String theory scales and gauge hierarchy

① The (minimal) SQFT hypothesis & heterotic th.

② Weakly-coupled type I & experimental bounds

③ Efforts to transform the E-desert into transverse space

based on:

CB, hep-ph/9807415
Antoniadis, CB, hep-th/9812093
" ", Dudas, hep-th/9906xxx

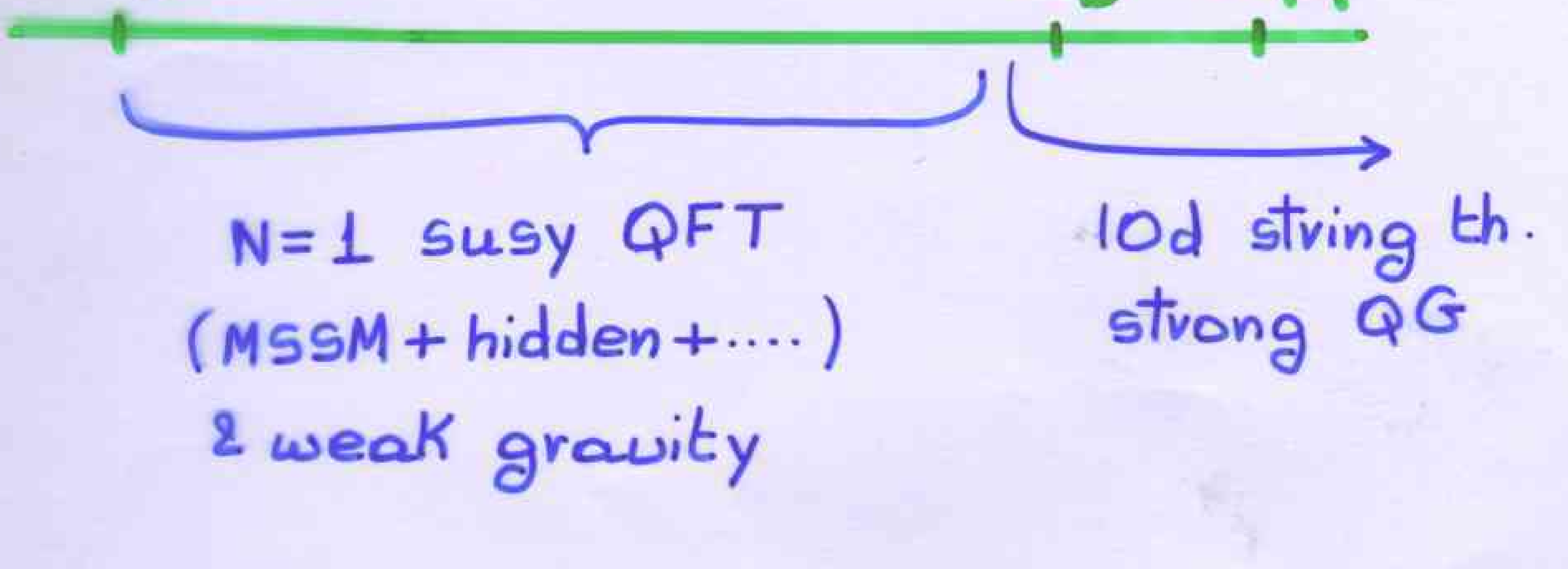
c.f. also talks by Antoniadis, Ibanez

The SQFT hypothesis

Conventional viewpoint on string/M theory scales is that all dimensionless 'parameters' and in particular vevs of moduli obey

$$\frac{1}{\text{a few}} \lesssim \langle \varphi_i \rangle \lesssim \text{a few}$$

implies that



Minimal ('desert') hypothesis : no light charged fields other than MSSM

'Faith' in SQFT hypothesis based on following facts:

↳ MSSM can be extrapolated consistently up to M_S, & is in particular stable under radiative corrections (solves technical aspect of gauge hierarchy)

↳ Hypothesis is 'automatic' in the weakly-coupled heterotic string

↳ 'Robust' and successful predictions from unification of gauge couplings, and of Yukawa couplings for mass matrix of qs & ℓs.

Let me expand on these 3 facts more ⤵

↳ UNIFICATION PREDICTIONS

parameters of SQFT receive log corrections

these are large for large E-span, but can be resummed by the RG

Threshold corrections from unknown UV effects relatively small

⇓ '<u>robust</u>' predictions

ex/ $$\alpha_i^{-1}(M_Z) = \alpha_U^{-1} + \underbrace{b_i \log \frac{M_Z}{M_U}}_{\sim 30} + \underbrace{\Delta_i}_{O(1)}$$

↲ $\lesssim 10\%$ theoretical uncertainty

Prediction for <u>two</u> measured parameters, <u>eg</u> $\alpha_3(M_Z)$ & $\log(M_Z/M_{Pl})$ good to ~10% .

Likewise successful predictions for masses of qs & ℓs, by imposing some boundary conditions at M_U (eg, unificn. of Yukawa's, textures from discrete syms) but without more detailed knowledge of UV physics.

In short: such 'robust' calculns only possible if SQFT valid for a large logE-span

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↳ TECHNICAL ASPECT OF GAUGE HIERARCHY

loop corrections do not modify drastically the (mass) parameters of the MSSM

$$\mathcal{L}_{MSSM}(\underset{\uparrow \text{MSSM fields}}{\Phi}, \overset{\swarrow \text{params}}{m_a})$$

loops of MSSM fields : at most log corrections

loops of SUGRA : cutoff at $\lesssim M_{Pl}$ so $o(1)$

Of course in string theory the MSSM parameters at classical level are functions of the vevs of moduli fields

$$m_a(\langle\varphi_i\rangle)$$

We must therefore also <u>assume</u> that loop corrections to $\mathcal{L}(\phi_i)$ do not destabilize those vevs (no tadpoles) — this is of course OK before $\cancel{\text{SUSY}}$.

