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SMR.1227 - 11

SUMMER SCHOOL ON ASTROPARTICLE PHYSICS AND COSMOLOGY

12 - 30 June 2000

PHYSICS AND COSMOLOGY IN LARGE EXTRA DIMENSIONS

Lectures I and II

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Please note: These are preliminary notes intended for internal distribution only.

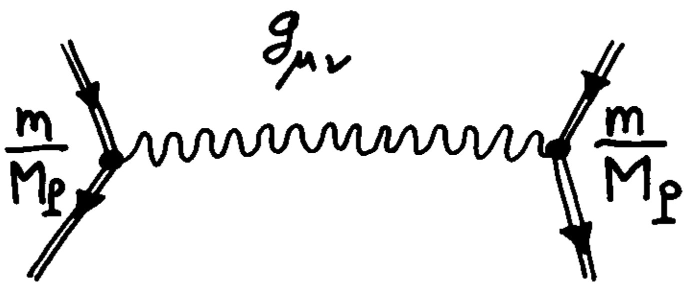
PHYSICS AND COSMOLOGY IN LARGE EXTRA DIMENSIONS

Gia Dvali

NYU

Newtons Law (measured at $\gtrsim$ cm)

$$V(r) = - G_N \frac{m^2}{r} \qquad G_N = \frac{1}{M_P^2}, \quad M_P \sim 10^{19}\,\text{GeV}$$



$$V(r) \sim \left(\frac{m}{M_P}\right)^2 \frac{1}{r}$$

for proton $\frac{m_p}{M_P} \sim 10^{-19}$!

$$S = \int d^4x \sqrt{-g}\, M_P^2 R^{(4)}$$

M_P the fundamental scale of quantum gravity?

Standard paradigm

Quantum gravity theory. Strings?

$M_{Pl} \sim 10^{19}\,\mathrm{GeV} \to \sim 10^{-33}\,\mathrm{cm}$

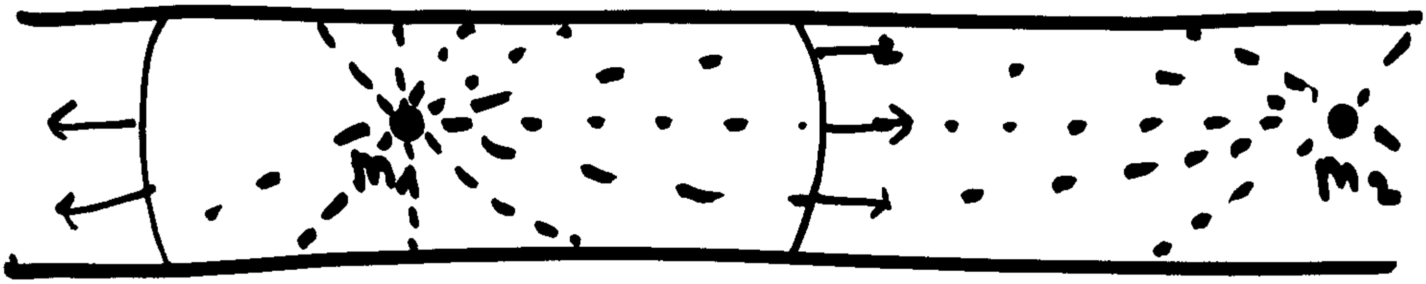
$V(r) \sim \left(\frac{m}{M_P}\right)^2 \frac{1}{r} \longrightarrow$

$m_W \sim \mathrm{TeV} \to \sim 10^{-17}\,\mathrm{cm}$

Hierarchy problem: why $\frac{m_W}{M_{Pl}} \sim 10^{-16-17}$?

Can $M_{Pf} \sim \mathrm{TeV}$?

FOR $r \gg R$, 3-DIMENSIONAL GAUSS LAW



FLUX THROUGH A 3-SPHERE

THE FORCE LAW:

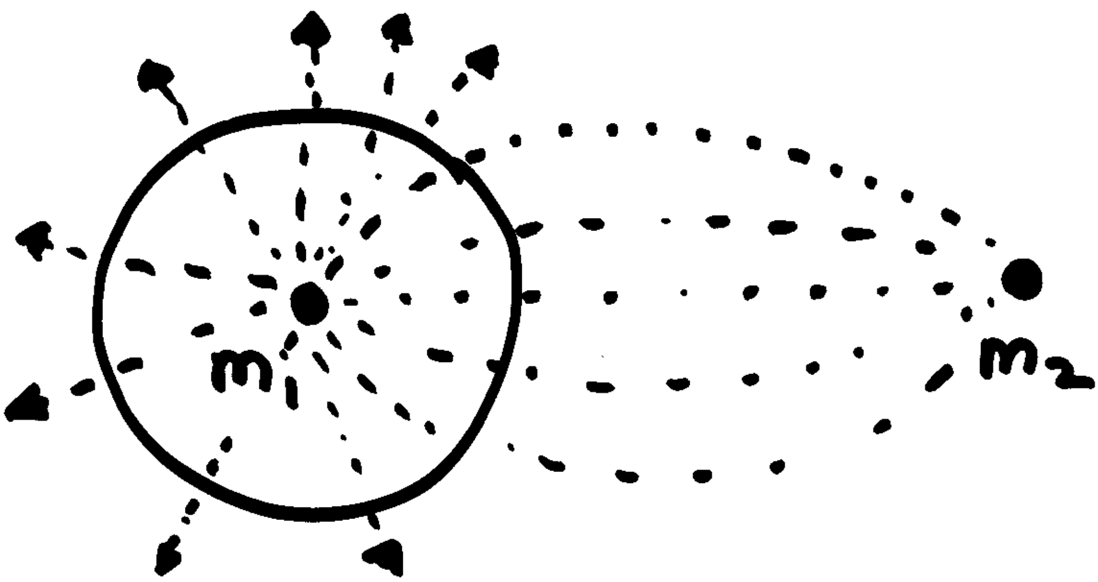
$$F = \frac{G_{(3+N)}}{R^N} \frac{m_1 m_2}{r^2} = G \frac{m_1 m_2}{r^2}$$

$$G = \frac{G_{(3+N)}}{R^N} \Rightarrow M_P^2 = M_{Pf}^{2+N} R^N$$

[redacted] FOR $r \ll R$

3+N-DIMENSIONAL GAUSS LAW

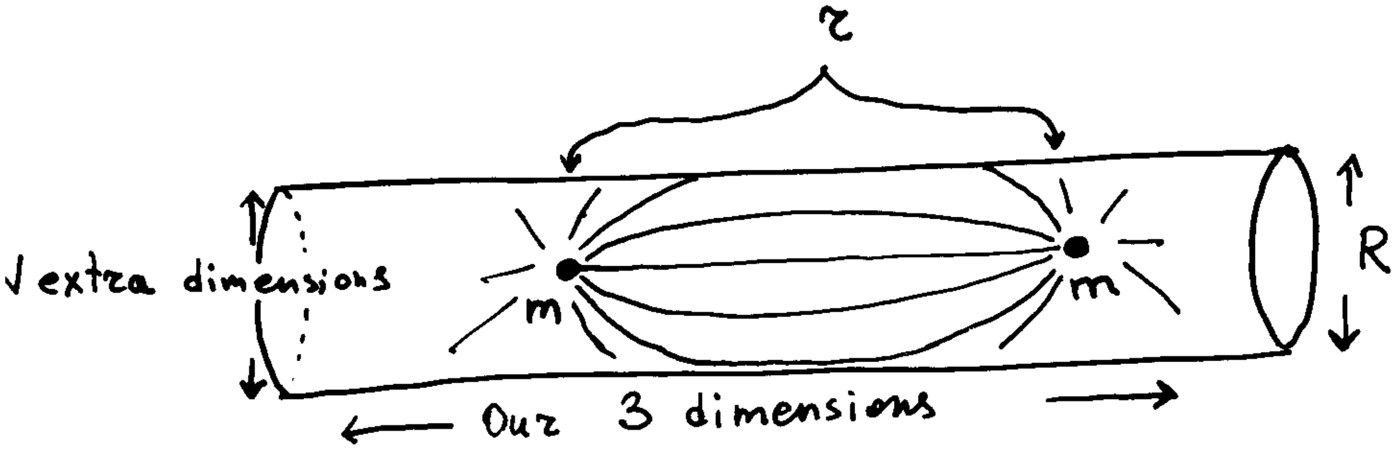
FLUX THROUGH A 3+N-1-SPHERE



FORCE LAW:

$$F = G_{(3+N)} \frac{m_1 m_2}{r^{2+N}}$$

Can $M_{Pf} \sim$ TeV ?



1+3+N Dimensional Gauss' Law:

for $r \ll R$ $\qquad V(r) = G_{N(4+N)} \dfrac{m^2}{r^{N+1}}$

for $r \gg R$

$$V(r) = G_N \frac{m^2}{r} \propto \frac{G_{N(4+N)}}{R^N} \frac{1}{r}$$

Relating the Planck scales:

$$M_P^2 = M_{Pf}^{2+N} R^N$$

$M_{Pf} \sim$ TeV $\longrightarrow$ $N \geq 2$

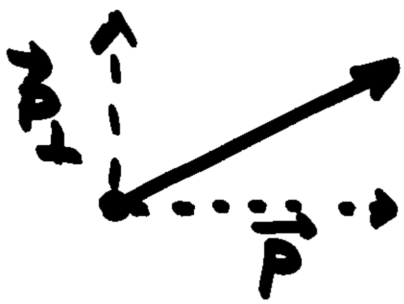
for $N = 2$ $\quad R \sim 1\,\mathrm{mm}$

PARTICLES MOVING IN 4D:

$$E^2 = |\vec{p}|^2 + m^2 \leftarrow \text{massive}$$

$$\text{massless} \rightarrow \quad E^2 = |\vec{p}|^2$$

PARTICLE MOVING IN 4+N D.



