now for

something

completely different.

"gauge theories"

a story

- *introduction*
- *uses of symmetry*
- *gauge principle*
- *weak interactions*
- *critical phenomena*
- *Broken symmetry*
- *Higgs, et al. mechanism*

all together:
the Weinberg-
Salam Model

we laugh at Kepler now

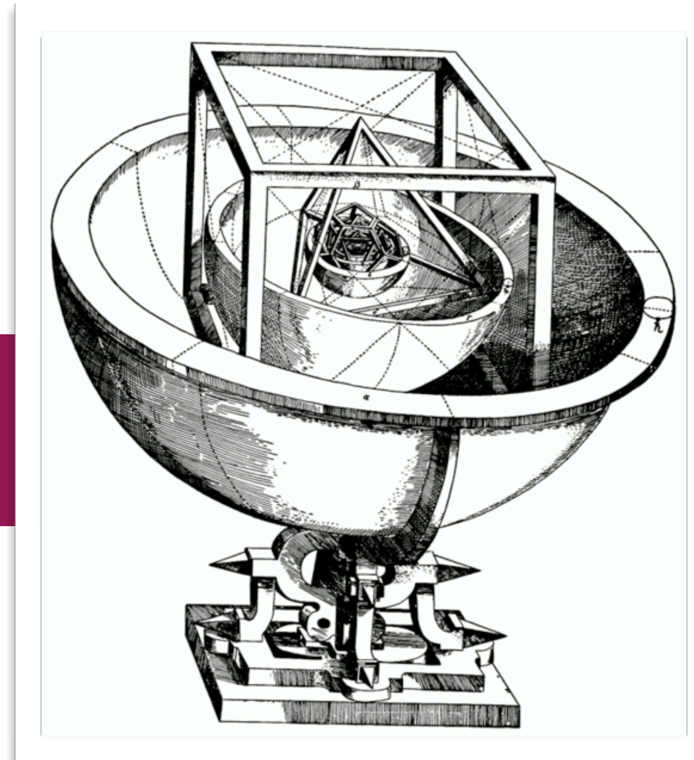
he believed in a symmetry

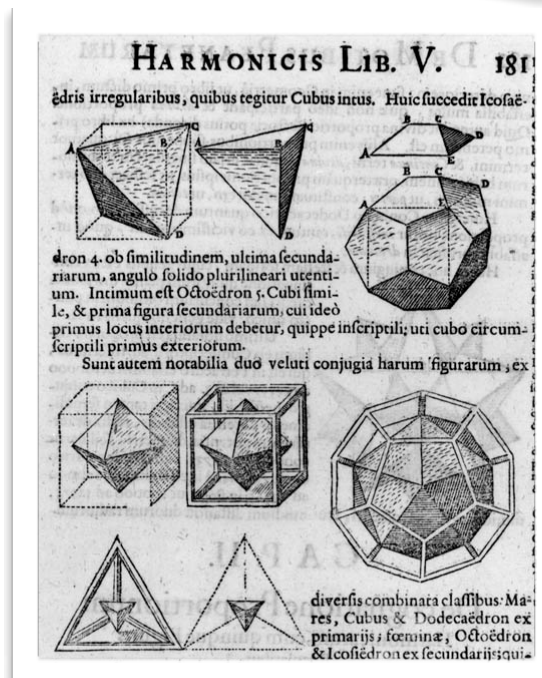
built his world around it

for others:

perfect symmetry ruled–circles

are we different?





HARMONICIS LIB. V. 181

ëdris irregularibus, quibus tegitur Cubus intus. Huic ſuccedit Icoſaë-
dron 4. ob ſimilitudinem, ultima ſecunda-
riarum, angulo ſolido plurilineari utenti-
um. Intimum eſt Octoëdron 5. Cubi ſimi-
le, & prima figura ſecundariarum, cui ideò
primus locus interiorum debetur, quippe inſcriptili; uti cubo circum-
ſcriptili primus exteriorum.

Sunt autem notabilia duo veluti conjugia harum figurarum, ex
diverſis combinata claſſibus: Ma-
res, Cubus & Dodecaëdron ex
primarijs; fœminæ, Octoëdron
& Icoſiëdron ex ſecundarijs; qui-

no

what about Einstein?

He didn't invent the transformations

done before him.

He didn't establish the mathematical rigor

done before him.

He derived the results

arguing for an a-priori prejudice about symmetry

field theory

primer

the players

Spin 0 Bosons: φ

Spin 1 Vector bosons: A_μ, B_μ, W_μ

Spin 1/2 Fermions: ψ

use Lagrangians

Lagrange's Equations

→ *quantum equations of motion*

$\partial_\mu \rightarrow \partial/\partial x^\mu$

a catalog will suffice

FREE LAGRANGIANS

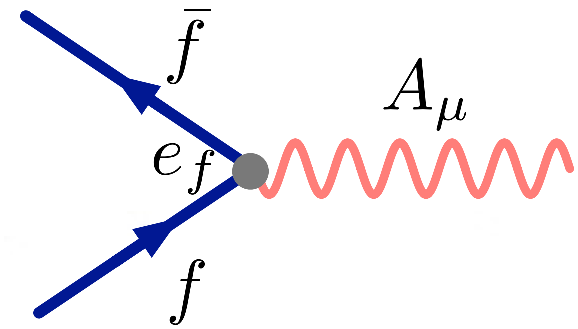
scalar fields:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2$$

EQUATIONS OF MOTION

$$\partial_\mu\partial^\mu\phi + m^2\phi^2 = 0$$

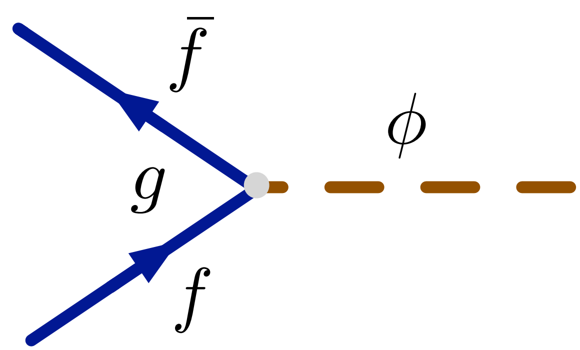
interactions



INTERACTIONS -

$$\mathcal{L}_{\text{electromagnetic - spin } 1/2} = e_f \bar{f}(x) \gamma^\mu f(x) A_\mu(x)$$

$$\mathcal{L}_{\text{YUKAWA}} = g \phi(x) \bar{\Psi}(x) \Psi(x)$$



particle creation

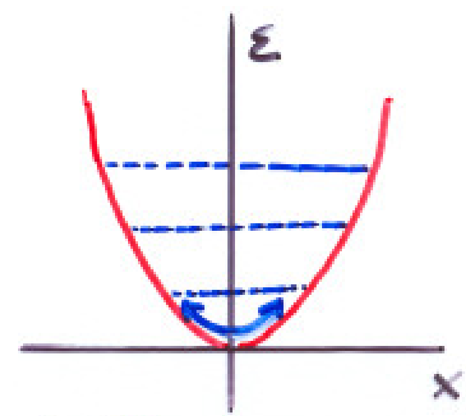
PARTICLE SPECTRA -

$$\phi(x) = \int \frac{d^3k}{(2\pi)^3 2\omega_k} \left[a(k) e^{-ikx} + a^\dagger(k) e^{ikx} \right]$$

creation operator

annihilation operator

just like the quantum oscillator from 1st year quantum mechanics



symmetry in quantum mechanics

Group operations represented by operators, U,

generated by G

in a linear vector space of vectors $|\alpha>$

vectors transform: $|\alpha\rangle \longrightarrow |\alpha'\rangle = U|\alpha\rangle$

operators transform: $\Theta \longrightarrow \Theta' = U\Theta U^{-1}$

If a system is symmetric wrt U, $[\mathcal{H}, G] = 0$

Noether's Theorem

If a system has a symmetry

there is an associated conservation law

space translation → momentum conservation, $\mathbf{p}$

time translation → energy conservation, E

Also, for "internal symmetries"

phase transformation → charge conservation, Q

- OF PARTICULAR INTEREST ARE SYMMETRY GROUPS WITH REPRESENTATIONS LIKE $U(\varepsilon) = e^{-i\sum_j \varepsilon^j Q^j}$

INFINITESIMAL PARAMETERS (→ ε^j)

"GENERATORS" OF THE GROUP & OPERATORS HAVING QUANTUM #'S AS EIGENVALUES (→ Q^j)

charges and conserved currents

- CONNECTION THROUGH "CHARGE" & A CONSERVED "CURRENT" –

$$Q \equiv \int d^3x \, j^0(x)$$

where $\partial_\mu j^\mu(x) = 0$ signifies a conservation law

Q plays a dual role: both a "charge" and the generator of the transformation

quantum field theory: 1 slide

- $\phi(x)$ IS AN OPERATOR $\qquad \phi \longrightarrow \phi' = U\phi U^{-1}$

$$= (1 - i\sum_j \varepsilon^j Q^j)\,\phi\,(1 + i\sum_j \varepsilon^j Q^j)$$

$$\vdots$$

$$= \phi + i\sum_j \varepsilon^j [Q^j, \phi(x)]$$

SO $[Q^j, \phi(x)] = \phi(x) \Rightarrow$

(note: often $U\phi U^{-1} = \exp(i\sum_j \varepsilon^j q^j)\,\phi(x)$ ... a phase)

$\uparrow$ eigenvalues of Q^j

- SUPPOSE $[H, Q] = 0 \quad \Rightarrow \quad \partial_0 Q = 0$

LET $H|\vec{p}_n\rangle = E_n|\vec{p}_n\rangle$

THEN $QH|\vec{p}_n\rangle = E_n Q|\vec{p}_n\rangle$

$\qquad\qquad \shortparallel$

$\qquad HQ|\vec{p}_n\rangle = E_n Q|\vec{p}_n\rangle$

} $|\vec{p}_n\rangle$ & $Q|\vec{p}_n\rangle$ ARE BOTH EIGENSTATES OF H WITH SAME E_n – degenerate

$\longrightarrow$ MAY REPRESENT ORTHOGONAL STATES WITH DISTINCT QUANTUM NUMBERS...

I lied...2 slides

- THERE IS A SPECIAL EIGENSTATE OF H... THE VACUUM.

  $H|0\rangle = 0$ IS ALWAYS TRUE FOR VACUUM STATE

  USUALLY, IT IS ASSUMED THAT, FOR $U = e^{iQ\alpha}$

  $U|0\rangle = |0\rangle$ FOR ALL SYMMETRIES

  $\Rightarrow Q|0\rangle = 0$

IF $Q|0\rangle \neq 0$, THEN THERE MUST BE DEGENERATE VACUA IF ALSO $[H, Q] = 0$. stay tuned!

a little bit of history...repeating

Soon after general relativity

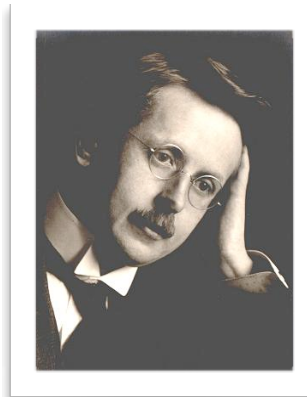
H. Weyl proposed:

HE ADDED INVARIANCE WITH RESPECT TO

a. $g'_{\mu\nu} = \lambda(x) g_{\mu\nu}$

b. $A'_\mu = A_\mu - \frac{\partial \lambda(x)}{\partial x^\mu}$

same $\lambda(x)$ phase



note: b. is E&M...a. is strange.

space and time can change...all over space and time

he called it a "gauge"

$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \longrightarrow \lambda ds^2$: LENGTHS ARE RE-"GAUGED"

The thing that holds spacetime together? The Photon

Einstein dug it…sorta

"Your ideas show a wonderful cohesion. Apart from agreement with reality, it is at any rate a grandiose achievement of mind."

This early attempt to unify E&M with gravity failed.

1927

London revived the idea

Not a scale of spacetime

*A **phase** in quantum fields*

first kind: GLOBAL U(1) symmetry

$$U(\theta) = e^{i\theta Q}$$

"GLOBAL" ⇒ SAME PHASE, INDEPENDENT OF SPACETIME $\theta \neq \theta(x)$

"U(1)" ⇒ 1 PARAMETER LIE GROUP HAVING Q AS GENERATOR

$$\psi(x) \longrightarrow \psi'(x) = U\,\psi(x)\,U^{-1}$$
$$= e^{i\theta q}\,\psi(x)$$

other kind: LOCAL U(1) symmetry

$U(\theta) = e^{i\theta(x)Q}$

"LOCAL" ⇒ POTENTIALLY DIFFERENT PHASE AT ALL SPACETIME POINTS $\theta = \theta(x)$

$\psi(x) \longrightarrow \psi'(x) = e^{i\theta(x)q}\psi(x)$

NOT SO SIMPLE...

the derivative is trouble

define a new divergence

to cancel the unwanted term

$$D_\mu \equiv \partial_\mu + X_\mu$$

as-yet unnamed vector operator

Goal: get the gradient to transform invariantly

$$(D_\mu \psi) \longrightarrow (D_\mu \psi)' = e^{iq\theta(x)} (D_\mu \psi)$$

- START OUT WITH $\mathcal{L} = \bar{\psi}(x)\left[i\gamma^\mu D_\mu - m\right]\psi(x)$

$$= \bar{\psi}(x)\left[i\gamma^\mu \partial_\mu + i\gamma^\mu X_\mu - m\right]\psi(x)$$

transform $\psi \rightarrow \psi'$

$$\mathcal{L}(\psi) \rightarrow \mathcal{L}(\psi') = \bar{\psi}'(x)\left\{i\gamma^\mu\left[\partial_\mu + \underline{X_\mu - iq\,\partial_\mu\theta(x)}\right] - m\right\}\psi'(x)$$

STILL NOT RIGHT!

one more ingredient

must simultaneously transform $X_\mu \longrightarrow X_\mu' = X_\mu - iq\partial_\mu \theta(x)$

aha! Denote $X_\mu \equiv iqA_\mu(x)$ so the gradient looks like

$$D_\mu \equiv \partial_\mu + iqA_\mu$$

& TOTAL TRANSFORMATION NECESSARY TO LEAVE $\mathcal{L}$ ALONE IS:

freaking amazing

Turns the utility of ʎɹʇǝɯɯʎs

upside down

If invariance with respect to a local U(1) symmetry is, a priori, of paramount importance:

ONE IS FORCED

TO INVENT THE PHOTON

demanding a symmetry

forces the inclusion of a spin-1 field

specifies the interaction with spin-1/2 fields

U(1) is good

How about SU(2)?

