Chapter 10:
Origin of Mass

The Origin of Mass

After the Big Bang
all the known particles were massless.

They are not massless now.

Their masses violate $SU(2)_L$ charge conservation!

HIGGS BOSON

H

The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe get its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.99% the speed of light.

Wool felt with gravel fill for maximum mass.

LIGHT ●●●●●●●●●●●● HEAVY

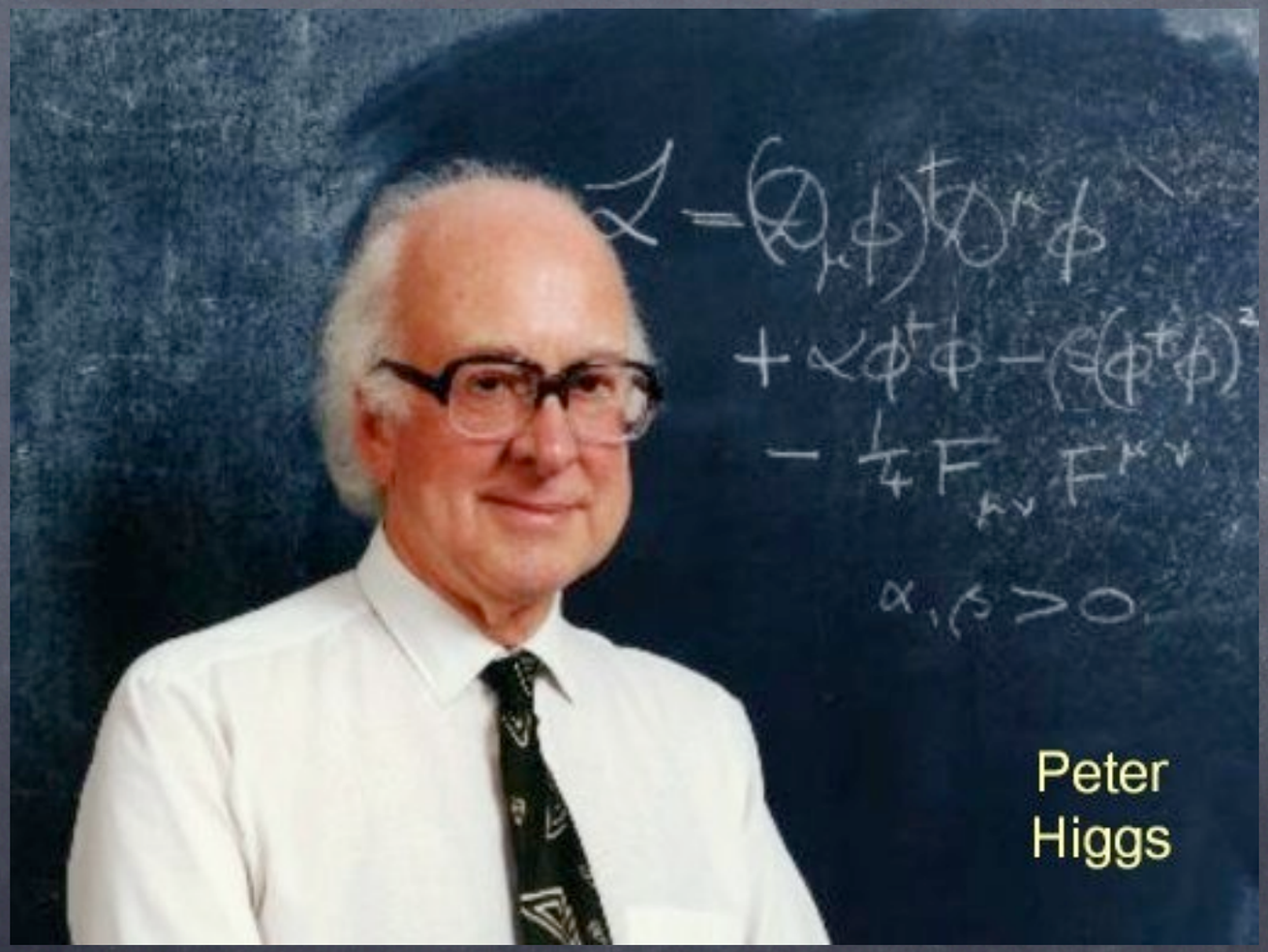
$9.75 PLUS SHIPPING

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK
NEUTRON DOWN QUARK TAU GLUON **HIGGS BOSON** NEUTRINO TACHYON ELECTRON UP QUARK DOWN
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY

