Snowmass Community Summer Study,
Seattle, July 17-26, 2022

String Theory and Particle Physics

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String Theory:

a prime candidate (actually, the only game in town) for unification of electromagnetic, strong and weak forces (Standard Model) with quantum gravity

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Focus on implications for particle physics

Useful references:

M. C. J. Halverson, G. Shiu, W. Taylor, ``Snowmass White Paper: String Theory and Particle Physics,'' arXiv:2204.01742

D. Harlow, S. Kachru and J. Maldacena, Section 2 of ``TF1 of Snowmass report: Quantum Gravity, String Theory and Black Holes,'' to appear

Key topics:

1. How precisely can we match observable particle physics with specific top-down string constructions? focus

2. What can be ruled out from string theory - swampland program? brief

3. What are typical features of string vacua & particle physics implications? comment

Disclaimer:

- Particle physics and cosmology are deeply Intertwined. Focus on particle physics aspects. Connection between string theory and cosmology:

R. Flauger, V. Gorbenko, A. Joyce, L. McAllister, G. Shiu and E. Silverstein, "Snowmass White Paper: Cosmology at the Theory Frontier," 2203.07629.

c.f., Dan Green's talk at Snowmass

- Emphasis due to my biases and limited expertise

Outline

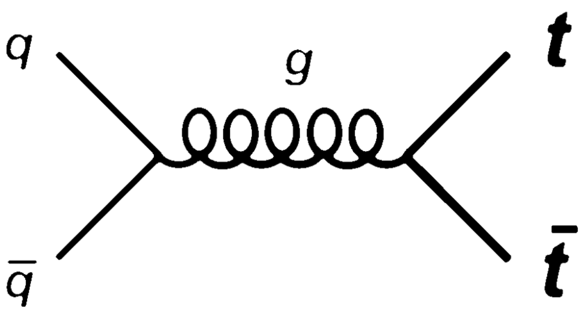
I. Top-down constructions of particle physics models → Modern developments

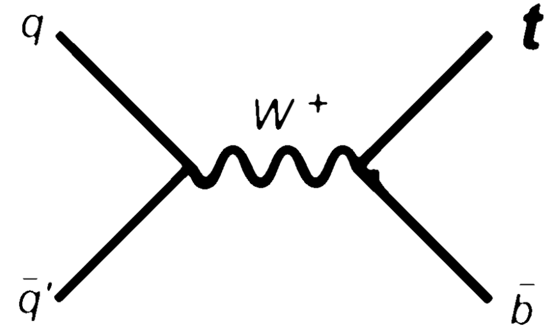
II. Current & Future efforts

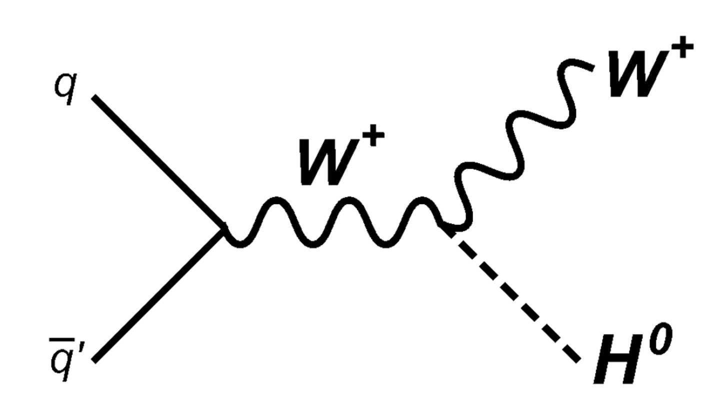
III. Impact on other fields

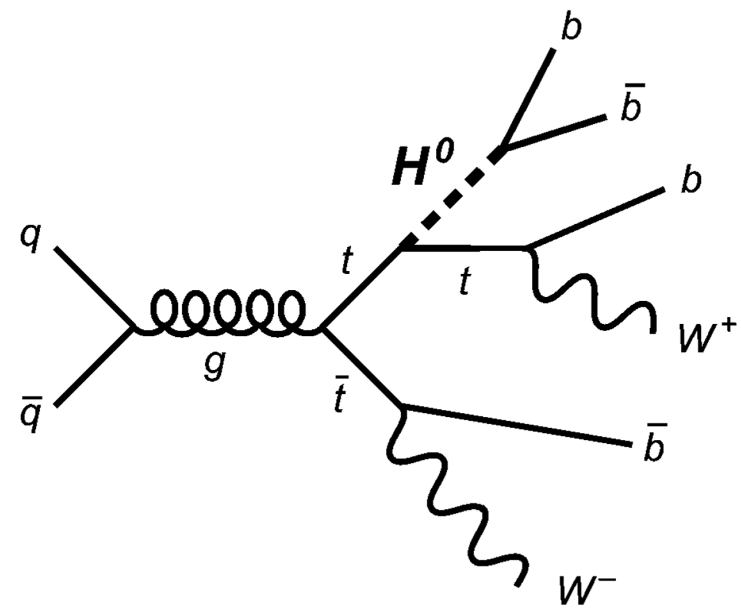
IV. Conclusions

Standard Model of elementary particles







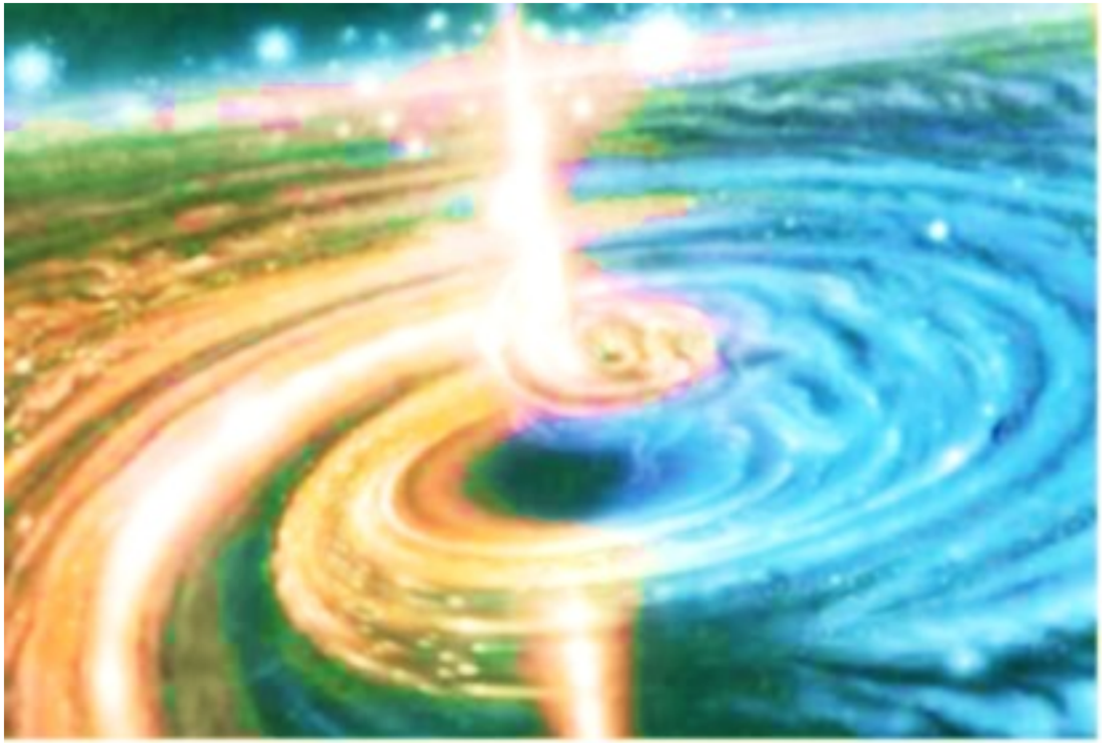


a consistent - ``renormalizable'' Quantum Field Theory of electromagnetic, strong and weak interactions

Gravity as Quantum Field Theory

with gravitons mediating quantum interactions with matter

→ infinities (``non-renormalizable") - inconsistent



Search for consistent Quantum Theory of Gravity

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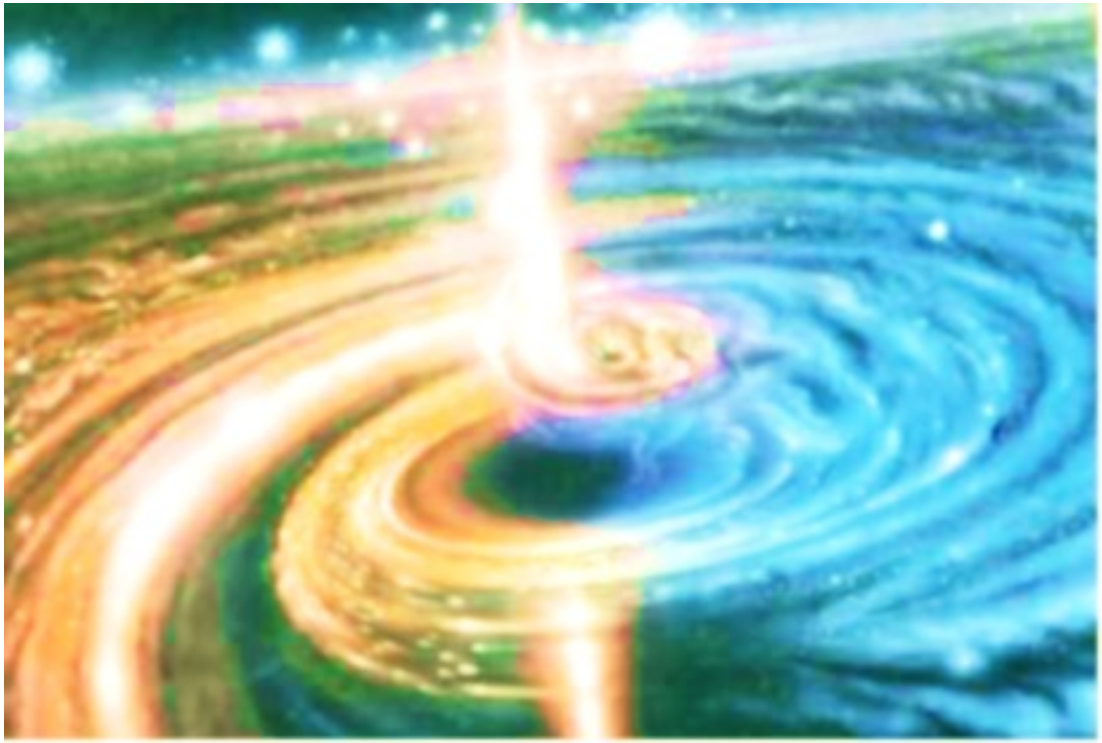
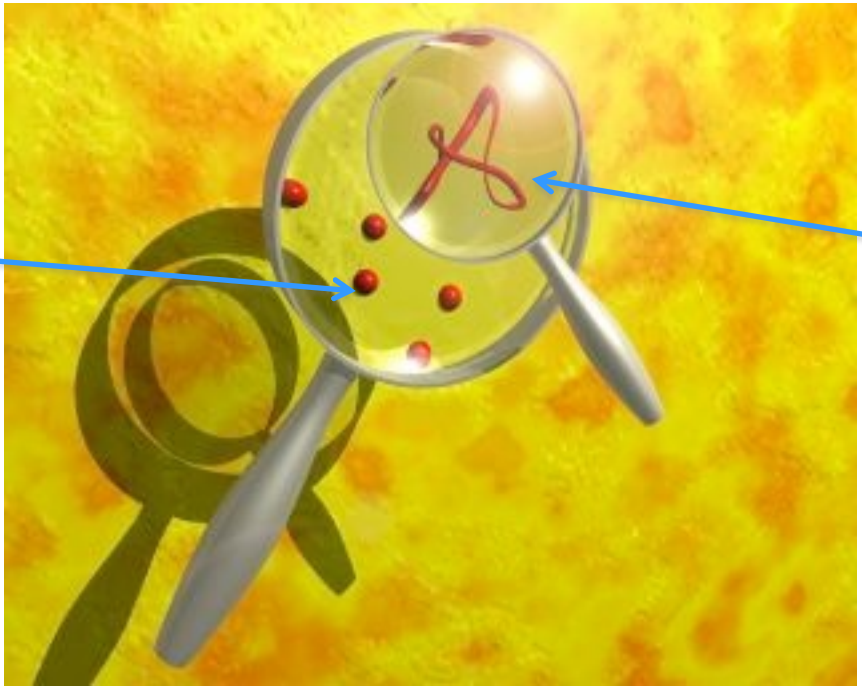


