# Strong coupling physics from general relativity

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# HEP faculty members

- Dave Tong
  (Holography, QFT)
- Harvey Reall
  (GR with apps in holo.)
- Dave Skinner
  (Amplitudes and twistors)
- Nick Dorey
  (SUSY, field theory, integrability)
- Malcolm Perry
  (Double field theory and SUGRA)
- Paul Townsend
  (String theory, SUGRA, ...)
- Michael Green
  (String theory amplitudes)
- Jorge Santos
  (To arrive next year...)

# HEP Postdocs

- Tim Adamo
  (Amplitudes and twistors)
- Daniele Dorigoni
  (Field theory)
- Tolya Dymarsky
  (AdS/CFT, CFT, ...)
- Pau Figueras
  (Numerical GR)
- Joao Gomes
  (Black holes, entropy)
- Carlos Mafra
  (Pure spinors)
- Eric Perlmutter
  (Higher spin, entanglement entropy)
- Joan Camps
  (GR and apps in holography)
- Mariano Chernicoff
  (Holography, string dragging)
- Benson Way
  (Holography, AdS/CFT)
- A. D.
  (AdS/CFT, Holography)

# Outline

- AdS/CFT in string theory
- Applied holography
- Applications in condensed matter

# AdS/CFT in string theory

- Strings are extended "1+1" dimensional objects moving in a D dimensional space-time

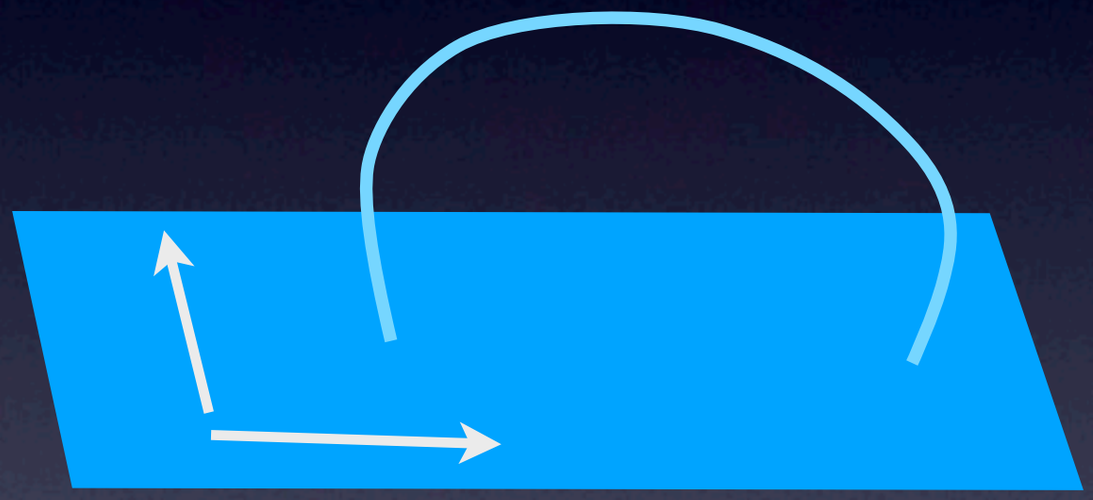
- Depending on boundary conditions they can be "closed" or "open"

Low energies → GR

Low energies → Photons

# AdS/CFT in string theory

- More generally open strings can end on 1+p -dim hyperplanes (Dp-branes)

