Rethinking the origin of Neutrino Mass: the Role of Gravity

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arXive 1602.03191

Why are neutrinos
so much lighter than
the other fermion
species?

In standar approaches (e.g., see-saw, Weinberg's operator or Large extra dimensions) one way or the other neutrino mass originates from the VEV of the Higgs doublet.

The whole song and dance is about explaining why the neutrino mass is much smaller than its source:

Why

$$m_\nu \ll \langle H \rangle \sim 100 \text{ GeV}?$$

e.g. Weinberg's operator

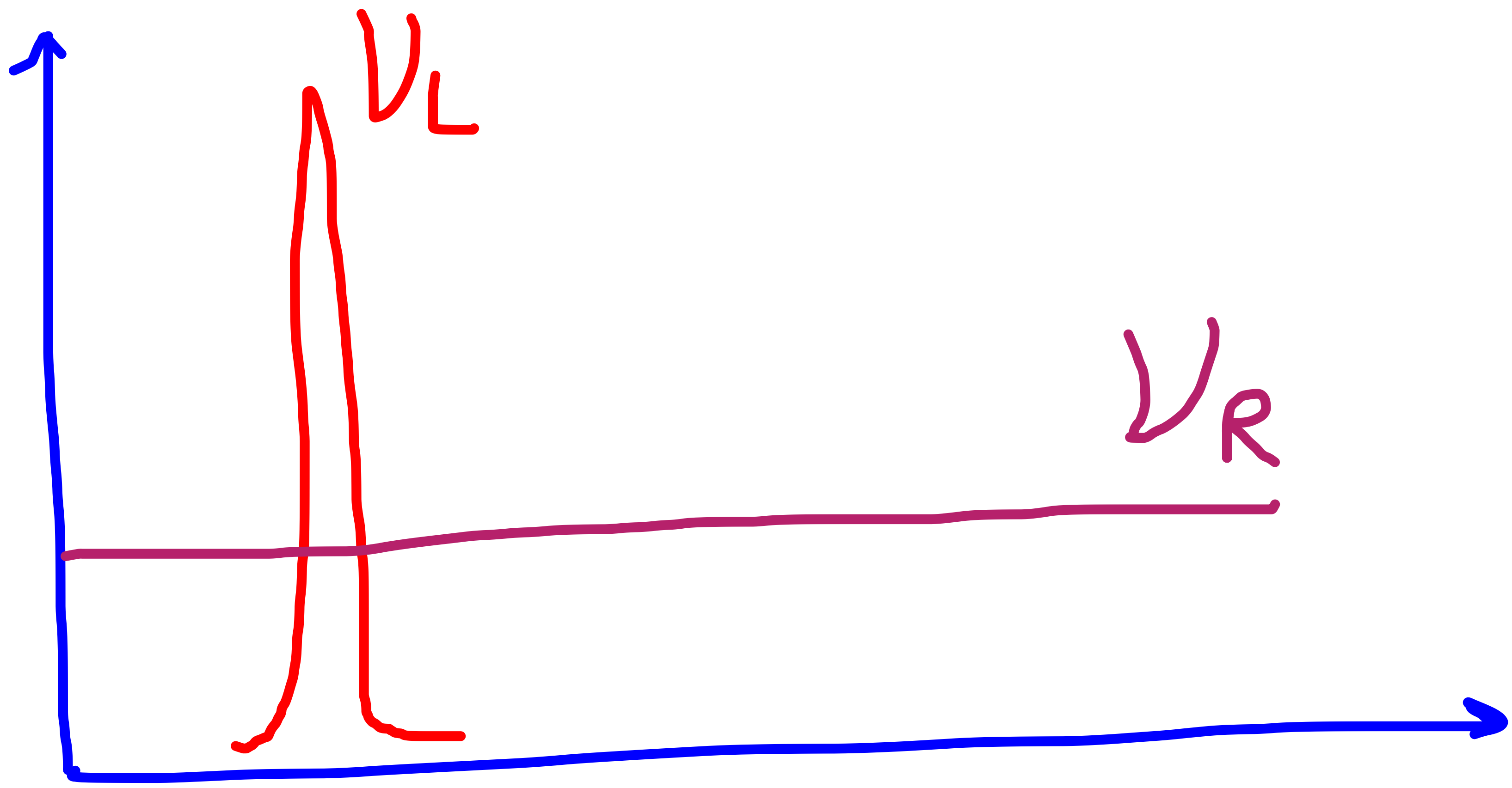
$$\frac{H_0 H_0}{M}\,\nu_L^T c\,\nu_L$$

$$\hookrightarrow \quad m_\nu = \frac{\langle H_0\rangle^2}{M}$$

SEE-SAW

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & H_0 \\ \nu_R & H_0 & M \end{array} \quad\text{i.e.}\quad \begin{pmatrix} 0 & H_0 \\ H_0 & M \end{pmatrix}$$

Large extra dimensions



$$g_\nu H_0 \overline{\nu}_L \nu_R$$

