# $1+\frac{1}{2}$ *decade of physics with Ignatios*

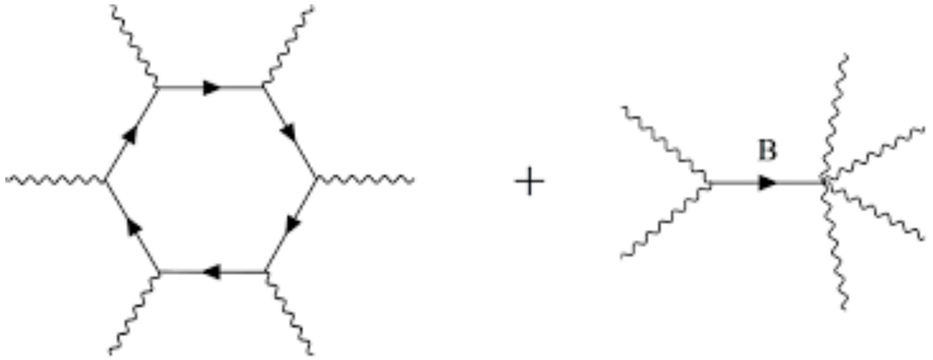
## *or Dark gravitons and string theory*

**Ignatios Fest - Planck 2022**

*Costas Bachas (LPENS)*

Although we overlapped for a year in Paris, I really met Ignatios at **SLAC** where we were both postdocs in the mid 80's

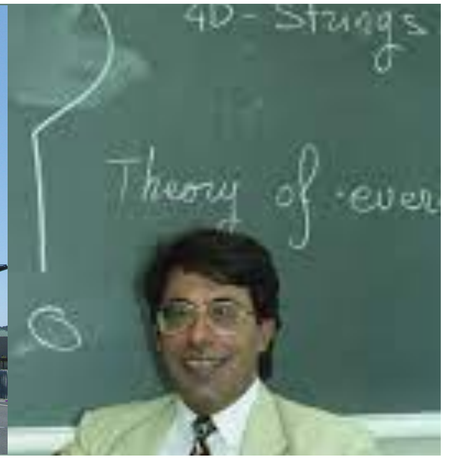
***It is hard to convey the excitement of the times***




The Green-Schwarz anomaly mechanism and the heterotic string were few months old, and optimists were predicting the solution to all problems of HE physics

We knew nothing about string theory, but dived head-first with two friends from across the Bay area, Costas Kounnas and Paul Windey






A day in the office looked like this:

-- because of the heavy cigarette smoke

-- and also because it was usually very late at night !

These were the times of the first **landscape** exploration

The *Candelas et al* paper had shown the existence of a vast landscape of N=1 CY vacua, but raised a host of questions: CY metric? stringy corrections? selection?

So there was a big effort to move beyond (Calabi-Yau) geometry, and to replace it by 2d SCFT. Some key papers :

*Dixon et al; Narain; Kawai et al; Lerche et al; Gepner*

*ours based on free fermions:*

Nuclear Physics B Volume 289, 1987, Pages 87-108

Four-dimensional superstrings

I. Antoniadis, C.P. Bachas, C. Kounnas

# Another key question was susy breaking

*Early hope: non-perturbative effects, but Dine & Seiberg argued that EFT not sufficient*

So we looked for a stringy mechanism & concluded that :

"tree-level supersymmetry breaking is necessarily linked to the size of some internal dimension . . ;
this is not *a priori* obvious, it is not true for the breaking of gauge symmetries"

Physics Letters B Volume 207, Issue 4, 30 June 1988, Pages 441-446

On supersymmetry breaking in superstrings

I. Antoniadis, C.P. Bachas, D. Lewellen, T. Tomaras

also: *Banks + Dixon*

This was an early appearance of a "distance conjecture" *(gravitino-conjecture problem)*:

$$m_{KK} \sim m_{3/2}^{\delta}$$

(for us $\delta = 1$ )

*Cribiori, Lust, Scalisi '21*
*Castellano, Font, Herraez, Ibanez '21*

It is thus tempting to consider this as a characteristic stringy signature at low energy. However, even though there is no direct experimental evidence against the existence of some extra dimension at say 100 TeV, such a scenario faces at least one serious difficulty:* couplings would, by naive dimensional analysis, become huge at the unification scale, invalidating the semiclassical description of the string and creating a new hierarchy problem.