The project of Yang and Mills in 1954

A local SU(2) symmetry

leads to an isotriplet of spin-1 fields

DEMANDING $u = e^{i \sum_a \vec{\theta}(x) \cdot \vec{\tau}/2} \rightarrow \vec{b}_\mu(x)$ ⟨ 2 charged / 1 neutral

isovector &
Lorentz vector

Yang - Mills Theory

AGAIN: $\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$

now $\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$ as bases for $SU(2)$ operators

close, but notsomuch

one might have hoped that the b might have turned out to be the $W^{\pm}$ Boson

But the weak interaction is short-ranged

and so the W would be heavy

Masslessness of b_μ was a fatal flaw.

weak interactions

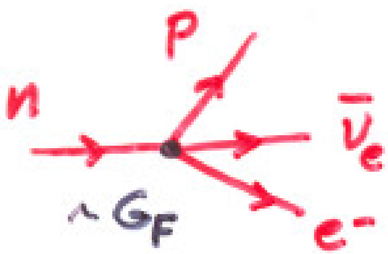
circa 1960...a primer

Since Pauli and Fermi in 1930s

There had been

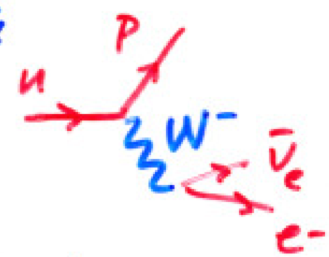
20 years of contradictory experimental results

a beautiful theory–1958 Feynman and Gell-Mann



$G_F \sim 10^{-5}/M_p^2$

... HURISTICALLY DESCRIBED BY:

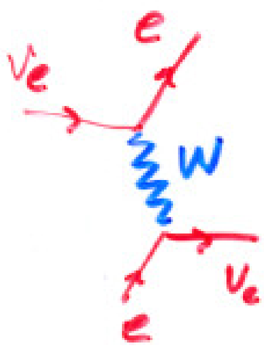


$W^\pm$: charged

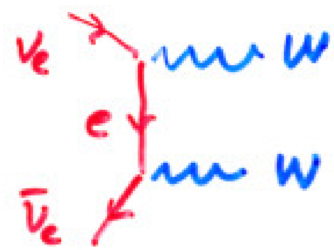
isospin raising/lowering

massive

there were problems:



violates unitarity



σ unbounded

2W production

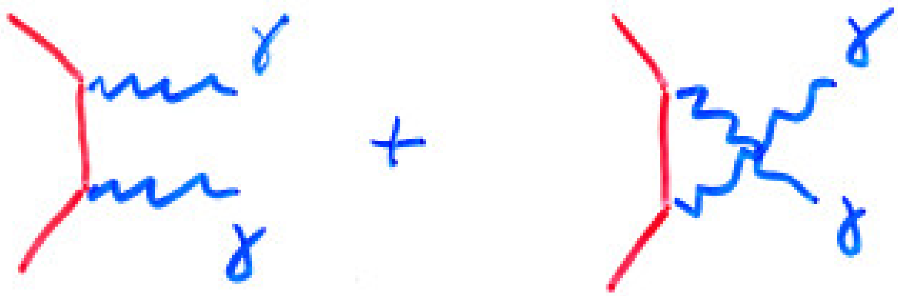
hint  : infinity is associated with the longitudinal degree of freedom

Massless spin 1: 2 dof...e.g. L,R polarizations

MassIVE spin 1: 3 dof...e.g. L,R polarizations
+ longitudinal polarization

$$\epsilon^\mu(\lambda = 0) \sim \frac{k^\mu}{M}$$

in E&M...2 photon production:



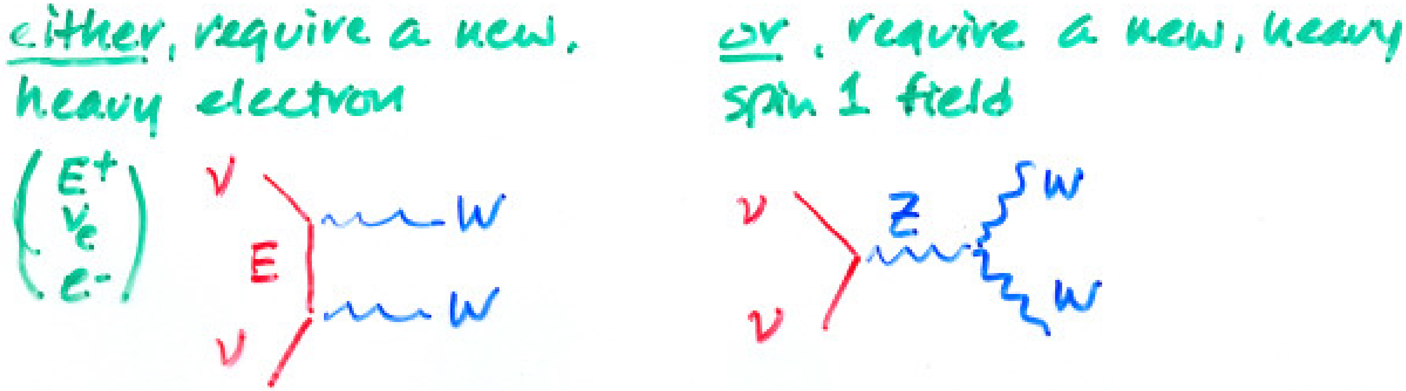
both graphs required because of gauge invariance

If you pretend that the photon had a mass...

the bad behavior term cancels between the graphs

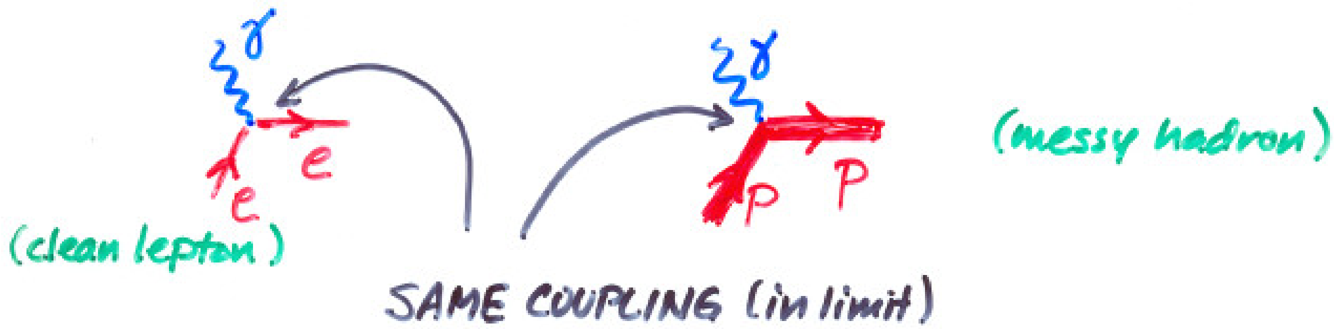
spoiler:

in hindsight: this cancellation can be arranged for weak interactions:

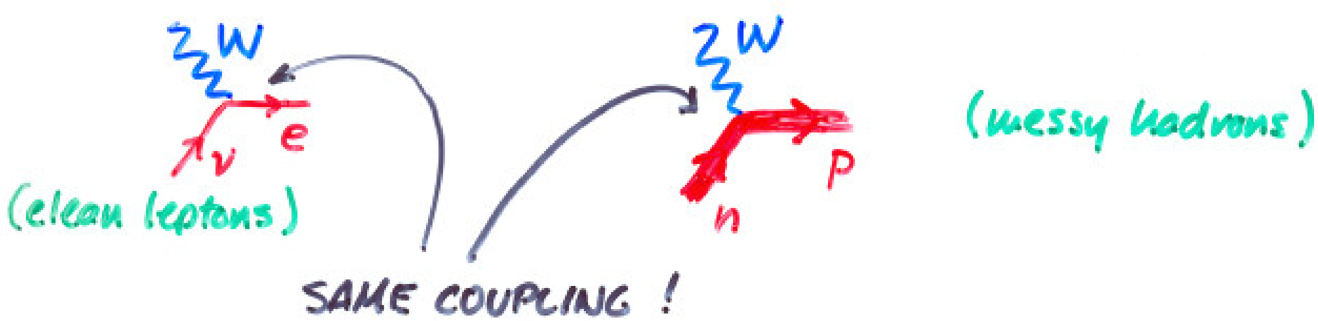


E&M is magic

same coupling of photon to electron & proton:



ditto, weak interactions:



could it be?

that the regal

electromagnetic interaction

might be related

to the rag-tag, ill-behaved, badly-bred

weak interaction?

many tried:

Schwinger, Salam, Ward, Glashow, Weinberg...

all used Yang-Mills theory

Salam: "dream" of Weak and Electromagnetic interaction unification...

$\begin{pmatrix} W^+ \\ \gamma \\ W^- \end{pmatrix}$? $\begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix}$ & γ

masslessness of W always blocked progress

critical phenomena

circa 1960...a primer

MENU

UN APERITIF

thermodynamics of phase transformations

UNE ENTRÉE

Mean Field theory and Ginsburg-Landau phenomenology

LE PLAT PRINCIPAL

Ferromagnetism as an example of a broken symmetry

LE FROMAGE

Goldstone Theorem

LE DESSERT

Dilute Bose Gas as an example of the G.T.

UN DIGESTIF

Superconductivity as an example of the loophole

what's a phase?

a region of analyticity of the free energy

$f = -k_B T \ln Z$ from statistical mechanics

$\hookrightarrow \mathrm{Tr}\, e^{-H/k_B T}$

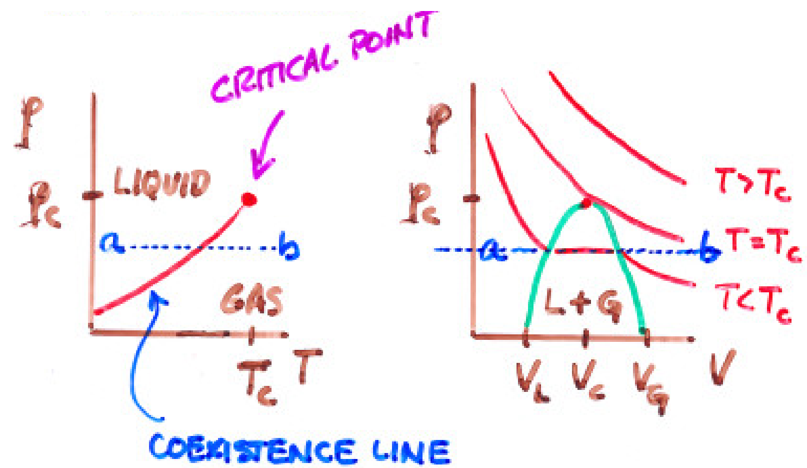
thermodynamics comes from derivatives of f

f: $F = U - TS$ (Helmholtz)

$G = F + pV$ (Gibbs)

from thermodynamics

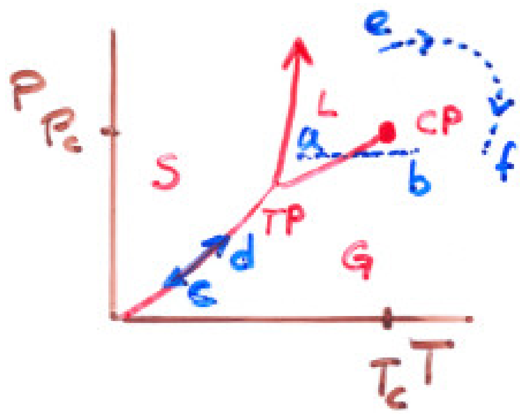
$$S = \left(-\frac{\partial G}{\partial T}\right)_{P,N} = \left(-\frac{\partial F}{\partial T}\right)_{V,N}$$



HEAT AT CONSTANT P & DENSITY, $a \to b$

$\Rightarrow dG_L = dG_G$ ACROSS COEXISTENCE LINE

latent heat



IMAGINE HEATING, WHILE MAINTAING EQUILIBRIUM BETWEEN S & G, c→d

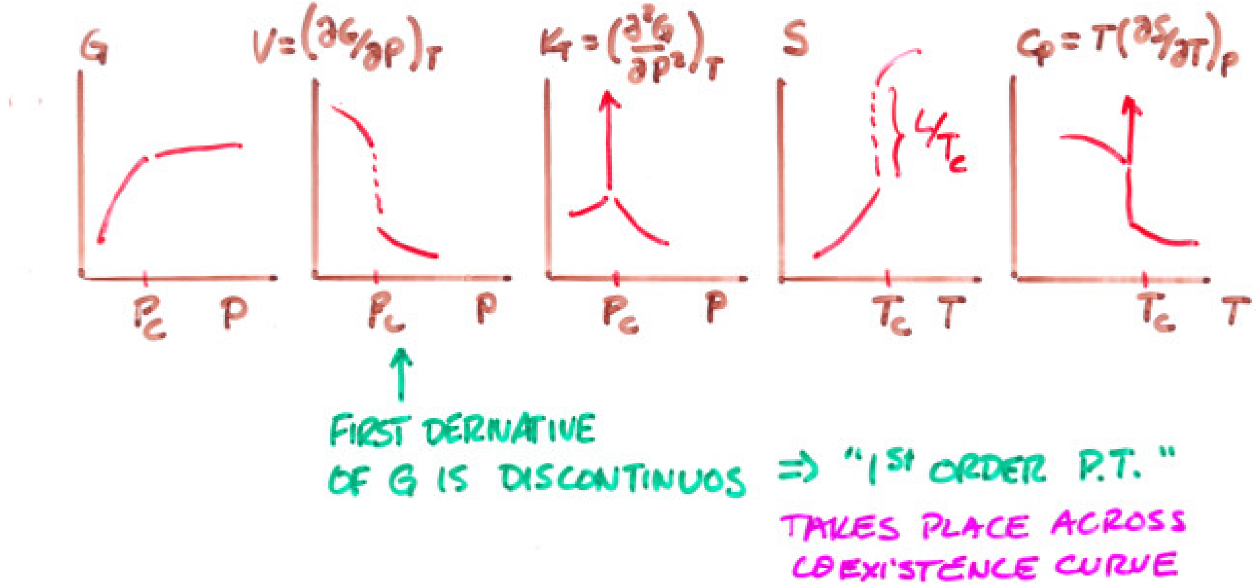
$$dG_S = dG_G \qquad dG_i = V_i dP - S_i dT$$

$$\frac{dP}{dT} = \frac{S_S - S_G}{V_S - V_G} = \frac{\Delta S}{\Delta V}$$

$$= \frac{L}{T\Delta T}$$

latent heat

action in the derivatives



Crucial: the concept of the symmetry of the phases

symmetry

due to Pierre Curie, actually:

If there is a symmetry change,
a Phase Transition has occurred.

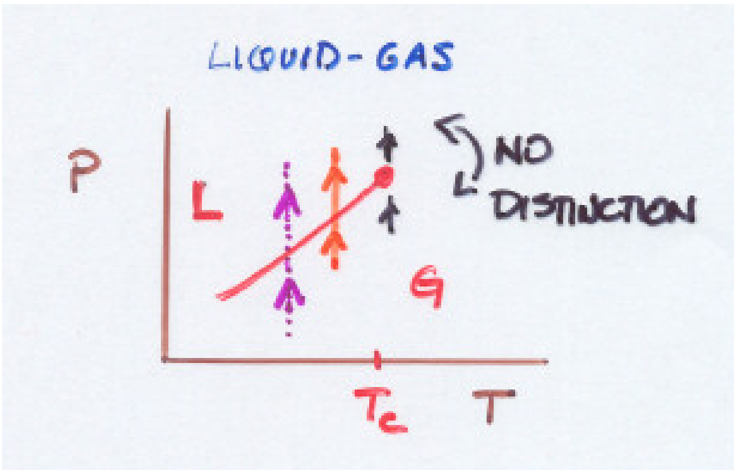
high degree of symmetry ⇒ lack of order

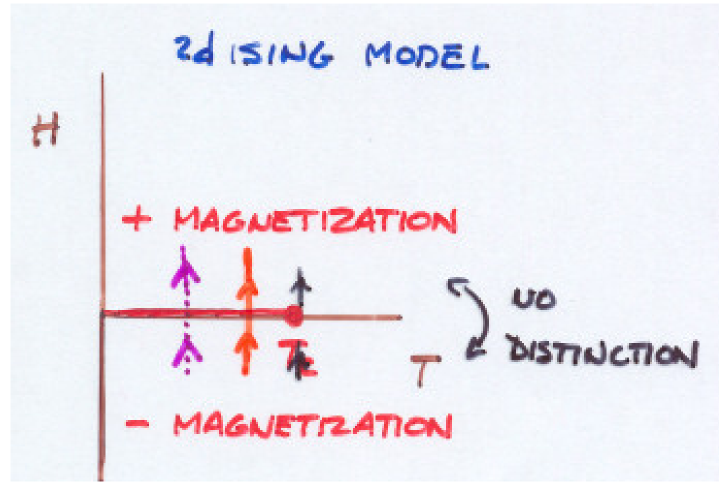
⇓ ⇓

more symmetry operations ⇒ high entropy

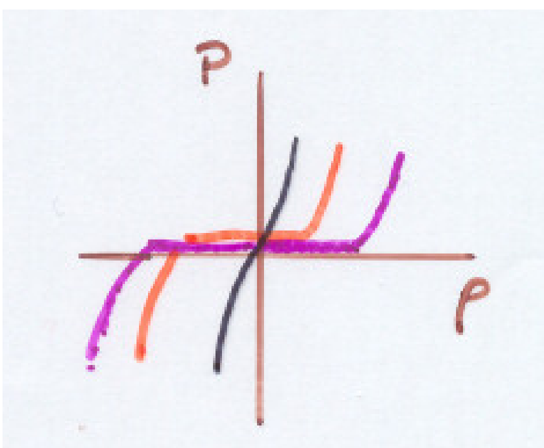
related to higher temperatures

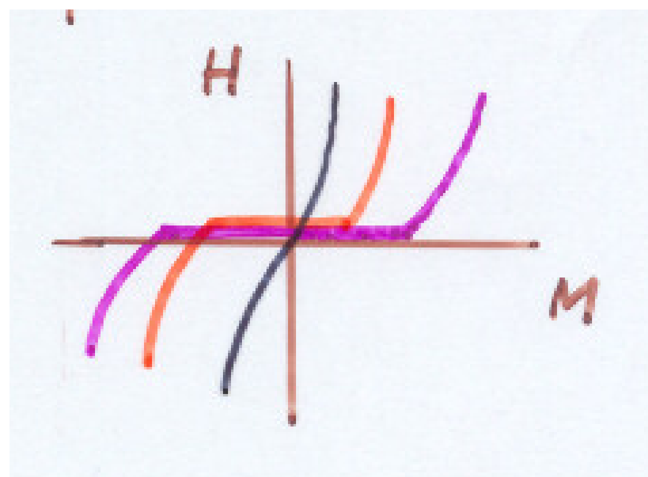
the more things are the same





but...plot differently:

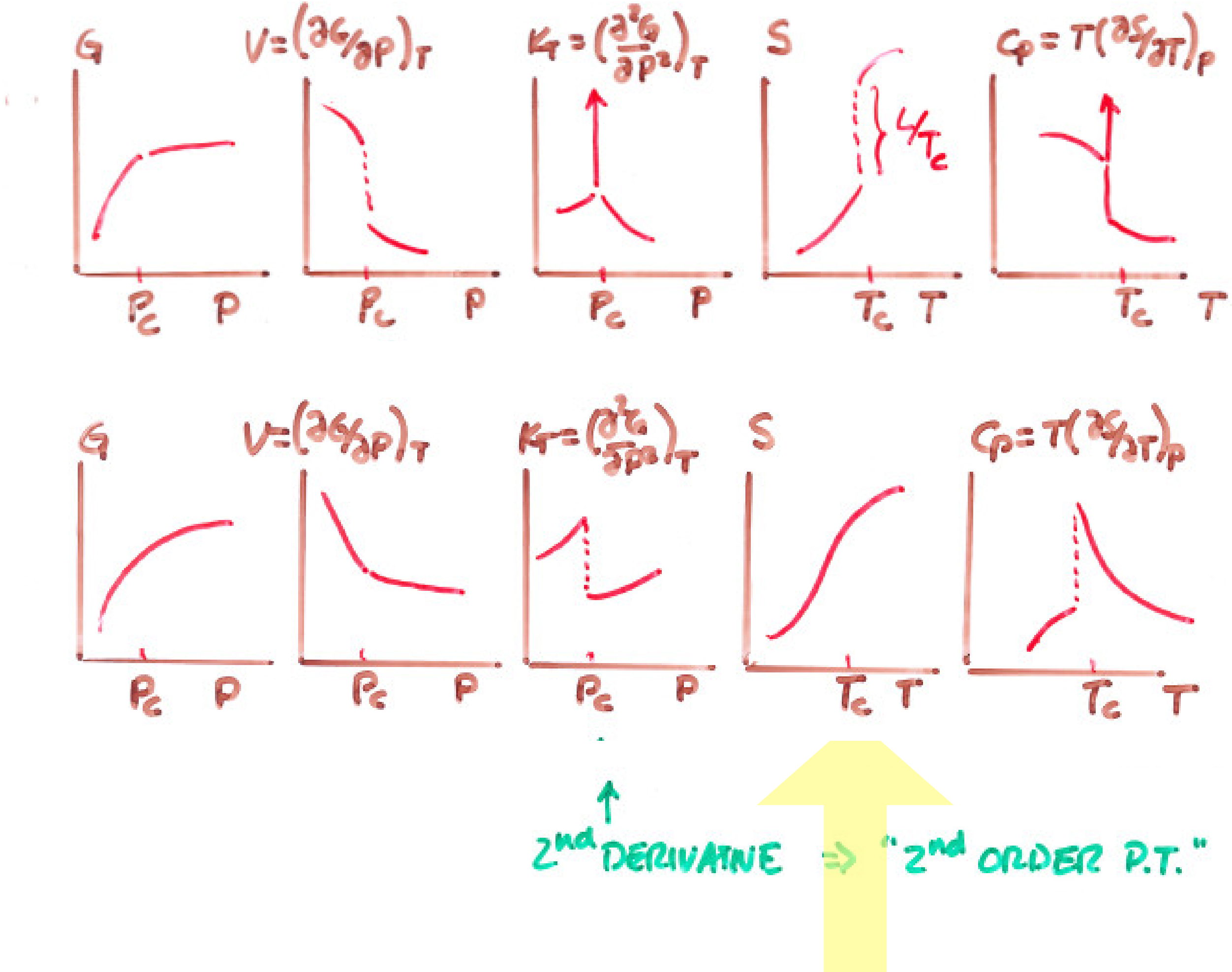




2nd order

1st

2nd



& no latent heat

order parameter

Landau and Ginsberg invented a parameter

to measure the order in a system

$\eta(T)$ *the order parameter*

universalizing the study of phase transitions

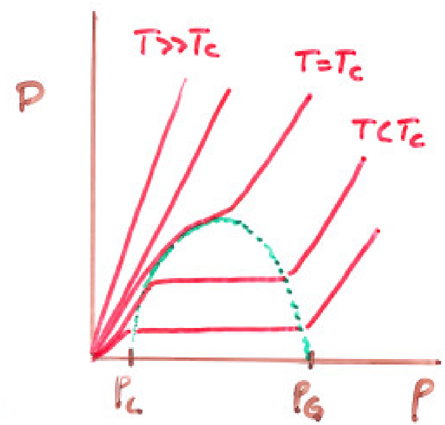
If η = 0, then the system is in an ordered phase

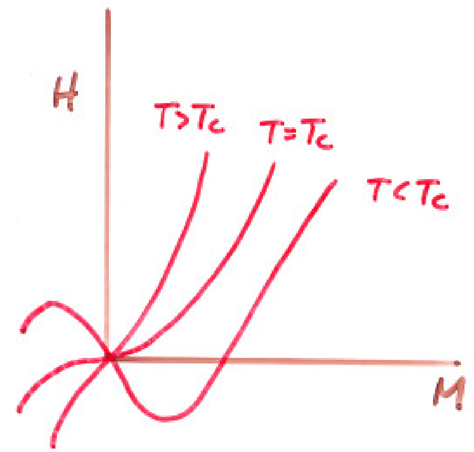
If $\eta \neq$ 0, then the system is in a disordered phase

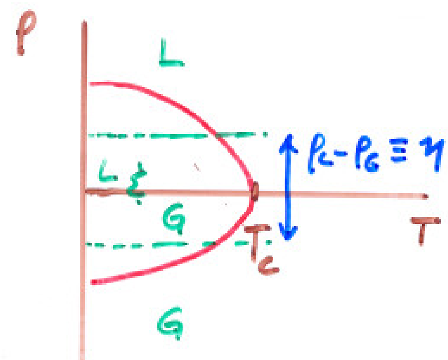
If $\eta(T) \rightarrow$ 0 continuously, the P.T. is second order

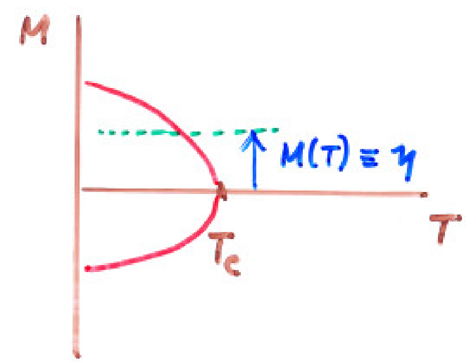
here they are:

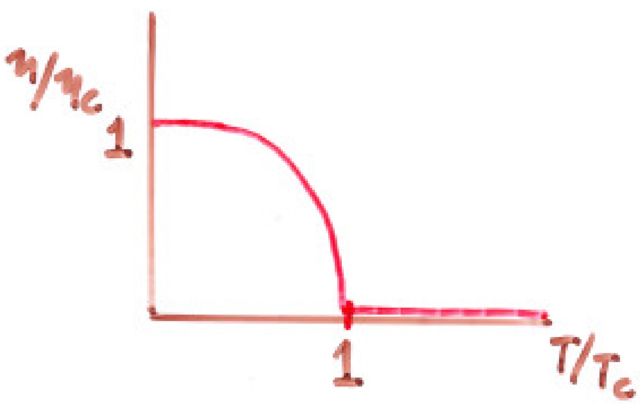
SYSTEM	η	EXAMPLE	T_c (K)
liquid-gas	$\rho_L - \rho_G$	H_2O	647
ferromagnet	M	Fe	1044
superfluid	$\psi_{\text{ground state}}$	^4He	2
superconductivity	$\psi_{\text{cooper pairs}}$	Pb	7
ferroelectrics	P	triglycerine sulfate	323
binary alloys	concentration	Cu-Zn	739











near T_C:

Landau postulated:

a function, L (the Landau Free Energy)...related to G

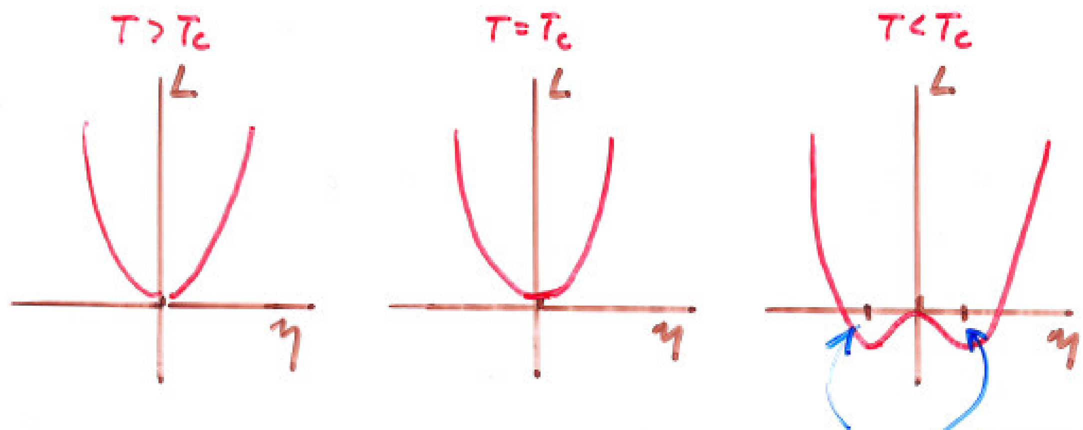
$$L(P,T,\eta) = L_0 + \beta(P,T)\eta^2 + \delta(P,T)\eta^4$$

$$\begin{aligned} \delta &> 0 \\ \beta > 0 &\Rightarrow T \geq T_C \\ \beta < 0 &\Rightarrow T < T_C \end{aligned}$$

flipping above and below the transition

ground state? minimize L

$$L = L_o + b(T-T_c)\eta^2 + \delta\eta^4$$



SIMPLE EXERCISE 3:

SHOW

$$\eta = \pm\sqrt{\frac{b}{2\delta}|T-T_c|}$$

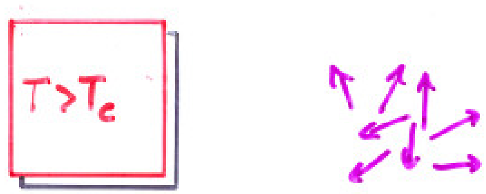
$$L = -\frac{b^2}{2\delta}(T-T_c)^2$$

two important things for $T < T_C$:

the ground state energy is lowered

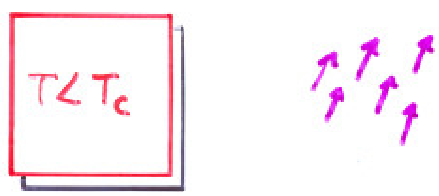
there are multiple ground state configurations

ferromagnetism



$\langle M \rangle = 0$

- ALL DIRECTIONS EQUALLY PROBABLE... GROUND STATE IS INVARIANT wrt $SO(3)$, U_3
- $[H, G] = 0$
  $\Rightarrow$ HAMILTONIAN INVARIANT wrt $SO(3)$



$\langle M \rangle \neq 0$

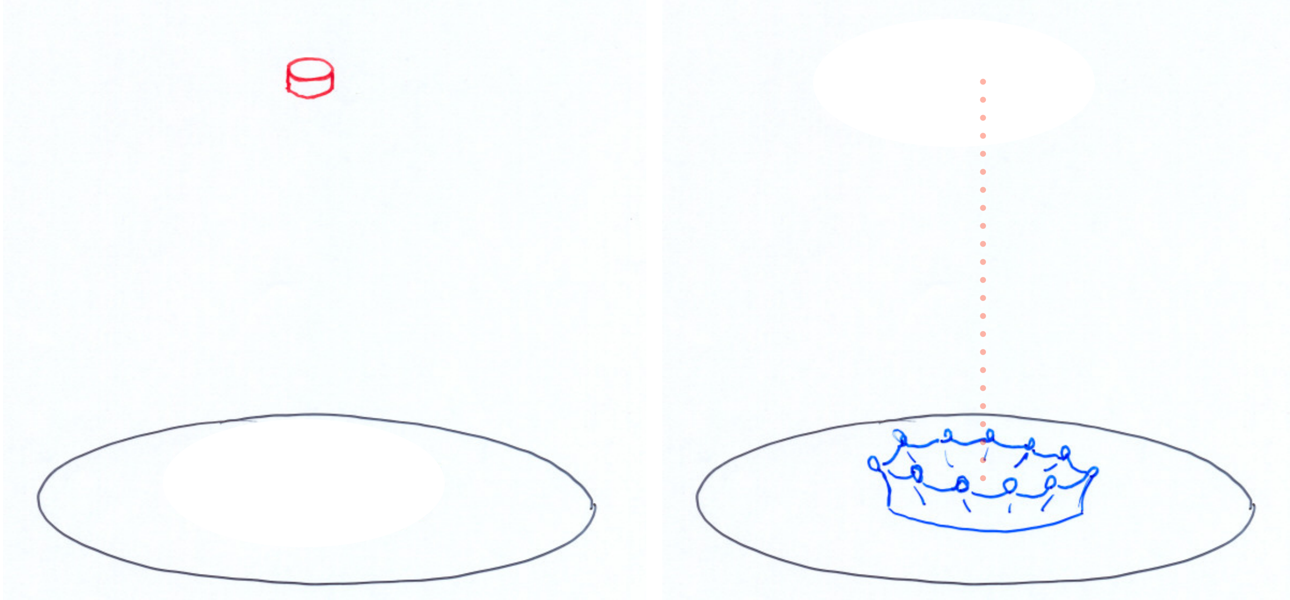
- A SINGLE, RANDOM DIRECTION IS SINGLED OUT
- SYMMETRY OF GROUND STATE IS LOWERED
  $SO(3) \rightarrow SO(2)$
- $[H, G] = 0$ still

Symmetry said to be "spontaneously broken"

Better: symmetry is "hidden"

beautiful example

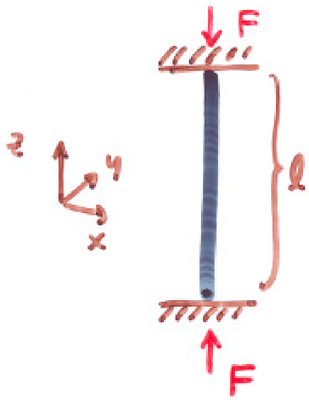
beautiful example



where did the symmetry go?

It's still there: inside of the ensembles of all potential splashes

here's another one: Euler



$$EI\frac{d^4x}{dz^4} + F\frac{d^2x}{dz^2} = 0$$

$$EI\frac{d^4y}{dz^4} + F\frac{d^2y}{dz^2} = 0$$

} $x = y = 0$ is a solution

BUT, WHEN $F > \frac{4\pi^2 EI}{\ell^2} \equiv F_c$

x (or y) $= C \sin kz$ $\qquad k = \sqrt{|F|/EI}$

SYMMETRY IS LOST... HIDDEN (same equation of motion)

→ ROD COULD HAVE PICKED AN INFINITE NUMBER OF DIRECTIONS TO BULDGE... IN ACCORDANCE WITH ORIGINAL SYMMETRY

... just like ferromagnet

CMP theorists were playing

with these ideas...exploring broken symmetries

Steven Weinberg got a whiff of this...

but, he failed to apply it correctly

Because of the dreaded Goldstone Boson.

Goldstone Theorem

A system which has a spontaneously broken symmetry **must** **have massless, Bose-like excitations in its spectrum.**

There are no spinless, massless particles.

So, Weinberg's initial attempts failed.

Works great in CMP!

eg ferromagnetism

? no...that's not what magnets do

energetics favor:

long wavelength

spin waves

long wavelength, macroscopic, quantizable, excitations

with an energy dispersion:

$$\epsilon = \hbar^2 S \sum_{\vec{a}} (1 - cos(\vec{q} \cdot \vec{a}))$$

as q $\longrightarrow$ 0, the energy goes to 0

$$\epsilon = \sqrt{q^2 c^2 + m^2 c^4}$$

bingo: massless

But...

The Hamiltonian - and the ground state - still respect the original symmetry.

If you lived inside of the magnet,

how would you ever discover that the symmetry of the Hamiltonian is SO(3)?

