Pheno 2021

Heavy Axion at DUNE

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Kelly, Kumar, ZL, 2011.05995

Axion needs no intro

$$L \supset \frac{\alpha_s}{8\pi}\theta\tilde{G}G + y_u\bar{Q}_L\tilde{H}u_R + y_d\bar{Q}_L H d_R$$

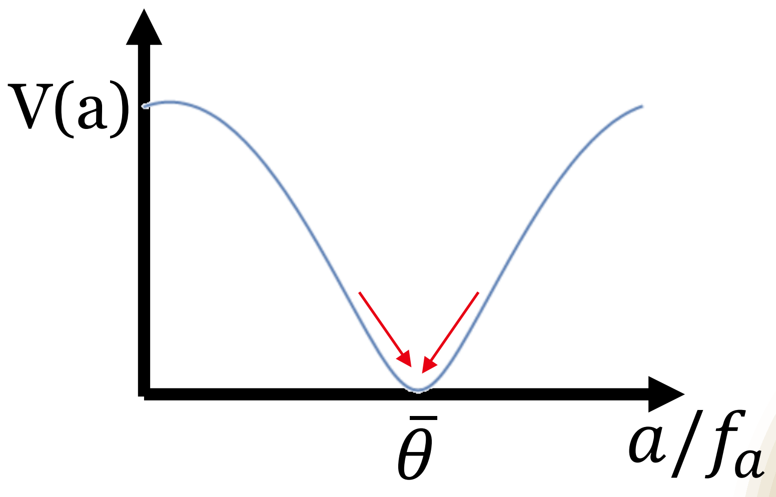
$$\bar{\theta} \equiv \theta + \mathrm{ArgDet}[Y_u Y_d] \leq 10^{-10}$$

While ArgDet$[Y_u Y_d]$ anticipated around $\delta_{CKM}{\sim}O(1)$

Strong CP puzzle of QCD

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

$$\frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$



But a quality problem

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

$$\frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$

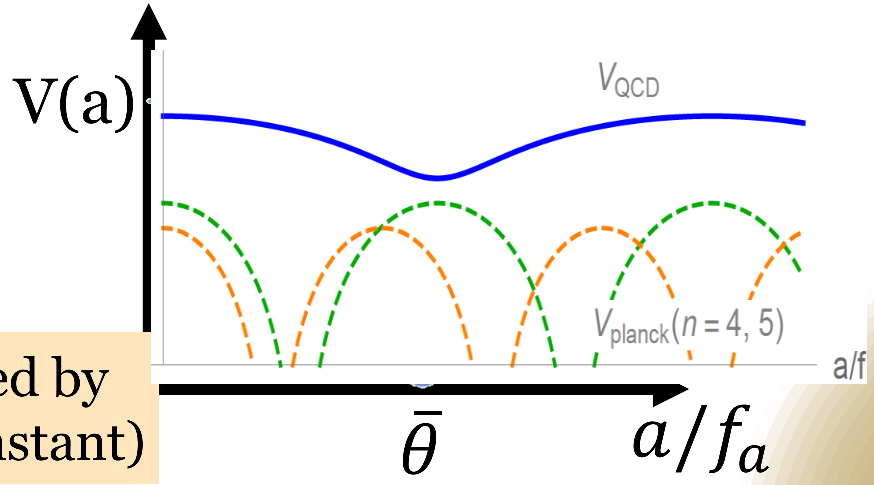
The axion fakes a dynamical angle.
How good of an imposter is it?

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

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

There are also many other scales :
GUT, Planck, Dark matter

$$V = \frac{\Phi^{14}}{M_{pl}^{10}} \qquad \Phi \equiv e^{i\frac{a}{f_a}}$$



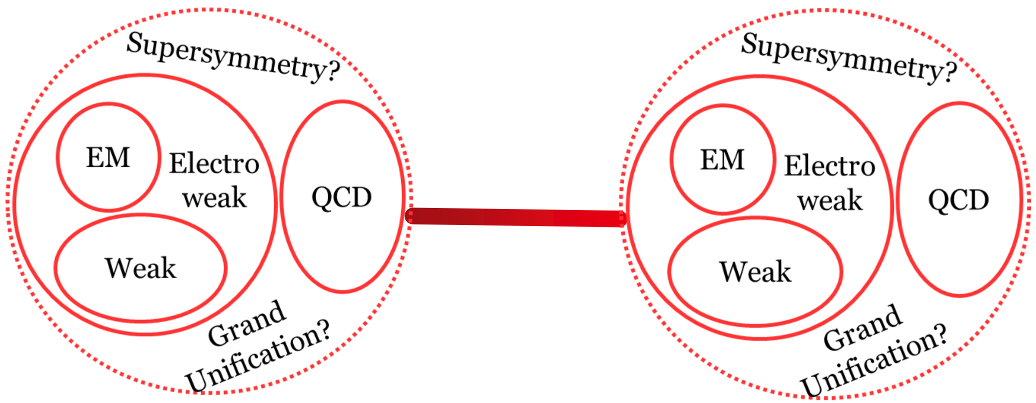
Leading order gravity suppressed operators must be suppressed by 10 powers of the Planck scale! (for 10^12 GeV Axion decay constant)

Other solutions (while not excluded by experiments) to the axion quality problem exists: e.g., delicate UV structure, Extra dimensions, etc.

Hook, Kumar, ZL, Sundrum, 1911.12364

The Quality Problem and reinforced Axion potential

Copying Mirror Gauge QCD + Weak and Chiral Matter fields, relates the Lagrangian parameters with a Z2 symmetry
one axion couples to both and solve both strong CP puzzles dynamically.



$$SU(2) \leftrightarrow SU(2)'$$
$$SU(3) \leftrightarrow SU(3)'$$
$$U(1) \leftrightarrow U(1)' \text{ or } U(1) \leftrightarrow U(1)$$
$$\Psi \leftrightarrow \Psi'$$

$\leftrightarrow$ represents the Z2 transformation
X' represents the mirror sector

Softly broken by
$$\mu^2 H^\dagger H + \mu'^2 H'^\dagger H'$$
with $\mu'^2 \gg \mu^2$

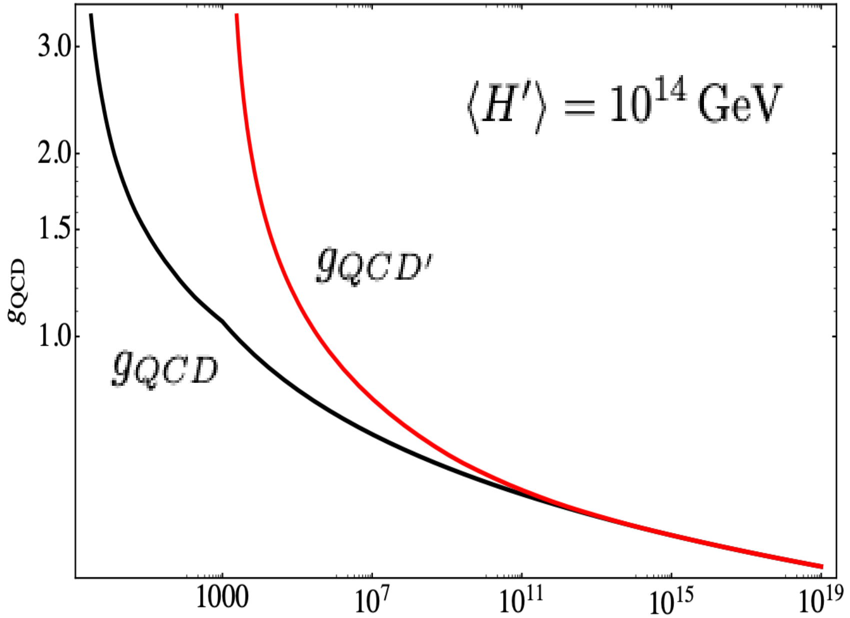
Rubakov '97, Berezhiani et al '01, Hook '15, Fukuda et al '15…

