(PSEUDO)NAMBU-GOLDSTONE BOSONS IN PARTICLE PHYSICS AND COSMOLOGY

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1. WHAT IS IT A NAMBU-GOLDSTONE BOSON?

Take a scalar field theory with U(1) global symmetry

$$\mathcal{L} = \partial_\mu \Phi \partial^\mu \Phi^* - V(\Phi, \Phi^*) \qquad V(\Phi, \Phi^*) = \lambda(\Phi\Phi^* - \frac{v^2}{2})^2$$

The ground state is for $\Phi\Phi^* = \frac{v^2}{2}$ And there is an infnite number of vacuum field configur

$$\Phi_0 = (v/\sqrt{2})e^{i\theta}$$

A CHOICE OF ONE BREAKS U(1) SPONTANEOUSLY

The angle θ is defined modulo pi

USING THE ANGULAR PARAMETRIZATION FOR THE COMPLEX SCALAR FIELD AND EXPANDING AROUND THE VACUUM

$$\Phi = \frac{1}{\sqrt{2}}(v + \rho(x)) \exp(i\frac{\eta(x)}{f})$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta(1+\rho/v)^2 - \frac{1}{2}m^2\rho^2 - \frac{\lambda}{4}\rho^4 - v\lambda\rho^3$$

Massless field $\eta(x)$ Nambu-Goldstone boson, only derivative couplings(no potential)

Invariance under $\eta(x) \rightarrow \eta(x) + \theta v$ in one to one correspondence with the original U(1)

The corresponding current:

$$J_\mu = -v(1+\frac{\eta(x)}{v})^2\partial_\mu\eta(x) = -v\partial_\mu\eta(x) + ...$$

THUS

$$< 0|J_\mu(x)|\eta >=< 0|v\partial_\mu\eta|\eta >= vk_\mu e^{-ikx}$$

NO LOOP CORRECTIONS TO THE NGB mass!

E.G. take a model with a scalar and chiral fermions:

FERMION-FERMION and BOSON-BOSON cancellations.

Supersymmetry: boson- fermion cancellations.

TWO WAYS TO STABILSE A SCALAR MASS: SUPERSYMMETRY OR MAKE IT A NGB

The properties of the (pseudo)NGB depend on the explict breaking of the original symmetry which often is determined by some physical ideas.

2. THE BEST KNOWN (PSEUDO) NAMBU-GOLDSTONE BOSON: A PION

SPONTANEOUS CHIRAL SYMMETRY BREAKING IN STRONG INTERACTIONS

TWO FLAVOURS, MASSLESS FERMIONS: GLOBAL $SU(2)_L \times SU(2)_R \to SU(2)_V$

QCD (massless quarks)

$$\mathcal{L} = \bar{\Psi}_L i D_\mu \gamma^\mu \Psi_L + \bar{\Psi}_R i D_\mu \gamma^\mu \Psi_R$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

AXIAL CHARGES $Q_A = Q_R - Q_L$ BROKEN BY A QUARK CONDENSATE

AXIAL CURRENT $\psi = \psi_L + \psi_R$

$$J_A^{\mu\alpha} = \bar{\psi}\gamma^\mu\gamma_5\sigma^\alpha\psi$$

PIONS AS NGB AND NONVANISHING MATRIX ELEMENT $< 0|J_A^{\mu\alpha}|\pi^\alpha(k) >= f_\pi k^\mu$

The original idea of Nambu – a dynamical origin of the order parameter sigma: fermion- antifermion pair condensation („Cooper pairs”)

$$< \Omega | \bar{\psi}^a_R \psi^b_L | \Omega > \neq 0$$

INTRODUCE A SCALAR OPERATOR $\Phi = \bar{\psi}\psi$

Beautiful mechanism in QCD: condensation scale (confinement scale) is linked to asymptotic freedom of QCD

$$< \Phi > = v \quad v \equiv f_\pi$$

$$v/Q = exp(-\pi/b\alpha(Q))$$

IS THE PION A GOLDSTONE BOSON? SMALL MASS BUT ALSO MORE ARGUMENTS

BASED ON THE STANDARD MODEL IDENTIFICATION OF THE TWO-FLAVOUR QCD LEFT-HANDED CURRENT WITH THE CURRENT OF THE WEAK INTERACTIONS

$$gJ_L^{\mu\alpha}W_{\mu\alpha} \qquad J_L^{\mu\alpha} = J_V^{\mu\alpha} - J_A^{\mu\alpha}$$