Soon after, Ignatios showed that the problem can be alleviated, at least at one loop, if the breaking were restricted to twisted sectors while the "bulk" was protected by N=4

*The second "string revolution" (dualities, D-branes, AdS/CFT) of the mid 90's shifted attention away from the very constrained heterotic string. Localizing gauge and possibly gravitational interactions "set free" the model-building scales*

*ADD, Randall-Sundrum*

With Ignatios (+ *Hervé, Emilian* & others) we wrote papers trying to:
*(a)* generate the Higgs hierarchy, and *(b)* salvage the unification of couplings.

This was happening at the CPhT/Polytechnique, where we were both in the 90's

It was a great group of people and a lot of fun

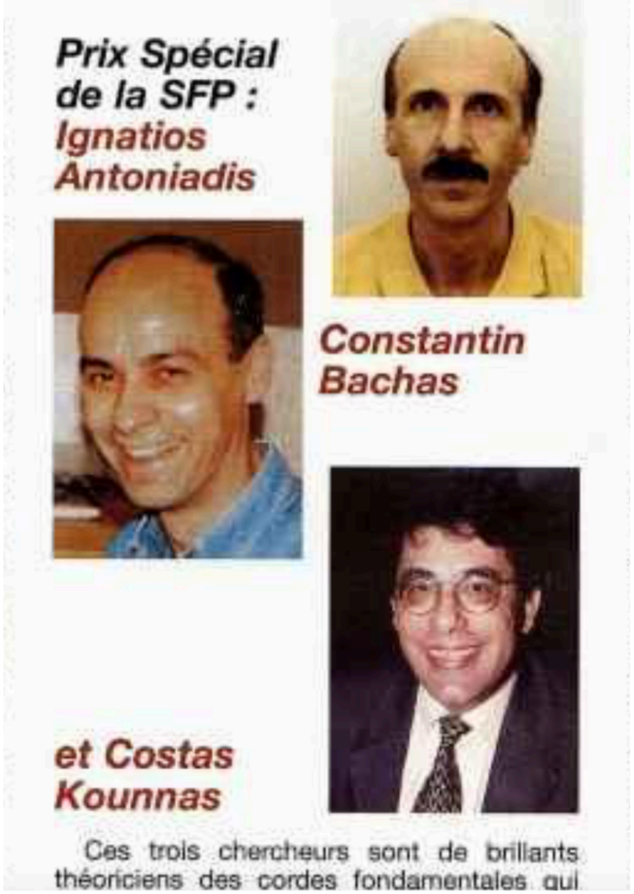
(Marios Petropoulos, Karim Benakli, Hervé Partouche, Boris Poiline, Pierre Vanhove . . . were PhD students;

Alberto Zaffaroni, Niels Obers, Damiano Anselmi, Fawad Hassan, Carlo Angelantonj . . were postdocs)

At the end of the decade Ignatios left for CERN and I left for the ENS,

and the group passed to safe younger hands.

RG




IR

UV

Few photos in these pre-smartphone times (& mine are in the form of slides in boxes)

Here is one at the time our worldlines parted

In the years since "landscaping" became much more sophisticated, with many impressive mathematical results: *new tools, less scared of strong coupling*


But the key questions are still with us:

Low-E susy ? de Sitter vacua ? Size of extra dimensions ?

The fact that there seems to be more than EFT is recomforting:

there is room for something <u>really</u> surprising/unexpected.

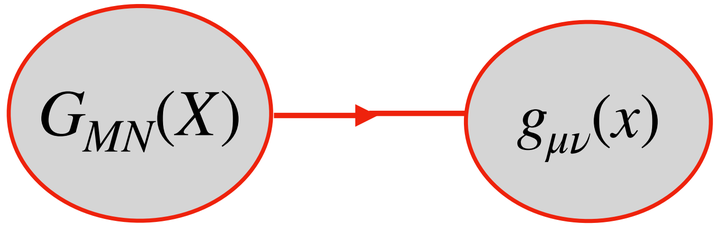
One of the deep questions about what q-gravity allows:

| | **Spin 1**<br>gauge bosons | **Spin 2**<br>graviton |
|---|---|---|
| Localized ? | *D-branes* ✓ | ? |
| massive ? | ✓ | ? |