That's our situation.

proof of the Goldstone Theorem

not here...in the handout

But, the consequences are the foll

But:

what's the "ground state" of a

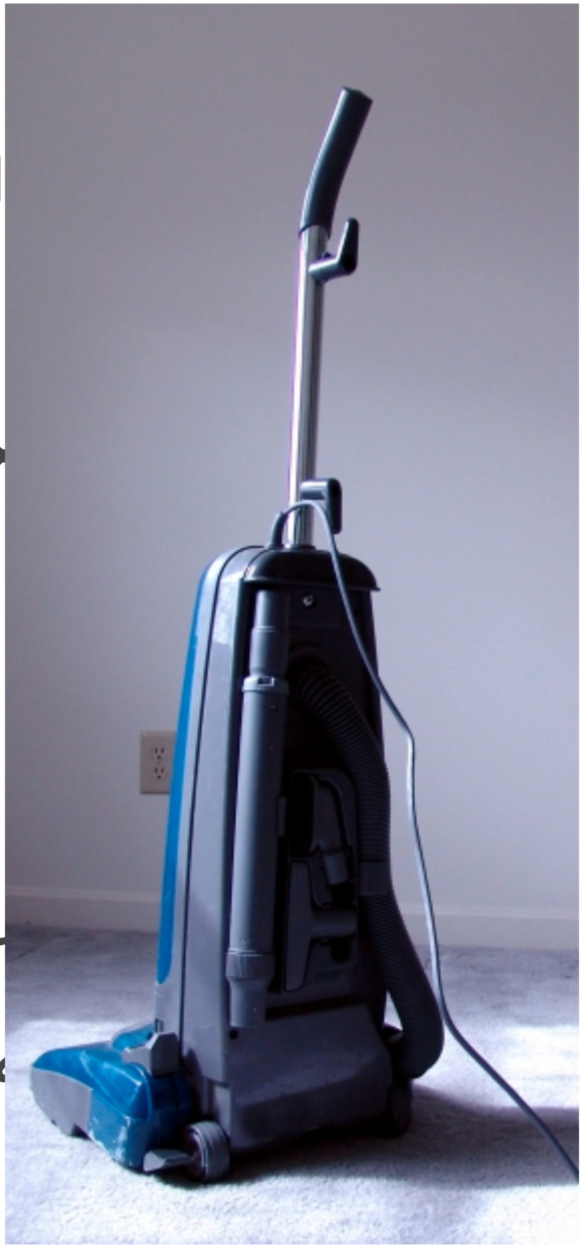
quantum field?

The vacuum.

It's typically simple: it carries t

dimensional representation of a

groups.



response of the vacuum to U:

Two ways:

the normal way: $U(Q)|0>=|0>$

$$U(Q) = e^{-iQ\theta} \quad \Rightarrow \quad Q|0>=0$$

the condensed matter way: $U(Q)|0>\neq|0>$

$$Q|0>\neq 0$$

Remember:

Relativistic quantum fields are operators:

they satisfy an algebra:

$$[Q, \phi(x)] = \phi'(x) \neq 0$$

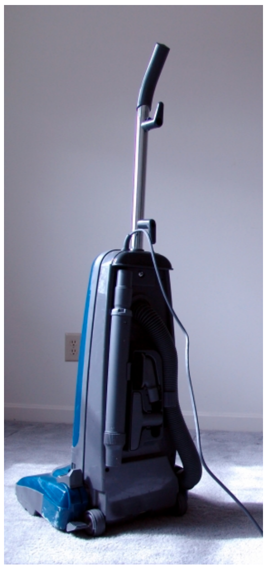
take the "vacuum expectation value"...aka "vev"

$$< 0|\,[Q, \phi(x)]\,|0 >=< 0|\phi'(x)|0 >\neq 0$$

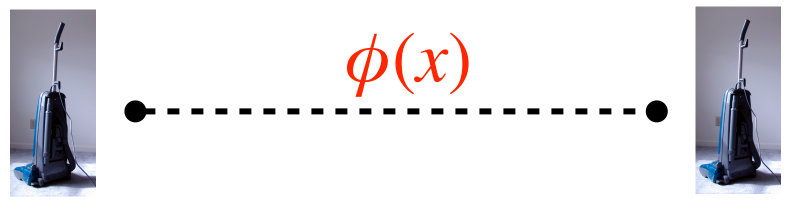
which says:

the field ϕ in the vacuum is non-vanishing!

at first blush? strange.



is full.



Observation of such a thing is a trigger for the Goldstone Theorem

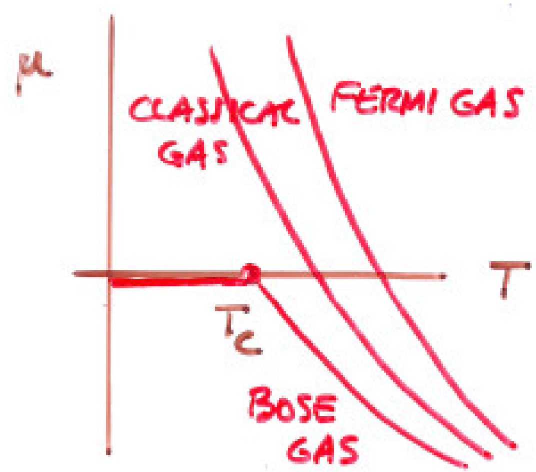
Dilute Bose Gas

remember your Stat Mech?

remember the occupation number for bosons?

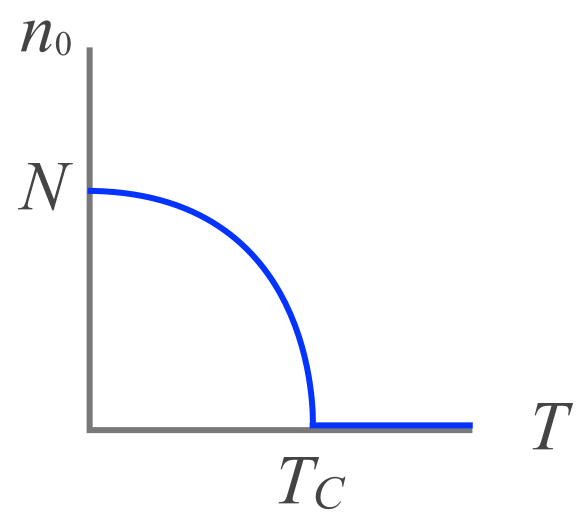
you treat the ground state differently

$$n_i = \frac{g_i}{e^{(\epsilon_i - \mu)/kT} - 1}$$



$$n_0 = N\left[1 - \left(\frac{T}{T_C}\right)^{3/2}\right]$$

Bose-Einstein Condensate



problem for a field theory

condensing into the ground state was a head-scratcher

in field theory–relativistic or non-relativistic–

need to build a particle spectrum from an empty vacuum

$$a^\dagger|0>=|1> \quad \Rightarrow \quad a|0>=0$$

But, this Bose-Einstein Condensate is a full vacuum!

Bogoliubov trick

the way out.

$$H = \int d^3x \; \psi^\dagger(x)\left[-\frac{\hbar^2}{2m}\nabla^2\right]\psi(x)$$ K.E. term

$$+ \int d^3x \int d^3x' \; \psi^\dagger(x)\psi^\dagger(x')\, v(x,x')\, \psi(x)\psi(x')$$ P.E. term ψ^4

$$+ \mu \int d^3x \; \psi^\dagger(x)\psi(x)$$ C.P. term ψ^2

μ is zero in the condensate

the number operator: $N = a^\dagger a \sim \bar{\psi}\psi$

$$a|0>_N = N^{1/2}|0>_{N-1} \sim N^{1/2}|0>_N$$

for large N

like: $\sim < 0|\psi|0 > \neq 0$

some broken symmetry

Number operator symmetry is broken

$e^{i\lambda N}$ $\quad U|0>_N \neq |0>_N$

$$N|0>_N \neq 0$$

shift it away

$a^\dagger$ and a *almost "c-numbers"* $a^\dagger \approx a \approx \sqrt{n_0}$

$$\psi(x) = \text{ vacuum value } + \chi(x)$$

$$< 0|\chi|0 >= 0 \qquad \chi(x) \sim \sum_{\vec{k}\neq 0} a_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}$$

substitute into H

yadda yadda yadda

$$H = N^2 + \sum_{\vec{k} \neq 0} \omega_k a_k^\dagger a_k + N \sum_{\vec{k} \neq 0} \left(a_k a_{-k} + a_k^\dagger a_{-k}^\dagger \right)$$

$$\text{where} \quad \omega_k = \frac{\hbar^2 k^2}{2m} + 2N f(\vec{k})$$

a mess...diagonalize with a canonical transformation:

$$\alpha_{\vec{k}} \equiv u_k a_k^\dagger + v_k a_{-k}^\dagger$$

$$\alpha_{-\vec{k}} \equiv u_{-k} a_{-k} + v_{-k} a_k^\dagger$$

α's have same commutation relations as a's.

the   create and annihilate a new particle spectrum

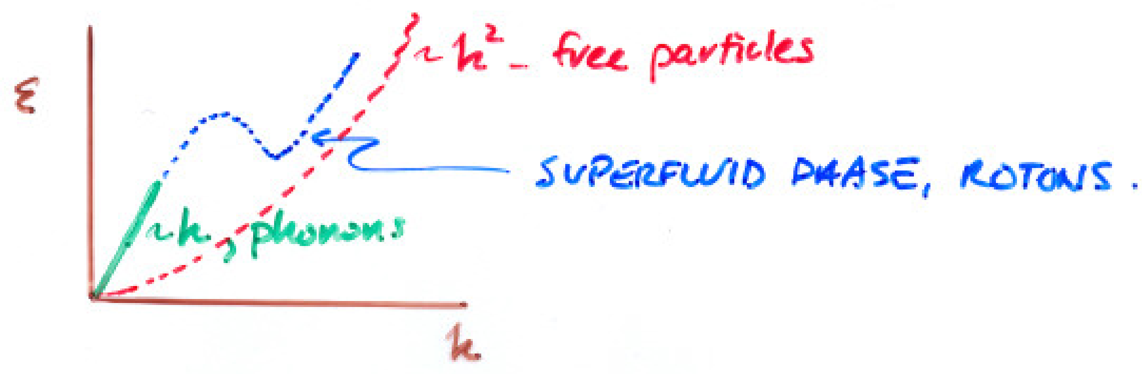
a quasi particle spectrum

$$H = N^2 - \frac{1}{2} \sum_{k \neq 0} \left(\omega_k - \varepsilon_k \right) + \frac{1}{2} \sum_{k \neq 0} \varepsilon_k \, \alpha_k^\dagger \alpha_k$$

$$\varepsilon_k = \sqrt{\frac{\hbar^4 k^4}{4m^2} + \frac{4\hbar^2 k^2 f(k)}{2m}}$$

phonons

The Goldstone Boson of the Bose Gas



multiple things going on

many phenomena involve broken symmetries

The symmetry is “there”: hidden, not respected by the ground state.

⇒

Ground state is full:

$\langle 0|\,\phi\,|0\rangle \neq 0$

Broken continuous symmetry?

Massless Goldstone Bosons must appear.

↓

shift field operators:

c-number vacuum term + quasi particle operator term

↓

insert into the model,

stir...out pops a quasi particle spectrum

Ginsburg Landau phenomenology:

identify order parameter-
induce phase transition

build a toy theory

A relativistic quantum field theory

Jeffery Goldstone, "Field Theories with Superconductor Solutions" 1960

$$\mathcal{L} = \underbrace{\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi}_{\text{KE term}} - \underbrace{a|\frac{\mu^2}{2}|\varphi^2}_{\text{mass term}} - \underbrace{\frac{1}{4}\lambda\varphi^4}_{\text{self interaction}}$$

(like μ in Bose gas)

$\Rightarrow$ $\partial_\mu\partial^\mu\phi + a\mu^2\phi = \lambda\phi^3$ ✓

ϕ has mass $\sqrt{a}\,\mu$ ...

The symmetry?

reflection symmetry $\phi \to -\phi$ LEAVES $\mathcal{L}$ ALONE

- IDENTIFY LANDAU FREE ENERGY WITH P.E TERM OF $\mathcal{L}$

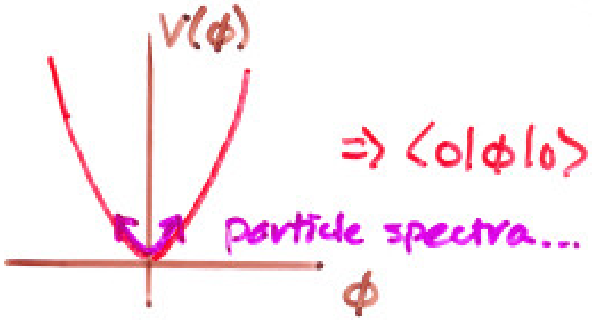
$$V(\phi) = \frac{a\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

- MINIMIZE TO FIND GROUND STATE:

minimum @ $V(\varphi) = 0$

phase transition, ala' L&G

before the phase transition:

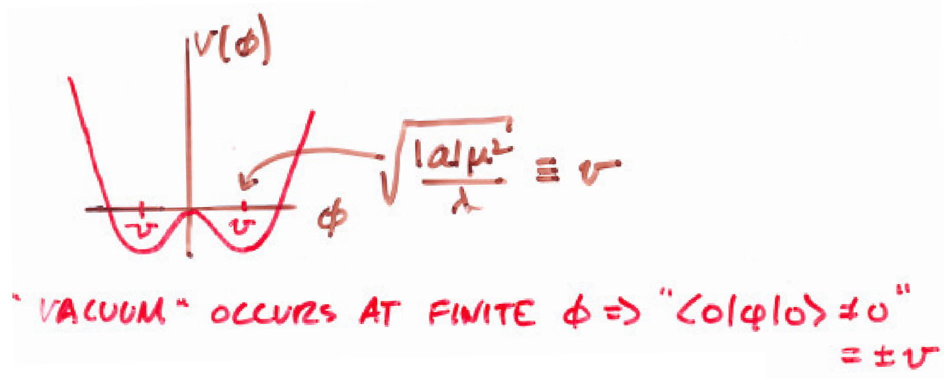


induce the phase transition as Landau-Ginsburg

$a \to -|a|$

$$V(\phi) = -\frac{a\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

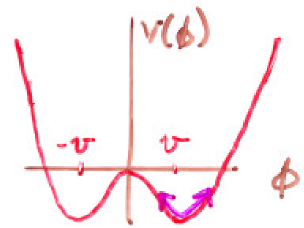
and minimize to find GS:



pick one of the vacua...

shift &

build a particle spectrum



$$\phi(x) = \langle 0|\varphi|0\rangle + \chi(x)$$
$$= v + \chi(x)$$

and substitute it back:

$$\mathcal{L}(\chi) = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - |a| \mu^2 \chi^2 + \text{quartic \& cubic self interactions}$$

the correct form for a <u>massive</u> boson!

Was the Goldstone Theorem violated?

no: this was a discrete symmetry

Goldstone Theorem holds for continuous symmetries

do it again...

a 2-component field

- FOR A CONTINUOUS SYMMETRY.. NEED MORE THAN 1-COMPONENT OBJECT: φ_1 & φ_2 or φ & $\varphi^\dagger = \frac{\varphi_1 \pm i\varphi_2}{\sqrt{2}}$

$$\mathcal{L}(\varphi) = \frac{1}{2}\partial_\mu \varphi^\dagger \partial^\mu \varphi - \frac{1}{2} a\, \varphi^\dagger \varphi - \frac{1}{4}\lambda (\varphi^\dagger \varphi)^2$$

SYMMETRY: $\varphi \longrightarrow \varphi' = e^{i\theta}\varphi$ LEAVES $\mathcal{L}$ ALONE...

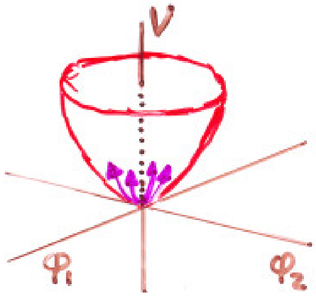
or $\begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix} \longrightarrow \begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix}' = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix}$

... Global $U(1)$ or $SO(2)$, which are isomorphic.

$$\mathcal{L}(\varphi) = \frac{1}{2}\partial_\mu \varphi_1 \partial^\mu \varphi_1 + \frac{1}{2}\partial_\mu \varphi_2 \partial^\mu \varphi_2 - \frac{a\mu^2}{2}(\varphi_1^2 + \varphi_2^2) - \frac{\lambda}{4}(\varphi_1^2 + \varphi_2^2)^2$$

$$V(\varphi_1, \varphi_2) = \frac{a\mu^2}{2}(\varphi_1^2 + \varphi_2^2) + \frac{\lambda}{4}(\varphi_1^2 + \varphi_2^2)^2$$

MINIMIZATION LEADS TO:



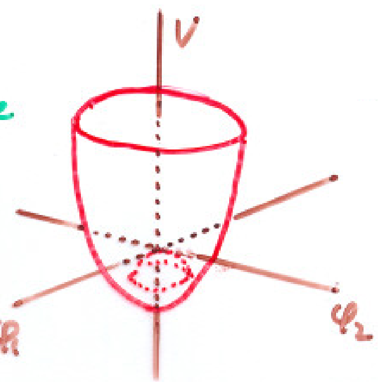
do the L-G thing

$a \rightarrow -a$ in: $V(\varphi_1,\varphi_2) = \frac{a\mu^2}{2}(\varphi_1^2+\varphi_2^2) + \frac{\lambda}{4}(\varphi_1^2+\varphi_2^2)^2$

MINIMIZATION LEADS TO: $\varphi_1^2 + \varphi_2^2 = \frac{|a\mu^2|}{\lambda}$

number of vacua is now infinite

→ CHOICE OF ONE INVOLVES A SLICE IN $\varphi_1 - \varphi_2$ & BREAKS THE SO(2) SYMMETRY



a circle @ RADIUS $v = \sqrt{\frac{a\mu^2}{\lambda}}$

LOCUS: $\langle 0|\varphi|0\rangle = v e^{i\alpha} = v\cos\alpha + i v \sin\alpha$

gotta pick a direction

to break the symmetry...and build a Bogoliubov-like spectrum:

CHOOSE TO BREAK SYMMETRY BY $\alpha = 0$

$$\left.\begin{array}{l} \langle 0|\varphi_1|0\rangle = v \\ \langle 0|\varphi_2|0\rangle = 0 \end{array}\right\} \quad \text{A } \varphi_2 = 0 \text{ SLICE}$$

$$\langle 0|\begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix}|0\rangle = \begin{pmatrix} v \\ 0\end{pmatrix}$$

SHIFT FIELDS USING COMPLEX REPRESENTATION...

