

L3

①

WORMHOLES

REFERENCES

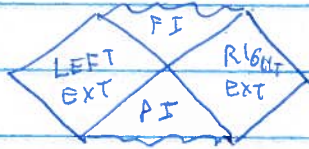
- J.M. & SUSSKIND : 1306.0533
- GAO, JAFFERIS-WALL : 1608.05687
- HAYDEN, PRESKILL - 0708.4025
- MALDACENA, STANFORD, YANG - 1709.05333

L3

WORMHOLES.

①

SIMPLEST:



Schw.

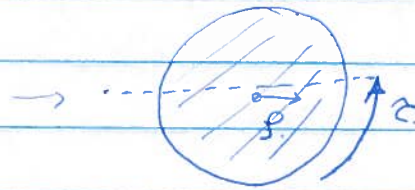
• NOT TRAVERSABLE \rightarrow AANEC. $\int dx T_{rr} = 0.$

+
EINSTEIN EQUATIONS.

• SIMILAR FOR ADS-SCH
& ANY NON-EXTREMAL
BLACK HOLE.



EUCLIDEAN.

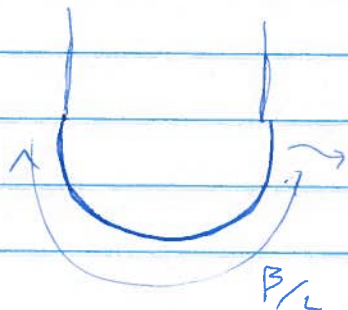


CUT IN $\frac{1}{2}$ \rightarrow TIME REFLECTION SYMMETRY

\leadsto ANALYTIC CONTINUATION IS REAL.

$$g(t^2) \rightarrow g(-t^2)$$

• IF WE HAVE A DUAL DESCRIPTION.



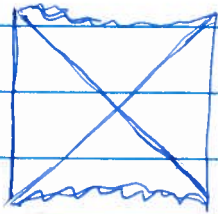
BDY
PATH
INTEGRAL

$$\sum_i e^{-\frac{\beta E_i}{2}} |i\rangle \langle i|$$

$$\int e^{-\frac{\beta E_i}{2}} |i\rangle \langle i|_R = |\text{TFD}\rangle$$

L3

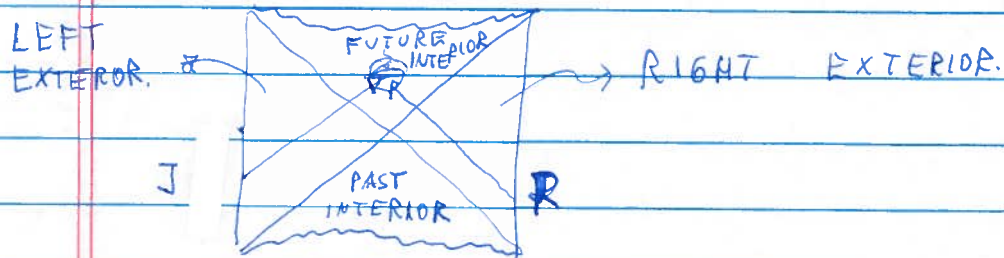
2



\leftrightarrow $|TFD\rangle$ STATE

ENTANGLED STATE
IN 2 COPIES OF
THE CFT.

• THIS IS STRANGE



NO SIGNAL TO R FROM RIGHT.
OUTSIDE

• WHAT HAPPENS IN THE INTERIOR
STAYS IN THE INTERIOR.

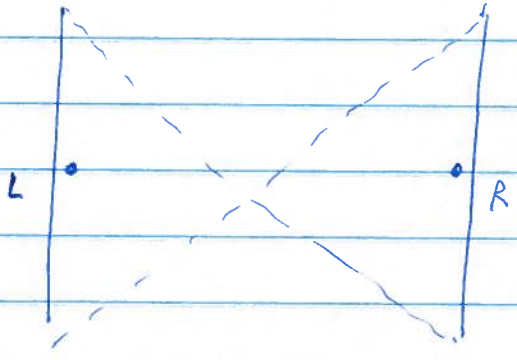
L3

3

• COUPLING THE LEFT & RIGHT SIDES WE FIND NEW PHENOMENON.

