Holography for Strongly Coupled Systems

Nick Evans

University of Southampton

The plan

Storytelling via ppt...

Calculations at the board...

Lecture 1: strong coupling in QCD
string theory
the AdS/CFT conjecture

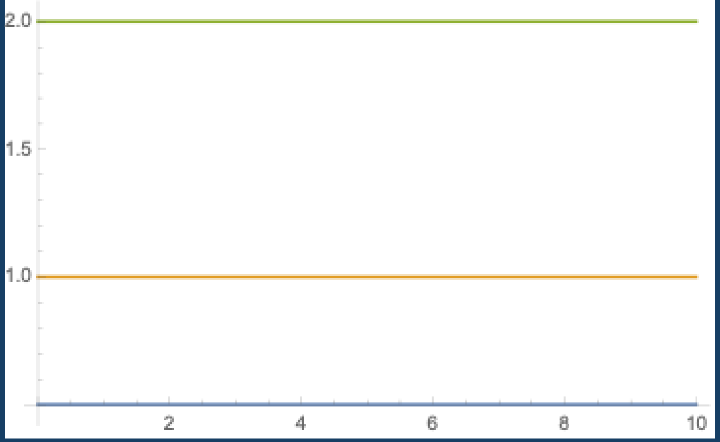
Lecture 2: How holography works
Instability in AdS
Dynamical chiral symmetry breaking

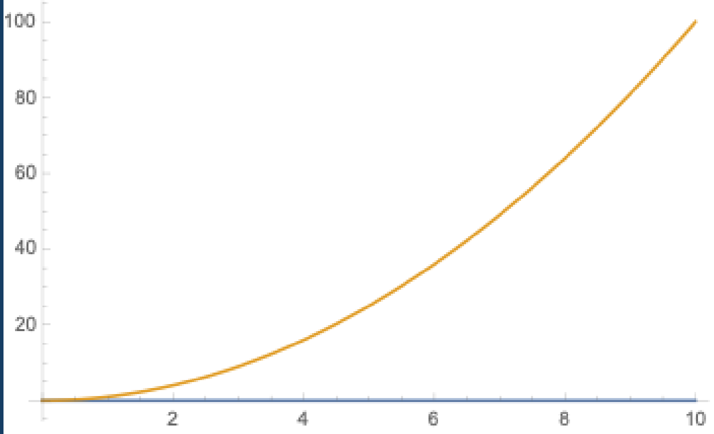
Lecture 3: AdS/QCD for meson masses
Confinement and string tension

Lecture 4: NJL interactions
Finite T and μ
Composite higgs models

Witten's multi-trace prescription hep-th/0112258 [hep-th]