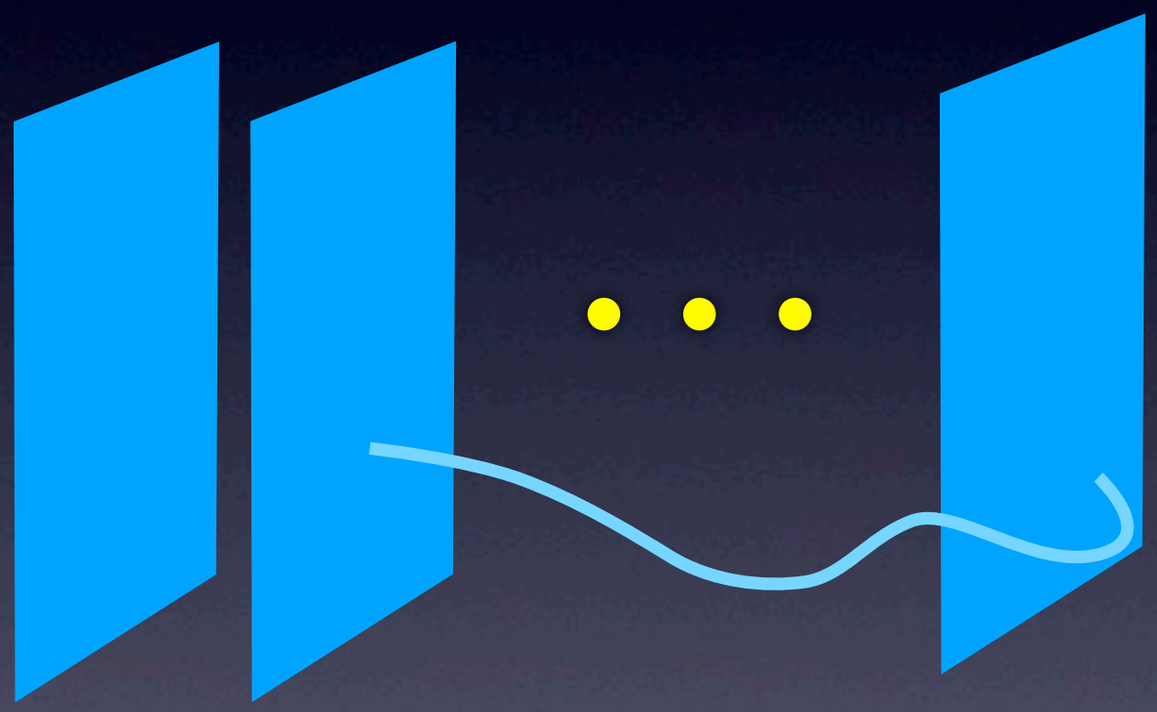


Endpoints moving freely on the "brane"

For the brane point of view the low energy excitations can be scalars or vectors (the photon!)

# AdS/CFT in string theory

- Even more generally we can have N parallel d-branes yielding $N^2$ different BCs



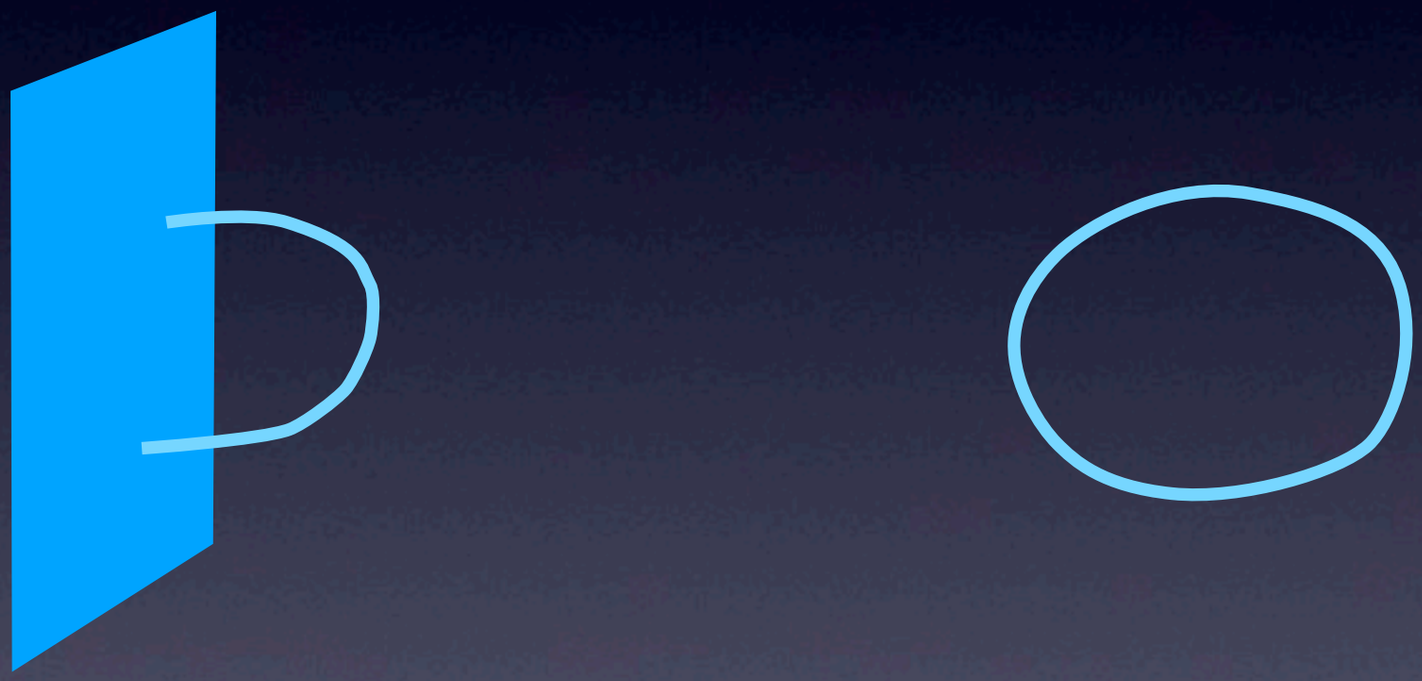
- When the N branes are coincident we have scalar matrices + non-linear "photons" → YM theory

# AdS/CFT in string theory

- d-branes have tachyonic modes in bosonic string theory → unstable
- Can be stable in supersymmetric theories
- Of particular interest are the planar D3-branes of type IIB closed string theory in D=10
- Yang-Mills theory in 1+3 dimensions at low energies