→ WORMHOLE CAN BECOME TRAVERSABLE

GAD-JAFFERIS-WALL



BULK

$$i\int \phi_L(\omega)\phi_R(\omega)$$

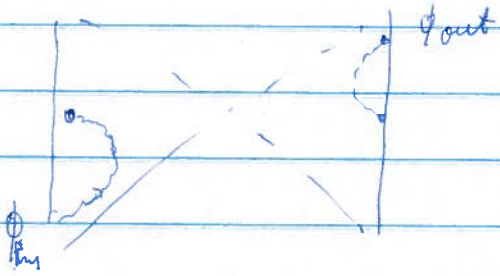
$$\approx e$$

BDY TH

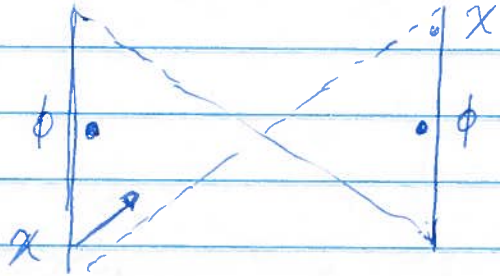
INSERT THIS OPERATOR.

• NOW THEY ARE COUPLED. INFORMATION CAN GO BETWEEN THE 2 SIDES.

• TRIVIAL WAY A SIGNAL CAN GO.



• WE WILL LOOK AT A MORE INTERESTING PROCESS.



L3

CRUCIAL OBSERVATION.

(4)

$\phi_L^{(0)} \phi_R^{(0)} \rightarrow$ CAN CREATE NEGATIVE ENERGY

$$T \sim \partial\phi\partial\phi$$

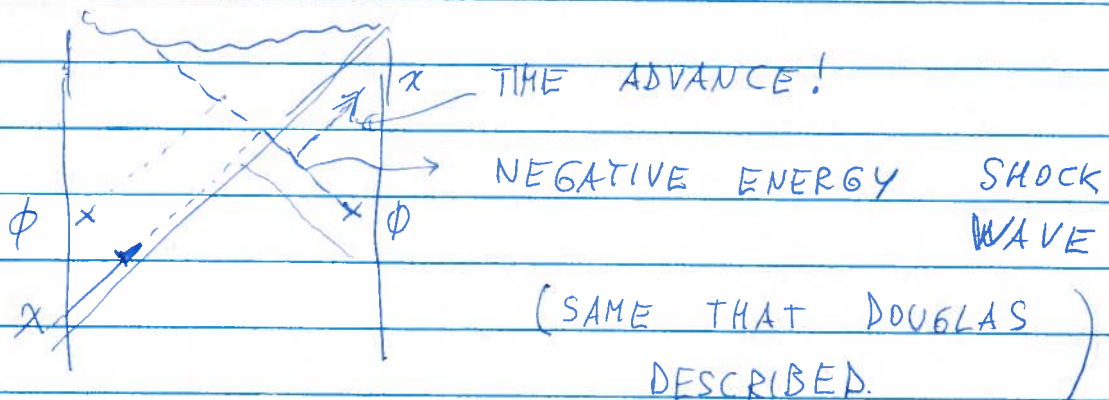


$$\langle T \rangle_g \approx g \langle [T, \phi_L^{(0)} \phi_R^{(0)}] \rangle$$

$$= g \langle \partial\phi \phi_L \rangle \langle \partial\phi \phi_R \rangle$$

\rightarrow ADJUSTING THE SIGN OF $g \rightarrow$ NEGATIVE ENERGY.

\rightarrow TAKES ADVANTAGE OF VACUUM CORRELATION



SIGNAL GOES THROUGH THE WORMHOLE!

