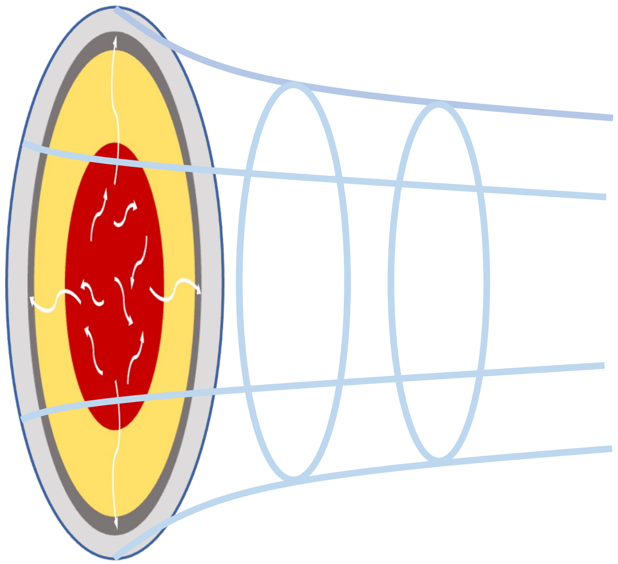
Holography for Astrophysics and Cosmology

Neutrino Transport in Holography



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20/10/22

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Goal

Compute the **neutrino radiative coefficients** in a strongly coupled **holographic medium** at finite **T and n_B**
→ **Simplest** toy model : SYM coupled to fundamental hypermultiplets (supersymmetric equivalents of quarks)

Outline

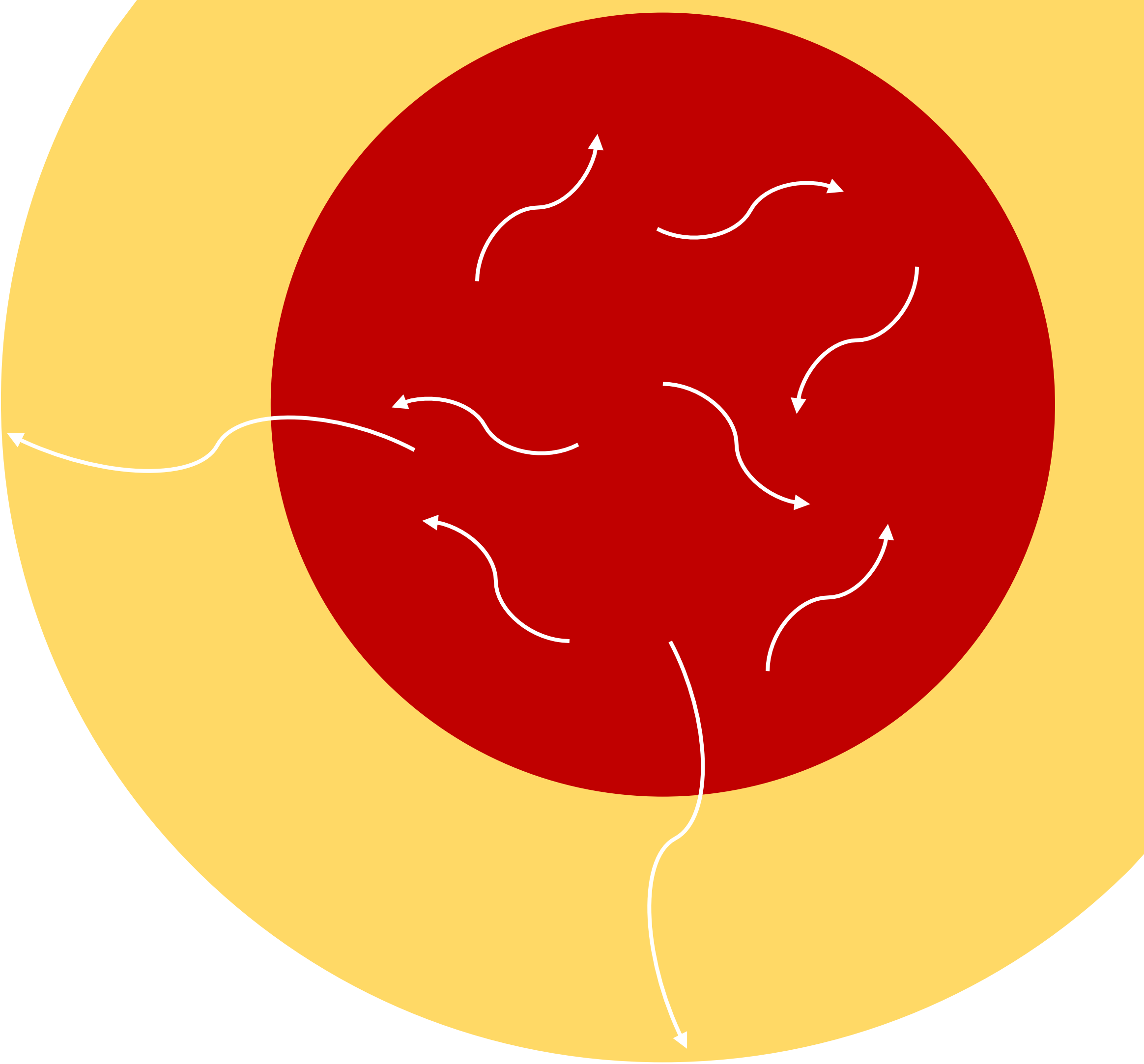
1) Motivation
2) Introduction 1 : Formalism for neutrino transport
3) Introduction 2 : Holographic 2-point function
4) Holographic Set-up
5) Holographic calculation of the chiral current correlators
6) Summary

Motivation

- **Neutrino (ν)** radiation is the main mechanism for **Neutron Star (NS) cooling**

- Requires the knowledge of ν interaction with **dense QCD matter** in the core

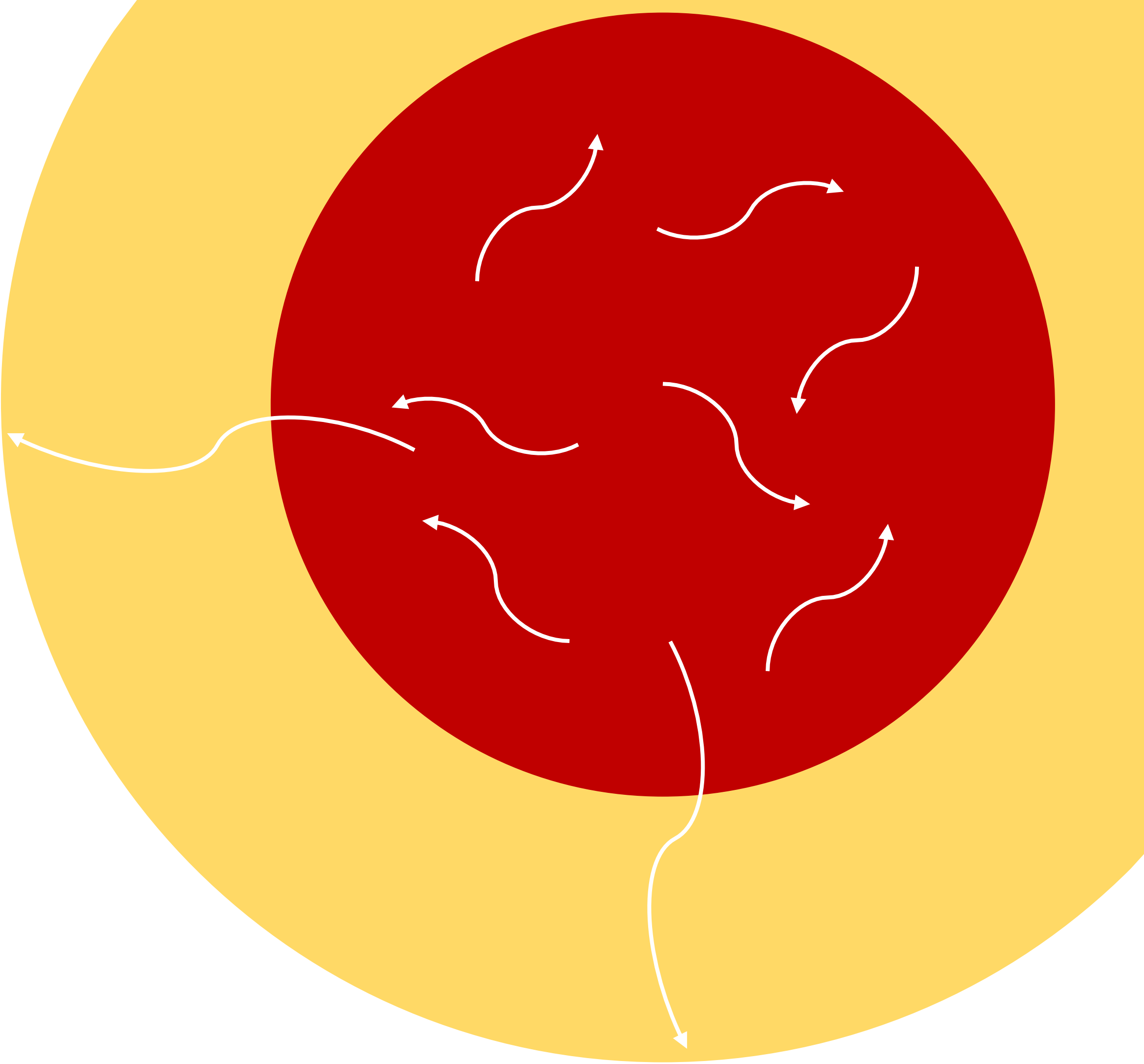
- **Simulations** need an **input** from particle physics : j & $\lambda \leftrightarrow \langle J_{L/R} J_{L/R} \rangle^R$



