

# The Higgs Boson for the Masses?

Chris Quigg

# Symmetry

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Indistinguishable  
before and after a transformation

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Indistinguishable  
before and after a transformation

*Unobservable*  
quantity would vanish if symmetry held

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Indistinguishable  
before and after a transformation

*Unobservable*  
quantity would vanish if symmetry held

Disorder  
order = reduced symmetry

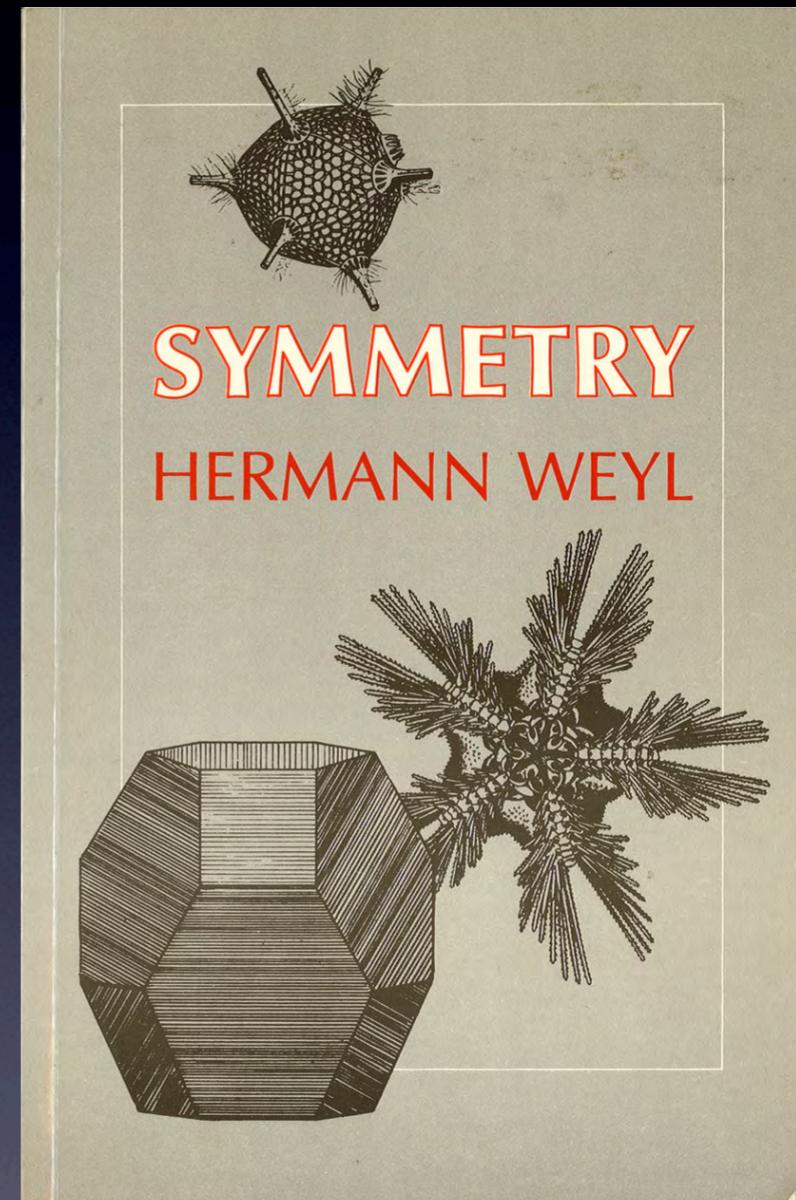
# Symmetry

Bilateral

Translational, rotational, ...

Ornamental

Crystals



# Symmetry

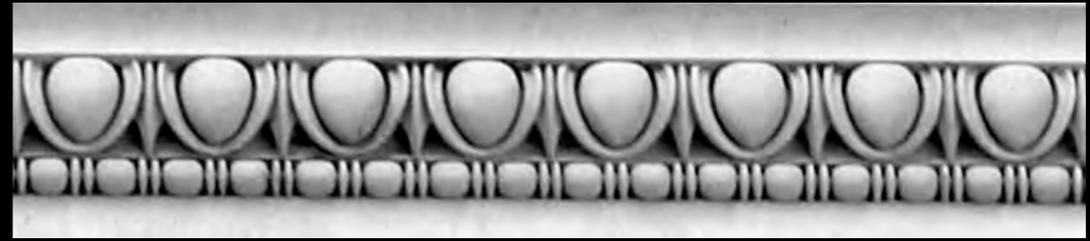
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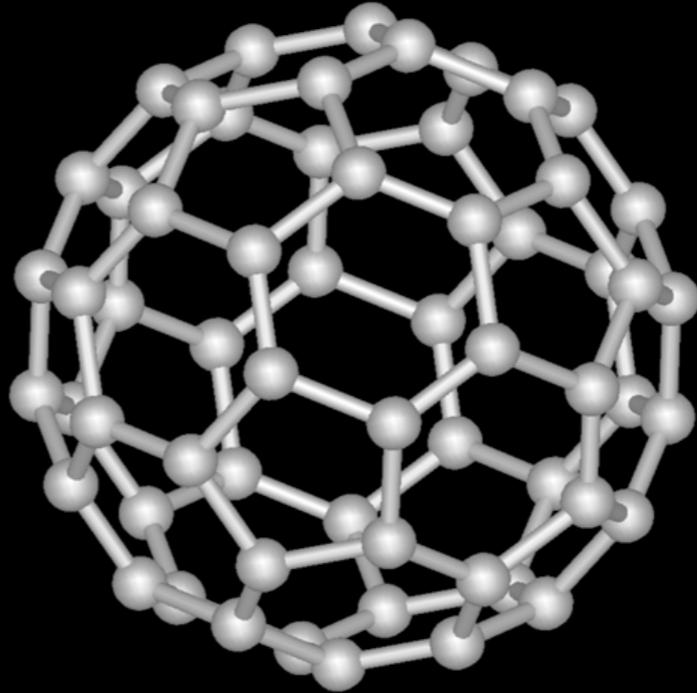
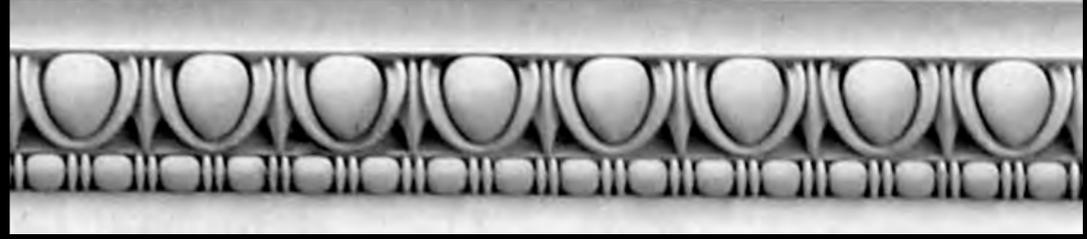
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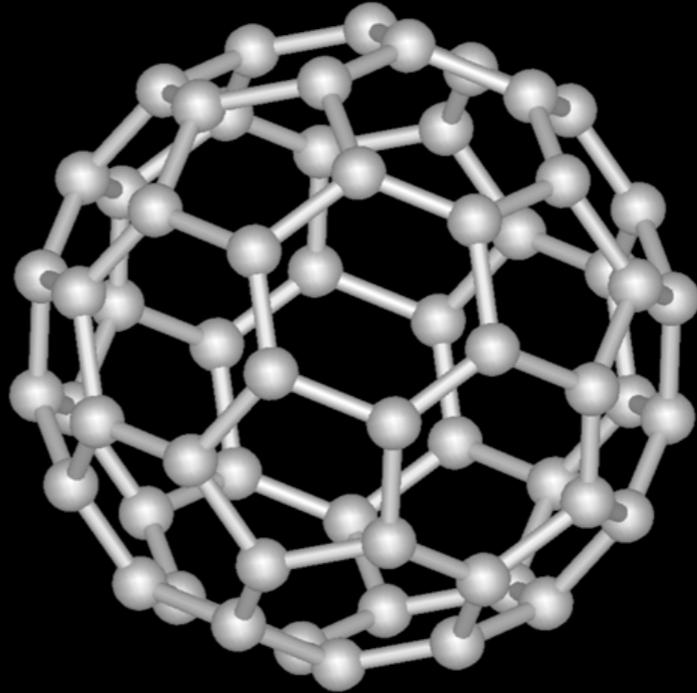
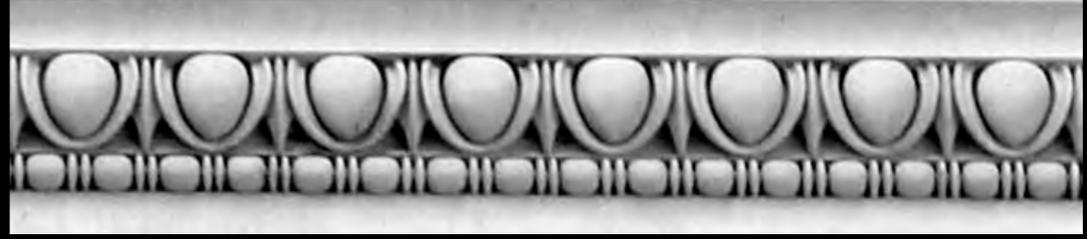


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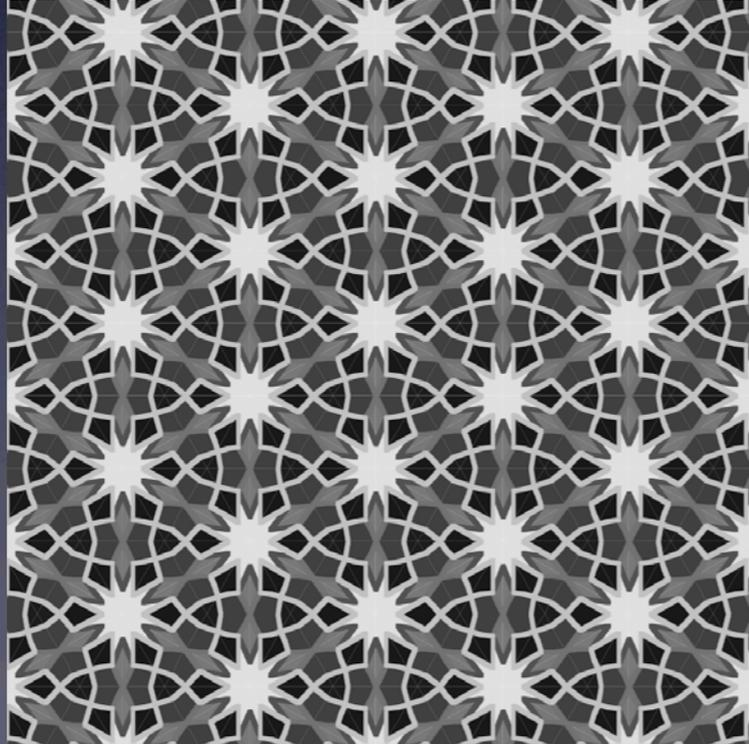


Fullerene C60 ball and stick created from a PDB using Piotr Rotkiewicz's [<http://www.pirx.com/iMol/iMol>]. `{{gtal}}` Source: English Wikipedia,

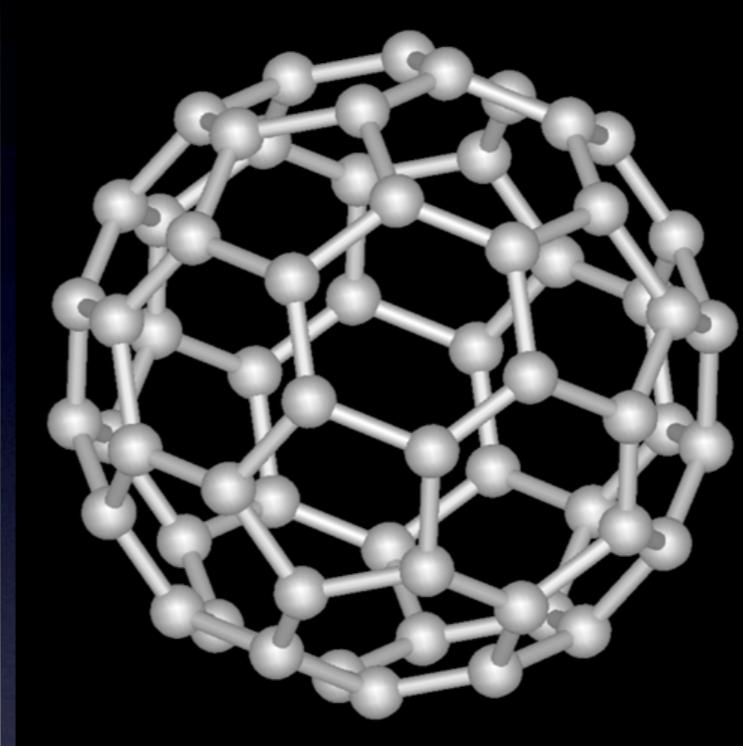
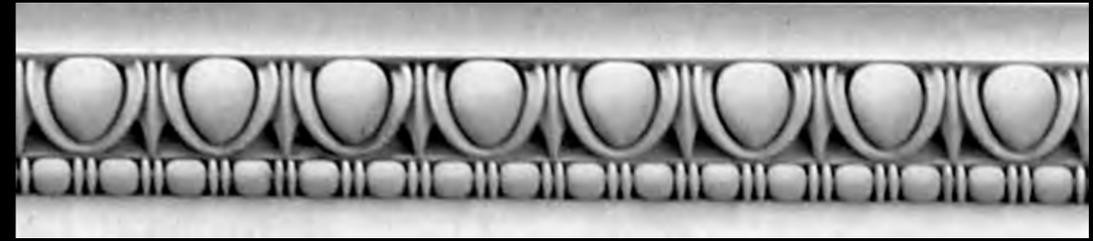
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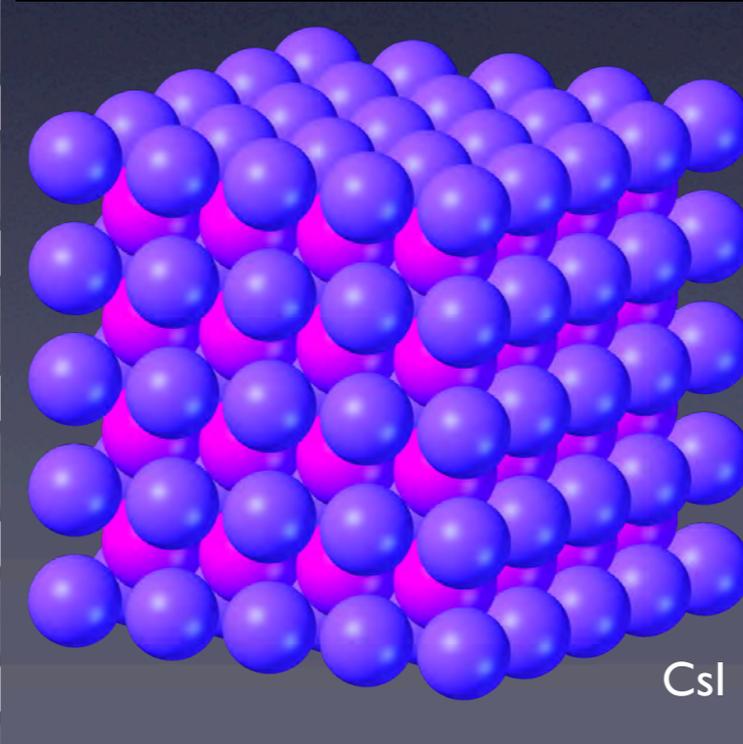
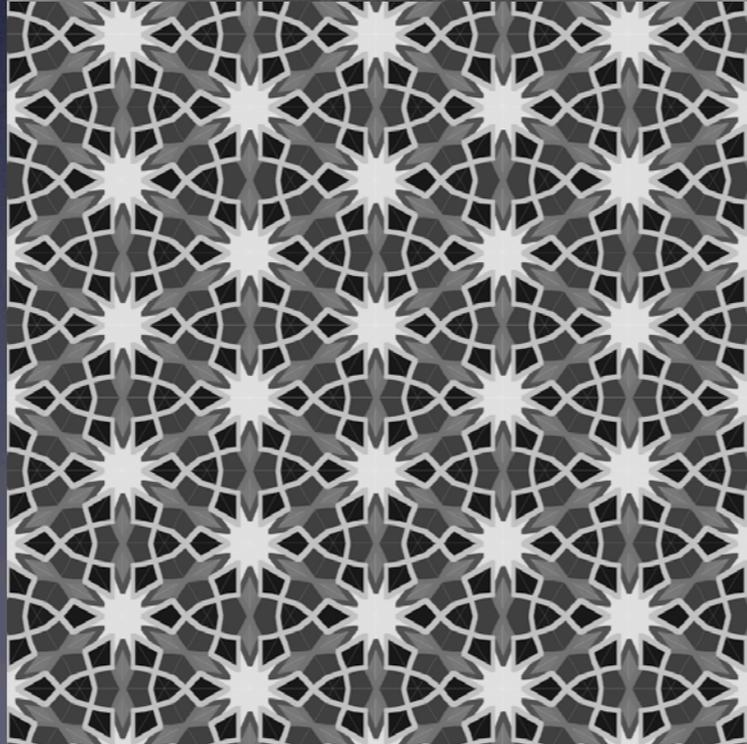
Fullerene C60 ball and stick created from a PDB using Piotr Rotkiewicz's [<http://www.pirx.com/iMol/iMol>]. `{{gtag}}` Source: English Wikipedia,



# Symmetry



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



CsI

# Symmetry (continuous)

# Symmetry (continuous)



# Symmetry (continuous)





Symmetry matters.

