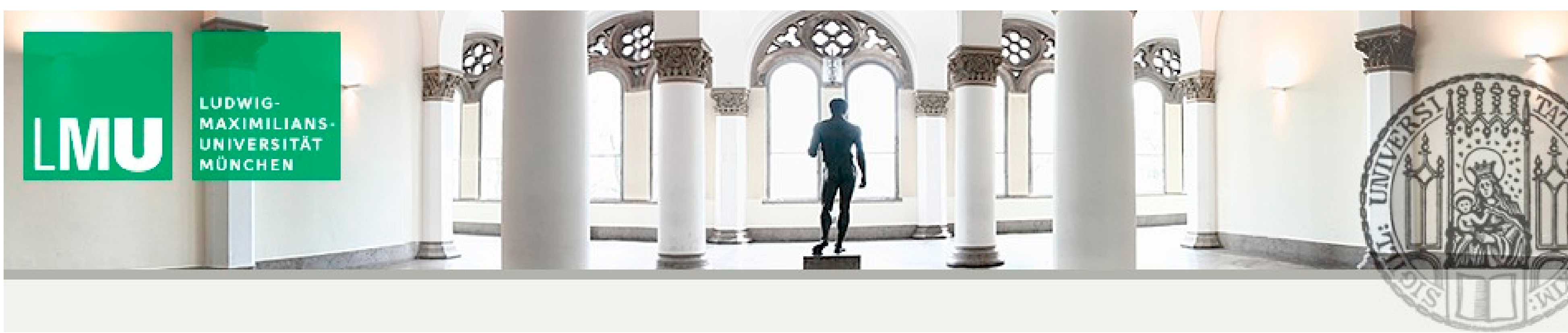
Seeing through the String Landscape (a string hunter's companion)

Dieter Lüst, LMU (Arnold Sommerfeld Center) and MPI München



RTN meeting Varna, 2008

Introduction:

Count the number of consistent string vacua ➤

Vast landscape with $N_{sol} = 10^{500-1500}$ vacua!

(Kawai, Lewellen, Tye (1986); Lerche, Lüst, Schellekens (1986); Antoniadis, Bachas, Kounnas (1986); Douglas (2003))

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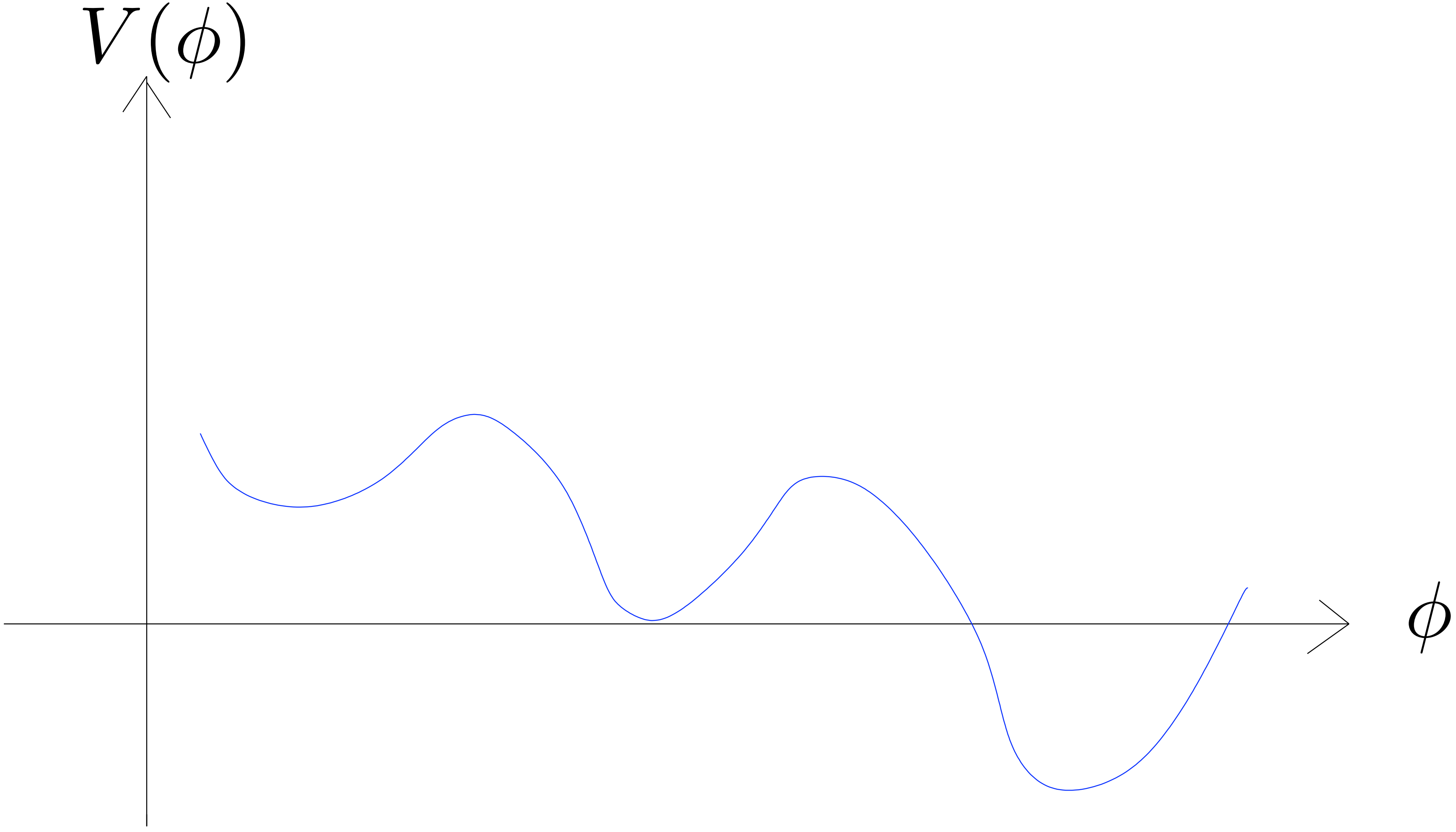
- Explore all mathematically consistent possibilities: top down approach (quite hard), string statistics.

- Do not look randomly - look for green (promising) spots in the landscape ➠ model building, bottom up approach.

Effective field theory description:

Non-flat moduli potential after turning on fluxes and non-perturbative effects:



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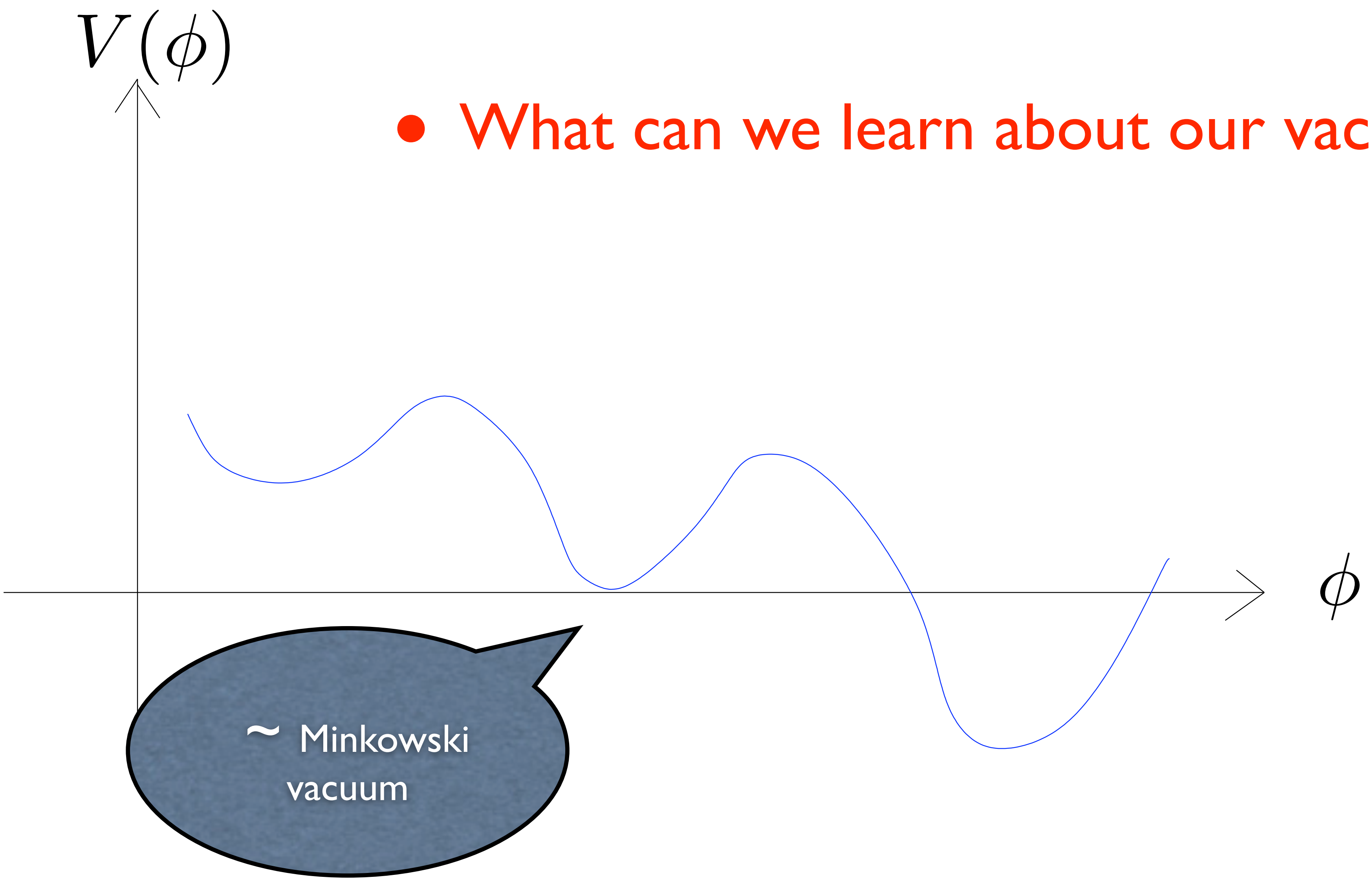

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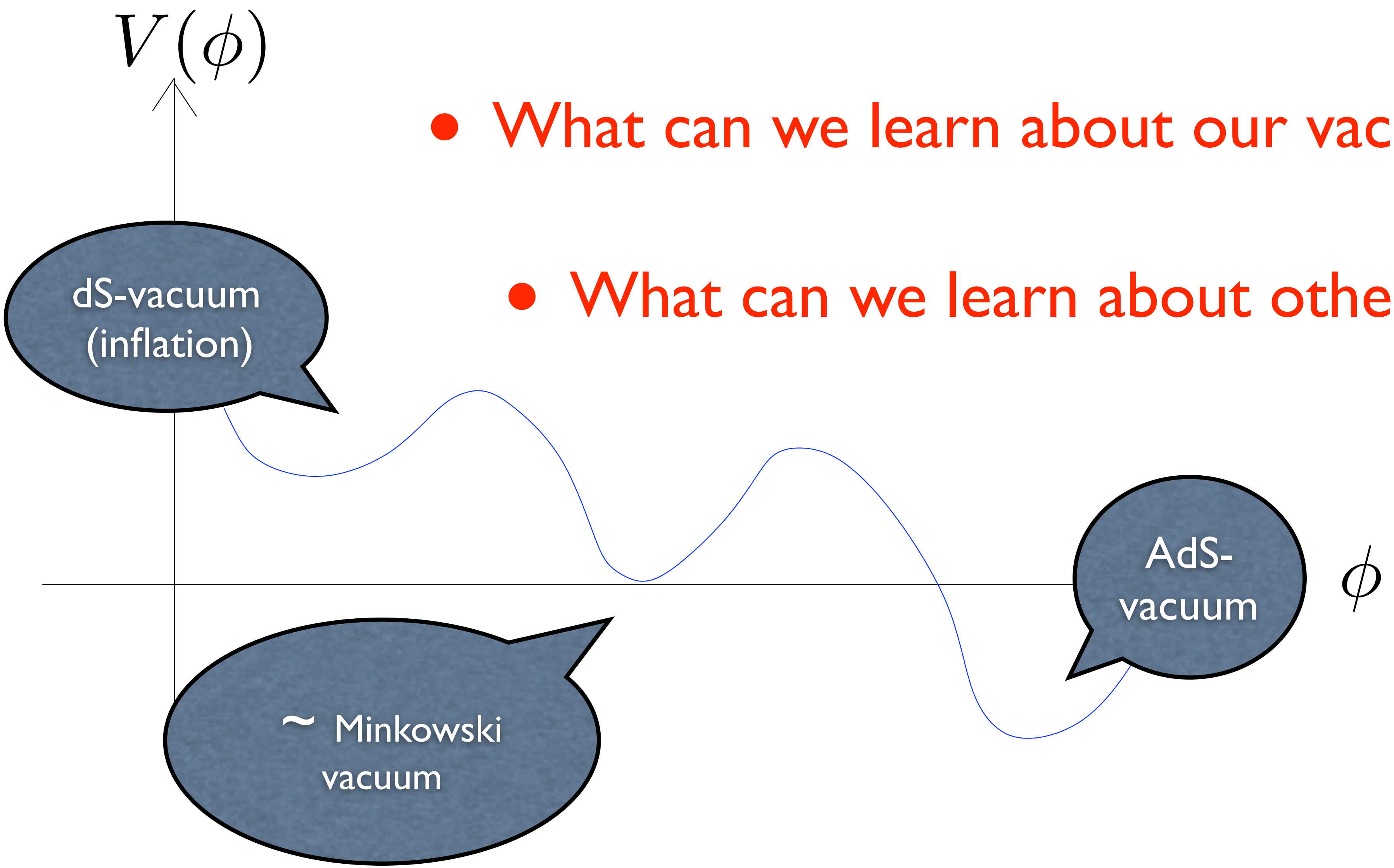

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Transition amplitudes between different vacua (wave function of the universe):

