Phenomenology of Heavy QCD Axion

arXiv:1607.01936, in preparation

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Outline

1. Heavy axion - Why and How?
2. Comprehensive Phenomenology of Visible Heavy Axion Models
3. Future search prospects

Strong CP Problem

- QCD should break CP symmetry

$$\theta = \theta_{\mathrm{YM}} + \arg\det(Y_u Y_d)$$

- The PQ mechanism can set $\theta = 0$.
  - The original model has been excluded.

What is the Alternative?

- Roughly, two choices:
  - Larger f_a / Heavier m_a

Axion Mass

- From QCD,

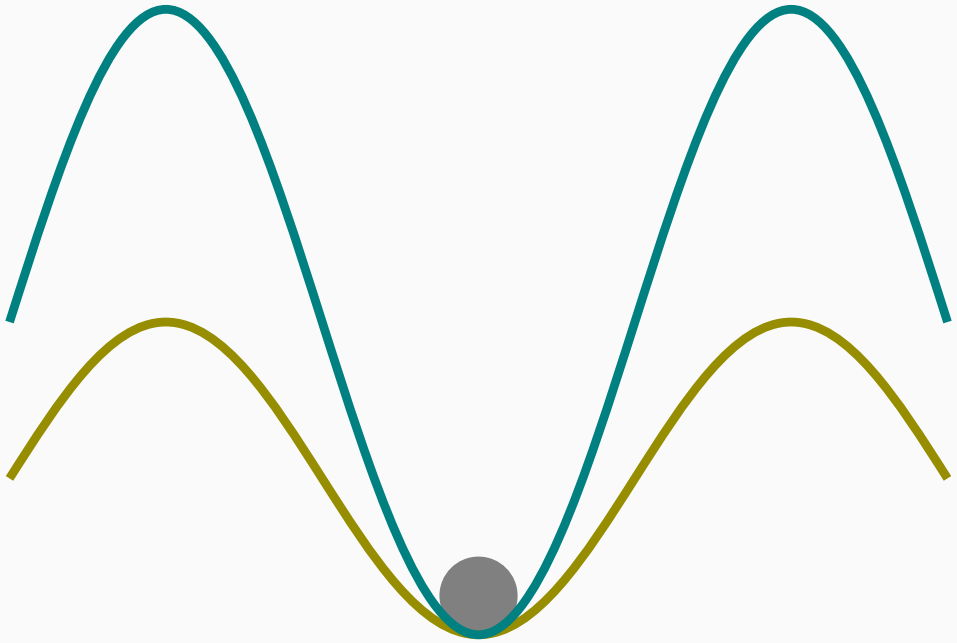
$$m_a{}^2 \simeq \frac{m_q \Lambda^3}{f_a{}^2}$$

Invisible Axion

- Large f_a is straightforward
  - Just adding a new scalar and a scalar/Fermion
- f_a has to be greater than $10^{9\text{-}10}$ GeV

How to Make an Axion Heavier?

- Another gauge theory with the same θ is needed



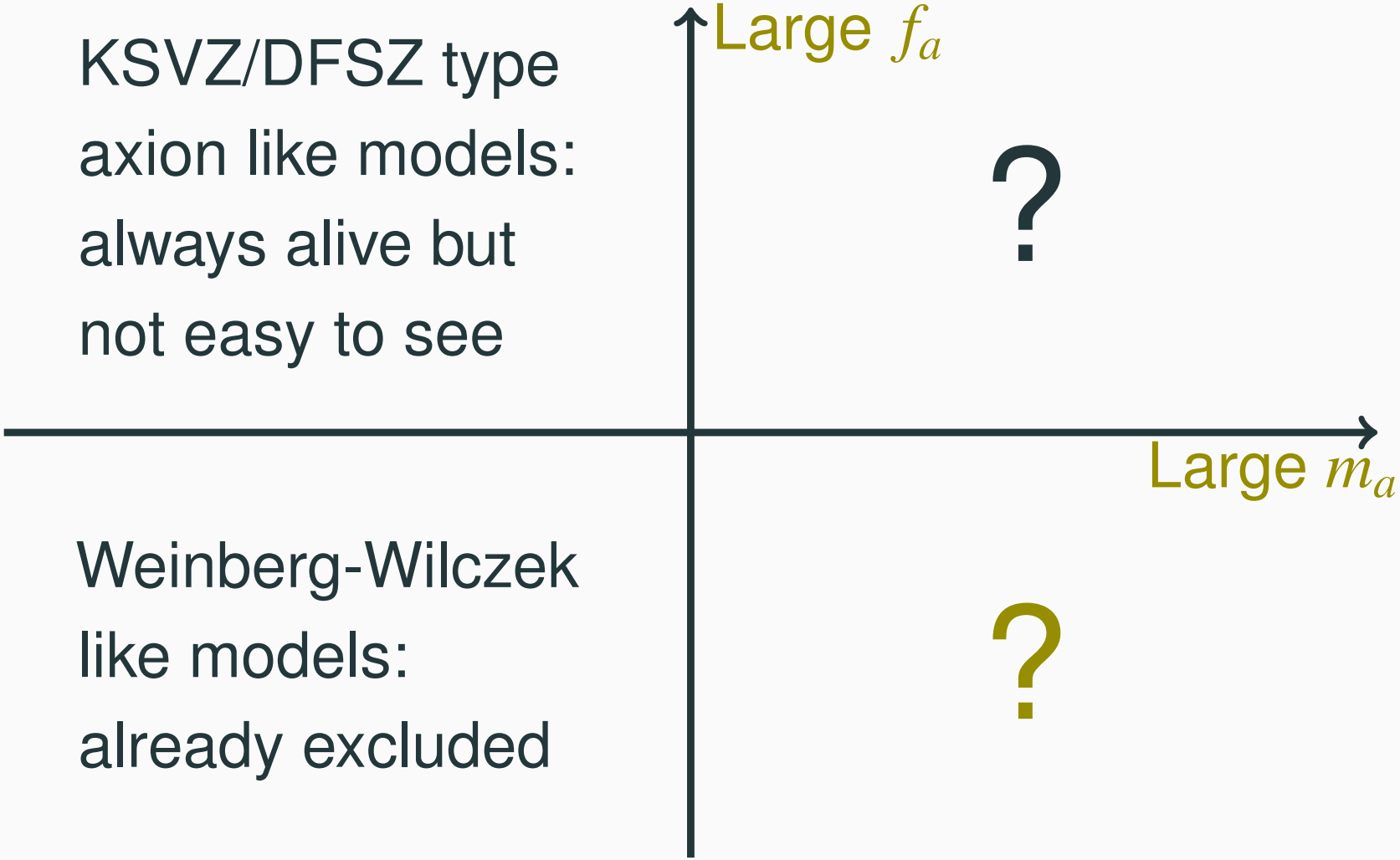
Rubakov 1997; Berezhiani, Gianfagna and Giannotti 2000
Hook 2014, HF, Harigaya, Ibe and Yanagida 2015, Albaid, Dine and Draper 2015
(Kobakhidze 2016), (Gherghetta, Nagata and Shifman 2016)