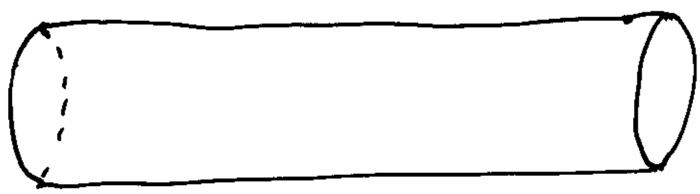
$$E^2 = |\vec{p}_{4+N}|^2 = |\vec{p}|^2 + |\vec{p}_\perp|^2$$

$$E^2 = \vec{p}^{\,2} + m^2$$

Some comments:

Momentum in extra-D $\equiv$ Mass in 4-D

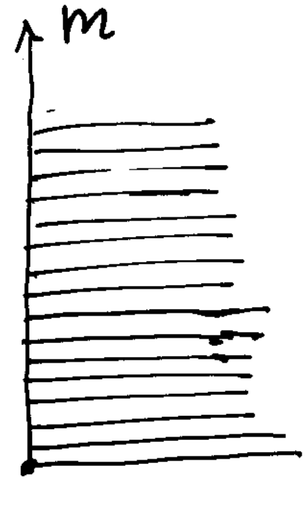
$$p_\mu p^\mu - p_\perp^2 = 0$$



$$p_\perp^2 = \frac{|n|^2}{R^2} \qquad |n|^2 = \sum_{i=1}^{N} n_i^2$$

Kaluza-Klein tower of massive states:

$$m_{(n_1 \ldots n_N)} = \frac{|n|}{R}$$



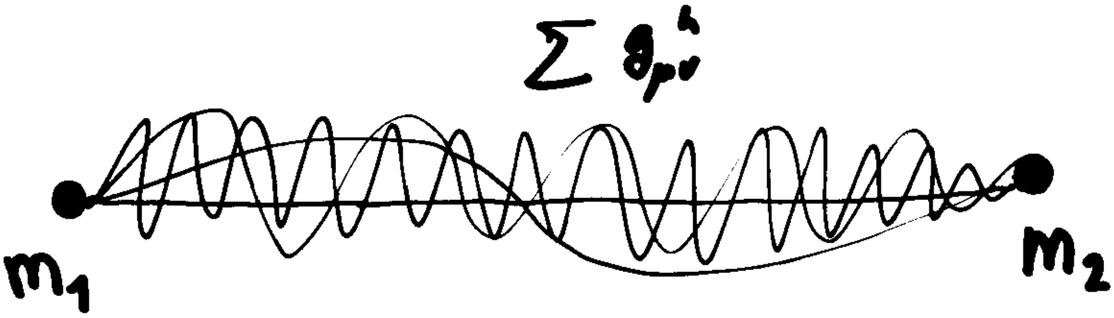
interactions via massive messengers

$$V(r) \sim \frac{e^{-mr}}{r} \quad \leftarrow \text{massive}$$

$$V(r) \sim \frac{1}{r} \quad \leftarrow \text{massless}$$

$$G_{\mu\nu} \rightarrow \sum_{n} g_{\mu\nu}^{(n)}$$

GRAVITON EXCHANGE



$$V(r) \sim \sum_{m=\frac{n}{R}} \frac{e^{-mr}}{r} \xrightarrow{r \ll R} \frac{1}{r^{1+N}}$$

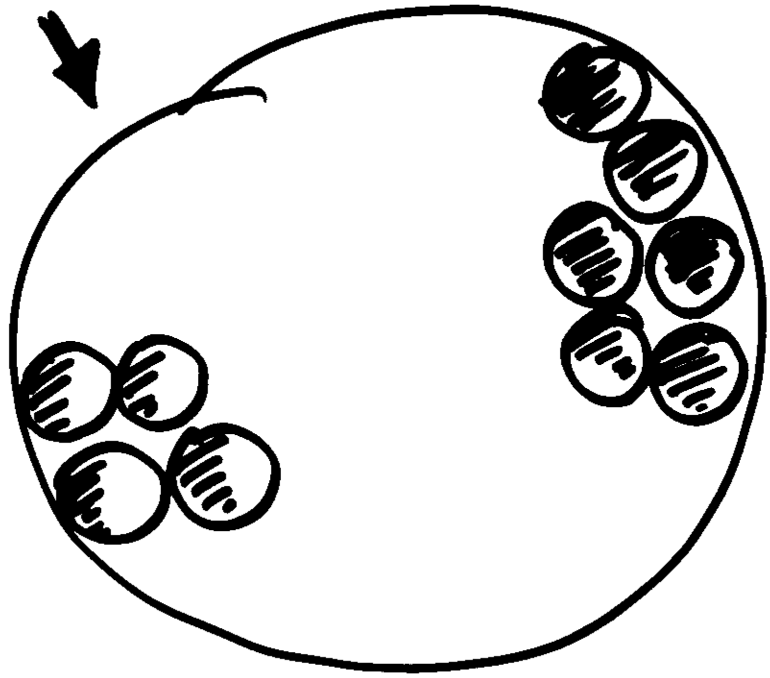
CAN BE DISTRUCTIVE ?

WHAT ABOUT MACROSCOPIC GRAVITY?

GRAVITY IS A BULK EFFECT

GRAVITATING BODY OF SIZE $d \gg R$

1mm BALL

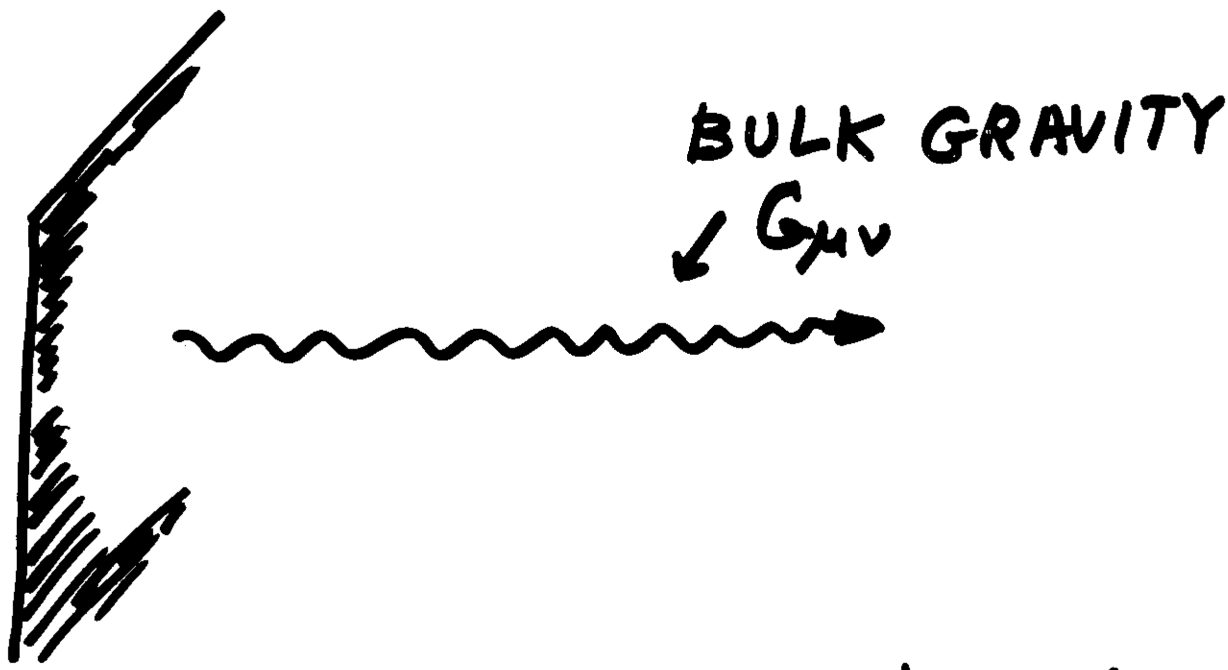


$$\frac{\Delta E_{grav}}{E_{grav}} \sim \frac{R^N}{d_{min}^{N-2}\, d^2} \xrightarrow{N=2} \frac{\Delta E_{grav}}{E_{grav}} \sim \left(\frac{mm}{d}\right)^2$$

