The Holographic Approach to Dense QCD Matter

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Introduction

- Gauge/gravity duality (aka Holographic Correspondence):
  a way to answer questions in strongly coupled QFTs theories by doing calculations in classical GR
- holographic models can provide a descriptions of many aspects of the non-perturbative physics and can in principle be used to study high-density QCD matter

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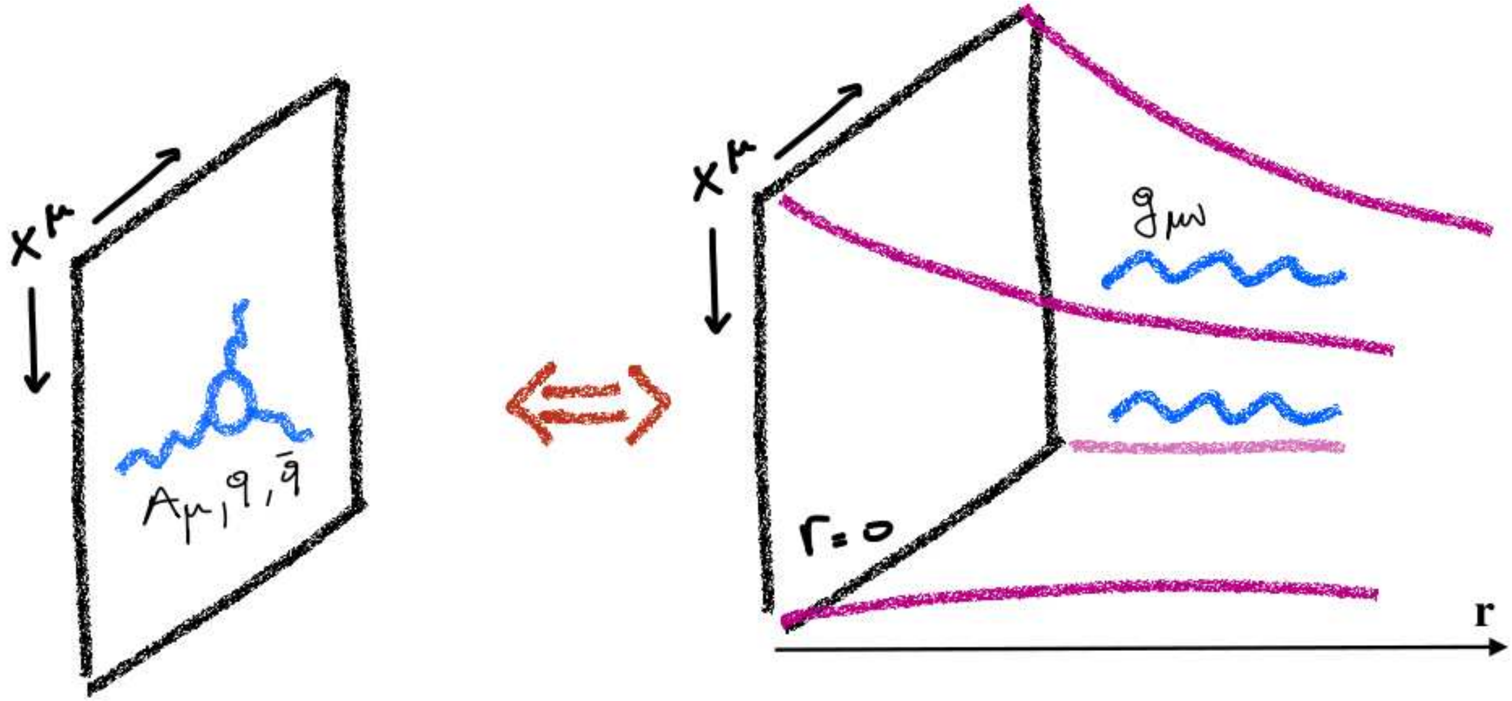
Outline

- What is the gauge/gravity duality?
- What good can it be for Neutron Star Physics?

The Gauge/Gravity Duality

Conjecture that some 4d quantum field theories have an equivalent description as gravitational theories in higher dimensions



- Well-grounded in the string theory context for SUSY QFTs.
- General features believed to be valid in the absence of SUSY (less under control).

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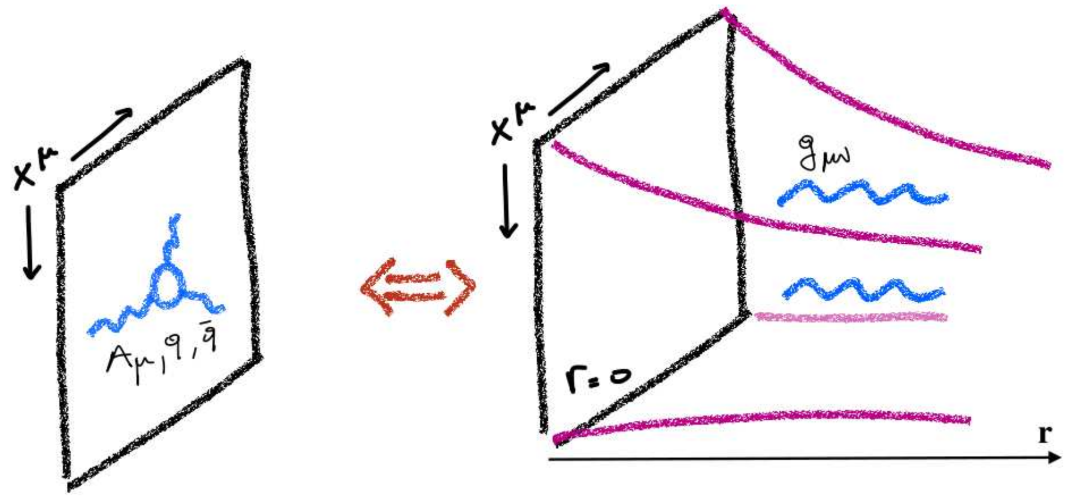

- Equivalent means that the two theories describe the same physics in terms of different degrees of freedom, but arranged in diffifernt ways.
- Weak QFT coupling: QFT description is perturbative;
- Strong QFT coupling: gravity side captured by classical GR

  (for large N gauge theories)

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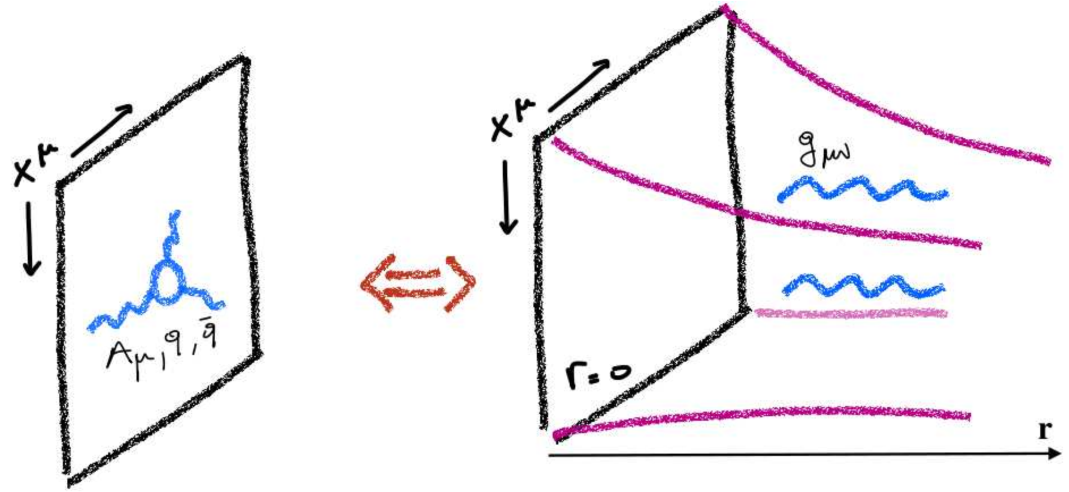


