

QUANTUM
GRAVITY

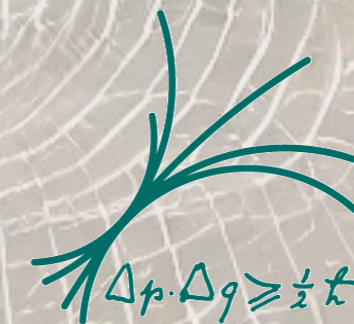
STRING THEORY

Exploring Quantum Gravity: -Insights from String Theory and the Swampland-

Towers of States & Black Holes, Emergence,
Dark Dimension, String Amplitudes
and much more

Alvaro Herraez (for the String Theory Group)

MAX-PLANCK-INSTITUT
FÜR PHYSIK



MPP Project Review 2024

Dec 9th, 2024

Who are we?

Meet the String Theorists/Swamp Rangers

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Meet the String Theorists/Swamp Rangers



Who are we?

Meet the String Theorists/Swamp Rangers



Who are we?

* New members

Past members

Director: Dieter Lüst

Students:

Edoardo Anastasi, Miquel Aparici*, Manuel Artime*, *Alessandro Borys*,
Xavier Kervin*, Hazem Riazi, Fotis Siammenos*, Giulia Tazzoli*

PhD
Students:

Leonardo Bersigotti*, *Andreas Bischof*, Aleksandar Gligovic, Christian Kneißl, Carmine Montella,
Joaquín Masias, Antonia Paraskevopoulou, Thomas Raml, Georgina Staudt

Postdocs:

Ivano Basile, *Nicolò Cribiori*, Matilda Delgado*, Bernardo Fraiman*,
Alvaro Herraiez, *Yixuan Li*, *Marco Scalisi*, Matteo Zatti*

Heisenberg
Fellow:

Daniel Junghans*

Scientists:

Ralph Blumenhagen

Stephan Stieberger

Admin:

Annette Sturm

What do we do?

What do we do? → Explore Quantum Gravity

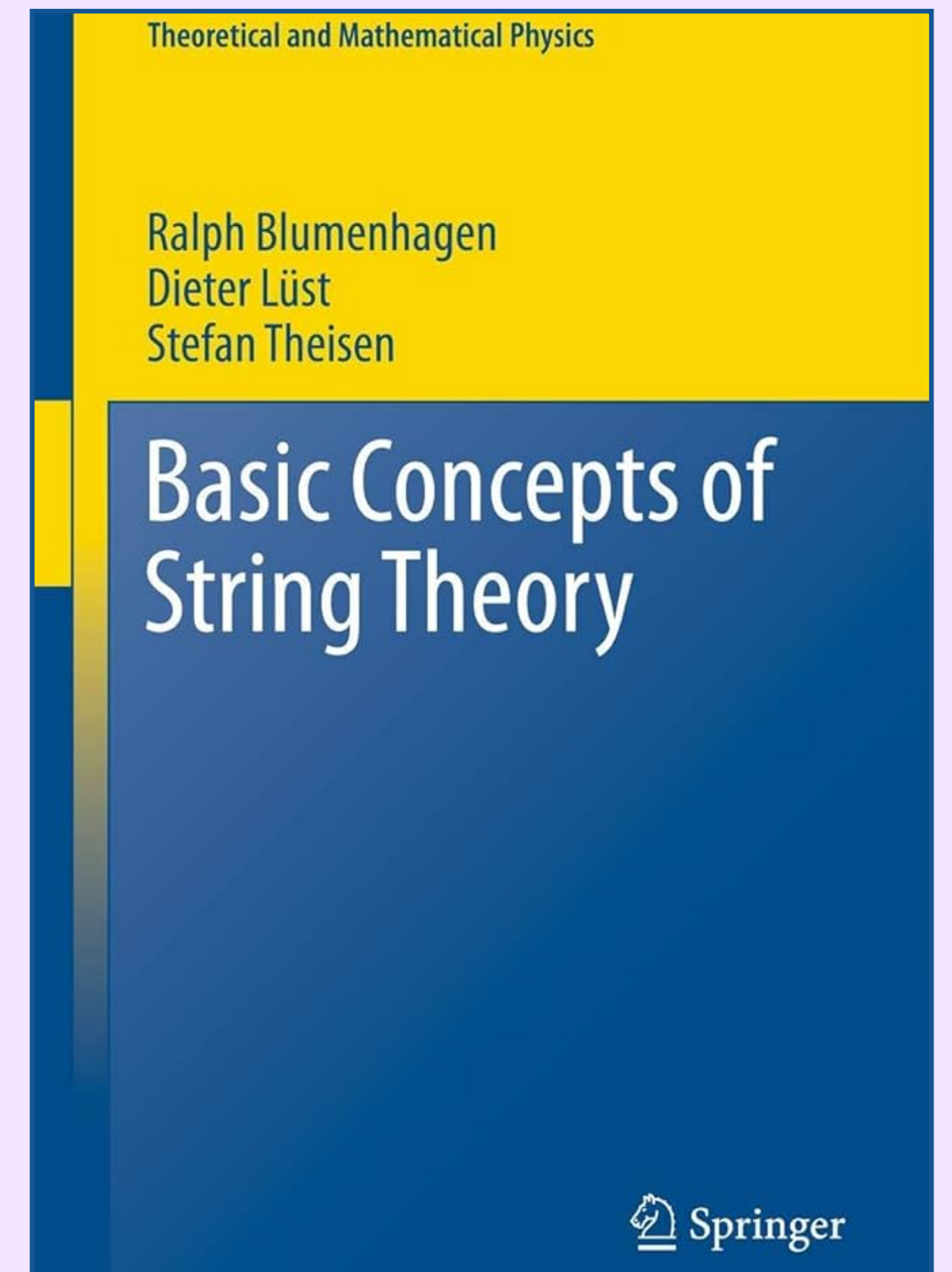
What do we do? → Explore Quantum Gravity

How do we do it?

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How do we do it?