Motivation

- Computing $\langle J_{L/R} J_{L/R} \rangle^R$ inside NS is a difficult problem: the matter is both **very dense** and **strongly coupled** (low energy QCD)
- The **holographic method** is a way of getting analytic insight into **strongly coupled** problems

Problem : compute $\langle J_{L/R} J_{L/R} \rangle^R$ in **holographic QCD** at finite T and n_B
→ This work : **simplest** toy model (SYM + hypermultiplets)



Formalism for neutrino transport

Neutrino Emissivity and Absorption

Exercice : compute the **exact propagator $\boldsymbol{G_\nu(\vec{x}_1, t_1; \vec{x}_2, t_2)}$** of ν's in a **dense QCD medium**

Assume $\lambda_{MFP} \gg \lambda_\nu$ de Broglie wavelength

→ $\boldsymbol{G_\nu}$ can be described by the **$\boldsymbol{\nu}$ distribution function $\boldsymbol{f_\nu(\vec{x}, t)}$** —Homogeneous→ $f_\nu(t)$

The transport of neutrinos is described by the **kinetic equation** obeyed by $f_\nu(t)$

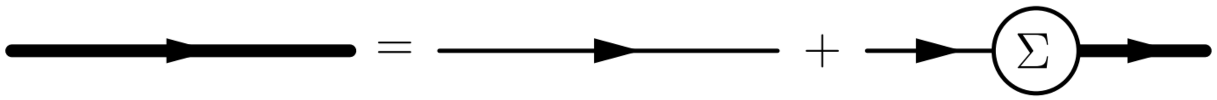
$$\partial_t f_\nu \equiv j(E_\nu)(1 - f_\nu) - \frac{1}{\lambda(E_\nu)} f_\nu \,.$$

Emissivity — **Mean Free Path**

Schwinger-Dyson equation

[2103.10636]

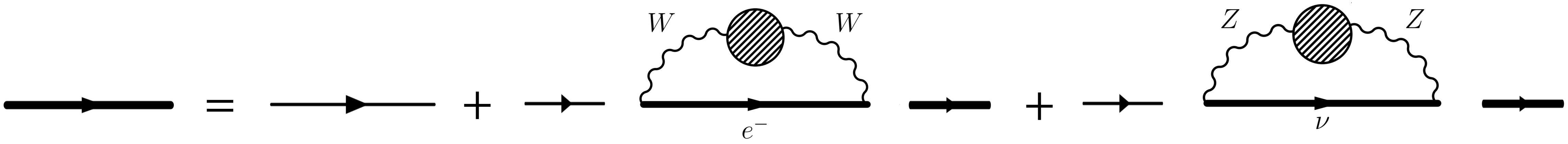
The kinetic equation can be derived from the finite temperature **Schwinger-Dyson equation**



The self-energy Σ **is expanded at order $\mathcal{O}(G_F^2)$** in the weak interaction

$\boldsymbol{\nu + n \leftrightarrow e^- + p}$

$\boldsymbol{\nu + n/p \leftrightarrow \nu + n/p}$

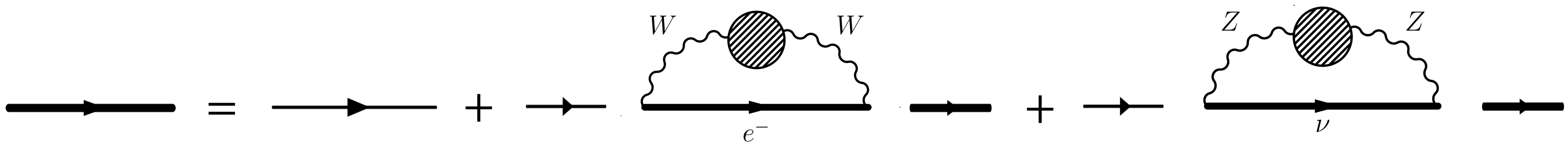


It is fully **non-perturbative** in the **strong** interaction

Schwinger-Dyson equation

The kinetic equation is derived from the finite temperature **Schwinger-Dyson equation**

$\boldsymbol{\nu + n \leftrightarrow e^- + p}$ $\boldsymbol{\nu + n/p \leftrightarrow \nu + n/p}$



$$j(E_\nu) = G_F^2 \int \frac{d\vec{k}_e^3}{(2\pi)^3} \underbrace{(\text{kins})^{\lambda\sigma}}_{\vec{k}_e,\,\vec{p}_\nu} \times \underbrace{(\text{stats})}_{f_e,\,f_W} \times \underbrace{\text{Im}(i\langle J_\lambda^- J_\sigma^+\rangle^R)}_{\text{Dense QCD}} + G_F^2 \int \frac{d\vec{k}_\nu^3}{(2\pi)^3} \underbrace{(\text{kins})^{\lambda\sigma}}_{\vec{k}_\nu,\,\vec{p}_\nu} \times \underbrace{(\text{stats})}_{f_\nu,\,f_Z} \times \underbrace{\text{Im}\left(i\langle J_\lambda^0 J_\sigma^0\rangle^R\right)}_{\text{Dense QCD}},$$

Dense QCD $\leftrightarrow \left\langle J_\lambda^{L/R} J_\sigma^{L/R} \right\rangle^R$

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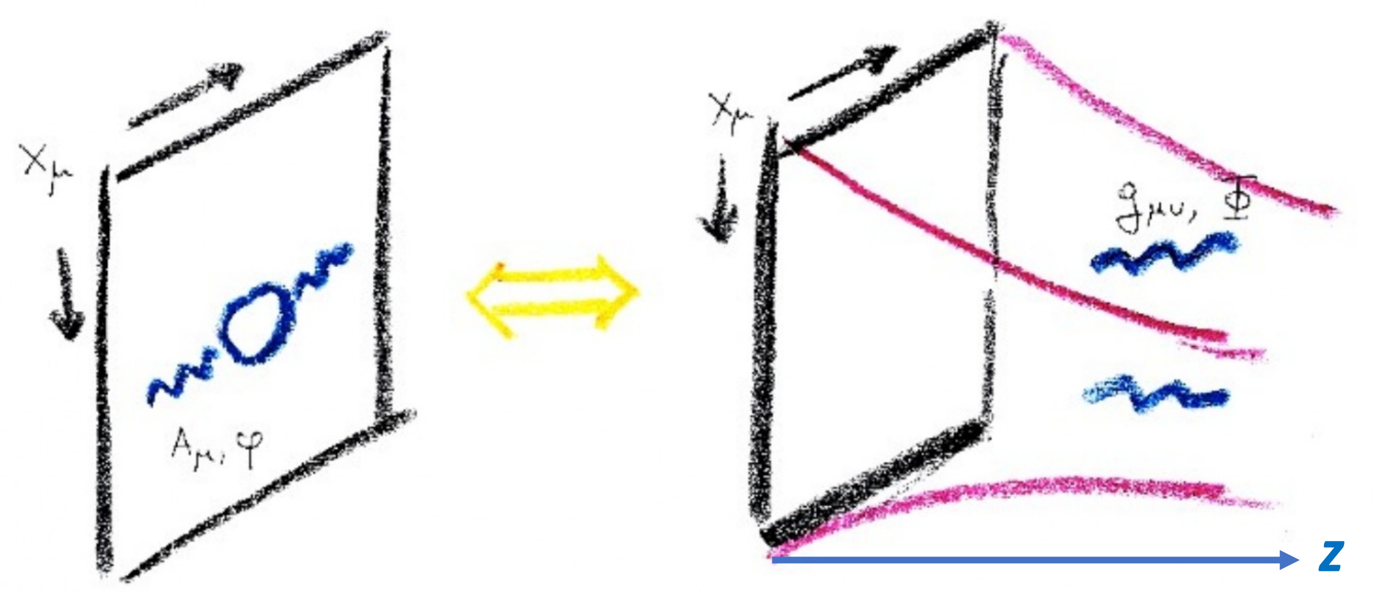
Holographic 2-point function

The Holographic Correspondence



Duality bewteen a QFT in 4D and a semi-classical **gravitational theory in 5D.**

If the QFT is strongly coupled, then the dual theory is **weakly curved.**

The dual 5D space-time (***bulk***) is asymptotically AdS^5 .