Examples from NE 1601.02824





In a supersymmetric theory $\Delta m^2 = 0$ the solutions are just L = m

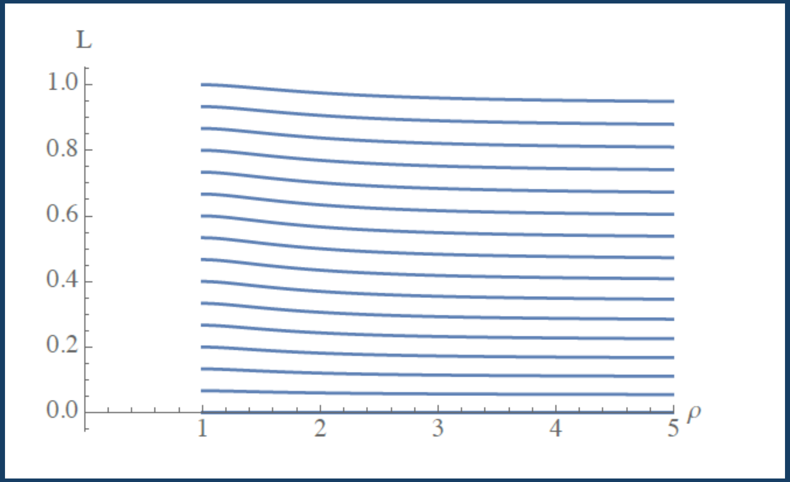
c=0 -> m=0 for all g

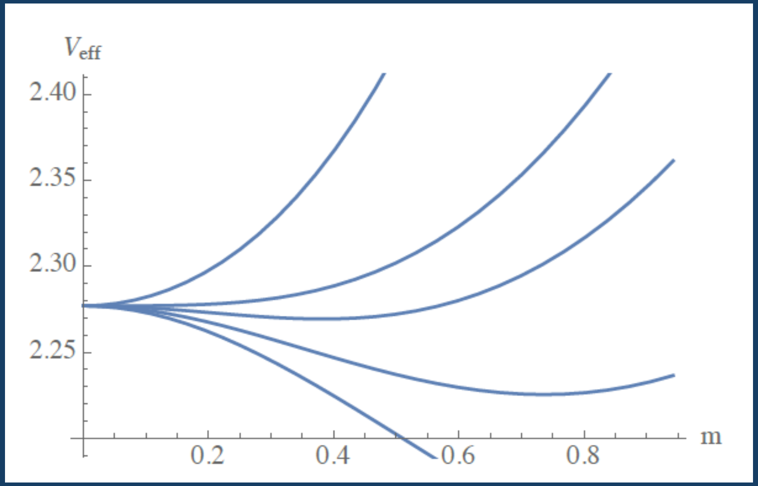
The action integrated over r is – V and vanishes – SUSY.

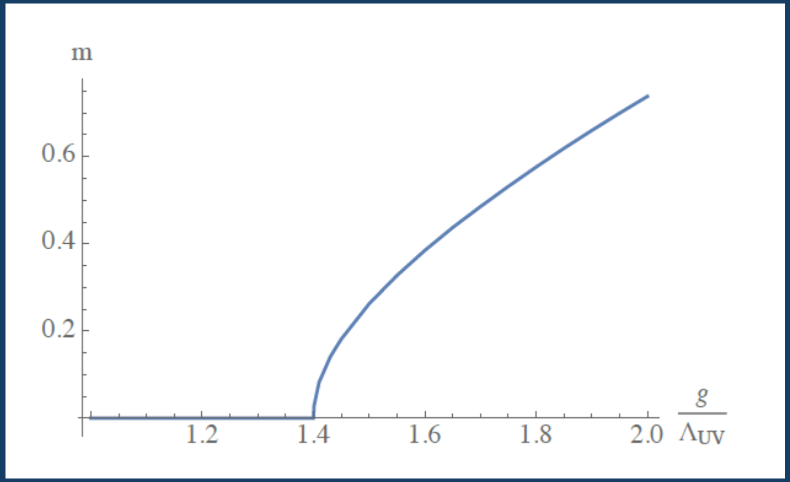
$$V = -\int dr\, r^3 (\partial_r L)^2$$

We see adding $m^2 L^2/g^2$ any g pins you at the origin m=0

Here we calculate with a Δm^2 but also an IR cut off so there is no BF bound violation

