Applications of AdS/CFT
to elementary particle and condensed matter physics

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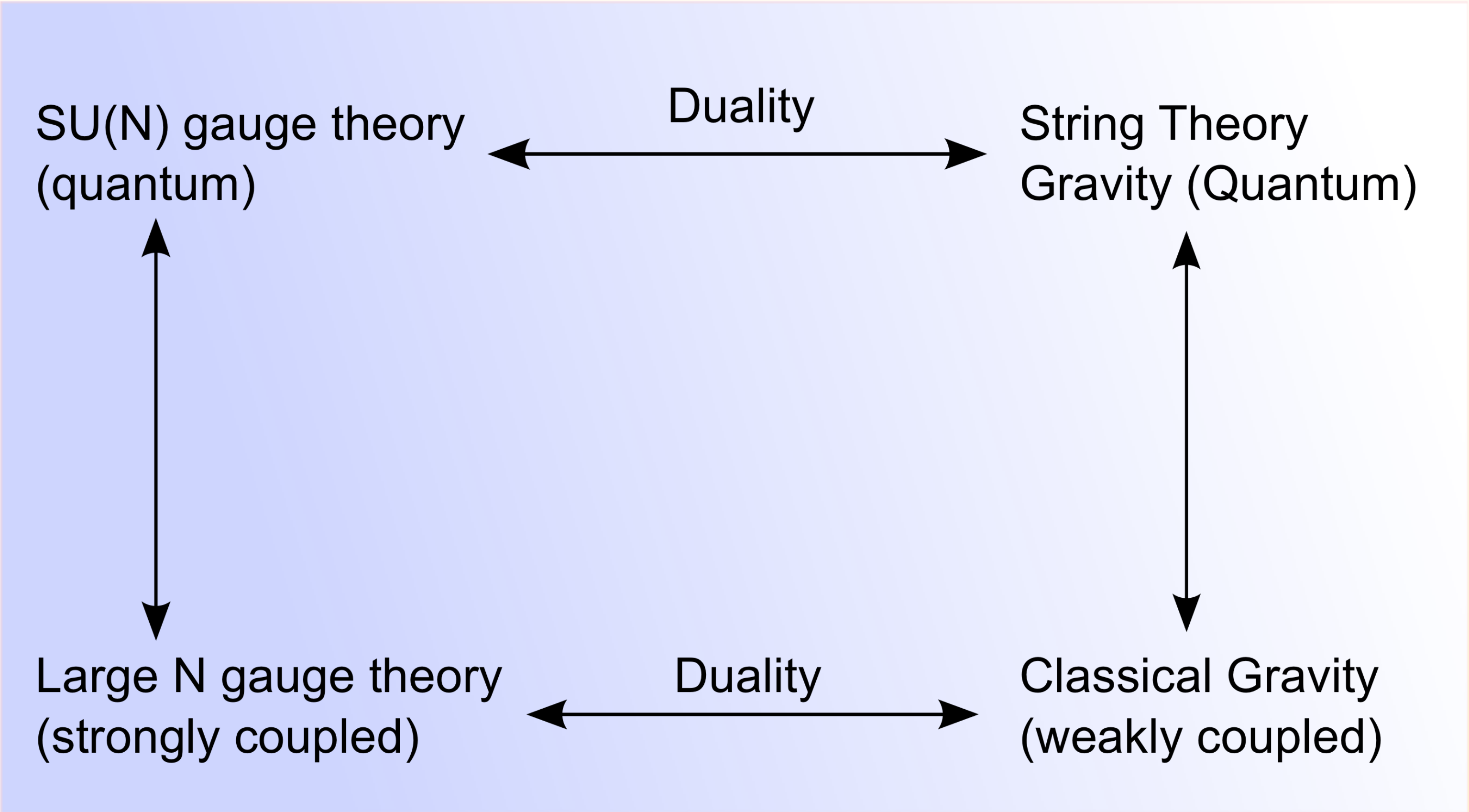
Starting point: AdS/CFT correspondence

Maldacena 1997



$N \to \infty \Leftrightarrow g_s \to 0$

't Hooft coupling λ large $\Leftrightarrow \alpha' \to 0$, energies kept fixed

Introduction

Conjecture extends to more general gravity solutions

$AdS_n \times S^m$ generalizes to more involved geometries

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Dual also to non-conformal, non-supersymmetric field theories

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Gauge/gravity duality

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Dual also to non-conformal, non-supersymmetric field theories

Gauge/gravity duality

- Important approach to studying strongly coupled systems
- New links of string theory to other areas of physics

Gauge/gravity duality

QCD:

- Quark-gluon plasma
- Lattice gauge theory
- External magnetic fields

Condensed matter:

- Quantum phase transitions
- Conductivities and transport processes
- Holographic superconductors
- Kondo model, Weyl semimetals

Universality

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- Renormalization group:

  Large-scale behaviour is independent of microscopic degrees of freedom

Universality

- Renormalization group:

  Large-scale behaviour is independent of microscopic degrees of freedom

- The same physical phenomenon may occur in different branches of physics

Introduction: Top-down and bottom-up approach

Top-down approach:

a) Ten- or eleven-dimensional (super-)gravity

b) Probe branes

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- Few parameters
- Many examples where dual field theory Lagrangian is known

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Bottom-up approach:

Choose simpler, mostly four- or five-dimensional gravity actions

QCD: Karch, Katz, Son, Stephanov; Pomerol, Da Rold; Brodsky, De Teramond; ....

Condensed matter: Hartnoll et al, Herzog et al, Schalm, Zaanen et al, McGreevy, Liu, Faulkner et al; Sachdev et al ....

Outline

1. Kondo effect

2. Condensation to new ground states; external magnetic field

3. Mesons

4. Axial anomaly

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Unifying theme: Universality

2. Kondo models from gauge/gravity duality

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Kondo effect:

Screening of a magnetic impurity by conduction electrons at low temperatures

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Motivation for study within gauge/gravity duality:

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1. Kondo model: Simple model for a RG flow with dynamical scale generation

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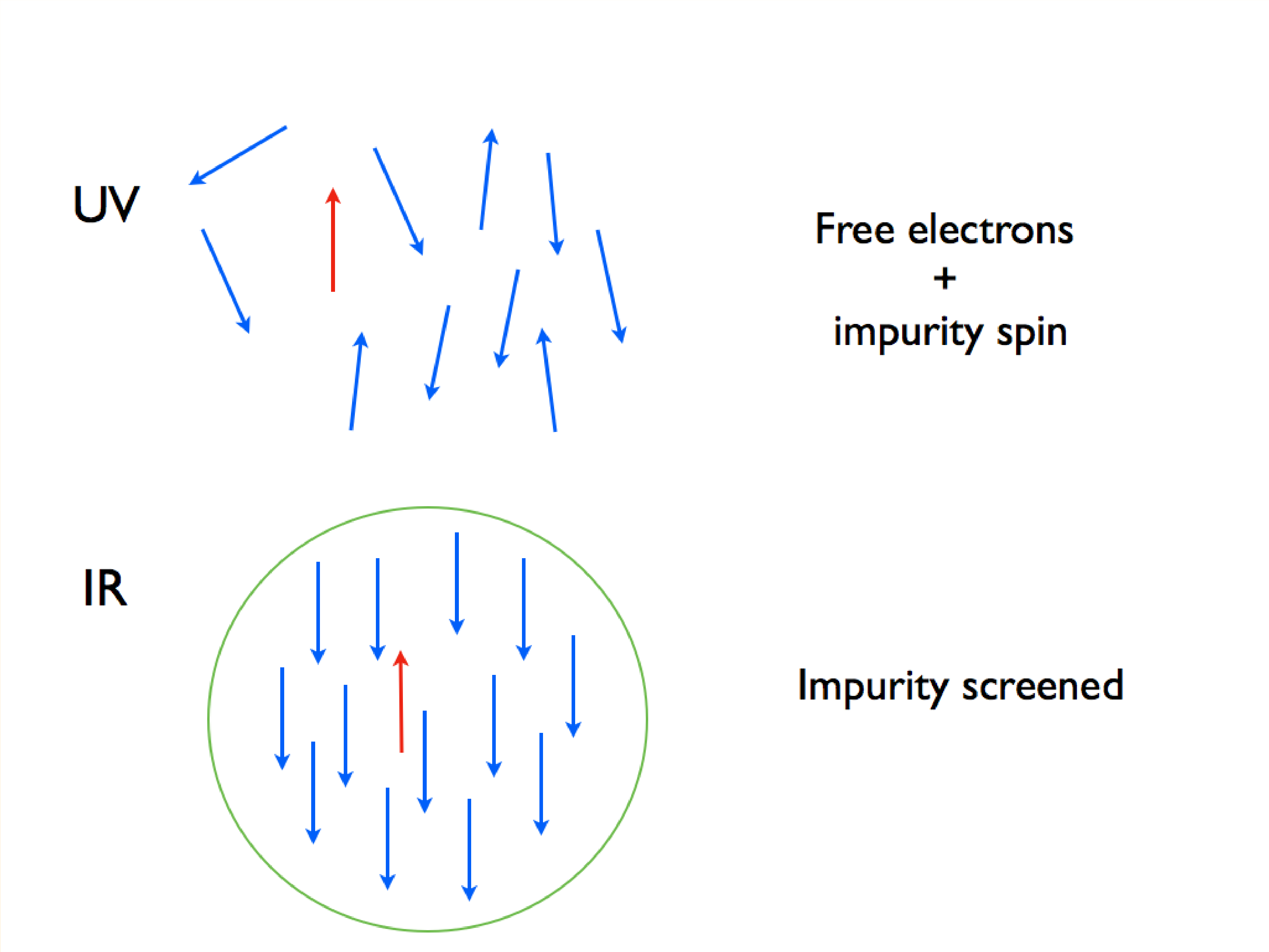
Motivation for study within gauge/gravity duality:

1. Kondo model: Simple model for a RG flow with dynamical scale generation
2. New applications of gauge/gravity duality to condensed matter physics

Kondo effect



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Logarithmic rise of conductivity at low temperatures

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Due to symmetries: Model effectively $(1+1)$-dimensional