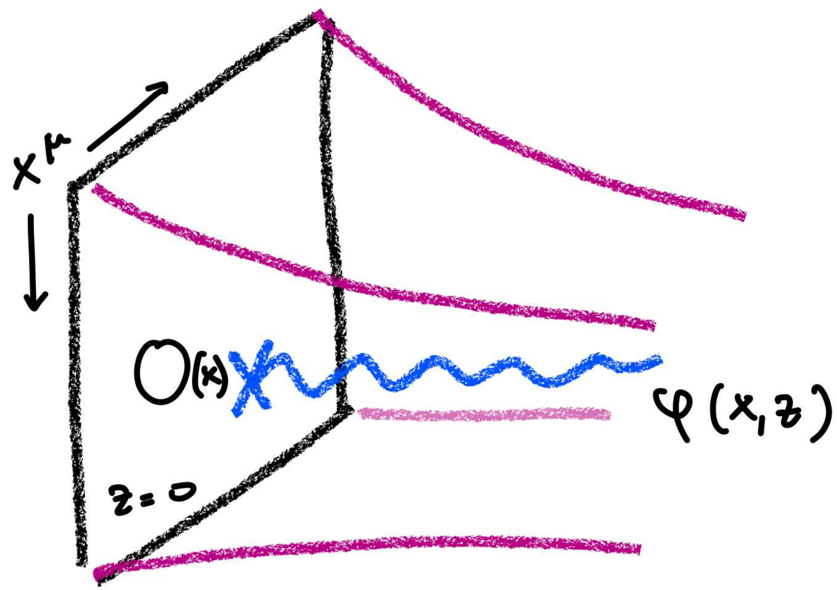
- QFT is conformal $\Leftrightarrow$ Gravity side is AdS spacetime

$$ds^2 = \frac{\ell^2}{r^2}(dr^2 + dx_\mu^2)$$

- $r = 0$: *boundary* of AdS = spacetime where the QFT lives (hence *holography*).
- Broken conformal invariance $\Leftrightarrow$ AdS deformed in the interior.

Field/Operator correspondence

- QFT operator ⇔ Dynamical bulk field :



- QFT correlation functions $\langle O(x_1) \ldots O(x_n) \rangle$ computed at strong coupling by solving classical equations for $\varphi(x,r)$.

Holographic models for QCD

- Dictionary:

4D Operator		5D Bulk field
TrF^2	$\Leftrightarrow$	Φ
$T_{\mu\nu}$ Stress tensor	$\Leftrightarrow$	$g_{\mu\nu}$ bulk metric
J^μ_L, J^μ_R $U(N_f)_L \times U(N_f)_R$ flavor currents	$\Leftrightarrow$	A^μ_L, A^μ_R $U(N_f)_L \times U(N_f)_R$ gauge fields
$\bar{\psi}^i \psi_j$ quark bilinear	$\Leftrightarrow$	T^i_j matrix of scalars

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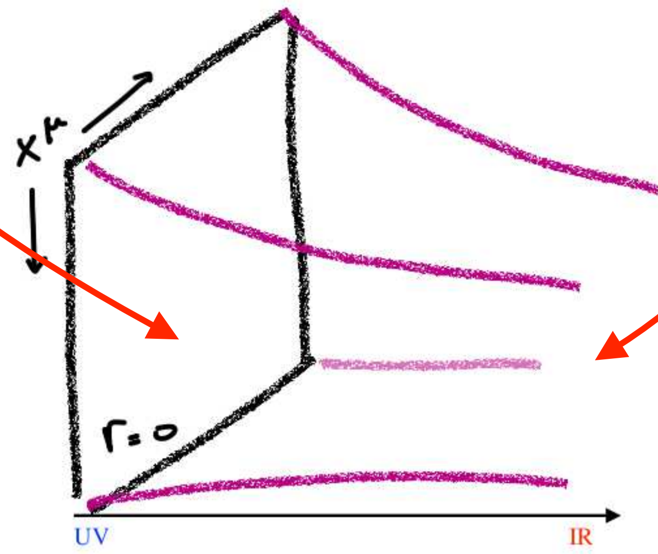
- Bottom-up: Einstein-Scalar-Yang-Mills action depending on *phenomenological potentials* (functions of the scalars)
- State of the art: V-QCD model Järvinen, Kiritsis ’11

Confinement

- UV of the QFT $\Leftrightarrow$ near-boundary region
- IR of the QFT $\Leftrightarrow$ interior



Conformal (AdS space)

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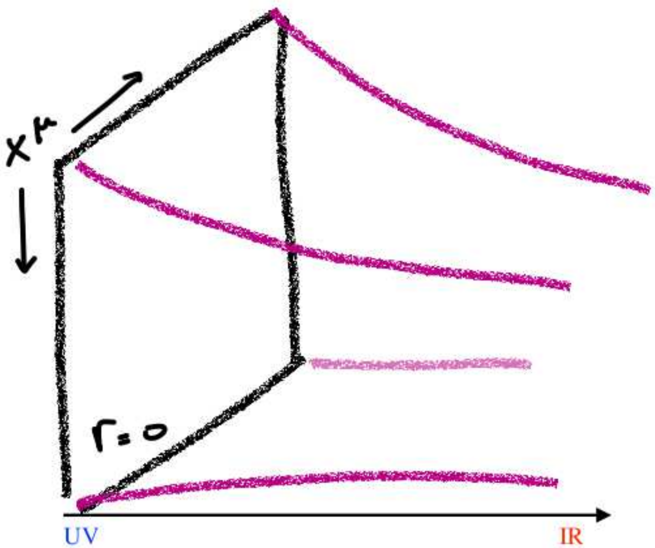

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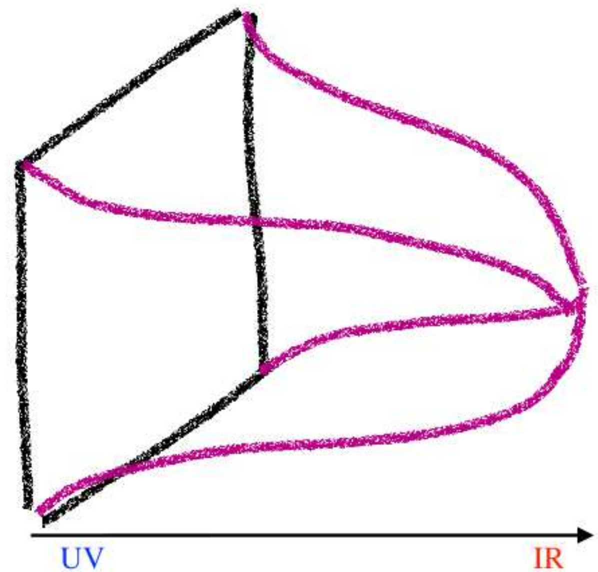
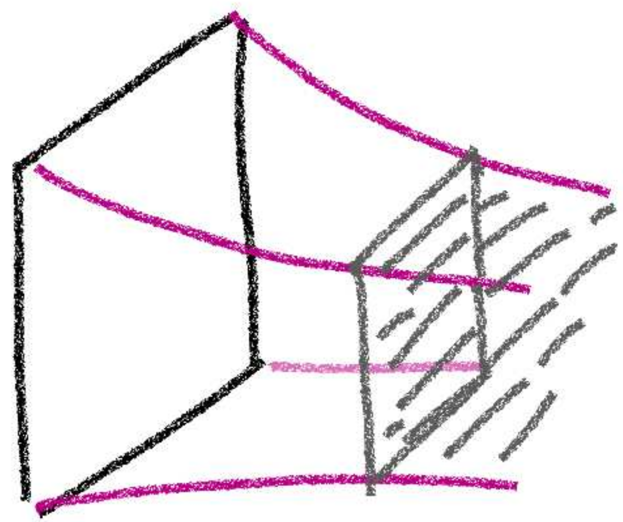


Confining

- Confinement is associated to properties of the interior geometry.
- Interior dynamically determined by bulk EOM.