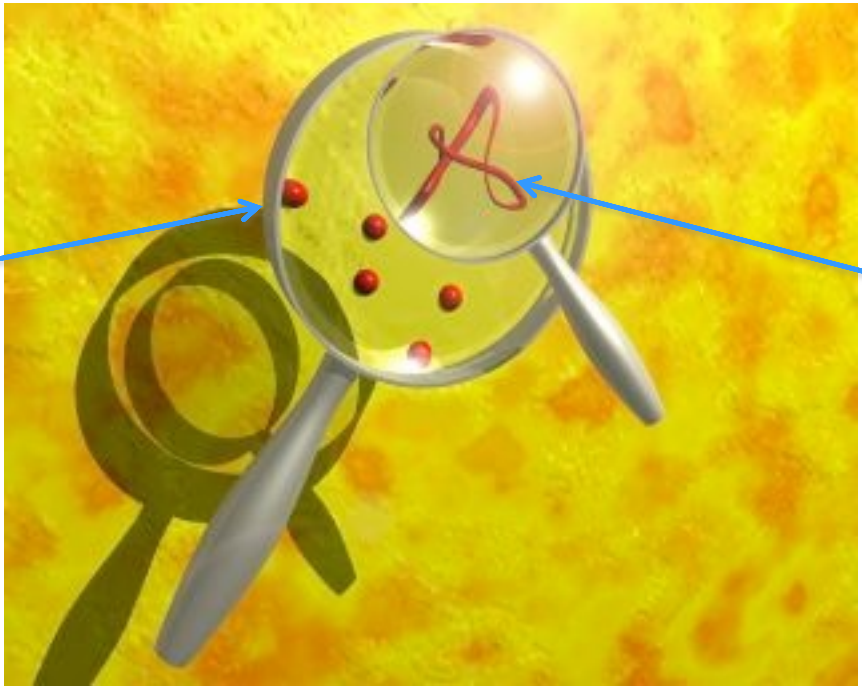
Search for consistent Quantum Theory of Gravity

→ String Theory



distances
~10^{-33} cm

Elementary particles as quantum excitations of strings



graviton

string

Graviton (mediating quantum gravitational interactions)

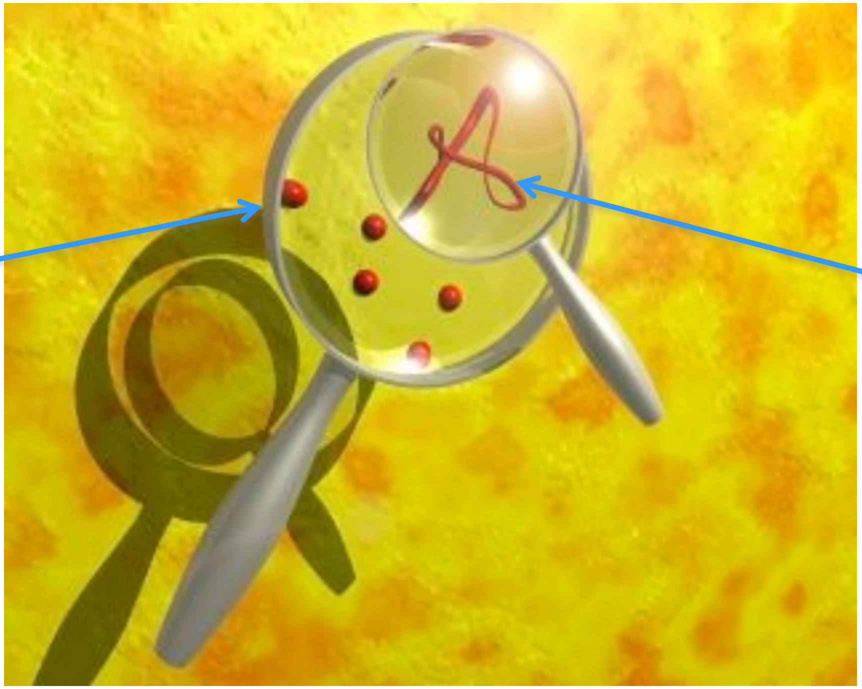
always appears a massless quantum excitation of strings

Built as a quantum state: $g_{\mu\nu} = |\tau+\sigma>_{\mu} \otimes |\tau-\sigma>_{\nu}$

μ,ν - space-time indices

τ, σ - string world-sheet coordinates

Left-moving Right-moving sectors



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μ,ν - space-time indices
τ, σ - string world-sheet coordinates

Left-moving ↑ (for $\tau+\sigma$)   Right-moving sectors ↑ (for $\tau-\sigma$)

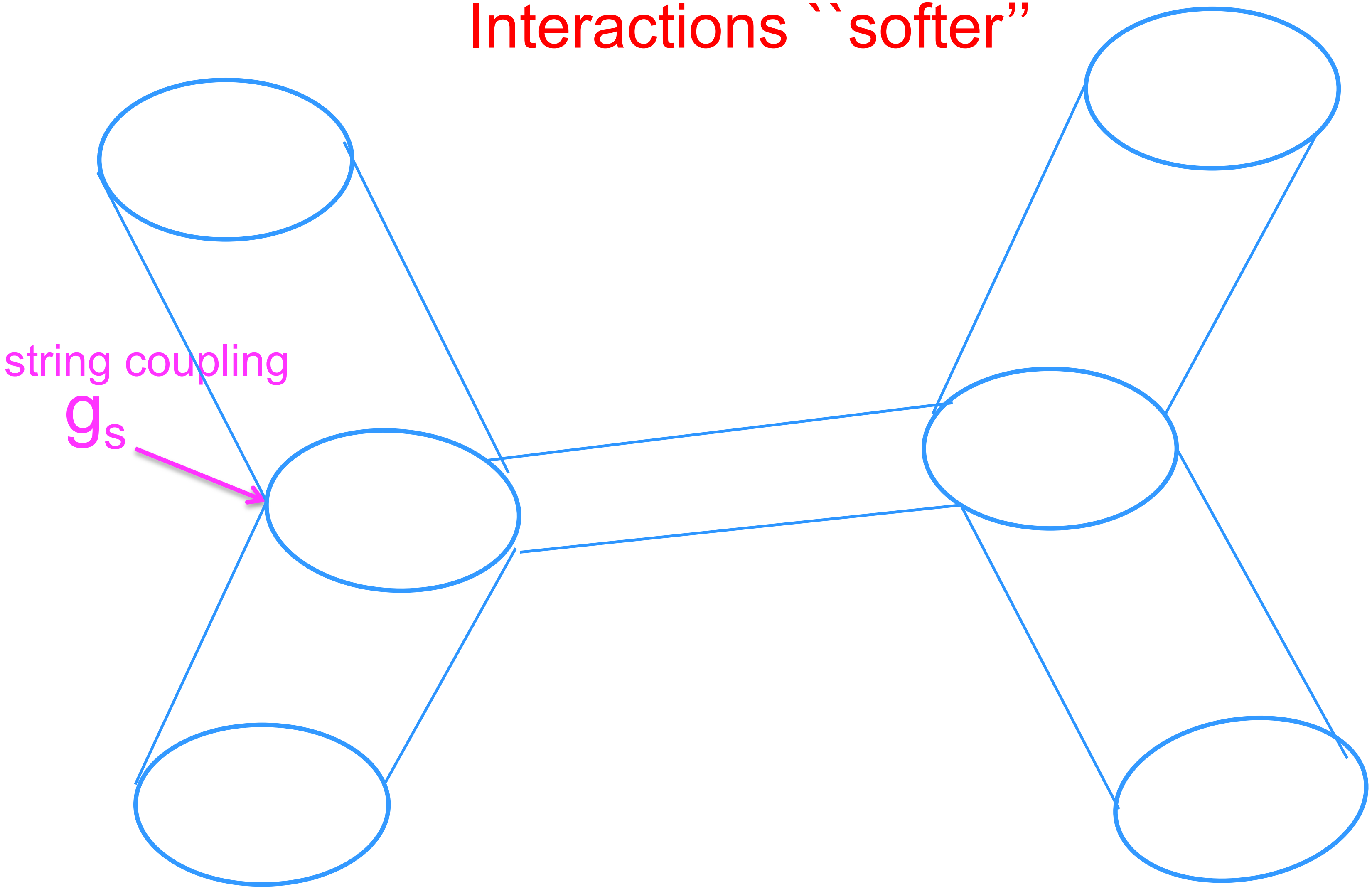
c.f., Shamit Kachru's talk

2-dimensional conformal field theory (CFT)

→ **String Theory contains quantum gravity!**

Quantum interactions: joining & splitting of strings

Interactions ``softer''