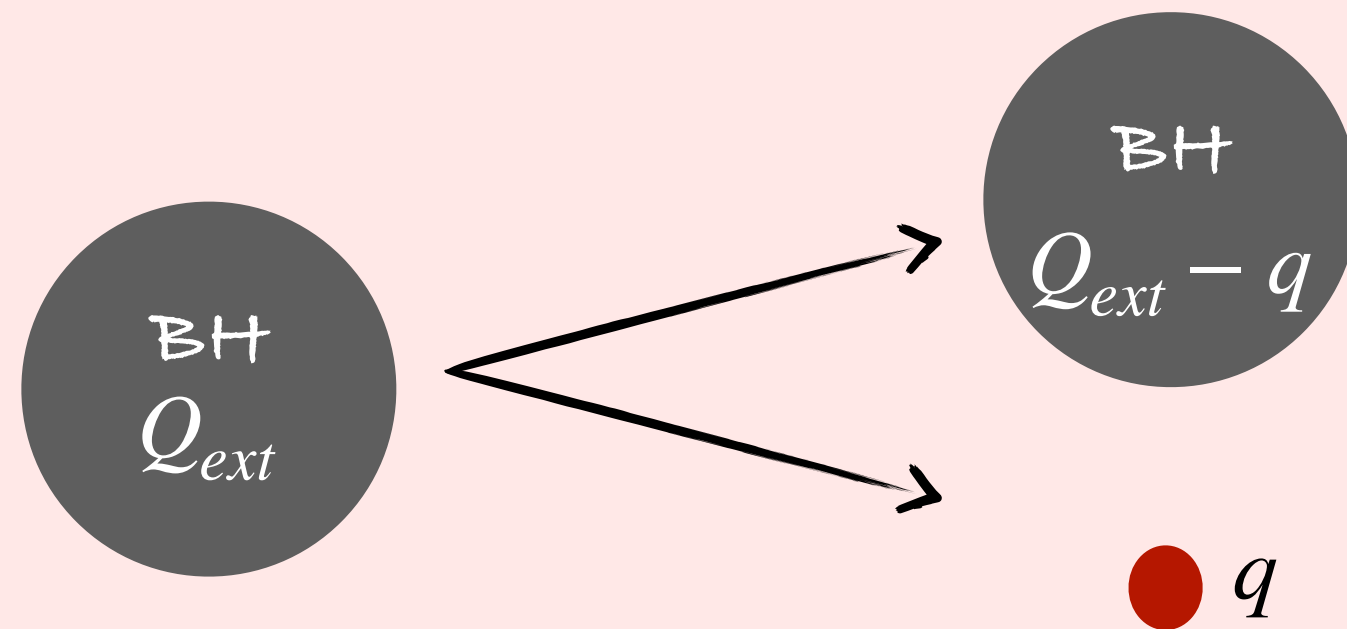
Top-Down: String Theory



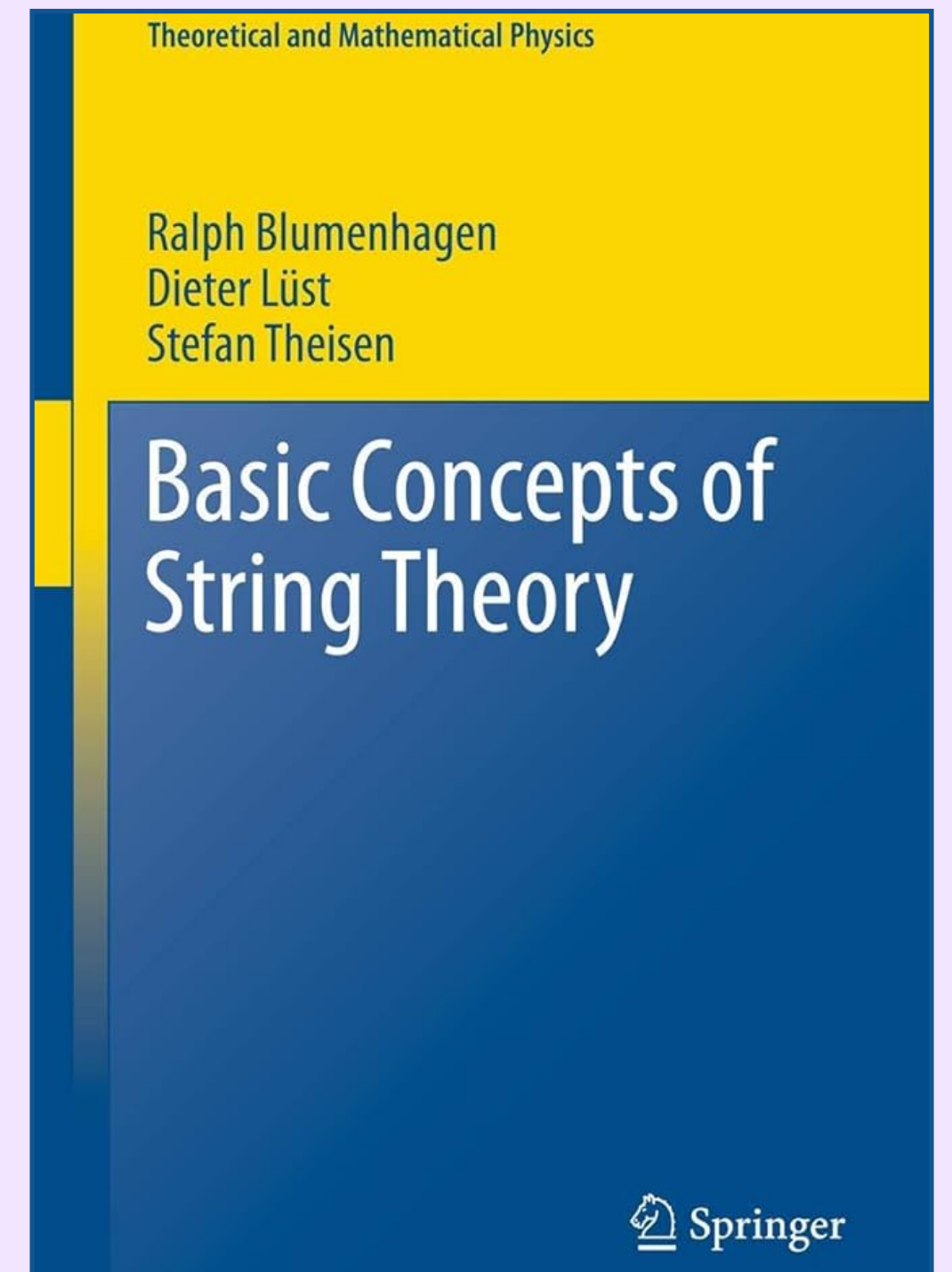
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Bottom-up:
Unitarity/Causality,
Black hole physics...



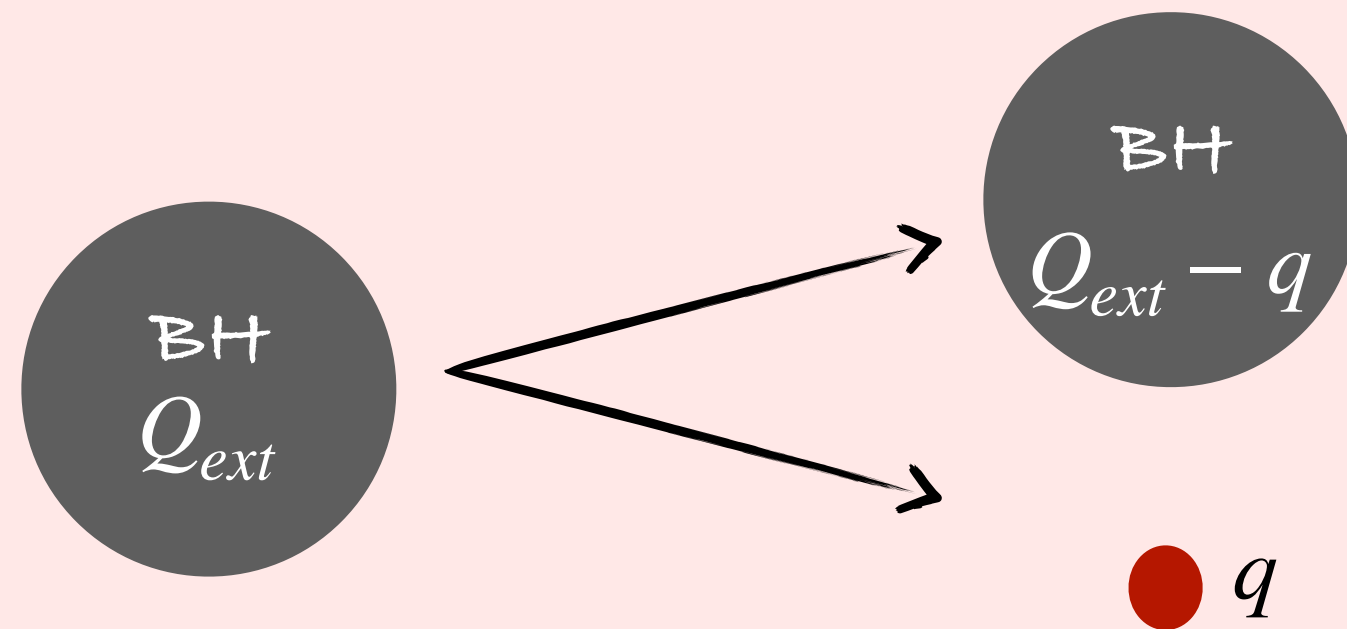
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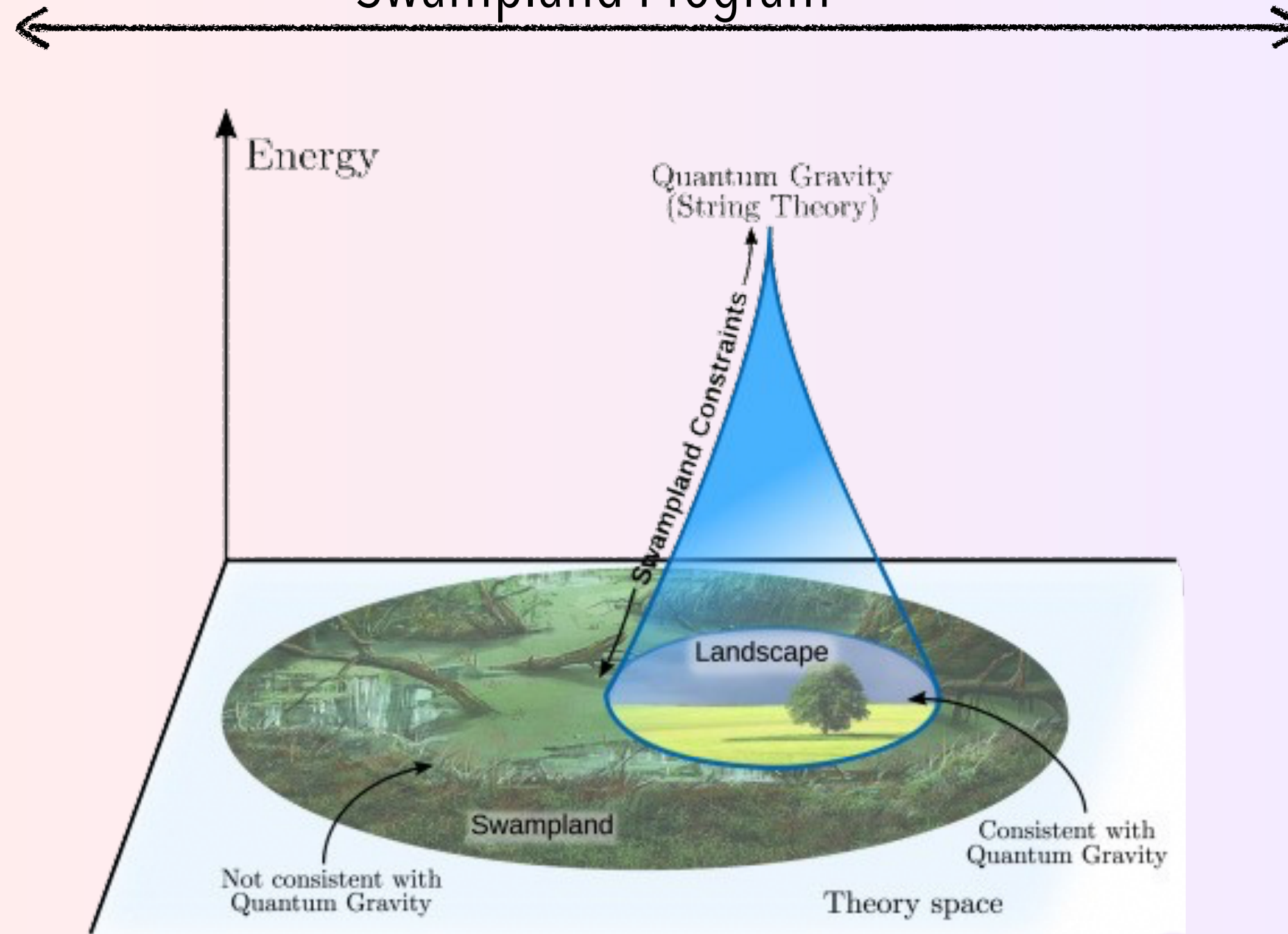
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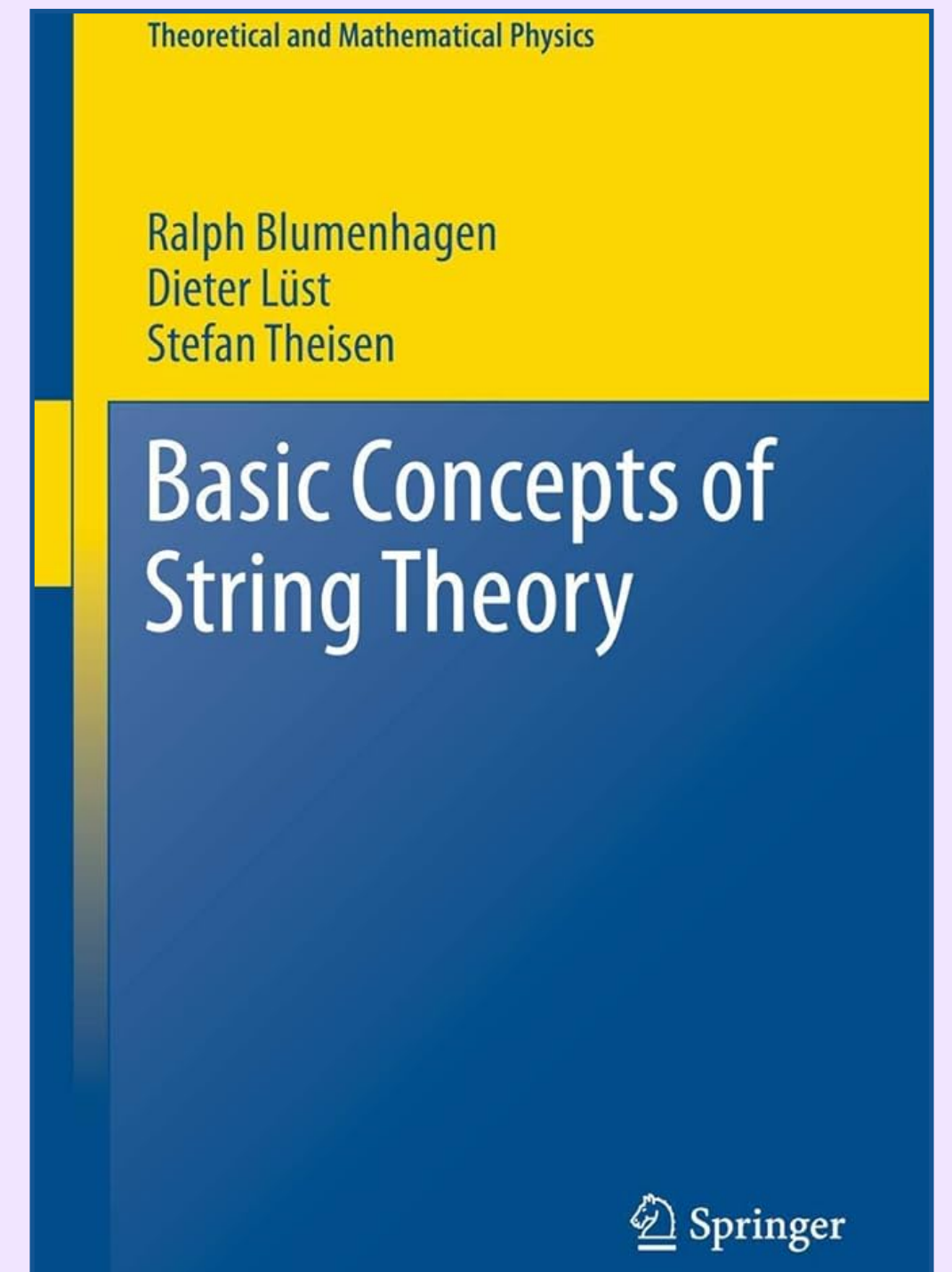
Bottom-up:
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Swampland Program



