MAX-PLANCK-INSTITUT FÜR PHYSIK

TUM LMU ORIGINS Excellence Cluster

The M-Theoretic Emergence Proposal

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in collaboration with N. Cribiori, A. Gligovic and A. Paraskevopoulou

[arXiv: 2309.11551+2309.11554+2404.01371]

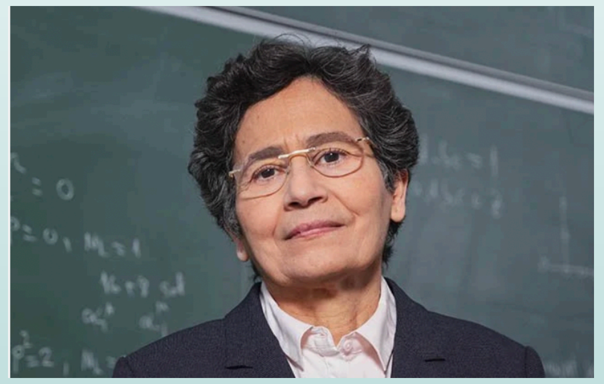
Review: [arXiv:2404.05801]

AnLy Meeting A. Font, April. 11, 2024

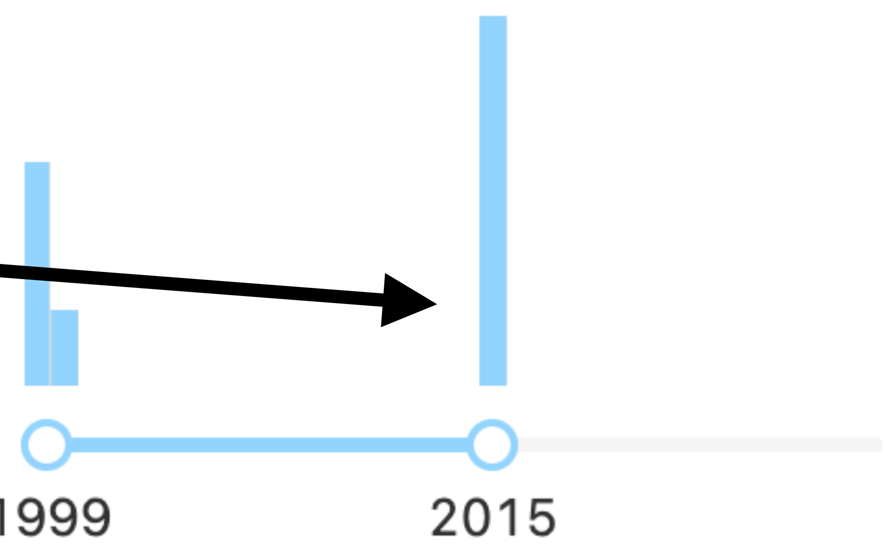
Collaboration with Anamaria

Visit to HU Berlin

Visit to LMU/MPP



'Veni, Vidi, Laboravi'



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Dilaton tadpoles, warped geometries and large extra dimensions for nonsupersymmetric strings

Ralph Blumenhagen (Humboldt U., Berlin), Anamaria Font (Humboldt U., Berlin)

