QFT, Strings

String Theory

AdS/CFT in many varieties: QCD, CMT,…
Black hole paradoxes, UV completions

Counting problems

String compactifications & pheno

String perturbation theory revival

Field Theory

Asymptotic series, resurgence, renormalons

Amplitudes

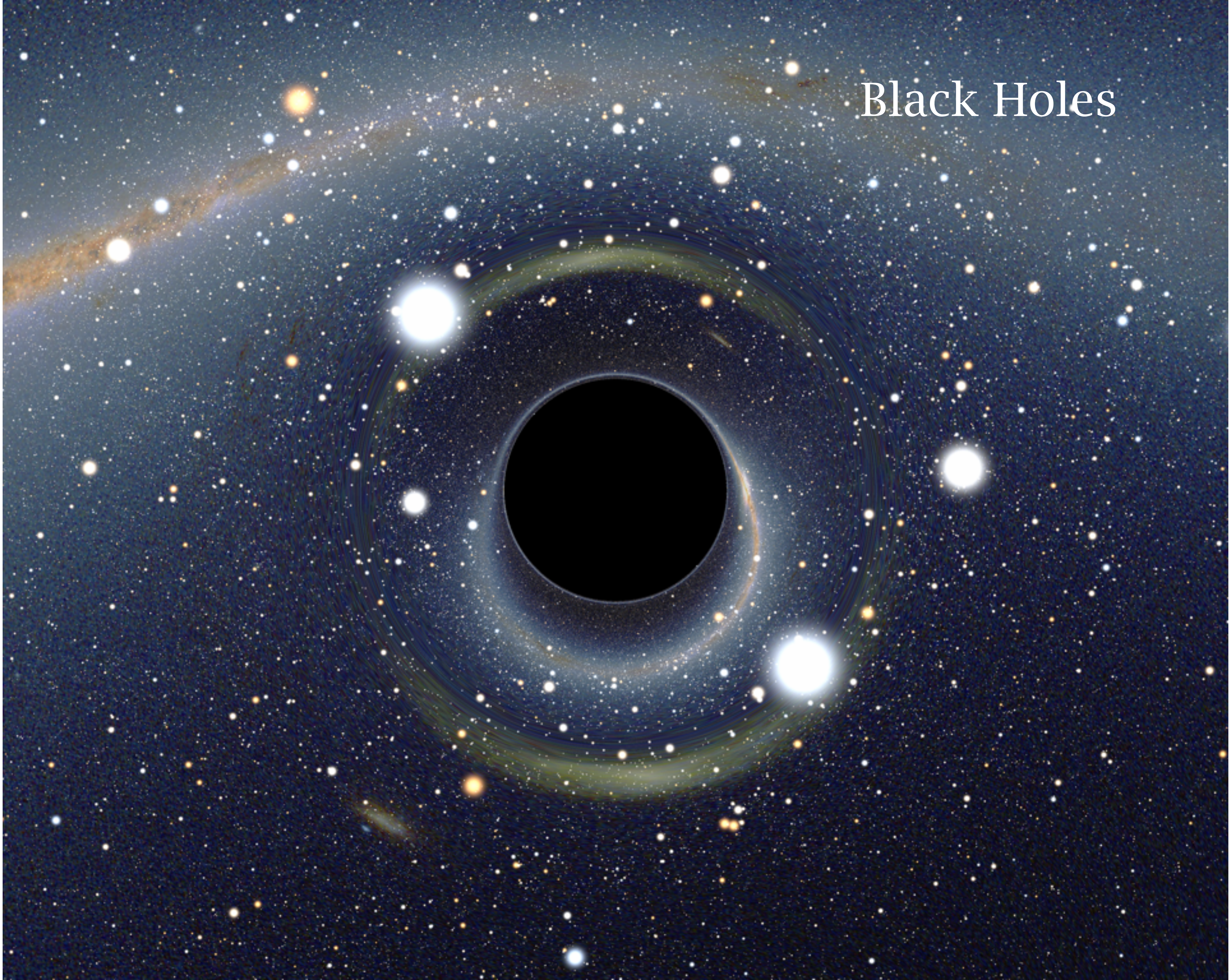
Localisation

Conformal bootstrap

New NP methods in QFT

High spin theories

Counting states


Black Holes

Black Holes Information paradox AMPS, complementarity issues, does the BH interior exist, can it be observed from the boundary

Equivalence principle vs QM unitarity

AdS/CFT vs semiclassical arguments, Fuzz vs Fire

Non-Wilsonian completion of QG

Black Holes, entropy counts.

Far beyond Bekenstein-Hawking

Siegel modular forms, functions, mock mfs

Wall crossing

Important properties of BPS states in theories with extended supersymmetry. Profound influence on mathematics KS formulae…

S-duality

$$\tau = \frac{\theta}{2\pi} + i\,\frac{4\,\pi}{g^2}$$

$$\theta \to \theta + 2\pi \qquad \alpha \to 1/\alpha$$

$$\tau \to \frac{a\tau + b}{c\tau + d} \qquad \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2, Z)$$

String compactifications

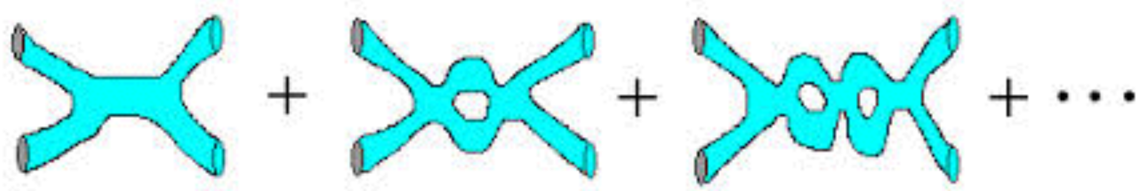
Geometry of Topological Strings and Branes

F-theory compactification. Local vs global

General quiver theories

String perturbation theory

A number of important issues left open in the 80's



Infrared singularity clarification
Off-shell amplitudes
Supermoduli space properties

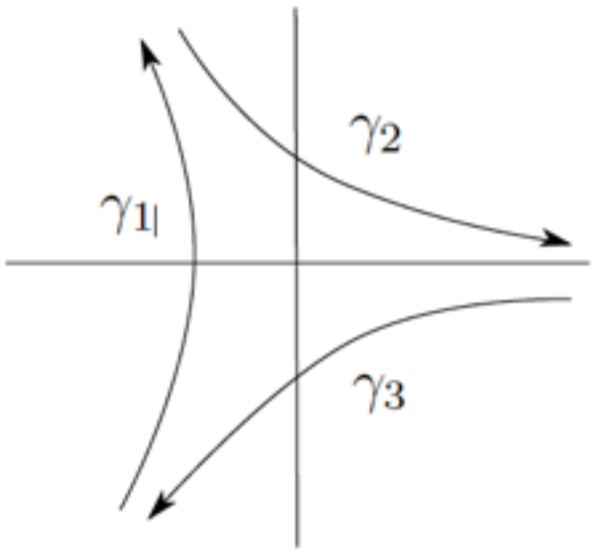
Quantum Field Theory

Divergent, asymptotic series

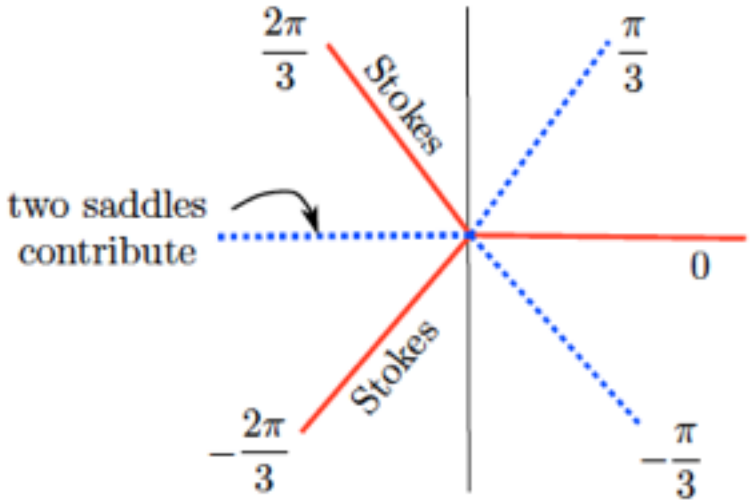
Instantons, renormalons

Stokes phenomena

Resurgence



$$\mathrm{Ai}(x) = \frac{1}{2\pi i}\int_\gamma dz\, e^{x\,z - \frac{z^3}{3}}$$



Slava Rychkov

New quantitative methods for strongly coupled QFTs

1. **Bootstrap approach to conformal theories**

Is becoming a standard QFT technique, on par with RG, epsilon-expansion, 1/N expansion. Gave the world's most precise calculation of the critical exponents in 3d Ising model

S. El-Showk, M.F. Paulos, D.Poland, S.Rychkov, D.Simmons-Duffin and A.Vichi, J.Stat.Phys. 157 (2014)

2. Hamiltonian finite-volume truncation techniques

- *in principle* for any theory, conformal or not. E.g. QCD
- *in practice* formerly has been demonstrated to work with success only in 2D (Light Cone quantization, Truncated Conformal Space Approach)

I have recently extended it to D>2 (with Balt and Matthijs):

M.Hogervorst, S.Rychkov and B.C.van Rees, "A Cheap Alternative to the Lattice?," arXiv:1409.1581

The idea has huge potential (in my opinion). Further work ongoing.

James Drummond

Interests:

Scattering amplitudes in gauge theory and string theory.

Loop integrals, polylogarithms, cluster algebras.

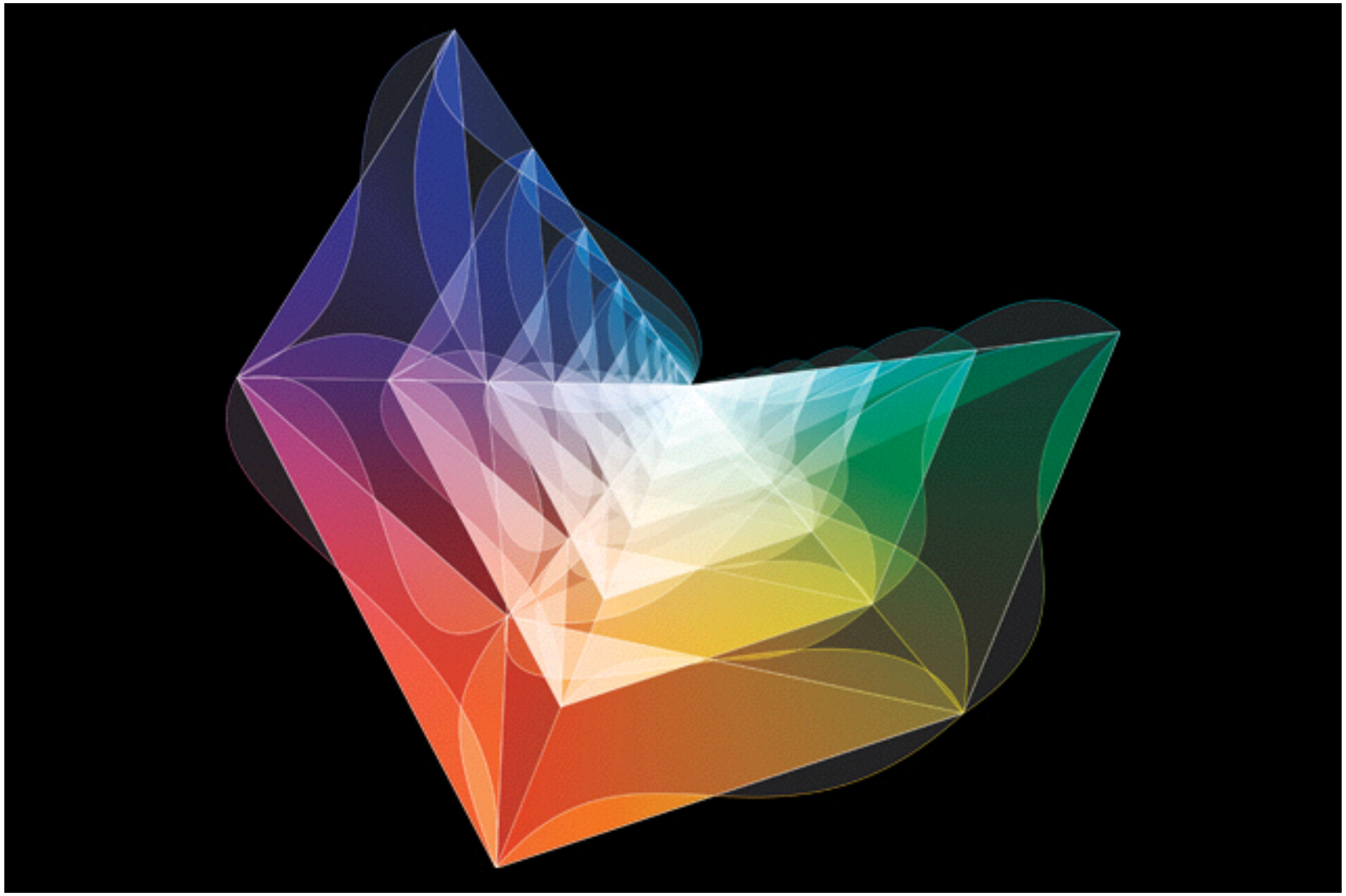
Integrability in gauge theory.

