Pencil Jets - aka
A High Quality Axion at the LHC

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AH, S. Kumar, Z. Liu, R. Sundrum : 1911.XXXX

Outline

- The Strong CP problem and Axions
- Quality problem and its solution
- Interesting and challenging displaced signatures

What is the QCD axion?

Classical

Simple solution to a simple problem

Quantum

Simple solution to a subtle problem

Only one or two parameters

Can naturally be Dark Matter

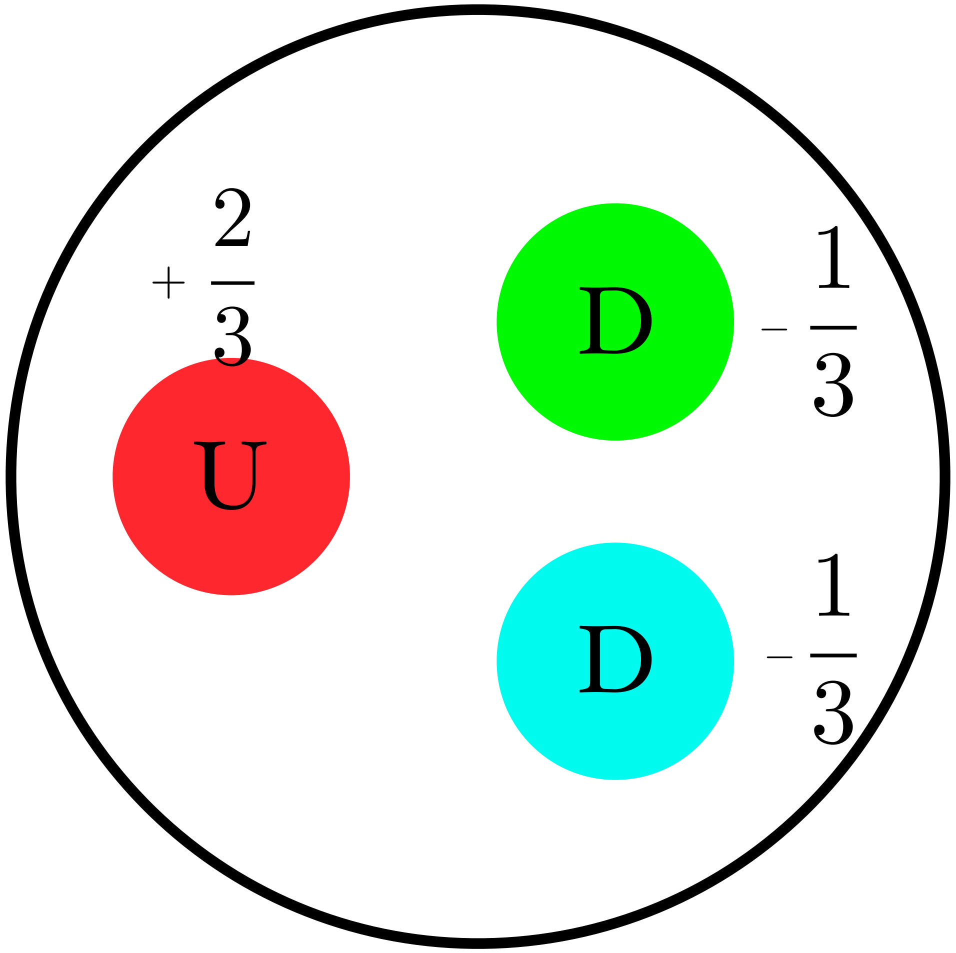
(Wrong) Classical Strong CP Problem

Draw a neutron

Neutron contains an up quark and two down quarks

(Wrong) Classical Strong CP Problem

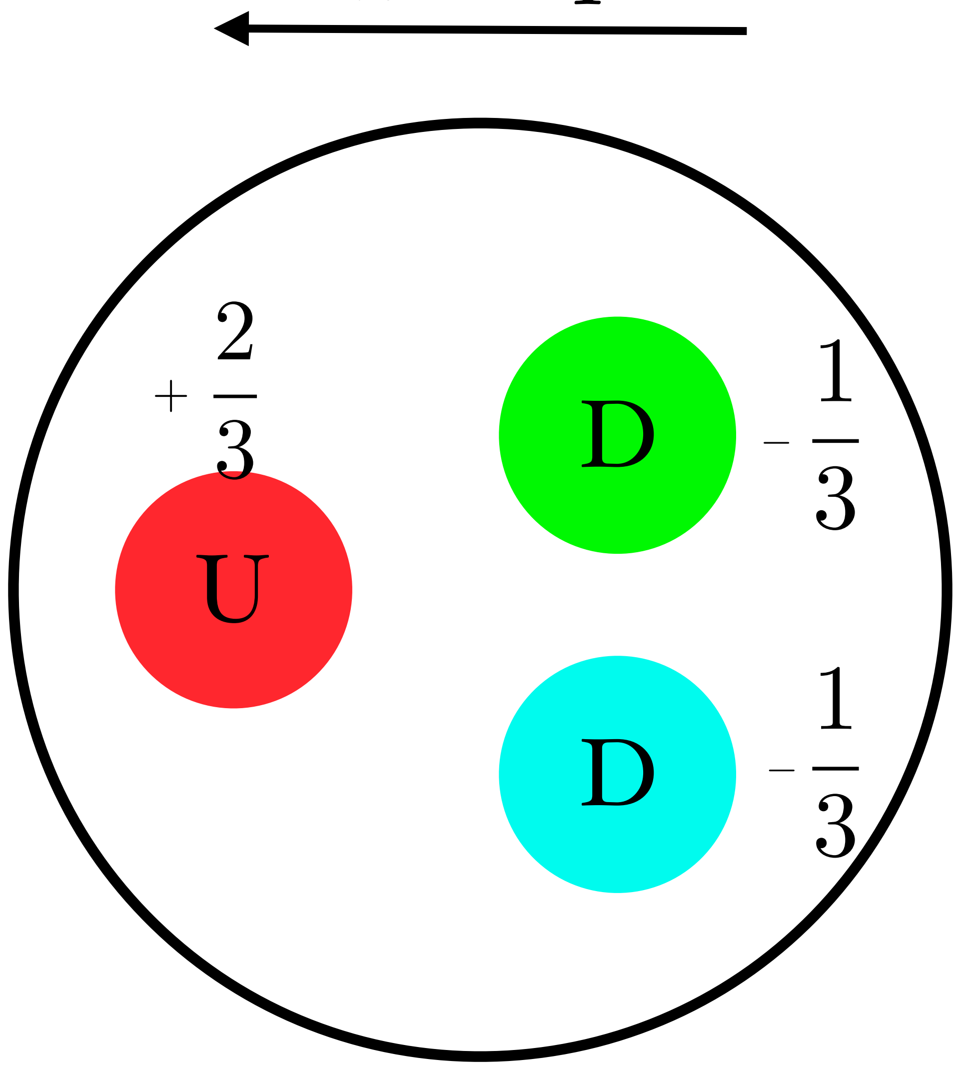
Neutron contains an up quark and two down quarks



(Wrong) Classical Strong CP Problem

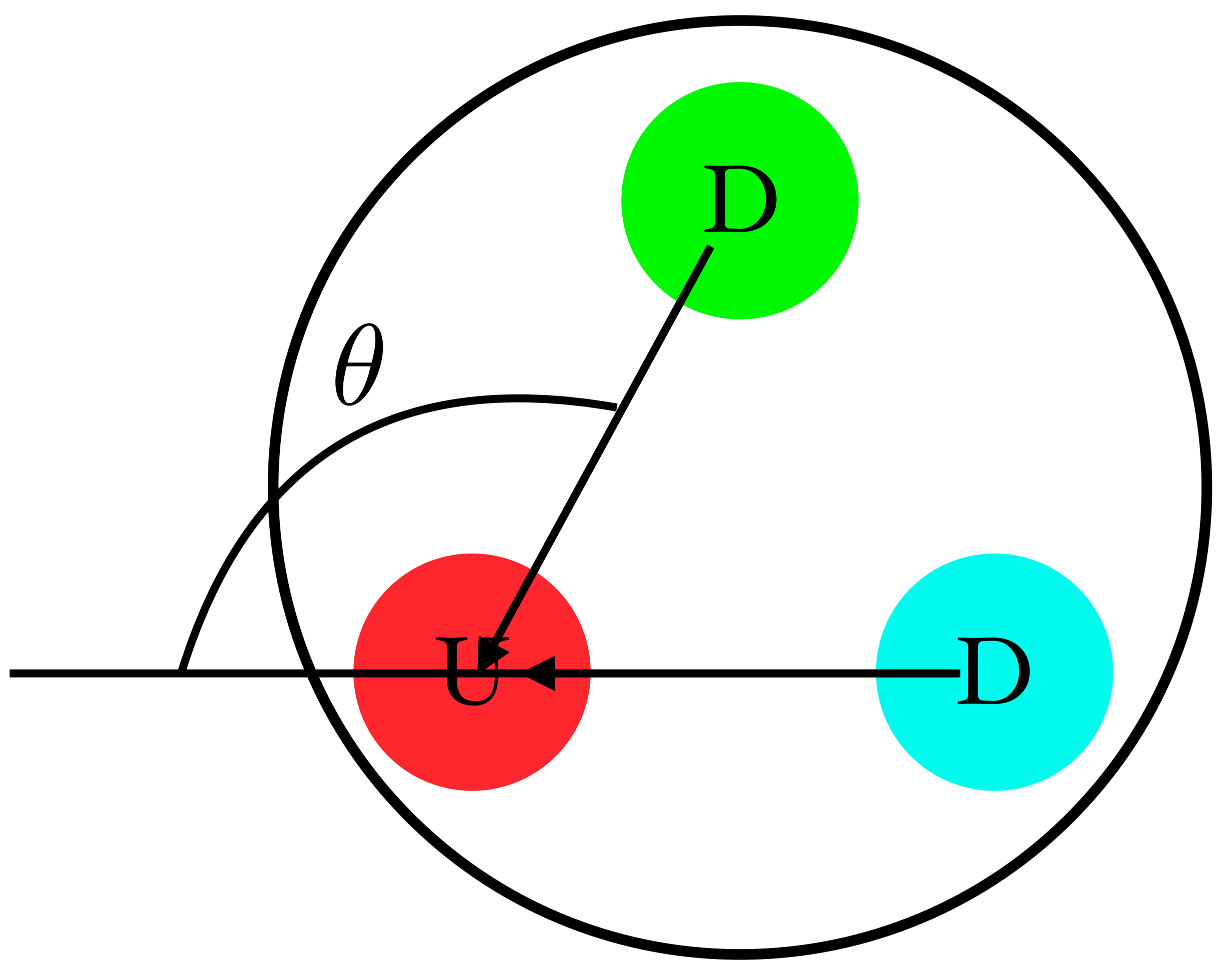
Calculate electric dipole moment

$$d_n = qx$$



(Wrong) Classical Strong CP Problem

$$
\begin{aligned}
|d_n| &\approx ex\sqrt{1-\cos\theta} \\
&\approx 10^{-14}\, e\, \sqrt{1-\cos\theta}\ \mathrm{cm}
\end{aligned}
$$

