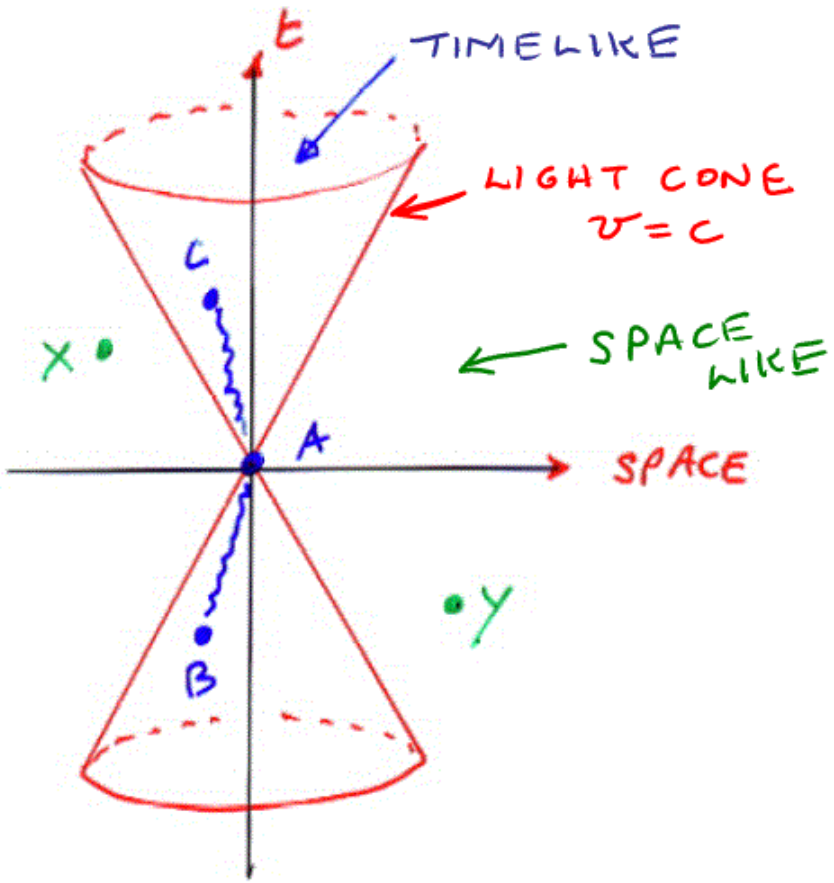
WHY DO ANTI-PARTICLE EXIST?

- COMBINATION OF SPECIAL RELATIVITY & QUANTUM MECHANICS
- FIRST → SPECIAL RELATIVITY.