GOLDBERGER-TREIMAN RELATION $g m_N = g_{\pi N} f_\pi$ (Amplitude for the neutron beta decay is used to derive it)

DECAY $\pi \to \mu\nu$ $\mathcal{L} = G_F J_L J_{lep}$ $\Gamma(\pi \to \mu\nu) \approx G_F^2 f_\pi^2 m_\pi m_l^2$

Pion-Pion elastic scaterring

3. THE BROUT-ENGLERT-HIGGS MECHANISM AND NAMBU-GOLDSTONE BOSONS

U(1) EXAMPLE:

$$\Phi = \frac{1}{\sqrt{2}}(v + \rho(x)) \exp(i\frac{\eta(x)}{f})$$

$$\mathcal{L} = -F^{\mu\nu}F_{\mu\nu} + (D_\mu\Phi) * (D_\mu\Phi) - V(|\Phi|^2)$$

APPLY GAUGE TRANSFORMATION

$-\eta'(x) = -\eta(x)/v$ ON $\Phi(x)$ and $A_\mu \to A_\mu + (1/gv)\partial_\mu\eta(x)$

$$\mathcal{L} = -F_{\mu\nu}F^{\mu\nu} + \partial_\mu\rho\partial^\mu\rho + g^2(\rho + v)^2 A_\mu A^\mu + ..$$

SM:

GLOBAL SU(2)xSU(2) SYMMETRY OF THE HIGGS POTENTIAL BROKEN TO SU(2);

THERE ARE 3 NGB EATEN UP BY THE GAUGE BOSONS AND THE RADIAL MODE = PHYSICAL HIGGS

MY LIFE AS A BOSON (by PETER HIGGS)

My revised paper was received by Physical Review Letters at the end of August (1964) (…). The referee who, I discovered later, was Nambu, drew my attention to a paper by Englert and Brout ,which had been received on the 22nd of June, before I even started my piece of work, and published on the 31st of August.

The reference to the so-called Higgs boson would never have appeared in print if Physics Letters had accepted the original version. One of the additions was the sentence ‘it is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons.’

MY LIFE AS A BOSON (PH)

The only thing that did not really go right was that I did not make any impact in terms of the possible applications.
All of us, Brout, Englert and myself, had been going in the wrong direction, looking at hadron symmetries.
(…..)

So it was left to Weinberg and Salam in 1967, as is well known, to bolt my and Brout and Englert's type of model onto Glashow's SU(2) × U(1) model of leptons, and the rest of the story is well-known to you.

4. THE HIGGS BOSON AS A GOLDSTONE BOSON

MOTIVATION: IT SOLVES THE BIG HIERARCHY PROBLEM

IMAGINE GLOBAL SO(5) SPONTANEOUSLY BROKEN TO SO(4) by the vacuum expectation value F --→ 4 NGBs

Isomorphism SO(4)=SU(2)xSU(2)

Imagine now that SO(5) is also explicitly broken so that the NGBs get a potential which breaks it spontaneously to SU(2) with the vacuum expectation value V of the one of the four NGB. Then 3 Goldstones remain in the spectrum for the BEH mechanism and one becomes the Higgs boson.

PREDICTION: ALL HIGGS COUPLINGS ARE MODIFIED BY A UNIVERSAL CORRECTION

$$\delta \approx \frac{v^2}{F^2}$$

5. AXIONS AND ALPs

THE STRONG CP PROBLEM:

$$\mathcal{L} \supset \Theta \frac{\alpha_3}{8\pi} G_c^{\mu\nu} \tilde{G}_{c\mu\nu}$$