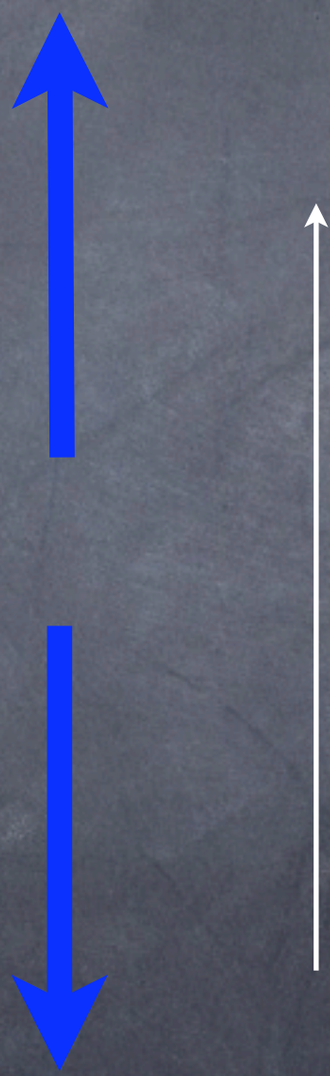
The PARTICLE ZOO

the missing piece

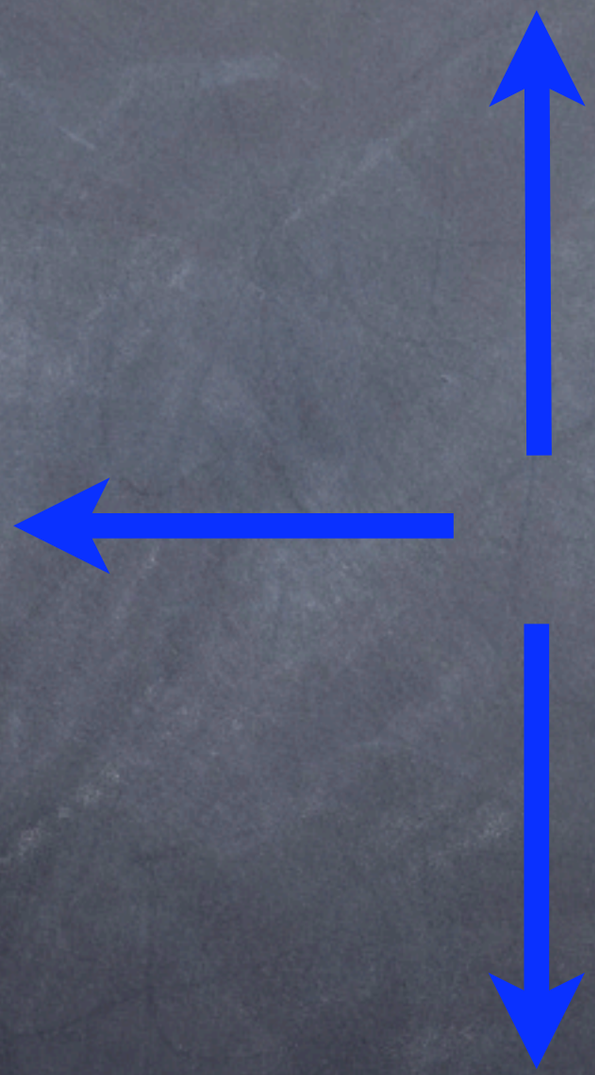
Peter Higgs



Massless Spin 1 Never at Rest



Massive Spin 1 at Rest



Spontaneous Symmetry Breaking

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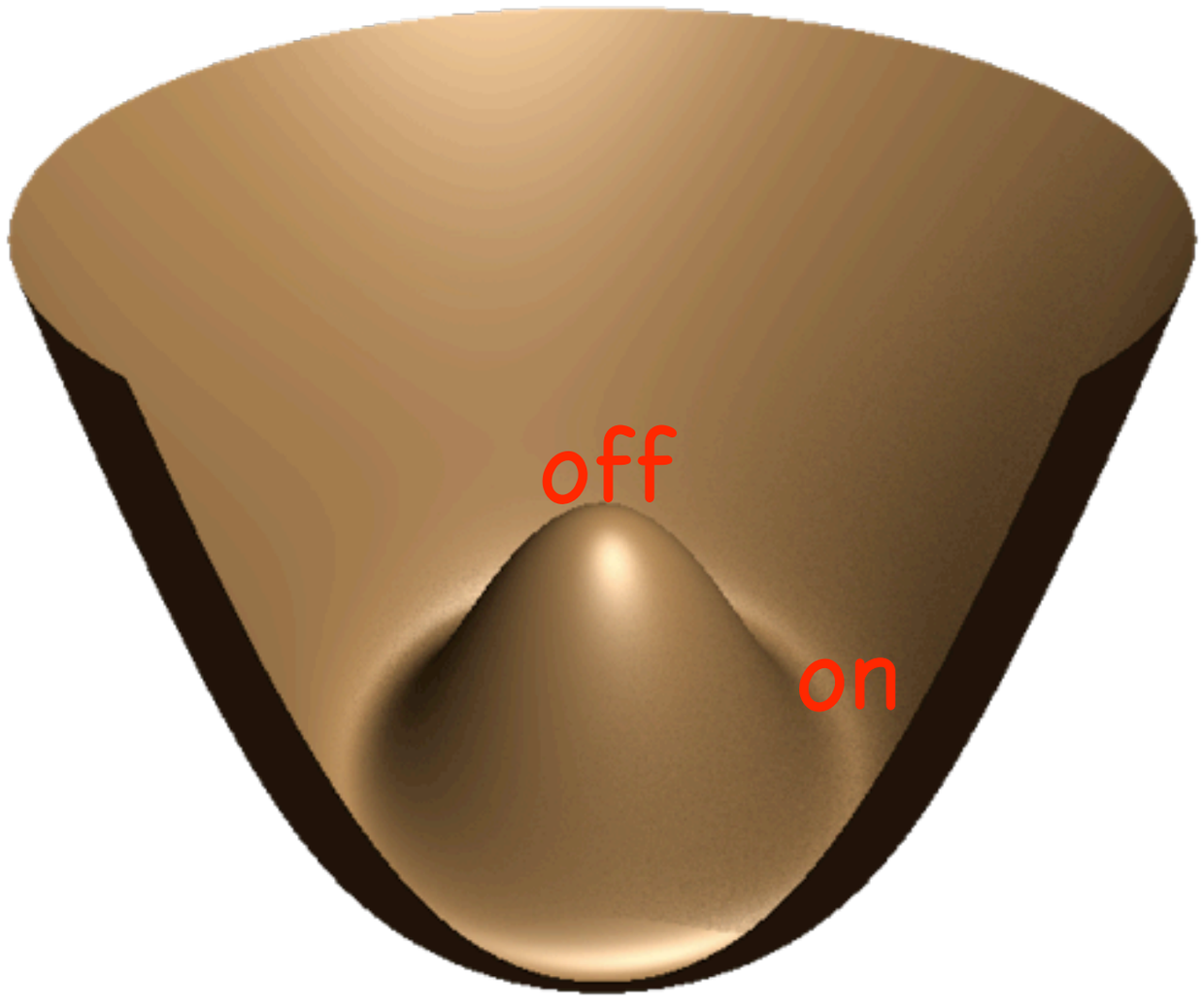
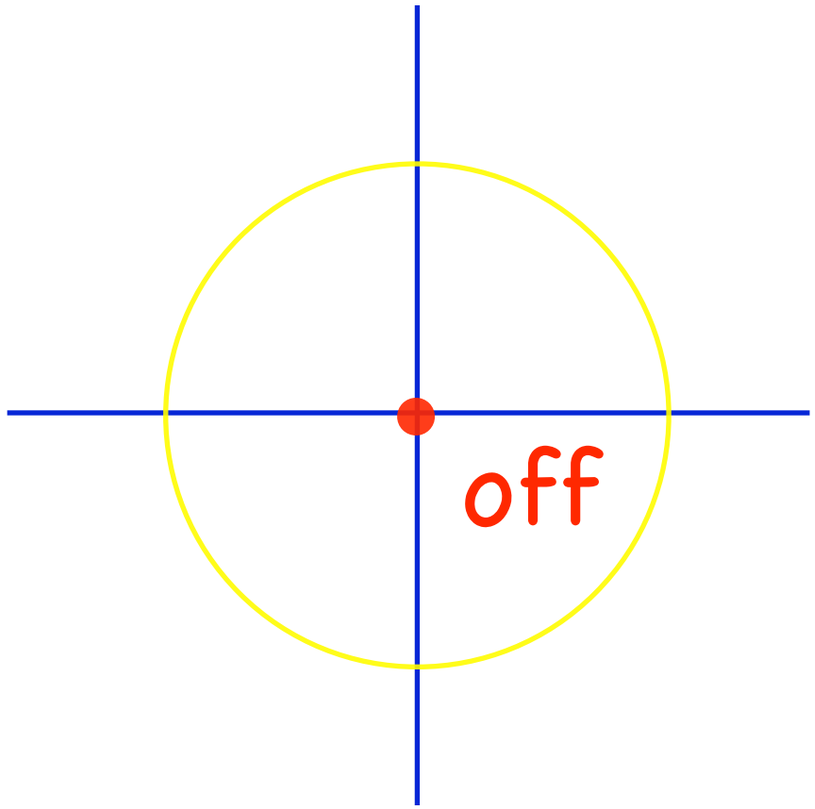
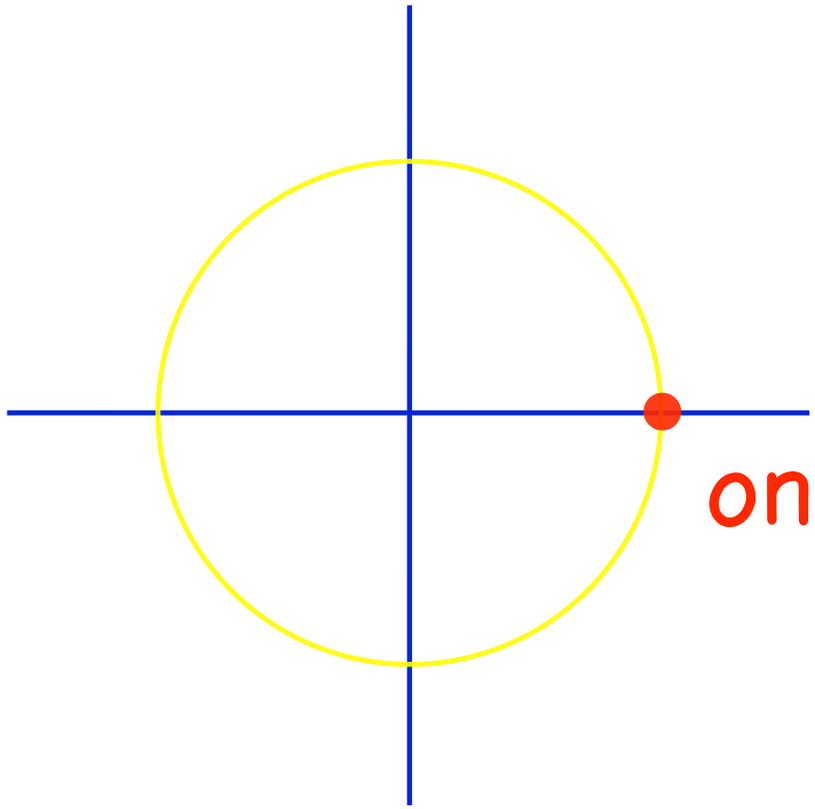
Higgs Energy Cost