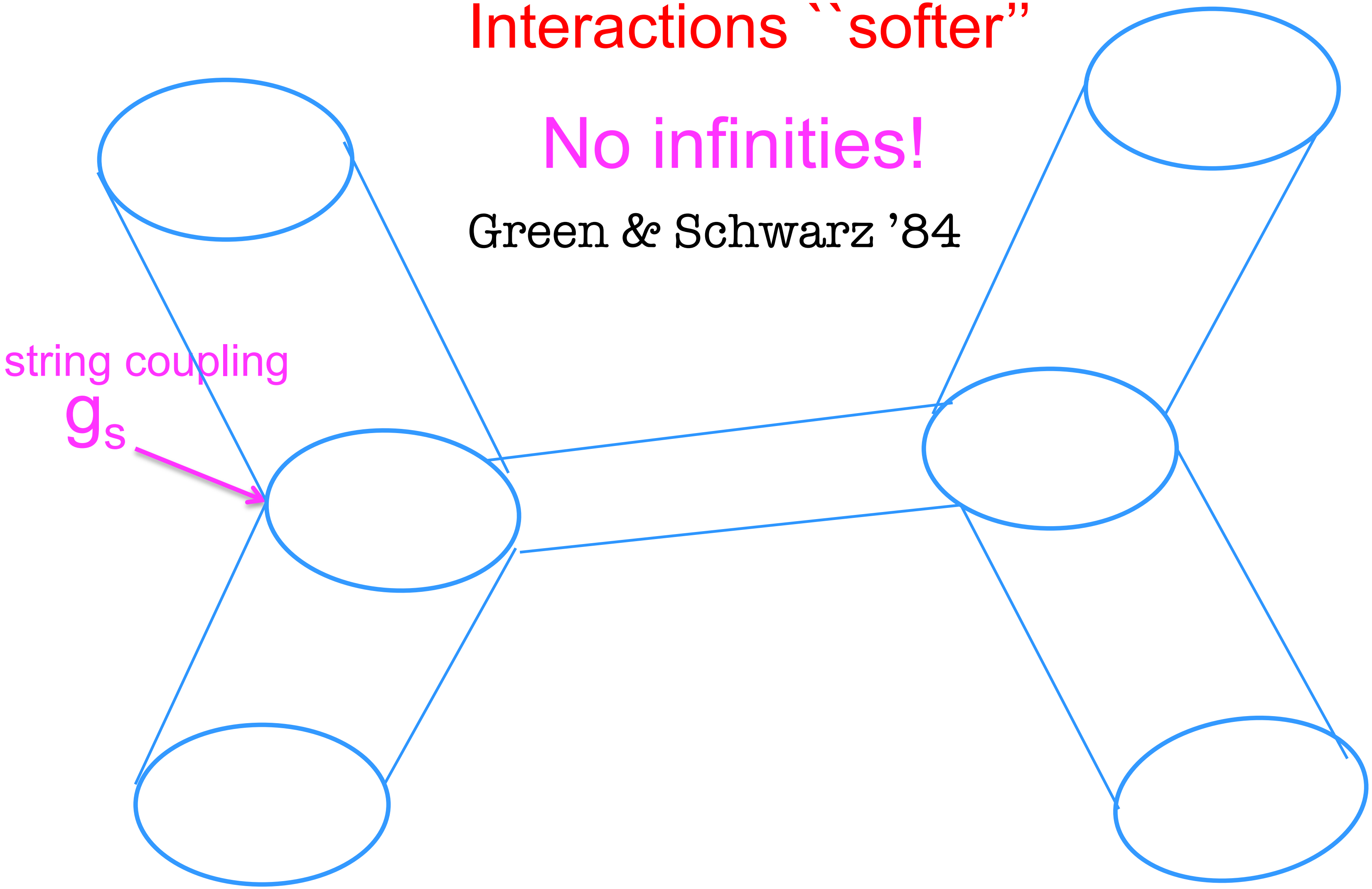


Quantum interactions: joining & splitting of strings

Interactions ``softer''

No infinities!

Green & Schwarz '84



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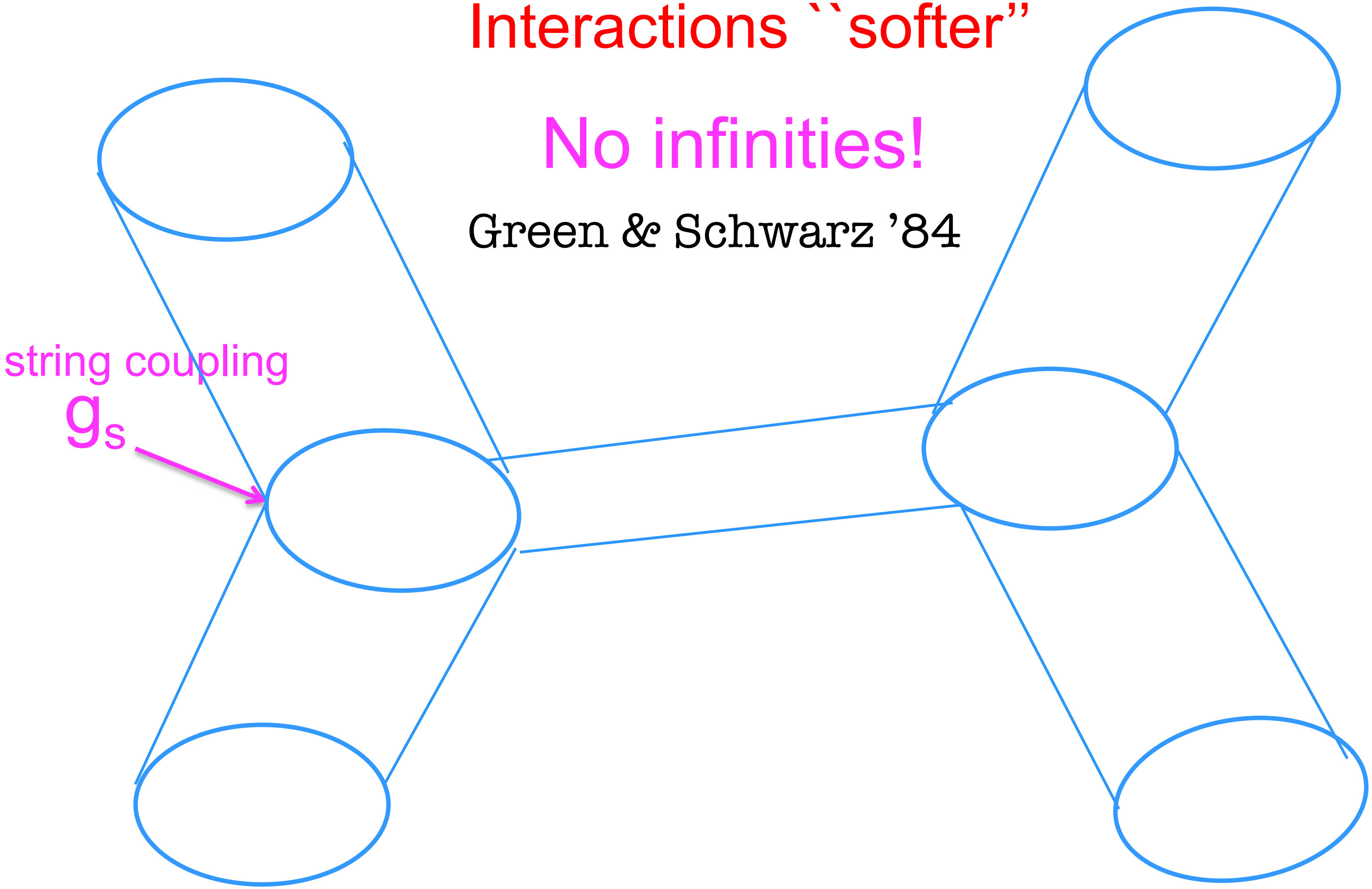

String Theory, a finite theory of quantum gravity!

- String Theory, a consistent quantum theory where particles, including graviton, appear as string excitations at distances $R_{planck}=10^{-33}$ cm

- As consistent quantum theory, without infinities, due to ``anomalies”, only in10 dimensions

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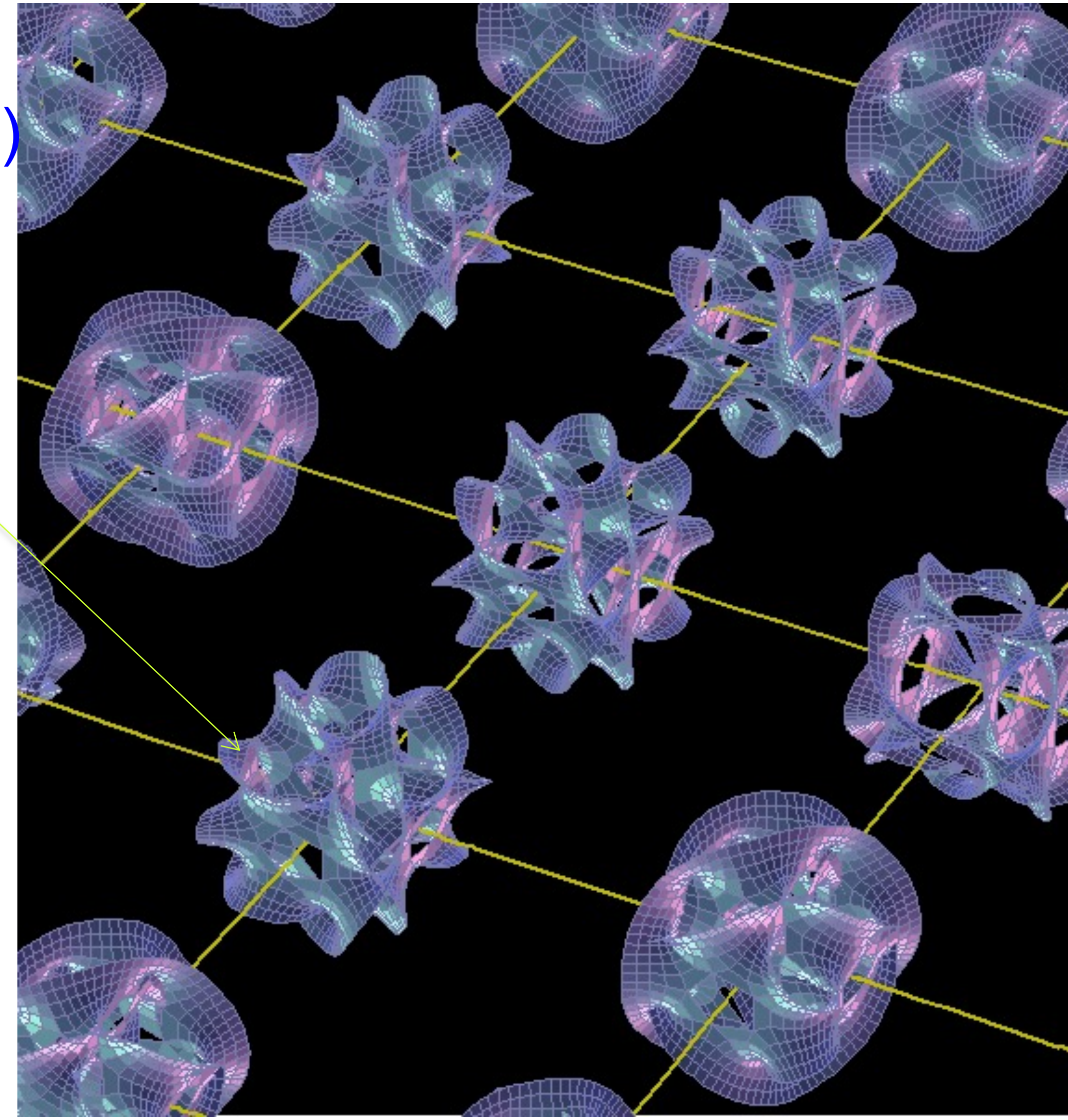
Six extra dimensions are compactified on

Calabi-Yau spaces

(supersymmetry/consistency)



