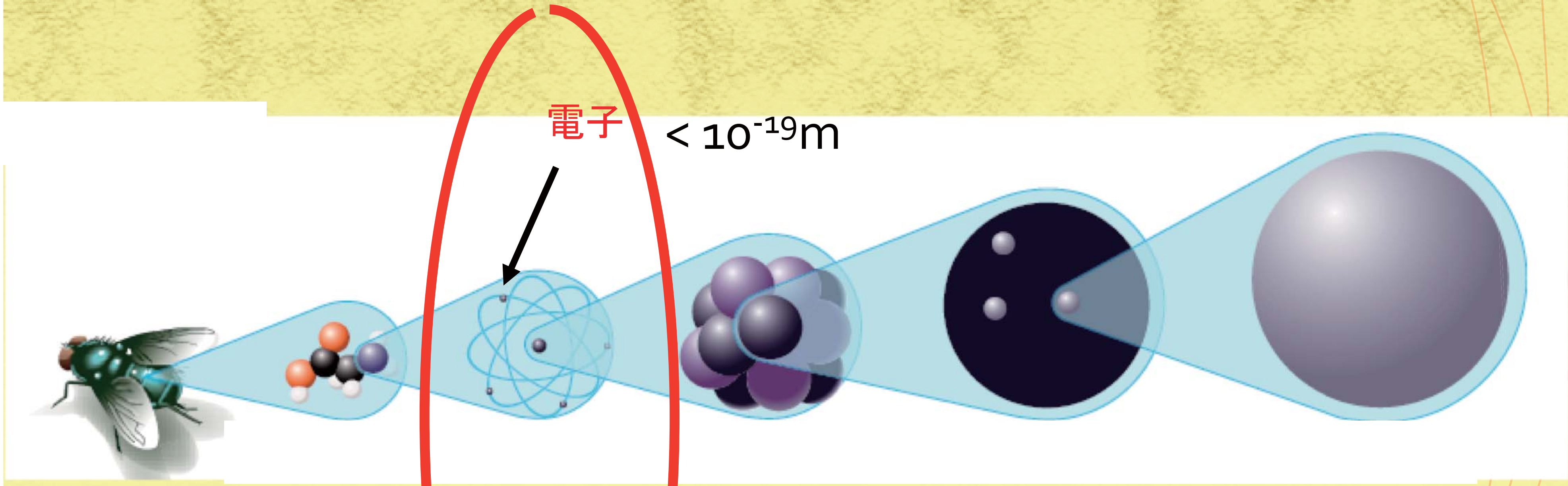
たまねぎの皮むくたびの涙かな・・・
ー複合理論とともにー

山脇幸一

退職最終講義
２０１０年３月２日

物質を顕微鏡で拡大して見てゆくと



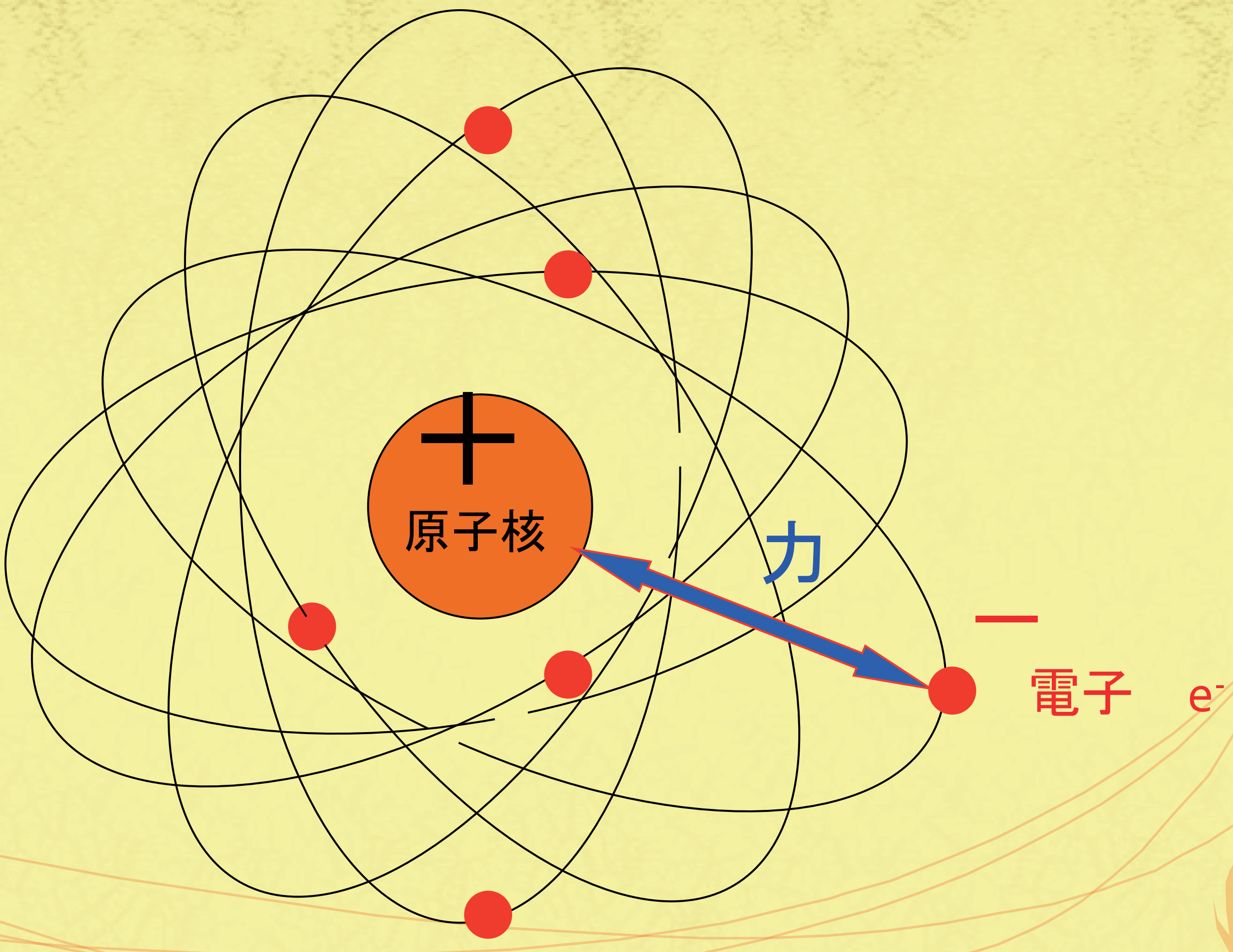
電子

< 10^{-19}m

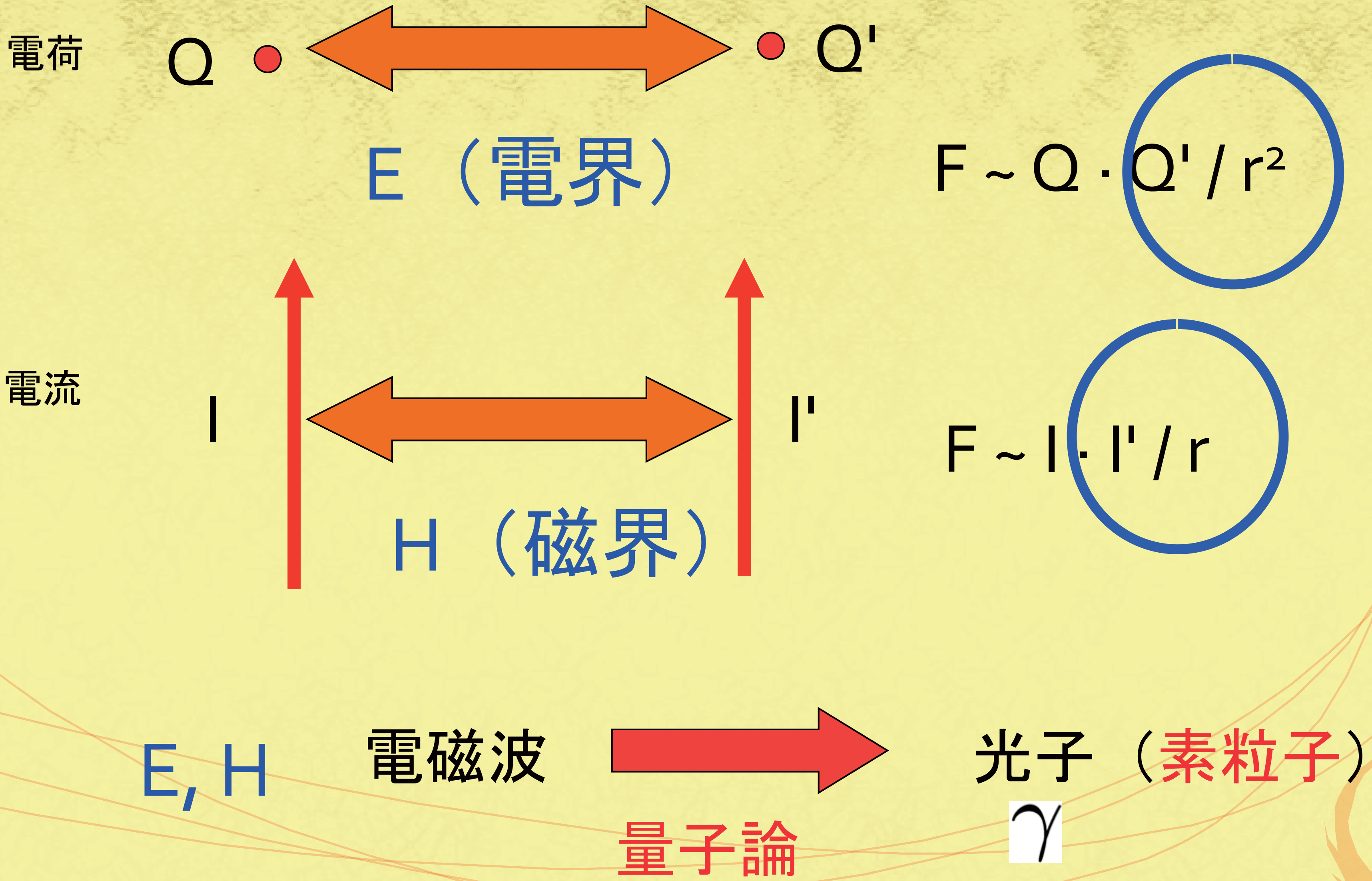
	分子	原子	原子核	陽子・中性子	クォーク
10^{-2}m	10^{-9}m	10^{-10}m	10^{-14}m	10^{-15}m	< 10^{-19}m

http://nobelprize.org/nobel_prizes/physics/laureates/2008/info.pdf　より

原子



（電磁気的）力の起源



電荷　Q　Q'

E（電界）

$F \sim Q \cdot Q' / r^2$

電流　I　I'

H（磁界）

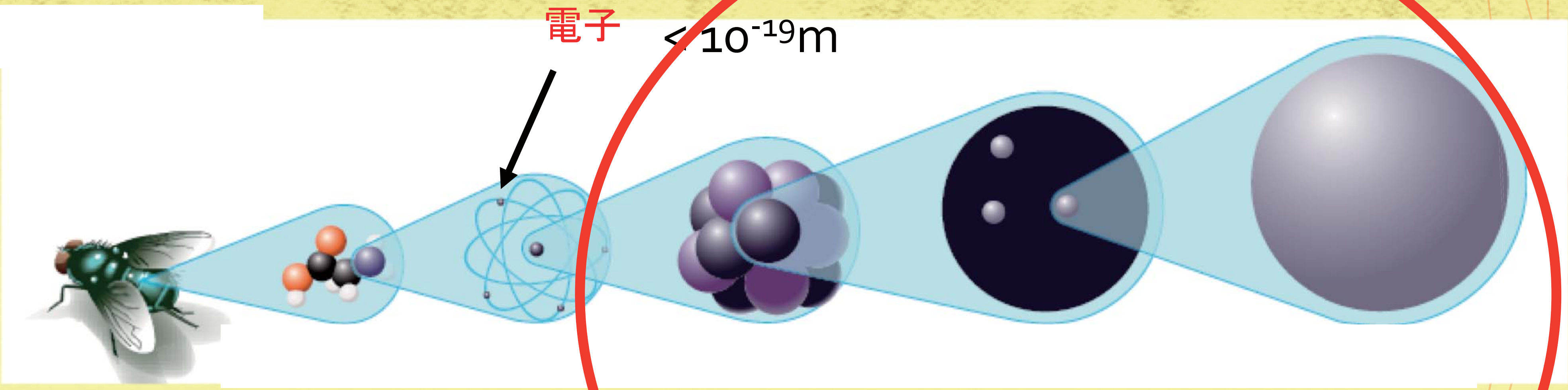
$F \sim I \cdot I' / r$

E, H　電磁波　光子（素粒子）

量子論

γ

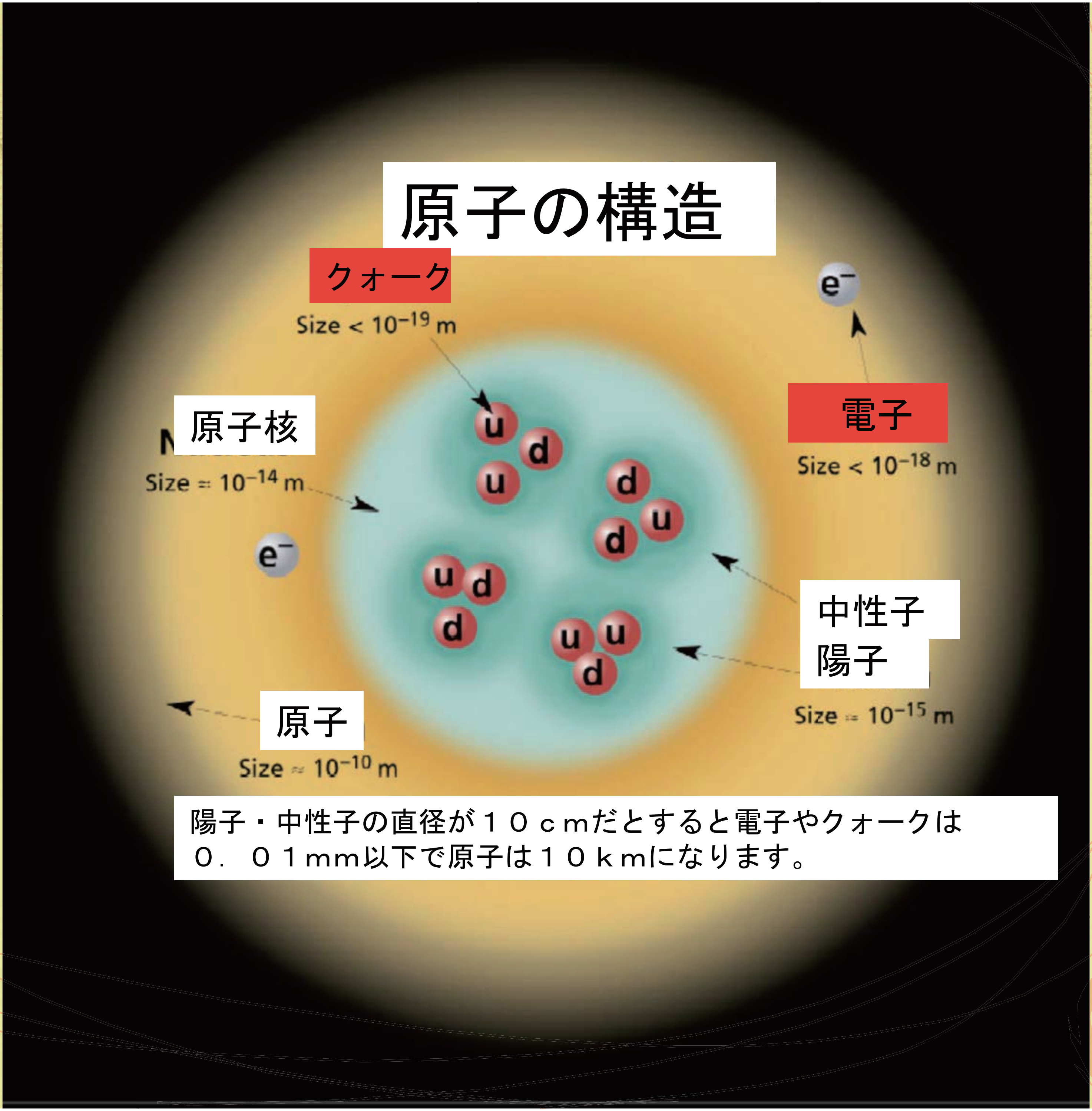
物質を顕微鏡で拡大して見てゆくと



	分子	原子	原子核	陽子・中性子	クォーク
10^{-2}m	10^{-9}m	10^{-10}m	10^{-14}m	10^{-15}m	$< 10^{-19}$m

http://nobelprize.org/nobel_prizes/physics/laureates/2008/info.pdf より

原子の構造



クォーク

Size $< 10^{-19}$ m

電子

Size $< 10^{-18}$ m

原子核

Size $\approx 10^{-14}$ m

中性子

陽子

Size $\approx 10^{-15}$ m

原子

Size $\approx 10^{-10}$ m

陽子・中性子の直径が１０ｃｍだとすると電子やクォークは
０．０１mm以下で原子は１０ｋmになります。

http://www.cpepweb.org/images/chart_details/Structure.jpg

物質の起源

小林・益川理論の予言

物質の構成要素

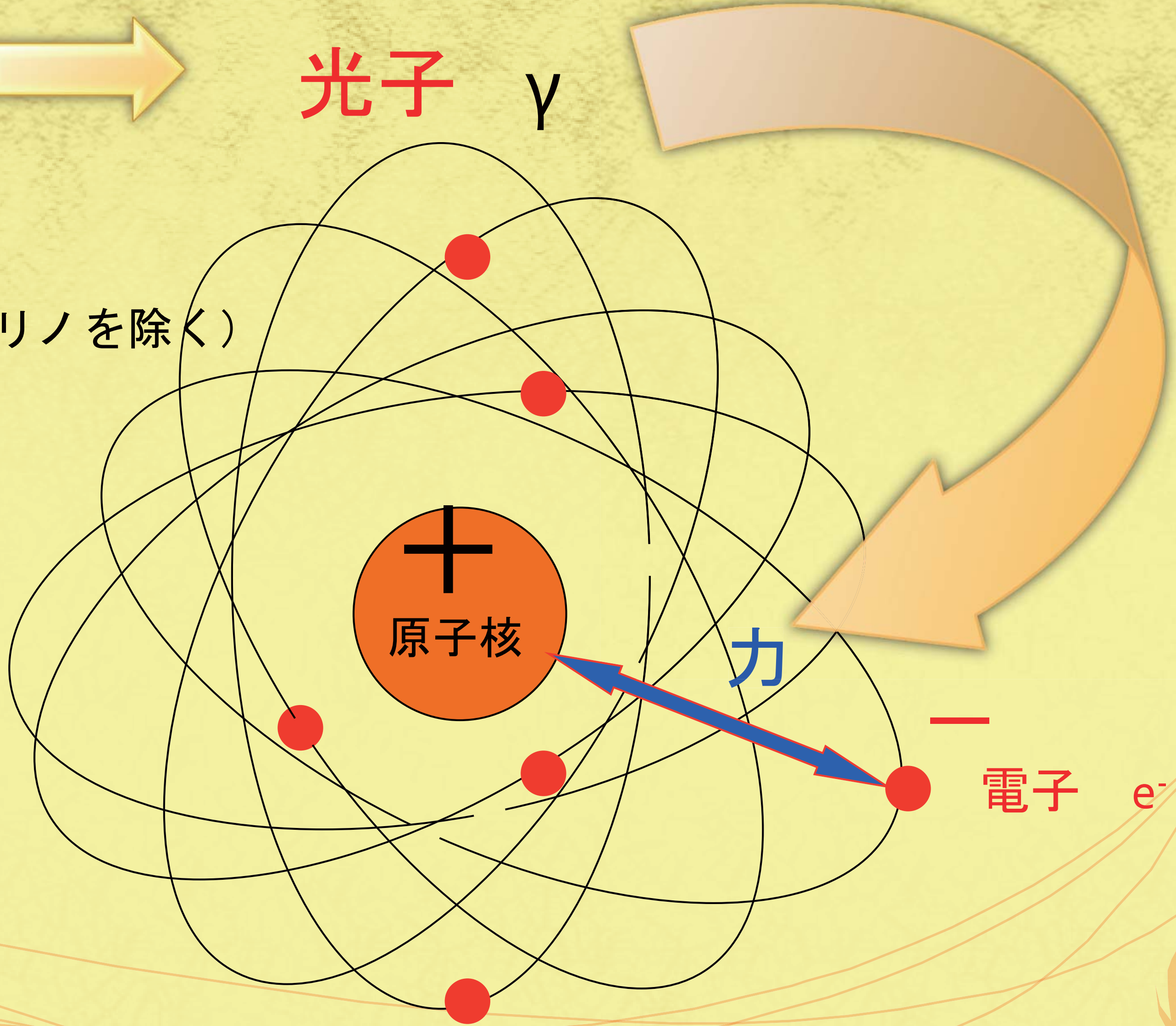
	レプトン			クォーク		
	種類（フレーバー）	質量 GeV/c^2	電荷 （e）	種類（フレーバー）	質量 GeV/c^2	電荷 （e）
第1世代	**e** 電子	0.000511	−1	**u** アップ	0.003	2/3
				d ダウン	0.006	−1/3
第2世代						
第3世代						

