Conference Summary

21 June – 2 July 2021 | ICTP-SAIFR, São Paulo

Hirosi Ooguri

Caltech & Kavli IPMU

Why Summary Talk?

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- Review and discuss progress in 2020 – 2021
  - Compare with past years
  - Highlight major developments
  - Look forward to the future

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- Guide to Strings 2021 YouTube Playlist

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- It’s good for you.

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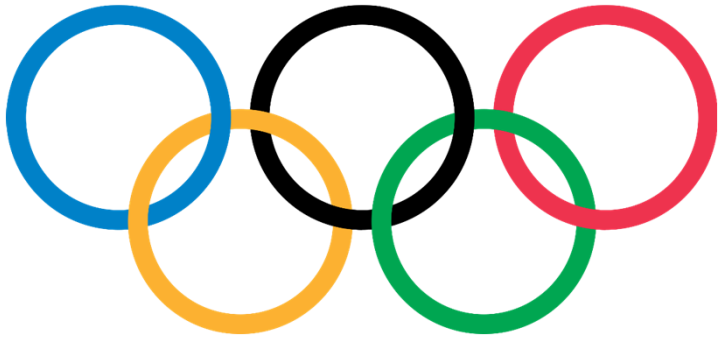
- Olympic



I have given summary talks at Strings 2004, 2008, and 2012.

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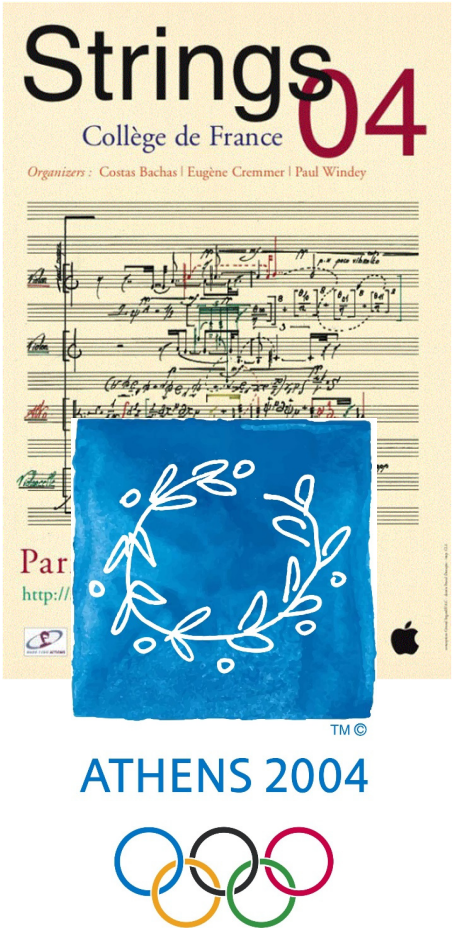

These were also Olympic years.

2021 is not divisible by 4, but …


Strings 04
Collège de France
Organizers : Costas Bachas | Eugène Cremmer | Paul Windey
Paris | June 28 - July 2
http://strings04.lpthe.jussieu.fr


STRINGS 2008
CERN | Geneva
18-23 August 2008
Organizers:
A. Alekseev (U Geneva)
L. Alvarez-Gaumé (CERN)
I. Antoniadis (CEFN)
J.-P. Derendinger (U Neuchatel)
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M. Gaberdiel (ETH Zurich)


MUNICH STRINGS 2012
July 23-28
Arnold Sommerfeld Center
LMU


Strings

TOKYO 2020


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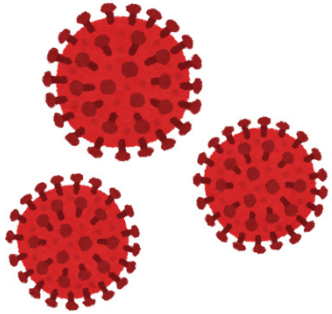


Strings 2004

Strings 2008

Strings 2012

Strings 2021

What I learned over the last two weeks

Black Holes and Wormholes

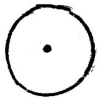
CONCLUDING REMARKS

HIROSI OOGURI
(CALTECH)

STRINGS 2004, PARIS

WHAT IS INSIDE A BLACK HOLE ?

THE ENTROPY PROBLEM:



$S = \frac{A}{4G}$

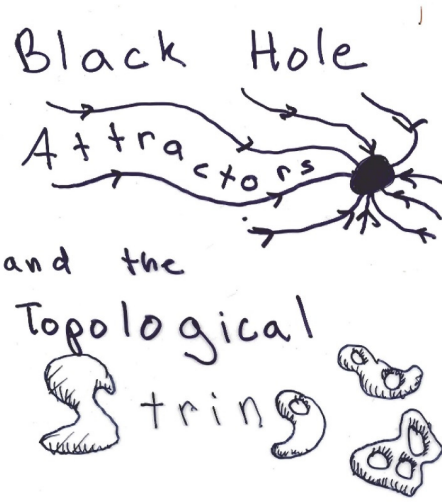
But black holes have no hair

$S = \ln 1 = 0$??

WHERE ARE THE STATES OF A BLACK HOLE?

THE INFORMATION PROBLEM:

HAWKING RADIATION → INFORMATION LOSS ??



In collaboration with

Hirosi Ooguri

and

Cumrun Vafa

hepth 0405146

Wormholes in AdS

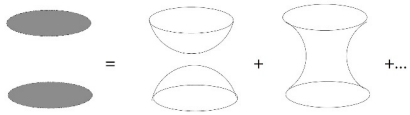
living on the edges

Liat Maoz (University of Amsterdam)

STRINGS 2004

J.Maldacena, L. Maoz, hep-th/0401024
JHEP02(2004)053

HOWEVER:



CFT: the CFT on $\mathcal{N} = \cup_i \mathcal{N}_i$ is the product of the theories on the different $\mathcal{N}_i$'s. Completely independent CFTs $\rightarrow$ Correlations should factorize.

BULK: expect correlations between the two regions.

(*) The puzzle is even more apparent when the wormhole is not only a classical solution, but also a stable solution (perturbatively and non-perturbatively)

SEARCHING FOR A 2-D BLACK HOLE

JUAN MALDACENA

STRINGS 04 - PARIS -

Concluding Remarks

Hirosi Ooguri
(Caltech)

Strings 2004, Paris

What is inside a black hole?

The entropy problem:

$S = \frac{A}{4G}$

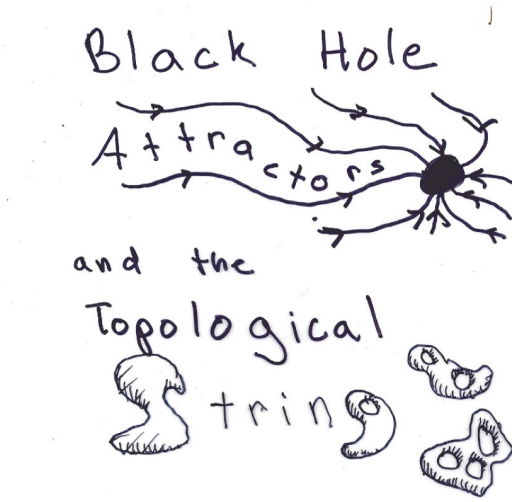
But black holes have no hair

$S = \ln 1 = 0$??

Where are the states of a black hole?

The information problem:

Hawking radiation → information loss ??



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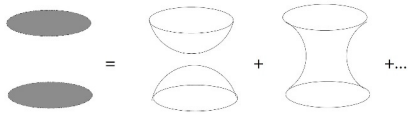

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SEARCHING FOR A 2-D BLACK HOLE

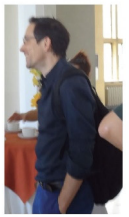
JUAN MALDACENA

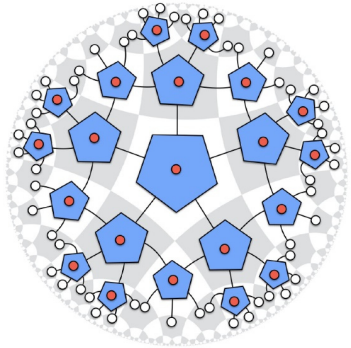
STRINGS 04 - PARIS -

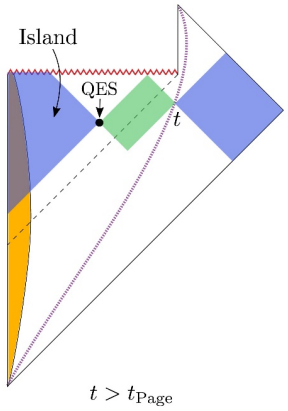
Black Holes: Complementarity vs Firewalls ⇦

Raphael Bousso

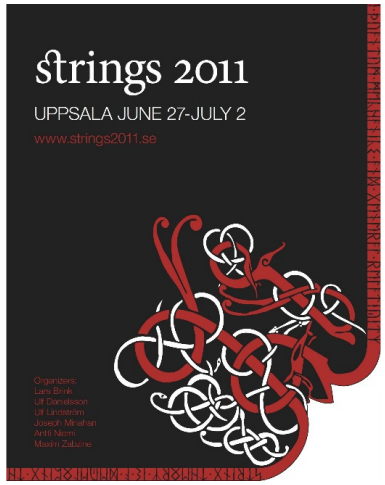
Bousso: assured us that we would not be burned to death when crossing black hole event horizons.







Connections to quantum information theory have inspired major progress over the past decade.



Strings 2011 talk by Tadashi Takayanagi

Strings 2011@Uppsala, July 1

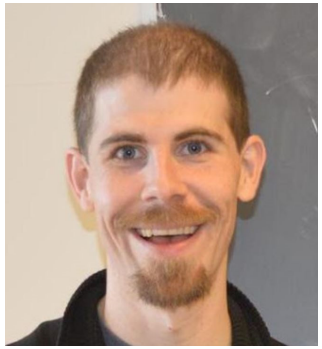
⇨ Holographic Entanglement Entropy and its New Developments

Tadashi Takayanagi
(IPMU, the University of Tokyo)

Ensemble averages and wormholes

Stephen Shenker reviewed the bulk explanation for the long-time behavior of thermal correlation functions.

- Wormholes and ensemble average
- Factorization puzzle



Kristan Jensen discussed how to calculate wormhole contributions to AdS observables when they are not saddle points of functional integrals and are UV sensitive.