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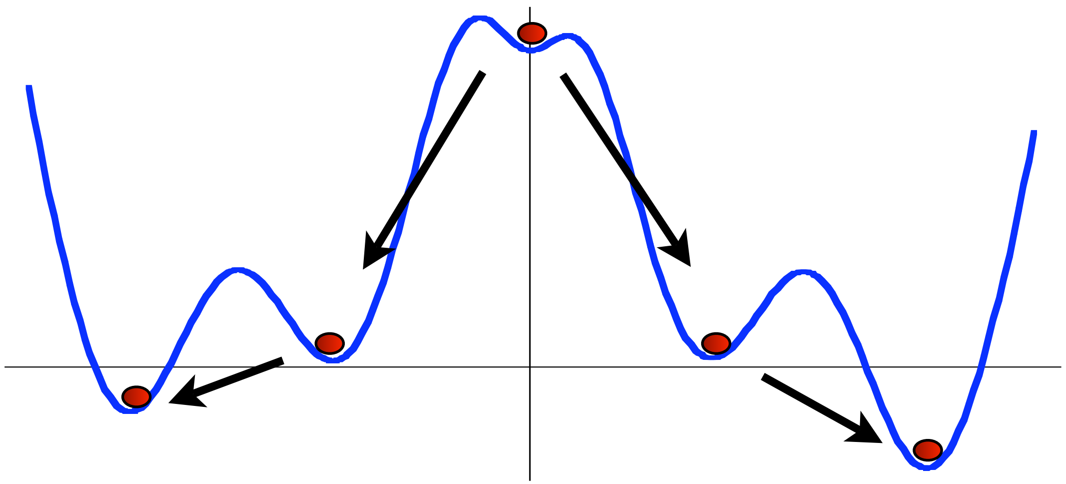

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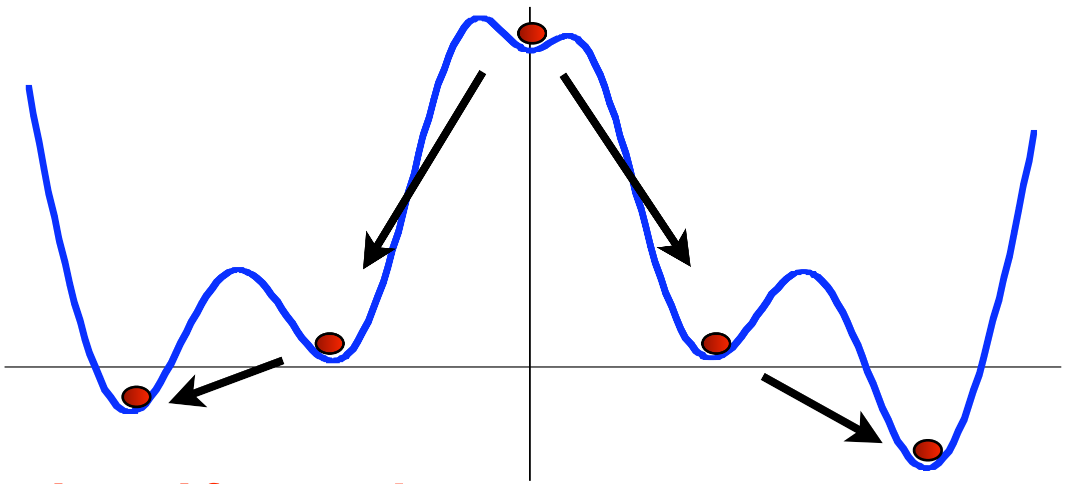
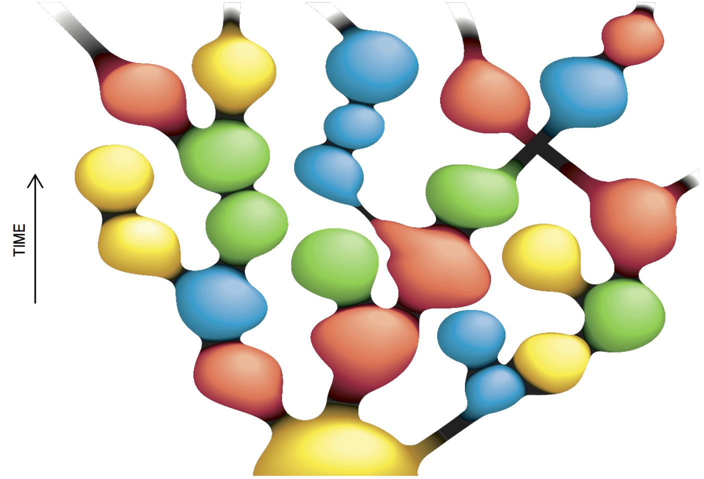


⇨ Eternal, self-producing universe:



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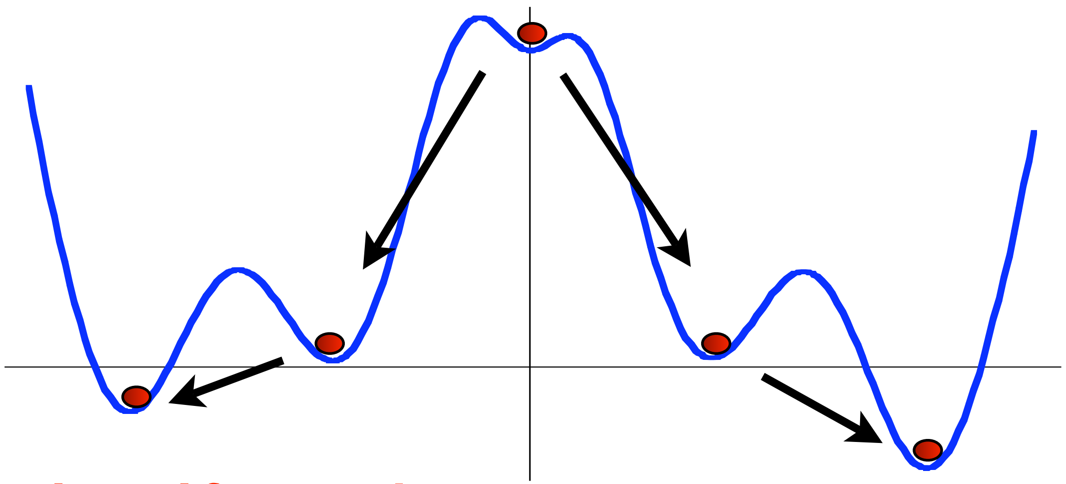

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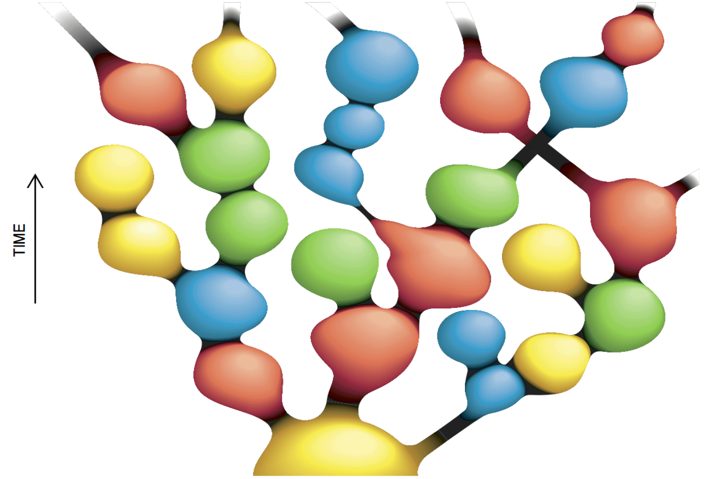

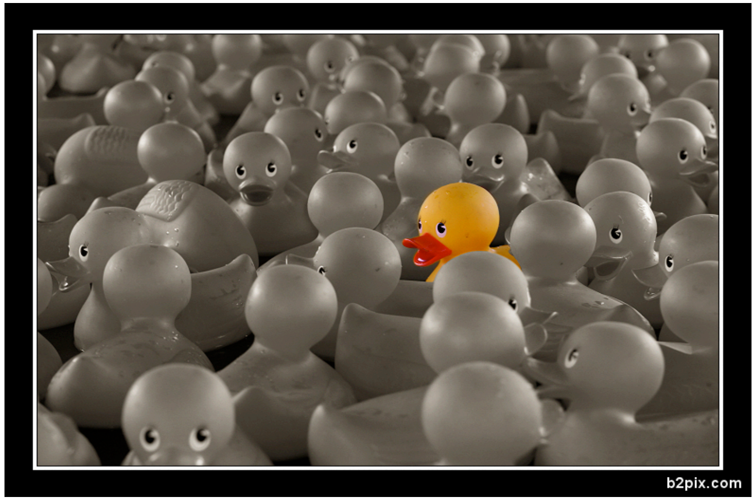

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Geometrization of particles and their interactions!

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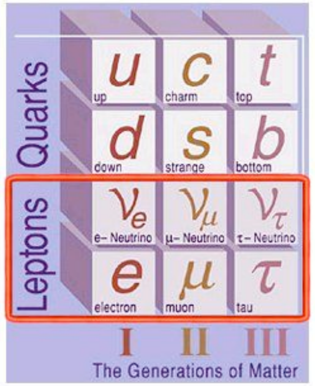
Dictionary:

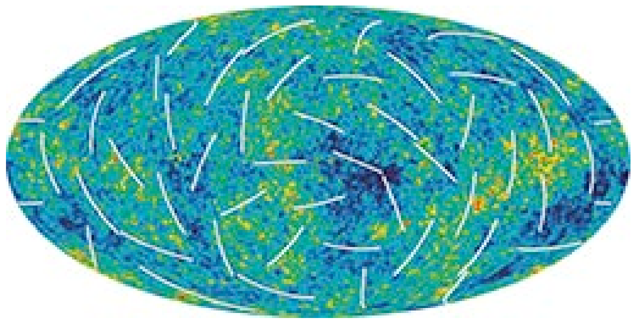
Particles physics

Cosmology



Gauge interactions:

$$G = SU(3) \times SU(2) \times U(1)$$



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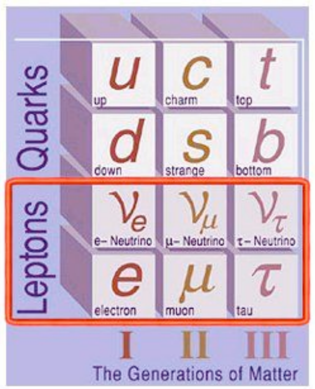

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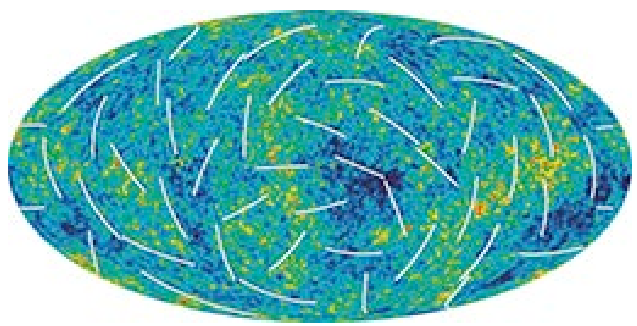
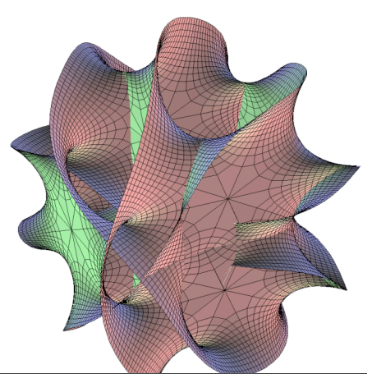


geometry & topology of strings and branes



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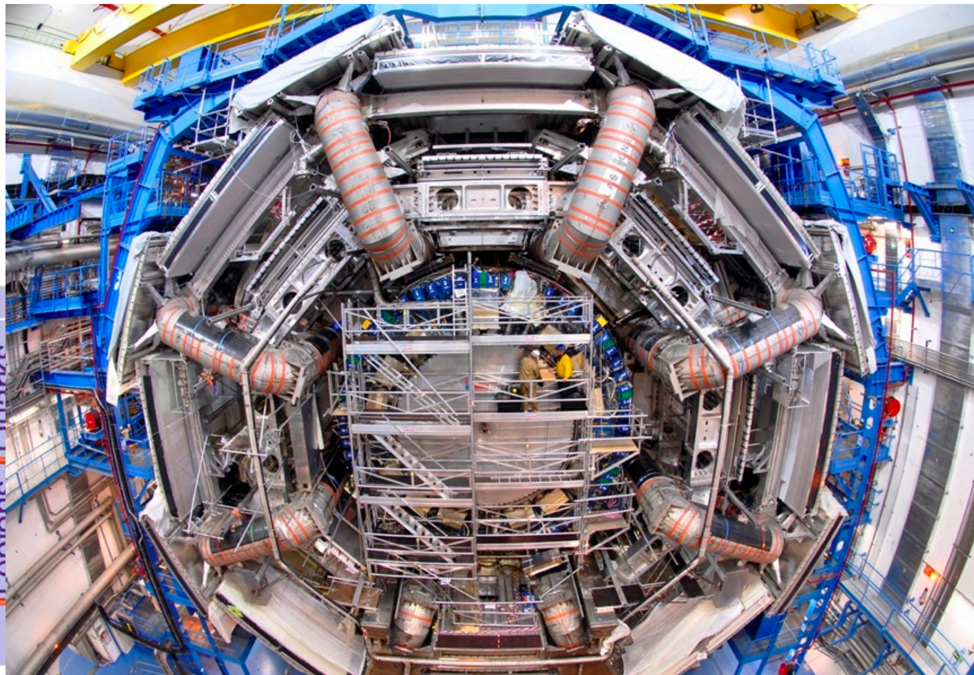