Hot and dense thermodynamics states

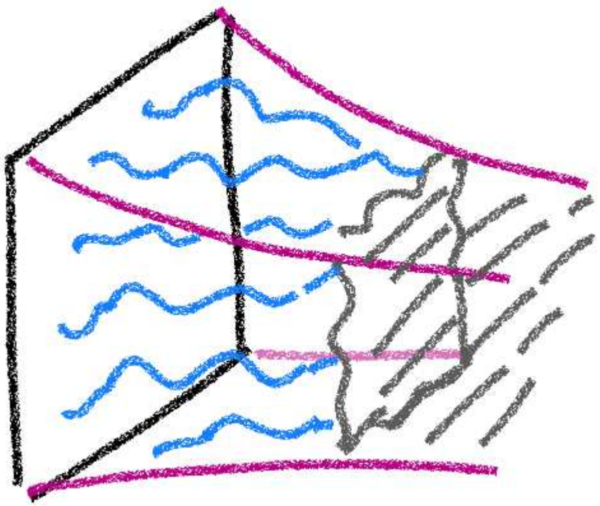
- Finite T and/or $\mu_B \Leftrightarrow$ 5D Black Hole geometry



- Describes deconfined phase ;
- Dominates partition function over the confined phase at large T or large μ
- EoS obtained from 5D Black Hole Thermodynamics (standard GR)
- Can be used to model presence of a deconfined core in NS

Beyond thermodynamics

- Out-of-equilibrium evolution can be obtained by evolving bulk state
- Linear hydro $\leftrightarrow$ linear perturbations around BHs in GR



- Can compute transport coefficients (viscosities) entering non-ideal hydro by a simple linearized GR calculation.

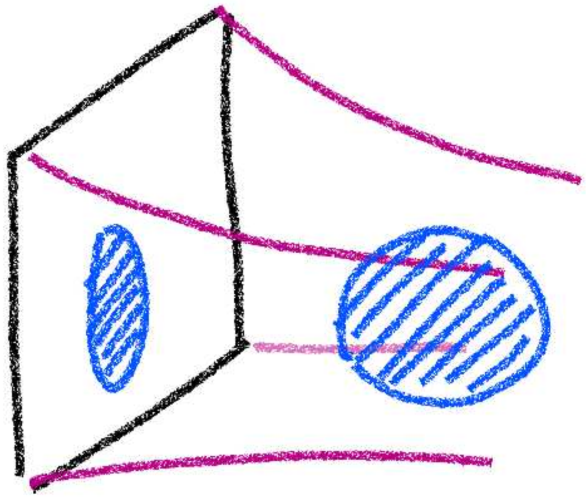
Holography applied to neutron stars

- Baryons
- EoS
- Hot phase
- Neutrino transport

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

Baryonic phase

- Single baryon $\Leftrightarrow$ bulk instanton of non-abelian gauge fields.



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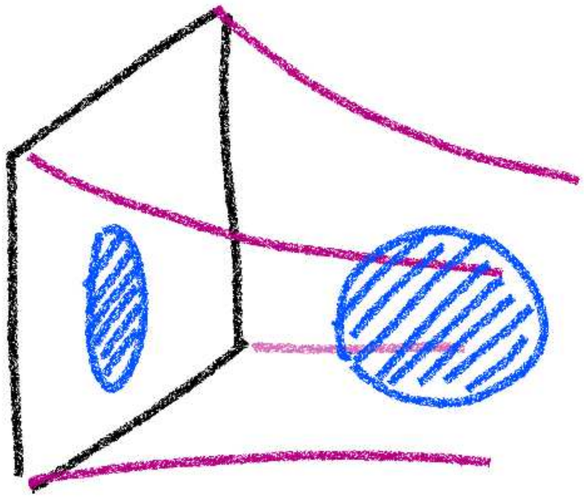
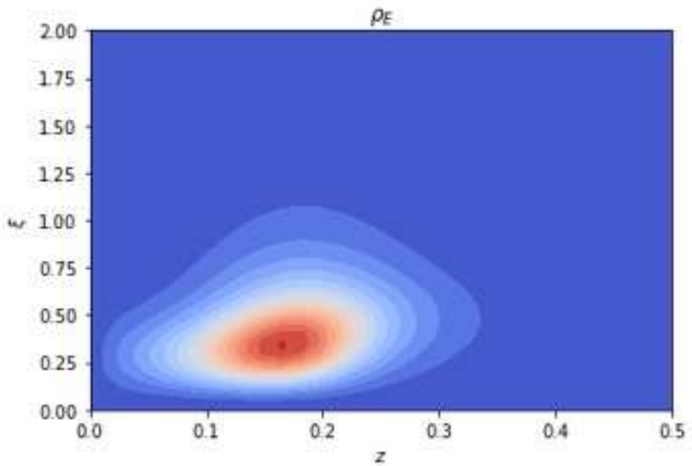
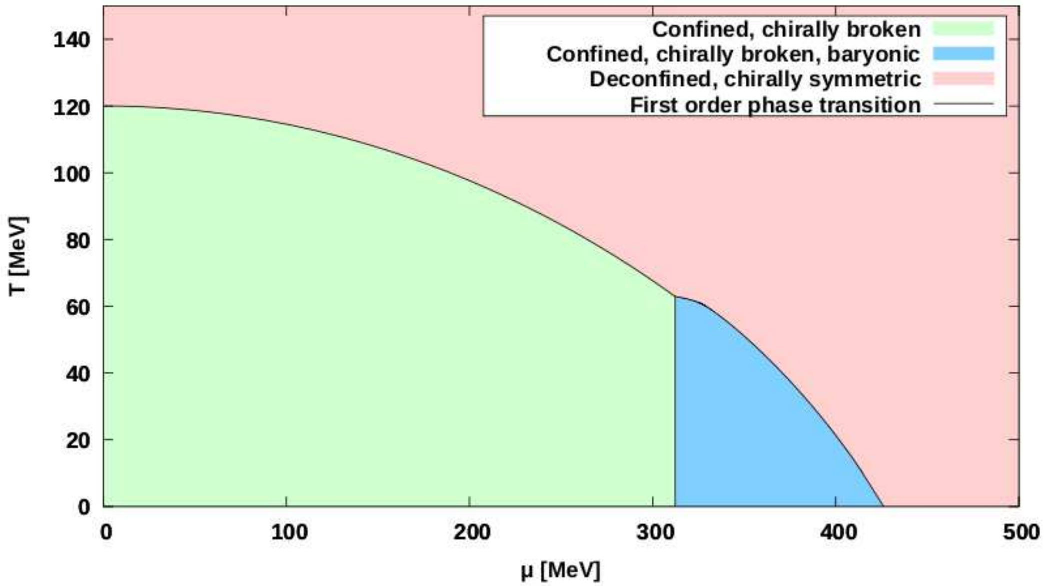