Ensemble averages and wormholes

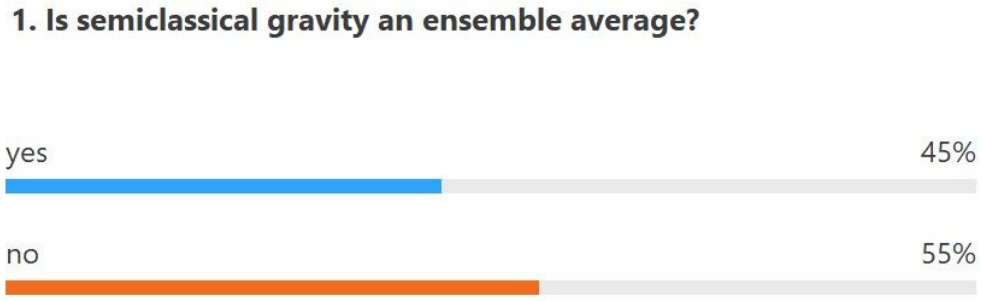
Discussion led by **Jan de Boer**, **Stephen Shenker**, and **Douglas Stanford**.



- A simple diagnostic to distinguish ensemble averaging from coarse graining?
- **How is factorization restored?** What should we add to a simple gravity to get a specific boundary quantum system?
- **How much do they generalize to higher dimensions?**

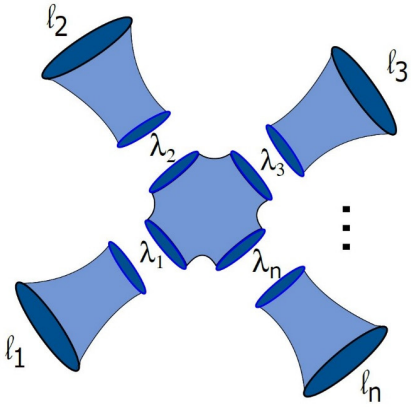
Juan Maldacena: If type IIB string in 10 d is not unique but has an ensemble average, which is the first operator that varies from a member to a member in the ensemble?

Xi Yin: Closed string field theory can compute in $AdS_5 \times S^5$ to all order in $1/N$. How do you go beyond, algorithmically?



JT gravity and SYK model

$$\left\langle \prod_{i=1}^{n} Z(\ell_i) \right\rangle = \prod_{i=1}^{n} \int d\mu(\lambda_i)$$

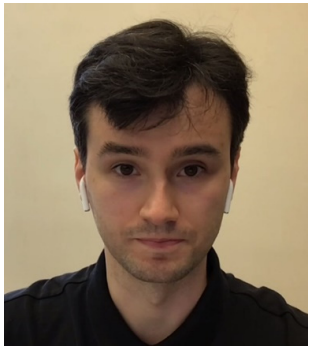


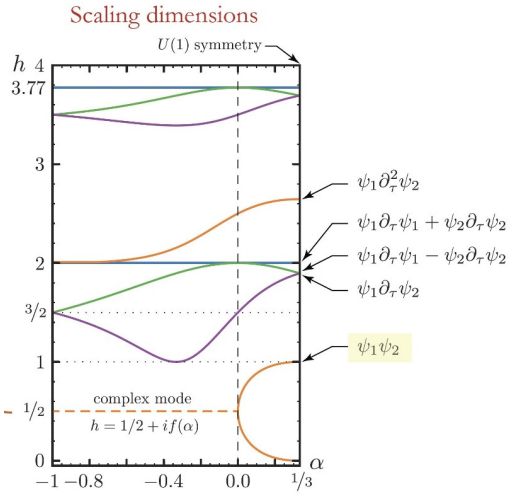
Thomas Mertens demonstrated the Liouville gravity is a q-deformation of the JT gravity.

Clifford Johnson showed that the JT gravity is described by a double-scaled large N random Hermitian matrix model and used it to construct the statistics of the first several energy and to compute the quenched free energy.

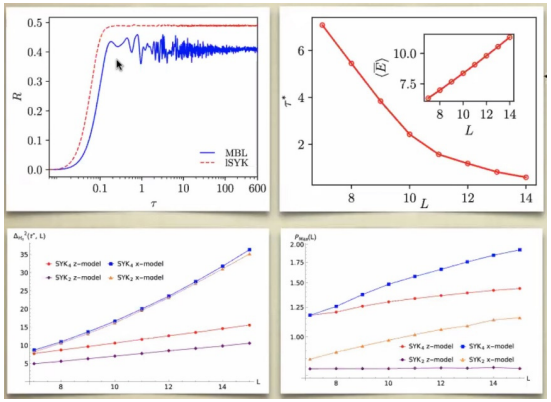
There is a **Slack thread** on uniqueness of non-perturbative completion.

JT gravity and **SYK model**



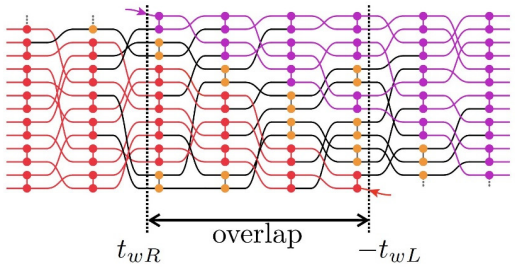


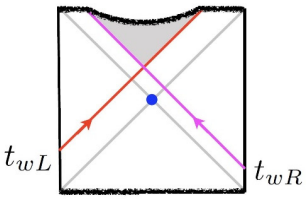
Gregory Tarnopolsky discussed a variety of SYK-like models using conformal perturbation theory, with rich structure in operator spectra, symmetry breaking patterns, and effective actions.



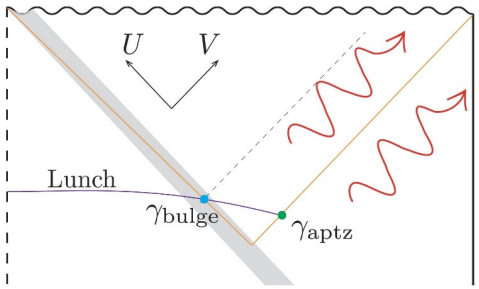
Jeff Murugan showed that non-locality in the SYK model and its efficient utilization for operator spreading on network lead to quantum advantage in its applications to quantum batteries.

Quantum information and gravity





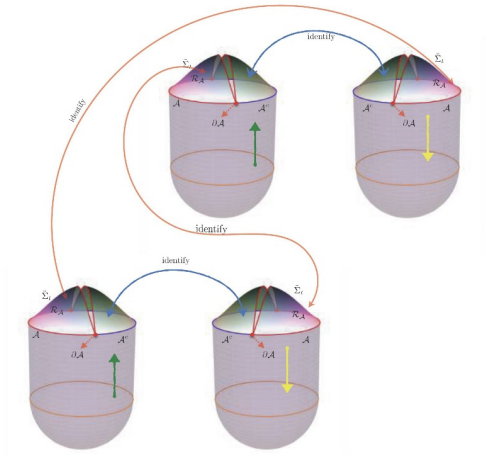
Ying Zhao described a meeting inside of a wormhole in terms of the quantum circuit that prepares the entangled state.



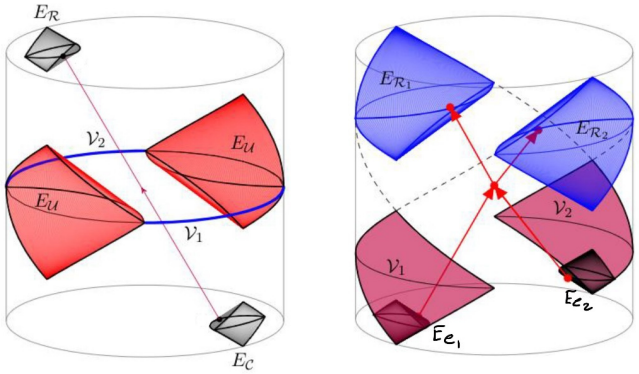
Geoff Penington showed quantum extremal surfaces help reconstruct the black hole interior even for non-evaporating black holes.

Reconstruction of interior outgoing modes is always exponentially complex.

Quantum information and gravity



Mukund Rangamani discussed real-time replica wormholes with complex saddles and demonstrated the computations of Rényi entropies and thermal correlators.



Alex May discussed how the bulk causality is reflected on boundary correlations:

Privacy-Duality Theorem
Connected Wedge Theorem

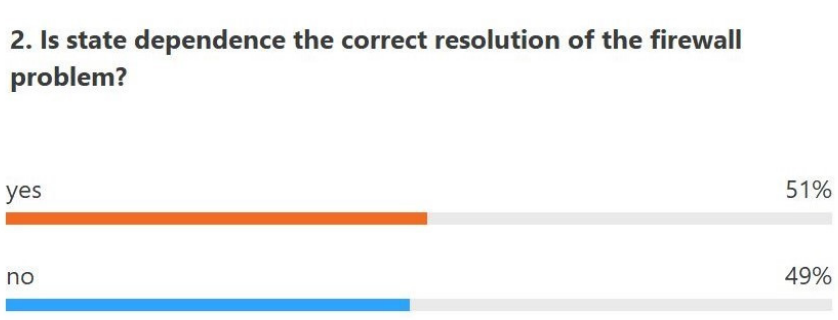
Black hole information problem

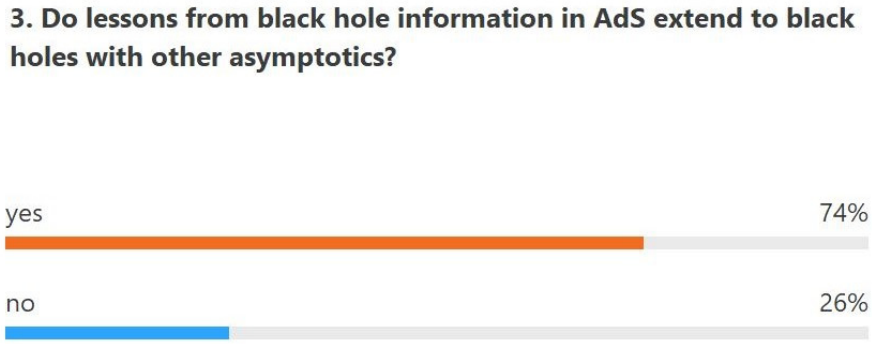
Discussion led by **Netta Engelhardt** and **Rob Myers**

With additional contributions by
Chris Akers and **Dominik Neuenfeld**.

Eva Silverstein: String theory has non-local effects that are consistent with causality.

Edward Witten: The difference between a piece of burning coal and an evaporating black hole is that the complicated state for the latter has a simple geometric description after the Page time. Non-locality arises when one tries to make a complex measurement on the outgoing state; it has a non-classical effect on the geometry.





Structure of black hole microstates

$$\mathcal{I}_N(\tau) \simeq \sum_{m,n} \exp\big(-S_{\text{eff}}(m,n;\tau)\big)$$

Sameer Murthy presented the asymptotic expansion of the superconformal index as a sum over complex saddle points in the bulk.

