Possible low energy manifestations of strings and gravity

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1. Motivations and low scale gravity proposals
2. Strings, branes and extra dimensions
3. Main experimental predictions
Beyond Einstein’s Gravity: Why?

- Quantum Mechanics
- Unification of all fundamental forces

Quantum Mechanics + Special Relativity $\Rightarrow$ Quantum Field Theory

Standard Model of electroweak + strong interactions

Quantum Mechanics + General Relativity $\Rightarrow$ String Theory

Point particle $\rightarrow$ extended objects

- $\rightarrow$ particles $\equiv$ string vibrations

Framework for unification of all interactions

Mass scale: String tension $M_s \leftrightarrow$ string size: $l_s$
cordes ouvertes

cordes fermées
**Experiment:** Relativistic dark energy 70-75% of the observable universe

negative pressure: \( p = -\rho \) \( \Rightarrow \) cosmological constant

\[
R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \Rightarrow \rho\Lambda = \frac{c^4\Lambda}{8\pi G} = -p\Lambda
\]

Two length scales:

- \([\Lambda] = L^{-2} \leftarrow \) size of the observable Universe
  
  \[\Lambda_{\text{obs}} \approx 0.74 \times 3H_0^2 / c^2 \approx 1.4 \times (10^{26} \text{ m})^{-2}\]
  
  Hubble parameter \( \approx 73 \text{ km s}^{-1} \text{ Mpc}^{-1}\)

- \([\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow \) dark energy length \( \approx 85 \mu\text{m}\)

\( \Rightarrow \) Gravity modification at large (cosmological) and short distances? [8]
Mass hierarchy problem

Higgs mass: very sensitive to high energy physics \( m_H \sim \text{UV cutoff} \Lambda \)

why gravity is so weak compared to the other interactions? \( \Lambda = M_P \)

Possible answer (alternative to supersymmetry): Low UV cutoff \( \Lambda \sim \text{TeV} \)

- low scale gravity \( \Rightarrow \)
  
  large extra dimensions, warped dimensions, DGP localized gravity

- low string scale \( \Rightarrow \) low scale gravity, ultra weak string coupling

Experimentally testable framework:

- spectacular model independent predictions

- radical change of high energy physics at the TeV scale
Type I string theory ⇒ D-brane world

• gravity: closed strings propagating in $4 + 6$ extra dims

• gauge interactions: open strings
  with their ends attached on membranes
  Dirichlet branes or D-branes

Dimensions of finite size: $n$ transverse $6 - n$ parallel

calculability ⇒ $R_{\parallel} \sim l_{\text{string}}$ ; $R_{\perp}$ arbitrary

$$M_P^2 \sim \frac{1}{\alpha^2} M_s^{2+n} R_{\perp}^n$$

$\alpha = g_s$ : weak string coupling \[16\]

Planck mass in $4 + n$ dims: $M_*^{2+n}$

small $M_s/M_P$ : extra-large $R_{\perp}$

$$M_s \sim 1 \text{ TeV} \Rightarrow R_{\perp} \sim .1 - 10^{-13} \text{ mm} \ (n = 2 - 6) \ [8]$$

distances $< R_{\perp}$ : gravity $(4+n)$-dim → strong at $10^{-16}$ cm \[9\]
Braneworld

2 types of compact extra dimensions:

- parallel ($d_\parallel$): $\lesssim 10^{-16}$ cm (TeV)
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)
\[ R_\perp \lesssim 45 \ \mu m \text{ at } 95\% \text{ CL} \]

- dark-energy length scale \( \approx 85 \mu m \) [4] [6] [17]
Experimental predictions

- Particle accelerators
  - Large TeV dimensions seen by SM gauge interactions
    \[ \Rightarrow \text{KK resonances of SM gauge bosons} \] \cite{11}
    I.A. ’90
    if lightest KK stable \( \Rightarrow \) dark matter candidate Servant-Tait ’02
  - Extra large submm dimensions transverse
    \[ \Rightarrow \text{missing energy from gravity radiation in the bulk} \] \cite{12,20}
  - String physics and possible strong gravity effects \cite{14}

