# Theoretical physics at MPP – a historical perspective

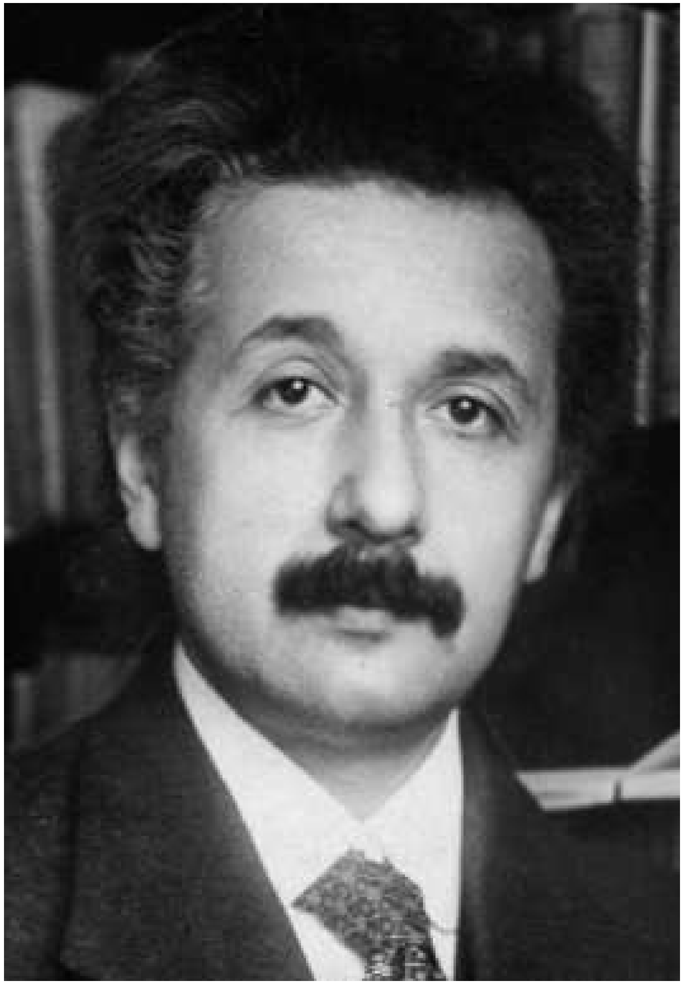
**100 Years Anniversary**

**MPI for Physics**

**10 – 12 October, 2017**

W. Hollik

Max-Planck-Institut für Physik, München



$$R_{\mu\nu} - g_{\mu\nu}R + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

$$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$$

now celebrating

now celebrating


a few years ago . . .

**July 11th, 2008**
**50th Anniversary of MPI**

in 2008: 50 Years of MPP in Munich

the MPP building in 1958

## Timeline of the MPP

1917 founded as Kaiser Wilhelm Institut für Physik in Berlin

1937 new building in Berlin Dahlem

1939 taken over by “Heereswaffenamt” (Army Ordnance)

1942 given back to Kaiser Wilhelm Gesellschaft

1945 occupied by US and Soviet troops

1946 re-established as Max Planck Institut für Physik, Göttingen

1958 moved to Munich

2021 move to Garching (?)

## a bit of terminology

| | |
|---|---|
| 1917 - 1945<br>1938 - 1945 | Kaiser Wilhelm Institut für Physik<br>Max Planck Institut für Physik (2nd name) |
| 1946 - 1958 | Max Planck Institut für Physik |
| 1958 - 1991 | Max Planck Institut für Physik und Astrophysik |
| 1991 - now | Max Planck Institut für Physik |

## during 100 years

- The era as Kaiser Wilhem Institut
  1917 - 1945

- The Institute at Göttingen
  1946 - 1958

- The Institute in Munich
  – the era Heisenberg 1958 - 1970
  – after 1970 until end of the millenium
  – the new millenium

# The Beginning

## farewell from classical physics at the upcoming 20th century

### space and time

- special relativity
  *Einstein 1905*
- general relativity
  field equations of gravitation
  *Einstein 1915*
- deflection of light
  *Einstein 1916*
- confirmed by observation
  *Eddington 1919*

### microcosm

- black body radiation
  Planck's constant $\hbar$
  *Planck 1900*
- photoelectric effect
  light quanta "photons"
  *Einstein 1905*
- specific heat of crystals
  *Einstein 1906*, *Debye 1912*
- atomic spectra
  *Bohr 1913*, *Sommerfeld 1916*

  semiclassical treatment
  not satisfactory

- 1911 Kaiser Wilhelm Gesellschaft founded
- proposal of an institute for physics *[by Max Planck et al.]*

  promoting research in theory and experiment

  scientists free of teaching and other duties

  ideal candidate: Albert Einstein *(at ETH Zurich)*

  in Berlin since 1914

  institute delayed by financial problems
- 1917 Kaiser Wilhelm Institut für Physik founded

no separate building for KWI Institut, private apartment of the director

part of institute's mission:
distributing money to support theor. and exp. research at other institutions

theory: support of quantum mechanics

*Born, Hund, Jordan at Göttingen*

**some highlights**

- confirmation of GRT *Eddington 1919*
- introduction of the cosmological constant *Einstein 1917*

$$R_{\mu\nu} - g_{\mu\nu} R + \Lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

- Nobelprize 1922 for Einstein
- Compton scattering experiment confirms light quanta

  *Compton 1922 at Washington University St. Louis*
- formulation of Bose–Einstein statistics *Einstein 1925-1926*

# Difficult Times

1933: end of first time segment *Einstein emigrated to US*

institute strongly affected

new director: Peter Debye 1935 - 1940

both theoretical and experimental credits
investigations on molecular structures
nuclear reactions in stars *[Weizsäcker ]*

Nobelprize 1936

Peter Debye *Leipzig Univ. 1927-1935*

⋆ Debye model of specific heat (1912)

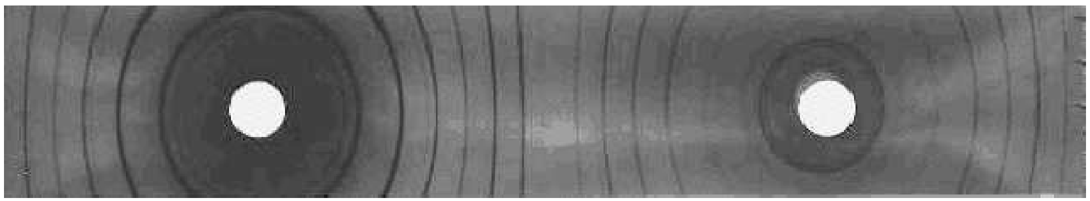
generalization of Einstein model

continuous spectrum up to $\omega_{\max} \sim 1/a$

$$\langle E \rangle = U = \int_0^{\omega_{\max}} d\omega \, \frac{g(\omega)\, \hbar\omega}{e^{\frac{\hbar\omega}{kT}} - 1}$$

