ICTP | International Centre for Theoretical Physics
SAIFR | South American Institute for Fundamental Research

Director:	Nathan Berkovits
Vice-Director:	Rogério Rosenfeld
Executive Manager:	Jandira de Oliveira
Executive Secretary:	Humberto Neto
Information Technology:	Lucas Sanches
Financial Manager:	Lilia Faria
Outreach Coordinators:	Lucas David, Ana Sério
Scientific Journalist:	Malena Stariolo

Motivation

- Theoretical physics institutes play an important role in efficiently bringing researchers together and organizing activities.
- Although there are dozens of such institutes in North America, Europe, and Asia, there are very few in South America.
- South America has a few countries with highly developed physics research (Brazil, Argentina, Chile) and several countries with excellent undergraduates but less developed physics research.
- Internationalization of physics research in South America is difficult because of excessive bureaucracy in hiring and few international advisory boards.
- Example of successful Mathematics institute: IMPA in Rio de Janeiro.
- ICTP's vision to create regional centres, with the first one at IFT-UNESP in Sao Paulo.

Why IFT-UNESP in São Paulo?

- Founded in 1952, IFT-UNESP is one of the oldest and most prestigious graduate schools in theoretical physics in South America with approximately 20 professors and 60 masters and PhD students.

- The São Paulo state research funding agency FAPESP is perhaps the most stable and well-funded agency in South America.

- IFT-UNESP is centrally located next to a major bus/train station near the largest South American airport and close to several large top-ranked universities.

- The original IFT building near the financial section of São Paulo is being restored and may soon be available for hosting scientific activities.

BRIEF HISTORY OF ICTP-SAIFR

IFT **1952**

IFT-UNESP **1987**

ICTP Partners **2010**

Inauguration Ceremony **2012**

SIMONS
FOUNDATION

FAPESP **1962**

Simons **1994**

ICTP-UNESP MoU **2010**

Simons Fellows **2014**

ICTP **1964**

Perimeter **1999**

Steering Committee **2011**

Perimeter MoU **2015**

serrapilheira

UNESP **1976**

UNESP Barra Funda **2009**

FAPESP grants **’11 ‘16**

Serrapilheira **2017**

ICTP-SAIFR Councils

Scientific council
Peter Goddard (chair) – IAS, Princeton
Seifallah Randjbar-Daemi - ICTP vice-director
Rogério Rosenfeld - IFT-UNESP director
Marcel Clerc - Univ. de Chile, Santiago
Eduardo Fradkin – U Illinois, Champagne
Gabriela Gonzalez - LIGO, Louisiana State U
Belita Koiller - UFRJ, Rio de Janeiro
Luis Lehner – Perimeter, Waterloo
Gabriel Mindlin - U. Buenos Aires
Barton Zwiebach - MIT, Cambridge

Steering committee
Fernando Quevedo (chair)-ICTP director
Julio Cezar Durigan - UNESP rector
Carlos Brito Cruz - FAPESP scientific director
Jacob Palis - Brazilian Academy of Science
Juan Maldacena – representing South America

Funding Sources

5 new permanent research professor positions (2 have been filled)

4 staff members

Infrastructure of IFT-UNESP

5 year grant (renewed until December 2021)

12 FAPESP postdoctoral positions

3 FAPESP young investigators

Funding for visitors and activities (schools, workshops, programs)

Fellowships for scientific journalism, technical support, and PhD

Funding for visitors from other South American countries

Training of secretaries

Joint schools and workshops

Funding Sources

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS	Joint faculty position Joint school Joint masters program Joint outreach activities
SIMONS FOUNDATION	Two tenure track positions
serrapilheira	Outreach coordinators and activities
Private Donation (Brazil)	Isaias Raw chair (salary bonus)
CNPq CAPES	Masters and PhD fellowships
ICTP, CERN, Fermilab, KITP, NORDITA, CEA-Saclay, CUNY-Princeton, IAM-Madrid, Perimeter, Mainz ITP, CLAF	Research exchange agreements

Research

- Current ICTP-SAIFR faculty:

Nathan Berkovits	**String theory**
Fabio Iocco	**Astrophysics**
Eduardo Ponton	**Particle physics**
Aline Ramires	**Condensed matter**
Rogério Rosenfeld	**Cosmology**
Pedro Vieira	**Quantum field theory**

- 12 International postdocs in diverse areas of theoretical physics
- 200 short and long-term visiting researchers per year
- Current international search for research professor in biological physics

Associate Members from Sao Paulo and other regions

Astrophysics/Cosmology/Gravitational Waves

Raul Abramo (IFUSP),
Marcos Lima (IFUSP),
Elisabete de Gouveia Dal Pino (IAG-USP),
Riccardo Sturani (ICTP-SAIFR/IIP-Natal);

Complex Systems with applications to Biology

Marcus Aguiar (Unicamp),
Hilda Cerdeira (IFT-UNESP),
Roberto Kraenkel (IFT-UNESP),
Paulo Prado (IB-USP);

Condensed Matter and Cold Atom Physics

Sadhan Adhikari (IFT-UNESP),
Leandro Aolita (IF-UFRJ)
Alexandre Rocha (IFT-UNESP);

String Theory/Field Theory/Mathematical Physics

Andrei Mikhailov (IFT-UNESP)
Horatiu Nastase (IFT-UNESP)
Victor Rivelles (IFUSP)
Diego Trancanelli (IFUSP)

Theoretical and Experimental Particle Physics

Gustavo Burdman (IFUSP),
Oscar Éboli (IFUSP),
Gastão Krein (IFT-UNESP),
Ricardo Matheus (IFT-UNESP),
Sérgio Novaes (NCC-UNESP/IFT-UNESP).

