Title: Marginal Fermi liquids and holography

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Abstract: I will discuss a holographic model whose low-energy physics may be used to build a marginal Fermi liquid. The model has several interesting features, including (i.) it is embedded in string theory and we possess a Lagrangian description of the field theory, (ii.) it exhibits a first-order transition between the non-Fermi liquid phase and a normal Fermi liquid phase, and (iii.) the model involves a lattice of heavy defects interacting with a sea of propagating fields.

Marginal Fermi liquids and holography

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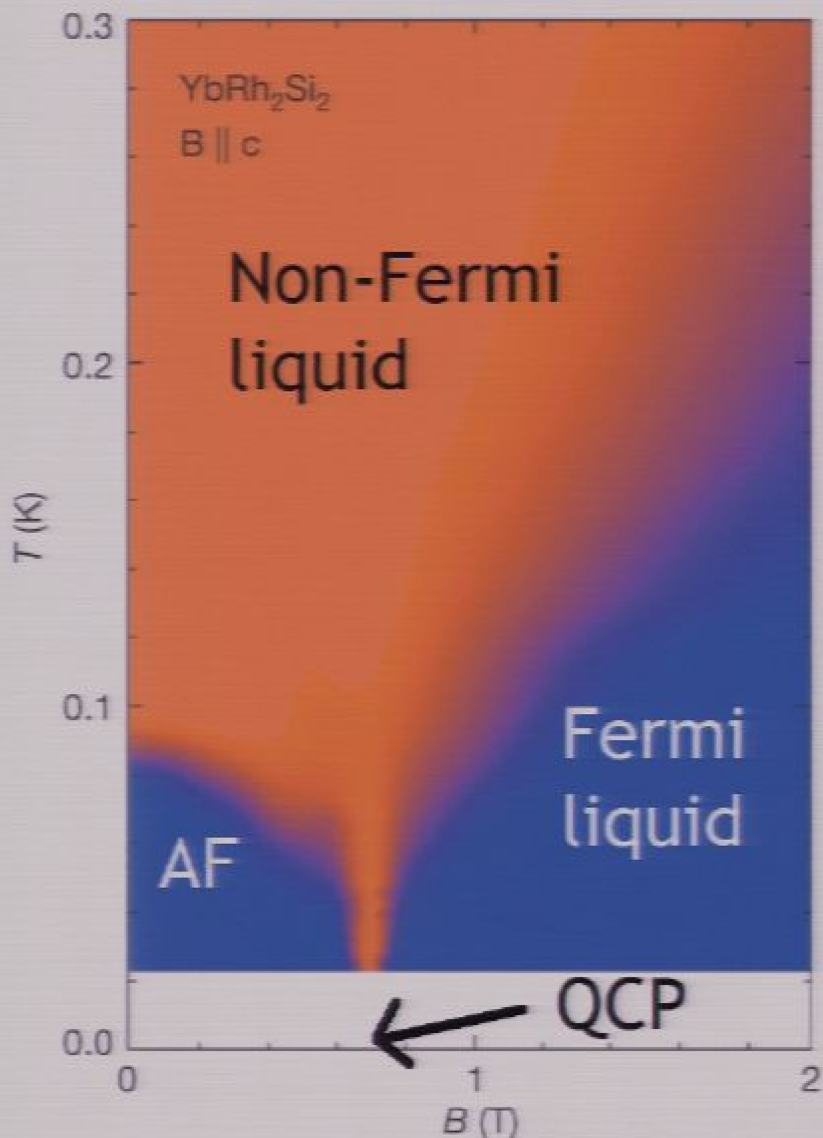
Perimeter Institute - April 11, 2011

based on:
KJ, Shamit Kachru, Andreas Karch, Joseph Polchinski, and Eva Silverstein - arXiv:1104.XXXX?

Outline

1. **[Some] Motivation**: heavy fermion systems.
2. Review: use of AdS/CFT to model non-Fermi liquids, **lattice** setups, &c
3. Holographic lattices: **generalities**.
4. The D3/D5 lattice
5. The M2/M2 lattice and the semi-holographic MFL.
6. Open questions.

Some motivation: heavy fermions - I



[Coleman,Schofield]

Features:

- Non-Fermi liquid phase related to..
- Existence of quantum critical point (QCP).
- Phase transitions may reorganize Fermi surface: FL/NFL
- Inherent lattice structure: rare earth defects embedded in sea of free electrons.

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Non-Fermi liquid phase:

- Good fit for dynamical spin susceptibility (e.g., $CeCu_{6-x}Au_x$),

$$\chi = \frac{1}{\omega + c_1 k^2 + T^{2/z} f(\frac{\omega}{T})}$$

- Anomalous thermodynamics, electrical transport:

$$c_V \sim cT, c \text{ grows near } B = B_c, \qquad \rho_{\mathrm{DC}} \propto T.$$

Marginal Fermi liquid:

