Summer School and Workshop on The SM and beyond
Corfu, 8-17 September 2012

String Theory and Applications

Elias Kiritsis

University of Crete APC, Paris

Bibliography

String theory books: several.

I am following "String Theory in a Nutshell"

Plan

• Prolegomena

♠ String theory

♠ The (many) string theories

♠ D-branes

♠ Motivations: Mathematics

♠ Applications: Physics Beyond The standard Model

♠ Applications: AdS/CFT and QCD

♠ Applications: Strongly coupled CM

String theory

A theory introduced because it incorporates (quantized) gravity

- Unlike other interactions the short-distance infinities of gravity are un-controlable

- → Non-renormalizability

String theory predicts (perturbatively) quantized gravity.

fundamental objects of string theory are strings (open and closed

- closed string always provide a graviton
- The theory contains gauge interactions (SM)
- Existence of fermions implies supersymmetry
- The theory is UV finite.

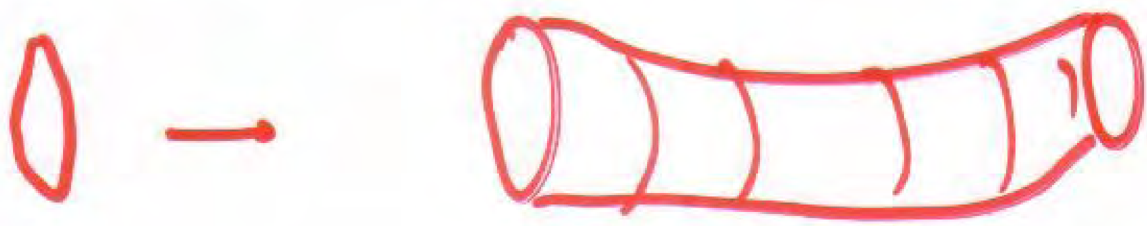
In field theory, fields (particles) are point-like.

world-lines

- quantum-mechanics

$$\sim \int (\text{paths})\, e^{-\text{length}}$$

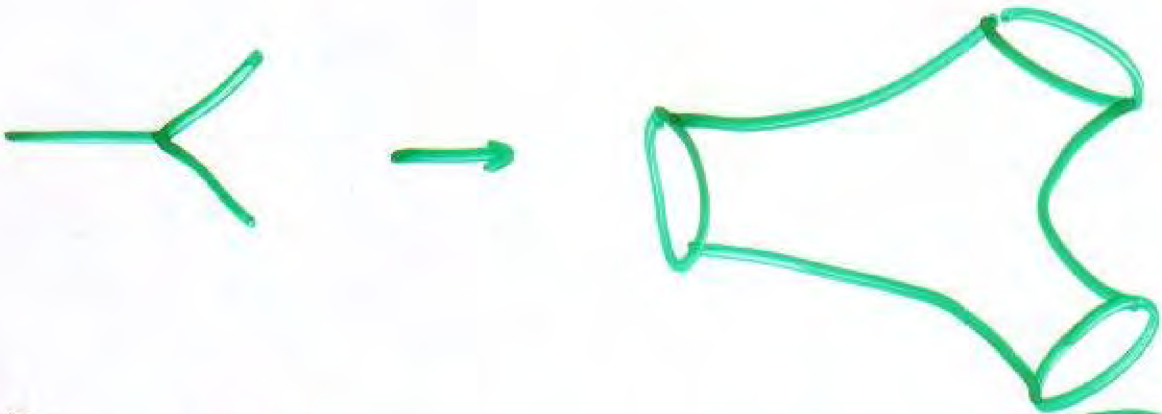
↓ world-lines



2-d world-volume

$$\sim \int (\text{wv})\, e^{-\text{Area}}$$

Unlike FT, in ST the interactions are unique:



⇒ geometry of Riemann surfaces

The theory is tightly constrained.

(resembles a theory with a smart cut-off)

The theory has one scale : M_s → string scale

and $l_s \sim M_s^{-1} \sim \sqrt{\alpha'}$

$T \sim \frac{1}{\alpha'}$

A string gives rise to an infinite ladder of particles with

$$M^2 \sim n\, M_s^2$$

When $E \ll M_s$ they are "invisible"

⇒ We must look at $l \sim l_s$ to see a string

Other "parameters" depend on the background.

(Superstring theory lives in 9+1 dimensions.)

- the string coupling constant g_s is an expectation value:

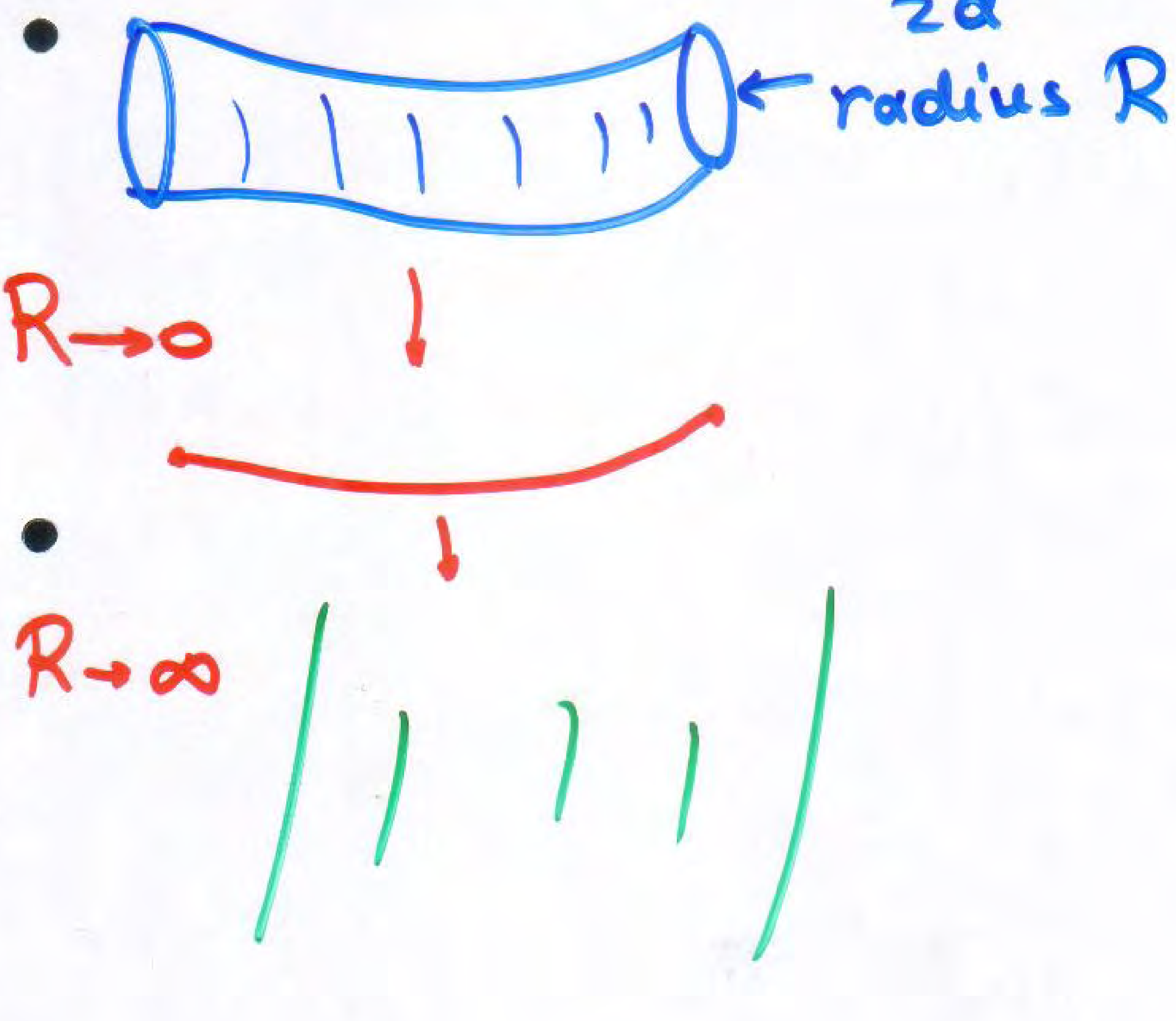
- $g_s = \langle e^{\Phi} \rangle$ → dilaton scalar

$$g_s^{-\chi} \sim g_s^{-2+2g}$$

Compactification

How are ten dimensions compatible with observations?

Kaluza-Klein idea



Example: 4+1 dimensions

circle of radius R.

and a scalar Φ (massless)

$$\Box \Phi = 0$$

- $\Rightarrow \quad p_0^2 - \vec{p}^{\,2} - p_5^2 = 0$

wave function $e^{i p_5 \cdot x^5}$

must be invariant under $x^5 \to x^5 + 2\pi R$

- $\Downarrow$

$$p_5 = \frac{n}{R} \qquad n \in \mathbb{Z}$$

$$\longrightarrow \quad p_0^2 - \vec{p}^{\,2} = \frac{n^2}{R^2}$$

Infinite collection of particles (KK part)

with $M_n^2 = \frac{n^2}{R^2}$

T-duality

In string theory there are other configurations.

- a string can wrap a compact dimension (m times)

energy cost $= T \cdot (2\pi m R)$

- mass formula:

$$M^2 = \frac{n^2}{R^2} + T^2 (2\pi m R)^2$$

invariant under:

$$R \longrightarrow \frac{1}{2\pi T \cdot R}$$

$\partial_\sigma X^\mu \leftrightarrow \partial_\tau X^\mu$

$\partial_{\sigma+\tau} X^\mu \rightarrow$ inv

$\partial_{\sigma-\tau} X^\mu \rightarrow -(\ )$

Consistent supersymmetric string theories in $D=10$

- Closed strings (type II) (super)

 $\longrightarrow x^\mu \rightarrow 10D$

- left movers ~ Right movers

Subtle diffence in fermion sector $\rightarrow$ II A, B.

- For both,

NSNS $\longrightarrow G_{\mu\nu}, B_{\mu\nu}, \Phi$

RR $\longrightarrow$

IIA: $A_\mu, C_{\mu\nu\rho}$

IIB: $\alpha, C_{\mu\nu}, C^+_{\mu\nu\rho\sigma}$

IIA : massless sector
= N=2 supergravity
(non-chiral)

IIB : massless sector
- N=2 supergravity (IIB)
chiral (+ anomaly free)

- Heterotic super-string theory

Closed strings:
left movers : superstring
x^μ, ψ^μ
$\mu = 0, 1, \ldots, 9$

Right movers → non-susy

x^μ, $X^{I=1,..,16}$

X^I compactified on even self-dual lattice — $E_8 \times E_8$, $O(32)$

- massless fields:

$G_{\mu\nu}$, $B_{\mu\nu}$, ϕ + fermions

N=1 supergravity multiplet in d=10

-

A_μ^a + fermions

S Yang Mills multiplet for SO(32), $E_8 \times E_8$

Type I string

Closed unoriented stringss.

projecte by orientation reversal $\underline{\Omega}$: L ↔ R

- $G_{\mu\nu}$, ϕ, $C_{\mu\nu}$ remain
  ($B_{\mu\nu}$, α, $C^{+}_{\mu\nu\rho\sigma}$) → projected out.

  N=1, d=10 sugra multiplet.

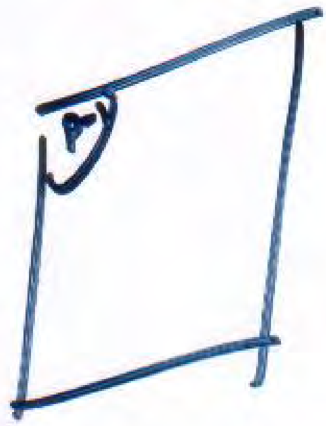
- Open (unoriented) strings

  O(32), N=1 d=10 SYM multiplet.

Antsymetric tensors and p-branes.

$A_{\mu_1 \dots \mu_p}$ → is a massless gauge field

- it couples minimally to a (p-1)-brane

- 

$$Q_{p-1} \int_{M_p} A_{\mu_1 \dots \mu_p} \epsilon^{\mu_1 \dots \mu_p}$$

generalization of the EM coupling of point particles.

$$\sim e \int dx^\mu A_\mu$$

All string theories (except-I) have a $B_{\mu\nu}$ → couples to a 1-brane ≈ string

This is the fundamental string itself (F_1)

There are no perturbative states that couples to the R-R forms in type-II string theory.

such configurations must be p-brane-like

Such p-brane solutions arise as quasi-solitonic solutions of the low-energy effective supergravity.

However, such solutions are

- generically singular (Dirac vs, t'Hooft monopole)

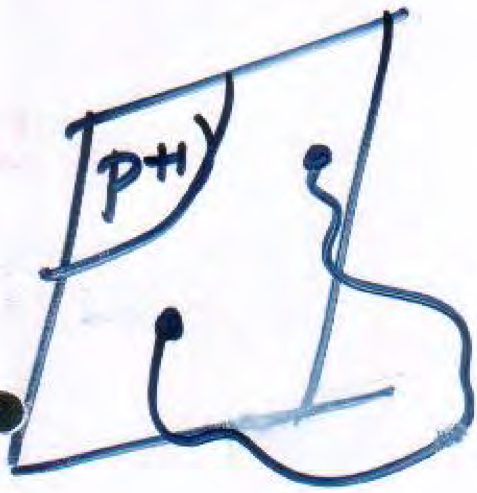
Do they correspond to

- states in the quantum theory?

Non-perturbative duality "symmetries" indicate that they should

D-branes

Consider a (p+1)-dimensional subspace (plane) of 10-d spacetime. We will describe open strings "stuck" on this subspace



$X^{\mu} \rightarrow$ longitudinal

$X^{I} \rightarrow$ transverse

$X^{\mu} \rightarrow$ Neuman boundary conditions

(free end points)

$$\partial_{\sigma} X^{\mu} \Big|_{\text{end point}} = 0$$

$X^I \to$ Dirichlet bc
(fixed end)

$$\partial_\tau X^I \Big|_{\text{end point}} = 0$$

$$\sim \quad X^I \Big|_{\text{end point}} = 0 \to \text{(fixed)}$$

Nbc allow momentum only
D-bc " winding only
(in compact cases)

Spectrum:

a vector $\to$ $\psi^{\mu}_{-1/2}|0\rangle$

(transverse) scalar $\to$ $\psi^{I}_{-1/2}|0\rangle$

+ fermions.

