Dense Quark Matter and Baryonic Black Branes

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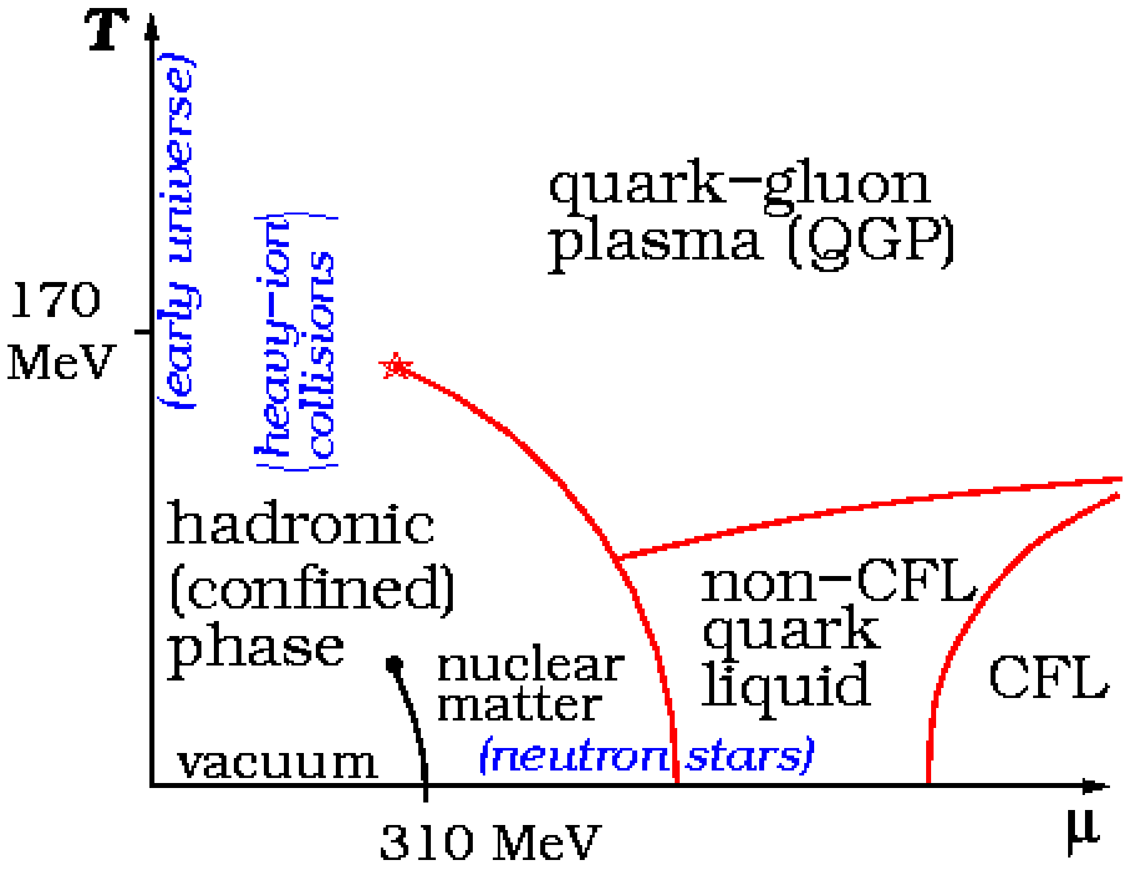
Work in progress with Carlos Hoyos and Niko Jokela

Phases of QCD



We will use…

GAUGE/GRAVITY DUALITY!

Holographic QCD

Exact dual of QCD not available → systematic uncertainties

…BUT theories with many similarities to QCD can be studied

Straightforward to add **non-zero chemical potential** (no sign problem!) and **temperature**

→ phase diagram can be mapped out, equation of state computed, etc.