- V-QCD Baryon constructed numerically Järvinen, Kiritsis, FN, Préau, '22
- In progress: multi-baryon fluid/solid (not a black hole)

Effective/hybrid models

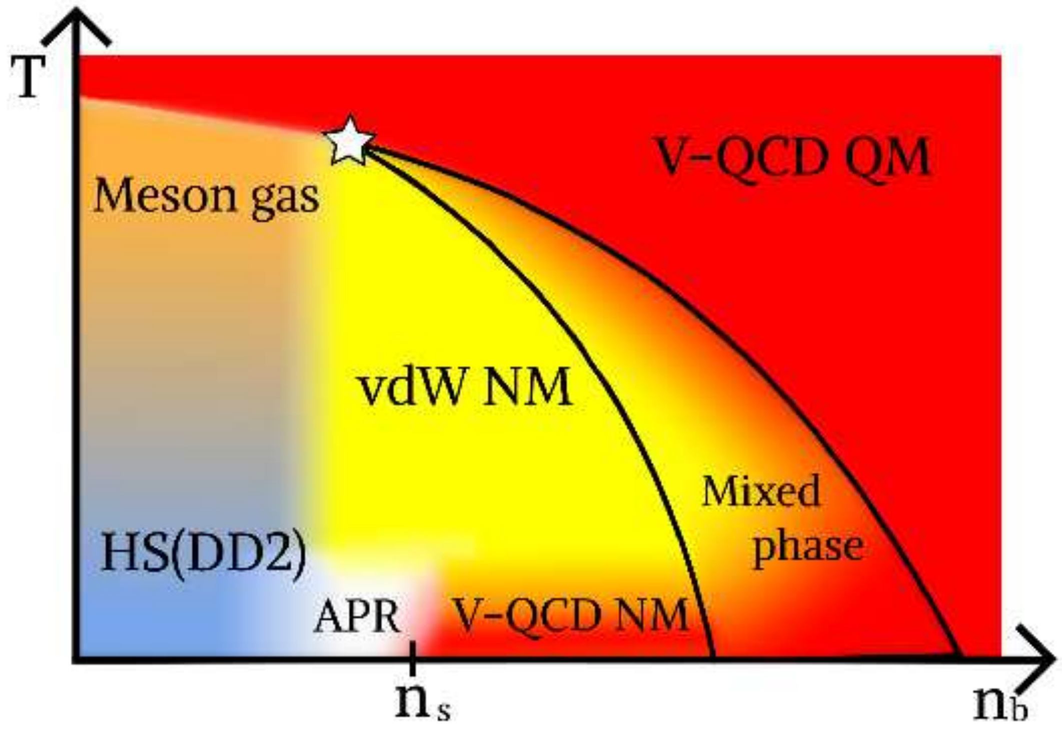
- Effective holographic description of baryonic matter in V-QCD
  Ishii, Järvinen, Nijs, '19.



Baryon distribution realized in the bulk as a homogeneous thin layer.

Effective/hybrid models

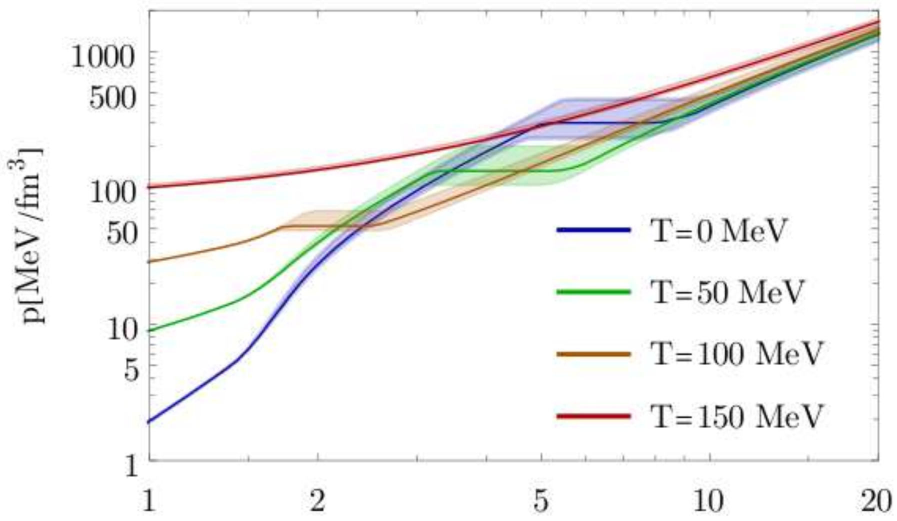
- State of the art Hybrid model Demircik, Ecker, Järvinen, '21

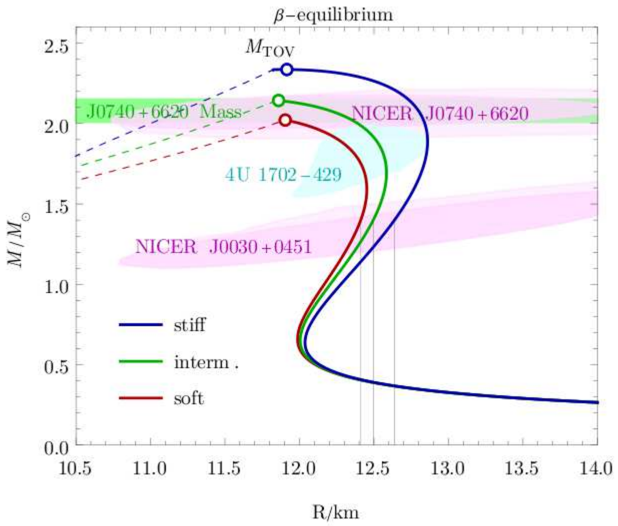


Baryonic phase EoS at finite T described by a VdW model

Neutron Star EoS

- Zero and finite temperature EoS from low to high density (hadronic to deconfined) Demircik, Ecker, Järvinen, '21.