$$\chi_{T=0} = \frac{1}{\omega - v_F k_{||} + c_1 \omega \ln \omega}$$

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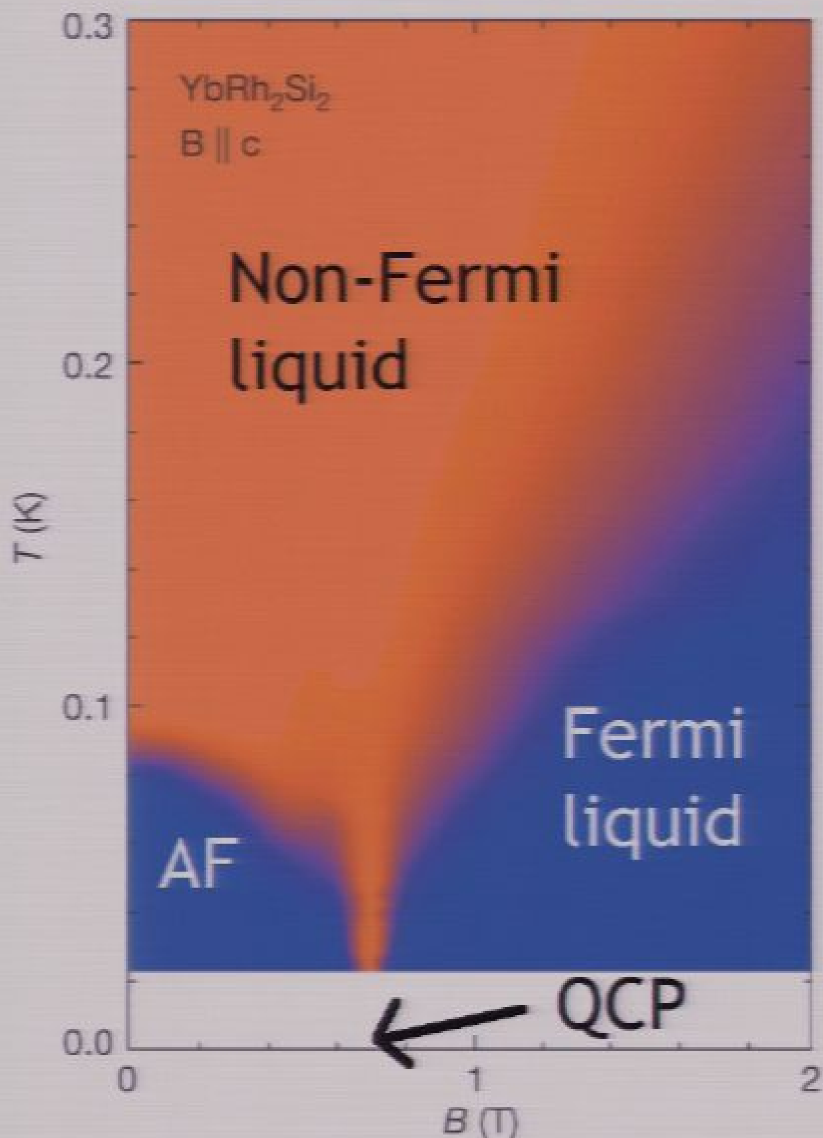

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What about holography?

Lots of attempts to model condensed matter phenomena with gravitational duals.

1. **NFL**: charged fermion in near-extremal AdS-RN background. [Cubrovic, et al], [Faulkner, et al].
2. **QCP**: adjust charge density, magnetic field for fundamental flavour [KJ, et al], [Evans, et al], holographic superfluid [Iqbal, et al]; multi-traces [Faulkner, et al].
3. Probe brane models realize **lattice** configutations, **FL/NFL transitions** [Kachru, Karch, Yaida].

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Semi-holographic theories

One way to get NFL: **semi-holographic** [Faulkner, Polchinski].

Idea: mix free fermion with fermion in large N $(0+1)$-d CFT

$$\mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{0+1} + g\psi\Psi_{\mathbf{x}}$$

ψ: conduction electron, Ψ: locally critical fermion (from AdS_2)

At $g=0$: $G_0 = \langle\bar{\psi}\psi\rangle = \frac{1}{\omega - v_F k_{||}}$,

$$\mathcal{G}_0 = \langle \bar{\Psi}_{\mathbf{x}'}\Psi_{\mathbf{x}}\rangle = \delta(\mathbf{x}'-\mathbf{x}) \times \begin{cases} c(i\omega)^{2\Delta-1} & T > 0 \\ T^{2\Delta-1} f(\frac{\omega}{T}) & T > 0, \end{cases}$$

Semi-holographic theories - II

Large $N \Rightarrow$ compute susceptibility via

$$\chi = \sum_{n=1}^{\infty} g^{2n} G_0^{n+1} \mathcal{G}_0^{n} = \frac{1}{G_0^{-1} - g^2 \mathcal{G}_0} = \frac{1}{\omega - v_F k_{||} - g^2 T^{2\Delta - 1} f(\frac{\omega}{T})}$$

Three interesting features:

1. For $\Delta \leq 1, \mathcal{G}_0$ dominates G_0^{-1} at small ω / T: **NFL**.
2. For $T > 0$, matches NFL susceptibility with $z = 2/(2\Delta - 1)$.
3. For $\Delta = 1, T = 0 : \mathcal{G}_0 \to c\,\omega \ln \omega$ which would give..

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i.e. a **marginal Fermi liquid**.

Ingredients

Necessary components:

1. Free propagating fermions (these are easy to get).
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AdS_2 arises in deep IR for low-T finite density systems, e.g. AdS-RN [Faulkner, et al], probe branes [KJ, et al].

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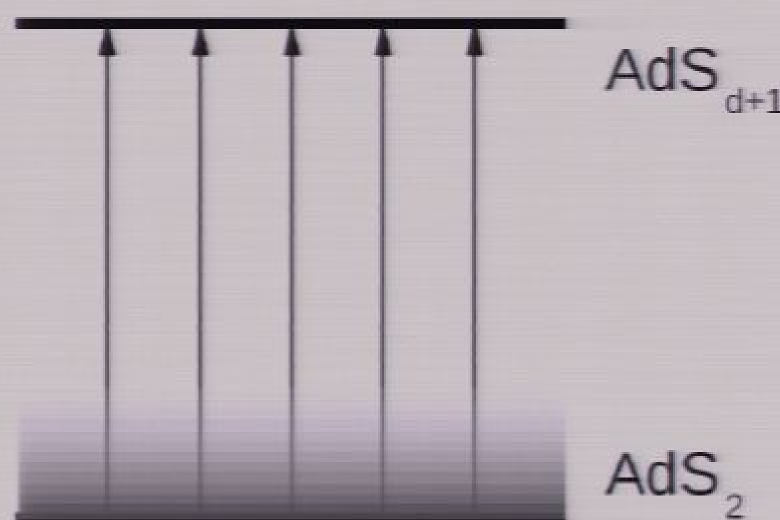