AdS/CFT was applied to build neutron stars in e.g. 1603.02943, 1711.06244

AdS/QCD – some previous work

Bottom-up

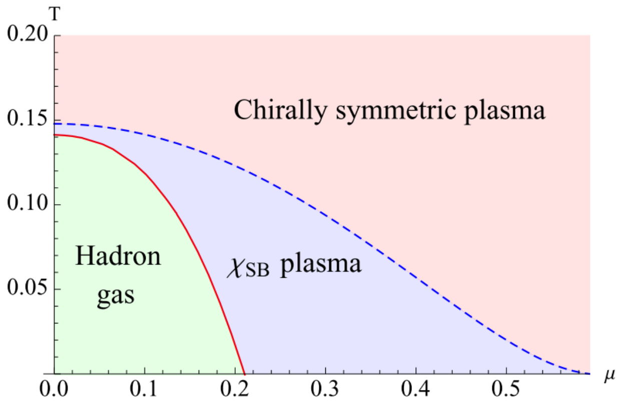
Improved holographic QCD, Veneziano-QCD, …

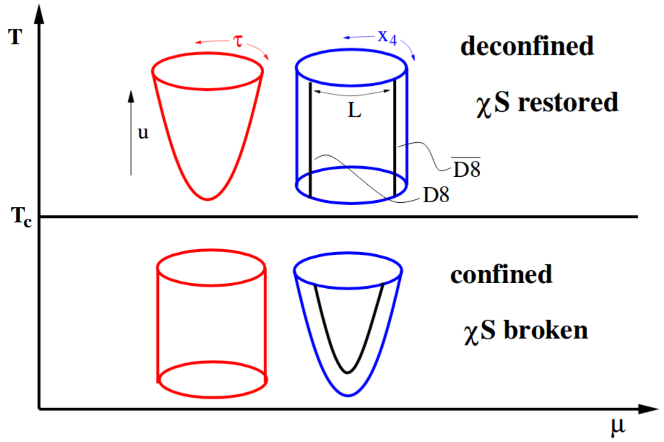
Top-down

E.g. D3/D7, Sakai-Sugimoto

Typically rely on probe branes to add fundamental flavors, baryon number

We want **backreaction** of baryonic charge in top-down setting





Baryons in AdS/CFT

In large-N limit: Meson masses $O(1)$ while baryon masses $O(N)$

→ baryons are *solitonic* objects

Witten: Holographic duals of baryonic operators are **wrapped branes**!

Baryon to us can mean N “quarks” in fundamental, but also other states whose masses scale as N

The conifold gauge theory

In IIB string theory, place D3-branes at **conifold** singularity

→ a superconformal $SU(N) \times SU(N)$ gauge theory

Matter fields in bifundamental rep of gauge group

Global baryonic $U(1)_B$ symmetry! Baryons $\sim$ wrapped D3's

Field theory spectrum splits into **mesonic** ($Q_B = 0$) and **baryonic** ($Q_B \neq 0$) operators

Baryonic Black Branes

Herzog-Klebanov-Pufu-Tesileanu considered truncation of full SUGRA keeping baryonic U(1) gauge field + scalar fields “squashing” the internal space

→ Constructed black brane solutions charged under $U(1)_B$

Baryonic Black Branes generalized

Herzog et al.'s branes are finite density states of a CFT →
equation of state not interesting!

We want to *deform* conifold theory to **break** conformal symmetry

Need to consider larger truncation to find relevant scalar

Easiest choice: dimension-2 scalar corresponding to "resolution" mode of conifold

Holographic renormalization

Scalar dual to dimension-2 operator, falls off as $\sim \frac{1}{r^2} + \frac{\log r}{r^2}$

Add counterterms: Gibbons-Hawking, “cosmological constant”, and scalar terms

UNFIXED FINITE COUNTERTERM! Should be possible to fix, e.g. from SUSY…?

Baryonic Black Branes – Results

→ Reproduce Herzog et al.

