String Phenomenology 2010
Paris, 8 June 2010

Gravity and axions from the chaotic gauge theory landscape

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Introduction

- Gravity is the oldest known but least understood force.

- The biggest puzzles today (dark energy and the cosmological constant problem) have gravity as their weak link.

- The major clash seems to be between gravity and the quantum theory.

• A proposal will be entertained that at the conceptual level borrows from several past ideas:

♠ The Aristarchus-Copernicus (AC) view that we are (probably) not at the center of the "universe".

♠ The H. Nielsen postulate (from the '80s) that the QFT describing physics in the UV is "large" and (almost) random.

♠ The idea that slowly emerged from high-energy physics that there are "hidden sectors" that are barely visible (or completely invisible) to us.

♠ The gauge-gravity correspondence that provided a fresh look both at gauge theories and the gravitational/string forces.

• Similar ideas have been discussed before, but have been since refined.

E. K. hep-th/0310001v2 (sections 7.5,7.8) Physics Reports 421:105-190,2005

WARNING: They are still speculative, and more effort is needed to make them precise.

The logic

• Gravity is the generic property/interaction of (closed) string theories.

• It can be generated effectively by many types of QFTs, in particular by 4d QFTs

• Assumption No 1. The complete description of physics is via UV-complete 4d QFTs

• Assumption No 2. The UV QFT is enormous and "random"

• Parts of this QFT are communicating via massive "messenger" fields

• The Standard Model is a tiny piece of the UV QFT.

• The physics they communicate to the Standard Model depends crucially on the "size" of the QFT

• A important avatar of the presence of large QFTs in the UV is the appearance of "gravity" (and PQ axions) in the SM.

String theory and Gravity

• String theories have been traditionally defined via 2-d σ-models.

• The string coordinates (bosonic or fermionic) are 2d-quantum fields.

• Continuum σ-models are CFTs and are parametrized by "coupling constants" that correspond to the massless (or tachyonic) string modes.

• The relevant couplings involve the σ-model coupling constant $\frac{\ell}{\ell_s}$ and g_s that controls string interactions BOTH at tree level and loops.

• In a sense, the "loop-expansion" is not inherent in the σ-model. It is an added ingredient. Also the space-time is "emergent": the coordinates are (2d) quantum fields and the metrics are coupling constants.

• Closed strings always include gravity. UV divergences are simply cutoff by the smart world-sheet cutoff of Riemann surfaces.

• The relevant conditions for conformal invariance have a simple expansion at weak σ-model coupling. For example, the dilaton β-function reads

$$\beta_\Phi = \left(D_b + \frac{1}{2}D_f\right) - D_{crit} + \frac{3}{2}\ell_s^2\left[4(\nabla\Phi)^2 - 4\Box\Phi - R + \frac{1}{12}H^2\right] + \mathcal{O}(\ell_s^4)$$

$D_{crit} = 26$ for the bosonic string and 15 for the fermionic strings.

• At weak coupling, conformal invariance imposes the critical dimension:

$$\left(D_b + \frac{1}{2}D_f\right) = D_{crit}$$

curvature corrections are small and the backgrounds are slowly varying.

• Subcritical strings, with $\left(D_b + \frac{1}{2}D_f\right) < D_{crit}$ quickly run to large curvatures and therefore to strong σ-model coupling. The relevant "flow" equations (summarized by the two derivative effective action) have AdS-like solutions.

• In the supercritical case with $\left(D_b + \frac{1}{2}D_f\right) > D_{crit}$ the equations have deSitter-like solutions.

Strings/Gravity from 4D gauge theories

• Strings emerge from higher-d QFTs in d=3,4 and maybe in d=6. I will focus in d=4 where the main QFT is a gauge theory coupled to fermions and scalars.

• Continuum string theories will emerge from conformal gauge theories.