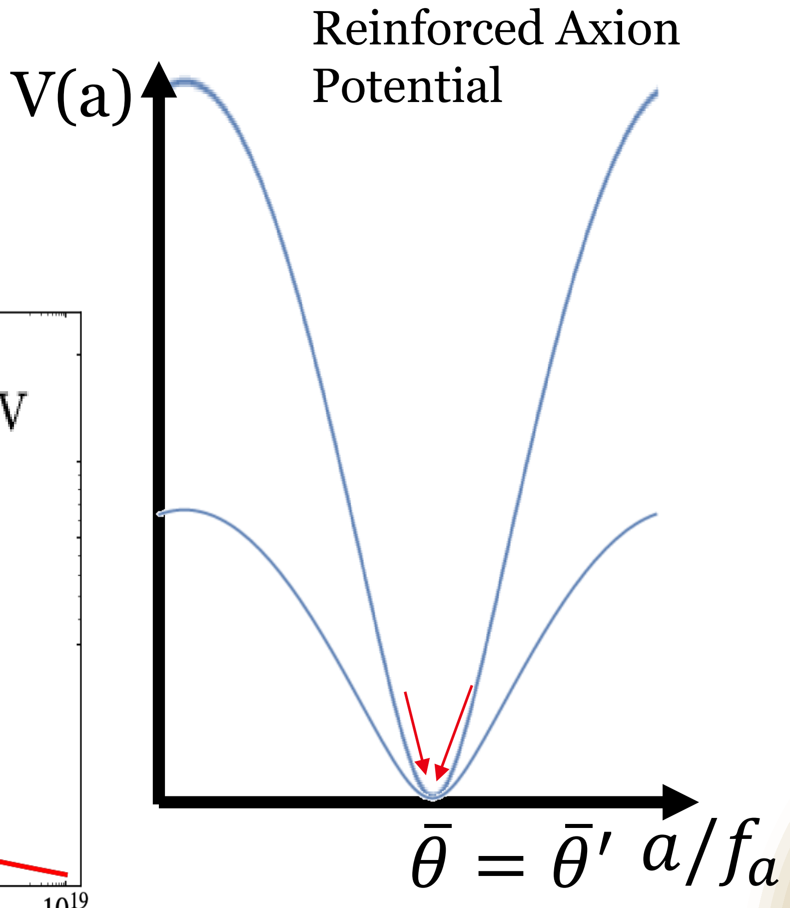
The Quality Problem and reinforced Axion potential

$$m_a^2 \simeq \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi f_\pi}{f_a^2}$$

$$m_a^2 \simeq \frac{\Lambda_{QCD'}^4}{f_a^2}$$

Soft Z2 breaking by giving Mirror Higgs large VEV
□massive fermions decouples earlier
□mirror QCD run fast and confines





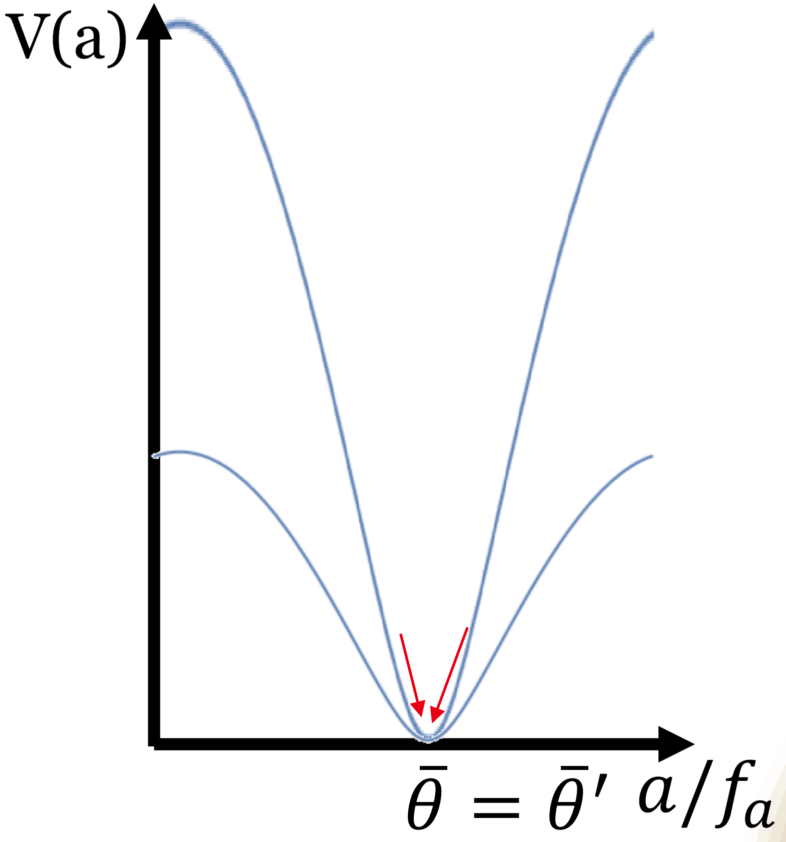
The Quality Problem and reinforced Axion potential

Makes the Quality problem better

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

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

Reinforced Axion Potential



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 4-loops and beyond
Not true for a generic theory!

The Quality Problem and reinforced Axion potential

Makes the Quality problem better

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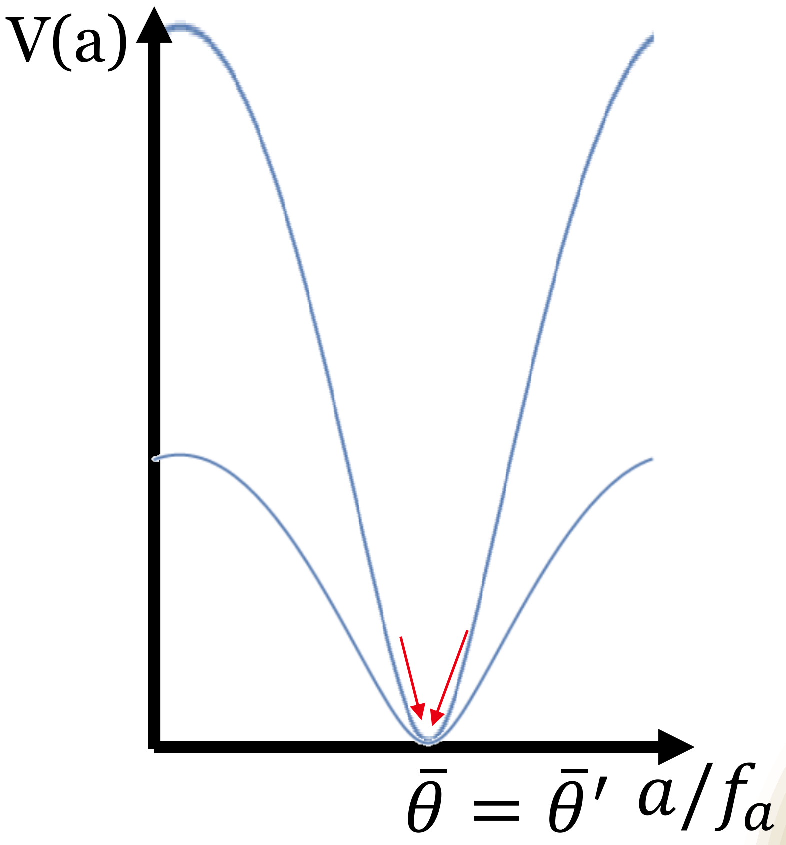
Reinforced Axion Potential



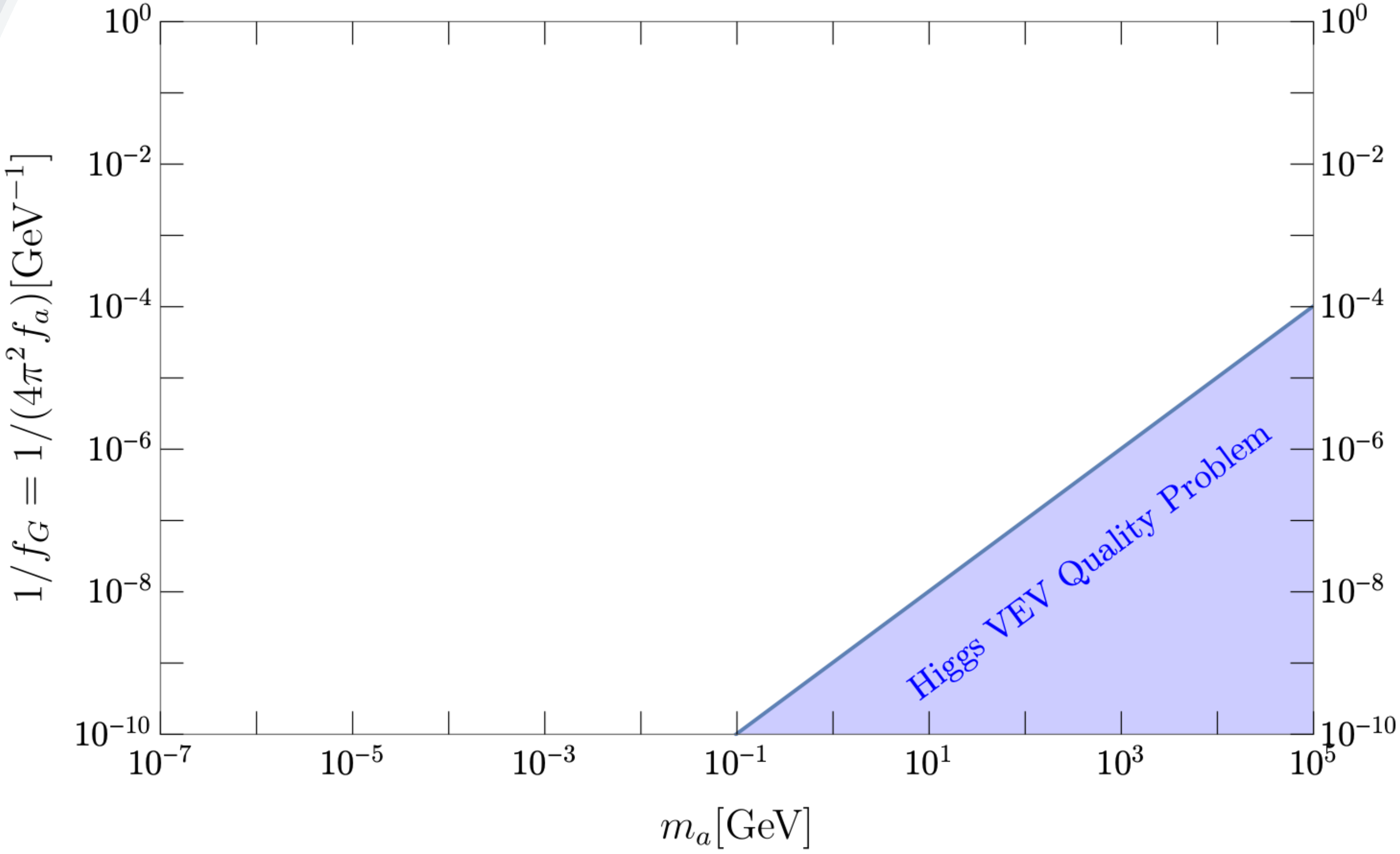
But generates a new quality problem:

$$\frac{g^2}{32\pi^2}\left(\frac{HH^\dagger}{M_{pl}^2} G\tilde{G} + \frac{H'H'^\dagger}{M_{pl}^2} G'\tilde{G}'\right)$$

$$H' \lesssim 10^{14}\,\mathrm{GeV}$$

Theory parameter space

$$m_a^2 \simeq \frac{\Lambda_{QCD'}^4}{f_a^2}$$



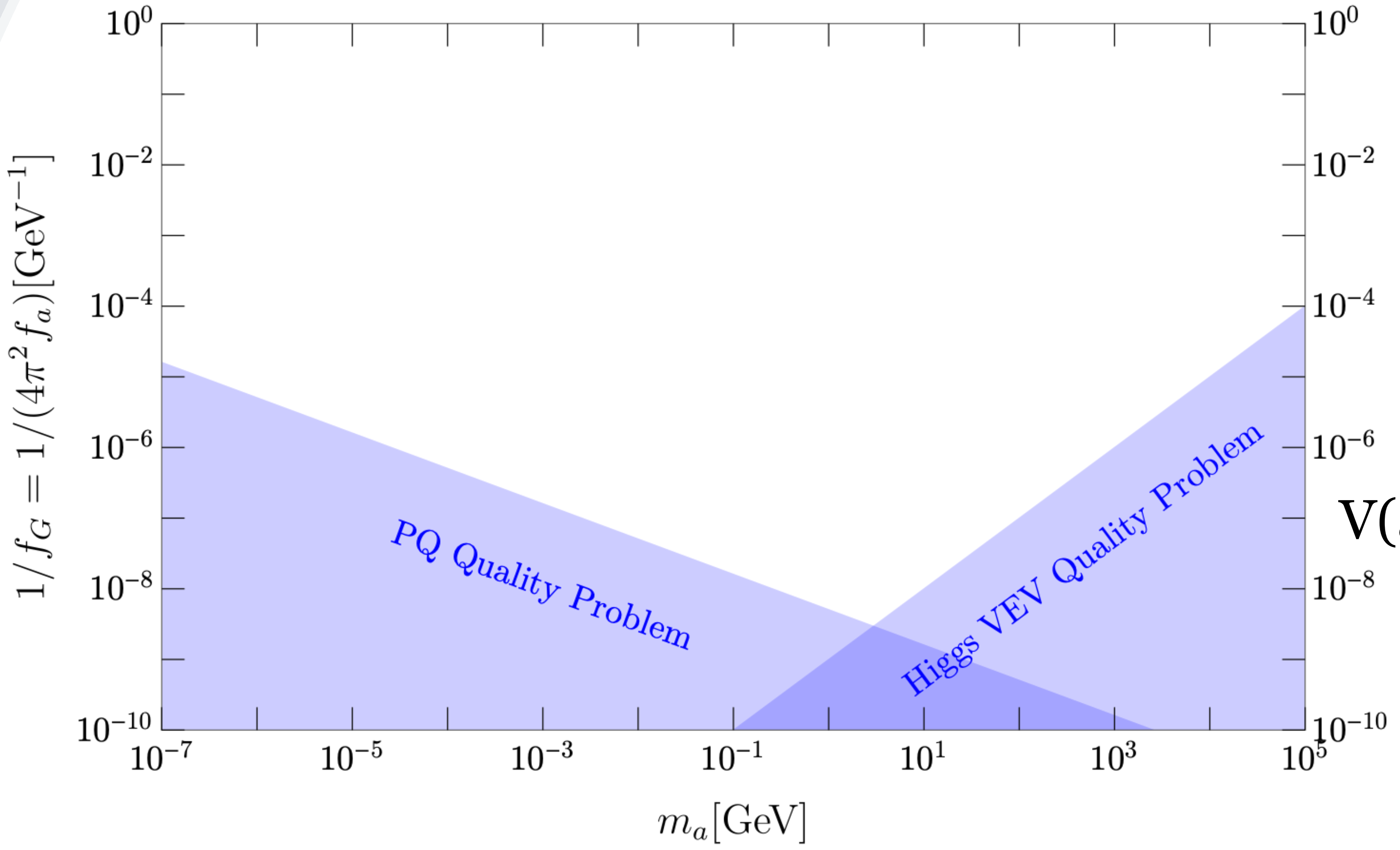
$$\frac{\alpha_3}{8\pi}\left(\frac{H^\dagger H}{M_p^2}G\tilde{G} + \frac{H'^\dagger H'}{M_p^2}G'\tilde{G}'\right)$$

$$\Rightarrow \langle H' \rangle = \mu' < 10^{14}\mathrm{GeV}$$

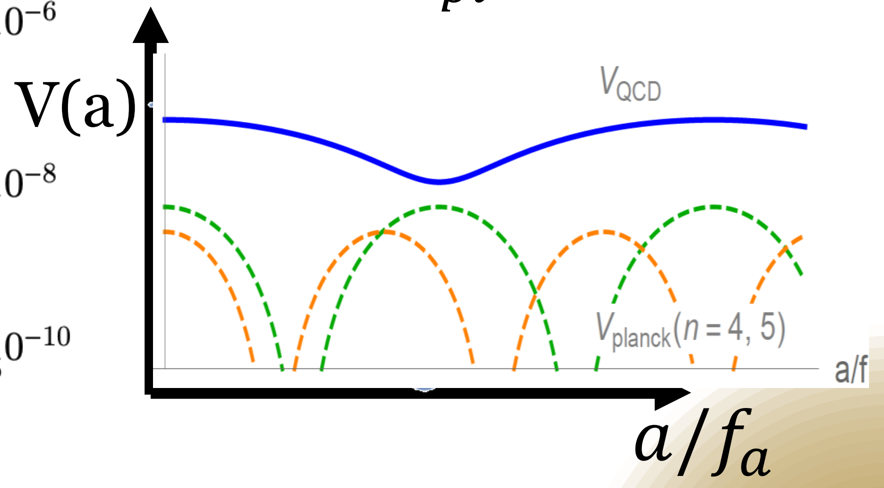
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Theory parameter space

