Particle Physics and the Theory of Nothing

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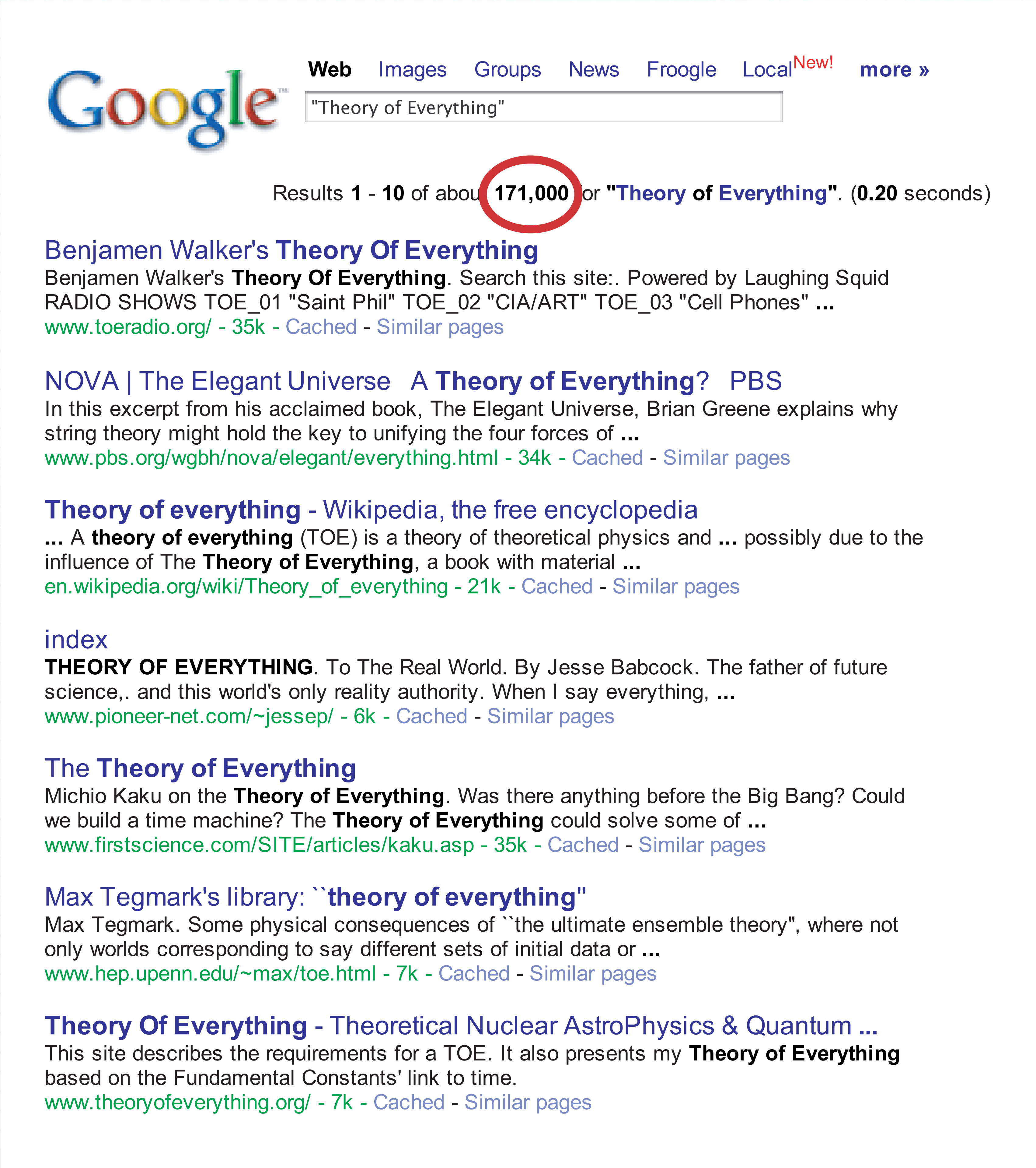
University of Toronto

Particle Physicists (and others) like to talk about finding a "theory of everything" ...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Theory Of Everything - Theoretical Nuclear AstroPhysics & Quantum **...**
This site describes the requirements for a TOE. It also presents my **Theory of Everything** based on the Fundamental Constants' link to time.
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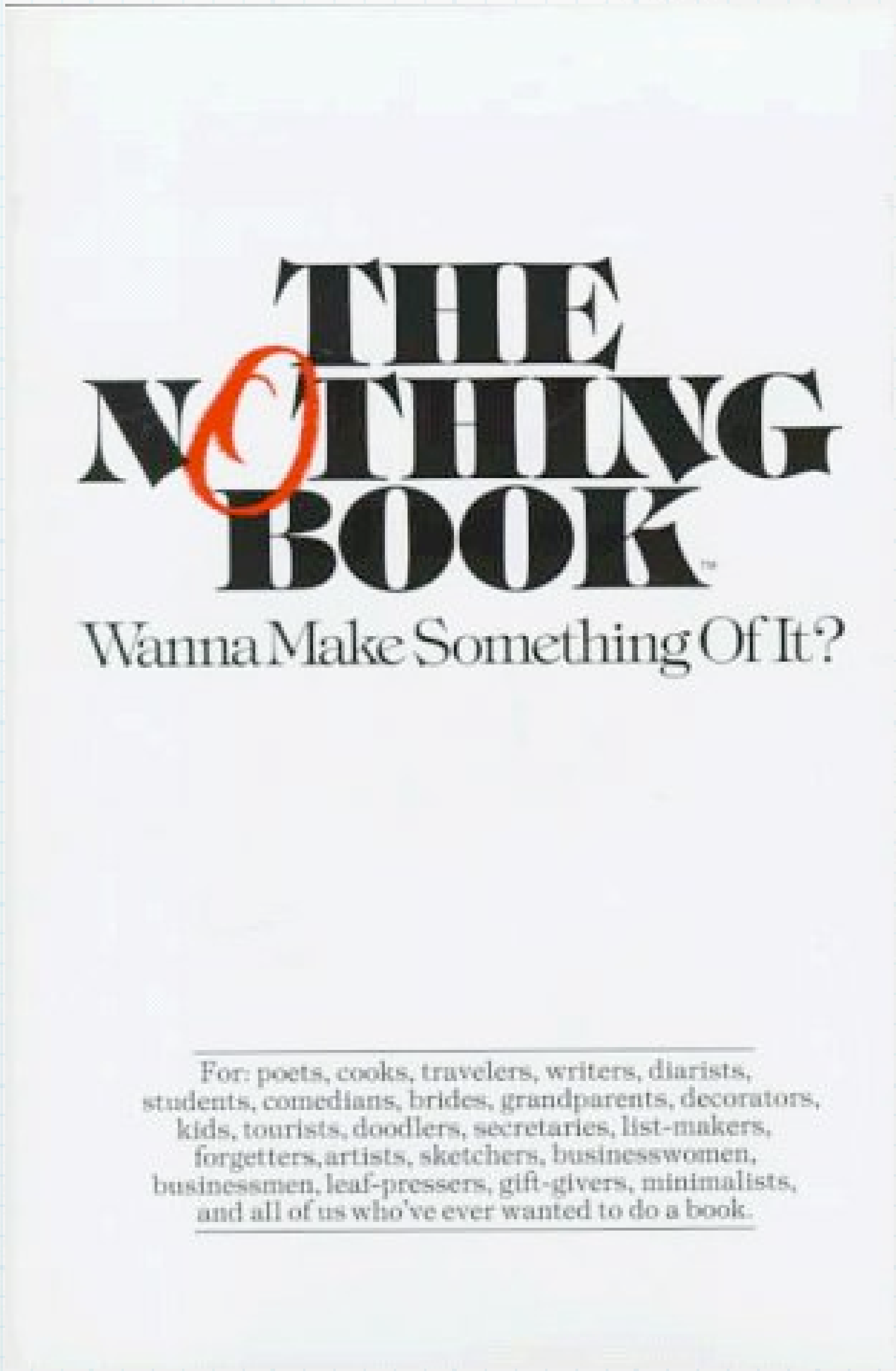
Particle Physicists
(and others)
like to talk about
finding a "theory of
everything" ...

... but what we could
really use is a theory
of Nothing.



Nothing (an experimental definition):

- seal the box and pump out all the air
- shield with 10^3 light-years of lead to keep out the neutrinos

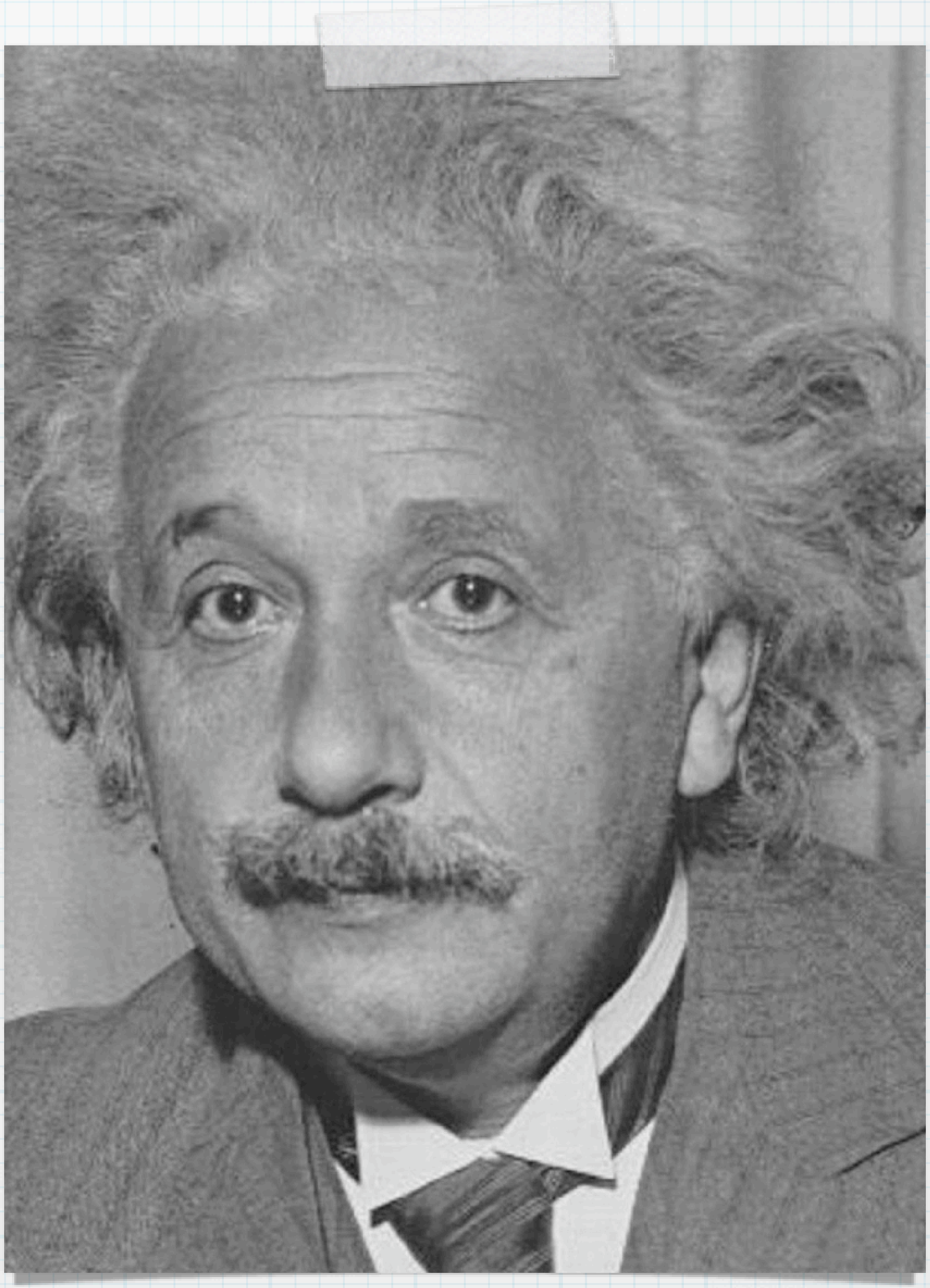
We do not understand what is in the box.

But I can tell you some of the things it does:

* screens charges (~dielectric)
* superconducts
* makes electrons (and other elementary particles) massive
* determines the nature of beta decay
* confines quarks into hadrons
* "melts" when heated to 10^{12} K
* is the same stuff as ~70% of the energy in the Universe

Understanding what is in an empty box is the central goal of particle physics!

back to 1905 ....



"On a Heuristic Point of View about the Creation and Conversion of Light" (Annalen der Physik. 17: 132, 1905)

Ann. Phys. (Leipzig) 14, Supplement, 164 – 181 (2005)

ANNALEN

DER

PHYSIK.

BEGRÜNDET UND FORTGEFÜHRT DURCH

F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. UND E. WIEDEMANN.

VIERTE FOLGE.

BAND 17.

DER GANZEN REIHE 322. BAND.

KURATORIUM:

F. KOHLRAUSCH, M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.

UNTER MITWIRKUNG

DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT

UND INSBESONDERE VON

M. PLANCK

HERAUSGEGEBEN VON

PAUL DRUDE.

MIT FÜNF FIGURENTAFELN.

LEIPZIG, 1905.

VERLAG VON JOHANN AMBROSIUS BARTH.

6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt; von A. Einstein.*

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagnetischen Zustandes eines Raumes kontinuierlicher räumlicher Funktionen, so daß also eine endliche Anzahl von Größen nicht als genügend anzusehen ist zur vollständigen Festlegung des elektromagnetischen Zustandes eines Raumes. Nach der Maxwellschen Theorie ist bei allen rein elektromagnetischen Erscheinungen, also auch beim Licht, die Energie als kontinuierliche Raumfunktion aufzufassen, während die Energie eines ponderabeln Körpers nach der gegenwärtigen Auffassung der Physiker als eine über die Atome und Elektronen erstreckte Summe darzustellen ist. Die Energie eines ponderabeln Körpers kann nicht in beliebig viele, beliebig kleine Teile zerfallen, während sich die Energie eines von einer punktförmigen Lichtquelle ausgesandten Lichtstrahles nach der Maxwellschen Theorie (oder allgemeiner nach jeder Undulationstheorie) des Lichtes auf ein stets wachsendes Volumen sich kontinuierlich verteilt.

Die mit kontinuierlichen Raumfunktionen operierende Undulationstheorie des Lichtes hat sich zur Darstellung der rein optischen Phänomene vortrefflich bewährt und wird wohl nie durch eine andere Theorie ersetzt werden. Es ist jedoch im Auge zu behalten, daß sich die optischen Beobachtungen auf zeitliche Mittelwerte, nicht aber auf Momentanwerte beziehen, und es ist trotz der vollständigen Bestätigung der Theorie der Beugung, Reflexion, Brechung, Dispersion etc. durch das

“On the Electrodynamics of Moving Bodies” (Annalen der Physik. 17:891, 1905)

Ann. Phys. (Leipzig) **14**, Supplement, 164 – 181 (2005)

ANNALEN DER PHYSIK.

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LEIPZIG, 1905.

VERLAG VON JOHANN AMBROSIUS BARTH.

Ann. Phys. (Leipzig) **14**, Supplement, 194-224 (2005) A. Einstein, Annalen der Physik, Band 17, 1905

3. *Zur Elektrodynamik bewegter Körper; von A. Einstein.*

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium“ zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität“ genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

“Does the Inertia of a Moving Body Depend Upon its Energy-Content?” (Annalen der Physik. 18: 639, 1905)

Ann. Phys. (Leipzig) **14**, Supplement, 225 – 228 (2005)

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LEIPZIG, 1905.

VERLAG VON JOHANN AMBROSIUS BARTH.

13. *Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?* *von A. Einstein.*

Die Resultate einer jüngst in diesen Annalen von mir publizierten elektrodynamischen Untersuchung[1]) führen zu einer sehr interessanten Folgerung, die hier abgeleitet werden soll.

Ich legte dort die Maxwell-Hertzschen Gleichungen für den leeren Raum nebst dem Maxwellschen Ausdruck für die elektromagnetische Energie des Raumes zugrunde und außerdem das Prinzip:

Die Gesetze, nach denen sich die Zustände der physikalischen Systeme ändern, sind unabhängig davon, auf welches von zwei relativ zueinander in gleichförmiger Parallel-Translationsbewegung befindlichen Koordinatensystemen diese Zustandsänderungen bezogen werden (Relativitätsprinzip).

Gestützt auf diese Grundlagen[2]) leitete ich unter anderem das nachfolgende Resultat ab (l. c. § 8):

Ein System von ebenen Lichtwellen besitze, auf das Koordinatensystem (x, y, z) bezogen, die Energie l; die Strahlrichtung (Wellennormale) bilde den Winkel φ mit der x-Achse des Systems. Führt man ein neues, gegen das System (x, y, z) in gleichförmiger Paralleltranslation begriffenes Koordinatensystem (ξ, η, ζ) ein, dessen Ursprung sich mit der Geschwindigkeit v längs der x-Achse bewegt, so besitzt die genannte Lichtmenge — im System (ξ, η, ζ) gemessen — die Energie:

$$l^* = l \frac{1 - \frac{v}{V} \cos\varphi}{\sqrt{1 - \left(\frac{v}{V}\right)^2}},$$

wobei V die Lichtgeschwindigkeit bedeutet. Von diesem Resultat machen wir im folgenden Gebrauch.

1) A. Einstein, Ann. d. Phys. **17**. p. 891. 1905.

2) Das dort benutzte Prinzip der Konstanz der Lichtgeschwindigkeit ist natürlich in den Maxwellschen Gleichungen enthalten.

42*

Two revolutions of 20th century physics: special relativity and quantum mechanics

$$E = mc^2$$

mass and energy are equivalent

$$E = h\nu = hc/\lambda$$

electromagnetic energy comes in individual "lumps" (photons) - an electromagnetic field (classical wave) is composed of particles (quantized modes of vibration)

What happens when we put relativity + QM together?