What is the gauge theory?

- Only known way is using a copy of SM
  - We assume $\mathbb{Z}_2$ parity
  - θs hardly run so $\mathbb{Z}_2$ may be spontaneously broken

m_a VS f_a

KSVZ/DFSZ type axion like models: always alive but not easy to see



Weinberg-Wilczek like models: already excluded

Setup

- SM and the copy is necessary
- How do we introduce PQ sym.?
  - Weinberg-Wilczek type
  - KSVZ type
- We mainly consider KSVZ-like model
  - $\mathcal{L} \sim \phi\bar{\psi}\psi + \phi\bar{\psi}'\psi'$, $-Q(\phi) = 1 = Q(\psi) = Q(\psi')$

What we want to do

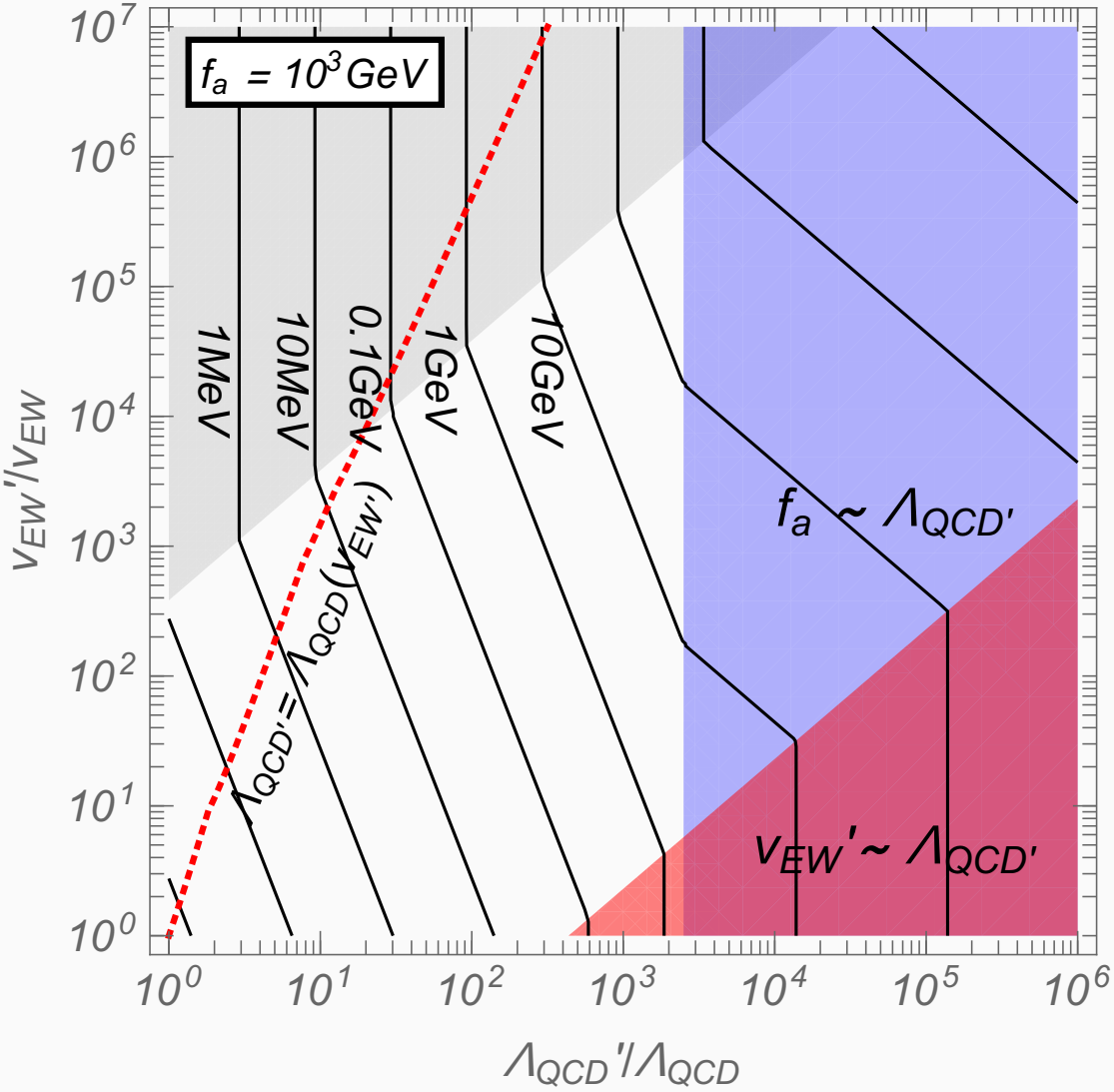
- We may freely choose v', Λ' and f_a with