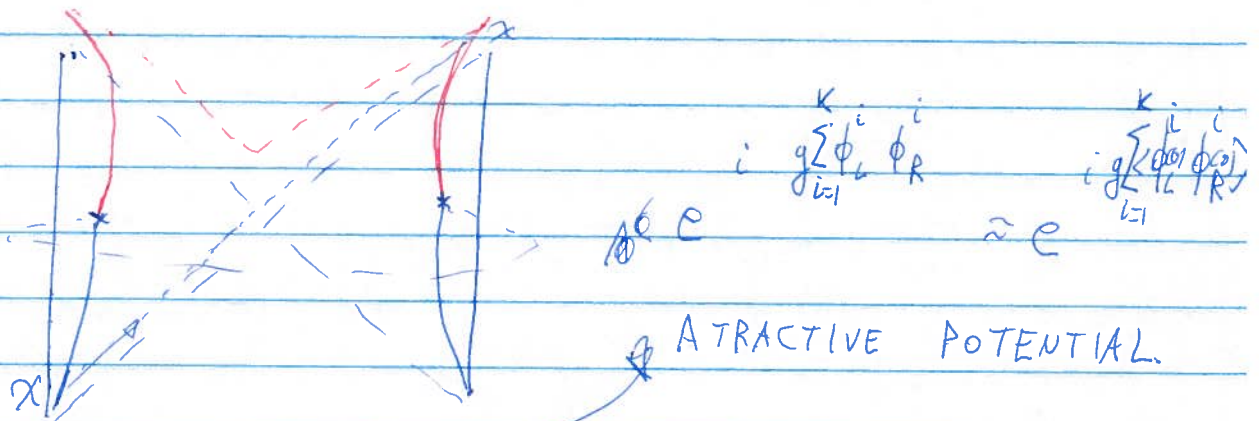
\rightarrow NEW TWIST TO ROMEO AND JULIET!

\rightarrow FAMILIES MAKE PEACE & COORDINATE A PROCEDURE TO EXTRA THEM!

L3

• AdS₂ GRAVITY

5



• IN AdS₂ THE X PARTICLE DOES NOT FEEL ANYTHING SPECIAL

(IN OTHER DIMENSIONS → COULD FEEL TIDAL FORCES...)

• SAME CORRELATORS IN SYK !

• LETS US EXPLORE THE REALITY OF THE INTERIOR.

MORE PRECISELY = THE REALITY OF THE CONTINUOUS SPACETIME

• ~~THEY~~ CAN WE APPROACH THE SINGULARITY ?

~ NO ~ LIKE THE POT OF GOLD AT THE END OF A RAINBOW.

• TO ENHANCE THE EFFECT.

g SMALL K FIELDS $\phi^i \phi^i$ $i=1, \dots, K$
 $gK \gg 1$

L3

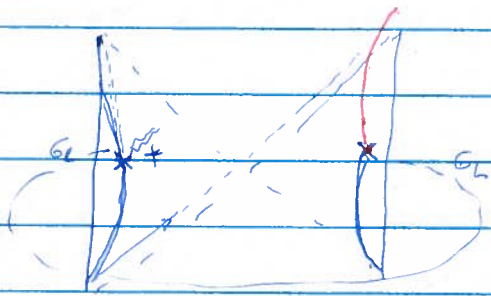
• THIS WAS A QUANTUM INTERACTION.

6

• REQUIRES TRANSPORTING Q-BITS.

• TELEPORTATION:

→ ONLY CLASSICAL SIGNALS



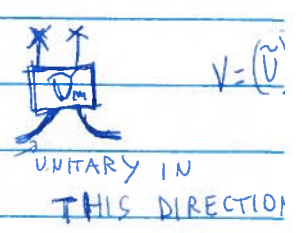
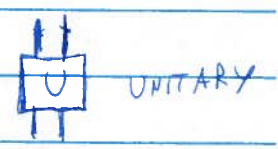
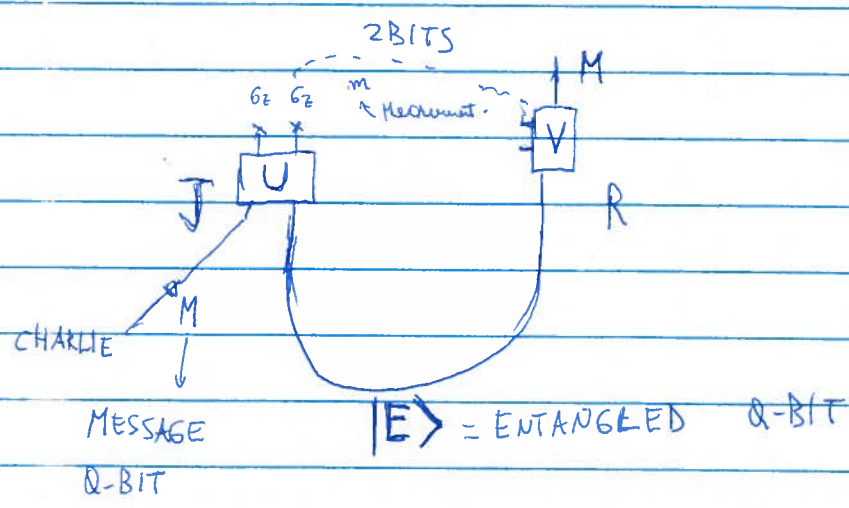
• MEASURE $\phi_L \rightarrow G_L = \text{EIGENVALUES}$