水素原子（陽子・中性子）の質量 ≒ 1 GeV/c^2

力の起源

電磁力 → 光子　γ

クォーク・
レプトン(ニュートリノを除く）



力の起源（光子の仲間）

弱い力 → ウィークボソン(弱ボソン） W, Z

放射能

$$n \rightarrow p + e + \bar{\nu}$$

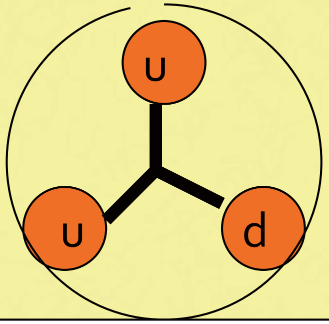
中性子　陽子　電子（ベーター線）　反電子ニュートリノ

クォーク・レプトン

強い力 → グルーオン　g

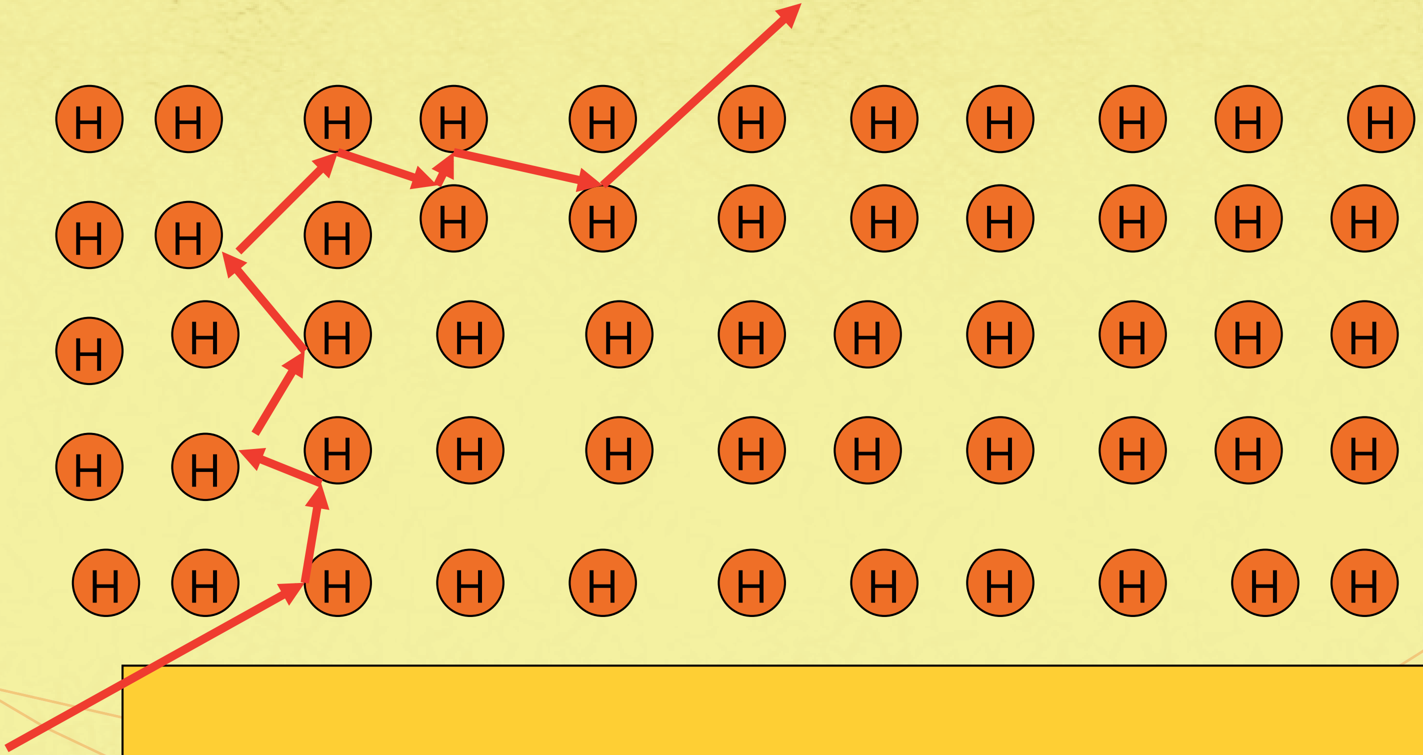
クォークのみ

陽子



質量の起源

ヒッグス粒子(未発見)



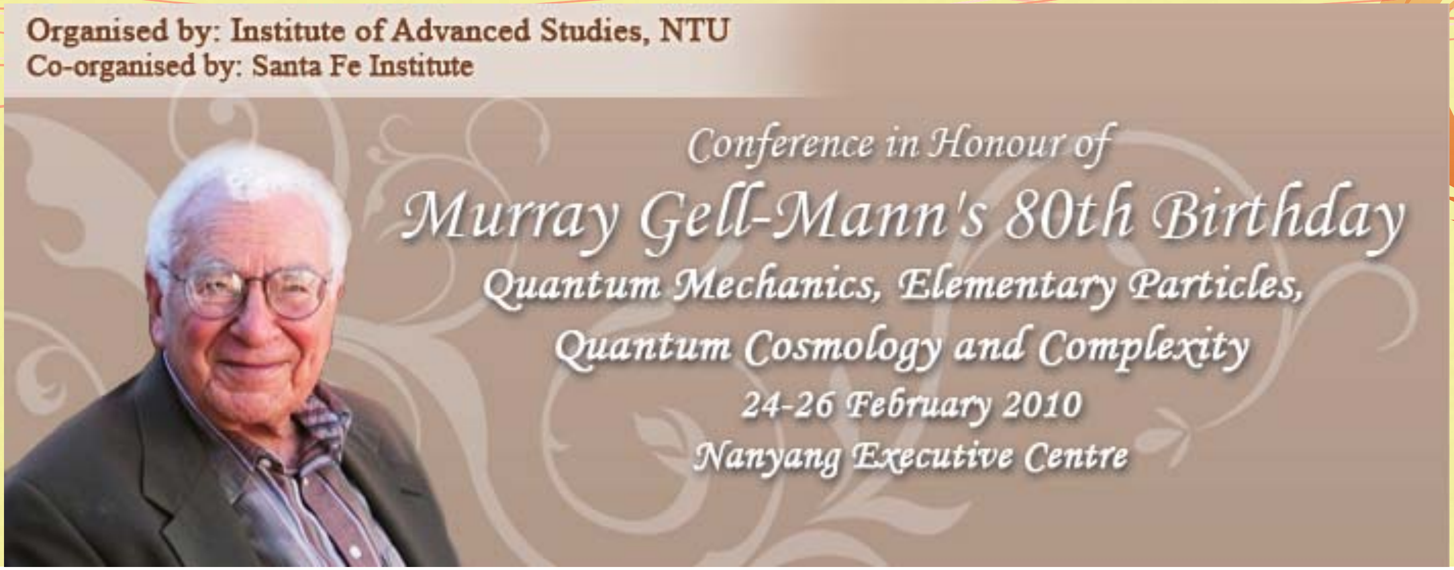
質量　〜　“衝突の強さ”×　＜H＞

たまねぎの
皮むくたびの
涙かな
ヒッグス粒子の
皮むける日は

Composite Higgs Particle
- Dynamical Origin of Mass -

K. Yamawaki
(Nagoya)

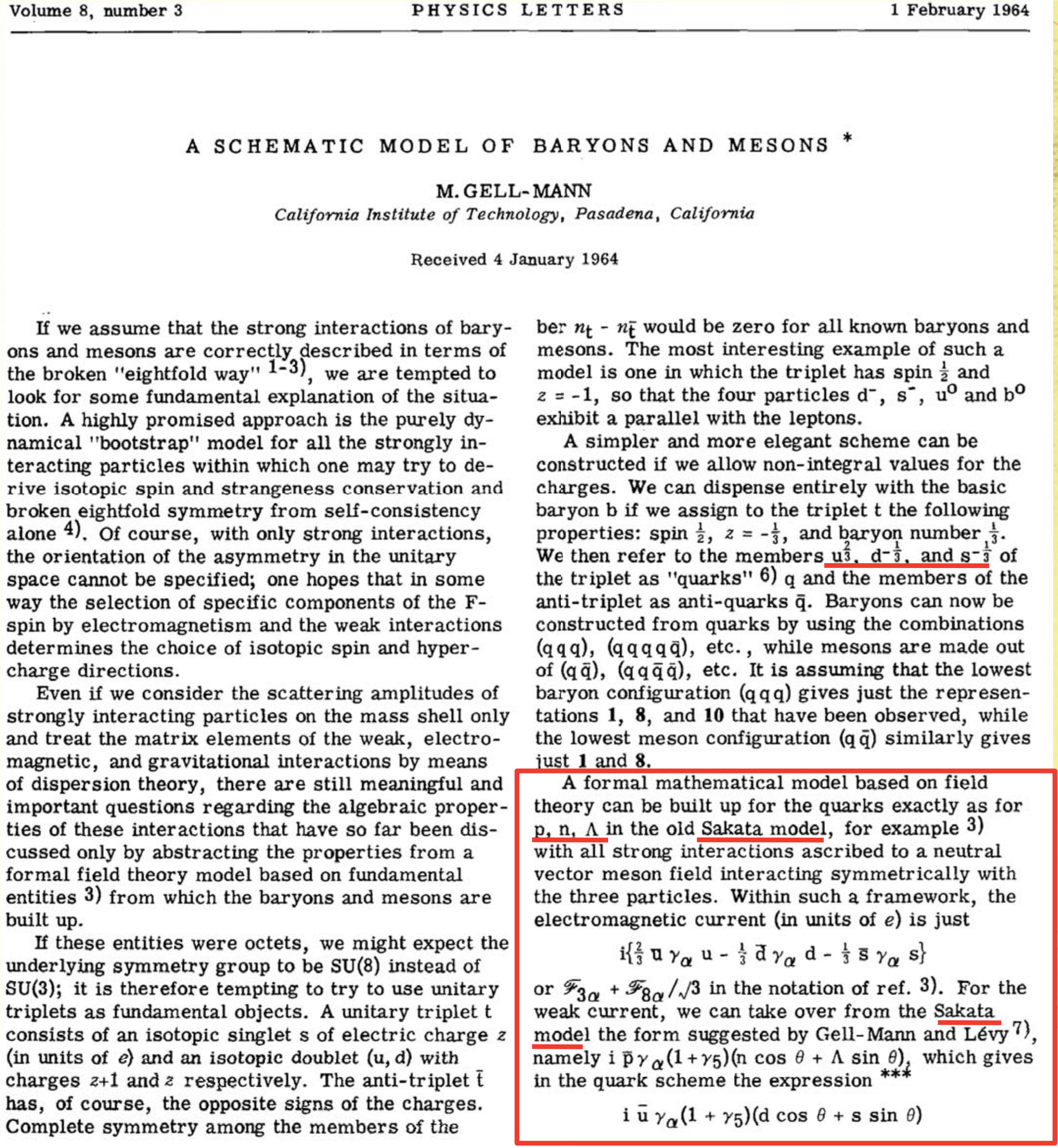
@ Feb. 25, 2010



Organised by: Institute of Advanced Studies, NTU
Co-organised by: Santa Fe Institute

Conference in Honour of
Murray Gell-Mann's 80th Birthday
Quantum Mechanics, Elementary Particles,
Quantum Cosmology and Complexity
24-26 February 2010
Nanyang Executive Centre

http://www.ntu.edu.sg/ias/upcomingevents/gm80conference/pages/default.aspx



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been discussed only by abstracting the properties from a formal field theory model based on fundamental entities 3) from which the baryons and mesons are built up.

If these entities were octets, we might expect the underlying symmetry group to be SU(8) instead of SU(3); it is therefore tempting to try to use unitary triplets as fundamental objects. A unitary triplet t consists of an isotopic singlet s of electric charge z (in units of e) and an isotopic doublet (u, d) with charges z+1 and z respectively. The anti-triplet $\bar{t}$ has, of course, the opposite signs of the charges. Complete symmetry among the members of the triplet gives the exact eightfold way, while a mass difference, for example, between the isotopic doublet and singlet gives the first-order violation.

For any value of z and of triplet spin, we can construct baryon octets from a basic neutral baryon singlet b by taking combinations $(b\,t\,\bar{t})$, $(b\,t\,t\,\bar{t}\,\bar{t})$, etc. **. From $(b\,t\,\bar{t})$, we get the representations 1 and 8, while from $(b\,t\,t\,\bar{t}\,\bar{t})$ we get 1, 8, 10, $\overline{10}$, and 27. In a similar way, meson singlets and octets can be made out of $(t\,\bar{t})$, $(t\,t\,\bar{t}\,\bar{t})$, etc. The quantum num-

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example 3) with all strong interactions ascribed to a neutral vector meson field interacting symmetrically with the three particles. Within such a framework, the electromagnetic current (in units of e) is just

$$i\{\tfrac{2}{3}\,u\,\gamma_\alpha\,u - \tfrac{1}{3}\,\bar{d}\,\gamma_\alpha\,d - \tfrac{1}{3}\,\bar{s}\,\gamma_\alpha\,s\}$$

or $\mathscr{F}_{3\alpha} + \mathscr{F}_{8\alpha}/\surd 3$ in the notation of ref. 3). For the weak current, we can take over from the Sakata model the form suggested by Gell-Mann and Lévy 7), namely $i\,\bar{p}\,\gamma_\alpha(1+\gamma_5)(n\cos\theta + \Lambda\sin\theta)$, which gives in the quark scheme the expression ***

$$i\,\bar{u}\,\gamma_\alpha(1+\gamma_5)(d\cos\theta + s\sin\theta)$$

SAKATA MODEL

50th Anniversary

25-26 November 2006, Nagoya, Japan

http://www.eken.phys.nagoya-u.ac.jp/sakata50/index-j.html

Composite Models

$u \quad d \quad s \quad c$

$p_0,\ n_0,\ \Lambda_0$

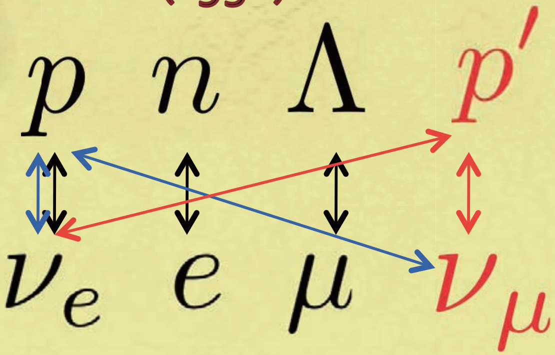
Gell-Mann, Zweig (1964)

http://www.ntu.edu.sg/ias/upcomingevents/gm80conference/pages/default.aspx

S. Sakata (Nagoya Univ.)

http://www.eken.phys.nagoya-u.ac.jp/images/sakata/4per.jpg

Sakata (1956)



$p \quad n \quad \Lambda \quad p'$

$\nu_e \quad e \quad \mu \quad \nu_\mu$

ν_e–ν_μ mixing

Maki-Nakagawa-Sakata (1962)

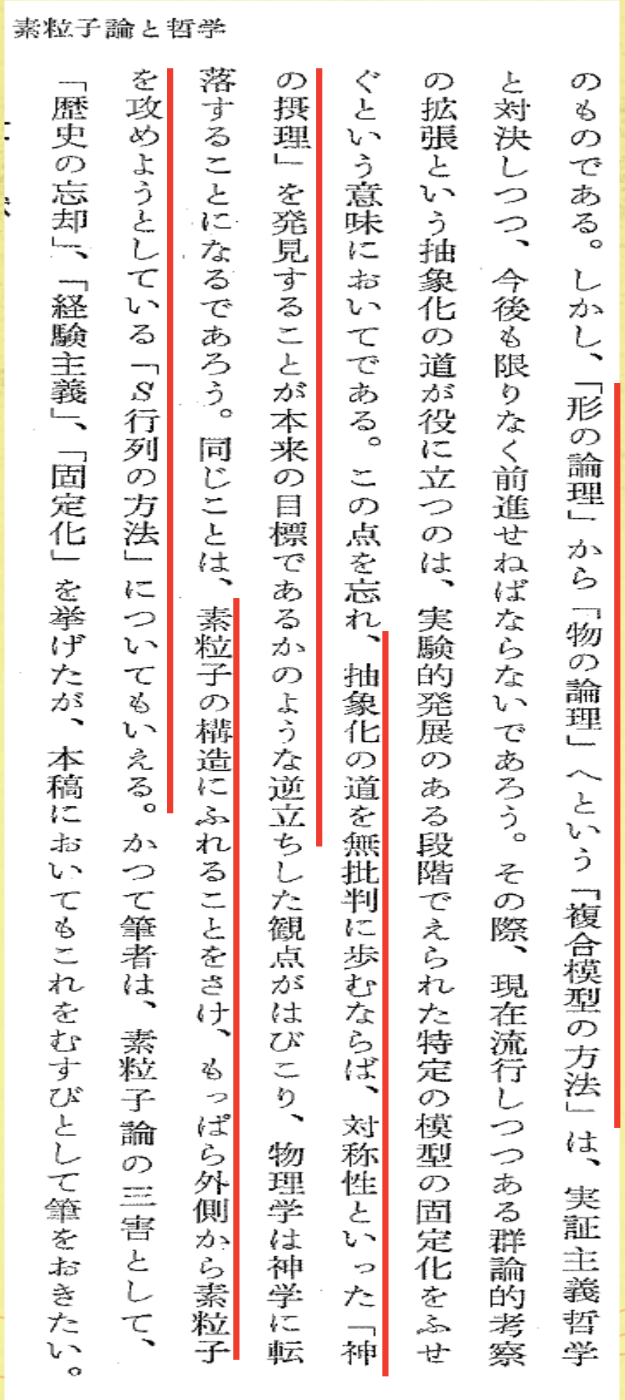
Kobayashi-Maskawa (1973)