# AdS/CFT in string theory

Open strings of the brane stack + closed strings moving in the bulk



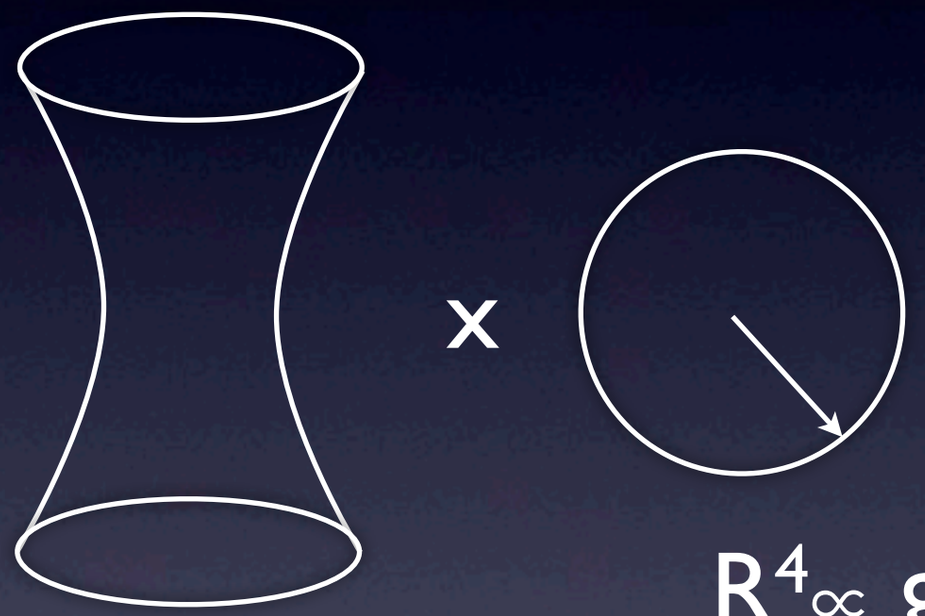
With increasing number of branes the background geometry the closed strings see gets warped!

# AdS/CFT in string theory

Geometry backreacts the least far away from the branes

10D Minkowski space

Close to the branes the geometry changes to




$AdS_5 \times S^5$

$R^4 \propto g_s N$

Low energy excitations governed by the near stack geometry

# AdS/CFT in string theory

Low energy limit → massless modes decouple

$g_s N$

$g_s N << 1$

$N > g_s N >> 1$

N=4, d=4, SYM

IIB SUGRA

# AdS/CFT in string theory

For each gauge invariant field theory observable there is a corresponding gravity (bulk) field

| N=4, d=4, SYM | | IIB SUGRA |
|---|---|---|
| $\Phi^I \to SO(6)_R$ | $\longleftrightarrow$ | $S^5 \to SO(6)$ |
| $\mathsf{CFT}_4$ | $\longleftrightarrow$ | $AdS_5$ |
| $\mathrm{Tr}\left(\cdots \Phi^I \cdots\right)$ | $\longleftrightarrow$ | $\phi^M$ |

$$\left\langle e^{\int \phi_0 \mathcal{O}} \right\rangle_{CFT} = \mathcal{Z}_{string}\left[\phi_{\partial AdS} = \phi_0\right]$$

# AdS/CFT in string theory

- Since the first appearance of the conjecture many checks have been carried out

- First robust checks based on protected observables (SUSY preserving operators) → extrapolate between weak/strongly coupled regimes

- Chiral primary operators :

$$Z = \Phi^1 + \imath\, \Phi^2, \quad \mathcal{O} = \mathrm{Tr}\left(Z^J\right)$$

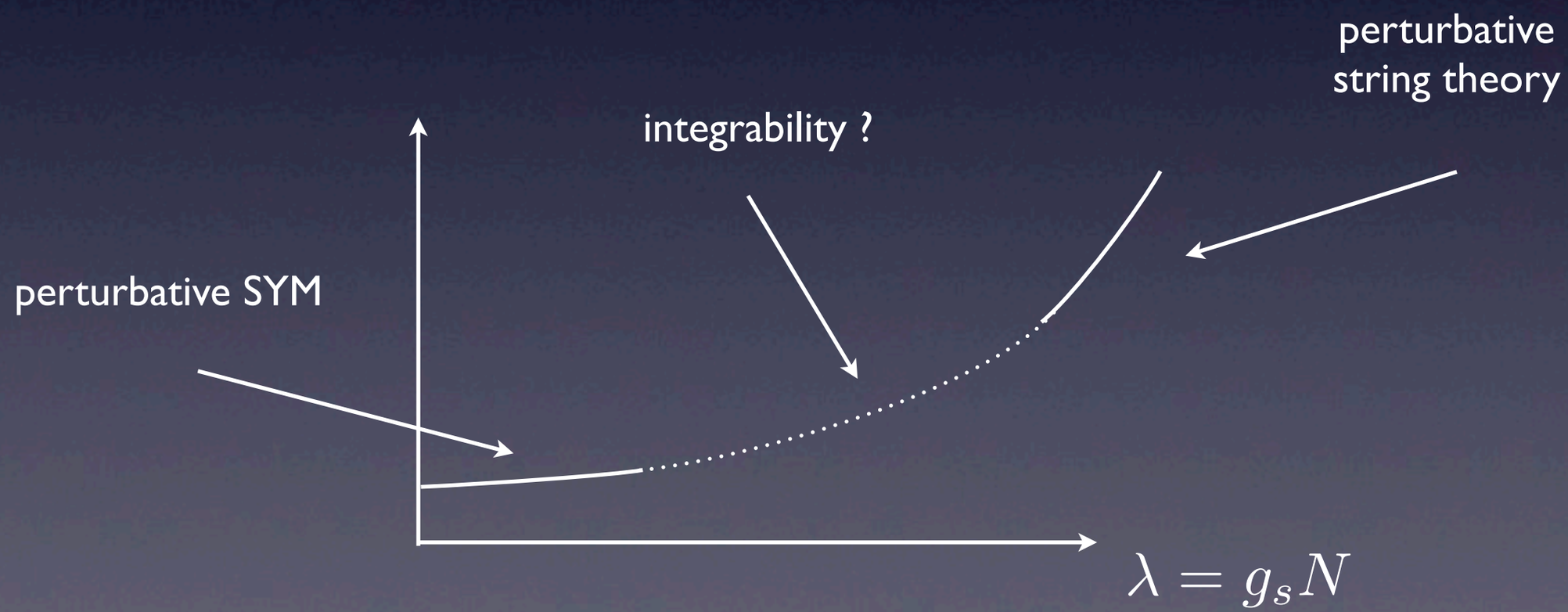
- Wilson-'t Hooft operators :