Hamiltonian:

$$H = \frac{v_F}{2\pi}\psi^\dagger i\partial_x\psi + \lambda_K v_F \delta(x)\vec{S}\cdot\vec{J}, \quad \vec{J} = \psi^\dagger \frac{1}{2}\vec{T}\psi$$

Decisive in development of renormalization group
IR fixed point, CFT approach Affleck, Ludwig '90's

Kondo models from gauge/gravity duality

Gauge/gravity requires large N: Spin group $SU(N)$

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In this case, interaction term simplifies introducing slave fermions:

$S^a = \chi^\dagger T^a \chi$

Totally antisymmetric representation: Young tableau with Q boxes

Constraint: $\chi^\dagger \chi = q, \quad Q = q/N$

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Screened phase has condensate $\langle \mathcal{O} \rangle$

Parcollet, Georges, Kotliar, Sengupta cond-mat/9711192
Senthil, Sachdev, Vojta cond-mat/0209144

Previous studies of holographic models with impurities:

Supersymmetric defects with localized fermions

Kachru, Karch, Yaida; Harrison, Kachru, Torroba
Jensen, Kachru, Karch, Polchinski, Silverstein

Benincasa, Ramallo; Itsios, Sfetsos, Zoakos; Karaiskos, Sfetsos, Tsatis

Mück; Faraggi, Pando Zayas; Faraggi, Mück, Pando Zayas

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Here: Model describing an RG flow

J.E., Hoyos, O'Bannon, Wu 1310.3271, JHEP 1312 (2013) 086

Kondo models from gauge/gravity duality

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Results:

- RG flow from perturbation by 'double-trace' operator
- Dynamical scale generation
- AdS_2 holographic superconductor
- Power-law scaling of conductivity in IR with real exponent
- Screening, phase shift

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- Generalizations: Quantum quenches, Kondo lattices

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Top-down brane realization

	0	1	2	3	4	5	6	7	8	9
N D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

- 3-7 strings: Chiral fermions ψ in 1+1 dimensions
- 3-5 strings: Slave fermions χ in 0+1 dimensions
- 5-7 strings: Scalar (tachyon)

Near-horizon limit and field-operator map

D3: $AdS_5 \times S^5$

D7: $AdS_3 \times S^5 \to$ Chern-Simons A_μ dual to $J^\mu = \psi^\dagger \sigma^\mu \psi$

D5: $AdS_2 \times S^4 \to \begin{cases} \text{YM } a_t \text{ dual to } \chi^\dagger\chi = q \\ \text{Scalar dual to } \psi^\dagger\chi \end{cases}$

Operator		Gravity field
Electron current J	$\Leftrightarrow$	Chern-Simons gauge field A in AdS_3
Charge $q = \chi^\dagger\chi$	$\Leftrightarrow$	2d gauge field a in AdS_2
Operator $\mathcal{O} = \psi^\dagger\chi$	$\Leftrightarrow$	2d complex scalar Φ

Bottom-up model

Action:

$$S = S_{CS} + S_{AdS_2}$$

$$S_{CS} = -\frac{N}{4\pi}\int \mathrm{Tr}\left(A \wedge dA + \frac{2}{3} A \wedge A \wedge A\right),$$

$$S_{AdS_2} = -N \int d^3x\, \delta(x)\sqrt{-g}\left[\frac{1}{4}\mathrm{Tr} f^{mn} f_{mn} + g^{mn}\left(D_m\Phi\right)^\dagger D_n\Phi + V(\Phi^\dagger\Phi)\right],$$

$$D_\mu\Phi = \partial_m\Phi + iA_\mu\Phi - ia_\mu\Phi$$

Metric: BTZ black hole

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = \frac{1}{z^2}\left(\frac{dz^2}{h(z)} - h(z)\, dt^2 + dx^2\right), \qquad h(z) = 1 - z^2/z_H^2$$

$$T = 1/(2\pi z_H)$$

‘Double-trace’ deformation by $\mathcal{O}\mathcal{O}^\dagger$

Boundary expansion

$$\Phi = z^{1/2}(\alpha \ln z + \beta)$$

$$\alpha = \kappa\beta$$

κ dual to double-trace deformation

Witten hep-th/0112258

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Φ invariant under renormalization $\Rightarrow$ Running coupling

$$\kappa_T = \frac{\kappa_0}{1 + \kappa_0 \ln\left(\frac{\Lambda}{2\pi T}\right)}$$

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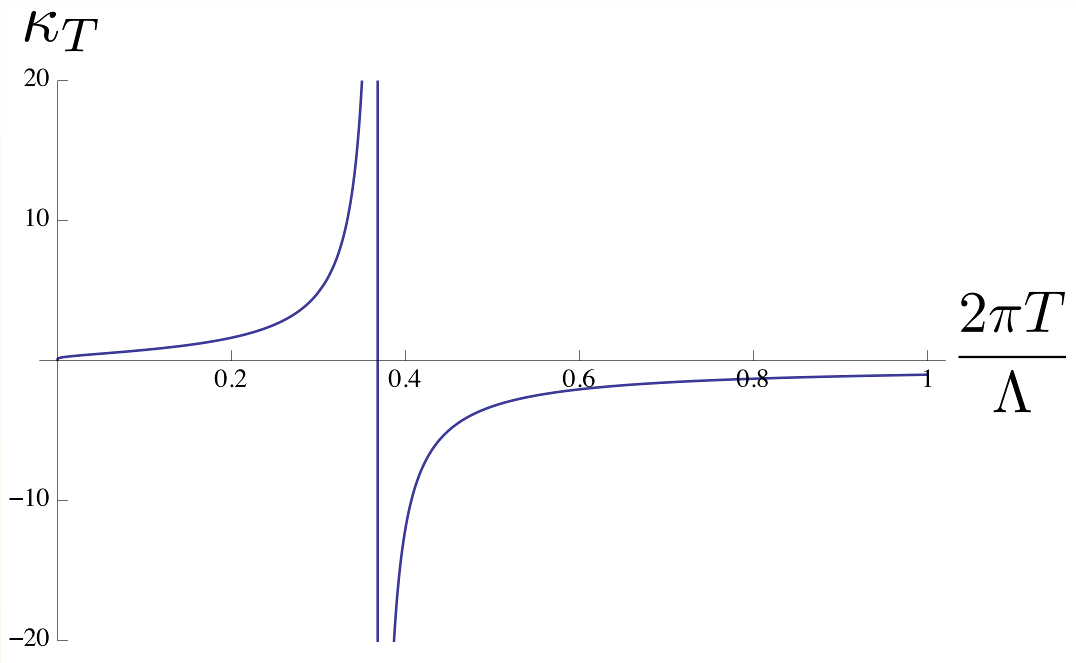
Dynamical scale generation

