Gauged Axions and their QCD Interactions

Giuseppe Nardulli Memorial Workshop

Claudio Coriano'
Physics Department
University of Salento, INFN Lecce

QCD at Work, Martina Franca 2010

Beppe has been a great friend, a great and respected Colleague who has done very significant work in our field. He has also been a strong supporter of our BA-21 group in Lecce. We all miss him, but we treasure his teachings and his efforts to maintain a very high standard for fundamental research in our region, Apulia.

I will briefly overview the (possible) implications of axion Physics following two separate routes

The first route: suggested by “completion theories” with a very light axion, both in the non-susy (MLSOM) And in the susy case (USSM-A)

with Antonio Mariano (University of Salento)
G. Lazarides (AUT, Thessalonikki)
M. Guzzi (SMU, Dallas, Texas)

The second route: (the discussion is much briefer in this case)
Axions from “decoupling” of some chiral fermions.
These are GeV axion, studied recently
(together with Marco Guzzi)

Gauged axions are extension of the traditional (invisible) Peccei-Quinn axions where the "shift parameter" is gauged.

The gauging, as we are going to show, has consequences at cosmological level, as in the PQ case.
We will try to highlight some of the main feature of this light particle, under the assumption that a mechanism of "sequential misalignment" is induced Both at the electroweak and at the QCD phase transition.

These types of axions, as we are going to argue, are typical of several types of high energy "completion theories" such as

INTERSECTING BRANE models
GAUGED SUPERGRAVITIES.

The role played by these axions are quite specific, since they could Take the role both of dark matter and of dark energy, under some conditions That we are going to discuss.

Antonio Mariano (UoS, Lecce)
Marco Guzzi (SMU, Dallas, Texas)
George Lazarides (Thessalonikki)

Roberta Armillis
Luigi Delle Rose

U(1) symmetries may play an important role both in connecting the Standard Model with its high energy extensions

The Peccei-Quinn mechanism has beeen, historically, the first example of such inclusion.

The axion emerges as a physical pseudo Nambu-Goldstone mode of a global (broken) abelian symmetry

The PQ axion: where the story commences

Why CP is conserved in Strong Interactions ?

$$L_\theta = \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \qquad L_m = \frac{\alpha_s Arg(\det M)}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta + Arg(\det M) \Rightarrow L_{\bar{\theta}} = \frac{\alpha_s \bar{\theta}}{8\pi} \vec{G}_{\mu\nu} \cdot \vec{\tilde{G}}^{\mu\nu}$$

$$L = \sum_{n=1}^{N} \bar{\psi}_n \left(i\gamma^\mu D_\mu - m_n \right) \psi_n - \frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} + \frac{\alpha_s \bar{\theta}}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

We do not observe any CP violating effect in the strong interactions, and this shows that THETA has to be small.

Smallness of the neutron electrical dipole moment shows that THETA has to be zero.

Indeed if we calculate the neutron electric dipole moment we get: $d_n \approx 10^{-16} \bar{\theta}$ e·cm

Given the experimental limit: $d_n < 0.63 \times 10^{-25}$ e·cm

→ $\bar{\theta} \approx 10^{-9}$

PECCEI and QUINN proposed in 1977 an extension of the SM With an anomalous U(1) symmetry U(1)_PQ

This is a symmetry of the theory at the lagrangean level, broken

Spontaneously at a large scale (f_a)

and

Explicitly at the QCD hadron transition

The axion is massless until the QCD transition. Instanton effects are held responsible for the generation of the axion potential

$$\mathcal{L}_{\rm QCD+a} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \sum_q \bar{q}(i\gamma^\mu\partial_\mu - m_q)q + \frac{g_s^2}{32\pi^2}(\theta + \frac{a}{f_a})G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

The axion interacts with photons, electrons, hadrons with a strength ~ f_a^{-1}

Initially f_a was tied to the Electroweak scale and the CP breaking with the Electroweak breaking

The realization that the axion scale can be very big (and its coupling very weak) initiated the 'invisible axion' models

Mass and couplings are related by the same scale

$$m_a \simeq 6\ \mu eV \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right) .$$

$$g \approx \frac{1}{f_a}$$

$$f_a \geq 10^{10}\, GeV$$

Astrophysical constraint linked to the stellar evolution

$$f_a \leq 10^{12}\, GeV$$

Cosmological constraint given by the dark energy amount

$$10^{-6}\, eV \leq m_a \leq 10^{-3}\, eV$$

DFSZ

- $f_a >> f_{ew}$
- Two Higgs fields and
- one scalar field.
- Fermions: carry PQ charge.

KSVZ

- $f_a >> f_{ew}$
- One Higgs field,
- one scalar field
- one exotic quark with PQ charge.

The axion dark matter scenario

Peccei-Quinn symmetry breaks at $T \sim f_a \leq 10^9$GeV

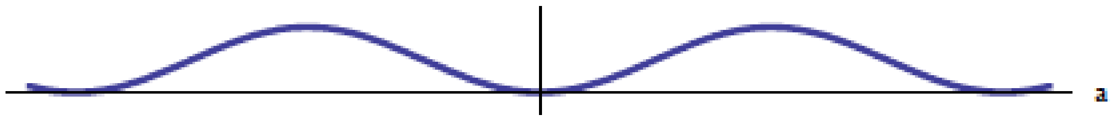
The axions acquire mass at $T \sim \Lambda_{QCD}$

$$m_a(T) = \begin{cases} m_a b(\frac{\Lambda}{T})^4, & T \gtrsim \Lambda, \\ m_a, & T \lesssim \Lambda. \end{cases}$$

b=0.018

Periodic potential and oscillations
Due to "vacuum misalignment"

$$V(\theta) = -C(T)\cos(\theta), \text{ where } \theta \equiv a/F_a.$$



Peccei & Quinn(1977), Weinberg(1978), Wilczek, (1978), J. E. Kim(1979),Shifman, Vainstein & Zakharov, (1980),Dine, Fischler & Srednicki(1981),Zhitnitskii(1980).

Temperature dependence of axion mass : instanton size integration

$C(T) = \int d\rho \, n(\rho, T)$.