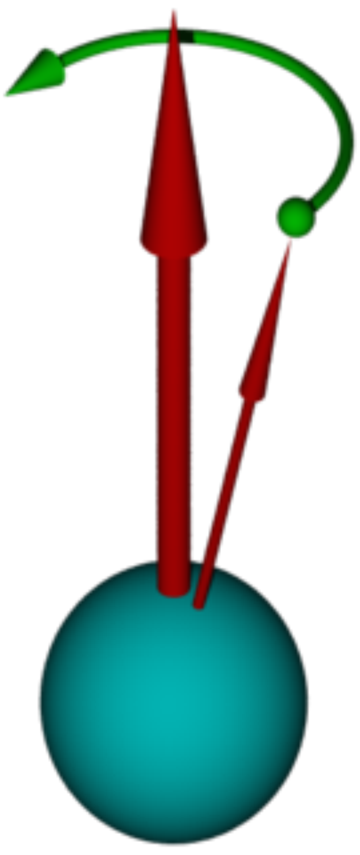


(Wrong) Classical Strong CP Problem

Measurement via Larmor frequency

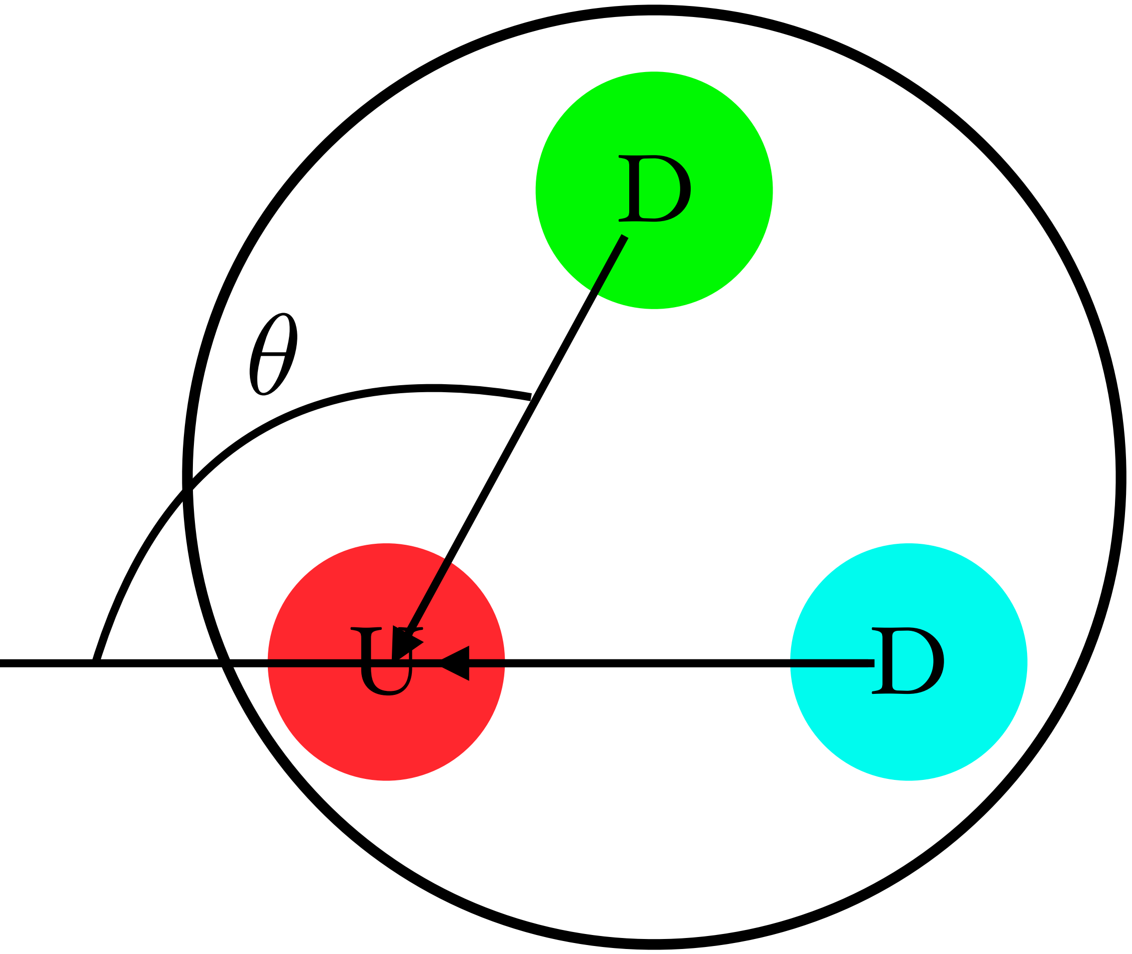
$$h\nu_{\uparrow\uparrow} = |2\mu_n B + 2d_n E|$$

$$h\nu_{\uparrow\downarrow} = |2\mu_n B - 2d_n E|$$



Measure number of spin up versus spin down neutrons for parallel and anti-parallel electric and magnetic fields

eDM estimate



Estimate

$$|d_n| \approx ex\sqrt{1-\cos\theta}$$
$$\approx 10^{-14}\, e\, \sqrt{1-\cos\theta}\ \mathrm{cm}$$

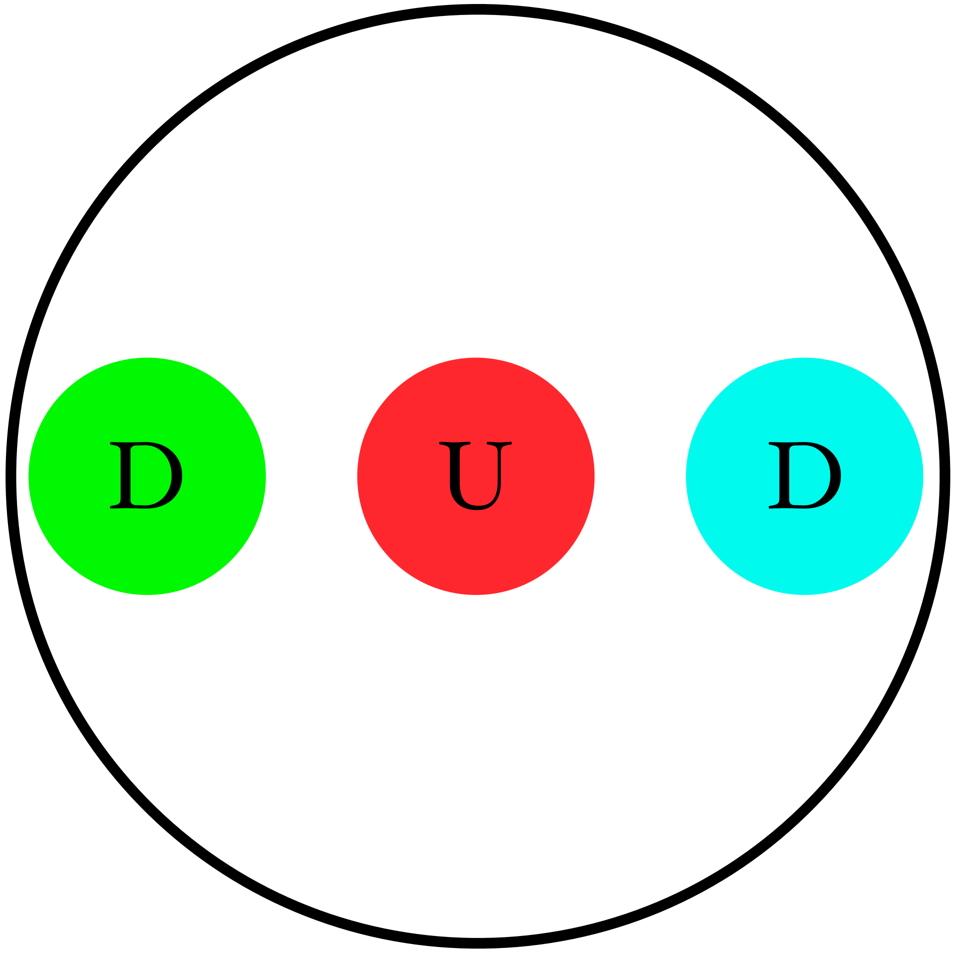
Measurement

$$|d_n| < 2.9 \times 10^{-26}\, e\, \mathrm{cm}$$

Baker et. al. hep-ex/0602020 :
Institut Laue-Langevin, Grenoble

(Wrong) Classical Strong CP Problem

Aka why does everyone draw the neutron wrong?



$$\theta < 10^{-12}$$

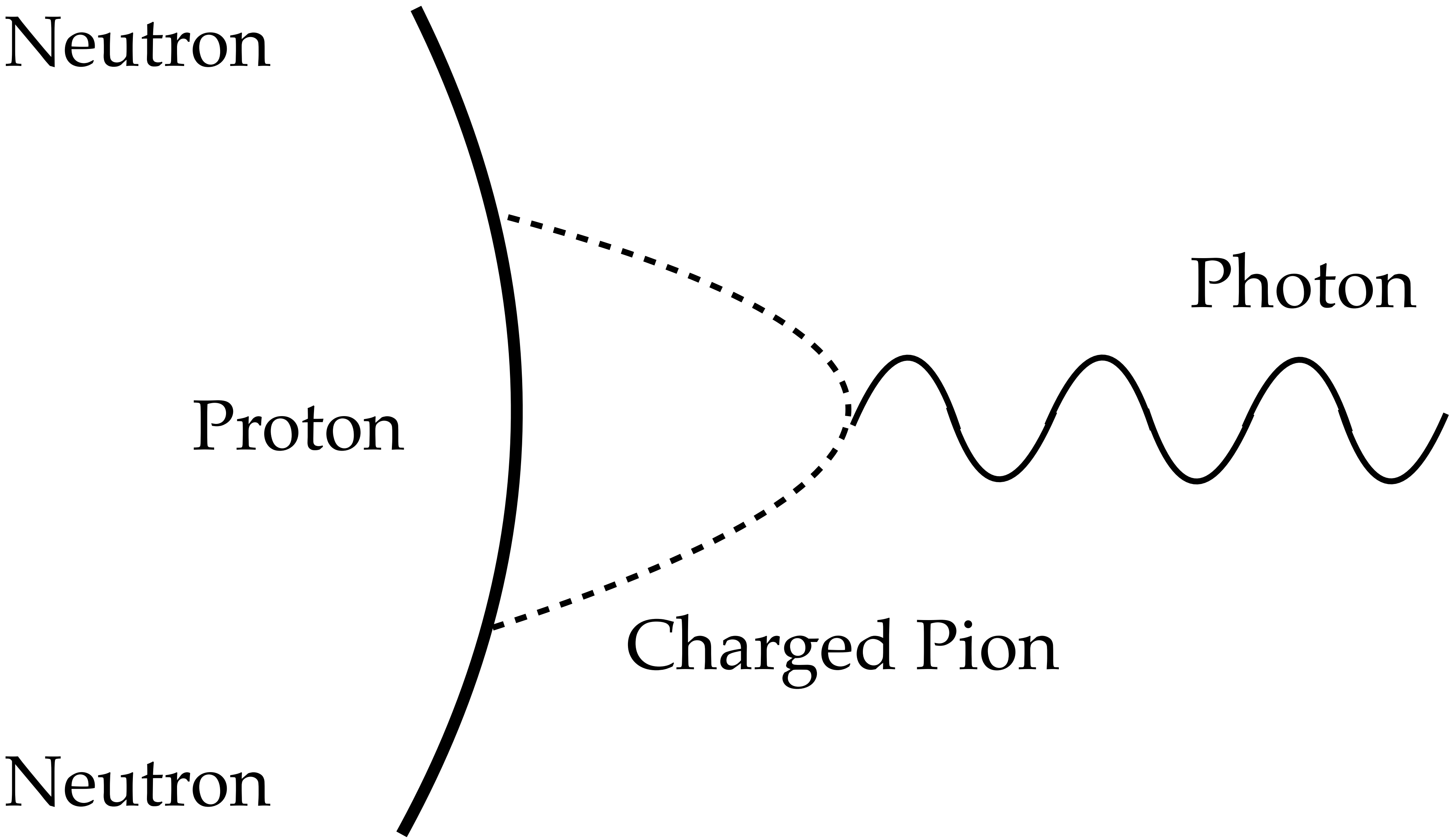
4D Quantum Strong CP problem

Theory of QCD

$$\frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu} + m_u e^{i\theta_u} u^c u + m_d e^{i\theta_d} d^c d$$

Use Chiral Perturbation theory to calculate neutron eDM

4D Quantum Strong CP problem



$$|d_n| = 3.2 \times 10^{-16}(\theta + \theta_u + \theta_d)\, e\, \mathrm{cm}$$

4D Quantum Strong CP problem

$$|d_n| < 2.9 \times 10^{-26}\, e\,\mathrm{cm}$$

$$\overline{\theta} \equiv \theta + \theta_u + \theta_d < 10^{-10}$$

QFT formulation of the Strong CP problem

Simple Solutions

Four simple solutions to this simple problem

1. Universe is Left-Right symmetric
2. Universe is Time reversal invariant
3. Massless up quark
4. Axions

Simple Solutions

Four simple solutions to this simple problem

1. ~~Universe is Left-Right symmetric~~
2. ~~Universe is Time reversal invariant~~
3. ~~Massless up quark~~
4. Axions

Weak interactions

Kaon oscillations

Lattice

(Wrong) Classical Axion

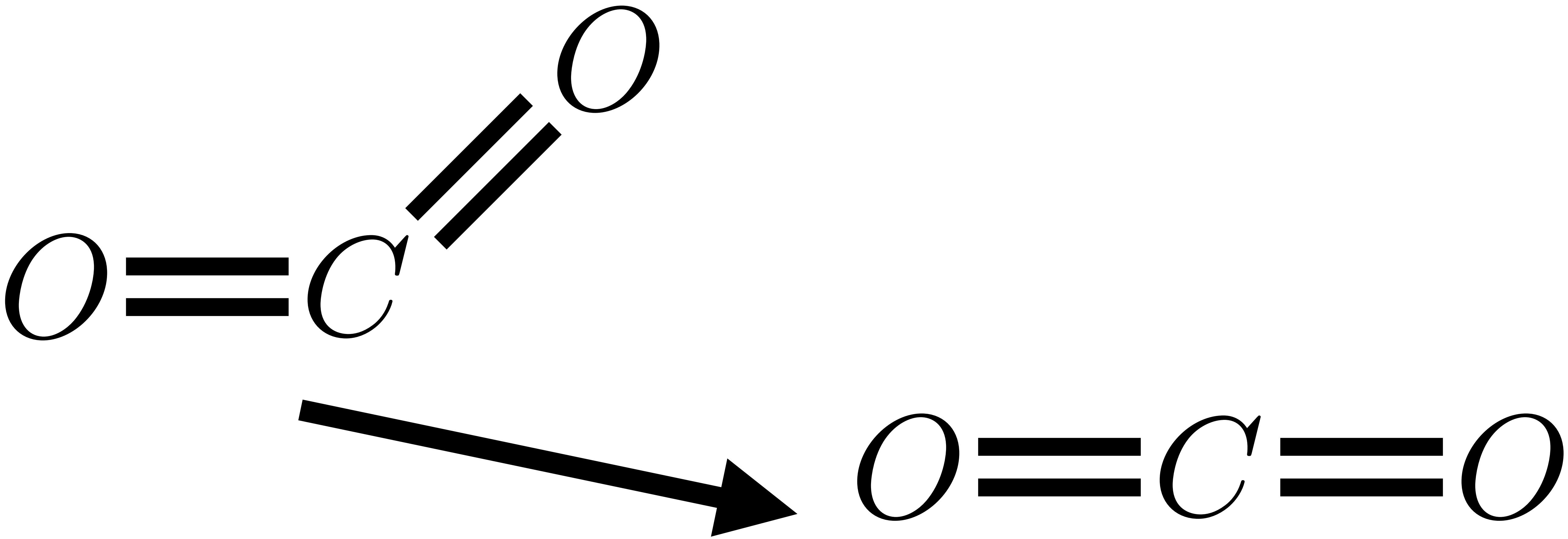
CO_2 also has a zero dipole moment

$$O = C = O$$

$$\delta_- \qquad \delta_+ \qquad \delta_-$$

Why is the dipole moment zero?