$$m_a^2 \simeq \frac{\Lambda_{QCD'}^4}{f_a^2}$$



$$\frac{\Phi^6}{M_{pl}^2}$$



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

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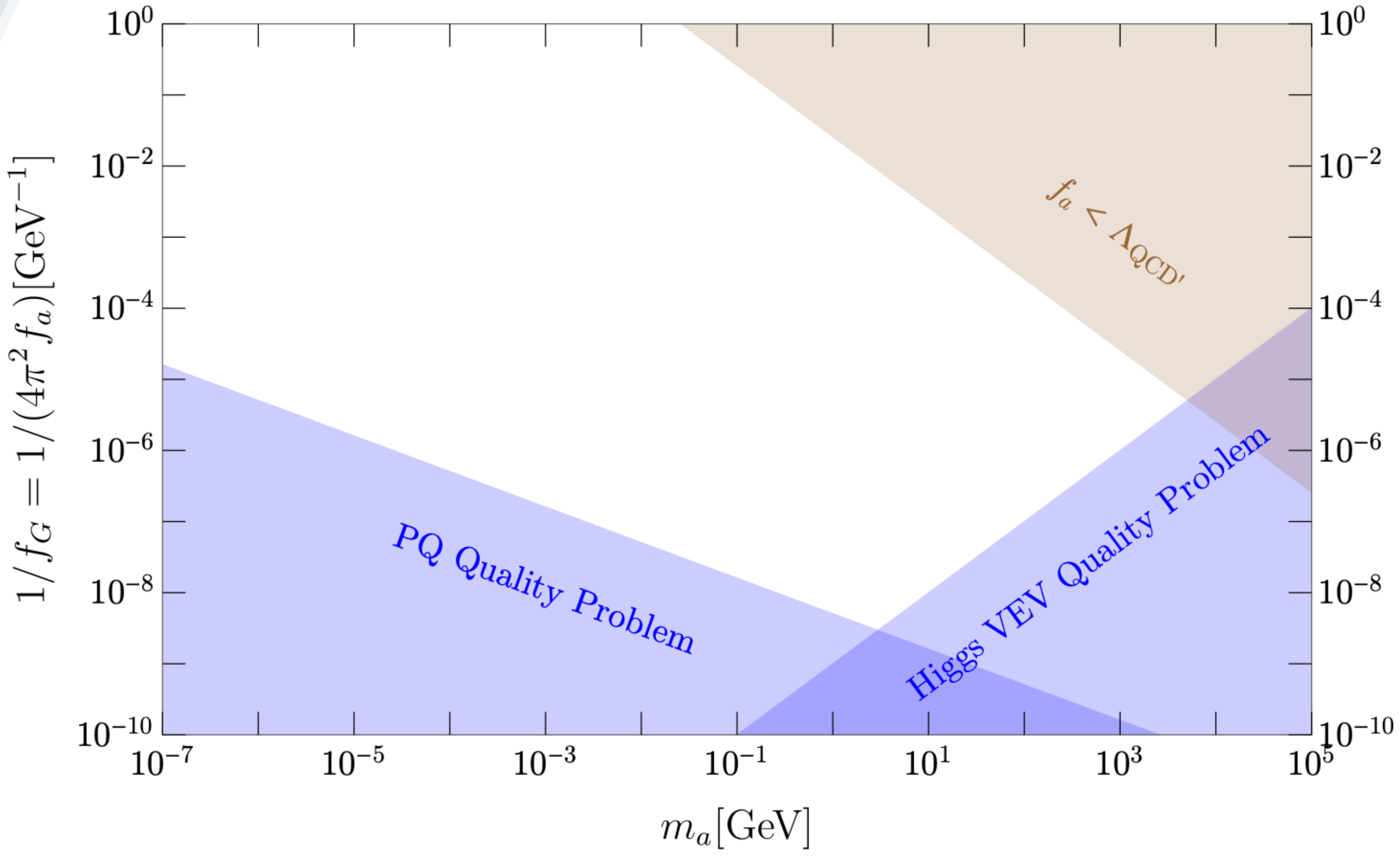


no axion EFT control

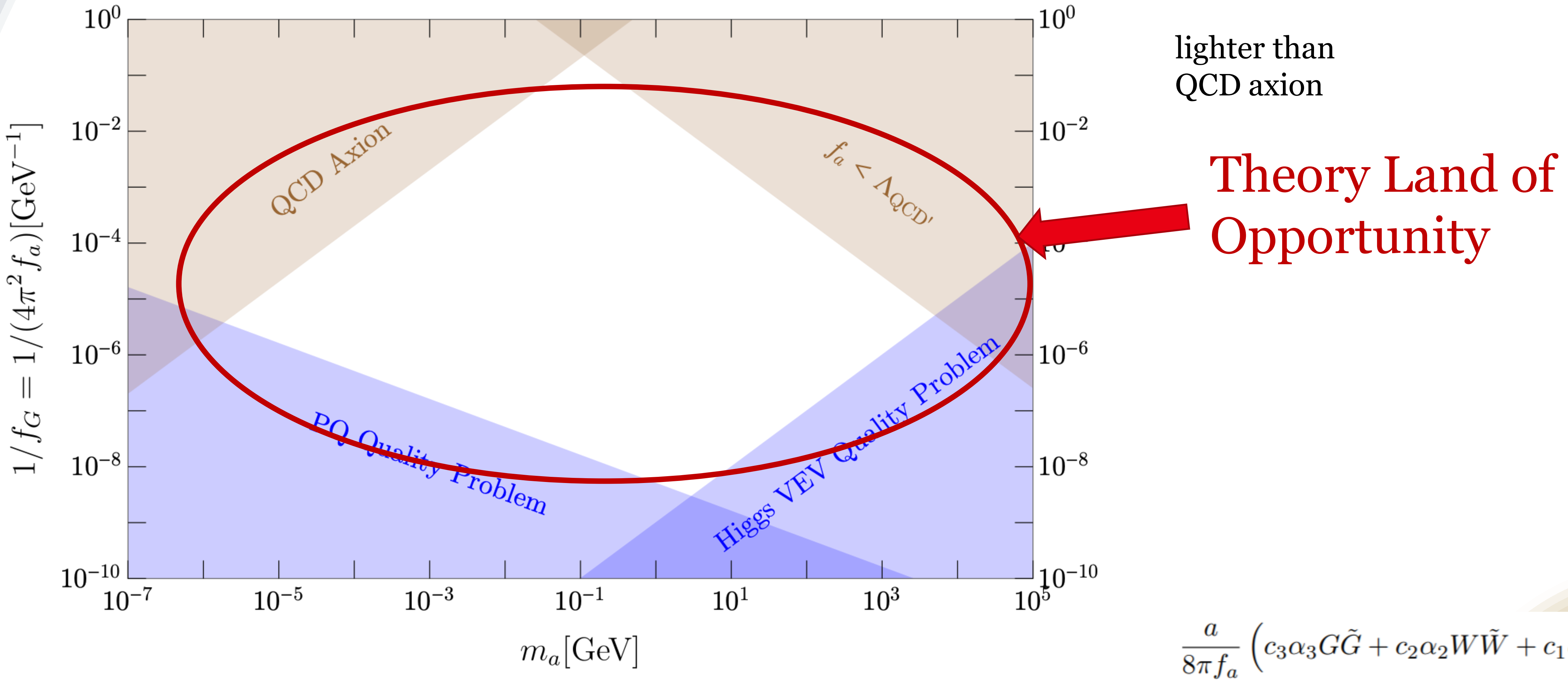
$$m_a > f_a$$

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

Theory parameter space

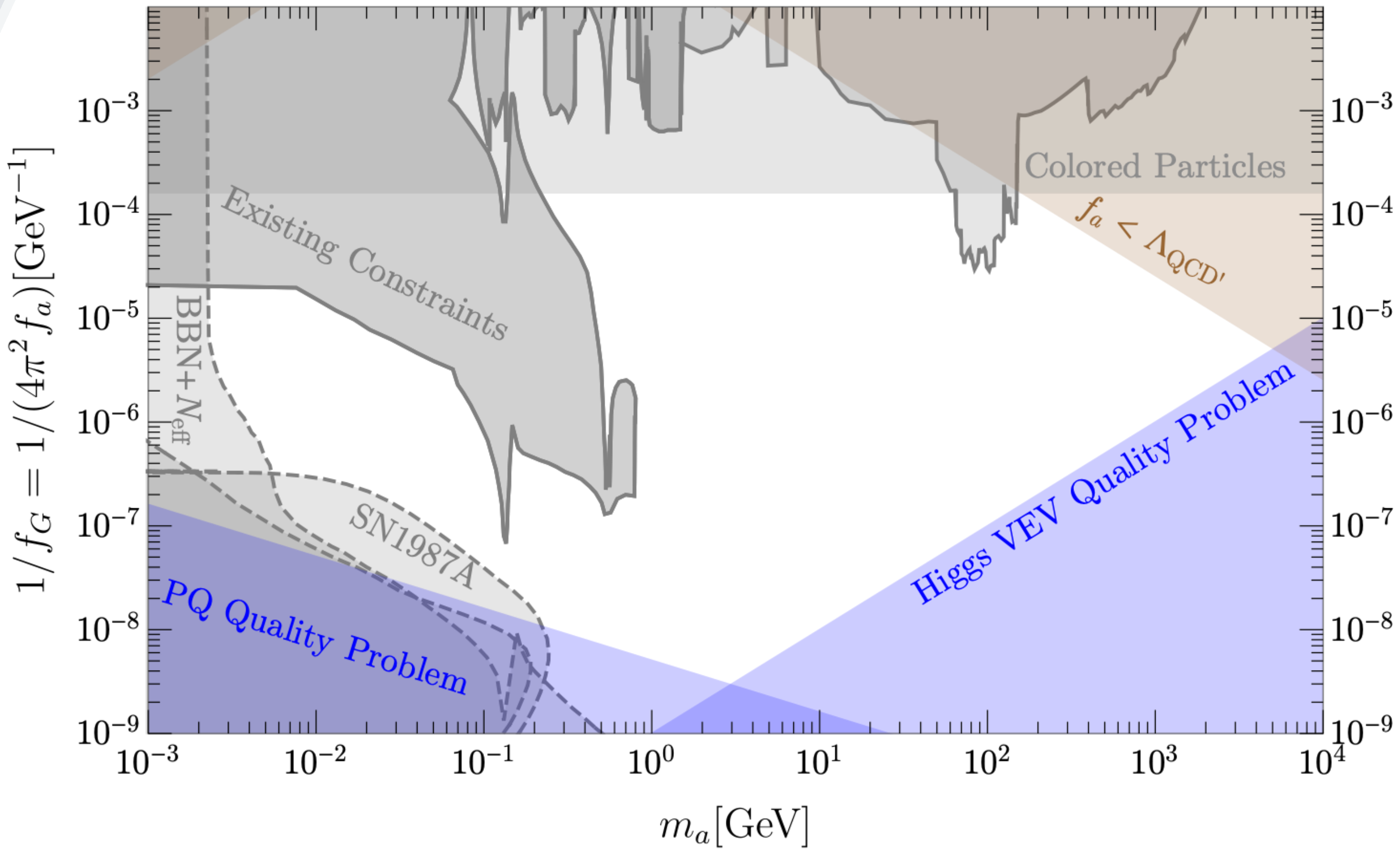
$$m_a^2 \simeq \frac{\Lambda_{QCD'}^4}{f_a^2}$$