⋆ Debye-Scherrer method (1916/17)

structure analysis by X-ray diffraction



1933: end of first time segment *Einstein emigrated to US*

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nuclear reactions in stars *[Weizsäcker ]*

Nobelprize 1936

**new building Berlin Dahlem 1937**

**official opening in May 1938**

- 1939 under Army Ordnance direction
  *Uranium research*
- Debye on leave → *Cornell University*
- 1942 institute returned to KWG
- director: Werner Heisenberg

⋆ *S-matrix theory [Heisenberg]*

⋆ *nuclear and astrophysics studies, first work on planetary system [Weizsäcker]*

⋆ *main topic: nuclear reactor research*

*terminated 1945 by US and Soviet army*

## Theoretical physics during the era of the KWI

- the development of quantum mechanics (1924 -1928)

  *Born, Heisenberg, Hund, Pauli, Jordan (mainly Göttingen)*

  *Schrödinger (Vienna)* *Dirac (Cambridge)*

- the emergence of quantum field theory (since 1928)

  quantum electrodynamics

  *Heisenberg (Leipzig)* *Pauli (Hamburg, Zurich)* *Dirac (Cambridge)*

- weak interaction: $\beta$-decay

  – neutrino postulate (1930) *Pauli (Zurich)*

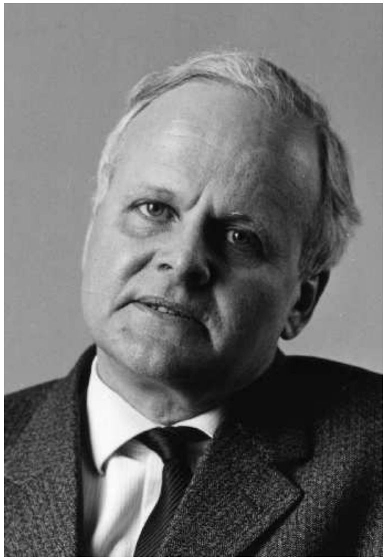
  – Fermi model (1934): current–current interaction *Fermi (Rome)*

- strong interaction: nuclei and nuclear forces

  – Isospin (1932) *Heisenberg (Leipzig)*

  – Yukawa model (1935): meson exchange *Yukawa (Kyoto)*

  – nuclear binding energy (1935) *Weizsäcker (Leipzig)*



## Carl Friedrich von Weizsäcker

student of Heisenberg at Leipzig (PhD 1933)

equivalent-photon method (1934)
*(Weizsäcker-Williams method)*

masses and binding energy of nuclei (1935)
liquid drop model *(Weizsäcker formula)*

- 1936 KWI für Physik *(Debye)* as expert for nuclear theory
  carbon cycle for energy production in stars (1938)
  $4H \rightarrow (C, N, O) \rightarrow He + 2e^{+} + 2\nu_e$ [*Bethe–Weizsäcker cycle*]
- 1942 - 1944 Professor at Strasbourg
- 1944 back to KWI
- 1946 MPI für Physik, Head of Theory Division until 1957
- 1957 Professor of Philosophy, Univ. Hamburg

# The Renaissance

## restart at Göttingen

- 1946 Heisenberg, Weizsäcker and others returned from internment at Farm Hall, UK
- 1946 rebuilding of former KWI Institute at Göttingen as *(official name 1948)*

  MAX PLANCK INSTITUT FÜR PHYSIK

  Director: Werner Heisenberg
- Division “Experimental Physics” *Head: Karl Wirtz*

  Division “Theoretical Physics” *Head: C.F. von Weizsäcker*

  besides elementary particles:

  common interest in cosmic rays and cosmic plasma physics
- 1947 new divison “Astrophysics” *Head: Ludwig Biermann*

  solar wind 1951
- increasing number of visiting scientists

- theoretical studies on astrophyics *Weizsäcker*
  - development of planetary system (started in 1943)
  - gas dynamics, turbulent processes, theory of turbulences

    $\Rightarrow$ evolution of planets, structure of galaxies
  - fundamental equations of plasma physics

  TRIGGERED ASTROPHYSICS AND PLASMAPHYSICS

  *students: Reimar Lüst* $\Rightarrow$ *Extraterrestric Physics*

  *Arnulf Schlüter* $\Rightarrow$ *Plasma Physics*

- foundations of quantum mechanics *Weizsäcker*

  *students: Georg Süßmann* $\rightarrow$ *LMU*

  *Peter Mittelstaedt* $\rightarrow$ *Univ. Köln*

- theory of elementary particles and quantum field theory

  *Heisenberg*

# The need for quantum field theory

- quantum mechanics insufficient

  – non relativistic

  – no description of photons

  – no spontaneous emission of light

- relativistic quantum mechanics *Dirac 1928*

  $(i\gamma^\mu \partial_\mu - m)\,\psi = 0$ *Dirac equation*

  $i\partial_\mu \to i\partial_\mu - eA_\mu$ *minimal substitution*

  • Lorentz invariant, contains spin and magnetic moment

  • fine structure of $H$ atom

  • correct prediction of positron

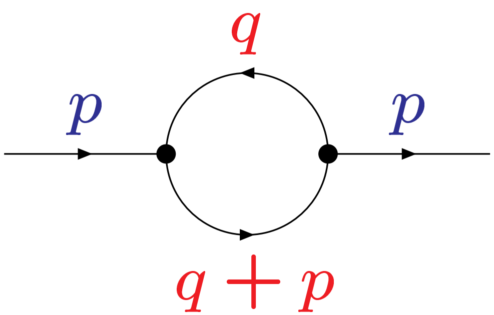
  – negative energy states, Dirac sea

  – not a one-particle equation (pair production)

## The rise of quantum field theory – and the problems

- quantization of electromagnetic field and matter
  *Dirac, Heisenberg, Jordan, Pauli, around 1928*
  - relativistic invariant, unifies quantum theory and relativity
  - quantum electrodynamics, processes with photons
  - higher-order predictions *Schwinger 1948*
    - ⋆ anomalous magnetic moment, Lamb shift
  - big push for perturbative treatment *Feynman 1949*
- theoretical problems: infinities in perturbation theory
  mathematically not defined expressions
  practical solutions by "renormalization"
  lack of clean mathematical basis
- in the 1950s: "golden age of quantum field theory"
  towards a rigorous mathematical formulation

