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Nuclear Force from String Theory

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arXiv/0806.3122 (PTP) Sakai, Sugimoto, KH
arXiv/0901.4449 (PTP) Sakai, Sugimoto, KH

Our results for static properties of nucleons

	Holographic QCD	Skyrmion	Experiment
$\langle r^2 \rangle_{E,\mathrm{p}}$	$(0.742\ \mathrm{fm})^2$	∞	$(0.875\ \mathrm{fm})^2$
$\langle r^2 \rangle_{E,\mathrm{n}}$	0	$-\infty$	$-0.116\ \mathrm{fm}^2$
$\langle r^2 \rangle_A^{1/2}$	$0.537\ \mathrm{fm}$	$-$	$0.674\ \mathrm{fm}$
μ_p	2.18	1.87	2.79
μ_n	-1.34	-1.31	-1.91
g_A	0.734	0.61	1.27
$g_{\pi NN}$	7.46	8.9	13.2
$g_{\rho NN}$	5.80	$-$	$4.2 \sim 6.5$

input : f_π, m_ρ [Sakai, Sugimoto, KH (arXiv/0806.3122)]

Our results for static properties of nucleons

	Holographic QCD	Skyrmion	Experiment	Lattice QCD
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$g_{\rho NN}$	5.80	$-$	$4.2 \sim 6.5$	
$\mu_{\Delta^{++}}$	4.43	$-$	$3.7 - 7.5$	4.99
$\mu_{\Delta^{+}}$	2.32	$-$	$2.7^{+1.0}_{-1.3} \pm 1.5 \pm 3$	2.49
$\mu_{\Delta^{0}}$	0.204	$-$	$-$	0.06
$\mu_{\Delta^{-}}$	-1.91	$-$	$-$	-2.45

Plan

Holographic QCD :

Derivation / Computation

Nuclear Force at Short Range

Superstring theory, D-branes

(ii) ⇩ Derivation

Holographic QCD

Low energy massless QCD at large *Nc*	=	Gravity in 5 dim. + Yang-Mills in 5 dim.

(i) ⇩ Computation

Meson, baryon, glueball sectors

How to compute things

1. Write the action, 5D gravity + 5D *U(N_f)* YM

$$S = \int d^5x \,\sqrt{-g}(R[g] + \Lambda) + \int d^5x \sqrt{-g} F_{MN}^2 + \cdots$$

Free parameters : g_s, Λ, N_c, N_f

2. Choose a gravity background

$$ds^2 = \left(\frac{U}{R}\right)^{3/2}(\eta_{\mu\nu}dx^\mu dx^\nu + f(U)d\tau^2) + \left(\frac{R}{U}\right)^{3/2}\left(\frac{dU^2}{f(U)} + U^2 d\Omega_4^2\right) \qquad e^\phi = g_s\left(\frac{U}{R}\right)^{3/4}, \quad F_4 = \frac{2\pi N_c}{V_4}\epsilon_4, \qquad f(U) = 1 - \frac{U_{KK}^3}{U^3}$$

3. Diagonalize fluctuations (Kaluza-Klein expansion)

$$A_\mu(x^\mu, z) = \sum_{n=0}^{\infty} \psi^{(n)}(z)\, \rho_\mu^{(n)}(x^\mu)$$

4a. Substitute the expansion into the action, and perform integration $\int dz$

⇒ Effective action of mesons and glueballs (Spectra and all interactions)

4b. Computations in soliton sectors (YM instanton, small blackholes, etc)