Its **boundary** is the 4D space-time on which the QFT is defined

The additional dimension ***z*** is called the **holographic coordinate** and identified with the **energy scale** such that:

UV ↔ boundary

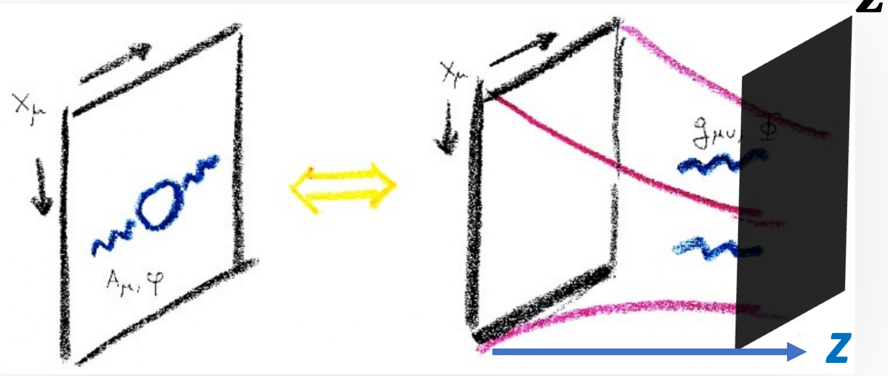
IR ↔ center

Retarded holographic 2-point function

[ArXiv:hep-th/0205051]
[0805.0150]

Consider **finite temperature**, with a **black hole** in the bulk

$z_H = (\pi T)^{-1}$



$\boldsymbol{O} \leftrightarrow \boldsymbol{\phi}$: $\langle OO \rangle^R$ is obtained by studying the **fluctuations** of ϕ

$$\delta\phi = \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \mathrm{e}^{ik.x} C_k(z) \delta\phi_0(k)\,, \quad \text{At } z \sim z_H : \delta\phi(z) \sim (z_H - z)^{-\frac{ik^0 z_H}{4}}$$

Infalling boundary condition

The **on-shell action** at **quadratic order** is

$$S_{on-shell} = -\frac{1}{2}\int \frac{\mathrm{d}^4 k}{(2\pi)^4} \delta\phi_0(-k) \langle \boldsymbol{OO} \rangle^R(\boldsymbol{k}) \delta\phi_0(k)\ .$$

The Holographic Set-up

A holographic toy model to compute chiral currents 2-point functions at finite T, n_B and n_3

$\mathrm{AdS}^5/\mathrm{CFT}^4$ at finite temperature

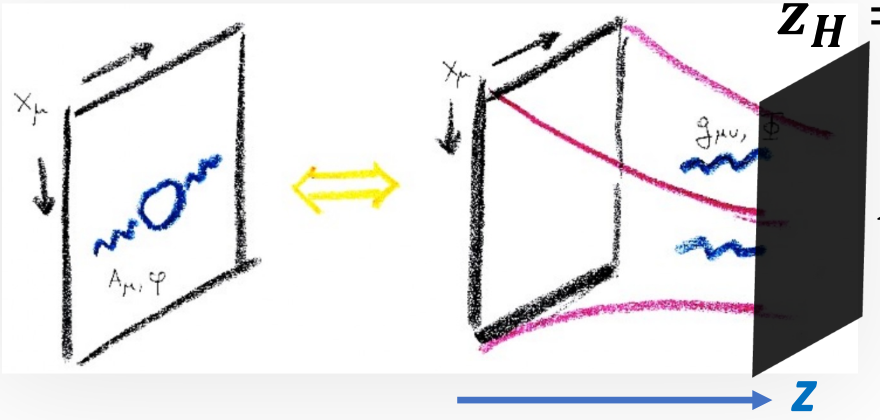
The original correspondence was formulated for an explicit 4D CFT :

$\mathcal{N}=4$ **SU(N) SYM** in 4d $\leftrightarrow$ type IIB string theory on AdS^5

A **thermal state** is dual to a planar **AdS-Schwarzschild black hole**

$z_H = (\pi\, T)^{-1}$

SYM at finite T



AdS^5-Schwarzschild

AdS^5/CFT^4 at finite T and n_B

Simplest holographic set-up with (**deconfined**) **baryon density n_B**

- Couple $\mathcal{N}$=4 SYM to **fundamental** hypermultiplets (~ **quarks**)
- The theory possesses a global **chiral symmetry** $U(N_f)_L \times U(N_f)_R$ with currents $J^\mu_{L/R}$

$$U(N_f)_L \times U(N_f)_R : \partial_\mu J^\mu_{L/R} = 0 \quad \leftrightarrow \quad U(N_f)_L \times U(N_f)_R : A^M_{L/R}$$

- **Baryon number** $U(1)_L \times U(1)_R : J^\mu_B$ is dual to $A^M_B \equiv \hat{A}^M_L + \hat{A}^M_R$ Abelian part
- Deconfined $n_B \leftrightarrow \mu_B$: boundary source for $A^B_0(z) = \mu_B + \mathcal{O}(z^2)$, at $z \to 0$

$\mathrm{AdS}^5/\mathrm{CFT}^4$ at finite T and n_B

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$$U(N_f)_L \times U(N_f)_R : \partial_\mu J^{\mu}_{L/R} = 0 \quad \leftrightarrow \quad U(N_f)_L \times U(N_f)_R : A^{M}_{L/R}$$

- Deconfined $n_B \leftrightarrow \mu_B$: boundary source for $A^0_B(z) = \mu_B + \mathcal{O}(z^2)$, at $z \to 0$
- **Isospin asymmetry** $(n_n \geq n_p) \leftrightarrow \mu_3$: source for $A^{L,3}_0(z) = \mu_3 + \mathcal{O}(z^2)$, at $z \to 0$

Action and vacuum solution

$$S = M_{Pl}^3 N_c^2 \int \mathrm{dx}^5 \sqrt{-g}\left(R + \frac{12}{\ell^2} - \frac{\kappa}{N_c}\mathbf{Tr}\left\{F_{MN}^{(L)} F_{(L)}^{MN} + F_{MN}^{(R)} F_{(R)}^{MN}\right\}\right),$$

Veneziano limit : $N_c \to \infty$, $N_f \to \infty$, $x \equiv N_f/N_c$ **fixed**

→ **Back-reaction** of the gauge field on the metric

Geometry dual to the vacuum at finite (T, n_B, n_3) : solution to the bulk **Einstein-Maxwell** equations such that

- Asymptotically AdS^5
- A_0^B and $A_0^{L,3}$ are **sourced** at the boundary by (μ_B, μ_3)
- **Regular** at the horizon : $A_0^B(z_H) = A_0^{L,3}(z_H) = 0$

AdS – Reissner Nordström (AdS-RN) with charge $Q^2 \propto \mu^2 \equiv \mu_B^2 + 2\mu_3^2$

Holographic calculation of the chiral current 2-point function

Perturbations of AdS-RN

[ArXiv:hep-th/0205051]
[0805.0150]

$\langle J_\lambda J_\sigma \rangle^R$ is obtained by considering **perturbations** of the fields on top of **AdS-RN**

$$A^M_{L/R} \to \bar{A}^M_{L/R} + \delta A^M_{L/R}\,, \qquad g_{MN} \to \bar{g}_{MN} + \delta g_{MN}\,,$$

$$\forall \boldsymbol{\varphi},\ \delta\varphi = \int \frac{\mathrm{d}^4k}{(2\pi)^4} \mathrm{e}^{ik.x} C_k(z)\delta\varphi_0(k)\,, \quad \text{At } z \sim z_H : \varphi(z) \sim (z_H - z)^{-\frac{ik^0 z_H}{4}}$$

