Signals of the QCD axion with mass of 17 MeV

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arXiv:2009.05578

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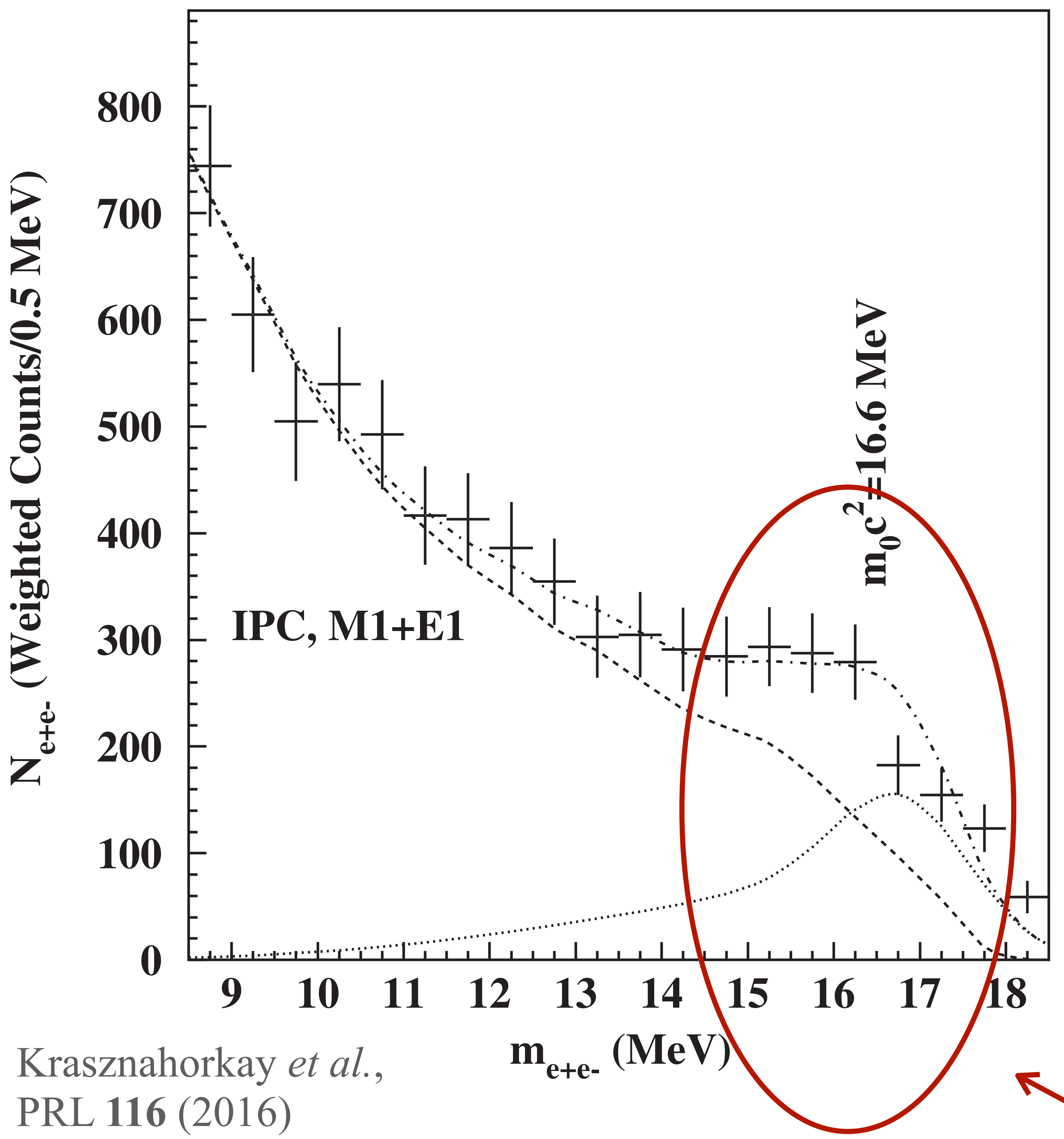
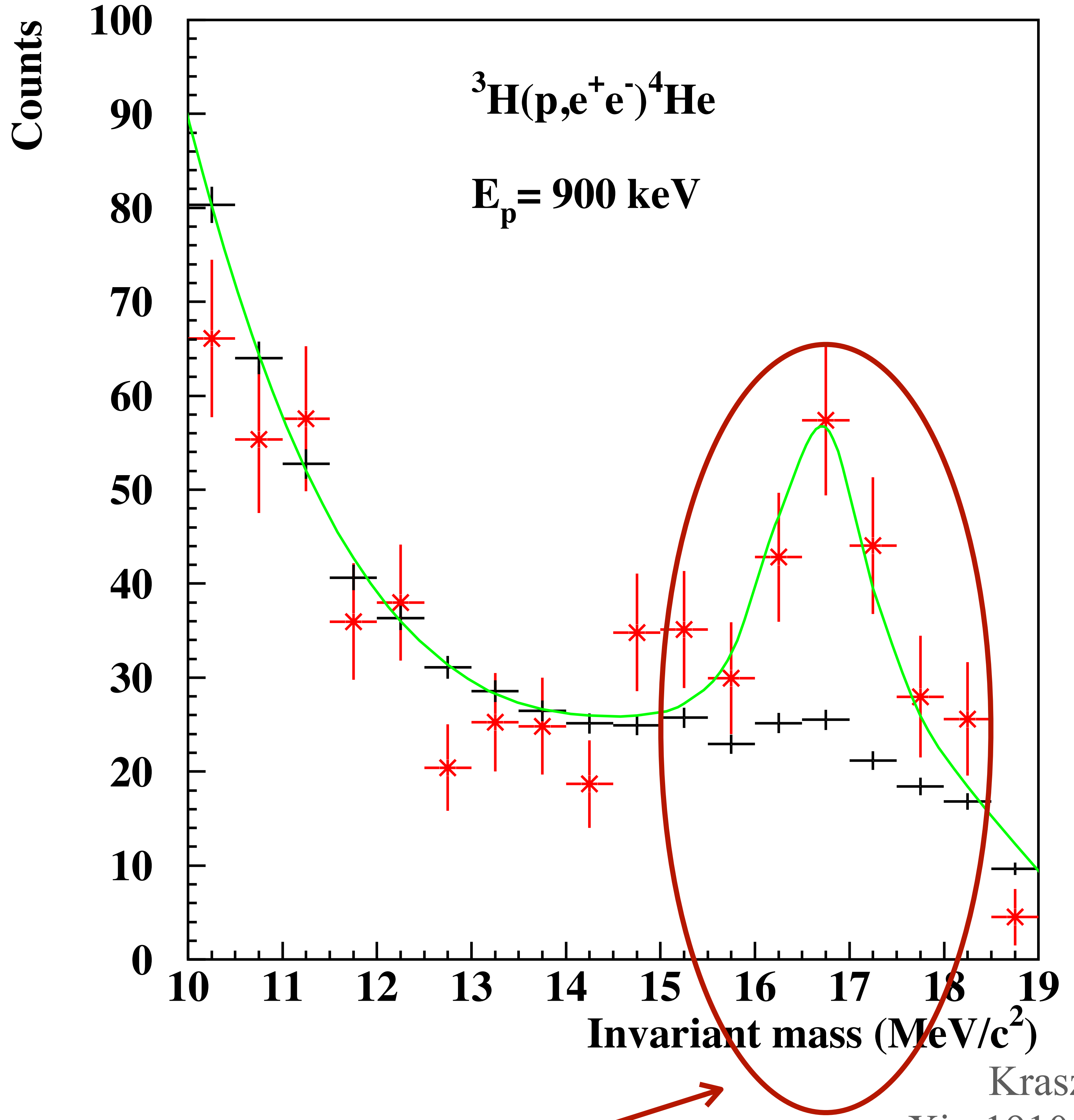
Anomalous $m_{e^+e^-}$ emission spectra from **magnetic* transitions of excited ^{8}Be and ^{4}He nuclei:

$^8\mathrm{Be}^*(18.15) \rightarrow \ ^8\mathrm{Be}(0) + e^+e^-$



Krasznahorkay *et al.*,
PRL **116** (2016)

$^4\mathrm{He}^*(21.01) \rightarrow \ ^4\mathrm{He}(0) + e^+e^-$

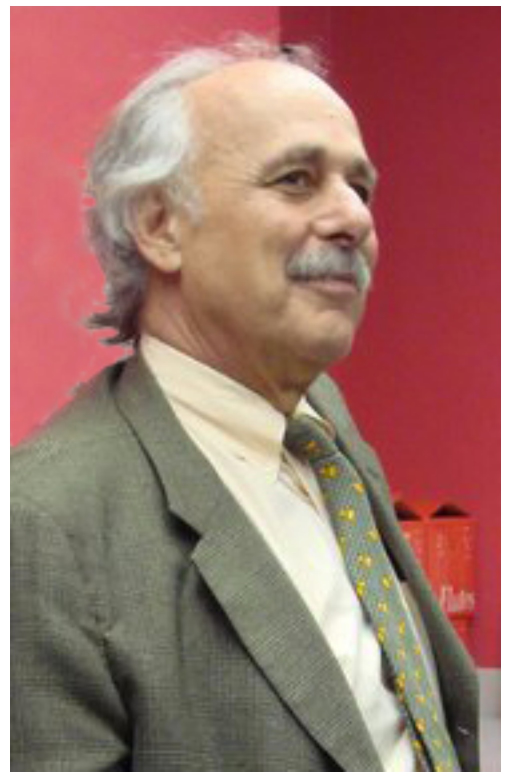


Krasznahorkay *et al.*,
arXiv:1910.10459 [nucl-ex]

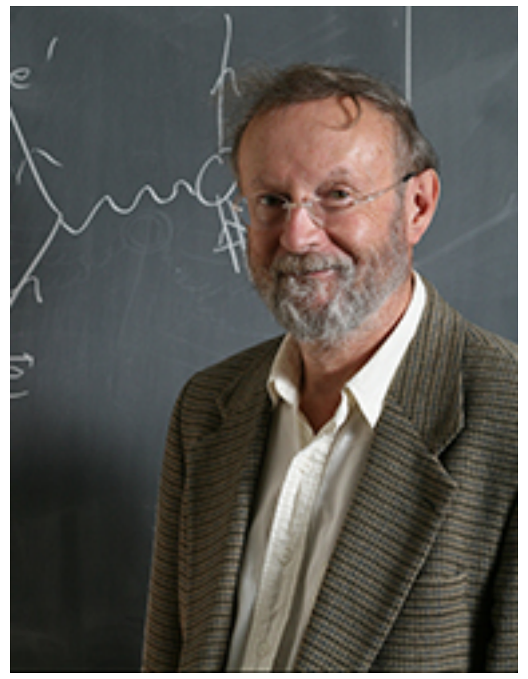
Bump at $m_{e^+e^-} \sim 16 - 17$ MeV: telltale sign of on-shell resonance decaying to e^+e^-

