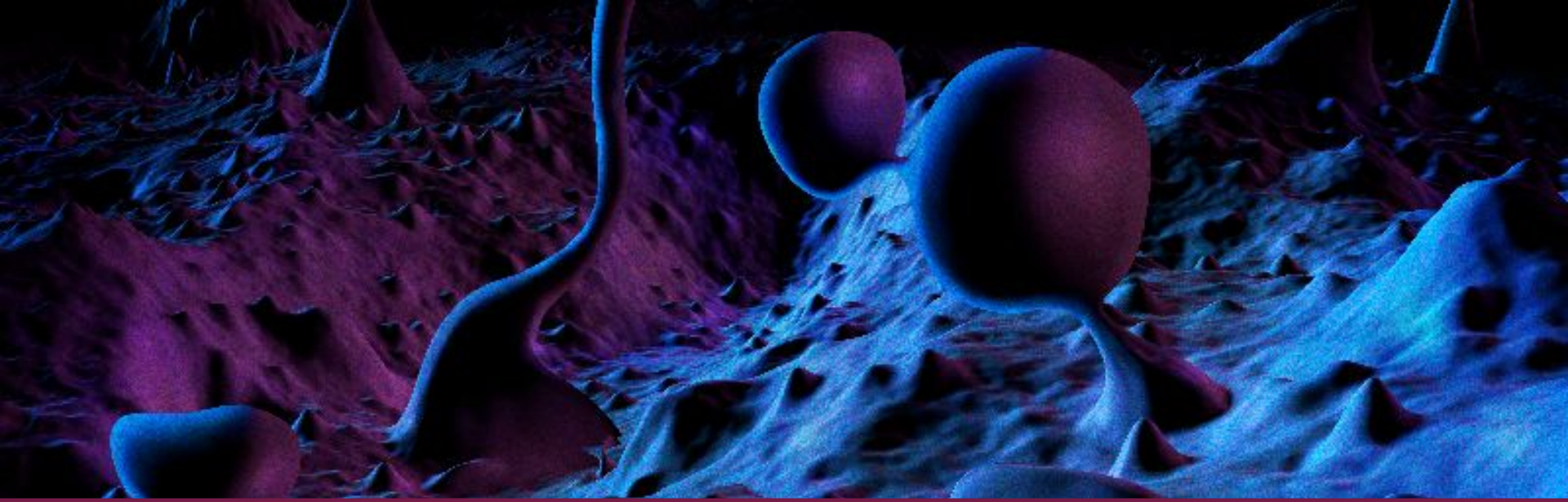

Emergent geometry in string theory

Ivano Basile | LMU

String phenomenology 101

- *basic pheno:* ***four*** *(big) dimensions*

- *weakly coupled strings:* ***new physics?***
  - *well... strings (duh)* 🙄
  - ***other stuff*** *(central charge)* 🤔

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if superstring — *spacetime* — *curvature(s)*

Weyl anomaly

$$(c_L, c_R) = 15 \text{ or } 26$$

total charges

RNS (N=1) — *Bose (N=0)*

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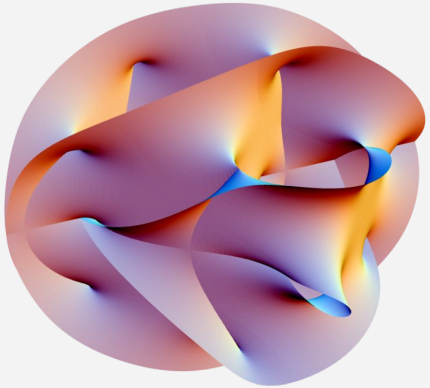
Q: what can it be?

check out Christian Aoufia's poster!

Take-home message



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  - *includes dualities & strong coupling subtleties*

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+ talks by: Herráez, Lüst, Masias, Montella, Raml

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  - *asymmetric orbifolds, rigid mirrors, holography, matrix models, fluxes, …*

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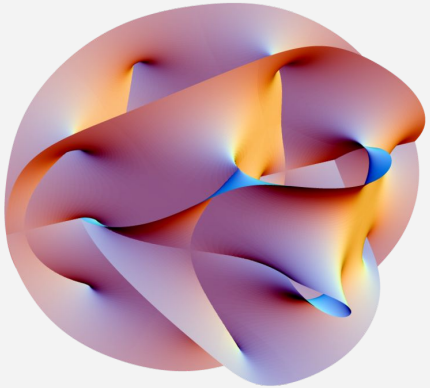

