Strings and fields

CERN Theory retreat 2017

Les Houches

Kyriakos Papadodimas

Fellows
David Andriot
Benjamin Assel
Cyril Closset
Alessandra Gnecchi
Daniel Krefl
Brenda Penante
Seung-Joo Lee
Diego Regalado
Kostas Siampos
Andreas Stergiou
Piotr Tourkine
Matthew Walters

Staff
Luis Alvarez-Gaume
Wolfgang Lerche
Kyriakos Papadodimas
Slava Rychkov
Amit Sever
Timo Weigand

Group activities

Journal Club: Monday 14:00

String Seminar: Tuesday 14:00

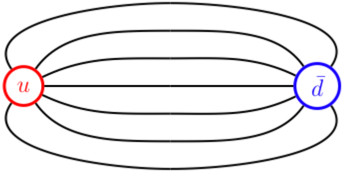
Events:

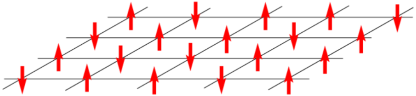
CERN winter school on strings and fields (12-16 February 2018)

TH-Institutes (Black holes and quantum information, August 2018)

What is formal theory?

Strongly coupled QFT





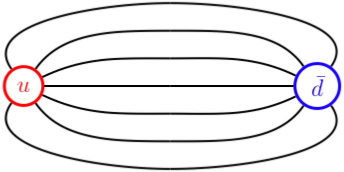
Confinement in QCD / Dynamics of QGP

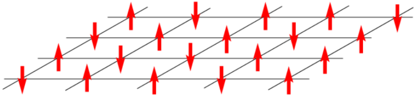
Possible applications to BSM physics

Condensed matter systems

Conceptual framework of QFT

Strongly coupled QFT





Confinement in QCD / Dynamics of QGP

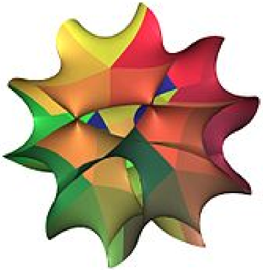
Possible applications to BSM physics

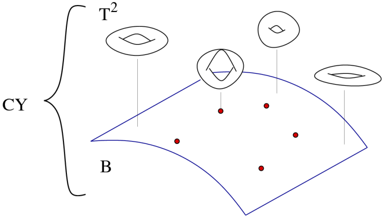
Condensed matter systems

Conceptual framework of QFT

Various approaches
Conformal bootstrap
Supersymmetry
Integrability
Amplitudes
Hamiltonian truncation
...

String-theory and phenomenology





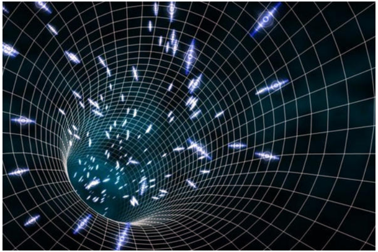
String-inspired model building

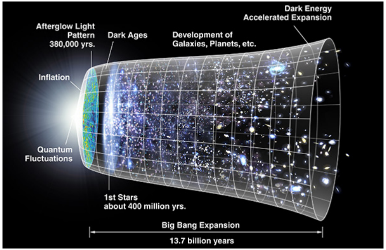
de-Sitter solutions

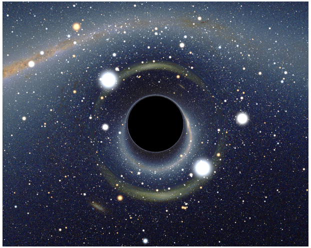
Top-down constraints for EFT

Formal aspects of string theory and connections with mathematics

Space-time and Quantum Gravity





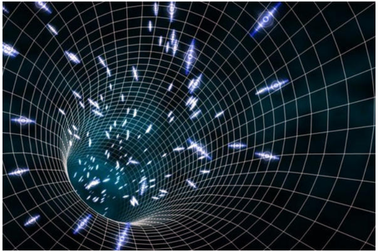


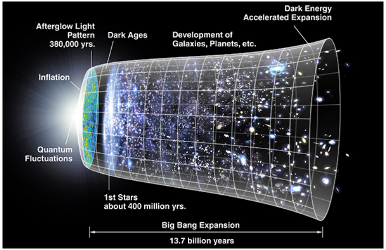
Quantum space-time at short scales

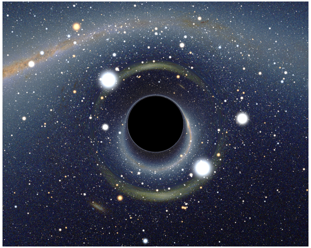
Cosmology

Black holes

Space-time and Quantum Gravity







Quantum space-time at short scales

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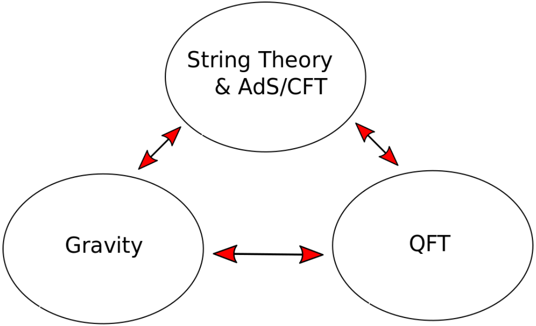
Potentially new perspective not only for UV, but also IR physics



Connections with other fields:

Mathematics

Condensed matter

Thermalization

Quantum information

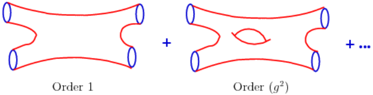
...

Some highlights

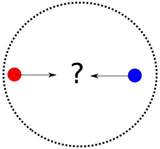
A personal view

Non-perturbative quantum gravity

String Theory: theory of quantum gravity, well understood at **perturbative** level



Not understood beyond perturbation theory, e.g. transplanckian scattering

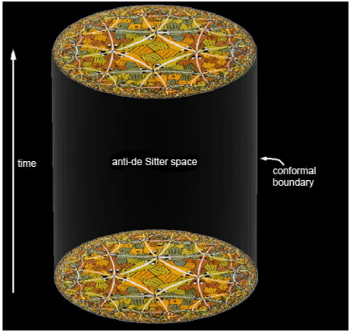


Black Hole

At the moment it is **impossible, even in principle,** to do this computation in string theory

AdS/CFT @ 20

[Maldacena, November 1997]



AdS/CFT: non-perturbative definition of Quantum Gravity by dual gauge theory

Gravity in AdS ⇒ solution of large N $\mathcal{N} = 4$ at strong coupling

Black Holes in AdS ⇔ QGP states in QFT

Black hole formation + evaporation ⇔ deconfinement + hadronization

Can in principle be used to address fundamental questions in quantum gravity and black holes

Applications to strongly coupled QGP + condensed matter systems

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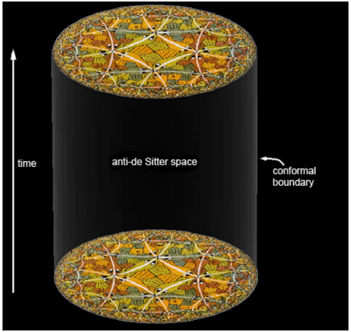

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Applications to strongly coupled QGP $+$ condensed matter systems

Spacetime is emergent

AdS/CFT

Can we prove AdS/CFT? Strings from planar diagrams of $\mathcal{N} = 4$?

AdS/CFT

Can we prove AdS/CFT? Strings from planar diagrams of $\mathcal{N} = 4$?

More generally:

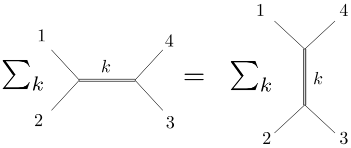
What are the fundamental principles? For which QFTs does it work?

Can it be extended to de Sitter/cosmological space-times?

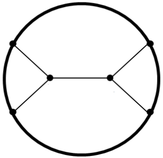
AdS/CFT

Some partial understanding

We need large N and strong coupling: large gap in dimension of conformal primaries with spin $s > 2$ [Heemskerk, Penedones, Polchinski, Sully]



Crossing symmetry constraints of CFT



Feynman diagrams in AdS

AdS/CFT

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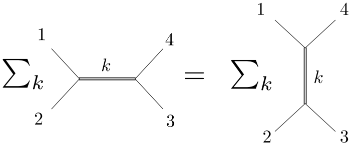
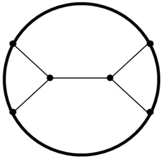


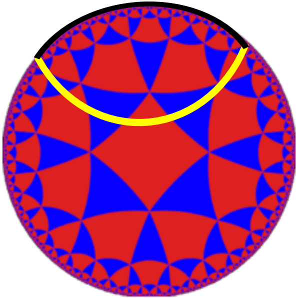
Crossing symmetry constraints of CFT

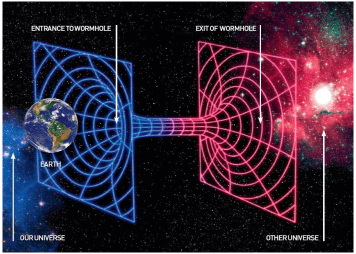


Feynman diagrams in AdS

Big question: how can we describe local physics in AdS from the CFT?

Entanglement, quantum mechanics and spacetime



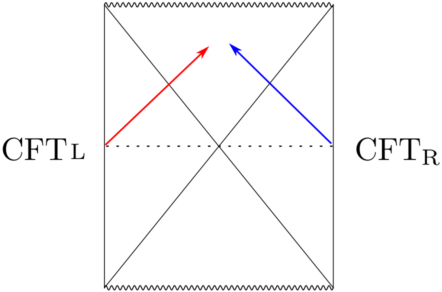


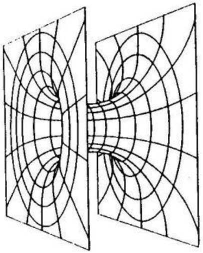
Ryu-Takayanagi proposal $S_E = \frac{A}{4G}$ ⇒ Entanglement determines geometry of spacetime

Einstein equations (partly) derived from dynamics of entanglement [Raamsdonk]

Entanglement, Quantum Mechanics and Spacetime

ER/EPR correspondence [Maldacena,Susskind]: two entangled black holes are connected by a wormhole

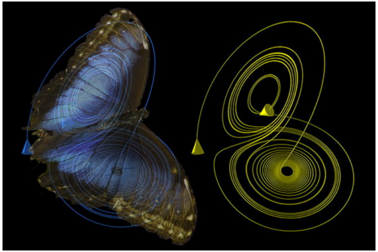


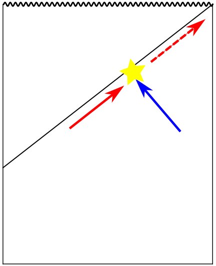


$$H = H_L + H_R$$

$$|\Psi_{\text{tfd}}\rangle = \sum_E \frac{e^{-\beta E/2}}{\sqrt{Z}} |E\rangle_L \otimes |E\rangle_R$$

Quantum chaos





$$\langle [W(t), V(0)]^2 \rangle \sim e^{\lambda t}$$

In any QFT: [Maldacena, Shenker, Stanford]

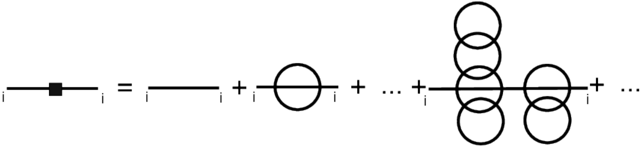
$$\boxed{\lambda \leq 2\pi T}$$

Black holes saturate this bound

SYK model

[Kitaev] N interacting fermions in $0+1$ dimensions

$$H = \sum_{ijkl} J_{ijkl}\ \psi^i \psi^j \psi^k \psi^l$$



Solvable model at large N, possible to study thermalization analytically

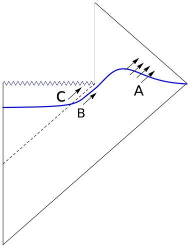
Maximally Chaotic $(\lambda = 2\pi T)$, toy model of black hole

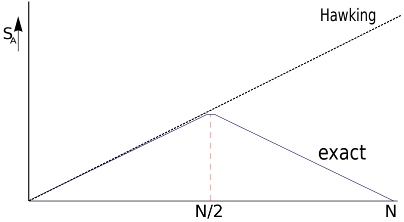
Flows to strongly interacting CFT in IR

Toy model of holography: dual to gravity in AdS$_2$

New type of “large N limit”. Higher dimensional generalizations?

The Black Hole information paradox





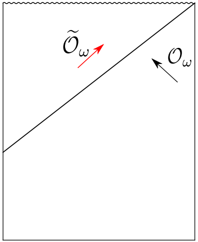
Unitarity inconsistent (?) with smooth horizon (firewall paradox)

[Mathur], [Almheiri,Marolf,Polchinski,Sully]

Is there spacetime behind the horizon?

Reconstruction of the black hole interior in AdS/CFT

[KP, Raju]



$$[\mathcal{O}_\omega, \mathcal{O}_\omega^\dagger] = 1$$

$$[H, \mathcal{O}_\omega^\dagger] = \omega \mathcal{O}_\omega^\dagger$$

$$[\widetilde{\mathcal{O}}_\omega, \widetilde{\mathcal{O}}_\omega^\dagger] = 1$$

$$[H, \widetilde{\mathcal{O}}_\omega^\dagger] = -\omega \widetilde{\mathcal{O}}_\omega^\dagger$$

Define the small algebra $\mathcal{A}$ of "simple operators". Apply Tomita-Takesaki construction

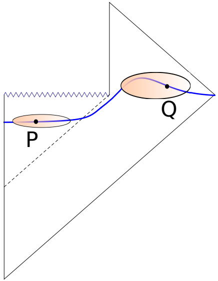
$$S\mathcal{O}|\Psi\rangle = \mathcal{O}^\dagger|\Psi\rangle$$

$$\Delta = S^\dagger S \qquad J = S\Delta^{-1/2}$$

$$\boxed{\widetilde{O} = JOJ}$$

- Identified CFT operators which can be used to reconstruct BH interior
- Reproduced predictions of Effective Field Theory, smooth horizon
- Consistent with unitarity

The Black Hole information paradox



Proposed resolution: [KP, Raju]

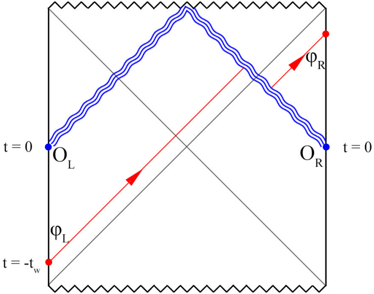
- Non-locality in quantum gravity: Hilbert space in quantum gravity does not factorize into interior × exterior

$$[\phi(P), \phi(Q)] = e^{-S}$$

- "State-dependence": operators describe the interior depend on BH microstate

Traversable wormholes

[Gao, Jafferis, Wall]



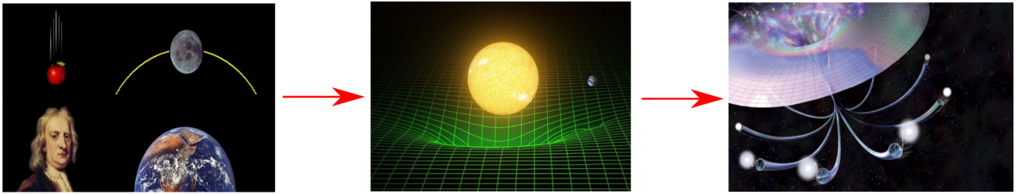
Possibility to probe black hole interior via simple CFT correlators

Equivalent to **quantum teleportation** between two CFTs

New evidence for smoothness of horizon and for state-dependent proposal

[van Breukelen, de Boer, Lokhande, KP, Verlinde]

Emergent space-time



Potentially revolutionary new perspective on nature of space-time and gravity

Quantum information and entanglement may be a natural language to describe it.

Only partly understood and a lot to be discovered.

Thank you

Amit Sever - QFT & String theory

Main interest

- Non perturbative QFT
- Holography

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Working on

I. Solving N=4 SYM at large N_c

The "**Hydrogen atom** of QFT"

II. S-matrix bootstrap

Old history, new more modest questions & ideas

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- **Non perturbative QFT**
- **Holography**

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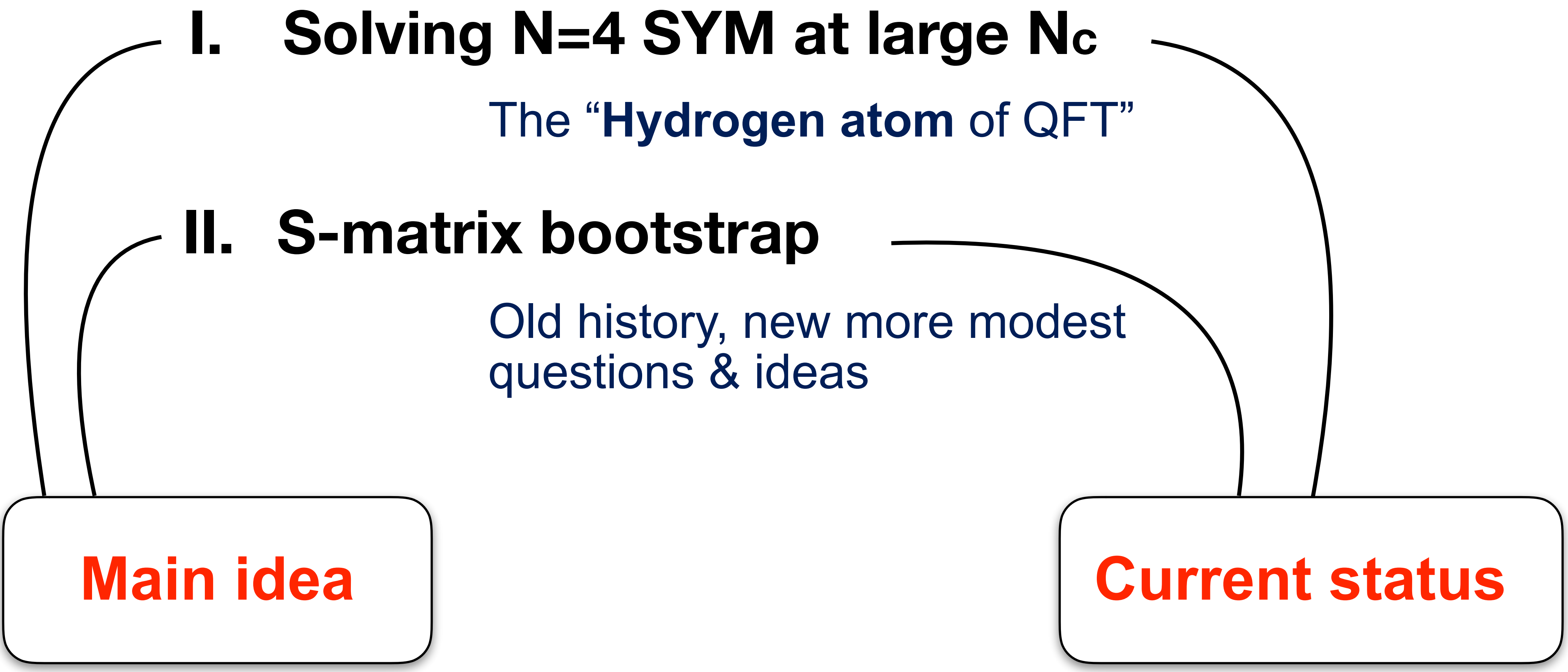

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The “**Hydrogen atom** of QFT”

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Old history, new more modest questions & ideas

Main idea

Current status

I. Solving N=4 SYM at large Nc

Main idea

No obvious small parameter 1/Nc

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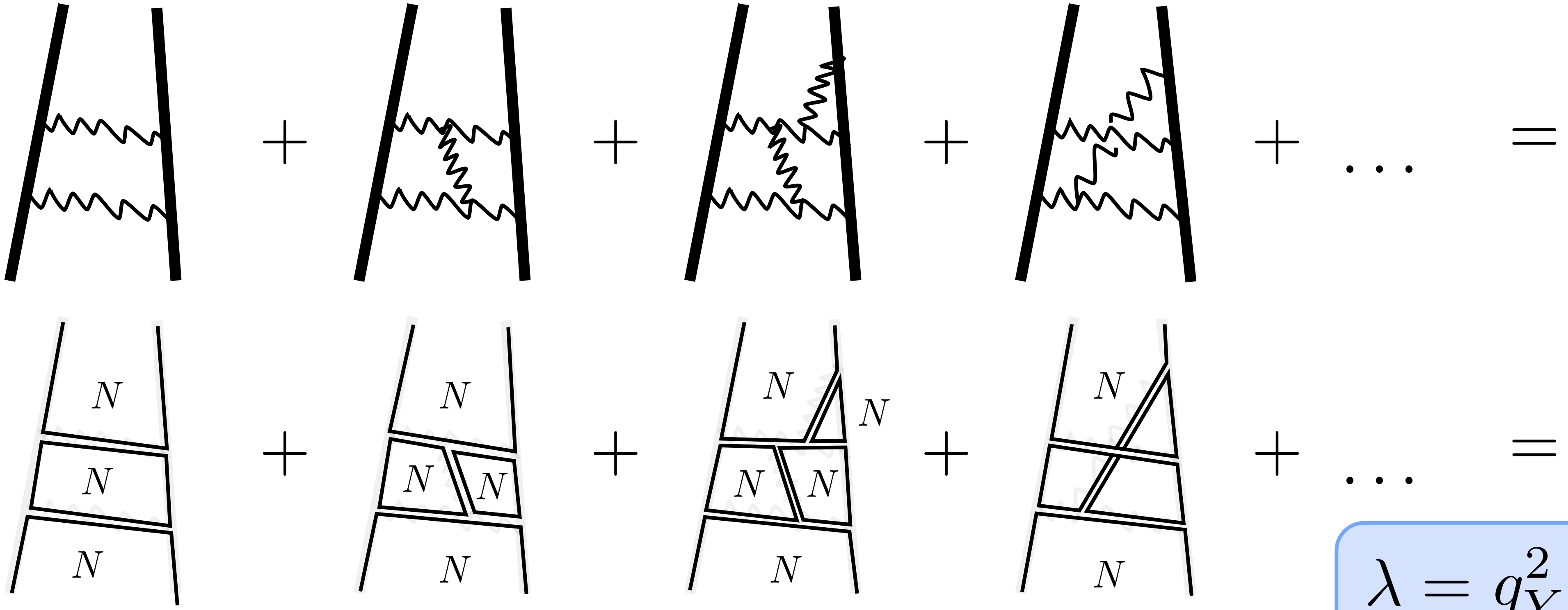
Large Nc gauge theories are theories of 2d strings ['t Hooft]



$$\lambda = g_{YM}^2 N$$

$$(\cdots + \lambda^2 + \lambda^3 + \lambda^4 + \dots) + \frac{1}{N^2}(\cdots + \lambda^3 + \dots) + \dots \quad =$$

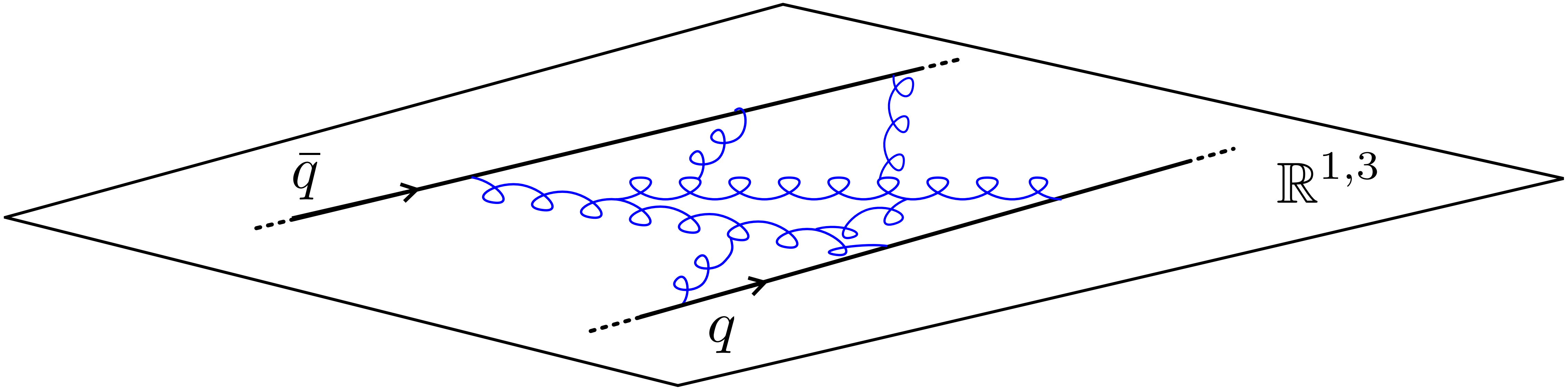
String Genus Expansion with tension related to λ and string coupled related to $1/N$

I. Solving N=4 SYM at large Nc

Main idea

The holographic ’t Hooft string

['t Hooft, Polyakov, Maldacena,...]



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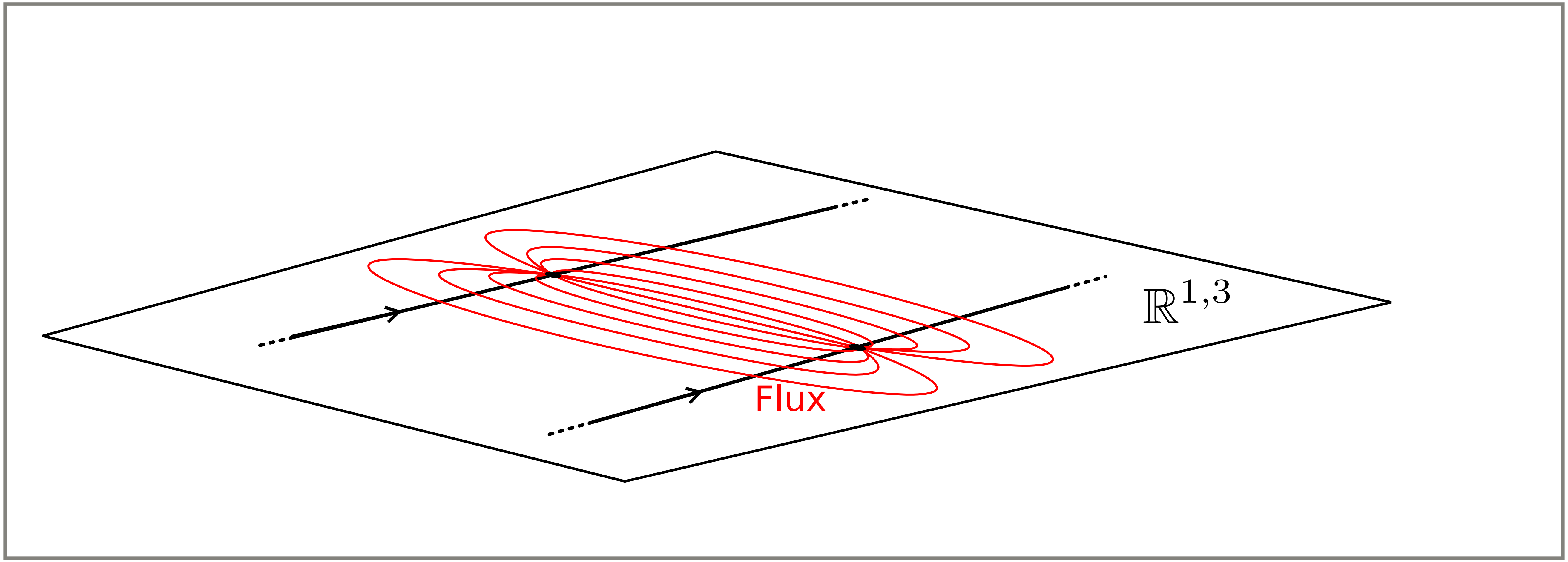

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$$\text{string tension} = \sqrt{\lambda}$$

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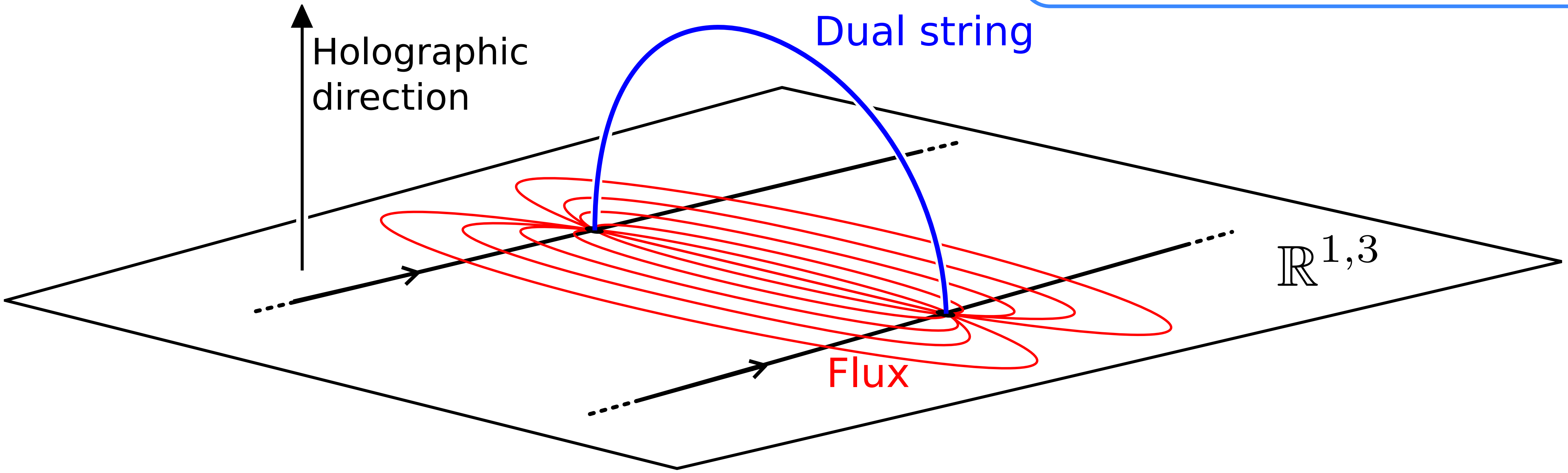

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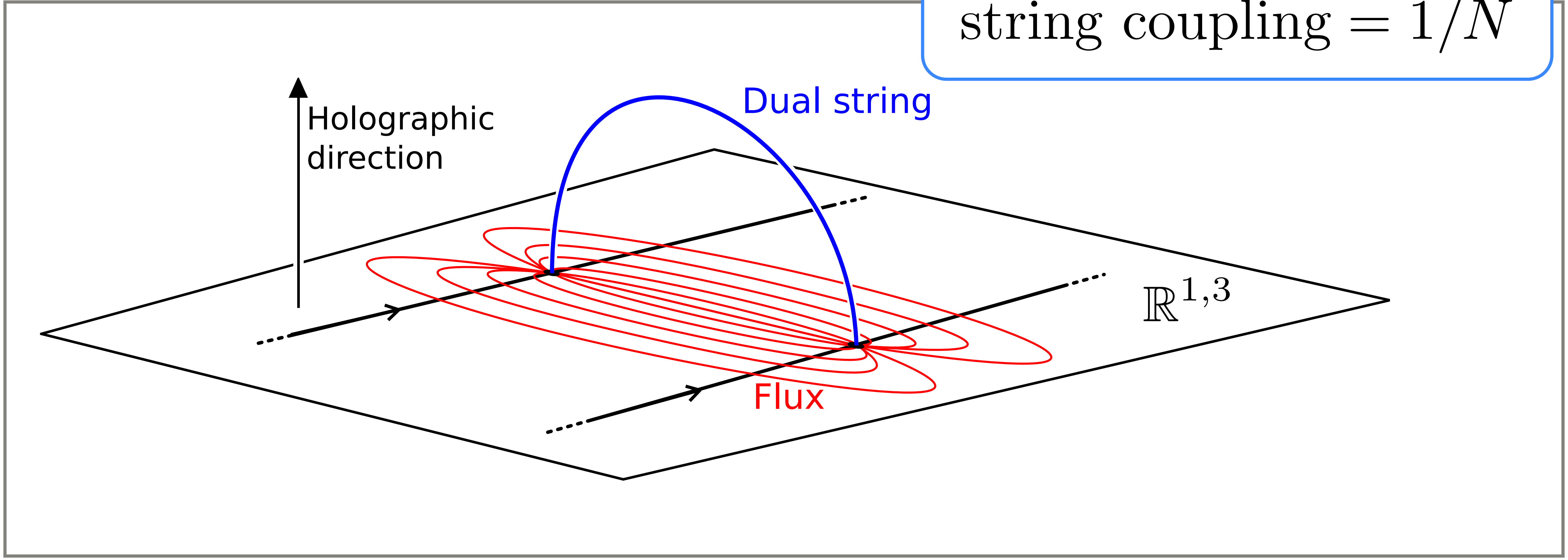
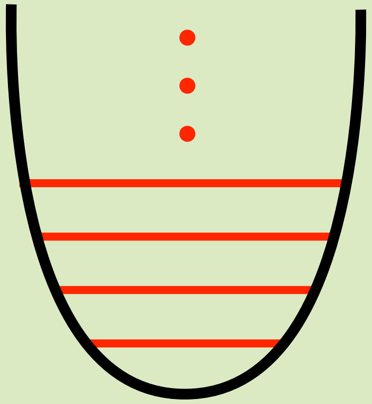


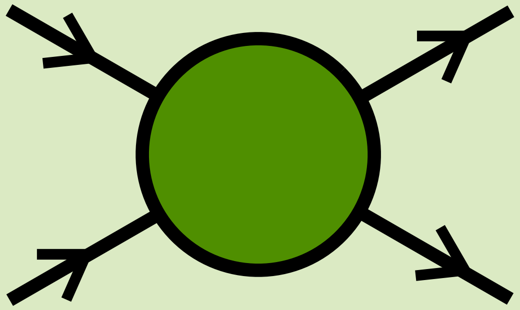
Use the artillery of exactly solvable models in 2d to 4d QFT