$$e^{i\phi_L} \phi_L \rightarrow G_L \phi_L(0) \rightarrow G_L$$

• SAME EFFECT \rightsquigarrow TELEPORTATION.

REMINDER ABOUT TELEPORTATION

• SEND A QUBIT $\sim \infty$ VARIABLES \rightsquigarrow SEND PAIR OF QUBITS.



THERE EXIST SUCH U'S

How DOES THE QBIT GOES?

[3]

6.5

BULK GIVES US A BETTER
PICTURE FOR WHY THE STATE
CAN BE TELEPORTED.

VAGUE REMARK

QBIT FROM "IT" \rightarrow BULK "TOPOLOGICAL" THEORY

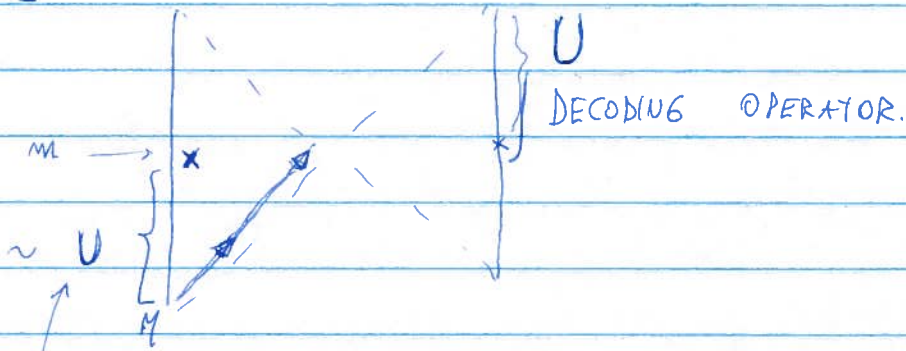
\rightarrow + BOUNDARIES \rightsquigarrow QUANTUM MECHANICS!

TELEPORTATION OF 1 QUBIT

"CONSUMES" $\left\{ \begin{array}{l} 1 \text{ ENTANGLED PAIR} \\ 2 \text{ CLASSICAL BITS OF INFO} \end{array} \right.$

L3

7



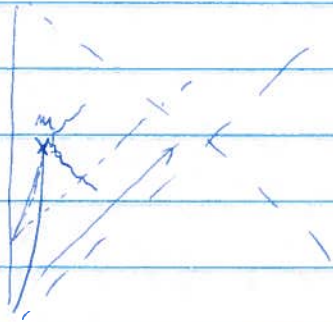
ENCODING \approx PART OF STANDARD EVOLUTION.

CONDITION THAT M DOES NOT DESTROY M .

\leadsto BULK COMMUTATIVITY.

BUT $[m, U M U^{-1}] \neq 0$

• ONCE WE MEASURE $m \rightarrow$ CANNOT RECOVER M



• OUT OF REACH FROM L SIDE.

WAITING TO BE EXTRACTED \rightarrow COULD OR COULD NOT BE EXTRACTED

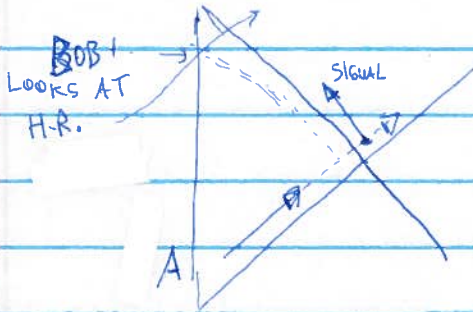
• RECOVERABLE FROM THE R SIDE!

\rightarrow ONLY IF WE APPLY THE RIGHT TRANSFORMATION!

L3

HAYDEN & PRESKILL "PARADOX"

8



LOOKS AT HAWKING

BOB

RAD & DECODES THE MESSAGE.

& JUMPS IN.