→ Add scalar + new vector fields in probe approximation

→ Add new fields with backreaction (numerics gets harder…)

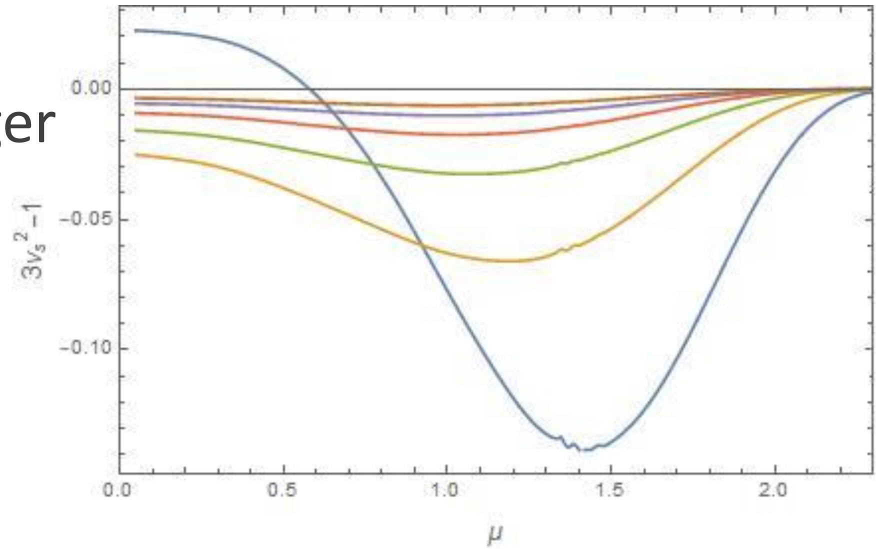
Equation of state/speed of sound

Compare with conformal value $v_s^2 = 1/3$

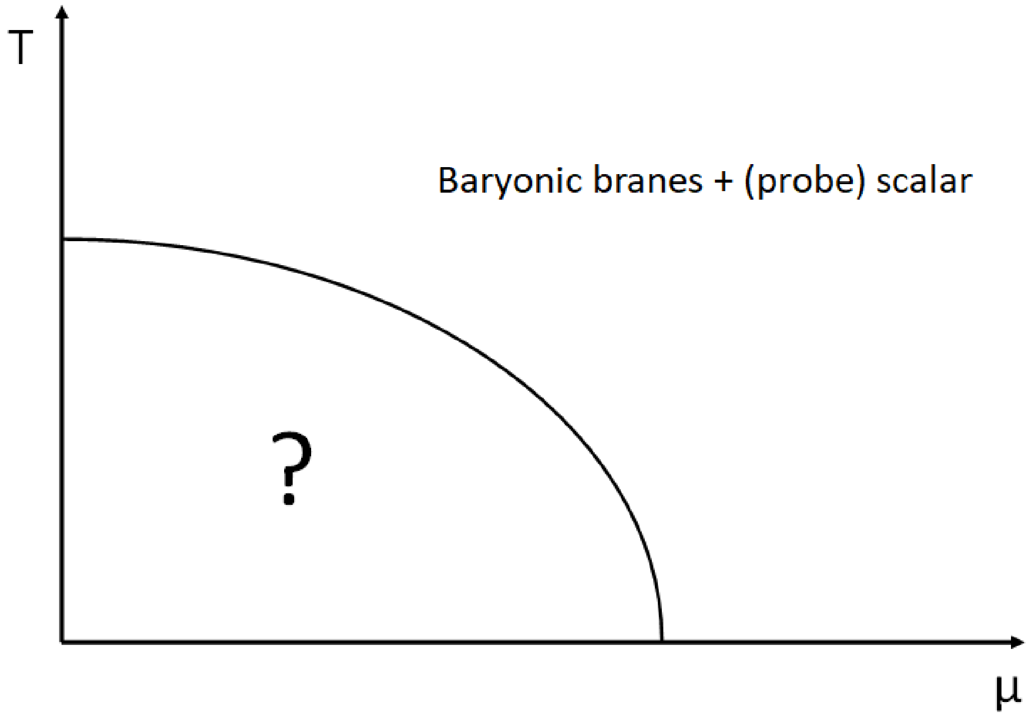
For small value of scalar source, close and below conformal value

At larger scalar source, numerics with backreaction hit a wall…

…but extrapolating probe approximation to larger values hints at interesting results



Full phase diagram



What happens at small T, μ? Confinement?

