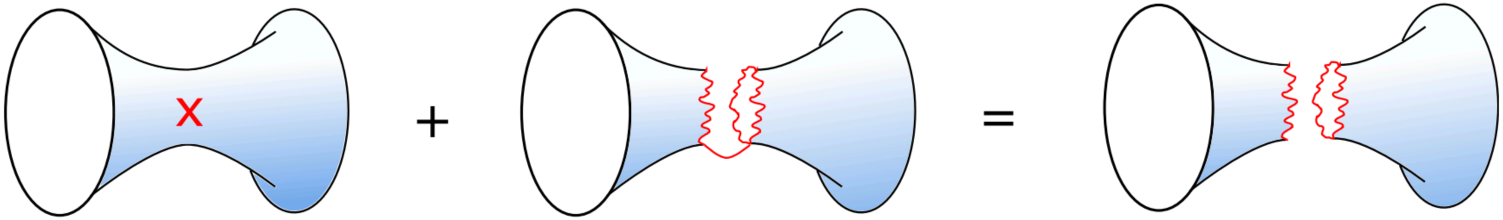
String/QFT group

CERN-TH retreat 2021



Fellows

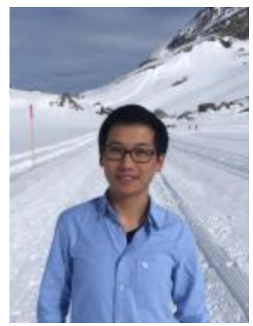
Pablo Bueno

Joao Caetano

Matthew Dodelson

Alex Belin

Shouvik Datta



Ling Lin

Guglielmo Lockhart

Gabor Sarosi

Staffs

Alba Grassi

Shota Komatsu

Kyriakos Papadodimas

Alexander Zhiboedov

Fellows

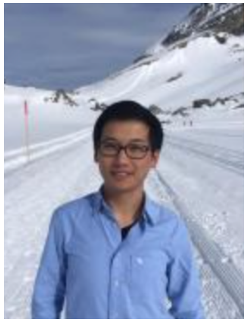
Pablo Bueno

Joao Caetano

Matthew Dodelson

Alex Belin

Shouvik Datta



Ling Lin

Guglielmo Lockhart

Gabor Sarosi

Staffs

Alba Grassi

Shota Komatsu

Kyriakos Papadodimas

Alexander Zhiboedov

Irene Valenzuela

Joining us in March!

Scientific Associates

Mirjam Cvetic

Emeri Sokatchev

Emeriti

Wolfgang Lerche

Sergio Ferrara

Students

Matijn Francois
(Working with Grassi)

Kelian Haering
(Working with Zhiboedov)

Miguel Correira
(Working with Zhiboedov)

Group Activities

- Journal Club: Monday 13:30

  Discussion of recent arXiv papers, Talks by members of the group, Discussion/review of important topics

- Seminar: Tuesday 14:00

Events

- CERN winter school on strings and fields: Feb 7-11, 2022

  Thomas van Riet: De Sitter in string theory,
  Dalimil Mazac: S-matrix/conformal bootstrap,
  Netta Engelhardt: Quantum gravity
  Matthias Gaberdiel: Exact AdS/CFT
  Fabian Ruehle: Machine learning
  Zohar Komargodski: Something cool about QFT

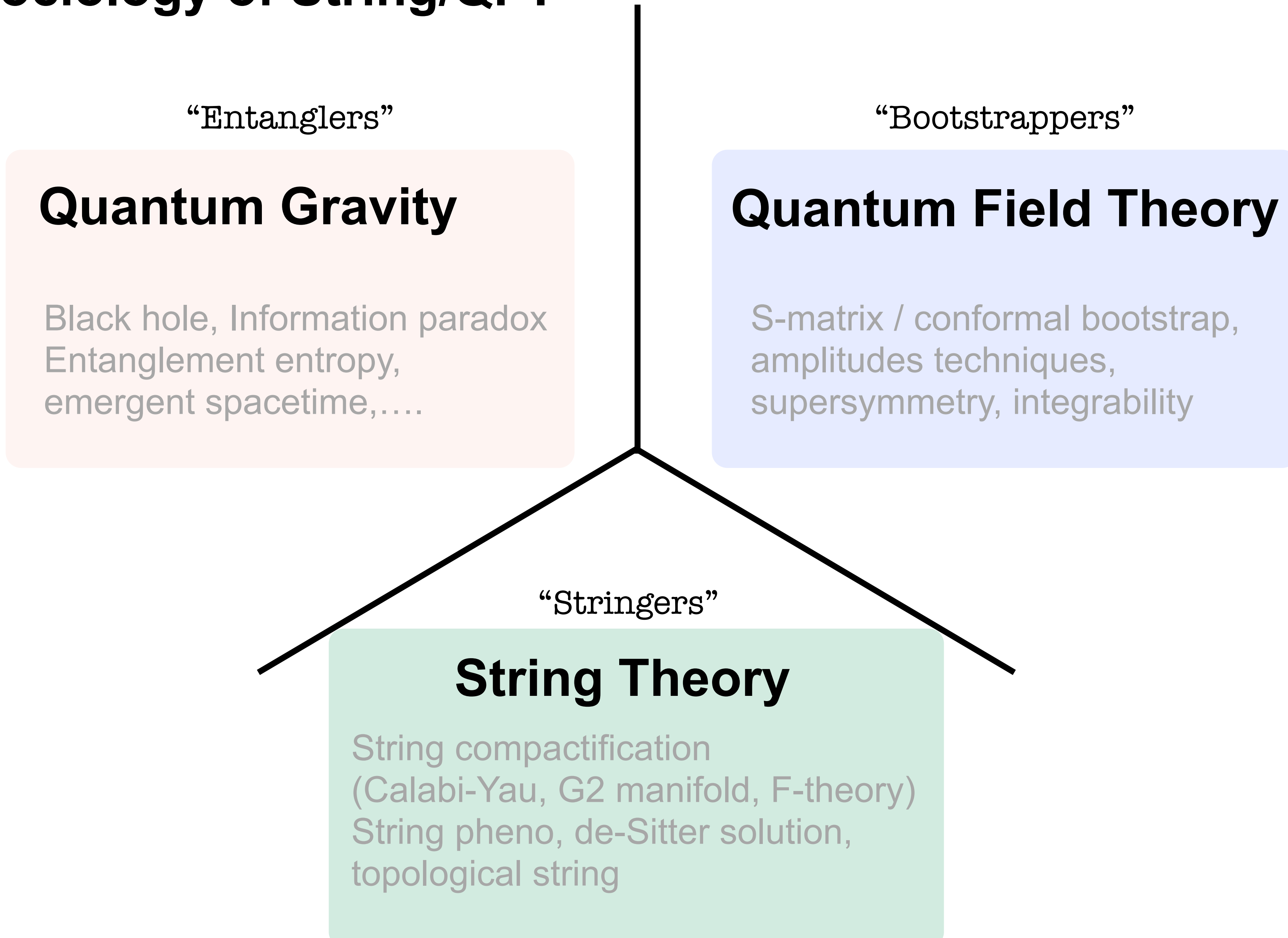
- TH-institutes, probably…?

  Non-perturbative QFT? De Sitter?….

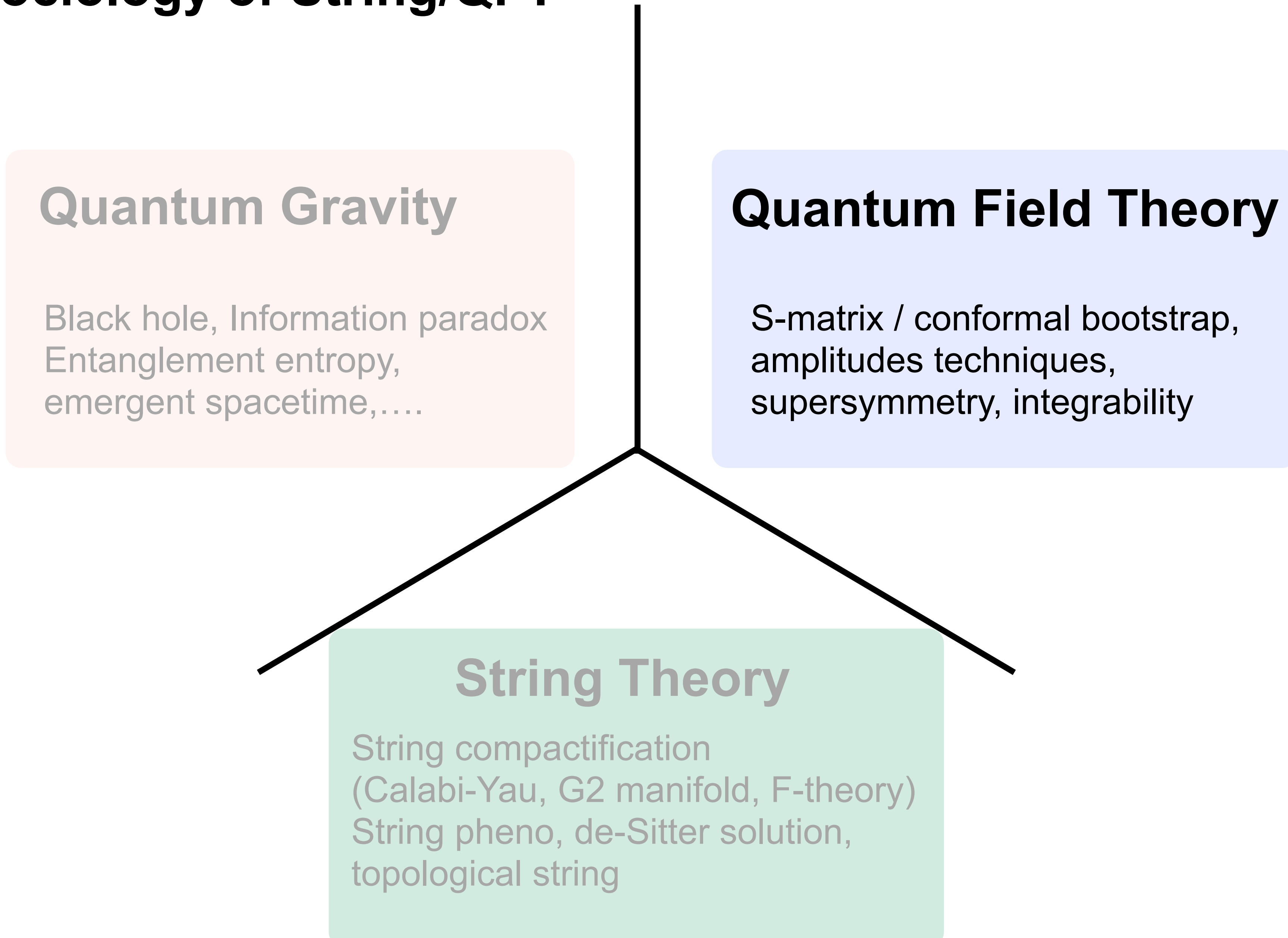
What’s String/QFT?

Highlights of recent developments

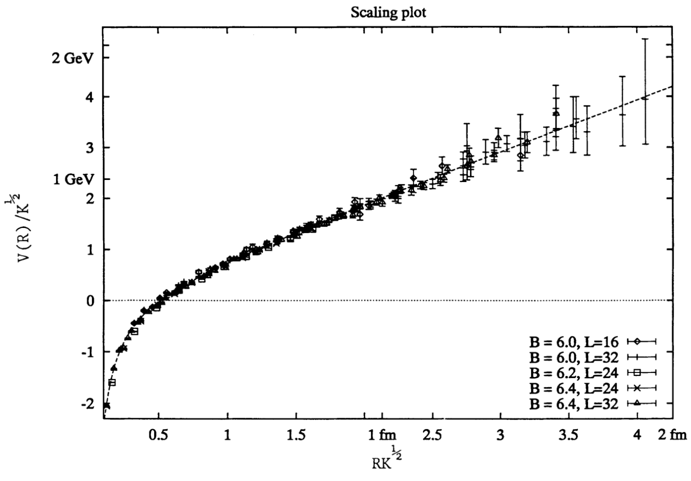
Sociology of String/QFT



Sociology of String/QFT



Quantum Field Theory, strongly coupled



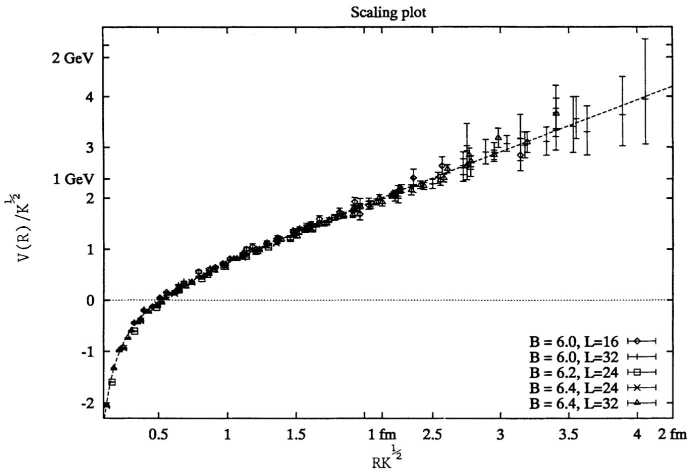
Questions

- Confinement in QCD
- Strongly coupled RG fixed point (3-d Ising)
- Phases of matter (topological insulator etc)

Tools

- S-matrix / conformal bootstrap
- “Generalized” symmetry & anomaly
- Supersymmetric toy models
- Integrability

Quantum Field Theory, strongly coupled



Questions

- Confinement in QCD
- Strongly coupled RG fixed point (3-d Ising)
- Phases of matter (topological insulator etc)

Tools

- S-matrix / conformal bootstrap
- “Generalized” symmetry & anomaly
- Supersymmetric toy models
- Integrability

S-matrix & conformal bootstrap

Basic idea: Constrain QFTs from basic principles (symmetry, unitarity etc)

Low energy data

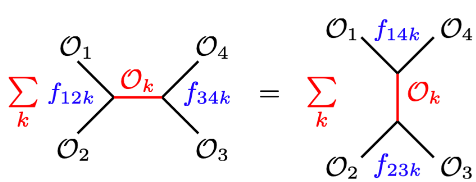
Wilson coefficients,
mass of bound states,

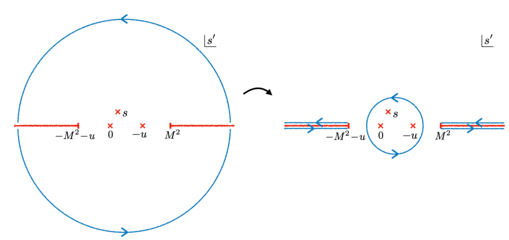
Bootstrap oracle

crossing symmetry, unitarity

No!

Maybe yes…





S-matrix & conformal bootstrap

Basic idea: Constrain QFTs from basic principles (symmetry, unitarity etc)

Low energy data

Wilson coefficients,
mass of bound states,

Bootstrap oracle
crossing symmetry, unitarity

No!

Maybe yes…

Mini S-matrix bootstrap revolution (End of 2020)

Caron-Huot, Mazac, Simmons-Duffin, Rastelli, Bellazini, Elias Miro, Rattazzi, Riembau, Riva, Huang, Arkani-Hamed …

- 2-sided bounds on Wilson coefficients from dispersion rel + crossing
- Full use of unitarity constraints: Positive moments, EFThedron
- Potentially useful for constraining (B)SM EFT

Non-invertible symmetry

Basic idea: Generalize the notion of symmetry and constrain RG.

Usual symmetry

$$g \cdot g^{-1} = I \qquad \text{for any } g$$

Non-invertible ("categorical") symmetry

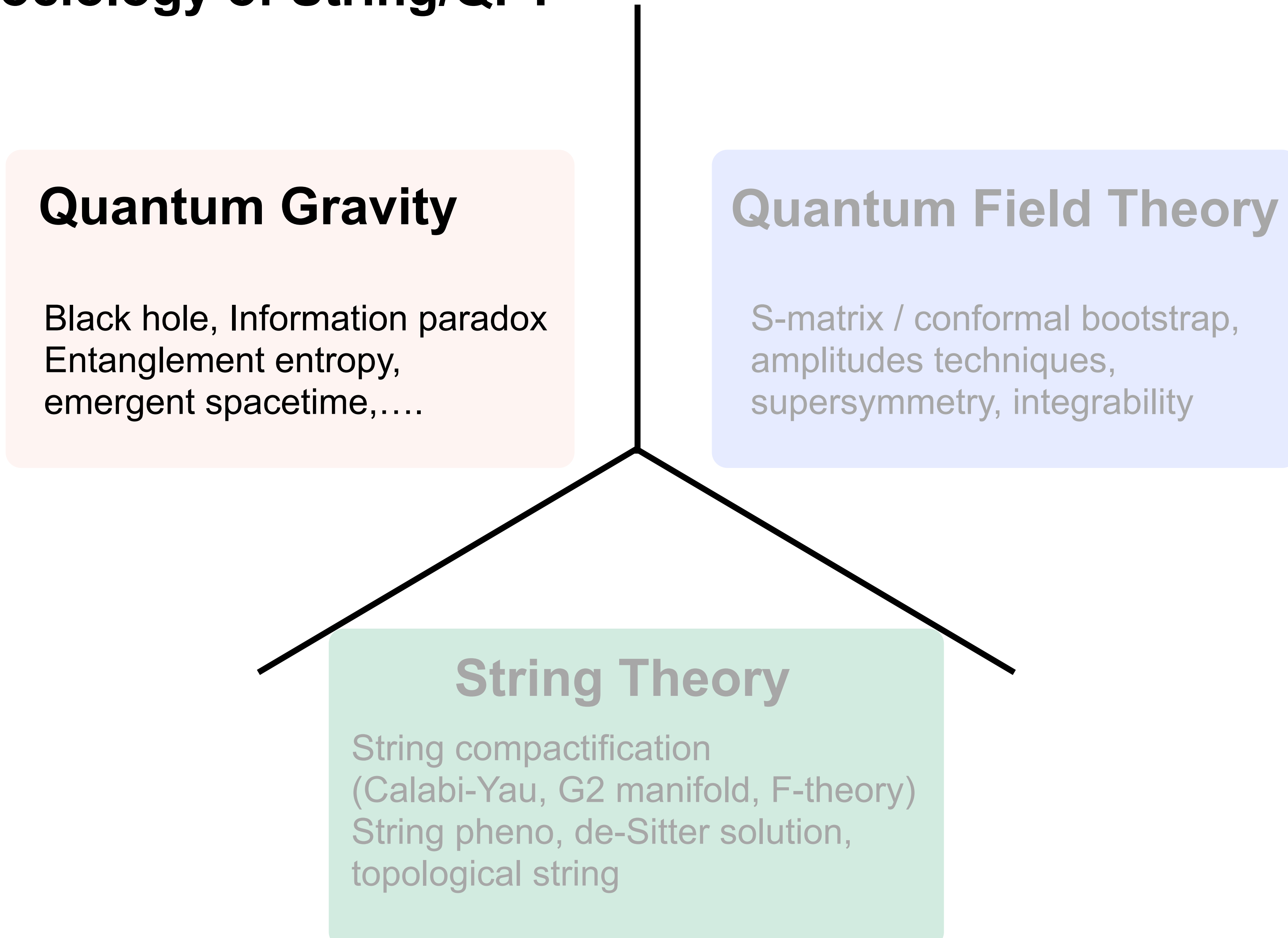
$$\eta^2 = I, \qquad N^2 = I + \eta, \qquad N\eta = \eta N = N$$

2d Ising: Tambara-Yamagami fusion category

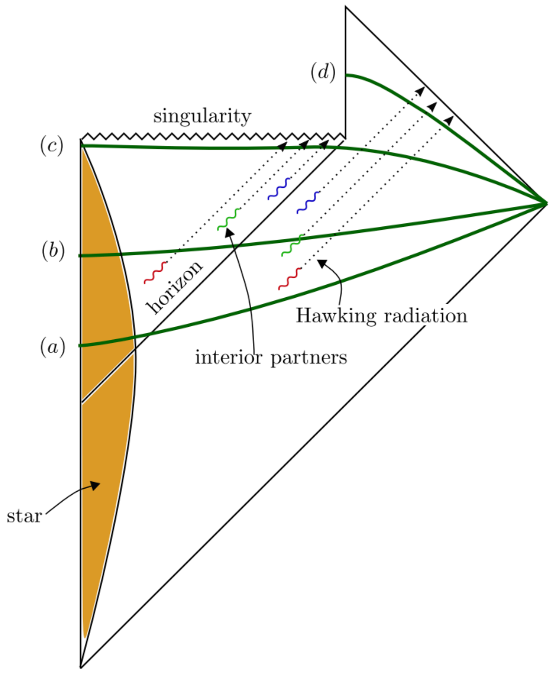
- Some examples in 4d: $SO(3)$ Yang-Mills at $\theta = \pi$
- Prohibit some terms in Lagrangian from being generated by RG.
  (Implication to naturalness…?) **cf. Talk by Komargodski in TH colloquium, August 2020**

Other generalizations: higher form symmetry, subsystem symmetry

Sociology of String/QFT



Quantum Gravity, black hole in particular…



Questions

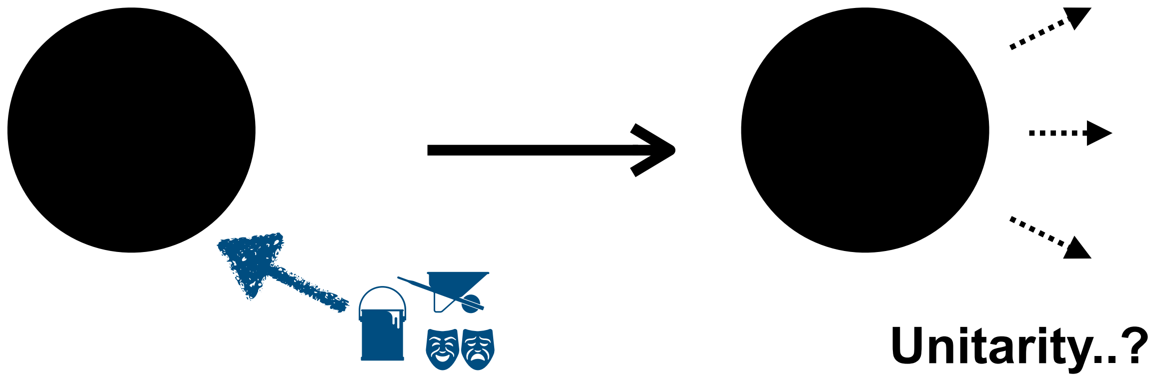
- Is black hole evaporation unitary?
- Emergence of spacetime
- Cosmology, singularity, ….

Tools

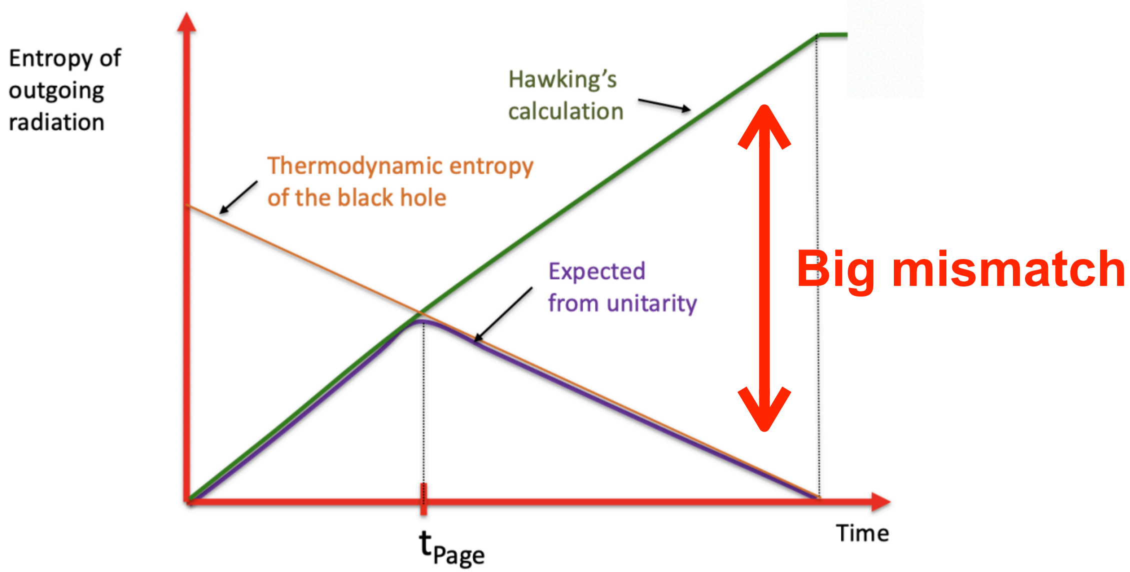
- Holography, AdS/CFT
- Entanglement entropy (spacetime = entanglement)
- Semiclassical gravitational path integral

Information paradox

Black hole formed by collapsing matter evaporates into thermal radiation.