DOES HE SEE A

2nd COPY OF

THE MESSAGE. ?

SOLUTION 1:

"TRANSPLANCKIAN SHADOW"
(FAIRY)

→ BOB TAKES LONG TIME TO DECODE

→ SIGNAL → SHOULD HAVE VERY HIGH ENERGY

HOW LONG?

- IF BOB OBSERVED THE BH FOR A LONG TIME

& HAS A QUANTUM HP COMPUTER → CREATED AN

ENTANGLED STATE FROM BH & HP COMPUTER.

THEN → BOB ONLY NEEDS TO OBSERVE A

NUMBER OF QBITS SLIGHTLY LARGER THAN
THE MESSAGE

(OR # OF BITS SLIGHTLY LARGER THAN

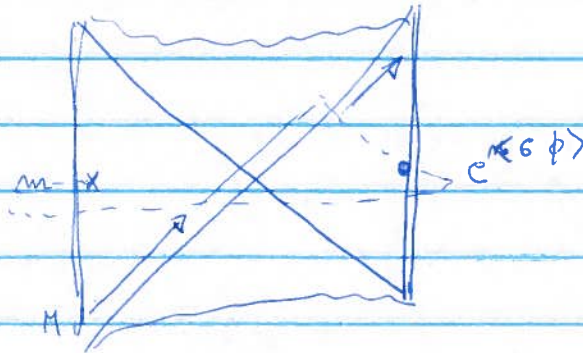
TWICE THE MESSAGE)

⇒ INFO COMES OUT "IMMEDIATELY" = BLACK HOLES AS MIRRORS.

L3

10

ALTERNATIVE ANALYSIS



1. **HP** → CREATES
THE **|TFD⟩**
(IS HARD, BUT
HP COMPUTERS ARE
GOOD
& FAST)

• NOW WE SEE HOW IT
HAPPENS.

- MESSAGE^R IS ONLY ONCE EVERYWHERE.

BULK POLICE IS HAPPY.

NO ILLEGAL BORDER CROSSING.

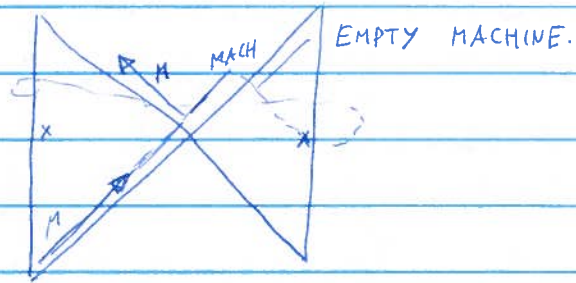
- ALL WITHIN THE BULK GRAVITY LAWS.

• LESSON:

- CANNOT IGNORE THE SPACETIME CREATED BY QUANTUM COMPUTERS.
- THE MESSAGE WAS EXTRACTED FROM THE "INSIDE"
- LIKE MAXWELL DEMON = INCLUDE ENTROPY OF DEMON.
- IF BOB EXTRACTS THE MESSAGE & JUMPS → DOES NOT SEE A 2ND COPY.

L3

(11)



• BOB JUMPS IN THE OTHER SIDE → SEES MESSAGE

• IF BOB EXTRACTS MACHINE & EVOLVES BACKWARD
IN TIME → GETS MESSAGE.

→ JUMPS INSIDE → NO MESSAGE.

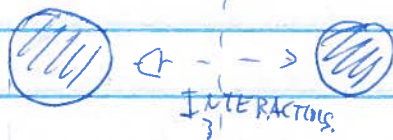
L3

12

• IS SUCH A "NON-LOCAL" INTERACTION NATURAL?

- IN CFT \rightarrow YES: WE ARE FREE TO COUPLE 2 DIFFERENT CFTs -

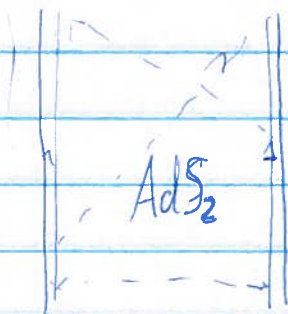
- IF WE HAVE 2 NEAR EXTREMAL BLACK HOLES?



ENTANGLED IN TFD

IF DISTANCE IS SMALL COMPARED TO β .
 \rightarrow CAN BE INSTANTANEOUS...