$$m_a{}^2 \simeq \frac{m'_q \Lambda'^3}{f_a{}^2}$$

- Which region is still alive? Is it still visible?
- We require DM is included

HF, Ibe and Yanagida, in preparation

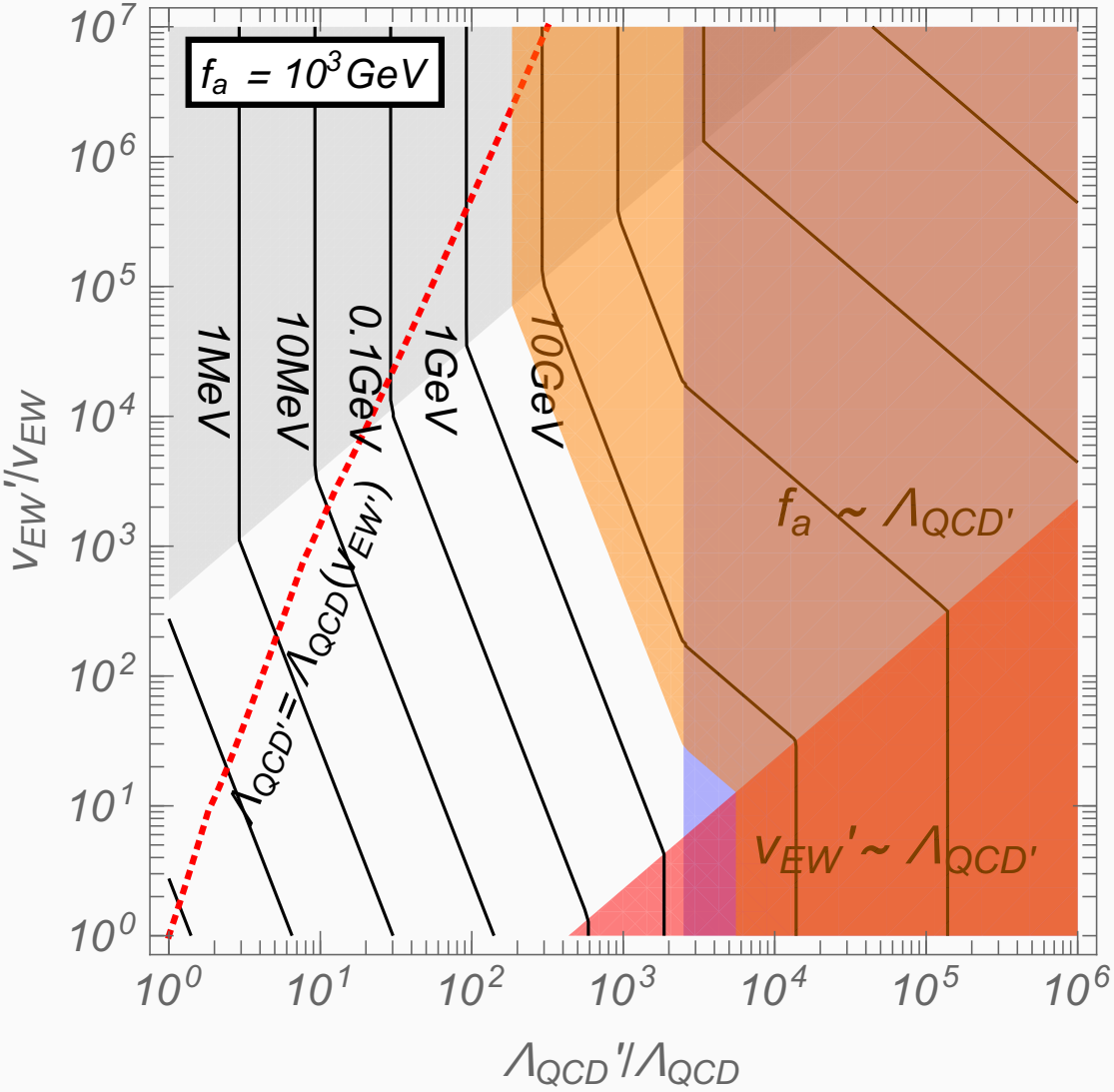
Axion mass


$f_a = 10^3\,\mathrm{GeV}$
1MeV
10MeV
0.1GeV
1GeV
10GeV
$\Lambda_{QCD'} = \Lambda_{QCD}(v_{EW'})$
$f_a \sim \Lambda_{QCD'}$
$v_{EW}' \sim \Lambda_{QCD'}$
v_{EW}'/v_{EW}
$\Lambda_{QCD}'/\Lambda_{QCD}$
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