Nov, 2000

15 pages

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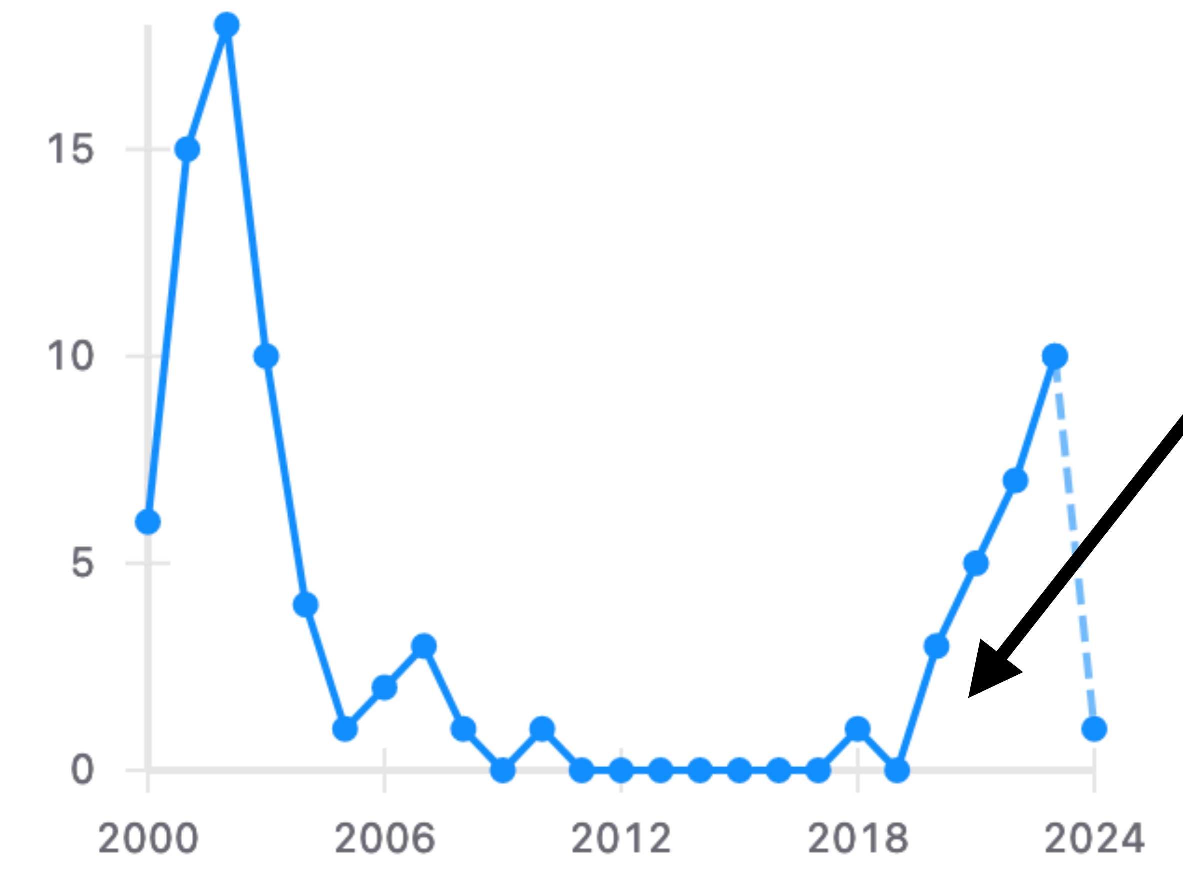


Dynamical Cobordism

Anamaria heard talk already in May 2023 in Pisa

Reflection on Emergence

In QG: Appearance of properties of a system that are novel with respect to other (more fundamental) descriptions of the same system and robust in the sense of characterizability and reproducibility. [Butterfield, (2011)]

Example: 1-loop annulus amplitude for D-branes → tree-level graviton exchange

a.) $g_s \ll 1$ regime: no open strings without closed strings
→ no emergence

b.) emergence of gravity: consistent QG theory with light D-branes
and decoupled open/closed strings