FOR NEUTRON STAR $d \sim 10\,km$

$$\frac{\Delta E_{grav}}{E_{grav}} \sim 10^{-12}!$$

BRANE UNIVERSE

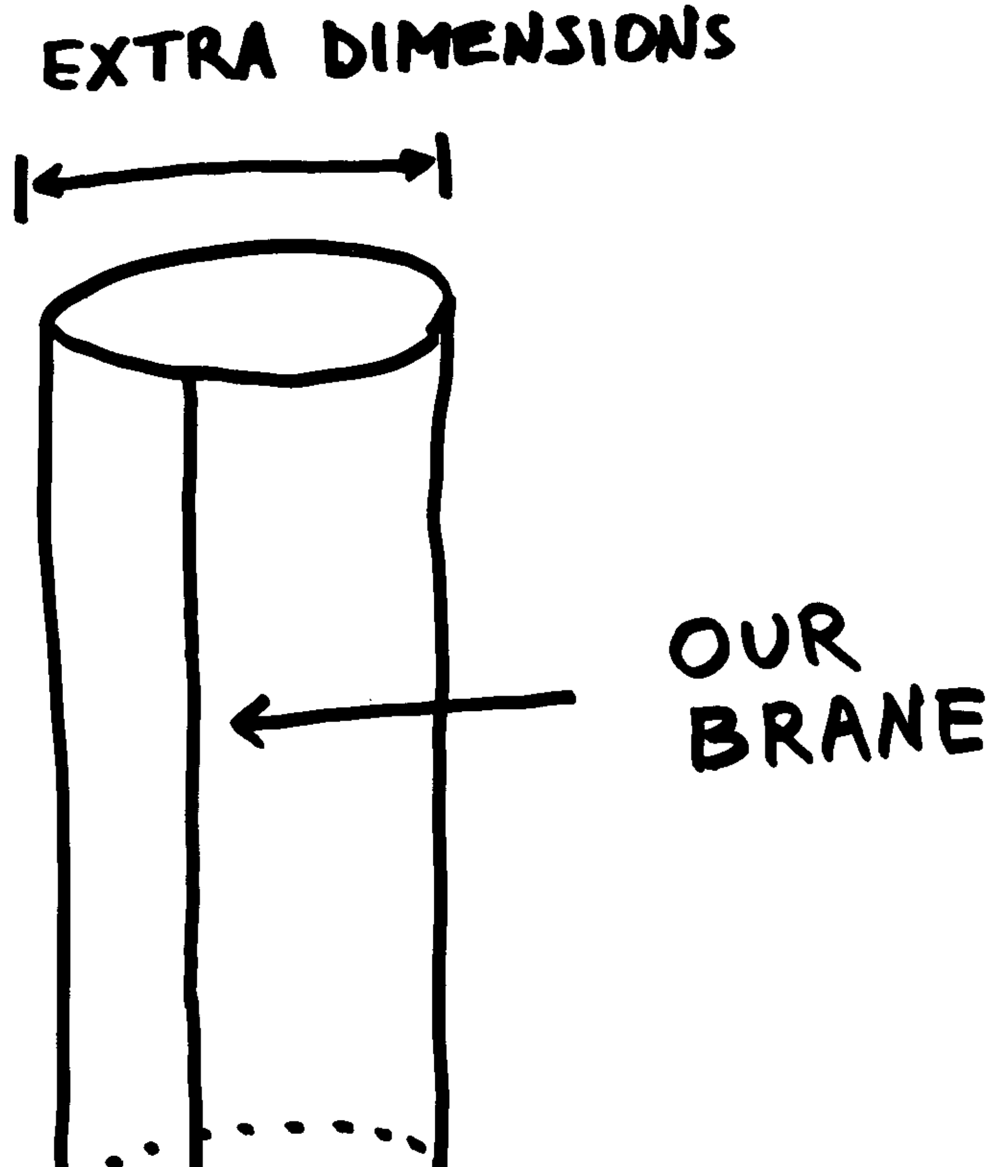


N EXTRA DIMENSIONS

$$M_P^2 = M_{Pf}^{2+N} V_N$$

$M \gtrsim \mathrm{TeV}$ $\quad \sqrt[N]{V_N} \lesssim 1\,\mathrm{mm}$

BRANE UNIVERSE



LOCALIZATION OF PARTICLES ON A (RIGID) BRANE

$$S_{4+N} = \int dx^{4+N}\, \partial_A \chi(x_B)\, \partial^A \chi(x_B)$$

$$+ \int dx^4\, \partial_\mu \varphi(x_\nu)\, \partial^\mu \varphi(x_\nu)$$

BRANE ACTION (RIGID)

$$+ \int dx^4\, \lambda\, \varphi^2(x_\nu)\, \chi^2(x_\nu, x_{EXTRA}=0)$$

$A, B = 0, 1 \dots 3+N$

$\mu, \nu = 0, 1 \dots 3$

FOR A DYNAMICAL BRANE

$$\int d^4x \longrightarrow \int d^4x \sqrt{-\det G}$$

$$G_{\mu\nu} = g_{\alpha\beta}\, \partial_\mu y^\alpha \partial_\nu y^\beta$$

INDUCED METRIC ON A BRANE

$G_{\mu\nu}$ IS CURVED EVEN IF $g_{\alpha\beta}$ IS FLAT

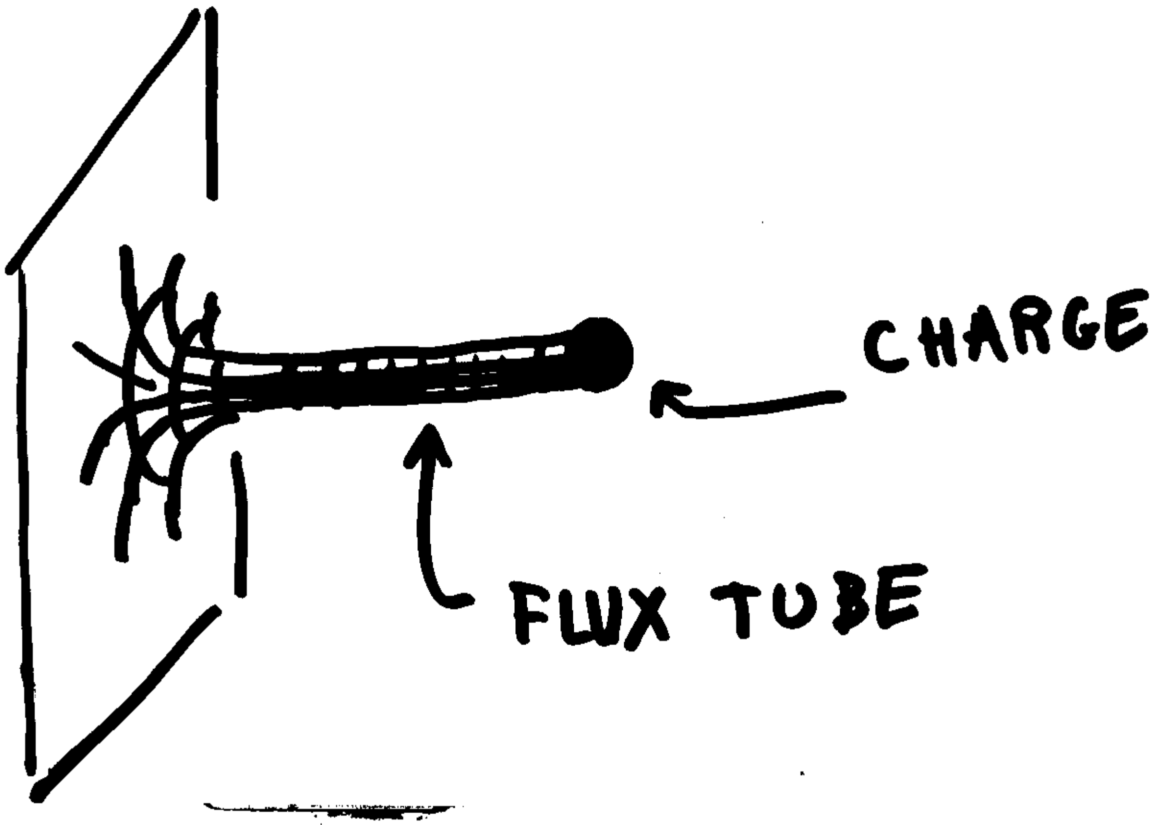
WORKS FOR SPIN = 0, 1/2

GAUGE FIELDS:

$$\int d^4x \; \frac{1}{4} F_{\mu\nu} F^{\mu\nu} +$$

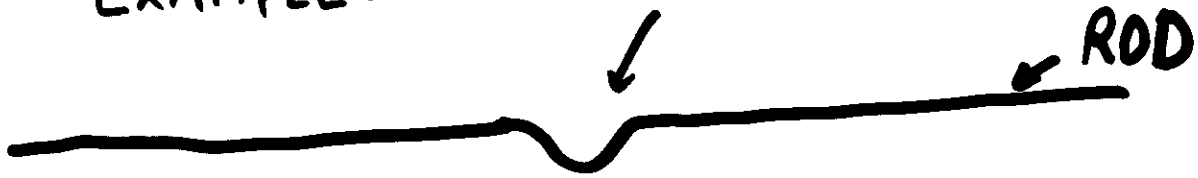
$$\int d^4x \; \left| D_\mu \chi(x_\nu, x_{EXTRA} = 0) \right|^2$$

CAN NOT BE!