- Microgravity experiments \cite{17}
  - Gravity modifications at short distances
  - New submillimeter forces
LHC

27 kms
\[ R^{-1} = 4 \text{ TeV} \] [9]

I.A.-Benakli-Quiros '94, '99

![Graph showing dilepton mass distribution with curves for \( \gamma + Z \), \( \gamma \), and \( Z \) events per GeV.](image)
Angular distribution $\Rightarrow$ spin of the graviton [9]
### Limits on $R_\perp$ in mm

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<th>Experiment</th>
<th>$R_\perp (n = 2)$</th>
<th>$R_\perp (n = 4)$</th>
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Massive string vibrations

\[ M_n^2 = M_s^2 n \quad \text{maximal spin: } n + 1 \]

e.g. higher spin excitations of quarks and gluons with strong interactions

Low energies \implies\ indirect effects:

virtual exchanges \implies\ effective interactions e.g. four-fermion operators

direct bounds on the string scale: \( M_s \gtrsim 500 \text{ GeV} - 3 \text{ TeV} \)

Cullen-Perelstein-Peskin, I.A.-Benakli-Laugier '00

High energies \implies\n
- direct production: string physics

- strong gravity: production of micro-black holes? \[16\]

Giddings-Thomas, Dimopoulos-Landsberg '01
Universal deviation from Standard Model in jet distribution

\[ M_s = 2 \text{ TeV} \]

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger ’08
Energy threshold for black hole production:

\[ E_{BH} \approx M_s / g_s^2 \quad \leftarrow \text{string coupling} \]

Horowitz-Polchinski '96, Meade-Randall '07

- string size black hole: \( r_H \approx l_s = M_s^{-1} \)
- black hole mass: \( M_{BH} \approx r_H^{d-3} / G_N \quad G_N \approx l_s^{d-2} g_s^2 \)

weakly coupled theory \( \Rightarrow \) strong gravity effects occur much above \( M_s, M* \)

\( g_s \approx \alpha_{YM} \approx 0.1 \quad ; \quad \text{Regge excitations: } M_n^2 = M_s^2 n \quad \Rightarrow \quad \text{gauge coupling} \quad [6] \)

Energy threshold of \( n \)-th string excitation: \( E_n \approx M_s \sqrt{n} \quad \Rightarrow \)

production of \( n \approx 1 / g_s^4 \approx 10^4 \) string states before reach \( E_{BH} \quad [9] \)
SUSY in the bulk?

- global SUSY: no need to be there at least for hierarchy
- SUGRA: probably unbroken in the bulk ⇒
  very weakly broken (volume suppressed)
  New forces at submm scales e.g. radion, gauge fields
- Radion ≡ \( \ln V_\perp \)
  mass: \( (\text{TeV})^2/M_P \sim 10^{-4} \text{ eV} \rightarrow \text{mm range} \)
  coupling: \( \frac{1}{m} \frac{\partial m}{\partial \ln V_\perp} = \sqrt{\frac{n}{n+2}} \times \text{gravity} \) I.A.-Benakli-Maillard-Laugier '02
  ⇒ can be experimentally tested for all \( n \geq 2 \) [8]
- Light \( U(1) \) gauge bosons: no derivative couplings
  ⇒ for the same mass much stronger than gravity: \( \gtrsim 10^6 \)
Experimental limits on short distance forces

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

Radion: \( M_* \gtrsim 6 \text{ TeV} \) 95% CL  Adelberger et al. '06 [23]
an order of magnitude improvement in the range 10-200 nm

