

Colloquium

Quantum Field Theory after “Revolution”

Pisa, Italy, March 14, 2017

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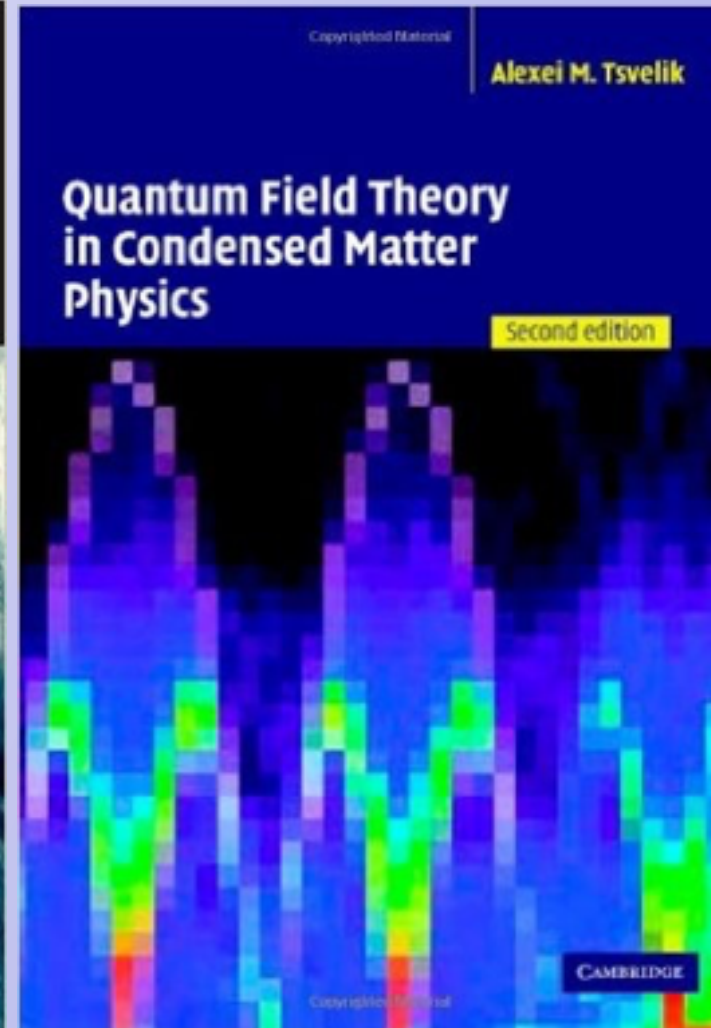
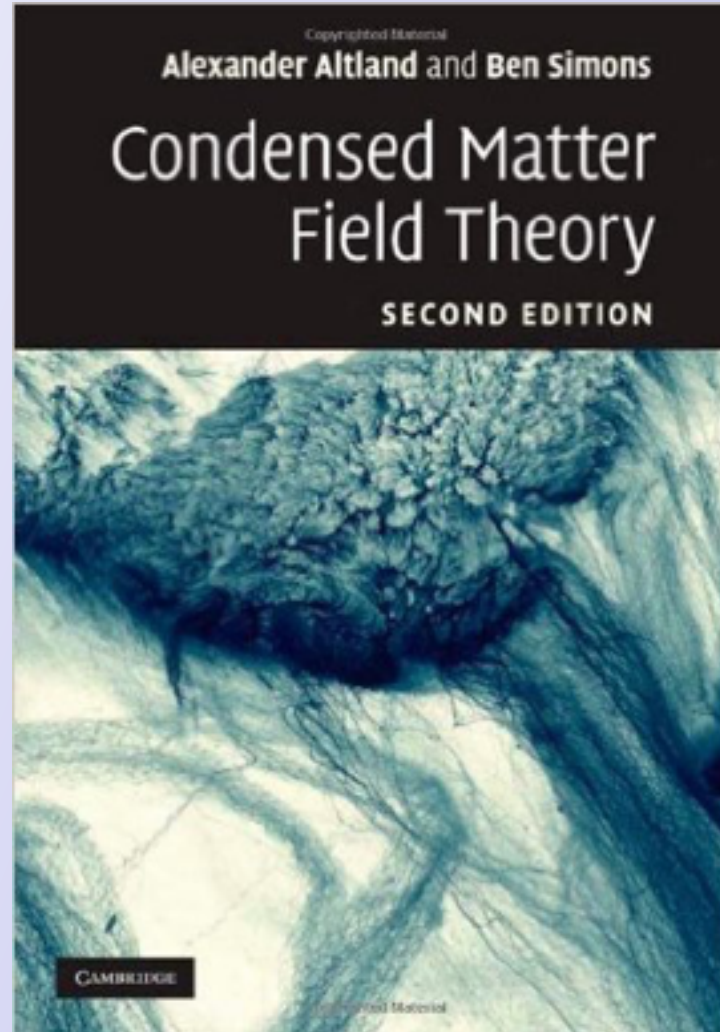
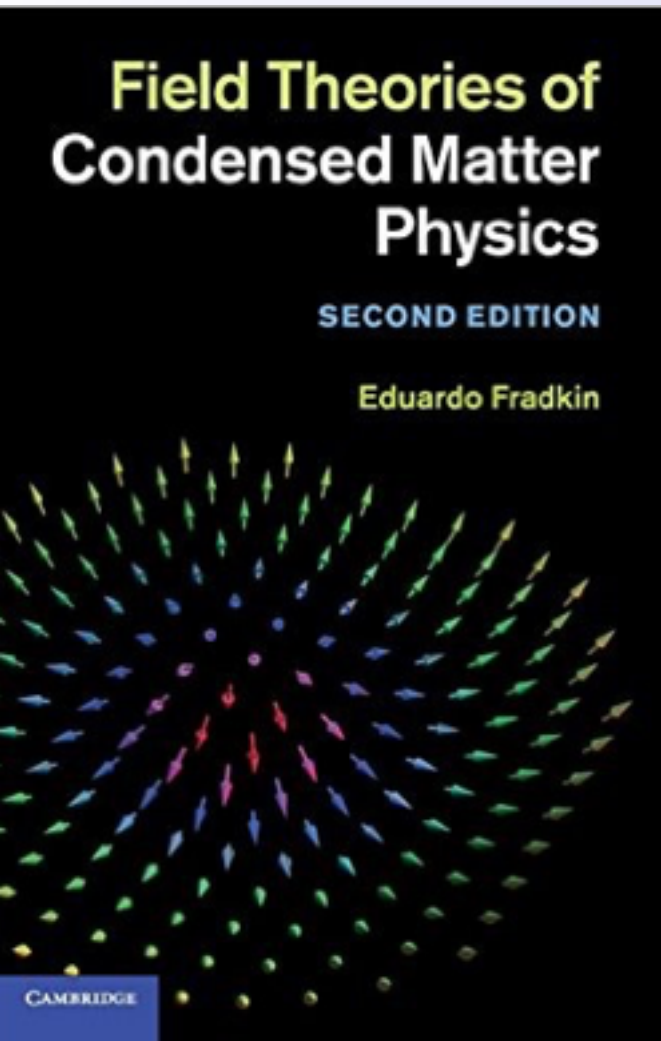
* Our today's understanding of Nature at the fundamental level is based on Quantum Field Theory (QFT) which is 90 years old