Since $\cancel{\text{susy}}$ leads generally to tadpoles & $\Lambda_{cosmo} \neq 0$, it is unclear how useful is the separation of the technical gauge-hierarchy aspect from the problem of vacuum stability.

(string islands ??)

↳ WEAKLY-COUPLED HETEROTIC STRING

Both graviton & (perturbative) gauge bosons live in 10d and interact at same order in string-loop expansion (sphere diagram).

∴ Universal relation

$$\underbrace{M^2_{\text{Planck}} \simeq M_H^2/\alpha_U}_{\text{4d quants}}$$

Ginsparg
Kaplunovsky
⋮

If $\boxed{\alpha_U \sim o(1/25)}$ * then M_H tied to M_{Planck}

Furthermore standard KK formula:

$$\alpha_U \simeq g_H^2/(RM_H)^6$$

with $RM_H \gtrsim o(1)$ by T-duality.

If we want to keep

$$\boxed{g_H \lesssim o(1)} \;{**}\quad \text{then } R^{-1} \text{ tied to } M_H$$

so SQFT hypothesis essentially imposed on us.

Early motivation to depart from this scenario was search for vacua with tree-level susy.

Known vacua essentially generaliznts of 'Scherk-Schwarz mechanism', so low-E susy requires $R^{-1} \sim \text{TeV}$

Rohm
Ferrara, Kounnas, Porrati
Antoniadis, CB, Lewellen, Tomaras

also Banks, Dixon
Dine, Seiberg

To achieve this must give up either

$\boxed{g_H \lesssim o(1)}$

or

$\boxed{\alpha_U \sim o(1/25)}$

but possible to keep some gauge couplings small at one loop (if 'no N=2 sectors')
Antoniadis

if $\alpha_U \ll 1$, conceivable that large (higher d) thresholds drive them to $\sim o(1)$ C.B.

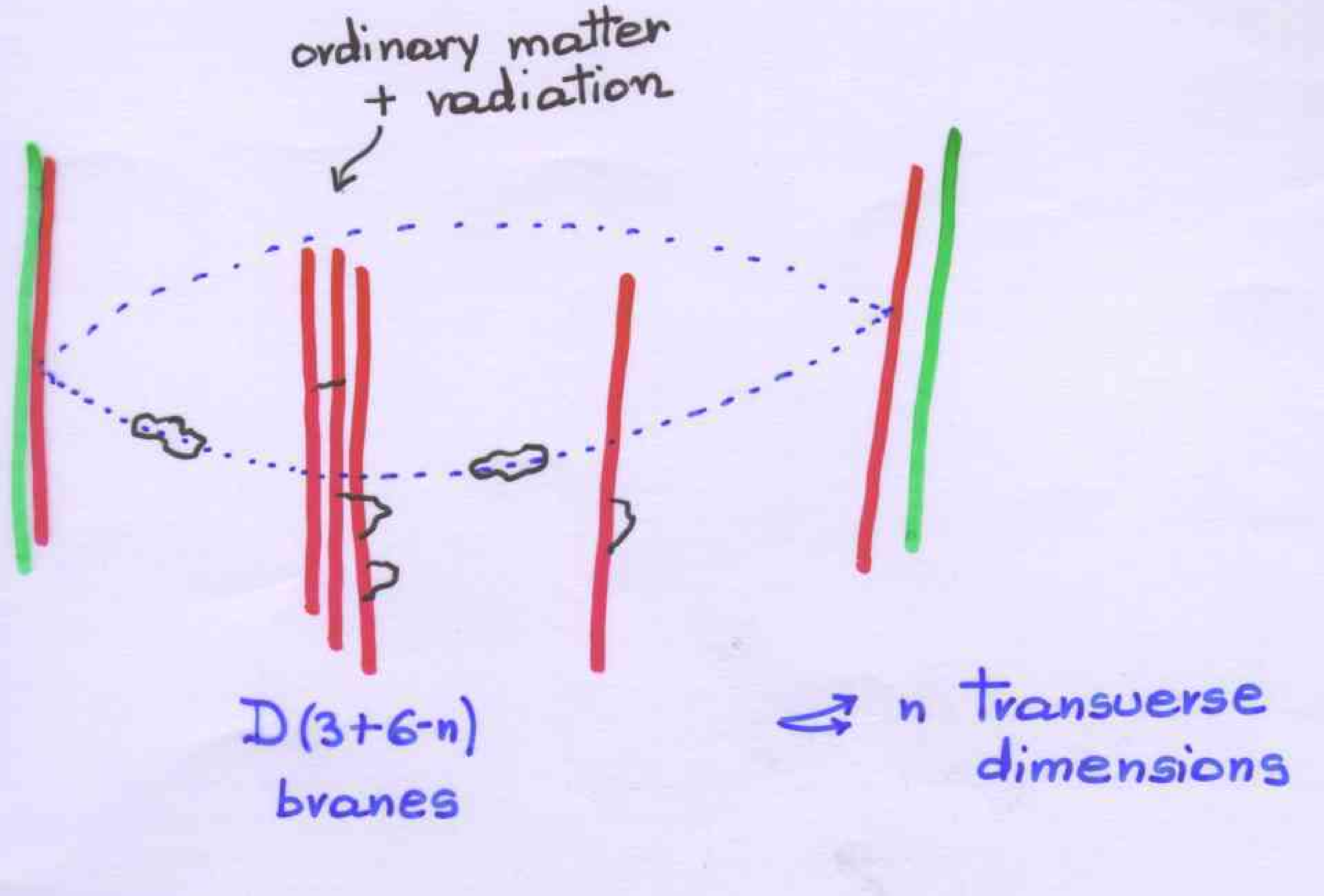
Though nice to have tree susy option, such breaking has not lead to new insights on problem of vacuum stability.