*Can gravity be modified in the IR ?*

An EFT exists:

*Pauli, Fierz '39 . . .*
*Arkani-Hamed, Georgi, Schwartz '02*
*. . .*




*mapping*: $X^M = \Phi^M(x)$

would-be Goldstone bosons

*diffeo-invariant local action*:

bigravity

$$S_{\rm bigrav} = -\frac{1}{2\kappa_1^2}\int d^4X\sqrt{G}\ [R(G)+\Lambda_1] - \frac{1}{2\kappa_2^2}\int d^4x\sqrt{g}\ [R(g)+\Lambda_2] + \frac{m^2}{2(\kappa_1^2+\kappa_2^2)}\int d^4x\sqrt{g}\ F(g_{\mu\nu},\hat{G}_{\mu\nu})$$

*pullback*: $\hat{G}_{\mu\nu} = \partial_\mu\Phi^M\partial_\nu\Phi^N G_{MN}$

$\kappa_1 \to 0$ freezes $G_{MN}(X)$ and leaves a massive $g_{\mu\nu}(x)$

But 4 would-be g.b., one (potential ghost) must decouple;

possible with 3-parameter choice of $F(g_{\mu\nu}, \hat{G}_{\mu\nu})$ *de Rham, Gabadadze, Tolley; Hassan, Rosen '11*

*breakdown scale*:

$$\Lambda_3 \sim \left(\frac{m^2}{\kappa}\right)^{1/3}$$ Minkowski

$$\Lambda_{\rm AdS} \sim \left(\frac{m}{\kappa\, \ell_{\rm AdS}}\right)^{1/3}$$ AdS

Is this EFT in landscape or swampland ?

The problem has a nice "translation" in 3-dimensional CFT

**CFT**

energy-momentum tensor

$t_{ij}$

dimension $\Delta$

**AdS**

graviton

$h_{\mu\nu}$

mass $m$

$$\Delta(\Delta - d) = m^2 \ell_{\rm AdS}^2$$

$$< tt > \sim c \sim (m_{\rm Pl} \ell_{\rm AdS})^{d-1}$$

The problem has a nice translation in 3-dimensional CFT

conserved $\partial^i t_{ij} = 0 \implies \Delta = 3 \implies \boxed{m = 0}$

leaking $\partial^i t_{ij} = V_j \longleftarrow$ Stückelberg $\boxed{m \neq 0}$

*Porrati '03* *In terms of representations of SO(2,3):* $\text{short} \oplus \text{short}' \to \text{long}$

Superconformal : *likewise but*

| |
|---|
| $\mathcal{N} \leq 4 \quad \text{in} \quad \text{AdS}_4$ |
| $\mathcal{N} \leq 2 \quad \text{in} \quad \text{AdS}_5$ |

*CB '19*

**Two leaking mechanisms:** $\mathrm{CFT} + \mathrm{cft} + \delta S_{\mathrm{int}}$

$$T_{ij}^{\mathrm{tot}} = \frac{t_{ij} + T_{ij}}{\sqrt{c + C}} \longleftarrow \text{massless}$$

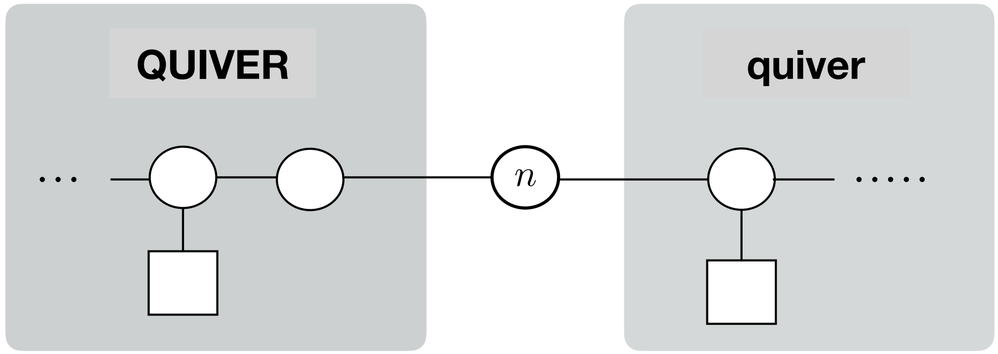
$$T_{ij}^{\mathrm{rel}} = \frac{C t_{ij} - c T_{ij}}{\sqrt{C^2 c + c^2 C}} \longleftarrow \text{massive}$$

