The High Quality QCD Axion and the High Luminosity LHC

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Strong CP problem

$$\mathscr{L}_{\text{SM}} \supset \frac{\alpha_3}{8\pi}\theta G\tilde{G} + Y_u \bar{Q}_L \tilde{H} u_R + Y_d \bar{Q}_L H d_R$$

- Observed $\bar{\theta} = \theta + \text{arg det}(Y_u Y_d) < 10^{-10}$

Neutron EDM, Baker '06

- But why so small given $\delta_{\text{CKM}} \sim \mathcal{O}(1)$?

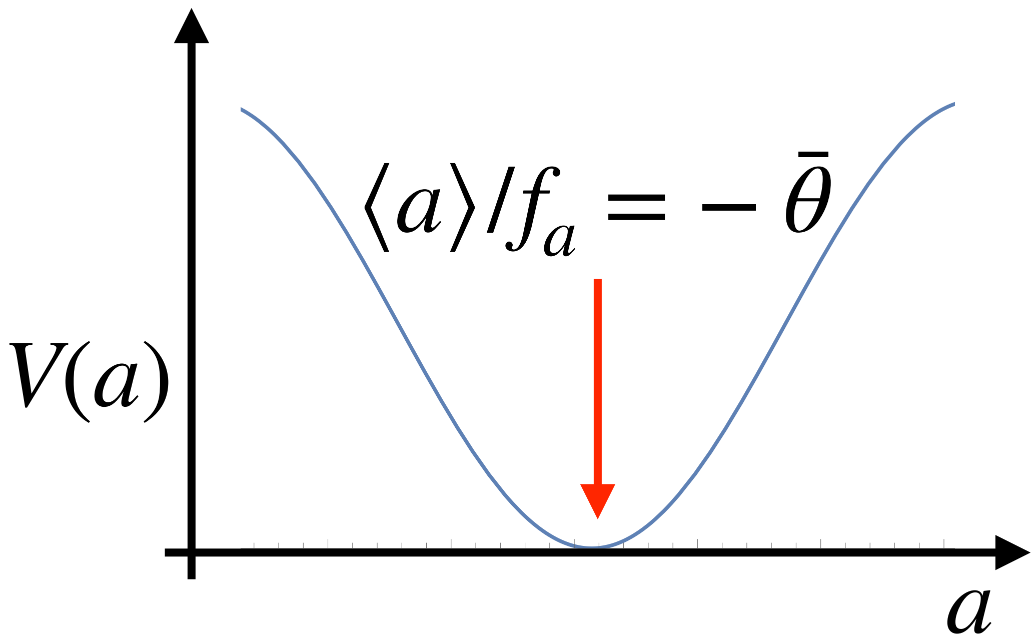
Strong CP Problem

Axion solution

- Axion solution:

$\bar{\theta}$ is a dynamical quantity

$$\mathscr{L}_{\text{SM+Axion}} \supset \frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G\tilde{G} \Rightarrow V(a) \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right)$$



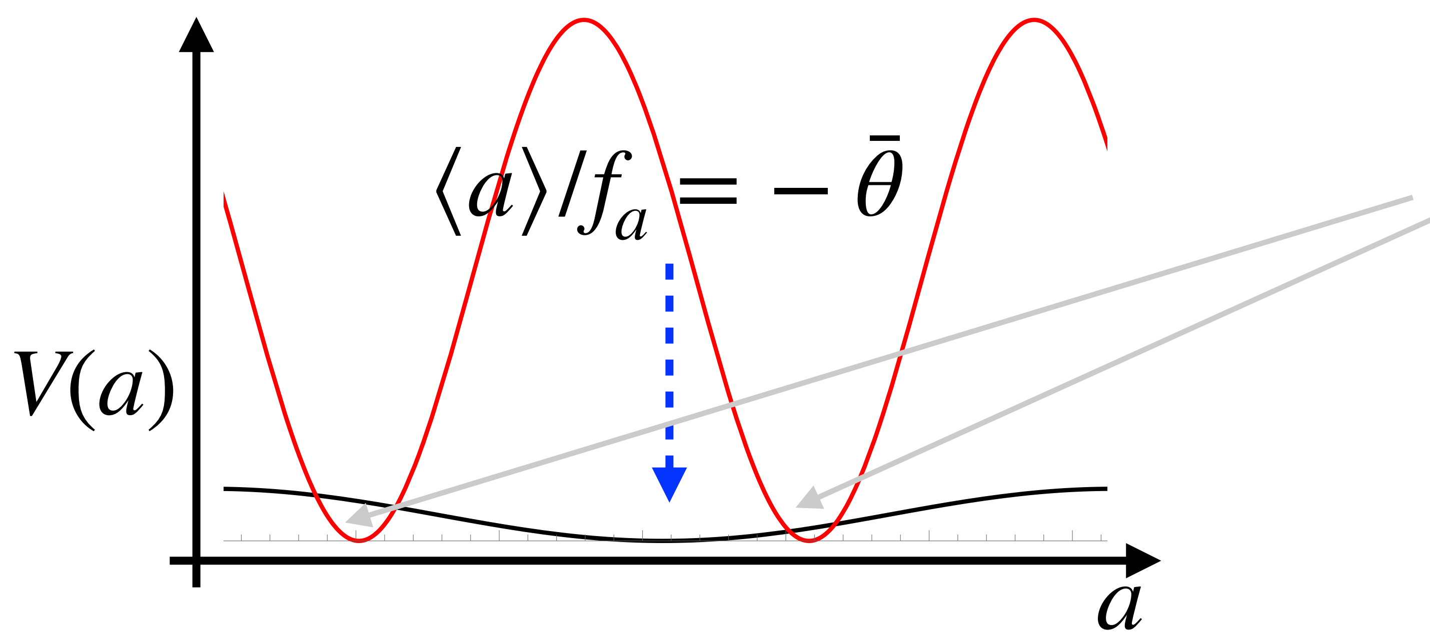
effective $\bar{\theta} = 0$!

elegant solution from IR EFT point of view

Axion quality problem

- But not so from UV! Imagine a arising as Goldstone from Peccei-Quinn scalar $\Phi \sim f_a e^{ia/f_a}$