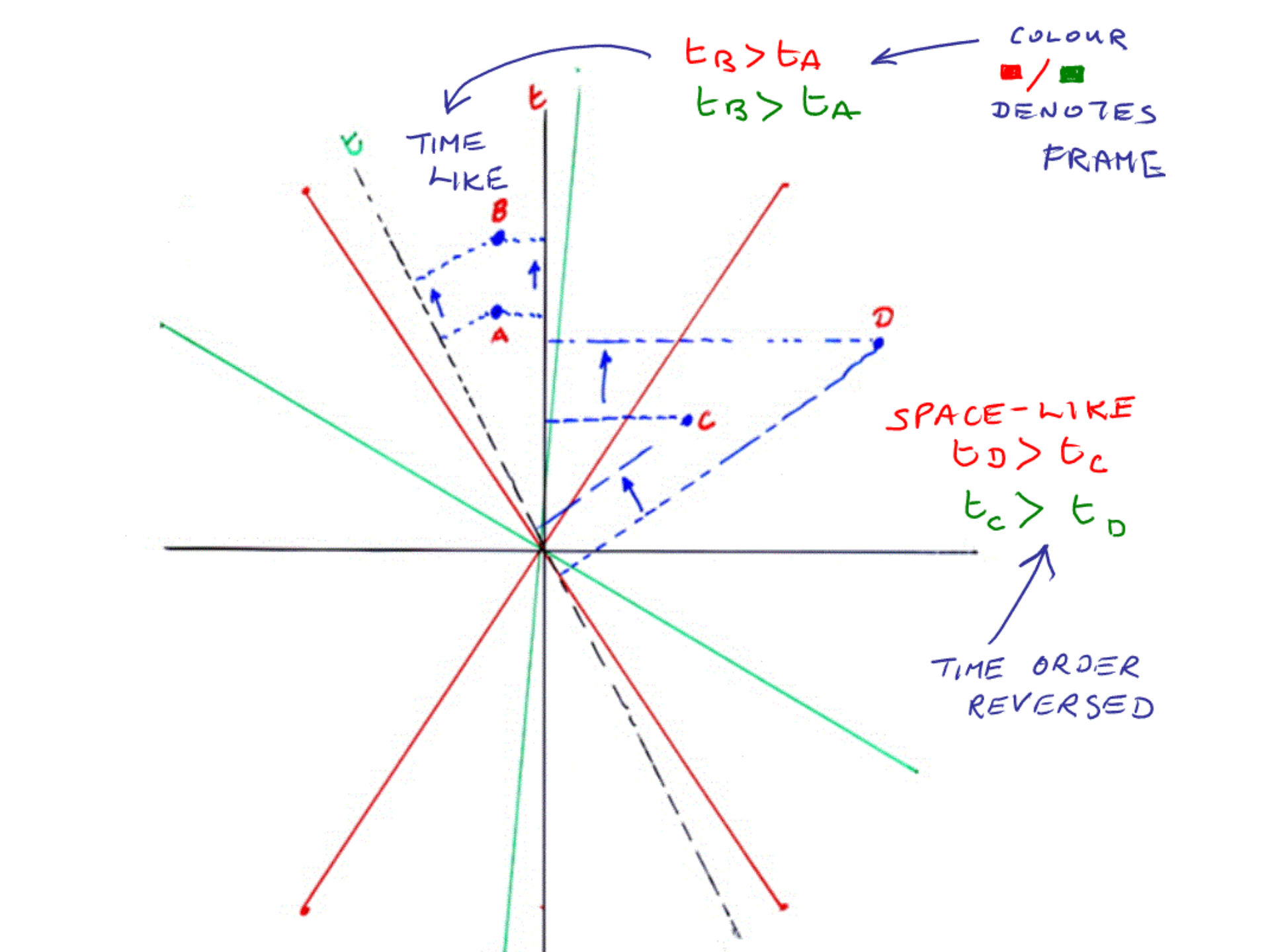
- ONWY EVENTS INSIDE THE LIGHT-CONE CAN BE CAUSALLY CONNECTED

$$B \rightarrow A \rightarrow C$$

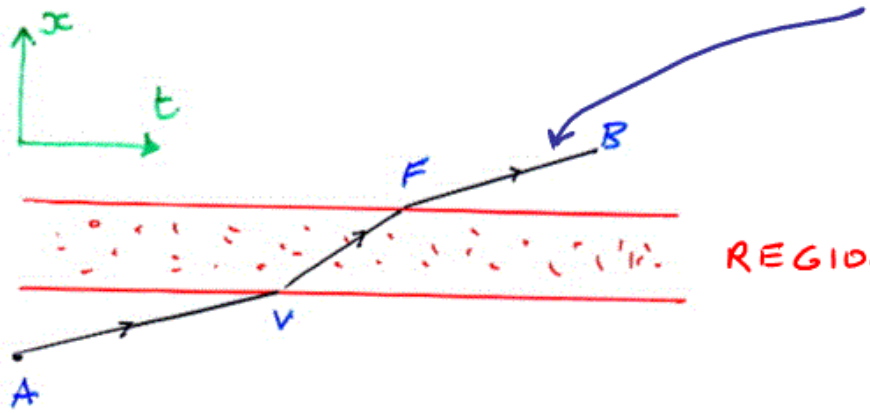
- X, A & Y CAN HAVE NO CAUSAL CONNECTIONS WOULD REQUIRE $v > c$

- TIMELIKE
  — SAME ORDERING OF EVENTS FOR ALL OBSERVERS

- SPACELIKE
  — TIME ORDERING CAN BE REVERSED FOR DIFFERENT OBSERVERS

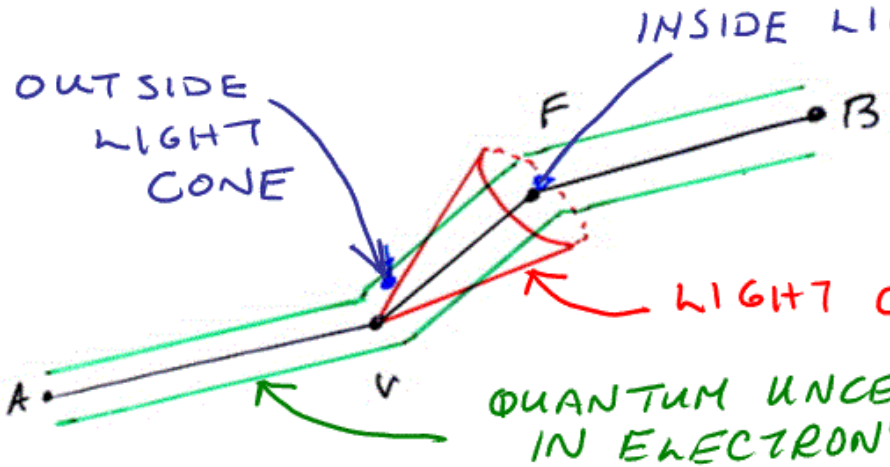