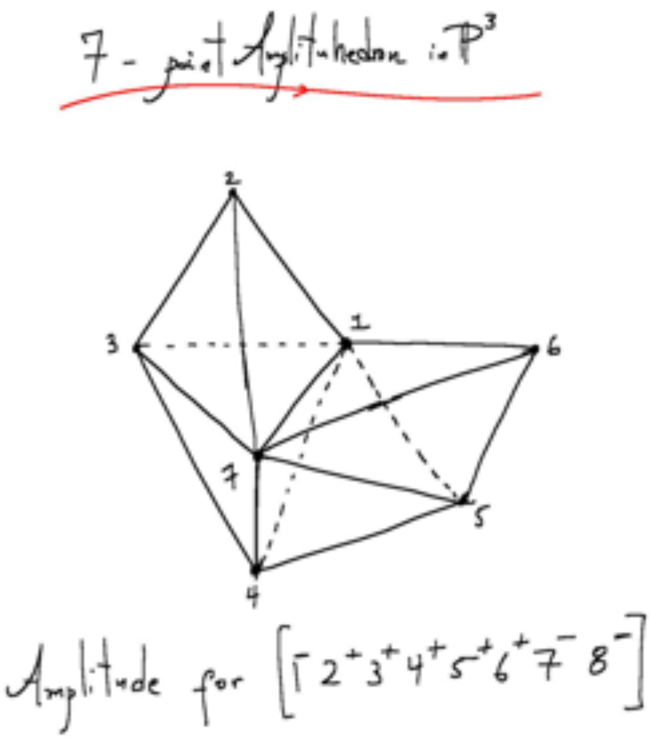
Extended symmetries, dual conformal & Yangian symmetry.

Conformal field theories, OPE, BFKL and bootstrap.

...

Amplituhedron





My activities

BMS symmetries in QFT scale vs conformal

Colour-kinematic dualities, KLT-like relations

Closed =|Open|^2 Gravity=|Gauge|^2

Time dependent AdS/CFT correspondence

BH-bulk formation and unitarity, BFKL saturation

Book writing…

Deputy TH, AT, CERN Schools…

Programme

Lerche 5'

Papadodimas 5'

Pioline 5'

El-Shook 12'

Klevers 12'

Paulos 12'

Samsonyan 12'

Triendl 12'

Florakis 12'

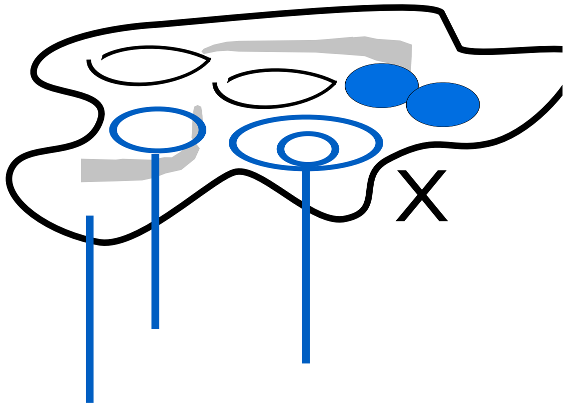
Van Rees 12'

Makareeya 12'

Geometry of Topological Strings & Branes

Motivation: string compactifications to 4d

Typical brane + flux configuration on a Calabi-Yau space X:



closed string (bulk) moduli t

open string (brane location + bundle) moduli u

3+1 dim world volume with effective N=1 SUSY theory

What are the exact effective superpotential, the vacuum states, gauge couplings (general F-terms), etc, as functions of moduli ?

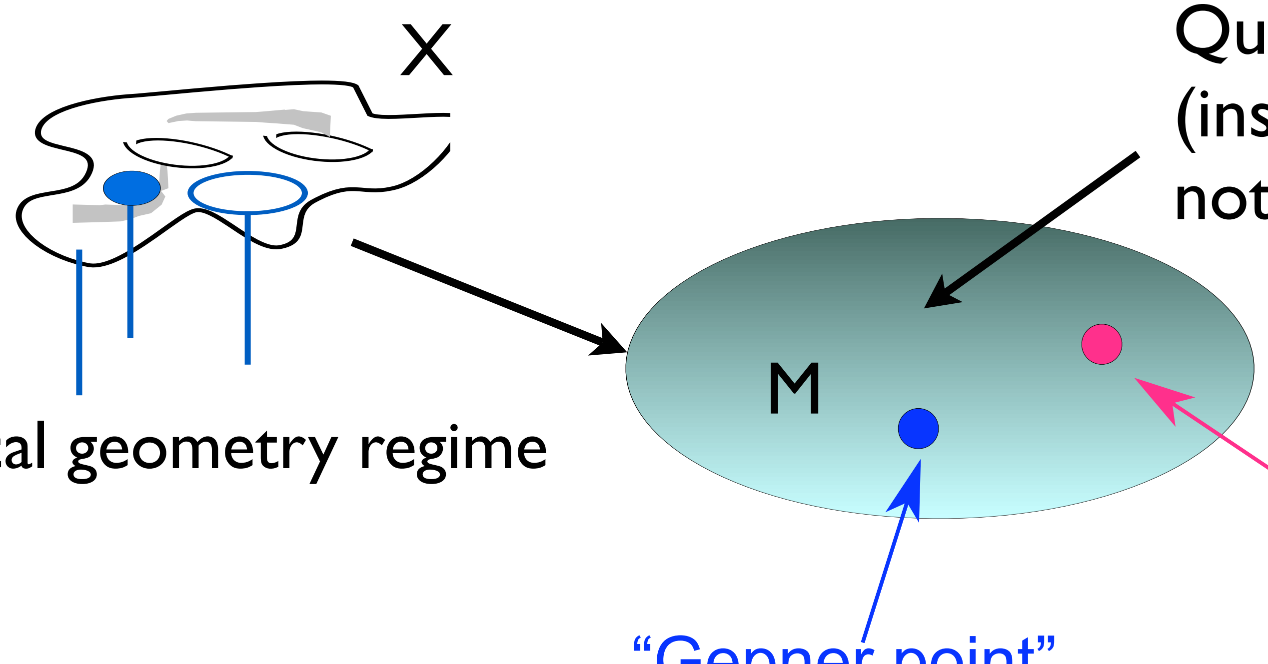
$$\mathcal{W}_{\rm eff}(\Phi, t, u) \ = ?$$

....well developed geometrical techniques mostly for non-generic brane configurations (non-compact, -intersecting) branes only !
(mirror symmetry, localization, integrable matrix models...)

Classical versus Stringy Quantum Geometry

cons. deformation families of 2d TCFTs over whole moduli space M

Classical geometrical notions ("branes wrapping p-cycles", gauge bundle configurations on top of them) makes sense only at weak coupling/large radius!



Quantum corrected geometry: (instanton) corrections wipe out notions of classical geometry

Classical geometry regime

“conifold point”
extra nonpert.
massles states

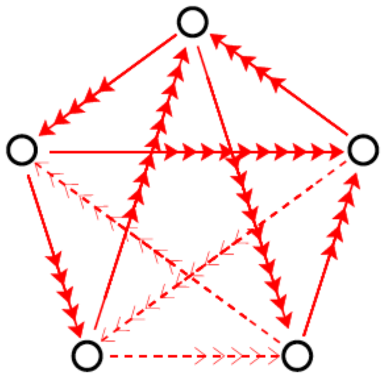
“Gepner point”
non-geometric;
exact RCFT partition fct,
but at one point only

Most of string phenomenology deals with (semi-)classical regime!

Proper mathematical/physical language?

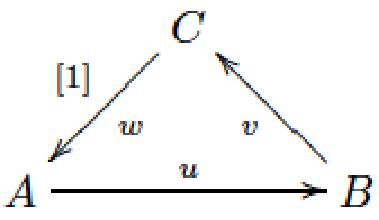
Important need to develop formalism capable of describing the physics of general D-brane configurations (here: topological D-branes)

Important concept (Kontsevich): derived/Fukaya categories

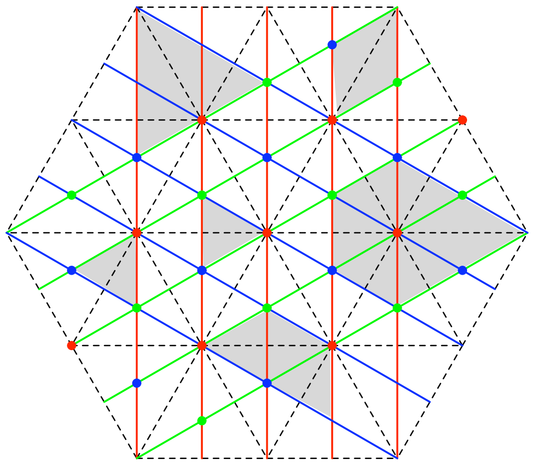


This is the only known language that is powerful enough to describe arbitrary brane configuration in arbitrary regimes!

What does it buy for physicists:



- more general than cohomology/ K-theory (RR charges) keeps track of moduli/brane positions
- describes bound state formation/tachyon condensation (triangulated category)
- Translate math. language to physics:
  homological mirror symmetry
  boundary Landau-Ginzburg theory/matrix factorizations