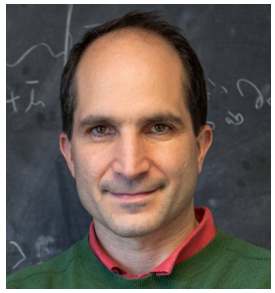
Universality of Logarithmic Corrections: Gravity

- Similar results for asymptotically $AdS_4 \times SE_7$ black holes with $SE_7 = \{S^7, V^{5,2}, N^{0,1,0}, Q^{1,1,1}, M^{1,1,1}\}$
- Every seven-dimensional, compact Einstein manifold of positive curvature has vanishing first Betti number, $R_{mn} = 6m^2 g_{mn} \Rightarrow \Delta_1 \geq 6m^2$.
- A universal macroscopic result that matches the field theory [PZ-Xin '20]:

$$S = S_{BH} \quad -\frac{1}{2}\log N + \cdots,$$

Leo Pando-Zayas successfully compared the $\log(N)$ term in gauge theory indices to the one-loop correction to black hole entropies.

Structure of black hole microstates



Discussion led by **Juan Maldacena** and **Samir Mathur**

- Can we see microstates directly at strong coupling, in Lorentzian signature?
- Fuzzballs appear to reproduce a faction < 1 of the entropy for some extremal black holes. How about at non-zero temperature? What is the typical microstate in the fuzzball picture?
- Bags of gold and singularities – do they cancel?

Questions/comments from the audience:

- Isn't every microstate a fuzzball? **What is the definition of fuzzballs?**
  [Maldacena answered in **Slack** that it is "**the idea that microstates are gravity solutions with no horizon**."]
- **What is wrong with the non-locality** used in the recent derivation of the Page curve when the geometry is emergent via the holography?

Microscopic AdS/CFT

Proving dualities

Matthias Gaberdiel proposed a string dual of the free $N = 4$ SYM in the planar limit is described by 8 symplectic boson and 8 free fermions and showed the spectra match, assuming that physical state conditions remove all out-of-the-wedge modes.

See also his lectures at Pre-Strings 2021: https://youtu.be/etXaIHofHCY

Lorenz Eberhardt demonstrated, in the tensionless string theory in AdS_3 with NS fluxes, the sum over target space geometries are carried out by string excitations.

- The perturbative string theory is background independent and does not need to sum over geometries.
- The string partition function on the wormhole factorizes.

Redundancy of sums over geometries may be related to the cobordism conjecture (message from **Cumrun Vafa**).

Proving dualities


Discussion led by **Rajesh Gopakumar** and **Xi Yin**

- **What we want to prove.**
- **How to prove.**

- Topological closed string ⇔ Chern-Simons theory
- Tensionless string ⇔ free $N = 4$ SYM

What can we learn from AdS/CFT by deriving it?

What about the Vasiliev theory?

Juan Maldacena: The Vasiliev theory has fields associated to currents, but we also need extra fields to describe the free SYM theory.

Ofer Aharony: We should say duality is proven when both sides are defined non-perturbatively. Otherwise, we should call it correspondence.

Nonperturbative Approaches

Ashoke Sen calculated **D-instanton contribution** to IIB string theory amplitudes in 10 dimensions and reproduced the result by Green and Gutperle **without assuming the S-duality**.

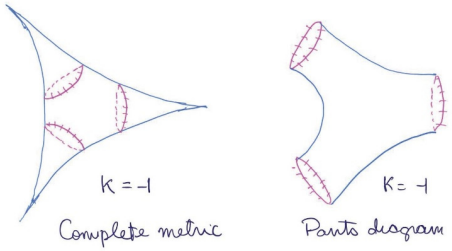
$$\frac{i}{4}\kappa^2 K_c \left[\frac{64}{stu} + 2\zeta(3) + \frac{2\pi^2}{3} g_s^2 + 4\pi g_s^{3/2} \sum_{k=1}^{\infty} \sqrt{k} \left(\sum_{d|k} d^{-2}\right) \left\{e^{2\pi i k\tau} + e^{-2\pi i k\tau^*}\right\} \{1 + O(g_s)\}\right]$$

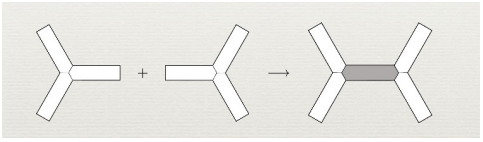
String (field) theory gives a systematic procedure for computing D-instanton contribution to the amplitudes.

Some discussion on whether this approach generalizes to non-supersymmetric quantities (asked by HO and Nathan Seiberg).

String Field Theory

Discussion led by **Yuji Okawa** and **Barton Zwiebach**





Achievements:

- Tachyon condensation
- Complete definition of string perturbation theory

Progress since 2015:

- Analytic solutions for any boundary CFT
- Superstring field theory
- String vertices and moduli spaces of Riemann surface
- Establishing field theory results

Recent directions:

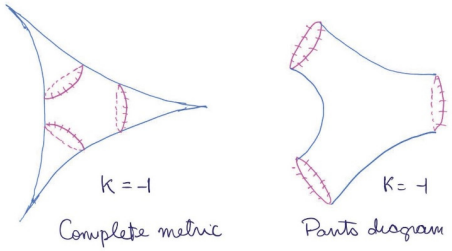
- Homological perturbation theory of homotopy algebras

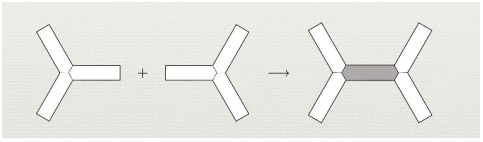
Open questions:

- Initial value formulation
- Classical solutions of closed string field theory
- Proof of the AdS/CFT correspondence: Is the open superstring field theory a consistent quantum theory?
- Manifest background independence (homework since 2011)

String Field Theory

Discussion led by **Yuji Okawa** and **Barton Zwiebach**





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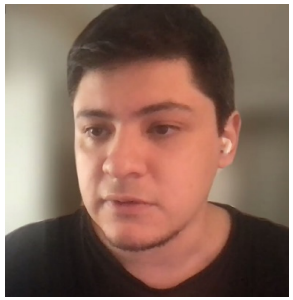
Nathan Berkovits: What is the space of string fields?

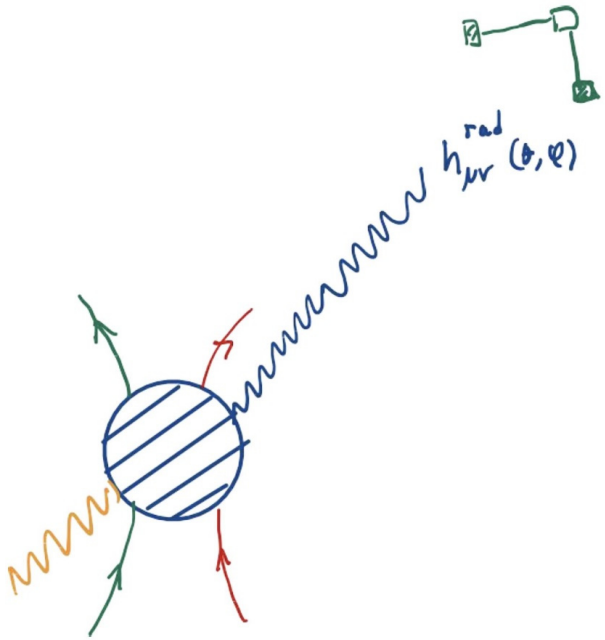
Xi Yin: String field theory seems to be the only way to describe RR flux backgrounds, so far.

Ashoke Sen: String field theory is a very good decoder to find out what the worldsheet want to tells us.

Amplitudes

Perturbative amplitudes





Alfredo Guevara reviewed how QFT scattering amplitudes can be used to define and compute GR observables for realistic time-dependent scenarios

Frank Coronado demonstrated that 4-point massive amplitudes in the Coulomb branch in $N = 4$ SYM have emergent 10-dimensional structure, combining spacetime and R-charge distances.

Perturbative amplitudes

Anastasia Volovich showed that planer 6 and 7-point amplitudes in $N = 4$ SYM are described by cluster algebras and discussed new features for $n \geq 8$ amplitudes: plabic graphs and tensor diagrams.

Freddy Cachazo and **Lionel Mason** led discussion on **worldsheet approaches to field theory amplitudes**.

Ambitwistor strings:

- Chiral strings in ambitwistor space
- Reproduce the CHY formula for scattering amplitudes

Nathan Berkovits: In the ambitwistor approach, how do you integrate over the moduli space?

Rajesh Gopakumar: How is the locality of the actual spacetime captured?

String perturbation

Oliver Schlotterer reviewed progress in computation of superstring amplitudes.

In 1, 2, and 3 loops,

- No spurious dependence on locations of picture changing operators or ghosts.
- Explicit integrals over the moduli spaces.

Multiple poly-logarithms, multiple zeta values, modular graph forms

- **Agreement between NSR and pure spinor formalisms**
- **Test of S-duality predictions**

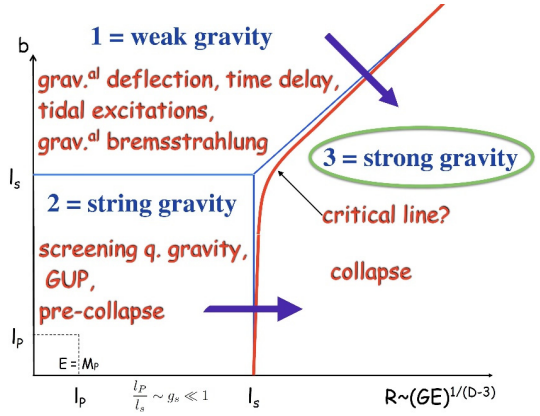
High energy limit

Discussion led by **David Gross** and **Gabriele Veneziano**

- Is there a high-spin gauge symmetry that controls the high energy, tensionless perturbative string?
- Can one use AdS/CFT to determine non-perturbative high energy string scattering in flat space?
- Can one describe in detail the properties of stringy black hole microstates?

Lesson

To explore short-distances... go to short distances, to small b!



$$A \sim e^{-\frac{\iota_s^2}{4}[s\ln s + t\ln t + u\ln u]} \sim e^{-sf(\theta)}$$

VERY SOFT

VIOLATES Cerulus and Martin Bound: $f(s,\theta) > e^{-\sqrt{s}(\ln s)\cdot c(\theta)}$

Juan Maldacena: The Regge behavior is related to the Lyapunov behavior (high energy in the bulk ⇔ chaos of black hole states).