* So far there is no direct evidence calling for going beyond QFT!

QUARKS	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$ u up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ c charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ t top	mass → 0 charge → 0 spin → 1 g gluon	mass → $\approx 126 \text{ GeV}/c^2$ charge → 0 spin → 0 H Higgs boson
	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ d down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ s strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$ b bottom	mass → 0 charge → 0 spin → 1 γ photon	
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ e electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ μ muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$ τ tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1 Z Z boson	GAUGE BOSONS
	mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$ ν_e electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_μ muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_τ tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → ± 1 spin → 1 W W boson	
LEPTONS					

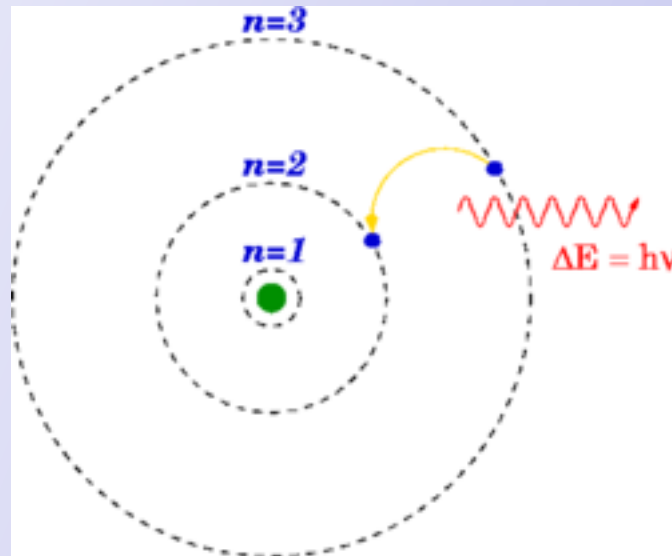
Standard model runs world at short distances.
It is (almost) complete and self-consistent

Modern condensed matter physics is based on Quantum Field Theory



* QFT = quantum mechanics (QM) + relativity

* * In 1926 relativity meant photons

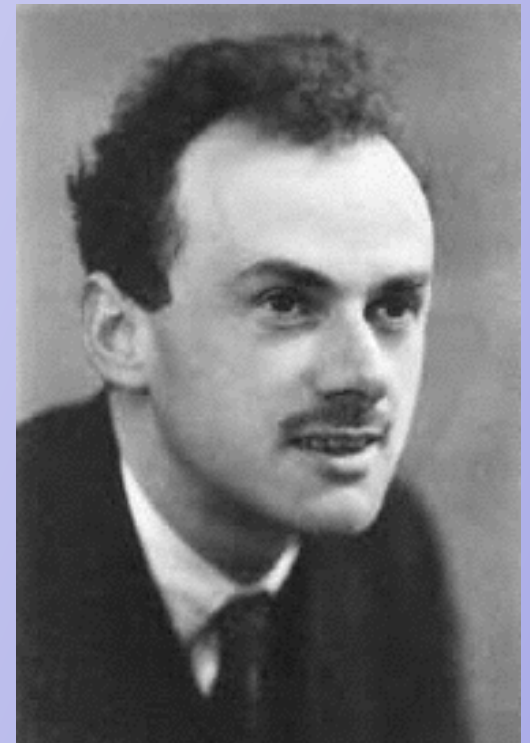
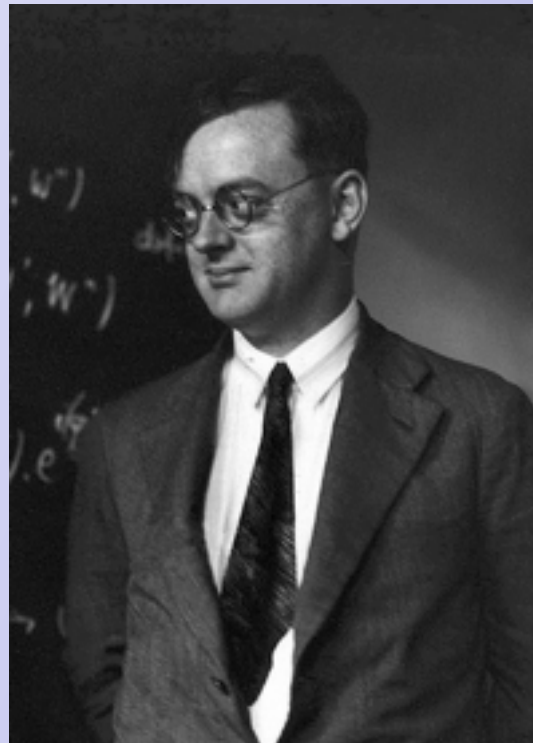