Infalling boundary condition

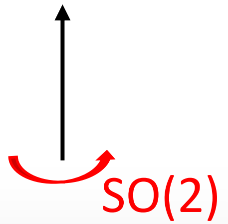
- Prescription : **radial gauge** $\delta A^z_{L/R} = 0\,,\ \delta g_{Mz} = 0$
- $\boldsymbol{\delta T_{MN}} \propto \delta X \equiv \mu_B \delta A_B + 2\mu_3 \delta A_{L,3}$ **couples to $\boldsymbol{\delta g}$**
- All the other gauge fields **decouple** from δg

Perturbations : Symmetries

The boundary plasma has an **SO(3) rotational invariance**

$$\langle J_\lambda J_\sigma \rangle^R(\omega, \vec{k}) = P^\perp(\omega, \vec{k})_{\lambda\sigma} i\boldsymbol{\Pi}^\perp(\boldsymbol{\omega}, \mathbf{k}) + P^\parallel(\omega, \vec{k})_{\lambda\sigma} i\boldsymbol{\Pi}^\parallel(\boldsymbol{\omega}, \mathbf{k})$$

$\vec{k} = k\vec{e}_3$



For a given **mode $(\boldsymbol{\omega}, \vec{\boldsymbol{k}})$**, it reduces to an **SO(2) subgroup**

The perturbations are divided into **helicity sectors** that decouple

Helicity	Gauge field	Metric
$h = 0$	$\delta A_0 , \delta A_3$	$\delta g_0^0 , \delta g_0^3 , \delta g_3^3 , \delta g_1^1 + \delta g_2^2$
$h = 1$	$\delta A_{1,2}$	$\delta g_0^{1,2} , \delta g_3^{1,2}$
$h = 2$	$-$	$\delta g_2^1 , \delta g_1^1 - \delta g_2^2$

Sector decoupled from the metric

Consider δA_μ that decouples from $\delta g_{\mu\nu}$

The modes are organized in terms of the **gauge-invariants** under

$$\mathrm{U}(1) : \delta A \to \delta A + \mathrm{d}\delta\lambda$$

$\boldsymbol{h = 1}$	$\boldsymbol{h = 0}$
$\delta A_1 \,, \delta A_2$	$E^{\parallel} \equiv \omega \delta A_3 + k \delta A_0$

The linearized **Maxwell equations** in each helicity sector can be written in terms of the gauge-invariants

The Π's are extracted from the **solutions near the boundary** $(z \to 0)$

$$\Pi^{\perp} \propto -\frac{\ell}{z} \frac{\partial_z \delta A_1}{\delta A_1}\bigg|_{z\to 0} \,, \qquad \Pi^{\parallel} \propto -\frac{\ell}{z} \frac{\partial_z \delta E^{\parallel}}{\delta E^{\parallel}}\bigg|_{z\to 0} \,.$$

Sector coupled to the metric

$\delta T_{MN} \propto \delta X_\mu$ couples to $\delta g_{\mu\nu}$

Again, organize the modes in terms of the **gauge-invariants** under :

- $U(1) : \delta X \to \delta X + \mathrm{d}\delta\lambda$
- **Diffeomorphisms** :

$$\delta X_M \to \delta X_M + \delta\xi^N \partial_N \bar{X}_M + \bar{X}_N \partial_M \delta\xi^N$$

$$\delta g_{MN} \to \delta g_{MN} + \nabla_M \delta\xi_N + \nabla_N \delta\xi_M$$

$\boldsymbol{h = 1}$	$\boldsymbol{h = 0}$
$\delta X_{1,2}$	$\delta S_1 \equiv \omega\delta X_3 + k\delta X_0 + a(z)\mu\, k(\delta g_1^1 + \delta g_2^2)$
$\delta Y^{1,2} \equiv k\delta g_0^{1,2} + \omega\delta g_3^{1,2}$	δS_2 $\equiv 2\omega k\delta g_0^3 + \omega^2\delta g_z^z - f(z)k^2\delta g_0^0 + b(z,\omega/k)k^2(\delta g_1^1 + \delta g_2^2)$

Sector coupled to the metric

The linearized **Einstein-Maxwell equations** in each helicity sector can be written in terms of the **gauge-invariants** :

- $\boldsymbol{h=1}$ **:** 2 coupled 2nd order ODE's for $\delta X_{1,2}$ and $\delta Y^{1,2}$
- $\boldsymbol{h=0}$ **:** 2 coupled 2nd order ODE's for δS_1 and δS_2

The Π's are extracted from the **solutions near the boundary** $(z \to 0)$

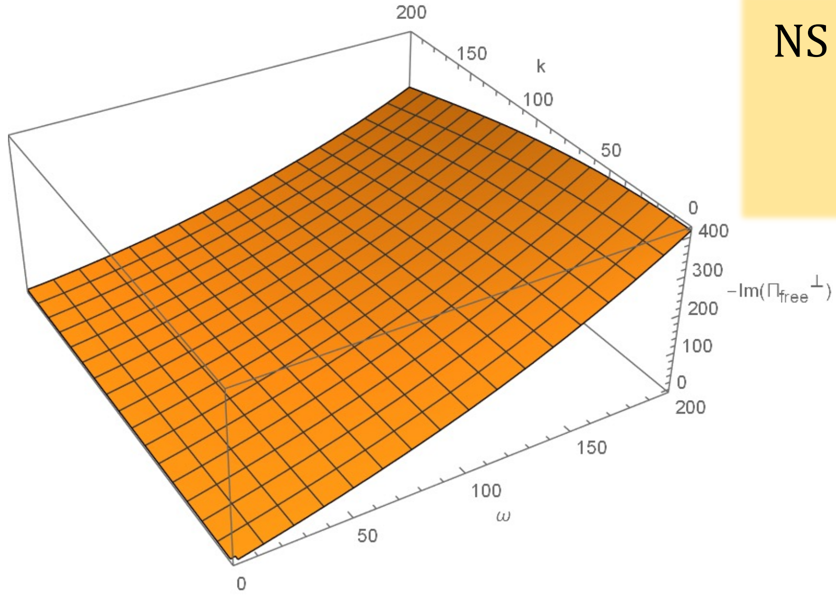
$$\boldsymbol{h=1:} \qquad \delta X_1 = \delta \hat{X}_1 + z^2 \delta \Pi_{X_1} + \cdots , \qquad \delta \Pi_{X_1} \equiv \boldsymbol{\Pi^{\perp}_{XX}} \delta \hat{X}_1 + \Pi^{\perp}_{XY} \delta \hat{Y}^1 ,$$

Compute **2 solutions** and invert the linear relation

$$\begin{pmatrix} \boldsymbol{\Pi^{\perp}_{XX}} & \Pi^{\perp}_{XY} \end{pmatrix} = \begin{pmatrix} \delta \Pi^{(1)}_{X_1} & \delta \Pi^{(2)}_{X_1} \end{pmatrix} \begin{pmatrix} \delta \hat{X}^{(1)}_1 & \delta \hat{X}^{(2)}_1 \\ \delta \hat{Y}^1_{(1)} & \delta \hat{Y}^1_{(2)} \end{pmatrix}^{-1}$$