I. Solving N=4 SYM at large Nc

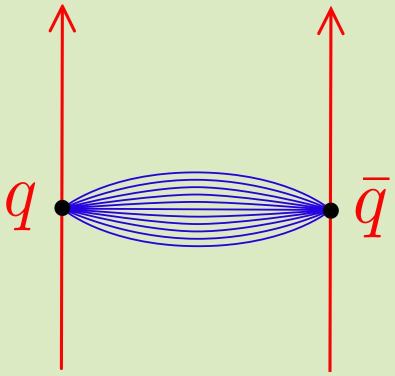
Current status



Spectrum



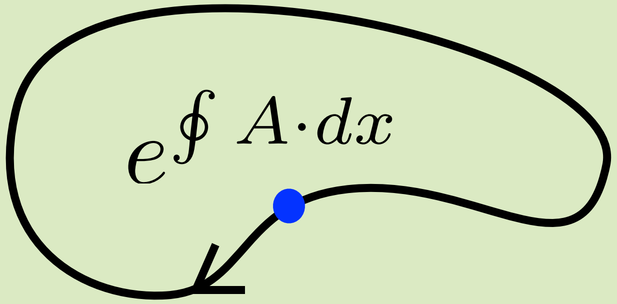
Scattering amplitudes



Quark anti-quark potential

$\langle \mathcal{O}(x)\mathcal{O}(y)\mathcal{O}(z)\rangle$

Correlation functions

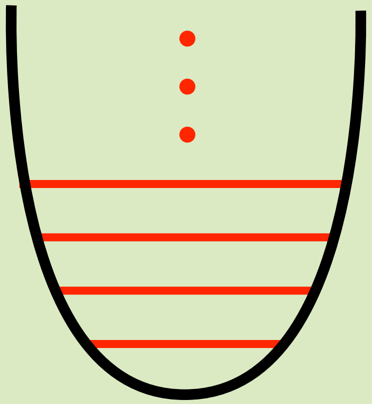


Wilson loops

I. map to 2d
II. cut into simpler blocks
III. Glue the pieces together

I. Solving N=4 SYM at large N_c

Current status



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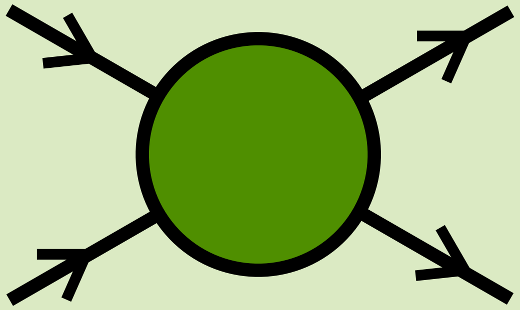

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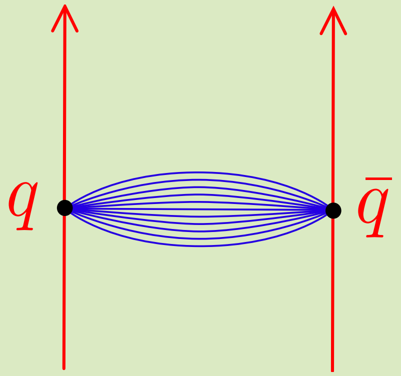

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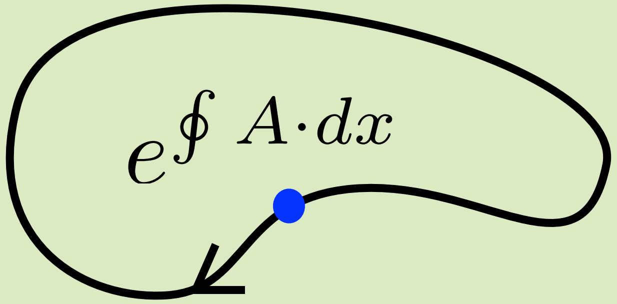

Wilson loops

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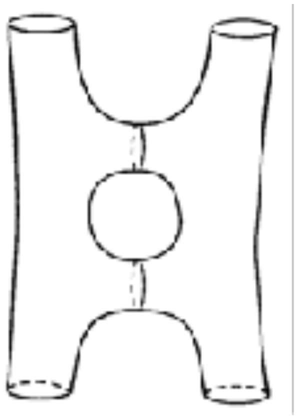
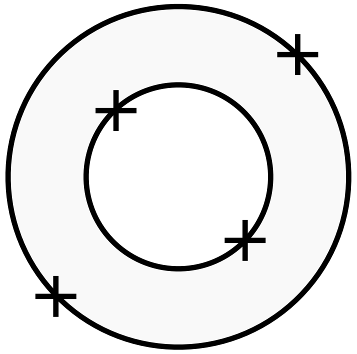
Starting moving towards non-planar corrections



handles



boundaries

II. S-matrix bootstrap

Main idea

Two new approaches

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Two new approaches

1. Assumption on low spectrum gap $\Rightarrow$ numerical bound on cubic couplings

II. S-matrix bootstrap

Main idea

Two new approaches

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   Idea - large coupling $\longrightarrow$ bound state $\longrightarrow$ contradiction with gap

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II. S-matrix bootstrap

Main idea

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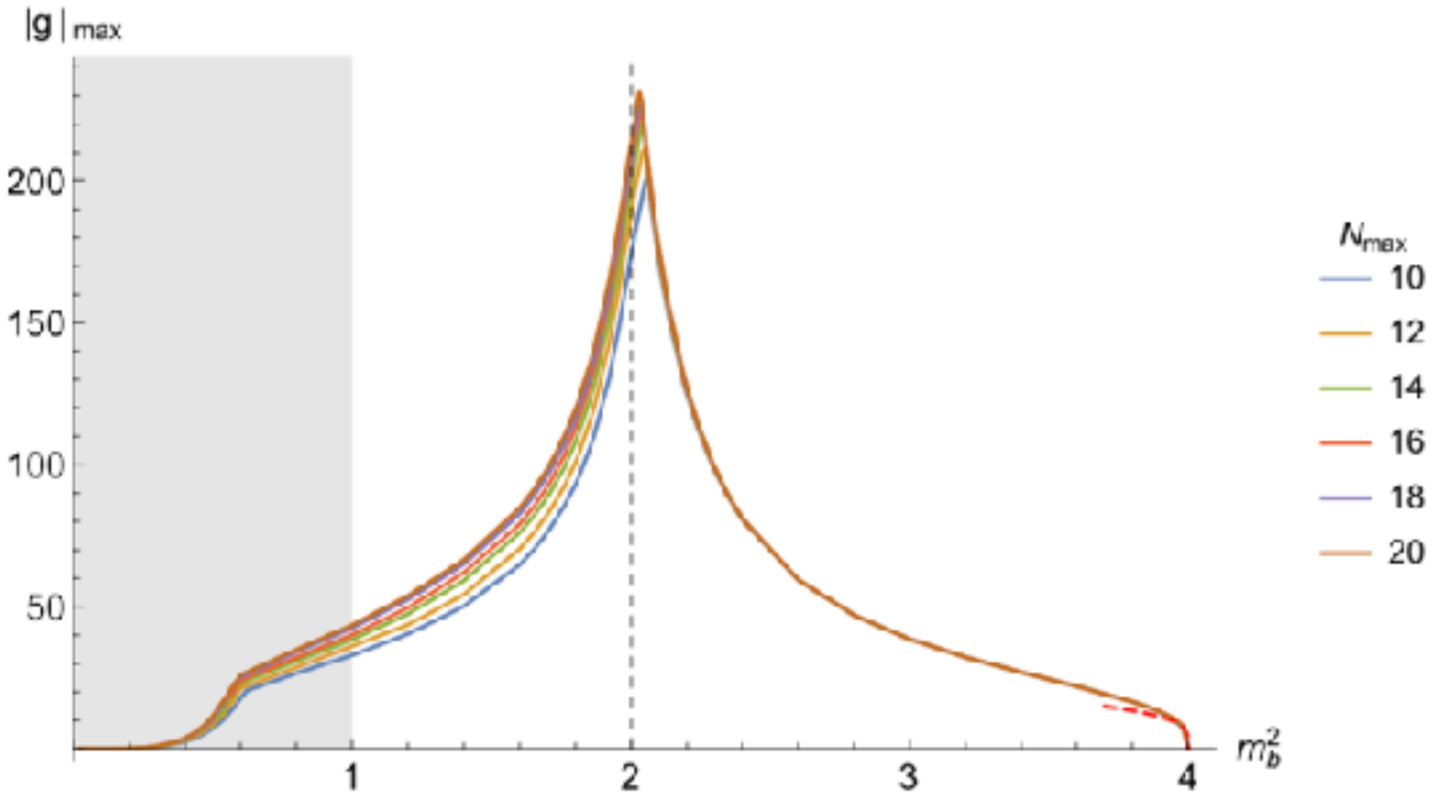

Current status

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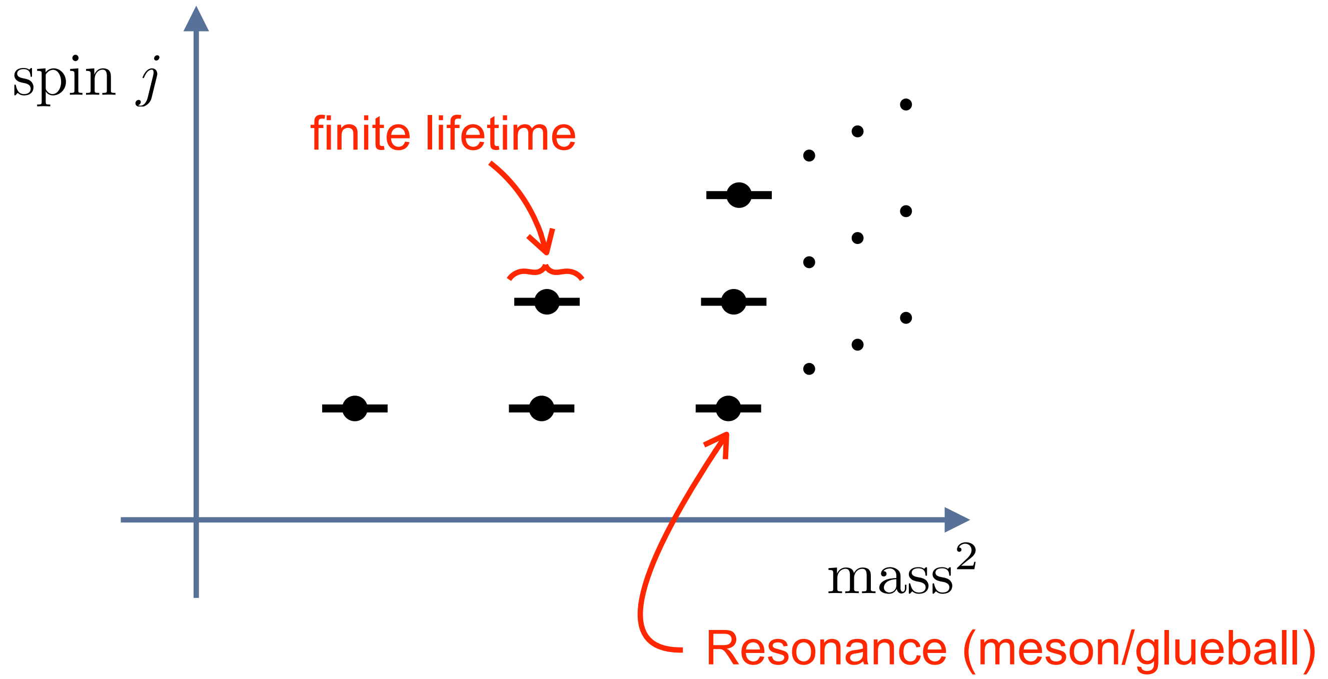
QCD



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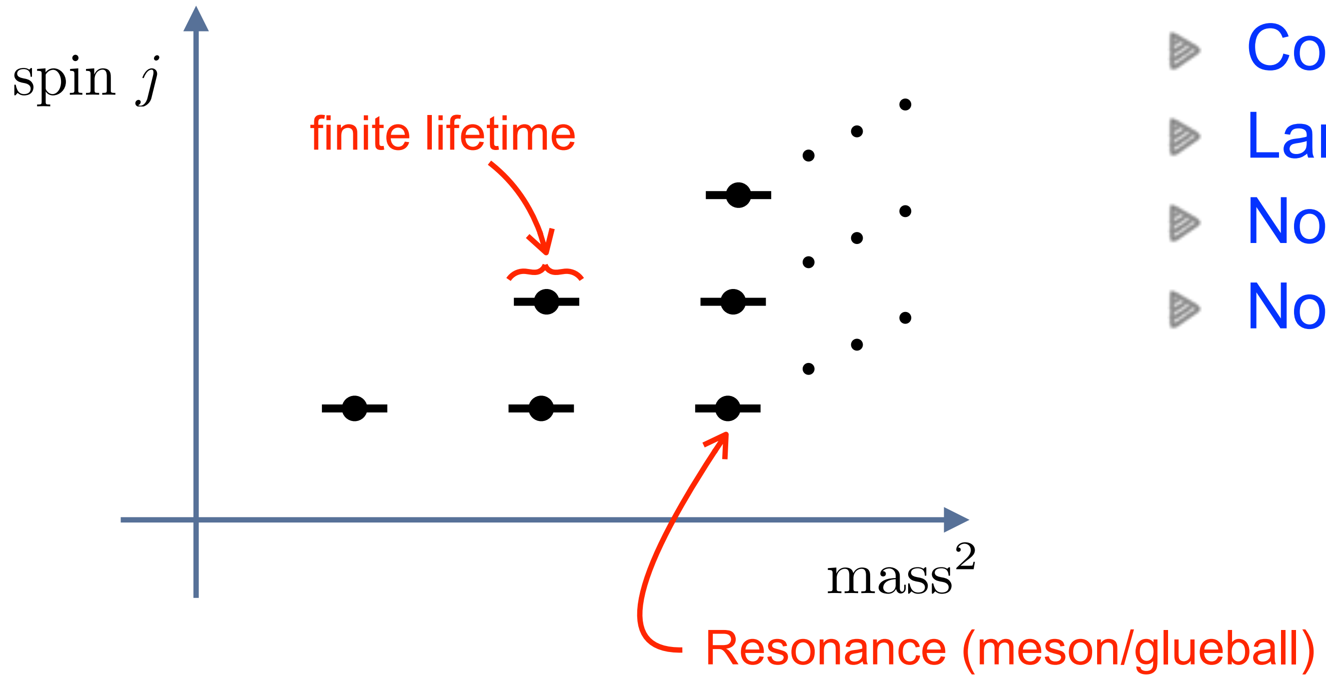

Large Nc

- Confinement $\Rightarrow$ ∞ many spins [Witten]
- Large N $\Rightarrow$ weakly interacting exactly stable
- No degeneracy (generic!)
- No single known exact example

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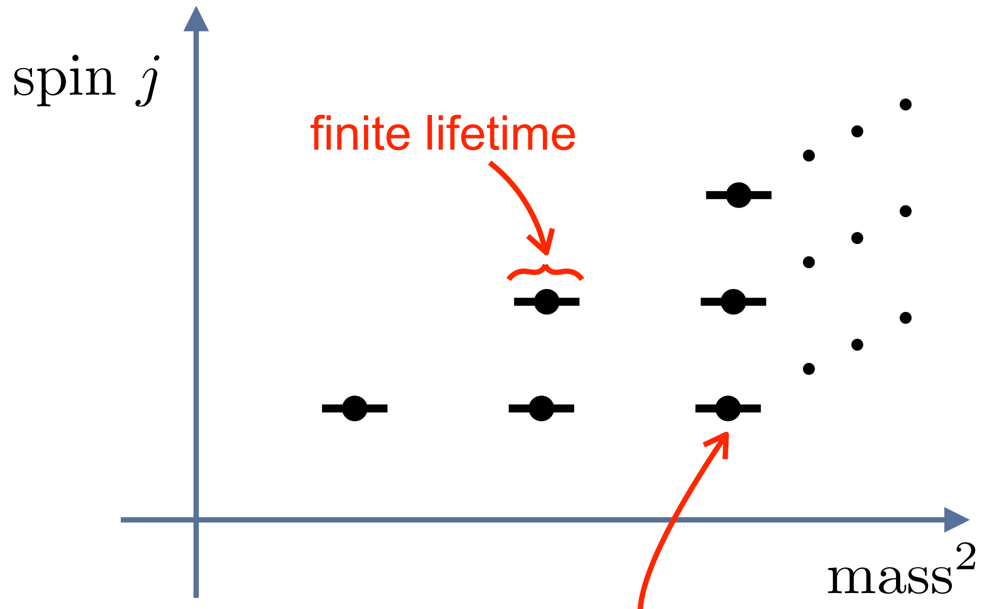

Resonance (meson/glueball)

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Generally, this structure follows from causality + spin >2

Aim - classify all theories of WIHS

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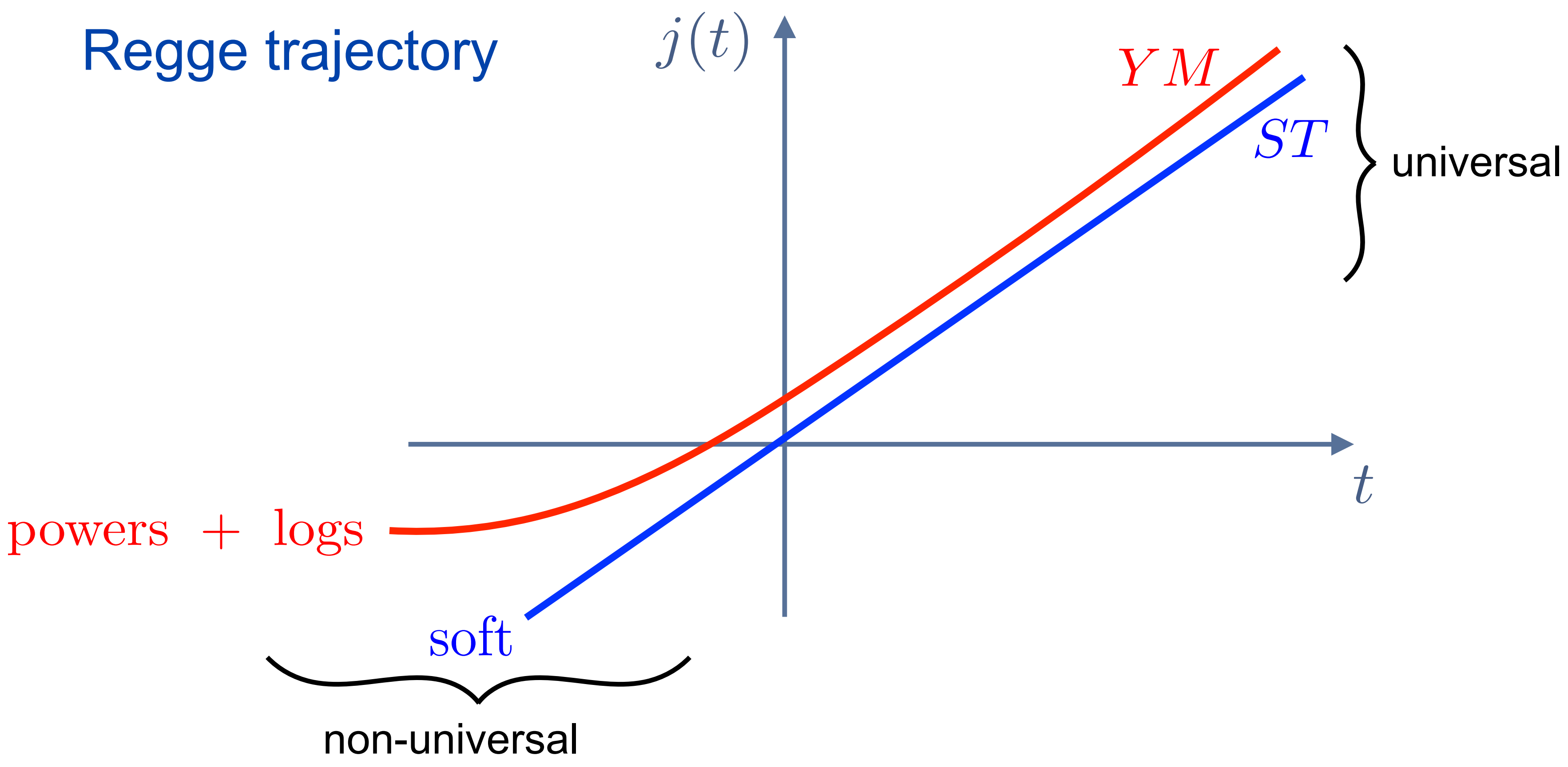

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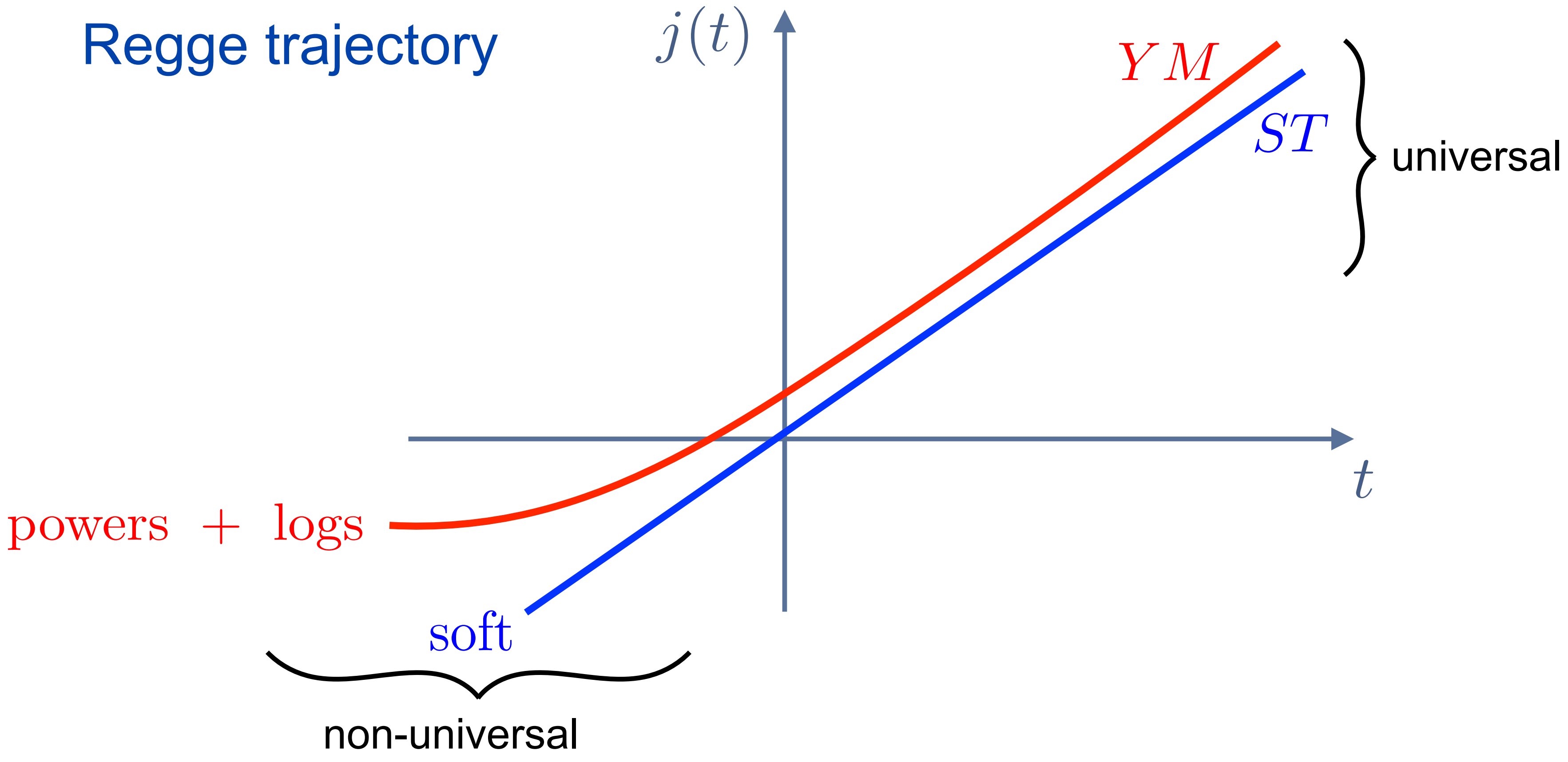
Regge trajectory



Derived - WIHS amplitudes have universal behaviour at the non physical regime $s, t \gg 0$

II. S-matrix bootstrap

Current status

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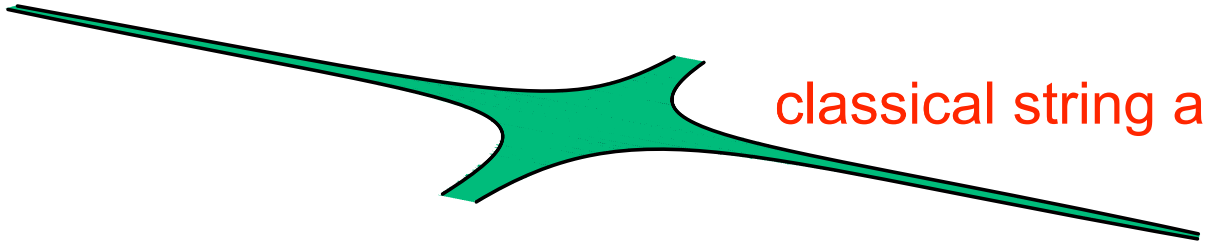
$$\lim_{\substack{s,t\to\infty \\ s/t\ \text{fixed}}} \log A(s,t) = \alpha' \left[(s+t)\log(s+t) - s\log(s) - t\log(t)\right] \qquad \sim E^2$$



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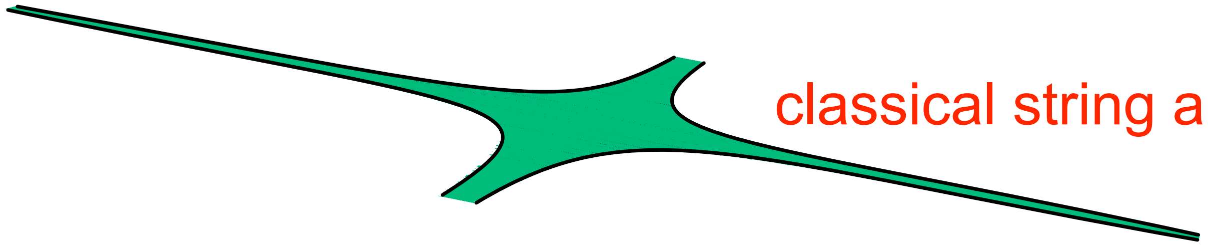
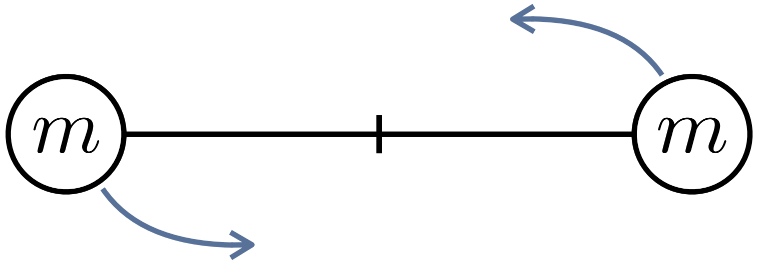


classical string amplitude

$$-\frac{16\sqrt{\pi}}{3}\alpha' m^{3/2}\left(\frac{s\,t}{s+t}\right)^{1/4}\left[\text{EllipticK}[\frac{s}{s+t}] + \text{EllipticK}[\frac{t}{s+t}]\right] \qquad \sim \sqrt{E}$$



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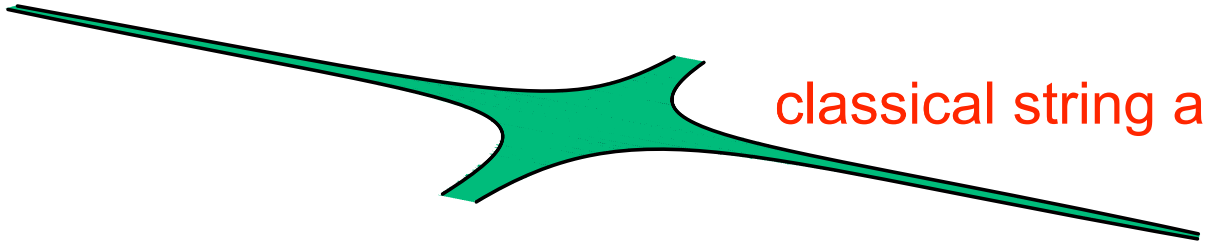

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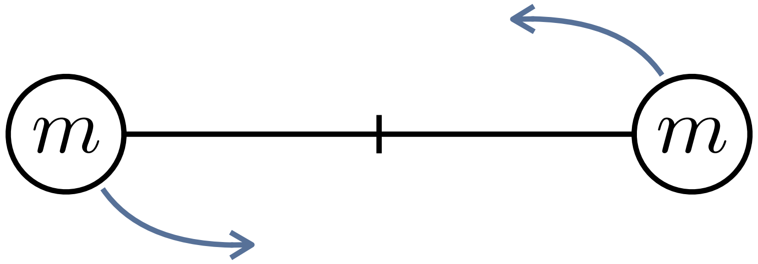


Massive endpoints correction

Effective theory of WIHS amplitudes

String Geometry

Timo Weigand

CERN and Heidelberg University

String Geometry

Extended objects probe spacetime differently from pointlike particles

$$\textbf{Physics in } d \leq 10 \quad \overset{\text{String}}{\underset{\text{Theory}}{\longleftrightarrow}} \quad \textbf{Geometry}$$

1) String Phenomenology := study of string compactifications to 4d

spacetime: $\mathbb{M}^{1,3} \times \underbrace{M_6}_{\text{compact, small}}$

- Views string theory as fundamental theory of quantum gravity (rather than 'only' a tool for mathematical physics)

- Is the Standard Model realized in the string landscape? Where?

- Explain phenomena which seem mysterious from 4d perspective?