ARGENTINA:

Gerardo Aldazabal (Bariloche)
Carlos Antonio Balseiro (Bariloche)
Daniel de Florian (Buenos Aires)
Reinaldo Gleiser (Córdoba)
Daniel Gómez (Buenos Aires)
Karen Hallberg (Bariloche)
Diego Harari (Bariloche)
Gabriel Mindlin (Buenos Aires)
Carmen Núñez (Buenos Aires)
Juan Pablo Paz (Buenos Aires)
Esteban Roulet (Bariloche)
Fidel Schaposnik (La Plata)
Hector Vucetich (La Plata)
Damian H. Zanette (Bariloche)

BRASIL (OUTSIDE SÃO PAULO):

Jailson Alcaniz (Rio de Janeiro)
Luiz Davidovich (Rio de Janeiro)
Ronald Dickman (Belo Horizonte)
Viktor V. Dodonov (Brasilia)
Julio Fabris (Vitória)
Álvaro Ferraz (Natal)
Jason Gallas (João Pessoa)
Reimundo Heluani (Rio de Janeiro)
Belita Koiller (Rio de Janeiro)
Gilberto Kremer (Curitiba)
Yan Levin (Porto Alegre)
Caio Lewenkopf (Niteroi)
Martin Makler (Rio de Janeiro)
Eduardo Marino (Rio de Janeiro)
Olivier Piguet (Vicosa)
Sergio Rezende (Recife)
Ilya Shapiro (Juiz de Fora)
Silvio Sorella (Rio de Janeiro)
Giovani Vasconcelos (Recife)
Ioav Waga (Rio de Janeiro)

CHILE:

Max Bañados (Santiago)
Claudio Dib (Valparaiso)
Gonzalo Gutierrez (Santiago)
Marcelo Loewe (Santiago)
Francisco Melo (Santiago)
Miguel Orszag (Santiago)
Gonzalo Palma (Santiago)
Andreas Reisenegger (Santiago)
Jorge Zanelli (Valdivia)

COLOMBIA:

Marta Losada (Bogotá)
Roberto Martinez (Bogotá)
Marek Nowakowski (Bogotá)
Hernan Ocampo (Cali)
Luis Quiroga (Bogotá)
Diego Restrepo (Medellín)

PERU:

Alberto Gago (Lima)
Orlando Pereyra (Lima)
Francisco de Zela (Lima)

URUGUAY:

Raul Donangelo (Montevideo)
Rodolfo Gambini (Montevideo)

VENEZUELA:

Fernando Cordero (Caracas)
Mario Cosenza (Mérida)
Anamaria Font (Caracas)
Ernesto Medina (Caracas)
Alejandra Melfo (Mérida)
Claudio Mendoza (Caracas)

Activities

1500 Visiting Researchers/Speakers
25 International Postdocs
50 PhD Schools
25 Advanced mini-courses
60 Workshops and Programs
4000 Students*

* 2500 From Brazil, 1000 From South America. 500 From other countries

(from 2012 to 2018)

~ 900 students and 300 researchers per year participate in ICTP-SAIFR activities. Online applications for the activities are judged by the organizing committees

- **International Schools** for ~ 2 weeks with ~ 5-6 lecturers and ~ 60 students. Students travel and local expenses covered. All lectures are recorded with ICTP equipment and put online.
- **Mini-courses** are given by one or two distinguished lecturers. Expenses are paid for participants from South America.
- **Programs/workshops** typically involve a few long-term visitors and a short workshop on a selected topic with invited participants.
- **Outreach activities** include monthly informal public lectures, classes for São Paulo high-school students and teachers, and an annual school for the top undergraduates in South America.

ICTP SAIFR
International Centre for Theoretical Physics
South American Institute for Fundamental Research

IMS InstitutoMoreiraSalles

Agosto - Novembro, 2018

CIÊNCIA EM DIÁLOGO NO IMS: FÍSICA E ARTE

GÊNESE
3 de Agosto
Betty Mindlin (IEA-USP)
Raul Abramo (IF-USP)

TEMPO
14 de Setembro
John Boudler (PIAP/IA-UNESP)
Nathan Berkovits (ICTP-SAIFR/IFT-UNESP)

LUZ
5 de Outubro
Millard Schisler (Johns Hopkins U.)
Pedro Vieira (ICTP-SAIFR/IFT-UNESP/Perimeter I.)

MATÉRIA
9 de Novembro
Convidado a confirmar
Aline Ramires (ICTP-SAIFR/MPI-PKS Dresden)

"Ciência em Diálogo: Física e Arte" é o novo programa de divulgação científica do ICTP-SAIFR, realizado no Instituto Moreira Sales. Nesta série mensal de debates organizada em parceria com o IMS, um cientista e um não-cientista são convidados a discutir sobre assuntos de interesse comum. O público terá a oportunidade de discutir com os convidados as convergências e divergências resultantes das diferentes perspectivas em relação a cada um dos temas.

No segundo semestre de 2018, os tópicos serão Gênese, Tempo, Luz e Matéria. A entrada é gratuita e haverá distribuição de senhas uma hora antes do início das apresentações.

Agosto a Novembro de 2018
Primeira sexta-feira do mês, 19h00
Instituto Moreira Salles
Av. Paulista, 2424 - Consolação

ims.com.br/eventos/ciencia-em-dialogo-fisica-e-arte/

outreach.ictp-saif.org/dialogo/

FAPESP Fundação de Amparo à Pesquisa do Estado de São Paulo
ICTP
unesp
IFT - UNESP

Papos de Física

$|\Psi\rangle = |$🍺$\rangle + |$☕$\rangle$

Tubaína Bar
Rua Haddock Lobo, 74 - Cerqueira César

Primeira quinta-feira do mês*, das 19h30 às 21h

Papos de Física é um evento mensal de divulgação científica organizado pelo ICTP-SAIFR para discutir as mais recentes descobertas científicas na área de física. Pensado para o público leigo, o evento começa com um seminário de no máximo 20 minutos de duração e é seguido por uma sessão informal de perguntas e respostas. O evento é gratuito. Participe!

