Dark Matter Candidates in a Heavy QCD Axion Model

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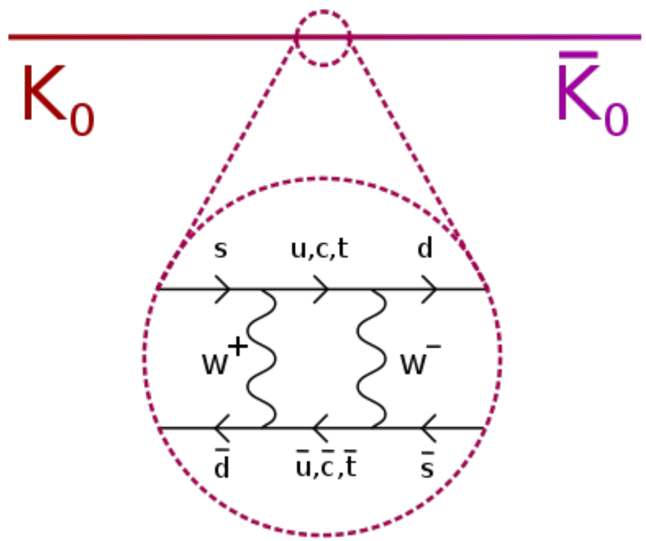
Strong CP problem

Experimentally, ***QCD*** is known to preserve ***CP*** symmetry very well.

- Hadron spectrum respects ***CP*** symmetry very well.

- ***CP*** violating transitions in the SM are caused by ***CP*** violation in the weak interaction (i.e. by the CKM phase).



Picture from : https://en.wikipedia.org/wiki/Kaon

Strong CP problem

This feature is not automatically guaranteed in ***QCD*** .

- ***QCD*** has its own ***CP***-violating parameter : ***θ***

$$S_{\rm QCD} = \int d^4x \left(-\frac{1}{4g^2} F^a_{\mu\nu} F^{a\mu\nu} + \boxed{\frac{i\theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}} + \sum_{i=1}^{N_f} \bar{q}_i (D - M) q_i \right)$$

- ***θ*** - term violates the ***P*** and ***CP*** symmetries

$$\int d^4x F_{\mu\nu}\tilde{F}^{\mu\nu} \to -\int d^4x F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- The ***θ*** - term is highly constrained experimentally!

d_n (neutron EDM) / m_n (neutron MDM) = O(θ)

[see e.g. '80 Shifman, Vainshtein, Zakharov]

Null observation of the ***neutron EDM*** :

d_n < 2.9 x 10^{-26} e cm @ 90%CL [hep-ex/0602020]

→ θ < 10^{-11}

Why so small ? = Strong CP Problem

Peccei-Quinn Mechanism ['77 Peccei, Quinn]

Two Higgs doublet Model (***H_u , H_d***)

$$\mathcal{L} = y_u H_u Q_L \bar{u}_R + y_d H_d Q_L \bar{d}_R - m_{H_u}^2 |H_u|^2 - m_{H_d}^2 |H_u|^2 - \cdots$$

U(1) Peccei-Quinn symmetry (anomaly of ***$SU(3)_c$***)

$$H_{u,d} \to e^{i\alpha} H_{u,d} \qquad u_R \to e^{-i\alpha} u_R \qquad d_R \to e^{-i\alpha} d_R$$

By the Peccei-Quinn rotation, ***θ*** can be shifted away !

$$\theta \to \theta' = \theta - 2N_g \alpha \qquad (N_g = 3)$$

so that the ***θ*** is unphysical !

Weinberg-Wilczek Axion ['78 Weinberg, '78 Wilczek]

U(1)$_{PQ}$ is spontaneously broken at the EWSB → axion

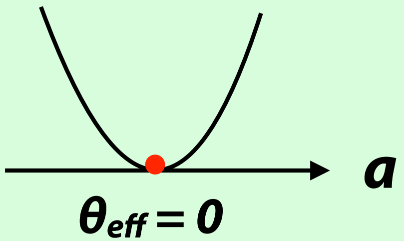
$$a = \frac{\sqrt{2} v_u v_d}{\sqrt{v_u^2 + v_d^2}} (\arg H_u + \arg H_d)$$

$$\mathcal{L}_{\text{eff}} = \frac{g_s^2}{32\pi^2} \left(\theta - \frac{6a}{f_a} \right) G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \qquad \left(f_a = 2\sqrt{2} v_u v_d / \sqrt{v_u^2 + v_d^2} \right)$$

Axion is massive due to the ***SU(3)$_c$*** anomalous breaking

$$m_a = \frac{N_g \sqrt{m_u m_d}}{m_u + m_d} \frac{f_\pi}{f_a} m_\pi \quad \sim \textbf{\textit{100 keV}}$$

In terms of the axion, the PQ mechanism can be interpreted as a dynamical tuning of the ***θ*** angle.

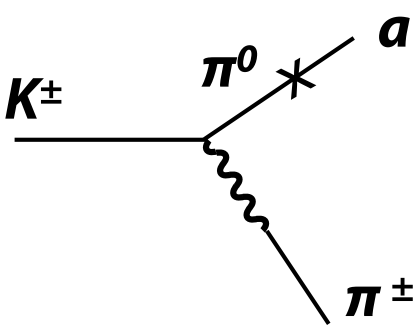


$$\mathcal{L} = \frac{1}{2} m_a^2 f_a^2 (a/f_a - \theta/6)^2 \longrightarrow \langle a/f_a \rangle = \theta/6$$

$$\theta_{\text{eff}} = \theta - 6 \langle a/f_a \rangle = 0$$

Weinberg-Wilczek Axion

$\boldsymbol{f_a}$ is constrained by meson decay into axion.



$$Br(K^\pm \to \pi^\pm + a\,(\text{invisible}))$$
$$= O(f_\pi^2/f_a^2) \times Br(K^\pm \to \pi^\pm + \pi^0)$$
$$< 5 \times 10^{-11}$$ [E787 hep-ex/0403034]

$$f_a > O(10)\,\text{TeV}$$

[Axion decays into two photon but the lifetime is so long for $m_a \sim 100$ keV.]

Original PQ-mechanism has been excluded !

Invisible Axion : $f_a >> v_{EW}$

['79 Kim, '80 Shifman, Vainshtein, Zakharov]

KSVZ axion : SM matter field are not $U(1)_{PQ}$ neutral.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + S q_L \bar{q}_R - \cdots$$

Singlet S Extra colored fermions q_L , q_R

$U(1)$ Peccei-Quinn symmetry ($SU(3)_c$ anomaly)

$S \to e^{ia} S$ $q_{L,R} \to e^{-ia/2} q_{L,R}$

$U(1)_{PQ}$ is spontaneously broken by $\langle S \rangle = v_s >> v_{EW}$

$$a = f_a \arg S \qquad f_a = \sqrt{2}\langle S \rangle$$

The axion coupling to the SM is suppressed by a large f_a .

The axion evades constraints from the meson decay rates!

Invisible Axion : $f_a >> v_{EW}$

Invisible axion is very light :

$$\boxed{m_a = \mathcal{O}(1)\mathrm{meV} \times \left(\frac{10^9\mathrm{GeV}}{f_a}\right)}$$

→ axion is subject to constraints from astrophysics !

Resultant constraint on the decay constant is

$f_a > 10^{8\text{-}9}$ GeV (KSVZ)

by Supernova explosion.

J.R. Ellis, K.A. Olive, Phys. Lett. B 193, 525 (1987).

R.Mayle, J.R.Wilson, J.R.Ellis, K.A.Olive, D.N.Schramm and G.Steigman, Phys. Lett.B203, 188 (1988).

Successful PQ mechanisms = Invisible Axion ?

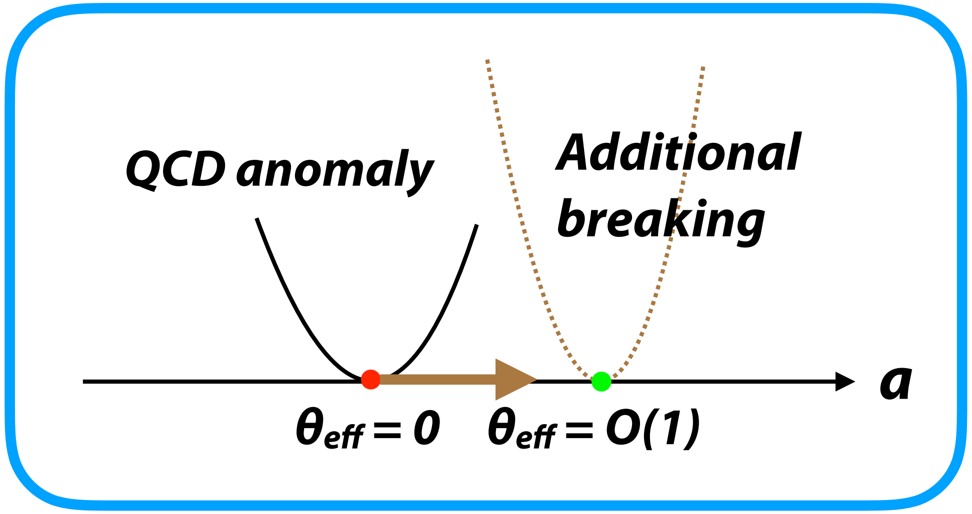
Heavy Axion : $m_a >> m_a^{PQWW}$? [15' Fukuda, Harigaya, Yanagida and MI]

Why is the axion so light?

$U(1)_{PQ}$ is explicitly broken only by the ***QCD*** anomaly.

We can make the axion ***HEAVY*** by adding other $U(1)_{PQ}$ breaking terms.