Example of loop integral:




$$\sim \int d^4q \frac{1}{(q^2 - m_1^2)\left[(q+p)^2 - m_2^2\right]}$$

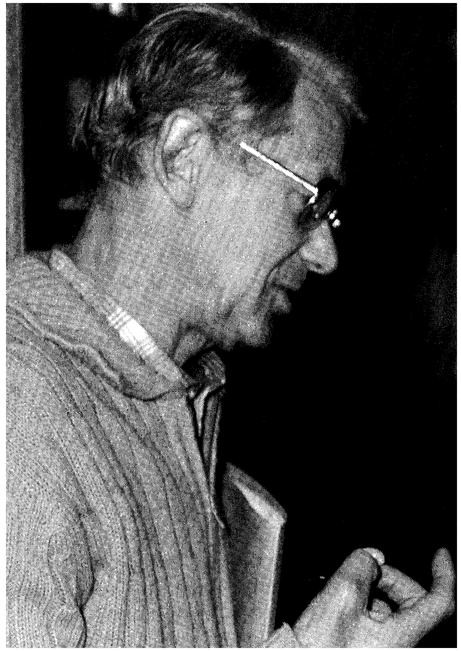
$$q \to \infty : \quad \sim \int^{\infty} \frac{q^3 dq}{q^4} = \int^{\infty} \frac{dq}{q} \quad \to \infty$$

$\Rightarrow$ integral diverges for large $q$

$\Rightarrow$ theory in this form not physically meaningful

**Quantum Field Theory at Göttingen 1952 -1956** **"Feldverein"**

*Harry Lehmann*



*Kurt Symanzik*

*Wolfhart Zimmermann*

Lehmann: from Jena *(assistent with Hund)*

Symanzik: student at Göttingen *(Heisenberg)*, PhD in 1954

Zimmermann: from Freiburg after PhD 1952 in mathematics

- LSZ formulation of quantum field theory on a solid mathematical basis

  definition of asymptotic fields and $S$-matrix elements

  LSZ reduction formulae for calculation of $S$-matrix elements

  *by now standard content of text books on QFT*

  *basis of pertubative calculations at any order*

  express matrix elements by correlation functions of local field operators *(Green functions)*

$$\tau(x_1, \ldots x_n) = \langle 0 | T\phi(x_1) \ldots \phi(x_n) | 0 \rangle$$

- avoiding the infinities:

  formulation of QFT in terms of finite, renormalized, Green functions

  general relation to $S$-matrix elements

IL NUOVO CIMENTO Vol. XI, N. 4 1° Aprile 1954

## Über Eigenschaften von Ausbreitungsfunktionen und Renormierungskonstanten quantisierter Felder.

H. Lehmann
*Max-Planck-Institut für Physik - Göttingen, Deutschland*

(ricevuto il 22 Gennaio 1954)

**Summary.** — It is attempted to derive some general properties of the propagation functions for coupled fields ($\Delta'_F$, $S'_F$) without the use of power series expansions and to show their connection with the renormalization constants for field operators and masses. Assuming that the coupled functions exist, it appears possible to discuss their behavior near the light-cone (or for large momenta) and to obtain some information about the singularities of these functions when continued analytically. Attempts at the treatment of unrenormalizable theories are criticised on the basis of these results. Formulae are given for the mentioned renormalization constants which contain inequalities for the constants $Z_2$ and $Z_3$. Finally it is pointed out that the methods introduced are advantageous also for computations by means of power series expansion. As an example the lowest order correction to the $S_F$-function in pseudoscalar meson theory is calculated without the appearance of infinite terms during the calculation.

IL NUOVO CIMENTO Vol. I, N. 1 1° Gennaio 1955

## Zur Formulierung quantisierter Feldtheorien.

H. Lehmann, K. Symanzik und W. Zimmermann
*Max-Planck-Institut für Physik - Göttingen (Deutschland)*

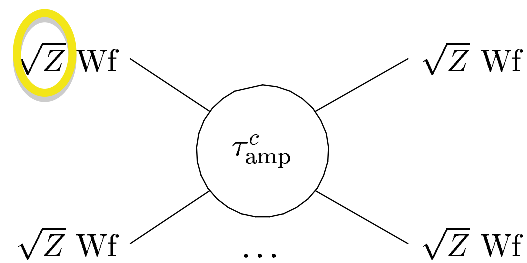
(ricevuto il 22 Novembre 1954)

**Summary.** — A new formulation of quantized field theories is proposed. Starting from some general requirements we derive a set of equations which determine the matrix-elements of field operators and the S-Matrix. These equations contain no renormalization constants, but only experimental masses and coupling parameters. The main advantage over the conventional formulation is thus the elimination of all divergent terms in the basic equations. This means that no renormalization problem arises. The formulation is here restricted to theories which do not involve stable bound states. For simplicity we derive the equations for spin 0 particles, however the extension to other cases (e.g. quantum electrodynamics) is obvious. The solutions of the equations are discussed in a power-series expansion. They are then identical with the renormalized expressions of the conventional formulation. However, the equations set up here are not restricted to the application of perturbation theory.

particle propagator

$$D(p^2) = \frac{Z}{p^2 - m^2} + \int_{s_0}^{\infty} ds\, \frac{\sigma(s)}{p^2 - s}$$

pole at mass-squared



# The Era in Munich

# Getting started in Munich

- 1958 institute moved from Göttingen to Munich
- covered now two institutes: for physics and for astrophysics
- former astrophysics divison upgraded to an institute