DYNAMICAL LOCALIZATION OF PARTICLES

EXAMPLE: SOUND-WAVE



SOUND-WAVES ON SOLITONS

$$S = \int d^5x \left[(\partial_A \phi)^2 - V(\phi) \right]$$

$$\Box_5 \phi + \frac{\partial V}{\partial \phi} = 0 \Longrightarrow \Phi = \Phi_{cl}(X_5)$$

SMALL PERTURBATIONS $\quad \Phi \to \phi_{cl} + \delta$

$$\Phi_{cl}(X_5 + y(x_\mu)) = \phi_{cl} + \phi_{cl}' \, y(x_\mu) + \cdots$$

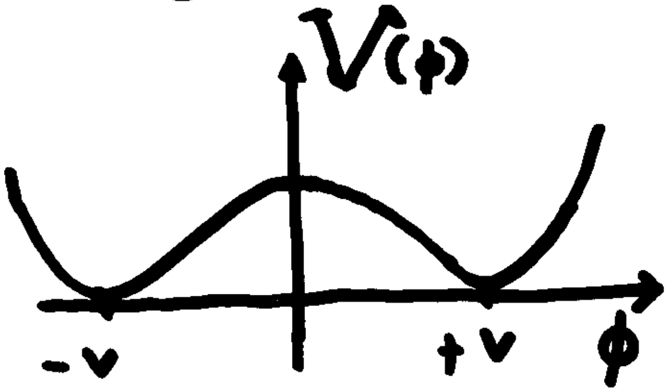
$$\Box_4 y = 0$$

$$S_{eff} = \int d^4x \, (\partial_\mu y)^2 \, T \Longrightarrow \int d^4x \, (\partial_\mu \delta)^2$$

$$T = \int d x_5 \, (\Phi_{cl}')^2$$

EXAMPLE: DOMAIN WALL (KINK)

$$S=\int d^5x\left[\frac{1}{2}(\partial_A\phi)^2-\frac{1}{4}(\phi^2-v^2)^2\right]$$

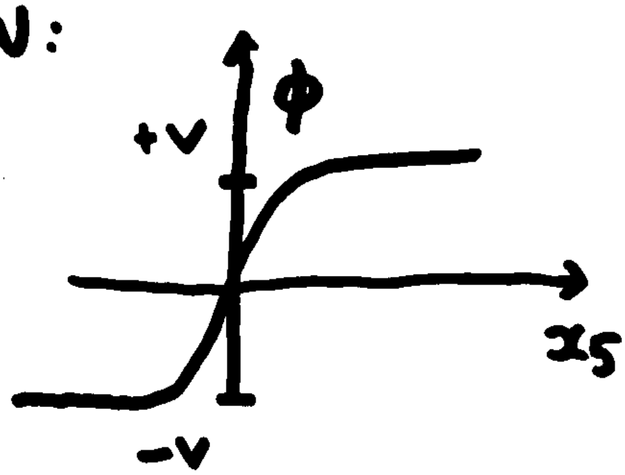


$$\langle\phi\rangle = \pm v$$

$$\Box_5\phi+\phi(\phi^2-v)=0$$

DOMAIN WALL SOLUTION:

$$\phi_{cl}(x_5)=v\,\mathrm{th}(v x_5)$$



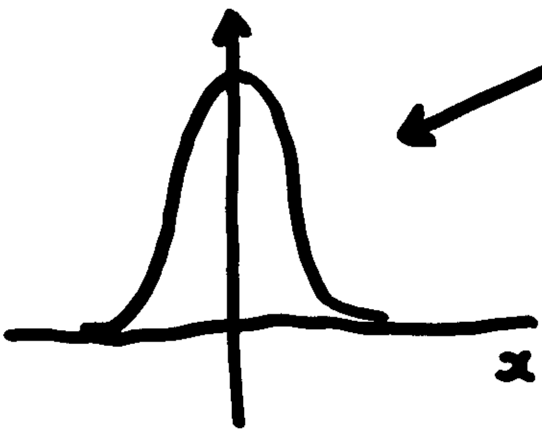
SMALL FLUCTUATIONS

$$\Phi_{cl}\to\Phi_{cl}+\delta(x_\mu)$$

SMALL TRANSVERSE VIBRATIONS

$$\Phi_{cl} \to v\, th\left[v(x_5 + y(x_\mu))\right]$$

$$\Phi = \Phi_{cl} + \frac{v^2}{ch(vx_5)}\, y(x_\mu)$$



$$S_{eff} = \int d^4x \left(\partial_\mu \delta\right)^2$$

$$\delta(x_\mu) = y(x_\mu)\sqrt{\int_{-\infty}^{+\infty} dx_5 \frac{v^4}{ch^2(vx_5)}}$$

WHAT IS GOING ON?

THE WALL BREAKS TRANSLATIONAL INVARIANCE $X_5 \to X_5 + \text{const}$ SPONTANEOUSLY

$$\delta(x_\nu) = y(x_\nu) \sqrt{\int dx_5 \, \varphi_{cl}'^2}$$

$\uparrow$ GOLDSTONE BOSON

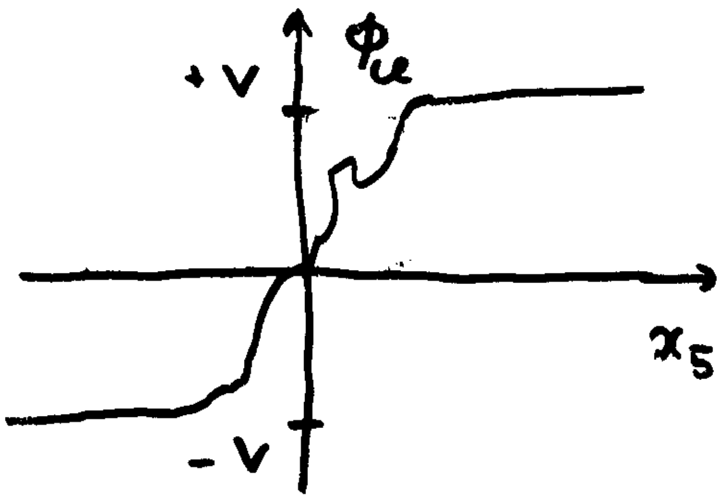
MUST BE LOCALIZED ON THE WALL

FERMIONS

Rubakov, Shaposhnikov; ...
index theorem: Jackiw, Rebbi; E. Weinberg.

$$S_5 = \int d^5x \;\; i\bar{\Psi}\not{\partial}_5 \Psi + \varphi_{cl} \bar{\Psi}\Psi$$

$$\varphi = \varphi_{cl}(x_5)$$



$$i\not{\partial}_4 \Psi + \hat{O}\Psi = 0$$

$$\hat{O} = -i\gamma_5 \partial_5 + \varphi_{cl}(x_5)$$

$$\hat{O}\Psi = 0$$

$$\Psi = \mathcal{E}(x_\mu)\,\Omega(x_5) \qquad \Omega(x_5) = \exp\left\{\pm\int_0^{x_5} \varphi_{cl}(x_5')\,dx_5'\right.$$

ZERO MODE

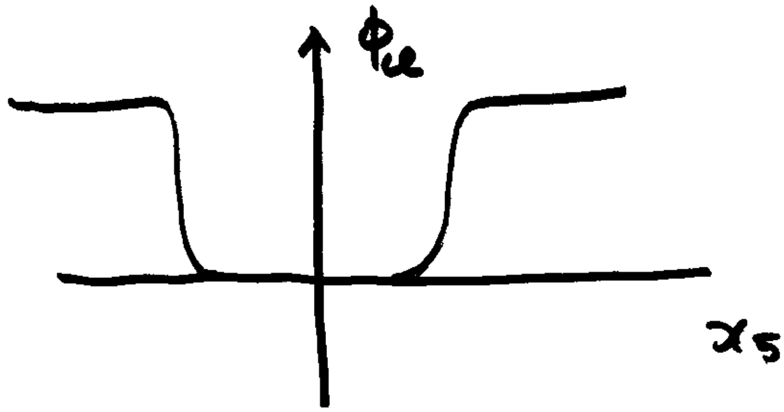
DYNAMICAL LOCALIZATION OF (MASSLESS) GAUGE FIELDS

I TRY

CHARGED SCALAR

$$S_5 = \int d^5x \;\; \frac{1}{4} F_{AB}F^{AB} + |\mathcal{D}_A \Phi|^2 + \cdots$$