Broken symmetry  
is interesting.

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 female professors, and then being a Jew-



**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 of how she felt about the difficulties she

# Symmetries & conservation laws

Spatial translation	<i>Momentum</i>
Time translation	<i>Energy</i>
Rotational invariance	<i>Angular momentum</i>
QM phase	<i>Charge</i>

Symmetries of laws

*need not imply*

symmetries of outcomes.

Symmetries of laws

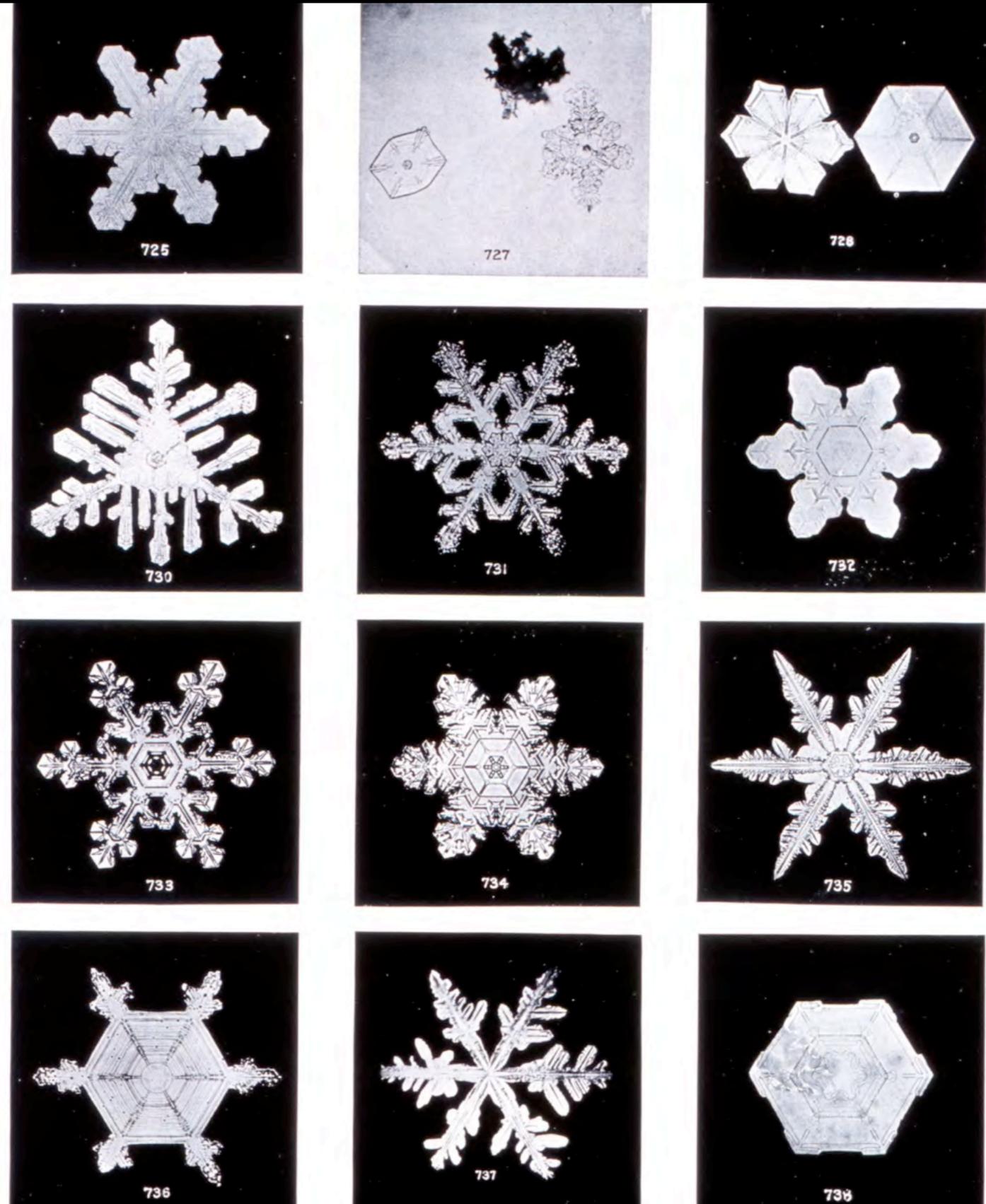
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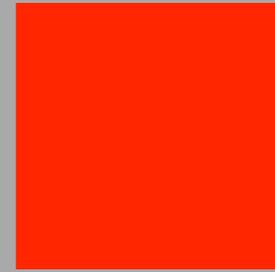
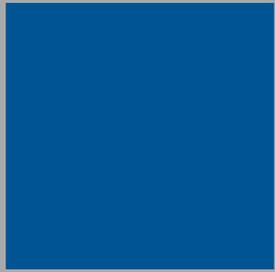
Secret (hidden) symmetries

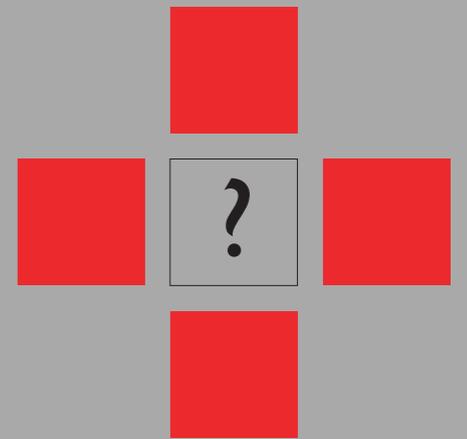
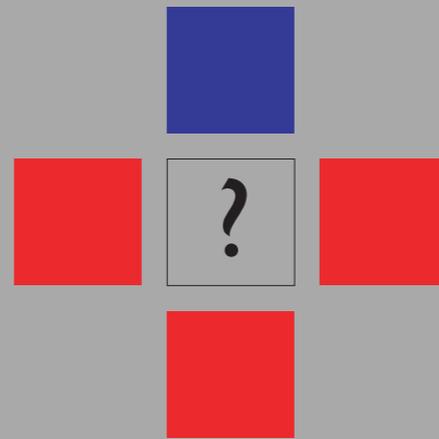
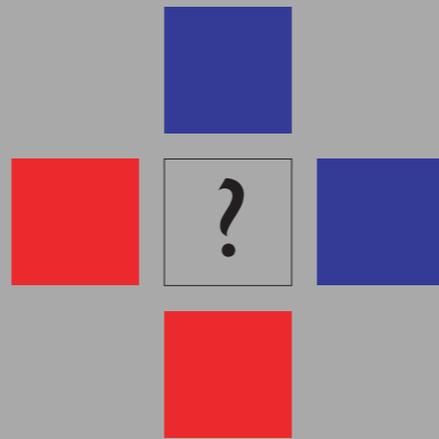
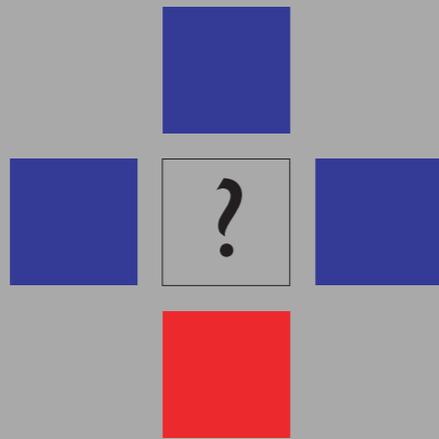
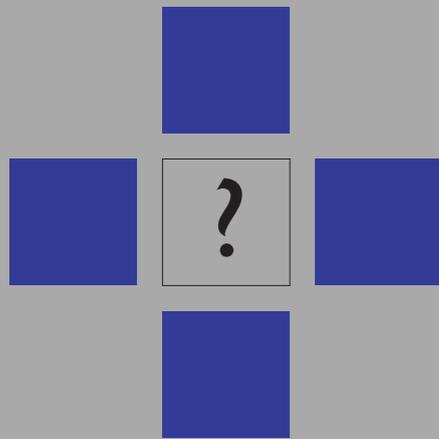
symmetries of laws  $\Rightarrow$  symmetries of outcomes

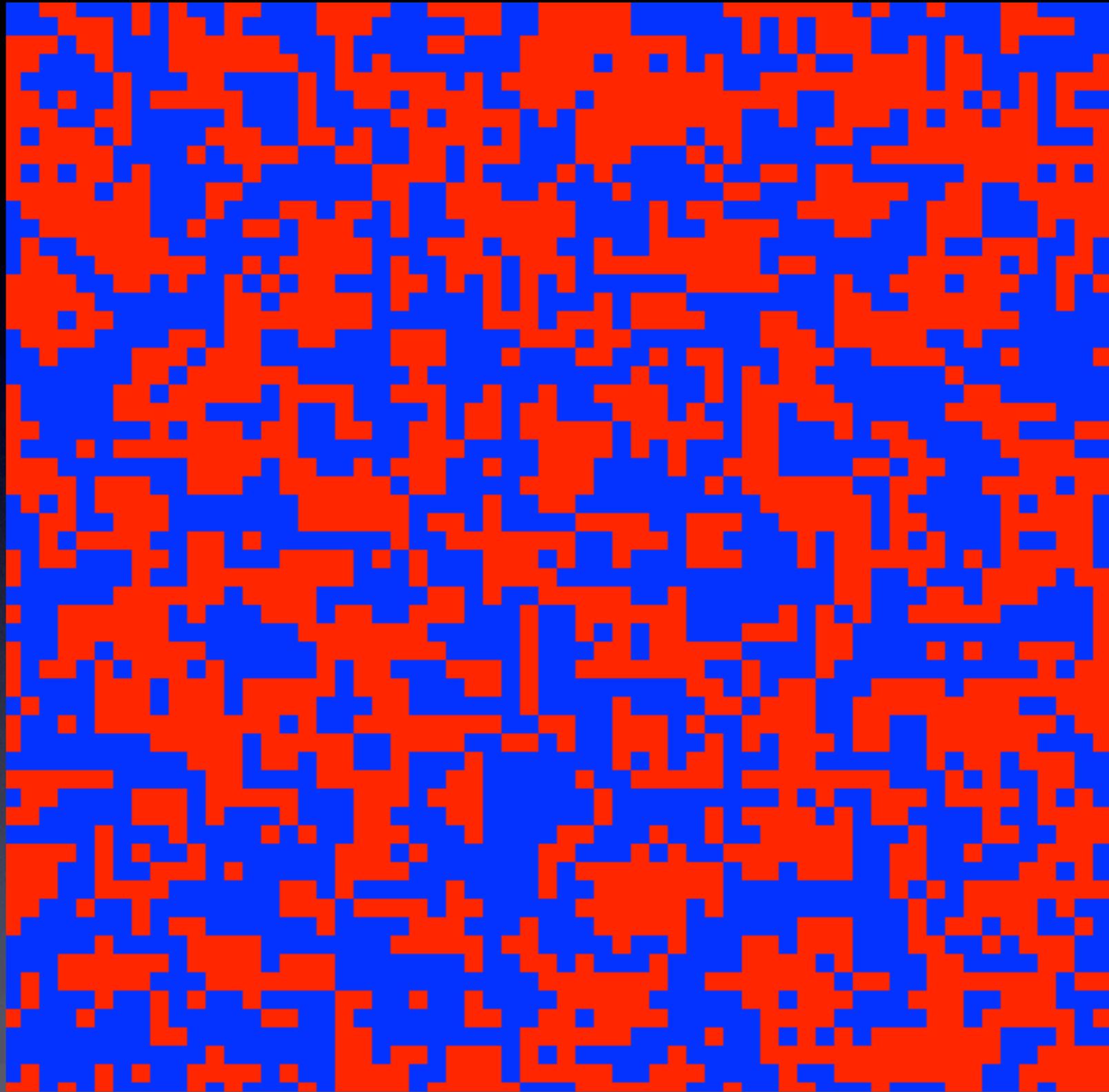
# symmetries of laws $\Rightarrow$ symmetries of outcomes



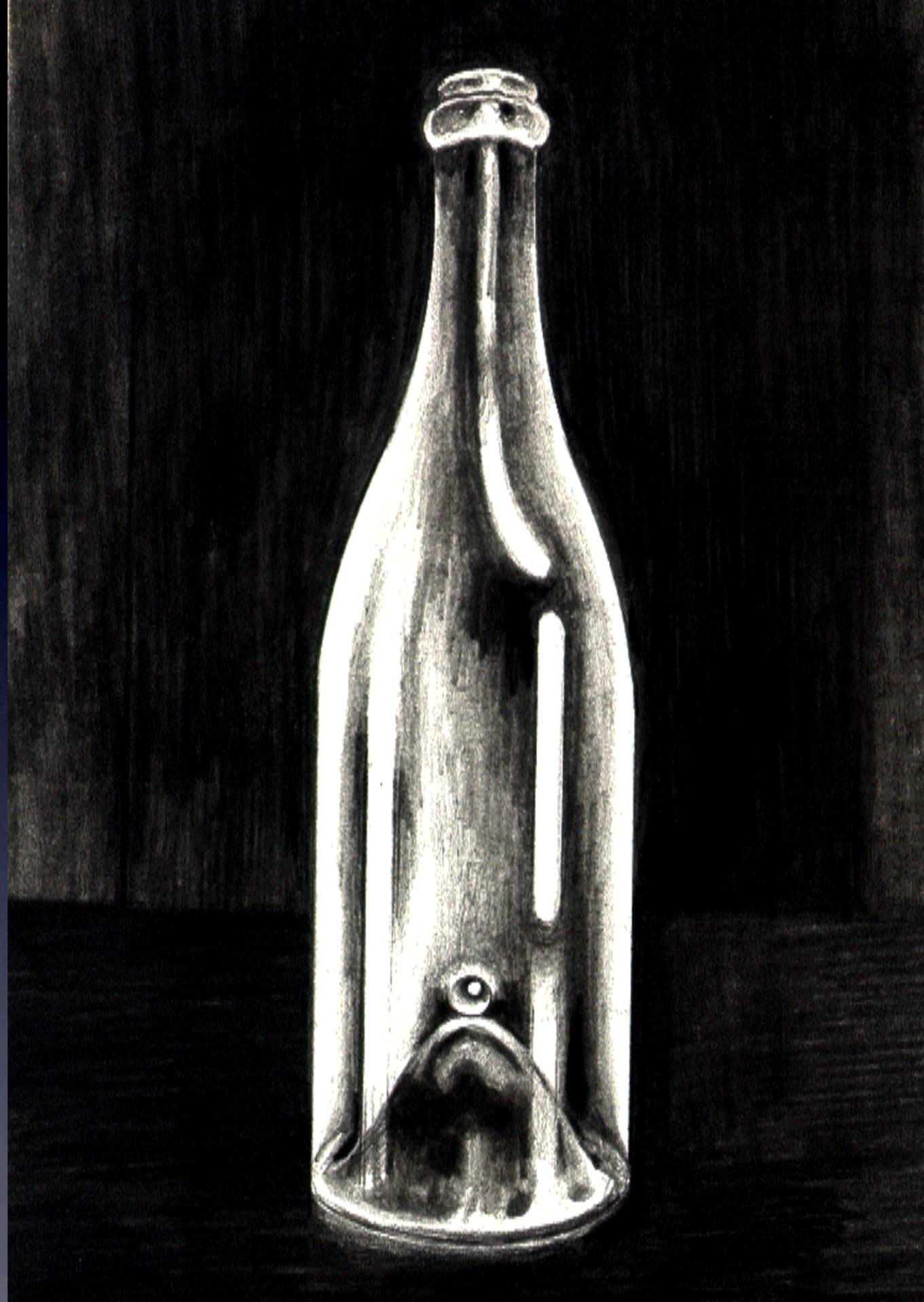
Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library