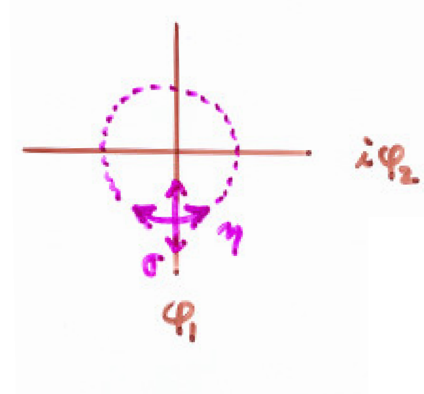
$$\varphi = \underbrace{v + \sigma(x)}_{\varphi_1} + \underbrace{i\eta(x)}_{i\varphi_2}$$

TO QUASI PARTICLE SET. $\sigma(x)$ & $\eta(x)$.

$$\mathcal{L} = \tfrac{1}{2}\partial_\mu \eta\, \partial^\mu \eta + \tfrac{1}{2}\partial_\mu \sigma\, \partial^\mu \sigma - a|\mu^2|\sigma^2 + \underbrace{\text{cubic \& quartic interactions}}_{\text{no } \eta^2 \text{ term}}$$

φ_2 LOST ITS MASS... η IS MASSLESS (THE GOLDSTONE BOSON)

σ IS MASSIVE, $m_\sigma = \sqrt{2a}\,\mu$



single loophole

Remember Local U(1) symmetries?

the Goldstone theorem: Global symmetries

Remember the routine:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \varphi^\dagger \partial^\mu \varphi - \frac{a\mu^2}{2}\varphi^\dagger\varphi - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2$$

WE KNOW HOW TO MAKE THIS LOCALLY GAUGE INVARIANT...

$\partial^\mu \rightarrow \partial^\mu + iga^\mu$ SUBSTITUTION + TRANSFORMATIONS:

$\varphi \rightarrow \varphi' = e^{ig\theta(x)}\varphi(x)$ & $a^\mu \rightarrow a^{\mu\prime} = a^\mu - \partial_\mu\theta(x)$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \underbrace{\frac{1}{2}(D_\mu\varphi)^\dagger D^\mu\varphi}_{} - \frac{a\mu^2}{2}\varphi^\dagger\varphi - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2$$

encryption of a-φ interaction

$\frac{1}{2}\partial_\mu\varphi^\dagger\partial^\mu\varphi + \frac{1}{2}g^2 a^\mu a_\mu \varphi^\dagger\varphi$

force a phase transformation

FORCE $a \to -|a|$ AND SHIFT FIELDS...

$$\langle 0|\varphi_1|0\rangle = v \equiv \frac{a\mu^2}{\lambda} \qquad \langle 0|\varphi_2|0\rangle = 0$$

$$\varphi = v + \sigma + i\eta \qquad \text{AGAIN}$$

and substitute back...

magic

$$\mathcal{L} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$- \frac{1}{2}\, 2gv\,\partial_\mu\eta\, a^\mu + g^2 v\sigma a^2 + \frac{1}{2}g^2v^2a^2 - a\mu^2\sigma + \text{cubic \& quart. interactions}$$

LOOK AT ▬▬ TERMS...

$$\frac{1}{2}\left(\partial_\mu\eta\partial^\mu\eta - 2gv\,\partial_\mu\eta\, a^\mu + g^2v^2a^2\right)$$

$$= \frac{1}{2}\left(gva_\mu - \partial_\mu\eta\right)^2 = \frac{1}{2}g^2v^2\left(a_\mu - \frac{1}{gv}\partial_\mu\eta\right)^2$$

(RE)DEFINE $\quad \alpha_\mu \equiv a_\mu - \frac{1}{gv}\partial_\mu\eta \quad$ (looks like gauge transformation -- doesn't affect F's)

so, $\quad \Phi_{\mu\nu} \equiv \partial_\mu\alpha_\nu - \partial_\nu\alpha_\mu \quad$ -- or Φ's...

ta-da

$$\mathcal{L} = \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{4}\Phi_{\mu\nu}\Phi^{\mu\nu} + \frac{1}{2}g^2 v^2 \alpha^2 - a\mu^2\sigma^2 + \text{int terms}$$

The η has disappeared!

no massless bosons

The σ is still there

but has gained a mass!

$$m_\sigma = \sqrt{2a\mu^2}$$

The a_μ has disappeared and replaced by α_μ

but has gained a mass!

$$m_\alpha = \frac{gv}{\sqrt{2}}$$

Higgs Mechanism

the original, massless a_μ

had 2 dof

the original η

existed as a gradient, $\partial_\mu \eta(x)$

together, making 3 dof!

The Goldstone boson was "eaten" by the (gradient of the) spin 1 massless field

to become a spin 1 massive field.

Discovered by:

Anderson, Nambu, Englert, Brout, Gilbert, Guralnik, Higgs, Hagen, and Kibble around 1964

so naturally called the Higgs Mechanism

that's superconductivity

Start out with:

2 component, degenerative Boson pair

massless spin 1 vector Boson

so, a local U(1) symmetry is assured-Gauge invariant

Do the Landau-Ginsburg mechanical inducement of a phase transition

End up with:

1 massive spin 0 Boson Higgs Boson

1 massive spin 1 Boson Makes you think of the W

"superconductivity," you say?

In a superconductor, the order parameter:

Cooper Pairs–a Bose-like excitation

A breaking of charge invariance

What happens when a magnetic field impinges on a superconductor?

It's quenched within a skin-depth: Meisner Effect.

LONDON EQUATION $\vec{j} = -\frac{n_s e^2}{mc}\vec{A}$

MANIPULATE: $\vec{\nabla}\times\vec{j} = -\frac{e^2 n_s}{mc}\vec{B}$

WITH Ampere's law $\vec{\nabla}\times\vec{B} = \vec{j}$

$$\nabla^2\vec{B} = -\frac{e^2 n_s}{mc}\vec{B}$$

$$\nabla^2\vec{B} + \frac{1}{\lambda}\vec{B} = 0$$

A Klein Gordon Equation for a photon of mass $1/\lambda$

WITH SOLUTION $\vec{B} = \vec{B}_0 e^{-x/\lambda}$ $\lambda = \frac{mc}{e^2 n_s}$

bingo

When an electromagnetic field encounters a superconductor

it gains a mass.

That's where we live: inside a Universal Superconductor.

where some "photons" are massive.

the chain of events:

weak interactions need massive, spin 1 $W^{\pm}$ bosons → Demand local SU(2) gauge invariance →

Yang-Mills, 1954

↓

get massless spin 1 bosons

and so on...

Bose-Gas-like
doublet scalar
fields

Ginsburg-
Landau,
1950

→

Higgs et al.,
1964

spontaneously
break that
LOCAL SU(2)
gauge
symmetry

↓

get massive spin 1
field, Higgs boson,
no photon

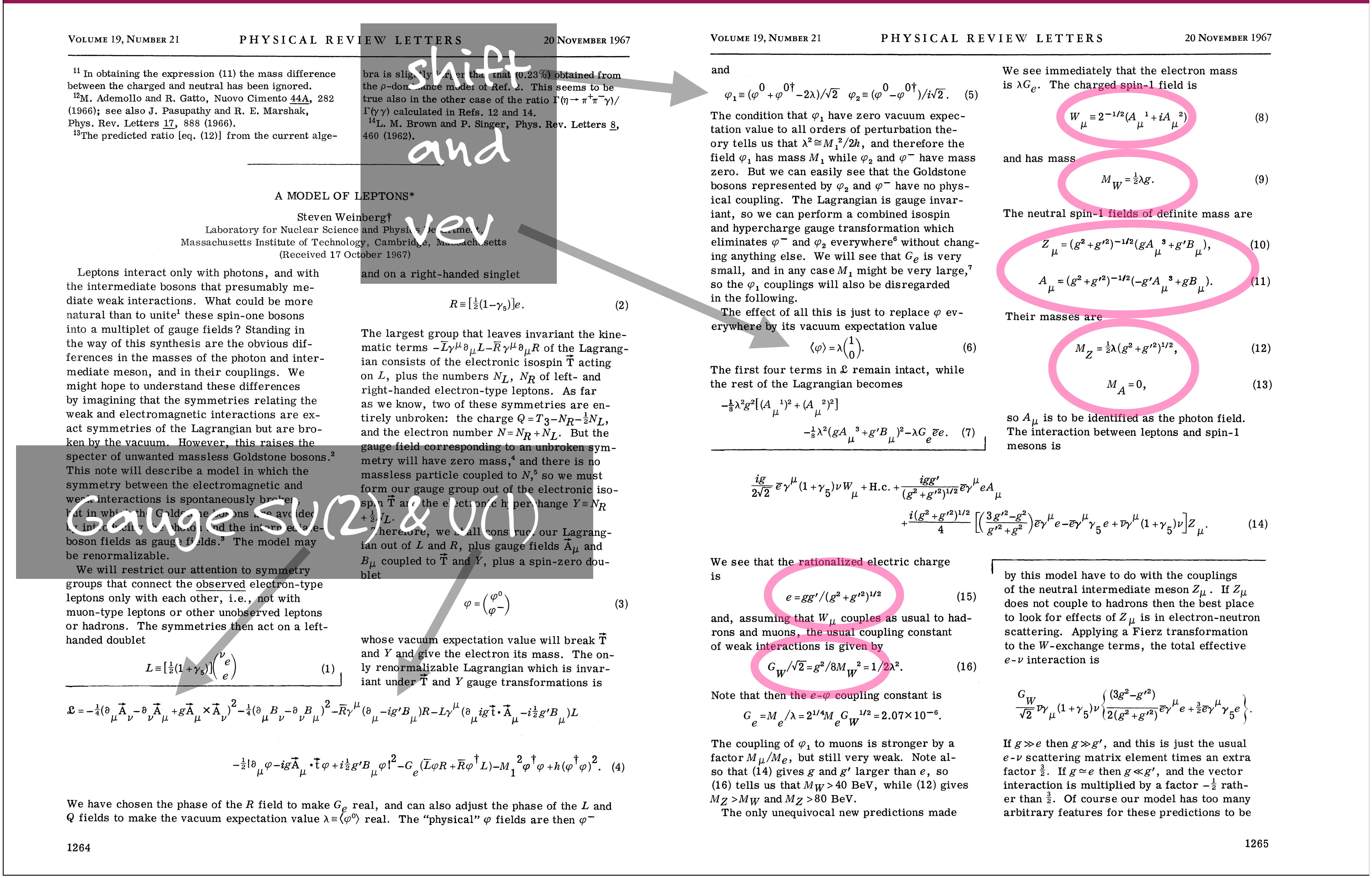
→

Steven
Weinberg,
1967

$SU(2) \otimes U(1)$

Weinberg, "A Model of Leptons" 1967

less than 3 pages.



[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.
[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).
[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.
[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

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Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac12(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and on a right-handed singlet

$$R \equiv [\tfrac12(1-\gamma_5)]e. \qquad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar L\gamma^\mu\partial_\mu L - \bar R\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec T$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac12N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec T$ and the electronic hypercharge $Y\equiv N_R+\frac12N_L$. Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec A_\mu$ and B_μ coupled to $\vec T$ and Y, plus a spin-zero doublet

$$\varphi = \binom{\varphi^0}{\varphi^-} \qquad (3)$$

whose vacuum expectation value will break $\vec T$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec T$ and Y gauge transformations is

$$\mathcal{L} = -\tfrac14(\partial_\mu\vec A_\nu - \partial_\nu\vec A_\mu + g\vec A_\mu\times\vec A_\nu)^2 - \tfrac14(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar R\gamma^\mu(\partial_\mu - ig'B_\mu)R - \bar L\gamma^\mu(\partial_\mu - ig\vec t\cdot\vec A_\mu - i\tfrac12g'B_\mu)L$$
$$-\tfrac12|\partial_\mu\varphi - ig\vec A_\mu\cdot\vec t\varphi + i\tfrac12g'B_\mu\varphi|^2 - G_e(\bar L\varphi R + \bar R\varphi^\dagger L) - M_1^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \qquad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

and

$$\varphi_1 \equiv (\varphi^0+\varphi^{0\dagger}-2\lambda)/\sqrt2 \quad \varphi_2\equiv(\varphi^0-\varphi^{0\dagger})/i\sqrt2. \qquad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2\cong M_1^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle = \lambda\binom{1}{0}. \qquad (6)$$

The first four terms in $\mathcal{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac18\lambda^2g^2[(A_\mu^{\ 1})^2+(A_\mu^{\ 2})^2] - \tfrac18\lambda^2(gA_\mu^{\ 3}+g'B_\mu)^2 - \lambda G_e\bar ee. \qquad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu \equiv 2^{-1/2}(A_\mu^{\ 1}+iA_\mu^{\ 2}) \qquad (8)$$

and has mass

$$M_W = \tfrac12\lambda g. \qquad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2+g'^2)^{-1/2}(gA_\mu^{\ 3}+g'B_\mu), \qquad (10)$$

$$A_\mu = (g^2+g'^2)^{-1/2}(-g'A_\mu^{\ 3}+gB_\mu). \qquad (11)$$

Their masses are

$$M_Z = \tfrac12\lambda(g^2+g'^2)^{1/2}, \qquad (12)$$

$$M_A = 0, \qquad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt2}\bar e\gamma^\mu(1+\gamma_5)\nu W_\mu + \text{H.c.} + \frac{igg'}{(g^2+g'^2)^{1/2}}\bar e\gamma^\mu eA_\mu + \frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar e\gamma^\mu e - \bar e\gamma^\mu\gamma_5e + \bar\nu\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \qquad (14)$$

We see that the rationalized electric charge is

$$e = gg'/(g^2+g'^2)^{1/2} \qquad (15)$$

and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

$$G_W/\sqrt2 = g^2/8M_W^{\ 2} = 1/2\lambda^2. \qquad (16)$$

Note that then the e-φ coupling constant is

$$G_e = M_e/\lambda = 2^{1/4}M_eG_W^{\ 1/2} = 2.07\times10^{-6}.$$

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W>40$ BeV, while (12) gives $M_Z>M_W$ and $M_Z>80$ BeV.

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

$$\frac{G_W}{\sqrt2}\bar\nu\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar e\gamma^\mu e + \tfrac32\bar e\gamma^\mu\gamma_5e\right\}.$$

If $g\gg e$ then $g\gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac32$. If $g\simeq e$ then $g\ll g'$, and the vector interaction is multiplied by a factor $-\frac12$ rather than $\frac32$. Of course our model has too many arbitrary features for these predictions to be

really...2 pages.

taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the electron-neutrino cross section may well be wrong.

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields. And if this model is renormalizable, then what happens when we extend it to include the couplings of $\vec{A}_\mu$ and B_μ to the hadrons?

I am grateful to the Physics Department of MIT for their hospitality, and to K. A. Johnson for a valuable discussion.

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†On leave from the University of California, Berkeley, California.

[1]The history of attempts to unify weak and electromagnetic interactions is very long, and will not be reviewed here. Possibly the earliest reference is E. Fermi, Z. Physik 88, 161 (1934). A model similar to ours was discussed by S. Glashow, Nucl. Phys. 22, 579 (1961); the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and therefore gets less definite predictions.

[2]J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3]P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

[4]See particularly T. W. B. Kibble, Phys. Rev. 155, 1554 (1967). A similar phenomenon occurs in the strong interactions; the ρ-meson mass in zeroth-order perturbation theory is just the bare mass, while the A_1 meson picks up an extra contribution from the spontaneous breaking of chiral symmetry. See S. Weinberg, Phys. Rev. Letters 18, 507 (1967), especially footnote 7; J. Schwinger, Phys. Letters 24B, 473 (1967); S. Glashow, H. Schnitzer, and S. Weinberg, Phys. Rev. Letters 19, 139 (1967), Eq. (13) et seq.

[5]T. D. Lee and C. N. Yang, Phys. Rev. 98, 101 (1955).

[6]This is the same sort of transformation as that which eliminates the nonderivative $\vec{\pi}$ couplings in the σ model; see S. Weinberg, Phys. Rev. Letters 18, 188 (1967). The $\vec{\pi}$ reappears with derivative coupling because the strong-interaction Lagrangian is not invariant under chiral gauge transformation.