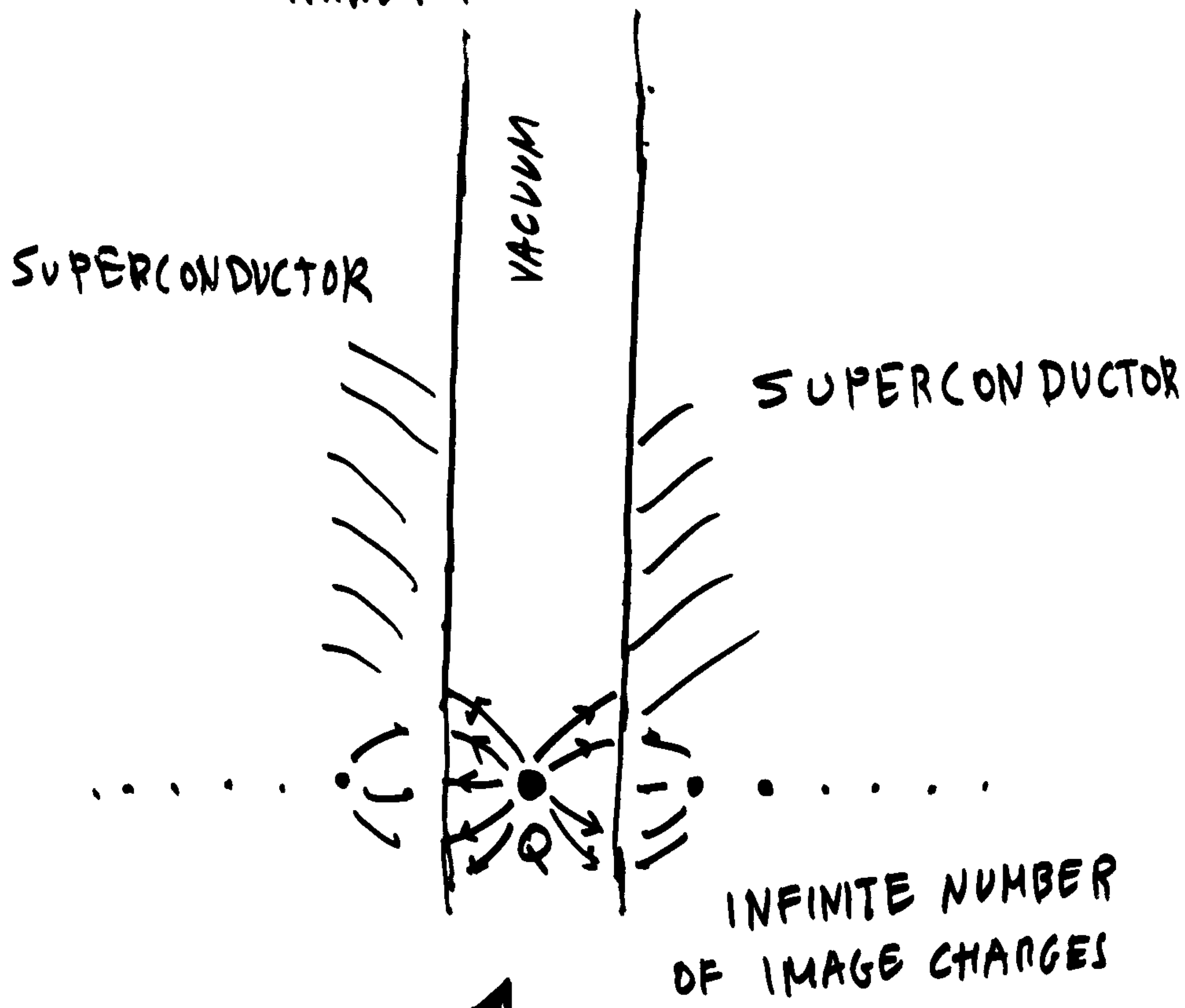
$\phi = \phi_{cl}(x_5) \longrightarrow$



$$\Box_4 A_\mu + \hat{O} A_\mu = 0$$

$\hat{O} = -\partial_5^2 + \phi_{cl}^2(x_5) \leftarrow$ HAS NO ZERO MODES !!!

WHAT HAPPHNED ?

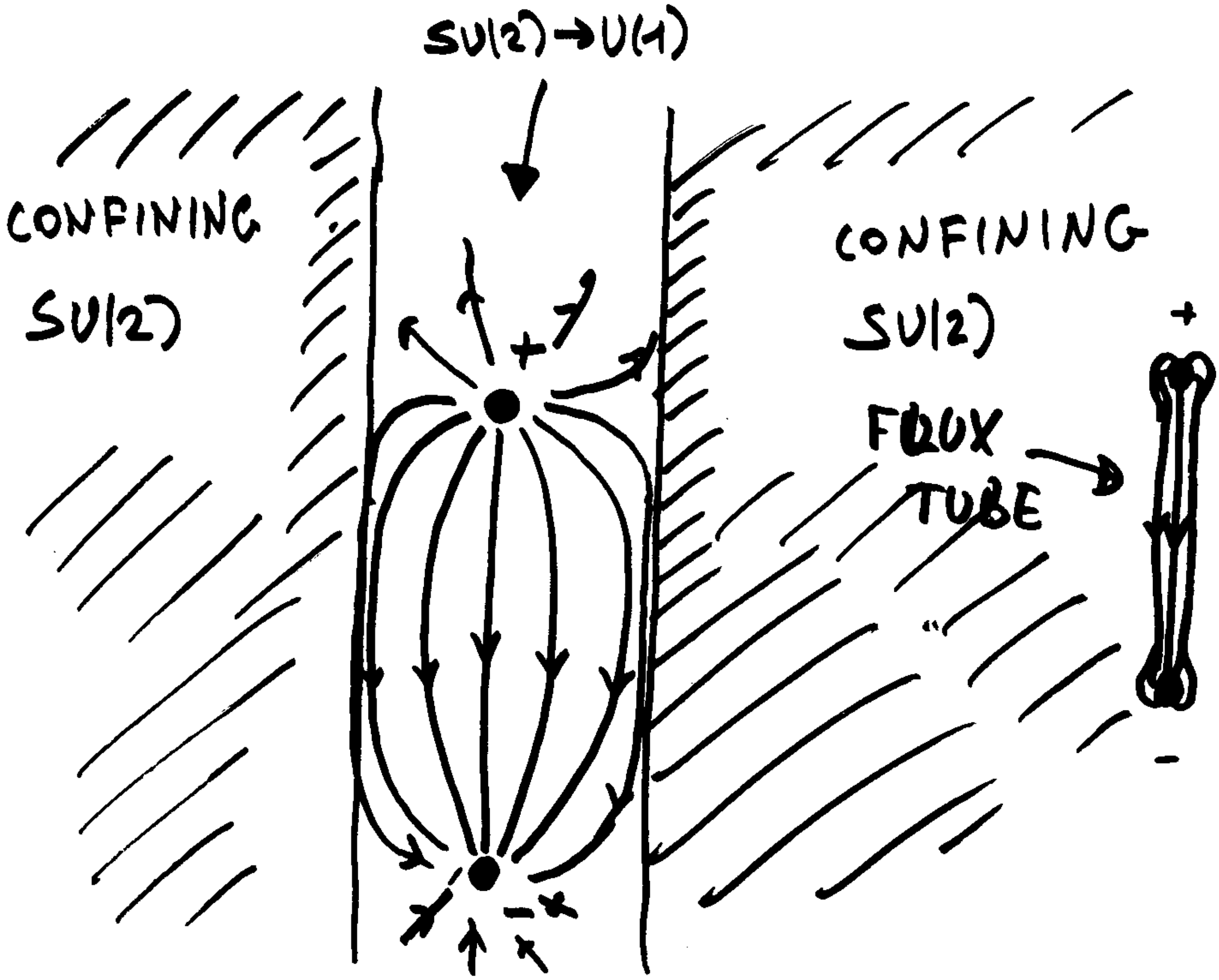


CHARGES ARE SCREENED
IN BETWEEN TWO SUPERCONDUCTORS

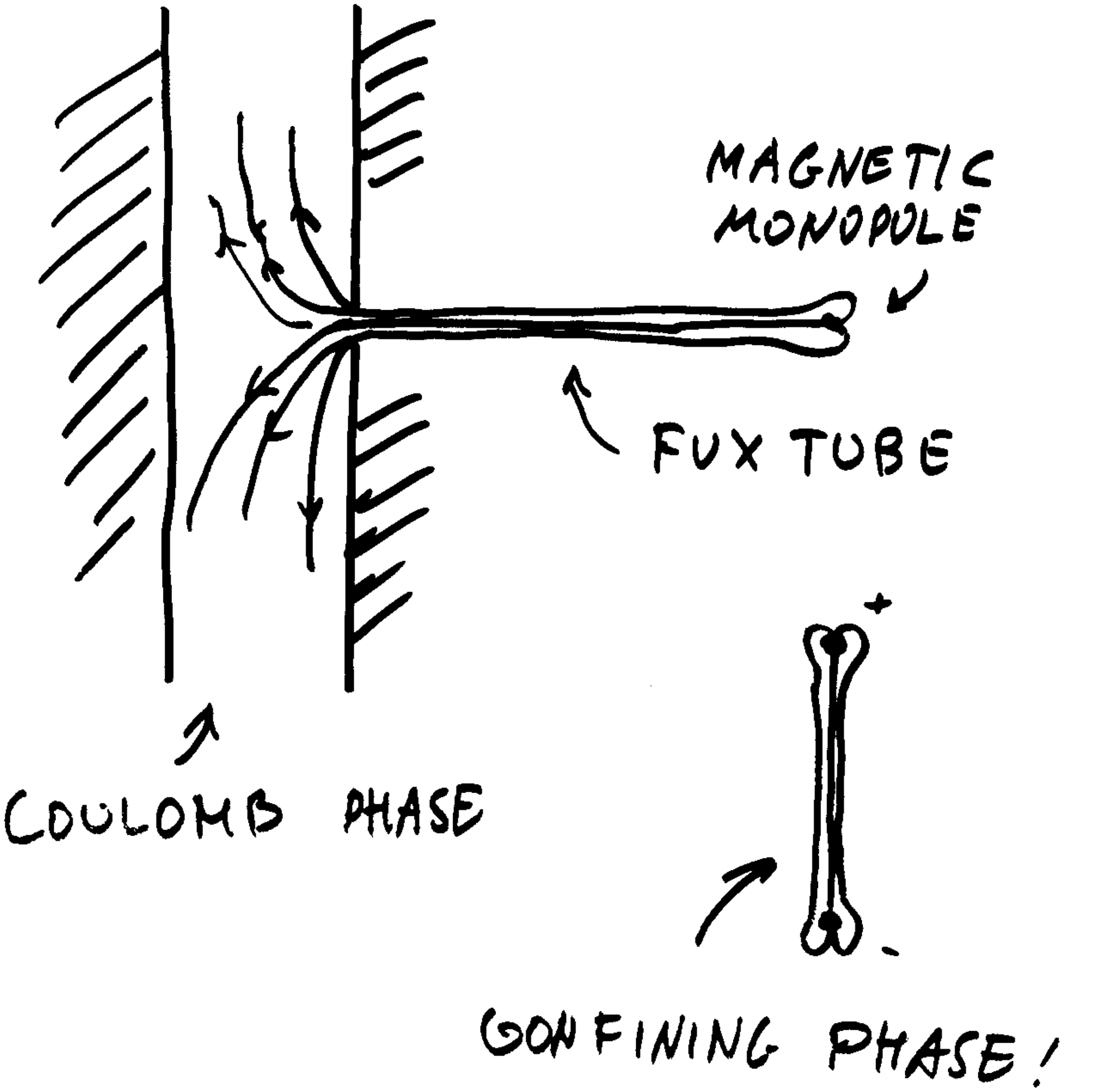
LESSON:

TO LOCALIZE MASSLESS PHOTON THE ELECTRIC FLUX LINES SHOLD NOT BE ABLE TO END ON AN OUTSIDE MEDIUM!!!