• At weak coupling and large enough N, the main contributions to the β functions come from adjoints (orientable case)

$$\beta(g) = -\frac{g^3}{(4\pi)^2}\left\{\frac{11}{3} - \frac{2}{3}N_F - \frac{N_s}{6}\right\}N - \frac{g^5}{(4\pi)^4}\{34 - 16N_F - 7N_s\}\frac{N^2}{3} + \cdots$$

with N_f Majorana fermions and N_s scalars in the adjoint of SU(N).

• The vanishing of the one-loop piece is analogous to being in the critical dimensions in the σ-model definition of string theory. There are two special cases:

♠ $N_f = 4, N_s = 6$, that includes the case of $\mathcal{N} = 4$ sYM. The higher loop contributions to the β-functions are cancelled by Yukawa and quartic scalar contributions.

• The maximal global symmetry in this case is $SO(6)$, realized in a minimal geometrical fashion on an S^5.

• The "emergent" geometrical dual holographic picture (at large N) involves also AdS_5 that geometrically realizes the conformal invariance. The gauge theory develops "extra dimensions" to total of 10. This is type-II superstring theory.

Maldacena

• The theory contains fermionic gauge invariant operators, and therefore there are space-time fermions in the string theory.

• There are other fixed points with $N_f = 4, N_s = 6$ that should also be described by the same superstring theory.

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• Another special case: $N_f = 0, N_s = 22$. In this case higher terms in β functions may be stabilized but probably at strong coupling.

• The maximal global symmetry is SO(22), and in a holographic dual it is geometrically realized by an S^{21}.

• Together with the conformal factor, the backgrounds makes $\mathrm{AdS}_5 \times S^{21}$ and is 26 dimensional.

• The associated gauge theory seems to correspond to a bosonic string. There are only bosonic gauge-invariant operators. But it can be shown that it is **a "bosonic" superstring.**

• It is not obvious whether an exact $AdS_5 \times S^{21}$ solution exists bosonic superstring (like type 0) . There are Bank-Zaks-like fixed points in 25 dimensions involving the condensation of flavor branes, that are conformal and may be related.

There are other cases that are "critical" for example

• $N_s = 18, N_f = 1$. The maximal symmetry here is $O(18)$ as the fermionic U(1) is anomalous. The expectation therefore is that in the most symmetric case the background will be $AdS_5 \times S^{17}$ and may correspond to a novel fermionic non-supersymmetric string theory in 22 dimensions. Yukawa couplings with fiber S^1 over S^{16}

• $N_s = 14$, $N_f = 2$. The maximal symmetry is O(14) for the bosons and SU(2) for the fermions. As there are always Yukawas in this case, the SU(2) will be embedded in O(14), and the expected internal space will probably be a fibering of S^3 over S^{10} leading to a fermionic non-supersymmetric string theory in 18 dimensions.

• $N_s = 10$, $N_f = 3$. The maximal symmetry is O(10) for the bosons and SU(3) for the fermions. As there are always Yukawas in this case, the SU(3) will be embedded in O(10), and the expected internal space will probably be an $SU(3)/SU(2) \times U(1)$ fibered over $S^2 \times S^3$ leading to a fermionic non-supersymmetric string theory in 14 dimensions. Etc...

• The evidence for such more exotic fermionic string theories is so far slim, but can be made more solid by investigating the RG patterns of appropriate gauge theories.

The UV Landscape of 4D gauge theories

♠ Our goal will be to derive (observable) gravity from the UV landscape of 4D gauge theories.

• We postulate that the UV theory is a 4D QFT (gauge theory) that is

1. Enormous and "Random"

H. Nielsen

2. UV complete (Conformal or AF). This does not prohibit IR free theories at low energies.

• The gauge group structure is $\prod_i G_i$. The SM group is a small part of this.

• Generically the G_i are groups of large rank. Focus on $SU(N_i)$ but conclusions are general.

• UV completeness is a very strong constraint. It is more stringent for larger N_i. Matter can only be in the representations, (adjoint, $\begin{smallmatrix}\square\\\square\end{smallmatrix}$ and $\square\square$, $\square$). Otherwise they can be vectors, fermions or scalars.