So little theoretical motiunt for giving up perturbative control & successful unificn. 'predictions' in WCHS.

Type I theory & 'Brane World'

Things are different in type I theory since gauge fields can now be trapped on D-branes :

$$M^2_{\text{Planck}} \simeq \frac{R_\perp^n R_\parallel^{6-n} M_I^8}{g_I^2} \quad ; \quad \alpha_U \simeq \frac{g_I}{(R_\parallel M_I)^{6-n}}$$



∴ M_I free parameter

less restrictive (predictive) than heterotic

Freedom could be used to remove factor ~20 discrepancy between M_U & M_{str}

Witten

or maybe to push M_I down to its experimental limit ~TeV

Lykken

requires from

$n=2$ mm $= R_\perp$

⋮

$n=6$ fm $= R_\perp$

* Arkani-Hamed, Dimopoulos, Dvali

Antoniadis, Arkani-Hamed, Dimopoulos, Dvali

Shiu, Tye

⋮

Besides being part of $\mathcal{M}$-theory moduli space, the remarks* that brought this idea into focus were

- that mesoscopic gravity does not rule out such large extra dims
- that this may open new approach to problem of gauge hierarchy.

A transverse desert ?

Bringing M_I to ~TeV looks 'antipodal' to SQFT hypothesis : even though MSSM is renormalizable QFT, one limits its stable range of validity to $\lesssim 1$ order of magn. !

Nevertheless, I will now argue that the type-I 'Brane World' with $n = 2$ large transverse dims may offer same 'robustness' & calculability as the energy-desert scenario.

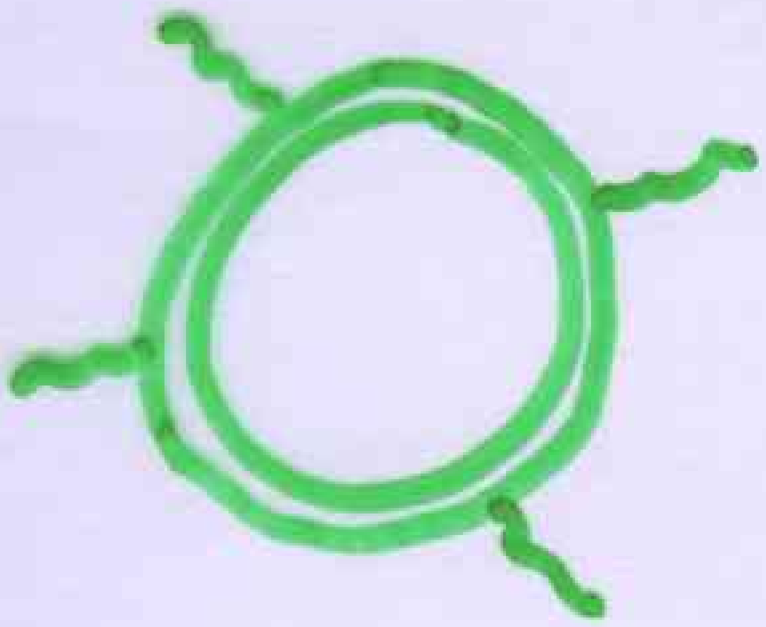
First note that type-I is only theory in which Brane World has perturbative realiznt.

Only D-branes can trap in pert. theory non-abelian gauge fields, & space-filling D-branes require orientifolds.

Now if $M_I \sim \text{TeV}$ all large quantum effects can be understood as large IR effects in 10 dims. However, for an observer on brane they can have very different interpretn:

eg/

↳



$\rightarrow (P_{\parallel}, \underset{\approx 0}{P_{\perp}})$

'soft' effects

at exceptional values of external momenta

↳

$\rightarrow (0, \underset{\approx 0}{P_{\perp}})$

'hard' effects

at all external momenta

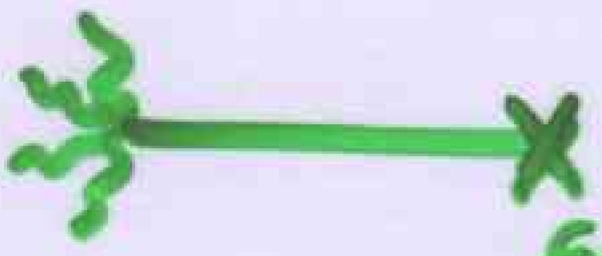
Of course $P_\perp = 0$ diagrams vanish

global tadpole cancelln

but $P_\perp \sim \frac{1}{R_\perp} \ll M_I$ generally dont

'charge densities' dont cancel

Large effects come from variations of massless bulk fields over the large transverse space



source $(\mathcal{O}_P, D_P)$

Polchinski, Witten

⋮

SM parameters functions $m_a(\varphi_i|_0)$

& $\varphi_i|_0$ can be very different from $\overline{\varphi_i}$

their spatial variation governed by:

$$\mathcal{L}_{SUGRA} + \mathcal{L}_{source} \sim \int d^n x_\perp \left\{ \frac{1}{g_s^2} (\partial \varphi_i)^2 + \frac{1}{g_s} f(\varphi_i)\, \delta(x_\perp) \right\}$$

↳ D-branes & orientifolds

weak sources ⇝ perturbative expansion

$$\varphi_i = \varphi_i^{(0)} + g_s \varphi_i^{(1)}(x_\perp) + \cdots\cdots$$

↳ sum of n-dim. Green's functions

Clearly sensitivity on $R_\perp$ (and hence $M_{P\ell}$) is

- linear if $n=1$
- logarithmic if $n=2$
- dies out if $n>2$

analogous to

- non-renormalizable
- renormalizable
- super renormalizable

QFT

Let us try to take analogy further :