Constraints on m_a

- When the axion is in the thermal bath, both sectors are in chemical equilibrium
- However, the entropy in the copied sector must small enough
  - The decoupling must occur before QCD PT
- Including the Boltzmann effect, $m_a \gtrsim \mathcal{O}(1)$ GeV
  - All the other constraints are weaker

Safe region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10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

Constraints on f_a

- For KSVZ type, the lower bound comes from the LHC
  - The vector like quark search $\rightarrow f_a \gtrsim 1$ TeV
- If f_a becomes large, m_a is now too small
- For $f_a \gtrsim 10^{10}$ GeV, a decouples before QCD PT

Constraints on v' and Λ'

- We have to consider thermal relics
- What will remain? $\Longleftrightarrow$ What symmetries remain in addition to γ'?

$$Q', L' \to 2 \text{ of } (e', \nu', \pi^{\pm\prime})$$

$$B' \to (p', n')$$

Conditions on ν'

- Lightest particle : $\lesssim \mathcal{O}(10)$ eV
- 3 possible choises
  - Giving up seesaw and
    - ν' DM
    - Unstable ν'
  - Ones of ν are massless
    - Natural if the number of N is 2

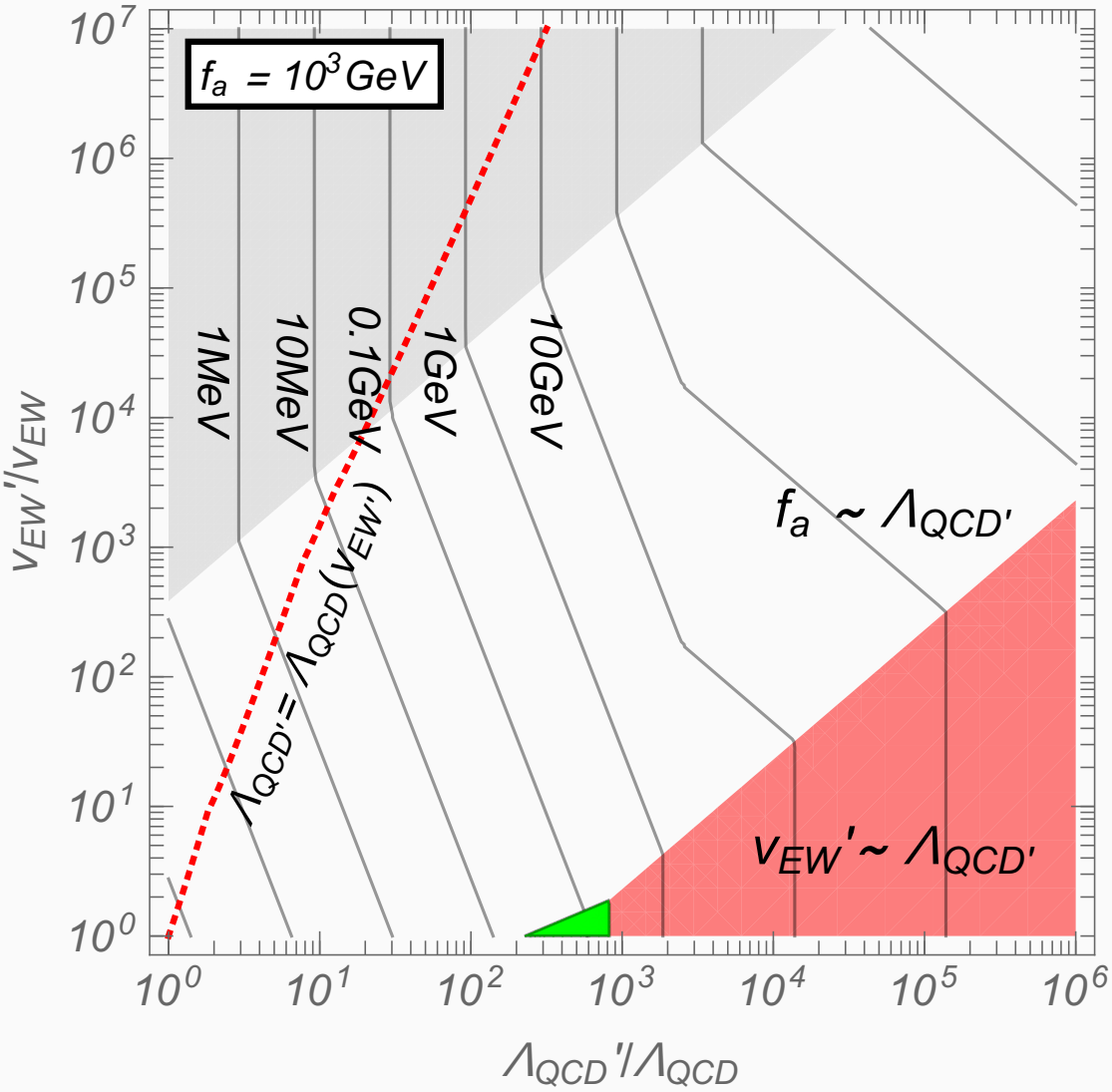
Case 1: ν' DM

- Just like ordinary WIMP,

$$\frac{\Omega_{\nu'}}{\Omega_{\mathrm{DM}}} \sim \frac{1\,\mathrm{pb}}{\langle \sigma v \rangle} \quad \therefore m'_\nu \sim 8\,\mathrm{GeV}\left(\frac{v'}{v}\right)^2 > m'_e$$

