QCD axion interpretation of the X17 anomalies

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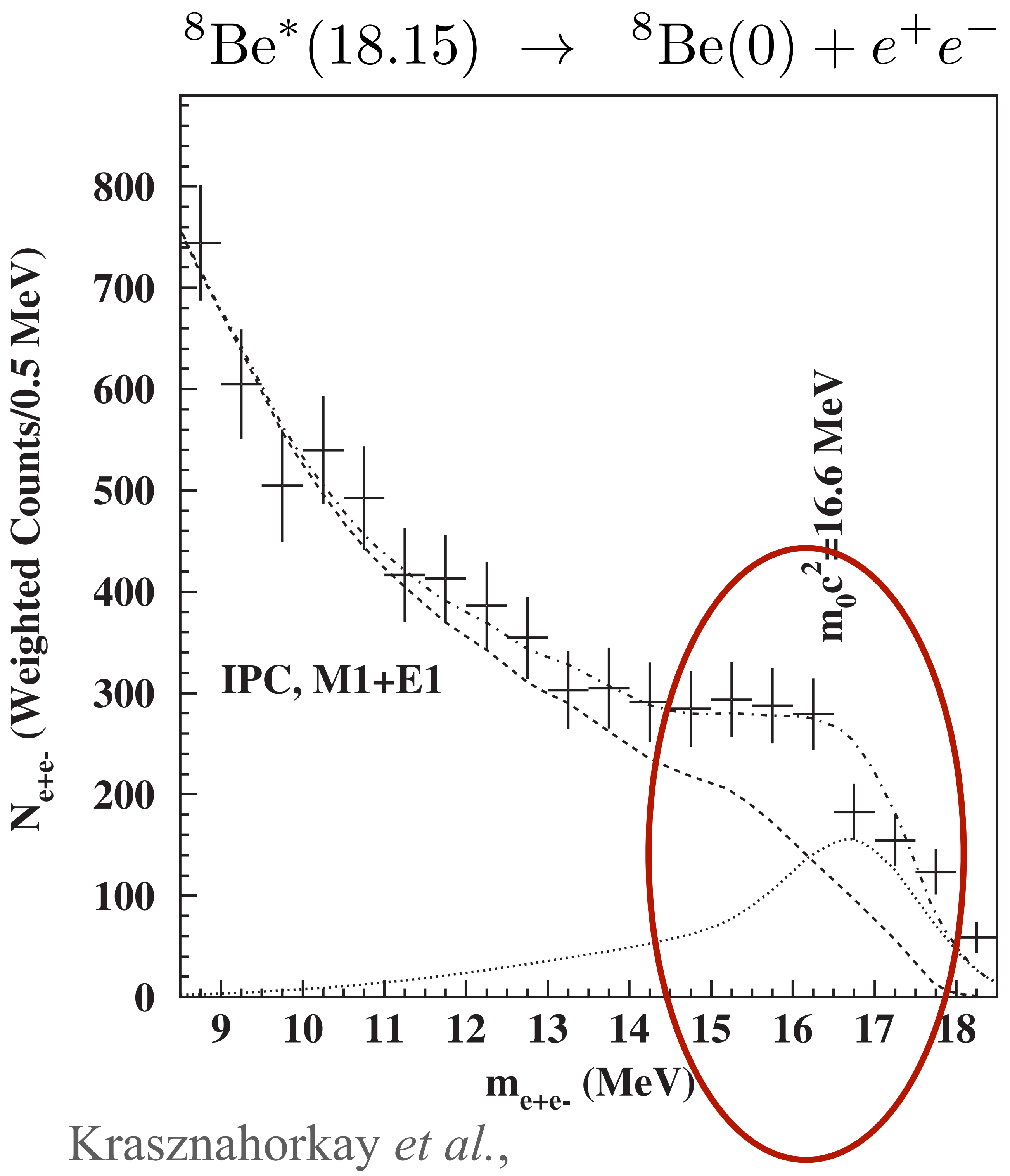
(LANL)