- large lg-corrections can be resummed by classical supergravity eqns

  analogous to RG eqns

since $\left.\begin{array}{l}\text{stringy}\\ \text{quantum grav.}\end{array}\right\}$ corrections are higher-derivative & hence involve extra powers of $\sim \frac{1}{\delta x_\perp} \ll 1$

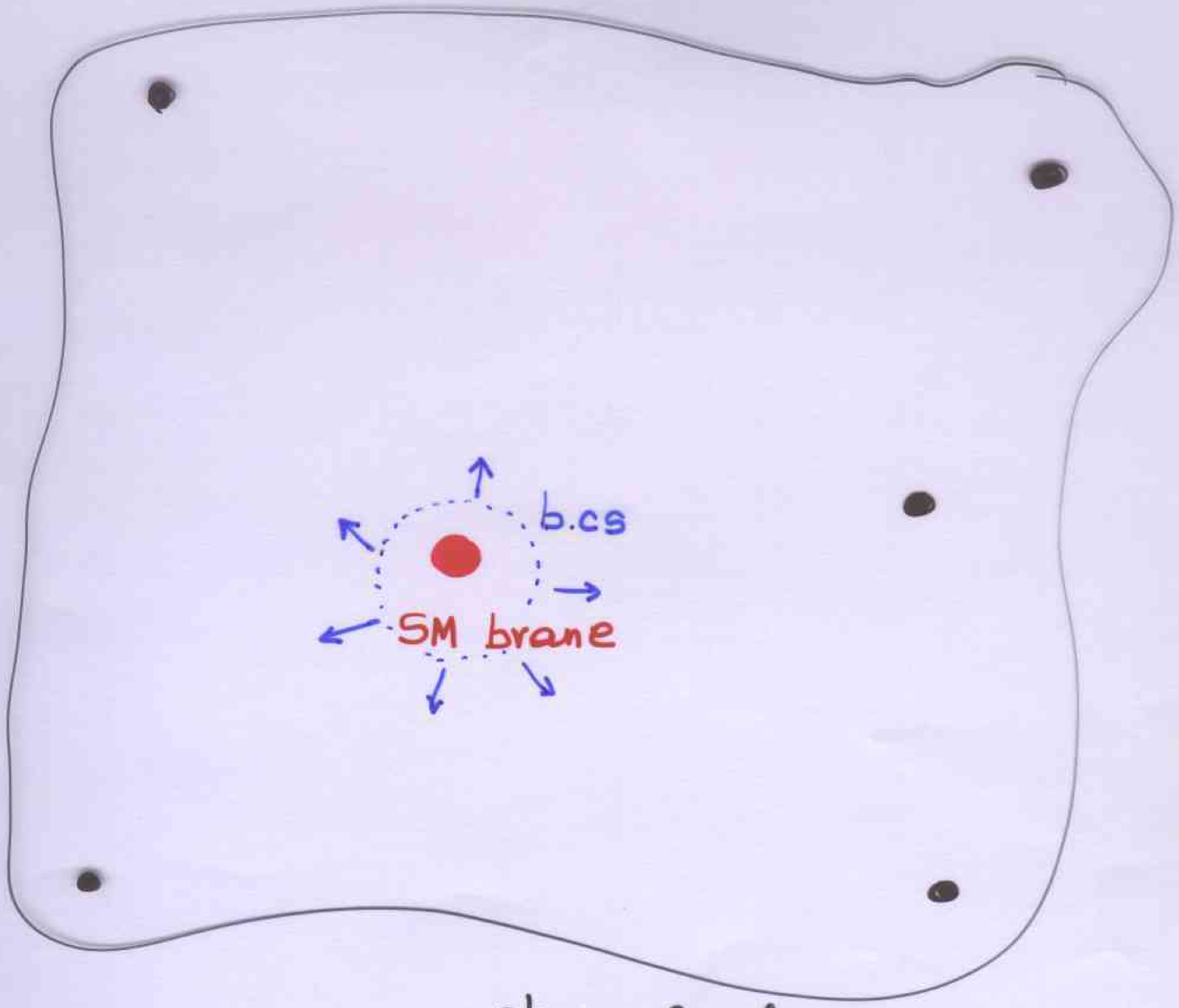
- boundary conds need be defined only in vicinity of our Brane World

  analogous to fixing low-E data

- 'shape' of transverse space, distant sources etc make subleading corrections

  ~threshold corrects

as long as they stay at distances $\sim o(R_\perp)$



shape & locations
of distant sources irrelevant
(subleading) threshold effects
as long as they stay at distances

$\sim o(R_\perp)$

↳ b.cs (for 2nd order diff. eqns) determined by source function $f(\varphi_i)$ & values of φ_i at position of our brane world

calculable given
explicit brane construction

Note: 'technical aspect' of gauge hierarchy solved at same level as with global susy: either for susy params, or after su/sy assuming no new tadpoles provided $n \geq 2$

(SM params receive at most logarithmic corrections)

