CPHT and string theory

memories recollection

I. Antoniadis

LPTHE, Sorbonne Université, CNRS Paris

CPHT, Ecole Polytechnique 1980-2014

but 20 years on leave

61st anniversary conference

Centre de Physique Théorique

25-26 March 2019, Paris

CPHT 1980 22 years after its creation by Louis Michel

6 years after it moved to Palaiseau

1980-82: postdoc in Particle Physics Group (formed in 1970)

Tran Truong, Georges Grunberg, Tri-Nang Pham, Bernard Pire, Claude Roiesnel (Amitabha Chakrabarti?)

visitors: A. Martin, E. de Rafael, S. Pokorski, ...

1982: was hired in CNRS (AR)

1983: Habilitation thesis (doctorat d'Etat) [4]

1983-88: SLAC/Stanford (3 years), CERN (2 years)

1988: Came back [5]

Publications with CPHT members 1980-82

moving from QCD to BSM

- Symmetry Breaking Effects in Grand Unified Theories
  Ignatios Antoniadis (Ecole Polytechnique), C. Kounnas (Ecole Normale Superieure), C. Roiesnel (Ecole Polytechnique). Oct 1981. 48 pp.
  Published in Nucl.Phys. B198 (1982) 317-364
  Print-82-0021 (ECOLE POLY)
  DOI: 10.1016/0550-3213(82)90561-2
  Cited by 34 records

- Lower Bound for Branching Ratio of $K^+ \to \pi^+ +$ Axion and Nonexistence of Peccei-Quinn Axion
  Ignatios Antoniadis, Tran N. Truong (Ecole Polytechnique). Jul 1981. 6 pp.
  Published in Phys.Lett. 109B (1982) 67-72
  Print-81-0526 (ECOLE POLY)
  DOI: 10.1016/0370-2693(82)90465-8
  Cited by 24 records

- Second Order QCD Analysis of the Photon Structure Function
  Ignatios Antoniadis, G. Grunberg (Ecole Polytechnique). Jun 1982. 22 pp.
  Published in Nucl.Phys. B213 (1983) 445-466
  Print-82-0720 (ECOLE POLY)
  DOI: 10.1016/0550-3213(83)90230-4
  Cited by 97 records

1982: 21st ICHEP, Paris, 26-31 July

one year before the W/Z discovery at CERN

THESE

PRESENTEE

A L'UNIVERSITE DE PARIS-SUD

CENTRE D'ORSAY

POUR OBTENIR

LE GRADE DE DOCTEUR ES-SCIENCES PHYSIQUES

PAR

Ignatios ANTONIADIS

SUJET : AU-DELA DU MODELE STANDARD $U(1) \times SU(2) \times SU(3)$

soutenue le : 10 Juin 1983 devant la Commission d'examen

MM. MEYER Philippe	Président
ALESSANDRINI Victor	
BOUCHIAT Claude	
DEGRANGE Bernard	
ILIOPOULOS Jean	
TRUONG N. Tran	

[2]

string theory group: period 1988-98

1987: Costas Bachas joined CPHT (Phys Math.) from SLAC as CR CNRS

while ongoing collaboration on four-dimensional strings

(with C. Kounnas, P. Windey and others)

Upon my return in 1988:

joint effort to built an active group on string theory

PhD students: Marios Petropoulos, Karim Benakli, Hervé Partouche, Boris Pioline, Pierre Vanhove, Cyrille Fabre

European Networks

- "String Theories and their Phenomenological Applications" 1992-96
  EP, U Athens, ICTP, UA Madrid, Oxford, SISSA
- "Physics Beyond the Standard Model" 1996-00
  EP, U Lisbon, UA Madrid, U Munich, Oxford, U Thessaloniki, U Valencia, INFN Padova + Pisa, SISSA, CNRS LPTENS + LPTHE, CERN [8]

2. **Supersymmetry Among Free Fermions and Superstrings**
Ignatios Antoniadis, Constantin Bachas (SLAC), C. Kounnas, Paul Windey (UC, Berkeley & LBL, Berkeley). Sep 1985.
Published in Phys.Lett.8171(1986) 51-56
Detailed record- Cited bY. 235 records

3. **Four-Dimensional Superstrings**
Ignatios Antoniadis (CERN), C.P. Bachas (Ecole Polytechnique), C. Kounnas (LBL, Berkeley). Dec 1986.
Published in Nuci.Phys.8289 (1987) 87
Detailed record - Cited bY. 836 records

