Baryon with Massive Strangeness in Holographic QCD

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work in progress

カイラル対称性 vs クォーク質量

	カイラル対称性	クォーク質量
D3-D7 D4-D6 etc.	不明	容易
D4-D8/$\overline{\mathrm{D8}}$ (酒井杉本模型)	良い	要工夫

現実のQCD

カイラル対称性
クォーク質量 ≠ 0

酒井杉本
+クォーク質量

Bound-State Approach

in Holographic QCD

c.f.) Bound-state approach to strangeness in the Skyrme model

[Callan-Klebanov '85]

Massive Strangeness

動機 $0 < m_{u,d} \ll m_s$ $\cancel{\mathrm{SU(3)}}_{\mathrm{f}}$

$\boxed{\text{Hyperon = SU(2)バリオン + Kメソン}}$

bound-state

	Skyrme	酒井杉本
SU(3)回転	80s	arXiv:0910.1179
bound-state	Callan-Klebanov '85	today

Contents

Bound-state approach

- Skyrme模型のとき [Callan-Klebanov]
- 酒井杉本模型のとき
- 議論

Skyrmion + Kaonゆらぎ

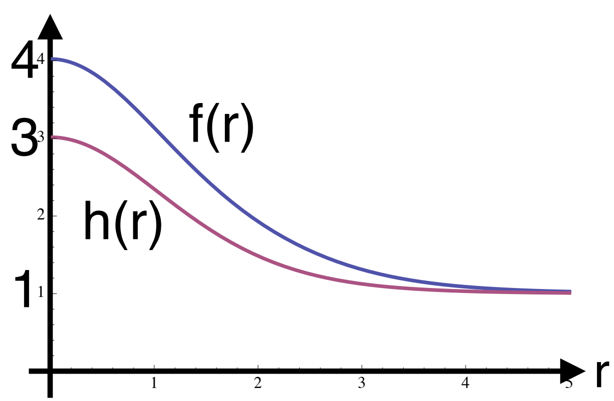
$$L \sim \mathrm{Tr}(U^{-1}\partial_\mu U)^2 + \mathrm{Tr}[U^{-1}\partial_\mu U, U^{-1}\partial_\nu U]^2$$

ansatz: $U = \sqrt{U_\pi} U_K \sqrt{U_\pi}$

$$U_\pi = \begin{pmatrix} e^{iF(r)\hat{x}\cdot\tau} & 0 \\ 0 & 1 \end{pmatrix}, \; U_K \sim \exp\left[\begin{pmatrix} 0 & K \\ K^\dagger & 0 \end{pmatrix}\right]$$

$$L \sim \int dr\, r^2 \left[f(r)\dot{k}^\dagger \dot{k} - h(r)\partial_r k^\dagger \partial_r k - (m_K^2 + V(r))k^\dagger k \right]$$