- $\pi^{\pm\prime}$ must decay, so $m_{\nu'} < m'_\pi \propto \sqrt{v'\Lambda'}$
  - $v' \sim v$, $\Lambda' \sim 10^3\Lambda$: m_a is too light $\rightarrow$ *EXCLUDED*
- Another choise
  - New interactions like $B' - L'$ only in copied sector
  - Little constaints and less interesting

Case 1: How excluded?



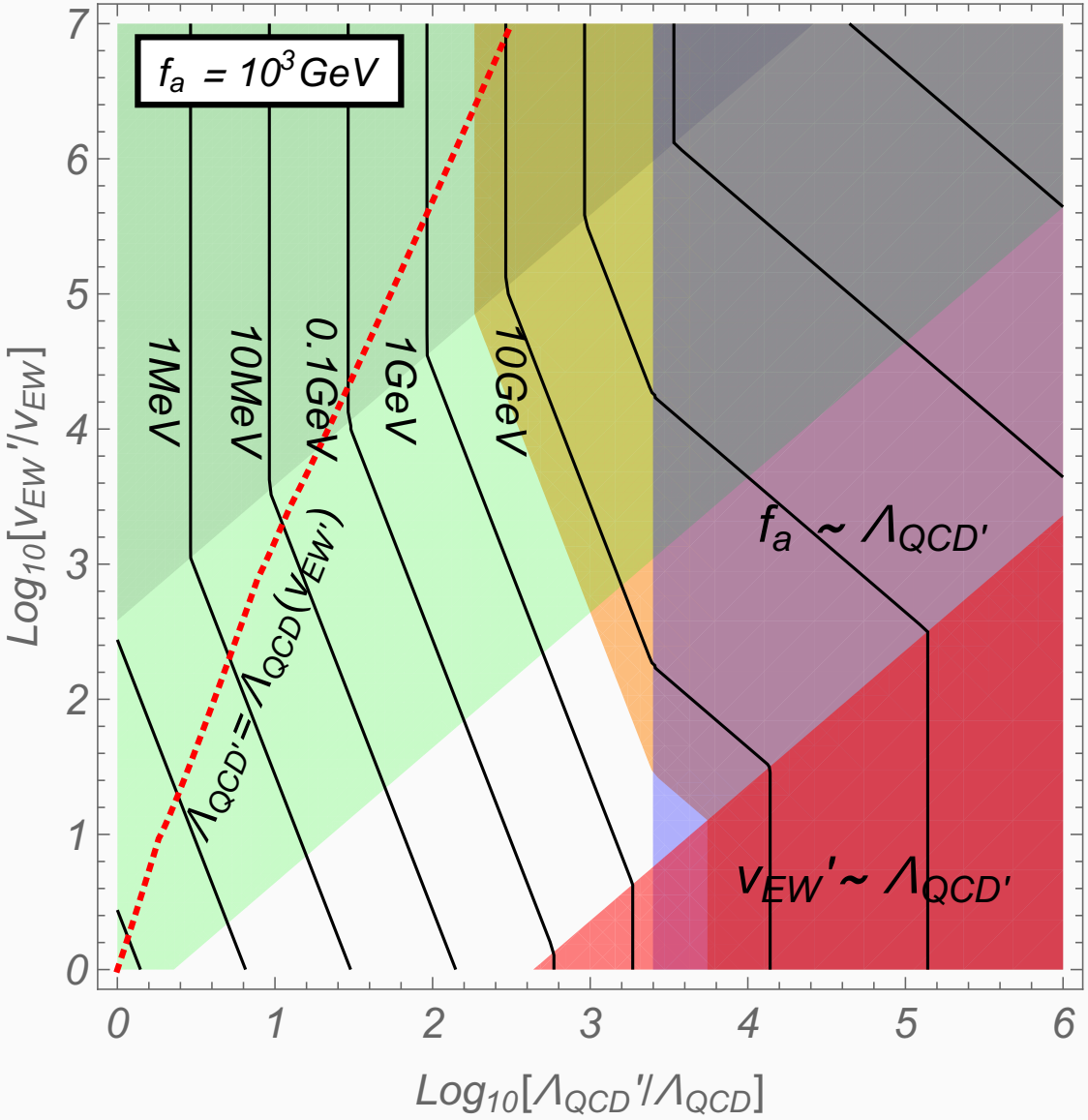
Case 2: One massless ν'

- e' or $\pi^{\pm\prime}$ is stable
  - $m'_e > m'_\pi$: $v'/v \sim 10^4 \frac{\Lambda'}{\Lambda} \gtrsim 10^6$; too much u', d' relics
- e' and (p' or n') are stable
  - Which one is DM?

