I. Antoniadis

Strings 99

Mass scales in string theories

Outline:

- large dimensions in heterotic string
- TeV strings

  type I : submm transverse dims

  type II : infinitesimal coupling
- duality relations to heterotic
- * - susy breaking
- Experimental tests / conclusions

* see also Sagnotti's talk

- gauge hierarchy / unification :

  see Bachas' talk

At what energies string theory becomes important ?

traditional thought: at $M_P \sim 10^{19}$ GeV

consistent with old view in perturbative heterotic theory:

single scale ⇒ UV cutoff

$$M_H \sim g M_P \simeq 10^{18} \text{ GeV}$$

$$\lambda \sim \sqrt{V} < 1$$

weak coupling ⇒ $V \sim$ string size

However physical motivations ⇒

large volume may be relevant

- unification : M_H vs M_{GUT}
- susy by compactification

Spontaneous ~~susy~~ by compactification (perturbatively)

10d → 4d on a compact 6d space

$\Rightarrow m_{3/2} \sim m_{1/2} \sim 1/R$ ← size of an internal dimension

I.A. - Bachas - Lewellen - Tomaras '88

$\Rightarrow$ $R^{-1} \sim \text{TeV}$ I.A. '90

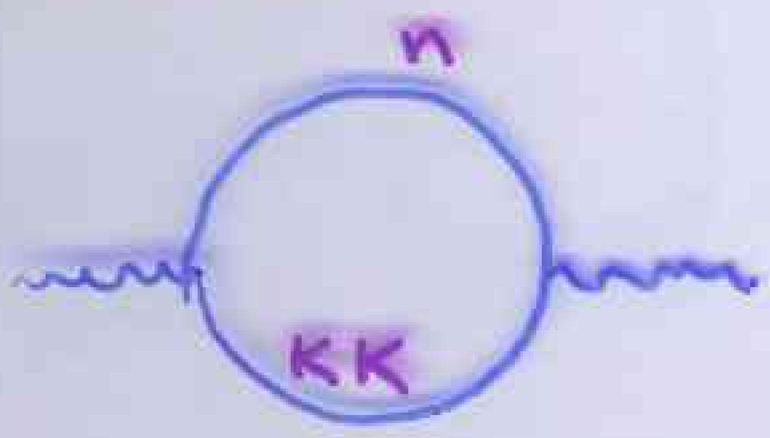
exp.: spectacular prediction

tower of KK excitations for SM particles

$X \equiv X + 2\pi R \Rightarrow p = \frac{n}{R} \quad n = 0, \pm 1, \ldots$

$$m_n^2 = m_0^2 + \frac{n^2}{R^2}$$

th. problem: they contribute to β-functions for $E \gg R^{-1}$



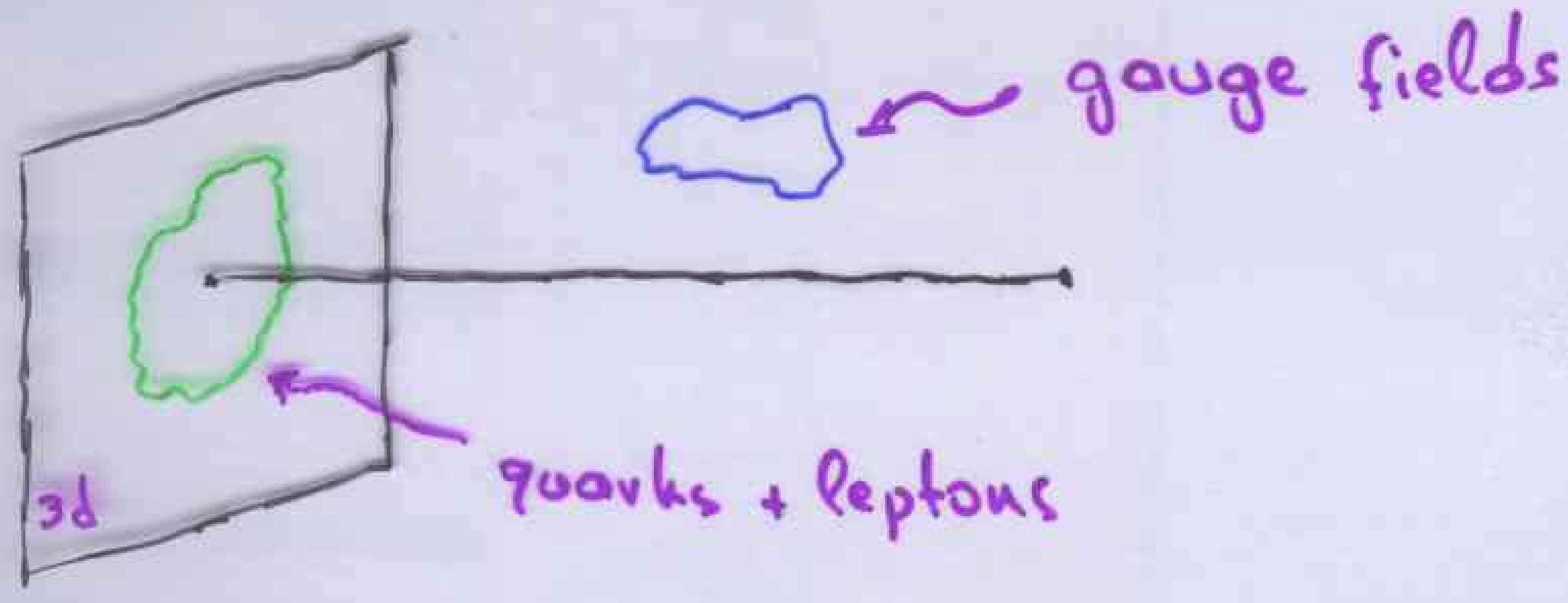
$\Rightarrow$ log evolution becomes power $g^2 R$