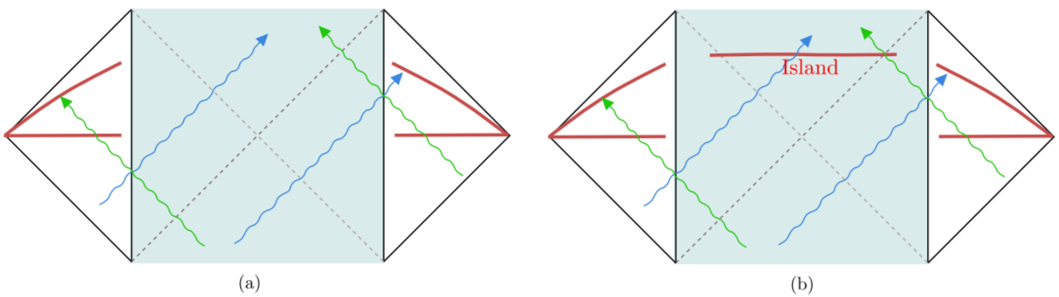
More precise measure: entanglement entropy of radiation.

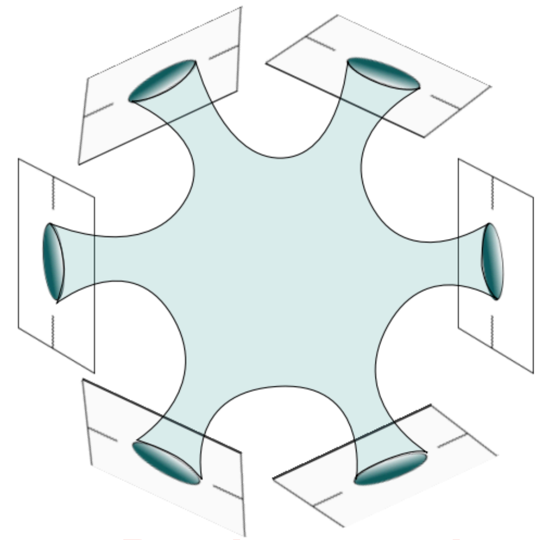


Island "revolution"

Pennington, Almheiri, Engelhardt, Maxfield, Maldacena, Hartman, Shagoulian, Tajdini…. 2019

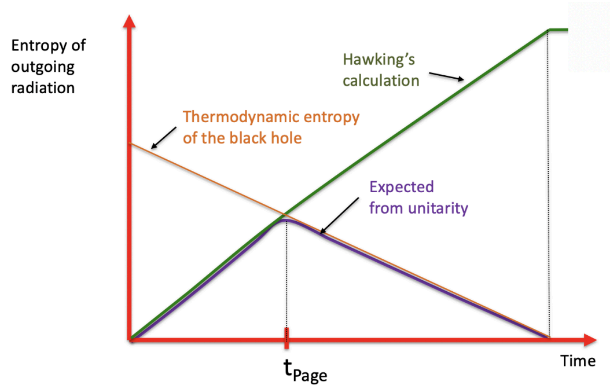
After the "Page time", different spacetime contributes to semiclassical gravity path integral!





Island **Replica wormhole**

Reproduces the "Page curve"



Sociology of String/QFT

Quantum Gravity

Black hole, Information paradox
Entanglement entropy,
emergent spacetime,….

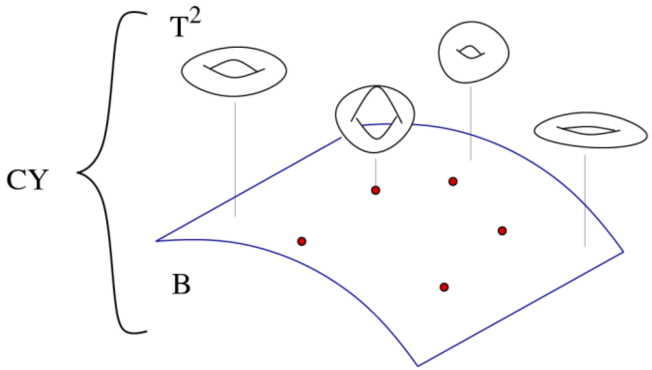
Quantum Field Theory

S-matrix / conformal bootstrap,
amplitudes techniques,
supersymmetry, integrability

String Theory

String compactification
(Calabi-Yau, G2 manifold, F-theory)
String pheno, de-Sitter solution,
topological string

String Theory, with emphasis on compactification



Questions

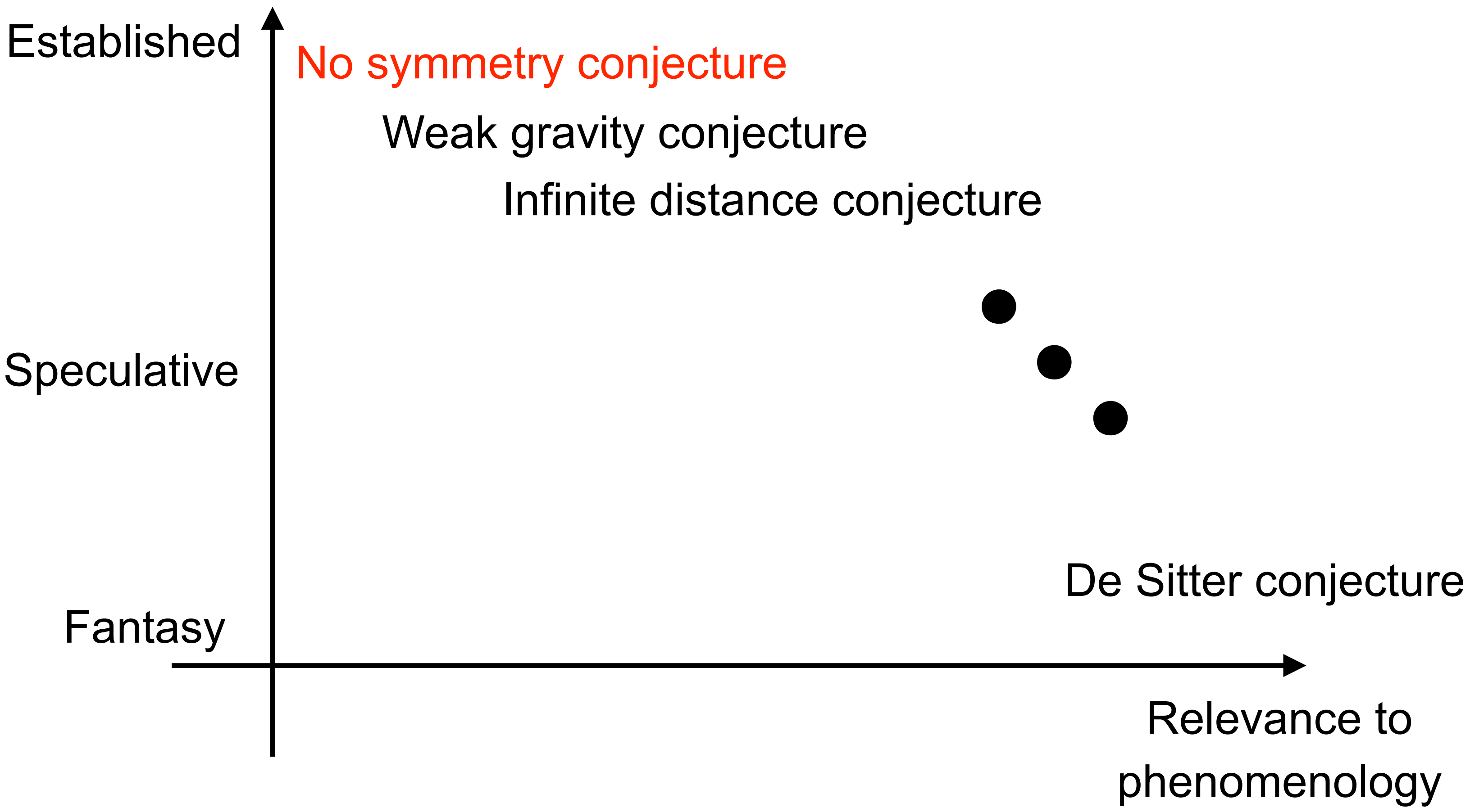
- Can we compactify string theory on 6d manifold and get SM + alpha?
- Can we construct de-Sitter solution?
- What’s the prediction?

Tools

- F-theory, Mathematical results on various manifolds (Calabi-Yau, G2 manifold,….)
- Topological string: String theory → math
- Inductive reasoning: construct examples and infer general properties, Swampland program

Swampland conjectures/programs

Basic idea: Not every EFT can be consistently coupled to quantum gravity

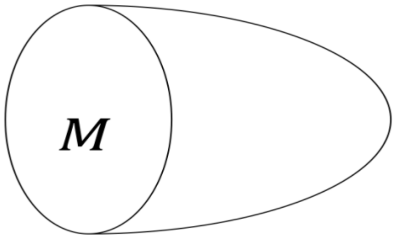


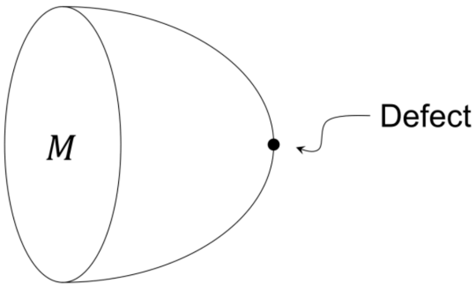
No symmetry conjecture

Claim: In quantum gravity, all symmetries are either gauged or broken.

Evidence:
- String perturbation theory.
- Black hole entropy. (No remnants with high entropy)
- AdS/CFT
- Gravity path integral (wormholes)

Recent generalization:
- No non-invertible symmetry → Charge completeness hypothesis
- Cobordism conjecture → prediction of new non-perturbative objects





Fruitful interactions

Quantum Gravity

Black hole, Information paradox
Entanglement entropy,
emergent spacetime,….

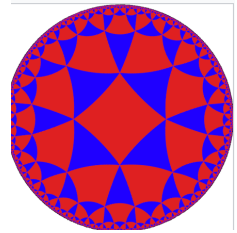
Quantum Field Theory

S-matrix / conformal bootstrap,
amplitudes techniques,
supersymmetry, integrability

String Theory

String compactification
(Calabi-Yau, G2 manifold, F-theory)
String pheno, de-Sitter solution,
topological string

AdS/CFT



Quantum Gravity = Quantum Field Theory

in asymptotically AdS

Quantum Gravity	Quantum Field Theory
Black hole	QGP / highly excited state
Classical Einstein gravity	Maximally chaotic quantum system
Black hole formation	Thermalization
Black hole horizon	Deconfinement
Gravity S-matrix bootstrap	Conformal bootstrap
Swampland conjectures	Conjectures on QFT

Fruitful interactions

Quantum Gravity

Black hole, Information paradox
Entanglement entropy,
emergent spacetime,….

Quantum Field Theory

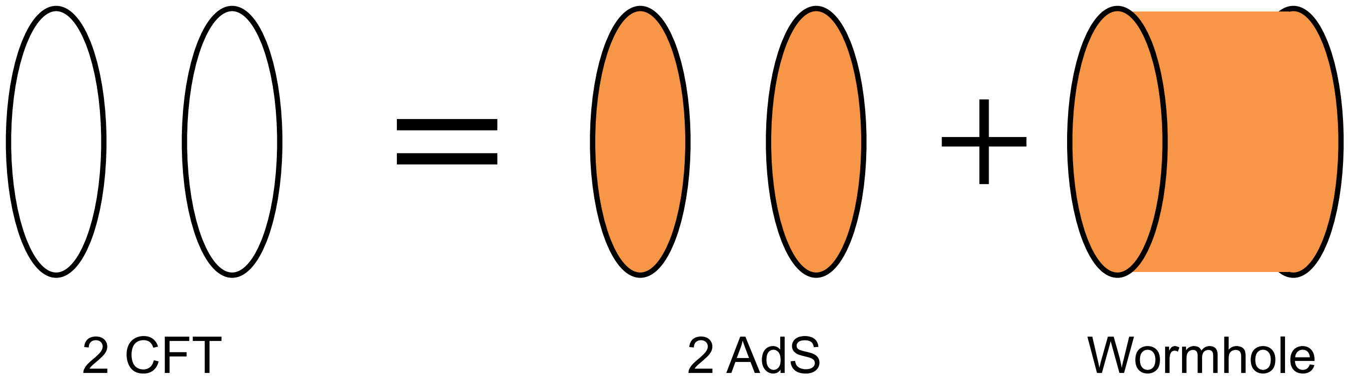
S-matrix / conformal bootstrap,
amplitudes techniques,
supersymmetry, integrability

String Theory

String compactification
(Calabi-Yau, G2 manifold, F-theory)
String pheno, de-Sitter solution,
topological string

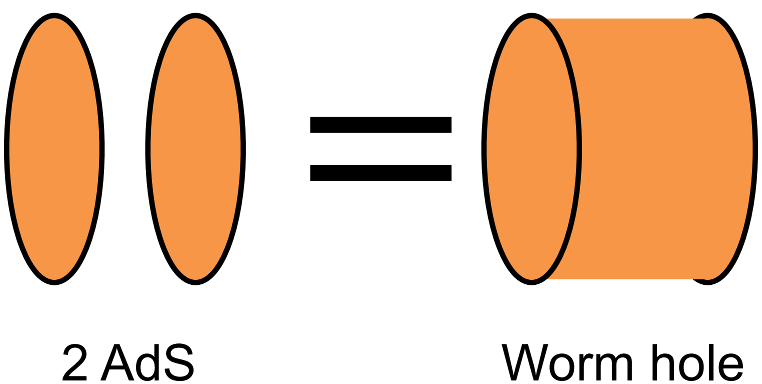
Factorization puzzle

Including wormholes in gravity path integral leads to a puzzle:



In a simplified setup, one can perform string theory path-integral and show

Eberhardt 2020



Maybe sum over geometries unnecessary/redundant in full string theory?

Fruitful interactions

Quantum Gravity

Black hole, Information paradox
Entanglement entropy,
emergent spacetime,….

Quantum Field Theory

S-matrix / conformal bootstrap,
amplitudes techniques,
supersymmetry, integrability

String Theory

String compactification
(Calabi-Yau, G2 manifold, F-theory)
String pheno, de-Sitter solution,
topological string

Bootstrapping swampland?

Swampland program and bootstrap share the common philosophy

Not everything in IR can be UV-completed

AdS/CFT + conformal bootstrap (or S-matrix bootstrap) can judge if the swampland conjectures are true or not:

What I expect to see from March.....

Conjectures →

← No / Maybe

String/QFT

Quantum Gravity

Black hole, Information paradox
Entanglement entropy,
emergent spacetime,….

Quantum Field Theory

S-matrix / conformal bootstrap,
amplitudes techniques,
supersymmetry, integrability

No border!

String Theory

String compactification
(Calabi-Yau, G2 manifold, F-theory)
String pheno, de-Sitter solution,
topological string

Shota Komatsu

Univ of Tokyo → Perimeter Institute → IAS → Staff at CERN from 2020

TH job: visitor committee, students

Research: past / present

- Solving to N=4 super Yang-Mills using Integrability
- Relating S-matrix/conformal bootstraps by flat space limit of AdS
- Analyticity / unitarity constraints in de-Sitter **Di Pietro, Gorbenko, SK**
- Generalizing amplitude techniques to AdS **Eberhardt, Mizera, SK**

2 questions I'm currently obsessed with

- Non-perturbative effects in heterotic string
- RG analysis of gravitational collapse

Alba Grassi - QFT & Strings

UNIVERSITÉ DE GENÈVE

Research interests:

Theoretical Physics

Mathematical Physics

LD staff

@ CERN (theory department) and

UniGe (mathematics department)

Alba Grassi - QFT & Strings

UNIVERSITÉ DE GENÈVE

Research interests:

Theoretical Physics

Use ideas and tools developed in the context of string theory and supersymmetric gauge theory to obtain new results in mathematical physics.

Mathematical Physics

Alba Grassi - QFT & Strings

CERN

UNIVERSITÉ DE GENÈVE

Research interests:

Theoretical Physics

Examples:

- Spectral theory of quantum mechanical operators
- Painlevé/gauge correspondence
- Matrix models
- Enumerative geometry

Mathematical Physics

Alba Grassi - QFT & Strings

CERN

UNIVERSITÉ DE GENÈVE

Research interests:

Theoretical Physics

Make some aspects of quantum field and string theory quantitively and structurally precise, for example at the non-perturbative level.

Mathematical Physics

Alba Grassi - QFT & Strings

CERN

UNIVERSITÉ DE GENÈVE

Research interests:

Theoretical Physics

Examples:

- String dualities (eg: testing AdS/CFT)
- Topological string theory (eg: non-perturbative effects)
- Simplifying regimes of QFT (eg: large N or large charge)

Mathematical Physics

Alba Grassi - QFT & Strings

CERN

UNIVERSITÉ DE GENÈVE

Something about me:

Life

Born and grew up in
Frasco, Ticino

Work

2012-2015: PhD @ UniGe

2015-2017: ICTP Trieste

2017-2020: Simons Center for Geometry and Physics, Stony Brook

Thank you!

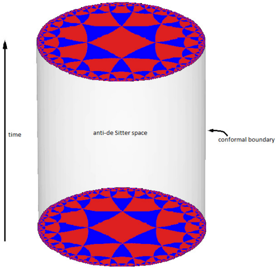
Kyriakos Papadodimas

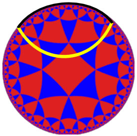
Staff member since 2020 (and before fellow, LD)

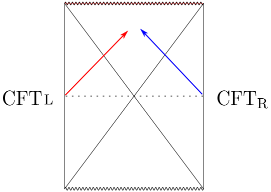
TH responsibilities: Fellows and Associates committee

Research interests:
Quantum Gravity
String Theory
AdS/CFT
Black Holes
Non-perturbative aspects of QFT

Quantum Gravity and Holography





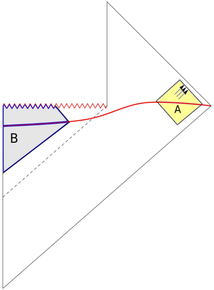


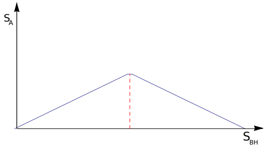
Quantum Gravity: UV vs IR, spacetime and gravity as emergent concepts, AdS/CFT

Fundamental principles of holography, role of entanglement and quantum information

Some general lessons: limitations of locality, quantum mechanics and observables in quantum gravity.

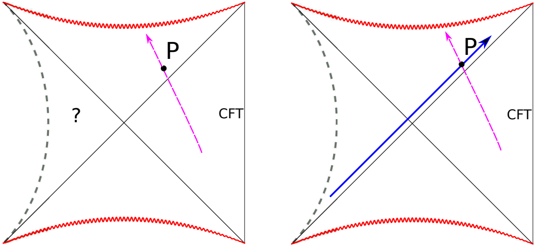
Black hole information paradox





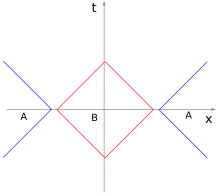
Unitarity of BH evaporation hints that $H_B \subset H_A$ (BH complementarity, islands, replica wormholes...)
Dramatic violation of locality at fundamental level, but not visible in effective field theory:$[\phi(x_{in}), \phi(x_{out})] = O(e^{-S})$
Operators corresponding to observables in region B are complicated combinations of those in A.
Observables in region B appear to be **state-dependent**. New intriguing feature of Q. Gravity.

Interior geometry of a typical BH microstate



BH entropy: $S = \frac{A}{4G} \to e^S$ BH microstates (in AdS/CFT dual to microstates of thermal plasma of $\mathcal{N} = 4$ SYM)
"Typical BH microstate": $\Psi = \sum_i c_i |E_i\rangle$, c_i = Haar-random
What geometry does an infalling observer see? How do we describe in CFT an operator inside the BH? Various techniques (Tomita-Takesaki modular theory, Quantum Error Correction, Petz map...) $\to$ State dependent CFT operators $\widetilde{\mathcal{O}}_P$.
Open questions: Dynamical principle/time evolution for infalling observer? Excited states?

(Approximate) factorization of Hilbert space in Quantum Gravity? Local diff invariant observables?



QFT without gravity ⇒ "Split property": can specify quantum state in A and B independently. Closely related to existence of local operators in QFT.
In gravity this is not the case:
1) **Simple reason:** mass in B can be measured in A.
2) **Deep reason:** Black hole complementarity/islands → factorization not possible at fundamental level. However, we do expect some type of approximate factorization at the level of effective field theory. *How to do this precisely is still an open question.*

Ongoing work: We have made some progress in understanding how to construct approximately local, diff-invariant observables in certain classes of states ⇒ a first step towards understanding approximate factorization

Sasha (Alexander) Zhiboedov

TH/CERN

- TH colloquium

- CERN colloquium

"Non-technical talk of general interest addressed to all people at CERN from all departments"
(a broad coverage of important scientific developments)

please send me an email if you have an idea!

My work

Nonperturbative methods in (Lorentzian) QFTs

(S-matrix bootstrap, CFT bootstrap, holography)

$$\text{SM+GR+Consistency} \stackrel{?}{=} \text{Strings}$$

(String theory exists because it is the only way that Nature can make sense)

“One is never sure to have completely exploited the axioms of QFT.”