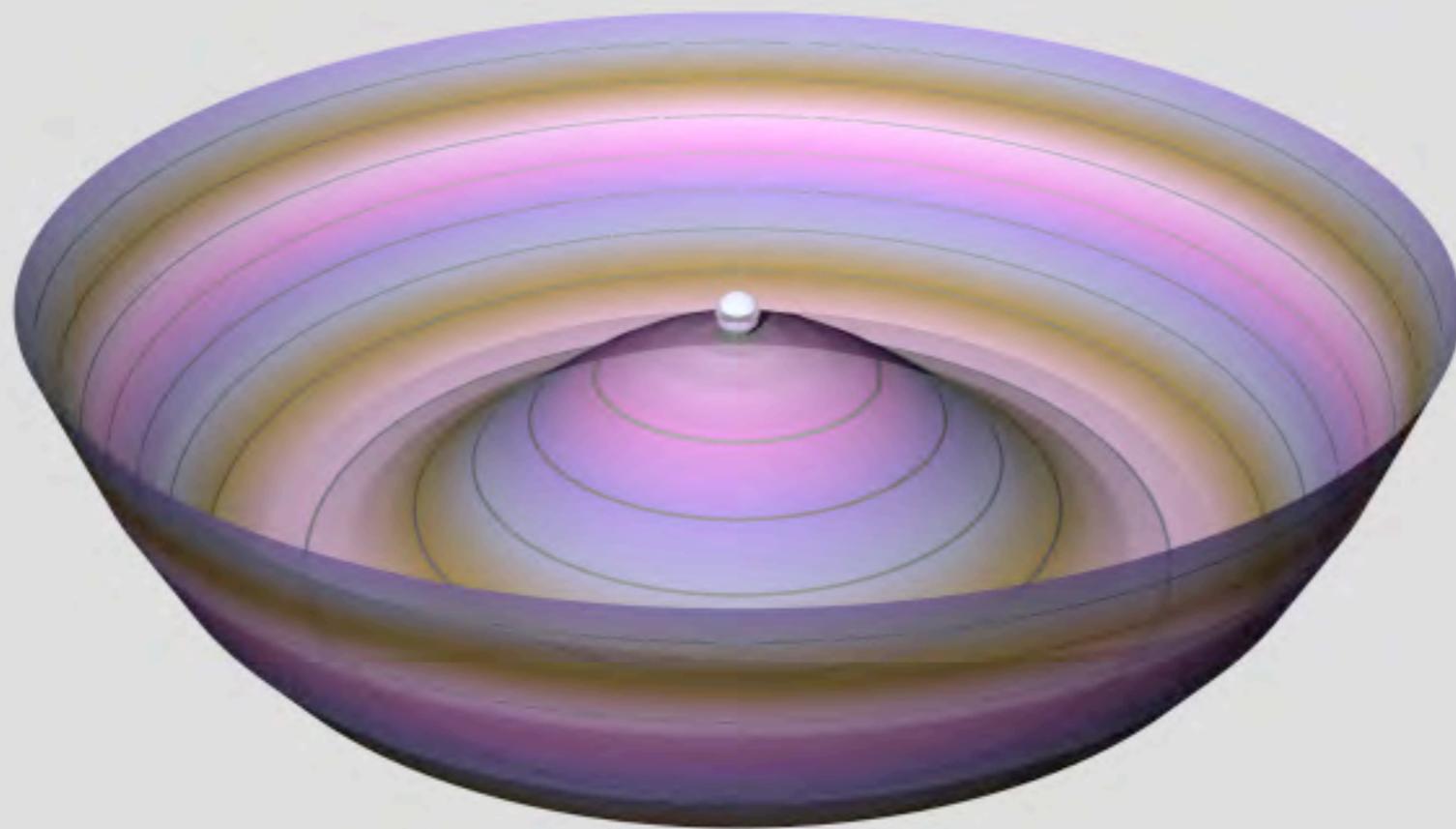


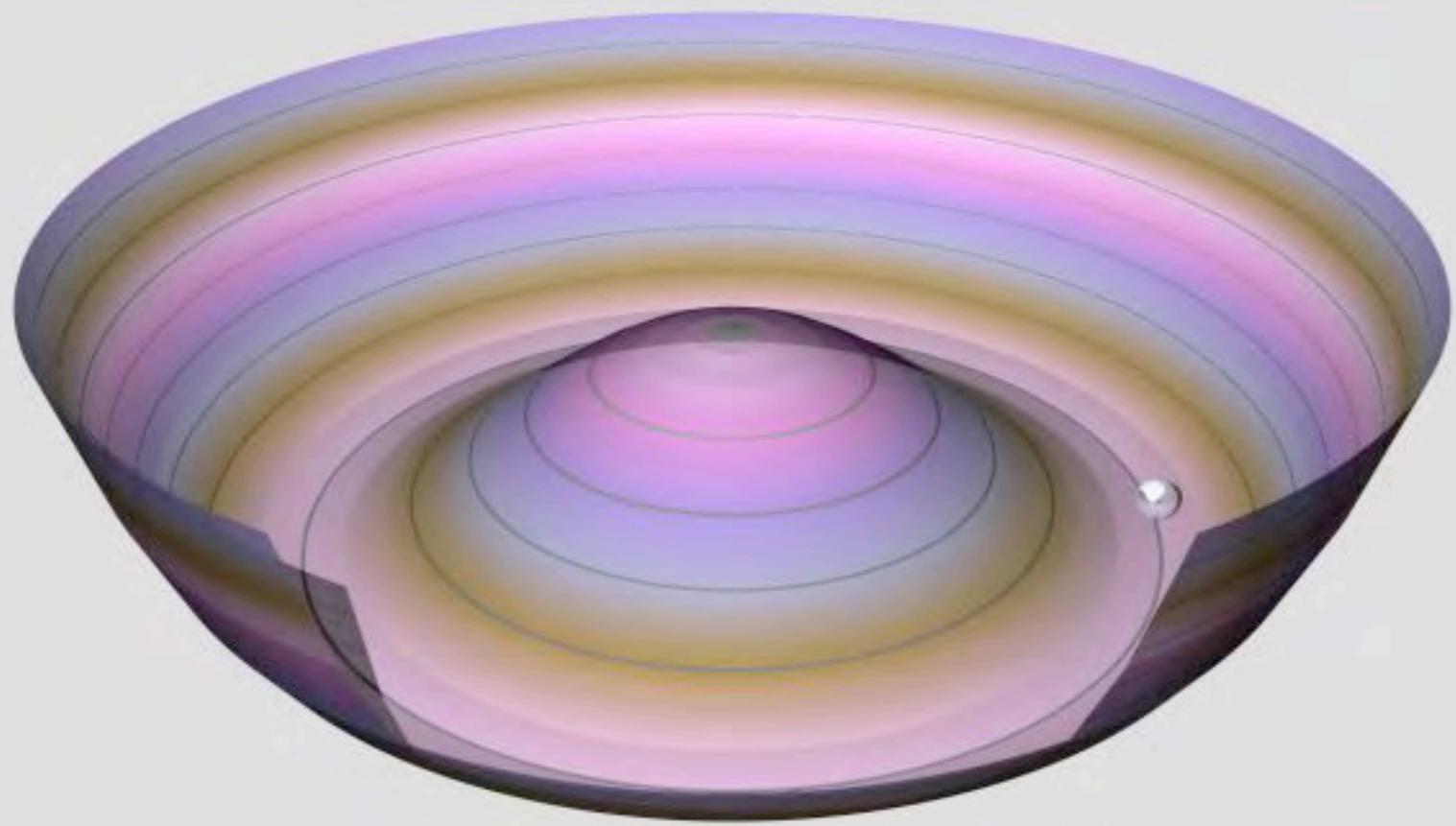




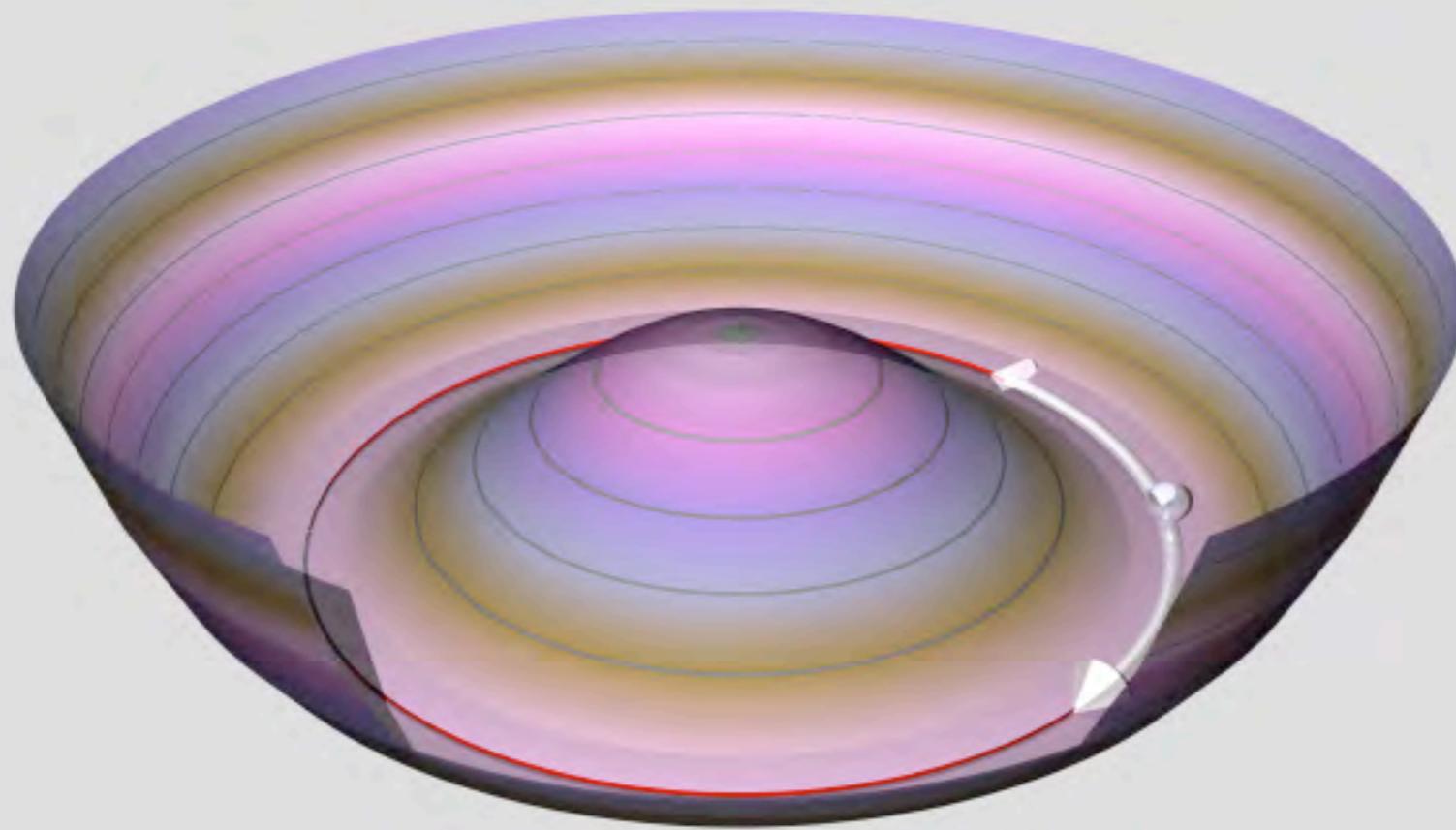


Continuum of degenerate vacua

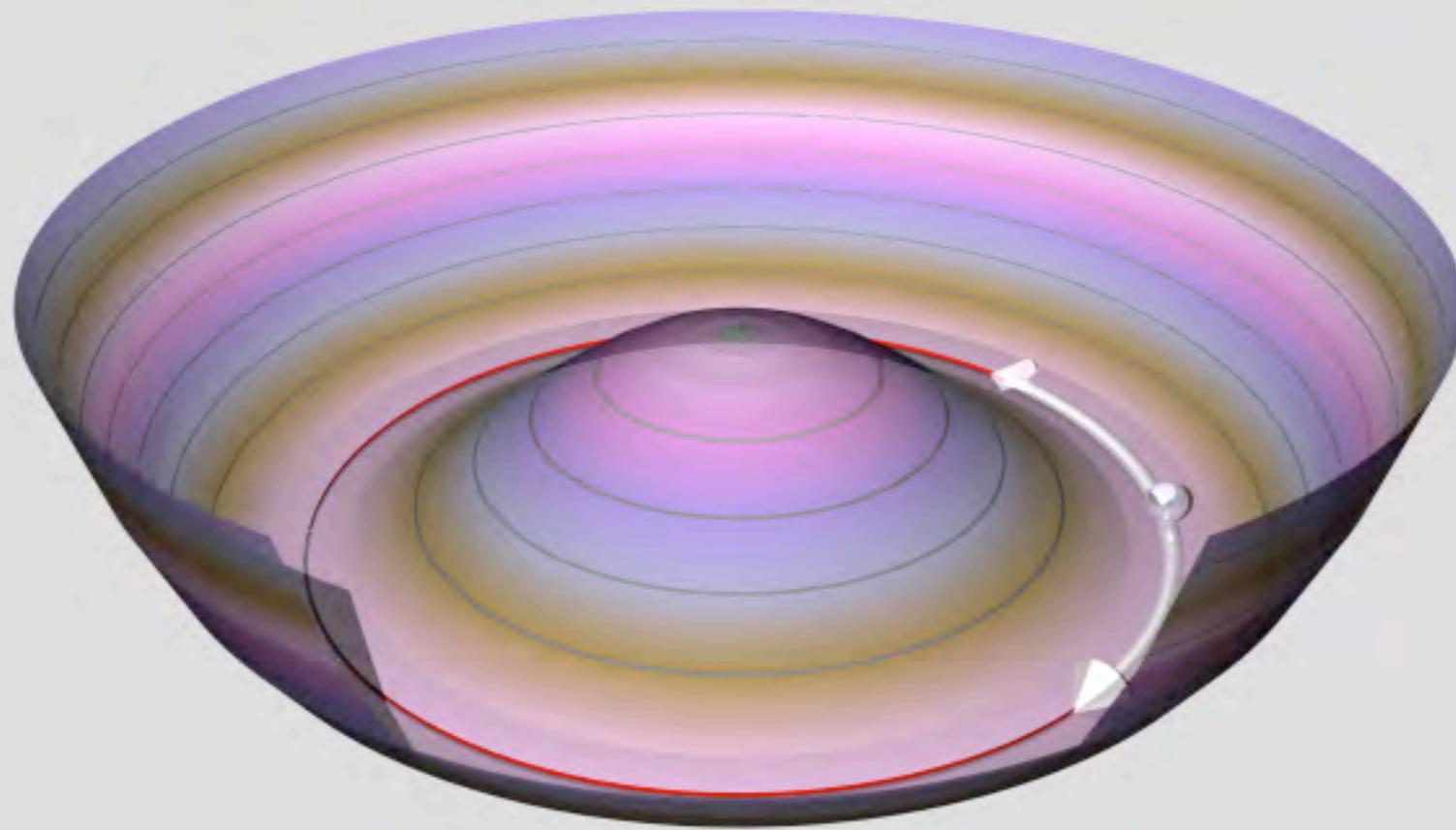




# Nambu–Goldstone bosons



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*NGBs as spin waves, phonons, pions, ...*