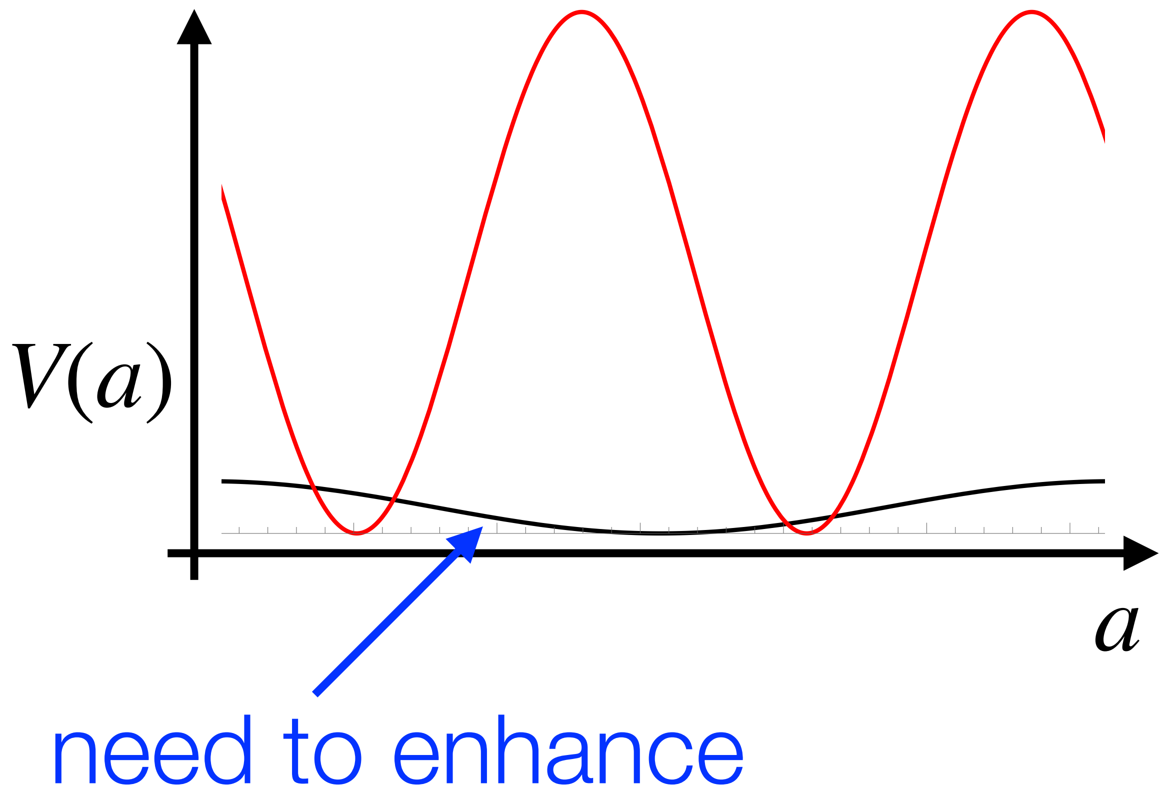
$$\frac{\Phi^N}{M_{pl}^{N-4}} \Rightarrow V(a) \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right) + \frac{f_a^N}{M_{pl}^{N-4}} \cos\left(\frac{a}{f_a} + \delta\right)$$



new axion minima
$\bar{\theta} \sim \mathcal{O}(1)$ again

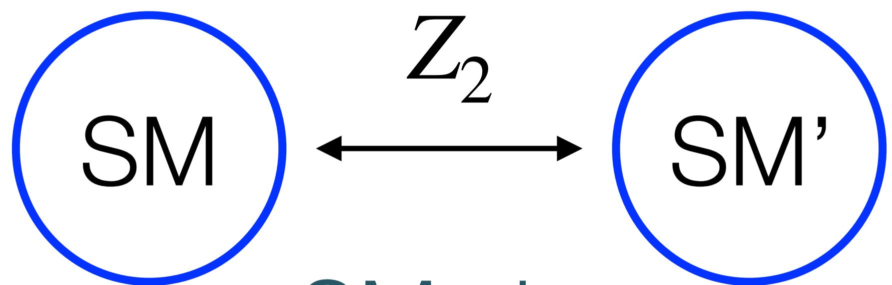
to avoid need $N > 9$
for $f_a > 10^9$ GeV!

Sketching a solution to the quality problem



- In minimal set-up, axion potential gets contribution from QCD.
- So why not imagine a QCD' sector?

Mirror solution to quality problem



Rubakov '97
Berezhiani et. al. '01

- SM' does not carry any SM charge and vice-versa

- Z_2 broken by the only relevant operator of SM: Higgs mass term, reasonable from "the Naturalness Principle"

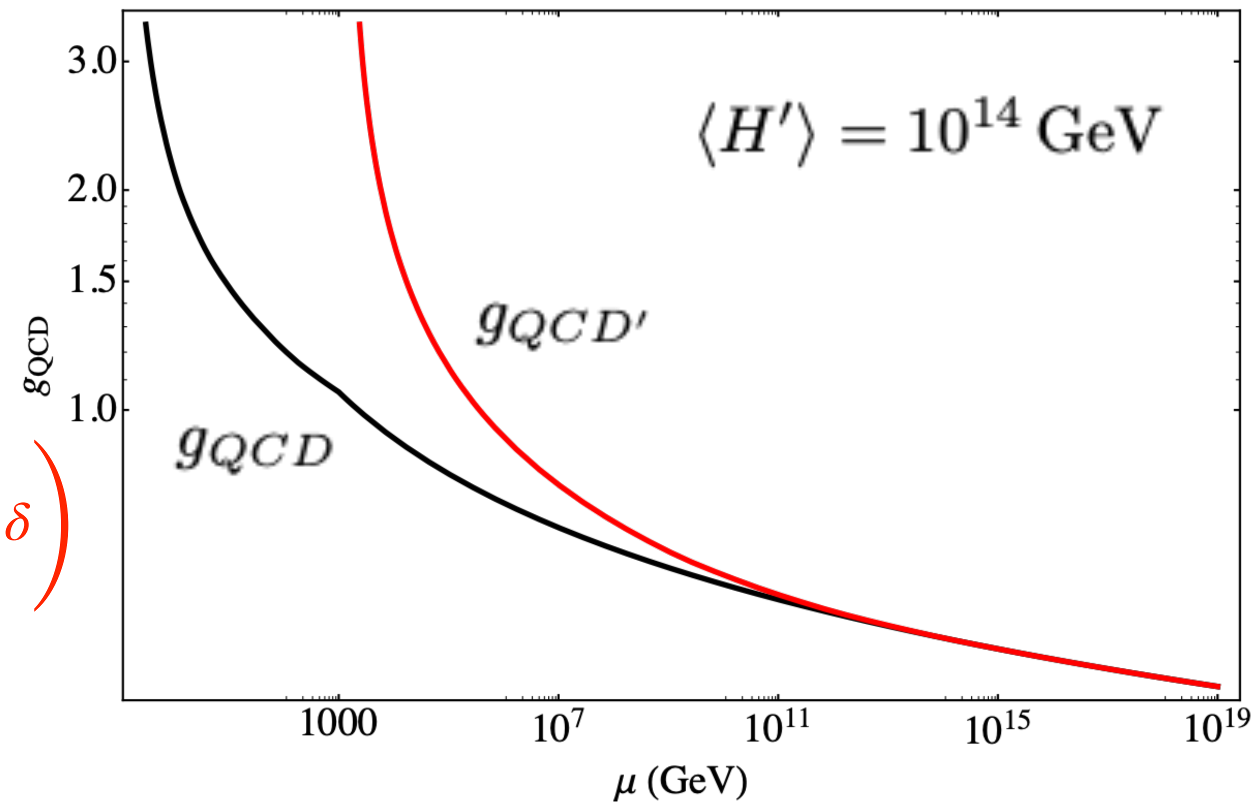
$$\mu^2 H^\dagger H + \mu'^2 H'^\dagger H' \text{ with } \mu'^2 \gg \mu^2$$

$$\frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right)\left(G\tilde{G} + G'\tilde{G}'\right)$$