*Director: L. Biermann*

# MPI für Physik und Astrophysik

## MPI für Physik

experimental particle physics

theory of particles and nuclei

quantum field theory

## MPI für Astrophysik

structure and evoution of stars

cosmic rays

plasma physics

1960 Plasmaphysik $\rightarrow$ Garching

*Director Theory: Arnulf Schlüter*

1963 Extraterrestrische Physik
$\rightarrow$ Garching

*Director: Reimar Lüst*

1979 Astrophysik $\rightarrow$ Garching

theory now without Weizsäcker

1963 Hans Peter Dürr
Head of Theory Division

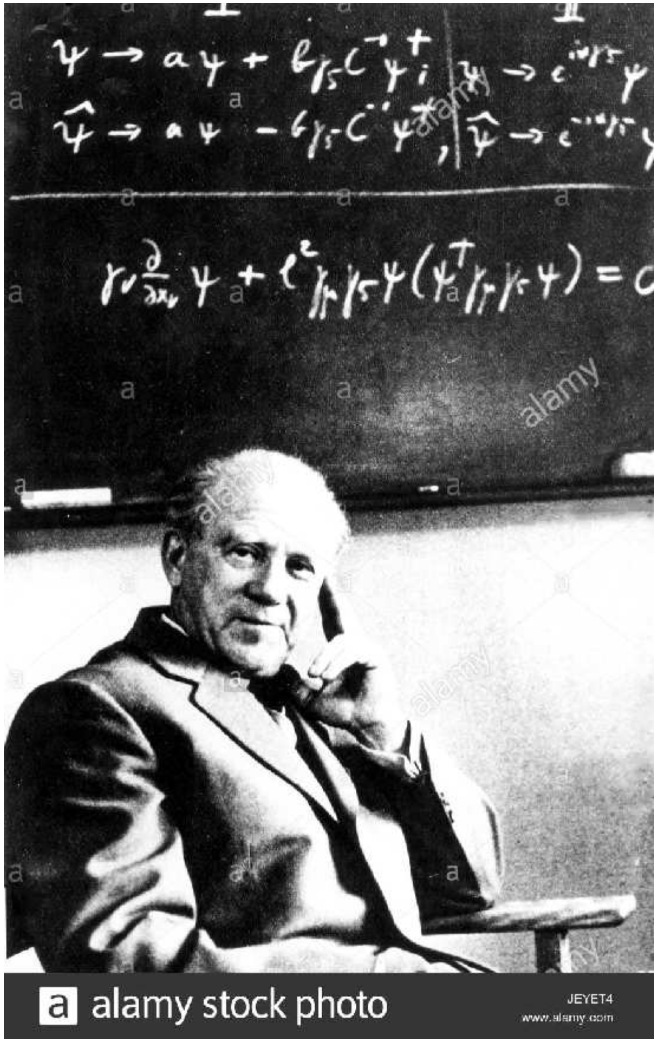
- rigorous formulation of quantum field theory

  CPT theorem *Gert Lüders 1954/1958*

  spin-statistic theorem *Gert Lüders (with B. Zumino)1958*

  Reeh-Schlieder theorem *Helmut Reeh, Siegfried Schlieder 1961*

- non-linear spinor theory *Heisenberg et al.*




## Heisenberg’s final goal

towards a unified theory of elementary particles *theory of everything “Weltformel”*

non-linear spinor theory

Lorentz invariant

isospin symmetry $SU(2)$

proton/ neutron as basic isospin doublet

other particle masses as solution of eigenvalue problem

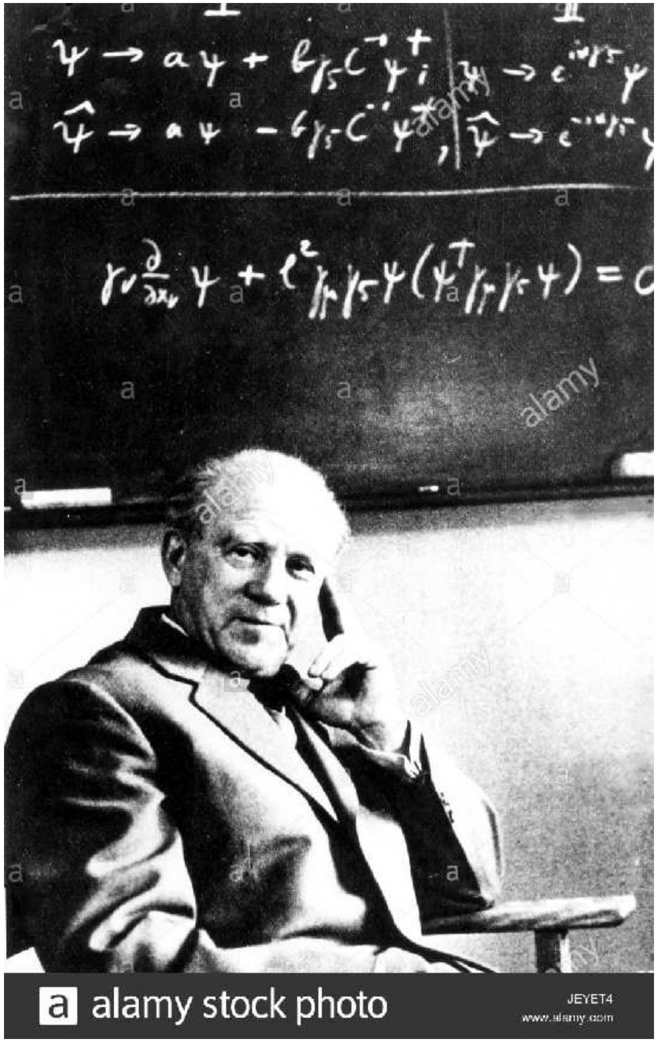
published in 1959

*[with H.P. Dürr, H. Mitter, H. Reeh, S. Schlieder]*

*big interest from media and society*


*Max Planck's 100th birthday celebration*

## *Heisenberg's final goal*




towards a unified theory of elementary particles *theory of everything "Weltformel"*

non-linear spinor theory

Lorentz invariant

isospin symmetry $SU(2)$

proton/ neutron as basic isospin doublet

other particle masses as solution of eigenvalue problem

published in 1959

**problems:**

- indefinite metric. negative probabilities
- symmetry not large enough $\rightarrow SU(3) \times SU(2) \times U(1)$
- proton and neutron are composed of quarks

# the rise of quarks and QCD

- quarks as constituents of hadrons

  *Gell-Mann 1964, Zweig 1964*

- parton model for deep-inelastic electron–nucleon scattering

  *Feynman 1969*

- deep-inelastic scattering experiments and scaling behaviour

  *SLAC 1967-1973*

- colour $SU(3)$ and quark dynamics, basis of QCD

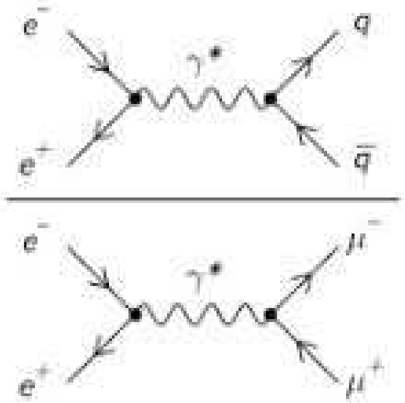
  *Fritzsch, Gell-Mann 1972, Fritzsch, Gell-Mann, Leutwyler 1973*