Xi Yin: To what extent, does string perturbation theory capture the hard scattering limit?

S-matrix bootstrap

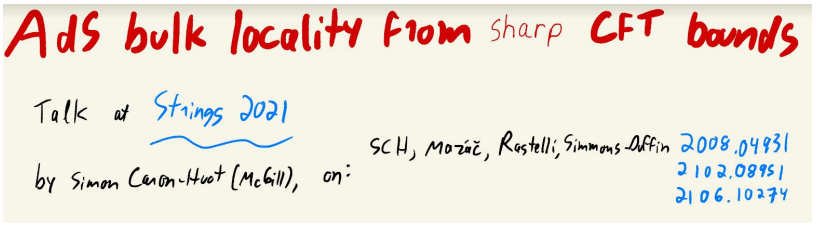
"Quantitative Swampland Program"

Leonardo Rastelli reviewed bootstrap constraints on effective field theory.

- Modern emphasis on theory space
- Success in conformal bootstrap
- AdS/CFT
- Modern computational methods

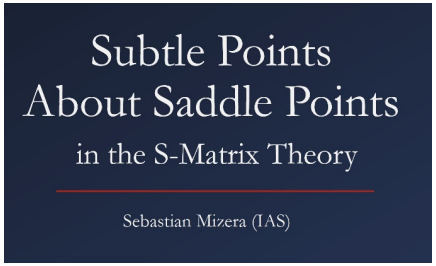
- **Including gravity with $\Lambda \leq 0$.**
- **Proof that large N CFTs with large gap have local AdS duals, with sharp bounds.**

Causality



Simon Caron-Huot
"Causal EFT is a pleonasm!"

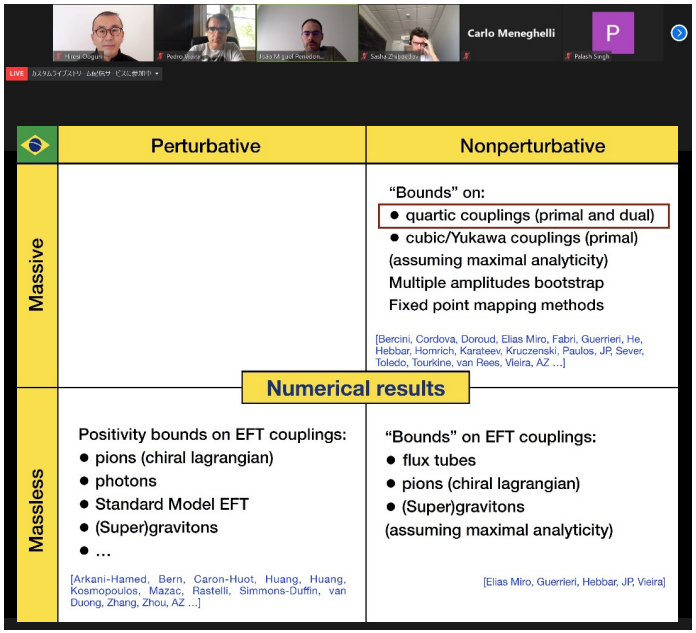
Crossing Symmetry

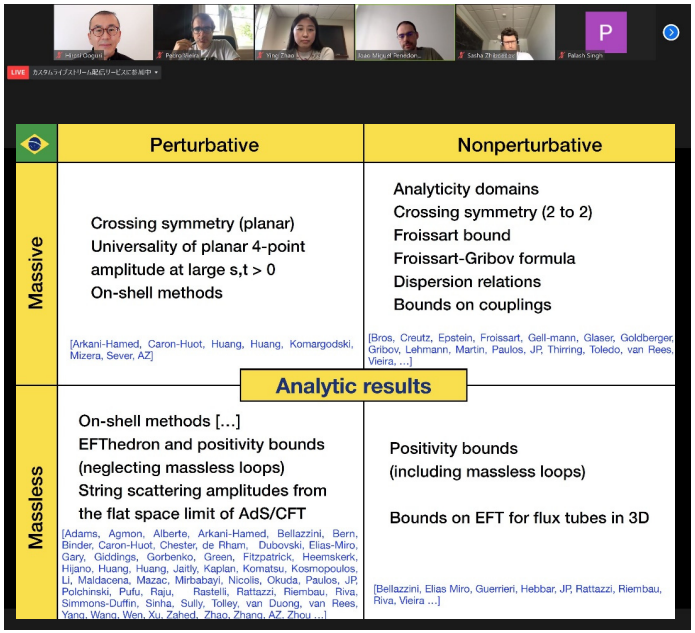


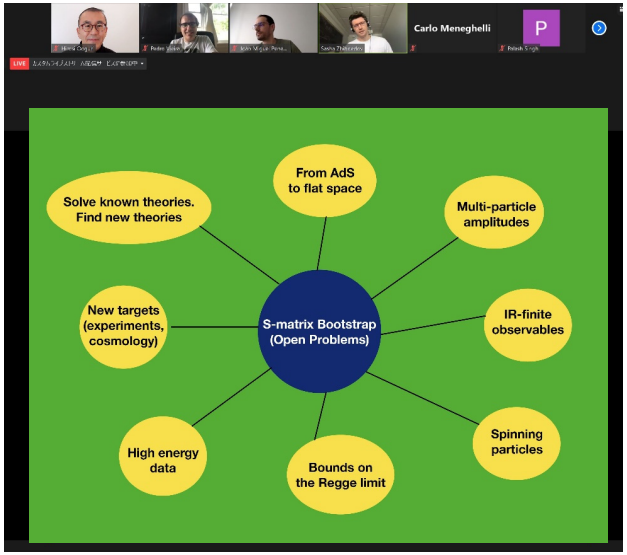
Sebastian Mireza
singularities ↔ worldline saddle points

S-matrix bootstrap

Discussion led by **João Penedones** and **Sasha Zhiboedov**





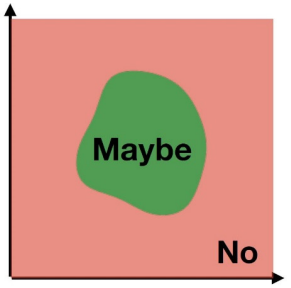


Xi Yin: Comparison of CFT bootstrap and S-matrix bootstrap. In S-matrix, 4-point amplitudes are not enough. Can we extend S-matrix by including resonances?

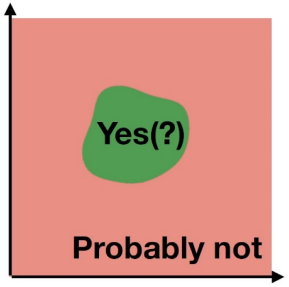
Vladimir Kazakov: (deviating from S-matrix bootstrap) Is there any progress in the search for non-SUSY CFT in 4d?

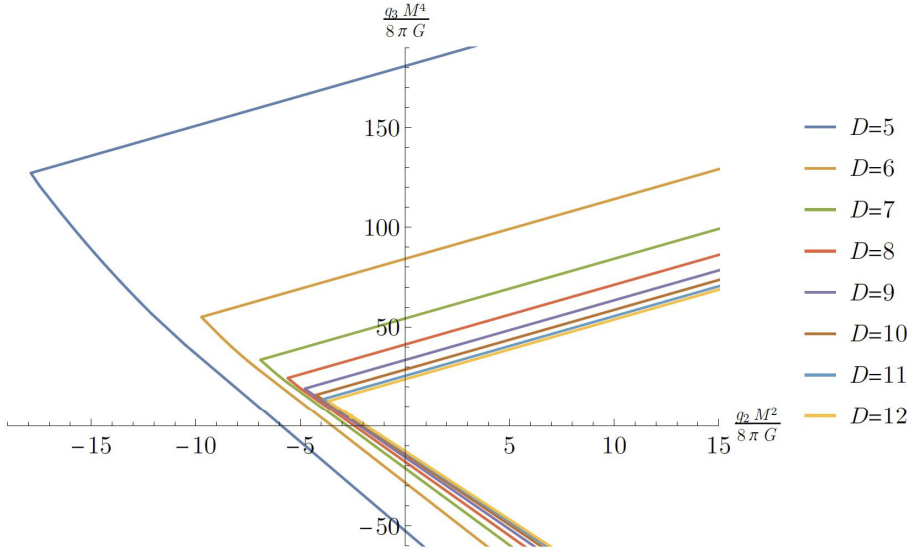
What is the space of theories?

Dual problem: exclude theories (bootstrap bounds)

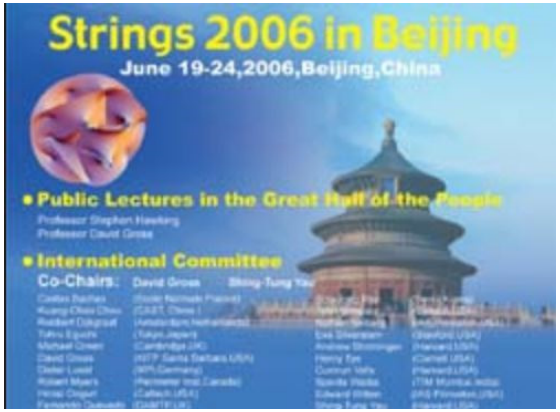


Primal problem: construct amplitudes (landscape)