$$W_R = \mathrm{Tr}_R P\, exp\left(\imath \int_C ds\ \left(A_\mu \dot{x}^\mu + \Phi_I \dot{y}^I\right)\right)$$

# AdS/CFT in string theory

- Several sectors of SYM operators appear to reduce to spin chains (SU(2) sector) → integrable

- Integrability not too surprising on the string worldsheet sigma model side (spinning strings, giant magnons)



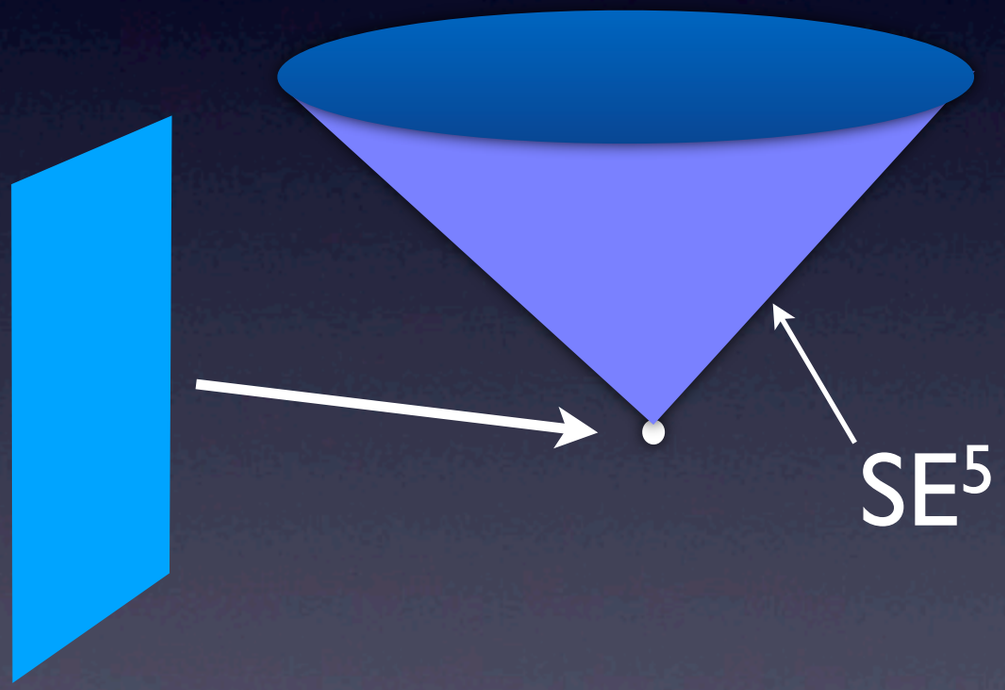

N. Dorey,
N. Gromov,
A. Tseytlin...

# AdS/CFT in string theory

- Is AdS/CFT true only for N=4 SYM?
- Generalizations to other setups with less SUSY? confinement?
- Geometries of the form $R^{1,3} \times CY^3$ preserve 8 SUSYs in Type IIB
  - $CY^3=R^6$ is special with 32 SUSYs
- Demanding the cone to be Calabi-Yau suggests an additional U(1) symmetry → R-symmetry of N=1 SUSY theories

# AdS/CFT in string theory

Replace the five-sphere by another five Sasaki-Einstein manifold




- Low energy limit $AdS_5 x SE5$
- N=1 SUSY → $U(1)_R$
- Significant generalization of known gravity/gauge duals

J. P. Gauntlett, J. Sparks, D. Martelli, D. Waldram, A. Hanany, S. Cremonesi, ...

# Applied holography

- AdS/CFT is a powerful tool to calculate correlators at strong coupling!
- Introduce boundary sources and use propagator to find bulk corrections


- Take functional derivatives in the end

# Applied holography

- The 2- and 3- point functions are constrained due to the conformal symmetry of AdS to be compatible with the boundary CFTs

- Use bulk action to define the CFT!