A. Martin

- Bounds on gravitational EFTs (QFT/QG landscape)

[Tolley,Wang,Zhou '20]
[Caron-Huot, Van Duong '20]
[Arkani-Hamed,Huang,Huang '20]

- S-matrix bootstrap (nonperturbative tools)

Bound on gravitational EFTs

[Bern, Kosmopolous, AZ '21]

$$\mathcal{M}_4(1^+,2^-,3^-,4^+) = (\langle 23\rangle[14])^4 f(s,u)$$

Consistency (unitarity+causality) requires that it can expressed through its discontinuity (dispersion relations)

$$f(t,-s-t) = \oint \frac{ds'}{2\pi i}\frac{f(t,-s'-t)}{s-s'} = \left(\frac{\kappa}{2}\right)^2 \frac{1}{stu} + |\beta_{R^3}|^2\frac{tu}{s} - |\beta_\phi|^2\frac{1}{s}$$
$$- \int_{m_{\rm gap}^2}^{\infty} \frac{dm^2}{\pi}\Bigg(\sum_{J=0}^{\infty}\frac{1+(-1)^J}{2}\frac{\rho_J^{++}(m^2)d^J_{0,0}(1+\frac{2t}{m^2})}{m^8}\frac{1}{s-m^2}$$
$$+\sum_{J=4}^{\infty}\frac{\rho_J^{+-}(m^2)d^J_{4,4}\left(1+\frac{2t}{m^2}\right)}{(t+m^2)^4}\frac{1}{-s-t-m^2}\Bigg).$$

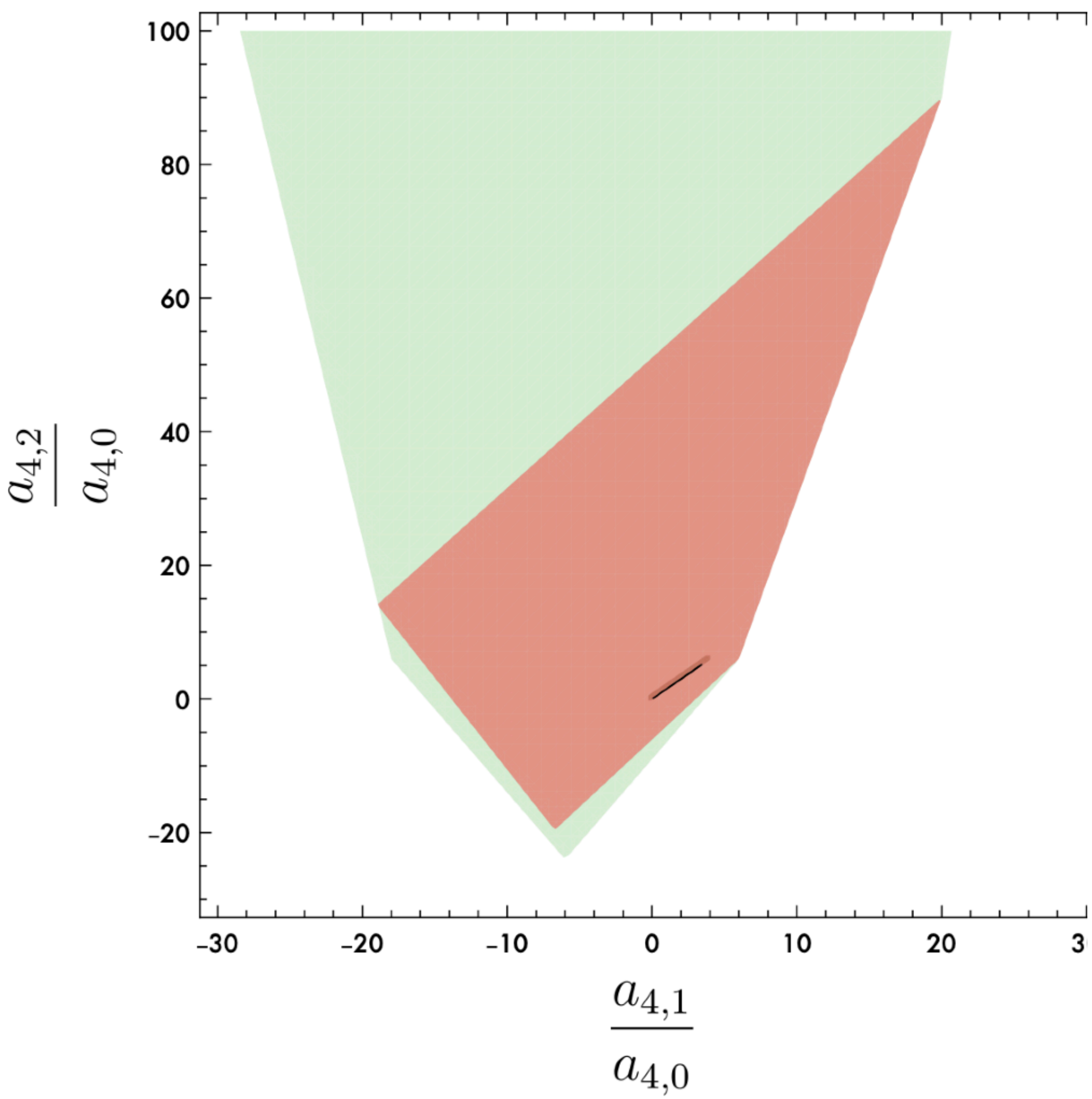
$$\rho_J(m^2) \geq 0$$

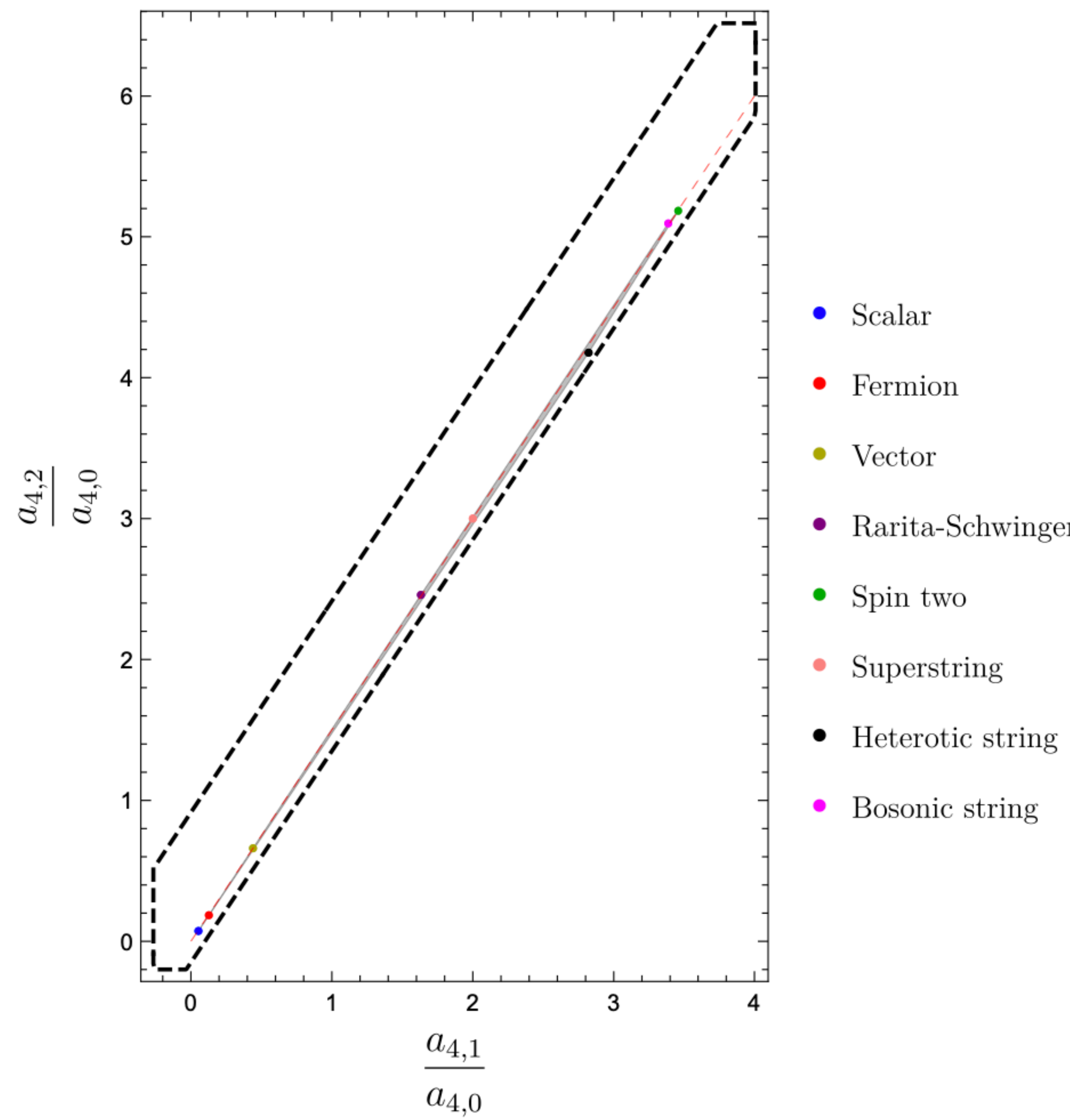
(unitarity/"optical theorem")

Bound on gravitational EFTs

[Bern, Kosmopolous, AZ '21]

EFT expansion: $f(s,u) \sim a_{k,i} s^i t^{k-i}$





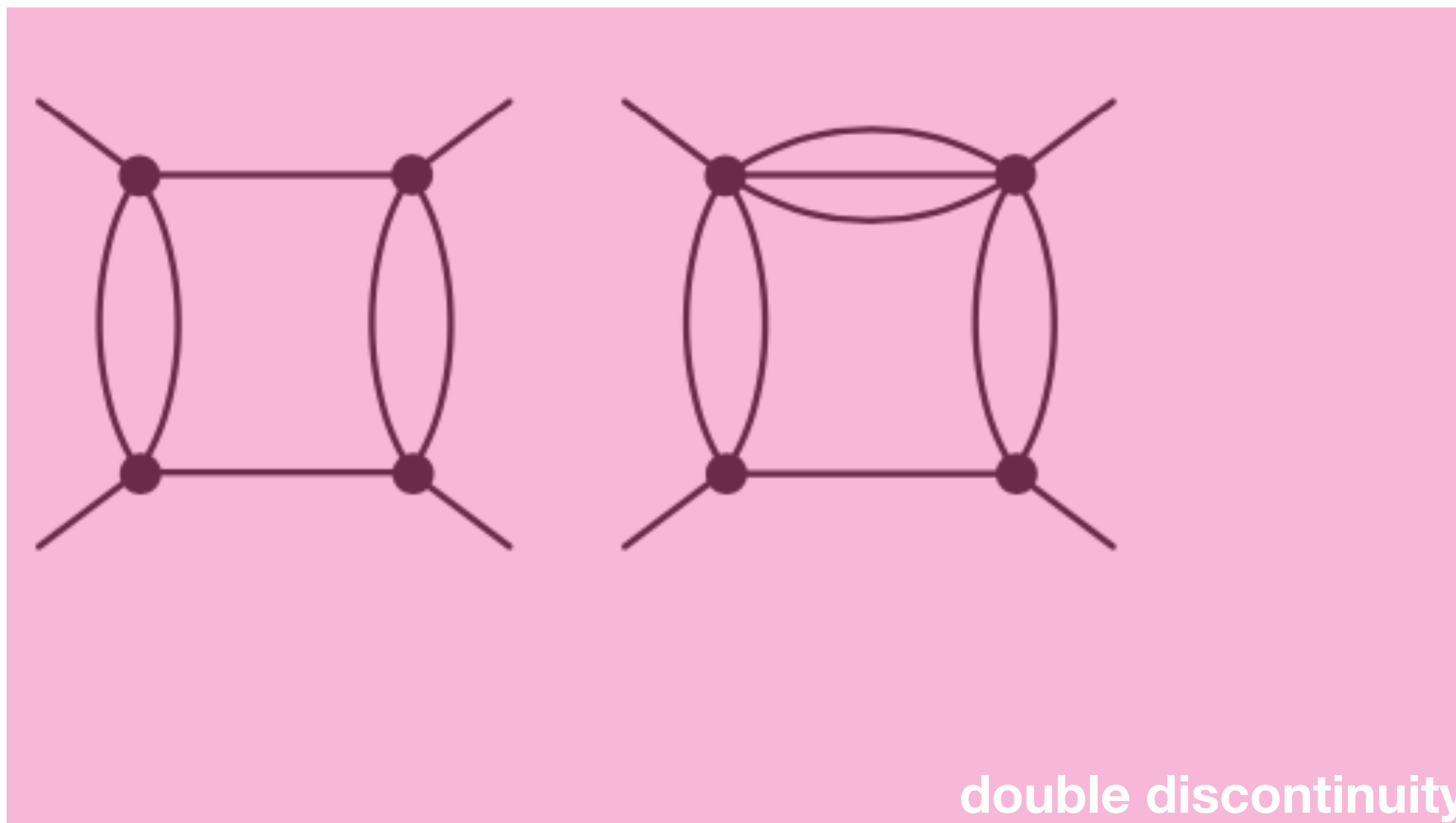
Conspiracy without symmetry (low spin dominance)

Multi-particle Landau Curves

Unitarity constrains the analytic properties of the amplitude

$$\mathrm{Disc}_s T(s,t) \equiv \frac{T(s+i\epsilon,t) - T(s-i\epsilon,t)}{2i} = \sum\!\!\!\!\!\!\!\int_n T_{2\to n} T^\dagger_{2\to n}$$

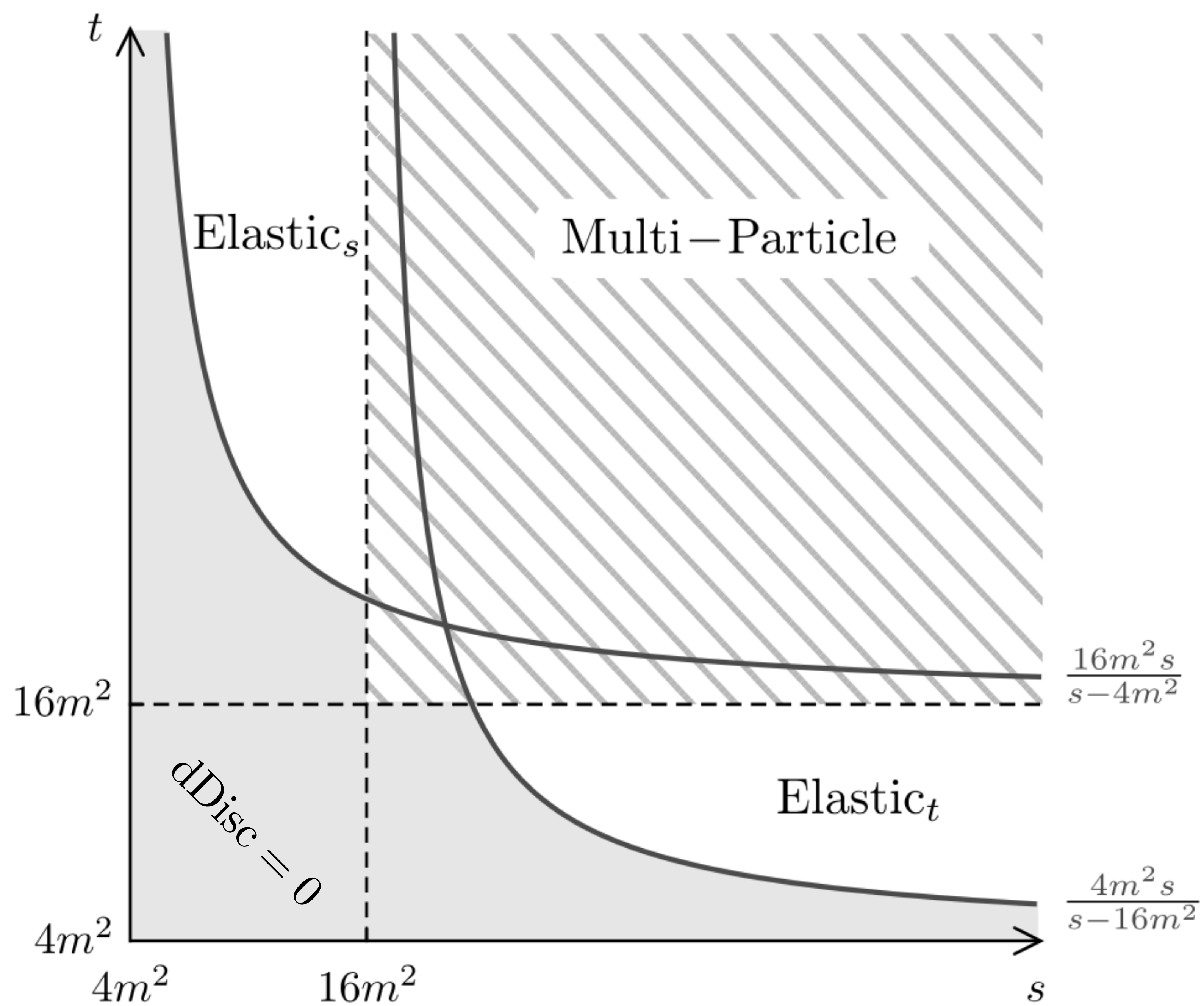
normal threshold



Double Discontinuity

Double discontinuity acquires nontrivial support along the Landau curves

[Mandelstam '58]

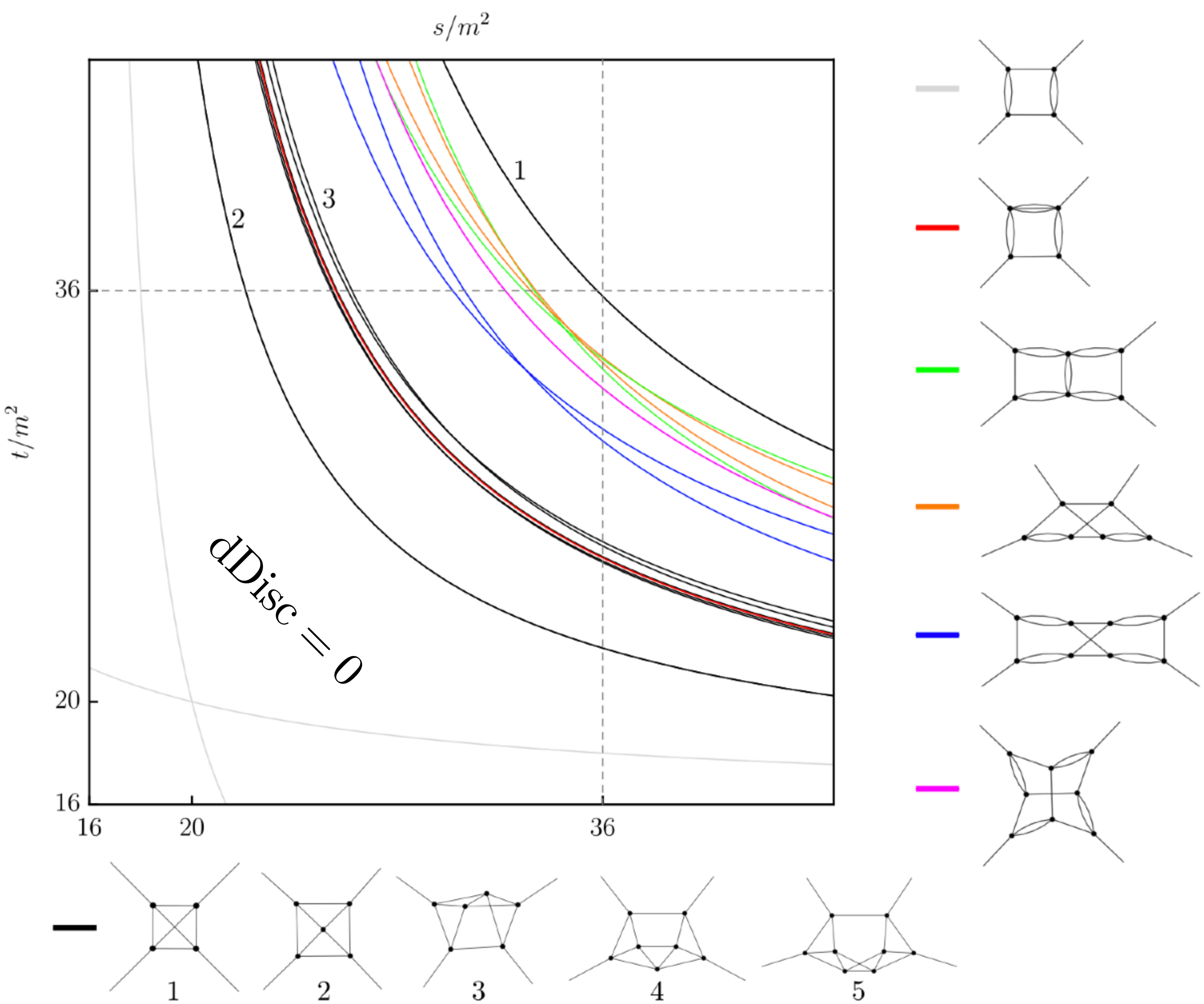


What are the consequences of multi-particle unitarity for 2-2 amplitude?

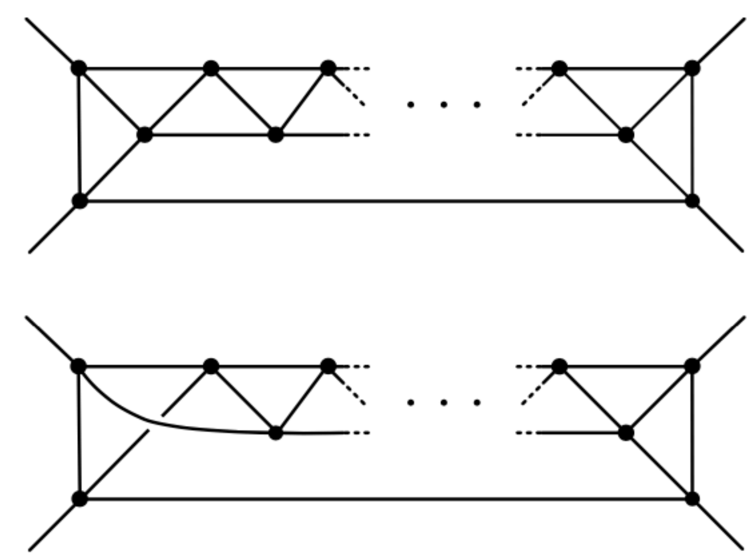
4-particle Landau Curves

[Correia, Sever, AZ, to appear]

Shadow that multi-particle unitarity casts on the 2-2 amplitude



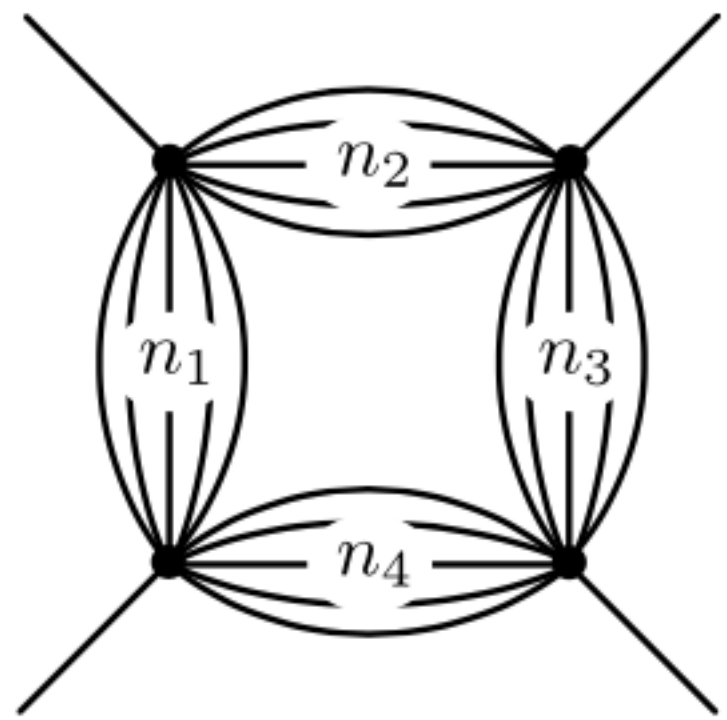
Infinitely many Landau curves at finite s&t



Analyticity

[Correia, Sever, AZ, to appear]

Multi-particle Landau curves accumulate on the physical sheet.



