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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR762 - 49

III

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

13 June - 29 July 1994

(0,2) STRING COMPACTIFICATION

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

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But now, since we have a theory with chiral fermions coupled to gauge field, need to worry about gauge anomaly

 $\propto \underbrace{\sum n_a^2 + d^2}_{\text{left-movers}} \underbrace{- \sum w_i^2 - m^2}_{\text{right-movers}} \equiv 0$

rearrange

$$\tfrac{1}{2}(-m^2 + \sum n_a^2) = \tfrac{1}{2}(-d^2 + \sum w_i^2)$$

or, in C.Y. phase,

$$c_2(V) = c_2(T) \qquad ! \quad \text{Yow!}$$

General principle: The condition $c_2(V) = c_2(T) \Longleftrightarrow$ cancellation of worldsheet gauge anomalies.

Ex 6 No need to restrict to hypersurfaces. Complete intersection Calabi-Yau's are just as easy $\Rightarrow$ several Γ^α

$$S_W = \int d^2z\, d\theta^- \quad \Gamma^\alpha W_\alpha(\Phi) + \Lambda^a P F_a(\Phi) + h.c.$$

Field	charge
Φ^i	w_i
P	$-m$
Λ^a	n_a
Γ^α	$-d_\alpha$

As before

$-\sum d_\alpha + \sum w_i = 0 \quad \Longleftrightarrow c_1(T) = 0$

$-m + \sum n_a = 0 \quad \Longleftrightarrow c_1(V) = 0$

absence of gauge anomaly $\quad \sum d_\alpha^2 - \sum w_i^2 = m^2 - \sum n_a^2 \Longleftrightarrow c_2(T) = c_2(V)$

N.b., in this, and Ex 5, $\sum$ scalar charges $\neq 0$ in general.

Easy to fix: Add:

field	charge
S	$m - \sum d_\alpha$
Ξ	$-m + \sum d_\alpha$

$$S_W = \int d^2z\, d\theta^- \ldots + \Xi S + h.c.$$

Setting $\mathcal{U} = 0 \Rightarrow S = 0$ & all deg's of freedom associated to Ξ & S are massive. They serve only to cancel the short-distance divergence in the one-loop correction to r.

Could go on & discuss more examples, but you get the idea...

Remarks on Renormalization of LσM's

- Theory is almost super-renormalizable. The only renormalizable coupling is t. But, unlike in NLσMs, t is coefficient of an F-term, $\frac{t}{2}\int d^2z d\theta^- \Upsilon$ So its renorm is tightly-constrained
- Beyond 1-loop (which we have already discussed) there are no further corrections to t to all orders in perturbation theory!

- Nonperturbatively, t should only be corrected by instantons (holomorphicity) and in favourable circumstances, one can show this vanishes.

A real discussion would get kinda technical. Instead, let's discuss...

Extracting some Physics

Calculate RG-invariant quantities

Rich class come considering "twisted" model.

Compute on cylinder with all right-movers periodic

Unbroken SUSY $\bar{Q}^+$, $\{\bar{Q}^+, \bar{Q}^-\} = \bar{L}_0$ ← in Minkowski

If we are interested in states with $\bar{L}_0 = 0$, we can represent these as elements of the $\bar{Q}^+$-cohomology.

This is eminently computable, so we obtain

- spectrum of states in right-moving R-sector (spacetime fermions) with $\bar{L}_0 = 0$

Similarly, we can compute matrix elements of $\bar{Q}^+$-inv operators between these fermion states:

- yukawa couplings (spacetime superpotential)

Landau-Ginzburg

As we saw, semiclassical analysis becomes exact for $r \to \pm\infty$.

$r \to +\infty$ weakly-coupled σ-model

$r \to -\infty$ L-G.

In both cases, instanton corrections to LσM suppressed. We will look at latter.