- Discover universal properties of holography

- Weakly coupled picture not clear (similar issue in string theory settings!)

- “stringy” corrections not clear!

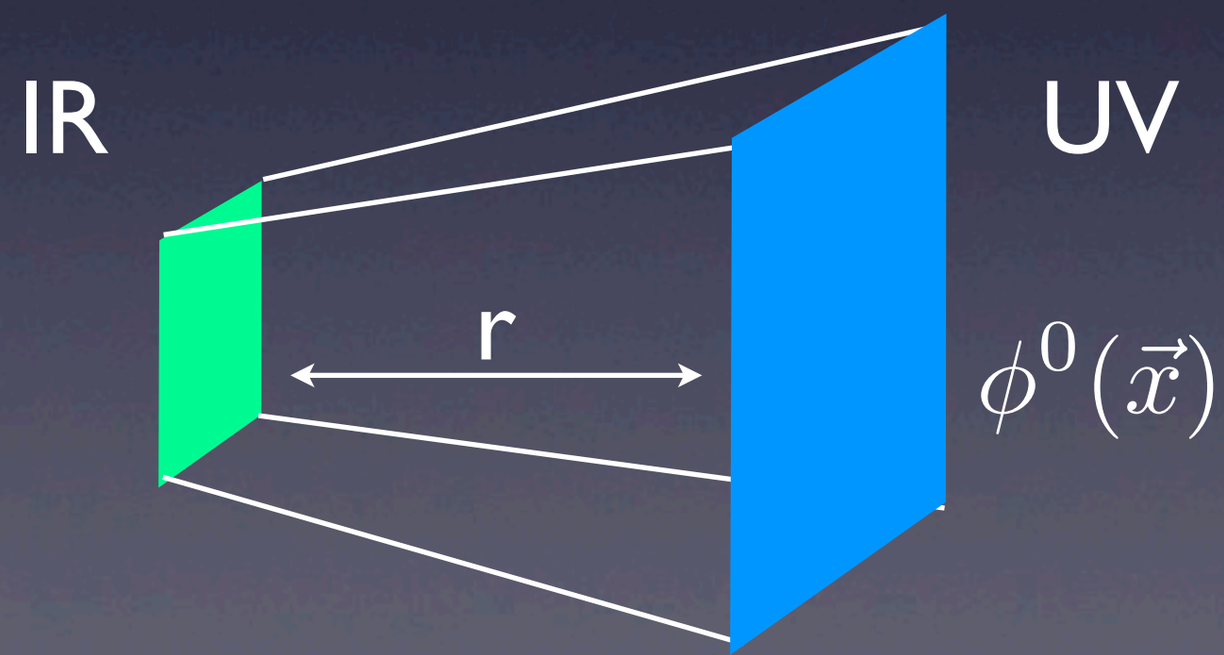
- Recent progress with “Higher spin theory” E. Perlmutter

# Applied holography

- Deforming the boundary CFT by a relevant operator corresponds to appropriate BCs for an appropriate bulk field
  → geometrization of RG flows