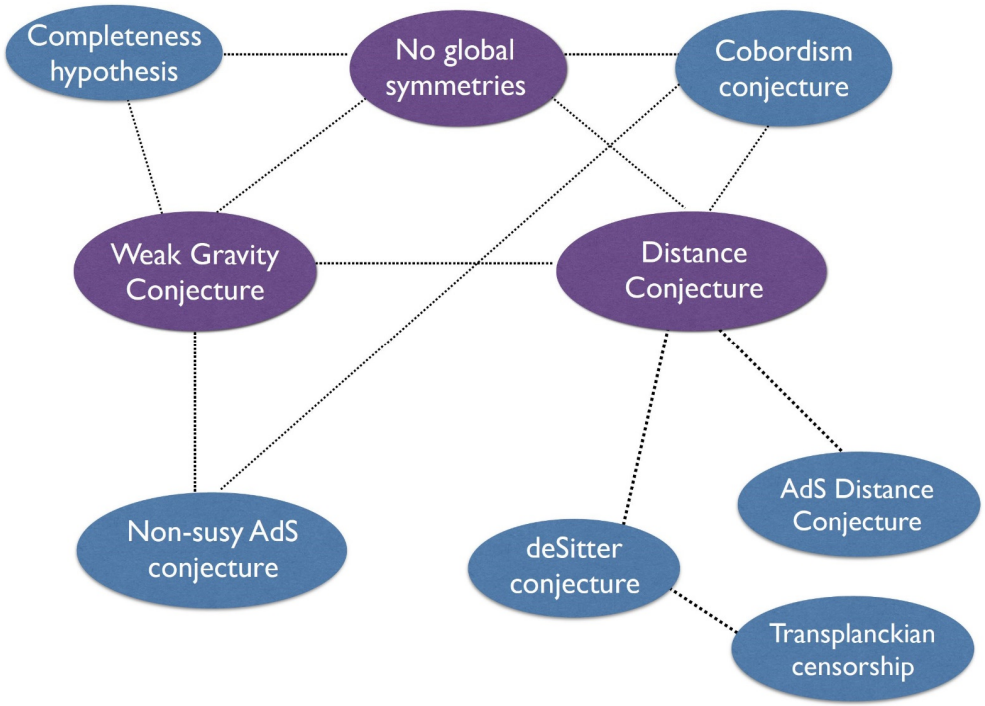


Swampland



String Landscape + the Swampland

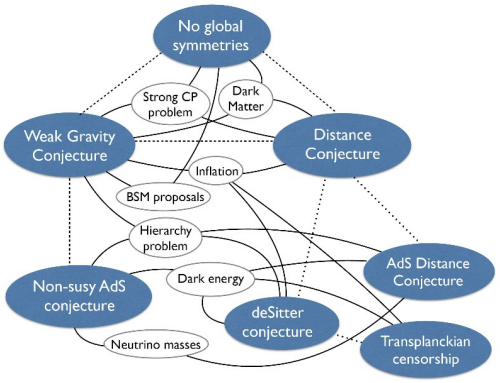
Irene Valenzuela reviewed progress since Reece's talk at Strings 2019.



Web of swampland conditions connected to the
3 basic conjectures: no global symmetries, weak gravity, distance.

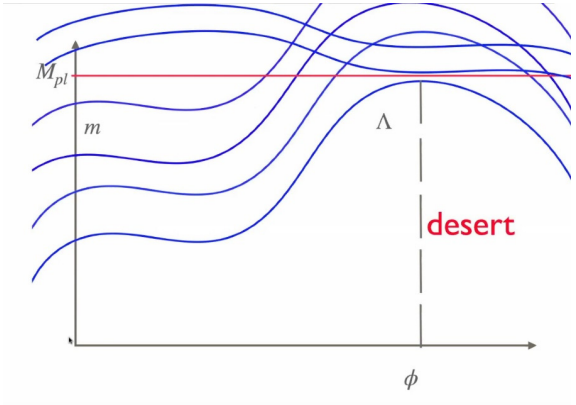
- Symmetry ⇒ (non-invertible) topological operators, cobordism
- Testing and sharpening by string compactifications
- Insights from AdS/CFT, positivity, black holes

Phenomenological implications:

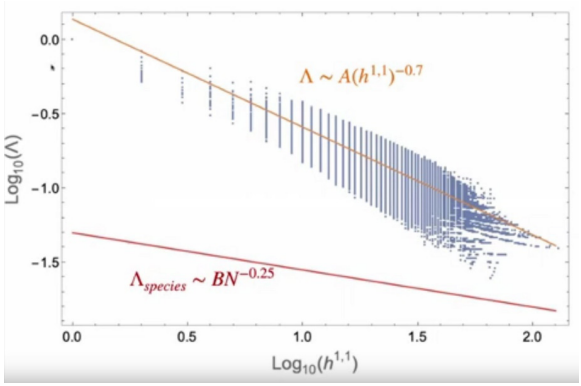


Cumrun Vafa conjectured that the landscape of consistent quantum gravity theories is finite.

Species bound: $N < 1/\Lambda^{d-2}$



N would be bounded if you can always find a point in the moduli space where UV cutoff Λ comes close to the Planck scale.



The species bound may also be related to the bound on topological types of Calabi-Yau manifolds.

Cosmology and Particle Physics

Cosmology and particle physics

Concluding Remarks

Hirosi Ooguri
(Caltech)

Strings 2004, Paris

KKLT proposal

(1) The tree level superpotential stabilizes complex structure moduli and dilaton.

Douglas conjectured $N_{vac} = L^{b_3} \int \det(-R-\omega)$

Kachru tested it with an explicit example and found an excellent agreement.

(2) Nonperturbative corrections may stabilize Kähler moduli

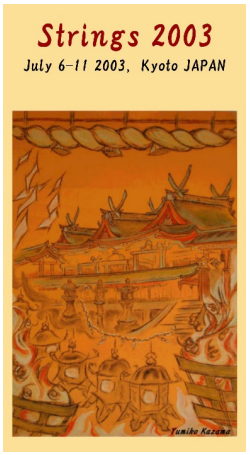
Douglas : D3 brane instantons

Trivedi : Nonperturbative gauge dymanics on D7 branes

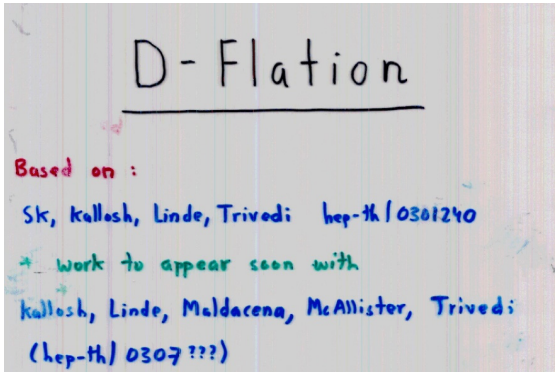
(3) SUSY breaking

Trivedi argued that an inflaton potential satisfying the slow-roll condition and the 60 e-folding can be generated.

The remarkable success of the conference can only be explained by the ~~Anthropic Principle~~.
Fine Tuning by the Organizers.



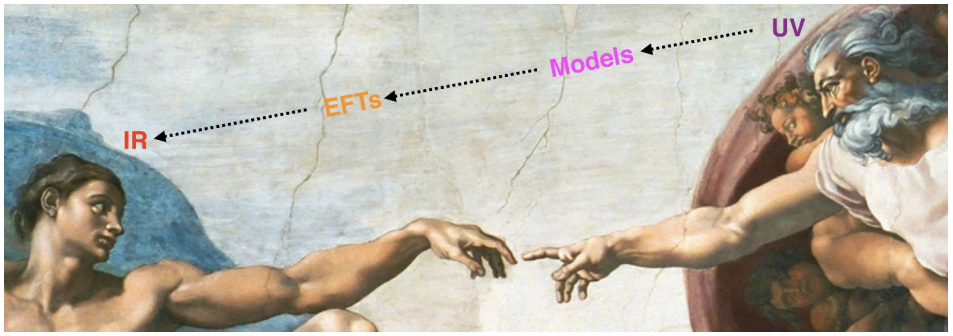
Strings 2003 transparency sheet by Shamit Kachru

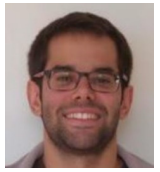


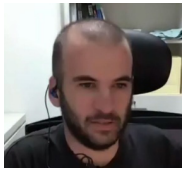
String universality, particle physics and cosmology

Discussion led by **Mirjam Cvetic** and **Gary Shiu**

General lessons from top-down construction:
No global symmetry, restriction on gauge and matter content, Soft UV, ubiquity of moduli and dualities…







With additional contributions by **Ling Lin**, **Miguel Montero**, and **Pablo Soler**

- Swampland implications on phenomenology
- Insights and challenges in de Sitter constructions

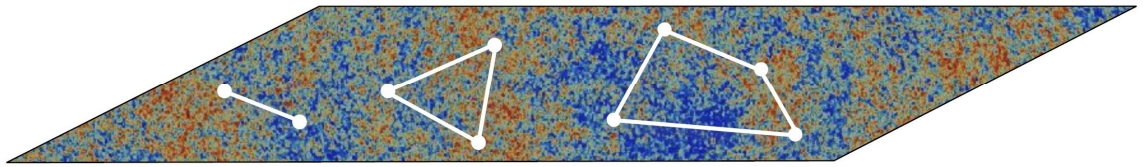
Thomas Van Riet: The first job should be to settle the question on moduli stabilization and scale separation. It affects the choices we make.

Eva Silverstein: Any universality claim must be consistent with all the ingredients we know and all the models we have.

Mark Van Raamsdonk: We need microscopic framework for cosmological solutions.

Cosmology and string theory

Discussion led by **Daniel Baumann** and **Eva Silverstein**



Unique challenges of cosmology

- Time may be emergent.
- Boundary theory is not unitary and not Lorentz invariant.
- Interactions are scale but not conformally invariant.
- Lack of rigorous nonperturbative observables.

All inflation models are UV sensitive. Landscape is rich but highly structures

- How do we systematically study non-Gaussianity?
- How to make the most of B-mode measurements? / How to test the inflationary framework?
- Do insights from bootstrap, holography, and BH information have implications for cosmology?
- Will the nuts and bolts of the string landscape guide us toward a measure?

Juan Maldacena: The question on whether there is an upper bound on r is important. It would be nice to understand that before r is bounded by experiments.

Mark Van Raamsdonk: In top-down construction, is it easier to construct stabilized de Sitter or rolling?

De Sitter constructions from string theory

Mariana Graña proposed Tadpole Conjecture:

$$Q_{\text{flux}} > \alpha N \text{ with } \alpha > \frac{1}{3} \text{ for large number } N \text{ of moduli}$$

If true,

- A large number of moduli in F-theory cannot be stabilized; "10^{272000} vacua are not phenomenologically relevant."
- No anti-brane uplift in long warped throat; no dS vacua à la KKLT.

Fernando Marchesano suggested a counter-example. ,
Graña's rebuttal is in **Slack**, with follow-up discussions there.

Gonzalo Torroba described de Sitter solutions in M-theory by compactification on negative curvature spaces.

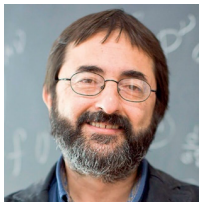
Potential terms from curvature, fluxes, and Casimir energy generate de Sitter minima.

Edward Witten asked whether the construction is parametrically controlled.

De Sitter constructions from string theory

Discussion led by **Shamit Kachru** and **Fernando Quevedo**

KKLT



Large Volume Scenario

- How do we arrange the ingredients the theory provides to make lower dimensional de Sitter space?
- How do we formulate quantum gravity in de Sitter space?

Arthur Hebecker: The singular-bulk problem (gaugino condensation requires a large Calabi-Yau region with negative warp factor) as one of serious challenges to KKLT.

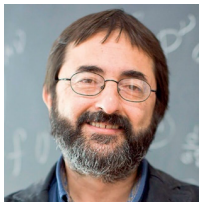
Sandip Trivedi: Since we do not have parametric control, we should compute the first corrections to check if the claims are reliable. We need to develop theoretical tools to compute in Ramond-Ramond background.