# Nambu–Goldstone bosons

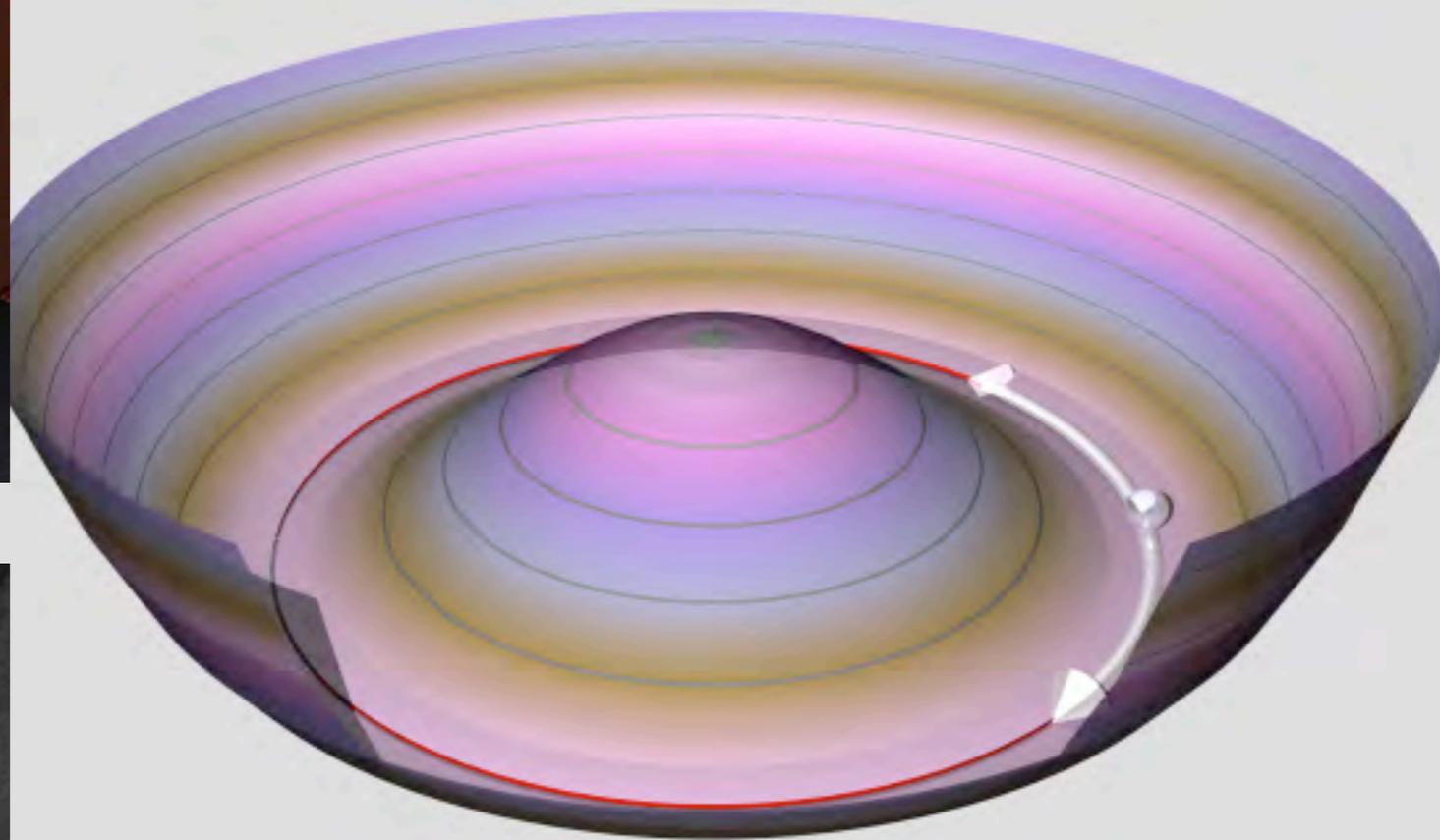
Betsy Devine



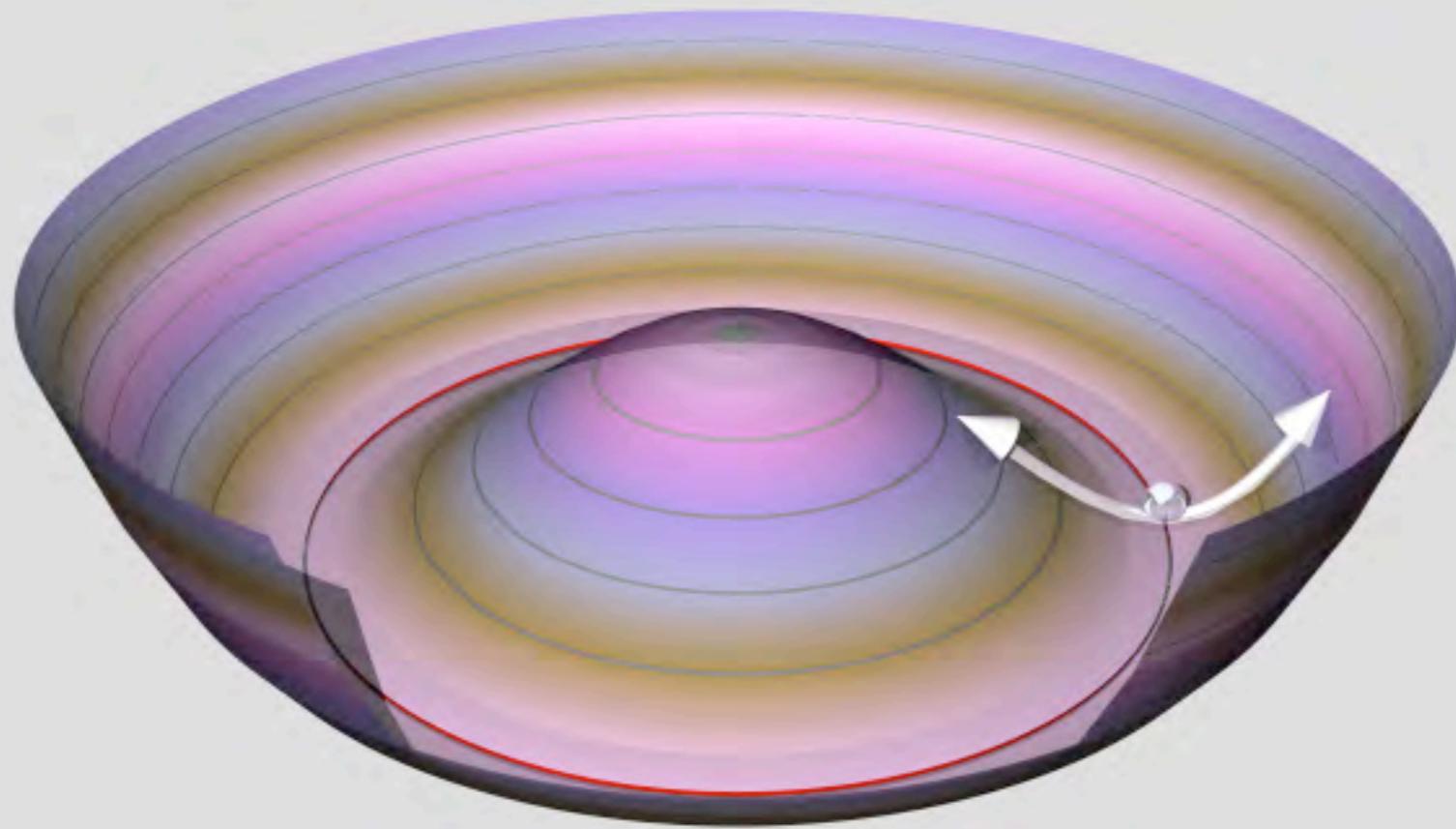
Yoichiro Nambu



Jeffrey Goldstone



*NGBs as spin waves, phonons, pions, ...*



*Massive scalar boson*

# Form follows function.

Carson, Pirie, Scott Building



Louis Sullivan (1896)

# Function follows form. I

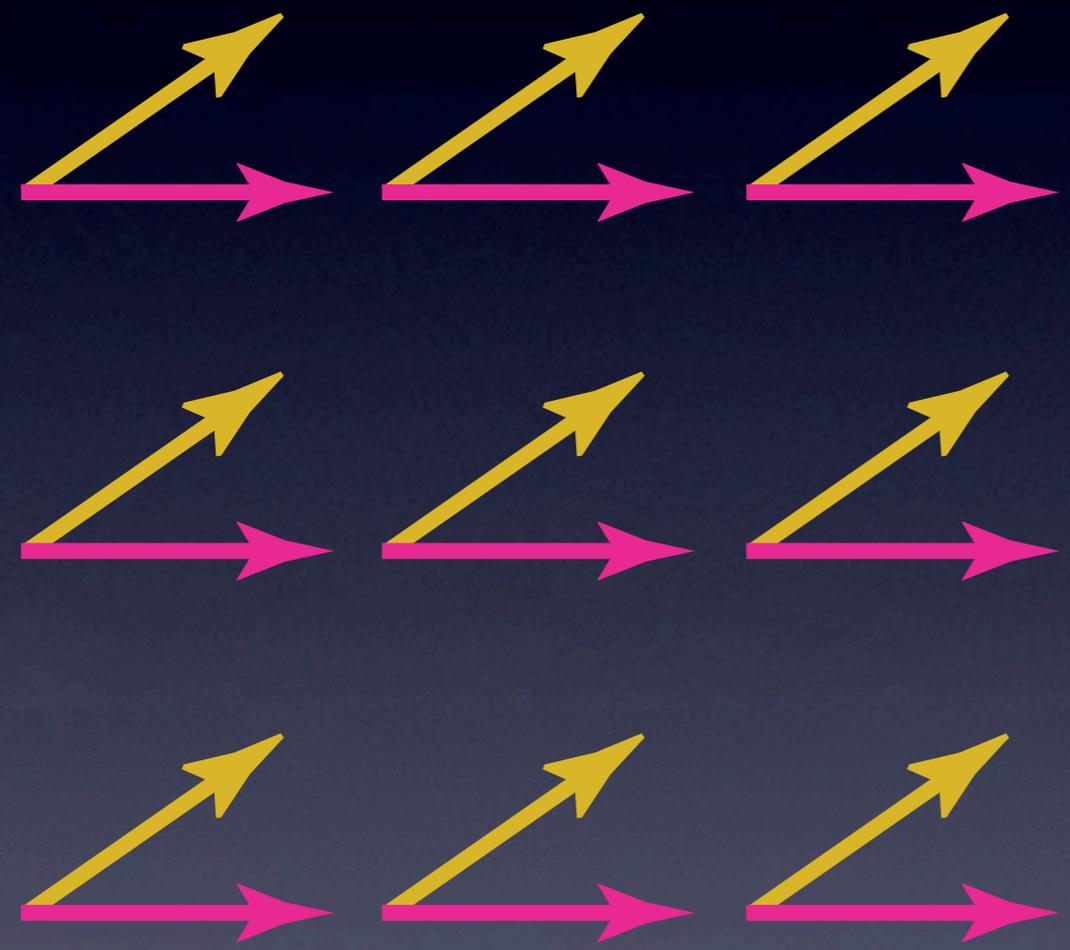


Hermann Weyl (1918, 1929)

# Complex phase in QM

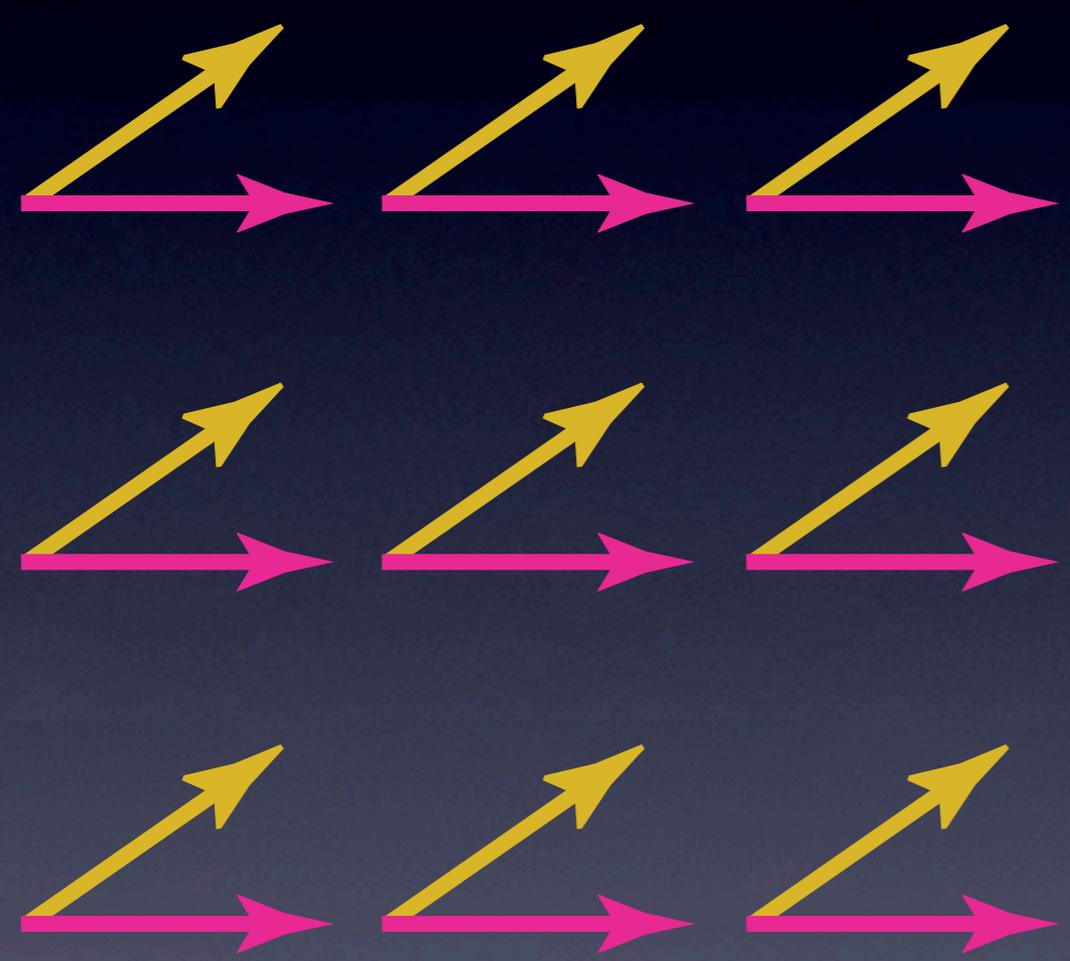


# Complex phase in QM

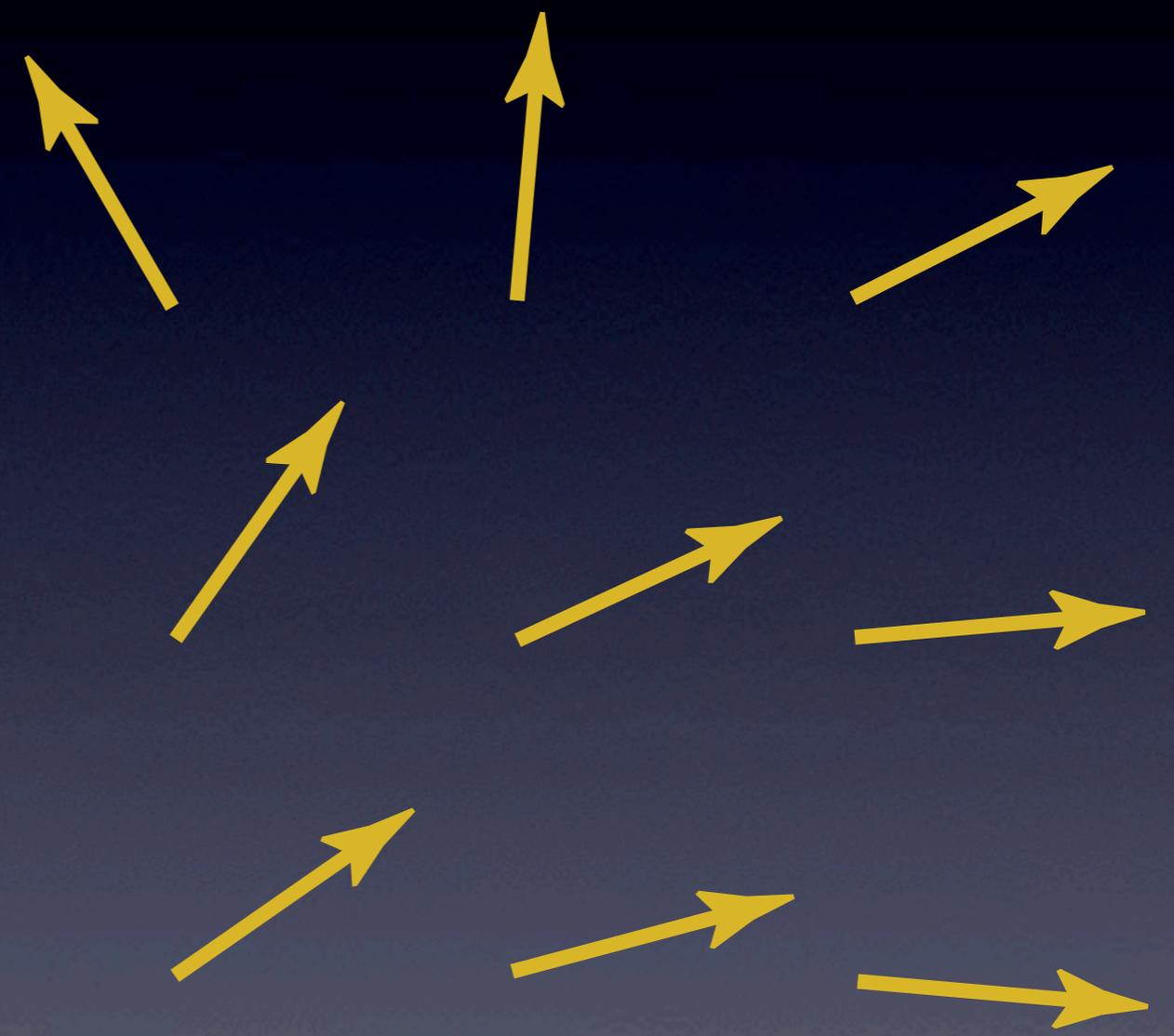


Global: free particle

# Complex phase in QM



Global: free particle



Local: interactions

# Maxwell's equations; QED



James Clerk Maxwell (1861/2)

massless photon  
coupled to conserved charge  
*no impediment to electron mass*

# Maxwell's equations; QED



James Clerk Maxwell (1861/2)

massless photon  
coupled to conserved charge  
*no impediment to electron mass*

( $e_L$  &  $e_R$  have same charge)

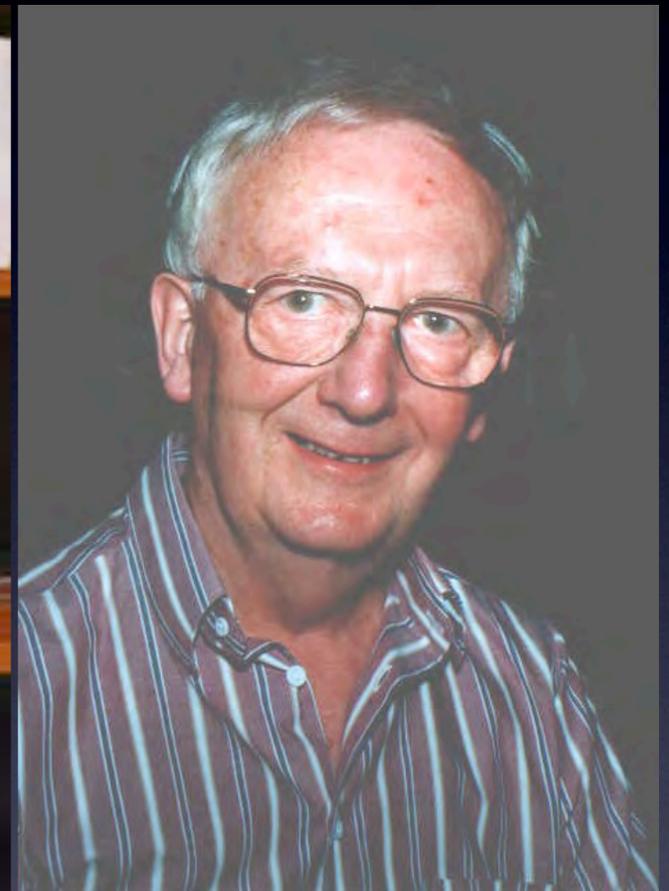
# Function follows form. II



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*

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# Might hiding symmetry help?