Baryon mass: which is lighter?

- $m_B \sim c_1 \sum m_q + c_2 \Lambda + c_3 q \alpha \Lambda$
  - c_i are all positive and $c_1 \sim 1$
- p'
  - QED contribution
- n'
  - Heavier constituent quarks

Baryon mass ratio



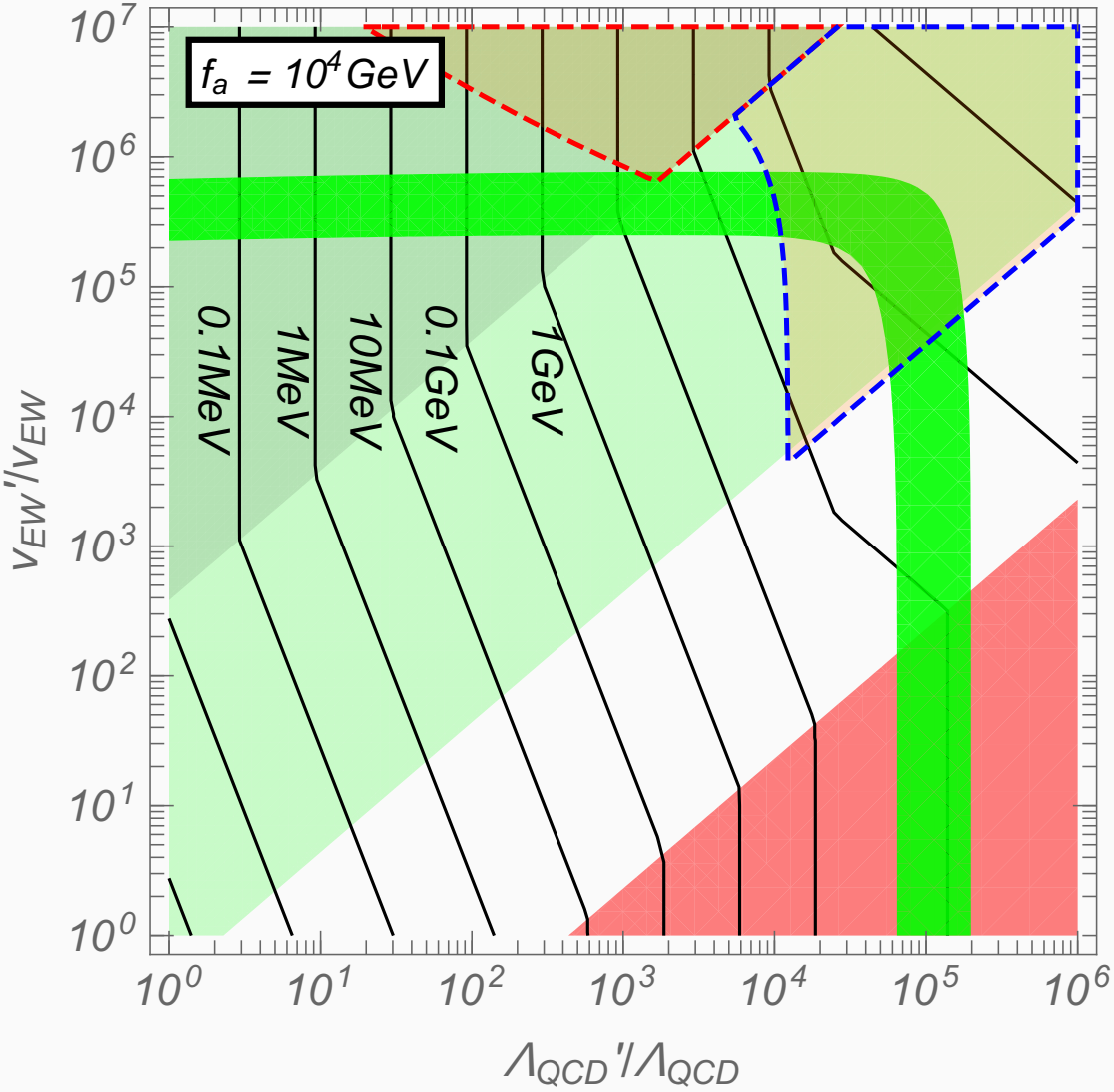
Is charged DM possible?

- Helo ellipticity constraint
  - $m_{\mathrm{DM}} \gtrsim 1\mathrm{TeV}$ for $\alpha^{-1} \sim 100$ Agrawal et al., 1610.04611
- Large Sommerfeld enhancement for late time annihilation
  - If DM + DM $\rightarrow$ SM is open, CMB might be disturbed

DM Candidates

- e'
  - WIMP mass ~ 50 GeV, inconsistent
- p' $(\Lambda^{++\prime}(u'u'u'))$
  - Ellipticity is not a problem
  - p' may annihilate into a and $a \rightarrow jj$
  - light q' region is excluded
- n'
  - No problem