- How such UV theory deformations affect low energy physics

- Search for new IR geometries/phases

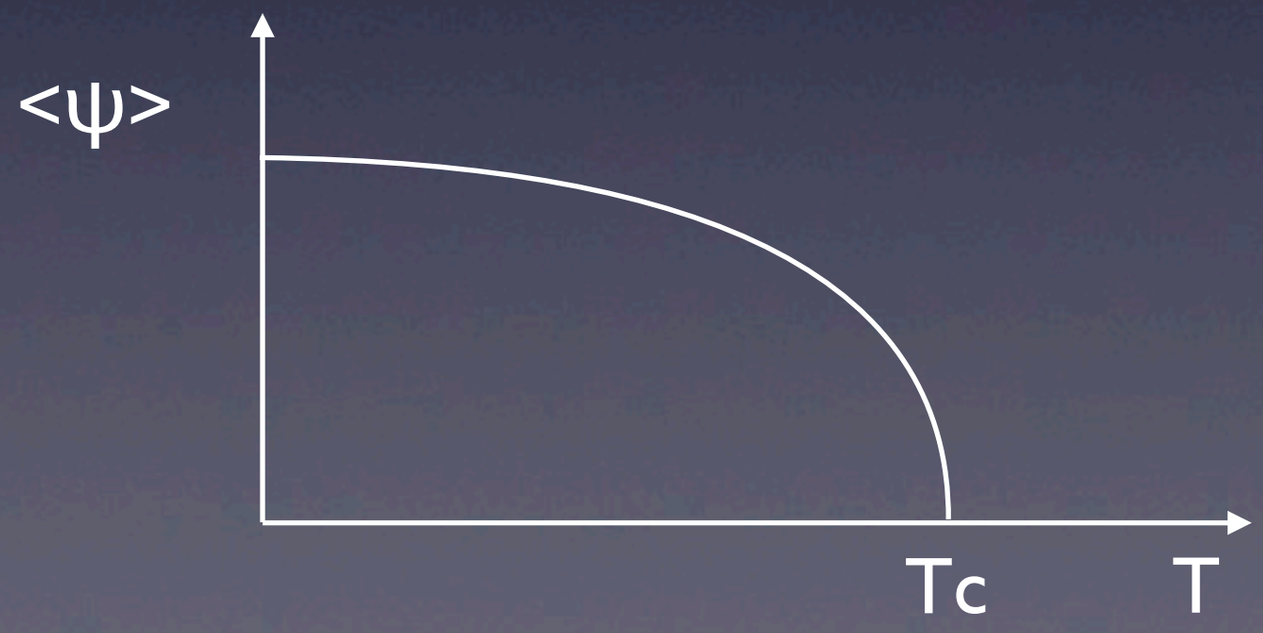


# AdS/CMT

- Framework to investigate strongly correlated systems e.g. high Tc superconductors
- What do we need to ask?
- What are the right variables?
- Finite temperature T → introduce black hole horizon, QFT entropy given by Hawking entropy!
- Chemical potential μ → electrically charged black holes under U(1) gauge fields
- Task: Find all black hole solutions for fixed T and μ

# AdS/CMT

- At high temperatures unique black hole solution → normal phase
- At low temperatures certain bulk fields can become unstable → phase transition
- Novel black hole phases previously unknown in gravity!
- Black holes phases which break the U(1) lead to holographic superconductors/ superfluids
- Can be scalar (s-wave), vector (d-wave), or rank-2 (d-wave)



# AdS/CMT

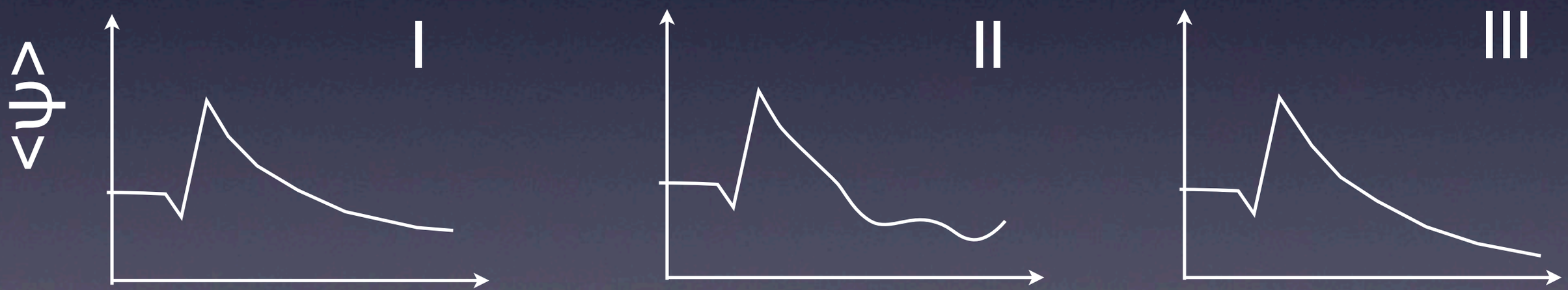
- What other phases are possible?
- Another class of bh instabilities breaks some of the Euclidean symmetries
  - Charge density waves
  - Current density waves
  - Helical superconducting bhs
  - FFLO

A.D, J. P. Gauntlett, C. Pantellidou, ...

# AdS/CMT

- How do the non-linear time dependent dynamics look like?
  - Translates to a time evolution problem in GR.

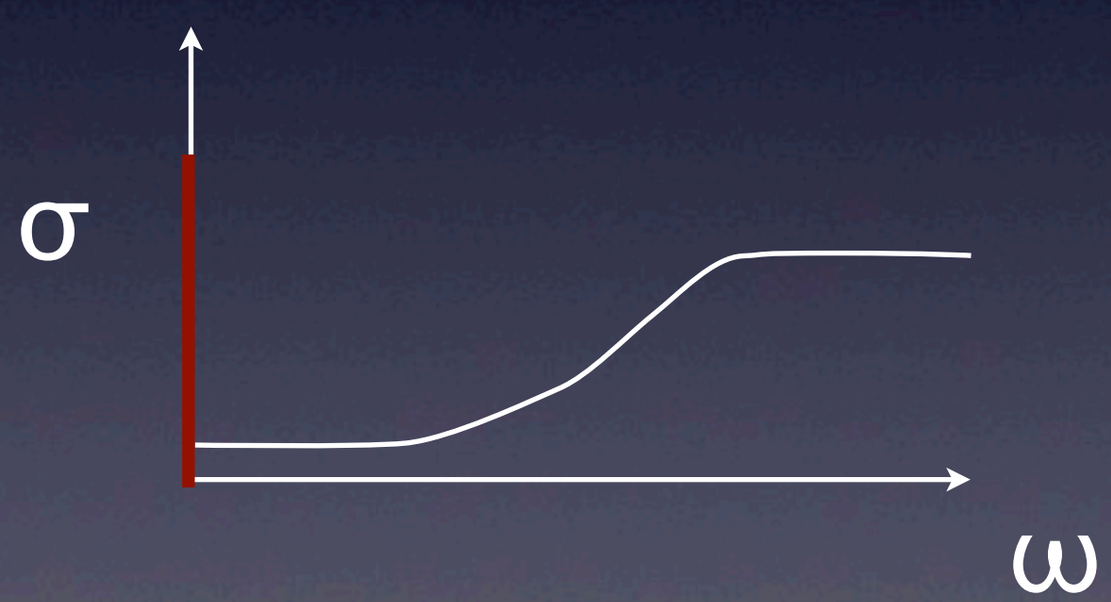
Hard but easier than QFT at strong coupling!