⇒ Spectra / interaction of baryons, QCD instantons, GUT monopoles

4c. Introduce classical configuration of a string

⇒ Quark-antiquark potential, Regge trajectory

D-branes giving the duality

Quantizing strings defined in 10D spacetime

Open string → Massless gauge field

Closed string → Massless graviton

D-branes = Object on which open strings can end

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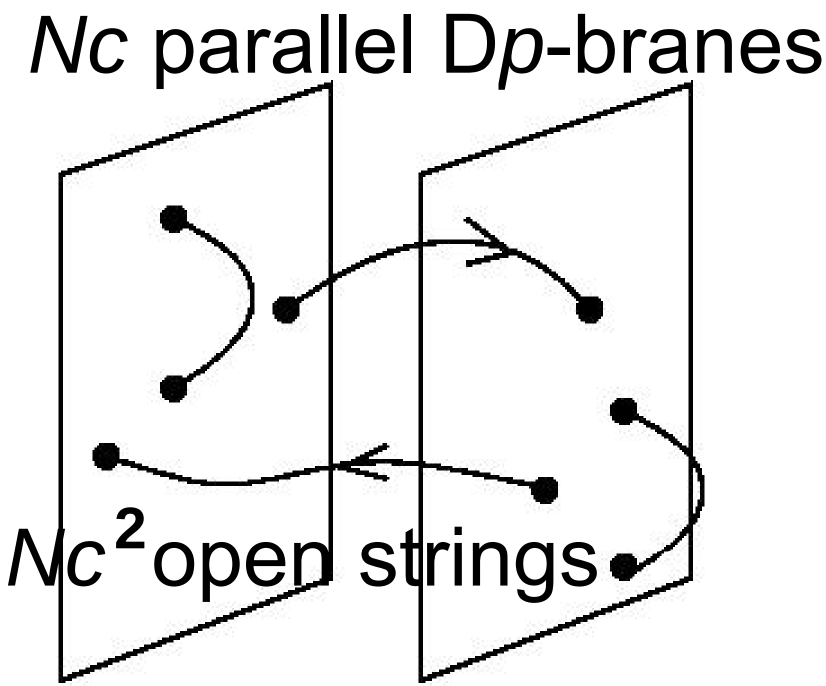

Open string theory on the Dp-brane is : *SU(Nc)* gauge theory in *p+1* dimensions

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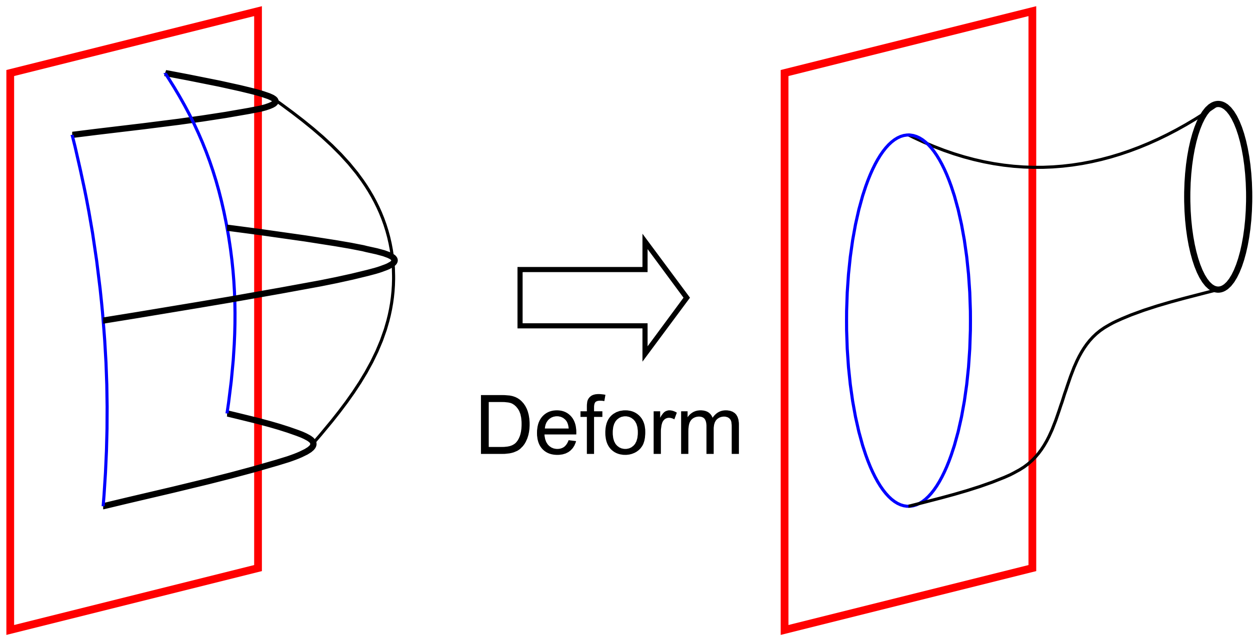


