

MORE ABOUT APPARENT ENERGY / ELECTRIC CHARGE NON-CONSERVATION.

How is it RECONCILED WITH 4-dim. GRAVITY / ELECTROMAGNETISM AT LARGE DISTANCES?

4-dim. ELECTROMAGNETISM:

GAUSS' LAW: $\text{div } \vec{E} = 4\pi \rho_{e.m.}$

"INSTANTANEOUS" EQUATION, NO TIME DERIVATIVES

[UNLIKE "CAUSAL" EQUATIONS DESCRIBING PROPAGATION OF FIELDS]

GIVEN $\rho_{e.m.}$, ELECTRIC FIELD DETERMINED EVERYWHERE IN SPACE AT SAME TIME.

$$\vec{E} = \frac{\vec{r}}{r^3} Q$$

IF CHARGE IS NOT CONSERVED, ITS CHANGE SHOULD GIVE RISE TO CHANGE OF \vec{E} EVERYWHERE IN SPACE INSTANTANEOUSLY.

CONTRADICTION WITH CAUSALITY.

SAME WITH GRAVITY / ENERGY

$R^0_0 - \frac{1}{2} g^0_0 R = 8\pi G T^0_0 \Leftrightarrow$ GAUSS' LAW OF GR \cong NEWTON'S LAW

YET RS2 COMBINES

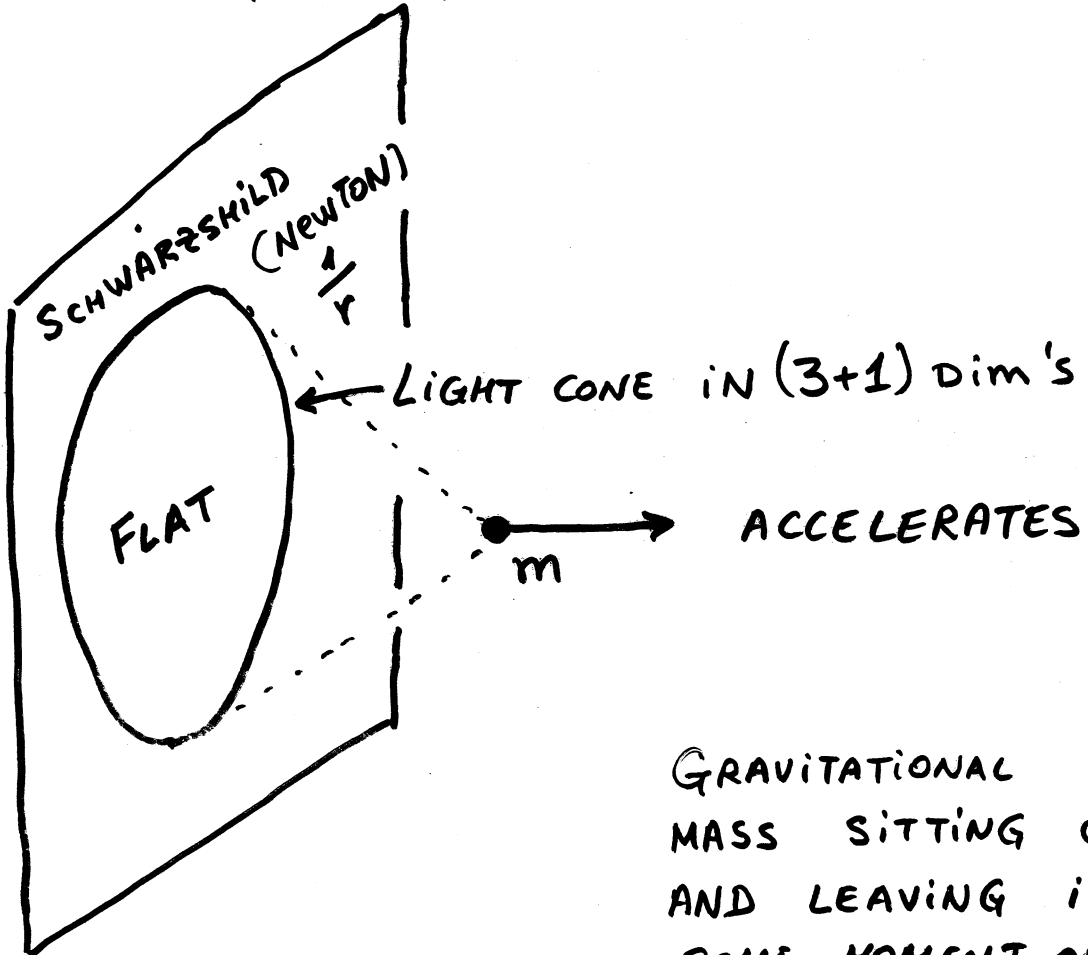
- 4-dim. GRAVITY ON BRANE
AT LARGE DISTANCES