J. Bhaseen, J. Gauntlett, B. Simons,
J. Sonner, T. Wiseman

# AdS/CMT

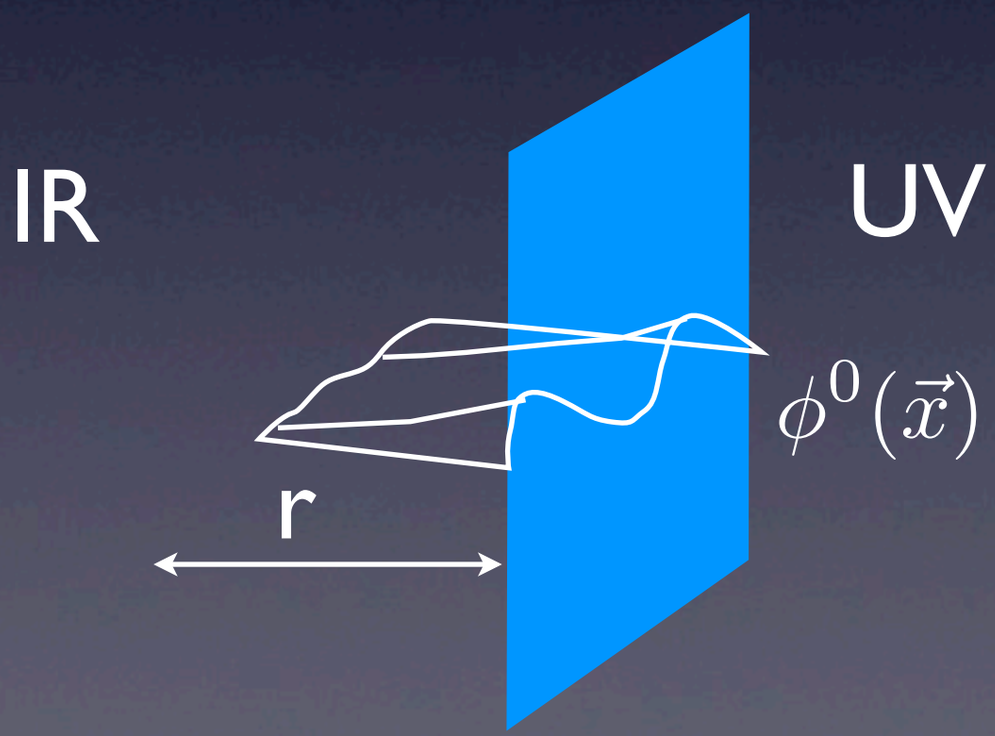
- Comparison with experimental data?
- Can study linear response → AC conductivity
- Momentum conservation leads to delta function at ω=0

