

Axions/ALPs at the Fundamental Frontier

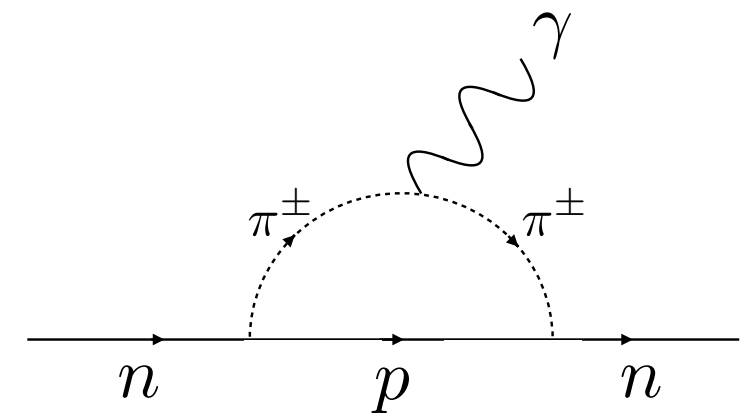
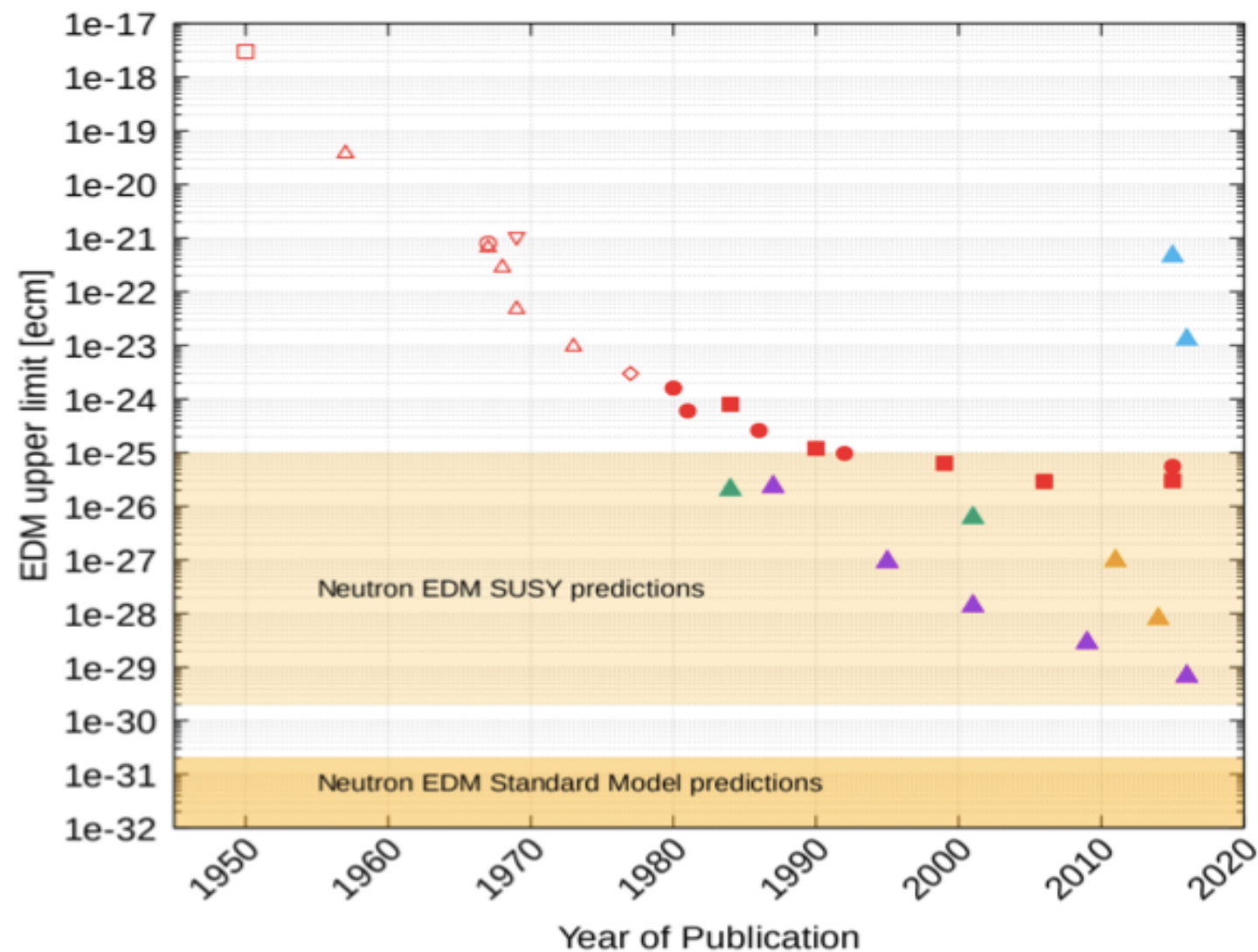


Sabyasachi Chakraborty (IIT-Kanpur)
(From Big Bang to Now: A Theory Experiment Dialogue)

2412.09678 with D. Bisht and A. Samanta
2403.12169 with A. Gupta and M. Vanvlassalaer

Introduction: Standard Model & CP

► Strong CP Phase: $\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{QCD}}^{\text{SM}} + \bar{\theta} \frac{\alpha_s}{8\pi} \underbrace{G_{\mu\nu}^a \tilde{G}^{\mu\nu a}}_{\partial^\mu K_\mu \neq 0}$



$$|d_n| < 1.8 \times 10^{-26} \text{ ecm}$$

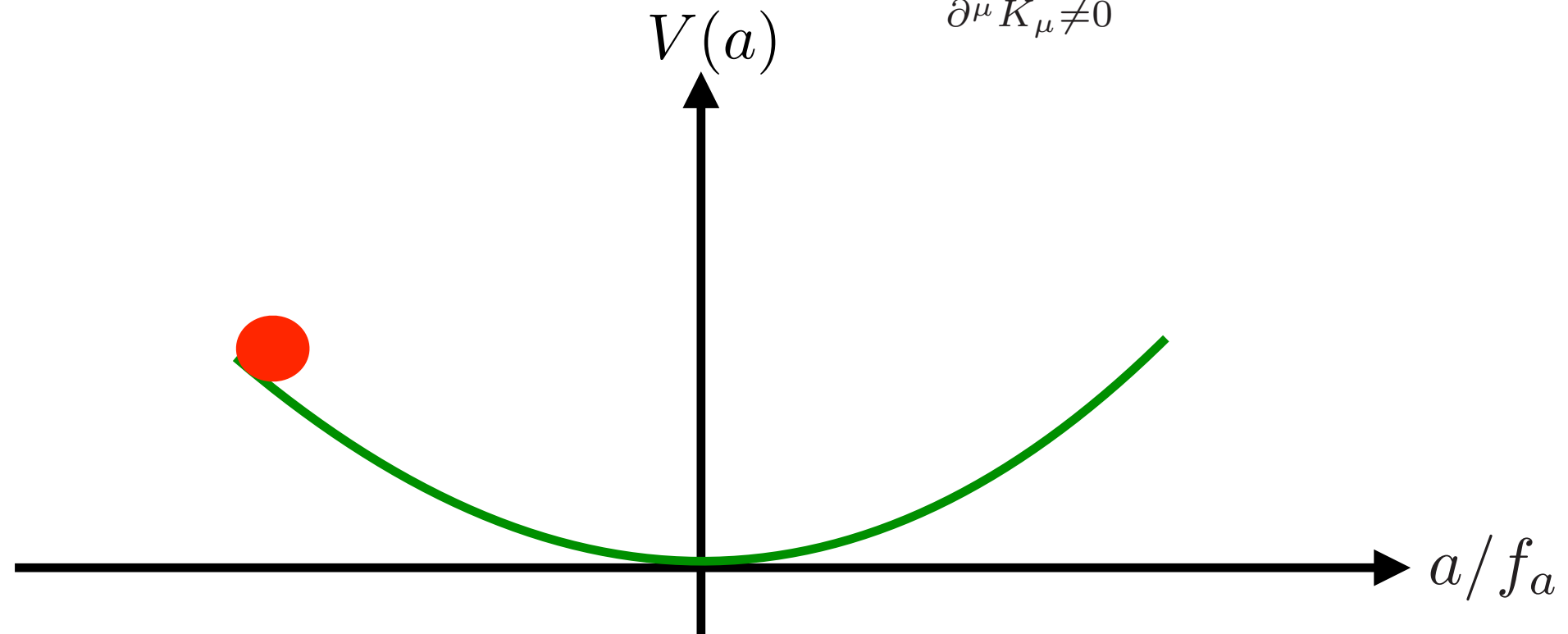
arXiv:2001.11966

$$\bar{\theta} = \theta + \text{Arg}(\text{Det}M) < 10^{-10}$$

: Strong CP problem

Introduction: Axion as a solution

► Solution to Strong CP: $\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{QCD}}^{\text{SM}} + \bar{\theta} \frac{\alpha_s}{8\pi} \underbrace{G_{\mu\nu}^a \tilde{G}^{\mu\nu a}}_{\partial^\mu K_\mu \neq 0} \Rightarrow \bar{\theta} = \frac{a}{f_a}$

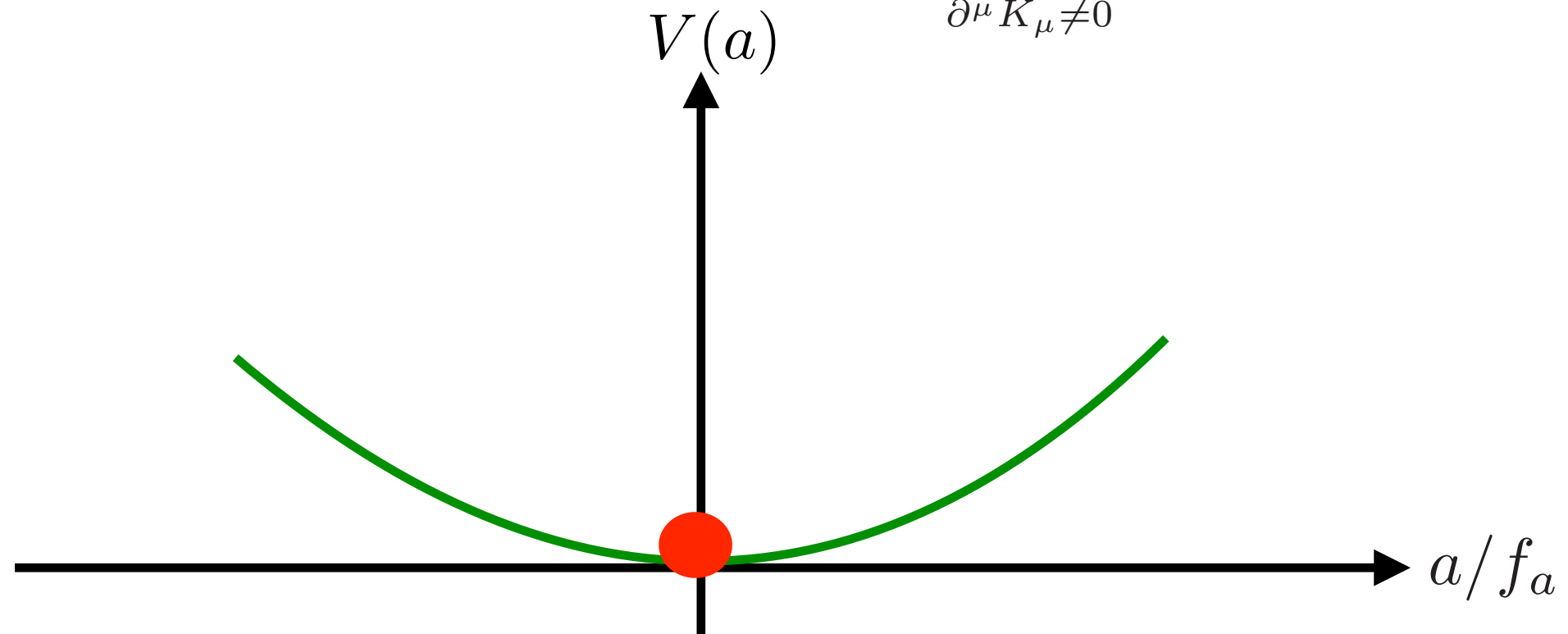


Dynamical solution to strong CP

Other Motivations: Dark matter candidate,
Hierarchy problem,
Matter-Antimatter asymmetry etc.

Introduction: Axion as a solution

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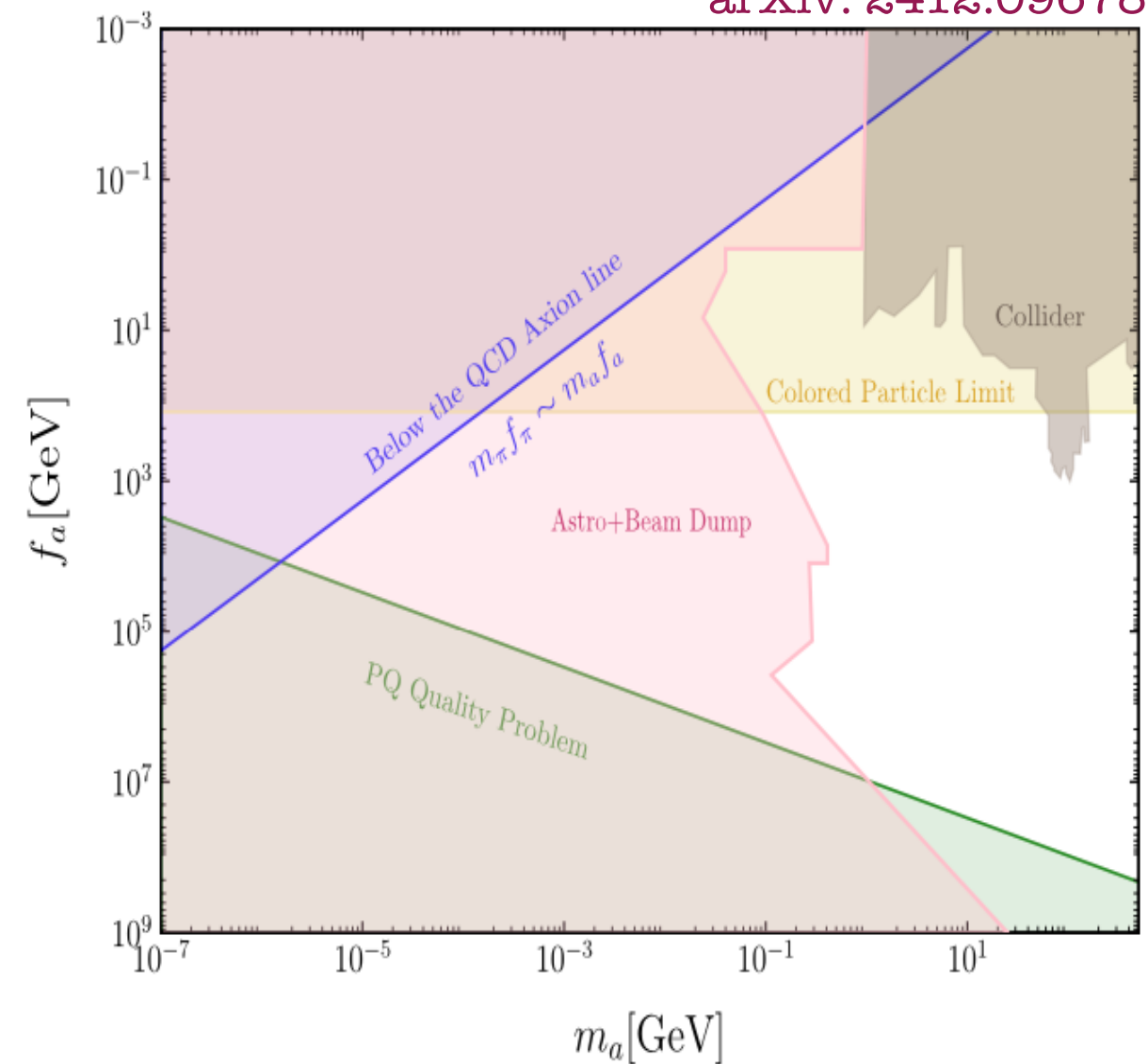
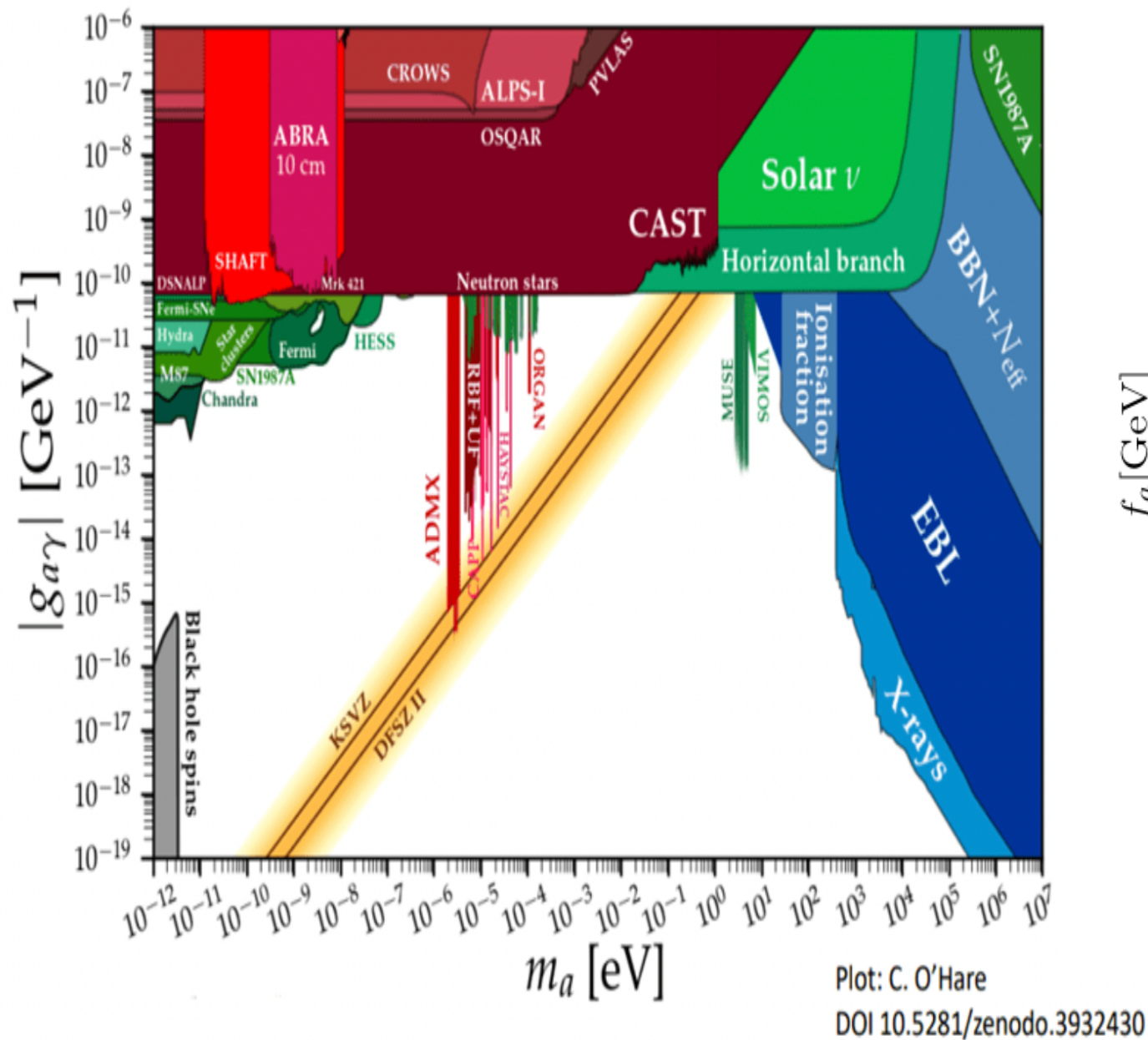


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Axions at the Fundamental Frontiers

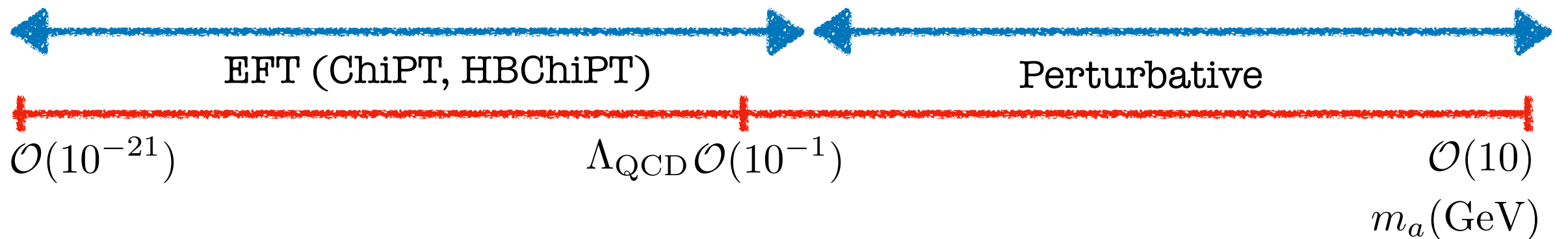
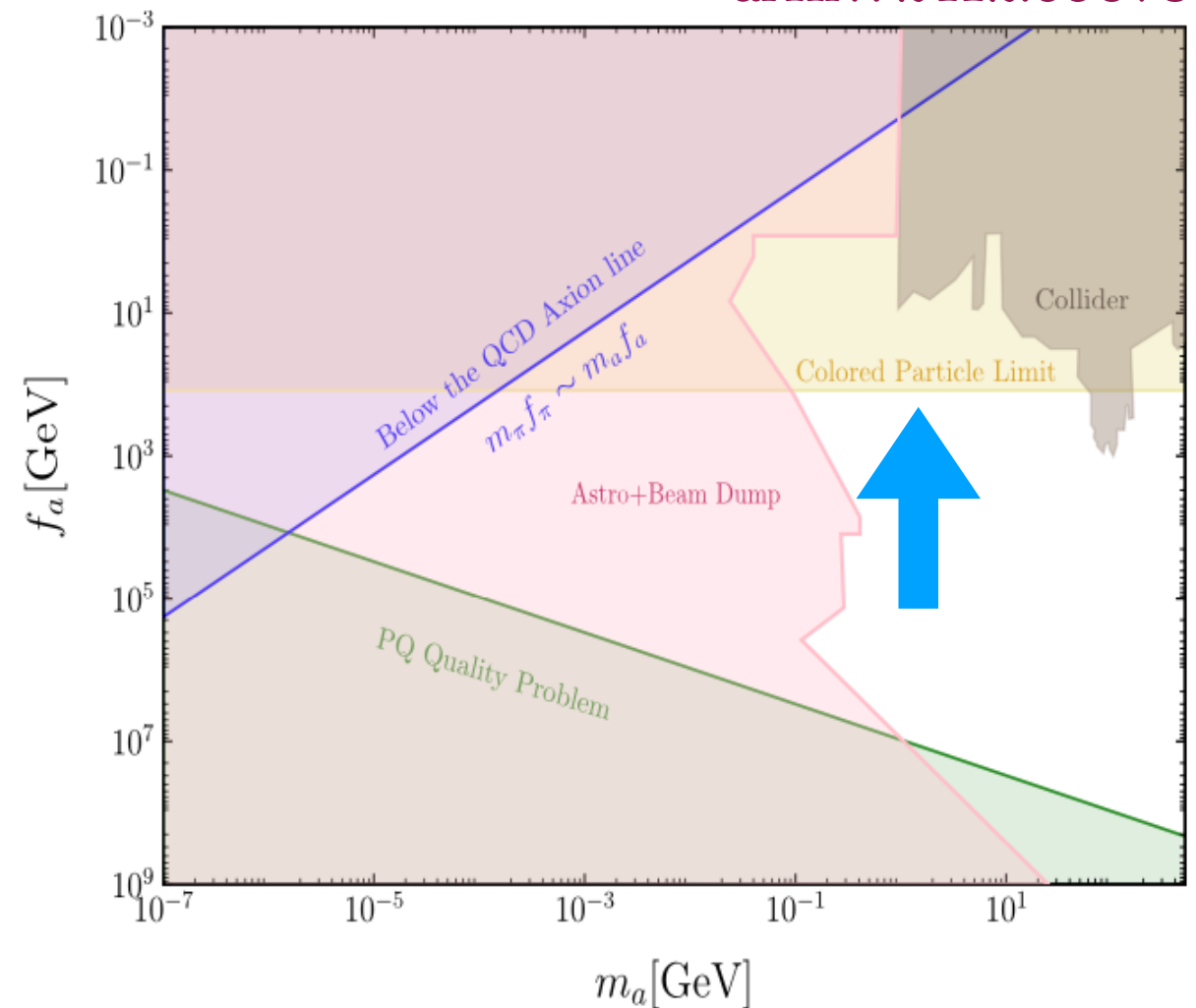
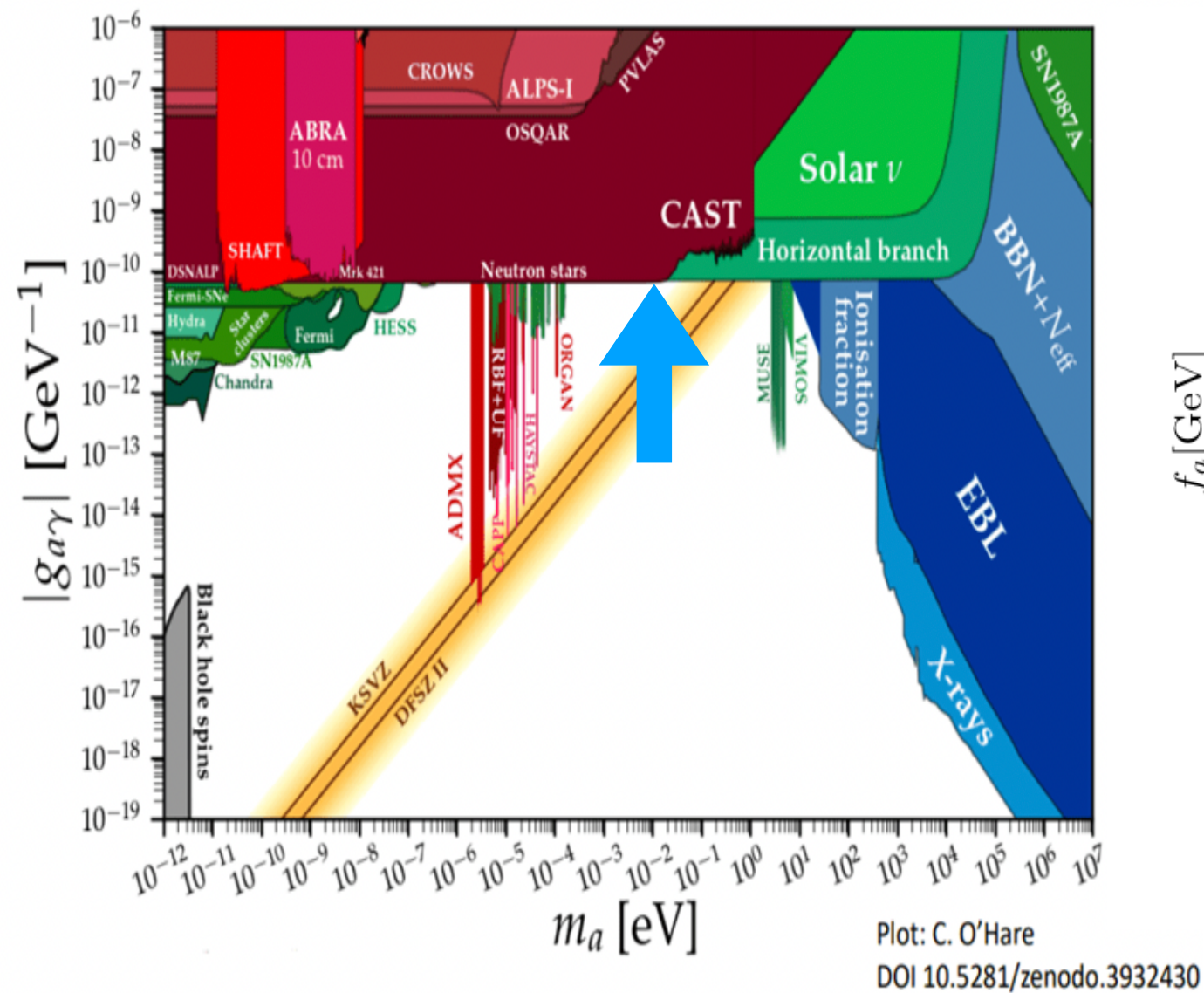
arXiv: 2412.09678



Another Motivation: There are dedicated experiments!