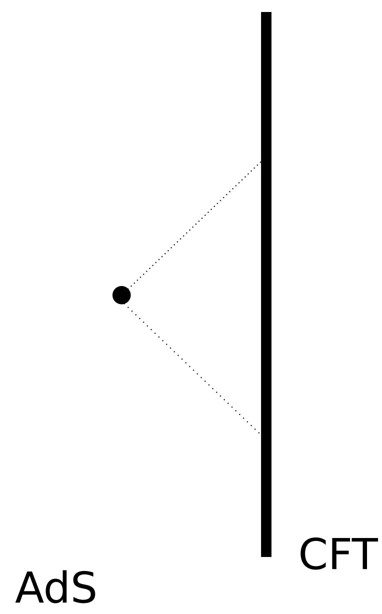


$$Q(x) \cdot Q(x) \;=\; W_{LG}(x)\, \mathbf{1}$$

Nonperturbative aspects of QFT

Quantum Gravity

AdS/CFT correspondence

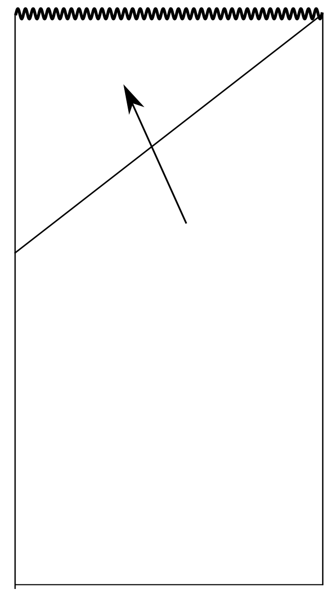

CFT
AdS

Black Holes

Crossing the horizon

Singularity

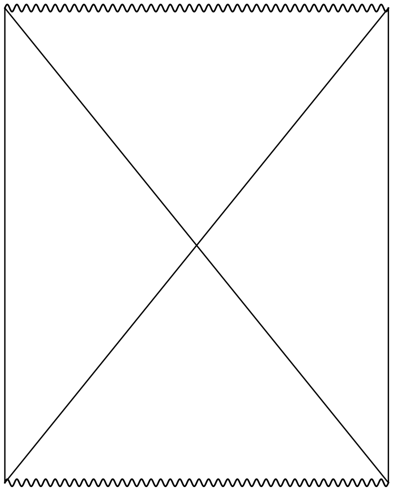
Information paradox



Black hole in AdS $\quad\Leftrightarrow\quad$ Quark-gluon plasma in gauge theory

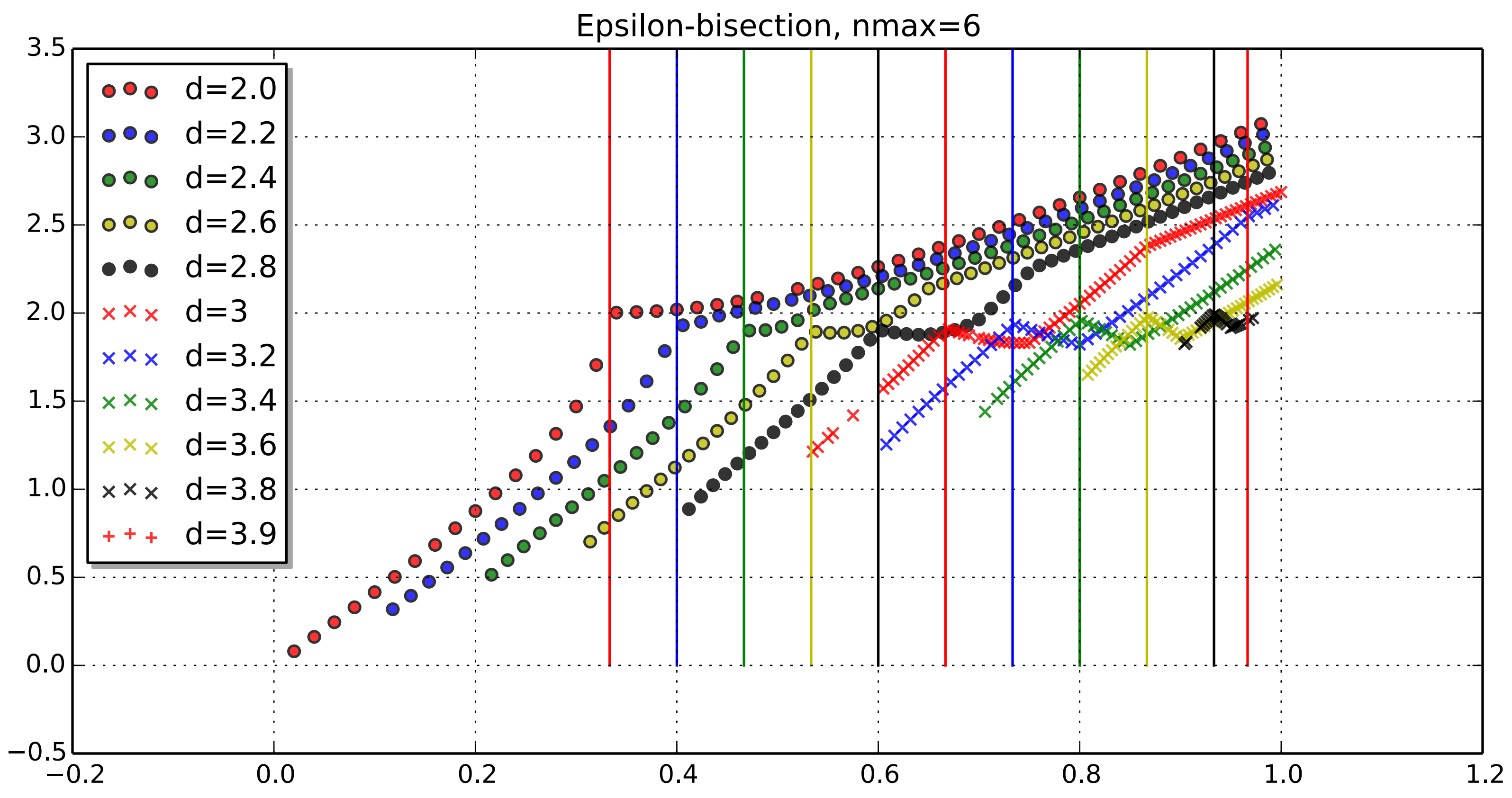
Black hole interior?

Thermalization, non-equilibrium correlation functions in large N gauge theories



Entanglement, spacetime and gravity

Applications to cosmology?


Epsilon-bisection, nmax=6
d=2.0
d=2.2
d=2.4
d=2.6
d=2.8
d=3
d=3.2
d=3.4
d=3.6
d=3.8
d=3.9
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2

Research Interests & Scientific Activities

Denis Klevers

CERN Theory Group Retreat

6th of November, 2014

A few words about myself

- PhD in 2011 from University of Bonn with Prof. Albrecht Klemm

- Postdoc 2011-2014 at UPenn

- Since September 2014 Fellow at CERN

A few words about myself

- PhD in 2011 from University of Bonn with Prof. Albrecht Klemm
  - D5-brane effective action
  - exact computations of D5/M5-brane superpotentials
  - mirror symmetry
  - F-theory, heterotic/F-theory duality
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  - mirror symmetry
  - F-theory, heterotic/F-theory duality
- Postdoc 2011-2014 at UPenn
  - topics in F-theory/M-theory
  - Landscape of Type I strings
  - dS-vacua in Type IIB with branes on singularities
- Since September 2014 Fellow at CERN

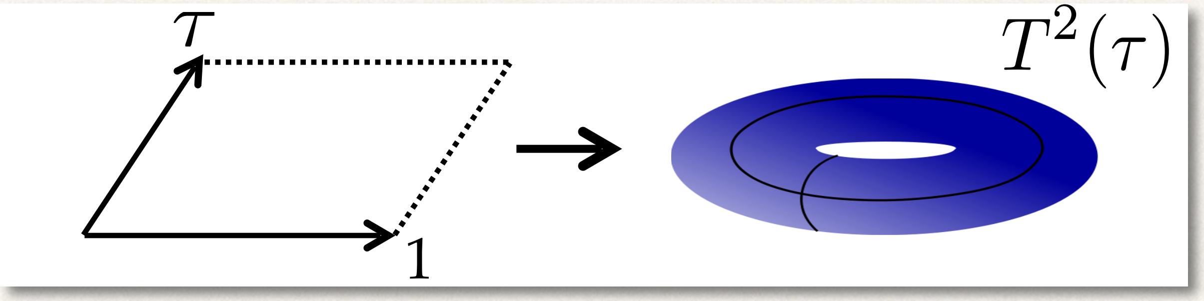
What is F-theory?

F-theory = non-perturbative, S-duality invariant formulation of Type IIB.

- Type IIB string theory has symmetry acting on complexified string coupling

$$\tau \equiv C_0 + i g_S^{-1} \mapsto \frac{a\tau + b}{c\tau + d} \quad \text{with} \quad \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}(2, \mathbb{Z})$$

- Obtain duality invariant description by replacing τ by a natural $\mathrm{SL}(2, \mathbb{Z})$ "gauge-invariant" object:



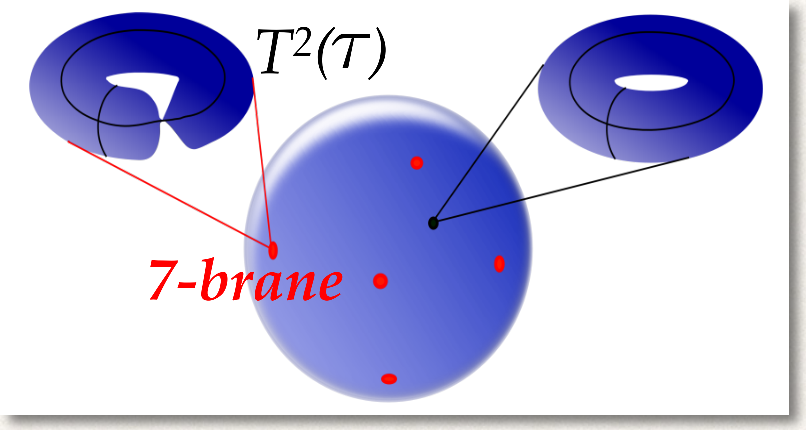
- Geometry of two-torus $T^2(\tau)$ is invariant under $\mathrm{SL}(2, \mathbb{Z})$ -action on τ

S-duality invariance achieved by trading $\tau \longrightarrow T^2(\tau)$

F-theory is geometry/physics dictionary

Non-trivial backgrounds of τ $\Leftrightarrow$ $T^2(\tau)$ -fibrations over space-time B.

- sources of τ are non-perturbative 7-branes.
  - ➡ τ blows up at 7-brane $\Leftrightarrow$ $T^2(\tau)$-fibration is singular over 7-brane



- SUSY setups of 7-branes on B $\Leftrightarrow$ T^2-fibered Calabi-Yau manifold X over B

Singularities of Calabi-Yau X $\Leftrightarrow$ setup of intersecting 7-branes

- At low energies: effective theory on 7-branes

Calabi-Yau geometry $\quad$ **Geometry** $\Leftrightarrow$ **Physics** $\quad$ *N=1* SUGRA effective theories in 6D & 4D

My research activities

1. Extend geometry / physics dictionary of F-theory:

Goal: extract all discrete data of F-theory gauge theory sector from geometry X

- Less explored: global properties of G

  a) $\pi_1(G)$ = U(1)-factors & quotients of G by finite Abelian groups

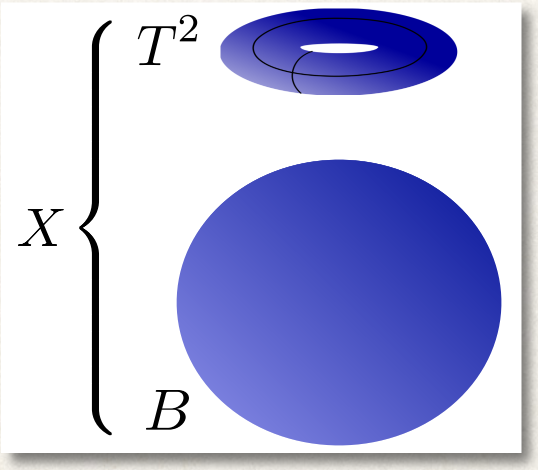
  b) $\pi_0(G)$ = discrete gauge group

  a) Mordell-Weil group of rational sections

  M.Cvetic, A.Grassi, D.K., H.Piragua, P.Song: arXiv:1303.6970, arXiv: 1306.3987arXiv:1307.6425, arXiv:1310.0463

  b) Tate-Shafarevich group of genus-one fibrations

  D.K., D.K.Mayorga-Pena,P.K.Oehlmann, J.Reuter, H.Piragua: arXiv:1408.4808



- global, number-theoretic properties of X: hard

  ➡ developed techniques to extract full 6D & 4D matter spectrum & Yukawas.

My research activities

2. Study M/F-theory duality via 3D N=2 theory on its Coulomb branch:

a) Geometric construction of G_4-flux in M-theory compactifications on new T^2-fibered Calabi-Yau fourfolds
M.Cvetič, A.Grassi, D.K., H.Piragua: arXiv: 1306.3987

b) Determination of conditions for uplift of G_4-flux to 4D F-theory
M.Cvetič, A.Grassi, D.K., H.Piragua: arXiv: 1306.3987

c) Derivation of 4D F-theory anomaly cancellation from relations among 3D CS-terms.
M.Cvetič, T.W.Grimm, D.K.: arXiv: 1210.6034

3. Computation of corrections to F-theory effective theories:

- Tested proposal: warping in F-theory encodes certain α'-corrections to its effective action
T.W.Grimm, D.K., M.Poretschkin: arXiv: 1202.0285

4. Computation of fourfold periods invoking mirror symmetry

- determine F-theory flux superpotential T.W.Grimm, T.Ha, A.Klemm, D.K.: arXiv:0909.2025
- dual superpotentials in Heterotic string theory & certain Type IIB brane superpotentials
T.W.Grimm, T.Ha, A.Klemm, D.K.: arXiv:0912.3250

Open questions & future research directions

1. Geometry:

- Algorithmic construction of Calabi-Yau manifolds X with arbitrary Mordell-Weil & Tate-Shafarevich groups?
- Moduli space of F-theory; finiteness of landscape of CY-vacua of F-theory?
- Definition of F-theory directly on singular geometry: matrix factorizations?