Note': $n =$ 'effective dim.' of (large) transverse space

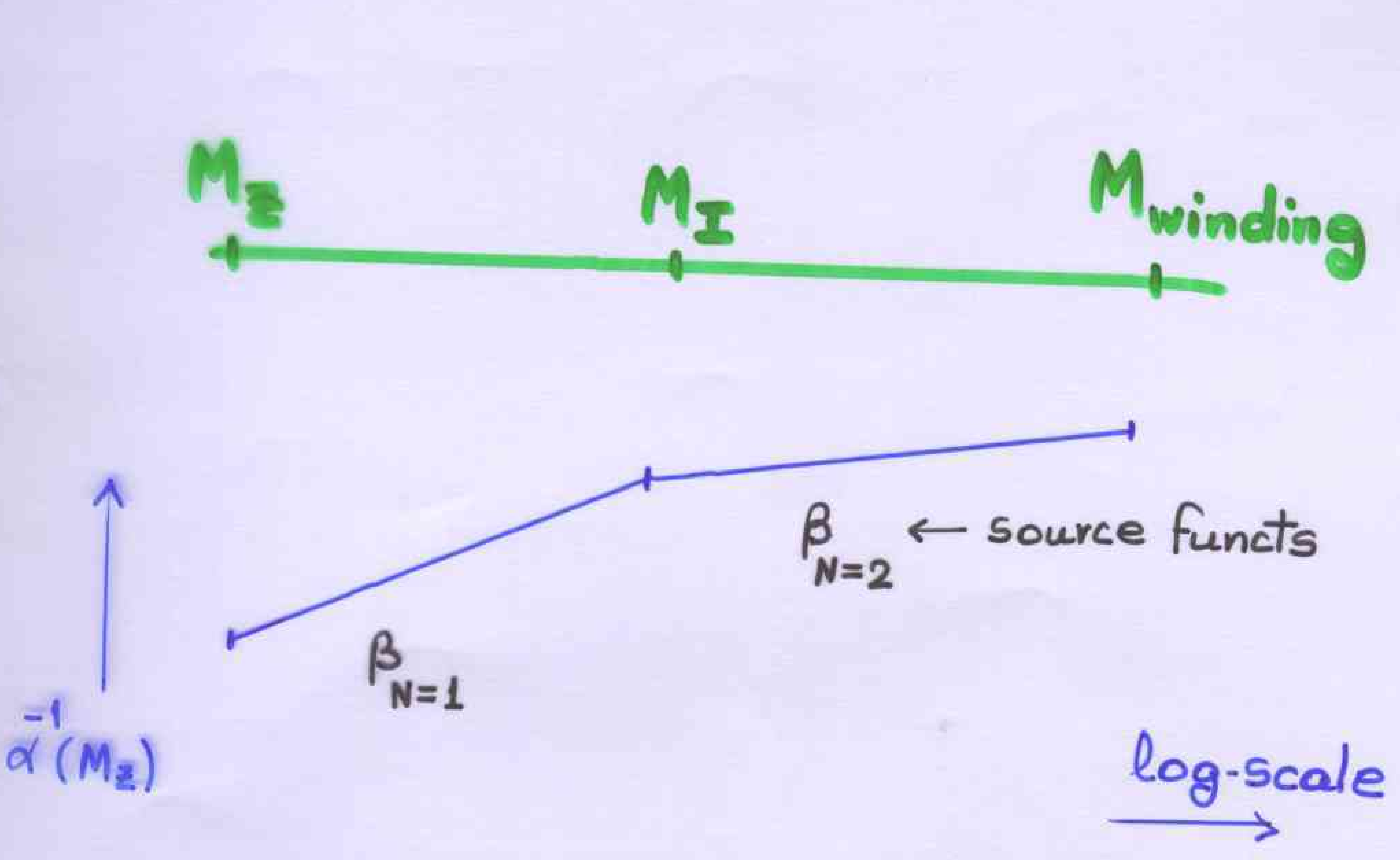
i.e. minimum # of large dims in which some massless scalar propagates (ex: $K_3 \times T_2$ orientifolds $n = 2$ if all volumes are large)

The puzzle of unification

Previous picture of course confirmed by explicit 'threshold' calculns in type I orientifold models

C.B, Fabre
Antoniadis, CB, Dudas

What one finds at one loop is:



where $M_{wind} \simeq M_I^2 R_\perp \simeq M_{Pl}$ (for n = 2 large dims)

* 'Evolution' not with E (above M_I) but rather dependence on values of $R_\perp$ & M_I.

For (N=2) $K_3 \times T_2$ orientifolds there is no discontinuity at M_I which drops completely out of calculnt (excited open strings non-BPS) Douglas, Li

For us here $M_I \sim M_Z$, so only SUGRA regime is relevant.

Question: can we understand unificn. with this real-space log evolnt. ?

First must ensure that coupling of bulk fields to SU(3) x SU(2) x U(1) not universal (or else $\alpha_3, \alpha_2, \alpha_1$ won't split apart)

This is (a priori) not hard to arrange.

ex. K3 * T2 orientifolds (other than $\mathbb{Z}_2$ model)

have extra tensor multiplets

Bianchi, Sagnotti
Gimon, Polchinski
Gimon, Johnson
Dabolkhar, Park
⋮

$$(\phi^k,\ B^{(+)k}_{\mu\nu} + \text{fermions})$$

$\nearrow$ twisted NS scalar

$\uparrow$ twisted RR 2-form

which are necessary for (generalized) Green-Schwarz anomaly cancelln. Sagnotti

---

These have non-universal couplings to gauge fields:

$$\sum_{\substack{\text{group factors}\\ a}} \frac{1}{g_s}\left(e^{\varphi} + s_a^k \varphi^k\right)\sqrt{\det(\eta + F_a)}$$

$$\left(+\ \text{WZ term} \sim B^k_\wedge F_\wedge F\right)$$

Explicit calculn
(or else susy +
anomaly canceln) give:

ABD
Ibanez, Rabadan, Uranga
(for $\mathcal{N}=1$)

$$S_a^k = \frac{\#}{\sqrt{N}} \sin\left(\frac{\pi k}{N}\right) \mathrm{tr}\left(Q_a^2 \gamma^k\right)$$

N of Z_N orientifold

normalized generator of ath group factor

action of Θ^k twist on Chan-Patton matrix

The logarithmic evoln of φ^k can thus split the gauge couplings <u>at</u> <u>the</u> <u>same</u> <u>point</u> $x_\perp$ apart.