$$K(x^\mu) = k(r,t)Y(\Omega_2)$$



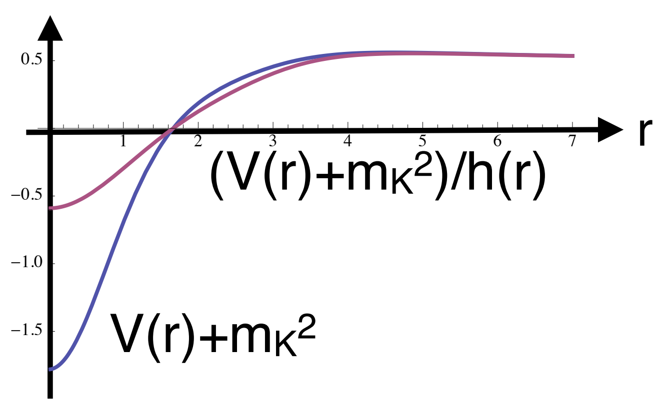
Skyrme項

⇒ non-canonical

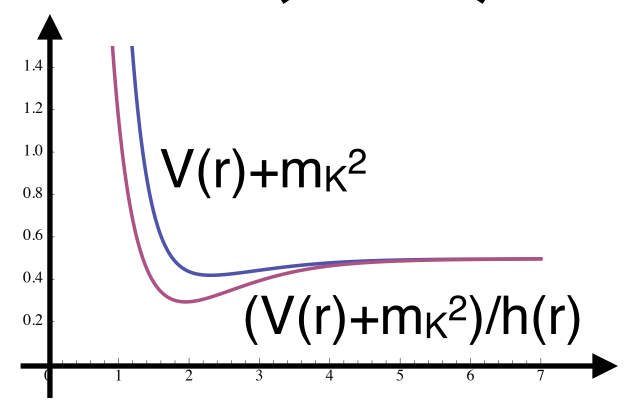
ポテンシャル問題

$$-\left[\frac{1}{r^2}\partial_r(h(r)r^2\partial_r) - V(r) - m_K^2\right]k = \left[f(r)E_n^2 + 2\lambda(r)E_n\right]k$$

Λ, Σ, Σ*



Λ(1405)



	Λ	Σ	Σ*	Λ(1405)
mass (theory)	1048	1122	1303	1281
mass (exp)	1115	1190	1385	1405

酒井杉本模型

5 dim U(Nf) YM-CS理論 [Sakai-Sugimoto]

$$S = -\kappa \int d^4x dz \, \mathrm{Tr} \left[\frac{1}{2} h(z) \mathcal{F}_{\mu\nu}^2 + k(z) \mathcal{F}_{\mu z}^2 \right] + \frac{N_c}{24\pi^2} \int_{\mathrm{M}_5} \omega_5$$

[μ=0,1,2,3]

曲がった時空：$h(z) = (1+z^2)^{-1/3}, \ k(z) = 1 + z^2$

２パラメータ：$\kappa = 0.00746, \ M_{\mathrm{KK}} = 948 \, [\mathrm{MeV}] \to 1$

バリオン (Nf=2) [Hata-Sakai-Sugimoto-Yamato]

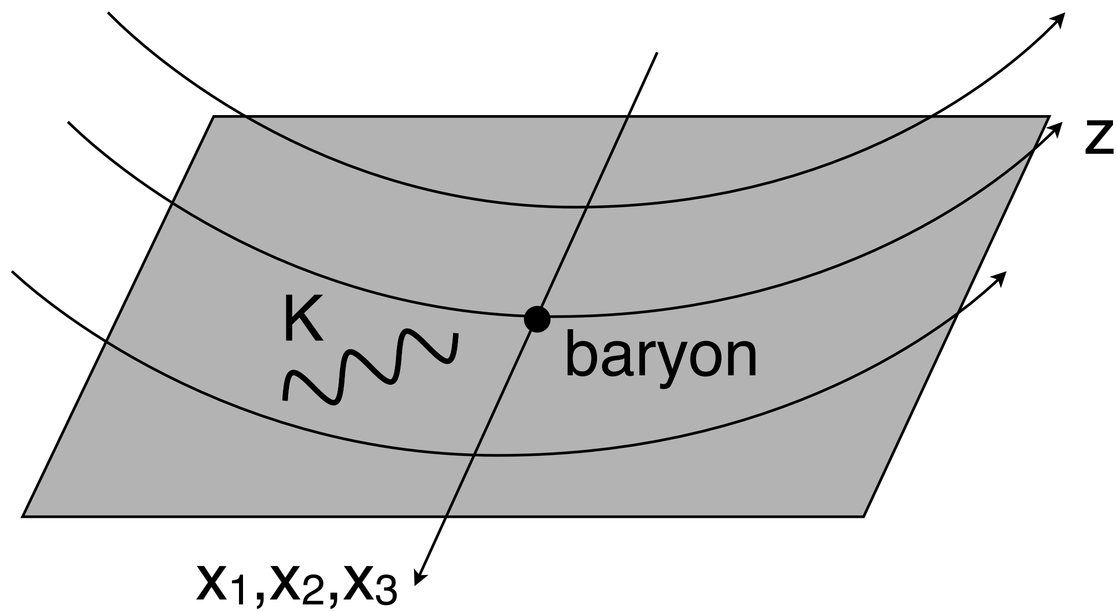
$$A_\alpha^{\mathrm{cl}} = -i f(\xi) g \partial_\alpha g^{-1}, \ \widehat{A}_0^{\mathrm{cl}} = \frac{27\pi}{\lambda} \frac{1}{\xi^2} \left[1 - \frac{\rho^4}{(\rho^2 + \xi^2)^2} \right], \ A_0^{\mathrm{cl}} = \widehat{A}_\alpha^{\mathrm{cl}} = 0$$