Special case $p=9$

$\Rightarrow$ Neuman only

$\rightarrow$ one vector $A_\mu(x)$

one MW spinor Ψ_a

$\rightarrow$ $N=1$ $D=10$ vector multiplet

arbitrary p:

one vector ($D=p+1$) $A_\mu(x)$

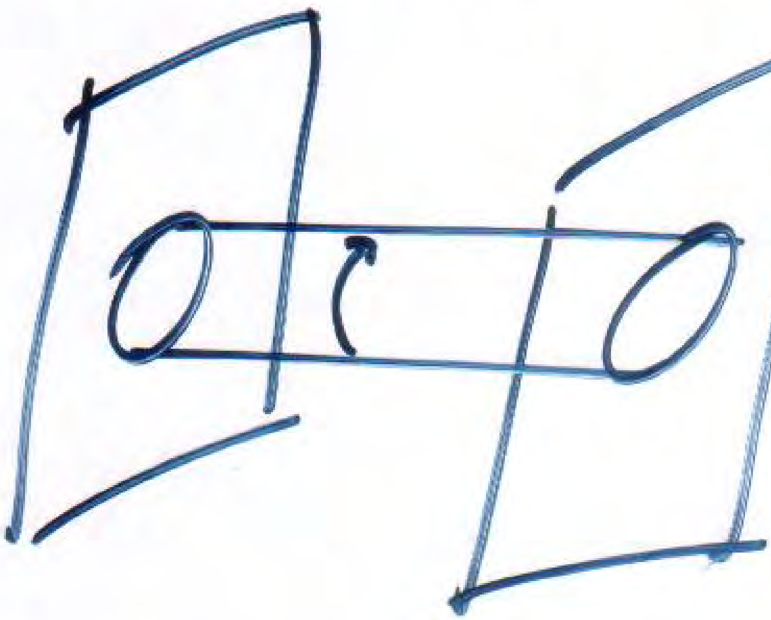
$9-p$ scalars $\Phi^I(x)$

plus the fermions.

Dimensional reduction to $D=p+1$ of $D=10$ vector multiplet.

D-branes

Force between D-branes (at distance $\vec{d}$)



one-loop open string amplit[ude]

= tree-level exchange of closed strings.

massless contribution due to $g_{\mu\nu}$, ϕ (attractive) and RR field (repulsive)

total = 0

D-branes carry RR charge. → a stringy description of such solitons.

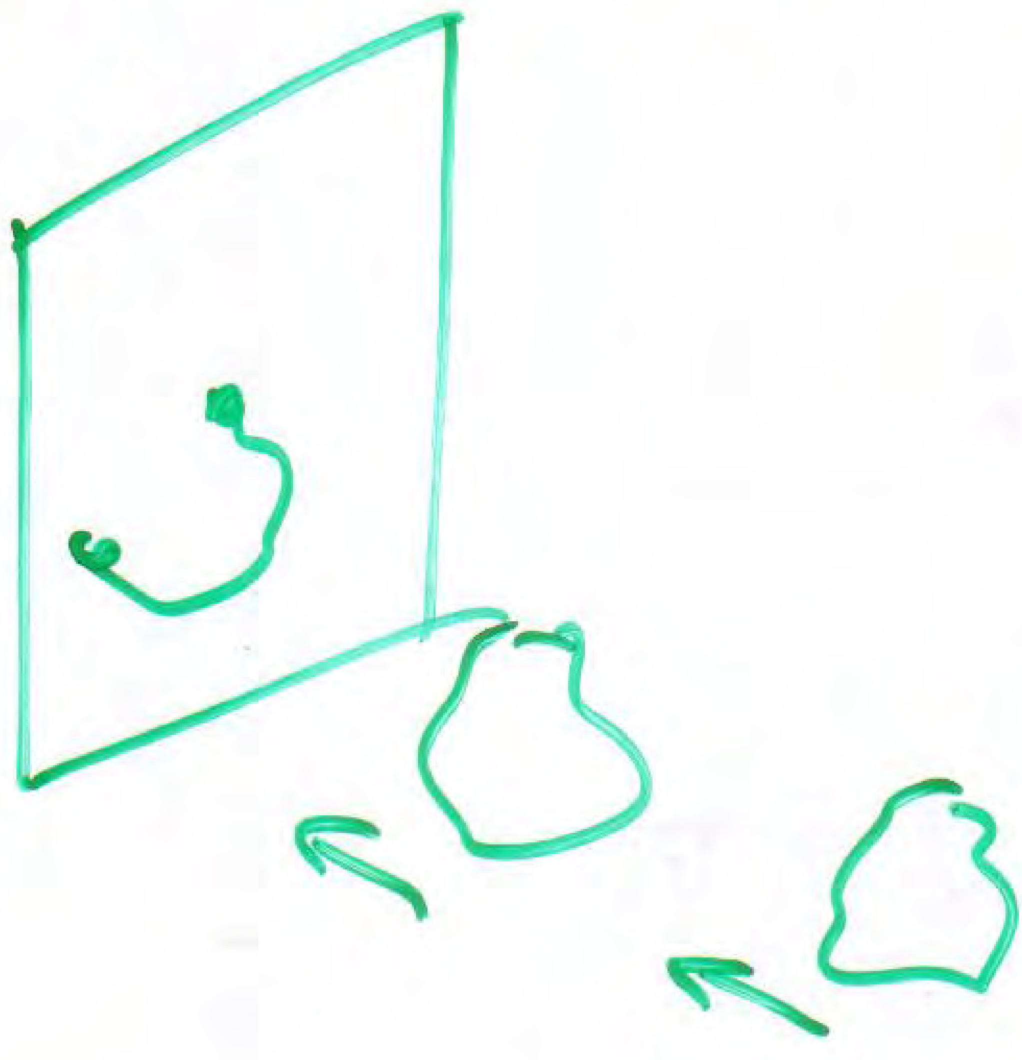
- So ...

D-branes are stringy solitons. Their tension

- $T_p \sim \dfrac{M_s^{p+1}}{g_s} = Q_p$ (BPS)

Their fluctuating modes are the open strings with endpoints on the brane.

They must interact withe the closed super-string modes (graviton dilaton, RR-forms) since they are charged



M-theory

What is the strong coupling limit of IIA string?

- → M-theory ($E \to 0$, D=11 supergravity)

  → G_{AB}, C_{ABC}

- Compactification on circle of radius R

⇒ IIA with coupling

$$g_s \sim R^{3/2}$$

$G_{AB} \rightarrow G_{\mu\nu} \rightarrow$ metric

$G_{\mu 11} \rightarrow A_\mu$ RR 1-form

$G_{11} \rightarrow \Phi \rightarrow$ dilaton

- $C_{ABC} \rightarrow C_{\mu\nu\rho} \rightarrow$ RB 3-form

  $C_{\mu\nu 11} \rightarrow B_{\mu\nu}$

- M5 → NS5
  M5 → D4

  M2 → D2
  M2 → F1

KK-grawitons → $D0$ branes

T-duality and D-branes

Consider a D_p brane and the end-point of an open string

- $\partial_\sigma X^\mu \big|_{end} = 0$ Neumann

$\partial_\tau X^I \big|_{end} = 0$

- T-duality along direction x^i:

$$\partial_\sigma X^i \leftrightarrow \partial_\tau X^i$$

Along longitudinal: $D_p \to D_{p-1}$

" transverse: $D_p \to D_{p+1}$

$$(2\pi\alpha') A_i \longleftrightarrow x^i$$

D-brane effective action

Spectrum : A_μ, Φ^I
fermions

(Dim. red. of $\mathcal{N}=1$ $D=10$ SYM multiplet)

- Invariance under 16 super-charges

- Leading contributions come from disk (tree-level)

in $\boxed{p=9}$ → only A_μ

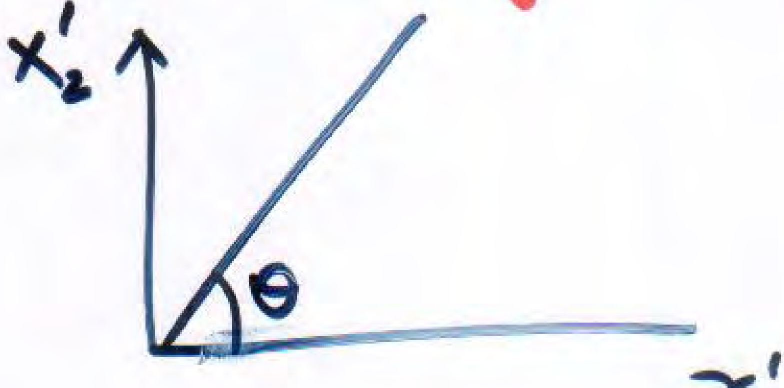
Another "quick argument"

D2 brane with constant F_{12}

$\Rightarrow \quad A_2 = X^1 F_{12}$

T-dualize $x^2 \Longrightarrow \quad X'^2 = (2\pi\alpha') X^1 F_{12}$

this is a D1 brane at an angle ($x^1 x^2$ axes)



$\tan\theta = (2\pi\alpha') F_{12}$

$$S_{D1} = \int ds = \int dx^1 \sqrt{1 + (\partial_1 X'_2)^2}$$

$$= \int dx^1 \sqrt{1 + (2\pi\alpha' F_{12})^2}$$

Generalizes to other dimensions

$$\left(\mathbb{1} + (2\pi\alpha') F_{\mu\nu} \right)$$

$\partial_I \to 0$

$$\downarrow$$

- $$\begin{array}{c} \\ \mu \\ I \end{array} \begin{pmatrix} \nu & J \\ \mathbb{1} + 2\pi\alpha' F_{\mu\nu} & \partial_\mu A_J \\ -\partial_\mu A_I & \mathbb{1} \end{pmatrix}$$

- $$\det \left(\quad \right) =$$

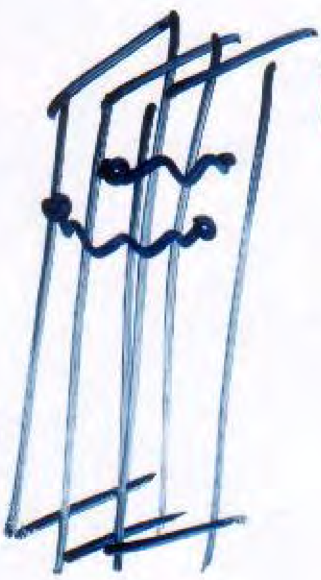
$$= \det \left(\delta_{\mu\nu} + (2\pi\alpha') \partial_\mu A^I \partial_\nu A^I + (2\pi\alpha') F_{\mu\nu} \right)$$

$$= \det \left(\delta_{\mu\nu} + \partial_\mu X^I \partial_\nu X^I + (2\pi\alpha') F_{\mu\nu} \right)$$

Non-abeliom symme-try:

We will consider N, identical parallel, coinciding D_p-brane

Only way to distinguish → index $i = 1, \ldots, N$



N^2 open strings → (i,j)

Massless spectrun

A_μ^{ij}, Φ_I^{ij} → N×N matrices

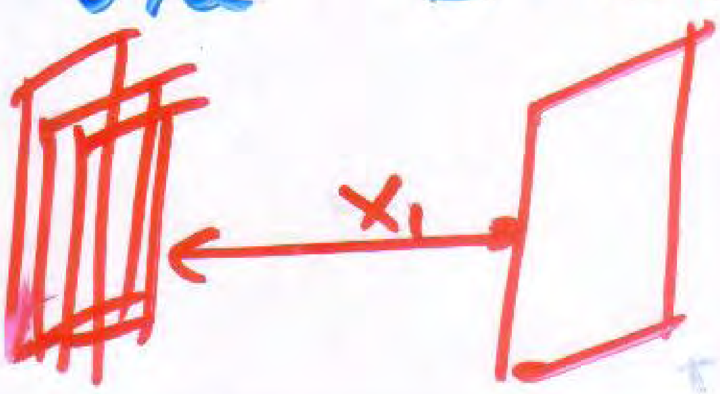
\+ fermions

string interactiom have now a U(N) non-abelian gauge symmetry

By a $U(N)$ rotation we can diagonalize Φ^I (hermitian)

$$\Phi^I \sim \begin{pmatrix} x_1^I & & & 0 \\ & x_2^I & & \\ & & \ddots & \\ 0 & & & x_N^I \end{pmatrix}$$

- x_a^i can be thought of as the transvers coordinates of the N D-branes
- Giving x_1^i an non-zero expectation value amounts to pulling one D-brane away



"Geometrization" of gauge dynamics.

A new viewpoint on

- the description of Spacetime via non-commutative coordinates.
-

Motivation: Mathematics

• String theory is a "theory" for which we do not have sophisticated mathematical tools to address and solve.

• In QFT we can easily find perturbative ground states.

• We can also do perturbation theory rather straightforwardly around each of them.

• Given a few ingredients at weak coupling (gauge group, matter content , interactions) most of the generic features of weakly coupled physics is evident without detailed calculations.

♠ None of the above is doable in string theory except is some VERY SPECIAL CASES!

• An important reason is that the relevant mathematic tools are not known or have not been developed.

• String theory provides many interesting new problems in mathematics.

• It is not an accident that about half of the Field's medals given in the last twenty years go to topics inspired by string theory.

• Riemannian geometry is enough to describe a point particle moving on a manifold. It is not for a string moving on a manifold.

• The classical physics of the string is the "quantum physics" of a two dimensional CFT (the σ-model)

• The classification of 2-d CFTs is a classification of a class of string vacua. This is an non-trivial mathematical problem.

• The classification of 4d CFTs is a classification of another class of vacua of string theory (see Kyriakos' lectures)

• Point particle propagation defines standard geometry. String propagation vis 2d CFTs provides an infinite dimensional generalization: stringy geometry. No good way is known on how to describe it unless we solve the CFTs.

• As geometry generates topology, the same way CFTs generate "quantum topology". Several examples are known, but the general rules and techniques for this are not known.

• When D-branes enter the game, the spectrum of mathematical problems becomes an order of magnitude more complex.

• Mathematicians already have developed K-theory that is the proper tool for topologically classifying D-banes

• The general classification of supersymmetric D-brane embeddings is an infinite-dimensional generalization of the theory of vector bundles on manifolds.

• In the case of non-supersymmetric embeddings the general formulation of the mathematical problem is not known at all.

• All of this make the connection between string theory, and physical observables a nightmare.

Applications: Physics Beyond the standard Model

• The original motivation for string theory in the seventies was to explain/describe the strong interactions.

• The focus shifted in the 80's: a unifying theory of all interactions including gravity.

• Physicists hoped for uniqueness of predictions based on enthusiasm and short-sightedness (always there when we do not understand a theory)

• It took twenty more years for people to realize that string theory has a large number of "vacua".

• The theory was hoped to provide (together with a quantum theory of gravity) a solution to the hierarchy and the cosmological constant problems and a unification of all known interactions.

• As we understand today:

♠ The theory has not provided a solution (but several “translations”) of the hierarchy problem.

♠ The theory suggests a solution to the cosmological constant problem that many physicists have a difficulty in accepting (the anthropic solution).

♠ The theory naturally unified all interactions.

• We have not been able to scan even a tiny spec of such a number of vacua.

• The traditional approach to make contact with low energy physics has included some ingredients:

♠ A vacuum or class of vacua where one can control the zero mass spectrum, and where the cosmological constant is zero at the tree and one loop level. This is done by requiring supersymmetry.

♠ The low energy field theory (a supergravity) is written down by matching string calculations to effective interactions.

♠ The scalar potential is minimized (moduli)

♠ The rest of the interactions in the "visible" sector is analyzed.

♠ Supersymmetry is broken dynamically (rare) or by fiat.