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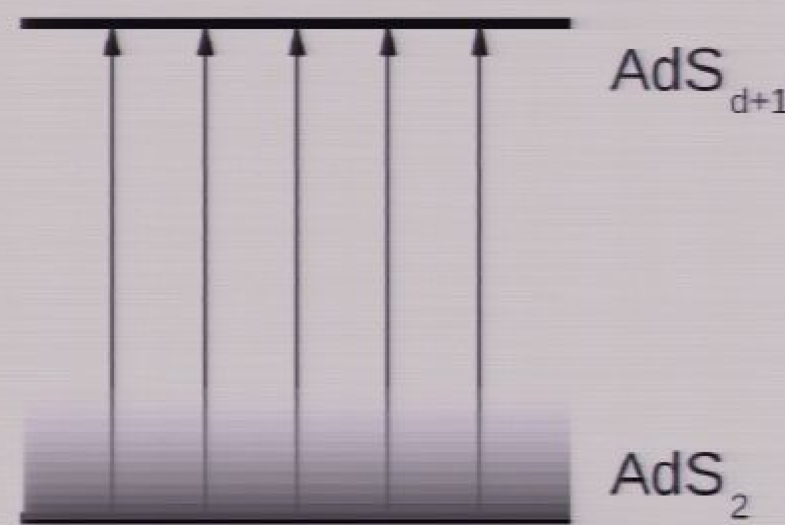

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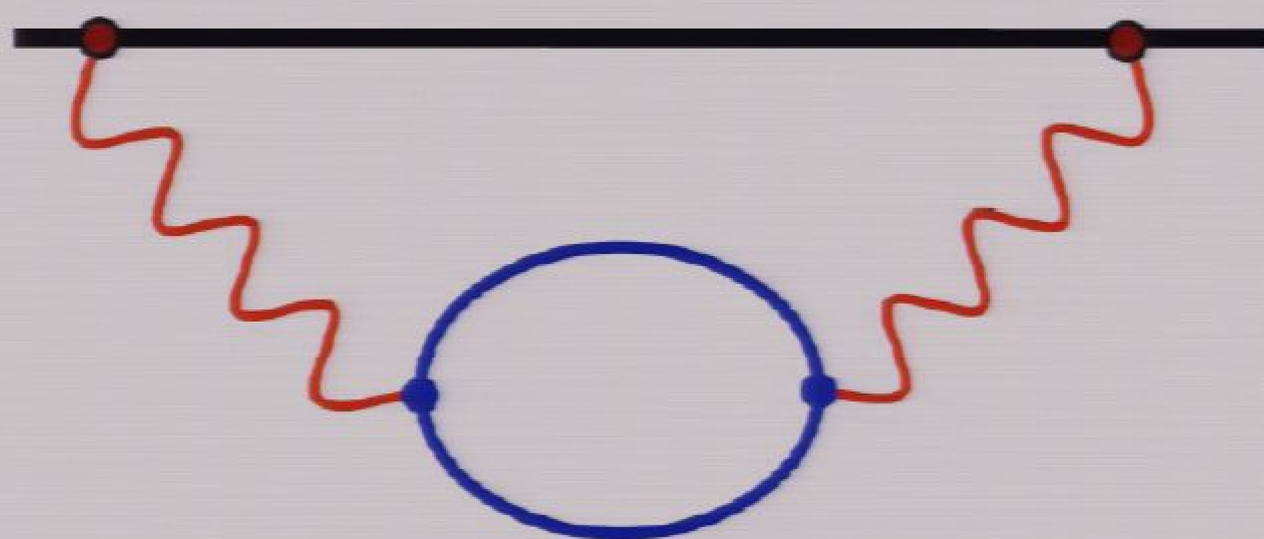
One-loop bulk calculation for AdS-RN [Faulkner, et al],



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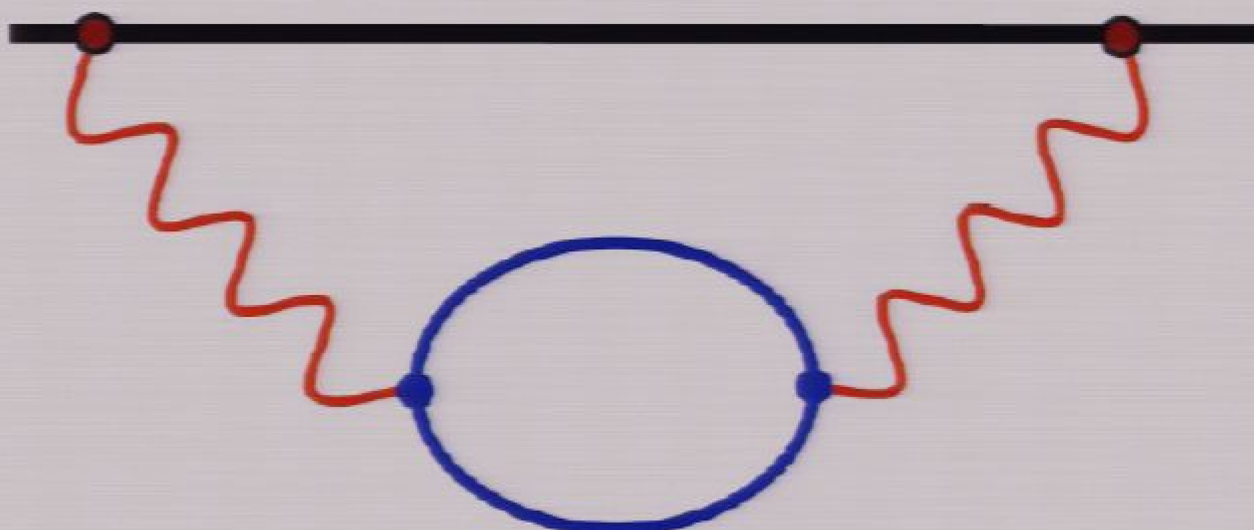

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A few more issues:

- Δ determined by field theory; what Δs are natural?
- AdS-RN has lots of low$-T$ instabilities.