**magnetic* transitions change the nucleus' total angular momentum and parity by $P = (-1)^{\ell+1}$

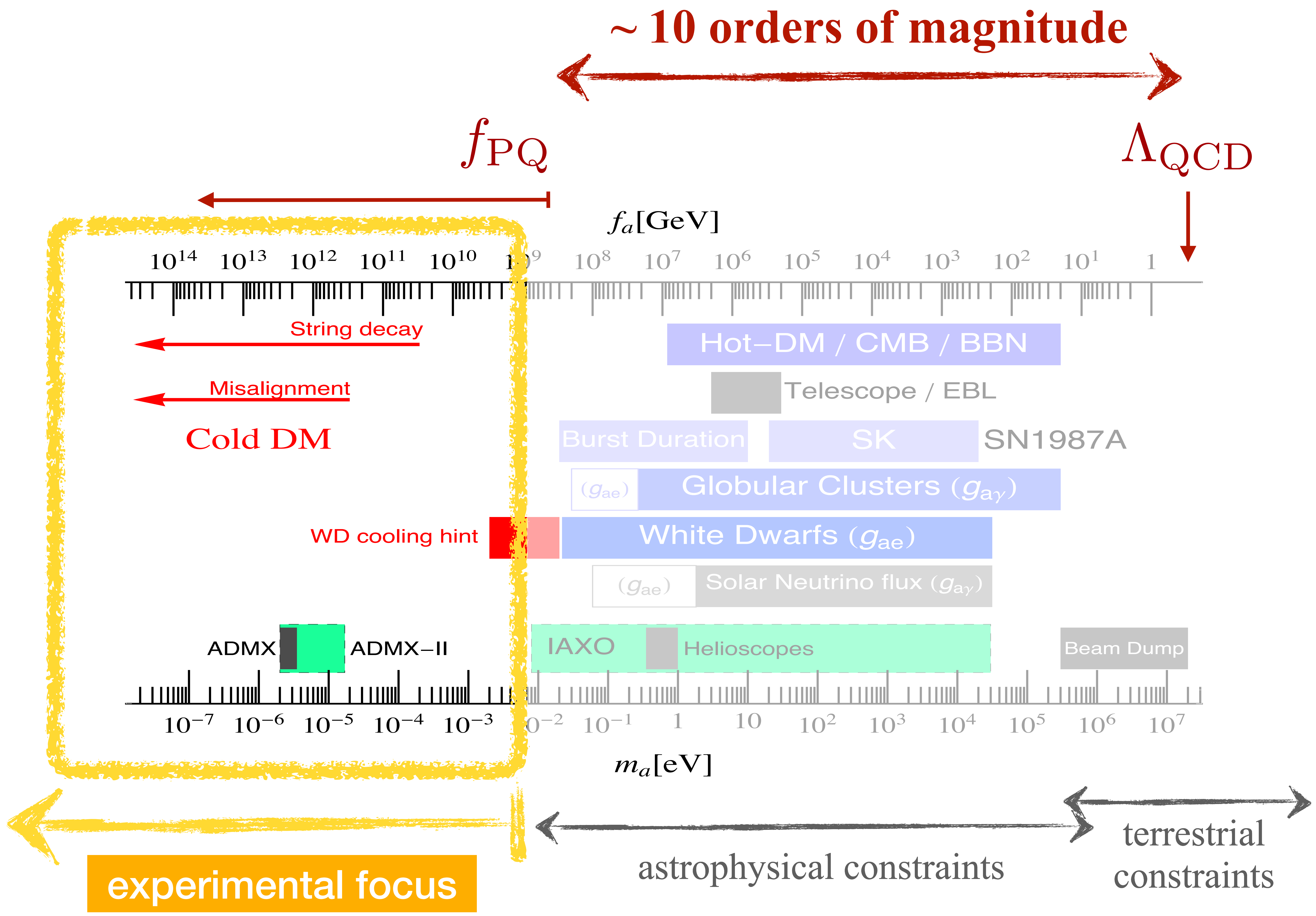
If this had happened in the 80's…



Could this be the QCD axion?



But today the consensus is that the QCD axion, if it exists, should be *ultralight* and *cosmologically long-lived* $\Rightarrow$ could be **dark matter**!



This possibility faces a <u>significant challenge</u>:

how to protect the PQ cancellation of the strong CP phase with such wide separation of scales?

From this perspective, it is worth considering implementations of the PQ mechanism closer to Λ_{QCD}

But is $f_{PQ} \sim \mathcal{O}(\Lambda_{QCD})$ even viable?

Let's go back to the anomalous excesses in de-excitations of ^{8}Be and ^{4}He nuclei via $e^{+}e^{-}$ emission

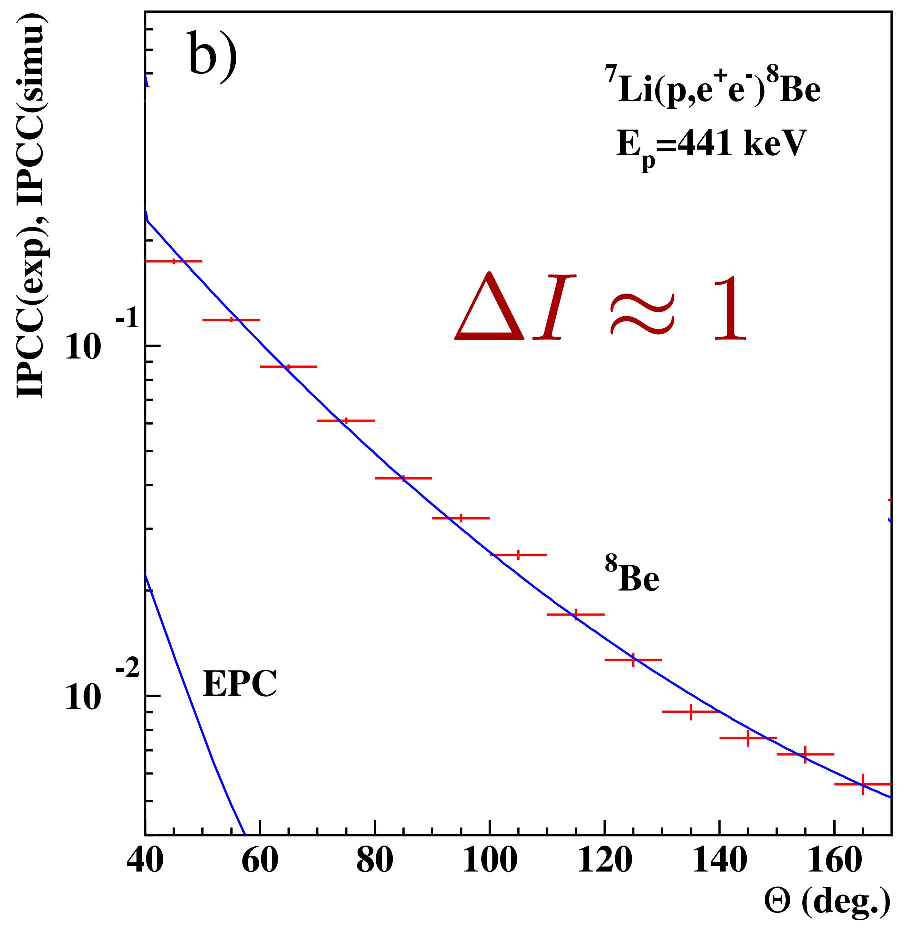
To explain the ^{8}Be and ^{4}He excesses via on-shell axion emission,
the QCD axion must have the following properties:

- $m_a \sim 17$ MeV $\Rightarrow$ $f_a \sim f_{\rm PQ} \sim \mathcal{O}({\rm GeV})$ $\Rightarrow$ new dynamical sector to break U(1)$_{\rm PQ}$ at GeV scale

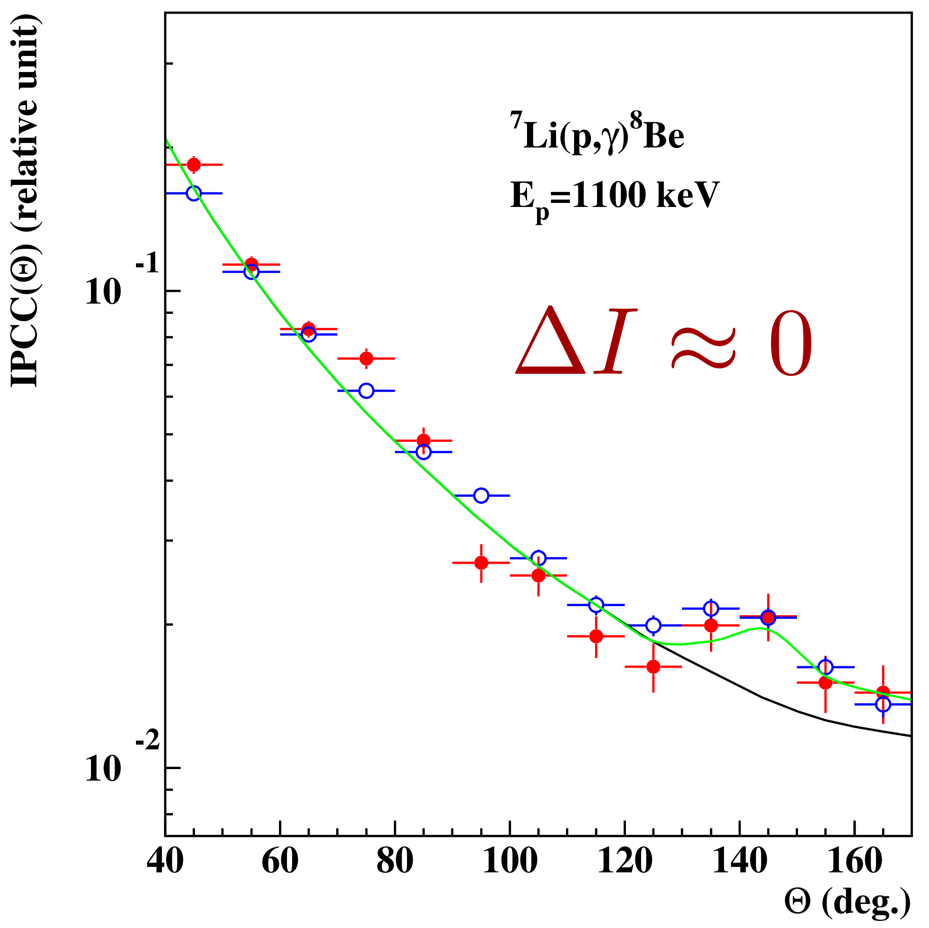
- suppressed isovector couplings to explain the spectra of the two isospin doublet states of ^{8}Be, *i.e.*,
  - why there is no excess in $\Delta I \approx 1$ transition
  - why excess in 18.15 MeV transition is not $10^4 \times$ larger