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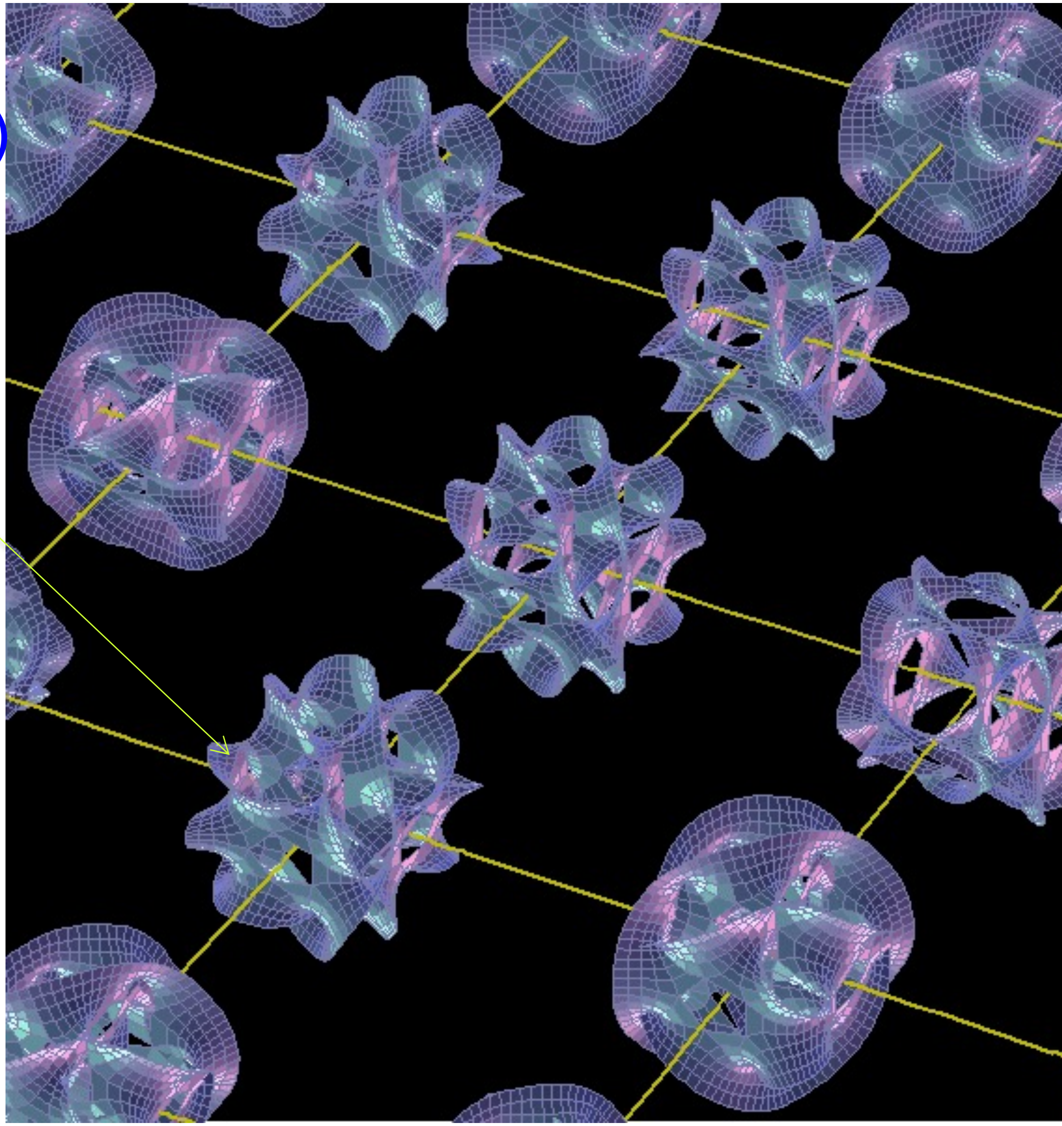

Calabi-Yau compactification & particle physics

1. Heterotic $E_8 x E_8$ string → originally most promising

- |left-moving sector⟩ ⊗ |right-moving sector⟩
  (superstring)   bosonic string w/ $E_8 x E_8$

⬇

- Calabi Yau compactification w/ vector bundles

Candelas, Horowitz, Strominger, Witten '85

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- Calabi Yau compactification w/ vector bundles

  Candelas, Horowitz, Strominger, Witten '85
- Standard Model constructions:
  - SM x $U(1)_{B-L}$ (w/ two Higgs doublets) He, Ovrut, Pantev '04…
  - MSSM (one Higgs doublets) Bouchard, Donagi '05; Bouchard, M.C., Donagi '05…
  - Orbifold constructions …Lebedev, Nilles, Raby, Ramos, Ratz, Vaudrevange, Wingerter '07-'10…
  - Free fermionic constructions…Cleaver, M.C., Espinosa, Everett, Langacker '97-'98
  - Landscape analysis (complete intersection Calabi-Yau's);10^{10}SMs; phenomenological issues… Anderson, Gray, Lukas '09-'18…

New perspective brought with introduction of extended objects → D-branes

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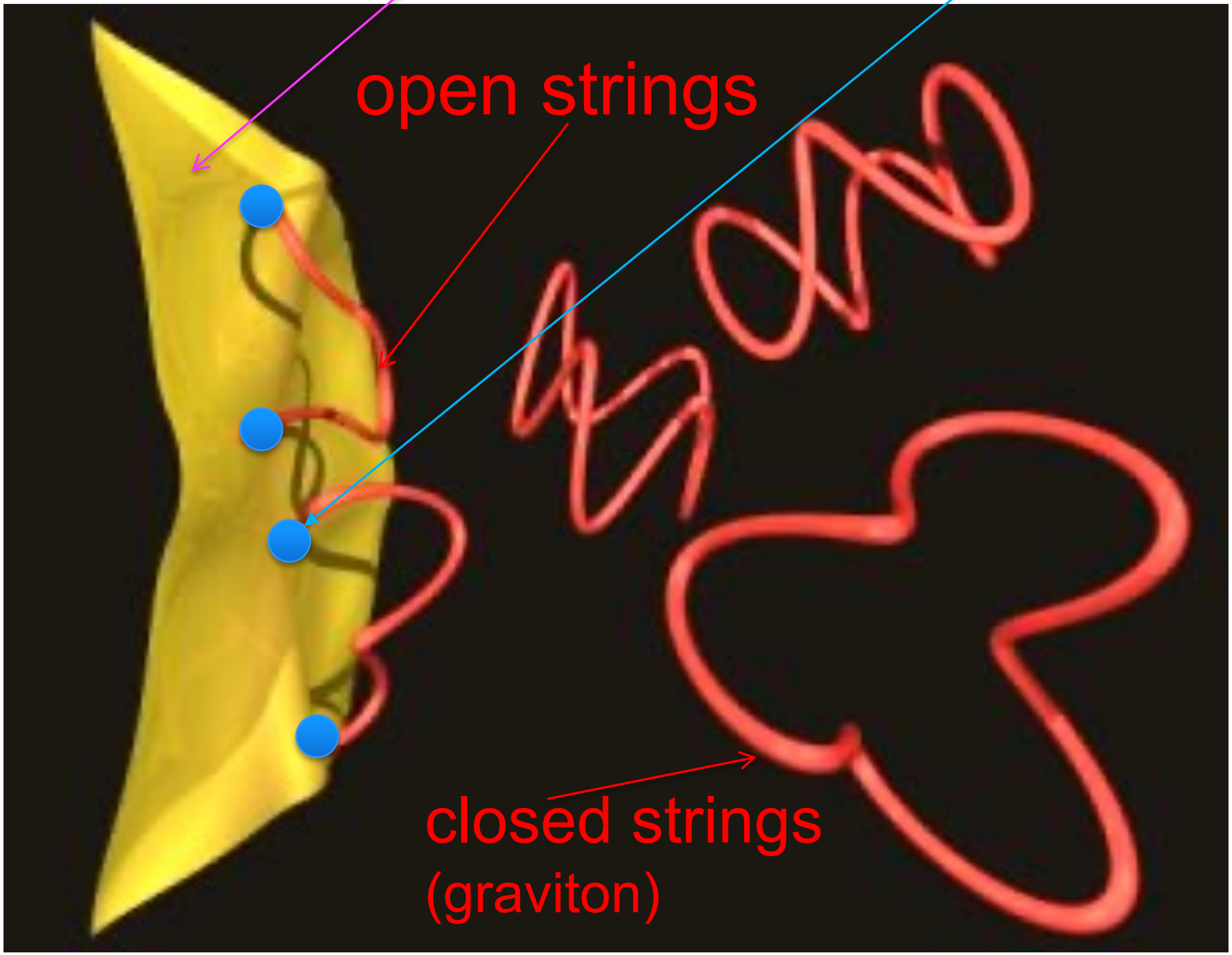
Modern String Theory &
New implications for particle physics