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For example, scalar condensation: $m_{\rm IR}^2 R_2^2 = \frac{m^2 R_{d+1}^2}{d(d-1)} - q^2 e^2$

- $m_{\rm IR}^2 < m_{\rm BF}^2$ in IR $\Rightarrow$ condensation at low T
- Charged condensate: superfluid [Hartnoll, Herzog, Horowitz]
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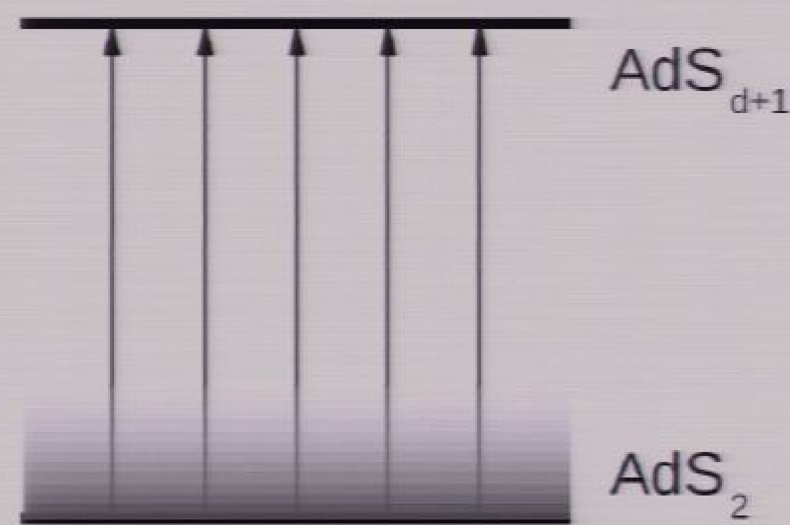

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BUT: in general Einstein-Maxwell setup, we could pick few charged scalars so maybe no superfluid instability.

BUT AGAIN: in most holographic examples we understand (coming from SUGRA compactifications), lots of SUSY, light charged scalars.

Plan for today

In lieu of shortcomings listed above, **goals for today**:

1. **New class** of non-Fermi liquids from holography:
   - Obtain stable locally critical CFT via string theory.
   - Use holography to write down Lagrangian for MFL.
   - Fix allowed choices for Δ by stringy embedding.

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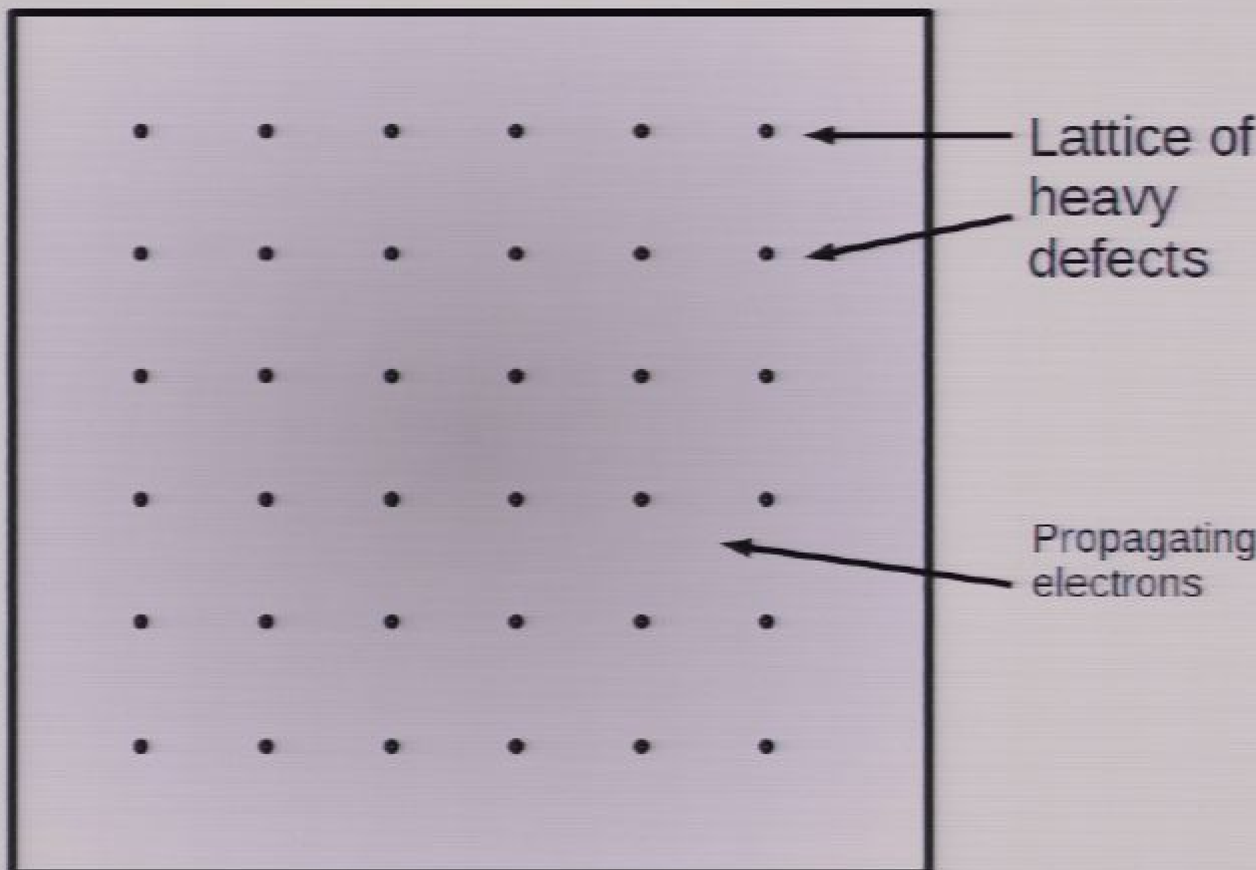
NOTE: (2), (3) already realized with probe brane lattices [Kachru, Karch, Yaida]