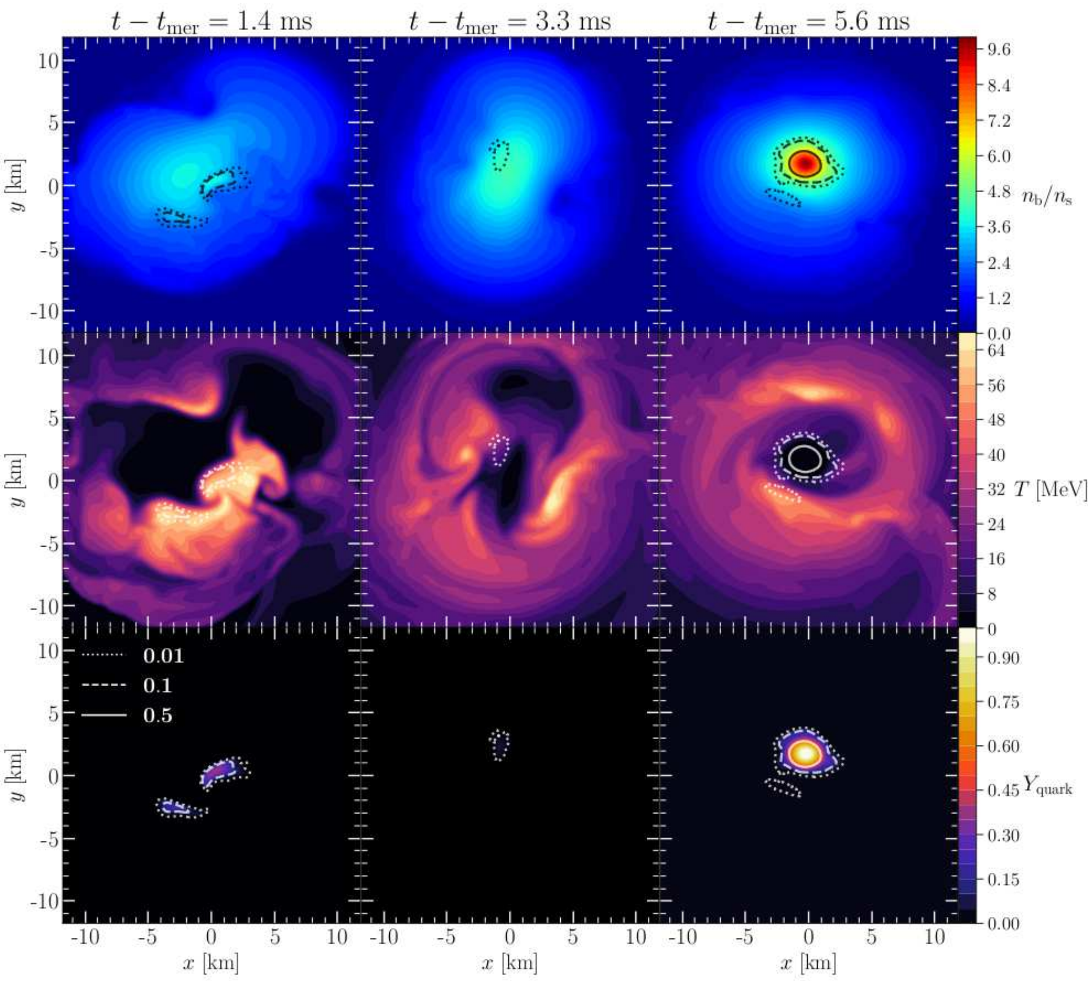


- Static EoS too stiff to support deconfined core. However...

BNS Mergers based on V-QCD

- Simulations based on V-QCD/hybrid EoS + ideal hydro

  Tootle, Ecker, Topolski, Demircik, Järvinen, Rezzolla, 22



- ...quark matter may form in post-merger state

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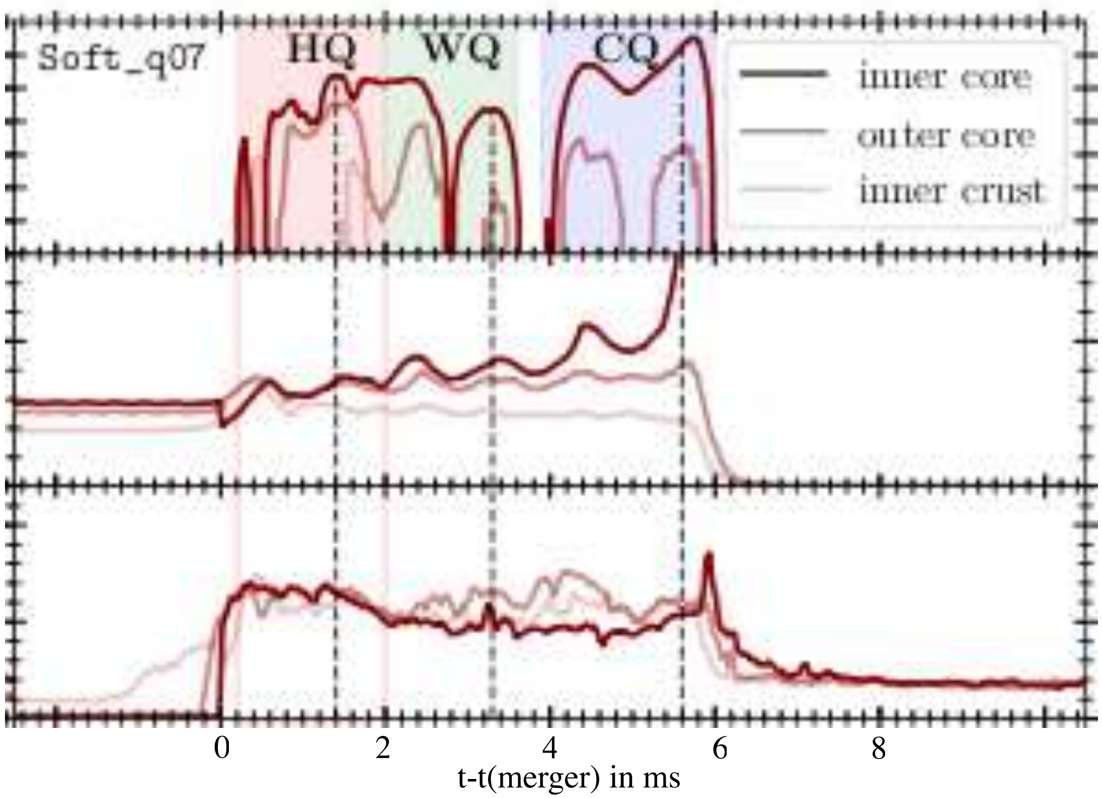
quark fraction

Maximal density

Maximal temperarture

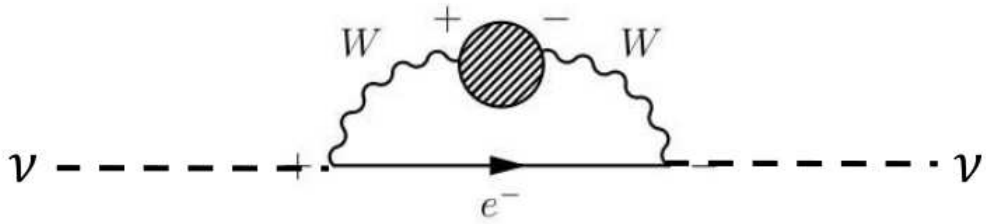


Three quark production mechanisms (hot, warm, cold)

Neutrino transport from holography

To compute the in-medium neutrino diffusion: need strong-interaction contribution to EW gauge bosons self energies:

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



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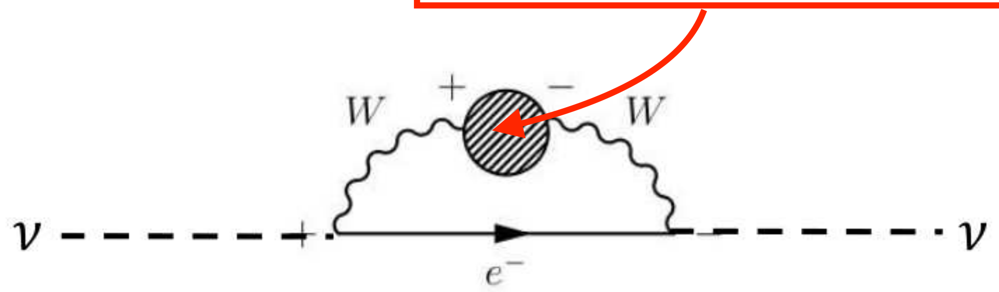

