mu$$

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If one could do the QCD integral:

$$Z = \int \mathcal{D}_{EW} e^{iS_{EW}[\nu,W,Z...]} [1-\tfrac{1}{2}\int W_\mu W_\nu \langle J^\mu J^\nu \rangle_{medium} + ...] \approx \int \mathcal{D}_{EW} e^{iS^{eff}[\nu,W,Z...]}$$

$$S^{eff} = S_{EW} + \frac{1}{2}\int W_\mu W_\nu \langle J^\mu J^\nu \rangle_{QCD\ medium}$$

Self energies from holography

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$$\Sigma^{\mu\nu}(p) = \Sigma^{\mu\nu}_{EW}(p) + \langle J^\mu(p) J^\nu(-p)\rangle_{QCD\ medium}$$

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From holography:

- Take the gravity dual geometry at finite density and temperature (and eventually out of equilibrium)
- Perturbe it with appropriate combination of bulk gauge fieds $A_\mu(r,p)$ which is dual to current operator $J^\mu(p)$
- Compute correlator:

$$\langle J^\mu(p) J^\nu(-p) \rangle = \frac{\delta^2}{\delta A_\mu(0,p)\delta A_\nu(0,-p)} S_{bulk}[A_\mu]$$

Conclusion

Holographic models are a valid complement to nuclear matter theory, perturbative QCD and effective field theory methods to describe neutron star phyics

- State-of-the-art models provide reasonable equations of state, compatible with observations, and have been used in BNS merger simulations all the way through.
- They can potentially descibe both dense quark matter and dense nuclear matter within the same model.
- They come out-of-the-box ready for computing finite temperature and transport properties
- Input needed from other communities to concentrate effort to do computations where it is most interesting and where other approaches are not reliable.