WHERE

$$\Theta = \theta_{QCD} + Arg\ det\ M_u M_d$$

NEUTRON EDM:

$$\Theta < 10^{-10}$$

The axion solution:

an electroweak singlet ϕ charged under CHIRAL $U(1)_{PQ}$ and responsible for its spontaneous breaking

$$\phi = (f/\sqrt{2})\exp(ia/f)$$

$U(1)_{PQ}$ MUST BE ANOMALOUS $U(1)_{PQ} \times SU(3)^2$

THE QCD ANOMALY GENERATES THE COUPLING (POTENTIAL FOR THE AXION a)

$$V_a \sim \frac{a}{f} G^{a\mu\nu} \tilde{G}_{a\mu\nu}$$

AXION SOLUTION

$$\mathcal{L} \supset (\Theta + \frac{a}{f}) G^{a\mu\nu} \tilde{G}_{a\mu\nu}$$

INSTANTON EFFECTS GIVE THE POTENTIAL

$$V_a = \Lambda^4 (1 - \cos(a/f + \Theta))$$

MINIMIZING THE POTENTIAL $a/f = -\Theta$

AND WE OBTAIN ALSO A MASS FOR THE AXION OF ORDER $(m_a^{QCD})^2 \sim \Lambda^4/f^2$

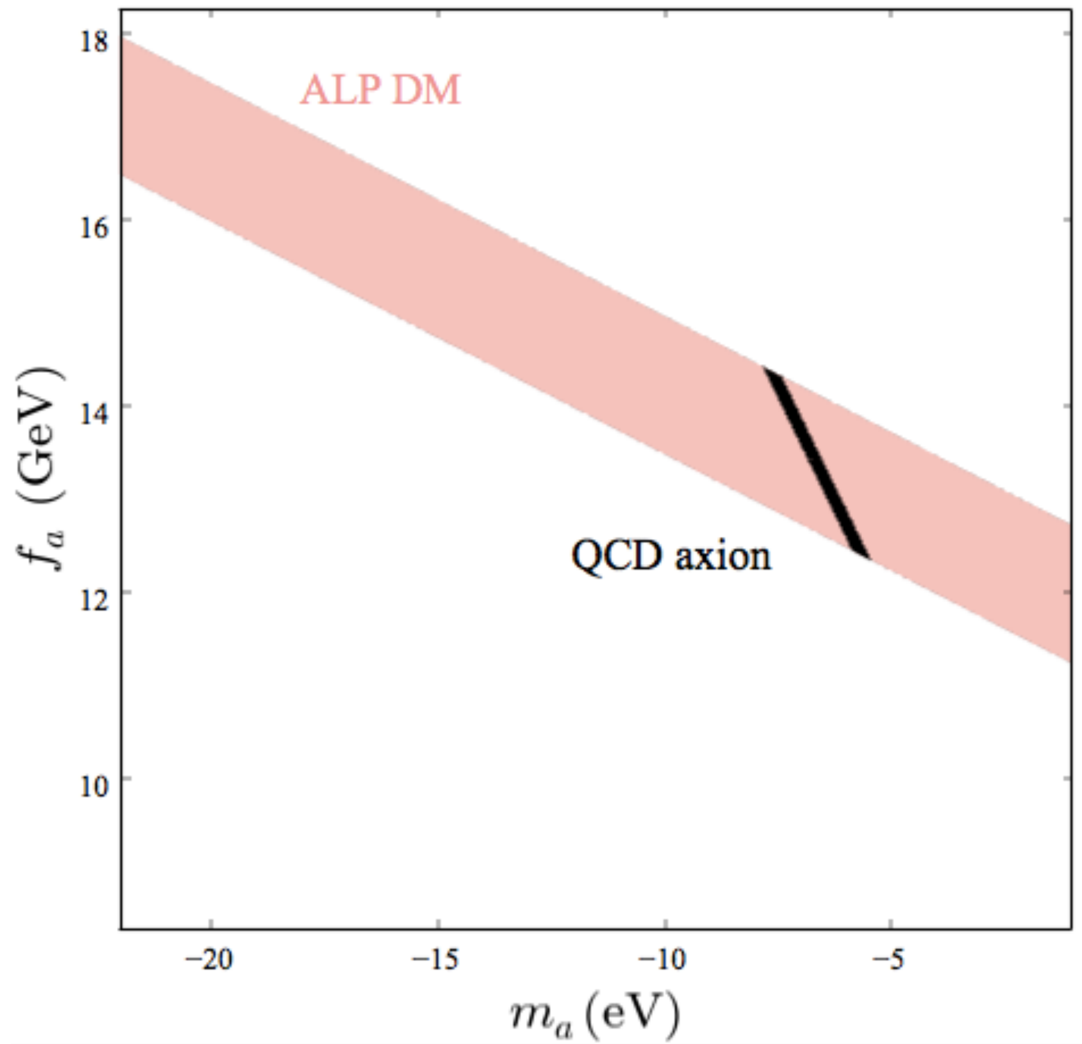
ADDITIONAL MOTIVATION: QCD AXION AND ALP IN GENERAL- GOOD CANDIDATES FOR COLD DM