(tHooft(1976), Gross, Yaffe & Pisarski(1981))

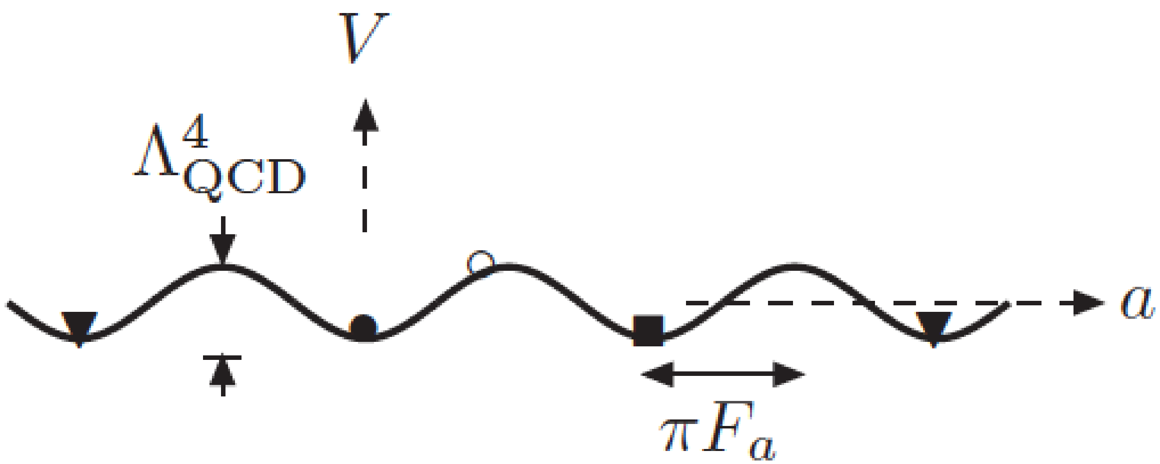
The PQ axion feels the QCD vacuum via the interaction $$\frac{a}{f_a}G\tilde{G}$$

The angle of misalignment is

$$\theta = \frac{a(x)}{f_a}$$

The mass is sizeable

$$10^{-3} - 10^{-4} eV$$



If this misalignment was caused by electroweak instantons, the axion mass would be much smaller. There could be a very slow rolling of the misplaced field (angle) towards the minimum of the potential.

The field, in this case, could contribute to dark energy.

Oscillations occur only if the condition

$$m_a(T) = 3H(T)$$

is satisfied. This defines (implicitly) the oscillation temperature T_{osc}

The oscillation temperature for the QCD axion is about the QCd scale

The mass induced by the electroweak instanton potential can be of the order

$$m_a^2 \sim \Lambda_{ew}^2 e^{-2\pi/\alpha_w(v)}$$

Where the instanton suppression pushes it towards tiny values

$$e^{-2\pi/\alpha_w(v)} \sim e^{-198}$$

In other words, if we had an axion sensitive both to the electroweak vacuum and to the QCD vacuum, then we could have a sequential misalignment

Clearly, the dominant contribution would come from the QCD phase transition, since the misalignment is far more sizeable.

Concerning the EW transition, the misalignment, in general, gives a misplaced but FROZEN angle.

The gauging of an anomalous symmetry generates an axion charged both under SU(2) and SU(3). The charges are fixed by the condition of Gauge invariance of the effective action, in which the anomalous variation Is cancelled by the Wess-Zumino (Peccei-Quinn) counterterms

For single U(1) models there is no way to remove the QCD charge of the axion, nut it may be possible in models with several U(1)'s.
If so, the axion gives a contribution to dark energy.

The gauging of an anomalous symmetry takes us very far away From the PQ picture, although its main features remain valid.

The pattern gets much more complicated and it will take some time before that we can draw a more complete picture of what is really going on at a phenomenological level.

But there is a lot to learn even from the most simplified models that one can costruct "bottom up", neglecting, at first sight, some formal details.

The models:
MLSOM (non supersymmetric) and **USSM-A** (supersymmetric)

MLSOM----> **a gauged axion generated at the electroweak phase transition**

USSM-A----> a saxion and a gauged axion.

Gauging of the axion symmetry: gauge anomalies

SU(3)xSU(2)xU(1)xU(1)

The simplest extension. The model is generated from special vacua of string theory.

1) **In general, these extensions involve fields which are deprived of a potential (moduli) and can be massive or massless.**

2) **They can be embedded into supergravity theories (gauged supergravities)**

Landscape of vacua of string theories is a landscape of supergravities

The basic string theories have a supergravity as field theory approximation

Also after the choice of a compact manifold one is left with an effective lower dimensional supergravity with number of supersymmetries determined by the Killing spinors of the compact manifold

Fluxes and non-perturbative effects lead to gauged supergravities

(see A Van Proeyen's lectures)

$(D=4)$ with fields of spin 2, 1, 0, 3/2, 1/2

$$e_\mu^a,\ A_\mu^I,\ \phi^u,\ \psi_\mu,\ \lambda^A$$

$$
\begin{aligned}
e^{-1}\mathcal{L} \;=\; & \tfrac{1}{2}R \\
& +\tfrac{1}{4}(\mathrm{Im}\,\mathcal{N}_{IJ})\mathcal{F}^{I}_{\mu\nu}\mathcal{F}^{\mu\nu J} - \tfrac{1}{8}(\mathrm{Re}\,\mathcal{N}_{IJ})\varepsilon^{\mu\nu\rho\sigma}\mathcal{F}^{I}_{\mu\nu}\mathcal{F}^{J}_{\rho\sigma} \\
& -\tfrac{1}{2}g_{uv}D_\mu\phi^u D^\mu\phi^v - V \\
& \left\{-\bar{\psi}_{\mu i}\gamma^{\mu\nu\rho}D_\nu\psi_\rho{}^i - \tfrac{1}{2}g_A{}^B\bar{\lambda}^A \not{D}\lambda_B + \text{h.c.}\right\} + \ldots
\end{aligned}
$$

It is expected that these theories have a unitarity bound, although this is Essentially related to the Planck scale.

Abelian extensions from intersecting branes provide another realization

$$U(N_1) \times U(N_2) \times \ldots \times U(N_k) = SU(N_1) \times U(1) \times SU(N_2) \times U(1) \times \ldots \times SU(N_k) \times U(1)$$

(o) The extra U(1)'s can be organized in terms of a U(1) of hypercharge times some extra U(1)'s which are anomaly free.