To describe Low Energy thy, need, in particular, two unbroken nonanomalous $U(1)$ sym. One will be the $U(1)_R \subset$ (right-moving $N=2$). The other will become the left-moving $U(1)$.

	q	$\bar{q}$ ← the R-symmetry		
Φ^i	q_i	q_i	$i=1,\dots,3+n$	$q_i = \frac{w_i}{m}$
Λ^a	$q_a - 1$	q_a	$a=1,\dots,r+1$	$q_a = \frac{n_a}{m}$
Γ^α	$q_\alpha - 1$	q_α	$\alpha = 1,\dots,n$	$q_\alpha = 1 - \frac{d_\alpha}{m}$

$$S_W = \int d^2z\, d\theta^- \left(\Gamma^\alpha W_\alpha(\Phi) + \Lambda^a F_a(\Phi\right.$$

We need to check

1) These are nonanomalous under the gauge sym. of the underlying theory $J, \bar{J}$
2) $J \cdot \bar{J}$ anomaly diagram J $\bar{J}$ vanishes, so these symmetries can be candidates for commuting L & R currents in conformal limit.

Both of these follow from the linear & quadratic conditions which we previously imposed on the gauge charges. Translated into our current notation, these are

$$\Sigma(q_\alpha - 1) = -\Sigma q_i$$

$$(*) \qquad \Sigma q_a = 1$$

$$\Sigma(q_\alpha - 1)^2 + \Sigma q_a^2 = 1 + \Sigma q_i^2$$

Now we can calculate the central charge of the IR $N=2$ superconformal algeb

Recall the OPE

$$\bar{J}(\bar{z})\, \bar{J}(\bar{w}) = \frac{\bar{c}/3}{(\bar{z}-\bar{w})^2}$$

in the $N=2$ algebra measures the central charge. But this is also simply a measure of the $\bar{J} \cdot \bar{J}$ anomaly, which we can again compute with a 1-loop diagram $\bar{J}$

$$\frac{\bar{c}}{3} = \Sigma(q_i - 1)^2 - \Sigma q_a^2 - \Sigma q_\alpha^2 = 3$$

Exactly as expected! Yow!

Similarly, the $J \cdot J$ anomaly computes the level of the left-moving $U(1)$ current algeb

$$r = \Sigma(q_\alpha - 1)^2 + \Sigma(q_a - 1)^2 - \Sigma q_i^2$$

But thinks are even better than this. The operators

$$T' = -\sum_i \left(\partial\phi_i \partial\bar{\phi}_i + \frac{q_i}{2}\partial(\phi_i \partial\bar{\phi}_i)\right) + \sum_a \left(\lambda_a \partial\bar{\lambda}_a - \frac{1-q_a}{2}\partial(\lambda_a\bar{\lambda}_a)\right) + \sum_\alpha \left(\gamma_\alpha \partial\bar{\gamma}_\alpha - \frac{1-q_\alpha}{2}\partial(\gamma_\alpha\bar{\gamma}_\alpha)\right)$$

$$J' = -\Sigma q_i \phi_i \partial\bar{\phi}_i + \Sigma(1-q_a)\lambda_a\bar{\lambda}_a + \Sigma(1-q_\alpha)\gamma_\alpha\bar{\gamma}_\alpha$$

commute with $\bar{Q}_+$ & generate a $\widehat{U(1)} \ltimes$ virasoro algebra on the $\bar{Q}_+$ cohomology.

To see this, note that rescaling the superpotential can be absorbed in a redefinition of the kinetic terms a $\bar{Q}_+$-trivial operation. Thus, while working on the level of the $\bar{Q}_+$-cohomology, one can use free-field OPE's. And it is easy to verify that these operators satisfy the correct algebra & commute with $\bar{Q}_+$ using free-field OPE's.

The central charge & $\widehat{U(1)}$ level are, as expected, $6+r$ & r, respectively. Also, J_0 differs from the previously-defined q by $\bar{Q}_+$-trivial terms, as does L'_0 from the canonical L_0.