Full phase diagram

Baryon condensation? → Compute effective potential of *wrapped probe D3*

No minimum, no condensation for our solutions (for simplest wrapping)

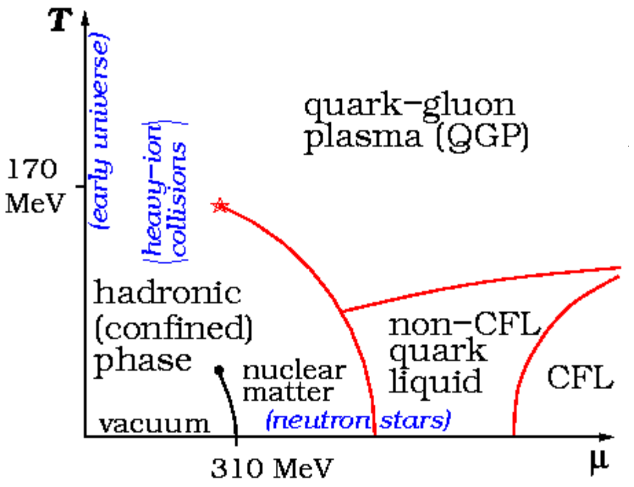
…but should check smaller T, μ!

If yes: phase with “cohesive” charge density? Or both “cohesive” and “fractionalized”?

Full phase diagram

“Fermi seasickness”/color superconductivity?

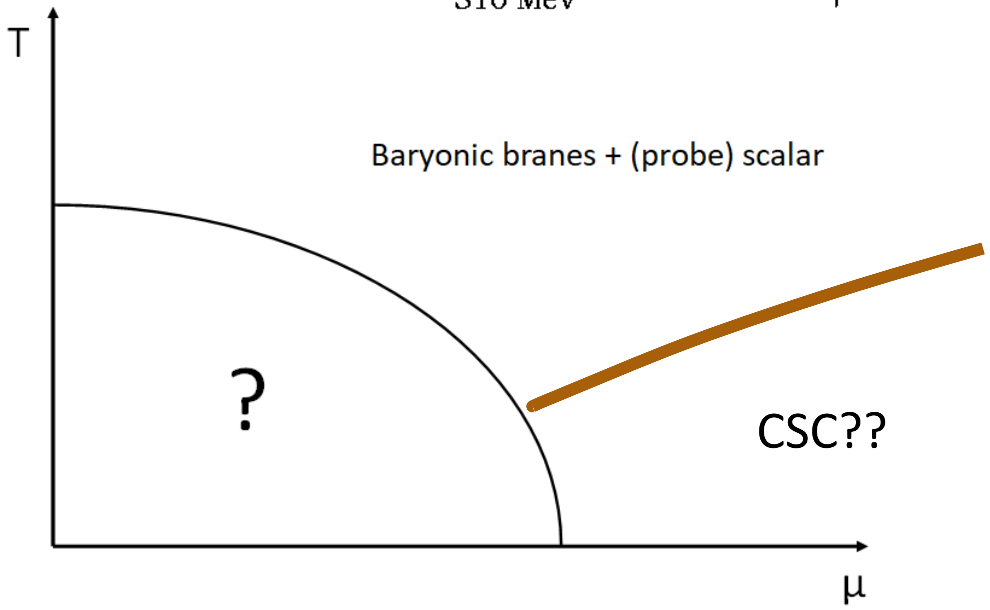
→ compute effective potential of *space-filling* D3-brane



Happens at low temperatures. Study for larger conformal symmetry breaking!