(oo) Several anomalous U(1)'s

(ooo) Just one physical axion

The physical axion emerges only AFTER electroweak symmetry breaking
Due to the appearance of an "extra potential" in the CP odd sector

The anomalous U(1)'s are in a "broken" form (Stuckelberg symmetry)

$$\mathcal{L}_{St} = \frac{1}{2}(\partial_\mu b - M_1 B_\mu)^2 + \frac{1}{2}(\partial_\mu c - M_2 C_\mu)^2 \,,$$

$$\delta_B B_\mu = \partial_\mu \theta_B \qquad \delta b = M_1 \theta_B$$

$$\delta_C C_\mu = \partial_\mu \theta_C \qquad \delta c = M_2 \theta_C,$$

Stuckelberg symmetries are "dual" descriptions of "A-F" theories (using a 2-form A coupled to a gauge field B)

$$\mathcal{L} \;=\; -\frac{1}{12}H^{\mu\nu\rho}H_{\mu\nu\rho} - \frac{1}{4g^2}F^{\mu\nu}F_{\mu\nu} + \frac{M}{4}\;\epsilon^{\mu\nu\rho\sigma}A_{\mu\nu}\;F_{\rho\sigma},$$

$$H_{\mu\nu\rho} = \partial_\mu A_{\nu\rho} + \partial_\rho A_{\mu\nu} + \partial_\nu A_{\rho\mu}, \qquad F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$H = dA$ **(constraint imposed by a multiplier, b(x))**

$$\mathcal{L}_0 = -\frac{1}{12}H^{\mu\nu\rho}H_{\mu\nu\rho} - \frac{1}{4g^2}F^{\mu\nu}\;F_{\mu\nu} - \frac{M}{6}\;\epsilon^{\mu\nu\rho\sigma}H_{\mu\nu\rho}\;B_\sigma + \frac{1}{6}b(x)\,\epsilon^{\mu\nu\rho\sigma}\partial_\mu H_{\nu\rho\sigma}.$$

$$H^{\mu\nu\rho} = -\epsilon^{\mu\nu\rho\sigma}\left(M B_\sigma - \partial_\sigma b\right).$$

Stuckelberg action for a U(1)

$$\mathcal{L}_A \;=\; -\frac{1}{4g^2}\;F^{\mu\nu}\;F_{\mu\nu} - \frac{1}{2}\left(M B_\sigma - \partial_\sigma b\right)^2$$

There is no potential for b(x). This sets a difference wrt the PQ axion.

U(1)xU(1) Model

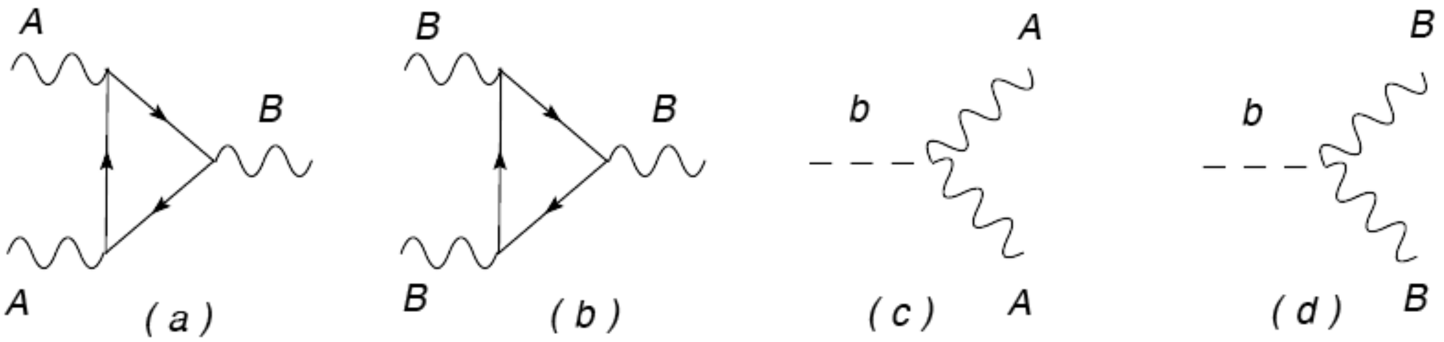
$$\mathcal{L}_0 = -\frac{1}{4}F_A^2 - \frac{1}{4}F_B^2 + \frac{1}{2}(\partial_\mu b + M_1 \; B_\mu)^2 + \overline{\psi} i\gamma^\mu(\partial_\mu + ieA_\mu + ig_B\gamma^5 B_\mu)\psi,$$

$$b \to b - M_1\theta_B \qquad \delta B_\mu = \partial_\mu\theta_B$$

$$\mathcal{L}_{gf} = -\xi\left(\partial \cdot B + \frac{M_1}{2\xi}b\right)^2$$

In the $A - B$ model the WZ counterterms are

$$\mathcal{L}_{WZ} = \frac{C_{AA}}{2!M_1} bF_A \wedge F_A + \frac{C_{BB}}{2!M_1} bF_B \wedge F_B,$$



In general, in the presence of an underlying anomalous symmetry, the Stuckelberg action is modified by the presence of Wess-Zumino counterterms for the restoration of gauge invariance.

There are some important differences between the PQ axion and a gauged axion.

1) In the PQ case the axion is a Nambu-Goldstone mode (of a global symmetry). As such cannot be gauged away. It remains as such until the QCD transition when it acquires its mass by an instanton potential.
2) A gauged axion is not a physical degree of freedom before the electroweak phase transition, when it becomes physical due to a phase-dependent potential

Possible phases

(o) The Stuckelberg phase. The Stuckelberg is a NG boson
(oo) After electroweak symmetry breaking from “b” we can extract a physical component that we call “the gauged axion”

Incorporating anomalous symmetries in a simple extension of the Standard Model

f	Q	u_R	d_R	L	e_R
q^B	q^B_Q	$q^B_{u_R}$	$q^B_{d_R}$	q^B_L	$q^B_{e_R}$

f	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
Q	3	2	1/6	q^B_Q
u_R	3	1	2/3	$q^B_Q + q^B_u$
d_R	3	1	−1/3	$q^B_Q - q^B_d$
L	1	2	−1/2	q^B_L
e_R	1	1	−1	$q^B_L - q^B_d$
H_u	1	2	1/2	q^B_u
H_d	1	2	1/2	q^B_d

