KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Holographic QCD

Status and perspectives for the future

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Claim :

String theory can be a theory of hadrons

The string scale here is around 1 GeV.

I’m NOT saying QCD is wrong.

QCD ⟷ dual ! String theory (in a certain curved background)

“ Holographic QCD ”

“Gauge/String duality”

[Maldacena 1997, ...]

How can we realize QCD in string theory?

(1+4) dim D-brane

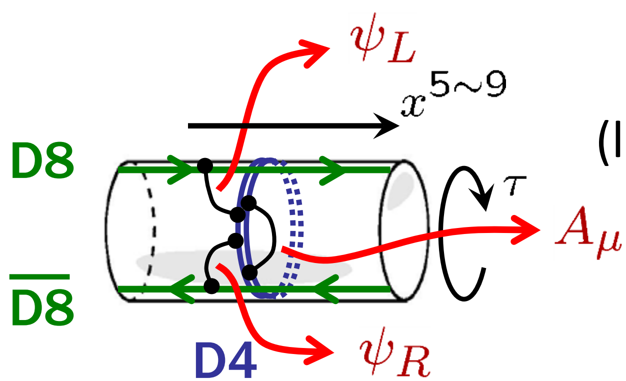
(1+8) dim D-brane

[Sakai-S.S. 2004]

		x^0	x^1	x^2	x^3	τ	x^5	x^6	x^7	x^8	x^9
D4	$\times N_c$	○	○	○	○	○	–	–	–	–	–
D8-$\overline{\text{D8}}$	$\times N_f$	○	○	○	○	–	○	○	○	○	○

4 dim (x^0–x^3)

S^1 (τ)



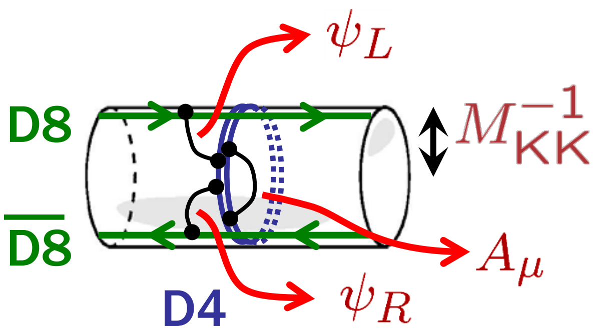
(low energy) →

A_μ : gluon

$\begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$: quark $\times N_f$

$SU(N_c)$ **QCD**
with N_f **massless quarks**

Comments



QCD + massive KK modes

mass $\sim M_{\rm KK} \sim 1$ GeV

Artifact of the model

- We try to get rid of the states that contain these unwanted modes as much as possible using a symmetry argument.
- These artifacts may contribute in loops.
  We simply hope the contributions are not large.
  cf) quench approximation in lattice QCD

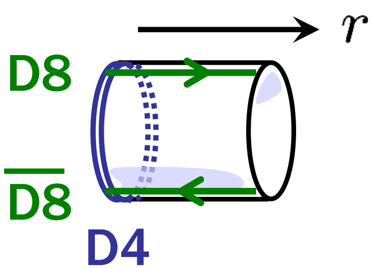
Holographic QCD

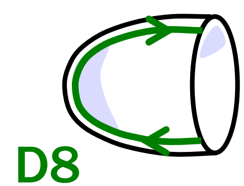
replace D4 with curved background

[Witten 1998]

N_c **D4-brane on** S^1
+ N_f **D8-$\overline{\text{D8}}$ pairs**

String theory in the D4 background
+ N_f **D8-branes**





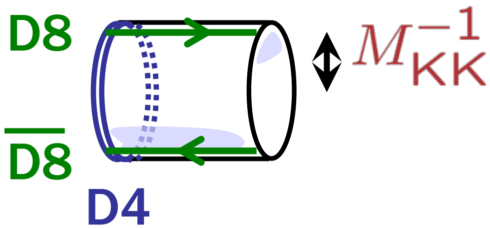
(low energy)