• LEAVE ON THE INTERACTION.



\rightarrow ETERNALLY TRAVERSABLE WORMHOLE

• BOTH IN SYK & AdS₂

$$g_{ij} \psi_L^i \psi_R^j$$

e

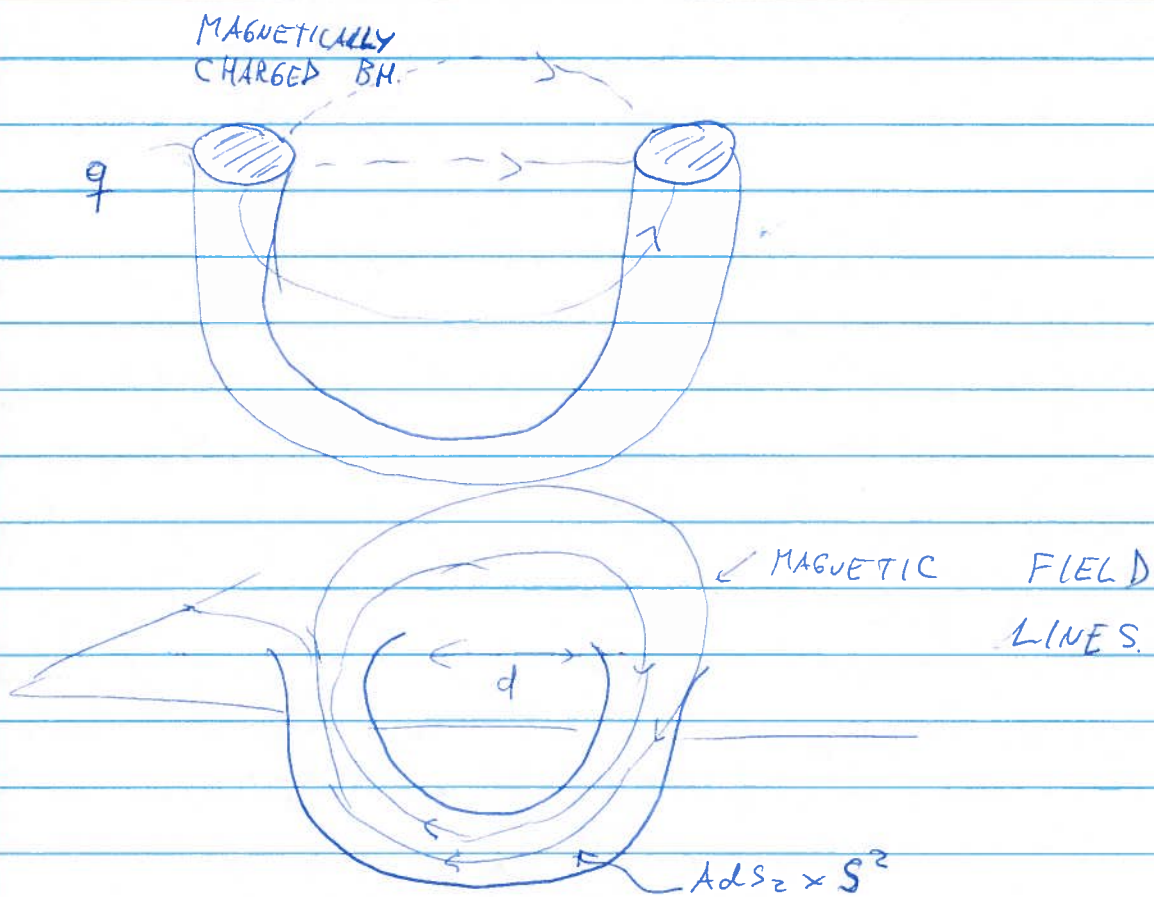
L3

13

• WHAT YOU ARE SAYING IS FOR UNREALISTIC 2d GRAVITY

WE LIVE IN 4d, NON SUSY, w/ THE STANDARD MODEL.

• WE HAVE ^{TRAVERSABLE} WORMHOLE SOLUTIONS IN THE S.M.



$d = 0$ FERMIONS $q =$ LOWEST LANDAU LEVEL ON S^2

\leadsto LONG WORMHOLE

$d <$ ELECTROWEAK SCALE, $q \rightarrow$ WEAK HYPERCHARGE

$U(1) \times SU(2) \times SU(3)$