• An important issue is communication between groups:

1. Matter ϕ_{ij} charged under both (G_i, G_j). Such fields must have non-zero (large) mass. They are the messengers.

For $N_i \gg 1$ they must be generically bifundamentals to not spoil UV completeness (fundamental messengers). Sometimes, for small rank, adjoints, and (A,S) reps can also be allowed (exceptional messengers). When integrated out, they generate double/multiple trace interactions between G_i and G_j.

2. Double trace interactions in the UV.

These can be relevant or marginal in a few cases of strongly coupled CFTs. At low energy they look similar to 1. but not at high energy. At large N_i they lead to boundary-boundary interactions of independent string theories.

, Kiritsis, Aharony+Clark+Karch, Kiritsis+Niarchos

♠ There are groups that communicate directly with the SM, and groups that do not. The ones that are relevant (to leading order) are those that do.

The leading IR interactions

• A generic simple group factor G_i of the UV theory is characterized by a rank N_i, and a gauge coupling constant λ_i as well as other couplings (Yukawa, quartic etc).

• If the theory is AF, then the spin-two glueball (as well as others) will be massive. Its mass is given by the characteristic scale Λ_i generated by dimensional transmutation. Unless this mass is unnaturally low, such glueballs that will be eventually weakly coupled to the SM (via gravitational messengers) will not be easily visible.

• If the theory is conformal, then there is a continuum of spin-two modes and these will survive in IR physics. The conclusion is that (not surprisingly) only CFTs can give effects in the SM at the extreme IR.

• Two more factors are important: λ_i and N_i.

• Intuition from AdS/CFT suggests that at weak coupling, RG instabilities are generic and important.

• Relevant operators generically destroy the conformal invariance in the IR, and therefore the chance that the CFT is "visible" to other sectors at low energy.

• A stable CFT has no relevant operators. Weak coupling CFTs have ALWAYS, many relevant operators (fermion bilinears, scalar bilinears and trilinears etc.).

• Supersymmetry helps but susy will be eventually broken by messagers. The expectation is that stable CFTs will have strong coupling.

• Large N CFTs will also dominate smaller N CFTs. The reason is that they are IR stable against messenger perturbations.

• The conclusion is that the leading relevant IR couplings to the SM will come from a QFT that

1. Has messenger couplings to the SM
2. Is a CFT
3. Has the largest possible N and the largest possible λ.

It has therefore a dual realization in terms on AdS geometry in more than 4 dimensions. The (emergent) dimensionality depends on the details of that CFT, is at least 5 and can be more than 10.

Coupling spin-2 fields

• Consider two finite rank CFTs coupled via messenger fields of mass M. Integrating them out induces a coupling in the EFT of the form

$$\int d^4x \quad \frac{T_1^{\mu\nu} T_{2,\mu\nu}}{M^4}$$

• Consider large rank (strongly coupled) CFT coupled to a finite rank CFT via messengers. Integrating them out induces at the linearized level

$$\int d^4x \sqrt{\hat{g}_1} \; \delta\hat{g}_1^{\mu\nu} \; T_{2,\mu\nu} \quad , \quad r = M$$

• Consider two large rank CFTs coupled to a finite rank CFT via messengers of mass M.

• The dual (geometrical) description is The product of two AdS spaces with their own string theory on them (with different, M_5, ℓ_{AdS}, N) "glued" at $r = M$. One of the two gravitons remains massless while the other acquires a mass at one-loop.

Kiritsis, Aharony+Adam+Karch

$$M_g^2 = h^2 \left(\frac{1}{c_1 \ell_1^2} + \frac{1}{c_2 \ell_2^2}\right) \frac{\Delta_1 \Delta_2 d}{(d+2)(d-1)} \sim h^2 \left(\frac{1}{N_1^2 \ell_1^2} + \frac{1}{N_2^2 \ell_2^2}\right) \frac{\Delta_1 \Delta_2 d}{(d+2)(d-1)}$$

$$\int d^4x \sqrt{\widehat{g}_1}\ \delta \widehat{g}_1^{\mu\nu}\ \delta \widehat{g}_2^{\mu\nu}$$

A messenger-friendly SM

• What kind of gravitational messengers are needed? What kind of SM structure is needed?