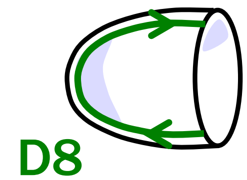
$SU(N_c)$ **QCD**
with N_f **massless quarks**

dual

Open + closed string theory in this background

" Holographic QCD "





(low energy)

$SU(N_c)$ **QCD** with N_f massless quarks	**dual**	Open + closed string theory in this background

parameters :

$$\begin{cases} M_{\rm KK} \sim \text{cut off scale} \\ \lambda = g_{\rm YM}^2 N_c \end{cases}$$

('t Hooft coupling)

$$\begin{cases} \text{string coupling} \ \propto 1/N_c \\ \text{string length} \ \propto \lambda^{-1/2} \end{cases}$$

good description for

$$\begin{cases} \text{large } N_c \\ \text{large } \lambda \leftrightarrow \text{low energy} \end{cases}$$

Chiral Sym Breaking

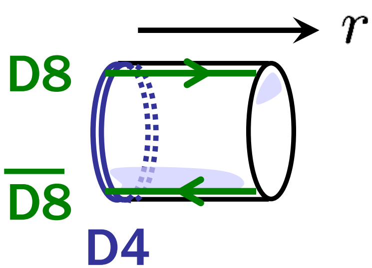
N_c **D4-brane on** S^1

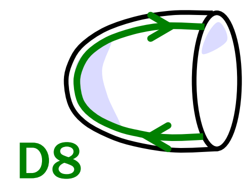
+ N_f **D8-$\overline{\text{D8}}$ pairs**

replace D4
with curved
background

String theory in the D4 background

+ N_f **D8-branes**





$$U(N_f)_L \times U(N_f)_R$$

D8 ↕ $U(N_f)_L$ and **$\overline{\text{D8}}$** ↕ $U(N_f)_R$

$$U(N_f)$$

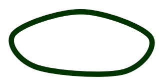
Connected D8 ↕ $U(N_f)$

As expected in QCD!

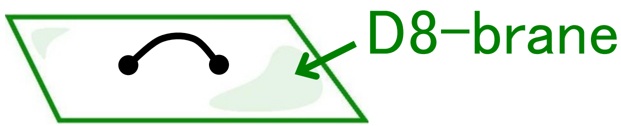
Do we have hadrons?

Particles in this system

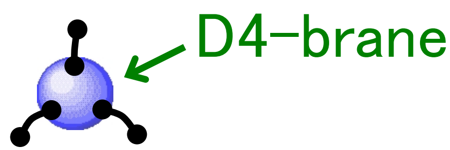
- Closed strings ↔ glueballs

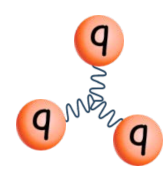


- Open strings on D8 ↔ mesons



- D4 wrapped on S^4 ↔ baryons





N_c strings are attached

Surprise :

A lot of properties of hadrons can be extracted using this new description!

Caution :

- We have only estimated the leading terms in the $1/N_c$ and $1/\lambda$ expansions.
- $M_{\rm KK}$ is around 1 GeV.
- Quark masses are neglected.

We should not expect too much.
But, don't be too pessimistic!

- Meson effective theory is written as a 5 dim $U(N_f)$ YM-CS theory in a curved background.

$(x^{0\sim3}, z)$

$$S_{5\text{dim}} \simeq S_{\text{YM}} + S_{\text{CS}}$$

$$S_{\text{YM}} = \kappa \int d^4x dz \, \text{Tr}\left(\frac{1}{2}h(z)F_{\mu\nu}^2 + k(z)F_{\mu z}^2\right) \qquad S_{\text{CS}} = \frac{N_c}{24\pi^2}\int_5 \omega_5(A)$$