  $\Rightarrow$ QCD axion must be *piophobic*, *i.e.*, have suppressed mixing with π^0 : $|\theta_{a\pi}| \lesssim 10^{-4}$

$^8{\rm Be}^*(17.64) \rightarrow {}^8{\rm Be}(0) + e^+e^-$



$^8{\rm Be}^*(18.15) \rightarrow {}^8{\rm Be}(0) + e^+e^-$



- isoscalar couplings $\theta_{a\eta}, \theta_{a\eta'} \sim \mathcal{O}(10^{-4} - 10^{-3})$ to explain size of the excesses in ^{8}Be and ^{4}He

- Prompt decay to e^+e^- pair

Remarkably, this variant of the QCD axion is the
only variant still viable in the $\mathcal{O}$(10 MeV) mass range

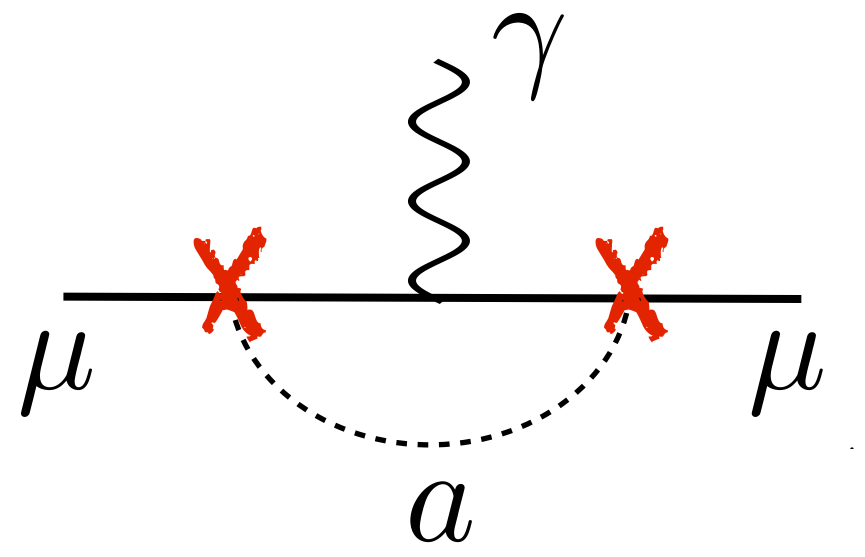
Overview of the *piophobic QCD axion* compatibility with existing constraints

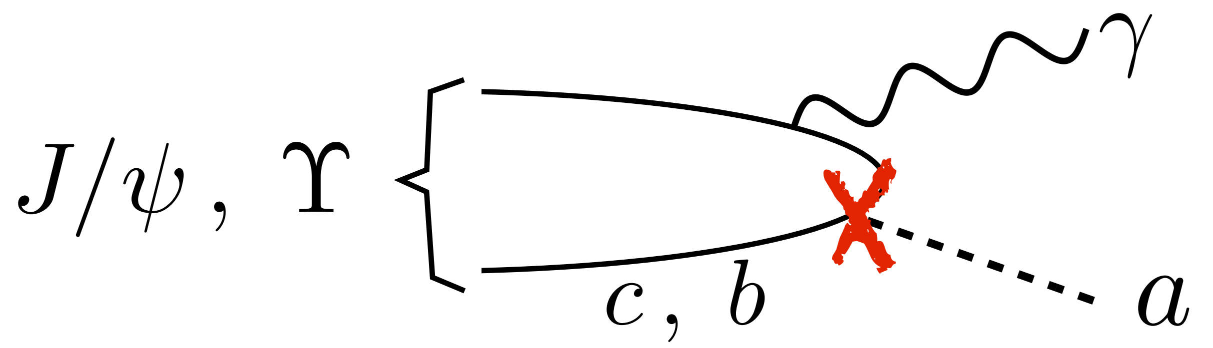
- $m_a \sim 17$ MeV $\Rightarrow$ $f_a \sim f_{\mathrm{PQ}} \sim \mathcal{O}(\mathrm{GeV})$ $\Rightarrow$ new dynamical sector to break $U(1)_{PQ}$ at GeV scale

Generic implication: only light SM fermions (with $m_f \ll f_{PQ}$) should be charged under $U(1)_{PQ}$ **

(** that is if one wishes to keep Yukawa couplings small and hope to find a *perturbative* completion of the PQ sector at the electroweak scale)

This is imposed anyways by experimental constraints from $(g\text{-}2)_\mu$ and radiative quarkonium decays





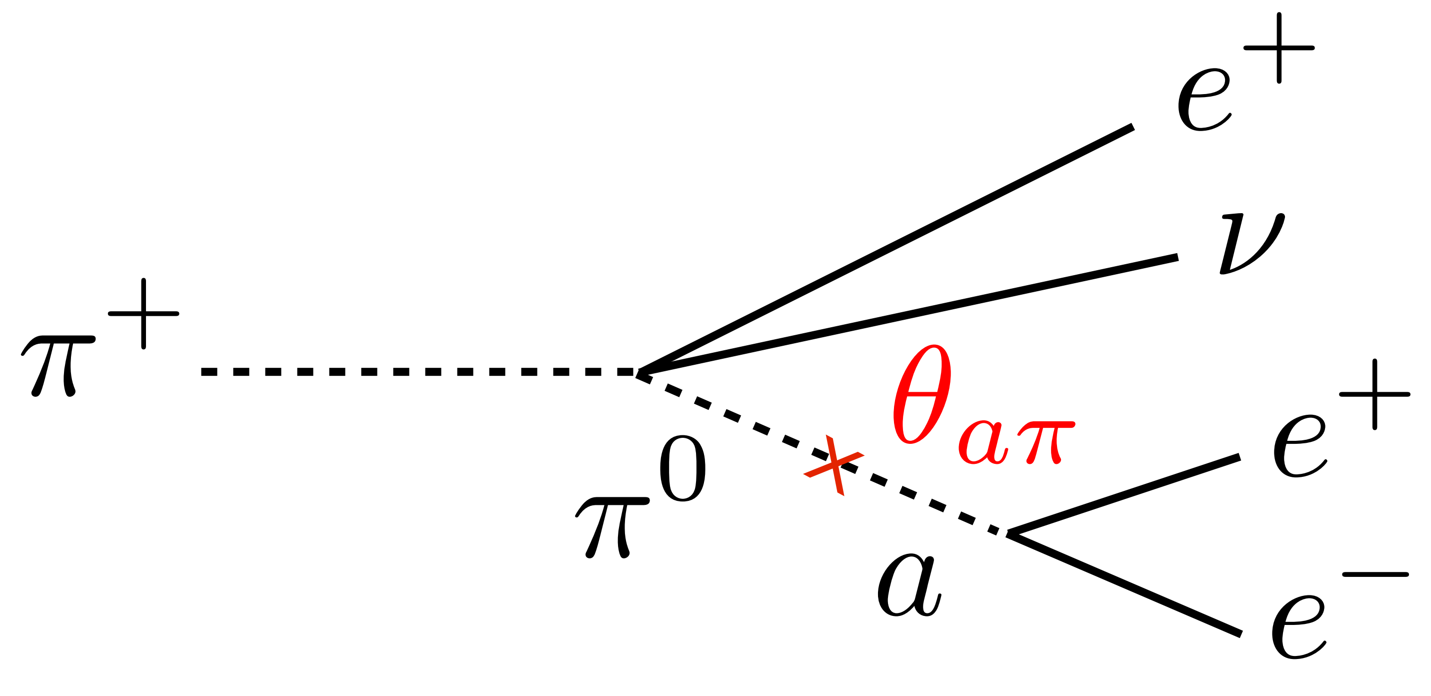
Low PQ breaking scale also disfavors a coupling of the type $(a/f_a)\, G\tilde{G}$, which is typically generated by integrating out heavy fermions (as in the case of the KSVZ axion)

- The axion must be have suppressed isovector couplings: $|\theta_{a\pi}| \lesssim 10^{-4}$

Compatible with bound on rare π^+ decay:

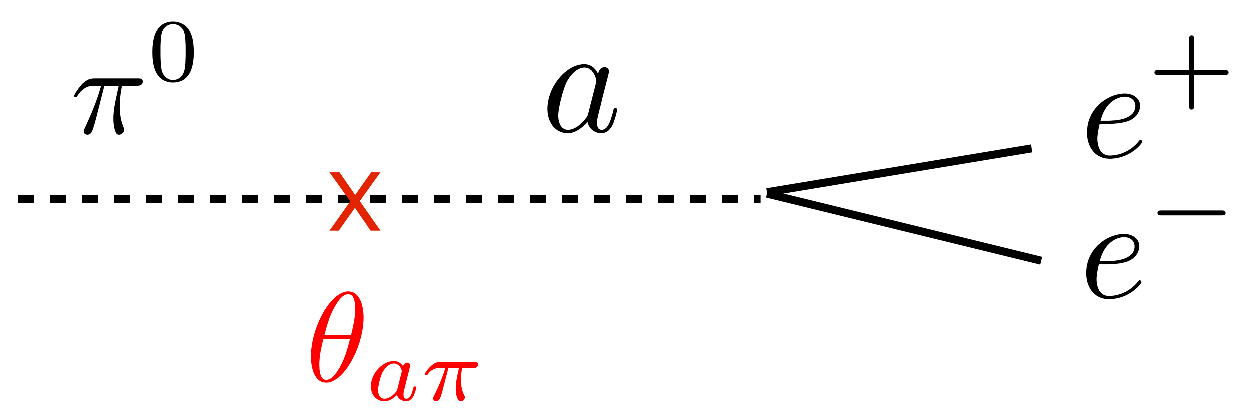
$$\mathrm{Br}[\pi^+ \to e^+\nu(a \to e^+e^-)] \lesssim 10^{-10}$$

SINDRUM collaboration, PLB **175** (1986)



Could explain KTeV measurement of $\Gamma(\pi^0 \to e^+e^-)$, which is $\sim 15\%$ higher than SM expectation ($\sim 2-3\sigma$ discrepancy)

KTeV collaboration, PRD **75** (2007)



$$\text{with} \quad \theta_{a\pi}\big|_{\mathrm{KTeV}} = \frac{(-0.6 \pm 0.2)}{q^e_{\mathrm{PQ}}} \times 10^{-4}$$

Is this level of "*piophobia*" realistic?