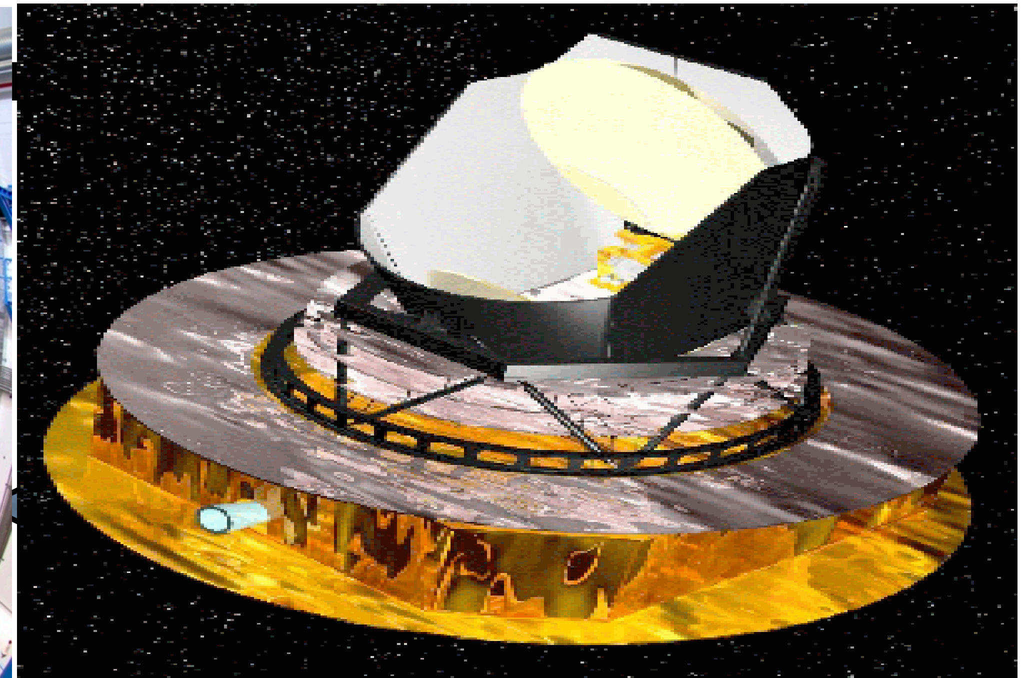

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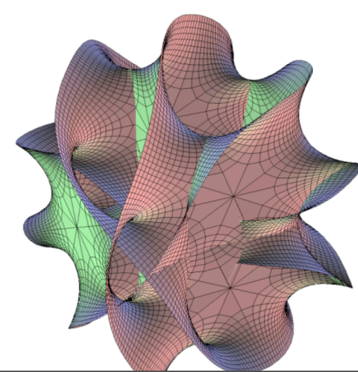

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Bottum-up approach has to meet top-down approach!

Outline

- Stringy signatures at LHC

  Intersecting brane models

(The LHC string hunter's companion)

(D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333)
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Alternative constructions: heterotic strings

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- Non-Abelian gauge bosons live as open strings on lower dimensional world volumes π of D-branes.
- Chiral fermions are open strings on the intersection locus of two D-branes: $N_F = I_{ab} \equiv \#(\pi_a \cap \pi_b) \equiv \pi_a \circ \pi_b$

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D6 wrapped on 3-cycles π_a , intersect at angles θ_{ab}

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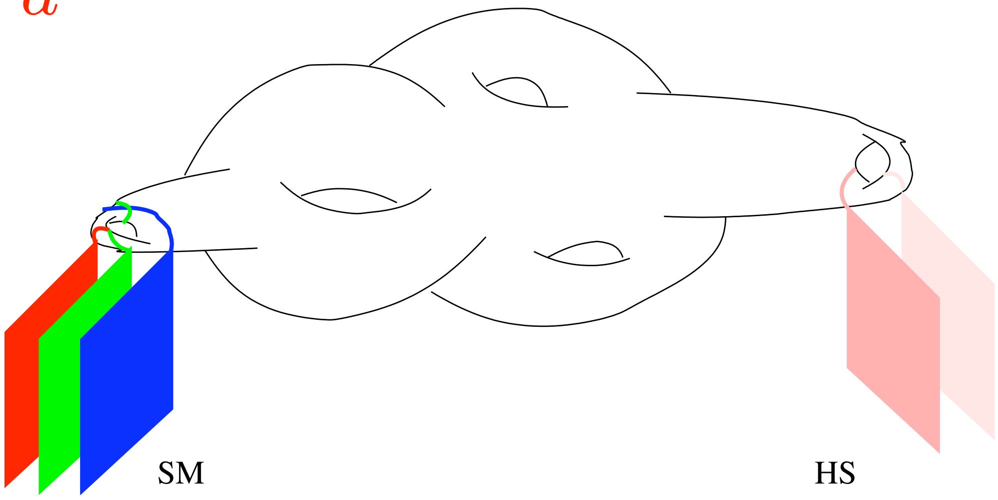

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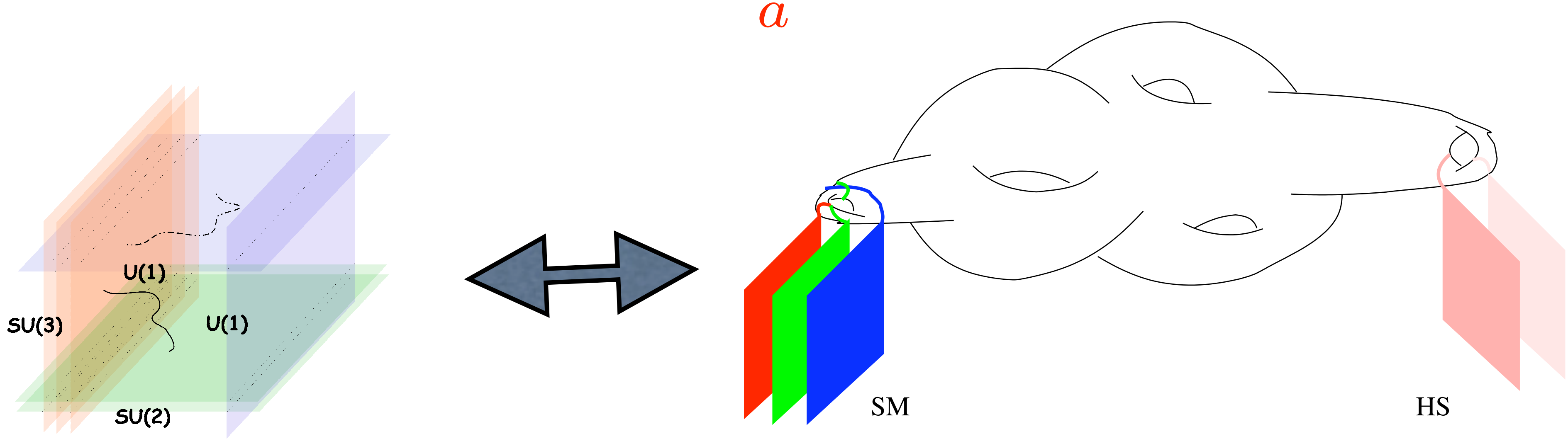

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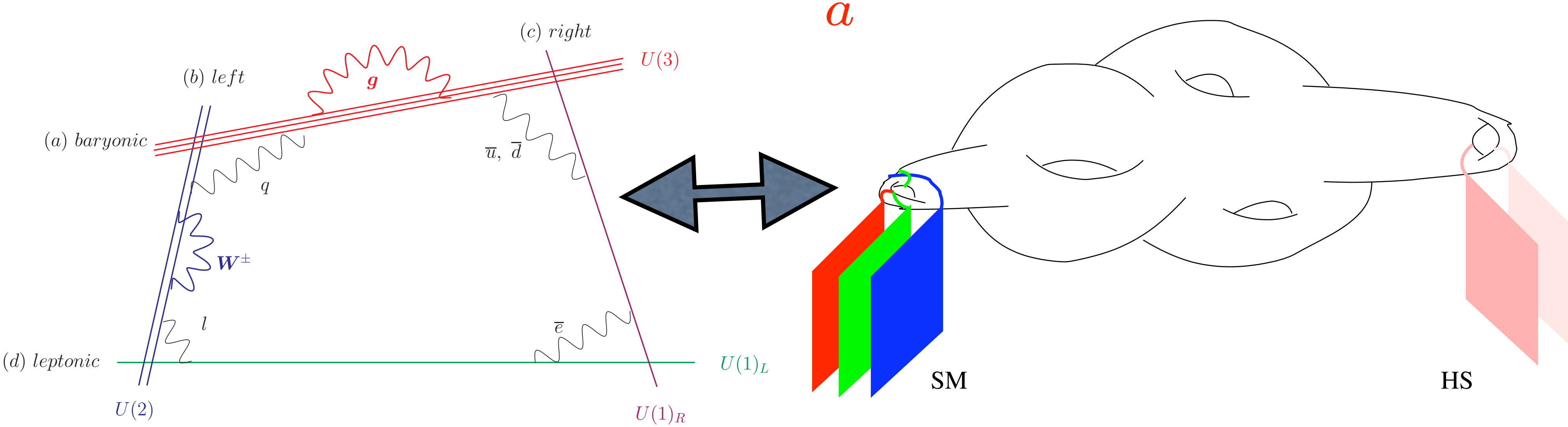

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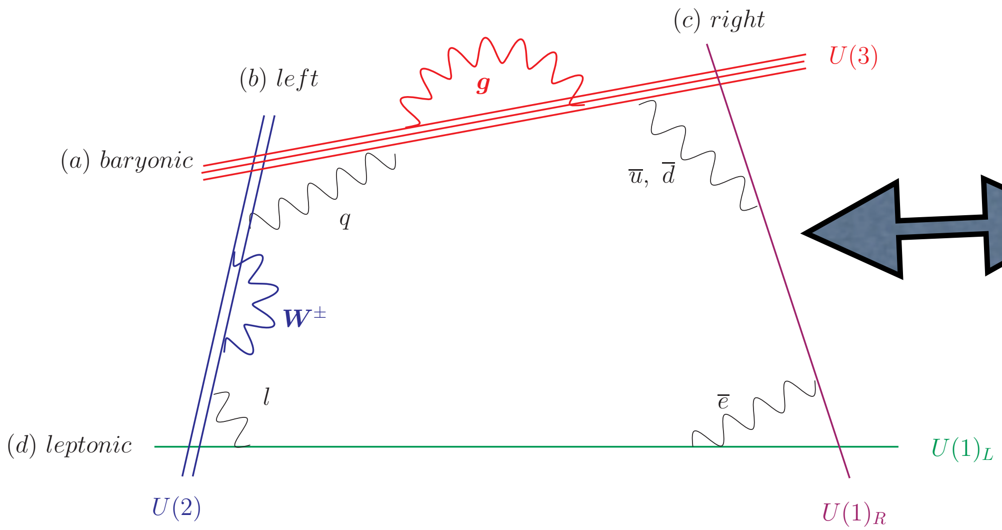

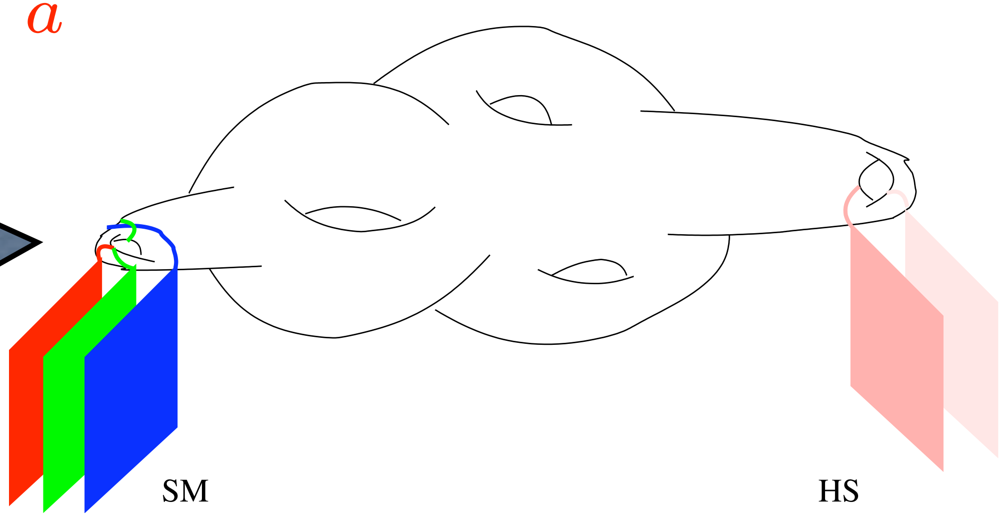

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Explicit orbifold constructions and their statistics $\Rightarrow$

(Blumenhagen, Gmeiner, Honecker, Lüst, Stein, Weigand (2004,2005); related work: Anastasopoulos, Dijkstra, Huiszoon, Kiritsis, Schellekens (2005,2006)) (Gmeiner, Honecker, arXiv:0806.3039)

Millions of standard models without chiral exotics!