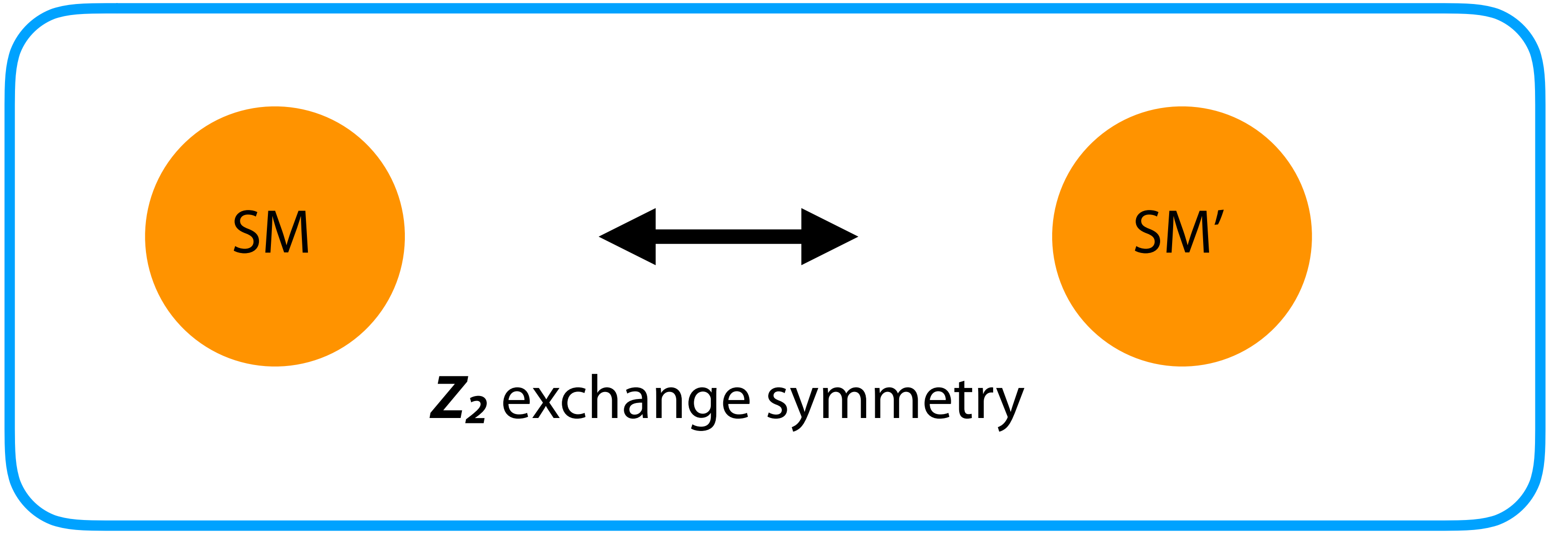
→ However, such additional breaking leads to a too large θ_{eff}!



Is there any way to make axion heavy while keeping $\theta_{eff} = 0$?

Heavy Axion : $m_a \gg m_a^{PQWW}$? [15' Fukuda, Harigaya, Yanagida and MI]

Use ***QCD*** in a mirror copied Standard Model ! ['97 Rubakov]



By the $\boldsymbol{Z_2}$ exchange symmetry, gauge couplings, etc are equal in these two sectors at high energy scale.

In particular $\boldsymbol{\theta_{SM} = \theta_{SM'}}$.

If the axion couples to both two sectors, axion settles at $\boldsymbol{\theta_{eff} = \theta_{eff'} = 0}$ ***!***

$$\mathcal{L} = \frac{1}{2} m_a^2{}_{QCD} f_a^2 (a/f_a - \theta_{\rm SM})^2 + \frac{1}{2} m_a^2{}_{QCD'} f_a^2 (a/f_a - \theta_{\rm SM})^2$$

Heavy Axion : $m_a >> m_a^{PQWW}$? [15' Fukuda, Harigaya, Yanagida and MI]

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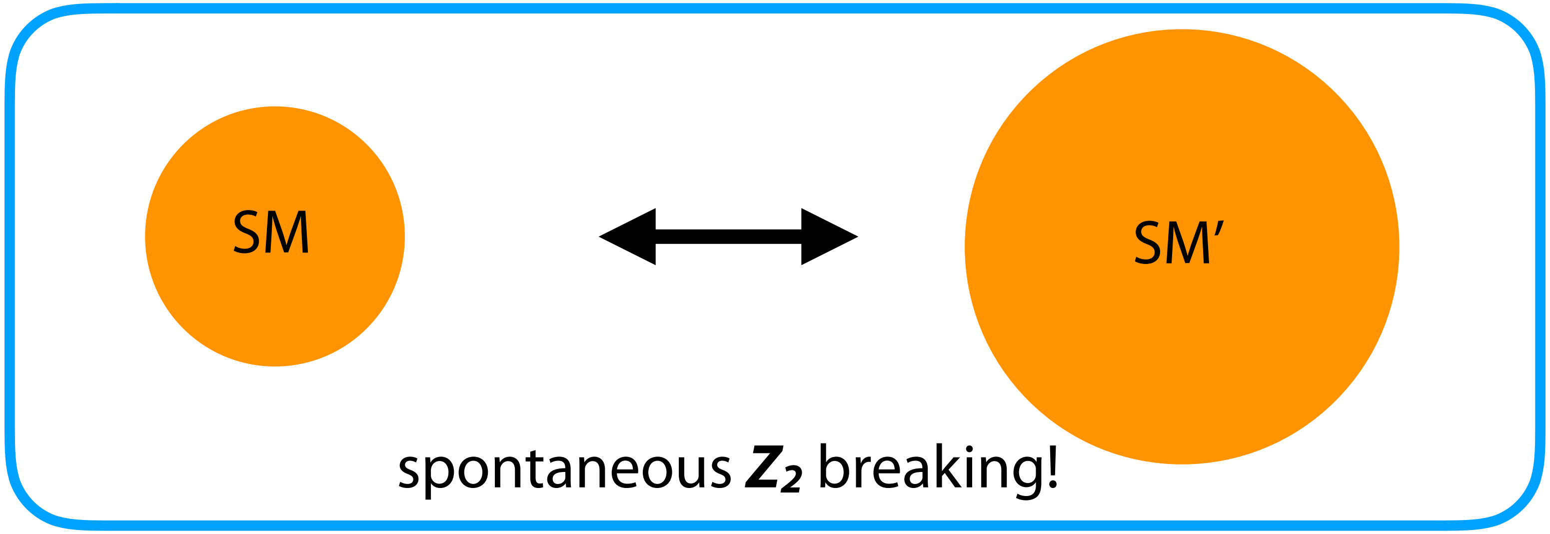


If Z_2 is spontaneously broken at intermediate scale, the mass scales in the SM' can be larger !

$$\mathcal{L} = \frac{1}{2} m_{a\,QCD}^2 f_a^2 (a/f_a - \theta_{\rm SM})^2 + \frac{1}{2} m_{a\,QCD'}^2 f_a^2 (a/f_a - \theta_{\rm SM})^2$$

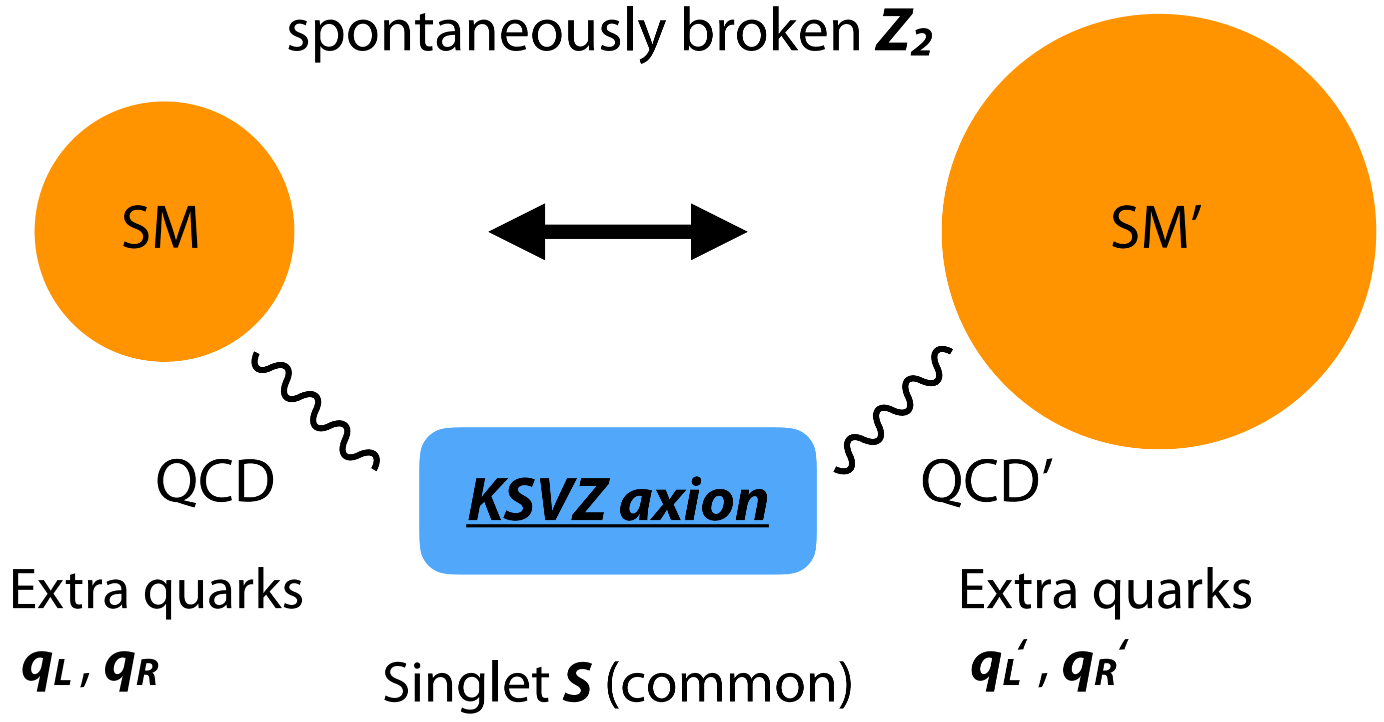
→ $m_{aQCD'} >> m_{aQCD}$ while the axion still settles at $\theta_{eff} = \theta_{eff'} = 0$ **!**

We can make the axion heavy while not spoiling the PQ-mechanism !