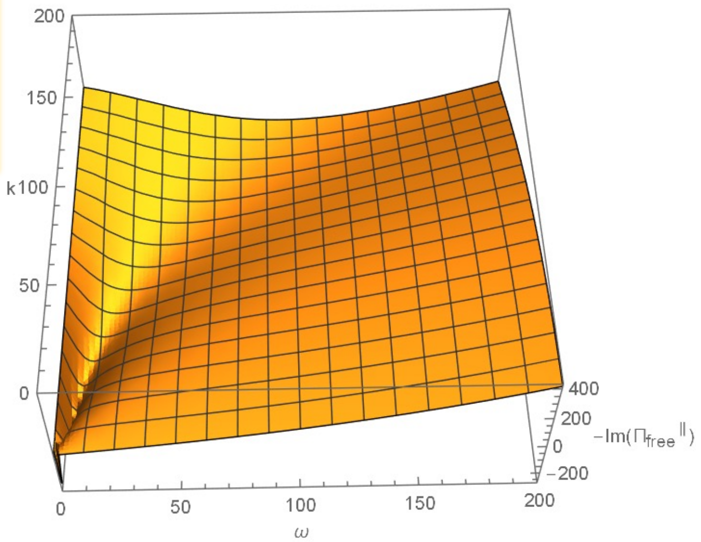
Some numerical results

Polarization functions for the free gauge fields



NS inner crust conditions

$$\frac{\mu}{T} = 887, Y_e = 0.15$$



$\boldsymbol{h = 1}$

$\boldsymbol{h = 0}$

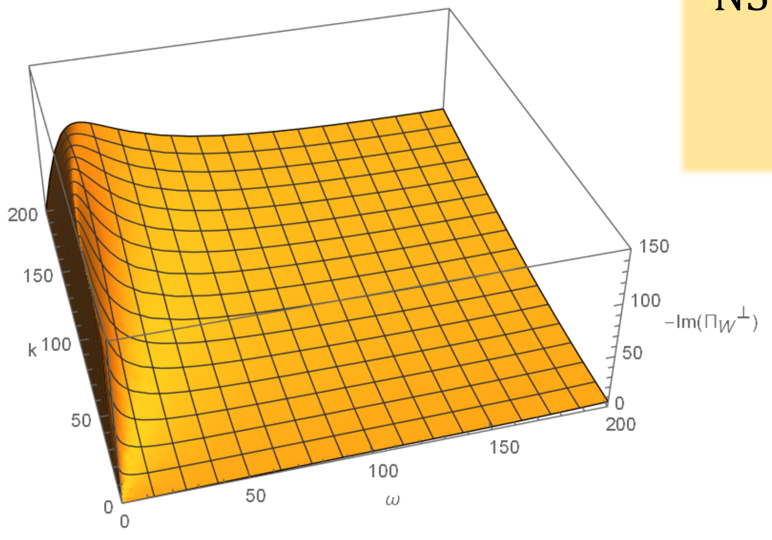
- No peak structure signaling a dominating pole

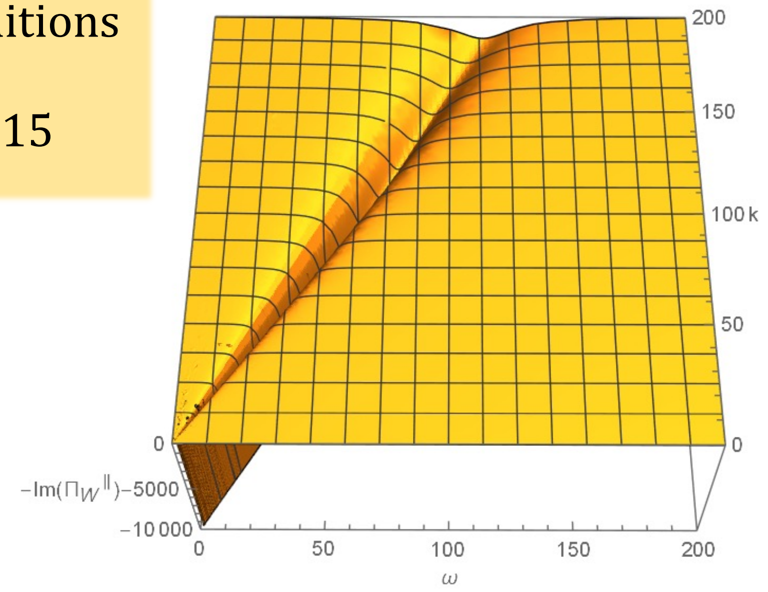
- **Diffusion pole** manifest in the hydrodynamic region $\boldsymbol{\omega = -iDk^2}$
- The diffusion peak **disappears at large k**

Polarization functions for δW_μ

NS inner crust conditions

$$\frac{\mu}{T} = 887, Y_e = 0.15$$





$h = 1$

- **Diffusion pole** in the hydrodynamic region
  → induced by the **coupling to the thermal bath** dual to the metric

$h = 0$

- **Sound pole** manifest in the hydrodynamic region $\omega = \frac{k}{\sqrt{3}} - iDk^2$
- The peak **disappears at large k**

Next Steps

- Compute the radiative coefficients **$j(E_\nu)$** and **$\lambda(E_\nu)$**
- Compare with approximate results for **quark stars**
- More realistic model of **holographic QCD :**
  → topological **CS term** and **full DBI action** for the flavor branes in SYM
  → bottom-up **V-QCD framework**
- Deconfined n_B → Baryonic matter **confined inside baryons**
- Use the resulting $j(E_\nu)$ and $\lambda(E_\nu)$ in actual **simulations** !

Summary

- Computing **transport of $\boldsymbol{\nu' s}$** in QCD matter $\leftrightarrow$ $\mathbf{Im}\left(\boldsymbol{i}\left\langle \boldsymbol{J_\lambda^{L/R} J_\sigma^{L/R}} \right\rangle^{\boldsymbol{R}}\right)$ **: strongly coupled** calculation

- We use the **holographic** approach to tackle this strongly coupled problem

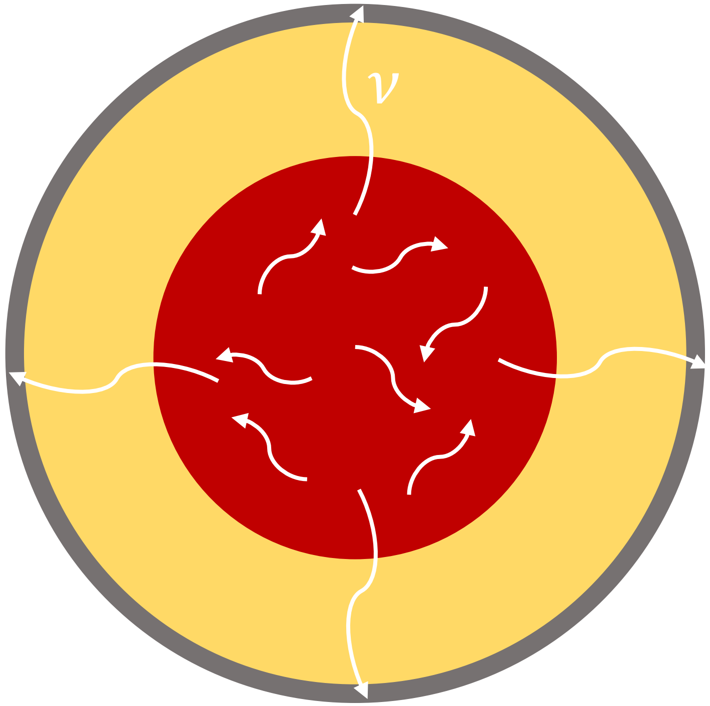
- First in a **toy model** : $\mathcal{N} = 4$ SU(N) SYM at **finite $\boldsymbol{(T, \mu_B, \mu_3)}$**

- $\mathrm{Im}\left(i\left\langle J_\lambda^{L/R} J_\sigma^{L/R} \right\rangle^R\right)$ is extracted from the **near-boundary behavior** of the solution of the **linearized Einstein-Maxwell** equations on top of the **AdS-RN background**

Appendix

Neutrino radiation in Neutron Stars

The cooling of a young NS core happens via neutrino (ν) emission



Inner core : neutrinos scatter off the strongly coupled dense QCD matter via the weak interaction

Problem : understand weak charge transport in strongly coupled dense QCD matter

The Holographic Dictionary

Every QFT operator has a **dual field** in the bulk of same spin

$T_{\mu\nu}$	$\leftrightarrow$	g_{MN}
O	$\leftrightarrow$	φ
G : $\partial_\mu J^\mu = 0$	$\leftrightarrow$	G : A^M

Near-boundary, source and vev

$$O(x) \leftrightarrow \phi(x,z)$$

The **near-boundary behavior** $(z \to 0)$ of ϕ is dictated by the $\boldsymbol{AdS^5}$ **geometry**

$$\phi(x,z) = \underbrace{\phi_0(x)}_{\text{Source}} \; \underbrace{z^{\Delta_-}}_{\text{Non-normalizable}}(1+\cdots) + \underbrace{\phi_1(x)}_{\text{Vev} \sim \langle O \rangle} \; \underbrace{z^{\Delta_+}}_{\text{Normalizable}}(1+\cdots)\,,$$

In **Euclidean signature**, the holographic correspondence is formally stated as

$$e^{W(\phi_0)} \equiv \left\langle e^{\int_{\partial\mathcal{M}} O\phi_0} \right\rangle = e^{-S^{5D}_{on-shell}[\phi]}\Big|_{\phi\sim\phi_0}\,.$$