DIEGO TRANCANELLI (IF-USP)
2 de agosto
Simetria e Escala: dos átomos às galáxias

MARINA NIELSEN (IF-USP)
13 de setembro
Essa tal de Física Quântica

BEATRIZ BARBUY (IAG-USP)
4 de outubro
O Bojo da Nossa Galáxia

LUANA SUCUPIRA PEDROZA (UFABC)
8 de novembro
Física da Água

*Em caso de feriado será na quinta-feira seguinte

http://www.ictp-saifr.org/papos/

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FAPESP
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IFT - UNESP

Aventuras em

Física Teórica 3

Ensino Médio no ICTP-SAIFR

IFT-UNESP, São Paulo 2018

7 a 28 de Abril (sábados)

A Física do Universo - Cosmologia

Minicurso para alunos

Rogério Rosenfeld
(ICTP-SAIFR/IFT-UNESP)

26 de Maio a 9 de Junho (sábados)

Relatividade e Gravitação

Minicurso para alunos

Pedro Vieira
(ICTP-SAIFR/IFT-UNESP & Perimiter Institute, Canadá)

15 a 29 de Setembro (sábados)

Mecânica Quântica

Minicurso para alunos

Pedro Vieira
(ICTP-SAIFR/IFT-UNESP & Perimiter Institute, Canadá)

6 a 13 de Outubro (sábados)

Ondas

Minicurso para alunos

Nathan Berkovits
(ICTP-SAIFR/IFT-UNESP)

29 e 30 de Setembro

Cutting-Edge In-class Physics Resources

Workshop for Teachers

Greg Dick
(Perimeter Institute, Canadá)

Inscrições e Informação em
www.ictp-saifr.org/outreach

III IFT-Perimeter-SAIFR

JOURNEYS

INTO THEORETICAL PHYSICS

JULY 16 - 22, 2018

IFT-UNESP, São Paulo

KEVIN COSTELLO
(Perimeter)
AN INTRODUCTION TO TOPOLOGY FOR PHYSICISTS

GASTÃO KREIN
(IFT)
EFFECTIVE QUANTUM FIELD THEORY

DAVID SCHWAB
(CUNY/Princeton)
CURRENT THEORETICAL PROBLEMS IN BIOPHYSICS

ALINE RAMIRES
(ETH Zurich / ICTP-SAIFR / MPI-PKS)
ASPECTS OF SUPERCONDUCTIVITY

KENDRICK SMITH
(Perimeter)
PHYSICS OF THE EARLY UNIVERSE

Financial support is available, and top students will be offered masters fellowships to spend one year at ICTP-SAIFR/IFT-UNESP and one year at either the Perimeter Scholars International program or the CUNY/Princeton Center for the Physics of Biological Function.

Application form and information at www.ictp-saifr.org/journeys

2019 ICTP-SAIFR SCHOOLS AND WORKSHOPS

Campus of IFT-UNESP - São Paulo, Brasil

ICTP SAIFR | International Centre for Theoretical Physics
South American Institute for Fundamental Research

FAPESP unesp ICTP PI PERIMETER INSTITUTE IFT - UNESP

VIII SOUTHERN-SUMMER SCHOOL ON MATHEMATICAL BIOLOGY

Jan 14-20

Org: M. Aguiar, M. Clerc,
R. Kraenkel, P.I. Prado

SCHOOL ON MATHEMATICAL MODELS OF EVOLUTION

Jan 21 - 26

Org: M. Aguiar, A. Celani, R. Kraenkel,
M. Marcili, L. Peliti, P.I. Prado

2019 MEETING OF SCIENTIFIC COUNCIL AND STEERING COMMITTEE

Feb 4 - 5

Org: N. Berkovits, P. Goddard,
F. Quevedo

4TH DUTCH-BRAZIL SCHOOL ON THEORETICAL PHYSICS

Feb 11 - 15

Org: E. Bergshoeff, N. Berkovits, J. de Boer,
A. Font., R. Kleiss

ICTP-SAIFR/FAIR WORKSHOP ON MASS GENERATION IN QCD

Feb 25 - Mar 1

Org: M.R. Cosentino, B. El-Bennich,
G. Krein, U. Wiedner

PREPARATORY SCHOOL FOR STATPHYS 2019

Jul 1 - 6

Org: P. Belenzuela, M. Copelli,
G. Mindlin

IFT-PERIMETER-SAIFR JOURNEYS INTO THEORETICAL PHYSICS

Jul 8 - 14

Org: N.Berkovits, R. Matheus, P. Vieira

2019 ICTP-SAIFR COMPETITION FOR YOUNG PHYSICISTS

Jul 13

Org: N.Berkovits, R. Matheus, P. Vieira

WORKSHOP ON PERSPECTIVES IN NONLINEAR DYNAMICS

Jul 15 - 19

Org: I.H. Cerdeira, S.P. Dawsen, N. Gupta,
R. Kraenkel, G. Mindlin,
R. Ramaswamy, , R. Viana