Same $\bar{\theta}$: strong CP still solved

Enhancing the axion potential

- Larger Higgs' VEV in mirror sector: earlier decoupling of mirror quarks



$$V(a)_{\rm old} \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{2f_a} + \frac{\bar\theta}{2}\right) + \frac{f_a^N}{M_{pl}^{N-4}} \cos\left(\frac{a}{f_a} + \delta\right)$$

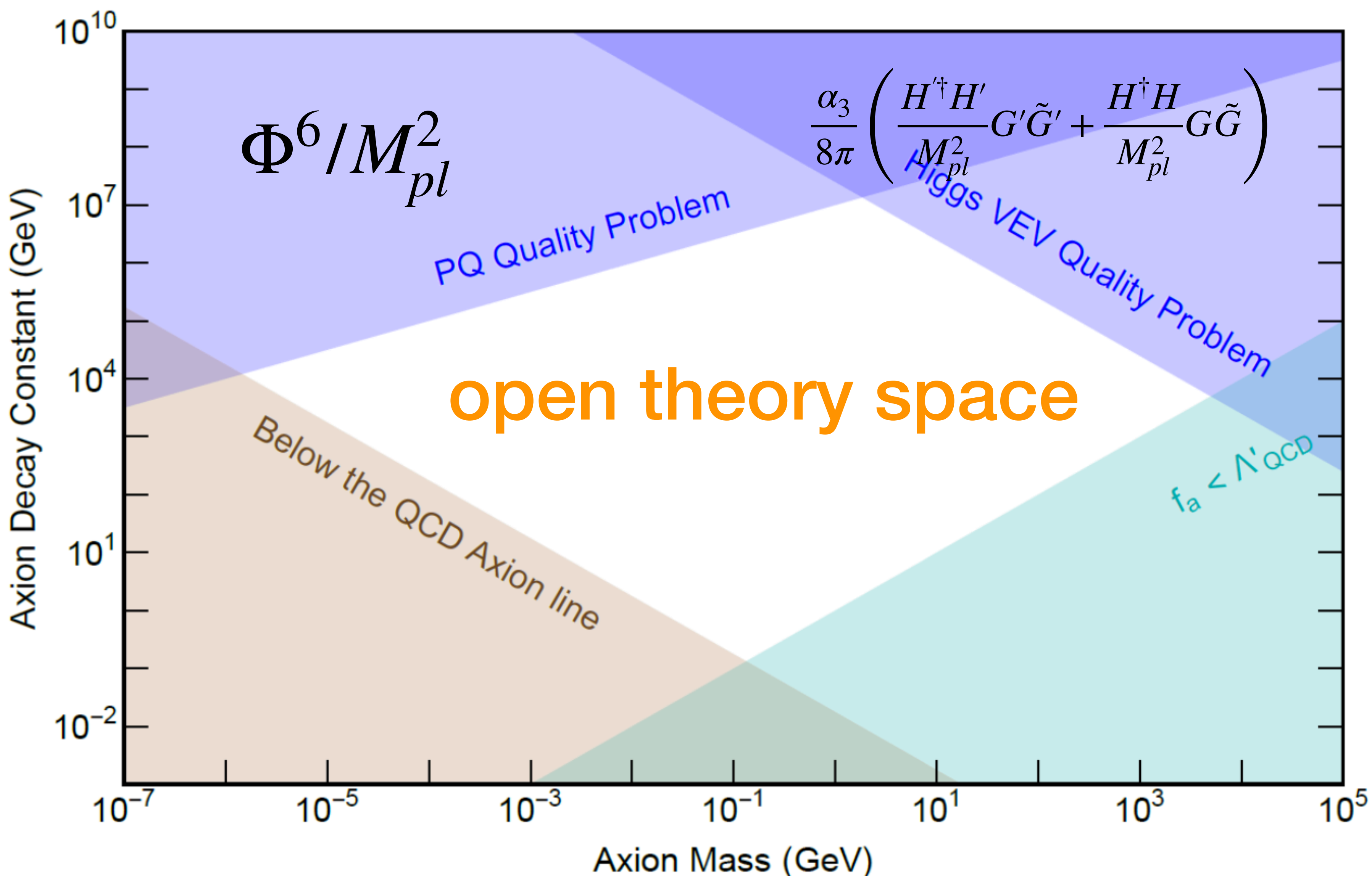
$$+\Lambda^4_{QCD'} \cos\left(\frac{a}{2f_a} + \frac{\bar\theta}{2}\right)$$

~ 100 MeV^4

$\sim$ TeV^4

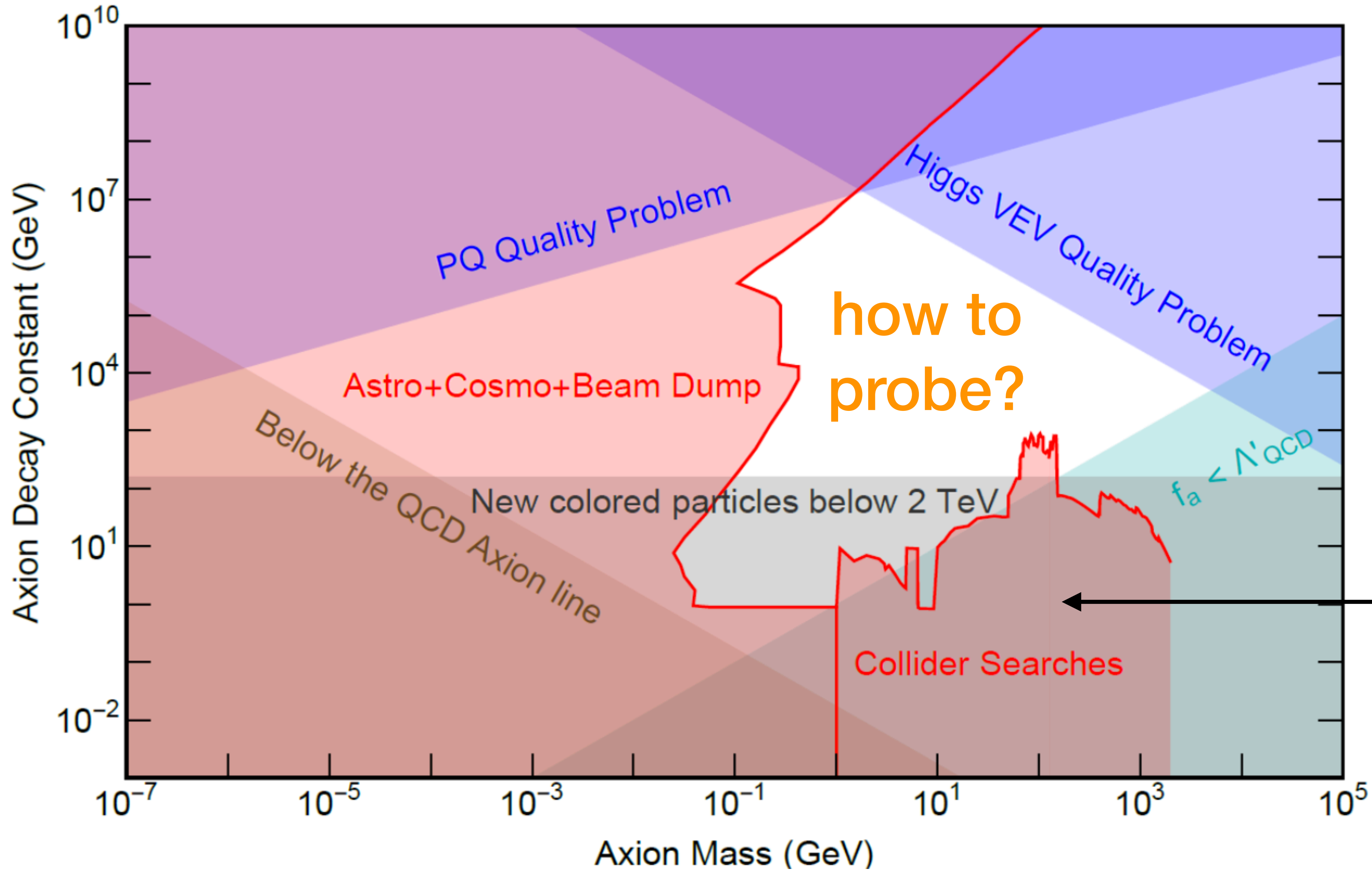
Less susceptible to quality problem!