lighter than
QCD axion



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

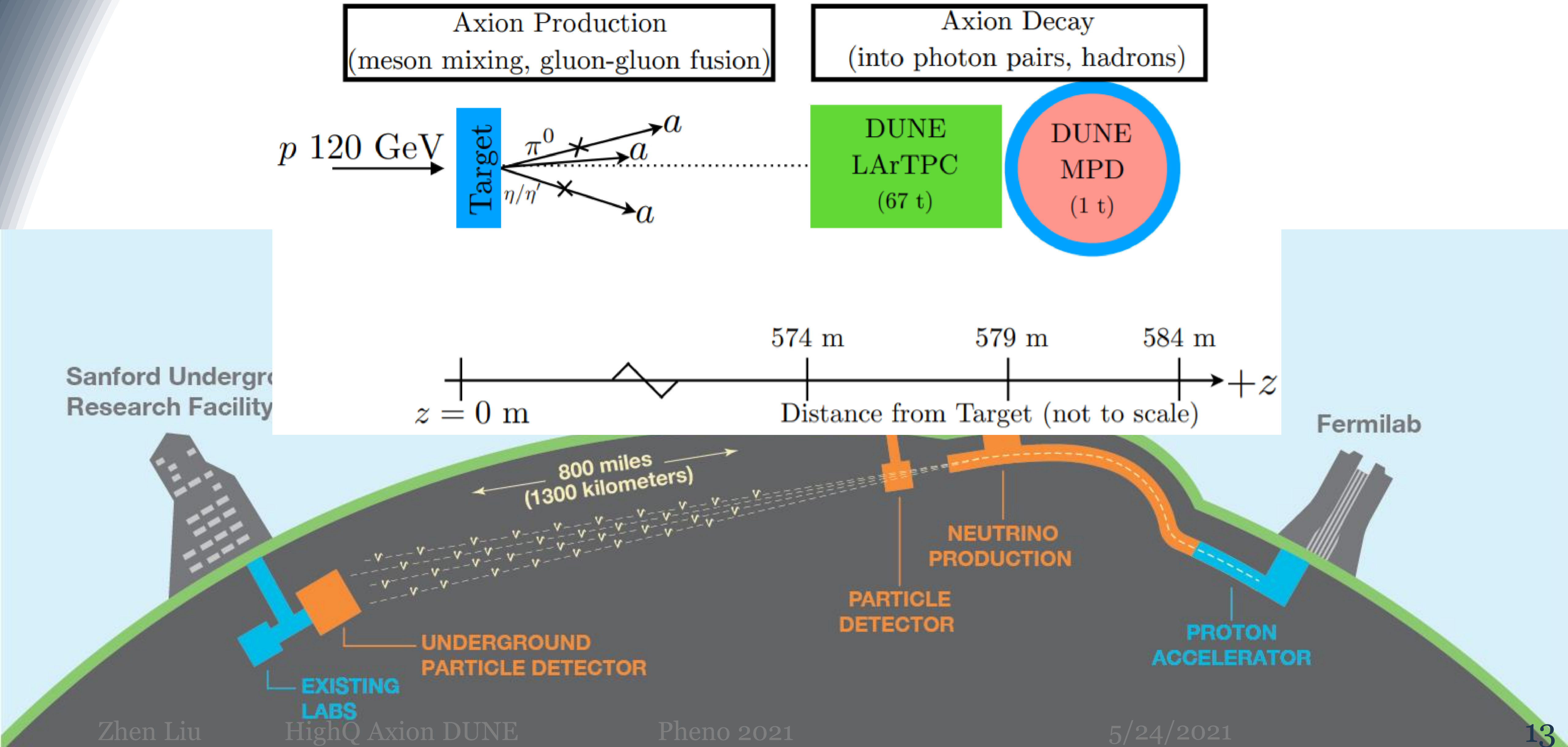
Existing constraints



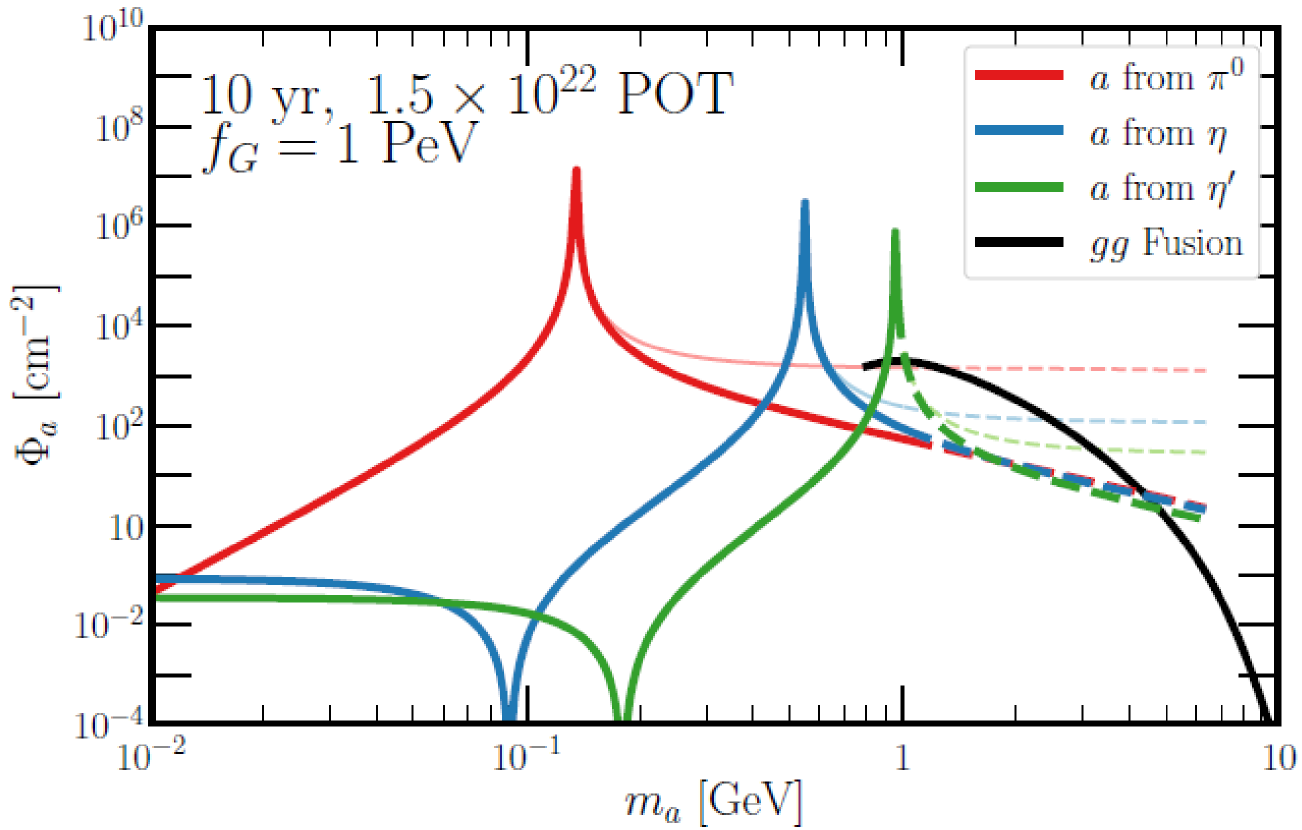
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

$$c_1 = c_2 = c_3 = 1$$

DUNE: excellent for heavy Axions



DUNE setup



large flux

1.47×10^{21} POT/yr.