['01 Berechiani, Gianfagna, Giannotti, '14 Hook, '16 Albaid, Dine, Draper]

For different approaches to make the axion heavy : ['16 Gherghetta, Nagata, Shifman]

Heavy Axion : $m_a >> m_a^{PQWW}$? [15' Fukuda, Harigaya, Yanagida and MI]



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SM'} + gS(q_L\bar{q}_R + q'_L\bar{q}'_R) - \cdots$$

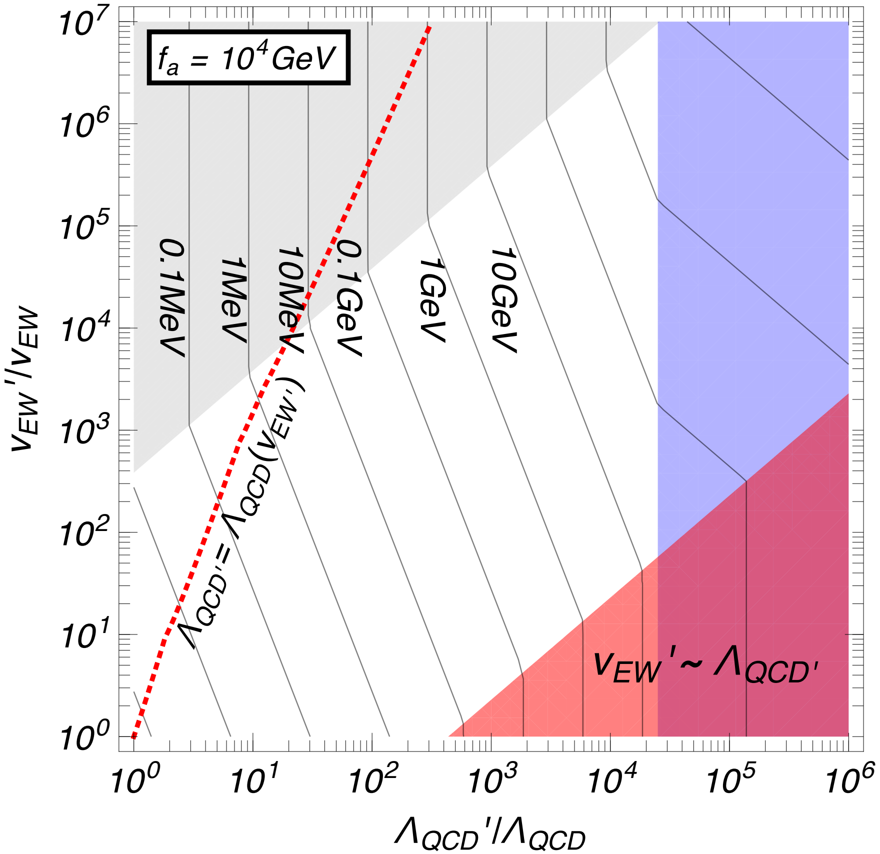
Two sectors share a single KSVZ axion.

Heavy Axion : $m_a >> m_a^{PQWW}$?

[15' Fukuda, Harigaya, Yanagida and MI]

✔ Axion mass is dominated by the QCD' anomaly effect

$$m_a \simeq \frac{\sqrt{z'}}{1+z'} \frac{f_{\pi'} m_{\pi'}}{f_a} \qquad z' \simeq 0.56$$



$$m'_f \simeq m_f \times \frac{v'_{EW}}{v_{EW}}$$

$$f'_\pi \simeq f_\pi \times \frac{\Lambda'_{QCD}}{\Lambda_{QCD}}$$

$$m'^2_{\pi^0} \simeq m^2_{\pi^0} \times \frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}} \frac{v'_{EW}}{v_{EW}}$$

$m_{quark}' >> \Lambda_{QCD}'$

PQ breaking by Λ_{QCD}'

EW' breaking by Λ_{QCD}'

A heavy axion is achieved from TeV scale physics !

Heavy Axion : $m_a >> m_a^{PQWW}$? [15' Fukuda, Harigaya, Yanagida and MI]

- Axion coupling below the scale of **<*S*>**

$$\mathcal{L}_{\rm eff} \simeq \frac{1}{32\pi^2}\left(\frac{a}{f_a}+\theta_{\rm eff}\right)(G\tilde{G}+G'\tilde{G}') + \frac{6Q_Y^2}{32\pi^2}\frac{a}{f_a}(Y\tilde{Y}+Y'\tilde{Y}') \ ,$$

- The ***$U(1)_{EM}'$*** is not broken and ***γ'*** is massless.

- Stable particles in the mirrored sector :

$$\begin{cases} \gamma' \ , \ e' \ , \ \pi'^{\pm} \ , \ N' \ , \ (\text{for } m'_\nu > m'_{\pi^\pm}) \ , \\ \gamma' \ , \ e' \ , \ \nu' \ , \quad N' \ , \ (\text{for } m'_\nu < m'_{\pi^\pm}) \ . \end{cases}$$

- Axion main decay modes:

For ***$m_a < 3\, m_\pi$***: ***$a \to 2\gamma, 2\gamma'$ (10^{-7}s for m_a=100MeV, f_a=TeV)***

For ***$m_a > 3\, m_\pi$***: ***$a \to$ hadrons, $2\gamma, 2\gamma'$***

For ***$m_a >> 3\, m_\pi$***: ***$a \to$ QCD jets***

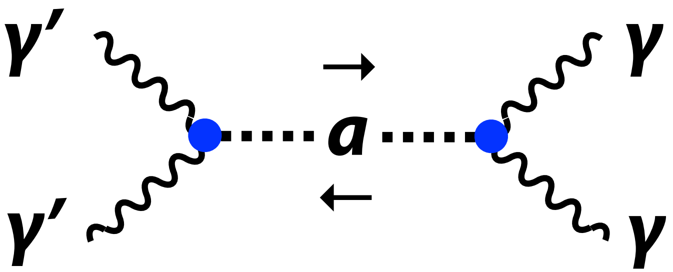
KFVZ axion has no decay modes into leptons at tree level .

Cosmological Constraints

Dark Radiation

In the minimal model, γ' in the copied sector is massless.

For $f_a = O(1)TeV$, γ' is in thermal equilibrium for $T > m_a$.



(on-shell axion exchange)

If, $m_a < T_{QCD}$, γ' decouples below T_{QCD} .

γ' contributes to N_{eff} by $8/7$.

$N_{eff}\,(SM) = 3.05$

$N_{eff} = 3.15 \pm 0.23$ (68%CL PLANCK 2015)

For $m_a \gg T_{QCD}$, γ' decouples above $T_{QCD} \sim O(100)MeV$

γ' contribution to N_{eff} is diluted by QCD phase transition.

$$\Delta N_{eff}\,(\gamma') = 8/7 \times (\, g(T_{QCD}) / g(m_a)\,)^{4/3} < 0.2$$

→ ***We take $m_a \gg T_{QCD}$***

Cosmological Constraints

✓ ***Neutrino' Abundance***

- ✓ In the Standard Model sector, we assume the ***seesaw mechanism*** as the origin of the neutrino mass.

- ✓ ***Seesaw mechanism*** is also good to explain the Baryon asymmetry via ***Leptogenesis***.

In the mirror sector, the neutrino masses get enhanced as the $v_{EW}' >> v_{EW}$ (say $v_{EW}' \sim 10^3 \times v_{EW}$)

$$m_{\nu'} = \frac{v_{EW'}^2}{v_{EW}^2} \times m_\nu$$

For $m_{\nu'} > O(100)\,\mathrm{keV}$, the ν' density exceeds the observed dark matter density!

Cosmological Constraints

✓ Neutrino' Abundance

✓ In the Standard Model sector, we assume the ***seesaw mechanism*** as the origin of the neutrino mass.

✓ ***Seesaw mechanism*** is also good to explain the Baryon asymmetry via ***Leptogenesis***.

We ``turn off" the seesaw' mechanism (by a trick of Z_2 breaking):

ν' in SM' are Dirac neutrinos: $m_{\nu'} = y_{\nu'} v_{EW'}$

In this case, ν' becomes heavy and they decay into π'

$$\nu' \to \pi' + e'$$

and hence, no contribution to the dark matter density !

✓ ***No Baryon' asymmetry in the SM' sector !***

It solves the over closure problem by the stable Baryon' dark matter.