Top-Down: String Theory



Take-home message:

Not everything is allowed in Quantum Gravity → Constraints

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EFT rules in QG



EFT expectations



Take-home message:

Not everything is allowed in Quantum Gravity \longrightarrow Constraints

EFT rules in QG



EFT expectations



(Unnatural in EFT = Natural in QG)

The Swampland and Towers of Light States

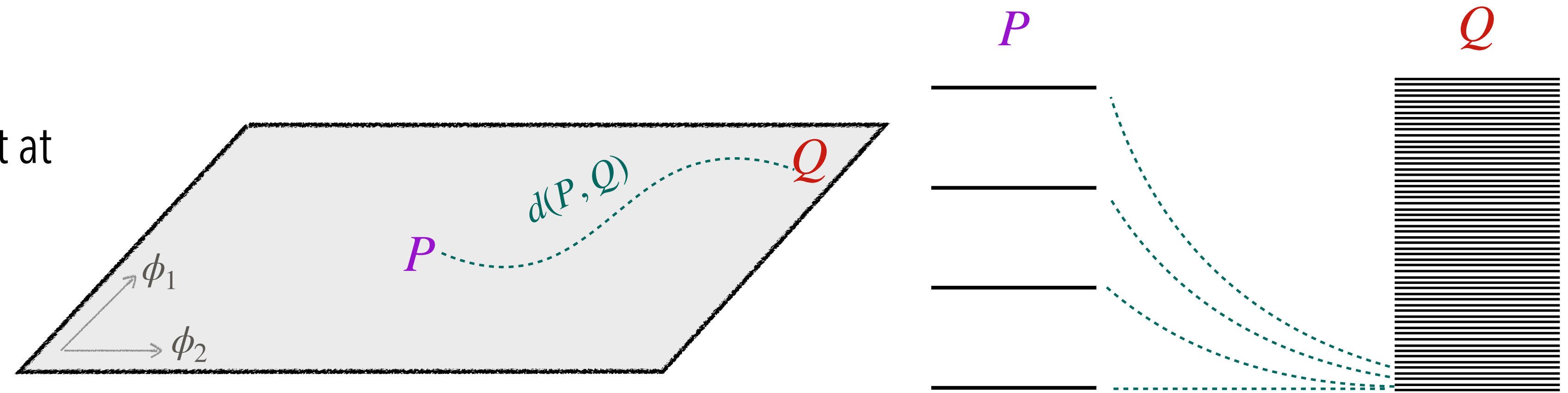
The Swampland and Towers of Light States

Distance Conjecture:

Infinite towers of states become light at extreme values of the parameters in gravitational EFTs.

[Ooguri, Vafa '06]

[Lüst, Palti, Vafa '19]



Large distance (=Extreme parameters) = Towers of states

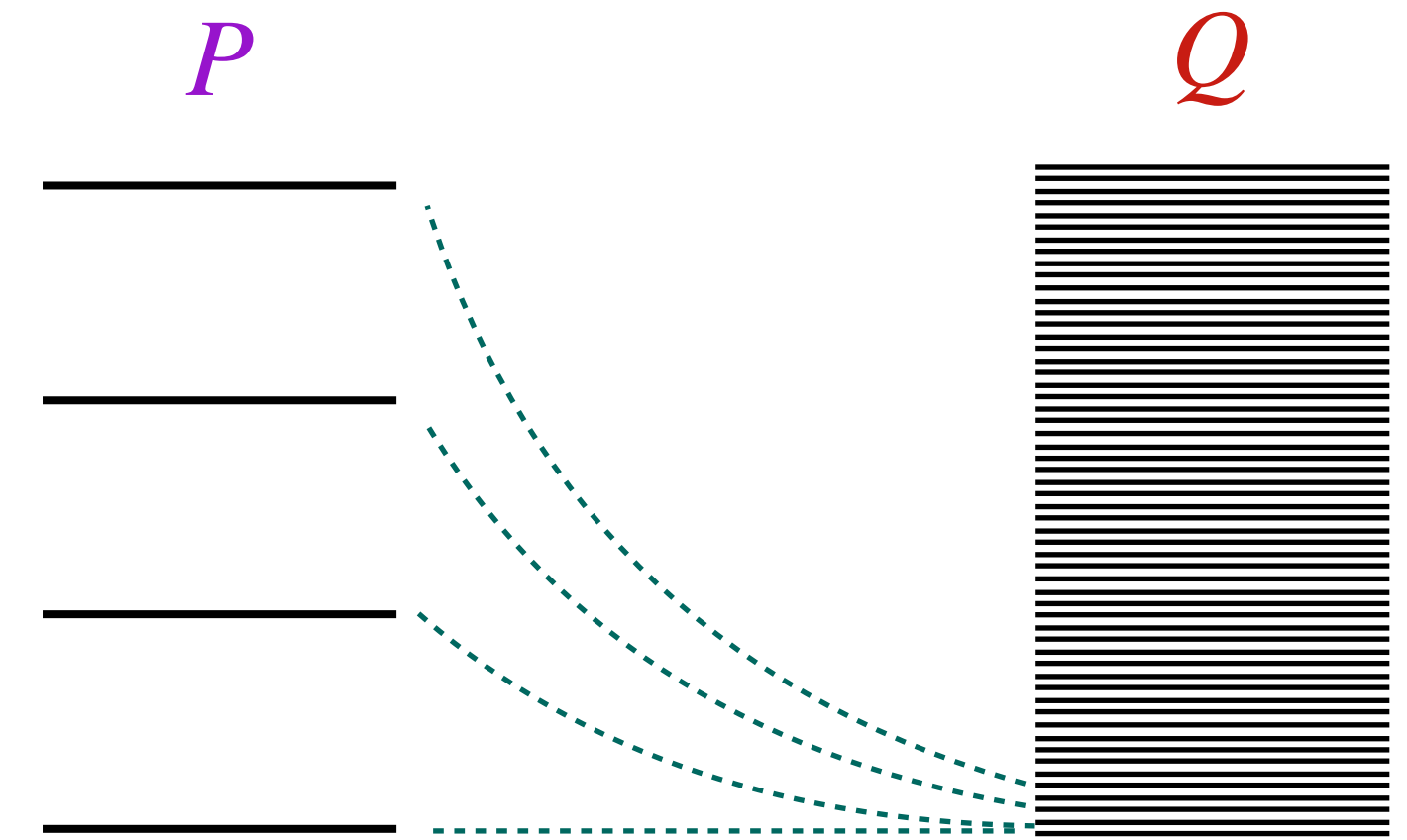
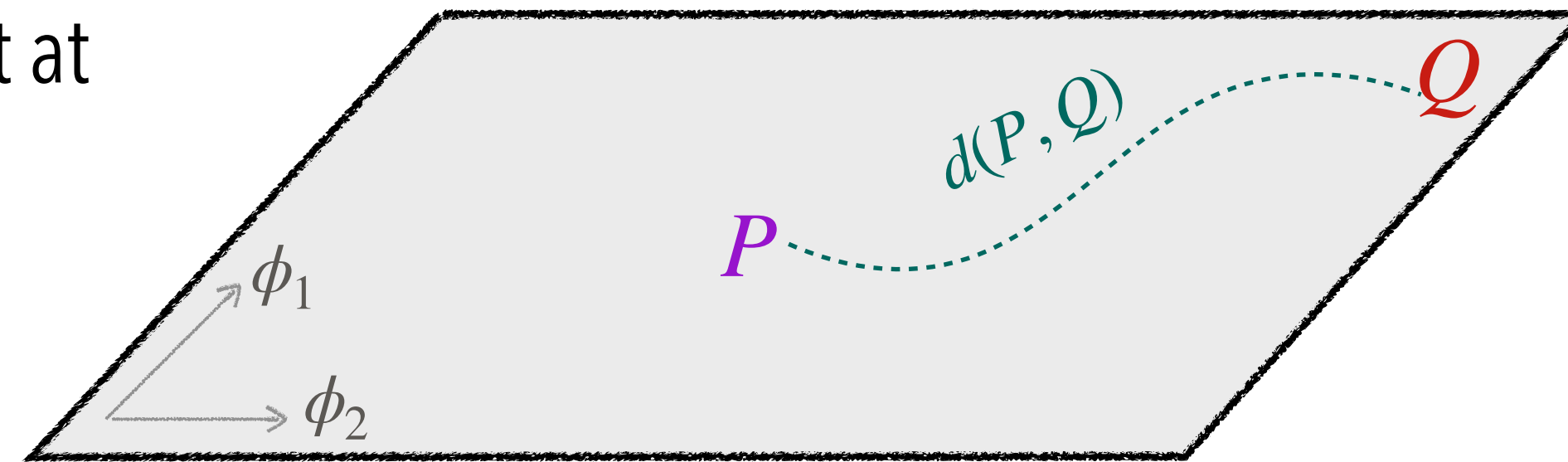
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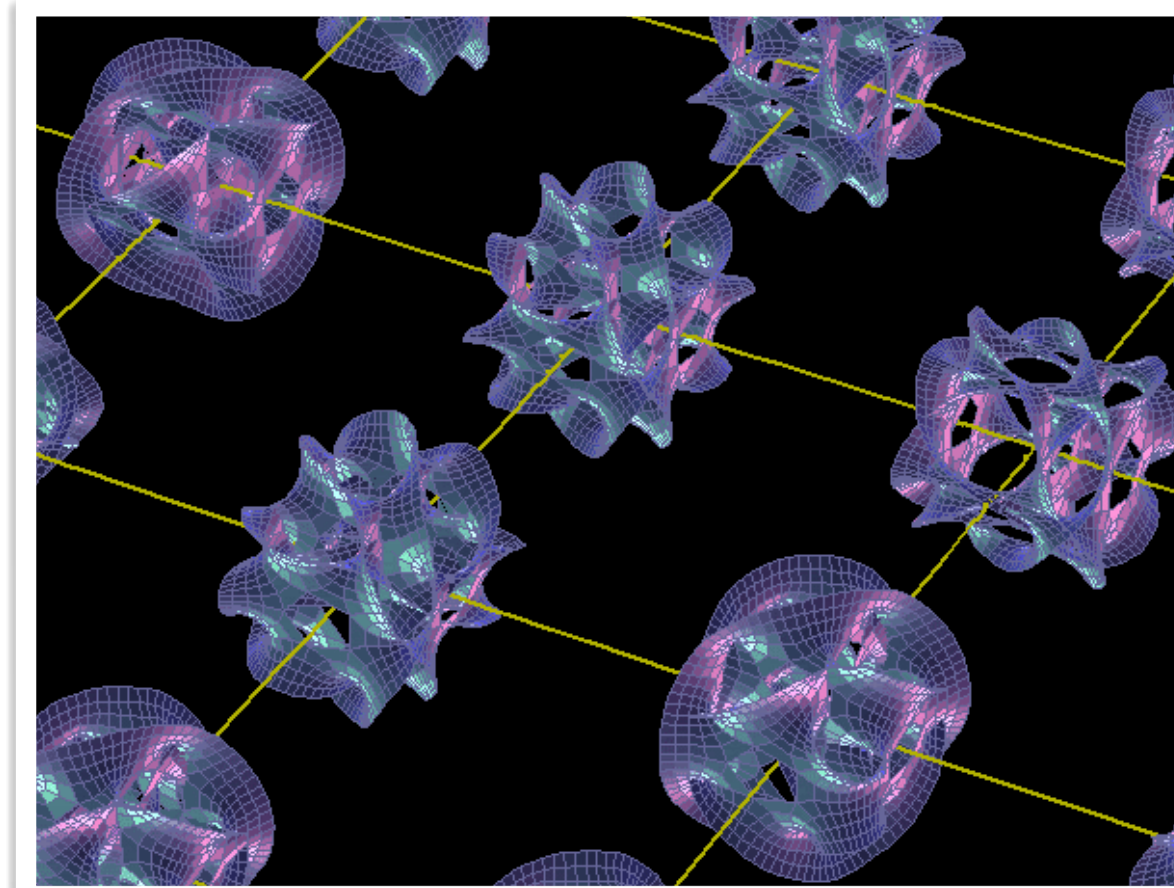