• As mentioned, the messengers must be bifundamentals for UV completeness*. They must be bosons and fermions to couple to all SM particles. We assume A^i_μ, χ^i, where i is a SM index, and the hidden SU(N) color is not shown.

• In order to have RENORMALIZABLE couplings of every SM field to two gravitational messenger fields, the SM must be written in a way that all representations are of the "bifundamental type".

• This can be done in several ways that have been classified when the embeddings of the SM spectrum in string-theory orientifolds was classified.

Anastasopoulos+Dijkstra+Kiritsis+Schellekens

• An orientable example is (including massive anomalous U(1)'s), with $Y = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$.

particle	$U(3)_c$	$SU(2)_w$	$U(1)$
$Q(\mathbf{3},\mathbf{2},+\frac{1}{6})$	V	V	0
$U^c(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	$\bar{V}$	0	V
$D^c(\bar{\mathbf{3}},\mathbf{1},+\frac{1}{3})$	$\bar{V}$	0	$\bar{V}$
$L\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$\bar{V}$	V
$e^c(\mathbf{1},\mathbf{1},+1)$	0	0	$\bar{S}$
$\nu^R(\mathbf{1},\mathbf{1},0)$	0	A	0
$H(\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$\bar{V}$	V

• If we denote the SM particles as B_μ^{ij}, q^{ij}, H^{ij} then the relevant couplings are

$$\bar{q}^{ij}\gamma^\mu\chi_i^a A_\mu^{a,j} \quad , \quad B_\mu^{ij}\bar{\chi}_i^a\gamma^\mu\chi_j^a \quad , \quad H^{ij}\bar{\chi}_i^a\chi_j^a$$

• There are subtler issues with the extra U(1)'s that must be always present and they are anomalous.

On the equivalence principle (I)

• In the absence of scalars in the SM, the issue of universality of the gravitational couplings is trivial.

• The metric couples to all spin two operators.

• Those that have dimension > 4 have a coupling suppressed by the gravitational messenger mass $\Lambda_{mes} \sim M_P$.

• If there are relevant couplings in the SM, then there could be "anomalous" gravitational couplings proportional to positive powers of Λ_{mes}.

• The SM (with composite Higgs) does NOT have relevant couplings.

• Marginal scalar operators of the large-N CFT can spoil the equivalence principle (more later).

RS without Randall and without Sundrum

• A caricature of the physics is given by a probe (stack of) branes (eg the SM) in a RS-like background.

$$S_{CFT} = M_5^3 \int d^5x \sqrt{g} \left[R_5 + \frac{12}{\ell^2} \right] + S_{SM}(\hat{g}) \quad , \quad (M_5 \ell)^3 = N^2$$

• There is NO UV cutoff in the 5d-geometry

• There is no IR cutoff.

• The probe brane stack is at a radial position associated with its energy scale. (as first considered by Lykken+Randall)

• This radial position is the mass of the messengers, Λ_{mes}.

• This mass is also due to an expectation value.

• We Consider the UV-complete theory (including the Standard model) to be "renormalized" in the UV. This means that counterterms are added so that the the vacuum energy vanishes in the UV.

• This is a "natural" definition, because it is a short-distance definition in the UV QFT .

• There is no 4d-graviton zero mode as in RS.

• Λ_{mes} is a cutoff for 5d-gravity+SM. Although there is an (AdS) geometry above Λ_{mes}, the SM does not "see it" as above Λ_{SM} it is not directly coupled to gravitons but only to the messengers.

DGP Revisited

• The main question now is: why gravity felt by the SM particles is 4d? An answer was given by

Dvali+Gabadadze+Porrati ('00)

• Loops of SM particles generate a four-dimensional Einstein term

$$S_{\text{grav}}^{\text{SM-loops}} = \Lambda_{mes}^2 \int d^4x \sqrt{\hat{g}}\; R_4 + \log(\Lambda_{mes}^2) R_4^2 + \cdots$$

The natural cutoff is indeed the gravitational messenger scale.