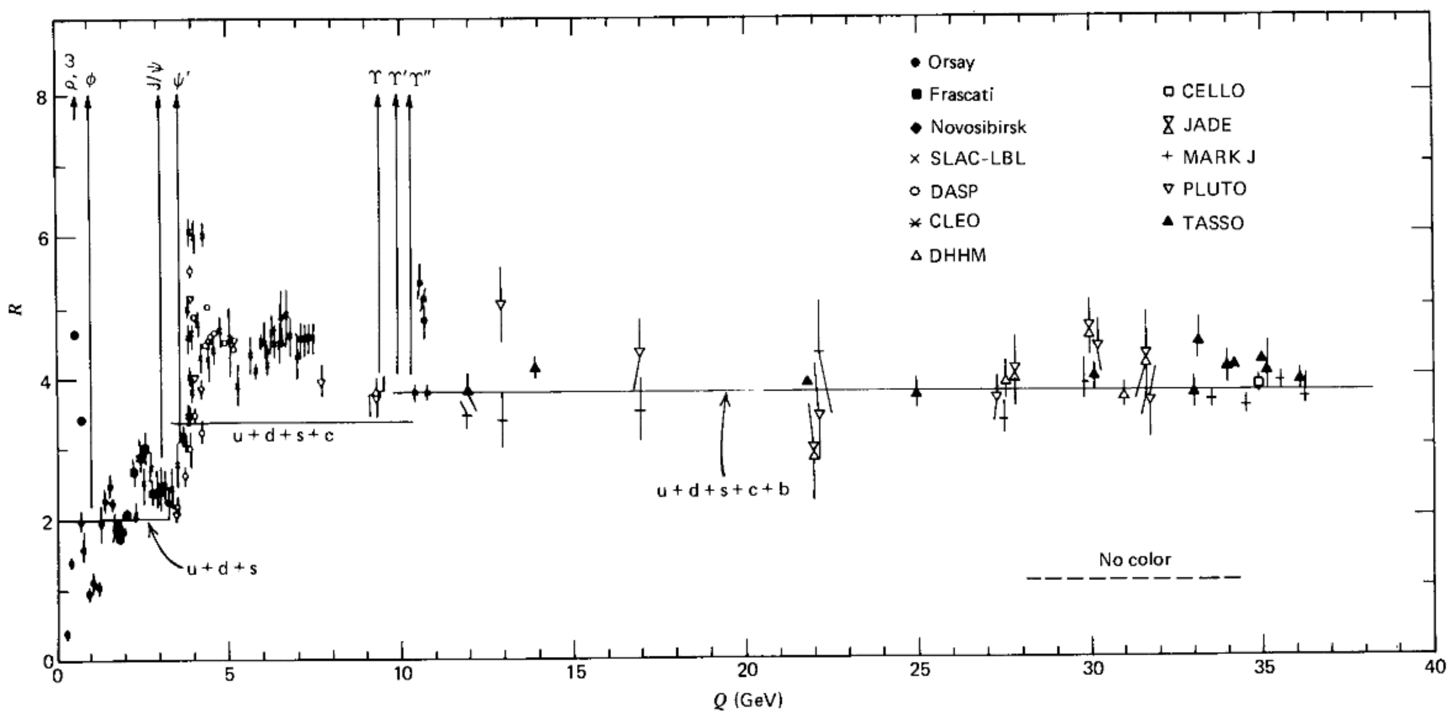
- asymptotic freedom of QCD

  *Gross, Wilczek 1973, Politzer 1973*

# electron–positron annihilation into hadrons via quark pairs

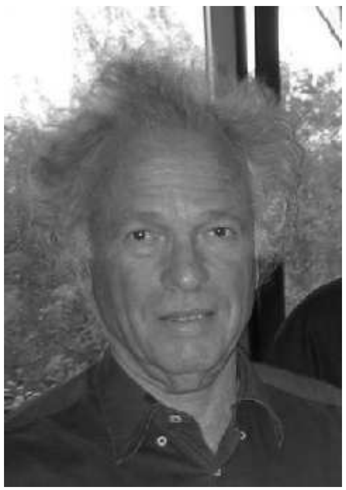
$$R = \frac{\sigma(e^- e^+ \to \text{hadrons})}{\sigma(e^- e^+ \to \mu^- \mu^+)} \approx$$



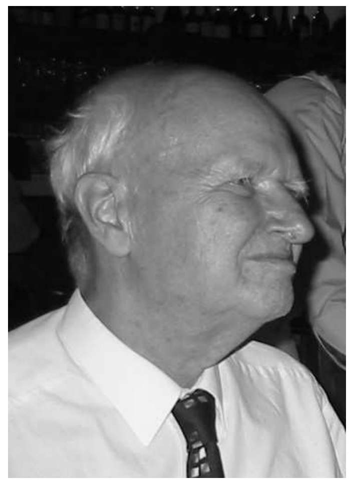



## the transition period

- 1970 retirement of Heisenberg
- Hans Peter Dürr as interim director
- 1971 installation of a directorial board
  chair: Leon van Hove (until 1974)
- appointment of new theory directors $\rightarrow$ new era



*1973: Leo Stodolsky*



*1974: Wolfhart Zimmermann*

## new directors in theory

- high energy behaviour of scattering cross sections *Leo Stodolsky*
- astroparticle physics, neutrinos and cosmology

  *Leo Stodolsky, Georg Raffelt*
- weakly interacting particles via scattering off nuclei

  measuring recoil energy by superconduction grains

  *Drukier, Stodolsky 1983*

  triggered direct search for WIMPS/ dark matter with cryogenic detectors $\Rightarrow$ CRESST experiment
- mixing of photons with low mass particles (axions)

  *Stodolsky, Raffelt 1987*

  $\Rightarrow$ topical MADMAX experiment for axion search

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

# Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
*Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany*
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

# Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

## new directors in theory

- mathematically rigorous formulation of quantum field theory
  *Zimmermann*

- systematic treatment of renormalization

  BPHZ renormalization *Bogoliubov, Parasiuk, Hepp, Zimmermann*

  “forest formula” *Zimmermann*

  basis of applications in higher-order calculations for
  QCD and electroweak precision tests