Based on: arXiv:1710.03764 (w/ Neal Weiner),
arXiv:2009.05578

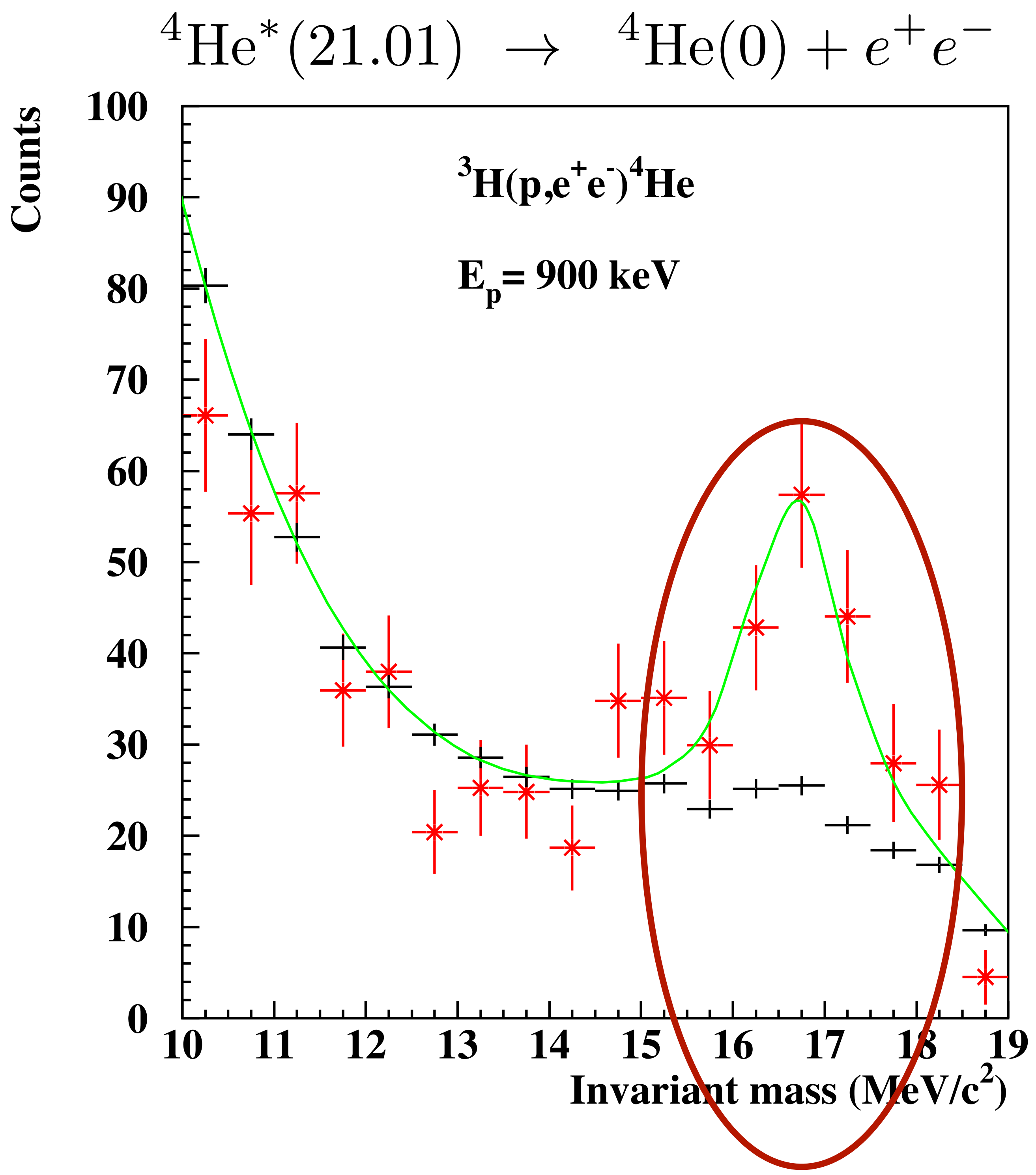
Shedding Light on X17 Workshop
September 6th - 8th , 2021

LA-UR-21-28812

If it is confirmed that correct interpretation of the ATOMKI ^{8}Be and ^{4}He anomalies is indeed a new “X17” particle,



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



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

many of us will be having an “Isaac Rabi’s existential moment”:

“WHO ORDERED THAT?”

While most X17 candidates seem apparently *ad hoc*,
one possible explanation is extremely well-motivated:

X17 = the QCD axion

Q: "WHO ORDERED THAT?"

A: QCD did.

Q: For what purpose?

A: To solve the strong CP problem.