Theory parameter space



Experimental constraints

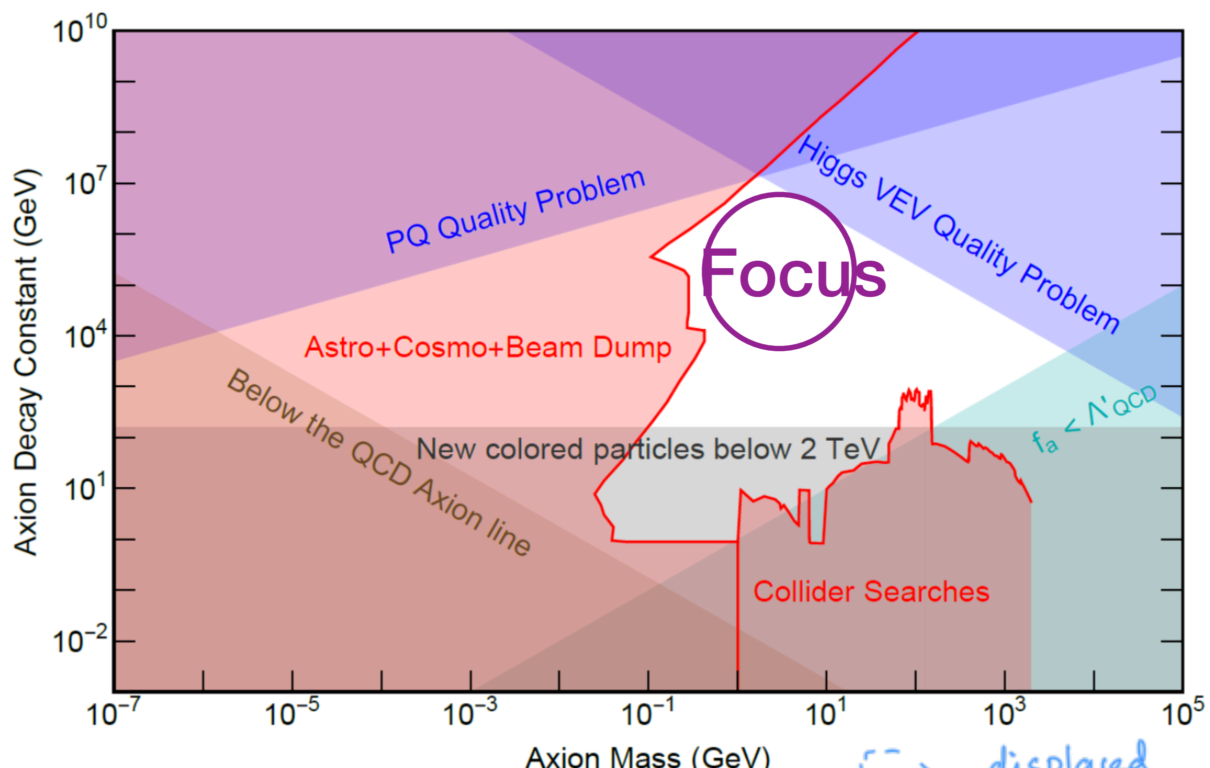
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$



$c_i = 1$

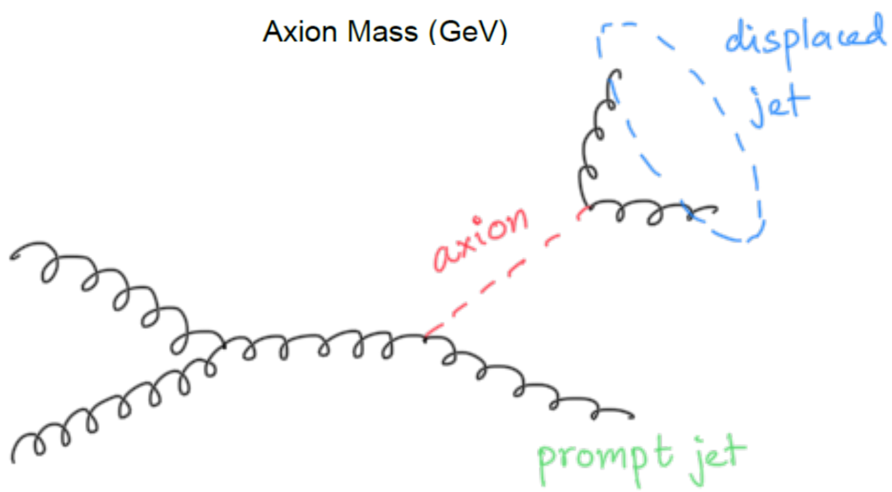
LHCb diphoton,
LHC diphoton,
$B \to K^{(*)} a(\gamma\gamma)$