♠ Several old supergravity models were reproduced, and many new ones proposed this way for the low energy theory.

The landscape

• We lack the toold to survey large classes of string vacua.

• The most extensive effort that was done in that direction used solvable CFTs, and computerized vacuum construction, using orientifolds and D-branes

Anastasopoulos+Dijkstra+Kiritsis+Schellekens

• Closed string vacua were constructed using Gepner CFTs.

• Orientifold projections using the symmetries, generated D-branes.

• Finally tadpoles were solved.

Scope of the search

- 168 Gepner model combinations

- 5403 MIPFs

- 49322 different orientifold projections.

- 45761187347637742772 ($\sim 5 \times 10^{19}$)combinations of four boundary labels (four brane-stacks).

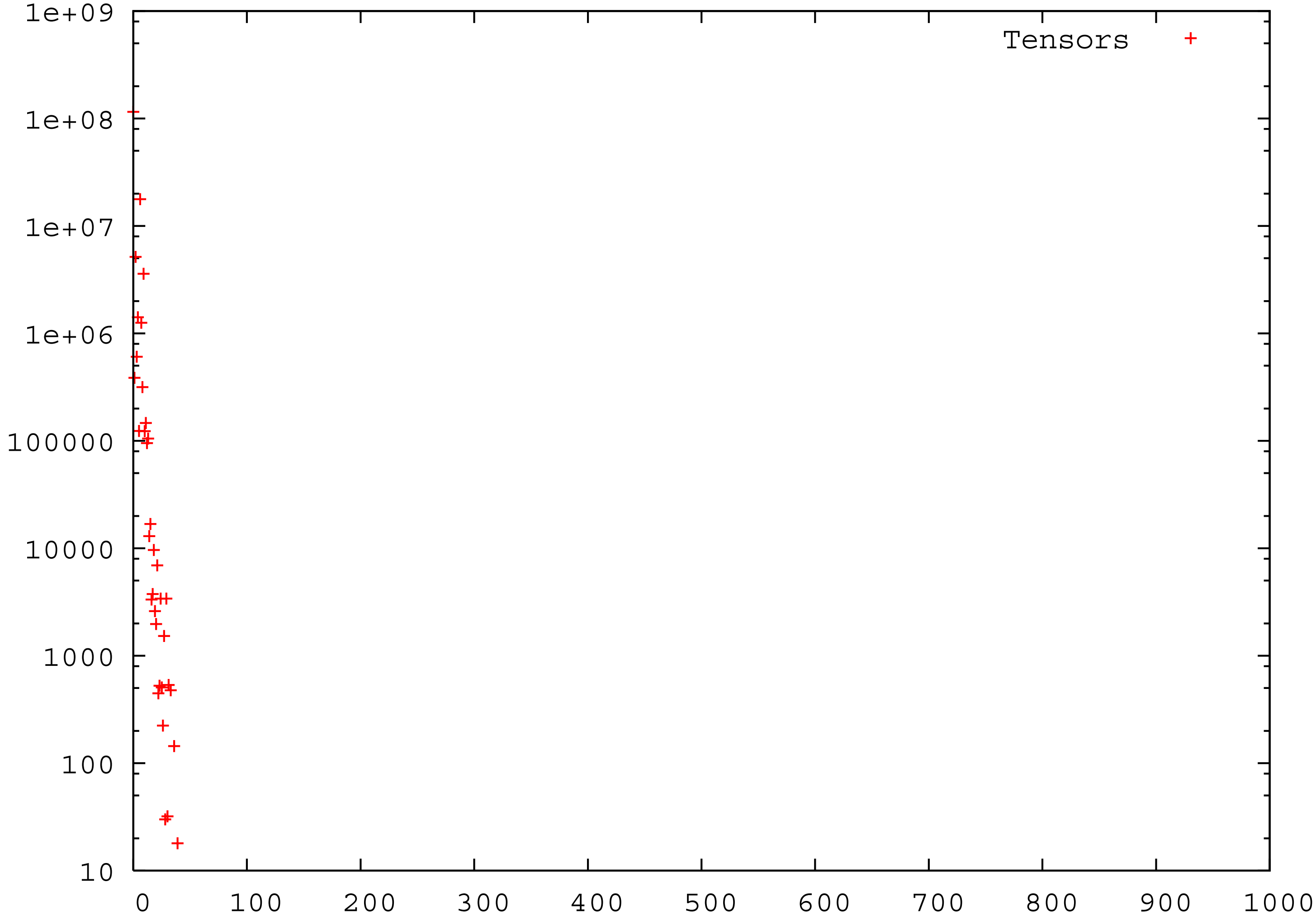
For more than 4 SM-stacks, the numbers grow exponentially.

♠ 19345 distinct realizations of the SM were found

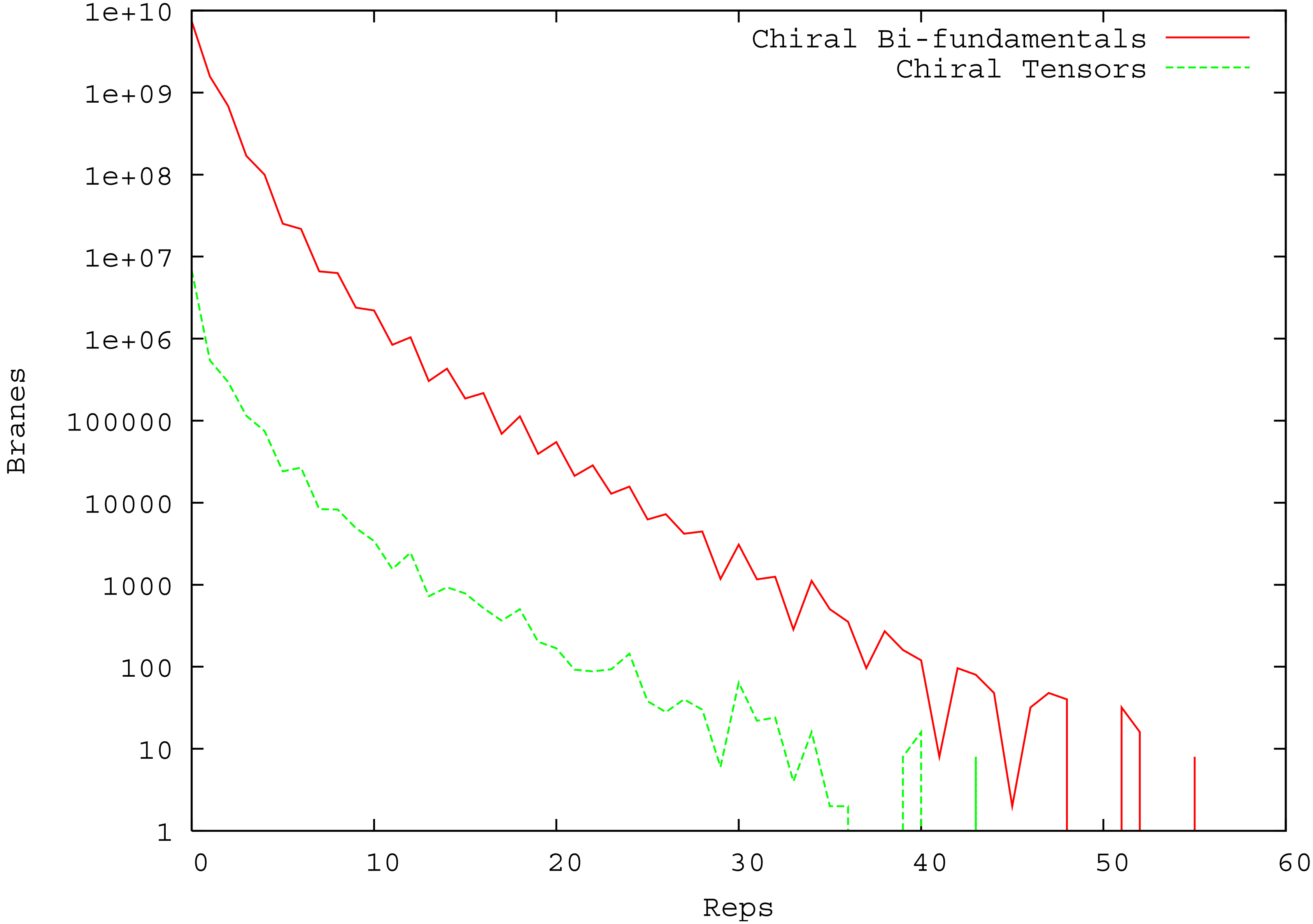
♠ In only 1900 the tadpoles were solved

The distribution of chiral A+S tensors

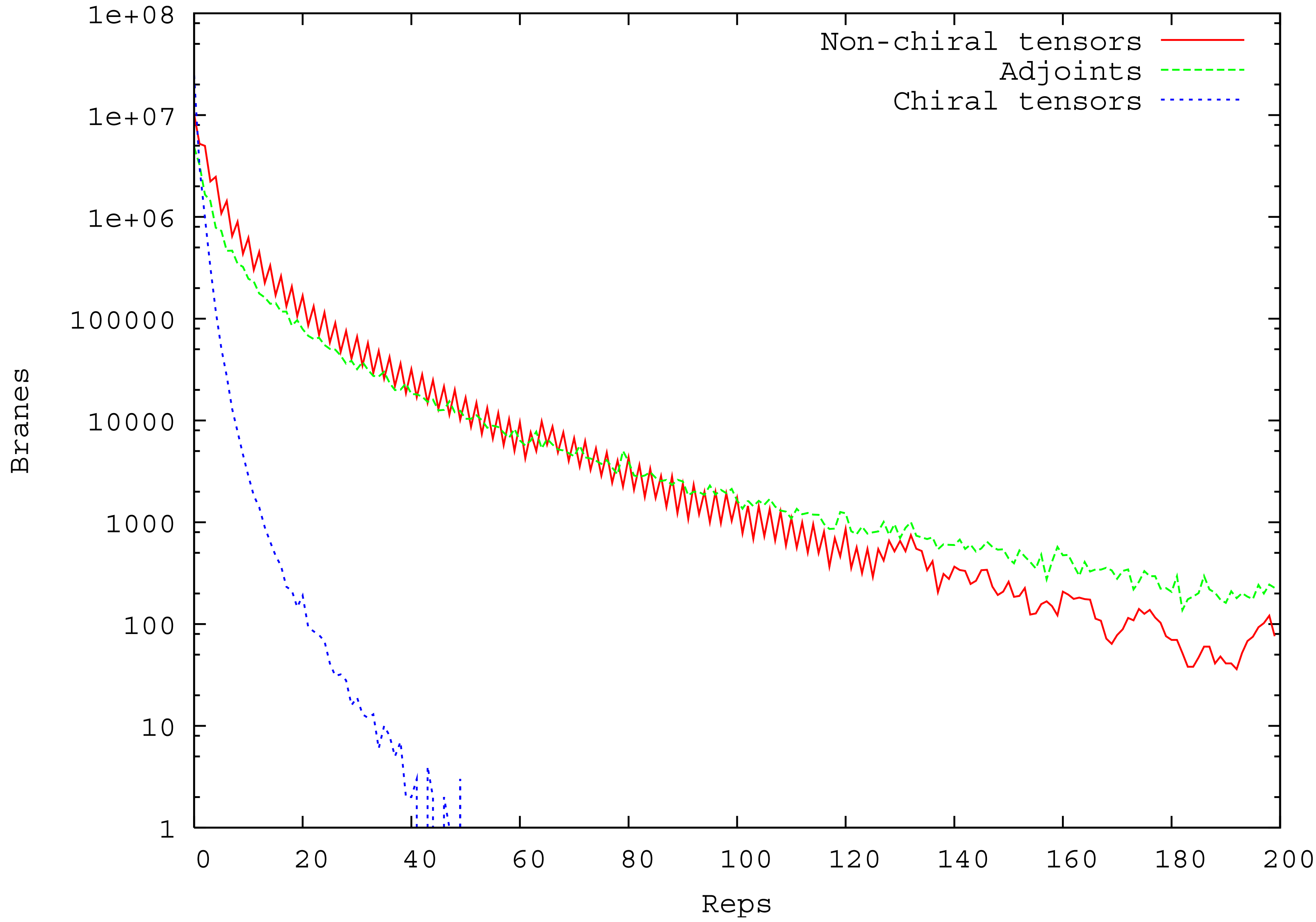
A key fact in order to explain the frequency of certain vacua is the that of chiral tensors, required in some case by (generalized) anomaly cancellation.