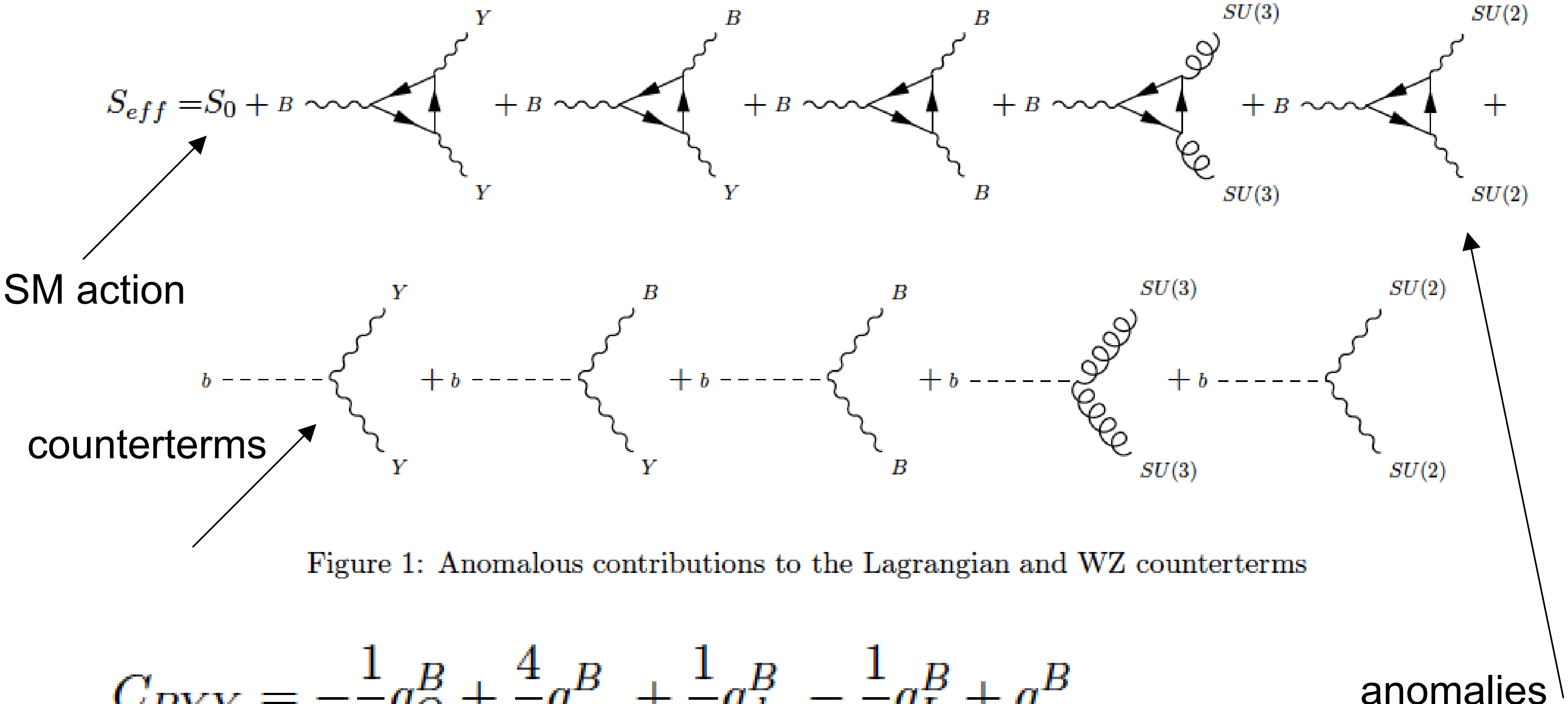


Figure 1: Anomalous contributions to the Lagrangian and WZ counterterms

$$C_{BYY} = -\frac{1}{6}q_Q^B + \frac{4}{3}q_{u_R}^B + \frac{1}{3}q_{d_R}^B - \frac{1}{2}q_L^B + q_{e_R}^B,$$

$$C_{YBB} = -(q_Q^B)^2 + 2(q_{u_r}^B)^2 - (q_{d_R}^B)^2 + (q_L^B)^2 - (q_{e_R}^B)^2,$$

$$C_{BBB} = -6(q_Q^B)^3 + 3(q_{u_R}^B)^3 + 3(q_{d_R}^B)^3 - 2(q_L^B)^3 + (q_{e_R}^B)^3,$$

$$C_{Bgg} = \frac{1}{2}(-2q_Q^B + q_{d_R}^B + q_{u_R}^B),$$

$$C_{BWW} = \frac{1}{2}(-q_L^B - 3q_Q^B).$$

YUKAWA COUPLING (gauge invariance)

$$q_Q^B - q_d^B - q_{d_R}^B = 0 \qquad q_Q^B + q_u^B - q_{u_R}^B = 0 \qquad q_L^B - q_d^B - q_{e_R}^B = 0.$$

SOLUTIONS in terms of FREE CHARGES

$$C_{BYY} = \frac{1}{6}(3q_L^B + 9q_Q^B + 8\Delta q^B),$$

$$C_{YBB} = 2\left[q_d^B(q_L^B + 3q_Q^B) + 2\Delta q^B(q_d^B + q_Q^B) + (\Delta q^B)^2\right],$$

$$C_{BBB} = (q_L^B - q_d^B)^3 + 3(q_d^B + q_Q^B + \Delta q^B)^3 + 3(q_Q^B - q_d^B)^3 - 2(q_L^B)^3 - 6(q_Q^B)^3,$$

$$C_{Bgg} = \frac{\Delta q^B}{2},$$

$$C_{BWW} = \frac{1}{2}(-q_L^B - 3q_Q^B).$$

The two Higgses can't have the Same charge otherwise The Stuckelberg is just a Goldstone

The electroweak potential for massless fields

$$V = V_{PQ}(H_u, H_d) + V_{\not{P}\not{Q}}(H_u, H_d, b).$$

$$\begin{aligned} V_{PQ} &= \mu_u^2 H_u^\dagger H_u + \mu_d^2 H_d^\dagger H_d + \lambda_{uu}(H_u^\dagger H_u)^2 + \lambda_{dd}(H_d^\dagger H_d)^2 \\ &\quad - 2\lambda_{ud}(H_u^\dagger H_u)(H_d^\dagger H_d) + 2\lambda'_{ud}|H_u^T \tau_2 H_d|^2 \end{aligned}$$

V' extra potential

$$\begin{aligned} V_{\not{P}\not{Q}} &= \lambda_0 (H_u^\dagger H_d e^{-ig_B(q_u - q_d)\frac{b}{2M}}) + \lambda_1 (H_u^\dagger H_d e^{-ig_B(q_u - q_d)\frac{b}{2M}})^2 \\ &\quad + \lambda_2 (H_u^\dagger H_u)(H_u^\dagger H_d e^{-ig_B(q_u - q_d)\frac{b}{2M}}) + \\ &\quad \lambda_3 (H_d^\dagger H_d)(H_u^\dagger H_d e^{-ig_B(q_u - q_d)\frac{b}{2M}}) + \text{h.c.}, \end{aligned}$$

We assume that V' is generated at the electroweak scale and generates Higgs-axion mixing

$$H_u = \left(\begin{array}{c} H_u^+ \\ v_u + H_u^0 \end{array} \right) \qquad H_d = \left(\begin{array}{c} H_d^+ \\ v_d + H_d^0 \end{array} \right).$$