→ potentially very similar to QCD…

→ **how to describe resulting phase?**



Summary

Dense QCD (and gauge theories in general) is theoretically rich area with room for improvements and relevance for current astrophysics

The conifold gauge theory provides a toy example of a gauge theory with a well-understood holographic dual, and with some qualitative similarities to QCD (baryon number)

We studied a conformal symmetry-breaking deformation of this theory

Computed equation of state, speed of sound, …

First steps towards mapping out the phase diagram

Work in progress: Full phase diagram – improved numerics, confinement, baryon condensation, color superconductivity, …

Extra slides…

Neutron stars

Rich physics!

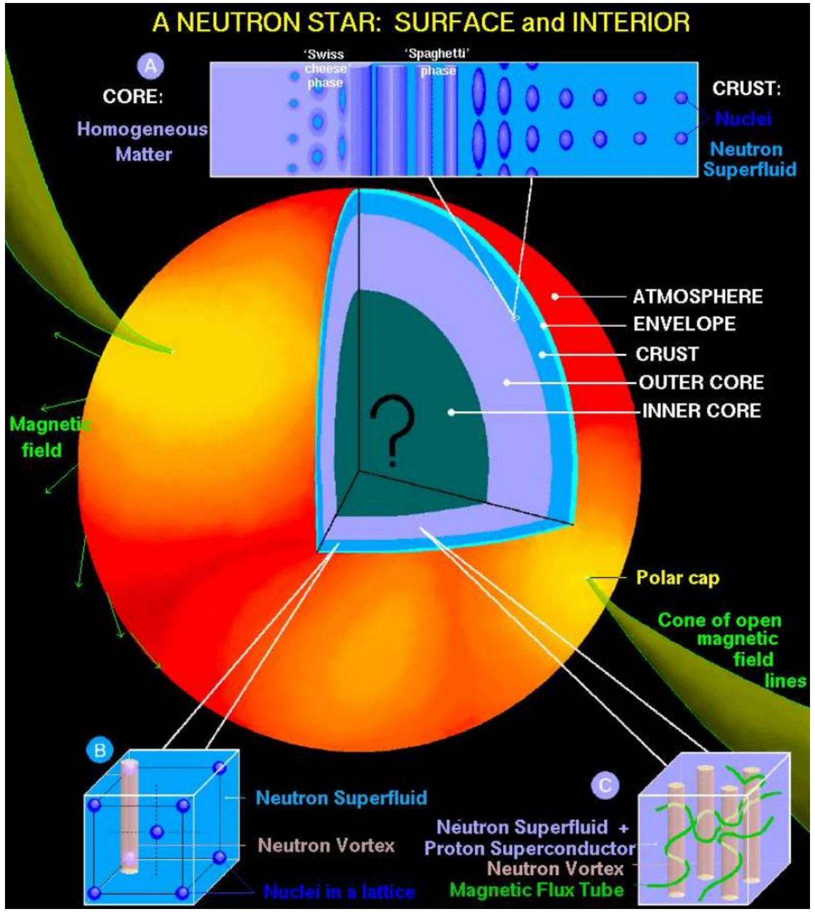
Can teach us about dense QCD

In particular:

Mass-radius relation

$\Updownarrow$

Equation of state $\epsilon = \epsilon(p)$



Holographic neutron stars

AdS/CFT was applied to build neutron stars in e.g. 1603.02943, 1711.06244

Used D3/D7 model to describe deconfined quark matter, and chiral effective theory to describe confined phase. Get transition by comparing free energies

→ Constructed novel hybrid stars

→ Further exploration worthwhile

The conifold gauge theory

Place coincident D3-branes at **singularity** instead of flat space

→ can engineer interesting dualities

A cone: $ds^2_{cone} = dr^2 + r^2 d\Omega^2$

If $d\Omega^2$ is metric for sphere, no singularity, otherwise conical singularity at $r = 0$