↳ But what is the analog of the high-E boundary condition ?? ($\alpha_1=\alpha_2=\alpha_3$)

↳ and why should the splitting be in the right proportion ?

I have no answer to these questions only speculations

(eg/ nearby $\sim \frac{1}{10} R_\perp$ brane on which ϕ^k develops potential $V \sim (\phi^k)^2$ fixing its value at 0 would be analog of unificn constraint).

But it seems to me that outside this context would be very hard to understand perturbative unificnt as not being a (unfortunate!) accident in TeV-scale string theory.

Gravity not tested at $\lesssim 1\,\text{mm}$

The reason is that (residual) electromagn. forces dominate, eg

for two H atoms : $$\frac{F_{\text{Van der Waals}}}{F_{\text{4d gravity}}} \sim \left(\frac{1\,\text{mm}}{r}\right)^5$$

Two types of expts:

↳ CAVENDISH TYPE (torsion balance) : measure deviations from inverse-square law

Suspend mass inside hollow cylinder & look for net force

↳ CASIMIR FORCE expts:

measure rapid variation with distance ($\sim 1/r^4$) of force between conducting or dielectric plates.

Considered in past to put limits on light scalars with gravitational strength couplings

Moody, Wilczek '84
De Rujula '87
Stacy '87

string moduli

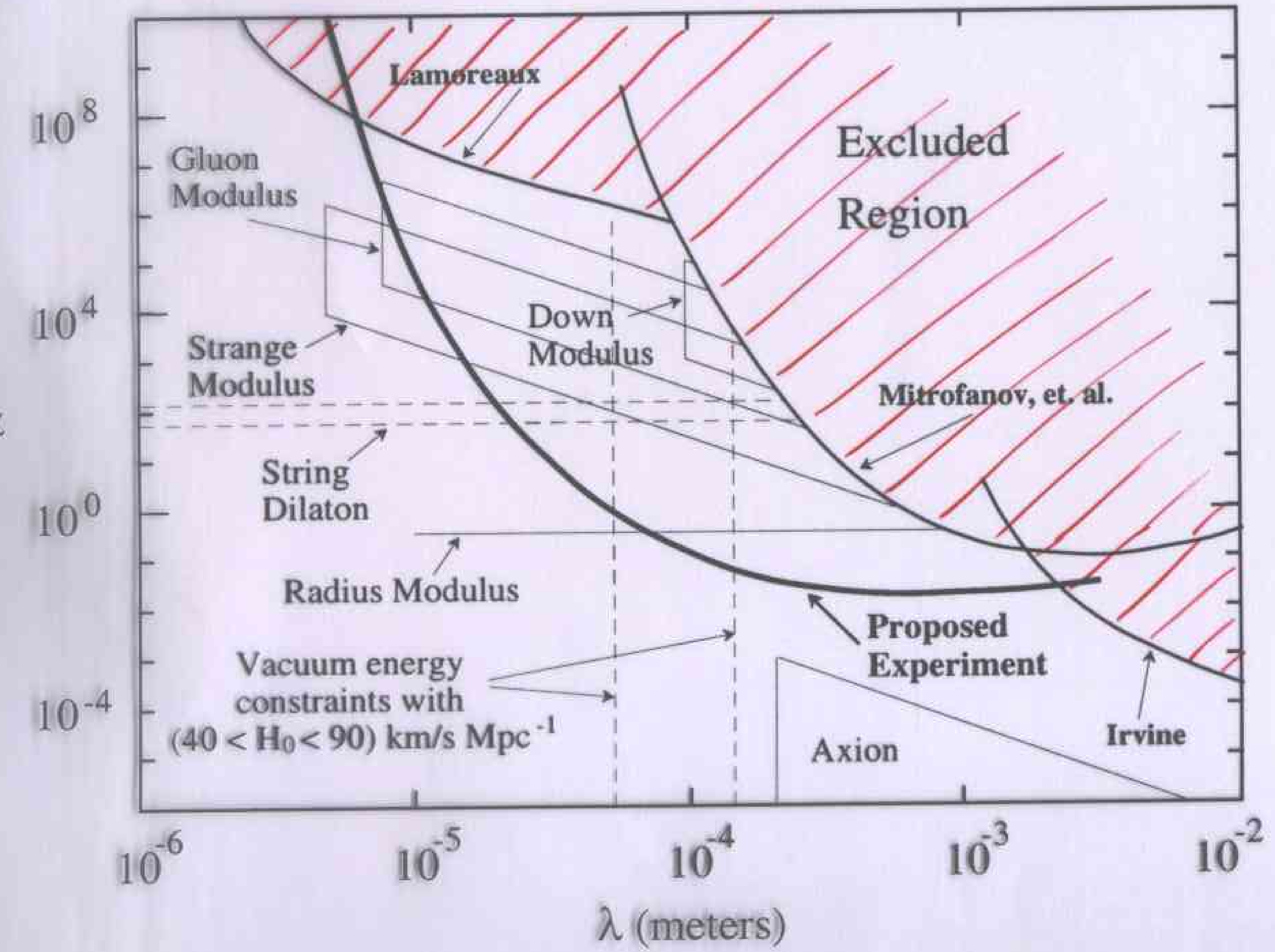
Taylor, Veneziano
Ellis, Tsamis, Voloshin
Kounnas, Pavel, Zwirner
Binetruy, Dudas
Dimopoulos, Giudice
Antoniadis, Dimopoulos, Dvali
Halyo
⋮

Similar limits for KK excitns of graviton

(though detailed analysis model-dependent: composition dependence of new forces, attractive/repulsive etc)

LIMITS ON NEW SUB MM GRAVITNL INTERACTIONS

from: Long, Chan, Price
hep-ph/9805217



Yukawa-force parametrization

$$V = - \frac{G m_1 m_2}{r}\left[1+\alpha e^{-r/\lambda}\right]$$

What about other restrictions ?