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A: when new physics comes soon, it’s geometry

When new physics comes soon

- *small **UV cutoff** (gravitons **weakly coupled**)*
  - **R⁴ *coefficient*** *from graviton scattering* $\alpha = \Lambda_{\rm UV}^{-6}$

$$\Lambda_{\rm UV} \ll M_{\rm Pl}$$

(Green, Schwarz, Brink, 1982) (Kiritsis, Pioline, 1997) (Green, Gutperle, Vanhove, 1997) (Obers, Pioline, 1999)
(Green, Vanhove, 1999) (Green, Russo, Vanhove, 2008) (Green, Russo, Vanhove, 2010) (Angelantonj, Florakis, Pioline, 2012)
(Blumenhagen, Cribiori, Gligovic, Paraskevopoulou, 2024) (Herráez, Castellano, Ibáñez, 2023) (Bedroya, van de Heisteeg, Vafa, Wiesner, Wu, 2023)

$$\alpha = \left(\frac{M_{\rm Pl}}{M_s}\right)^{8-d}\left(\underbrace{2\zeta(3)\left(\frac{M_{\rm Pl}}{M_s}\right)^{d-2}}_{\text{tree- level}} + \underbrace{2\pi\int_{\mathcal{F}} d\mu\, \widetilde{\mathcal{Z}}}_{\text{1-loop}}\right)$$

"reduced" partition function
(Afkhami-Jeddi, Cohn, Hartman, Tajdini, 2021)

If it quacks like geometry…

- *using modular invariance,* ***can prove*** *(Aoufia, IB, Leone, 2024)* [*UV/IR mixing –* ***talk by Abel***]
  - *Wilson coefficient* ***diverges*** ⇔ ∃ ***light tower***
  - *scaling w/ spectral gap is* ***geometric*** *(“emergent geometry”)*

∞ distance
(Stout, 2021-2022)
(Ooguri, Wang, 2024)

$$\int_{\mathcal{F}} d\mu\, \widetilde{\mathcal{Z}}(t) \overset{t\gg 1}{\sim} \Delta_{\rm gap}(t)^{-\frac{c_{\rm int}}{2}}$$

bonus: *limiting CFT contains* $\mathbb{R}^N$ *sigma model + KK tower* ✓ *(Ooguri, Wang, 2024)*

It's a generic feature of quantum gravity

- *when new physics comes soon, black holes know about it*

  (Veneziano, 2001) (Dvali, 2007) (Dvali, Gomez, Lüst, Isermann, Stieberger, 2009-2014) (Cribiori, Lüst, Staudt, 2022)

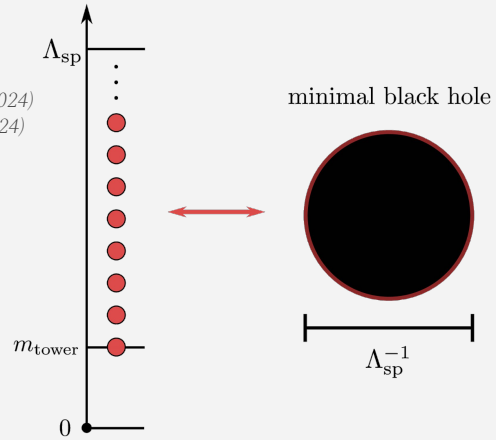
  - *minimal BHs* ⟷ *species:* ***thermodynamic constraints***

    (IB, (Cribiori), Lüst, Montella, 2023-2024) (Bedroya, Mishra, Wiesner, 2024) (Herráez, Lüst, Masias, Scalisi, 2024)

  - *S-matrix bootstrap constraints*

    (Camanho, Edelstein, Maldacena, Zhiboedov, 2014) (Caron-Huot, Komargodski, Sever, Zhiboedov, 2016)
    (Geiser, Lindwasser, 2022) (Caron-Huot, Li, Parra-Martinez, Simmons-Duffin, 2022) (Cheung, Remmen, 2022-2024)
    (Häring, Zhiboedov, 2023) (Arkani-Hamed, Cheung, Figueiredo, Remmen, 2023) (Eckner, Figueroa, Tourkine, 2024)
    (Berman, Elvang, 2024) (Bhardwaj, Spradlin, Volovich, Weng, 2024) (Albert, Knop, Rastelli, 2024)
    + non-perturbative: (Guerrieri, (Murali), Penedones, Vieira, 2021-2022)