These operators are actually specializations of operators which exist in the linear σ-model. Simply replace $\bar{\partial} \to \mathcal{D}$ & add a term involving the gauge fields.

Silverstein & Witten verified that the operators in the LσM obey the correct algebra (modulo $\bar{Q}_+$-trivial terms) provided $(*)$ is satisfied.

GSO projection

$$g = e^{-i\pi q}(-1)^{F_{\lambda\bar{\psi}}}$$

Since we are projecting, we must as in usual orbifold constructions add twisted sectors. As all charges are multiples of $1/m$, this is a $\mathbb{Z}_{2m}$ orbifold.

(Alternatively, we can think of first projecting onto integer $U(1)$ charges using $e^{2\pi i q}$ & then projecting with g. Either way, the result is the same.)

$\mathbb{Z}_{2m}$ orbifold: sectors labelled by $k = 0, 1, \ldots, 2m-1$

k even $\Longleftrightarrow$ left-moving R sector

k odd $\Longleftrightarrow$ left-moving NS sector

We will see how to compute spectrum of states with $\bar{L}_0 = 0$ in Right-moving R sector (spacetime fermions

Modular Invariance

Level-matching (which is certainly satisfied in our construction) is not obviously sufficient here. (unlike usual toroidal orbifolds)

Principle: worldsheet anomalies $\Longleftrightarrow$ spacetime anomalies

Can check whether the $\mathbb{Z}_{2m}$ quantum symmetry of the L-G. orbifold (a discrete R-symmetry in spacetime) is anomalous in spacetime.

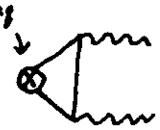
The quantum symmetry had better be anomaly-free!

In fact, this holds for all (2,2) theories and for most (0,2) theories, but is violated for some (0,2) theories which should be rejected (presumably violate modular invariance).

Details are in hepth/9406091.

We define the generator of the quantum symmetry by composing it with a gauge transformation (in the $U(1) \subset G$, where $G = E_6$ $(r=3)$, $SO(10)$ $(r=4)$ or $SU(5)$ $(r=5)$) to make it commute with the left-spectral flow (so that rep's of G transform homogeneously)

rk-28

$A_1 =$  G-gauge bosons mod $2mr$

$A_2 =$  E_8 gauge bosons mod $2mr$

$A_3 =$  gravitons mod $2mr$

Each of these has expressions in terms of traces of degrees of freedom in right-moving R-sector.

You might think we should demand that each of these anomalies vanish separately. But this is false, and would fail even for well-known (2,2) theories (eg, the 3-generation Gepner model). All we should demand is that these should vanish for combinations of gauge & gravitational instantons which satisfy $\mathrm{tr} R^2 = \mathrm{tr} F_1^2 + \mathrm{tr} F_2^2$ or

$$\left.\begin{aligned} A_1 - A_2 &= 0 \\ A_3 - 24 A_2 &= 0 \\ A_3 - 24 A_1 &= 0 \end{aligned}\right\} \mod 2mr$$

A more direct worldsheet interpretation of this anomaly would be desirable (hint, hint.)

Constructing the spectrum

Basic idea: rescaling L.G. superpotential is a $\bar{Q}_+$-trivial operation (since can be compensated by rescaling D-terms), so we can scale its coefficient to be as small as we want & use free-field OPE's

So we have a fairly standard orbifold construction: we have free fields with twisted b.c.'s. We build up Fock spaces using the (fractionally-moded) oscillators acting on the twisted sector ground states. Then we need to calculate the $\bar{Q}_+$ -cohomology on this Fock space.