↳ PRECISION OBSERVABLES
& COMPOSITENESS BOUNDS

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no significant model-independent restrictions on framework, eg

$$\mathcal{O}_{4\text{-fermi}} = \frac{1}{\Lambda^2}(\bar{\psi}\psi)^2 \text{ constrained}$$

from LEP to $\Lambda \gtrsim$ TeV

similarly

$$\mathcal{O}_{g-2} = \frac{m_e}{\Lambda^2}\bar{\psi}\sigma_{\mu\nu}F^{\mu\nu}\psi$$

↑ because violates chiral sym.

gives $\frac{\delta(g-2)}{g-2} \sim \frac{1}{\alpha}\left(\frac{m_e}{\Lambda}\right)^2 \lesssim 10^{-10}$ for $\Lambda \gtrsim$ TeV

much below expt. uncertainty $(\sim 10^{-8})$

Arkani-Hamed, Dimopoulos, Dvali
Kostelecky, Samuel
Antoniadis, Benakli, Pomarol, Quiros
Nath, Yamaguchi
Marciano
Rizzo . . . . .

↳ EXOTICA

need to suppress proton decay,
large flavor violation in K-system .....

One type of model-independent rare event: emission of gravitons in bulk

- Model-independent since coupling to gravity universal:

$$\int d^{4+n}x \left\{ \frac{M_I^{2+n}}{g_I^2} \mathcal{L}_{GRAV} + \frac{1}{g_I} \delta^{(n)}(x_\perp) \mathcal{L}_{SM} \right\}$$

'form factor' cuts off transverse momenta $\sim M_I$

- Weak but can build up due to phase-space basic conclusion:

signal strong when QG becomes strong, power-suppressed at lower E, $M_I \gtrsim$ TeV currently safe.

Giudice, Rattazzi, Wells
Mirabelli, Perelstein, Peskin
Han, Lykken, Zhang
Hewett
Rizzo
Mathews, Raychaudhuri, Sridhar
Shiu, Shrock, Tye
⋮

Can think of other constraints:

eg, high-E cosmic rays? but diffractive scattering

supernova cooling

⋮

from: Giudice, Rattazzi, Wells
hep-ph/9811291

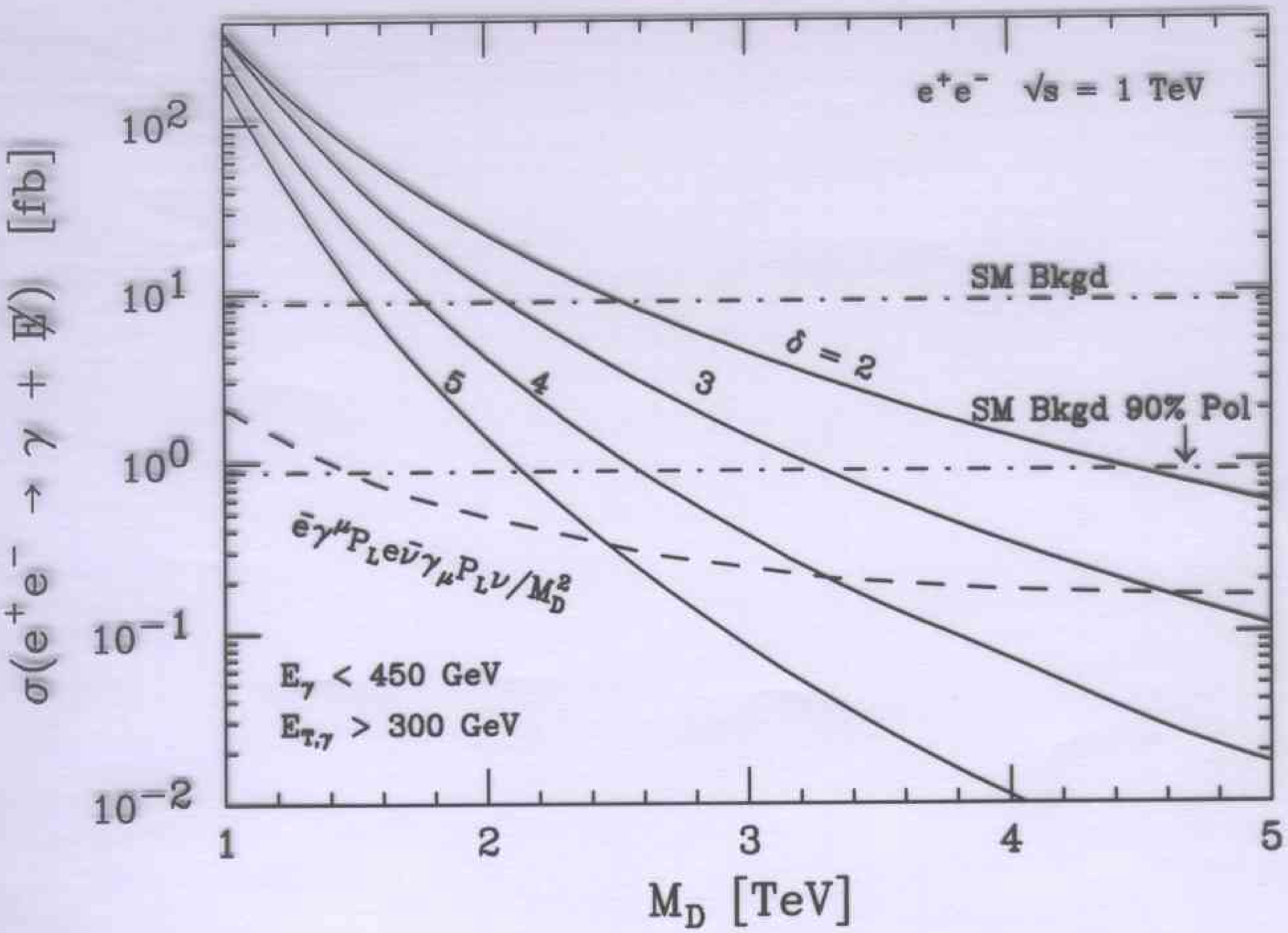

Figure 2: Total $e^+e^- \to \gamma +$ nothing cross-section at a 1 TeV centre-of-mass energy e^+e^- collider. The signal from graviton production is presented as solid lines for various numbers of extra dimension ($\delta = 2, 3, 4, 5$). The Standard Model background for unpolarized beams is given by the upper dash-dotted line, and the background with 90% polarization is given by the lower dash-dotted line. The signal and background are computed with the requirement $E_\gamma < 450\,\text{GeV}$ in order to eliminate the $\gamma Z \to \gamma\bar{\nu}\nu$ contribution to the background. The dashed line is the Standard Model background subtracted signal from a representative dimension-6 operator.

$e^+e^- \to \gamma +$ bulk graviton

polarized beam reduces background
from virtual W exchange

From: Giudice, Rattazzi, Wells
hep-ph/9811291

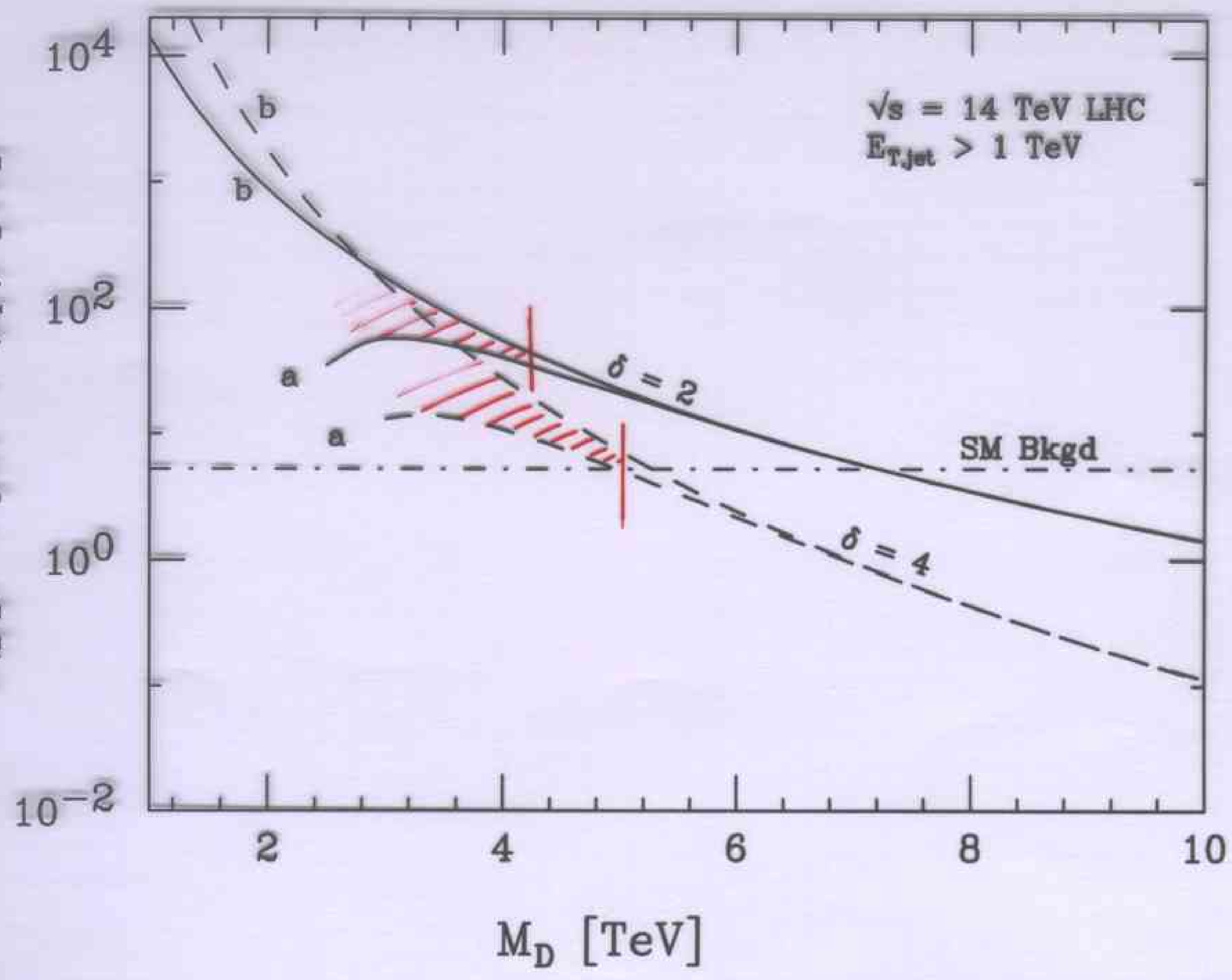

Figure 4: The total jet + nothing cross-section versus M_D at the LHC integrated for all $E_{T\,\text{jet}} > 1$ TeV with the requirement that $|\eta_{\text{jet}}| < 3.0$. The Standard Model background is the dash-dotted line, and the signal is plotted as solid and dashed lines for $\delta = 2$ and 4 extra dimensions. The **a** (**b**) lines are constructed by integrating the cross-section over $\hat{s} < M_D^2$ (all $\hat{s}$).

PP → jet + bulk graviton

to left of |
effective theory
cannot be trusted