- POSSIBILITY OF ENERGY FLOWING
AWAY FROM BRANE TO $y \rightarrow \infty$,
i.e., APPARENT ENERGY NON-CONSERVATION
FOR BRANE-BASED OBSERVERS, US.

IS THIS TRUE? CAN MATTER ESCAPE FROM
BRANE?

YES. QUANTUM MECH.: "K-K" MODES FROM
CONTINUUM \Leftrightarrow PARTICLES MOVING TO $y \rightarrow \infty$.

CLASSICALLY: TEST MASS IS
ACTUALLY REPELLED FROM BRANE.



GRAVITATIONAL FIELD OF
MASS SITTING ON BRANE
AND LEAVING IT AT
SOME MOMENT OF TIME.

NO PROBLEM WITH CAUSALITY

- Viewpoint #1 ; MULTIDIMENSIONAL:

GRAVITY NO LONGER 4-DIMENSIONAL
FOR SOURCES OUTSIDE BRANE

KEY: CONTINUUM OF KK gravitons

STARTING FROM $m^2 = 0$.

↕ adS/CFT

- Viewpoint #2 , BRANE-BASED

MASS DECAYED INTO CONFORMAL MATTER

THAT DISSIPATES ALONG LIGHT CONE.

THIS CONFORMAL MATTER INTERACTS WITH
BRANE PARTICLES GRAVITATIONALLY ONLY

EFFECTIVE 4D DESCRIPTION OF RS^2
IN TERMS OF CONFORMAL MATTER.

ELECTRIC CHARGE NON-CONSERVATION:

SIMILAR , BUT INTERPRETATION IN TERMS
OF CHARGED CONFORMAL MATTER QUESTIONABLE.

$e^- \rightarrow \text{NOTHING}$

CONTRADICTS NOTHING.

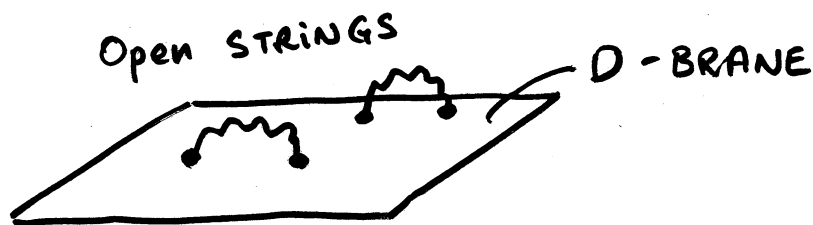
WOULD BE STRONGEST INDICATION OF
EXTRA DIMENSIONS

$\tau_{e \rightarrow \text{NOTHING}} > 6 \cdot 10^{24}$ yrs.

STRING/D-BRANE PICTURE OF QUASI-LOCALIZATION

Few NOTIONS OF STRING THEORY

- IN QUANTUM THEORY, STRING HAS QUANTIZED SPECTRUM OF STATES \Leftrightarrow PARTICLES. IN RELATIVISTIC THEORY, SOME OF THESE STATES (PARTICLES) MAY BE MASSLESS.
- GAUGE BOSONS, CHARGED PARTICLES ARE LOWEST STATES OF OPEN STRINGS.
- OPEN STRINGS HAVE ENDS ON D-BRANES.



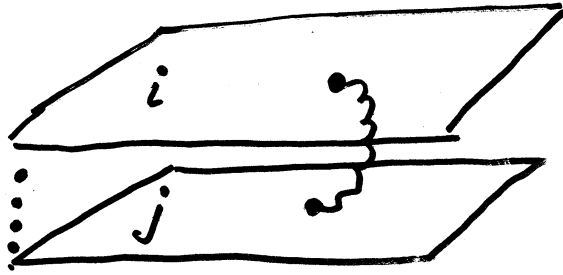
NB: D-BRANES MAY HAVE DIVERSE DIMENSIONALITIES. IN PARTICULAR, DIMENSIONALITY MAY BE THE SAME AS DIM'S OF ENTIRE SPACE \Rightarrow D-BRANE FILLS WHOLE SPACE.