$t_B > t_A$
$t_B > t_A$
COLOUR
DENOTES
FRAME
t
x
TIME
LIKE
B
A
D
C
SPACE-LIKE
$t_D > t_C$
$t_C > t_D$
TIME ORDER
REVERSED

• SO WHAT HAPPENS WHEN WE INTRODUCE QUANTUM MECHANICS?



CLASSICAL TRAJECTORY OF PARTICLE INTERACTING WITH POTENTIAL

REGION WITH SOME POTENTIAL (EQ. EM)

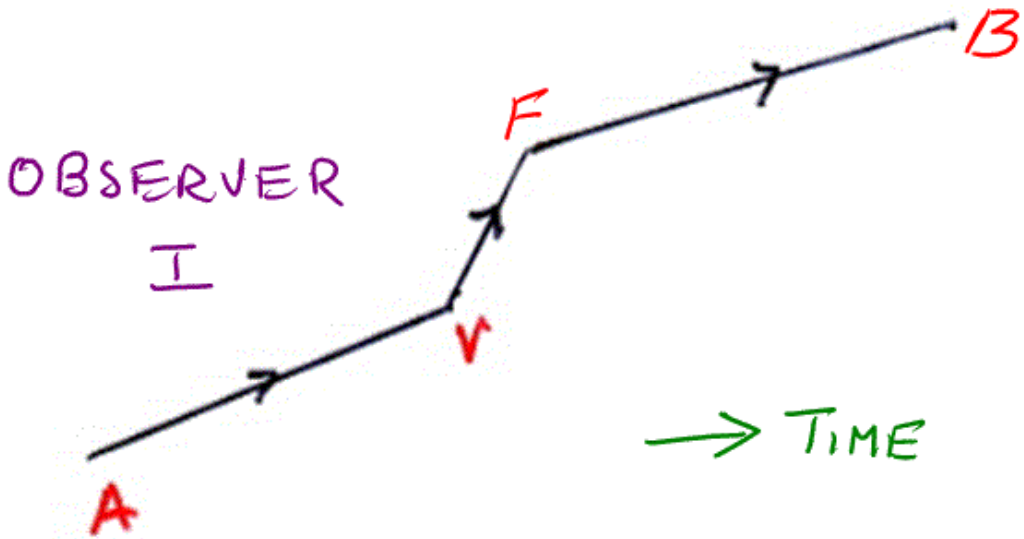


• IN QUANTUM WORLD TRAJECTORY & HENCE LIGHT CONE ARE "FUZZY"