Kondo lattice - I

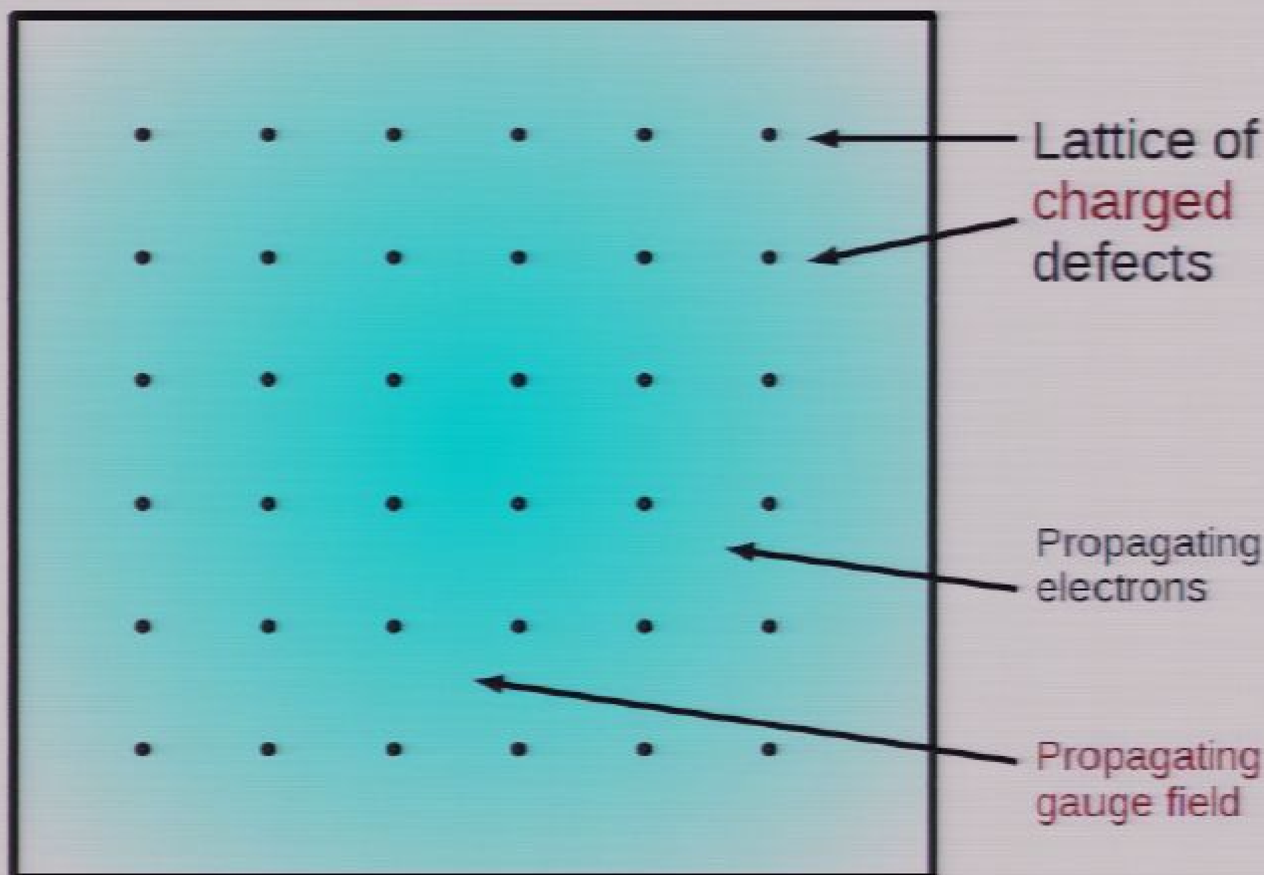


Localized spin d.o.f., $H \sim \sum J_{ij} \vec{S}_i \cdot \vec{S}_j..$

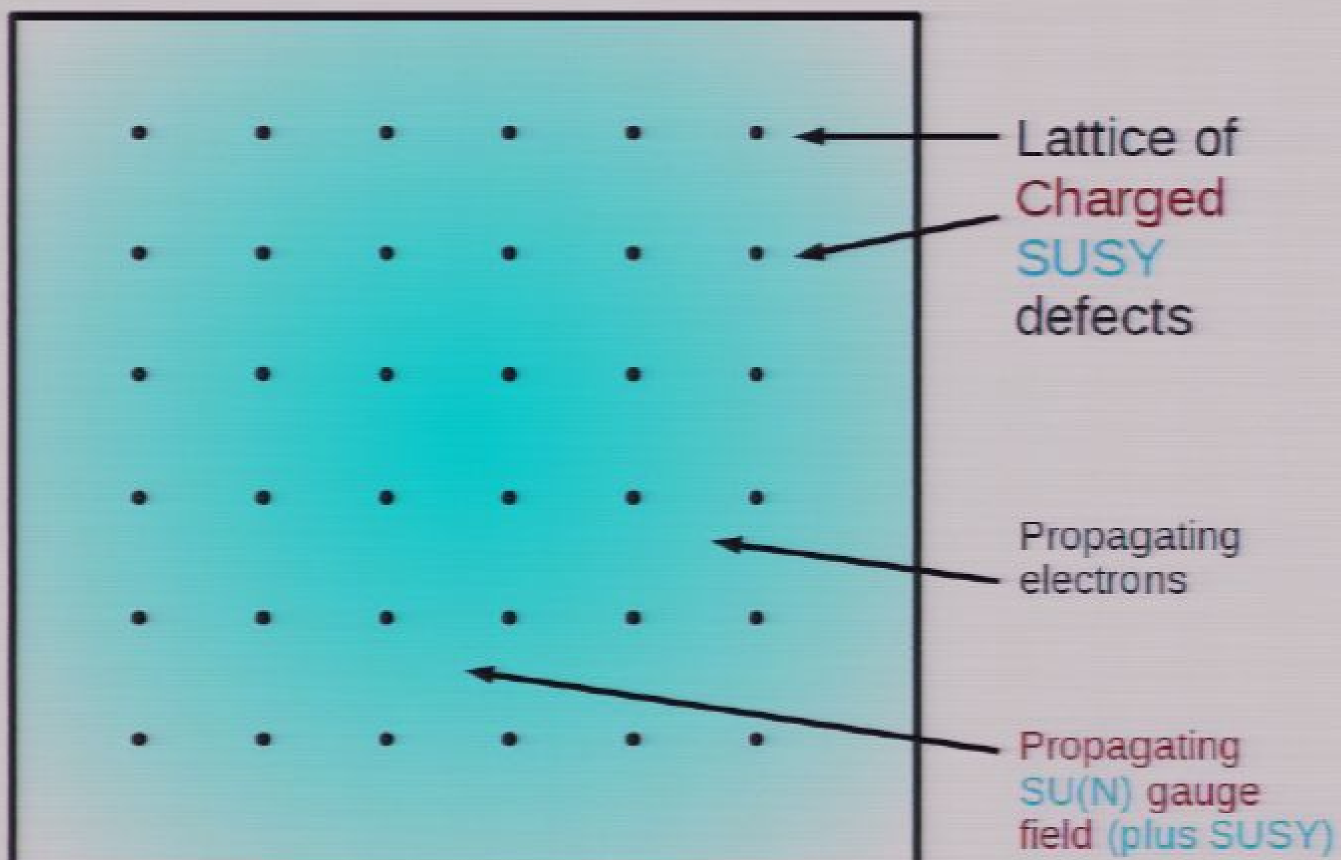
Also interactions with itinerant electrons (hopping, &c).