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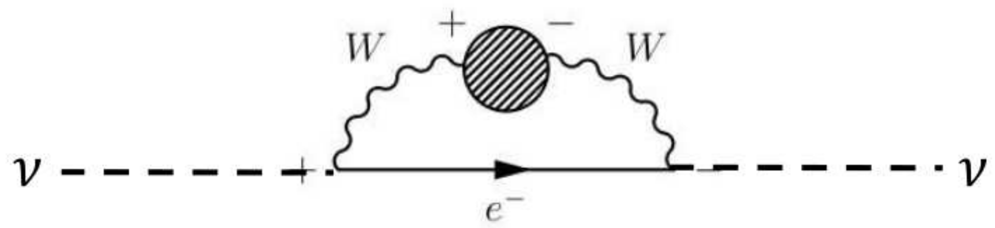
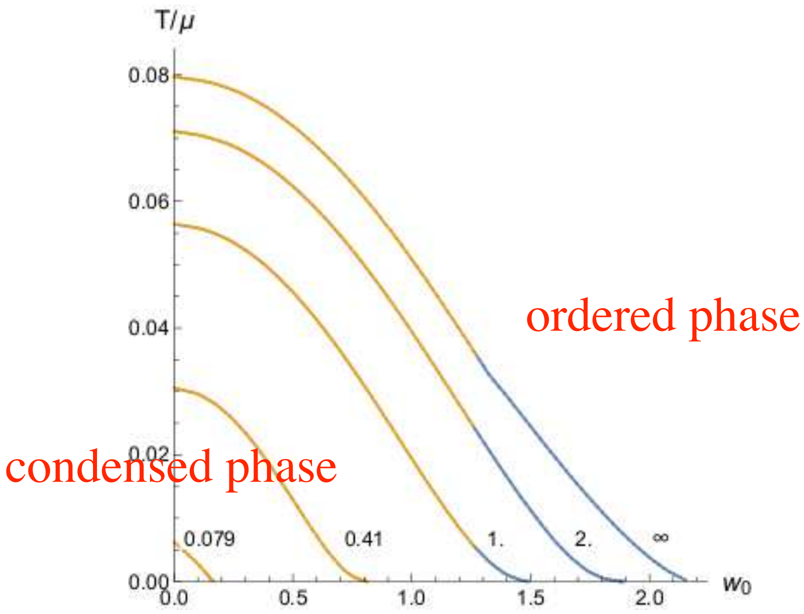


- Can compute real-time $\langle J^\mu J^\nu \rangle_{QCD}$ using holography at finite density and temperature, by a liner perturbation calculation in the bulk.
- Proof of principle calculation in the deconfined phase and in a simplified model Jarvinen, Kiritsis, FN, Préau, '23

Exotic phases

- Holography predicts *exotic phases* in the presnce of both baryon and isospin chemical potential: condensation of a vector order parameter

  Jarvinen, Kiritsis, FN, Préau, '24



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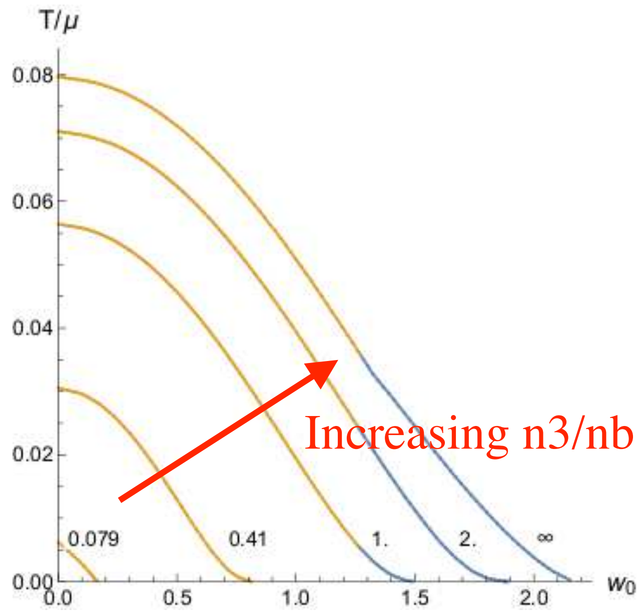

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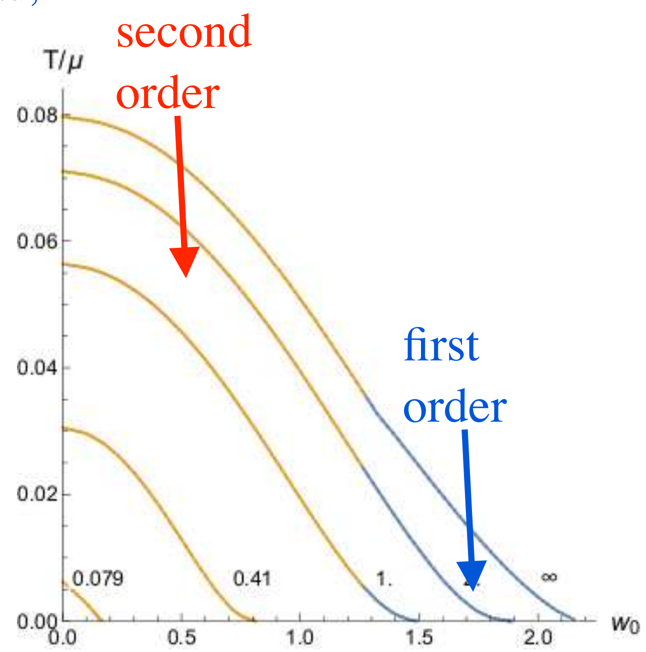

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Conclusion

- State-of-the-art holographic models give reasonable static EoS compatible with observations;
- Can descibe various phases, at low and high temperture, in and out of equilibrium, all within the same model.
- Can go beyond ideal hydro at no additional (theoretical) cost.
- Currently most reliable: description of deconfined quark matter

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- Baryons Construct realistic holographic fluid for confined case
- Finite temperature Relevant for post-merger transient states?
- Go beyond ideal hydro in simulations?
- EW processes: neutrino transport in realistic models.
- where can holography be most helpful?

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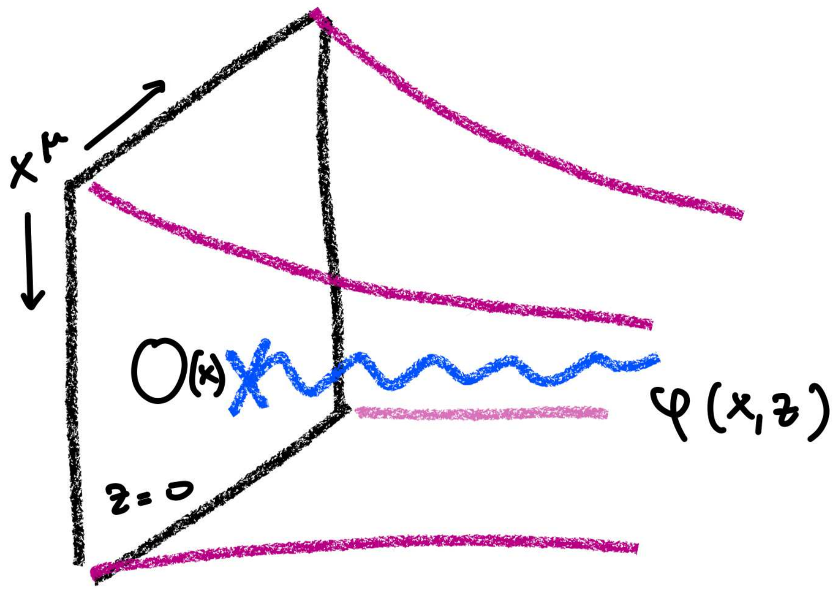
Field/Operator correspondence

- 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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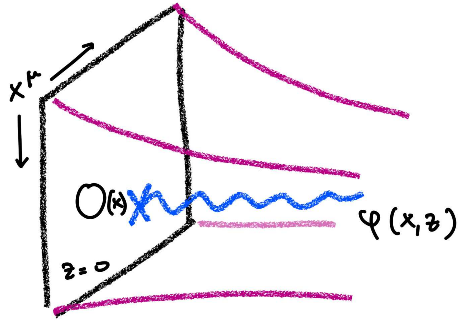

Dimension Δ of O determined by the mass of Φ: $m^2 = \Delta(\Delta - d)$.