JOINT ICTP-TRIESTE/ICTP-SAIFR SCHOOL ON OBSERVATIONAL COSMOLOGY

Jul 22 - Aug 2

Org: R. Abramo, P. Creminelli,
A. Melchiorri, R. Rosenfeld, R. Sheth

SCHOOL ON HIGH ENERGY ASTROPHYSICS

Aug 5 - 16

Org: P. Blasi, F. Iocco,
J. Knapp, V. de Souza

WORKSHOP ON AMERICAN MONSOONS

Aug 19 - 24

Org: F. A. Calvacanti, A. M. Grimm,
F. Kucharski

SCHOOL ON LIGHT INTERACTIONS WITH COLD ATOMS

Sep 16 - 27

Org: R.P.M. Bachelard, R.C. Teixeira,
J.T.M. Walraven

WORKSHOP ON DETERMINATION OF FUNDAMENTAL QCD PARAMETERS

Sep 30 - Oct 4

Org: D. Boito, M. Gelterman,
V. Mateu, J. Piclum

ICTP-SAIFR PROGRAM ON PARTICLE PHYSICS

Sep 30 - Nov 30

Org: E. Pontón, M. Quirós, R. Rosenfeld

WORKSHOP ON SKILLS FOR YOUNG SCIENTISTS/INCREASING DIVERSITY IN PHYSICS

Oct 7 - 11

Org: A. Avila-Bernal, M. Barbosa,
S.P. Dawson, L. Meza-Montes

WORKSHOP ON CONFORMAL FIELD THEORIES AND TENSOR CATEGORIES

Oct 16 - 18

Org: I. Angiono, V. Futorny, A. Solotar,
L. Vendramin, C. Walton

WORKSHOP ON THE DARK UNIVERSE

Oct 21 - 25

Org: B. Dutta, A. Mazumdar,
F. Queiroz, R. Rosenfeld

SCHOOL ON PARALLEL PROGRAMMING FOR HIGH PERFORMANCE COMPUTING

Dec 2 - 13

Org: N. Berkovits, R. Cobe, L. Girotto,
R. Iope, B. Leal, S. Novaes

SCHOOL ON DATA SCIENCE AND MACHINE LEARNING

Dec 16 - 20

Org: R.M.O. Cobe, I. Girotto, B.C. Leal,
S. Novaes, G.A. von Winckler

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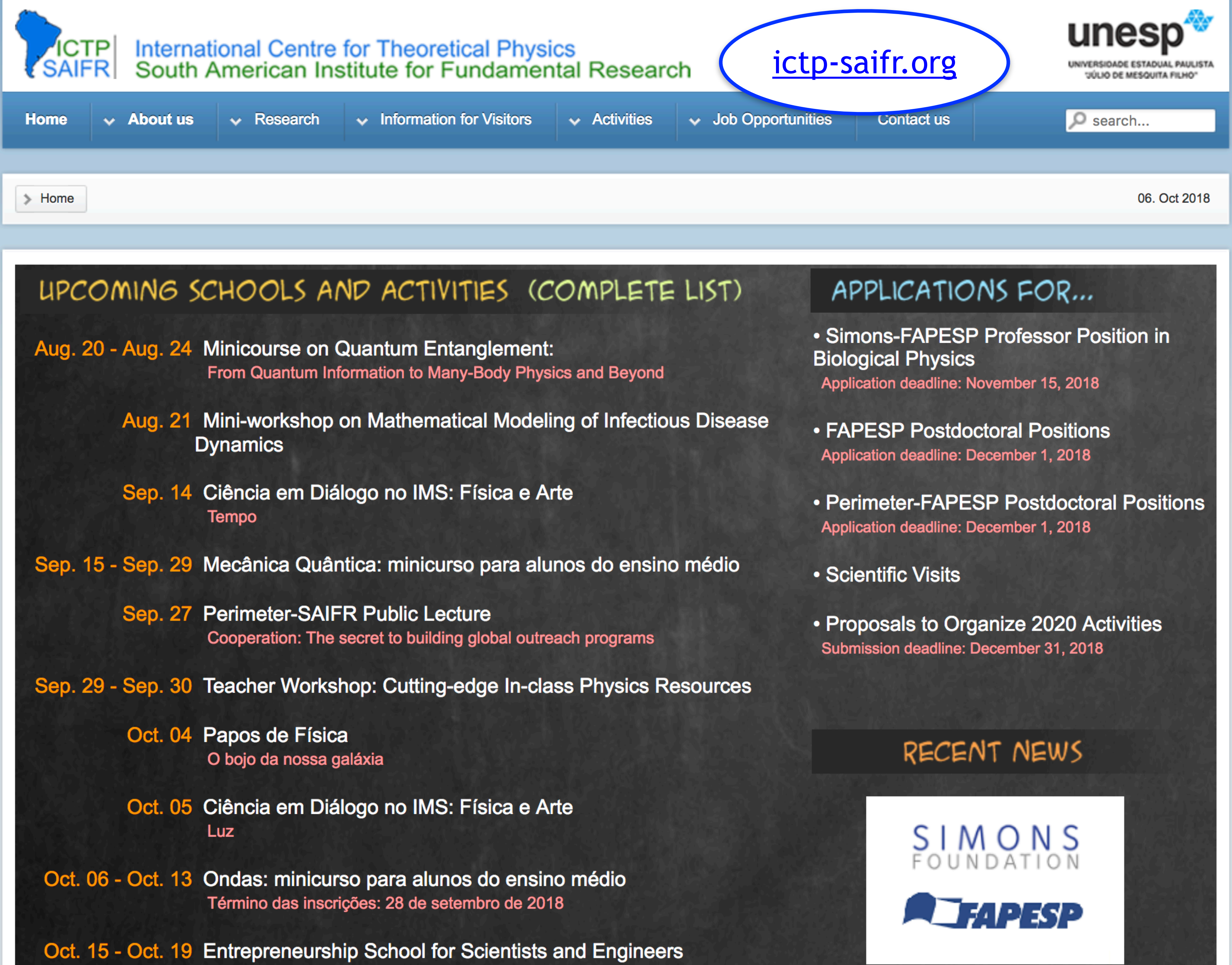

UPCOMING SCHOOLS AND ACTIVITIES (COMPLETE LIST)

Aug. 20 - Aug. 24 Minicourse on Quantum Entanglement:
From Quantum Information to Many-Body Physics and Beyond

Aug. 21 Mini-workshop on Mathematical Modeling of Infectious Disease Dynamics

Sep. 14 Ciência em Diálogo no IMS: Física e Arte
Tempo

Sep. 15 - Sep. 29 Mecânica Quântica: minicurso para alunos do ensino médio

Sep. 27 Perimeter-SAIFR Public Lecture
Cooperation: The secret to building global outreach programs

Sep. 29 - Sep. 30 Teacher Workshop: Cutting-edge In-class Physics Resources

Oct. 04 Papos de Física
O bojo da nossa galáxia

Oct. 05 Ciência em Diálogo no IMS: Física e Arte
Luz

Oct. 06 - Oct. 13 Ondas: minicurso para alunos do ensino médio
Término das inscrições: 28 de setembro de 2018

Oct. 15 - Oct. 19 Entrepreneurship School for Scientists and Engineers

APPLICATIONS FOR...