Kondo models from gauge/gravity duality

Scale generation

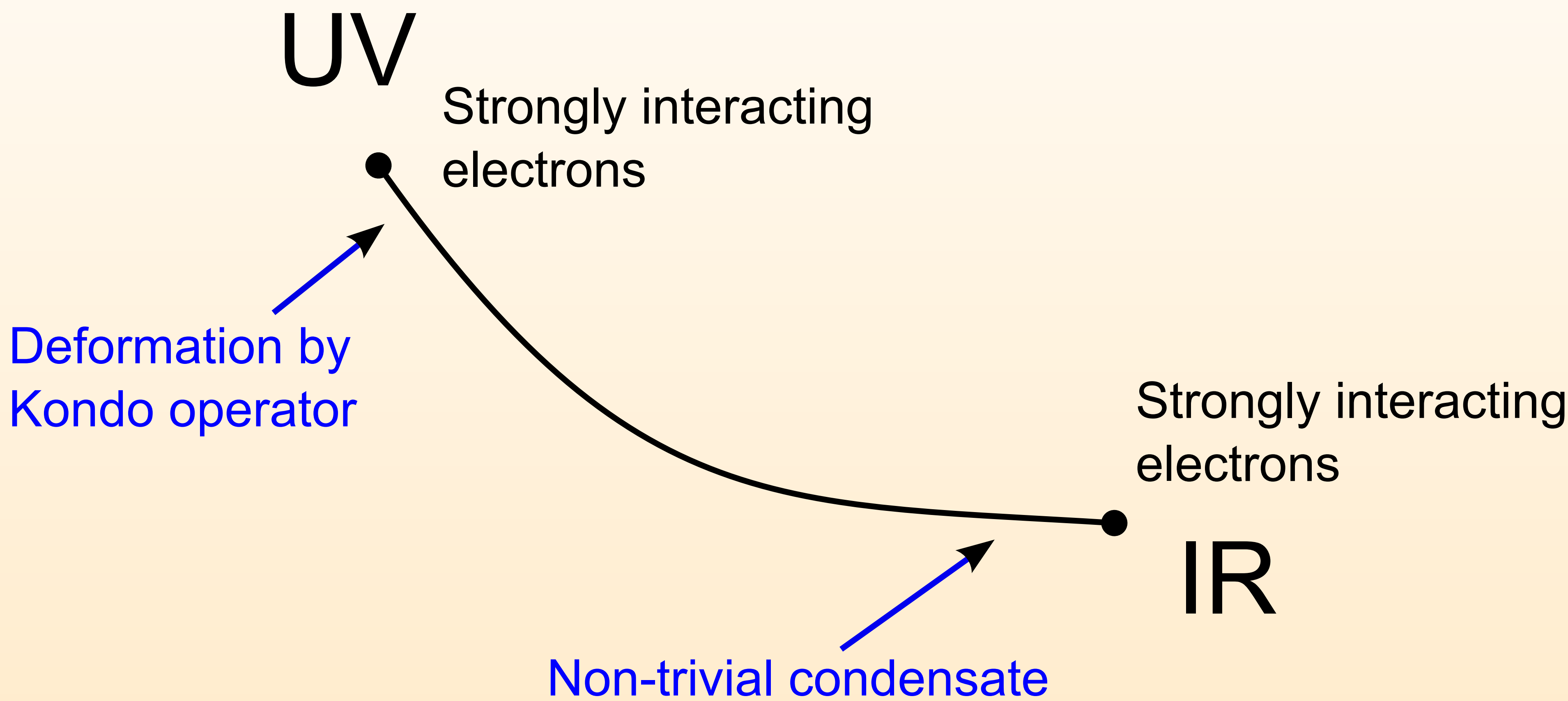


Divergence of Kondo coupling determines Kondo temperature

Below this temperature, scalar condenses

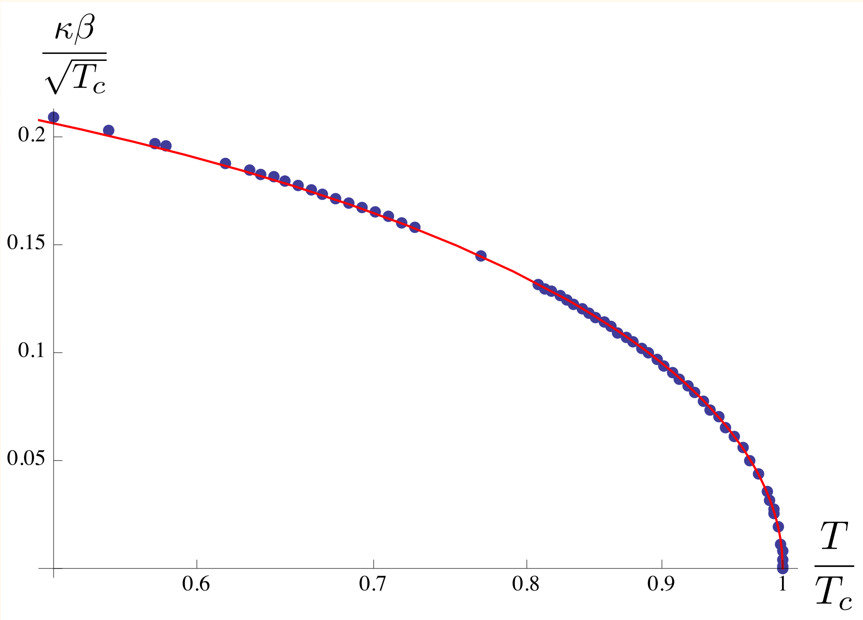
Kondo models from gauge/gravity duality

RG flow

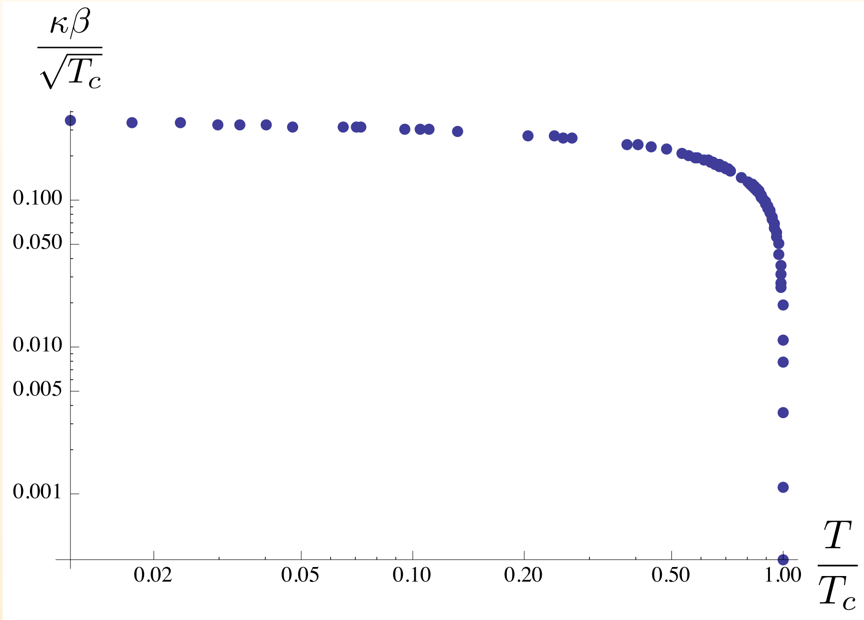


Kondo models from gauge/gravity duality

Normalized condensate $\langle \mathcal{O} \rangle \equiv \kappa\beta$ as function of the temperature



(a)



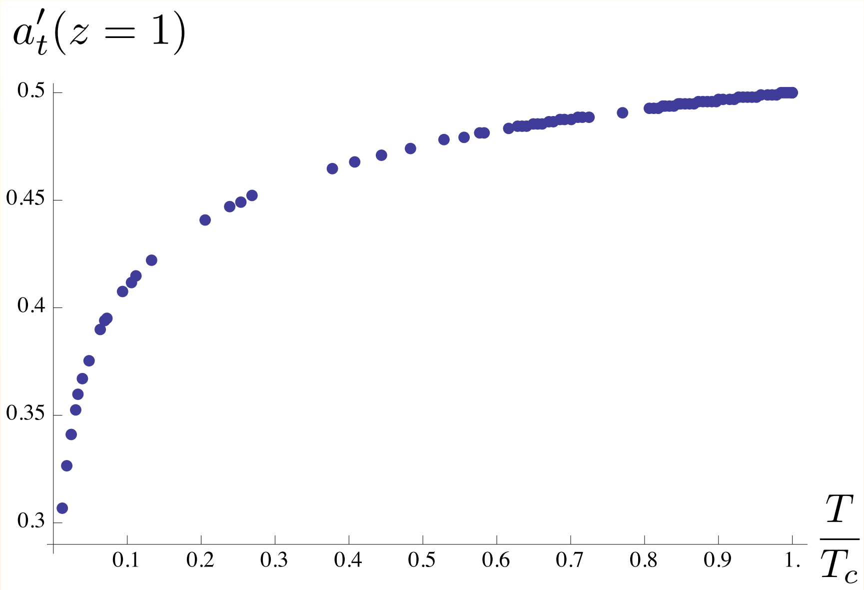
(b)

Mean field transition

$\langle \mathcal{O} \rangle$ approaches constant for $T \to 0$

Kondo models from gauge/gravity duality

Electric flux at horizon



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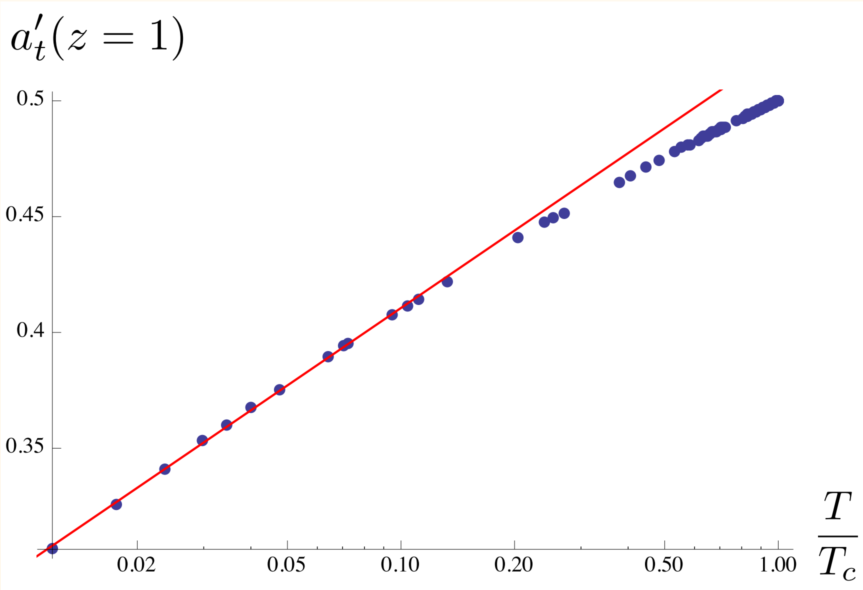


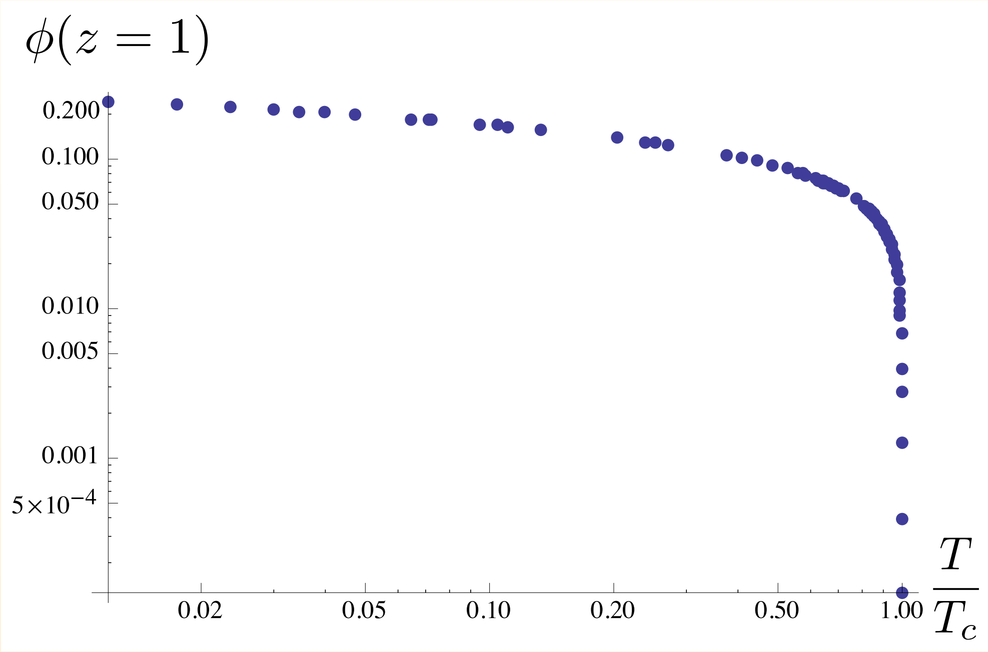
(b)

$$\sqrt{-g}f^{tr}\Big|_{\partial AdS_2} = q = \chi^\dagger \chi$$

Impurity is screened

Kondo models from gauge/gravity duality

Resistivity from leading irrelevant operator (No log behaviour due to strong coupling)



IR fixed point stable:

Flow near fixed point governed by operator dual to 2d YM-field a_t

$$\Delta = \frac{1}{2} + \sqrt{\frac{1}{4} + 2\phi_\infty^2}\,, \qquad \phi(z=1) = \phi_\infty$$

Resistivity from leading irrelevant operator

Entropy density: $s = s_0 + c_s \lambda_{\mathcal{O}}^2 T^{-2+2\Delta}$

Resistivity: $\rho = \rho_0 + c_+ \lambda_{\mathcal{O}}^2 T^{-1+2\Delta}$

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Outlook:

- Transport properties, thermodynamics; entanglement entropy
- Quench
- Kondo lattice

2. Condensation to new ground states

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Starting point: Holographic superconductors

Gubser 0801.2977; Hartnoll, Herzog, Horowitz 0803.3295

Charged scalar condenses (s-wave superconductor)

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P-wave superconductor: Current dual to gauge field condenses

Gubser, Pufu 0805.2960; Roberts, Hartnoll 0805.3898

Triplet pairing

Condensate breaks rotational symmetry

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Probe brane model reveals that field-theory dual operator is similar to ρ-meson:
Ammon, J.E., Kaminski, Kerner 0810.2316

$$\langle \bar{\psi}_u \gamma_\mu \psi_d + \bar{\psi}_d \gamma_\mu \psi_u + \ bosons \, \rangle$$

p-wave holographic superconductor

Einstein-Yang-Mills-Theory with $SU(2)$ gauge group

$$S = \int \mathrm{d}^5x \sqrt{-g} \left[\frac{1}{2\kappa^2} (R - 2\Lambda) - \frac{1}{4\hat{g}^2} F^a_{\mu\nu} F^{a\mu\nu} \right]$$

$$\alpha = \frac{\kappa_5}{\hat{g}}$$

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Gauge field ansatz

$$A = \phi(r)\tau^3 \mathrm{d}t + w(r)\tau^1 \mathrm{d}x$$

$$\phi(r) \sim \mu + \dots \qquad w(r) \sim d/r^2$$

μ isospin chemical potential, explicit breaking $SU(2) \to U(1)_3$

condensate $d \propto \langle J^1_x \rangle$, spontaneous symmetry breaking

Universality: Shear viscosity over entropy density

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Transport properties

Universal result of AdS/CFT: Kovtun, Policastro, Son, Starinets

$$\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$$

Shear viscosity/Entropy density

Proof of universality relies on isotropy of spacetime

Metric fluctuations $\Leftrightarrow$ helicity two states

Anisotropic shear viscosity

Rotational symmetry broken $\Rightarrow$ shear viscosity becomes tensor

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p-wave superconductor:

Fluctuations characterized by transformation properties under unbroken $SO(2)$:

Condensate in x-direction:

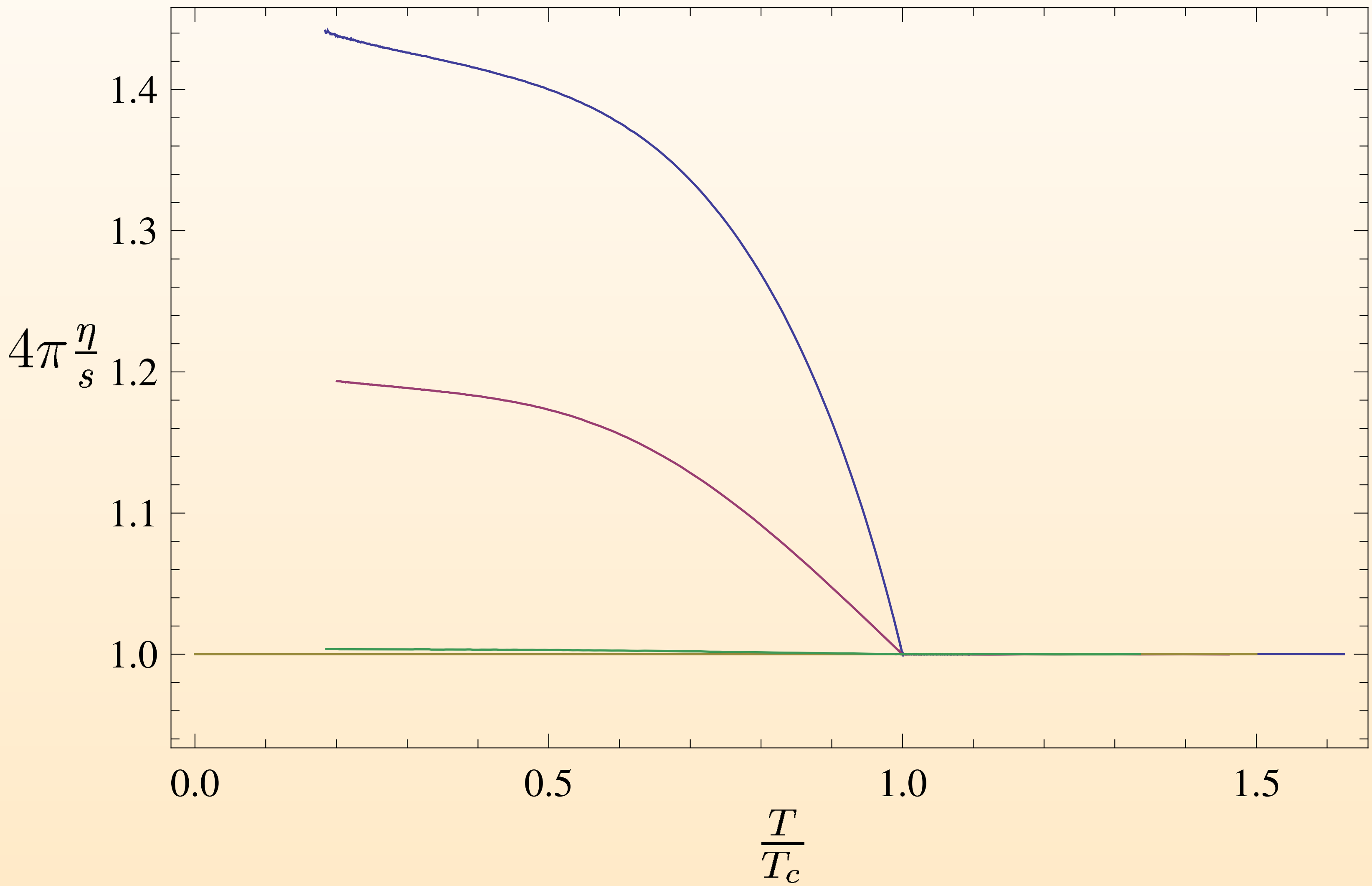
h_{yz} helicity two, h_{xy} helicity one

J.E., Kerner, Zeller 1011.5912; 1110.0007

Backreaction: Ammon, J.E., Graß, Kerner, O'Bannon 0912.3515

Anisotropic shear viscosity

J.E., Kerner, Zeller 1011.5912



Anisotropic shear viscosity

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Non-universal behaviour at leading order in λ and N

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Energy-momentum tensor remains spatially isotropic,
$T^{xx} = T^{yy} = T^{zz}$

Donos, Gauntlett 1306.4937

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Rebhan, Steineder 1110.6825

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Further recent anisotropic holographic superfluids:

Jain, Kundu, Sen, Sinha, Trivedi 1406.4874;   Critelli, Finazzo, Zaniboni, Noronha 1406.6019

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Recall: Necessary isospin chemical potential provided by non-trivial $A_t^3(r)$

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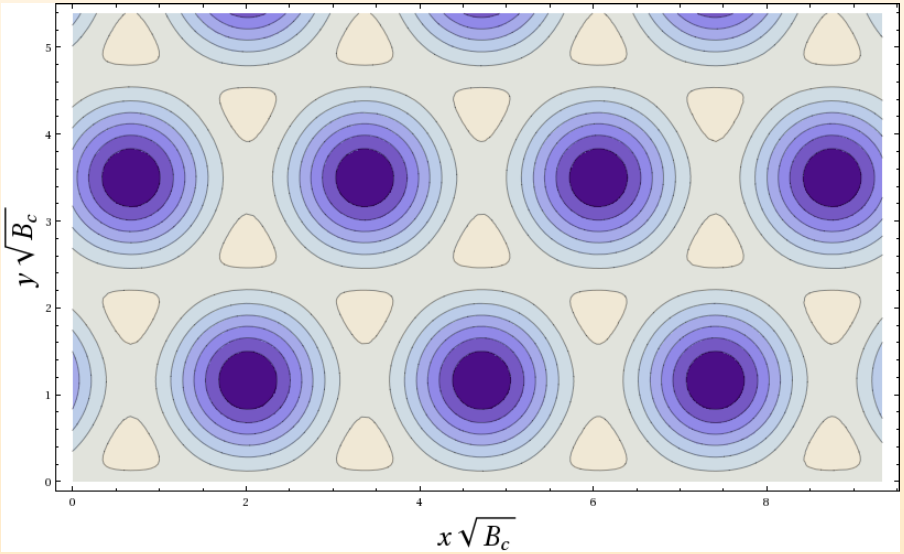
For $B > B_c$, the new ground state is a triangular lattice



Bu, J.E., Strydom, Shock 1210.6669

External electromagnetic fields

A magnetic field leads to

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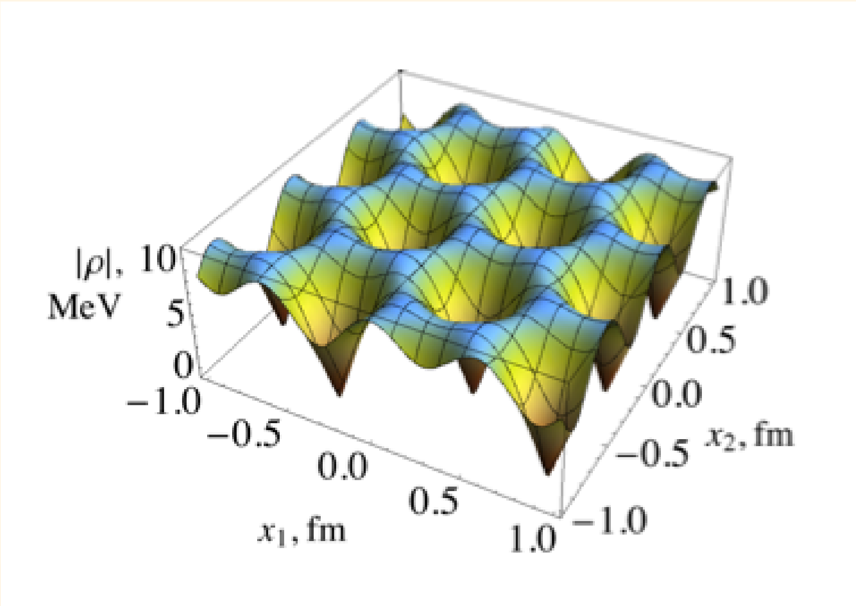
Effective field theory:

Chernodub 1101.0117



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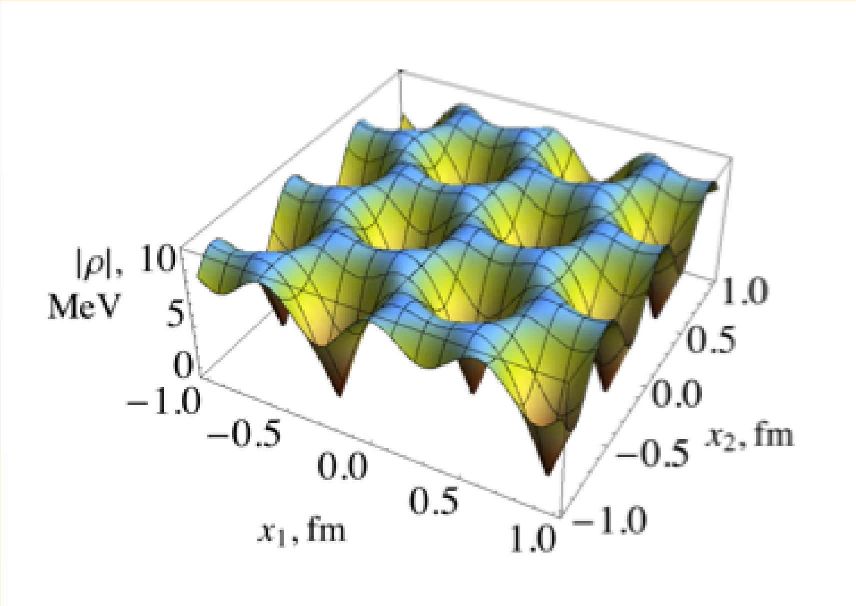
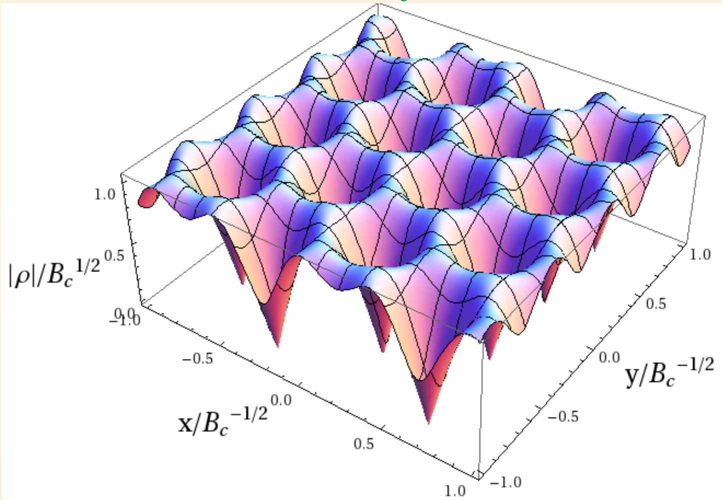


Gauge/gravity duality

magnetic field in black hole supergravity background

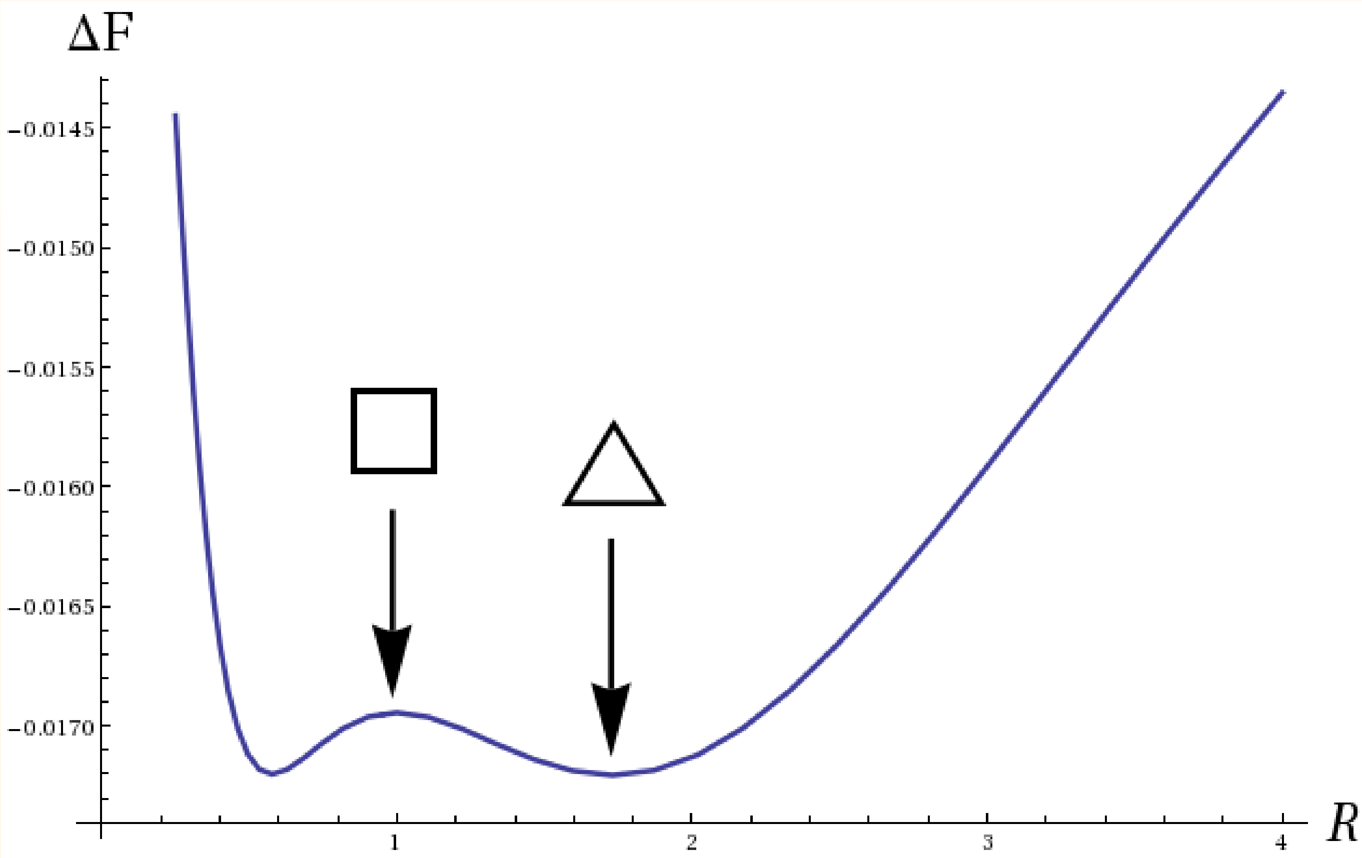
Bu, J.E., Shock, Strydom 1210.6669



Free energy

Free energy as function of $R = \frac{L_x}{L_y}$

Bu, J.E., Shock, Strydom 1210.6669



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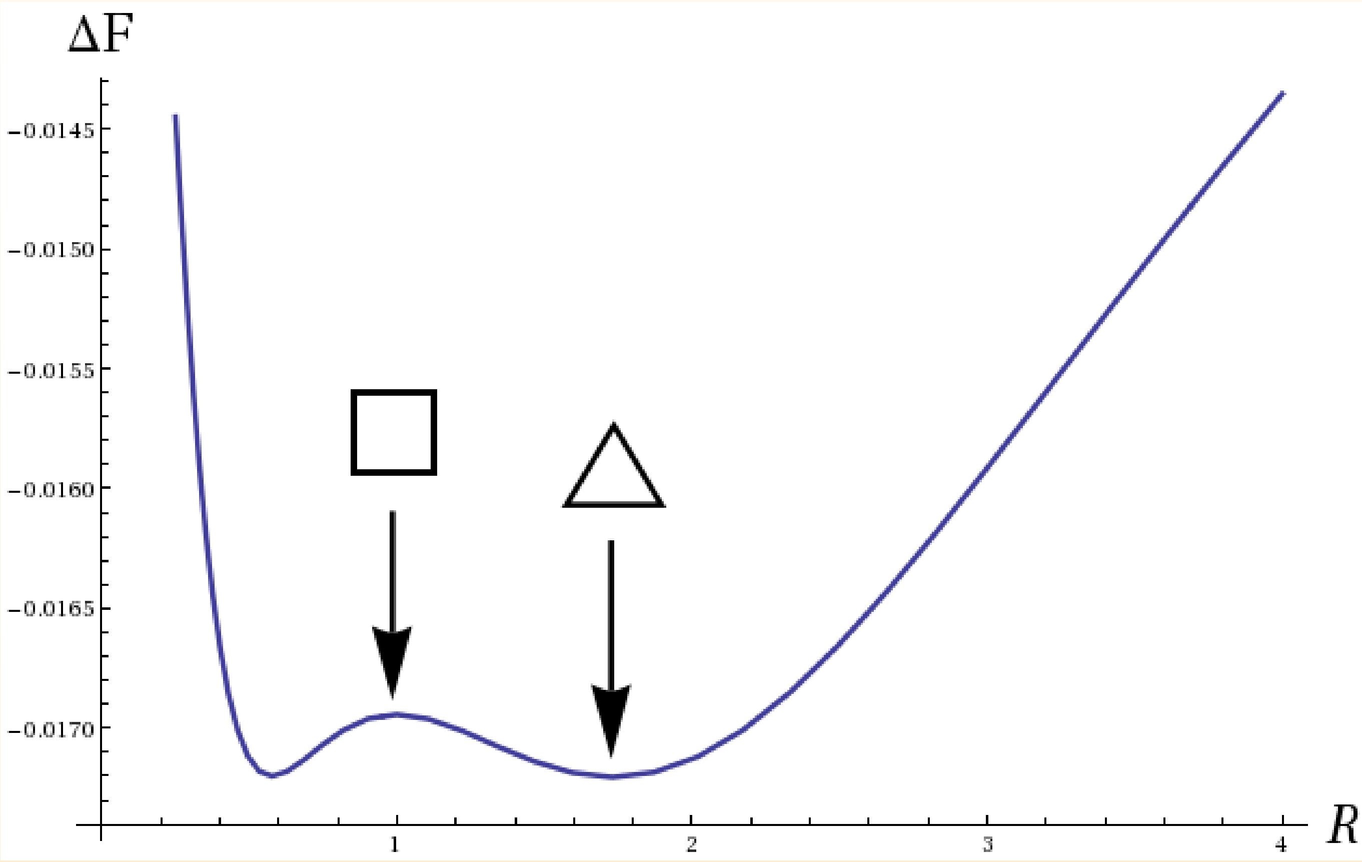