(accumulation points of infinitely many Landau curves)

THEORY RETREAT 2021

PABLO BUENO

2006 – 2011 } UG — UNIVERSIDAD DE OVIEDO

2010 } Summer Student — DESY

2011 } Sumer Student — CERN

2006–2011 } UG — UNIVERSIDAD DE OVIEDO

2010 } Summer Student — DESY

2011 } Sumer Student — CERN

2011–2013 } M.Sc. — UNIVERSIDAD AUTÓNOMA DE MADRID

2011–2015 } Ph.D. — IFT, MADRID

2013–2014 } Visiting Grad. Fellow — PERIMETER

2006 – 2011 } UG — UNIVERSIDAD DE OVIEDO

2010 } Summer Student — DESY

2011 } Sumer Student — CERN

2011 – 2013 } M.Sc. — UNIVERSIDAD AUTÓNOMA DE MADRID

Universidad Autónoma de Madrid

2011 – 2015 } Ph.D. — IFT, MADRID

Instituto de Física Teórica UAM-CSIC

2013 – 2014 } Visiting Grad. Fellow — PERIMETER

PERIMETER INSTITUTE

2015 – 2018 } POSTDOC — KU LEUVEN

KU LEUVEN

fwo

2018 – 2021 } POSTDOC — CENTRO ATÓMICO BARILOCHE

Instituto Balseiro

It from Qubit

Simons Collaboration on Quantum Fields, Gravity and Information

2021 – ... } POSTDOC — CERN

2006–2011 } UG — UNIVERSIDAD DE OVIEDO

2010 } Summer Student — DESY

2011 } Sumer Student — CERN

2011–2013 } M.Sc. — UNIVERSIDAD AUTÓNOMA DE MADRID

Universidad Autónoma de Madrid

2011–2015 } Ph. D. — IFT, MADRID

Instituto de Física Teórica UAM-CSIC

2013–2014 } Visiting Grad. Fellow — PERIMETER

PERIMETER INSTITUTE

2015–2018 } POSTDOC — KU LEUVEN

KU LEUVEN fwo

2018–2021 } POSTDOC — CENTRO ATÓMICO BARILOCHE

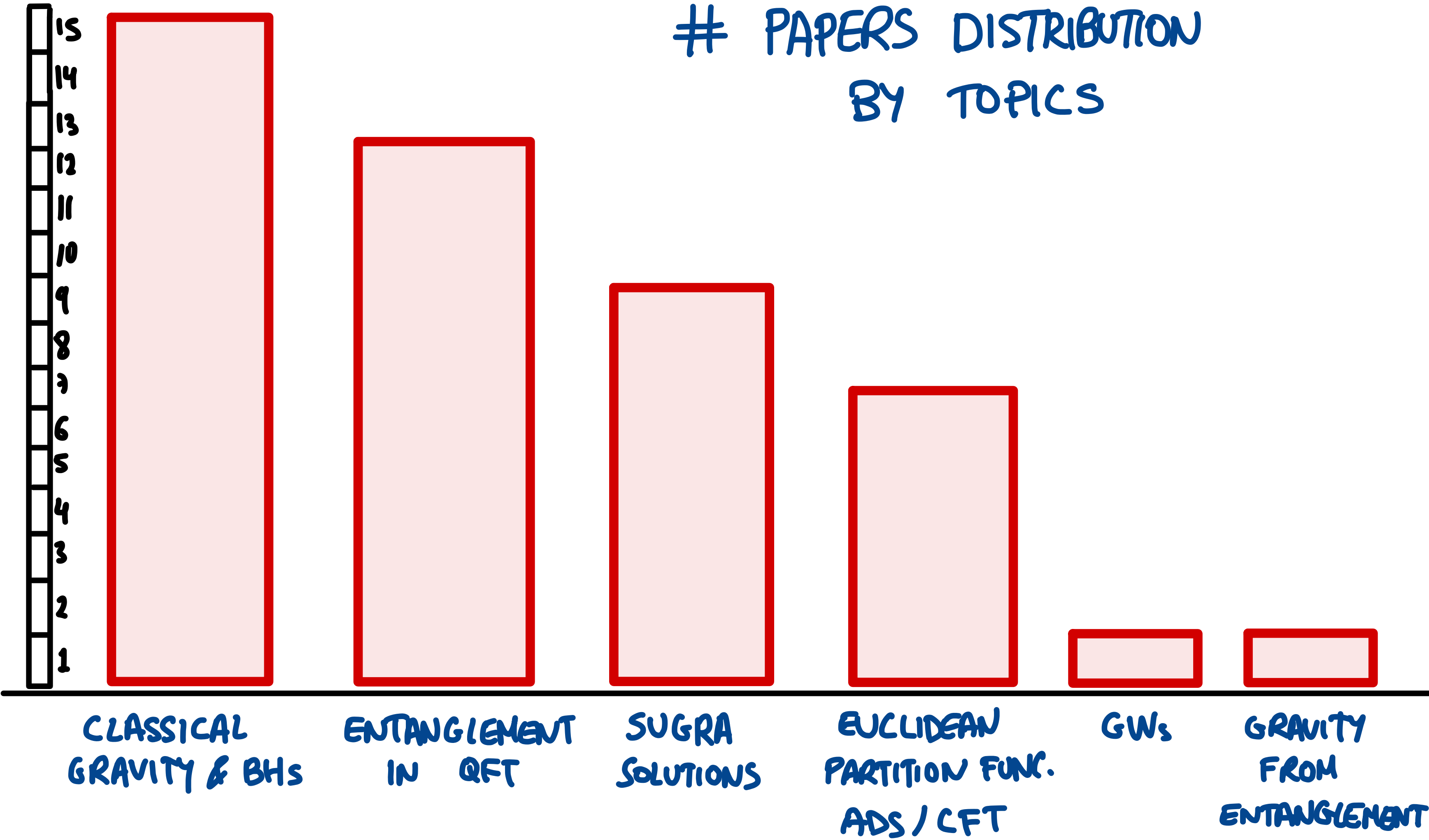
Instituto Balseiro

It from Qubit
Simons Collaboration on Quantum Fields, Gravity and Information

2021–... } POSTDOC — CERN

~2023 } JUNIOR — UNIVERSITAT DE BARCELONA

UNIVERSITAT DE BARCELONA



PAPERS DISTRIBUTION BY TOPICS
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
CLASSICAL GRAVITY & BHs
ENTANGLEMENT IN QFT
SUGRA SOLUTIONS
EUCLIDEAN PARTITION FUNC. ADS / CFT
GWs
GRAVITY FROM ENTANGLEMENT

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

- IDENTIFYING / CLASSIFYING HIGHER-CURVATURE EXTENSIONS OF EINSTEIN GRAVITY WITH SPECIAL PROPERTIES

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

- IDENTIFYING / CLASSIFYING HIGHER-CURVATURE EXTENSIONS OF EINSTEIN GRAVITY WITH SPECIAL PROPERTIES

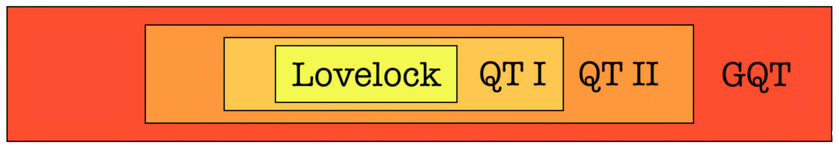
CRITERION. 2nd-ORDER EOM ON CERTAIN BACKGROUNDS

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

- IDENTIFYING / CLASSIFYING HIGHER-CURVATURE EXTENSIONS OF EINSTEIN GRAVITY WITH SPECIAL PROPERTIES

CRITERION. 2nd-ORDER EOM ON CERTAIN BACKGROUNDS



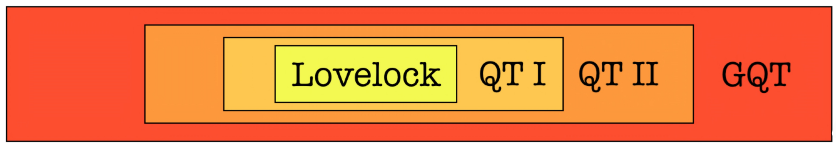
"GENERALIZED QUASITOPOLOGICAL GRAVITIES"

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

- IDENTIFYING / CLASSIFYING HIGHER-CURVATURE EXTENSIONS OF EINSTEIN GRAVITY WITH SPECIAL PROPERTIES

CRITERION. 2^{nd}-ORDER EOM ON CERTAIN BACKGROUNDS



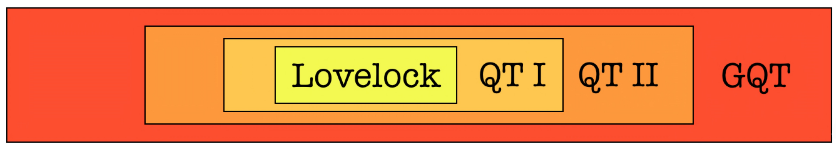
"GENERALIZED QUASITOPOLOGICAL GRAVITIES"

- 2^{nd}-order EOM on MSB
- Non-hairy BHs with $g_{tt}\, g_{rr} = -1$
- Continuous Einstein limit
- Non-trivial examples in $D=4$
- Subset also 2^{nd}-order EOM on FLRW

CURRENT RESEARCH 1/2 :
CLASSICAL GRAVITY & BHs

- IDENTIFYING / CLASSIFYING HIGHER-CURVATURE EXTENSIONS OF EINSTEIN GRAVITY WITH SPECIAL PROPERTIES

CRITERION. 2^{nd}-ORDER EOM ON CERTAIN BACKGROUNDS



"GENERALIZED QUASITOPOLOGICAL GRAVITIES"

- 2^{nd}-order EOM on MSB
- Non-hairy BHs with $g_{tt} g_{rr} = -1$
- Continuous Einstein limit
- Non-trivial examples in $D=4$
- Subset also 2^{nd}-order EOM on FLRW
- Analityc thermodynamics
- Via AdS/CFT → Identification of universal properties (valid for general CFTs).
- Accessible at arbitrary orders
  ↳ Toy models of QG ...

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

- FINDING CONNECTIONS BETWEEN SEEMINGLY UNRELATED THEORIES & GENERAL PATTERNS

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

- FINDING CONNECTIONS BETWEEN SEEMINGLY UNRELATED THEORIES & GENERAL PATTERNS

e.g. 1 ANY GRAVITY EFFECTIVE ACTION CAN BE MAPPED VIA FIELD REDEFINITIONS TO A GQT

CURRENT RESEARCH 1/2 :
CLASSICAL GRAVITY & BHs

- FINDING CONNECTIONS BETWEEN SEEMINGLY UNRELATED THEORIES & GENERAL PATTERNS

e.g. 1 ANY GRAVITY EFFECTIVE ACTION CAN BE MAPPED VIA FIELD REDEFINITIONS TO A GQT

e.g. 2 EVOLUTION OF SCALE FACTOR FOR ALL-ORDER GQTs

$\longleftrightarrow$ EVOLUTION OF SCALE FACTOR FOR ALL-ORDER $O(d,d)$ α' CORRECTED STRINGY EFFECTIVE ACTION

CURRENT RESEARCH 1/2 :
CLASSICAL GRAVITY & BHs

- FINDING CONNECTIONS BETWEEN SEEMINGLY UNRELATED THEORIES & GENERAL PATTERNS

e.g. 1 ANY GRAVITY EFFECTIVE ACTION CAN BE MAPPED VIA FIELD REDEFINITIONS TO A GQT

e.g. 2 EVOLUTION OF SCALE FACTOR FOR ALL-ORDER GQTs
$\leftrightarrow$ EVOLUTION OF SCALE FACTOR FOR ALL-ORDER $O(d,d)$ α' CORRECTED STRINGY ACTION

e.g 3 HOLOGRAPHIC COUNTERTERMS $\leftrightarrow$ SPECIAL THEORIES

CURRENT RESEARCH 1/2 :

CLASSICAL GRAVITY & BHs

THESE DAYS :

- → FULL CLASSIFICATION AT GENERAL ORDERS AND $D \geq 4$
- → GQTs IN $D=3$
- → HOLOGRAPHIC COUNTERTERMS ⟷ SPECIAL THEORIES
- → BIRKHOFF THEOREMS IN HIGHER-CURVATURE GRAVITIES?

KEY COLLABORATORS: PABLO A. CANO, ROBIE HENNIGAR, JAVIER MORENO, ROBERTO EMPARAN, QUIM LLORENS

Current Research 2/2:

Entanglement in QFT

CURRENT RESEARCH 2/2 :

ENTANGLEMENT IN QFT

- IDENTIFYING UNIVERSAL FEATURES OF ENTANGLEMENT MEASURES (VALID FOR GENERAL THEORIES)

CURRENT RESEARCH 2/2 :

ENTANGLEMENT IN QFT

- IDENTIFYING UNIVERSAL FEATURES OF ENTANGLEMENT MEASURES (VALID FOR GENERAL THEORIES)

e.g. 1 ENTANGLEMENT ENTROPY (EE) OF SINGULAR REGIONS
FULL CHARACTERIZATION, UNIVERSAL RESULTS

CURRENT RESEARCH 2/2:

ENTANGLEMENT IN QFT

- IDENTIFYING UNIVERSAL FEATURES OF ENTANGLEMENT MEASURES (VALID FOR GENERAL THEORIES)

e.g. 1 ENTANGLEMENT ENTROPY (EE) OF SINGULAR REGIONS
FULL CHARACTERIZATION, UNIVERSAL RESULTS

e.g. 2 DISK REGIONS MAXIMIZE EE IN D=3

CURRENT RESEARCH 2/2 :

ENTANGLEMENT IN QFT

- IDENTIFYING UNIVERSAL FEATURES OF ENTANGLEMENT MEASURES (VALID FOR GENERAL THEORIES)

e.g. 1 ENTANGLEMENT ENTROPY (EE) OF SINGULAR REGIONS
FULL CHARACTERIZATION, UNIVERSAL RESULTS

e.g. 2 DISK REGIONS MAXIMIZE EE IN D=3

e.g. 3 NEW UNIVERSAL RELATION BETWEEN TWO DIFFERENT MEASURES: MUTUAL INFORMATION AND REFLECTED ENTROPY

CURRENT RESEARCH 2/2 :

ENTANGLEMENT IN QFT

- "QFT FROM ENTANGLEMENT" APPROACH

AXIOMATIZING QFT IN TERMS OF VACUUM ENTANGLEMENT MEASURES (MUTUAL INFORMATION)

CURRENT RESEARCH 2/2:

ENTANGLEMENT IN QFT

- "QFT FROM ENTANGLEMENT" APPROACH

AXIOMATIZING QFT IN TERMS OF VACUUM ENTANGLEMENT MEASURES (MUTUAL INFORMATION)

↳ WHAT ARE THE AXIOMS?

CURRENT RESEARCH 2/2 :

ENTANGLEMENT IN QFT

- "QFT FROM ENTANGLEMENT" APPROACH

AXIOMATIZING QFT IN TERMS OF VACUUM ENTANGLEMENT MEASURES (MUTUAL INFORMATION)

↳ WHAT ARE THE AXIOMS?

↳ HOW DO WE RECONSTRUCT A QFT FROM ITS MI's?

CURRENT RESEARCH 2/2:

ENTANGLEMENT IN QFT

- "QFT FROM ENTANGLEMENT" APPROACH

AXIOMATIZING QFT IN TERMS OF VACUUM ENTANGLEMENT MEASURES (MUTUAL INFORMATION)

↳ WHAT ARE THE AXIOMS?

↳ HOW DO WE RECONSTRUCT A QFT FROM ITS MI'S?

↳ CAN WE OBTAIN GENERAL CONSTRAINTS, BOUNDS, ETC. VALID FOR GENERAL THEORIES?

CURRENT RESEARCH 2/2 :

ENTANGLEMENT IN QFT

THESE DAYS :

→ N-PARTITE INFORMATION IN QFT

→ CONFORMAL BOUNDS IN $D=3$ FROM ENTANGLEMENT

→ BOSON-FERMION DUALITY IN $D=2$ FROM ENTANGLEMENT

→ EE GEOMETRIC EXTREMIZATION IN $D\geq 5$

KEY COLLABORATORS : HORACIO CASINI, JAVIER MAGÁN, CÉSAR AGÓN
ÓSCAR LASSO, ALEJANDRO VILAR

OUTREACH


INVESTIGACIÓN Y CIENCIA

Edición española de SCIENTIFIC AMERICAN

INFORME ESPECIAL

Descifrar la gravedad

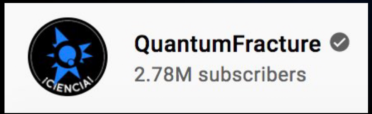
De los agujeros negros a la gravitación cuántica

NEUROTECNOLOGÍA
La máquina que puede leer nuestras intenciones

MICROBIOLOGÍA
La importancia de las simbiosis microbianas

TERREMOTOS
Señales de alerta sísmica en la ionosfera

QUANTUMFRACTURE



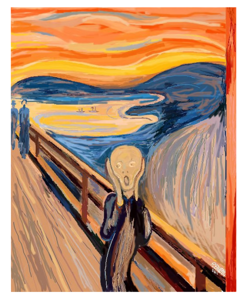
YouTube

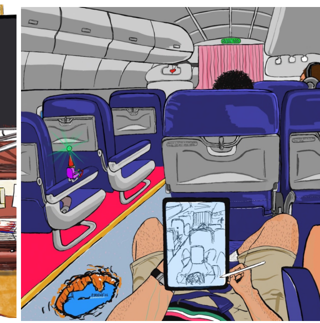
BEYOND PHYSICS ...

- CURRENTLY STUDYING A BACHELOR DEGREE IN ECONOMICS (~ 42,5% COMPLETED)
- I ALSO LIKE READING/STUDYING ABOUT HISTORY, POLITICS, HUMAN BEHAVIOR, ETC.

BEYOND PHYSICS ...

- CURRENTLY STUDYING A BACHELOR DEGREE IN ECONOMICS (~ 42,5% COMPLETED)
- I ALSO LIKE READING/STUDYING ABOUT HISTORY, POLITICS, HUMAN BEHAVIOR, ETC.
- ALSO ENJOY DRAWING ...



- SPORTS: USED TO PLAY A LOT OF TENNIS (LET ME KNOW IF YOU ARE UP FOR A PRACTICE) ALSO FOOTBALL, BASKET, GYM ...

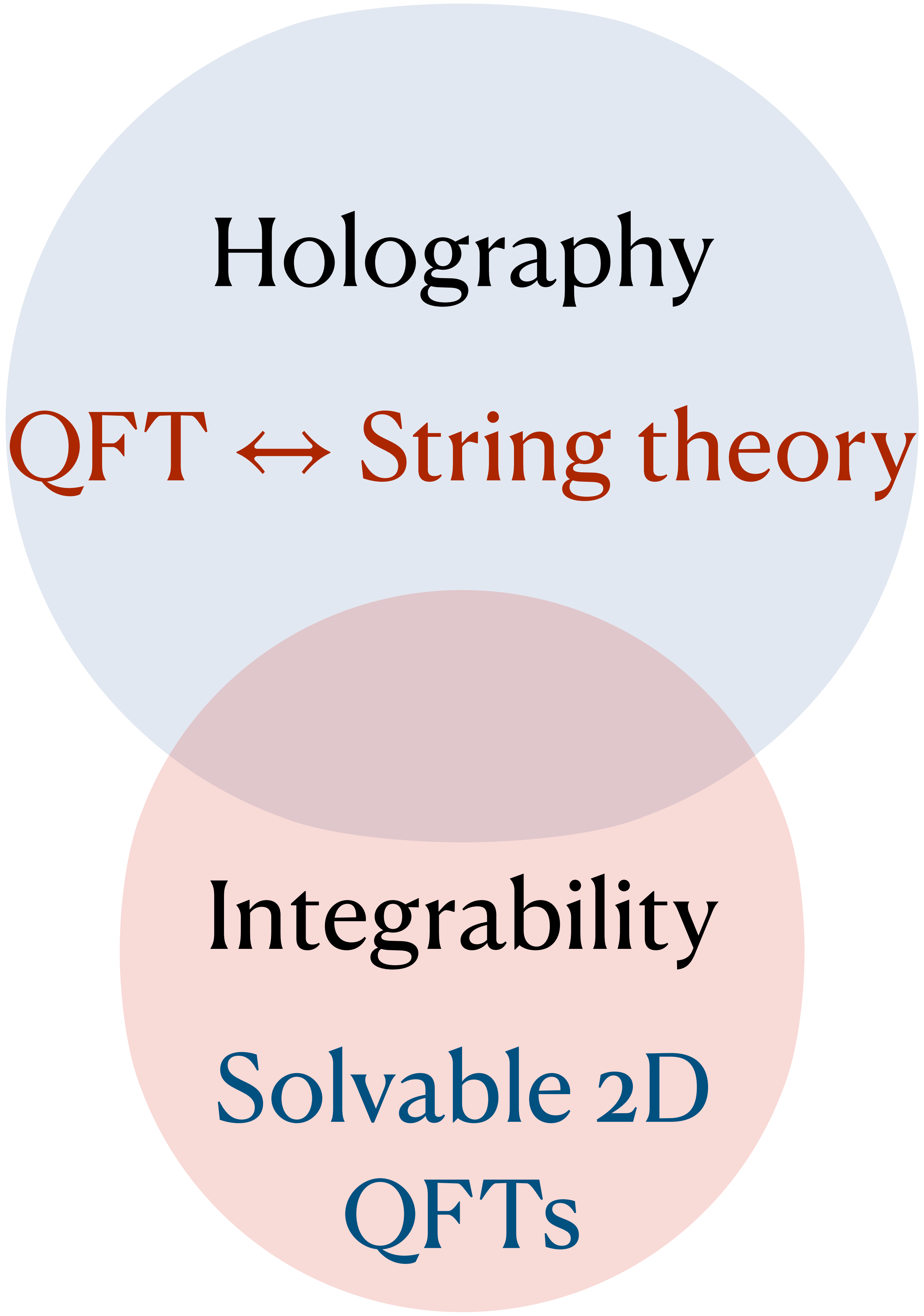
CERN Theory group retreat 2021

João Caetano
CERN, Geneva, Switzerland

3/11/2021


PhD
London,
King's College
PhD
Waterloo,
Perimeter Institute
Postdoc
Stony Brook,
Simons Center &
YITP
Porto
Fellow
Geneva,
CERN
Postdoc
Paris,
ENS

How does Quantum Field Theory look at finite coupling?



How does Quantum Field Theory look at finite coupling?

Holography

QFT ↔ String theory

Integrability

Solvable 2D QFTs

Holography

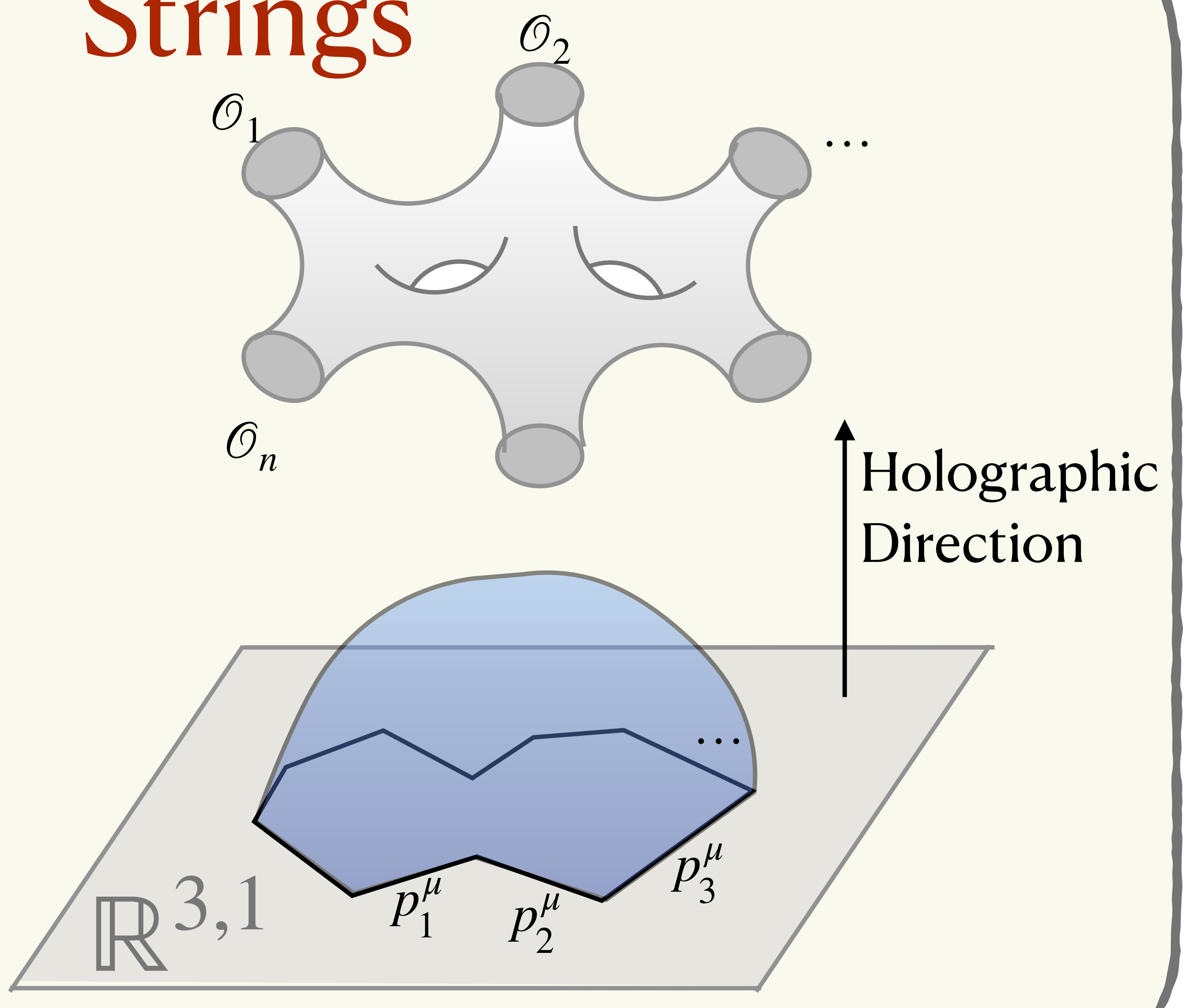
QFT

$\langle \mathcal{O}_1 \mathcal{O}_2 \ldots \mathcal{O}_n \rangle$

$\mathcal{A}(p_1, \ldots, p_N)$

etc.