- The axion must be have suppressed isovector couplings: $|\theta_{a\pi}| \lesssim 10^{-4}$

With low PQ breaking scale $f_{PQ} \sim \mathcal{O}(\text{GeV})$, the most natural parametrization of axion couplings is:

$$\mathcal{L}_{\text{PQSM}} \supset \left(m_u\, e^{i\, q^u_{\text{PQ}}\, a/f_a}\right) uu^c + \left(m_d\, e^{i\, q^d_{\text{PQ}}\, a/f_a}\right) dd^c + \left(m_s\, e^{i\, q^s_{\text{PQ}} \to 0\; a/f_a}\right) ss^c$$

It follows from LO χPT:

$$\theta_{a\pi} \approx \underbrace{\frac{\left(m_u\, q^u_{\text{PQ}} - m_d\, q^d_{\text{PQ}}\right)}{(m_u + m_d)} \frac{f_\pi}{f_a}}_{\mathcal{O}(10^{-2}) \times \left(\frac{q^u_{\text{PQ}}}{q^d_{\text{PQ}}} - \frac{m_d}{m_u}\right)} + \underbrace{\frac{q^s_{\text{PQ}} \to 0}{2} \frac{(m_u - m_d)}{(m_u + m_d)} \frac{f_\pi}{f_a}}_{\mathcal{O}(10^{-2}) \times q^s_{\text{PQ}} \;\Rightarrow\; q^s_{\text{PQ}} \lesssim 10^{-2}} + \mathcal{O}\left(\frac{m_{u,d}}{m_s}\right) \frac{f_\pi}{f_a}$$

$\Rightarrow$ accidental cancellation if $\frac{q^u_{\text{PQ}}}{q^d_{\text{PQ}}} = 2$

Indeed, using exact expression for $\theta_{a\pi}|_{\text{LO}}$ and plugging in $m_u/m_d = 0.485 \pm 0.027$

Fodor *et al.*, PRL **117** (2016)

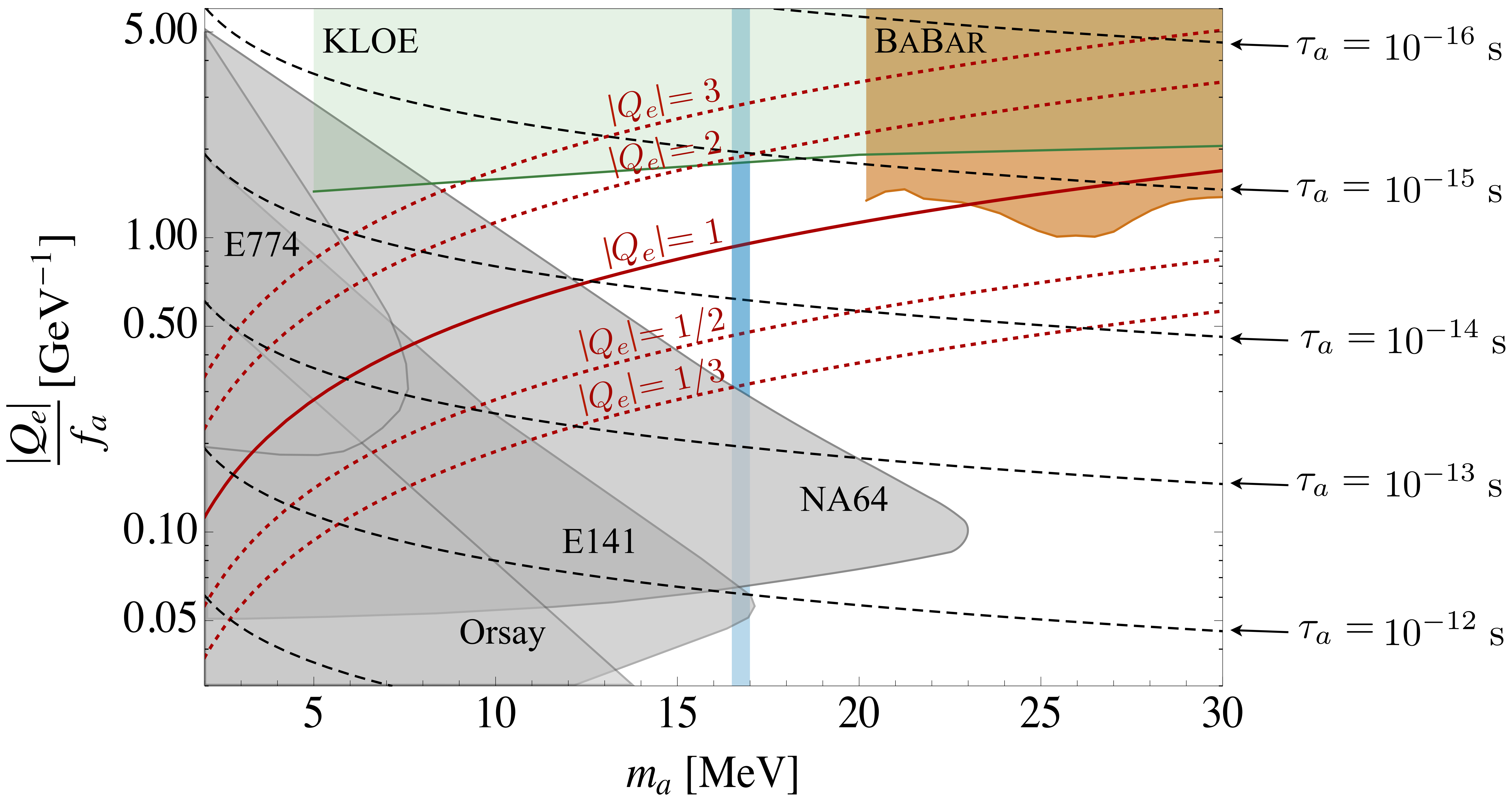
$$\theta_{a\pi}\big|_{\chi\text{PT LO}} = (-0.02 \pm 3) \times 10^{-3}$$

Compatible with the required level of piophobia and with the range that explains the KTeV anomaly

- The axion must decay promptly to e^+e^-

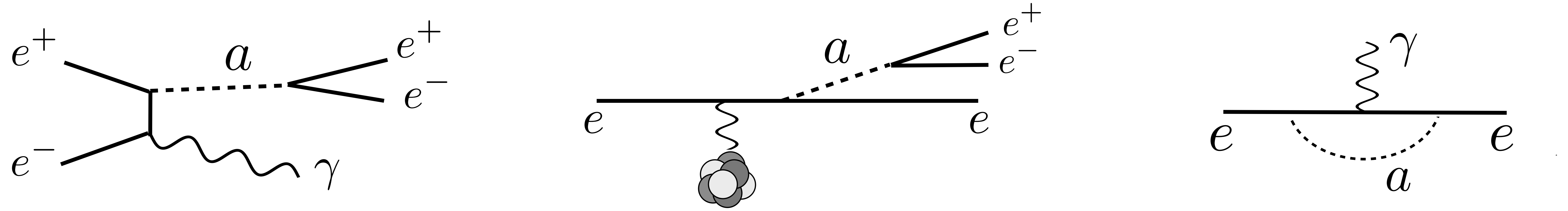
Natural consequence of charging the electron under $U(1)_{PQ}$: $Q_e^{PQ} \dfrac{m_e}{f_a} a\, \bar{e}\gamma_5 e$

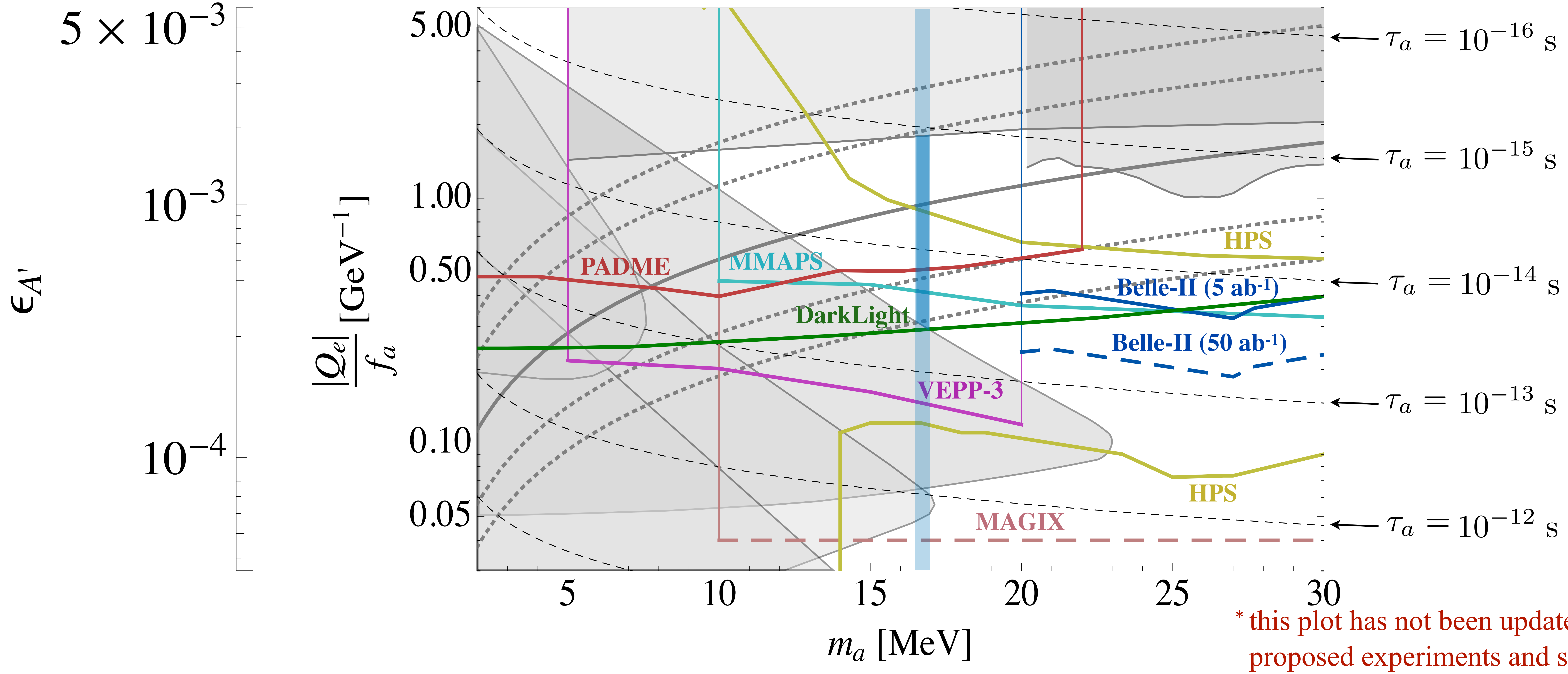
Needed to avoid constraints from beam dumps / fixed target experiments



- The axion must decay promptly to e^+e^-

Also probable in upcoming experimental searches for visibly decaying dark photons*





* this plot has not been updated with most recent proposed experiments and sensitivity studies

- The axion must be have isoscalar couplings $\theta_{a\eta},\ \theta_{a\eta'} \sim \mathcal{O}(10^{-4} - 10^{-3})$