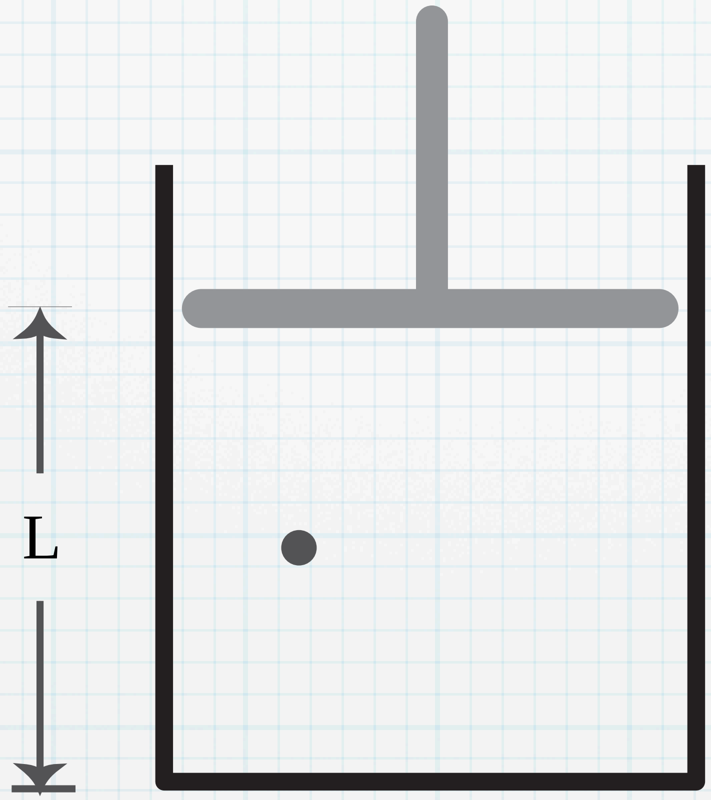
"Particle in a Box"

Quantum (Heisenberg)

$$\Delta x \Delta p \sim \hbar$$

$$\Rightarrow \Delta p \sim \hbar / L$$

$$\Rightarrow \Delta v \sim \hbar / (mL)$$



$$L \gg \frac{\hbar}{mc}$$

Relativity (Einstein)

$$\Delta v \ll c$$

(no problem!)

What happens when we put relativity + QM together?

"Particle in a Box"

Quantum (Heisenberg)

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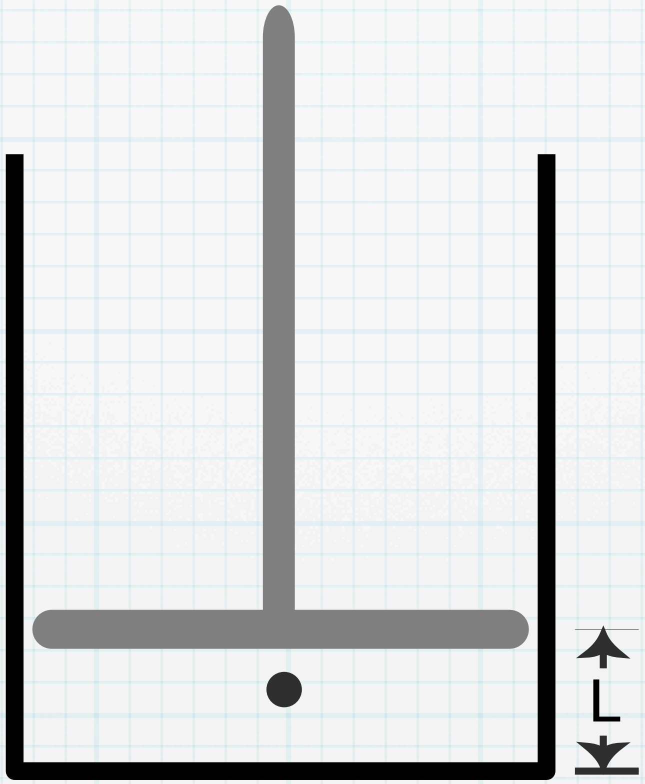


$$L \ll \frac{\hbar}{mc}$$

Relativity (Einstein)

$$\Delta v \gg c \text{ ??}$$

use relativistic kinematics!

$E=(p^2c^2+m^2c^4)^{1/2}$

$$\Delta E \gg mc^2$$

What happens when we put relativity + QM together?

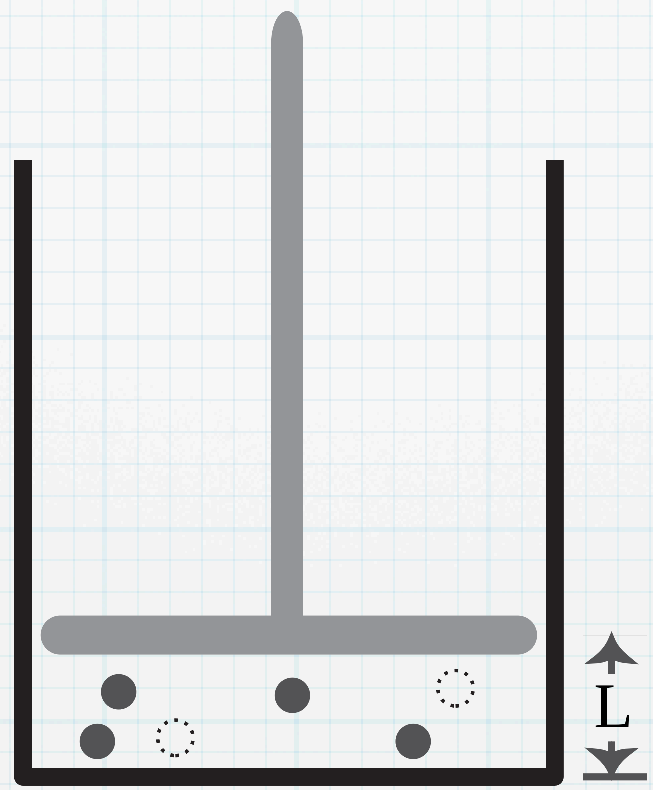
"Particle in a Box"

Quantum (Heisenberg)

$$\Delta x \Delta p > \hbar$$

$$\Delta p \sim \hbar / L$$

$$\Delta v \sim \hbar / (mL)$$



$$L \ll \frac{\hbar}{mc}$$

Relativity (Einstein)

$$\Delta v \gg c$$??

use relativistic kinematics!

$E=(p^2c^2+m^2c^4)^{1/2}$

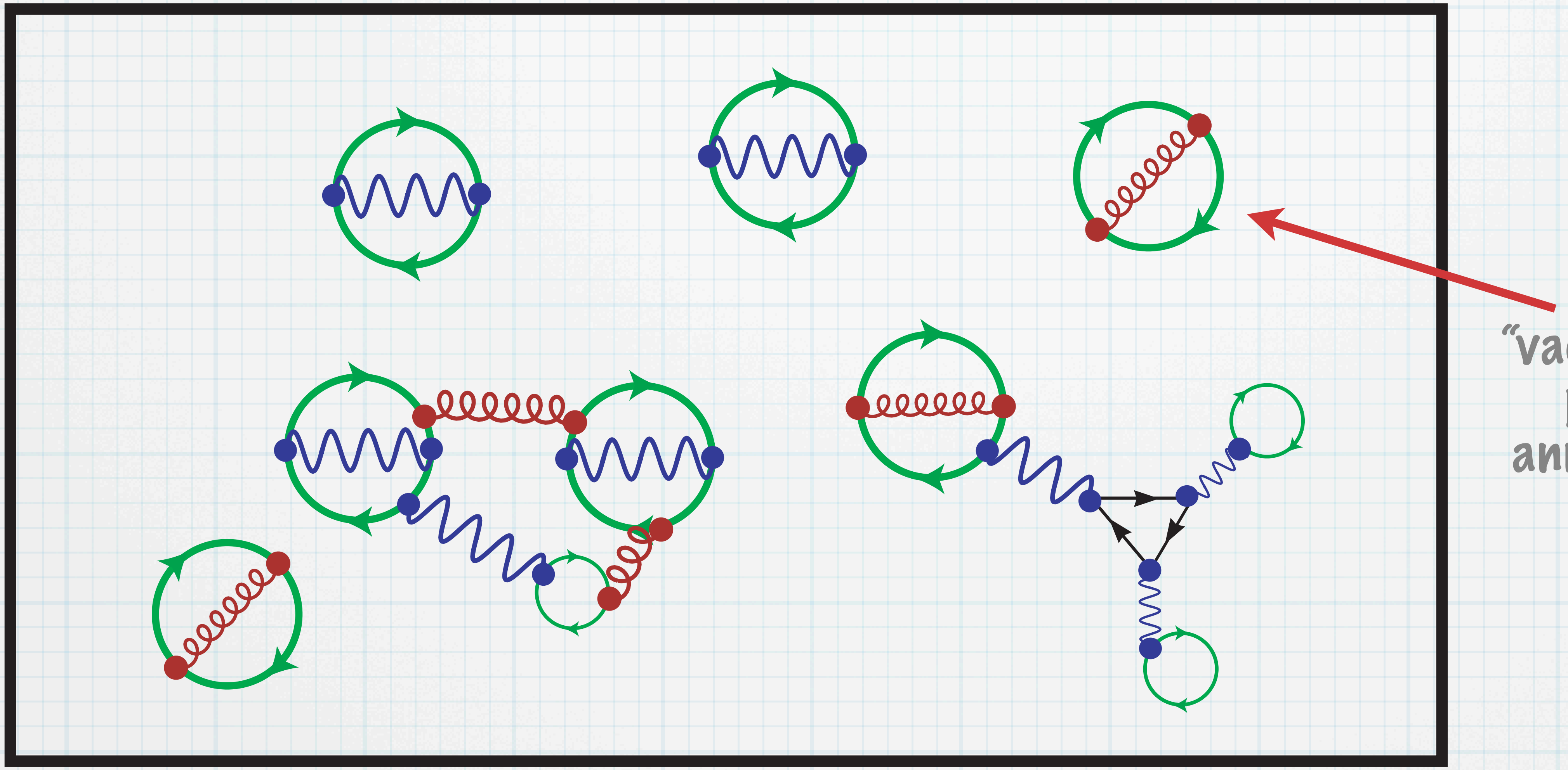
$$\Delta E \gg mc^2$$

number of particles in the box is uncertain!

"virtual particles"

- relativity when you are not moving fast!

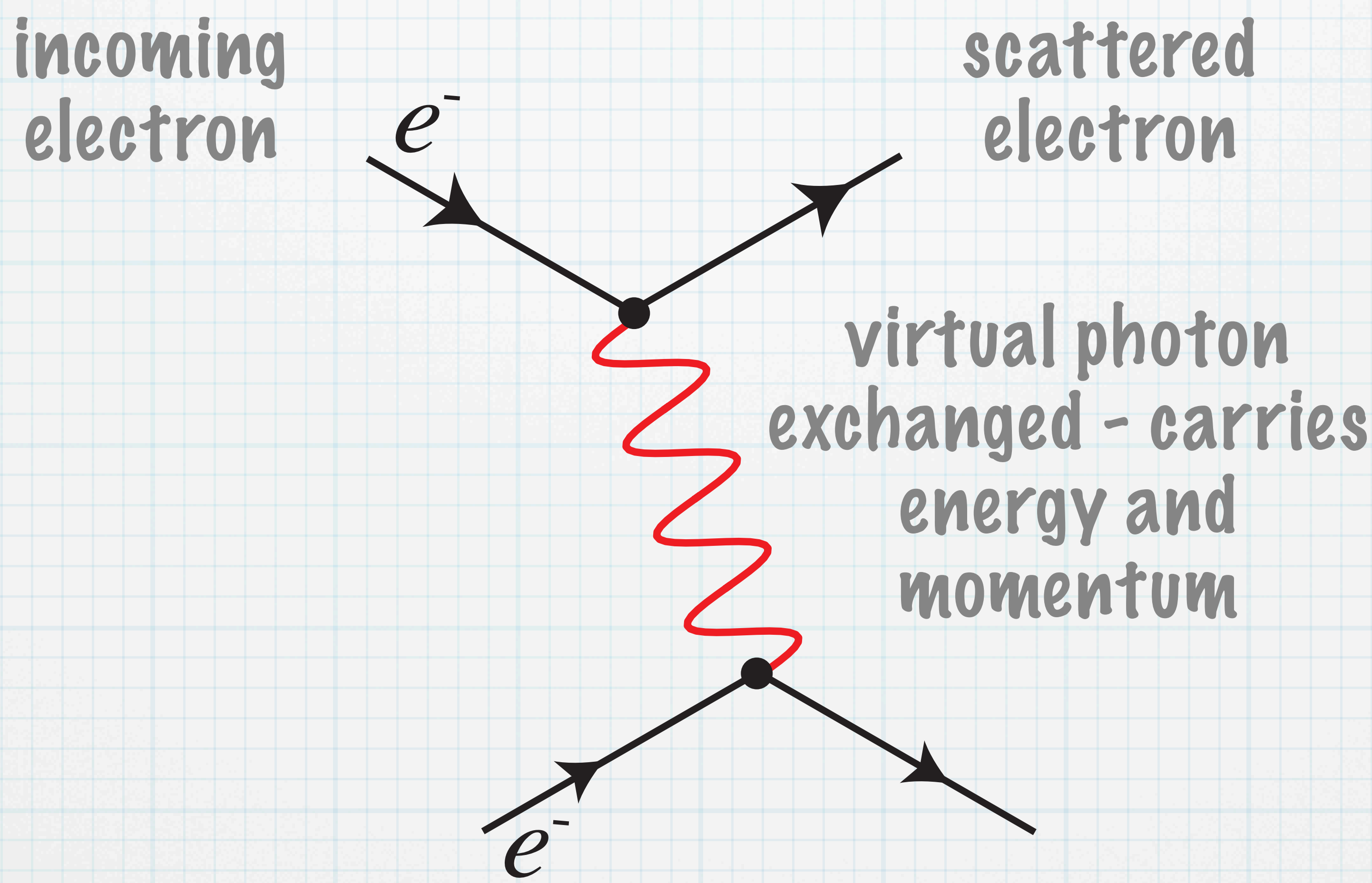
- even an "empty" box is complicated ...



"vacuum bubbles": virtual particle creation/ annihilation allowed by the Uncertainty Principle

- nature of the Vacuum depends on all of the details of all of the interactions! ... and it changes depending on the distance scale you look at

The exchange of virtual particles also provides the microphysical origin of forces:



energy of system is raised when the "clouds" of virtual photons around the electrons overlap -> repulsive force

MORAL:

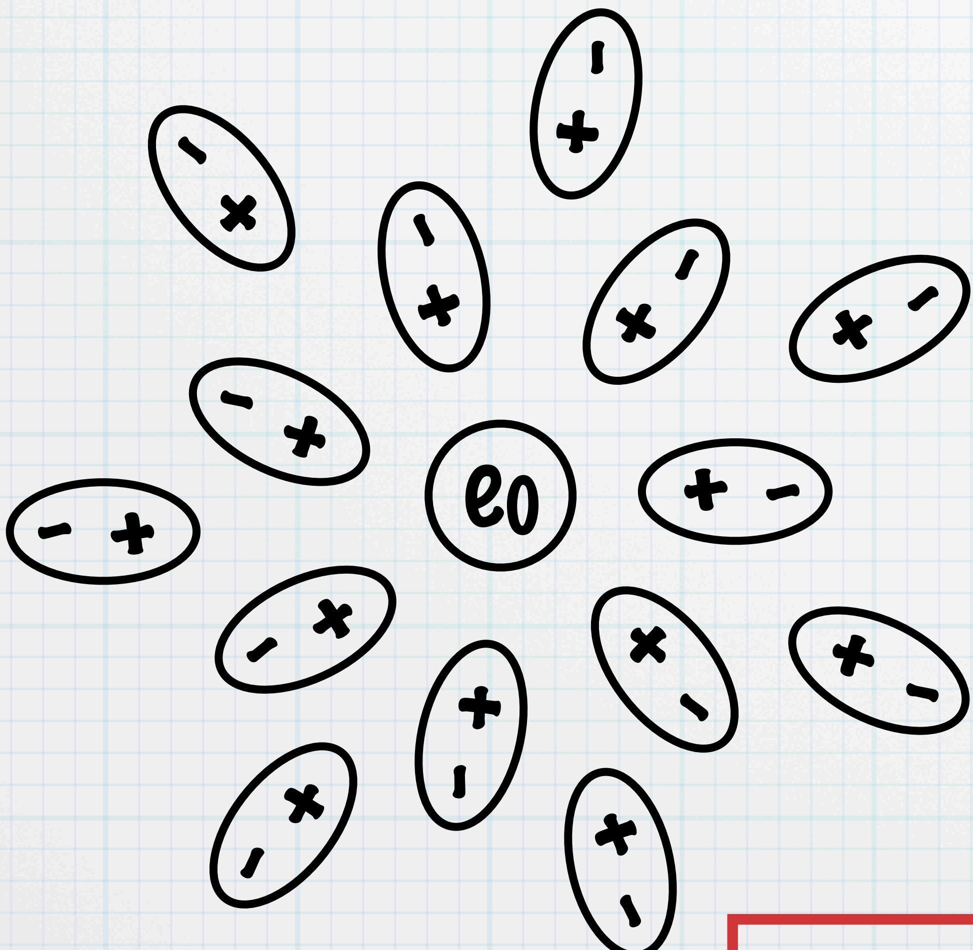
The Vacuum is NOT empty.

Vacuum = State of Lowest Energy (INCLUDES mass energy, potential energy, ... - complicated trade-off to get the ground state)

The Vacuum is a MEDIUM.

The Vacuum as a Dielectric:

- like a dielectric, the Vacuum screens charge
- virtual electron-positron pairs are effectively dipoles, which screen the charge of the electron at long distances



experiment:

$$\alpha \equiv \frac{e^2}{\hbar c}$$

("fine structure constant")

$$\alpha(r \to \infty) = \frac{1}{137.03599911(46)}$$

measured in Quantum Hall Effect

$$\alpha(r = 2 \times 10^{-18}\ \mathrm{m}) = \frac{1}{127.918(18)}$$

measured in high energy collisions

$$\frac{e(r = 2 \times 10^{-18}\ \mathrm{m})}{e(r \to \infty)} \simeq 1.035$$

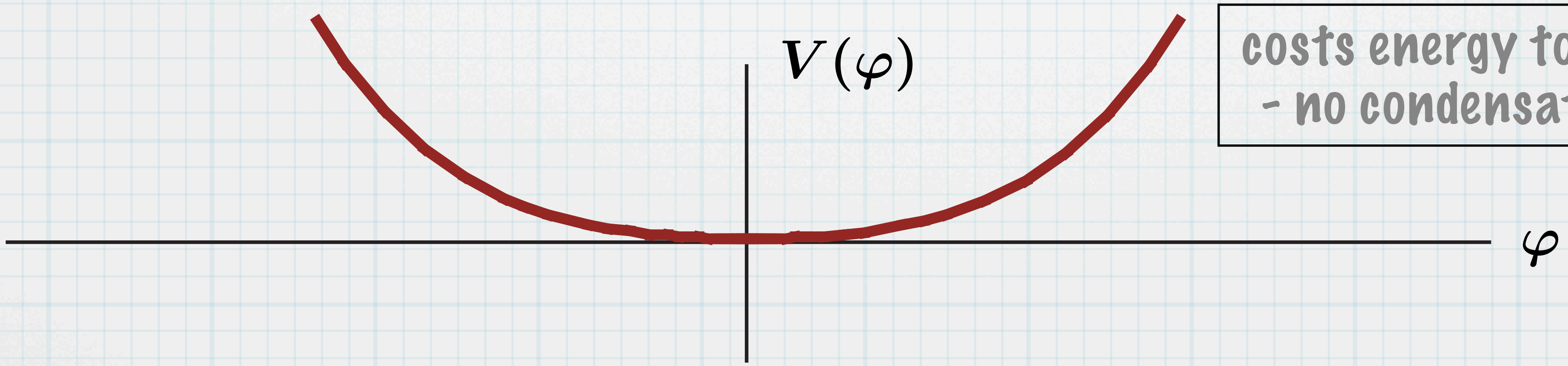
at shorter distances, effective charge on electron increases! (less screening)

"Condensates"

The nature of the Vacuum can be very complicated...