Examples: Geometric rationale for hierarchical couplings $Y_{ijk} \simeq e^{-S_{\text{inst}}}$

Axions and ALPs are 'generic' in string theory

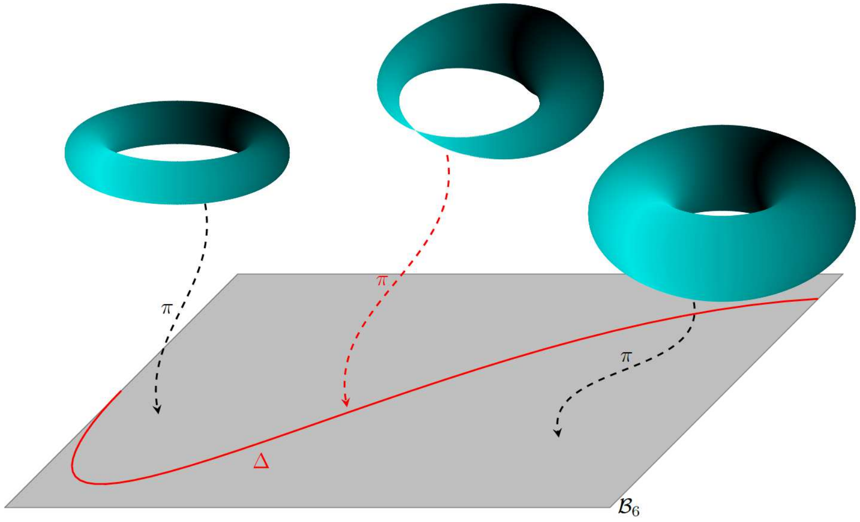
$\leftrightarrow$ topology of M_6: # axions = # holes of M_6

String Geometry

2) Geometric engineering of QFTs in various dimensions

- (Non-perturbative) Gauge dynamics from string geometry
- Insights into geometry from QFT via string theory

F-theory: most general framework to study non-perturbative
string compactifications in geometric regime



- Spacetime: $\mathbb{M}^{1,d-1} \times B_{10-d}$
- string coupling τ
  $=$ shape of auxiliary torus
- τ varies on B_6
- **torus fibration:**
  string coupling over compact space

Geometry of torus fibration $\xleftrightarrow[\text{Theory}]{\text{F}-}$ **Effective Physics**

String Geometry

Programme: Map out F-theory compactifications to $\mathbb{M}^{1,d-1}$

- Understand resulting coupling of QFTs to Quantum Gravity
- In 4d: Analyse in addition consequences for String Pheno

New types of F-theory geometries (beyond Weierstrass):

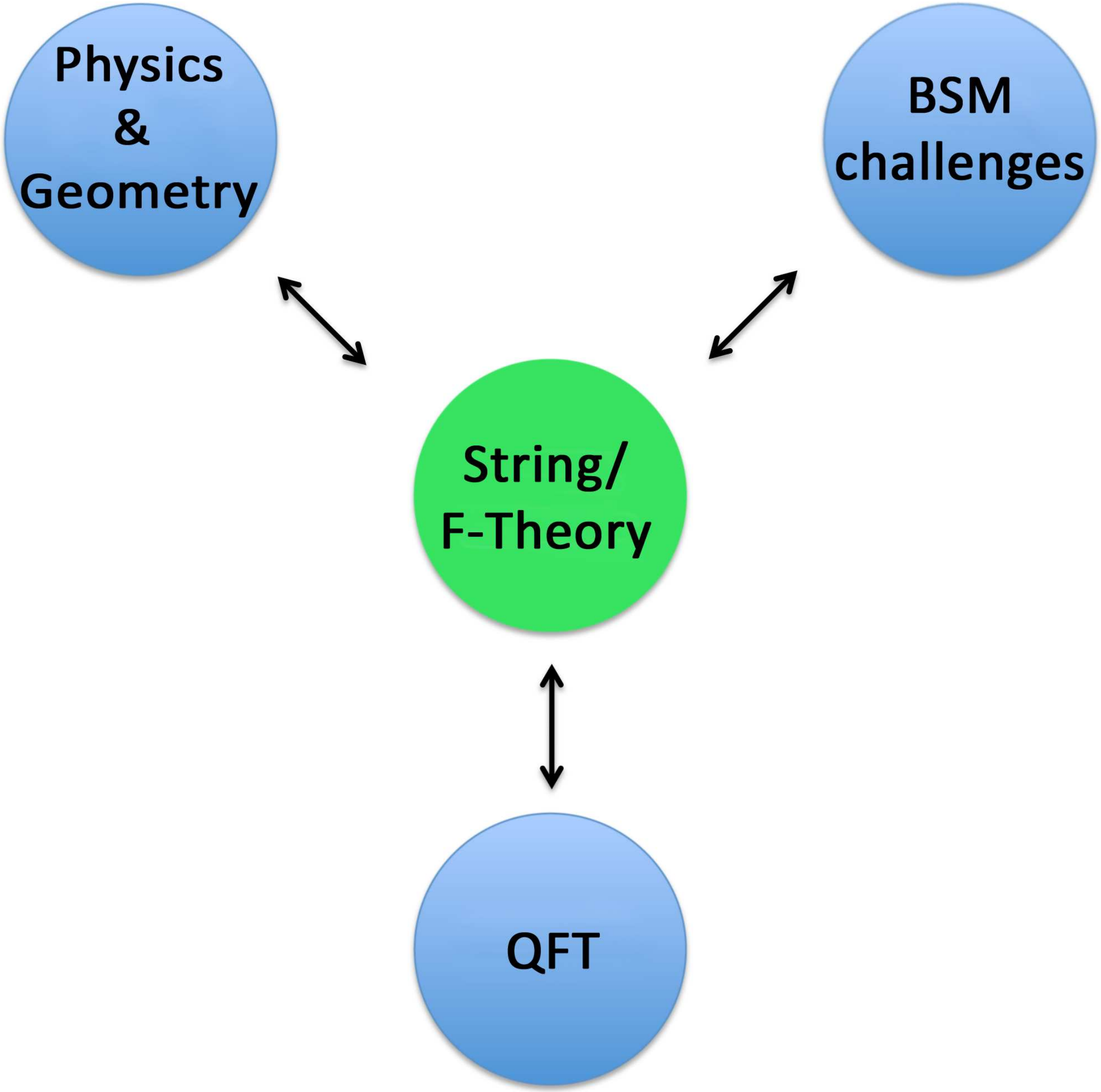
extra sections	extra U(1) gauge symmetry
no section	$\mathbb{Z}_n$ gauge symmetry
non-resolvable	extra matter
XXX	*in progress with* *S.-J. Lee and D. Regalado*

Opened up 'new' dimensions:

2d (0,2) compactifications on Calabi-Yau 5-folds

New constraints on geometry from physics

Anomalies imply relations in Chow ring



Physics
&
Geometry

BSM
challenges

String/
F-Theory

QFT

CERN Theory Group Retreat 2017
Career and Research Presentation

David ANDRIOT

CERN, Geneva, Switzerland

17/11/2017
Centre de Physique, Les Houches, France

Career

- 2003 - 2006: Licence (L3), Master (M1,M2) in **ENS Lyon**
- 2006 - 2010: Ph.D. in LPTHE, **UPMC Paris 6**
  Supervisor: Michela Petrini
- 2010 - 2013: Post-doc in **Ludwig-Maximilians-Univ.**
  then in **Max-Planck-Institut**
  (Munich, Germany)
- 2013 - 2017: Post-doc in **Max-Planck-Institut** (**AEI**)
  (Potsdam-Golm, Germany)
- 2017 - 2019: Post-doc at **CERN**
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Connecting string theory and phenomenology ?
(cosmology, particle physics, ...)

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Low energy effective theory: 10-dimensional (10d) type II supergravities with branes
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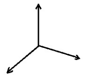
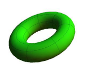
⇒ 6 extra space dimensions → **compactification**:

4d space-time (de Sitter, Minkowski)×6d compact manifold $\mathcal{M}$





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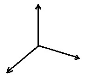

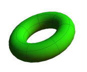

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For cosmology and inflation:

1. Find a “de Sitter” solution in 10d
2. 10d → 4d: get $V(\varphi)$ ✓ for inflation.

To cosmology: classical de Sitter solutions

4d de Sitter space-time ($\Lambda_4 > 0$) × 6d compact manifold $\mathcal{M}$

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3 de Sitter points in universe evolution:

- present/future universe
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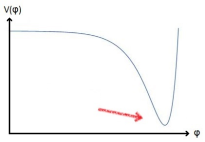
- $\sim$ inflation phase



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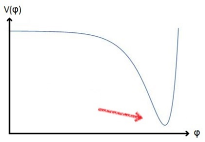

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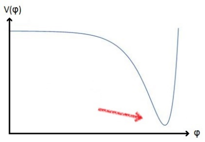

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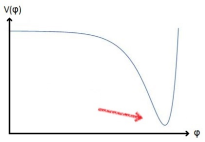

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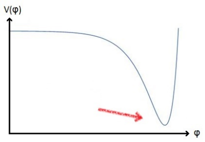

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Project: study of existence and stability of de Sitter solutions

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Connect GW (from astrophysical sources) and string theory?

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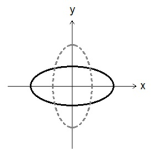

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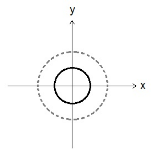

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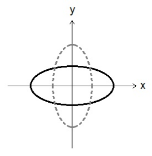

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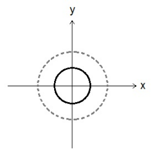

Tests of scalar-tensor theories

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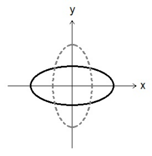

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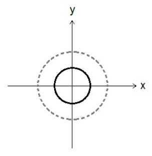


Tests of scalar-tensor theories
Project: connection to string theory

Thank you for your attention!

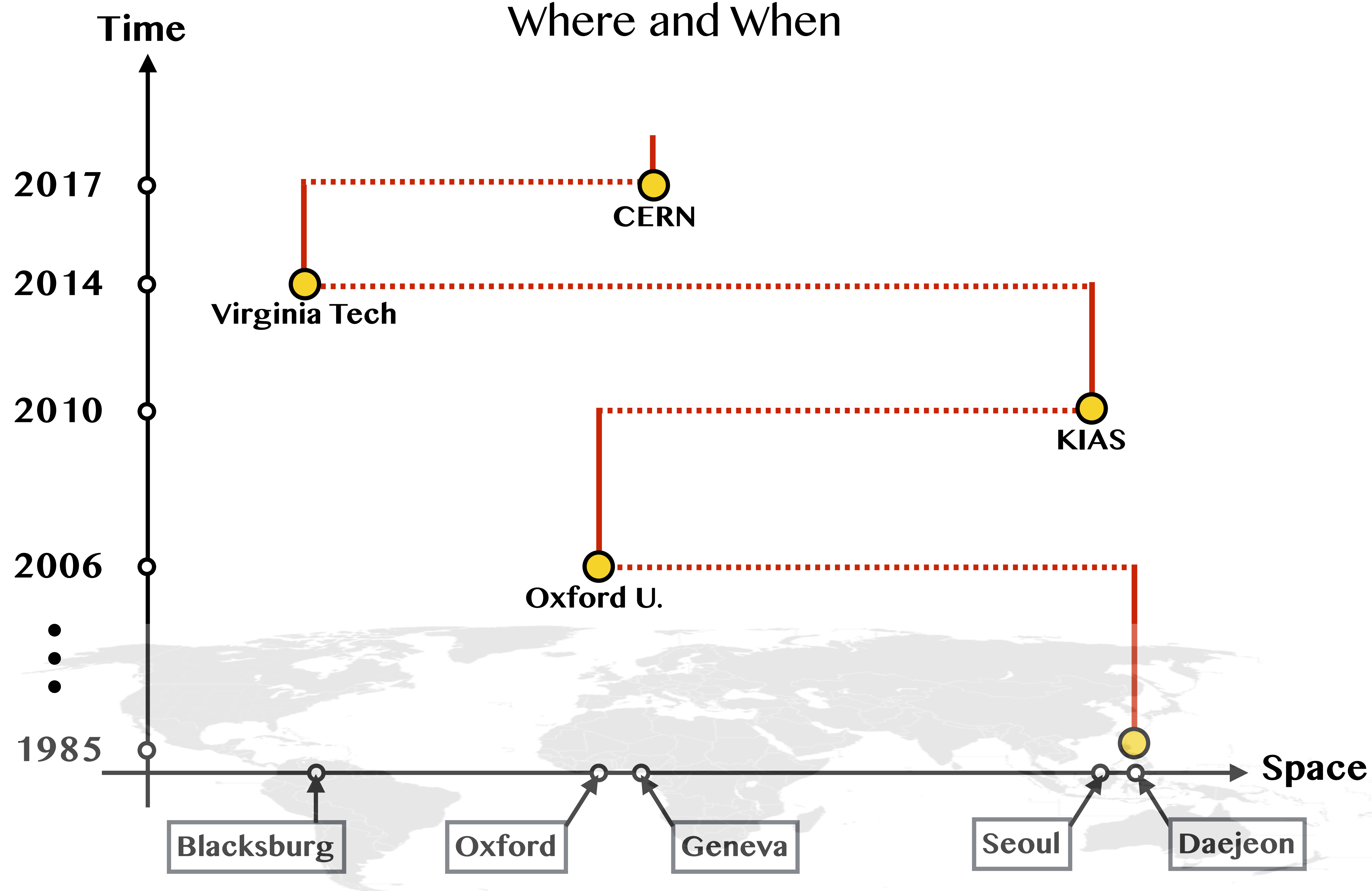
Strings and Geometry

Seung-Joo Lee

Theory Group Retreat
Les Houches Centre de Physique
17/11/2017

My World Line

Where and When



Strings and Geometry

String EFTs

- Some Facts about String Theory
  - Particles are realized as a quantum oscillation of string
  - Different oscillation modes lead to different particle species
  - Graviton is always one of them
  - Spacetime dimension is fixed

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  - String compactification: $X_{10} = \mathbb{R}^D \times M_{10-D}$

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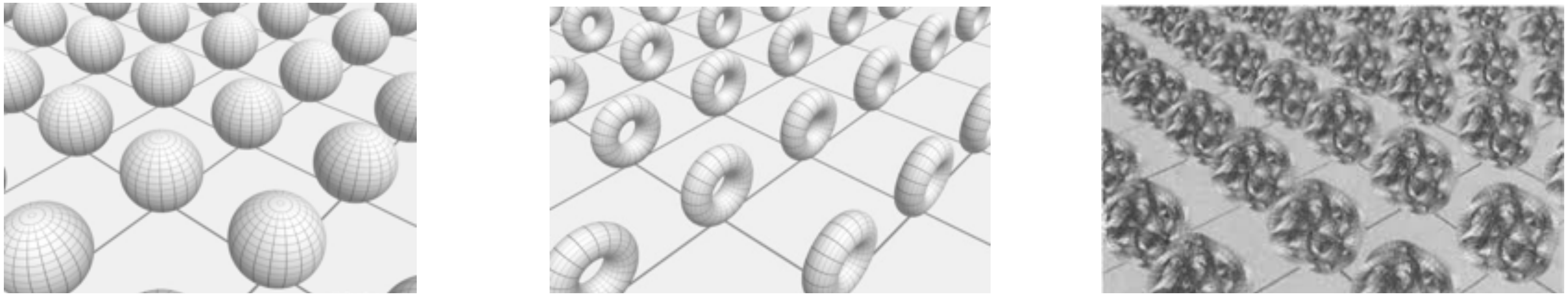
  - **The effective physics is determined by the geometry of the internal space**



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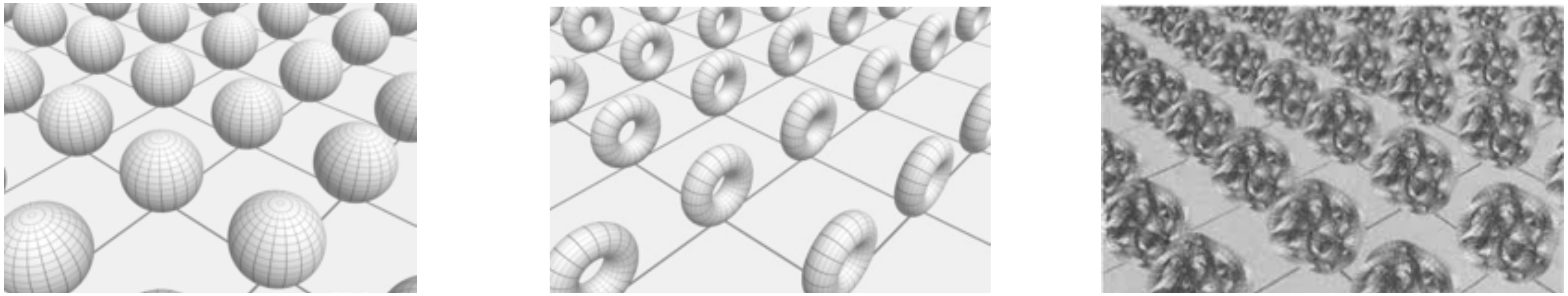

Topics of My Interest

Strings and Geometry

- **String Phenomenology**
- **String Compactifications**
- **Bound State Counting**

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Strings and Geometry

o String Phenomenology

Connect string theory to the **real world** in 4 dimensions via appropriate string geometries

o String Compactifications

Produce and investigate **supersymmetric theories** in various dimensions via string compactifications

o Bound State Counting

Study the formation and the spectrum of supersymmetric(BPS) **bound states** of particles in the context of string theory

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String Phenomenology

Realistic Particle Physics from **Heterotic** String Theory

- Constraining the Geometry (M_6 , ⋯)
  - Supersymmetry at compactification scale?

    M_6 is a **Calabi-Yau space** — *over a billion*

  - Right gauge group?

    (Slope-stable) gauge **bundle**

  - Right particle spectrum?

    Constrains the geometry of the **internal spaces & bundles** thereon

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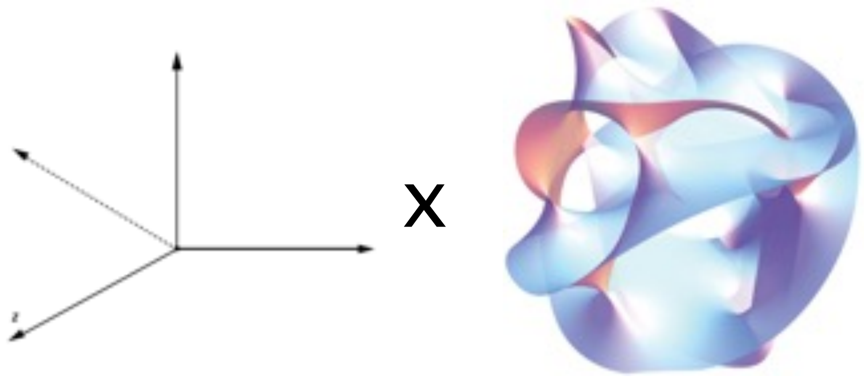

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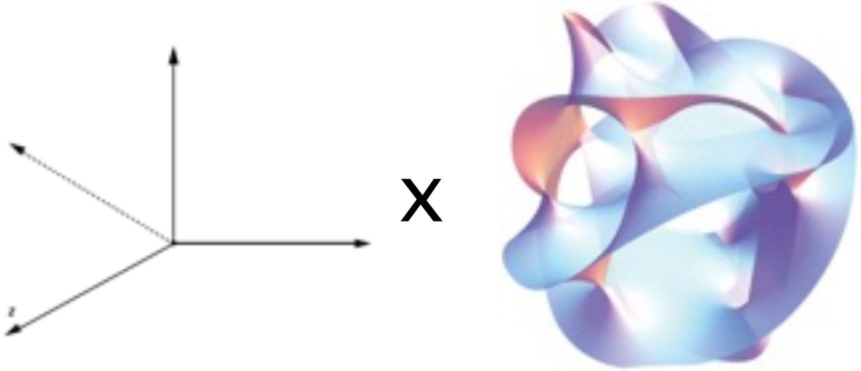

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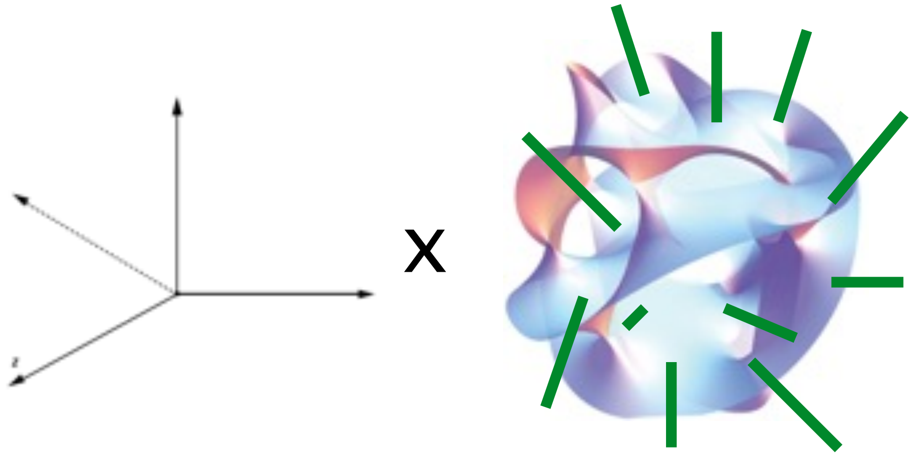

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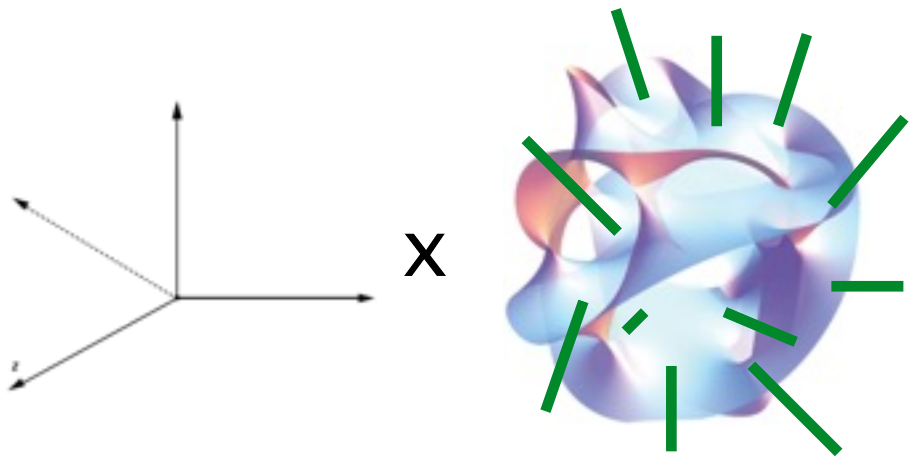

String Phenomenology

Where We Are

String Phenomenology

Where We Are

in the heterotic smooth Calabi-Yau model building

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Time

1985 The question first posed [Candelas-Horowitz-Strominger-Witten]

String Phenomenology

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(a) SM gauge interaction, (b) exact matter spectrum of minimal supersymmetric SM, (c) one or more Higgs doublets,
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String Phenomenology

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Time

Impose other phenomenological constraints?

Get rid of massless uncharged scalar fields?

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Constraints on String Geometries

- What are possible for Calabi-Yau Spaces?

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Internal dimensions d=2, 4, 6, … , lead to EFTs in D=8, 6, 4, … dimensions

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Thank you!

Diego Regalado

Theory retreat, November 2017

Bilbao, Spain

UPV EHU

Madrid, Spain

ift

Munich, Germany

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

String Phenomenology

- ST produces a huge number of effective field theories.
- Is there a theory which reduces to the SM at low energies?
- General relativity + non-Abelian gauge group + chiral matter (+ problems).
- Not all the problems can be addressed at the same time.
- Steady progress and many spin-offs.
- I’m still working on this.

String theory and QFT

- Instead of aming for the SM at low energies, one can look for other kinds of QFTs (without gravity).
- This gives a new perspective on (supersymmetric) QFT which has been very fruitful.
  - The (2,0) theory in six dimensions
  - Class S theories
  - Dualities
  - …

$\mathcal{N}=4$ theories in four dimensions

- Given a Lie algebra: Lagrangian
- The theory depends on a Lie group, not a Lie algebra (instantons).
- Different Lie groups can have the same algebra: $SU(2)$ and $SO(3)$.
- $SO(3)$ has 'more instantons' than $SU(2)$ so there are 'more theta angles'.

$$Z = \sum_{n \in \mathbb{Z}} e^{i\theta n} Z_n \qquad \text{(instanton number)}$$

- This produces slightly different $\mathcal{N}=4$ theories with the same gauge algebra: $SU(2)$, $SO(3)^+$, $SO(3)^-$

$\mathcal{N} = 4$ theories from String Theory

(in progress with I. García-Etxebarria, B. Heidenreich)

- Can all these different variants be obtained from String Theory?
  Yes
- How are these extra ‘theta angles’ encoded in the construction?
  Depends on the particular construction.
  The resulting structure is always the same.
- Is there room for new $\mathcal{N} = 4$ theories beyond those?
  The answer seems to be ‘yes’, but this is still work in progress.
- Generalization to other (less supersymmetric) theories.

All-loop non-Abelian Thirring model

K. SIAMPOS

CERN Theory Group Retreat,
Les Houches Centre de Physique,
17 November 2017

INTRODUCTION AND MOTIVATION

Exact β-functions and anomalous dimensions

1. In a renormalizable field theory, its quantum behaviour is depicted by:
   - The *n*-point correlation functions.
   - The dependence of the coupling with the energy scale.
2. Their dependence is encoded within the RG flow equations:

$$\beta_\lambda = \frac{d\lambda}{d\ln\mu^2}$$

   usually perturbatively determined.

3. Can we obtain the all-loop β-function? New fixed points towards the IR?
4. Can we also calculate the all-loop correlators of various operators?

We study these aspects for the non-Abelian bosonized Thirring model.

FOCAL POINTS

- Non-Abelian bosonized Thirring model
- The resumed effective action
- Current correlators
- Conclusion and Outlook

NON-ABELIAN THIRRING MODEL

The non-Abelian Thirring model is defined by:

$$S = S_{\mathrm{WZW},k} + k\,\frac{\lambda}{2\pi}\int \mathrm{d}^2\sigma\, J_+^a\, J_-^a\,,$$

$$J_\pm^a(x_1)J_\pm^b(x_2) = \frac{\delta_{ab}}{x_{12}^2} + \frac{f_{abc}\,J_\pm^c(x_2)}{\sqrt{k}\,x_{12}} + \text{regular}\,, \qquad J_\pm^a(x_1)J_\mp^b(x_2) = \text{regular}$$

1. The model is not conformal; the perturbation is not exactly marginal

   Kutasov (1989) $\qquad \beta_\lambda = -\dfrac{c_G\,\lambda^2}{2k\,(1+\lambda)^2} \leqslant 0$

2. The corresponding effective action is invariant under the inversion of the coupling

   Kutasov (1989) $\qquad \lambda \mapsto \lambda^{-1}\,, \qquad k \mapsto -k\,, \qquad k \gg 1$

THE RESUMMED ACTION

The proposed effective action

$$S_{k,\lambda}(g) = S_{\mathrm{WZW},k} + \frac{k}{2\pi}\int \mathrm{d}^2\sigma\,\left(\lambda^{-1} - D^T\right)^{-1}_{ab} J^a_+ J^b_- \,, \quad 0 \leqslant \lambda < 1$$

describing integrable interpolations from a WZW to (non-abelian T-duals) PCM models.
Sfetsos (2013), Itsios–Sfetsos–KS–Torrieli (2014)

Properties

- For $\lambda \ll 1$ we get the non-Abelian Thirring model.
- Weak-strong duality:
$$S_{-k,\lambda^{-1}}(g^{-1}) = S_{k,\lambda}(g)$$
- There are two interesting limits around $\lambda = \pm 1$.

RESULTS

Perturbative results, well defined behaviour at $\lambda = \pm 1$ and weak-strong duality:

1. β-function and anomalous dimension of the current operator

$$\beta_\lambda = -\frac{c_G\,\lambda^2}{2k\,(1+\lambda)^2} \leqslant 0\,, \qquad \gamma^{(J)} = \frac{c_G\,\lambda^2}{k\,(1-\lambda)(1+\lambda)^3} \geqslant 0$$

These results are in agreement with those derived directly from the effective action.
Itsios, Sfetsos, KS (2014), Appadu, Hollowood (2015), Georgiou, Sfetsos, KS (2015)

2. All-loop two and three-point functions

$$\langle J^a(x_1) J^b(x_2)\rangle_{k,\lambda} = \frac{\delta_{ab}}{x_{12}^{2+\gamma^{(J)}}\,\bar{x}_{12}^{\gamma^{(J)}}}\,, \quad \langle J^a(x_1) \bar{J}^b(\bar{x}_2)\rangle_{k,\lambda} = -\gamma^{(J)}\,\frac{\delta_{ab}}{|x_{12}|^2}\,.$$

$$\langle J^a(x_1) J^b(x_2) J^c(x_3)\rangle_{k,\lambda} = \frac{1+\lambda+\lambda^2}{\sqrt{k(1-\lambda)(1+\lambda)^3}}\,\frac{f_{abc}}{x_{12}x_{13}x_{23}}\,,$$

$$\langle J^a(x_1) J^b(x_2) \bar{J}^c(\bar{x}_3)\rangle_{k,\lambda} = \frac{\lambda}{\sqrt{k(1-\lambda)(1+\lambda)^3}}\,\frac{f_{abc}\bar{x}_{12}}{x_{12}^2\bar{x}_{13}\bar{x}_{23}}$$

Georgiou, Sfetsos, KS (2016)

CONCLUSION & OUTLOOK

Our proposed resummed action

$$S_{k,\lambda}(g) = S_{\mathrm{WZW},k} + \frac{k}{2\pi}\int \mathrm{d}^2\sigma\ \left(\lambda^{-1} - D^T\right)^{-1}_{ab} J_+^a\, J_-^b\,, \quad 0 \leqslant \lambda < 1$$

encaptures the all-loop isotropic Thirring model at leading order in the $1/k$*-expansion*

$$S = S_{\mathrm{WZW},k} + k\,\frac{\lambda}{2\pi}\int \mathrm{d}^2\sigma\, J_+^a\, J_-^a$$

The agreement is based upon:

1. Symmetries of the actions
2. Invariance under the weak–strong duality, i.e. $\lambda \mapsto \lambda^{-1}\,, \quad k \mapsto -k$
3. β-function and the anomalous dimension $\gamma^{(J)}$

APPENDIX: FERMIONIC MODEL

Exactly solvable QFT describing self-interacting massless Dirac fields in 1+1 dimensions.

- An 1+1 dimensional action with fermions in the fundamental representation of $SU(N)$

$$\text{Dashen–Frishman (1973)\&(1975)}: \quad \mathcal{L}_{int} = -\frac{g_B}{2} J_\mu J^\mu - \frac{g_V}{2} J^a_\mu J^{a\mu}\,, \quad \mu = 0,1\,,$$

  where $J^a_\mu = \bar{\Psi} t^a \gamma_\mu \Psi$, with $a = 1, \ldots, N^2 - 1$, are the $SU(N)$ currents and J_μ the $U(1)$.

- For $N = 1$ we recover the Abelian case (prototype) Thirring (1958)

- It is invariant under $SU(N) \times U(1)$ (vector) and $U(1)_{Axial}$

- The non-Abelian term breaks $SU(N)_{Axial}$, i.e. $\partial^\mu J^{5a}_\mu = g_V f_{abc} J^{b\mu} J^{5c}_\mu$

- The theory is scale-invariant only for $g_V = 0$ and $g_V = \frac{4\pi}{n+1}$

- There is a current algebra at level one $J^a_\pm(x_1) J^b_\pm(x_2) = \frac{\delta_{ab}}{x_{12}^2} + \frac{f_{abc} J^c_\pm(x_2)}{x_{12}}$

‘the supergravity / (twistor) string / scattering amplitudes guy’

Piotr Tourkine

- map

- hot topic : “scattering equation” business

- personal interest: reformulation of loop expansion

- and also : new bizarre “string” theories

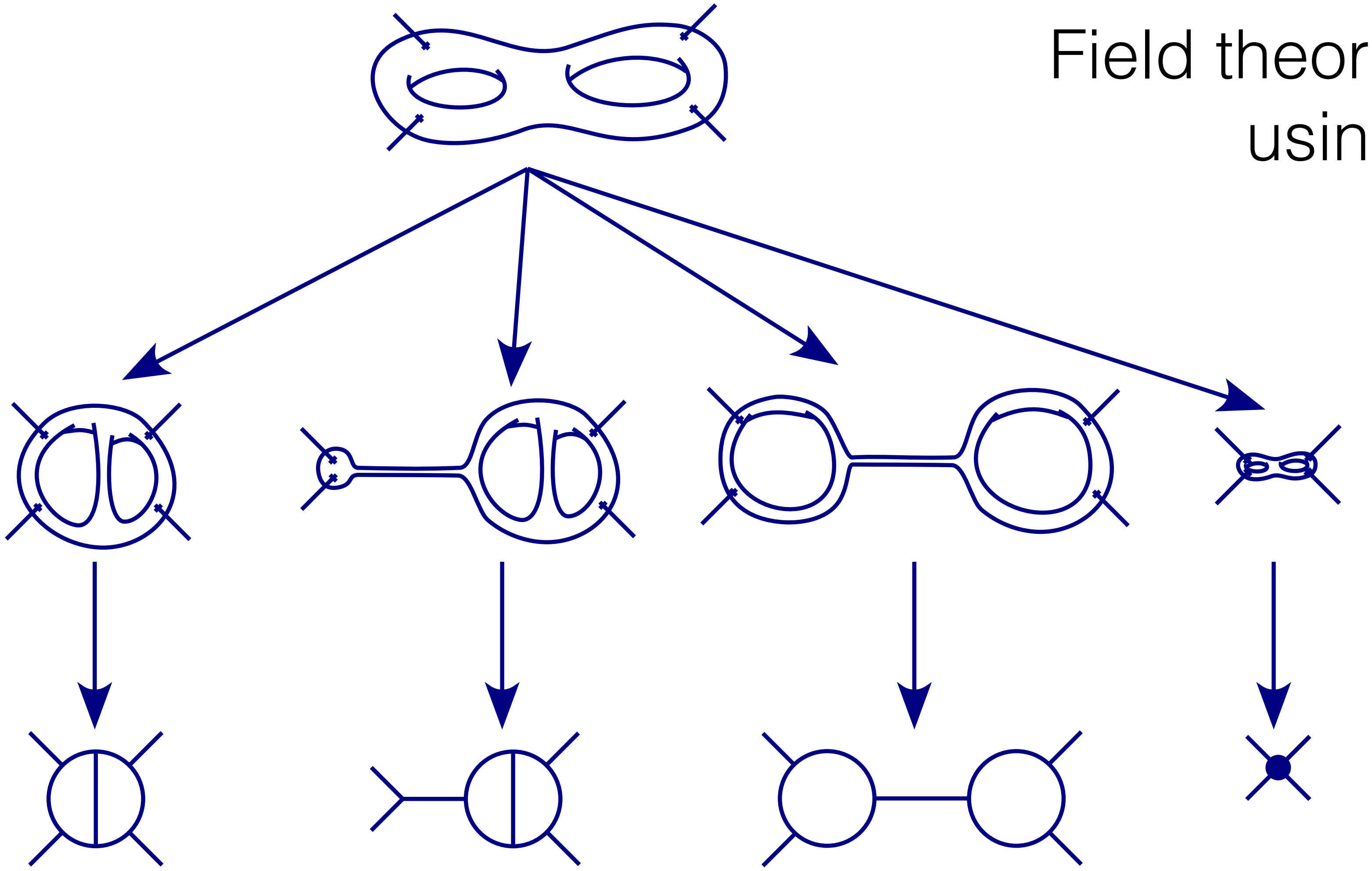
PhD (2010-2014): CEA Saclay,
with Pierre Vanhove, on
UV behaviour of supergravity theories
using string theory, scattering amplitudes

Postdoc (2014-2017) : Cambridge, DAMTP
Ambitwistor strings, scattering amplitudes

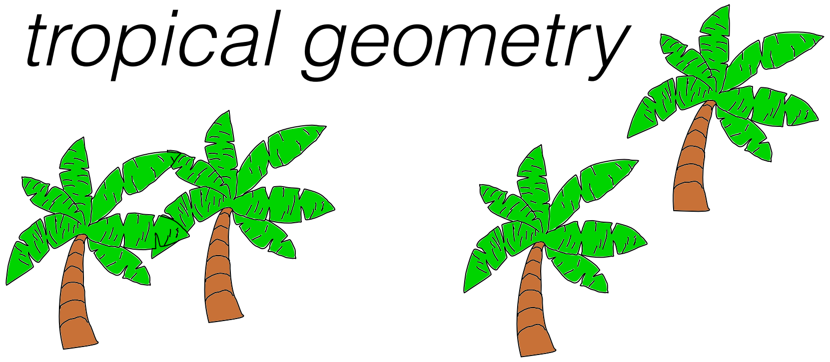
Collaborators in DAMTP and Oxford

2017 : CERN

phd : UV of supergravity and relation between string and field theory



Field theory limit of string amplitudes using *tropical geometry*



actually useful for me in a totally different context now

hot topic : “scattering equations”

New formulation for amplitudes

$$\text{tree-level amplitudes} = \int \prod_{i=1}^{n} dz_i \, \bar{\delta}(\text{sc. eqns.}) \, F(k_i, \epsilon_j, z_i)$$

2014

mostly massless,
any dimension
gravity, gauge theories, scalar theories,
some effective field theories, etc

New formulation for amplitudes

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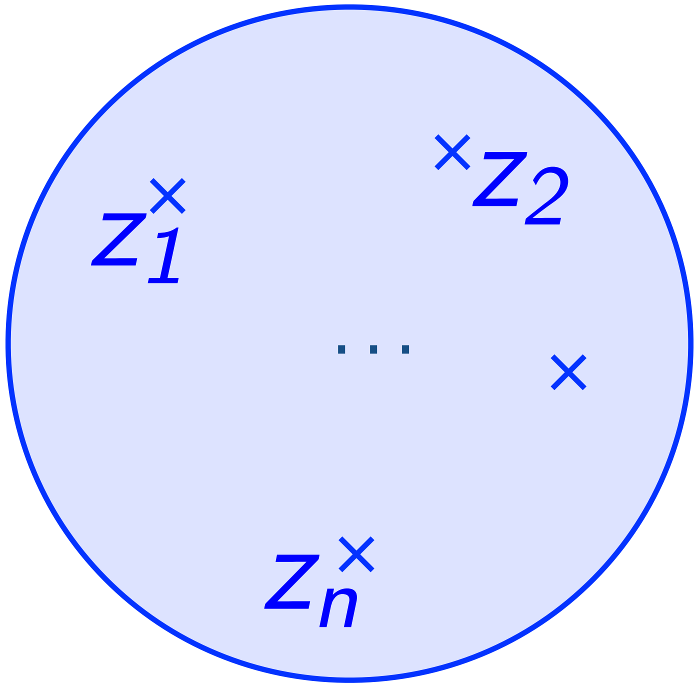

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scattering data:
kinematics, polarisations,
colour structure, …

New formulation for amplitudes

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$$\sum_{i \neq j}^{n} \frac{k_i \cdot k_j}{z_i - z_j} = 0$$

n-3 equations, degree ***(n-3)!***

Scattering equations

New formulation for amplitudes

$$\text{tree-level amplitudes} = \int \prod_{i=1}^{n} dz_i \, \bar{\delta}(\text{sc. eqns.}) \, F(k_i, \epsilon_j, z_i)$$

$$\sum_{\text{solutions}} \left(\frac{F}{\text{Jac}} \right) = \quad \text{n-point field theory amplitude}$$

$$\sum_{i \neq j}^{n} \frac{k_i \cdot k_j}{z_i - z_j} = 0$$

n-3 equations, degree *(n-3)!*

Ambitwistor strings

- New strings models (Mason & Skinner 2014)
- Describe field theory only (supergravity in d=10)
- Inspired by Penrose's theories on *twistors*
- **Amplitudes produce CHY formulae.**
- curved space formulations

Remarks / conundrums

- Truly remarkable reformulation
- What does it mean for field theory ?
- How far can it be used ?
- Conundrums :

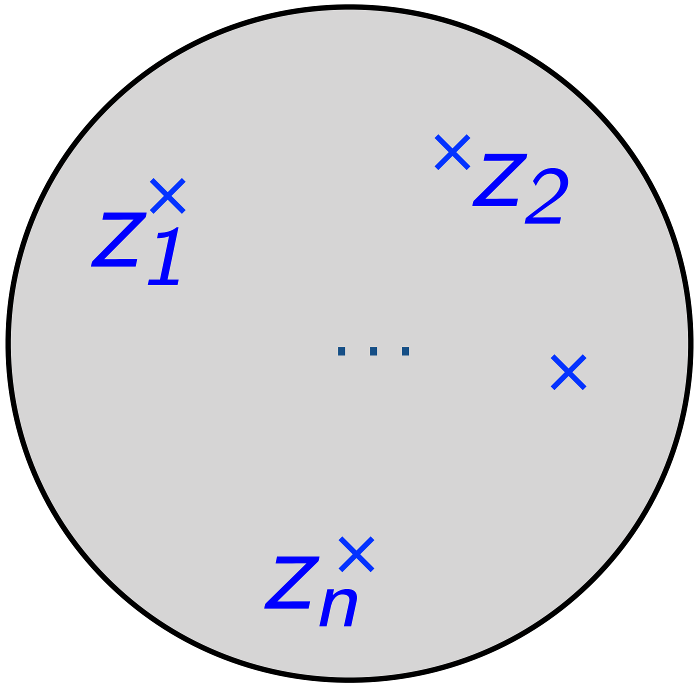
  Ambitwistor strings are “good strings”, they have *modular invariance*. In normal string theory : grants UV finiteness. How could that work for supergravities which are not UV finite ?