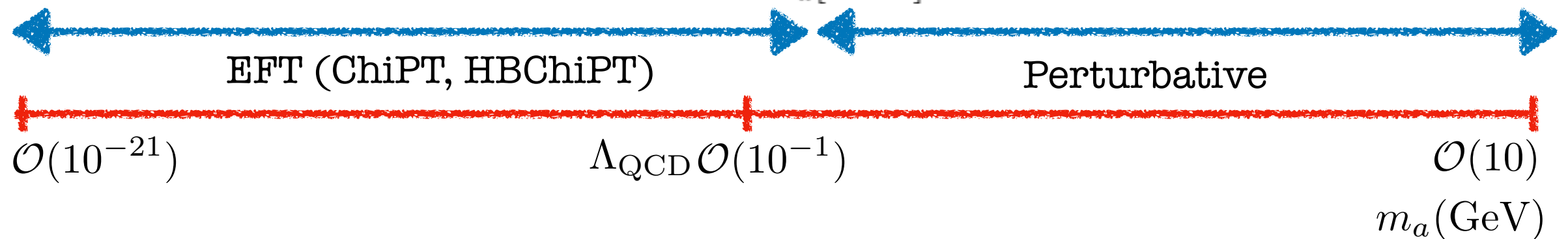
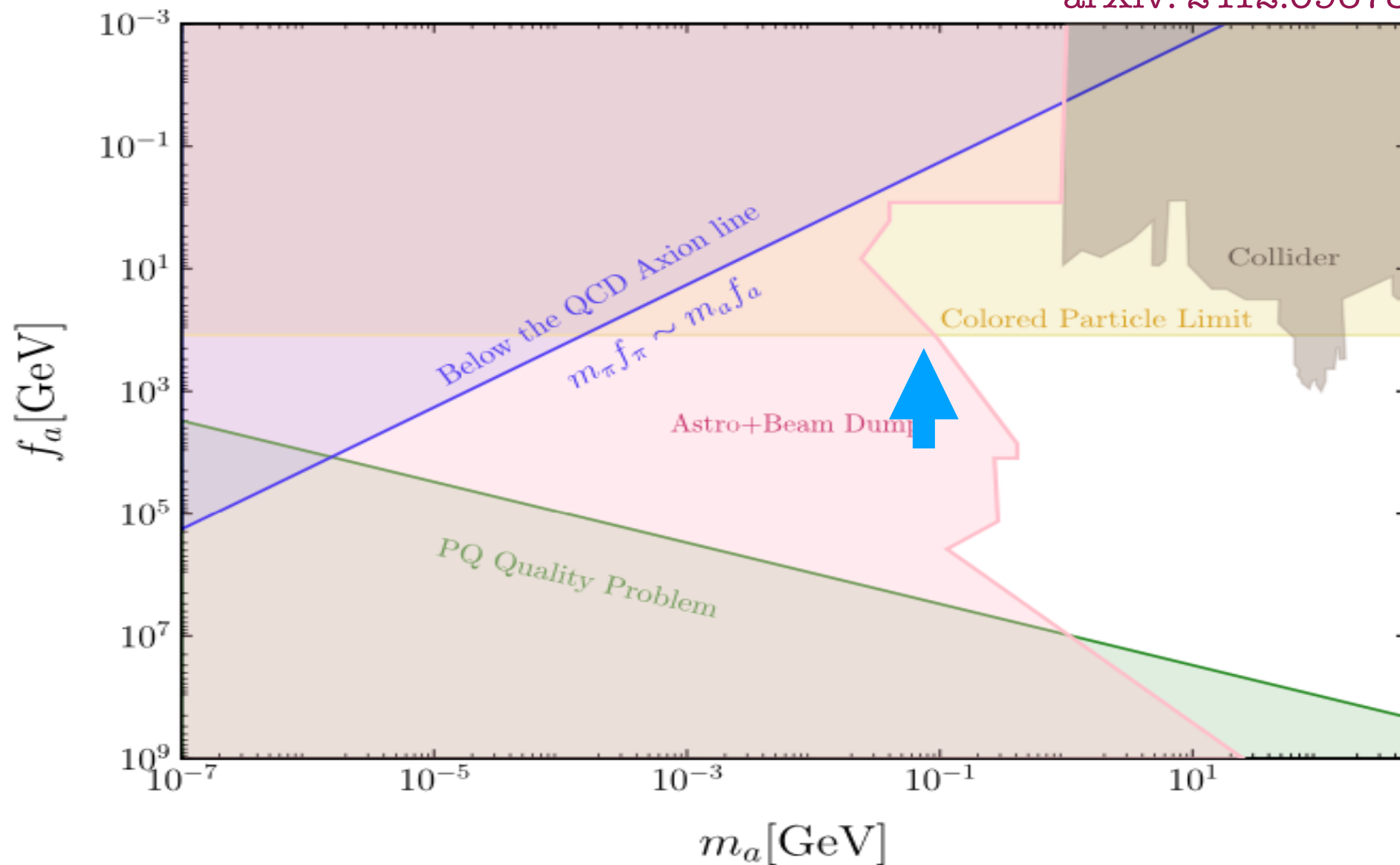
Our Focus

arXiv: 2412.09678



Axions/ALPs @ intensity frontier

arXiv: 2412.09678



ChiPT and Axions

► Dynamical Solution, Axion $a(x)$:

$$\mathcal{L}_{\text{eff}} \supset \bar{q} (i\not{D} - \mathcal{M}_q) q + \left(\frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{\mu\nu a} + \dots \quad \star \quad q \rightarrow \text{Exp} \left(i\kappa_q \frac{a}{2f_a} \gamma_5 \right) q$$

However generates

$$\mathcal{L}_{\text{eff}} \supset \bar{q} \left(i\not{D} - \hat{\mathcal{M}}_q \right) q - \frac{\partial^\mu a}{2f_a} \bar{q} \gamma_\mu \gamma_5 q + \dots \quad \text{where} \quad \hat{\mathcal{M}}_q = e^{i\kappa \frac{a}{f_a} \gamma_5} \mathcal{M}_q e^{i\kappa \frac{a}{f_a} \gamma_5}$$

Matching with ChPT

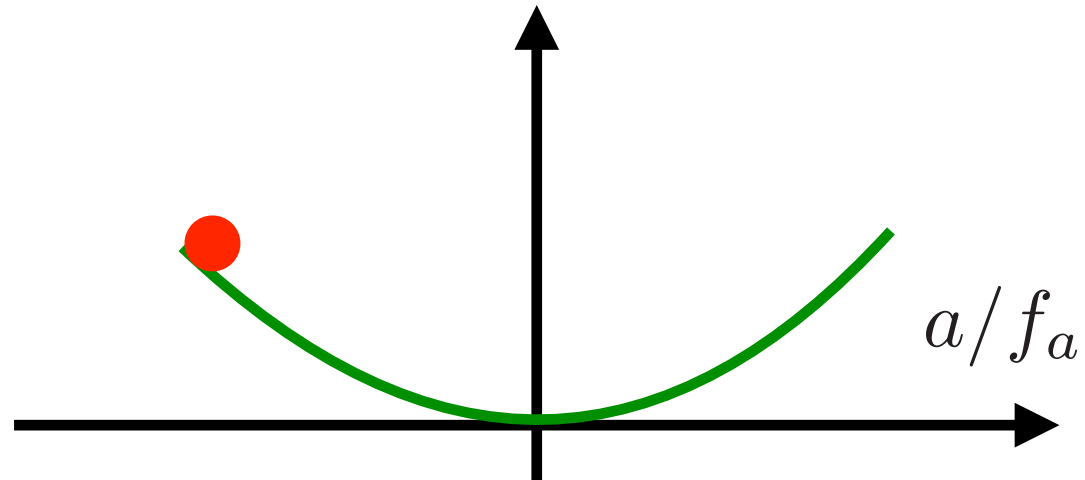
$$\mathcal{L}_{\chi\text{PT}} \supset \frac{f_\pi^2}{8} \text{Tr} [D^\mu \Sigma D_\mu \Sigma^\dagger] + \frac{f_\pi^2}{4} 2B_0 \text{Tr} \left[\Sigma \hat{\mathcal{M}}_q^\dagger + \text{h.c.} \right] + \dots \quad \left[\Sigma = \text{Exp} \left[i \frac{\sqrt{2} \pi^a \tau^a}{f_\pi} \right] \right]$$

ChiPT and Axions

► ChPT + Axions

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$$\theta \, G\tilde{G} \rightarrow \frac{a}{f_a} G\tilde{G} \Rightarrow$$



Dynamical solution to strong CP

- Mass and mixing $V_{\pi,a} \rightarrow m_a \sim \frac{m_\pi f_\pi}{f_a}$, $g_{aff} \sim g_{\pi^0 ff} \times \left(\frac{f_\pi}{f_a} \right) \Rightarrow \sin \theta$

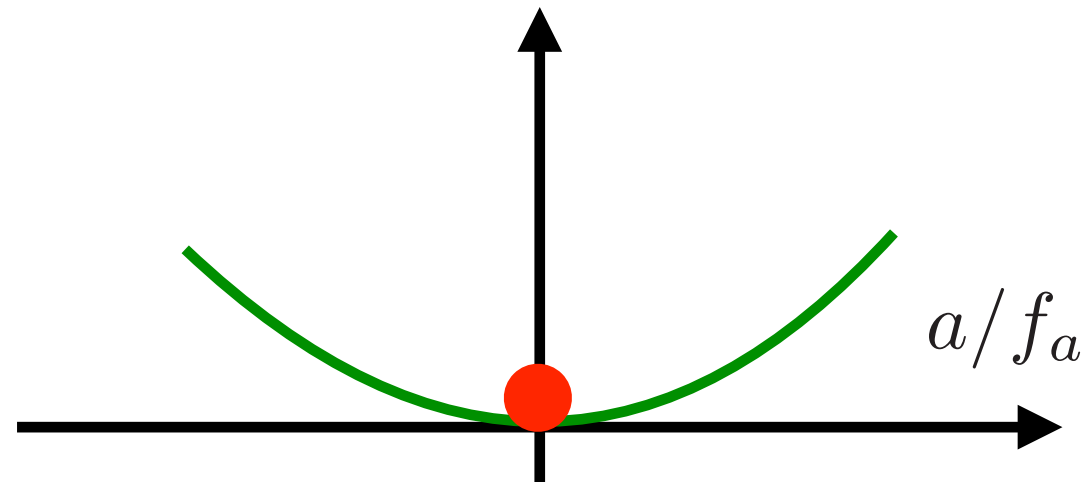
$$\text{ALP} : m_a \neq \frac{m_\pi f_\pi}{f_a}$$

ChiPT and Axions

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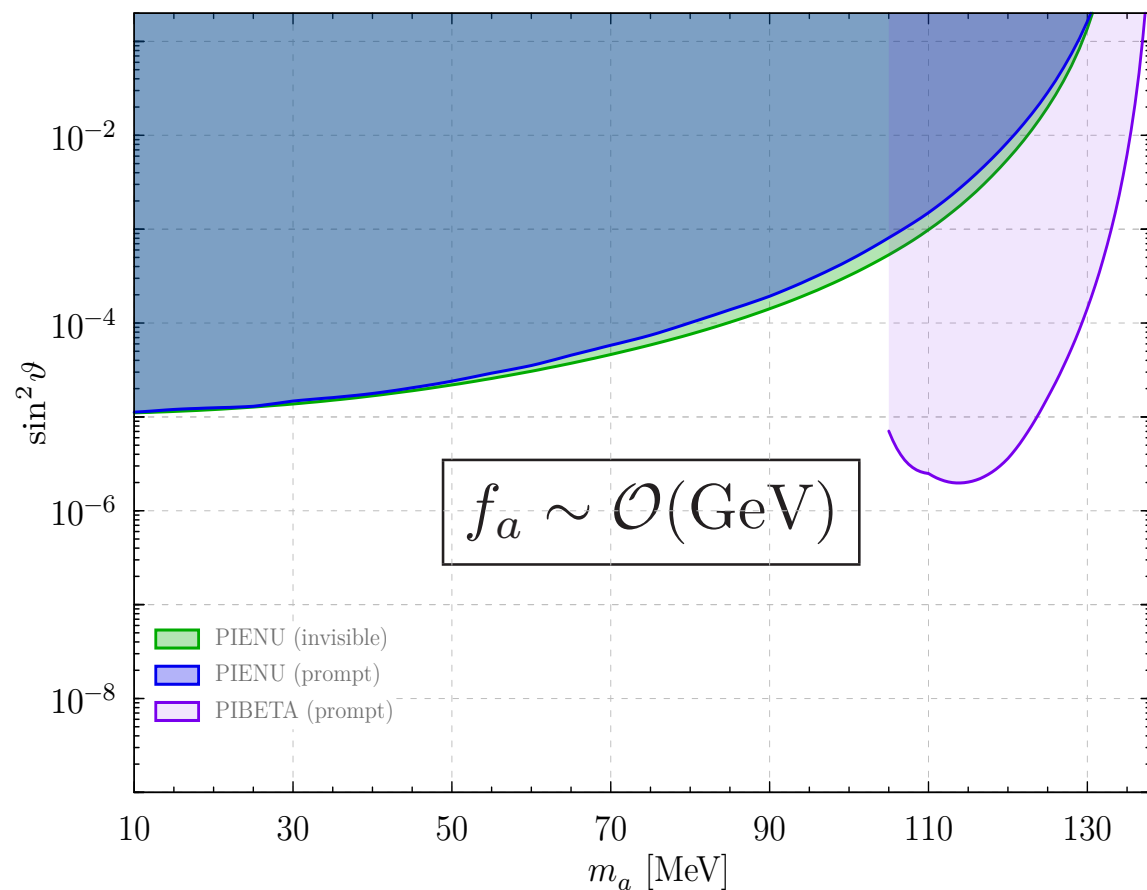
$$\text{ALP : } m_a \neq \frac{m_\pi f_\pi}{f_a}$$

Intensity Frontier: Bounds from Meson decay

$$g_{aff} \sim g_{\pi^0 ff} \times \frac{f_\pi}{f_a} \Rightarrow \sin \theta$$

$$\pi^+ \rightarrow \pi^0 (a) e^+ \nu$$

Altmannshofer, Gori, Robinson 1909.00005

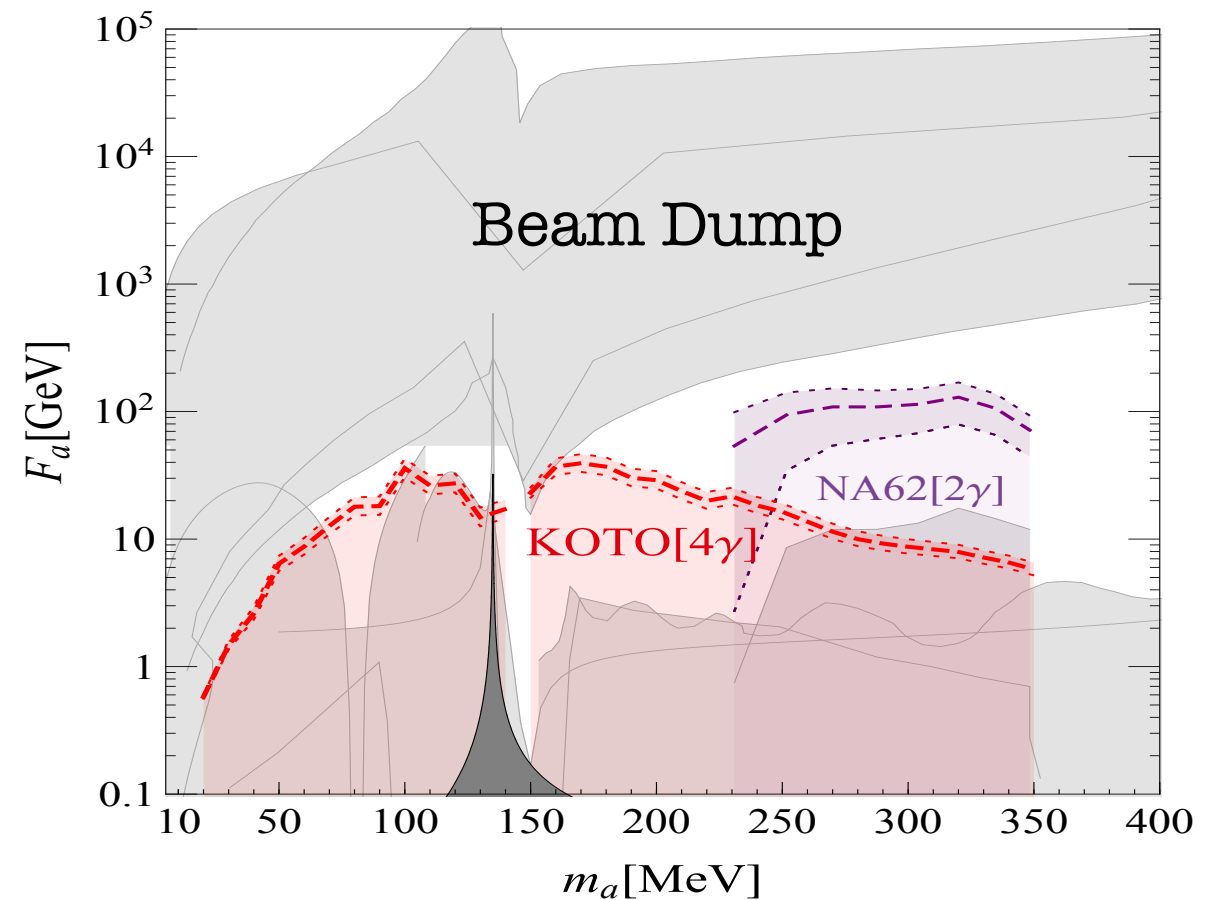


PIBETA Exp. $\text{Br} [\pi^+ \rightarrow \pi^0 e \nu] \sim 10^{-8}$

PIENU Exp. $\text{Br} [\pi^+ \rightarrow e \nu] \sim 10^{-4}$

$$K^+ \rightarrow \pi^+ a, K_L \rightarrow \pi^0 a$$

Gori, Perez, Tobioka 2005.05170

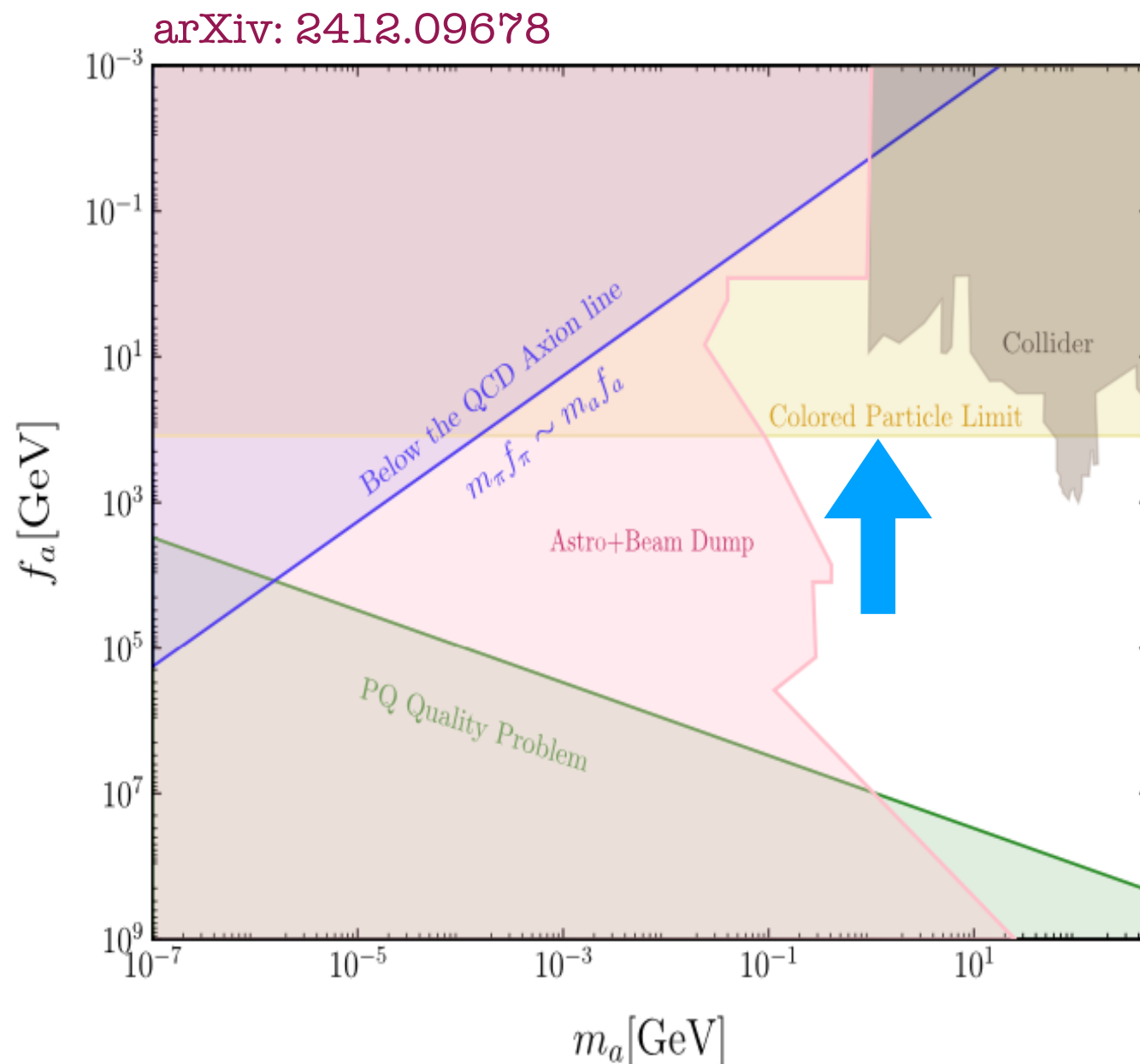


NA62 Exp: $\text{Br} [K^+ \rightarrow \pi^+ \nu \bar{\nu}] \sim 10^{-10}$

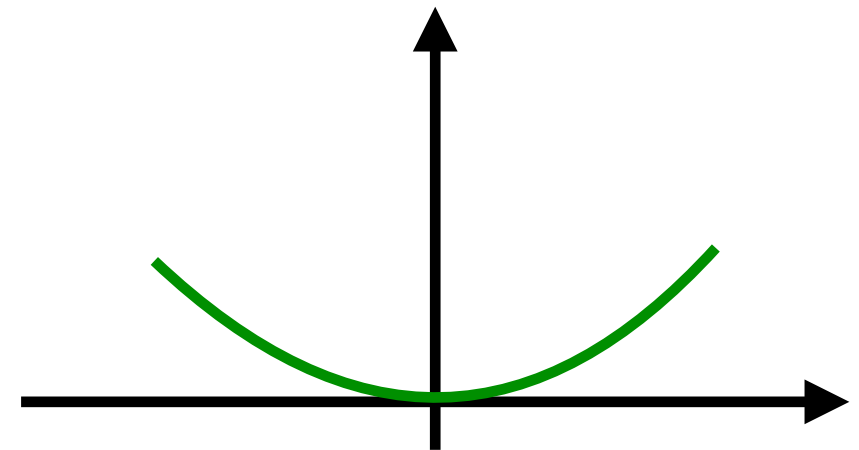
KOTO Exp: $\text{Br} [K_L \rightarrow \pi^0 \nu \bar{\nu}] \sim 10^{-9}$

Indirect Probes: Triparno, Subhagit, Tuhin 2022

Axion and Quality Problem



- QCD Axion with large f_a is problematic $\Rightarrow$ Quality Problem



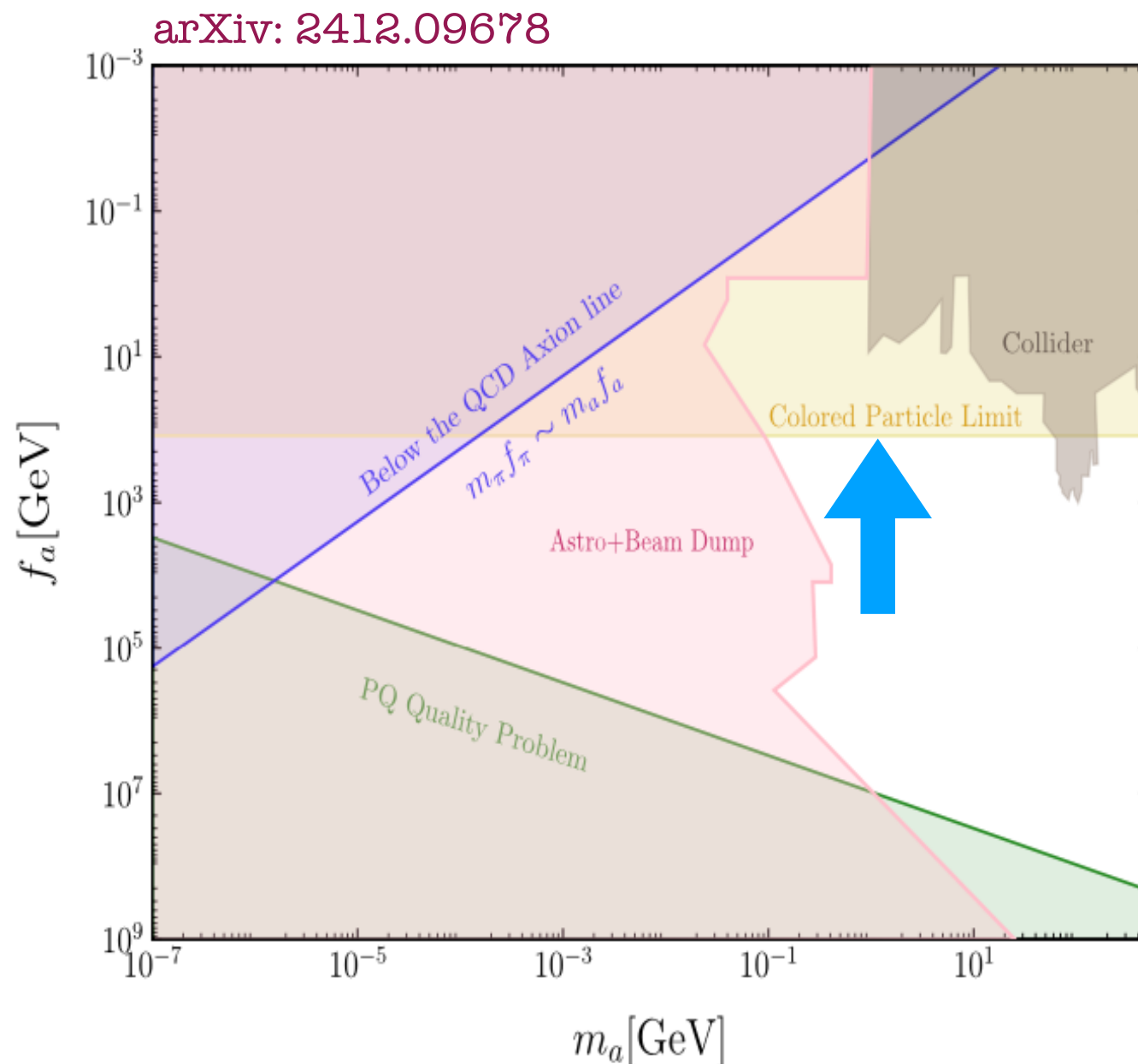
$$\frac{\lambda f_a^5}{M_{\text{pl}}} < \Lambda_{\text{QCD}}^4 \implies \lambda < 10^{-10} \left(\frac{10^5}{f_a} \right)^5$$

See: Rubakov 9703409

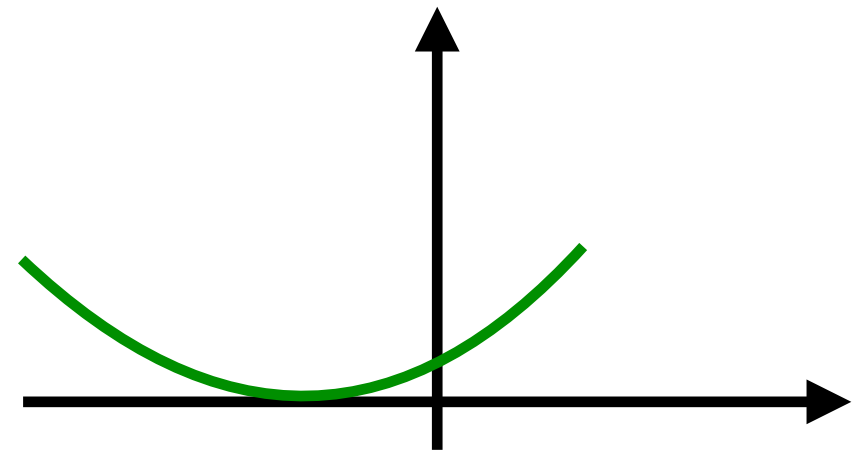
Fukuda, Harigaya, Ibe, Yanagida 1504.06084

Hook, Kumar, Liu, Sundrum 1911.12364 etc.