Seems to add massless NGBs  
to massless gauge bosons

*Goldstone theorem proved  
with ever-increasing rigor*

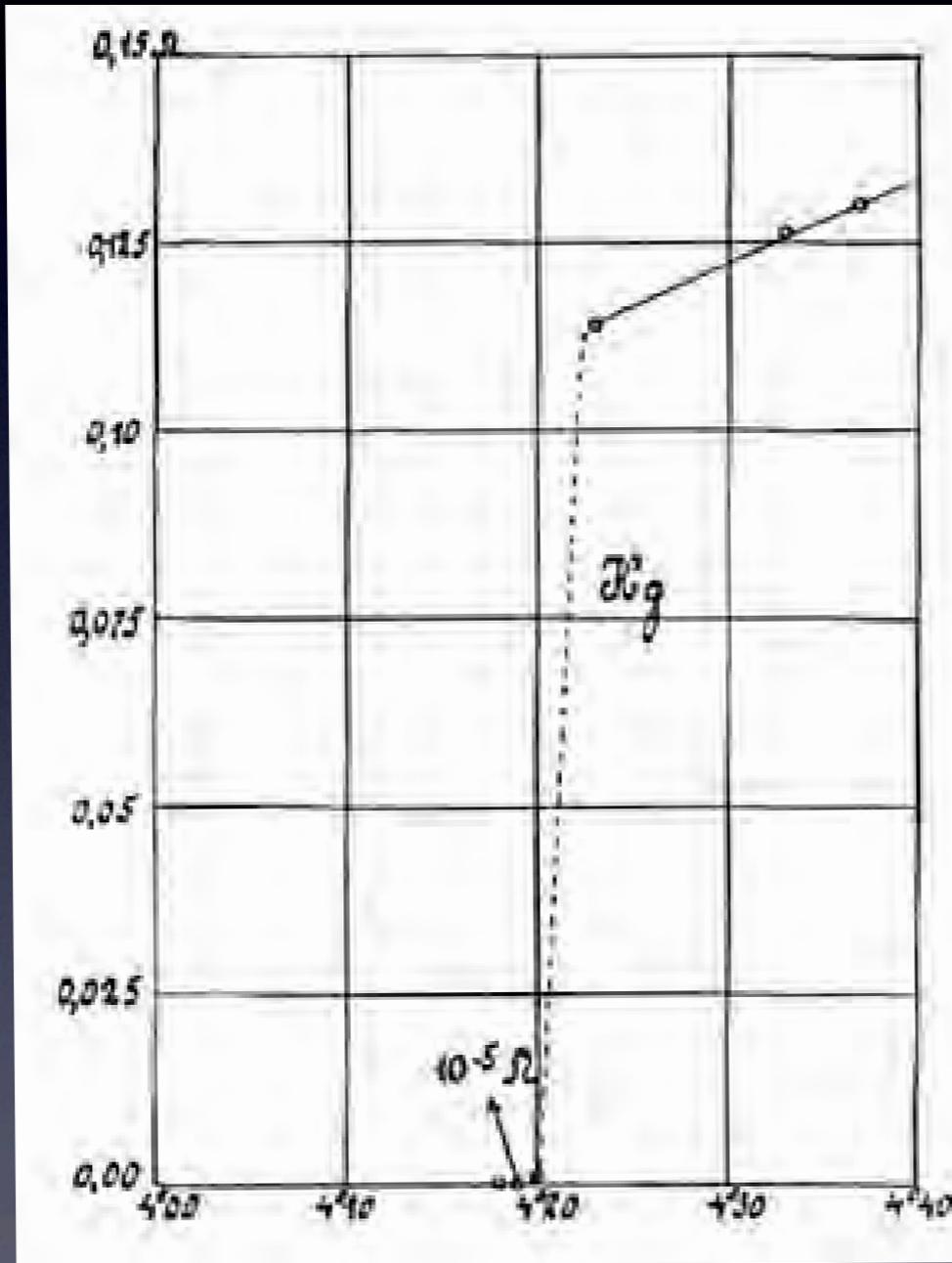
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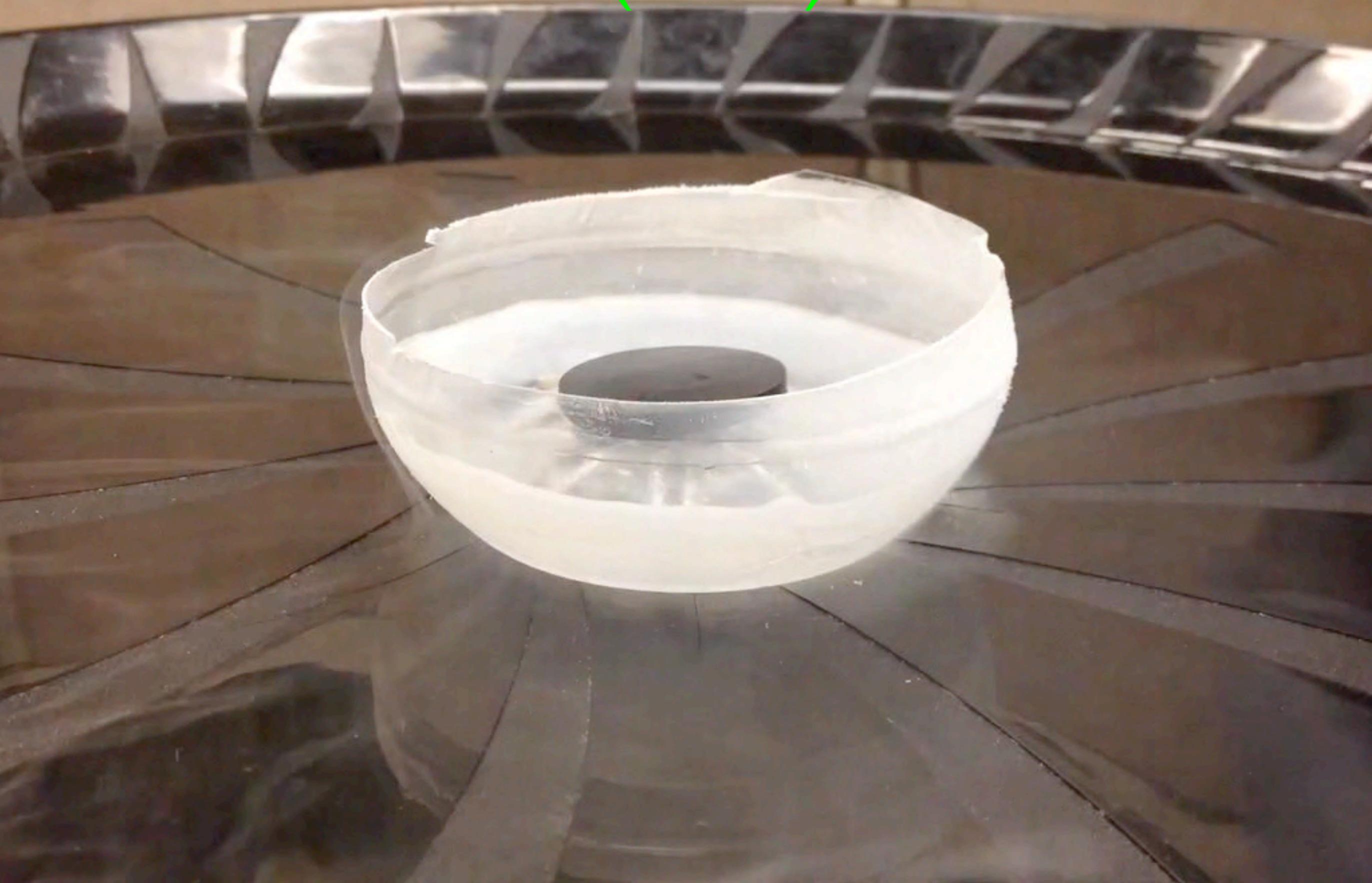
*Goldstone theorem proved  
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# Superconductivity (1911)



Heike Kamerlingh Onnes

# Meissner effect (1933)



# Magnetic fields excluded

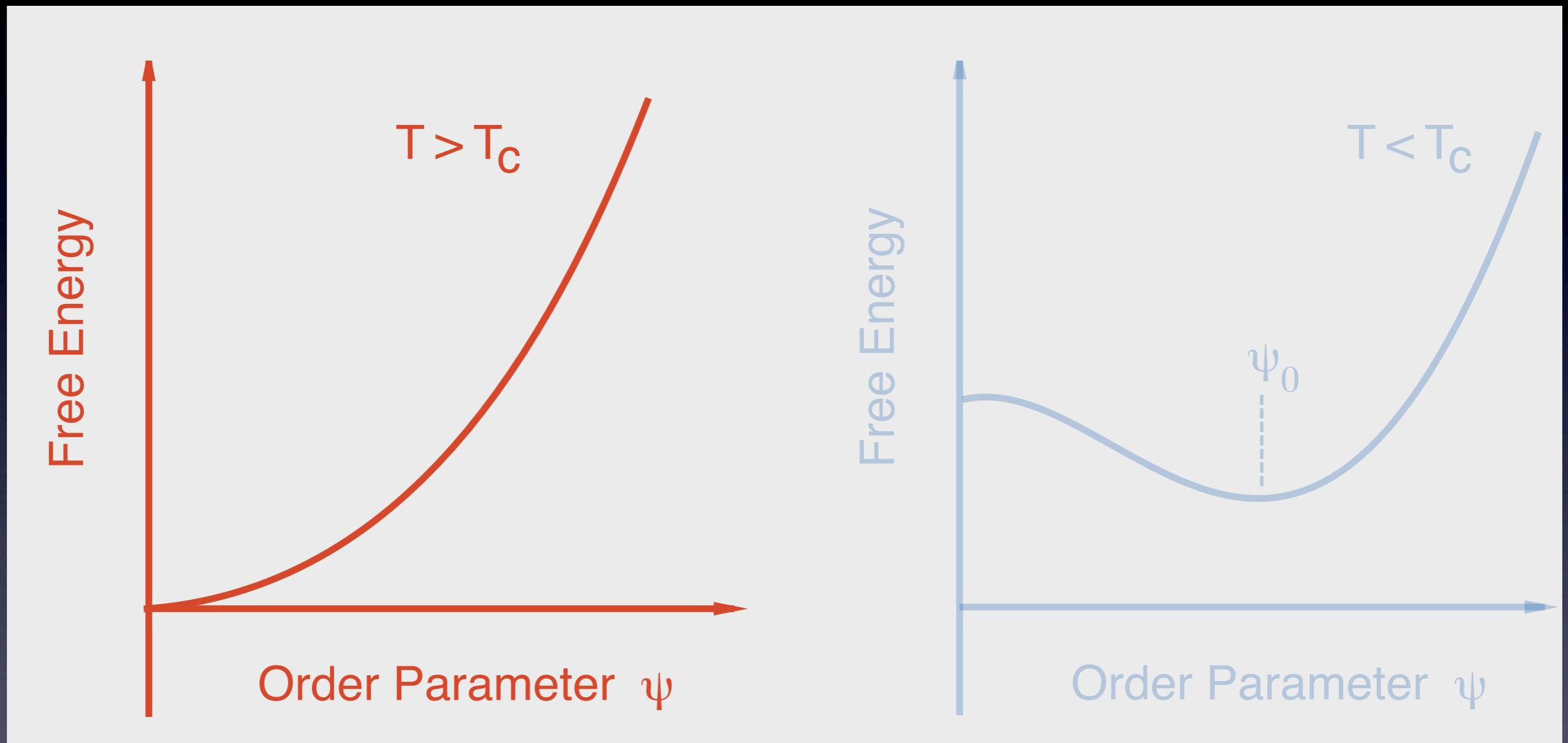


Walther Meißner

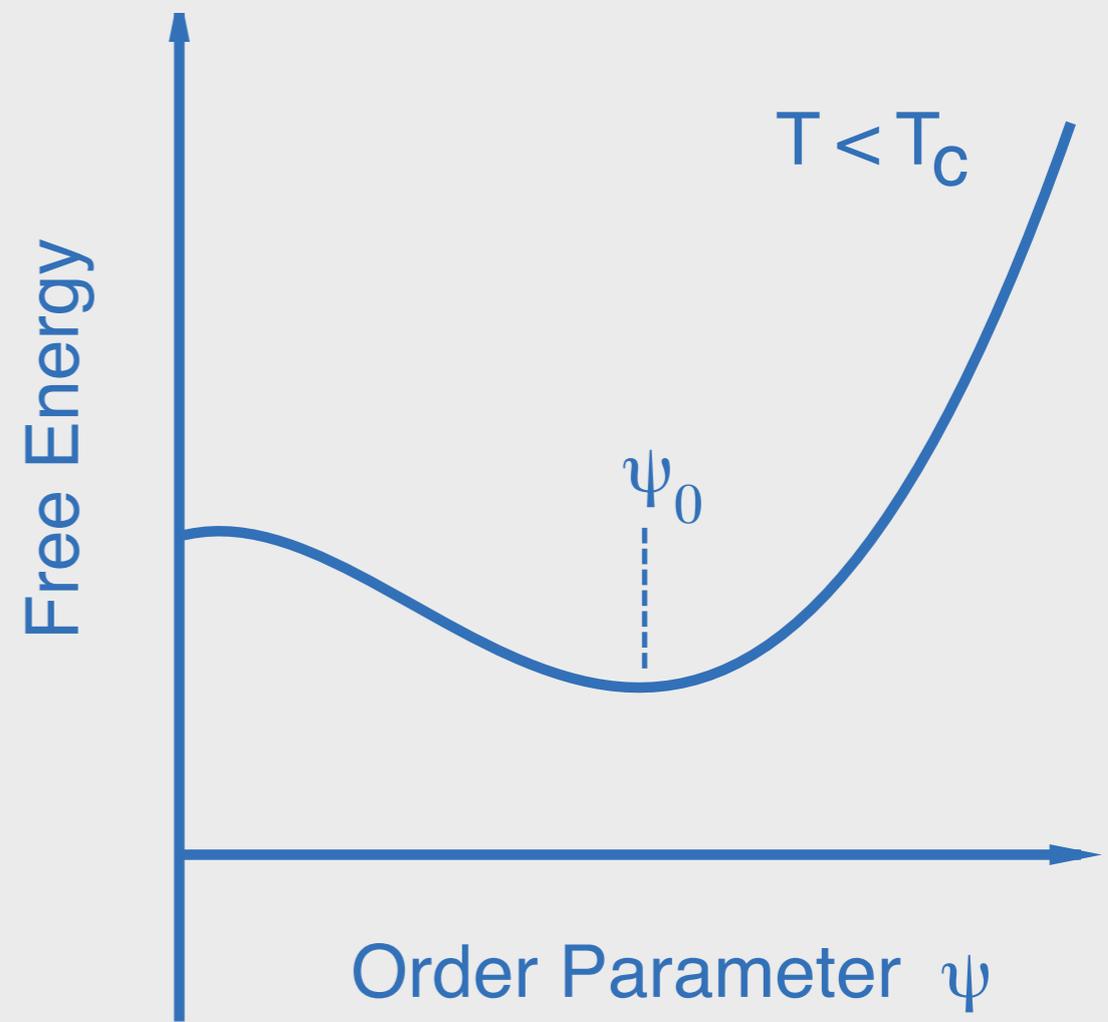
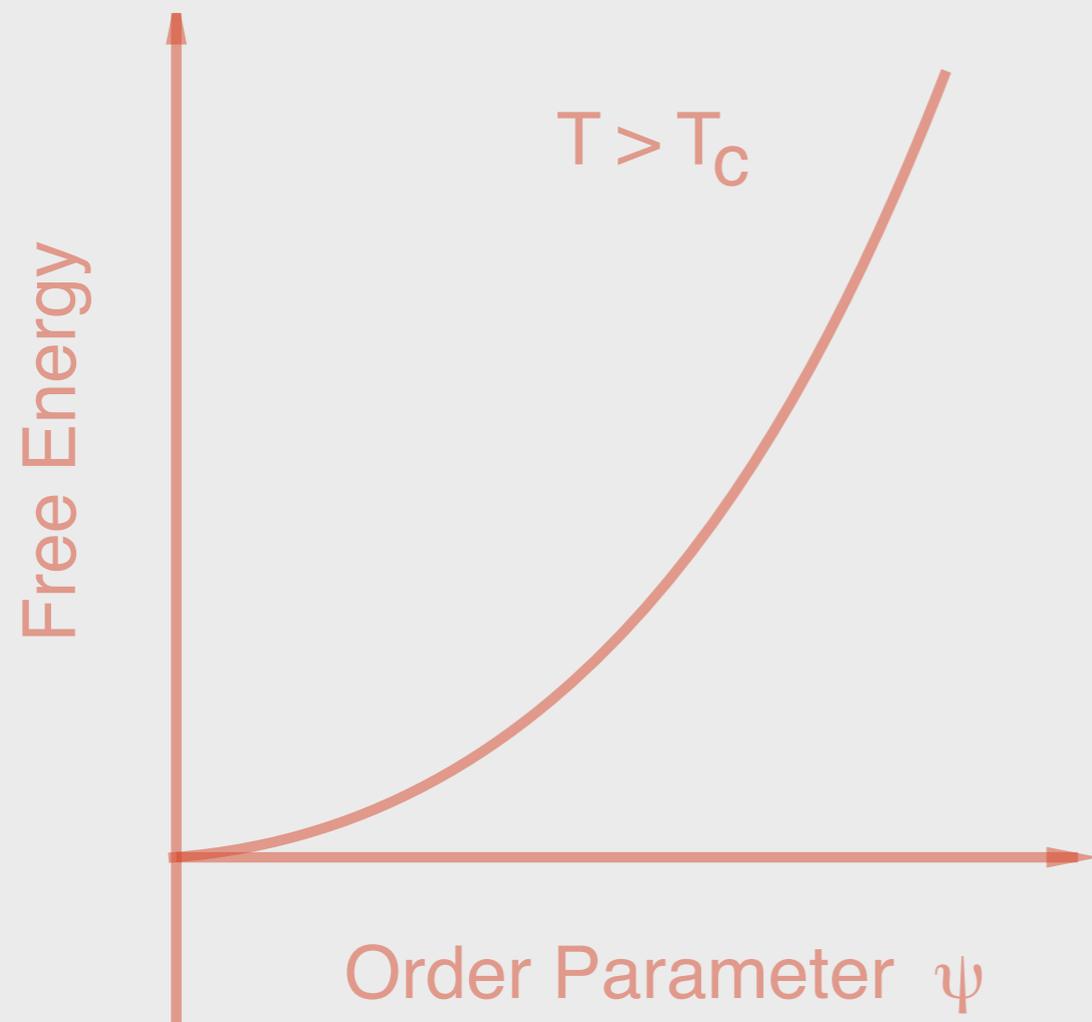
Robert Ochsenfeld