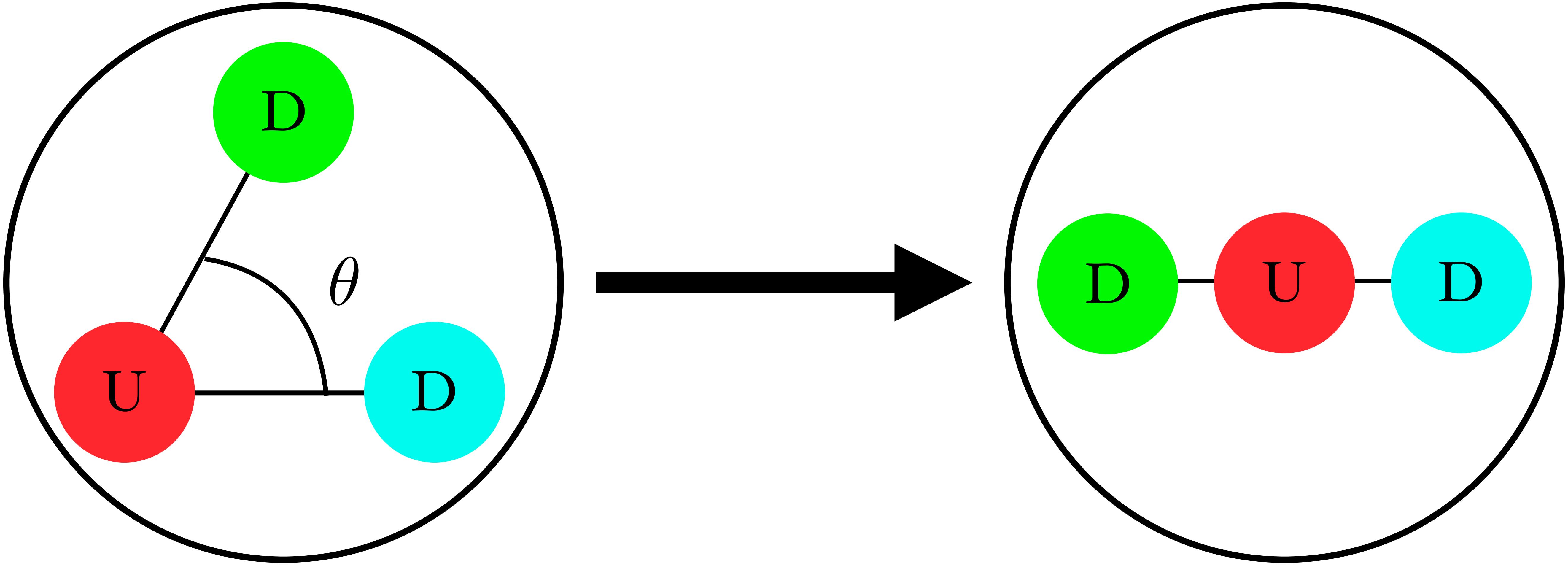
(Wrong) Classical Axion



Angle relaxes itself to zero!

(Wrong) Classical Axion

Plausible that if angle were dynamical maybe it would relax itself to a symmetric state



Quantum Axion

$$\frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu} \to \frac{g^2}{32\pi^2}\left(\theta - \frac{a}{f_a}\right)G_{\mu\nu}\tilde{G}^{\mu\nu}$$

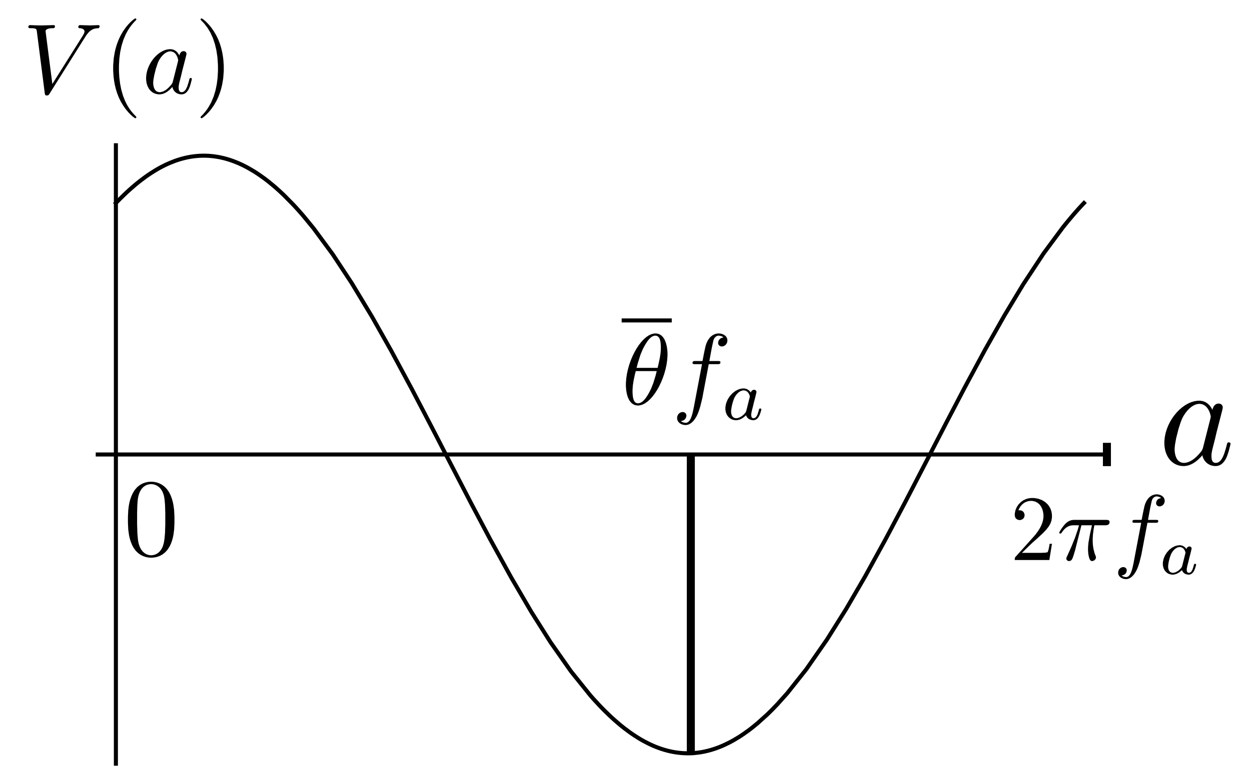
Introduce a field whose sole purpose is to make the angle dynamical

Quantum Axion

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\overline{\theta} - a/f_a}{2}\right)}$$

Axion dynamically sets the neutron EDM to 0

$$|d_n| = 3.2 \times 10^{-16}\, (\overline{\theta} - \langle \frac{a}{f_a} \rangle)\, e\,\mathrm{cm}$$



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Quantum Axion : Quality Problem

The axion fakes a dynamical angle

How good of an imposter is it?

Very difficult because in the Quantum world,
if something can happen, it will happen

Quantum Axion : Quality Problem

The axion fakes a dynamical angle

How good of an imposter is it?

$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\overline{\theta} - \frac{a}{f_a}\right) + \Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

$$\Lambda_{\mathrm{contamination}} < 0.1\,\mathrm{MeV}$$

Quantum Axion : Quality Problem

$$\Lambda_{\rm contamination} < 0.1\,{\rm MeV}$$

This is really really hard!

In the SM, there is the weak scale

Due to SM's very special flavor structure

$$\Lambda_{CKM} \sim 0.003\,{\rm MeV}$$

Quantum Axion : Quality Problem

$$\Lambda_{\text{contamination}} < 0.1\,\text{MeV}$$

There are also many other scales :
GUT, Inflation, Gravity, Dark matter

Quantum Axion : Quality Problem

$$\Lambda_{\text{contamination}} < 0.1\,\text{MeV}$$

There are also many other scales :
GUT, Inflation, Gravity, Dark matter

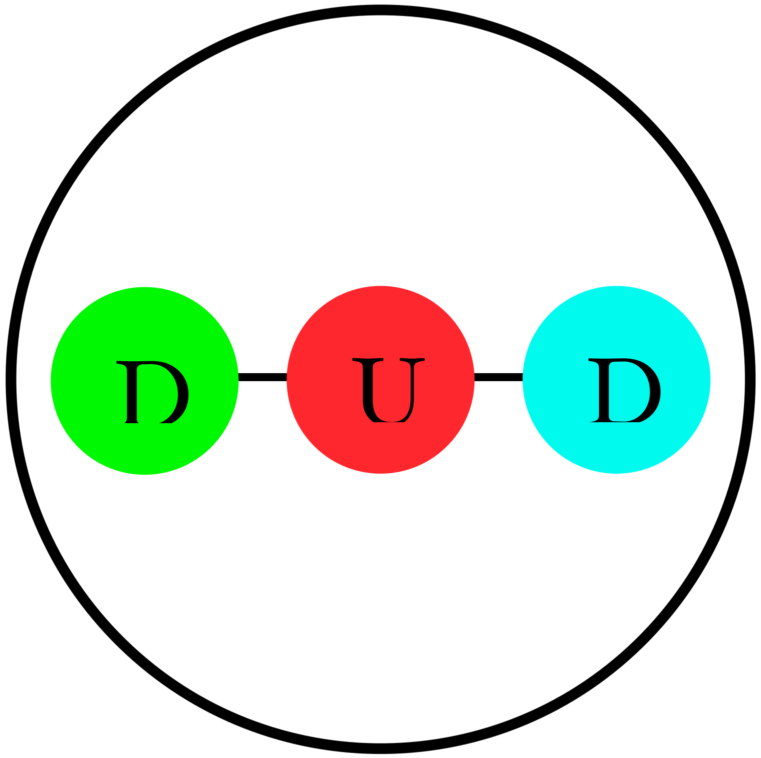
$$V = \frac{\Phi^{14}}{M_{pl}^{10}}$$

Leading order gravity suppressed operators must be suppressed by 10 powers of the Planck scale!