The CP- odd sector induces a mixing between the Higgs phases and the Stuckelberg b

$$\begin{pmatrix} G_0^1 \\ G_0^2 \\ \chi \end{pmatrix} = O^\chi \begin{pmatrix} \mathrm{Im} H_d^0 \\ \mathrm{Im} H_u^0 \\ b \end{pmatrix},$$

$$b = O_{13}^\chi G_0^1 + O_{23}^\chi G_0^2 + O_{33}^\chi \chi,$$

$$g_{\chi\gamma\gamma} \chi F_\gamma \tilde{F}_\gamma \qquad g_{\gamma\gamma}^\chi = \left(F O_{W_3\gamma}^A O_{W_3\gamma}^A + C_{YY} O_{Y_\gamma}^A O_{Y_\gamma}^A \right) O_{33}^\chi.$$

$$g^{\chi}_{\gamma\gamma} = \frac{g_B g_Y^2 g_2^2}{32\pi^2 M g^2} O^{\chi}_{33} \sum_f \left(-q^B_{f\,L} + q^B_{f\,R} \left(q^Y_{f\,R}\right)^2 - q^B_{f\,L} \left(q^Y_{f\,L}\right)^2 \right).$$

v/M

Notice that this expression is cubic in the gauge coupling constants, since factors such as g_2/g and g_Y/g are mixing angles while the factor $1/\pi^2$ originates from the anomaly. Therefore one obtains a general behaviour for $g^{\chi}_{\gamma\gamma}$ of $O(g^3 v/M^2)$, with charges which are, in general, of order unity.

$$H_u^0 = \frac{1}{\sqrt{2}} \left(\sqrt{2} v_u + \rho_u^0(x) \right) e^{i \frac{F_u^0(x)}{\sqrt{2} v_u}} \qquad H_d^0 = \frac{1}{\sqrt{2}} \left(\sqrt{2} v_d + \rho_d^0(x) \right) e^{i \frac{F_d^0(x)}{\sqrt{2} v_d}}$$

$$\theta(x) \equiv \frac{g_B(q_d - q_u)}{2M} b(x) - \frac{1}{\sqrt{2} v_u} F_u^0(x) + \frac{1}{\sqrt{2} v_d} F_d^0(x),$$

Theta is a combination of Higgs phases and of the Stuckelberg

Angle of misalignment generated at the electroweak scale

$$\theta(x) \equiv \frac{\chi(x)}{\sigma_\chi},$$

The role of f_a is now taken by a new variable

$$\sigma_\chi \equiv \frac{2v_u v_d M}{\sqrt{g_B^2(q_d - q_u)^2 v_d^2 v_u^2 + 2M^2(v_d^2 + v_u^2)}}.$$

$$\sigma_\chi \sim v$$

$$V' = 4v_u v_d \left(\lambda_2 v_d^2 + \lambda_3 v_u^2 + \lambda_0\right) \cos\left(\frac{\chi}{\sigma_\chi}\right) + 2\lambda_1 v_u^2 v_d^2 \cos\left(2\frac{\chi}{\sigma_\chi}\right),$$

$$m_\chi^2 = \frac{2v_u v_d}{\sigma_\chi^2}\left(\bar{\lambda}_0 v^2 + \lambda_2 v_d^2 + \lambda_3 v_u^2 + 4\lambda_1 v_u v_d\right) \approx \lambda v^2.$$

The axion mass is parameterically small since lambda is exponentially Suppressed.

$$\lambda \sim e^{-2\pi/\alpha_w(v)}$$

$$\frac{b}{M} F \wedge F \rightarrow \frac{\chi}{\frac{M^2}{v}} F \wedge F$$

Misalignment $\frac{\chi}{v}$

In the PQ case $\frac{a}{f_a} F \wedge F$ $\theta = \frac{a}{f_a}$

$$M \sim 10^7$$

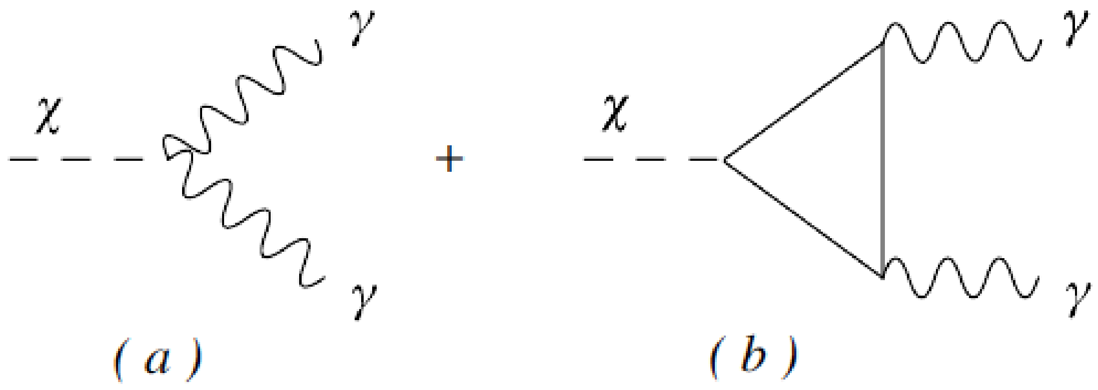
At the QCD transition the instanton potential generates a misalignment

$$\frac{\chi}{M^2/v}$$

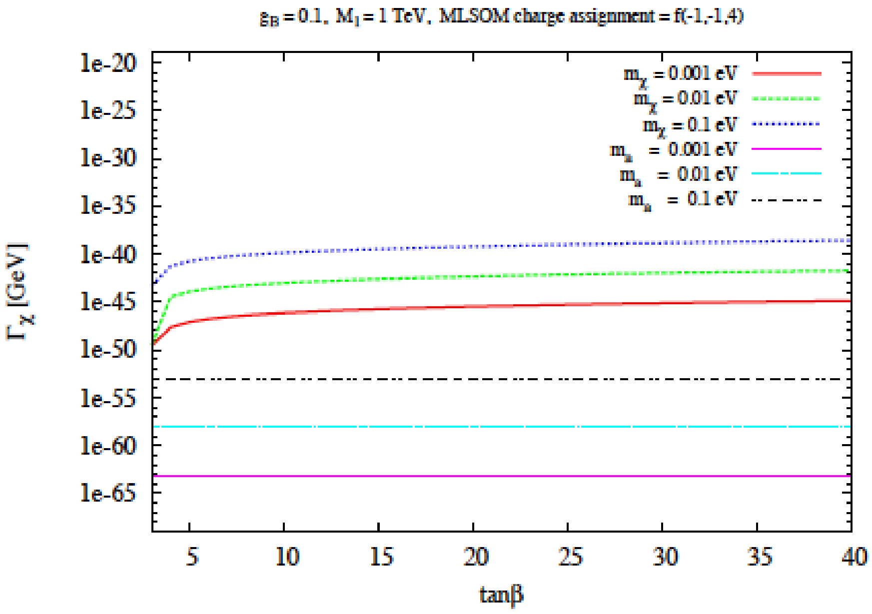
The relic densities of a gauged axion depend critically on the size of this scale