• CLASSICALLY ALL OBSERVERS SEE $V \rightarrow F$

• IN QM → ELECTRON CAN "FUZZILY" BE OUTSIDE LIGHT CONE → ∴ OBSERVERS MUST EXIST WHO SEE $F \rightarrow V$

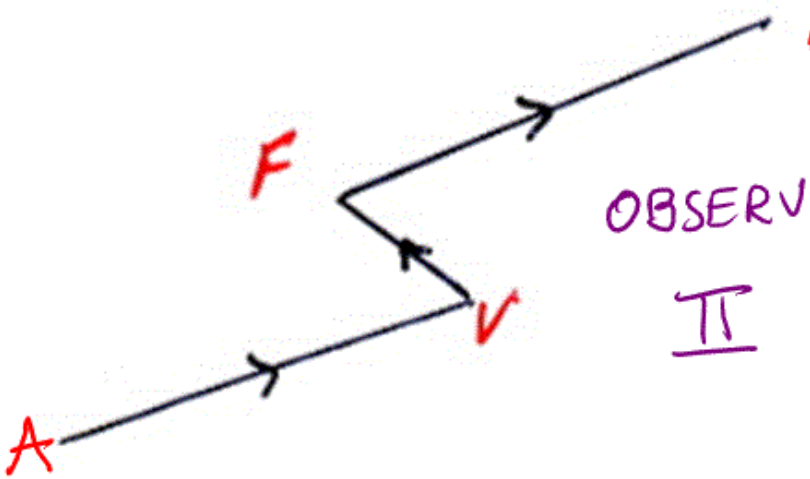
DEPENDING ON OBSERVER



→ OK TIME ORDER

→ TIME

WHAT'S THIS ?
V → F PARTICLE GOES BACK IN TIME ?



· WHAT ABOUT CAUSALITY ?

. 2 PARTICLES APPER AT F
— ONE GOES TO B
— ONE MEETS PARTICLE FROM A AT V

→ THEY MUTUALLY ANNIHILATE

→ PROPERTIES OF ANTI-PARTICLES OBVIOUS

- SPECIAL RELATIVITY — CAUSALITY WITHIN LIGHT CONE

+

- QUANTUM MECHANICS — $\not{x}$ → SMEARS TRAJECTORY & HENCE LIGHT CONE

↓

ANTI PARTICLES

+

TOTAL NUMBER OF PARTICLES CAN CHANGE IN INTERACTION

- COMES NATURALLY OUT OF THE DIRAC EQUATION.

ANTI PARTICLES ↔ PARTICLES

- SAME MASS, SPIN, LIFETIME, OPPOSITE CHARGE, COLOR, FLAVOR
- PROFOUNDLY CONNECTED TO LORENTZ INVARIANCE IN Q.M.

$$E^2 = p^2 + m^2 \qquad c = 1$$

$$E = \pm\sqrt{p^2 + m^2}$$

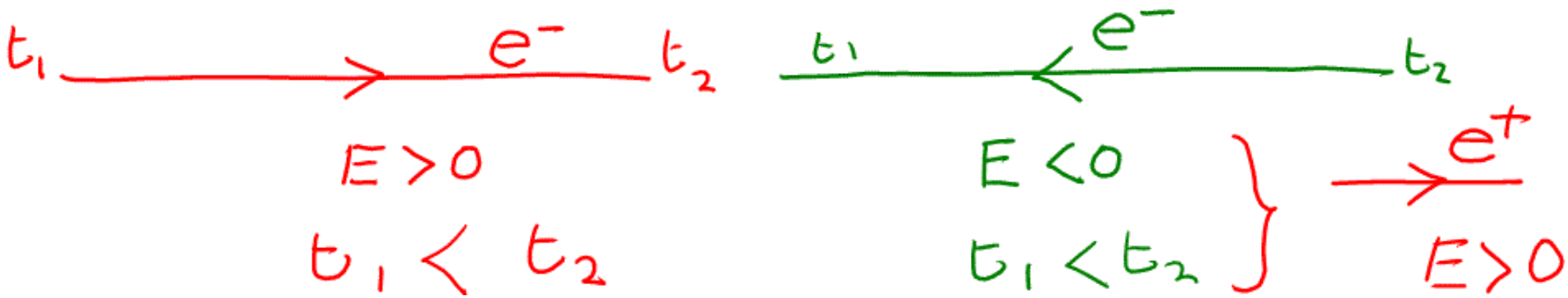
- NEGATIVE SIGN MEANINGLESS CLASSICALLY $E = \frac{1}{2} m v^2$
- DO -VE ENERGIES MEAN SOMETHING IN Q.M.?