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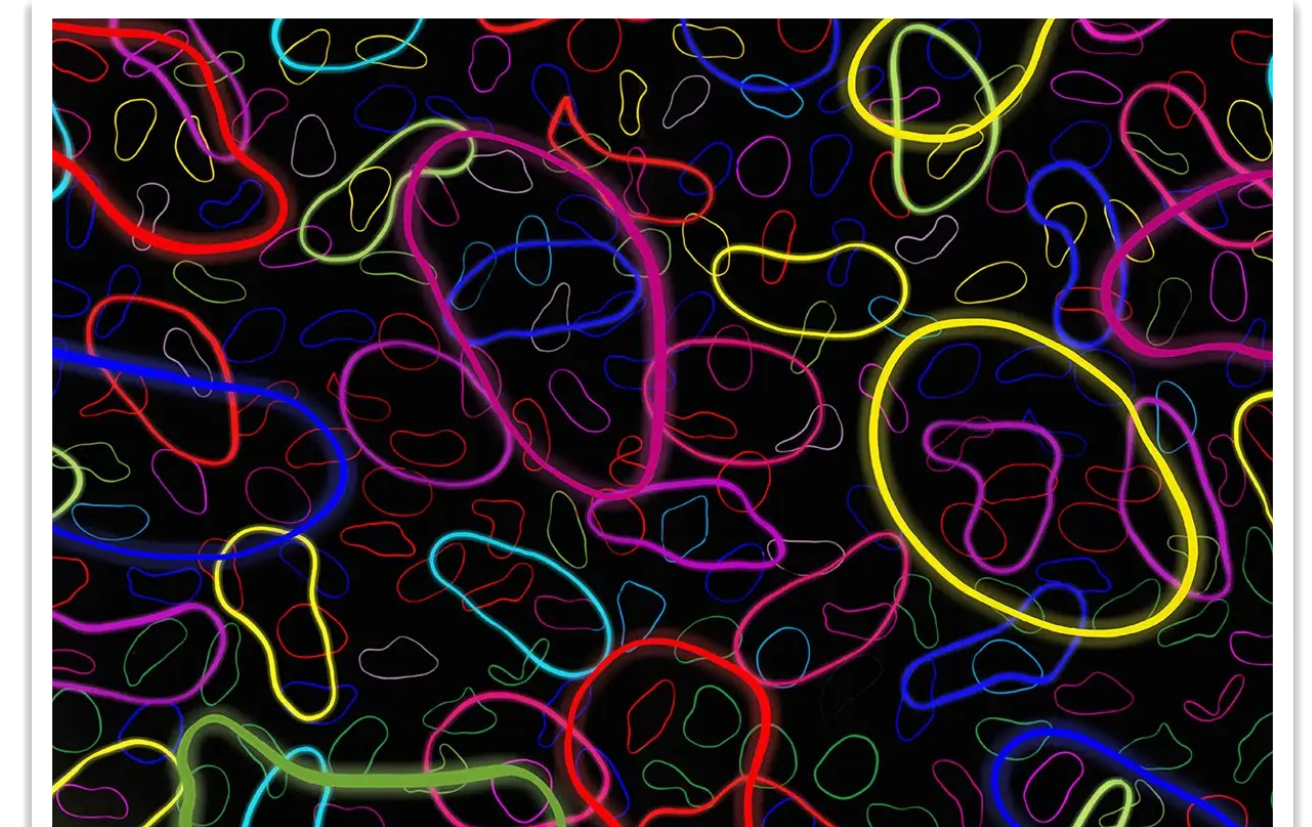
Emergent String Conjecture:

Towers are either Kaluza-Klein (like) or excitations of a weakly coupled (critical) string

[Lee, Lerche, Weigand '19]



Extra dimensions



Weakly coupled strings

Towers of states and Black Holes

Research group leader: Dieter Lüst

- **Bottom-up** derivation for the **emergent string conjecture** from matching of thermodynamic properties of small black-holes. Generalization of the black hole - string correspondence to a **black hole - tower correspondence**

Cribiori, Lüst, Montella, JHEP 10 (2023) 059
Basile, Lüst, Montella, JHEP 07(2024)208
Basile, Cribiori, Lüst, Montella, JHEP 06 (2024) 127
Herraez, Masias, Lüst, Scalisi, arXiv:2406.17851

Distance Conjecture away from moduli spaces

[Lüst, Palti, Vafa '19]

- Notion of distance **between sets of isolated EFT vacua**, also connecting it to **holographic RG flows**.

Basile, Montella, JHEP 02 (2024) 227

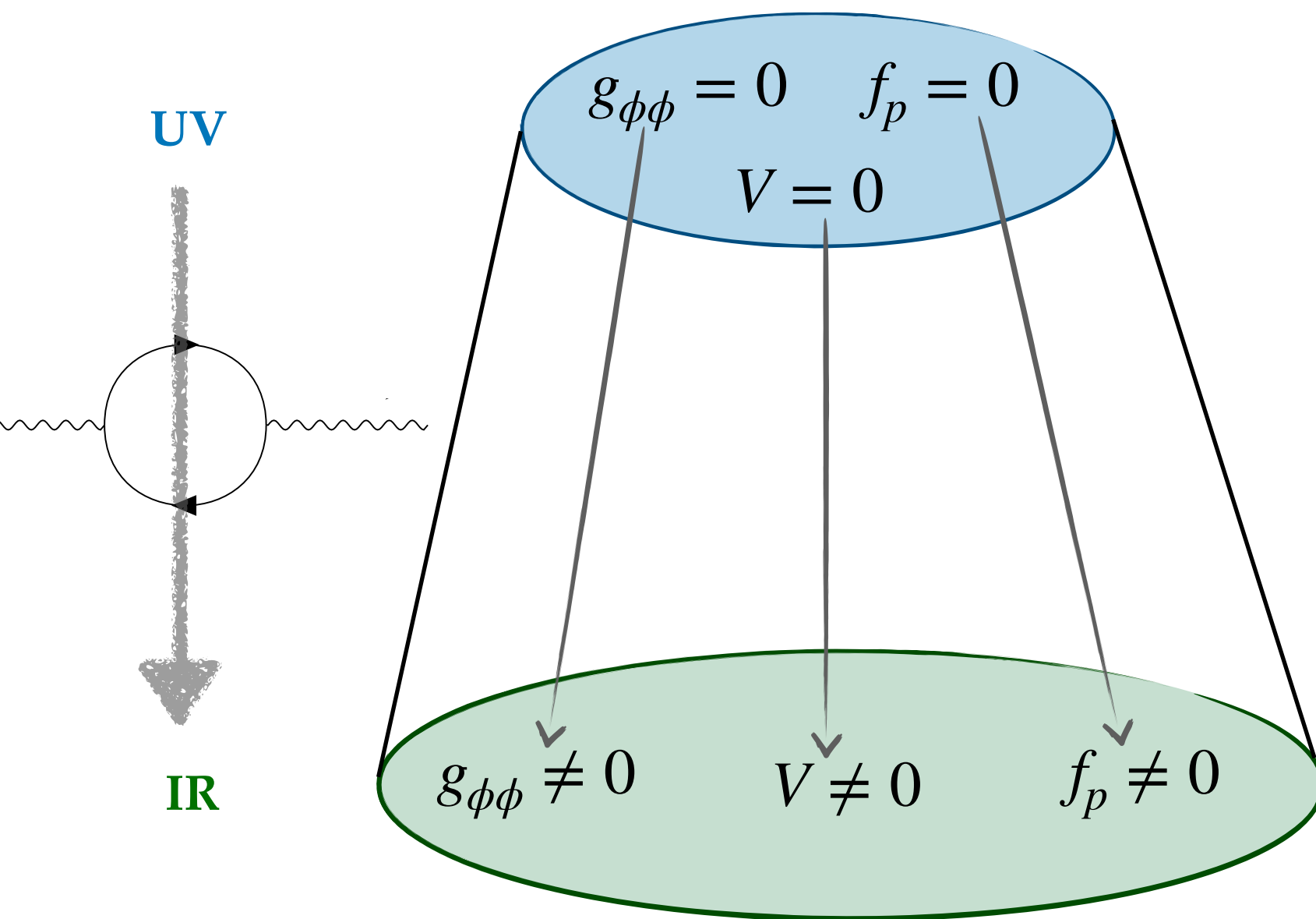
- Distance Conjecture in the presence of **potentials, topology change** and **non-geometry**.