Physicists knew about electromagnetic field. First application of QM to fields came in founding paper of QM itself (1926). **Born, Heisenberg, and Jordan** considered electromagnetic field in empty space, in the absence of any electric charges or currents.

* If quantum mechanics was a revolution, QFT was a humble child

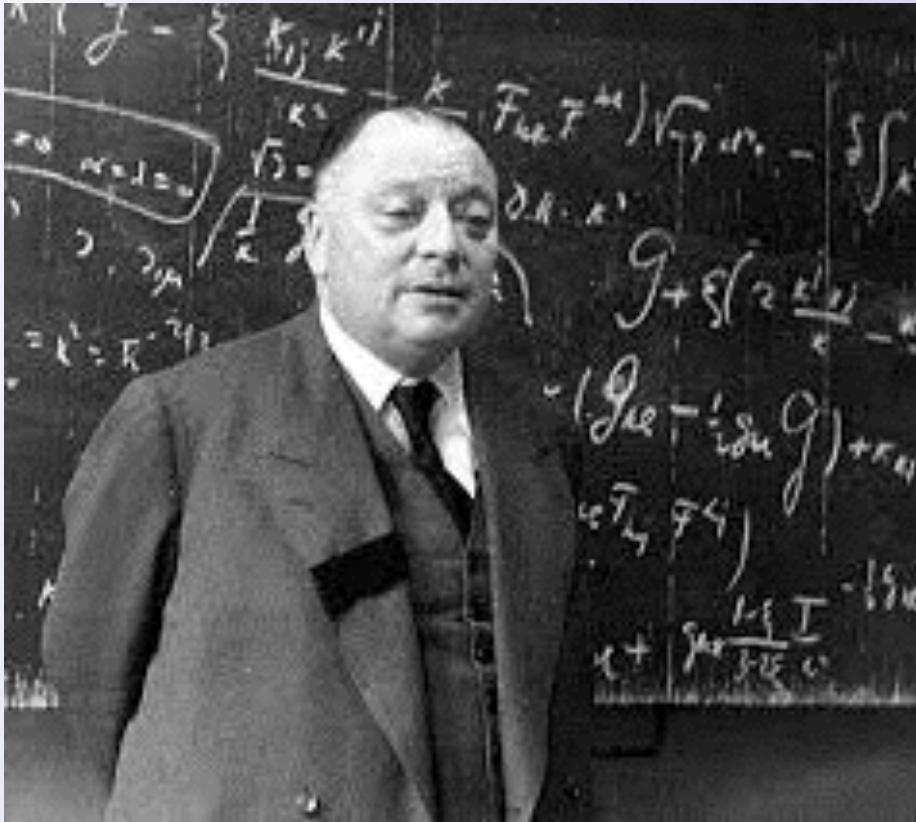
Born, Heisenberg, and Jordan canonically quantized γ field using creation & annihilation operators

* * "Practical" QED with electrons: 1927, P. Dirac



★ Final touches (1929–30): Heisenberg and Pauli →

“Material particles could be understood as the quanta of various fields, in just the same way that the photon is the quantum of the electromagnetic field...”



Subsequent 18 years:
struggle with $\infty \infty \infty$.
Mysterious holy grail
searches.

QED remained the only
respectable QFT till
1970s!



Renormalizability: 1948–51; Feynman et al.



Awe before renormalizable QFT (QED,...)



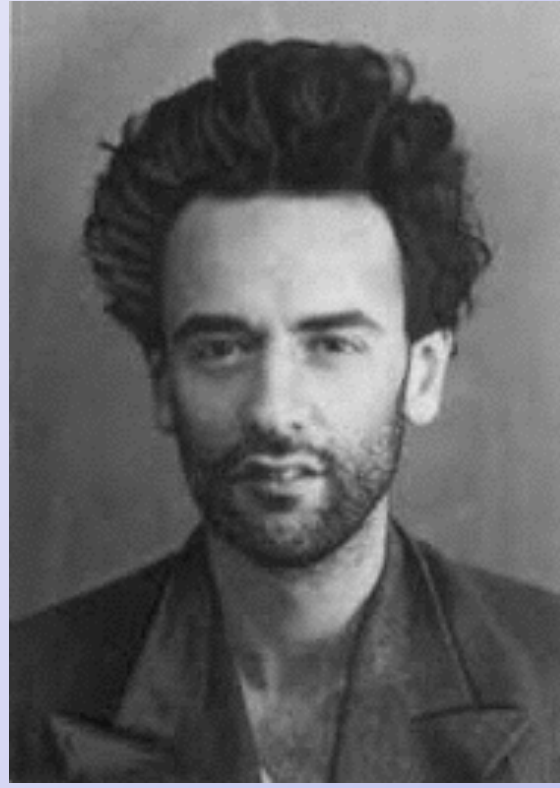
(1953–54: Landau's zero charge)

$$M_{uv} = \infty$$

Landau: QFT is DEAD!

