Electroweak Symmetry Breaking
(Historical Perspective)

Chris Quigg

40th SLAC Summer Institute · 2012

History is not just a thing of the past!

Symmetry

Indistinguishable
before and after a transformation

Unobservable
quantity would vanish if symmetry held

Disorder
order = reduced symmetry

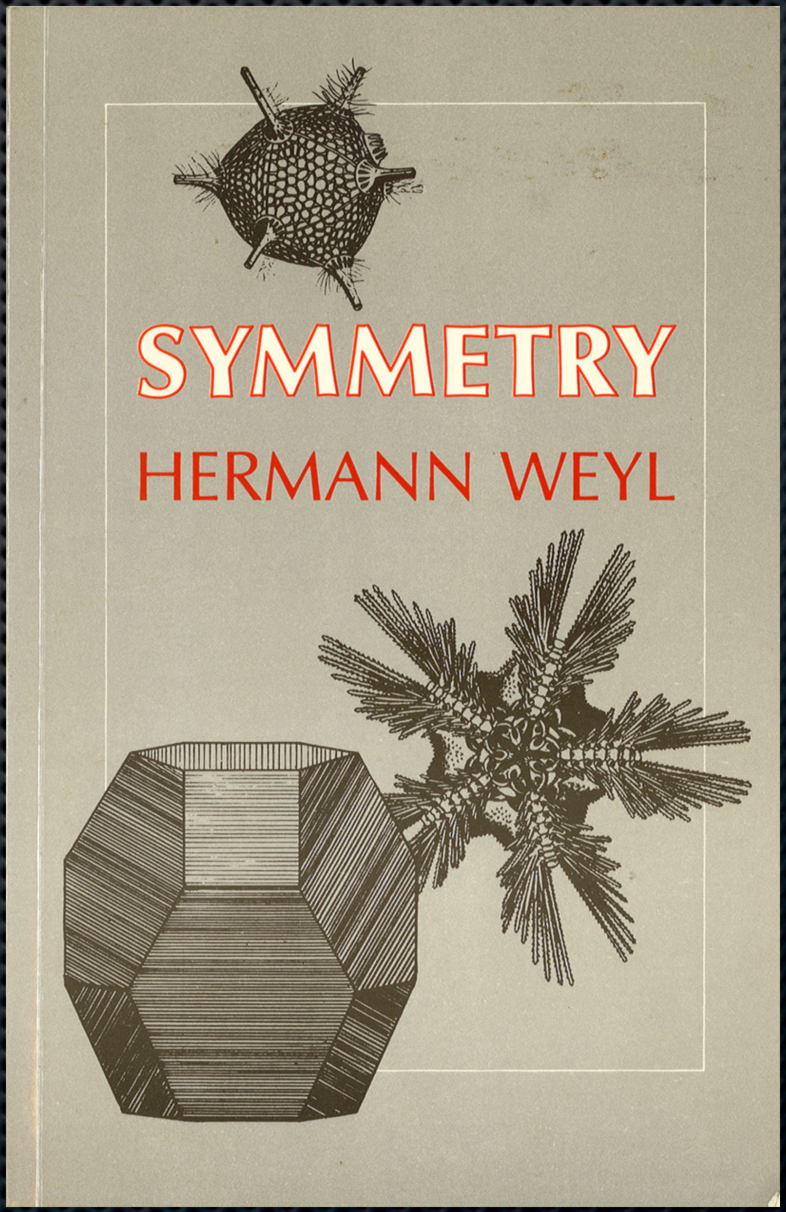
Symmetry

Bilateral

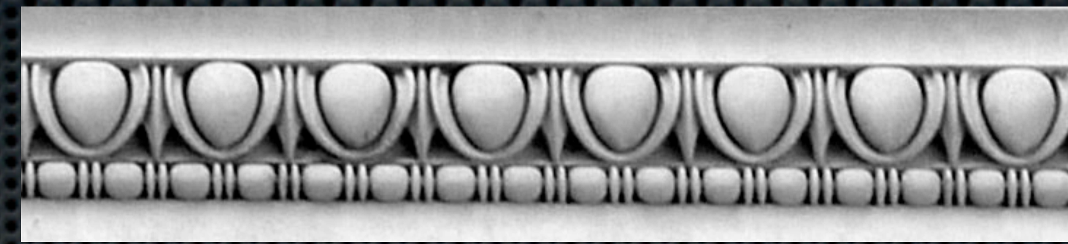
Translational, rotational, …

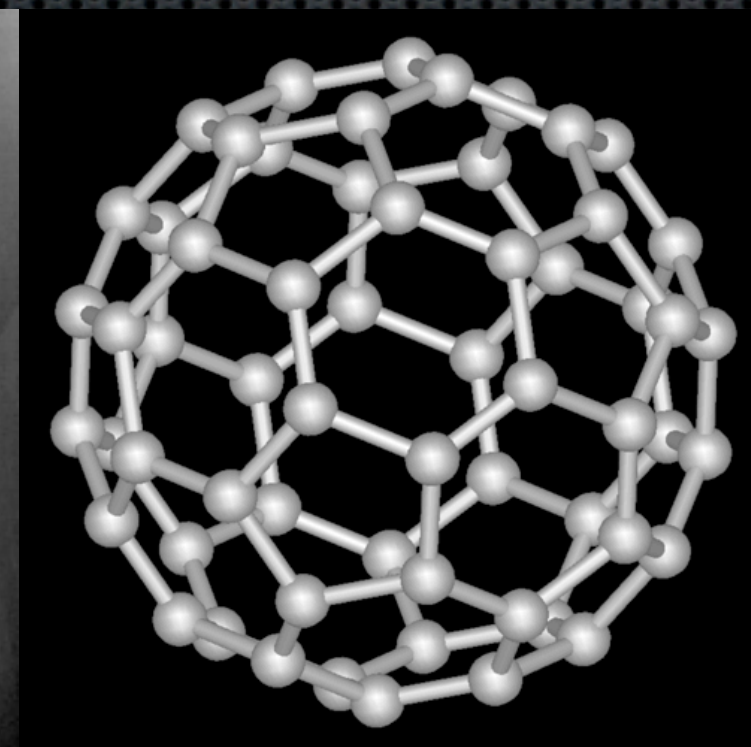
Ornamental

Crystals

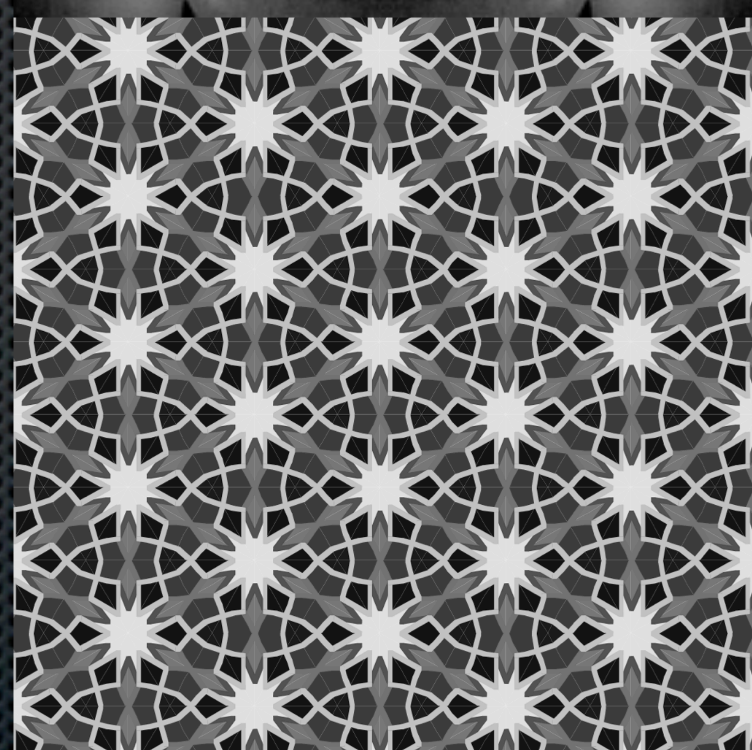


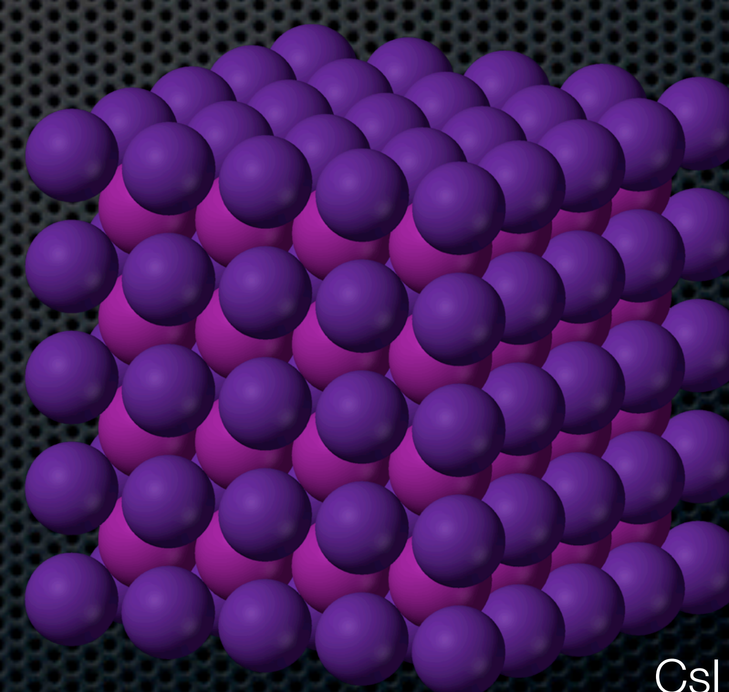
Symmetry





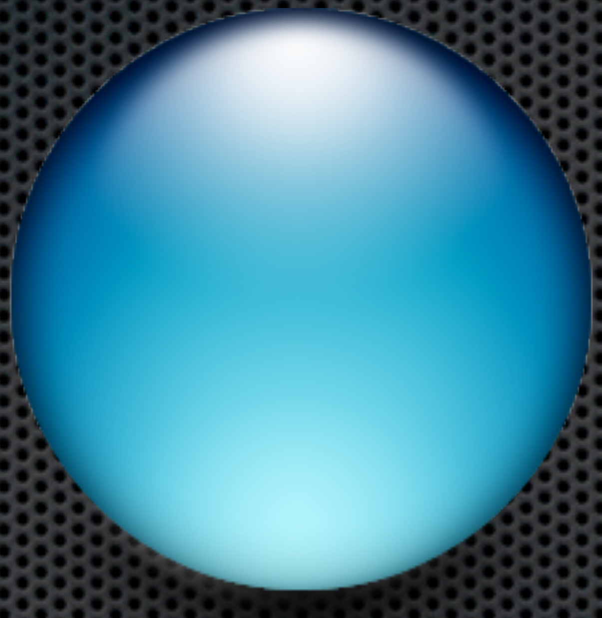
Fullerene C60 ball and stick created from a PDB using Piotr Rotkiewicz's [http://www.pirx.com/iMol/ iMol]. {{gfdl}} Source: English Wikipedia,





CsI

Symmetry (continuous)



Symmetry matters.

BASICS | Natalie Angier

The Mighty Mathematician You've Never Heard Of

Scientists are a famously anonymous lot, but few can match in the depths of her perverse and unmerited obscurity the 20th-century mathematical genius Amalie Noether.

Albert Einstein called her the most "significant" and "creative" female mathematician of all time, and others of her contemporaries were inclined to drop the modification by sex. She invented a theorem that united with magisterial concision two conceptual pillars of physics: symmetry in nature and the universal laws of conservation. Some consider Noether's theorem, as it is now called, as important as Einstein's theory of relativity; it undergirds much of today's vanguard research in physics, including the hunt for the almighty Higgs boson. Yet Noether herself remains utterly unknown, not only to the general public, but to many members of the scientific community as well.

When Dave Goldberg, a physicist at Drexel University who has written about her work, recently took a little "Noether poll" of several dozen colleagues, students and online followers, he was taken aback by the results. "Surprisingly few could say exactly who she was or why she was important," he said. "A few others knew her name but couldn't recall what she'd done, and the majority had never heard of her."

Noether (pronounced NER-ter) was born in Erlangen, Germany, 130 years ago this month. So it's a fine time to counter the chronic neglect and celebrate the life and work of a brilliant theorist whose unshakable number love and irrationally robust sense of humor helped her overcome severe handicaps — first, being female in Germany at a time when most German universities didn't accept female students or hire fe-

RS

GROUNDBREAKING Emmy Noether's theorem united two pillars of physics: symmetry in nature and the universal laws of conservation.

symmetry in nature, some predictability or homogeneity of parts, you'll find lurking in the background a corresponding conservation — of momentum, electric charge, energy or the like. If a bicycle wheel is radially symmetric, if you can spin it on its axis and it still looks the same in all directions, well, then, that symmetric translation must yield a corresponding conservation. By applying the principles and calculations embodied in Noether's theorem, you'll see it's angular momentum, the Newtonian impulse that keeps bicyclists upright and on the move.

Some of the relationships to pop out of the theorem are startling, the most profound one linking time and energy. Noether's theorem shows that a symmetry of time — like the fact that whether you throw a ball in the air tomorrow or make the same toss next week will have no effect on the ball's trajectory — is directly related to the conservation of energy, our old homily that energy can be neither created nor destroyed but merely changes form.

The connections that Noether forged are "critical" to modern physics, said Lisa Randall, a professor of theoretical particle physics and cosmology at Harvard. "Energy, momentum and other quantities we take for granted gain meaning and even greater value when we understand how these quantities follow from symmetry in time and space."