$$\bar{Q}_+ = \bar{Q}_{+R} + \bar{Q}_{+L}$$

$$\bar{Q}_{+R} = \oint i \bar{\psi}_i \bar{\partial} \phi_i$$

$$\bar{Q}_{+L} = \oint \gamma^\alpha W_\alpha(\phi) + \lambda^a F_a(\phi)$$

Spectral sequence (or above perturbation argument)

$$\Rightarrow H^*_{\bar{Q}_+} = H^*_{\bar{Q}_{+L}}\left(H^*_{\bar{Q}_{+R}} \right)$$

- But, since $\bar{Q}_{+R}$ is quadratic, its cohomology is easy to compute its cohomology:

$$H^*_{\bar{Q}_{+R}} = \text{indep of } \psi_i, \bar{\psi}_i \text{ oscillators}$$

& (in untwisted sector) holomorphic in zeromode of ϕ_i

So one just needs to compute $H^*_{\bar{Q}_{+L}}$ on this smaller Fock space.

Straightforward...

Much more to say. The best I can do is refer you to:

J.D & S. Kachru, Nucl. Phys. B413 (1994) 213, hep-th/9309110

J.D & S. Kachru, hep-th/9406091

J.D & S. Kachru, hep-th/9406090

S. Kachru & E. Witten, Nucl. Phys. B407 (1993) 637, hep-th/9307038

E. Silverstein & E. Witten, hep-th/9403054

E. Witten, Nucl. Phys. B403 (1993) 159, hep-th/9301042

and references therein.

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QUANTUM MECHANICS OF BLACK HOLES

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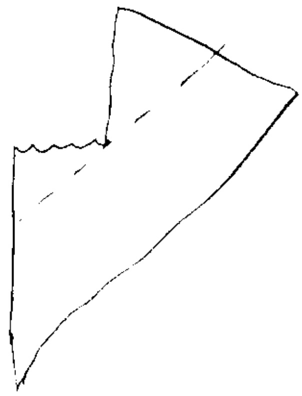
Please note: These are preliminary notes intended for internal distribution only.

Info problem

what happens to info ?

1. Lost (Hawking ...)
conservative
but radical ;
— QM breaks down



2. Returned (in HR) ('t Hooft, Verlindes, Susskind)
— mistake ? (unlikely ?)
— violate locality/causality ?

Return after $M \sim m_{P\ell}$:

4d : $S \sim M^2$, $E \sim m_{P\ell}$

state @ ∞ :
soft γ : 1 bit / photon $\Rightarrow$ M^2 photons ;

$$E_\gamma \sim \frac{1}{M^2}$$

decay time : 1 photon $\Gamma_\gamma \sim \frac{1}{E_\gamma} \sim M^2$

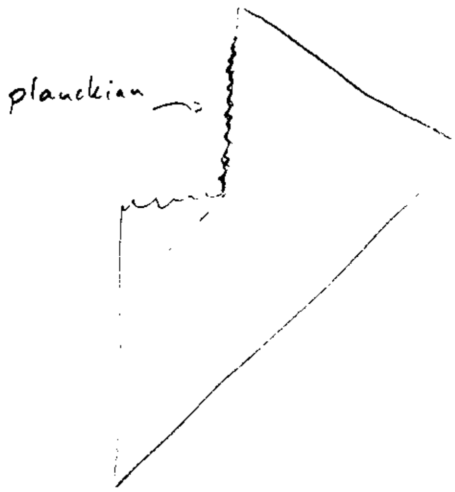
$$\Rightarrow \quad \tau \sim \left(\frac{M}{m_{P\ell}}\right)^4 t_{P\ell}$$

$$\left[\xrightarrow{\tau = T_{univ}} (10\,m)^3 \text{ of } \quad \rho = 10\, H_2O \right]$$

$\sim$ T_{univ} for $M = M_{building}$

$\Rightarrow$

3. <u>Remnants</u> — stable <u>or</u> long lived (Banks?, SG, ...)



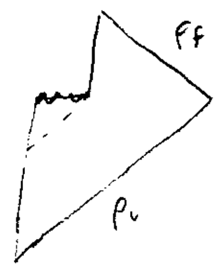
In Rorsach blot !!