$u \quad d \quad s \quad c \quad b \quad t$

Nagoya University

http://nobelprize.org/nobel_prizes/physics/laureates/2008/

坂田哲学



のものである。しかし、「形の論理」から「物の論理」へという「複合模型の方法」は、実証主義哲学と対決しつつ、今後も限りなく前進せねばならないであろう。その際、現在流行しつつある群論的考察の拡張という抽象化の道が役に立つのは、実験的発展のある段階でえられた特定の模型の固定化をふせぐという意味においてである。この点を忘れ、抽象化の道を無批判に歩むならば、対称性といった「神の摂理」を発見することが本来の目標であるかのような逆立ちした観点がはびこり、物理学は神学に転落することになるであろう。同じことは、素粒子の構造にふれることをさけ、もっぱら外側から素粒子を攻めようとしている「S行列の方法」についてもいえる。かつて筆者は、素粒子論の三害として、「歴史の忘却」、「経験主義」、「固定化」を挙げたが、本稿においてもこれをむすびとして筆をおきたい。

坂田昌一

「素粒子論と哲学」（「科学」１９６５年４月号）から

物質の起源

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

小林・益川行列
（1973）

名古屋模型

坂田模型（1956）
（複合模型）

牧・中川・坂田行列
（1962）

名古屋模型

坂田模型（1956）
（複合模型）

個人的年表（１９８０～２０１０）

- 名大着任　（１９８０）
- Ｗ、Ｚ発見　（１９８３）
  - 隠れた局所対称性　（坂東、九後らとの共著、１９８４）
  - ウォーキングテクニカラー　（坂東、松本との共著、１９８５）
  - トップクォーク凝縮　（ミランスキー、棚橋との共著、１９８８）
- ＳＳＣ中止　（１９９３）
- トップクォーク発見　（１９９４）
- 牧・中川・坂田理論（ニュートリノ振動）の検証　（１９９８）
- 小林・益川理論の最終検証（２００１）
- ＬＨＣ本格稼動　（２０１０）

SCGT Workshop (1988,1990,1996,2002,2006,2009)

目次

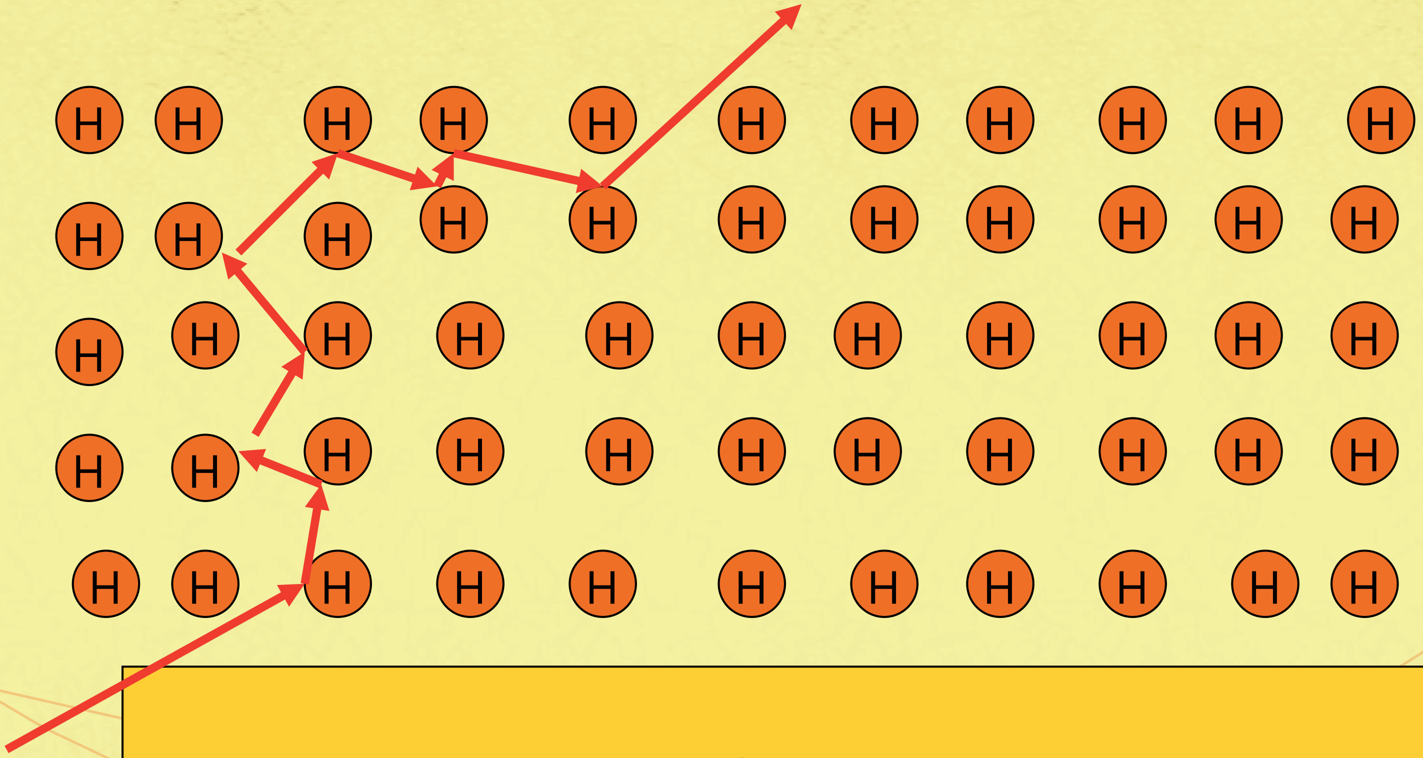
- 複合模型と名古屋大学
- 質量の起源（ヒッグス粒子と南部機構）
- 複合ヒッグス I （トップクォーク凝縮模型）
- 複合ヒッグス II
  （ウォーキングテクニカラー模型）
- 複合ゲージ粒子（隠れた局所対称性と
  余剰次元理論）

質量の起源

？

質量の起源

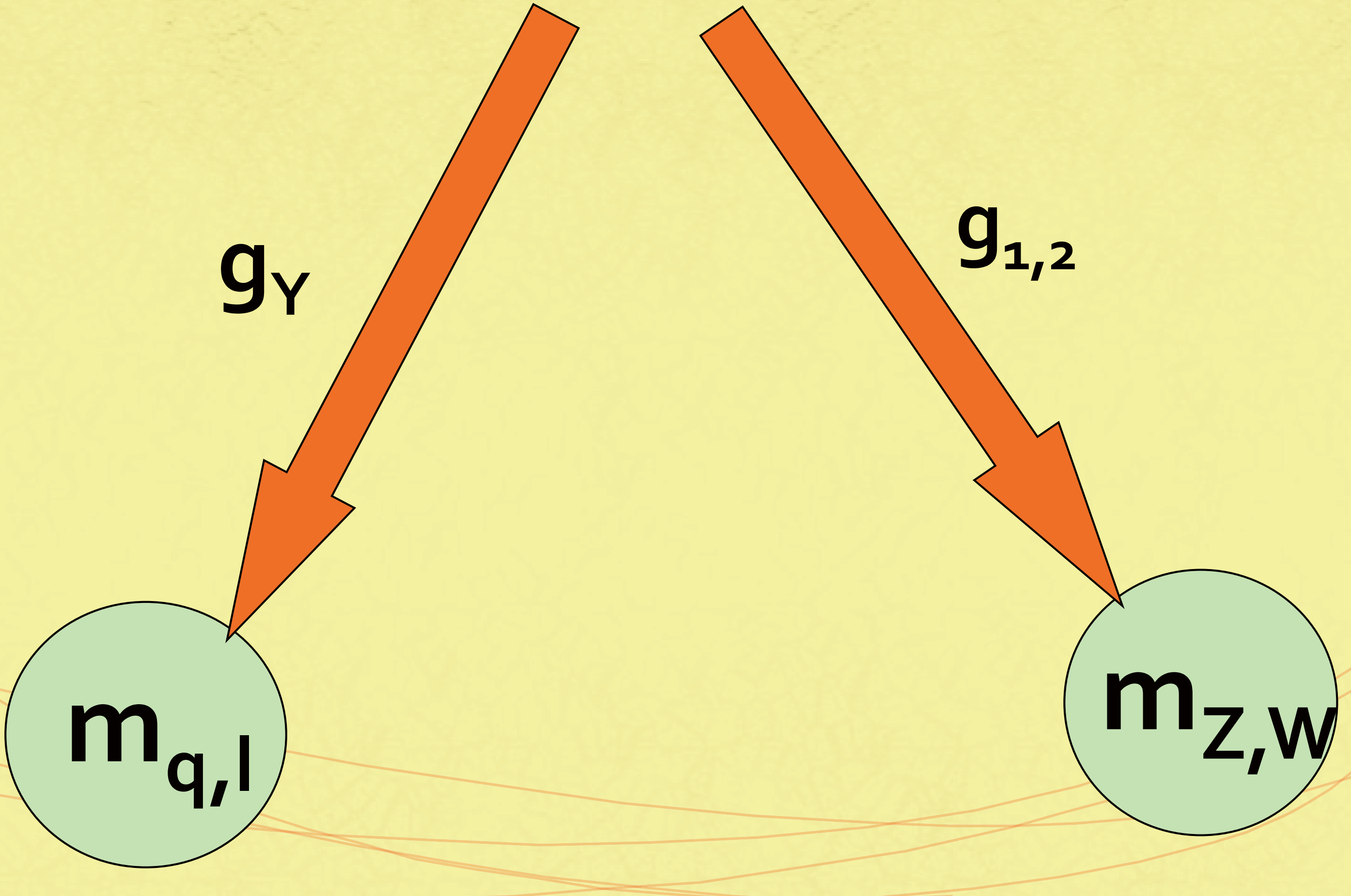
ヒッグス粒子(未発見）



質量　〜　"衝突の強さ"×　＜H＞

ヒッグス

$$v = \langle H \rangle = 246\,\mathrm{GeV}$$



g_Y

$g_{1,2}$

$m_{q,l}$

$m_{Z,W}$

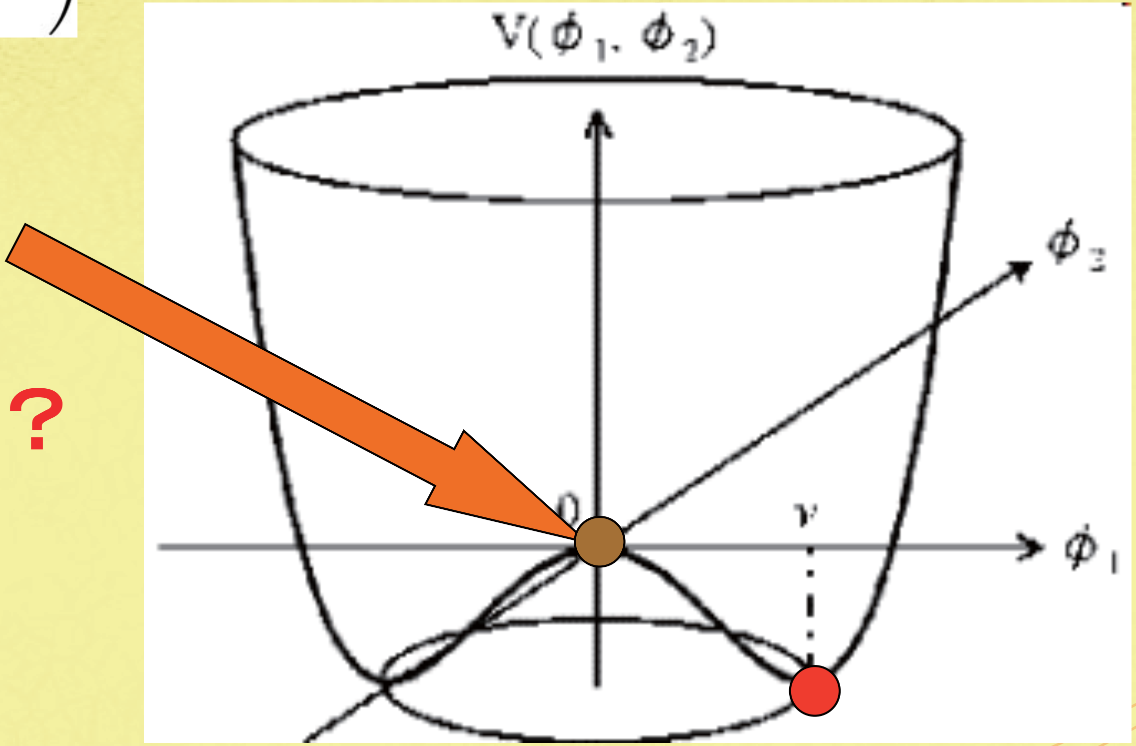
$$\mathcal{L}_{\text{Higgs}} = |\partial_\mu \phi|^2 - \mu^2|\phi|^2 - \lambda|\phi|^4$$

$$v = \langle Re\,\phi^0 \rangle = \langle H \rangle = 246\,\text{GeV}$$

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$$

$$\boxed{\mu^2 < 0}$$

タキオン！？



$= Im\,\phi^0$

$= Re\,\phi^0$

質量の起源

$$\|$$

$$\mu^2 (< 0)?$$

$$\mathcal{L}_{\text{Higgs}} = |\partial_\mu \phi|^2 - \mu^2 |\phi|^2 - \lambda |\phi|^4$$

$$v = \langle H \rangle = 246\ \text{GeV}$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} i\pi_1 + \pi_2 \\ \sigma - i\pi_3 \end{pmatrix}$$

等価 $\boxed{H \leftrightarrow \sigma}$

$\mu^2 < 0$ タキオン!

$$\mathcal{L}_{\text{GL}} = \frac{1}{2}\left((\partial_\mu \pi_a)^2 + (\partial_\mu \sigma)^2 - \mu^2(\pi_a^2 + \sigma^2)\right) - \frac{1}{4}\lambda(\pi_a^2 + \sigma^2)^2$$

線型シグマ模型
（Gell-Mann-Levy)
１９６０

$$v = \langle \sigma \rangle = 93\ \text{MeV} = f_\pi$$

対称性の力学的破れ
(質量の力学的生成）

‖

南部理論（１９６０）

BCS機構の類比（フェルミオンの対凝縮）

2008ノーベル物理学賞受賞論文

素粒子＝p、n、（Λ）；（π、・・・）

Ｆｅｒｍｉ－Ｙａｎｇ

(坂田）

2008ノーベル物理学賞

http://nobelprize.org/nobel_prizes/physics/laureates/2008/

"for the discovery of the mechanism of
spontaneous broken symmetry （対称性の自発的破れ）
in subatomic physics"

対称性の自発的破れ

は

対称性の力学的破れ

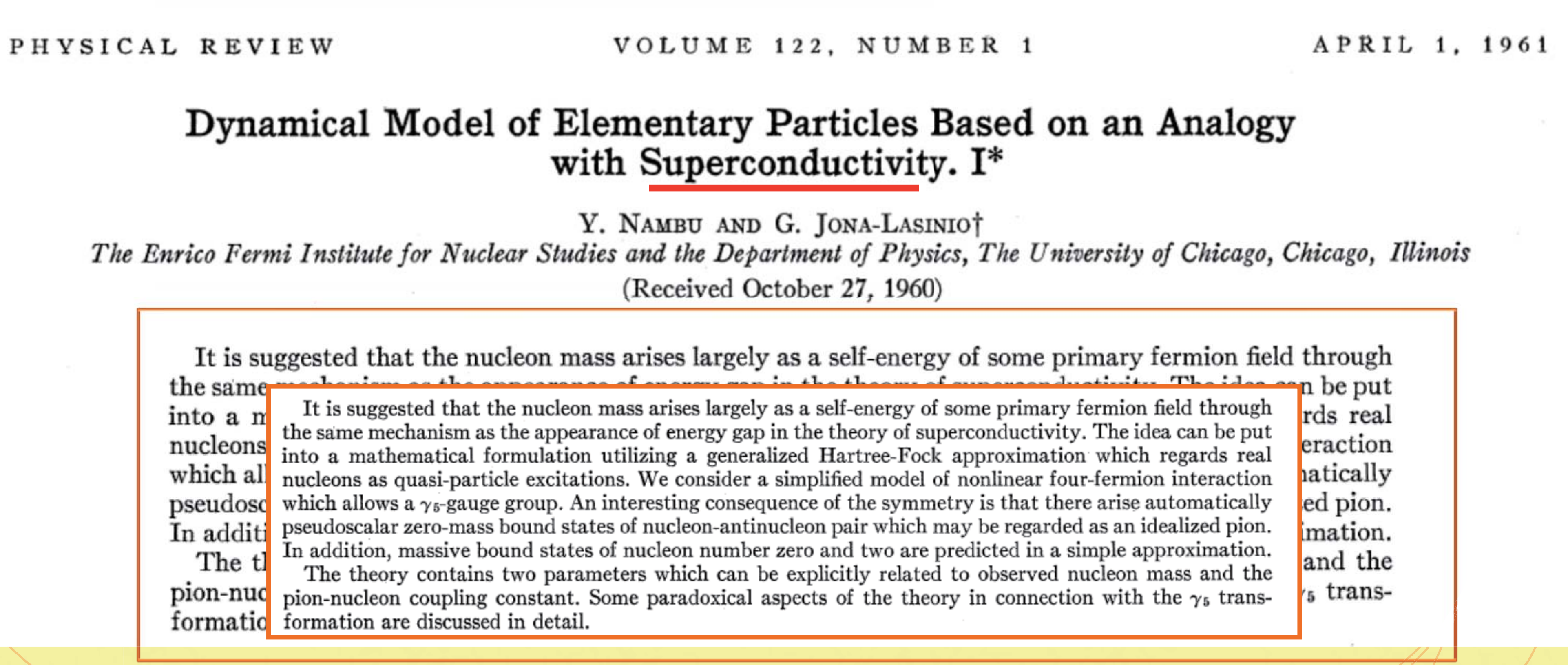
として発見された！

質量の起源　（核子）

タキオン

引力

(BCS 不安定性)