Dark Matter Candidates

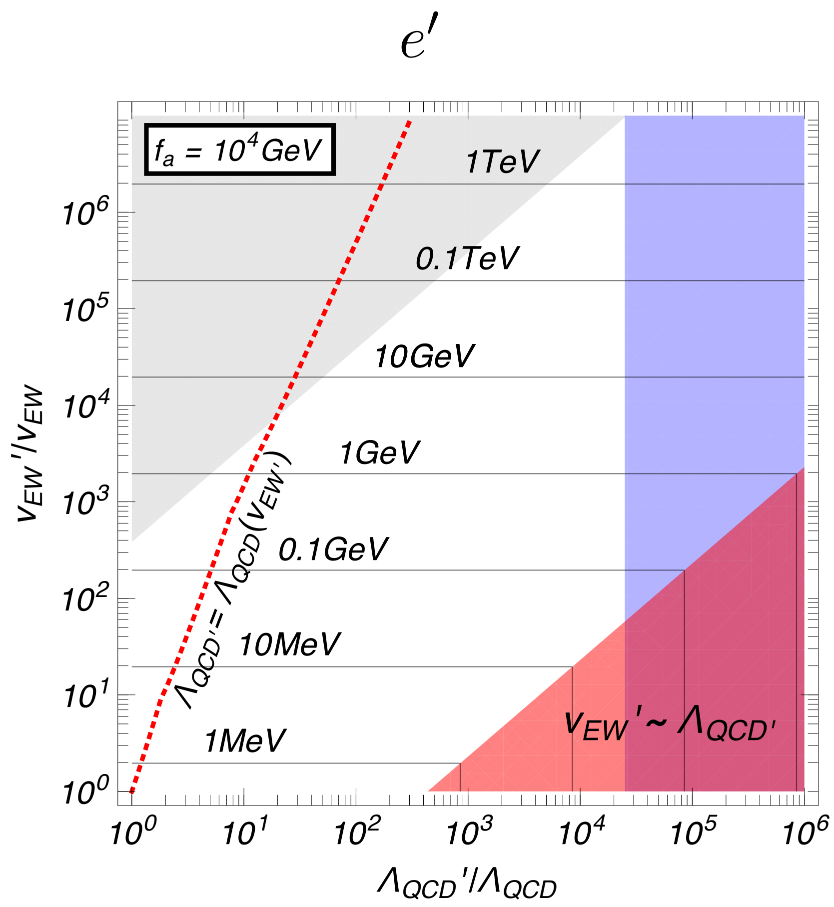
Axion is too heavy and too short lived to be a dark matter candidate…

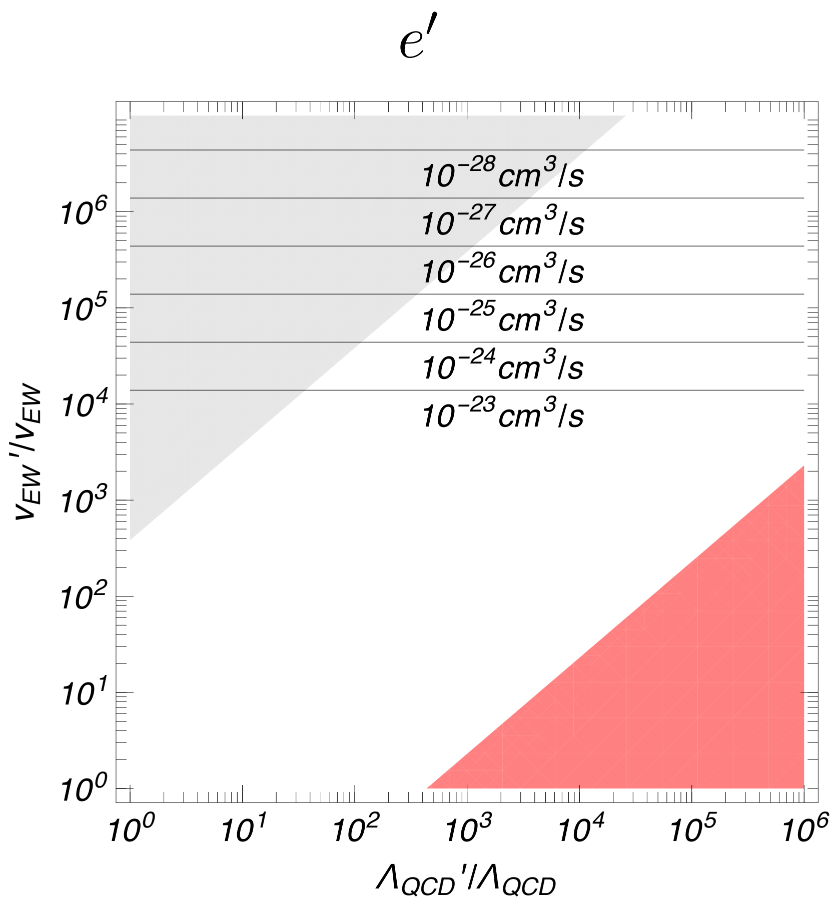
Still we have many stable particles in the mirrored sector !

$$\begin{cases} \gamma' \ , \ e' \ , \ \pi'^{\pm} \ , \ N' \ , \ (\text{for } m'_\nu > m'_{\pi^\pm}) \ , \\ \gamma' \ , \ e' \ , \ \nu' \ , \quad N' \ , \ (\text{for } m'_\nu < m'_{\pi^\pm}) \ . \end{cases}$$

Can they be dark matter candidates ?

Dark Matter Candidates





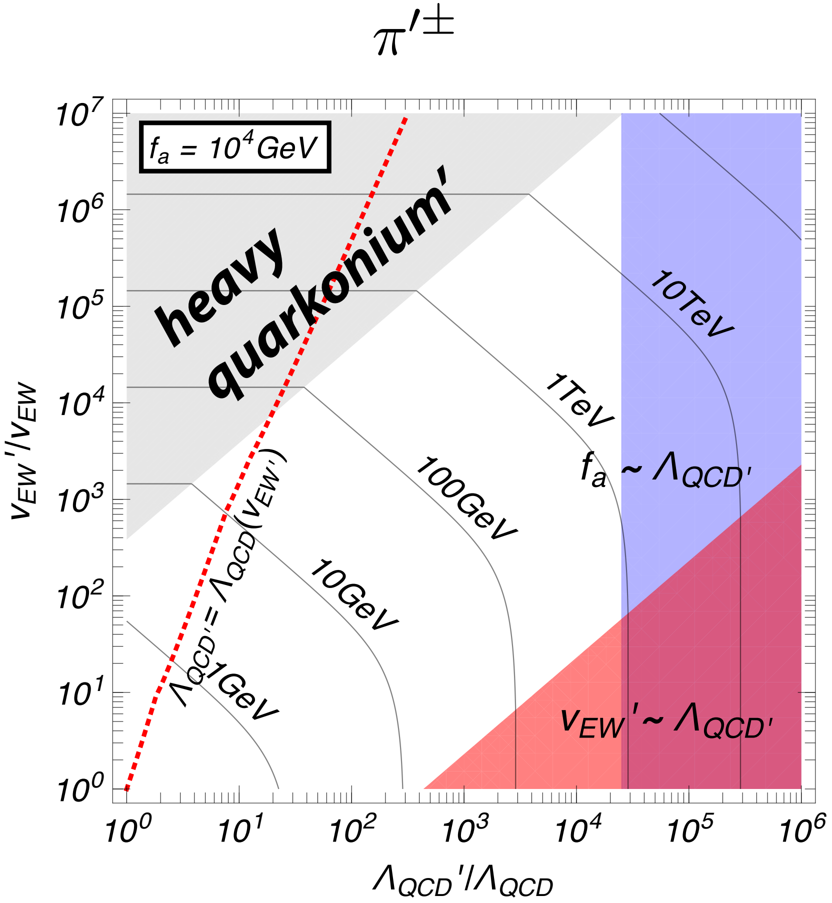
✔ **Electron' Mass**

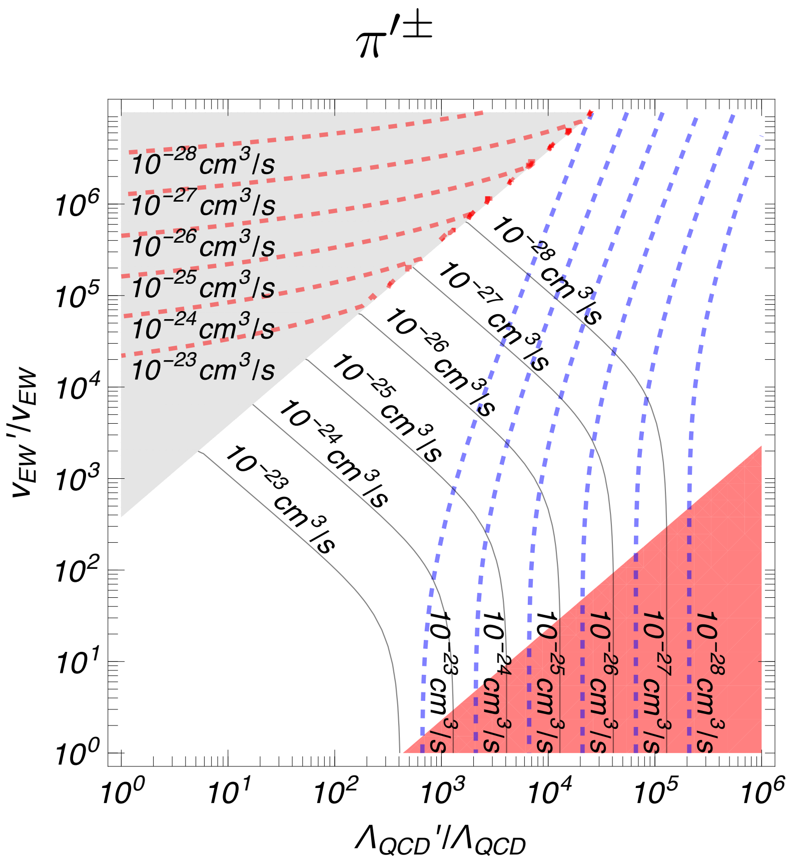
$$m_e' = m_e \times \frac{v_{EW}'}{v_{EW}} \, .$$

✔ $\boldsymbol{e^{-\prime} + e^{+\prime} \rightarrow \gamma' + \gamma'}$

$$\langle \sigma v_{\rm rel} \rangle = \frac{\pi \alpha_{\rm QED}'^2}{2 m_e'^2}$$