$$\rightarrow g_\nu \ll 1$$

$$m_D = g_\nu \langle H_0 \rangle$$

In this talk we suggest to rethink the origin of m_ν:

Extraordinary smallness of m_ν may be an indication that its origin is very different from other fermions.

Standar model + Gravity has a built-in source of neutrino mass, which is completely independent of the VEV of the Higgs-doublet.

The generation of fermion mass requires breaking of chiral symmetry:

Dirac $\quad \psi \to e^{i\alpha\gamma_5}\psi$

$$m_D \bar{\psi}\psi = m_D \bar{\psi}_L \psi_R + h.c.$$

Majorana

$$m_M \psi_L^T C \psi_L \qquad \psi_L \to e^{i\alpha}\psi_L$$

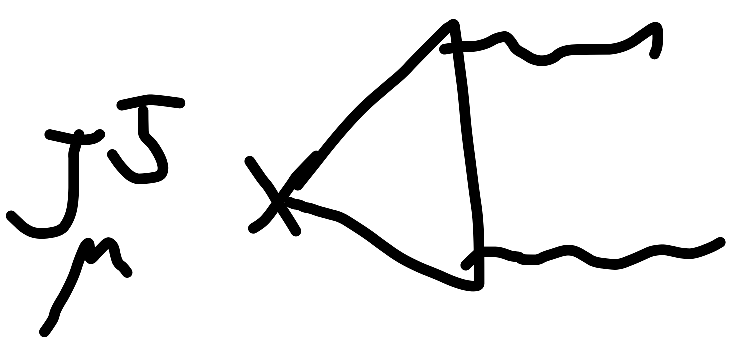
This breaking can be:
explicit or spontaneous,
dynamical or non-dynamical.

In SM this breaking
is acomplished by
Yukawa couplings to the
Higgs VEV:

$$\sum_{f} g H \bar{\psi}_L \psi_R$$

However, there is another source of chiral symmetry breaking which aslo generates fermion mass and is well understood in QCD:

ABJ-anomaly



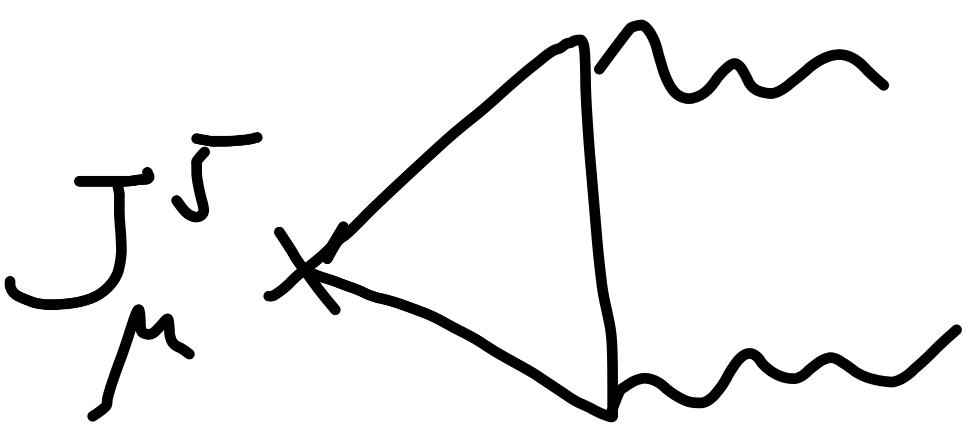
Quark axial symmetry

$$q \to e^{i\alpha\gamma_5} q$$

Axial current

$$J_\mu^5 \equiv \bar{q}\gamma_\mu\gamma^5 q$$

ABJ-anomaly



$$\partial_\mu J_5^\mu = F\tilde{F}$$

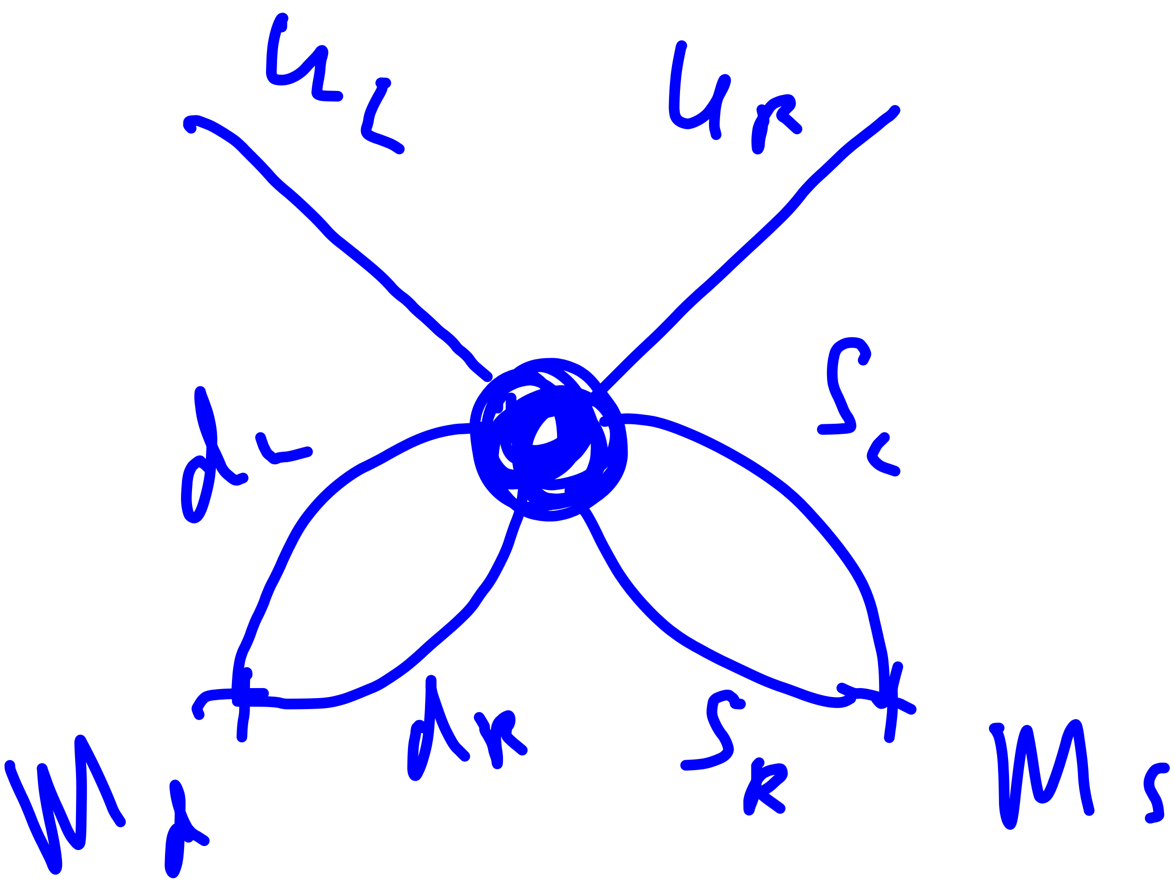
The fermion mass-generation through anomaly in QCD is connected to the topological structure of QCD vacuum, i.e., with physicality of θ-term

$$\theta F \tilde{F}$$

In the presence of a quark with zero bare mass, θ-term becomes unphysical.