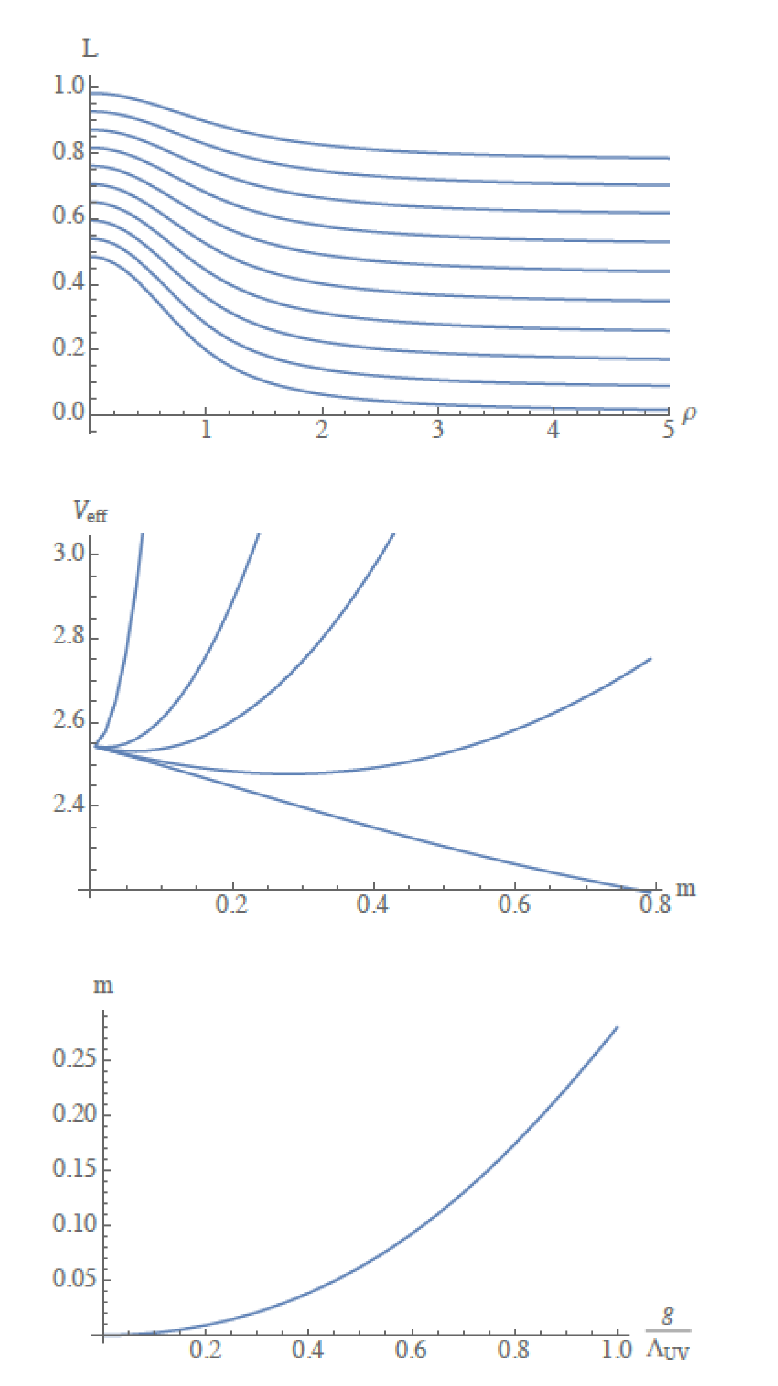






The action is non-zero and falls… Witten's prescription gives NJL like behaviour…

$$V = -\int dr r^3 (\partial_r L)^2$$



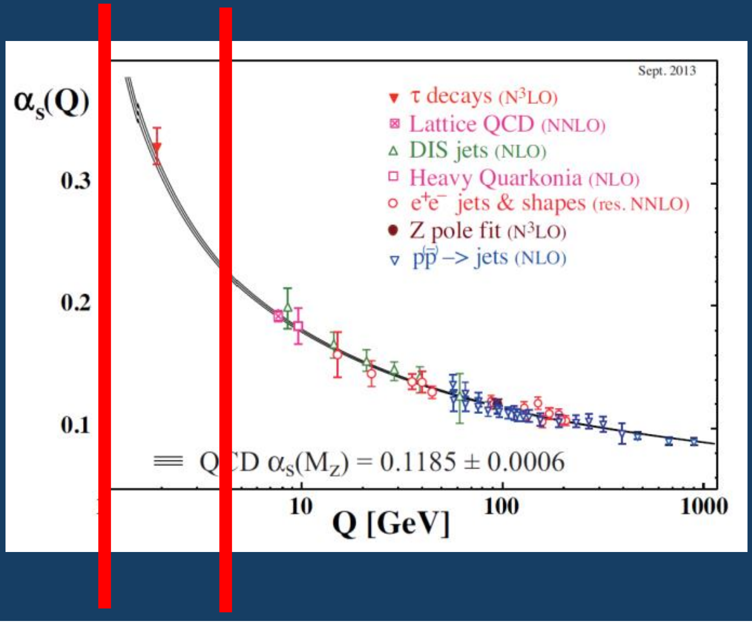
If you remove the IR cut off so there is a BF bound violation and m_{IR} is non-zero when m_{UV}=0…