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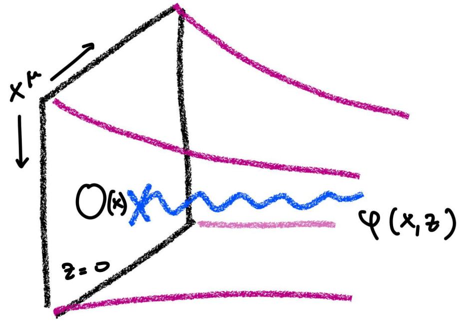

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in the large-N limit:

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

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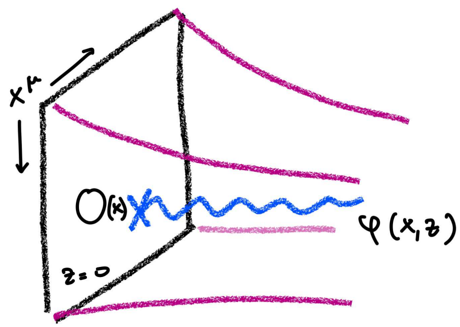

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$$\langle O(x_1) \dots O(x_n) \rangle = \frac{\delta}{\delta\Phi_0(x_1)} \dots \frac{\delta}{\delta\Phi_0(x_n)} S_{cl}[\Phi_0]$$

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	$N \int e^{-\Phi} TrF^2$
$T_{\mu\nu}$	$\Leftrightarrow$	$g_{\mu\nu}$	$\int g_{\mu\nu} T^{\mu\nu}$

$\lambda = N g_{YM}^2 = e^\Phi$ (finite in the large N limit).

- 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, FN, 2007

Bulk dynamics described by a 2-derivative action:

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

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- Effective Planck scale $\sim N_c^2$ is large.

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- UV: $e^A \to \infty, \ \lambda \to 0,$ $V(\lambda) \sim \frac{12}{\ell^2} \left(1 + v_0\lambda + v_1\lambda^2 \ldots\right)$
- IR: λ large, $e^A \to 0;$ $V(\lambda) \sim \lambda^{4/3}(\log\lambda)^{1/2}$

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- IR: λ large, $e^A \to 0; \qquad V(\lambda) \sim \lambda^{4/3} (\log \lambda)^{1/2}$
- Features: asymptotic freedom, confinement, discrete linear glueball spectrum, correct thermodynamics and phase diagram

Five dimensional setup: Yang-Mills

The Poincaré-invariant vacuum solution has the general form:

$$ds^2 = e^{2A(r)}(dr^2 + dx_\mu dx^\mu), \quad \lambda = \lambda(r), \quad 0 < r < +\infty$$

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- $e^A(r) \propto$ 4D energy scale
- $\lambda(r) \propto$ running 't Hooft coupling
- $A(r), \lambda(r)$ determined by solving bulk Einstein's equations.

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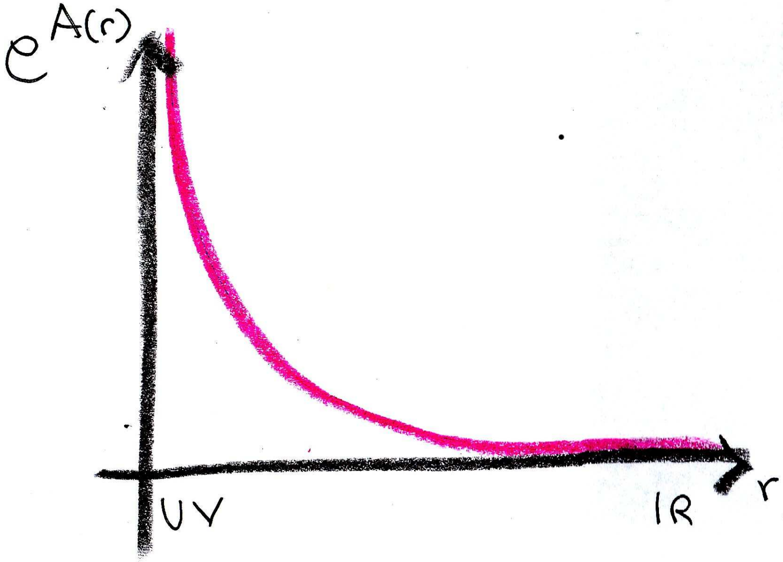
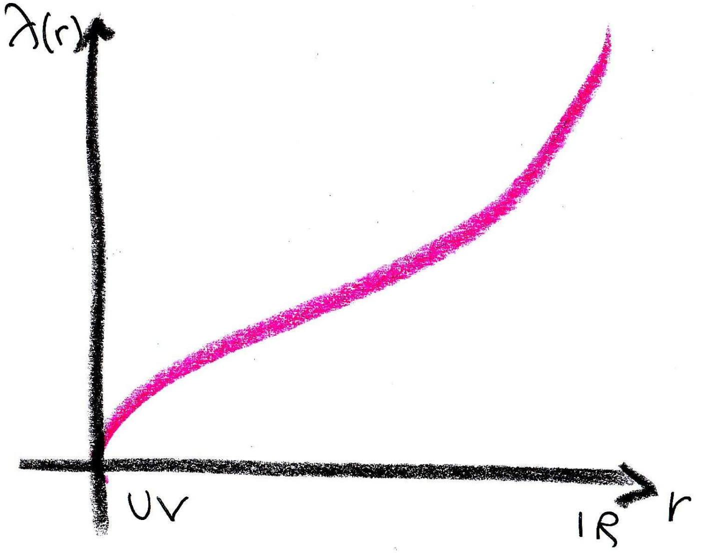
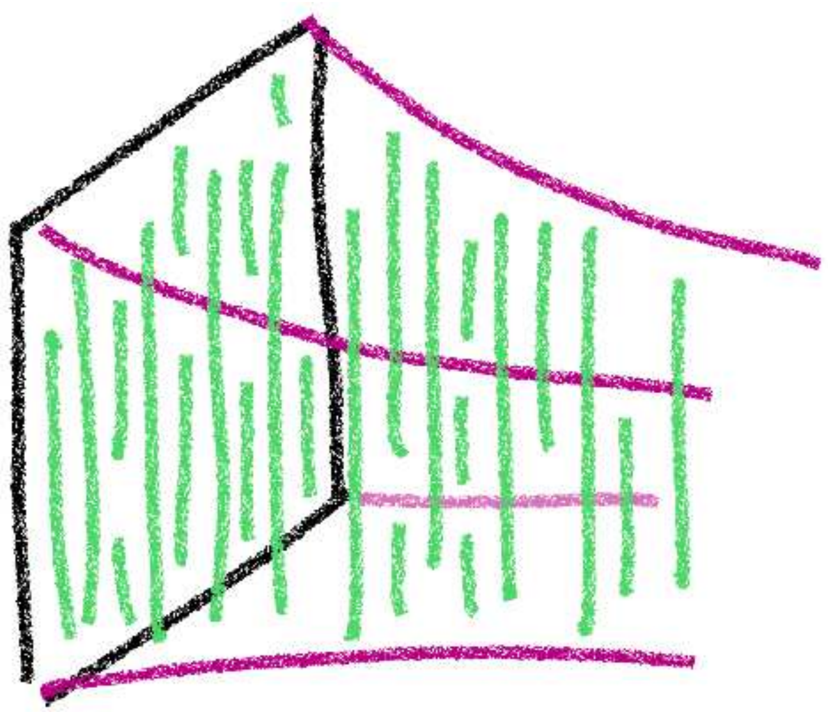