Tune J to QCP.

Kondo lattice - II



SUSY large N Kondo



Holographic setup:

Consider $N \gg 1$, with localized hypermultiplets.

$O(N^2)$ bath, $O(N)$ lattice.

The D3/D5 system

IIB brane setup [Camino, Parades, Ramallo]

	0	1	2	3	4	5	6	7	8	9
N D3	X	X	X	X						
N_f D5	X	::	::	::	X	X	X	X	X	

where :: indicates a lattice direction.

In usual holographic limits with $N_f \sim O(1)$, get IIB strings on $AdS_5 \times \mathbb{S}^5$ plus D5 branes wrapping $AdS_2 \times \mathbb{S}^4$ cycles.

Field theory: $\mathcal{N} = 4$ SYM plus lattice fermions. Up to 8 SUSYs.

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ASIDE: Naive slipping mode instability stabilized by mixing with AdS_2 gauge field via WZ term, $T_5 \int \mathrm{P}[C_4] \wedge F$.

D3/D5 - spectrum

Brane embedding: wrap $\mathbb{S}^4$ at constant θ, $2\pi\alpha' F = \cos\theta dt \wedge dr$
$\rightarrow$ with $g_{\mathbb{S}^5} = d\theta^2 + \sin^2\theta g_{\mathbb{S}^4}$

System preserves $SO(5)_{\text{int}} \times SO(3)_{\text{AdS}}$

Some AdS_2 fields and dual operator spectrum:

field	$SO(5)_{\text{int}}$	$SO(3)_{\text{AdS}}$	Δ
x^i	**l**	**3**	l
$(A, x^9)_\pm$	**l**	**1**	$l + 2 \pm 2$

Slipping mode/AdS_2 A dual to $\sim \bar{\psi} X^l \psi$.

Fermionic superpartners have $\Delta_l = l + 1/2 + \mathbb{Z}$ by SUSY.

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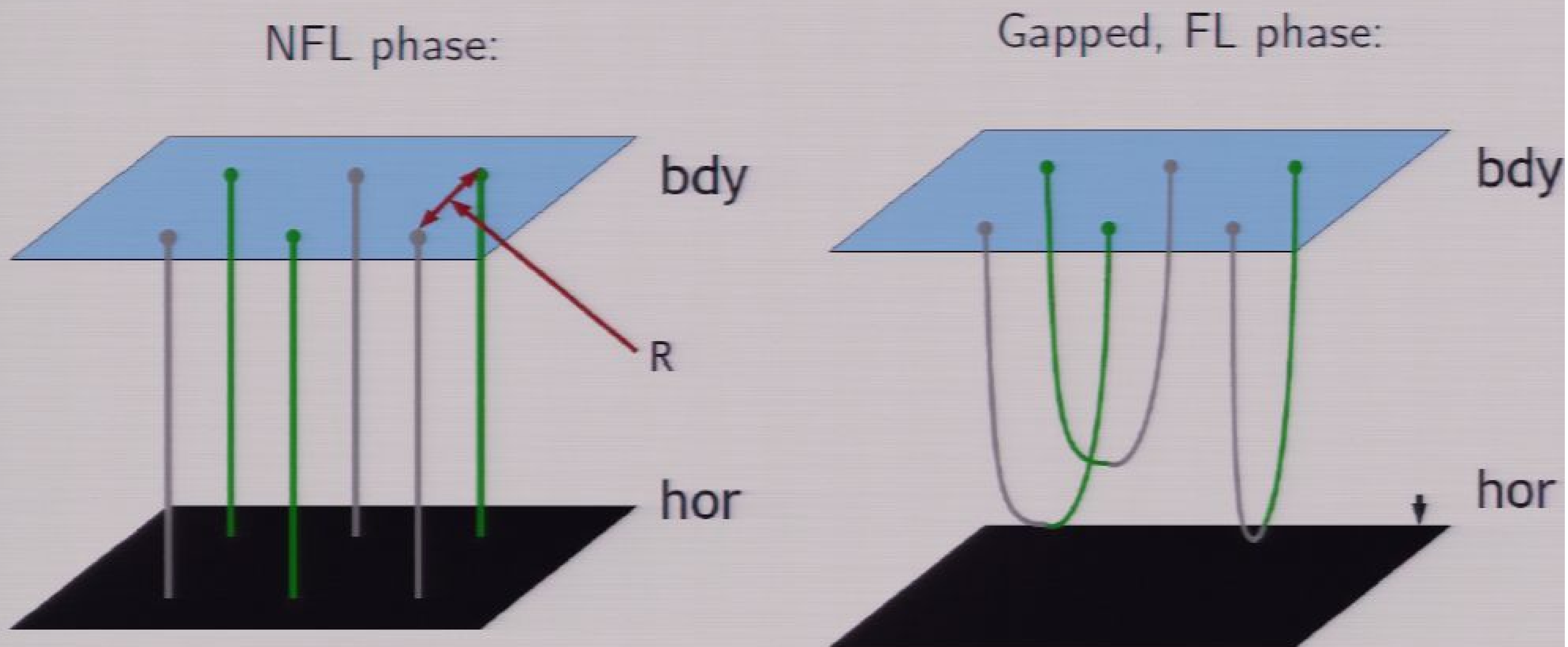
BAD: No $\Delta = 1$ in spectrum.
GOOD: New way of getting AdS_2; stable in probe limit $N_f \ll N$.

D3/D5 - transitions

System also has a FL phase: consider $D5/\bar{D}5$ lattice.



First-order transition; order parameter: $\bar{\psi}\psi$. Holographic **glass**.

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$\rightarrow$ Didn't work because SUSY protects dimensions to be $1/2 + \mathbb{Z}$.