  Scattering equations actually describe high energy usual strings

contributions

program : get scattering equations formalism to all loop orders

Geyer, Mason, Monteiro, Tourkine; 2016, 2017



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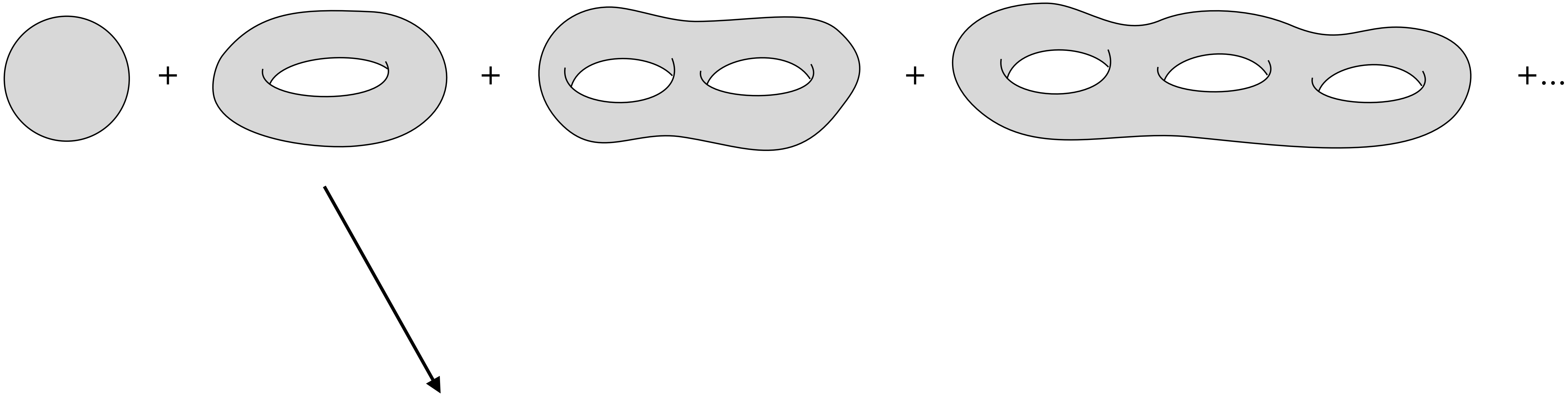


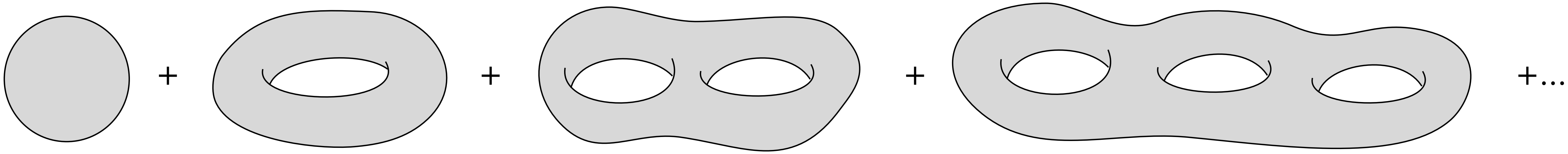
there are new scattering equations here,
transcendental functions;
numerics ?!!!

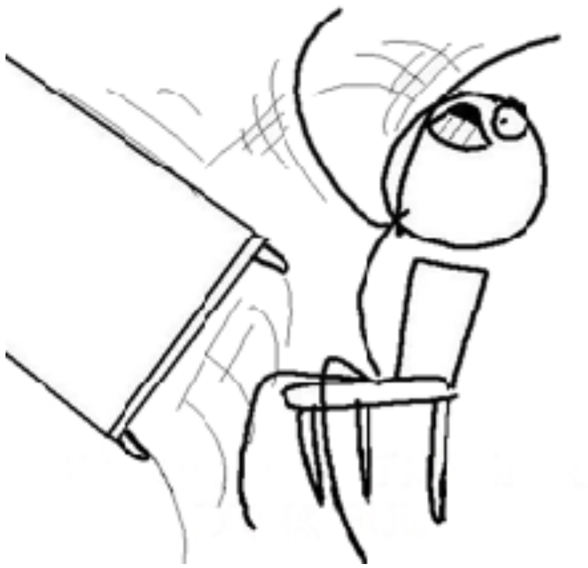
Partial solution

Casali Tourkine 2015

program : get scattering equations formalism to all loop orders

Geyer, Mason, Monteiro, Tourkine; 2016, 2017





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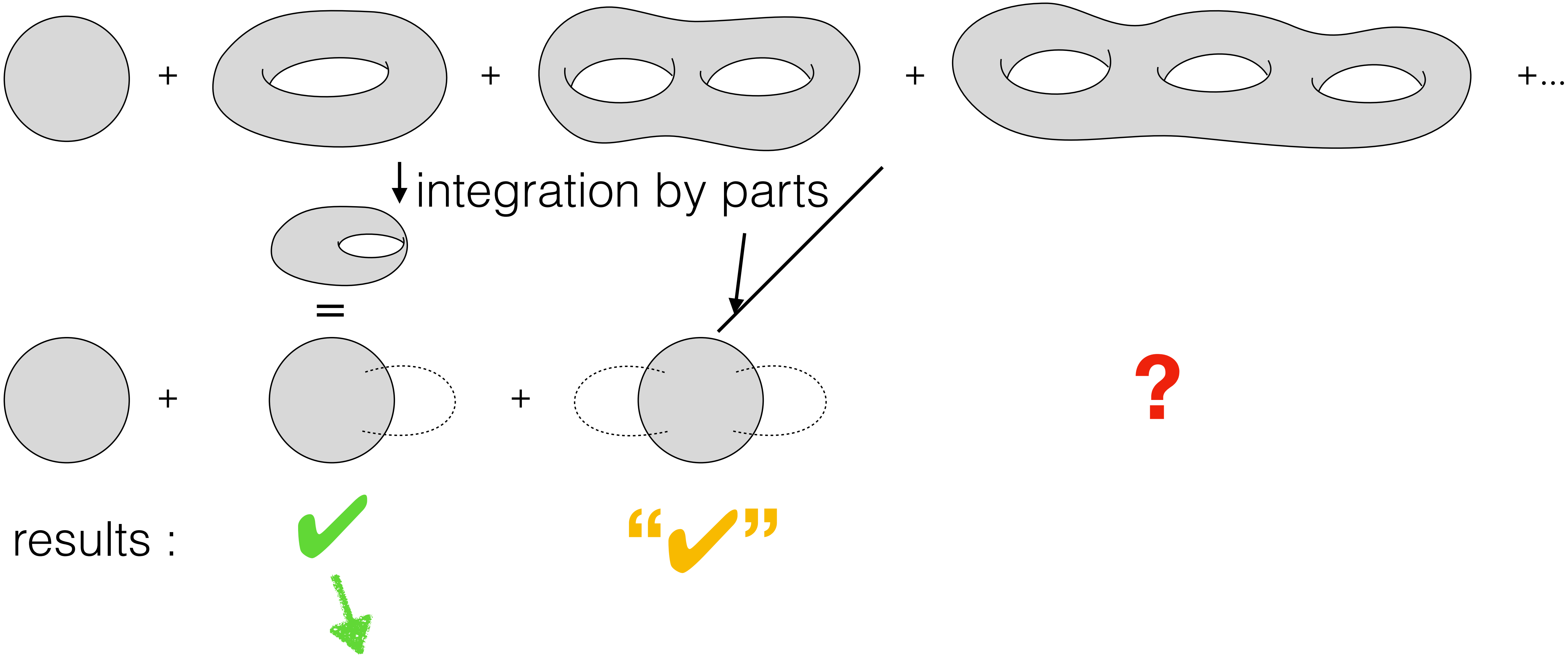
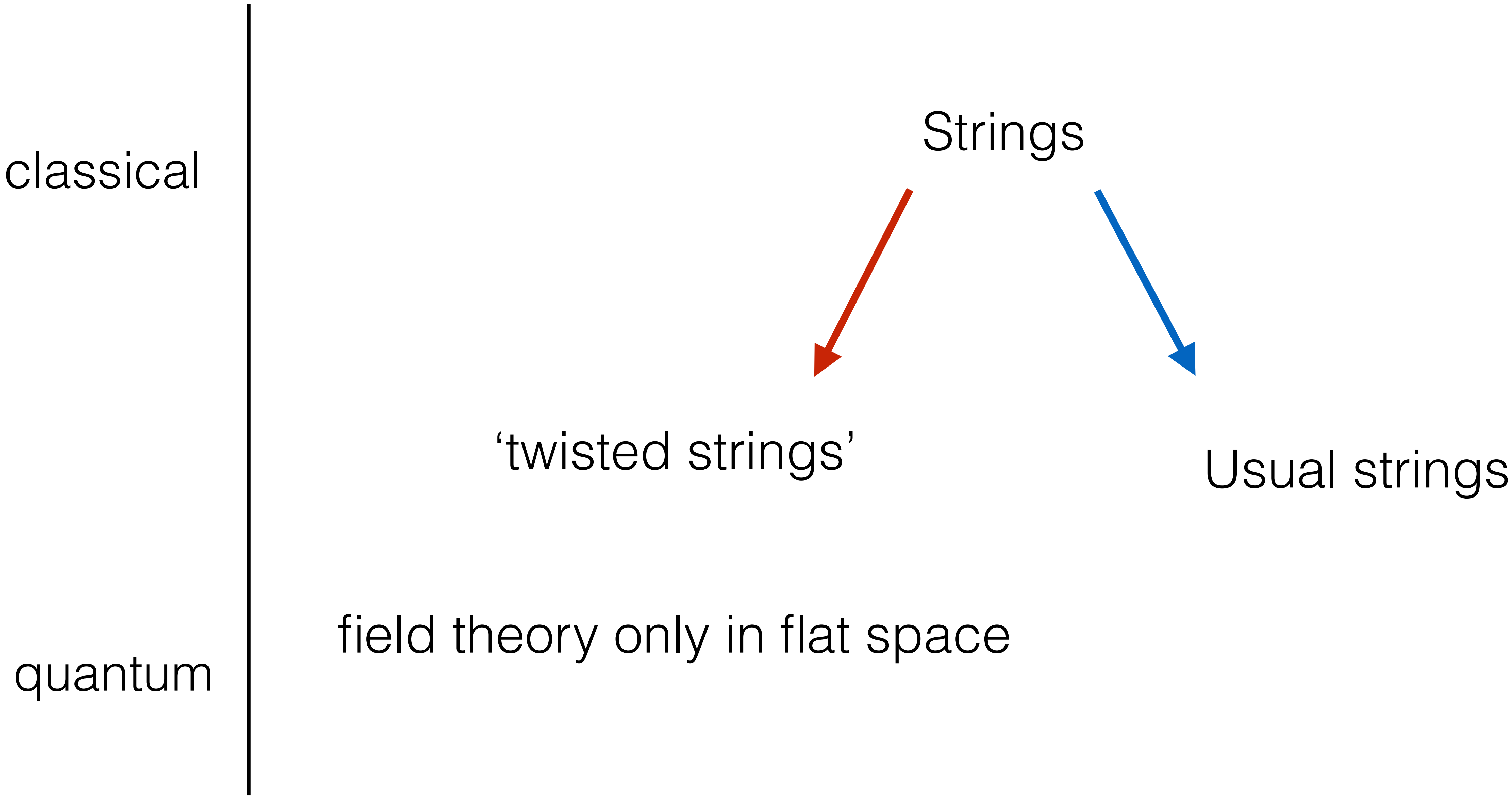
Geyer, Mason, Monteiro, Tourkine; 2016, 2017



integrands for all type of theories, n-point, one-loop ;
gauge, gravity, scalars, susy, non-susy, etc

The global picture that emerges

Casali, Tourkine; 2016, 2017



classical

Strings

'twisted strings'

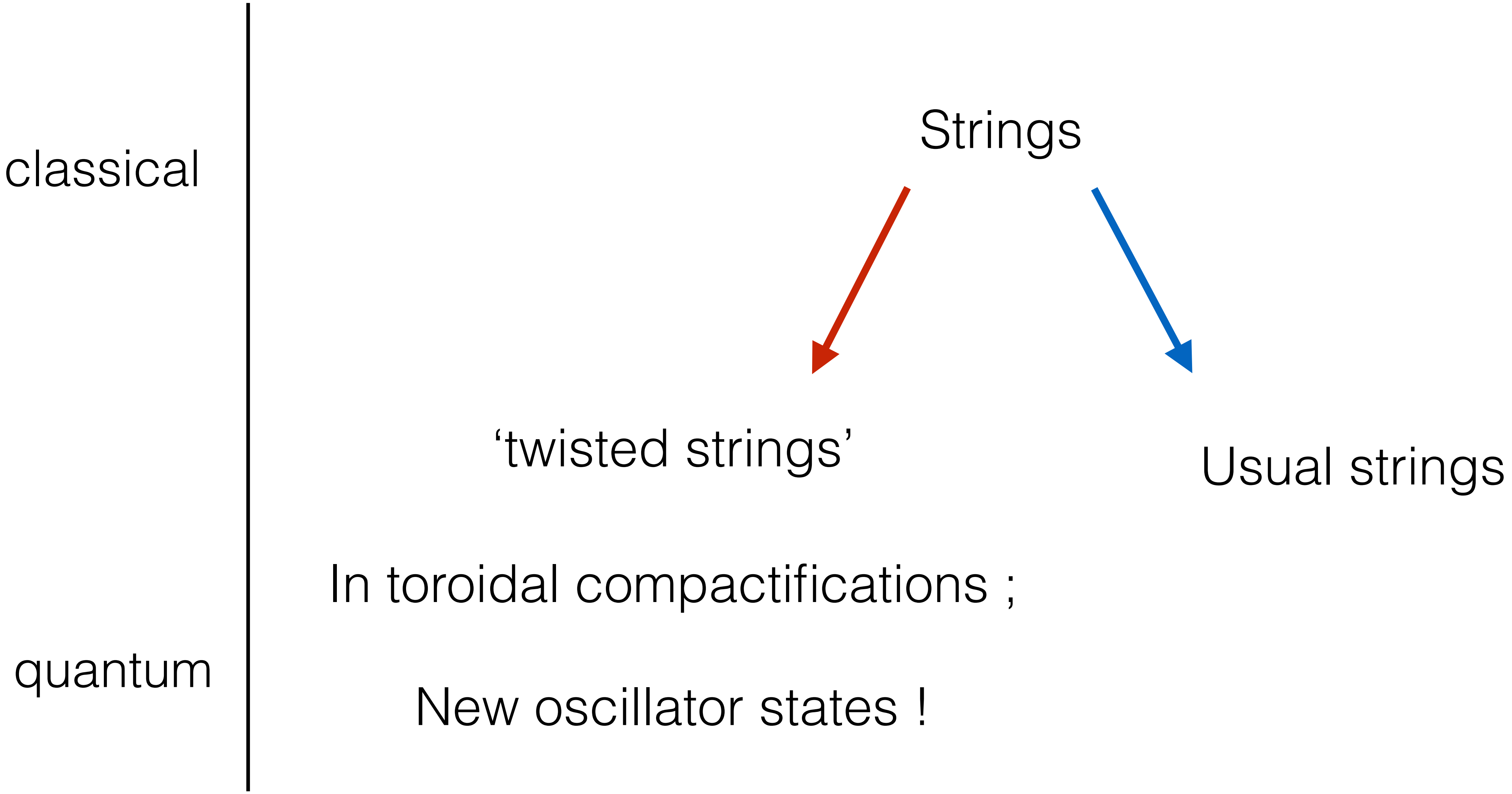
Usual strings

quantum

field theory only in flat space

The global picture that emerges

Casali, Tourkine; 2016, 2017



classical

Strings

‘twisted strings’

Usual strings

In toroidal compactifications ;

New oscillator states !

quantum

New strange higher-spin theories

Casali, Tourkine; 2017

Change of paradigm ?

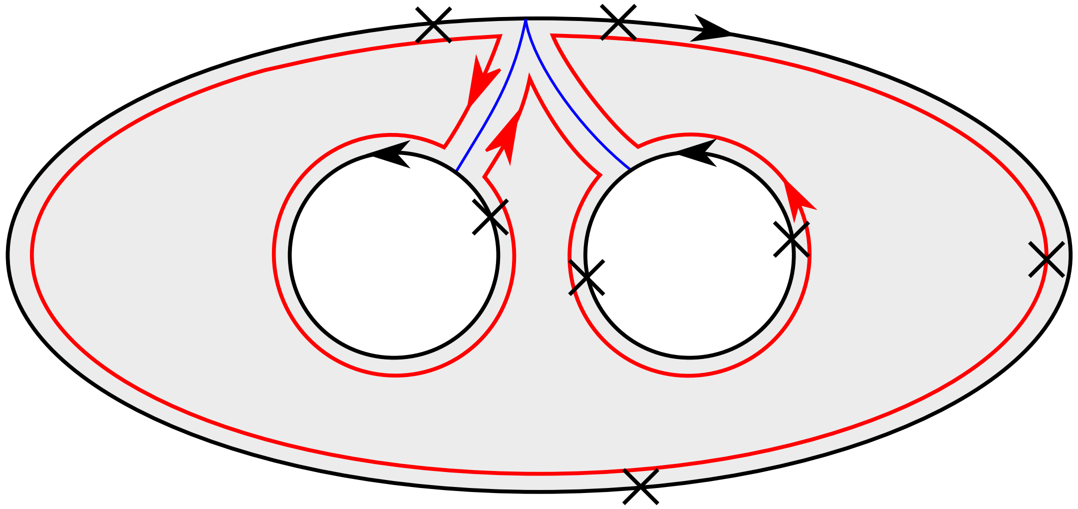
- Compact dimensions allow oscillations of the string
- Higher spins massive modes
- More of a field theory though
- T-dual spectrum
- but, ghosts in toroidal compactifications.

Main research questions

- What are twistor strings and how far can you go ? (amplitudes for standard model ? windings : formalism with generic masses ?)
- 2 to 3 gluons at 2 loops in massless QCD
- Reformulate loop expansion of quantum field theory
- Relate to normal strings
- How come a theory that is only sugra in d=10 can become such a beast when compactified ?

Also interested in ;

- string theory amplitudes and connection to field theory



Relation between string and gauge theory integrands at all loops;
connects planar and non-planar etc,
more physical processes oriented applications ?

- “colour-kinematics” and “double-copy” in gauge theory and gravity scattering amplitudes

CERN Retreat:
String Theory Group Presentations

Benjamin Assel

Before CERN:

- PhD in Ecole Normale Supérieure in Paris.
- Three-year postdoc at King's College in London.

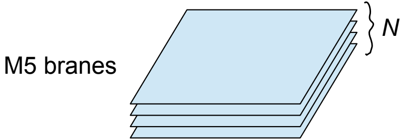
My main field of interest so far has been the study of **supersymmetric gauge theories**: RG-flows, super-conformal fixed points, exact computations of supersymmetric observables, BPS local operators, BPS defects, holography, ...

About SCFTs:

- Exist in $D = 1, 2, \cdots, 6$.
- Enjoy spectacular dualities.
- Can be realized as the low energy theory of D-brane setups in string theory/M-theory. This provides a lot of insights.
- Allow for tests of holography.

A short illustrative story

The M5 brane theory or (2,0) theory is the **conjectured** low-energy theory on N M5 branes (in M-theory). It is superconformal in 6d and it has maximal supersymmetry $\mathcal{N} = (2, 0)$.



A short illustrative story

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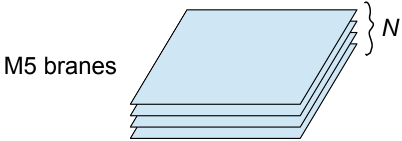

We do not know about an action for the theory.
It has no coupling constant, so there is no classical regime.
It has a simple holographic dual M-theory background: $AdS_7 \times S^4$.

One thing we know is that, when compactified on a circle S^1 of radius R, it flows to 5d $\mathcal{N} = 2$ SYM theory with gauge group $U(N)$ and coupling $g^2 = R$,

$$\begin{tikzcd}
\text{6d (2,0) theory on } \mathbb{R}^{1,4} \times S^1_R \arrow[d, "R \to 0"] \\
\text{5d } \mathcal{N} = 2 \ U(N) \text{ SYM theory on } \mathbb{R}^{1,4},\ g^2 = R
\end{tikzcd}$$

$$\begin{tikzcd}
& \text{6d (2,0) theory on } S^1_{R_1} \times S^1_{R_2} \arrow[dl, "R_1 \to 0"'] \\
\text{5d SYM on } S^1_{R_2},\ g^2_{\mathrm{5d}} = R_1 \arrow[d, "R_2 \to 0"] & \\
\text{4d } \mathcal{N} = 4\ U(N) \text{ SYM},\ g^2 = \frac{R_1}{R_2} &
\end{tikzcd}$$

$$\begin{tikzcd}
 & \text{6d (2,0) theory on } S^1_{R_1} \times S^1_{R_2} \arrow[dl, "R_1 \to 0"'] \arrow[dr, "R_2 \to 0"] & \\
\text{5d SYM on } S^1_{R_2},\ g^2_{5\mathrm{d}} = R_1 \arrow[d, "R_2 \to 0"] & & \text{5d SYM on } S^1_{R_1},\ \hat{g}^2_{5d} = R_2 \arrow[d, "R_1 \to 0"] \\
\text{4d } \mathcal{N} = 4\ U(N) \text{ SYM, } g^2 = \frac{R_1}{R_2} & & \text{4d } \mathcal{N} = 4\ U(N) \text{ SYM, } \hat{g}^2 = \frac{R_2}{R_1}
\end{tikzcd}$$

$$\begin{tikzcd}
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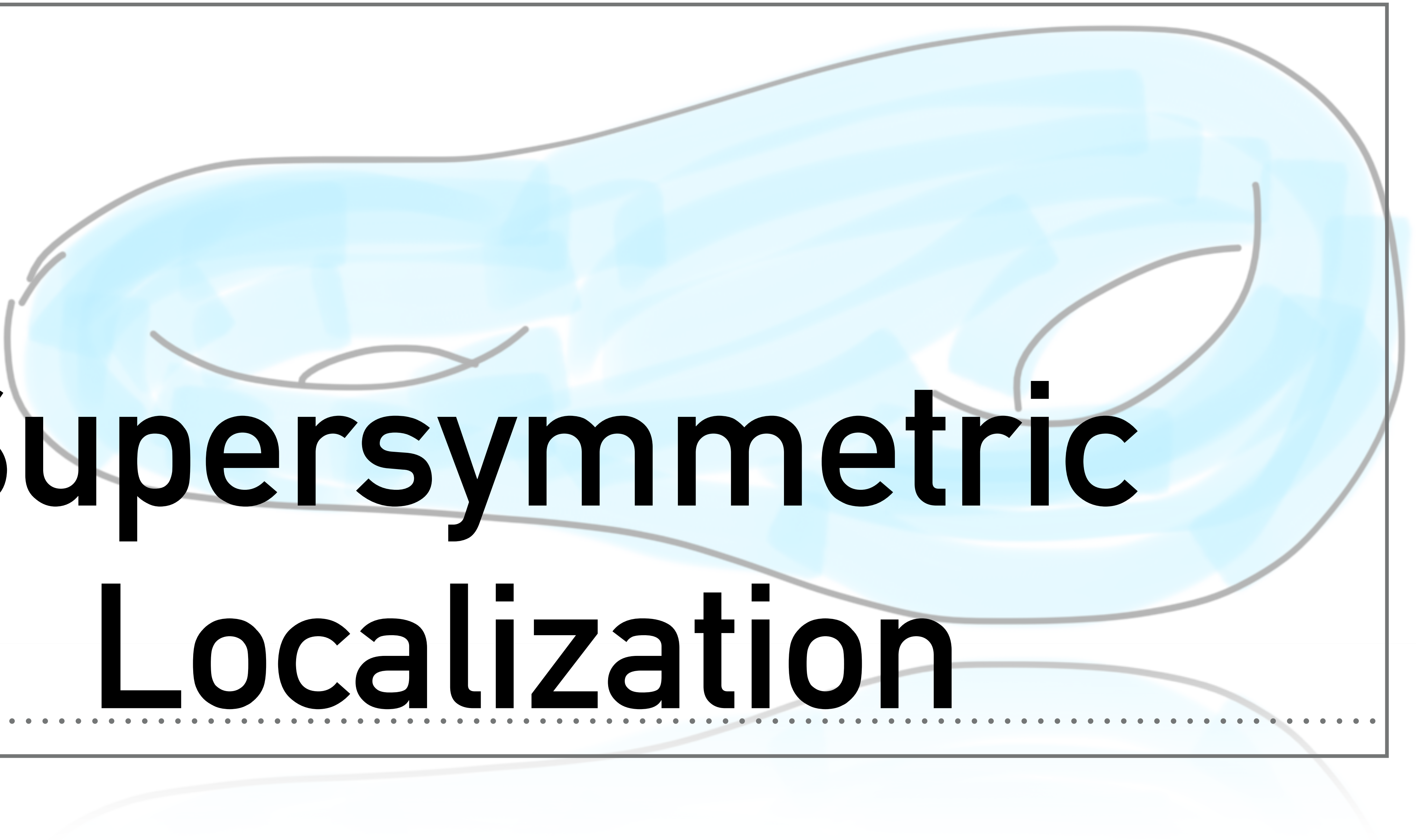
\left[\text{4d } \mathcal{N} = 4\ U(N) \text{ SYM, } g^2 = \frac{R_1}{R_2}\right] & \equiv & \left[\text{4d } \mathcal{N} = 4\ U(N) \text{ SYM, } \hat{g}^2 = \frac{R_2}{R_1}\right]
\end{tikzcd}$$

Electro-magnetic duality !

This illustrates several points.