SU(2)

U(1)

[α=1,2,3,z]

Holographic bound-state approach



５次元でやるのは難しい ⇒ **４次元の作用を作る**

質量項：$m_K^2 K^\dagger K$

c.f.) [Scoccola-Min-Nadeau-Rho,'89]
in Hidden Local Symmetry Model

バリオン + Kメソンゆらぎ

SU(3) YM

$$S_{SU(3)} = -\kappa \int d^4x dz \, \mathrm{Tr} \left[\frac{1}{2} h(z) F_{\mu\nu}^2 + k(z) F_{\mu z}^2 \right]$$

SU(2)バリオン：A^{inst}

K成分ゆらぎ：a_z (K), a_μ (K*)

$$A_0 = \begin{pmatrix} \frac{1}{3} A_0^{\mathrm{inst}} & a_0 \\ a_0^\dagger & -\frac{2}{3} c_0 \end{pmatrix}, \quad A_\alpha = \begin{pmatrix} A_\alpha^{\mathrm{inst}} & a_\alpha \\ a_\alpha^\dagger & 0 \end{pmatrix}$$

$$A_0^{\mathrm{inst}} = c_0 \mathbf{1}_2$$

ゆらぎの５次元作用

$$S_{\rm fluc} = -2\kappa \int d^4x dz \, \mathrm{Tr}\Big[h(z)(\bar{D}^{(\rm inst)}_\mu a^\dagger_\nu D^{(\rm inst)}_\mu a_\nu - \bar{D}^{(\rm inst)}_\mu a^\dagger_\nu D^{(\rm inst)}_\nu a_\mu - i\, a^{\dagger\mu} F^{(\rm inst)}_{\mu\nu} a^\nu)$$
$$+ k(z)\Big(\bar{D}^{(\rm inst)}_\mu a^\dagger_z D^{(\rm inst)}_\mu a_z - \bar{D}^{(\rm inst)}_\mu a^\dagger_z D^{(\rm inst)}_z a_\mu - \bar{D}^{(\rm inst)}_z a^\dagger_\mu D^{(\rm inst)}_\mu a_z$$
$$+ \underline{\bar{D}^{(\rm inst)}_z a^\dagger_\mu D^{(\rm inst)}_z a_\mu + i(a^\dagger_z F^{(\rm inst)}_{\mu z} a_\mu - a^\dagger_\mu F^{(\rm inst)}_{\mu z} a_z)}\Big)\Big]$$

$$D^{(\rm inst)}_M a_N = \partial_M a_N + i A^{\rm inst}_M a_N$$
$$\bar{D}^{(\rm inst)}_M a^\dagger_N = \partial_M a^\dagger_N - i a^\dagger_N A^{\rm inst}_M$$

※バリオンがないとき

$(\partial_z a_\mu)^2$: ベクトルメソンの質量項

ベクトルメソンを近似で消す

ベクトルメソン質量項

$$\int dz\, k(z)\partial_z a_\mu^\dagger\, \partial_z a_\mu = \int dz\, h(z) \sum_{n,\,m} \lambda_n B_\mu^{(n)\dagger} B_\mu^{(m)} \psi_n \psi_m = \sum_n \lambda_n B_\mu^{(n)\dagger} B_\mu^{(n)}$$

平方完成

$$\begin{aligned} &\partial_z a_\mu^\dagger\, \partial_z a_\mu + i(a_z^\dagger F_{\mu z}^{(\mathrm{inst})} a_\mu - a_\mu^\dagger F_{\mu z}^{(\mathrm{inst})} a_z) \\ &= h(z)^4 \sum_{n,\,m} \lambda_n \underline{|B_\mu^{(n)} \psi_n - \frac{i}{\lambda_n} h(z)^{-4} F_{\mu z}^{(\mathrm{inst})} a_z|^2} \\ &\qquad - L_{\mathrm{KK}} h(z)^{-4} a_z^\dagger F_{\mu z}^{(\mathrm{inst})} F_{\mu z}^{(\mathrm{inst})} a_z \end{aligned}$$