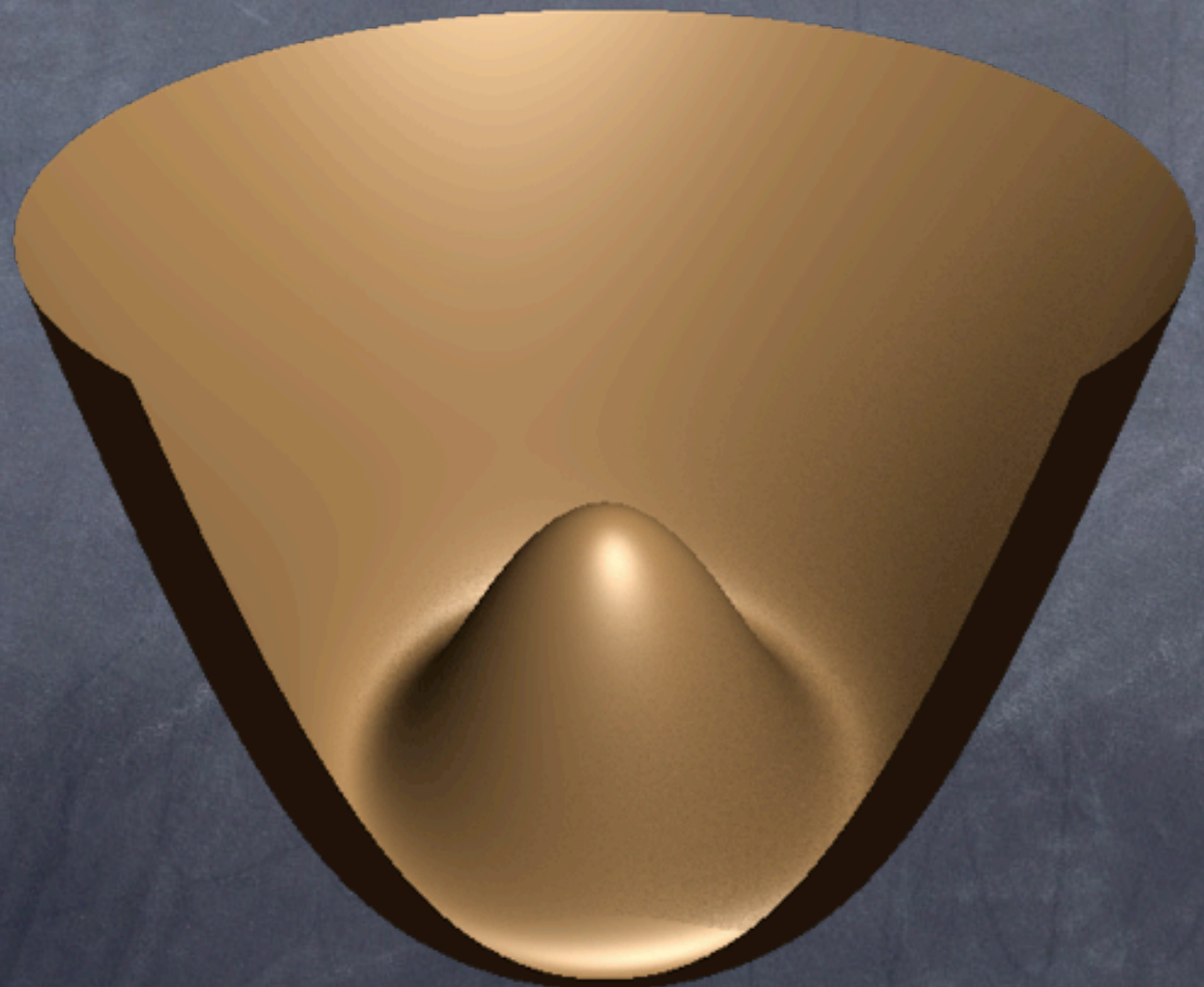


Broken Symmetry





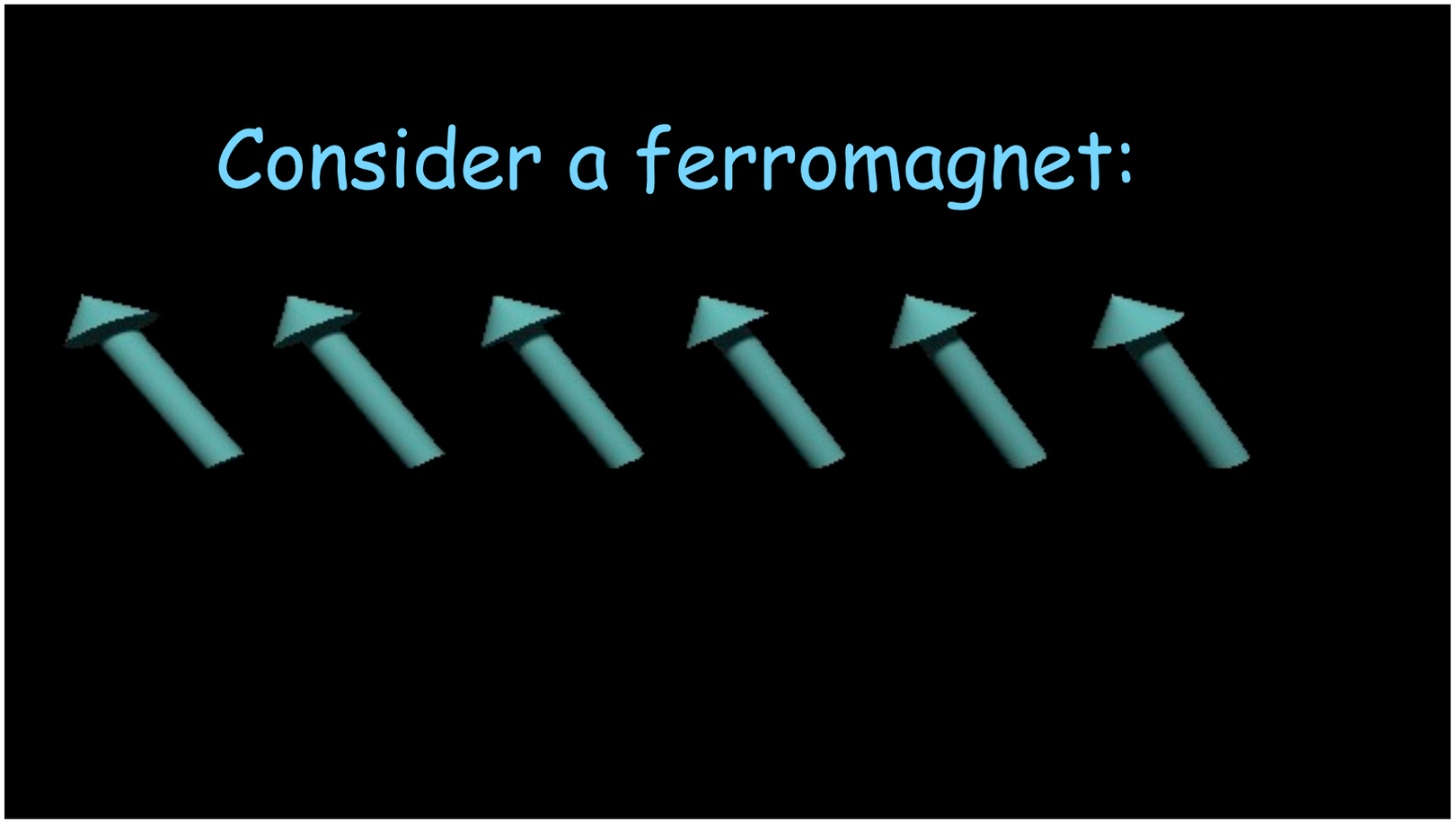
SM Potential Energy



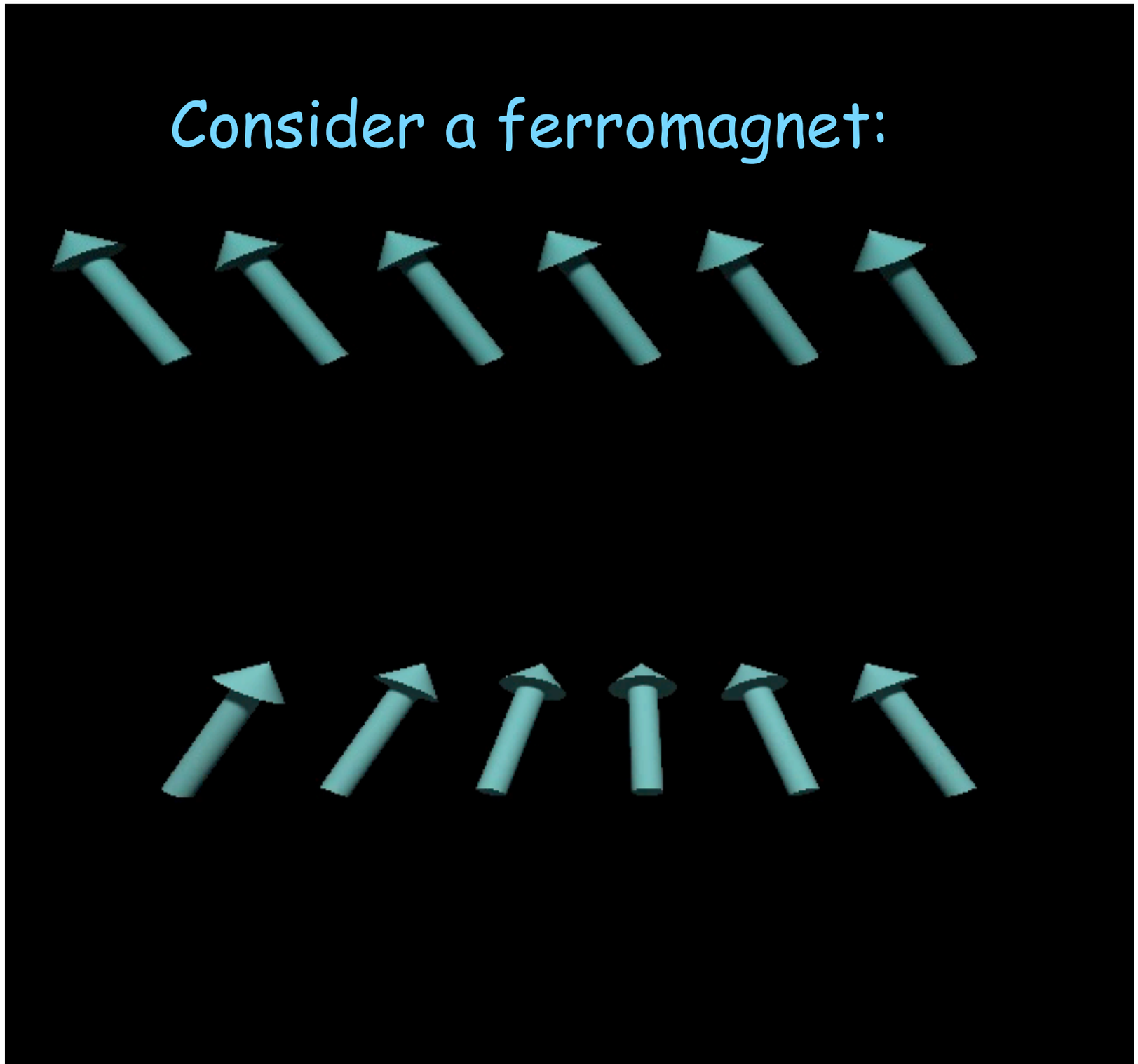
Goldstone's Theorem

There is a massless mode whenever the ground state transforms under a continuous symmetry of the Hamiltonian