$k(z) = 1 + z^2$

CS5-form

$\mu, \nu = 0 \sim 3$

$h(z) = (1+z^2)^{-1/3}$

$$A_\mu(x^\mu, z) = \sum_{n\geq1} B_\mu^{(n)}(x^\mu)\psi_n(z)$$

$$A_z(x^\mu, z) = \sum_{n\geq0} \varphi^{(n)}(x^\mu)\phi_n(z)$$

complete sets of functions of z

$\varphi^{(0)} \sim$ pion $\quad B_\mu^{(1)} \sim \rho$ meson $\quad B_\mu^{(2)} \sim a_1$ meson $\quad \cdots$

$$\Rightarrow \quad S_{5\text{dim}}(A) = S_{4\text{dim}}(\pi, \rho, a_1, \rho', a_1', \cdots)$$

traditional meson effective action

- A lot of models are reproduced without making any phenomenological assumptions!
  - Skyrme model [Skyrme 1961]
  - Vector meson dominance [Sakurai 1960, Gell-Mann-Zachriasen 1961]
  - Gell-Mann Sharp Wagner model [Gell-Mann –Sharpe-Wagner 1962]
  - Hidden local symmetry [Bando-Kugo-Uehara-Yamawaki-Yanagida 1985]
  - Son-Stephanov's bottom up holographic model [Son-Stephanov 2003]

next slide

- masses and couplings roughly agree with experimental data. [Sakai-S.S. 2004, 2005]

mass	ρ	a_1	ρ'
exp.(MeV)	776	1230	1465
our model	[776]	1189	1607
ratio	[1]	1.03	0.911

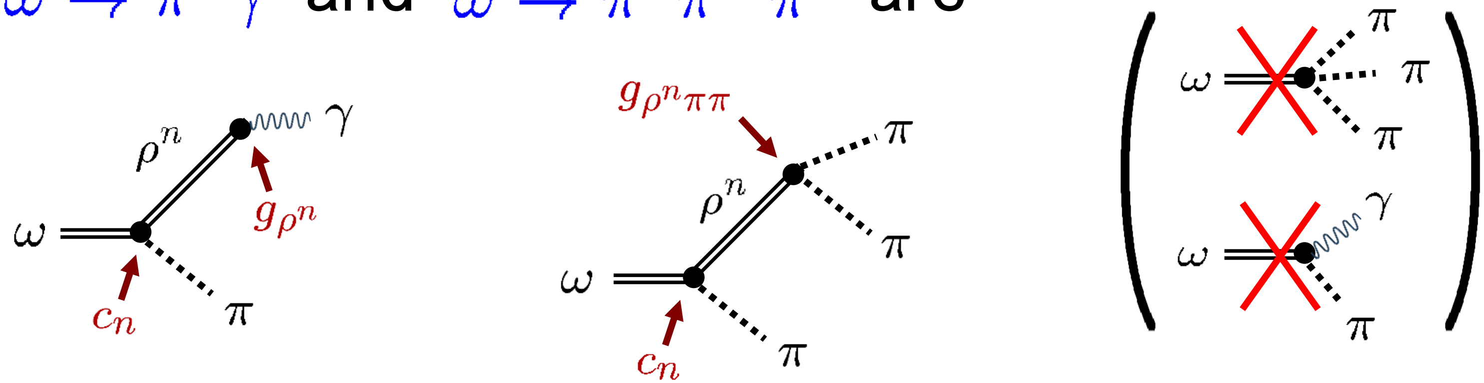
input

(to fix M_{KK}, λ)

coupling	our model	experiment
f_π	[92.4 MeV]	92.4 MeV
L_1	0.584×10^{-3}	$(0.1 \sim 0.7) \times 10^{-3}$
L_2	1.17×10^{-3}	$(1.1 \sim 1.7) \times 10^{-3}$
L_3	-3.51×10^{-3}	$-(2.4 \sim 4.6) \times 10^{-3}$
L_9	8.74×10^{-3}	$(6.2 \sim 7.6) \times 10^{-3}$
L_{10}	-8.74×10^{-3}	$-(4.8 \sim 6.3) \times 10^{-3}$
$g_{\rho\pi\pi}$	4.81	5.99
g_ρ	0.164 GeV^2	0.121 GeV^2
$g_{a_1\rho\pi}$	4.63 GeV	$2.8 \sim 4.2$ GeV

ω meson decay ($\omega \to \pi^0\gamma$ and $\omega \to \pi^0\pi^+\pi^-$)