- Simons-FAPESP Professor Position in Biological Physics
  Application deadline: November 15, 2018
- FAPESP Postdoctoral Positions
  Application deadline: December 1, 2018
- Perimeter-FAPESP Postdoctoral Positions
  Application deadline: December 1, 2018
- Scientific Visits
- Proposals to Organize 2020 Activities
  Submission deadline: December 31, 2018

RECENT NEWS

Twistors and the Superstring

Nathan Berkovits
ICTP South American Institute for Fundamental Research
IFT-UNESP, São Paulo

Brief history of string theory

1) 1968-1975: Model for strong interactions

String resonances describe “democracy” of hadronic bound states.

D=26 (bosonic string) or D=10 (spinning string) was a problem.

2) 1976-1982: Model for quantum gravity

Spinning string describes quantum supergravity in D=10.

String resonances are massive states needed for consistency.

3) 1983-1994: Model for unification of forces

After compactification to D=4, superstring spectrum contains massless states and gauge groups that might be related to the Standard Model.

4) 1995 – 1997: M-theory and dualities

Superstring theory is the perturbative description of a larger theory.

By studying this larger theory, superstring theory can be related to other theories such as d=11 supergravity or N=4 d=4 super-Yang-Mills theory.

- After 1997, much of string theory research has involved a specific duality (AdS-CFT) which relates string theory compactified in a d-dimensional Anti-de-Sitter spacetime to a conformal field theory in d-1 dimensions
- Different choices of the AdS spacetime relate string theory to d=4 Yang-Mills gauge theories or to d=3 conformal field theories appearing in condensed matter physics
- Researchers have also used AdS-CFT to study black holes and quantum gravity through holography and quantum entanglement
- Scattering amplitudes of conformal field theories have special properties such as integrability which should be related to scattering amplitudes of superstring theory
- Despite great progress in understanding these amplitudes from the CFT side, very little progress has been made on the superstring side which would be useful for finding a “proof” of AdS-CFT duality.
- To relate these amplitudes, “twistors” seem to play a useful role.

Introduction

- Both twistors and the superstring have a long history beginning in the late 60´s
- Twistor theory was proposed in 1967 by Roger Penrose (Oxford) as an alternative to field theory in which the fundamental role played by spacetime points is replaced by light-like trajectories.
- Twistor theory is especially convenient for describing massless theories in four dimensions (such as Yang-Mills) since conformal invariance can be made manifest.
- Although Penrose did not consider (and dislikes) supersymmetric theories, Alan Ferber showed in 1977 that twistors have an elegant generalization to supertwistors which describe supersymmetric versions of d=4 Yang-Mills .
- Until 2004, most of the twistor research was done at Oxford.

- String theory began in 1968 with the observation by Gabriele Veneziano that a certain product of Gamma functions describes 4-point S-matrix amplitudes with properties similar to those found in hadron scattering.
- This amplitude was easily generalized to n-point amplitudes and, in 1969, was shown to come from a theory in which point-like particles are replaced by one-dimensional strings.
- Vibrations of these strings describe the massless particles of Yang-Mills and gravity, as well as an infinite tower of massive particles whose $(mass)^2$ is proportional to the string tension.
- In 1970, a fermionic version of this string was developed , and in 1976, the massless vibrations of this superstring were shown to describe super-Yang-Mills and supergravity .
- Unlike point-particle theories, superstring theory is consistent only in 10 dimensions, but it describes quantum gravity without the ultraviolet divergences of quantum general relativity.

- For 35 years, the twistor and string communities rarely intersected.
- But in 2004, Edward Witten showed that the scattering amplitudes of maximally supersymmetric Yang-Mills in four dimensions (``N=4 d=4 super-Yang-Mills”) could be computed using a string theory constructed from twistor variables.
- Unlike ordinary Yang-Mills in which quantum corrections break the classical conformal invariance and the coupling constant depends on the energy scale, N=4 d=4 super-Yang-Mills is conformally invariant at the quantum level .
- Using twistor methods, N=4 d=4 super-Yang-Mills scattering amplitudes can now be computed in a much more efficient manner than by using Feynman diagrams.
- Many of these twistor methods extend to ordinary Yang-Mills and have led to more accurate predictions for the LHC, e.g. compare twistor expression for the 5-point gluon tree amplitude:

$$A_5 = (\lambda_1 \lambda_2)^4 / (\lambda_1 \lambda_2)(\lambda_2 \lambda_3)(\lambda_3 \lambda_4)(\lambda_4 \lambda_5)(\lambda_5 \lambda_1) \quad \text{with}$$

Result of evaluation (actually only a small part of it):

$k_1 \cdot k_4 \, \varepsilon_2 \cdot k_1 \, \varepsilon_1 \cdot \varepsilon_3 \, \varepsilon_4 \cdot \varepsilon_5$

Messy combination of momenta and gluon polarization vectors.

- As shown by Juan Maldacena in 1997, N=4 d=4 super-Yang-Mills is dual to superstring theory in an $AdS_5 \times S^5$ background with Ramond-Ramond flux
- Superstring theory with Ramond-Ramond flux cannot be described using the conventional "Ramond-Neveu-Schwarz" formalism and can only be quantized using the "pure spinor" formalism which is manifestly spacetime supersymmetric.
- In addition to the usual fermionic spinor variables θ^α of (x^m, θ^α) ten-dimensional superspace, the pure spinor formalism for the superstring also includes bosonic spinor variables λ^α which satisfy the d=10 pure spinor relation $\lambda^\alpha \gamma^m_{\alpha\beta} \lambda^\beta = 0$
- The d=10 bosonic variables (λ^α, x^m) naturally combine into a d=10 twistor which transforms covariantly under d=10 conformal transformations.
- Work is in progress on relating these d=10 twistors of the superstring with the d=4 twistors of N=4 d=4 super-Yang-Mills.