Each stridently advocated

Each seems to violate sacred low energy principles

1. Info loss — violates qm
also <u>energy conservation</u>
(we're very attached to this!)

information $\longleftrightarrow$ energy



want Effective description of BH evap: $\rho_i \rightarrow \rho_f$

useful model: Two Hilbert spaces, $\mathcal{H}_o$, $\mathcal{H}_h$ — exchange info

$$H = H_o + \underbrace{H_i}_{\text{interaction}} + H_h$$

BH: $\mathcal{H}_o$ = exterior
$\mathcal{H}_i$ = interior

(other types of info loss possible, but this = good enough for BH ?)

Note: info loss repeatable:
n experiments, $\Delta t \geq \tau_{evap} \Rightarrow \Delta S_n = n \, \Delta S_0$

$\rightsquigarrow$ energy violations, expect $\Delta E \sim 1/\tau_{evap}$.

reason: assume <u>not</u>, ie $H_h = 0$

eg $\mathcal{H}_h = \{ |x\rangle \}$

$$H_i = \underbrace{\sigma}_{\text{ext.}} \hat{x}$$

Then solve

$$i\dot{\Psi} = (H_0 + H_i)\Psi,$$

define $\rho = \mathrm{tr}_i\, |\Psi\rangle\langle\Psi|$

$\Delta S_0 \downarrow$ (pf.: Coleman - appendix: Black holes as red herrings)

reason: (familiar from wormholes)

if initially $|\psi_0\rangle\,|x\rangle$, $H = H_0 + \mathcal{O}x$

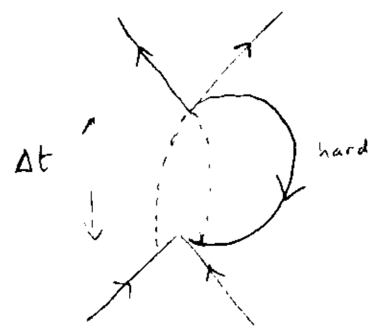
coupling const

if not: distribution for coupling consts, measurements $\rightsquigarrow$ determination

similarly for $H = \sum_\alpha \mathcal{O}_\alpha \lambda_\alpha \Rightarrow H_h \neq 0$, energy loss.

Worse: quantum principles $\Rightarrow$ $\left\{\begin{matrix}\text{info}\\ \text{energy}\end{matrix}\right\}$ loss in virtual processes

e.g.



$\Delta E \sim 1/\Delta t$

probability $\sim \dfrac{1}{V_{pl}\, t_{pl}}$, $\Delta E \sim m_{pl}$

$\sim$ thermal dist. w/ $T = T_{pl}$!

Not our world

$\cancel{\rho \to S \rho S}$

Indeed : Hawking: $\rho \to \$ \rho$

linear,

...

BPS : violates E conserv.

these arguments : $\sim$ thermal bath, $T = \infty$!

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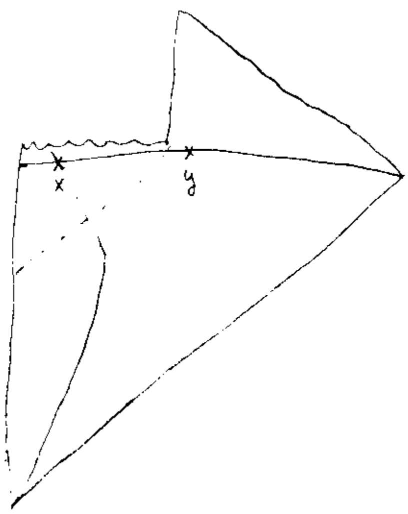
2. Info return - violates <u>locality/causality</u>



mistake?

$\frac{dE}{dt} \sim N$

<u>also</u> want $\frac{dI}{dt} \sim N$ after $m \sim \frac{M}{2}$

(Page)

no obvious evidence?

also if state not Hawking state, trace back, difficult to get something that looks like vac.