Energy of a field comes from mass energy and potential energy. If potential energy wins, a field (i.e. particles) can "condense" in the ground state!

Whether or not a condensate forms is a detailed dynamical question.



costs energy to condense out field
- no condensate in ground state

"Condensates"

The nature of the Vacuum can be very complicated...

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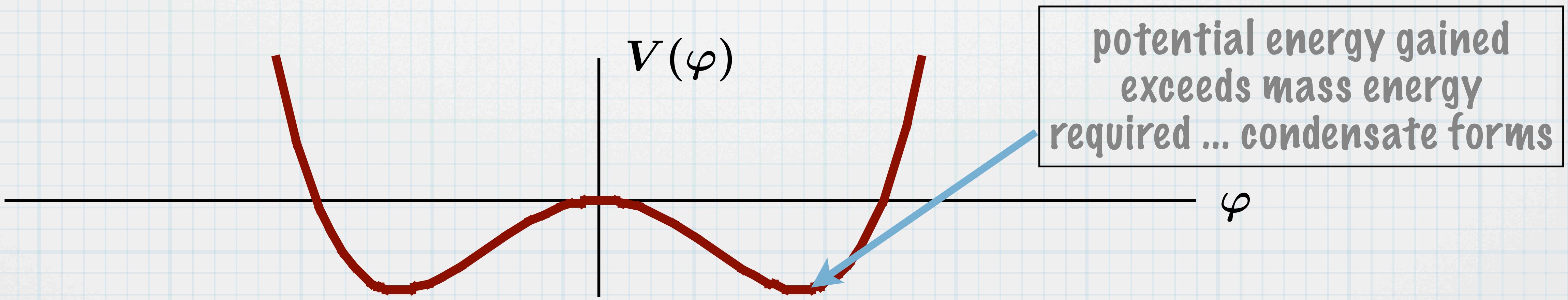


The known elementary particles, and their properties:

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

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

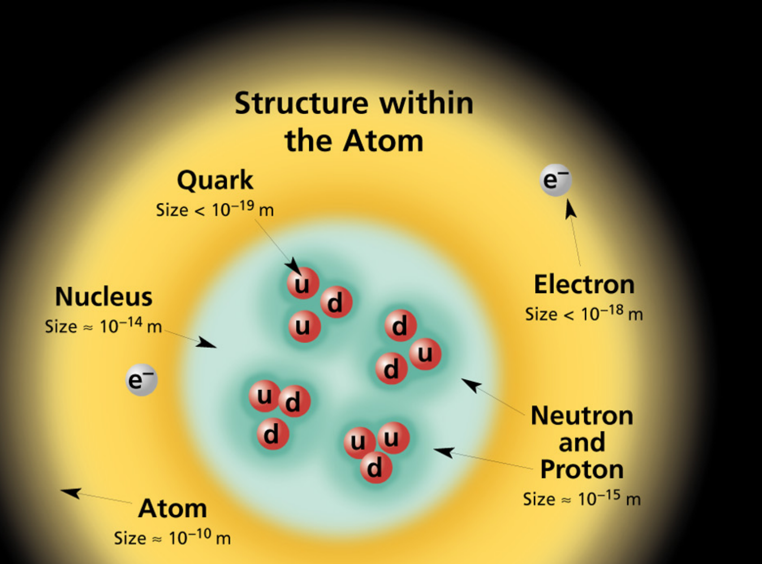
Quarks spin = 1/2

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

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

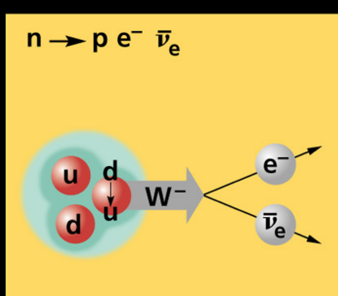
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

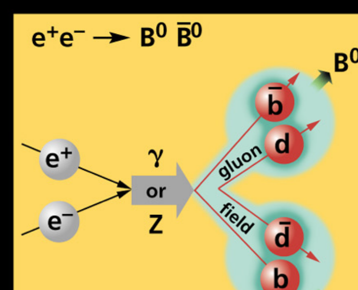
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

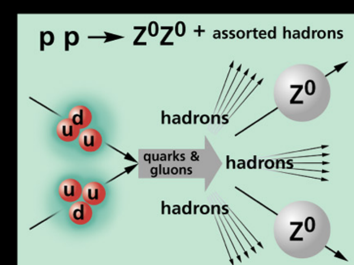
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

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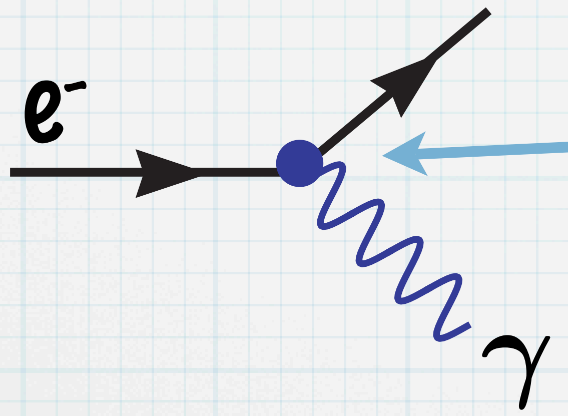
Forces: strong, weak, electromagnetic

... are all just variations on a theme ("gauge theories"*)

*Only freedom is overall charge of particles. The rest is dictated by symmetry (gauge invariance)

(1) Electromagnetism ("QED")



fundamental process: photon emission/ absorption proportional to electric charge

- couples to **electric** charge

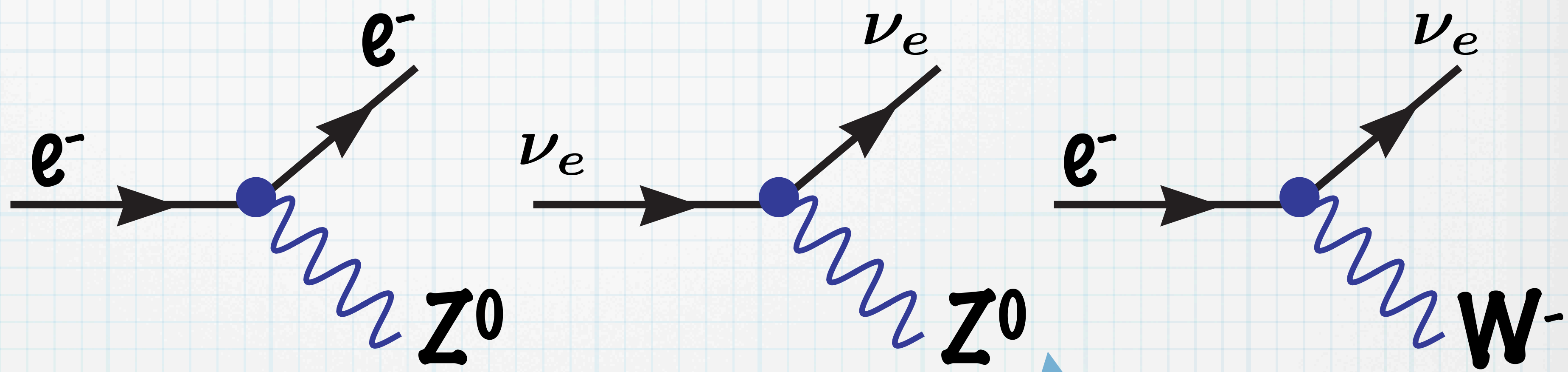
(Feynman, Schwinger, Tomonaga - Nobel Prize, 1965)

Forces: strong, weak, electromagnetic

... are all just variations on a theme ("gauge theories")

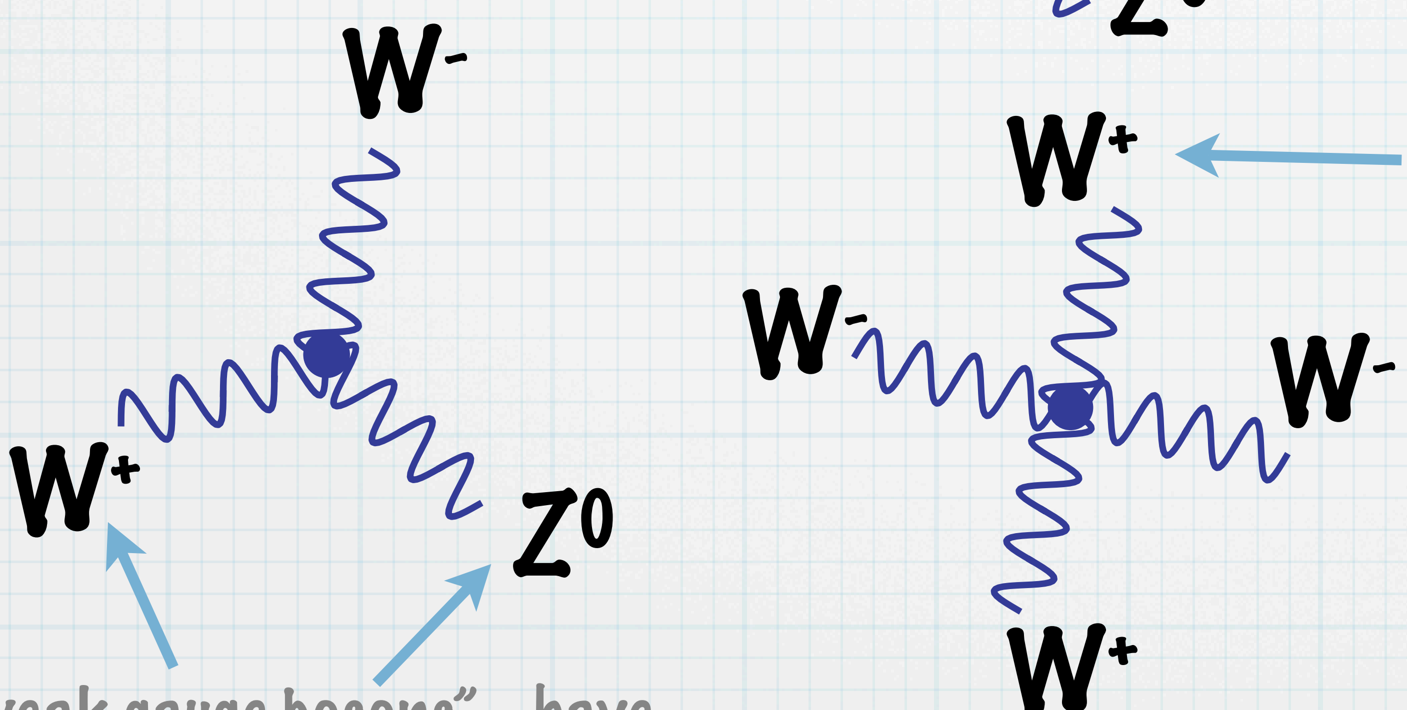
(2) Weak Force

(responsible for beta decay, neutrino interactions, ...)



3 force carriers

+ quarks + ...



"weak gauge bosons" - have SELF-interactions

- couples to "flavour" charge

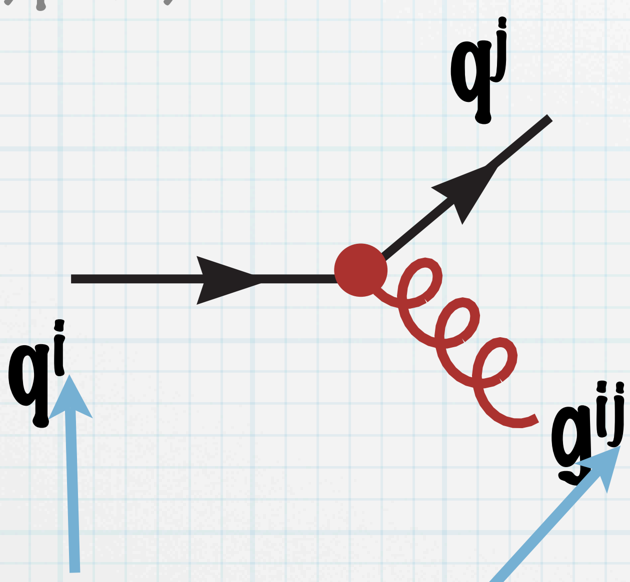
(Glashow, Salam, Weinberg - Nobel Prize, 1979)

Forces: strong, weak, electromagnetic

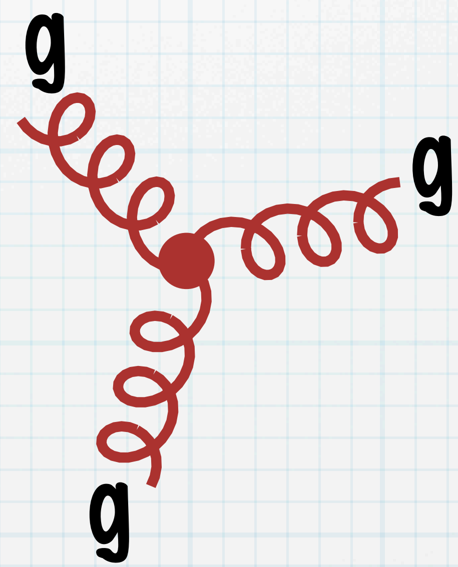
... are all just "variations on a theme"

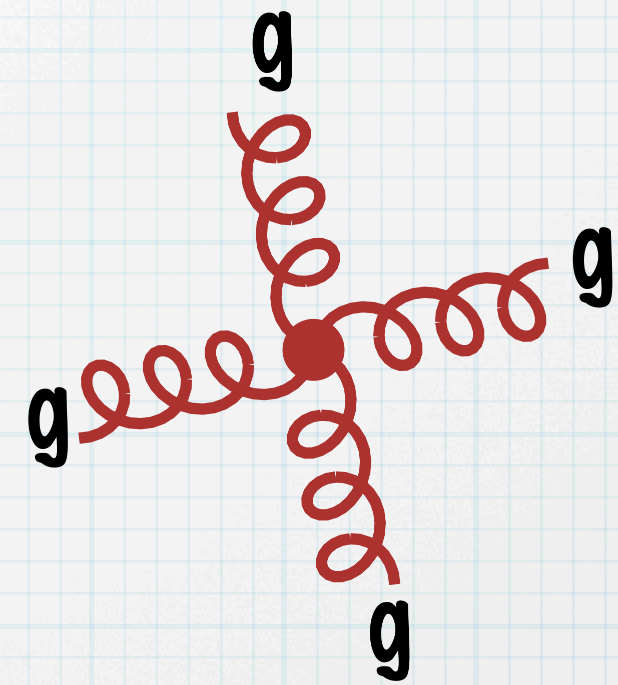
(3) Strong Force ("QCD")

(binds quarks and gluons into composite "hadrons" i.e. proton, neutron, pions, ...)



"colour" of quark/gluon
(just a label)





- couples to "colour" charge

(Gross, Politzer, Wilczek - Nobel Prize, **2004**)

but they don't look ANYTHING alike!

trical interaction that binds electric
viewed as the exchange of mesons

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

10^{-18} m=1/1000 radius of proton

but they don't look ANYTHING alike!

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for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

at distances of 10^{-18} m, the weak and electromagnetic forces are essentially the same strength

but they don't look ANYTHING alike!

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but at a distance 30 × greater, the weak force is 4 orders of magnitude weaker!

but they don't look ANYTHING alike!

trical interaction that binds electric
viewed as the exchange of mesons

PROPERTIES OF THE INTERACTIONS

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at distances of 10^{-18} m, the strong force is
25 × stronger than electromagnetism

but they don't look ANYTHING alike!

trical interaction that binds electri
viewed as the exchange of mesons

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
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for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

but at a distance 30 × greater, the strong force is 60 × stronger!

but they don't look ANYTHING alike!

trical interaction that binds electric
viewed as the exchange of mesons

PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
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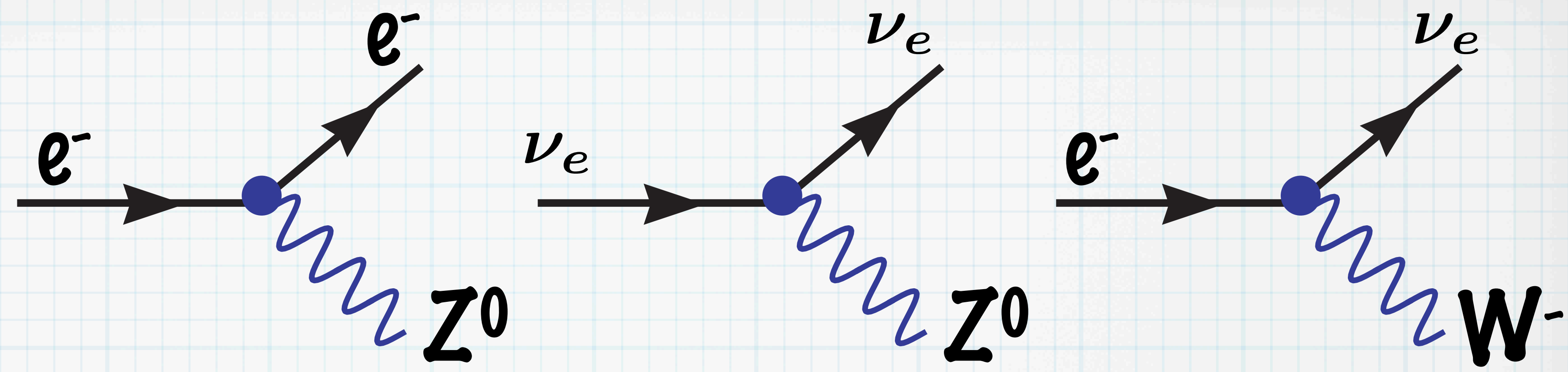
SOLUTION: the differences arise from the properties of the **Vacuum**!

(This is why you get a Nobel Prize for showing they are variations on a theme ...)