Pb: 40 nm penetration

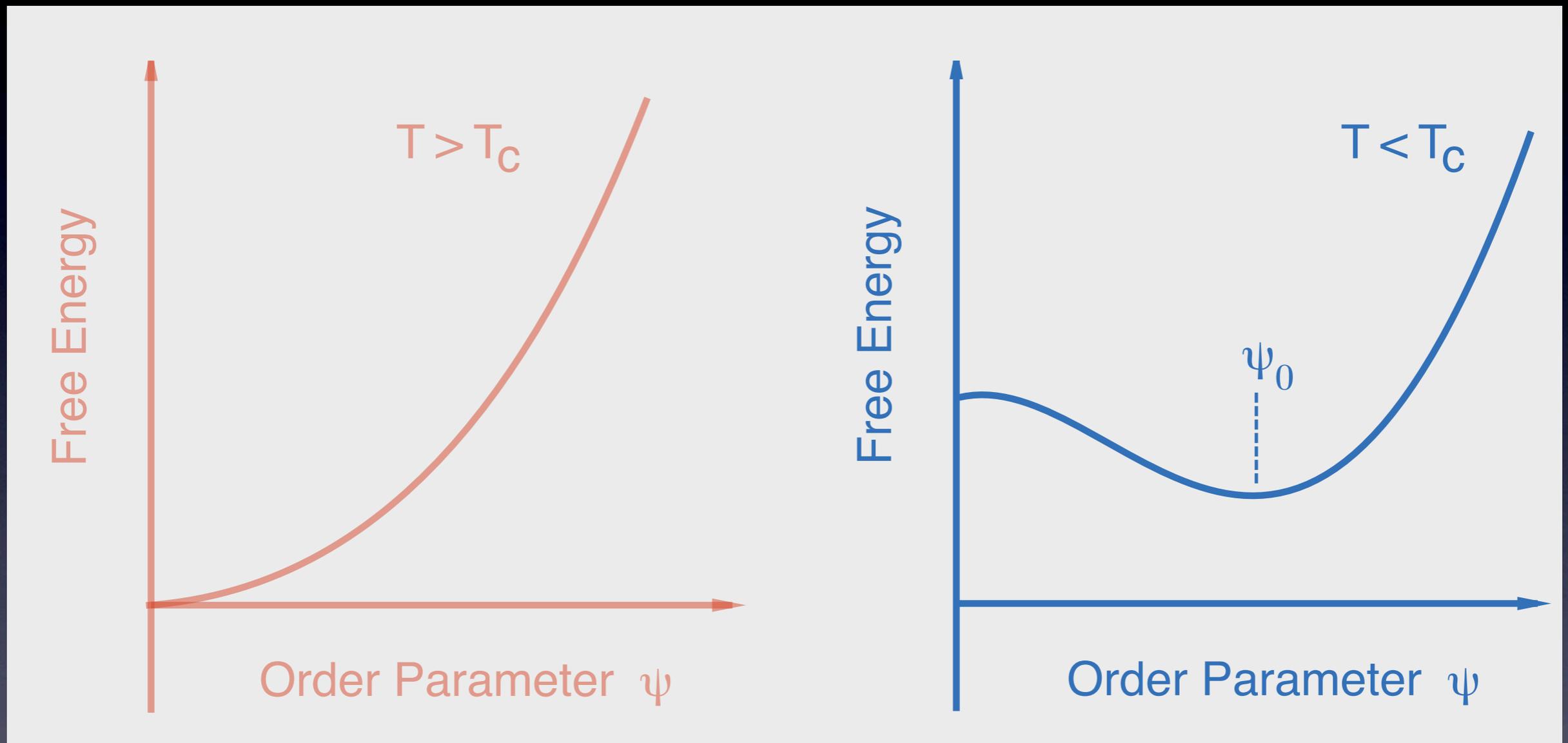
# Ginzburg–Landau model (1950)



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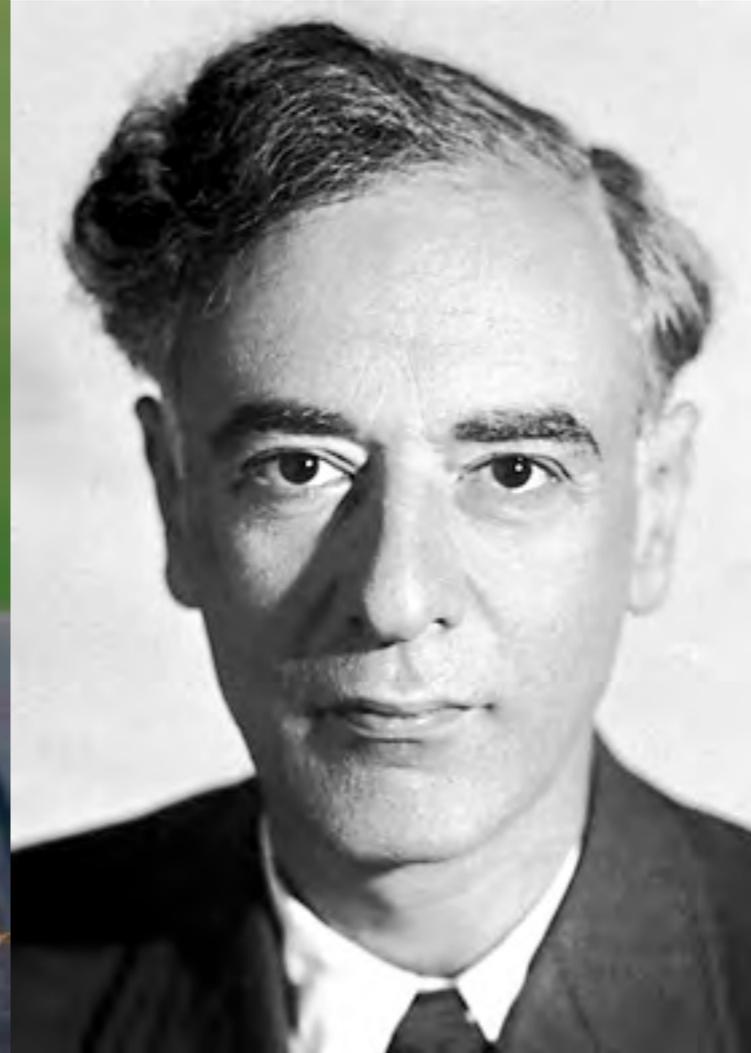
# Ginzburg–Landau model (1950)



Photon acquires mass in superconductor



Vitaly Ginzburg



Lev Landau

# BCS theory (1957)



John Bardeen

Leon Cooper

Robert Schrieffer

# Some hints



Julian Schwinger

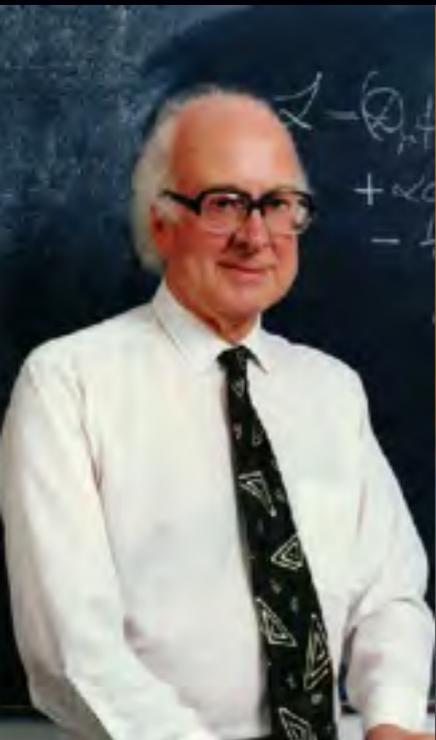
(1962) Photon can acquire mass in  $1+1$ -dimensional QED



Phil Anderson

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

# Spontaneous symmetry breaking



Higgs

Kibble

Guralnik

Hagen

Englert

Brout<sup>†</sup>

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.

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

Yields massive photon  
+  
a massive scalar particle  
*“Higgs boson”*

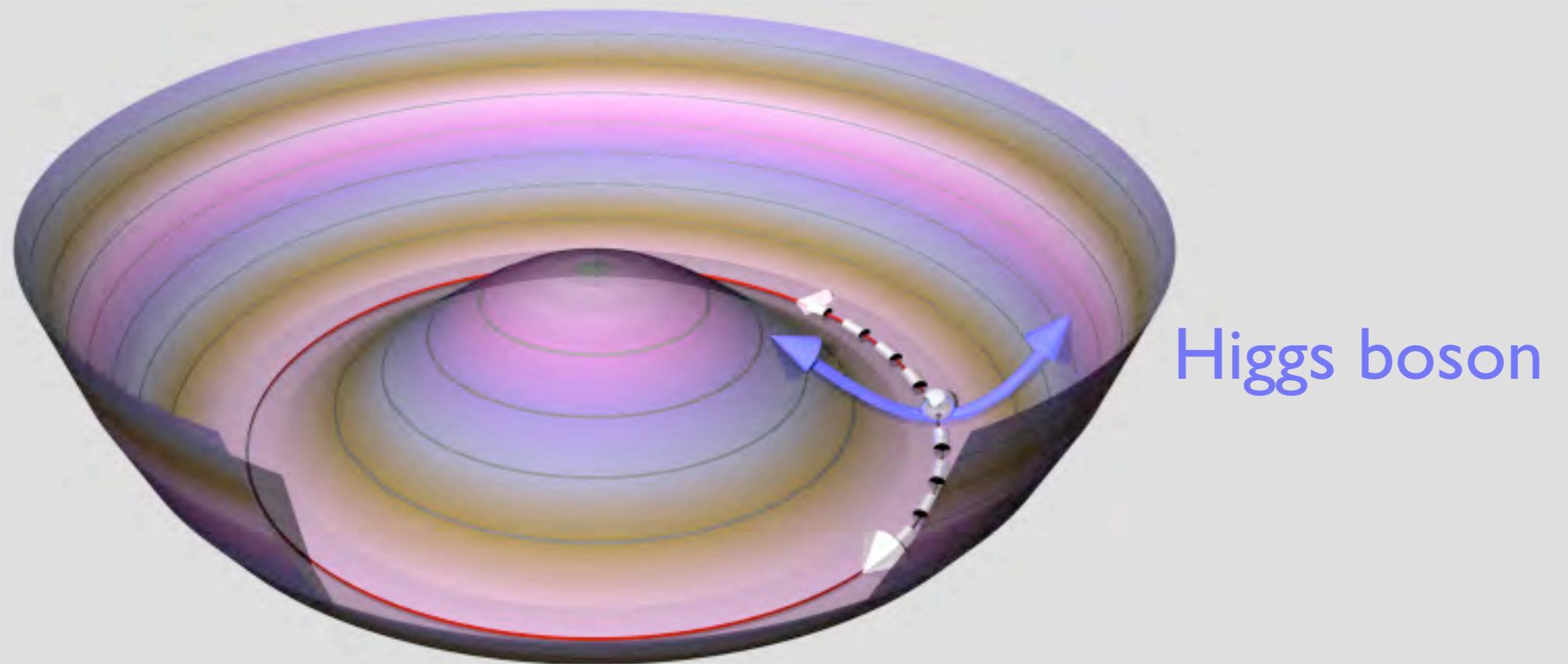
Simplest example: *Abelian Higgs model*  
= Ginzburg–Landau in relativistic notation

Yields massive photon  
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No mention of weak interactions.

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

# Spontaneously broken gauge theory



Longitudinal component

# 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<sup>1</sup> but had been introduced three years earlier by Schwinger<sup>2</sup>. And "the Higgs mechanism" was first described by Philip Anderson<sup>3</sup>: 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<sup>4</sup>.

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*

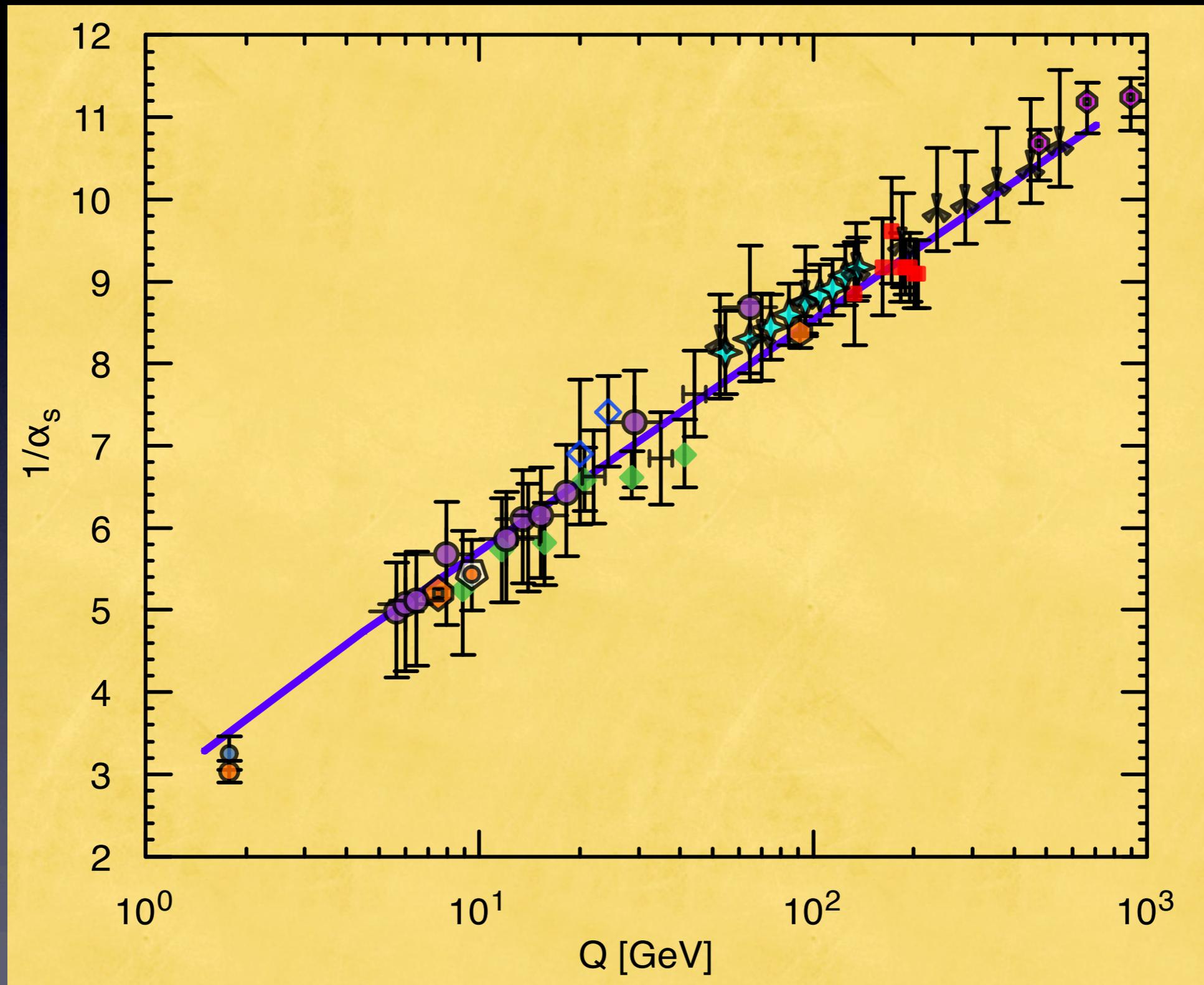
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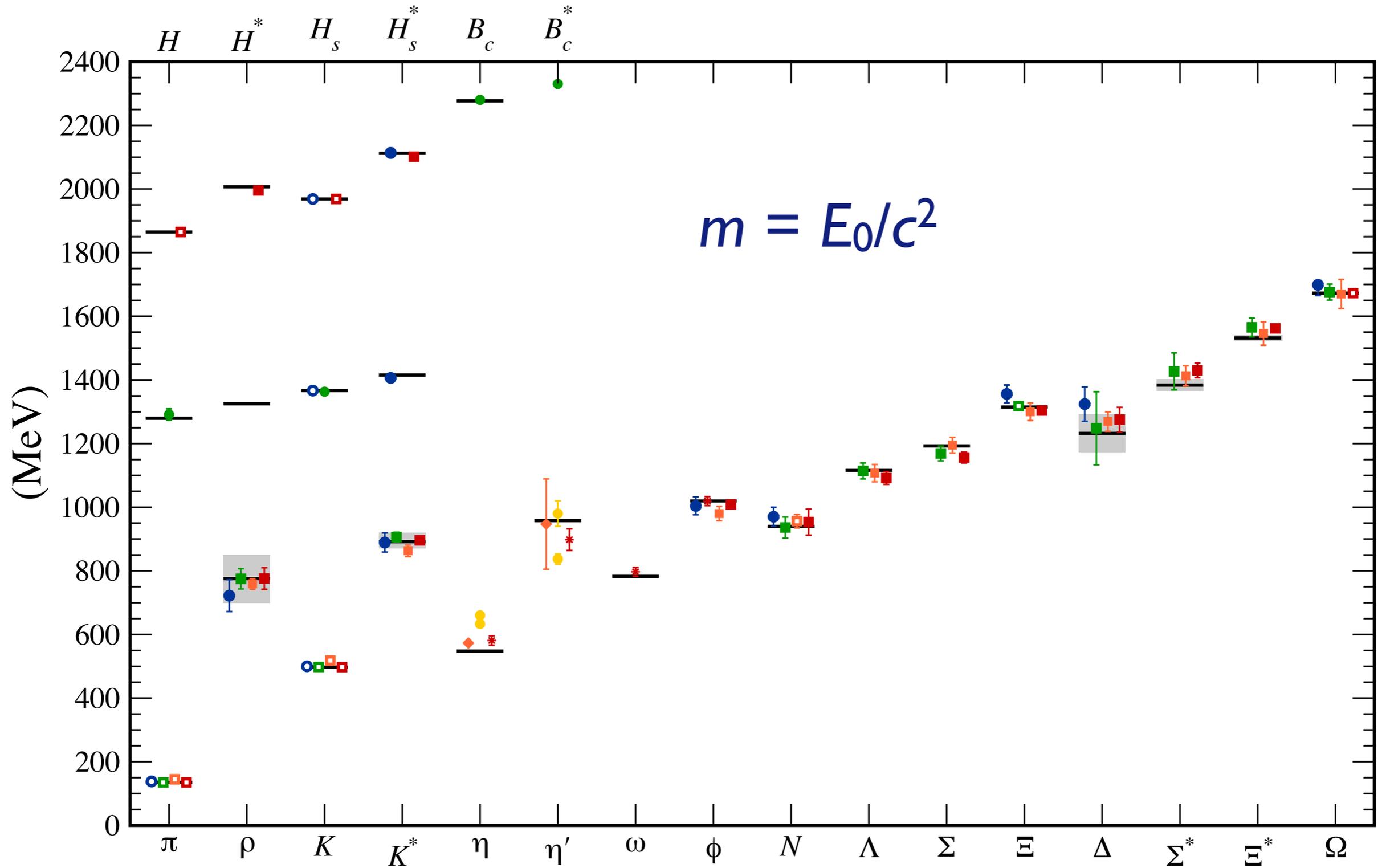
*Right idea, wrong symmetry, wrong constituents*