2. Effective field theory

Computation of all N=1 coupling functions of chiral 4D F-theory compactifications:

a) matter couplings unknown: no quantitative control.

b) bulk sector better understood: moduli stabilization in realistic models?

3. Degrees of freedom specifying F-theory compactifications:

- Proposals for defining data of F-theory: CY X, G_4-flux, Hitchin system on discriminant locus of Calabi-Yau X, T-branes/gluing branes… ?
- Microscopics of F-theory (like M-theory) elusive: no consensus.

Geometry and Scattering Amplitudes

Miguel F. Paulos

CERN Theory Retreat

06-11-2014

About me:

- Undergraduate in Lisbon 2000-2005
- Masters+PhD in Cambridge, UK – 2005-2010
- PostDoc Jussieu, Paris – 2010-2012
- PostDoc Brown U. – 2012-2014

- Interested in Holography, CFT (bootstrap – see S. El-Showk's talk), and aspects of scattering amplitudes.

The Conformal Bootstrap Program:

Use

Conformality + *Unitarity* + *Crossing symmetry*

to construct CFTs **non-perturbatively.**

The Method

Example [edit]

Suppose that a farmer has a piece of farm land, say L km^2, to be planted with either wheat or barley or some combination of the two. The farmer has a limited amount of fertilizer, F kilograms, and insecticide, P kilograms. Every square kilometer of wheat requires F_1 kilograms of fertilizer and P_1 kilograms of insecticide, while every square kilometer of barley requires F_2 kilograms of fertilizer and P_2 kilograms of insecticide. Let S_1 be the selling price of wheat per square kilometer, and S_2 be the selling price of barley. If we denote the area of land planted with wheat and barley by x_1 and x_2 respectively, then profit can be maximized by choosing optimal values for x_1 and x_2. This problem can be expressed with the following linear programming problem in the standard form:

Maximize:	$S_1 \cdot x_1 + S_2 \cdot x_2$	(maximize the revenue—revenue is the "objective function")
Subject to:	$x_1 + x_2 \leq L$	(limit on total area)
	$F_1 \cdot x_1 + F_2 \cdot x_2 \leq F$	(limit on fertilizer)
	$P_1 \cdot x_1 + P_2 \cdot x_2 \leq P$	(limit on insecticide)
	$x_1 \geq 0, x_2 \geq 0$	(cannot plant a negative area).

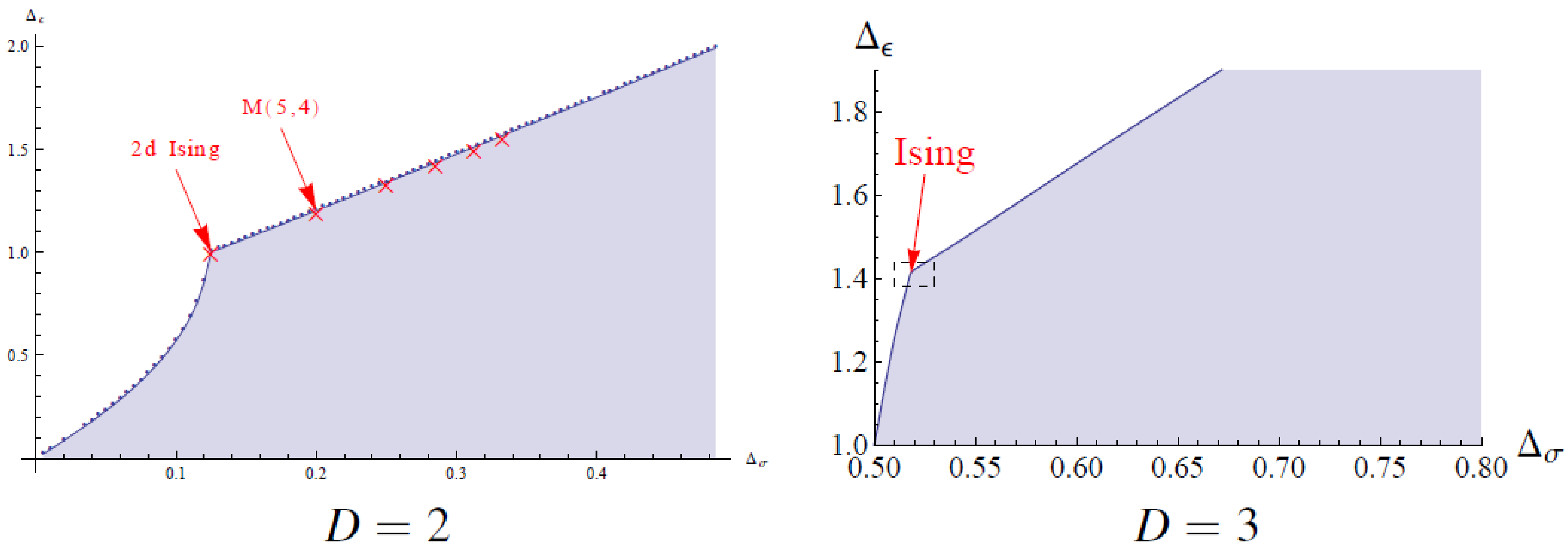
Which in matrix form becomes:

$$\text{maximize} \begin{bmatrix} S_1 & S_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\text{subject to} \begin{bmatrix} 1 & 1 \\ F_1 & F_2 \\ P_1 & P_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \leq \begin{bmatrix} L \\ F \\ P \end{bmatrix}, \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \geq \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Universal Bounds

$$\langle \sigma(x_1)\sigma(x_2)\sigma(x_3)\sigma(x_4)\rangle \quad \sigma \times \sigma \sim 1+\varepsilon+\ldots$$



Kinks signal spectrum rearrangements – “null states”. Hints of integrability?

Geometry in Amplitudes

Seeds, quivers and mutations

- Cluster algebras are built iteratively, starting with a “seed”: a set of cluster coordinates and a quiver.
- Quivers tell us how to “mutate” – a rule to generate a new seed.

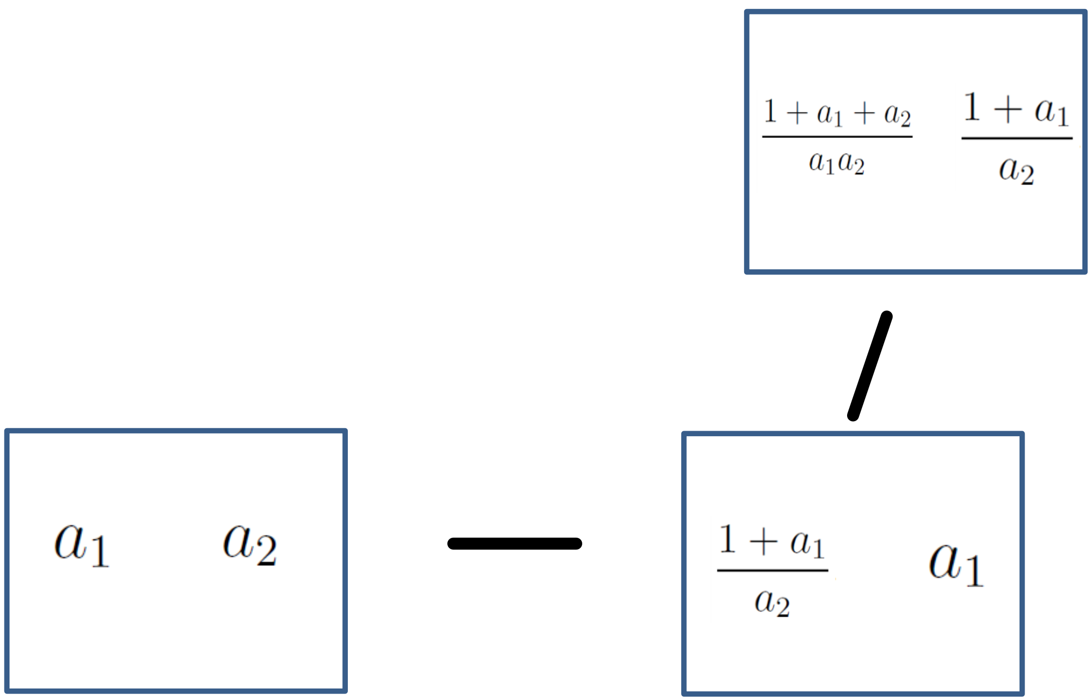
$$a_1 \longrightarrow a_2$$

Seeds, quivers and mutations

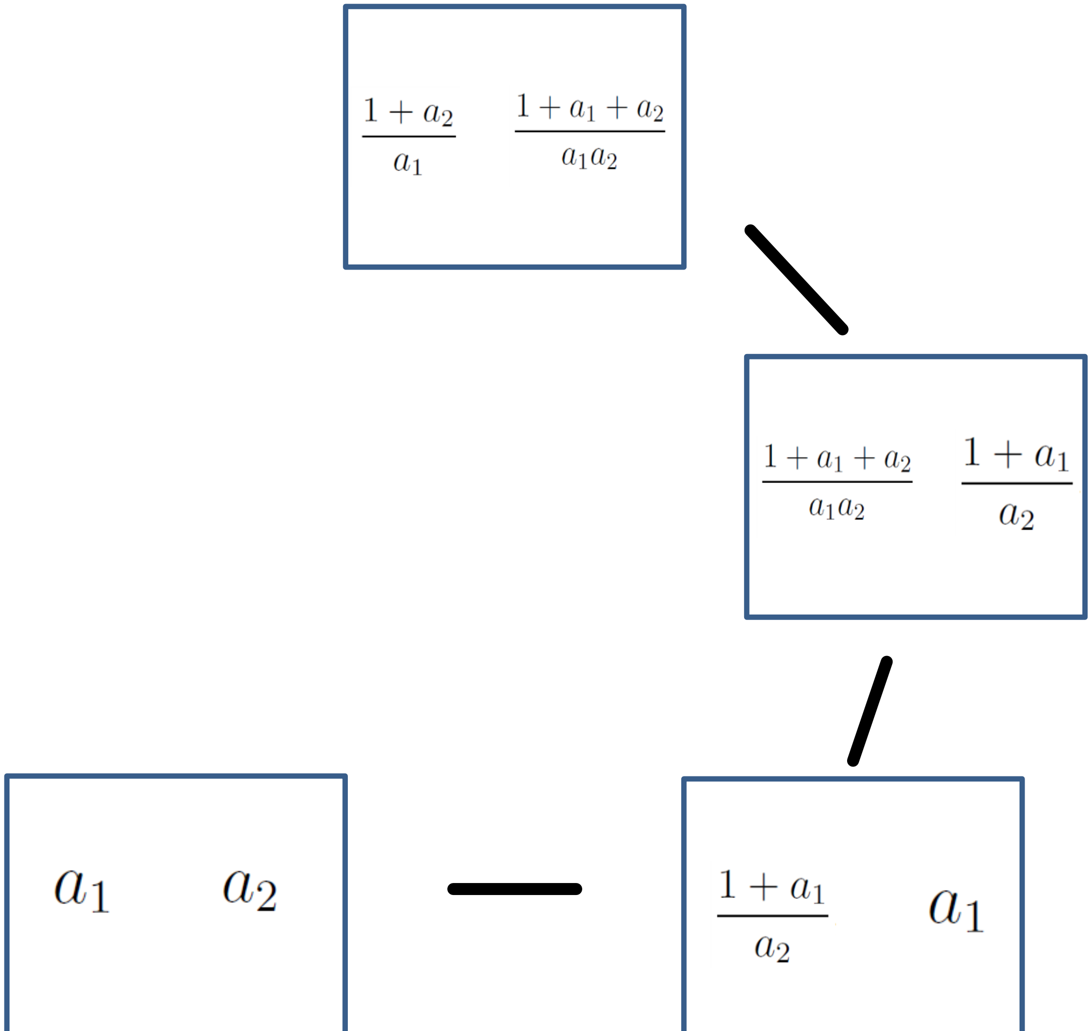
Mutation moves us from one seed to the next

$$\boxed{a_1 \longrightarrow a_2} \quad \text{———} \quad \boxed{\frac{1+a_1}{a_2} \longrightarrow a_1}$$