The Weak Force



Gauge Invariance makes several unambiguous predictions:

$$m_{Z^0} = m_{W^\pm} = 0 \qquad m_{\text{quarks}} = m_{\text{leptons}} = 0$$

Experiment:

$$m_{Z^0} = 91.2 \text{ GeV} \qquad m_{W^\pm} = 80.4 \text{ GeV}$$

quarks: from 5 MeV to 150 GeV
leptons: from ~0 to 1.5 GeV
(1 GeV=10^3 MeV≈mass of proton)

the Weak force is weak because virtual W's and Z's can only propagate ~ $\hbar/mc$ ~ 10^{-18} m (by the uncertainty principle)

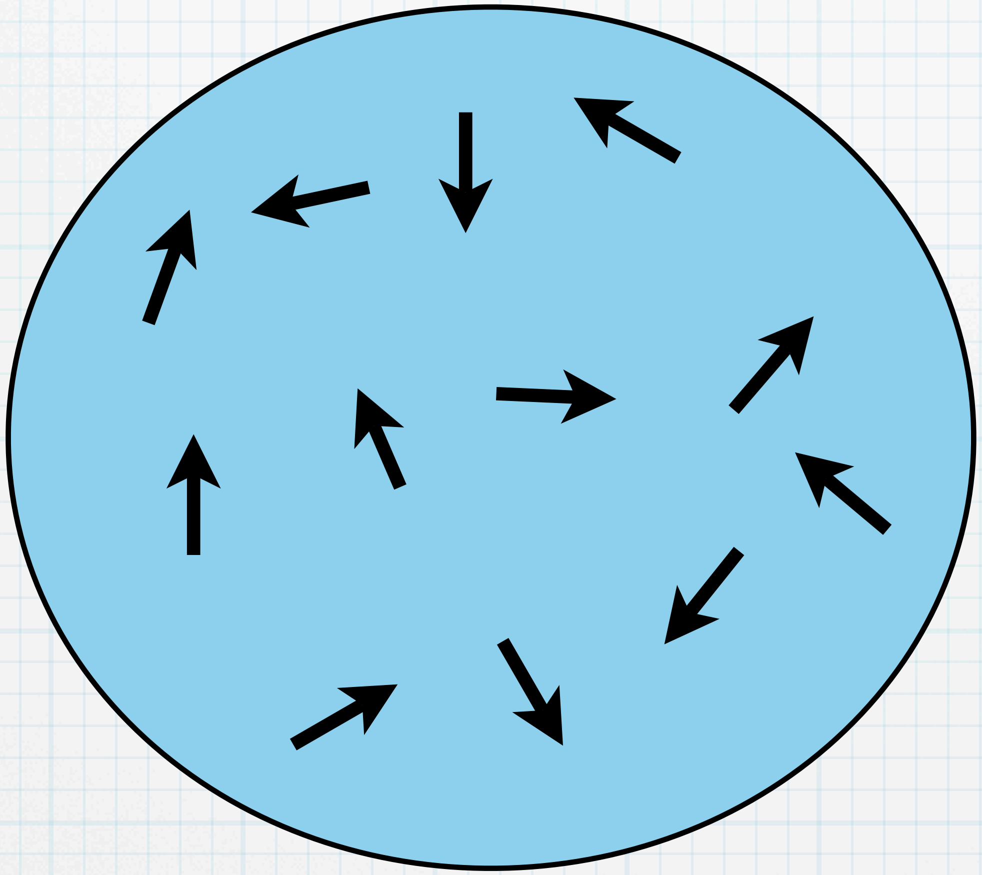
LOOPHOLE: This only holds if the Vacuum is EMPTY

this sort of thing is seen all the time in condensed matter physics ...

"Spontaneous Symmetry Breaking"

- the ground state of a material can be less symmetric than the corresponding laws of physics

ex: ferromagnet



$T > T_c$

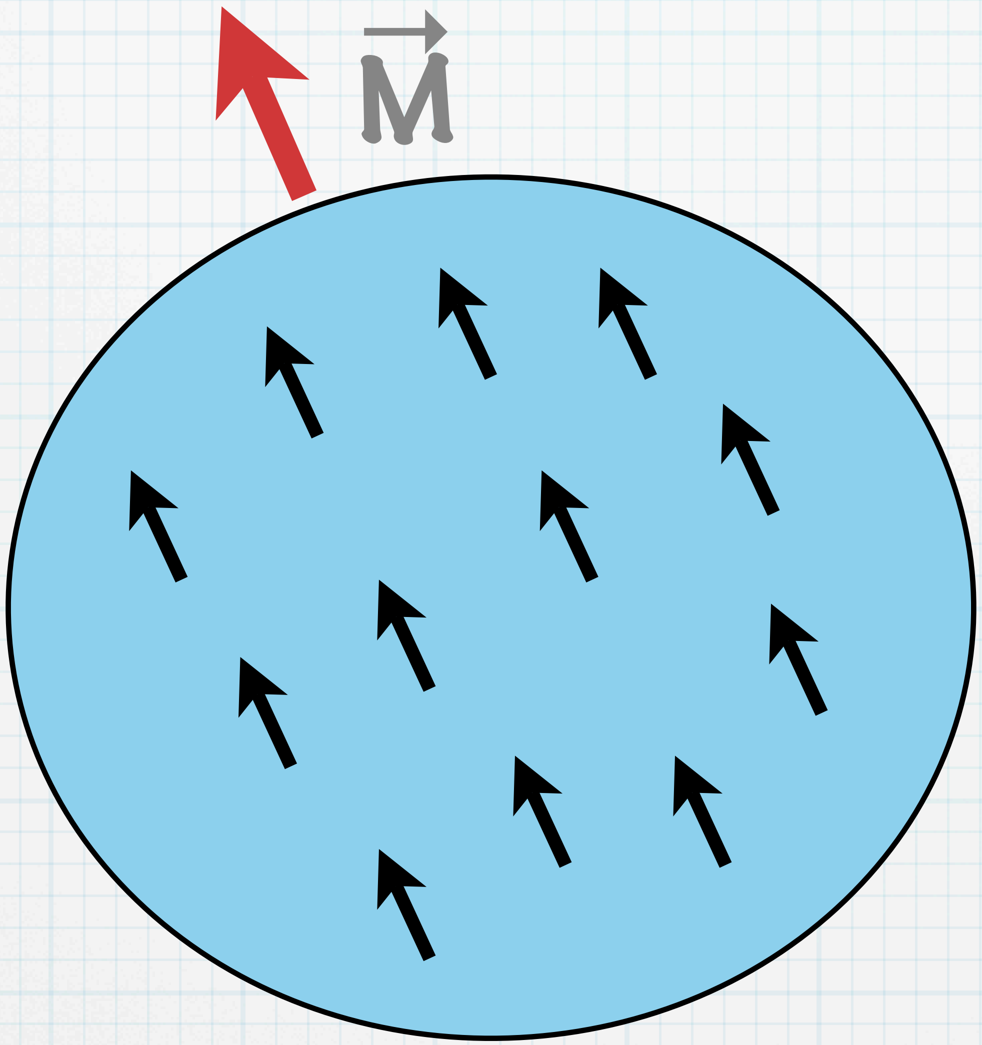
- spins aligned randomly; no net magnetization

- ground state is rotationally invariant

"Spontaneous Symmetry Breaking"

- the ground state of a material can be less symmetric than the corresponding laws of physics

ex: ferromagnet

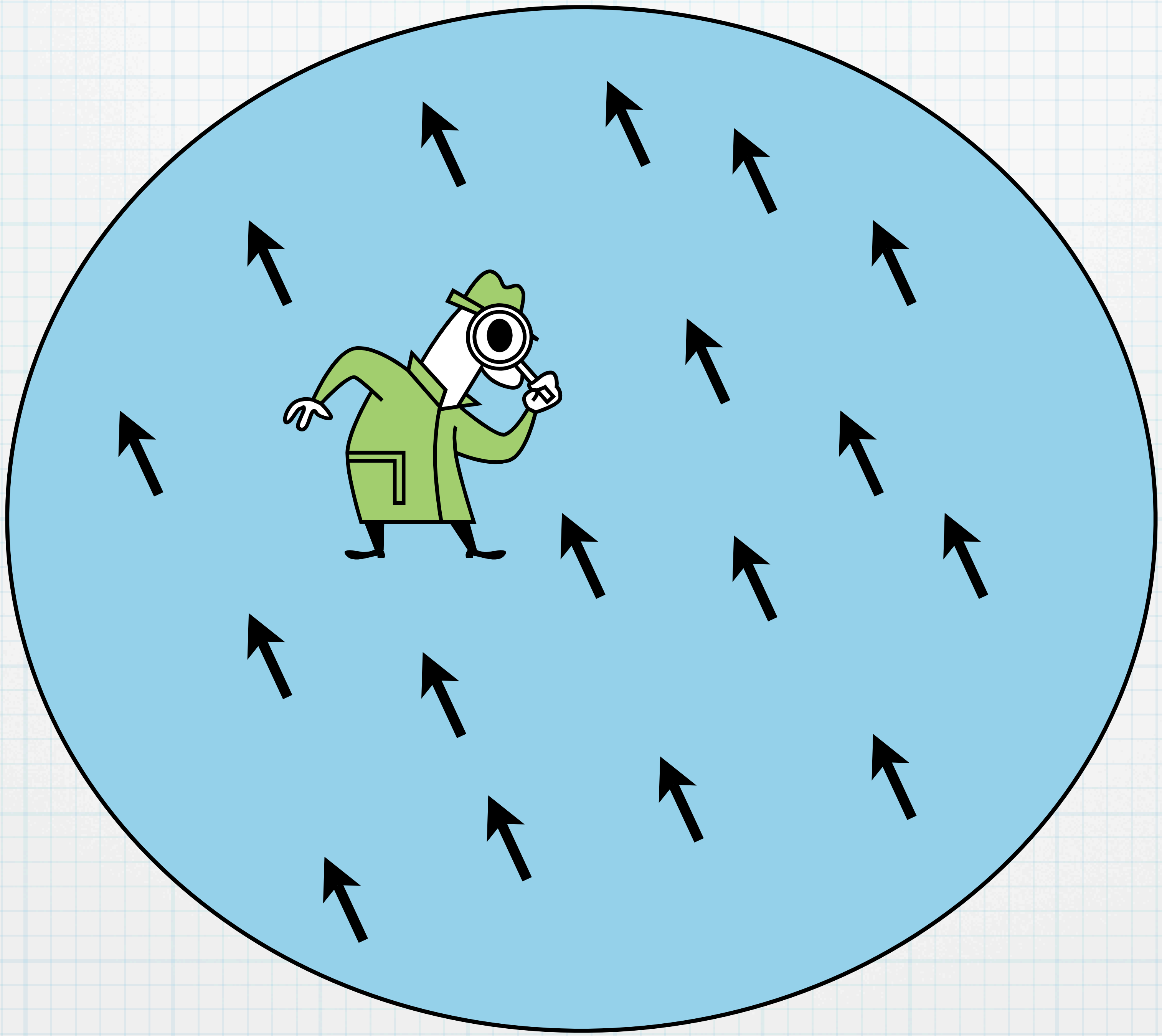


$T < T_c$

- spins aligned along a single (arbitrary) direction - net magnetization

- ground state is NOT rotationally invariant

... and a physicist living in the ferromagnet would have no idea that the laws of Nature were rotationally invariant.



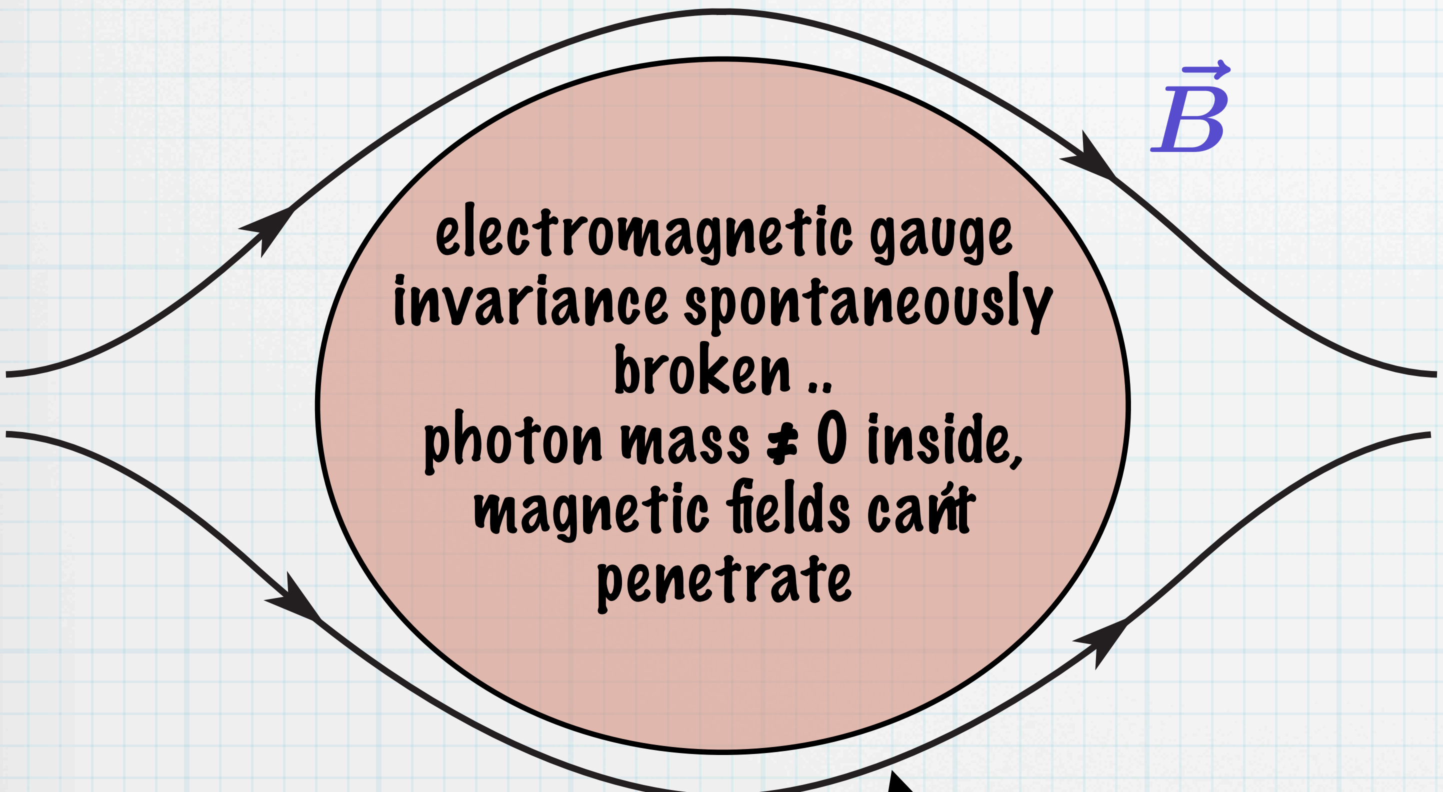
rotational invariance is said to be "spontaneously broken" in a ferromagnet

Superconductor (a theorists' definition): a material in which electromagnetic gauge invariance is spontaneously broken

$$\psi \to e^{i\theta(x)}\psi$$

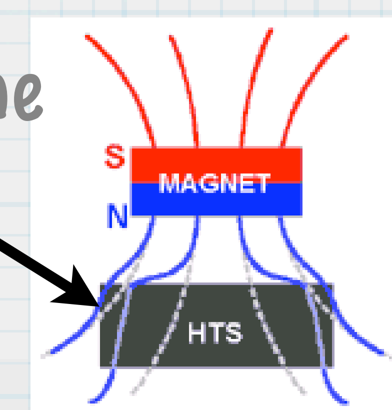
$$A_\mu \to A_\mu - ie\partial_\mu\theta(x)$$

electromagnetic gauge invariance⇔massless photon



Meissner Effect

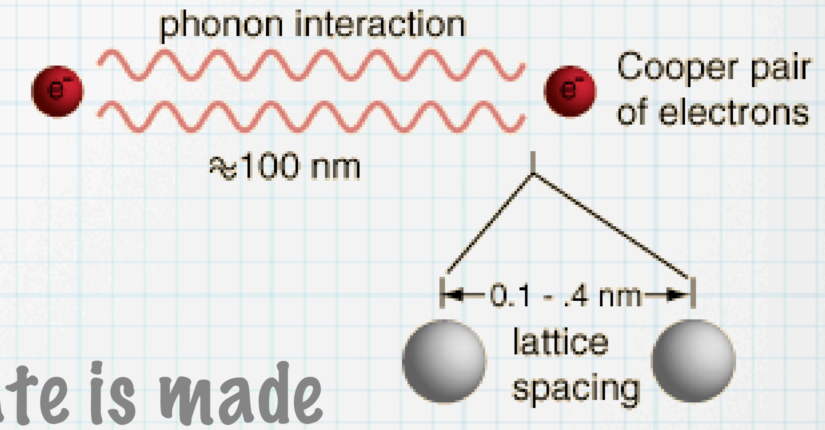
magnetic fields cannot penetrate the superconductor!



Claim: the weak force is weak because the Vacuum is in a **superconducting** phase! (with $T_c \sim 10^{16}$ K)

Why is the Universe a giant superconductor?

BCS Theory: condensate of Cooper pairs in a superconductor breaks EM gauge invariance, gives photon a mass (complicated, dynamical)



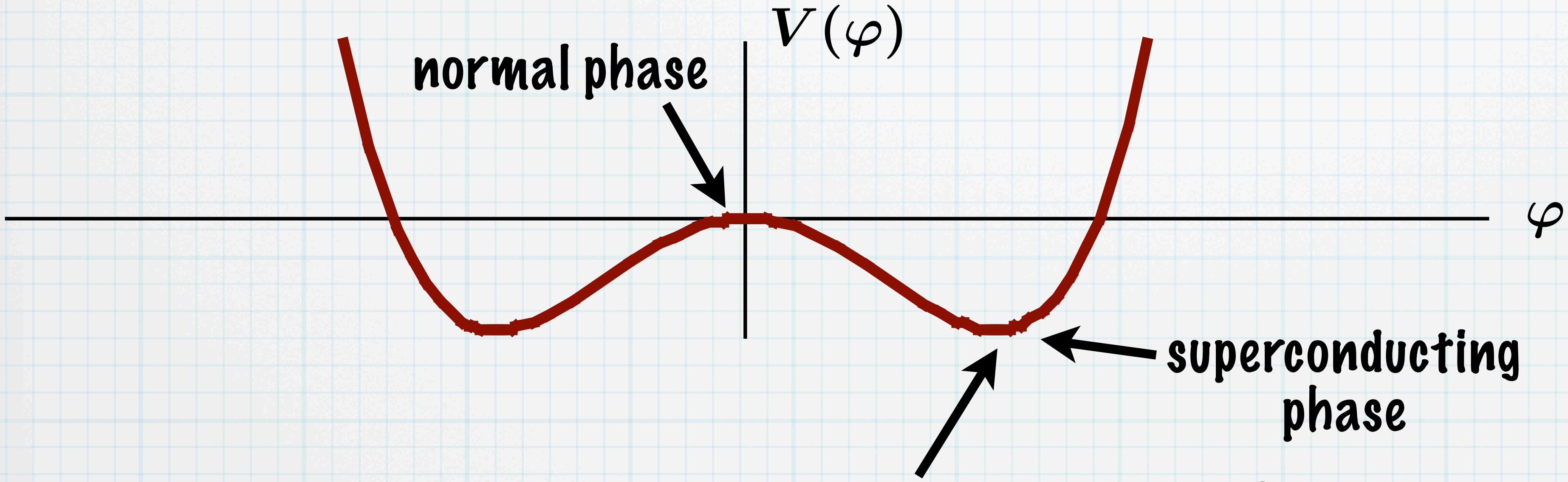
Weak interactions: we have no clue what the condensate is made of ... presumably the mechanism is something equally complicated and dynamical. BUT ...