The NJL interaction makes the mass gap grow with g…

“NJL assisted” condensation…

Some example physics cases using AdS/QCD

Perfecting QCD with HDOs



The weakly coupled gravity dual should only live between the red lines… probably we need HDOs at the UV scale to include matching effects… and stringy effects in the gravity model….

$$\frac{g_S^2}{\Lambda_{UV}^2}|\bar{q}q|^2\,, \qquad \frac{g_V^2}{\Lambda_{UV}^2}|\bar{q}\gamma^\mu q|^2\,, \qquad \frac{g_A^2}{\Lambda_{UV}^2}|\bar{q}\gamma^\mu\gamma_5 q|^2\,, \qquad \frac{g_B^2}{\Lambda_{UV}^5}|qqq|^2\,,$$

Observables (MeV)	QCD	Dynamic AdS/QCD	HDO coupling
M_V	775	775	sets scale
M_A	1230	1230	fitted by $g_A^2 = 5.76149$
M_S	500/990	597	prediction $+20\%/-40\%$
M_B	938	938	fitted by $g_B^2 = 25.1558$
f_π	93	93	fitted by $g_S^2 = 4.58981$
f_V	345	345	fitted by $g_V^2 = 4.64807$
f_A	433	444	prediction $+2.5\%$
$M_{V,n=1}$	1465	1532	prediction $+4.5\%$
$M_{A,n=1}$	1655	1789	prediction $+8\%$
$M_{S,n=1}$	990/1200-1500	1449	prediction $+46\%/0\%$
$M_{B,n=1}$	1440	1529	prediction $+6\%$

Table 2: The spectum and the decay constants for two-flavour QCD with HDOs from fig. 7 used to improve the spectrum.

Pretty good… but we've lost some predictivity….

Composite Higgs Models

Here the higgs is identified with the pions…

A baryon plays the role of a top like quark… so an extra set of fermions are often introduced in a different representation…

Let's not worry about SM symmetry groups but look at the strong dynamics sector of a model

We describe two representations by 2 L fields with different running masses appropriate to the rep

SU(4) 3 F 3 $\bar{F}$ 5 A_2

G. Ferretti, "UV Completions of Partial Compositeness: The Case for a SU(4) Gauge Group," JHEP **06** (2014) 142, arXiv:1404.7137 [hep-ph].

In this model the A2 symmetry breaking generates the SM higgs and the Fs are to give F A_2 F top partners

V. Ayyar, T. DeGrand, M. Golterman, D. C. Hackett, W. I. Jay, E. T. Neil, Y. Shamir, and B. Svetitsky, "Spectroscopy of SU(4) composite Higgs theory with two distinct fermion representations," Phys. Rev. D **97** no. 7, (2018) 074505, arXiv:1710.00806 [hep-lat].

The lattice has simulated (unquenched) SU(4) 2 F 2 F 4 A_2

	Lattice [80] $4A_2, 2F, 2\bar{F}$ unquench	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ no decouple	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ no decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ quench
$f_{\pi A_2}$	0.15(4)	0.0997	0.0997	0.111	0.111	0.102
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109	0.892
M_{VA_2}	1.00(4)	1*	1*	1*	1*	1*
f_{VA_2}	0.68(5)	0.489	0.489	0.516	0.516	0.517
M_{VF}	0.93(7)	0.933	0.939	0.890	0.904	0.976
f_{VF}	0.49(7)	0.458	0.461	0.437	0.491	0.479
M_{AA_2}		1.37	1.37	1.32	1.32	1.28
f_{AA_2}		0.505	0.505	0.521	0.521	0.522
M_{AF}		1.37	1.37	1.21	1.23	1.28
f_{AF}		0.501	0.504	0.453	0.509	0.492
M_{SA_2}		0.873	0.873	0.684	0.684	1.18
M_{SF}		1.03	1.02	0.811	0.798	1.25
M_{JA_2}	3.9(3)	2.21	2.21	2.21	2.21	2.22
M_{JF}	2.0(2)	2.07	2.08	1.97	2.00	2.17
M_{BA_2}	1.4(1)	1.85	1.85	1.85	1.85	1.86
M_{BF}	1.4(1)	1.74	1.75	1.65	1.68	1.81

The pattern is right...

The A2-F gap is very well described...

Adding extra flavours is not a huge change...