$\boxed{\textbf{近似:}\ a_\mu = i L_{\mathrm{kk}} h(z)^{-4} F_{\mu z}^{(\mathrm{inst})} a_z}$ $\qquad L_{\mathrm{kk}} = \sum_n \frac{1}{\lambda_n}$

決まらないパラメータ：L_{KK}

$$L_{\mathrm{kk}} = \sum_n \frac{1}{\lambda_n}$$

n	1	2	3	4	5	6	7
λ_n	0.67	1.6	2.9	4.6	6.6	9.0	12
$\lambda_n^{1/2} M_{KK}$[MeV]	[776]	1187	1607	2021	2434	2845	3256

収束？ $$\sum_{n=1}^{7} \frac{1}{\lambda_n} = 3.0 \qquad \sum_{n=1}^{30} \frac{1}{\lambda_n} = 3.5$$

しかしこれは m_q=0 での値

とりあえず L_{KK}=3

簡単なところでやってみる

近似: $a_\mu = iL_{\mathrm{kk}} h(z)^{-4} F^{(\mathrm{inst})}_{\mu z} a_z$

$$\boxed{L_{\mathrm{kk}}^2 h(z)^{-4}\left(|F^{(\mathrm{inst})2}_{\mu z}|\partial_\mu a_z^\dagger\,\partial_\mu a_z - \partial_\mu a_z^\dagger F^{(\mathrm{inst})}_{\nu z} F^{(\mathrm{inst})}_{\mu z}\partial_\nu a_z\right)}$$

$$\begin{aligned} S_{\mathrm{fluc}} = &- 2\kappa \int d^4x dz\, \mathrm{Tr}\Big[h(z)\big(\underline{\bar{D}^{(\mathrm{inst})}_\mu a_\nu^\dagger D^{(\mathrm{inst})}_\mu a_\nu - \bar{D}^{(\mathrm{inst})}_\mu a_\nu^\dagger D^{(\mathrm{inst})}_\nu a_\mu} - i\, a^{\dagger\mu} F^{(\mathrm{inst})}_{\mu\nu} a^\nu\big) \\ &+ k(z)\Big(\underline{\bar{D}^{(\mathrm{inst})}_\mu a_z^\dagger D^{(\mathrm{inst})}_\mu a_z} - \bar{D}^{(\mathrm{inst})}_\mu a_z^\dagger D^{(\mathrm{inst})}_z a_\mu - \bar{D}^{(\mathrm{inst})}_z a_\mu^\dagger D^{(\mathrm{inst})}_\mu a_z \\ &+ \underline{\bar{D}^{(\mathrm{inst})}_z a_\mu^\dagger D^{(\mathrm{inst})}_z a_\mu + i(a_z^\dagger F^{(\mathrm{inst})}_{\mu z} a_\mu - a_\mu^\dagger F^{(\mathrm{inst})}_{\mu z} a_z)}\Big)\Big] \end{aligned}$$

$$\boxed{L_{\mathrm{kk}} h(z)^{-4} |F^{(\mathrm{inst})}_{\mu z}|^2 a_z^\dagger a_z}$$