• The SM-generated "cosmological" constant Λ_{mes}^4 has already been subtracted in the UV.

• The total gravity action is

$$S_{grav} = M_5^3 \int d^5x \sqrt{g} \left[R_5 + \frac{12}{\ell^2} \right] + S_{\text{grav}}^{\text{SM-loops}}$$

- The static graviton propagator (on the SM "brane") is

$$G \sim \frac{1}{M_5^3}\frac{1}{|\vec{p}| + r_c \vec{p}^2} \quad , \quad r_c = \frac{\Lambda_{mes}^2}{M_5^3}$$

- At long distances $|\vec{p}| r_c \ll 1$ gravity is 5d: $V_{grav} \sim \frac{M_5^3}{r^2}$.

- At short distances $|\vec{p}| r_c \gg 1$ gravity is 4d: $V_{grav} \sim \frac{\Lambda_{mes}^2}{r^2}$.

$$M_{Planck} = \Lambda_{SM}$$

- The transition (length) scale is

$$M_c = \frac{1}{r_c} \lessapprox 10^{-33} \text{ eV}$$

RS meets DGP

• The standard DGP analysis is valid in 5 flat dimensions.

• In the standard fine-tuned RS model, we can superpose an extra four-dimensional Einstein term $M_P^2\ R_4$ coming from SM loops.

• We have two characteristic length scales, ℓ the AdS scale and $r_c = \frac{M_P^2}{M_5^3}$, the DGP scale.

♠ When $r_c \gg \ell$, gravity is 4d at all scales with 4d Plank scale equal to M_P.

♠ When $\ell \gg r_c$ gravity is 4d at length scales shorter than r_c with Planck scale M_P, 5D when the length scale is between r_c and ℓ and 4d with Planck scale $M_5^3\ell$, when the length scale is longer than ℓ.

Kiritsis+Tetradis+Tomaras ('02)

Here effectively, as there is no RS cutoff, $\ell \to \infty$, and physics is five dimensional (and AdS-like) at scales longer than r_c.

Therefore, $M_P = 10^{19}$ GeV, and

• Asking for the 5d gravity scale to be perturbative $10^{-3} eV \lesssim M_5$

• Asking for the transition scale to be at the size of the universe, $M_5 \lesssim 100 MeV$.

In total we have a range spanning 11 orders of magnitude

$$10^{-3}\ eV \quad \lesssim \quad M_5 \quad \lesssim \quad 100\ \ MeV$$

• The dark energy observed today could be due to the DGP acceleration mechanism or mixing with other light gravitons.

The equivalence principle revisited

• We do not expect relevant operators, we may however marginal operators. The leading and only relevant example are scalar operators. An example in N=4 is the dilaton (gauge coupling constant).

• Such operators will couple to the SM via the same gravitational messengers.

• They will correspond to scalar massless "gravitons". They might destroy the equivalence principle.

• The same SM quantum corrections will provide a localized effective action for them.

• (Unlike the graviton), nothing prohibits an induced mass for them.

$$S_{\text{induced}} = \Lambda^2_{SM} \int d^4x \sqrt{\hat{g}} \left[(\partial\phi)^2 + \Lambda^2_{SM}\phi^2 + \log(\Lambda^2_{SM})\phi^4 + \cdots \right]$$

Therefore they have Planck scale masses, and they are irrelevant for low scale physics. They do not violate the equivalence principle.

The axion

• There is always a universal pseudoscalar marginal operator in the hidden group namely the instanton density $a \sim Tr[F \wedge F]$.