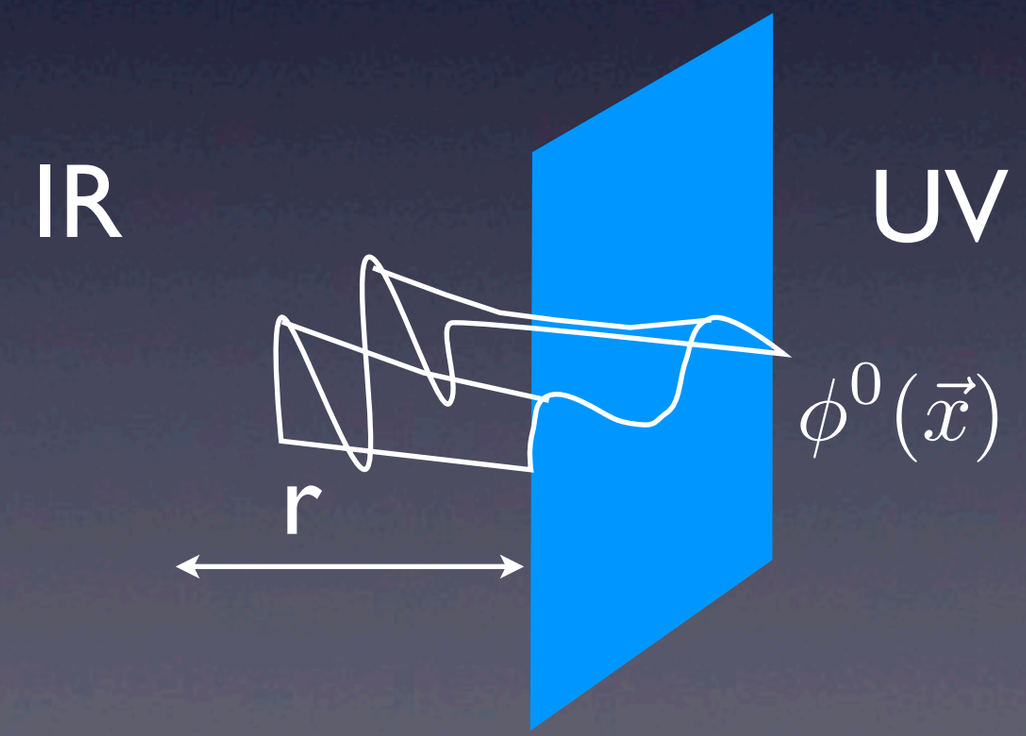



To resolve the delta function need to relax momentum
→ black holes with a field theory lattice!

# AdS/CMT

- 2 ways this can happen
  - lattice fades in the IR
  - lattice dramatically changes the IR



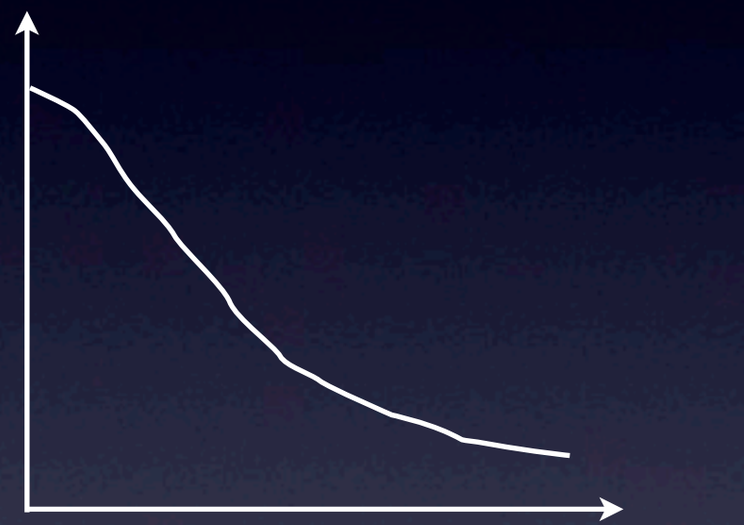



# AdS/CMT

Solutions now depend on (at least) two variables → need to solve PDEs

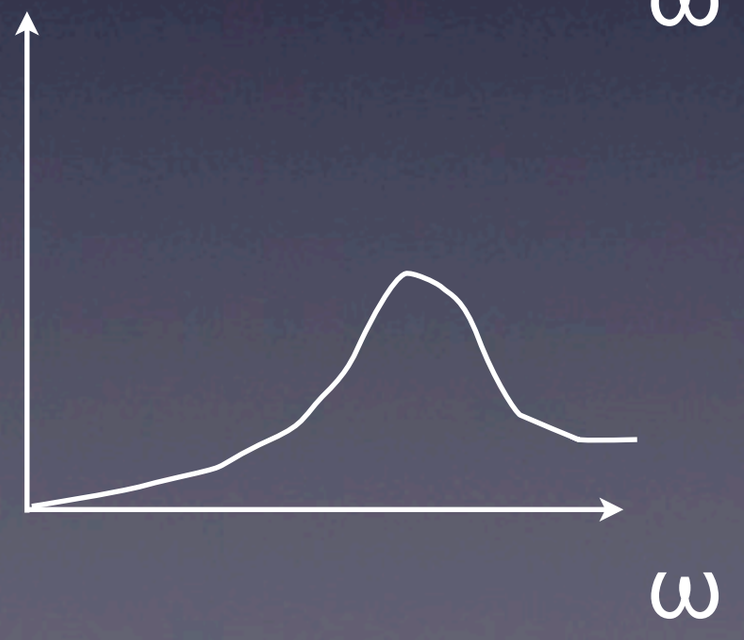
a)
- Spectral weight smeared to a Drude peak at $\omega=0$
- Claim for curious mid-infrared scaling $\sigma=C+\omega^{-2/3}$

G. Horowitz, D. Tong, J. Santos




b)
- Novel IR geometries
- Spectral weight transferred to mid-infrared
- Insulating at $\omega=0$

A.D., S. Hartnoll



# AdS/CMT

- What about non-linear reponse/current noise?
- Drive the geometry by a non-linear boundary current + current study noise
- GR problem very hard → non-linear problem in 1+2 dim
- Stable time dependent solutions are highly non-obvious. Consider theories on probe branes in a heat bath


Results for all source regimes agreeing with previously known FT results

A. Green, J. Sonner

# Summary

- Holography, one of the few tools to study systems at strong coupling
- Holographic construction of superfluids/superconductors, metal/insulator transitions, far from equilibrium dynamics
- More applications not mentioned!
  - Gravity/Fluid correspondence
  - Shock wave collisions
  - Entanglement entropy
  - Quantum criticality