Dr. Randall, the author of the newly published "Knocking on Heaven's Door," recalled the moment in college when she happened to learn that the author of Noether's theorem was a she. "It was striking and even exciting and inspirational," Dr. Randall said, admitting, "I was surprised by my reaction."

For her part, Noether left little record

Symmetries & conservation laws

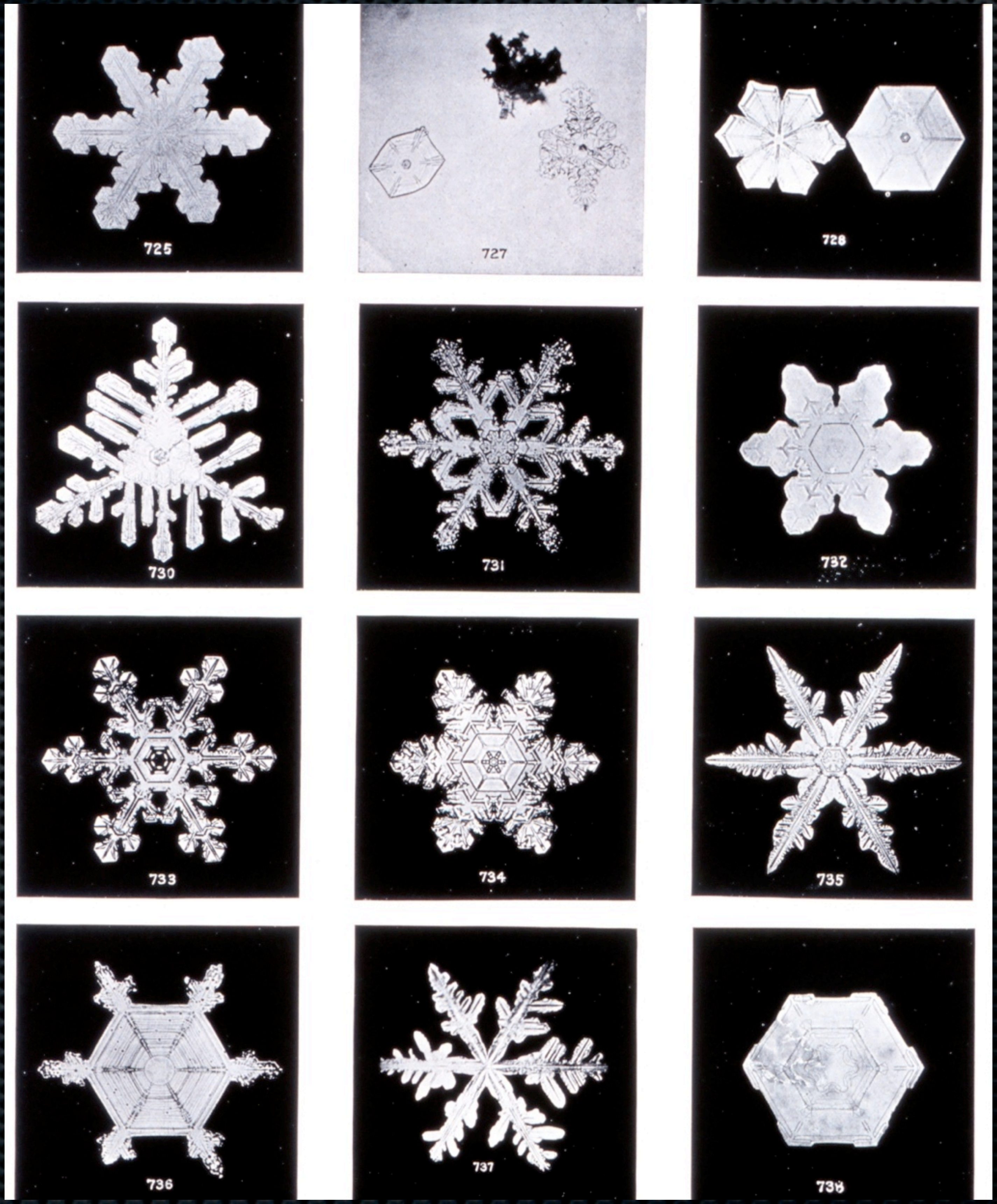
Spatial translation	*Momentum*
Time translation	*Energy*
Rotational invariance	*Angular momentum*
QM phase	*Charge*

Symmetric laws

need not imply

symmetric outcomes.

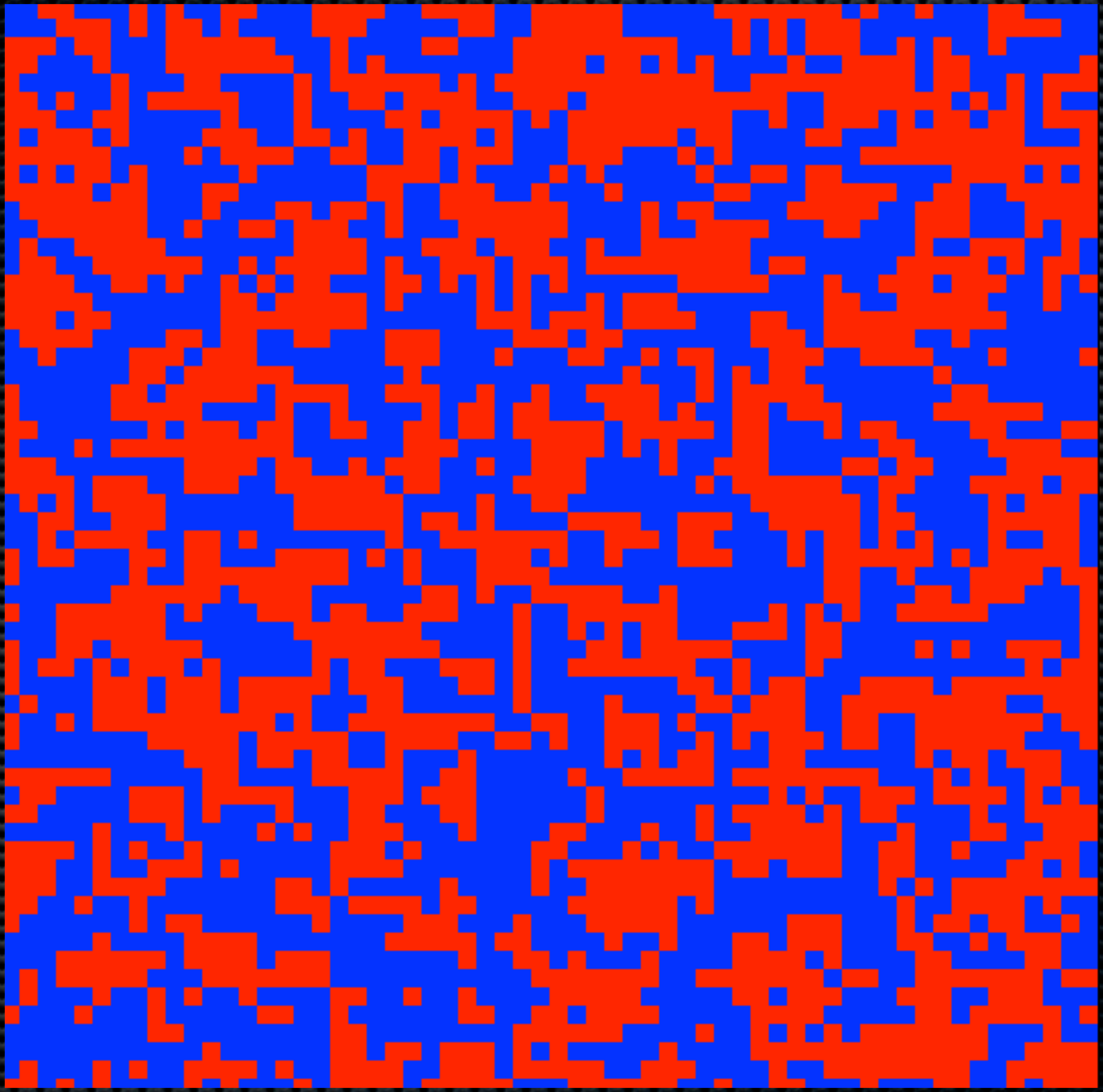
symmetries of laws $\not\Rightarrow$ symmetries of outcomes



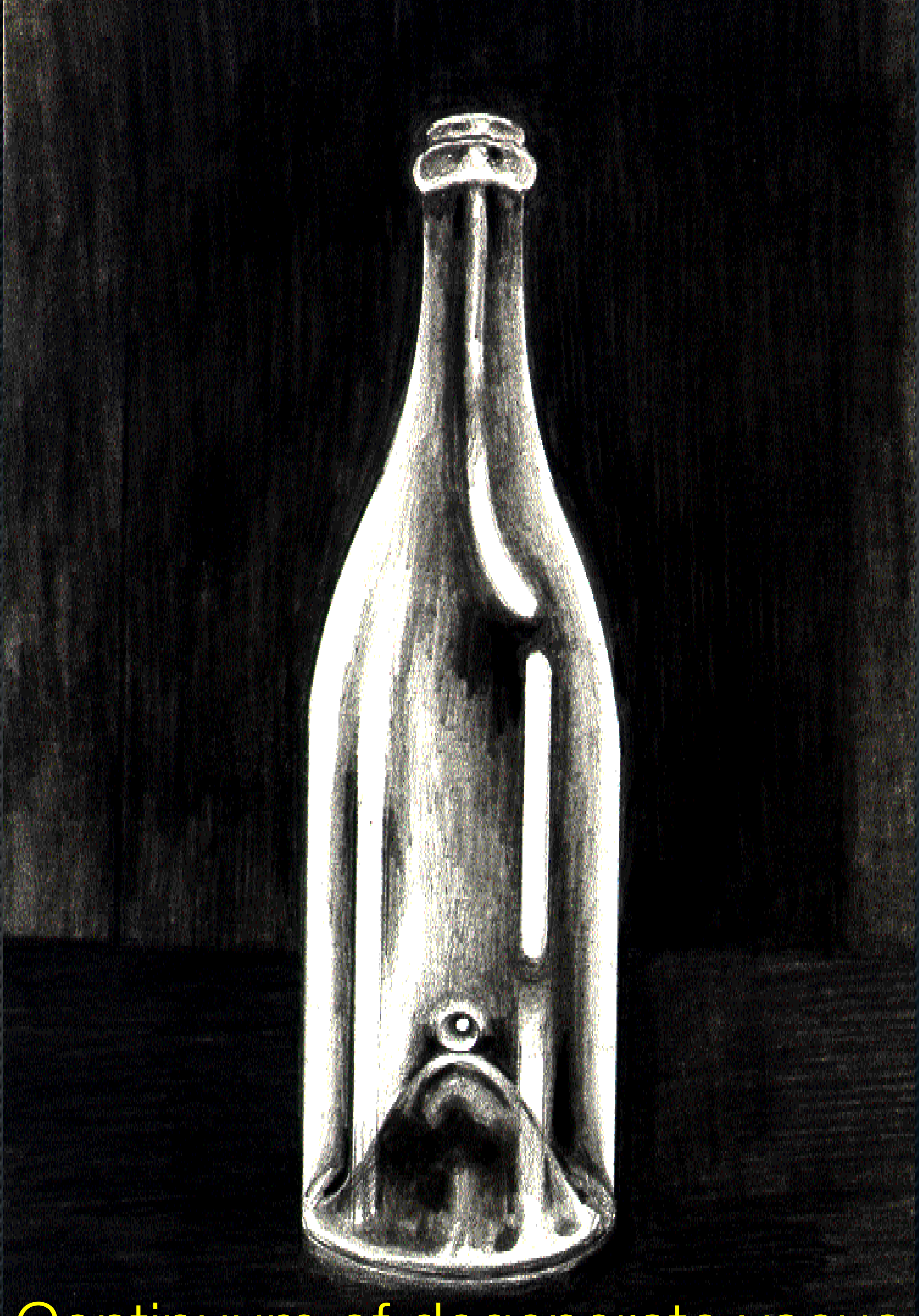
Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library

Broken symmetry is interesting.