GAUGE BOSONS PROPAGATE ALONG D-BRANES.

- STACK OF K COINCIDENT D-BRANES HAS $U(K)$ GAUGE THEORY ON ITS HYPER SURFACE



K^2 GAUGE BOSONS, ACCORDING TO # OF WAYS STRING ENDS CAN BE ATTACHED TO D-BRANES.



A^i_j

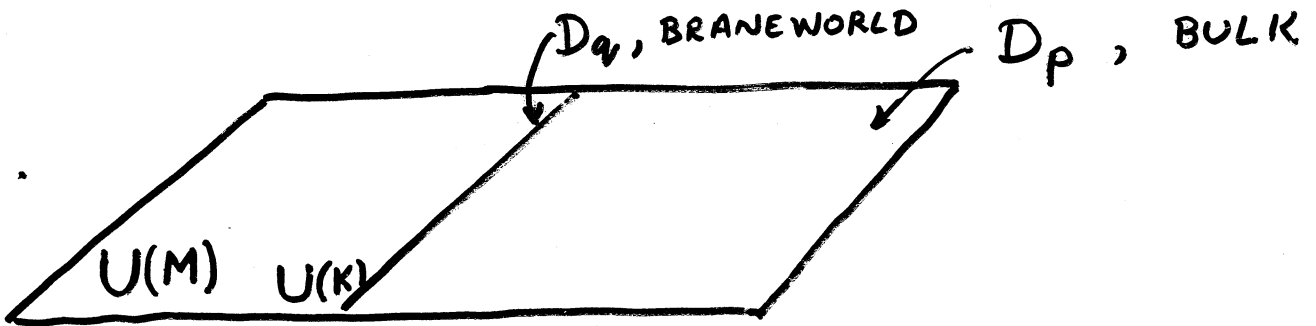
fundamental rep. (70)

(omitting space-time vector index)

anti-fundamental rep.

(fundamental) \times (anti-fundamental) = adjoint

- D-BRANES OF SMALLER DIMENSIONALITY q MAY SIT WITHIN D-BRANES OF LARGER DIMENSIONALITY p . CALL D_q BRANEWORLD, D_p BULK $U(K), U(M)$ - CORRESPONDING GAUGE GROUPS



THEN THERE ARE



$U(K)$ $U(M)$
p-p - STRINGS \Leftrightarrow BULK GAUGE FIELDS
(1, ADJOINT)



$q-q$ -STRINGS \Leftrightarrow BRANeworld GAUGE FIELDS
(ADJOINT, 1)



P-q - STRINGS \Leftrightarrow BRANeworld FIELDS
(FUNDAMENTAL, ANTIFUNDAM.)

↑
THESE CONTAIN SCALARS WRT
BRANeworld LORENTZ GROUP.

(7)

IF GAUGE SYMMETRIES ARE
UNBROKEN, CHARGED BRANEWORLD FIELDS,
BRANEWORLD $U(K)$ GAUGE BOSONS CANNOT
ESCAPE INTO BULK.

EFFECTIVE FIELD THEORY DESCRIPTION

$$S_{\text{EFF}} = \int_{D_p} d^p X F_{AB} F^{AB} \quad U(M) \text{ IN BULK}$$

$$+ \int_{D_q} d^q x F_{\mu\nu} F^{\mu\nu} \quad U(K) \text{ IN BRANEWORLD}$$

$$+ \int_{D_q} d^q x \text{tr} [D_\mu \Phi]^\dagger \cdot D_\mu \Phi + \dots$$

$$D_\mu \Phi = \partial_\mu \Phi - ig_K A_\mu \Phi - ig_M \Phi A_\mu$$

 Φ^x_m

fundamental under $U(K)$ antifundam. under $U(M)$

Symmetry breaking in braneworld:
 Φ gets v.e.v. (HIGGS PHASE ON D_q)

$$D_\mu \phi \rightarrow -i (g_K A_\mu \langle \phi \rangle + g_M \langle \phi \rangle A_\mu)$$