Euclidean holographic 2-point function

Consider **finite temperature**, with a **black hole** in the bulk

$$z : 0 \to z_H \propto \frac{1}{T} \, ,$$

$\boldsymbol{O} \leftrightarrow \boldsymbol{\phi}$: $\langle OO \rangle^E$ is obtained by studying the **fluctuations** of ϕ

$$\delta\phi = \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \mathrm{e}^{ik.x} f_k(z) \delta\phi_0(k) \, , \quad \text{At } z \sim z_H : \phi(z) \text{ **regular**}$$

$$\underbrace{W[\delta\phi_0]} = -S^{5D}_{on-shell}[\delta\phi]\Big|_{\delta\phi(z\to 0)=\delta\phi_0}$$ → the **on-shell action** at **quadratic order** is

Generating functional for correlation functions of O

$$S^{5D}_{on-shell} = -\frac{1}{2}\int \frac{\mathrm{d}^4 k}{(2\pi)^4} \delta\phi_0(-k) \langle \boldsymbol{OO} \rangle^{\boldsymbol{E}}(\boldsymbol{k}) \delta\phi_0(k) \, .$$

The holographic retarded correlator [ArXiv:0205051]

$$J^{\mu}_{L/R} \leftrightarrow A^{\mu}_{L/R}$$

$\langle J^{\mu} J^{\nu} \rangle^{R}$ is obtained by studying the fluctuations of A^{μ}

$$\delta A^{\mu} = \int \frac{d^4 k}{(2\pi)^4} \mathrm{e}^{ik.x} f_k(z) A^{\mu}_0(k) \,, \quad \text{At } z \sim z_H : \mathrm{A}^{\mu}(z) \sim (z_H - z)^{-\frac{ik^0 z_H}{4}}$$

Infalling boundary condition

The on-shell action at quadratic order is

$$S_{on-shell} = -\frac{1}{2} \int \frac{\mathrm{d}^4 k}{(2\pi)^4} A^{\mu}_0(-k) \boldsymbol{\langle J_{\mu} J_{\nu} \rangle^{R} (k)} A^{\nu}_0(k) \,,$$

Correlator at finite density

Goal : compute $\text{Im}\langle J^{L/R} J^{L/R}\rangle^R(k)$ in a dense matter composed of baryons

→ Easier problem : baryon number fractionalized

Finite fractionalized baryon density ↔ finite chemical potential μ_B

$$\text{Source} : \underbrace{\hat{L}^0 + \hat{R}^0}_{\text{Baryon gauge field } \hat{V}} = \mu_B + \mathcal{O}(z^2) \,,$$

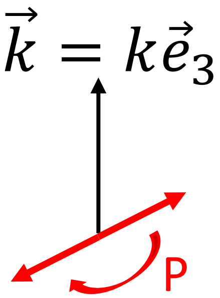
Isospin asymmetric $(n_n \geq n_p)$ ↔ finite μ_3

$$\text{Source} : \underbrace{L_3^0}_{\text{Weak isospin gauge field}} = \mu_3 + \mathcal{O}(z^2)$$

Intermediate Goal : compute $\text{Im}\langle J^{L/R} J^{L/R}\rangle^R(k)$ at finite (T, μ_B, μ_3) in V-QCD

Sector coupled to the metric

δW_μ couples to $\delta g_{\mu\nu}$



Again, organize the modes in **P-odd and P-even** sectors and in terms of the **gauge-invariants** under :

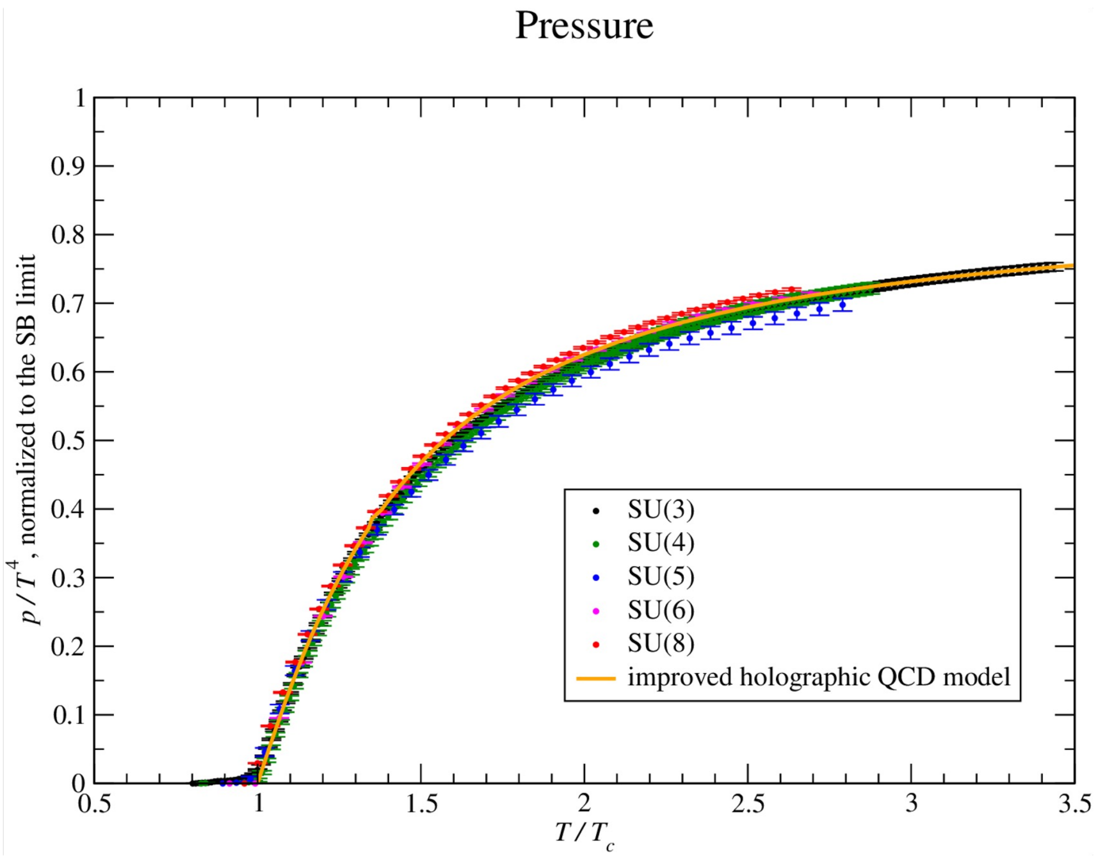
- $\delta W \to \delta W + \mathrm{d}\delta\lambda$
- **Diffeomorphisms** :

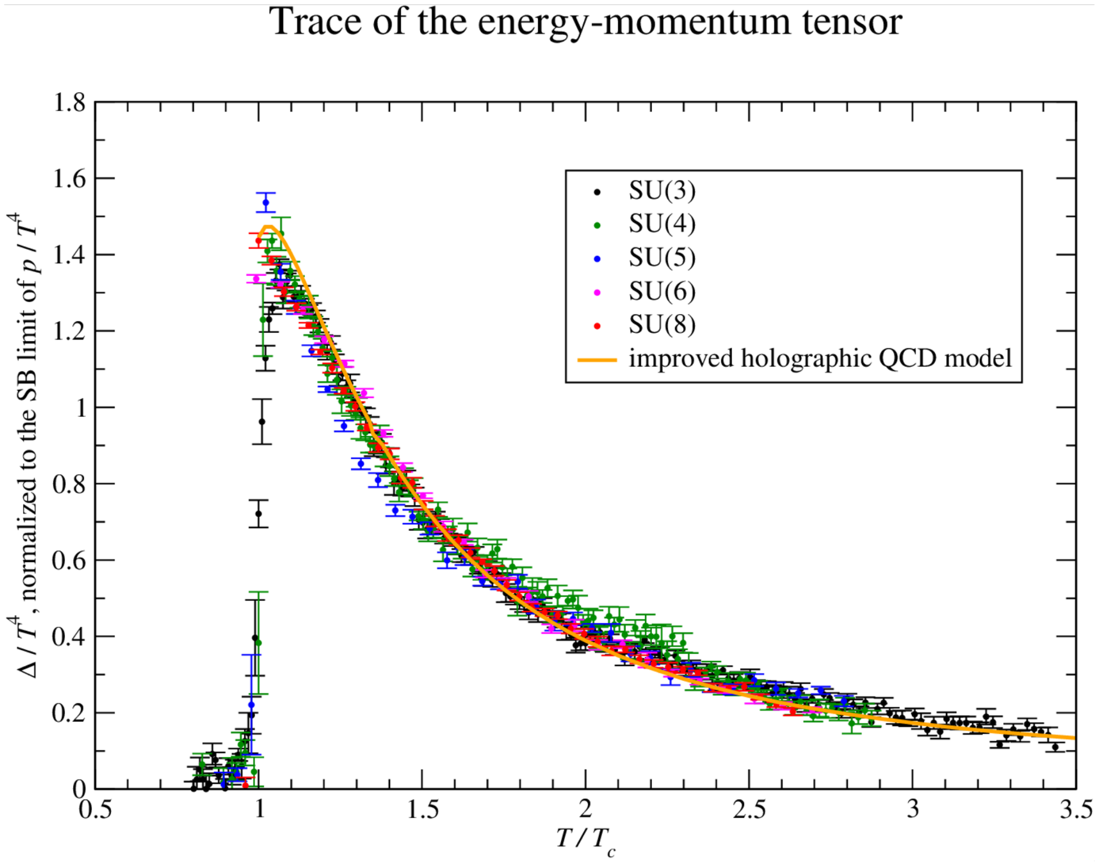
$$\delta W_M \to \delta W_M + \delta\xi^N \partial_N \bar{W}_M + \bar{W}_N \partial_M \delta\xi^N$$