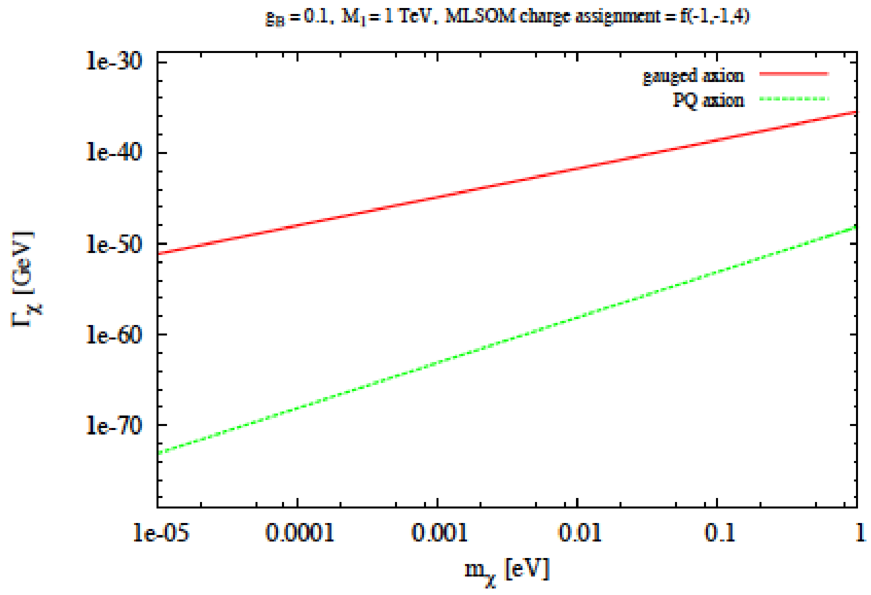
$$M^2/v$$

A Stuckelberg mass $M \sim 10^7$ GeV Is sufficient to give sizeable relic densities



Contact and loop contribution to the decay of the axion





The decay rate of the gauged axion are rather small and as such it can actually be dark matter.

Relic densities at the electroweak scale are negligible

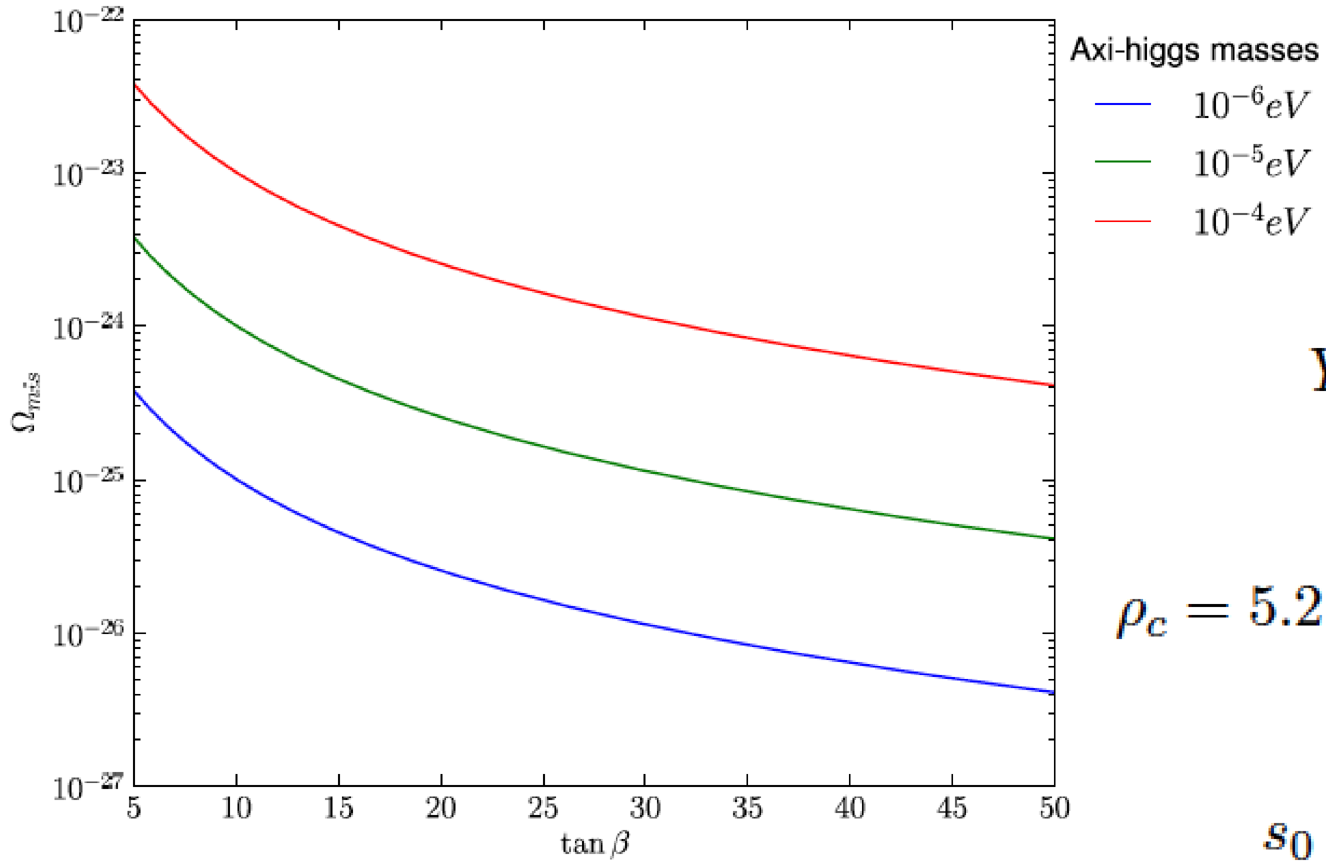


Fig ısity of the axi-Higgs as a function of v_u

$$Y_\chi(T_i) \equiv \left.\frac{n_\chi}{s}\right|_{T_i}$$

$$\rho_c = 5.2 \cdot 10^{-6}\mathrm{GeV/cm}^3$$

$$s_0 = 2970\ \mathrm{cm}^{-3}$$

$$\Omega_\chi^{mis} = \left.\frac{n_\chi}{s}\right|_{T_i} m_\chi \frac{s_0}{\rho_c}.$$

$$Y_\chi(T_i) = \frac{45\sigma_\chi^2\theta_i^2}{2\sqrt{5\pi g_{*,T_i}}T_i M_P},$$