Wolfhart Zimmermann Memorial Symposium

Zimmermann's Forest, Infrared Divergences
& the 5 Loop β function in QCD

Franz Herzog (Nikhef)

## new directors in theory

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  BPHZ renormalization *Bogoliubov, Parasiuk, Hepp, Zimmermann*

  “forest formula” *Zimmermann*

  basis of applications in higher-order calculations for
  QCD and electroweak precision tests

- reduction of couplings *Zimmermann*

  less free parameters in renormalizable theories

  prediction of Higgs boson mass in SM

  right Higgs mass range predicted in supersymmetric SM

## new directors in theory

- mathematically rigorous formulation of quantum field theory
  *Zimmermann*

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  BPHZ renormalization *Bogoliubov, Parasiuk, Hepp, Zimmermann*

  “forest formula” *Zimmermann*

  basis of applications in higher-order calculations for
  QCD and electroweak precision tests

- renormalization of gauge theories *Breitenlohner, Maison, Sibold*

- quantum field theory on the lattice *Weisz*

  numerical studies of non-perturbative aspects of
  non-Abelian gauge theories

## particle physics phenomenology

- rich activity from late 1970's on
  parallel to exp discoveries: *quarks, gluons,* $W^{\pm}$, $Z$ *bosons, ...*
  electroweak precision tests   LEP, SLC, TEVATRON
- weak interactions of hadrons, flavour physics, $CP$-violation
- precision calculations for $e^+e^-$ annihilation,
  ew precision observables
- substantial turnover of scientists during 1980 - 2000

  *Roberto Peccei 1978 - 1984*   *[axion: Peccei,Quinn 1977]*

  *Andrzej Buras 1982 -1988*

  *Jean-Marc Gerard 1985 -1989*

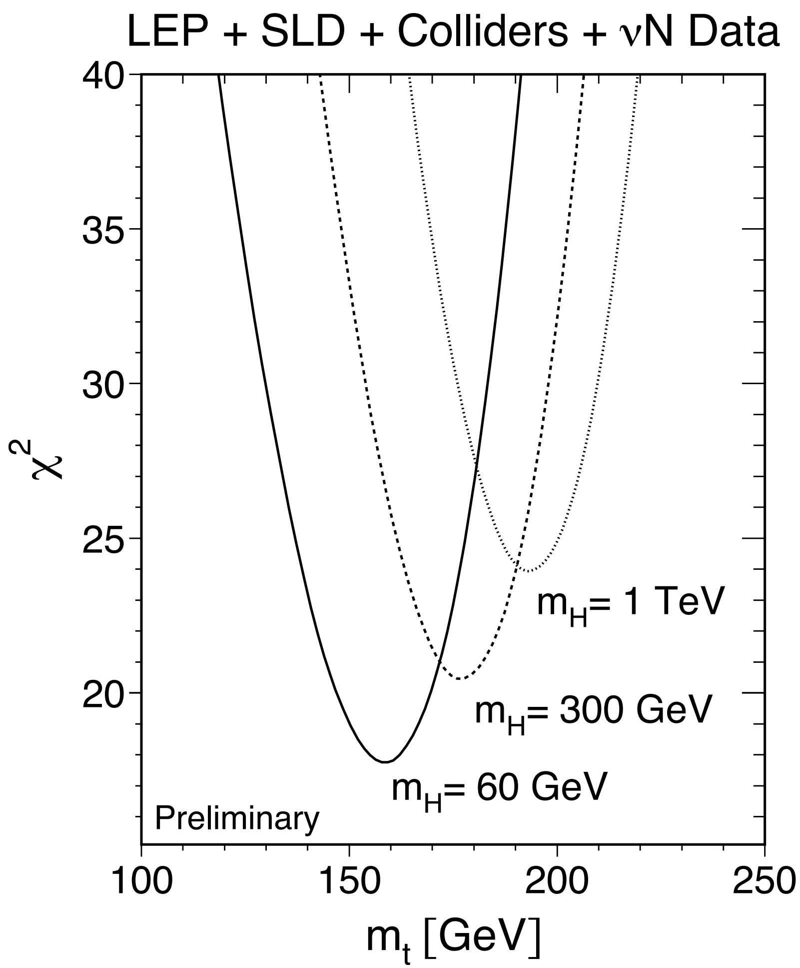
  *Johann Kühn 1984- 1990*

  *Wolfgang Hollik 1990 - 1993*

  *Bern Kniehl 1994 - 1999*

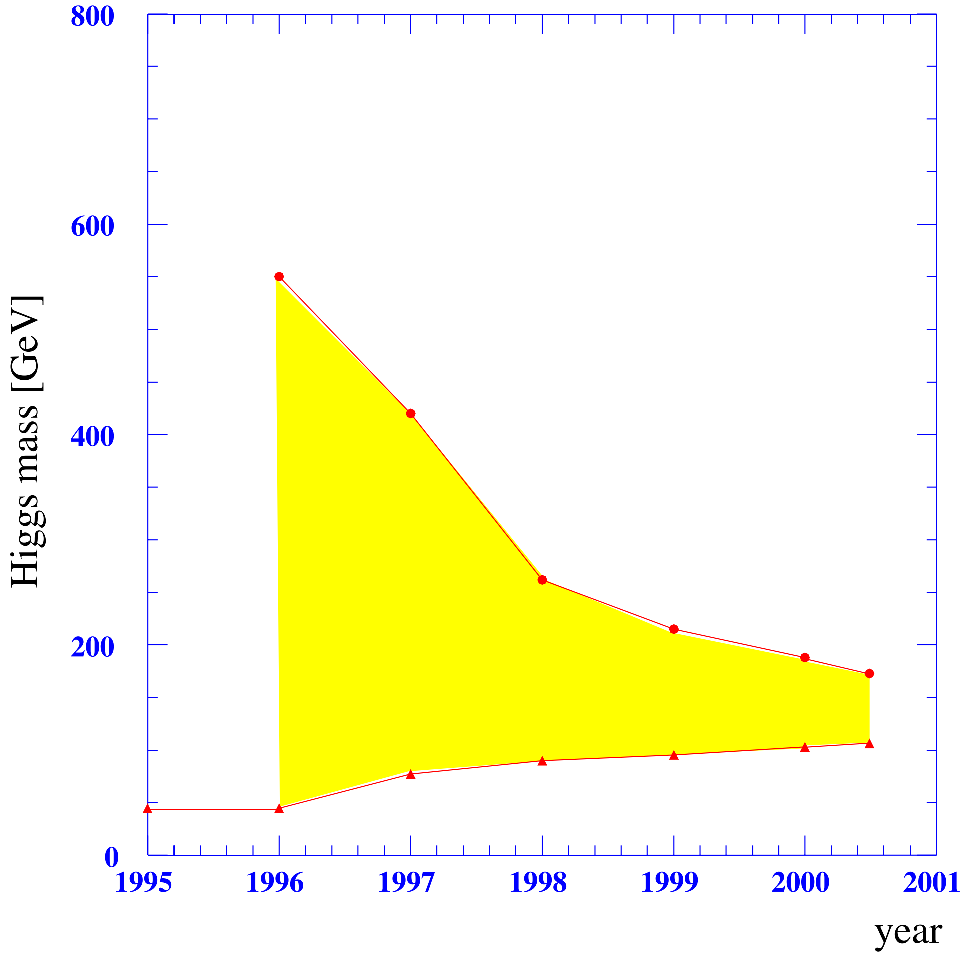
before the top quark was discovered (< 1995):