Scalar masses get lighter as add extra flavours

SU(4) 3 F $3\bar{F}$ 5 A_2

G. Ferretti, "UV Completions of Partial Compositeness: The Case for a SU(4) Gauge Group," JHEP **06** (2014) 142, arXiv:1404.7137 [hep-ph].

In this model the A2 symmetry breaking generates the SM higgs and the Fs are to give F A_2 F top partners

The lattice has simulated (unquenched) SU(4) 2 F 2 F 4 A_2

	Lattice [80] $4A_2, 2F, 2\bar{F}$ unquench	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ no decouple	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ no decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ quench
$f_{\pi A_2}$	0.15(4)	0.0997	0.0997	0.111	0.111	0.102
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109	0.892
M_{VA_2}	1.00(4)	1*	1*	1*	1*	1*
f_{VA_2}	0.68(5)	0.489	0.489	0.516	0.516	0.517
M_{VF}	0.93(7)	0.933	0.939	0.890	0.904	0.976
f_{VF}	0.49(7)	0.458	0.461	0.437	0.491	0.479
M_{AA_2}		1.37	1.37	1.32	1.32	1.28
f_{AA_2}		0.505	0.505	0.521	0.521	0.522
M_{AF}		1.37	1.37	1.21	1.23	1.28
f_{AF}		0.501	0.504	0.453	0.509	0.492
M_{SA_2}		0.873	0.873	0.684	0.684	1.18
M_{SF}		1.03	1.02	0.811	0.798	1.25
M_{JA_2}	3.9(3)	2.21	2.21	2.21	2.21	2.22
M_{JF}	2.0(2)	2.07	2.08	1.97	2.00	2.17
M_{BA_2}	1.4(1)	1.85	1.85	1.85	1.85	1.86
M_{BF}	1.4(1)	1.74	1.75	1.65	1.68	1.81

The pattern is right…

The A2-F gap is very well described…

Adding extra flavours is not a huge change…

Scalar masses get lighter as add extra flavours

SU(4) 3 F $3\bar{F}$ 5 A_2

In this model the A2 symmetry breaking generates the SM higgs and the Fs are to give F A_2 F top partners

The lattice has simulated (unquenched) SU(4) 2 F 2 F 4 A_2

	Lattice [80] $4A_2, 2F, 2\bar{F}$ unquench	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ no decouple	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ no decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ quench
$f_{\pi A_2}$	0.15(4)	0.0997	0.0997	0.111	0.111	0.102
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109	0.892
M_{VA_2}	1.00(4)	1*	1*	1*	1*	1*
f_{VA_2}	0.68(5)	0.489	0.489	0.516	0.516	0.517
M_{VF}	0.93(7)	0.933	0.939	0.890	0.904	0.976
f_{VF}	0.49(7)	0.458	0.461	0.437	0.491	0.479
M_{AA_2}		1.37	1.37	1.32	1.32	1.28
f_{AA_2}		0.505	0.505	0.521	0.521	0.522
M_{AF}		1.37	1.37	1.21	1.23	1.28
f_{AF}		0.501	0.504	0.453	0.509	0.492
M_{SA_2}		0.873	0.873	0.684	0.684	1.18
M_{SF}		1.03	1.02	0.811	0.798	1.25
M_{JA_2}	3.9(3)	2.21	2.21	2.21	2.21	2.22
M_{JF}	2.0(2)	2.07	2.08	1.97	2.00	2.17
M_{BA_2}	1.4(1)	1.85	1.85	1.85	1.85	1.86
M_{BF}	1.4(1)	1.74	1.75	1.65	1.68	1.81

The pattern is right...

The A2-F gap is very well described...

Adding extra flavours is not a huge change...