$\Rightarrow$ very rapidly in a non-perturbative domain way out: vanishing of β-functions level by level I.A. '90

e.g. KK into $\mathcal{N}=4$ multiplets

1 vector + 4 fermions + 6 scalars

⇒ special models: orbifold examples



other couplings (Yukawa's, etc) ? more conditions

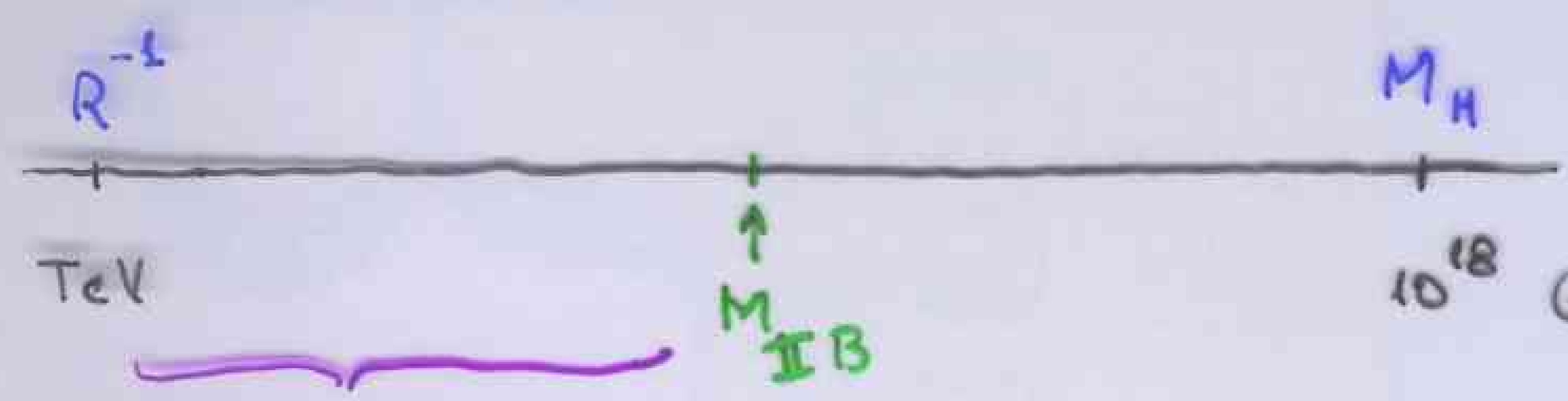
strong coupling can be addressed using string dualities '96

$\lambda \to 1/\lambda$

strong weak

strongly coupled heterotic: type I/I', IIA/B or M-theory

- one large dim ⇒ IIB   I.A.-Pioline '99



$\lambda \lesssim 1$

non-trivial fixed-point theory: tensionless string

⇒ all conditions of soft UV behavior

- two or more large dims ⇒ I/I', IIA

but $M_{dual} \lesssim R^{-1} \sim$ TeV !