Outline

1) Basics of twistor theory
2) Basics of superstring theory
3) Pure spinor formalism of the superstring
4) Combining twistors and the superstring

Basics of Twistor Theory

- In d=4, any light-like vector P^m satisfying $P_m P^m = 0$ can be expressed in terms of a pair of bosonic spinors $(\lambda^a, \bar{\lambda}^{\dot{a}})$ as

$$P^m = \sigma^m_{a\dot{a}} \lambda^a \bar{\lambda}^{\dot{a}}$$

where $\sigma^m_{a\dot{a}}$ are Pauli matrices for $m = 0 \text{ to } 3 \text{ and } a, \dot{a} = 1 \text{ to } 2$

- Instead of defining fields in terms of vectors (x^m, P_m), define fields in terms of spinors (λ^a, μ_a) and $(\bar{\lambda}^{\dot{a}}, \bar{\mu}_{\dot{a}})$ where μ_a and $\bar{\mu}_{\dot{a}}$ are conjugate to λ^a and $\bar{\lambda}^{\dot{a}}$ and are defined by $\mu_a = x^m \sigma^m_{a\dot{a}} \bar{\lambda}^{\dot{a}}$ and $\bar{\mu}_{\dot{a}} = x^m \sigma^m_{a\dot{a}} \lambda^a$.
- Under spacetime conformal transformations, the “twistor” variables $(\lambda^a, \bar{\lambda}^{\dot{a}}, \mu_a, \bar{\mu}_{\dot{a}})$ transform linearly, unlike the usual spacetime variables (x^m, P_m) which transform nonlinearly.

- Spacetime conformal transformations SO(4,2) = SU(2,2):

Lorentz rotations $\delta x^m = \Lambda^{mn} x_n$

Translations $\delta x^m = c^m$

Conformal boosts $\delta x^m = (f_n x^n) x^m - \frac{1}{2} f^m (x^n x_n)$

Dilatations $\delta x^m = -h x^m$

- Twistor variables $(\lambda^a, \bar{\mu}_{\dot{a}}, \bar{\lambda}^{\dot{a}}, \mu_a)$ transform linearly as:

$$\delta\lambda^a = \Lambda^a_b \lambda^b + h\lambda^a + f^{a\dot{b}} \bar{\mu}_{\dot{b}}$$

$$\delta\bar{\mu}_{\dot{a}} = \Lambda^{\dot{b}}_{\dot{a}} \bar{\mu}_{\dot{b}} - h\bar{\mu}_{\dot{a}} + c_{b\dot{a}} \lambda^b$$

$$\delta\bar{\lambda}^{\dot{a}} = \Lambda^{\dot{a}}_{\dot{b}} \bar{\lambda}^{\dot{b}} + h\bar{\lambda}^{\dot{a}} + f^{a\dot{a}} \mu_a$$

$$\delta\mu_a = \Lambda^b_a \mu_b - h\mu_a + c_{a\dot{b}} \bar{\lambda}^{\dot{b}}$$

where

$$\Lambda^{mn} = (\sigma^{mn})^a_b \Lambda^b_a + (\sigma^{mn})^{\dot{a}}_{\dot{b}} \Lambda^{\dot{b}}_{\dot{a}}, \quad c^m = \sigma^m_{a\dot{b}} c^{a\dot{b}}, \quad f^m = \sigma^m_{a\dot{b}} f^{a\dot{b}}.$$

- Supersymmetric theories contain both bosonic and fermionic fields, and it is convenient to combine these fields into a "superfield".
- For example, N=4 d=4 super-Yang-Mills $(j = 1 \text{ to } 4)$ contains:

  1 gluon $a_m(x)$ with 2 physical polarizations

  4 Majorana spinors $(\xi_j^a(x), \bar{\xi}^{\dot{a}j}(x))$ with 8 physical components

  6 scalar bosons $\phi_{jk}(x) = -\phi_{kj}(x)$

- These 8+8 bosons and fermions can be combined into 6 superfields

$$\Phi_{jk}(x,\theta) \;=\; \phi_{jk}(x) + \theta_{a[j}\xi^a_{k]}(x) + (\theta_{aj}\sigma^{ab}_{mn}\theta_{bk})F^{mn}(x) + \ldots$$

where θ^a_j is a fermionic "superspace" variable and $\cdots$ denotes terms which contain higher powers of θ^a_j. However, computing scattering amplitudes using $\Phi_{jk}(x,\theta)$ is complicated because of its complicated dependence on θ^a_j.

- Using "supertwistor" variables, N=4 d=4 super-Yang-Mills can instead be described by a single superfield Φ depending on the 4 bosonic variables $(\lambda^a, \bar{\mu}^{\dot{a}})$ and the 4 fermionic variables η^j as

$$\Phi(\eta) = a_- + \eta^j \xi_j + \eta^j \eta^k \phi_{jk} + (\eta)^3_j \, \bar{\xi}^j + (\eta)^4 a_+$$

where $a_\pm$ are the 2 physical gluon polarizations and $(\xi_j, \bar{\xi}^j)$ are the 8 physical spinor polarizations which depend on $(\lambda^a, \bar{\mu}^{\dot{a}})$.

- The supertwistor variables $(\lambda^a, \bar{\mu}^{\dot{a}}, \eta^j)$ transform linearly under N=4 d=4 superconformal transformations which include both supersymmetry and conformal transformations $(\eta^j = \lambda^a \theta^j_a)$.
- The n-point tree-level "MHV" scattering amplitude is given by

$$A_n = (\textstyle\sum_{r=1}^n \lambda_r \frac{\partial}{\partial \eta_r})^8 \quad \Phi_1(\eta_1)...\Phi_n(\eta_n)/(\lambda_1\lambda_2)(\lambda_2\lambda_3)...(\lambda_n\lambda_1)$$

which reduces for 5 gluon scattering with polarizations $(++---)$

to $A_5 = (\lambda_1\lambda_2)^4/(\lambda_1\lambda_2)(\lambda_2\lambda_3)(\lambda_3\lambda_4)(\lambda_4\lambda_5)(\lambda_5\lambda_1)$

- Scattering amplitudes for n gluons in QCD are functions of the gluon polarizations ϵ_r^m and momenta P_r^m for r=1 to n.

- Using the Feynman diagram methods of quantum field theory, amplitude expressions are very complicated for 4 or more external gluons. Makes it difficult to compare with experiments.