D(irichlet) - Branes

Polchinski ’96

boundaries of open strings with charges at their ends



g_s - small

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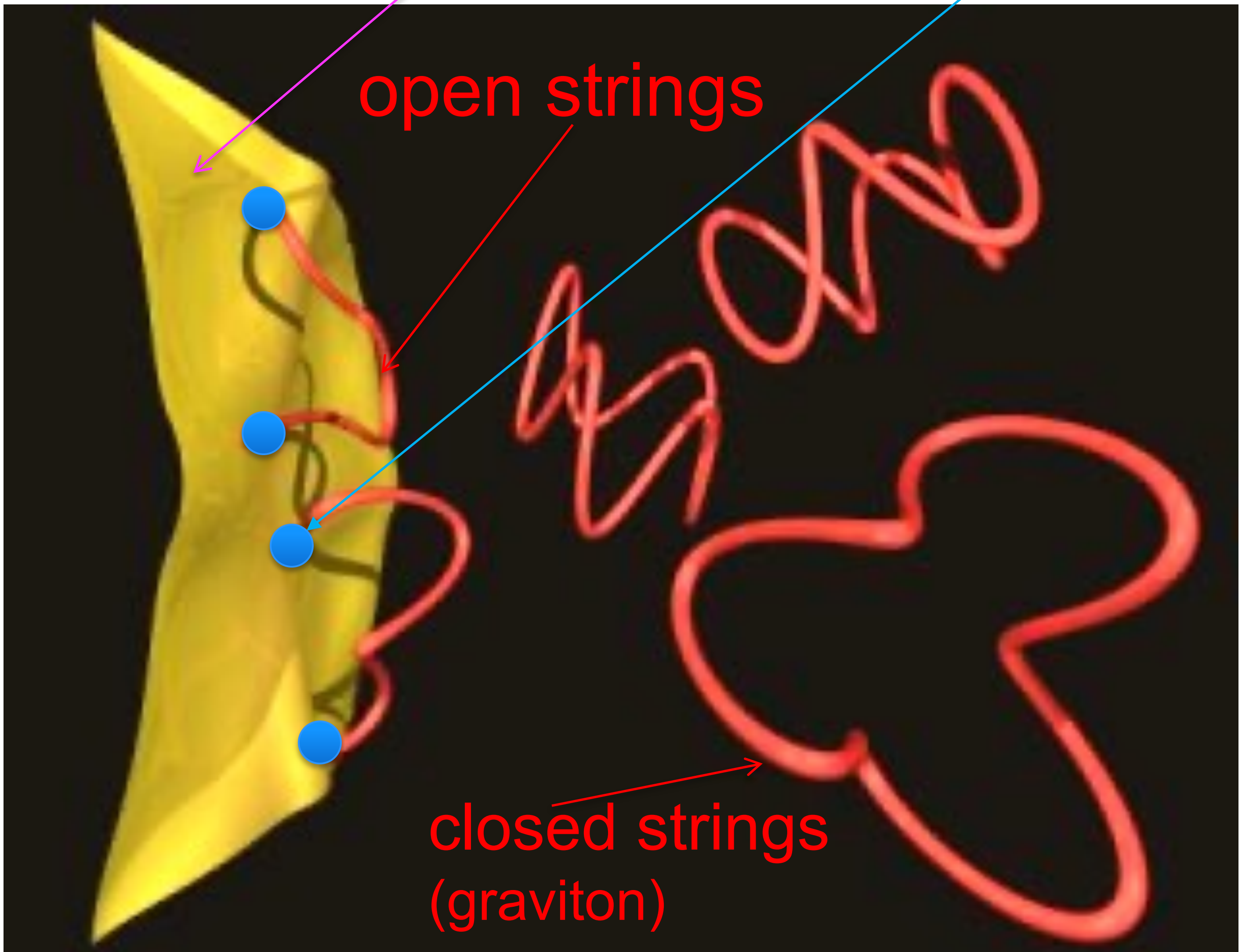
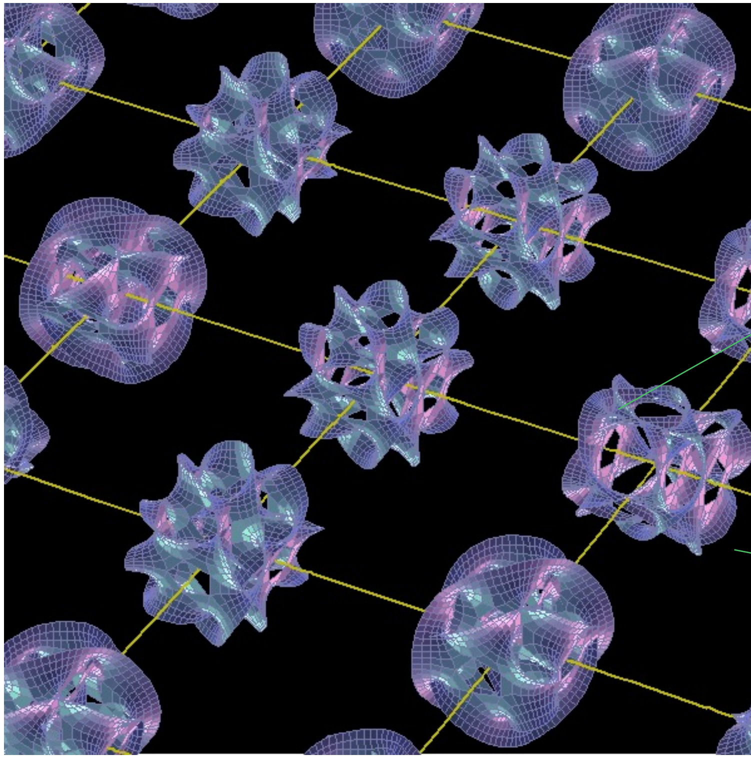


g_s - small

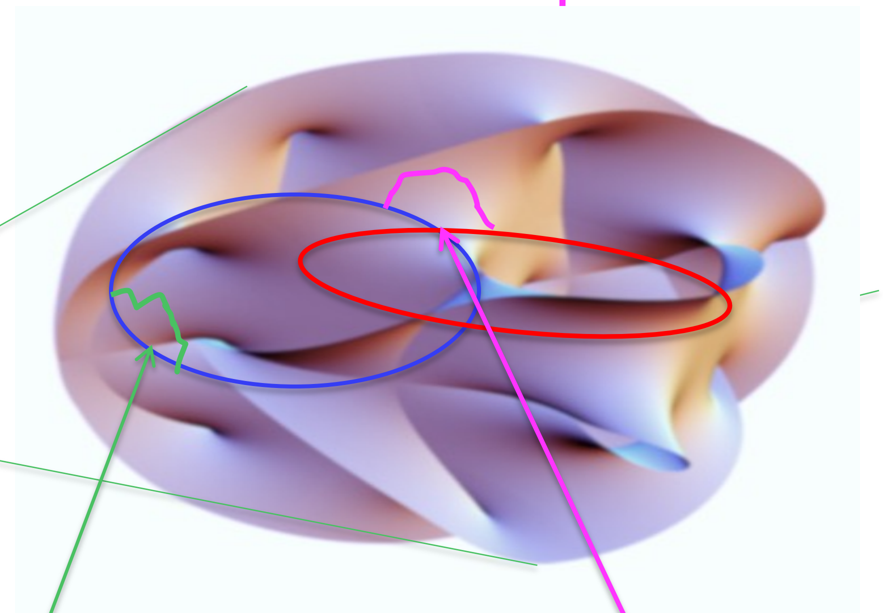
Open string excitations charged and ``live'' on branes

→ brane-world scenarios

D-Branes fill out 4 dimensions &



on Calabi-Yau space



wrap different cycles which intersect

(photon, gluons, W) (matter: quarks, leptons)

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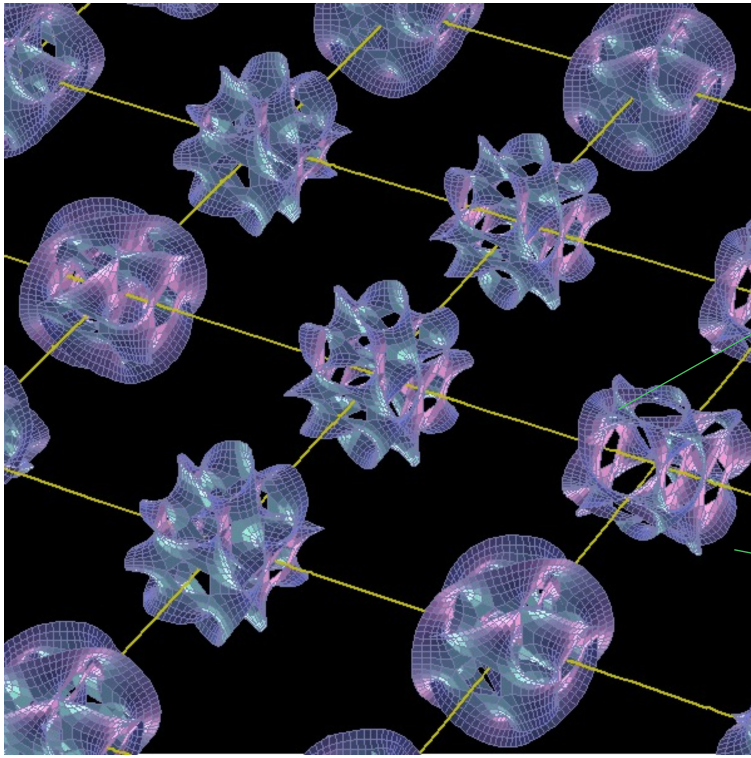

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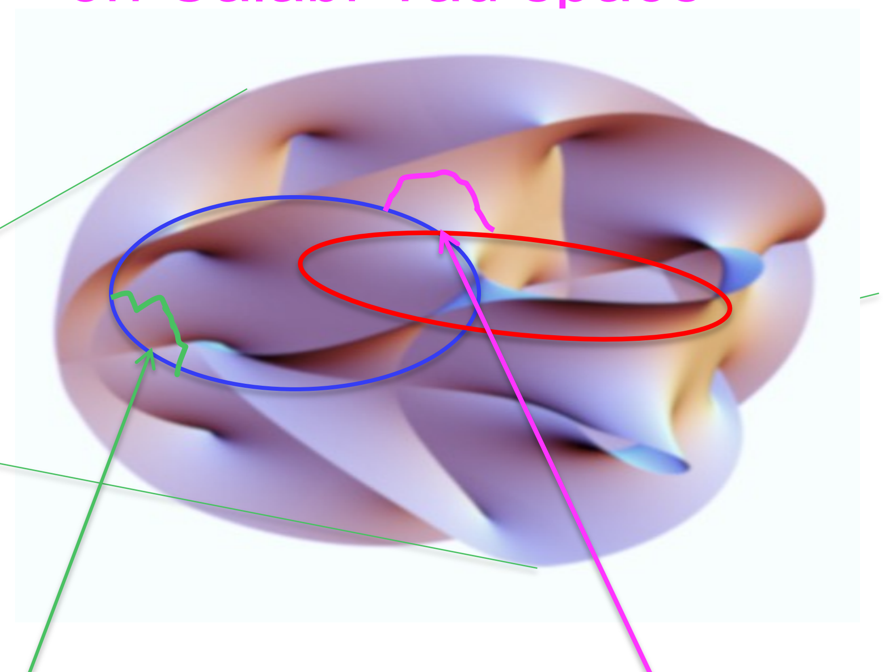

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→ Intersecting D-brane solutions of particle physics where gauge symmetry, matter & number of matter families geometric!

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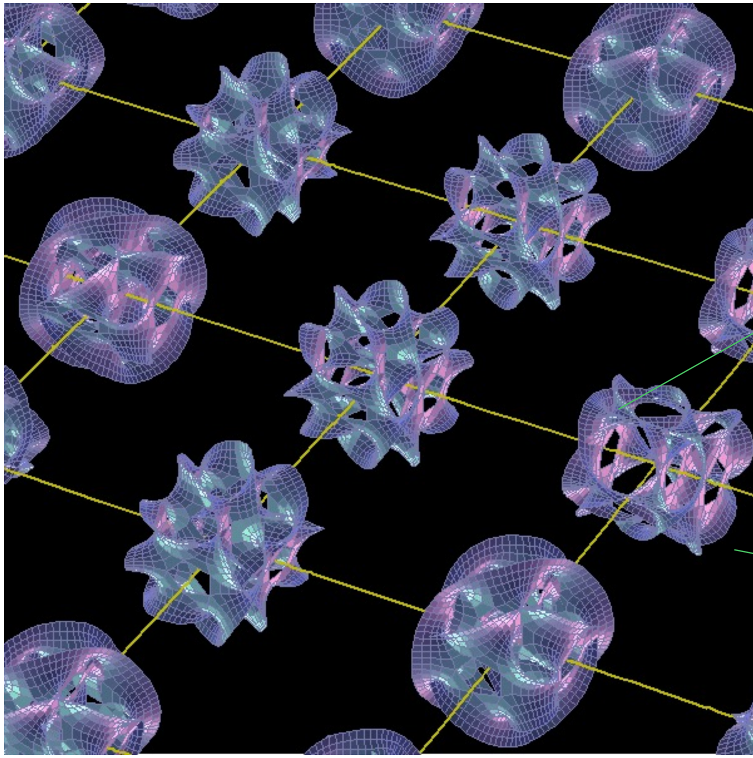