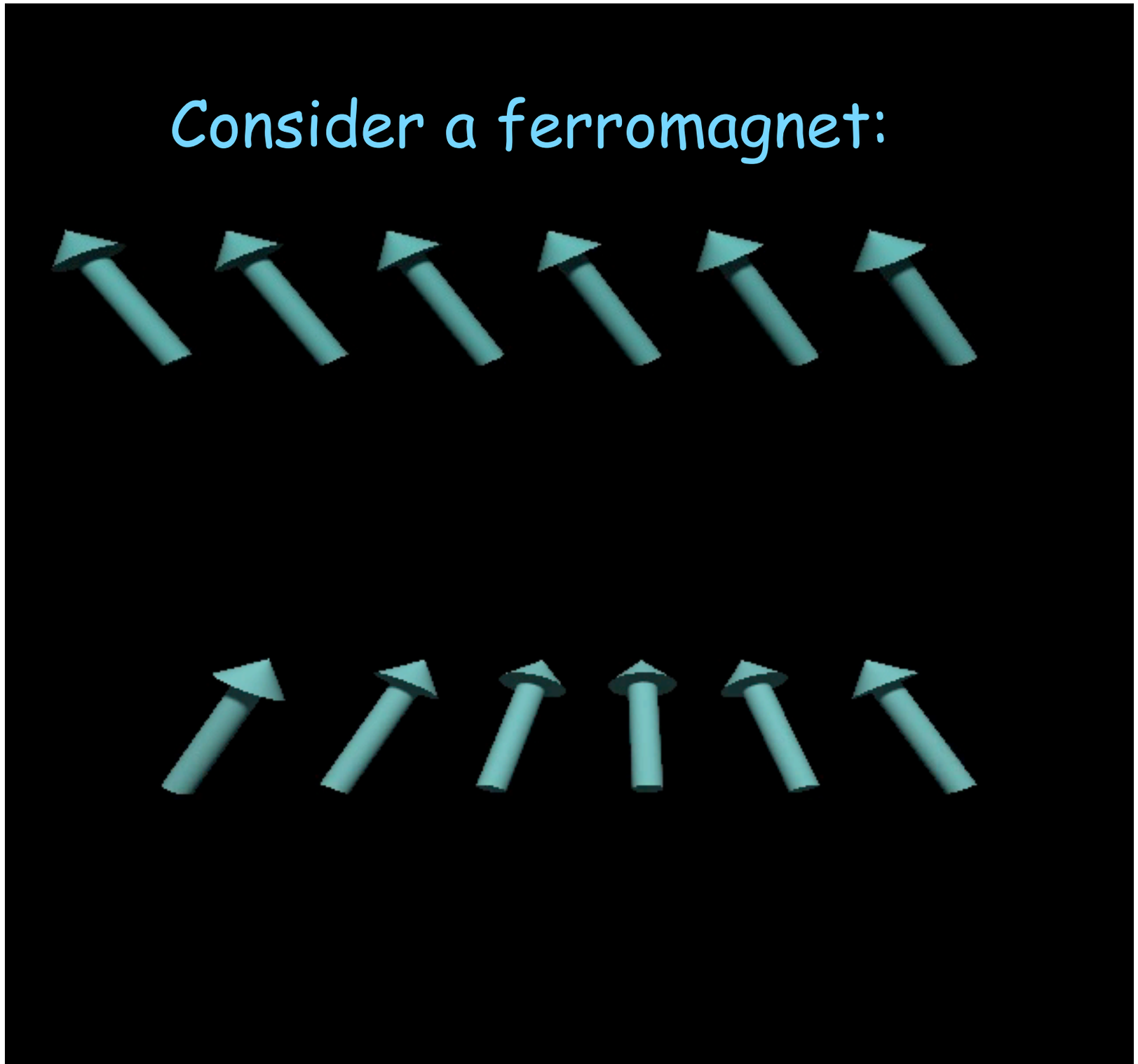
Goldstone's Theorem



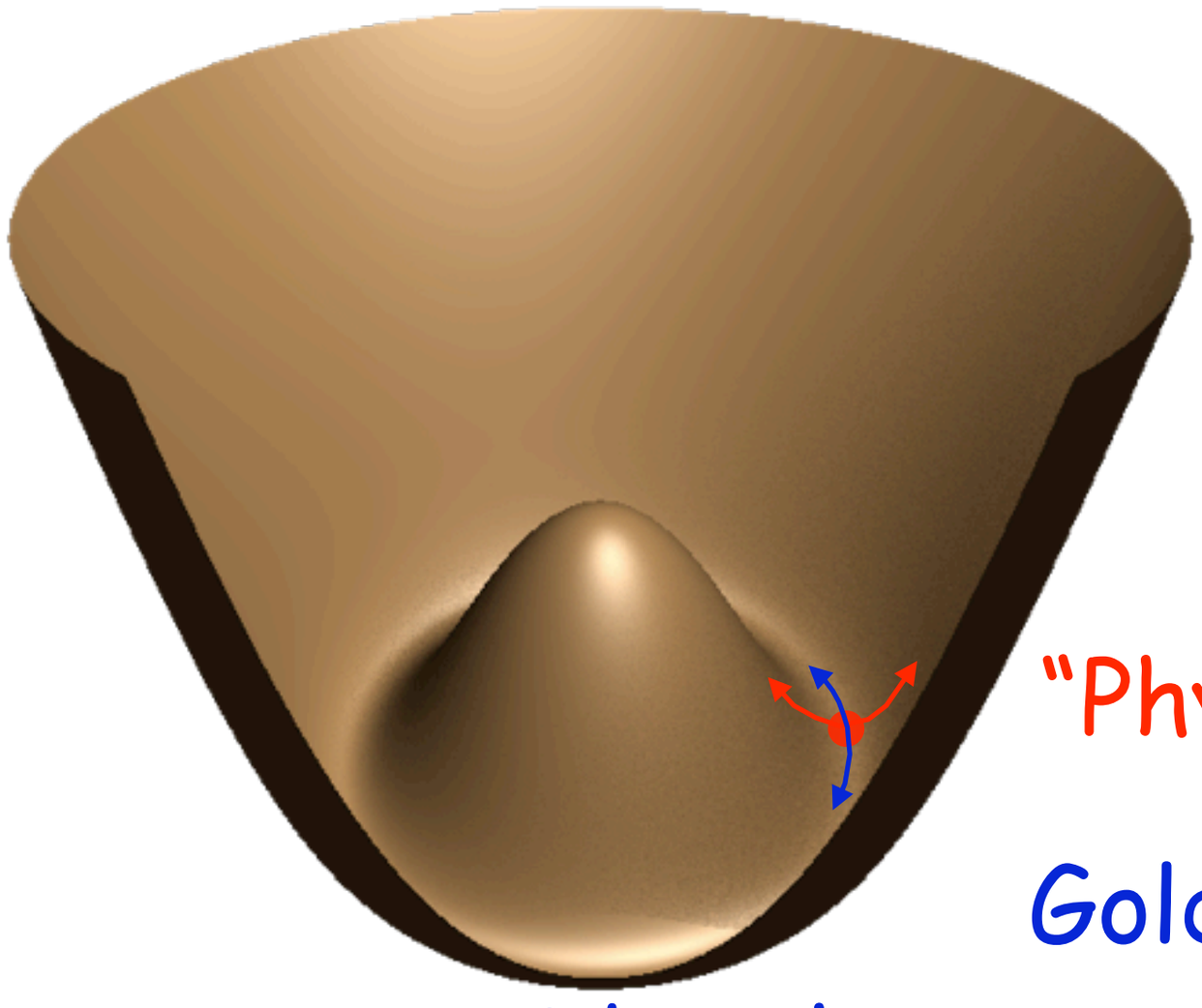
Goldstone's Theorem



Goldstone's Theorem



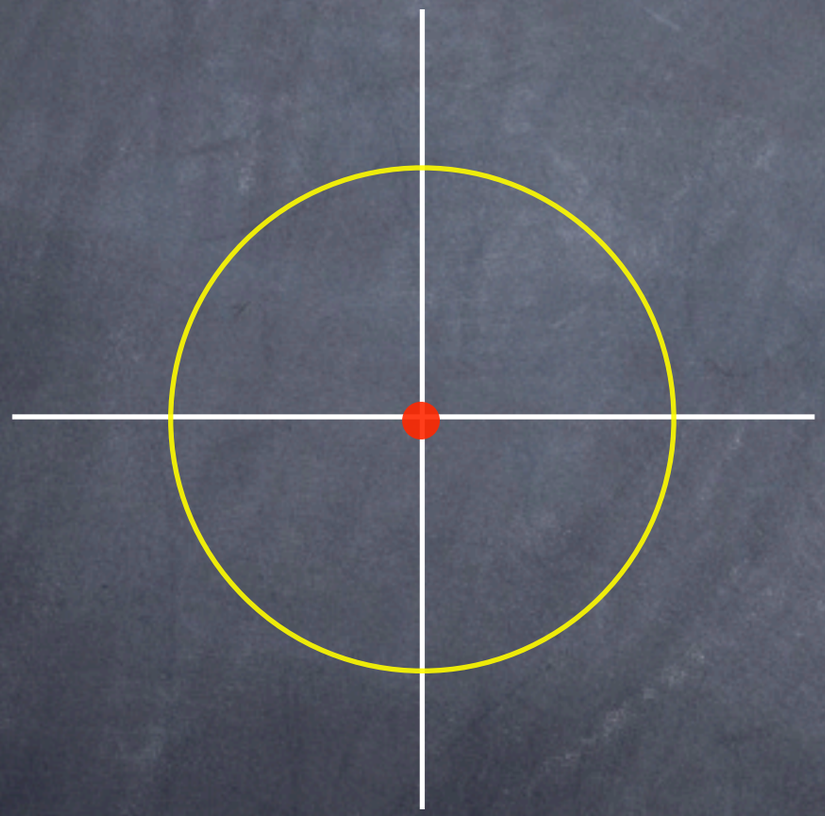
Higgs Potential

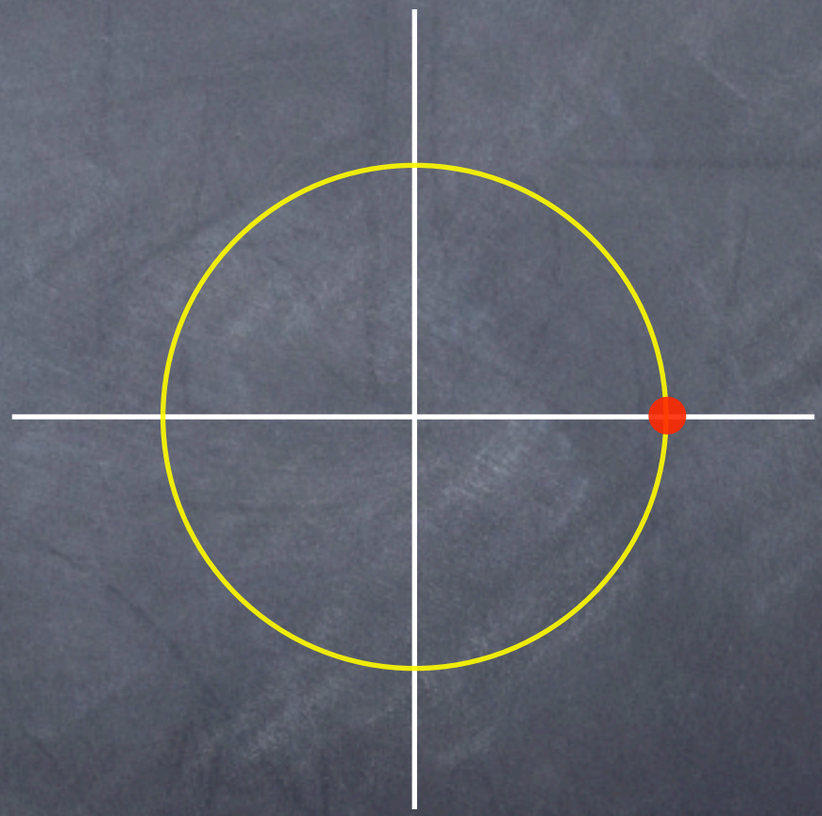


"Physical" Higgs

Goldstone Boson
provides the extra polarization

Broken Symmetry

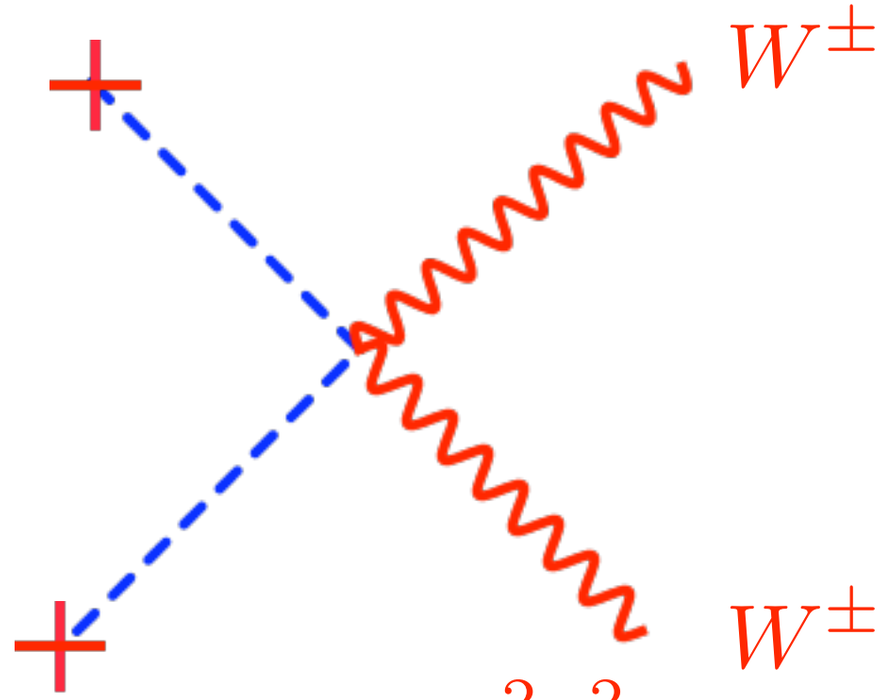