PHYSICAL REVIEW VOLUME 122, NUMBER 1 APRIL 1, 1961

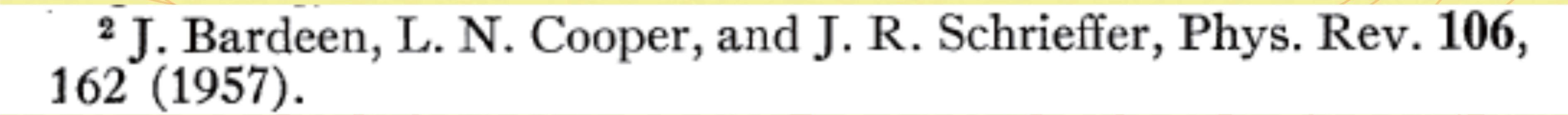
Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

Y. Nambu and G. Jona-Lasinio†
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

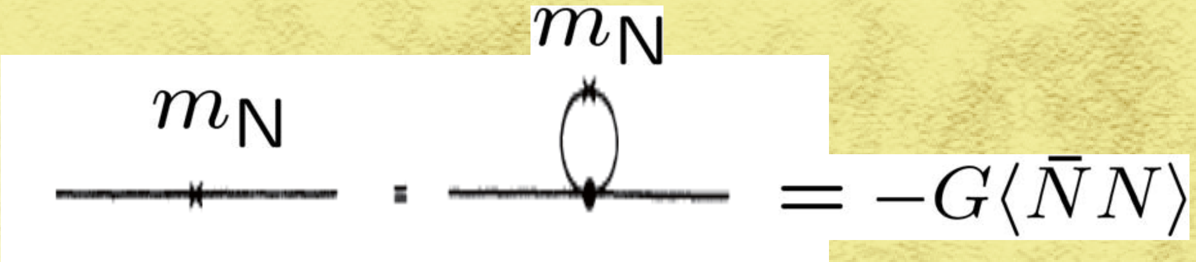
(Received October 27, 1960)

It is suggested that the nucleon mass arises largely as a self-energy of some primary fermion field through the same mechanism as the appearance of energy gap in the theory of superconductivity. The idea can be put into a mathematical formulation utilizing a generalized Hartree-Fock approximation which regards real nucleons as quasi-particle excitations. We consider a simplified model of nonlinear four-fermion interaction which allows a γ_5-gauge group. An interesting consequence of the symmetry is that there arise automatically pseudoscalar zero-mass bound states of nucleon-antinucleon pair which may be regarded as an idealized pion. In addition, massive bound states of nucleon number zero and two are predicted in a simple approximation.

The theory contains two parameters which can be explicitly related to observed nucleon mass and the pion-nucleon coupling constant. Some paradoxical aspects of the theory in connection with the γ_5 transformation are discussed in detail.

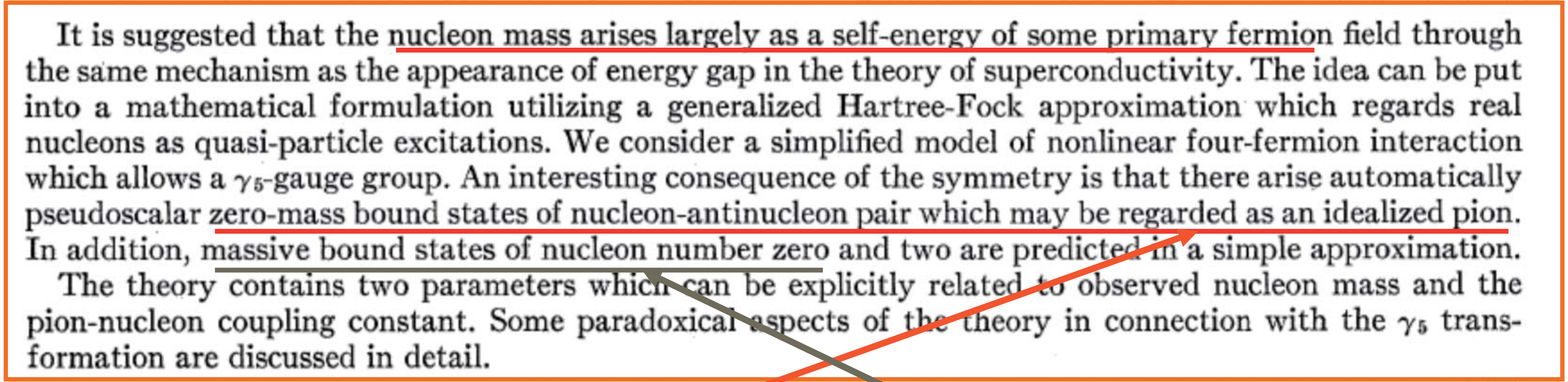


[2] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **106**, 162 (1957).



$$\frac{G}{2}(\bar{N}N)(\bar{N}N)$$

Gap eq. $G > G_{cr}$



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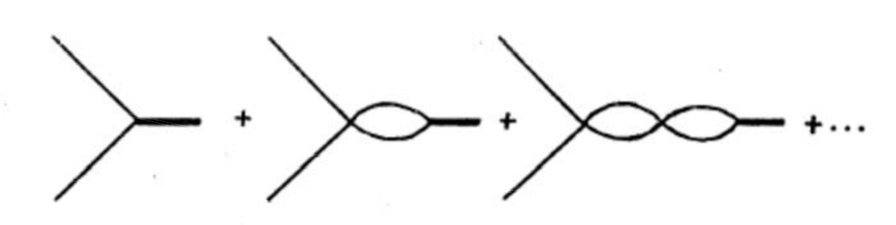
$\pi \sim \bar{N} N$

σ (``Higgs")



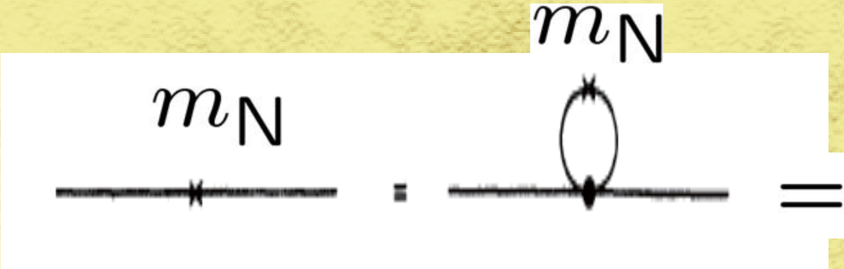
Fermi-Yang Model (1948)

p
n

→

p
n
Λ

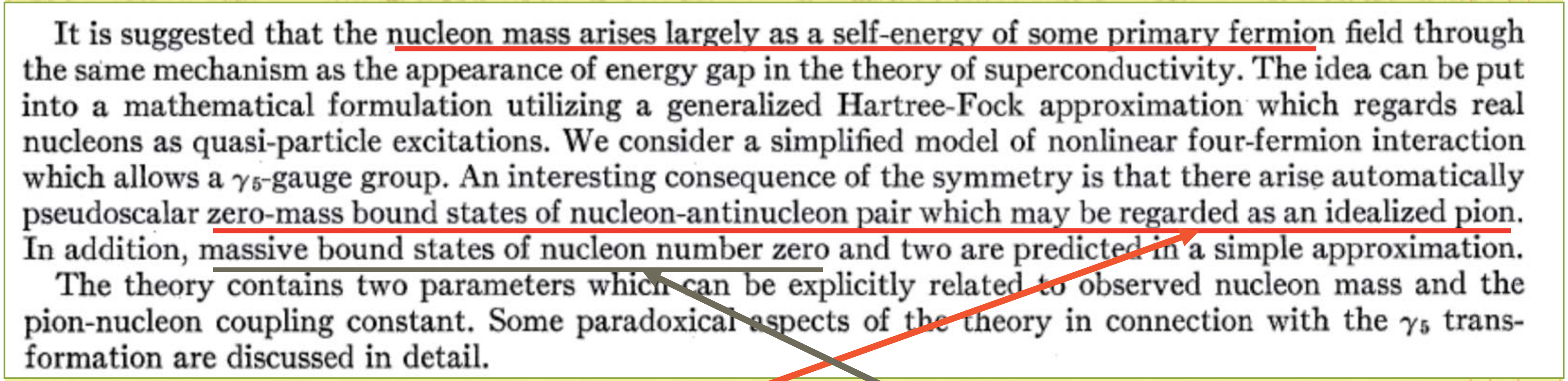
Sakata Model (1956)



$$= -G\langle \bar{N} N \rangle$$

$$\frac{G}{2}\left(\bar{N} N\right)\left(\bar{N} N\right)$$

Gap eq.



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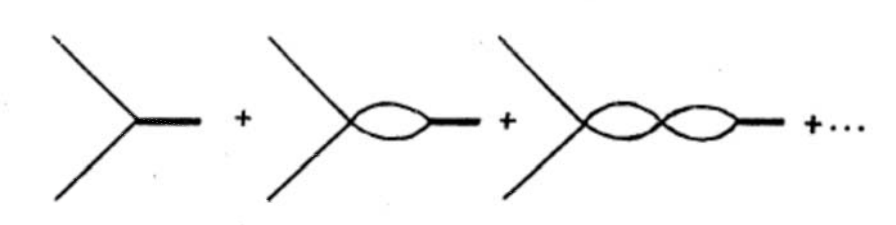
σ (``Higgs")



Fermi-Yang Model (1948)

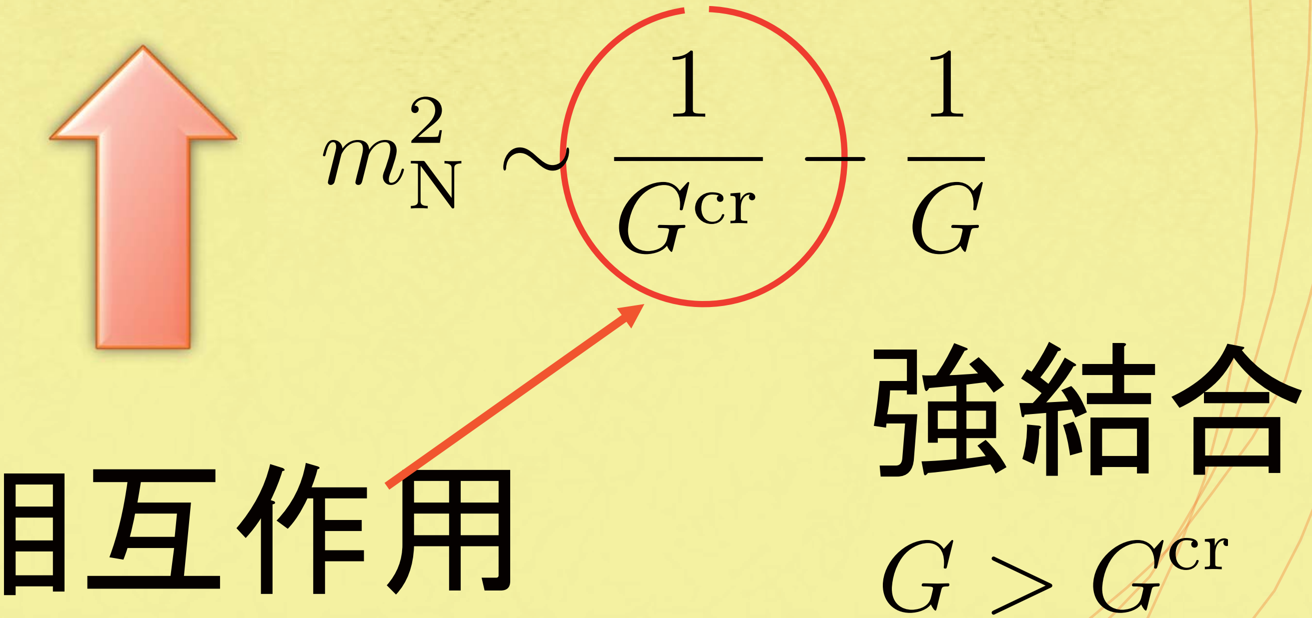
p
n

→

p
n
Λ

Sakata Model (1956)

質量の起源



$$m_\mathrm{N}^2 \sim \boxed{\frac{1}{G^\mathrm{cr}}} - \frac{1}{G}$$

相互作用

強結合

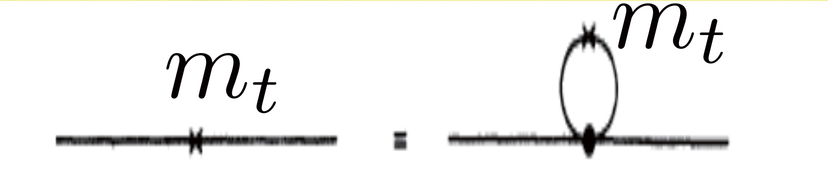
$G > G^\mathrm{cr}$

複合ヒッグス模型　I

トップクォーク凝縮模型
(トップモード標準模型)

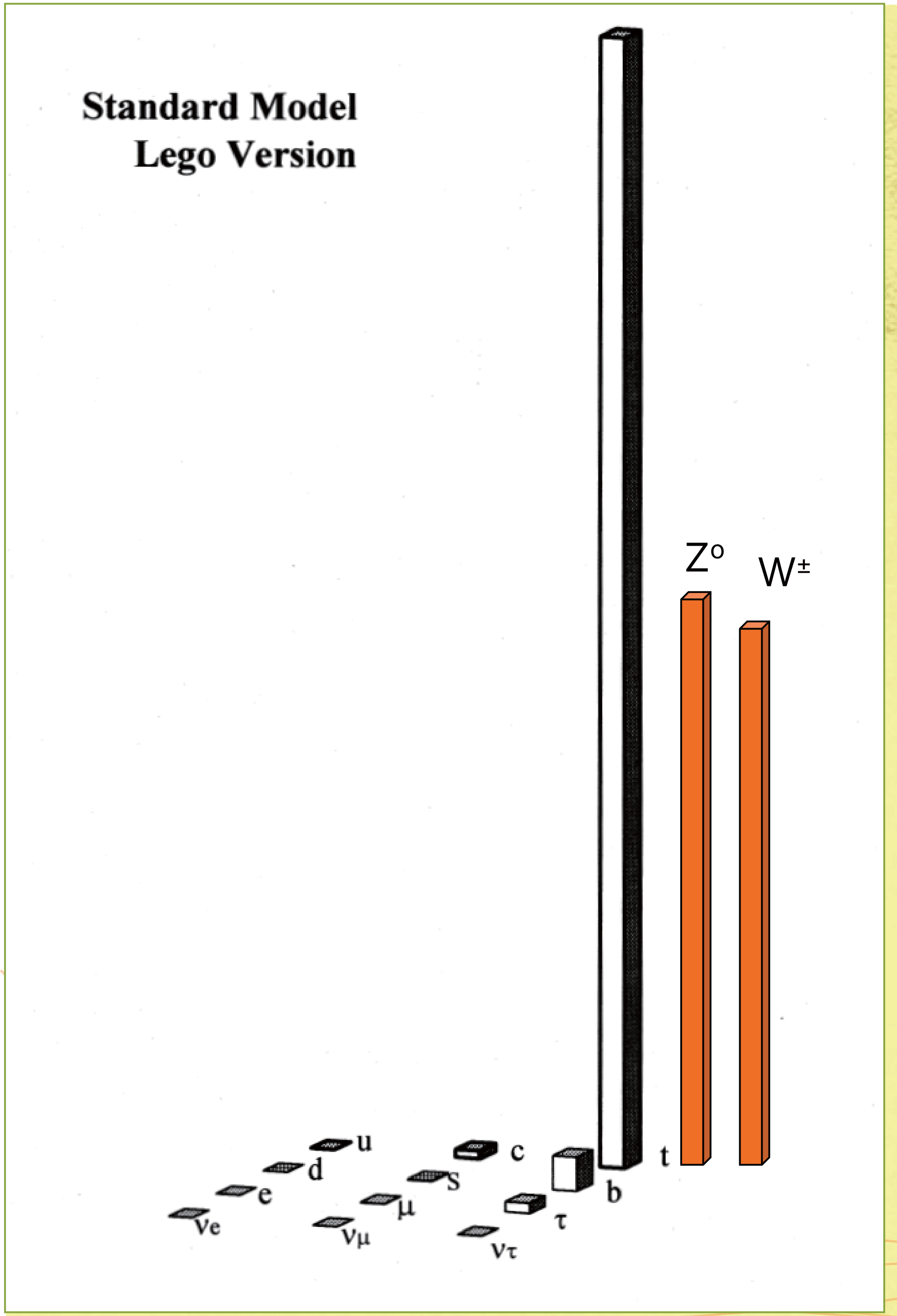
Miransky,Tanabashi and K.Y. (Dec. 1988)
Nambu (Feb. 1989)
Bardeen, Hill and Lindner (July, 1989)

$$N \Rightarrow t$$



$$= -G\langle \bar{t}\, t\rangle$$

$$H \sim \bar{t}t$$



- $m_t,\, m_Z,\, m_W \sim v$
- $m_H \simeq 2m_t$

$$m_H \simeq \sqrt{2}\, m_t$$

(QCD effects)

$$\simeq m_t$$

(+ other effects)

Refinements:

- Top seesaw
- Technicolor-assisted Topcolor (TC^2)
- Top condensate in SM with extra dimensions

$$\boxed{m_H > m_t}$$

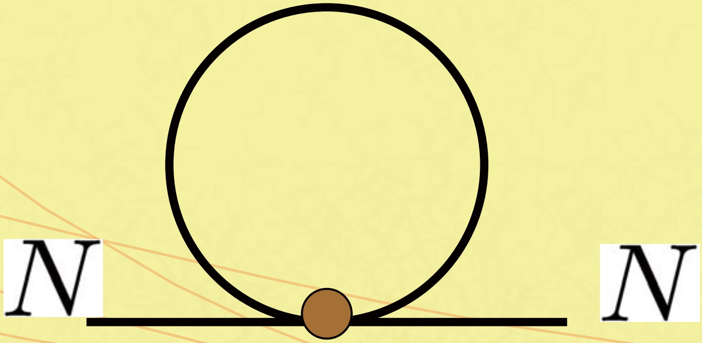
ＱＣＤでも本質的に同じ機構

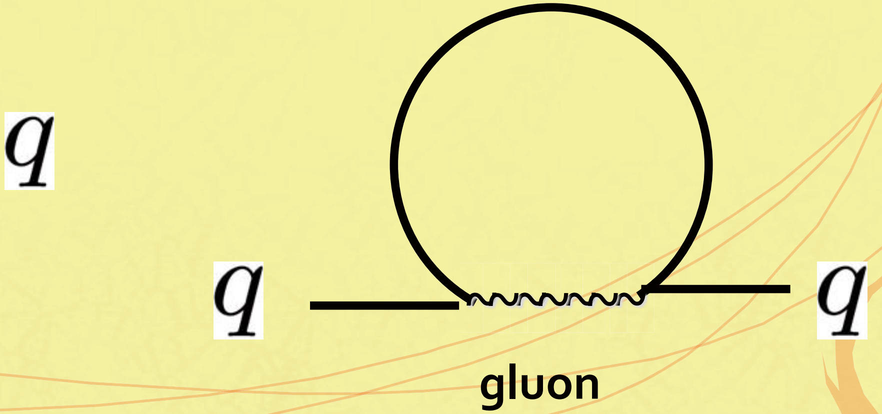
- 核子　　　　クォーク

$$\langle \bar{N} N \rangle \quad \rightarrow \quad \langle \bar{q} q \rangle$$

$$M_\mathrm{N} \qquad m_\mathrm{q}^* \approx \frac{M_\mathrm{N}}{3}$$

- 4体フェルミ相互作用　　　　ゲージ相互作用





質量の起源（核子）

南部理論！

線型シグマ模型
(Gell-Mann-Levy)