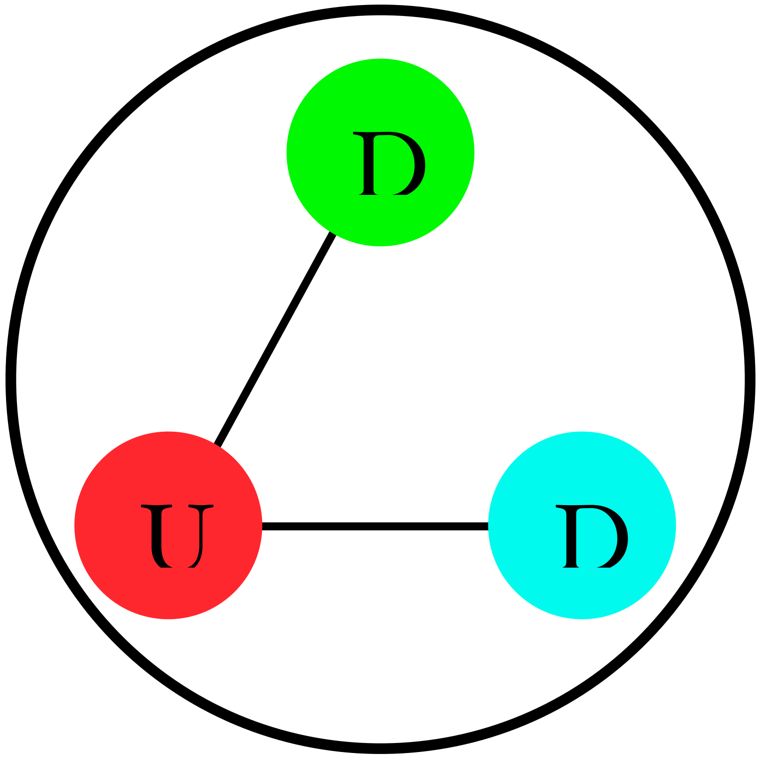
A High Quality Axion

Hard to modify the axion story

Want to relax to here



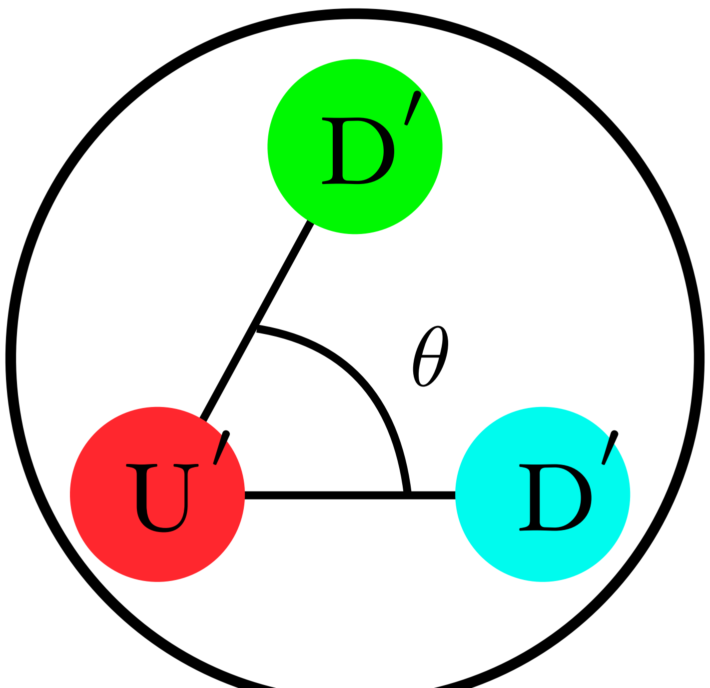
Don't want to relax to here

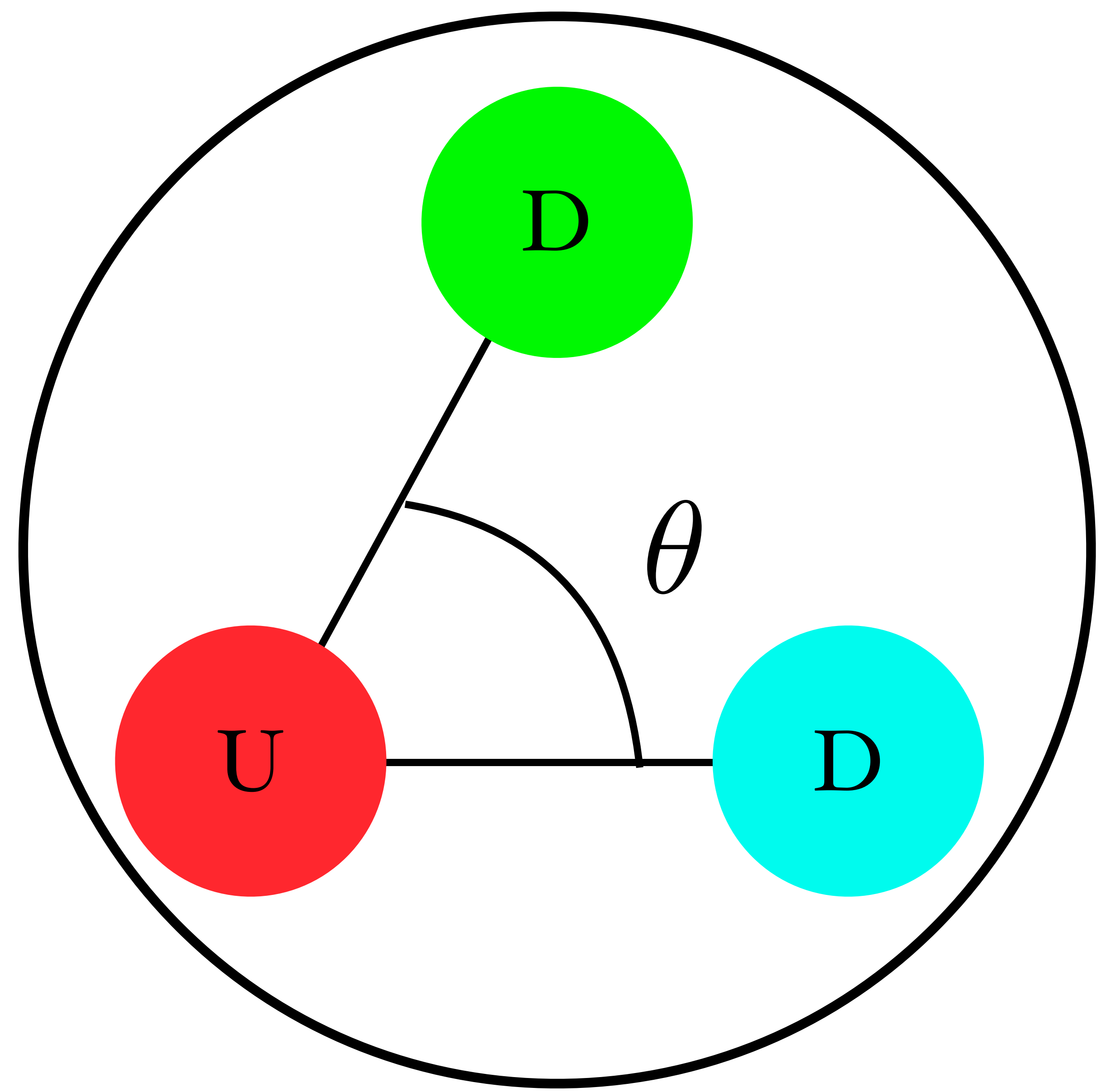


$$V \approx -(100\,\text{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right) - \Lambda^4 \cos\left(\theta' - \frac{a}{f_a}\right)$$

A High Quality Axion

What if axion relaxes neutron and neutron′ at the same time?





A High Quality Axion

$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\overline{\theta} - \frac{a}{f_a}\right) - \Lambda^4 \cos\left(\theta' - \frac{a}{f_a}\right)$$

1. Both neutron and neutron′ need the same angle θ
2. Neutron′ should be heavier

A High Quality Axion

1. Both neutron and neutron′ need the same angle θ
2. Neutron′ should be heavier

Extremely hard because Neutron′ needs to be heavier but still be a faithful copy to within 10 orders of magnitude!

Consider a copy of the Standard Model

A High Quality Axion

In extra dimensions, the Standard Model are the degrees of freedom living on a brane

Like an molecules : degrees of freedom such as position

Just like there can be many molecules, there can be many Standard Models

A High Quality Axion

Consider a copy of the Standard Model

Neutron' needs to be very similar to actual neutron

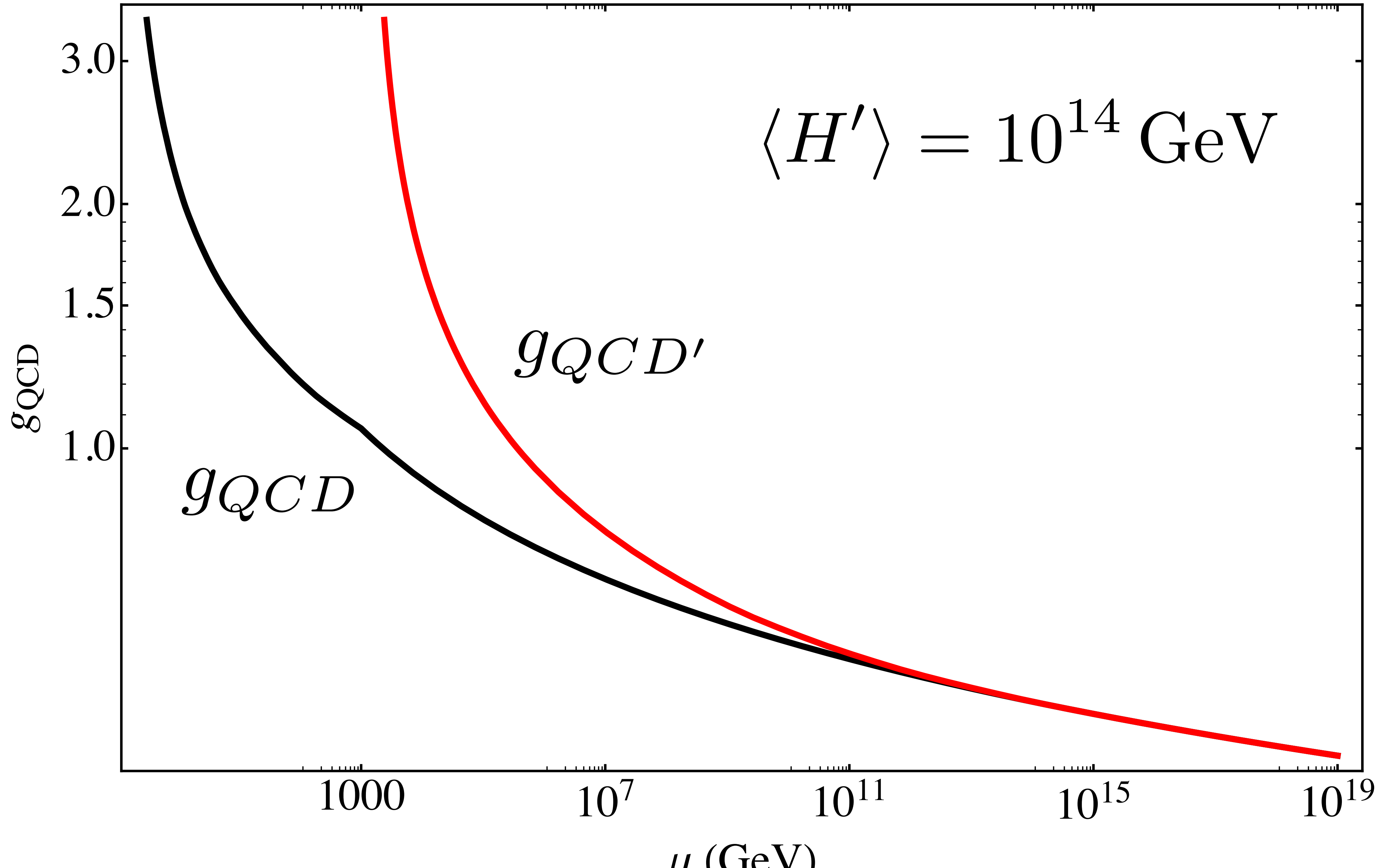
What is the first thing that changes in this copy?

The object most sensitive to any change is the Higgs mass

Electroweak Hierarchy Problem

A High Quality Axion

Effect of different Higgs mass



A High Quality Axion

Very non-trivial fact

If the Higgs mass were the only thing different between the two copies, the neutron angles are still the same!

Flavor structure of the SM ensures that any change occurs at 7-loops and beyond

Not true for a generic theory!

A High Quality Axion

Makes the Quality problem better

$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right) - (10^8\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right)$$
$$+\Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

$$\Lambda_{\mathrm{contamination}} < 10^5\,\mathrm{MeV}$$

Quality Problem

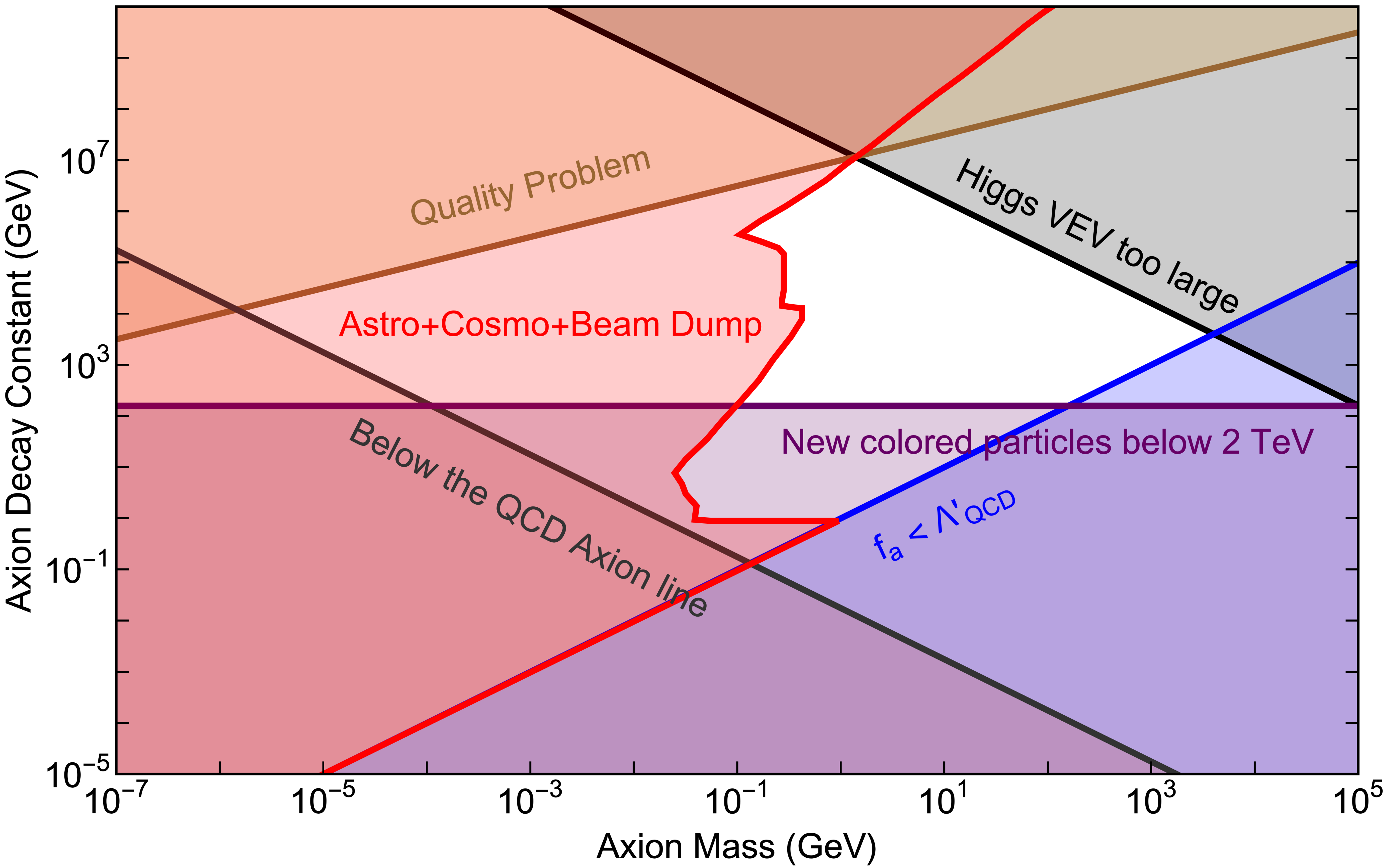
Old Quality problem

$$V = \frac{\Phi^n}{M_{pl}^{n-4}}$$

New Quality problem

$$\frac{g^2}{32\pi^2}\left(\frac{HH^\dagger}{M_{pl}^2}G\tilde{G} + \frac{H'H'^\dagger}{M_{pl}^2}G'\tilde{G}'\right) \qquad H' \lesssim 10^{14}\,\mathrm{GeV}$$