Conifold means choosing $d\Omega^2$ to be …

$$ds^2_{T^{1,1}} = \frac{1}{6}\sum_{i=1}^{2}\left(d\theta_i^2 + \sin^2\theta_i d\phi_i^2\right) + \frac{1}{9}\left(d\psi + \cos\theta_1 d\phi_1 + \cos\theta_2 d\phi_2\right)^2$$

Type IIB supergravity on $AdS_5 \times T^{1,1}$

Can get *consistent* truncation of IIB supergravity on $AdS_5 \times T^{1,1}$ by keeping modes invariant under $SU(2) \times SU(2)$ (Cassani & Faedo)

IIB fields	scalars	1-forms	2-forms	5d metric
10d metric	$u,\ v,\ w,\ t,\ \theta$	A		$g_{\mu\nu}$
ϕ	ϕ			
B	$b^J,\ b^\Phi,\ b^\Omega$	b_1	b_2	
C_0	C_0			
C_2	$c^J,\ c^\Phi,\ c^\Omega$	c_1	c_2	
C_4	a	$a_1^J,\ a_1^\Phi,\ a_1^\Omega$	a_2^Ω	

$\mathcal{N}=2$ multiplet	field fluctuations	m^2	Δ	dual operators
gravity	$A - 2a_1^J$	0	3	$\mathrm{Tr}(W_{1\alpha}\overline{W}_{1\dot\alpha} + W_{2\alpha}\overline{W}_{2\dot\alpha}) + \dots$
	$g_{\mu\nu}$	0	4	
universal hyper	$b^\Omega - i\,c^\Omega$	-3	3	$\mathrm{Tr}(W_1^2 + W_2^2) + \dots$
	$\phi,\ \ C_0$	0	4	
Betti vector	w	-4	2	$\mathrm{Tr}\,Ae^{V_2}\overline{A}e^{-V_1} - \mathrm{Tr}\,Be^{V_1}\overline{B}e^{-V_2}$
	a_1^Φ	0	3	
Betti hyper	$t\,e^{i\theta}$	-3	3	$\mathrm{Tr}(W_1^2 - W_2^2)$
	$b^\Phi,\ \ c^\Phi$	0	4	
massive gravitino	$b_1,\ c_1$	8	5	$\mathrm{Tr}(W_1^2\overline{W}_{1\dot\alpha} + W_2^2\overline{W}_{2\dot\alpha}) + \dots$
	a_2^Ω	9	5	
	$b_2,\ c_2$	16	6	
massive vector	$u - v$	12	6	$\mathrm{Tr}(W_1^2\overline{W}_1^2 + W_2^2\overline{W}_2^2) + \dots$
	$A + a_1^J$	24	7	
	$b^\Omega + i\,c^\Omega$	21	7	
	$4u + v$	32	8	

Numerics

Use **shooting method**:

- Create near-horizon IR expansion of all fields
- Tune free parameters until desired UV asymptotics are found

Problem: Several fields are dual to irrelevant operators → diverge for general horizon parameters

Solution: Integrate up to small, finite radius and impose boundary conditions. Take resulting horizon parameters as starting values for new integration to slightly larger radius. Repeat until sufficiently far into the UV

Problem: Many fields, many parameters to fix in shooting. Slow search.

Solution: Better numerics…?

Baryonic Black Branes

Herzog et al. considered smaller truncation, keeping baryonic U(1) gauge field + scalar fields "squashing" the internal space

$$ds^2_{10} = e^{-\frac{5}{3}\chi} ds^2_M + L^2 e^{\chi}\left[\frac{e^{\eta}}{6}\sum_{i=1}^{2}\left(d\theta_i^2 + \sin^2\theta_i d\phi_i^2\right) + \frac{e^{-4\eta}}{9} g_5^2\right]$$