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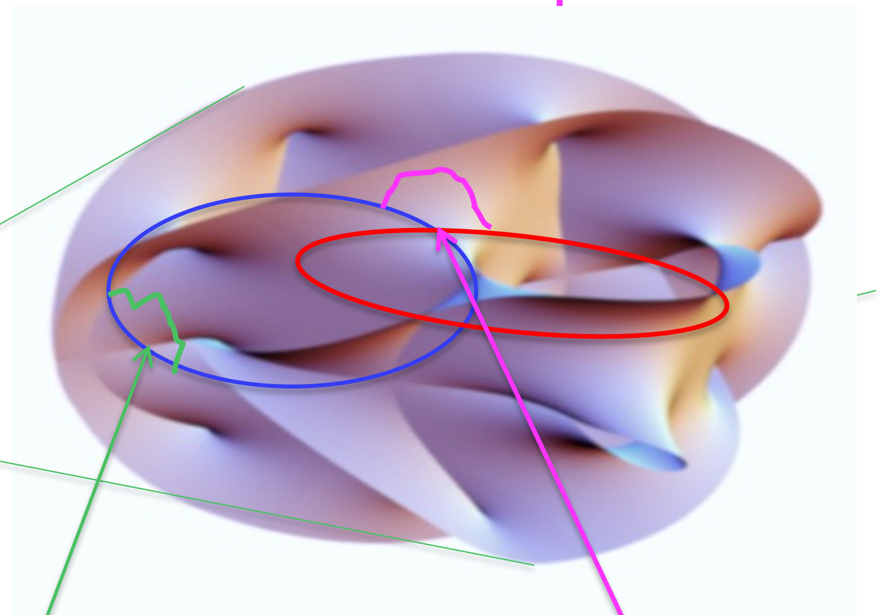

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→ First three-family Standard Model M.C., Uranga, Shiu '01…

no time for details

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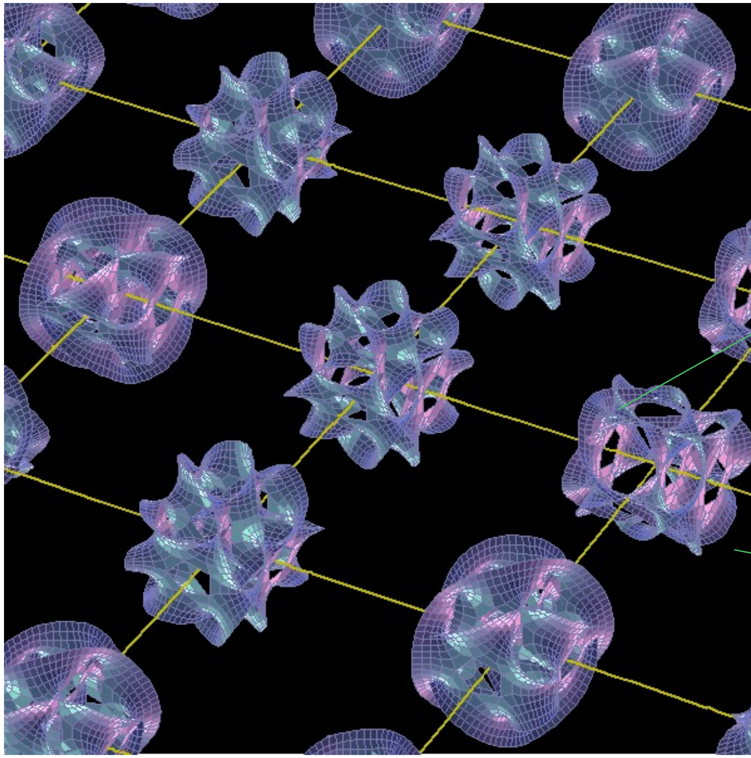

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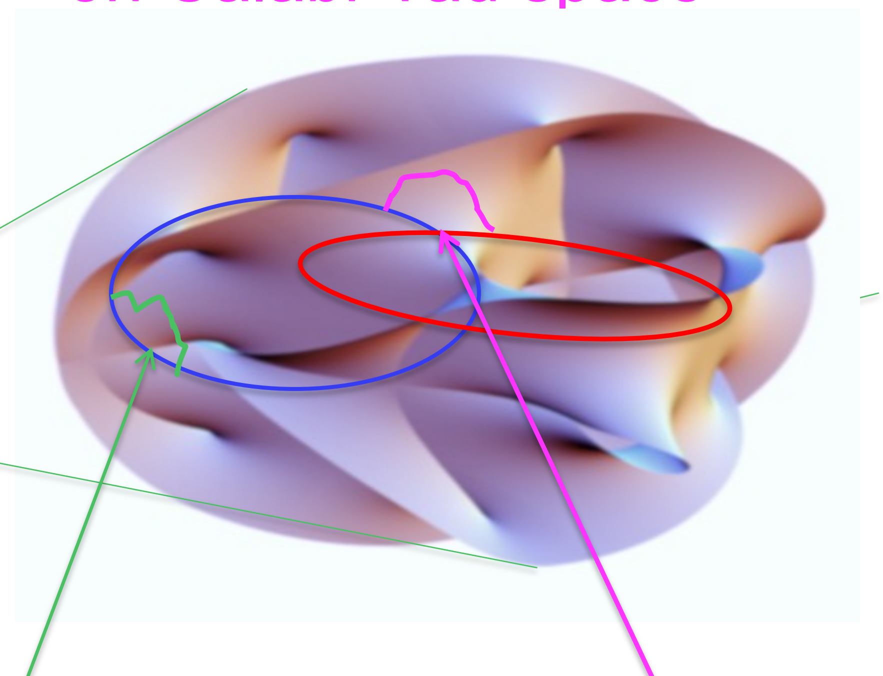

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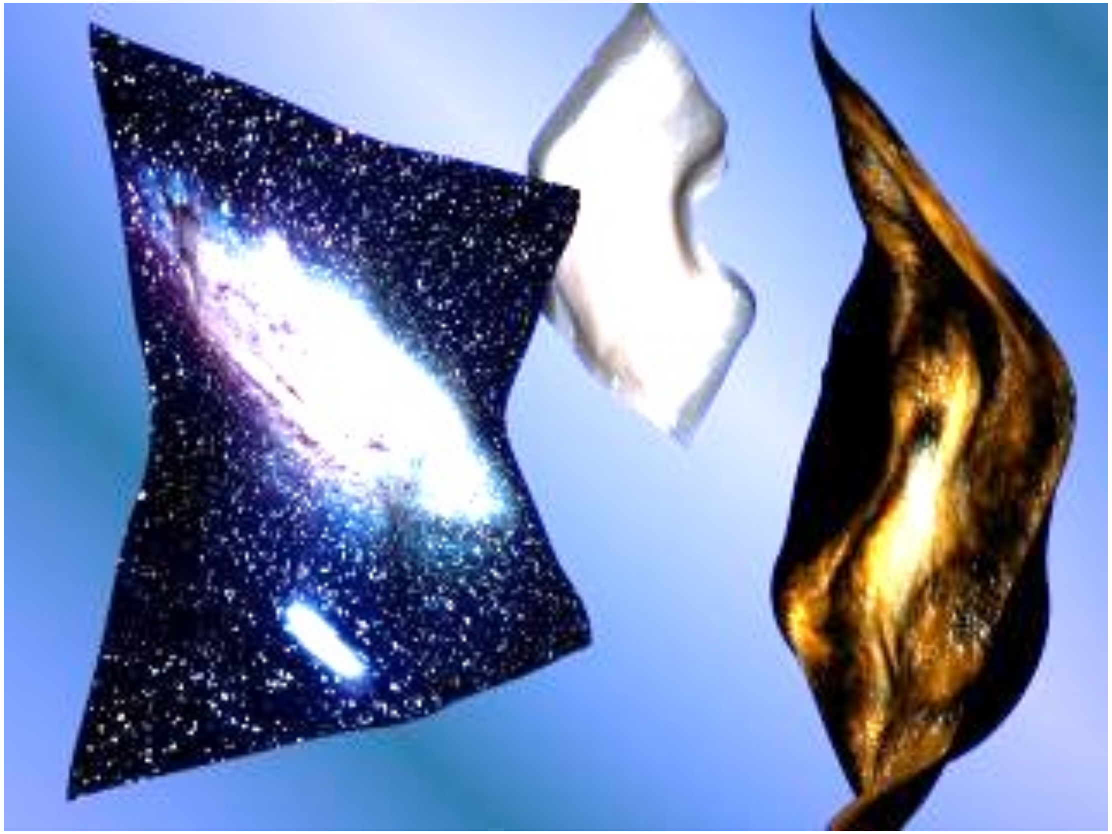
Landscape analysis limited: primarily on orbifolds (due limitations of conformal field theory techniques) no time for details

D-branes also have dual interpretation:

extended massive sources, curve space-time

(“back-reacted” gravitational objects at finite-large g_s)



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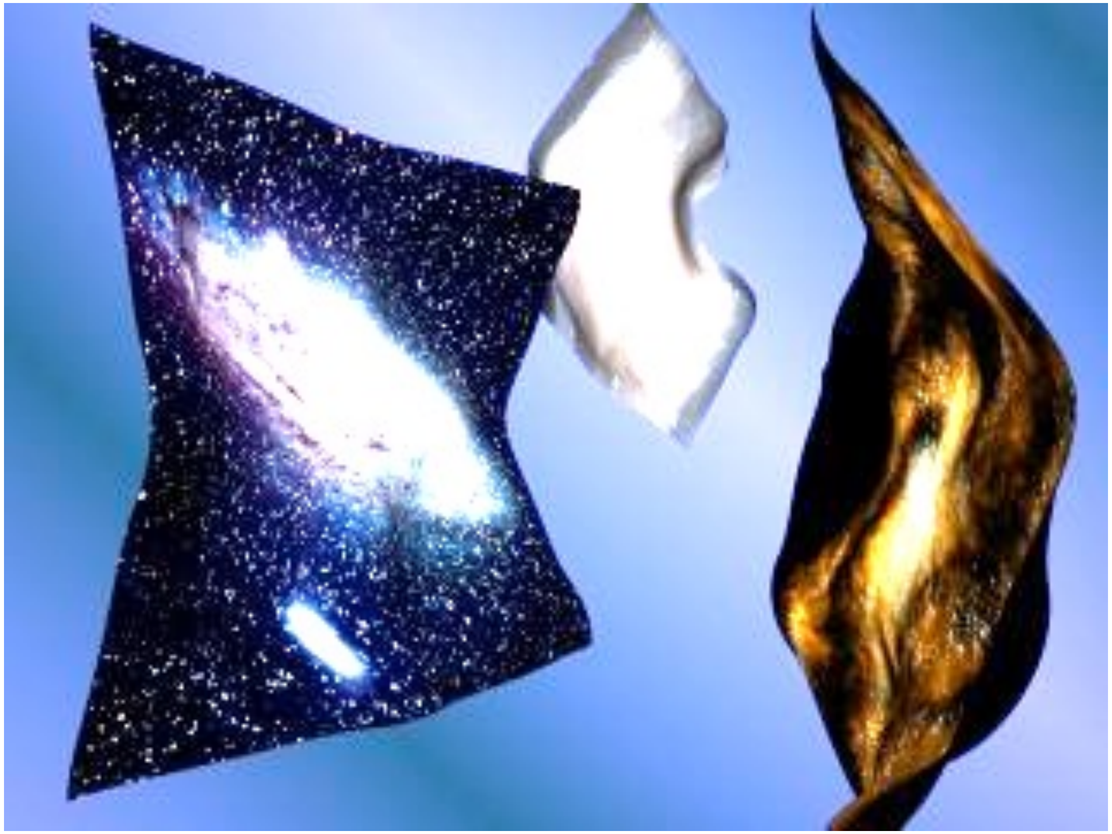

String Theory in geometric & non-perturbative regime!