(1) low energy (<100 GeV) physics is almost independent of the details (universality) - so it's hard to find!

(2) quantized excitations of the condensate MUST show up at the few × 100 GeV scale ("unitarity") - this is the energy scale we are currently probing at accelerators!

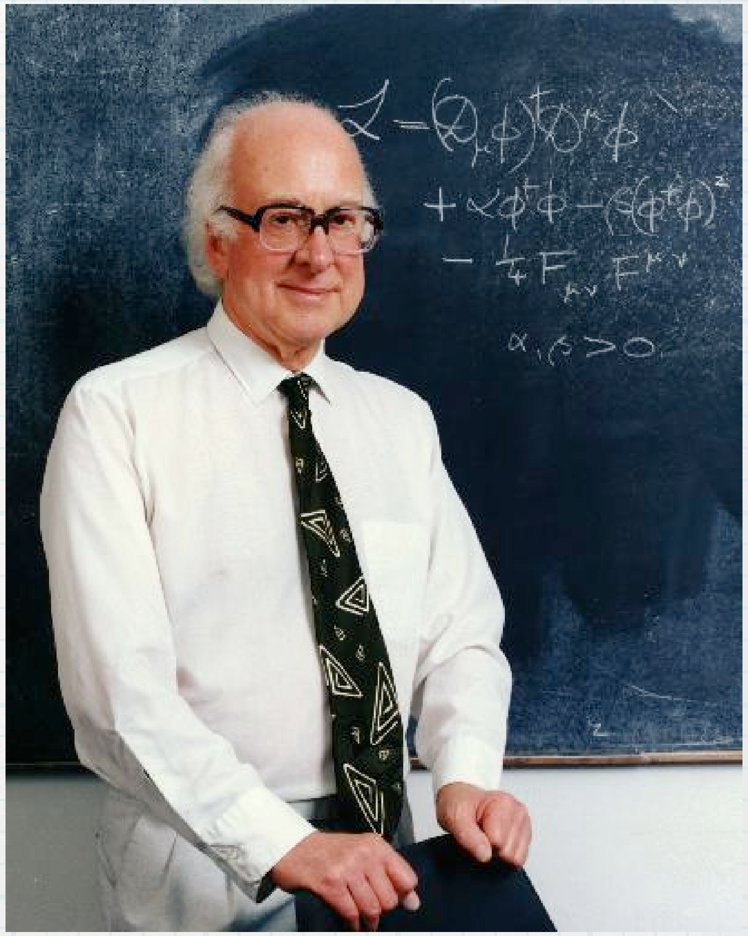
Why is the Universe a giant superconductor?

Standard Model (Weinberg, Salam): "Higgs Field" condenses in Vacuum (simplest possible mechanism - like Landau-Ginsberg theory) ... put in by hand



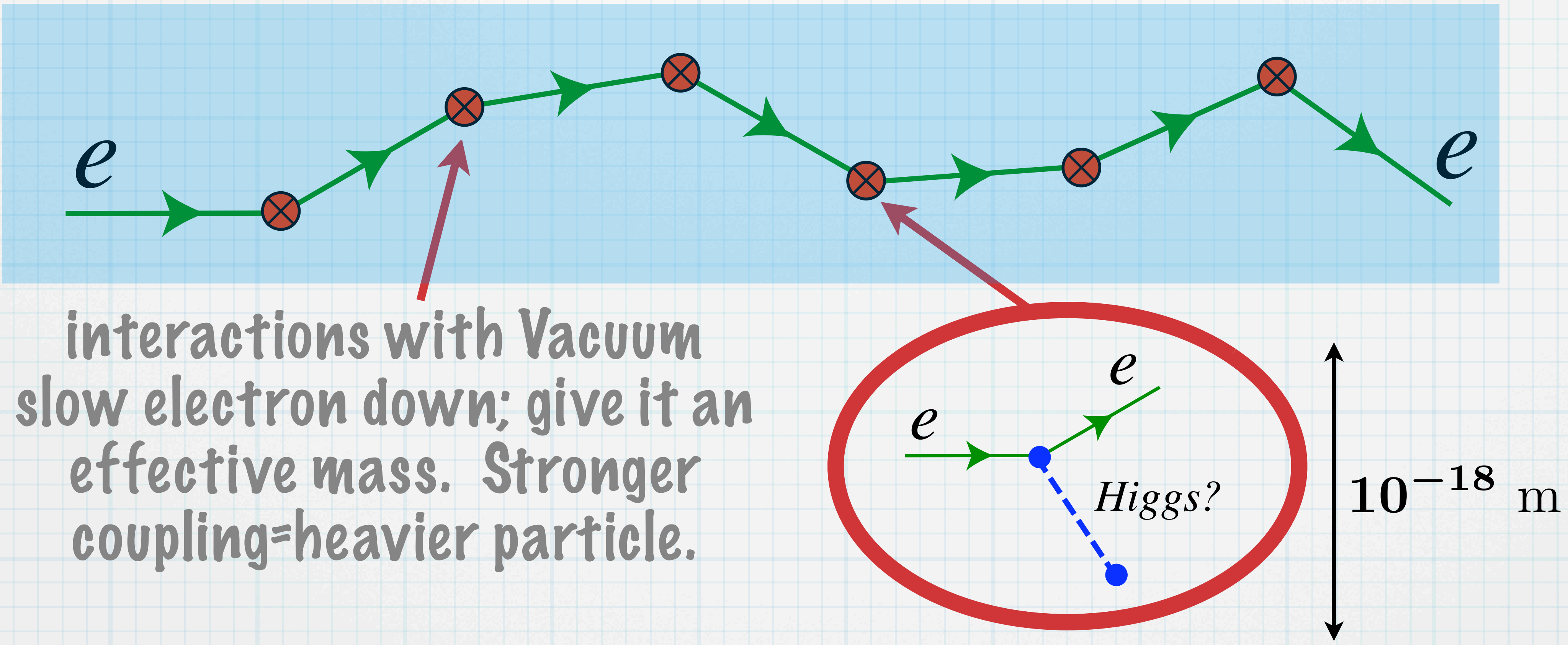
Quantized excitations about the minimum ≡ "Higgs boson"

- new particle with mass in the 100 GeV range, signature of symmetry breaking



Peter Higgs

The masses of the quarks and leptons are also determined by the strength of their interactions with the Vacuum:



interactions with Vacuum slow electron down; give it an effective mass. Stronger coupling=heavier particle.

10^{-18} m $\Leftrightarrow$ 200 GeV

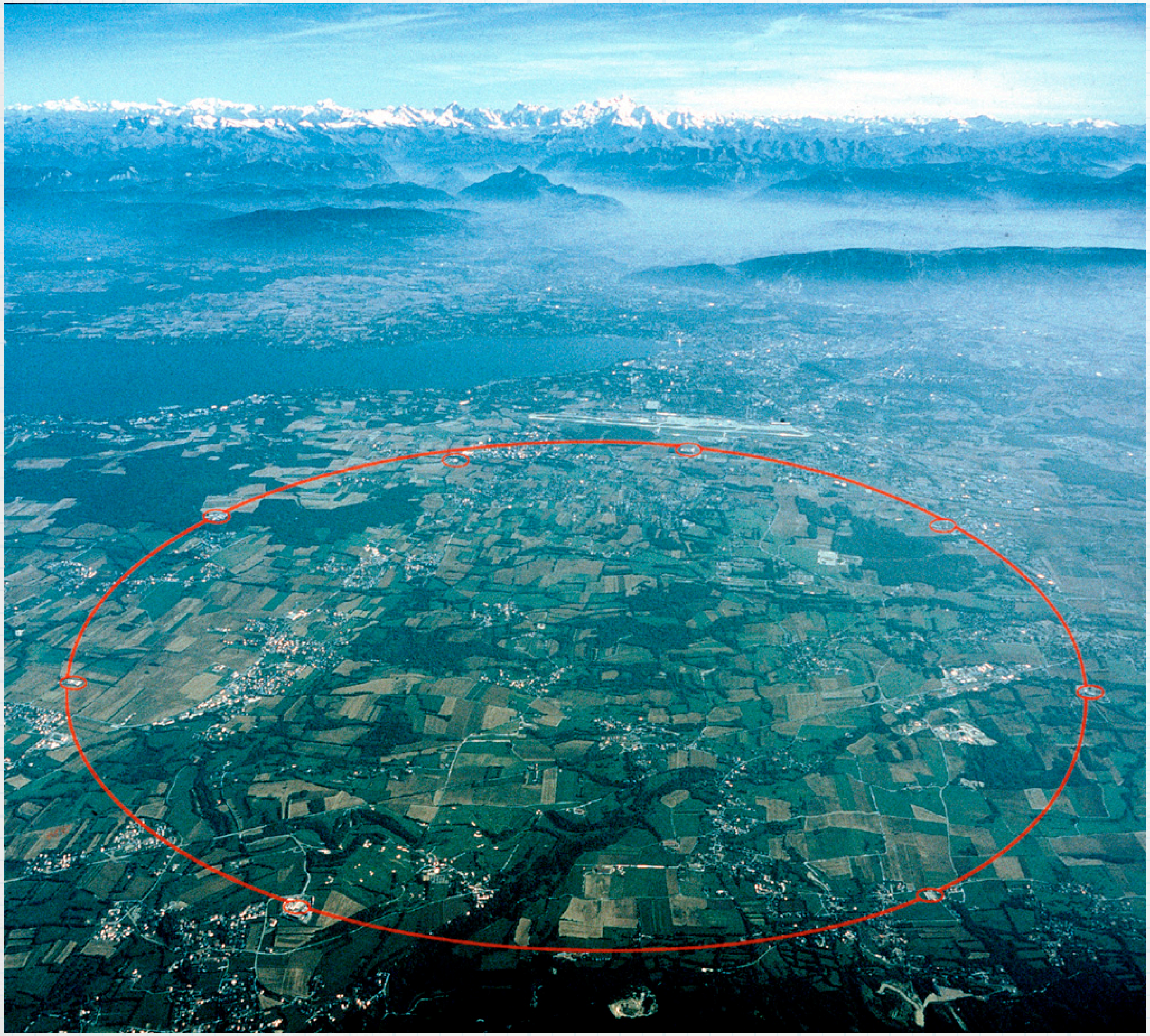
(10^{-3} $\times$ radius of proton)

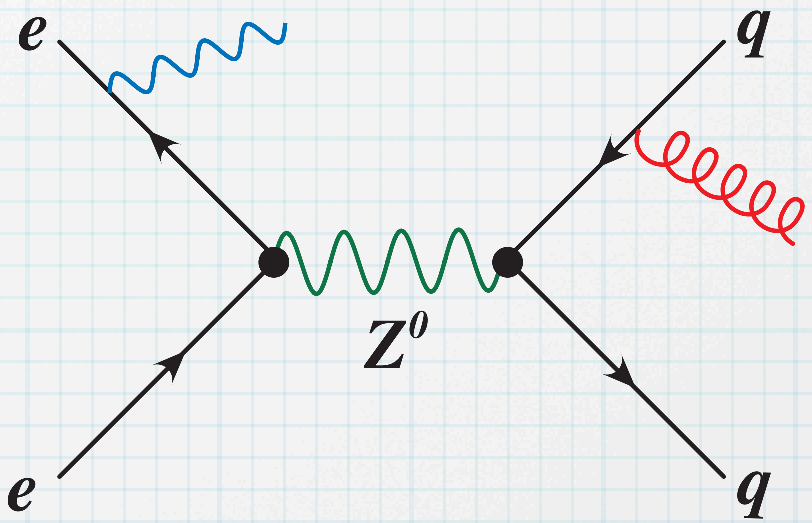
- physics changes qualitatively at this scale

- weak force is no longer weaker than electromagnetism
- Vacuum undergoes superconducting phase transition

To study physics at this distance scale, need to scatter particles at the corresponding energy ...

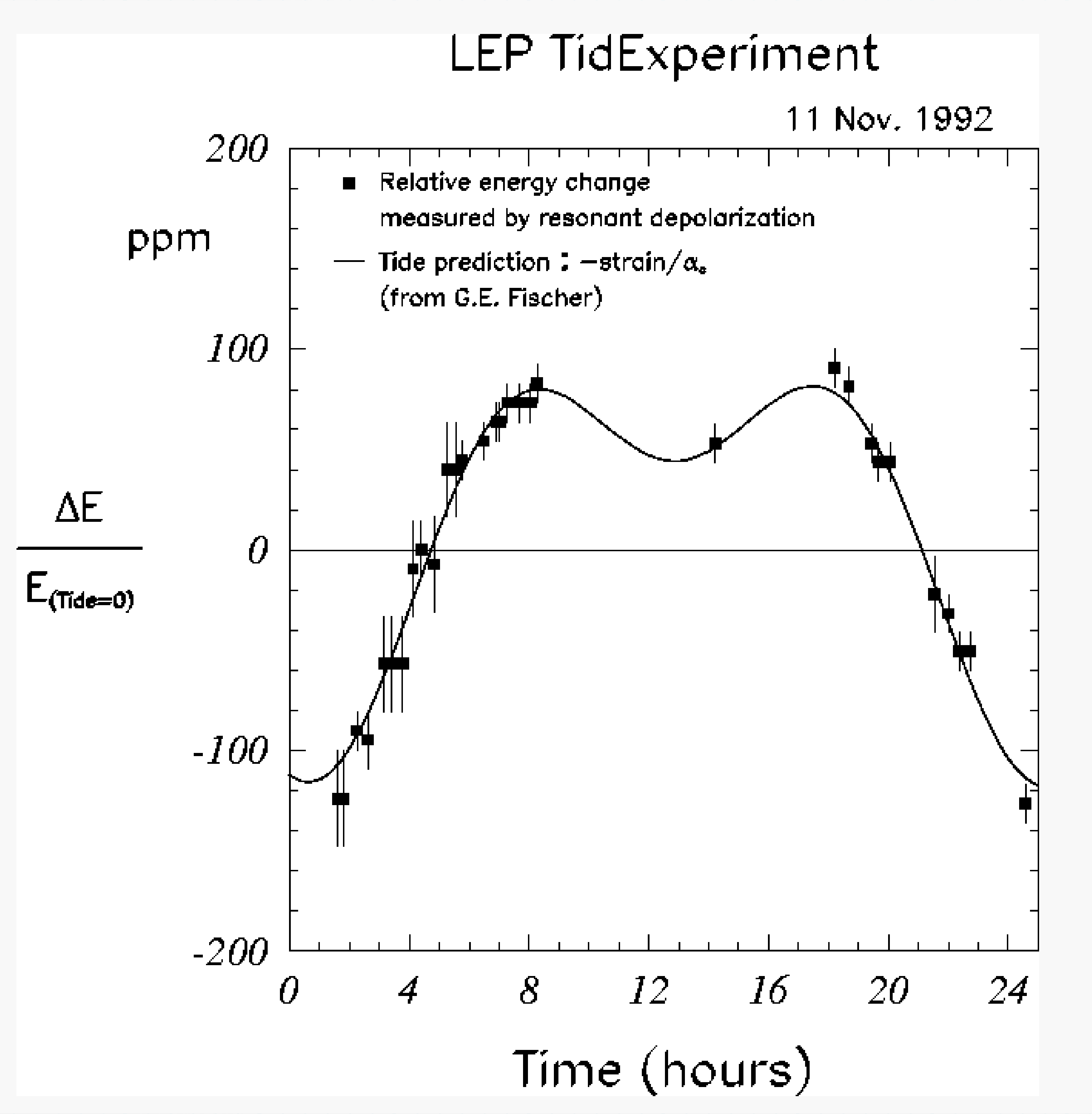
LEP (1989-1999) - electron-positron collider at 90 GeV c.o.m. energy (later up to 200 GeV)





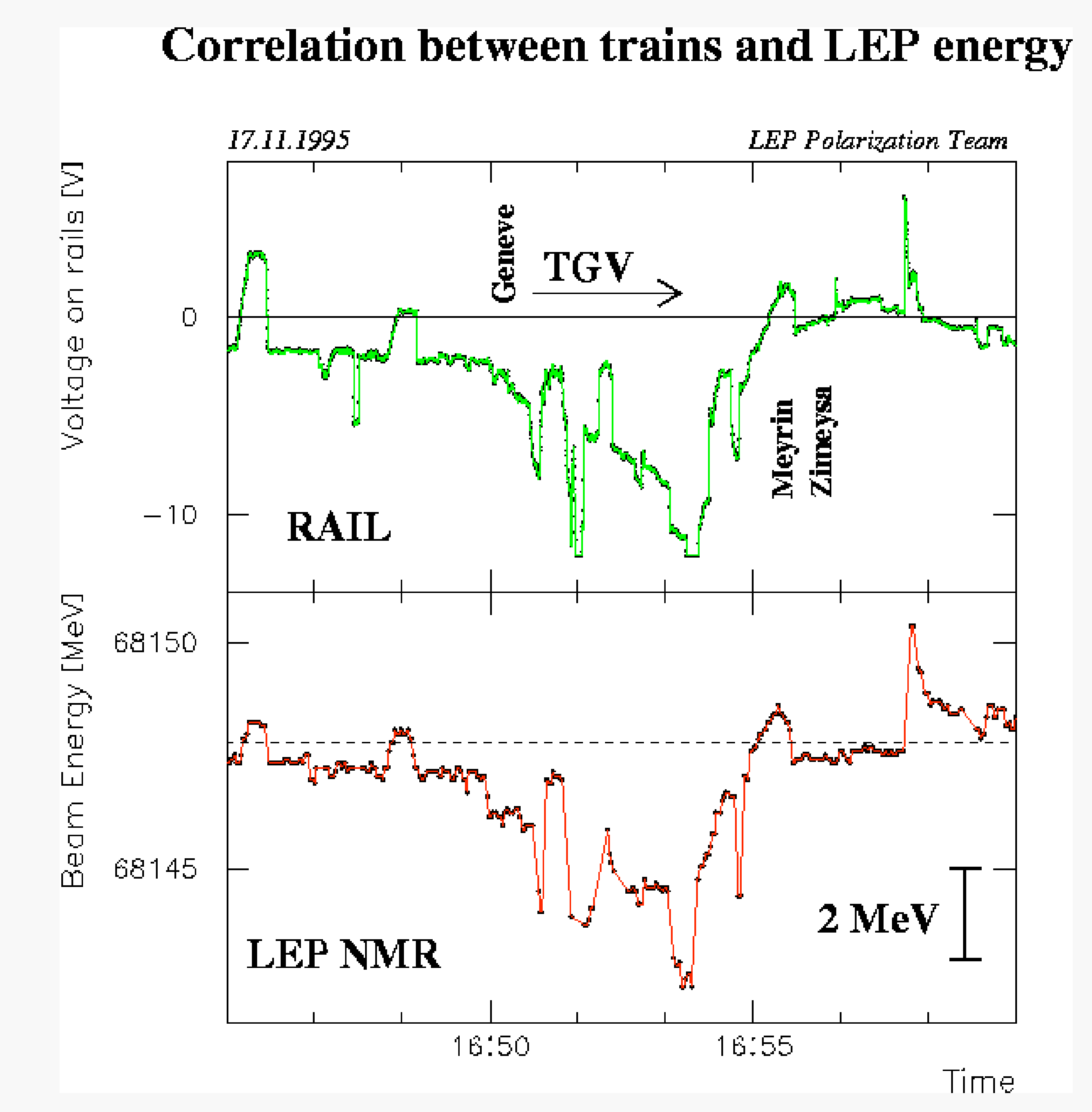
a "Z^0 factory"

The LEP experiment was phenomenally precise ...