Strings

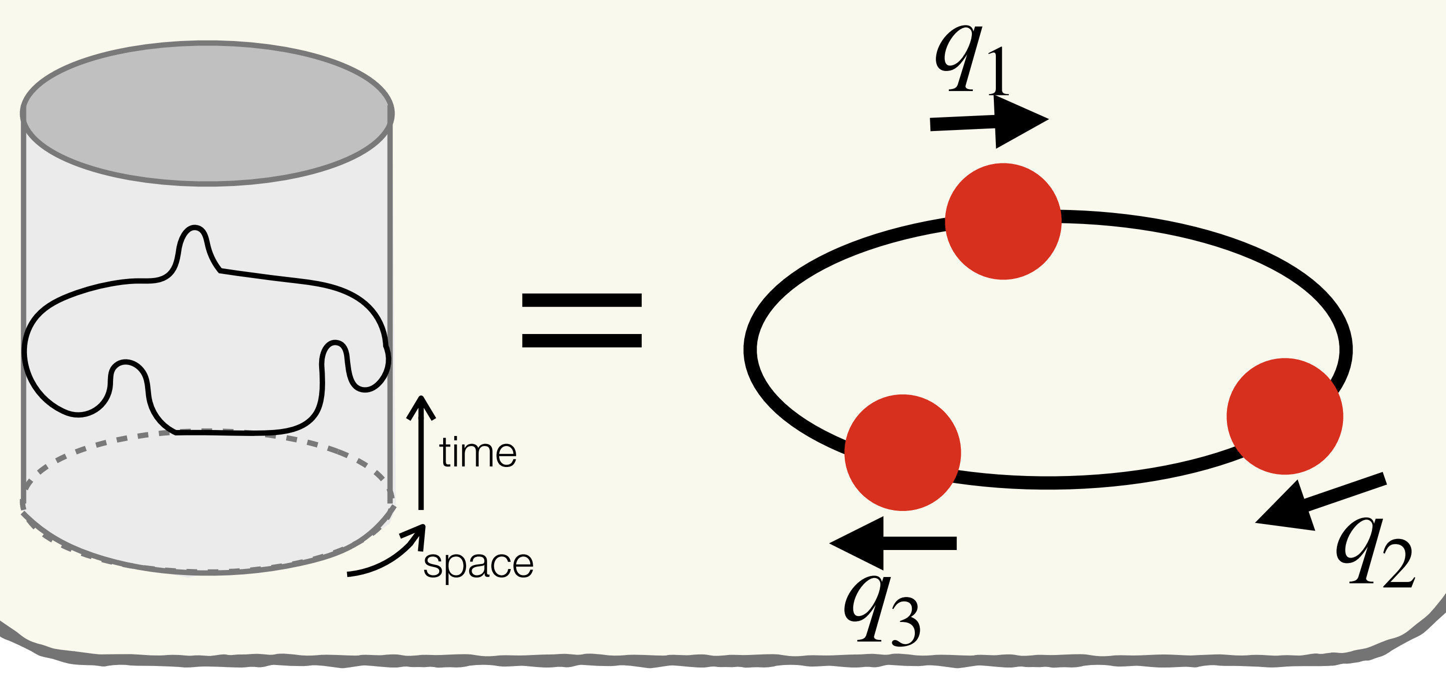


Integrable

2D worldsheet

(sometimes, e.g. N=4 SYM)

Factorized scattering in 2D

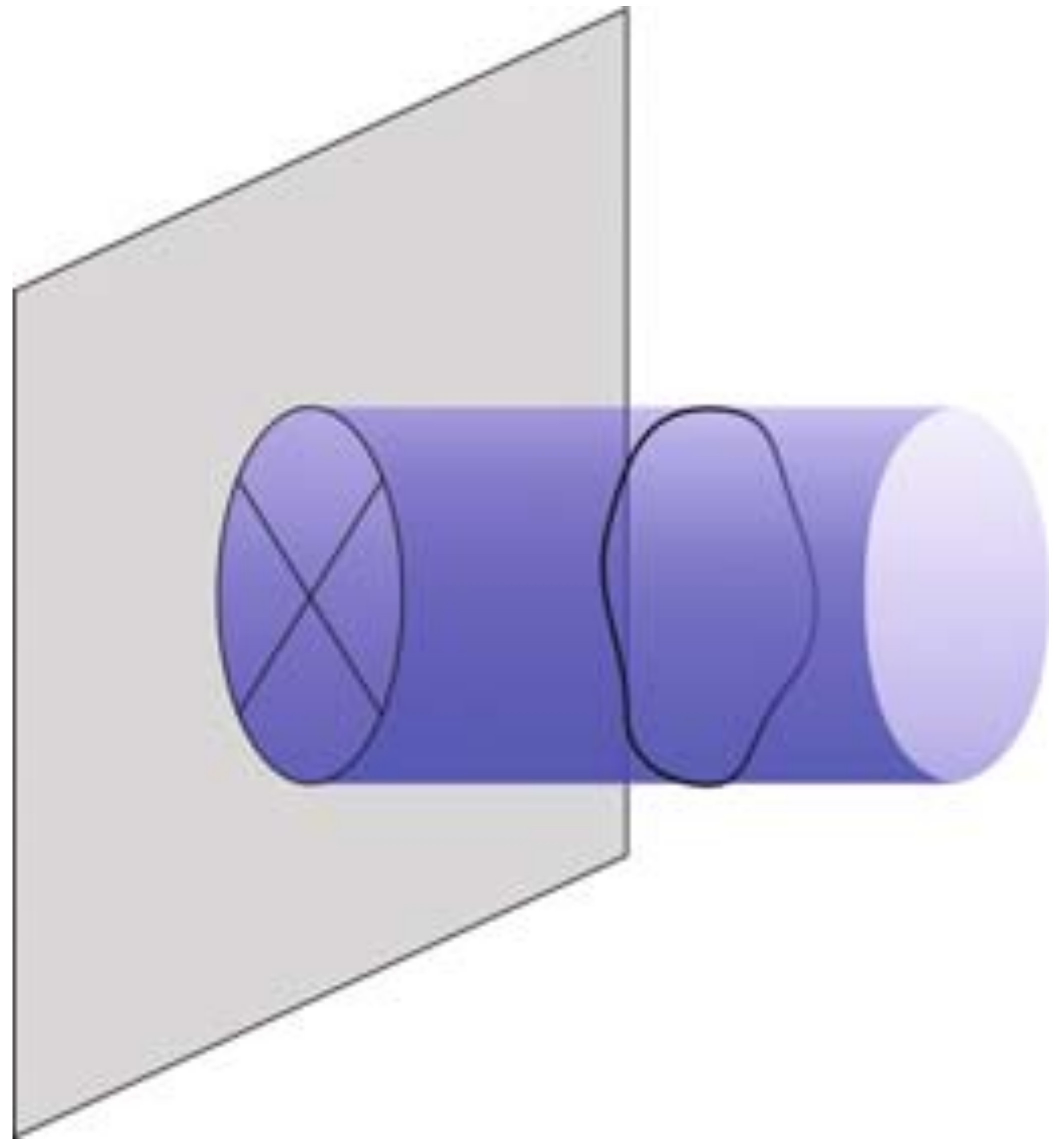


Current interests:
QFTs on non-orientable manifolds, like $\mathbb{RP}^{2n}$

(real projective spaces)

[works in progress w/ L. Rastelli and also S. Komatsu]

For holographic CFTs: New setups for AdS/CFT involving less standard ingredients like orientifolds



What happens when we place an integrable theory on a crosscap?

Observables are more sensitive to fine details of the theory, such as topological couplings (e.g. θ-angles)

Current interests:

Good old SU(N) $\mathcal{N}=4$ SYM in flat space

Instantons in large N [w.i.p. w/ S. Komatsu & Y. Wang]

Leading instanton correction to the spectrum

Current interests:

Good old SU(N) $\mathcal{N}=4$ SYM in flat space

Instantons in large N [w.i.p. w/ S. Komatsu & Y. Wang]

Leading instanton correction to the spectrum

$$\Delta = \left(\Delta_{0,0}(\lambda) + \frac{\Delta_{0,1}(\lambda)}{N^2} + \dots \right) + (e^{2\pi i \tau} + e^{-2\pi i \bar{\tau}}) \left(\Delta_{0,0}(\lambda) + \frac{\Delta_{1,1}(\lambda)}{N^2} + \dots \right) + \dots$$

"Planar" correction

Integrability: 2002-2018

What we are aiming

Hint: D-instanton = **Integrable** boundary state on the world-sheet. Bootstrap it!

Current interests:

Good old SU(N) $\mathcal{N}=4$ SYM in flat space

Finite N & Large charge [w.i.p. w/ S. Komatsu & Y. Wang]

Finite N spectrum: no integrability, but still lot of symmetry!

Goal: exact Spectrum for finite N, in the large charge limit.

Thank you!

CERN Theory Group Retreat
Matthew Dodelson
11/2/2021

Until now:

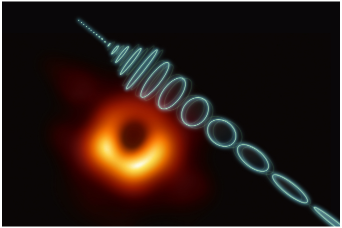
- Grew up in Chicago, did undergrad at Brown.
- Ph.D at Stanford in 2018 (advised by Eva Silverstein).
- Postdoc at Kavli IPMU in Tokyo (2018-2021).

Broad overview of research interests

1. **Lorentzian singularities as probes of bulk locality**: The AdS/CFT correspondence provides a tool for studying quantum field theories at strong coupling. At infinite coupling new singularities can arise in correlation functions, related to light rays in the bulk. These singularities allow us to probe local bulk physics, and are often sensitive to stringy effects. Can we understand the implications for the boundary theory?
2. **Holographic CFTs at finite temperature**: CFTs at finite temperature are dual to black holes in Anti de Sitter space. I am interested in what this duality tells us about correlation functions at finite temperature, and thermalization in general.
3. **Stringy effects near horizons:** Black holes can act as natural particle accelerators, with large energies near the horizon. Are there any signatures of string theory that arise from these large energies? What are the proper observables for detecting these signatures (possibly in our universe)?

Recent work, Part I:
Stringy effects in the thermal two-point function[1]

- Consider the two point function at finite temperature. What kinds of singularities can arise?
- At infinite coupling there is a new singularity that comes from null geodesics in the bulk connecting two boundary points. These geodesics can wind around the black hole photon sphere many times.
- What about when we take stringy effects into account? These effects can be analyzed exactly by zooming in on the geodesic (going to the Penrose limit). It turns out that the probability for the string to be tidally excited grows as we approach the singularity. This resolves the singularity.



[1]With Ooguri

Recent work, Part II:
Averaging over free boson CFTs[2]

- A recent development in holography is that bulk theories can be dual to averages of CFTs. One example is a duality between free boson theories and Chern-Simons theories in the bulk.
- Given a general lattice with quadratic form Q, one can construct a corresponding free boson theory. This theory has a moduli space called the Narain moduli space. We computed the averaged partition function for general lattices,

  $$\langle \vartheta_Q(\tau) \rangle = E_Q(\tau).$$

  This formula was known to the mathematician Siegel a century ago.
- In the bulk, one can consider a (spin)-Chern-Simons theory with level matrix Q. The partition function is obtained by summing over geometries, and reproduces the Eisenstein series E_Q. This is an interesting set of examples of averaged dualities with spin-structure dependence and a gravitational anomaly.

[2]with Ashwinkumar, Kidambi,Leedom,Yamazaki

Ongoing work:
Stringy effects near Kerr black holes[3]

- For near-extremal Kerr black holes, the photon sphere is very close to the horizon. The black hole therefore acts as a particle accelerator, which speeds up ingoing particles so that they collide at very high energies,

$$E_{\rm cm}^2 \sim \frac{E_1 E_2}{1 - r_{\rm H}/r}.$$

- For particles that collide very close to the horizon this energy can become string scale. Can we use this accelerator to detect string theory? We need to find the proper observable.
- The kinematics of collisions in the black hole are highly constraining, and do not allow the high energy behavior to be detected by observers at infinity.
- We are investigating a thought experiment where one detector is sent into the black hole, and a few other detectors sit at infinity. The correlation function measured by these detectors is one candidate observable for measuring the high energy behavior.

[3] With Ooguri

Looking ahead: some ideas

1. **Long-lived states at finite temperature**: A generic perturbation to a thermal system will thermalize quickly. The dual statement in AdS/CFT is that the perturbation will create an excitation which falls into the black hole. On the other hand, there are classically stable orbits around a black hole which do not fall in. Can we compute their lifetime? What are the implications for the boundary theory?
2. **Signatures of the plane wave in boundary correlators**: One simple limit of AdS/CFT is the plane wave limit. This corresponds to zooming in on a null geodesic traveling on the five-sphere in $AdS_5 \times S^5$. In this limit the bulk string theory is exactly solvable. Is there a kinematic limit of boundary correlators that is sensitive to the plane wave geometry? If so, can we sum up the stringy corrections in this limit?

Alex Belin

Undergrad — Université de Genève → **PhD** — McGill → **Postdocs** — Stanford University → University of Amsterdam → CERN

NWO Netherlands Organisation for Scientific Research — **VENI Grant**

I am happy to help with:

- Restaurants
- Bars
- Concerts
- Hiking, Skiing

Various TH/String group activities:

- Organizer of the String Journal Club 2019-2020
- Organizer the String Seminars 2019-present
- Organizer of QIQG 6 (cancelled COVID)
- Organizer of Island Hopping 2020

- Contact physicist for Arts at Cern
- TH “consultant” for the quantum world exhibit

The two main avenues of my research

- Q1: What is the space of consistent theories of quantum gravity?

- Q2: How is the gravitational information encoded in the microscopic description?

Quantum gravity with $\Lambda < 0$

Consistent Theories of Q.G. $\Longrightarrow$ CFTs

"Exotic" CFTs:

- Large N
- Strong Coupling
- Few operators with $\Delta \sim \mathcal{O}(1)$

Use bootstrap $\Longrightarrow$ Efficient constraints on CFT

The big open problem

So far, we have studied theories with

$$\lambda_{\mathrm{matter}} \sim G_N$$

The question we would like to answer:

Can we consistently couple the Standard Model to gravity?

The big open problem

So far, we have studied theories with

$$\lambda_{\rm matter} \sim G_N$$

The question we would like to answer:

Can we consistently couple the Standard Model to gravity?

$$S_{\rm CFT} = S_{\rm CFT} + N^{\#} \int d^d x \, [Tr(O)]^k$$

Main tools for an emergent spacetime

1. Quantum Information Theory
2. Quantum Chaos

Main tools for an emergent spacetime

1. Quantum Information Theory

2. Quantum Chaos

Quantum chaos

Strongest form of universality in physics!

1. $H \sim$ Random matrix

2. Eigenstate Thermalization Hypothesis (ETH)

$$\langle E_i | \, O_a \, | E_j \rangle = \delta_{ij} \bar{O}_a + e^{-S(\bar{E})/2} g_a(\bar{E}, \delta E) R_{ij}$$

Chaos and black holes

What does this have to do with black holes?

Chaos and black holes

What does this have to do with black holes?

Quantum system $\longrightarrow \mathcal{N} = 4$ SYM

Universality of Δ_i, C_{ijk} for O_i with $\Delta_i \sim N^2$

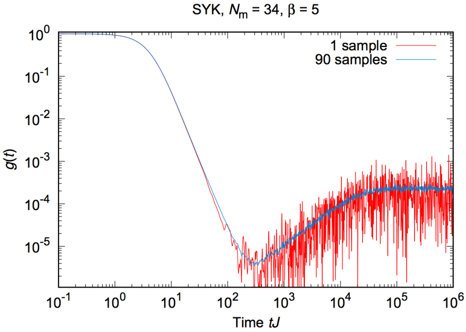
$\Longrightarrow$ Black hole microstates

Special to CFTs: C_{ijk} with $\Delta_{i,j,k} \to \infty$

The BH information paradox

The spectral form factor:

$$g(t) = |Z(\beta+it)|^2 = \sum_{m,n} \rho(E_m)\rho(E_n)e^{-\beta(E_m+E_n)+it(E_n-E_m)}$$



$S_{BH} = \frac{A_{\text{Hor}}}{4G_N} \longrightarrow$ discrete spectrum, info. paradox

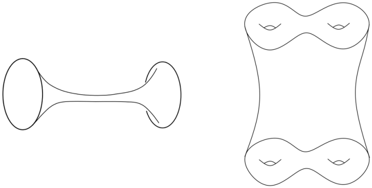
Quantum Gravity meets Statistical Physics

Proposal:

Semi-classical general relativity

$=$

Thy of statistical distribution of $\rho(E_i)$ and C_{ijk}



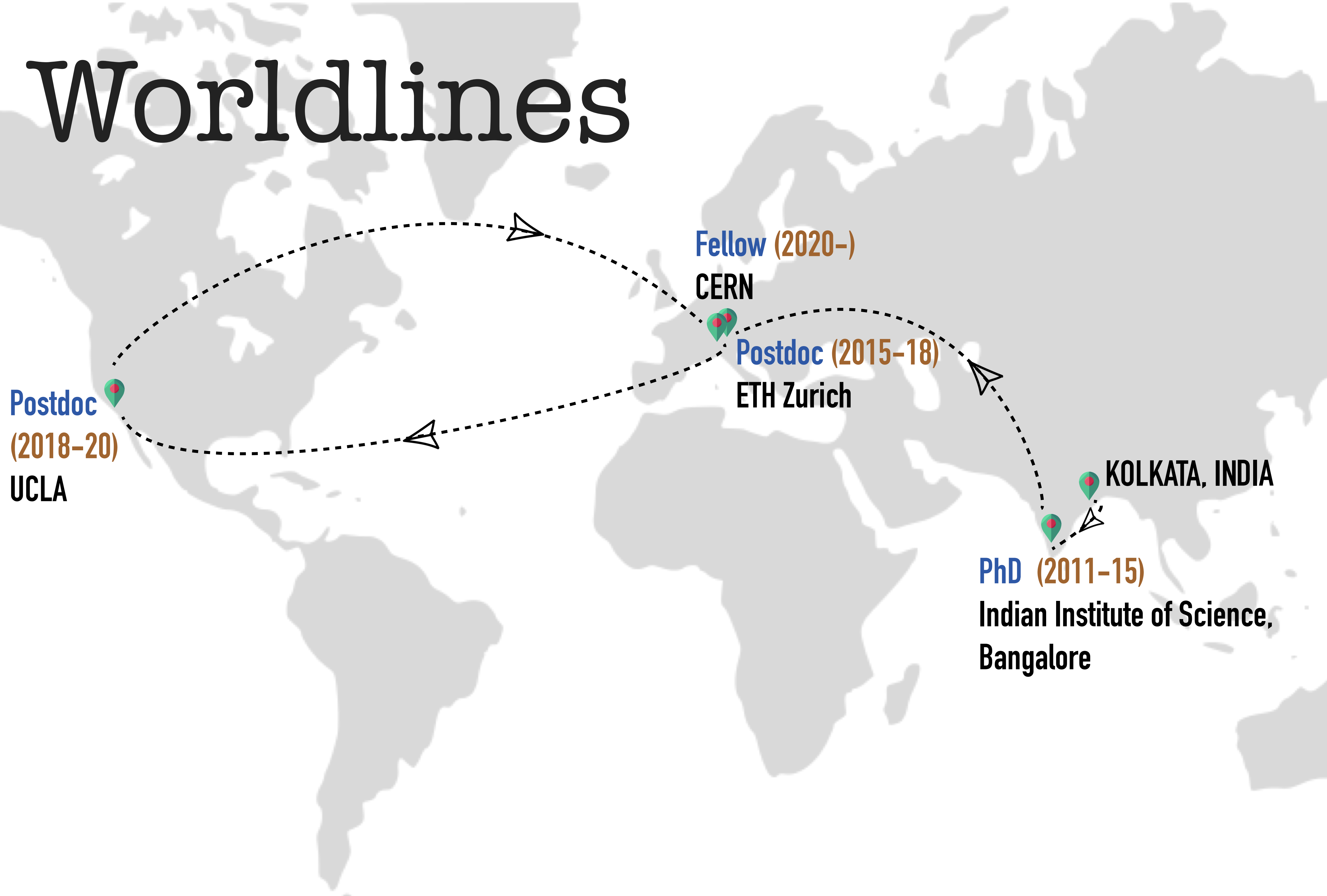
$\Longrightarrow$ Encodes this through Euclidean wormholes

Thank you!

Conformal field theory, gravity and all that

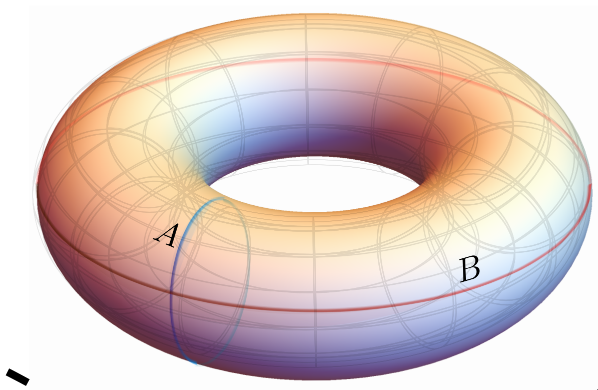
Shouvik Datta

Worldlines



Fellow (2020-)
CERN
Postdoc (2015-18)
ETH Zurich
Postdoc
(2018-20)
UCLA
KOLKATA, INDIA
PhD (2011-15)
Indian Institute of Science,
Bangalore

My research interests



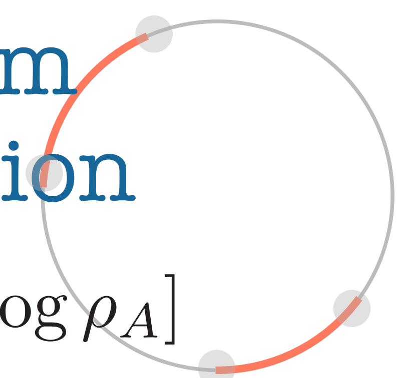
Conformal field theories

Implications for black holes

$$S_{\mathrm{BH}} = \frac{kc^3}{4\hbar G} A$$

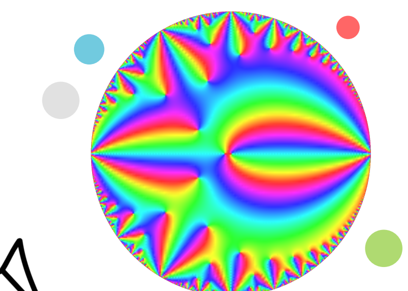
Deformations of CFTs

Quantum information



$$S_{\mathrm{E}} = -\mathrm{tr}[\rho_A \log \rho_A]$$

Modular functions



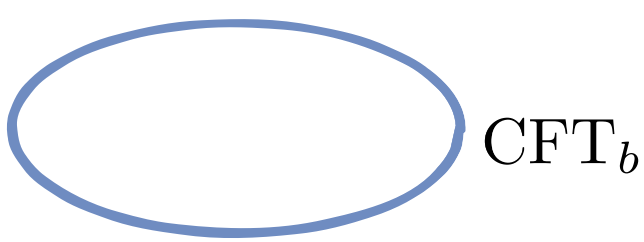
How robust are our techniques for quantizing gravity?

Holography and partition functions

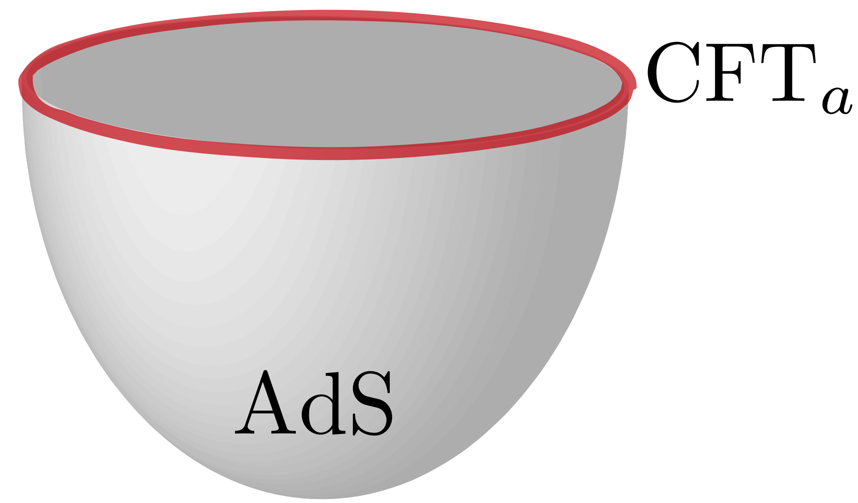
$$Z_{\mathrm{AdS}} = Z_{\mathrm{CFT}}$$

AdS/CFT provides us with a non-perturbative framework to tackle quantum gravity path integrals.