$$\pi = \pi_{\rm phys} + \theta_{a\pi} a_{\rm phys} + \cdots \approx \pi_{\rm phys} + \frac{1}{6}\frac{f_\pi}{f_a}\frac{m_a^2}{m_a^2 - m_\pi^2} a_{\rm phys} + \cdots ,$$

$$\eta = \eta_{\rm phys} + \theta_{a\eta} a_{\rm phys} + \cdots \approx \eta_{\rm phys} + \frac{1}{\sqrt{6}}\frac{f_\pi}{f_a}\left(\frac{m_a^2 - \frac{4}{9}m_\pi^2}{m_a^2 - m_\eta^2}\right) a_{\rm phys} + \cdots ,$$

$$\eta' = \eta'_{\rm phys} + \theta_{a\eta'} a_{\rm phys} + \cdots \approx \eta'_{\rm phys} + \frac{1}{2\sqrt{3}}\frac{f_\pi}{f_a}\left(\frac{m_a^2 - \frac{16}{9}m_\pi^2}{m_a^2 - m_{\eta'}^2}\right) a_{\rm phys} + \cdots$$

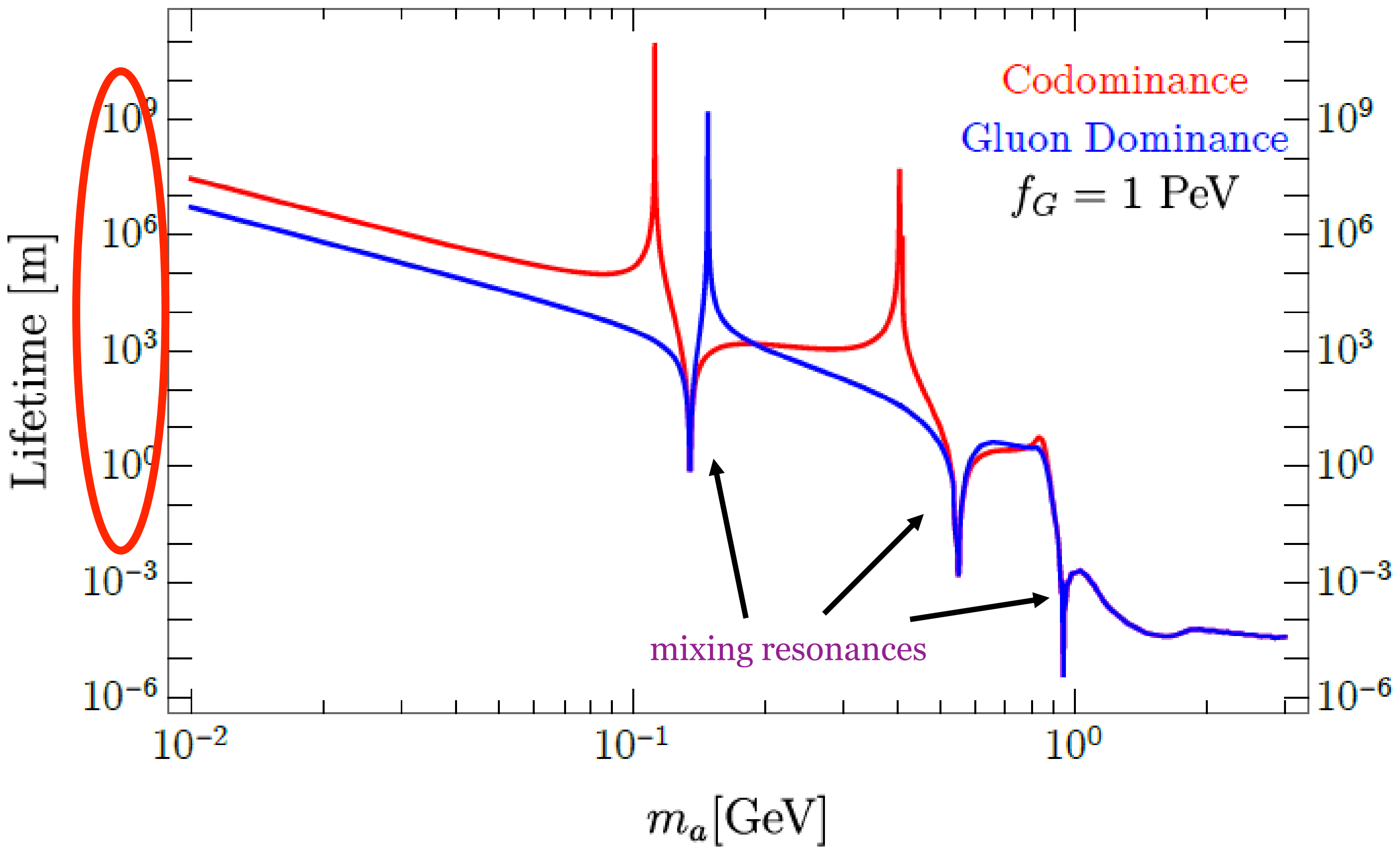
$$N_{\rm axions} = N_{\rm POT} \times \left[2.89|\theta_{a\pi}|^2 f(m_\pi, m_a) + 0.33|\theta_{a\eta}|^2 f(m_\eta, m_a) + 0.03|\theta_{a\eta'}|^2 f(m_{\eta'}, m_a)\right]$$

$$f(m_{\rm meson}, m_a) = \begin{cases} \left(\frac{m_a}{m_{\rm meson}}\right)^{-1.6} & \text{if } m_a > m_{\rm meson} \\ 1 & \text{if } m_a \le m_{\rm meson}. \end{cases}$$

Decay via $\gamma\gamma$ and hadronic states

- DUNE can detect both $\gamma\gamma$ and hadronic final states

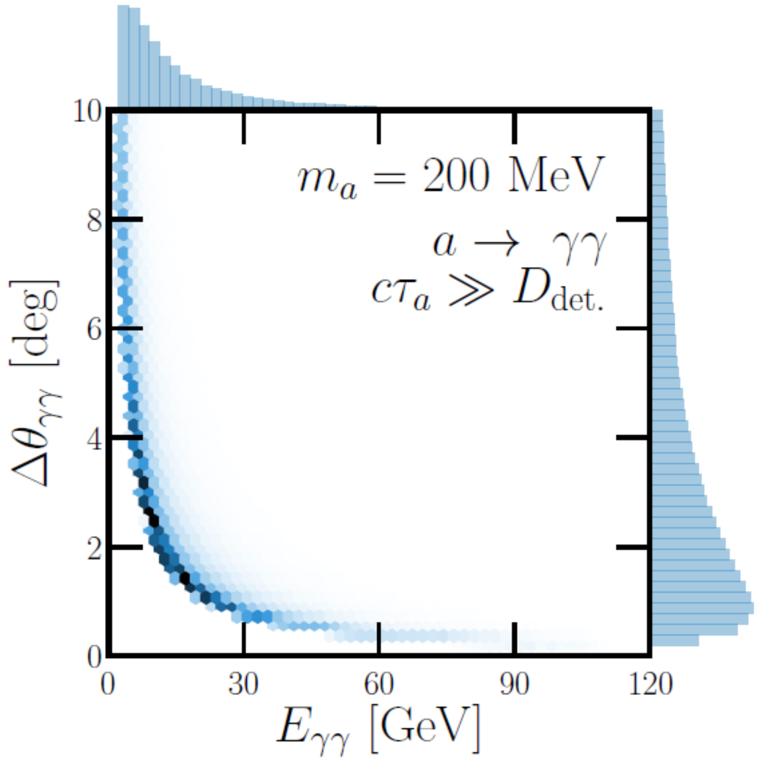
Aloni et. al. '18

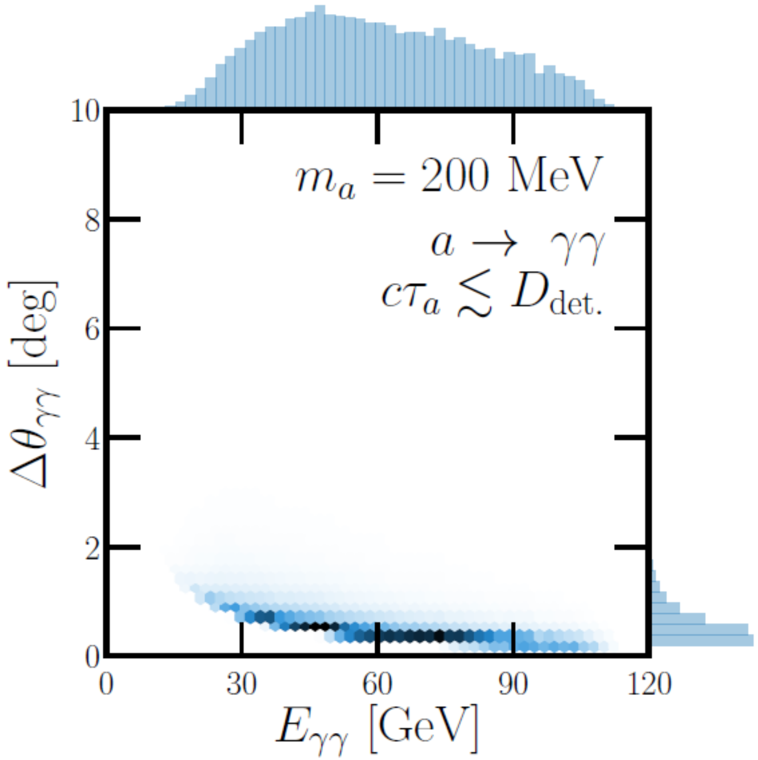


$$c_{\gamma\gamma}^{\text{eff}}(m_a \lesssim \text{GeV}) \approx c_2 + \frac{5}{3}c_1 - 1.92c_3 - c_3 \frac{m_a^2}{m_\pi^2 - m_a^2}\frac{m_d - m_u}{m_d + m_u} + \cdots$$