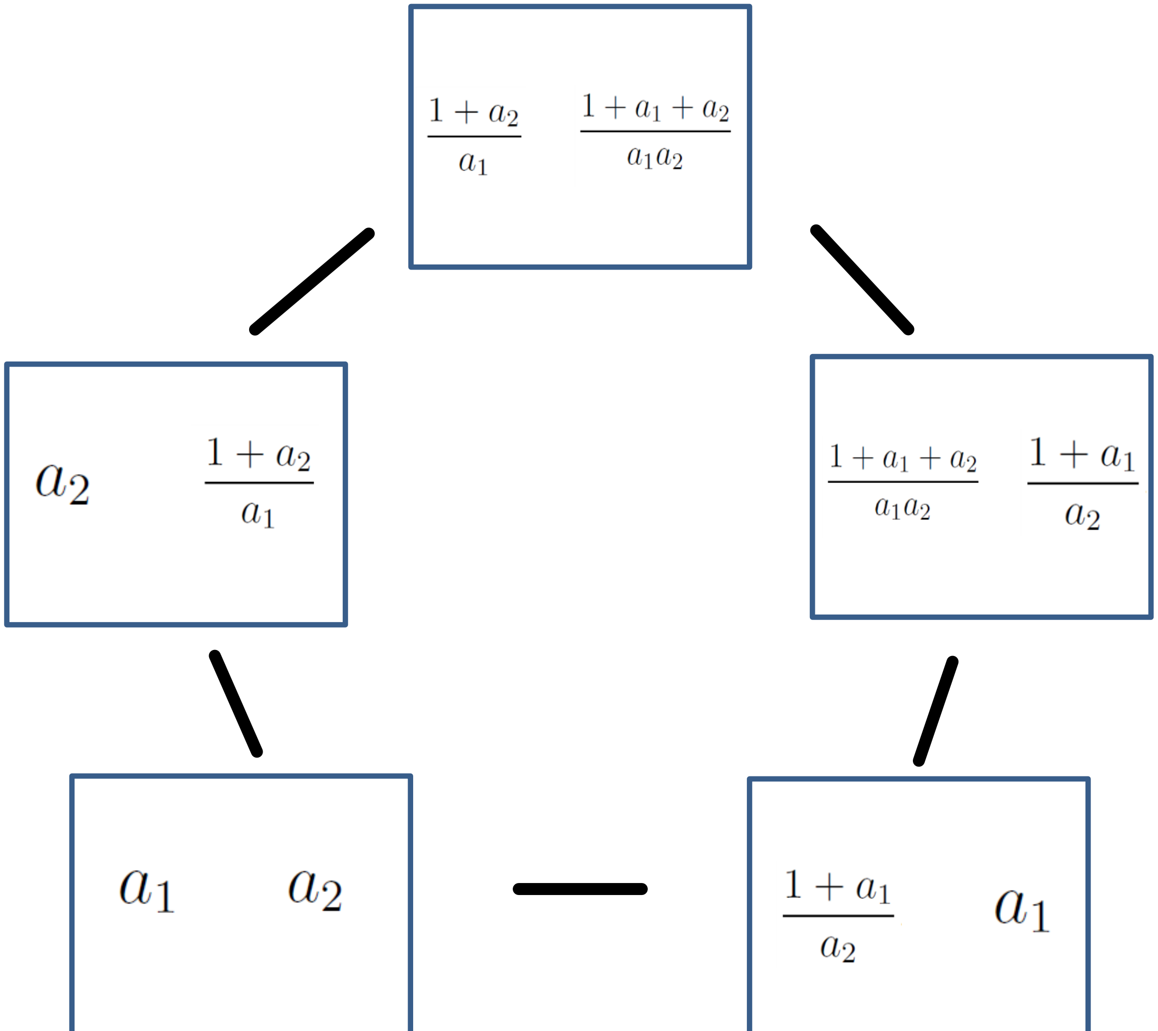
Seeds, quivers and mutations



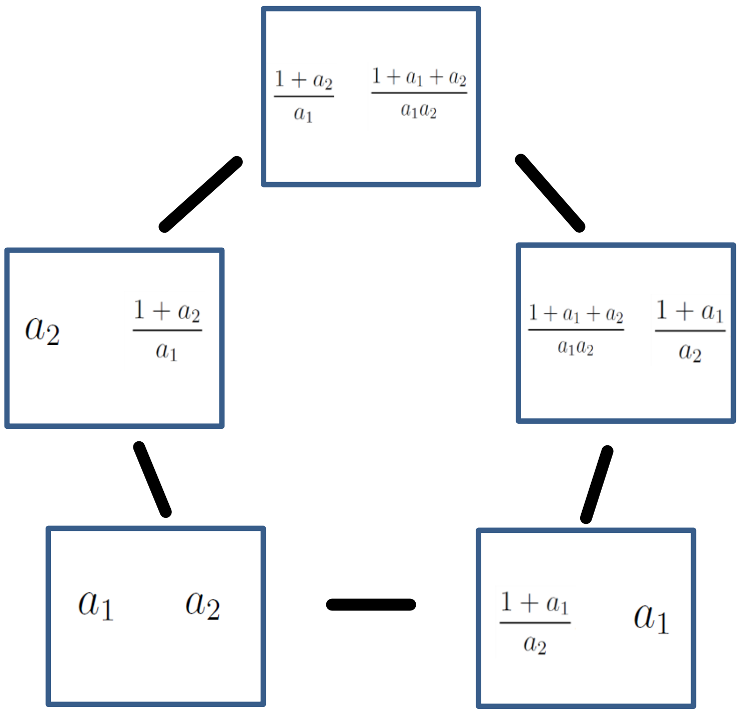
Seeds, quivers and mutations



Seeds, quivers and mutations

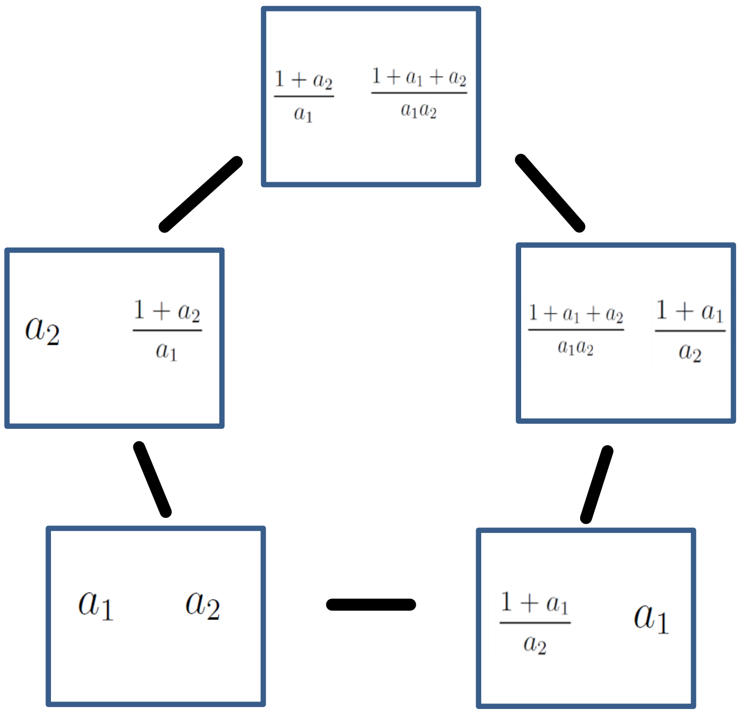


Seeds, quivers and mutations



- Cluster algebras of finite type have ADE classification
- Coordinate rings of Grassmannian positroid varieties furnish nice example of cluster algebras.
- These are the ones relevant for the physics of scattering amplitudes

Seeds, quivers and mutations



- **Cluster algebras** of finite type have ADE classification
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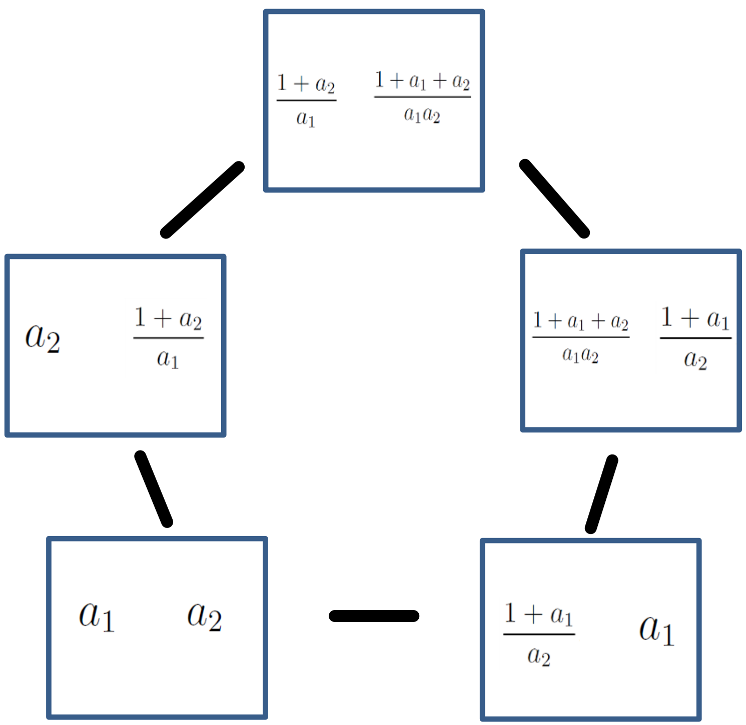
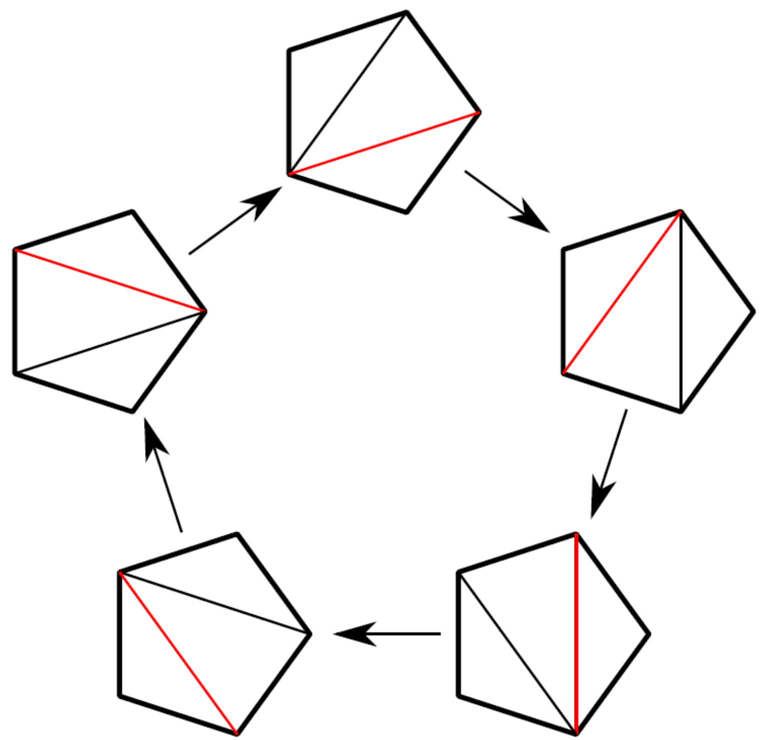
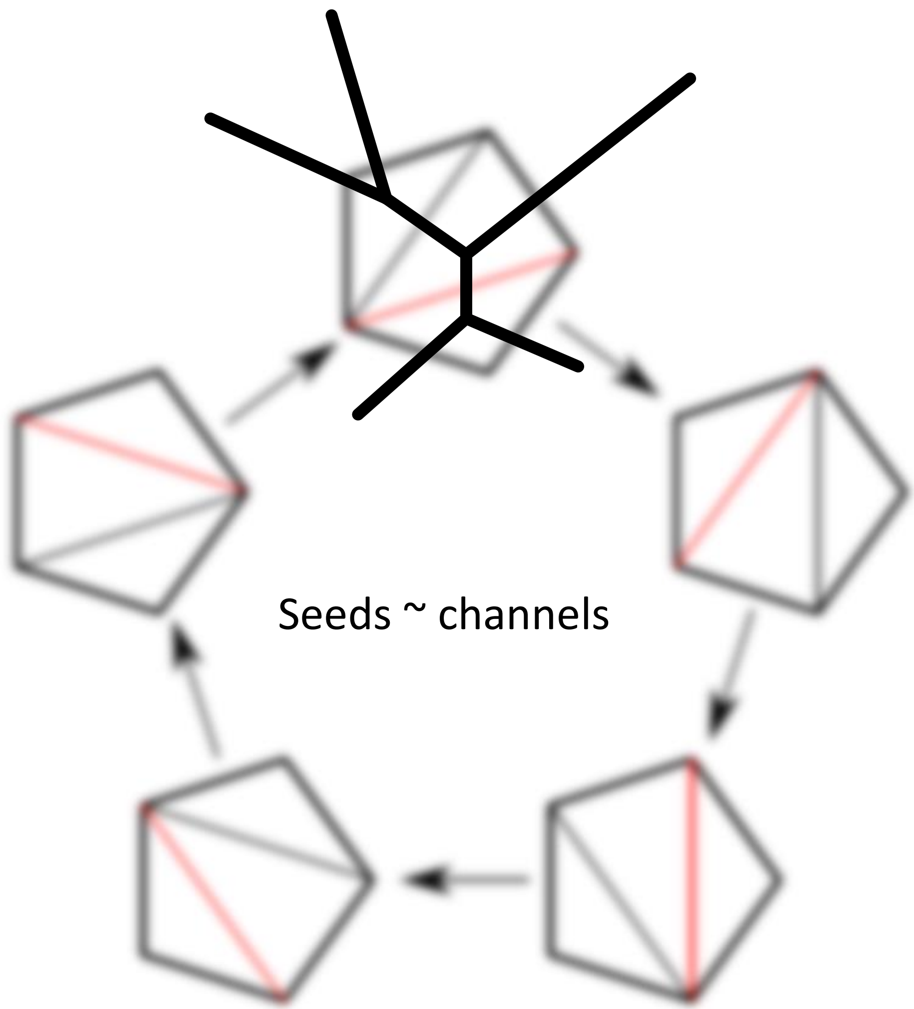
- These are the ones relevant for the physics of **scattering amplitudes**