In general: M_{str} arbitrary parameter Witten '96

why not at TeV ? Lykken '97

$M_{str} \sim TeV \Rightarrow$ nullification of gauge hierarchy

(I.A.) - Arkani Hamed - Dimopoulos - Dvali '98

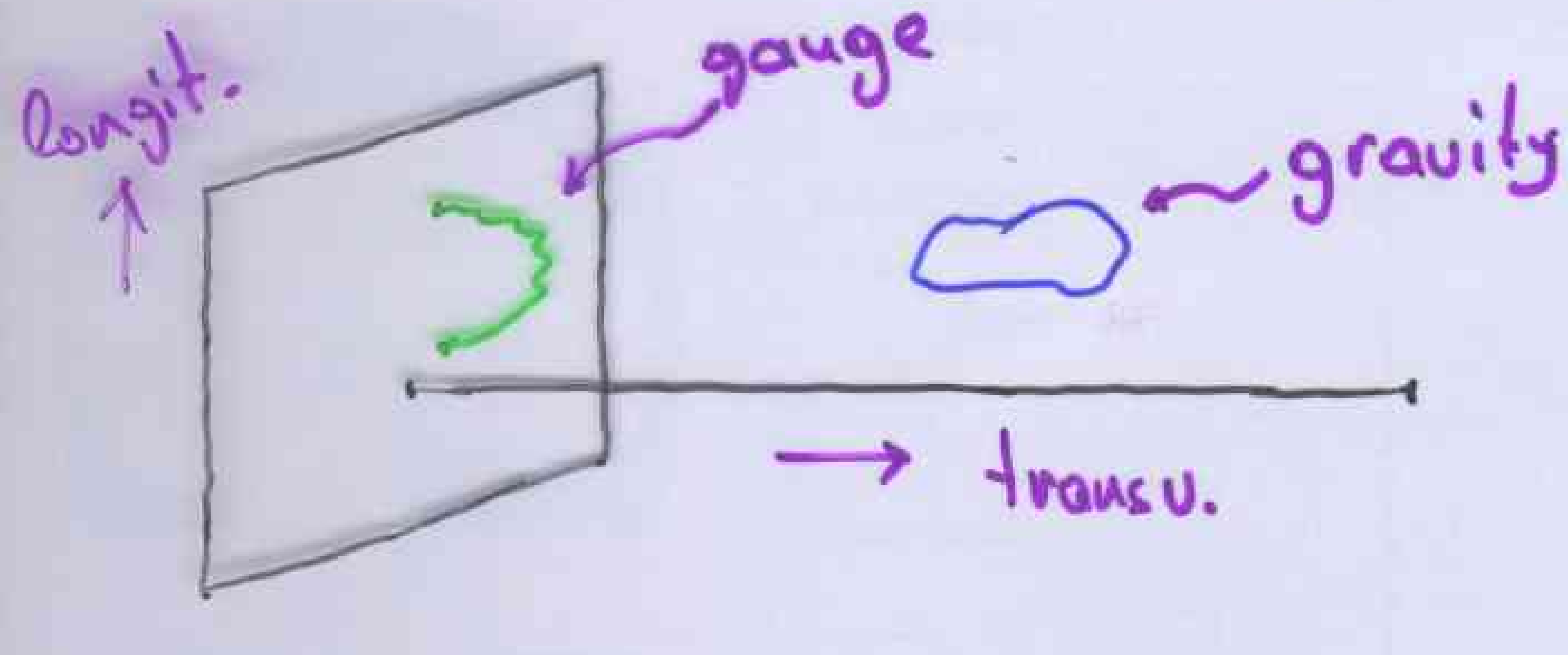
I.A. - Bachas '98

type $I/I' \Rightarrow$ submm dims

type $II \Rightarrow$ tiny coupling

Type I: closed strings → gravity

open strings → gauge sector on D-branes



weak coupling ⇒ longitudinal dims $\sim l_I \equiv M_I^{-1}$

transverse dims : no constraint

p dims of radius r

$\Rightarrow$

6-p " " ℓ_I

$$M_P^2 = \underbrace{\frac{1}{g^2} M_I^{2+p}}\ r^p$$

$M_{P(4+p)}^{2+p}$ Planck scale of 4+p dims

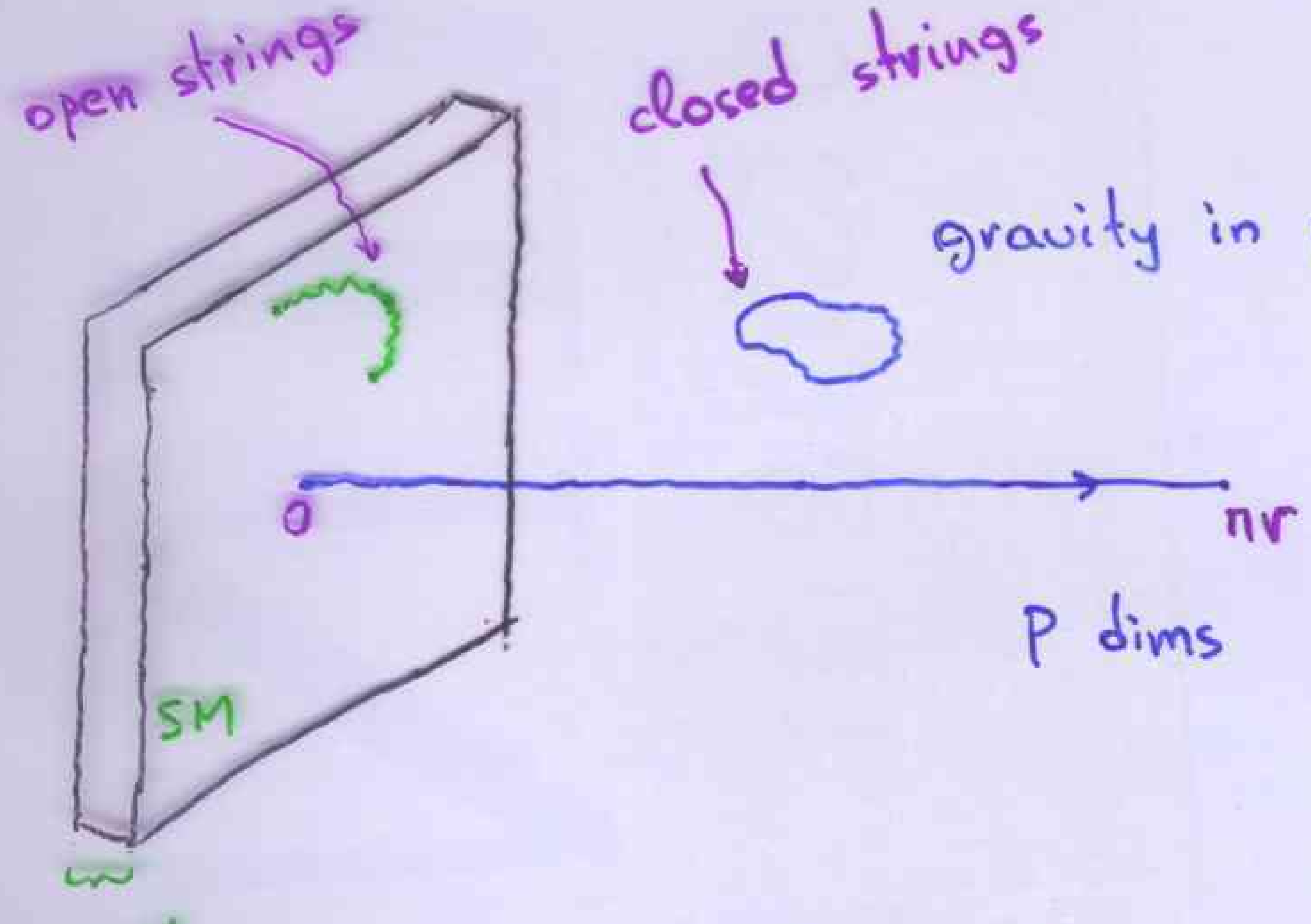
Largeness of $M_P/M_I \Rightarrow$ extra-large r