Parameter Space



Disclaimer

Unfortunately, collider axion/ALP literature is not standardized

$$\mathcal{L} \supset \frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a(x)}{f_a}\right) G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

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Decays

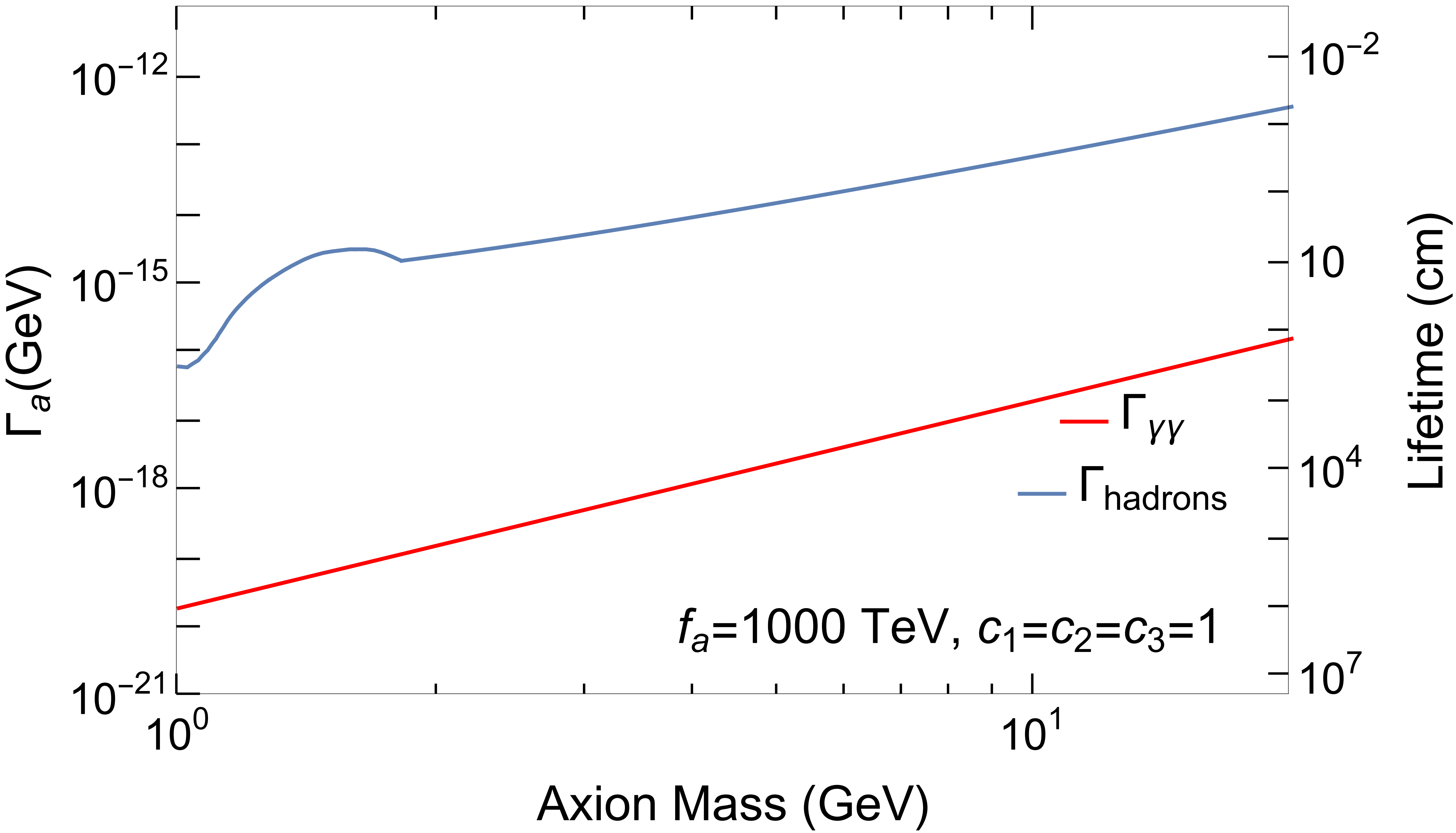
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Due to large gauge coupling, decay is dominated by decays into gluons

$$m_q e^{ia/f} q q^c$$

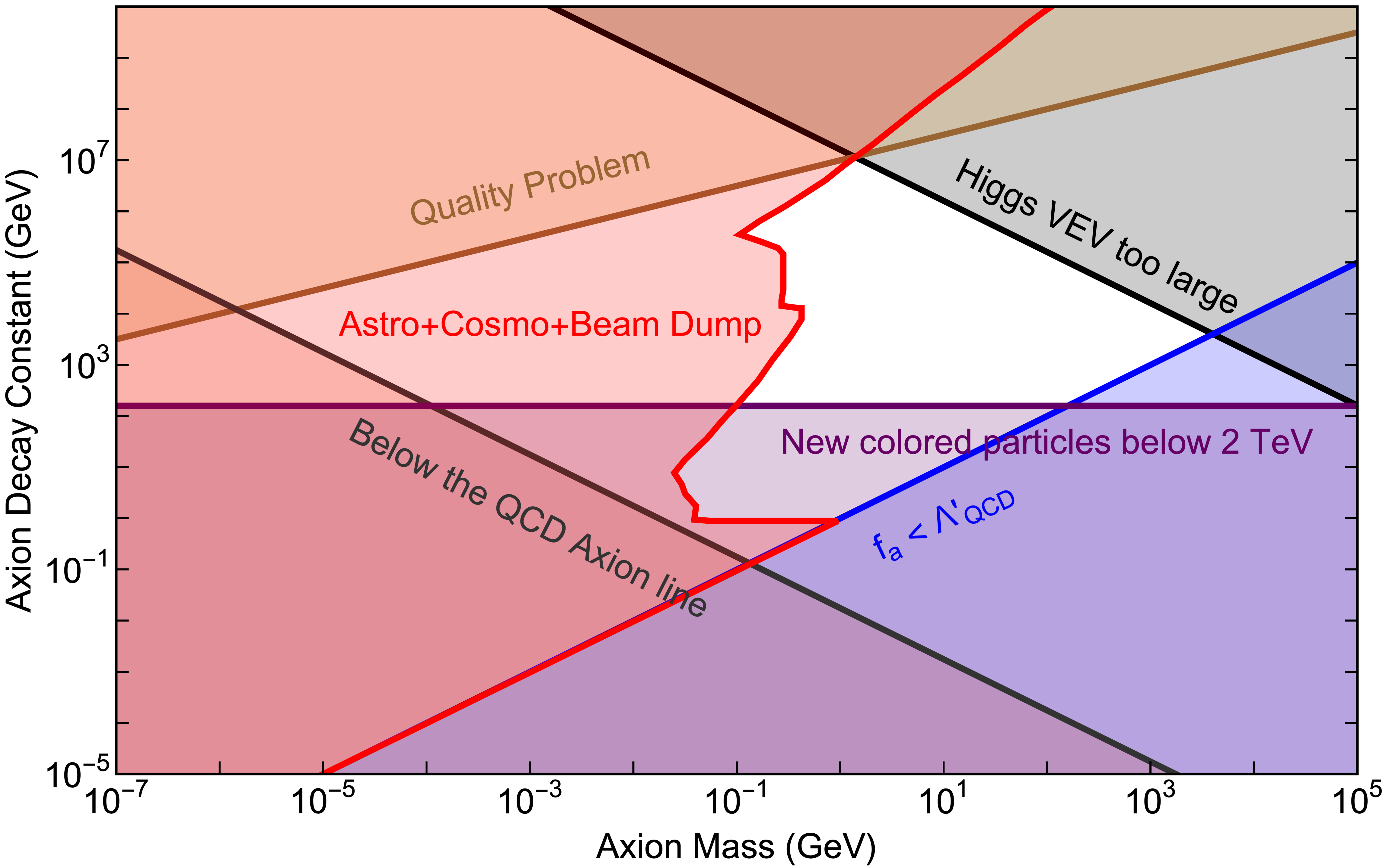
Mass suppression and usually not present at tree level

Decays

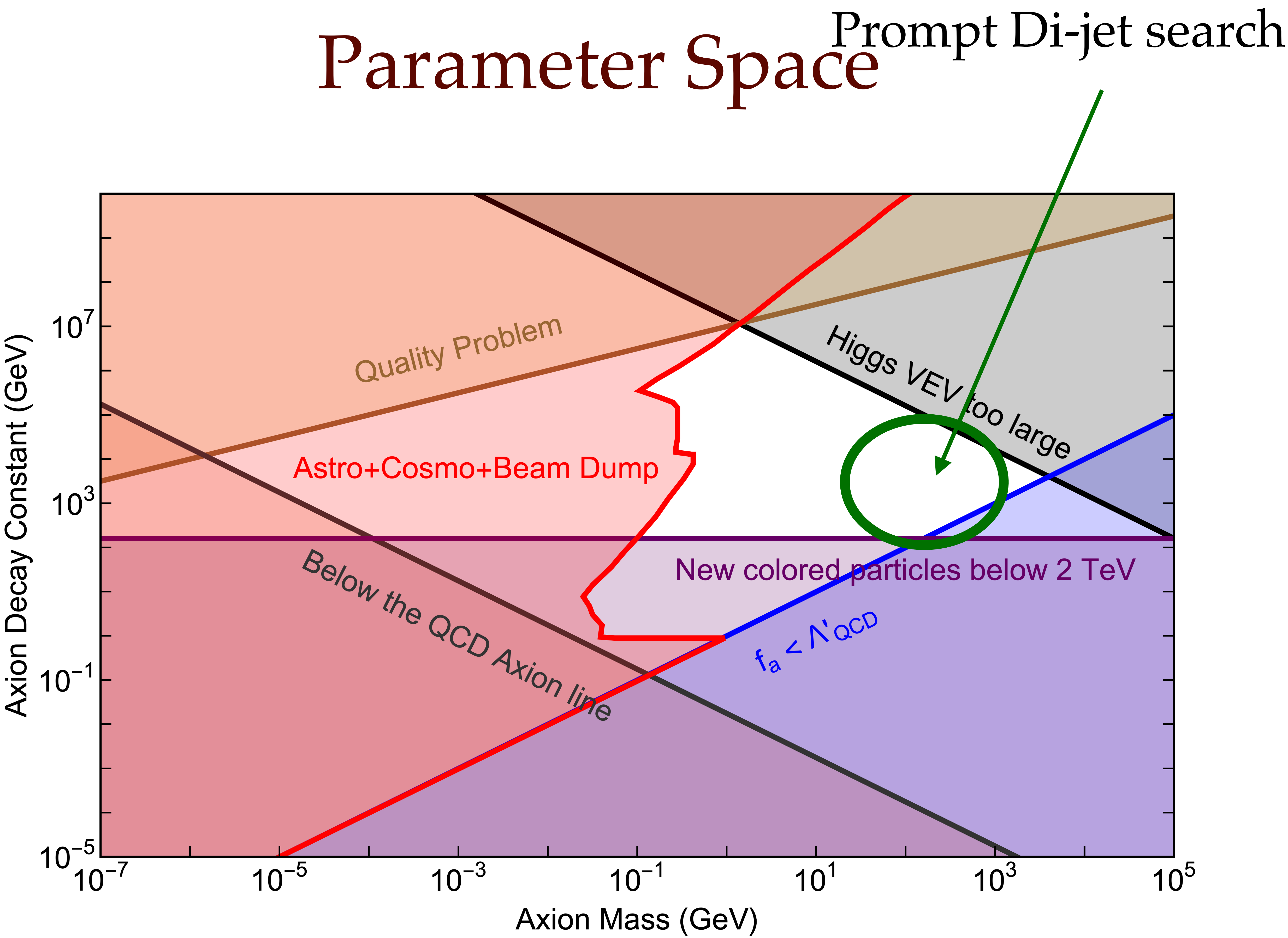


10^{-12}
10^{-15}
10^{-18}
10^{-21}
Γ_a(GeV)
10^{-2}
10
10^{4}
10^{7}
Lifetime (cm)
$\Gamma_{\gamma\gamma}$
$\Gamma_{\rm hadrons}$
f_a=1000 TeV, c_1=c_2=c_3=1
10^{0}
10^{1}
Axion Mass (GeV)