$\mu^2 < 0$ タキオン

$\langle\sigma\rangle = f_\pi = 93\text{MeV}$

σ

π

$M_\mathrm{N} = G_{\mathrm{NN}\pi}\langle\sigma\rangle$

$$\xrightarrow[p \gg f_\pi]{}$$

QCD

引力
(BCS 不安定)

$\langle\bar{q}q\rangle \sim f_\pi^3$

$\bar{q}q$

$\bar{q}i\gamma_5 q$

$$\boxed{m_N \approx 3m_q^*}$$

質量の起源(QCD)

$\mathcal{L}_{\mathrm{QCD}}(m_q = 0)$: スケール不変性（古典論）

スケール異常（量子論）

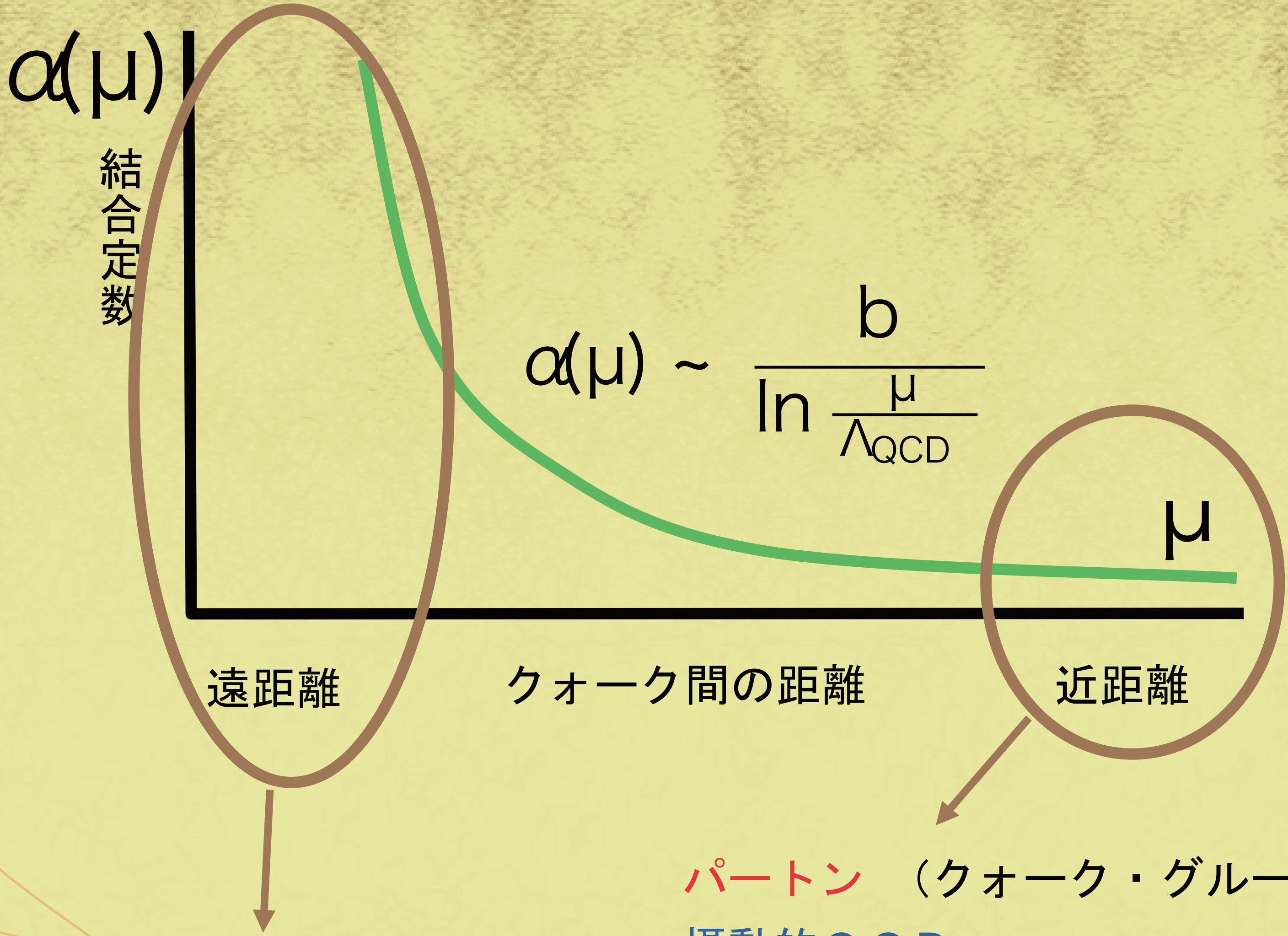
$$\Lambda_{\mathrm{QCD}} = \mu \exp\left(- \int^{\alpha(\mu)} \frac{d\alpha}{\beta(\alpha)} \right) \simeq \mu\, e^{-\frac{1}{b\alpha(\mu)}}$$

$$\alpha(\mu) \sim \frac{b}{\ln \frac{\mu}{\Lambda_{\mathrm{QCD}}}}$$

BCS-南部

$$f_\pi,\ m_q^*,\ \langle \bar{q} q \rangle, \cdots \qquad = \mathcal{O}(\Lambda_{\mathrm{QCD}})$$

1973年　・・・　ＱＣＤの漸近的自由性



$\alpha(\mu)$

結合定数

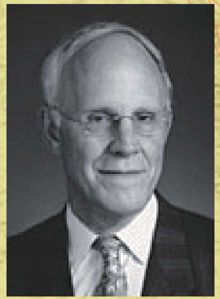
$$\alpha(\mu) \sim \frac{b}{\ln \frac{\mu}{\Lambda_{QCD}}}$$

μ

遠距離　　クォーク間の距離　　近距離

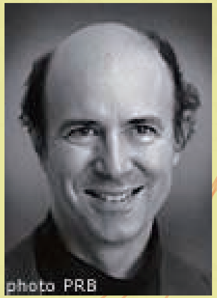
閉じ込め
南部機構

パートン　（クォーク・グルーオン）
摂動的ＱＣＤ



Gross

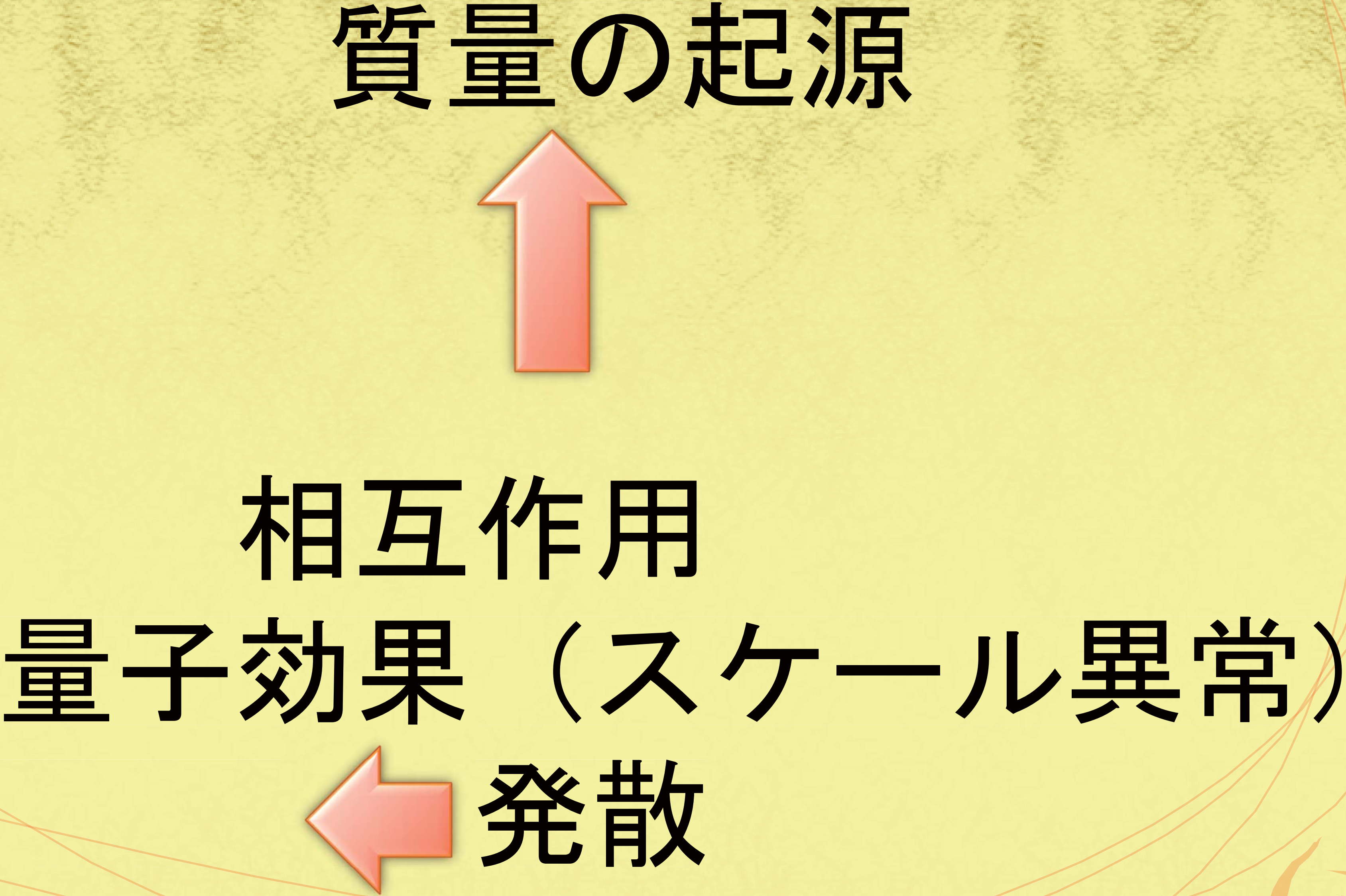
Politzer



Wilczek

2004年ノーベル賞

http://nobelprize.org/nobel_prizes/physics/laureates/2004/



質量の起源

相互作用

量子効果（スケール異常）

発散

複合ヒッグス模型 II

テクニカラー： QCD のスケーアップ

$H \sim \bar{F}F \qquad F_\pi = 246\ \mathrm{GeV}$

S. Weinberg (1976)
L. Susskind (1979)

$\langle \bar{F}F \rangle \sim (700\ \mathrm{GeV})^3$

$\frac{N_{\mathrm{TC}}}{N_{\mathrm{C}}}$

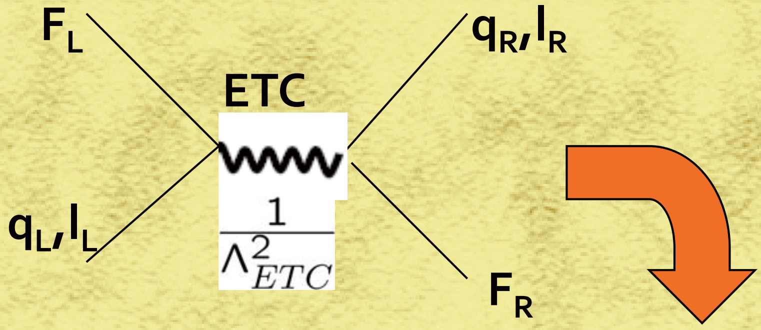
$\sqrt{\frac{N_{\mathrm{C}}}{N_{\mathrm{TC}} N_{\mathrm{D}}}}$

X 2600

$\sigma \sim \bar{q}q \qquad f_\pi = 93\ \mathrm{MeV}$

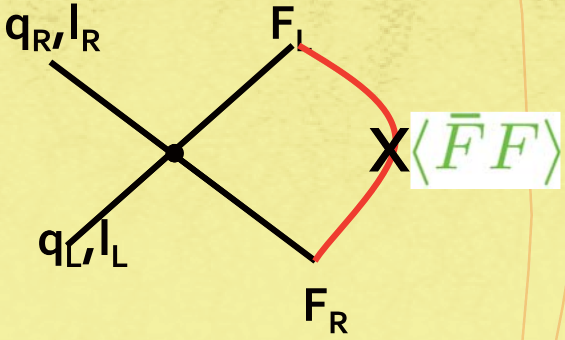
$\langle \bar{q}q \rangle \sim (250\ \mathrm{MeV})^3$

FCNC 問題：

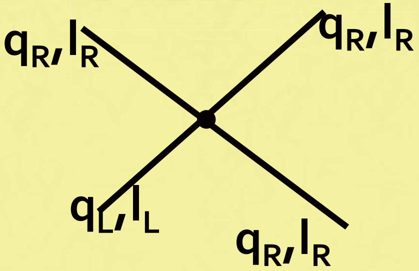


クォーク・レプトンの質量

$$m_{q,l} \sim \frac{1}{\Lambda_{ETC}^2} \langle \bar{F}F \rangle_{\Lambda_{ETC}}$$



FCNC



$$\frac{1}{\Lambda_{ETC}^2} \bar{s}d\bar{s}d < 10^{-6} \quad \mathrm{TeV}^{-2}$$

$$m_s < 10^{-6}\ \mathrm{TeV}^{-2} \times (0.7\ \mathrm{TeV})^3 \sim 10^{-1}\,\mathrm{MeV}$$

10³の増幅が必要

ウォーキング・コンフォーマルテクニカラー

http://www.kmi.nagoya-u.ac.jp/

益川・中島 解（1974)

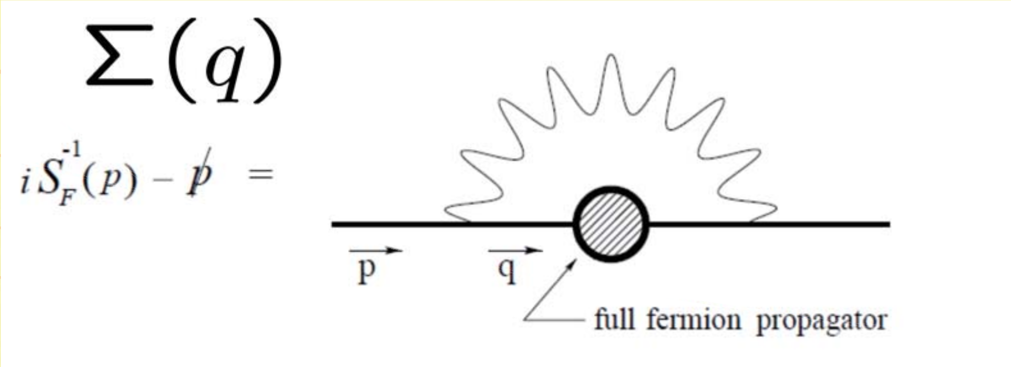
- K.Y., Bando, Matumoto (Dec. 1985)
- Akiba, Yanagida (Jan. 1986)
- Appelquist, Karabali, Wijewardhane (Jun.1986)

(Holdom (Jan. 1985))

$$\alpha(Q) \equiv \alpha(> \alpha_{\rm cr} = \mathcal{O}(1))$$

はしご Schwinger-Dyson方程式

スケール不変（コンフォーマル）



$$\boxed{\gamma_m = 1}$$

$$\alpha \simeq \alpha_{\rm cr}$$

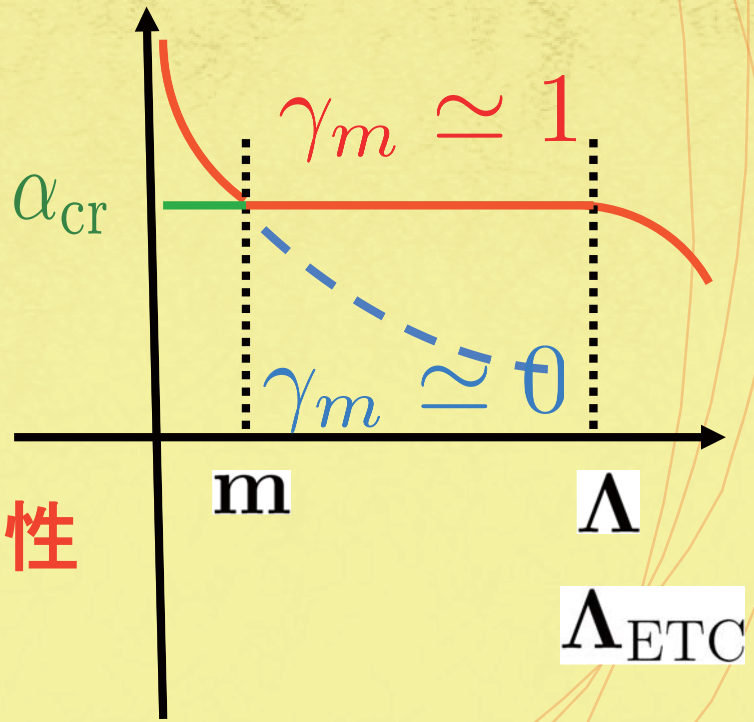
ウォーキング／コンフォーマル　テクニカラー

$$\mathbf{m} = \mathbf{\Lambda} \exp\left(-\frac{\pi}{\sqrt{\frac{\alpha}{\alpha_{\rm cr}} - \mathbf{1}}}\right) \ll \mathbf{\Lambda}$$

大きな階層性

$$\alpha = \alpha(\mathbf{\Lambda}) \to \alpha_{\rm cr} \quad (\mathbf{\Lambda} \to \infty)$$