[7]For a similar argument applied to the σ meson, see Weinberg, Ref. 6.

[8]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1957).

SPECTRAL-FUNCTION SUM RULES, ω-φ MIXING, AND LEPTON-PAIR DECAYS OF VECTOR MESONS*

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and

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Within the framework of vector-meson dominance, the current-mixing model is shown to be the only theory of ω-φ mixing consistent with Weinberg's first sum rule as applied to the vector-current spectral functions. Relations among the leptonic decay rates of ρ^0, ω, and φ are derived, and other related processes are discussed.

We begin by considering Weinberg's first sum rule[1] extended to the (1+8) vector currents of the eightfold way[2]:

$$\int dm^2[m^{-2}\rho_{\alpha\beta}^{(1)}(m^2)+\rho_{\alpha\beta}^{(0)}(m^2)]=S\delta_{\alpha\beta}+S'\delta_{\alpha 0}\delta_{\beta 0}, \qquad (1)$$

that's it.

Citations in the next 4 years?

something like 3...all by Weinberg

Then, all hell broke loose in 1979

definitive predictions:

The W exists and the Z exists

The Z would couple everywhere that γ couples

like atoms 1984

like interfering with electron scattering ~1990?

like "weak neutral currents" 1979

The mass of the Z is related to the mass of the W

$$cos\theta_W = \frac{M_W}{M_Z}$$ 1983

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

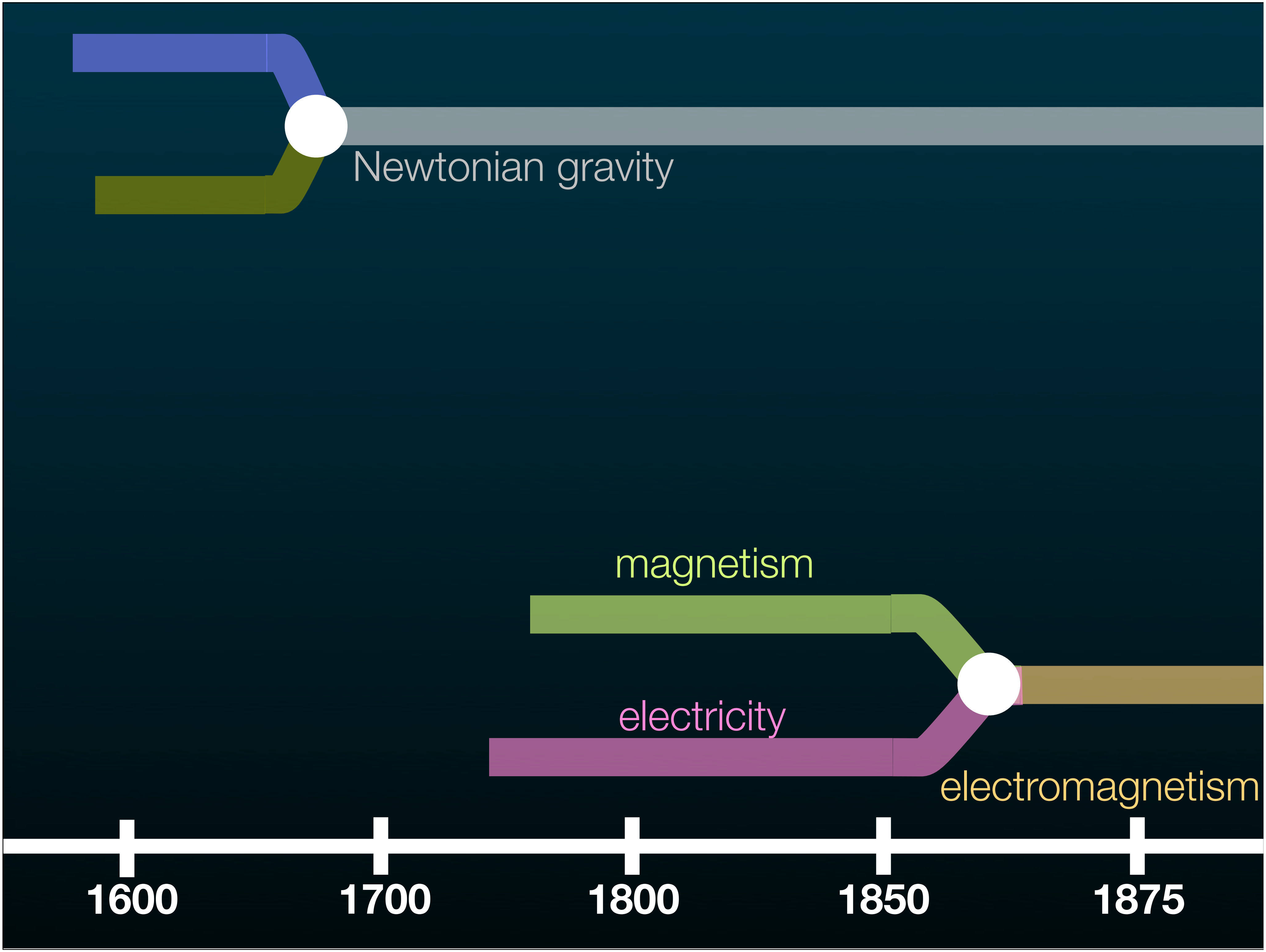
The Standard Model is the most precise theory in the history of physics

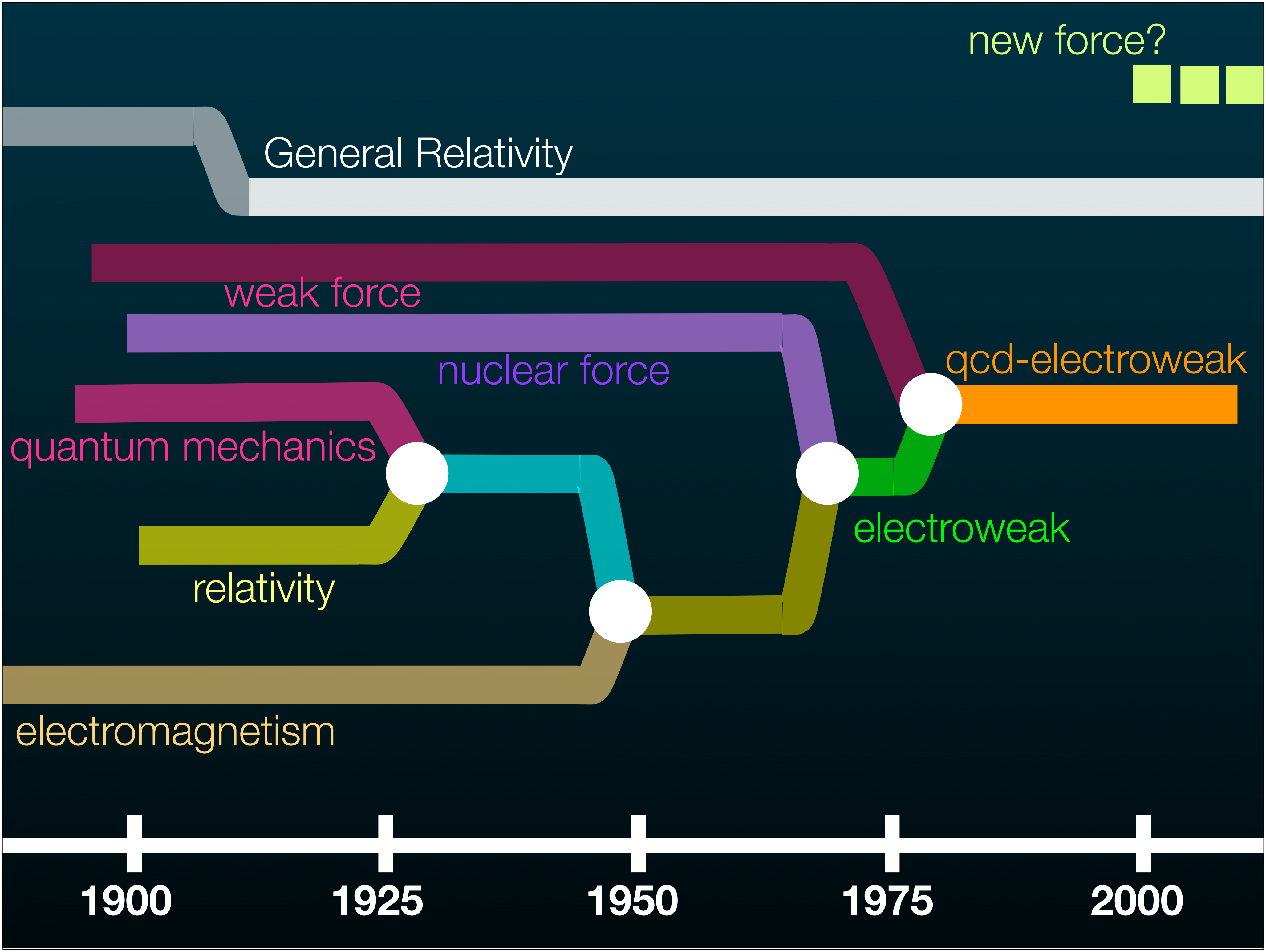
pretty damn good.

Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		−1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
A_τ	0.136 ± 0.015		−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\text{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

June 12, 2007 11:05

The Review of Particle Physics
W.-M. Yao et al., Journal of Physics, G 33, 1 (2006)


Newtonian gravity
magnetism
electricity
electromagnetism
1600
1700
1800
1850
1875


new force?
General Relativity
weak force
nuclear force
qcd-electroweak
quantum mechanics
relativity
electroweak
electromagnetism
1900
1925
1950
1975
2000

The Standard Model is also a model of the Universe

a^0 0
B^0 0
B^+ +
B^- -
ϕ (+ / 0)
ϕ^* (- / 0)

γ
Z
$W^\pm$
H^0

t = the beginning 0 s → t = 10^{-12} s → t = 10^{+18} s

This...is:

The “Higgs Mechanism”

H^0

The remaining primordial scalar is the Higgs Field.

The Higgs Boson creates mass

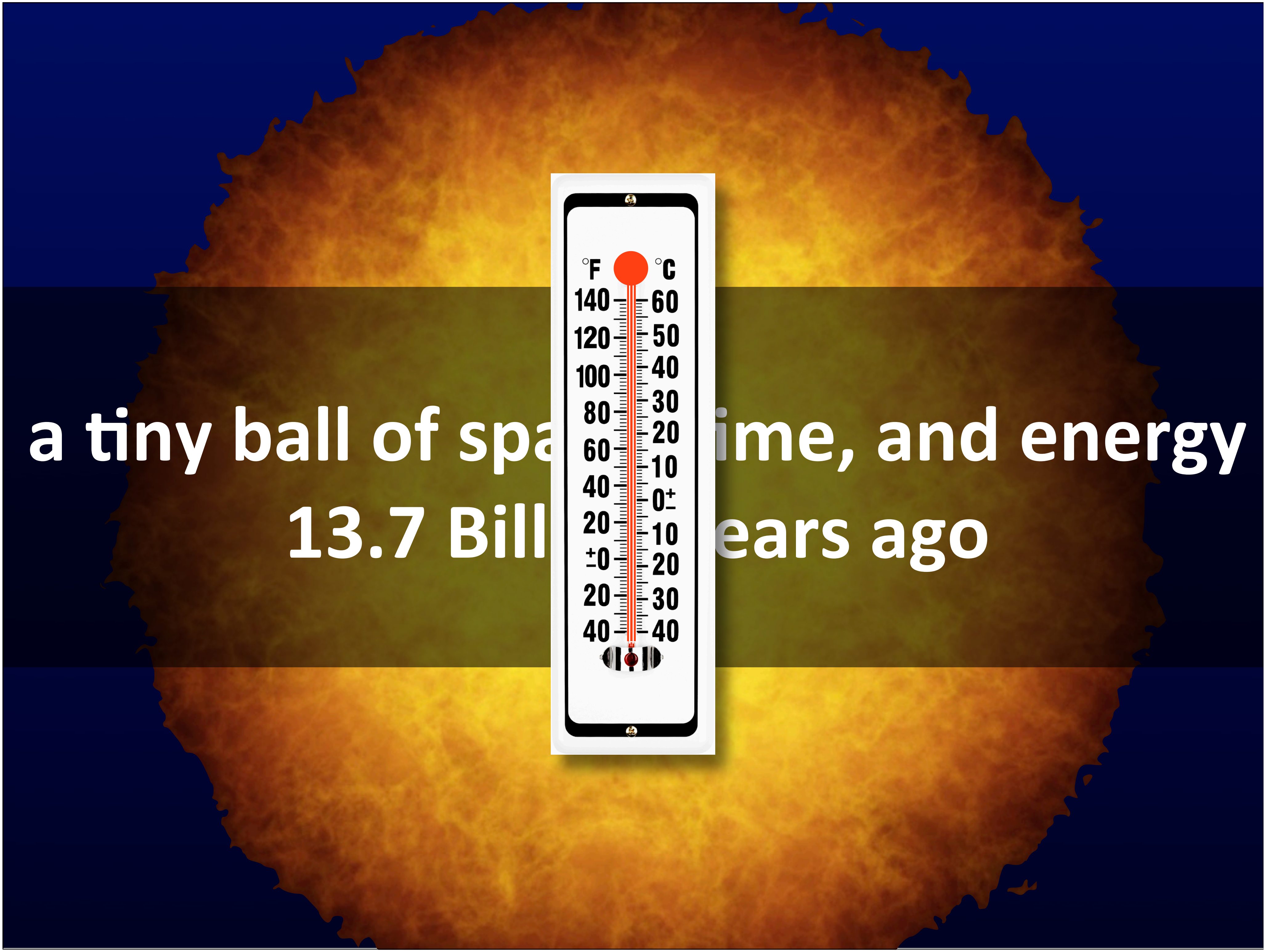
mass may not be an inherent property...