The Strong CP Problem

CP is not a good symmetry of the Standard Model
(it is maximally violated in the weak sector)

Yet, the strong interactions are CP-symmetric to an incredible accuracy!

expected “natural” value of neutron EDM: $|d_n| \sim \mathcal{O}(10^{-16})\ \mathrm{e} \cdot \mathrm{cm}$

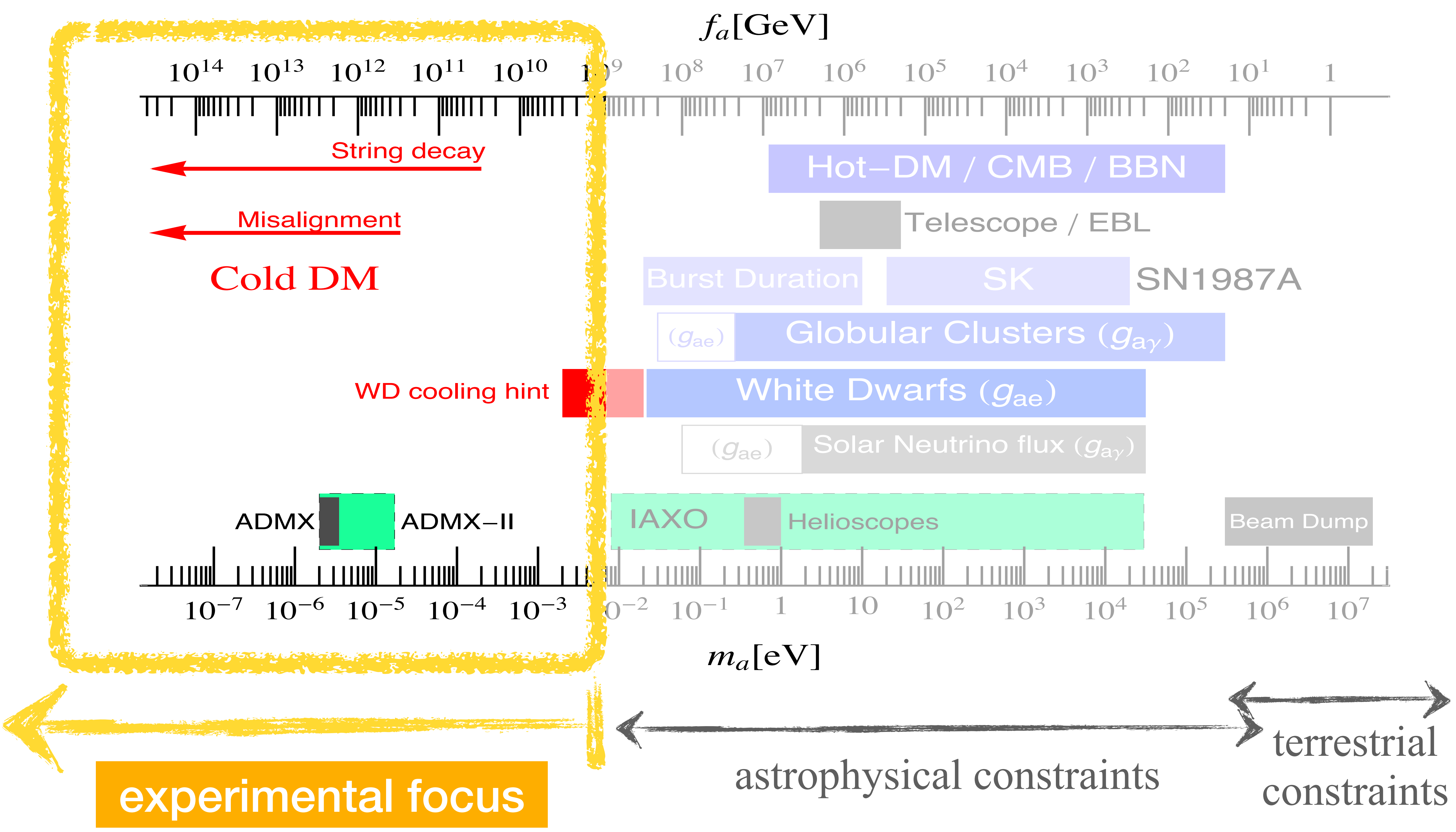
current experimental bound on neutron EDM: $|d_n| < 3 \times 10^{-26}\ \mathrm{e} \cdot \mathrm{cm}$

This is considered a strong indication of a *dynamical mechanism* relaxing the strong CP phase to zero