indirect mass determination $\Rightarrow$ $\mathrm{m_t} = 178 \pm 8\,^{+17}_{-20}\,\mathrm{GeV}$




top discovery: *Tevatron 1995* $\mathrm{m_t} = 180 \pm 12\,\mathrm{GeV}$

bounds on Higgs mass from direct and indirect searches



**appoIntment of new director**

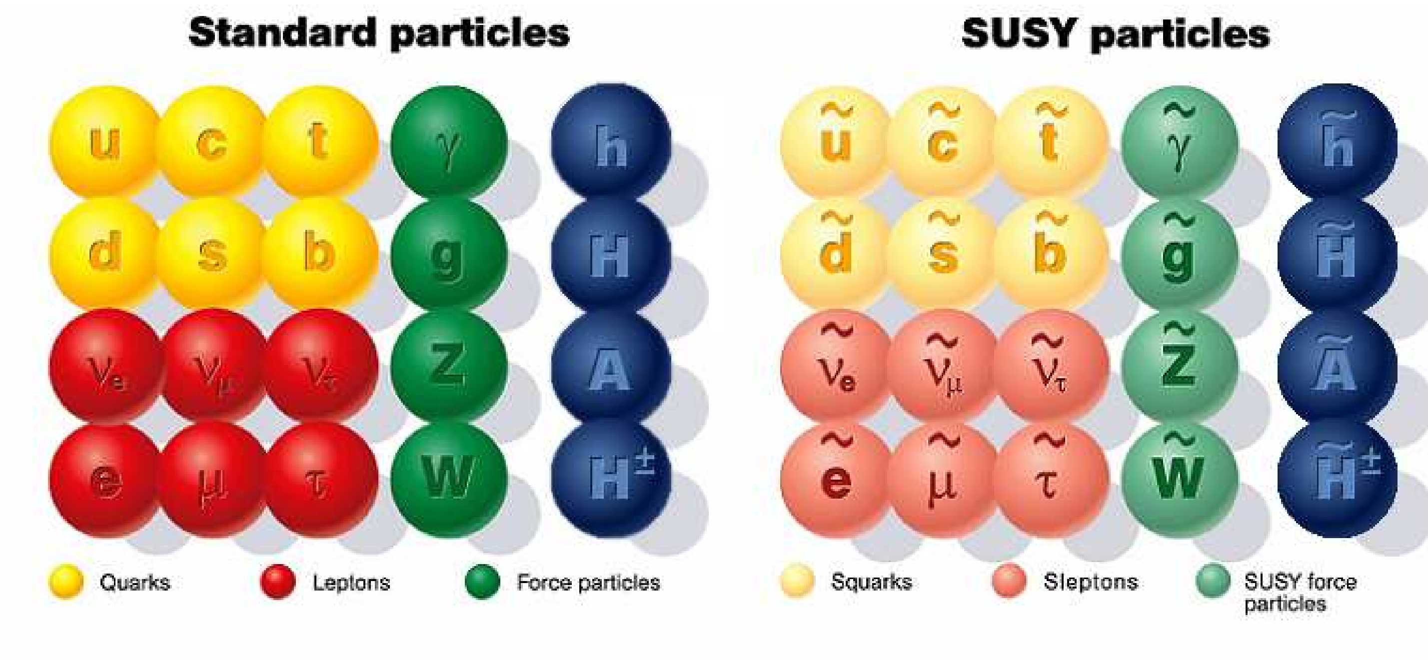
**Julius Wess 1990**

*1974 supersymmetry in relativistic QFT*

$\Rightarrow$ *supersymmetric standard model*

*(research topic of phenomenology group)*

# minimal supersymmetric standard model




- stabilization of the electroweak scale
- gauge coupling unification
- new sources of CP violation
- dark matter candidate (lightest SUSY particle, LSP)
- physical Higgs bosons: $h^0, H^0, A^0, H^\pm$

  lightest Higgs boson $h^0$ $< 130\,\mathrm{GeV}$

**appoIntment of new director**

**Julius Wess 1990**

*1974 supersymmetry in relativistic QFT*

$\Rightarrow$ *supersymmetric standard model*

*(research topic of phenomenology group)*

- non-commutative geometry

  space–time variables do not commute at small distances

  attempt towards microscopic theory of gravitation

- phenomenological predictions, like $Z \to \gamma\gamma$

Eur. Phys. J. C 29, 441–446 (2003)
Digital Object Identifier (DOI) 10.1140/epjc/s2003-01207-4

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**The $Z \to \gamma\gamma,\ gg$ decays in the non-commutative standard model**