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Landau: QFT is DEAD!



Revolutions of mid-1950–mid-1970s

Yang-Mills; fall 1954

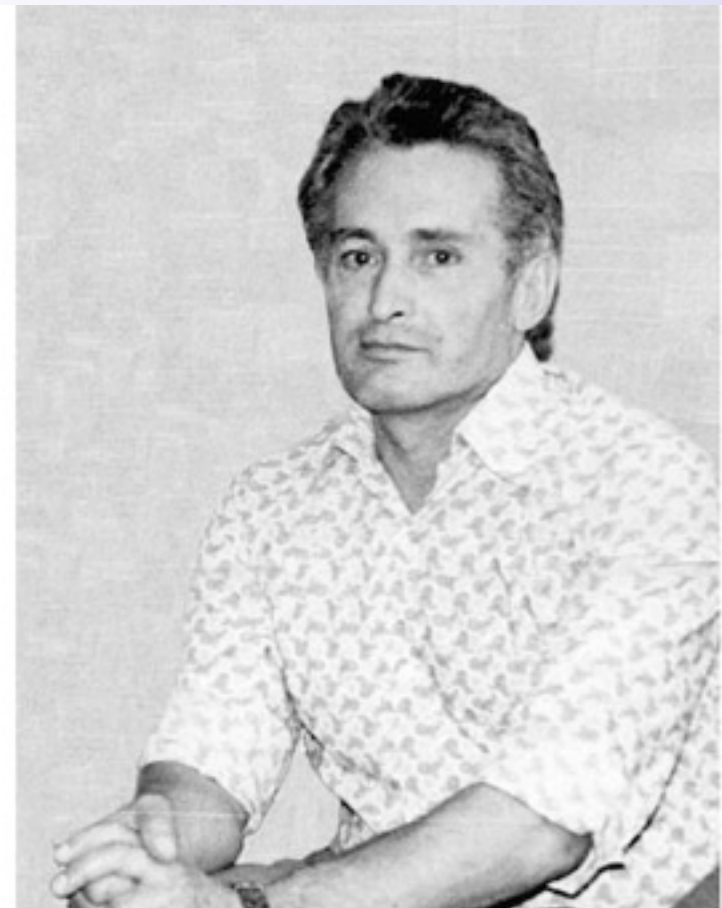


C. N. Yang (1922 -) and Robert Mills (1927 - 1999)
at Stony Brook in 1999.

Pauli studied Yang-Mills first, before Yang-Mills, see letter to Pais, “Meson Nucleon Interaction and Differential Geometry” (written “to see what it looks like,” on July 22-25 1953).

$$\{\bar{Q}_{\dot{\alpha}}, Q_{\beta}\} = 2\sigma^{\mu}_{\dot{\alpha}\beta} P_{\mu}$$

Superalgebra and 4D SUSY Theories 1970; Golfand and Likhtman



N=1 SUSY without
central extensions

(Defying Coleman-
Mandula theorem)

JETP
Letters
1971:

SQED
with
photon
mass
and
massive
matter

Точный вид гамильтониана в представлении взаимодействия, можно восстановить по нему лагранжиан в гейзенберговском представлении:

$$\begin{aligned}
 L(x) = & (\partial_\alpha \phi^* - ig A_\alpha \phi^*)(\partial_\alpha \phi + ig A_\alpha \phi) - m^2 \phi^* \phi + (\partial_\alpha \omega^* - ig A_\alpha \omega^*) \times \\
 & \times (\partial_\alpha \omega + ig A_\alpha \omega) - m^2 \omega^* \omega + \frac{i}{2} \bar{\psi}_1 \gamma_\alpha \overleftrightarrow{\partial}_\alpha \psi_1 - m \bar{\psi}_1 \psi_1 - g \bar{\psi}_1 \gamma_\alpha \psi_1 A_\alpha + \\
 & + \frac{i}{2} \bar{\psi}_2 \gamma_\alpha \overleftrightarrow{\partial}_\alpha \psi_2 - \mu \bar{\psi}_2 \psi_2 - \frac{1}{2} (\partial_\beta A_\alpha)^2 + \frac{\mu^2}{2} A_\alpha A_\alpha + \frac{1}{2} (\partial_\alpha \chi)^2 - \frac{\mu^2}{2} \chi^2 + \\
 & + g\mu (\phi^* \phi - \omega^* \omega) \chi - \frac{g^2}{2} (\phi^* \phi - \omega^* \omega)^2 + \sqrt{2} g (\bar{\psi}_1 \bar{s} \psi_2 \phi + \bar{\psi}_2 s \psi_1 \phi^*) - \\
 & - \sqrt{2} g (\psi_1^c \bar{s} \psi_2 \omega^* + \bar{\psi}_2 \bar{s} \psi_1^c \omega) .
 \end{aligned} \tag{7}$$

Таким образом, получена модель взаимодействия квантованных полей с несохранением четности, инвариантная относительно алгебры (1).