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

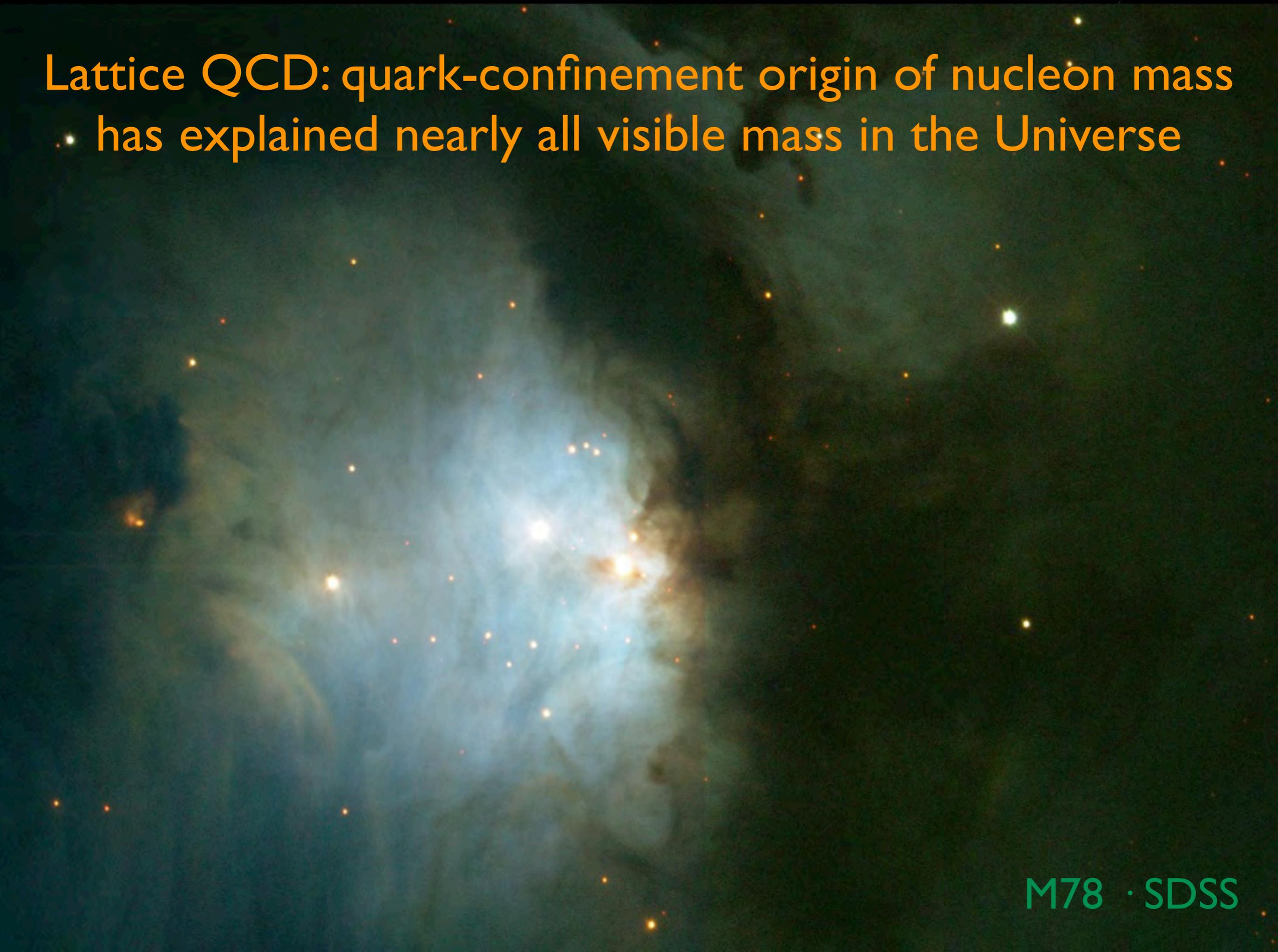
# Asymptotic freedom in QCD



# Light hadrons (dynamical fermions)

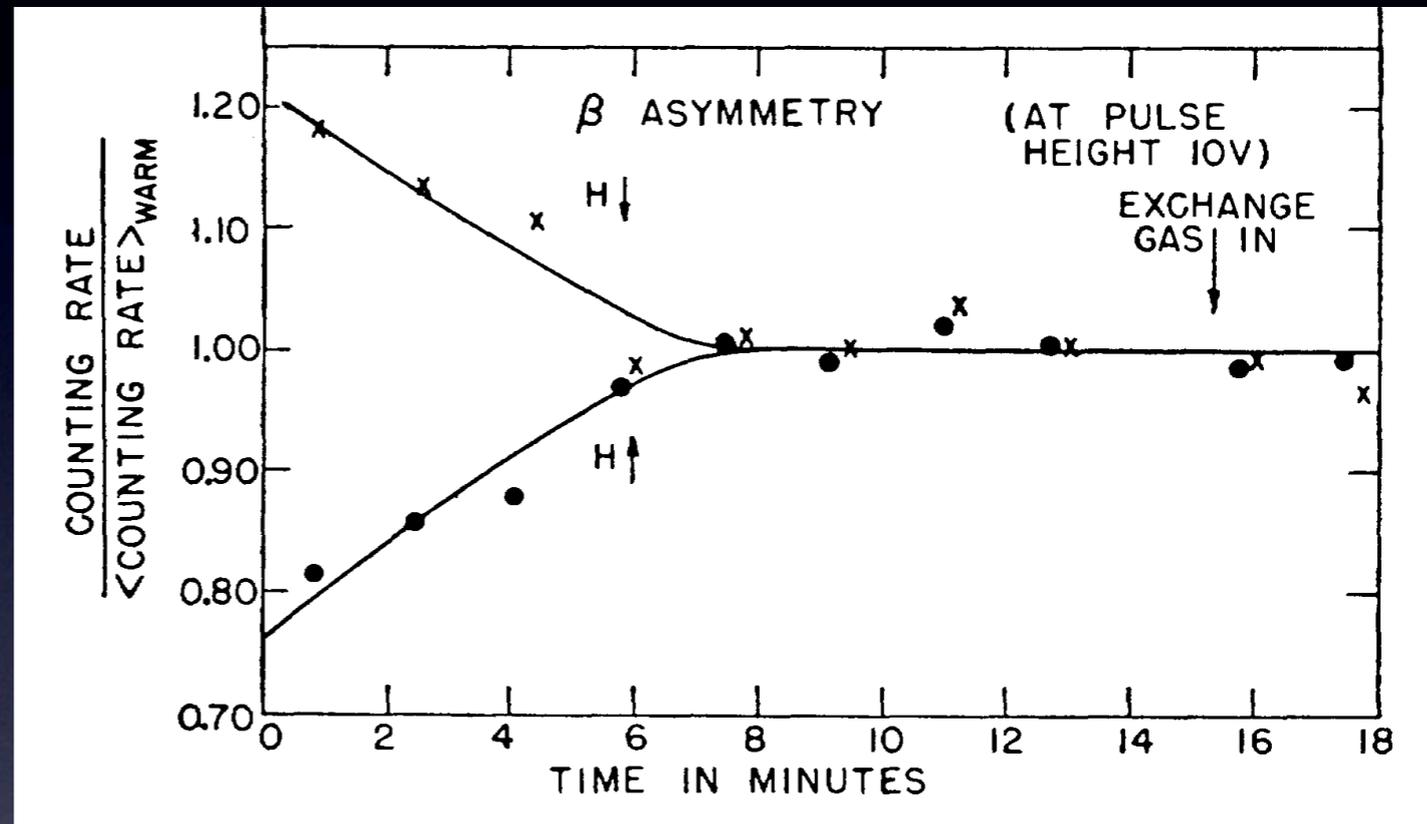
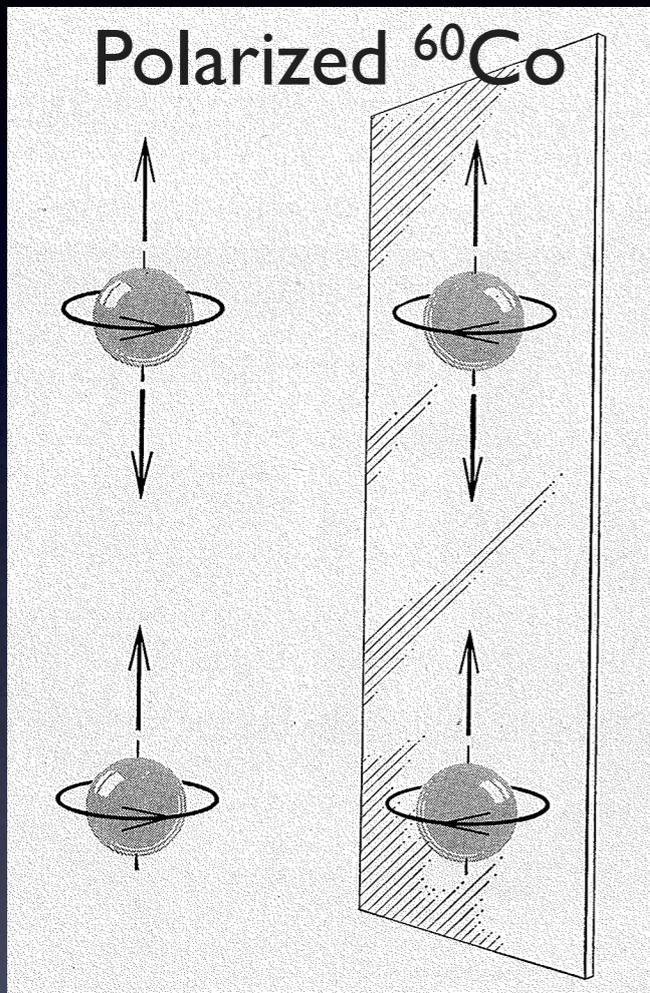


Lattice QCD: quark-confinement origin of nucleon mass  
has explained nearly all visible mass in the Universe

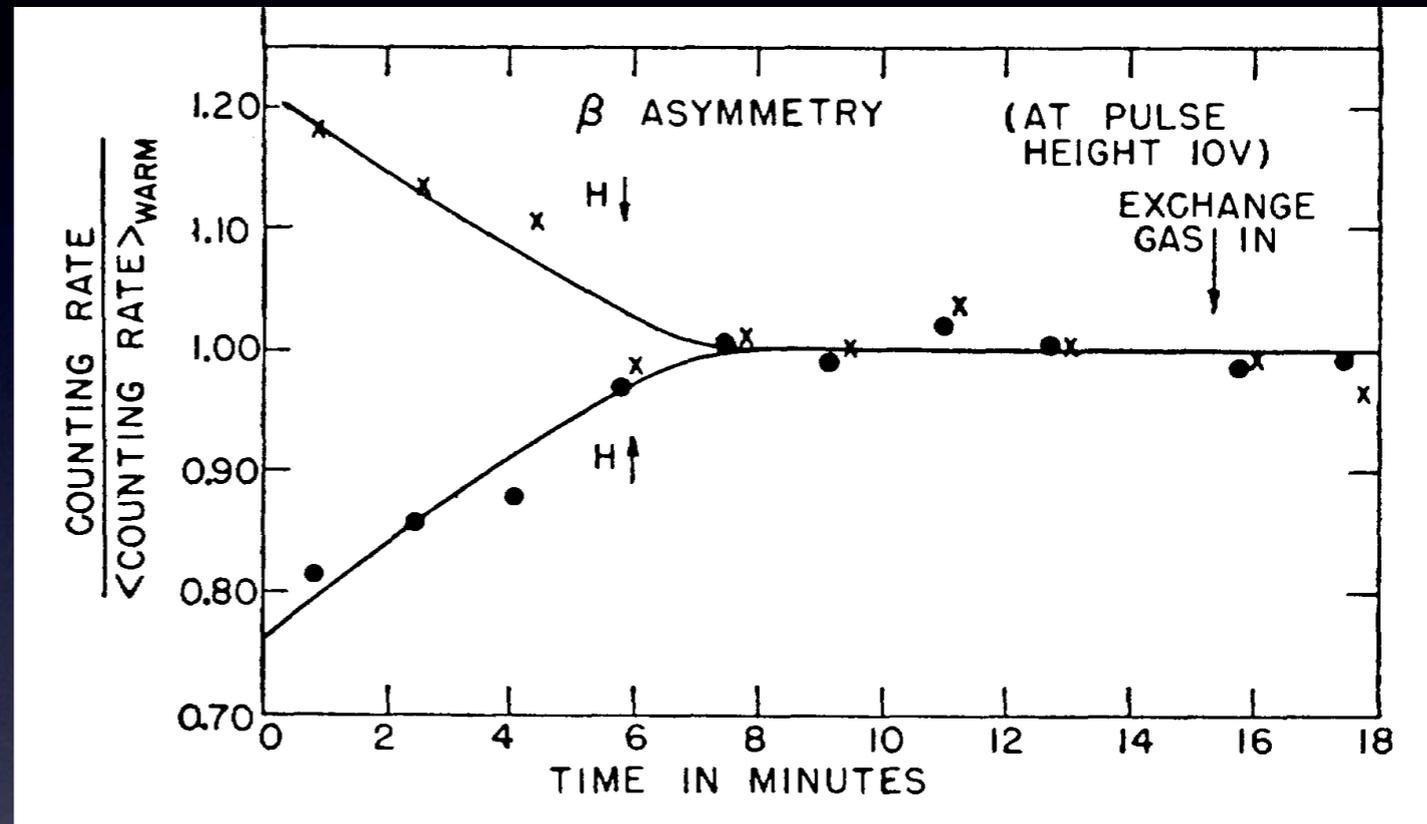
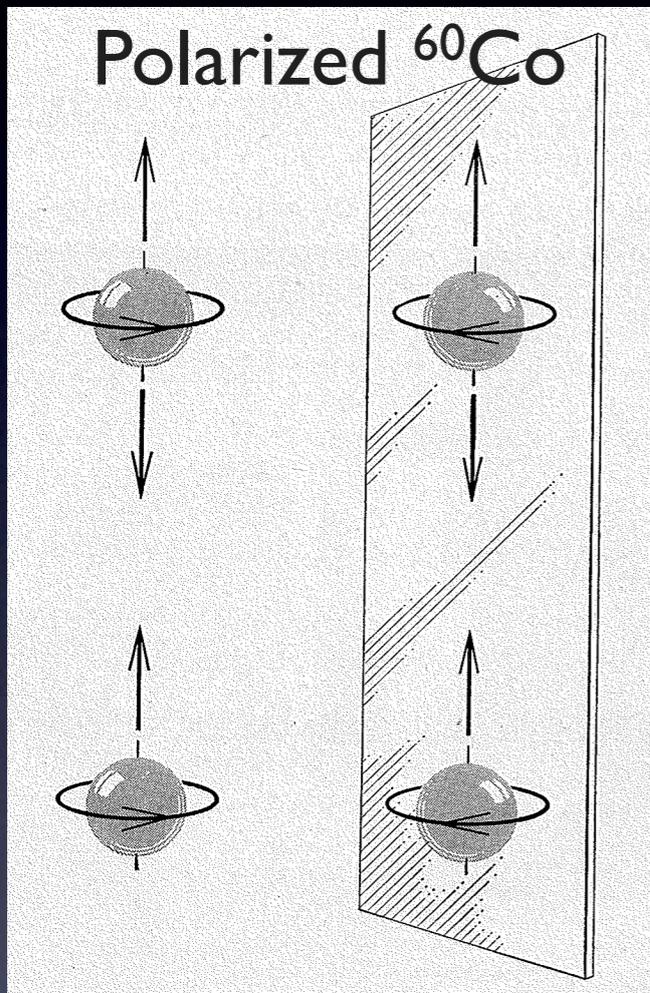