LHC String Hunter's Companion -

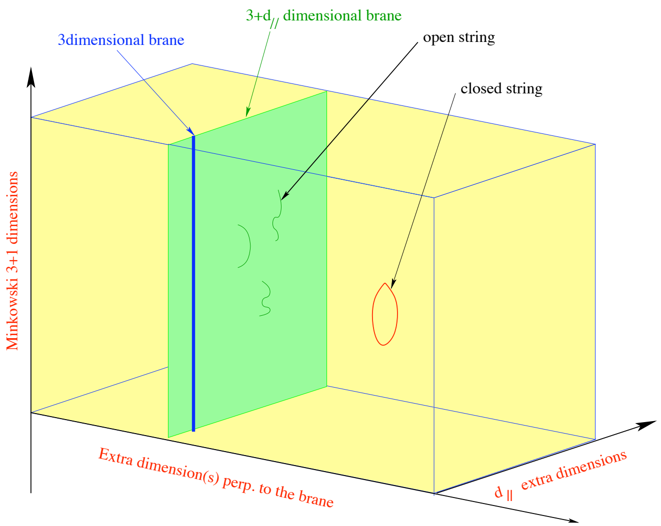
Test of D-brane models at the LHC:

New stringy physics of beyond the SM:

New massive particles:

- Z'
- Massive black holes
- Regge excitations of higher spin
- Kaluza Klein (KK) and winding modes

Low string scale and large extra dimensions (ADD):

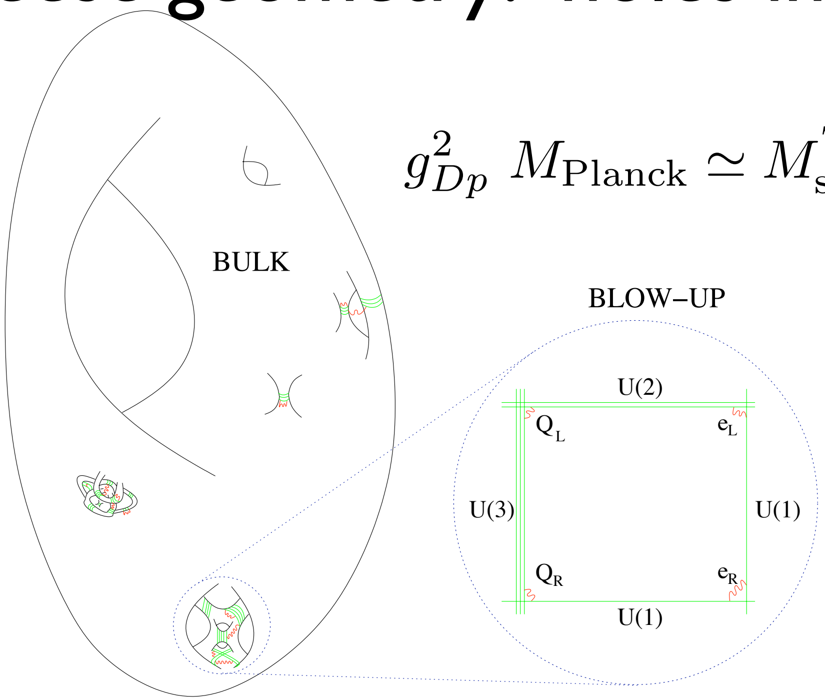


$$M^2_{\rm Planck} \simeq M^8_{\rm string}\, V_6$$

$$V_6 M^6_{\rm string} = \mathcal{O}(10^{32}) \;\Rightarrow\; M_{\rm string} = \mathcal{O}(1\ {\rm TeV})$$

Swiss cheese geometry: holes in a Calabi-Yau space:

$$g^2_{Dp}\, M_{\rm Planck} \simeq M^{7-p}_{\rm string} \left(\prod_{j=1}^{d_\perp} R^\perp_j\right)^{1/2} \left(\prod_{i=1}^{d_\parallel} R^\parallel_i\right)^{-1/2} .$$



SM lives on small cycles of the CY!

(Balasubramanian, Berglund, Conlon, Quevedo, hep-th/0502058)

Parton model cross sections of SM-fields:

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Disk amplitude among 4 external SM fields $(q, l, g, \gamma, Z^0, W^{\pm})$:

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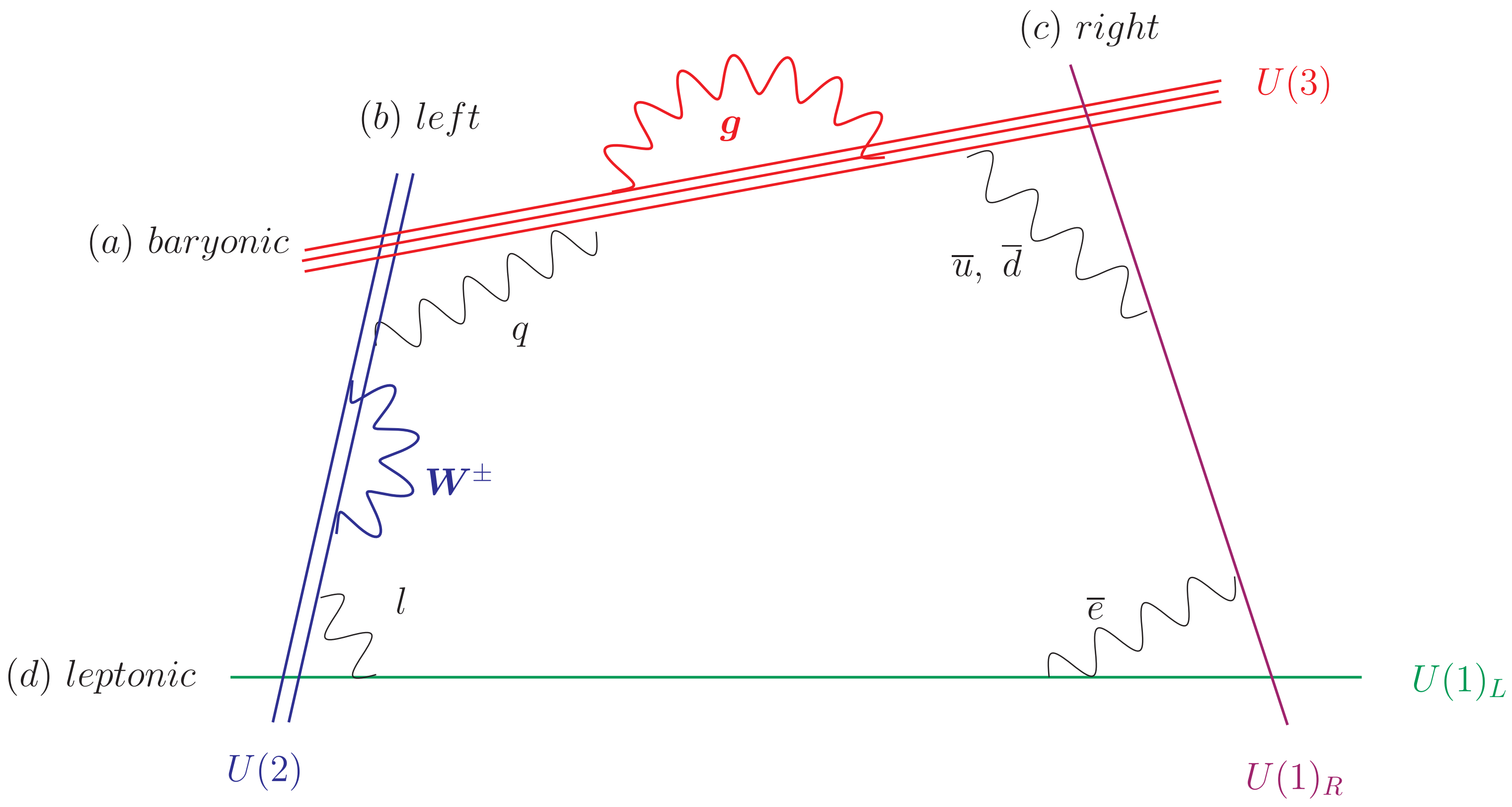

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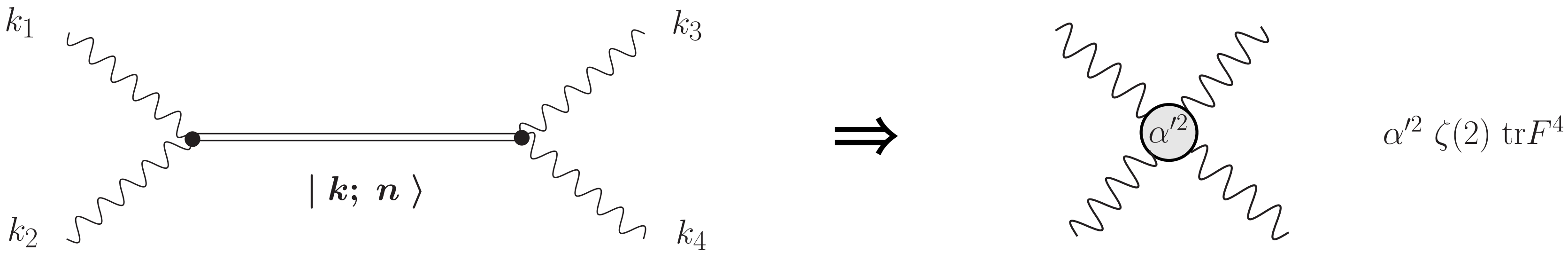
- Exchange of SM fields
- Exchange of string Regge resonances (Veneziano like ampl.)

$\Rightarrow$ new contact interactions:



$$\mathcal{A}(k_1, k_2, k_3, k_4; \alpha') \sim -\frac{\Gamma(-\alpha' s)\ \Gamma(1-\alpha' u)}{\Gamma(-\alpha' s - \alpha' u)} = \sum_{n=0}^{\infty} \frac{\gamma(n)}{s - M_n^2} \sim \frac{t}{s} - \frac{\pi^2}{6}\ tu\ (\alpha')^2 + \dots$$

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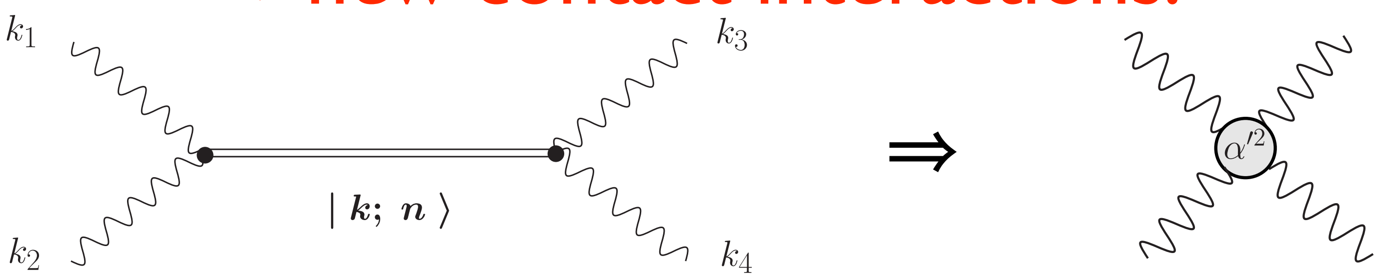

$\alpha'^2\ \zeta(2)\ \mathrm{tr} F^4$

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- Exchange of KK and winding modes (model dependent)

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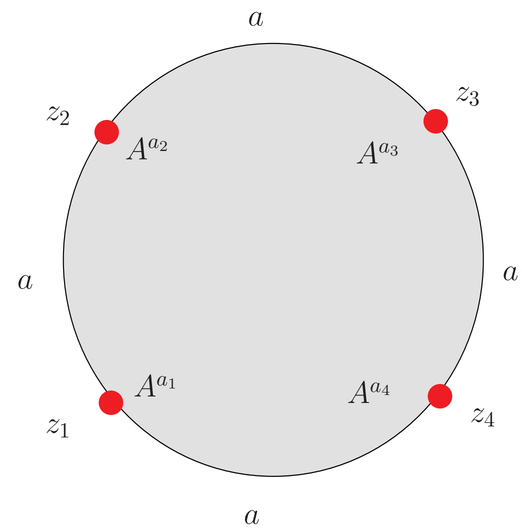

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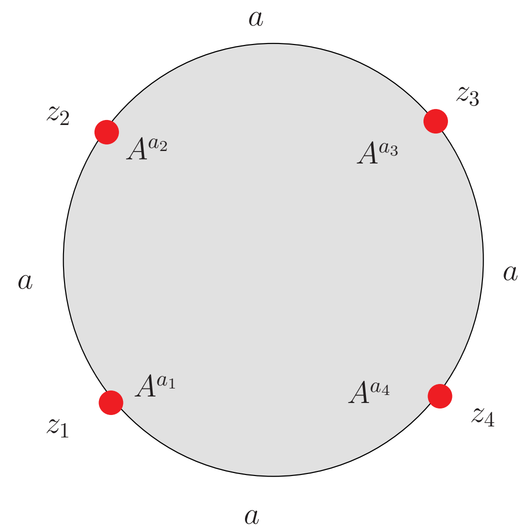

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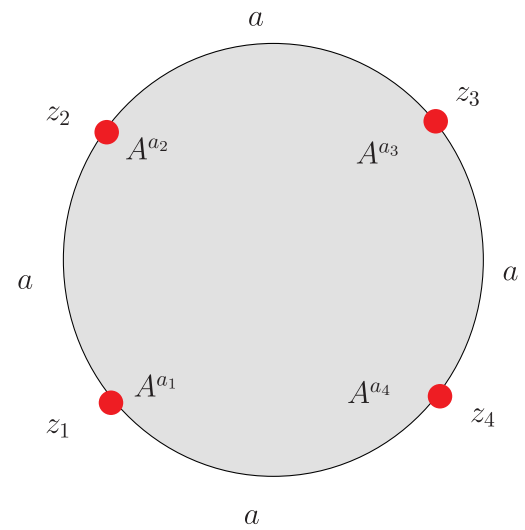

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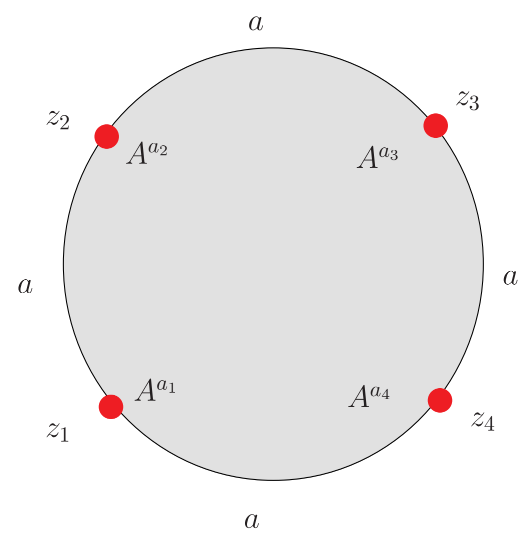

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$$|\mathcal{M}(gg \to gg)|^2 = g_3^4 \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \left[\frac{9}{4} s^2 V_s^2(\alpha') - \frac{1}{3} (\, s V_s(\alpha'))^2 + (s \leftrightarrow t) + (s \leftrightarrow u) \right]$$

(Stieberger, Taylor)

$\Rightarrow$ dijet events

$$|\mathcal{M}(gg \to g\gamma(Z^0))|^2 = g_3^4 \frac{5}{6} Q_A^2 \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) (\, s V_s(\alpha') + t V_t(\alpha') + u V_u(\alpha')\,)^2$$

(Anchordoqui, Goldberg, Nawata, Taylor, arXiv:0712.0386)