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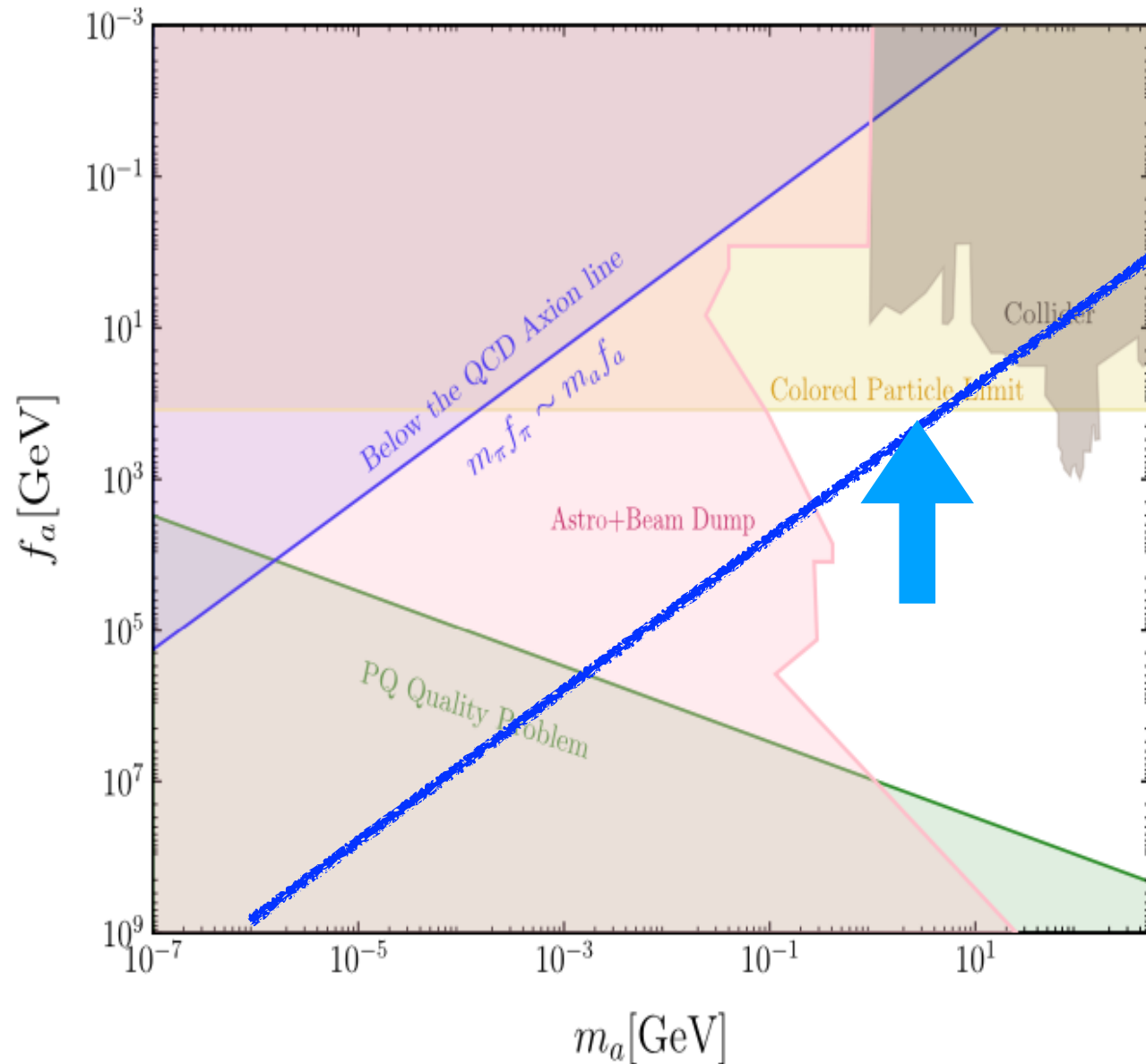
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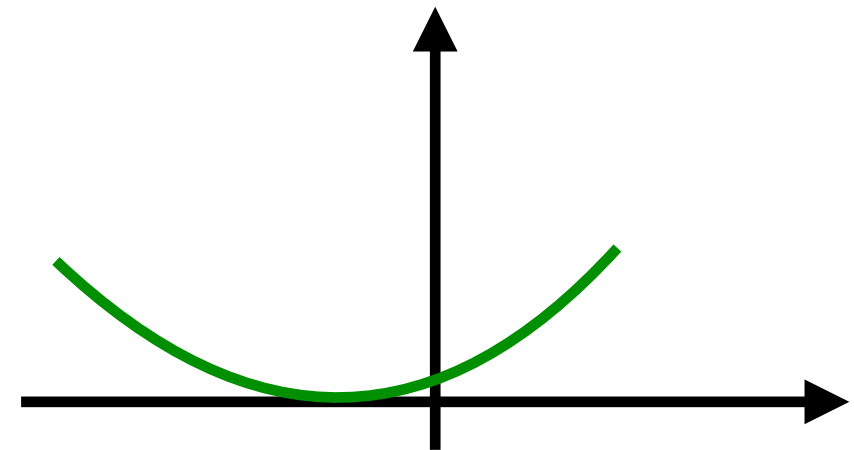
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Axions/ALPs @ Intensity frontier



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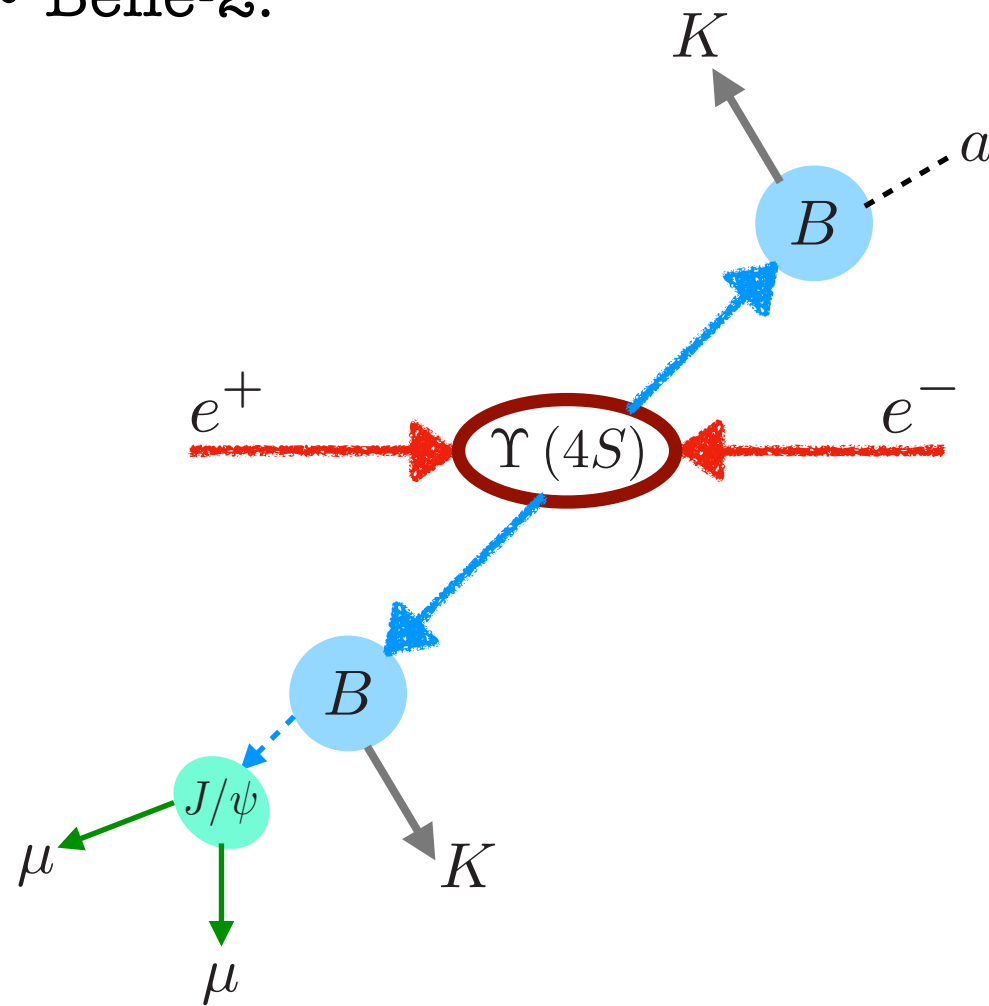
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ALPs from B-decays

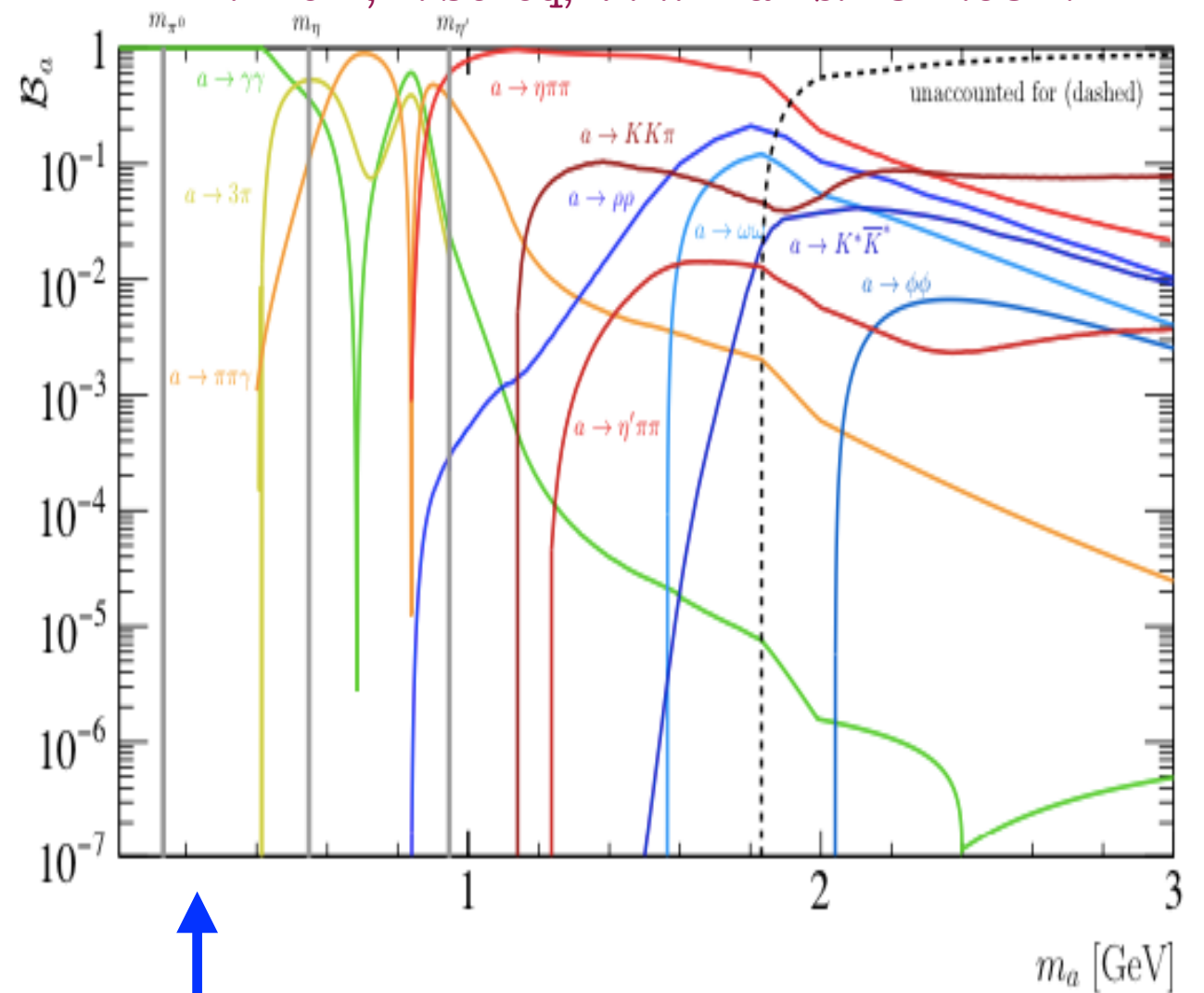
- Belle-2:



Belle Experiment

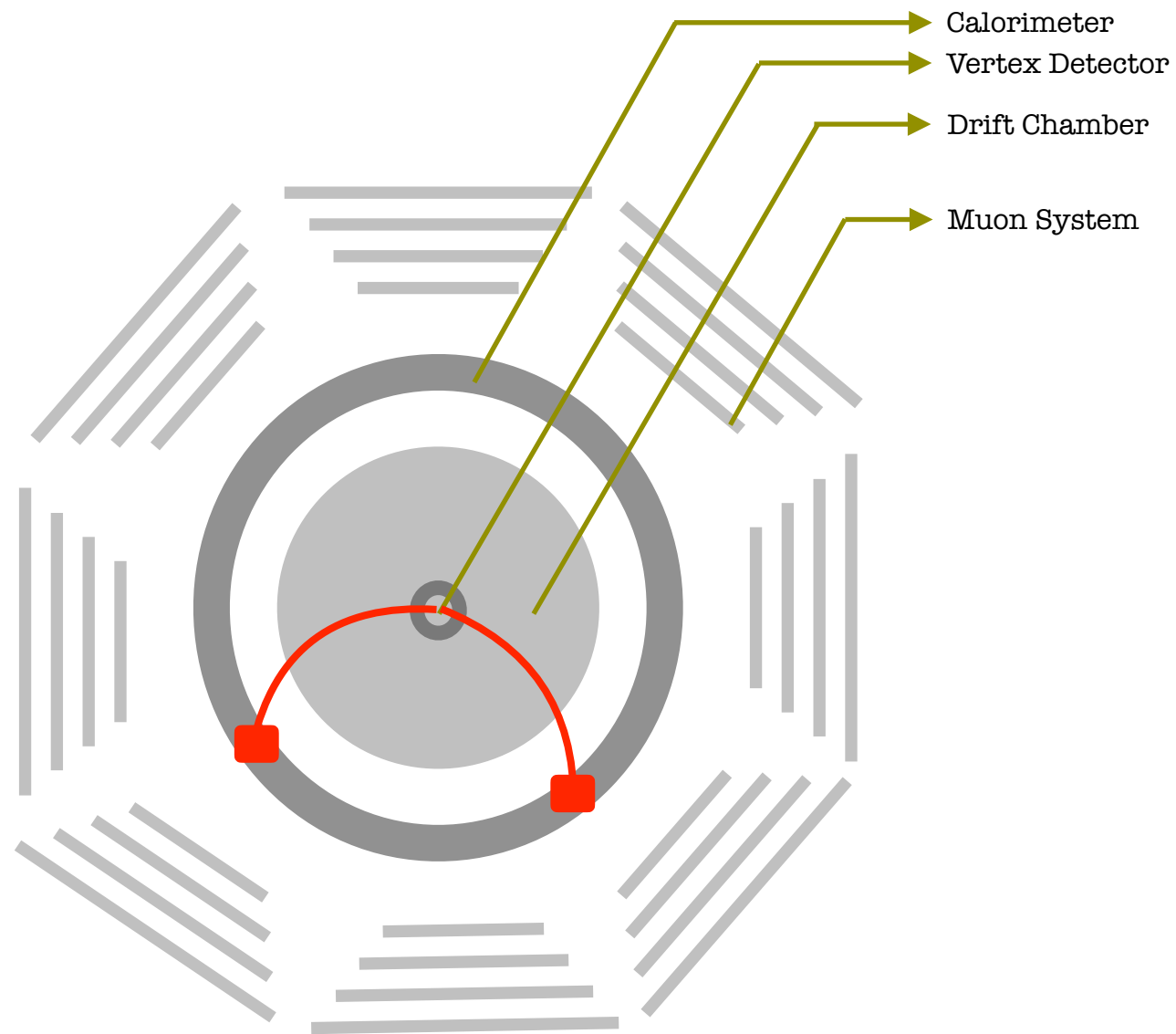
$a \rightarrow (\eta\pi\pi, KK\pi, 3\pi, \phi\phi)$

D. Aloni, Y. Soreq, M. Williams: 1811.03474



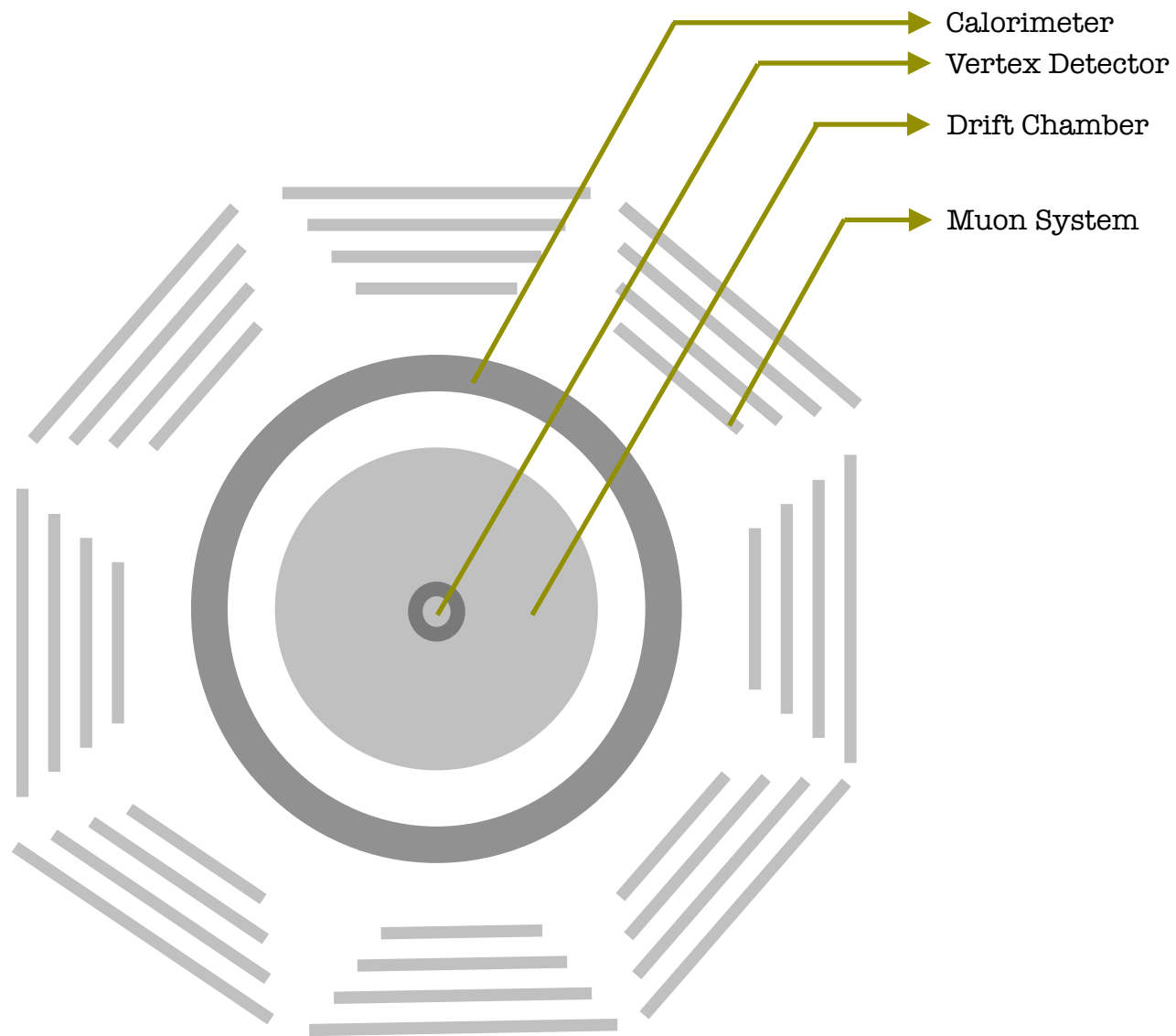
$$N_{\text{sig}} = \underbrace{N_{BB}}_{10^8} \times \underbrace{\text{BR}(B \rightarrow Ka)}_{\text{Our Calculation}} \times \underbrace{\text{BR}(a \rightarrow X)}_{\text{Required}} \times \underbrace{\epsilon_{\text{eff}}}_{\text{Isospin Factors}} \times \underbrace{\mathcal{O}(1)}_{\text{Isospin Factors}}$$

Prompt vs Displaced



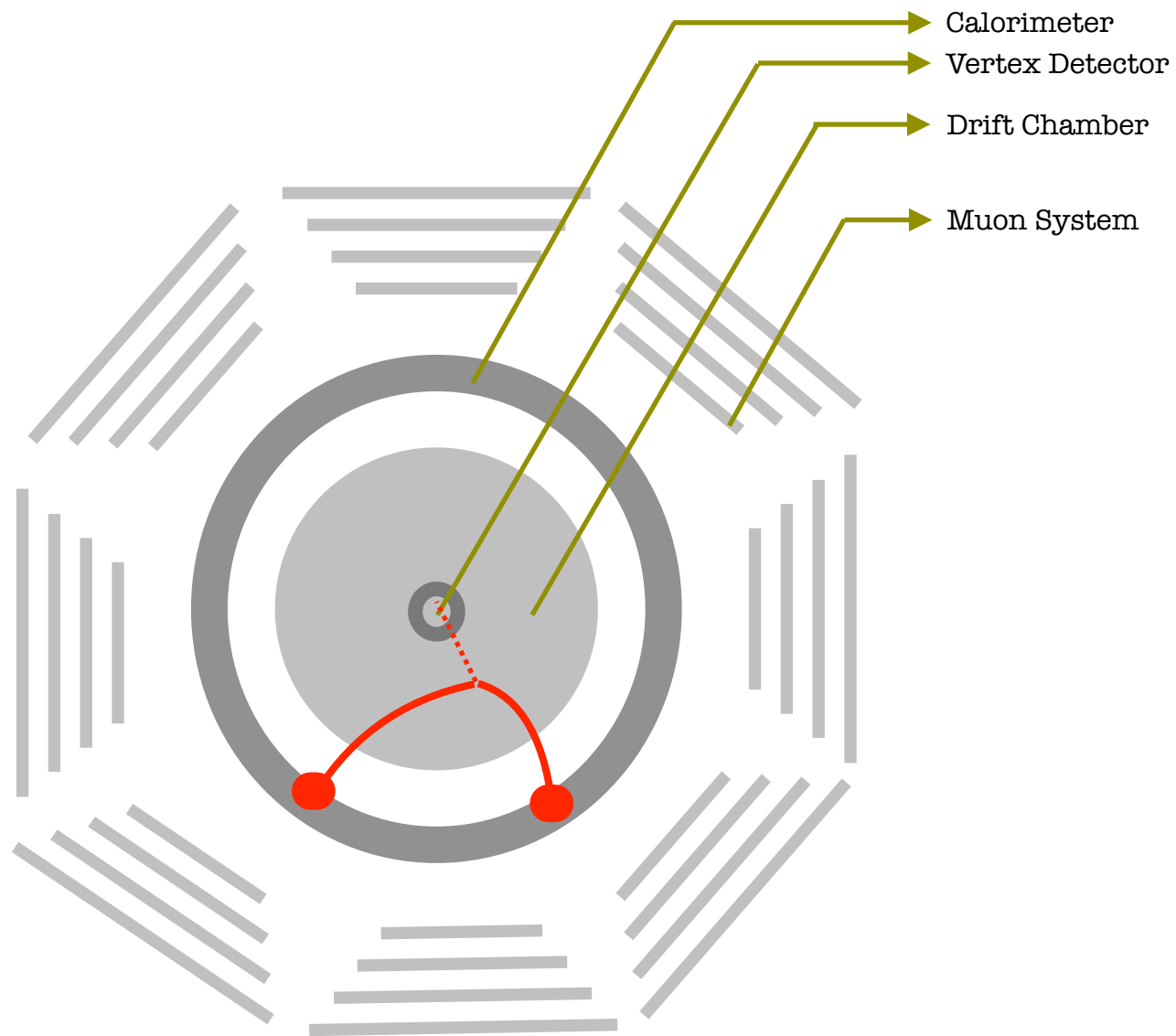
Recent Works at Belle: 1908.09719,
1911.03176, 2108.10331 etc.