In the 80's, these mixing angles were estimated at LO in χPT, and, due to their contribution to $K^+ \to \pi^+ a$, it was argued that the QCD axion with $m_a \gtrsim$ few MeV was excluded

Antoniadis & Truong, PLB **109** (1982)
Bardeen, Peccei, Yanagida, NPB **279** (1987)

However, LO χPT estimates of $\theta_{a\eta}, \theta_{a\eta'}$ are *unreliable*: these angles receive $\mathcal{O}(1)$ contributions from operators at $\mathcal{O}(p^4)$ in the chiral expansion (some of which have poorly determined/unknown LECs)

$$\begin{aligned}
\mathcal{L}_\chi^{\mathcal{O}(p^4)} \supset\ & L_7 \,\mathrm{Tr}\left[(2BM_q)\,U - U^\dagger\,(2BM_q)^\dagger\right]^2 + i\,\lambda_2\,F^2\,\frac{\eta_0}{F}\,\mathrm{Tr}\left[(2BM_q)\,U - U^\dagger\,(2BM_q)^\dagger\right] \\
& + L_5\,\mathrm{Tr}\left[\partial^\mu(2BM_q\,U)\,\partial_\mu U^\dagger\,U + \mathrm{h.c.}\right] + L_8\,\mathrm{Tr}\left[(2BM_q)\,U\,(2BM_q)\,U + \mathrm{h.c.}\right] \\
& + L_{18}\,\mathrm{Tr}\left[U^\dagger\partial^\mu U\right]\,\mathrm{Tr}\left[\partial_\mu\left(U^\dagger\,(2BM_q)^\dagger - (2BM_q)\,U\right)\right] \\
& + i\,L_{25}\,\frac{\eta_0}{F}\,\mathrm{Tr}\left[U^\dagger\,(2BM_q)^\dagger\,U^\dagger\,(2BM_q)^\dagger - (2BM_q)\,U\,(2BM_q)\,U\right] \\
& + i\,L_{26}\,\frac{\eta_0}{F}\left(\mathrm{Tr}\left[U^\dagger\,(2BM_q)^\dagger\right]^2 - \mathrm{Tr}\left[(2BM_q)\,U\right]^2\right) + \ldots
\end{aligned}$$

These introduce large uncertainties in the determination of the axion isoscalar couplings,

e.g., $\quad \theta_{a\eta_{ud}} \approx (-2 \pm 3) \times 10^{-3}$

- The axion must be have isoscalar couplings $\theta_{a\eta},\ \theta_{a\eta'} \sim \mathcal{O}(10^{-4} - 10^{-3})$

We therefore treat the axion isoscalar mixing angles as phenomenological parameters of the *physical* axion current (i.e., the mass eigenstate):

$$J_\mu^{a_{\rm phys}} \equiv f_a\,\partial_\mu a_{\rm phys} \equiv \frac{f_a}{f_\pi}\left(f_\pi\,\partial_\mu a + \theta_{a\pi}\,J_{5\,\mu}^{(3)} + \theta_{a\eta_{ud}}\,J_{5\,\mu}^{(ud)} + \theta_{a\eta_s}\,J_{5\,\mu}^{(s)}\right),$$

$$J_{5\,\mu}^{(3)} \equiv \frac{\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d}{2} \equiv f_\pi\,\partial_\mu\pi_3\,,$$

$$J_{5\,\mu}^{(ud)} \equiv \frac{\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d}{2} \equiv f_\pi\,\partial_\mu\eta_{ud}\,,$$

$$J_{5\,\mu}^{(s)} \equiv \frac{\bar{s}\gamma_\mu\gamma_5 s}{\sqrt{2}} \equiv f_\pi\,\partial_\mu\eta_s\,.$$

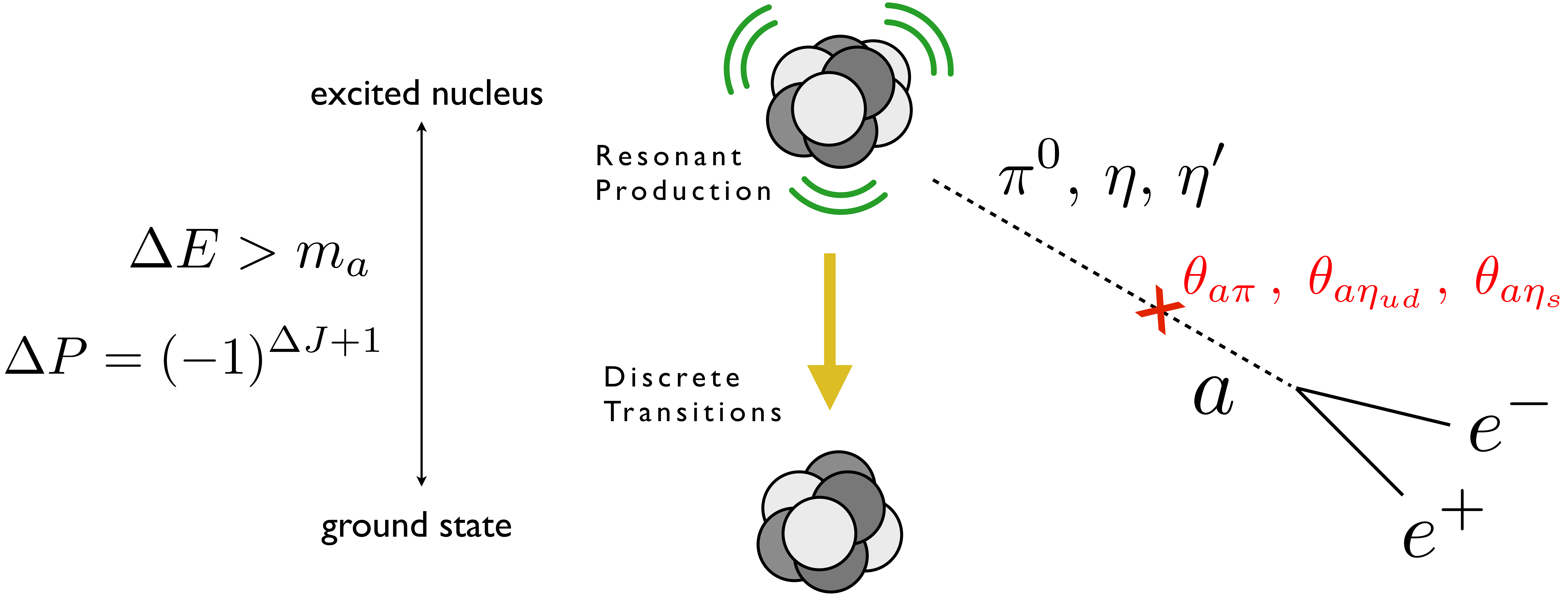
The d.o.f.'s $a,\ \pi_3,\ \eta_{ud},\ \eta_s$ mix amongst themselves to yield the mass eigenstates $a_{\rm phys},\ \pi^0,\ \eta,\ \eta'$

Explaining the the anomalous excesses in de-excitations of ^{8}Be and ^{4}He nuclei via *piophobic QCD axion* emission

From our adopted parametrization, the axion nuclear couplings are: $a\,\overline{N}\,i\gamma^5\left(g_{aNN}^{(0)} + g_{aNN}^{(1)}\tau^3\right)N$