Parameter Space

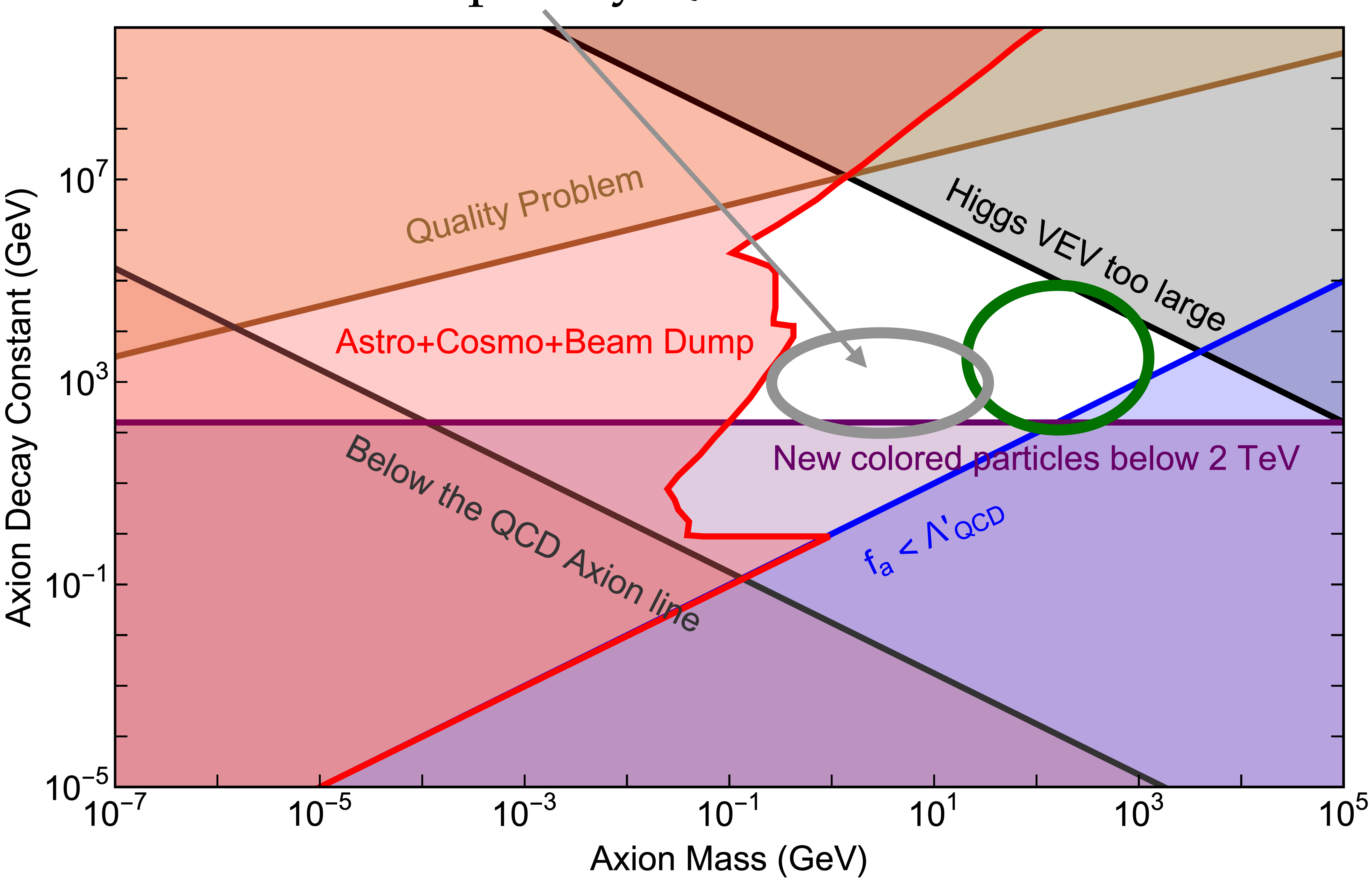


Parameter Space



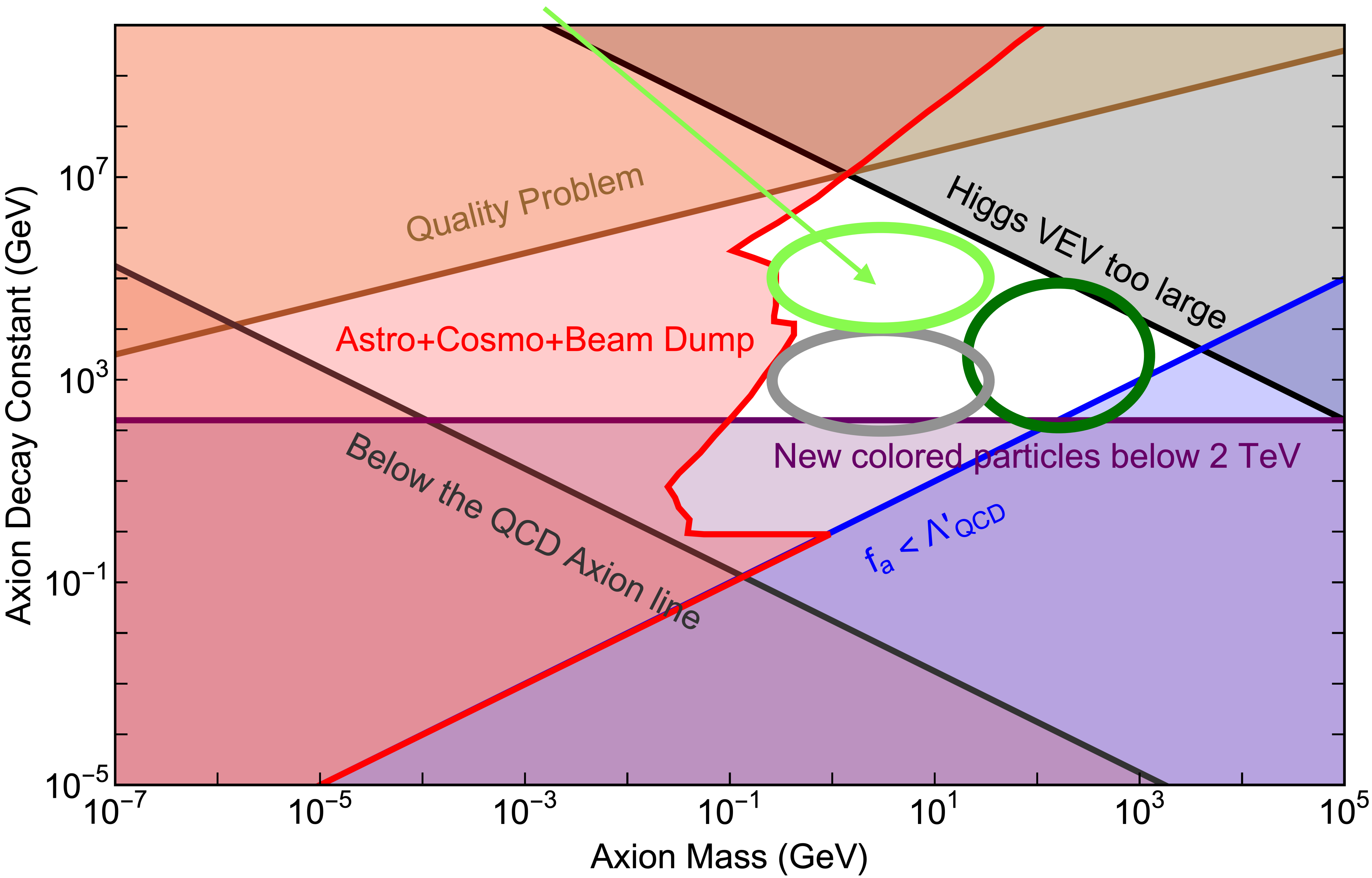
Parameter Space

Swamped by QCD



Parameter Space

Displaced Vertex Search!

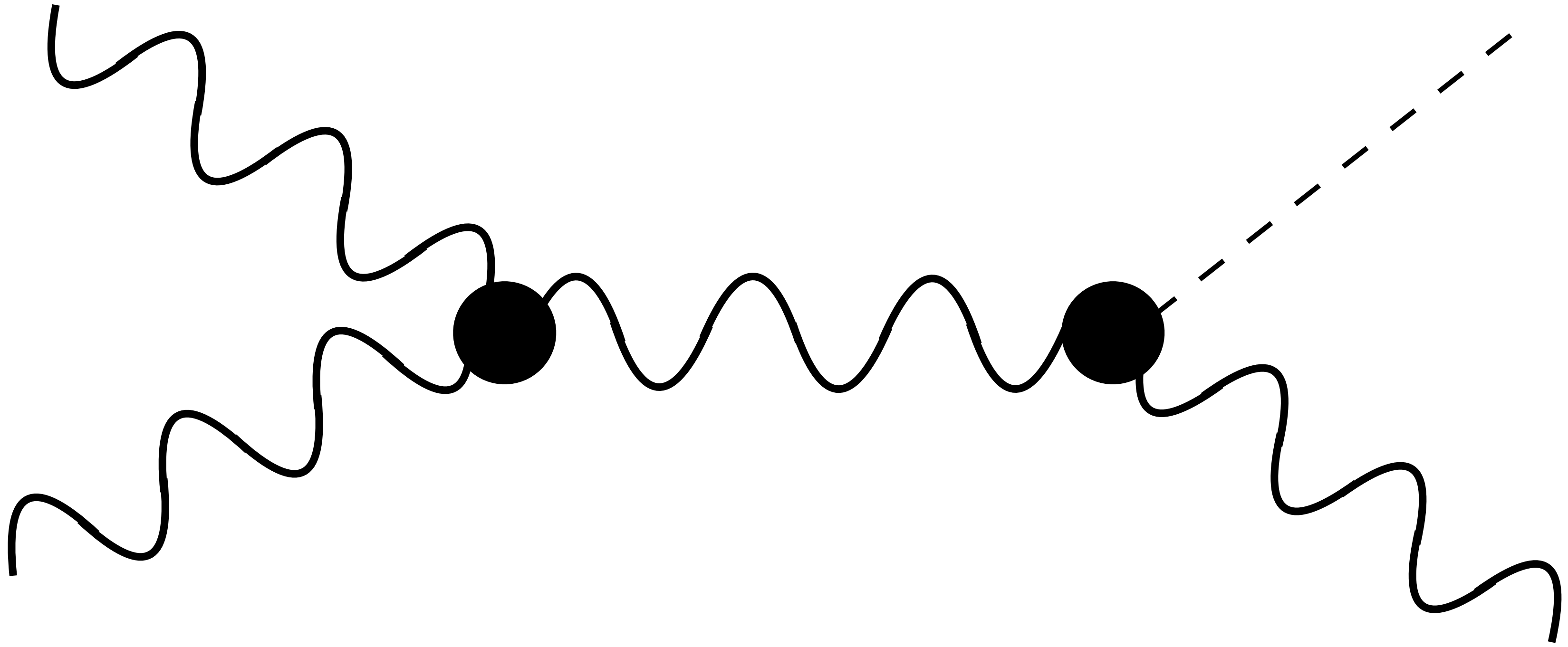


Possible?

- Most displaced vertex searches come from exotic Higgs decay
  - Need large coupling for production
  - Need to couple to something heavier to avoid decay
- Gluon coupling is unique
  - Low energy gluons are ubiquitous
  - Large PDFs mean much larger production cross section

Possible?

ISR + axion production channel



Goal

- Displaced vertex searches are hard
  - Even harder for theorists to replicate
- Well motivated signal
- Give a plausibility argument that finding a signal of this type is possible

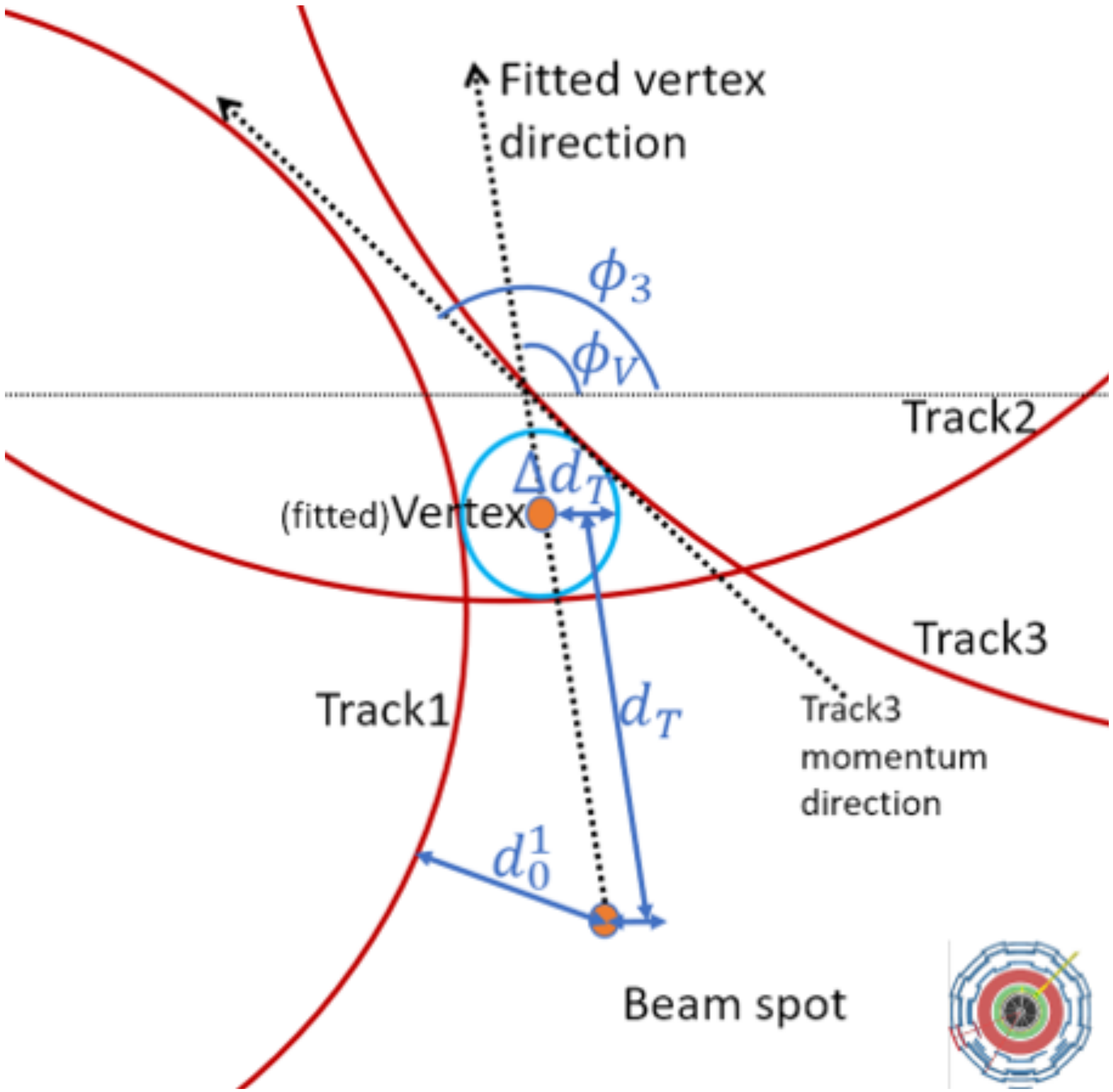
Trigger

- At least 3 tracks with $p_T > 2$ GeV
- At least 3 tracks have $d_0 > 1$ mm
- $|\eta| < 2.4$
- $d_T > 5$ mm & $d_T < 35$ cm
- $H_T > 100$ GeV