1) $[\mathcal{O}(x), \mathcal{O}(y)] = 0 \quad \Rightarrow \quad \psi \text{ "=" } \sum_\alpha |\psi_\alpha\rangle_{in} |\psi_\alpha\rangle_{out}$

2) Infalling guy carries info, no trouble @ horizon
$\Rightarrow$ non-trivial correlations

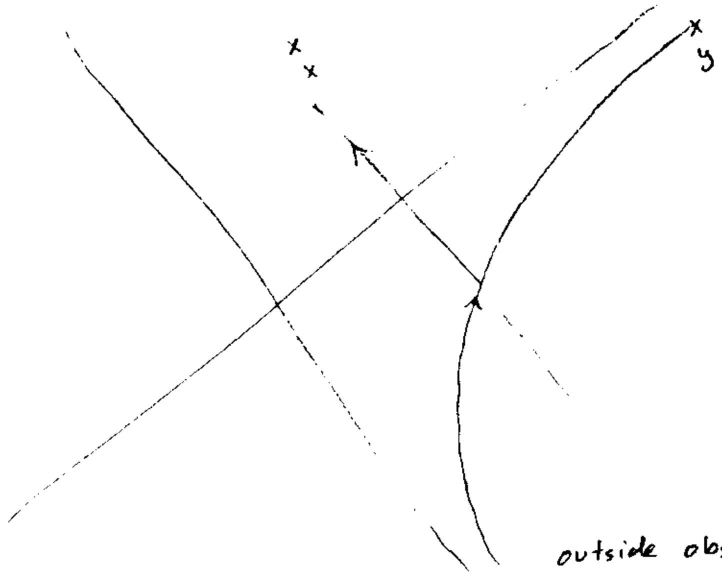
$\Rightarrow \quad \Delta I \neq 0, \quad \sim M^2$

defining observables notoriously difficult in QG

(cf Hermann)

maybe nonlocal ?

extreme case: $M \to \infty$: Rindler space



all info in left half of universe is actually on or to R of horizon; $[\mathcal{O}(x), \mathcal{O}(y)] \neq 0$.

't Hooft } new physics responsible
Susskind }

't Hooft : cellular automata (can't assess)

Susskind : strings — <u>are</u> nonlocal

(... ...)

String thy: $\underset{R_1}{\text{}}$ $\underset{R_2}{\text{}}$ Info. 7

$$[\mathcal{O}(R_1), \mathcal{O}(R_2)] \sim e^{-|R_1-R_2|^2/\ell_{st}^2}$$ ordinary measuremen

$$\sim 1$$ high energy measuremen (Lowe, Susskind, Uglum)

$\Rightarrow$ maybe all info is in state on R half of world!

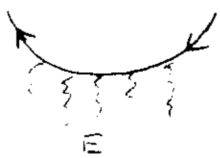
Problem : transfer to HR? (no demonstrated mechanism)

(indeed, could stay @ horizon $\rightsquigarrow$ remnant!)

3. Remnants violate naive crossing

E.g. if charged

$\rightarrow$



: <u>Schwinger production</u>

$$\Gamma_{vac} \propto \underset{\substack{\downarrow \\ \infty}}{N} \; e^{-\frac{\pi m^2}{qE}} = \infty$$

likewise : Hawking: $\frac{dM}{dt} \propto \underset{\substack{\downarrow \\ \infty}}{N} \cdot \frac{1}{M^2} = \infty$ (is self consistent)

Thermal : $n \sim N \cdot e^{-m/T} = \infty$

(can't really make)

Summary :

proposal	violates
Info loss	energy conservation
Info return	locality / causality
Remnants	naive crossing

-- each objection phrased in terms of low E physics

⇝ Information "paradox"

Relevance of planck scale ⇝ <u>problem</u>

(Hermann;
next time)