Double trace: $\delta\mathcal{L} = \lambda\, \mathrm{tr}(o)\mathrm{tr}(\mathcal{O})$

Kiritsis, Niarchos '06

Aharony, Clark, Karch '06

Mediation:




CB, Lavdas '18

To keep mixing "small" need : $\begin{cases} \lambda \ll 1 \\ \dfrac{n^2}{C} \ll 1 \end{cases}$

For the case of mediation by gauging a common global symmetry we have

exact IIB string-theory solutions at disposal:

D'Hoker, Estes, Gutperle '07

Aharony, Berdichevsky, Berkooz, Shamir '11

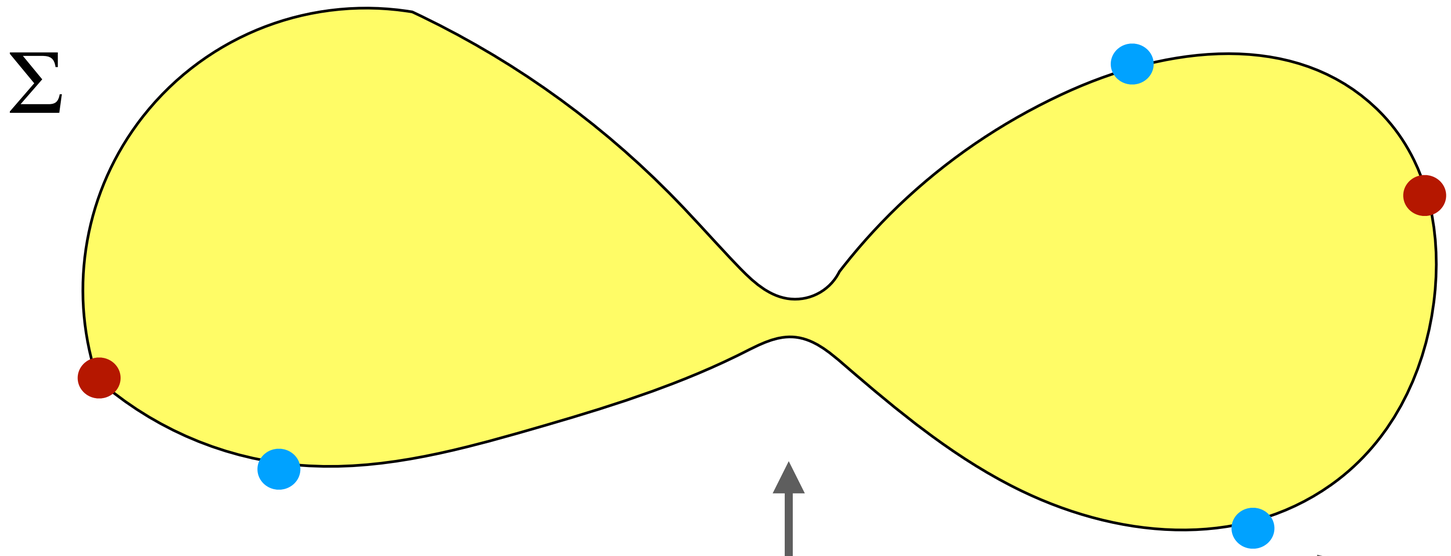
Assel, CB, Estes, Gomis '11, '12

in 1-to-1 correspondence with dual Gaiotto-Witten $\mathrm{SCFT}_3$

so we could compute the mixing from the geometry

This works as follows : the geometry has the fibered form

$$AdS_4 \times_w M_6 \quad \text{where} \quad M_6 = (\underbrace{\mathrm{S}_2 \times \hat{\mathrm{S}}_2}_{SO(4)_R}) \times_w \Sigma$$



Convenient: *the spin-2 specrum depends only on geometry, not fluxes*

Csaki, Erlich, Hollowood, Shirman '00

CB, Estes '11

$$\Delta_{\rm BE}\psi = m^2\psi\ , \qquad \Delta_{\rm BE} = -\frac{1}{\sqrt{g}}e^{-2A}\partial_m\sqrt{g}g^{mn}e^{4A}\partial_n$$