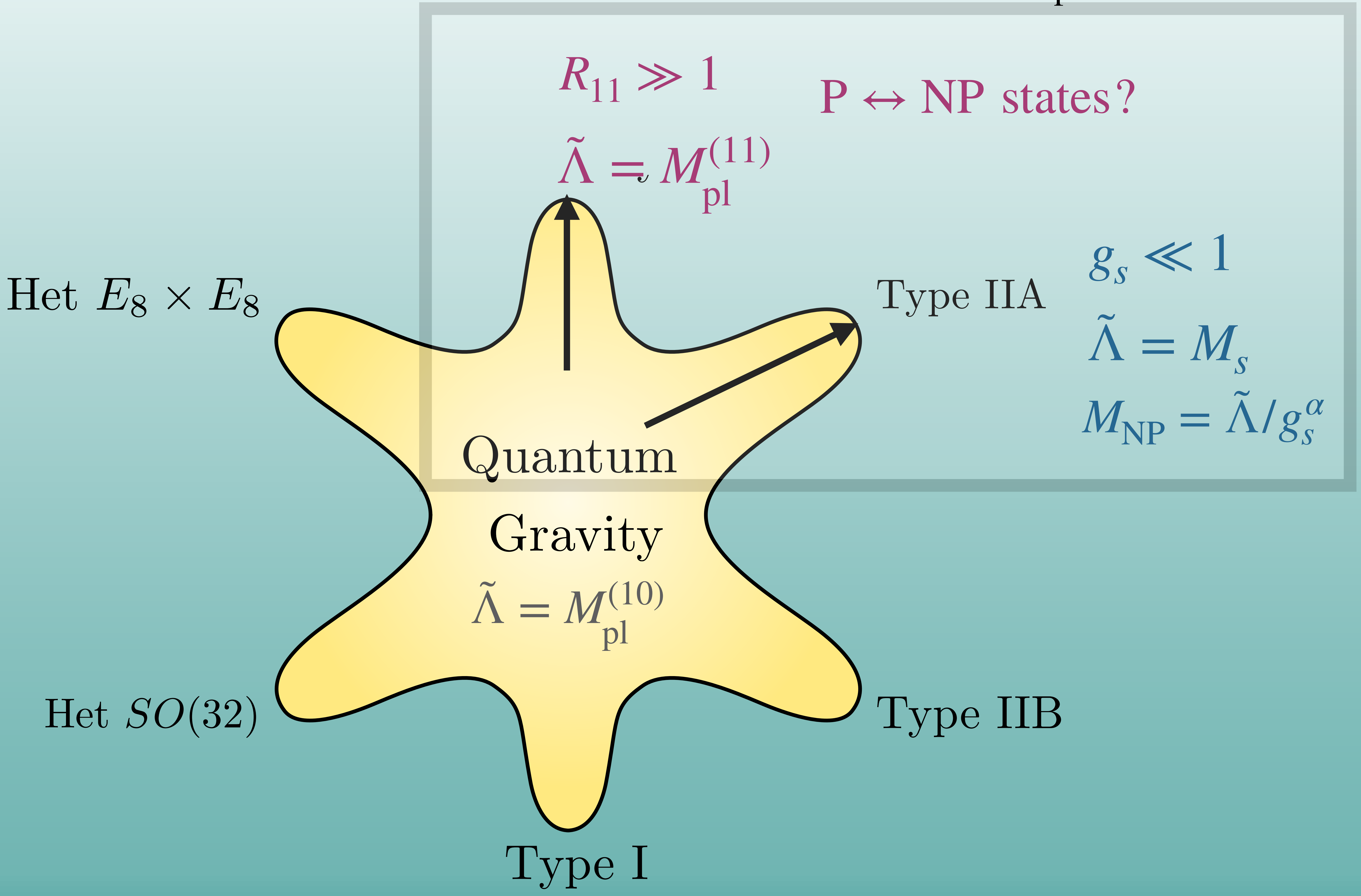
hierarchical pattern: $m_{\rm pert} \sim g^{\alpha}\Lambda\,, \qquad m_{\rm class} \sim \dfrac{\Lambda}{g^{\beta}} \qquad (\alpha \geq 0, \beta > 0)$

(string case: $\Lambda = M_s\,, \quad g = g_s$)

Introduction

Historically: One explores the realm of Quantum Gravity from one of its perturbative corners

Equi-dimensional limits with $M_{\mathrm{pl}}^{(d)} = \mathrm{const}$



QG in infinite distance limits

- SDC: towers of states become light
  [Ooguri, Vafa (2006)]