string coupling $\lambda_I = g^2$

$p = 1 \quad \Rightarrow \quad r \simeq 10^8$ km   excluded

2	.1 mm	possible if SM on a "3-brane"
⋮		
6	.1 fm	

⇒ no KK modes



TeV^{-1}: 3+ extra possible TeV^{-1} dims $(6-p)$

several exp constraints $\Rightarrow M_I \gtrsim$ TeV

most severe: graviton emission on cooling of supernovae

$\Rightarrow M_{P(6)} \gtrsim 50$ TeV $\quad (p=2)$ A-H-D-D

Cullen- Perelstein '99

Type II strings

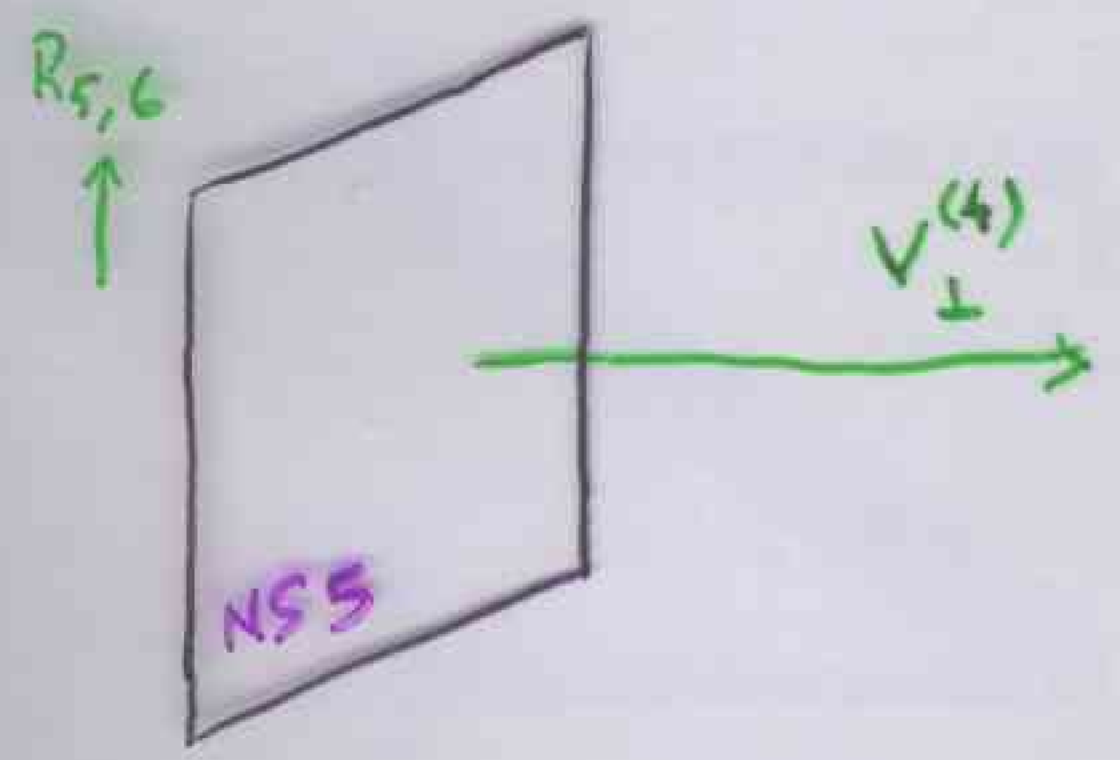
I.A. - Pioline '99

Non abelian symmetries : non-perturb on a NS 5-brane

localized at singularities of the internal manifold

e.g. IIA in $d=6$: D2 branes wrapped around collapsing

2-cycles of a singular K3



$$\frac{1}{\alpha_G} = R_5 R_6 M_{II}^2$$

$$\lambda_{6A} = \lambda_{IIA} \Big/ \sqrt{V_\perp^{(4)} M_{II}^2}$$

$$M_P^2 = \frac{1}{\alpha_G} \frac{1}{\lambda_{6A}^2} M_{II}^2$$

new possibility: largeness of $M_P \Rightarrow$ superweak string coupling

e.g. all radii $\sim l_{II} \sim \mathrm{TeV}^{-1}$, $\lambda_{IIA} \simeq 10^{-14}$

- No strong gravity at TeV

- only signal: KK modes with gauge interactions ($R_{5,6}$)

  - KK in $N=4$ susy

  - no KK for quarks + leptons (localized every where)

$R_5 R_6 \sim \ell_{II}^2$ but $R_5 \gg \ell_{II}$ $\Rightarrow$ $R_6 \ll \ell_{II}$

T-duality to <u>IIB</u>: $R_6 \to \ell_{II}^2 / R_6$, $\lambda_{IIA} \to \lambda_{IIB} \frac{\ell_{II}}{R_6}$ $\Rightarrow$

IIB: $\frac{1}{g^2} = \frac{R_5}{R_6} \Rightarrow R_5 \sim R_6 \sim R$

$$M_p^2 = \frac{1}{g^2} \frac{R^2}{\lambda^2_{6B}} M_{II}^4 \Rightarrow \lambda_{6B} < 1 : \quad M_{II} < \left(M_p / R\right)^{1/2}$$

new possibility: $R \sim \text{TeV}^{-1}$, $M_{II} \sim 10^{11}$ GeV, $\lambda_{IIB} \sim 1$

- strong gravity at 10^{11} GeV
- main signal as in IIA
- only example of large "longitudinal" dims at weak string coupling

$R^{-1} < E < M_{II}$: gauge interactions are described by 6d

tensionless string (non trivial fixed-pt theories)

↑

D3 branes around collapsing 2-cycles

	long. dims (gauge) TeV^{-1}	transv. dims (gravity)	gravity scale	string scale	GUT scale
type I	6-p	p mm - fm	TeV	TeV	TeV - 10^{16}
type II A	2	TeV	10^{19}	TeV	10^{16}
type II B	2	10^{11}	10^{11}	10^{11}	10^{11} - 10^{16}