D-branes giving the duality

Quantizing strings defined in 10D spacetime

Open string → Massless gauge field

Closed string → Massless graviton

D-branes = Object on which open strings can end

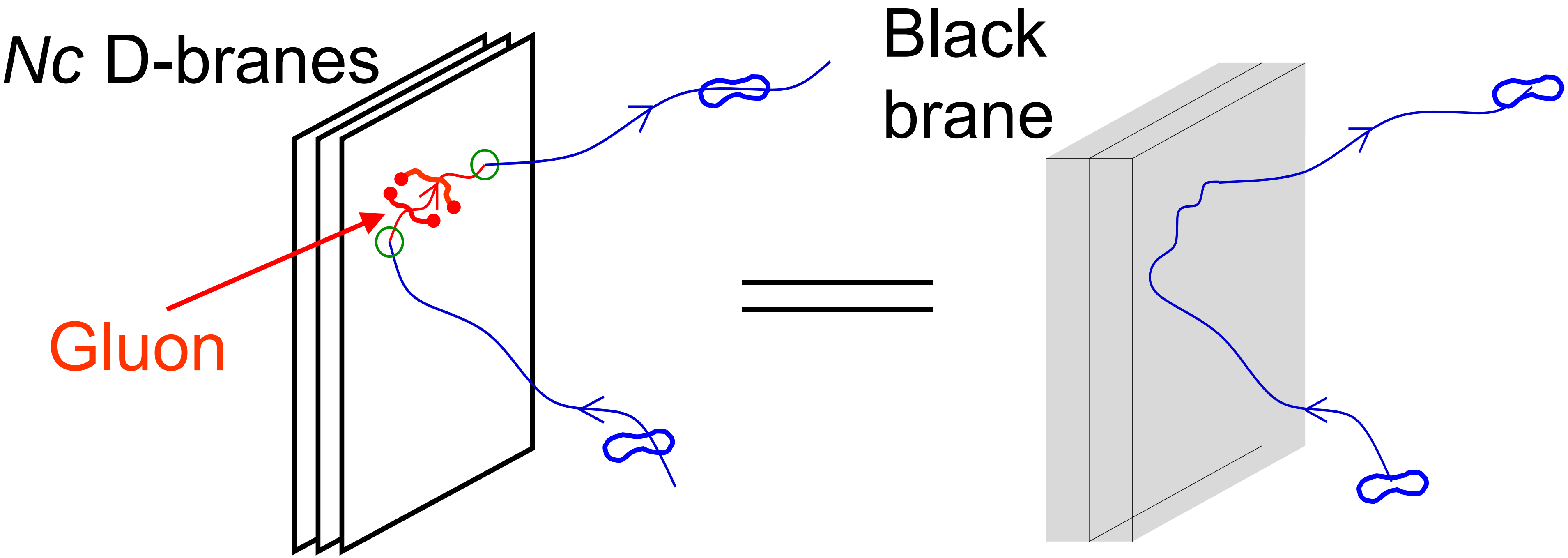
= Source of closed strings

= Source of gravity

= Extended blackhole

"blackbrane" in 10D

Holography (Gauge/Gravity duality)



Propagation of SU(Nc) gauge theory composite states

$\mathrm{tr} F_{\mu\nu} F^{\mu\rho}$

(Glueball)