- Our model predicts that the relevant diagrams for $\omega \to \pi^0\gamma$ and $\omega \to \pi^0\pi^+\pi^-$ are



➡ Exactly the same as the **GSW model !**

[Gell-Mann -Sharp-Wagner 1962]

- Furthermore, we find

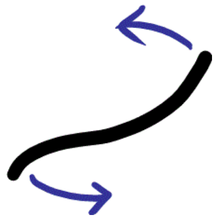
$$\Gamma(\omega \to \pi^0\gamma) = \frac{N_c^2}{3}\frac{\alpha}{64\pi^4 f_\pi^2}\left(\sum_{n=1}^{\infty}\frac{c_n\, g_{\rho^n}}{m_{\rho^n}^2}\right)^2 |\mathbf{p}_\pi|^3 = \frac{N_c^2}{3}\frac{\alpha}{64\pi^4 f_\pi^2}\, {g_{\rho\pi\pi}}^2 |\mathbf{p}_\pi|^3$$

➡ reproduces the proposal given by Fujiwara et al !

[Fujiwara-Kugo-Terao-Uehara-Yamawaki 1985]

- Other mesons, including higher spin mesons, are obtained as excited open string states.

[Imoto-Sakai-S.S. 2010]



rotating open string → higher spin meson

- 1^{st} excited states

→ $a_2(1320),\ b_1(1235),\ \pi(1300),\ a_0(1450),\ \cdots$

- 2^{nd} excited states

→ $\rho_3(1690),\ \pi_2(1670),\ \cdots$

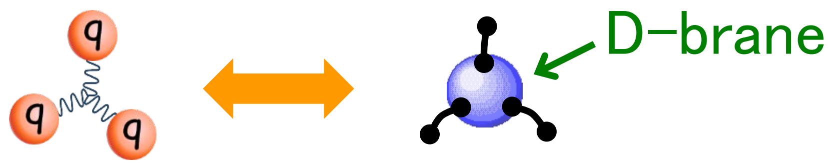
- The existence of isovector mesons with $2^{--},\ 1^{+-},\ 0^{++}$ around 1700 MeV is suggested.

- No good candidate states for $a_0(980),\ \pi_1(1400)$

→ Suggesting that they are 4 quark states.