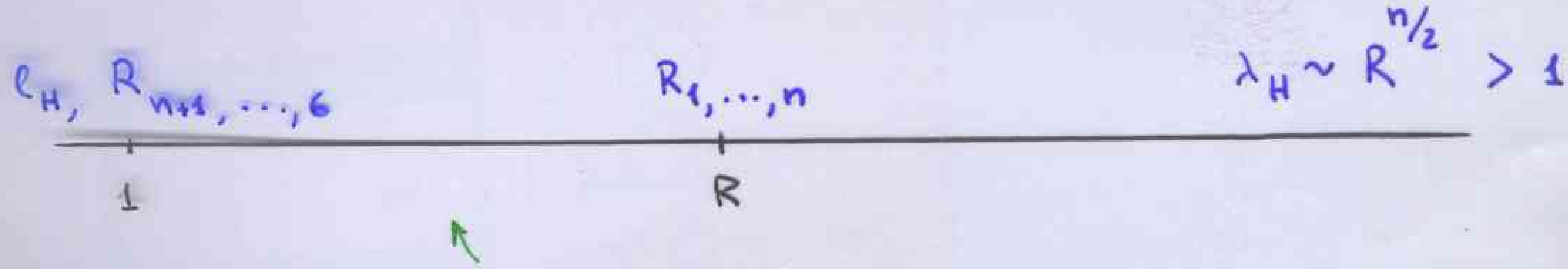
Are there more possibilities?

presumably No because these describe

heterotic string with any number of large dims

Heterotic with n dims at $R > \ell_H = M_H^{-1}$

$6-n$ " " ℓ_H



$n=1 \Rightarrow$ IIB : $\ell_{II} \sim \sqrt{R}$

$n=2,3 \Rightarrow$ IIA : $\ell_{II} \sim R$

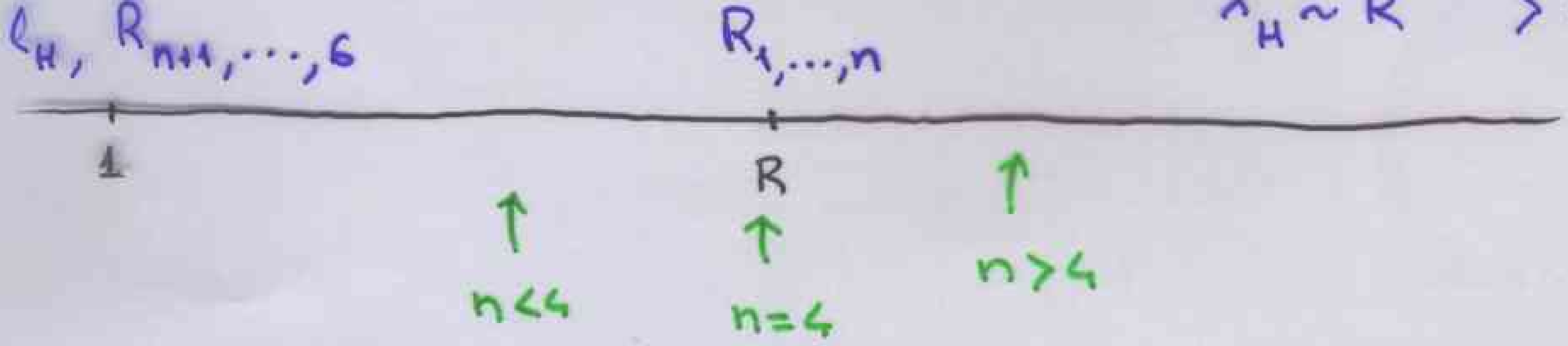
$n \geq 4 \Rightarrow$ type I : $\ell_I \gtrsim R$

Relation with heterotic

Heterotic with n dims at $R > \ell_H$

$6-n$ " " $\ell_H \equiv M_H^{-1}$

$\lambda_H \sim R^{n/2} > 1$



Type I : $\lambda_I = \frac{1}{\lambda_H} < 1$ $\ell_I = \lambda_H^{1/2}\,\ell_H \sim R^{n/4} > 1$

however some dims $R_i < \ell_I \Rightarrow$

closed string: very light winding modes $\sim \frac{R_i}{\ell_I^2} < 1$

$\Rightarrow$ T-duality $R_i \rightarrow \tilde{R}_i = \frac{\ell_I^2}{R_i}$

$$\lambda_I \rightarrow \tilde{\lambda}_I = \lambda_I \frac{\ell_I}{R_i} \nearrow$$

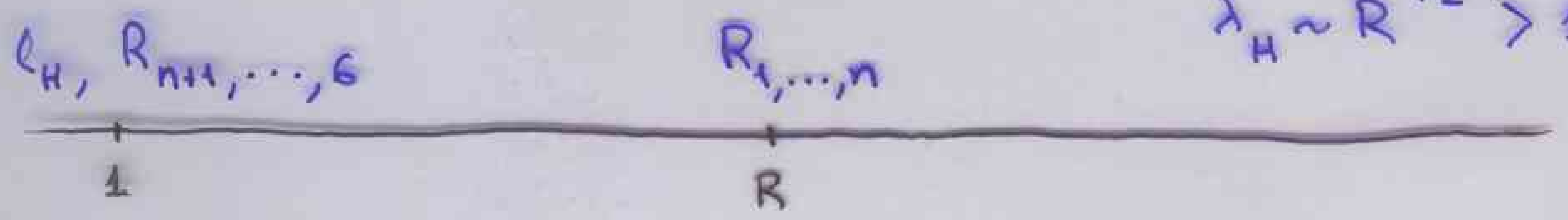
$\tilde{\lambda}_I < 1 \Rightarrow n \geqslant 4$ $\tilde{\lambda}_I \sim 1$