- Using twistor methods, manifest d=4 conformal invariance allows expressions to be simplified into a few lines, e.g.

$$A_5 = (\lambda_1\lambda_2)^4/(\lambda_1\lambda_2)(\lambda_2\lambda_3)(\lambda_3\lambda_4)(\lambda_4\lambda_5)(\lambda_5\lambda_1)$$

- Twistor expressions can then be translated back into standard expressions as a function of the gluon polarization and momenta where the polarizations are in Lorentz gauge, i.e. $\epsilon_{rm}P_r^m = 0.$

$P_r^m = \sigma^m_{a\dot{a}}\lambda_r^a\bar{\lambda}_r^{\dot{a}}$ and $\epsilon_r^m = \sigma^m_{a\dot{a}}\lambda_r^a\bar{u}_r^{\dot{a}} + \sigma^m_{a\dot{a}}u_r^a\bar{\lambda}_r^{\dot{a}}$ for some $(u_r^a, \bar{u}_r^{\dot{a}})$

Basics of Superstring Theory

- String theory is obtained from point particle theory by replacing the worldline trajectory $x^m(\tau)$ of the point particle with the worldsheet trajectory $x^m(\tau, \sigma)$ of the one-dimensional string.

- For the superstring, one also has fermionic variables which are described using a spacetime vector $\psi^m(\tau, \sigma)$ in the original Ramond-Neveu-Schwarz version (1971) but are described by a spacetime spinor $\theta^\alpha(\tau, \sigma)$ in the Green-Schwarz version (1984).

- Spacetime supersymmetry $\theta^\alpha(\tau, \sigma) \to \theta^\alpha(\tau, \sigma) + \epsilon^\alpha$ is manifest in the Green-Schwarz version, but quantization is complicated.

- Unlike in general relativity, multiloop scattering amplitudes of gravitons in superstring theory are perturbatively finite.
- It is possible that some compactification of d=10 superstring theory to four dimensions describes our universe where different particles correspond to different vibrational modes of the superstring.
- Duality symmetries found in superstring theory have been applied to other areas of physics through the AdS-CFT correspondence which relates the superstring in certain gravitational Anti-de-Sittter backgrounds with strongly coupled gauge theories.
- These Anti-de-Sitter backgrounds require Ramond-Ramond flux and can only be described using the Green-Schwarz version of the superstring which, because of its quantization problems, has made it difficult to prove the correspondence.
- The simplest version of the AdS-CFT correspondence relates the superstring in an $AdS_5 \times S^5$ background with N=4 d=4 super-Yang-Mills.

- In 2003, Witten developed a new d=4 string theory constructed out of supertwistor variables and computed tree-level N=4 d=4 super-Yang-Mills amplitudes in twistor space.
- Since 2003, hundreds of papers on twistors and d=4 super-Yang-Mills amplitudes have been written, and the d=4 tree-level results were soon extended to multiloop "planar" amplitudes which dominate the scattering amplitude when the dimension of the gauge group is very large.
- However, to connect to the original d=10 superstring, one needs a d=10 version of twistors related to "pure spinors".
- This "pure spinor" formalism for the superstring was developed over the last 15 years and is the only approach currently available for covariantly quantizing the Green-Schwarz superstring with manifest d=10 super-Poincaré invariance.

Pure Spinor Formalism

- In any even dimension D, can define a "pure spinor" to be λ^α satisfying constraint that $\lambda^\alpha \lambda^\beta \sim \gamma^{\alpha\beta}_{m_1 \ldots m_{\frac{D}{2}}} (\lambda \gamma^{m_1 \ldots m_{\frac{D}{2}}} \lambda)$

- In d=10, α =1 to 16 and the pure spinor constraint implies that λ^α contains 11 independent components and satisfies

$$\lambda^\alpha \gamma^m_{\alpha\beta} \lambda^\beta = 0$$

- By combining the variables (x^m, θ^α) of the Green-Schwarz superstring with the pure spinor variable λ^α, the Green-Schwarz superstring can be covariantly quantized with manifest d=10 supersymmetry (NB, 2000).

- In this “pure spinor formalism”, the worldsheet action in a flat d=10 background is

$$S = \int d^2 z [\partial x^m \bar{\partial} x_m + p_\alpha \bar{\partial} \theta^\alpha + w_\alpha \bar{\partial} \lambda^\alpha \ + \ complex\ conjugate]$$

where $z = \tau + i\sigma$ is the complexified worldsheet coordinate.

- Physical states are annihilated by the BRST operator $Q = \lambda^\alpha d_\alpha$ where $d_\alpha = p_\alpha - (\partial x^m - \frac{1}{2}\theta\gamma^m \partial\theta)(\gamma_m \theta)_\alpha$ is the supersymmetric fermionic momentum satisfying the second-class constraint $\{d_\alpha, d_\beta\} = \gamma^m_{\alpha\beta}(\partial x_m - \theta\gamma_m \partial\theta)$

- The pure spinor constraint $\lambda\gamma^m\lambda = 0$ implies that $Q^2 = 0.$

- Since the action is quadratic, worldsheet variables are free fields and quantization is straightforward. Spacetime supersymmetry under $\theta^\alpha \to \theta^\alpha + \epsilon^\alpha, \ x^m \to x^m + \epsilon\gamma^m\theta$ is manifest.

- In "pure spinor superspace", the d=10 super-Yang-Mills superfield is
$$V(x^m, \theta^\alpha, \lambda^\alpha) = \lambda^\alpha A_\alpha(x,\theta)$$
where $$A_\alpha(x,\theta) = a_m(x)(\gamma^m\theta)_\alpha + \xi^\beta(x)(\gamma^m\theta)_\alpha(\gamma_m\theta)_\beta + \ldots$$
and $a_m(x)$ and $\xi^\alpha(x)$ are the onshell gluon and gluino.

- d=10 spacetime supersymmetry is manifest where the gluon and gluino transform into each other as
$$\delta a_m(x) = \epsilon\gamma_m\xi(x), \quad \delta\xi^\alpha(x) = \partial_m a_n(x)(\gamma^{mn}\epsilon)^\alpha$$

- Similarly, the d=10 supergravity superfield in pure spinor superspace is
$$V(x^m, \theta^\alpha, \lambda^\alpha, \bar\theta^\alpha, \bar\lambda^\alpha) = \lambda^\alpha\bar\lambda^\beta A_{\alpha\beta}(x,\theta,\bar\theta)$$
where $$A_{\alpha\beta}(x,\theta,\bar\theta) = g_{mn}(x)(\gamma^m\theta)_\alpha(\gamma^n\bar\theta)_\beta + \ldots$$
and $g_{mn}(x)$ is the onshell graviton.