KEEPING m_a AND f_a AS FREE PARAMETERS, WE HAVE FOR ALP

$$\Omega_a \approx 2 \times 10^2 (\frac{m_a}{10^{-22} eV})^{1/2} (\frac{f_a}{M_{PL}})^2 \Theta^2$$

REQUIRING $\Omega_a = 0.25$ ONE GETS A CORRELATION BETWEEN ACCEPTABLE MASSES AND THE SCALES f_a

WHERE THE MODELS PLACE US ON THIS BAND?



ALP DM
QCD axion
18
16
14
12
10
f_a (GeV)
−20
−15
−10
−5
m_a (eV)

RECENT DEVELOPEMENTS

A unified framework where the approximate symmetry of the QCD axion is identified with the simplest flavor symmetry of the FN mechanism.

The structure of quark and lepton masses and mixings follows from a spontaneously broken U (1) flavor symmetry which generically has a QCD anomaly.

FROGGATT-NIELSEN MODELS FOR FERMION MASSES:

$$\mathcal{L} = a^u_{ij} Q_i U^c_j H (\Phi/\Lambda)^{q_i + u_j} + \ldots$$

$$\Phi = (V + \phi) e^{ia/V}$$ $V/\Lambda = \epsilon$ CABIBBO ANGLE

IDENTIFIED WITH AN AXION

$$\mathcal{L}_{aff} = \lambda_{ij} a F_i F^c_j + hc$$

AXION COUPLINGS TO FERMIONS ARE CONTROLLED BY THE FERMION MASSES

FLAVOURFULL AXION

E.G. $K^+ \to \pi^+ a$

SUMMARY

AT PRESENT:

NGBs= PRECISION HIGGS MEASUREMENTS

AND

NGBs= SEARCH FOR VERY LIGHT AND VERY WEAKLY COUPLED NEW PARTICLES, WHICH ARE INTERESTING POSSIBILITY IN ADDITION TO HEAVY NEW PARTICLES

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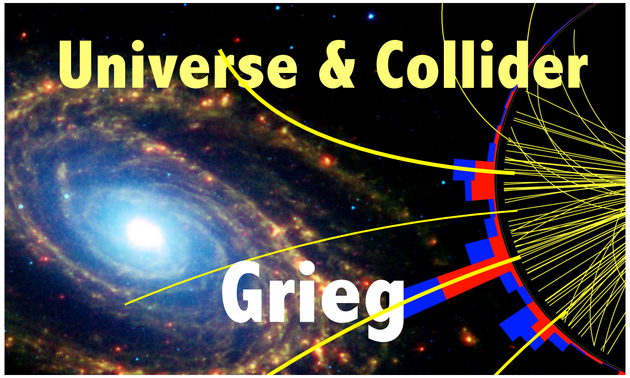

Understanding the Early Universe:
interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen

SPONTANEOUS CHIRAL SYMMETRY BREAKING
IN STRONG INTERACTIONS

TWO FLAVOURS, MASSLESS FERMIONS: GLOBAL $SU(2)_L \times SU(2)_R \to SU(2)_V$

Sigma model description: fermions and elementary scalar

$$\Sigma = \begin{pmatrix} \sigma + i\pi^3 & -i\pi^1 + \pi^2 \\ \pi^2 + i\pi^1 & \sigma - i\pi^3 \end{pmatrix}, \quad \Sigma \to g_L \Sigma g_R^\dagger$$

$$\mathcal{L} = i\bar{\Psi}\partial_\mu\gamma_\mu\Psi - g\bar{\Psi}_L\Sigma\Psi_R - g\bar{\Psi}_R\Sigma^+\Psi_L + \mathcal{L}(\Sigma)$$

Spontaneous symmetry breaking is described by an
ad hoc ansatz for the potential for the scalar field, giving

$$< \sigma > = f_\pi \qquad \to 3\pi + \rho$$