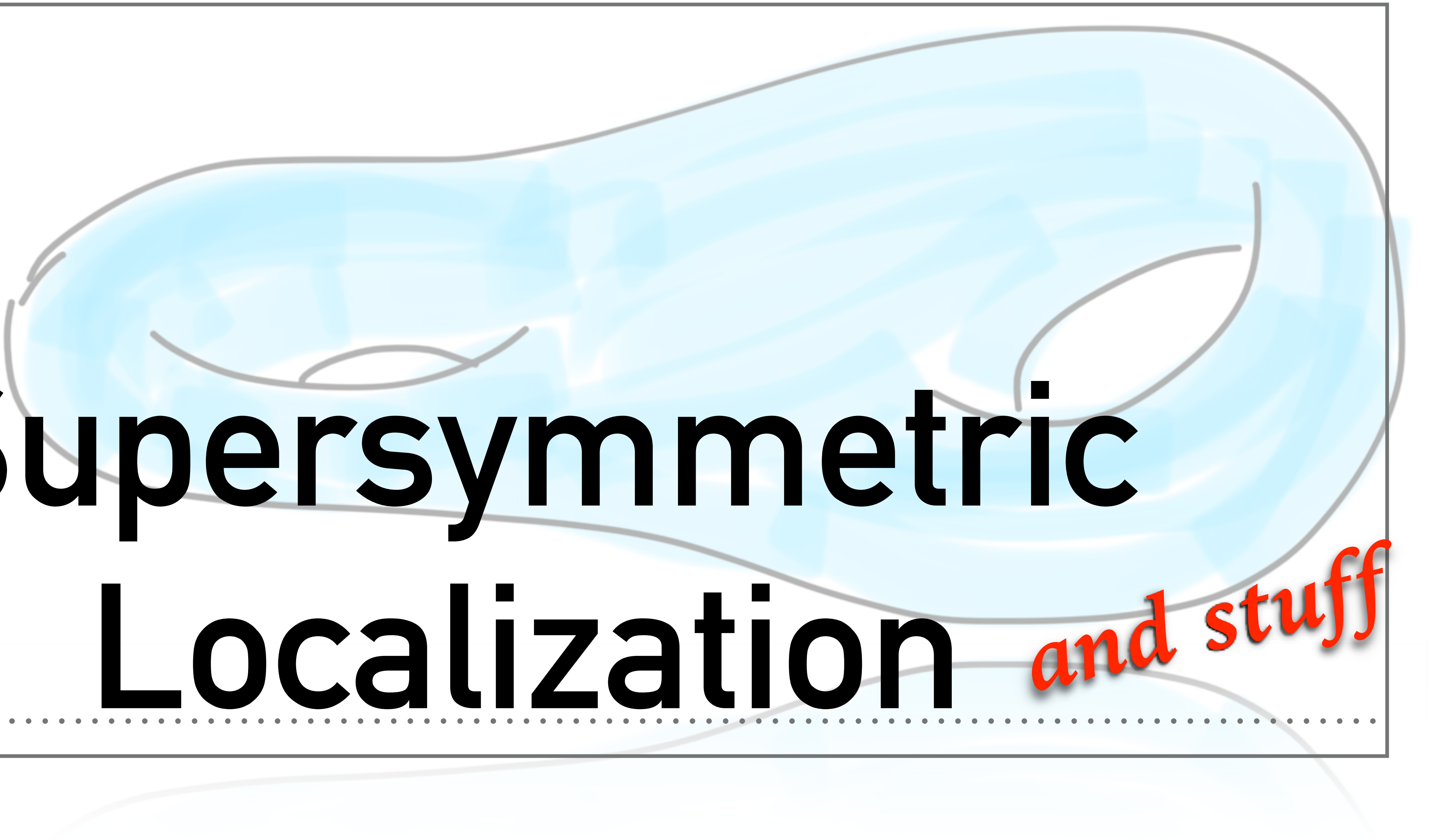
- It is important to study QFTs in various spacetime dimensions and their compactifications;
- There are SCFTs without Lagrangian descriptions (generic situation in 4d);
- There might be alternative descriptions of QFTs where dualities are manifest;
- We can learn deep lessons about gauge theories from string theory



Supersymmetric Localization

Cyril Closset, CERN

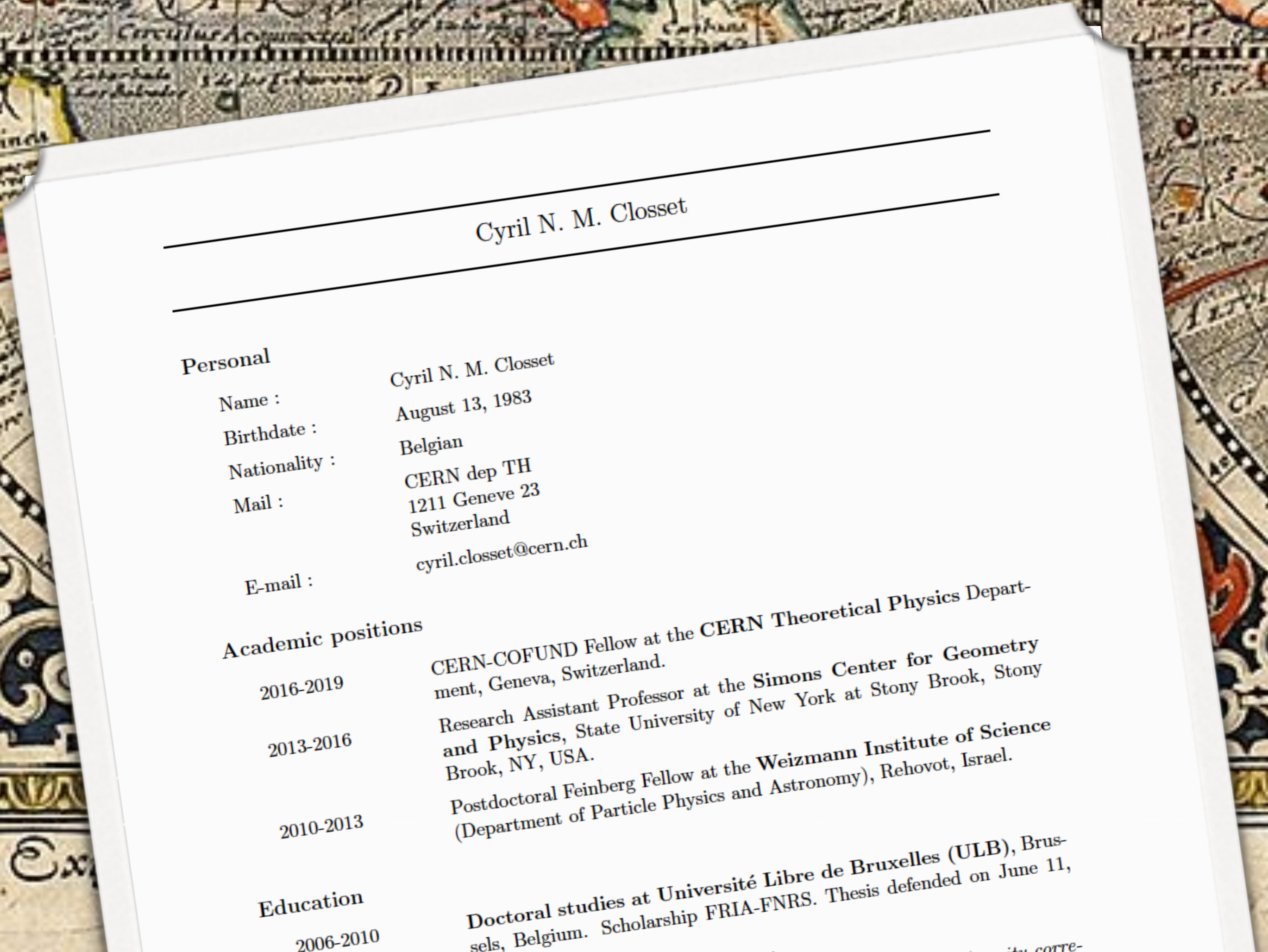
CERN TH Retreat—17 Nov 2017



Supersymmetric Localization *and stuff*

Cyril Closset, CERN

CERN TH Retreat—17 Nov 2017



Cyril N. M. Closset

Personal

Name :	Cyril N. M. Closset
Birthdate :	August 13, 1983
Nationality :	Belgian
Mail :	CERN dep TH 1211 Geneve 23 Switzerland
E-mail :	cyril.closset@cern.ch

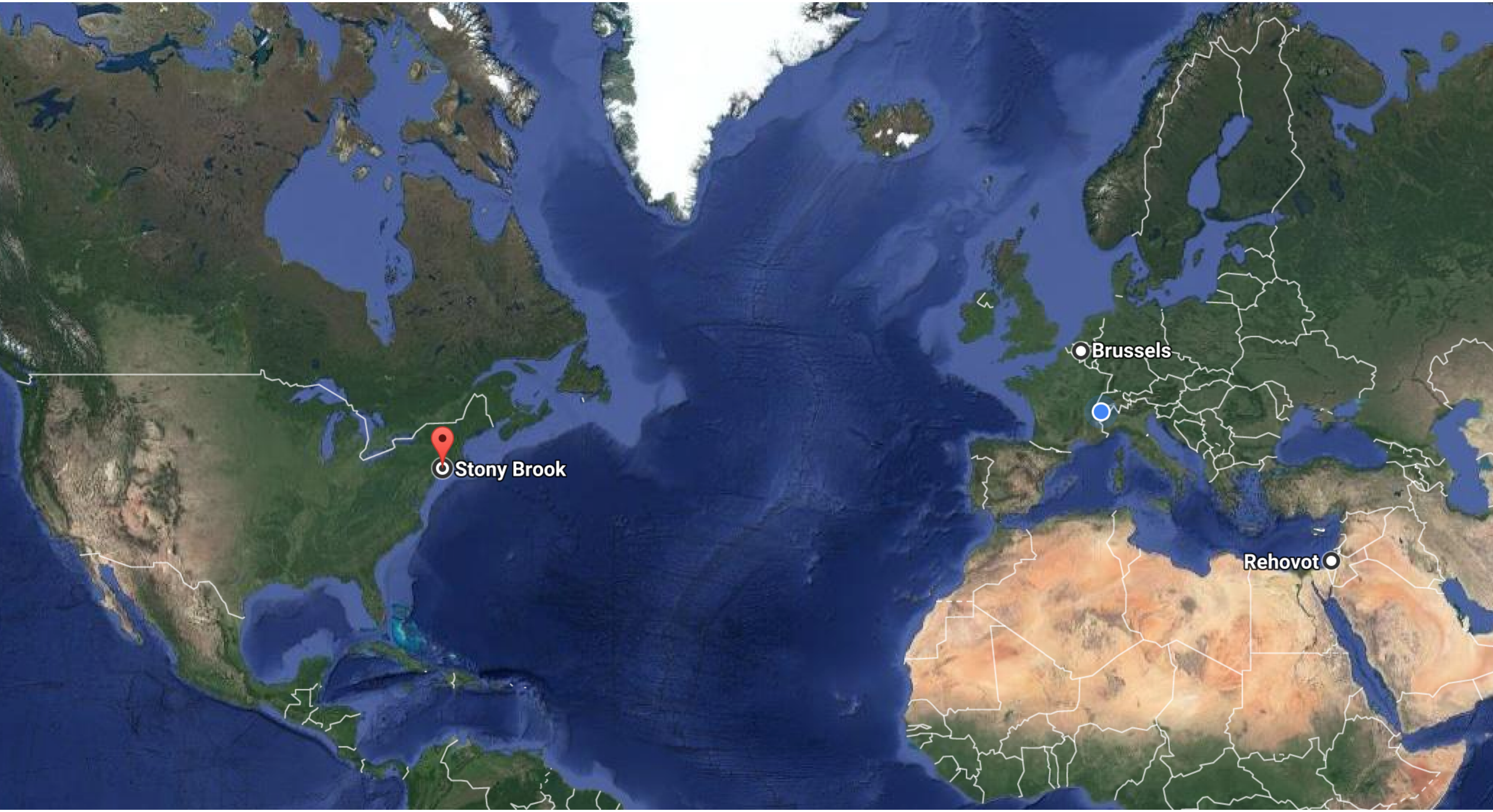
Academic positions

2016-2019	CERN-COFUND Fellow at the **CERN Theoretical Physics** Department, Geneva, Switzerland.
2013-2016	Research Assistant Professor at the **Simons Center for Geometry and Physics**, State University of New York at Stony Brook, Stony Brook, NY, USA.
2010-2013	Postdoctoral Feinberg Fellow at the **Weizmann Institute of Science** (Department of Particle Physics and Astronomy), Rehovot, Israel.

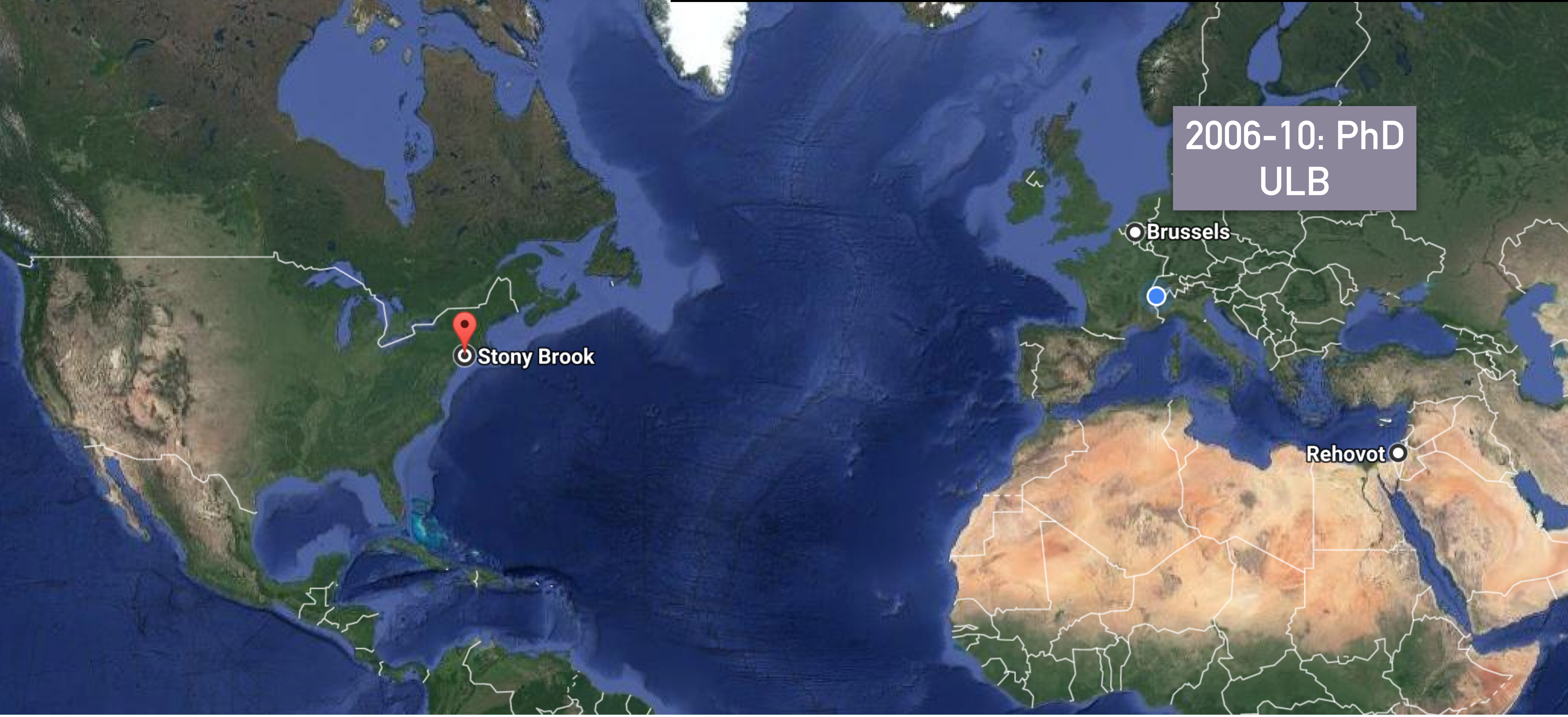
Education

2006-2010	**Doctoral studies at Université Libre de Bruxelles (ULB)**, Brussels, Belgium. Scholarship FRIA-FNRS. Thesis defended on June 11,

JOURNEY TO CERN



JOURNEY TO CERN



2006-10: PhD
ULB

JOURNEY TO CERN

2006-10: PhD
ULB

2010-13:
Weizmann Institute

JOURNEY TO CERN

2006-10: PhD
ULB

2013-16:
SCGP

2010-13:
Weizmann Institute

JOURNEY TO

2006-10: PhD
ULB

2013-16:
SCGP

2016-18:
CERN

2010-13:
Weizmann Institute

JOURNEY TO CERN AND AWAY

WHAT I WORK ON: (HINT: IT'S NOT BEEN FOUND AT LHC YET.)


flux
terms
choice
results
field
fields
chiral
dual
find
term
result
vacua
two
Σ
g
Mg,f
one
Bethe
group
phys
Let
SBE
define
check
limit
effective
may
must
symmetry
along
line
large
Phys
related
fluxes
F2Φ
F1Φ
2πi
πi
sum
sign
work
vacuum
finite
order
point
torus
useful
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a=1
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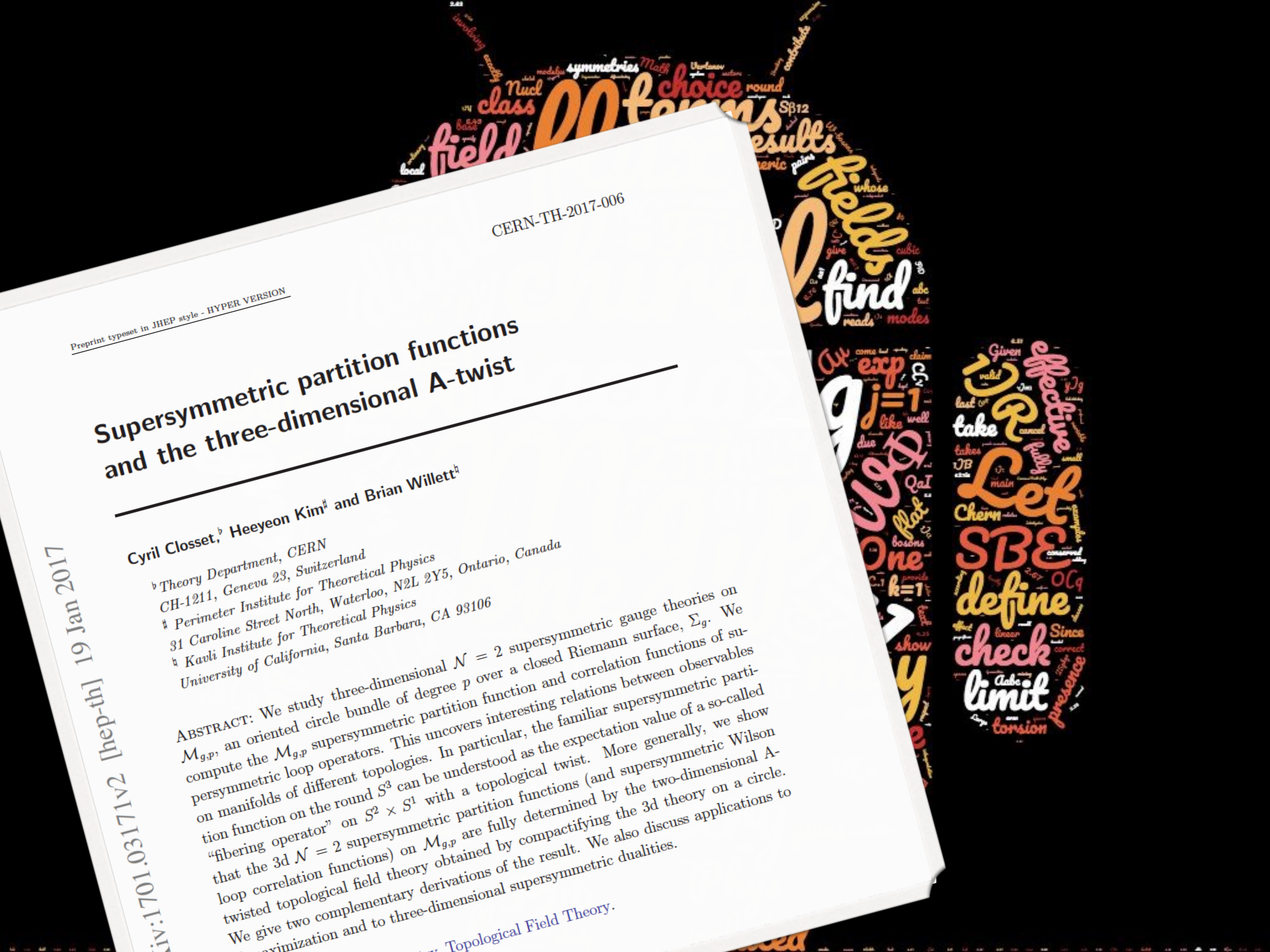

CERN-TH-2017-006

Preprint typeset in JHEP style - HYPER VERSION

Supersymmetric partition functions and the three-dimensional A-twist

Cyril Closset,[♭] Heeyeon Kim[♯] and Brian Willett[♮]

[♭] *Theory Department, CERN*
CH-1211, Geneva 23, Switzerland
[♯] *Perimeter Institute for Theoretical Physics*
31 Caroline Street North, Waterloo, N2L 2Y5, Ontario, Canada
[♮] *Kavli Institute for Theoretical Physics*
University of California, Santa Barbara, CA 93106

iv:1701.03171v2 [hep-th] 19 Jan 2017

ABSTRACT: We study three-dimensional $\mathcal{N}=2$ supersymmetric gauge theories on $\mathcal{M}_{g,p}$, an oriented circle bundle of degree p over a closed Riemann surface, Σ_g. We compute the $\mathcal{M}_{g,p}$ supersymmetric partition function and correlation functions of supersymmetric loop operators. This uncovers interesting relations between observables on manifolds of different topologies. In particular, the familiar supersymmetric partition function on the round S^3 can be understood as the expectation value of a so-called "fibering operator" on $S^2 \times S^1$ with a topological twist. More generally, we show that the 3d $\mathcal{N}=2$ supersymmetric partition functions (and supersymmetric Wilson loop correlation functions) on $\mathcal{M}_{g,p}$ are fully determined by the two-dimensional A-twisted topological field theory obtained by compactifying the 3d theory on a circle. We give two complementary derivations of the result. We also discuss applications to aximization and to three-dimensional supersymmetric dualities.

Topological Field Theory.

CERN-TH-2017-006

Preprint typeset in JHEP style - HYPER VERSIO

Supersymmetric
and the three-

Cyril Closset,♭ Heeyeon

♭ Theory Department, CE
CH-1211, Geneva 23, S
♯ Perimeter Institute fo
31 Caroline Street Nort
♮ Kavli Institute for Th
University of Californi

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We give two compl
ximization an

CERN-TH-2017-180

Preprint typeset in JHEP style - HYPER VERSION

$\mathcal{N} = 1$ supersymmetric indices and the four-dimensional A-model

Cyril Closset,♭ Heeyeon Kim♯ and Brian Willett♮

♭ *Theory Department, CERN*
CH-1211, Geneva 23, Switzerland
♯ *Perimeter Institute for Theoretical Physics*
31 Caroline Street North, Waterloo, N2L 2Y5, Ontario, Canada
♮ *Kavli Institute for Theoretical Physics*
University of California, Santa Barbara, CA 93106

Xiv:1707.05774v2 [hep-th] 14 Aug 2017

Abstract: We compute the supersymmetric partition function of $\mathcal{N} = 1$ supersymmetric gauge theories with an R-symmetry on $\mathcal{M}_4 \cong \mathcal{M}_{g,p} \times S^1$, a principal elliptic fiber bundle of degree p over a genus-g Riemann surface, Σ_g. Equivalently, we compute the generalized supersymmetric index $I_{\mathcal{M}_{g,p}}$, with the supersymmetric three-manifold $\mathcal{M}_{g,p}$ as the spatial slice. The ordinary $\mathcal{N} = 1$ supersymmetric index on the round three-sphere is recovered as a special case. We approach this computation from the point of view of a topological A-model for the abelianized gauge fields on the base Σ_g. This A-model—or A-twisted two-dimensional $\mathcal{N} = (2,2)$ gauge theory—encodes all the information about the generalized indices, which are viewed as expectations values of some canonically-defined surface defects wrapped on T^2 inside $\Sigma_g \times T^2$. Being defined by compactification on the torus, the A-model also enjoys natural modular properties, the four-dimensional 't Hooft anomalies. As an application of our results, We also present a new evaluation formula for

Cy Twombly, 1963

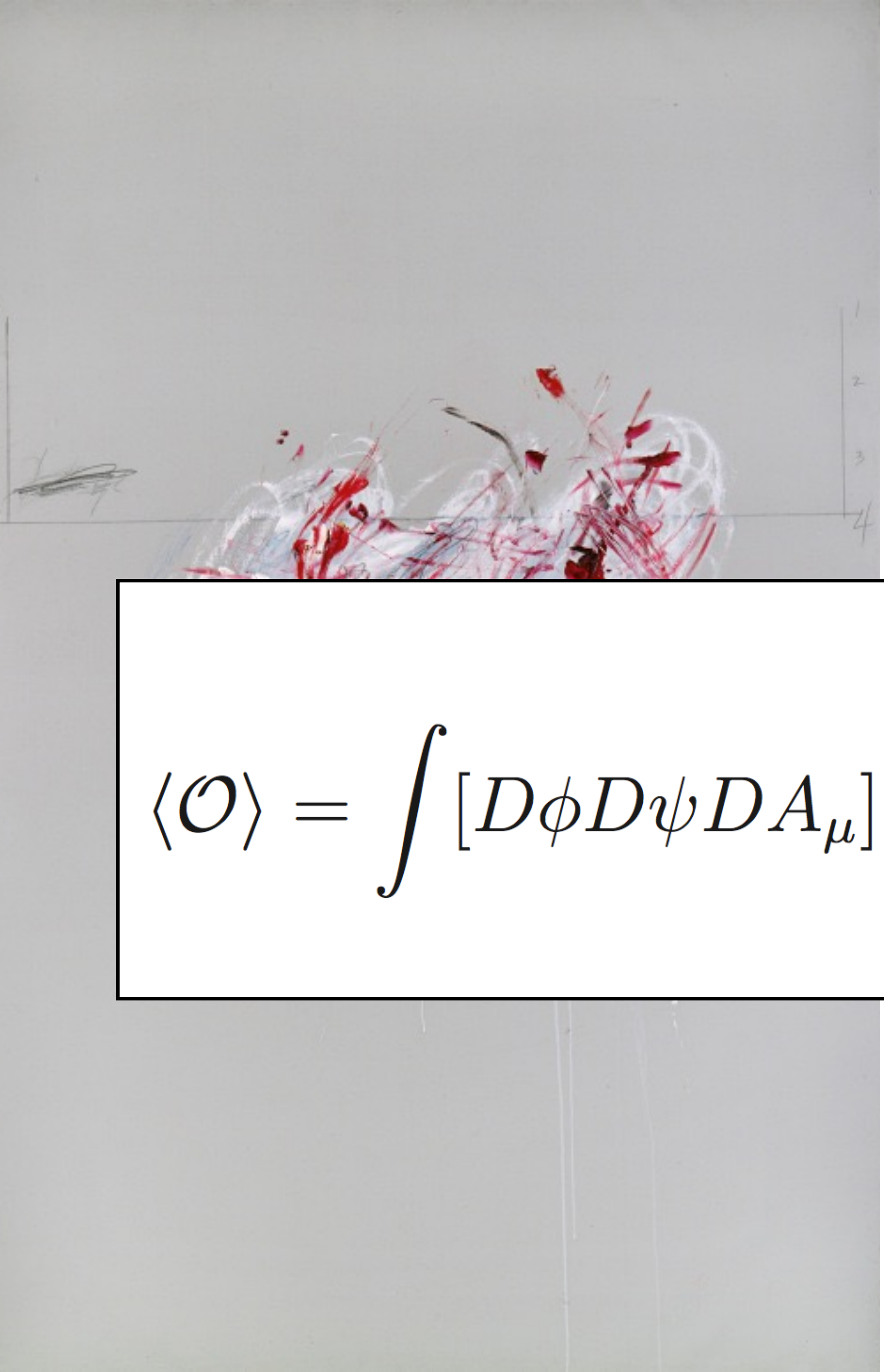
SUPERSYMMETRY IN CURVED SPACE

- QFT is hard.


Cy Twombly, 1963

SUPERSYMMETRY IN CURVED SPACE

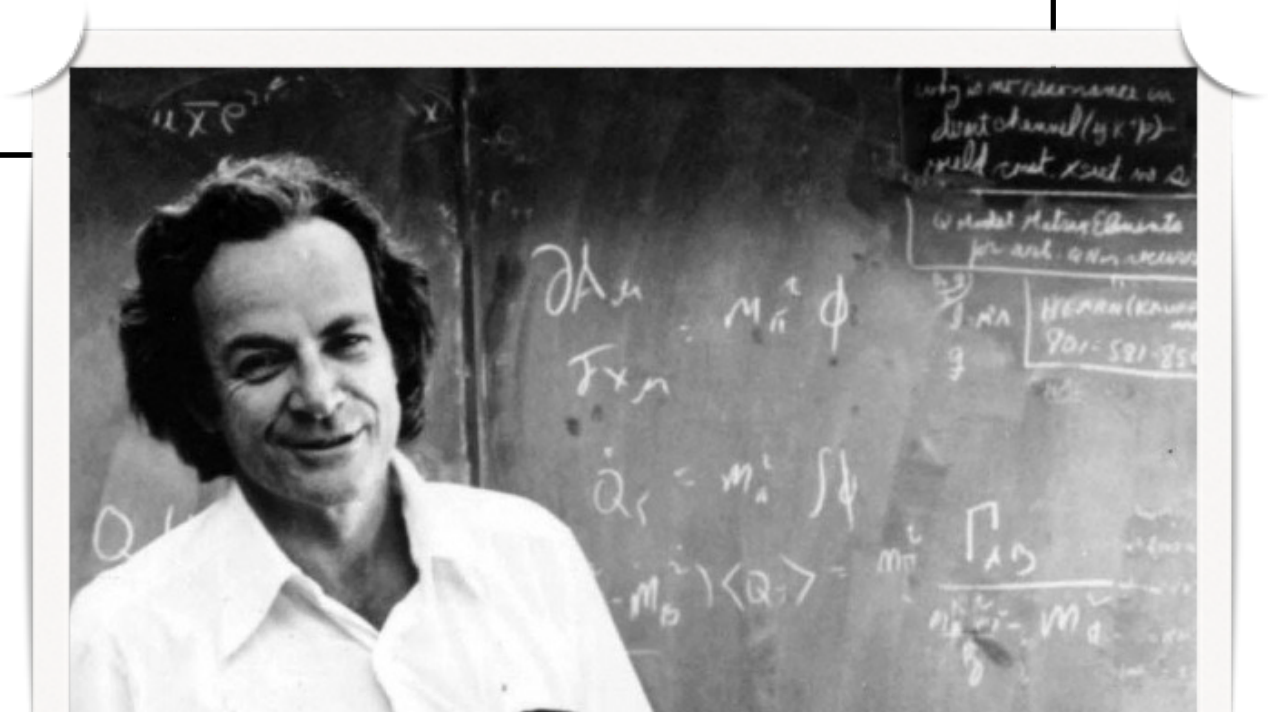
- QFT is hard.
- Like, really hard.

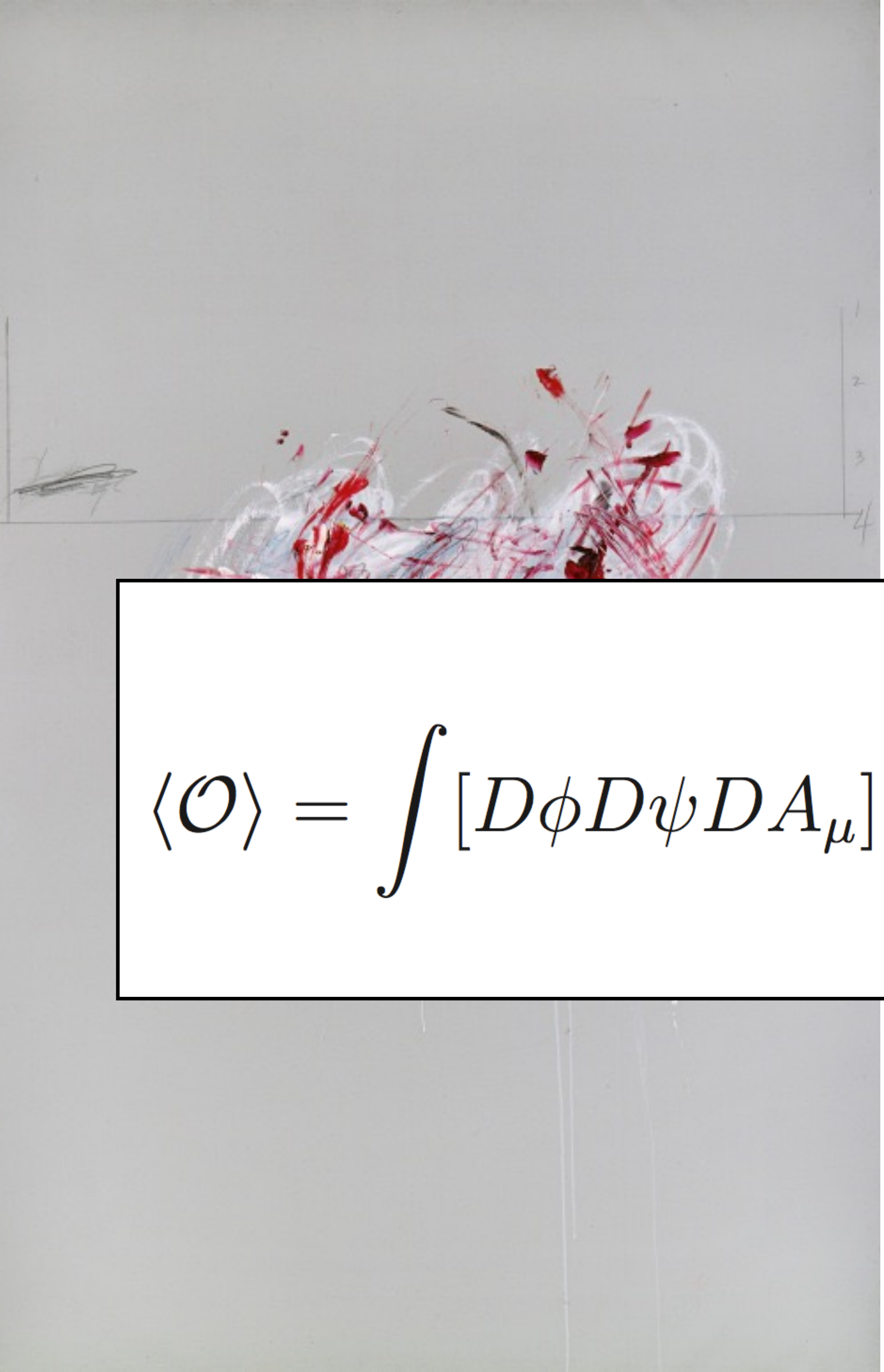


SUPERSYMMETRY IN CURVED SPACE

- QFT is hard.
- Like, really hard.
- (Thanks for nothing, Dick.)

$$\langle \mathcal{O} \rangle = \int [D\phi D\psi DA_\mu]\, \mathcal{O}(\phi, \psi, A_\mu)\, e^{-S[\phi,\psi,A_\mu]}$$





SUPERSYMMETRY IN CURVED SPACE

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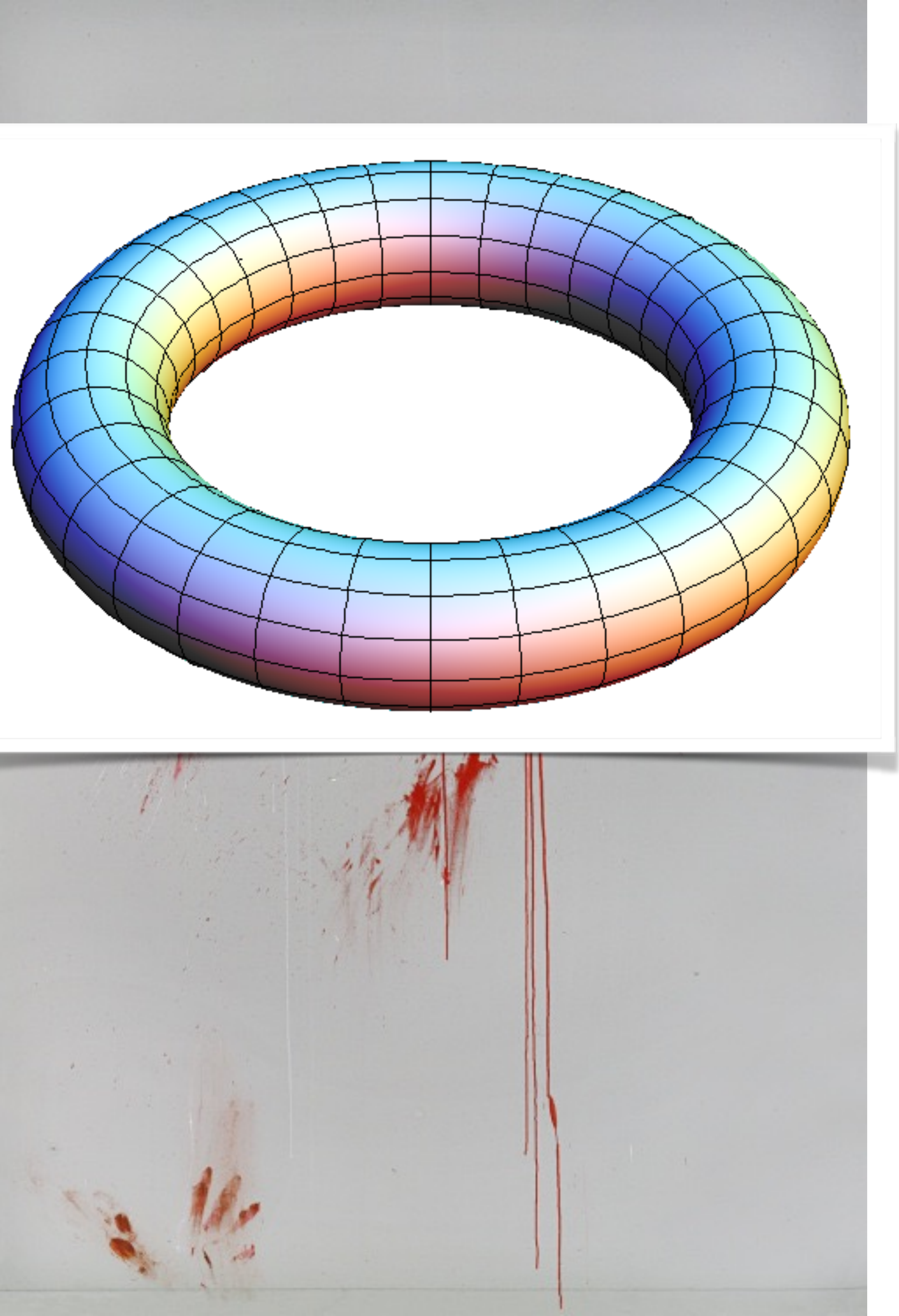
$$\langle \mathcal{O} \rangle = \int [D\phi D\psi D A_\mu]\, \mathcal{O}(\phi, \psi, A_\mu)\, e^{-S[\phi,\psi,A_\mu]}$$

- That's why (some) formal theorists like **supersymmetry** so much. (I'm one of them.)