- n-point g-loop superstring scattering amplitudes are computed as the correlation function of n vertex operators on a genus g worldsheet:

$$A_{g,n} = \prod_{r=1}^{3g-3} \int d^2\tau_r \int d^2 z_1 ... d^2 z_n \langle\ V_1(z_1)...V_n(z_n) | \prod_r (\int \mu_r b)|^2\ \rangle$$

where $\tau_1 ... \tau_{3g-3}$ are the 3g-3 complex parameters needed to describe a genus g surface and $\prod_r (\int \mu_r b)$ is their associated measure factor.

- Since the worldsheet action is quadratic, it is straightfoward to compute the correlation function as a function of the momenta and polarizations of the external states.
- Amplitude expressions are much simpler than those obtained using quantum field theory techniques since the hundreds of Feynman diagrams which appear in the quantum field theory computation are replaced by a single genus g worldsheet in the string theory computation.

- Worldsheet action is manifestly d=10 super-Poincaré covariant, so all cancellations due to spacetime supersymmetry are manifest.
- Perturbative multiloop graviton scattering amplitudes have been proven to be finite using this approach.
- This pure spinor approach is the most powerful method for computing multiloop superstring scattering amplitude (e.g. 3-loop 4-point computation by Mafra and Gomez is the only 3-loop superstring computation up to now).
- Anti-de-Sitter backgrounds with Ramond-Ramond flux can be studied using the pure spinor formalism.
- Although superstring theory in an $AdS_5 \times S^5$ background is more complicated than in a flat background, the worldsheet action can be simplified by introducing d=10 twistor-like variables.

Combining twistors and the superstring

- The first step is to define d=10 twistors which replace (x^m, P_m) for m=0 to 9. In any even dimension, Hughston (1990) showed that twistors are a pair of pure spinors $(\lambda^\alpha, \mu_\alpha)$ defined to satisfy

$$\mu_\alpha = x^m(\gamma_m\lambda)_\alpha$$

- In d=10, $(\lambda^\alpha, \mu_\alpha)$ contain 16 independent components and transform linearly under SO(10,2) conformal transf´s (Cherkis and NB, 2004).

- One would like to build a superstring theory where the d=10 spacetime variables and pure spinor variables are replaced by the d=10 twistor variables $(\lambda^\alpha, \mu_\alpha)$.

- In one of his first papers in 1978, Witten used d=4 supertwistors to find classical solutions of d=4 Yang-Mills, and in 1988, he showed that twistor integrability along d=10 light-like trajectories is related to a local fermionic symmetry of the Green-Schwarz superparticle and superstring.
- In 1991, Howe showed that twistor integrability along d=10 pure spinor trajectories implied the equations of motion for d=10 super-Yang-Mills and supergravity theories.
- Between 1989-1995, several proposals for worldsheet actions were constructed using twistor variables which are classically equivalent to the Green-Schwarz superstring (Sorokin, Tonin, NB, Howe, …).
- However, all of these classical twistor-string actions contained the same quantization problems as the original Green-Schwarz action caused by the presence of second-class constraints.

For the superstring (NB 2016), the bosonic variables of the pure spinor formalism can be combined into left and right-moving d=10 twistor variables $(\lambda^\alpha_L, \mu_{L\,\alpha})$ and $(\lambda^\alpha_R, \mu_{R\,\alpha})$ and their conjugate momenta $(w_{L\,\alpha}, \nu^\alpha_L)$ and $(w_{R\,\alpha}, \nu^\alpha_R)$.

These bosonic twistor variables combine with the fermionic variables of the pure spinor formalism to form N=(1,1) worldsheet superfields

$$\Theta^\alpha_L = \theta^\alpha_L + \kappa_L\,(\lambda^\alpha_L + \nu^\alpha_L), \quad \Theta^\alpha_R = \theta^\alpha_R + \kappa_R\,(\lambda^\alpha_R + \nu^\alpha_R),$$

$$\Phi_{L\,\alpha} = \mu_{L\,\alpha} + w_{L\,\alpha} + \kappa_L\, p_{L\,\alpha}, \quad \Phi_{R\,\alpha} = \mu_{R\,\alpha} + w_{R\,\alpha} + \kappa_R\, p_{R\,\alpha},$$

where N=1 worldsheet susy is generated by $(Q_L + b_L, Q_R + b_R)$.

The N=(1,1) worldsheet action in a flat background is

$$S = \int d^2z d^2\kappa[-\Phi_L D_R \Theta_L + \Phi_R D_L \Theta_R + (\Theta_L \gamma^m D_L \Theta_L)(\Theta_R \gamma_m D_R \Theta_R)]$$

and the N=(1,1) worldsheet action in an $AdS_5 \times S^5$ background is

$$S = r^2 \int d^2z d^2\kappa [D_L \Theta^J_S D_R \Theta^S_J + D_L \Theta^J_S \Theta^S_K D_R \Theta^K_T \Theta^T_J]$$

where (Θ^J_S, Θ^S_J) are linear combinations of $(\Theta^\alpha_L, \Theta^\alpha_R)$.

- This worldsheet action in an $AdS_5 \times S^5$ background can be covariantly quantized and used to construct vertex operators for the massless states of the superstring

Some Open questions

- Can one compute scattering amplitudes in $AdS_5 \times S^5$ for these massless states and show they agree with the expected scattering amplitudes in N=4 d=4 super-Yang-Mills theory?
- How are the d=10 twistors related to the d=4 twistors of N=4 d=4 super-Yang-Mills?
- Will this twistor description of the superstring be useful for proving the AdS-CFT correspondence by showing equivalence of the scattering amplitudes when the AdS radius is small and the N=4 d=4 super-Yang-Mills is weakly coupled?