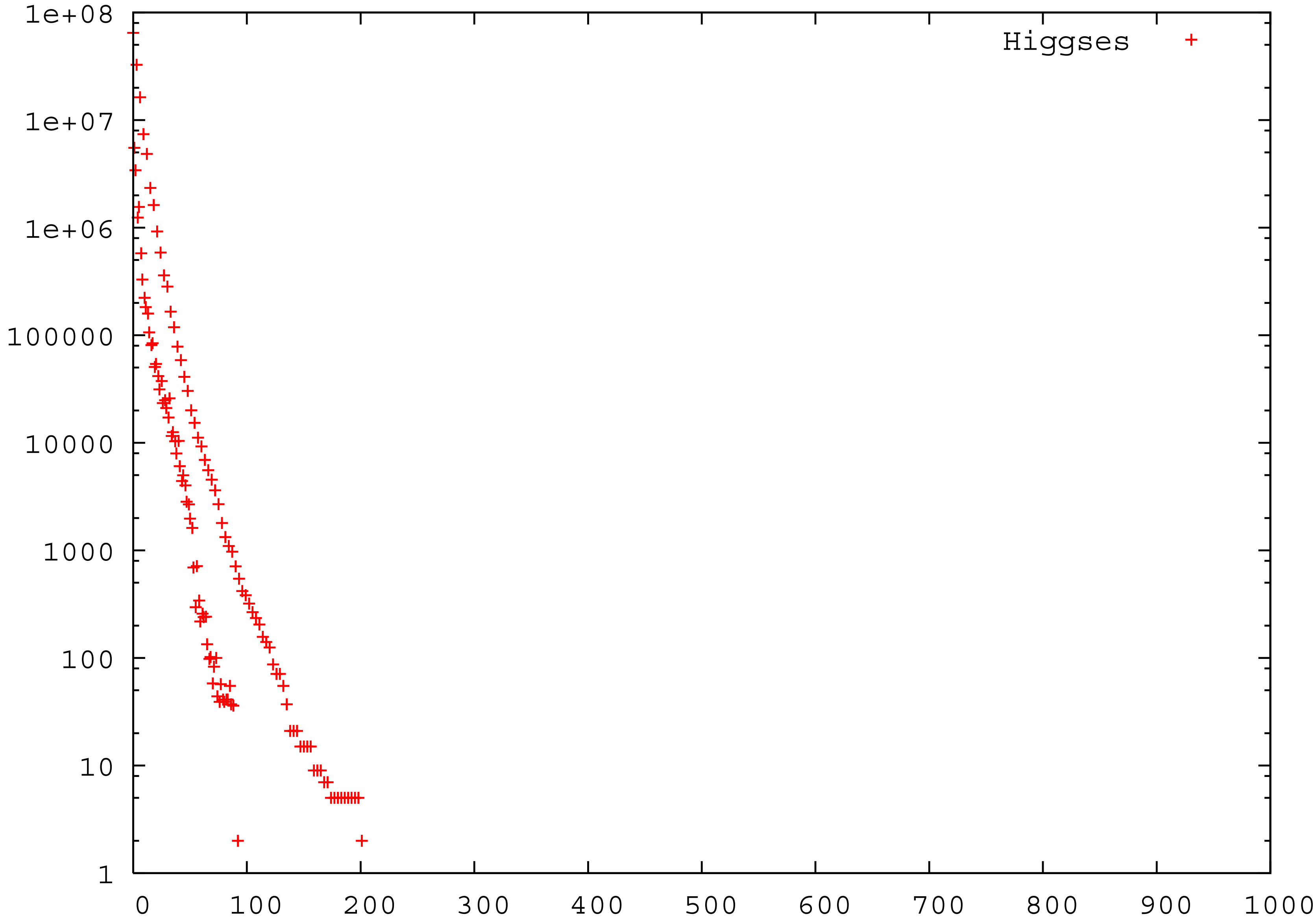
Tensors versus bifundamentals



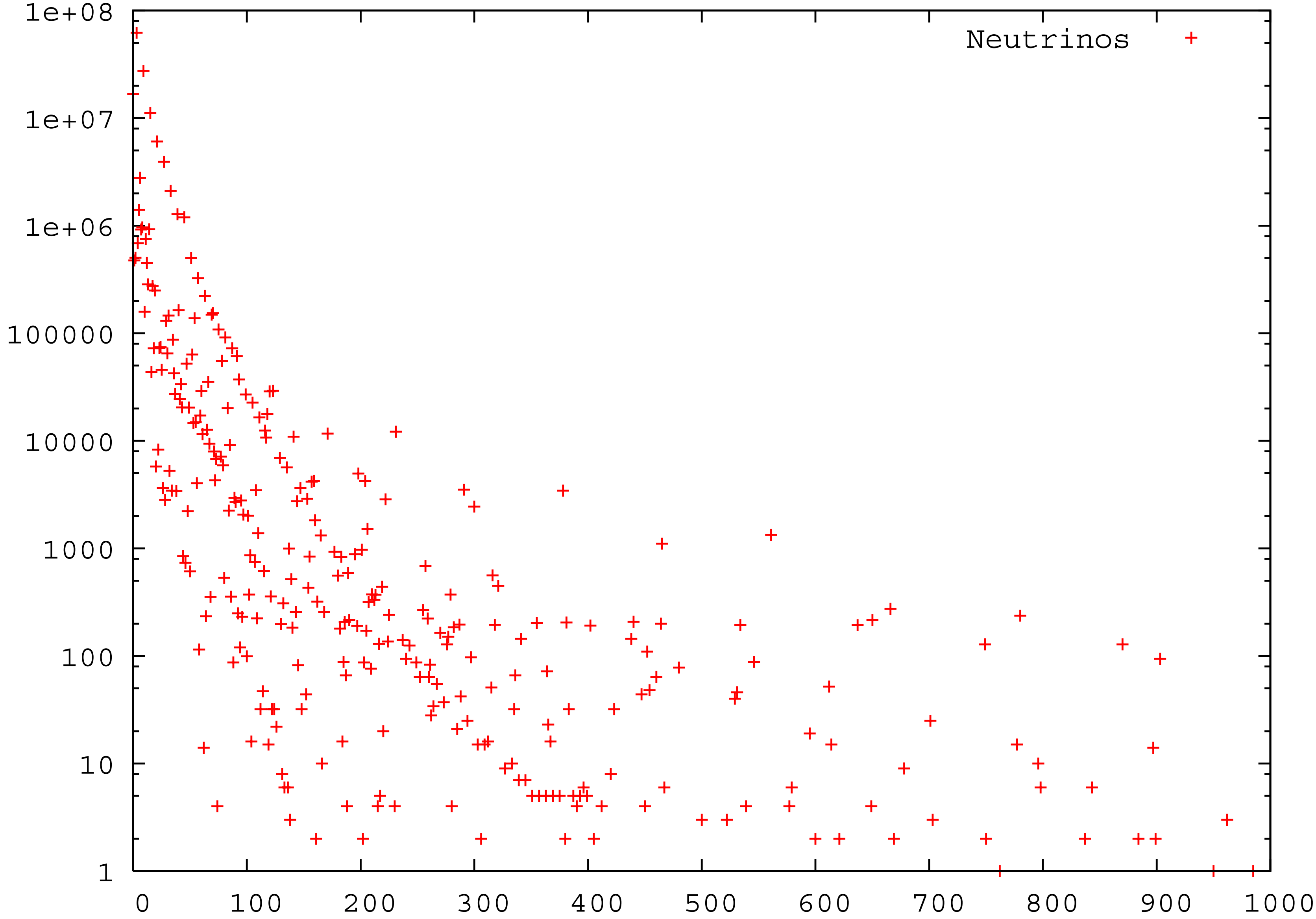
The distribution of tensor representations



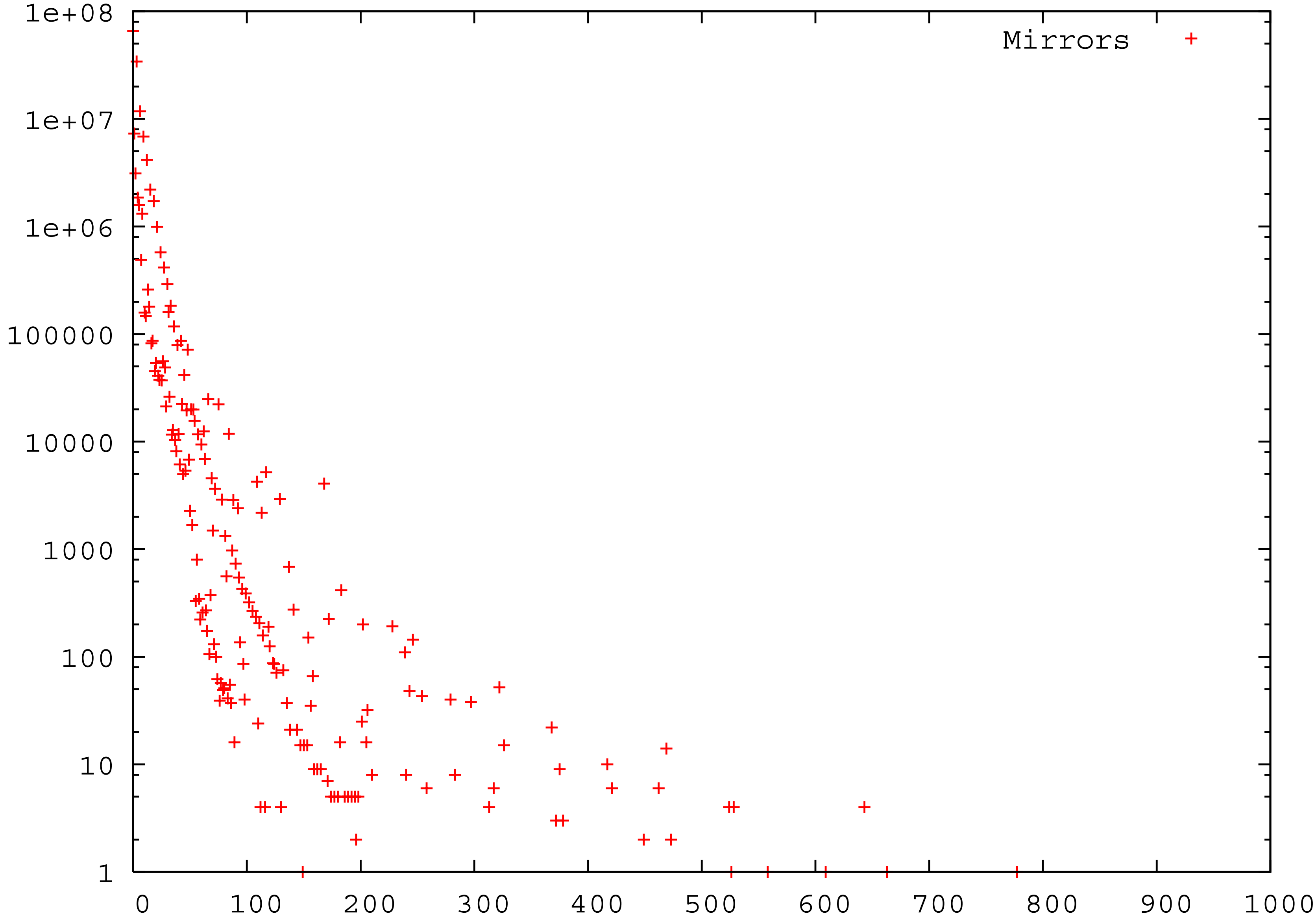
The distribution of potential Higgs pairs



The distribution of right-handed neutrino singlets



The distribution of mirrors



BSM Outlook

- It is not clear how to proceed further, without serious help from mathematics

- It is not clear if we are looking at a single theory with many vacua or a collections of theories that are interconnected like QFTs

- AdS/CFT suggests that the second point of view may be the case, but.....

- New ideas, new tools, and young people are needed to tackle these problems!

Applications: Holography and QCD

• The AdS/CFT correspondence opened the way to understand N=4 sYM in d=4 at strong coupling and large N_c.

• Progress has been made to reduce the theory to an integrable string model.

• How is this helping with QCD?

♠ Two approaches $\to$ The N=4 extrapolation: study N=4 and deformations, and try to calculate in these observables relevant to QCD: give an idea on what strong coupling effects do.

♠ Example: consider a finite temperature N=4 plasma, and study energy loss of a heavy quark: This is not the same as QCD but the mechanism is new and tells us also what to qualitatively expect in QCD.

♠ The Effective Holographic Theory approach (Bottom Up): construct (super) gravity models that come close to QCD using effective reasoning:

For YM, ihQCD is a well-tested holographic, string-inspired bottom-up model with action

Gursoy+Kiritsis+Nitti, 2007, Gubser+Nelore, 2008

$$\mathcal{S}_{\rm g} = M^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3}(\partial\phi)^2 + V_g(\phi) \right]$$

- $g_{\mu\nu}$ is dual to $T_{\mu\nu}$

- ϕ is dual to $tr[F^2]$.

We expect that these two operators capture the important part of the dynamics of the YM vacuum. The vacuum saddle point is given by a Poincaré-invariant metric, and radially depended dilaton.

$$ds^2 = e^{2A(r)}(dr^2 + \eta_{\mu\nu}dx^\mu dx^\nu)$$

- The potential $V_g \leftrightarrow$ QCD β-function

- $A \to \log\mu$ energy scale.

- $e^\phi \to \lambda$ 't Hooft coupling

In the UV $\lambda \to 0$ and

$$V_g(\lambda) = V_0 + V_1\ \lambda + V_2\ \lambda + \mathcal{O}(\lambda^3)$$

In the IR $\lambda \to \infty$ and

$$V_g \sim \lambda^{\frac{4}{3}}\sqrt{\log\lambda} + \cdots$$

• This was chosen after analysing all possible asymptotics and characterising their behavior.

The IR asymptotics is uniquely fixed by asking for confinement, discrete spectra and asymptotically linear glueball trajectories.

Gursoy+Kiritsis+Nitti

• With an appropriate tuning of two parameters in V_g the model describes well both $T = 0$ properties (spectra) as well as thermodynamics.

YM Entropy

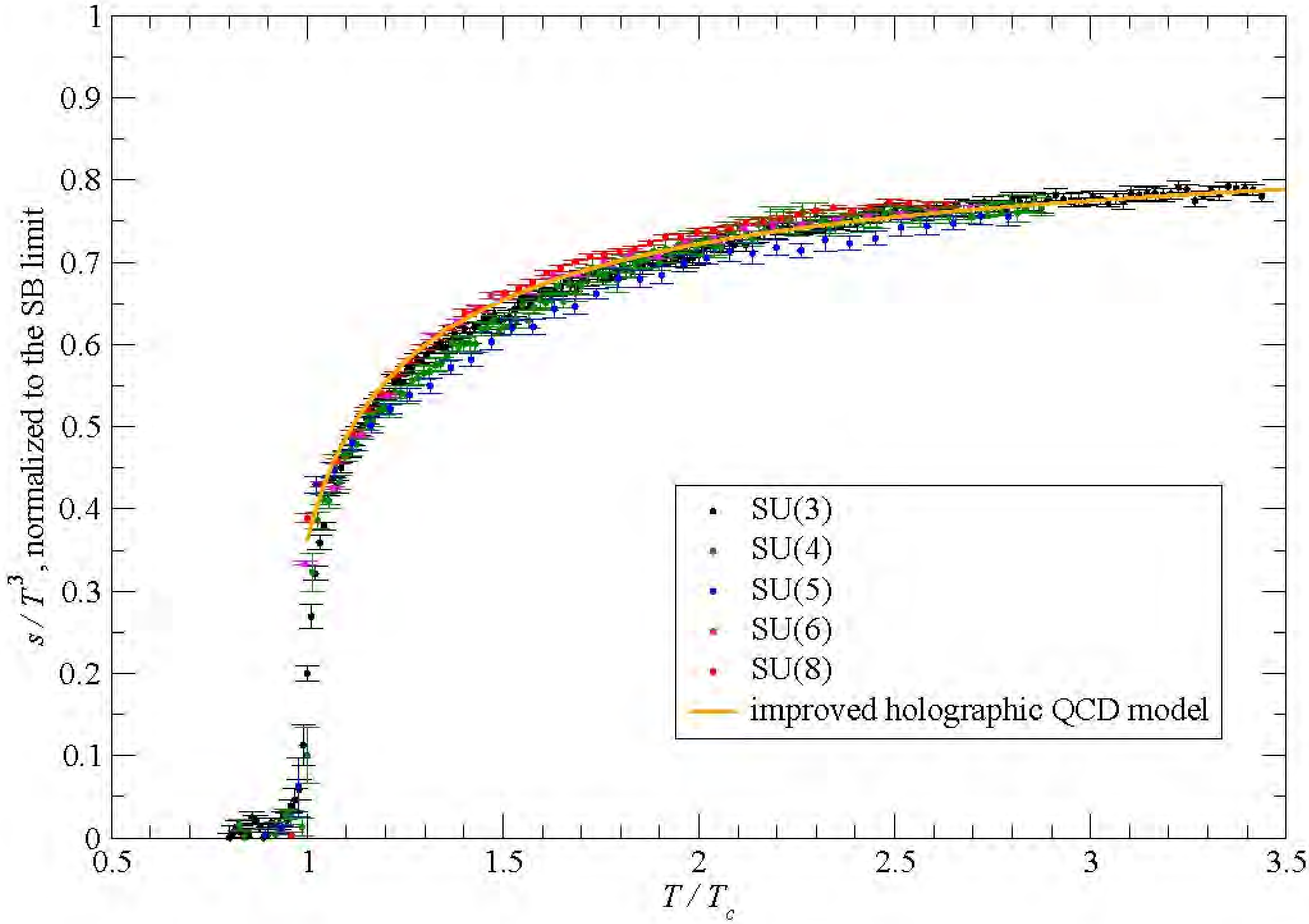


Figure 4: (Color online) Same as in fig. 1, but for the s/T^3 ratio, normalized to the SB limit.