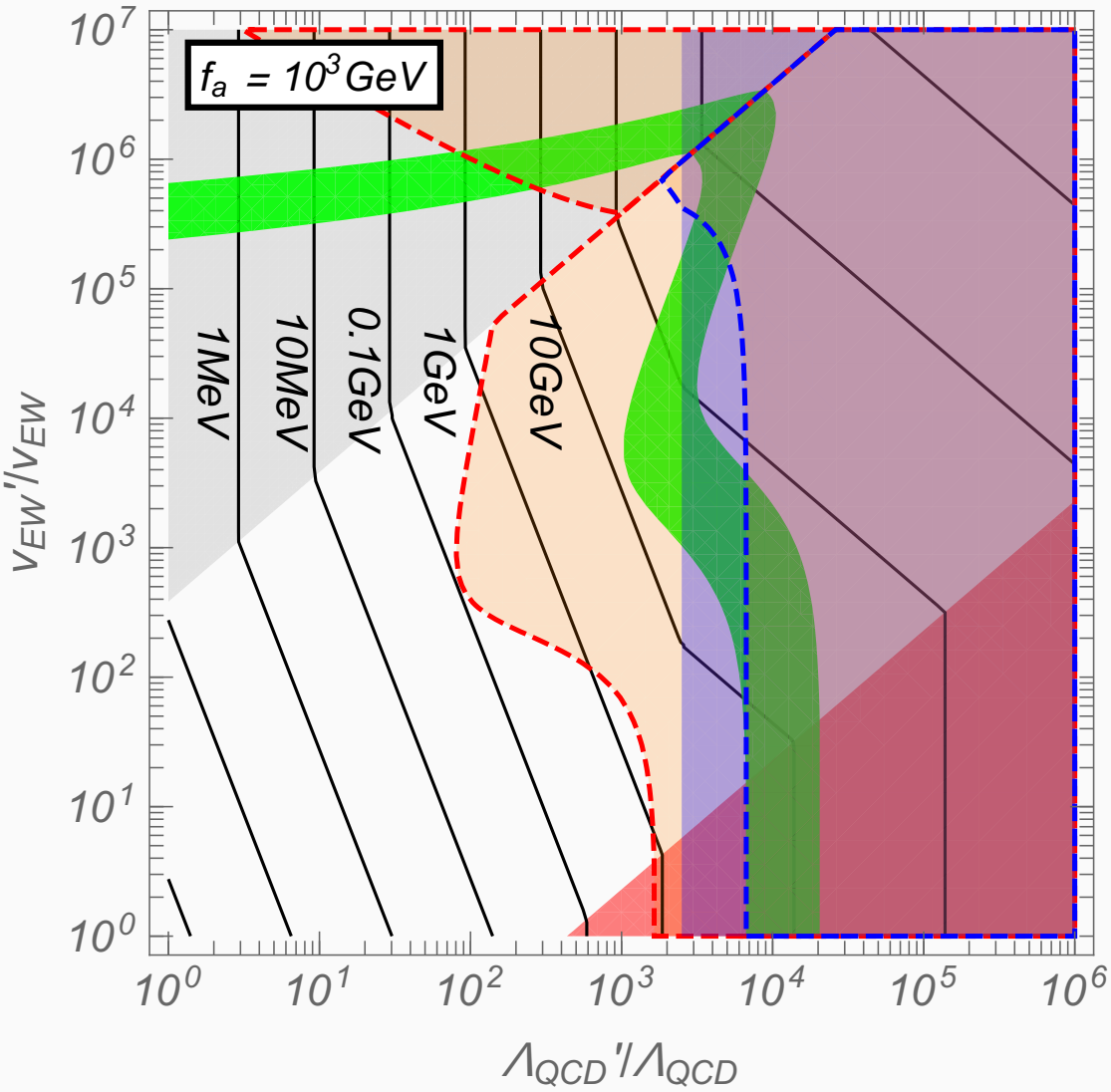
Case 2: Available region



Case 3: Unstable ν'

- $\pi^{\pm\prime}$, e' and (p' or n') are stable
- Baryons
  - For light q′, $\Omega_{\pi^{\pm\prime}} > \Omega_{B'}$ since $\pi^{\pm\prime}$ annihilates by QED′
- $\pi^{\pm\prime}$
  - light q′ region is excluded
- $\Lambda^{++\prime}$ may be the DM

Case 3: Available region



Short summary

- Allowed possibilities are
  - n' DM + one massless ν'
  - $\Lambda^{++\prime}$ DM (?)
- NOTE: If we consider exotic cosmology like low reheating temperature, constraints becomes weaker
  - However, the model is not closed and there are still some problems like BAU

Detection methods

- Collider experiments
  - Vector like quark detection
  - Axion / Dilaton detection
- Astrophysical experiments
  - For charged DM
    - Ellipticity
    - Cosmic ray
  - Decay of Baryon' relics
- Neutrino