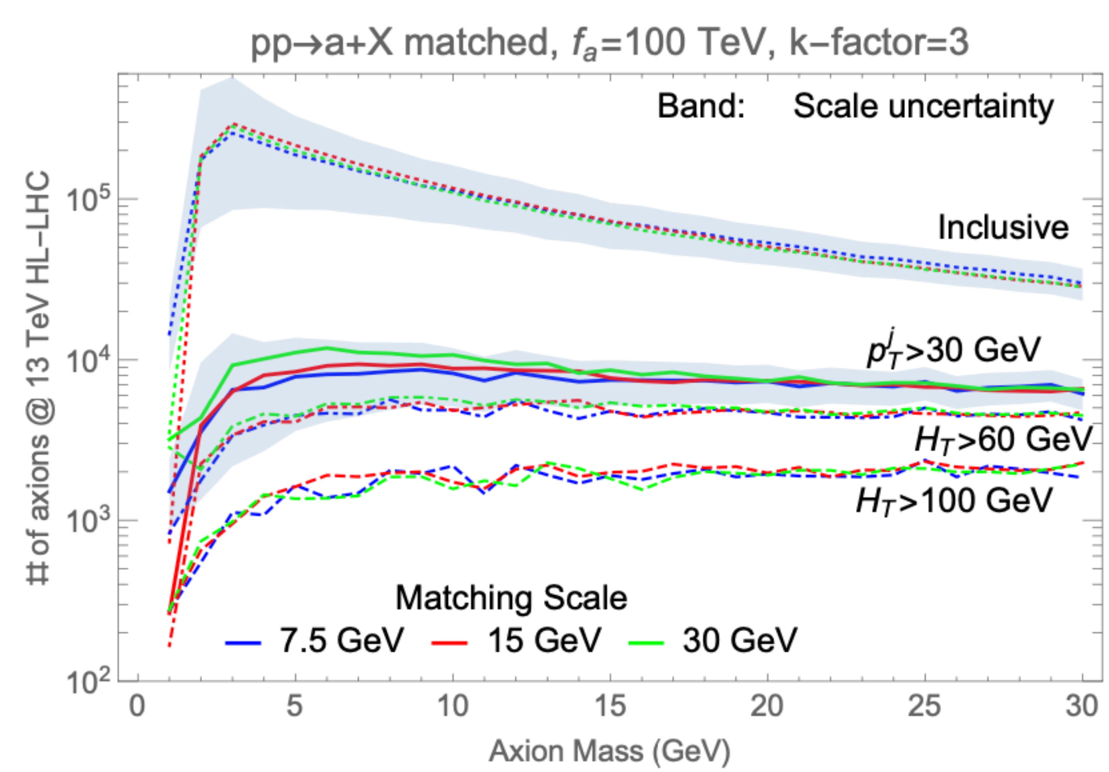
Long-lived axion!



$$c\tau \simeq 0.8 \left(\frac{f_a}{100\ \text{TeV}}\right)^2 \left(\frac{2\ \text{GeV}}{m_a}\right)^3 \text{mm.}$$

macroscopic decay-length





non-negligible production

How to trigger?

- *Displaced Track Trigger* at HL-LHC will be crucial!

Gershtein '17
CMS-PAS-FTR-18-018

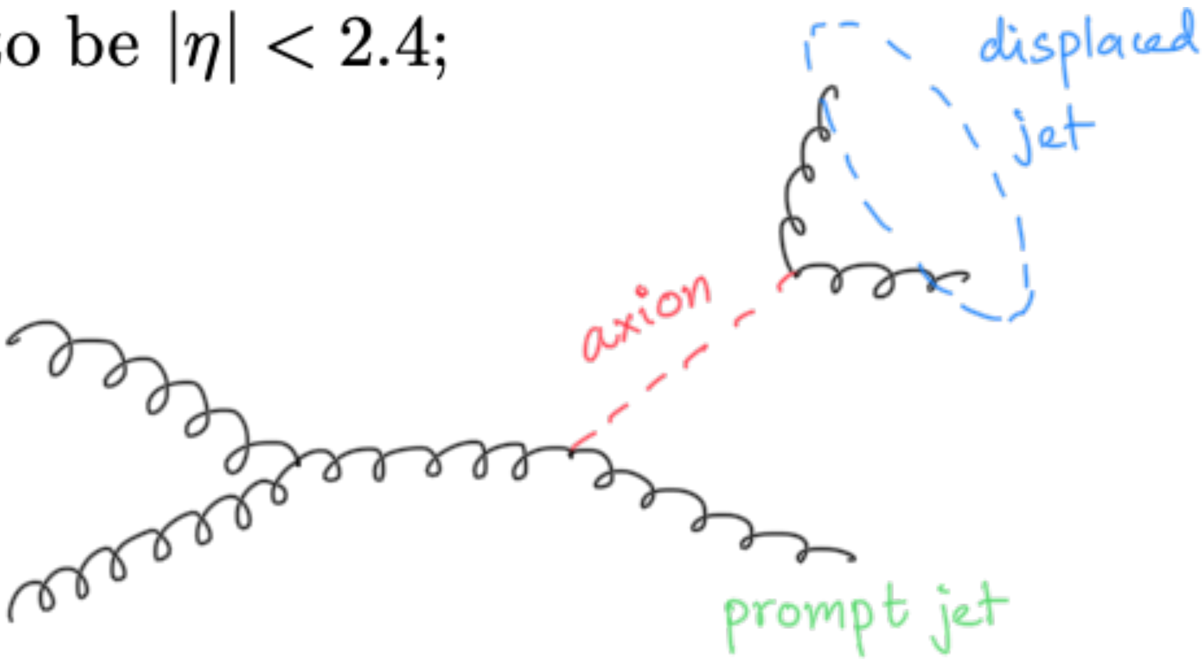
At least three $p_T > 2$ GeV tracks within an Level-1 (L1) trigger jet;

Amongst the above tracks, at least three of them have the transverse impact parameter $d_0 > 1$ mm;

Gershtein, Knapen '19

The pseudo-rapidity of the tracks to be $|\eta| < 2.4$;

The event has $H_T > 100$ GeV.



Leading background from fake-tracks

- Arise from misconnections of tracker hits and instrumental noise.
- Difficult to model, requires dedicated experimental analysis.
- Here we take a rough empirical model approach to suggest the fake-tracks can be plausibly suppressed.