$$F_5 = \frac{1}{g_s}\left(\mathcal{F} + *\mathcal{F}\right) \ ,$$

$$\mathcal{F} = \frac{2L^4}{27}\omega_2 \wedge \omega_3 + \frac{L^3}{9\sqrt{2}} F \wedge \omega_3$$

$$\omega_2 \equiv \frac{1}{2}\left(\sin\theta_1 d\theta_1 \wedge d\phi_1 - \sin\theta_2 d\theta_2 \wedge d\phi_2\right)$$

$$\omega_3 \equiv g_5 \wedge \omega_2 \ ,$$

$$g_5 \equiv d\psi + \cos\theta_1 d\phi_1 + \cos\theta_2 d\phi_2 \ .$$

Baryonic Black Branes

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$$\mathcal{L}_{\text{eff}} = R - \frac{1}{4} e^{-\frac{4}{3}\chi + 2\eta} F_{\mu\nu}^2 - 5(\partial_\mu \eta)^2 - \frac{10}{3}(\partial_\mu \chi)^2 - V(\eta, \chi)$$

$$V(\eta, \chi) \equiv \frac{8}{L^2} e^{-\frac{20}{3}\chi} + \frac{4}{L^2} e^{-\frac{8}{3}\chi} \left(e^{-6\eta} - 6e^{-\eta}\right)$$

Baryonic Black Branes generalized

More general ansatz (also from Herzog et al.):

$$ds_{10}^2 = e^{-5\chi/3} ds_M^2 + L^2 e^{\chi} \left[\frac{e^{\eta+\lambda}}{6}(d\theta_1^2 + \sin^2\theta_1 d\phi_1^2) + \frac{e^{\eta-\lambda}}{6}(d\theta_2^2 + \sin^2\theta_2 d\phi_2^2) + \frac{e^{-4\eta}}{9}\left(g_5 + \frac{3}{\sqrt{2}L} A_R \right)^2 \right]$$

$$F_5 = \frac{1}{g_s}(\mathcal{F} + *\mathcal{F}) \ ,$$

$$\mathcal{F} = \frac{2L^4}{27}\omega_2 \wedge \omega_2 \wedge g_5 + \frac{L^3}{9\sqrt{2}} F \wedge \omega_2 \wedge g_5^A - \frac{L^3}{18\sqrt{2}} \tilde{F}_R \wedge dg_5 \wedge g_5^A + \frac{L^3}{18\sqrt{2}} \tilde{A}_R \wedge dg_5 \wedge dg_5$$

$$\omega_2 \equiv \frac{1}{2}(\sin\theta_1 d\theta_1 \wedge d\phi_1 - \sin\theta_2 d\theta_2 \wedge d\phi_2)$$

$$\omega_3 \equiv g_5 \wedge \omega_2 \ ,$$

$$g_5 \equiv d\psi + \cos\theta_1 d\phi_1 + \cos\theta_2 d\phi_2 \ .$$

Baryonic Black Branes generalized

Resulting 5D Lagrangian:

$$\begin{aligned}\mathcal{L} =& R - \frac{10}{3}(\partial_\mu \chi)^2 - 5(\partial_\mu \eta)^2 - (\partial_\mu \lambda)^2 - V \\ &- \frac{1}{4} e^{2\eta - \frac{4}{3}\chi} \left[\cosh(2\lambda) \left((F_{\mu\nu})^2 + (\tilde{F}^R_{\mu\nu})^2 \right) - 2\sinh(2\lambda) F_{\mu\nu} \tilde{F}^{\mu\nu}_R \right] \\ &- \frac{1}{8} e^{-4\eta + \frac{8}{3}\chi} (F^R_{\mu\nu})^2 - 4 e^{-4\eta - 4\chi} (A^R_\mu + \tilde{A}^R_\mu)^2 \,,\end{aligned}$$

$$V = 8 e^{-\frac{20}{3}\chi} + 4 e^{-\frac{8}{3}\chi} \left(e^{-6\eta} \cosh(2\lambda) - 6 e^{-\eta} \cosh(\lambda) \right)$$