- Emergent string conjecture $\begin{cases} \text{fund. string} \\ \text{decomp.} \end{cases}$
  [Lee, Lerche, Weigand (2019)]

- QG cut-off: species scale $\tilde{\Lambda} \sim \dfrac{M_{\mathrm{pl}}^{(d)}}{N_{\mathrm{sp}}^{\frac{1}{d-2}}}$
  [Dvali (2007)]

QG in the bulk

- QG cut-off at $M_{\mathrm{pl}}^{(10)}$
  [Long, Montero, Vafa, Valenzuela (2021)]

Emergent string limit

Perturbative fundamental string

- Lighest towers are strings, mass scale M_s, string coupling $g_s \ll 1$
- Accompanied by particle like states of mass $M \sim M_s$, KK + winding
- Species scale $\tilde{\Lambda} \sim M_s$
- All other towers are non-perturbative: $m_{Dp} \simeq \frac{\tilde{\Lambda}}{g_s}\,, \qquad m_{NS5} \simeq \frac{\tilde{\Lambda}}{g_s^2}$
  (classical = coherent quantum states)

Can appear in different disguises (dual descriptions)

- Type IIA on K3 fibered CY_3 in the infinite distance limit $t_b \to \lambda t_b\,, g_s \to \lambda^{1/2} g_s$
  so that $M_{\mathrm{pl}}^{(4)} = \mathrm{const}$, emergent string = NS5 wrapped on K3

Decompactification Limit

Consider type IIA compactified to d-dimensions on X_k, $\quad d+k=10$

Decompactification limit: $\quad g_s \to \lambda^{\frac{3(d-2)}{2(d-1)}} g_s\,, \qquad M_s \to \lambda^{\frac{d-4}{2(d-1)}} M_s\,, \qquad R_I \to \lambda^{\frac{1}{d-1}} R_I\,.$

$(\lambda \gg 1,\ M_{\rm pl}^{(d)} = const.)$

Via the relations $\quad M_s^2 = M_*^3 R_{11}\,, \qquad g_s = (M_* R_{11})^{\frac{3}{2}}\,.$

this is the M-theory limit $\quad R_{11} \to \lambda R_{11}\,, \qquad M_* \to \dfrac{M_*}{\lambda^{\frac{1}{d-1}}}\,, \qquad R_I \to \lambda^{\frac{1}{d-1}} R_I,$

Lightest degrees of freedom: D0-branes with $\quad M_{D0} \sim M_s/g_s \sim M_{\rm pl}^{(d)}/\lambda$

For such a KK-like tower, the species scale is $\quad \tilde\Lambda \sim M_{\rm pl}^{(d)}/\lambda^{1/(d-1)} \sim M_{\rm pl}^{(d+1)} \sim M_*$

Room for additional light towers $\quad M_{D2,NS5} \sim M_s/g_s^{1/3} \sim M_{\rm pl}^{(d)}/\lambda^{1/(d-1)} \sim \tilde\Lambda$