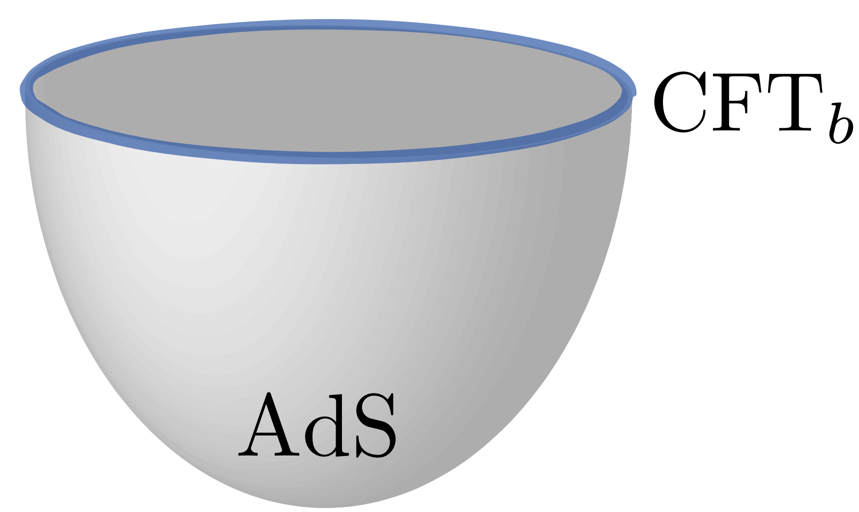
Factorization puzzle in AdS/CFT



$$Z(\beta_a, \beta_b) = Z(\beta_a) Z(\beta_b)$$

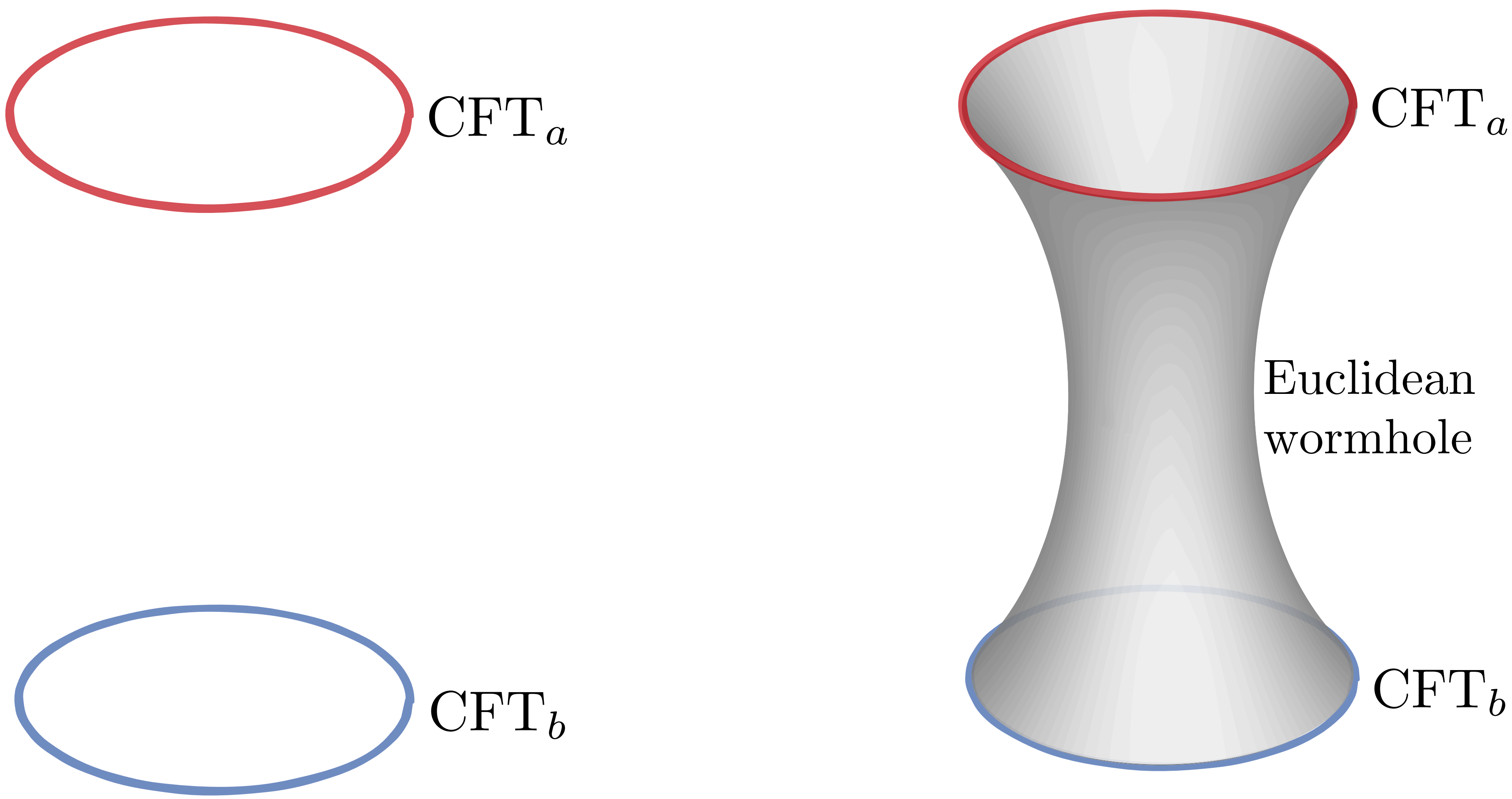


$$Z_{\mathrm{AdS}} = Z_{\mathrm{CFT}}$$



Factorization puzzle in AdS/CFT

There can be a scenario where
the partition function does not factorize.



$$Z(\beta_a, \beta_b) \neq Z(\beta_a) Z(\beta_b)$$

A possible resolution?

$$Z(\beta_a, \beta_b) \neq Z(\beta_a)Z(\beta_b)$$

Potential resolution: the dual CFT isn't a single theory, but an average of an ensemble of theories.

$$\langle Z(\beta_1)Z(\beta_2)\cdots\rangle = \int_{\mathcal{M}} [D\mu_i]\; Z_{\mu_i}(\beta_1)Z_{\mu_i}(\beta_2)\cdots$$

average over couplings

This leads to connected pieces of observables.

$$\langle Z(\beta_1)Z(\beta_2)\rangle = \langle Z(\beta_1)\rangle\langle Z(\beta_2)\rangle + \langle Z(\beta_1)Z(\beta_2)\rangle_{\text{conn.}}$$

[Saad-Shenker-Stanford; Marolf-Maxfield; …]

Ensemble averaged holography

$$\langle Z(\beta_1)Z(\beta_2)\cdots\rangle = \int_{\mathcal{M}} [D\mu_i]\; Z_{\mu_i}(\beta_1)Z_{\mu_i}(\beta_2)\cdots$$

average over couplings

This idea originates from disorder averaging in the context of spin-glasses.

[Parisi, …]

Further support: 2d JT gravity is dual to an ensemble of large random Hermitian matrices.

[Saad-Shenker-Stanford]

How does this generalize in higher dimensions?

Averaging in 2d CFT

How can one possibly construct a random/averaged 2d CFT?

$$\langle Z(\beta_1)Z(\beta_2)\cdots\rangle = \int_{\mathcal{M}} [D\mu_i]\; Z_{\mu_i}(\beta_1)Z_{\mu_i}(\beta_2)\cdots$$

average over couplings

1 Average over the moduli space of marginal couplings. This has been studied recently for D free bosons.

[Maloney-Witten, A'Jeddi-Cohn-Hartman-Tajdini, Benjamin-Keller-Ooguri-Zadeh, Ashwinkumar-Dodelson-Kidambi-Leedom-Yamazaki]

2 Take a bootstrap approach. Find properties of the averaged theory from some constraints, such as modular invariance.

[Cotler-Jensen]

Averaged flavored partition function

Grand canonical partition function

$$Z\left(\tau,\bar{\tau},z_L^I,z_R^I\right) = \mathrm{Tr}\left[e^{2\pi i\tau(L_0-\frac{c}{24})}e^{-2\pi i(L_0-\frac{c}{24})}e^{2\pi i z_L^I J_0^I}e^{-2\pi i z_R^I \bar{J}_0^I}\right]$$

The result is given by a Jacobi-Eisenstein series.

$$\langle Z(\tau,z)\rangle = \frac{1}{|\eta(\tau)|^{2D}}\sum_{(c,d)=1}\frac{e^{-i\pi\left(\frac{cz_L^2}{c\tau+d}-\frac{cz_R^2}{c\bar{\tau}+d}\right)}}{|c\tau+d|^D}$$

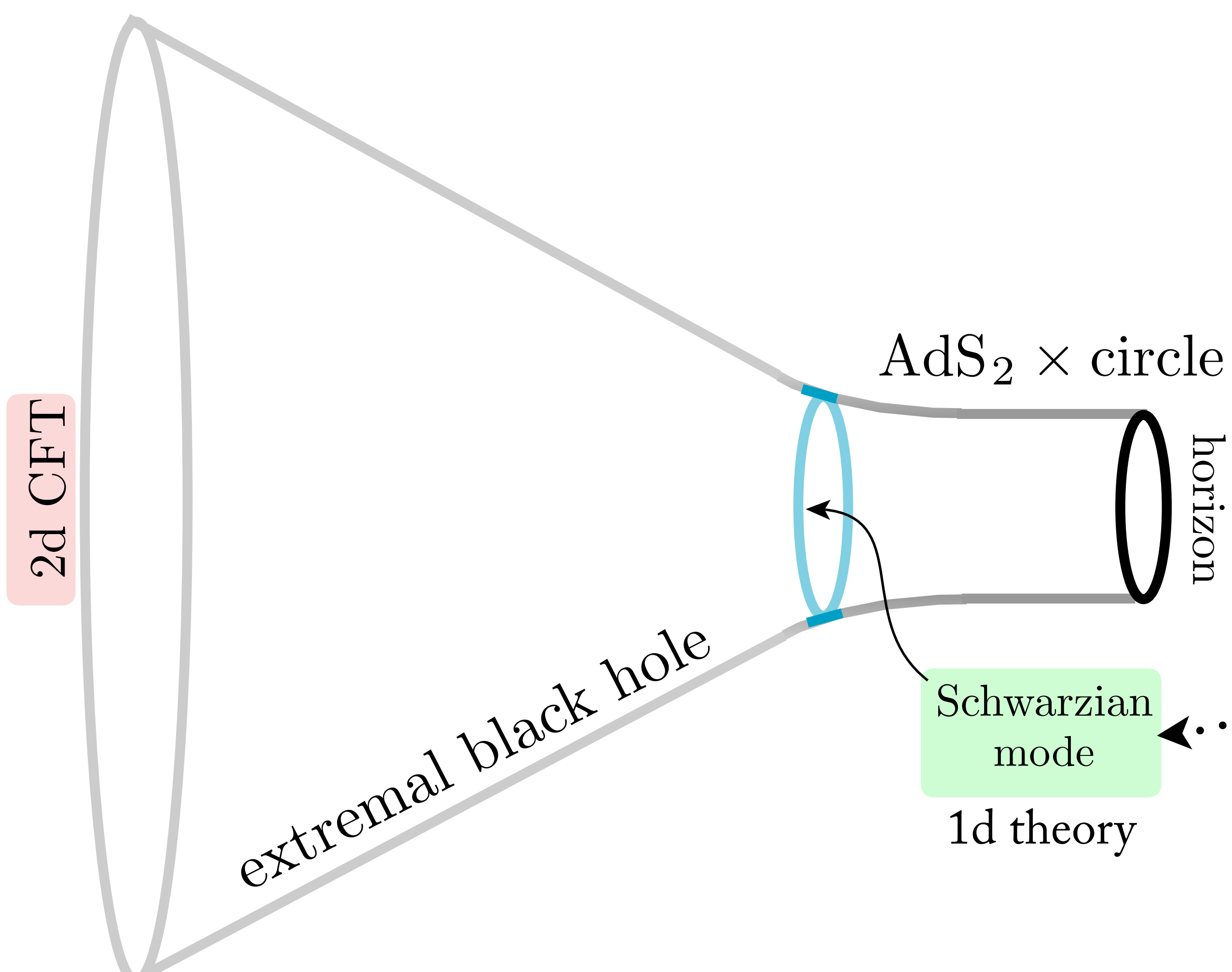
[SD-Duary-Kraus-Maity-Maloney (arXiv 2021)]

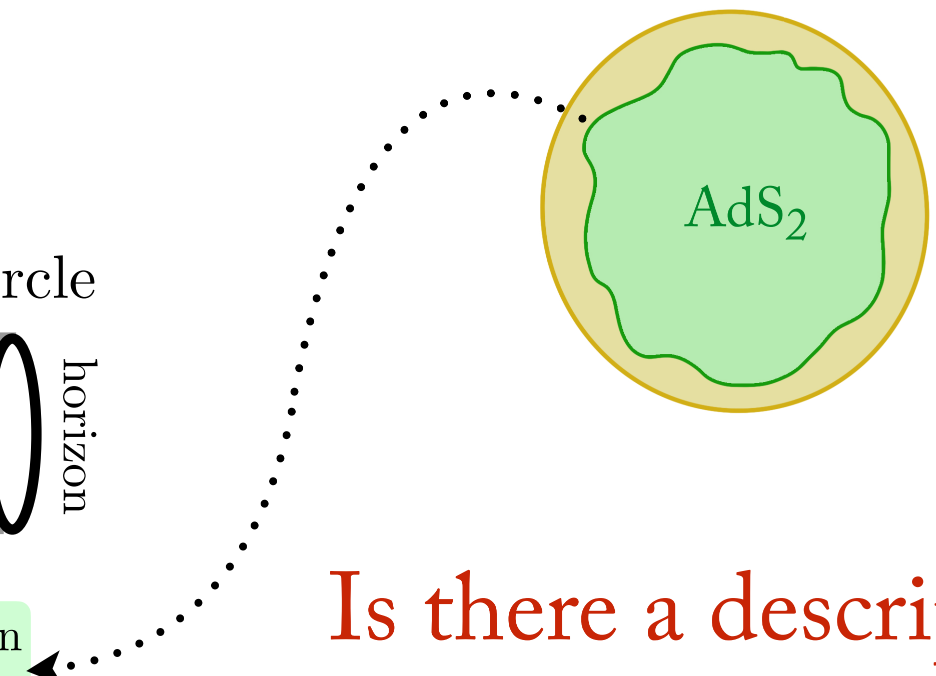
This has the expected modular properties and matches with a holographic theory of "U(1)" gravity.

Extremal black holes

Excitations near the horizon of extremal black holes
in 3d anti-deSitter space.

[Ghosh-Maxfield-Turiaci 2020,
SD (JHEP 2021)]





Is there a description using random matrices for more general theories of gravity?

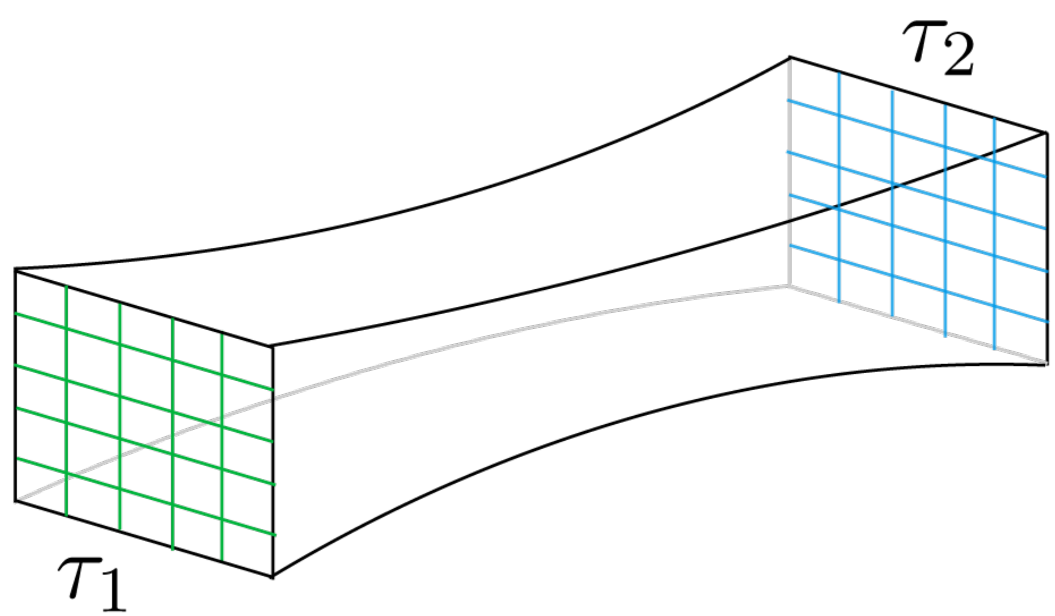
$$Z_{\text{2d CFT}} \to Z_{\text{Schwarzian}}$$

[Saad-Shenker-Stanford]

Wormholes in higher spin gravity

[Das-SD (JHEP 2021)]

We can consider CFTs with higher spin conserved currents living at the boundaries.



$$Z_{\text{hs}}(\tau_1, \tau_2) = \mathcal{C}\, Z_0(\tau_1)^{N-1} Z_0(\tau_2)^{N-1} \sum_{\gamma \in \text{PSL}(2,\mathbb{Z})} \left(\frac{(\text{Im}(\tau_1)\text{Im}(\gamma\tau_2))}{|\tau_1 + \gamma\tau_2|^2} \right)^{N-1}$$

Spectral correlations between high energy microstates can be extracted.

Averaged CFTs

$$\langle Z(\beta_1)Z(\beta_2)\cdots\rangle = \int_{\mathcal{M}} [D\mu_i]\ Z_{\mu_i}(\beta_1)Z_{\mu_i}(\beta_2)\cdots$$

A new class of theories to explore, which are turning out to be interesting in their own right.

This offers an avenue to apply ideas from bootstrap, localization, conformal manifolds and matrix models.

What is the description that interpolates between an averaged and a non-averaged CFT?

How does information spread in a quantum system?

Irreversibility in quantum systems

The process of relaxation to thermal equilibrium is a part of our everyday experience.

However, it is not always clear how macroscopic phenomena emerge microscopic/quantum-mechanical details.

Microscopic laws are time-reversal invariant.
But, thermodynamic laws aren't.

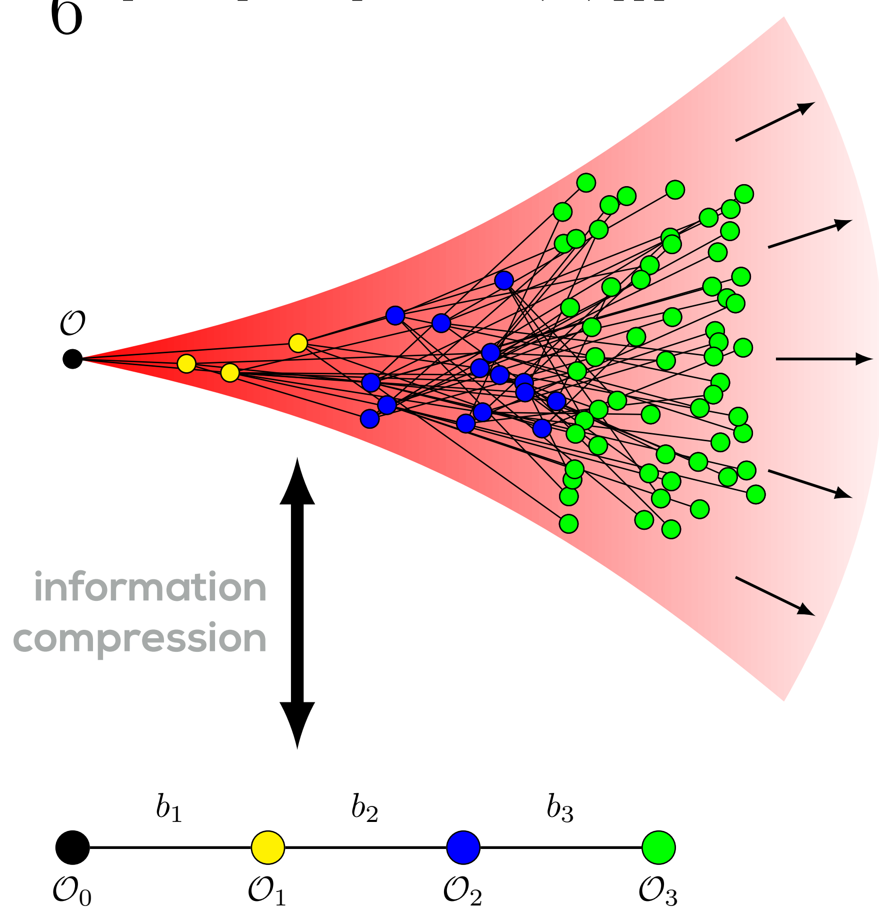
How does this irreversible behaviour emerge microscopically?

Operator growth

Consider the Heisenberg evolution of a local operator

$$e^{iHt}\mathcal{O}(0)e^{-iHt} = \mathcal{O}(0) + it[H,\mathcal{O}(0)] - \frac{t^2}{2}[H,[H,\mathcal{O}(0)]] - \frac{it^3}{6}[H,[H,[H,\mathcal{O}(0)]]] + \cdots \ .$$

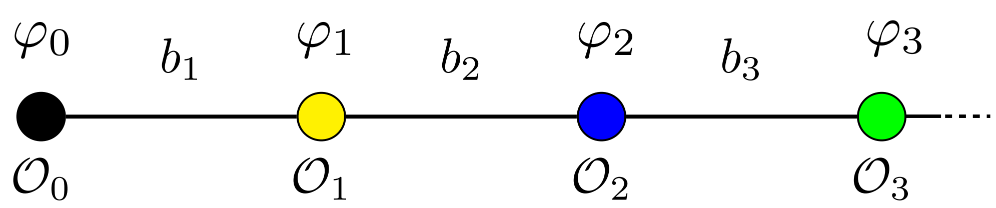
Let O be a simple local operator and the Hamiltonian has few-body interactions.

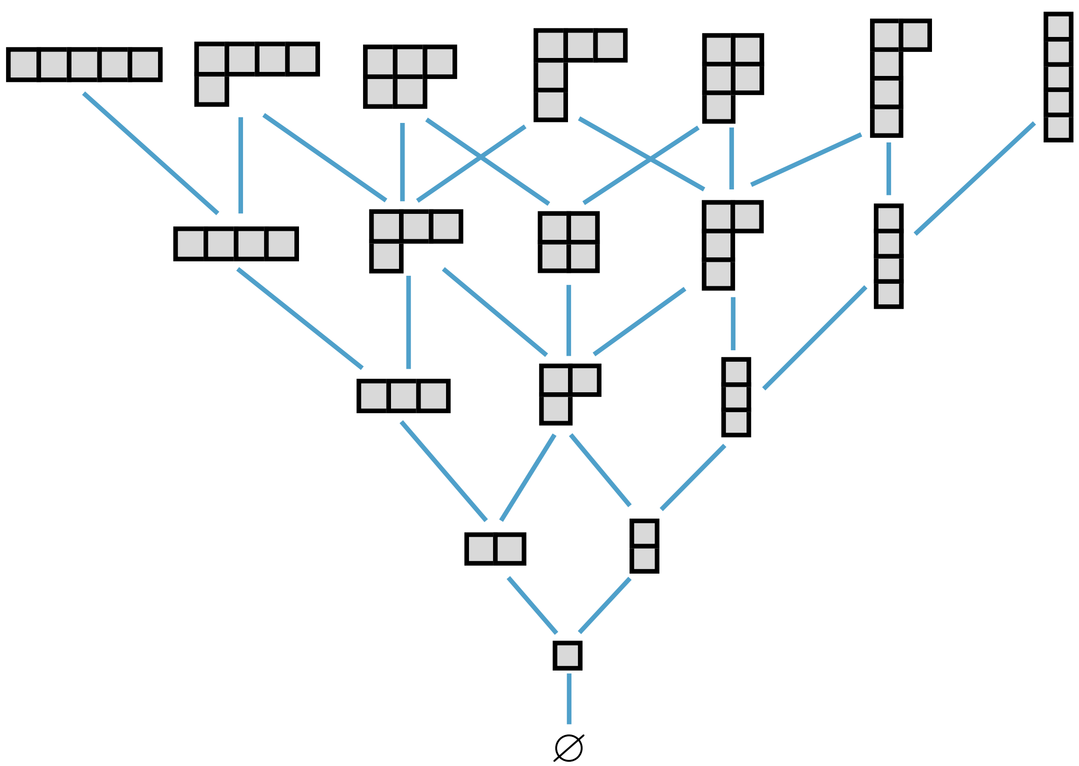


However, the effect of the operator spreads throughout the system at late times.

[Parker-Cao-Avdoshkin-Scaffidi-Altman]

Operator growth in 2d CFTs





operator growth in 2d CFTs

↓

spreading along the Young's lattice

A specific path along the lattice saturates
the conjectured upper bound on operator growth.

Simple local operators grow into ones with higher 'complexity'.
This growth in exponential.

[Caputa-SD (arXiv 2021)]

Thank you.

Ling Lin

2013 — 2016 (PhD) → 2016 — 2019 → since 10/2019

CERN-TH Retreat, Nov 5, 2021

Research interests: “String geometry”

In the past: model building (construct “realistic” string compactifications)

More recently:

- ⋆ Understanding non-perturbative aspects of QFTs
- ⋆ Explore generic features of quantum gravity

Geometric engineering

Geometric engineering

Starting from a theory in $D = d + n$ dimensions, obtain d-dimensional theory by dimensionally reducing on an n-dimensional manifold X.

Geometric engineering

Starting from a theory in $D = d + n$ dimensions, obtain d-dimensional theory by dimensionally reducing on an n-dimensional manifold X.

- Geometry / topology of X determine physics in $\mathbb{R}^d$.

Geometric engineering

Starting from a theory in $D = d + n$ dimensions, obtain d-dimensional theory by dimensionally reducing on an n-dimensional manifold X.

- Geometry / topology of X determine physics in $\mathbb{R}^d$.

⋆ Geometric restrictions on X constrain possible physics in $\mathbb{R}^d$.

Geometric engineering

Starting from a theory in $D = d + n$ dimensions, obtain d-dimensional theory by dimensionally reducing on an n-dimensional manifold X.

- Geometry / topology of X determine physics in $\mathbb{R}^d$.

⋆ Geometric restrictions on X constrain possible physics in $\mathbb{R}^d$.