4. **4-D Fermionic Superstrings with Arbitrary Twists**
Ignatios Antoniadis (CERN), C. Bachas (Ecole Polytechnique). Jun 1987.
Published in Nuci.Phys.8298 (1988) 586-612
Detailed record- Cited bY. 311 records

5. **Higgs Phenomenon in String Theories**
Ignatios Antoniadis (CERN), C. Bachas (Ecole Polytechnique), C. Kounnas (UC, Berkeley & LBL, Berkeley). Oct 1987.
Published in Phys.Lett.8200 (1988) 297-304
Detailed record- Cited bY. 48 records

6. **On Supersymmetry Breaking in Superstrings**
Ignatios Antoniadis (CERN), Constantin Bachas, David C. Lewellen (SLAC), T.N. Tomaras (Ecole Normale Superieure). Mar 1988.
Published in Phys.Lett.8207 (1988) 441-446
Detailed record- Cited bY. 120 records

7. **Cosmological String Theories and Discrete Inflation**
Ignatios Antoniadis, C. Bachas, John R. Ellis (CERN), Dimitri V. Nanopoulos (Wisconsin U., Madison). May 1988.
Published in **Phys.Lett. 8211 {1988) 393-399**
Detailed record - Cited by 296 records

8. **An Expanding Universe in String Theory**
Ignatios Antoniadis, C. Bachas (Ecole Polytechnique), John R. Ellis (CERN), Dimitri V. Nanopoulos (Texas A-M). Nov 1988.
Published in **Nuci.Phys. 8328 {1989) 117-139**
Detailed record- Cited by 297 records

10. Gauged Supergravity Vacua in String Theory

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas (CERN), A. Sagnotti (RomeU., Tor Vergata & INFN, Rome). Oct 1989.
Published in **Phys.Lett. 8235 (1990) 255-260**
Detailed record - Cited bY- 65 records

11. $N = 2$ Superliouvilie and Noncritical Strings

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas (CERN), C. Kounnas (Ecole Normale Superieure). Mar 1990.
Published in **Phys.Lett. 8242 (1990) 185-190**
Detailed record - Cited bY- 19 records

12. Comments on cosmological string solutions

Ignatios Antoniadis (Ecole Polytechnique), C. Bachas, John R. Ellis (CERN), Dimitri V. Nanopoulos (Texas A-M). Nov 1990.
Published in **Phys.Lett. 8257 (1991) 278-284**
Detailed record - Cited bY. 104 records

13. Aspects of type 1 - type II - heterotic triality in four-dimensions

I. Antoniadis (Ecole Polytechnique & CERN), C. Bachas, C. Fabre, H. Partouche (Ecole Polytechnique), T.R. Taylor (CERN &
Published in **Nuci.Phys. 8489 (1997) 160-178**
hep--th/9608012 ı **PDF**
Detailed record - Cited bY. 119 records

14. Branes and the gauge hierarchy

Ignatios Antoniadis (Ecole Polytechnique), Constantin Bachas (Ecole Normale Superieure). Dec 1998.
Published in **Phys.Lett. 8450 (1999) 83-91**
hep--th/9812093 ı **PDF**
Detailed record - Cited bY. 143 records

15. Gauge couplings in four-dimensional type 1 string orbifolds

I. Antoniadis (Ecole Polytechnique), C. Bachas (Ecole Normale Superieure), E. Dudas (Orsay, LPT). Jun 1999.
Published in **Nuci.Phys. 8560 (1999) 93-134**
hep--th/9906039 ı **PDF**
Detailed record - Cited bY. 166 records

string theory group: period 1988-98

Postdocs/Marie-Curie fellowships (institutional + individual)

Ioannis Rizos, Niels Obers, Nick Tsamis, Alberto Zaffaroni, Katrin Foerger, Carlo Angelantonj, Fawad Hassan, Adi Armoni, Damiano Anselmi

Long term collaboration contracts

- IN2P3/CICYT since 1991 (Mariano Quiros)
- NATO grant with Los Alamos 1991-95 (Emil Mottola and Pawel Mazur)
- CNRS/NSF with Northeastern University PICS since 1993 (Tom Taylor)
- POLONIUM with U Warsaw University (group of Stefan Pokorski)

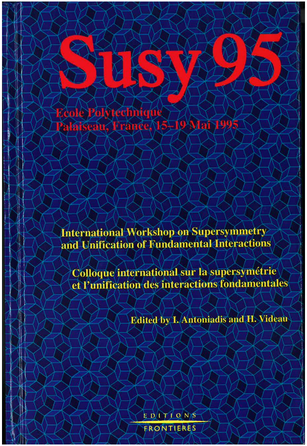
Other frequent visitors:

Kumar Narain, Edi Gava, Augusto Sagnotti, Gianfranco Pradisi, ...

string theory group: period 1988-98 stories

1993: Marios Petropoulos as CR2 CNRS (Lyon → CPHT phys math)

1995: SUSY 95



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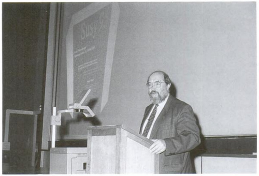
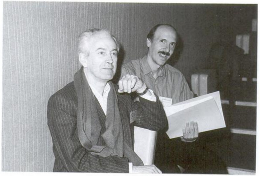




SUSY 95

CONTENTS

SUSY 95

string theory group: period 1988-98 stories

1999: Bogdanov's theses defence

Igor: failed, Grishka: in mathematics upon publications

string theory group changes: period 1998-00

- 1997: On leave one year at CERN
- 1998: Costas Bachas $\rightarrow$ LPTENS
- 1999: CNRS CR1 position $\rightarrow$ Ruben Minasian (moved to Saclay in 2005)
- 1999: Hervé Partouche as CR2 CNRS
- 2000: I moved to CERN as staff
- 2000: Françoise Andalo $\rightarrow$ Florence Auger
- 2001: Emilian Dudas from LPT Orsay
- 2002: CNRS DR2 position $\rightarrow$ Elias Kiritsis (moved to APC in 2010)
- string theory group became independent in CPHT
- new office space (thanks to Levy's building fire)

string theory group: after 2000

European networks still managed by CPHT:

- "Physics Across the Energy Frontier" 2000-04
  EP, U Lisbon, UA Madrid, U Bonn, Oxford, U Thessaloniki, U Valencia, U Warsaw, INFN, SISSA, CEA-Saclay, CERN
- "Quest for Unification" 2004-08
- "Unification in the LHC era" 2009-13

Also an ERC advanced grant with EP second host

"Mass Hierarchy and Particle Physics at the TeV Scale" 2008-14

New arrivals

CNRS: Guillaume Bossard 2010 and Andrea Puhm 2017

MC in the EP Physics department: Blaise Goutéraux 2018

HEP Master program

2003: first proposal with Henri Videau and Paul Windey

Fundamental Forces of the Universe

2 years program in english on high-energy physics theory and experiment

based on a reformed physics dept program of 3rd year EP

EP Phys Dept and Paris community hostile with the idea

- 2007: revised version with Henri Videau
- start discussions with ETH for a joint international program
- help from the bureau des Masters de l'EP (Thanh-Tâm Lê)
- 2008: proposal of joint Master in HEP
- 2009: Approved by the French Ministry of Education
- 2010: Agreement EP-ETH
- 2011: start of the program (M1 and M2) [18]

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

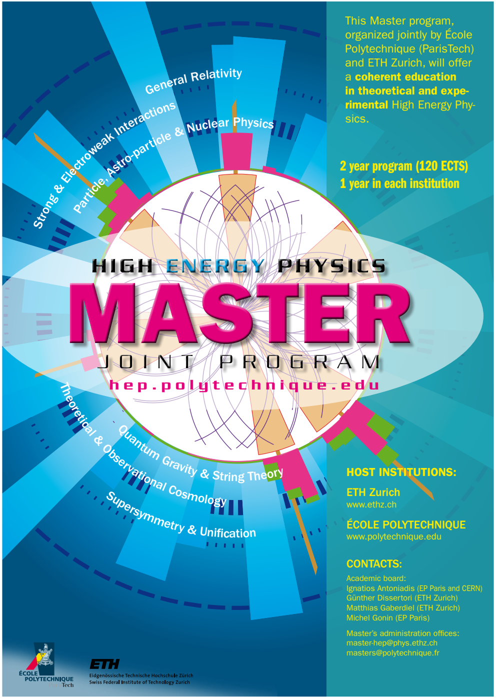
Proposal for an IDEA League Joint Master's Degree Programme ETH Zürich - Ecole Polytechnique Paris

Master in Physics with Specialisation in High Energy Physics

Proponents : G. Dissertori / M. Gaberdiel (ETH)