Q.M. → FREE PARTICLE → PLANE WAVE

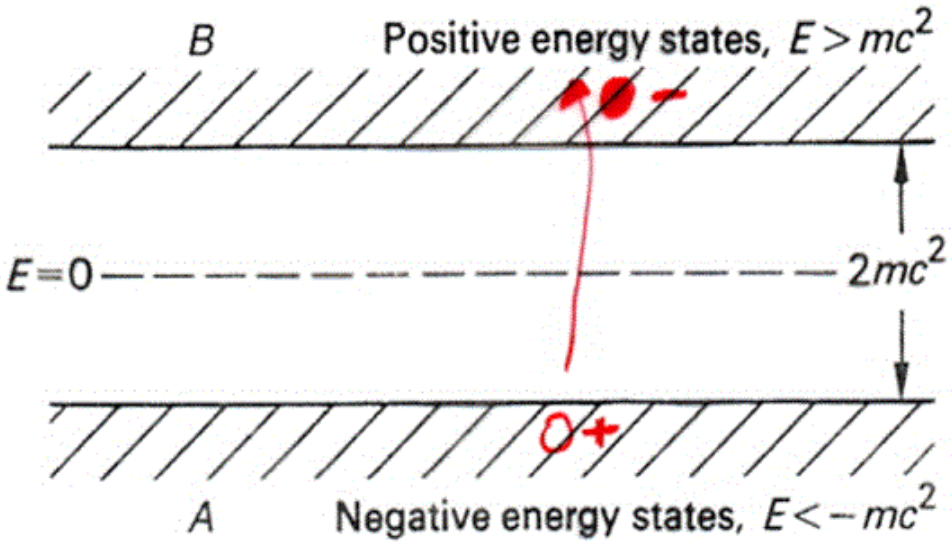
$\hbar = 1$ $\psi = A e^{-i(E \cdot t - p \cdot x)}$

$t \to +VE$; PHASE INCREASES FOR +VE x
$t \to -VE$; PHASE INCREASES FOR −VE x

$Et \to (-E)(-t) \qquad px \to (-p)(-x)$



DIRAC → "HOLE IN ELECTRON SEA" PICTURE



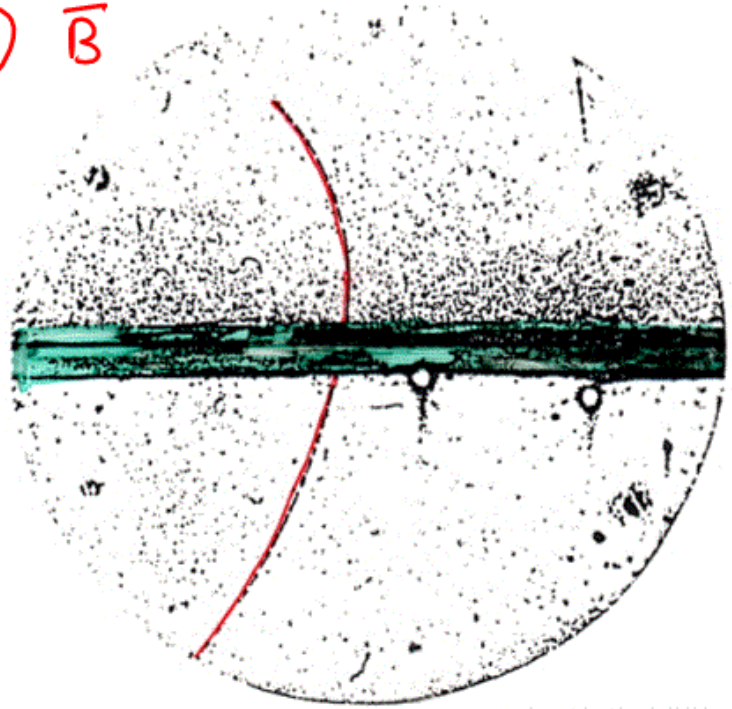
- ALL -VE ENERGY STATES FILLED DUE TO PAULI EXCLUSION
- IF GIVE -VE ENERGY ELECTRON $E > 2m_e c^2$