A novel class of CFTs with features such as large central charge, dead-end, and sparse spectrum is prerequisite for KKLT. Can we prove their existence by CFT methods?

De Sitter constructions from string theory

Discussion led by **Shamit Kachru** and **Fernando Quevedo**

KKLT



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Landscapers : Anthropic Principle | Swamplanders : Universality

Both sides are making extraordinary claims.

Fortunately, a lot of technical progress in scrutinizing these proposals.

Concluding Remarks

Hirosi Ooguri
(Caltech)

Strings 2004, Paris

Michael Douglas' talk at Strings 2004

Since the vast majority of CY's have more than 20 moduli, and we need many moduli to tune the c.c., this argument seems to predict **high scale supersymmetry breaking**.

Thus, if $M_{high} \geq 10^{15}$ GeV (well below M_s given string scale compact dimensions), we start to have the gist of an argument predicting that **we will not see superpartners at LHC.**

So will we see superpartners at LHC ? If we believe in the joint distribution we just discussed of F breaking parameters of otherwise acceptable vacua, then apparently not.

No SUSY at LHC ?

Douglas described a statistical approach to study the space of string vacua.

Artificial intelligence and string theory

Lara Anderson discussed progress in $N = 1$ 4d heterotic string compactification.

- Topological vanishing of Yukawa couplings;

  Small Yukawa couplings may be explained by non-perturbative effects.

- Machine learning of metrics; it can do non-Kahler $SU(3)$ structure equally well.

Discussion led by **Michael Douglas** and **Fabian Ruehle**

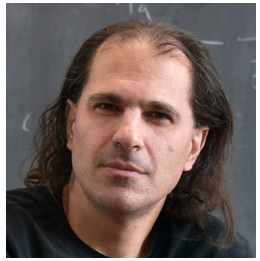
What can ML and AI do for physics?

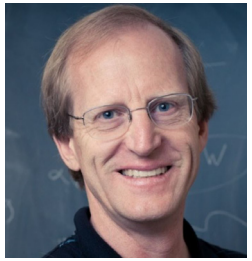
- Pattern recognition in Diophantine equations
- Conjecture generation and natural language processing in knot theory
- Interpolation and CY metrics

Ning Bao: Many problems in string theory that are complete problems of high complexity classes, but whose average case complexity is much lower. The exclusion of hard instances of these problems could lead to new effective constraints on high energy physics.

Experiments and Observations

Xavier Siemens reported on nanohertz gravitational waves search by NANOGrav, which is a **Pulsar Timing Array**, and discussed its prospect of detecting gravitional waves from supermassive black hole mergers and **cosmic strings**.





Nima Arkani-Hamed and **Lance Dixon** led discussion on **particle physics challenges**.

- Think of new theoretically compelling and experimentally predictive framework for new physics
- Compute precise consequences of SM
- Apply theoretical technology to new areas (e.g., scattering amplitudes to LIGO)

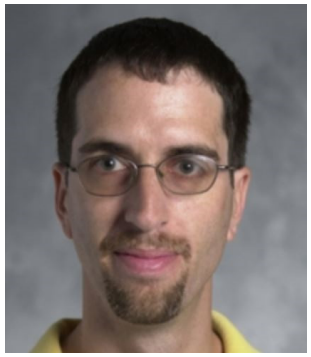
Fate of B-L symmetry; Dark Energy and Neutrino Masses; Axions; …

Gabriele Veneziano : If moduli are stabilized, you have predictions.

Quantum Field Theory

Symmetry, Integrability,
Applications to CMP

Effective strings



Ofer Aharony reviewed the universal aspects of long effective strings.

- Several universal terms that control low energy properties
- Large N confining strings should have worldsheet description at all energy scales, *i.e.*, they are fundamental strings.

John McGreevy discussed the mean string theory as generalization of the Landau paradigm for one-form symmetry

Effective strings

Sergei Dubovsky and **Igor Klebanov** led discussion on QCD string.

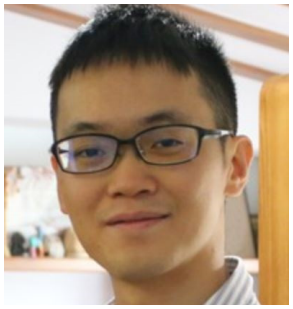
- Don't take confinement for granted.
- Asymptotic freedom + confinement = (asymptotic) integrability

John McGreevy: Migdal-Polyakov loop equations are analogue of integrability equations of the 2d chiral sigma-model. Is it the same as the worldsheet integrability discussed here?

Shota Komatsu: They are different as Migdal-Polyakov integrability acts on a more abstract space.

Ref. London Integrability Journal Club talk, https://youtu.be/cBXP5okprbQ

Generalize symmetries and new phases of matter



Shu-Heng Shao reviewed symmetries and their generalizations in topological phases of matter.

- **Higher-form symmetries**

  Nontrivial ‘t Hooft anomalies imply the low energy phase cannot be trivially gapped.

- **Subsystem symmetries**

  Supported on certain higher-codimensional manifolds.
  UV/IR mixing, fractons, …

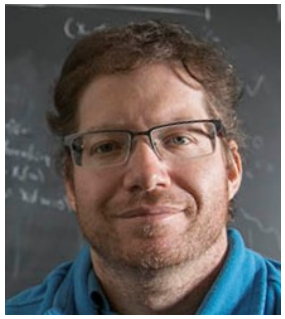
- **Non-invertible topological operators**

  Gauging non-abelian finite group symmetries
  Many examples in 1+1 d: RCFT, Wilson lines, lattice

Generalize symmetries and new phases of matter

Sakura Schafer-Nameki discussed higher form symmetries in non-Lagrangian theories derived from string/M theory and diagnosed confinement in these theories.

Jaume Gomis derived necessary and sufficient conditions to determined the gapped 2d QCD's and provided their complete catalogue.



Zohar Komargodski defined new central charges to diagnose the absence of a gapped 1+1 d boundary. They are necessary and sufficient for abelian theories.

Generalize symmetries and new phases of matter

Horacio Casini showed generalized symmetries is related to the failure in simple properties of the algebra-region relations in quantum field theory (multiple algebras for the same region), giving rise to entropic order parameters.

Dam Son discussed new developments in fractional quantum Hall effect.

- Nature of $\nu = 5/2$ state is still an open problem.
- Q=0 Magnetoroton has spin 2 or -2 depending on the quantum Hall state.

Generalize symmetries and new phases of matter

Discussion led by **Nathan Seiberg** and **Xiao-Gang Wen**

- What is QFT: formulations, new methods
- Generalization: UV/IR mixing

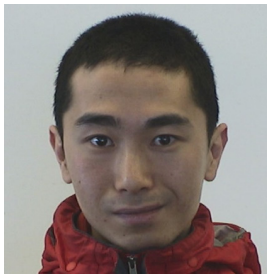
Swampland: no UV completion by local qubit models without symmetry

Stephen Shenker: $T\bar{T}$ deformation is another extension of QFT, with non-local aspects but without UV/IR mixing.

Nima Arkani-Hamed: Completeness with gravity has a lot to do with black holes. Is there an analogous reason in condense matter?

Response by Daniel Harlow: In holography, Swampland conditions for gravity and for system with tensor product Hilbert space are close.

Integrability and exact results



Shota Komatsu reviewed integrability in $N = 4$ super Yang-Mills.

- $1/N$ expansion coefficients at finite λ

  Finite radius of convergence in λ, a cut starting at $\lambda = -\pi^2$

- Heavy operators with $\Delta \sim O(N)$, but not $O(N^2)$.

  Determinant operators = D-branes, but not black holes

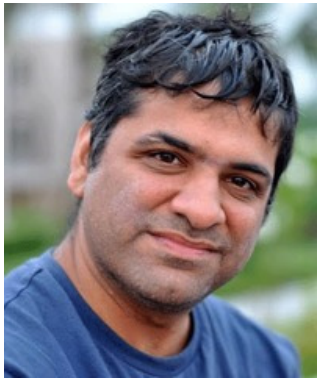
Large N Feynman diagrams
= string worldsheet in AdS is demonstrated in a precise sense.

Congkao Wen calculated integrals of correlators of in $N = 4$ super Yang-Mills and showed their modular invariance.

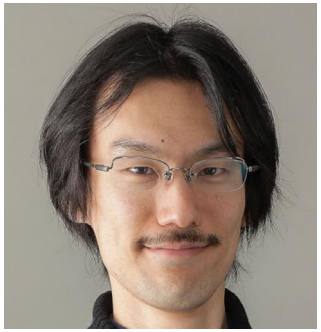
$$\mathcal{G}_N(\tau,\bar\tau) \sim \frac{N^2}{4} - \frac{3N^{\frac12}}{2^4}E(\tfrac32;\tau,\bar\tau) + \frac{45}{2^8N^{\frac12}}E(\tfrac52;\tau,\bar\tau)$$
$$+ \frac{3}{N^{\frac32}}\left[\frac{1575}{2^{15}}E(\tfrac72;\tau,\bar\tau) - \frac{13}{2^{13}}E(\tfrac32;\tau,\bar\tau)\right] + \frac{225}{N^{\frac52}}\left[\frac{441}{2^{18}}E(\tfrac92;\tau,\bar\tau) - \frac{5}{2^{16}}E(\tfrac52;\tau,\bar\tau)\right]$$
$$+ \frac{63}{N^{\frac72}}\left[\frac{3898125}{2^{27}}E(\tfrac{11}{2};\tau,\bar\tau) - \frac{44625}{2^{25}}E(\tfrac72;\tau,\bar\tau) + \frac{73}{2^{22}}E(\tfrac32;\tau,\bar\tau)\right]$$
$$+ \frac{945}{N^{\frac92}}\left[\frac{31216185}{2^{31}}E(\tfrac{13}{2};\tau,\bar\tau) - \frac{41895}{2^{26}}E(\tfrac92;\tau,\bar\tau) + \frac{1639}{2^{27}}E(\tfrac52;\tau,\bar\tau)\right] + \cdots .$$

They are determined by four derivatives of the S^4 partition function of $N = 2^*$ SYM computed by SUSY localization.

Integrability and exact results



Shiraz Minwalla showed that the partition function of large N Chern-Simmon matter theories on $S^2 \times S^1$ is effectively that of the Fock space constrained to WZW singlets.



Yuji Tachikawa used the Segel-Stolz-Teichner conjecture to show that the constant term in the q-expansion of the elliptic genus of an $N = (0,1)$ SCFT with $(c_L, c_R) = (24, 12)$ is divisible by 24, ensuring the cancellation of the $\mathbb{Z}_{24}$ global anomaly in 2d heterotic compactifications.