I. Antoniadis / M. Gonin (EP)

 18.2.2008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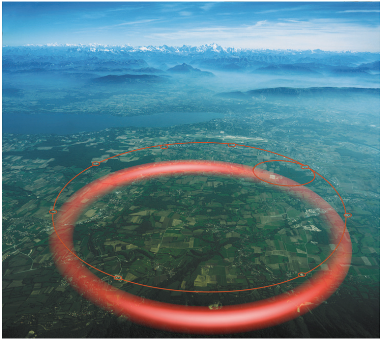
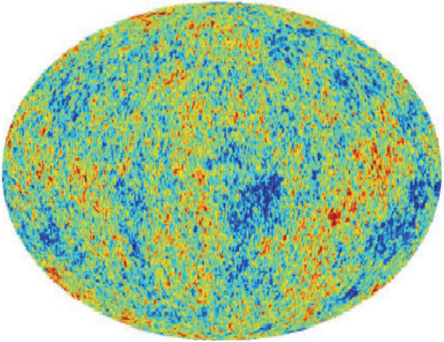
Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- If theory of Nature can it describe both particle physics and cosmology?





Problem of scales

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

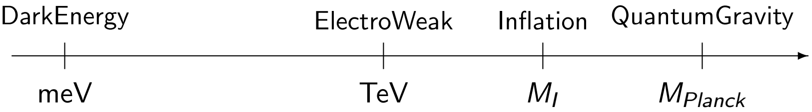
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant [22]

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter) [23]

$\Rightarrow$ 3 very different scales besides M_{Planck} : [24]



Supersymmetry

A well motivated proposal addressing several open problems of the SM

- natural elementary scalars
- realise unification of the three Standard Model forces
- natural dark matter candidate (lightest supersymmetric particle)
- addressing the hierarchy problem
- prediction of light Higgs ($\lesssim$ 130 GeV)
- rich spectrum of new particles
- soft UV behavior and important ingredient of string theory

But no experimental indication of any BSM physics at LHC

It is likely to be there at some (more) fundamental level

Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho \;\Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\Rightarrow\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

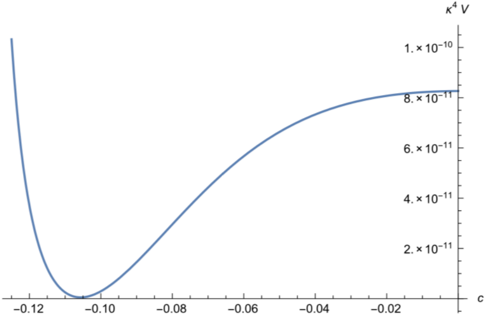
  $\nwarrow$ Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$ [20]

Inflation:

Theoretical paradigm consistent with cosmological observations

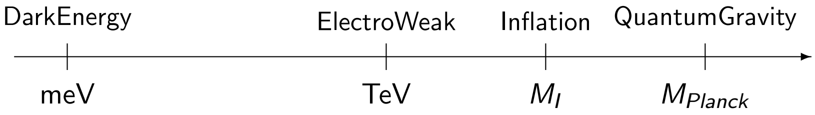
But phenomelogical models with not real underlying theory [20]



Inflaton potential:

slow-roll region with V', V'' small compared to dS curvature

Problem of scales: connections



Direct connection of inflation and supersymmetry breaking:

identify the inflaton with the partner of the goldstino

Goldstone fermion of spontaneous supersymmetry breaking

while accommodating observed vacuum energy [32]

Inflation in supergravity: main problems

Inflaton: part of a chiral superfield X

- slow-roll conditions: the eta problem $\Rightarrow$ fine-tuning of the potential

  $$\eta = V''/V\,, \quad V_F = e^K(|DW|^2 - 3|W|^2)\,, \quad DW = W' + K'W$$

  K: Kähler potential, W: superpotential Planck units: $\kappa = 1$

  canonically normalised field: $K = X\bar{X} \Rightarrow \eta = 1 + \ldots$

- trans-Planckian initial conditions $\Rightarrow$ break validity of EFT

  no-scale type models that avoid the η-problem $K = -3\ln(T + \bar{T})$

- stabilisation of the (pseudo) scalar companion of the inflaton

  chiral multiplets $\Rightarrow$ complex scalars

- moduli stabilisation, de Sitter vacuum, ...