Prompt vs Displaced



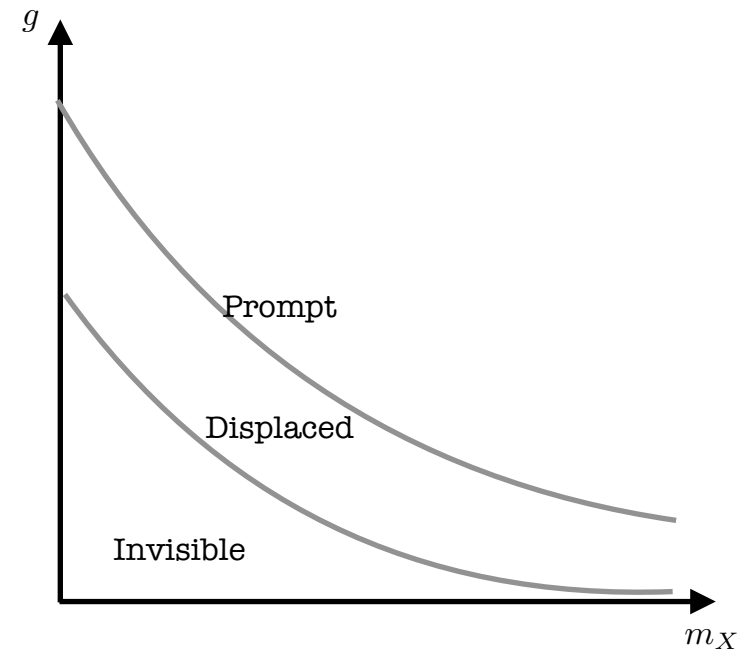
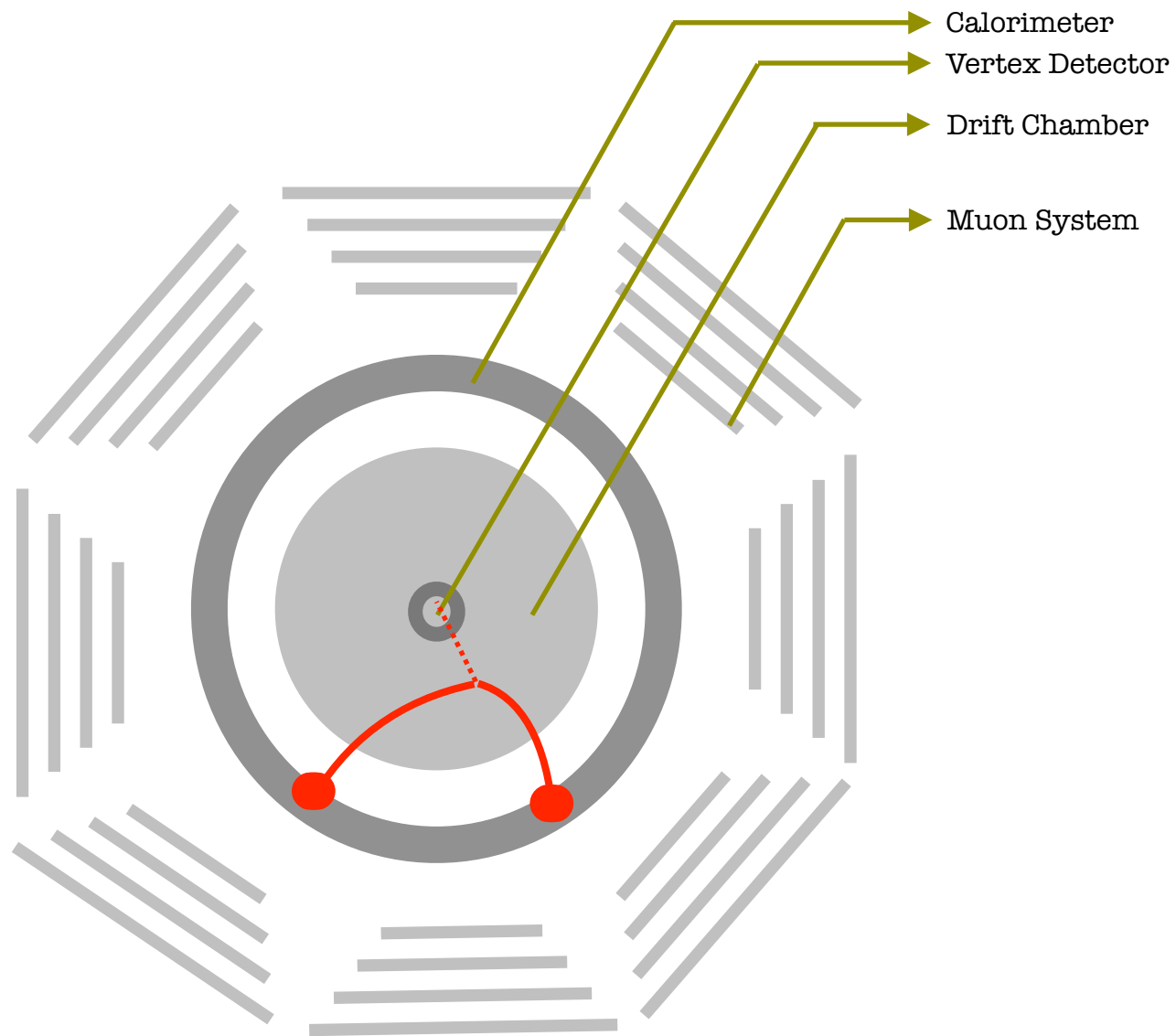
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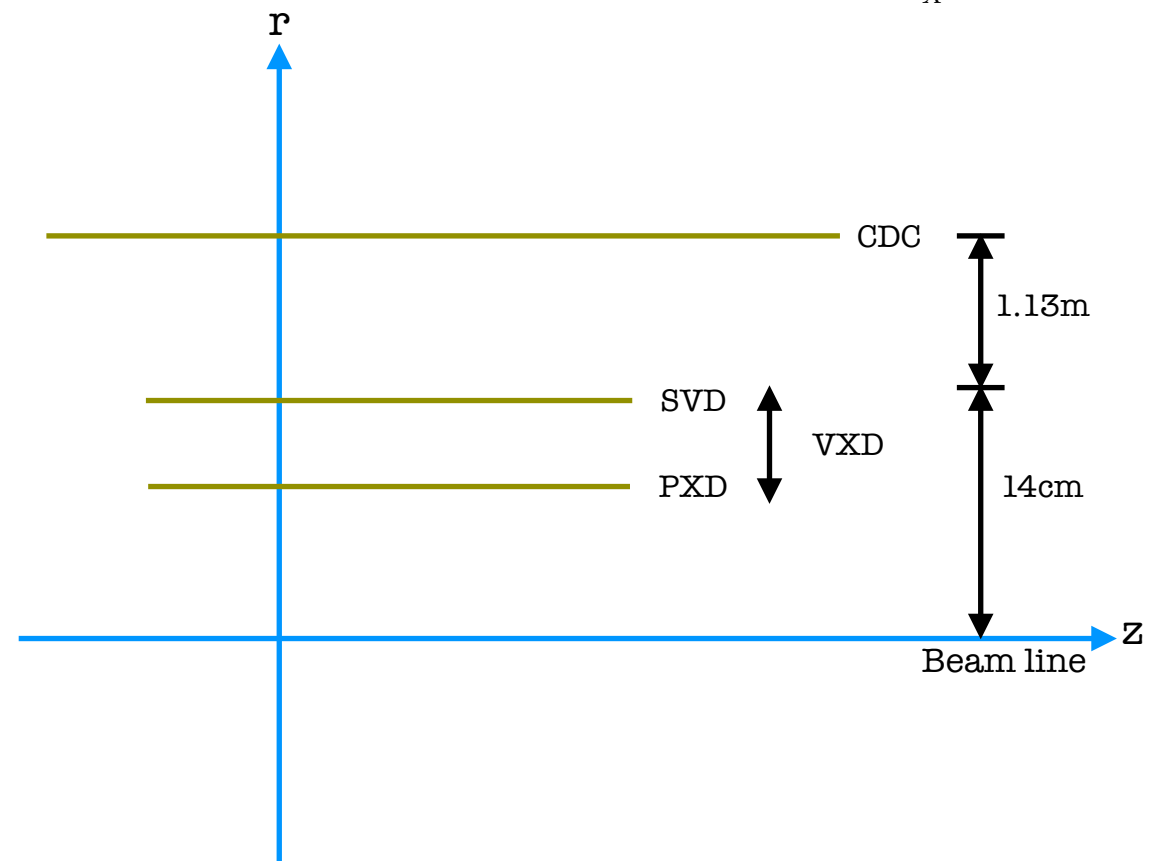
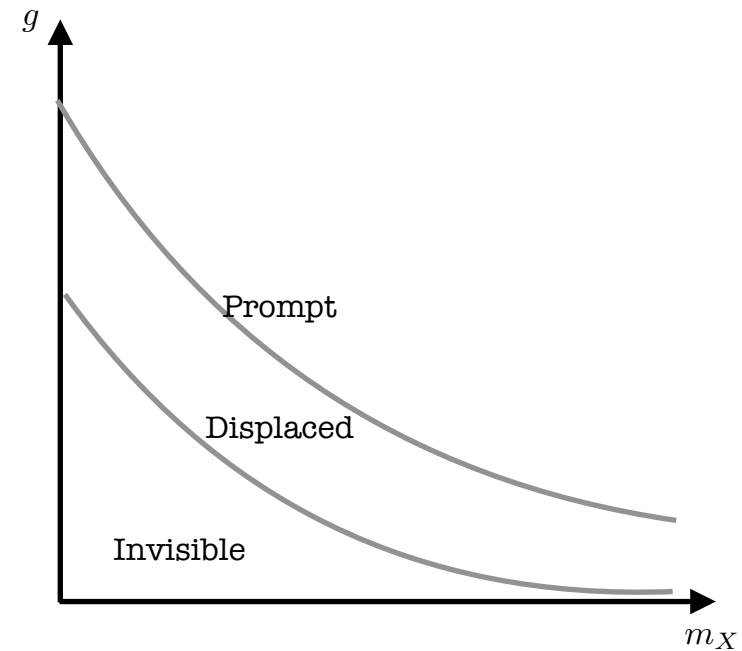
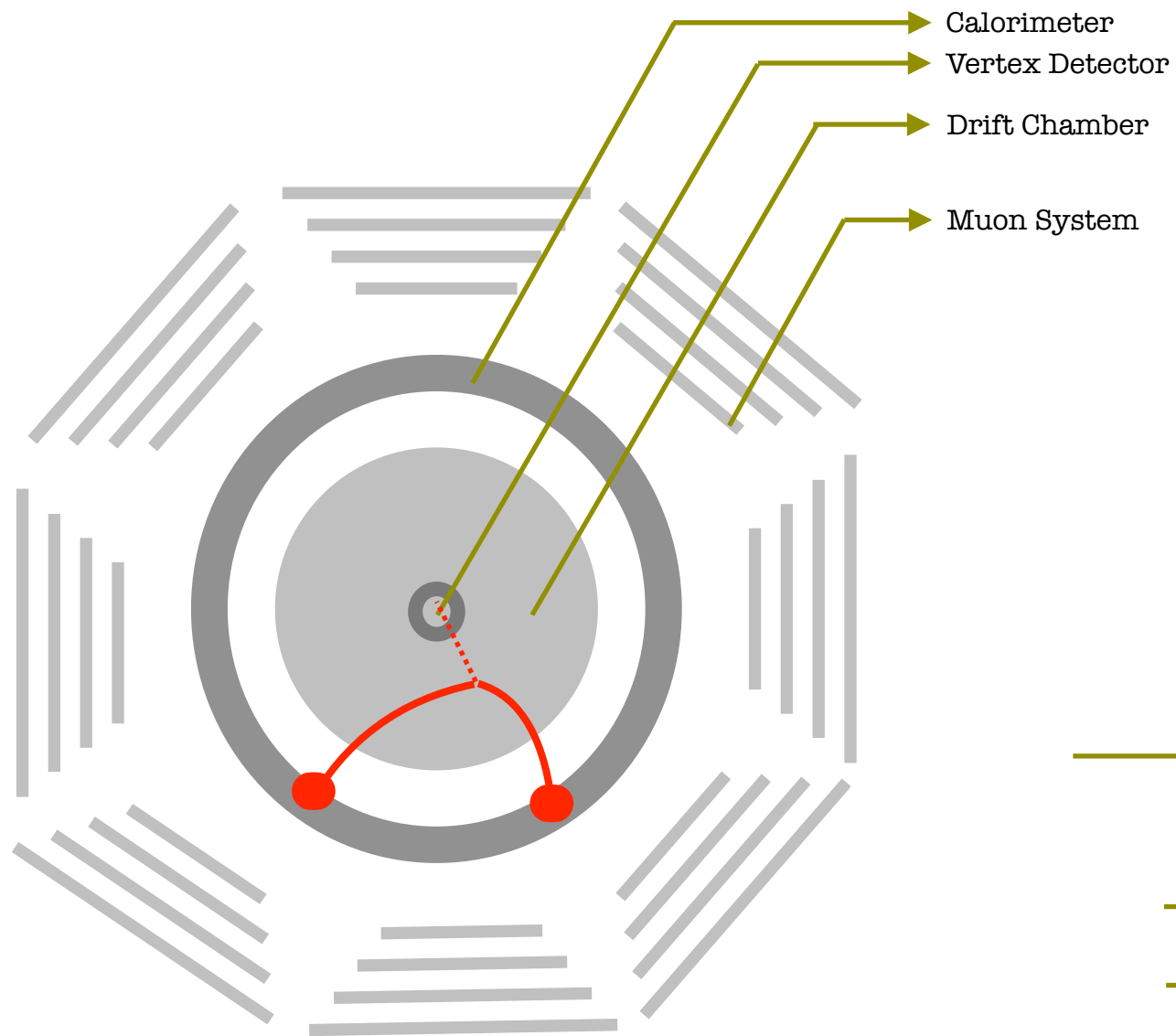
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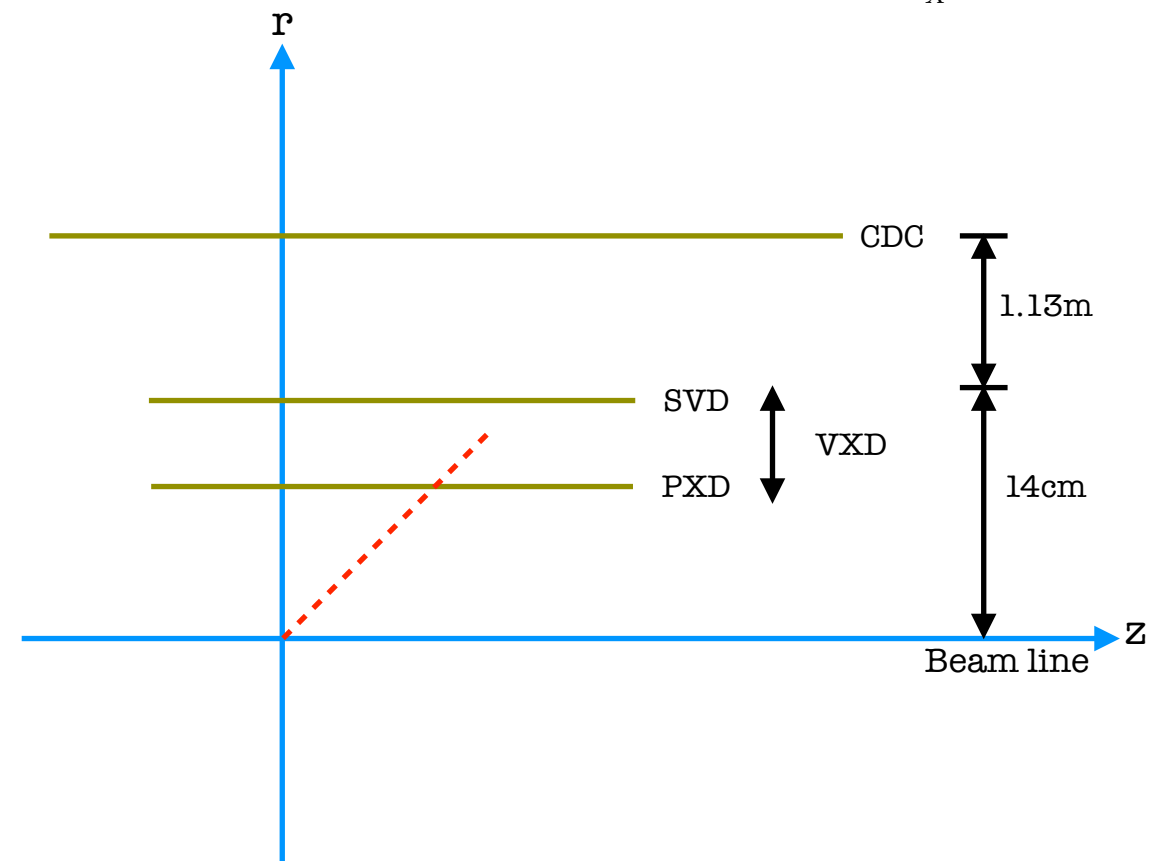
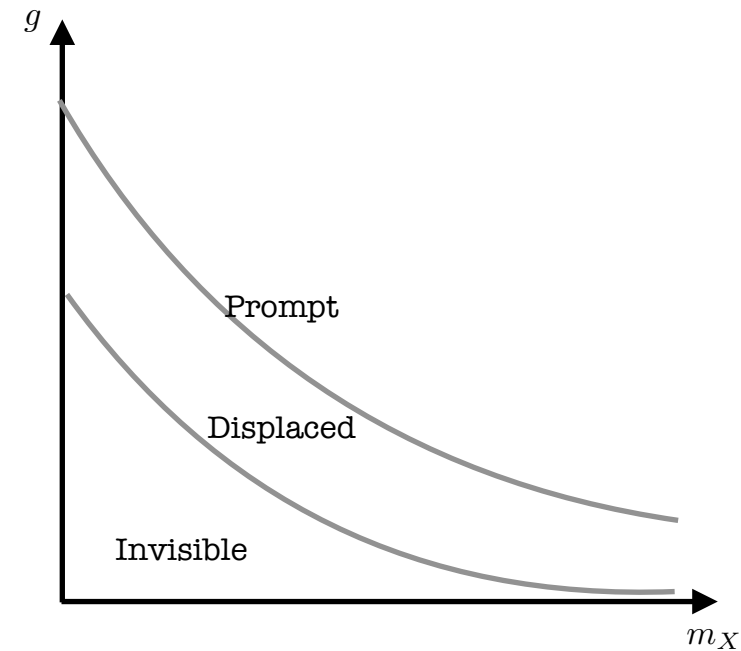
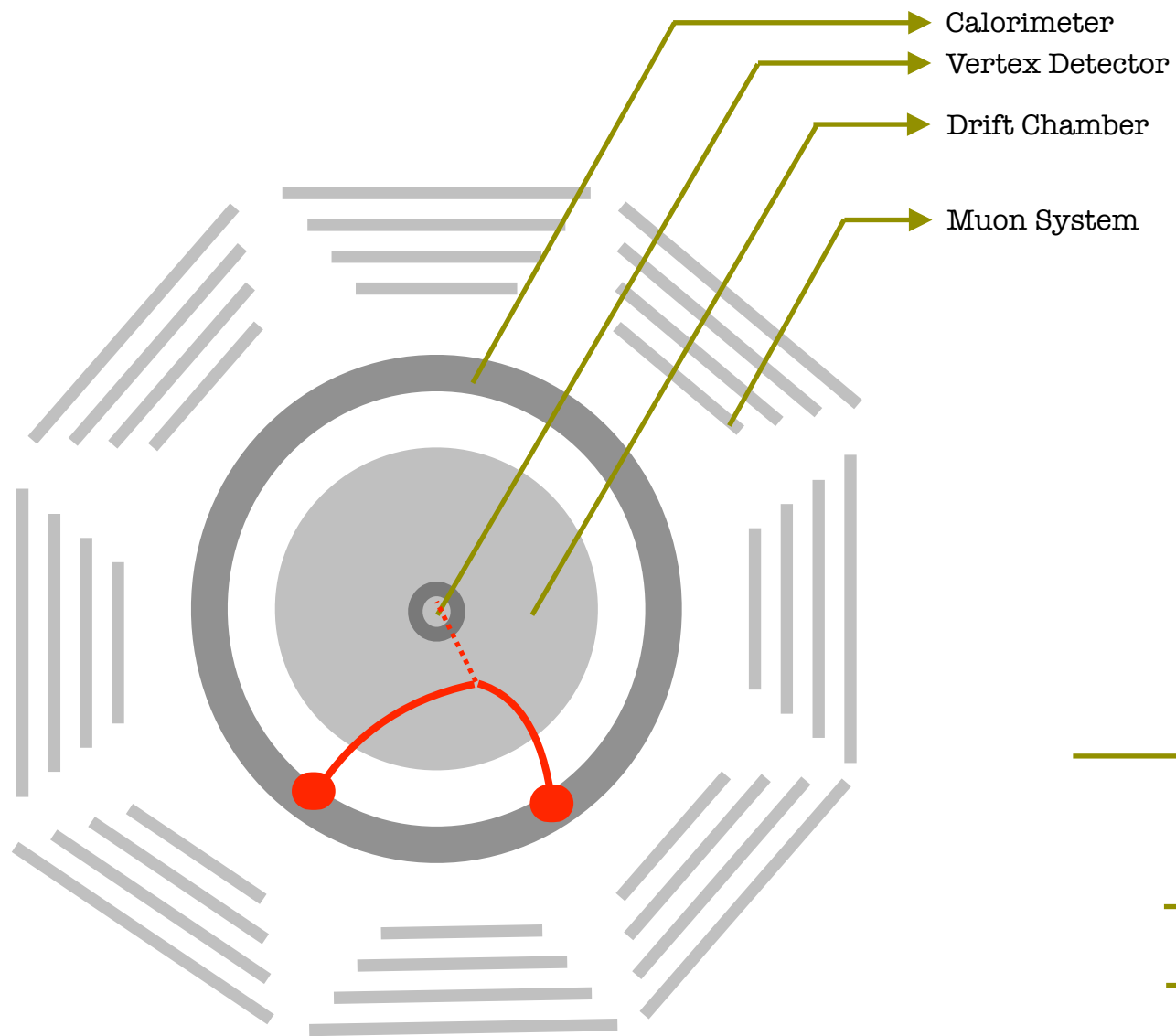
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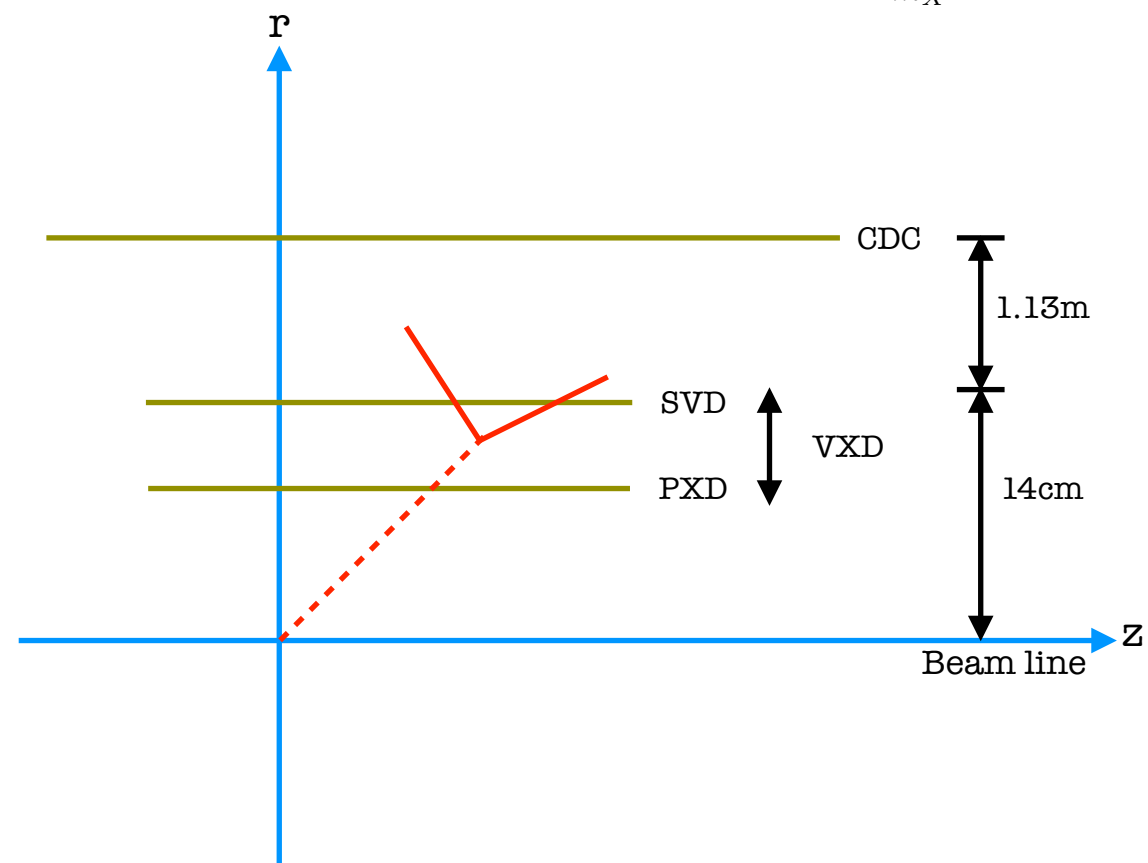
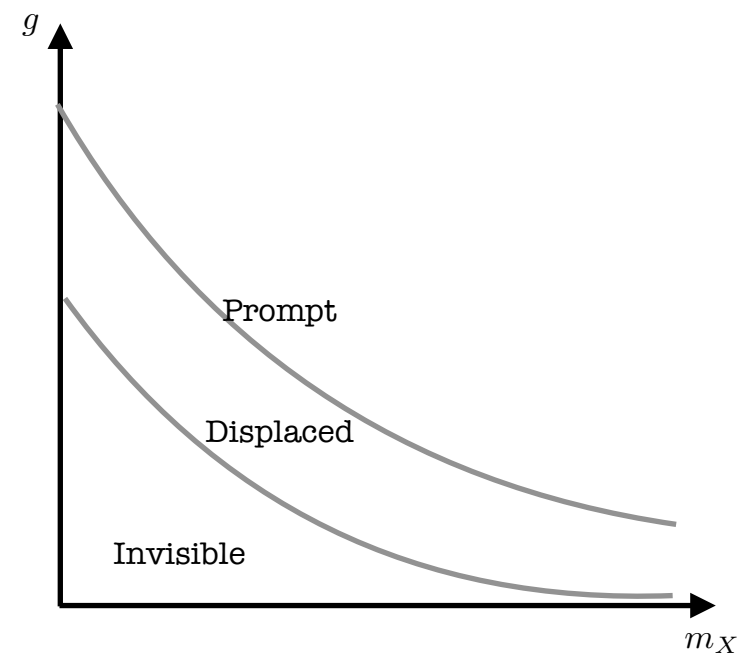
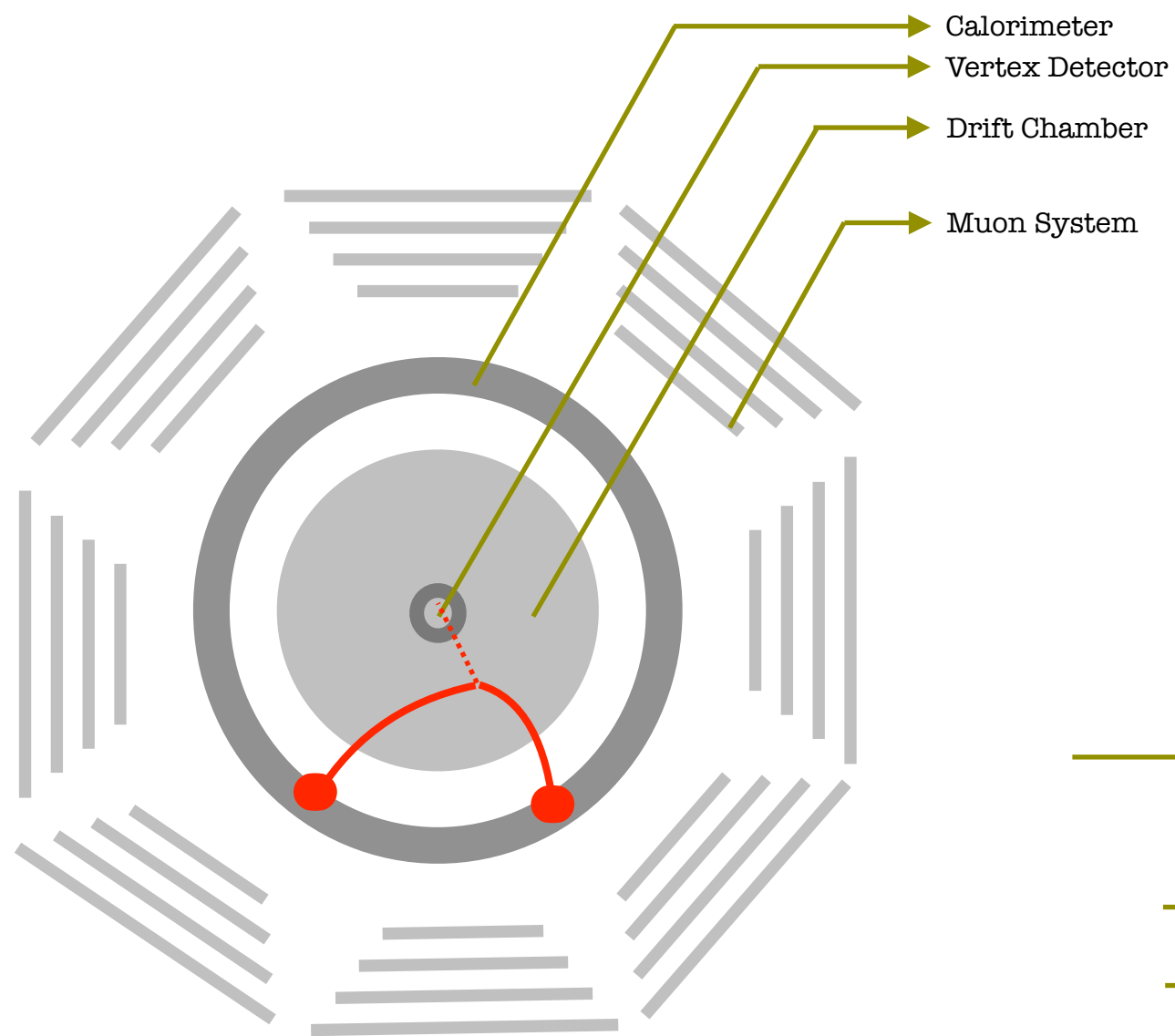
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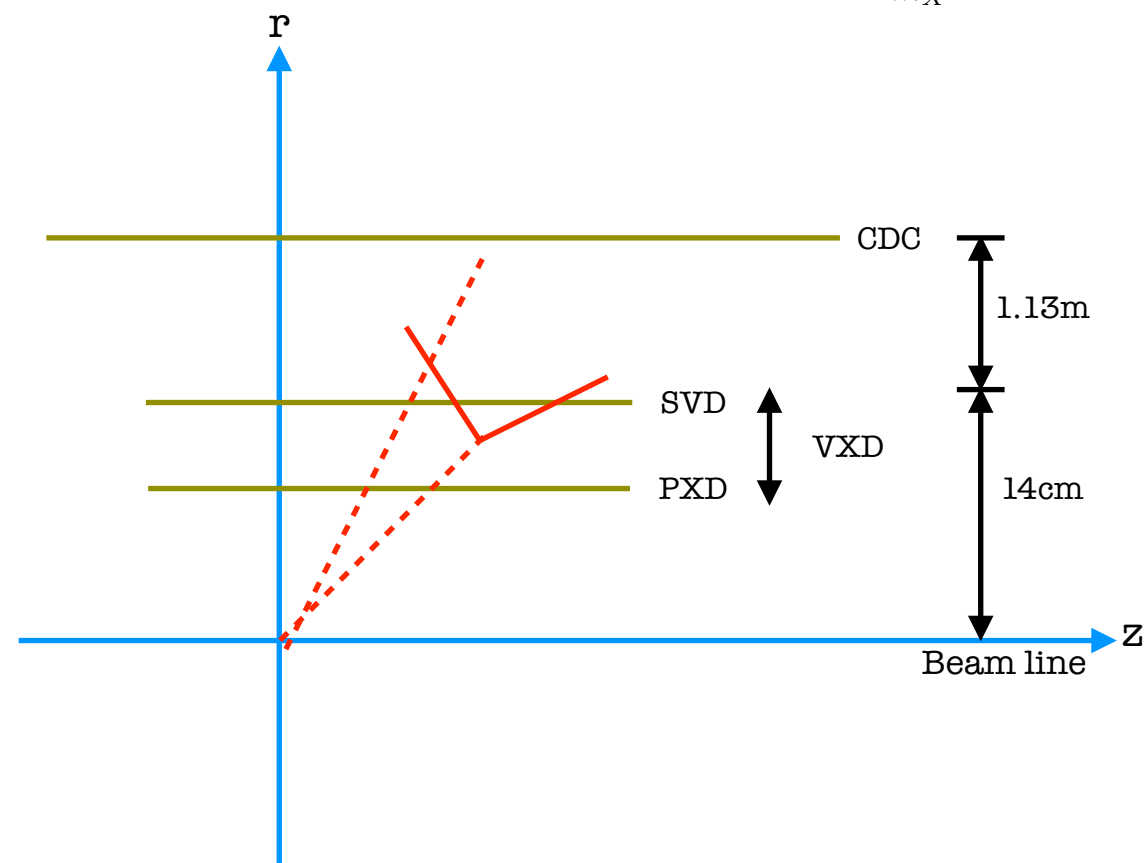
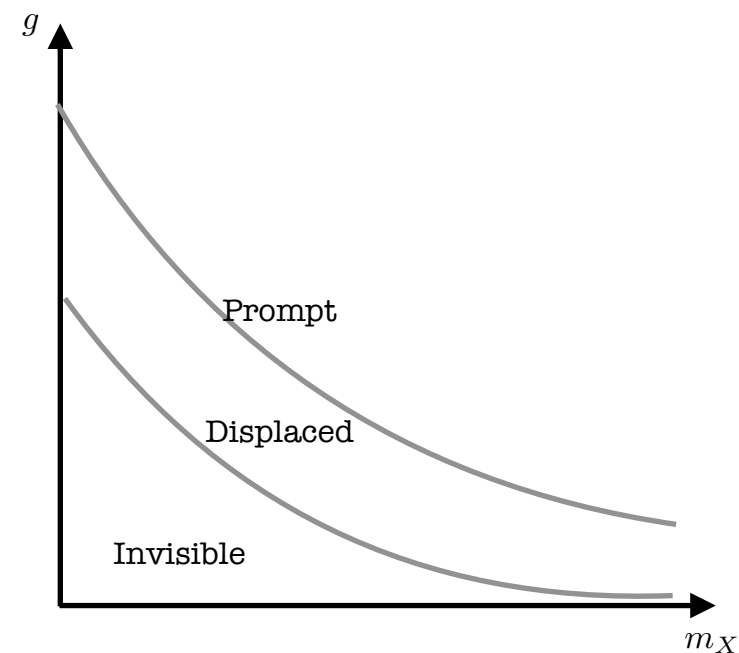
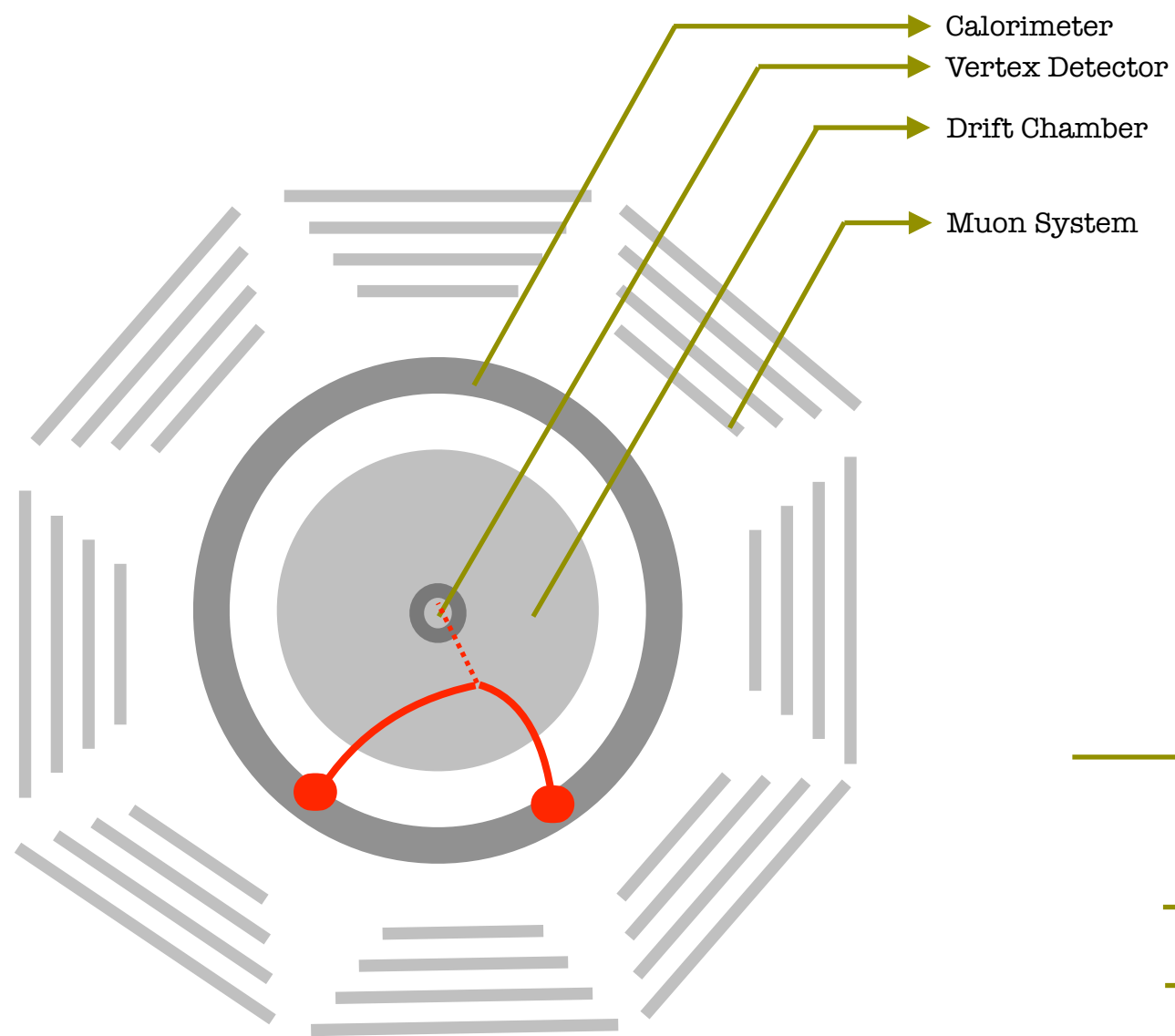
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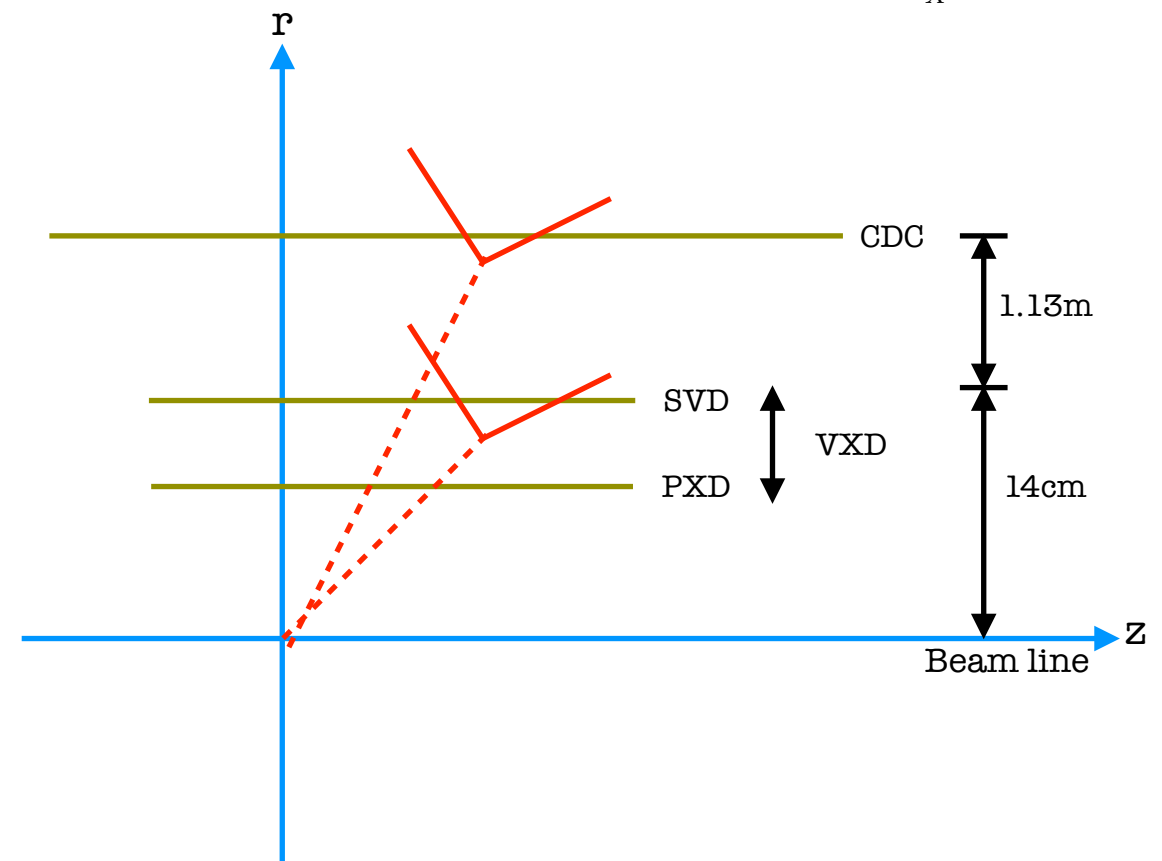
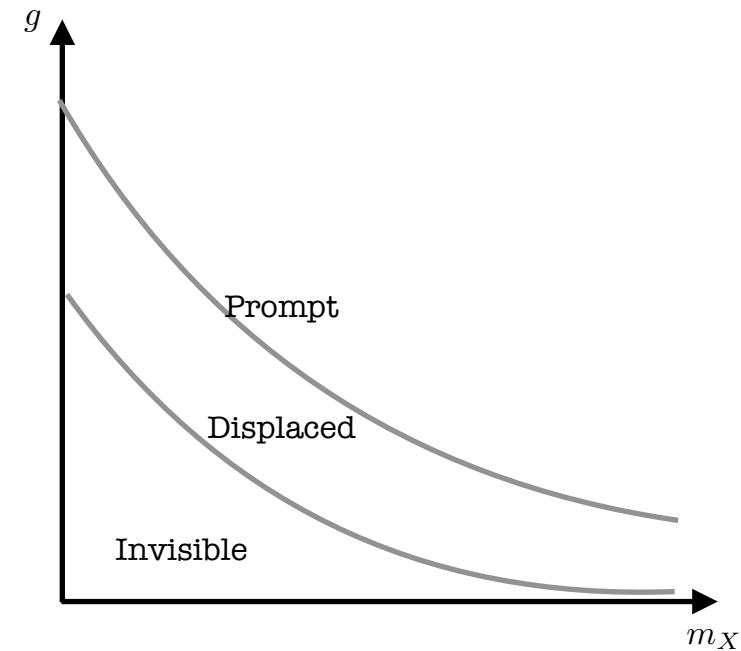
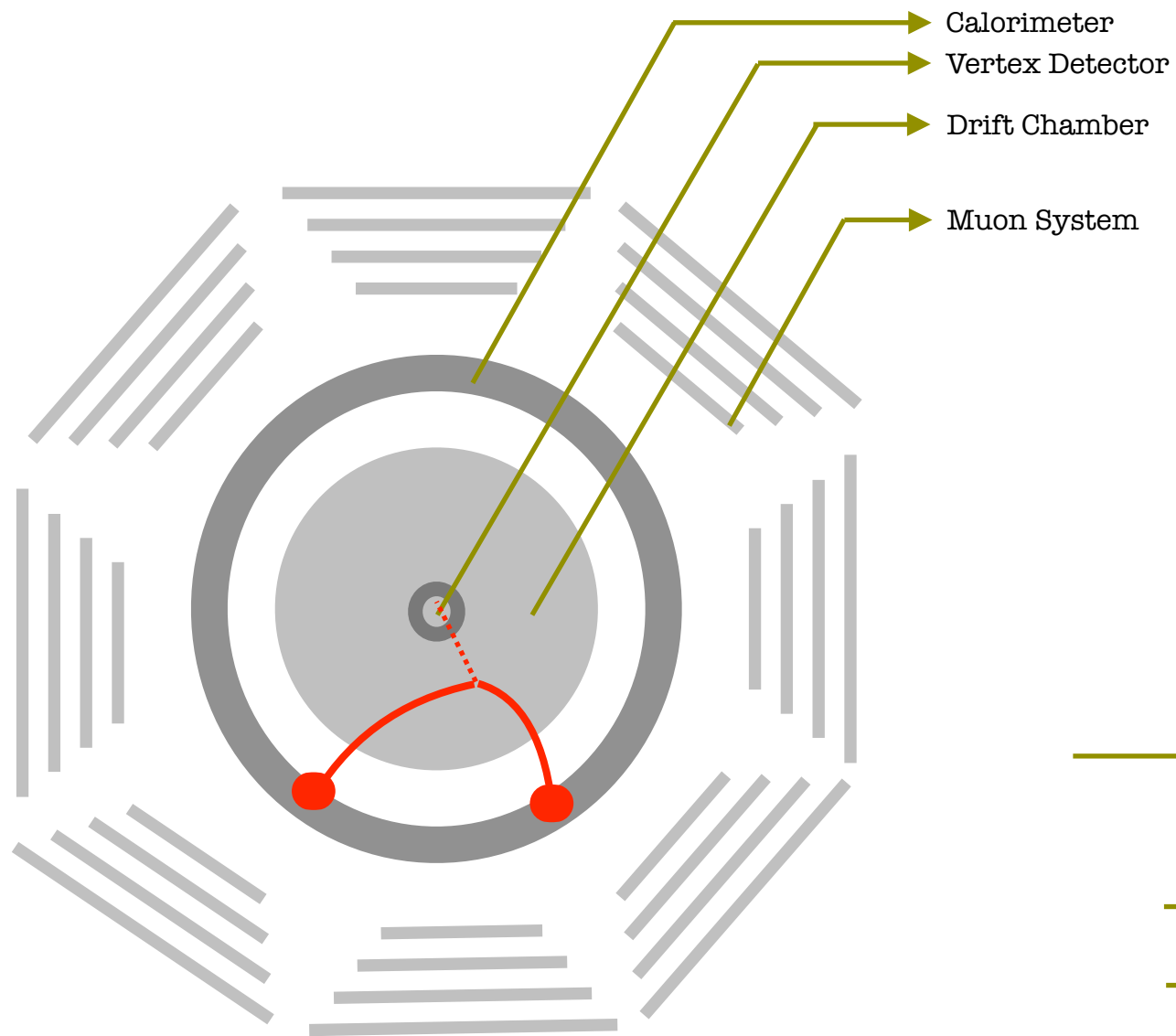
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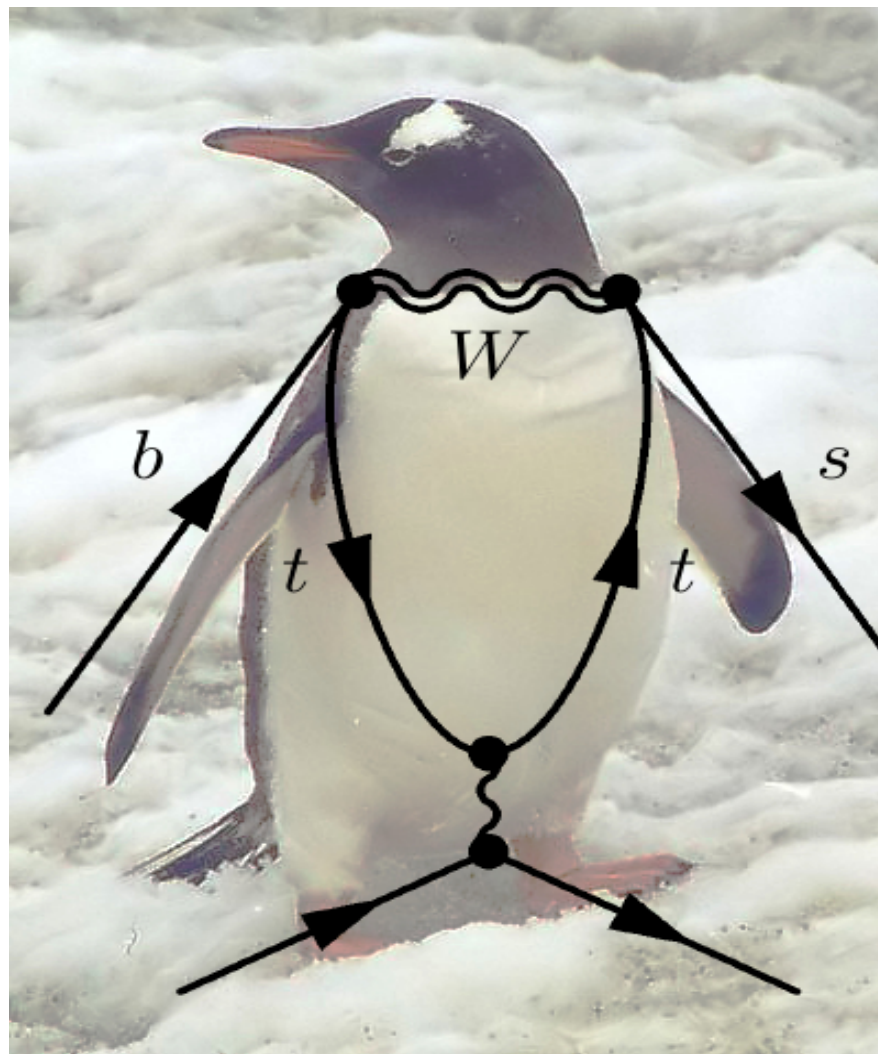
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MeV-GeV region – Minimal ALP