Relation with heterotic

Heterotic with n dims at $R > \ell_H$

$6-n$ " " $\ell_H \equiv M_H^{-1}$

$\lambda_H \sim R^{n/2} > 1$



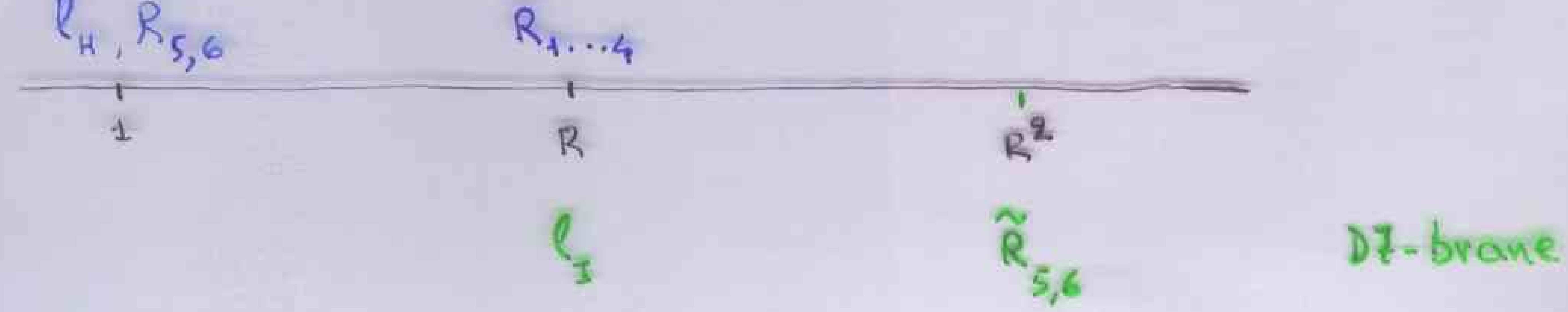
Type I : $\lambda_I = \frac{1}{\lambda_H}$ $\quad \ell_I = \lambda_H^{1/2} \ell_H$

Type IIA in $d=6$: (on K3 to break half susy's)

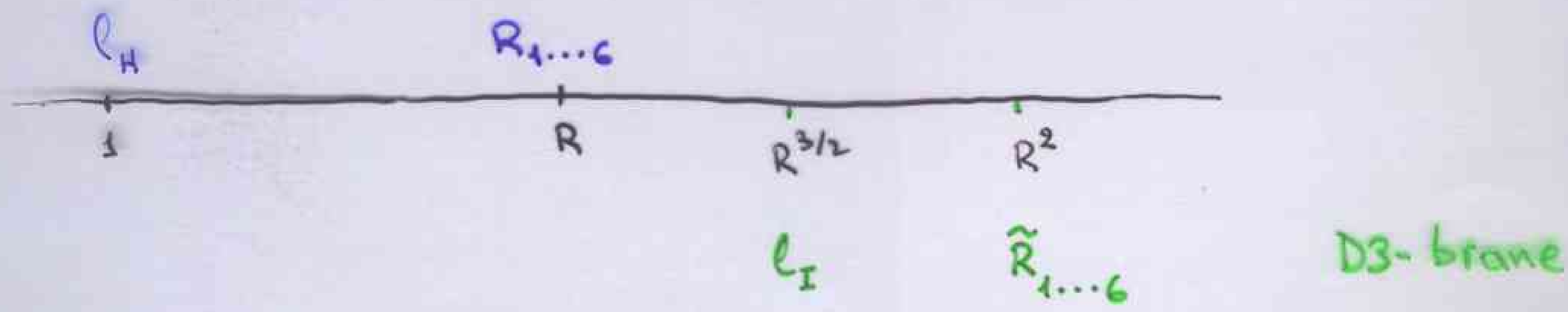
$$\lambda_{6A} = \frac{1}{\lambda_{6H}} \qquad \ell_{II} = \lambda_{6H} \ell_H$$

how T^4 is mapped on K3 ?

n = 4



n = 6



what about $n = 1, 2, 3$?

M-theory on

$$I(R_I) \times S^1(R_1) \times T^3(R_2, R_3, R_4)$$

$R_{11} \equiv R_I \Rightarrow$ Het $E_8 \times E_8$ on $T^4(R_1, R_2, R_3, R_4)$

$R_{11} \equiv R_1 \Rightarrow$ IIA on $K3 \simeq I(R_I) \times T^3(\tilde{R}_2, \tilde{R}_3, \tilde{R}_4)$