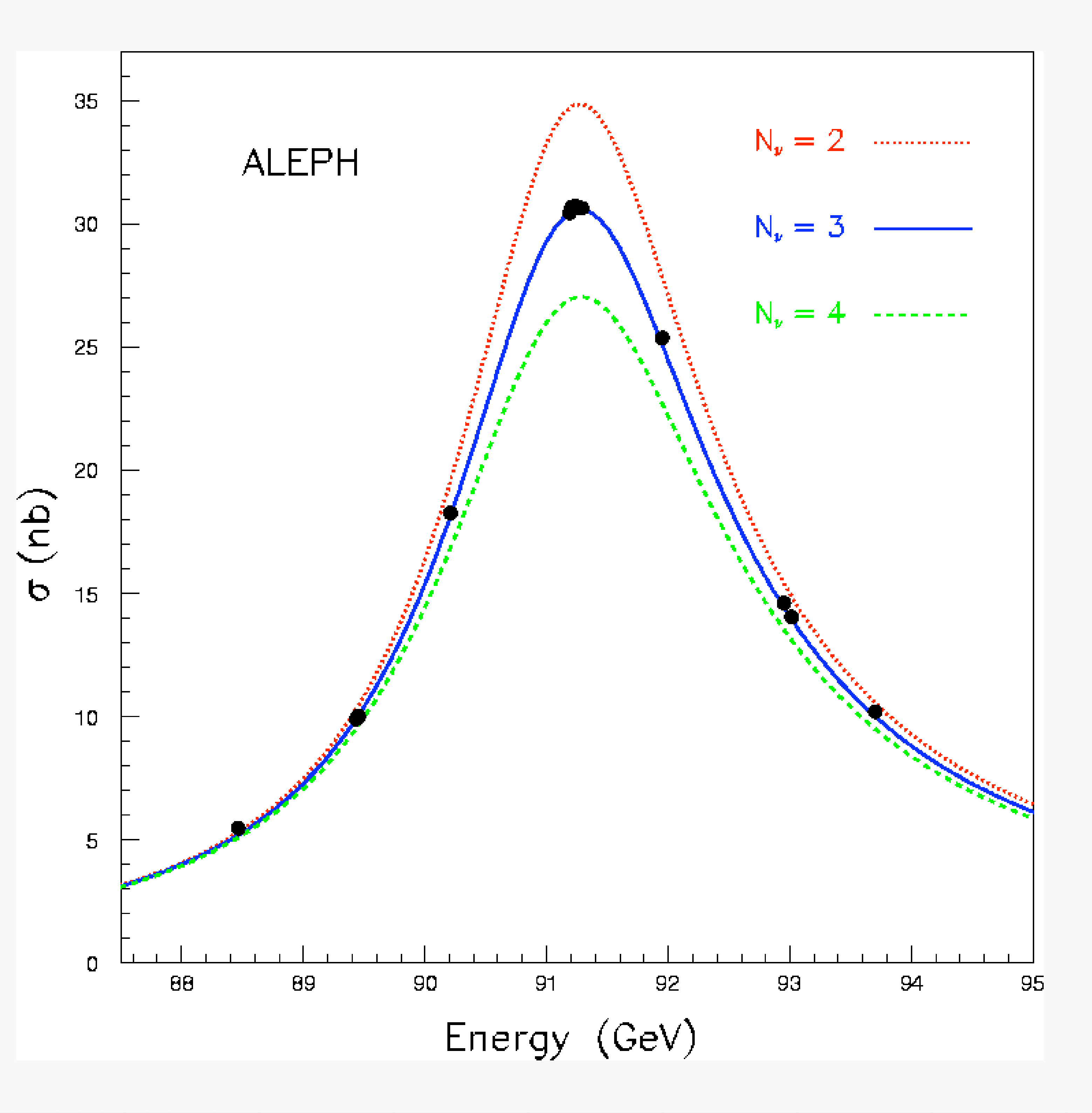
LEP discovered the moon ...

The LEP experiment was phenomenally precise ...

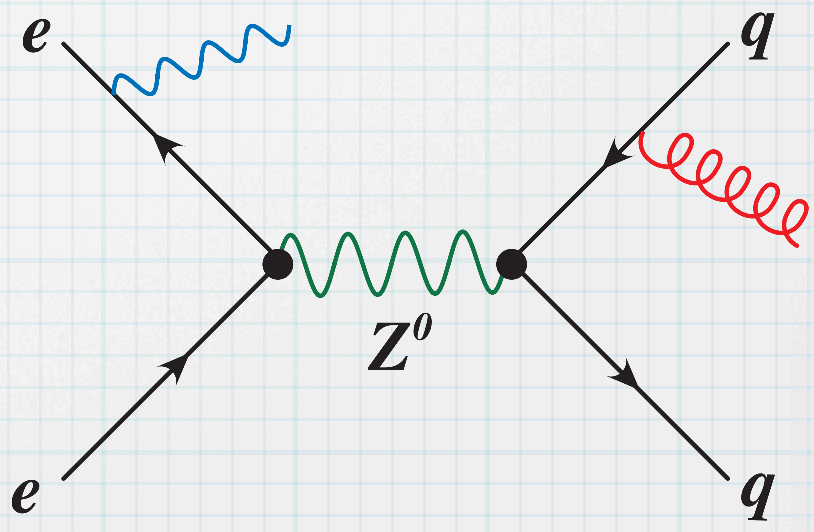


... and measured the TGV schedule ...

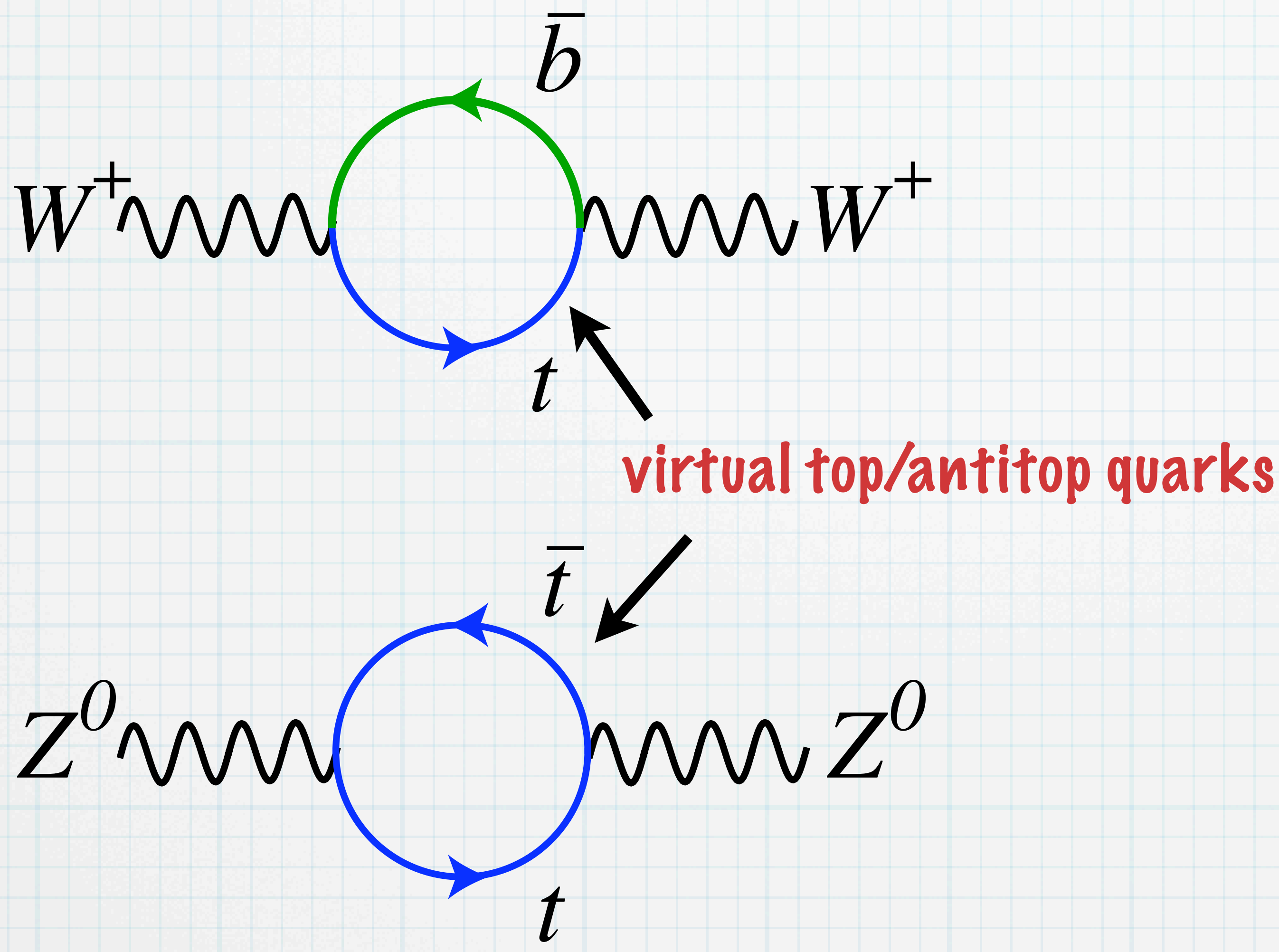
The LEP experiment was phenomenally precise ...



... and the number of neutrino species ...



The LEP experiment was phenomenally precise ...



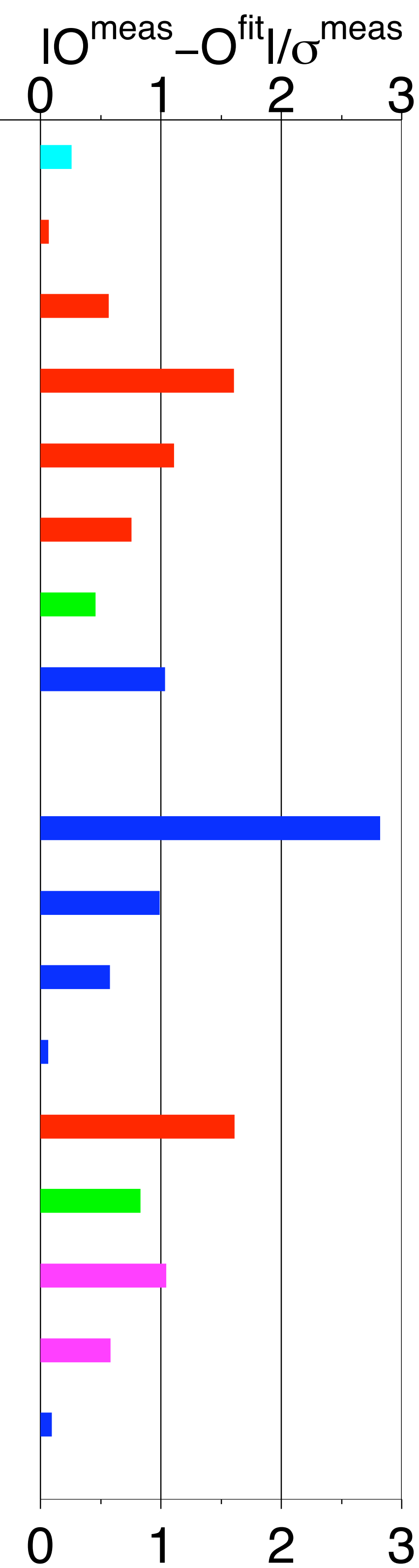
... and measured the mass of the top quark VIRTUALLY before the top quark was discovered! (in 1995) ...

1994: $m_{\rm top} = 169^{+16\ +17}_{-18\ -20}$ GeV (indirect)

2004: $m_{\rm top} = 174.3 \pm 5.1$ GeV (direct)

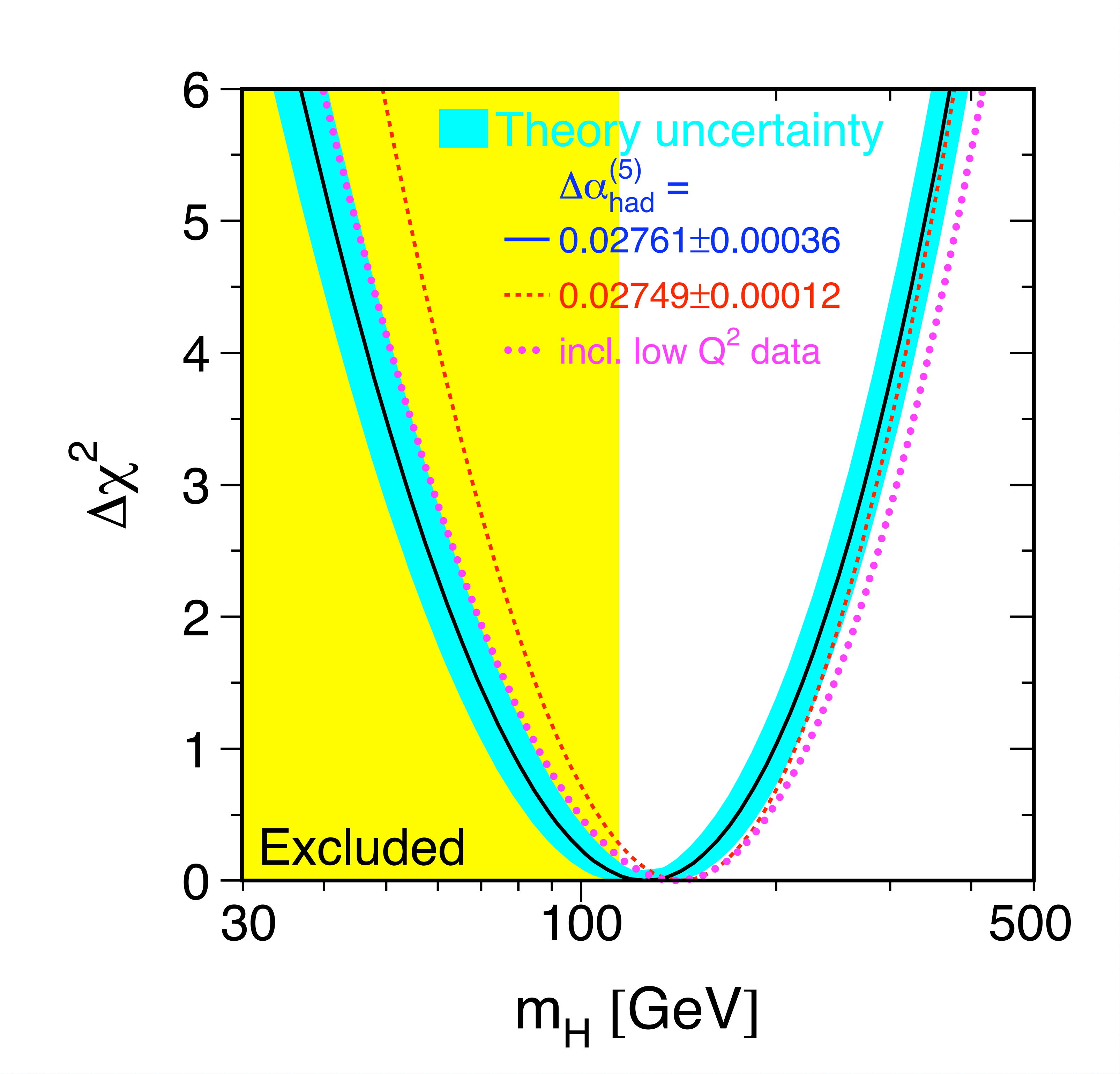
... and tested the gauge theory of Glashow, Weinberg and Salam to unprecedented precision:

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02770
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.390
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.4



but didn't find the source of symmetry breaking.