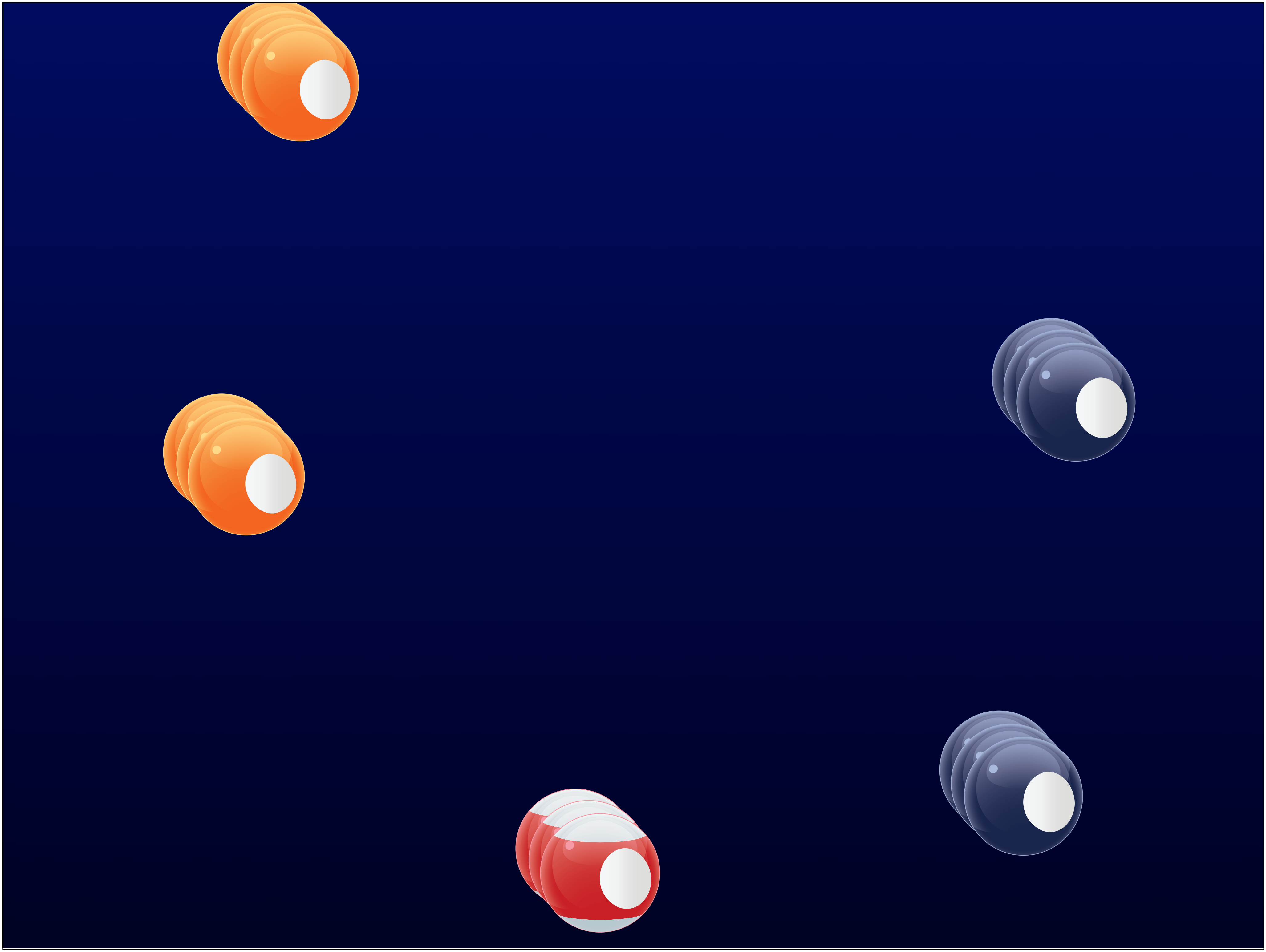
but an *acquired* one

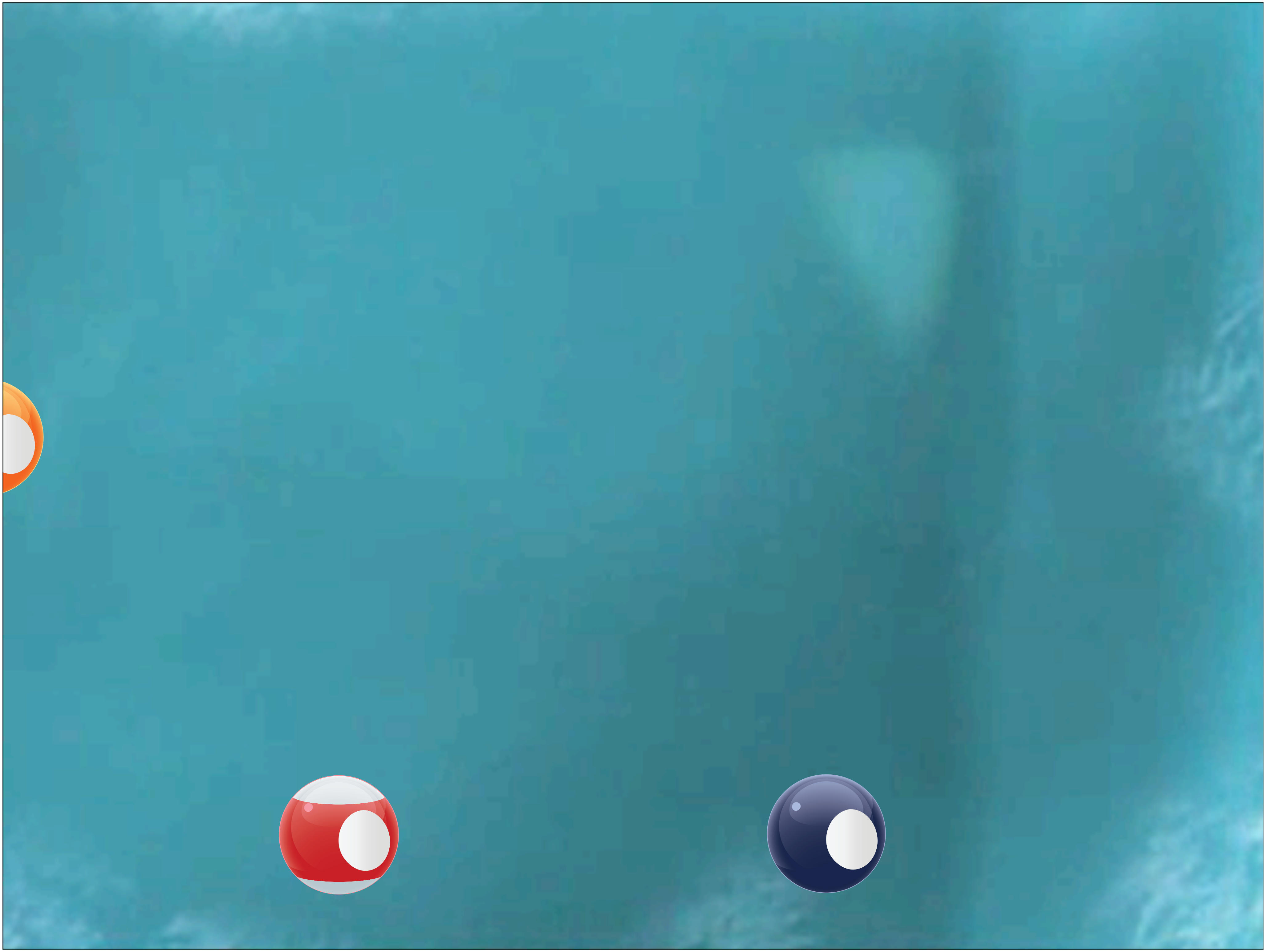
about nothing

the action

in the vacuum


a tiny ball of spa ime, and energy
13.7 Bill ears ago





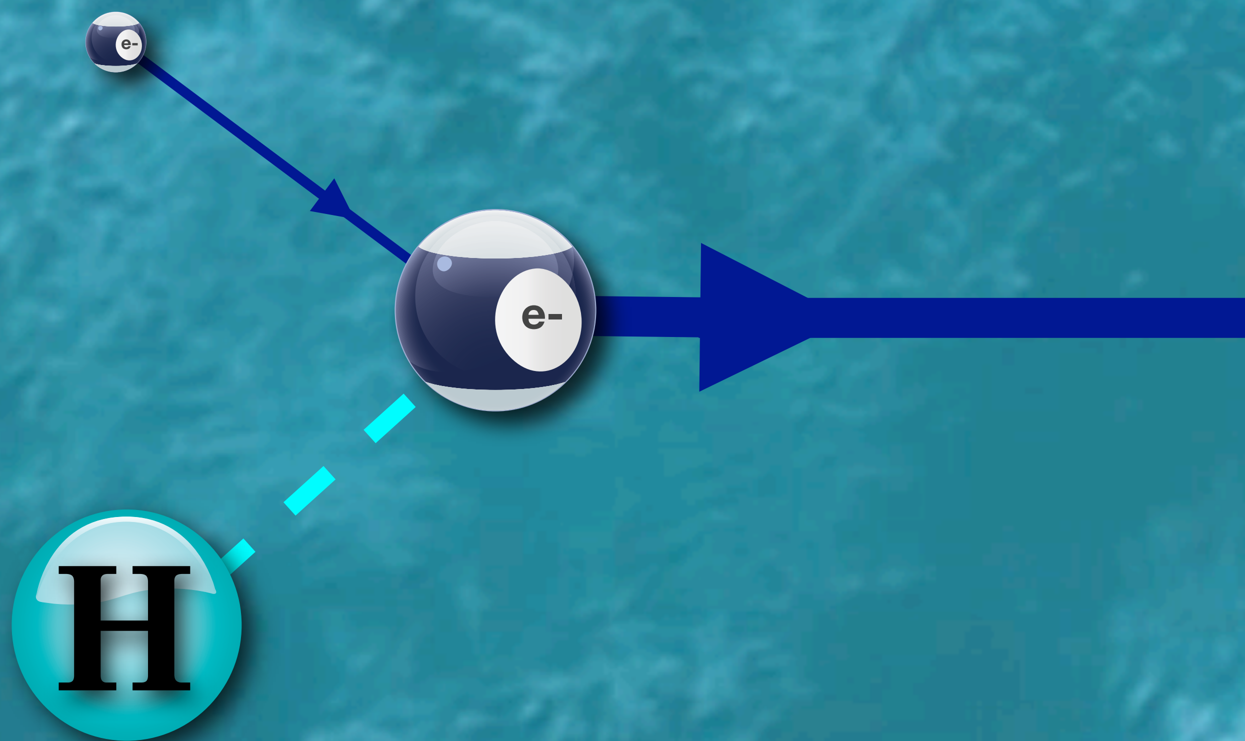
vacuum

empty

Nature is clumpy

Higgs *Boson*

Higgs Field



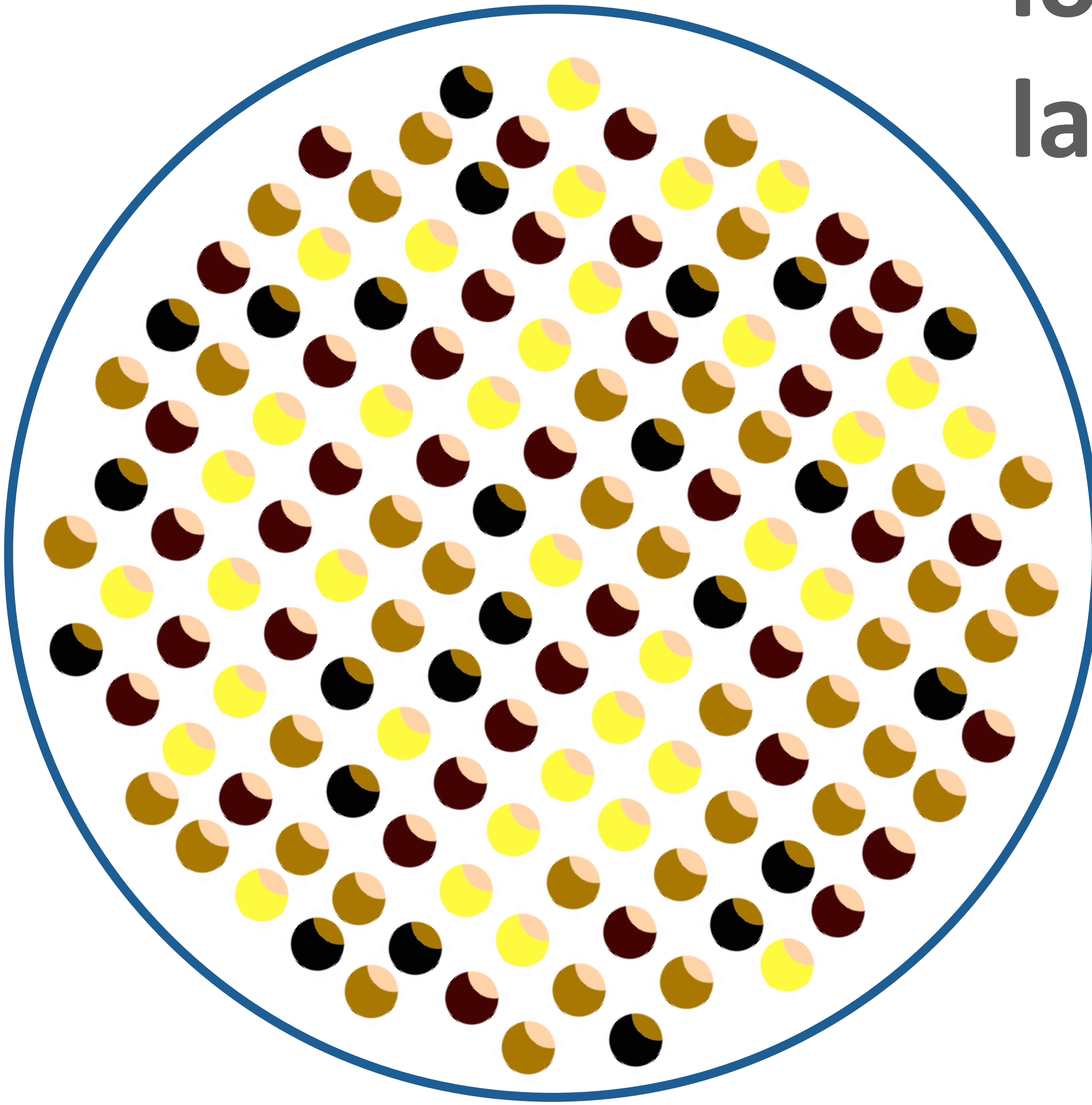
Higgs Boson

a Higgs metaphor

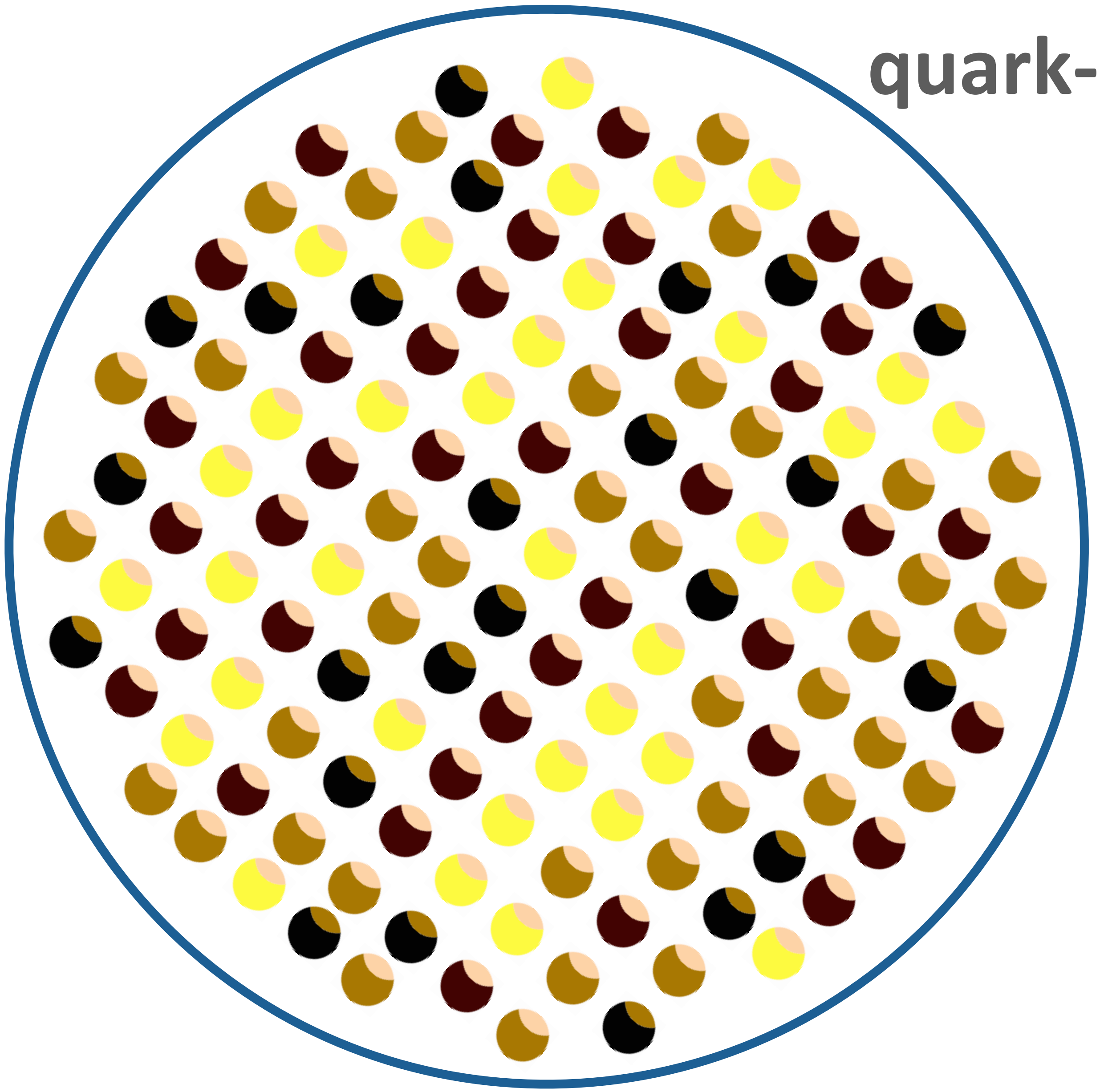
the crowd: Higgs Field

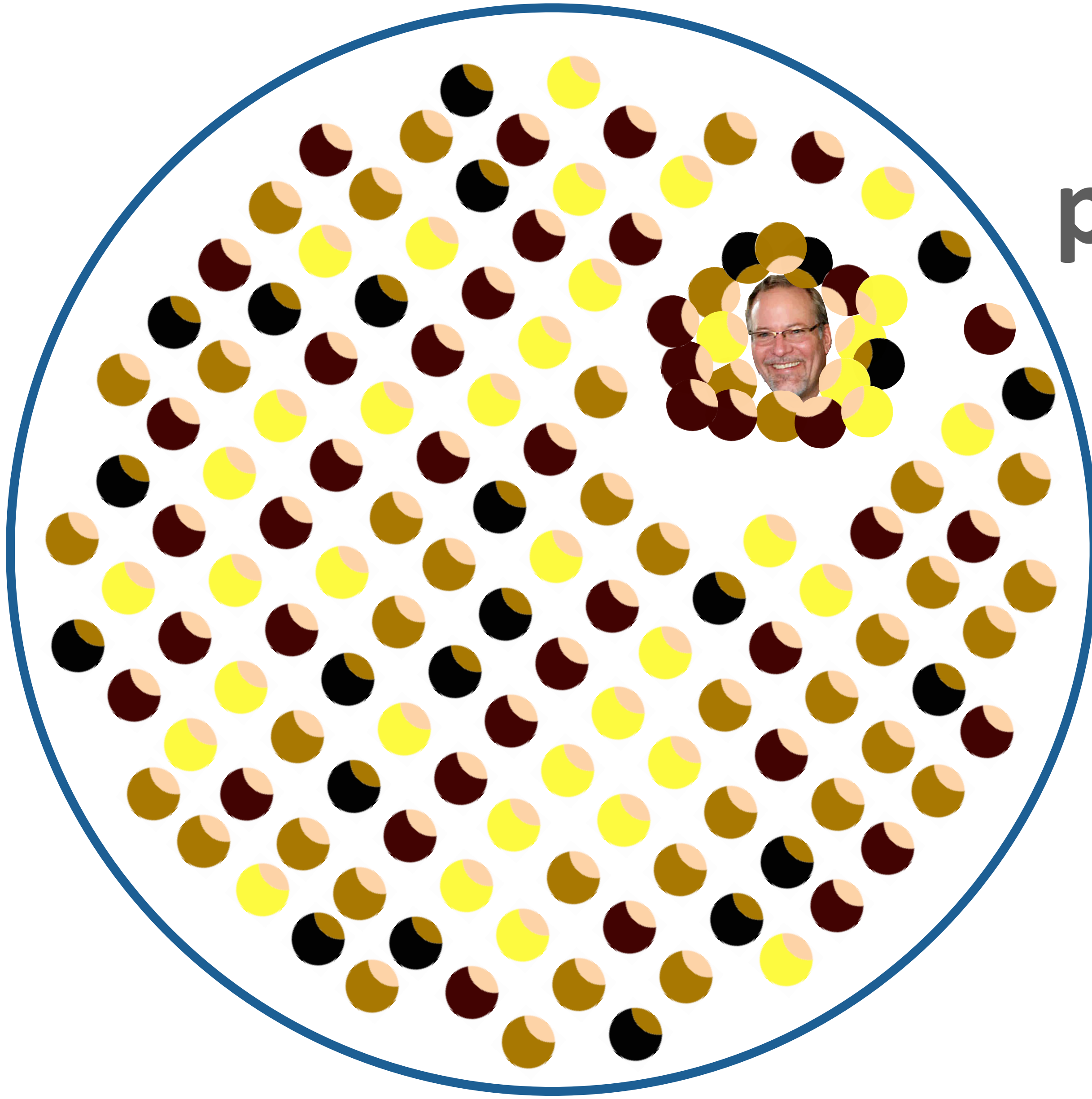
(after David Miller)