Dark Matter Candidates





✔ ***Pion' Mass***

$$m'^2_{\pi^0} \simeq m^2_{\pi^0} \times \frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}} \frac{v'_{EW}}{v_{EW}}$$

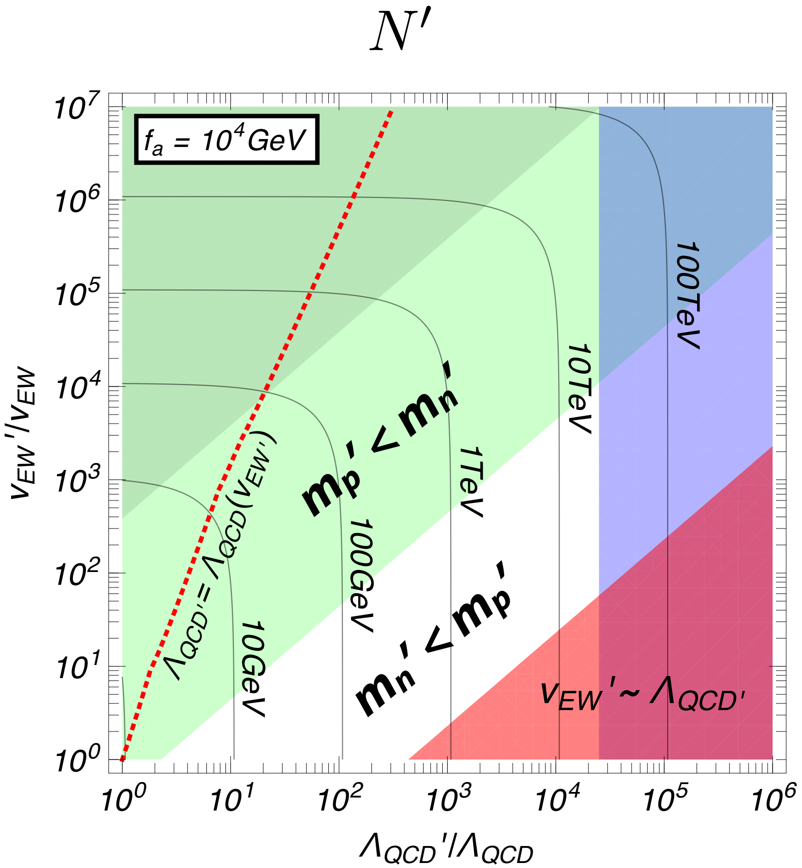
$$m'^2_{\pi^\pm} \simeq m'^2_{\pi^0} + \alpha'_{QED} \Lambda'^2_{QCD}$$

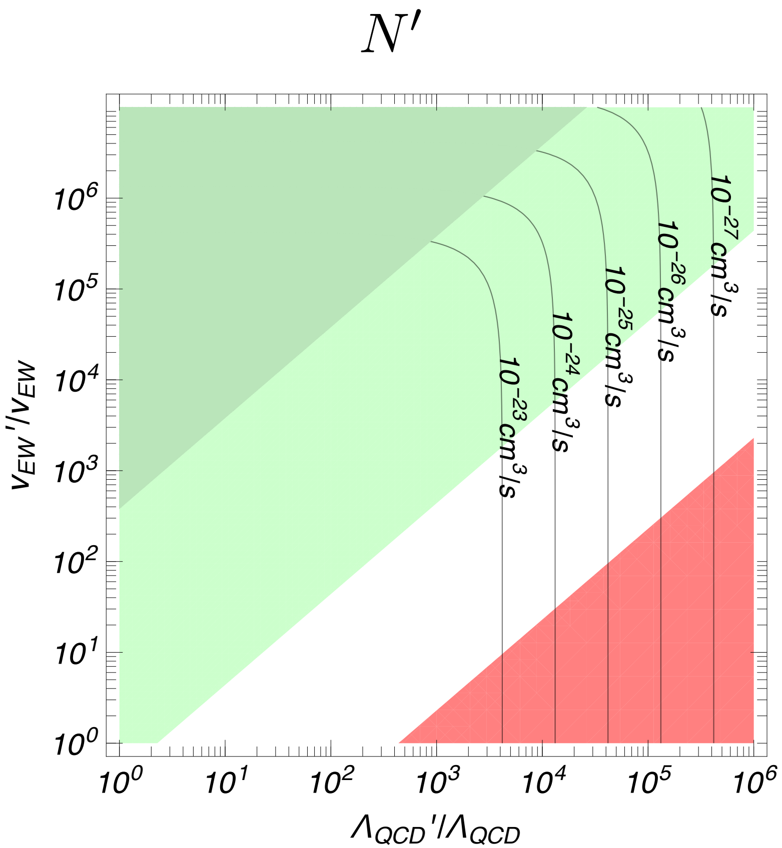
✔ ***$\pi^{-\prime} + \pi^{+\prime} \rightarrow \pi^{0\prime} + \pi^{0\prime}$ (blue dashed)***

✔ ***$\pi^{-\prime} + \pi^{+\prime} \rightarrow \gamma' + \gamma'$ (black solid)***

✔ ***$\pi^{-\prime} + \pi^{+\prime}$ [heavy quarkonium'] $\rightarrow$ jets (red solid)***

Dark Matter Candidates





✔ **N′ Mass (both n′, p′ are stable)**

$$m'_N \simeq \left(\frac{m_N}{2} - 3\bar{m}\right) \times \frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}} + 3\bar{m} \times \frac{v'_{EW}}{v_{EW}}$$

$$m_{n'} - m_{p'} \simeq$$

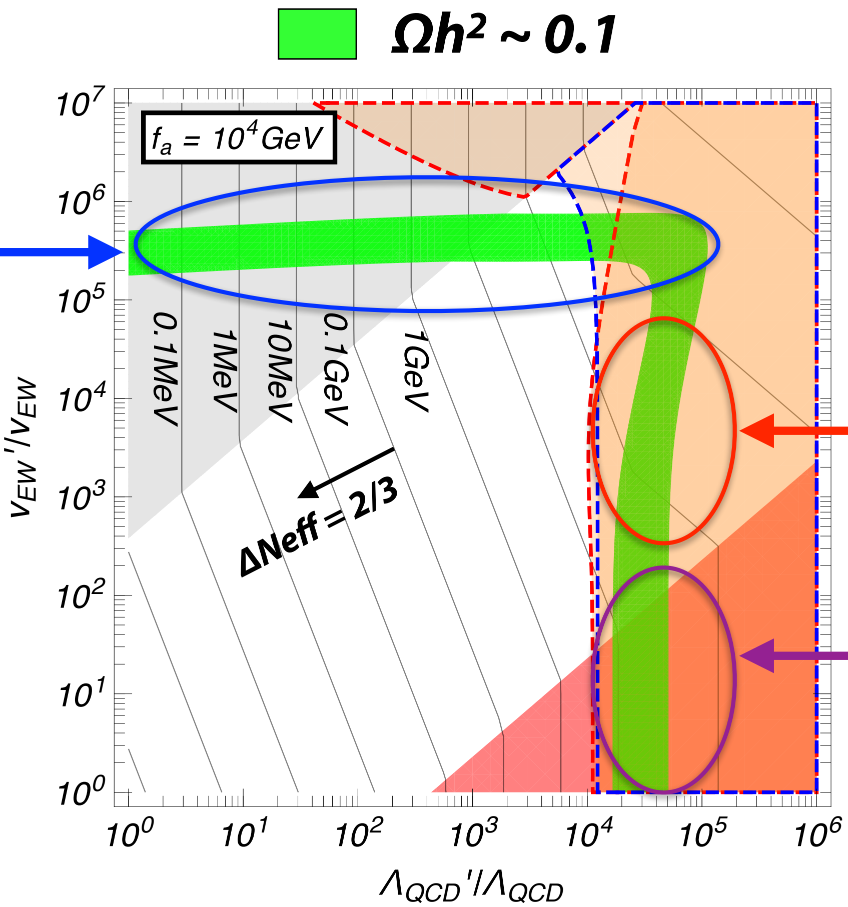
$$\delta m^{\rm QED}_{n-p} \times \frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}} + \kappa_N(m_d - m_u) \times \frac{v'_{EW}}{v_{EW}}$$

✔ **$N^{-\prime} + N^{+\prime} \rightarrow \pi' + \pi'$**

saturating the unitarity limit

$$\langle \sigma v_{\rm rel} \rangle \sim \frac{8\pi}{m'^2_N}$$

Dark Matter Candidates



e', $\pi^{\pm}{}'$ DM dominant

(n', p') DM dominant

$\pi^{\pm}{}'$ DM dominant

Dark Matter = Darkly Charged !