From M. Panero, arXiv:0907.3719

Equation of state

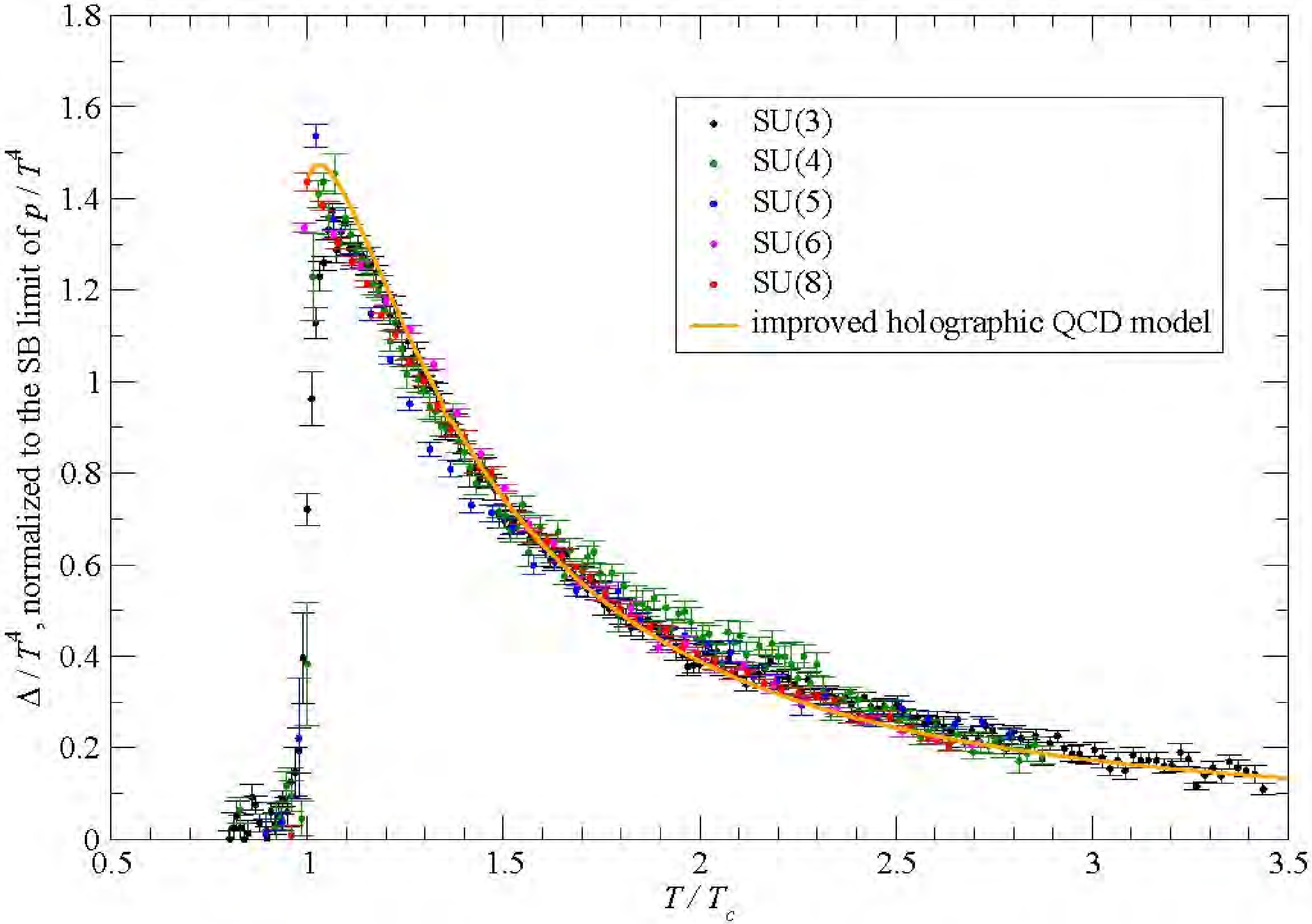
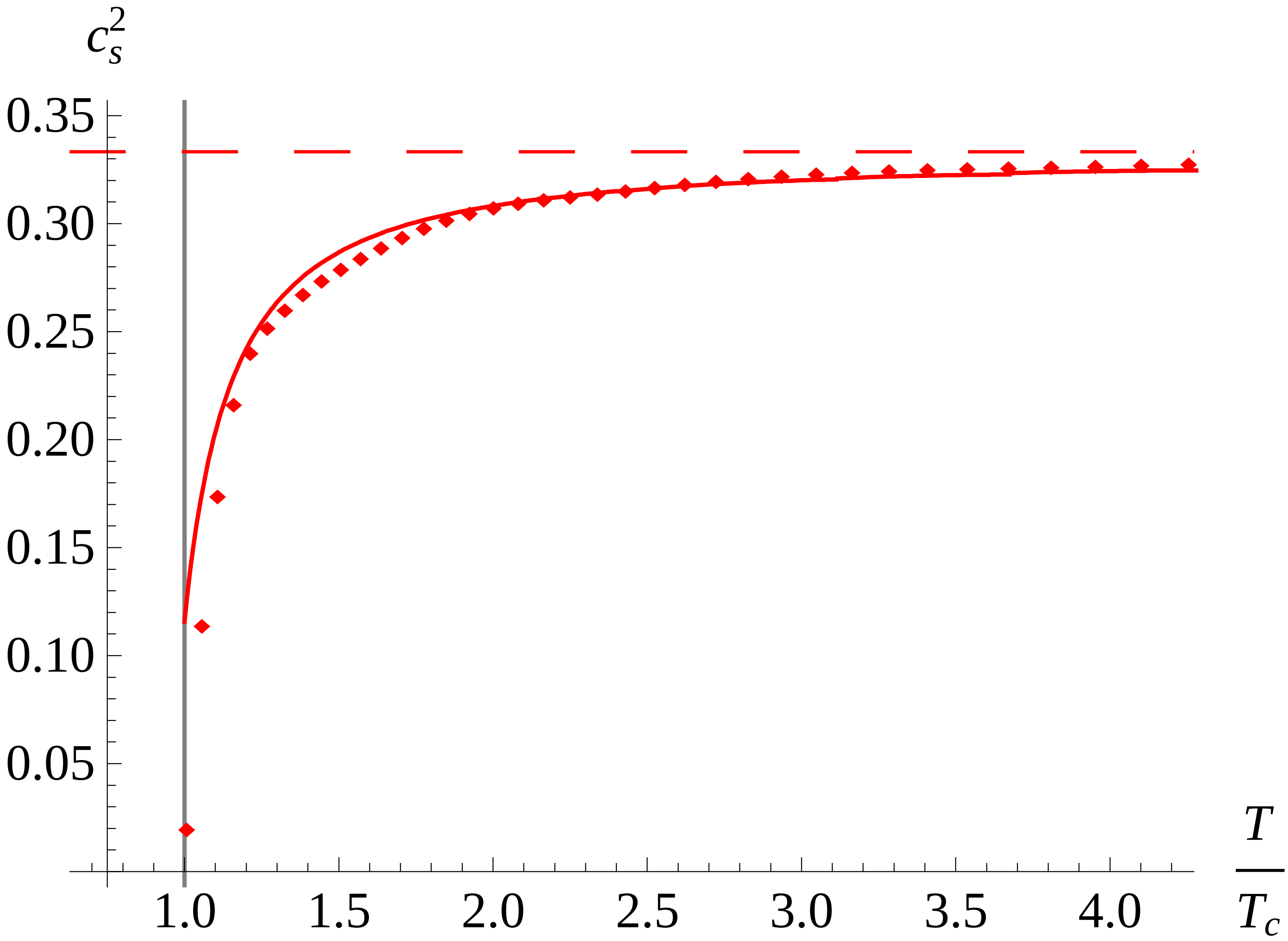


Figure 2: (Color online) Same as in fig. 1, but for the Δ/T^4 ratio, normalized to the SB limit of p/T^4.

From M. Panero, arXiv:0907.3719

The sound speed



The holographic models: flavor

- Fundamental quarks arise from $D4$-$\bar{D}4$ branes in 5-dimensions.

$$D4 - D4 \quad \text{strings} \quad \to \quad A_\mu^L \quad \leftrightarrow \quad J_\mu^L = \bar\psi_L \sigma_\mu \psi_L$$

$$\overline{D4} - \overline{D4} \quad \text{strings} \quad \to \quad A_\mu^R \quad \leftrightarrow \quad J_\mu^R = \bar\psi_R \bar\sigma_\mu \psi_R$$

$$D4 - \overline{D4} \quad \text{strings} \quad \to \quad T \quad \leftrightarrow \quad \bar\psi_L \psi_R$$

- For the vacuum structure only the tachyon is relevant.

- An action for the tachyon motivated by the Sen action has been advocated as the proper dynamics of the chiral condensate, giving in general all the expected features of χSB.

Casero+Kiritsis+Paredes

$$\mathcal{S}_{\text{TDBI}} = -N_f N_c M^3 \int d^5x\ V_f(T)\ e^{-\phi} \sqrt{-\det(g_{ab} + \partial_a T \partial_b T)}$$

- It has been tested in a 6d asymptotically-AdS confining background (with constant dilaton) due to Kuperstein+Sonneschein.

Iatrakis+Kiritsis+Paredes

It was shown to have the following properties:

- Confining asymptotics of the geometry trigger chiral symmetry breaking.

- A Gell-Mann-Oakes-Renner relation is generically satisfied.

- The Sen DBI tachyon action with $V \sim e^{-T^2}$ asymptotics induces linear Regge trajectories for mesons.

- The Wess-Zumino (WZ) terms of the tachyon action, computed in string theory, produce the appropriate flavor anomalies, include the axial $U(1)$ anomaly and η'-mixing, and implement a holographic version of the Coleman-Witten theorem.

- The dynamics determines the chiral condensate uniquely as function of the bare quark mass.

- By adjusting the same parameters as in QCD (Λ_{QCD}, m_{ud}) a good fit can be obtained of the light meson masses.

The chiral vacuum structure

• We take the potential to be the flat space one

$$V = V_0 \; e^{-T^2}$$

with a maximum at $T = 0$ and a minimum at $T = \infty$.

• Near the boundary $z = 0$, the solution can be expanded in terms of two integration constants as:

$$\tau = c_1 z + \frac{\pi}{6} c_1^3 z^3 \log z + c_3 z^3 + \mathcal{O}(z^5)$$

• c_1, c_3 are related to the quark mass and condensate.

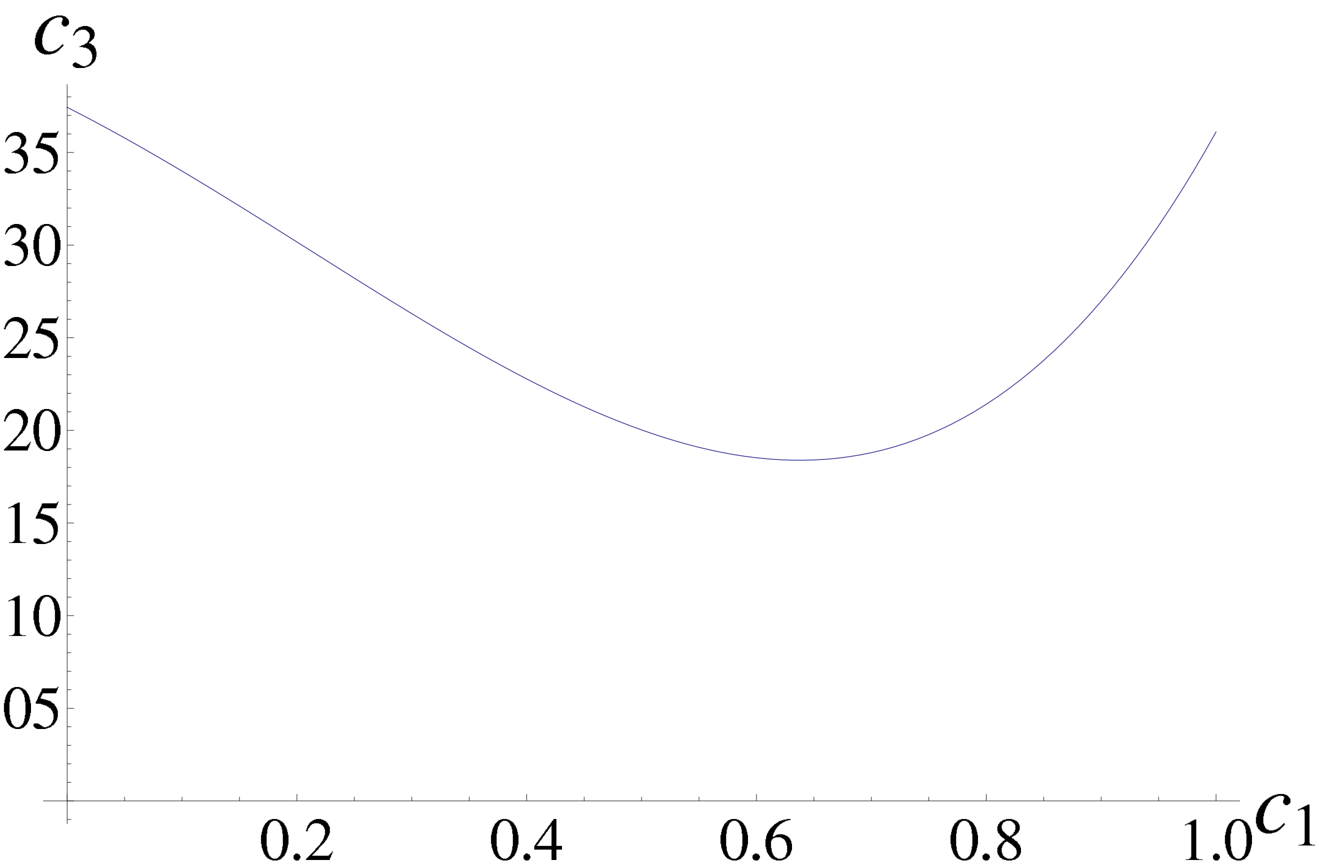
• At the tip of the cigar, the generic behavior of solutions is

$$\tau \sim constant_1 + constant_2 \sqrt{z - z_\Lambda}$$

• With special tuned condition there is a one-parameter family of diverging solutions in the IR depending on a single parameter:

$$\tau = \frac{C}{(z_\Lambda - z)^{\frac{3}{20}}} - \frac{13}{6\pi C}(z_\Lambda - z)^{\frac{3}{20}} + \ldots$$

• This is the correct "regularity condition" in the IR as τ is allowed to diverge only at the tip.