$$\delta g_{MN} \to \delta g_{MN} + \nabla_M \delta\xi_N + \nabla_N \delta\xi_M$$

P-odd	P-even
$\delta W_{1,2}$	$Z_1 \equiv \omega\delta W_3 + k\delta W_0 + \frac{k\,z}{4}\partial_z \bar{W}_0(\delta g_1^1 + \delta g_2^2)$
$\delta Y^{1,2} \equiv k\delta g_0^{1,2} + \omega\delta g_3^{1,2}$	$Z_2 \equiv 2\omega k\delta g_0^3 + \omega^2\delta g_z^z - f(z)k^2\delta g_0^0 + \frac{f(z)k^2(\delta g_1^1 + \delta g_2^2)}{2}\left(1 - \frac{zf'(z)}{2f(z)} - \frac{\omega^2}{f(z)k^2}\right)$

Lattice YM thermodynamics in the large N_c limit



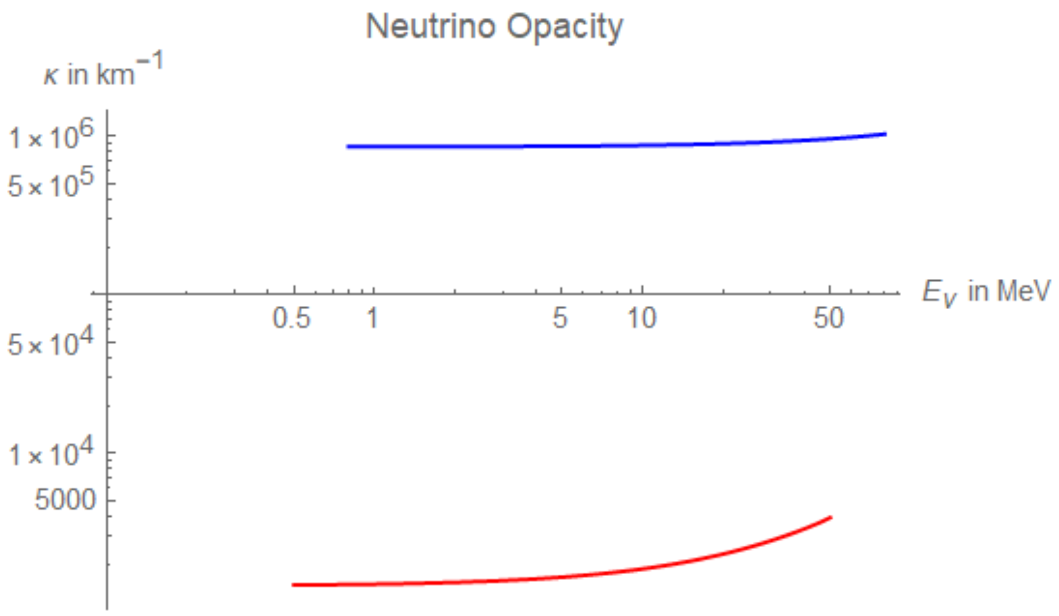


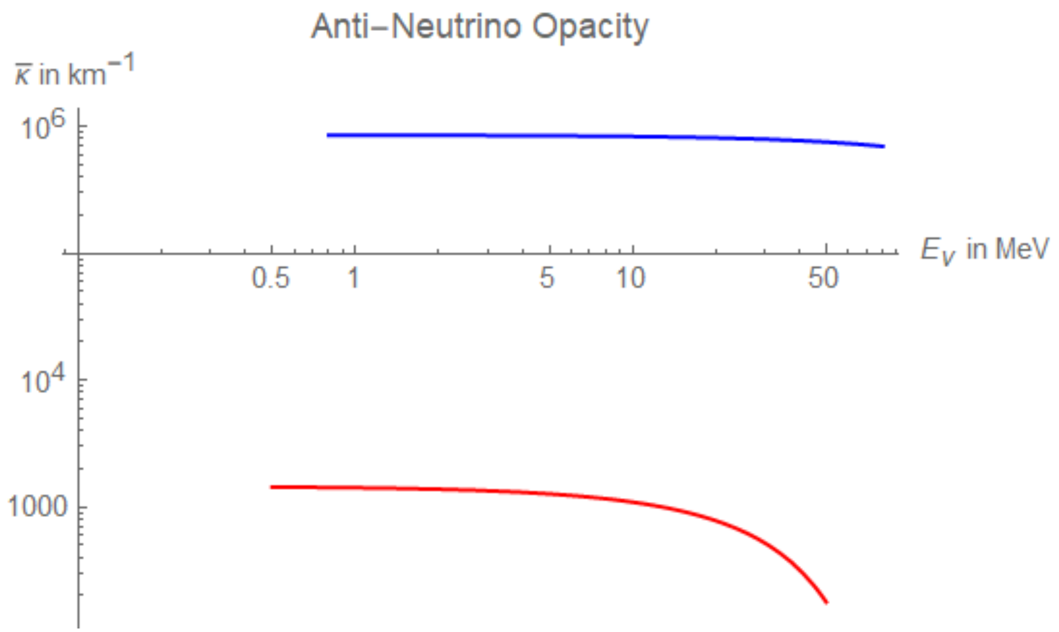
[0907.3719]

Thermodynamic quantities converge fast in the large N_c limit → $N_c = 3$ close to large N_c

Opacities (preliminary)

$$\kappa(E_\nu) \equiv j(E_\nu) + \frac{1}{\lambda(E_\nu)}$$





T=8 MeV, n_B=0.11 fm^{-3}, Y_e=0.05

T=5 MeV, n_B=0.01 fm^{-3}, Y_e=0.15

Holographic QCD : field content

In practice, the only operators relevant to the vacuum structure of low-energy QCD are

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{2g_{YM}^2}\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + \sum_{i=1}^{N_f}\bar{\psi}^i\left(i\,\gamma^\mu D_\mu - m_i\right)\psi^i$$

$T_{\mu\nu}$	$\leftrightarrow$	g_{MN}	**Color**
$\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu}$	$\leftrightarrow$	φ	$\frac{N_f}{N_c}$ finite
$\bar{\psi}^i\,\psi^j$	$\leftrightarrow$	$\mathcal{T}^{ij}$	**Flavor**
$U(N_f)_{\mathrm{L}}\times U(N_f)_{\mathrm{R}} : \partial_\mu J^\mu_{\mathrm{L/R}} = 0$	$\leftrightarrow$	$U(N_f)_{\mathrm{L}}\times U(N_f)_{\mathrm{R}} : A^{\mathrm{M}}_{\mathrm{L/R}}$	
$\mathrm{Tr}\,F\wedge F$	$\leftrightarrow$	a	$\boldsymbol{\theta_{\mathrm{QCD}} = 0}$

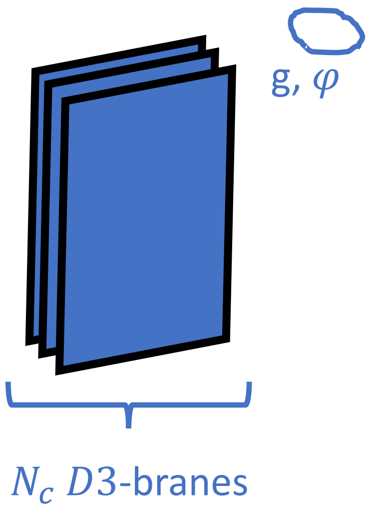
The V-QCD Model : Action

The V-QCD action is built by deforming what is known from top-down holography with phenomenological parameters of the bulk theory

$$S_{V-QCD} = S_c + S_f + S_{CS}$$

$$S_c = M_{Pl}^3 N_c^2 \int \mathrm{dx}^5 \sqrt{-g} \left[R - \frac{4}{3} (\partial \varphi)^2 + V_g(\varphi) \right] ,$$