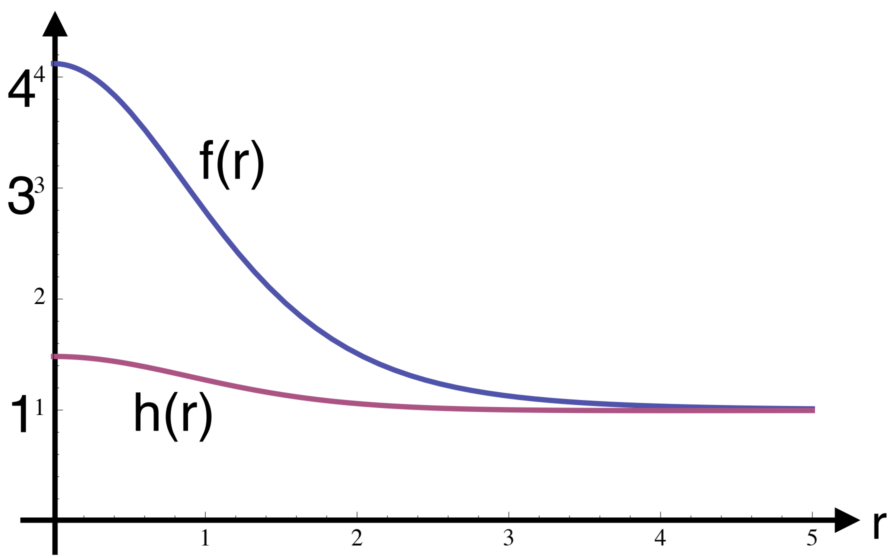
モード展開 $a_z \sim K(x^\mu)\phi_0(z)$

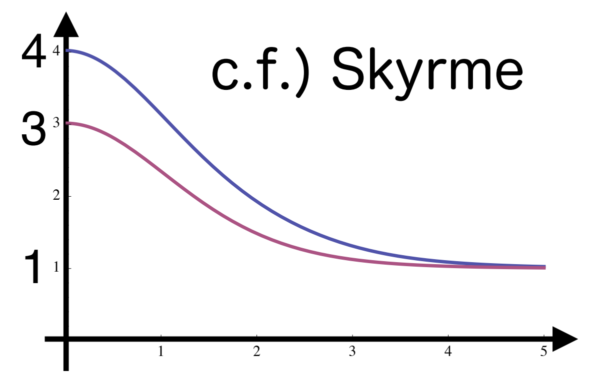
Skyrme模型に似る

$$\mathcal{L}_{\rm kaon} = \left[f(r)\dot{k}^\dagger \dot{k} - h(r)\partial_r k^\dagger \partial_r k - (m_K^2 + V(r))k^\dagger k + \cdots \right]$$

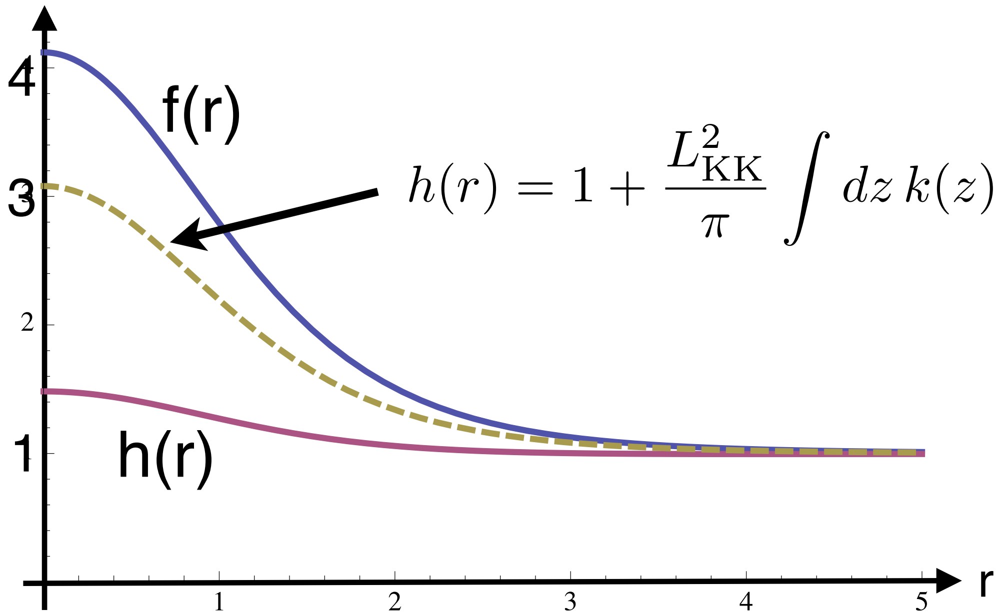
$$f(r) = 1 + \frac{L_{\rm KK}^2}{\pi}\int dz\, k(z)^{1/3} |F_{iz}^{({\rm inst})\,2}|$$

$$h(r) = 1 + \frac{L_{\rm KK}^2}{\pi}\int dz\, k(z)^{1/3} \left(\frac{2}{3}|F_{iz}^{({\rm inst})\,2}| - |F_{0z}^{({\rm inst})\,2}|\right)$$