⟺

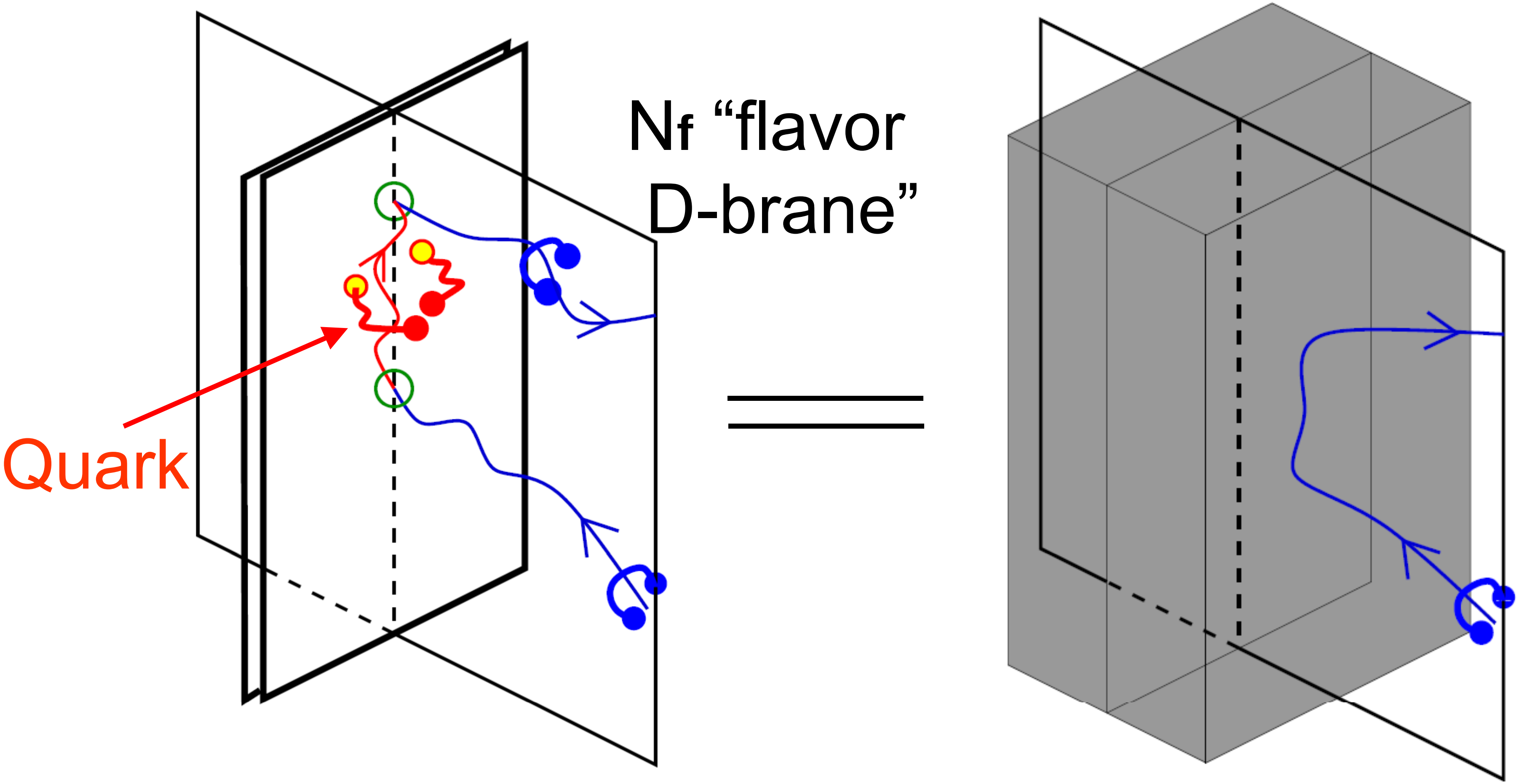
Large *Nc*

Large λ

Propagation of graviton in near-horizon geometry of black p-brane

$g_{\nu}{}^{\rho}$

Holographic QCD



Propagation of meson

$\bar{q}\gamma\ldots q$

SU(Nf) gauge fields in higher dim. D-brane on curved background

Plan

Holographic QCD :