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

Signal and BG considerations for $a \to \gamma\gamma$

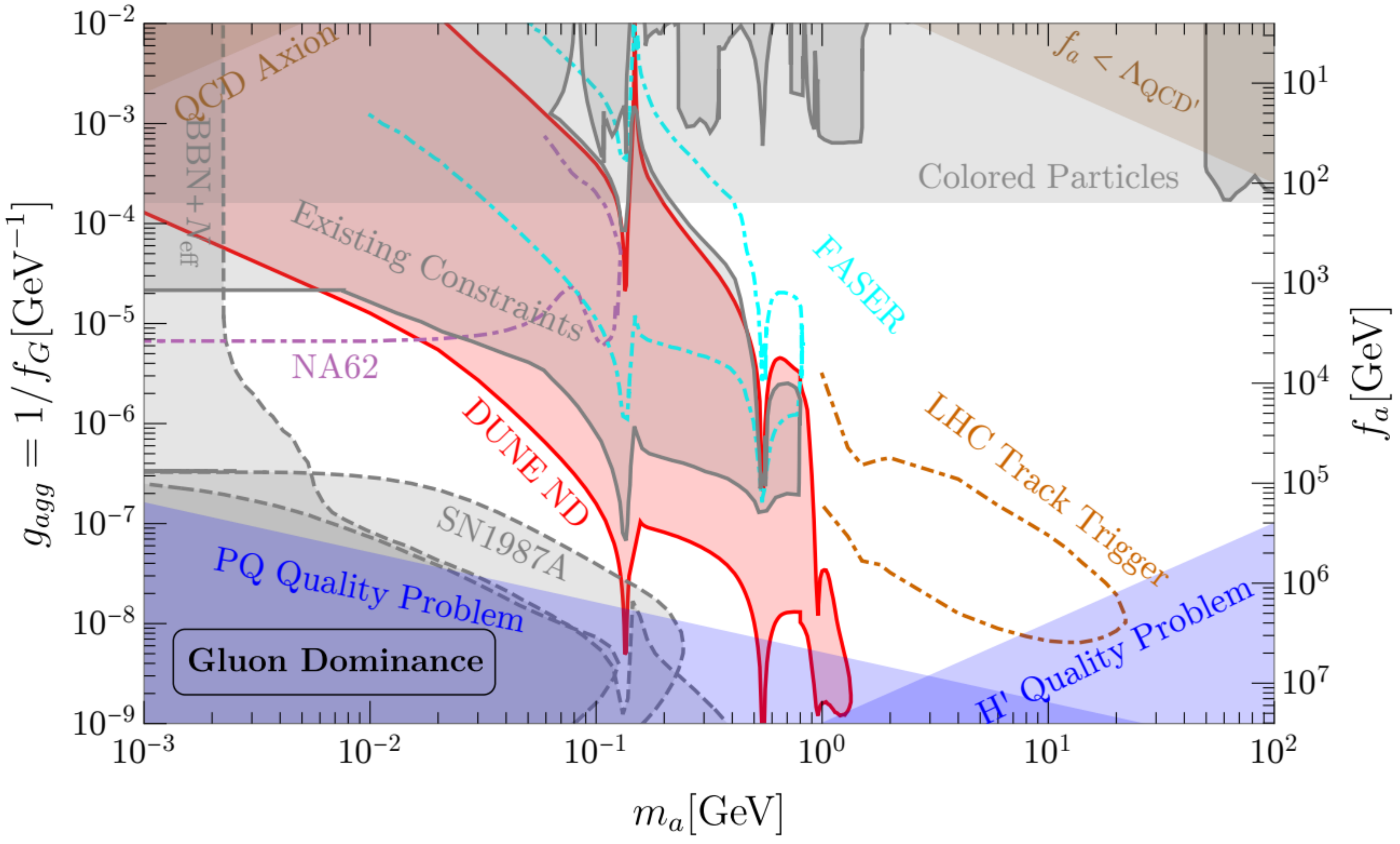




Backgrounds from neutral current π are low energy ($\lesssim$ 5GeV) and isotropic

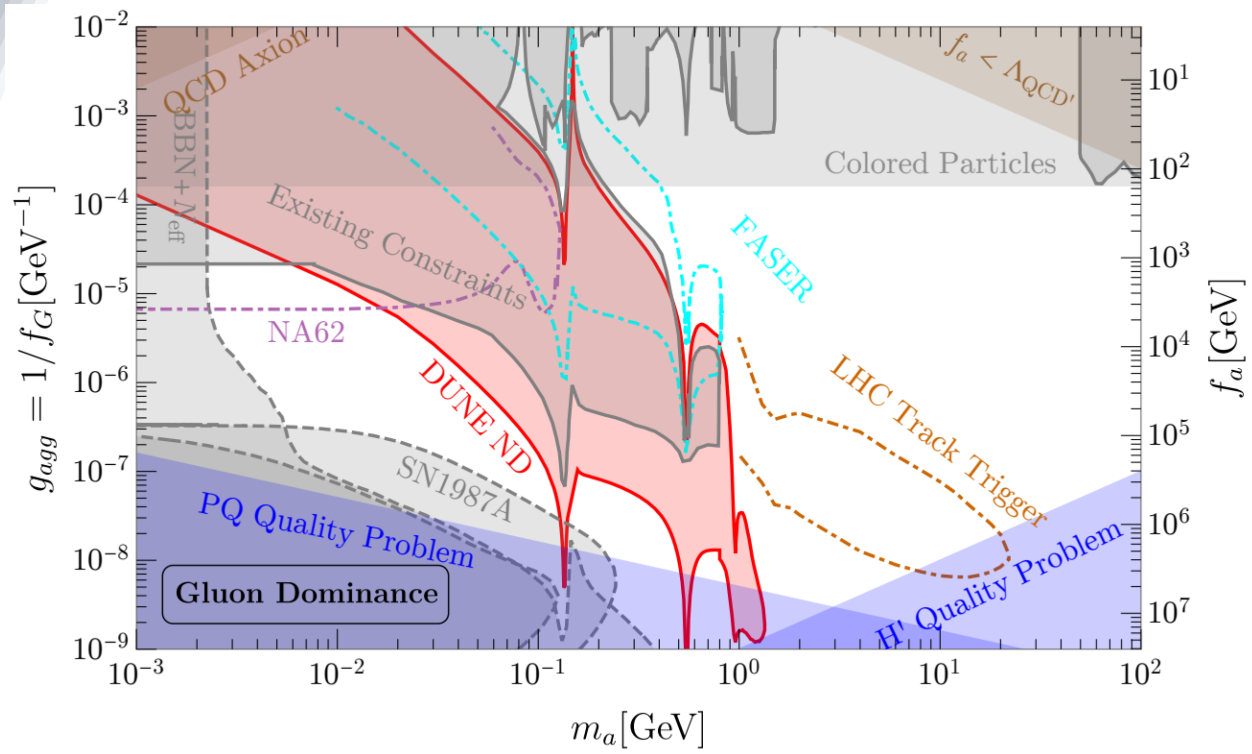
Signature	Liquid Argon ArgonCube		Gaseous Argon MPD	
	Signal	**Background**	**Signal**	**Background**
$a \to \gamma\gamma$	Invariant Mass $\gamma\gamma$ Direction High-Energy	NCπ^0 Nearly-Isotropic Low-Energy	Invariant Mass $\gamma\gamma$ Direction High-Energy	NCπ^0 Nearly-Isotropic Low-Energy Low-energy recoils
$a \to$ hadrons	Invariant Mass Opening angle High-energy gg Direction	CC1μ2π DIS Low-energy Nearly-Isotropic	Invariant Mass Opening angle High-Energy gg Direction	CC1μ2π DIS Low-Energy Nearly-isotropic Low-energy recoils

DUNE coverage



High-quality axion (or generic Axion-like-particles) shows an exciting opportunity for particle physics

Summary and Outlook



- Axion is an elegant solution to the Strong CP puzzle via its IR robustness.
- Quality problem demands new thoughts, and a heavy axion would help.
- A mirror hidden sector with shared axion solve both problems.