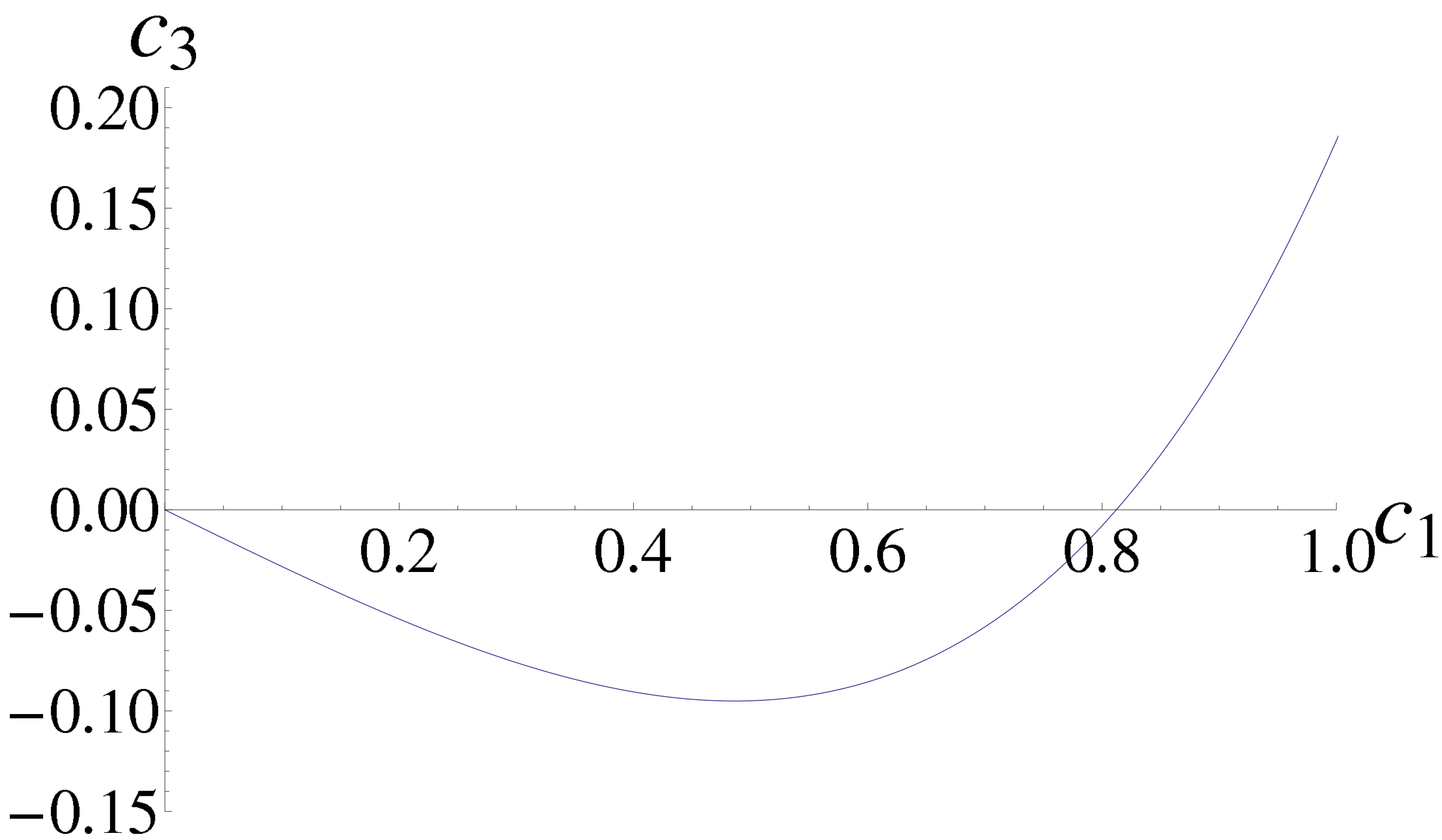


• Chiral symmetry breaking is manifest.

Chiral restoration at deconfinement

- In the deconfined phase, the bulk metric is that of a bh.

- The branes now are allowed to enter the horizon without recombining.



Applications: Condensed Matter

• In CM physics many interesting systems are strongly coupled:

1. Materials at the border with magnetism (Cuprate high-Tc superconductors, pnictides, heavy fermion metals, Al-Mn alloys etc)

2. A variety of Quantum Hall systems

3. Graphene

• Almost always, sign-problems and critical behavior make numerical simulation prohibitive.

• In the UV we have a well understood theory=electrons+ions+photons. Generically

$$\text{potential energy} \quad \gg \quad \text{kinetic energy} \quad \to \quad \text{Strong Coupling}$$

• By "luck" sometimes dressed electrons (quasiparticles) are weakly coupled $\to$ Landau theory of Fermi-liquids $\to$ standard metals.

• In other cases we may expect emergent IR degrees of freedom, that are strongly coupled and YM-like:

1. In spin/fermion systems

Laughlin 80's, Sachdev(2010)

2. Non-abelian CS seems to emerge in several contexts. Coupled to matter $\rightarrow$ M2 class of theories.

Aharony+Bergman+Jafferis+Maldacena (2008)

3. Massless (2+1)-d fermions+EM seem to have a non-abelian large N structure

S. S. Lee (2009), Metlitski+Sachdev (2010), Mross+McGreevy+Liu+Senthil (2010)

• The behavior generated is known as strange metal (non-fermi liquid), and exists in all systems at the border with magnetism.

• They are several benchmarks of non-fermi liquid behavior: 2d-behavior, linear resistivity, linear electronic heat capacity, power scaling of the AC conductivity, etc.

Observables

The most generic and (relatively) easy to measure observables are:

- Equilibrium thermodynamics

a) Entropy, specific heat, other susceptibilities.

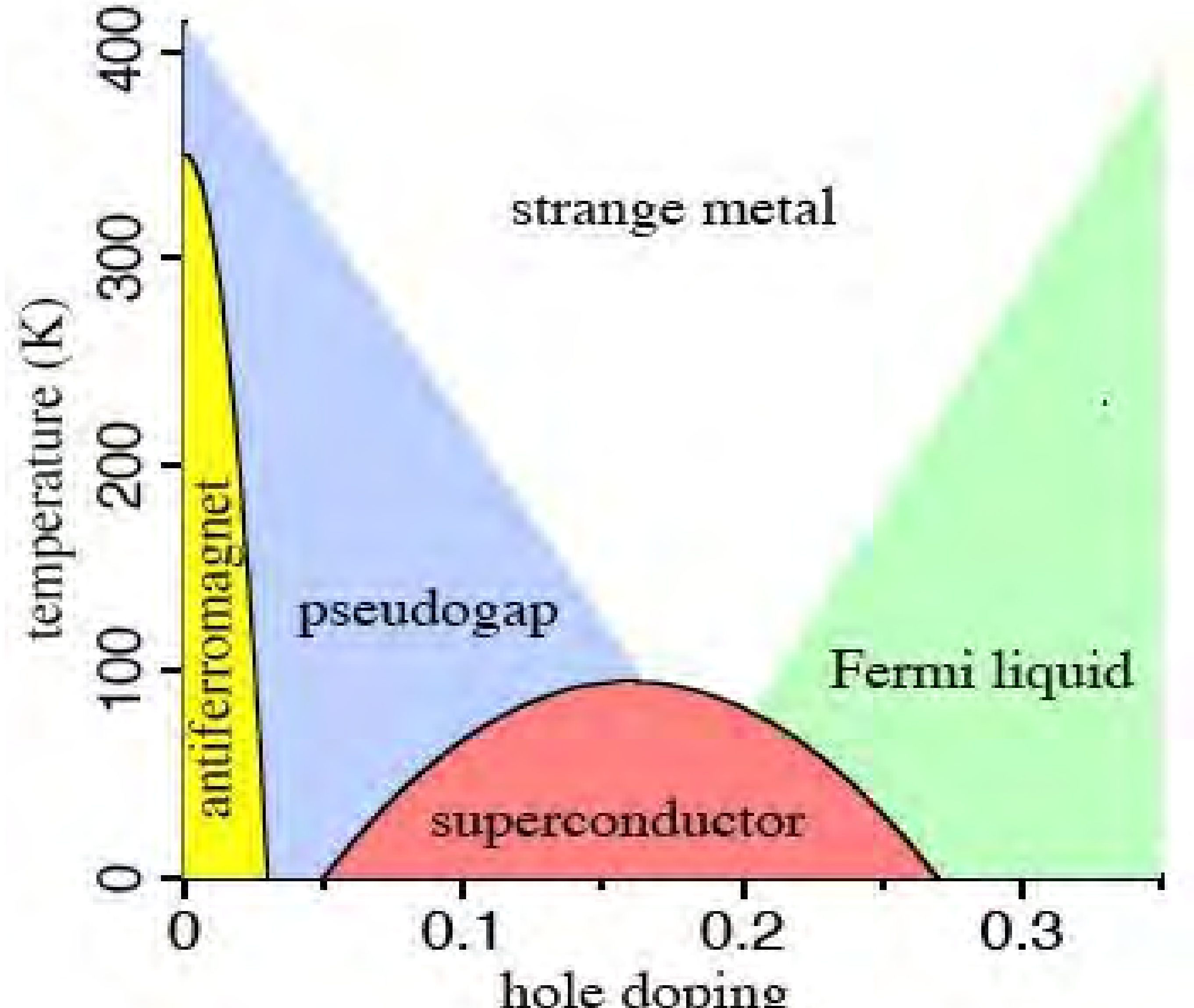
b) Phase structure (phases, order and characteristics of phase transitions)

- Transport

a) Charge transport, conductivities, DC and AC

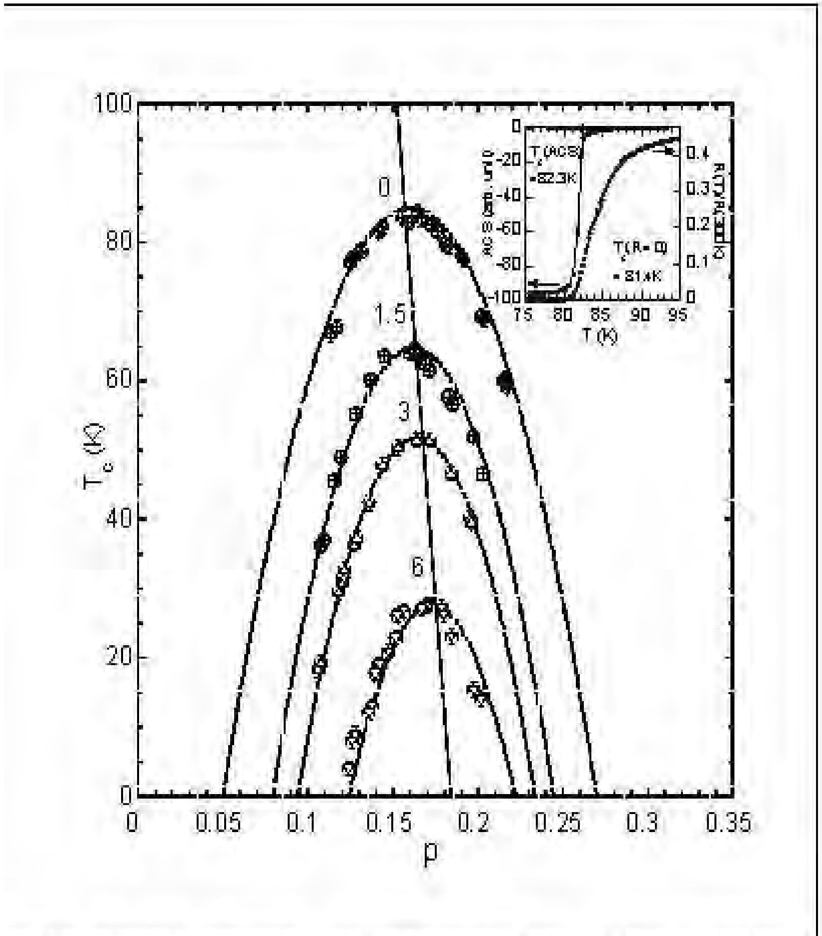
b) transport in presence of magnetic fields

A typical phase diagram

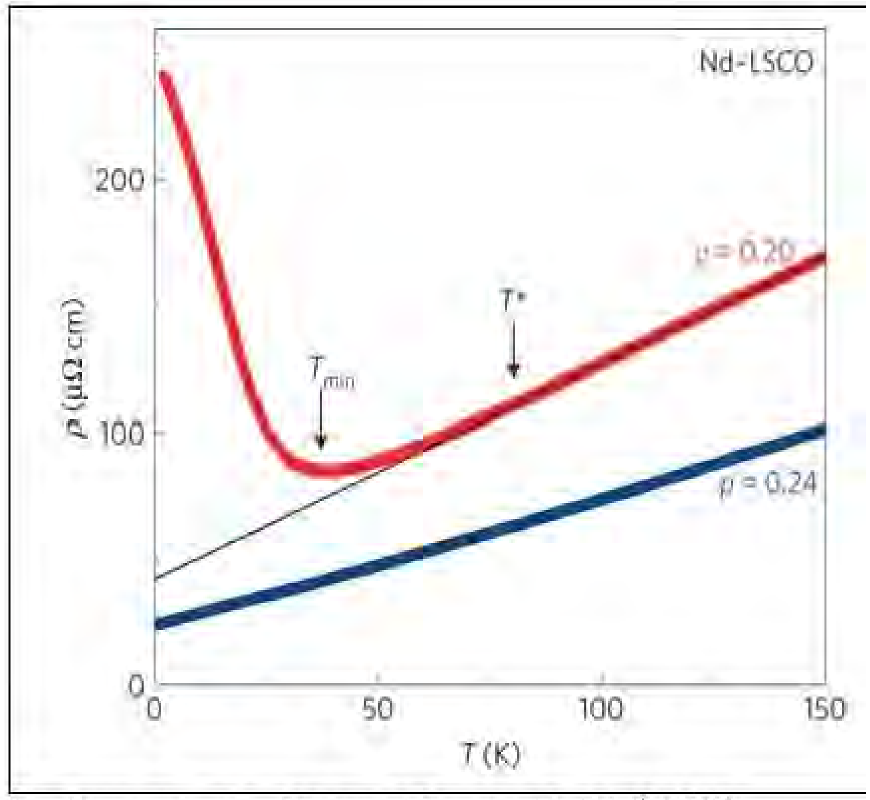


Phase diagram of hole-doped cuprates.In other systems the pseudogap region is much smaller, the superconducting region can shrink to almost nothing etc.

Linear Resistivity



S. H. Naqib et. al., Physica C 387, 365 (2003)



R. Daou et. al., Nature Physics 5, 31 (2009)
& R. A. Cooper, et. al., Science 323, 603(2009)
Nicolas Doiron-Leyraud, et. al., arXiv:0905.0964

- Suppress superconducting dome with *Zn* substitution or large magnetic field
- Linear temperature dependence of resistivity around the critical point

The hope and strategy

• If Quantum Critical (scale invariant) points control the physics, then we should use such scale invariant theories to to explore the physics.