2D-4D selection procedure

Fake-track background (BG)

$\sim 10^{12}$ after L1

2D-4D selection strategy

1. The 2D tracks fit a common vertex with standard deviation $\Delta d_T < 1$ cm;
2. The 2D common vertex has a minimal distance to the interaction point of 0.5 cm and maximal distance of 35 cm, $0.5 \text{ cm} < d_T < 35$ cm;
3. The 2D common vertex is significantly displaced away from the interaction point, $d_T/\Delta d_T > 5$;
4. The corresponding 4D vertex has a standard deviation in z direction $\Delta d_z < 5$ cm;
5. The corresponding 4D vertex has a z-direction location $d_z < 20$ cm;
6. The corresponding 4D vertex has a standard deviation in time $\Delta d_t < 500$ ps;
7. The corresponding 4D vertex has a time $d_t <$ 1000 ps;
8. The tracks are within 0.4 in pseudorapidity of the reconstructed displaced jet direction $|\eta_i - \eta_V| < 0.4$ for all the three tracks;
9. The tracks are within 0.4 in azimuthal angle of the reconstructed displaced jet direction $|\phi_i - \phi_V| < 0.4$ for all the three tracks,

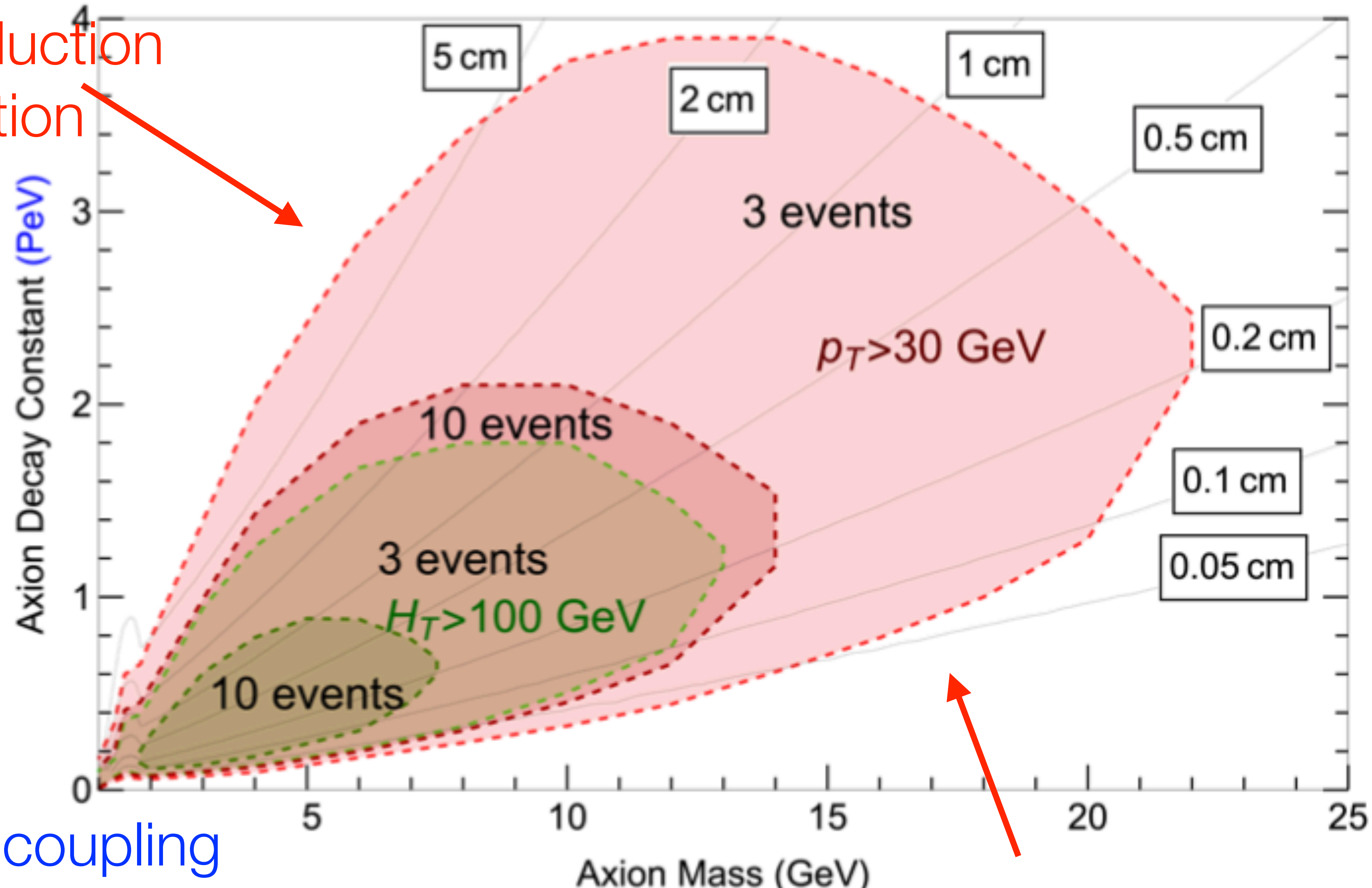
BG $\sim 10^3$

matching between sub-detectors:

BG $\sim \mathcal{O}(1)$

Coverage of High Quality Axion Search

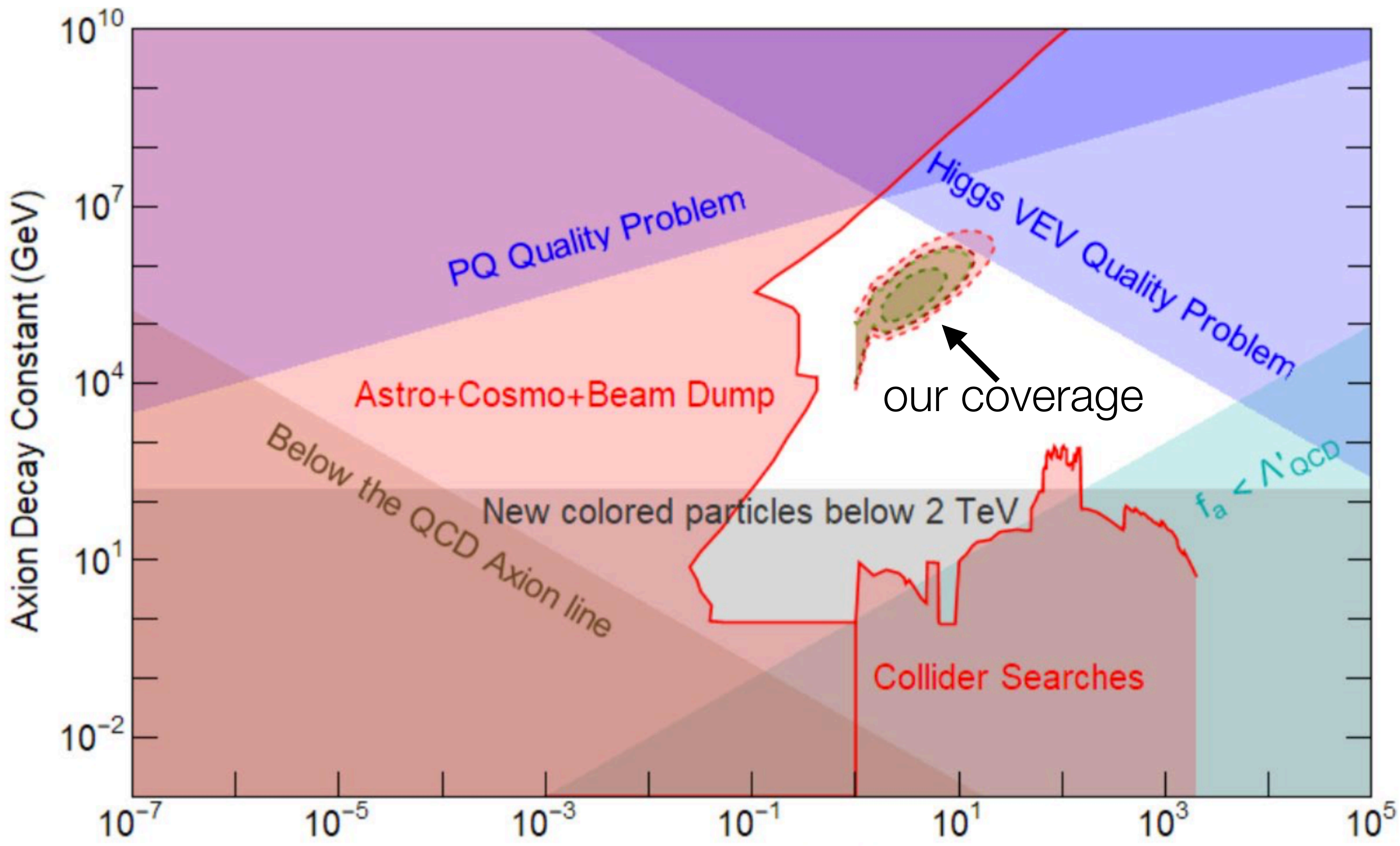
determined
by small production
cross-section