IF the simple Higgs model is correct, it looks like they just missed it:

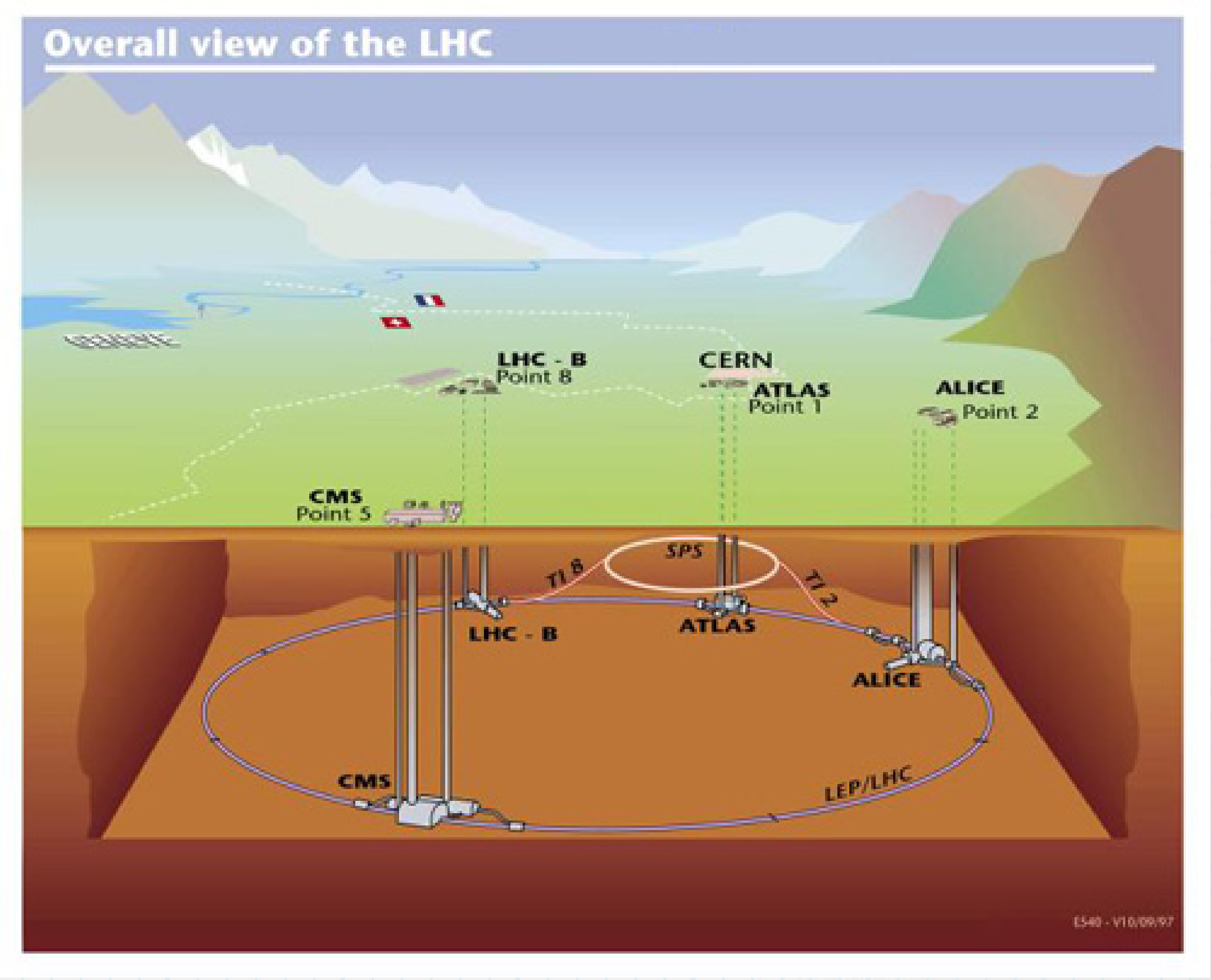


The Energy Frontier: Large Hadron Collider at CERN (LHC)

14000 GeV protons on 14000 GeV protons

1000 GeV=1 TeV = energy of a flying mosquito
(but crammed into a space 10^{12} times smaller)

switches on in 2007 ... has enough energy to tell us what the quantized excitations of the Vacuum are ("no-lose" theorem)



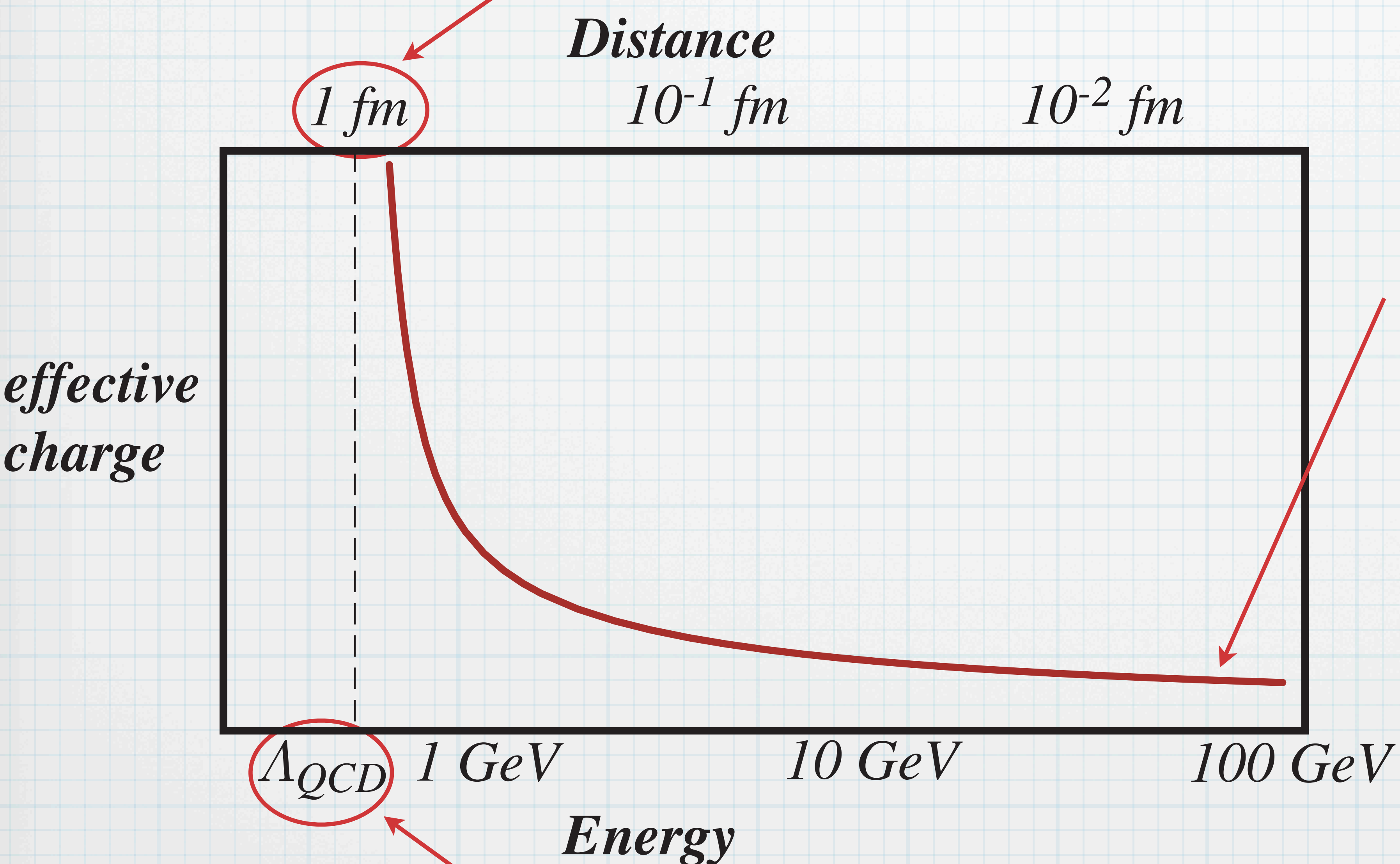
What else does the Vacuum do?

The Vacuum ANTISCREENS the strong interactions ...

virtual gluons counteract effects of quark-antiquark dipoles

(Gross, Politzer, Wilczek - Nobel Prize, 2004)

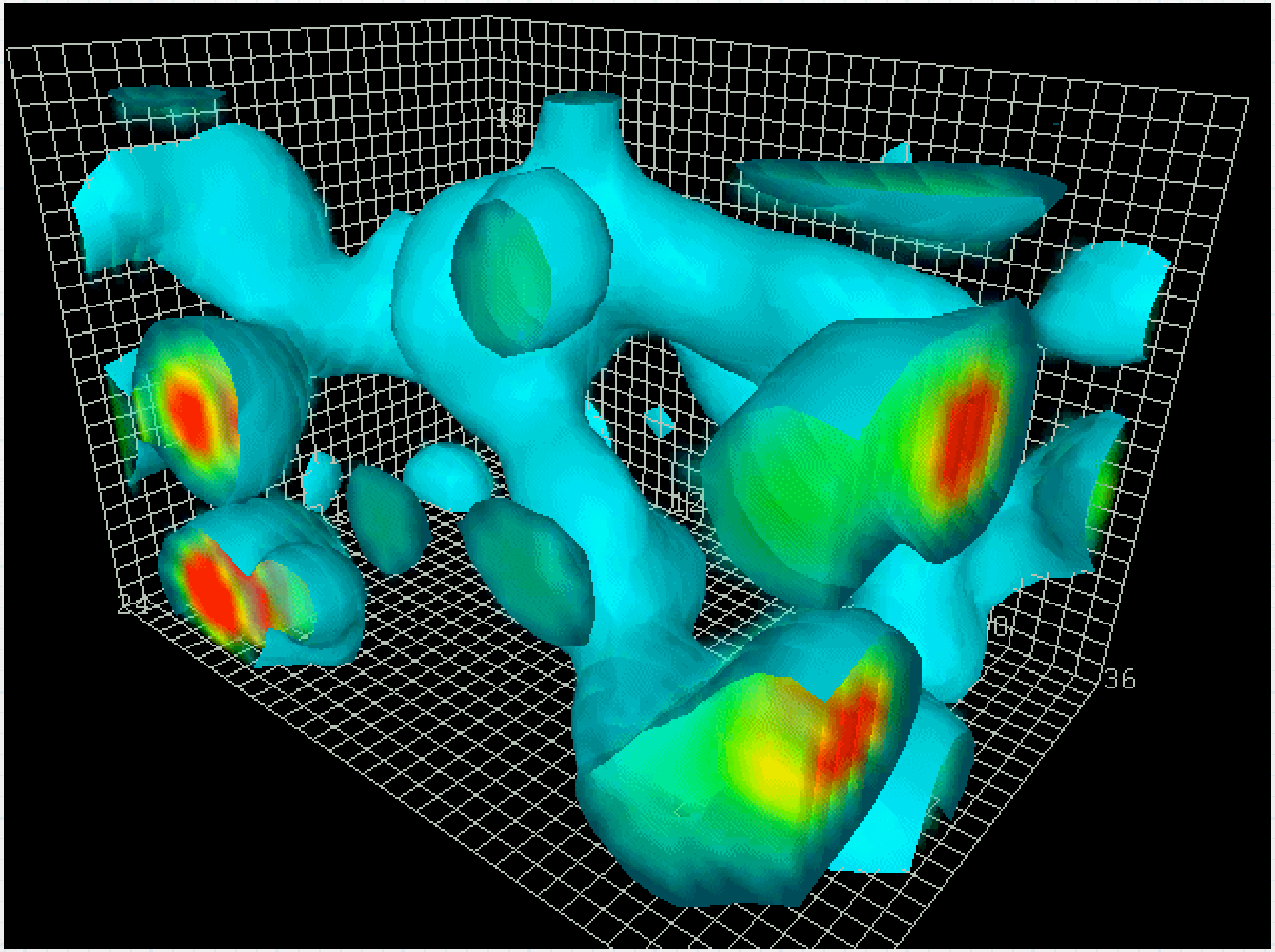
1 fm = 10^{-15} m ~ radius of proton



asymptotic freedom:
effective QCD CHARGE of quarks/gluons under is small at SHORT distances (large energies), large at LONG distances (low energies)

Λ_{QCD} ~300 MeV sets the scale for nonperturbative effects

So at large (O[1 fm]) distances, the QCD Vacuum is a complicated place:

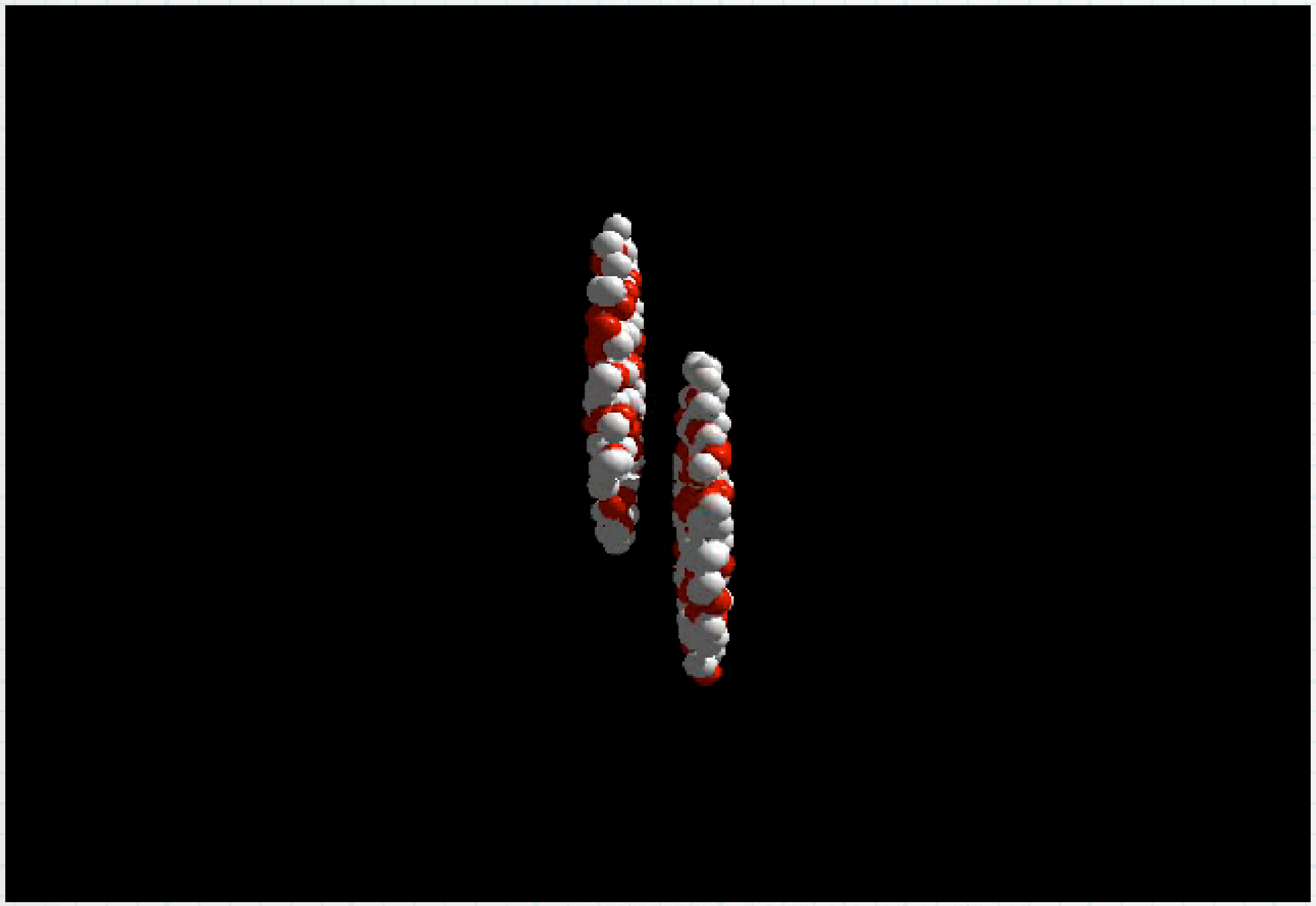


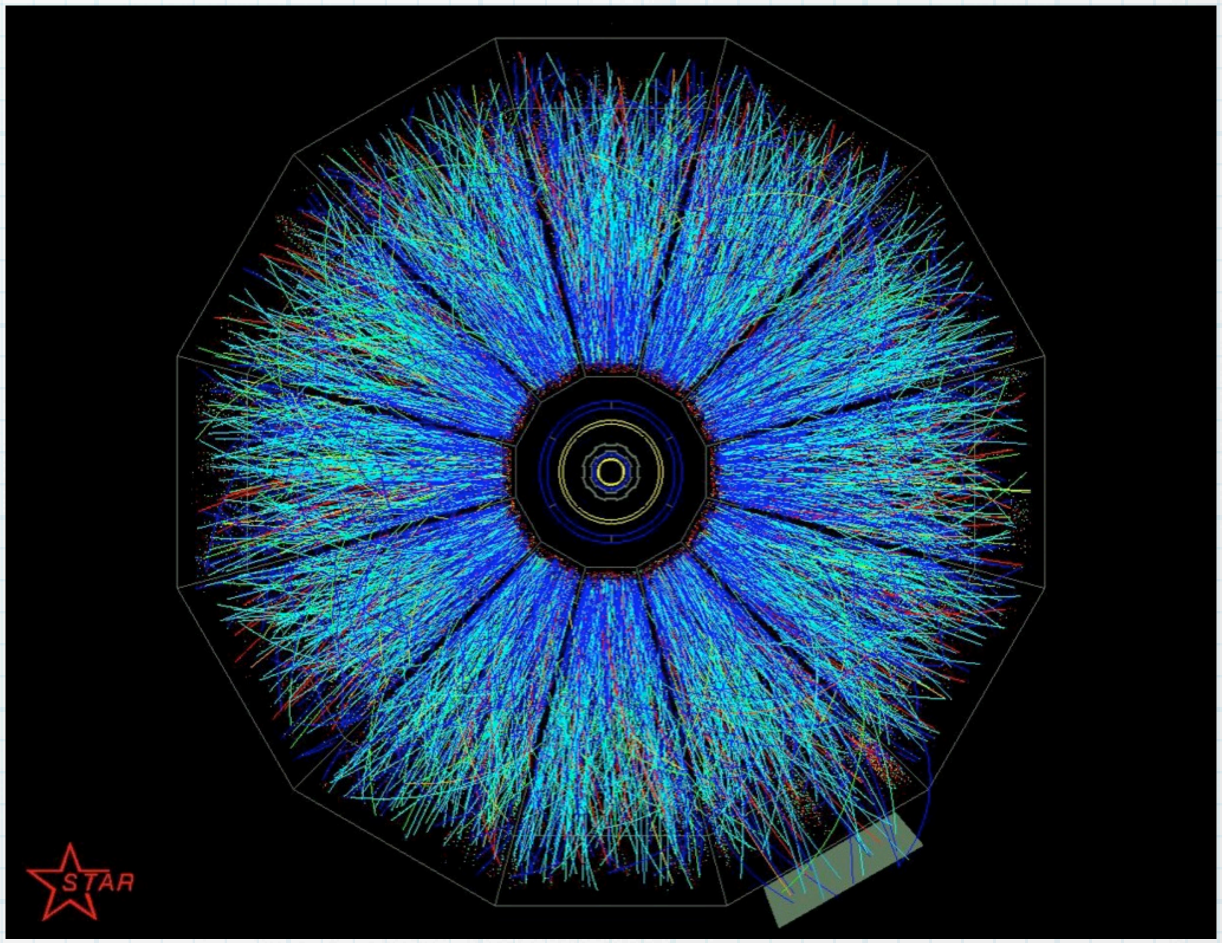
This is "Euclidean time", so you're probably supposed to think of the Vacuum as a superposition of these states...

and it exhibits many of the superconducting properties of the electroweak Vacuum ...