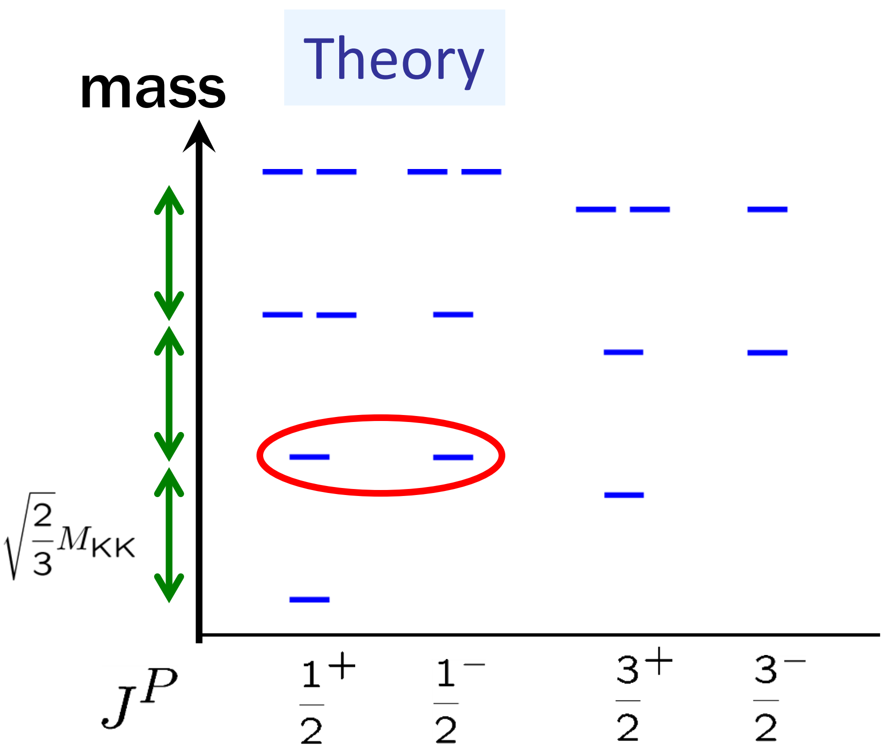
Baryon spectrum

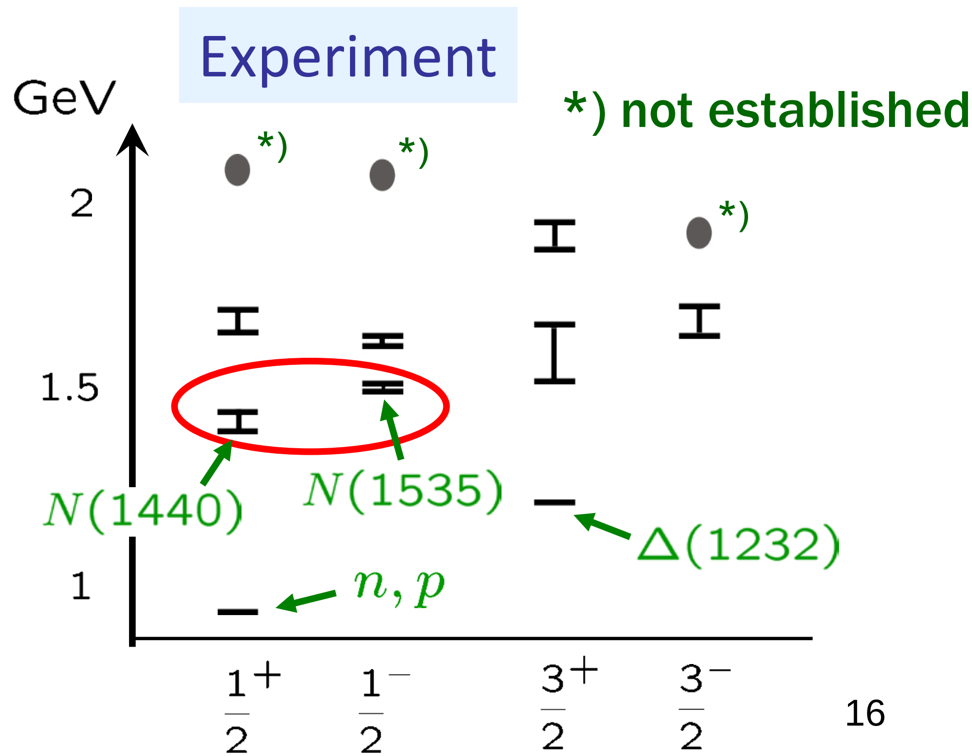
[Hata-Yamato-Sakai-S.S. 2007]



= **soliton** in the 5dim theory

We can analyze the spectrum, magnetic moments, charge radii by quantizing this soliton   cf) Skyrme model