From clusters to scattering

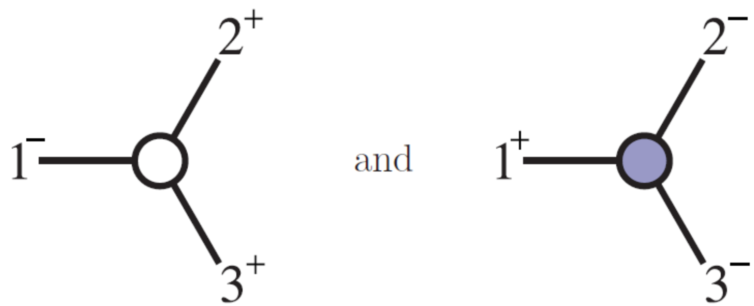


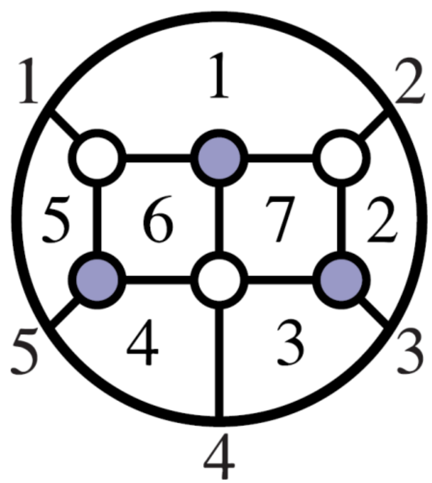


From clusters to scattering



Clusters in N=4 SYM

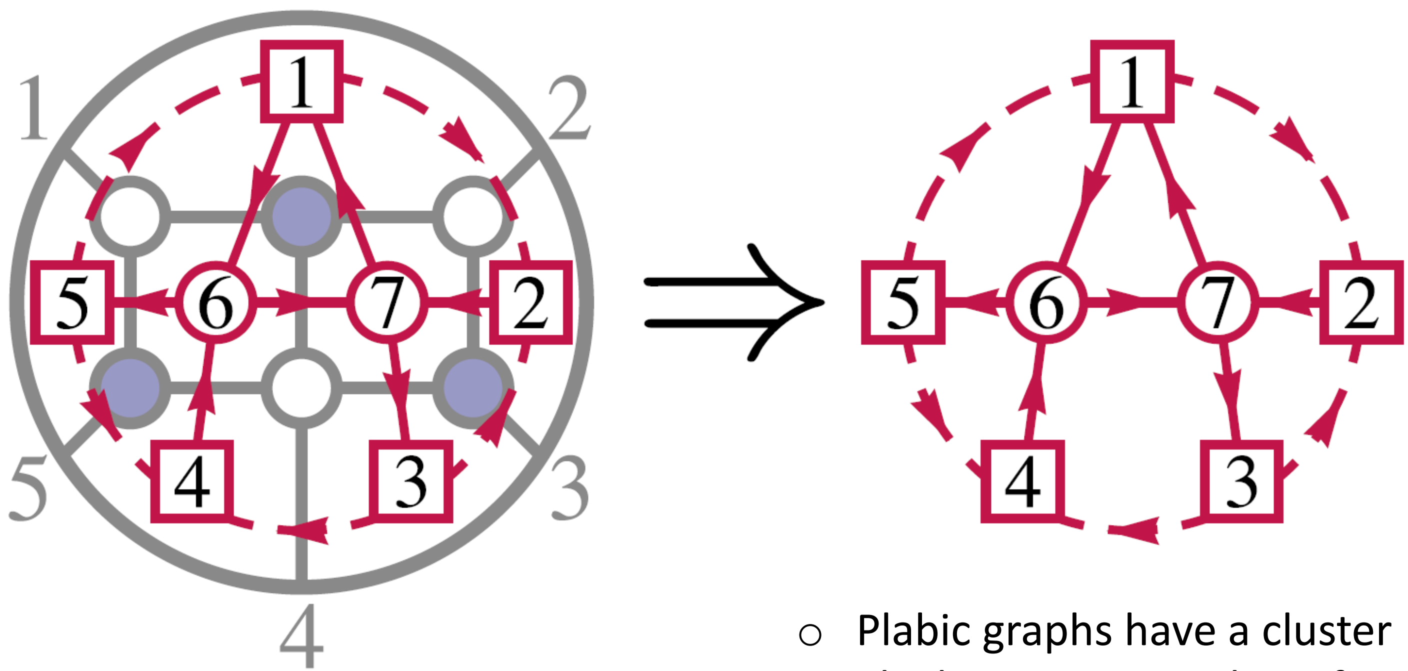




e.g. *this graph represents 5pt (-- +++) amplitude, in* **any** *Yang-Mills theory.*

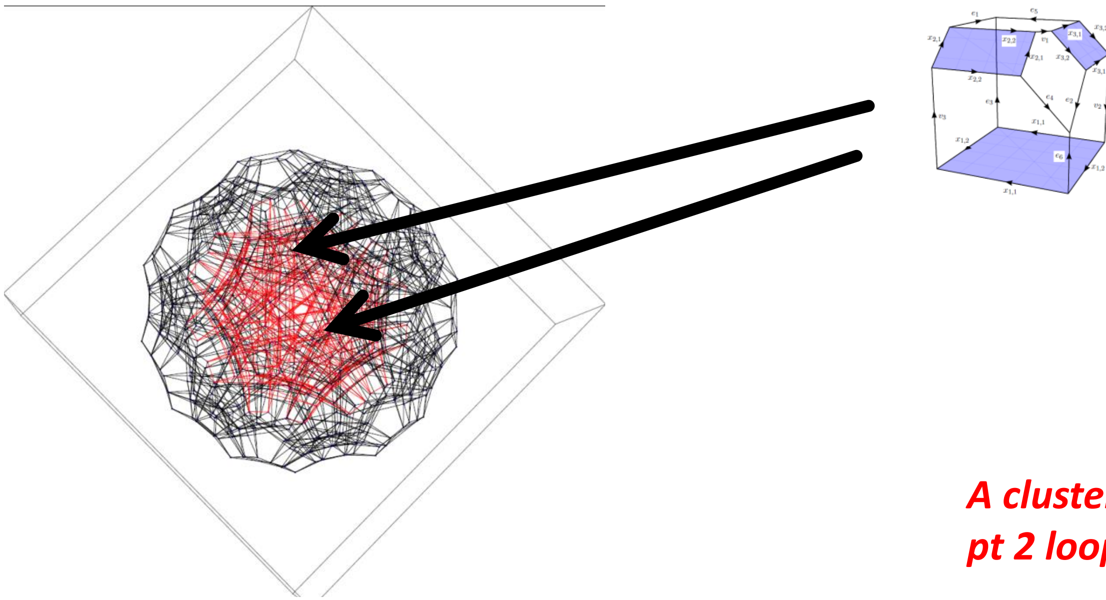
- Tree amplitudes (same as in QCD!) given by plabic graphs.
- These are nothing but on-shell three point vertices glued together by momentum conservation.
- Loop *integrands* can also be constructed using such graphs.

Clusters in N=4 SYM



- Plabic graphs have a cluster algebra structure: that of a Grassmannian cluster algebra.