Физический институт
им. П.Н.Лебедева
Академии наук СССР

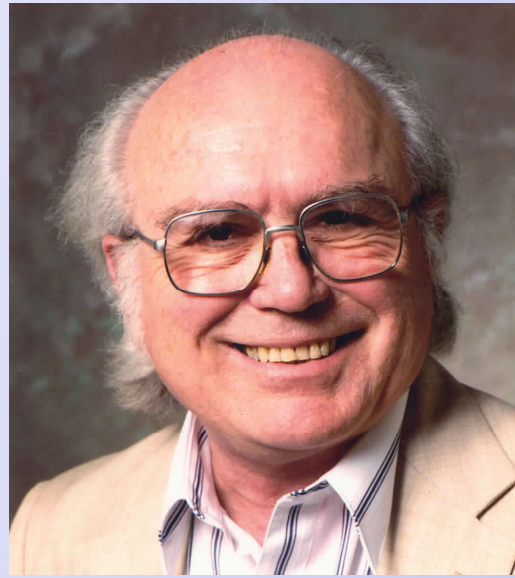
Поступила в редакцию
10 марта 1971 г.

Литература

[1] С.Швебер. Введение в релятивистскую квантовую теорию поля .
ИИЛ, 1963.

(Couple of
typos)

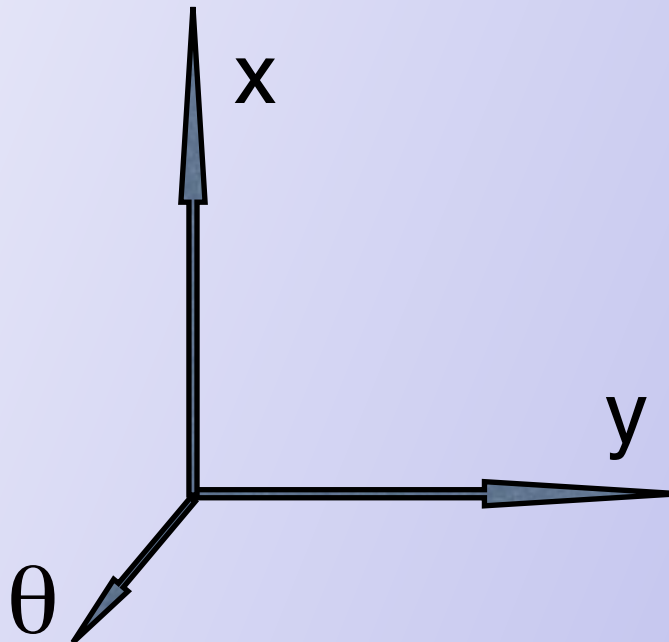
1973 and later



Wess & Zumino, 73

$$\theta^2 = 0$$

“fermion” direction
of the superspace



Superspace

Salam and
Strathdee, 1975

In 1+3 dimensions

$$\{t, x, y, z\} \longrightarrow \{t, x, y, z; \theta_{\alpha}^i\}$$

New QFT born after the revolution

Dramatic Conceptual Changes

- ★ Infinities are not an issue, $M_{uv} \neq \infty$

Renormalizable QFT are singled out technically; no need in UV completion