Derivation / Computation

Nuclear Force at Short Range

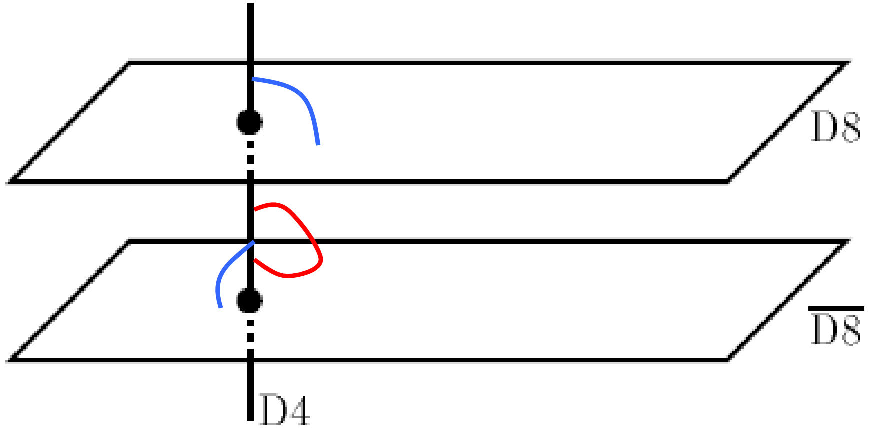
Sakai-Sugimoto model

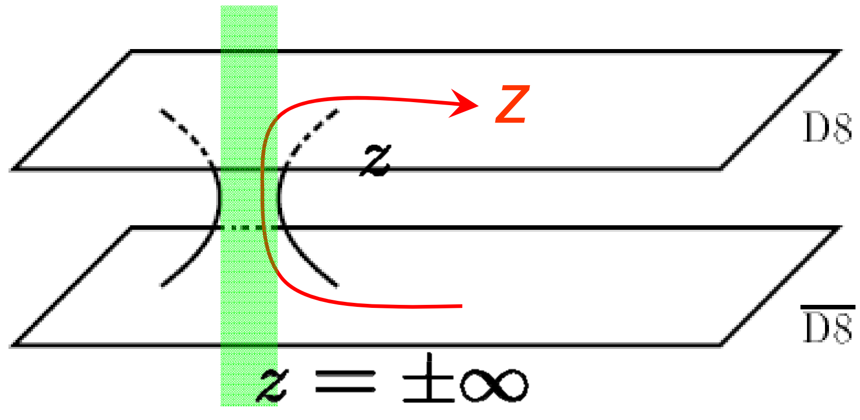
5d *U(Nf)* Yang-Mills-Chern-Simons theory in curved space

$$(M_{\mathrm{KK}} = 1)$$

$$-\frac{\lambda N_c}{216\pi^3}\int d^4x dz \,\mathrm{tr}\left[\frac{1}{2}(1+z^2)^{-1/3}F_{\mu\nu}^2 + (1+z^2)F_{\mu z}^2\right] + \frac{N_c}{24\pi^2}\mathrm{tr}\int\left[AF^2 - \frac{i}{2}A^3F - \frac{1}{10}A^5\right]$$

This is the holographic dual of massless QCD,
with large N_c and large 'tHooft coupling $\lambda = N_c g_{\mathrm{YM}}^2$





Sakai-Sugimoto model

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$(M_{\mathrm{KK}} = 1)$

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Important features:

Extra “holographic” dimension z .

The gauge group is flavor *U(Nf).*

Chiral rotation is defined at $z = \pm\infty$

Mesons = flavor gauge fields

A_μ → Vector mesons, A_z → Massless pion

$$S = \int d^4x \left(\frac{f_\pi^2}{4} \mathrm{tr}\,(U^{-1}\partial_\mu U)^2 + \frac{1}{32e^2} \mathrm{tr}\,[U^{-1}\partial_\mu U, U^{-1}\partial_\nu U]^2 \right)$$

$$f_\pi^2 = \frac{1}{54\pi^4}(g_{YM}^2 N_c) M_{KK}^2 N_c \qquad e^2 = \frac{27\pi^7}{2b}\frac{1}{(g_{YM}^2 N_c) N_c}$$

Baryons = YM instantons

Baryon = Instanton in (x^1, x^2, x^3, z) [Sakai, Sugimoto(04)]

$$+\frac{N_c}{24\pi^2}\mathrm{tr}\int \left[A F^2 + \cdots \right]$$

Instanton charge sources U(1)v

Quantization of instantons → Baryon spectrum

[Hata, Sakai, Sugimoto, Yamato (07)] [Hong, Rho, Yee, Yi (07)]

Nuclear force at short distance

Inserting 2-instanton solution to the action gives

$$H = H^{(1)} + H^{(2)} + \boxed{H_1(r)}$$

Interaction hamiltonian

$$H_1(r) = \frac{1}{r^2} f(\text{ Instanton moduli }) + \mathcal{O}(1/r^3)$$

Nucleon-nucleon potential = VEV $\langle H_1(r) \rangle$
with 2-baryon asymptotic wavefunction $|p\uparrow\rangle_1 |p\uparrow\rangle_2$

$$\langle H_1(r) \rangle = V_C(r) + (3\hat{\mathbf{r}}\cdot\sigma_1 \hat{\mathbf{r}}\cdot\sigma_2 - \sigma_1\cdot\sigma_2) V_T(r)$$

$$V_C(r) = \pi \left(\frac{27}{2} + \frac{32}{5} \vec{s}_1 \cdot \vec{s}_2 \, \vec{I}_1 \cdot \vec{I}_2 \right) \frac{N_c}{\lambda} \frac{1}{r^2}$$

$$V_T(r) = \frac{8\pi}{5} \vec{I}_1 \cdot \vec{I}_2 \frac{N_c}{\lambda} \frac{1}{r^2}$$