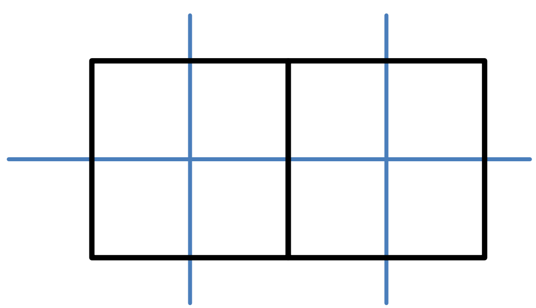
Cluster structure of loop amplitudes

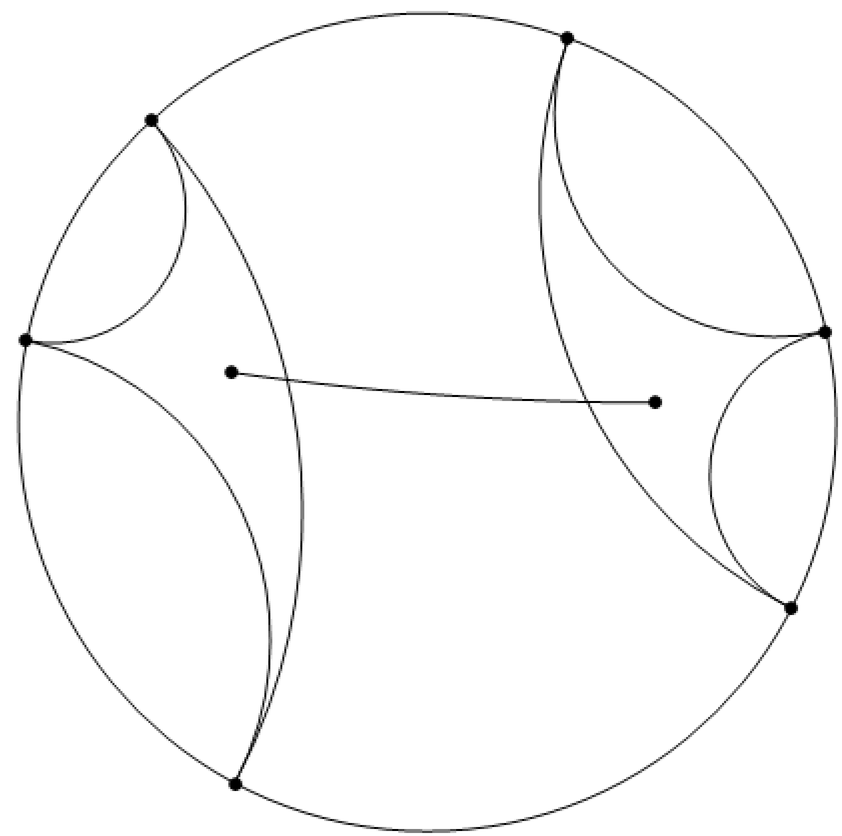


A clustery expression for the 7 pt 2 loop MHV amplitude

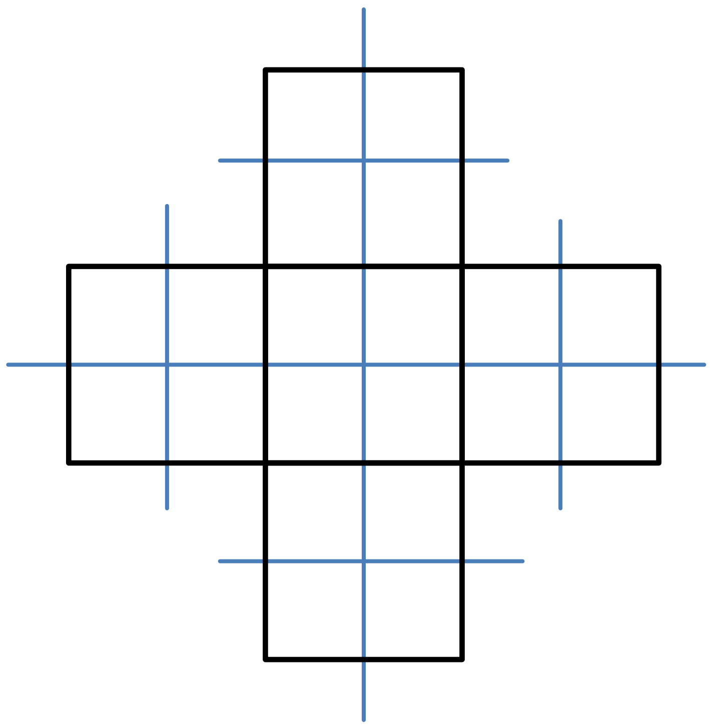
$$
\begin{aligned}
R_7^{(2)} \sim\ & \frac{1}{2} f_{A_3}\left(\frac{\langle 1245\rangle\langle 1567\rangle}{\langle 1257\rangle\langle 1456\rangle}, \frac{\langle 1235\rangle\langle 1456\rangle}{\langle 1256\rangle\langle 1345\rangle}, \frac{\langle 1234\rangle\langle 1257\rangle}{\langle 1237\rangle\langle 1245\rangle}\right) + \frac{1}{2} f_{A_3}\left(\frac{\langle 1345\rangle\langle 1567\rangle}{\langle 1357\rangle\langle 1456\rangle}, \frac{\langle 1235\rangle\langle 3456\rangle}{\langle 1356\rangle\langle 2345\rangle}, \frac{\langle 1234\rangle\langle 1357\rangle}{\langle 1237\rangle\langle 1345\rangle}\right) \\
& + \mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1256\rangle}{\langle 1236\rangle\langle 1245\rangle}\right) + \mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1257\rangle}{\langle 1237\rangle\langle 1245\rangle}\right) + \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1357\rangle}{\langle 1237\rangle\langle 1345\rangle}\right) + \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1456\rangle}{\langle 1246\rangle\langle 1345\rangle}\right) \\
& - \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1257\rangle\langle 1356\rangle}{\langle 1237\rangle\langle 1256\rangle\langle 1345\rangle}\right) + \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1267\rangle\langle 1356\rangle}{\langle 1237\rangle\langle 1256\rangle\langle 1346\rangle}\right) + \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1235\rangle\langle 1456\rangle}{\langle 1256\rangle\langle 1345\rangle}\right) \\
& - \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1257\rangle\langle 1456\rangle}{\langle 1247\rangle\langle 1256\rangle\langle 1345\rangle}\right) - \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1267\rangle\langle 1456\rangle}{\langle 1247\rangle\langle 1256\rangle\langle 1346\rangle}\right) - \frac{1}{4}\mathrm{Li}_4\left(-\frac{\langle 1234\rangle\langle 1457\rangle}{\langle 1247\rangle\langle 1345\rangle}\right) \\
& + \text{ dihedral} + \text{parity conjugate.} \qquad (5.7)
\end{aligned}
$$

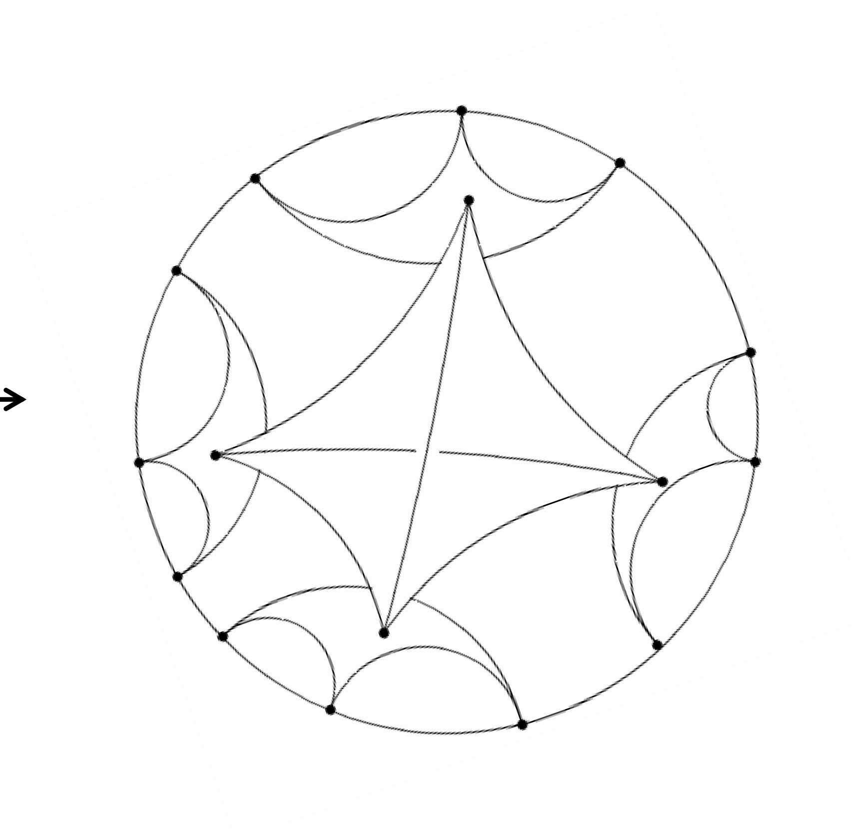
Geometry of loops





Geometry of loops





Non-perturbative aspects in gauge and string theories

Marine Samsonyan

CERN

November 5-7, 2014

Instantons

- Non-perturbative effects are strong coupling phenomena. They can not be seen through small coupling expansion, i.e. through the ordinary perturbation theory.
- Instantons are non-perturbative effects scaling as $e^{-1/g^2_{YM}}$. ADHM construction
- Important role in supersymmetric theories.
- Instantons in String Theory. Worldsheet, brane, unoriented D-brane (gauge and exotic).
- Instantons in AdS/CFT.

- Superconformal field theory on the world-volume of N parallel D3-branes corresponds to the type IIB theory on $AdS_5 \times S^5$.
- M-theory on $AdS_7 \times S^4$ is dual to superconformal field theory on N M5-branes.
- M-theory on $AdS_4 \times S^7$ corresponds to superconformal field theory which lives on the world-volume of N parallel M2-branes.

ABJM

$$\mathcal{N} = 6 \leftarrow \mathcal{N} = 3 \leftarrow \mathcal{N} = 4 \leftarrow \mathcal{N} = 2 \leftarrow \mathcal{N} = 1 \ (d = 4)$$

11-d M-theory on $AdS_4 \times S^7/\mathbb{Z}_k$, corresponding to the near horizon geometry of N M2-branes at a $\mathbb{C}^4/\mathbb{Z}_k$ singularity, is expected to be dual to $\mathcal{N} = 6$ Chern-Simons theory in $d = 3$ with gauge group $U(N)_k \times U(N)_{-k}$

In the 't Hooft limit the theory is dual to Type IIA on $AdS_4 \times \mathbb{CP}^3$

Compactification on S^7

Spin	$SO(8)$	$4(ML)^2$	Δ	ℓ
2^+	$(\ell, 0, 0, 0)$	$\ell(\ell+6)$	$\Delta = \frac{\ell}{2} + 3$	$\ell \geq 0$
1_1^-	$(\ell, 1, 0, 0)$	$\ell(\ell+2)$	$\Delta = \frac{\ell}{2} + 2$	$\ell \geq 0$
1_2^-	$(\ell-2, 1, 0, 0)$	$(\ell+6)(\ell+4)$	$\Delta = \frac{\ell}{2} + 4$	$\ell \geq 2$
1^+	$(\ell-1, 0, 1, 1)$	$(\ell+2)(\ell+4)$	$\Delta = \frac{\ell}{2} + 3$	$\ell \geq 1$
0_1^+	$(\ell+2, 0, 0, 0)^*$	$(\ell+2)(\ell-4)$	$\Delta = \frac{\ell}{2} + 1$	$\ell \geq 0$
0_2^+	$(\ell-2, 0, 0, 0)$	$(\ell+10)(\ell+4)$	$\Delta = \frac{\ell}{2} + 5$	$\ell \geq 2$
0_3^+	$(\ell-2, 2, 0, 0)$	$\ell(\ell+6)$	$\Delta = \frac{\ell}{2} + 3$	$\ell \geq 2$
0_1^-	$(\ell, 0, 2, 0)$	$(\ell-2)(\ell+4)$	$\Delta = \frac{\ell}{2} + 2$	$\ell \geq 0$
0_2^-	$(\ell-2, 0, 0, 2)$	$(\ell+8)(\ell+2)$	$\Delta = \frac{\ell}{2} + 4$	$\ell \geq 2$

Table: Bosonic KK towers after compactification on S^7

Polynomial representations for $SO(8)$ and $U(4)$

KK harmonics on $S^7 = SO(8)/SO(7) \to$ KK harmonics on $\mathbb{CP}^3 = U(4)/U(3) \times U(1)$.
Construction of arbitrary representations of $SO(8)$ in the space of polynomials of 12 variables. The latter are the coordinates of the subgroup $Z_+^{SO(8)}$ generated by the raising operators of $SO(8)$.
Polynomials corresponding to the highest weight of $SO(6)$ repr.s depend only on 6 variables satisfying the following equations:

$$
\begin{aligned}
&(a_{23}\partial_{a_{13}} + a_{24}\partial_{a_{14}})^{\ell_1+1} f(a) = 0 \\
&(a_{13}\partial_{a_{12}} + a_{34}\partial_{a_{24}})^{\ell_2+1} f(a) = 0 \\
&(a_{14}\partial_{a_{13}} + a_{24}\partial_{a_{23}})^{\ell_3+1} f(a) = 0 \\
&(\partial_{a_{34}})^{\ell_4+1} f(a) = 0
\end{aligned}
$$

Close look at the KK spectrum

Large k limit only $SO(2)$ singlets survive.
Only states with ℓ even on S^7 give rise to neutral states. Parent theory could be either a compactification on S^7 or on $\mathbb{RP}^7 = S^7/\mathbb{Z}_2$. Both lead to $SO(8)$ gauged supergravity corresponding to the 'massless' multiplet

$$\{g_{\mu\nu}, 8\psi_\mu, 28A_\mu, 56\lambda, 35^+ + 35^-\varphi\}$$

From S^7 to $S^7/\mathbb{Z}_k \approx \mathbb{CP}^3 \ltimes S^1$ not a spontaneous supersymmetry breaking.
Massless scalars with $\Delta = 3$(marginal operators) only in $\mathbf{840_{vc}} = (2,0,2,0)$ and $\mathbf{1386} = (6,0,0,0)$. None of these plays the role of Stückelberg field for the 12 coset vectors in the $\mathbf{6}_{+2} + \mathbf{6}_{-2}$ of $SO(8)/SO(6) \times SO(2)$.