- ★ Asymptotic freedom makes QFT self-consistent

Landau pole evaded

Wilson's renormalization group (RG) flow logic

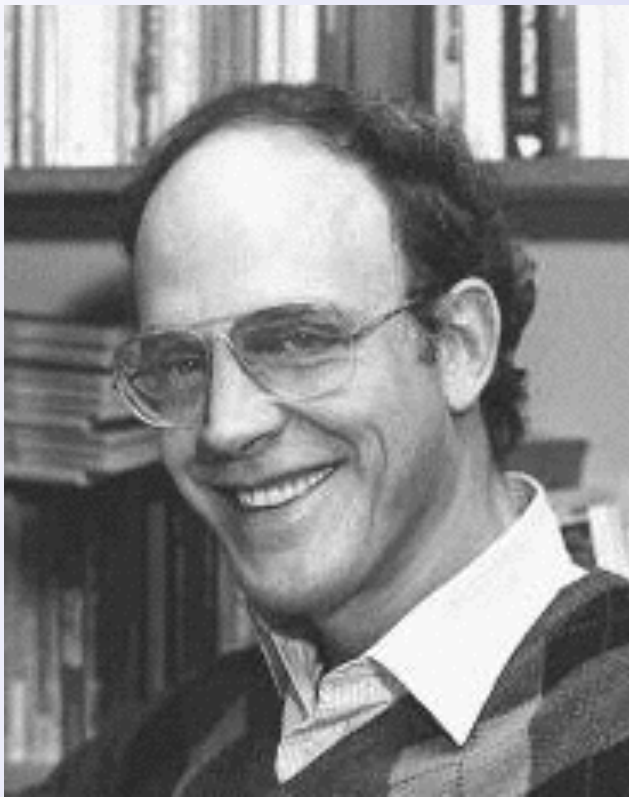
- ★ Uniqueness of vacuum gone

Multiple vacua, highly complicated vacua, not reducible to harmonic oscillations

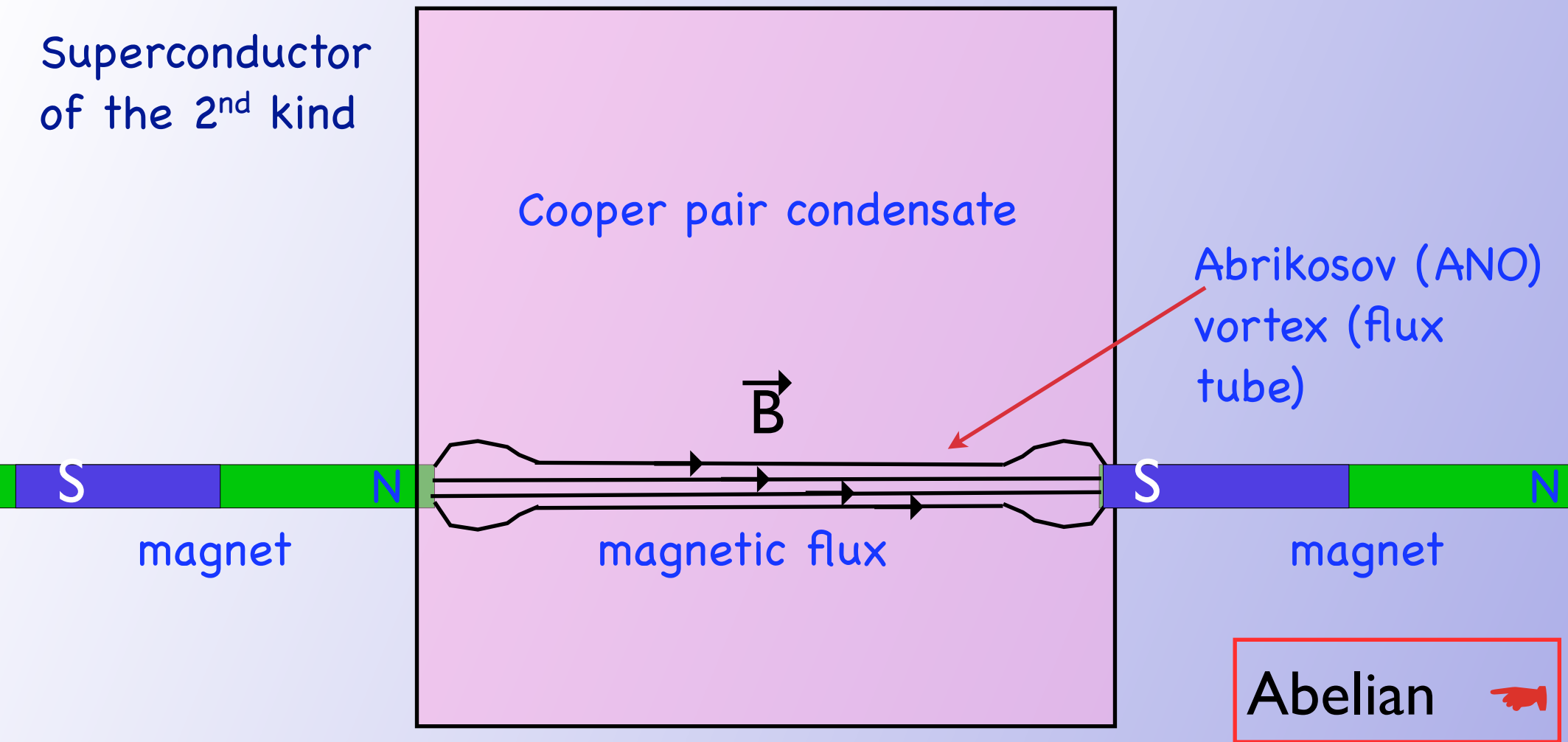
★ Logic: Asymptotically free QFT is given by a local \mathcal{L} at M_{uv} where couplings are small. Use Wilson flow.

If Higgs does **not** stop RG flow, arrive at strong coupling in IR

★ Strong coupling in YM \rightarrow Confinement, conformality or other phases unknown previously



What is confinement? (Example)