► MeV-GeV range, $b \rightarrow s$ transition is the relevant process! $B \rightarrow K a$



Wikipedia

- Our Starting Point:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} (\partial_\mu a)^2 - \frac{m_a^2}{2} a^2 + \boxed{\frac{a}{f_a} \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{\mu\nu a}}$$

$$C_W(M_W) \frac{\partial_\mu a}{f_a} \bar{s}_L \gamma^\mu \gamma_5 b_L + \text{h.c.}$$

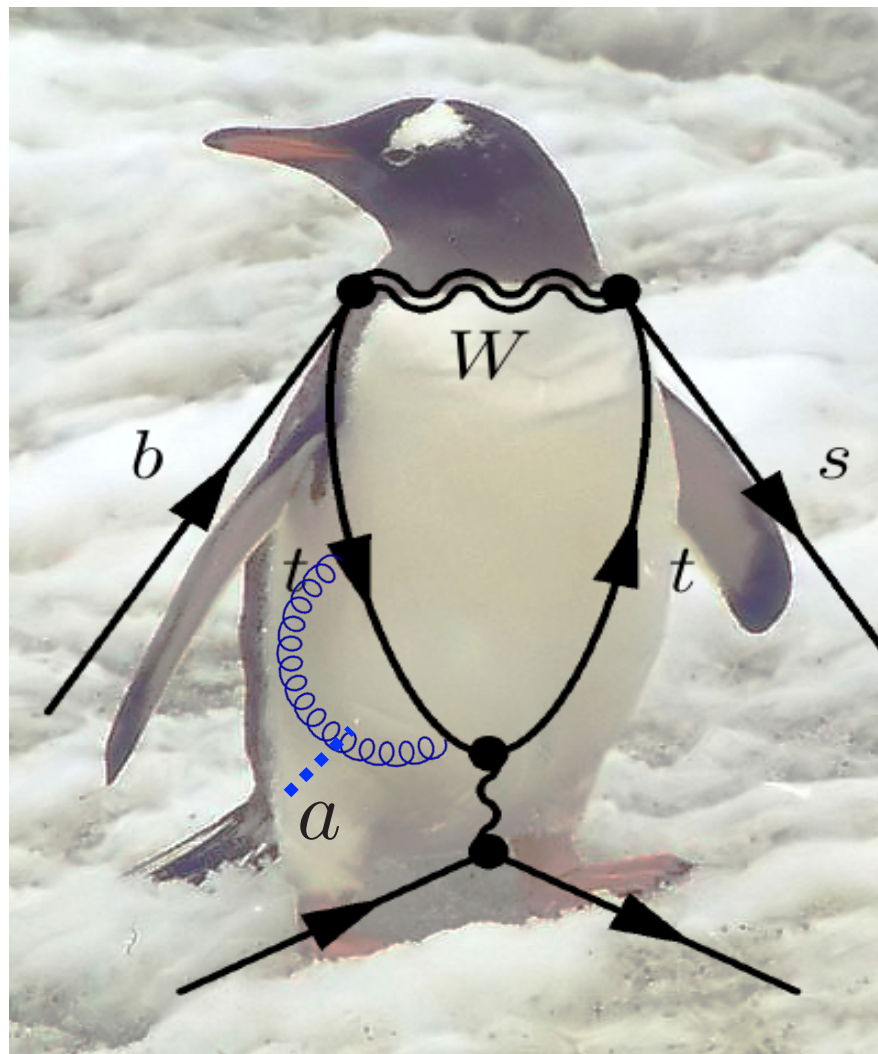
Matching Operator

- Need to know what else gets generated

SC et. Al. 2102.04474,
SC, Bisht, Samanta 2412.09678

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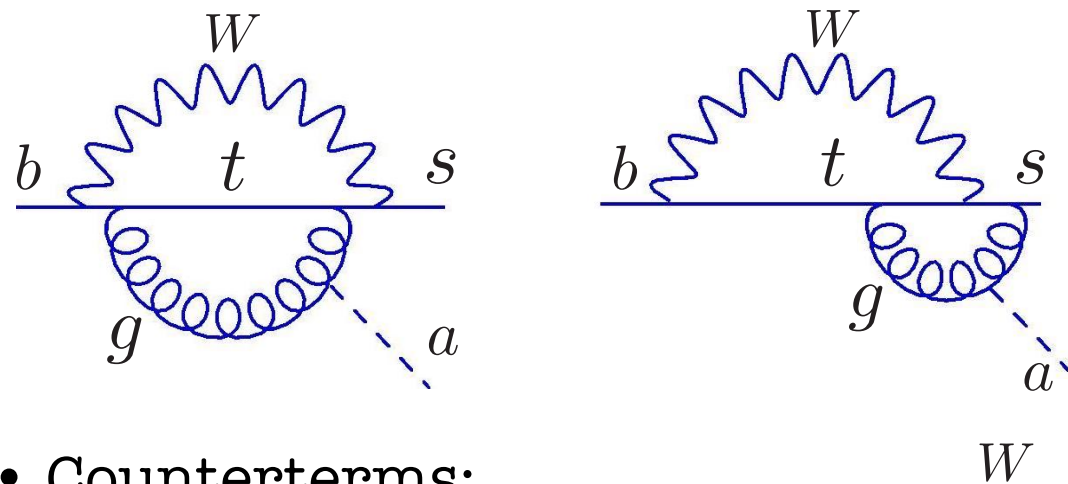
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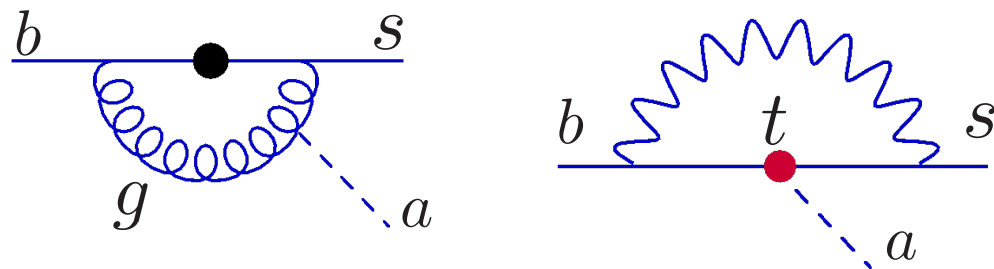
UV divergence $\rightarrow$ Counterterms

- Two Loop Diagrams:



$$\mathcal{M} = \frac{\mathcal{A}}{\epsilon_{UV}^2} + \frac{\mathcal{B}}{\epsilon_{UV} \epsilon_{IR}} + \frac{\mathcal{C}}{\epsilon_{UV}} + \frac{\mathcal{D}}{\epsilon_{IR}} + \mathcal{E}$$

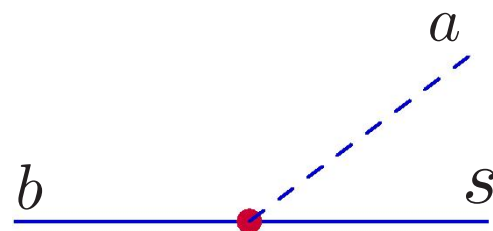
- Counterterms:



$$\mathcal{M} + \mathcal{M}_{ct} = \frac{\cancel{\mathcal{A}}}{\cancel{\epsilon_{UV}^2}} + \frac{\cancel{\mathcal{B}}}{\epsilon_{UV} \epsilon_{IR}} + \frac{\mathcal{C}}{\epsilon_{UV}} + \frac{\mathcal{D}}{\epsilon_{IR}} + \mathcal{E}$$

$\Rightarrow$ Need aqq operator, $\mathcal{C}_{aqq}$

- Overall counter term:

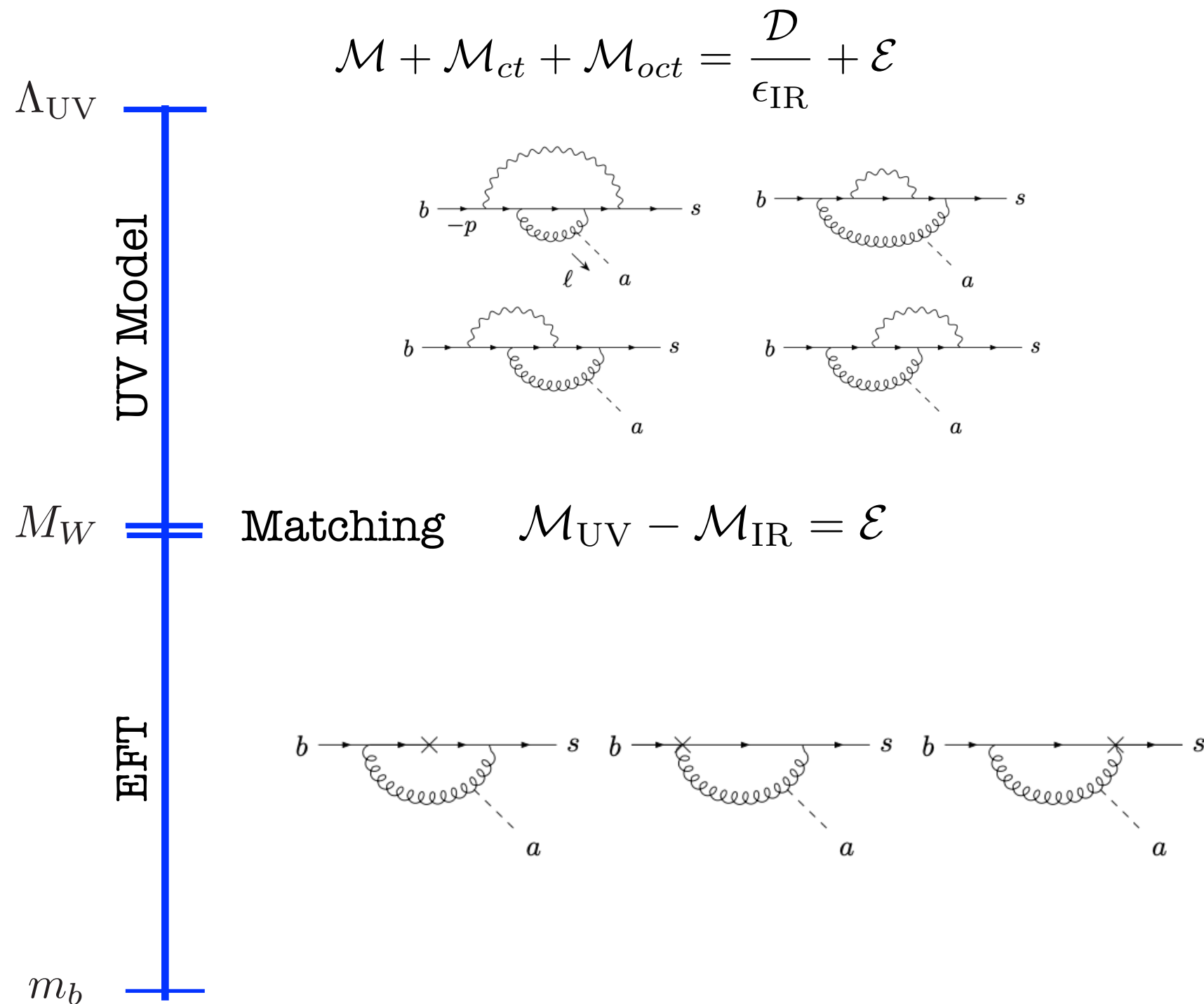


$$\mathcal{M} + \mathcal{M}_{ct} + \mathcal{M}_{oct} = \frac{\cancel{\mathcal{C}}}{\cancel{\epsilon_{UV}}} + \frac{\mathcal{D}}{\epsilon_{IR}} + \mathcal{E}$$

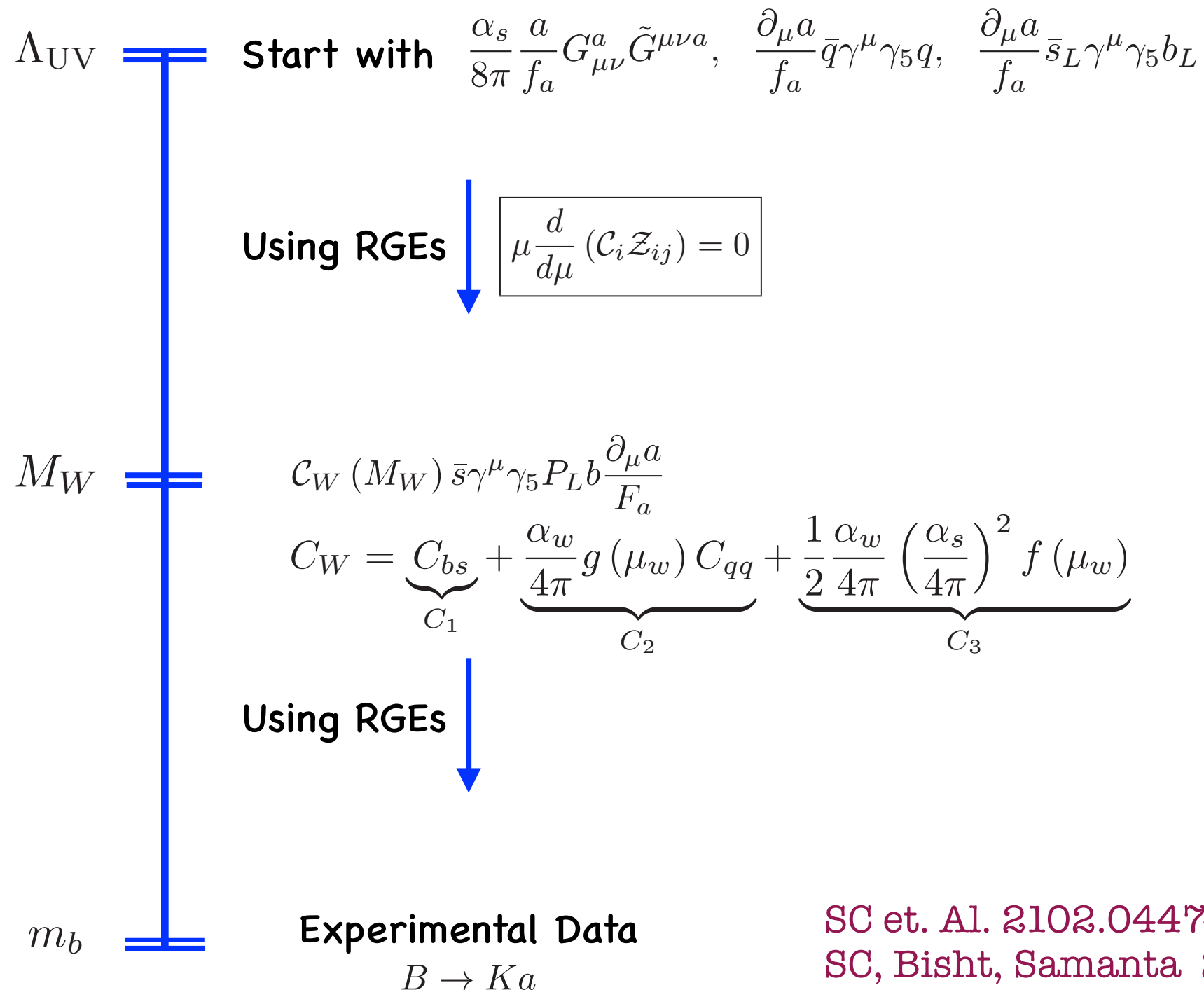
$\Rightarrow$ Need abs operator, $\mathcal{C}_{abs}$