F_{0z}が効く



$$h(r) = 1 + \frac{L_{\mathrm{KK}}^2}{\pi}\int dz\, k(z)^{1/3}\left(\frac{2}{3}|F_{iz}^{(\mathrm{inst})\,2}| - \cancel{|F_{0z}^{(\mathrm{inst})\,2}|}\right)$$

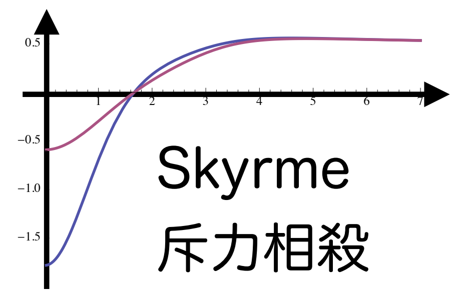
Skyrme vs 酒井杉本：$U^{-1}\partial_\mu U \leftrightarrow F_{\mu z}^{(\mathrm{inst})}$

$\boxed{A_0^{\mathrm{inst}} \sim \frac{1}{\lambda}}$　小さいはず ⇒ 意外と大きい

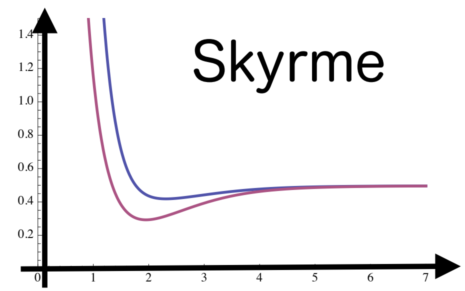
束縛は微妙

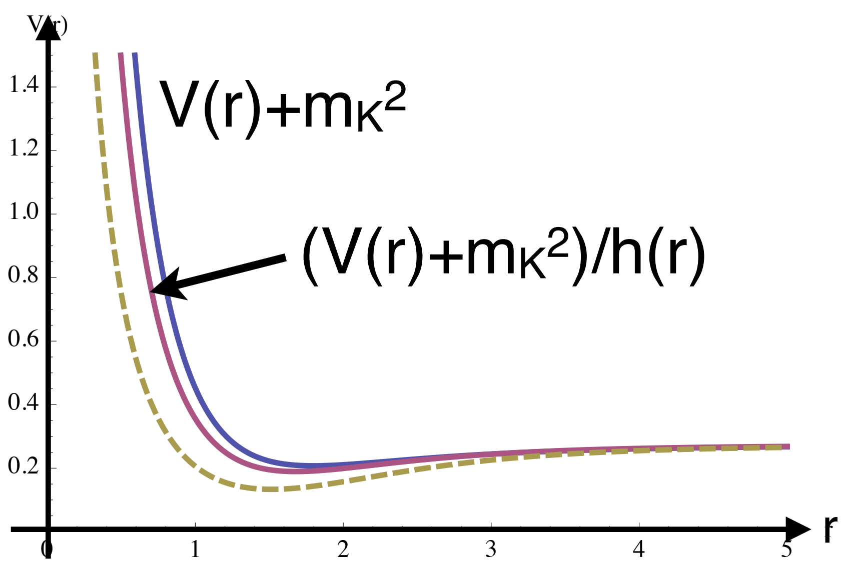
Λ, Σ, Σ*: 無いかも

斥力 vs L_{KK}: fine-tuning



Λ(1405): 弱く束縛か





E ~ 473 [MeV]

940+473=1413?

Toward Holographic Bound-State Approach to Strangeness

アプローチ自体は自然

∵) ５次元ゲージ対称性が強力

Skyrmeのと似ている構造

バリオンは硬い？

A_0の効果が強い

メソンとバリオンくっきり区別？

Λ(1405)はN-$\bar{K}$の束縛状態？