+VE E ELECTRON

& -VE E "HOLE"

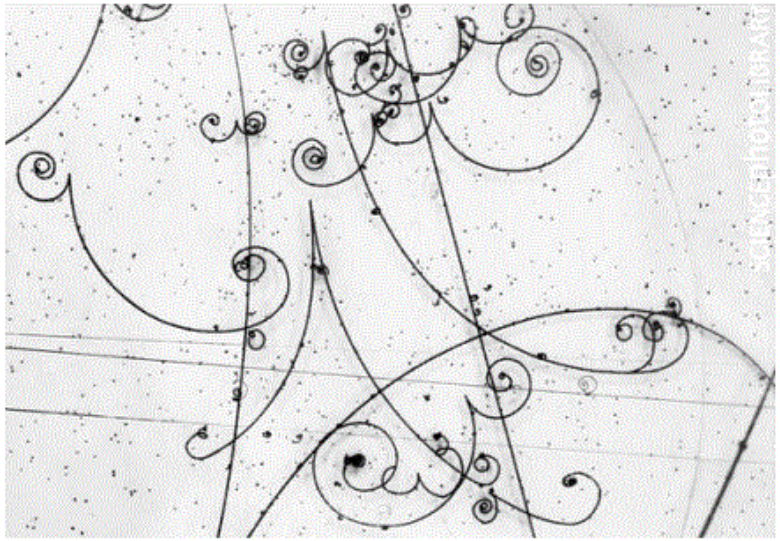
↘ e^+

- THIS A NON RELATIVISTIC, SINGLE PARTICLE "THEORY"
- REPLACE BY QUANTUM FIELD THEORY WHERE PARTICLES / ANTIPARTICLES CAN BE CREATED & ANNIHILATE.

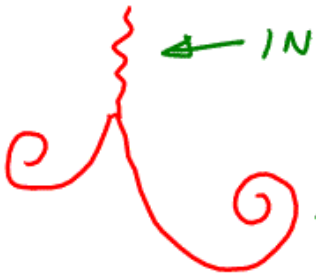


A 63 million volt positron ($H\rho = 2.1 \times 10^4$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

- DISCOVERY OF POSITRON BY CARL ANDERSON 1933
- PARTICLE SLOWS DOWN IN Pb PLATE ∴ COMING FROM BELOW
- FROM SIGN OF MAGNETIC FIELD MUST B +VE
- 10X RANGE OF PROTON (ONLY +VE PARTICLE KNOWN)



$\gamma \rightarrow e^+e^-$ IN A LARGE MODERN BUBBLE CHAMBER



QUANTUM MECHANICAL WAVE EQUATIONS

SCHRÖDINGER — NON RELATIVISTIC

$$E = p^2/2m - V$$

$$p \to +i\hbar\nabla \to E\psi = -\hbar^2/2m\,\nabla^2\psi - V\psi$$

$$E \to +i\hbar\,\partial/\partial t \to +i\hbar\,\partial\psi/\partial t + \hbar^2/2m\,\nabla^2\psi = -V\psi = 0 \quad \text{(FREE)}$$