Higgs Mechanism

Gauge Boson Masses

$$\langle H \rangle = \frac{v}{\sqrt{2}}$$

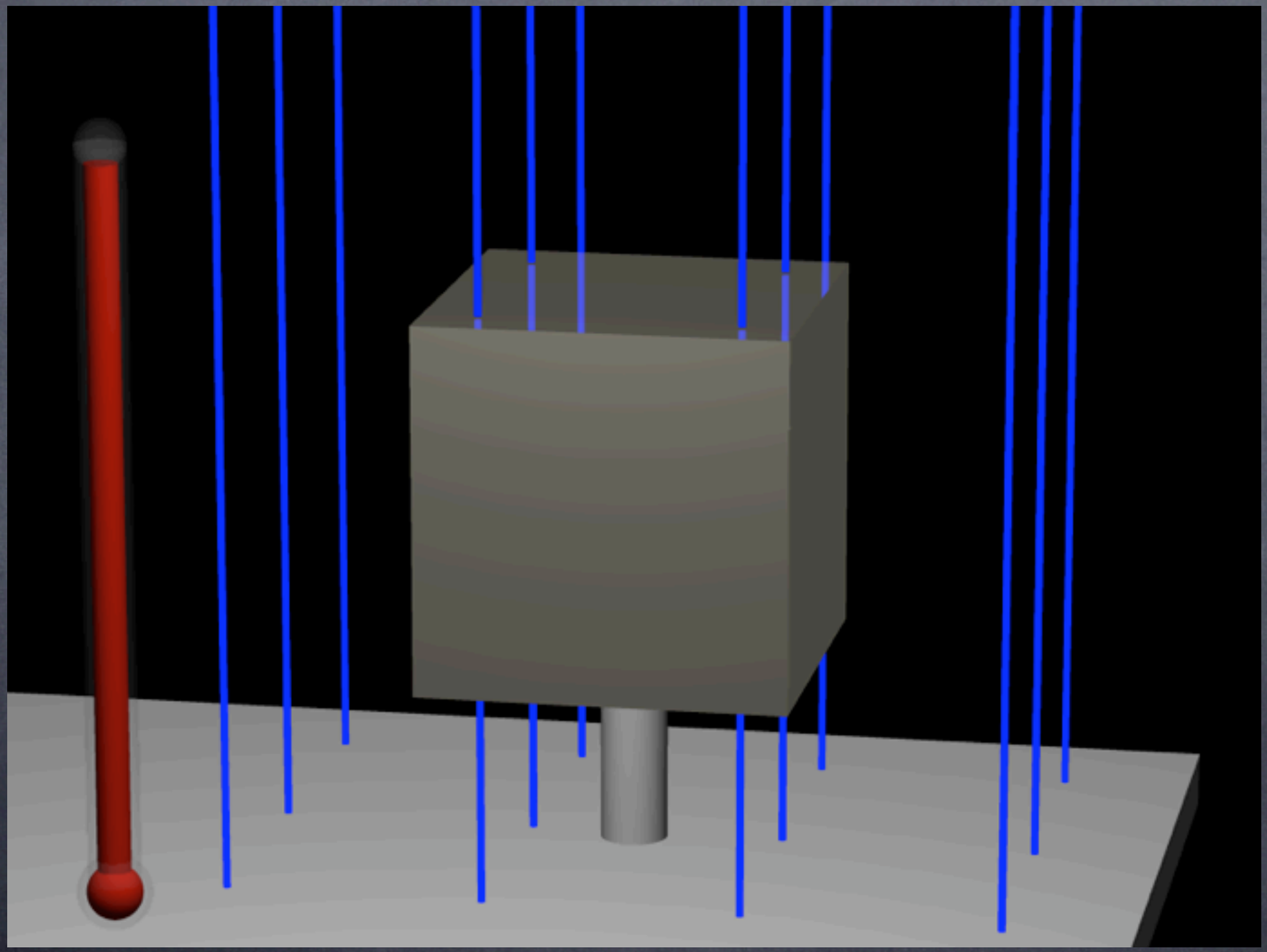


$$M_W^2 = \frac{g^2 v^2}{4}$$

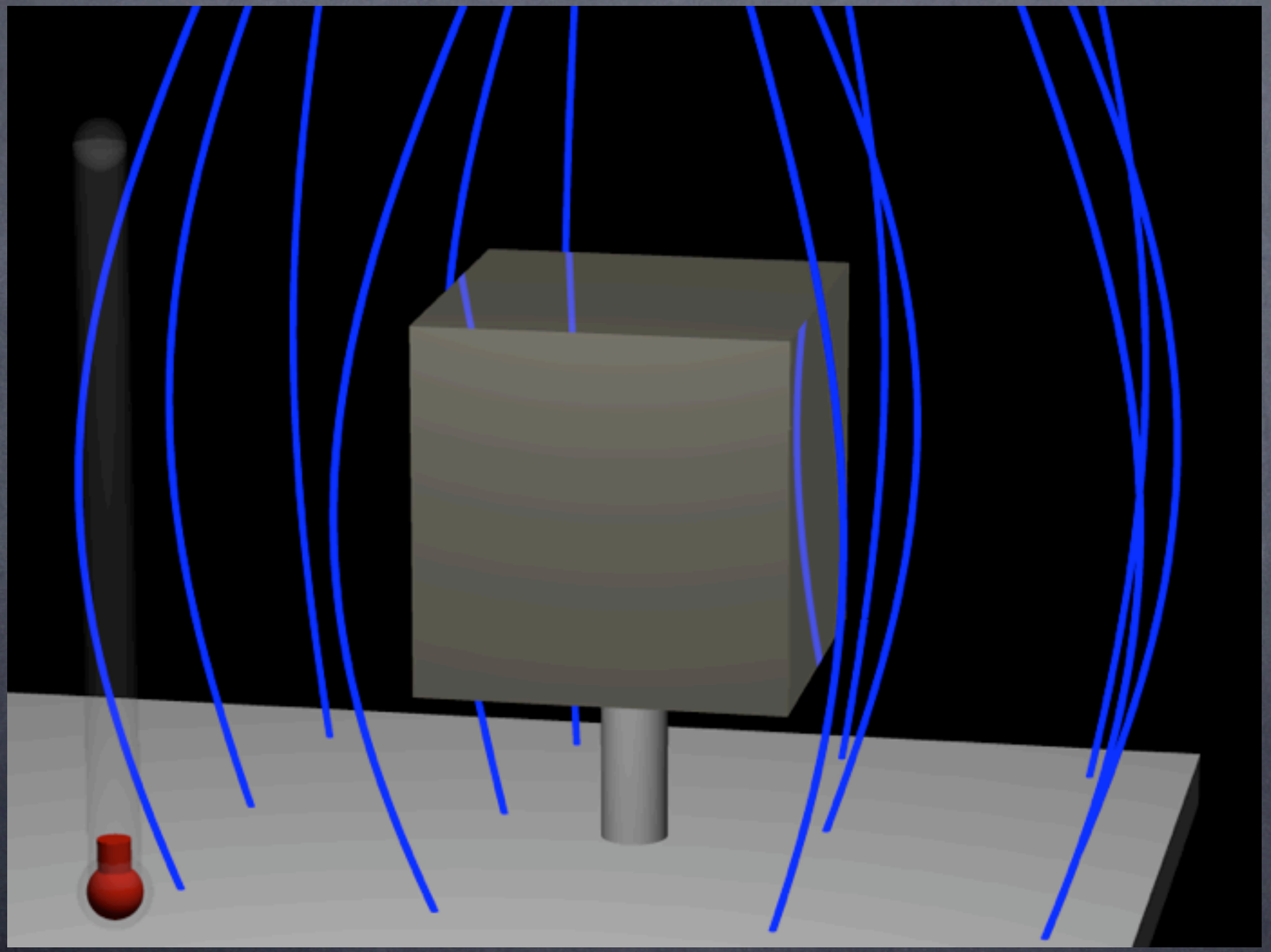
$$M_W = 80.4\,\mathrm{GeV}$$

Superconductor

Phase Transition



Phase Transition

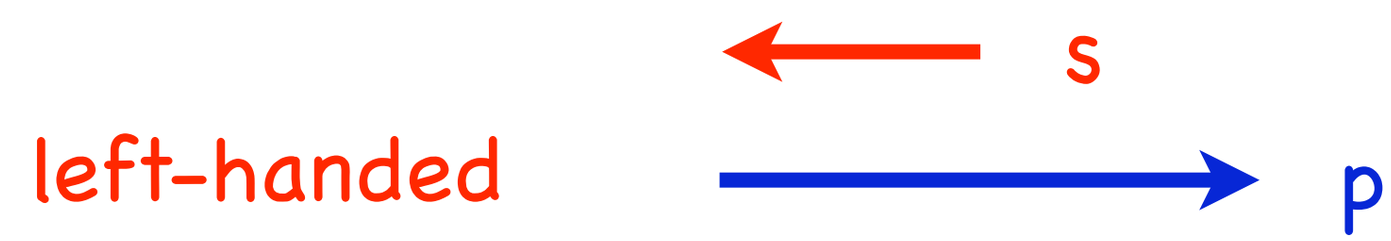


Superconducting Vacuum