Two-dimensional Ising model of ferromagnet



http://boudin.fnal.gov/applet/IsingPage.html

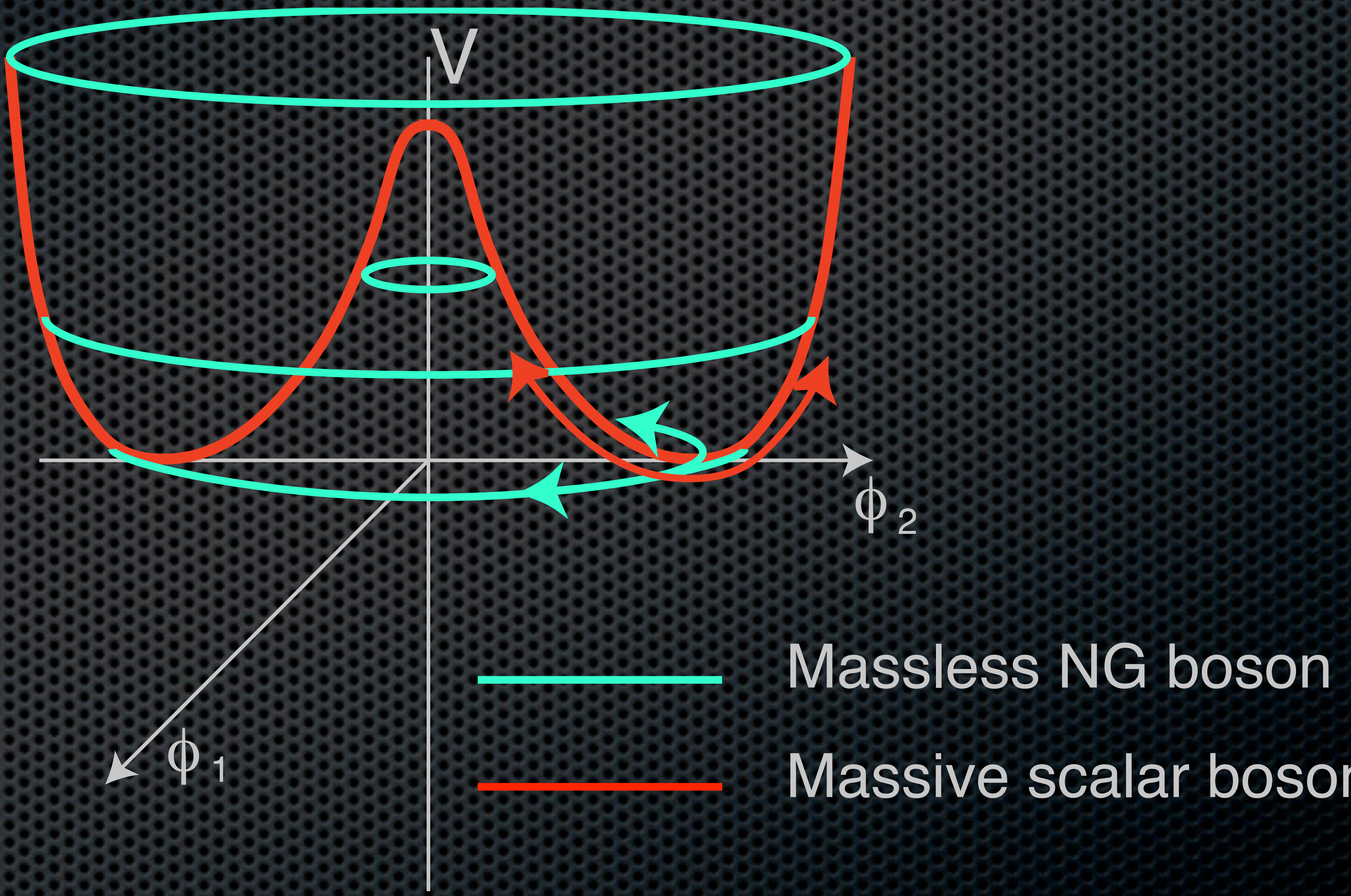


Continuum of degenerate vacua

Nambu–Goldstone bosons

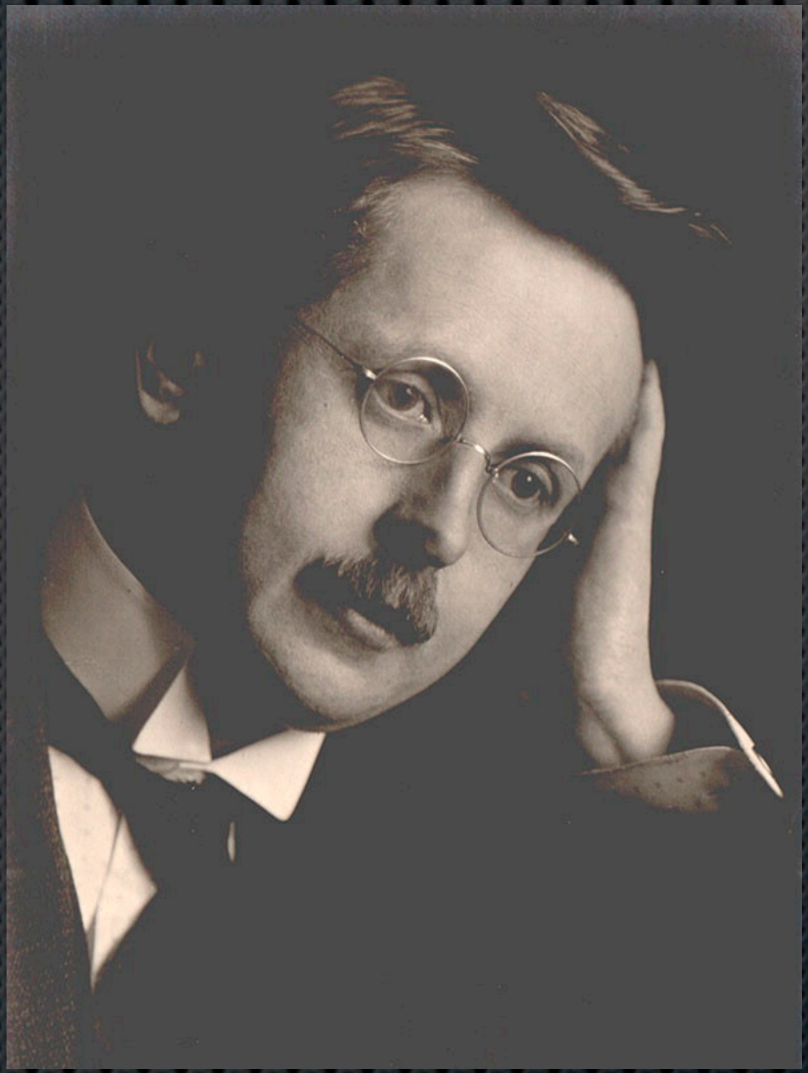
Yoichiro Nambu

Jeffrey Goldstone



NGBs as spin waves, phonons, pions, …

Symmetries imply forces. I: *scale symmetry to unify EM, gravity*



Hermann Weyl (1918, 1929)

Complex phase in QM

Global: free particle

Local: interactions

Maxwell's equations; QED

James Clerk Maxwell (1861/2)

massless spin-1 photon
coupled to conserved charge

no impediment to electron mass

(e_L & e_R have same charge)

$$\bar{\psi}\psi = \bar{\psi}_{\mathsf{L}}\psi_{\mathsf{R}} + \bar{\psi}_{\mathsf{R}}\psi_{\mathsf{L}}$$

$$\psi(x) \to e^{iq\alpha(x)}\psi(x)$$

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x)$$

$$\mathcal{D}_\mu \equiv \partial_\mu + iqA_\mu(x)$$

$$\begin{aligned} \mathcal{L} &= \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m)\psi \\ &= \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - qA_\mu \bar{\psi}\gamma^\mu \psi \\ &= \mathcal{L}_{\text{free}} - J^\mu A_\mu \end{aligned}$$

QED

Fermion masses allowed

Gauge-boson masses forbidden

Photon mass term

$$\tfrac{1}{2} m_\gamma^2 A^\mu A_\mu$$

violates gauge invariance:

$$\boxed{A^\mu A_\mu \to (A^\mu - \partial^\mu \Lambda)\,(A_\mu - \partial_\mu \Lambda) \neq A^\mu A_\mu}$$

Massless photon predicted

observed: $m_\gamma \lesssim 10^{-22}\, m_e$

Symmetries imply forces. II:
non-Abelian gauge symmetry

Robert Mills

C. N. Yang
(1954)

Ron Shaw

Can one choose independently
at each point in spacetime
the convention to name
proton and neutron?

Local isospin symmetry implies
3 massless gauge bosons ☹
coupled to isospin

no impediment to nucleon mass

(N_L & N_R have same isospin)

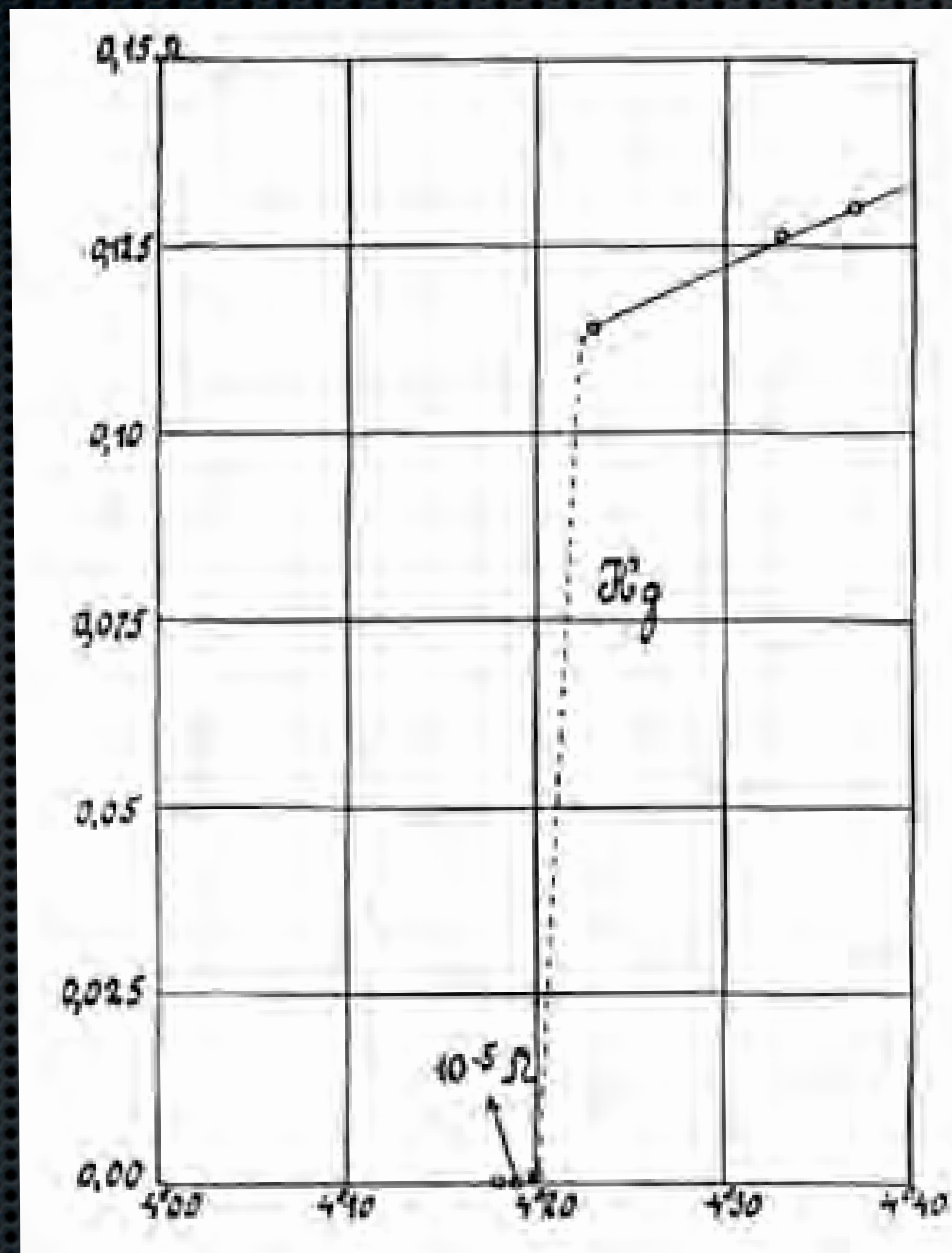
Might hiding the symmetry help?

Seems to add massless NGBs ☹

to massless gauge bosons ☹

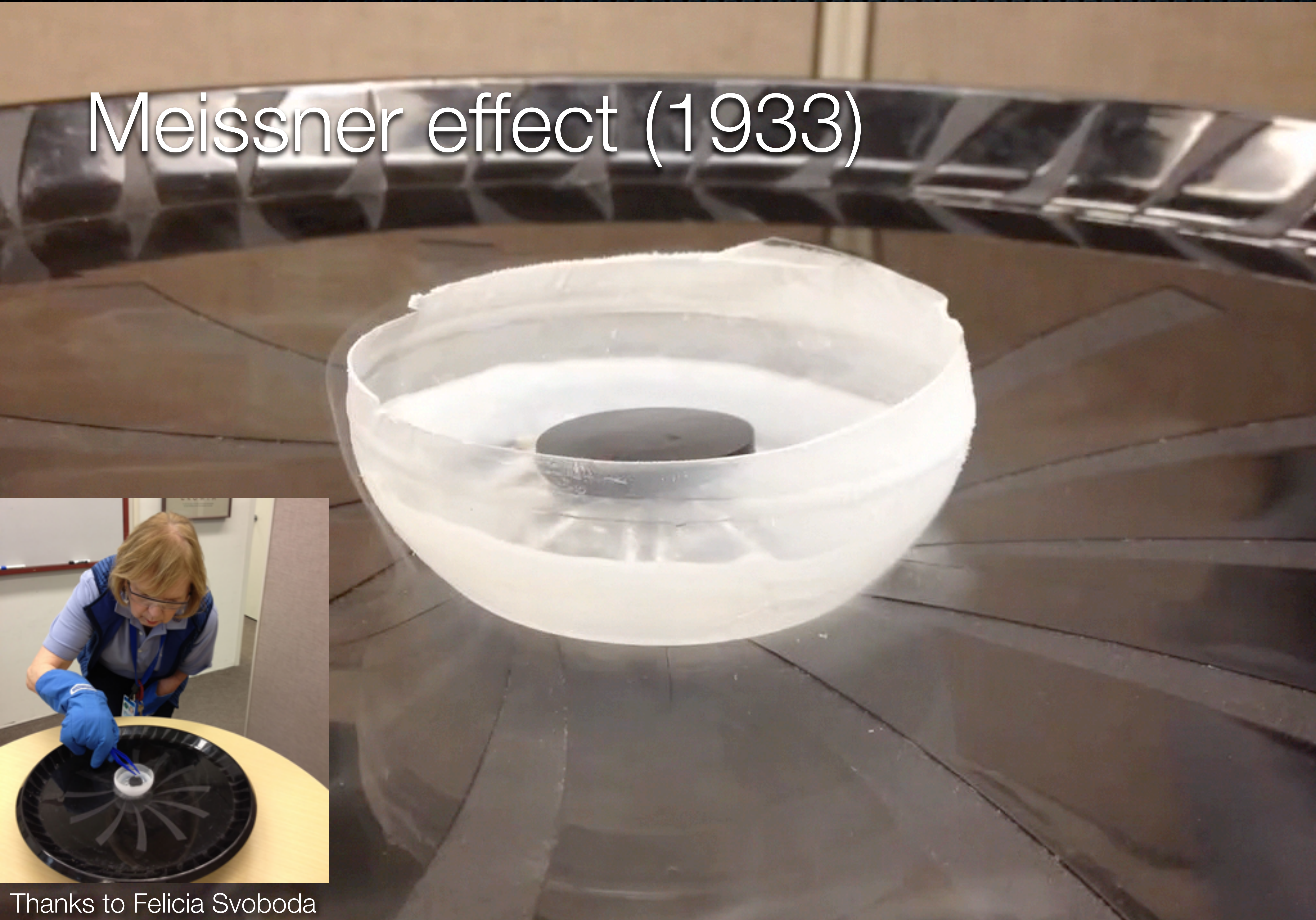
Goldstone theorem proved with ever-increasing rigor