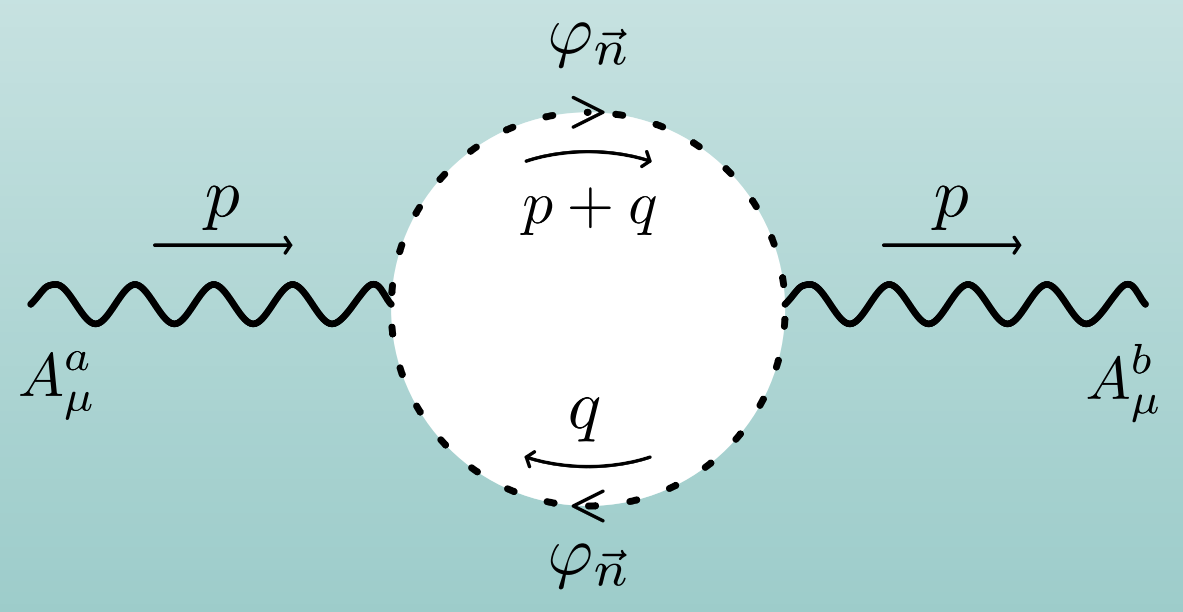
[Blumenhagen, Cribiori, Gligovic, Paraskevopulou, 2309.11554]

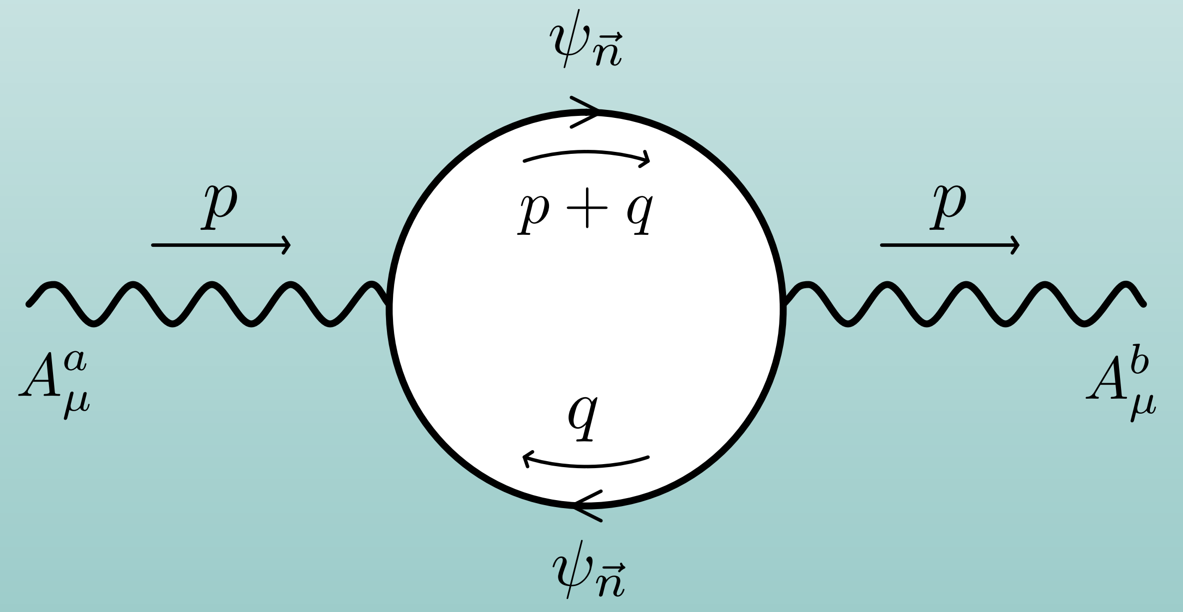
Emergence Proposal

Emergence Proposal: [Heidenreich, Reece, Rudelius (2018)],[Grimm, Palti, Valenzuela (2018)]
see also [Marchesano, Melotti (2022)] [Castellano, Herráez, Ibáñez (2022)] [Bhg, Gligovic, Paraskevopulou (2023)]

from review [Palti, (2019)]

> The dynamics (kinetic terms) for all fields are emergent in the infrared by integrating out towers of states down from an ultraviolet scale, which is below the Planck scale.