- **CMB Constraints on the annihilation cross-section @ recombination**
  - **Sommerfeld Enhanced $\pi^+ + \pi^- \to \pi^0{}' + a$ ($a \to$ SM)**
  - **Sommerfeld Enhanced $p^+ + p^- \to \pi^0{}' + a$ ($a \to$ SM)**

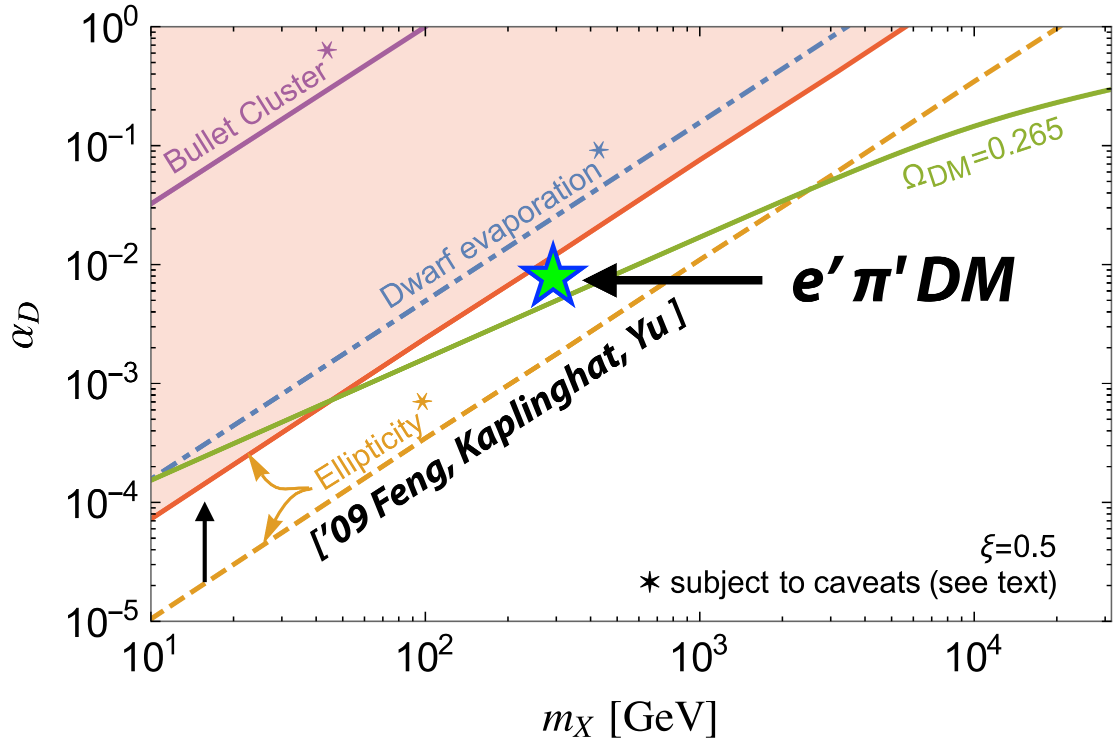
[see e.g. '16 Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia]

Dark Matter Candidates

Are Darkly Charged DM consistent ?

Long range forces affect dwarf Spheroidal galaxies such as sphericity.

['16 Agrawal, Cyr-Racine, Randall, Scholtz]



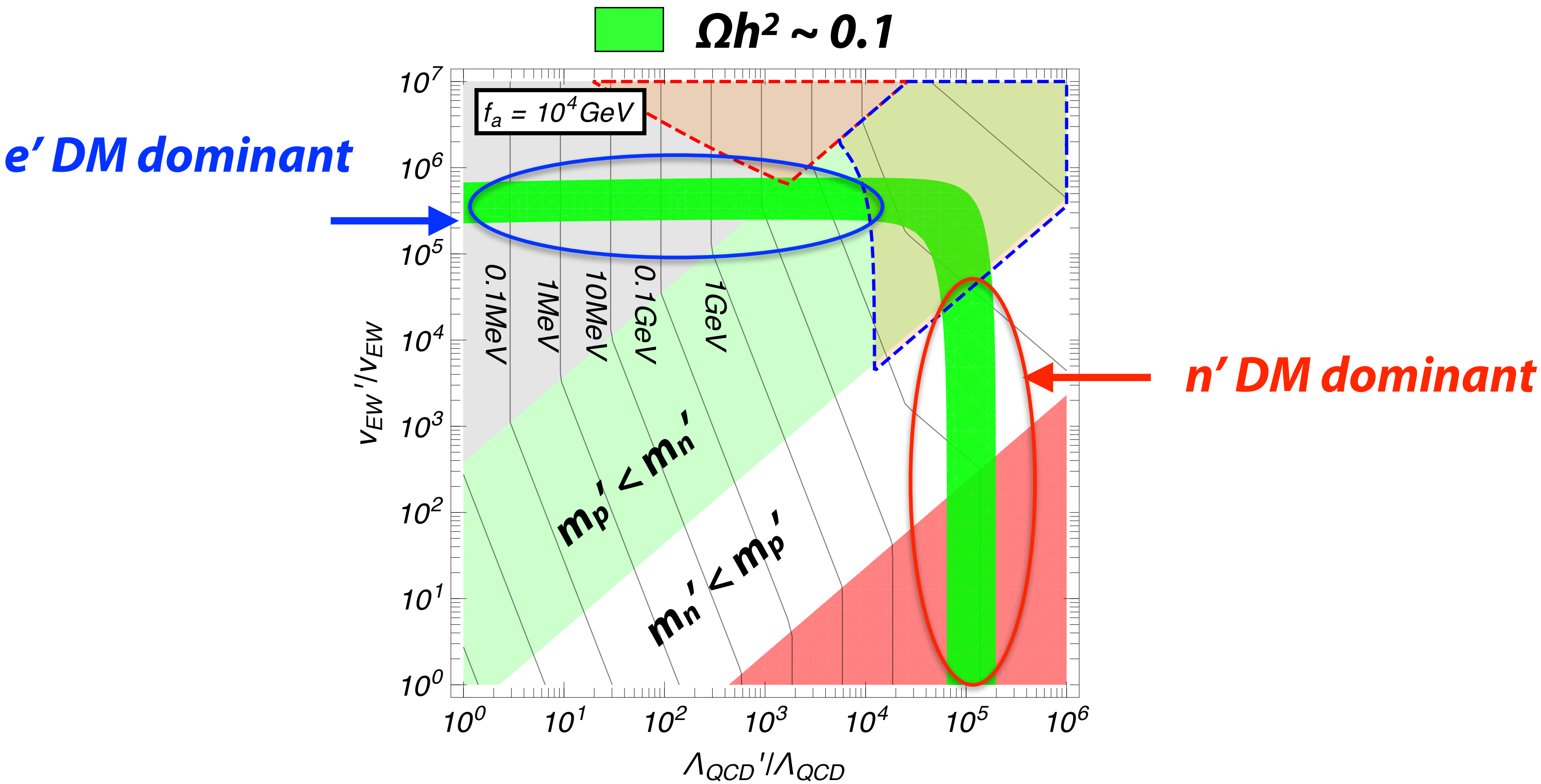
✔ ***Our model is at least consistent with the sphericity constraint…***

✔ ***More should be studied such as core formation in dSph…***

Dark Matter Candidates

✔ If we allow the lightest ***ν′*** very light ***π***$^{\pm}$ and ***p*** can decay.

$$\pi' \rightarrow e' + \nu' \qquad\qquad p' \rightarrow n' + e' + \nu'$$



Neutron′ DM at 100TeV is also possible !

Dark Matter Candidates

Constraints on 100TeV Neutron′ DM?

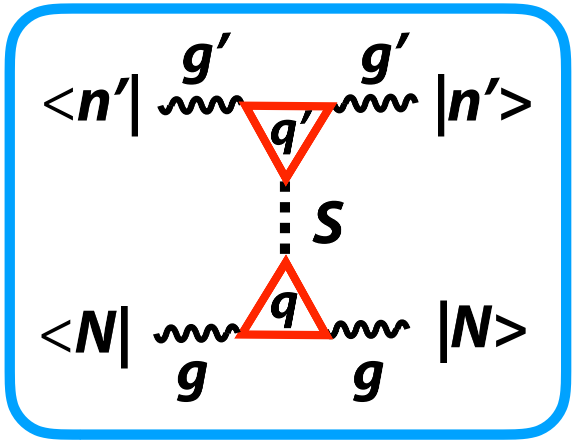
- Annihilation into the SM though the axion :

$$n' + n' \to \pi^{0\prime} + a \; (a \to SM)$$

with the WIMP cross section ($\sim 10^{-26} cm^3/s$)

→ to small to be constrained.

- Direct Detection



Nucleon-Nucleon′ cross section :

$$\sigma_{\rm SI} \sim 10^{-48}{\rm cm}^2 \times \left(\frac{1\,{\rm TeV}}{m_s}\right)^4 \left(\frac{10\,{\rm TeV}}{f_a}\right)^4 \left(\frac{m_N}{1\,{\rm GeV}}\right)^4 \left(\frac{m'_N}{100\,{\rm TeV}}\right)^2$$

→ to small to be constrained.

Dark Matter Candidates

Constraints on 100TeV Neutron' DM?

- Decay via Planck suppressed proton decay operator ?

$$\Gamma(n' \to \nu' + \pi'^0) \sim \frac{1}{32\pi} \frac{m_{N'}^5}{M_{\rm PL}^4}$$

$$\tau(n' \to \nu' + a) \sim \ 10^{28}\,{\rm s} \times \left(\frac{100\,{\rm TeV}}{m_{N'}}\right)^5 \left(\frac{f_a}{100\,{\rm TeV}}\right)^2 \left(\frac{10\,{\rm TeV}}{f'_\pi}\right)^2$$

→ can be tested by the extra-galactic gamma ray background (EGRB) observation !

cf. For DM → $W^+ + W^-$ (M_{DM} = 10TeV)

$$\tau(n' \to \nu' + a) \gtrsim 10^{28}\,{\rm s}$$

by the Fermi-LAT observation.

[e.g. '16 Ando, Ishiwata]

[Not very precise comparison : m_n' = 100TeV, final state = gluon]

Dark Matter Candidates

✓ Constraints on 100TeV Neutron' DM?

✓ Decay via Planck suppressed proton decay operator ?

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→ can be tested by the extra-galactic gamma ray background (EGRB) observation !

✓ If the proton decay in the SM is observed in near future, the model can be immediately excluded !

Baryon symmetry $\xleftrightarrow[Z_2]{}$ ***Baryon' symmetry***

Summary :

- ✓ Axion mass is dominated by the copied sector contributions while solving the strong ***CP***-problem.