UVFP



自然さ ⟷ コンフォーマル対称性

$$\langle \bar{F}F \rangle_\Lambda = Z_m^{-1} \langle \bar{F}F \rangle_m = \left(\frac{\Lambda}{m}\right)^{\gamma_m} \langle \bar{F}F \rangle_m$$

$$10^0 \simeq 1$$

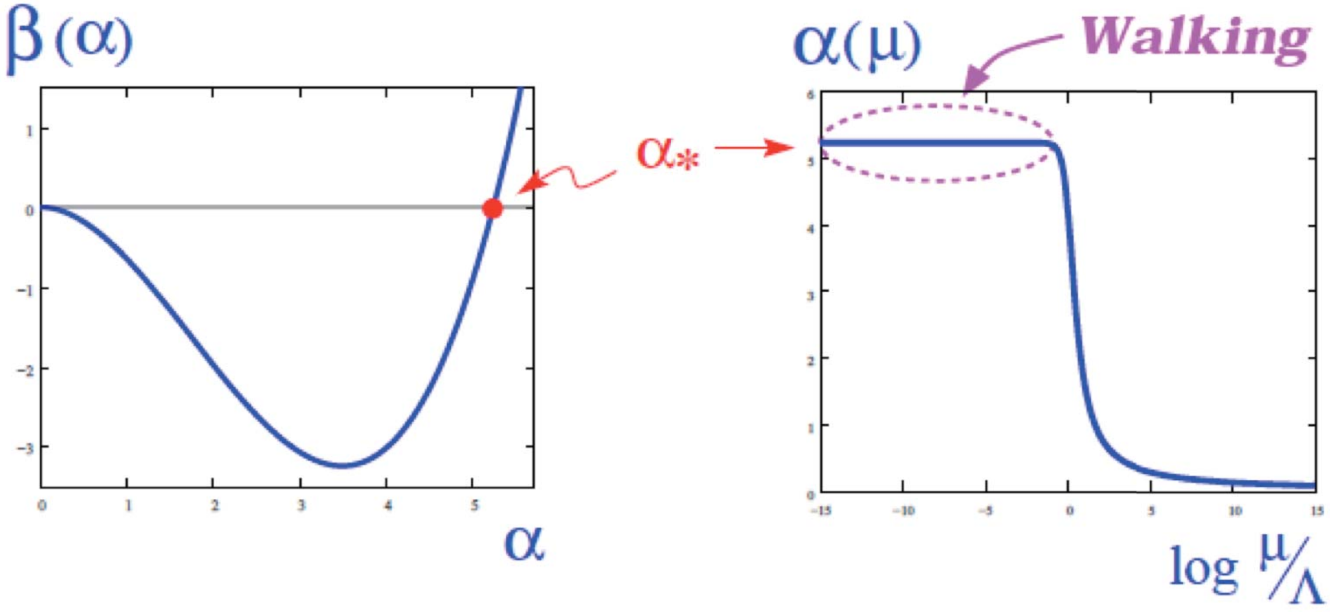
$$(10^3)^1$$

Two-loop running coupling in the large N_f QCD

Caswell(1974)
Banks, Zaks(1982)

RGE $$\mu\frac{d}{d\mu}\alpha(\mu) = -b\,\alpha^2(\mu) - c\,\alpha^3(\mu)$$

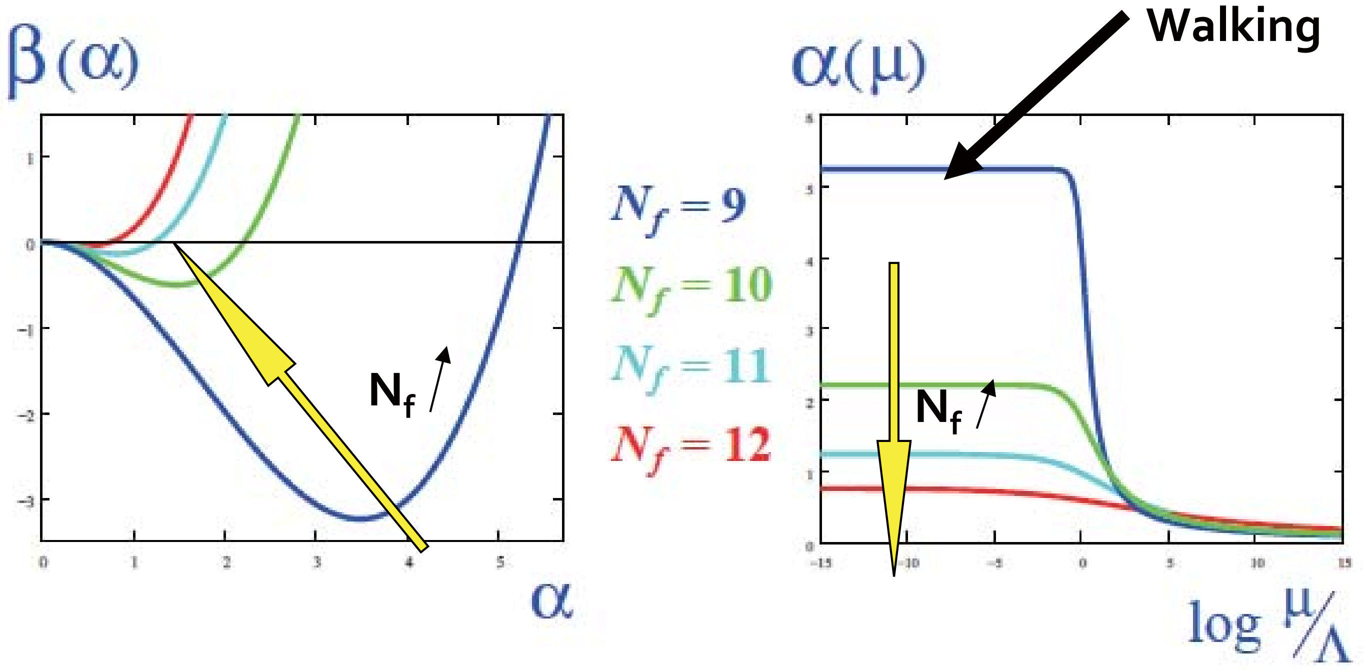
$(N_c = 3)$	$N_f < 8.05$	$8.05 < N_f < 16.5$	$16.5 < N_f$
$b = \frac{1}{6\pi}(33 - 2N_f)$	+	+	−
$c = \frac{1}{12\pi^2}(153 - 19N_f)$	+	−	−



$$(\alpha_* = -c/b)$$ 赤外固定点

``Conformal Window”

$N_f^{cr} < N_f < 11N_c/2$



対称性の破れ回復（質量の消失）

$$\alpha_* = \alpha_*(N_f, N_c) < \alpha_{cr} = \frac{\pi}{4}$$

← **SD 方程式**

$$N_f^{cr} \simeq 4N_c = 12$$

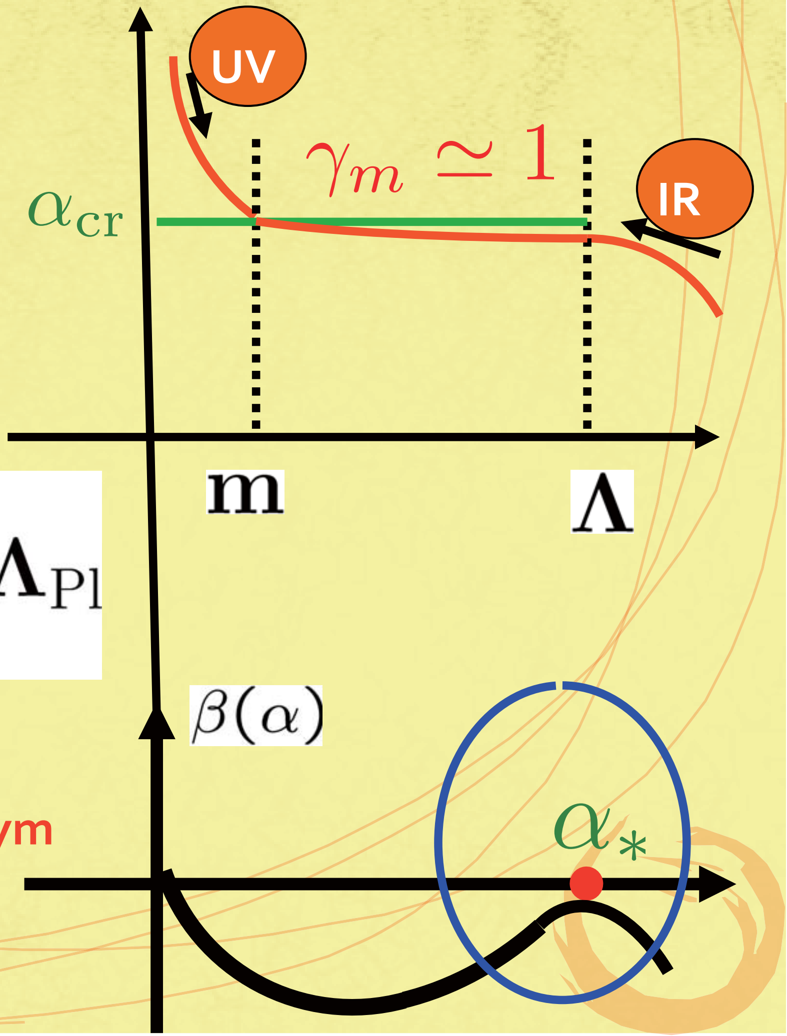
Appelquist,Terning,Wijewardhana (1996)

$$\Lambda \equiv \mu \exp\left[-\frac{1}{b\,\alpha_*}\log\left(\frac{\alpha_*-\alpha(\mu)}{\alpha(\mu)}\right)-\frac{1}{b\,\alpha(\mu)}\right] = \mu \exp\left(\int^{\alpha(\mu)}\frac{d\alpha}{\beta(\alpha)}\right)$$

$$\leftrightarrow \Lambda_{\mathrm{QCD}}$$

$$\frac{\Lambda}{m} \sim \frac{\Lambda_{\mathrm{ETC}}}{m} \sim 10^3$$

IRFP $\alpha_* \simeq \alpha_{\mathrm{cr}}$



$$\mathbf{m} = \mathbf{\Lambda} \exp\left(-\frac{\pi}{\sqrt{\frac{\alpha_*}{\alpha_{\mathrm{cr}}}-\mathbf{1}}}\right) \ll \mathbf{\Lambda} \ll \mathbf{\Lambda}_{\mathrm{Pl}}$$

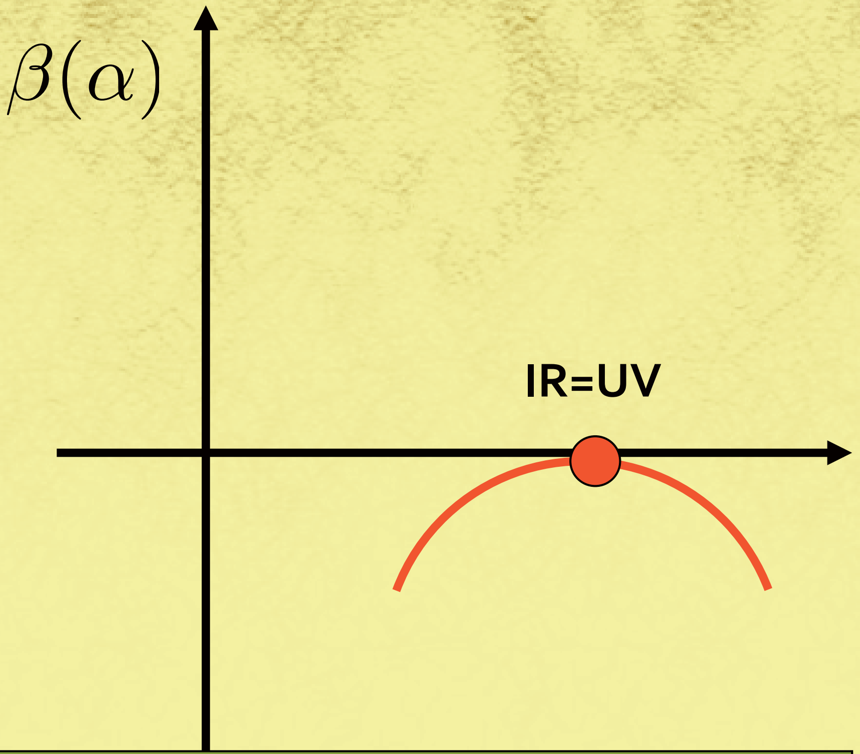
Conformal sym

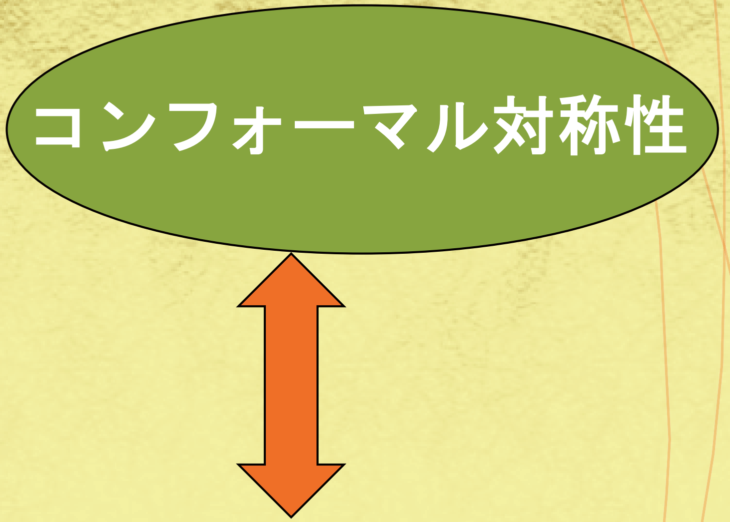
$$\alpha_* = \alpha(\mathbf{\Lambda}) \to \alpha_{\mathrm{cr}}$$

IRFT UVFT

コンフォーマル相転移

Miransky-KY (1997)





コンフォーマル対称性

Naturalness

テクニディラトン
(複合ヒッグス粒子)

KY-Bando-Matumoto (1986)

$$\mathbf{m}_{\mathrm{TD}} \simeq \sqrt{\mathbf{2}}\,\mathbf{m} \sim \mathbf{500}\ \mathrm{GeV}$$

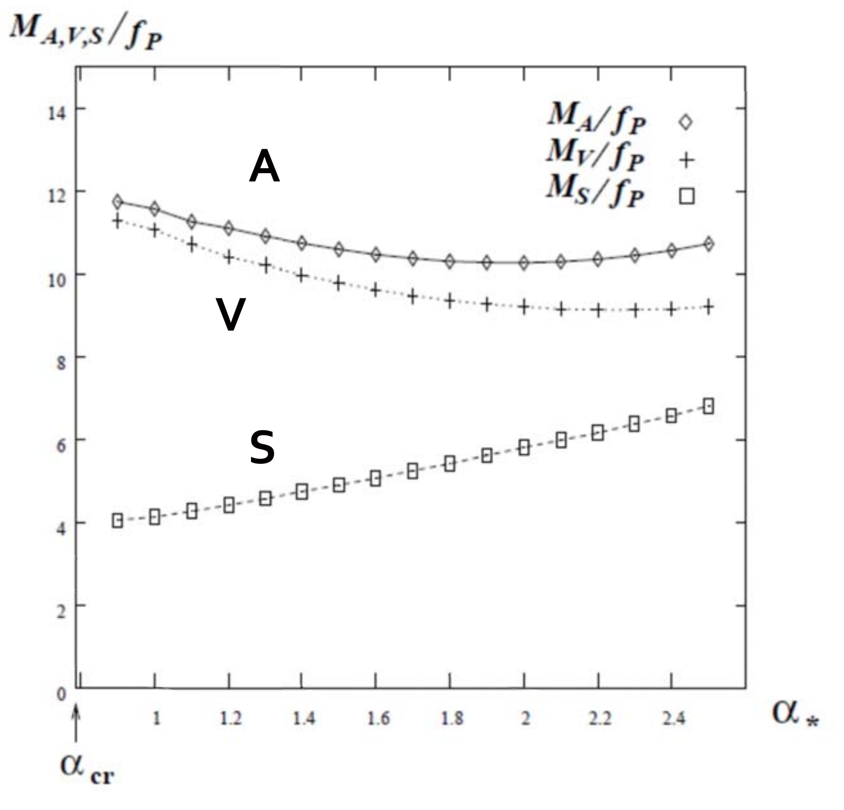
軽い複合スペクトル(SD+斉次BS)

$f_\pi \to 0$

Harada-Kurachi-KY (2003)

$$f_\pi^2 : M_S^2 : M_V^2 : M_A^2 \simeq 1 : 17 : 121 : 132$$

$$m^2 : M_S^2 : M_V^2 : M_A^2 \simeq 1 : \boxed{2.4} : 17 : 18.5$$



$$\frac{(M_V/f_P)_{\rm WL}}{(M_\rho/f_\pi)} \simeq 1.3$$

$$\frac{(M_A/f_P)_{\rm WL}}{(M_{a_1}/f_\pi)} \simeq 0.86\,,$$

$$\frac{(M_S/f_P)_{\rm WL}}{(M_{a_0}/f_\pi)} \simeq 0.38\,.$$

Kurachi-Shrock (2006)

はしご近似

$$M_{dilaton} \sim \sqrt{2}m$$

質量の起源

相互作用
量子効果（スケール異常）

質量の起源　(W/C TC)

$\mathcal{L}_{\rm W/C\,TC}$:スケール不変性（古典論）

スケール異常（量子論）

$$\Lambda_{\rm W/C\,TC} = \mu \exp\left(\int^{\alpha(\mu)} \frac{d\alpha}{\beta(\alpha)}\right) \sim \Lambda_{\rm ETC}$$

BCS-南部

$$f_\pi,\ m_F,\ \langle \bar{F}F\rangle, \cdots \qquad \ll \Lambda_{\rm W/C\,TC}$$

``コンフォーマル対称性"

~~通説:~~

~~テクニカラー＝ヒッグスレス模型~~

~~（軽いスカラーなし）~~

ウォーキング／コンフォーマル　TC

近似的コンフォーマル対称性

→ テクニディラトン

↔ **LHC**

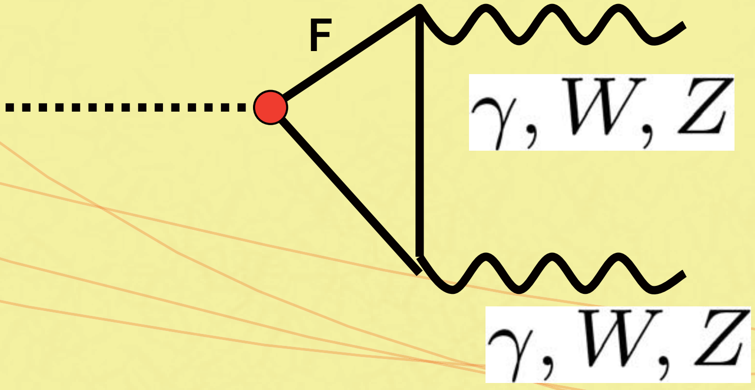
LHC でのシグナル

- 湯川結合

$$g_Y = \frac{3-\gamma_m}{F_{\mathrm{TD}}} M_F \neq \frac{1}{F_\pi} M_F$$

$$\frac{g_y}{\sqrt{2}} = \frac{3-\gamma_m}{F_{\mathrm{TD}}} m_{q/l} \neq \frac{1}{F_\pi} m_{q/l}$$