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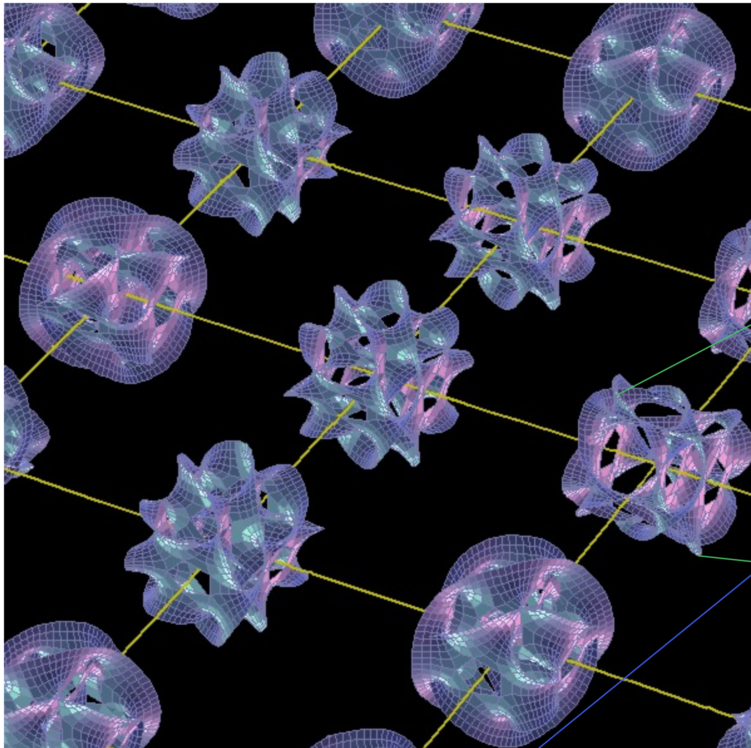
Implications for particle physics

D-branes as gravitational objects



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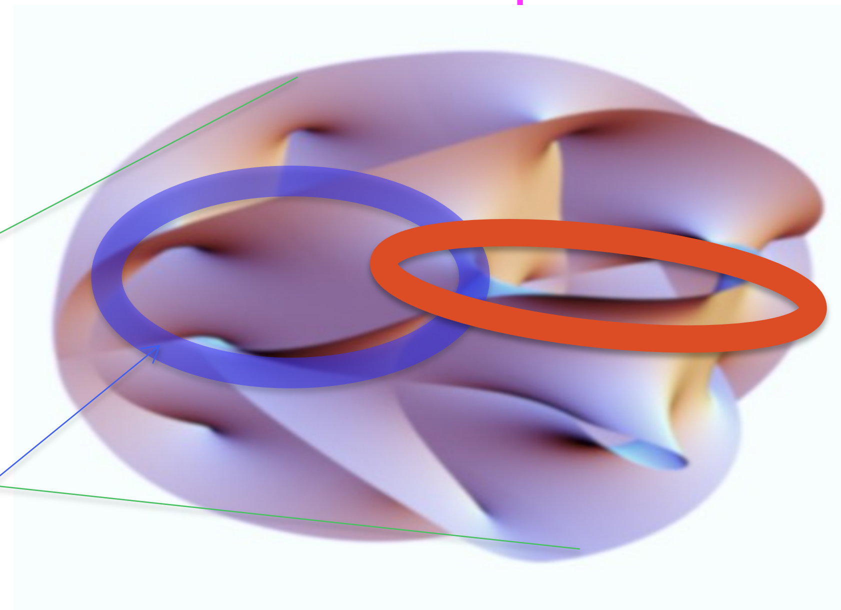


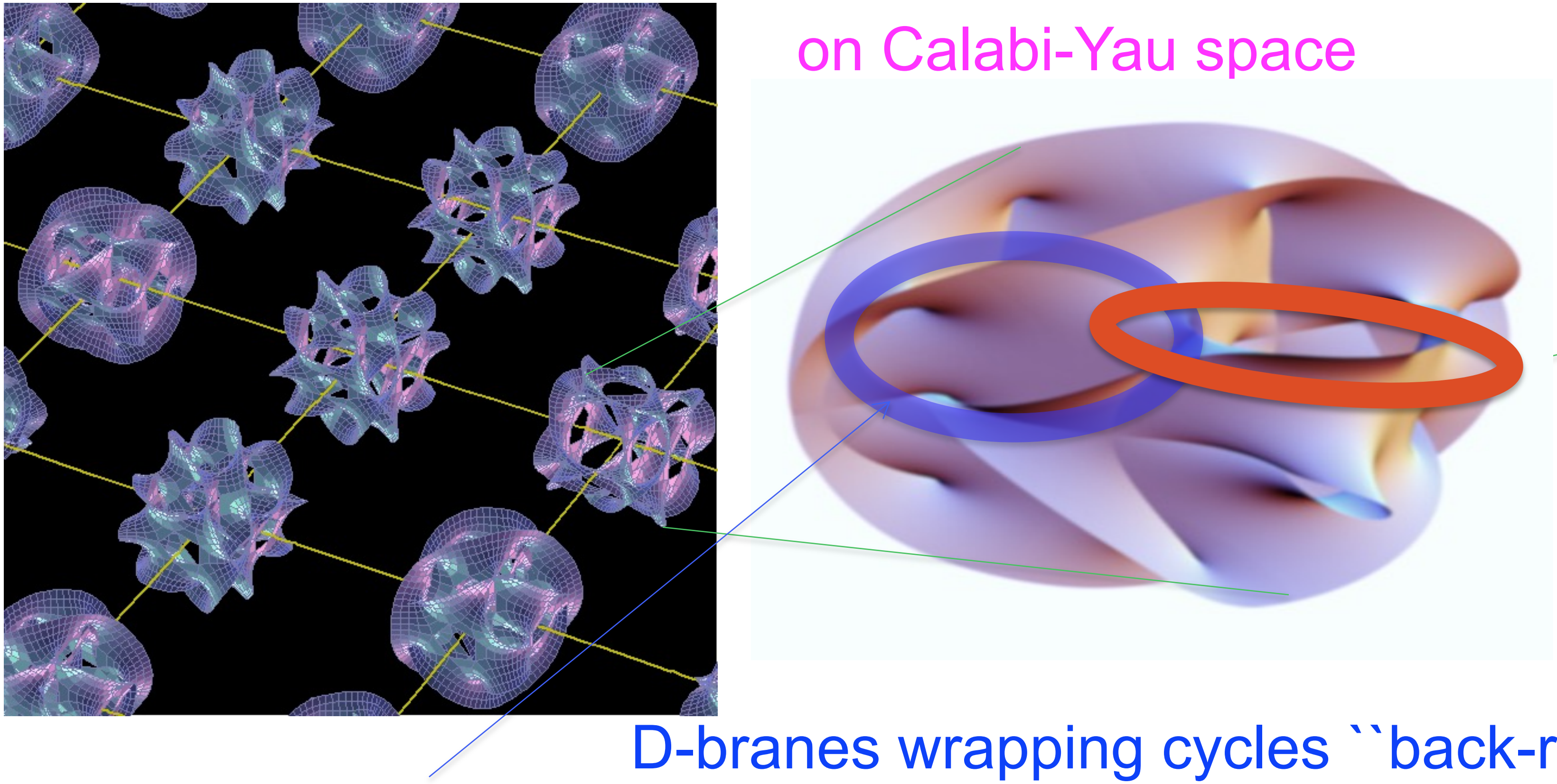
B

D-branes wrapping cycles ``back-react”→

cause highly curved - singular space along cycles ($g_s \rightarrow \infty$)

B – new space with back-reacted D-branes

D-branes as gravitational objects



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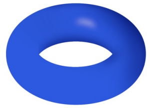
F-theory

Vafa'96; Morrison, Vafa'96,...review Weigand'18

Key features of F-theory

- F-theory, a powerful framework that geometrizes string coupling $\tau \equiv C_0 + i g_s^{-1}$ as a modular parameter of a torus - ``doughnut''



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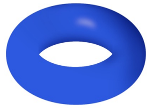
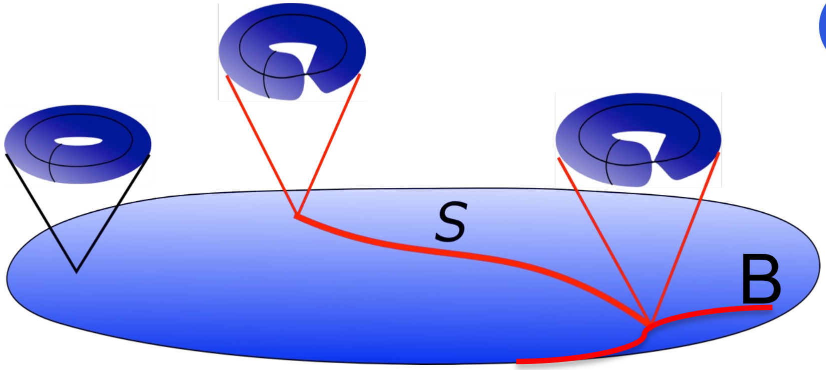


- Compactification on torus-fibered over base B → singular Calabi-Yau space



Vafa'96; Morrison,Vafa'96,...review Weigand'18

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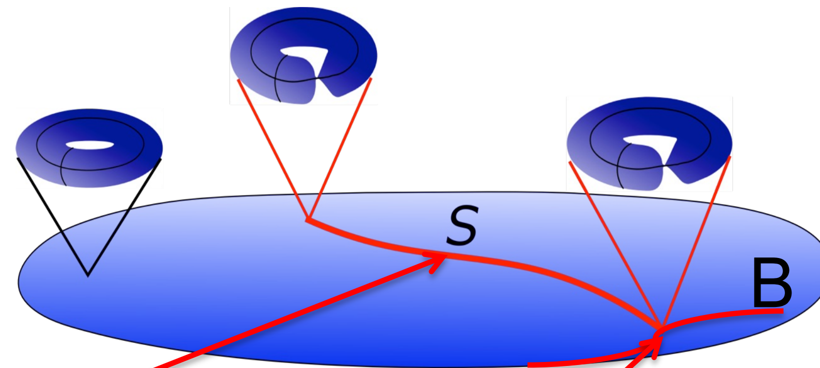

- Gauge bosons - encoded by the type of of torus singularity over back-reacted D-brane cycles *S*
- Matter - encoded by the type of torus singularity over the intersection of two back-reacted D-brane cycles

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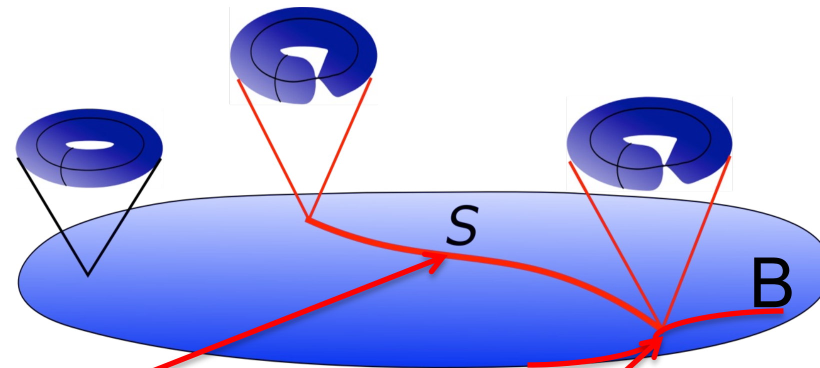

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Development of geometric techniques

Donagi,Wijnholt'08; Beasley,Heckman,Vafa'08...