MONOPOLE CONDENSATION?



DUAL ANALOGY WITH MAGNETIC MONOPOLES



String theory picture

D-branes

I. Antoniadis,
N. Arkani-Hamed,
S. Dimopoulos,
G.D.

Open strings

$\Downarrow$

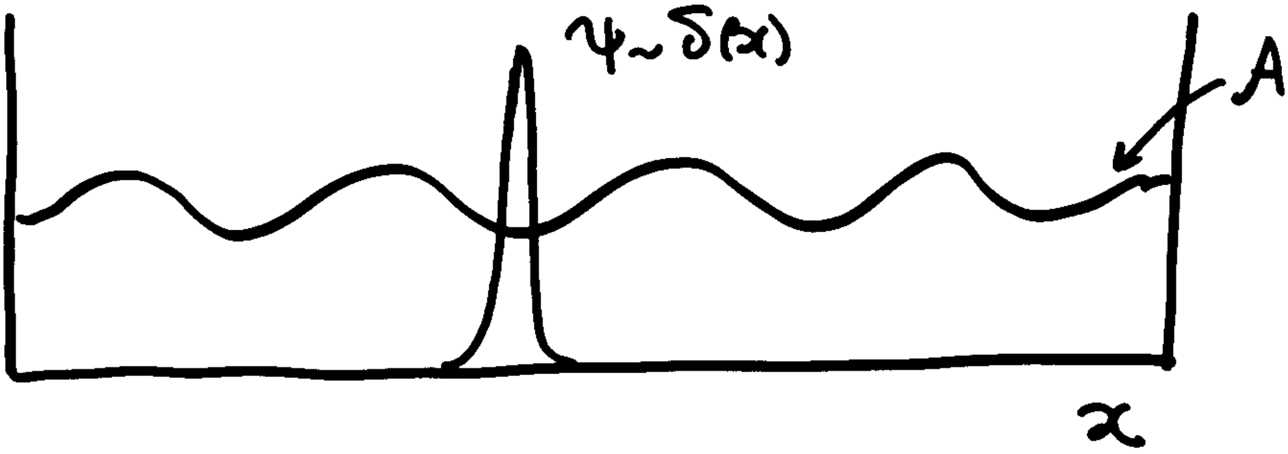
Standard model particles

Closed string

$\Downarrow$

Gravity

COUPLING OF BRANE- TO BULK- MODES:



$$\bar{\Psi} A \Psi \frac{1}{\sqrt{\text{VOLUME}}} \longrightarrow \bar{\Psi} A \Psi \frac{1}{(M_{Pf} R)^{\frac{N}{2}}}$$

EFFECTIVE 4-D (GAUGE) COUPLING

$$\frac{1}{(M_{Pf} R)^{\frac{N}{2}}} \sim \frac{M_{Pf}}{M_P} \sim 10^{-16-15}$$

ALL POSSIBLE

N. Arkani-Hamed, S. Dimopoulos
G.D. .

Constraints:

① Macroscopic gravity;

② Mesoscopic gravity;

③ Precision observables;

④ Rare decays to higher dimensional gravitons.

$K \to \pi$ + graviton ;

⑤ Astrophysics: star cooling;

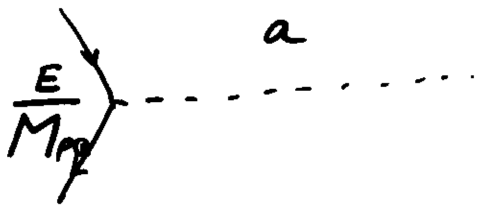
⑥ Cosmology: Big Bang nucleosynthesis;
overclosure by KK modes;
late decays to photons;
Cosmological moduli problem;
Inflation . . .

⑦ Flavor physics in the bulk . . .

New $\frac{1}{\text{TeV}}$-coupled massless particle.

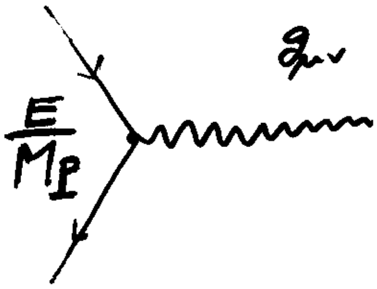
What saves graviton?

e.g. for axion $M_{PQ} \sim \text{TeV}$
would be disaster.



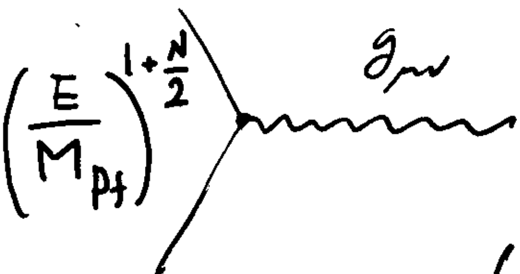
$$M_{PQ} \gtrsim 10^8 \text{ GeV}$$

The high-D gravity is <u>infrared-soft</u>.



$$\longrightarrow \quad V(r) \sim \left(\frac{m}{M_P}\right)^2 \frac{1}{r}$$

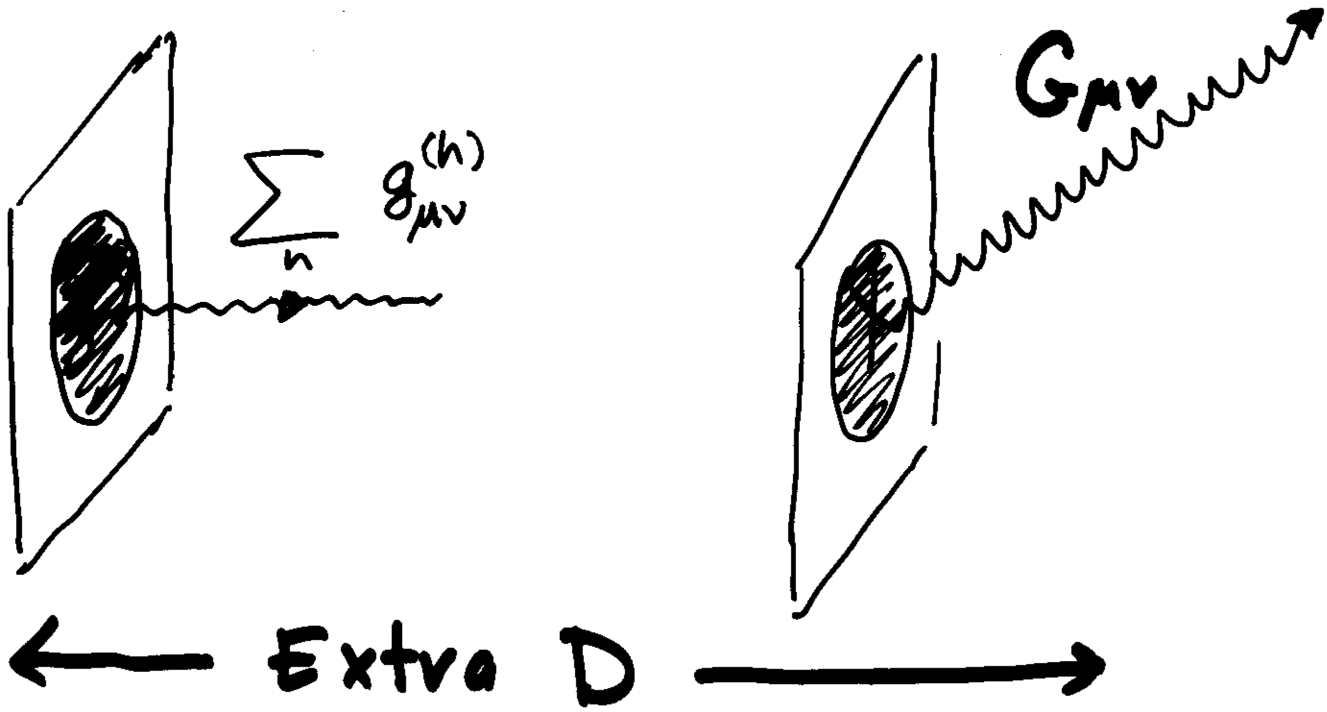
4+N-gravity



$$\longrightarrow \quad V(r) \sim \left(\frac{m}{M_{Pf}}\right)^2 \frac{1}{(M_{Pf}\, r)^N\, r}$$

$$\left(\frac{E}{M_P}\right)^2 \longleftrightarrow \frac{E^{2+N}}{M_P^{2+N}}$$

STAR COOLING



$$\text{Rate} \propto \frac{T^2}{M_P^2} \times (TR)^N \sim \frac{T^{N+2}}{M_{pf}^{N+2}}$$

Strongest bound:

Supernova 1987A

for $N=2 \longleftrightarrow M_{pf} \gtrsim 30-50$ TeV

for $N>2 \longleftrightarrow M_{pf} \gtrsim$ TeV is OK

Experimental signatures

I) Change of gravity at $r < R$

$$\frac{1}{r} \rightarrow \frac{1}{r^{1+N}}$$

IF there are gauge fields in the bulk (B, L, Flavor-gauge fields)

For any N ➡ Gravity-competing forces

(Isotop-dependent, in general)

flavor dependent?