SC et. Al. 2102.04474,
SC, Bisht, Samanta 2412.09678

IR divergence → Matching with EFT



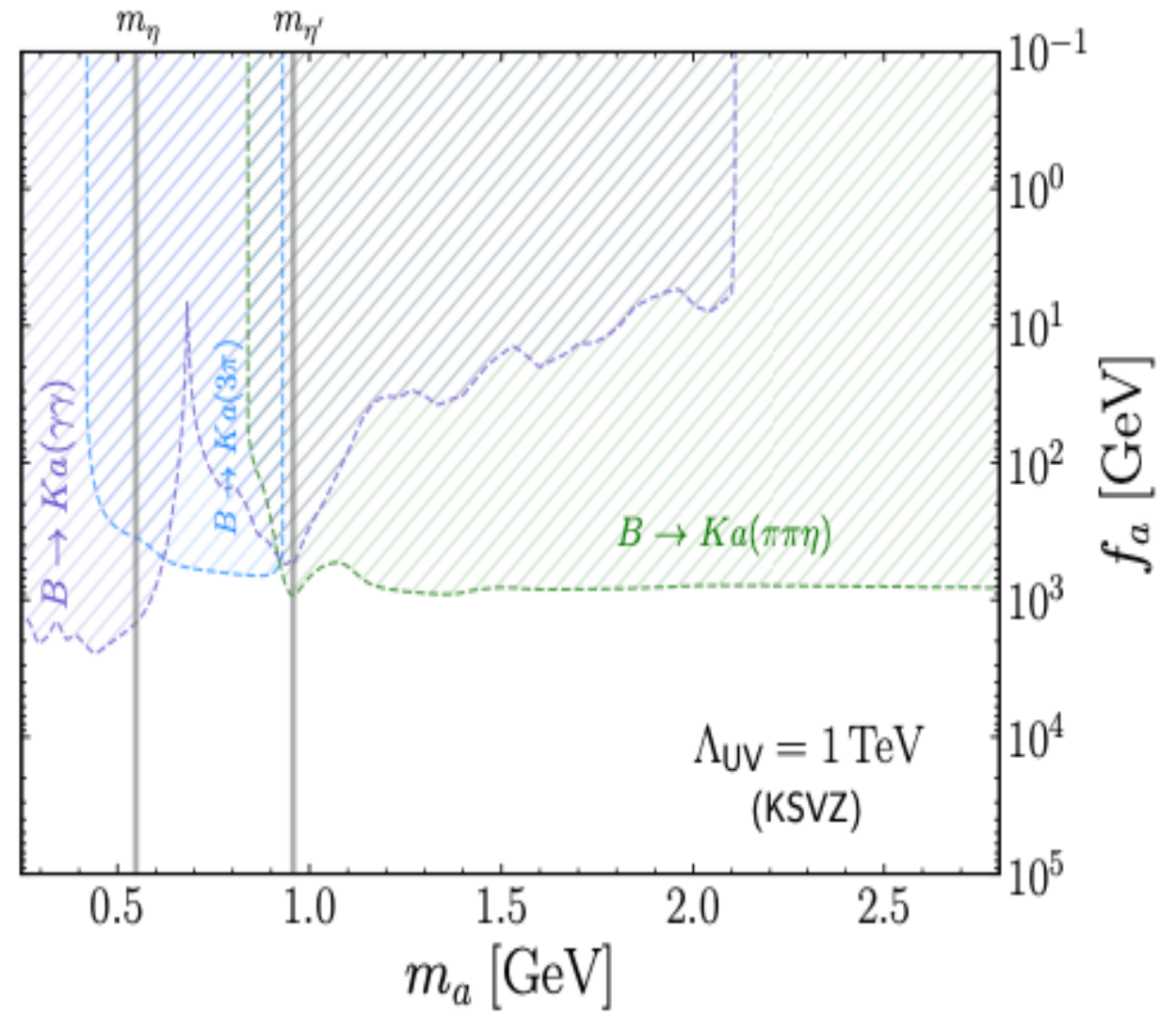
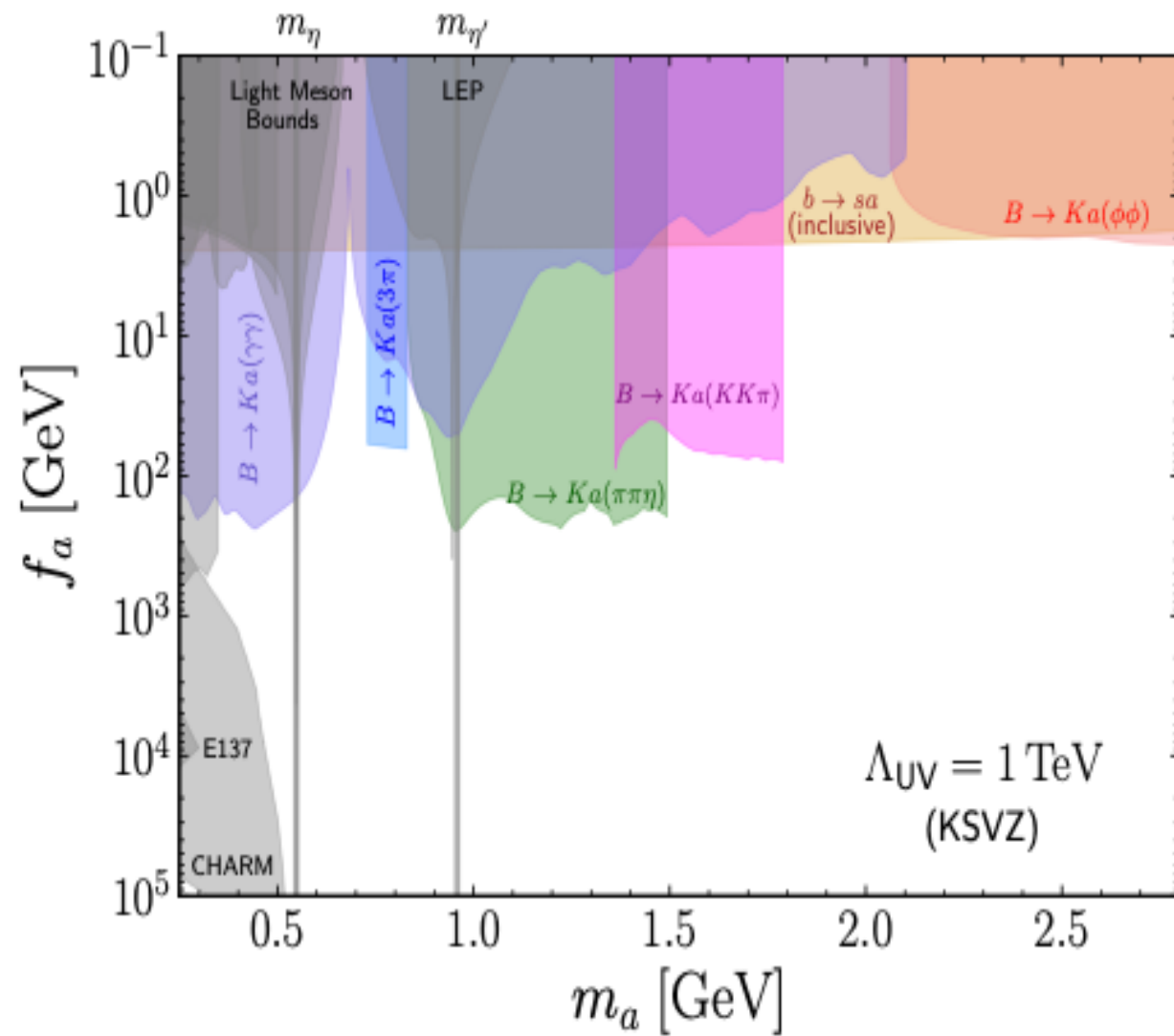
Running and Matching



SC et. Al. 2102.04474,
SC, Bisht, Samanta 2412.09678

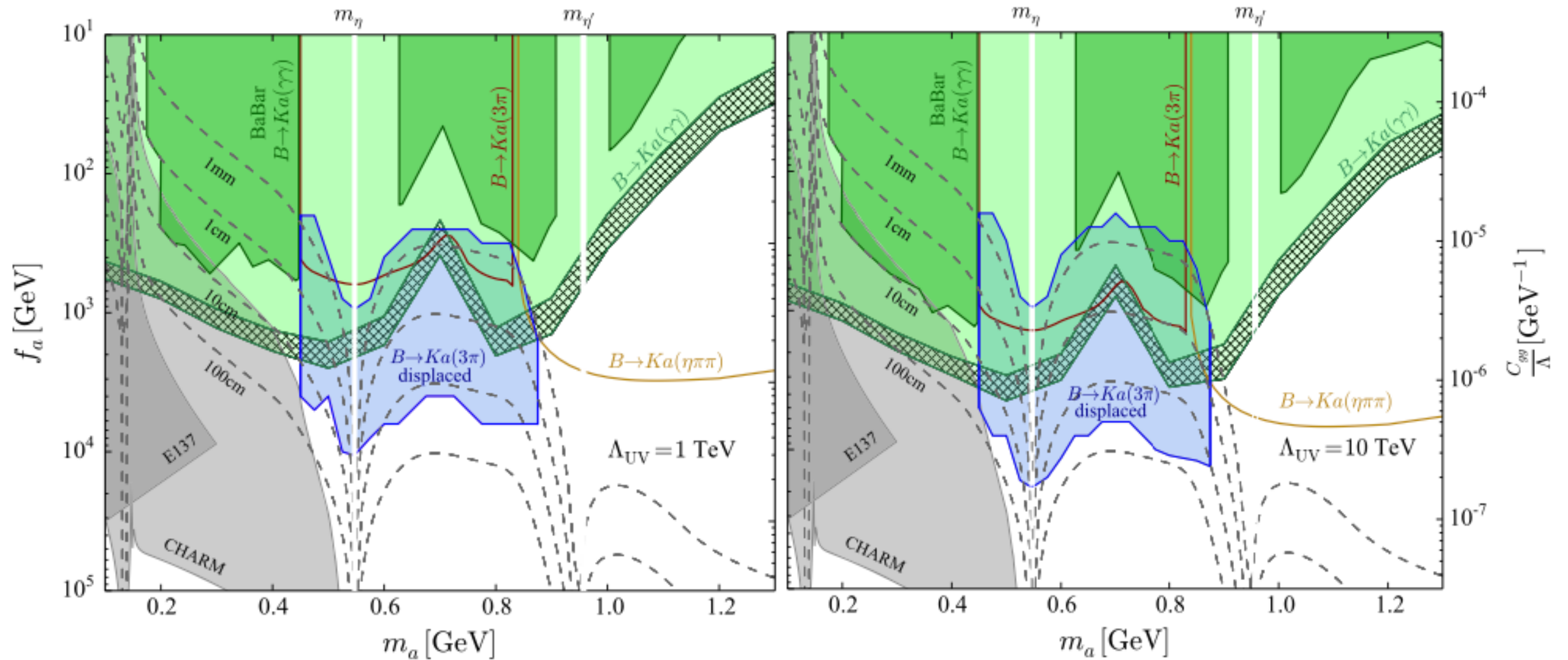
Prompt Searches: KSVZ

SC, Bisht, Samanta 2412.09678



Displaced Searches: Minimal Coupling

SC et. Al. 2108.10331



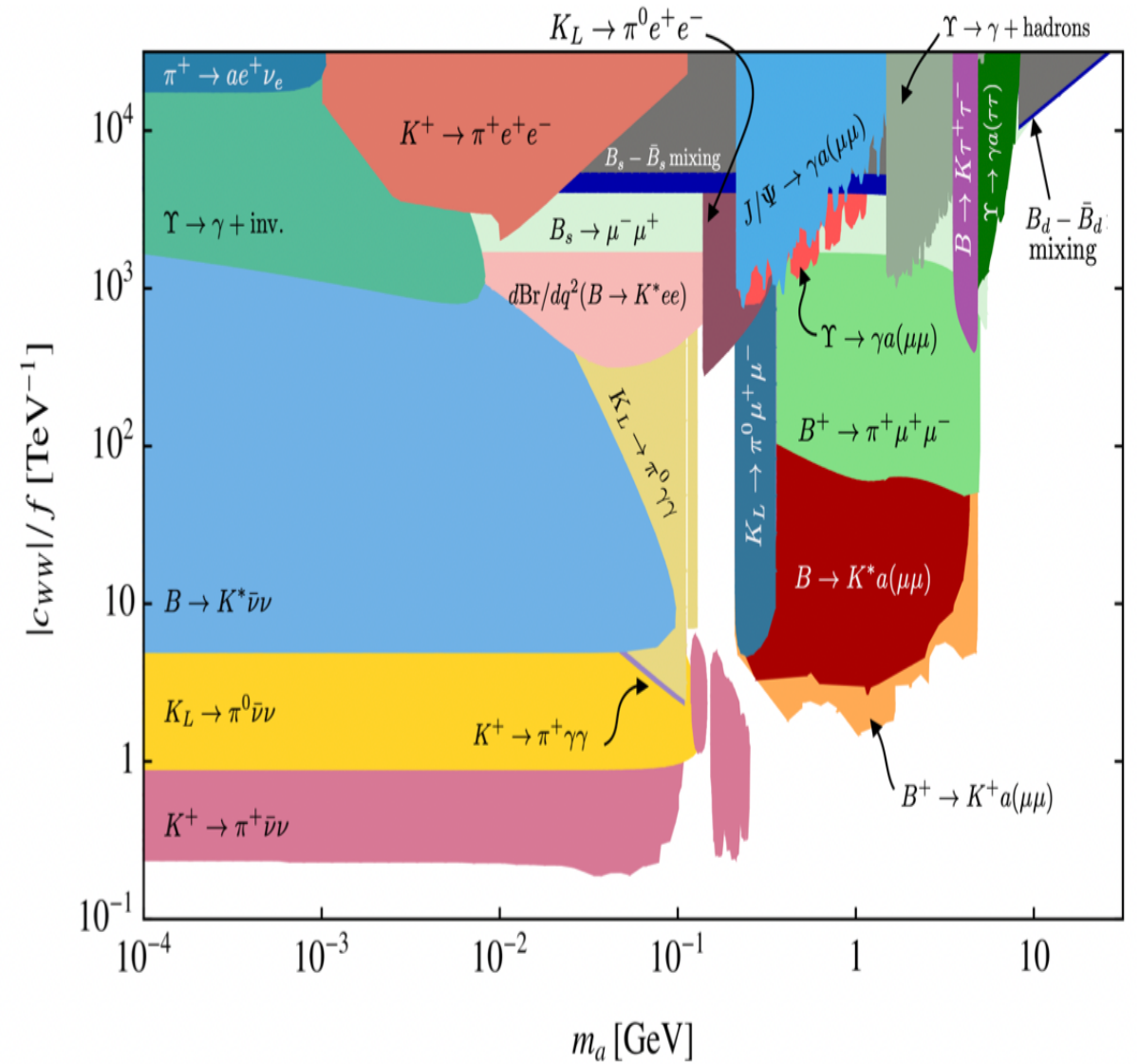
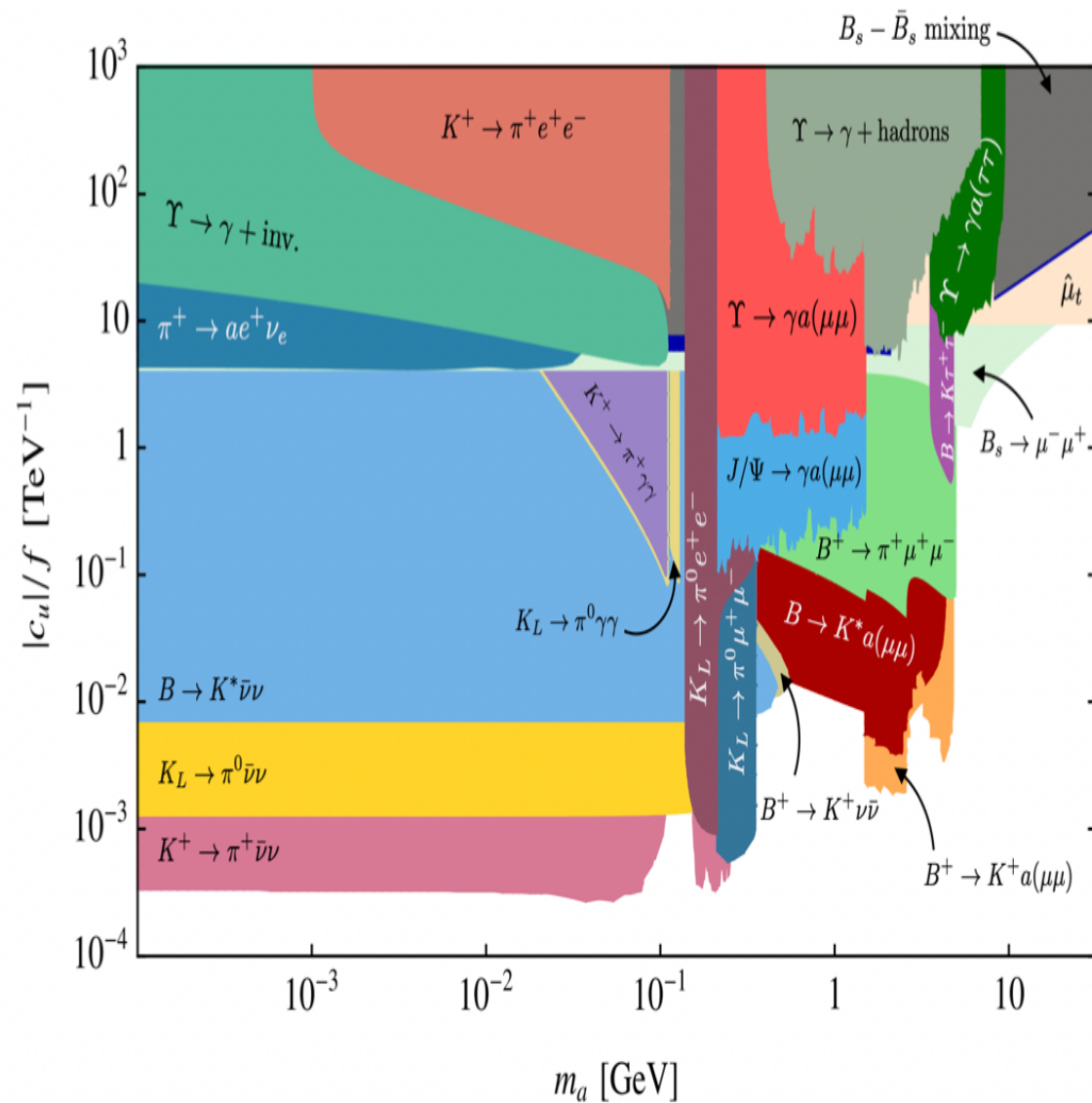
$$\Lambda_{UV} = 1 \text{ TeV}$$

$$\Lambda_{UV} = 10 \text{ TeV}$$

Backgrounds: $B \rightarrow K\omega(3\pi)$, $B^- \rightarrow K^- K_L (\pi^+ \pi^- \pi^0)$, $B^- \rightarrow K^- K_0^* (K_s \pi^0)$

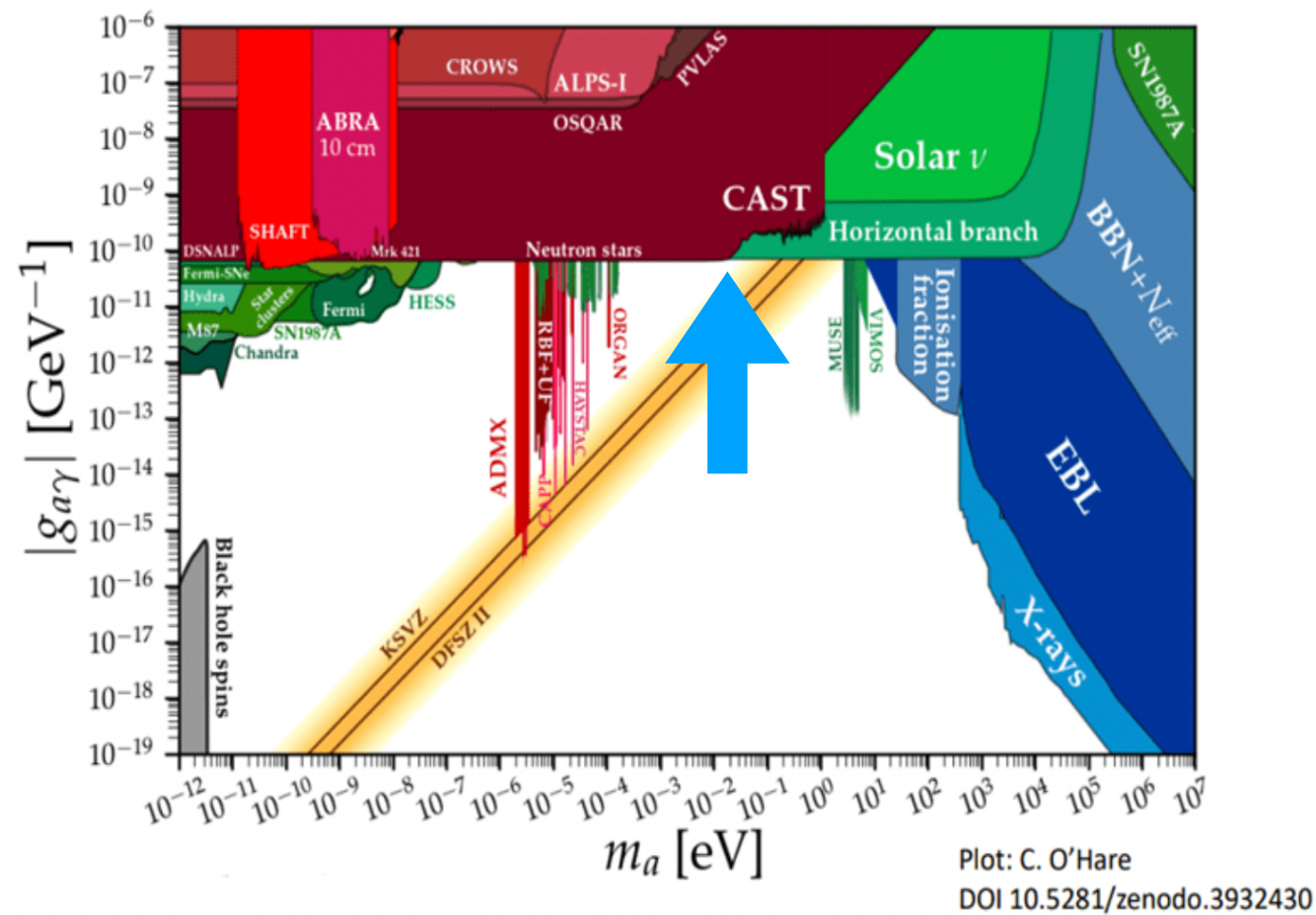
Other Couplings of ALP

$$\mathcal{L} \supset C_{agg} \frac{a}{f_a} G\tilde{G} + C_{aWW} \frac{a}{f_a} W\tilde{W} + C_{aBB} \frac{a}{f_a} B\tilde{B} + C_{aq_i q_j} \sum_{i,j} \frac{\partial_\mu a}{f_a} \bar{q}_i \gamma^\mu \gamma_5 q_j$$

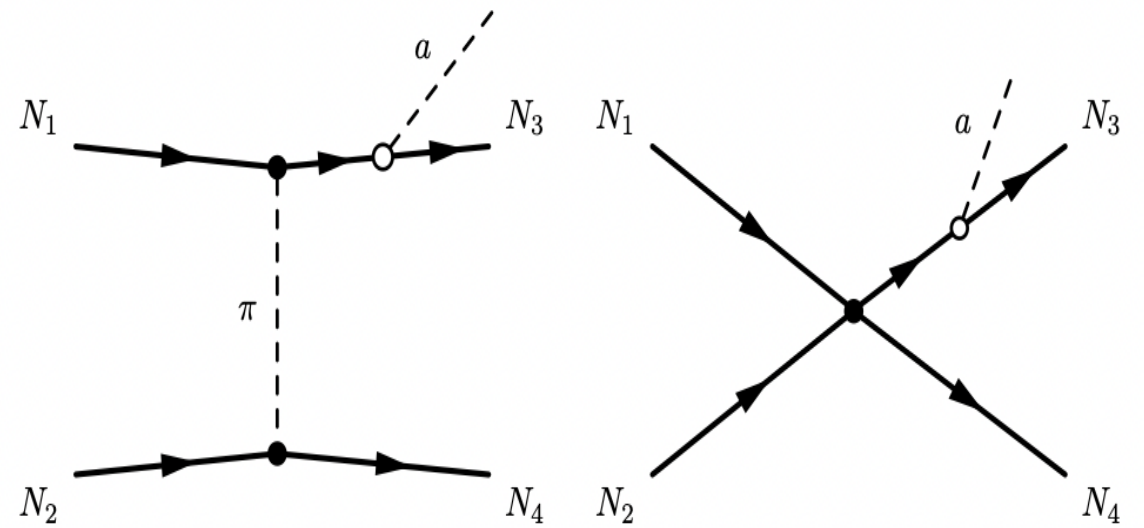


Bauer et. Al. 2110.10698

Axions/ALPs at the cosmic frontier

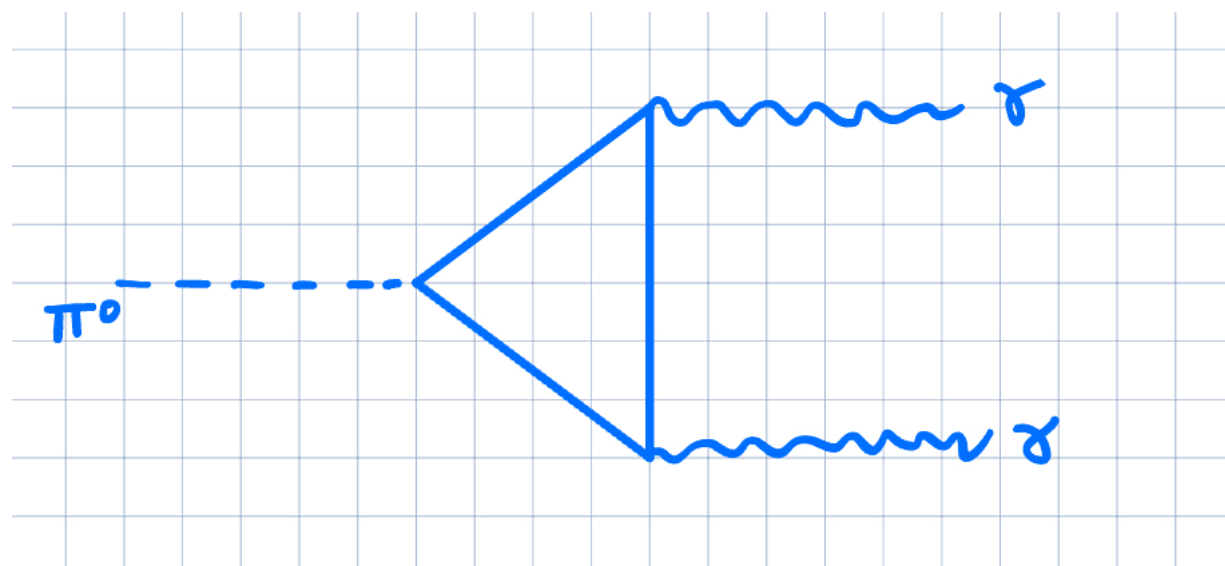


$$\mathcal{L}_{\text{eff}} \supset \bar{q} \left(iD - \hat{\mathcal{M}}_q \right) q - \frac{\partial^\mu a}{2f_a} \bar{q} \gamma_\mu \gamma_5 q + \dots$$

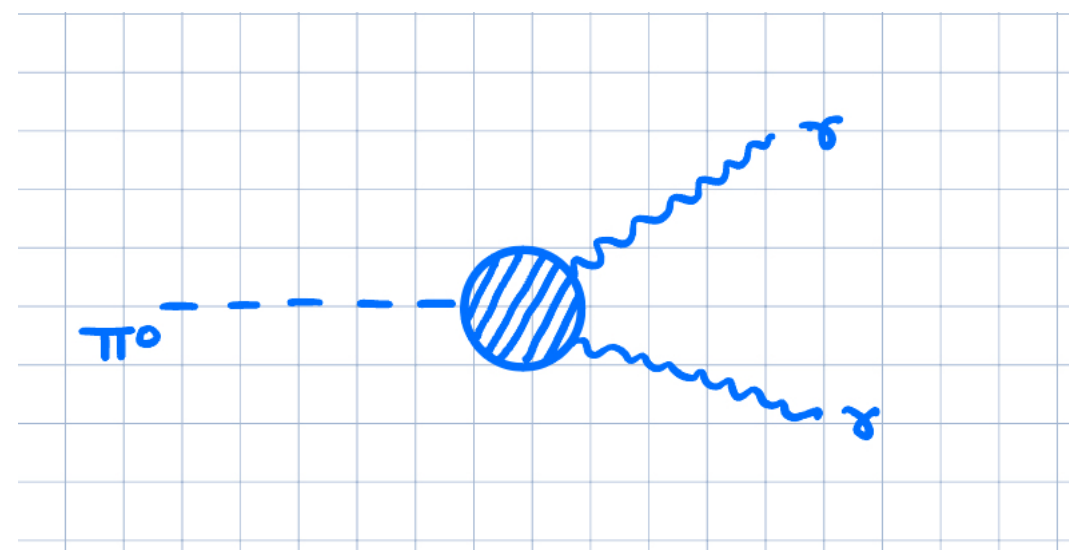


Anything Else?