"good species" quack like KK or strings



Outlook

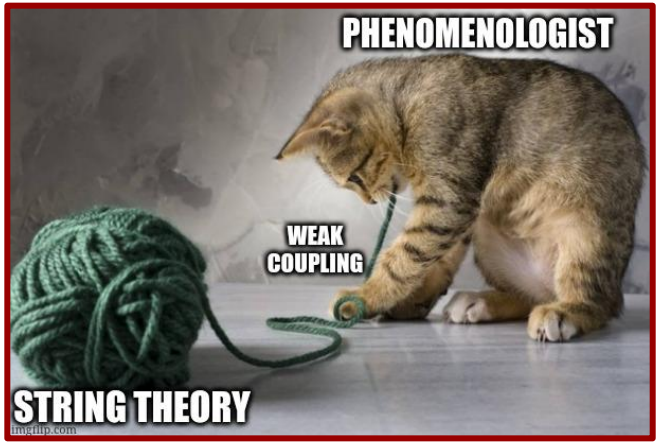
- *does string theory require* ***extra dimensions?***
  - ***when new physics comes soon!*** *(and strings don't)*
  - *includes* ***small dark energy*** *limits (if any)*

(Lüst, Palti, Vafa, 2019) (Montero, Vafa, Valenzuela, 2022)

- *complementary* ***bottom-up*** *arguments*
  - *S-matrix & black hole thermodynamics*

talks by: Herráez, Lüst, Masias, Montella

thank you!



Some gory details — existence of light tower

- *assume* N *states go below some threshold weight* Δ_{th}
  - *bound modular integral with strip integral* $[\tau = x+iy]$

$$|\widetilde{\mathcal{Z}_{T^2}}| \leq y^{\frac{c}{2}} \sum_{j,\Delta>0} e^{-2\pi\Delta y} + |E_{\frac{c}{2}} - y^{\frac{c}{2}}|$$

  - *split sum into* $Z_{\text{below}} + Z_{\text{above}}$ *with* $Z_{\text{below}} \leq N$ ⟶ *modular invariance*

$$Z_{\text{above}} \overset{y>1}{\leq} \frac{e^{2\pi\left(\frac{1}{y}-y\right)\Delta_{\text{th}}}}{1-e^{2\pi\left(\frac{1}{y}-y\right)\Delta_{\text{th}}}} Z_{\text{below}} \qquad Z_{\text{above}} \overset{y<1}{\leq} \frac{1}{1-e^{2\pi\left(y-\frac{1}{y}\right)\Delta_{\text{th}}}} Z_{\text{below}}$$

⟶ ***finite N ⇒ finite Wilson coeff.***

More gory details — modular differential equation

- *assume weights are **light** $\Delta = \Delta_0 f(t) \sim \Delta_0/t$* ✔ *or **heavy** $\Delta \gg 1$*
  - ***asymptotic** differential equation (akin to Narain lattice sum)*

$$\left(-t^2\partial_t^2 - (2-c)t\partial_t\right)\mathcal{Z}_{T^2} \overset{t\gg 1}{\sim} \left(\Delta_\tau - \frac{c}{2}\left(1-\frac{c}{2}\right)\right)\mathcal{Z}_{T^2}$$

- *regulate & integrate over fundamental domain*

(Rankin, 1939) (Selberg, 1940) (Zagier, 1982) (Angelantonj, Florakis, Pioline, 2011) (Angelantonj, Cardella, Elitzur, Rabinovici, 2011)

  - ***geometric scaling** of integral*

$$I(t) \overset{t\gg 1}{\sim} t^{\frac{c}{2}} \sim \Delta_{\text{gap}}^{-\frac{c}{2}}$$

Last one, I promise — factorized CFT limits

- *relax spectrum to factorization* Z(t) = A(t)B *("partial decompactification")*
  - ***harmonic decomposition*** *w.r.t. fundamental domain*

(Benjamin, Collier, Fitzpatrick, Maloney, Perlmutter, 2021)

$$\widetilde{A} = \frac{3}{\pi} I_A(t) + \sum_{n>0} a_n(t)\,\nu_n + \int_{\mathrm{Re}(s)=\frac{1}{2}} ds\,\alpha_s\,E_s$$

preceding result — *Maass cusp forms* — *real analytic Eisenstein series*

$$I_{AB}(t) \overset{t\gg 1}{\sim} a\,t^{\frac{c_A}{2}} + b\,t^{\frac{c_A+c_B-2}{2}}$$

QG geometric scaling — *field theory gap contribution*

bonus: *log threshold terms* [*when expected*] ✓