(G.D., Berezhiani)

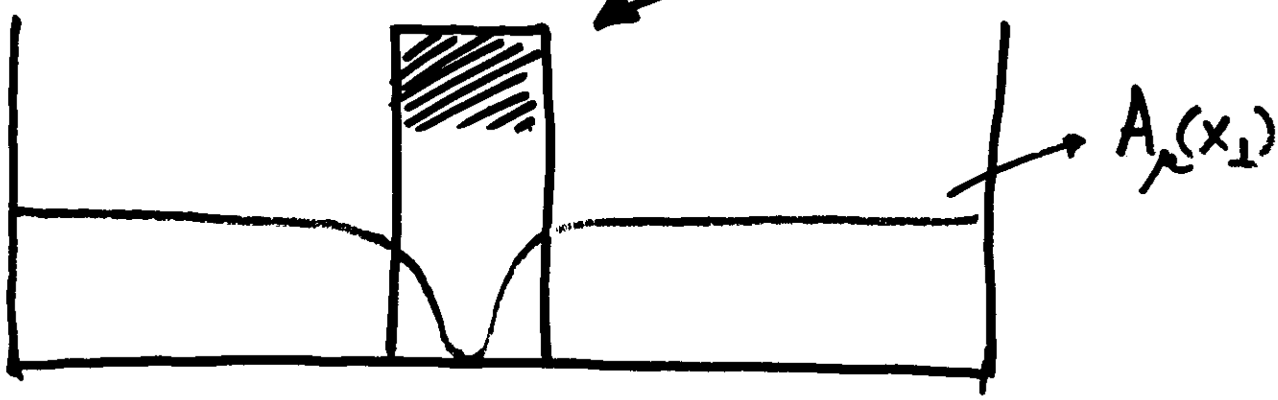
How strong?

Simplest estimate (N. Arkani-Hamed, S. Dimopoulos, G.D.)

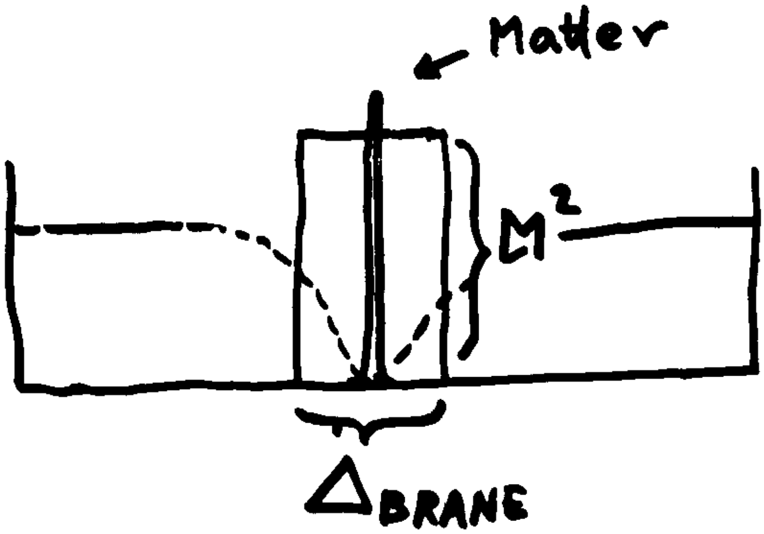
$$g_{Eff} \sim \frac{M_{Pf}}{M_P} \sim 10^{-16} \Rightarrow 10^{6} - 10^{8} \text{ times Gravity}$$

May be <u>much</u> weaker (G.D., G. Gabadadze, M. Porrati; .... + M. Kolanovic)

Due to suppression of the wave-function of the lowest mode on <u>our brane</u>



Effective coupling: $g_{eff} \sim \dfrac{M_{P5}}{M_P}\, e^{-M\Delta_{Brane}}$



$$g_{eff} \ll \frac{m_{proton}}{M_P}$$

$$m_{eff} \ll (1mm)^{-1}$$

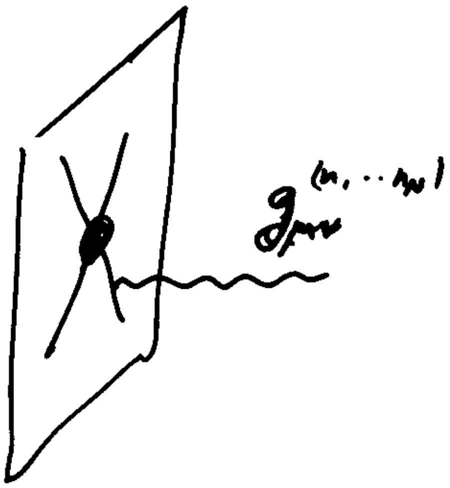
Sub-mm gravity measurements:

A. Kapitulnik et. al,
J.C. Price et. al.
Adelberger et. al.

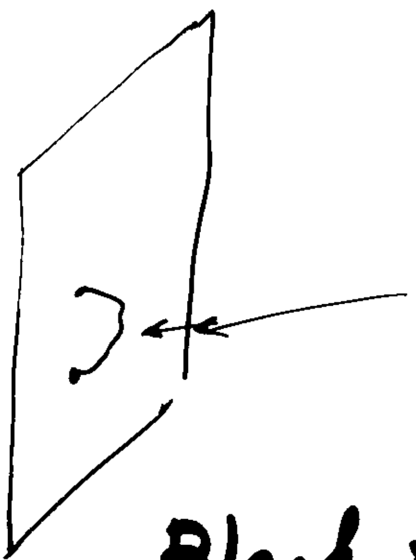
② Collider signatures:

$e^+ e^- \to$ nothing

Graviton emission in the bulk.



In string picture

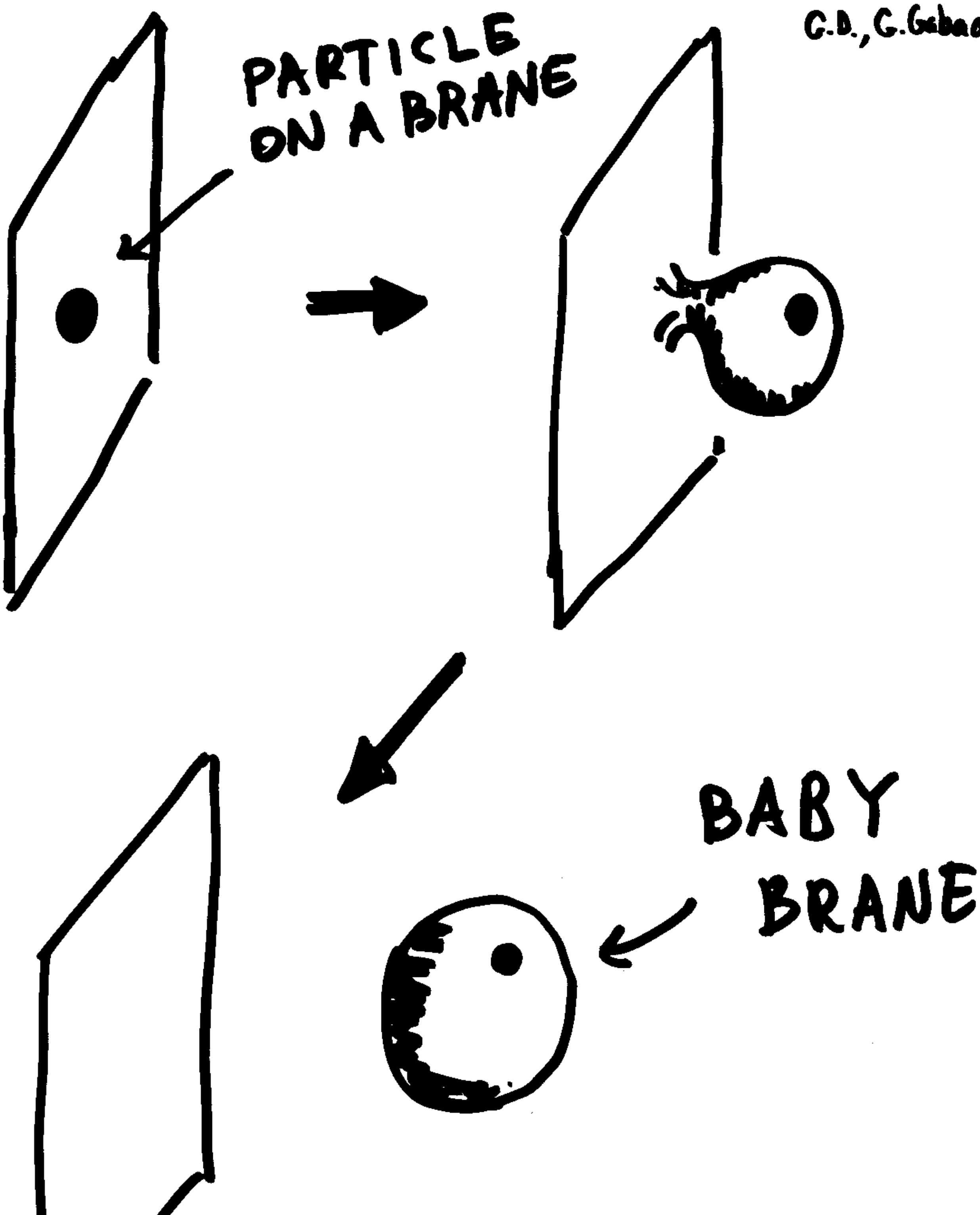


higher Regge resonances from open strings.