Initial focus: F-theory with SU(5) grand unification

Donagi,Wijnholt'08; Beasley,Heckman,Vafa'08…

Early Model Constructions:

Local Donagi,Wijnholt'09-10…Marsano,Schäfer-Nameki,Saulina'09-11…

Review: Heckman'10

Global

Blumehagen,Grimm,Jurke,Weigand'09; M.C., Garcia-Etxebarria,Halverson'10…
Marsano,Schäfer-Nameki'11-'12…Clemens,Marsano,Pantev,Raby,Tseng '12…
Also SO(10) …Buchmüller, Dierigl,Oehlmann, Rühle'17

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Towards Standard Models

...Lin, Weigand '15...

F-theory compactification on elliptically fibered Calabi-Yau fourfolds led, for specific elliptic fibration (F_{11}polytope) to D=4 N=1 effective theory with

M.C., Klevers, Peña, Oehlmann, Reuter '15

Standard Model gauge group SU(3) x SU(2) x U(1)

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Standard Model gauge group

with gauge group topology

(also geometric!)

$$\frac{SU(3) \times SU(2) \times U(1)}{\mathbb{Z}_6}$$

M.C., Lin '17

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with gauge group topology
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M.C., Lin '17

geometry techniques
(toric bases B)

M.C., Halverson, Lin, Liu, Tian '19, PRL

Quadrillion Standard Models
with 3-chiral families, and gauge coupling unification

[gauge cycles in *anti-canonical divisor $\bar{K}$ class*]

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Quadrillion Standard Models
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[gauge cycles in *anti-canonical divisor $\bar{K}$ class*]

- Further systematic analysis of the F-theory Standard Model landscape… Raghuram, Taylor, Turner, et al. '19 -'22

Current efforts

- Exact matter spectra

  including vector pairs & # of Higgs pairs

  Technically difficult: for SMs - Limit root bundles ($K^{\{\text{frac no}\}}|_{\text{curve}}$)

  Bies, M.C., Donagi,(Liu), Ong '21,'22

- Yukawa couplings

  First calculation for a global (toy) SU(5) x U(1) model:

  explicit complex structure moduli dependence

  w/ rank >1 & allowing large hierarchies

  M.C., Lin, Liu, Zoccarato, Zhang '19

  SM Yukawa couplings technically difficult:

  multiple triple intesections, rank > 2 matter curves w/ large genera

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Those are important future directions!

Moduli stabilization

Interconnected with supersymmetry breaking; axions;

dark matter candidates; cosmological constant problem;

cosmological implications… c.f., D. Green's talk

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Broad,active field: reliable results for moduli stabilization via effective field theory techniques w/ g_s perturbative (à la KKLT or Large Volume Scenario)

c.f., Snowmass White Paper: Cosmology at the Theory Frontier

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Moduli stabilization for F-theory SMs

M.C., Long, Halverson, Lin '20

Study in the parametrically reliable/perturbative regime:

Moduli stabilization

Interconnected with supersymmetry breaking; axions; dark matter candidates; cosmological constant problem; cosmological implications… c.f., D. Green's talk

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Moduli stabilization for F-theory SMs

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Study in the parametrically reliable/perturbative regime:

i) gauge coupling constraint: $\alpha_{1,2,3} = \alpha_{GUT} = (g_s \ell_s^4)/\mathrm{Vol}(\bar{\mathrm{K}}) \sim 1/25$

→ $\mathrm{Vol}(\overline{\mathcal{K}}) \lesssim \mathcal{O}(100)$,

ii) all divisor and curves w/ volumes $\mathrm{vol}(C_a) \geq 1$ (in string units).

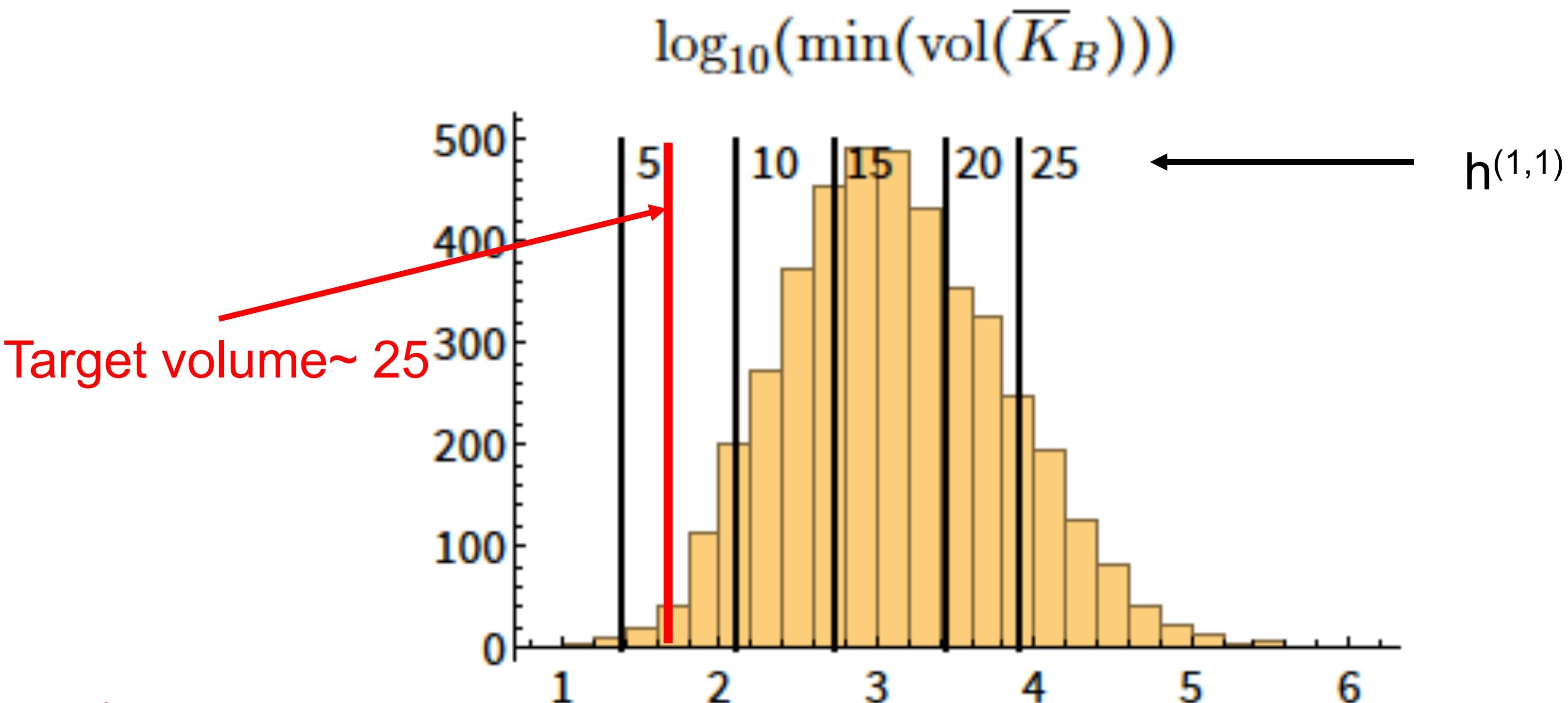
to suppress world-sheet & ED3 instanton contributions, c.f., $e^{-2\pi n \mathrm{vol}(c)} \ll 1$.

→ Stretched Kähler cone

- where all divisors & curves w/volumes >1
- Since $\overline{\mathcal{K}} = -\sum D_i$ → Vol($\overline{\mathcal{K}}$) expected to be typically large

Distribution of *Min*(Vol($\overline{\mathcal{K}}$))

[one triangulation per each of 4319 polytopes]



$h^{(1,1)}$<7 →~10^5 out of quadrillion models satisfy constraints

Recent related developments

Digression

- String Theory includes quantum gravity and particle physics with constraints due to geometry of compactified space

- Particle physics with consistent quantum gravity should be subject to additional constraints → Swampland Program

Vafa '06...

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↓

- Finding physical conditions (including higher-form symmetries) in consistent quantum gravity

History: ...Kumar, Taylor '09; Adams, DeWolfe, Taylor '10;...
García-Etxebarria, Hayashi, Ohmori, Tachikawa, Yonekura '17;
Kim, Tarazi, Vafa '19; M.C., Dierigl, Lin, Zhang '20;
Montero,Vafa '20; Hamada, Vafa '21; Tarazi, Vafa '21;...

- In 8D one-form symmetry fixes topology of gauge groups.
Byproduct → all 8D string vacua M.C., Dierigl, Lin, Zhang '22-'22.

→ A long way to 4D...

Connections to other areas

- Mathematics, due to use of geometry in string compactifications:
  - elliptically fibered Calabi-Yau compactif.
  - G_2 holonomy spaces (twisted connected sums)
- Machine Learning, w/ recent focus: numerical Calabi-Yau metrics & applications

Concluding remarks

- Highlighted modern developments in String Theory & insights they shed into geometric origin of particle physics in top-down constructions

- Focus on F-theory: geometric, nonperturbative regime of String Theory provides by far broadest class of supersymmetric solutions, including 3-family Standard Models

Concluding remarks

- Highlighted modern developments in String Theory & insights they shed into geometric origin of particle physics in top-down constructions

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Important insights into the structure of the whole string landscape

- Axions and strongly coupled hidden sectors ubiquitous → natural dark matter candidates & avenues for cosmological constraints
- Outstanding:
  - high scale SUSY breaking & non-supersymmetric solutions
  - small positive cosmological constant

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String Theory has great potential for new insights into electroweak hierarchy & naturalness problems

Final Message

Connections between UV-complete quantum gravity theories - String Theory - & the observed Standard Model of particle physics, promise to be exciting dynamic areas of research, bringing together the research efforts of formal theorists with those of particle physicists working closer to experiment.

Thank you!