Observable at LHC for $M_{\text{string}} = 3 \text{ TeV}$

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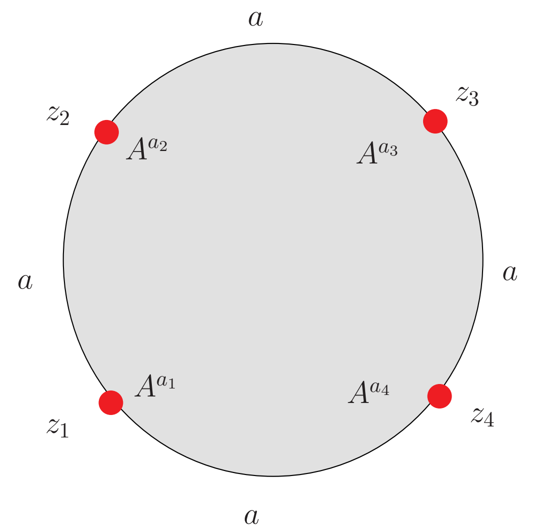

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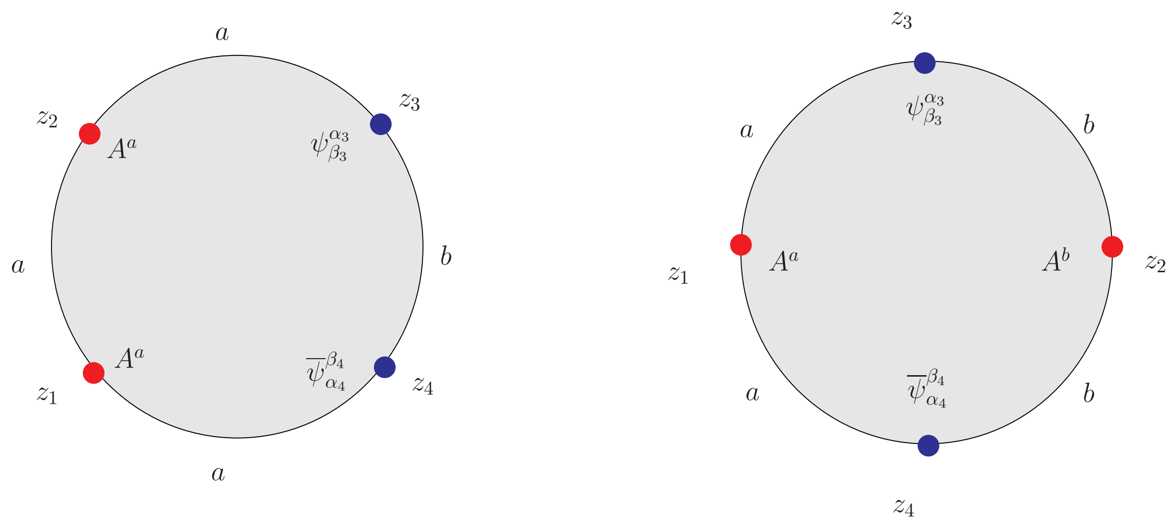
Examples:

$\alpha' \to 0$: agreement with SM!

$$|\mathcal{M}(gg \to gg)|^2_{\alpha' \to 0} \to \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2}\right)\frac{9}{4}(s^2 + t^2 + u^2)$$

$$|\mathcal{M}(gg \to \gamma(Z^0))|^2_{\alpha' \to 0} \to 0$$

2 gauge boson - two fermion amplitude:



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$$|\mathcal{M}(qg \to qg)|^2 = g_3^4 \frac{s^2+u^2}{t^2}\left[V_s(\alpha')V_u(\alpha') - \frac{4}{9}\frac{1}{su}(sV_s(\alpha') + uV_u(\alpha'))^2\right]$$

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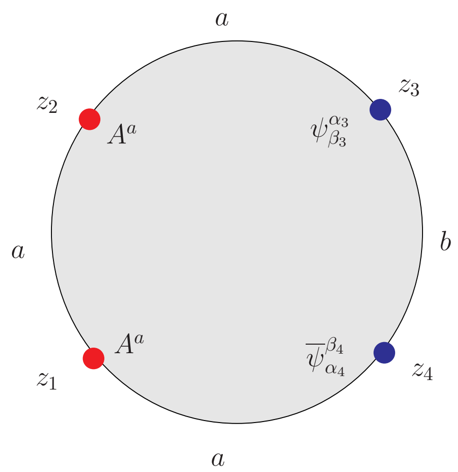

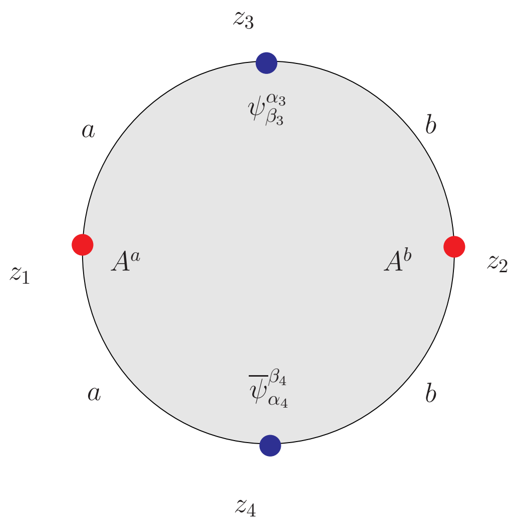

Fermions: boundary changing operators!

Note: Cullen, Perelstein, Peskin (2000) considered: $e^+e^- \to \gamma\gamma$

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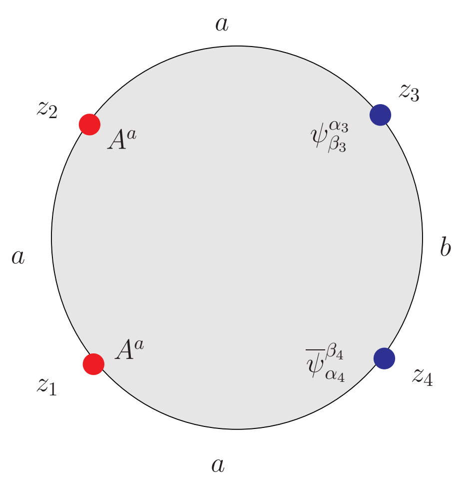

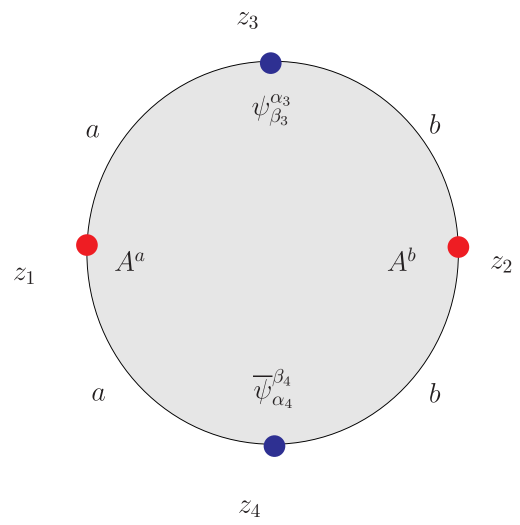

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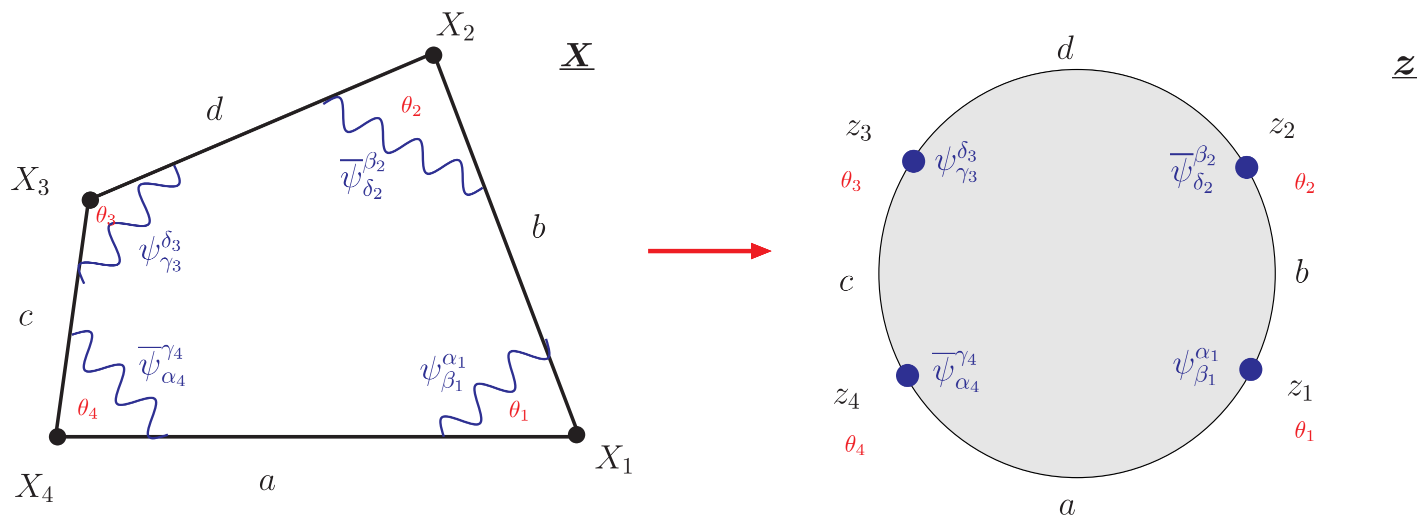

Exchange of Regge, KK and winding resonances.

These amplitudes are more model dependent and test the internal CY geometry.

Constrained by FCNC's and/or proton decay.

(Klebanov, Witten, hep-th/0304079; Abel, Lebedev, Santiago, hep-th/0312157)

E.g.

$$|\mathcal{M}(qq\to qq)|^2 = \frac{2}{9}\frac{1}{t^2}\Big[\big(sF^{bb}_{tu}(\alpha')\big)^2 + \big(sF^{cc}_{tu}(\alpha')\big)^2 + \big(uG^{bc}_{ts}(\alpha')\big)^2 + \big(uG^{cb}_{ts}(\alpha')\big)^2\Big] + \frac{2}{9}\frac{1}{u^2}\Big[\big(sF^{bb}_{ut}(\alpha')\big)^2 + \big(sF^{cc}_{ut}(\alpha')\big)^2 + \big(tG^{bc}_{us}(\alpha')\big)^2 + \big(tG^{cb}_{us}(\alpha')\big)^2\Big] - \frac{4}{27}\frac{s^2}{tu}F^{bb}_{tu}(\alpha')F^{bb}_{ut}(\alpha') + F^{cc}_{tu}(\alpha')F^{cc}_{ut}(\alpha')\big)$$

depend on internal geometry

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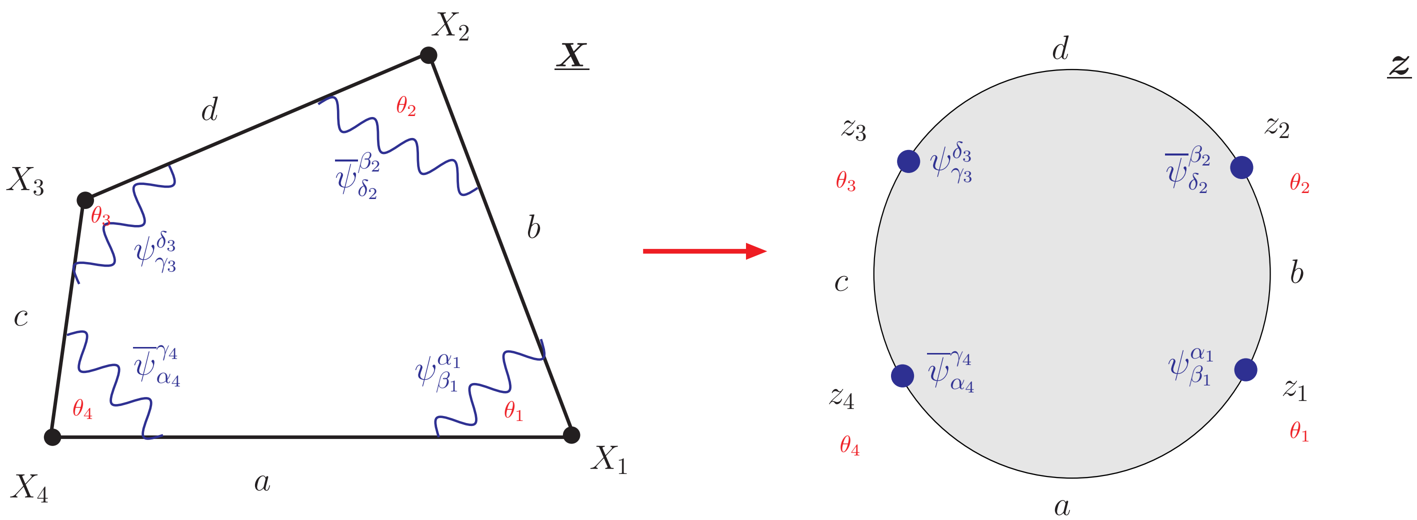