Demulder, Lüst, Raml, JHEP 06 (2024) 079

The Emergence Proposal

In a theory of QG the low energy dynamics of light particles appear as an infra-red effect after integrating out infinite towers of states

[Harlow '15][Grimm, Palti, Valenzuela '18] [Heidenreich, Reece, Rudelius '18][Ooguri, Palti, Shiu, Vafa '18][Palti '19]

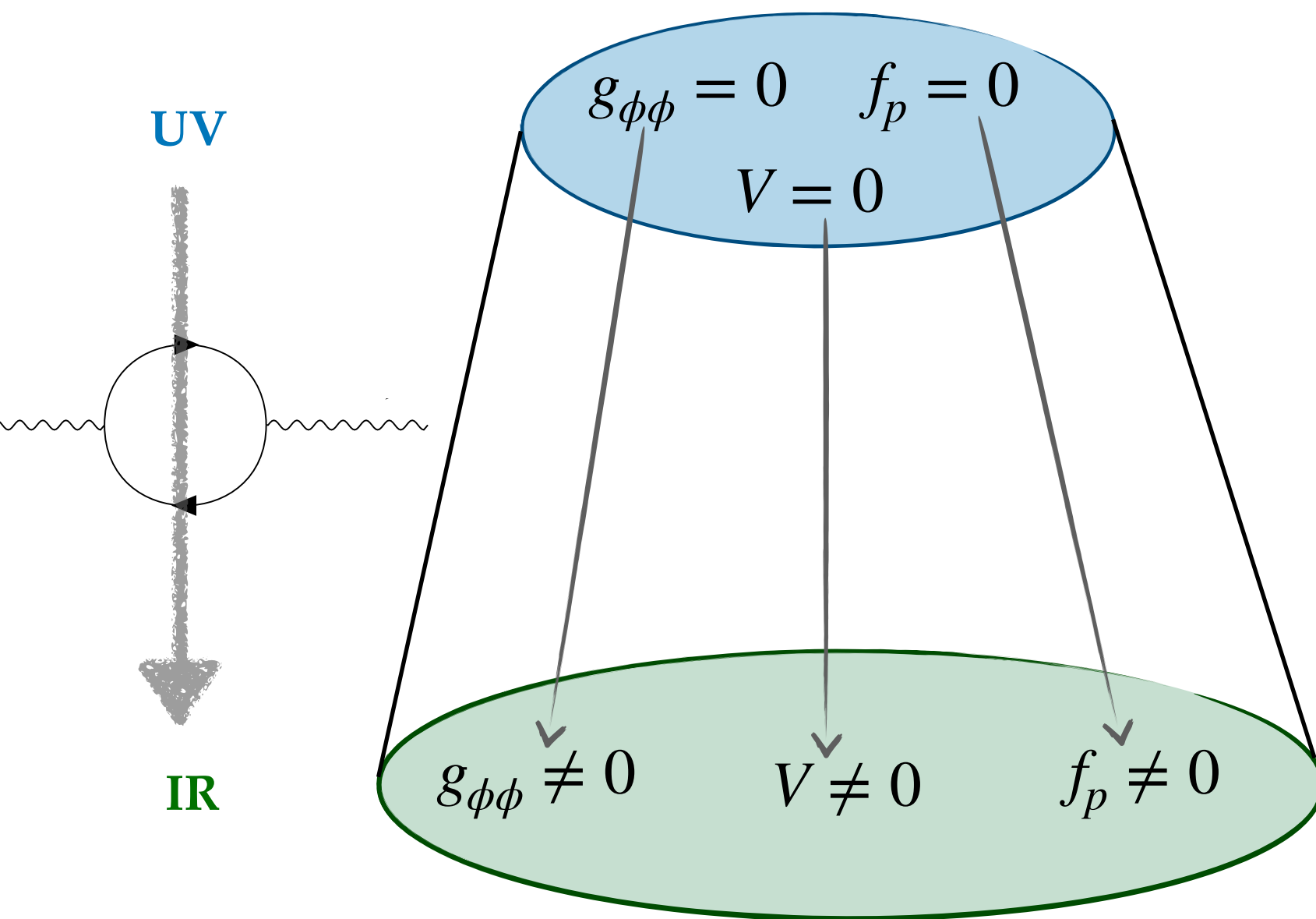


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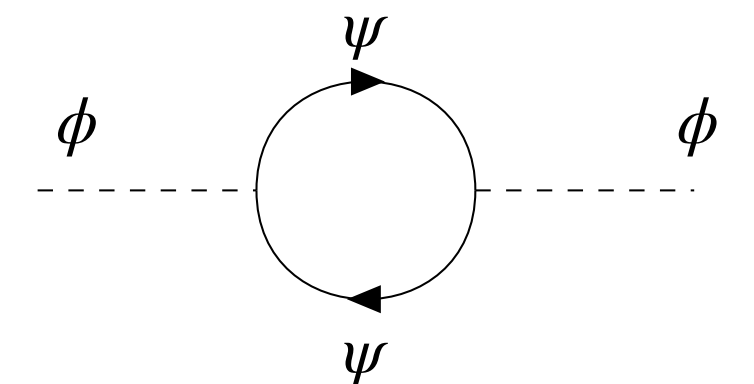
[Harlow '15][Grimm, Palti, Valenzuela '18] [Heidenreich, Reece, Rudelius '18][Ooguri, Palti, Shiu, Vafa '18][Palti '19]

- Emergent infinite distances in moduli space \longrightarrow **Infinite distances** appear as a consequence of an **infinite tower** of particles **becoming light** (related to the SDC)



$$S_{\text{kin}} = \int g_{\phi\phi} d\phi \wedge \star d\phi$$

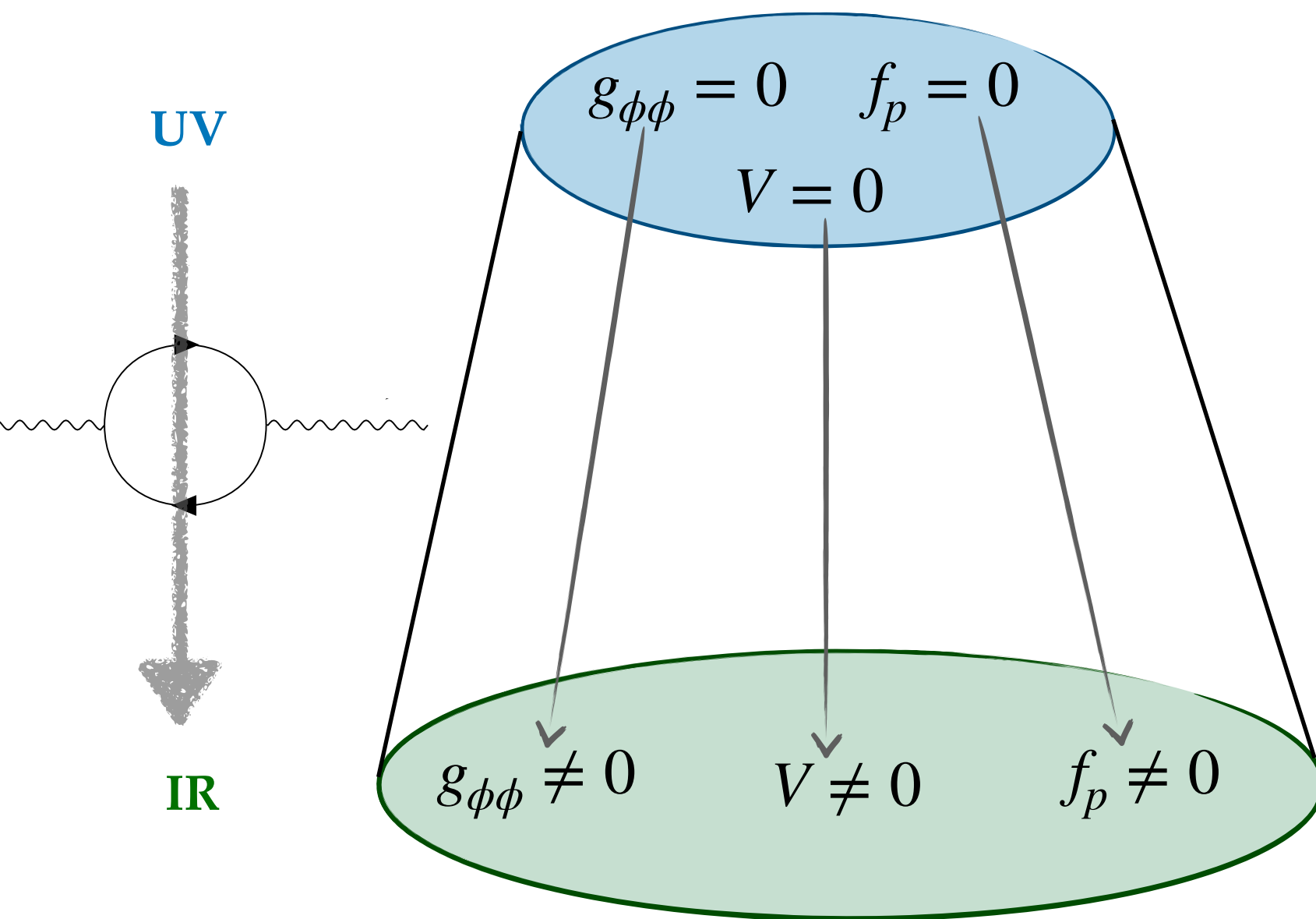
$$g_{\phi\phi}^{\text{IR}} \sim \cancel{g_{\phi\phi}^{\text{UV}}} + g_{\phi\phi}^{\text{tower}}$$