At the QCD phase transition

$$g_{*,1GeV} = 61.75.$$

$$Y_\chi(T_i) = \frac{45\left(M^2/v\right)^2\left(\theta'(T_i)\right)^2}{2\sqrt{5\pi g_{*,T}}T_i M_P},$$

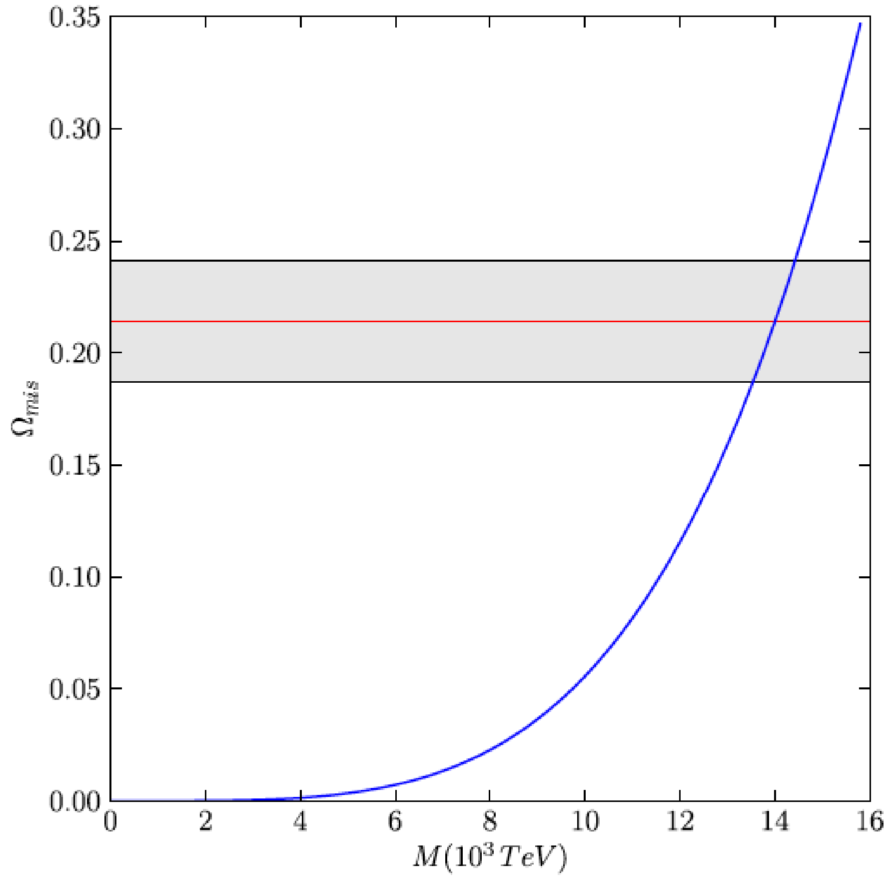
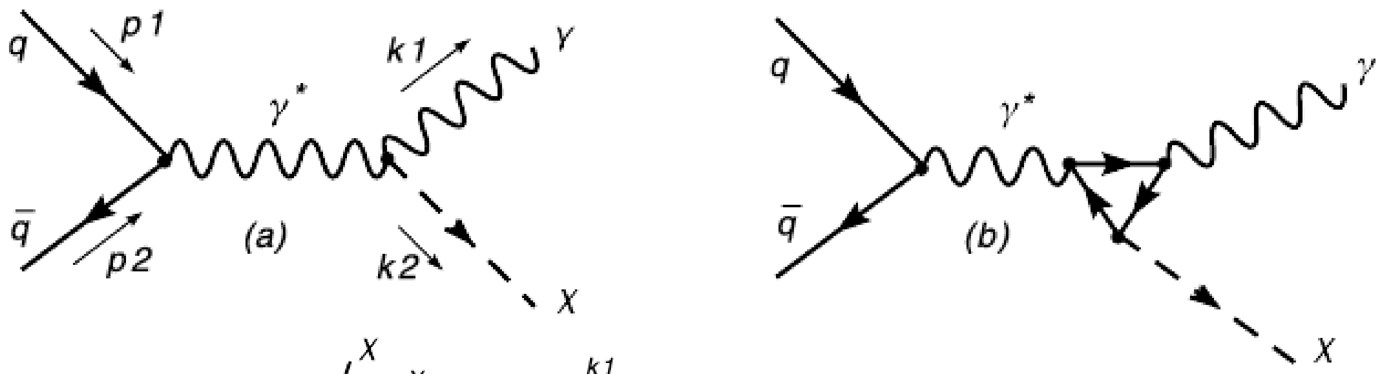


Figure 5: Relic density of the axi-Higgs as a function of M. The grey bar represents the measured value of $\Omega_{DM} = 0.214 \pm 0.027$