Adding Flavor: V-QCD

Jarvinen, Kiritsis 2011

N_f quark flavors $\Leftrightarrow$ N_f space-filling branes-antibranes.



Adding Flavor: V-QCD

Jarvinen, Kiritsis 2011

Flavor brane worldvolume fields:

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

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

$a = 1 \ldots N_f^2, \; i, j = 1 \ldots N_f$

$U_B(1)$ current $\Leftrightarrow$ abelian vector $A_\mu^{(L)} + A_\mu^{(R)}$

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- Bi-fundamental scalars Scalars

$$\mathcal{T}_j^i \Leftrightarrow \bar{q}^i q_j \qquad m^2 = -3 \Leftrightarrow \Delta = 3$$

Adding Flavor: V-QCD

Jarvinen, Kiritsis 2011

Flavor brane worldvolume fields:

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

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

$a = 1 \ldots N_f^2, \; i, j = 1 \ldots N_f$

$U_B(1)$ current $\Leftrightarrow$ abelian vector $A_\mu^{(L)} + A_\mu^{(R)}$

- Bi-fundamental scalars Scalars

$$\mathcal{T}_j^i \Leftrightarrow \bar{q}^i q_j \qquad m^2 = -3 \Leftrightarrow \Delta = 3$$

$$S_{VQCD} = S_c + S_{DBI} + S_{CS}$$

Action: DBI term

$$S_{DBI} = -M_p^3 N_c Tr \int d^5x\, V_f(\lambda, \mathcal{T}^\dagger \mathcal{T}) \left[\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}}\right]$$

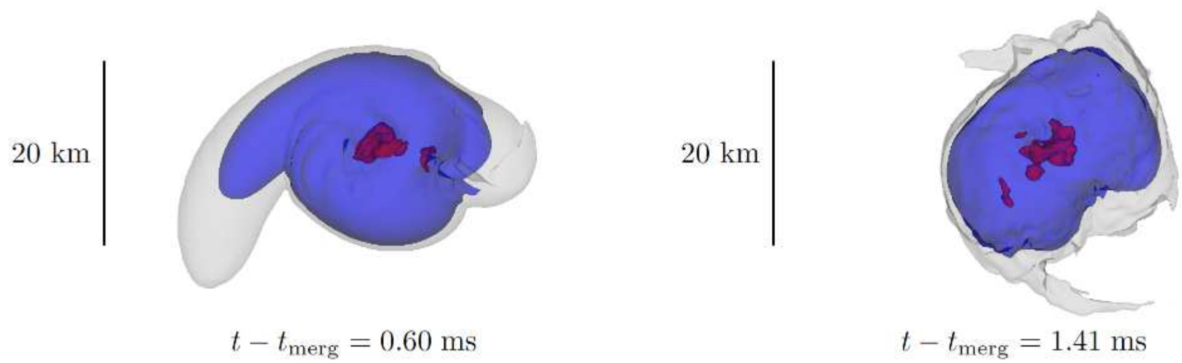
$$\mathbf{A}_{ab} = g_{ab} + w(\lambda, \mathcal{T}^\dagger \mathcal{T}) F_{ab} + \kappa(\lambda, \mathcal{T}^\dagger \mathcal{T}) (D_a \mathcal{T})^\dagger D_b \mathcal{T} \; + \; h.c.$$

To quadratic order:

$$S_{DBI} \simeq M_p^3 N_c \int d^5x\, V_f\, w^2 \left(Tr F_L^2 + Tr F_R^2\right)$$

Phase transitions in BNS mergers

Hot/Compressed spots in post-merger state



Prakash, Radice, Logoteta *et al.*; ’22, Tootle, Ecker, Topolski, *et al.* ’22...

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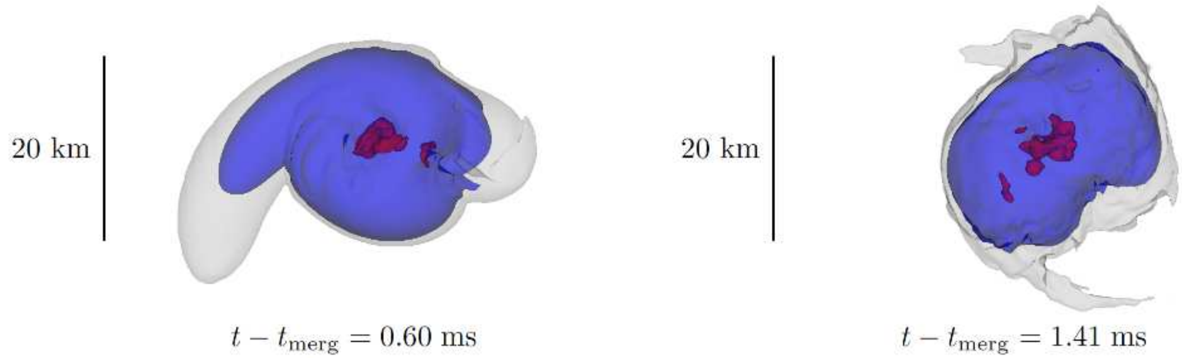
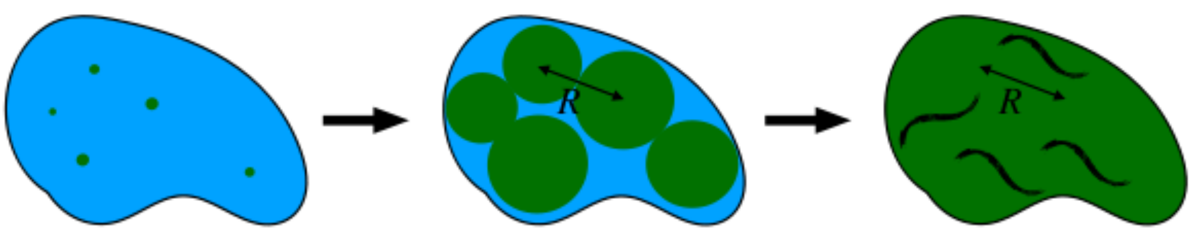


Prakash, Radice, Logoteta *et al.*; '22, Tootle, Ecker, Topolski, *et al.* '22...

investigate phase transitions and bubble nucleation / collisions



Casalderey-Solana, Mateos, Sanchez-Garitaonandia '22

Potential signals in the MHz range from bubble collisions