Charged Bose Condensate	$\longleftrightarrow$	$\langle H \rangle \neq 0$
Meissner Effect	$\longleftrightarrow$	Massive Gauge Bosons
Inverse Penetration Depth	$\longleftrightarrow$	M_W, M_Z

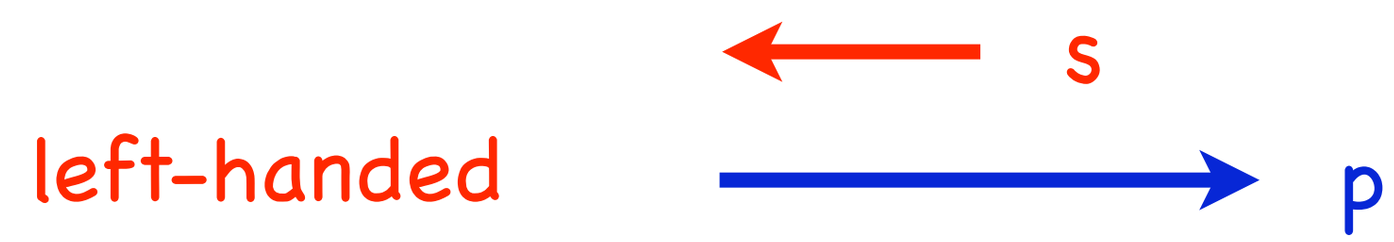
Massless Fermion

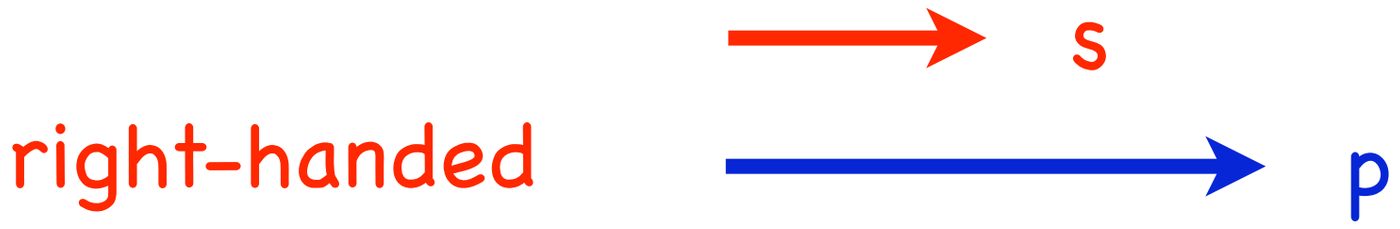
can't move faster than the fermion:
handedness is invariant