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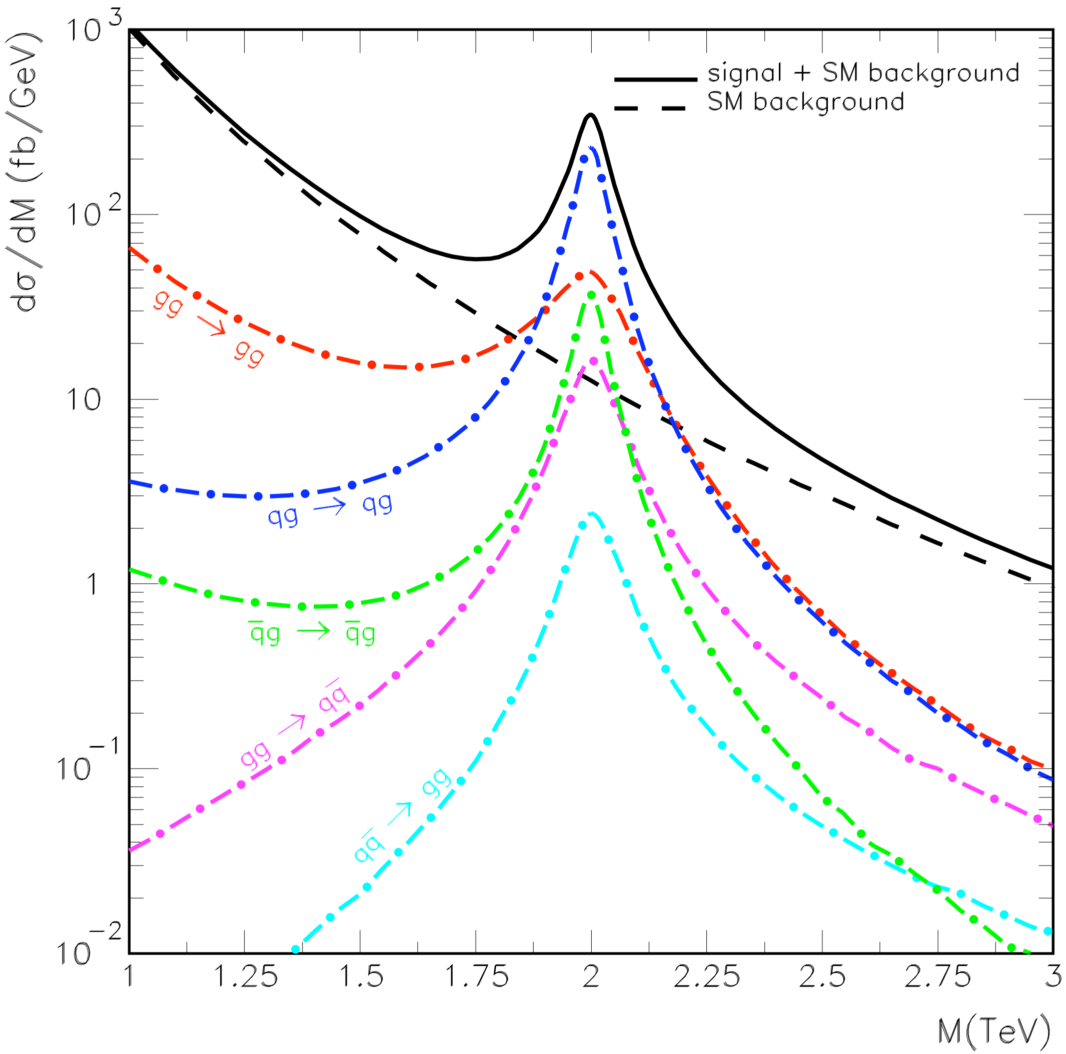

(Anchordoqui, Goldberg, Lüst, Nawata, Stieberger, Taylor, arXiv:0808.0497[hep-ph])

$$M_{\text{Regge}} = 2 \text{ TeV}$$

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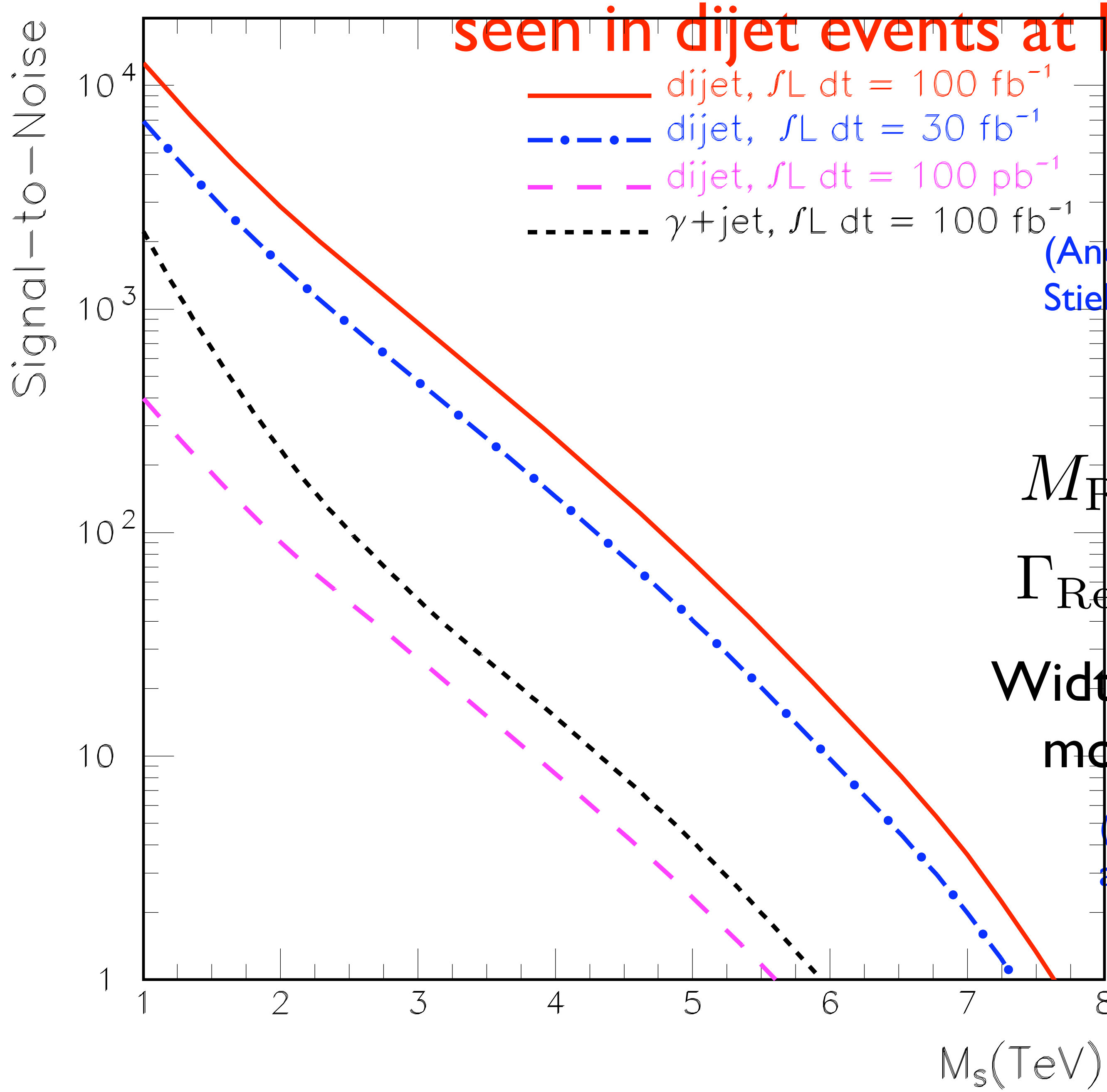

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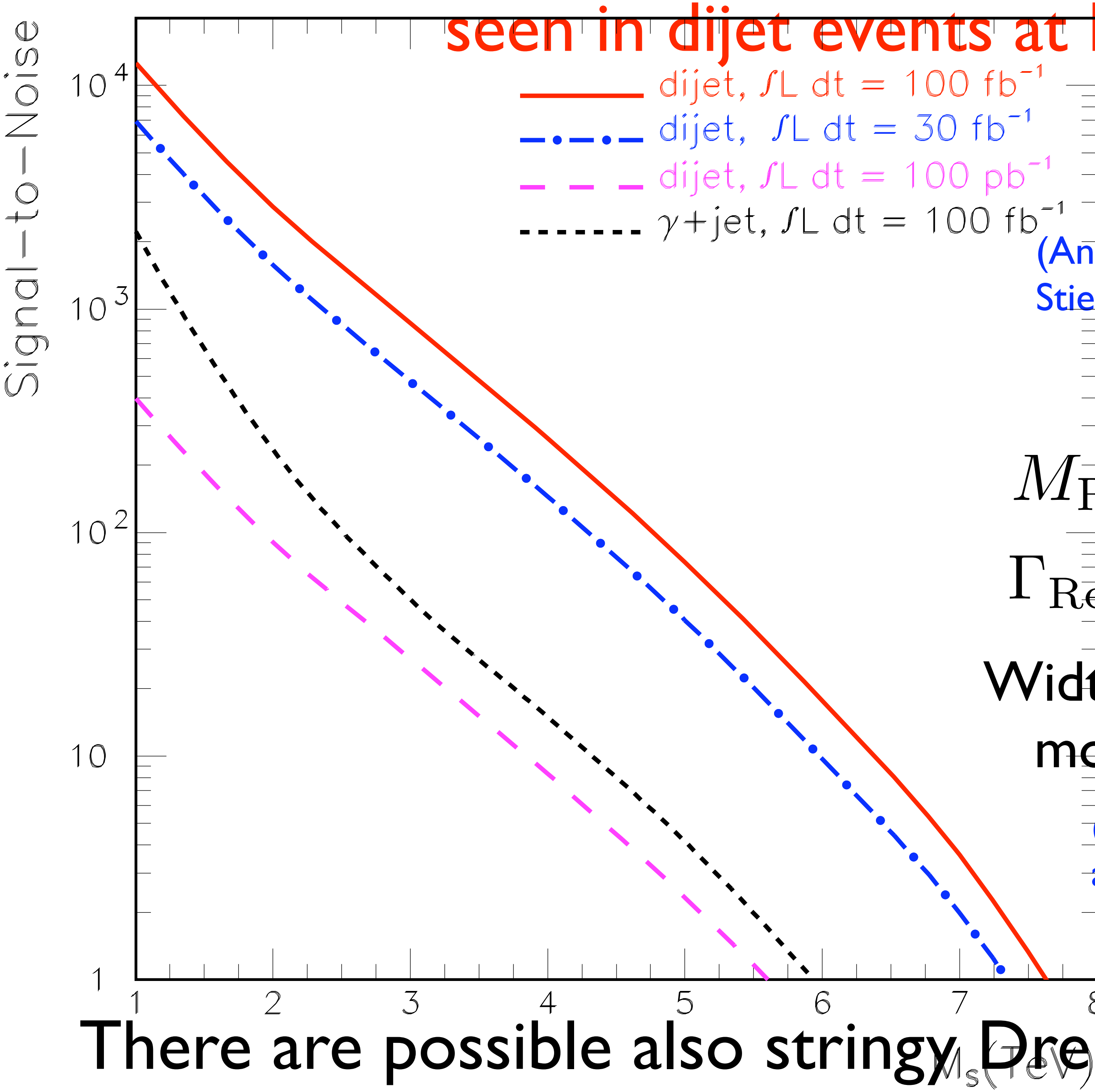

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There are possible also stringy Drell-Yan processes like

$$q\bar{q} \to l\bar{l}$$

Intermediate summary:

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Now we want to make use of other gravitational effects in order to get more informations about the landscape.

Outline

- Stringy signatures at LHC

  Intersecting brane models

  (The LHC string hunter's companion)

- Seeing into the landscape

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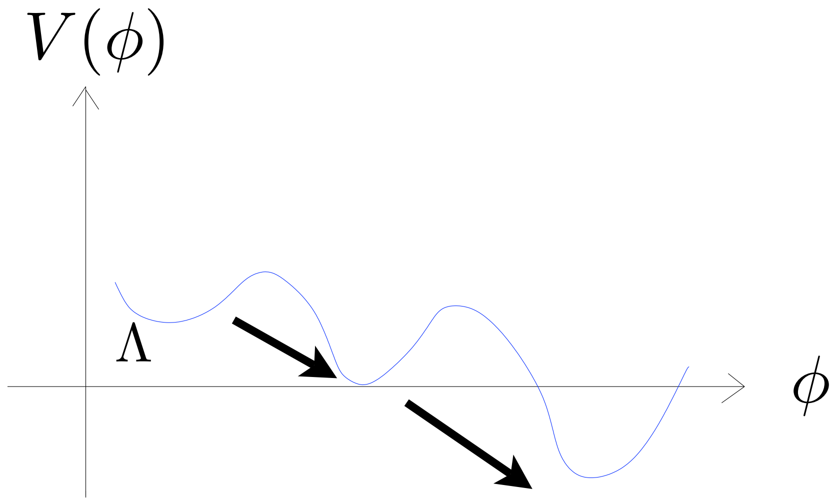

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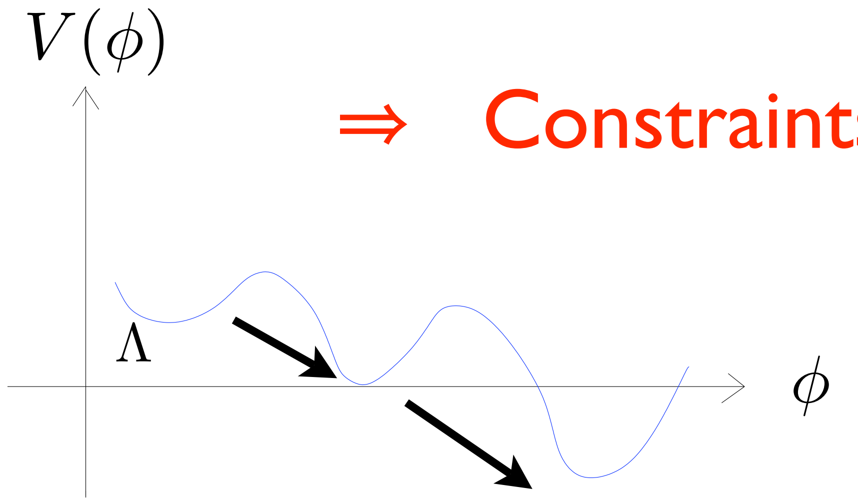

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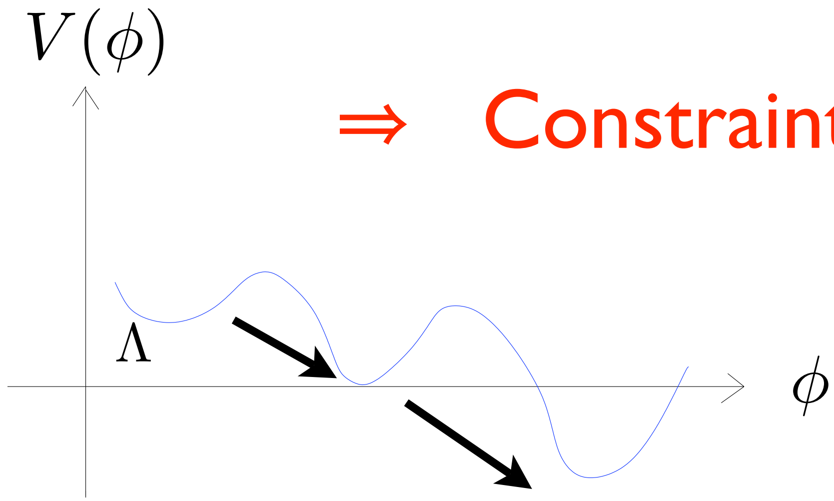

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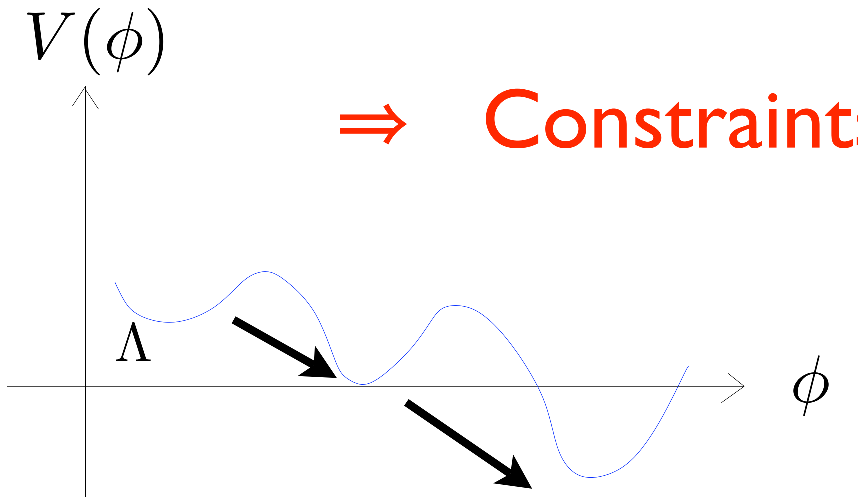

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$\Rightarrow$ Bounds on the landscape from decays of black holes!