* Condensate consisting of correlated quark-antiquark pairs and gluons forms
* breaks "chiral symmetry" ... condensate sticks to massless quarks to form big fat heavy "constituent" quarks
* this also breaks the weak gauge symmetry! so even if there were no Higgs, the W and Z would be massive. Unfortunately, the mass from the QCD Vacuum is two orders of magnitude too small. But it's an existence proof that complicated dynamics naturally break gauge symmetries. (Not "put in by hand" like the Higgs)

RHIC ("Relativistic Heavy Ion Collider") at Brookhaven is trying to melt the QCD Vacuum by colliding gold nuclei, heating the system to 10^{12} K



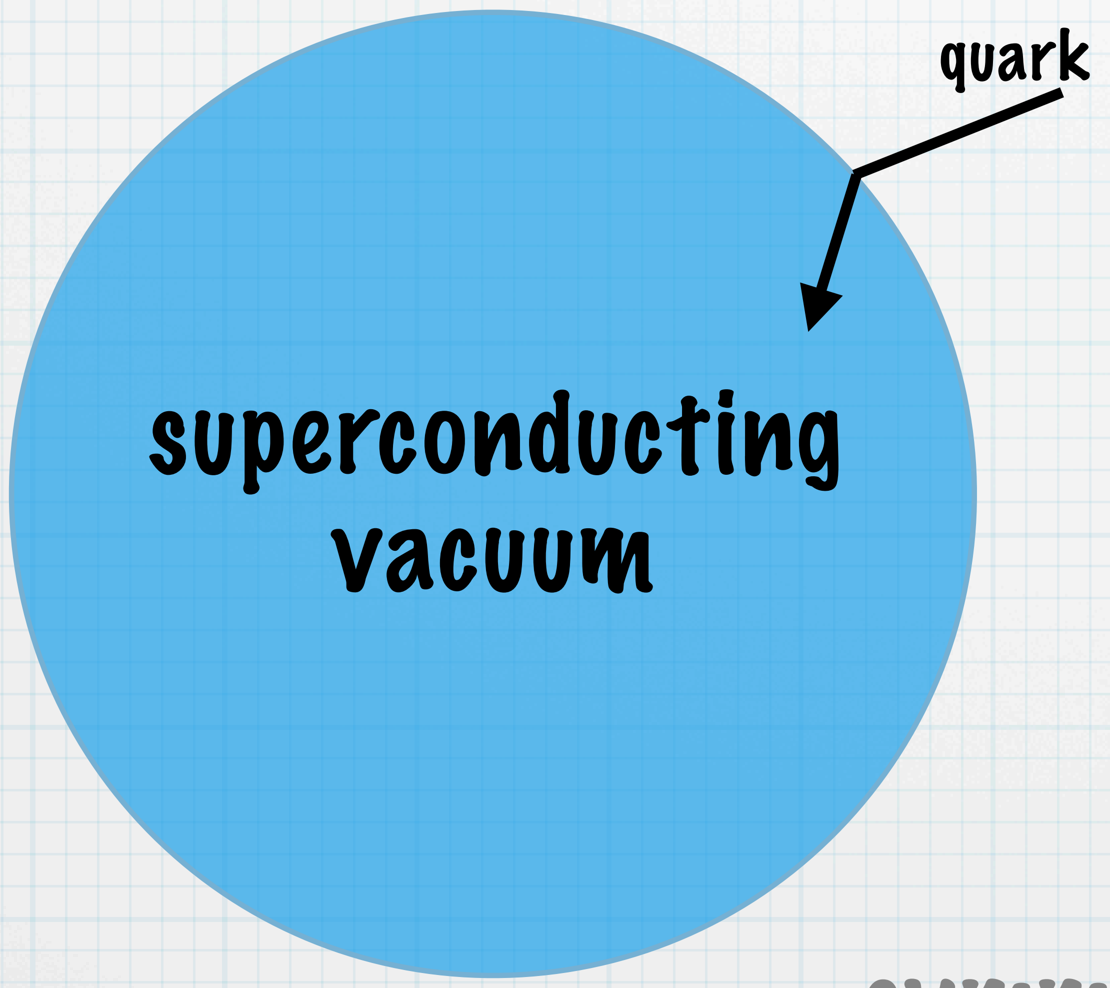


high temperature phase: chiral symmetry restoration, deconfining ... conditions of early Universe a few microseconds after Big Bang

At higher Temperatures (10^{16} K) the Higgs (or whatever) condensate melts ...

Early Universe: at $T>10^{16}$ K (10^{-11} s after Big Bang) the Universe was in a symmetric (nonsuperconducting) phase ... weak and electromagnetic forces were UNIFIED

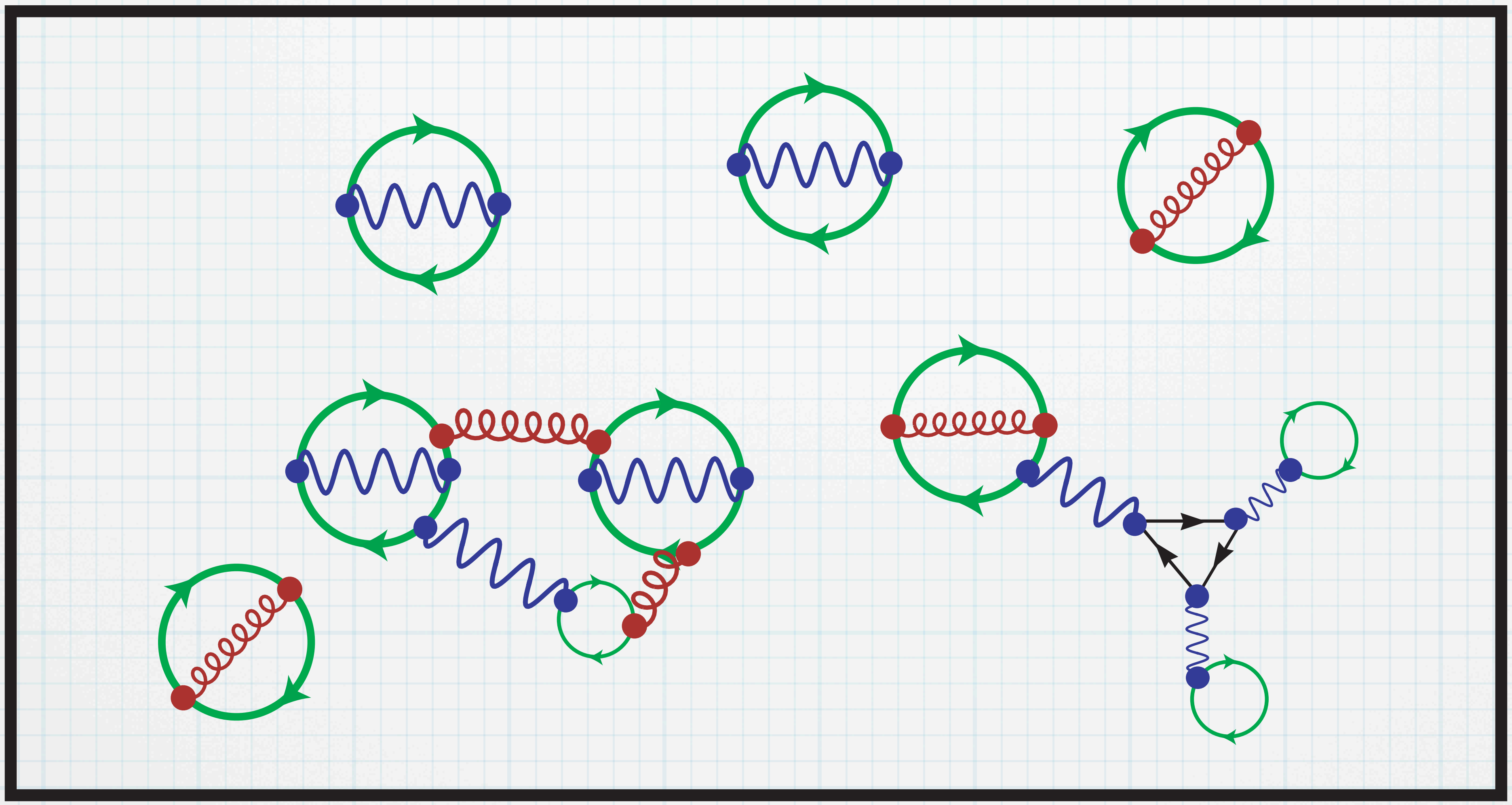
... as the Universe cooled, bubbles of broken phase formed and expanded ...



and particles scattering off the bubble walls are believed to have created the matter-antimatter asymmetry we observe in the Universe today.

symmetric vacuum

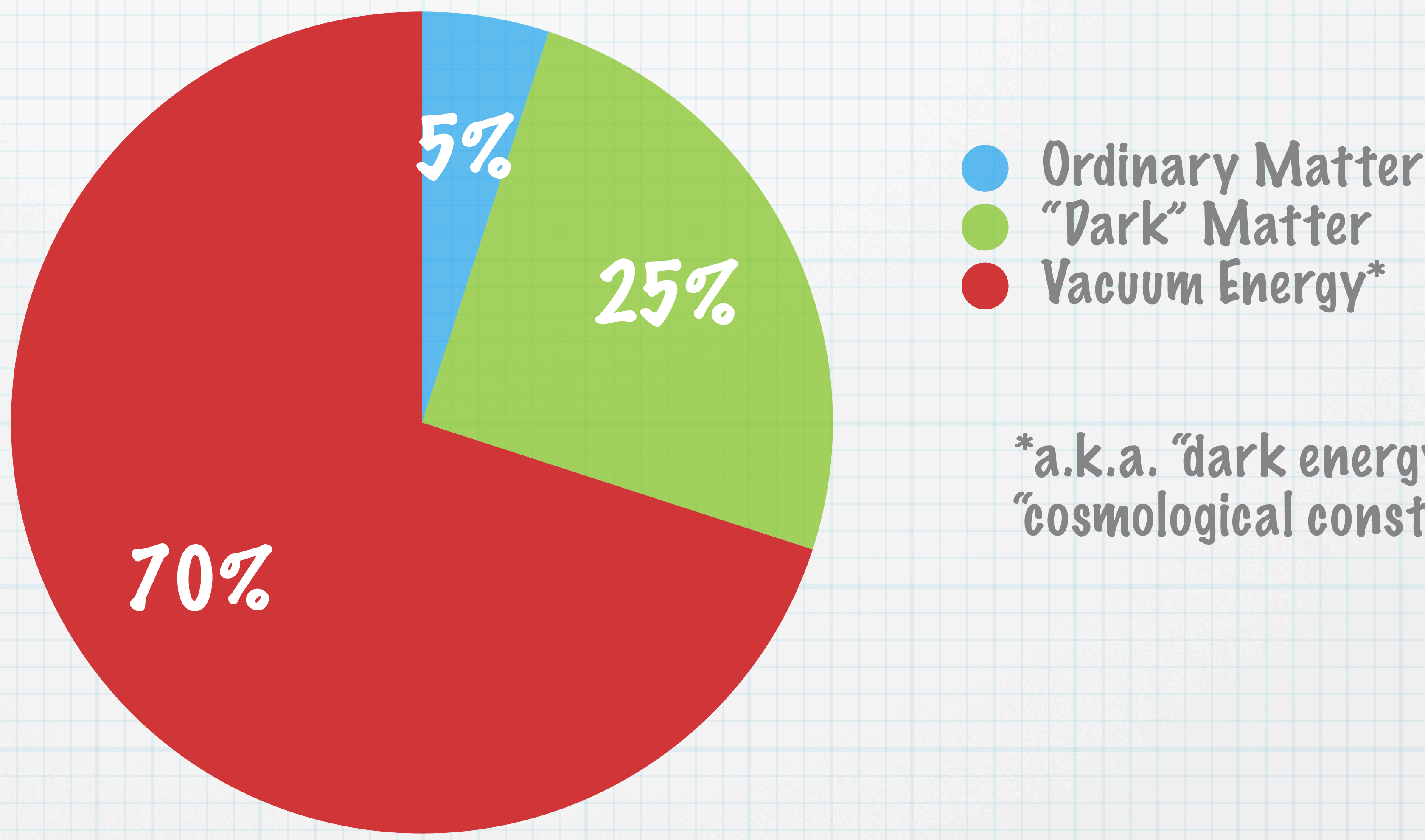
The Energy of the Vacuum:



all these excitations have energy ... how much?

The energy density of the Vacuum can be measured by the expansion of the Universe (recall, in relativity energy=mass)

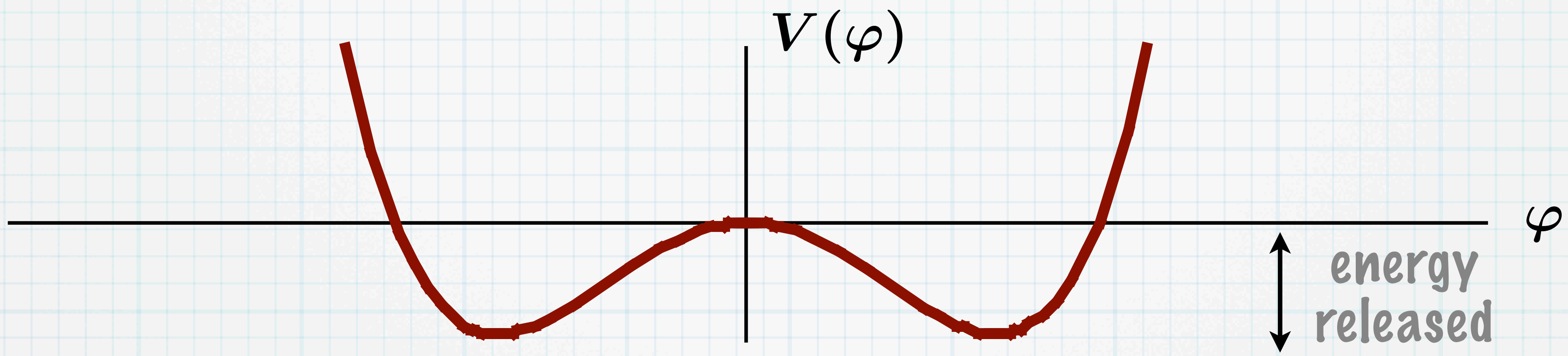
Energy budget of the Universe:



*a.k.a. "dark energy" or "cosmological constant"

70% of the energy density in the Universe ≈ 10^{-26} kg/m^3

We don't know how Nature sets the "zero" of energy, but compare this with the change in Vacuum energy in each of the two known phase transitions:



(1) Electroweak: energy density drops by **10^{30} kg/m^3**
(2) QCD: energy density drops by **10^{14} kg/m^3**

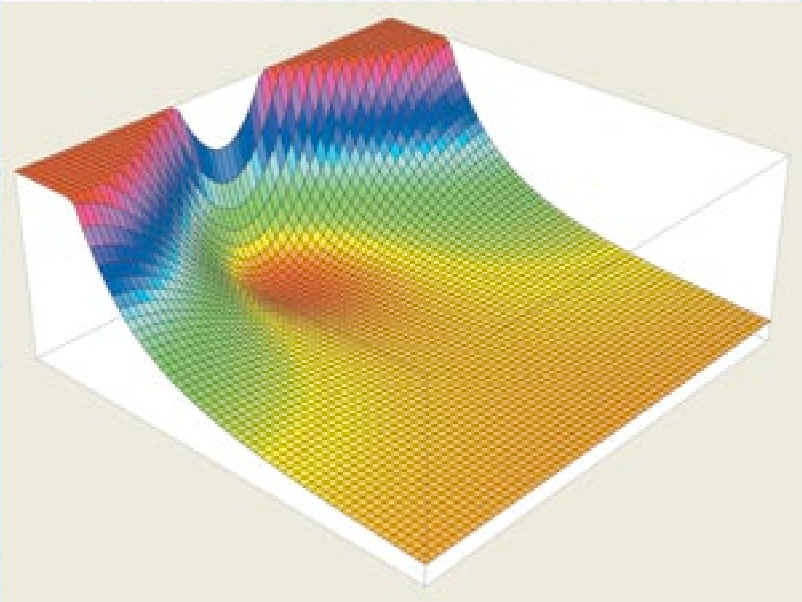
yet somehow everything conspired so that we are left with an energy density 56 orders of magnitude smaller than the energy released in the electroweak phase transition ...

(or there's something fundamental we don't understand about Vacuum energy and/or gravity).

The Vacuum and String Theory:

The "true" Vacuum (global minimum) in string theory appears to be flat 10 dimensional Minkowski space-time.

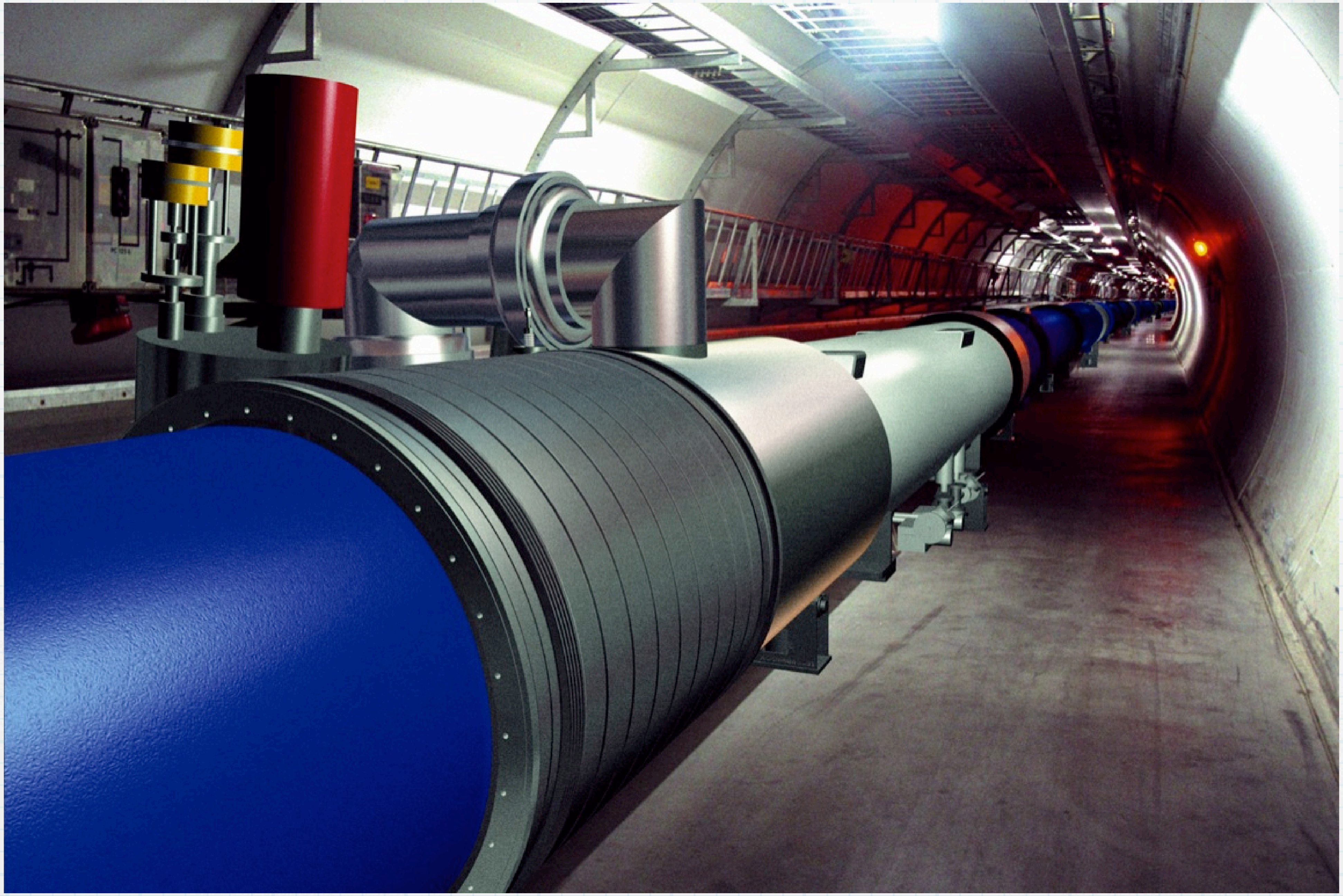
- the Vacuum with a positive energy density must be a METASTABLE state



- current estimates suggest there are easily a googleplex* of discrete metastable vacua, each with different laws of physics, numbers of dimensions, etc., and no known mechanism for preferring one over the other ...

"STRING LANDSCAPE"

*1 google=10^{100}
1 googleplex=10^{google}



So the LHC will teach us something (but not everything) about Nothing.

The End