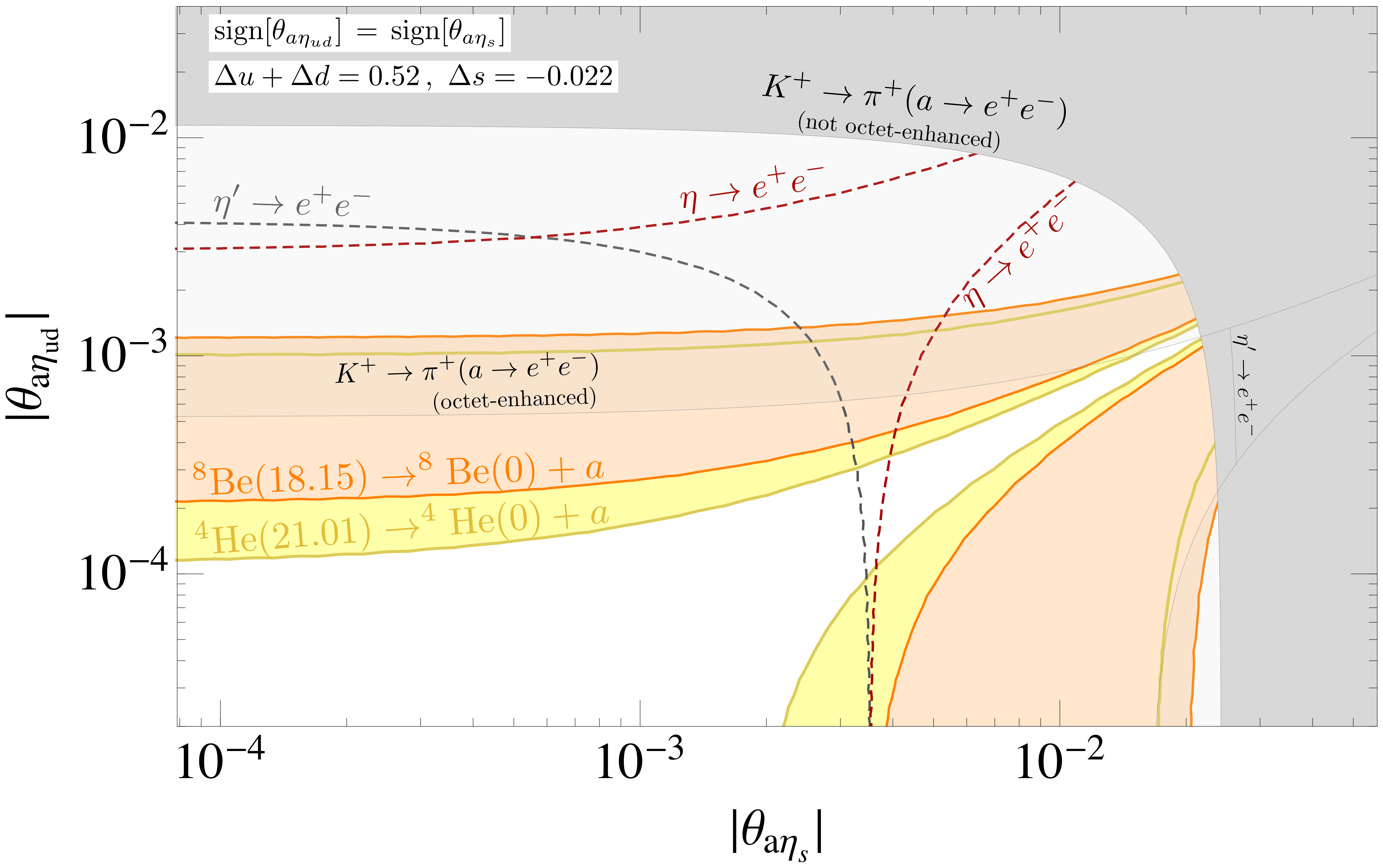
with

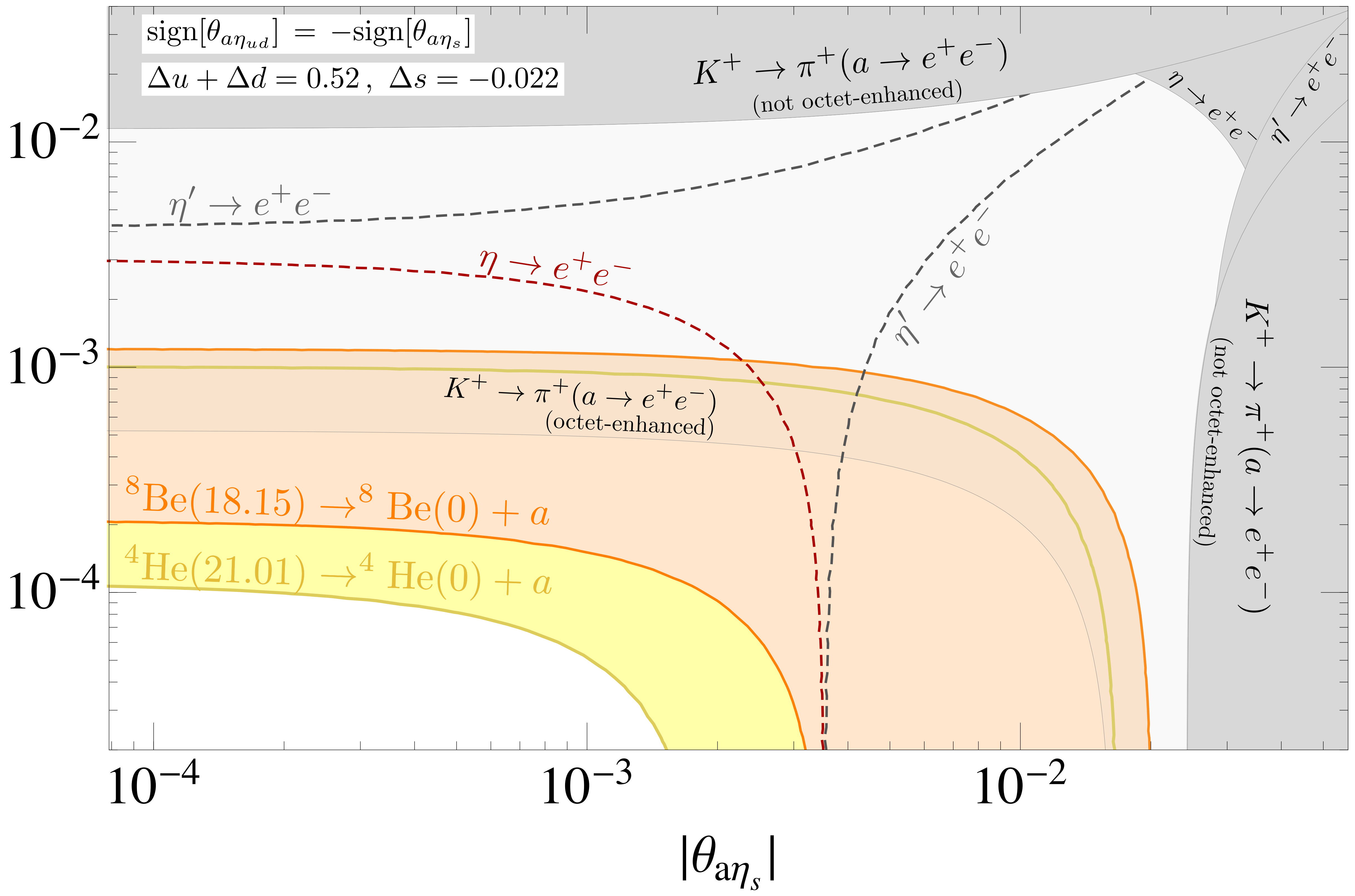
$$\begin{cases} \text{isovector:} & g_{aNN}^{(1)} = \theta_{a\pi}\, g_{\pi NN} = \theta_{a\pi}\,(\Delta u - \Delta d)\,\dfrac{m_N}{f_\pi}\,, \\ \text{isoscalar:} & g_{aNN}^{(0)} = \left(\theta_{a\eta_{ud}}(\Delta u + \Delta d) + \sqrt{2}\,\theta_{a\eta_s}\Delta s\right)\dfrac{m_N}{f_\pi} \end{cases}$$



adapted from F. Tanedo

We use the axion emission rates in nuclear transitions estimated by Donnelly *et al.*, PRD **18** (1978)





Bands include uncertainties in nuclear matrix elements, nuclear structure parameters, and in $\theta_{a\pi}$ KTeV fit

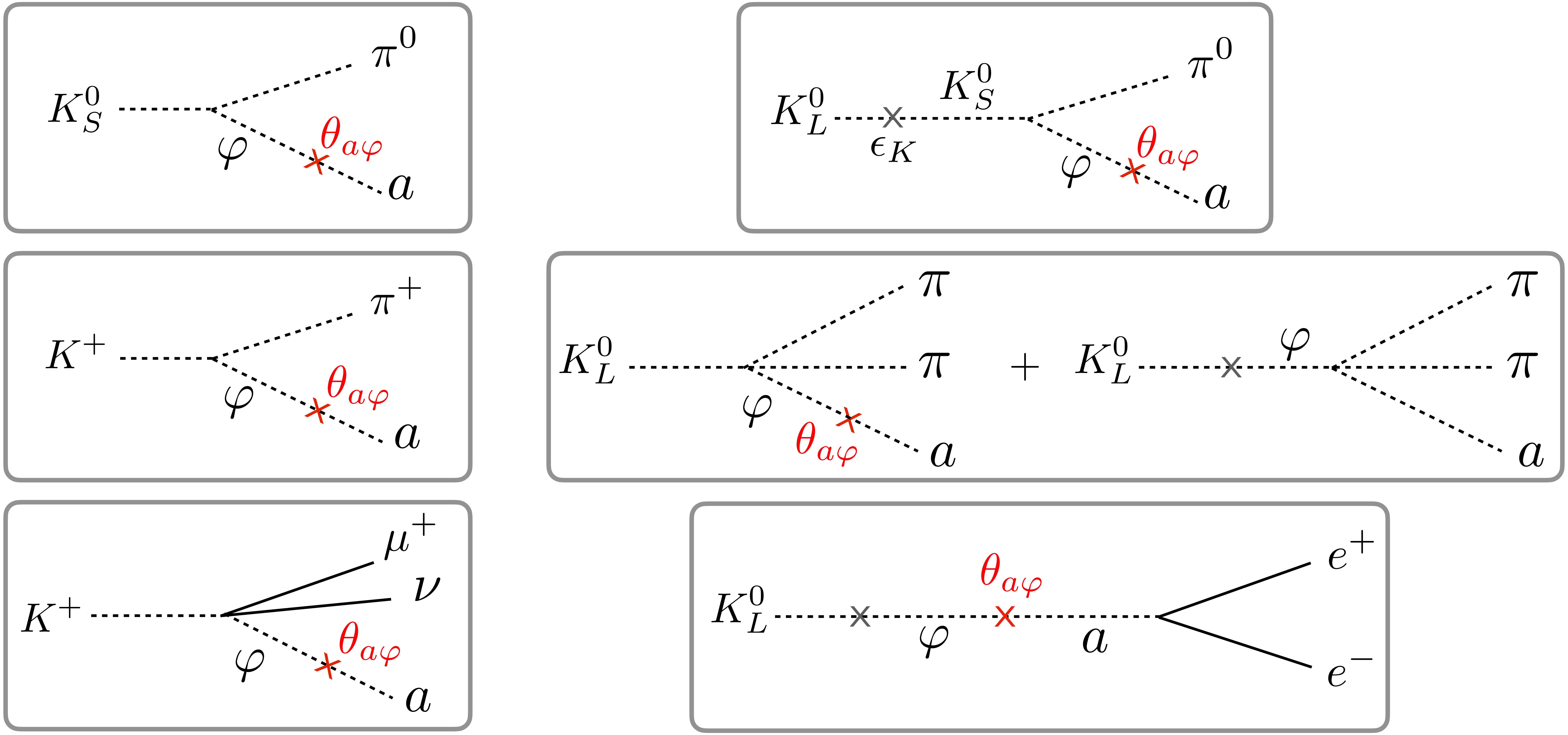
^{8}Be and ^{4}He excesses are compatible with the *same* range of isoscalar axion couplings

This QCD axion hypothesis also explains the absence of excesses in *electric* ($P = (-1)^\ell$) and (predominantly) *isovector* magnetic transitions

Signals of the *piophobic QCD axion*
in rare decays of charged and neutral Kaons

Axionic Kaon decays follow from SM amplitudes weighted by axion-meson mixing angles

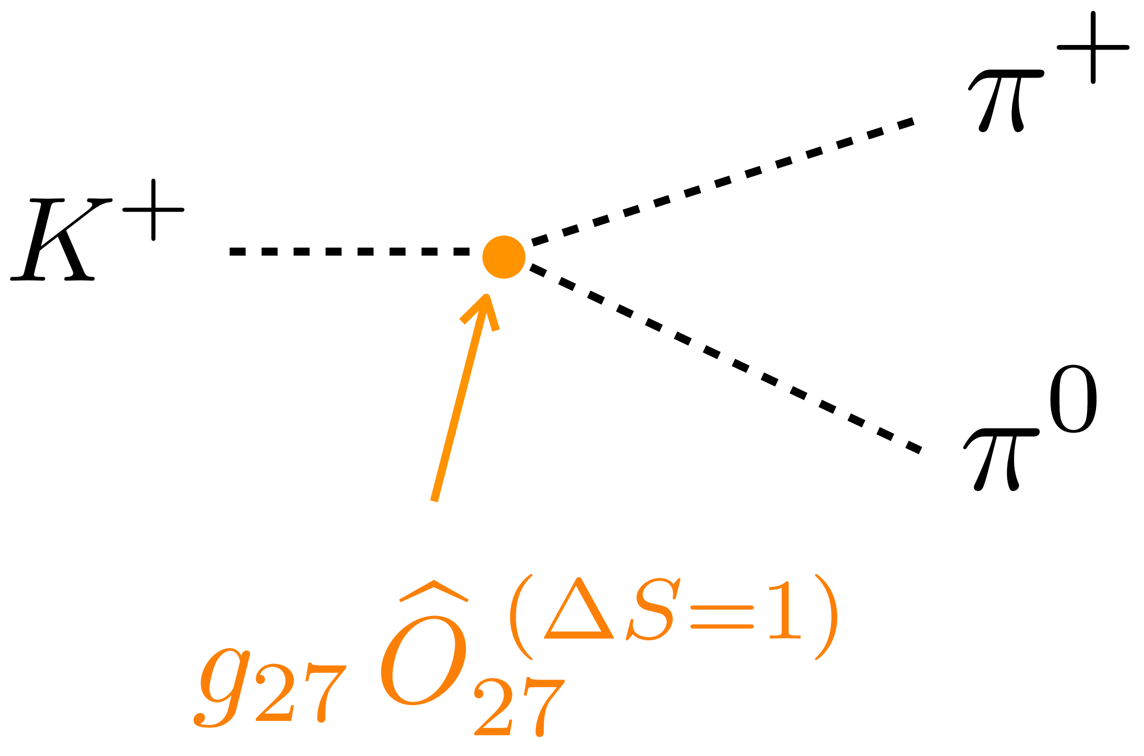
$$\varphi \equiv \pi^0, \ \eta_{ud}\,, \ \eta_s$$