SUPERSYMMETRY IN CURVED SPACE

- With supersymmetry, we can often "perform the path integral" explicitly.
- Still, no free lunch…



SUPERSYMMETRY IN CURVED SPACE

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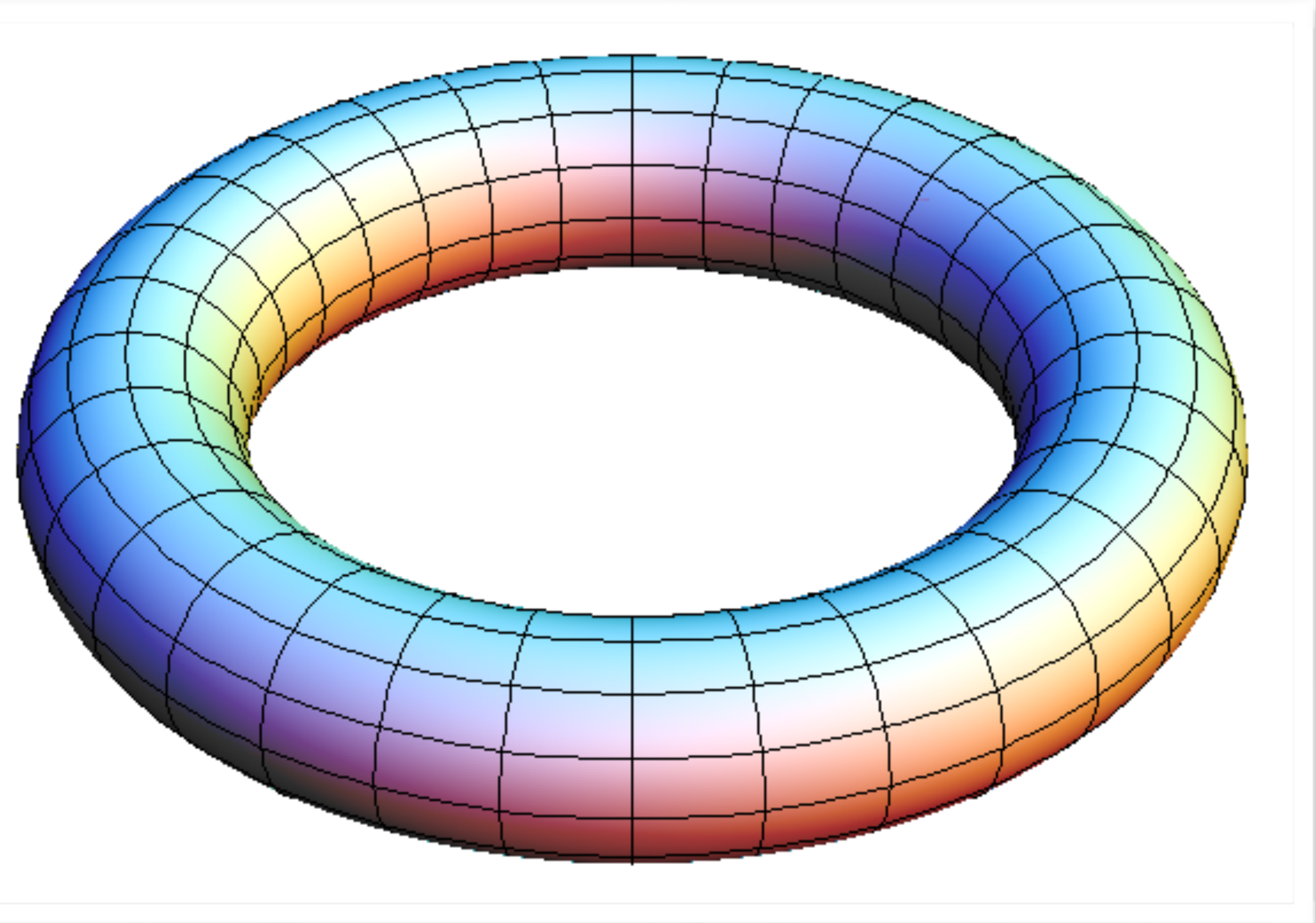
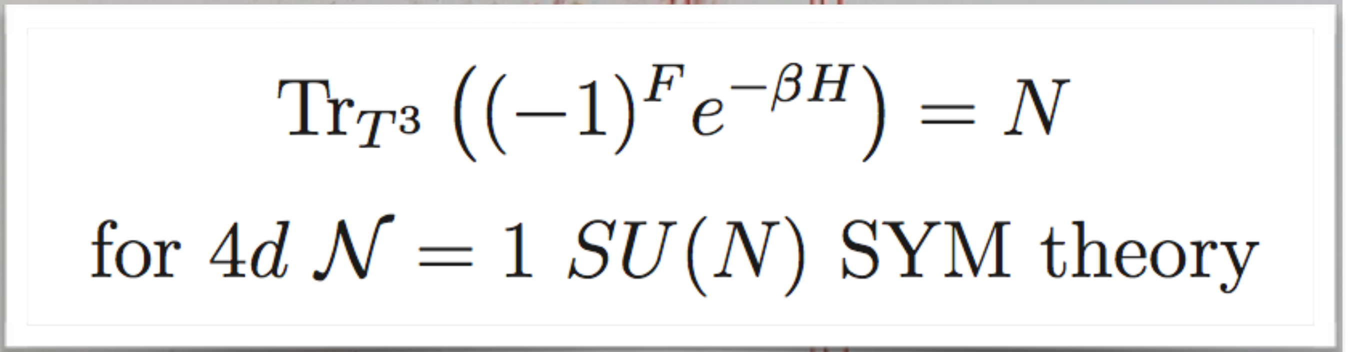
- It is convenient to consider the theory on compact spaces: Gives IR cutoff.
- In UV, supersymmetry comes to the rescue.

SUPERSYMMETRY IN CURVED SPACE

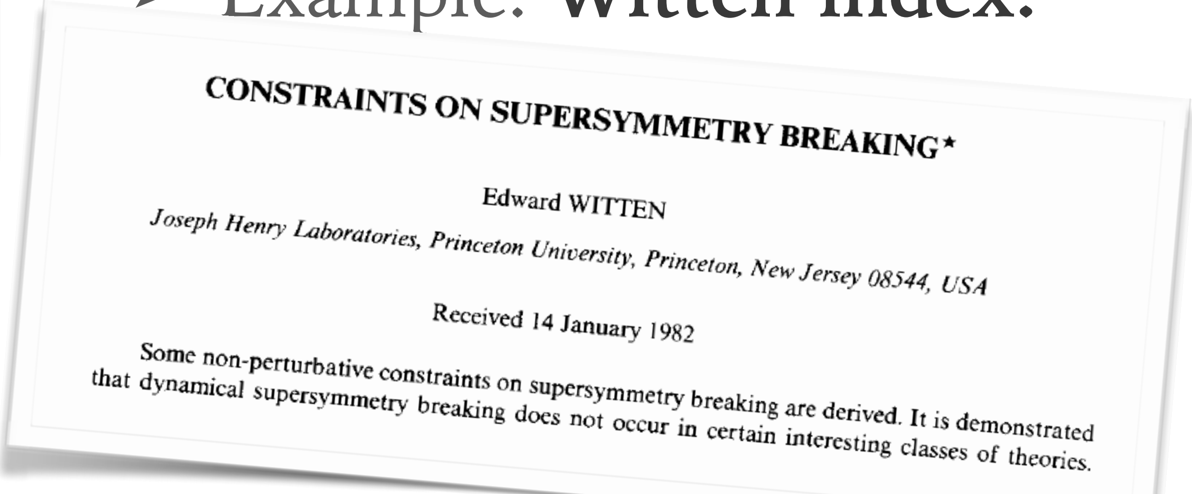




$$\mathrm{Tr}_{T^3}\left((-1)^F e^{-\beta H}\right) = N$$

for 4d $\mathcal{N} = 1$ $SU(N)$ SYM theory

- With supersymmetry, we can often "perform the path integral" explicitly.
- Still, no free lunch…
- It is convenient to consider the theory on compact spaces: Gives IR cutoff.
- In UV, supersymmetry comes to the rescue.
- Example: **Witten index.**



CONSTRAINTS ON SUPERSYMMETRY BREAKING*

Edward WITTEN

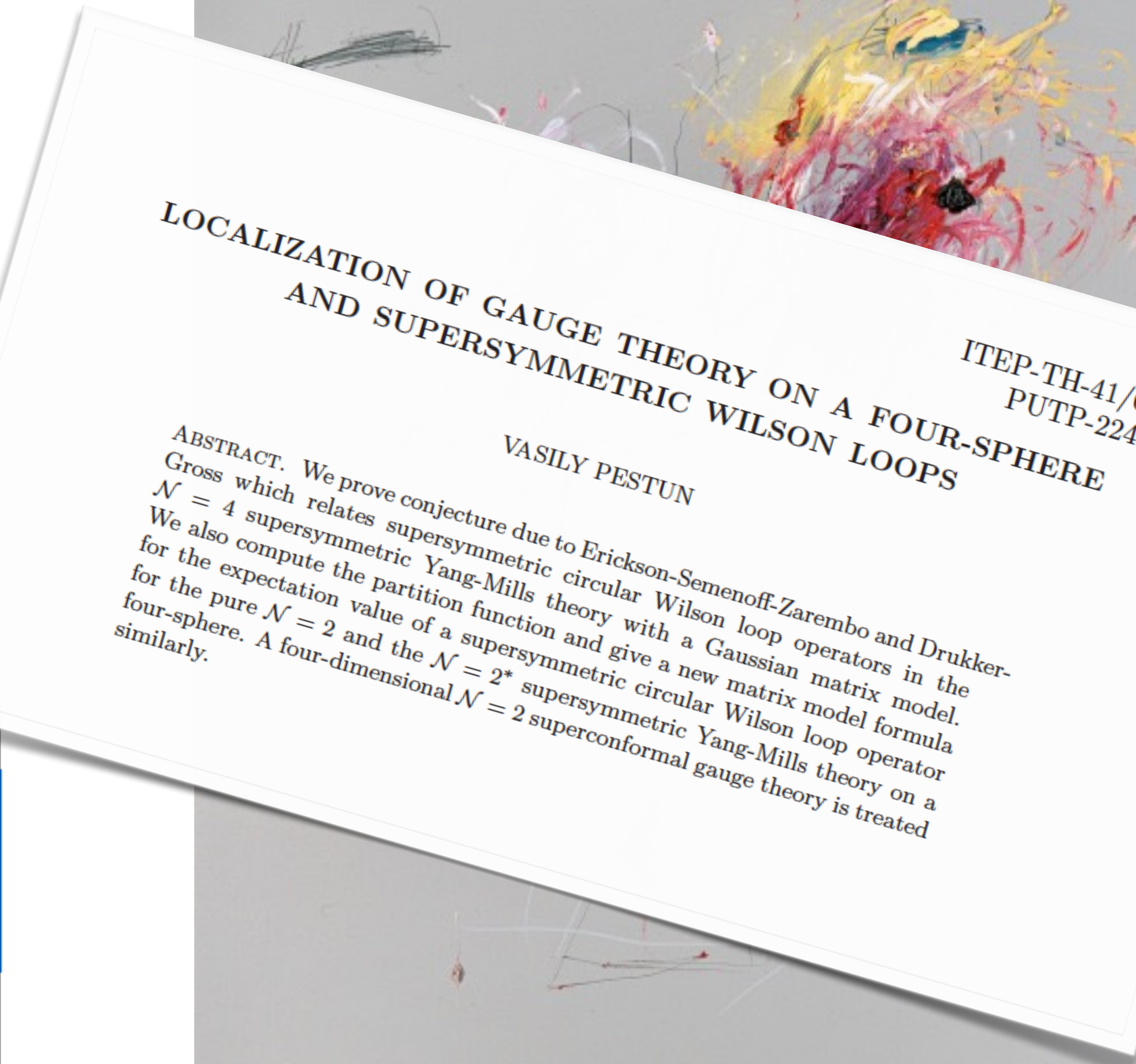
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544, USA

Received 14 January 1982

Some non-perturbative constraints on supersymmetry breaking are derived. It is demonstrated that dynamical supersymmetry breaking does not occur in certain interesting classes of theories.

SUPERSYMMETRY IN CURVED SPACE

- In the last 10 year, there was an explosion of so-called **“supersymmetric localization”** results.



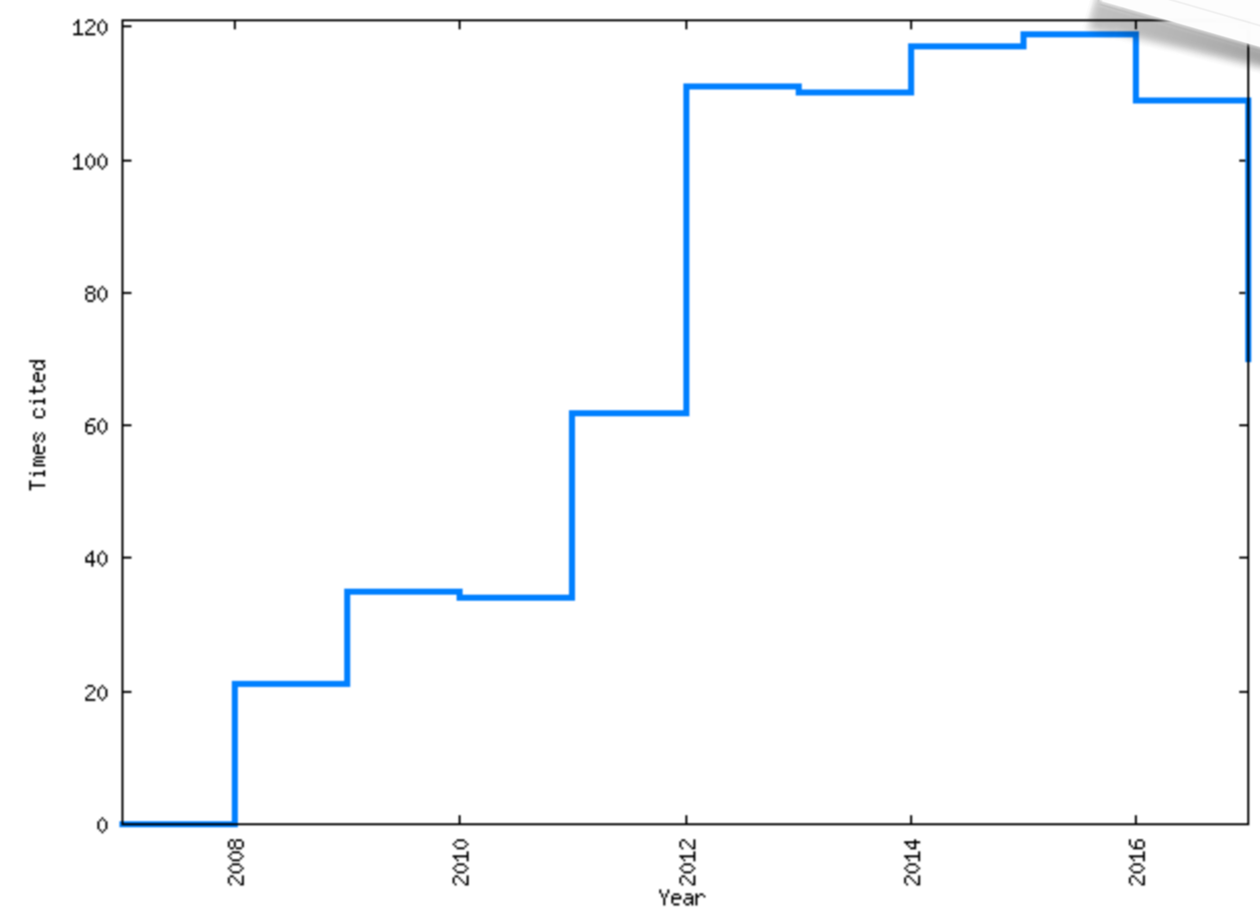
ITEP-TH-41/
PUTP-224

LOCALIZATION OF GAUGE THEORY ON A FOUR-SPHERE AND SUPERSYMMETRIC WILSON LOOPS

VASILY PESTUN

ABSTRACT. We prove conjecture due to Erickson-Semenoff-Zarembo and Drukker-Gross which relates supersymmetric circular Wilson loop operators in the $\mathcal{N} = 4$ supersymmetric Yang-Mills theory with a Gaussian matrix model. We also compute the partition function and give a new matrix model formula for the expectation value of a supersymmetric circular Wilson loop operator for the pure $\mathcal{N} = 2$ and the $\mathcal{N} = 2^*$ supersymmetric Yang-Mills theory on a four-sphere. A four-dimensional $\mathcal{N} = 2$ superconformal gauge theory is treated similarly.

Citation history:



SUPERSYMMETRY IN CURVED SPACE

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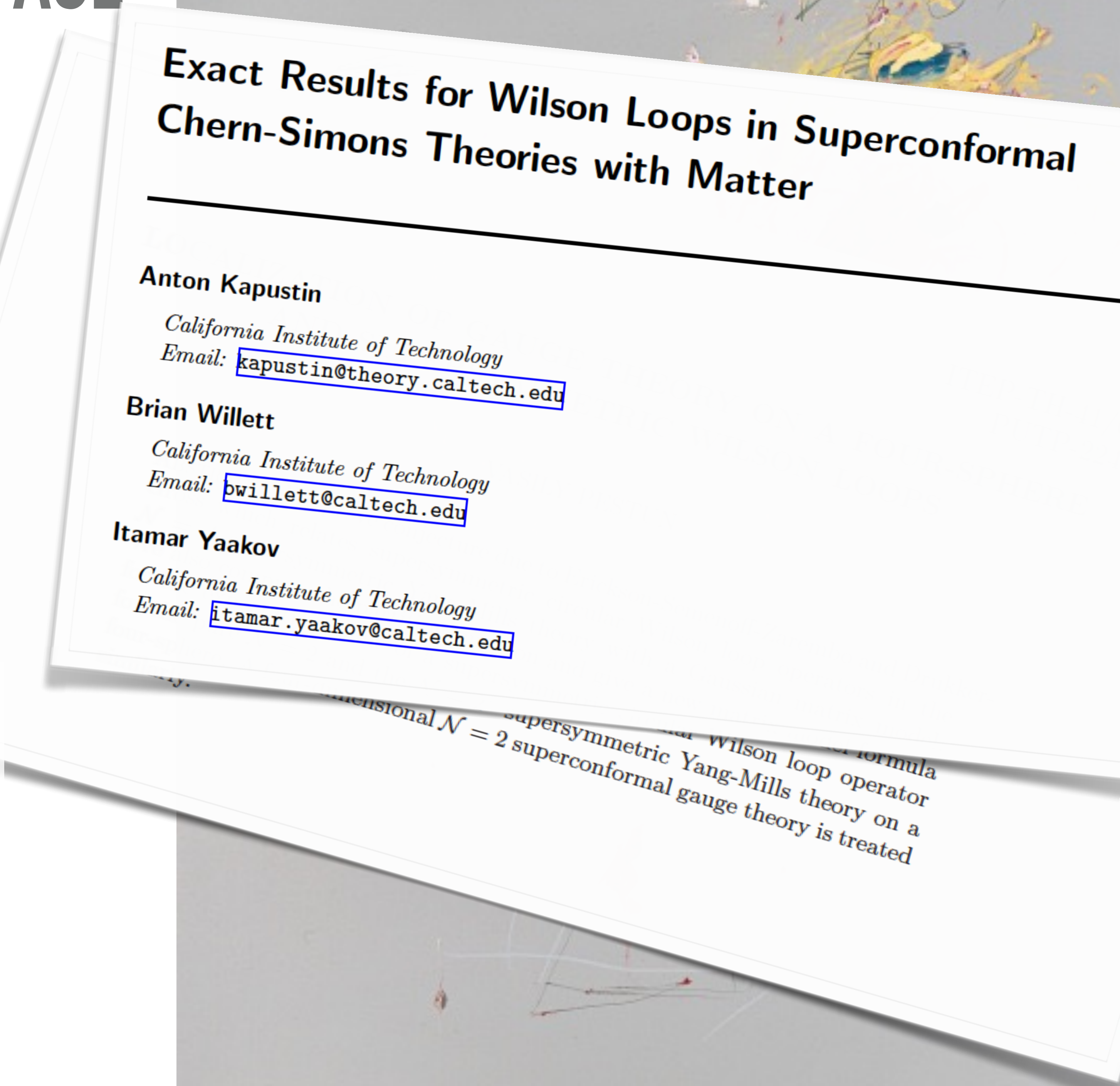


Exact Results for Wilson Loops in Superconformal Chern-Simons Theories with Matter

Anton Kapustin

California Institute of Technology
Email: kapustin@theory.caltech.edu

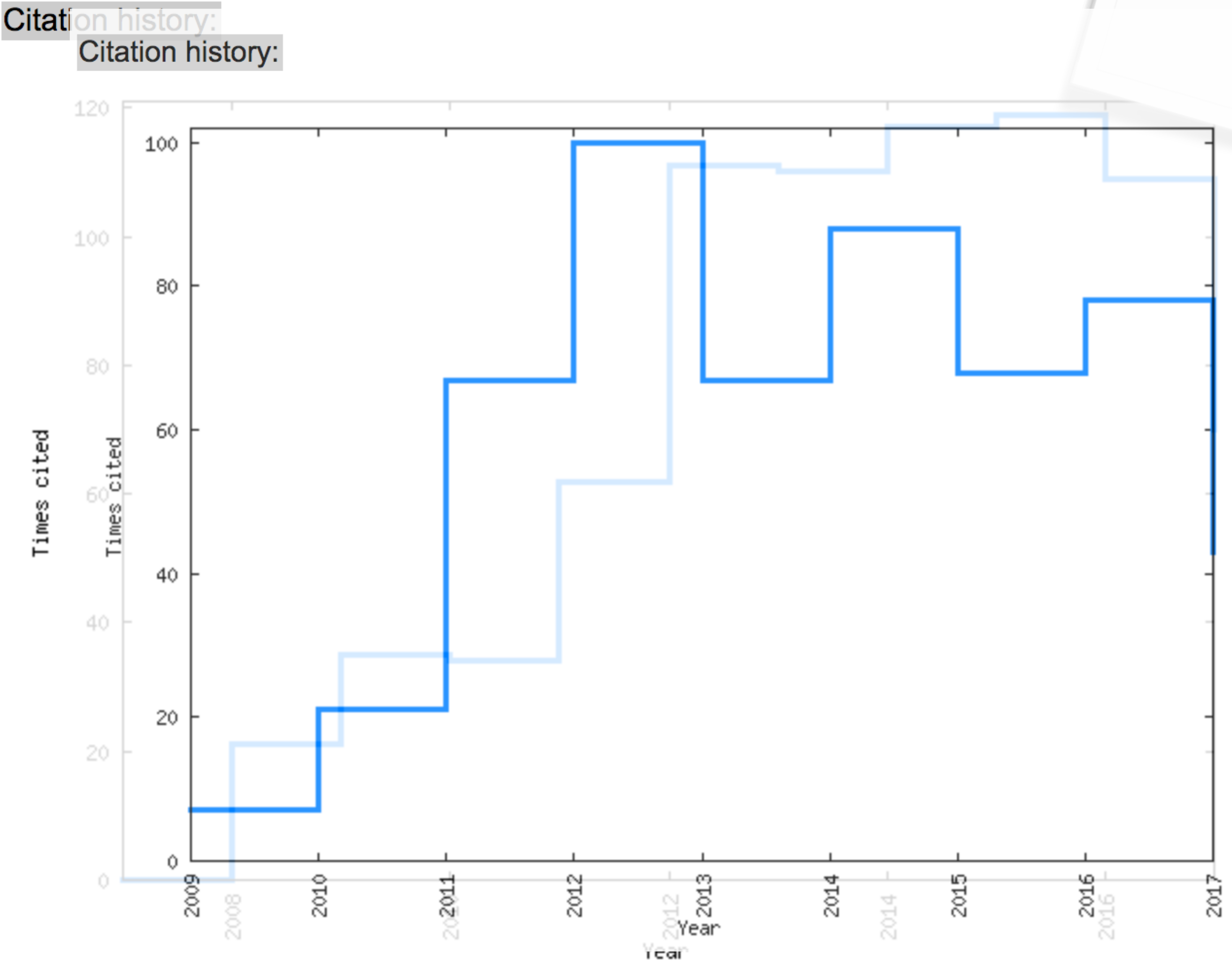
Brian Willett

California Institute of Technology
Email: bwillett@caltech.edu

Itamar Yaakov

California Institute of Technology
Email: itamar.yaakov@caltech.edu

formula
Wilson loop operator
supersymmetric Yang-Mills theory on a
ensional $\mathcal{N} = 2$ superconformal gauge theory is treated

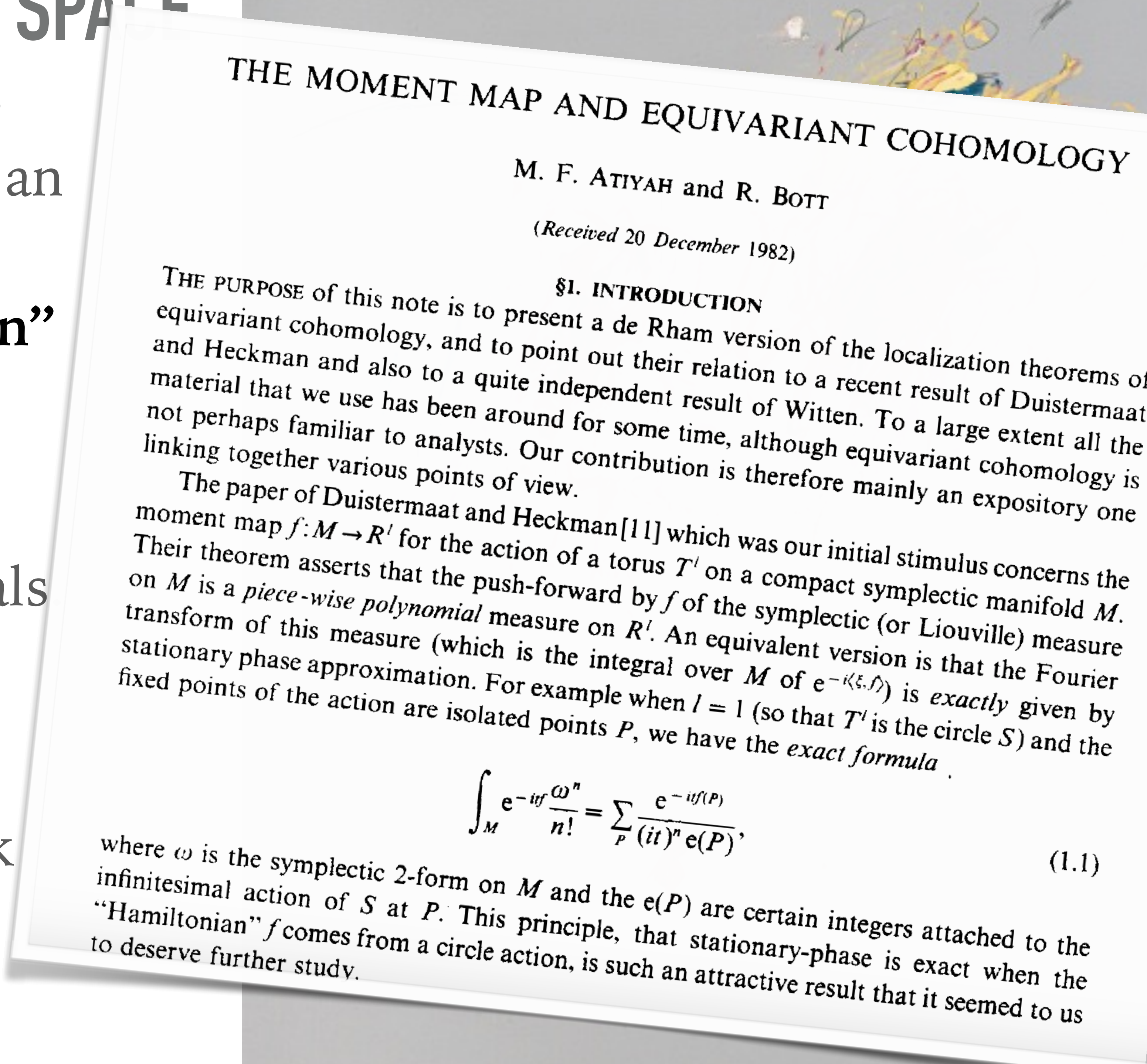


SUPERSYMMETRY IN CURVED SPACE

- In the last 10 years, there was an explosion of so-called **“supersymmetric localization”** results.
- **Localization** is a property of supersymmetric (path) integrals. It’s the usual **fermion-boson cancelation** in fancy garb.

SUPERSYMMETRY IN CURVED SPA

- In the last 10 years, there was an explosion of so-called **“supersymmetric localization”** results.
- Localization is a property of supersymmetric (path) integrals It’s the usual fermion-boson cancelation in fancy garb.
- It’s also something we can talk to mathematicians about…



THE MOMENT MAP AND EQUIVARIANT COHOMOLOGY

M. F. ATIYAH and R. BOTT

(*Received 20 December 1982*)

§1. INTRODUCTION

THE PURPOSE of this note is to present a de Rham version of the localization theorems of equivariant cohomology, and to point out their relation to a recent result of Duistermaat and Heckman and also to a quite independent result of Witten. To a large extent all the material that we use has been around for some time, although equivariant cohomology is not perhaps familiar to analysts. Our contribution is therefore mainly an expository one linking together various points of view.