Axion / Dilaton detection

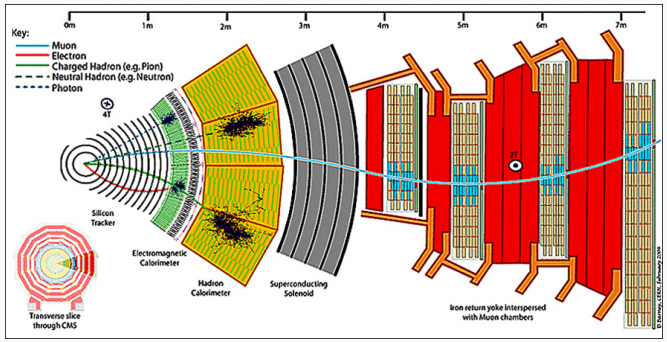
- For large enough $\sqrt{s}$,

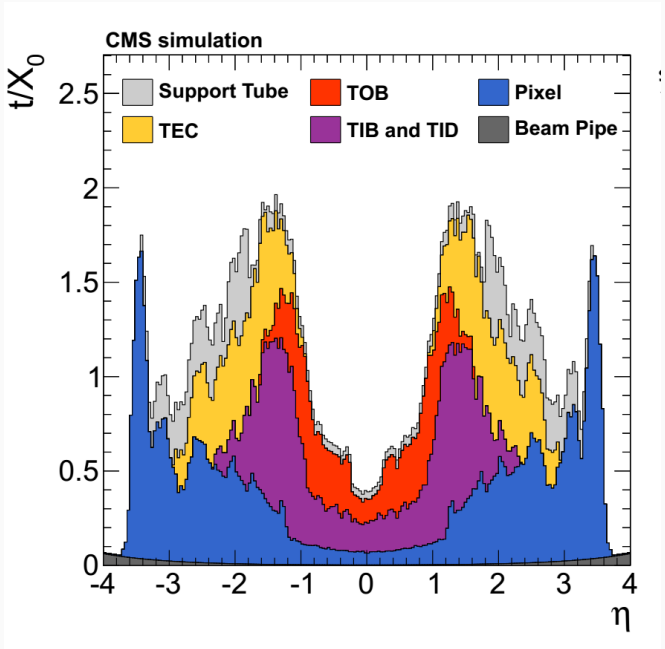
$$\sigma(pp \to a, s) \sim \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{1}{f_a^2} \sim 10\,\text{fb}\left(\frac{1\,\text{TeV}}{f_a}\right)^2$$

- $s \to jj\gamma\gamma$ might be hopeful?

Difference b/w γs and γ-jets

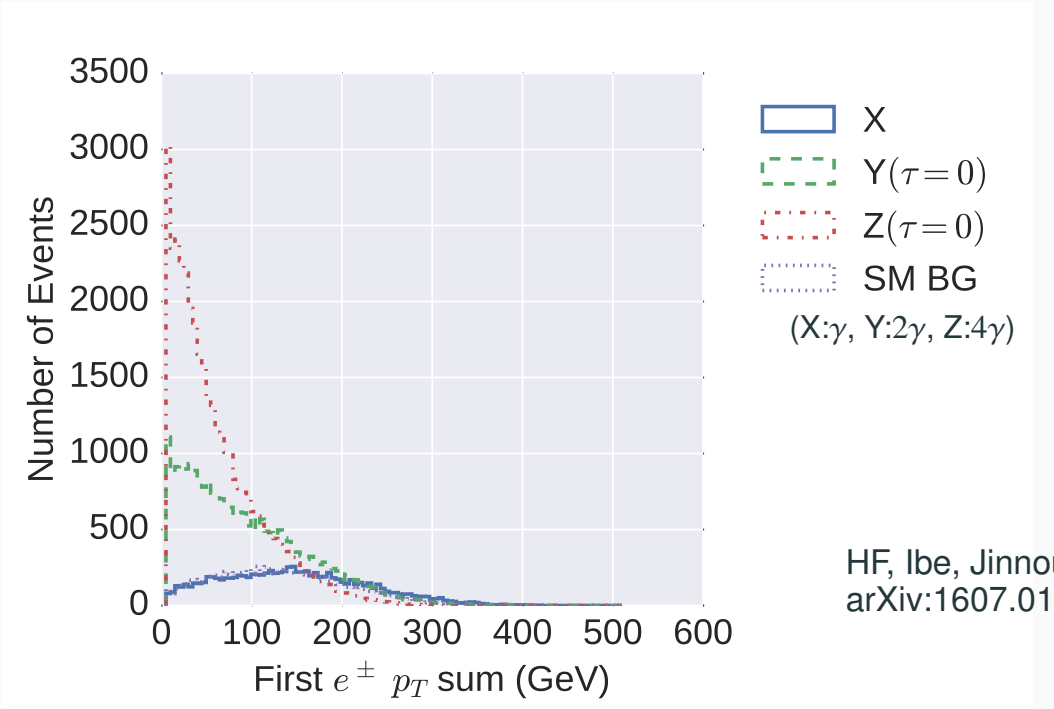
- Some γs are “converted”





How to Distinguish the Jet

- We simulate trackers in CMS.
  - Conversion, bremsstrahlung, . . .
- p_T^{track} has greater discrimination power!



HF, Ibe, Jinnouchi and Nojiri, arXiv:1607.01936

Decay of Baryon′ relics

- Naturally, p'/n' is unstable like SM p
- $\Gamma \propto m^5$, Short lifetime!
- Extragalactic gamma ray background tells

$$\tau(N' \to l' + a) \gtrsim 10^{28}\,\mathrm{s} \times \left(\frac{\Omega_{N'}}{\Omega_{DM}}\right)$$

- If $\Omega_{N'} = \Omega_{DM}$, $\Lambda_{\not B} \sim M_{\mathrm{Pl}}$

Summary

- We have investigated all the low-energy region for heavy axions
- Depending the scenario, some region is still alive