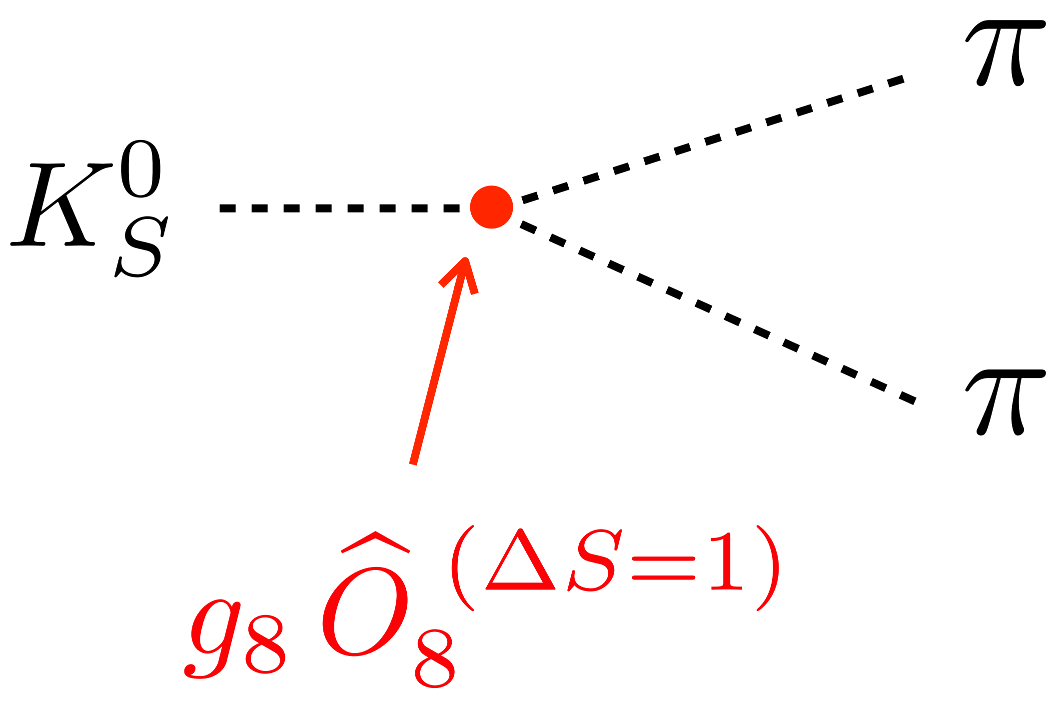


Subtlety: *octet enhancement*

In the SM, there are large disparities between the hadronic widths of different Kaon states,

e.g., $\Gamma_{K^+} \sim \mathcal{O}(10^{-8})\,\text{eV}$ $\Gamma_{K_S} \sim \mathcal{O}(10^{-5})\,\text{eV}$





In χPT, these disparities are parametrized as: $\dfrac{|g_8|}{|g_{27}|} \simeq 31.2$

This effect will similarly appear in axionic Kaon decays:
some amplitudes will be *octet enhanced*

Additional ambiguity:

Octet enhancement can in principle be implemented in χPT with two distinct octet operators,

$$O_8^{(\Delta S=1)}\Big|_{\mathcal{O}(p^2)} = g_8\, f_\pi^2\, \mathrm{Tr}\big(\lambda_{ds}\,\partial_\mu U\,\partial^\mu U^\dagger\big) + \mathrm{h.c.}$$

standard implementation

or

$$O_8'^{(\Delta S=1)}\Big|_{\mathcal{O}(p^4)} = -g_8'\,\frac{f_\pi^2}{\Lambda^2}\,\mathrm{Tr}\big(\lambda_{ds}\,2B_0 M_q^\dagger(a)\,U^\dagger\big)\,\mathrm{Tr}\big(\partial_\mu U\,\partial^\mu U^\dagger\big) + \mathrm{h.c.}$$

has also been considered

Gerard & Weyers, PLB **503** (2001)

Crewther & Tunstall, PRD **91** (2015)

Enhancement of either g_8 or g_8' provides equally good phenomenological fit to data

However, these two different possibilities yield different predictions for axio-hadronic Kaon decay rates

Axionic Kaon decay predictions via enhancement of g_8 (standard implementation)

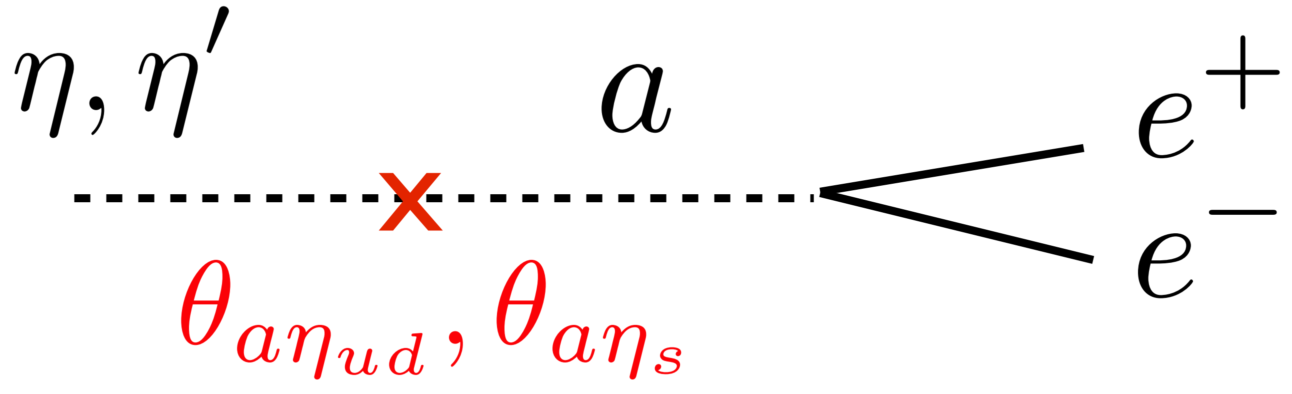
Dashed lines show the branching ratio benchmark of 10^{-8} for *all* decay channels

Axionic Kaon decay predictions via enhancement of g'_8 (alternative implementation)

Dashed lines show the branching ratio benchmark of 10^{-8} for *all* decay channels

Signals of the *piophobic QCD axion*
in rare eta and eta prime decays

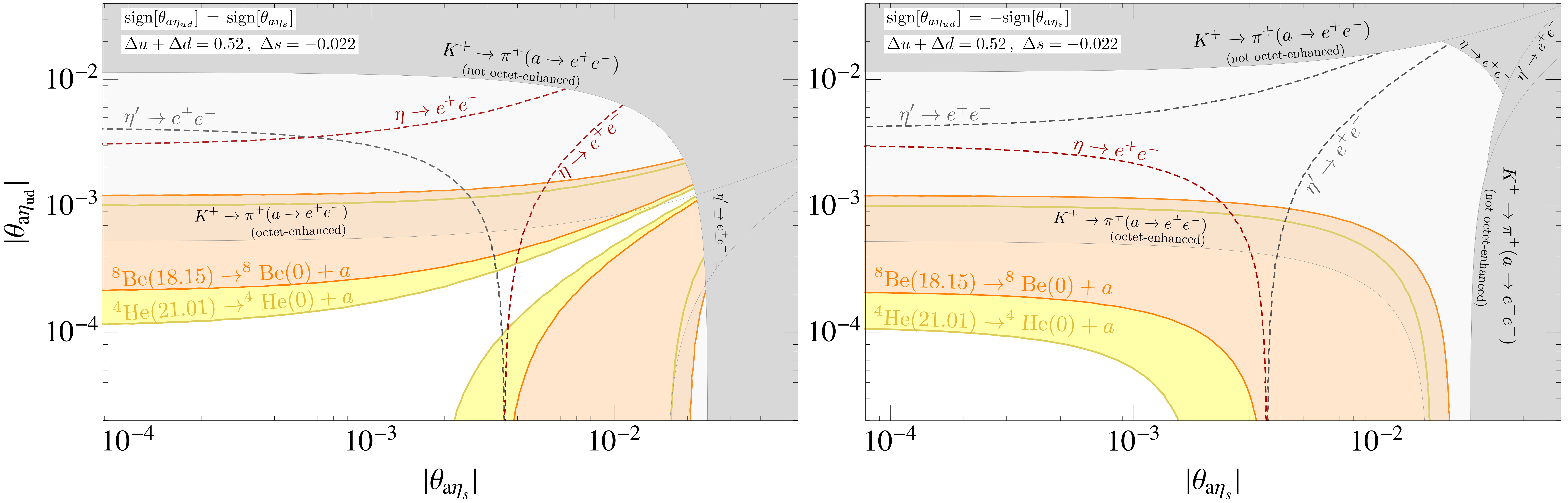
Di-electronic decay widths of η, η' (which have not yet been observed) can be substantially modified by a-η and a-η' mixing



$$\mathrm{Br}(\eta \to e^+e^-)_{\mathrm{exp}} < 7 \times 10^{-7}$$
$$\mathrm{Br}(\eta \to e^+e^-)_{\mathrm{SM}} \approx (4.6 - 5.4) \times 10^{-9}$$

$$\mathrm{Br}(\eta' \to e^+e^-)_{\mathrm{exp}} < 0.56 \times 10^{-8}$$
$$\mathrm{Br}(\eta' \to e^+e^-)_{\mathrm{SM}} \approx (1 - 2) \times 10^{-10}$$

Constraints on $\theta_{a\eta_{ud}}$, $\theta_{a\eta_s}$ from current upper bounds on $\mathrm{Br}(\eta^{(\prime)} \to e^+e^-)$ are very weak, but future experimental sensitivity makes these important channels for discovery/exclusion