- ゲージ結合　(ツリーなし)



$$\neq \; H\gamma\gamma, HWW, HZZ, \cdots$$

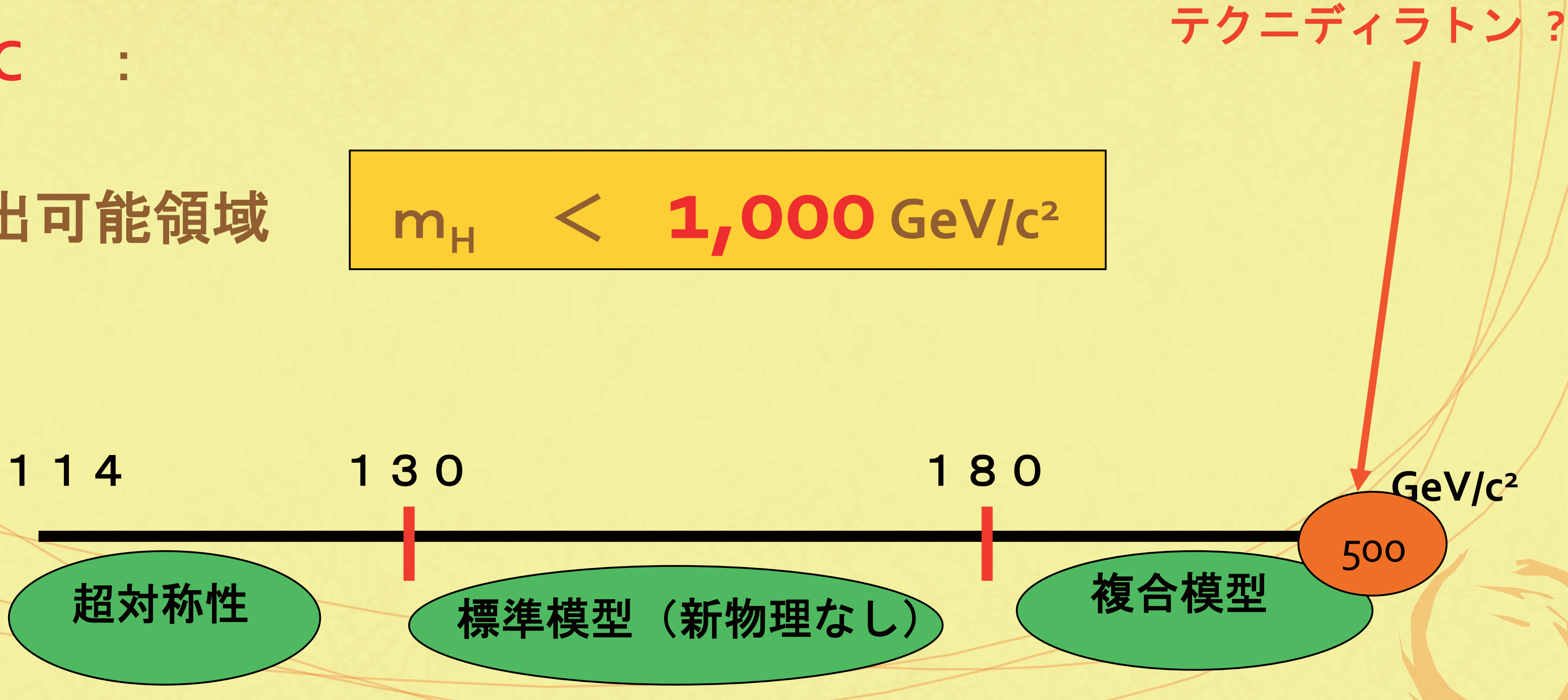
ヒッグスボソン探索

- 実験の制限　（LEP)

$m_H > 114\ \mathrm{GeV}/c^2$

- LHC　：

検出可能領域　$m_H < 1{,}000\ \mathrm{GeV}/c^2$



複合ゲージボソン

- 隠れた局所対称性Hidden Local Symmetries (HLS)

Bando-Kugo-Uehara-K.Y.-Yanagida (1985)

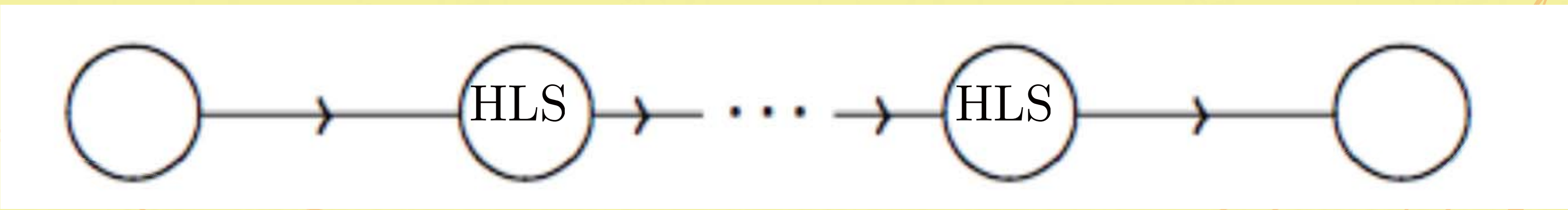
M. Bando, T.Kugo, K.Y., Phys. Rep. 164('88) 217

M. Harada, K.Y., Phys. Rep. 381('03) 1

$$G/H \simeq G_{\text{global}} \times H_{\text{local}}$$

HLS

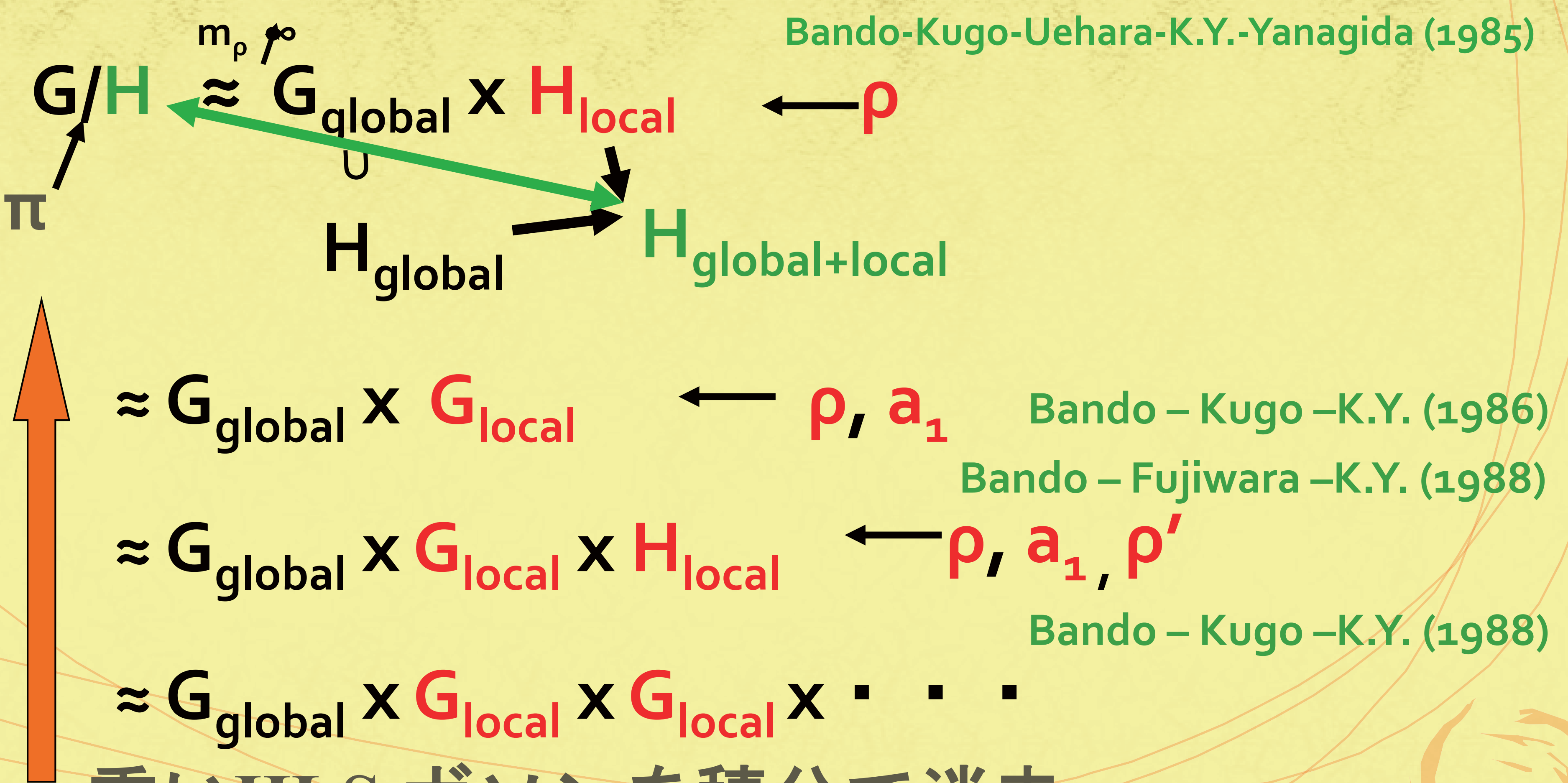
HLSとしての５次元ゲージ理論



~ KK tower

隠れた局所対称性（ＨＬＳ）

Reviews: M. Bando, T.Kugo, K.Y., Phys. Rep. 164('88) 217 (tree)
M. Harada, K.Y., Phys. Rep. 381('03) 1 (loop)



m_ρ ∞

$G/H \approx G_{\text{global}} \times H_{\text{local}}$ ← ρ

Bando-Kugo-Uehara-K.Y.-Yanagida (1985)

∪

π

$H_{\text{global}} \rightarrow H_{\text{global+local}}$

$\approx G_{\text{global}} \times G_{\text{local}}$ ← ρ, a_1

Bando – Kugo –K.Y. (1986)

Bando – Fujiwara –K.Y. (1988)

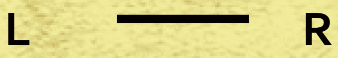
$\approx G_{\text{global}} \times G_{\text{local}} \times H_{\text{local}}$ ← ρ, a_1, ρ'

Bando – Kugo –K.Y. (1988)

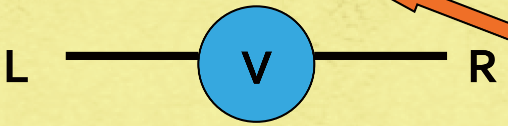
$\approx G_{\text{global}} \times G_{\text{local}} \times G_{\text{local}} \times \cdots$

重いHLS ボソンを積分で消去

$$U(x) = e^{i\frac{2\pi(x)}{f_\pi}} \quad \to g_L U(x) g_R^\dagger$$



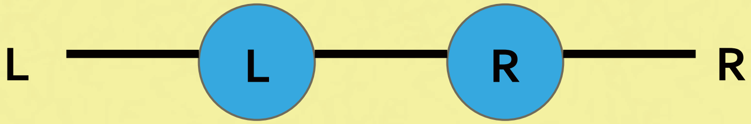
$$= \xi_L^\dagger(x) \cdot \xi_R(x)$$



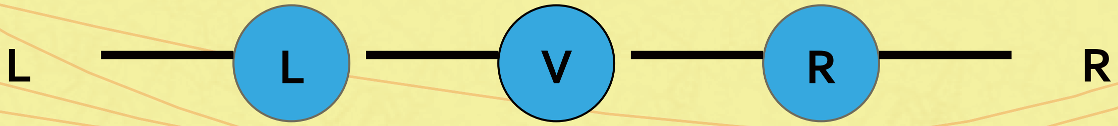
$$\xi_{L,R}(x) \to \xi'_{L,R}(x) = h(x)\xi_{L,R}(x)g^\dagger_{L,R}$$

任意性＝ゲージ対称性

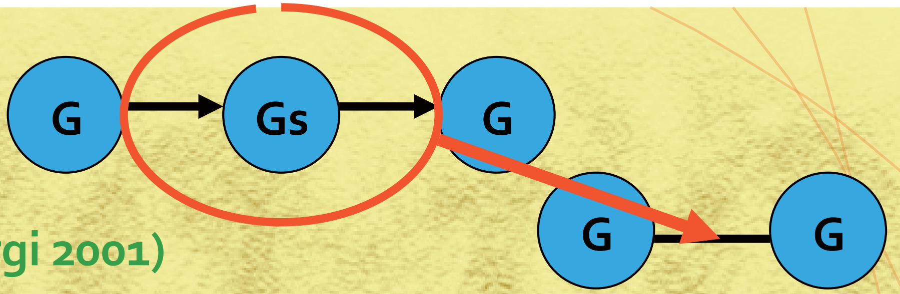
$$= \xi_L^\dagger(x) \cdot \xi_M(x) \cdot \xi_R(x)$$



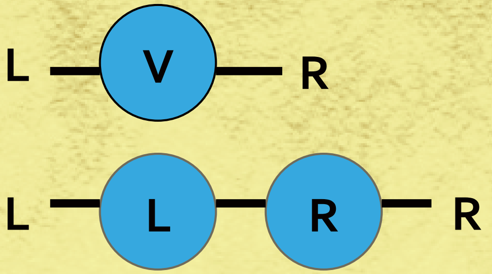
$$= \xi_{L_1}^\dagger(x) \cdot \xi_{L_2}^\dagger(x) \cdot \xi_{R_2}(x) \cdot \xi_{R_1}(x)$$



ムース図 (Georgi 1986)



凝縮ムース (Arkani-Hamed-Cohen-Georgi 2001)



G_{global} x H_{local} "3-site 模型"

G_{global} x G_{local} "5-site 模型"

.
.
.

5次元 ゲージ場の
デコンストラクト化/格子化

HLS

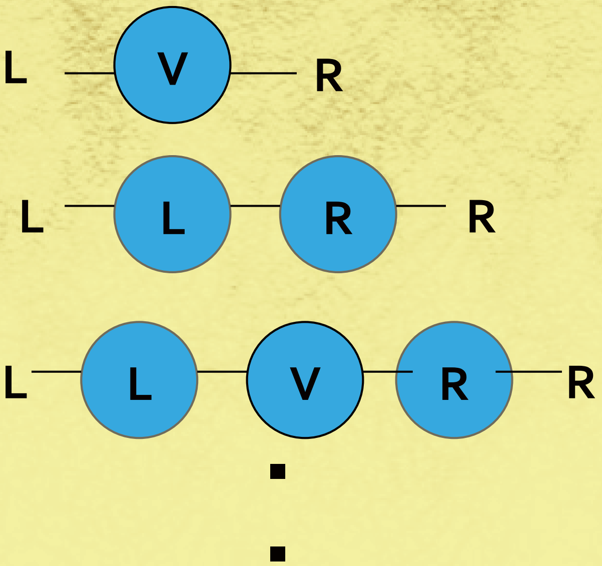
Arkani-Hamed-Cohen-Georgi(2001)

Cheng-Hill-Pokorski-Wang (2001)

AdS/QCD, ホログラフィックQCD
ヒッグスレス模型, リトルヒッグス

（線型）ムースの無限シリーズ

Son-Stephanov(2004)



G_{global} x H_{local} “3-site 模型” ρ

G_{global} x G_{local} “4-site 模型” ρ, a_1

G_{global} x G_{local} x H_{local} “5-site 模型” ρ, a_1 , ρ’

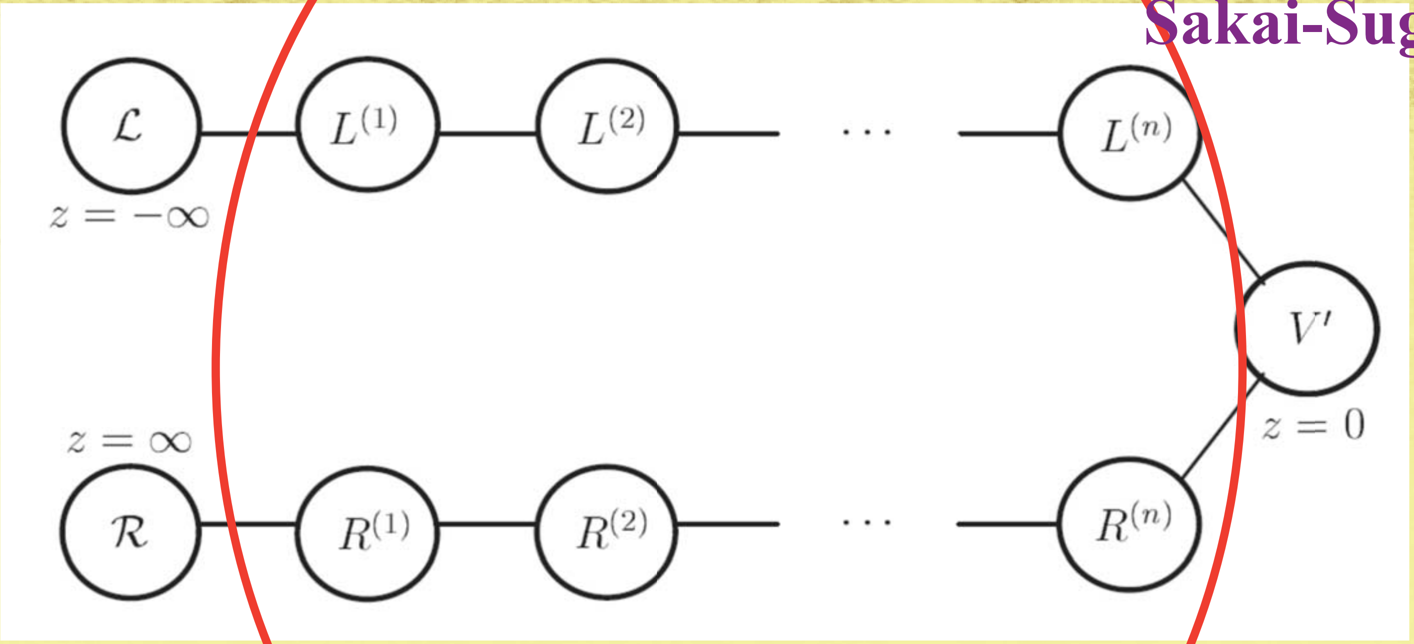
５次元フレーバーゲージ場の
デコンストラクト化・格子化

↓ ボトムアップ アプローチ

AdS/QCD, ホログラフィックQCD

Infinite Sequence of Linear Moose

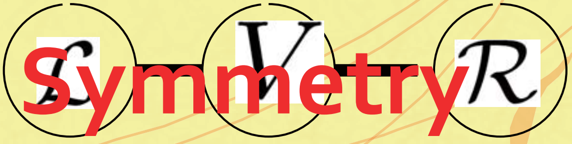
Son-Stephanov(2004)
Sakai-Sugimoto(2005)



$$L^{(i)} = V^{(i)} - A^{(i)},\; R^{(i)} = V^{(i)} + A^{(i)}$$

5D Gauge Theory for Flavor Symmetry

Integrating out via Eq. Mot.