1-loop correction to gauge coupling: tower $M_n = n\Delta m$ with $M_n, q \leq \Lambda_{UV}$,

Schwinger integral: $$\left.\frac{1}{g^2_{U(1)}}\right|_{1-\text{loop}} \sim \sum_{n=1}^{n_{\max}} Q_n^2 \log\left(\frac{M_n^2}{\mu^2}\right) \sim \left.\frac{1}{g^2_{U(1)}}\right|_{\text{class}}$$

Emergence Proposal

Originally checked at leading order in a (toy) QFT approach with $M_n \leq \tilde{\Lambda}$

Is it realized in full quantum gravity (string theory)?

Problem: Quantization of M-theory?

Objective

- Collect evidence from 1/2 BPS saturated amplitudes which admit geometric formulation
- Higher derivative R^4-terms in theories with maximal supersymmetry by Green-Gutperle-Vanhove (1997) (and Kiritsis,Obers,Pioline)

  [Blumenhagen, Cribiori, Gligovic, Paraskevopulou, 2404.01371]
- Topological amplitudes $\mathcal{F}_g$ in 4D with N=2 supersymmetry a la Gopakumar-Vafa (1998)

  [Blumenhagen, Cribiori, Gligovic, Paraskevopulou, 2309.11551]
  [Hattab, Palti, 2312.15440+2404.05176]

Swampland program provides a new view on these seminal works

Emergent String: 1-loop correction to R^4 term

Higher derivative term

$$S_{R^4} \simeq M_s^{d-8}\, V_k \int d^d x \sqrt{-g}\, a_d\, t_8 t_8\, R^4 ,$$

General expansion in g_s

$$a_d = \frac{c_0}{g_s^2} + \underbrace{\left(c_1 + \mathcal{O}\left(e^{-S_{\rm ws}}\right)\right)}_{1-\text{loop}} + \mathcal{O}\left(e^{-S_{\rm st}}\right)$$

with the one-loop contribution

$$a^{(1)}_{d,\text{string}} \simeq \frac{2\pi}{V_k} \overline{\sum_{m_i, n^i \in \mathbb{Z}}} \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^{\frac{d-6}{2}}}\, e^{-\pi\tau_2 M^2 - 2\pi i \tau_1 m_i n^i}$$

1/2 BPS: $m_i n^i = 0$

KK+ winding numbers $\quad M^2 = m_i G^{ij} m_j + n^i G_{ij} n^j$

undo integral τ_1: $\quad a^{(1)}_d \simeq \frac{2\pi}{V_k} \overline{\sum_{m_i, n^i \in \mathbb{Z}}} \int_0^\infty \frac{dt}{t^{\frac{d-6}{2}}}\, \delta(\text{BPS})\, e^{-\pi t M^2} ,$

UV divergence

Regularizing UV divergence

Example 9D: $$a^{(1)}_{9,\text{string}} \simeq \frac{2\pi^2}{3}\left(1+\frac{1}{\rho^2}\right).$$ (string comp.)