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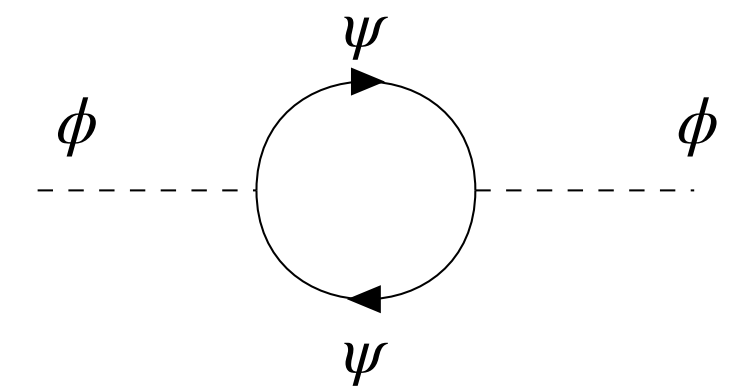
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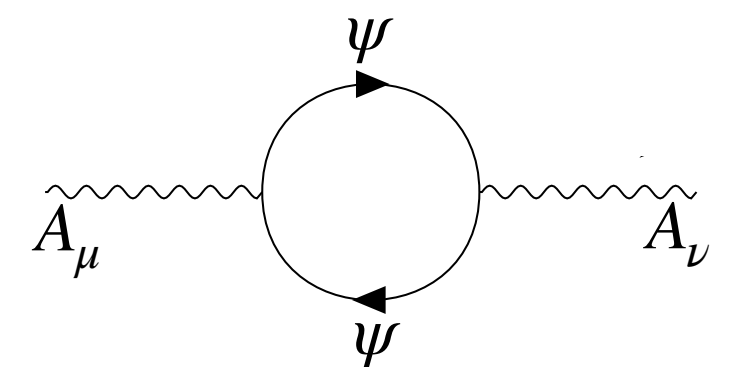
$$g_{\phi\phi}^{\text{IR}} \sim \cancel{g_{\phi\phi}^{\text{UV}}} + g_{\phi\phi}^{\text{tower}}$$



- Emergent gauge couplings \longrightarrow **Weak coupling** points appear as a consequence of an **infinite tower** of **charged** states becoming **light** (related to the WGC)

$$S_{\text{kin}} = \int \frac{1}{g^2} dC_p \wedge \star dC_p$$

$$\frac{1}{g_{\text{IR}}^2} \sim \cancel{\frac{1}{g_{\text{UV}}^2}} + \frac{1}{g_{\text{tower}}^2}$$



M-theoretic Emergence Proposal

Research group leader: Ralph Blumenhagen

[Blumenhagen, (Cribiori,) Gligovic, Paraskevopoulou, '23]

- **Pedagogical review** of the current status of the Emergence Proposal in Quantum Gravity, relating it to earlier ideas of emergence. While **still exploratory**, it argues that **decompactification limits, rather than emergent strings**, may naturally realize the proposal, connecting intriguingly to concepts from M(atric) theory and inspiring further speculations.

Blumenhagen, Cribiori, Gligovic, Paraskevopoulou, PoS CORFU2023 (2024) 238

- Exploration of the **strong Emergence Proposal in M-theory**, suggesting it involves integrating out all light towers of states with masses up to the species scale, such as transverse **M2- and M5-branes carrying KK momentum**. Revisiting R^4 interactions in M-theory, the study introduces a **novel UV-regularization of Schwinger-like integrals**, clarifies its significance, and demonstrates its utility in both string perturbation theory and toroidal compactifications, providing further evidence for the proposal.

Blumenhagen, Cribiori, Gligovic, Paraskevopoulou, JHEP 07, 018 (2024)

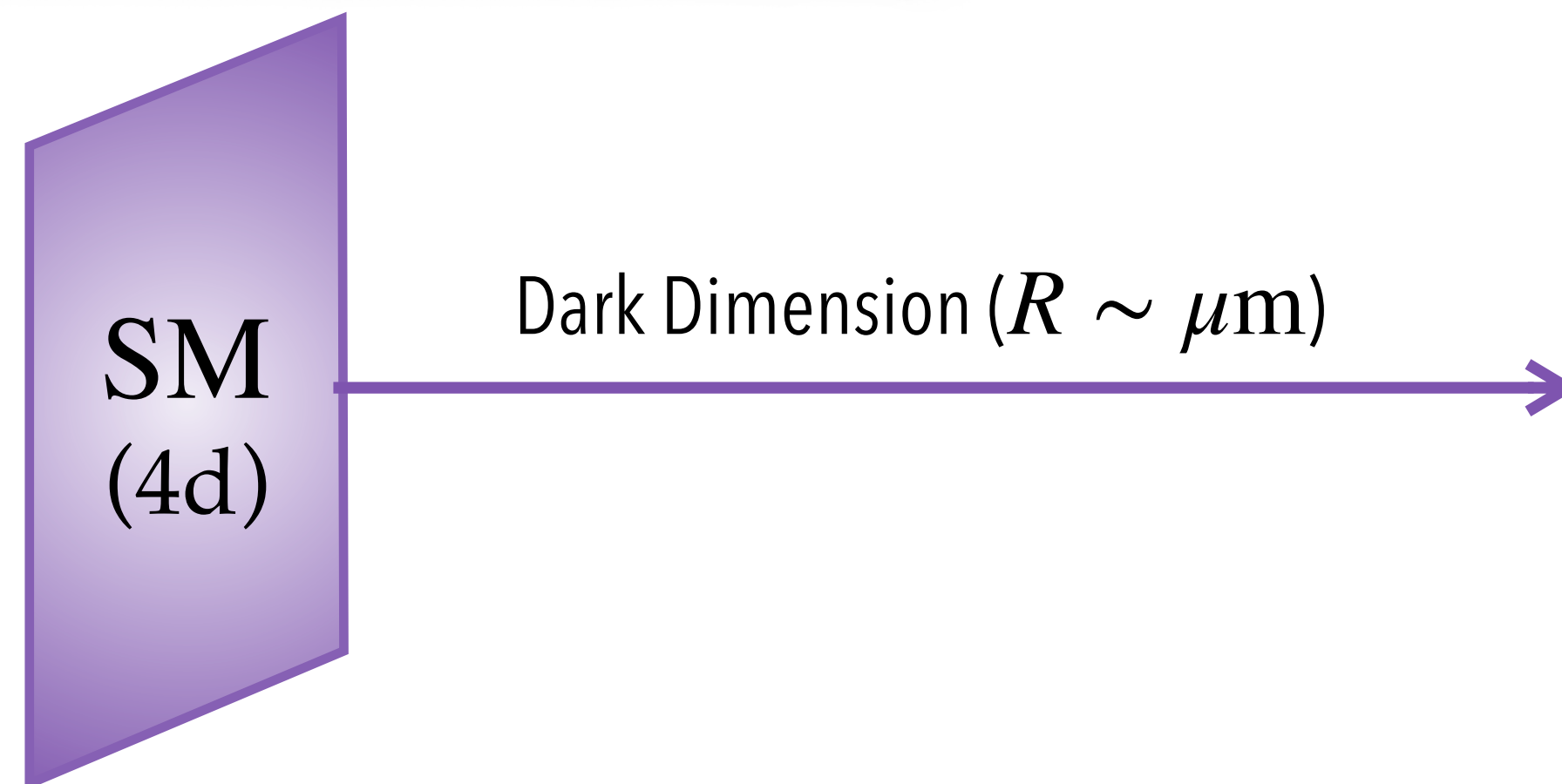
The Dark Dimension Scenario

[Montero, Vafa, Valenzuela '22]

Theoretical basics:

- * Based on Large Extra Dimension Scenarios [Arkani-Hamed, Dimopoulos, Dvali '98]
- * Generalized Distance Conjecture ($m_{\text{tower}} \lesssim \Lambda^{1/4}$) [Lüst Palti, Vafa '17]
- * Emergent String Conjecture (DC) \longrightarrow
Tower is KK or strings [Lee, Werche, Weigand '21]
- * UV cut-off \longrightarrow Species Scale Λ_{sp}
[Dvali, (Redi) '07] [Dvali, Lüst '09]
[Dvali, Gómez '10]

- Observation \longrightarrow **Tiny** cosmological constant $\Lambda_{cc} \simeq 10^{-122} M_{\text{pl}}^2$
- Interpretation \longrightarrow **Light tower** of states $m_{\text{tower}} \lesssim \Lambda^{1/4} \simeq 10^{-2} \text{ eV}$
- Not observed stringy effects/strongly coupled gravity \longrightarrow
Tower from **extra dimensions** $V_n \sim m_{\text{tower}}^n$
- Experimental bounds on Newton's law valid up to $r \sim 30 \mu\text{m}$ $\left(F \sim \frac{1}{r^2} \right)$



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Top-down discussions of the DD

Research group leader: Dieter Lüst

- Top down discussion of **Casimir Energy in String Theory** and its implications for the Dark Dimension Scenario

*Anchordoqui, Antoniadis, [Lüst](#), Lüst,
Eur.Phys.J.C 83 (2023) 11, 1016*

- **Modular invariance of the worldsheet CFT**, combined with **observations** leads to a dark dimension with a sort-of-weakly coupled string, 5d SUSY and D-brane/O-plane GUT-like braneworld.

[Basile, Lüst](#), arXiv:2409.12231

Primordial BHs as Dark Matter in the DD

- **Phenomenological investigation** of the dark dimension scenario, focusing on previous proposal (from the authors) of **5d primordial black holes** as **dark matter candidates**. Confrontation to observations, the cosmology of dark dimension and Hubble tension.