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Coleman, De Luccia:

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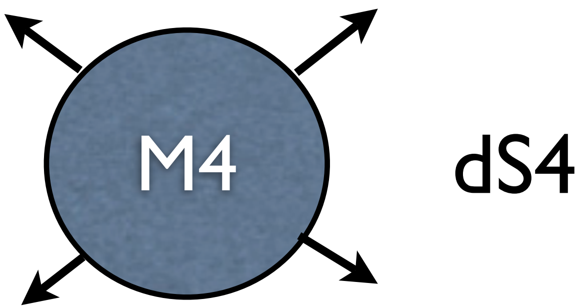

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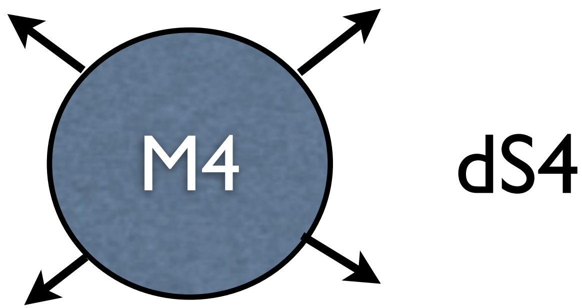

The transition amplitudes are computed using the interpolating (Euclidean) metrics from vacuum (a) to vacuum (b):

$$\Gamma \simeq M_P \exp\left(-\frac{24\pi^2 M_P^4}{\Lambda(\phi)}\right)$$

Stringy transitions between different flux vacua:

(C. Kounnas, D. Lüst, M. Petropoulos, D. Tsimpis, work in progress)

Interpolating (4d) domain walls separating vacuum (a) from vacuum (b):

They can be constructed from flux vacua as intersecting brane systems: e.g (D4. NS5, D8)

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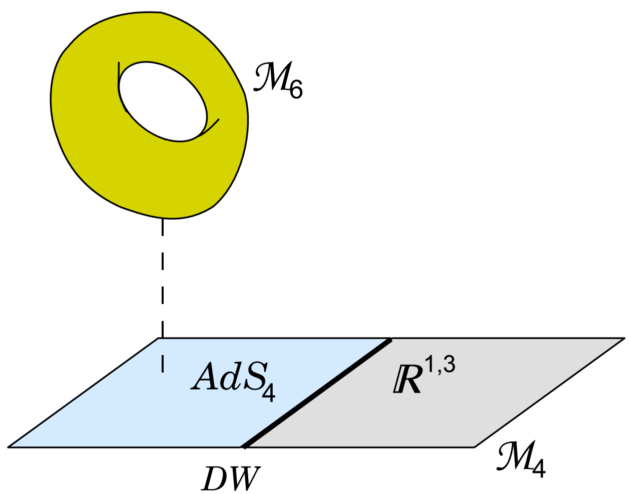

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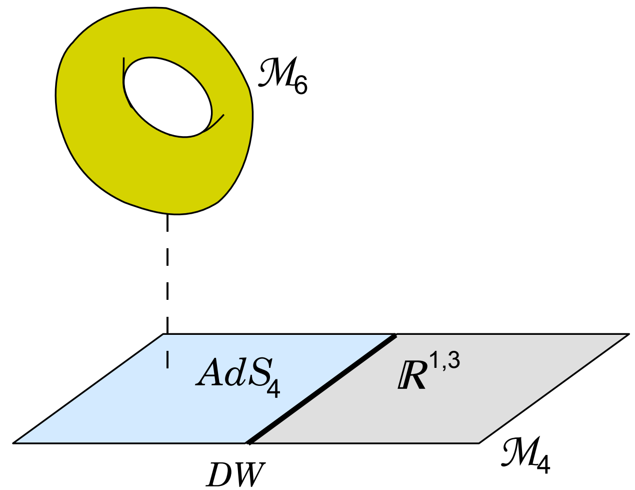

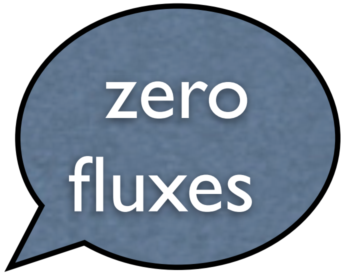

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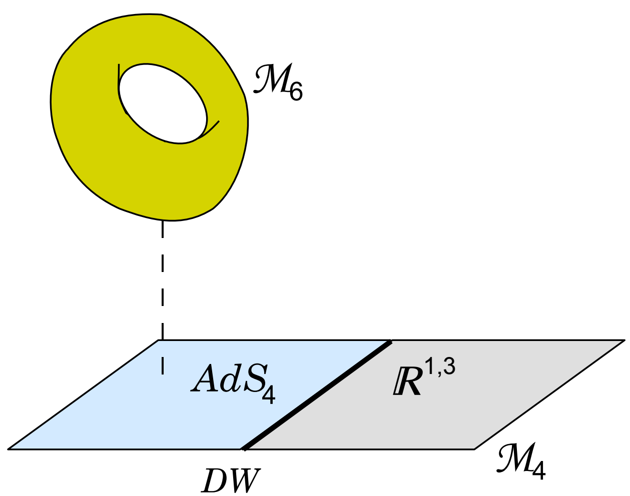

zero fluxes

Domain wall supergravity solution from intersecting branes:

	ξ^0	ξ^1	ξ^2	y	x^1	x^2	x^3	x^4	x^5	x^6
D4	$\otimes$	$\otimes$	$\otimes$		$\otimes$	$\otimes$				
D4$'$	$\otimes$	$\otimes$	$\otimes$				$\otimes$	$\otimes$		
D4$''$	$\otimes$	$\otimes$	$\otimes$						$\otimes$	$\otimes$
NS5	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$		$\otimes$	
NS5$'$	$\otimes$	$\otimes$	$\otimes$		$\otimes$			$\otimes$		$\otimes$
NS5$''$	$\otimes$	$\otimes$	$\otimes$			$\otimes$		$\otimes$	$\otimes$	
NS5$'''$	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$			$\otimes$
D8	$\otimes$	$\otimes$	$\otimes$		$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$

Explicit form of the solution:

$$
\begin{aligned}
\mathrm{d}s_{10}^2 = & \left\{H^{\mathrm{D8}}\left(\prod_{\alpha=1}^{3} H_\alpha^{\mathrm{D4}}\right)\right\}^{-\frac{1}{2}} \eta_{\mu\nu}\mathrm{d}\xi^\mu \mathrm{d}\xi^\nu \\
& + \left(\prod_{\alpha=1}^{4} H_\alpha^{\mathrm{NS5}}\right)\left\{H^{\mathrm{D8}}\left(\prod_{\alpha=1}^{3} H_\alpha^{\mathrm{D4}}\right)\right\}^{\frac{1}{2}} \mathrm{d}y^2 \\
& + \sqrt{\frac{H_2^{\mathrm{D4}} H_3^{\mathrm{D4}}}{H_1^{\mathrm{D4}} H^{\mathrm{D8}}}}\left\{H_3^{\mathrm{NS5}} H_4^{\mathrm{NS5}} (\mathrm{d}x^1)^2 + H_1^{\mathrm{NS5}} H_2^{\mathrm{NS5}} (\mathrm{d}x^2)^2\right\} \\
& + \sqrt{\frac{H_1^{\mathrm{D4}} H_3^{\mathrm{D4}}}{H_2^{\mathrm{D4}} H^{\mathrm{D8}}}}\left\{H_2^{\mathrm{NS5}} H_3^{\mathrm{NS5}} (\mathrm{d}x^3)^2 + H_1^{\mathrm{NS5}} H_4^{\mathrm{NS5}} (\mathrm{d}x^4)^2\right\} \\
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\mathrm{e}^{2\phi} = & \left(\prod_{\alpha=1}^{4} H_\alpha^{\mathrm{NS5}}\right)\left(\prod_{\alpha=1}^{3} H_\alpha^{\mathrm{D4}}\right)^{-\frac{1}{2}}\left(H^{\mathrm{D8}}\right)^{-\frac{5}{2}}; \\
H_{x^2x^4x^6} = & -\partial_y H_1^{\mathrm{NS5}}\left(H^{\mathrm{D8}}\right)^{-1}; \quad H_{x^2x^3x^5} = -\partial_y H_2^{\mathrm{NS5}}\left(H^{\mathrm{D8}}\right)^{-1}; \\
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F_{x^3x^4x^5x^6} = & \partial_y H_1^{\mathrm{D4}}; \quad F_{x^1x^2x^5x^6} = \partial_y H_2^{\mathrm{D4}}; \\
F_{x^1x^2x^3x^4} = & \partial_y H_3^{\mathrm{D4}}; \quad F = -\partial_y H^{\mathrm{D8}}\left(\prod_{\alpha=1}^{4} H_\alpha^{\mathrm{NS5}}\right)^{-1}.
\end{aligned}
$$

Properties of this solution:

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- Smeared (thick) branes:

$$H_\alpha^{\mathrm{D4}} = \begin{cases} c_\alpha^{\mathrm{D4}} y\{1 - \frac{1}{2}\left(\frac{y}{y_0}\right)\}, & y < y_0 \\ \frac{1}{2} c_\alpha^{\mathrm{D4}} y_0, & y \geq y_0 \end{cases}$$

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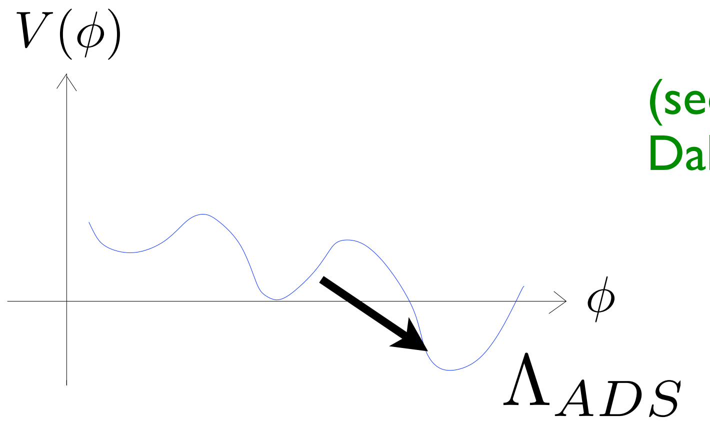
- All moduli take finite, fixed values at horizon, agree with those from minimizing the flux superpotential.
- Non-vanising tadpole: need (smeared) D6-branes and O6-plane.