Massless Fermion

can't move faster than the fermion:
handedness is invariant

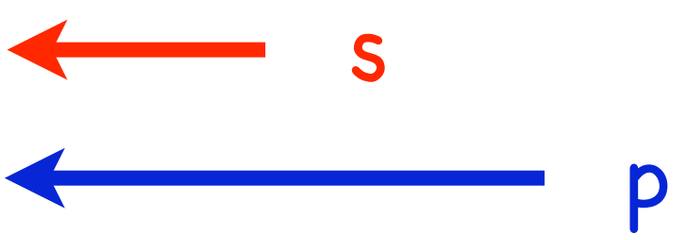


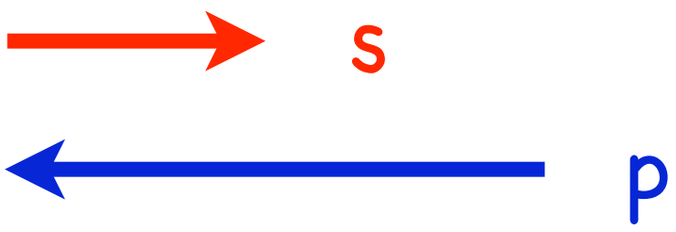


for massless fermions helicity = chirality
chirality is always Lorentz invariant

Massive Fermion

moving faster than the fermion flips p
also flips handedness





Massive Fermion

moving faster than the fermion flips p
also flips handedness

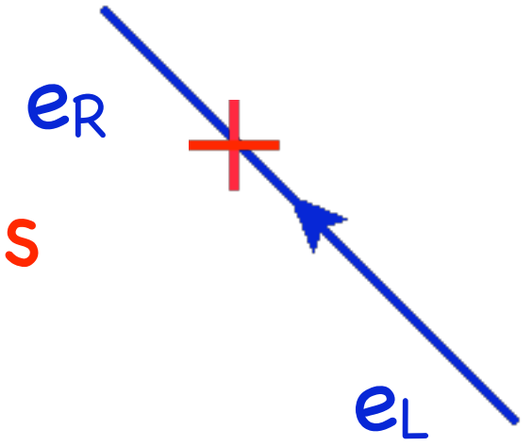
s

right-handed p

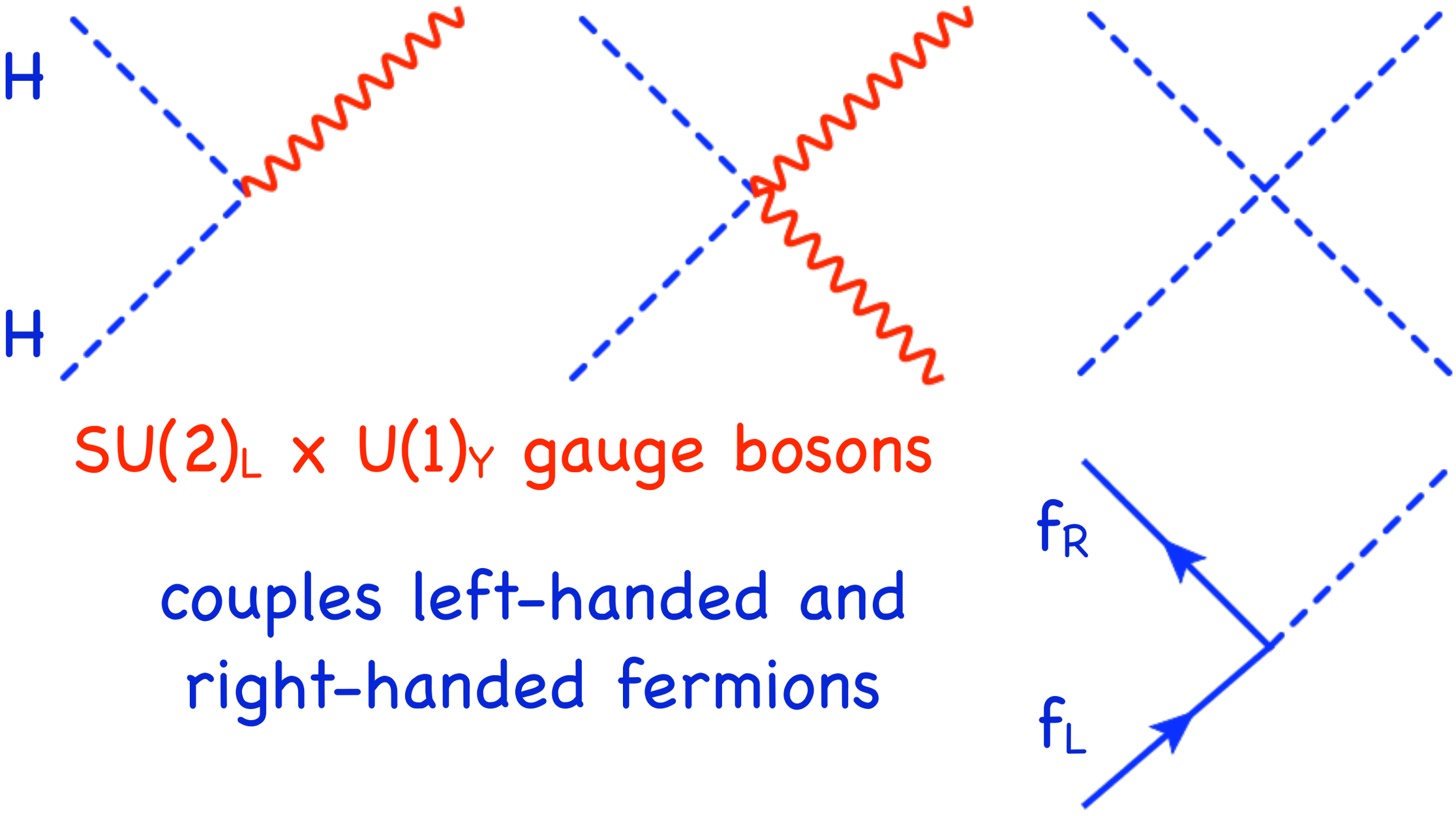
s

left-handed p

but just propagating flips handedness
weak charge is not conserved



Higgs Boson



$SU(2)_L \times U(1)_Y$ gauge bosons

couples left-handed and right-handed fermions

Higgs Field and Mass

$$2\,s+1 \text{ states}$$

$s = \frac{1}{2}$ mass connects left-handed and right-handed electrons

$s = 1$ massless gauge bosons have 2 polarizations
but
massive gauge bosons have 3 polarizations

Fermions and Bosons

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Mass comes from Higgs field
that pervades all space.

Fermions and Bosons

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Mass comes from Higgs field
that pervades all space.
Just like the ether...