• Before AdS/CFT, only two such theories were known: free field theory and Wilson-Fisher fixed point (ϕ^4). None gives strange metal behavior.

• After holography and ABJM, we have millions of holographic conformal theories plus an Effective Field Theory strategy.

• The hope: that some of them will give computable strange metal physics.

The progress

• The basic Mechanism of Holographic Superconductivity is understood

Gubser, Hartnoll+Herzog+Horowitz

• The strongly-coupled fermionic dynamics in at simple finite density holographic systems provides new non-Fermi liquid behavior.

S.S.Lee, Faulkner+Liu+McGreevy+Vegh, Cubrovic+Schalm+Zaanen

• The presence of unexpected (AdS_2) scaling symmetries at zero temperature and finite density was found.

Faulkner+Liu+McGreevy+Vegh

• Many tools have been developed for the calculation of transport coefficients, notably conductivities.

Policastro+Son+Starinets, Hartnol+Herzog, Karch+O'Bannon

• A infinite class of finite density QC points have been found in general characterized by a Lifshitz exponent z and a hyperscaling exponent θ.

Charmousis+Gouteraux+E.K.+BS Kim+Meyer, Gouteraux+E.K.

• A large subclass of them describe normal systems with linear resistivities.

Hartnoll+Polchinski+Silverstein+Tong, Charmousis+Gouteraux+E.K.+BS Kim+Meyer

A holographic strange metal

.

E.K.+Kim+Panagopoulos

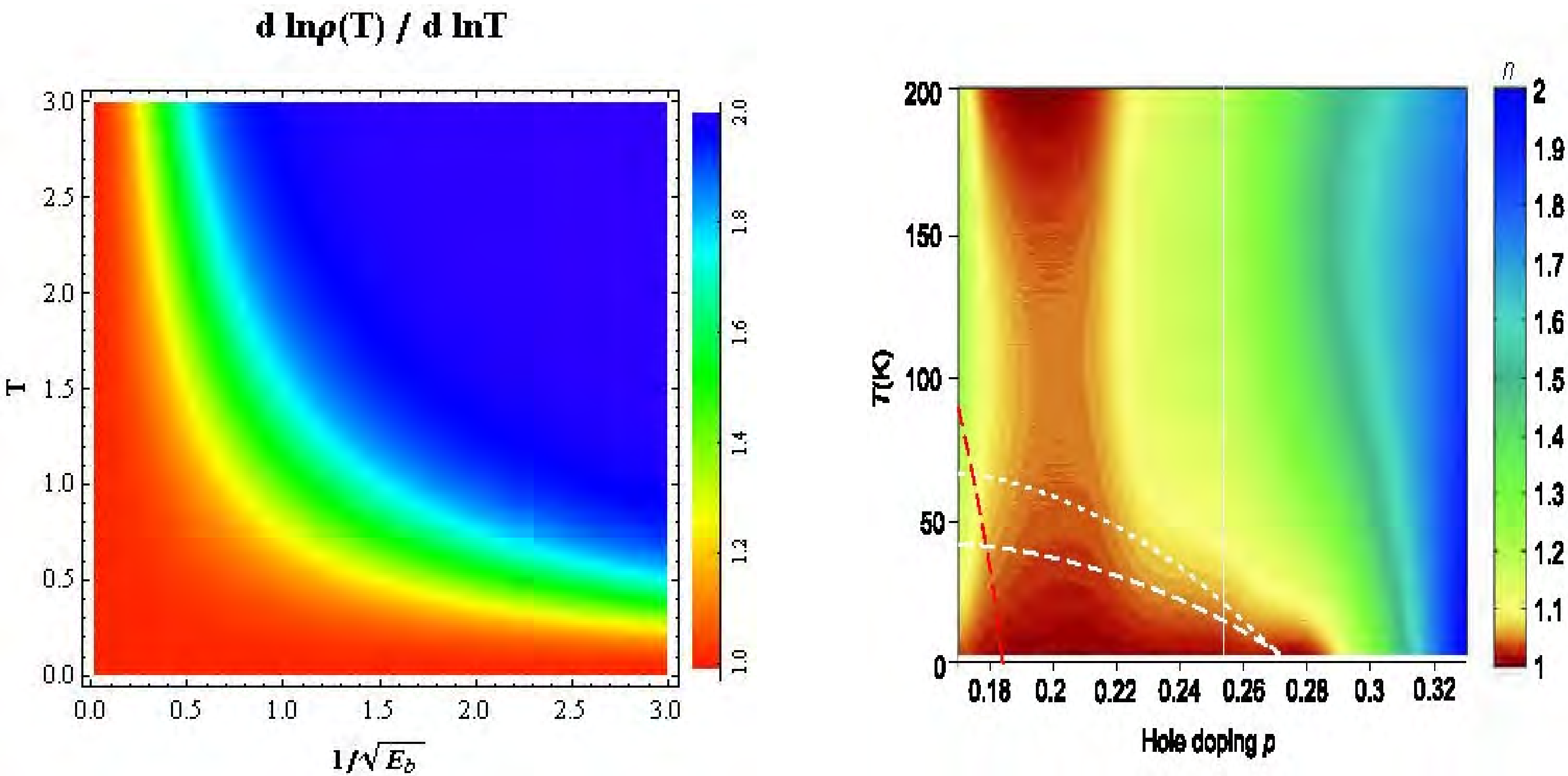
- AdS/Bh in Schrödinger (light cone frame) + probe carriers with light-cone electric and magnetic fields.

$$\sigma^{xx} = \sigma_0 \frac{\sqrt{\mathcal{F}_+ J^2 + t^4 \sqrt{\mathcal{F}_+}\mathcal{F}_-}}{\mathcal{F}_-} \;, \qquad \sigma^{xy} = \bar{\sigma}_0 \frac{\mathcal{B}}{\mathcal{F}_-} \;,$$

$$\mathcal{F}_\pm = \sqrt{\left(\mathcal{B}^2 + t^4\right)^2 + t^4} \mp \mathcal{B}^2 + t^4 \;,$$

where

$$\bar{\sigma}_0 = \frac{\langle J^+ \rangle}{b E_b} \;, \qquad \mathcal{B} \simeq \frac{B_b}{E_b} \;, \quad t \simeq \frac{T}{\sqrt{E_b}}$$



The exponent of $\frac{d \ln \rho(T)}{d \ln T}$ as a function of a tuning parameter $\frac{1}{\sqrt{E_b}}$ and temperature T at low temperatures. Note that the linear temperature dependence of the resistivity extends over the low temperature range, with $\rho \sim T + T^2$. Left plot from Fig. 3 of Science **323**, 603 (2009)..

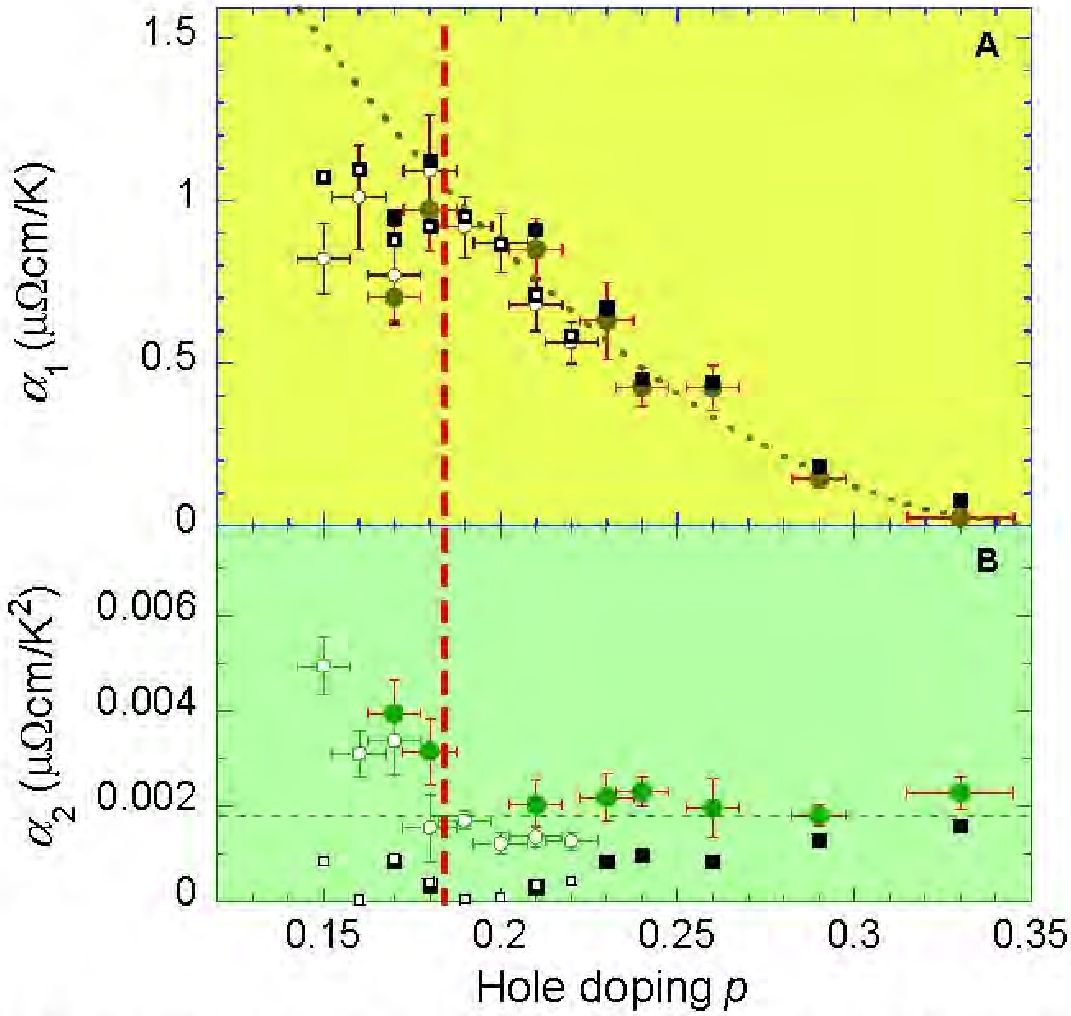
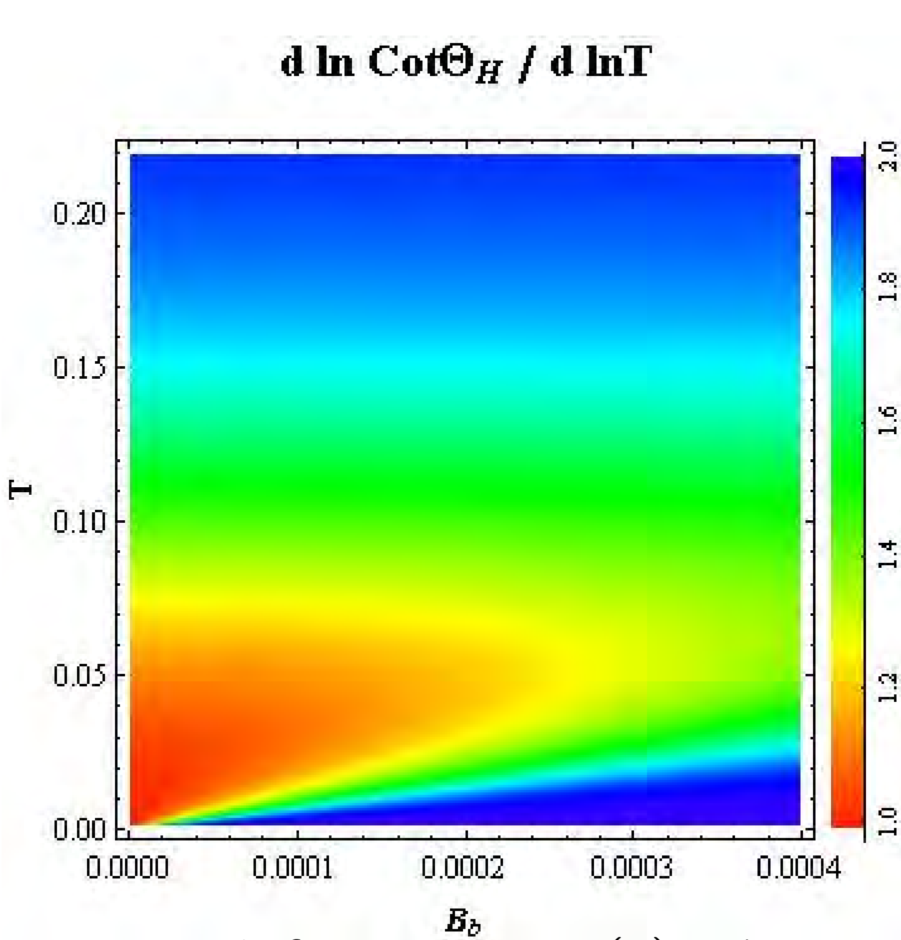
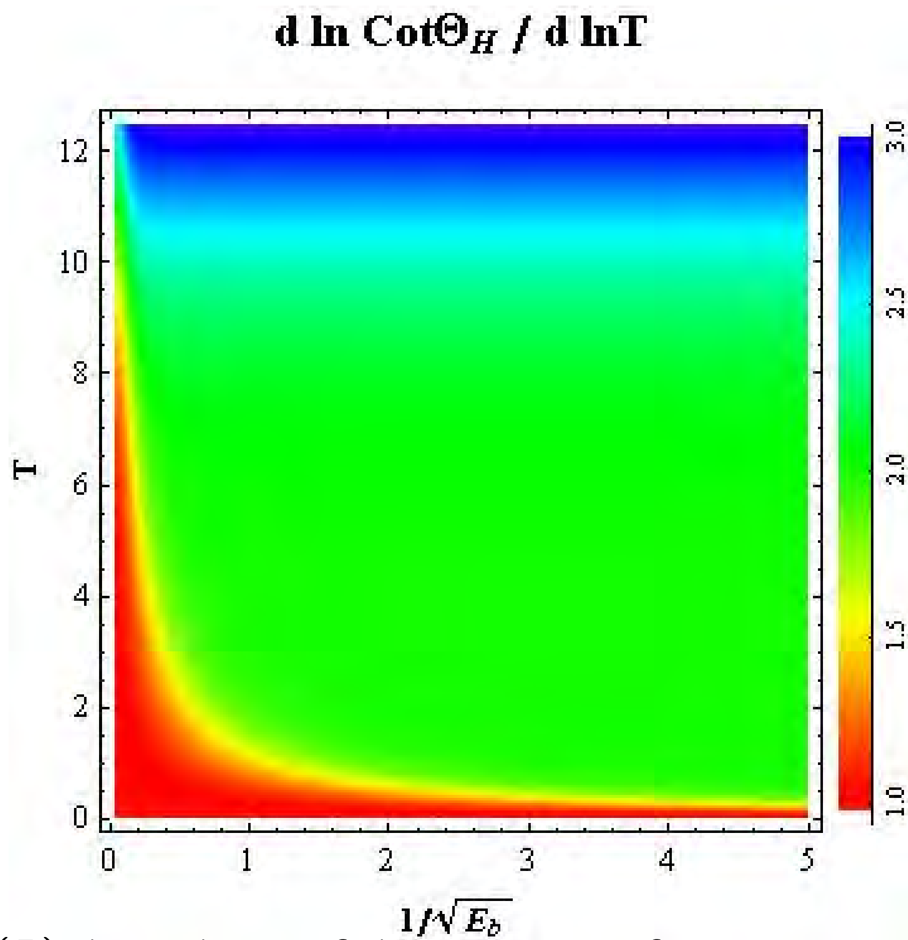


Fig. 4. Doping evolution of the temperature-dependent coefficients of $\rho_{ab}(T)$. (**A**) Doping dependence of α_1, the coefficient of the T-linear resistivity component. (**B**) Doping dependence of α_2, the coefficient of the T^2 resistivity component. In both panels, solid squares are coefficients obtained from least-square fits of the $\rho_{ab}(T)$ curves for $T \leq 200$ K to the expression $\rho_{ab}(T) = \alpha_0 + \alpha_1 T + \alpha_2 T^2$, whereas the solid circles are obtained from fits over the same temperature range to a parallel-resistor formalism $1/\rho_{ab}(T) = 1/(\alpha_0 + \alpha_1 T + \alpha_2 T^2) + 1/\rho_{max}$ with $\rho_{max} = 900 \pm 100$ μohm cm. The open symbols are obtained from corresponding fits made to the $\rho_{ab}(T)$ data of Ando *et al.* (*5*) between 70 K and 200 K. The dashed lines are guides to the eye. The error bars are a convolution of standard deviations in the values of α_1 and α_2 (1σ) for different temperature ranges of fitting plus systematic uncertainty in the absolute magnitude of ρ_{max}.