Regularize via minimal subtraction + zeta function:

$$a^{(1)}_{9,m=0} \simeq \frac{2\pi}{\rho}\sum_{n\neq 0}\int_\epsilon^\infty \frac{dt}{t^{3/2}}e^{-\pi t\rho^2 n^2} = -4\pi^2 \underbrace{\sum_{n\neq 0}|n|}_{=2\zeta(-1)} = \frac{2\pi^2}{3}, \qquad a^{(1)}_{9,n=0} \simeq \frac{2\pi^2}{3\rho^2},$$

with $$\int_\epsilon^\infty \frac{dt}{t^{3/2}}e^{-\pi t A} = \cancelto{0}{\frac{2}{\sqrt{\epsilon}}} - 2\pi\sqrt{A} + \mathcal{O}(\sqrt{\epsilon}),$$

No emergence!

works except 10D $$a^{(1)}_{10,\text{string}} \simeq \frac{2\pi^2}{3}$$ $$a^{(1)}_{10} \simeq 0$$

M-theoretic Emergence of R^4 term

Higher derivative term

$$S_{R^4} \simeq M_s^{d-8}\, V_k \int d^d x \sqrt{-g}\, a_d\, t_8 t_8\, R^4,$$

with the coefficient

$$\boxed{a_{d,\mathrm{M}}^{(1)} \simeq \frac{2\pi}{r_{11}\mathscr{V}_k} \overline{\sum_{N^I, m \in \mathbb{Z}}} \int_0^\infty \frac{dt}{t^{\frac{d-6}{2}}}\, \delta(\mathrm{BPS})\, \exp\left(-\pi t\, N^I \mathscr{M}_{IJ} N^J - \pi t \frac{m^2}{r_{11}^2} \right),}$$

KK, M2, M5 transverse wrapping numbers $\quad (N^I) = \left(m_i, n^{ij}, n^{ijklm} \right).$

particle masses $\quad \mathscr{M} = \mathrm{diag}\left(\frac{1}{r_i^2}, t_{ij}^2, t_{ijklm}^2 \right)$ (axions will induce off-diagonal entries)

Emergence of R^4 term

1/2 BPS conditions

$$n^{ij} m_j = 0\,, \qquad \# = k$$

$$n^{[ij} n^{kl]} + m_p n^{pijkl} = 0\,, \qquad \# = \binom{k}{4}$$

$$n^{i[j} n^{klmnp]} = 0\,, \qquad \# = k\binom{k}{6}$$

equivalent to section constraints in ExFT

(analogous truncation of modes)

[Bossard, Kleinschmidt (2015)]

Particle states and 1/2 BPS conditions

d	k	Particles $SL(k)$ reps.	$E_{k(k)}(Z)$	Λ_{E_k}	1/2-BPS: λ_{E_k}
9	1	$[1]_p$	1	1	0
8	2	$[2]_p + [1]_{M2}$	$SL(2)$	3	2
7	3	$[3]_p + [3]_{M2}$	$SL(3) \times SL(2)$	(3,2)	(3,1)
6	4	$[4]_p + [6]_{M2}$	$SL(5)$	10	5
5	5	$[5]_p + [10]_{M2} + [1]_{M5}$	$SO(5,5)$	16	10
4	6	$[6]_p + [15]_{M2} + [6]_{M5}$	E_6	27	27

Emergence in 9D

Example 9D: Evaluate

$$a_{9,\mathrm{M}}^{(1)} \simeq \frac{2\pi}{r_{11}\, r_1} \sum_{(m,n)\neq(0,0)} \int_{\epsilon}^{\infty} \frac{dt}{t^{3/2}}\, e^{-\pi t\left(\frac{m^2}{r_{11}^2}+\frac{n^2}{r_1^2}\right)} .$$

invoking Poisson resummation of n and the same regularization procedure

as before plus $$\int_0^\infty \frac{dx}{x^{1-\lambda}}\, e^{-\frac{b}{x}-cx} = 2\left|\frac{b}{c}\right|^{\frac{\lambda}{2}} K_\lambda\left(2\sqrt{|b\,c|}\right)$$

yields

$$a_9 \simeq \boxed{\frac{2\zeta(3)}{g_s^2}} + \frac{2\pi^2}{3}\left(1+\frac{1}{\rho_1^2}\right) + \boxed{\frac{8\pi}{g_s}\sum_{m\neq 0}\sum_{n\geq 1}\left|\frac{m}{n}\right| K_1\left(2\pi|m|n\frac{\rho_1}{g_s}\right)}$$

tree level

missing (reminiscent to 10D string)