Scalar masses get lighter as add extra flavours

SU(4) 3 F $3\bar{F}$ 5 A_2

In this model the A2 symmetry breaking generates the SM higgs and the Fs are to give F A_2 F top partners

The lattice has simulated (unquenched) SU(4) 2 F 2 F 6 A_2

	Lattice [80] $4A_2, 2F, 2\bar{F}$ unquench	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ no decouple	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ no decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ quench
$f_{\pi A_2}$	0.15(4)	0.0997	0.0997	0.111	0.111	0.102
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109	0.892
M_{VA_2}	1.00(4)	1*	1*	1*	1*	1*
f_{VA_2}	0.68(5)	0.489	0.489	0.516	0.516	0.517
M_{VF}	0.93(7)	0.933	0.939	0.890	0.904	0.976
f_{VF}	0.49(7)	0.458	0.461	0.437	0.491	0.479
M_{AA_2}		1.37	1.37	1.32	1.32	1.28
f_{AA_2}		0.505	0.505	0.521	0.521	0.522
M_{AF}		1.37	1.37	1.21	1.23	1.28
f_{AF}		0.501	0.504	0.453	0.509	0.492
M_{SA_2}		0.873	0.873	0.684	0.684	1.18
M_{SF}		1.03	1.02	0.811	0.798	1.25
M_{JA_2}	3.9(3)	2.21	2.21	2.21	2.21	2.22
M_{JF}	2.0(2)	2.07	2.08	1.97	2.00	2.17
M_{BA_2}	1.4(1)	1.85	1.85	1.85	1.85	1.86
M_{BF}	1.4(1)	1.74	1.75	1.65	1.68	1.81

The pattern is right…

The A2-F gap is very well described…

Adding extra flavours is not a huge change…

Scalar masses get lighter as add extra flavours

Sp(4) + 4 Weyl fermions

NE, Porod, Erdmenger, Liu. 2404.14480

The pseudo-reality means the flavour symmetry is U(4) on the 4 Weyl

$${}_i = \begin{pmatrix} U_L^C \\ D_L^C \\ D_R \\ U_R \end{pmatrix}$$

The vacuum condensate is anti-symmetric in spin ($2\times2=1_A+3_S$), anti-symmetric in colour, so anti-symmetric in flavour... possible vacua

$$X = \begin{pmatrix} 0 & L_0 & 0 & 0 \\ -L_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -L_0 \\ 0 & 0 & L_0 & 0 \end{pmatrix}$$

$$X = \begin{pmatrix} 0 & 0 & 0 & -Q \\ 0 & 0 & Q & 0 \\ 0 & -Q & 0 & 0 \\ Q & 0 & 0 & 0 \end{pmatrix}$$

Both break U(4)-> Sp(4).... The first is $SU(2)_L$ invariant the second breaks $SU(2)_L$

$$X = \begin{pmatrix} 0 & L_0 & 0 & 0 \\ -L_(& 0 & 0 & 0 \\ 0 & 0 & 0 & -L_0 \\ 0 & 0 & L_0 & 0 \end{pmatrix}$$

Biased with $SU(2)_L$ preserving masses

$$M = \begin{pmatrix} 0 & m_1 & 0 & 0 \\ -m_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 \\ 0 & 0 & -m_2 & 0 \end{pmatrix}$$