Inflation from supersymmetry breaking

I.A.-Chatrabhuti-Isono-Knoops '16, '17

Inflaton : goldstino superpartner in the presence of a gauged R-symmetry

- linear superpotential $W = f\,X \Rightarrow$ no η-problem

$$\begin{aligned} V_F &= e^K \left(|DW|^2 - 3|W|^2\right) \\ &= e^K \left(|1 + K_X X|^2 - 3|X|^2\right) |f|^2 \qquad K = X\bar{X} \\ &= e^{|X|^2} \left(1 - |X|^2 + \mathcal{O}(|X|^4\right) |f|^2 = \mathcal{O}(|X|^4) \quad \Rightarrow \eta = 0 + \dots \end{aligned}$$

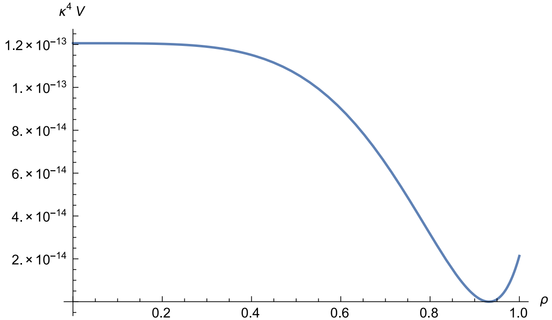
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  no large field initial conditions

- gauge R-symmetry: (pseudo) scalar absorbed by the $U(1)_R$
- vacuum energy at the minimum: tuning between V_F and V_D

Two classes of models

- Case 1: R-symmetry is restored during inflation (at the maximum)



- Case 2: R-symmetry is (spontaneously) broken everywhere

  (and restored at infinity)

Case 1: R-symmetry restored during inflation [30]

$$\mathcal{K}(X,\bar{X}) = \kappa^{-2}X\bar{X} + \kappa^{-4}A\,(X\bar{X})^2 \qquad A>0$$

$$W(X) = \kappa^{-3}f\,X \qquad \Rightarrow$$

$$f(X) = 1 \qquad (+\beta \ln X \text{ to cancel anomalies but } \beta \text{ very small})$$

$$\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$$

$$\mathcal{V}_F = \kappa^{-4}f^2 e^{X\bar{X}(1+AX\bar{X})}\left[-3X\bar{X} + \frac{\left(1+X\bar{X}(1+2AX\bar{X})\right)^2}{1+4AX\bar{X}}\right]$$

$$\mathcal{V}_D = \kappa^{-4}\frac{q^2}{2}\left[1+X\bar{X}(1+2AX\bar{X})\right]^2$$

Assume inflation happens around the maximum $|X| \equiv \rho \simeq 0 \quad \Rightarrow$

Predictions

slow-roll parameters $(q \simeq 0)$

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = -4A + \mathcal{O}(\rho^2)$$

$$\epsilon = \frac{1}{2\kappa^2}\left(\frac{V'}{V}\right)^2 = 16A^2\rho^2 + \mathcal{O}(\rho^4) \simeq \eta^2\rho^2$$

η naturally small since A is a correction

inflation starts with an initial condition for $\phi = \phi_*$ near the maximum

and ends when $|\eta| = 1$

$\Rightarrow$ number of e-folds $N = \int_{end}^{start} \frac{V}{V'} = \kappa \int \frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{|\eta_*|} \ln\left(\frac{\rho_{\rm end}}{\rho_*}\right)$

Planck '15 data : $\eta \simeq -0.02 \Rightarrow N \gtrsim 50$ naturally

Predictions

$$\text{amplitude of density perturbations} \quad A_s = \frac{\kappa^4 V_*}{24\pi^2 \epsilon_*} = \frac{\kappa^2 H_*^2}{8\pi^2 \epsilon_*}$$

$$\text{spectral index} \quad n_s = 1 + 2\eta_* - 6\epsilon_* \simeq 1 + 2\eta_*$$

$$\text{tensor} - \text{to} - \text{scalar ratio} \quad r = 16\epsilon_*$$

Planck '15 data : $\eta \simeq -0.02$, $A_s \simeq 2.2 \times 10^{-9}$, $N \gtrsim 50$

$\Rightarrow r \lesssim 10^{-4}$, $H_* \lesssim 10^{12}$ GeV assuming $\rho_{\rm end} \lesssim 1/2$

Question: can a 'nearby' minimum exist with a tiny +ve vacuum energy?

Answer: Yes in a 'weaker' sense: perturbative expansion [28]

valid for the Kähler potential but not for the slow-roll parameters

need D-term contribution and next (cubic) correction in $\mathcal{K}$

Conclusions

Challenge of scales: at least three very different (besides M_{Planck})

electroweak, dark energy, inflation, SUSY?

their origins may be connected or independent

General class of models with inflation from SUSY breaking:

identify inflaton with goldstino superpartner

- (gauged) R-symmetry restored (case 1)

  small field, avoids the η-problem, no (pseudo) scalar companion

- D-term inflation is also possible using a new FI term

CPHT

61 years of scientific excellence