⇓

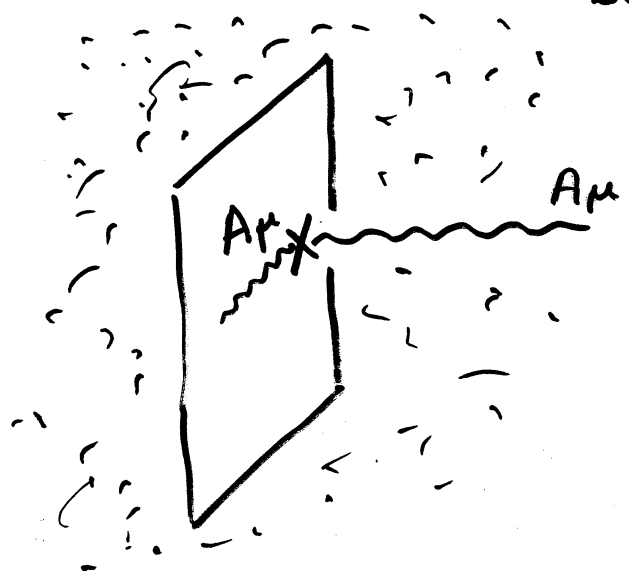
$$|D_\mu \Phi|^2 \rightarrow g_K^2 \langle \phi \rangle^2 A_\mu^2 + g_M^2 \langle \phi \rangle^2 A_\mu^2 + g_K g_M \langle \phi \rangle^2 A_\mu A_\mu$$

MASS FOR BULK GAUGE FIELD

Potential for bulk gauge field on brane:
 $\langle \phi \rangle^2 \neq 0$ on brane.

AWAY FROM BRANE, A_μ still massless

MIXING BETWEEN BRANE MASSIVE BRANEWORLD GAUGE FIELD AND MASSLESS BULK GAUGE FIELD.



"DECAY" WIDTH SMALL AT SMALL $\langle \phi \rangle$

$$\Gamma \sim \frac{g^4 \langle \phi \rangle^4}{M^3} \sim \frac{m_g^4}{M^3}$$

↑ characteristic scale OF UNDERLYING THEORY

⇓

INVISIBLE DECAYS ARE CHARACTERISTIC

TO D-BRANE CONSTRUCTIONS.

Fields carrying unbroken charges CANNOT ESCAPE. $e^- \rightarrow$ NOTHING

SUBSTANTIAL IF FUNDAMENTAL SCALE IN TeV RANGE.

SOME LESS UNDERSTOOD ISSUES:

1. VIOLATION OF LORENTZ INVARIANCE.

BACK TO WARPED GEOMETRY.

Imagine time and space HAVE DIFFERENT WARP FACTORS

HOW CAN THIS EMERGE IN NATURAL WAY?

$$ds^2 = a^2(y) dt^2 - b^2(y) d\vec{x}^2 - dy^2$$

• By rescaling t and \vec{x} :

$$a(0) = b(0) = 1, \text{ on the brane}$$

NO VIOLATION OF LORENTZ-INVARIANCE STRICTLY ON THE BRANE. 4-DIM. LORENTZ-INV.

VIOLATED IN BULK.

BRANE PARTICLES HAVE WAVE FUNCTIONS EXTENDING SLIGHTLY INTO BULK \Rightarrow LORENTZ-INV. SLIGHTLY VIOLATED.

SAY, SCALAR FIELD IN BINDING POTENTIAL $V(y)$:

$$\phi = e^{i\omega t - i\vec{k}\vec{x}} \cdot \phi_{m_0}(y)$$

Eigenvalue eqn. for frequency:

$$\omega^2 \phi = \frac{a^2(y)}{b^2(y)} \cdot \vec{k}^2 \phi + \mathcal{H} \phi$$

\uparrow TRANSVERSE OPERATOR

Our particle has WAVE FUNCTION ϕ_0 AT $\vec{k} = 0$;

$$\mathcal{H} \phi_0 = m_0^2 \phi_0 \quad ; \quad \omega(\vec{k} = 0) = m_0, \text{ rest mass.}$$