Reduce backgrounds

Enough hits in outer tracker

Variables



Fitted vertex
direction
ϕ_3
ϕ_V
Track2
Δd_T
(fitted)Vertex
Track3
Track1
d_T
Track3
momentum
direction
d_0^1
Beam spot

Background

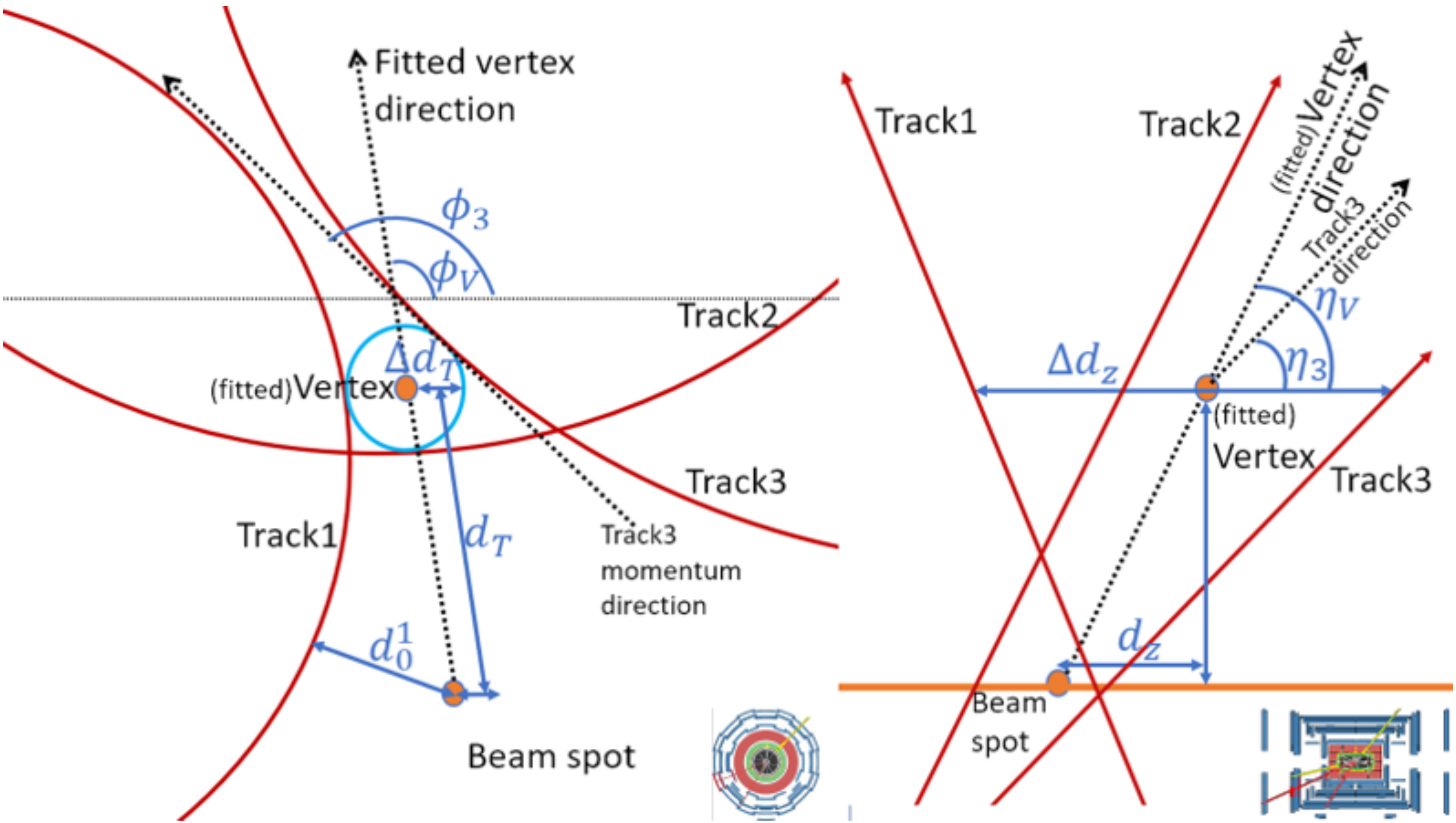
- 10 kHz of events make it through L_1 trigger
- Background dominated by fake tracks
- Model background as flat distribution subject to
  - $|d_0| < 15$ cm
  - $1/R < 1/(1.8$ m$)$
  - $|\eta| < 2.4$
  - $t_0 < 6$ ns
  - $z_0 < 15$ cm
- 10 kHz 10^8 s = 10^{12} events

Further Cuts

Find x-y vertex location and then find z-t value

- 35 cm > d_T > 5 mm
- Δd_T < 1 cm
- $d_T/\Delta d_T$ > 5
- Δd_z < 5 cm
- d_z < 20 cm
- Δd_t < 500 ps
- d_t < 1000 ps
- $|\eta_i - \eta_V| < 0.4$
- $|\phi_i - \phi_V| < 0.4$

Variables



Fitted vertex direction
ϕ_3
ϕ_V
Track2
Δd_T
(fitted)Vertex
Track3
Track1
d_T
Track3 momentum direction
d_0^1
Beam spot
Track1
Track2
(fitted) Vertex direction
Track3 direction
η_V
Δd_z
η_3
(fitted) Vertex
Track3
d_z
Beam spot

Further Cuts

So far only used outer tracker information

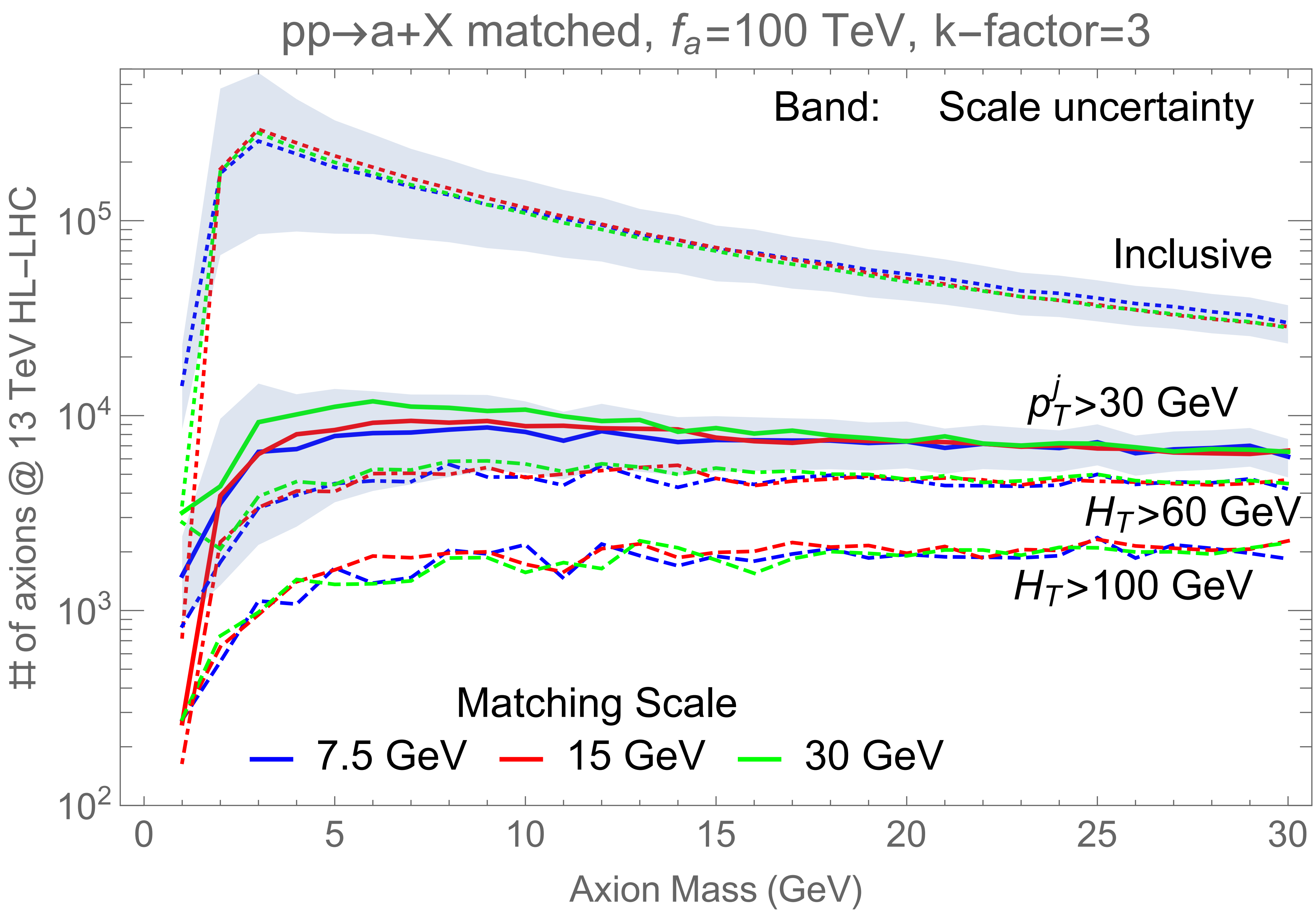
- 10^{12} events 3 10^{-9} = 3000 remaining events