Parameters of the bulk theory	
M_{Pl}	$V_g(\varphi)$



The V-QCD Model : Action

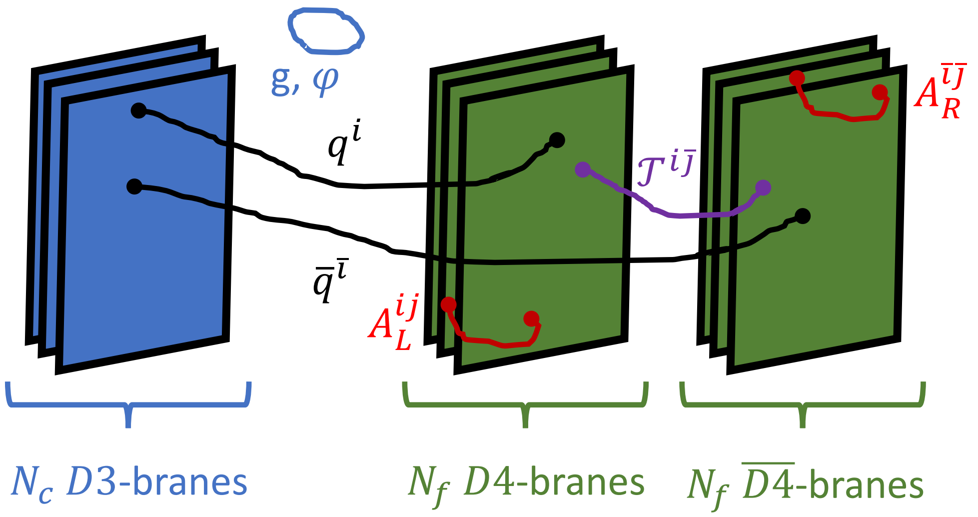
The V-QCD action is built by deforming what is known from top-down holography with phenomenological parameters of the bulk theory

$$S_{V-QCD} = S_c + S_f + S_{CS}$$

Sen :

$$\begin{cases} S_f = -\frac{1}{2} M_{Pl}^3 N_c \mathrm{STr} \int \mathrm{dx}^5 V(\mathcal{T}) \left[\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}} \right], \\ \mathbf{A}_{MN}^{(L)} \equiv g_{MN} + F_{MN}^{(L)} + \frac{1}{2} \left[(D_M \mathcal{T})^\dagger (D_N \mathcal{T}) + h.c. \right], \end{cases}$$

[hep-th/0303057]
[hep-th/0012210]



The V-QCD Model : Action

The V-QCD action is built by deforming what is known from top-down holography with phenomenological parameters of the bulk theory

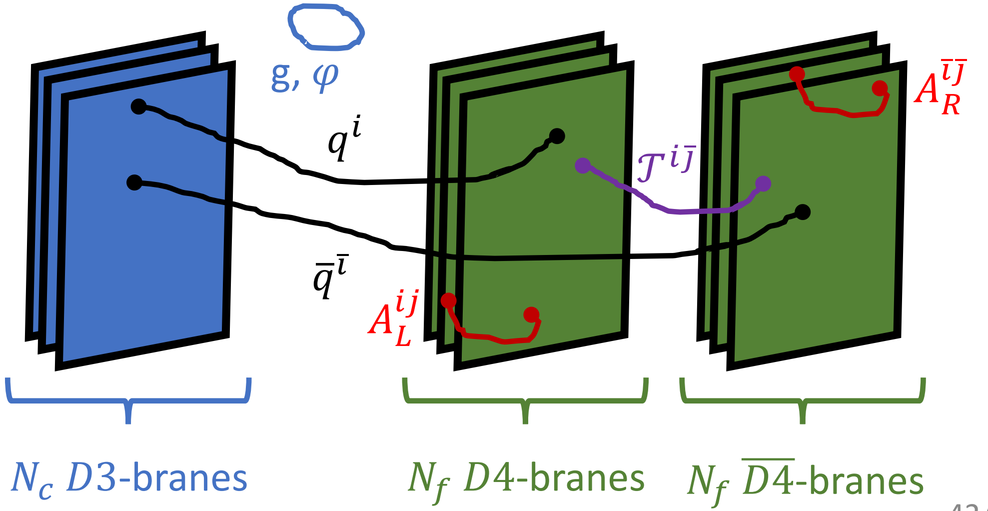
$$S_{V-QCD} = S_c + S_f + S_{CS}$$

V-QCD :

$$\begin{cases} S_f = -\frac{1}{2} M_{Pl}^3 N_c \mathrm{Tr} \int \mathrm{dx}^5 V_f(\varphi, \mathcal{T}) \left[\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}} \right], \\ \mathbf{A}_{MN}^{(L)} \equiv g_{MN} + w(\varphi, \mathcal{T}) F_{MN}^{(L)} + \frac{\kappa(\varphi, \mathcal{T})}{2} \left[(D_M \mathcal{T})^\dagger (D_N \mathcal{T}) + h.c. \right], \end{cases}$$

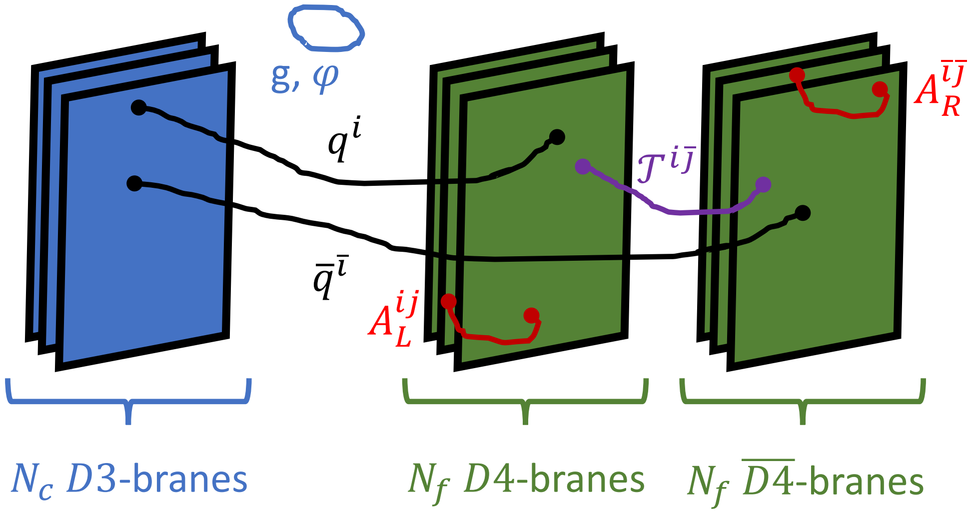
[1112.1261]

Parameters of the bulk theory		
$V_f(\varphi, \mathcal{T})$	$w(\varphi, \mathcal{T})$	$\kappa(\varphi, \mathcal{T})$



The V-QCD Model : Action

The V-QCD action is built by deforming what is known from top-down holography with phenomenological parameters of the bulk theory



$$S_{V-QCD} = S_c + S_f + S_{CS}$$

$$S_{CS} = \frac{iN_c}{4\pi^2} \int \Omega_5(\mathcal{T}, A_{(L/R)}) \ ,$$

[hep-th/0012210]
[hep-th/0702155]

Parameters of the bulk theory
$f_i(\mathcal{T})$

When $\mathcal{T} = 0$, Ω_5 is the CS 5-form

In String Theory, the tachyon dependence is known only in the maximally supersymmetric case

We generalize this result : Ω_5 is the sum of all 5-forms built from $(A, F, D\mathcal{T})$ with coefficients $f_i(\mathcal{T})$

Previous Results in V-QCD

At T = 0 and $n_b = 0$ [1112.1261]

- Bulk solution dual to the QCD vacuum
- Meson and glueball spectra

At $T \neq 0$ and $n_b = 0$ [1210.4516]

- Deconfinement phase transition
- Chiral phase transition

At $T \neq 0$ and $n_b \neq 0$ [1312.5199]

Phase diagram when the baryon number is fractionalized (deconfined quarks)

We don't know how the picture is modified when we allow for baryons to appear

V-QCD phase diagram