. . . .

Black Hole production?

G.D., G.Gabadadze

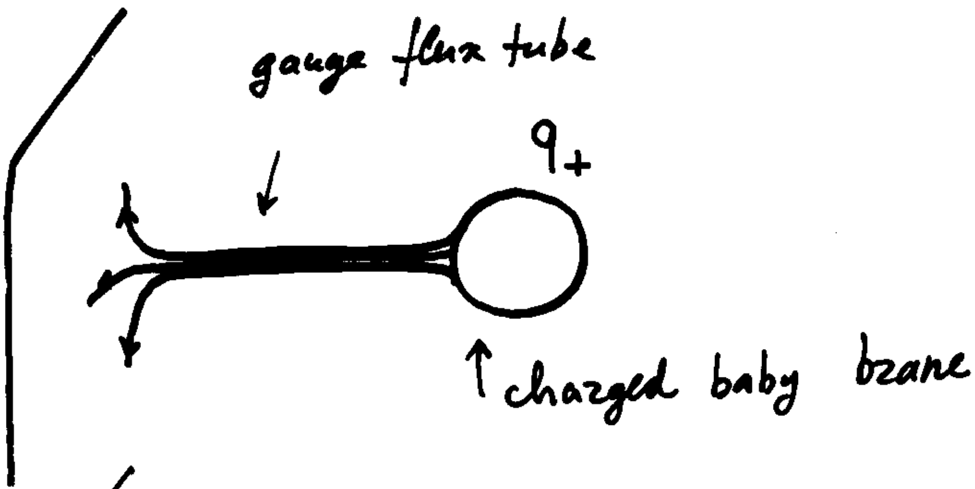


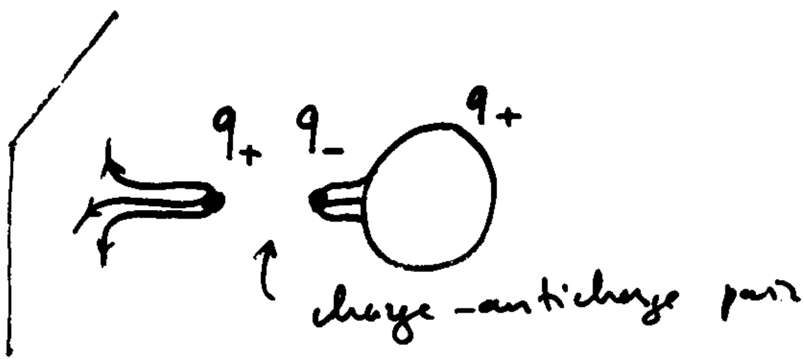
$$\text{rate} \sim \exp\left(-\frac{E_B}{T}\right)$$

Local SM charges must be conserved on the brane:

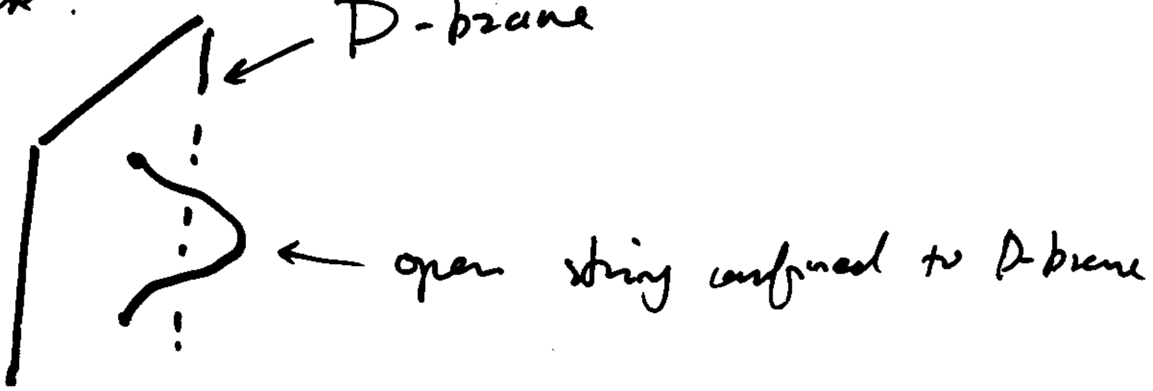
To localize SM gauge fields (massless), bulk must be charge-confining!

M. Shifman, G. Dvali

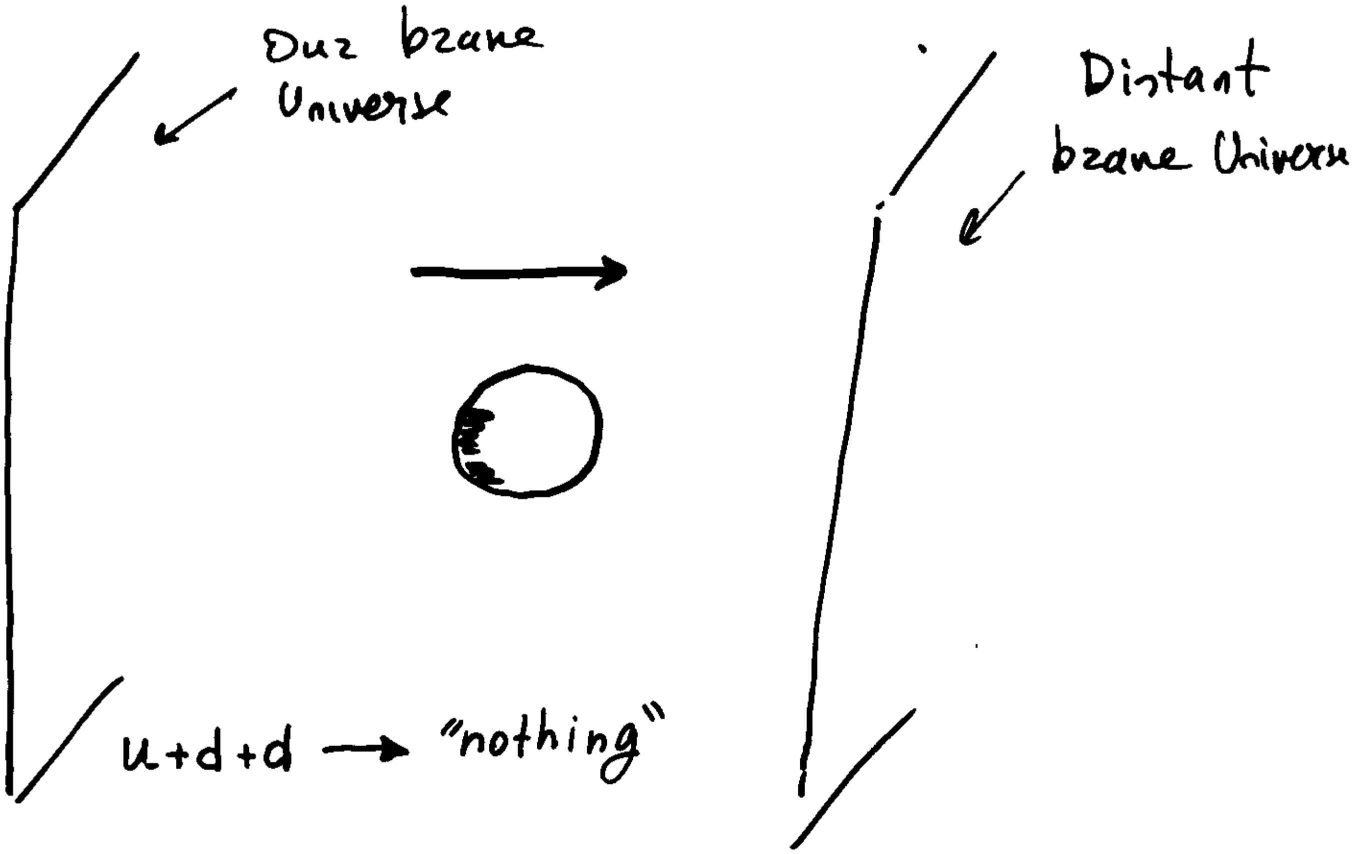




Stringy interpretation: there are no open strings with SM quantum numbers in the bulk.



Baryon number inflow to our Universe



Implications for baryogenesis?

Out of equilibrium:

Collision of two brane Universes after the period of brane inflation

WHAT IS GOING ON?

FERMIONS LOCALIZED ON DIFFERENT BRANES

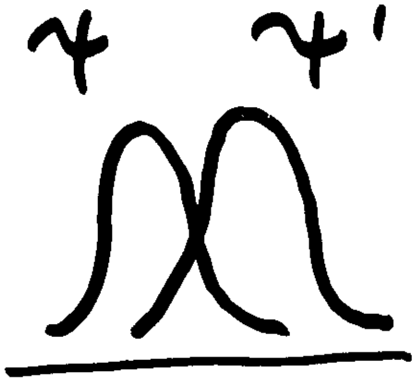
THERE ARE <u>TWO</u> $U(1)_B \otimes U(1)'_B$ SYMMETRIES

COUPLINGS LIKE THIS:

$$\psi \psi' e^{-Mr}$$

ARE <u>EXPONENTIALY</u> SUPPRESSED!!!

WHEN BRANES ARE COINCIDENT THERE IS ONLY <u>ONE</u> $U(1)_{B_{diag}}$ SYMMETRY



$$U(1)_B \otimes U(1)_{B'} \to U(1)_{B_{diag}}$$

NOW TRANSITIONS LIKE THIS:

$$\psi^n \to \psi'^n$$

ARE POSSIBLE !!!