- ✓ A heavy axion with $\boldsymbol{m_a >> O(100)MeV}$ evades constraints from
  (1) collider experiments (2) astrophysics (3) cosmology
  even for $\boldsymbol{f_a = O(1)TeV}$! ↔ ***Keith's constraint*** $\boldsymbol{f_a > O(10^{8\text{-}9})\ TeV}$

- ✓ The heavy axion is durable to explicit PQ-symmetry breaking by Planck suppressed operators for $\boldsymbol{f_a = O(1)TeV}$.

- ✓ The model provides a lot of DM candidates.

For $\boldsymbol{m_\nu' > m_\pi'}$

DM candidate: e' and $\boldsymbol{\pi^\pm}$ ***with*** $\boldsymbol{m_{DM} = 300GeV - 1TeV}$

They are "darkly charged" which could affect dwarf spheroidal galaxies !

Summary :

- ✓ Axion mass is dominated by the copied sector contributions while solving the strong ***CP***-problem.

- ✓ A heavy axion with $\boldsymbol{m_a \gg O(100)MeV}$ evades constraints from
  (1) collider experiments (2) astrophysics (3) cosmology
  even for $\boldsymbol{f_a = O(1)TeV}$! $\leftrightarrow$ ***Keith's constraint*** $\boldsymbol{f_a > O(10^{8\text{-}9})\ TeV}$

- ✓ The heavy axion is durable to explicit PQ-symmetry breaking by Planck suppressed operators for $\boldsymbol{f_a = O(1)TeV}$.

- ✓ The model provides a lot of DM candidates.

For a very light lightest $\boldsymbol{\nu'}$

Neutron' DM with $\boldsymbol{m_{DM} \sim 100\ TeV}$.

The model can be tested by EGRB & proton decay.

Happy Birthday Keith !

Thank you very much for a lot of influential works !

Back Up Slides

Dark Matter Candidates

Are Darkly Charged DM consistent ?

✓ Cross-section / DM mass

$$\frac{\sigma_T}{m_X} = \frac{8\pi\alpha_D^2}{m_X^3 v^4}\log\Lambda = \begin{cases} 1.7\times10^4 \ \frac{\mathrm{cm}^2}{\mathrm{g}} \left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3 \left(\frac{\log\Lambda}{45}\right) \left(\frac{30\ \mathrm{km/s}}{v}\right)^4 & \text{Dwarf galaxies} \\ 2.1\times10^0 \ \frac{\mathrm{cm}^2}{\mathrm{g}} \left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3 \left(\frac{\log\Lambda}{60}\right) \left(\frac{300\ \mathrm{km/s}}{v}\right)^4 & \text{Galaxies} \\ 2.0\times10^{-2} \ \frac{\mathrm{cm}^2}{\mathrm{g}} \left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3 \left(\frac{\log\Lambda}{72}\right) \left(\frac{1000\ \mathrm{km/s}}{v}\right)^4 & \text{Clusters.} \end{cases}$$

✓ mean-free path / object size

$$Kn \simeq \begin{cases} 10^{-3} \left(\frac{1\,\mathrm{kpc}}{R}\right) \left(\frac{9\,\mathrm{GeV/cm}^3}{\rho}\right) \left(\frac{1.7\times10^4\mathrm{cm}^2/\mathrm{g}}{\sigma_T/m_X}\right) & \text{Dwarf galaxies} \\ 10^1 \left(\frac{30\,\mathrm{kpc}}{R}\right) \left(\frac{0.3\,\mathrm{GeV/cm}^3}{\rho}\right) \left(\frac{2.1\mathrm{cm}^2/\mathrm{g}}{\sigma_T/m_X}\right) & \text{Galaxies} \\ 10^5 \left(\frac{10\,\mathrm{Mpc}}{R}\right) \left(\frac{9\times10^{-6}\,\mathrm{GeV/cm}^3}{\rho}\right) \left(\frac{2.0\times10^{-2}\mathrm{cm}^2/\mathrm{g}}{\sigma_T/m_X}\right) & \text{Clusters.} \end{cases}$$

['16 Agrawal, Cyr-Racine, Randall, Scholtz]

Dark Matter Candidates

- Nucleon' mass

$$m_{N'} \equiv \frac{m'_n + m'_p}{2} \simeq \left(\frac{m_n + m_p}{2} - 3\bar{m} \right) \times \frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}} + 3\bar{m} \times \frac{v'_{EW}}{v_{EW}}$$

$$m_{n'} - m_{p'} \simeq \delta m^{\rm QED}_{n-p} \times \frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}} + \kappa_N (m_d - m_u) \times \frac{v'_{EW}}{v_{EW}}$$

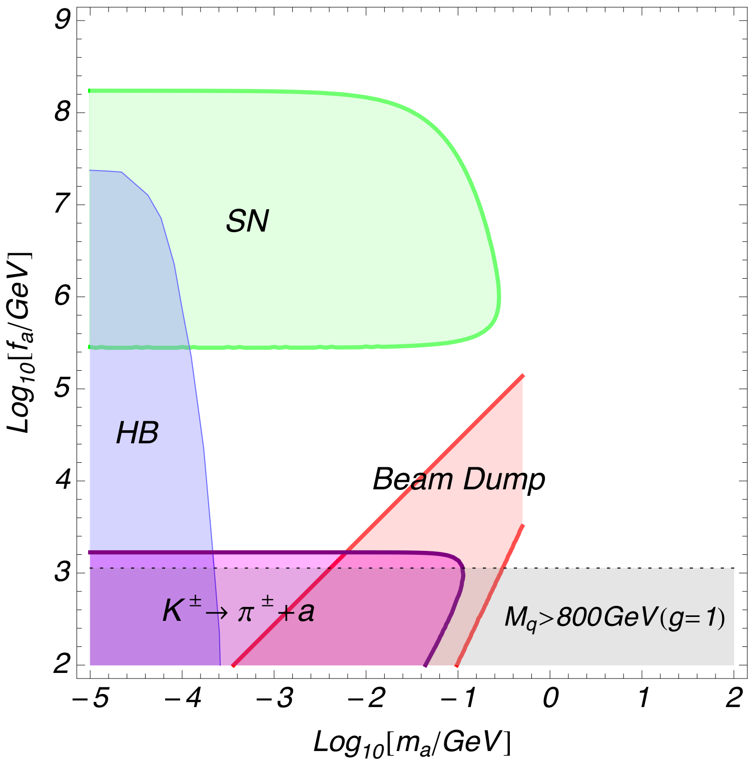
$$\delta m^{\rm QED}_{n-p} = -0.178^{+0.0004}_{-0.064}\,{\rm GeV} \times \alpha_{\rm QED}$$

$$\kappa_N = 0.95^{+0.08}_{-0.06}\ .$$

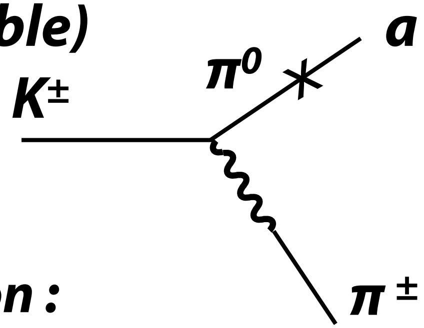
[Walker-Loud, arXiv:1401.8259 [hep-lat]]

Summary of experimental/astrophysical Constraints.

[Fukuda, Harigaya, Yanagida and MI arXiv:1504.06084]



$K^{\pm} \to \pi^{\pm} + a$ (invisible)



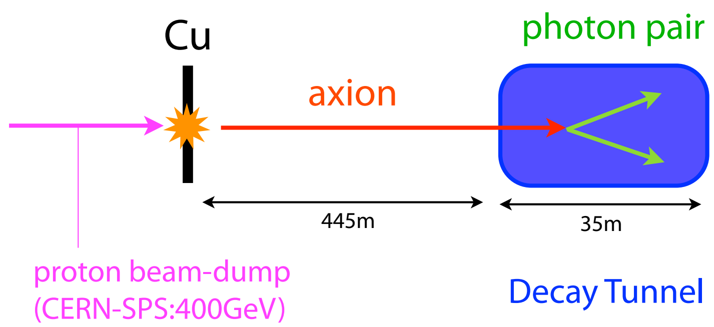
Purple shaded region :

$Br(K^{\pm} \to \pi^{\pm} + a$ (invisible) $) > 5 \times 10^{-11}$

(E787 [hep-ex/0403034])

[Weaker than the DFSZ type model due to the lack of direct coupling to heavy quarks and leptons!
e.g. No constraints from $B \to K + a(\to ll)$]

Beam Dump (CHARM Experiment)



Axion production rate
$\sim$ pion production rate x $(f_{\pi} / f_a)^2$

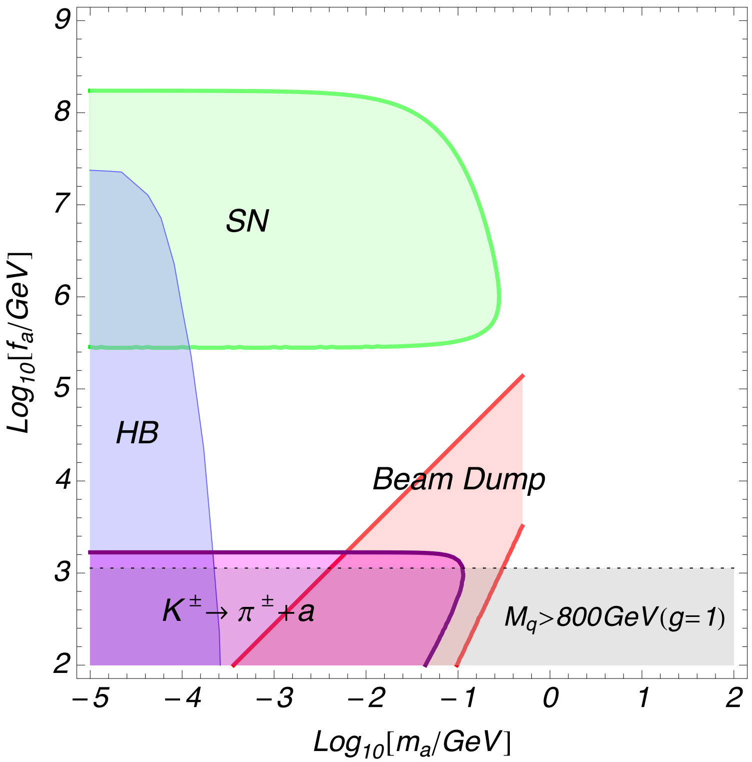
Red shaded region :

#[Axion decay in distance from 445m to 480m from the beam target] > 3

['82 CHARM]

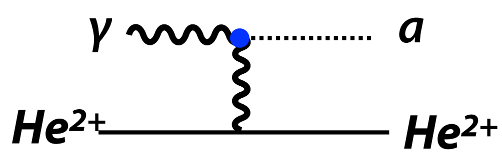
Summary of experimental/astrophysical Constraints.