Integrability and exact results

Mykola Dedushenko discussed interfaces between different gauge theories with 8 supercharges.

- Physical realization of stable envelopes
- Quantum algebras from the Nakajima quiver variety

Kevin Costello described a remarkable QFT in 4d:

- Constructed from the holomorphic Chern-Simons theory coupled to the Kodaira-Spencer theory on the 6d twistor space.
- Non-renormalizable but no counter-terms
- Integrable, periodic RG, relation to the celestial holography

Integrability and exact results


Vladimir Kazakov and **Gregory Korchemsky** led discussion on lessons from integrability

$N = 4$ SYM and ABJM models are integrable in planar limit.

- How about non-conformal gauge theories?

  Gabriele Veneziano: How can the Regge limit be integrable?

  Leonardo Rastelli: Is the long string effective action integrable?

  $\Longrightarrow$ **Victor Gorbenko:** No. But, integrability is restored in UV.

- **Igor Klebanov:** How about reduced SUSY models.

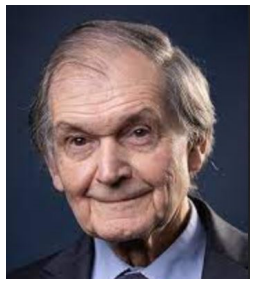
  $\Longrightarrow$ **Elli Pomoni:** $N = 2$ superconformal models with elliptic-type integrability.


The Last Day

Sabrina Pasterski reviewed progress in celestial amplitudes.

Pavel Putrov reported on spin-cobordisms, surgeries, and fermionic modular bootstrap.

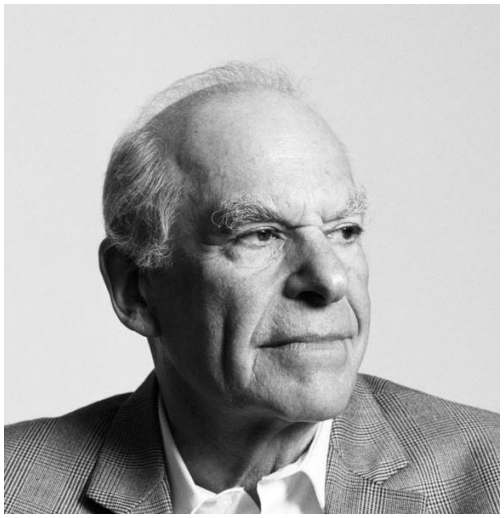
Alba Grassi reported on a geometric approach to black hole spectral theory.



Roger Penrose explained why he thinks current string theory cannot resolve the gravitational singularity issue.

Andrew Strominger and **Tomasz Taylor** led discussion on celestial holography.

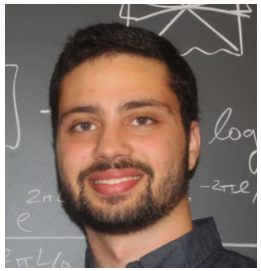
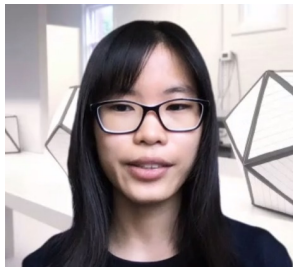
Some Perspectives on String Theory

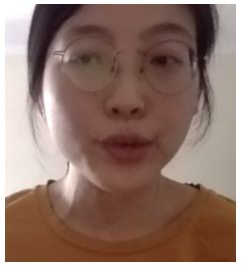
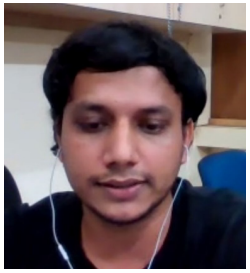
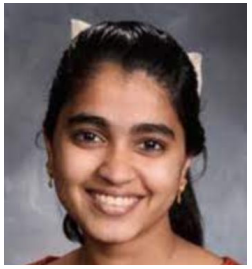
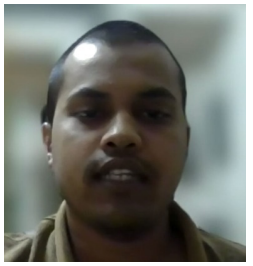

Discussion led by **Michael Green**, **John Schwarz**, and **Edward Witten**.

Gong Show



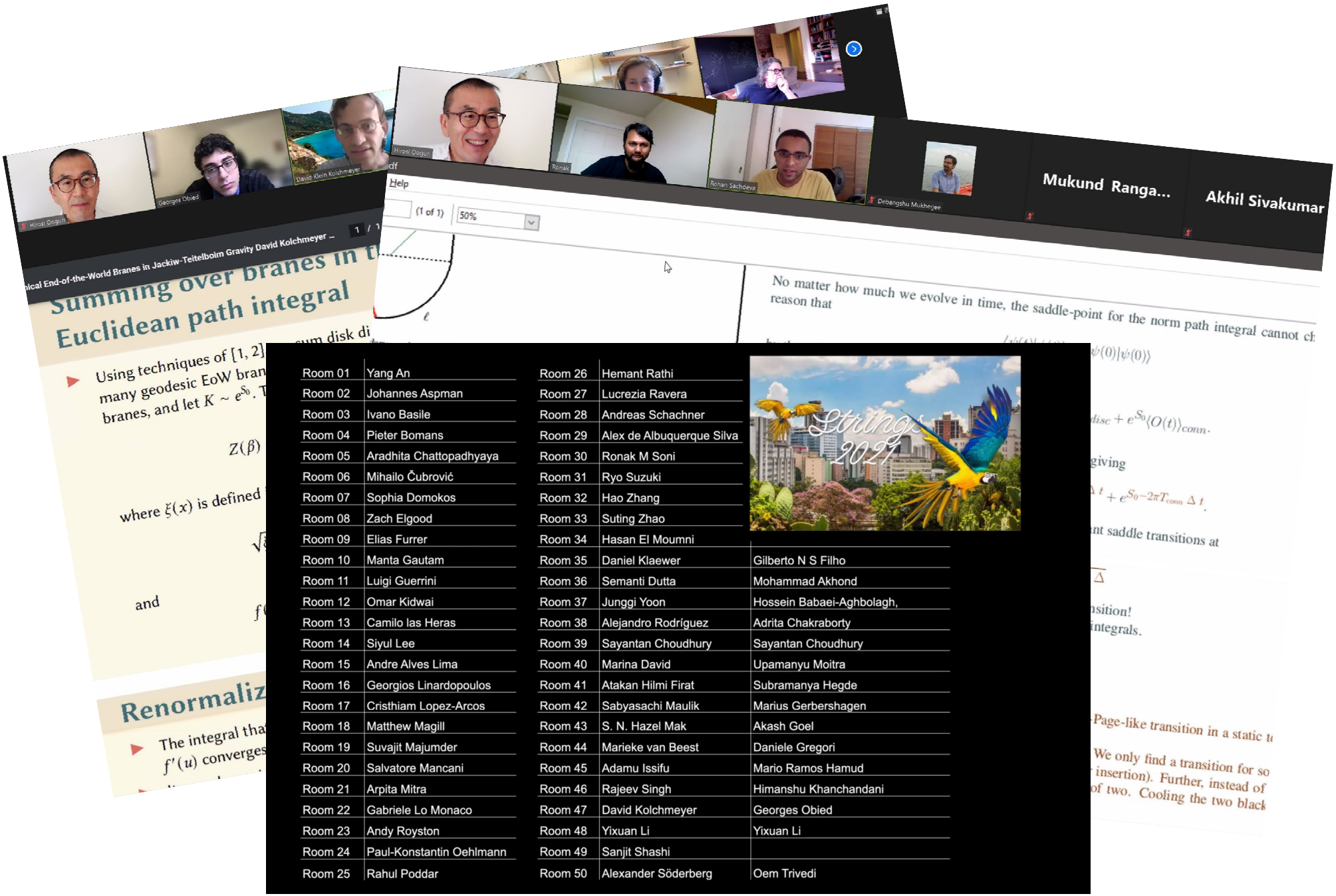





- **Alek Bedroya** Thermal de Sitter and the swampland
- **Akash Goel** Towards a string dual of SYK
- **Eduardo Gonzalo** New constraints on neutrinos from the swampland
- **Yangrui Hu** Solving a 40-year-old problem: 11D superfield (shared talk)
- **Jonah Kudler-Flam** Distinguishing random states and black holes
- **Suman Kundu** Bounds on Regge growth of flat space scattering from bounds on chaos
- **Hazel Mak** Solving a 40-year-old problem: 11D superfield (shared talk)
- **Sruthi Narayanan** State-operator correspondence in celestial conformal field theory
- **Erez Urbach** The entanglement entropy of typical pure states and replica wormholes
- **Ahmadullah Zahed** Quantum field theory and the Bieberbach conjecture
- **Zhenghao Zhong** Magnetic quivers and SCFTs