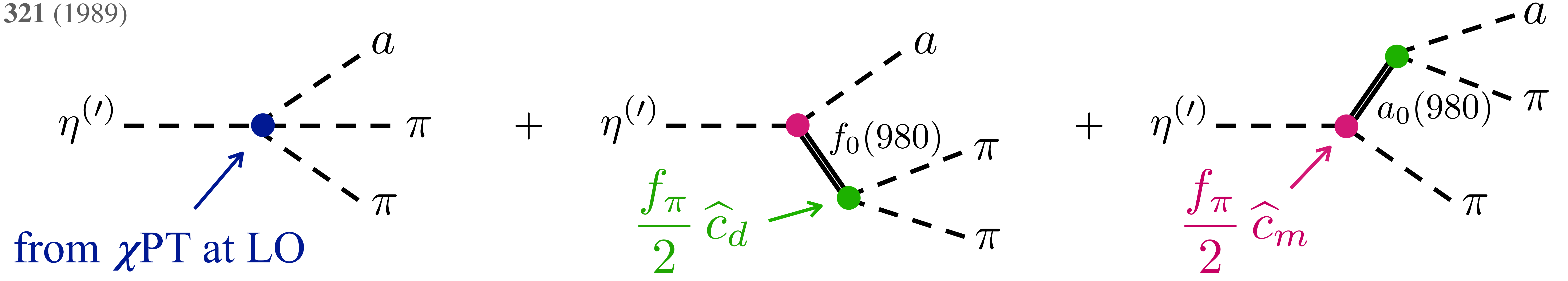


Dashed lines assume that axionic and SM contributions to e^+e^- decay amplitude are comparable

Axio-hadronic decays of η, η'

Estimated in the framework of *Resonance Chiral Theory* (RχT), a “UV completion” of χPT which incorporates the low-lying QCD resonances and extends the principle of vector meson dominance

Ecker *et al.*, NPB **321** (1989)

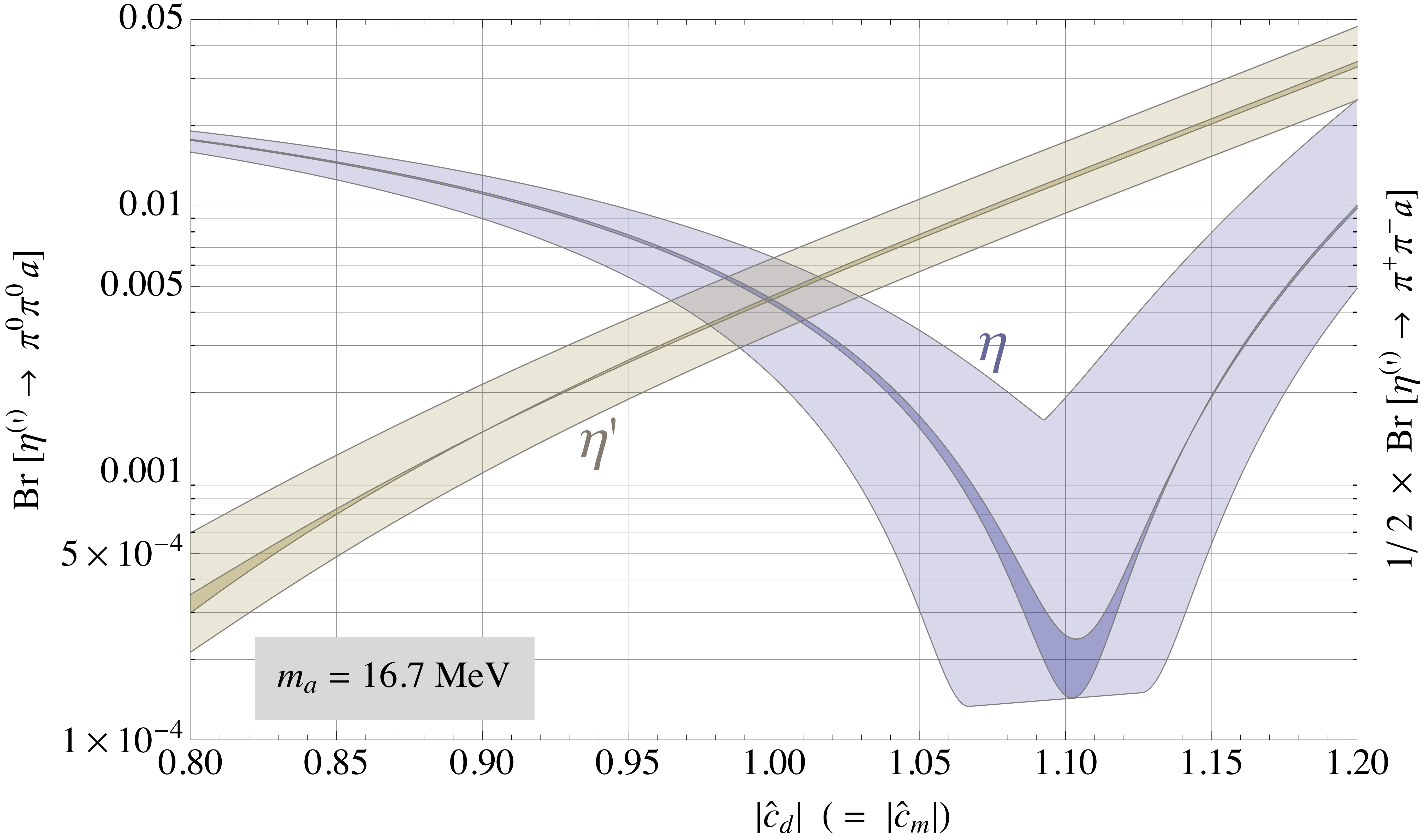


In the large N_c limit, the RχT couplings are expected to satisfy:

$$|\widehat{c}_d| = |\widehat{c}_m| = 1 \quad \text{and} \quad \widehat{c}_d\,\widehat{c}_m > 0$$

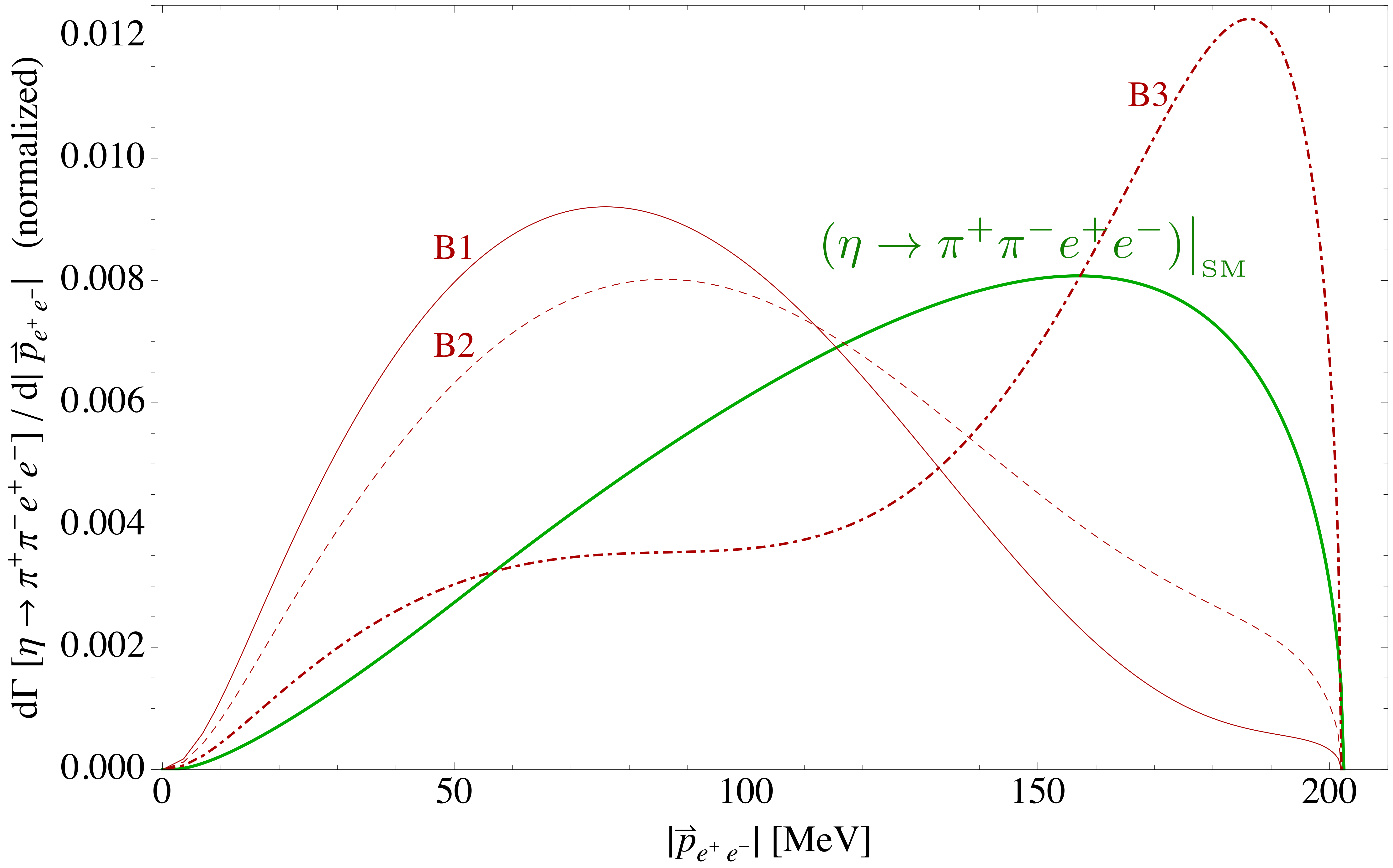
Pich, hep-ph/0205030

Large variation in the estimated branching ratios due to destructive interference between quartic and resonance exchange amplitudes



Axio-hadronic decays of η, η'

Large variation in predictions for Dalitz phase space as well



	m_{a_0} [MeV]	Γ_{a_0} [MeV]	m_{f_0} [MeV]	Γ_{f_0} [MeV]	$\lvert\widehat{c}_d\rvert = \lvert\widehat{c}_m\rvert$	$\text{Br}(\eta \to \pi^+\pi^- a)$
B1	980	40	980	200	1.125	0.96×10^{-3}
B2	980	50	980	100	1.125	1.1×10^{-3}
B3	1000	50	1000	100	1.125	0.49×10^{-3}

Summary

The *piophobic QCD axion*, with mass of ~17 MeV, offers a highly-motivated, compatible explanation for the ^{8}Be, ^{4}He, and KTeV anomalies

It also naturally explains the absence of excesses in electric and isovector magnetic transitions of nuclear de-excitations and radiative capture reactions

Its predicts a variety of other testable signals in searches for visibly decaying dark photons, and in rare meson decays that could be searched for in future Kaon and Eta factories