loud laughter

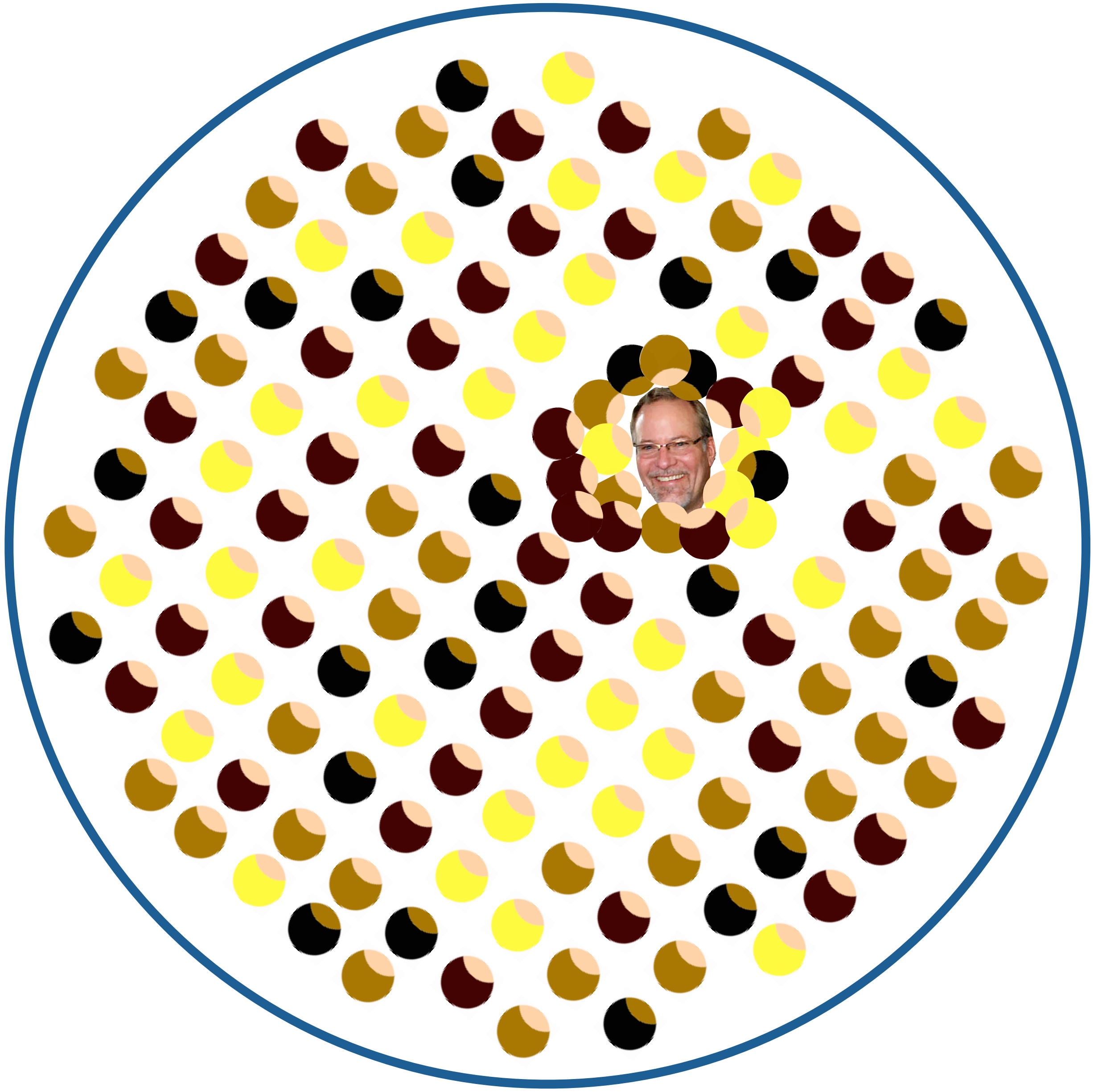


quark-Karl-Gude

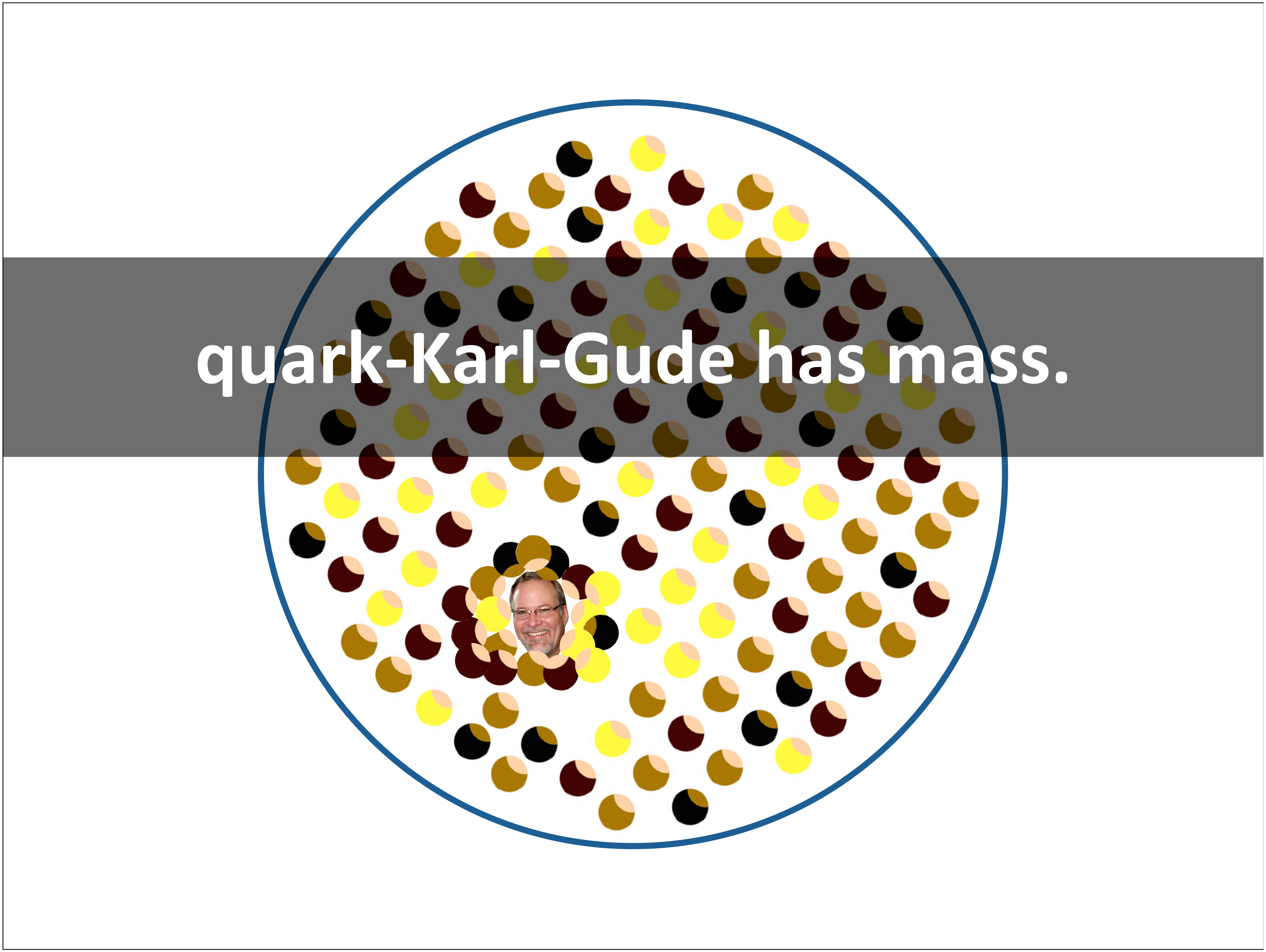


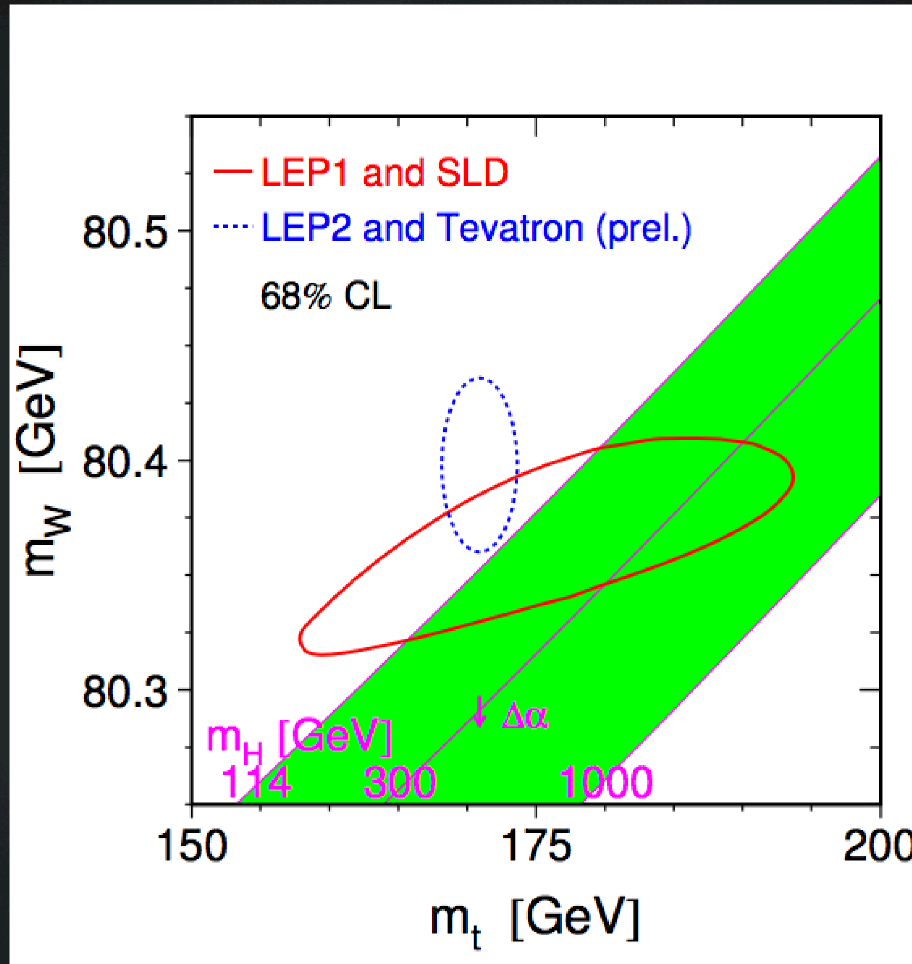


popular




quark-Karl-Gude has gained inertia


quark-Karl-Gude has mass.



By constraining SM measurements:

$\{M_H < 182\ GeV/c^2 ; > 114\ GeV/c^2\}$ and: $M_H = 76\ +36\ -24\ GeV/c^2$

SM is a renormalizable theory

with issues... Higgs loops. and Gravity.

mass corrections

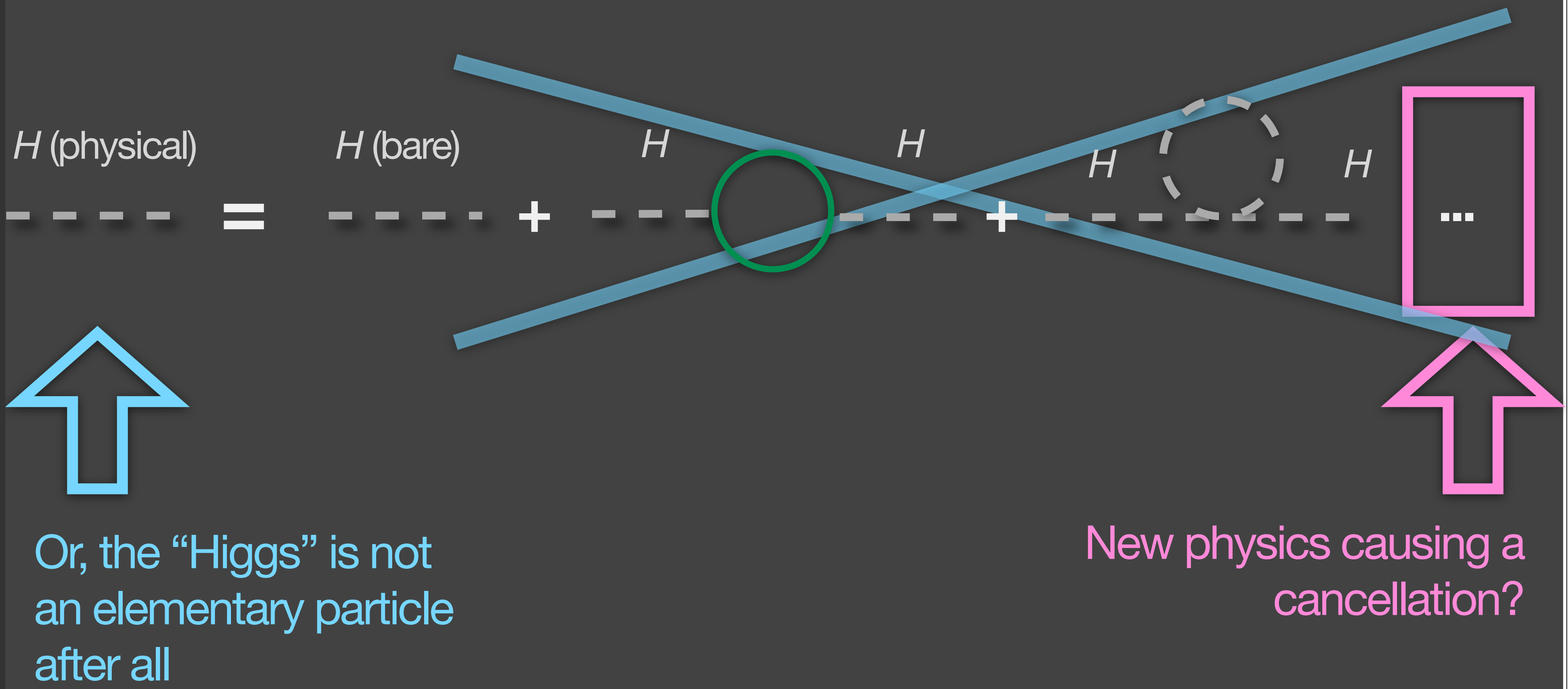
~ (10² GeV)²?

$$m^2(p^2) = m_0^2 + Cg^2 \int_{p^2}^{\Lambda^2} \text{stuff } dk^2$$

$$m^2(p^2) \propto \Lambda^2$$ ← That same scale problem as with the  !

~ (10¹⁹ GeV)²?

2 ways out?


H (physical)
H (bare)
H
H
H
H
...
Or, the “Higgs” is not an elementary particle after all
New physics causing a cancellation?