Poster Session

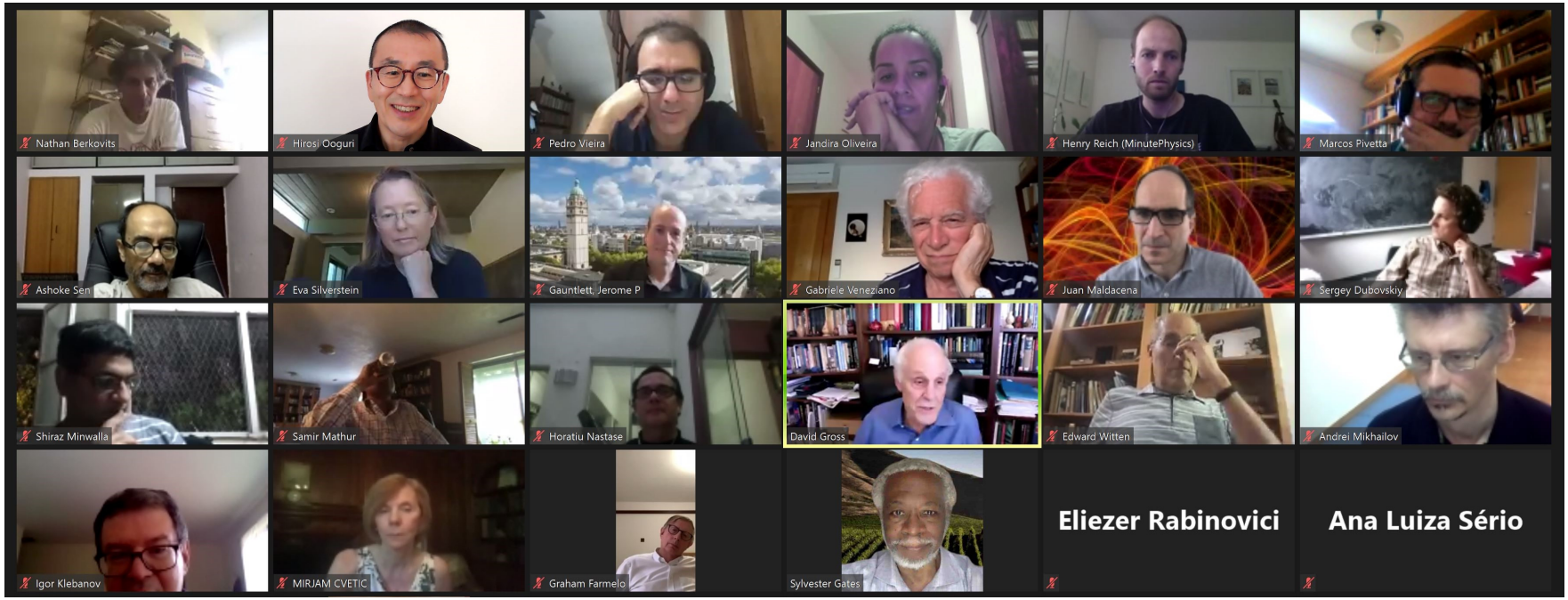


Room 01	Yang An	Room 26	Hemant Rathi	
Room 02	Johannes Aspman	Room 27	Lucrezia Ravera	
Room 03	Ivano Basile	Room 28	Andreas Schachner	
Room 04	Pieter Bomans	Room 29	Alex de Albuquerque Silva	
Room 05	Aradhita Chattopadhyaya	Room 30	Ronak M Soni	
Room 06	Mihailo Čubrović	Room 31	Ryo Suzuki	
Room 07	Sophia Domokos	Room 32	Hao Zhang	
Room 08	Zach Elgood	Room 33	Suting Zhao	
Room 09	Elias Furrer	Room 34	Hasan El Moumni	
Room 10	Manta Gautam	Room 35	Daniel Klaewer	Gilberto N S Filho
Room 11	Luigi Guerrini	Room 36	Semanti Dutta	Mohammad Akhond
Room 12	Omar Kidwai	Room 37	Junggi Yoon	Hossein Babaei-Aghbolagh,
Room 13	Camilo las Heras	Room 38	Alejandro Rodríguez	Adrita Chakraborty
Room 14	Siyul Lee	Room 39	Sayantan Choudhury	Sayantan Choudhury
Room 15	Andre Alves Lima	Room 40	Marina David	Upamanyu Moitra
Room 16	Georgios Linardopoulos	Room 41	Atakan Hilmi Firat	Subramanya Hegde
Room 17	Cristhiam Lopez-Arcos	Room 42	Sabyasachi Maulik	Marius Gerbershagen
Room 18	Matthew Magill	Room 43	S. N. Hazel Mak	Akash Goel
Room 19	Suvajit Majumder	Room 44	Marieke van Beest	Daniele Gregori
Room 20	Salvatore Mancani	Room 45	Adamu Issifu	Mario Ramos Hamud
Room 21	Arpita Mitra	Room 46	Rajeev Singh	Himanshu Khanchandani
Room 22	Gabriele Lo Monaco	Room 47	David Kolchmeyer	Georges Obied
Room 23	Andy Royston	Room 48	Yixuan Li	Yixuan Li
Room 24	Paul-Konstantin Oehlmann	Room 49	Sanjit Shashi	
Room 25	Rahul Poddar	Room 50	Alexander Söderberg	Oem Trivedi

Outreach Activities

“How to describe quantum gravity particles & physics from a starship”

Public Lecuture by Sylvester James Gates Jr.



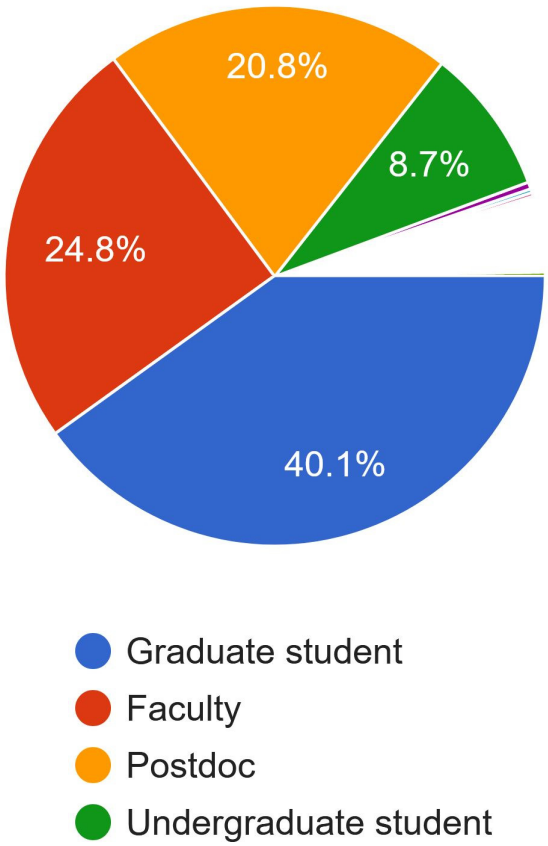
“Ask a String Theorist”

moderated by David Gross

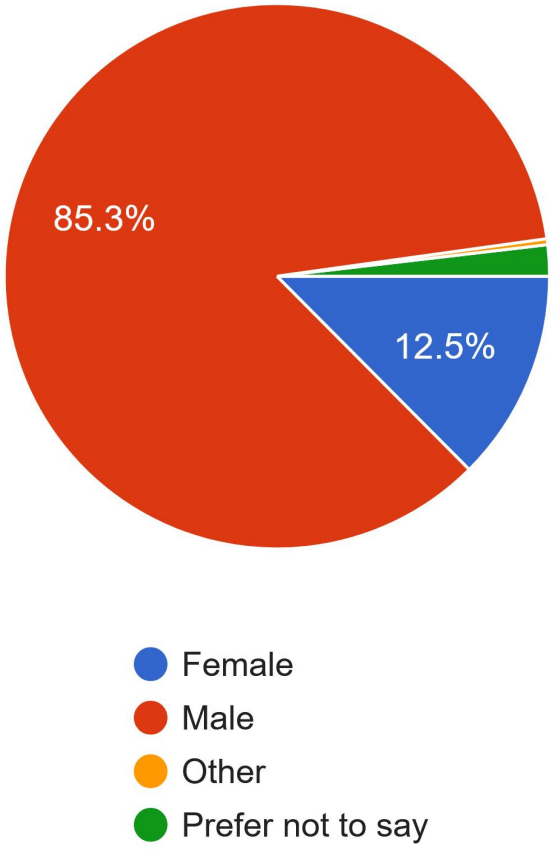
Strings 2021 Demographics

2,633 participants | 100 speakers

Position



Gender



18% of speakers were female.

4 generations of women in string theory

Discussion led by **Miranda Cheng**, **Chiara Nappi**, **Shruti Paranjape**, and **Silvia Penati**

Pipeline: leaks and bottlenecks

- 1st bottleneck: The role of the educational system
- 2nd bottleneck: Staring your career. Need of a support system.
- 3rd bottleneck: Recognition, glass ceiling, etc.

- ✓ Safe, inclusive, and welcoming work environment
- ✓ Keep curbing our unconscious bias
- ✓ Outreach, mentors, childcare support

Henriette Elvang on the University of Michigan study about **pandemic inequalities**:

"33% reported challenges due to caregiving; parents found it especially difficult to manage work while assisting their children who were accessing school remotely through online instruction."

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Job advertisement: assistant professor in STEM gender research at KAVLI IPMU

https://www.ipmu.jp/en/job-opportunities/DIVERSITY2021; Inquiries to academicjob-inquiry@ipmu.jp

Are we getting younger ?

My years after Ph.D.:

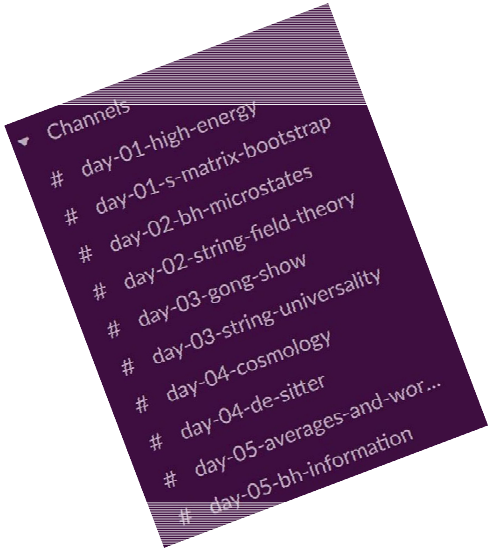
Strings **2004**: top **58** % of speakers
Strings **2008**: top **48** %
Strings **2012**: top **40** %

……..

Strings **2021**: top **22** %

This suggests I would be at (**64 – 2X**) % in **Strings 20X**.

Chat & Slack


Channels
day-01-high-energy
day-01-s-matrix-bootstrap
day-02-bh-microstates
day-02-string-field-theory
day-03-gong-show
day-03-string-universality
day-04-cosmology
day-04-de-sitter
day-05-averages-and-wor...
day-05-bh-information

The organization of this year's Strings conference has been amazing. I have never before seen this level of open, honest, reflective discussions in a conference with 300+ live participants.

Facebook post by a distinguished string theorist

"The format … makes the conference a much more accessible experience for many."

"The organizers have done a superb job, and in particular **Pedro** has been consistently amazing in moderating the discussions."

Message from a distinguished string theorist

Thank you!

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

Director: Nathan Berkovits

Former and Current ICTP-SAIFR Council Members including:

Atish Dabholkar, Michael Green, Juan Maldacena, Fernando Quevedo, Peter Goddard, Seif Randjbar-Daemi, and Barton Zwiebach

Thank you!

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

FAPESP CNPq ICTP unesp IFT - UNESP

SIMONS FOUNDATION

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Thank you!

STRINGS 2021 LOCAL ORGANIZERS

Nathan Berkovits
(ICTP-SAIFR/IFT-UNESP)

Andrei Mikhailov
(IFT-UNESP)

Horatiu Nastase
(IFT-UNESP)

Victor de Oliveira Rivelles
(IF-USP)

Diego Trancanelli
(IF-USP/Modena U.)

Pedro Vieira
(ICTP-SAIFR/Perimeter I.)

Wir sehen uns
auf **Strings 2022**
in Wien.