Transition amplitude from M4 to AdS4



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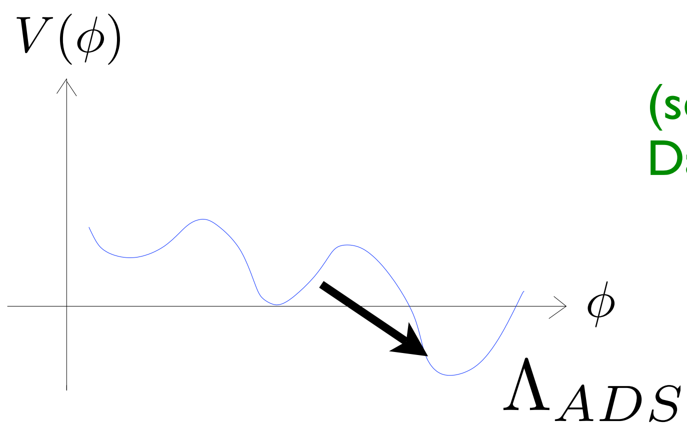

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$$\mathrm{d}s^2 = a(r)^2(-\mathrm{d}t^2 + \mathrm{d}x^2 + \mathrm{d}y^2) + \mathrm{d}r^2\,, \quad \frac{a(r)'}{a(r)} = Z(r)$$

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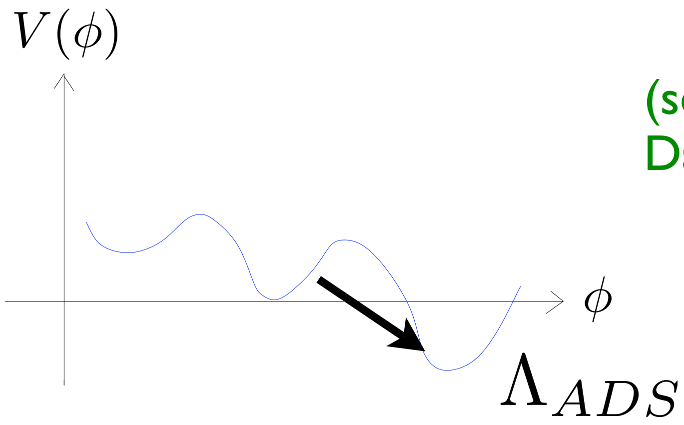

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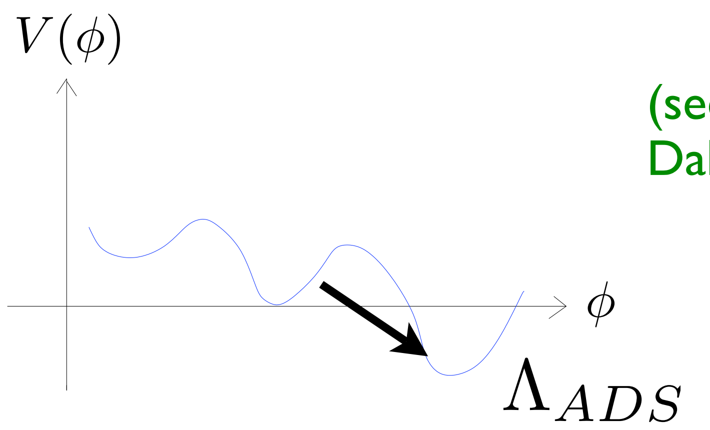

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Transition amplitude:

$$\Gamma \simeq \exp\left(-\frac{24\pi^2 C M_P^4}{\sigma^2}\right) = \exp\left(\frac{24\pi^2 C M_P^4}{\Lambda_{\mathrm{ADS}}}\right)$$

$\Rightarrow$ Constraints on Λ_{ADS} in order to avoid too fast decay into neighboring AdS vacua:

$$\frac{|\Lambda_{ADS}|}{M_P^4} \simeq \frac{|a_0 c_1 c_1 c_3|(|m_0 e_1 e_2 e_3|)^{5/2}}{(e_1 e_2 e_3)^4} << 1$$

(For $|\Lambda_{ADS}| = \mathcal{O}(m_{3/2}^4)$ the lifetime of our universe is still long enough!

b) Bounds from black hole decays:

(G. Dvali, arXiv:0706.2050)

Consider a theory with N species of particles with mass M:

$$N < N_{max} = \frac{M^2_{Planck}}{M^2}$$ M: scale of new physics

(A quantum black hole can emit at most N_{max} different particles)

This bound must be satisfied in every effective string vacuum that is consistently coupled to gravity!

E.g. if a scalar field in the effective potential gives mass to N particles via the Higgs effect: $M = M(\phi)$

$$M(\phi)^2 < \frac{M^2_{Planck}}{N}$$

E.g:

$$N = 10^{32} \quad \Longrightarrow \quad M < 10^{-16} M_{Planck} \simeq 1\ TeV$$

This bound gives also a possible explanation of the hierarchy problem:

M can be seen as the fundamental scale of gravity, which is diluted by the presence on the N particle species.

(Large extra dimensions: N KK-states of mass M.)

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$$\ddot{\phi} + 3H\,\dot{\phi} + V(\phi)' = 0$$

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$$V(\phi) = \frac{1}{2}m^2\phi^2 + g\phi\bar{\psi}_j\psi_j$$ slow roll condition: $\phi \geq M_P$

$$g\phi \leq M_P\left(\frac{m\phi}{M_P^2}\right)^{\frac{1}{3}}$$ ϕ cannot be arbitrarily large!

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$\Rightarrow$ Problem to see gravitational waves?

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(Silverstein, Westphal: large field range due to monodromy!)

(arXiv:0803.3085)

Similar bounds can be derived for D-term inflation.

$$V(\phi) \simeq \mu^4 \left[1 + \frac{g^2}{16\pi^2} \ln \frac{g|\phi|}{Q}\right]$$

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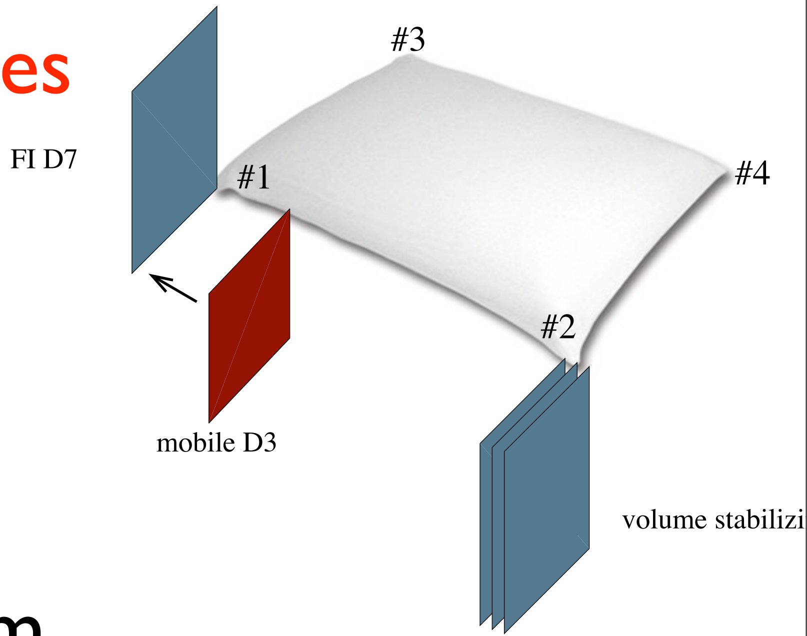
- String inflation on concrete IIA/IIB orientifolds:

K3 x T2 orientifold with D3/D7-branes

(Dasgupta, Herdeiro, Hirano Kallosh (2002);
Haack, Kallosh, Krause, Linde, Lüst, Zagermann, arXiv:0804.3961)

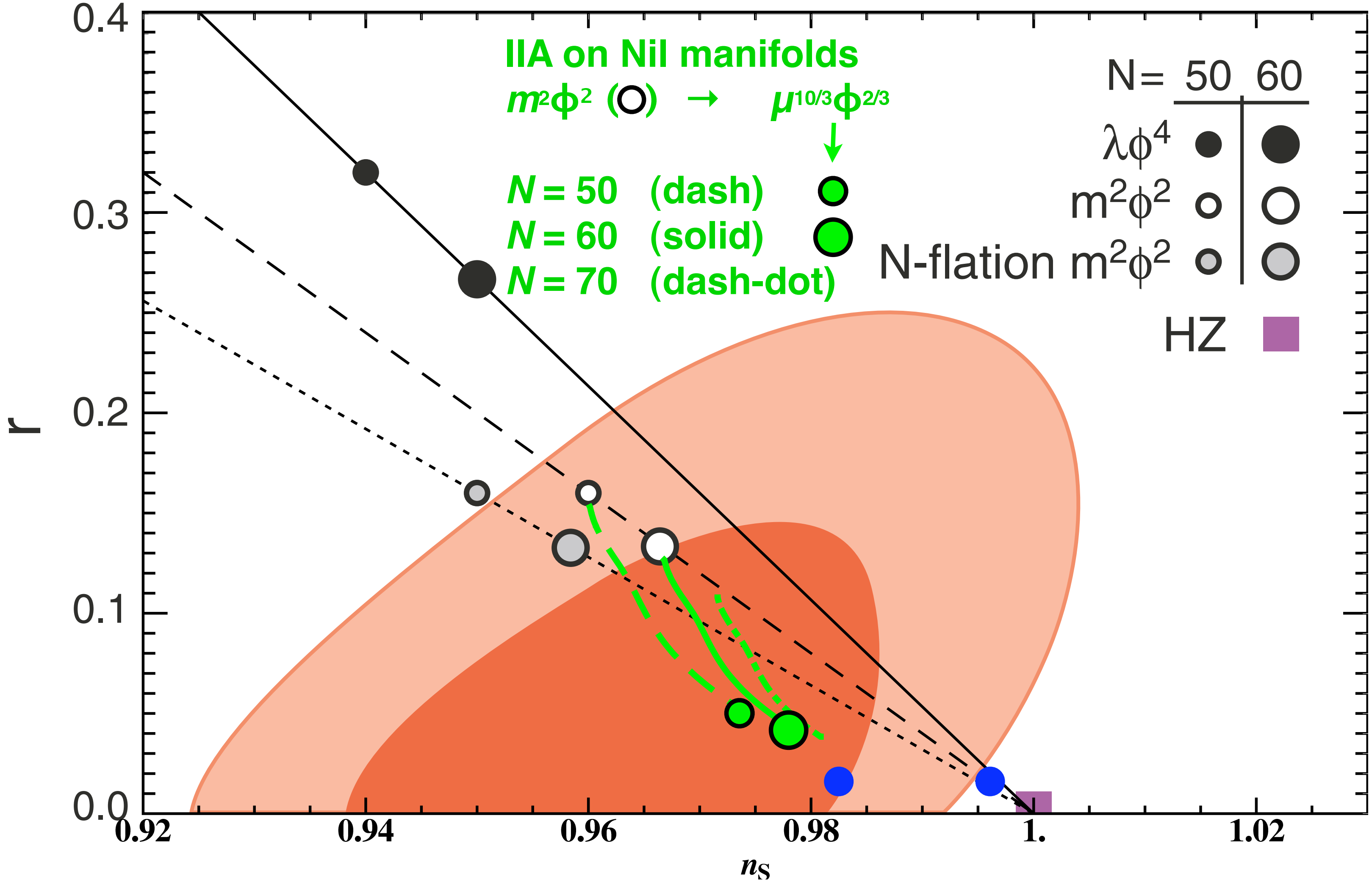


$$V = \frac{g^2\xi^2}{2}\left(1 + \frac{g^2}{4\pi^2}\ln\frac{\phi}{\sqrt{\xi}}\right) - \frac{m^2}{2}\phi^2$$

D-term

n.p. F-term

Chaotic Inflation



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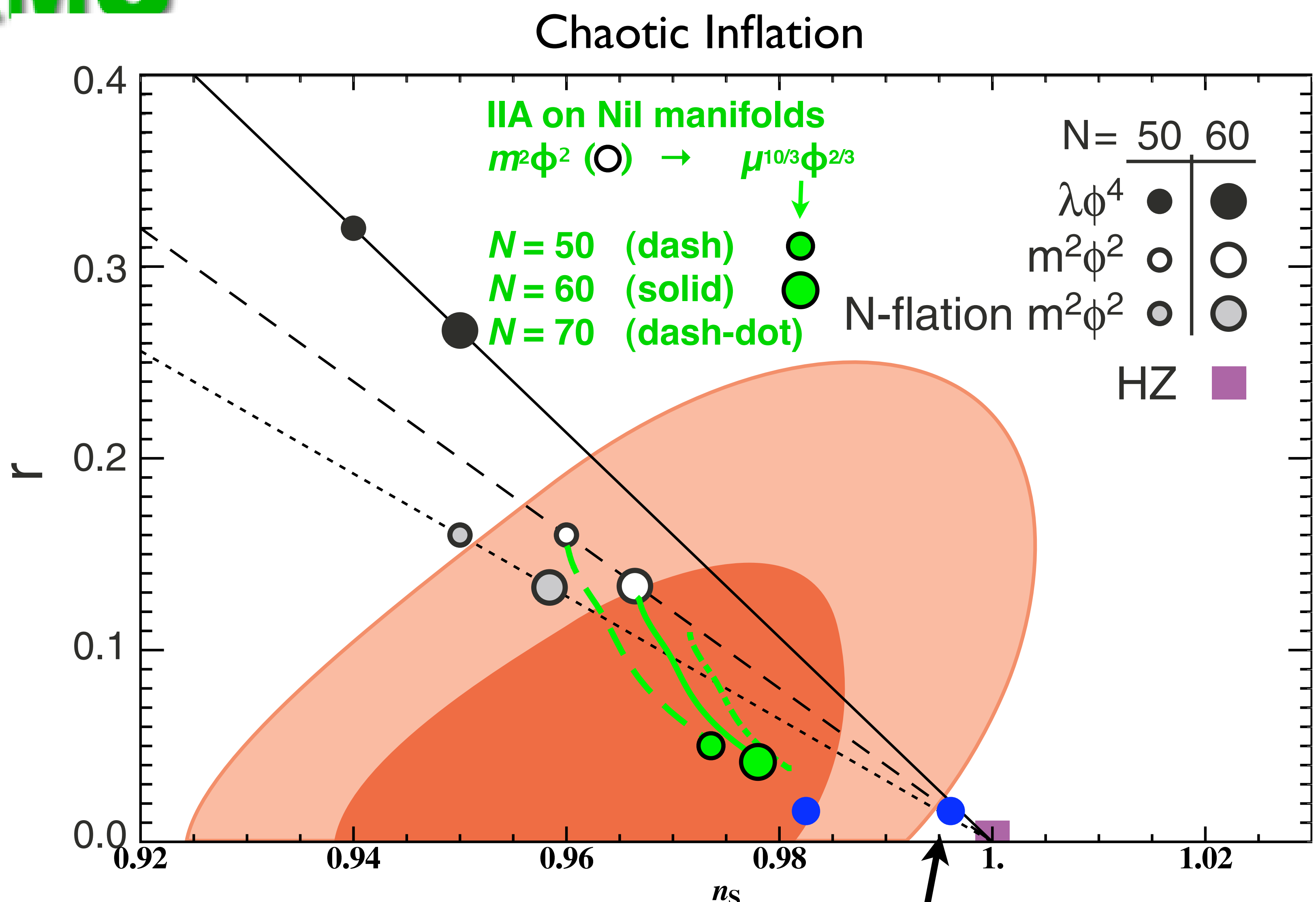

K3 x T2 orientifold

In addition cosmic strings $G\mu = 7 \times 10^{-7}$

(Bevis, Hindmarsh, Kunz, Urrestilla, arXiv:astro-ph/0702223))

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(Independent of amount of (unbroken) supersymmetry!)

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(Inde … metry!)

Strin … ons … ??

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Questi … s change tree level signatures? Onset of n.p. physics: $M_{b.h.}$

INTERESTING TIMES FOR STRING PHENOMENOLOGY ARE AHEAD OF US.

THANK YOU !!

- Further informations about landscape from black holes (string inflation)