Decca et al '07
Randal Sundrum models

spacetime = slice of AdS$_5$  
our universe = 4d flat boundary

d$s^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$

UV-brane  
$y = 0$

IR-brane  
$y = \pi r_c$

- fine-tuned tensions:  $T = -T' = 24 M^3 k^2$  
$\Lambda = -24 M^3 k^2$

- exponential hierarchy:  $M_W = M_P e^{-2\pi kr_c}$  
$M_P^2 \sim M^3 / k$

- 4d gravity localized on the UV-brane, but KK gravitons on the IR
- main prediction: spin-2 resonances at the TeV scale
\[ m_n = c_n k e^{-2\pi kr_c} \quad c_n \simeq (n + 1/4) \text{ for large } n \]
weakly coupled for \( m_n < M e^{-2\pi kr_c} \quad \Rightarrow \quad k < M \)
- viable models: Standard Model gauge bosons in the bulk,
fermions near the UV-brane, Higgs on the IR-brane
- AdS/CFT duals to strongly coupled 4d field theories
  composite Higgs models, technicolor-type \( g_{YM} = M/k > 1 \) [9] [26]
Two Einstein-Hilbert actions in $4+n$ and $4$ dimensions

$$M_{2+n}^2 \int d^4x d^n y \mathcal{R}^{(4+n)} + M_P^2 \int d^4x \mathcal{R}^{(4)} \bigg|_{y=0} \Rightarrow M_{2+n}^2 \ p^2 \ (p^{-n} + r_c^n)$$

$y = 0$:

- $p^{2-n} \quad M_{2+n}^2 \ r_c^n \quad p^2$

**short distances**: $p^{-1} \ll r_c \Rightarrow 4d$

**large distances**: $p^{-1} \gg r_c \Rightarrow (4+n)d$

**crossover scale**

However: “brane thickness” $w \Rightarrow$ important effects
\[ V(r) = -G \frac{m_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]
Friedman equations:

\[
H^2 \pm \frac{H}{r_c} = \frac{8\pi G_N}{3}\rho(t) \leftarrow 4 \text{dim energy density} \quad H = \frac{\dot{a}}{a}
\]

+ sign \implies \text{FRW cosmology extrapolating between 4d to 5d at large scales}

- sign \implies \text{self-accelerating solution at late times} \quad \text{Deffayet '01}

\implies \text{can account for dark energy if } r_c \simeq 10^{28} \text{ cm}

However: van Dan-Veltman-Zakharov discontinuity of massive gravity

\implies \text{new strong coupling scale at shorter distances:}

Vainshtein radius \( r_V = (r_c^2 w)^{1/3} \) \quad w: \text{UV cutoff}
\( n = 1: \quad M_P^2 = M^3 \; r_c \quad r_c \gtrsim 10^{28} \text{ cm} \Rightarrow M \lesssim 100 \text{ MeV} \)

\( n \geq 2: \) UV divergences in the bulk \( \Rightarrow \)

\( w = 0: \) always 4d behavior on the ‘brane’

\( w \neq 0: \) crossover scale becomes \( R_c = w \left( \frac{r_c}{w} \right)^{n/2} \)

\[
\begin{array}{c|c}
4d & \text{higher d} \\
\hline
R_c & \end{array}
\]

\( w \sim l_P \quad \Rightarrow \quad R_c \sim M^{-1}(M_P/M)^{n/2} \)

\( M \sim 1 \text{ TeV} \quad \Rightarrow \quad R_c \sim 10^{8(n-2)} \text{ cm} \gtrsim 10^{28} \text{ cm} \Rightarrow n \geq 6 \)

string realization: type II strings in non-compact Calabi-Yau manifolds

I.A.-Minasian-Vanhove ’02
Conclusions

TeV strings and large extra dimensions: Physical reality or imagination?

- Well motivated theoretical framework
  - with many testable experimental predictions
  - new resonances, missing energy

- Stimulus for micro-gravity experiments
  - look for new forces at short distances
  - higher dim graviton, scalars, gauge fields

But:
- unification has to be dropped
  - physics is radically changed above string scale

LHC: will explore the physics beyond the Standard Model