• Its dual bulk action is large-N suppressed (RR field, or θ angle)

$$S_a = \frac{M_5^3}{N^2} \int d^5x (\partial a)^2$$

• If the gravitational messengers generate a mixed anomaly $Tr[T_{\text{SM}_i} T_{\text{SM}_i} Q_{\text{m-chiral}}] = N \; I_i \neq 0$, then the messengers induce a coupling of the axion to the pseudoscalar densities

$$S_{PQ} = \sum_i \int d^4x \; a \; \frac{I_i}{N} \; Tr[F_i \wedge F_i]$$

• Loop effects of the SM gauge bosons generate a 4d-kinetic term for the axion but no mass term or potential.

$$\delta S_{PQ} = \sum_i I_i^2 \; \frac{\Lambda_{SM}^2}{N^2} \; (\partial a)^2 \quad , \quad f_{PQ} \sim \frac{M_{\text{Planck}}}{N}$$

• QCD instantons generate a potential for the axion as usual $V_a \sim \Lambda_{QCD}^4 \cos a$.

Outlook

• The postulates assumed (AC vision, randomness of UV QFT, gauge-gravity duality) do not predict/postdict any concrete number (so far) but:

• They turn "upside down" our view of gravity and how it interacts with the Standard model.

• They make the cosmological constant problem look like a natural UV tuning of the theory.

• They "explain" the emergence of gravitational force which is semiclassical, and of "thermodynamic" nature.

• They suggest the UV degrees of freedom of gravity (the "partons" of the large N, strongly coupled CFT).

• They suggest that the universality of the gravity couplings is an IR "accident".

• They suggest why the PQ axion is as universal as gravity is.

• The suggest the presence of extra massive "anomalous" U(1) bosons in the SM.

• They paint a gravitational picture of the UV QFT in terms of super-structure (the hyper-universe) where small-N sectors (our universe) are small brane stacks floating in a (potential superposition) of semiclassical manifolds containing many such universes.

• It remains to be seen whether these ideas will lead to a fruitful reconsideration of the mariage between QFT and gravity.

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THANK YOU!

Generalized Bank-Zaks fixed points

Consider the general β function coefficients and set

$$\frac{11}{3}-\frac{2}{3}N_F-\frac{N_s}{6}=a \quad , \quad 0\leq a\leq\frac{11}{3} \tag{1}$$

and choose the number of flavors so that

$$b_1=aN-\frac{2}{3}n_F-\frac{n_s}{6}=\epsilon>0 \quad , \quad \epsilon\ll 1 \tag{2}$$

$$b_2=-\left[\frac{50+4N_F+5N_s}{4}N^2+\frac{n_s}{4N}(N^2-3)\right]+\mathcal{O}(\epsilon)<0 \tag{3}$$

For $\epsilon\to 0$ there is a Bank-Zaks fixed point at

$$\frac{\lambda_*}{(4\pi)^2}=\frac{g_*^2N}{(4\pi)^2}\simeq\frac{4N\epsilon}{(50+4N_F+5N_s)N^2+\frac{n_s}{N}(N^2-3)} \tag{4}$$

The maximum number of emerging dimensions is obtained by $N_F=0, N_s=21$, where $a=\frac{1}{6}$ and $\epsilon=\frac{N}{6}-\frac{2}{3}n_F-\frac{n_s}{6}$. Take $n_F=0$ and $n_s=N-1$, so that $\epsilon=1$ and

$$\frac{\lambda_*}{(4\pi)^2}\simeq\frac{4}{155N+(N-1)\frac{N^2-3}{N^2}}\simeq\frac{1}{39N}+\mathcal{O}(N^{-2}) \tag{5}$$

The couplings of the SM

• We have learned in the past decades that the couplings of the QFT of the SM may be dynamical

$$S_{SM} \sim \int d^4x \;\; T^{\mu\nu,\rho\sigma} \; Tr[F_{\mu\nu}F_{\rho\sigma}] + e^{\mu}{}_{a}\bar{q}(\gamma^a(i\partial_\mu + A_m))q + H\bar{q}q + \theta F \wedge F$$

• $T^{\mu\nu,\rho\sigma} \sim \frac{\sqrt{g}\;\, g^{\mu\rho}g^{\nu\sigma}}{4g^2_{YM}}$

• $H \to \quad Higgs$

• $\theta \to$ PQ axion

⋮

• String theory is another theory where coupling constants are dynamical variables.

Plan of the presentation

- Generalized Bank-Zaks fixed points 34 minutes
- The couplings of the SM 35 minutes