UV Model



EFT

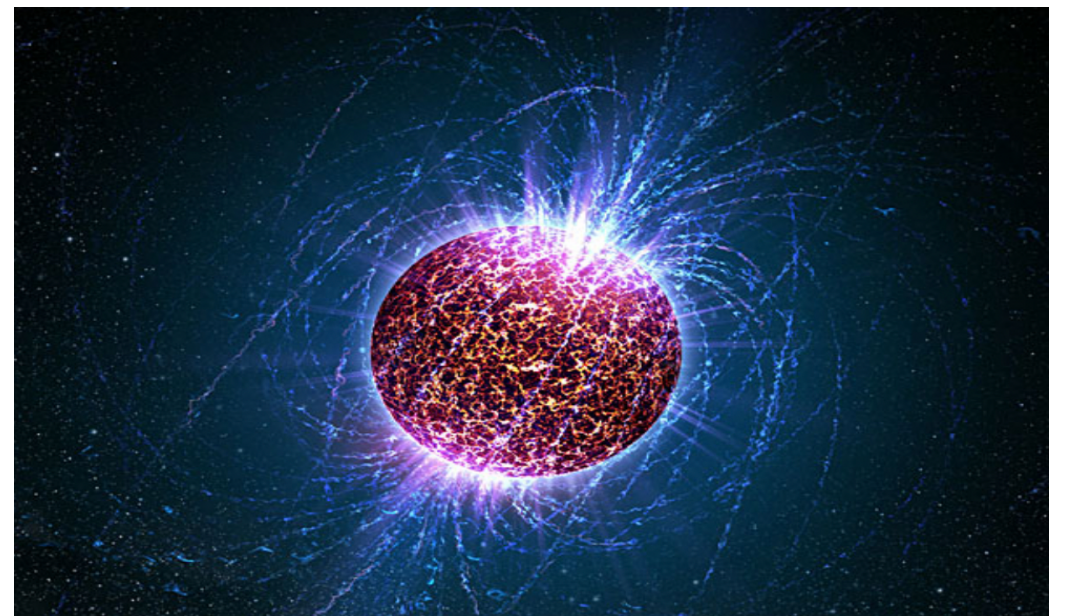
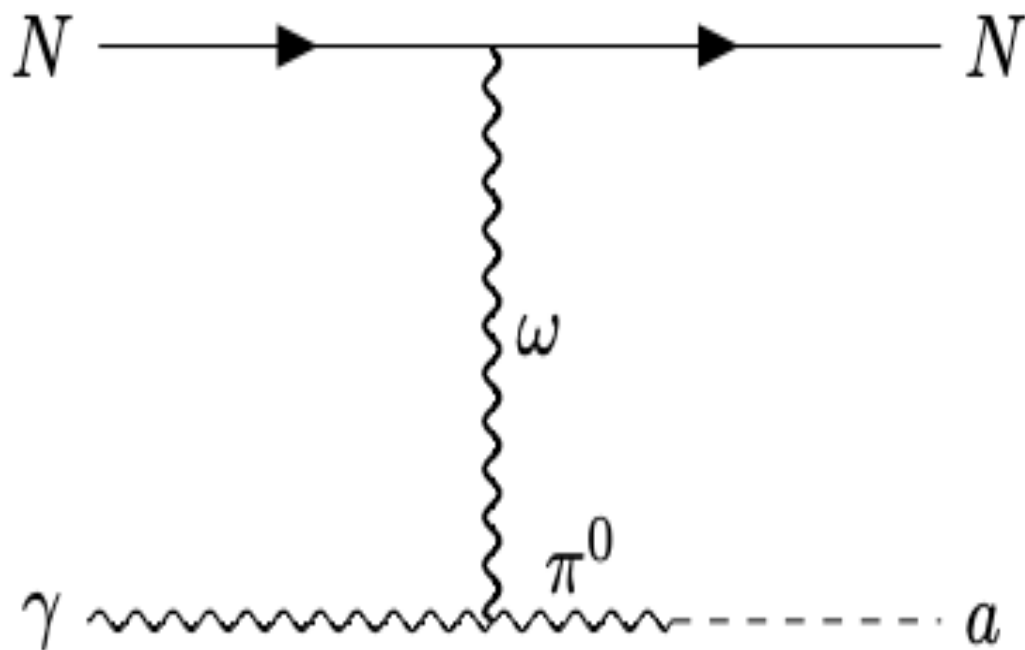


Wess-Zumino(1971), Witten(1983)

$$\Rightarrow \mathcal{L}_{WZW}^a \supset \epsilon^{\mu\nu\rho\sigma} \partial_\mu a F_\nu{}_\rho \omega_\sigma$$

Implications of WZW term

$$\Rightarrow \mathcal{L}_{WZW}^a \supset \epsilon^{\mu\nu\rho\sigma} \partial_\mu a F_{\nu\rho} \omega_\sigma$$



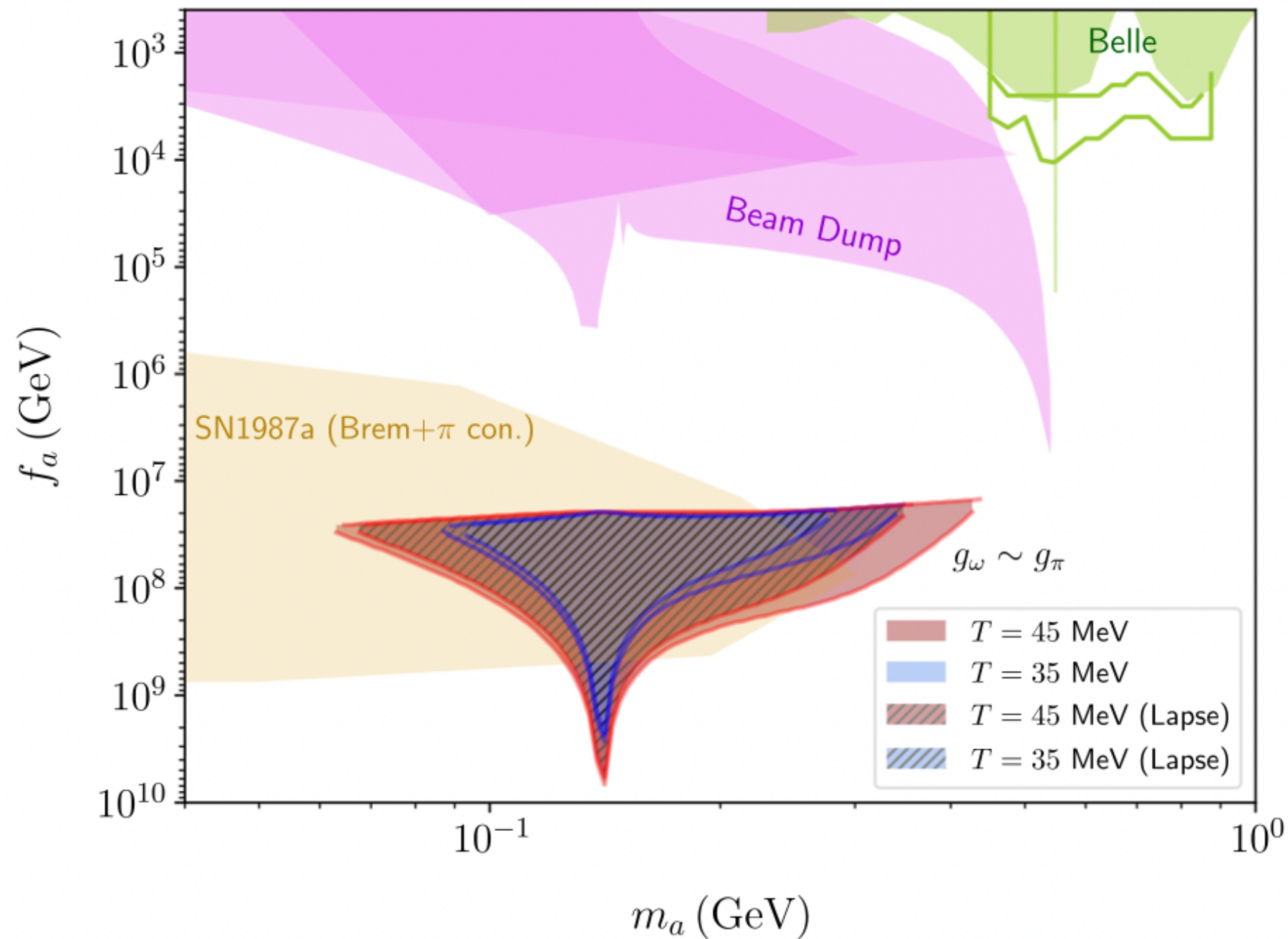
SC, Gupta, Vanvlassaelaer (to appear)

- Cooling of Neutron Stars/Supernovae
- Probing such interactions at the intensity frontiers, GlueX etc.

Harvey, Hill, Hill (0712.1230), SM WZW for MiniBooNE

SC, Gupta, Vanvlassaelaer (JCAP 2023), SM WZW Neutron Star Cooling

WZW terms & Supernovae Cooling



Fantastic Axions & where to find them

Intensity Frontier

- ▶ Rare processes, Intensity Frontier Experiments, Developing EFTs (ongoing)
- ▶ Probing WZW interactions

Energy Frontier

- ▶ Lepton Colliders, MATHUSLA (Long Lived Axions)

Cosmic Frontier

- ▶ Cooling of neutron stars
- ▶ Axion-Meson Oscillations: $\partial_\mu a F_{\nu\rho} \omega_\sigma$
- ▶ Kinetic Misalignment, Axion Co-genesis (Harigaya, Hall, Co 2019, SC, Okui, Jung 2021)

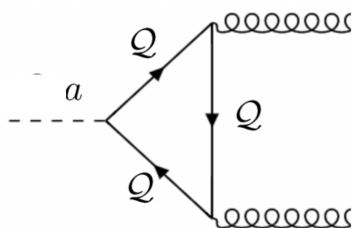
Backup4: Axions

$$P = \frac{S + f_a}{\sqrt{2}} e^{i \frac{a}{f_a}} \quad \star$$

Example of a UV model

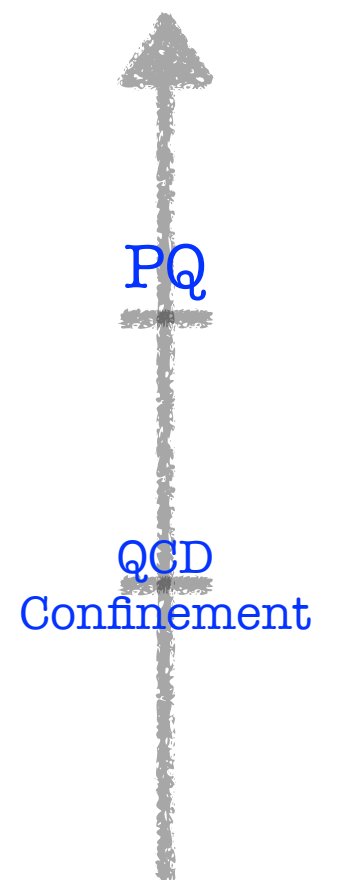
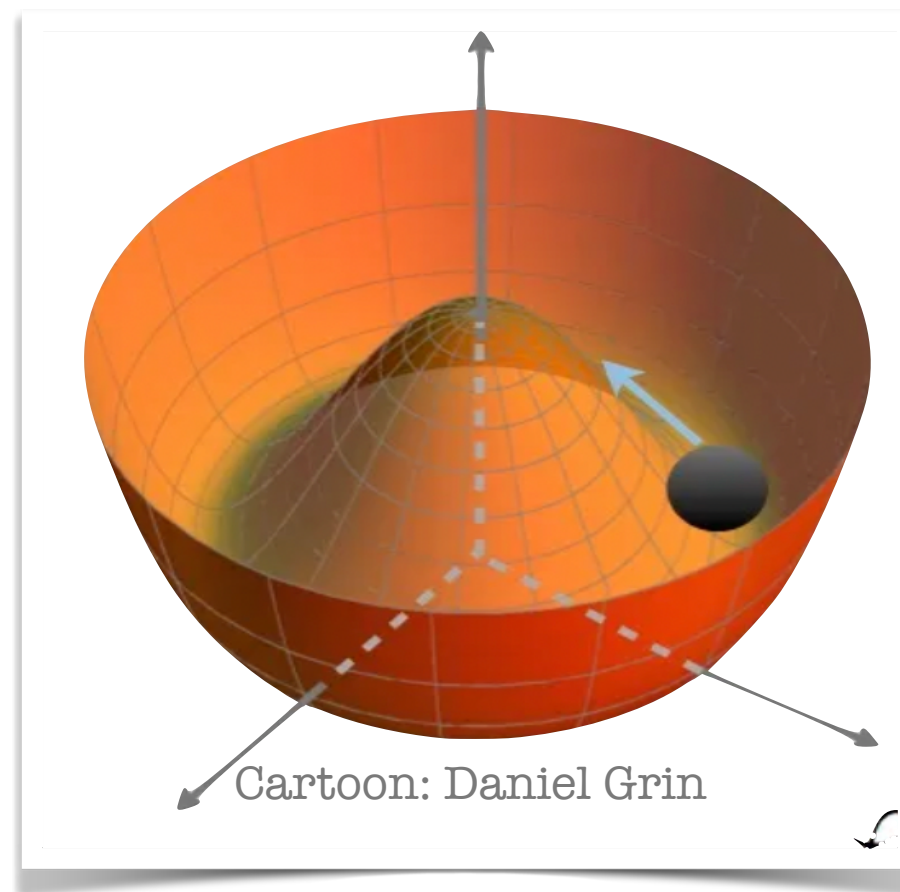
- After SB, P becomes a GB
- Heavy quarks generate a coupling

$$-\frac{\lambda f_a}{\sqrt{2}} \exp\left(i \frac{a}{f_a}\right) \bar{Q}_L Q_R + \text{h.c.}$$

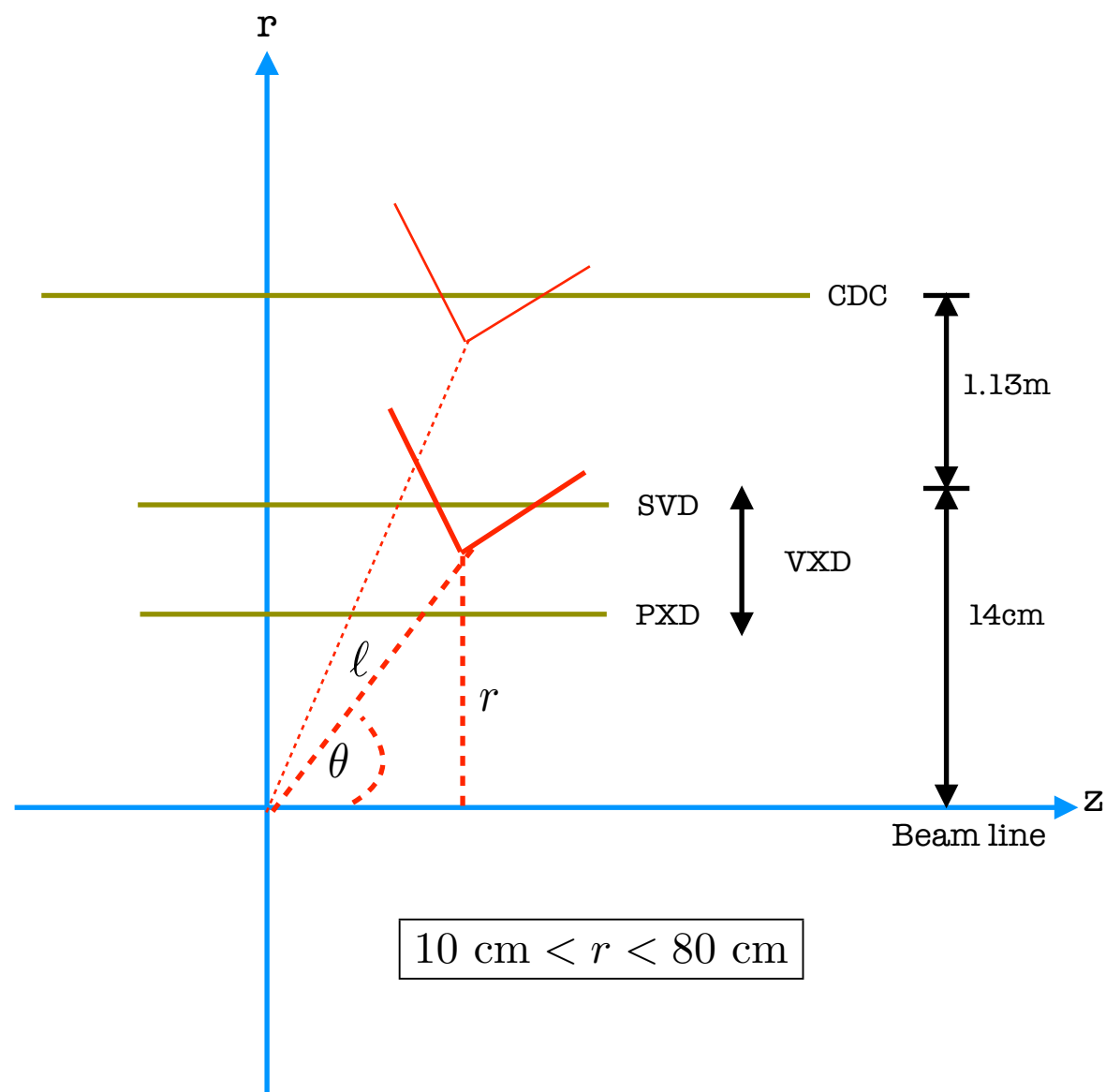


- Chiral rotation removes this
- However, generates: $\frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G}$

$$\mathcal{L}_{\text{KSVZ}} = (\partial_\mu P)^\dagger (\partial^\mu P) + \bar{Q} i D Q - (y_Q P \bar{Q}_L Q_R + \text{h.c.}) - V(|P|^2)$$



Displaced Searches at Belle



► Linear Filling Efficiency:

$$\epsilon(r) = \frac{r_{\max} - r}{r_{\max} - r_{\min}}$$

► Probability for decay

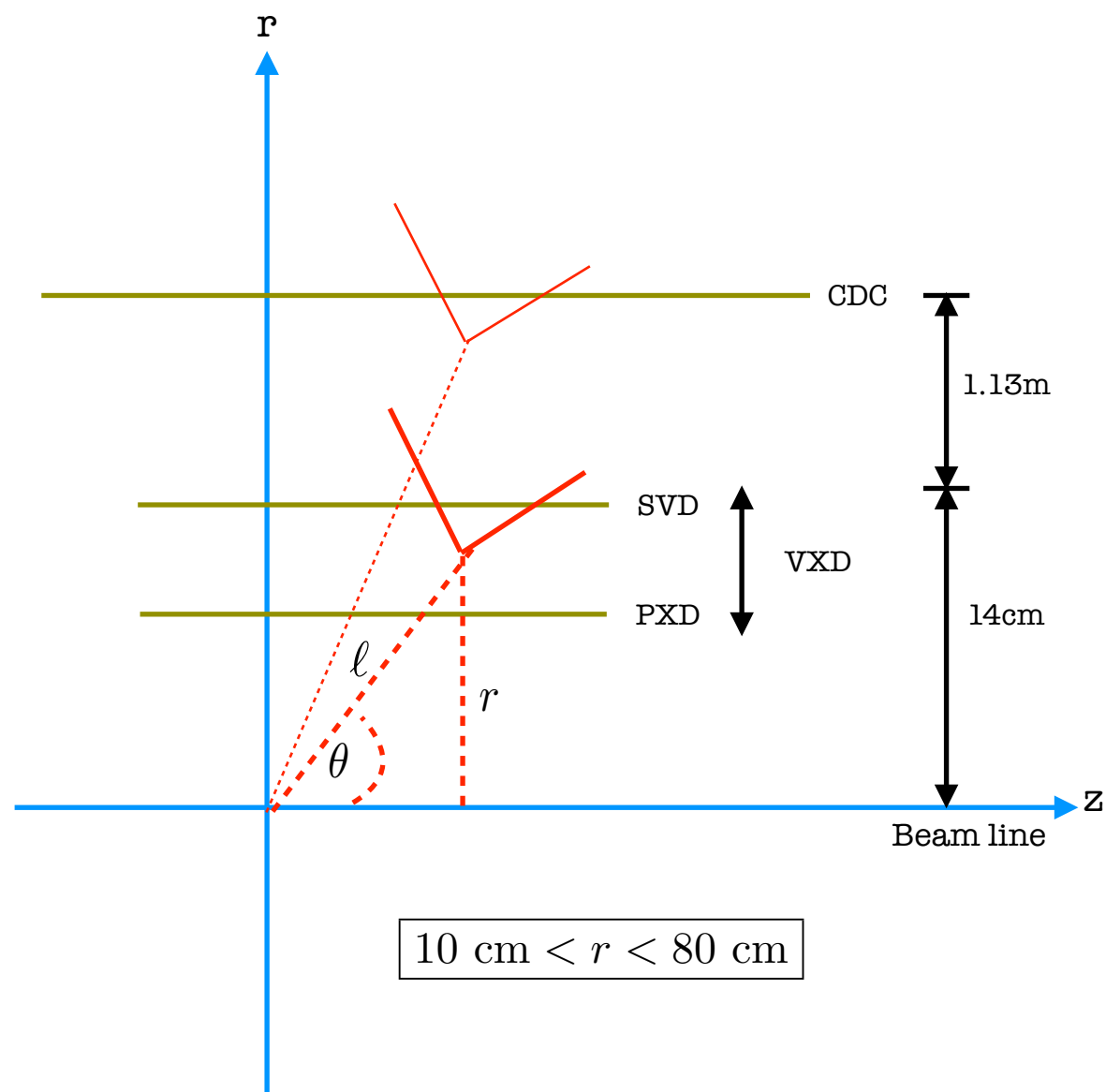
$$P(\ell) = \frac{e^{-\ell/\lambda}}{\lambda}$$

► Probability for identifying displaced vertex

$$\epsilon(\theta) = \frac{\int_{\ell_{\min}}^{\ell_{\max}} d\ell \frac{e^{-\ell/\lambda}}{\lambda} (r_{\max} - \ell \sin \theta) \bar{\theta}(\ell)}{\int_{\ell_{\min}}^{\ell_{\max}} d\ell \frac{e^{-\ell/\lambda}}{\lambda} (r_{\max} - r_{\min}) \bar{\theta}(\ell)}$$

$$N_{\text{signal}} = \text{Production} \times \text{Decay Branching} \times \text{Efficiency}$$