Anchordoqui, Antoniadis, [Lüst](#), Phys.Rev.D 109 (2024) 9, 095008

Anchordoqui, Antoniadis, [Lüst](#), Noble, Soriano, Phys.Dark Univ. 46 (2024) 101715

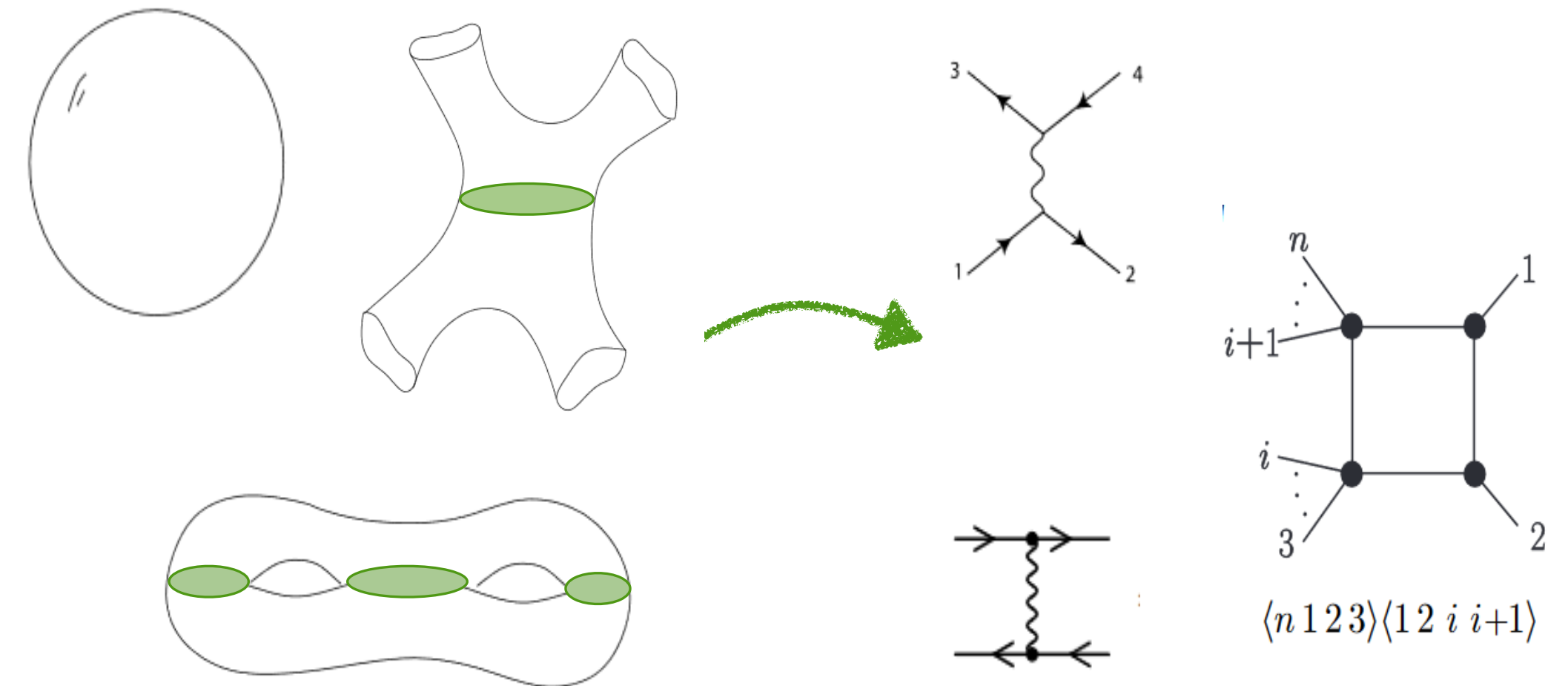
Anchordoqui, Antoniadis, [Lüst](#), Castillo, Phys.Dark Univ. 46 (2024) 101714

Anchordoqui, Antoniadis, [Lüst](#), Castillo, arXiv: 2411.07029

String Amplitudes and the Double-Copy

Investigating the mathematical structure of QFT amplitudes has revealed new properties - **color kinematic duality** and deep **connections between gravity and gauge theory - double copy**. String theory allows to explain the origin of mathematical identities observed in QFT scattering amplitudes.

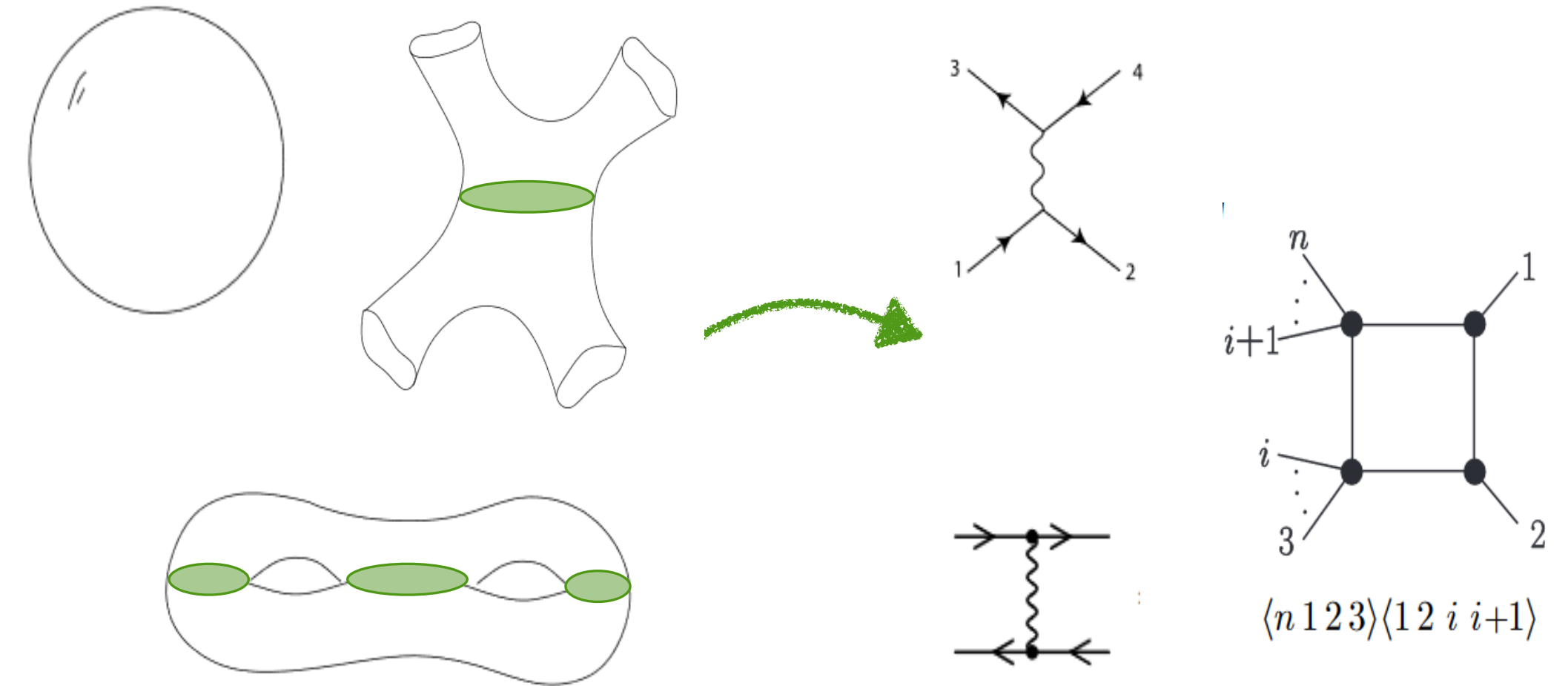
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- Understanding **one-loop double-copy as geometric description** leading to a gauge/gravity relation at the perturbative level

Mazloumi, Stieberger, JHEP 10 (2024) 148

- Understanding **closed string tree-level scattering** in the presence of **orientifolds** at higher point level (so far only understood at the trivial two-point level)

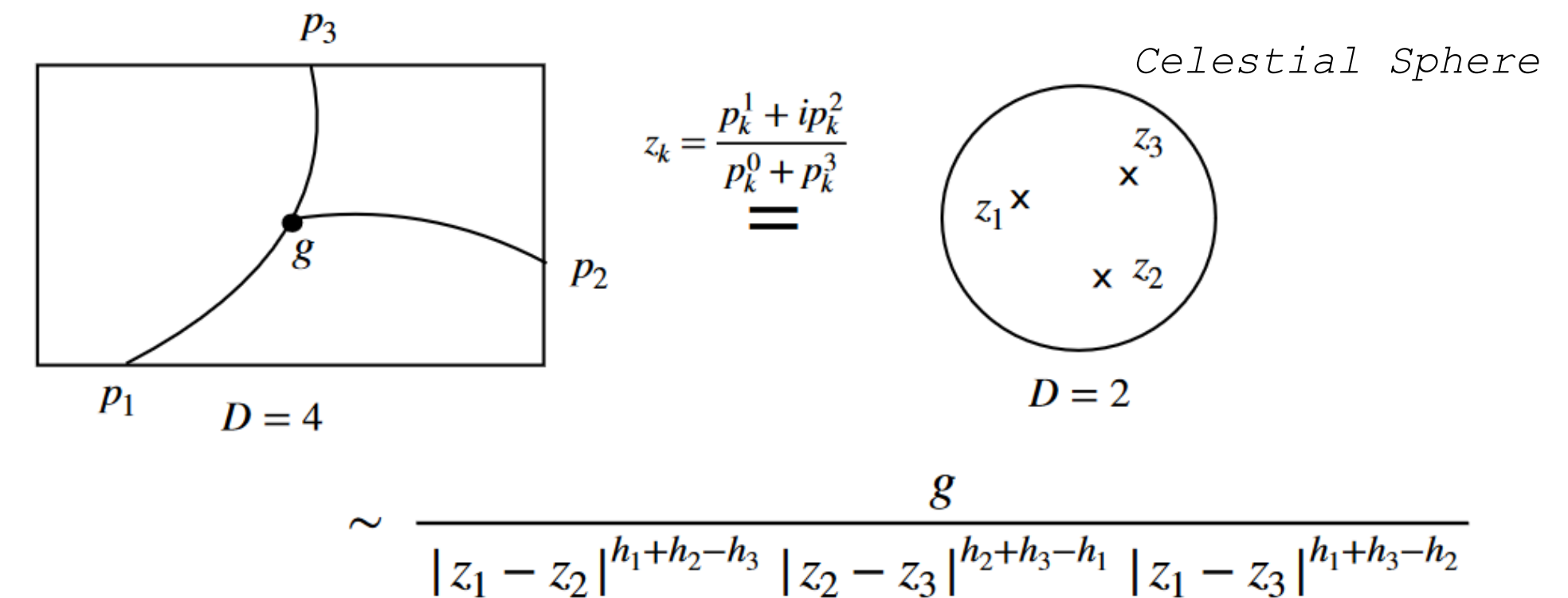
Bischof, Stieberger, To appear

Celestial and Carrollian Conformal Field Theories

Research group leader: Stephan Stieberger

Frameworks used to describe the **holographic duals of 4d gravity** in **asymptotically flat spacetime**.
Key to extending the holographic principle beyond AdS/CFT to more realistic models of our universe.

- Celestial CFTs involve a **2D CFT at the celestial sphere**, capturing the symmetries and scattering amplitudes of the bulk theory.



- Carrollian CFTs are **3D theories at null infinity**, encoding the radiative aspects of gravitational dynamics.