[Fukuda, Harigaya, Yanagida and MI arXiv:1504.06084]



Constraint from Horizontal Branch

The axion enhances the energy loss rate of the stars in Horizontal Branch of globular clusters via the Primakoff conversion

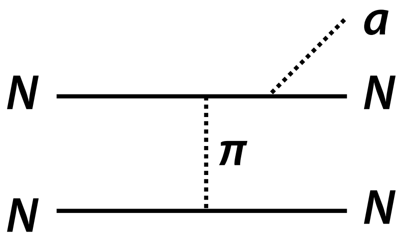


Blue shaded region:

$E_{loss} > 10\ g^{-1}\ erg\ s^{-1}$ ($T_{HB\ core} \sim 10keV$)

[arXiv:1110.2895]

Supernovae Constraint (1987a)



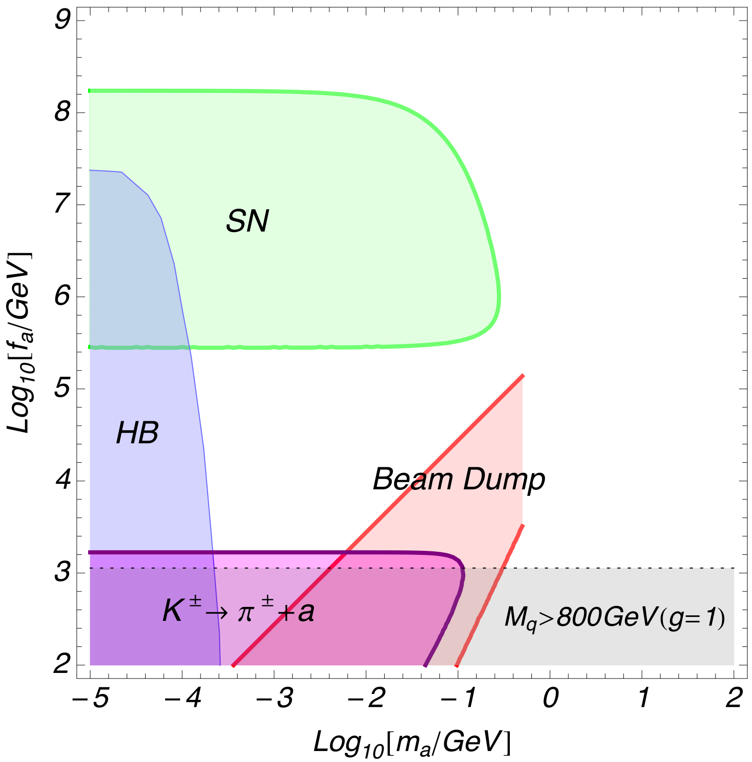
Green Shaded region:

$E_{\text{loss by axion}} < E_{\text{loss by neutrino}}$ [arXiv:1008.0636]

($T_{SN} \sim 30MeV$, mean free path > 10km)

Summary of experimental/astrophysical Constraints.

[Fukuda, Harigaya, Yanagida and MI arXiv:1504.06084]



Constraints on Extra Quarks

We assume small mixing of them with the SM quarks

$$\mathcal{L} = \xi_i q_L \bar{d}_{Ri} + \xi'_i q'_L \bar{d}'_{Ri} + \mathrm{h.c.}\ ,$$

Leading to a small coupling to the SM

$$\mathcal{L} = \xi_3\, y_d\, H^\dagger Q_3 \bar{q}_R + h.c.$$

The extra quarks decay into ***H* + *b*, *Z* + *b*, *W* + *t*** (***1:1:2*** for ***SU(2)*** singlet)

LHC constraint : $m_{extra\ quark}$ > 800GeV (8TeV, 19.7fb^{-1})

[CMS : arXiv:1507.07129]

leading to $f_a = \sqrt{2}\, m_{extra\ quark}/g > 1120 GeV/g$

Effects of Explicit Breaking

- Axion mass is dominated by the coped sector contributions.

  e.g) $\boldsymbol{m_a = O(100)\,MeV - O(1)\,GeV}$ is possible for

  $$v_{EW'} = 10^3 \times v_{EW}\,,\ \Lambda_{QCD'} = 10^3 \times \Lambda_{QCD}\,,\ f_a = 10^3\,\mathrm{GeV}.$$

- A heavy axion with $\boldsymbol{m_a > O(100)\,MeV}$ evades constraints from

  (1) collider experiments (2) astrophysics (3) cosmology

  even for $\boldsymbol{f_a = O(1)\,TeV}$!

  [It is safe to switch off the seesaw mechanism in the copied sector.]

- ***The heavy is durable to explicit PQ-symmetry breaking by Planck suppressed operators***

e.g.) The effects of dimension 5 PQ-breaking operator leads to

$$\Delta\theta_{\mathrm{eff}} \sim 10^{-11} \times \kappa \left(\frac{f_a}{10^3\,\mathrm{GeV}}\right)^3 \left(\frac{1\,\mathrm{GeV}}{m_a}\right)^2$$

which is consistent with current upper limit on $\boldsymbol{\theta_{eff}}$.

Effects of Explicit Breaking

This is much better than the invisible axion.

If the physics at the Planck scale breaks PQ symmetry we would have

$$\Delta\mathcal{L} = \frac{S^m}{M_{\rm PL}^{m-4}} + h.c.$$

which distorts the axion potential.

$$\mathcal{L} = \frac{1}{2} m_a^2 f_a^2 (a/f_a - \theta/6)^2 + \frac{f_a^m}{M_{\rm PL}^{m-4}} \frac{a}{f_a} + \cdots$$

As a result the effective ***θ_{eff}***-parameter becomes non-vanishing !

$$\Delta\theta_{\rm eff} = \frac{f_a^m}{f_\pi^2 m_\pi^2 M_{\rm PL}^{m-4}}$$

If we require ***$\theta_{eff} << 10^{-11}$***, we forbid ***$m < 10$*** for ***$f_a > 10^9$GeV***.

How to arrange the $\boldsymbol{Z_2}$ breaking ?

We've assumed $\boldsymbol{Z_2}$ to set $\boldsymbol{\theta_{SM} = \theta_{SM'}}$.
Naively, $\boldsymbol{Z_2}$ also leads to $\boldsymbol{v_{SM} = v_{SM'}}$.

Let us assume spontaneous breaking of $\boldsymbol{Z_2}$ by a vacuum expectation value of a scalar field $\boldsymbol{\sigma}$ which is ***ODD*** under the $\boldsymbol{Z_2}$.

Then, we can differentiate $\boldsymbol{v_{SM}}$ and $\boldsymbol{v_{SM'}}$ when the Higgs mass parameters depend on $\boldsymbol{\sigma}$

$$\begin{aligned} m_H^2(\sigma) &= m_0^2 + m_1\sigma + c\,\sigma^2 \\ m_{H'}^2(\sigma) &= m_0^2 - m_1\sigma + c\,\sigma^2 \end{aligned}$$

With parameter tunings, we can realize $\boldsymbol{v_{SM} << v_{SM'}}$.

[Here, we do not care the tuning of dimensional parameter…]

How to arrange the Z_2 breaking ?

How about ***QCD*** and ***QCD'*** scales?

Similarly, by introducing colored scalar whose masses depend on σ, we can differentiate $\Lambda_{QCD'}$ from Λ_{QCD}.

$$\mathcal{L} = \sum_{i=1}^{N_{\tilde{q}}} \left(m_{\tilde{q}}^2(\sigma)\,|\tilde{q}_i|^2 + m_{\tilde{q}'}^2(\sigma)\,|\tilde{q}_i'|^2 \right) \;,$$

[Scalar quarks are better. Extra Fermions may bring back strong CP problem.]

How about ***seesaw mechanism?***

We can also switch off the seesaw mechanism by controlling the mass of ***B-L*** breaking field by ***σ***.

$$m_{B-L}^2(\langle\sigma\rangle) < 0 \qquad m_{B-L}'^2(\langle\sigma\rangle) > 0$$

How to arrange the $\boldsymbol{Z_2}$ breaking ?

CAUTION : if the **<*σ*>** is too large, it causes the strong ***CP*** problem via ,

$$\mathcal{L} = \frac{\sigma}{M_{\rm PL}} G\tilde{G} - \frac{\sigma}{M_{\rm PL}} G'\tilde{G}'$$

$\rightarrow$ $\boldsymbol{\Delta\theta_{eff} = 2\sigma/M_{PL}}$

Thus, **<*σ*>** should satisfy

$$\frac{\sigma}{M_{\rm PL}} \lesssim 10^{-12}$$

to avoid the strong ***CP*** problem.

Domain wall problem at Z_2 breaking might cause problem
(low reheating temperature? consistent with thermal Leptogenesis?)