Superconductivity (1911)



Heike Kamerlingh Onnes

Meissner effect (1933)



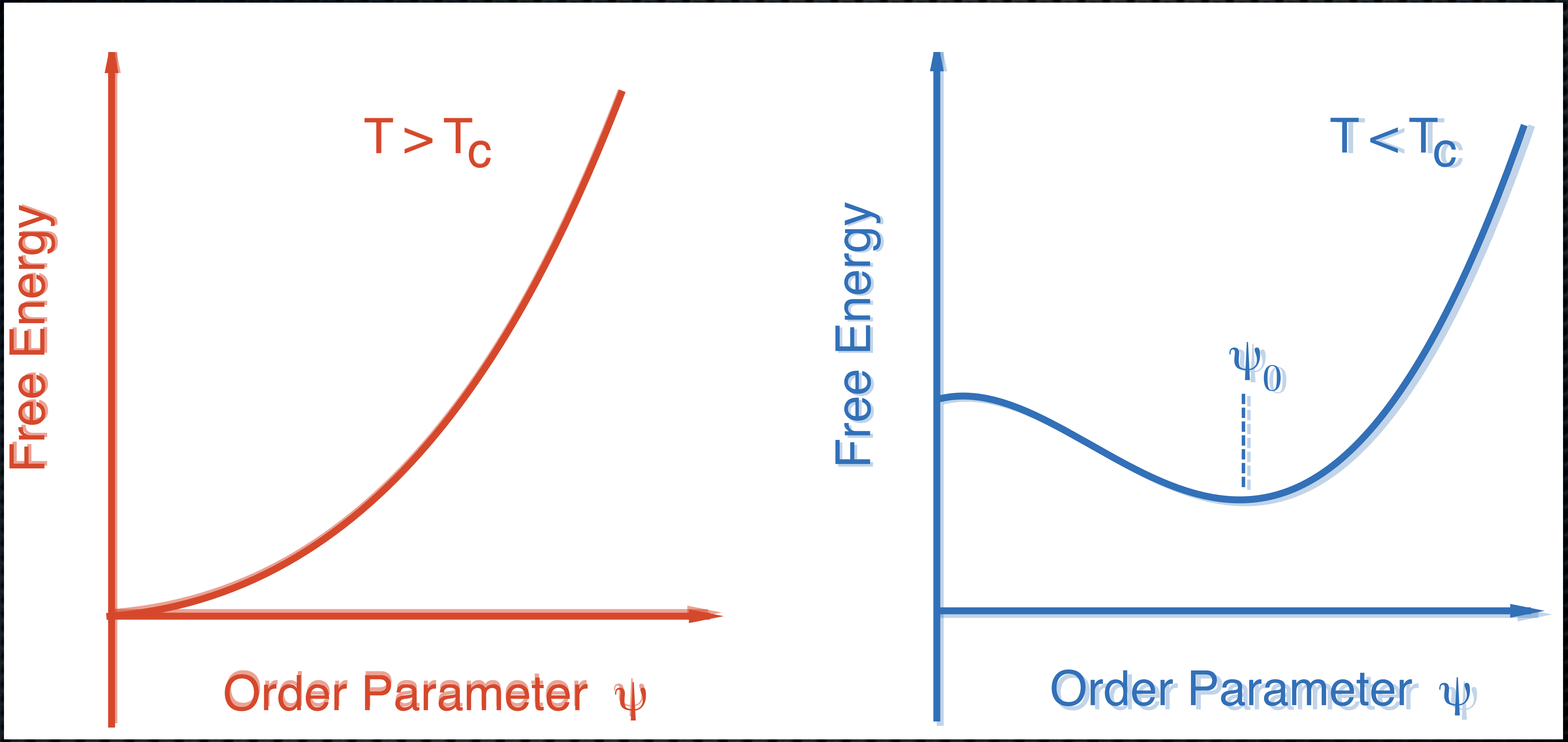
Thanks to Felicia Svoboda

Magnetic fields excluded

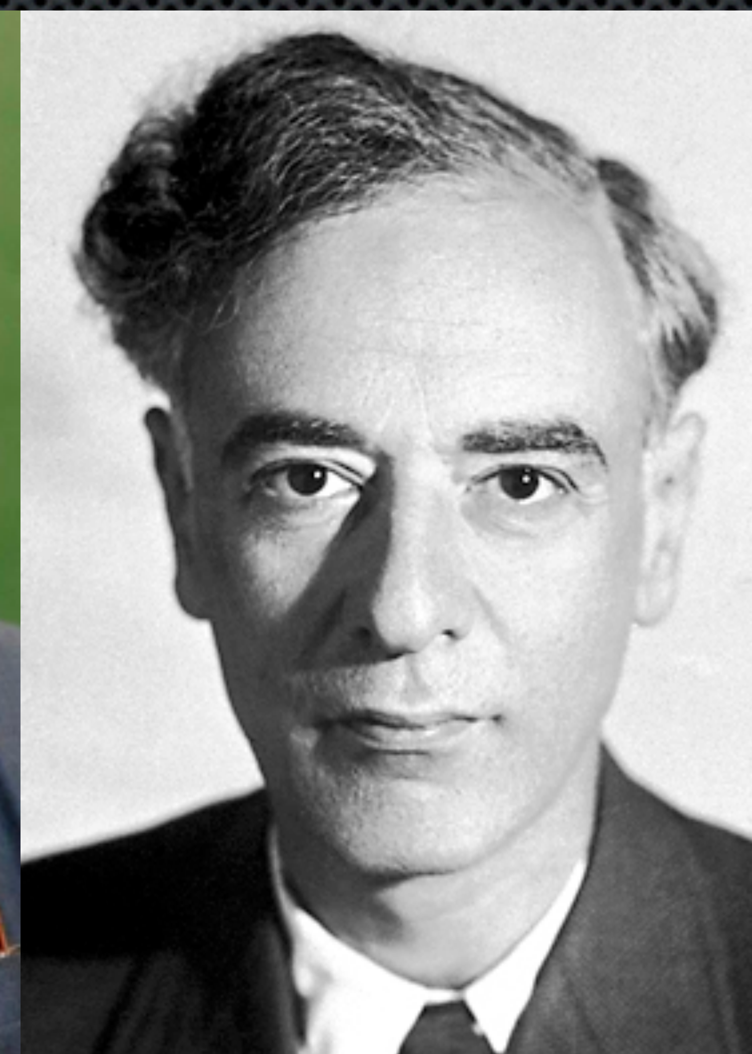
Walther Meißner Robert Ochsenfeld

Pb: 40 nm penetration

Ginzburg–Landau model (1950)

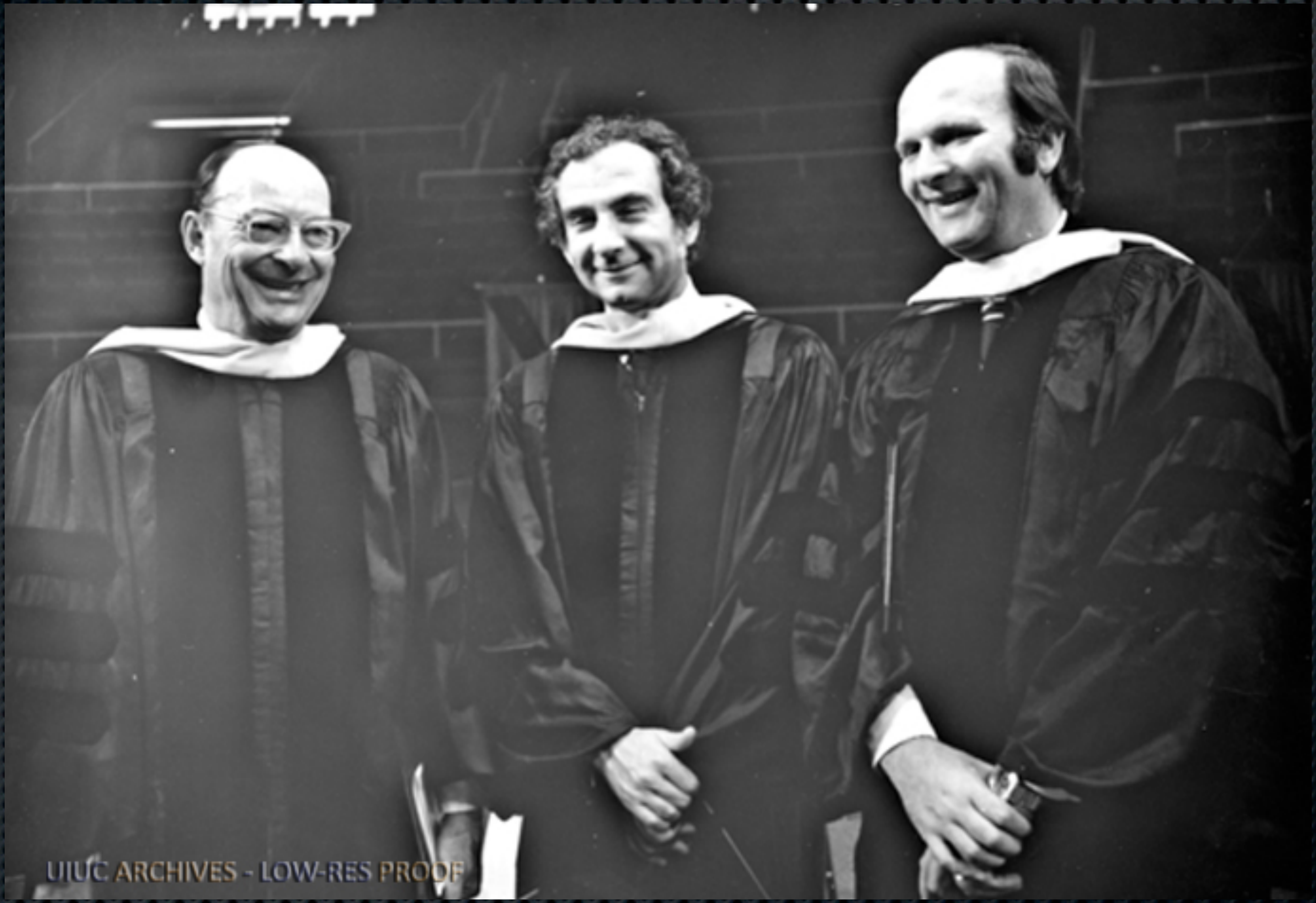


Photon acquires mass in superconductor



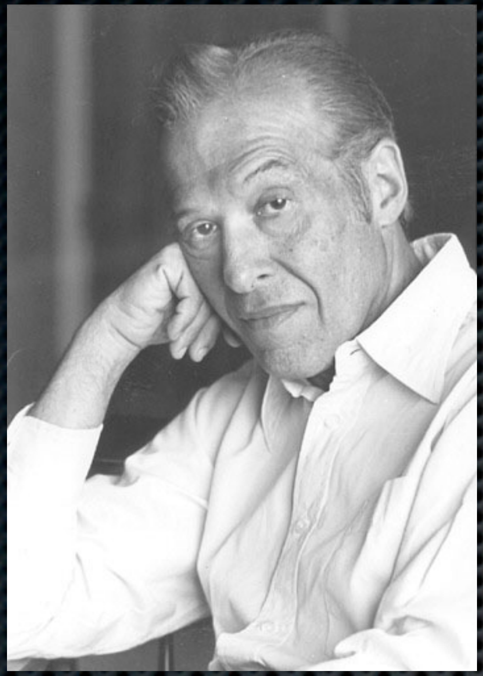
Vitaly Ginzburg   Lev Landau

BCS theory (1957)



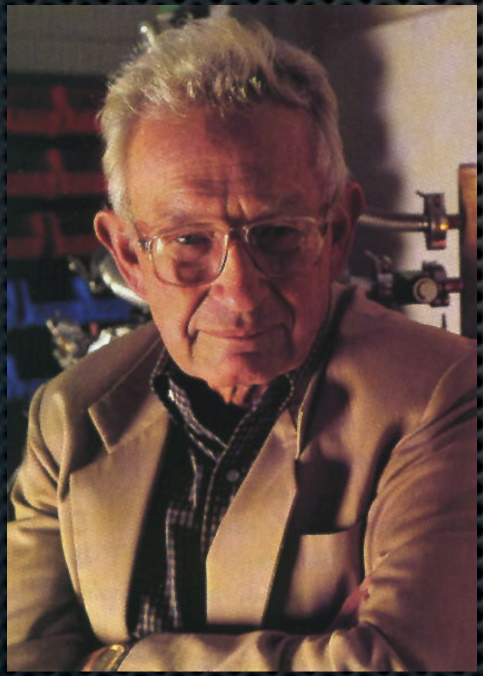
John Bardeen Leon Cooper Robert Schrieffer

Some hints



Julian Schwinger

(1962) Photon can acquire mass in 1+1-dimensional QED



Phil Anderson

(1963) Superconductor: massive photon, hidden gauge symmetry. Model for strong interactions?