M78 · SDSS

# $\beta$ -decay: parity not conserved!



# $\beta$ -decay: parity not conserved!



Unobservable observed

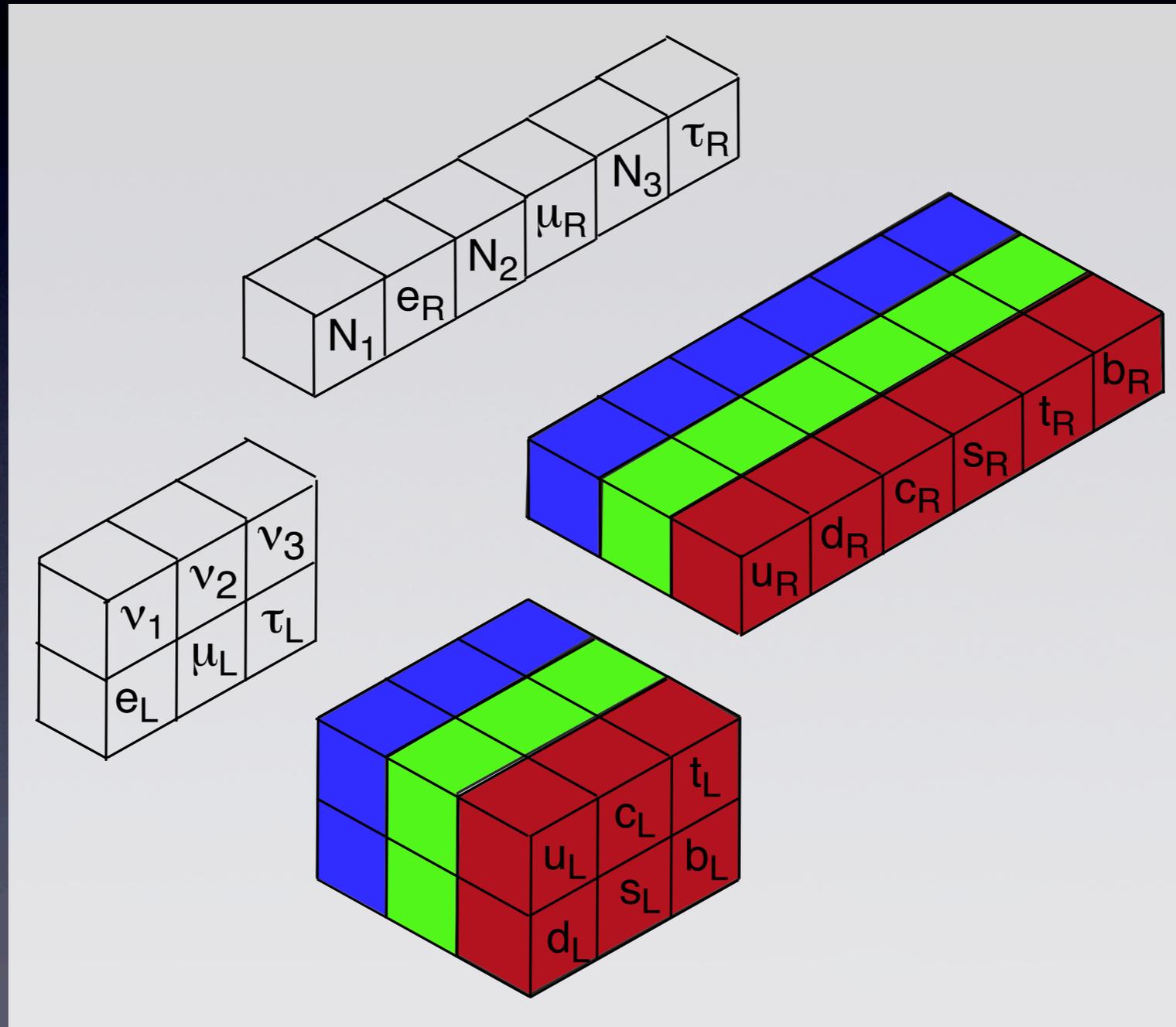
90 PARITY NOT CONSERVED!  
Dec 27, 1956.

# 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

# An electroweak theory

Weak isospin (left-handed)  
+  
weak hypercharge phase symmetry



Scan ©American Institute of Physics

Sheldon Glashow

# An electroweak theory

Weak isospin (left-handed)  
+  
weak hypercharge phase symmetry

3 massless gauge bosons  
coupled to weak isospin

1 massless hyperphoton  
coupled to weak hypercharge

massless quarks & leptons



Scan ©American Institute of Physics

Sheldon Glashow

# An electroweak theory

Weak isospin (left-handed)  
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Scan ©American Institute of Physics

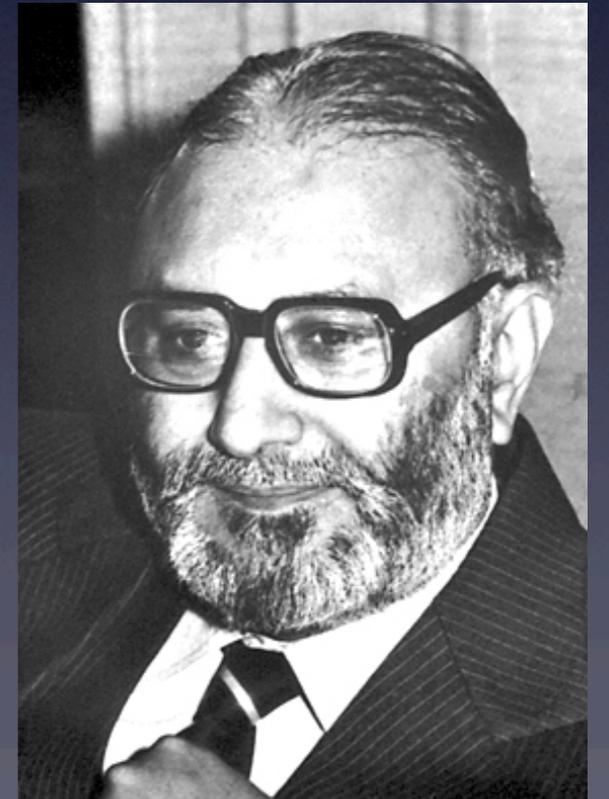
Sheldon Glashow

# An electroweak theory (1967)

Contrive a vacuum to hide EW symmetry  
(need 4 new fields)



Steven Weinberg



Abdus Salam

# An electroweak theory (1967)

Contrive a vacuum to hide EW symmetry

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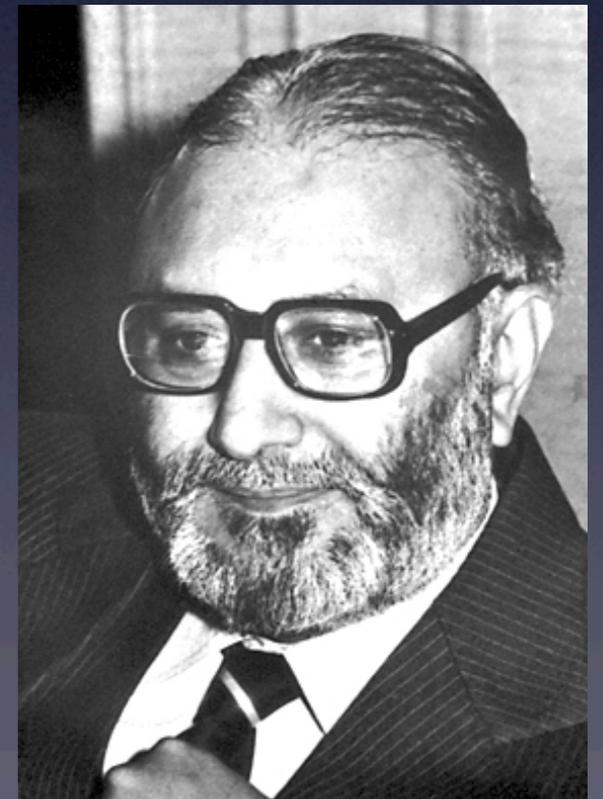
Massive  $W^+$ ,  $W^-$ ,  $Z^0$

Massless photon

Massive Higgs boson

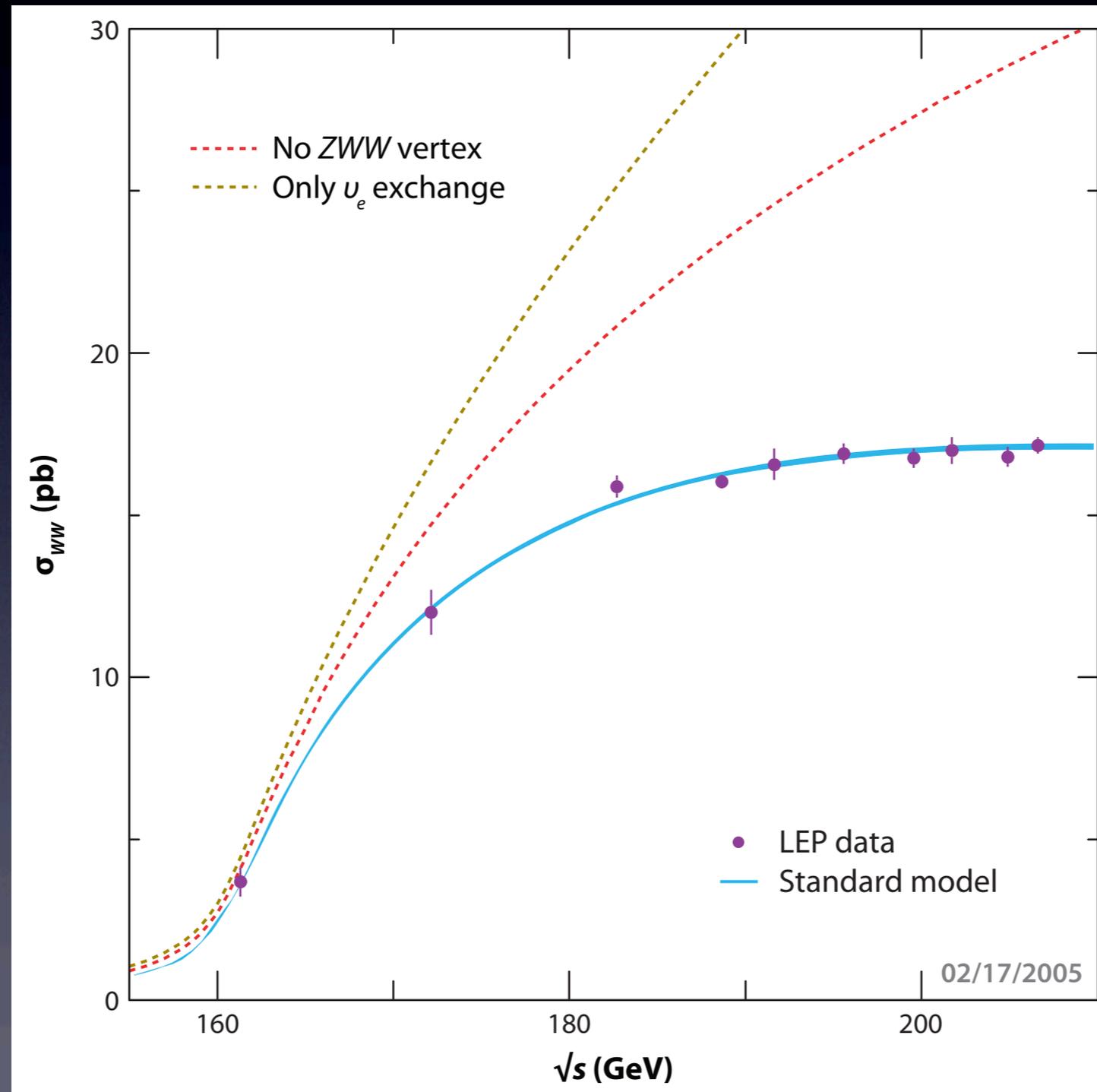


Steven Weinberg



Abdus Salam

# Electroweak symmetry: *secret*, but real



# Higgs bosons: incomplete multiplets

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

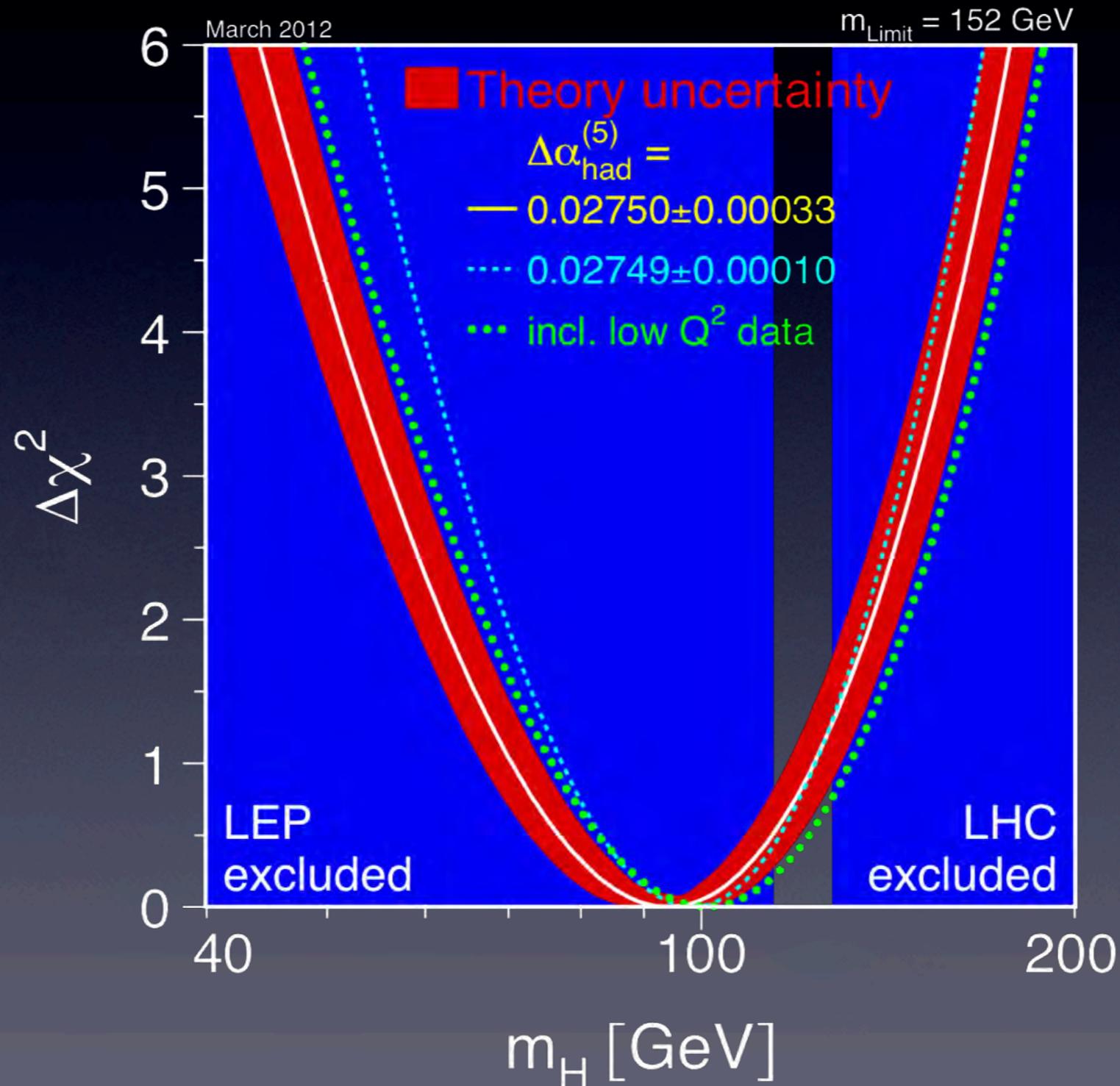
$w_1, w_2, z$  become longitudinal  $W^+, W^-, Z^0$

$h$  becomes  $H$ , remembers its roots

*High-energy behavior, unitarity bound, ...*

See end of §III, *Phys. Rev. D* 16, 1519 (1977)

# H couplings to W, Z tested indirectly



# Fermion mass after SSB

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

Neither fixes values nor relates them

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*Highly economical, but is it true?*

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Fermion masses: physics beyond standard model

The Higgs field is not molasses

The Higgs field is not molasses

*Viscosity* resists motion

# The Higgs field is not molasses

*Viscosity* resists motion

*Mass* resists acceleration

# 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, ...



July 4, 2012

Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

*Top from production,  
need direct observation for b,  $\tau$*

Accounts for fermion masses?

*Fermion couplings  $\propto$  masses?*

Are there others?

Quantum numbers?

SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of  $M_H \approx 126$  GeV?

Any sign of new strong dynamics?