In the same time the η'-meson and the quark become massive.

E.g., One source of up-quark mass



't Hooft vertex

This is simplest to understand in the language of a 3-form Higgs effect

(G.D., arXiv: 0507215)

Consider pure QCD (no quarks).

θ is physical because of topological susceptibility of vacuum

$$\langle F\tilde{F}, F\tilde{F}\rangle_{p\to 0} = \text{const} \neq 0$$

Notice,

$$E \equiv F\tilde{F} = dC = \varepsilon^{\mu\nu\alpha\beta}\partial_\mu C_{\nu\alpha\beta}$$

Chern-Simons 3-form:

$$C \equiv A\,dA - \frac{2}{3}AAA$$

$A \equiv$ gluon

under QCD gauge transformation

$$C \longrightarrow C + d\Omega$$

2-form

$$\langle F\tilde{F}, F\tilde{F}\rangle_{p\to 0} = \langle E, E\rangle_{p\to 0} = \text{const} \neq 0$$

$$\Big\downarrow \quad \text{since } E \equiv dC$$

$$\langle C, C\rangle_{p\to 0} = \frac{\text{const}}{p^2}$$

$$\downarrow$$

C is a massless field!

(don't be surprised it is non-propagating (no waves))

Thus, effective theory

$$\mathcal{L} = \underbrace{E^2 + \dots}_{\text{Algebraic in } E} + \text{high derivativ}$$

Vacuum equation

$$\partial_\mu E = 0$$

$\downarrow$ Vacua (θ-vacua)

$$E = \Theta$$

when we add a massless quark flavor $q \to e^{i\alpha\gamma_5} q$ the Goldstone boson η' is eaten-up by C and they form a massive pseudo-scalar

$$\mathcal{L} = \frac{1}{2} E^2 - \eta' E + \frac{1}{2} (\partial \eta')^2$$

where

$$\eta' = \bar{q} \gamma_5 q \qquad \partial_\mu \eta' = \bar{q} \gamma_5 \gamma_\mu q$$

$$\partial_\mu \eta' = J_\mu^5$$

$$\mathcal{L} = \frac{1}{2}E^2 - \eta' E + \frac{1}{2}(\partial_\mu \eta')^2$$

$$\downarrow$$

$$\partial_\mu (E - \eta') = 0 \rightarrow E = \eta' + \theta_0$$

$$\Box \eta' + E = 0$$

$$\hookrightarrow \Box \eta' + (\eta' + \theta_0) = 0$$

1. η' is massive
2. vacuum is at $E = \theta = 0$

Topological language is very powerful and allows to generalize effect to an arbitrary theory with

* Topological CP-density E
* Anomalous current $\partial_\mu J^\mu = E$

G.D., Jackiw, Pi PRL 96 (2006) 081602

Thus, there is an eaten-up Goldstone boson

$$\partial_\mu \eta' \equiv J^5_\mu$$

Thus, there is a condensate that breaks symmetry!

Gravity has all the ingredients!

(G.D., 2005; G.D., Folkerts, Franca PRD 89 (2014) 105025)

In gravity + massless neutrinos we have:

* Topological CP density:

$$E_g \equiv R\tilde{R} = dC_g$$

Gravitational CS 3-form

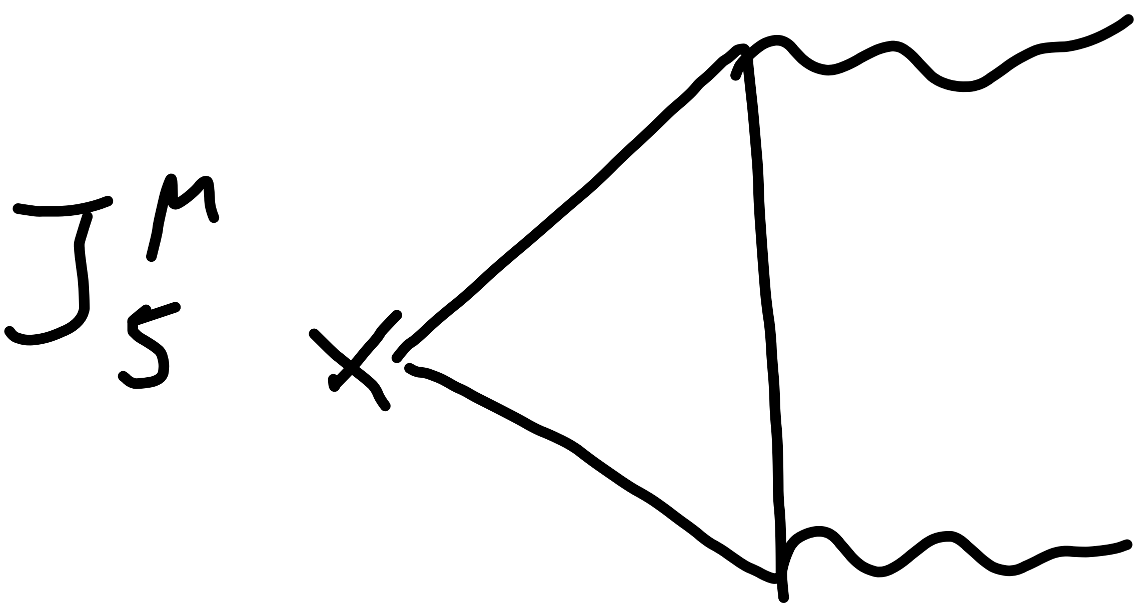
$$C_g \equiv \Gamma d\Gamma - \frac{2}{3}\Gamma\Gamma\Gamma$$

⊛ Neutrino chiral current

$$J^5_\mu \equiv \bar{\nu}\gamma_\mu\gamma^5\nu$$

which is anomalous

$$\partial_\mu J^\mu_5 = R\tilde{R} = E$$



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(Delbourgo, Salam; Eguchi, Freund; Alvarez-Gaume, Witten)

QCD	Gravity
$q \to e^{i\alpha\gamma_5} q$	$\nu \to e^{i\alpha\gamma_5} \nu$
$J_\mu^5 = \bar{q}\gamma_\mu\gamma_5 q$	$J_\mu^5 = \bar{\nu}\gamma_\mu\gamma^5\nu$
$E = F\tilde{F} = dC$	$E_g \equiv R\tilde{R} = dC_g$
$C = AdA - \frac{3}{2}AAA$	$C_g = \Gamma d\Gamma - \frac{3}{2}\Gamma\Gamma\Gamma$
If quarks are massive:	If ν-s are massive
$\langle E, E\rangle_{p\to 0} \neq 0$	$\langle E_g, E_g\rangle_{p\to 0} \neq 0$?

Thus, if gravity (without massless fermions) has non-zero topological vacuum

$$\langle R\tilde{R}, R\tilde{R} \rangle_{p\to 0} = \text{const} \neq 0$$

then with neutrinos included the same story repeats as in QCD

* The chiral neutriono condensate is generated

$$\langle \bar{\nu} \nu \rangle \neq 0$$

* The Goldstone boson $\eta_\nu \equiv \bar{\nu}\gamma_5\nu$ is eaten up by C_g and becomes massive.

* The same condensate gives mass to neutrino!