Spontaneous symmetry breaking

Higgs Kibble Guralnik Hagen Englert Brout†

1964– : Goldstone theorem doesn't apply to gauge theories!
Each would-be massless NGB joins with a would-be massless gauge boson to form a massive gauge boson, leaving an incomplete multiplet of massive scalar bosons.

Simplest example: Abelian Higgs model
= Ginzburg–Landau in relativistic notation

Yields massive photon

+

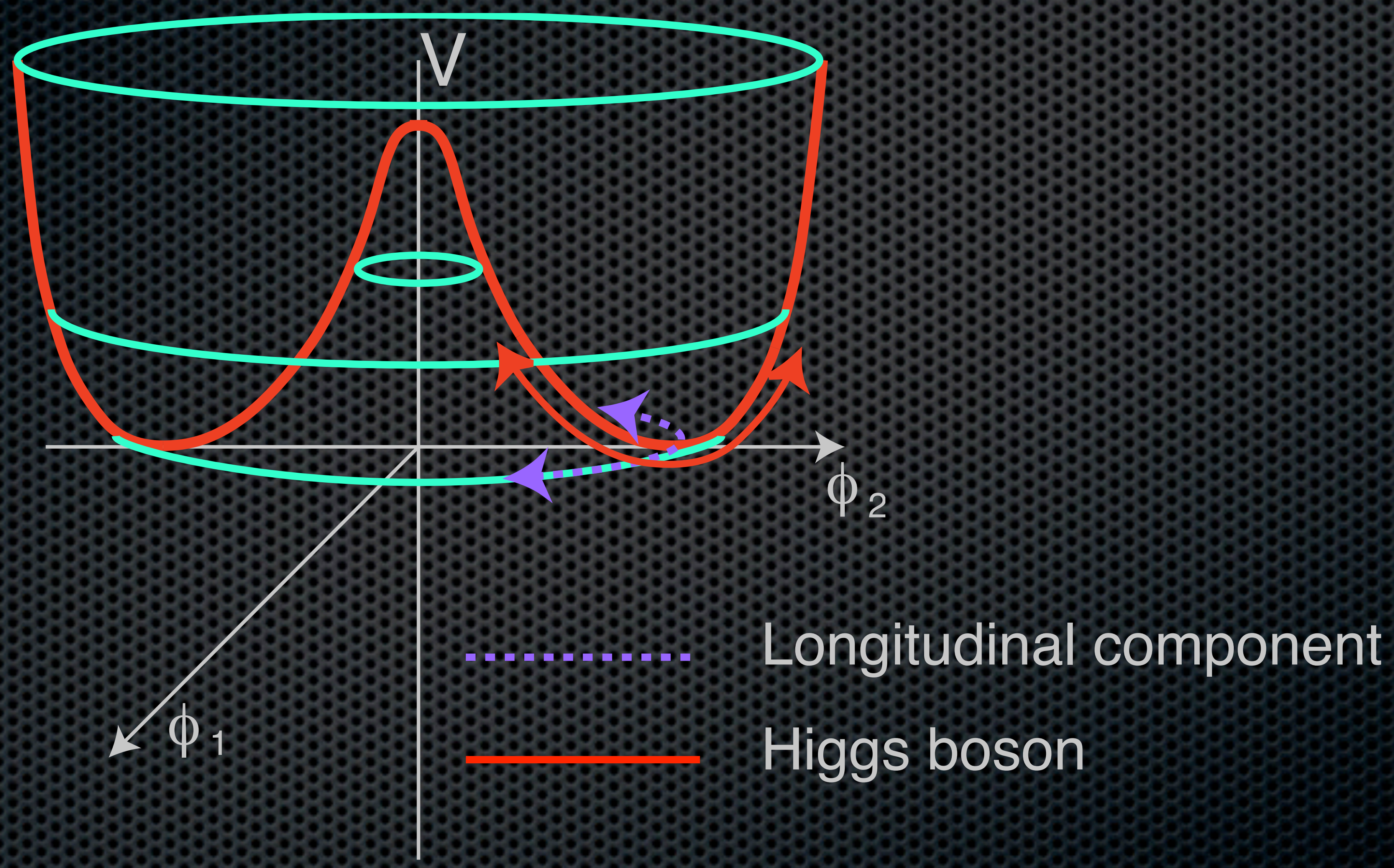
a massive scalar particle

"Higgs boson"

No mention of weak interactions.

No question of fermion masses
(not an issue for Yang–Mills theory).

Spontaneously broken gauge theory



1981: massive collective mode (Raman scattering in $NbSe_2$)

Many fingers in the pie ....

"Higgs fields", for example, are just the scalar fields of a linear sigma model, which was discussed in 1960 by Gell-Mann and Lévy[1] but had been introduced three years earlier by Schwinger[2]. And "the Higgs mechanism" was first described by Philip Anderson[3]: perhaps it should be called "the ABEGHHK'tH.... mechanism" after all the people (Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, 't Hooft) who have discovered or rediscovered it! However, I do accept responsibility for the Higgs boson; I believe that I was the first to draw attention to its existence in spontaneously broken gauge theories[4].

Peter Higgs, *50 Years of Weak Interactions,* Wingspread (1984)

The Schwinger-Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble ~~boson~~ mechanism

Ian Aitchison, "The unbearable heaviness of being," *Physics World* (July 1989)

What of Yang–Mills (isospin) theory?

After SSB, still not the theory of nuclear forces

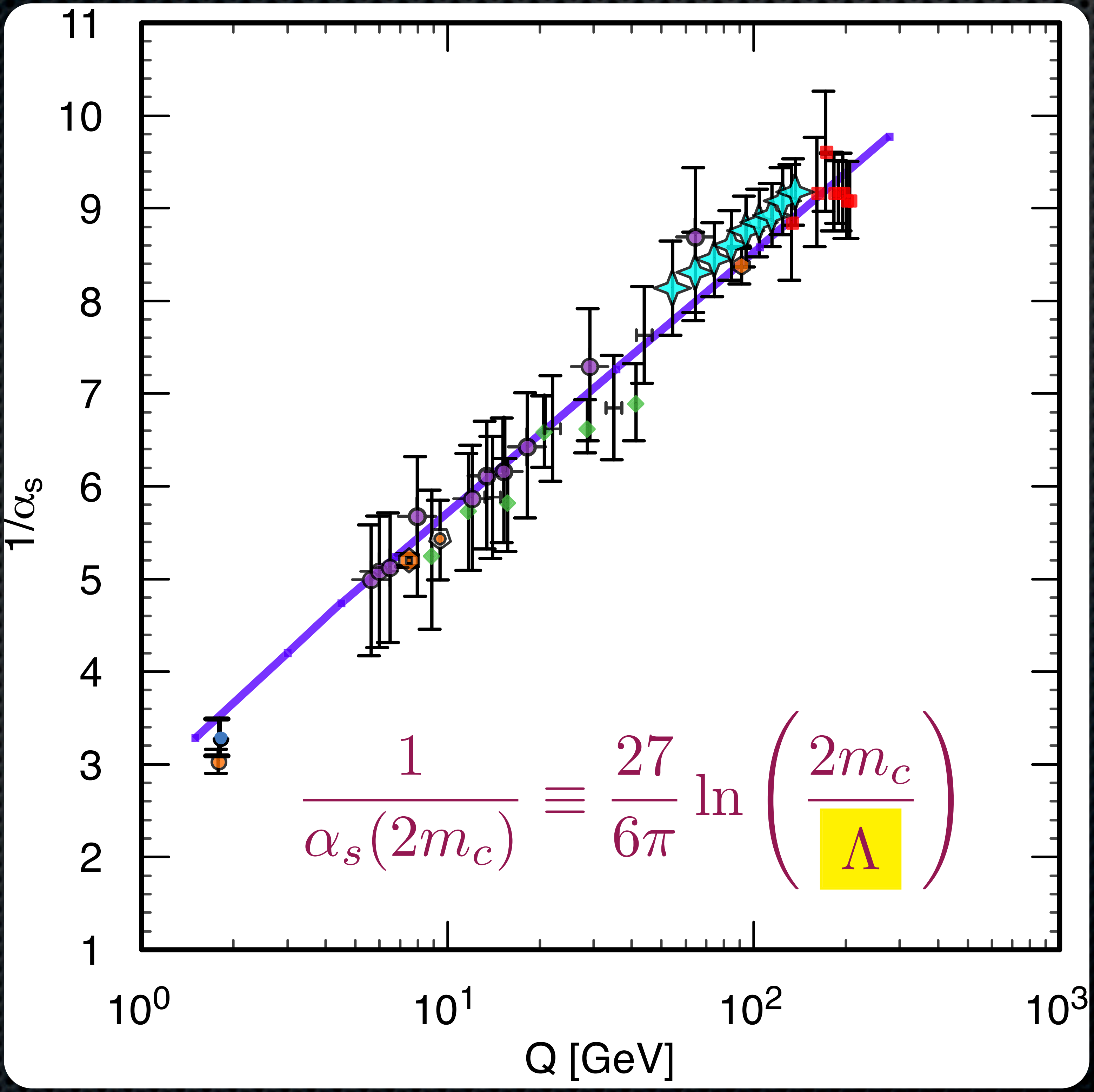
Right idea, wrong symmetry, wrong constituents

Precursor of Quantum Chromodynamics
based on SU(3) color gauge symmetry
for interactions among quarks

In contrast to biological evolution, unsuccessful lines in theoretical physics do not become extinguished, never to rise again.

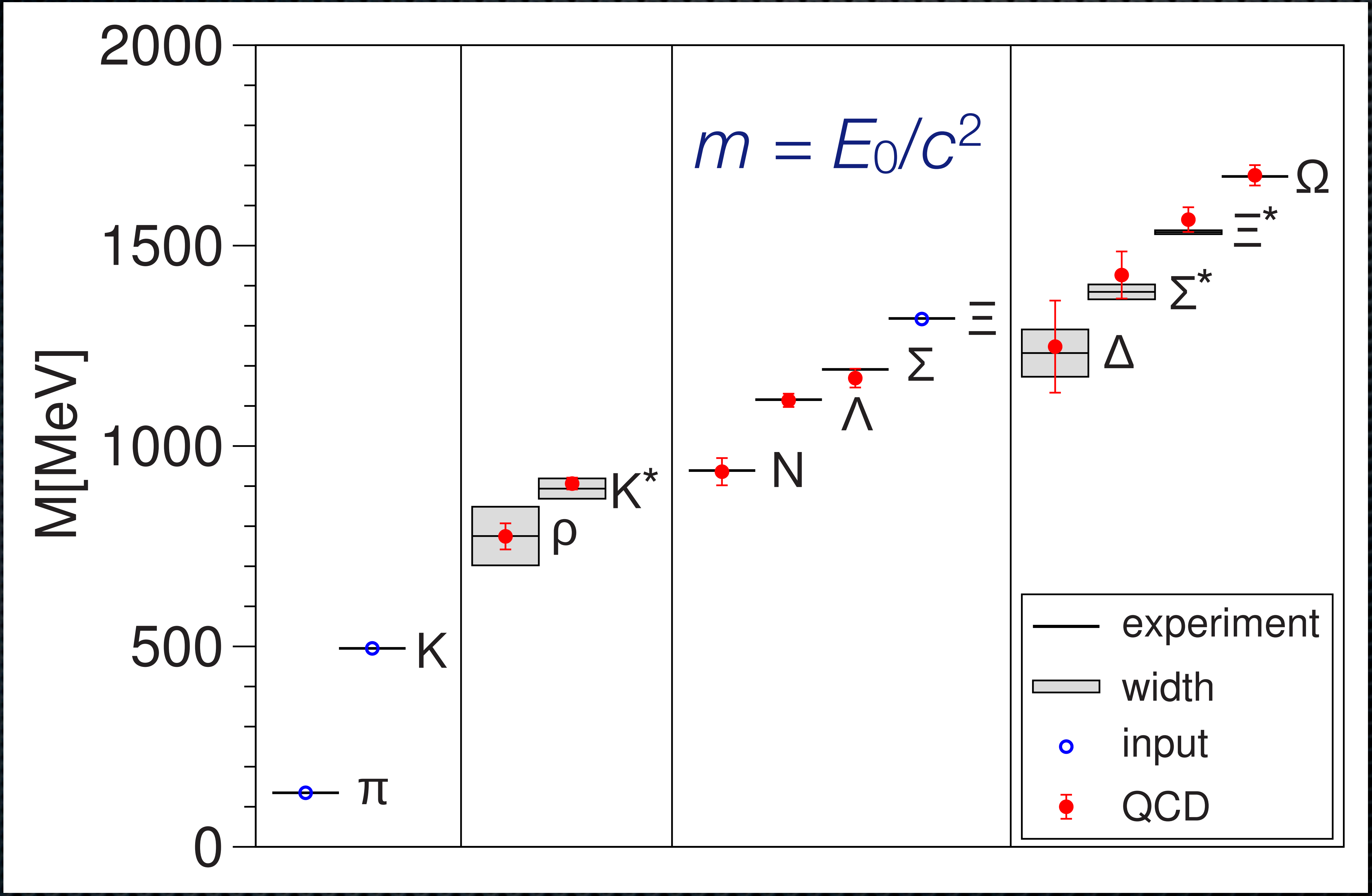
We are free to borrow potent ideas from the past and to apply them in new settings, to powerful effect.