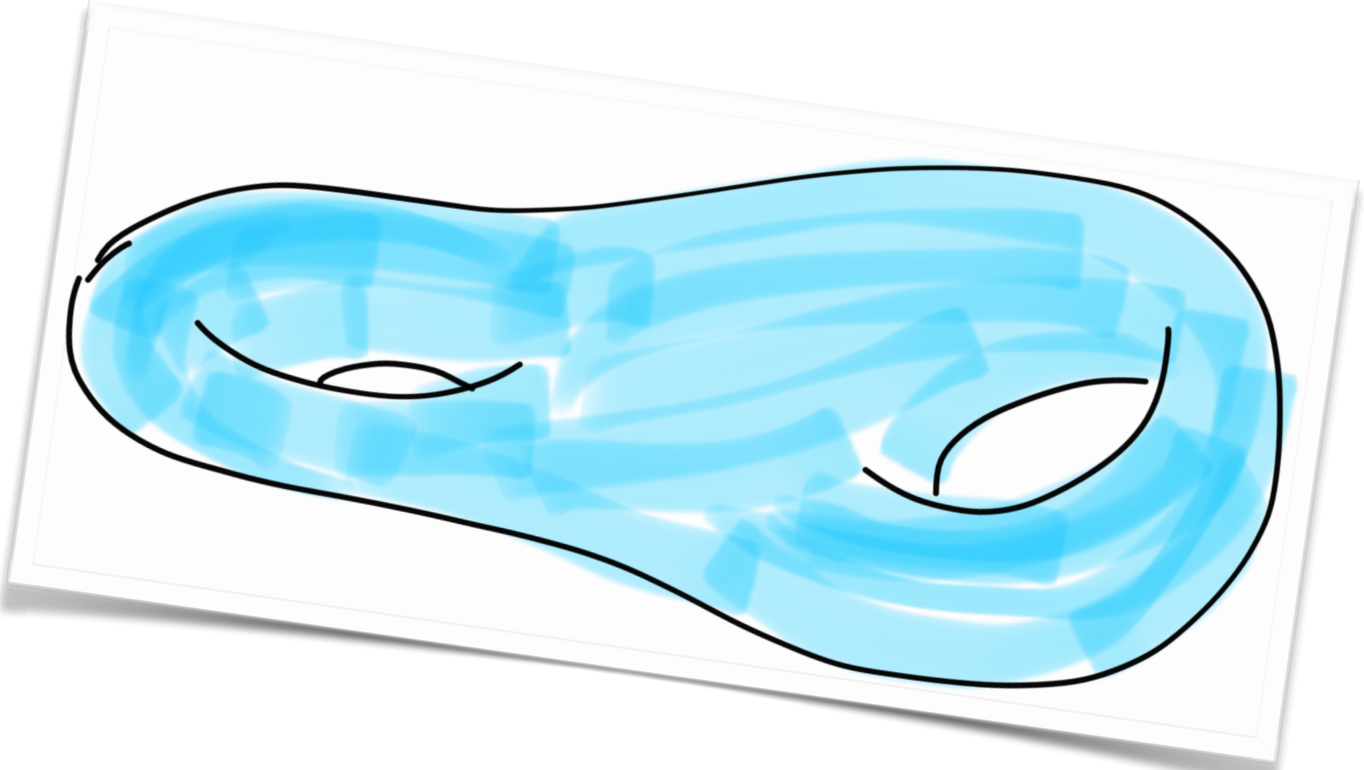
The paper of Duistermaat and Heckman[11] which was our initial stimulus concerns the moment map $f: M \to R^l$ for the action of a torus T^l on a compact symplectic manifold M. Their theorem asserts that the push-forward by f of the symplectic (or Liouville) measure on M is a *piece-wise polynomial* measure on R^l. An equivalent version is that the Fourier transform of this measure (which is the integral over M of $e^{-i\langle\xi,f\rangle}$) is *exactly* given by stationary phase approximation. For example when $l = 1$ (so that T^l is the circle S) and the fixed points of the action are isolated points P, we have the *exact formula* .

$$\int_M e^{-itf}\frac{\omega^n}{n!} = \sum_P \frac{e^{-itf(P)}}{(it)^n e(P)}, \qquad (1.1)$$

where ω is the symplectic 2-form on M and the $e(P)$ are certain integers attached to the infinitesimal action of S at P. This principle, that stationary-phase is exact when the “Hamiltonian” f comes from a circle action, is such an attractive result that it seemed to us to deserve further study.

SUPERSYMMETRY IN CURVED SPACE

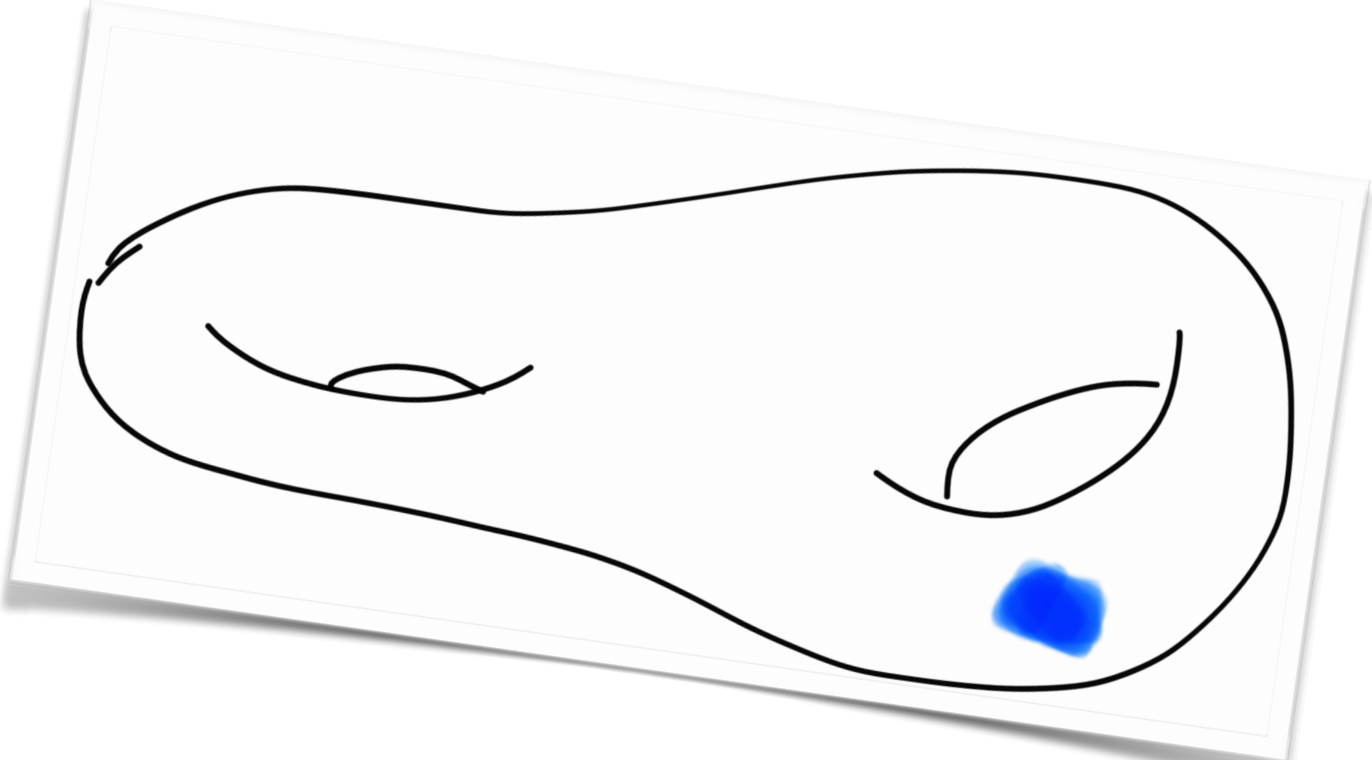
- A key ingredient in the recent line of development is to consider supersymmetric QFT on curved spaces **M**.
- There is a whole technology that goes into just defining supersymmetric couplings to **M**, which kept me busy for a bit (2011-2014).



Cy Twombly, 1963

SUPERSYMMETRY IN CURVED SPACE

- From the study of curved space SUSY, it was realised that localisation results are “almost” topological in nature.
- One of my current goal in life is to build the corresponding almost-TFT structure.



Cy Twombly, 1963

SUPERSYMMETRY IN CURVED SPACE

- From the study of curved space SUSY, it was realised that localisation results are “almost” topological in nature.
- One of my current goals in life is to build the corresponding almost-TFT structure.
- As part of this, I build “geometry-generating operators”.


Cy Twombly, 1963

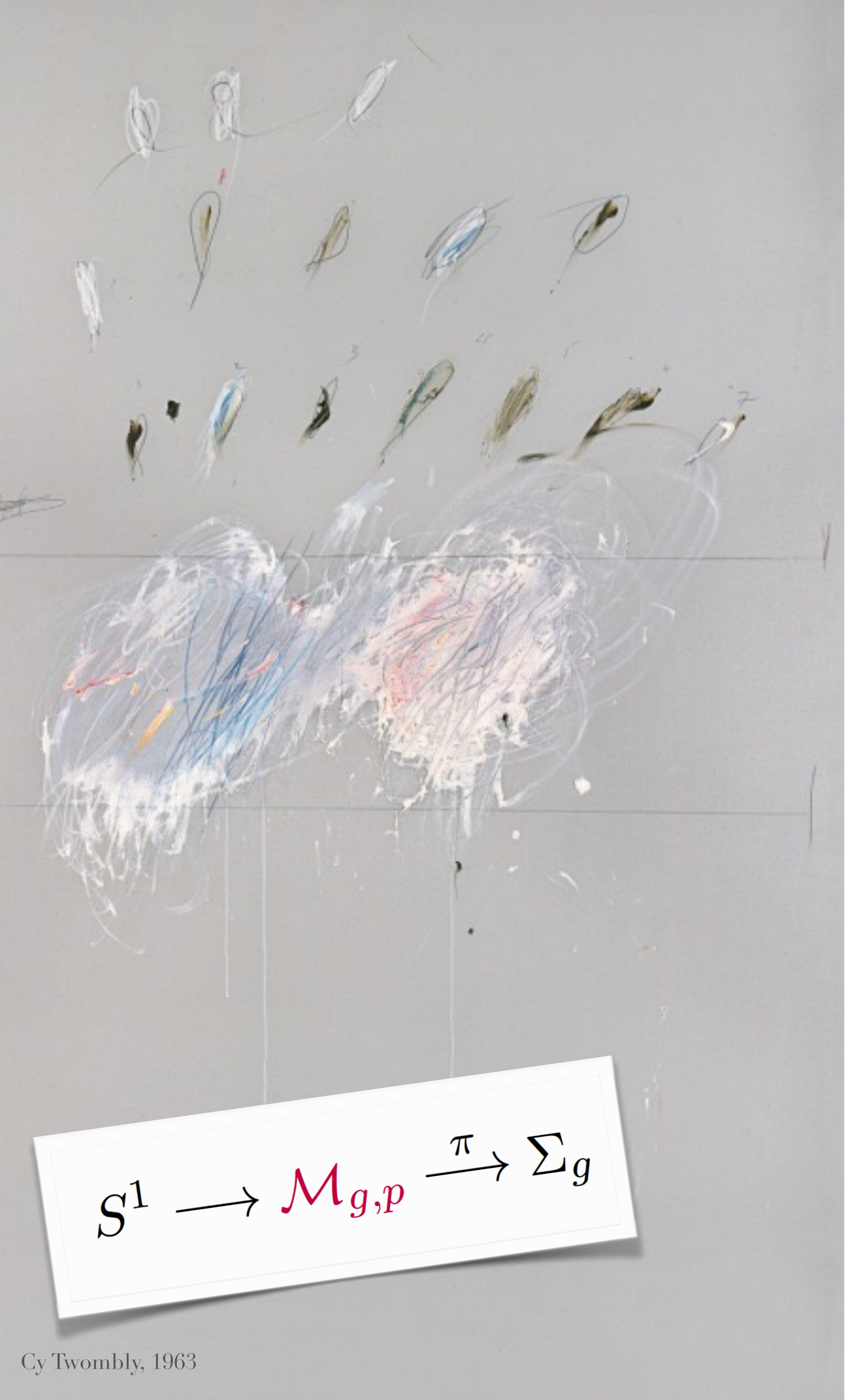

Cy Twombly, 1963

4D SUPERSYMMETRIC INDICES

- Consider the 4 manifold:

$$T^2 \longrightarrow \mathcal{M}_{g,p} \times S^1 \longrightarrow \Sigma_g$$

4D SUPERSYMMETRIC INDICES



$$S^1 \longrightarrow \mathcal{M}_{g,p} \xrightarrow{\pi} \Sigma_g$$

Cy Twombly, 1963

- Consider the 4 manifold:

$$T^2 \longrightarrow \mathcal{M}_{g,p} \times S^1 \longrightarrow \Sigma_g$$

- The partition function on this 4-manifold computes an **index**:

$$\mathbf{I}_{\mathcal{M}_{g,p}} = \mathrm{Tr}_{\mathcal{M}_{g,p}} \left((-1)^F q^{2J+R} y^{Q_F} \right)$$

- It is defined for any 4d $\mathcal{N} = 1$ supersymmetric gauge theory with an R-symmetry.

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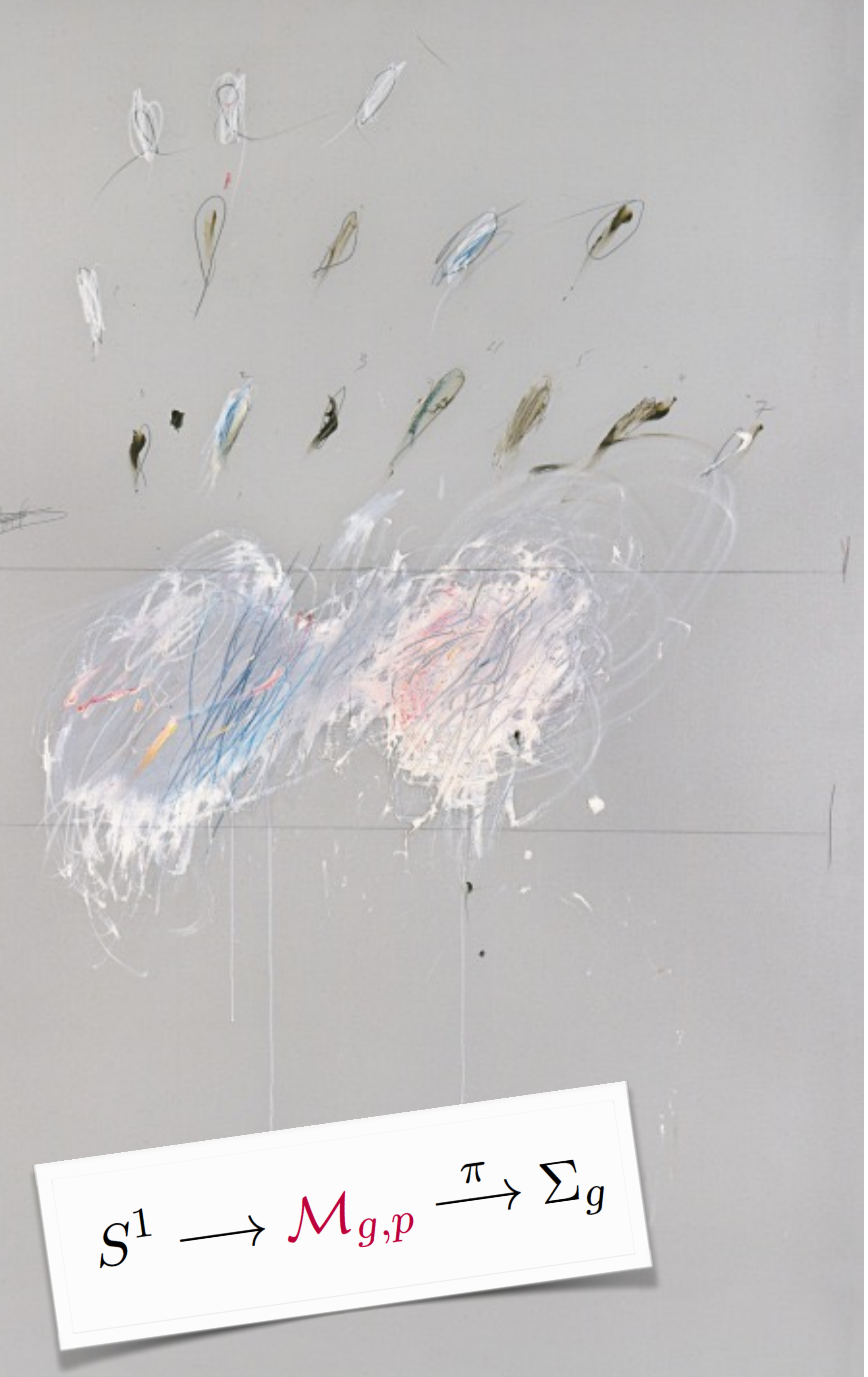
- It is defined for any 4d $\mathcal{N} = 1$ supersymmetric gauge theory with an R-symmetry.
- It can be computed by “building up” the geometry as a torus fibration.



$$S^1 \longrightarrow \mathcal{M}_{g,p} \xrightarrow{\pi} \Sigma_g$$

Cy Twombly, 1963

Cy Twombly, 1963

THE WITTEN INDEX OF SQCD

- Consider minimally SUSY SU(N) gauge theory with Nf flavors—a.k.a. **SQCD**
- As a nice spin-off of our result, we can compute the “regulated Witten index of SQCD”. That’s the special case of the above with p=0, g=1.
- We find:

$$\mathbf{I}_{SU(N),N_f} = \binom{N_f - 2}{N - 1}$$

- Simple new tests of Seiberg duality.

WORK IN PROGRESS; OUTLOOK

- We (i.e. friends and I and everyone else) only studied the simplest **half-BPS geometries** so far.

WORK IN PROGRESS; OUTLOOK

- We (i.e. friends and I and everyone else) only studied the simplest **half-BPS geometries** so far.
- We're currently building the tools to study *any* half-BPS geometry. Mathematics of **Seifert geometry** is mirrored in QFT.
  - An important motivation is to study half-BPS **surface defects** in $4\text{d}\ \mathcal{N}=1$ theories and their *fusion algebra.*

Cy Twombly, 1963

WORK IN PROGRESS; OUTLOOK

Exciting mathematical physics ahead!

CERN TH Retreat

16/11/17

Scattering Amplitudes in N=4 SYM

Brenda Penante


Paolo Panci
Wei Xue
Alberto Salvio
Diego Blas Temiño
Zvonimir Vlah
Bernhard Mistlberger
Diego Regalado
Amit Sever
Brenda Penante
Sophia Borowka
Kyriakos Papadodimas
Guido D'Amico
Seung-Joo Lee
Jonathan Gaunt
Claude Duhr
David Andriot
Cyril Closset
Timo Weigand
Piotr Tourkine
Eleni Vryonidou
Daniel Krefl
Andreas Stergiou
Lorenzo Tancredi
Alessandra Gnecchi
Benjamin Assel
Marius Wiesemann
Stefano Carrazza
Gavin Salam
Konstantinos Siampos
Stefan Kallweit
Jacopo Ghiglieri
Michelangelo Mangano
Emanuele Re
Giulia Zanderighi
Matthew Walters
Agostino Patella
Pier Monni
Patrick Fritzsch
Alexander Huss
Maxwell Hansen
Keith Hamilton
Dingyu Shao
Aleksi Kurkela
Konrad Tywoniuk
Andrey Katz
Marek Schoenherr
Matthew Philip Mccullough
Gian Giudice
Peter Richardson
Urs Wiedemann
Robert Ziegler
Jacobo Lopez Pavon
Andrea Thamm
Bin Wu
Marco Nardecchia
Francesco Riva
Andrea Wulzer
Rodrigo Alonso De Pablo
Riccardo Torre
Kfir Blum
Jorge Martin Camalich
Martin Gonzalez-Alonso
Tien-Tien Yu


MSc
2011-12
PERIMETER INSTITUTE
PhD
2013-16
Queen Mary
University of London
PD
2015-16
HUMBOLDT-UNIVERSITÄT · ZU BERLIN ·
Fellow
2017-present
CERN
UG
2007-10
VIRTUS IMPAVIDA
UFPE
TA
2012
AIMS
African Institute for Mathematical Sciences
SOUTH AFRICA

Overview of N=4 SYM

4-dimensional max. supersymmetric Yang-Mills theory

Field content combined into one multiplet

$$\begin{array}{cccccc} \Phi & g^{+} & \psi & \phi & \bar{\psi} & g^{-} \\ & & 4 & 6 & 4 & \end{array}$$

$$\longrightarrow$$

$$Q_I\,, \quad I = 1, 2, 3, 4$$

Only one particle, massless

Why study N=4 SYM?

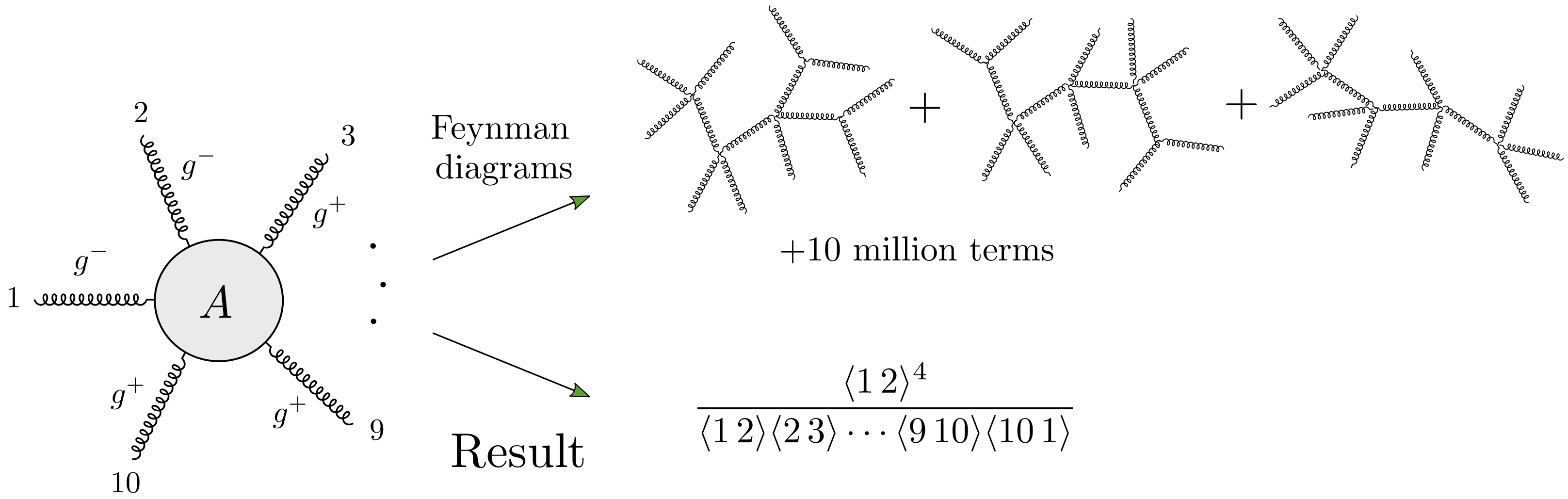
Simple, yet non-trivial 4D QFT---

Safe environment for testing methods ---

Conceptually interesting --- Symmetries/dualities

Tree-level scattering

Hidden simplicity



Feynman diagrams

+10 million terms

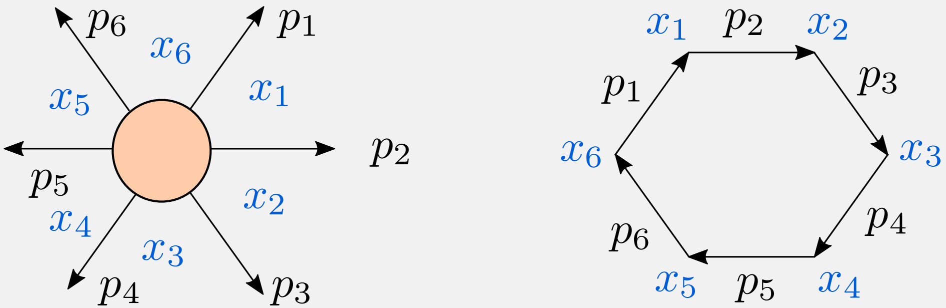
Result

$$\frac{\langle 1\,2\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\cdots\langle 9\,10\rangle\langle 10\,1\rangle}$$

Symmetries / Dualities

Conformal - $\beta_g = 0$

Planar limit - SU(N), N $\rightarrow \infty$



$p_i = x_{i+1} - x_i$

Dual conformal symmetry

Conformal + dual conformal = ∞-dimensional symmetry

Integrability, AdS/CFT

Scattering in N=4

Simplicity - loop

~~Symmetry~~

IR divergences

Integrand

- Unitarity cuts
- Recursion
- Geometric description

Grassmannian/Amplituhedron/etc

Remainders

(IR subtraction)

Understand functions + special limits

↓ Bootstrap

Results for high loop/multiplicity

Interests & work in progress

Form factors

On shell

Off shell

$$\langle 1,\ldots,n|0\rangle$$

$$p_i^2 = 0$$

$$\langle 1,\ldots,n|\mathcal{O}(x)|0\rangle$$

$$\langle 0|\mathcal{O}_1(x_1)\cdots\mathcal{O}_n(x_n)|0\rangle$$

$$F_{\mathcal{O}}(1,\ldots,n;q) = \int d^4x e^{-iqx}\langle 1,\ldots,n|\mathcal{O}(x)|0\rangle$$

$$q^2 \neq 0$$

Applications in EFT $\mathcal{L}_{\mathrm{EFT}} = \mathcal{L} + \frac{c_i}{\Lambda}\mathcal{O}_i$

Purpose: Extend amplitudes-inspired techniques to more generic objects and N<4 with Brandhuber, Kostacinska, Spence, Travaglini, Young, Wen

Protected

$\mathrm{Tr}(\phi^k) \to k$ scalars @ 2-loops "minimal"

$\mathrm{Tr}(\phi^k) \to n$ particles @ 1-loop

Non-protected

$\mathrm{Tr}(X[Y,Z]), \mathrm{Tr}(\psi\psi) \to X, Y, Z$ @ 2-loops

3 complex scalars

$\mathrm{Tr}(F^3_{\mathrm{ASD}}) \to g^+ g^+ g^+$ @ 2-loops (also for N<4 cut constructible)

Protected operators encompass max. transc. part of other FFs with Brandhuber, Kostacinska, Spence, Travaglini, Young, Wen

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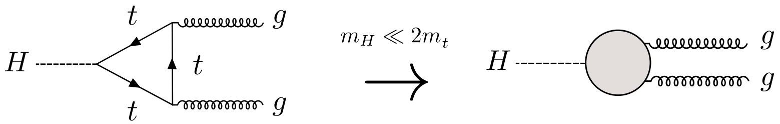
3 complex scalars

$\mathrm{Tr}(F_{\mathrm{ASD}}^3) \to g^+g^+g^+$ @ 2-loops (also for N<4 cut constructible)

Protected operators encompass max. transc. part of other FFs

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L} + H\,\mathrm{Tr}(F^2) + \frac{1}{m_{\mathrm{top}}^2}\sum_{i=1}^{4} c_i \mathcal{O}_i + \mathcal{O}\left(\frac{1}{m_{\mathrm{top}}^4}\right)$$

$$\mathrm{Tr}(F_{\mathrm{SD}}^3) + \mathrm{Tr}(F_{\mathrm{ASD}}^3)$$



other work + in progress

with Franco, Galloni, Meidinger, Nandan, Wen

On-shell diagrams (1/N corrections)
Form factors & Grassmannians

with Caron-Huot, Del Duca, Duhr, Dulat

Scattering amplitudes in multi-Regge kinematics

with Duhr, Tancredi

Mathematical properties of loop integrals (elliptic)

other work + in progress

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Thank you!

CERN-TH Retreat
15-17 Nov 2017

Alessandra Gnecchi

H2020-MSCA-IF-2015
702548 GaugedBH

About me:

UNIVERSITÀ DEGLI STUDI DI PADOVA

2009-2012 advisor G. Dall'Agata

(CERN 2008)

Utrecht University
2012-2014

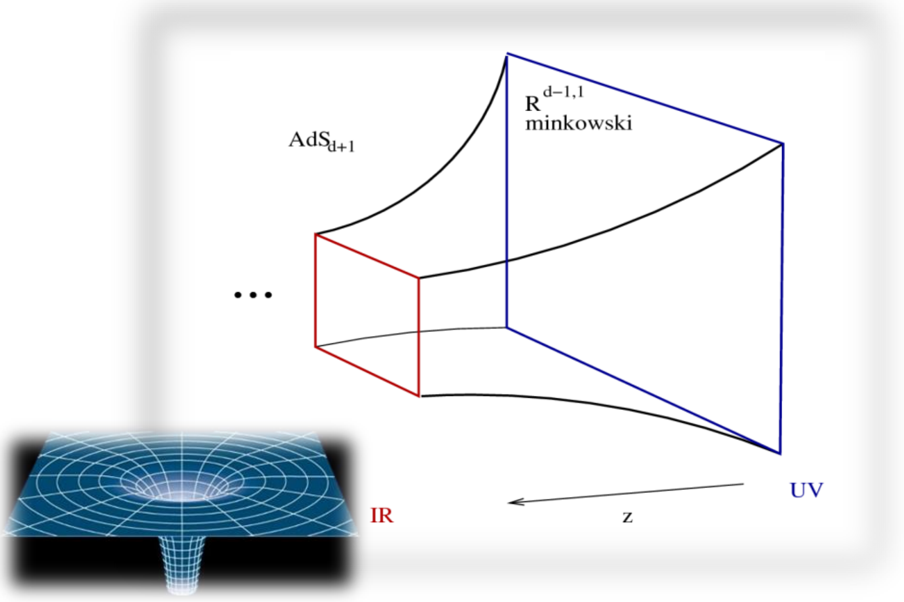
2014-2017
KU LEUVEN

CERN

European Commission
April 2017

About my research

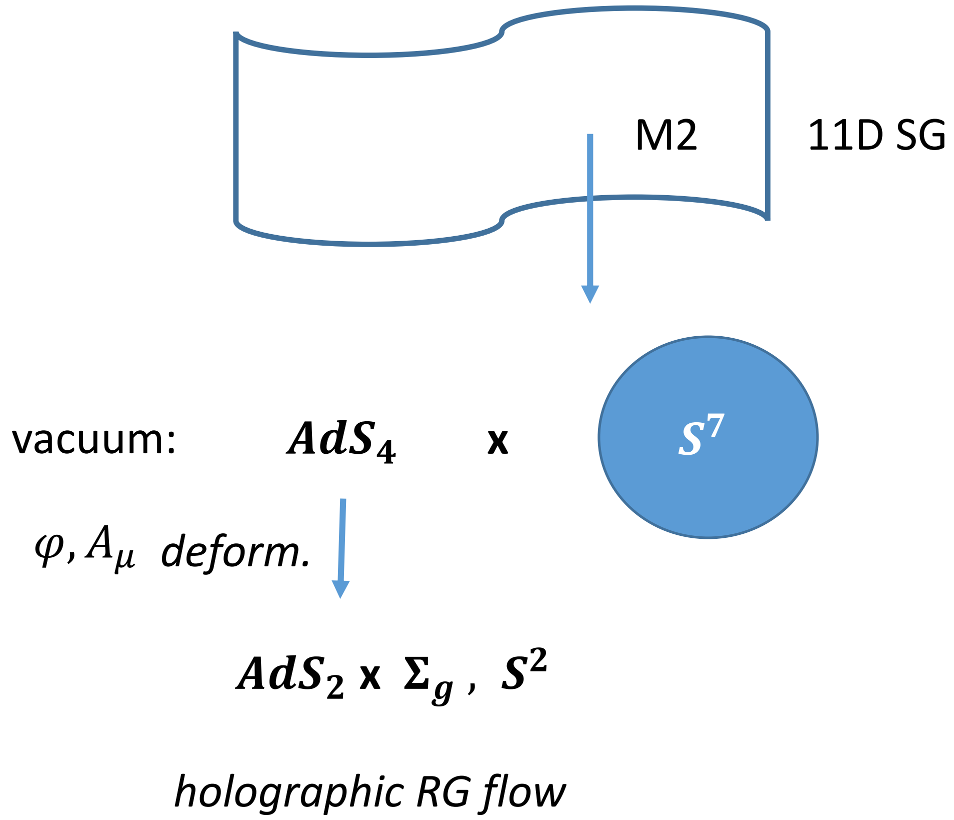
- Black holes
  - what is the origin of black hole entropy?
  - how is unitarity preserved in black hole evaporation?
- Supergravity
  - ✓ Count black hole microstates from D-branes constituents
- Holography
  - Formulate the information paradox through quantum mechanics and quantum information theory
  - Study black holes in AdS as states of a dual field theory



Black holes in Supersymmetric theories

- Construction of BPS states from String/M-theory
  - Origin from intersecting branes
- Holographic renormalization
  - Dual state ≡ gravity solution + boundary conditions
- Thermodynamics
  - Quantum phase transitions

    Supersymmetry selects specific ensemble and boundary conditions!



vacuum: $\boldsymbol{AdS_4}$ **x** $\boldsymbol{S^7}$

φ, A_μ *deform.*

$\boldsymbol{AdS_2}$ **x** $\boldsymbol{\Sigma_g}$, $\boldsymbol{S^2}$

holographic RG flow

Black holes in Supersymmetric theories

- Construction of BPS states from String/M-theory
  - Origin from intersecting branes
- Holographic renormalization
  - Dual state ≡ gravity solution + boundary conditions
- Thermodynamics
  - Quantum phase transitions

Supersymmetry selects specific ensemble and boundary conditions!

$$m_{\varphi}{}^{2}\ell^{2} = -2$$

$$\varphi(r) \sim \frac{\alpha}{r} + \frac{\beta(\alpha)}{r^{2}} + \ \ldots$$

$$A_{\mu}dx^{\mu} = \mathrm{p}\ \cos\theta\ d\phi$$

$$S_{on-shell} = \ \beta_{t}(M - TS\ - q\ \Phi) = -\log\mathcal{Z}$$

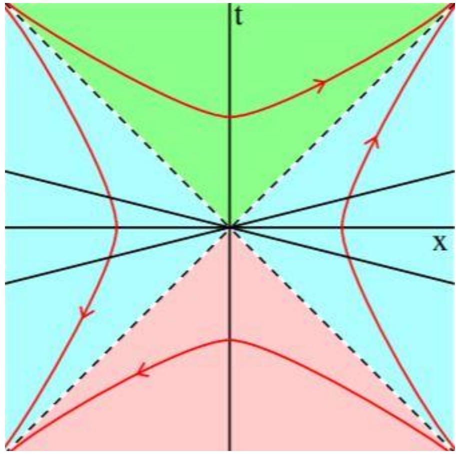
$$dM = T\ dS + \Phi\ dq\ + \chi\ dp$$

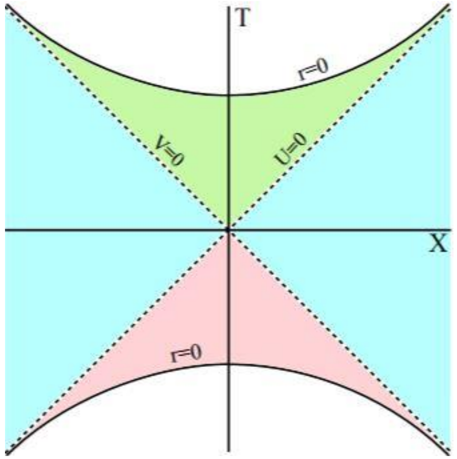
w/ Gursoy,
Papadoulaki,
Toldo, Cassani

Holography for the Information Paradox

- Old Information paradox
  - Hawking radiation has a thermal distribution
  - A possible resolution: information is stored in the entanglement among emitted quanta
  - Mathur: the effective description breaks down at horizon scales