Observation: d-dim. supergravity theories obtained from string / M-theory are highly restricted $\rightsquigarrow$ feature or bug?

The “Swampland” Program

The “Swampland” Program

- Idea / hypothesis: most effective field theories (such as supergravity models) cannot be *consistently* completed in the UV with gravity [Vafa ’06].

The “Swampland” Program

- Idea / hypothesis: most effective field theories (such as supergravity models) cannot be *consistently* completed in the UV with gravity [Vafa ’06].
- Evidence: restrictive features of string compactifications.

The “Swampland” Program

- Idea / hypothesis: most effective field theories (such as supergravity models) cannot be *consistently* completed in the UV with gravity [Vafa ’06].
- Evidence: restrictive features of string compactifications.
- Predicting+Testing: formulate *general principles* (independent of string theory) that enforce the features.

The “Swampland” Program

- Idea / hypothesis: most effective field theories (such as supergravity models) cannot be *consistently* completed in the UV with gravity [Vafa ’06].

- Evidence: restrictive features of string compactifications.

- Predicting+Testing: formulate *general principles* (independent of string theory) that enforce the features.

My current interests: explore such restrictions on *gauge symmetries* in EFTs with gravity (+SUSY) and find rigorous arguments for these.

Example 1: global structure of gauge groups

Example 1: global structure of gauge groups

- From EFT perspective: a model can have either G or G/Z as gauge group (Z: subgroup of center of G).

Example 1: global structure of gauge groups

- From EFT perspective: a model can have either G or G/Z as gauge group (Z: subgroup of center of G).
- Famous example: Standard Model can have $SU(3) \times SU(2) \times U(1)$, or $[SU(3) \times SU(2) \times U(1)]/Z$ with $Z \in \{\mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_6\}$; cannot be tested currently!

Example 1: global structure of gauge groups

- From EFT perspective: a model can have either G or G/Z as gauge group (Z: subgroup of center of G).

- Famous example: Standard Model can have $SU(3) \times SU(2) \times U(1)$, or $[SU(3) \times SU(2) \times U(1)]/Z$ with $Z \in \{\mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_6\}$; cannot be tested currently!

- Question: Are there any physical restrictions on Z?

Example 1: global structure of gauge groups

- From EFT perspective: a model can have either G or G/Z as gauge group (Z: subgroup of center of G).
- Famous example: Standard Model can have $SU(3) \times SU(2) \times U(1)$, or $[SU(3) \times SU(2) \times U(1)]/Z$ with $Z \in \{\mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_6\}$; cannot be tested currently!
- Question: Are there any physical restrictions on Z?
- In string compactifications, Z tied to geometric properties — not anything goes! Can tie these geometric restrictions (at least in higher dimensions) to *generalized / higher-form symmetries* [Gaiotto/Kapustin/Seiberg/Willet '14].

High Energy Physics – Theory

[Submitted on 20 Aug 2020 (v1), last revised 18 Sep 2020 (this version, v2)]

The Fate of Discrete 1-Form Symmetries in 6d

Fabio Apruzzi, Markus Dierigl, Ling Lin

High Energy Physics – Theory

[Submitted on 24 Aug 2020]

String Universality and Non-Simply-Connected Gauge Groups in 8d

Mirjam Cvetic, Markus Dierigl, Ling Lin, Hao Y. Zhang

Example 2: gauge algebra/group in 6d $\mathscr{N} = (1,0)$ SUGRA

Example 2: gauge algebra/group in 6d $\mathscr{N} = (1,0)$ SUGRA

- 6d $\mathscr{N} = (1,0)$ gauge theories highly-constrained by chiral anomalies; yet, not every anomaly-free model can be constructed in string theory.

Example 2: gauge algebra/group in 6d $\mathcal{N} = (1{,}0)$ SUGRA

- 6d $\mathcal{N} = (1{,}0)$ gauge theories highly-constrained by chiral anomalies; yet, not every anomaly-free model can be constructed in string theory.

- Observation: in certain cases, model can only have gauge symmetry $\mathfrak{g}$ + matter M if *additional* symmetry factor $\mathfrak{h}$ present ("automatic enhancement") [Raghuram/Taylor/Turner '20].

Example 2: gauge algebra/group in 6d $\mathcal{N} = (1{,}0)$ SUGRA

- 6d $\mathcal{N} = (1{,}0)$ gauge theories highly-constrained by chiral anomalies; yet, not every anomaly-free model can be constructed in string theory.

- Observation: in certain cases, model can only have gauge symmetry $\mathfrak{g}$ + matter M if *additional* symmetry factor $\mathfrak{h}$ present ("automatic enhancement") [Raghuram/Taylor/Turner '20].

- Can show: $\mathfrak{h}$ is only anomaly-free subalgebra of *flavor symmetry* of $(\mathfrak{g}, M)$; No-Global-Symmetries Hypothesis $\Longrightarrow$ $\mathfrak{h}$ gauged in theory of gravity.

High Energy Physics – Theory

[Submitted on 30 Sep 2021 (v1), last revised 14 Oct 2021 (this version, v2)]

Flavor Symmetries and Automatic Enhancement in the 6d Supergravity Swampland

Mirjam Cvetic, Ling Lin, Andrew P. Turner

Example 2: gauge algebra/group in 6d $\mathcal{N} = (1,0)$ SUGRA

- 6d $\mathcal{N} = (1,0)$ gauge theories highly-constrained by chiral anomalies; yet, not every anomaly-free model can be constructed in string theory.

- Observation: in certain cases, model can only have gauge symmetry $\mathfrak{g}$ + matter M if *additional* symmetry factor $\mathfrak{h}$ present ("automatic enhancement") [Raghuram/Taylor/Turner '20].

- Can show: $\mathfrak{h}$ is only anomaly-free subalgebra of *flavor symmetry* of $(\mathfrak{g}, M)$; No-Global-Symmetries Hypothesis $\Longrightarrow$ $\mathfrak{h}$ gauged in theory of gravity.

- "Microscopic" explanation: $\mathfrak{g}$ by itself is inconsistent with BPS-strings of theory.

Ongoing/future works

Ongoing/future works

- Utilize higher-form symmetries in geometric engineering of lower-dimensional (super-)conformal field theories from reduction of 6d SCFTs.

Ongoing/future works

- Utilize higher-form symmetries in geometric engineering of lower-dimensional (super-)conformal field theories from reduction of 6d SCFTs.
- In 4d theories, θ-term related to 1-form center symmetries ➡ interplay between axion dynamics and gauge group structure of SM / dark sectors?

Ongoing/future works

- Utilize higher-form symmetries in geometric engineering of lower-dimensional (super-)conformal field theories from reduction of 6d SCFTs.
- In 4d theories, θ-term related to 1-form center symmetries ➡ interplay between axion dynamics and gauge group structure of SM / dark sectors?
- Swampland principles in holographic settings ⇝ CFT “swampland”?

Ongoing/future works

- Utilize higher-form symmetries in geometric engineering of lower-dimensional (super-)conformal field theories from reduction of 6d SCFTs.
- In 4d theories, θ-term related to 1-form center symmetries ➡ interplay between axion dynamics and gauge group structure of SM / dark sectors?
- Swampland principles in holographic settings ⤳ CFT "swampland"?

Thank you!

Gábor Sárosi

MŰEGYETEM 1782

VUB VRIJE UNIVERSITEIT BRUSSEL

Penn UNIVERSITY of PENNSYLVANIA

It from Qubit
Simons Collaboration on
Quantum Fields, Gravity and Information

CERN

CERN

???

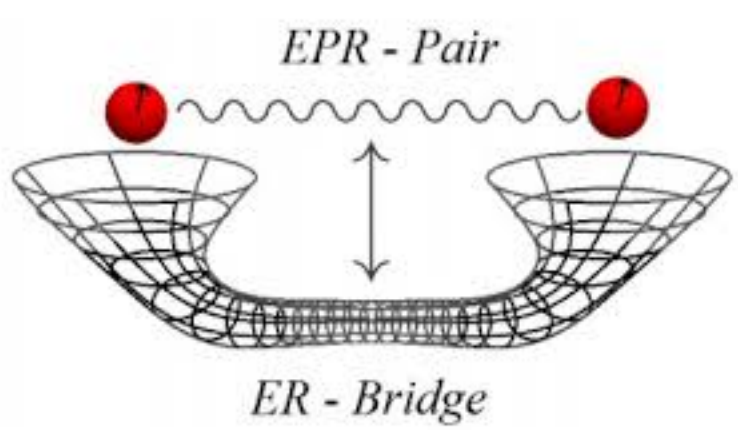
Main interests

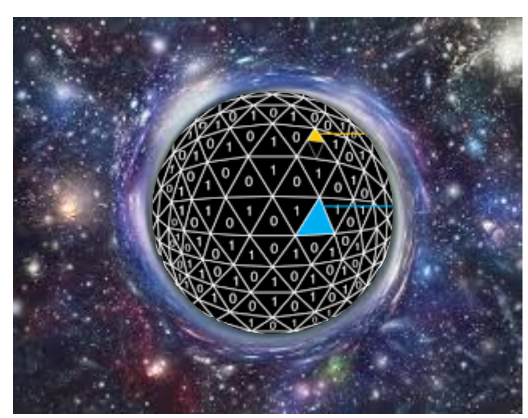
AdS/CFT

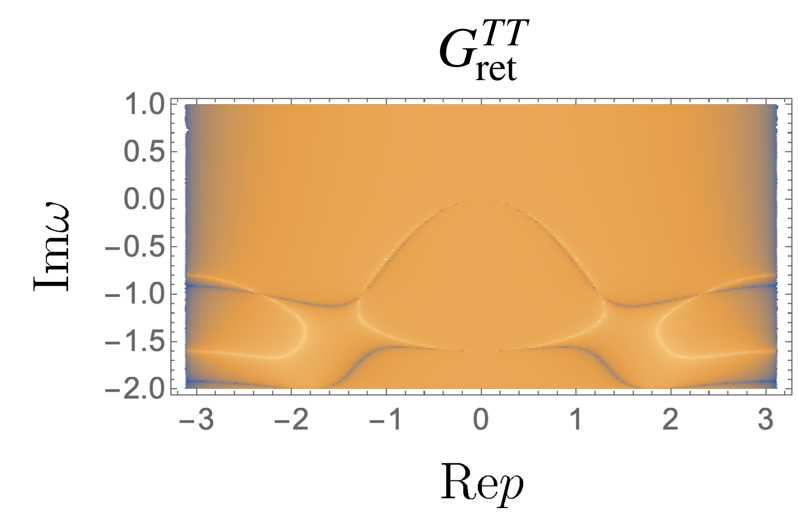
How does spacetime emerge from strongly coupled physics

Properties of quantum black holes

What do we learn about thermal physics in strongly coupled QFT

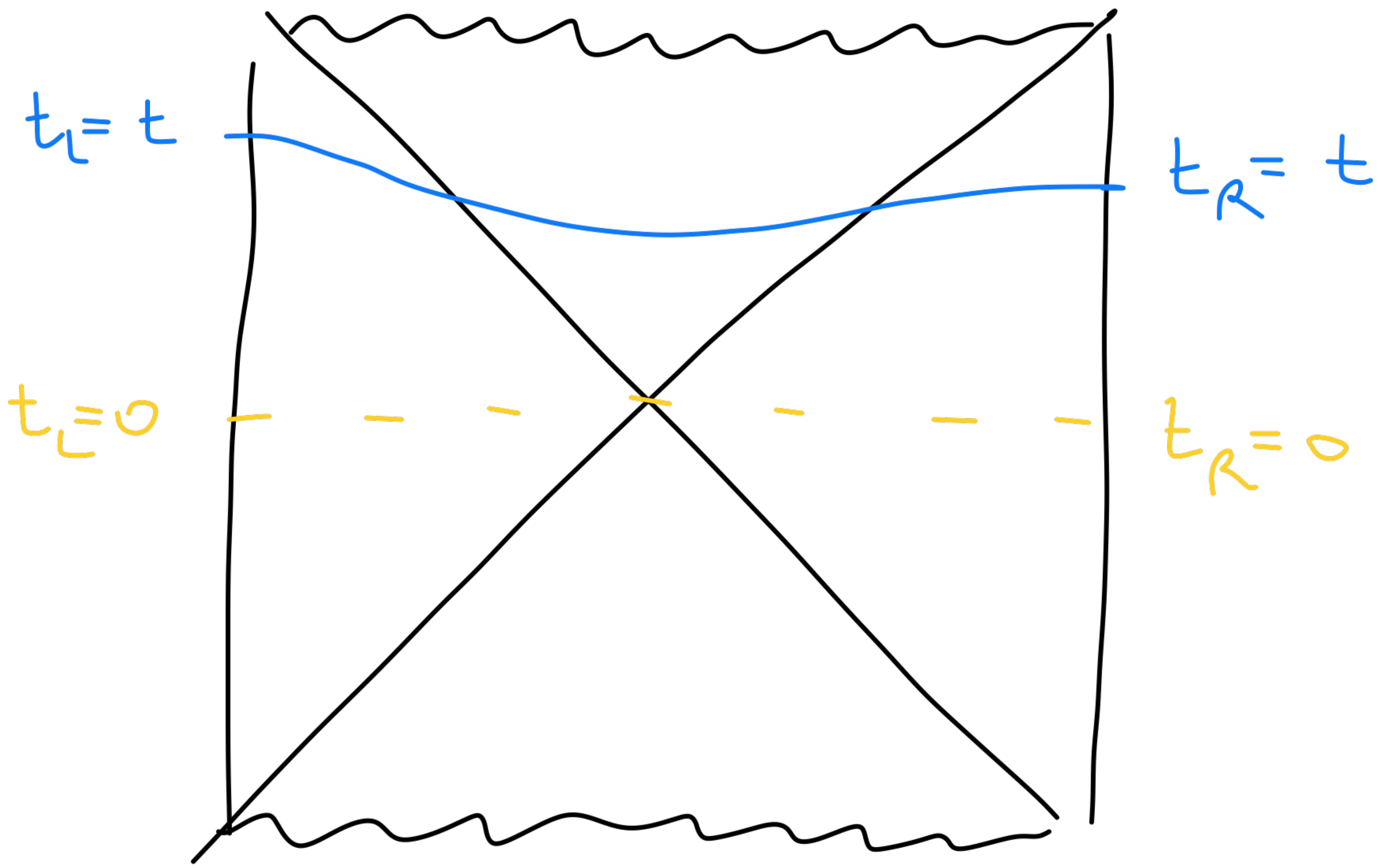






Growth of the interior

Black hole interior: an expanding cosmology



volume of maximal Cauchy slice $\propto Mt$

Question: what is the microscopic origin of this "creation of space"?

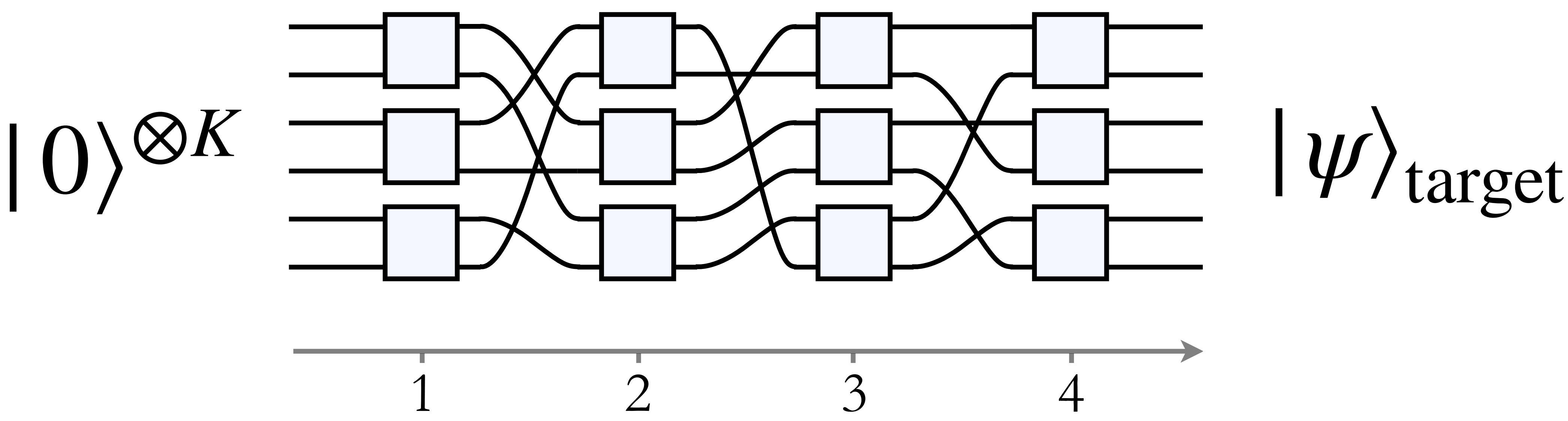
Growth of the interior

Perturbative corrections in G_N are unlikely to terminate this growth

Upshot: We need a quantity that is not thermalizing

for $\propto e^{\frac{1}{G_N}}$ times

Candidate: complexity of a state [Susskind et. al.]

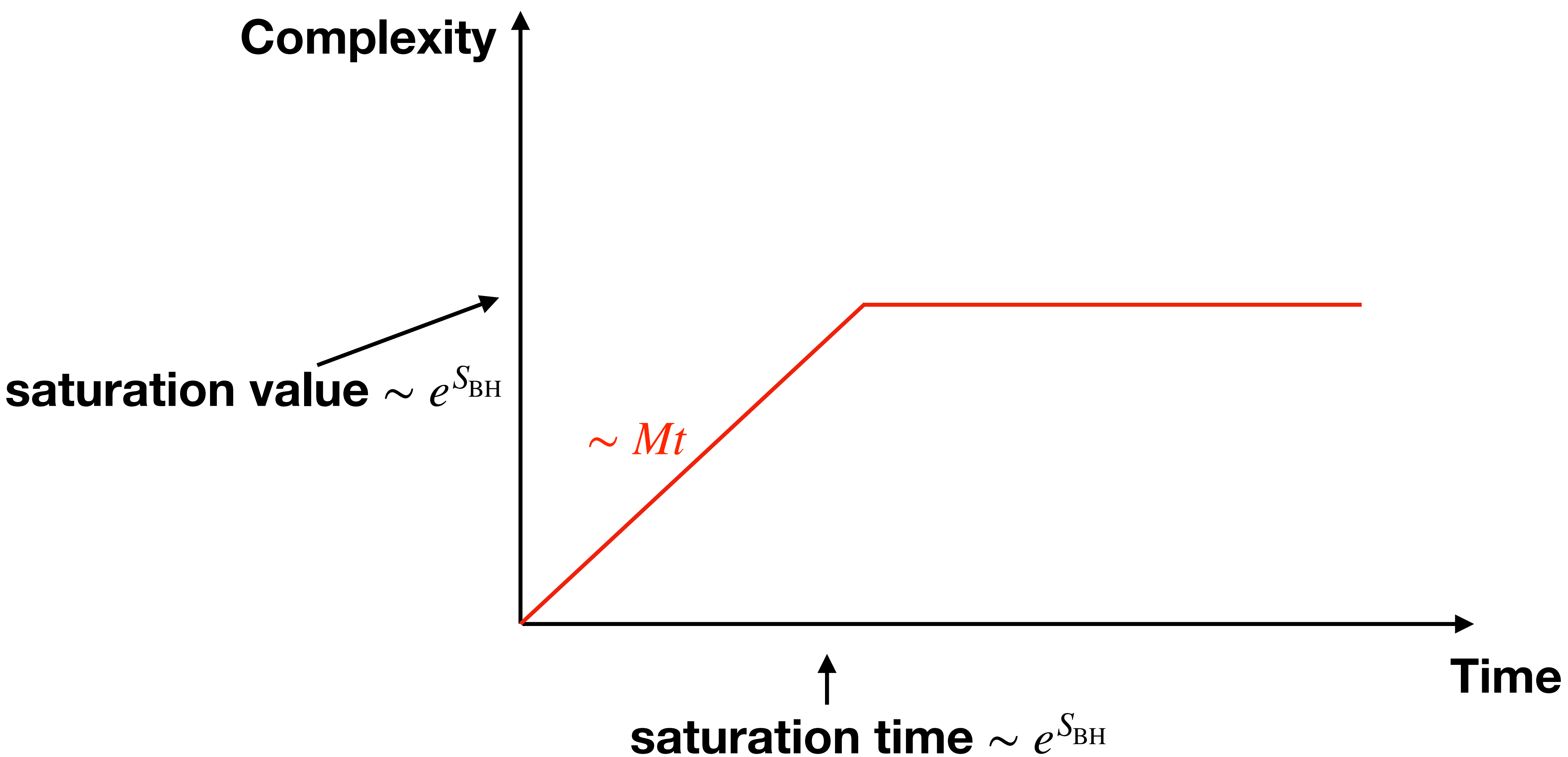


Size of the minimal quantum circuit producing the target

Complexity growth

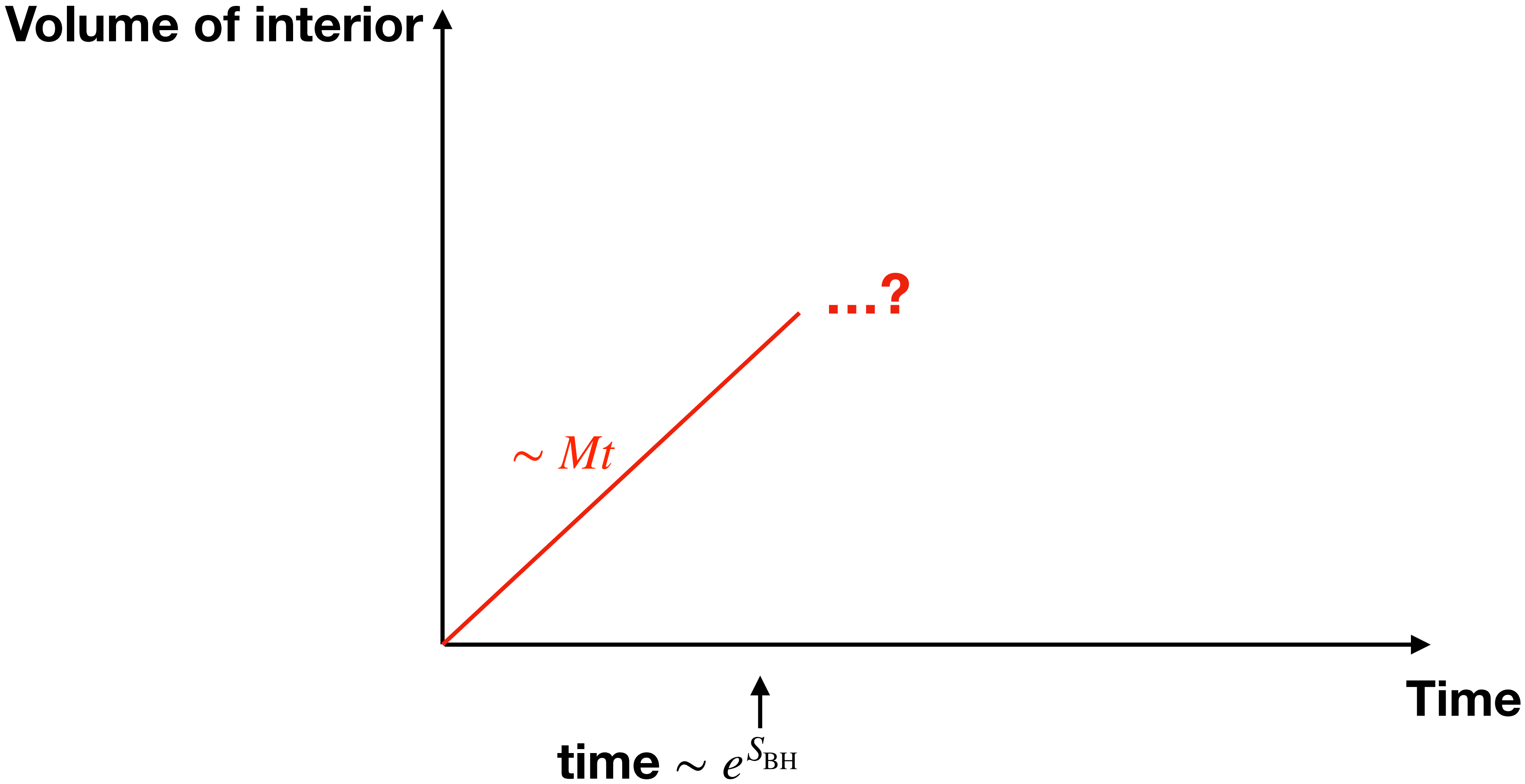
Conjectured time dependence of complexity in chaotic systems
[Susskind,Brown-Susskind-Zhao]

$$|\psi\rangle_{\rm target} = e^{-iHt}|\textbf{black hole}\rangle$$



Volume growth

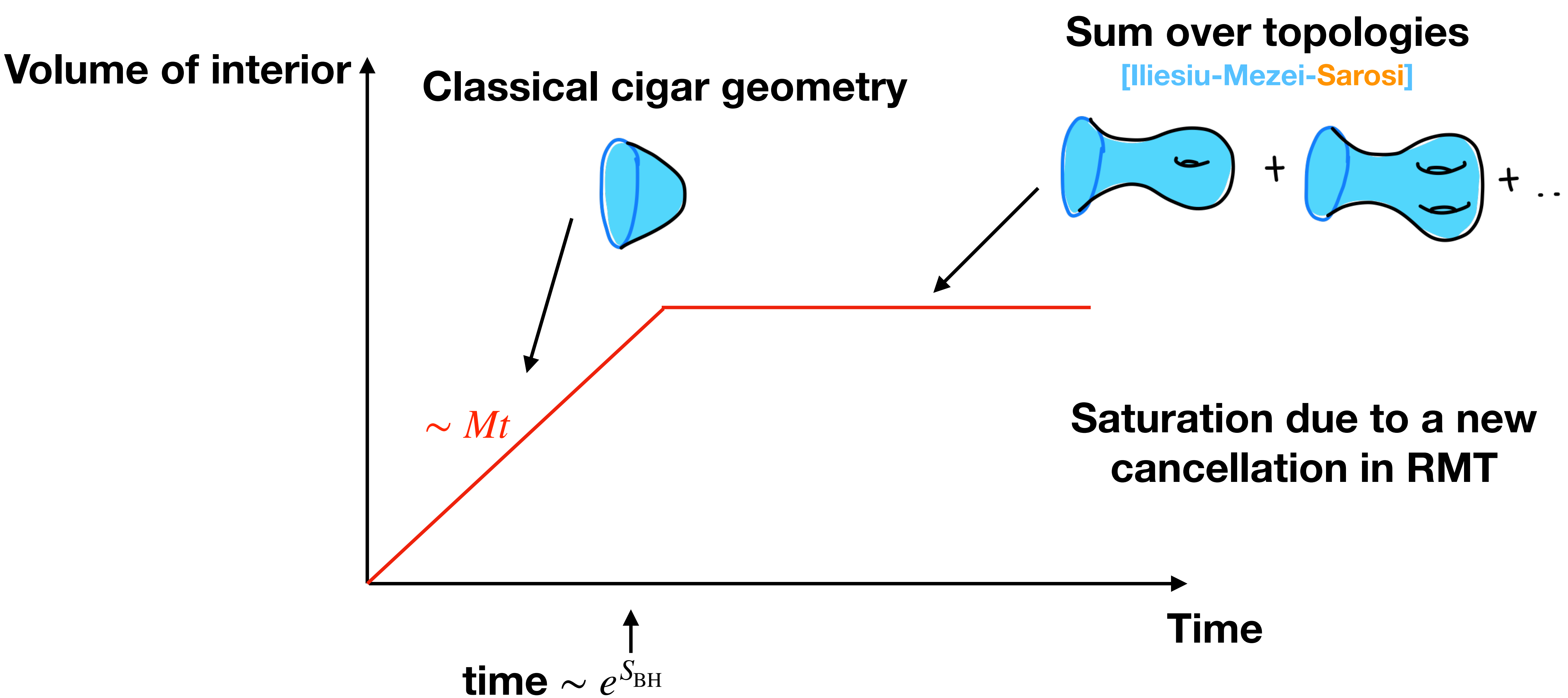
$$|\psi\rangle_{\text{target}} = e^{-iHt}|\textbf{black hole}\rangle$$