Asymptotic freedom in QCD



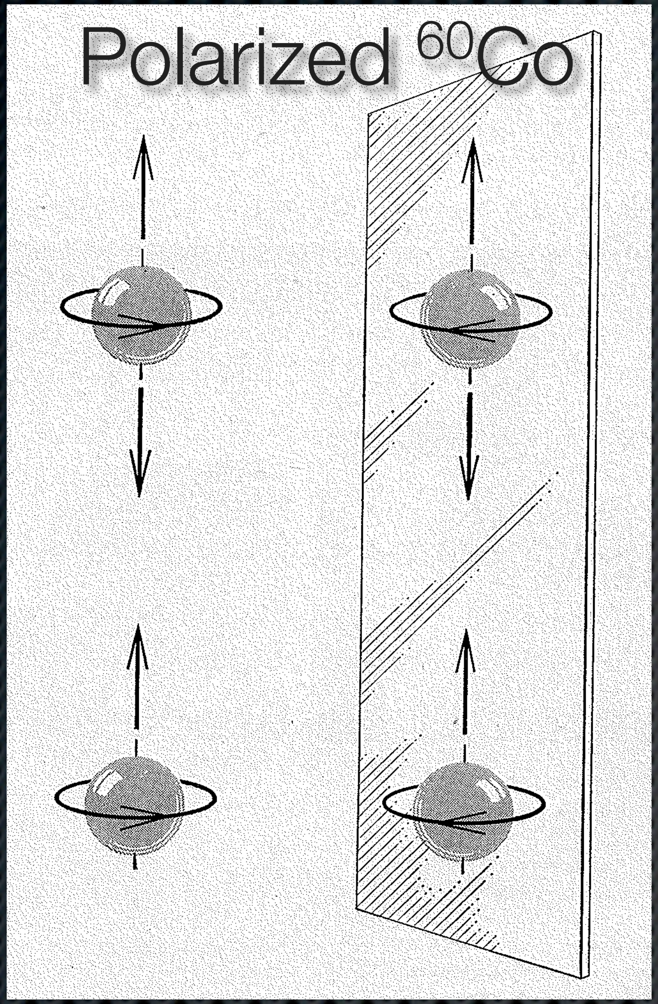
QCD explains most of visible mass

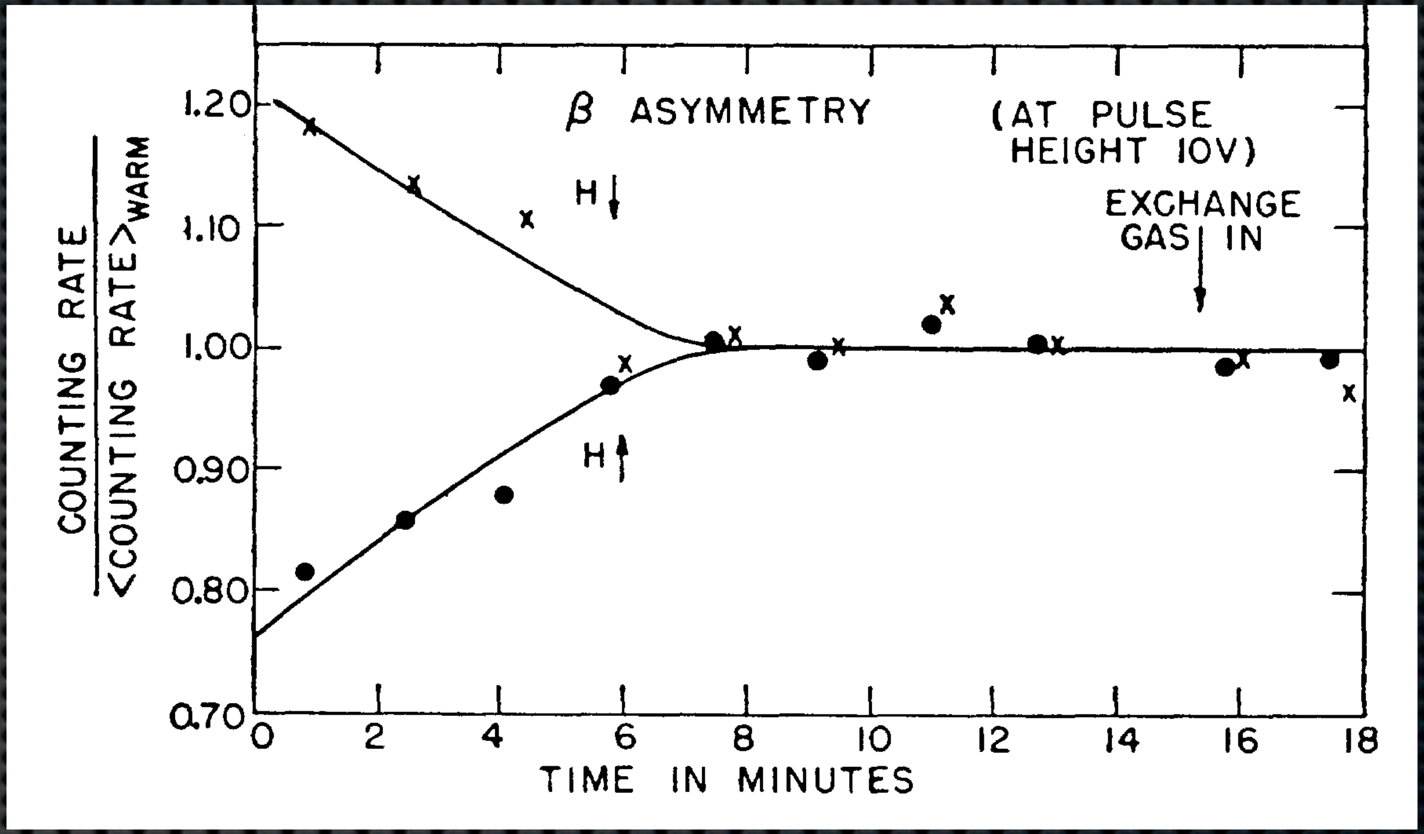
Light hadrons (dynamical fermions)



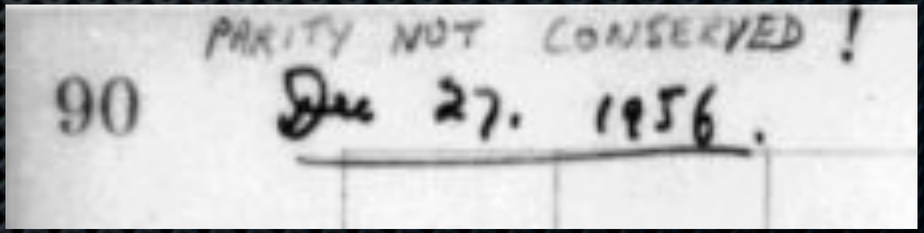
BMW

β-decay: parity not conserved!





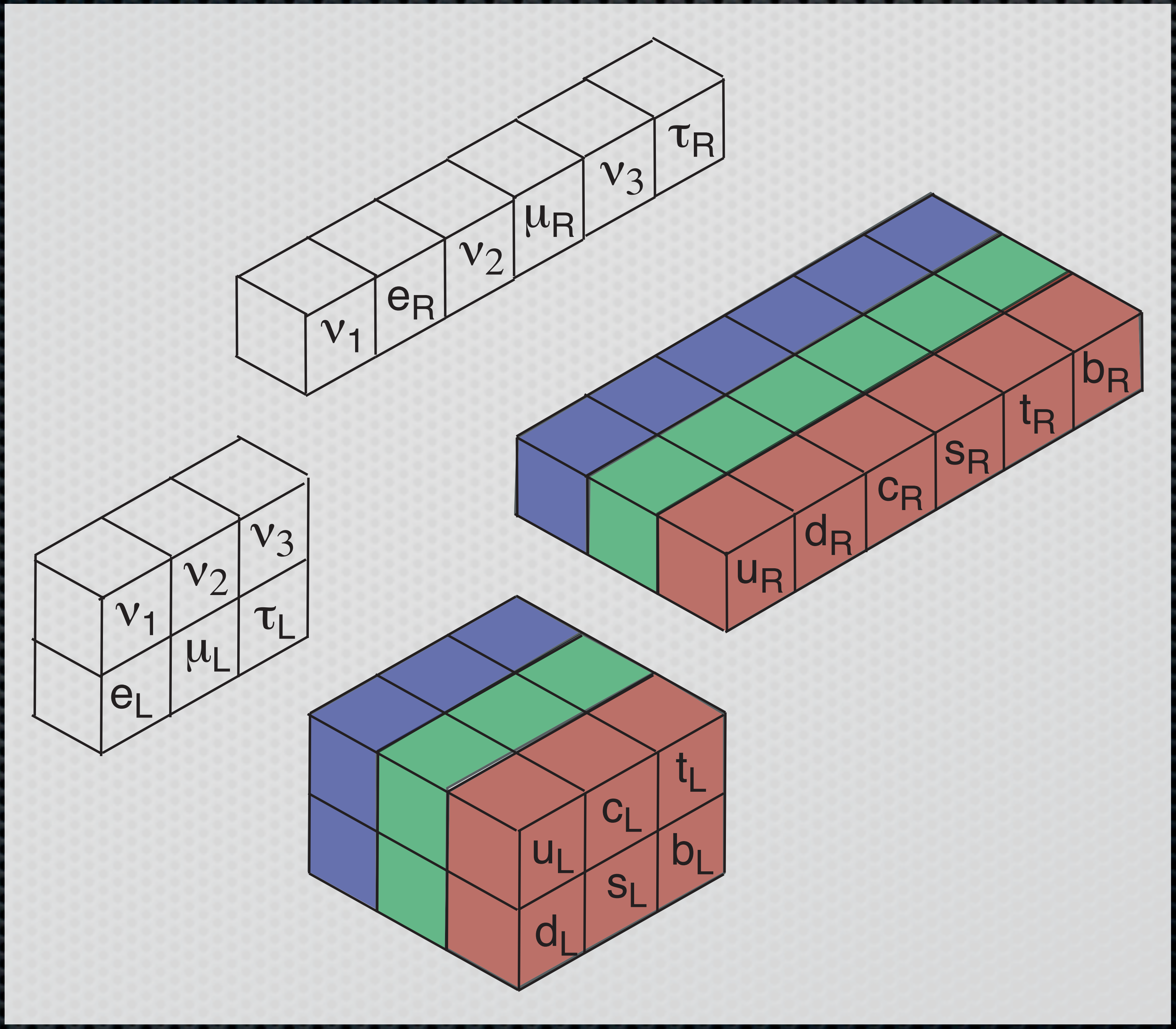
*Un*observable observed



Parity violated in weak interactions

Chien-Shiung Wu (1956) Eric Ambler

Chiral quarks and leptons



An electroweak theory

Weak isospin (left-handed)

+

weak hypercharge phase symmetry

Sheldon Glashow

3 massless gauge bosons coupled to weak isospin ☹

1 massless hyperphoton coupled to weak hypercharge ☹

massless quarks & leptons ☹

An electroweak theory (1967)

Contrive a vacuum to hide EW symmetry

(need 4 new fields)

Massive W^+, W^-, Z^0
Massless photon

Massive Higgs boson

Steven Weinberg

Abdus Salam

Hide EW symmetry to give masses to quarks, leptons, and gauge bosons

"Higgs mechanism" breaks

$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$

g $\qquad$ g'