$R_{11} = \lambda \ell$

$\ell_M^3 = \lambda \ell^3$

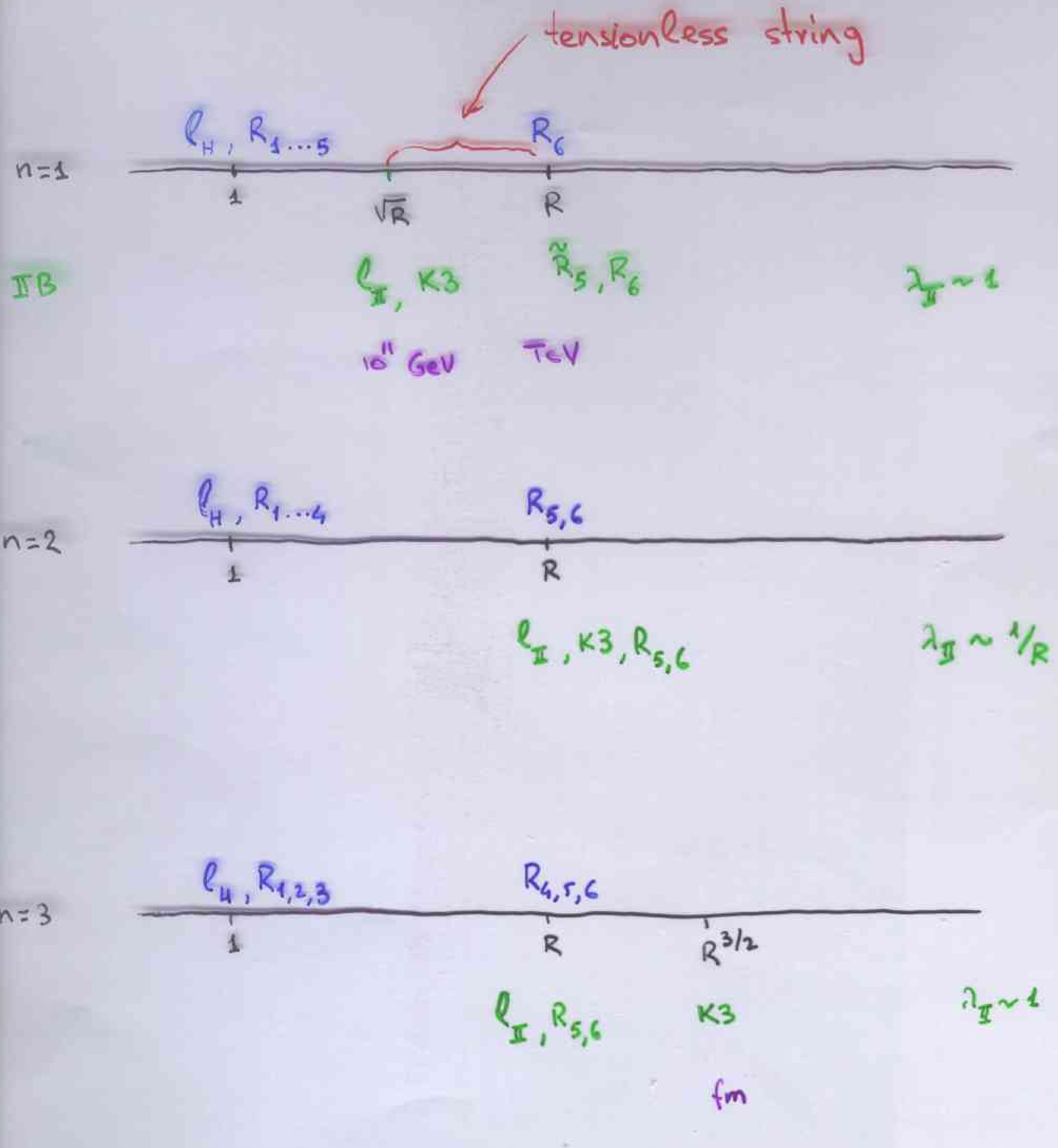
$$\tilde{R}_i = \frac{\ell_M^3}{R_j R_k} \Rightarrow$$

Obers-Pioline '98

$R_1 \longleftrightarrow V_{K3}^{1/2}$

$V_{T_4}^{1/2} \longleftrightarrow R_I$

$$\frac{R_i}{R_j} = \frac{\tilde{R}_i}{\tilde{R}_j}$$


tensionless string
$l_H, R_{1\ldots5}$
R_6
n=1
1
$\sqrt{R}$
R
IIB
l_{II}, K3
$\tilde{R}_5, R_6$
$\lambda_{II} \sim 1$
10^{11} GeV
TeV
$l_H, R_{1\ldots4}$
$R_{5,6}$
n=2
1
R
l_{II}, K3, $R_{5,6}$
$\lambda_{II} \sim 1/R$
$l_H, R_{1,2,3}$
$R_{4,5,6}$
n=3
1
R
$R^{3/2}$
$l_{II}, R_{5,6}$
K3
$\lambda_{II} \sim 1$
fm

Do we need susy if $M_{str} \sim$ TeV ?

Type I : non susy string models $\Rightarrow$

$$\Lambda_{bulk} \sim M_I^{4+p} \Rightarrow \Lambda_{brane} \sim M_I^{4+p} r^p \sim M_I^2 M_P^2$$

analog of quadratic div. to Λ in softly broken susy

$Str\, M^2$

absence of quadratic sensitivity :

$$\Lambda_{brane} \sim M_I^4 \Rightarrow \Lambda_{bulk} \sim M_I^4 / r^p$$

satisfied if appoximate susy in the bulk

e.g. susy is broken primordially only on the brane

A-A-D-D '98

Type II : may be not (IIA)

$$\text{IIB}: \quad m_{susy} \sim R^{-1} \qquad M_{IIB} \sim (m_{susy} M_P)^{1/2}$$

$\Rightarrow$ susy spont. broken at TeV

Brane susy breaking in type I theory

I.A. - Dudas - Sagnotti to appear

type IIB superstring / Ω (L $\leftrightarrow$ R) projection

$\Rightarrow$ O9 and O5 orientifold planes

$\Rightarrow$ open strings : D9 and D5 branes

tadpole cancellations $\equiv$ vanishing of the total RR-charge in compact space

O-planes : -ve D-branes : +ve

$\Rightarrow$ absence of gauge + gravitational anomalies

However sometimes O5 : +ve charge $\Rightarrow$ some $O\bar{5}$

$\Rightarrow$ naively no solutions to tadpole conditions

Solution: introduce some $D\bar{5}$ branes

$\Rightarrow$ break supersymmetry !