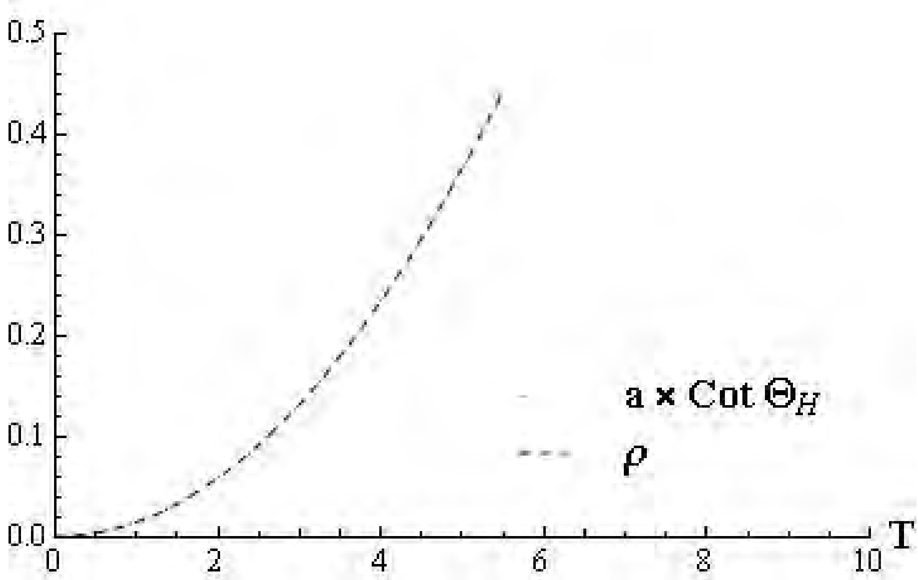


Left: Temperature (T) and magnetic field (B) dependence of the exponent of

$$\cot\Theta_H \equiv \frac{\sigma^{xx}}{\sigma^{xy}}$$

in the low T, low B regions.

Right: the effective power dependence of $\cot\Theta_H$ at small magnetic field, as a function of temperature and $1/\sqrt{E_b}$.



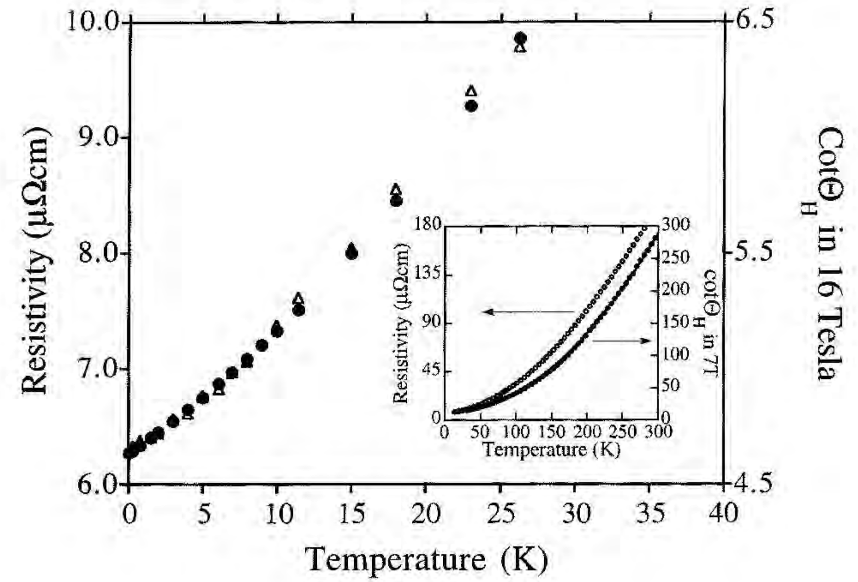
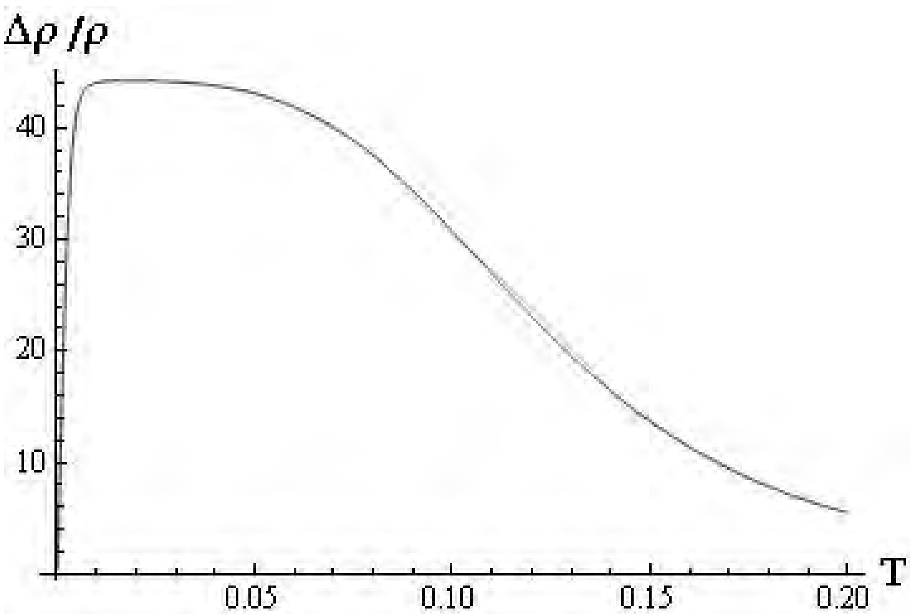


FIG. 9. The cotangent of the Hall angle and the resistivity plotted on linear axes in the low-temperature and (inset) high-temperature regimes. The high-temperature data for cotΘ_H vary as

Plot of the resistivity and inverse Hall angle, in the model, for the low-temperature regime with small magnetic field. Note that the inverse Hall angle has been scaled by a constant factor $a = B_b/(32\sqrt{2}\langle J^+\rangle$. This plot is to be compared with left figure from McKenzie et al. Phys. Rev. B **53**, 5848 (1996).



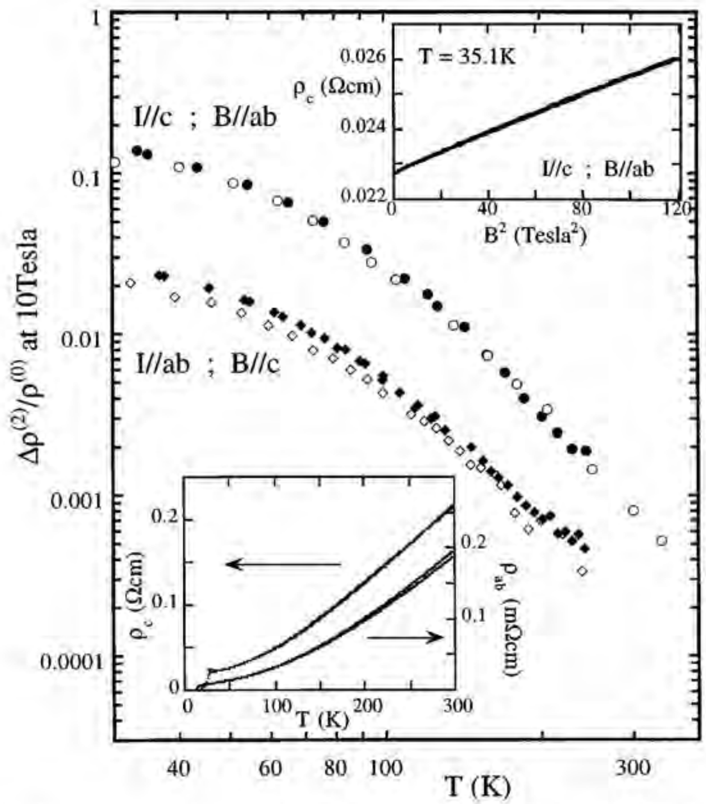
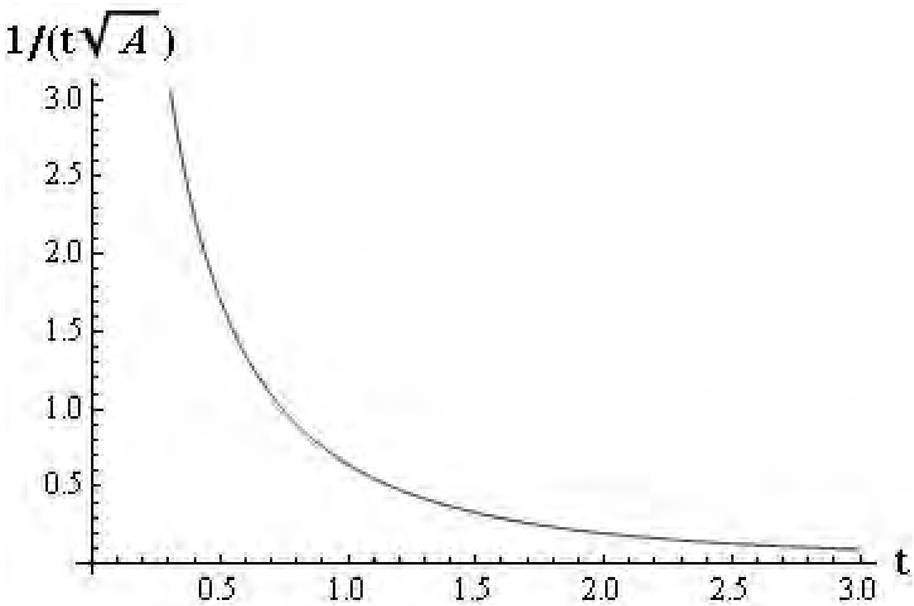


FIG. 1. T dependences of the B^2 terms $\Delta\rho^{(2)}/\rho^{(0)}$ at 10 T for c-axis MR (circles) and a-b plane MR (diamonds) in overdoped $Tl_2Ba_2CuO_6$. Data for two crystals are shown in each case.

The plot depicts the magnetoresistance

$$\frac{\Delta\rho}{\rho} \equiv \frac{\rho_{xx}(B) - \rho_{xx}(0)}{\rho_{xx}(0)} .$$

for a heavily overdoped sample at lower temperature, which is to be contrasted the left figure from Hussey et al. Phys. Rev. Lett. **76**, 122 (1996).



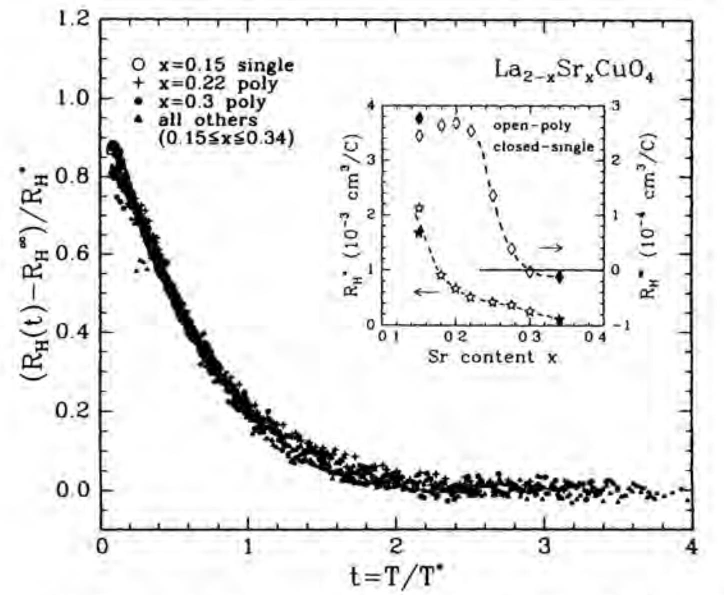


FIG. 2. The Hall coefficient (R_H) for $La_{2-x}Sr_xCuO_4$ with $0 \le x \le 0.34$, plotted rescaled as $[R_H(t) - R_H^\infty]/R_H^*$ vs t, where $t = T/T^*$. R_H^∞ is the high temperature limit of R_H, R_H^* rescales the magnitude, and T^* is the temperature scale. Inset: The parameters R_H^∞ and R_H^* vs Sr composition x. Note the rapid dropoff of R_H^∞ above $x = 0.2$.

Temperature dependence of the normalized Hall coefficient.

$$R_H \equiv \frac{\rho_{xy}}{B}$$

We compare this to the plot (left) of the quantity, $\frac{R_H(T/T_*) - R_H(\infty)}{R_H^*}$ in Hwang et al., Phys. Rev. Lett. **72**, 2636 (1994).

• Köhler rule for metals:

$$K = \rho^2 \frac{\Delta\rho}{\rho}$$

is independent of temperature. This is claimed to fail for YBCO and LSCO above 50 K (Harris et al..) Instead, a modified Köhler rule is valid

$$(\cot\Theta_H)^2 \frac{\Delta\rho}{\rho}$$

is independent of temperature.

At low temperatures ($T < 20$ K) however both are correct!!!

Outlook

- String theory has been around for 44 years.

- In the process it has stimulated enormous progress both for gravity and QFTs.

- We are far away of controlling string theory, as our tools are still very primitive.

- It has had an important impact in efforts of unification.

- It has provided mathematics with a load of interesting oroblems to solve.

- It seems to be a new and powerful tool for QCD

- It may have an impact in condensed matter problems,

- and who knows what else...

.

Thank you

Detailed plan of the presentation