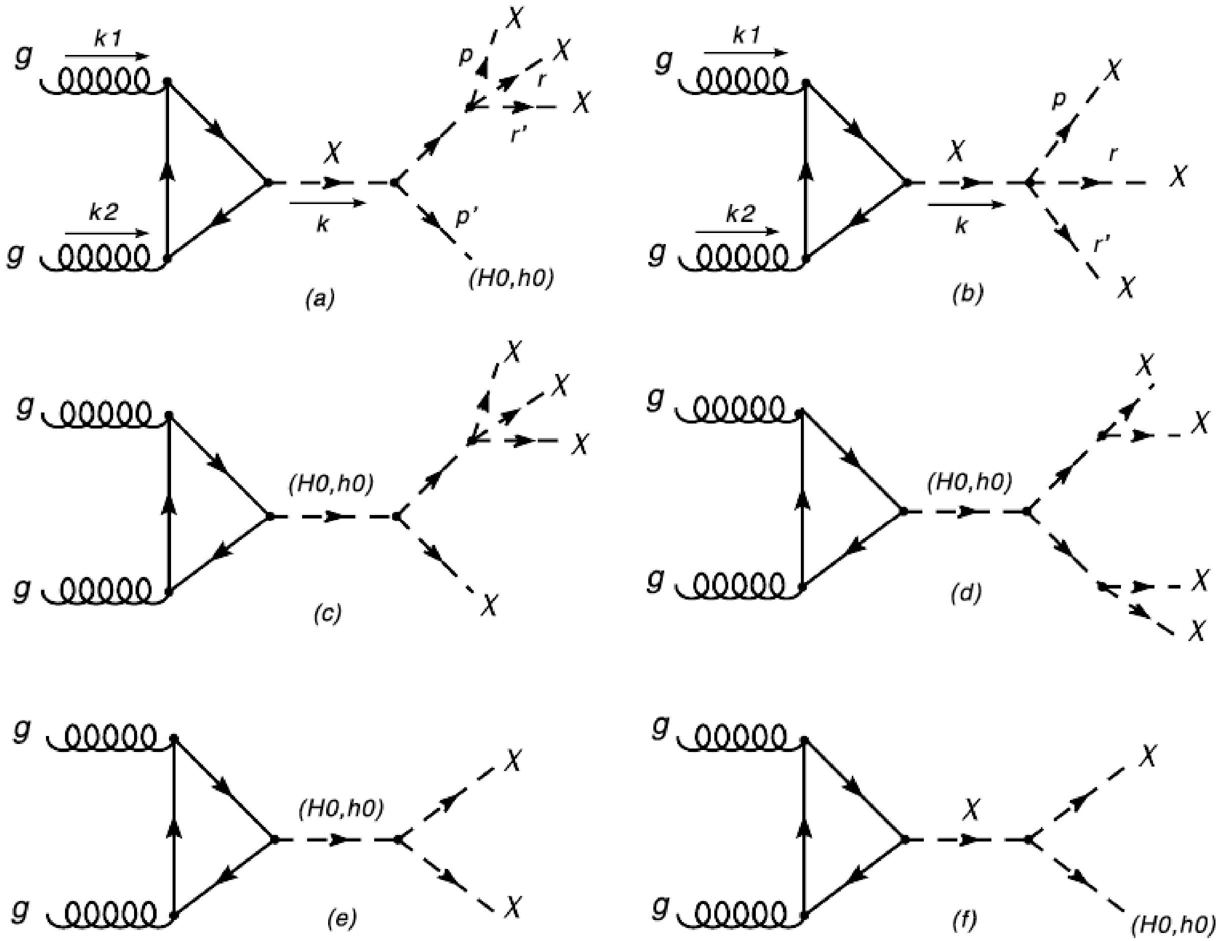
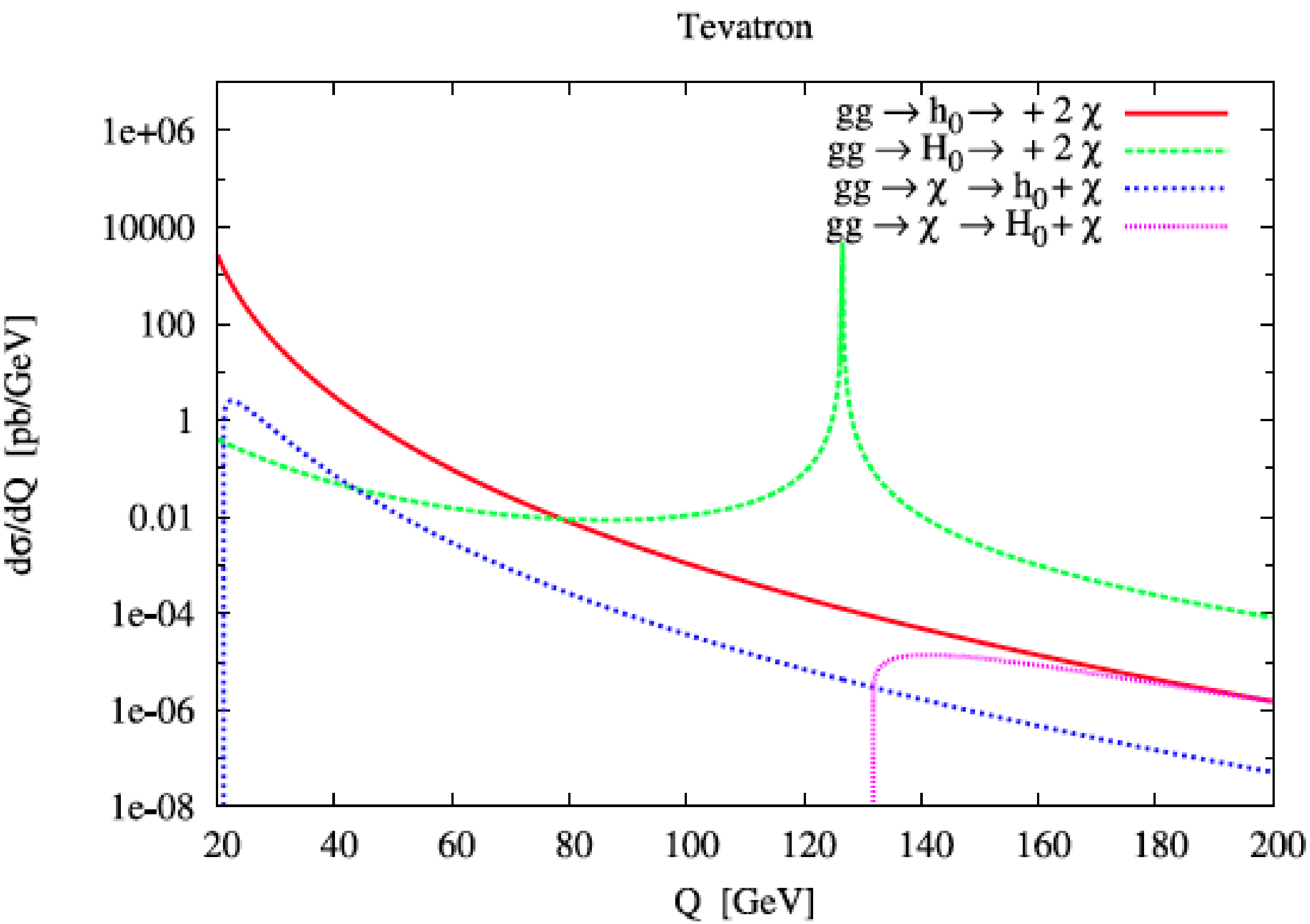


Fig. 12. Channels for multi axion production from gluon–gluon fusion.

Multiple Chi production



Tevatron
gg → h_0 → + 2 χ
gg → H_0 → + 2 χ
gg → χ → h_0 + χ
gg → χ → H_0 + χ
dσ/dQ [pb/GeV]
1e+06
10000
100
1
0.01
1e-04
1e-06
1e-08
20
40
60
80
100
120
140
160
180
200
Q [GeV]

Conclusions

Gauged Axions may come from completely different routes into
Current phenomenology.
They can be very light but also be Higgs-like.
In the first case, clearly, they are connected to “completion theories” (gauged supergravities, orientifold vacua etc..) and play an important role in cosmology.

In the second case, they are “generated” by a mechanism of “partial decoupling of a chiral fermion.