Aside: AdS_2 from probe branes without lattice

Also get AdS_2 from flavour at nonzero density.

$AdS_{d+1} \rightarrow AdS_2$ "holographic RG flow" for open string metric.

Similar two-point functions as for charged fields in AdS-RN.

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BUT: no SUSY, no lattice, unclear how to get pure Fermi liquids.

2+1d lattice → D2/D2 system

Consider another lattice in IIA:

	0	1	2	3	4	5	6	7	8	9
N D2	X	X	X							
N_f D2	X	::	::	X	X					

- 4 ND system ⇒ scalars, fermions at lattice sites
- Up to 8 SUSYs again.
- Field theory: $\mathcal{N} = 8$ SYM ⊕ fundamental hypers.
- 8 SUSYs $+SO(5)$ ⇒ Coulomb branch metric not renormalized beyond 1-loop.

Manifest global symmetry in theory: $SO(5) \times U(1)_{34} \times U(1)_{12}$.

$$\mathcal{L}_{\rm defect} = \sum_j \bar{\psi}_j \left(i\partial_0 + A_0 + \sum_{m=5}^{9} \Gamma^m \Phi_m \right) \psi_j + \ldots$$

RG flow to M2/M2 system

$\mathcal{N} = 8$ SYM not conformal $\rightarrow$ flows to fixed point.
Captured by uplift to M-theory:

	0	1	2	3	4	5	6	7	8	9	10
N M2	X	X	X								
N_f M2	X	::	::	X	X						

- For $N \gg 1$, $N_f \sim O(1)$, get M-theory on $AdS_4 \times \mathbb{S}^7$ plus M2 probes wrapping $AdS_2 \times \mathbb{S}^1$ cycles.
- Global symmetry **enhanced**: $SO(5) \rightarrow SO(6)$

M2/M2 - spectrum

Compute spectrum by analyzing fluctuations of M2 embedding:
$\rightarrow$ No A_μ on M2: only geometric fluctuations.

field	$SO(6)$	$U(1)_{34}$	$U(1)_{12}$	Δ
$w_\pm$	$\mathbf{1}$	l	± 1	$\frac{l}{2} - 1$
y^i	$\mathbf{6}$	l	0	$\frac{l}{2} + \frac{1}{2}$

- To match to field thy: consider $SO(5) \subset SO(6)$
- This gives $\mathbf{6} \rightarrow \mathbf{5} + \mathbf{1}$.

Under $SO(5)$, flavour scalars neutral, flavour ψ's a $\mathbf{4}$.

Claim: the $\mathbf{5}$ is dual to $\bar{\psi}\Phi^l_{34}\psi$ with $\Delta_l = \frac{l}{2} + \frac{1}{2}$.

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Compute spectrum by analyzing fluctuations of M2 embedding:
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field	$SO(6)$	$U(1)_{34}$	$U(1)_{12}$	Δ
$w_\pm$	**1**	l	± 1	$\frac{l}{2} - 1$
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- To match to field thy: consider $SO(5) \subset SO(6)$
- This gives $\mathbf{6} \to \mathbf{5} + \mathbf{1}$.

Under $SO(5)$, flavour scalars neutral, flavour ψ's a **4**.

Claim: the **5** is dual to $\bar{\psi}\Phi^l_{34}\psi$ with $\Delta_l = \frac{l}{2} + \frac{1}{2}$.

NOTE: flavour fields have dimensions $[\psi] = \frac{1}{4}$, $[q] = -\frac{1}{4}$.
→ Interpretation: $\bar{\psi}\Gamma^m\Phi_m\psi$ dominates $\bar{\psi}iD_0\psi$.

2+1d lattice $\to$ D2/D2 system

Consider another lattice in IIA:

	0	1	2	3	4	5	6	7	8	9
N D2	X	X	X							
N_f D2	X	::	::	X	X					

- 4 ND system $\Rightarrow$ scalars, fermions at lattice sites
- Up to 8 SUSYs again.
- Field theory: $\mathcal{N} = 8$ SYM $\oplus$ fundamental hypers.
- 8 SUSYs $+SO(5) \Rightarrow$ Coulomb branch metric not renormalized beyond 1-loop.

Manifest global symmetry in theory: $SO(5) \times U(1)_{34} \times U(1)_{12}$.

$$\mathcal{L}_{\text{defect}} = \sum_j \bar{\psi}_j \left(i\partial_0 + A_0 + \sum_{m=5}^{9} \Gamma^m \Phi_m \right) \psi_j + \ldots$$

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M2/M2 - fermions

What about the fermionic spectrum? Rather than analyzing fermionic part of M2 action [Grisaru, Knutt]

$$S_\psi \sim \int d^3\xi \sqrt{-\mathrm{P}[g]}\bar{\psi}(1 - \Gamma_{M2})\Gamma^i D_i \psi,$$

use SUSY:

- Superpartners of slipping modes: $\Delta_l = \frac{l}{2} + 1$.
- Transform as $\mathbf{4}$ of $SO(5)$.
- Candidate operator: $\bar{\psi}\Phi^l_{34}\partial_t q + \mathrm{h.c.}$

Comparison with goals

Let's compare again!

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(4.) Get **MFL** (i.e. $\Delta = 1$) with stringy embedding: ✓
$\rightarrow$ superpartner of half-integer Δ bosonic operator.

Beyond holography?

So far we found these results in the probe regime $N \gg N_f$, neglecting $O(N_f/N)$ effects.

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Two ways to answer: (work in progress)

1. In field theory, use non-renorm. thms plus IR dual
2. In holography, consider Veneziano limit $N_f/N \sim O(1)$.

Dual description: ABJM

IR fixed point of $\mathcal{N} = 8$ SYM also described by ABJM at $k = 1$.