- Recent formulation of the Information paradox *aka* “firewalls” [AMPS]
  - Entangled emitted quanta violate the strong subadditivity of entropy
  - **Is the interior of black holes smooth?**
  - Proposal: the dual CFT contains all black hole degrees of freedom [Papadodimas, Raju]



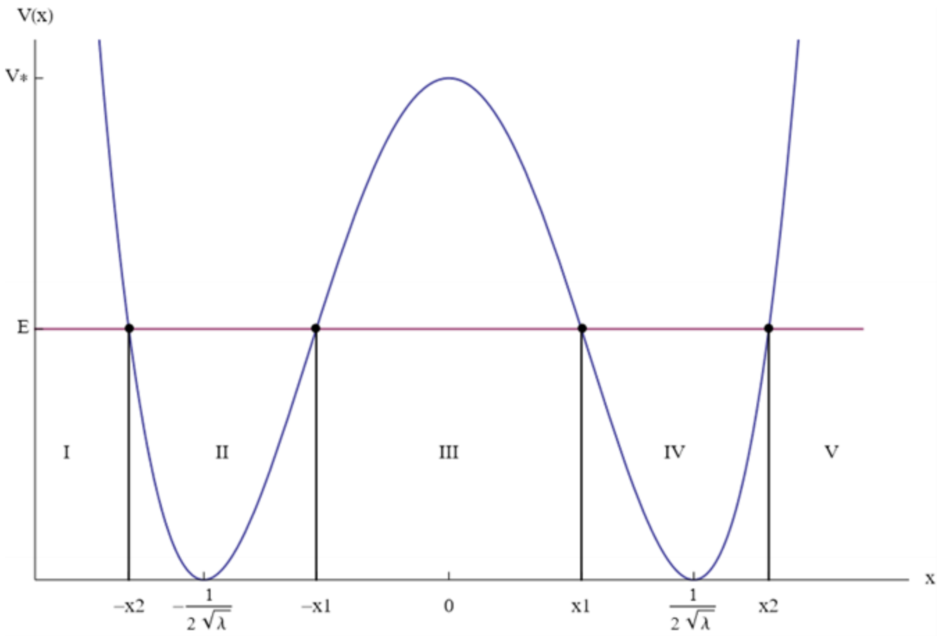


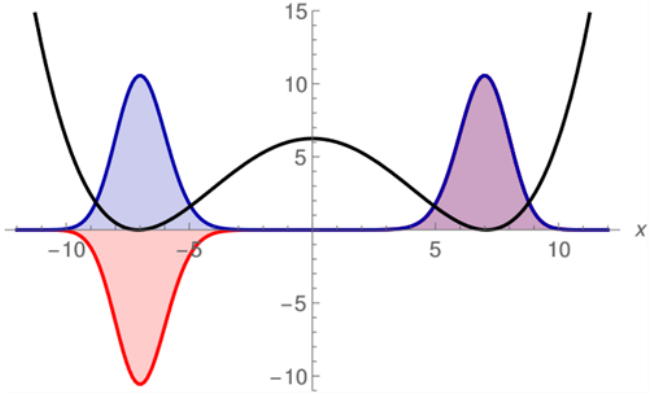
WIP: Explore the effective theory with a toy model

Double well potential

- is solvable
- perturbative parameter $\lambda \sim \frac{1}{N^2}$
- scattering matrix from black hole = inverted h.o.

$$\psi \mapsto \psi^{\mathrm{dbl}} = \frac{1}{\mathcal{N}} \sum_{i,j=0}^{\infty} \gamma_i^L \gamma_j^R \, \Psi_i^L \otimes \Psi_j^R \in \mathcal{H}_L \otimes \mathcal{H}_R$$





The effective theory creates degeneracy among states

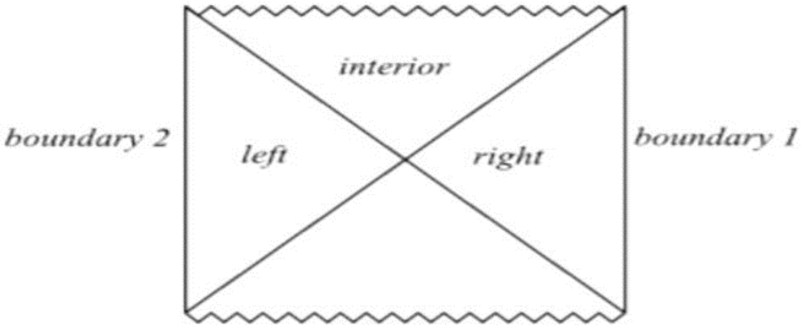
Interactions between the two minima manifest in non perturbative effects

w/Bzowski, Hertog

WIP: Double sided eternal black hole in anti-de Sitter

From the point of view of the observer on one side, the black hole state is thermal

$$|\Psi_{\mathrm{tfd}}\rangle = \frac{1}{\sqrt{Z(\beta)}} \sum_E e^{-\frac{\beta E}{2}} |E, E\rangle.$$



is a purification of the thermal state in a double copy CFT

- Entanglement structure

$$\langle \mathcal{O}_R \mathcal{O}_L \rangle_{tfd} \;\sim\; O(1)$$

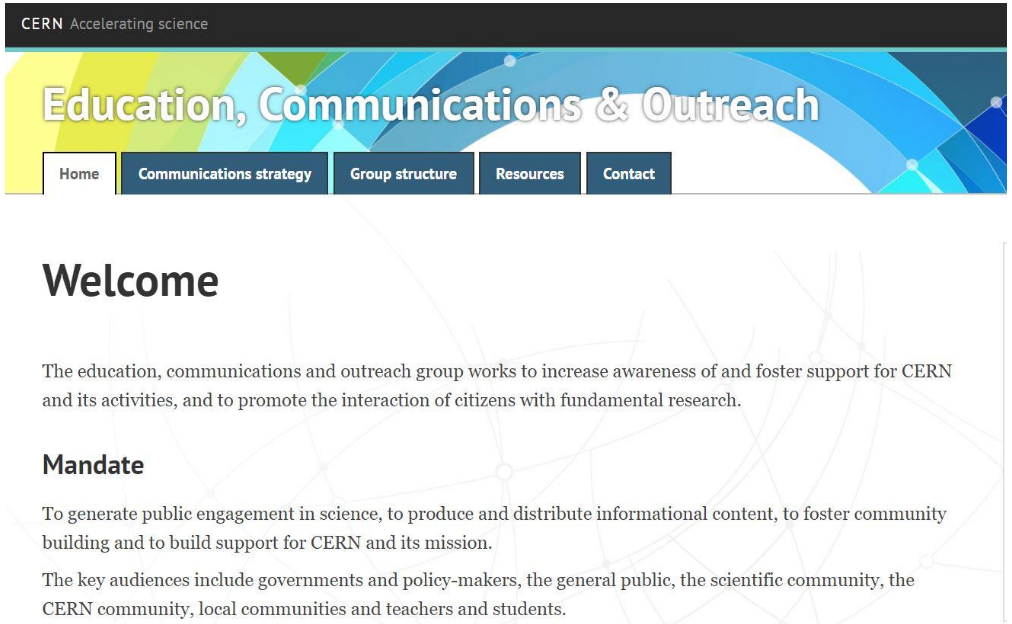
Does the entropy of the eternal black hole have the same statistical interpretation of RN black holes?
(as counted, e.g. for BPS black holes, from holography) or is it just entanglement?
Are there other *micro*states in the dual CFT?

- Can the dual CFT describe the black hole interior?

w/ Kyriakos Papadodimas

MSCA ⊃ Outreach

- CERN ECO Department
- Events related to EC programs, e.g. Marie Curie Day (win a photo shoot!)
- Italian Teachers Program (coordinator: Antonella del Rosso)



Welcome

The education, communications and outreach group works to increase awareness of and foster support for CERN and its activities, and to promote the interaction of citizens with fundamental research.

Mandate

To generate public engagement in science, to produce and distribute informational content, to foster community building and to build support for CERN and its mission.

The key audiences include governments and policy-makers, the general public, the scientific community, the CERN community, local communities and teachers and students.

CERN TH Institute

<u>Black holes, quantum information and the reconstruction of space-time</u>
August 20-31, 2018
AG, Kyriakos Papadodimas (local)
Monica Guica (Saclay), Andrea Puhm (Ecole Polythecnique)

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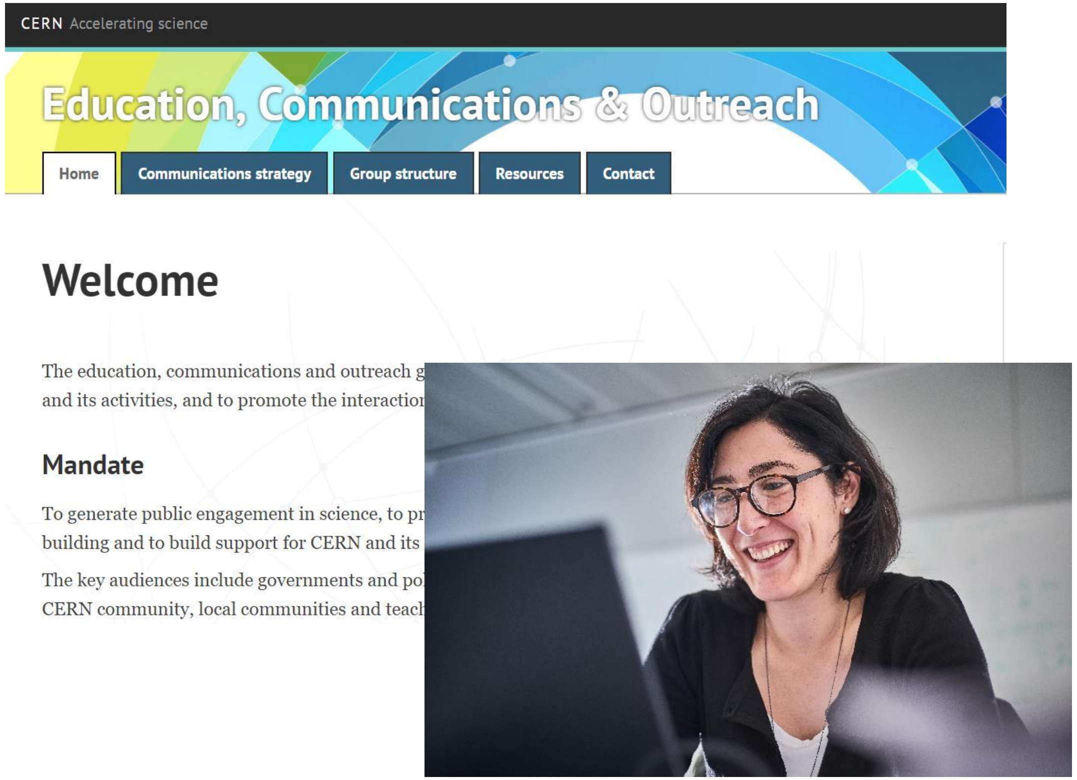

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Italian Teacher Programme

19 Nov 2017, 17:00 → 24 Nov 2017, 12:30 Europe/Zurich

CERN

Antonella Del Rosso (CERN) , Jeff Wiener (CERN) , Silvia Miozzi (Universita e INFN Roma Tor Vergata (IT))

Description The **Italian Teacher Programme 2017** will take place from 19-24 November 2017. Lectures, on-site visits, exhibitions, and hands-on workshops will introduce its participants to cutting-edge particle physics. We hope our participants will go back to Italy as ambassadors, who pass on the subject to our next generation of physicists, engineers, IT specialists ...

Italian Teacher Programme 2017:
https://indico.cern.ch/e/ITTP17-3

Teacher Programme Manager:
Jeff Wiener: 0041 75 411 9010

In case of emergency:
CERN fire brigade: 0041 22 76 74444

CERN TH Institute

<u>Black holes, quantum information and the reconstruction of space-time</u>
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AG, Kyriakos Papadodimas (local)
Monica Guica (Saclay), Andrea Puhm (Ecole Polythecnique)

Thank you!

From formal theory to ML and back

Daniel Krefl

* Research topics and interests *

But first a little background intro …

CV

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Academia:

- PhD at LMU Munich
  Most of my relevant research done at CERN as Marie-Curie fellow
  (Open string mirror symmetry, unoriented topological strings)

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- 1y research stay at IPMU, Tokyo
  (B-model formalism for Ω-deformed $\mathcal{N}=2$ gauge theories and top. strings)

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  (B-model formalism for Ω-deformed $\mathcal{N} = 2$ gauge theories and top. strings)
- Simons fellow at UC Berkeley
  (Perturbative quantum geometry for top. strings in the NS limit)

CV

Academia:

- Researcher at Seoul National University (Non-perturbative quantum geometry, all N gauge/string duality)

CV

Academia:

- Researcher at Seoul National University
  (Non-perturbative quantum geometry, all N gauge/string duality)
- Fellow at CERN
  (Non-perturbative quantum geometry)
  (Machine learning -> Mathematics/Theory -> Machine learning)

Some beef …

ML -> Physics/Mathematics

The question (in a nutshell):

(with R.-K. Seong)

- Can we do formal theory / mathematics in a data science way ? (How would an AI do math ?)

ML -> Physics/Mathematics

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- "Learning by looking at examples … (vast amounts of)"

ML -> Physics/Mathematics

The question (in a nutshell):

(with R.-K. Seong)

- Can we do formal theory / mathematics in a data science way ? (How would an AI do math ?)
- "Learning by looking at examples … (vast amounts of)"
- Uncovering hidden relations and statistical "proofs/evidence" => LHC of the theorist

ML -> Physics/Mathematics

Concrete example:

(with R.-K. Seong)

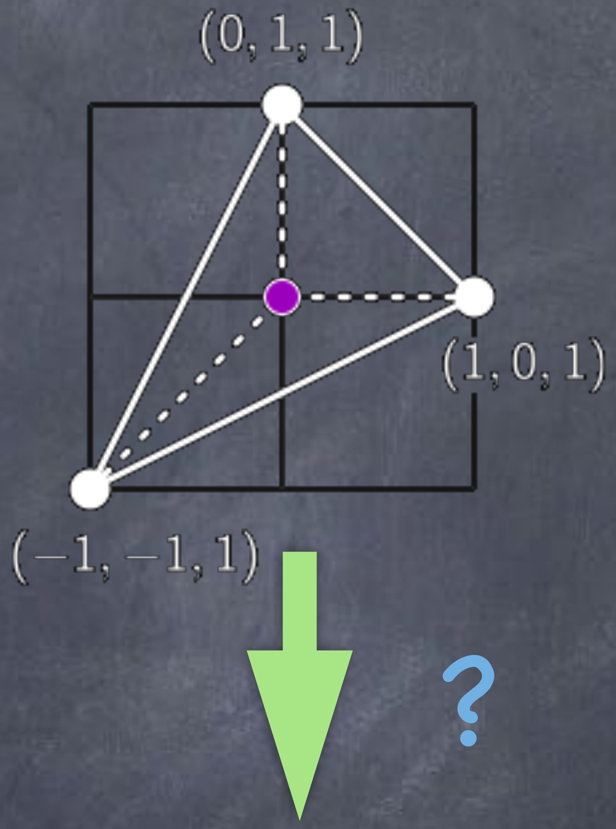
Toric Calabi-Yau 3-fold (non-compact)

D3-branes

AdS/CFT

$a \sim 1/V$

$$\underset{R}{\operatorname{argmax}}\, a(R)$$



$$V_{min} = \underset{b}{\operatorname{argmin}}\, V(b_i)$$

ML -> Physics/Mathematics

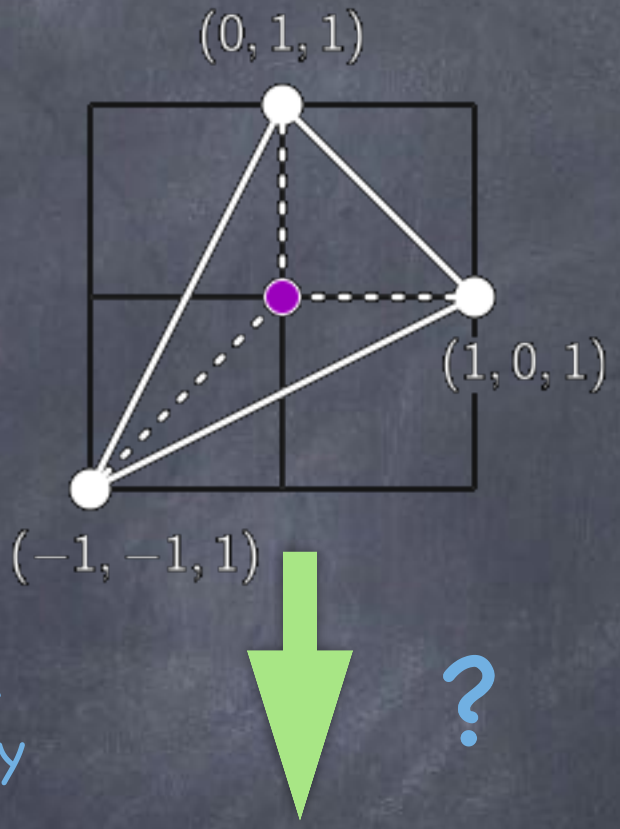
Concrete example:

(with R.-K. Seong)

$$V_{min} \overset{?}{=} F(\mathcal{T})$$

Some function

Topological data of the geometry



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ML -> Physics/Mathematics

Concrete example:

(with R.-K. Seong)

$$V_{min} \overset{?}{=} F(\mathcal{T})$$

The (novel) idea:

"Experimental mathematics"

Use machine learning to approximate such a function !

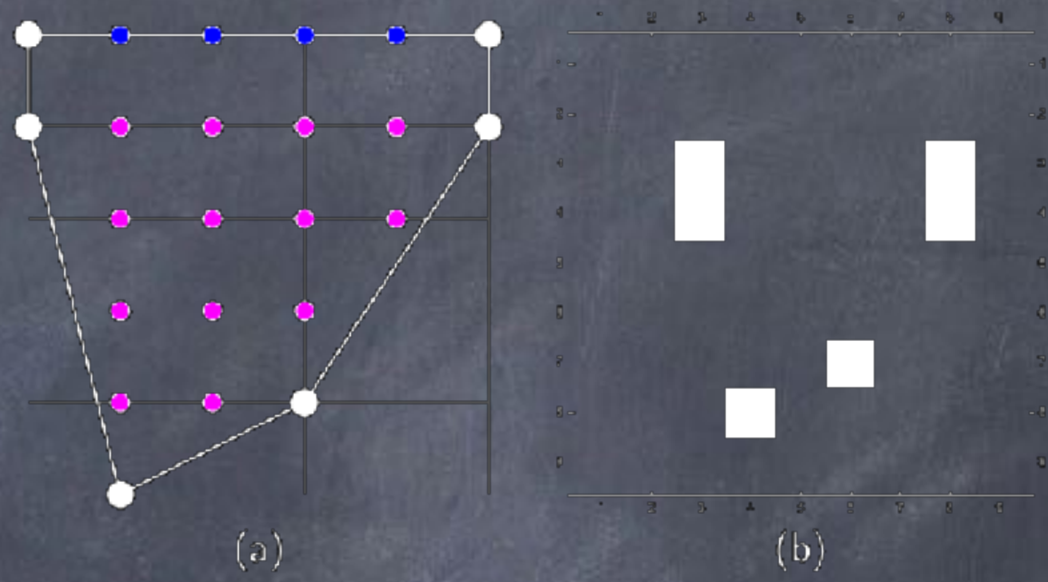
→ Evidence for existence
(if one is careful enough)

ML -> Physics/Mathematics

Train / Test data:

(with R.-K. Seong)

Use the geometric as input +
some handcrafted features



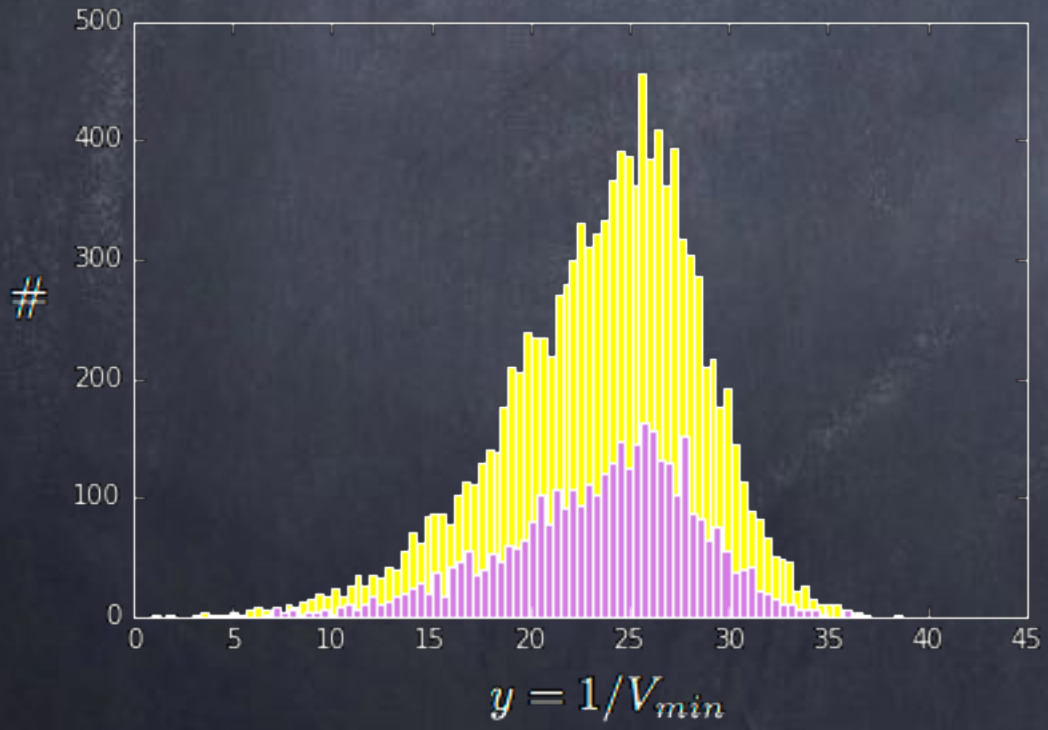
(a) (b)

$$1/V_{min} = 28.6533\ ,\ f_1 = I = 13\ ,\ f_2 = E = 10\ ,\ f_3 = V = 6$$

$$\mathcal{D} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(c)

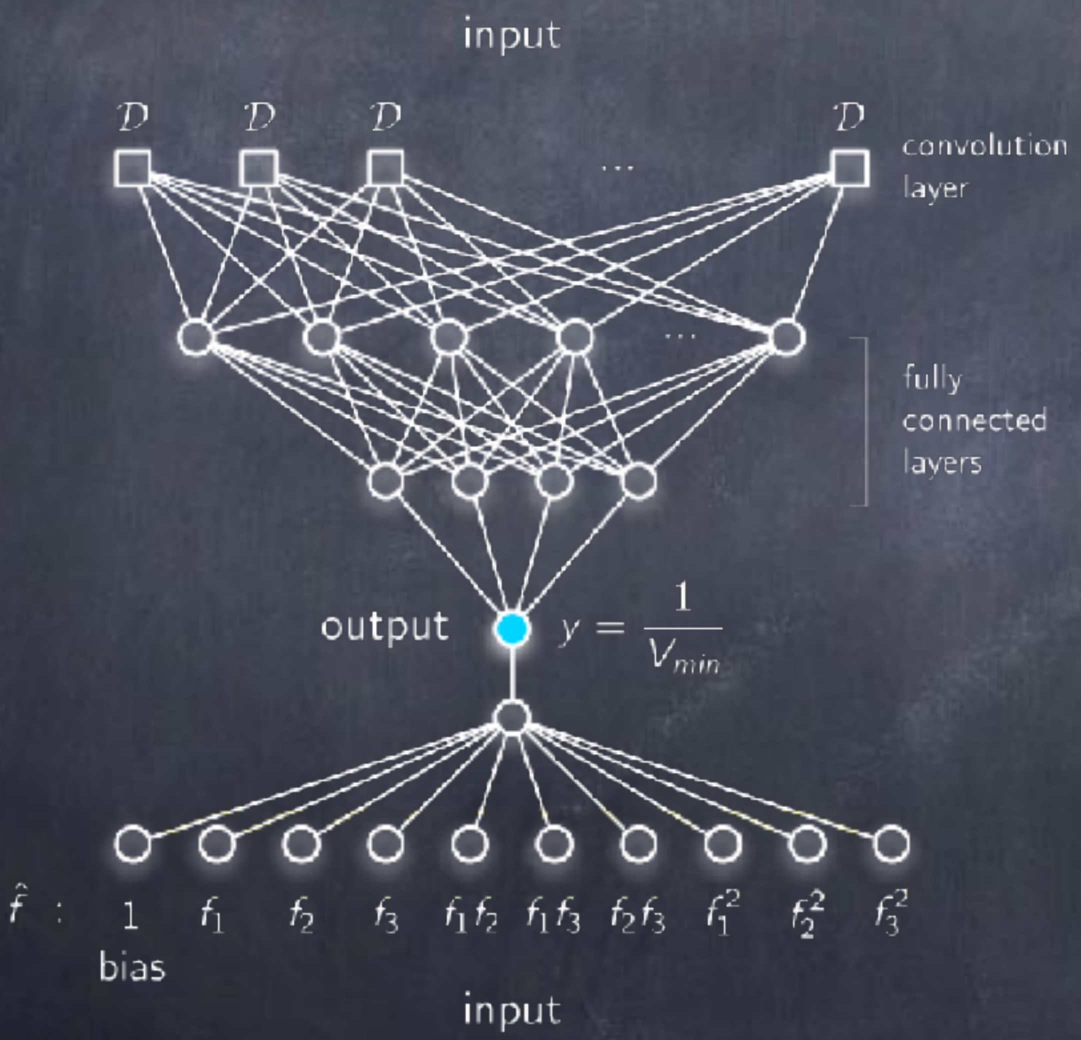
15k datapoints with 75/25 split



ML -> Physics/Mathematics

Train a deep and wide net:

(with R.-K. Seong)



Use the geometric as input +
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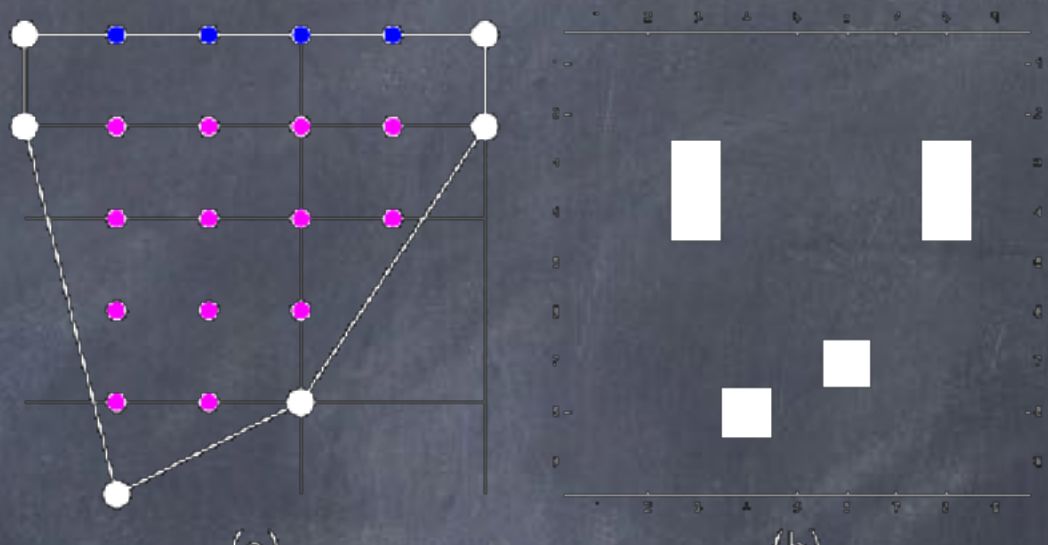

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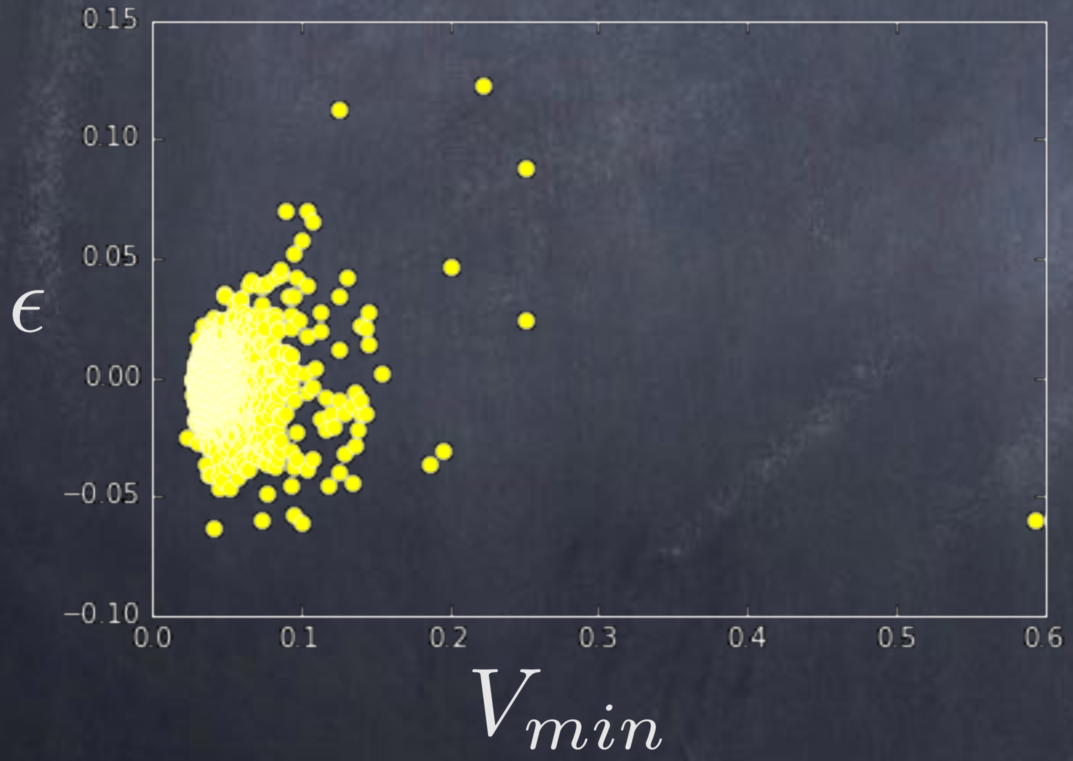
(c)

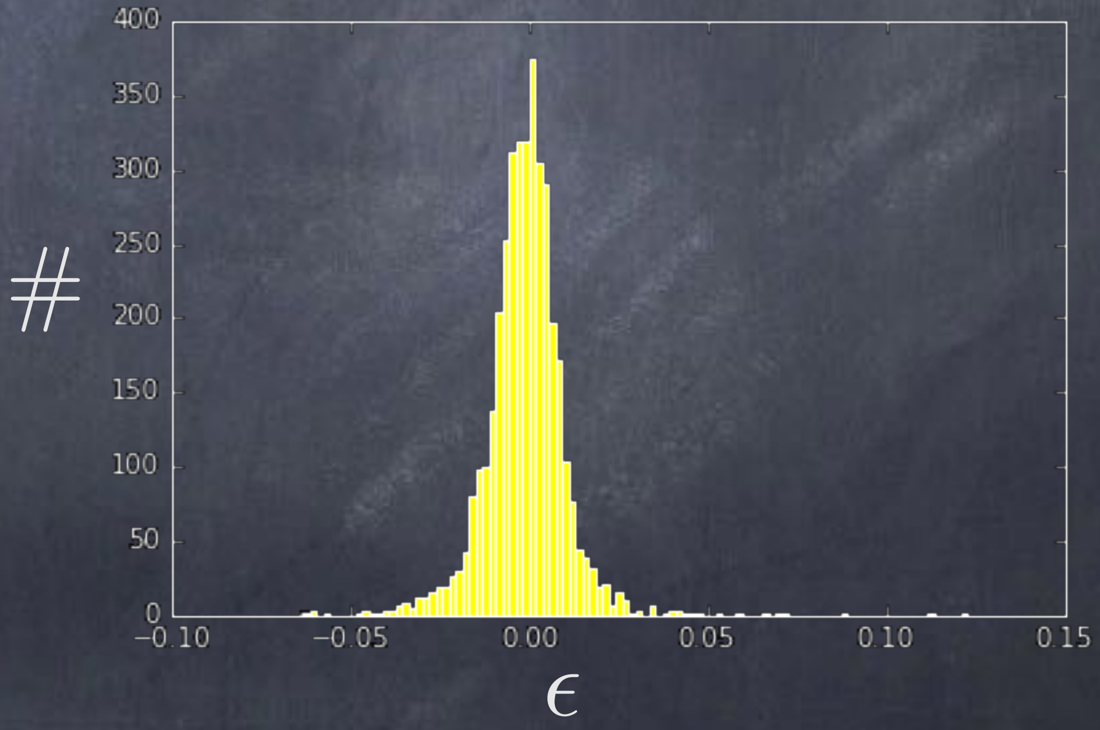
ML -> Physics/Mathematics

Result:

(with R.-K. Seong)

Expected error on independent test set < 1%





Appetizer …

ML <- Physics/Mathematics

Skunk Works project:

ML <- Physics/Mathematics

Skunk Works project:

with S. Carrazza, B. Haghighat, J. Kahlen
*** TBR end-of-year 2017 ***

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- Novel ML/AI framework harnessing the power of higher mathematics

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✷ Novel ML/AI framework harnessing the power of higher mathematics

Python code will be released as open source project

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*** TBR end-of-year 2017 ***

- Novel ML/AI framework harnessing the power of higher mathematics
- Python code will be released as open source project
- Opening up novel research area ... stay tuned !

… Thank you …