KLEIN – GORDON — RELATIVISTIC

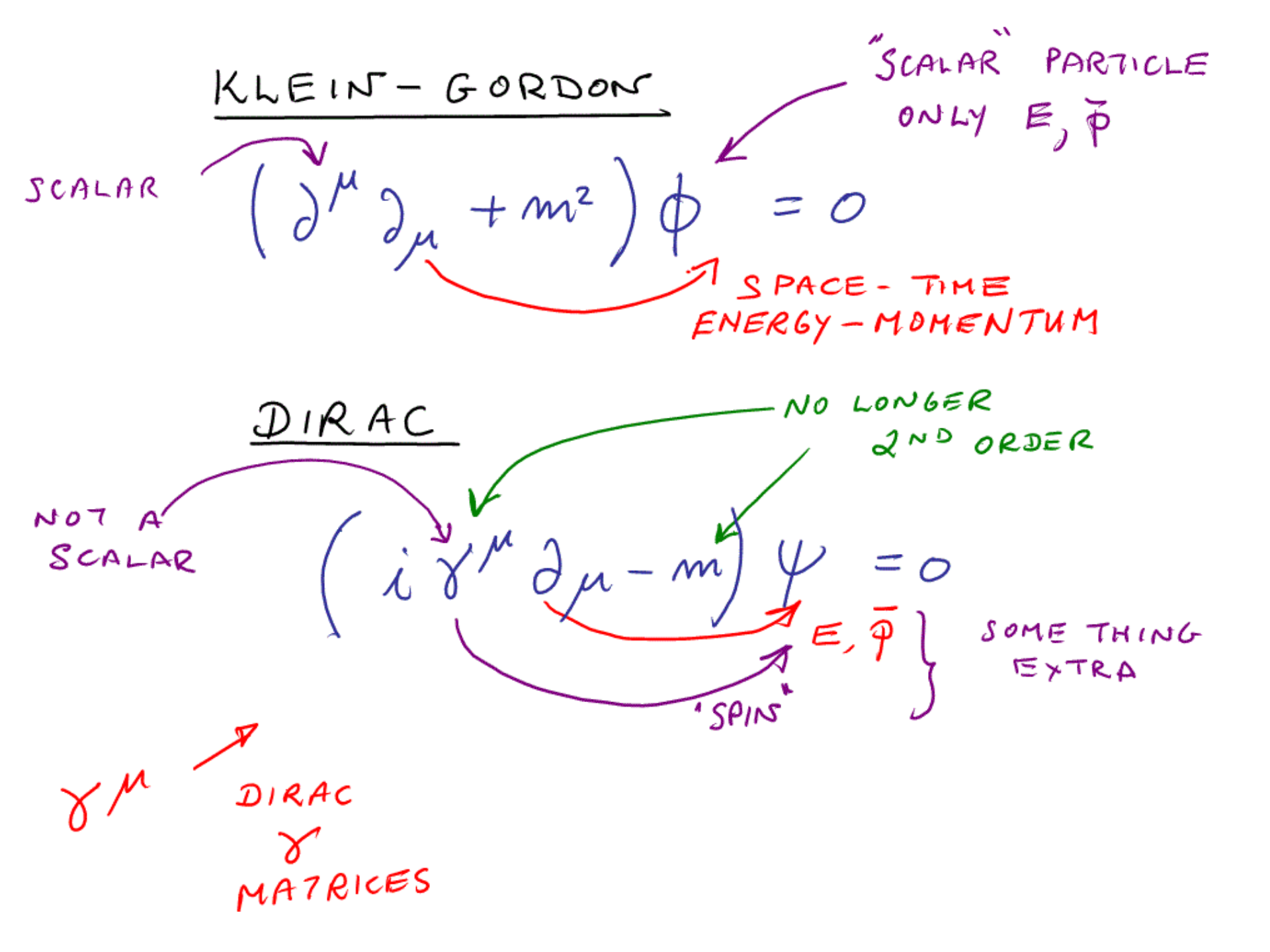
$$p^\mu p_\mu = m^2 \to p^\mu \to i\partial^\mu$$

cf NON RELATIVISTIC $p \to i\hbar\nabla$ (→ 1)

$$(\partial^\mu\partial_\mu + m^2)\,\phi = -V\phi = 0 \quad \text{(FREE)}$$

$$E^2 = p^2 + m^2 \to E = \pm\sqrt{p^2+m^2}$$ — VE ENERGY

DIRAC TRIED TO AVOID $\sqrt{\ } \to \partial^\mu\partial_\mu \to \partial^\mu$


KLEIN-GORDON
"SCALAR" PARTICLE
ONLY E, p̃
SCALAR
$(\partial^\mu \partial_\mu + m^2)\phi = 0$
SPACE-TIME
ENERGY-MOMENTUM
DIRAC
NO LONGER
2ND ORDER
NOT A
SCALAR
$(i\gamma^\mu \partial_\mu - m)\psi = 0$
E, p̄
SOME THING
EXTRA
'SPIN'
γ^μ
DIRAC
γ
MATRICES