- Recall: $\mathcal{N} = 6$ $U(N)_k \times U(N)_{-k}$ Chern-Simons matter theory
- SUSY enhanced to $\mathcal{N} = 8$ for $k = 1, 2$.
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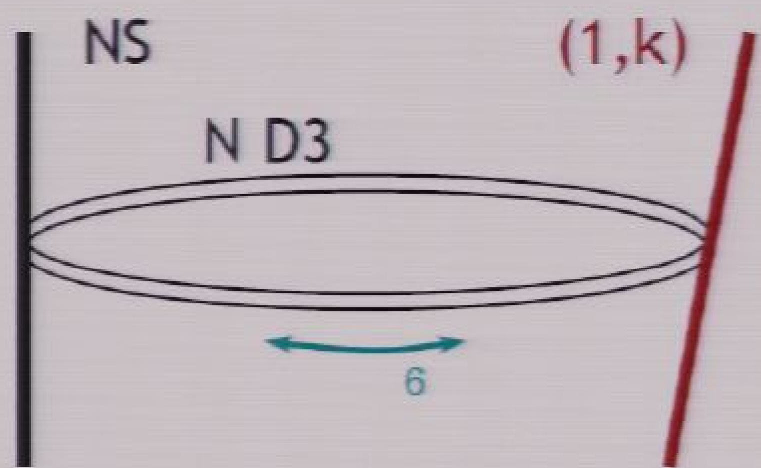
Engineer ABJM with IIB brane setup: [Hanany, Witten], [ABJM]



- N D3s along 0126
- NS along 012345
- $(1, k)$ along $012[3, 7]_\theta[4, 8]_\theta[5, 9]_\theta$
- 6 direction compact

Lifts to N M2s probing $\mathbb{C}^4/\mathbb{Z}_k \to \mathbb{C}^4$ for $k = 1$.

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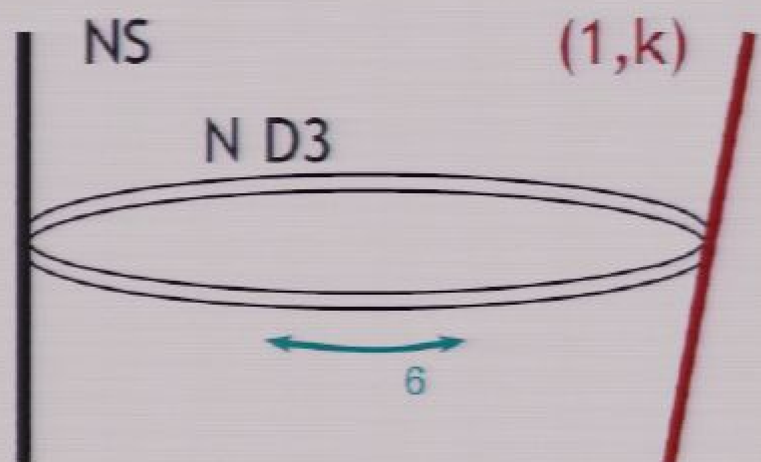

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Manifest global symmetry of ABJM: $SU(4) \times U(1)$.
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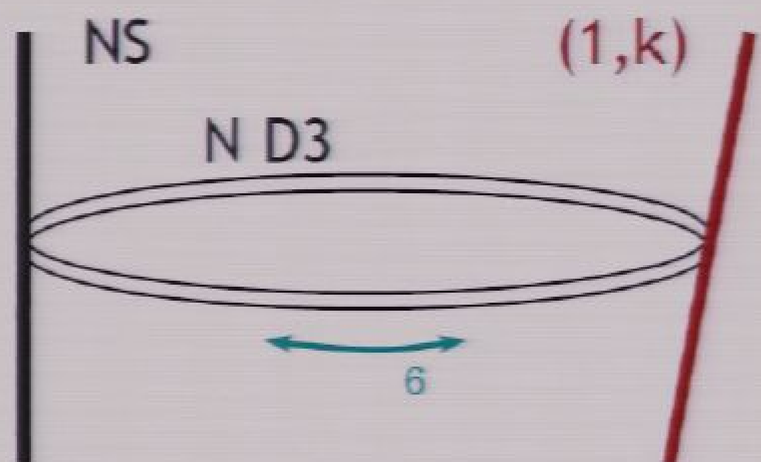

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ADVANTAGES: ABJM description gives extra **"knob"**, k.
Also: CSM useful to describe IR dynamics.

Operator spectrum, fermions

In M-theory and probe limits ($N \gg 1, k^5 \ll N, N_f \sim O(1)$), bosonic spectrum:

$\rightarrow$ slipping modes decompose as $\mathbf{2}_0 \oplus \mathbf{1}_{+1/2} \oplus \mathbf{1}_{-1/2} \oplus 2 \times \mathbf{1}_0$

field	$SU(2)$	$U(1)_\psi$	$U(1)_{34}$	$U(1)_{12}$	Δ
$w_\pm$	$\mathbf{1}$	0	l	± 1	$\frac{l}{2} - 1$
ξ_i	$\mathbf{2}$	0	l	0	$\frac{l}{2} + \frac{1}{2}$
$\psi_\pm$	$\mathbf{1}$	$\pm\frac{1}{2}$	l	0	$\frac{l}{2} + \frac{1}{2}$
θ_i	$\mathbf{1}$	0	l	0	$\frac{l}{2} + \frac{1}{2}$

i.e. spectrum k-independent.

Candidates: $\sim \bar{\psi}_1 A_1 (A_2 B_2)^{l_1} \psi_2 + \ldots, \ \bar{\psi}_1 A_1 B_2 (A_2 B_2)^{l_2} \psi_1 + \ldots$.

$\rightarrow$ Consistent with **free field dimensions**.

Get $\Delta = 1$ fermion for all k, $\bar{\psi}_1 A_1 \partial_t q_2 + \ldots$.

IIA description

Also get holographic description for $k^5 \gg N$, $N/k \gg 1$:

- IIA strings on $AdS_4 \times \mathbb{CP}^3$
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Same spectrum as for M-theory limit!

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Same spectrum as for M-theory limit!

NOTE: Gauge field mixes with slipping mode; these are the θ_i.

Remaining questions

Lots of interesting questions to answer:

1. Do lattice d.o.f. **induce** local criticality for bulk fields?
2. Alternatively, does the IR theory flow to $z = 1$?
3. What does bulk geometry look like for $N_f \sim N$?
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Today, we looked at holographic lattice models which give (among other things)

- New **holographic NFL** phases
- Lagrangian description of MFL
- NFL/FL **transitions**
- Stabilize AdS_2 with SUSY (in probe limit)

Thank you!