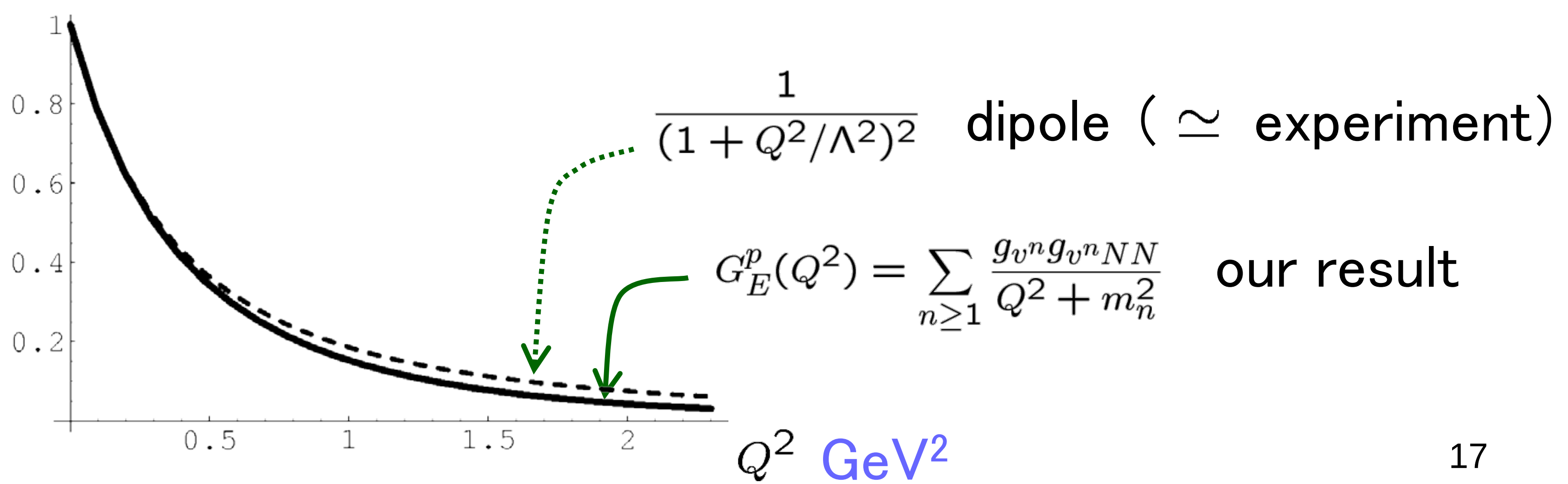
Properties of nucleons

[Hashimoto-Sakai-S.S. 2008]

[See also,
Hong-Rho-Yee-Yi 2007,
Hata-Murata-Yamato 2008,
Kim-Zahed 2008]

	our result	exp.
$\langle r^2 \rangle^{1/2}_{I=0}$	0.74 fm	0.81 fm
$\langle r^2 \rangle^{1/2}_{I=1}$	0.74 fm	0.94 fm
$\langle r^2 \rangle^{1/2}_{A}$	0.54 fm	0.67 fm
$g_{I=0}$	1.7	1.8
$g_{I=1}$	7.0	9.4
g_A	0.73	1.3

nucleon ele-mag form factor



Summary of Status

- Qualitative features

  Confinement, Chiral symmetry breaking, ...
  understood from the geometry of the background.

- Spectrum of hadrons

  glueballs, mesons and baryons
  $\longleftrightarrow$ closed, open strings and D−branes

  Comparison with experimental data is encouraging.

- Structure of interaction

  Many old phenomenological models are reproduced.

  A lot of couplings are calculated and compared with experimental data.

Perspectives

- More accurate calculation

  $1/\lambda,\ 1/N_c$ corrections

  $\longleftrightarrow$ α', loop corrections in string theory

- Connection to perturbative QCD

  Go beyond $1/\lambda$ expansion

  Need some clever ideas

- Phase structure

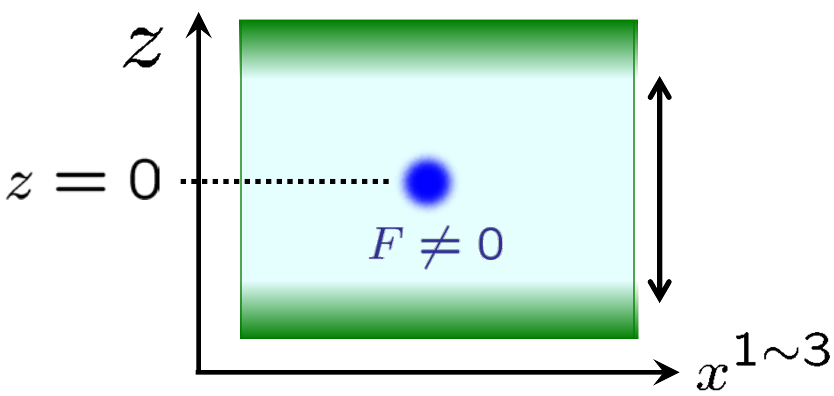
  Many works including $T,\ \mu,\ E,\ B,\ \cdots$

  Actively developing area of research.

  Large T and/or density are more challenging.