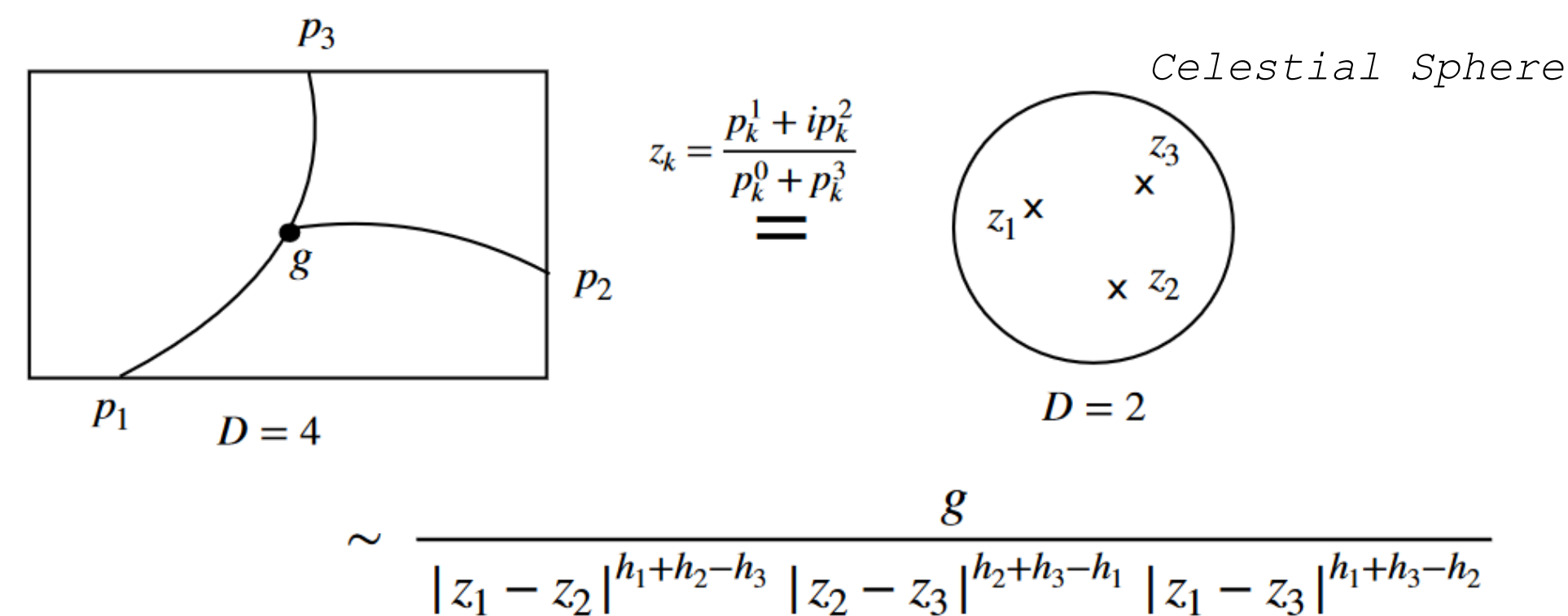
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From S. Stieberger, talk at Amplitudes 2020

- Carrollian CFTs are **3D theories at null infinity**, encoding the radiative aspects of gravitational dynamics.

- Understanding Carrollian Conformal Field Theories in **D=3** as **holographic description of D=4 gravity**.

Stieberger, Taylor, Zhou, JHEP 04 (2024) 127

Ruzziconi, Stieberger, Taylor, Zhou, JHEP 09 (2024) 149

Anomalies and (co)bordisms

- Global anomalies & bordism of non-supersymmetric strings, *Basile, Debray, Delgado, Montero*, JHEP 02 (2024) 092
- Anomaly constraints for heterotic strings and supergravity in six dimensions, *Basile, Leone*, JHEP 04 (2024) 067
- Spin cobordism and the gauge group of type I/heterotic string theory, *Kneißl*, arXiv:2407.20333

String Dualities

- Finiteness and the Emergence of Dualities, *Delgado, van de Heisteeg, Raman, Torres, Vafa*, arXiv: 2412.03640

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NEW POSTDOC: MATILDA DELGADO

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Cosmology & Swampland

- Starobinsky inflation in the swampland, *Lüst, Masias, Muntz, Scalisi*, JHEP 07 (2024) 186
- Shedding light on dark bubble cosmology, *Basile, Danielsson, Giri, Panizo*, JHEP02(2024)112
- Species Scale and Primordial Gravitational Waves, *Scalisi*, Fortsch.Phys. 72 (2024) 6, 2400033

The cutoff for gravitational EFTs

- On the Species Scale, Modular Invariance and the Gravitational EFT expansion, *Castellano, Herraes, Ibañez*, JHEP12(2024)019

Black Holes

- A note on the Noether-Wald and generalized Komar charges, *Ortin, Zatti*, arXiv: 2411.10420
- On the thermodynamics of the black holes of the Cano-Ruipérez 4-dimensional string effective action *Ortin, Zatti*, arXiv: 2411.10420 2405.03683

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Heterotic string theory

- Open Strings and Heterotic Instantons, *Álvarez-García, Kneißl, Leedom, Righi*, arXiv:2407.20319

Worldsheet implications for UV/IR mixing, non-geometry, & Non-SUSY Strings

- Species scale, worldsheet CFTs and emergent geometry, *Aoufia, Basile, Leone*, arXiv: 2405.03683
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NEW POSTDOC: BERNARDO FRAIMAN

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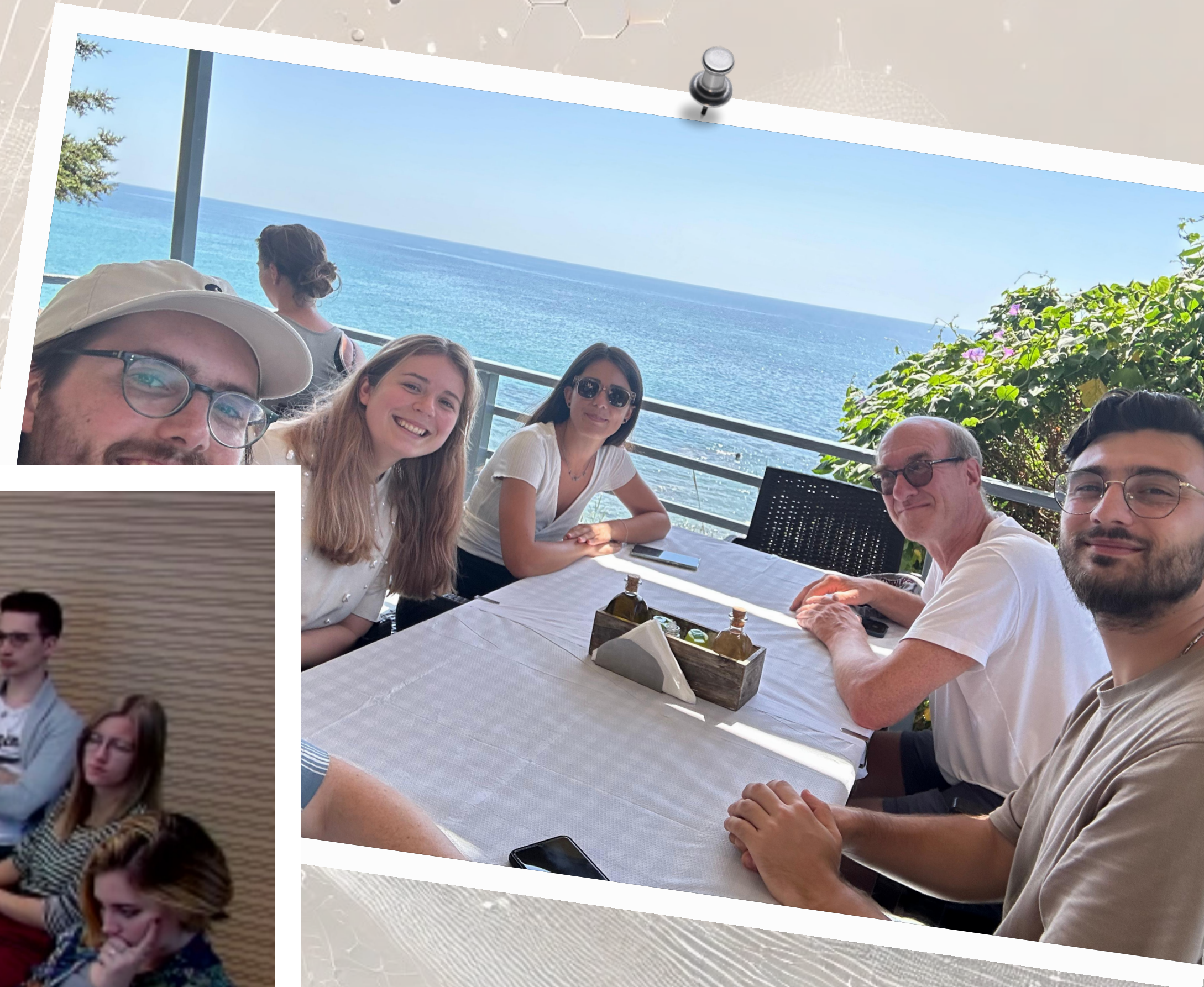
Conferences, workshops, meetings and networking

- **Invited talks at international conferences** such as String Phenomenology 2024, Supersymmetry 2024, Strings and Geometry 2024... and **invited seminars** at Harvard, CMSA, Vienna ESI, Oxford University, CGI Florence, IFT Madrid...
- **DFG German-Israel-Project** on Swampland and Holography [*Dieter Lüst*]
- **DFG Research Group** on Scattering Amplitudes [*Stephan Stieberger*]
- **DFG Heisenberg Fellowship** [*Daniel Junghans*]
- Organization of **Online Seminars in String Phenomenology**, January-June 2024 [*Matilda Delgado, Alvaro Herrera*]
- Organization of **workshop "Geometry, Strings and the Swampland Program"**, in Ringberg, March 18-22, 2024 [*Ralph Blumenhagen, Niccolò Cribiori, Dieter Lüst, Annette Sturm*]
- Organization of Conference **"Swamplandia in Bavaria"**, in Abbey Seeon, May 27-29, 2024 [*Dieter Lüst, Annette Sturm*]
- Mentoring & co-organization of the **"String Theory Mentoring Program: QuantumGuides,"** worldwide program targeted at under-represented groups in the String Theory community. [*Ivano Basile, Matilda Delgado, Alvaro Herrera, Dieter Lüst, Joaquín Masias, Antonia Paraskevopoulou, Matteo Zatti*]

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Thank you!



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