$+\mathcal{O}(p^4)$

Harada-Matsuzaki-KY (2006)

ホログラフィック
ウォーキング・コンフォーマル
テクニカラー

Holographic Walking/Conformal TC (with Techni-gluon Condensate)

Haba-Matsuzaki-KY, 2008
および　準備中

$$S_5 = \int d^4x \int_\epsilon^{z_m} dz\, \sqrt{-g}\, \frac{1}{g_5^2} e^{c g_5^2 \Phi_X(z)} \Big(-\frac{1}{2} \mathrm{Tr}\left[L_{MN}L^{MN} + R_{MN}R^{MN}\right] + \mathrm{Tr}\left[D_M\Phi^\dagger D^M\Phi - m_\Phi^2 \Phi^\dagger\Phi\right] + \partial_M\Phi_X\partial^M\Phi_X \Big),$$

$\sim 1 + (z/z_m)^4$ (solution)

$$m_5^2 = \frac{\Delta(\Delta-4)}{L^2}$$

$\Delta = 3 - \gamma_m \simeq 2$ for $\Phi \sim \bar{T}T$

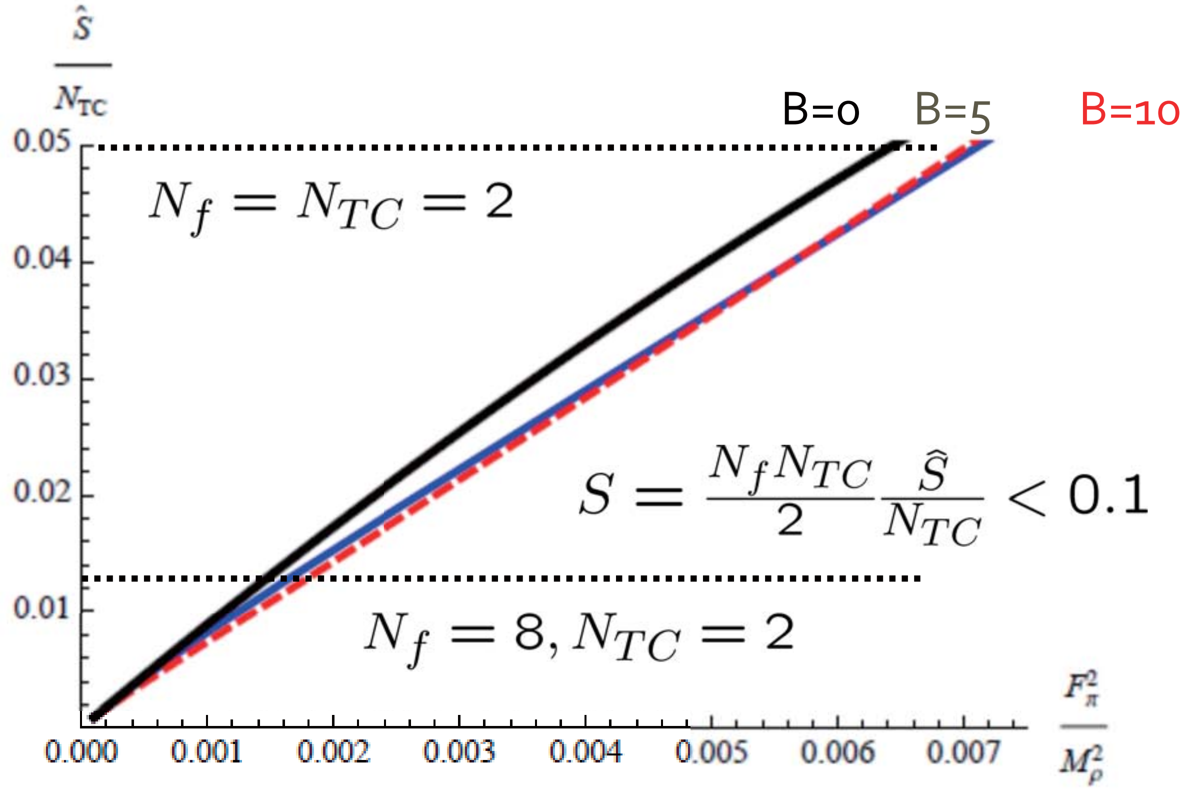
$\Delta = 0$ for $\Phi_X \sim G_{\mu\nu}^2$

Φ_X Improves OPE:

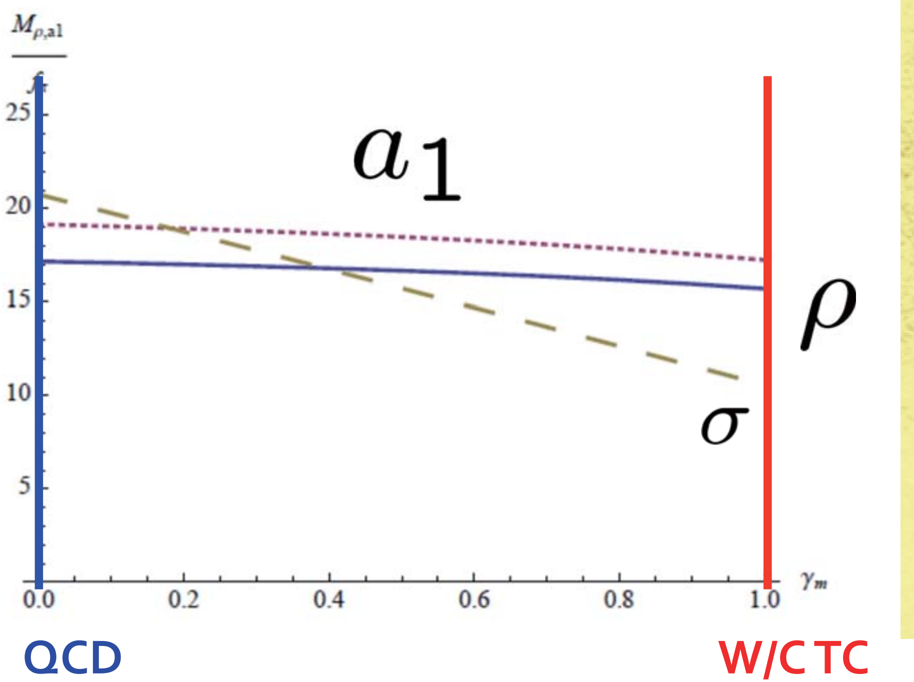
$$\boxed{\Pi_{JJ} \sim \frac{\alpha\langle G_{\mu\nu}^2\rangle}{Q^4}} \quad \text{vz} \quad \frac{\langle \bar{T}T\rangle^2}{(Q^2)^{3-\gamma_m}}$$

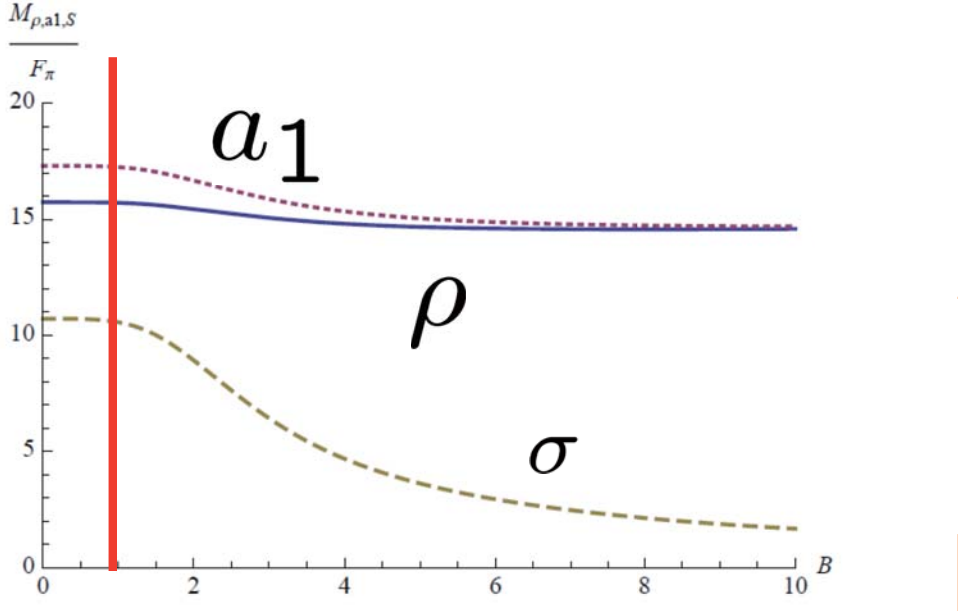
$\Phi_X = 0,\ \gamma_m = 0$ Erlich-Katz-Son-Stephanov; Da Rold-Pomarol (2005)

$\Phi_X = 0,\ \gamma_m \simeq 1$ Hong-Yee; Piai (2006); Haba-Matsuzaki-KY(2008)



$$B = \left(\frac{\left(\alpha_s\langle G_{\mu\nu}^2\rangle/f_\pi^4\right)_{\rm ref}}{\left(\alpha_s\langle G_{\mu\nu}^2\rangle/f_\pi^4\right)_{\rm QCD}}\right)^{1/4} = \left(\frac{\left(\alpha_s\langle G_{\mu\nu}^2\rangle/f_\pi^4\right)_{\rm ref}}{\left(0.012\pi{\rm GeV}^4/(92.4{\rm MeV})^4\right)_{\rm QCD}}\right)^{1/4}.$$





$B = 1$

$\gamma_m = 1$

$S = 0.1$

Ladder result

$$\partial^\mu D_\mu = \theta^\mu_\mu = 4\theta^0_0 = \lim_{\Lambda\to\infty} \frac{\beta(\alpha)}{4\alpha} G_{\mu\nu}G^{\mu\nu},$$

$$m = \Lambda e^{-\pi/\sqrt{\alpha/\alpha_c - 1}}$$

$$\beta(\alpha) = -\frac{2}{3C_2(F)}\left(\frac{\alpha}{\alpha^{\rm crit}} - 1\right)^{\frac{3}{2}} = -\frac{2\pi^3}{3C_2(F)}\left(\ln 4\frac{\Lambda}{m}\right)^{-3} .$$

$$\langle\theta^0_0\rangle = -\frac{N_f N_c}{\pi^4} m^4$$

$$B \simeq 8 - 9 \qquad \Lambda_{ETC}/F_\pi = 10^4 - 10^5$$

$$m_\sigma \simeq 500 - 600 \mathrm{GeV}$$

(one-family model)

Search for Higgs

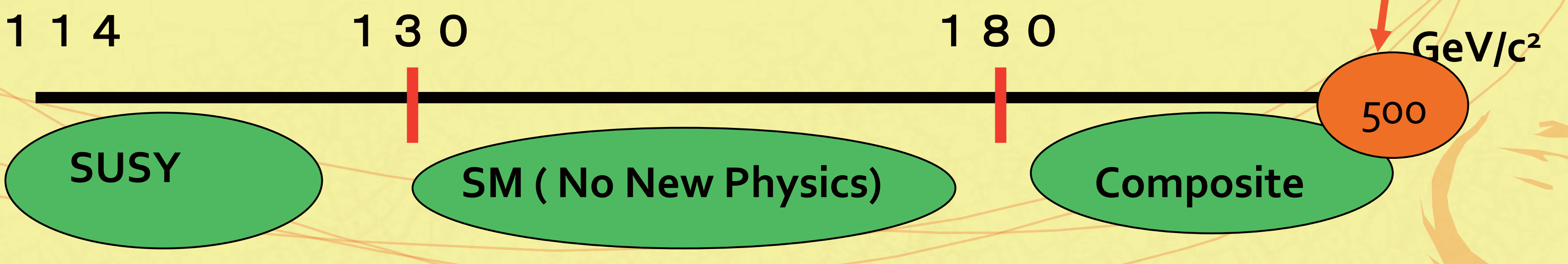
- Present Lower Limit （LEP)

$m_H > 114$ GeV/c^2

- LHC :

Could be searched for $m_H < 1$ TeV/c^2

テクニディラトン ？



１１４ １３０ １８０ GeV/c^2

500

SUSY

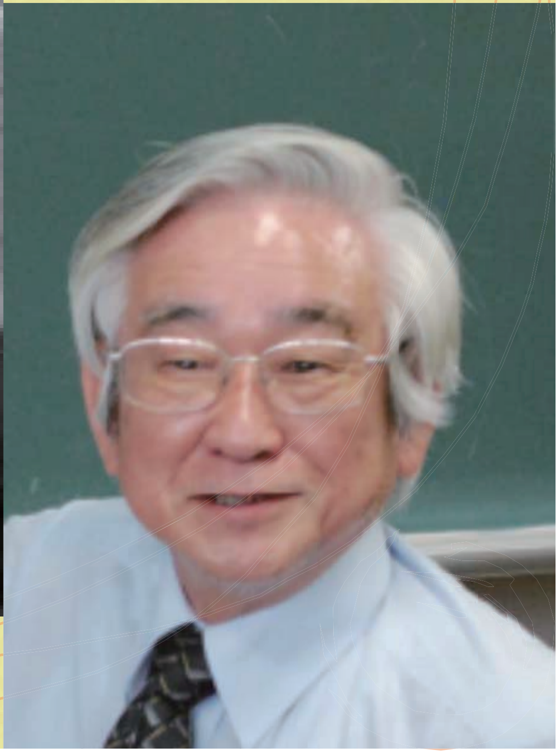
SM (No New Physics)

Composite

質量の起源：　歴史は繰り返す?

http://www.eken.phys.nagoya-u.ac.jp/images/sakata/4per.jpg

http://nobelprize.org/nobel_prizes/physics/laureates/2008/



http://www.kmi.nagoya-u.ac.jp/

質量の起源

||

相互作用
量子効果
（スケール異常）

今後の課題

格子シミュレーション

Appelquist et al, Sannino et al,
Lombardo et al, Kuti et al. ,
Onogi et al, Hayakawa et al,
Kogut-Sinclair, ……

1. Existence of IR fixed point

2. Determination of N_f^{cr}

3. Light spectrum

$M_\sigma, M_\rho, M_a : vs. F_\pi$

テクニディラトン

$\frac{F_\pi}{M_\rho}$ $\frac{F_\pi}{M\sigma}$

Gluonic contr.

4. S Parameter

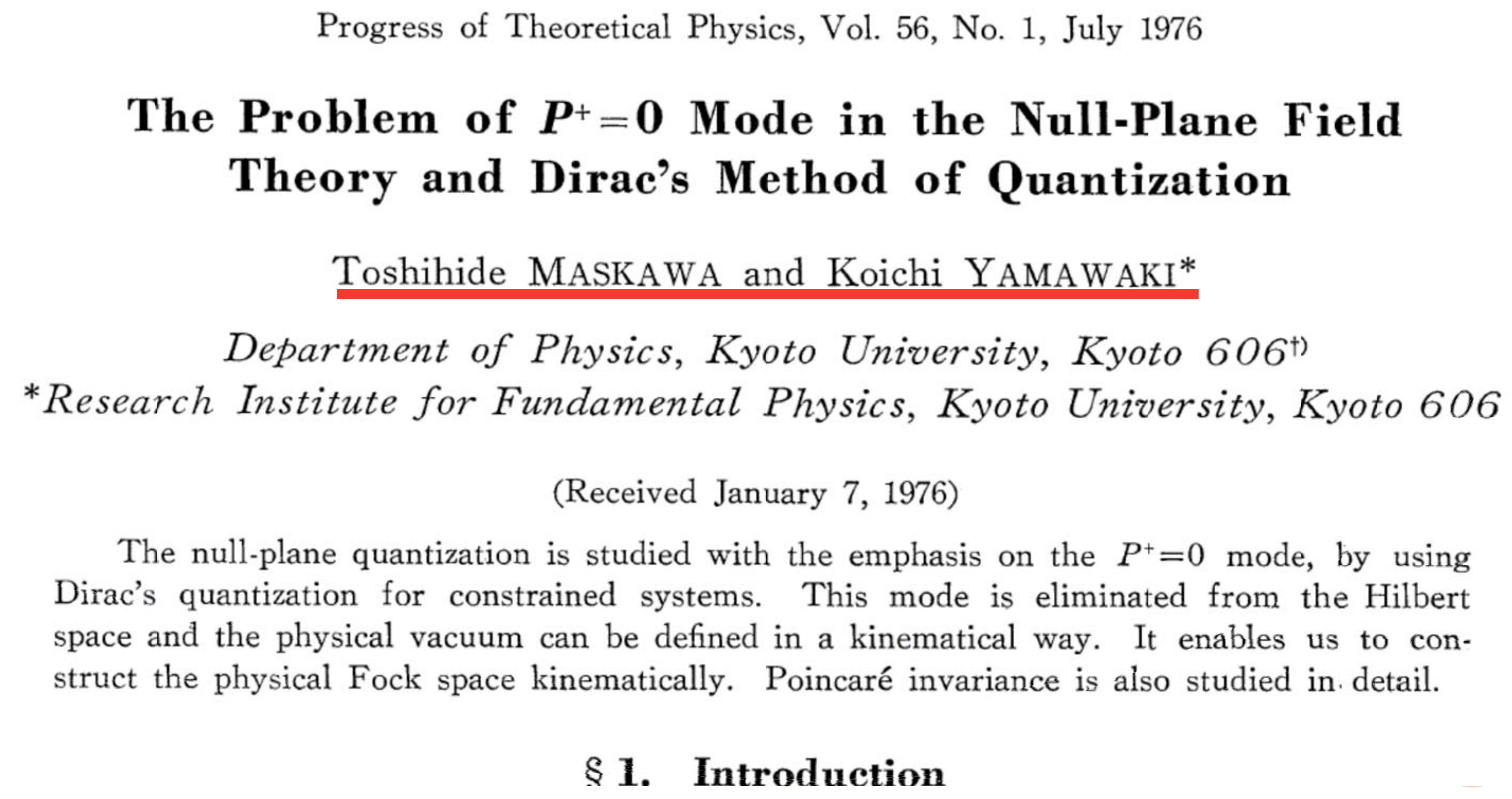
⋮

(Phenomenological issues: m_t, explicit ETC model, ...)

⋮

素粒子の
皮むく夢や
果てもなし
寄る年波に
船出せむかも

270



Progress of Theoretical Physics, Vol. 56, No. 1, July 1976

The Problem of $P^{+}=0$ Mode in the Null-Plane Field Theory and Dirac's Method of Quantization

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(Received January 7, 1976)

The null-plane quantization is studied with the emphasis on the $P^{+}=0$ mode, by using Dirac's quantization for constrained systems. This mode is eliminated from the Hilbert space and the physical vacuum can be defined in a kinematical way. It enables us to construct the physical Fock space kinematically. Poincaré invariance is also studied in detail.

§ 1. Introduction

２０１１年４月完成

名古屋大学工学研究科中央棟・素粒子宇宙研究棟（ＥＳ総合館）

三十年

夢追ふ日々の
をはりかな
まだ覚めやらぬ
夢のかずかず