Consistent chiral models:

- RR tadpole cancellations ⇒ no anomalies
- No tachyons
- SUSY is broken on $D\bar{5}$ branes
- NS tadpoles ⇒ (tree-level) potential

localized on the (non-susy) branes

explicit toy examples:

- $T^4/\mathbb{Z}_2$: change Ω projection in the twisted sector

17 tensor multiplets

- $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ with discrete torsion

see Sagnotti's talk

No susy in our world (brane)

but it may exist 1 mm away!

to protect the gauge hierarchy against gravit. corrections

Prediction: possible new forces at submm scales

e.g. light scalars: $\frac{(\text{TeV})^2}{M_p} \sim 10^{-4}\,\text{eV} = 1\,\text{mm}^{-1}$

modulus $\equiv \ln r$

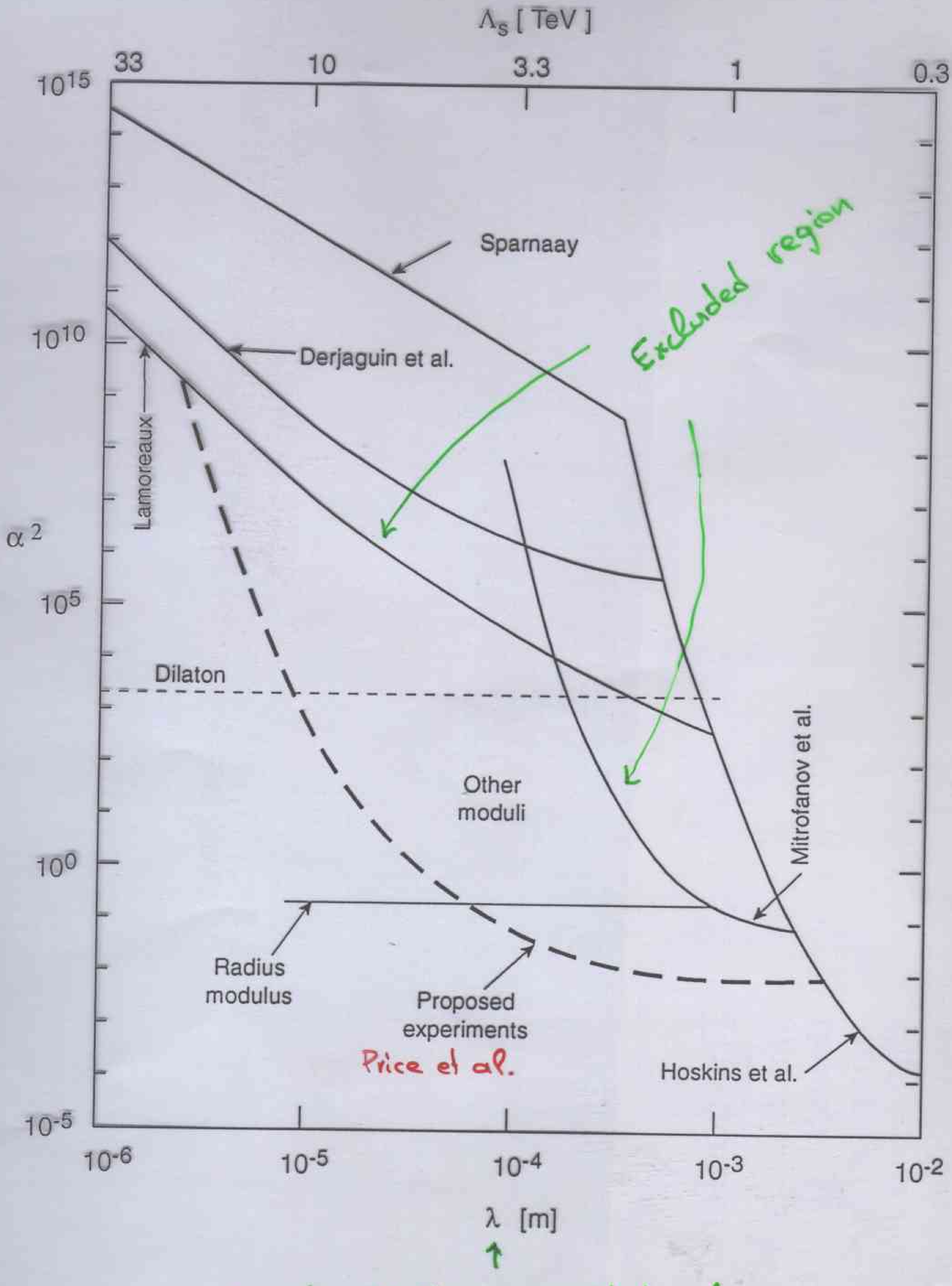
coupling to nucleons relative to gravity:

$$\frac{1}{m_N}\frac{\partial m_N}{\partial \ln r} = \frac{\partial \ln \Lambda_{QCD}}{\partial \ln r} \qquad m_N \sim \Lambda_{QCD} \sim e^{-\frac{1}{b_{QCD}}\frac{2\pi}{\alpha_{QCD}}}$$

$$\sim \frac{\partial}{\partial \ln r}\alpha_{QCD}$$

$\mathcal{O}(1)$ in models with log sensitivity in r e.g. $d_\perp = 2$

$\Rightarrow$ can be experimentally tested



Λ_s [TeV]
33
10
3.3
1
0.3
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
α^2
Sparnaay
Excluded region
Derjaguin et al.
Lamoreaux
Dilaton
Other moduli
Mitrofanov et al.
Radius modulus
Proposed experiments
Price et al.
Hoskins et al.
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
λ [m]
Van der Walls ≃ gravitational

Conclusions

Completely new and exciting physics

→ Spectacular experimental predictions

- Particle accelerators:

KK resonances of TeV^{-1} dimensions

RR resonances with higher spin of TeV strings

Graviton emission into the extra dims (mm → fm)

very different sparticle spectrum

- Testing gravity in (sub) mm region:

new scalar forces , change of Newton's law

→ Theoretical issues

challenge to address all problems at the TeV

proton stability, flavor and FCNC, Λ and large radius

stabilization, cosmology, model building ...