DUNE will cover a large and unique parameter spaces of such motivated scenarios, high energy and intense source, and multi-purpose near detector
Lots of new opportunities:
new search strategies and other facilities (LHC, displaced tracks, etc.)

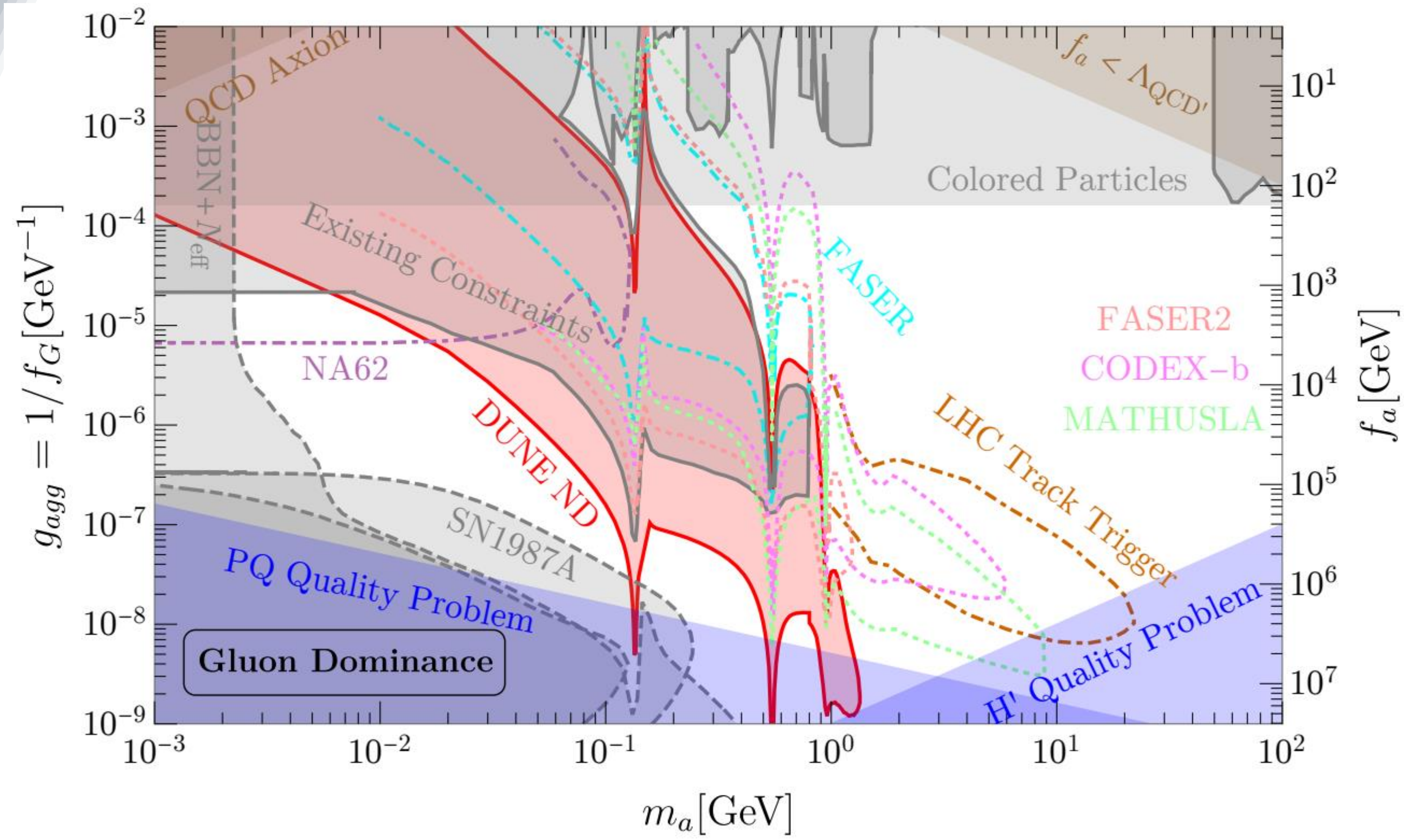
Thanks you!

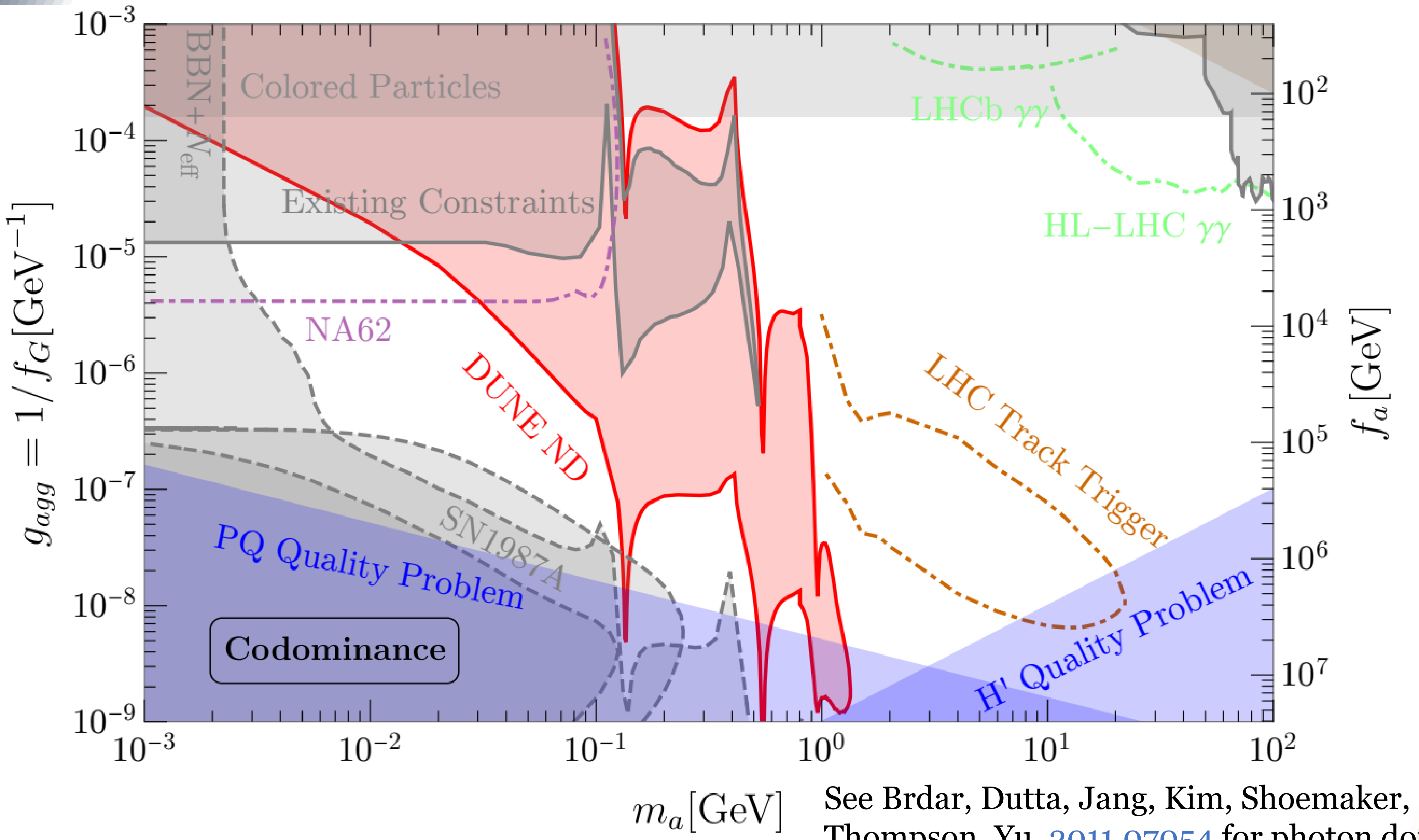
Axion EFT

- Axion EFT: $$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$
- $aG\tilde{G}$ coupling induces photon coupling via anomaly
- For $m_a > 3m_\pi$ hadronic decay modes dominate $\rightarrow$ significant change in phenomenology compared to $c_3 = 0$.

$$c_{\gamma\gamma}^{\mathrm{eff}}(m_a \lesssim \mathrm{GeV}) \approx c_2 + \frac{5}{3}c_1 - 1.92c_3 - c_3\frac{m_a^2}{m_\pi^2 - m_a^2}\frac{m_d - m_u}{m_d + m_u} + \cdots$$

DUNE coverage — complementarity





See Brdar, Dutta, Jang, Kim, Shoemaker, Tabrizi, Thompson, Yu 2011.07054 for photon dominance case