same gluon coupling
controls
production AND decay

axion no longer long-lived

In view of the broad parameter space

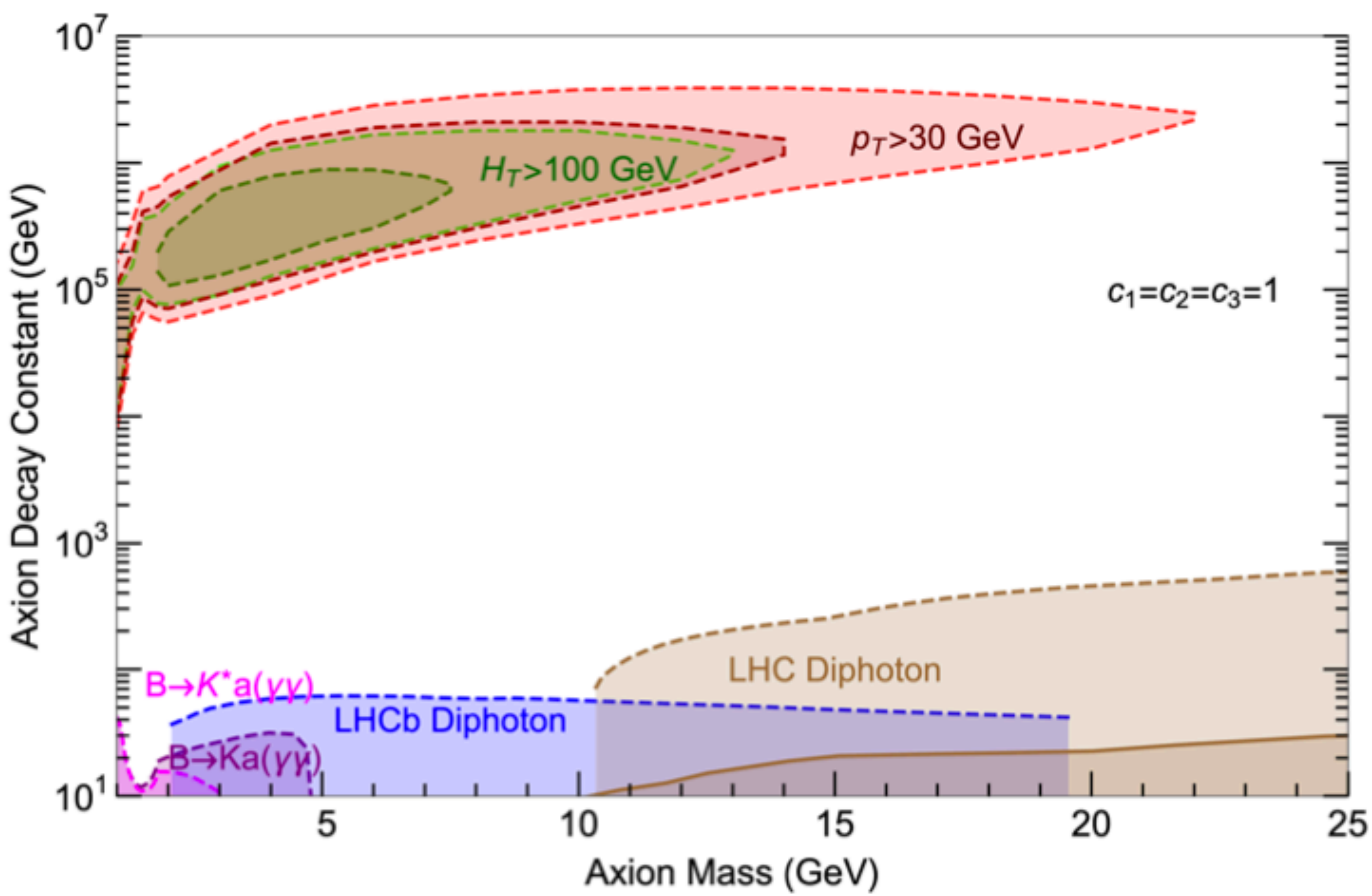


Conclusion

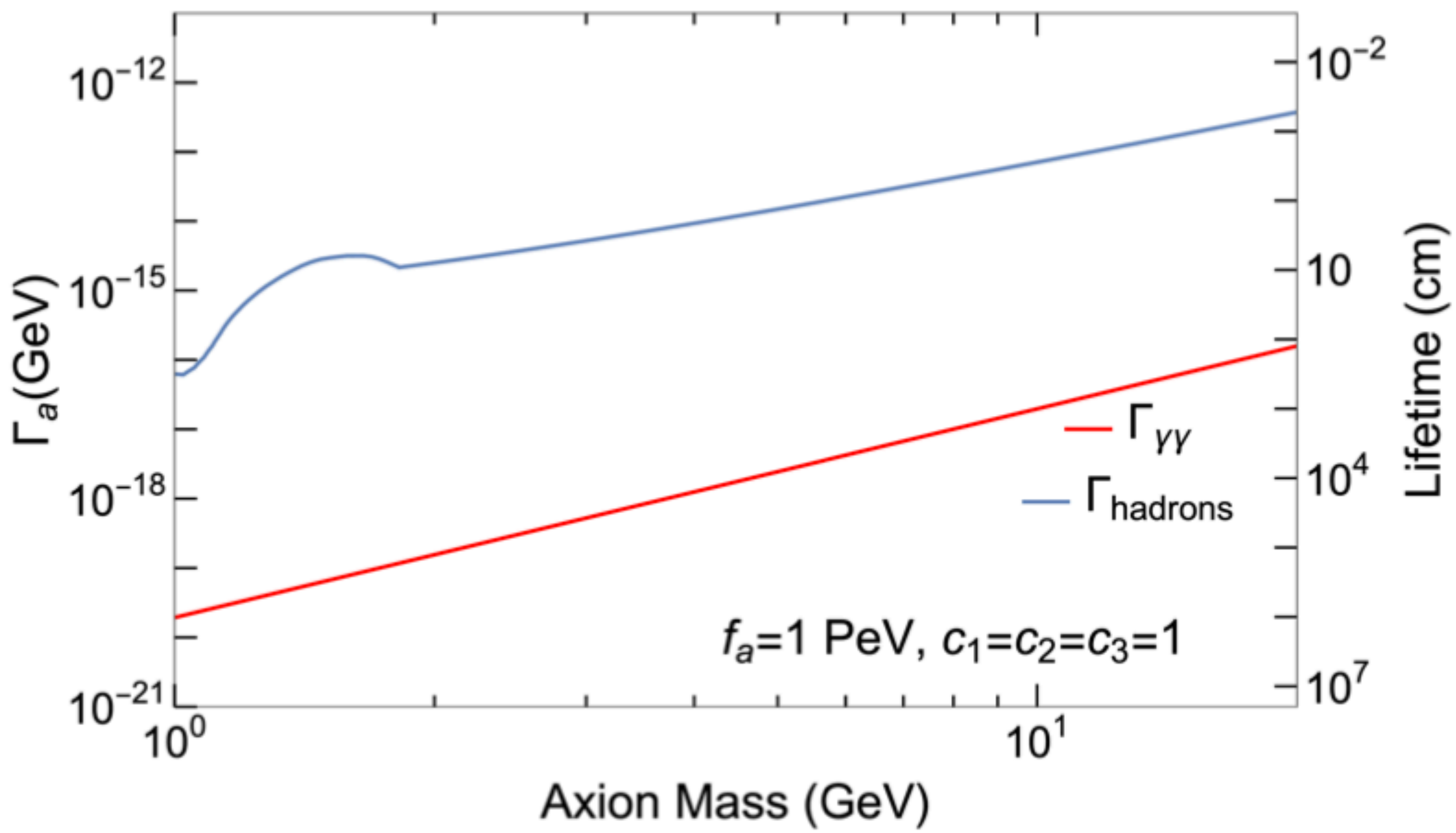
- Axion is an elegant IR solution, but suffers from quality problem.
- Discussed a mirror sector based solution: ameliorated quality problem.
- Very interesting phenomenology signal: long-lived axions
- 2D-4D selection criteria to reduce fake-track background