Ecal, Hcal, inner tracker

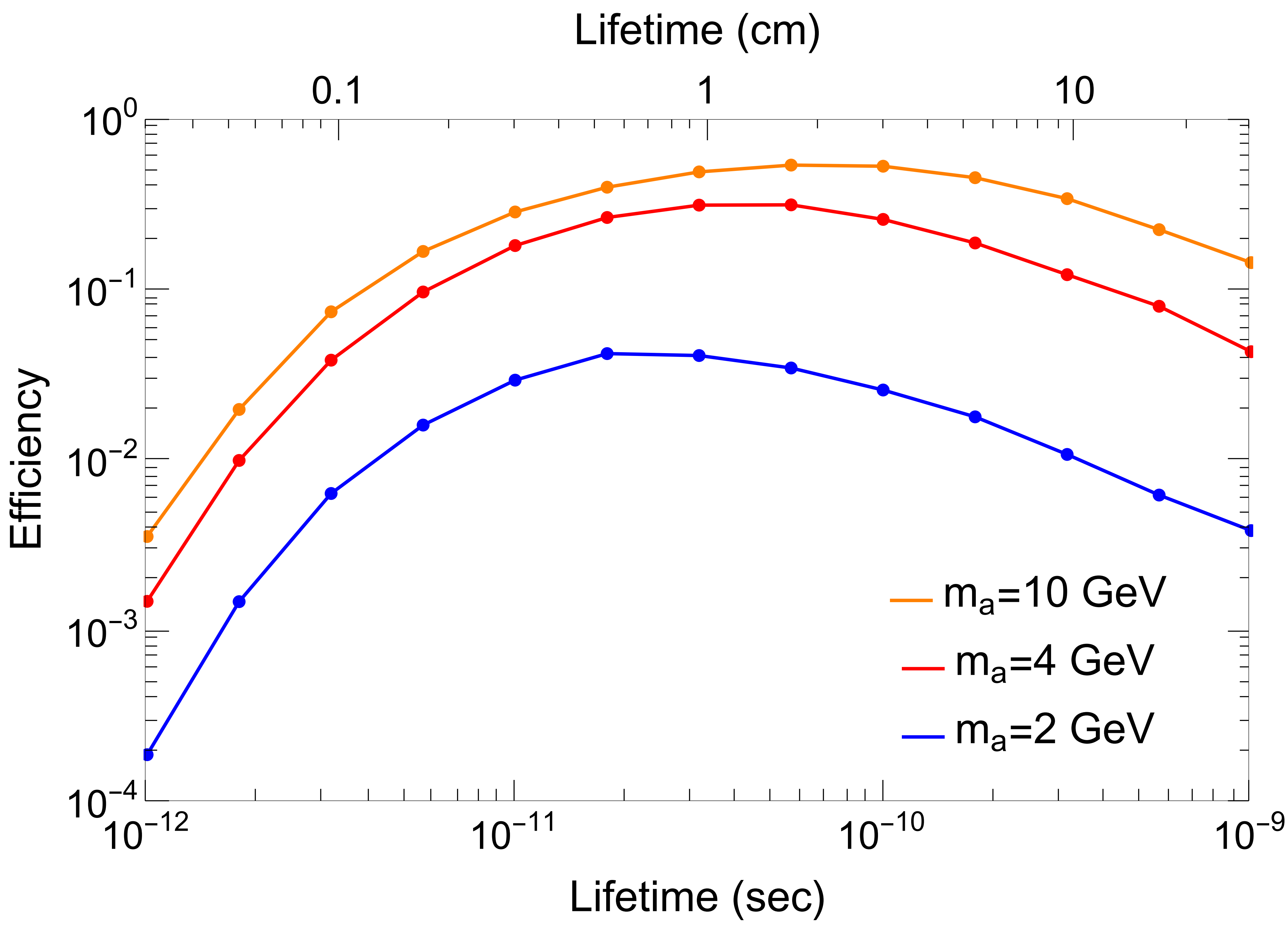
- 3000 $(10^{-1})^3$ ~ 3 events

Plausible that backgrounds can be suppressed to negligible levels

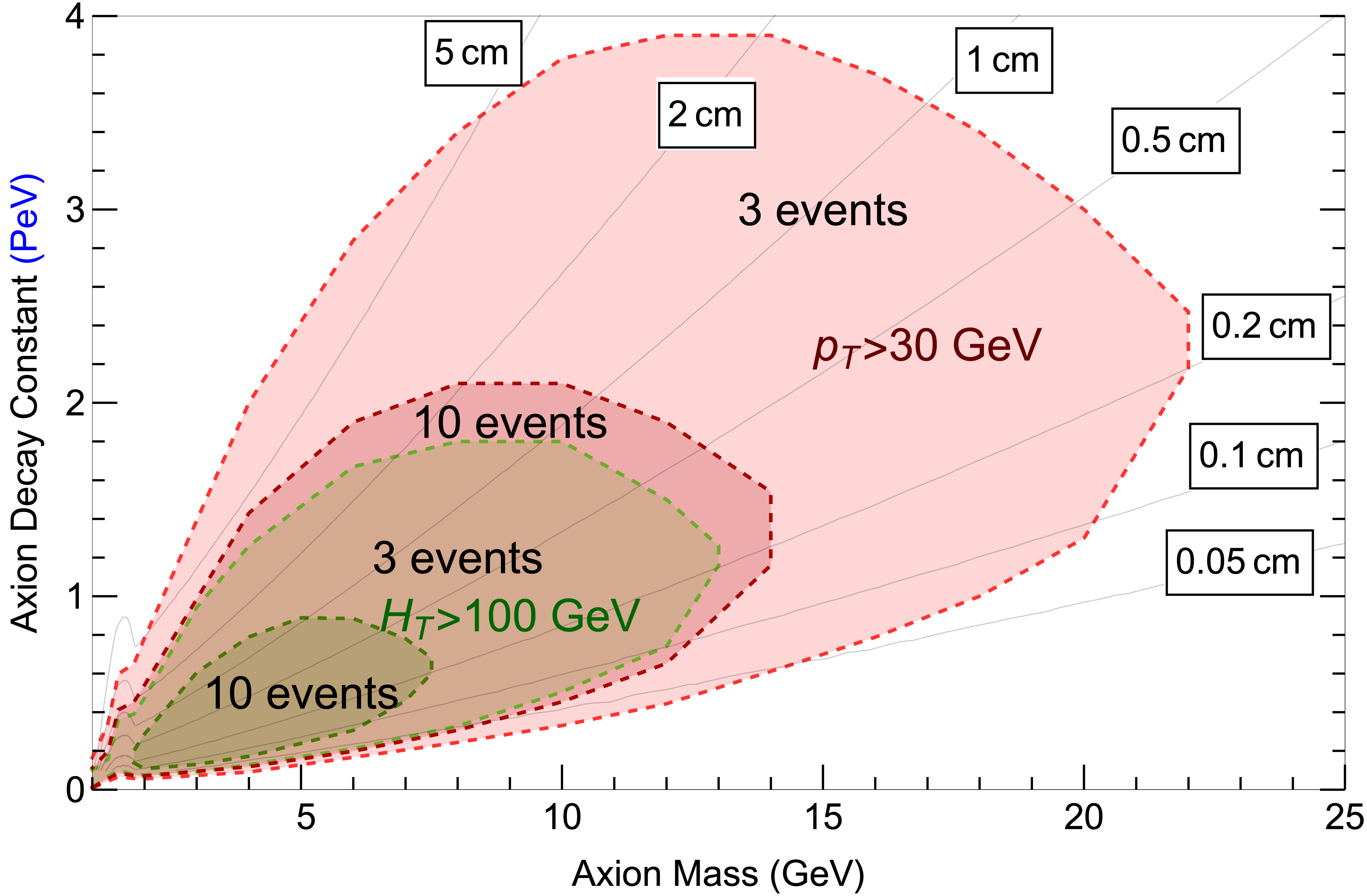
Signal efficiencies



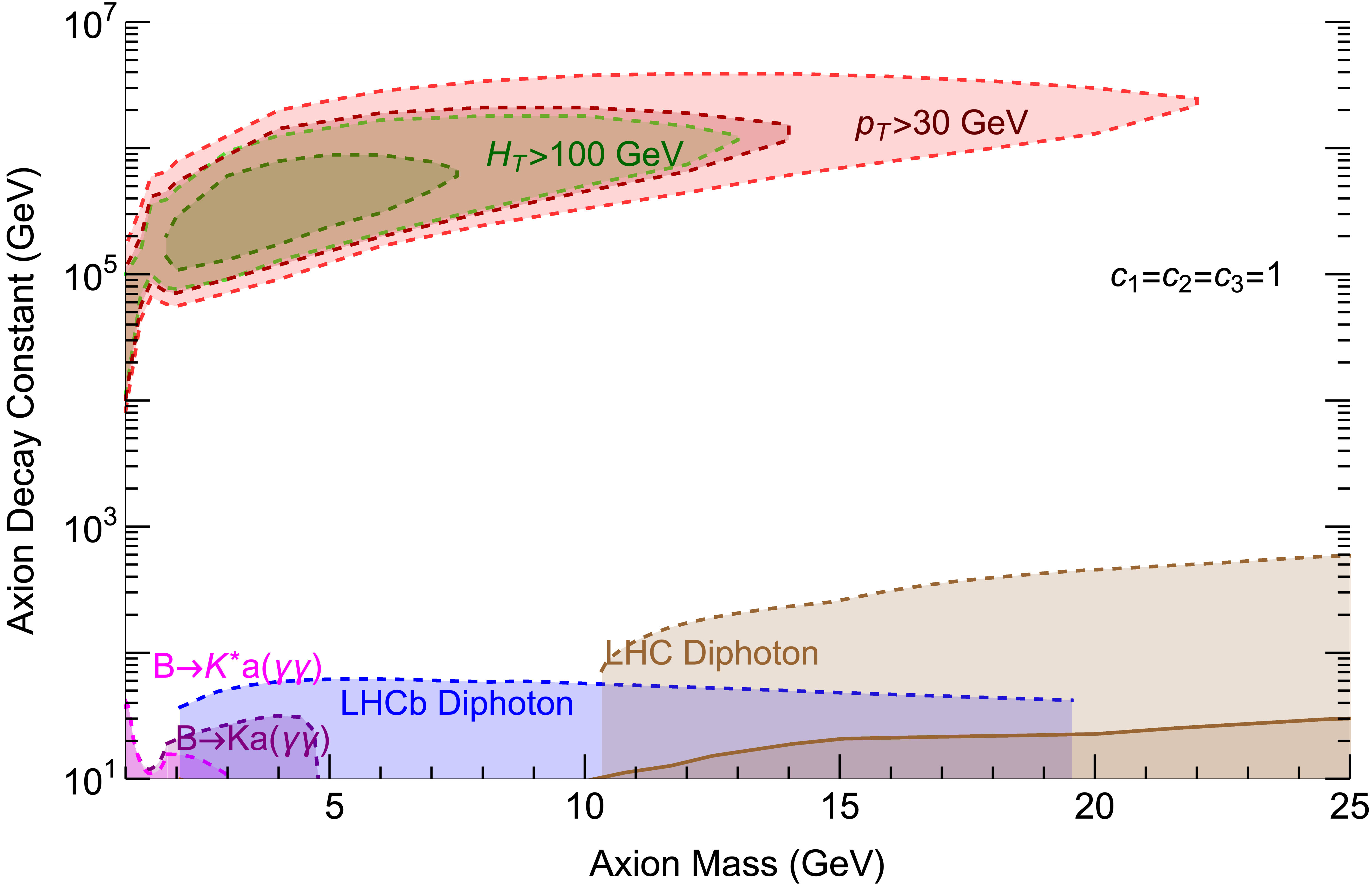
Signal efficiencies



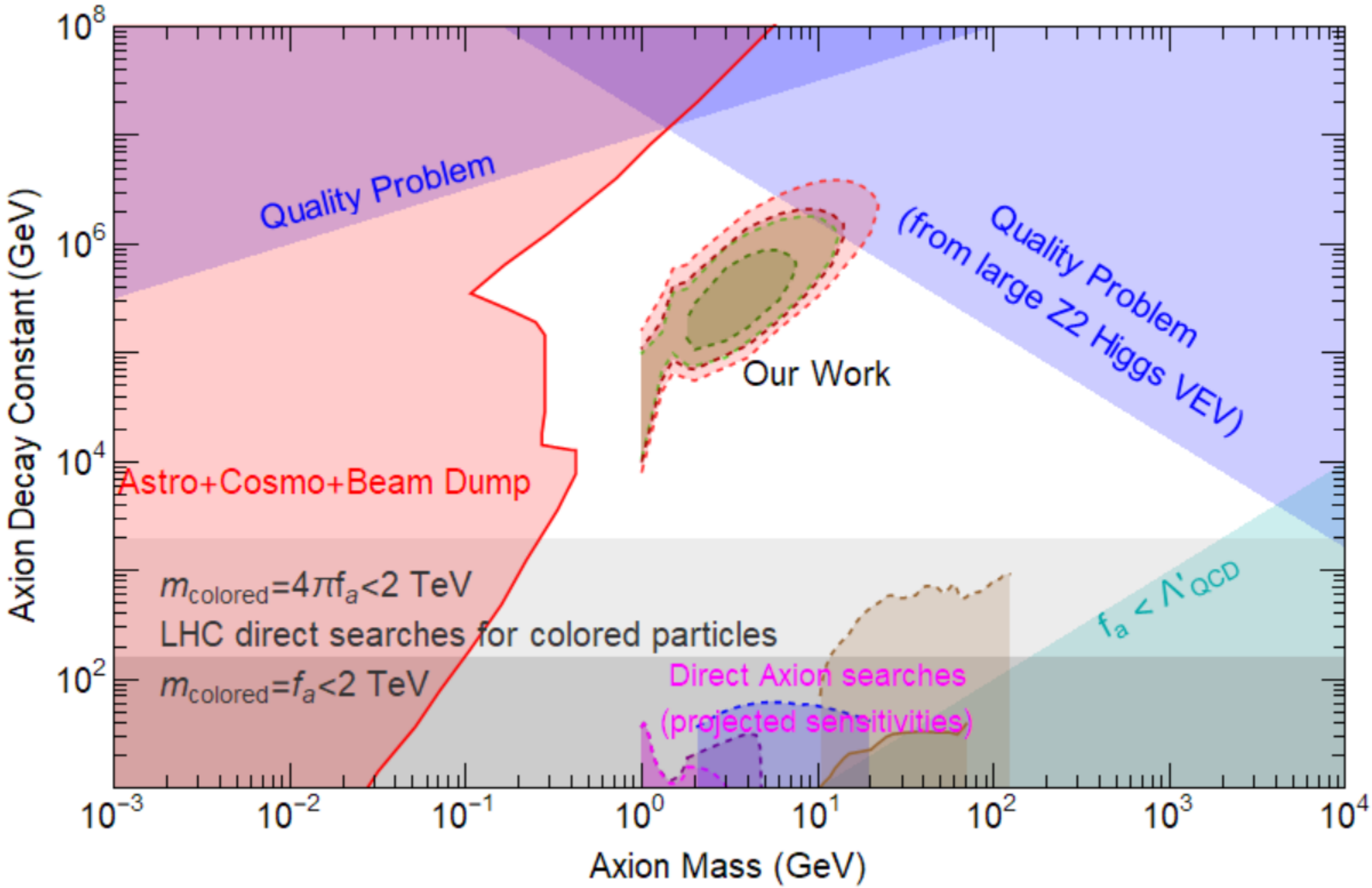
Projected Reach



Projected Reach



Projected Reach



Conclusion

Axion is a simple solution to a “simple” problem

Has a deep problem called the Quality problem

Z_2 models naturally ameliorate this problem

Very interesting pheno! Displaced vertex search

Similar to hadronic tau but displaced instead