Volume growth

Can be addressed in 2d dilaton gravity!
[Iliesiu-Mezei-Sarosi]

AdS/CFT dual: random matrix theory
[Saad-Shenker-Stanford,Maxfield-Tuiraci,Witten]



Volume growth

The saturation is nice, but many puzzles are raised, volume of the interior is far from understood…

Thanks!

Guglielmo (Guli) Lockhart

B.S. 2010

Ph.D. 2015

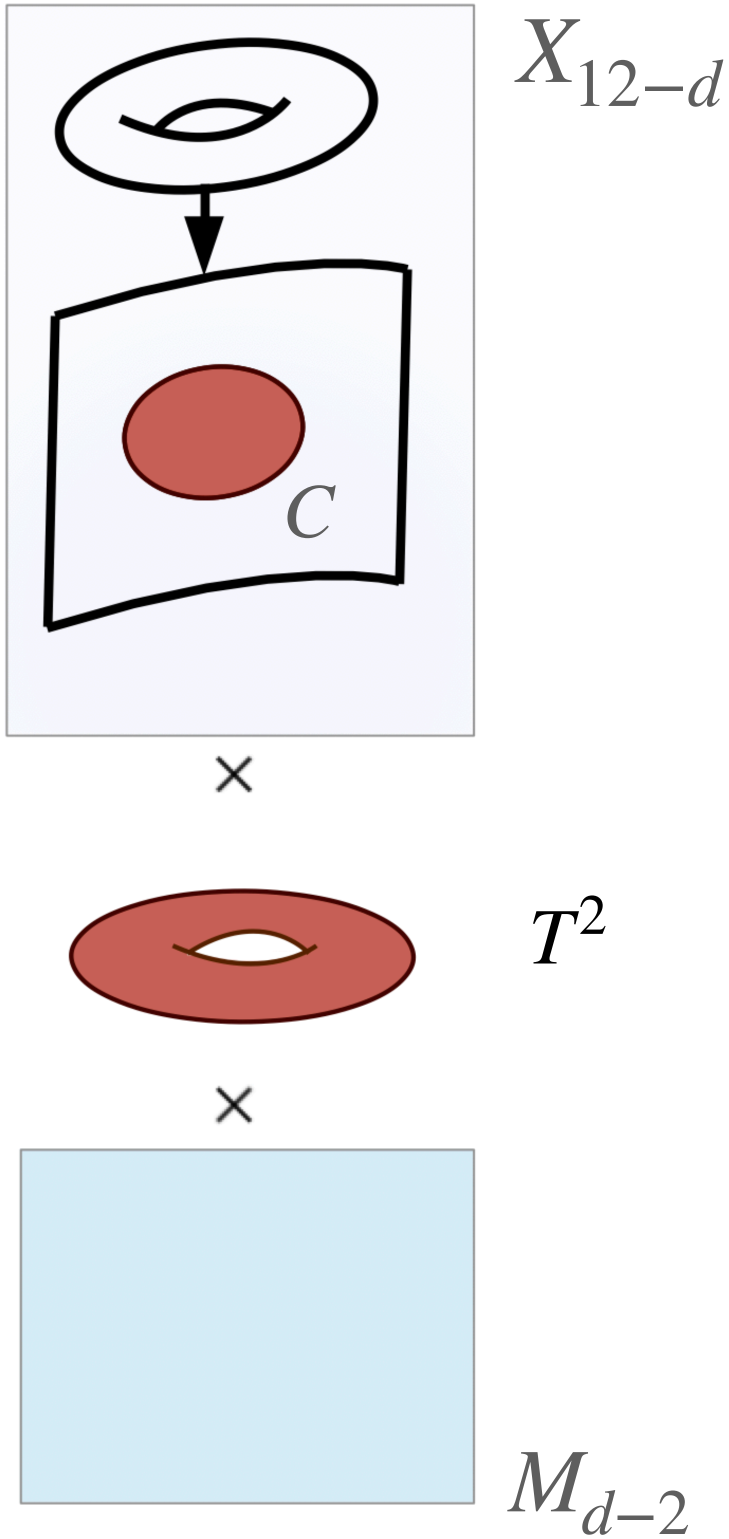
UNIVERSITY OF AMSTERDAM

Postdoc 2015-2019

Fellow 2019 -

TH Retreat 2021

F-theory



The main topics of my research are two-dimensional conformal field theories (CFTs) and their applications to string theory compactification.

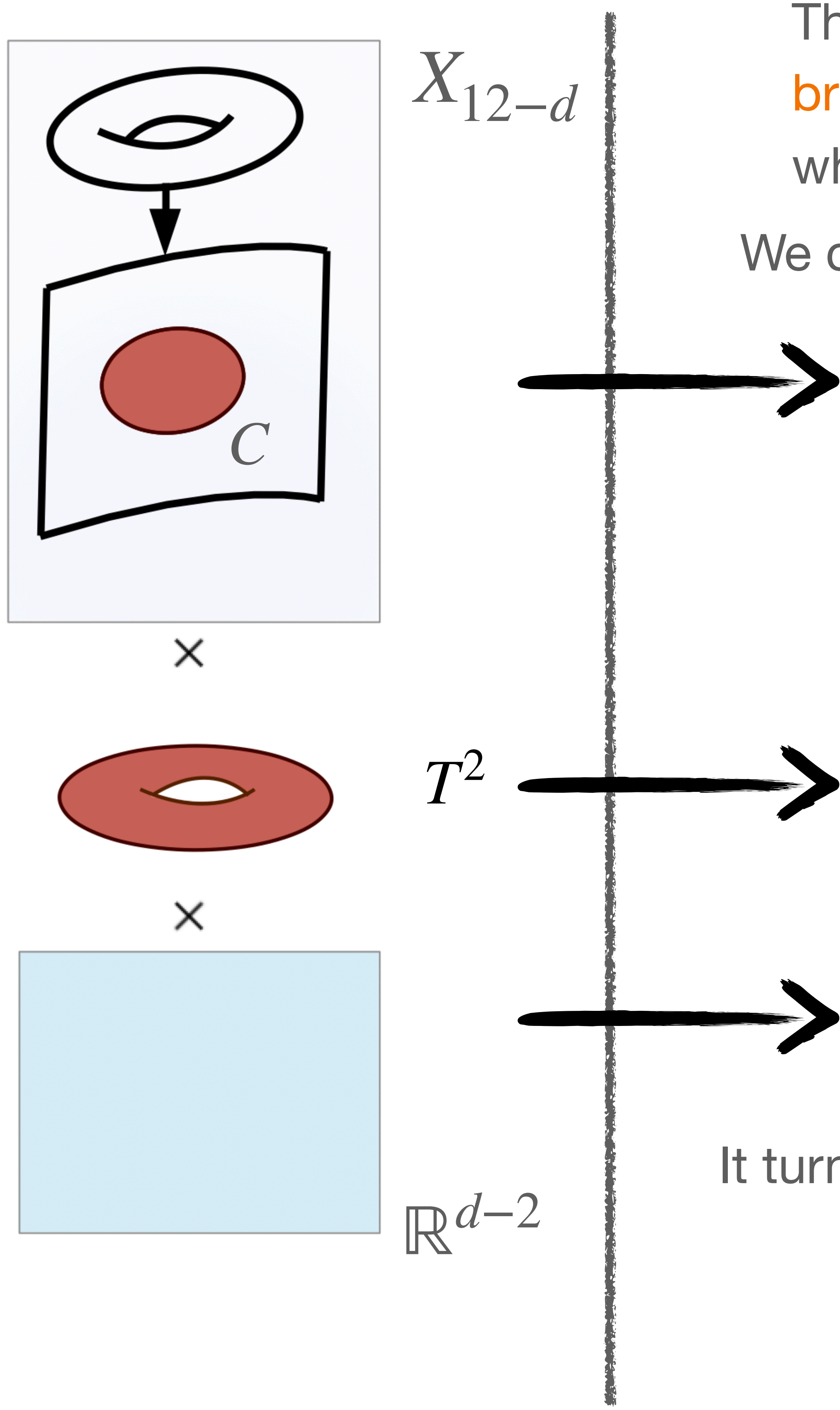
String theory provides a very general and insightful way to construct quantum field theories and quantum gravity theories in various dimensions. This approach goes by the name of geometric engineering.

We will take our starting point to be the 12-dimensional corner of string theory that goes by the name of F-theory.

We split the twelve dimensions into a d-dimensional spacetime $T^2 \times M_{d-2}$, and an internal space X_{12-d} of dimension 12-d (an elliptic Calabi-Yau manifold). For the talk, we choose $M_{d-2} = \mathbb{R}^{d-2}$, but other choices are also interesting.

Different choices of internal manifold X_{12-d} give rise to different physical theories living on $T^2 \times M_{d-2}$.

F-theory



The key object in this 12-dimensional setup are D3 branes wrapped on a holomorphic curve C in X, which give rise to strings on T^2.

We can compute three seemingly unrelated quantities:

Geometric viewpoint: $Z(X)$, a generating function which counts holomorphic maps from a Riemann surfaces to X (enumerative invariants)

Worldsheet viewpoint: $\mathbb{E}_C$, a collection of elliptic genera that count the supersymmetric excitations of the strings

Spacetime viewpoint: $Z(T^2 \times \mathbb{R}^{d-2})$, the Nekrasov partition function of the QFT/QG theory.

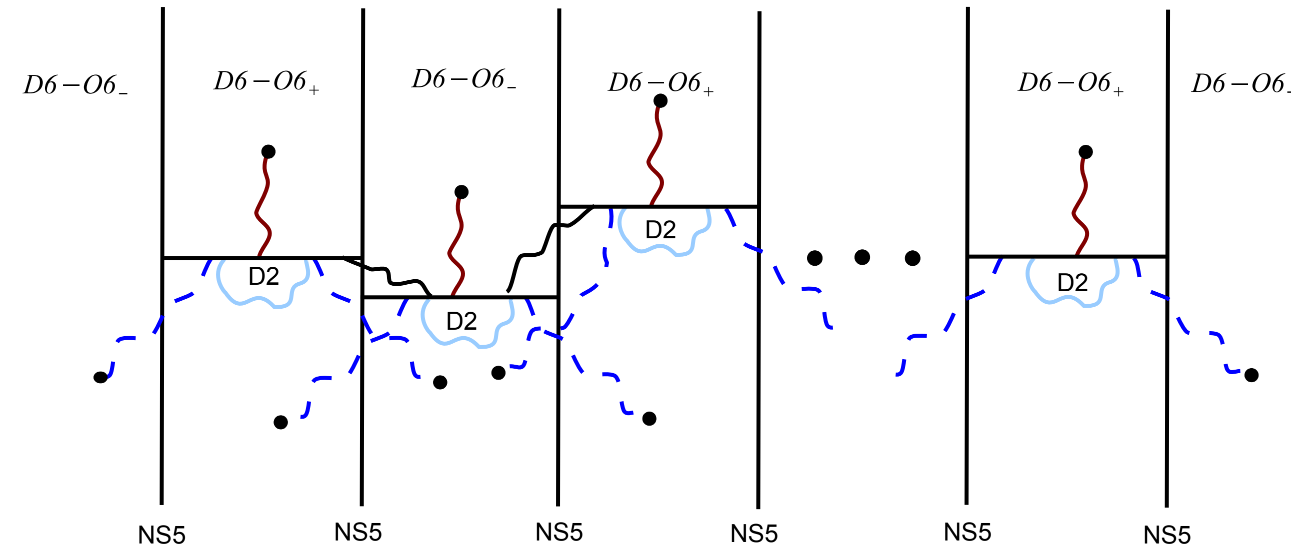
It turns out that the three quantities are equivalent!

$$Z(T^2 \times \mathbb{R}^{d-2}) = Z(X) = \sum_C Q_C \cdot \mathbb{E}_C$$

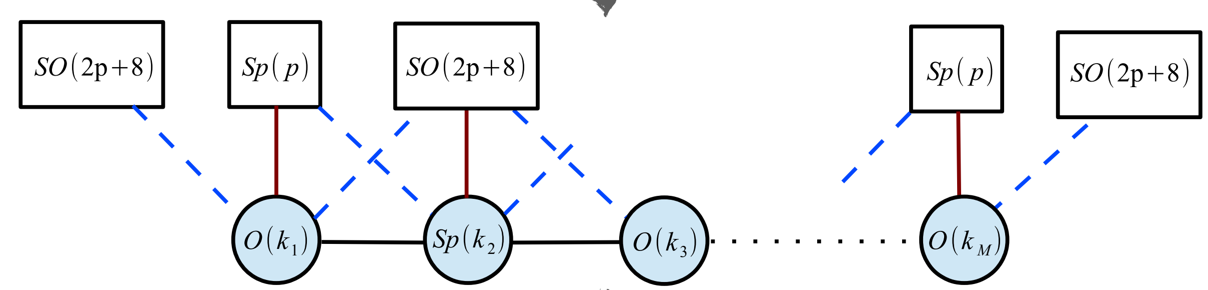
The worldsheet viewpoint is very powerful if one can determine the theory describing the strings exactly.

$$Z(T^2 \times \mathbb{R}^{d-2}) = Z(X) = \sum_C Q_C \cdot \mathbb{E}_C$$

For example, in some cases it may be read off by using a brane construction, giving rise to a a 2d quiver gauge theory.



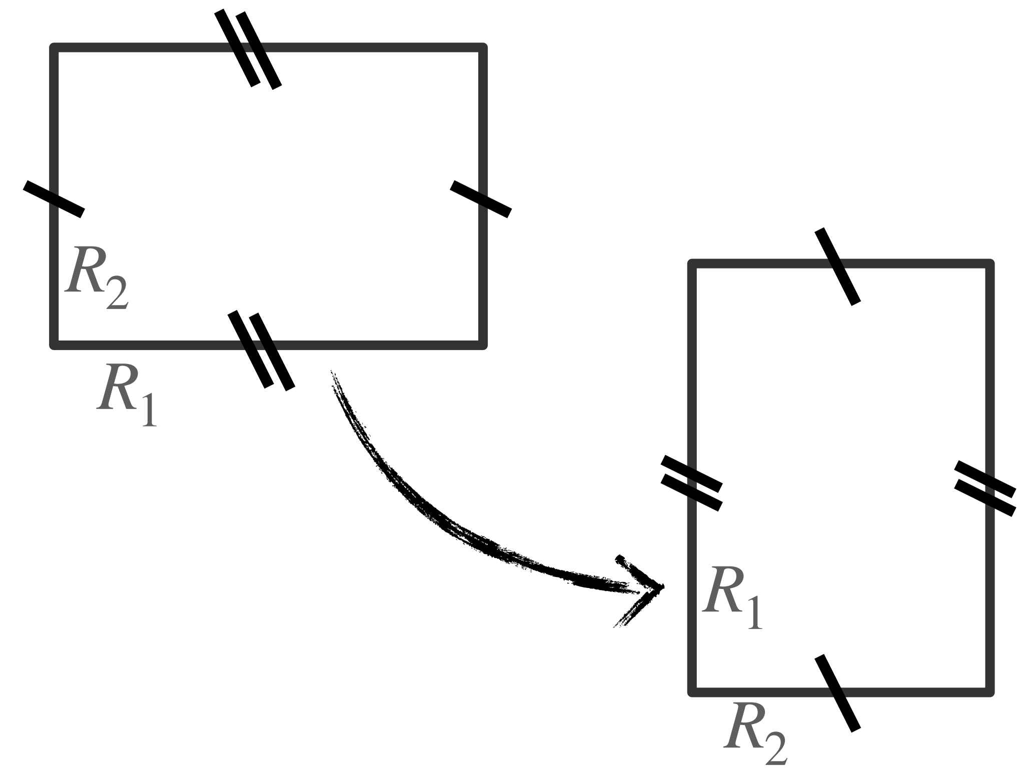
In this case supersymmetric localization can be used to obtain an explicit answer.



Other exact techniques allow exact solutions for large classes of theories (e.g. blowup equations for 6d SCFTs) even if no weakly-coupled description of the worldsheet theory exists.

$$\mathbb{E}_C = \frac{1}{4} \oint du \eta^2 \sum_{i=1}^{4} \left(\frac{\eta^2}{\theta_1(\epsilon_1)\theta_1(\epsilon_2)} \right) \left(\prod_{\ell=1}^{4} \frac{\theta_i(m_\ell^{(L)})}{\eta} \right) \left(\prod_{\ell=1}^{4} \frac{\theta_i(m_\ell^{(g)})}{\eta} \right) \left(\frac{\theta_1(2u)^2 \theta_1(2\epsilon_+)\theta_1(2u+2\epsilon_+)\theta_1(-2u+2\epsilon_+)}{\eta^3 \theta_1(\epsilon_1)\theta_1(\epsilon_2)} \right)$$
$$\times \left(\prod_{\ell=1}^{4} \frac{\eta^4}{\theta_1(\epsilon_+ + m_\ell^{(g)} + u)\theta_1(\epsilon_+ + m_\ell^{(g)} - u)\theta_1(\epsilon_+ - m_\ell^{(g)} + u)\theta_1(\epsilon_+ - m_\ell^{(g)} - u)} \right) \left(\frac{\theta_i(\epsilon_- - u)\theta_i(\epsilon_- + u)}{\theta_i(-\epsilon_+ - u)\theta_i(-\epsilon_+ + u)} \right)$$

A key property of elliptic genera is their behavior under modular transformations that exchange the two cycles of the torus.



A weight-k modular form $f(\tau)$ is a function of the parameter $\tau = iR_2/R_1$ which transforms in a prescribed way under modular transformations:

$$f(-1/\tau) = \tau^k f(\tau).$$

The elliptic genera of the strings are generalizations of modular forms that can depend in addition on the chemical potentials $\vec{z}$ of the global symmetries (elliptic parameters).

In the case where X is a CY threefold, the elliptic genera transform as weight-0 Jacobi forms:

$$E_C(-1/\tau, \vec{z}/\tau) = e^{\vec{z}^T \cdot M \cdot \vec{z}/2\tau} E_C(\tau, \vec{z})$$

where M is the index with respect to the elliptic variables. The index is tightly connected to the anomaly polynomial of the string CFT, as well as that of the spacetime theory on $T^2 \times \mathbb{R}^4$.

In the case where X is a CY fourfold, the elliptic genera depend on a choice of four-form flux G_n of type $n = 0, -1$, or -2. Surprisingly in work with Wolfgang Lerche, Timo Weigand and Seung-Joo Lee we found that the elliptic genera are quasi-Jacobi forms, which transform anomalously:

$$E_{C,G_n}(-1/\tau, \vec{z}/\tau) = \tau^n e^{\vec{z}^T \cdot M \cdot \vec{z}/2\tau} E_{C,G_n}(\tau, \vec{z}) + \text{anomalous terms}.$$

The anomalous modular behavior is tightly connected to the existence of an intricate network of holomorphic anomaly equations that relate the elliptic genera for different choices of fluxes:

$$\mathbb{E}_{C,G_{-1}} = \frac{1}{2\pi i}\partial_z \mathbb{E}_{C,G'_{-2}} \qquad \mathbb{E}_{C,G_0} = \frac{1}{2\pi i}\partial_z \mathbb{E}_{C,G'_{-1}} + \frac{1}{2\pi i}\partial_\tau \mathbb{E}_{C,G'_{-2}}$$

for suitable G'_{-1} and G'_{-2}.

For a given modular weight and index, the spaces of Jacobi and quasi-Jacobi forms are both finite dimensional. This implies that the elliptic genera are uniquely determined once one fixes a finite number of Fourier coefficients.

Question: Which (quasi)-Jacobi forms are allowed as elliptic genera?

The answer to this question is connected to the generalized cohomology theory $TMF_\bullet$ of Topological Modular Forms.

Conjecture [Segal-Stolz-Teichner]: The space of deformation classes of 2d QFTs with (0,1) supersymmetry coincides with $TMF_\bullet$.

There exists a map ϕ from $TMF_\bullet$ to the ring of modular forms with integer coefficients. For a given element of $TMF_\bullet$, it determines the elliptic genus (with no chemical potentials) of the corresponding QFT.

It is known that this map is not surjective, so not all modular forms can be interpreted as elliptic genera. For example, there exists a CFT with elliptic genus

$$Z = \frac{2E_4(\tau)E_6(\tau)}{\eta(\tau)^{24}} = 2 - 480q - 282888q^2 - 17058560q^3 - \ldots \qquad q = e^{2\pi i\tau}$$

but according to the SST conjecture there exists no CFT with the following elliptic genus:

$$\frac{1}{2}Z = 1 - 240q - 141444q^2 - 8529280q^3 - \ldots$$

To determine which Jacobi forms can appear as elliptic genera with chemical potentials requires understanding the equivariant version of $TMF_{\bullet}$, which is not yet fully developed.

Nevertheless, using what is known about equivariant $TMF_{\bullet}$ one can verify that elliptic genera of 6d SCFTs are consistent with the equivariant version of the SST conjecture.

A question I hope to address is whether the SST conjecture makes nontrivial predictions about the features of the elliptic genera of strings in F-theory compactification, and therefore about the spectra of the compactified theories.

A related question is whether a combination of SST conjecture, modularity, and basic consistency conditions of the worldsheet CFTs such as unitarity can be used to classify the lower dimensional theories, without resorting directly to their string theory origin.

Thanks!