Strongly repulsive
with $1/r^2$ potential

Conclusion

Nuclear force from string theory :

We compute Nuclear force at short distances

= First analytic result reproducing repulsive core, from strongly coupled "QCD"

[Sakai, Sugimoto, KH, 0901.4449]

We compute also static properties of baryons, including meson-baryon coupling. → Long range nuclear force

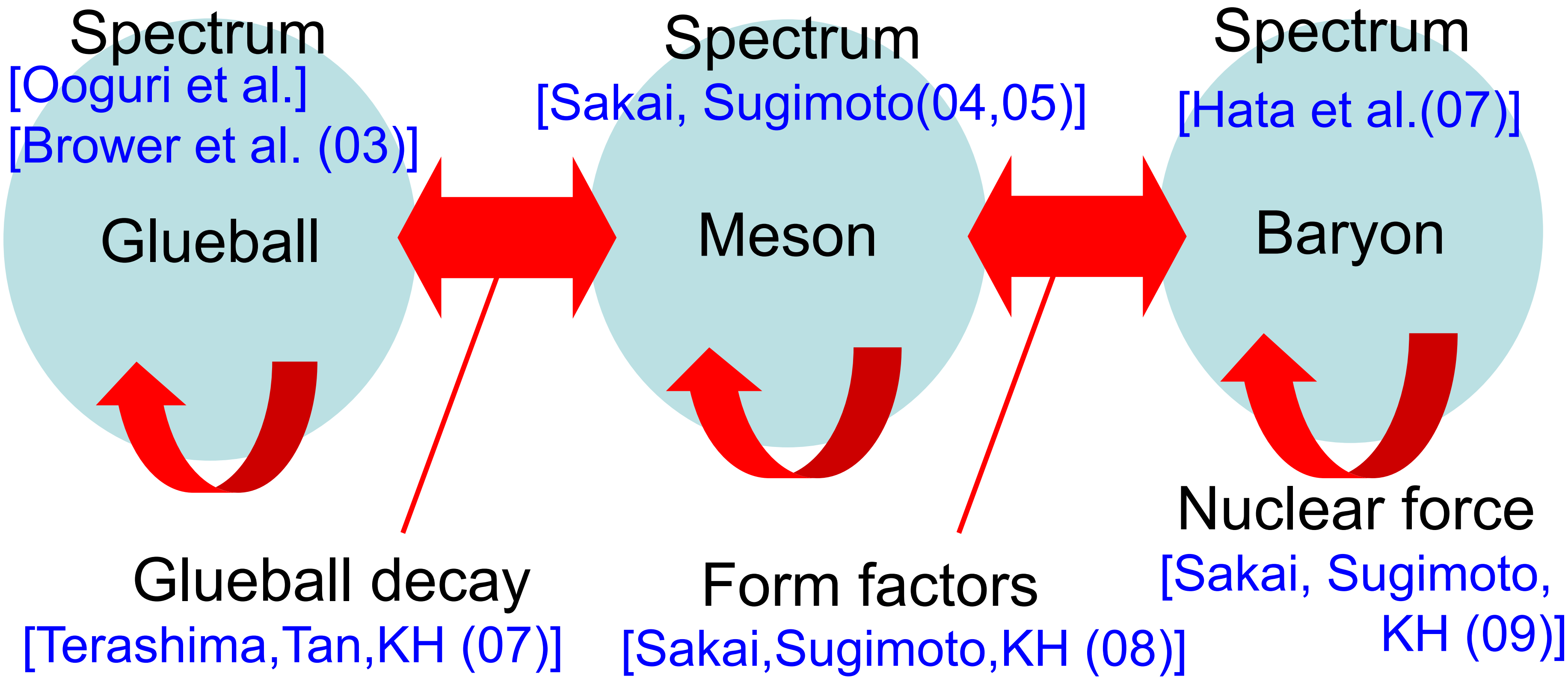
They nicely match exp. data

[Sakai, Sugimoto, KH, 0806.3122]

Work in progress : 3-body nuclear force, YN potential, Quark mass dependence, Color-flavor locking

Ref: [0906.0402, 0909.1296, 0909.????]

What can holographic QCD compute?



More : hidden local symmetry, vector meson dominance,
Jet quenching parameters, viscosity of plasma,
Quark drag force, meson melting and decay width,
Finite temperature, Chemical potential, Phase diagram