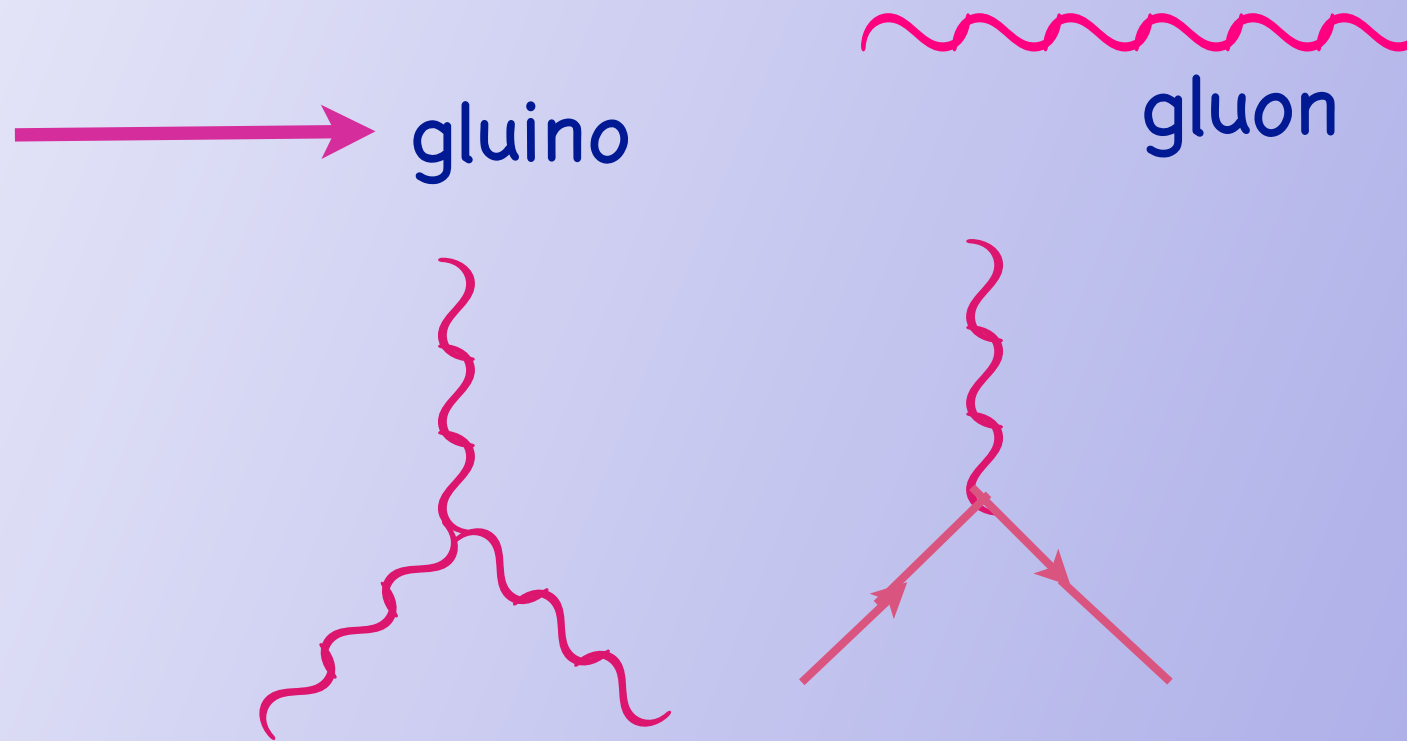


👉 The Meissner effect: 1930s, 1960s

DUAL MEISSNER EFFECT (Nambu-'t Hooft-Mandelstam, ~1975)

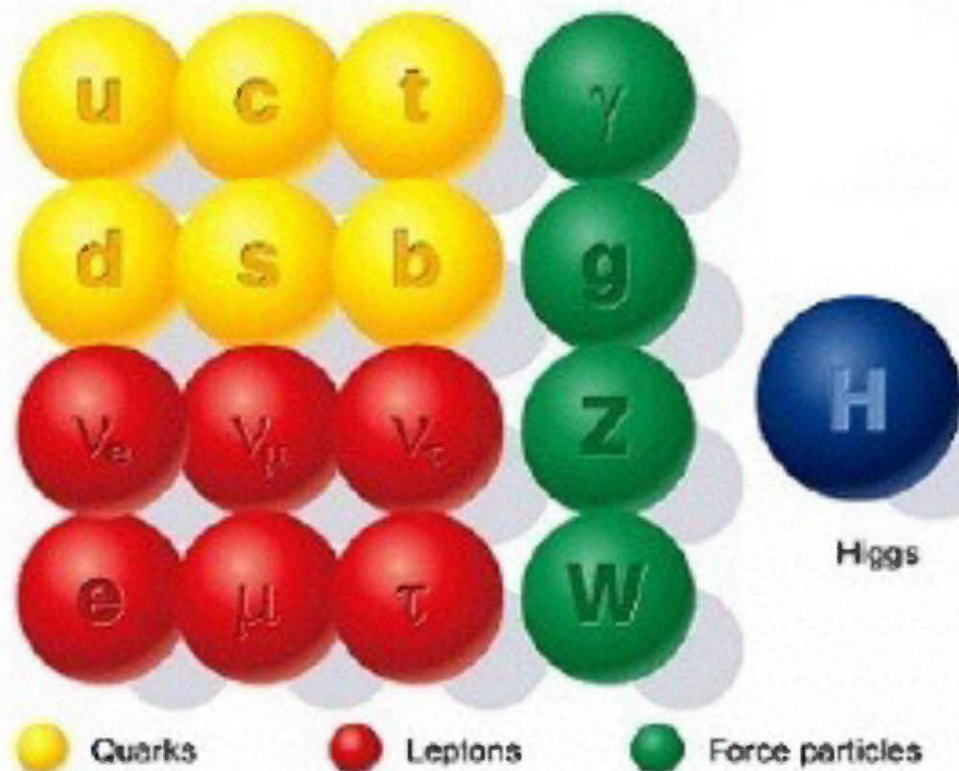
Here comes power of supersymmetry

$$L = -\frac{1}{4g^2} G_{\mu\nu}^a G^{\mu\nu a} + \frac{i}{2} \bar{\lambda} \not{D} \lambda$$