Lattice generated dynamically

Spontaneously generated lattice ground state in magnetic field

- Ambjorn, Nielsen, Olesen ’80s: Gluon or W-boson instability

  Fermions: $\mathbb{Z}_2$ topological insulator Beri,Tong, Wong 1305.2414

- Chernodub ’11-’13: ρ meson condensate in effective field theory, lattice

  Note: $B_{\rm crit} \sim m_\rho^2/e \sim 10^{16}$ Tesla

- Here: Holographic model with $SU(2)$ magnetic field

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Similar condensation in Sakai-Sugimoto model
Callebaut, Dudas, Verschelde 1105.2217

Spontaneously generated inhomogeneous ground states

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With magnetic field:

Bolognesi, Tong; Donos, Gauntlett, Pantelidou; Jokela, Lifschytz, Lippert; Cremonini, Sinkovics; Almuhairi, Polchinski.

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With Chern-Simons term at finite momentum:

Domokos, Harvey;

Helical phases: Nakamura, Ooguri, Park; Donos, Gauntlett

Charge density waves: Donos, Gauntlett; Withers;
Rozali, Smyth, Sorkin, Stang.

3. Quarks in the AdS/CFT correspondence

D7-Brane probes

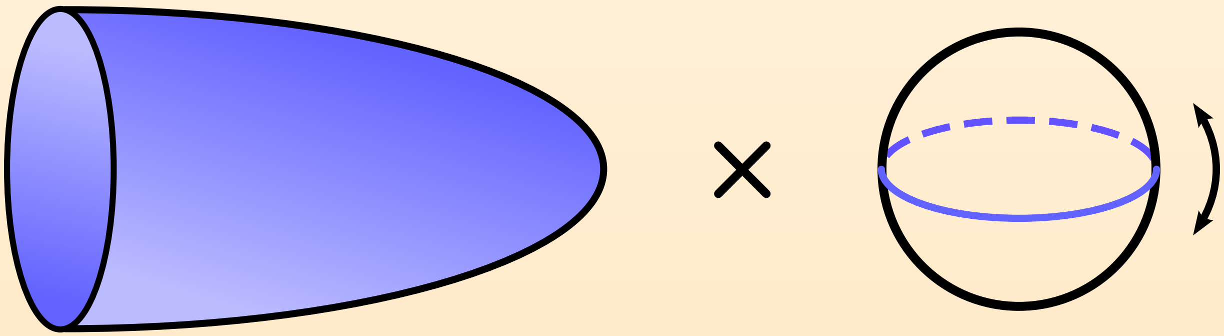
Karch, Katz 2002

	0	1	2	3	4	5	6	7	8	9
N D3	X	X	X	X						
1,2 D7	X	X	X	X	X	X	X	X		

Quarks: Low-energy limit of open strings between D3- and D7-branes

Meson masses from fluctuations of the D7-brane as given by DBI action:

Mateos, Myers, Kruczenski, Winters 2003

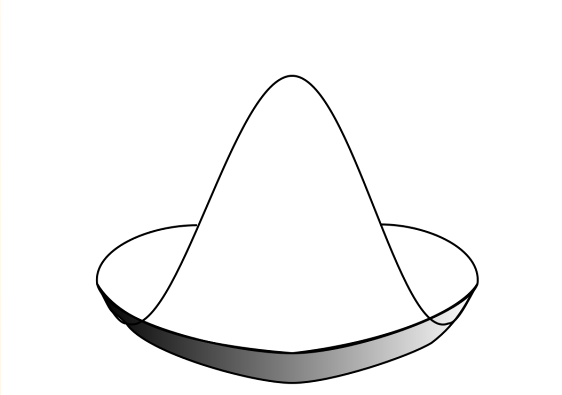


Light mesons

Babington, J.E., Evans, Guralnik, Kirsch hep-th/0306018

Probe brane fluctuating in confining background:

Spontaneous breaking of $U(1)_A$ symmetry



New ground state given by quark condensate $\langle\bar{\psi}\psi\rangle$

Spontaneous symmetry breaking $\rightarrow$ Goldstone bosons

Comparison to lattice gauge theory

Mass of ρ meson as function of π meson mass^2 (for $N \to \infty$)

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Gauge/gravity duality:

π meson mass from fluctuations of D7-brane embedding coordinate

Bare quark mass determined by embedding boundary condition

ρ meson mass from D7-brane gauge field fluctuations

J.E., Evans, Kirsch, Threlfall 0711.4467

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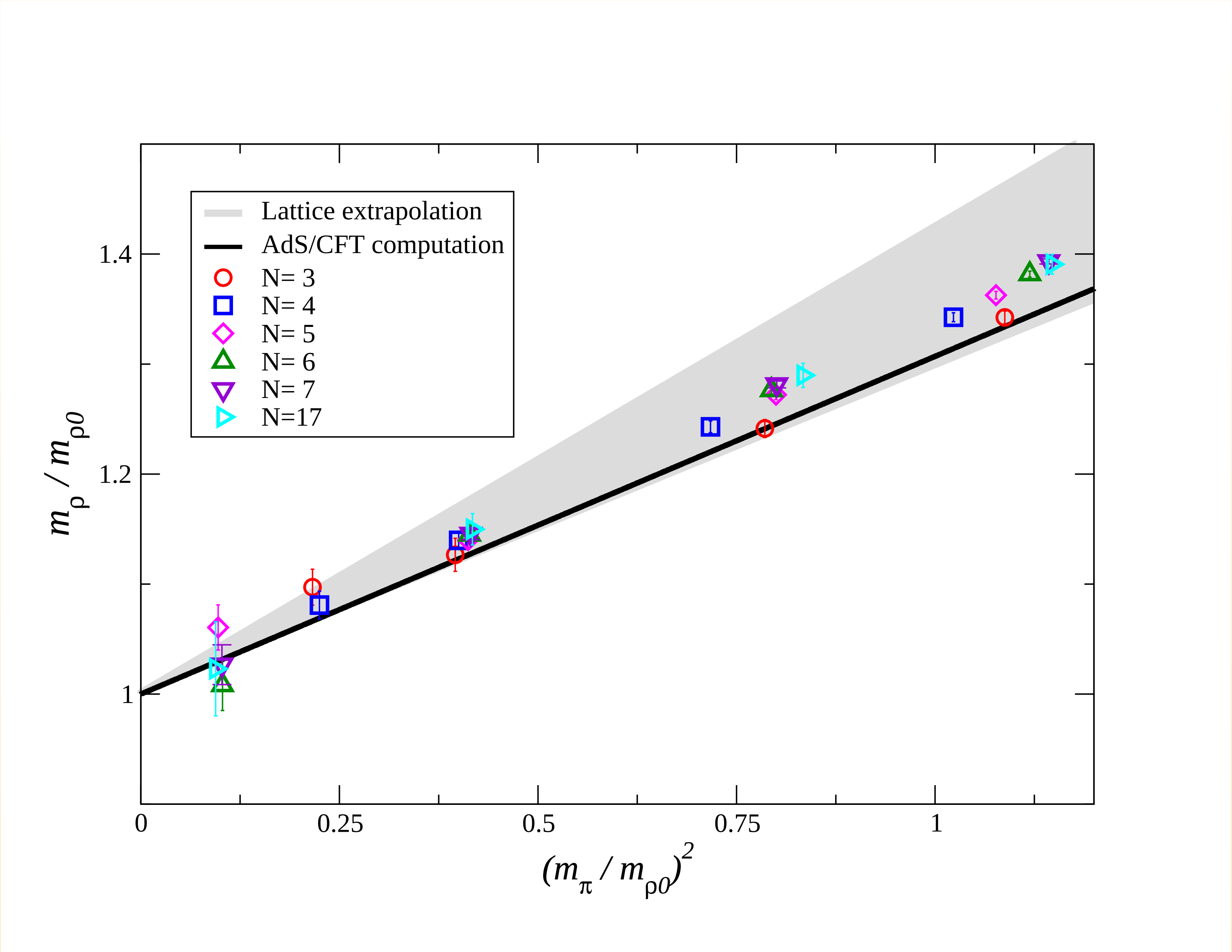
Lattice: Bali, Bursa, Castagnini, Collins, Del Debbio, Lucini, Panero 1304.4437

Comparison to lattice gauge theory

Figure by B. Lucini



Comparison to lattice gauge theory

D7 probe brane DBI action expanded to quadratic order:

$$S = \tau_7 \mathrm{Vol}(S^3)\mathrm{Tr} \int \mathrm{d}^4x \mathrm{d}\rho\, \rho^3 \left[\frac{1}{\rho^2 + |X|^2} |DX|^2 + \frac{\Delta m^2 R^2}{\rho^2} |X|^2 + (2\pi\alpha' F)^2 \right]$$

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Phenomenological model:

Evans, Tuominen 1307.4896

Metric

$$ds^2 = \frac{R^2 d\rho^2}{\rho^2 + |X|^2} + \frac{(\rho^2 + |X|^2)}{R^2} \mathrm{d}x^2$$