- Covers novel parameter space: exciting case for further experimental exploration!

Thanks!

Back up - comparison with other searches

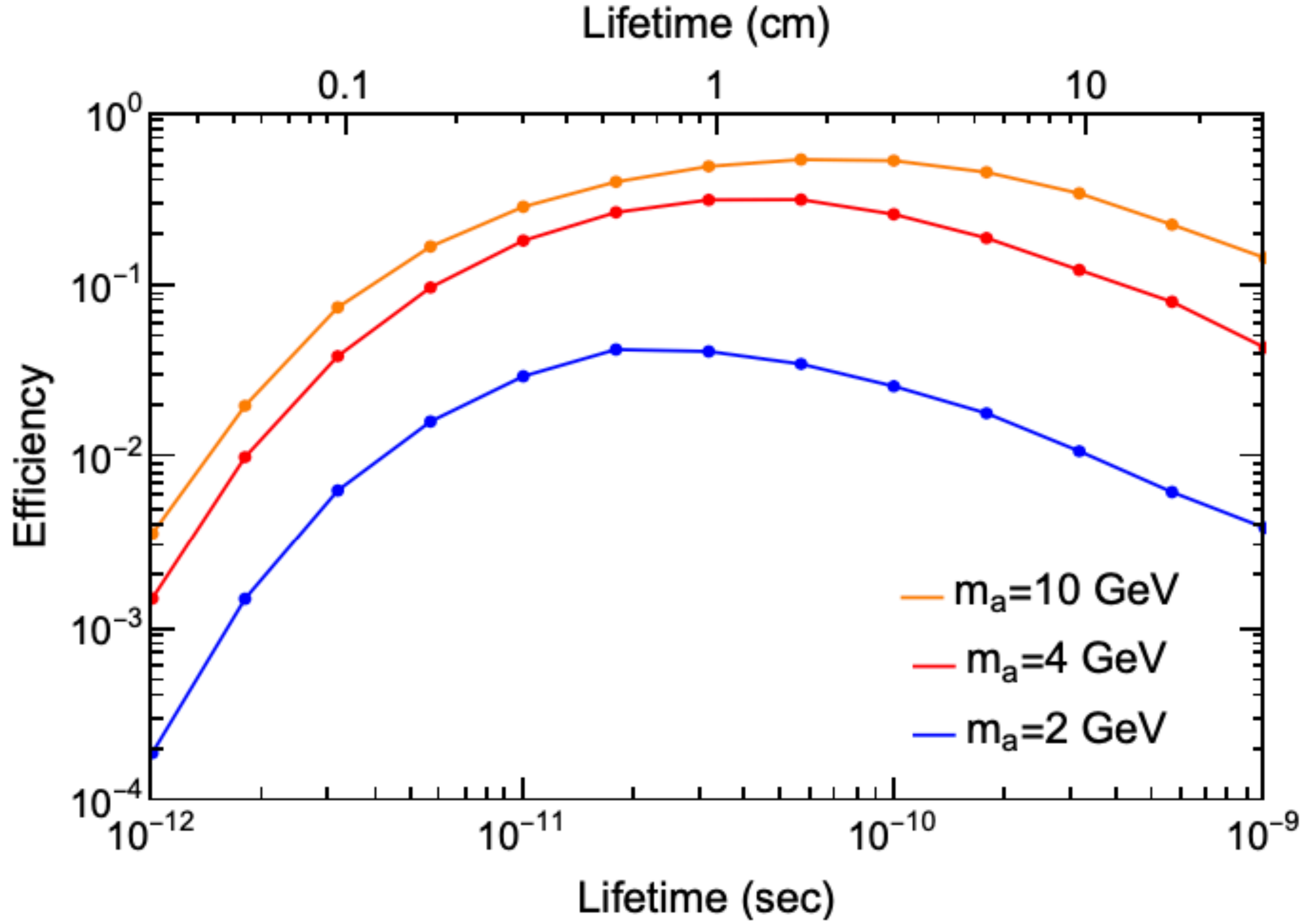


Decay width



10^{-12}
10^{-15}
10^{-18}
10^{-21}
Γ_a(GeV)
10^{-2}
10
10^4
10^7
Lifetime (cm)
$\Gamma_{\gamma\gamma}$
$\Gamma_{hadrons}$
f_a=1 PeV, c_1=c_2=c_3=1
10^0
10^1
Axion Mass (GeV)

Selection efficiency



Kinematic distribution of tracks