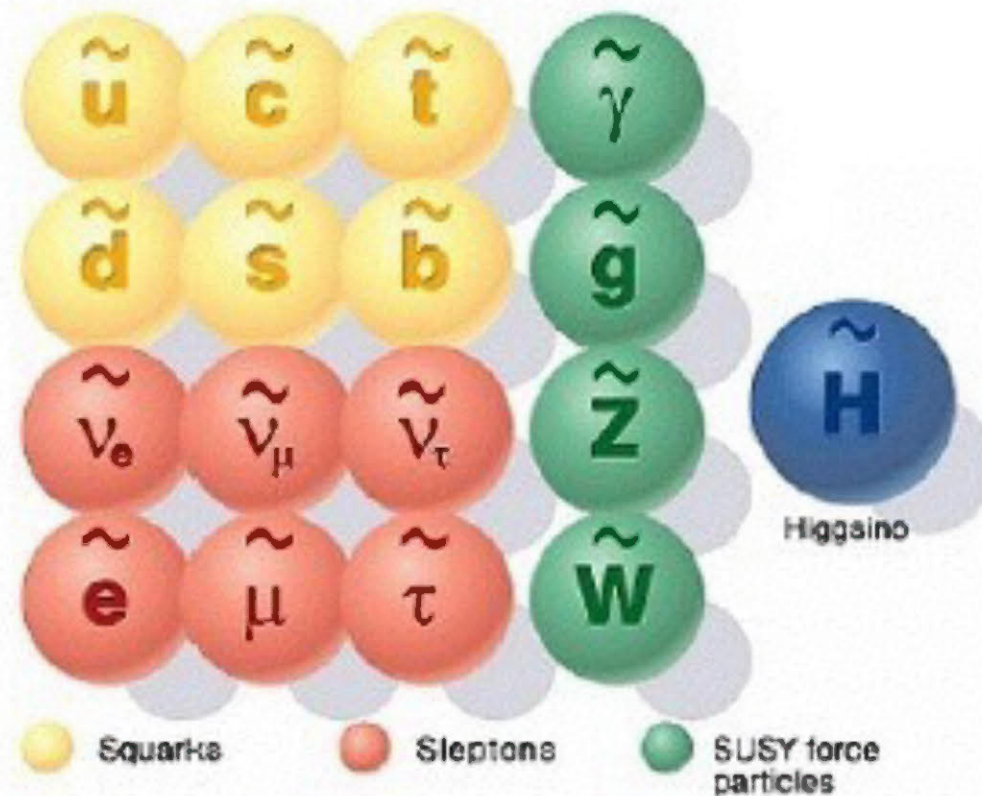


Pure SUSY Yang-Mills = supersymmetric
gluodynamics

SUPERSYMMETRY



Standard particles



SUSY particles

😊 First demonstration of the dual Meissner effect: Seiberg & Witten, 1994 😊



- gluons+complex scalar superpartner
- two gluinos
- Georgi-Glashow model built in

$SU(2) \rightarrow U(1)$, monopoles \rightarrow

Monopoles become light if $|\varphi^3| \lesssim \Lambda \rightarrow$ At two points, massless!

$N=1$ deform. forces M condensation \rightarrow

$U(1)$ broken, electric flux tube formed \rightarrow

Exact results in QFT are possible!

Gauge symmetry is a redundancy!!

Hence, Seiberg dualities !!!

$SU(N)_{\text{gauge}}, N_f \text{ flavors} =$

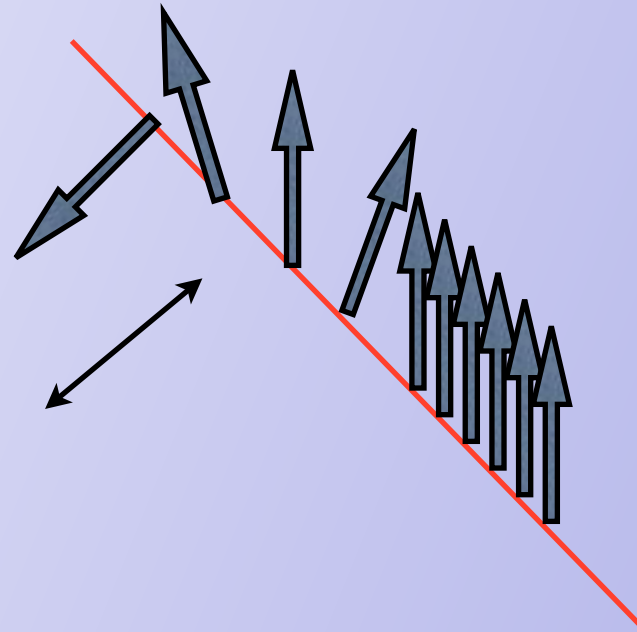
$SU(N_f - N)_{\text{gauge}}, N_f \text{ flavors}$

NSVZ β function: Conformal Window

Glino condensate: order parameter (N vacua)


“Non-Abelian” string is formed if all non-Abelian degrees of freedom participate in dynamics at the scale of string formation

2003: Hanany, Tong
Auzzi et al.
Yung + M.S.



classically gapless excitation

$SU(2)/U(1) = CP(1) \sim O(3)$ sigma model

- 
- A horizontal red line represents a soliton vortex string. A dark blue circle, representing a kink or confined monopole, is positioned on this line. Two black arrows point from the text below towards the circle and the line.
- * Kinks appear on soliton vortex strings
 - * Kink = Confined Monopole
- 2D kink mass = 4D monopole mass!!!

4D \leftrightarrow 2D Correspondence

☞ World-sheet theory \leftrightarrow strongly coupled bulk theory inside



Dewar flask

Instead of conclusions

- ➡ With new understanding and reformulation QFTs thrive. New theories and new phases are being discovered!!!

A treasure trove of novel
ideas, methods, solutions.
Rejuvenation!

Thank you!

MAP OF HEP THEORY