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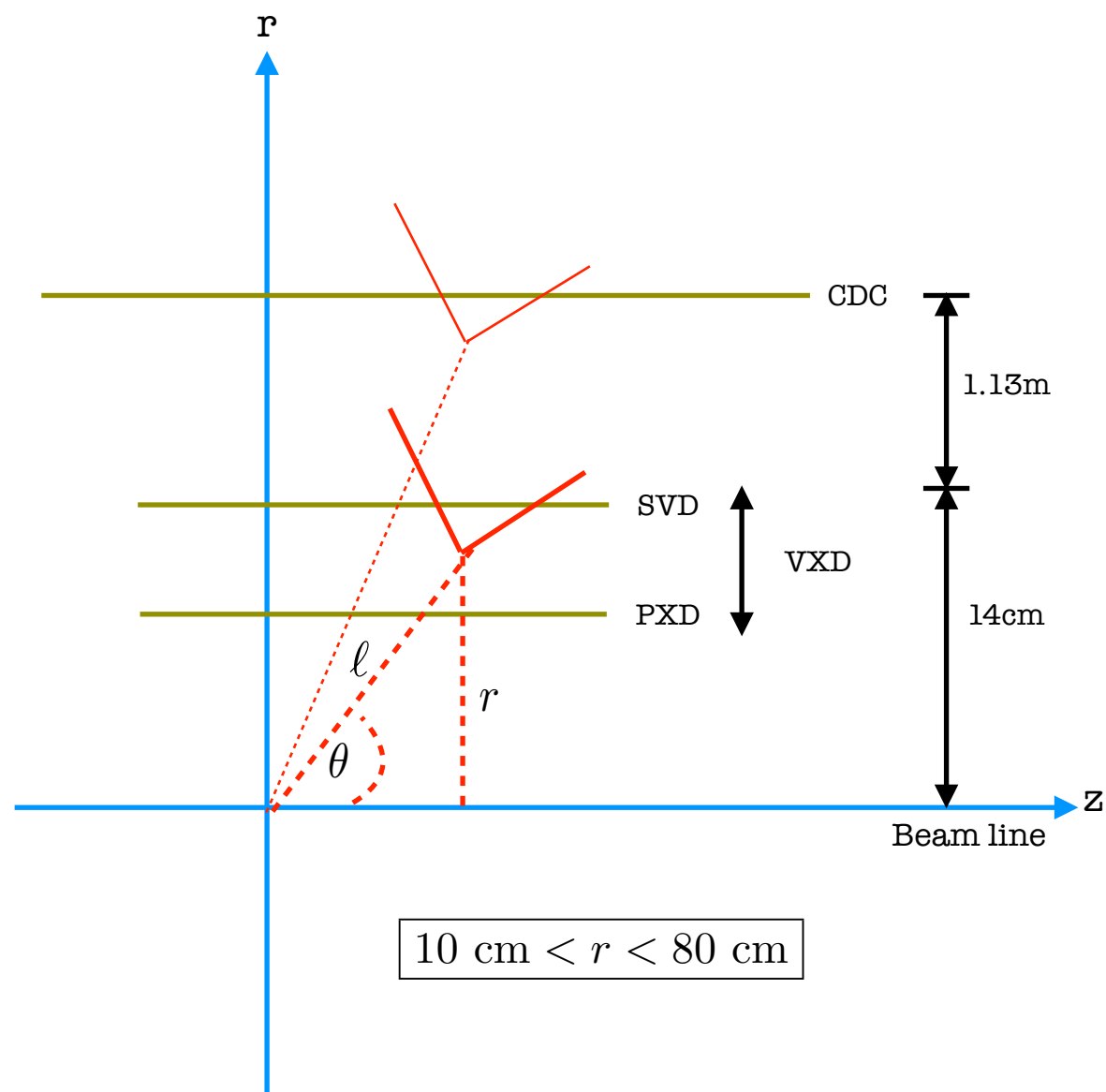
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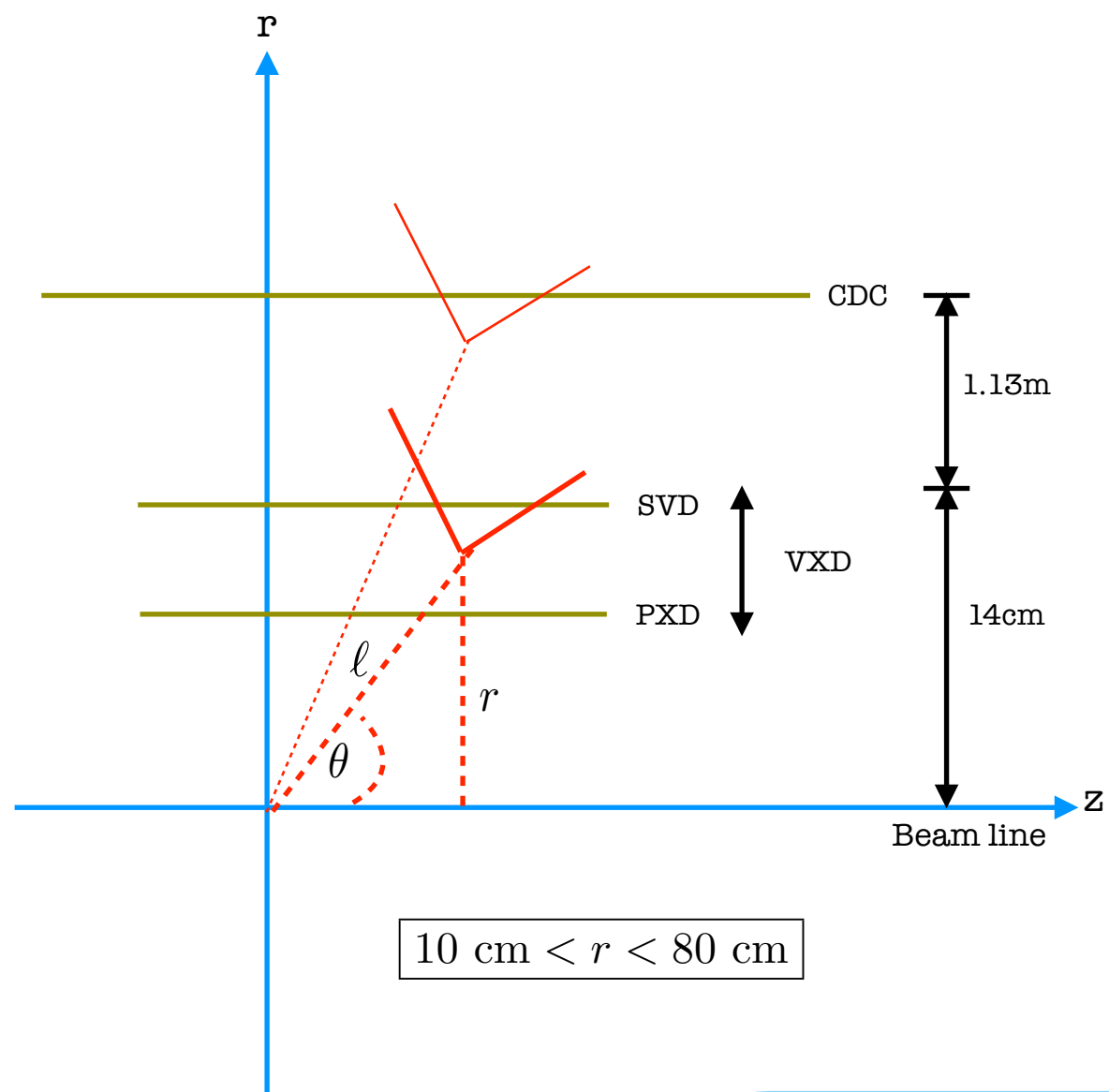
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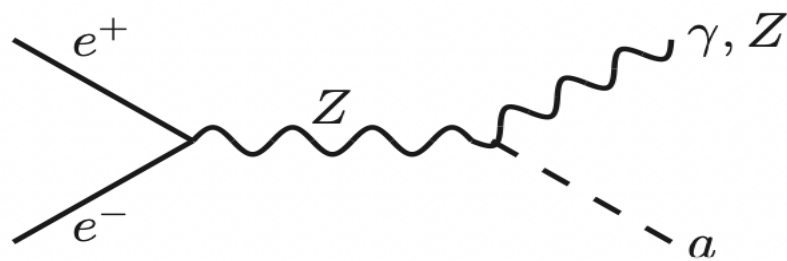
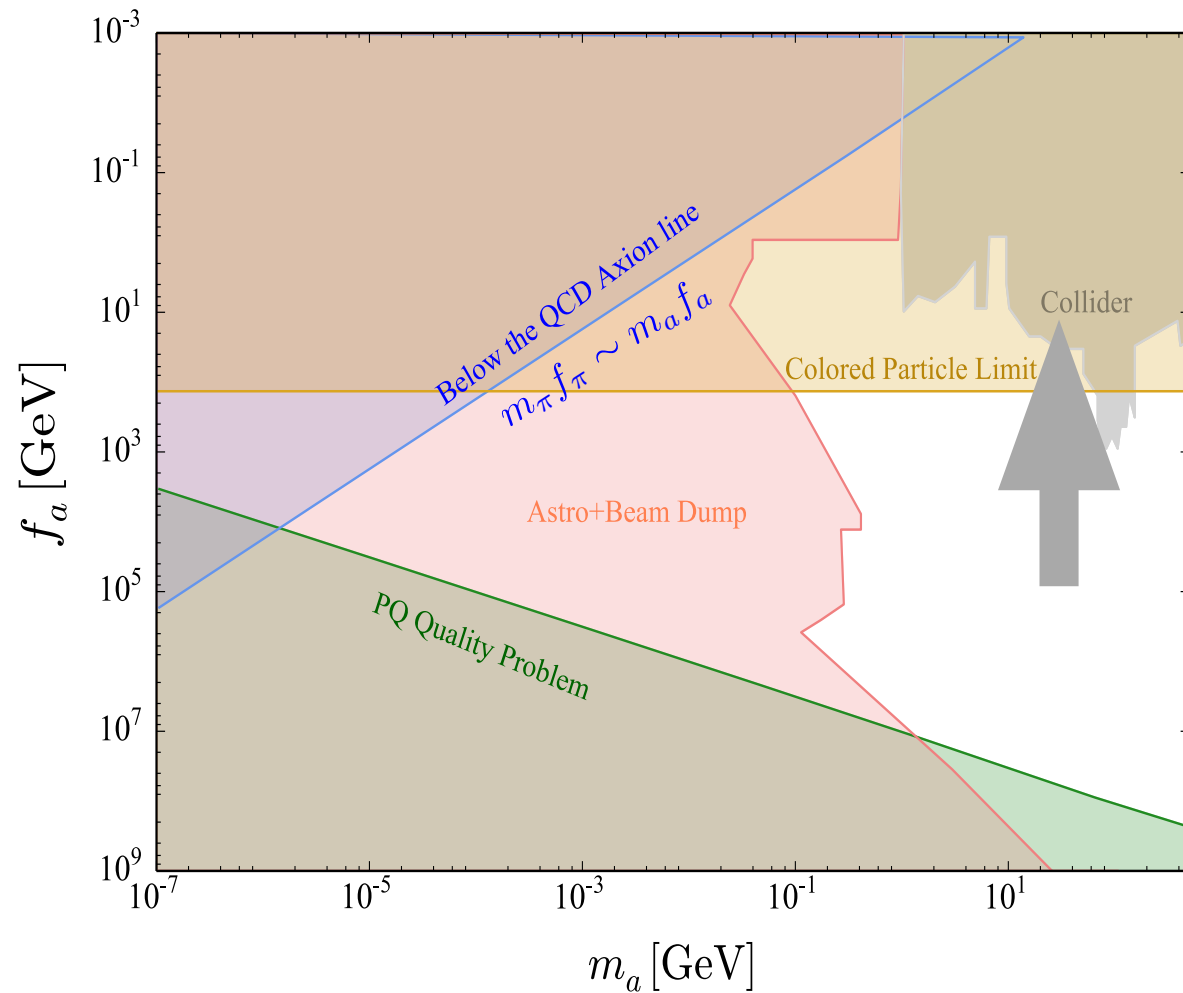
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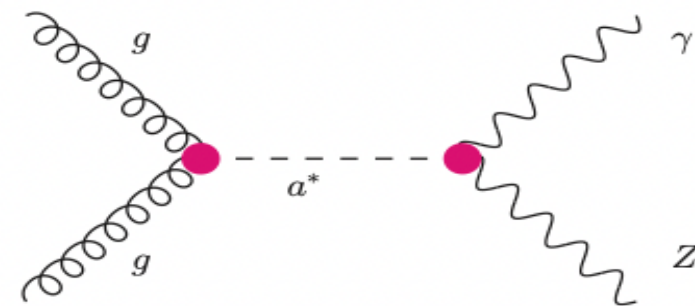
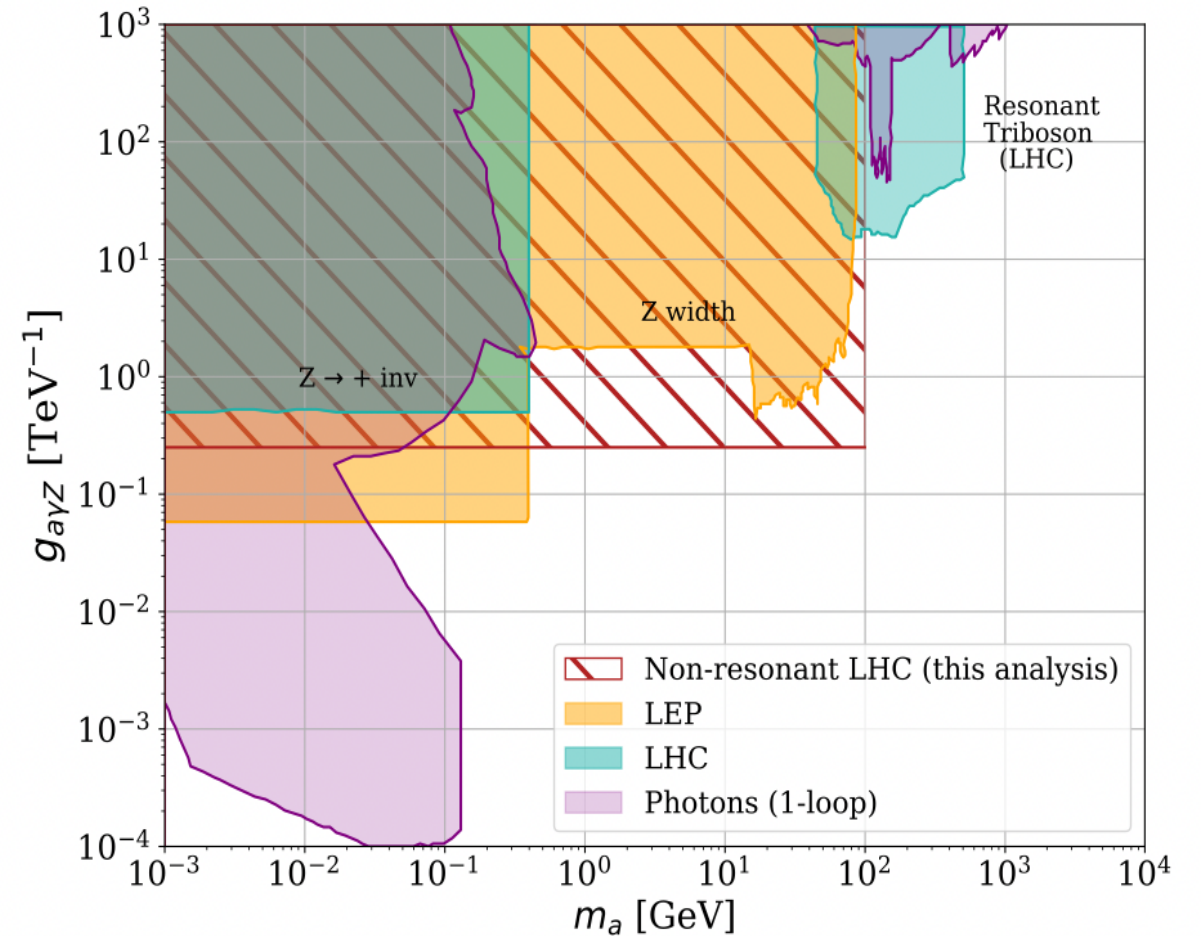
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ALPs: Energy Frontier

Bauer et. Al. 1808.10323

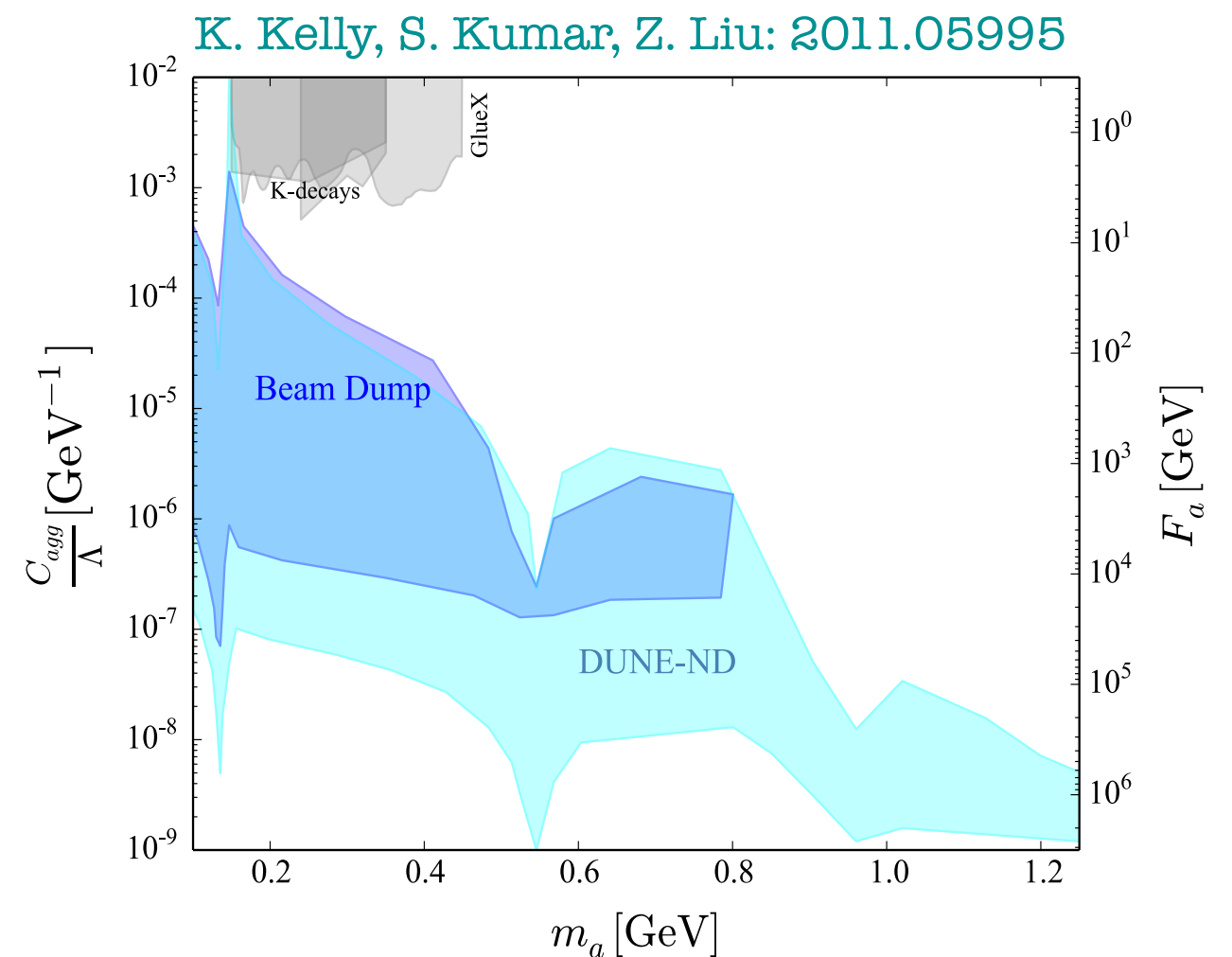
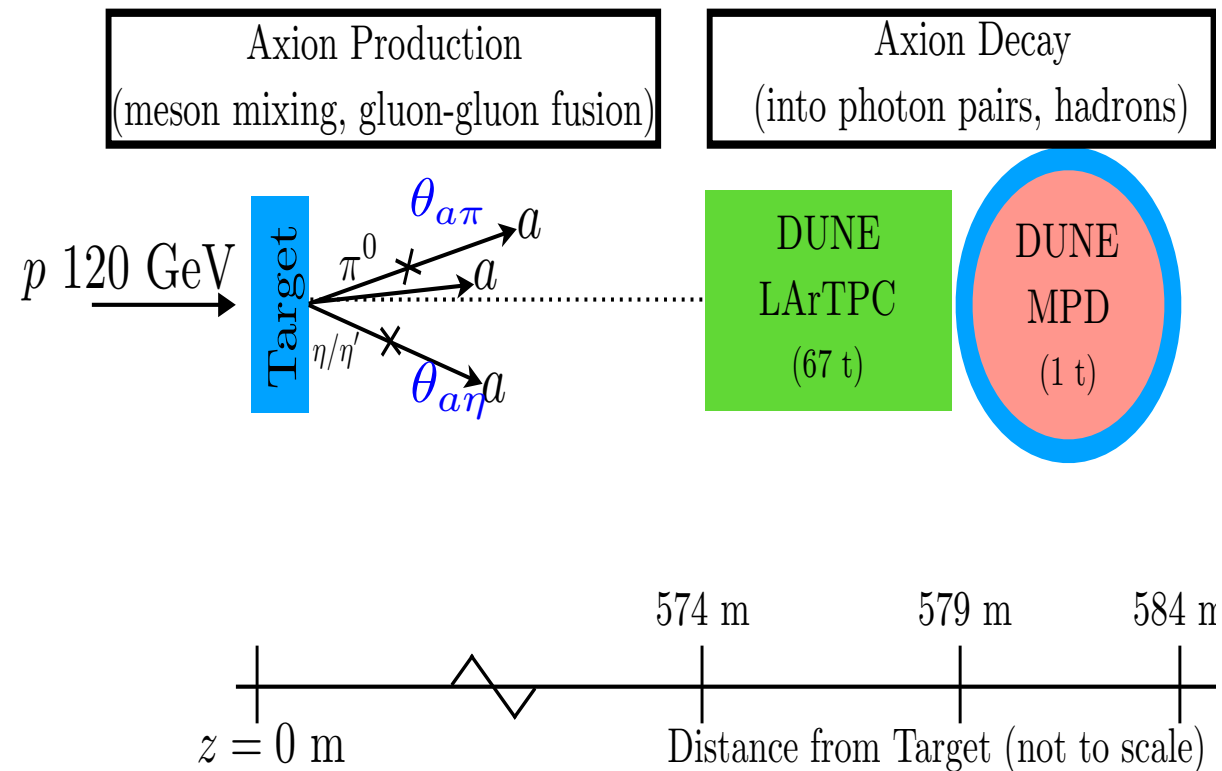


Tisa Biswas. 2312.05992

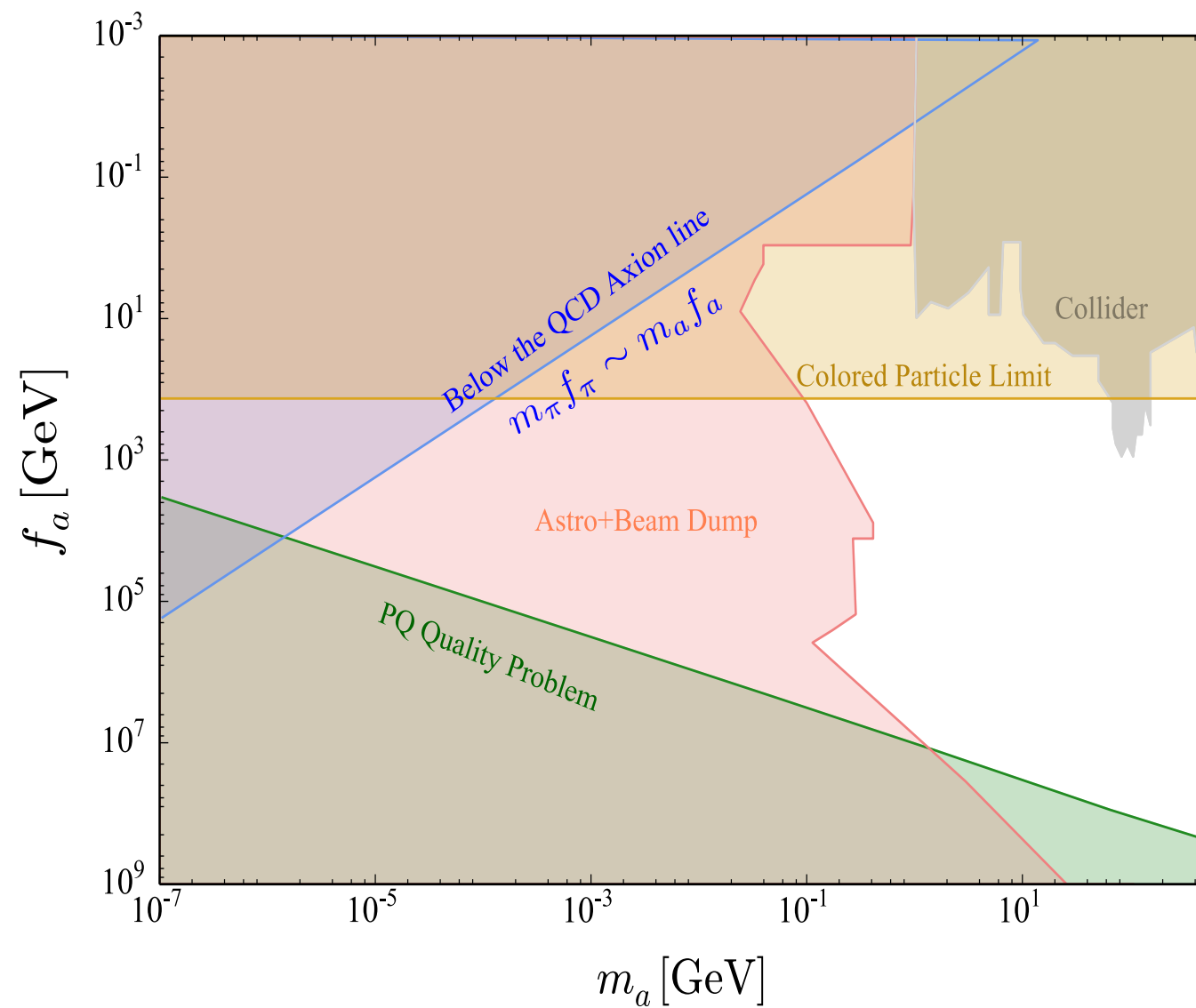


Intensity Frontier: Bounds from Beam-dump

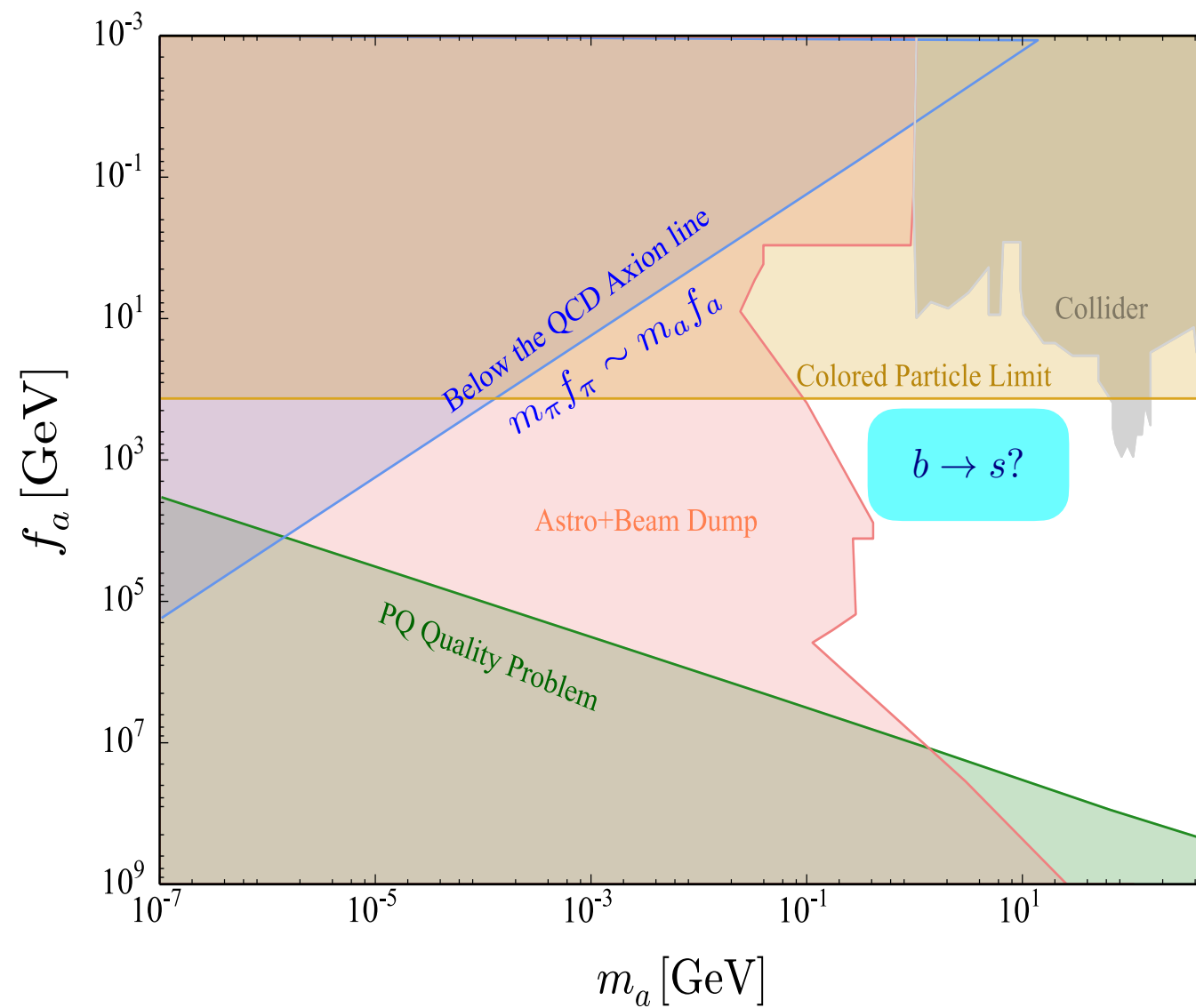
Example: DUNE (Also could be MiniBooNE, microBooNE etc.)



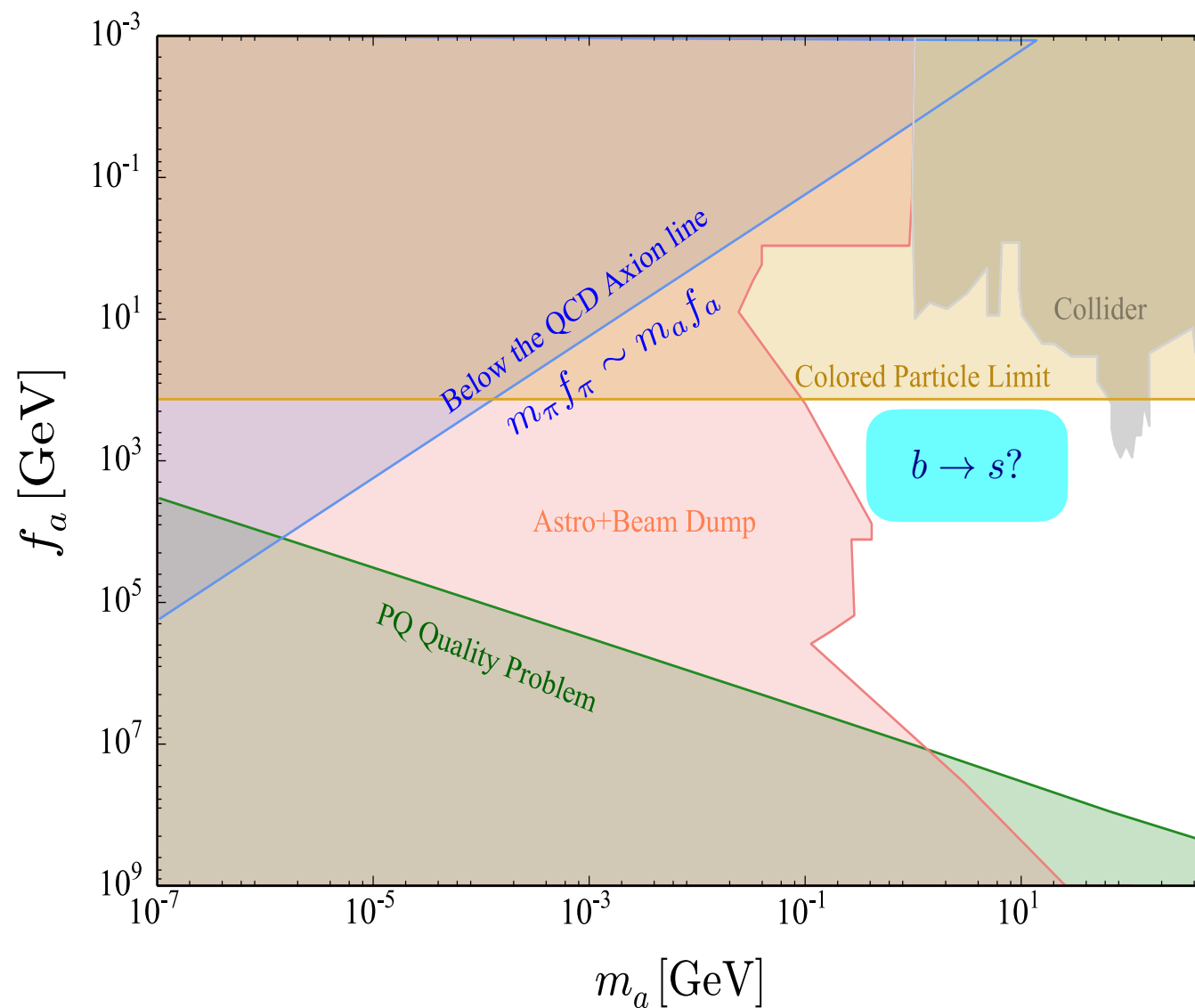
MeV–GeV region open! Technically Challenging



MeV–GeV region open! Technically Challenging



MeV–GeV region open! Technically Challenging



► Recall, the chiral Lagrangian for matching

$$\mathcal{L}_{\chi PT} \supset \frac{f_\pi^2}{8} \text{Tr} [D^\mu \Sigma D_\mu \Sigma^\dagger] + \frac{f_\pi^2}{4} 2B_0 \text{Tr} [\Sigma \hat{\mathcal{M}}_q^\dagger + \hat{\mathcal{M}}_q \Sigma^\dagger] + \dots$$

► Infinite number of operators beyond LO

$$\left(\frac{\partial}{\Lambda} \right)^n : \Lambda \sim 4\pi f_\pi \sim 1 \text{ GeV}$$

► Breaks down for momentum for $p > 1 \text{ GeV}$