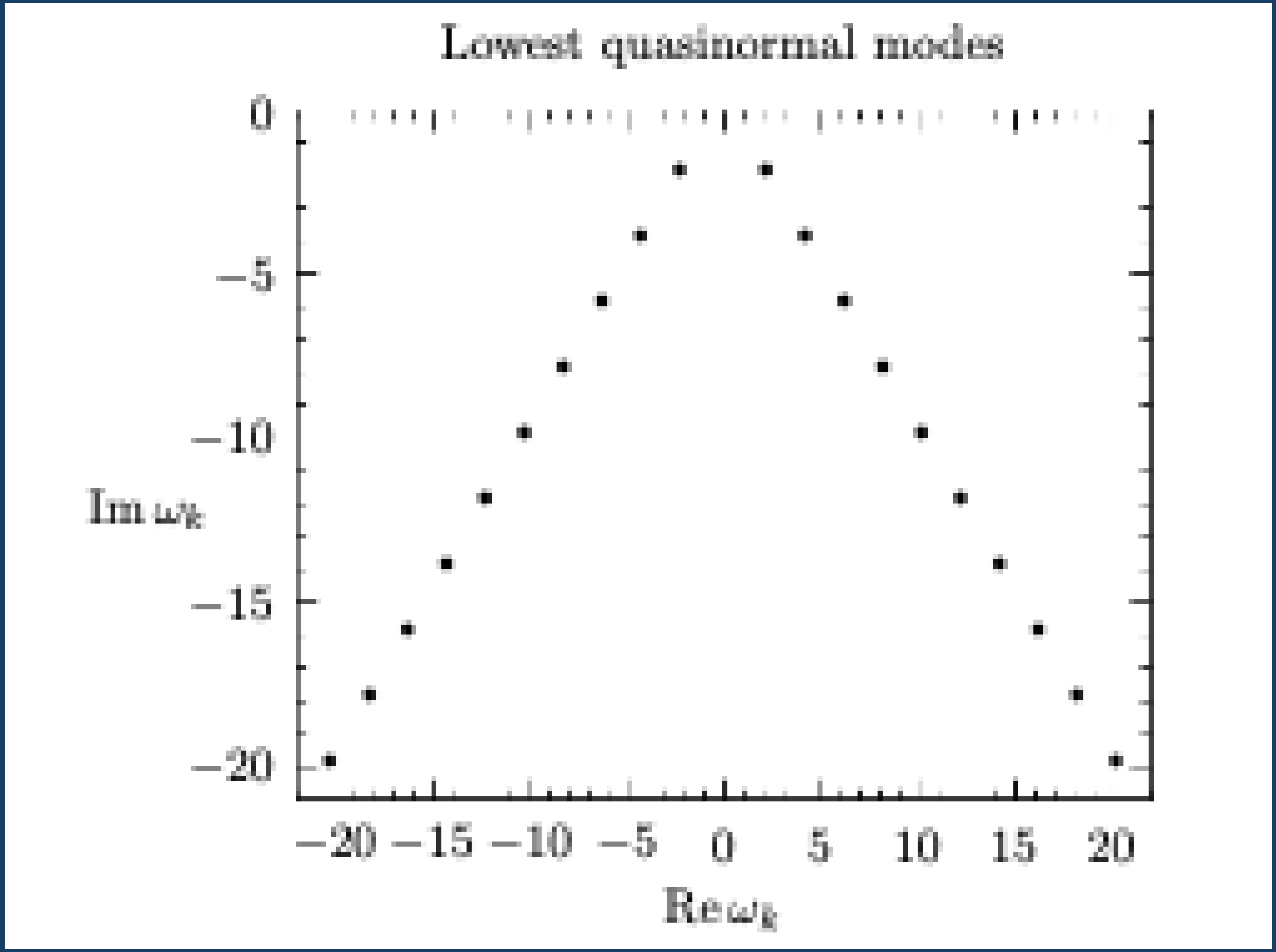
$$X_f = \begin{pmatrix} 0 & \sigma - Q_5 + iS - i\pi_5 & Q_2 - \pi_2 + i\pi_1 - iQ_1 & -Q_4 + \pi_4 + iQ_3 - i\pi_3 \\ -\sigma + Q_5 + i\pi_5 - iS & 0 & Q_4 + \pi_4 + iQ_3 + i\pi_3 & Q_2 + \pi_2 + iQ_1 + i\pi_1 \\ \pi_2 - Q_2 + iQ_1 - i\pi_1 & -Q_4 - \pi_4 - iQ_3 - i\pi_3 & 0 & \sigma + Q_5 + iS + i\pi_5 \\ Q_4 - \pi_4 + i\pi_3 - iQ_3 & -Q_2 - \pi_2 - iQ_1 - i\pi_1 & -\sigma - Q_5 - iS - i\pi_5 & 0 \end{pmatrix}$$

NJL Competition

$$\mathcal{L} = \frac{g^2}{\Lambda_{UV}^2}(\bar{\Psi}_L U_R \bar{U}_R \Psi_L + \bar{\Psi}_L D_R \bar{D}_R \Psi_L)$$

$$L = \begin{pmatrix} 0 & L_0 & 0 & -Q \\ -L_0 & 0 & Q & 0 \\ 0 & -Q & 0 & L_0 \\ Q & 0 & -L_0 & 0 \end{pmatrix}.$$

Now one needs the full non-abelian holographic model...



Example quasi-normal mode spectrum from Hoyos and Landsteiner

0612169