Neutral singlets of $SO(6)$ appear in the decomposition of $\mathbf{35}_s$ parity odd scalars 0_2^- with $M^2 L_{AdS}^2 = 10$, $\Delta = 5$. Other neutral singlets from the $SO(8)$ singlet parity even scalar with $M^2 L_{AdS}^2 = 18$, *i.e.* $\Delta = 6$. Don't belong to the supergravity multiplet. Correspond to the 'stabilized' complexified Kähler deformation $\mathcal{J} + iB$ and couple to the Type IIA world-sheet instanton.
Bosonic action:

$$S_{wsi} = \int \mathcal{J} + iB = L^2/\alpha'$$

$B = 0$ in the ABJM model, while $B = l/k$ with $l = 1, ..., k-1$ in the ABJ model. Effects induced by world-sheet instantons in Type IIA on $\mathbb{CP}^3$ should be dual to the non-perturbative corrections.

Hagen Triendl

4.1-072

Overview over my work

Research interests

I am interested at the interplay of physics and geometry within string theory and supergravity.

Recently:

- Hidden supersymmetries and string corrections
- Moduli spaces of supersymmetric AdS backgrounds
- Supersymmetric black holes in string theory
- Supersymmetric field theories on curved backgrounds

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Moduli space

Space of flat (supersymmetric) deformations in a (supersymmetric) vacuum

- In supergravity: moduli correspond to scalar vevs
- Couplings usually depend on these vevs, e.g. gauge kinetic term

$$S = \frac{1}{2}\int g_{ij}(\phi)\mathrm{d}\phi^i \wedge * \mathrm{d}\phi^j + f_{ab}(\phi)F^a \wedge * F^b + \ldots$$

metric of moduli space

Gauge couplings

- Supersymmetry constrains moduli space and couplings

Goal: Understand these moduli spaces

Moduli space of Calabi-Yau compactifications

- Simplest supersymmetric Minkowksi backgrounds correspond to Calabi-Yau (CY) compactifications of string theory
- Moduli space is here characterized by certain functions that fully determine $g_{ij}(\phi)$
- Vector mult. moduli z^a depend on single holomorphic function:

$$F = d_{abc}(CY) z^a z^b z^c + \zeta(3)\,\chi(CY) + \sum_{\{k_a\}} n_{k_a}(CY)\,\mathrm{Li}_3\left(e^{2\pi \mathrm{i} k_a z^a}\right)$$

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- Classical contribution:

  $d_{abc}(CY)$ are topological intersection numbers

  (easy to compute)

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- All perturbative corrections:

  proportional to Euler number $\chi(M)$

  (easy to compute)

Moduli space of Calabi-Yau compactifications

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- Non-perturbative corrections more refined:

$n_{k_a}(M)$ is number of rational curves (Gromov-Witten inv.)

(often very difficult to compute)

Hidden supersymmetries

[Kashani-Poor, Minasian, HT]

- If Euler number vanishes, **all** perturbative corrections vanish
- This can be explained by existence of extra supersymmetries that are spontaneously broken at the compactification scale
- A field theory would not care about these supersymmetries at low energies, but one can show that string theory does (using mirror symmetry)
- These hidden supersymmetries also highly constrain non-perturbative contributions: many $n_{k_a}(M)$ vanishing
- There are indications that such hidden supersymmetries are relevant to more general cases

AdS moduli spaces

- AdS backgrounds of string theory can be rather complicated
- The holographic duals of moduli fields are marginal deformations of the CFT on the boundary
- Approach: Understand supersymmetric moduli space in general AdS backgrounds in 4d or 5d supergravity
- In particular: Certain structures (like R-symmetry) on moduli space relate to non-renormalization theorems
- As usually a classical analysis in the AdS background corresponds to the large-N limit on the boundary

AdS moduli spaces

- AdS_4:

  $\boldsymbol{N = 1}$ moduli space real

  $\boldsymbol{N = 2}$ moduli space real x Kähler

  [de Alwis, McAllister, Louis, HT, Westphal]

  $\boldsymbol{N = 4}$ moduli space none

  [Louis, HT]

- AdS_5:

  [Louis, HT, Zagermann]

  $\boldsymbol{N = 2}$ moduli space Kähler (?)

  $\boldsymbol{N = 4}$ moduli space $\boldsymbol{SU(1,n)/(U(1) \times SU(n))}$

CERN Theory Retreat

Ioannis Florakis

CERN Theory Retreat

Ioannis Florakis

5-7 November 2014

Les Houches

Profile

- Born in Athens
- Doctorat from Ecole Normale Supérieure (University of Paris)

string thermodynamics & cosmology

- Previous postdoc position : MPI for Physics, Munich
- Joined the TH as Fellow in September

Interested in both mathematical aspects of string theory & applications

- string perturbation theory at loop level (BPS saturated amplitudes)
- spontaneous breaking of supersymmetry & perturbative corrections
- topological amplitudes & connection to SUSY gauge theories

Overview of Recent Research

String theory - Supergravity - SUSY gauge theory (& techniques in Number theory)

- Radiative corrections to gauge couplings in non-supersymmetric string vacua

  arXiv: 1407.8023

  with: C. Angelantonj and M. Tsulaia

- New methods for one-loop amplitudes based on Poincaré series

  arXiv: 1304.4271, 1203.0566, 1110.5318

  with: C. Angelantonj and B. Pioline

- Proposal for refinement of topological string & connection to Nekrasov partition function

  arXiv: 1309.6688, 1302.6993

  with: I. Antoniadis, S. Hohenegger, K.S. Narain and A. Zein Assi

- Gauged supergravity (non geometric fluxes) & string uplift

  arXiv: 1307.0999, 1202.6366

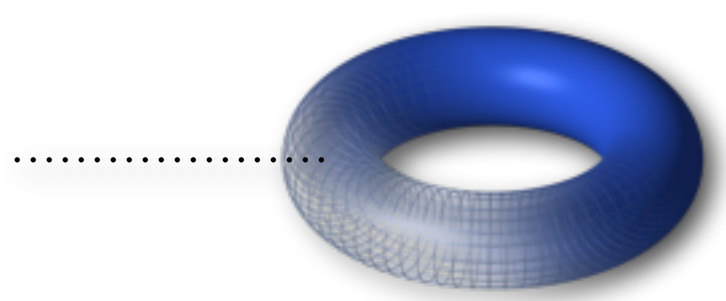
  with: C. Condeescu and D. Lüst

Spontaneous SUSY breaking and radiative corrections to gauge couplings

- Over last 20+ years : significant progress in String Phenomenology
- Semi-realistic vacua incorporating salient features of MSSM
- Reconstruction of low energy effective action with $\mathcal{N}=1$ SUSY at tree level
- Supersymmetry breaking and loop corrections : unmarked territory

Hagedorn problem - classical vacuum typically unstable

- In special situations, may be circumvented : fluxes / special orientifolds
- If classical vacuum is stable it is meaningful & important to study one-loop corrections to couplings in the effective action



$\neq 0$

Higher loops : non-trivial backreaction

Heterotic vacuum

Start with $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic string in 10d

reduce on $\mathrm{K3} \sim T^4/\mathbb{Z}_N$, with N = 2, 3, 4, 6

$\mathrm{E}_8 \times \mathrm{E}_7$

$\mathcal{N} = 1$ heterotic vacuum in 6d

Scherk-Schwarz reduction on T^2

+ trivial Wilson line background

Alvarez-Gaumé, Ginsparg, Moore, Vafa 1986
Dixon, Harvey 1986
Itoyama, Taylor 1987

$\mathrm{SO}(16) \times \mathrm{SO}(12)$ heterotic vacuum in 4d with $\mathcal{N} = 0$ SUSY

This setup is relevant for more realistic constructions of $\mathcal{N} = 1 \longrightarrow \mathcal{N} = 0$ breaking

$\mathcal{N} = 2$ sectors encode moduli dependence

universality ?

Supersymmetric Universality

If supersymmetry is unbroken

$$-\frac{1}{4g_{\mathcal{G}}^2}\, F_{\mu\nu}\, F^{\mu\nu}$$

BPS saturated term

only BPS states run in the loop

Difference of thresholds for gauge group factors $\mathcal{G}_1$, $\mathcal{G}_2$

$$\Delta_{\mathcal{G}_1} - \Delta_{\mathcal{G}_2} = \delta\beta_{12} \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\, \Gamma_{2,2}(T,U)$$

$$= -\delta\beta_{12}\ \log\left(T_2 U_2\, |\eta(T)\,\eta(U)|^4 \right) + \text{constant}$$

Dixon, Kaplunovsky, Louis '91

Independently of the details of the vacuum (almost)

universality

Non-supersymmetric Universality

Supersymmetry is spontaneously broken

$$-\frac{1}{4g_{\mathcal{G}}^2}\,F_{\mu\nu}\,F^{\mu\nu}$$

no longer BPS saturated

ALL states run in the loop

$$\Delta_{\mathcal{G}} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\,\Gamma_{2,2}(T,U)\,\Phi_{\mathcal{G}}(\bar\tau)$$

previous simple expression is
no longer valid

$$\Delta_{\mathcal{G}} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\,\frac{1}{2}\sum_{H,G=0}^{1}\Gamma_{2,2}\big[{}^{H}_{G}\big]\,\Phi_{\mathcal{G}}\big[{}^{H}_{G}\big](\tau,\bar\tau)$$

explicitly non-holomorphic

Non-supersymmetric Universality

Full Result for $\mathrm{K3} \sim T^4/\mathbb{Z}_N$

Angelantonj, I.F. Tsulaia '14

difference of beta function coefficients

$$\Delta_{\mathrm{SO}(16)} - \Delta_{\mathrm{SO}(12)} = \alpha \log\left[T_2 U_2 \left|\eta(T)\,\eta(U)\right|^4\right] + \beta \log\left[T_2 U_2 \left|\vartheta_4(T)\,\vartheta_2(U)\right|^4\right]$$
$$+ \gamma \log\left|\hat{j}_2\,(T/2) - \hat{j}_2\,(U)\right|^4 \left|j_2(U) - 24\right|^4$$

$\boxed{\text{universality}}$

Non-supersymmetric Universality

Full Result for $\mathrm{K3} \sim T^4/\mathbb{Z}_N$

$$\Delta_{\mathrm{SO}(16)} - \Delta_{\mathrm{SO}(12)} = \alpha \, \log\left[T_2 U_2 \left|\eta(T)\,\eta(U)\right|^4\right] + \beta \, \log\left[T_2 U_2 \left|\vartheta_4(T)\,\vartheta_2(U)\right|^4\right]$$
$$+ \gamma \log \left|\hat{\jmath}_2\left(T/2\right) - \hat{\jmath}_2\left(U\right)\right|^4 \left|j_2(U) - 24\right|^4$$

jump in beta function coefficients

$\boxed{\text{universality}}$

Non-supersymmetric Universality

Full Result for $\mathrm{K3} \sim T^4/\mathbb{Z}_N$

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$$+\gamma \log\left|\hat{\jmath}_2\left(T/2\right) - \hat{\jmath}_2\left(U\right)\right|^4 \left|j_2(U) - 24\right|^4$$

logarithmic singularity at $T/2 = U$ (plus images)

extra charged massless states

Drastically different than the supersymmetric case

Further Questions

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☑ Gravitational thresholds - renormalization of Planck mass ?

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☑ Cosmological constant - backreaction ?

Further Questions

- ☑ Gravitational thresholds - renormalization of Planck mass ?
- ☑ Cosmological constant - backreaction ?
- ☑ Semi-realistic vacua ?