Bakry - Emery operator, cf De Luca, De Ponti, Mondino, Tomasiello '21

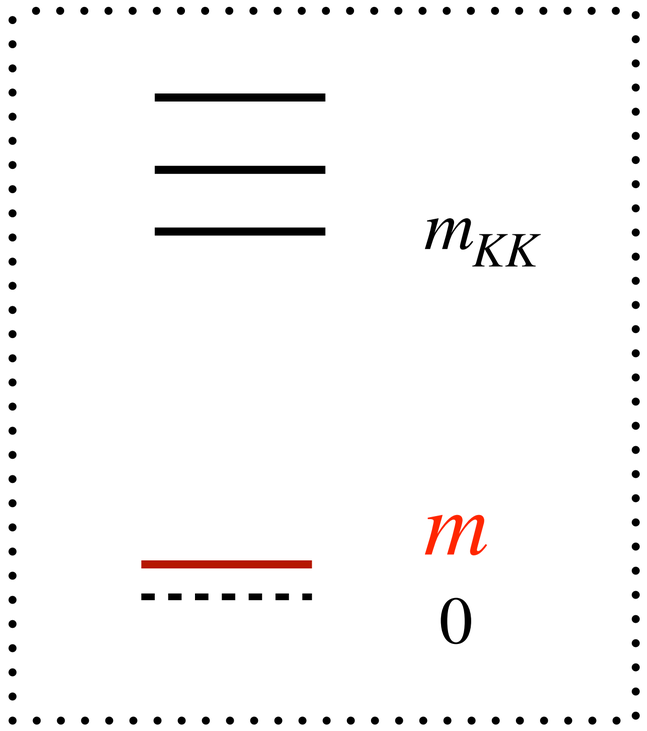
The two would-be massless modes in the pinching limit give a massless

( $\psi = const$ ) mode & one with mass $\propto$ mixing

This does show up in the pinched ABEG geometries as a tower of non-BPS

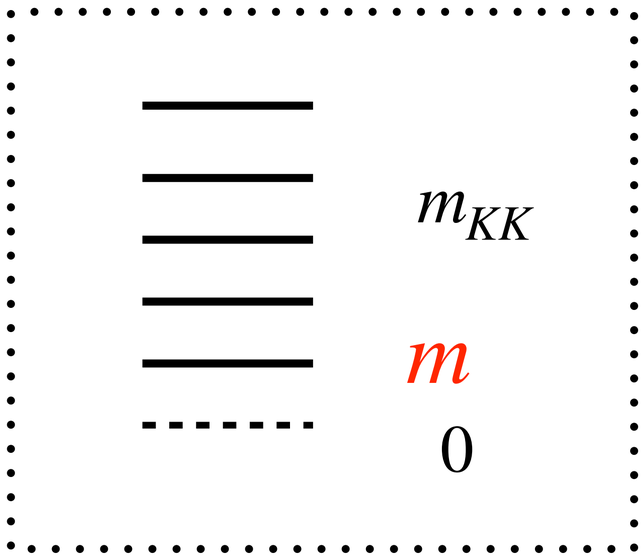
The pinching limit looks superficially smooth in CFT, but must be singular in geometry

KK throat states below the breakdown scale of EFT, but hierarchically separated from the dark graviton mass $m$




constrast with dark dimension

*cf Vafa's talk*




different phenomenology

Anyway cannot yet cry "victory" because of infamous scale-separation problem

Can the radius of $\mathrm{AdS}_4$ be made $\gg \ell_{KK}$ ?

The exact ABEG solutions have **N=4 susy**, & the answer is no:

the radius of the 2-spheres cannot be decoupled from that of $\mathrm{AdS}_4$

General no-go argument for extended (N >1) supersymmetry:

Polchinski, Silverstein '09

All allowed (R-symmetry) charges present in spectrum, and BPS condition relates charge to scaling dimension, *viz* mass

So we need to study the harder N=0,1 case. Opinions remain split:

*Swamplanders*: **NO** Lüst, Palti, Vafa '11

*Landscapers*: **WHY NOT ?** KKLT, . . . .

Settling this question (*boostrap?*) is essential, both for the existence of dS vacua and for the embedding of massive gravity or bigravity in the Landscape

***stay tuned*** . . .

in the meantime


*Χρονια πολλα Ιγνατιε !*