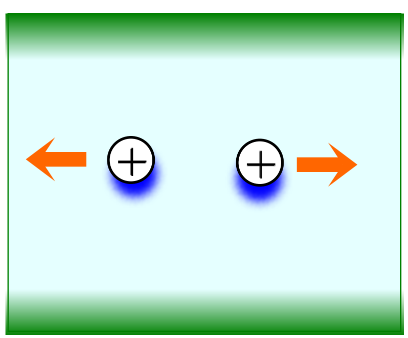
What happens if we have many baryons?

Baryon = soliton in 5dim U(N_f) theory ↖ $(x^{0\sim3}, z)$



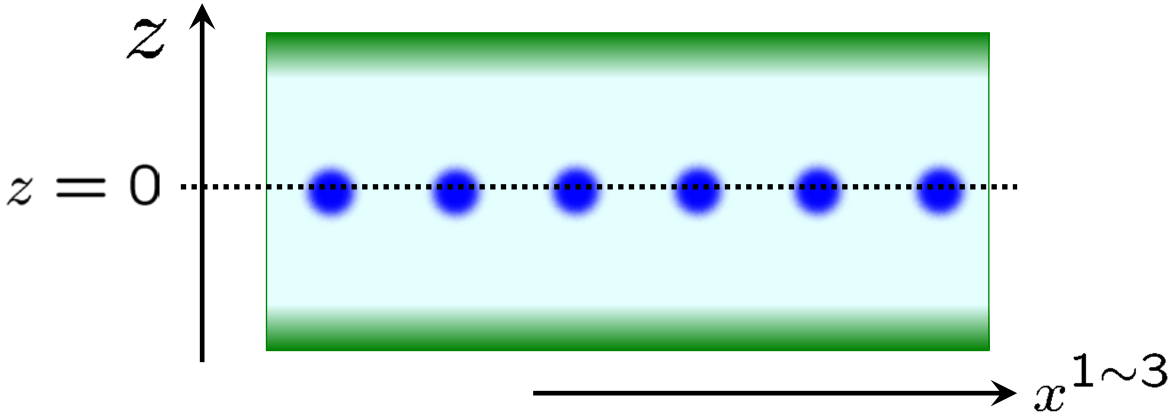
- Baryon # : $N_B = \frac{1}{8\pi^2}\int \mathrm{Tr}(F \wedge F)$
- Size of the soliton is small
- Behaves like a point charge
- Soliton wants to be near z=0

- Repulsive at short distance mainly because of U(1) charge.

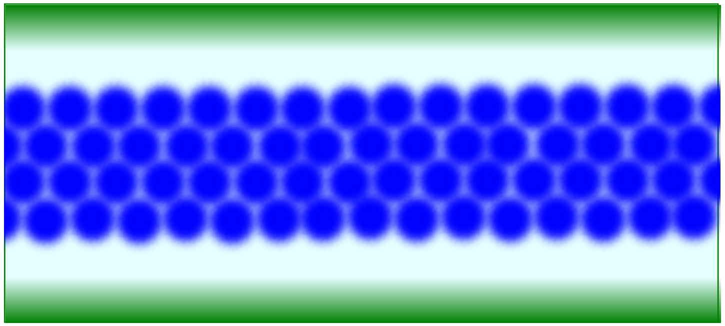


U(1) part $\ni \omega$-meson

- Finite density



- higher density



[Rozali-Shieh-Van Raamsdonk
-Wu 2007, Kaplunovsky-Melnikov
-Sonnenschein 2012, de Boer
-Chowdhury-Heller-Jankowski 2012]

Quarkyonic phase?

Interpretation is not clear to me yet.

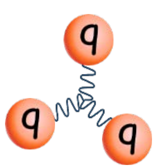
Conclusion :

String theory can be a theory of hadrons

QCD ⟷ dual ! String theory (in a certain curved background)

" Holographic QCD "

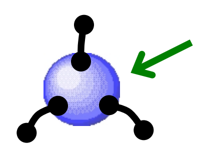
meson



baryon

⟷


string


D-brane

D-brane with Nc strings