ED0 brane instanstons

Emergence in dim=d

For 8D, new sector with D2-branes and mass $M^2 = n^2 t_{12}^2 + \frac{m^2}{r_{11}^2}$

$$a^{(1)}_{8,\mathrm{M};M2} \simeq \frac{2\pi^2}{3} + \frac{8\pi}{r_{11}t_{12}} \sum_{n_1,n_2\geq 1} \frac{1}{n_2} e^{-2\pi n_1 n_2 r_{11} t_{12}} = -\frac{2\pi}{T} \log\left(\left|\eta(iT)\right|^4 \right)$$

The full amplitude from 1-loop Schwinger-integral!

- Full result for 7D, partial results $d \leq 6$
- Transverse M2,M5 yield all instantons $\longrightarrow$
- Conjecture: $\underbrace{a^{(1)}_{d,\mathrm{M}}(\text{transv})}_{\text{pert. } r_{11} \gg 1} = \underbrace{a^{(1)}_{d,\mathrm{M}}(\text{transv} + \text{longi})}_{\text{desert: } r_{11} = O(1)}$

Particle states	Instantons
$(D0, \mathrm{KK}_{(k)})$	$ED0_{(k)}$
$(D2_{(ij)}, \mathrm{KK}_{(k)})$	$ED2_{(ijk)}$
$(NS5_{(ijklm)}, \mathrm{KK}_{(n)})$	$ENS5_{(ijklmn)}$
$(D2_{(ij)}, D0)$	$EF1_{(ij)}$
$(NS5_{(ijklm)}, D0)$	$ED4_{(ijklm)}$
$(NS5_{(ijklm)}, D2_{lm})$	$ED2_{(ijk)}$

proof for $d \geq 4$ [Bossard, Kleinschmidt (2015)] [Bossard, Pioline (2016)]

M-theoretic Emergence Proposal

In the equi-dimensional infinite distance M-theory limit $M_* R_{11} \gg 1$, a perturbative QG theory arises whose low energy effective description emerges via quantum effects by integrating out the full infinite towers of states with a mass scale parametrically not larger than the 11D Planck scale. These are transverse M2-, M5-branes carrying momentum along the eleventh direction (D0-branes) and along any potentially present compact direction

pert. string theory | desert | pert. M-theory

$g_s \ll 1$ | $g_s = O(1)$ | $g_s \gg 1$

$$a_d = \frac{c_0}{g_s^2} + \underbrace{\left(c_1 + \mathcal{O}\left(e^{-S_{\rm ws}}\right)\right)}_{1-\text{loop}} + \mathcal{O}\left(e^{-S_{\rm st}}\right) \quad = \quad a^{(1)}_{d,\mathrm{M}}(\text{transv} + \text{longi}) \quad = \quad a^{(1)}_{d,\mathrm{M}}(\text{transv})$$

$$\mathcal{E}^{E_{k+1(k+1)}}_{\Lambda_{E_{k+1}}, s=\frac{k}{2}-1} \qquad \qquad \mathcal{E}^{E_{k(k)}}_{\Lambda_{E_k}\oplus 1, s=\frac{k}{2}-1}$$

Outlook

- More evidence from 1/2 BPS amplitudes in theories with lower susy
- Non BPS amplitudes like 10D kinetic terms

△ Requires quantization of M-theory, i.e. include non-BPS states

△ Space-time itself has to emerge

△ Problem: susy implies vanishing Schwinger integrals

△ Compute appropriate couplings, like 1-loop(!) graviton scattering in BFSS matrix model

$$V = -\frac{15}{16}\frac{v^4}{r^7} + \ldots \,,$$

(velocity v breaks susy)

Anamaria,

congrats for L'Oréal-UNESCO International Award

"For Women in Science" !

and thanks for your friendship

Looking forward to 2031