W. Behr[1,a], N.G. Deshpande[2,b], G. Duplančić[3,c], P. Schupp[4,d], J. Trampetić[5,6,e], J. Wess[7,8]

# The New Millenium

- retirement of theory directors

  *Zimmermann 1996, Dürr 1997, Wess 2002, Stodolsky 2005*

- appointment of new directors

  **Wolfgang Hollik 2002: Phenomenology**

  *precision tests of SM and beyond (supersymmetry ....)*

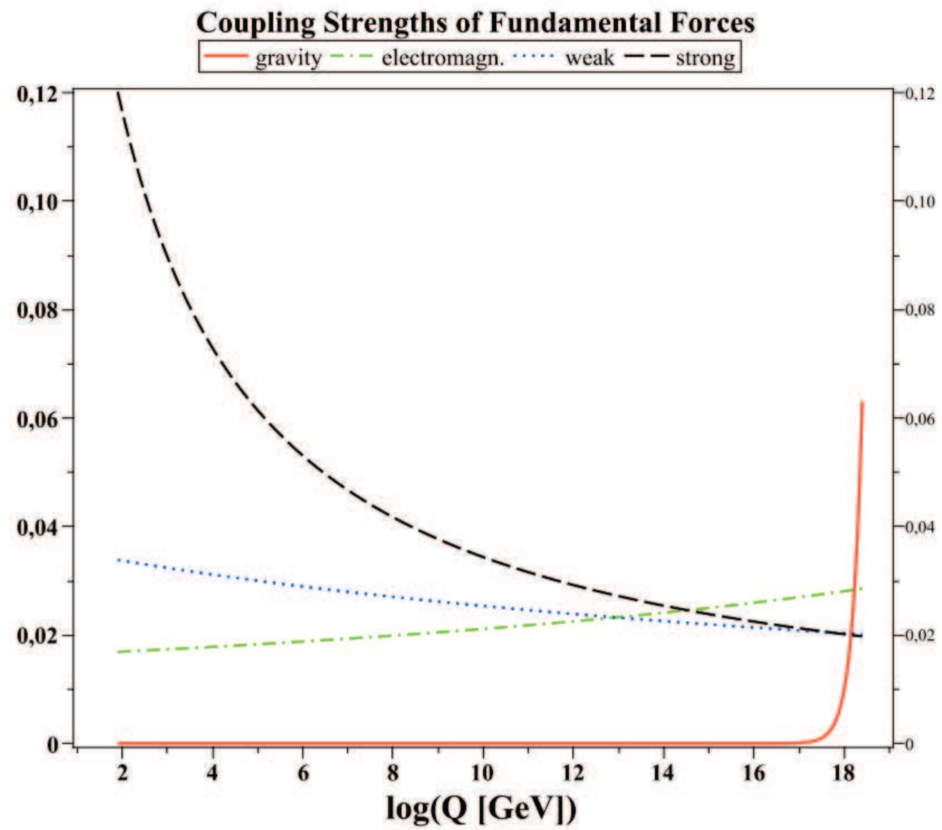
  **Dieter Lüst 2003: String Theory**

  *towards unification of SM with gravity*

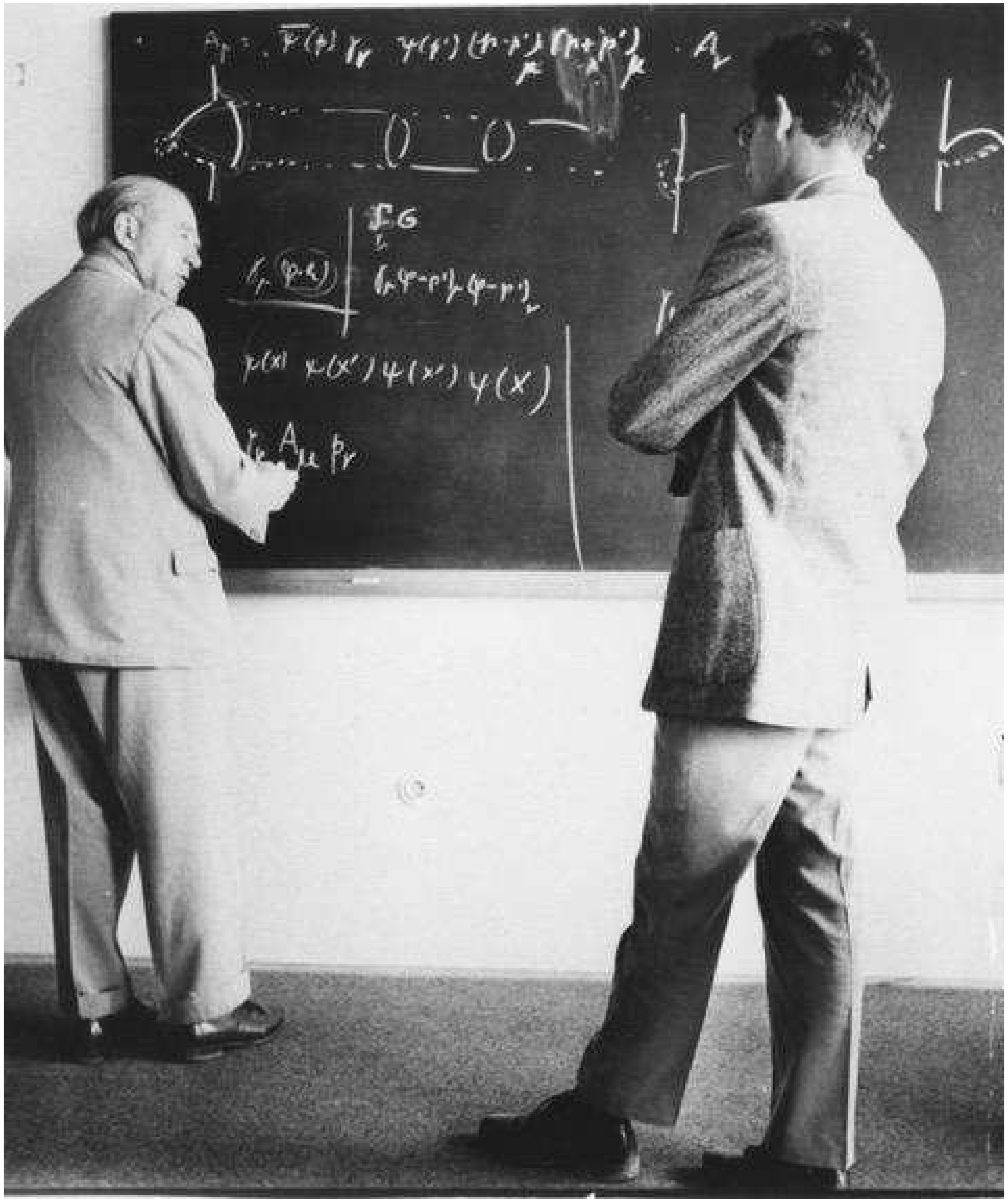
  **Georgi Dvali 2009: Particle Cosmology**

  *relating microscopic and macroscopic structure of gravity*

- aiming finally at a unified description of the fundamental interactions




- unfication of forces?
- how connect SM to gravity?
- missing $CP$-violation for baryon asymmetry of the universe?
- nature of dark matter and dark energy?



# The Future

# The Future

not part of history

# Thank You!