AT SMALL \vec{k} , TREAT

$$\frac{a^2(y)}{b^2(y)} \vec{k}^2 \quad \text{as perturbation}$$

\Downarrow

$$\omega^2(\vec{k}) = m_0^2 + c^2 \vec{k}^2$$

$$c^2 = \frac{\int d\mu(y) \frac{a^2(y)}{b^2(y)} |\phi_0|^2}{\int d\mu(y) |\phi_0|^2}$$

NOT UNIVERSAL;
depends on ϕ_0 .
DIFFERENT PARTICLES
HAVE DIFFERENT $\omega(\vec{k})$.

c close to 1 FOR NARROW $|\phi_0|^2$

(since $\frac{a(0)}{b(0)} = 1$) \Rightarrow weak violation of

4-dim. Lorentz-invariance.

• SURPRIZING POSSIBILITY

$$\omega^2 \phi = \frac{a^2(y)}{b^2(y)} \vec{k}^2 \phi + \mathcal{H} \phi$$

SUPPOSE LOWEST EIGENVALUE IS ZERO, $\mathcal{H} \phi = 0 \Rightarrow$
MASSLESS PARTICLE ON BRANE. ASSUME

$$\frac{a^2}{b^2} \rightarrow 0 \quad \text{AS } |y| \rightarrow \infty$$

\Downarrow

CONTINUUM STARTS AT ZERO ENERGY ω
EVEN FOR FINITE MOMENTUM \vec{k} . \Rightarrow MOVING
particles (even MASSLESS) get QUASI-LOCALIZED
The larger spatial momentum/energy, the
larger the width against escape into bulk.

2. LONG-DISTANCE MODIFICATION OF GRAVITY

MOTIVATED BY ACCELERATION OF UNIVERSE'S EXPANSION TODAY.

INSTEAD OF HAVING TINY COSMOLOGICAL CONSTANT, MODIFY GRAVITY AT COSMOLOGICAL DISTANCES.

OFF HAND: WHY NOT, IF GRAVITON IS QUASI-LOCALIZED.

NOT CLEAR WHETHER THERE EXISTS CONSISTENT AND TRACTABLE SET UP.

BEST CANDIDATE TO DATE - DGP.

3. COSMOLOGICAL CONSTANT PROBLEM

VACUUM ENERGY DENSITY OF OUR MATTER = TENSION OF OUR BRANE.

LET IT MAKE BULK CURVED, NOT BRANE.

DOES NOT WORK.

APPEARS HOPELESS.

TO SUMMARIZE :

EXTRA DIMENSIONS + BRANE WORLD

- OFFER FRAMEWORK TO ASK EXOTIC QUESTIONS (ENERGY/CHARGE NON-CONSERVATION, PROPERTIES OF CONFORMAL MATTER, VIOLATION OF NEWTON'S LAW...)
- SUGGEST A VARIETY OF EXOTIC PHENOMENA BOTH AT HIGH AND LOW ENERGIES
WHETHER ANY OF THOSE WILL BE FOUND IS A MATTER OF EFFORT AND LUCK.

REVIEWS ON VARIOUS ASPECTS OF EXTRA DIMENSIONS / BRANE WORLDS

INCOMPLETE LIST; PLEASE TELL IF
YOU KNOW OTHERS

INVERSE TEMPORAL ORDER; MANY
PUBLISHED IN JOURNALS / PROCEEDINGS

- R. Maartens, Brane world gravity
gr-qc/0312059
- E. Kiristis, D-BRANES IN STANDARD MODEL
BUILDING, gravity and COSMOLOGY, hep-th/0310001
- G. Gabadadze, ICTP lectures on large
extra dimensions, hep-ph/0308112
- E. Adelberger, B. Heckel, A. Nelson, Tests of
gravitational inverse-square law hep-ph/0307100
- F. Quevedo, Lectures on string/brane
cosmology, hep-th/0210292
- D. Langlois, Brane cosmology: an
introduction hep-th/0209261
- Yu. KUBYSHIN, Models with EXTRA DIMENSIONS
AND THEIR phenomenology hep-ph/0111027
- S. FORSTE, Strings, BRANES and extra
dimensions, hep-th/0110055
- V. Rubakov, Large and infinite extra
dimensions, hep-ph/0104152
- S. Kachru, Lectures on warped compactifications and
stringy brane constructions, hep-th/0009247