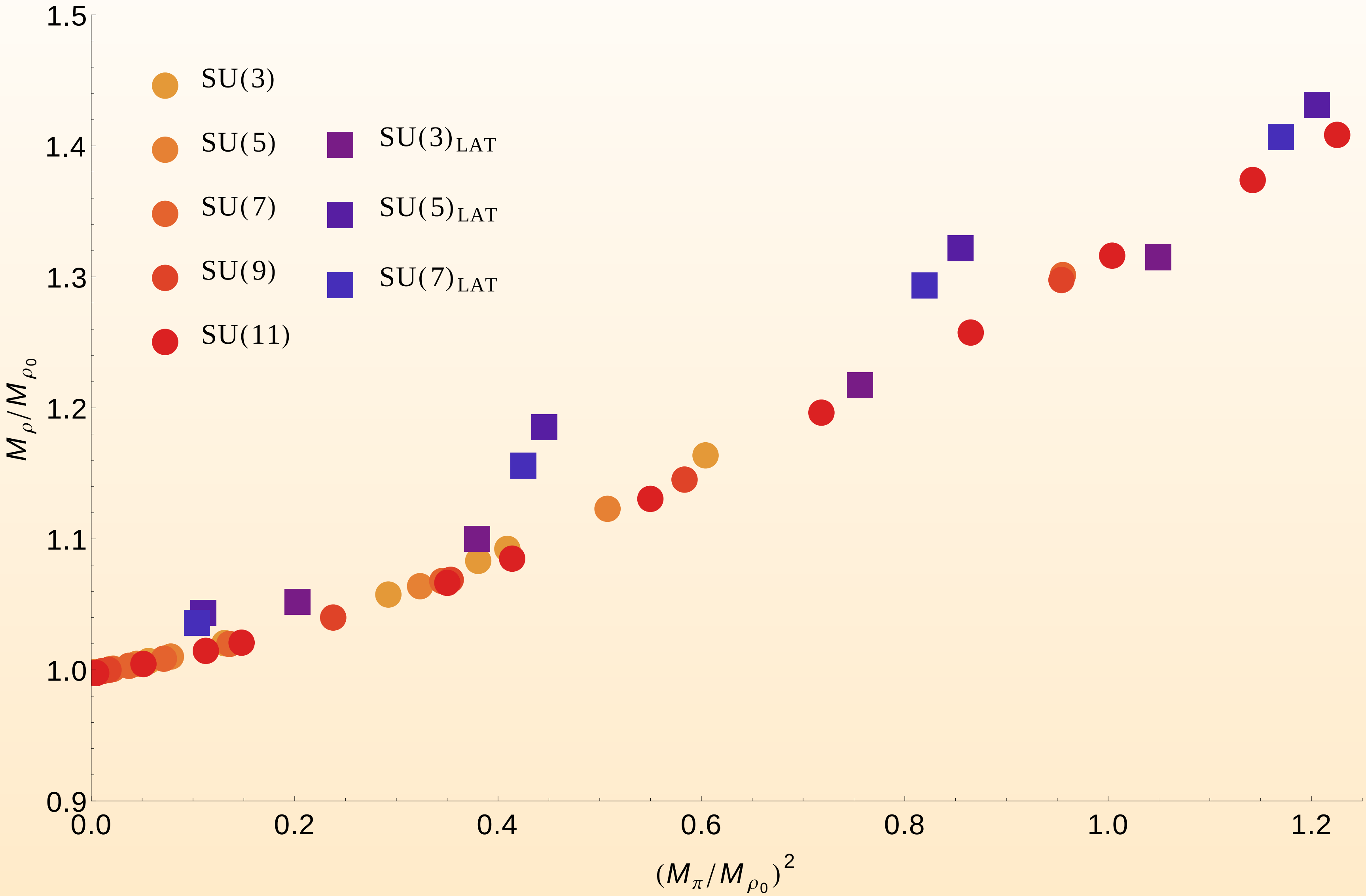
Fluctuations $X = L(\rho) e^{2i\pi^a T^a}$

Make contact with QCD by chosing

$$\Delta m^2 R^2 = -2\gamma = -\frac{3(N^2-1)}{2N\pi} \alpha$$

ρ meson vs. π meson mass^2

Figure by N. Evans, M. Scott



Comparison to lattice gauge theory

Bottom-up AdS/QCD model:

Chiral symmetry breaking from tachyon condensation

Iatrakis, Kiritsis, Paredes 1003.2377, 1010.1364

Comparison to lattice gauge theory

Bottom-up AdS/QCD model:

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Iatrakis, Kiritsis, Paredes 1003.2377, 1010.1364

$SU(N)$ Yang-Mills theory

Panero: Lattice studies of quark-gluon plasma thermodynamics 0907.3719

Pressure, stress tensor trace, energy and entropy density

Comparison with AdS/QCD model of Gürsoy, Kiritsis, Mazzanti, Nitti 0804.0899

4. Axial anomalies

J.E., Haack, Kaminski, Yarom 0809.2488;
Banerjee, Bhattacharya, Bhattacharyya, Dutta, Loganayagam, Surowka 0809.2596

Action of $\mathcal{N} = 2$, $d = 5$ Supergravity:
From compactification of $d = 11$ supergravity on a Calabi-Yau manifold

$$S = -\frac{1}{16\pi G_5} \int \left[\sqrt{-g} \left(R + 12 - \frac{1}{4} F^2 \right) - \frac{1}{2\sqrt{3}} A \wedge F \wedge F \right] d^5x$$

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Chern-Simons term leads to axial anomaly for boundary field theory:

$$\partial^\mu J_\mu = \frac{1}{16\pi^2} \varepsilon_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma}$$

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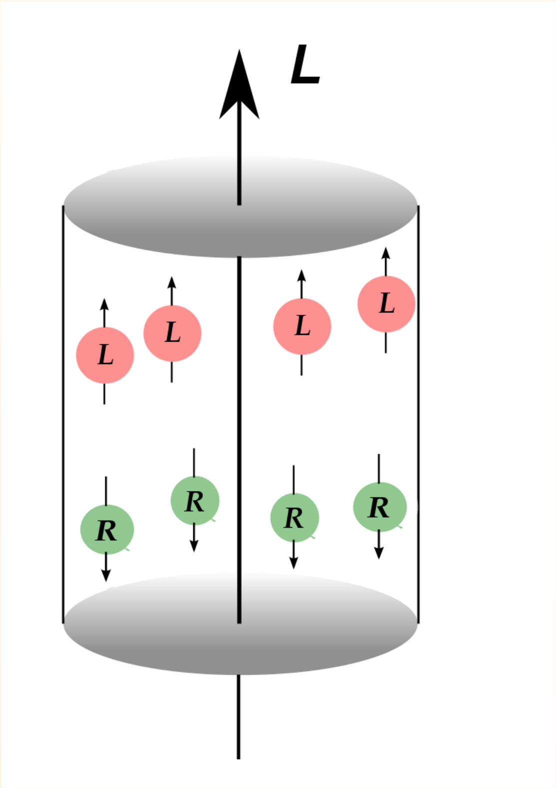
Contribution to relativistic hydrodynamics, proportional to angular momentum:

$J_\mu = \rho u_\mu + \xi \omega_\mu$, $\quad \omega_\mu = \frac{1}{2} \epsilon_{\mu\nu\sigma\rho} u^\nu \partial^\sigma u^\rho$, in fluid rest frame $\vec{J} = \frac{1}{2} \xi \nabla \times \vec{v}$

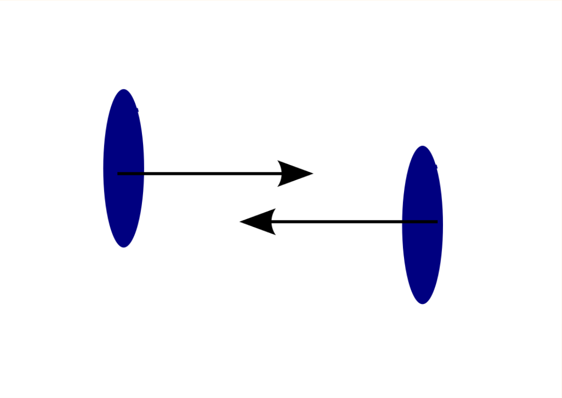
Chiral vortex effect

Chiral separation: In a volume of rotating quark matter, quarks of opposite helicity move in opposite directions. (Son, Surowka 2009)

Chiral vortex effect



Non-central
heavy ion collision



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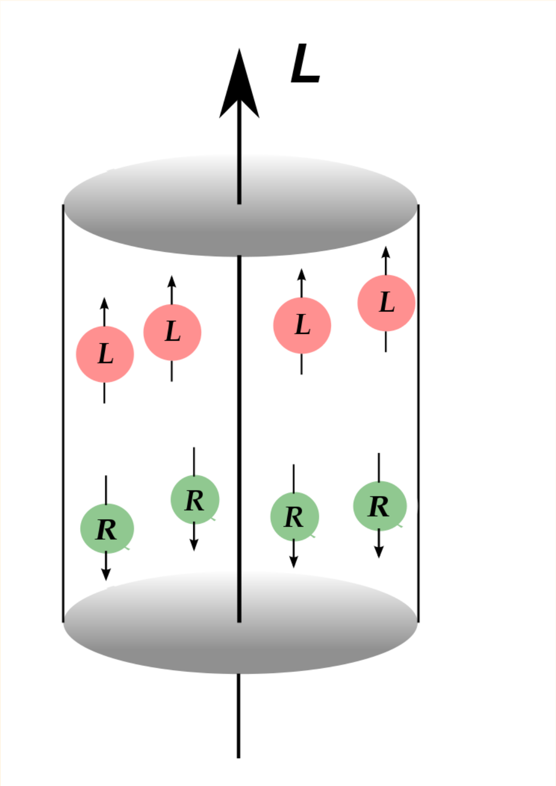

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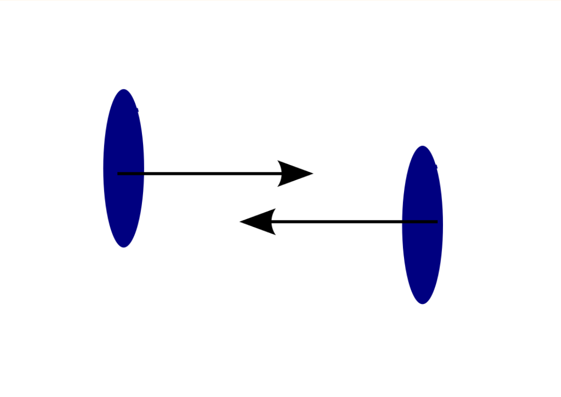

Chiral vortex effect $\Leftrightarrow$ Chiral magnetic effect
Kharzeev, Son 1010.0038;
Kalaydzhyan, Kirsch 1102.4334