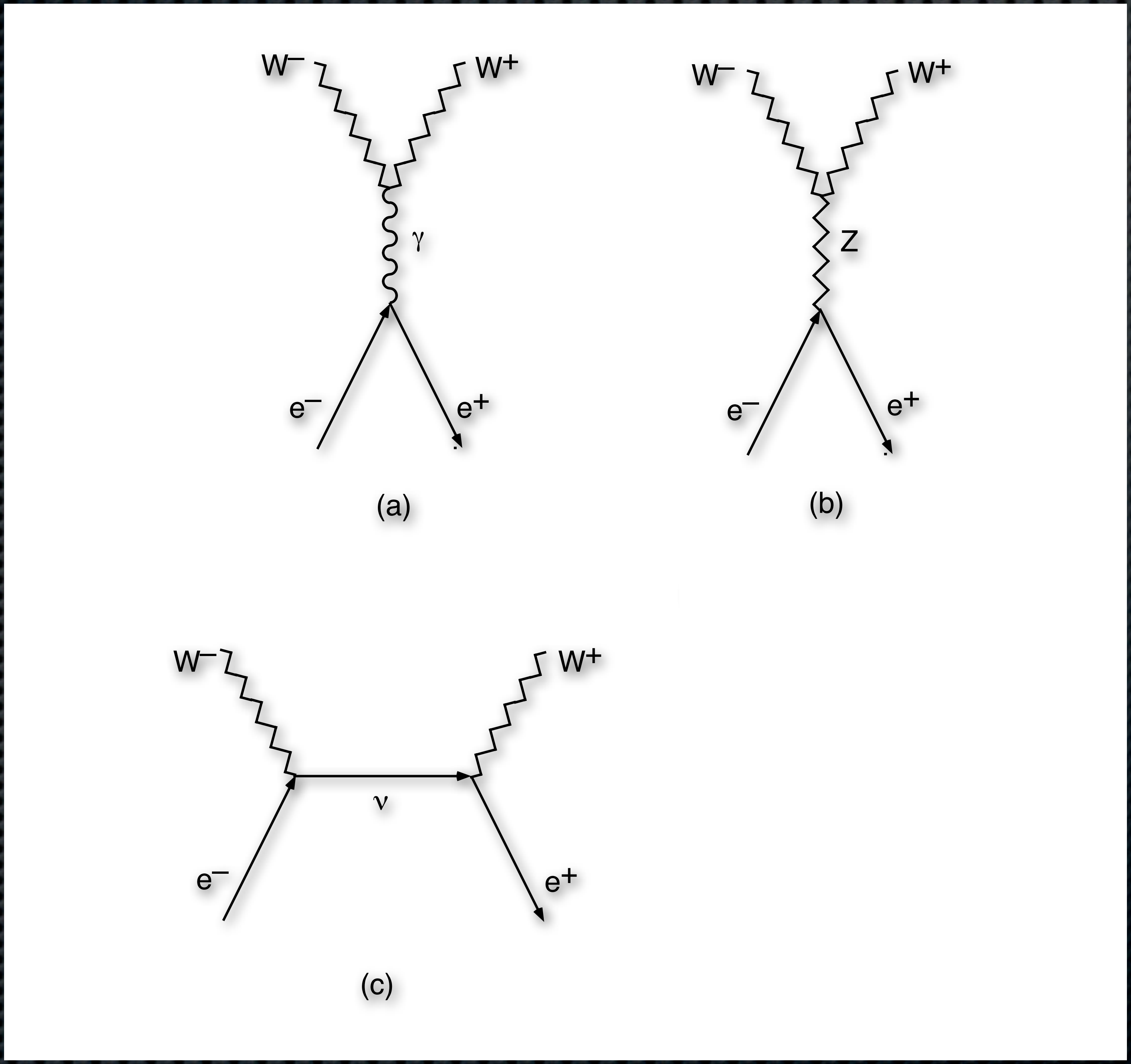
$M_W = gv/2$

$M_Z = M_W/\cos\theta_W$

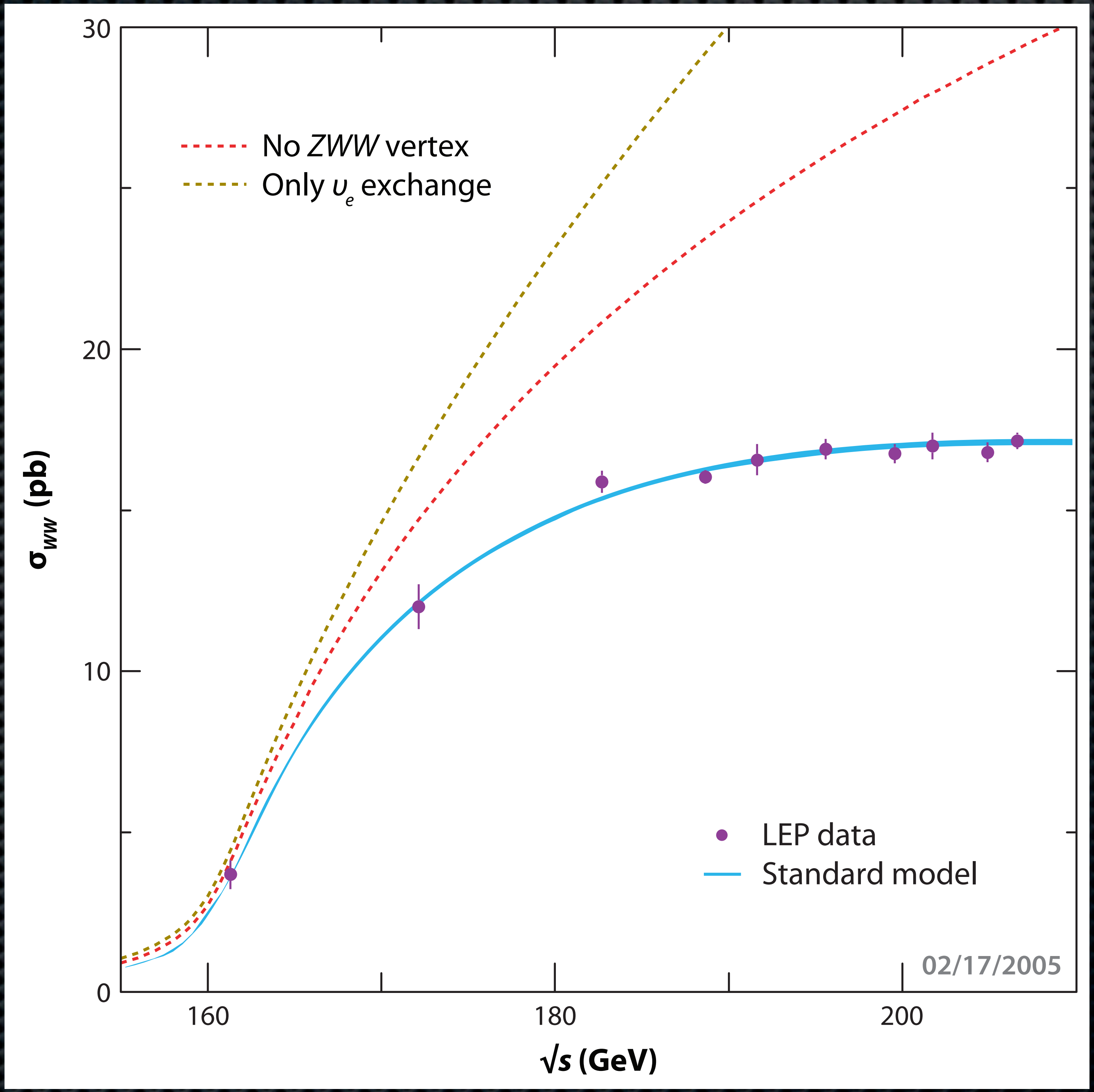
$\tan\theta_W = g'/g$ $\qquad$ $v = 246$ GeV

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



Electroweak symmetry is real



Higgs bosons: incomplete multiplets

(w_1, w_2, z, h) form O(4) multiplet

w_1, w_2, z become longitudinal W^+, W^-, Z^0

h becomes H, remembers its roots

High-energy behavior, unitarity bound, …

See end of §III, *Phys. Rev. D16,* 1519 (1977)

Fermion mass after SSB

By decree, Weinberg & Salam add interactions between fermions and scalars that give rise to quark and lepton masses.

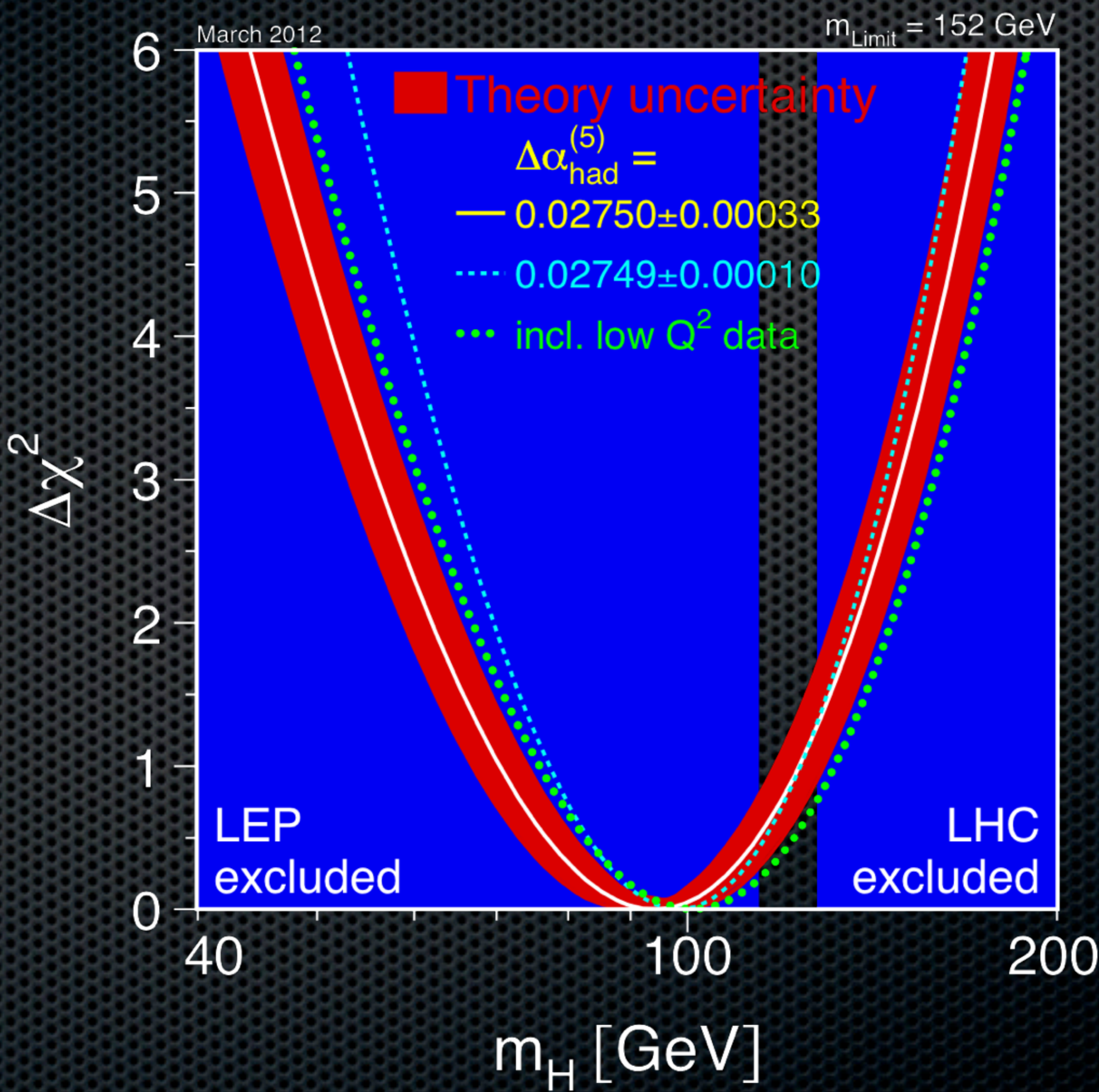
$$\zeta_e \left[(\overline{e_{\mathsf{L}}}\Phi)e_{\mathsf{R}} + \overline{e_{\mathsf{R}}}(\Phi^\dagger e_{\mathsf{L}})\right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

ζ_e : picked to give right mass, not predicted

fermion mass implies physics beyond standard model

Highly economical, but is it true?

H couplings to W, Z tested



World without SSB

Electron and quarks have no mass

QCD confines quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD hides EW symmetry,

gives tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

arXiv:0901.3958

Four tasks for the SM Higgs boson

Hide electroweak symmetry
(distinguish EM, weak interactions)

Give masses to $W^{\pm}$, Z^0

Give masses and mixings to fermions

Keep EW theory from misbehaving

High-energy behavior of EW theory

W^+W^-, ZZ, HH, HZ *s*-waves approach constants,
thanks to gauge cancellations

… satisfy *s*-wave unitarity

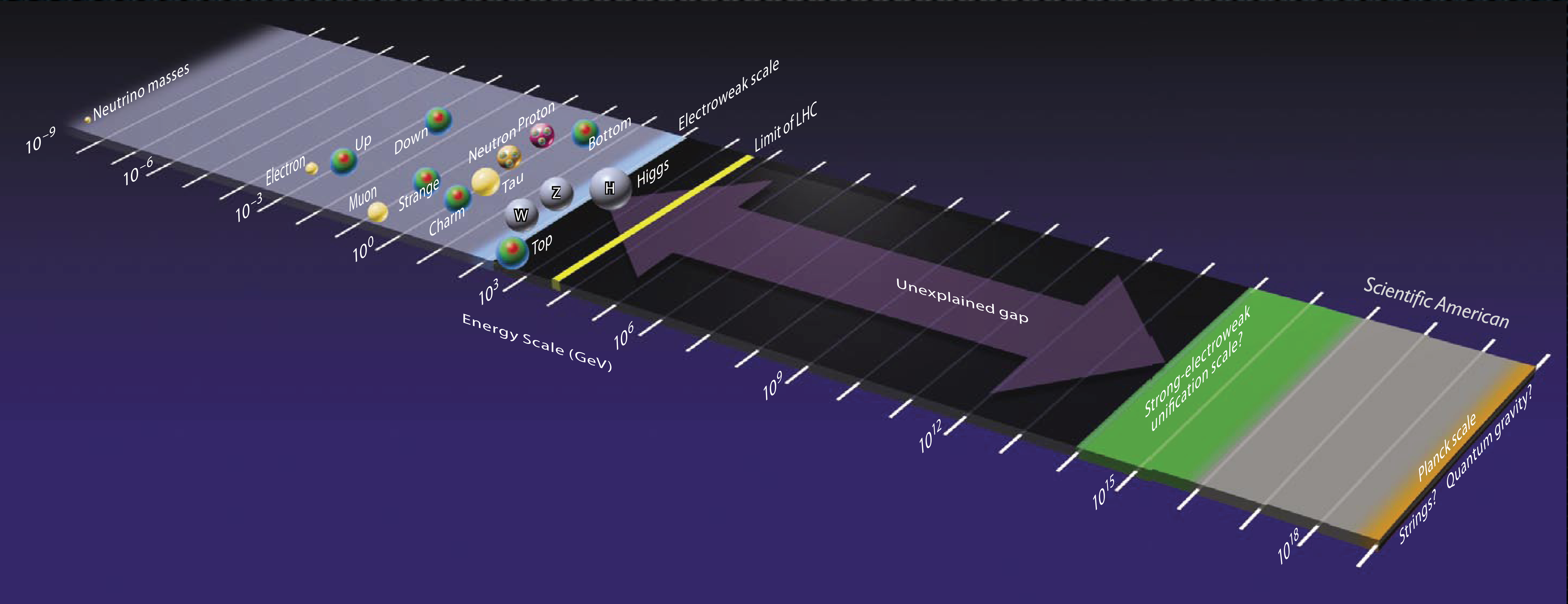
provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\ \text{TeV}}$

- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^{\pm}$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

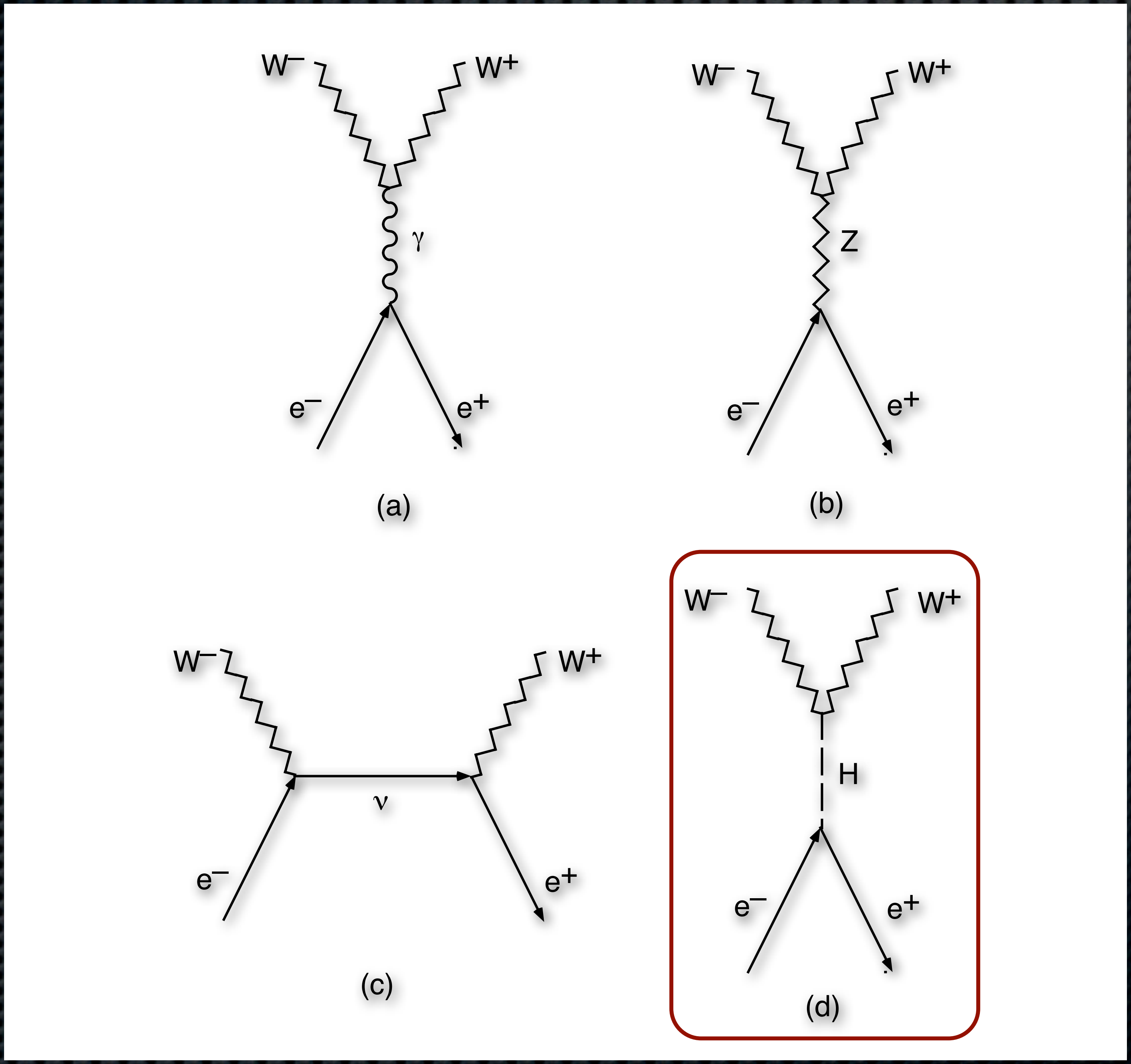
Does M_H < 1 TeV make sense?

The peril of quantum corrections



Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



Vacuum energy problem

Higgs potential $V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$

At the minimum, $V(\langle\varphi^\dagger\varphi\rangle) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0.$

Identify $M_H^2 = -2\mu^2$

$V \neq 0$ contributes position-independent vacuum energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{24} \text{ g cm}^{-3}$$

Observed vacuum energy density $\varrho_{\text{vac}} \lesssim 10^{-46} \text{ GeV}^4$

Mismatch by 54 orders of magnitude

EWSB and other questions

Origin of fermion masses and mixings
Meaning of CP violation
Lessons for cosmic inflation?
Connection to dark matter?
Insights for dark energy problem?
Link with extra spacetime dimensions?
Connection to gravity through supersymmetry?

From “Unanswered Questions in EW Theory”

1. What is the agent that hides the electroweak symmetry? Specifically, is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
4. What stabilizes the Higgs boson mass below 1 TeV?
5. Do the different behaviors of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?
6. What will be the next symmetry recognized in nature? Is nature supersymmetric? Is the electroweak theory part of some larger edifice?
7. Are there additional generations of quarks and leptons?
8. What resolves the vacuum energy problem?
9. Is electroweak symmetry breaking an emergent phenomenon connected with strong dynamics? Is electroweak symmetry breaking related to gravity through extra spacetime dimensions?
10. What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

The new world is here. Time to explore!

?

The 2012 SSI Challenge:
Name that boson!

If the particle discovered by ATLAS & CMS is the avatar of electroweak symmetry breaking, what would *you* call it?

Submit your proposal plus
≤3 sentences explaining
etymology, making the case, etc.

All entries are welcome, but
only students may compete for prizes
including a bottle of
California's finest sparkling wine
signed by a gaggle of SLAC luminaries

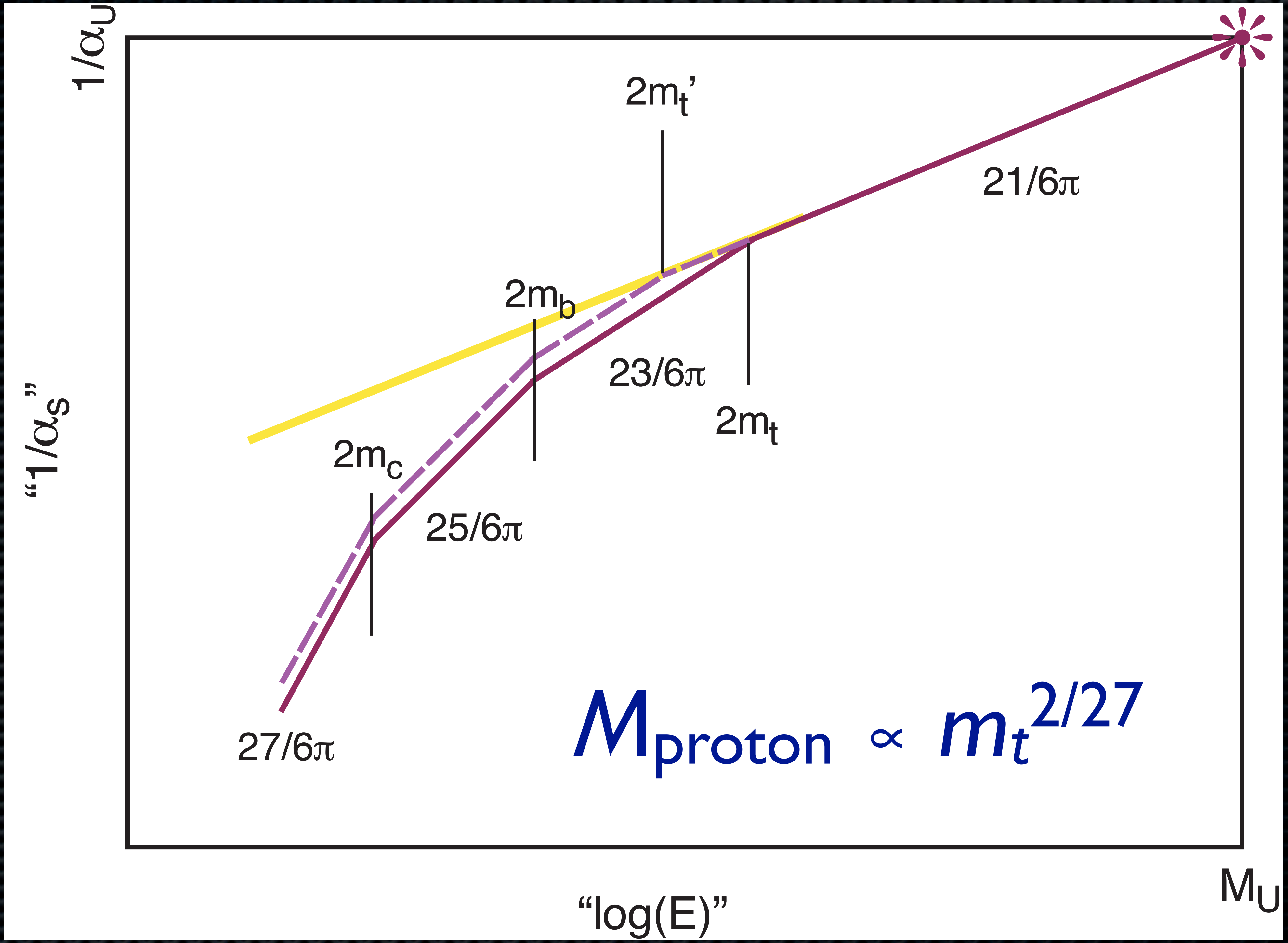
Inspirational Reading

The case for change: http://j.mp/OibSpI

The case for brand loyalty: http://j.mp/MUAse7

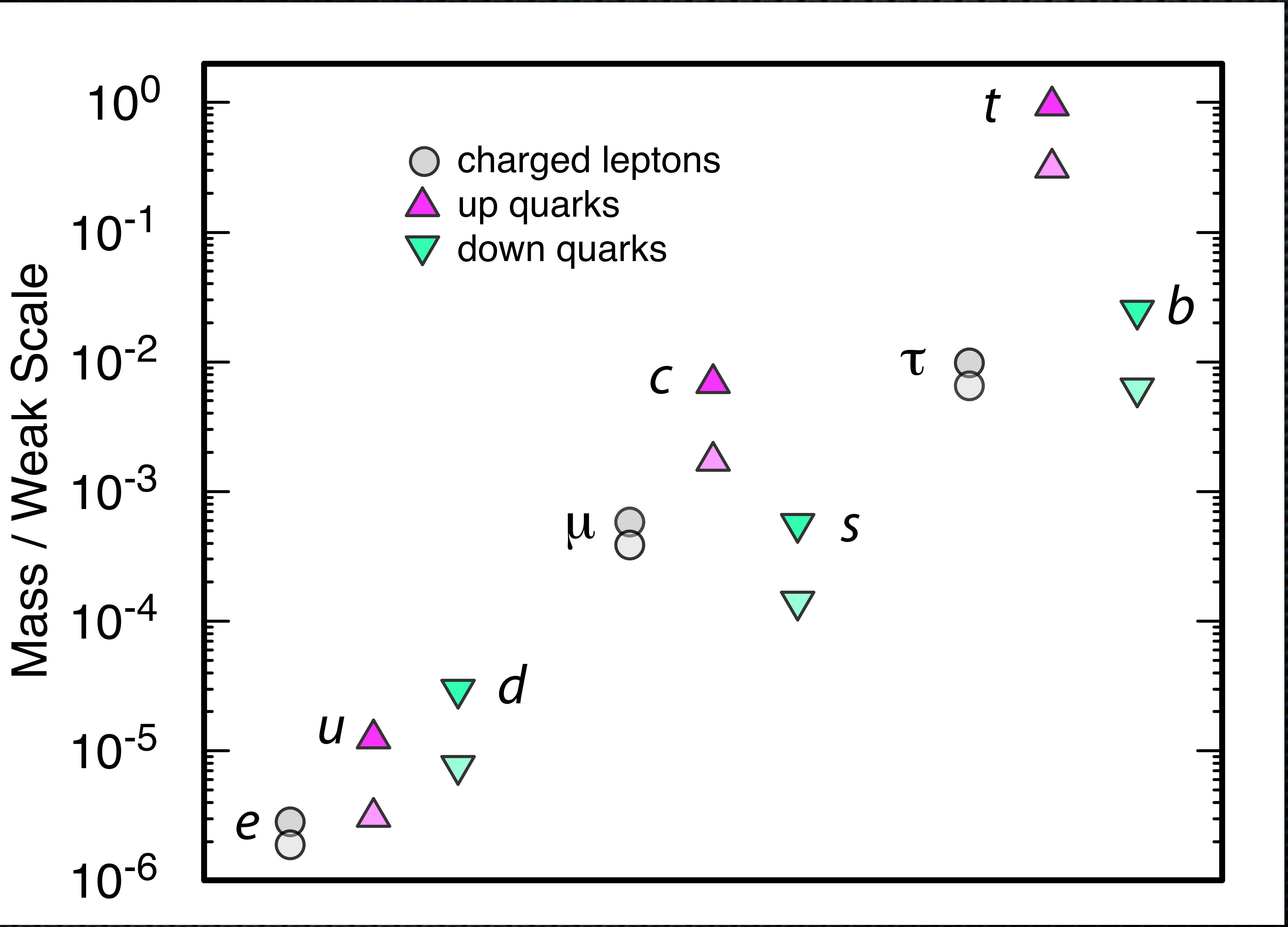
Supplementary slides

Unified theory: Smaller top mass means smaller α_s



hep-ph/9704332

Fermion Masses



Running mass *m*(*m*) … *m*(*U*)

Might we live in a metastable vacuum?