Critical connection

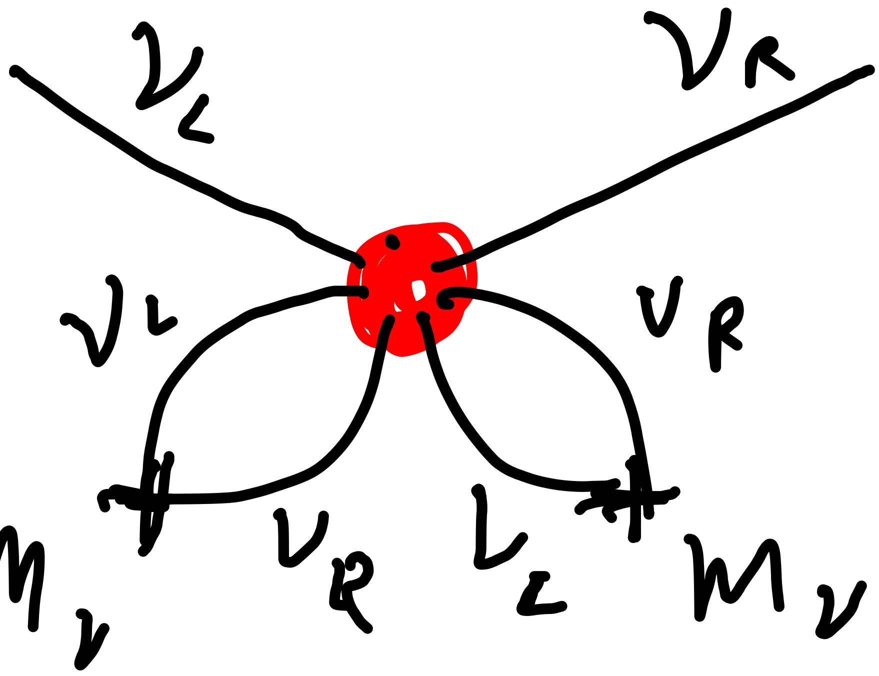
$$\langle R\tilde{R}, R\tilde{R}\rangle_{\rho \to 0} = \text{const} \neq 0$$

$$\langle \bar{\nu}\nu \rangle \neq 0$$

Once we have $\langle \bar{\nu}\nu \rangle \neq 0$, which breaks neutrino chiral symmetry, nothing prevents generation of m_ν from the same condensate.

How many neutrinos can get masses in this way?

At least one



But, potentially all via interaction with the condensate.

Constraints on scale Λ_g

$$\langle R\tilde{R}, R\tilde{R}\rangle_{p\to 0} = \Lambda_g^8$$

$$\langle \bar{\nu}\nu \rangle = \Lambda_g^3$$

must be $\Lambda_g \ll M_e$

So natural candidate for neutrino mass scale

$$\Lambda_g \sim 10^{-1} - 10^{-2}\,\mathrm{eV}$$

Many new phenomenological questions:

* Pion-like pseudo-Nambu-Goldstone bosons from breaking of

$$U(3)_L^{(2)} \otimes U(3)_R^{(2)} \text{ - symmetry}$$

can be searched for by axion-like experiments.

* Very late phase transition with generation of m_ν.
The cosmological bounds on neutrino abundance must be reconsidered.

* Other cosmological consequences: Skyrmion type topological defects formed after phase-transition, new contribution to dark matter?

Another motivation for this scenario of neutrino mass:

If $m_\nu \neq 0$ is generated by gravitational anomaly, neutrino protects the axion mass from gravity!

$$\partial^\mu J_\mu^{axion} = F\tilde{F} + R\tilde{R}$$

$$\partial^\mu(\bar{\nu}\gamma_\mu\gamma_5\nu) = R\tilde{R}$$

Axion screens $\langle F\tilde{F}\rangle_{QCD}$

and gets mass

and

Neutrino screens $\langle R\tilde{R}\rangle_{gravity}$

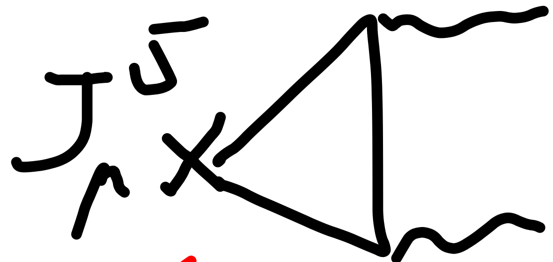
and gets mass!

Take a theory with

$$\langle E , E \rangle_{p \to 0} = \text{const} \neq 0$$

and

$$\partial^\mu J^5_\mu = E$$



$$\mathcal{L} = E^2 + E \frac{\partial_\nu}{\Box} J_5^\nu$$

$$\Box E = - E$$

Mass gap is generated!