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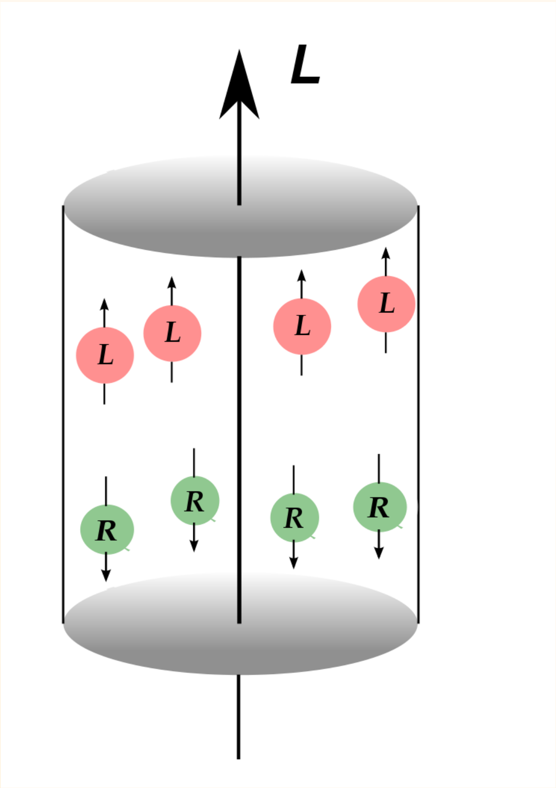

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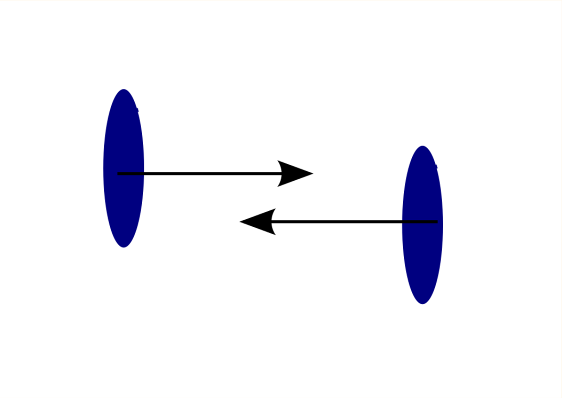

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Anomaly induces topological charge $Q_5 \Rightarrow$ Axial chemical potential $\mu_5 \leftrightarrow \Delta Q_5$
associated to the difference in number of left- and right-handed fermions

Chiral vortex effect for gravitational axial anomaly

Chiral vortex effect for gravitational axial anomaly

Similar analysis for gravitational axial anomaly

$$\partial^\mu J^5_\mu = a(T)\,\varepsilon_{\mu\nu\rho\sigma} R^{\mu\nu}{}_{\alpha\beta} R^{\rho\sigma\alpha\beta}$$

Both holographic and field-theoretical analysis reveal $a(T) \propto T^2$

Landsteiner, Megias, Melgar, Pena-Beñitez 1107.0368
Landsteiner, Megias, Pena-Beñitez 1103.5006 (QFT)
Chapman, Neiman, Oz 1202.2469
Jensen, Loganayagam, Yarom 1207.5824

Chiral vortex effect for gravitational axial anomaly

Linear response

$$\vec{J}^5 = \sigma \vec{\omega}$$

$$\sigma = \lim_{p_j \to 0} \sum_{i,k} \frac{i}{p_j} \epsilon_{ijk} \langle \, J_5^i(\vec{p}) \, T^{k0}(0) \, \rangle \; \sim \frac{T^2}{24}$$

Chiral vortex effect for gravitational axial anomaly

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Conversely,

$$J_E^i = T^{0i} = \sigma B_5^i$$

B_5 axial magnetic field

couples with opposite signs to left-and right-handed fermions

Axial magnetic effect Braguta, Chernodub, Landsteiner, Polikarpov, Ulybyshev 1303.6266

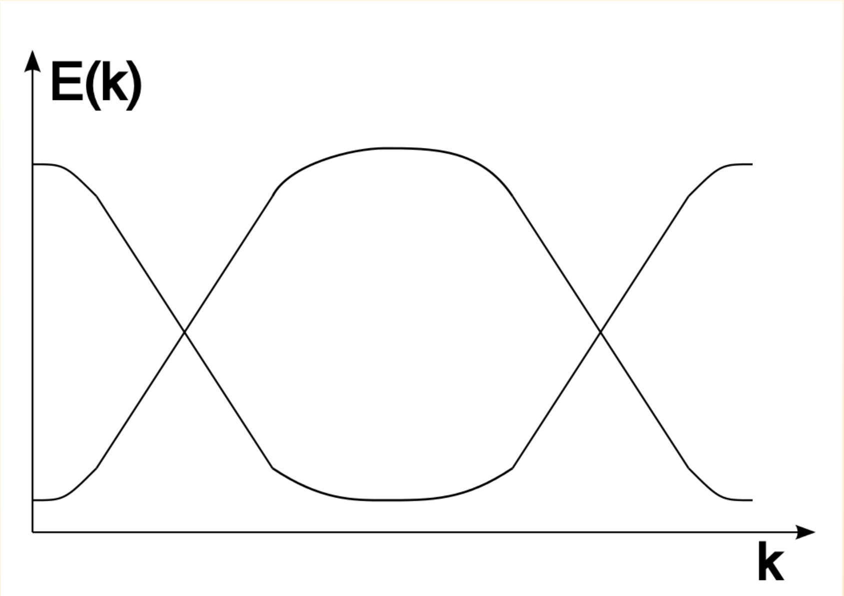
Proposal for experimental observation in Weyl semimetals

Chernodub, Cortijo, Grushin, Landsteiner, Vozmediano 1311.0878

Semimetal: Valence and conduction bands meet at isolated points

Dirac points: Linear dispersion relation $\omega = v|\vec{k}|$, as for relativistic Dirac fermion

Weyl fermion: Two-component spinor with definite chirality (left- or right-handed)



Band structure of Weyl semimetal

Proposal for experimental observation in Weyl semimetals

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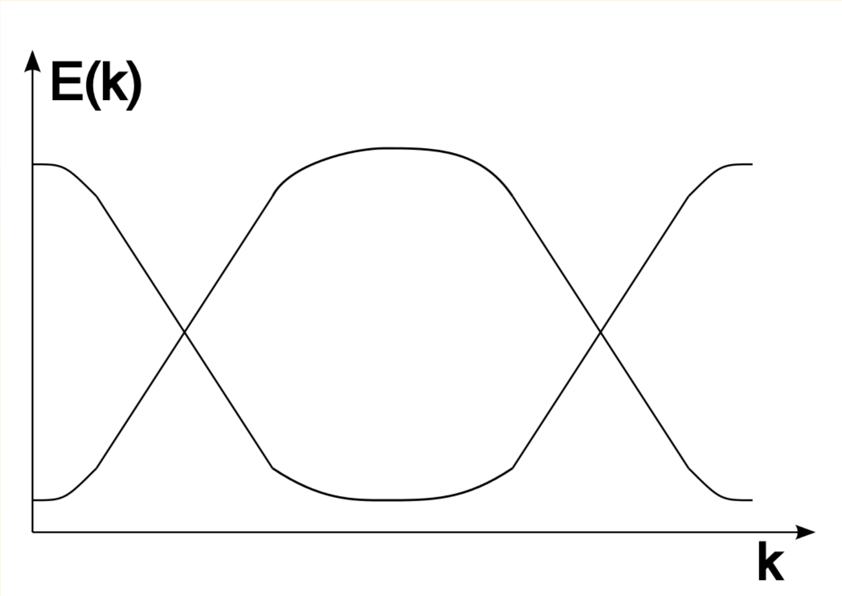


Band structure of Weyl semimetal

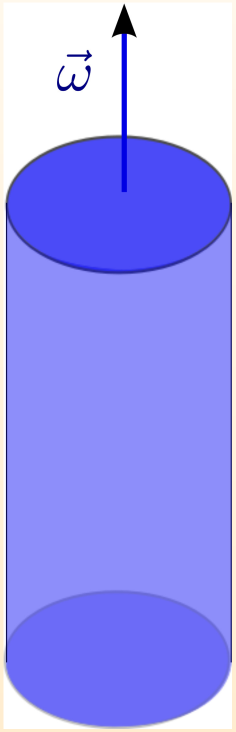
Experimental observation of Dirac semimetals:
'3D graphene'

Cd_3AS_2:	1309.7892 (Science), 1309.7978
Na_3Bi:	1310.0391 (Science)

Proposal for experimental observation in Weyl semimetals

Chernodub, Cortijo, Grushin, Landsteiner, Vozmediano 1311.0878

- Weyl points separated by wave vector
- Wave vector corresponds to axial vector potential
- This induces an axial magnetic field at edges of a Weyl semimetal slab
- Via Kubo relation this generates angular momentum $L_k = \int_V \epsilon_{ijk}\, x^i T^{0j}$
- By angular momentum conservation, this leads to a rotation of the slab
- This depends on T^2



Summary

1. Holographic Kondo model: RG flow
2. New inhomogeneous ground states
3. Mesons: Comparison to lattice gauge theory
4. Axial anomalies: Quark-gluon plasma $\Leftrightarrow$ Condensed matter physics

At this conference:

- Quantum phases of matter
- Time dependence
  (Turbulence, non-equilibrium, quantum quenches)
- Holographic entanglement entropy
- Lattices and transport

Conclusion and Outlook

- Gauge/gravity duality:
  Established approach for describing strongly coupled systems

Conclusion and Outlook

- Gauge/gravity duality:
  Established approach for describing strongly coupled systems
- Unexpected relations between different branches of physics $\Leftrightarrow$ Universality
- Comparison of results with lattice gauge theory, effective field theory, condensed matter physics
- Gauge/gravity duality has added a new dimension to string theory

Conclusion and Outlook

- Gauge/gravity duality:
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- Unexpected relations between different branches of physics $\Leftrightarrow$ Universality

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- Gauge/gravity duality has added a new dimension to string theory

In the future:

- Mutual influence: Fundamental $\Leftrightarrow$ applied aspects of gauge/gravity duality

- First step: $1/N$, $1/\sqrt{\lambda}$ corrections