The most popular such mechanism is the one proposed by *Peccei and Quinn*,
whose smoking-gun prediction is a new light pseudoscalar,

the QCD axion

But today the consensus is that the QCD axion, if it exists, should be *ultralight* and *cosmologically long-lived* ⇒ an attractive **dark matter** candidate!



experimental focus

astrophysical constraints

terrestrial constraints

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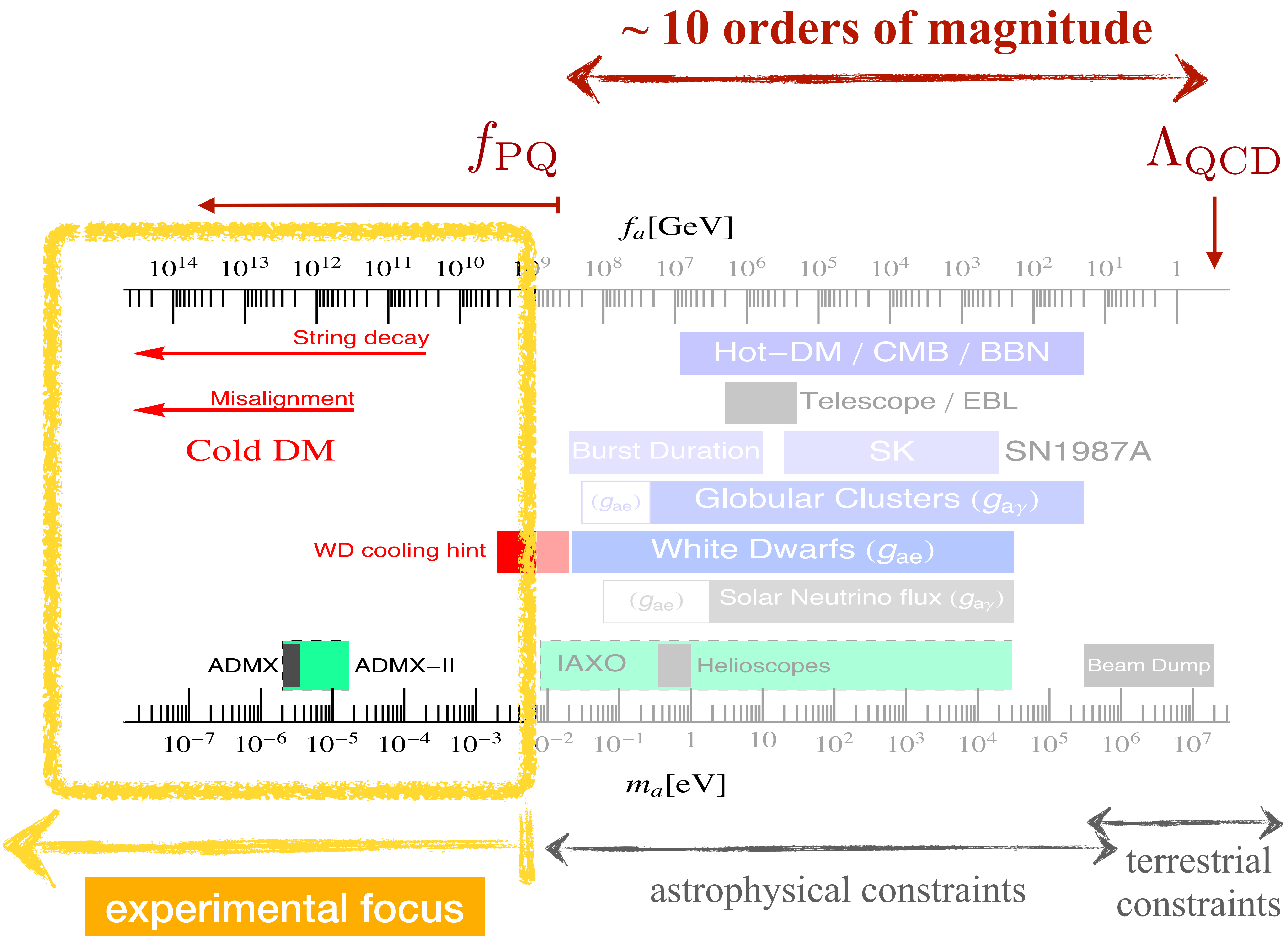

This possibility faces a <u>significant challenge</u>:

The wide separation between the PQ and QCD dynamical scales makes the cancellation of the strong CP phase highly vulnerable to spoiling effects (the "*axion quality problem*").

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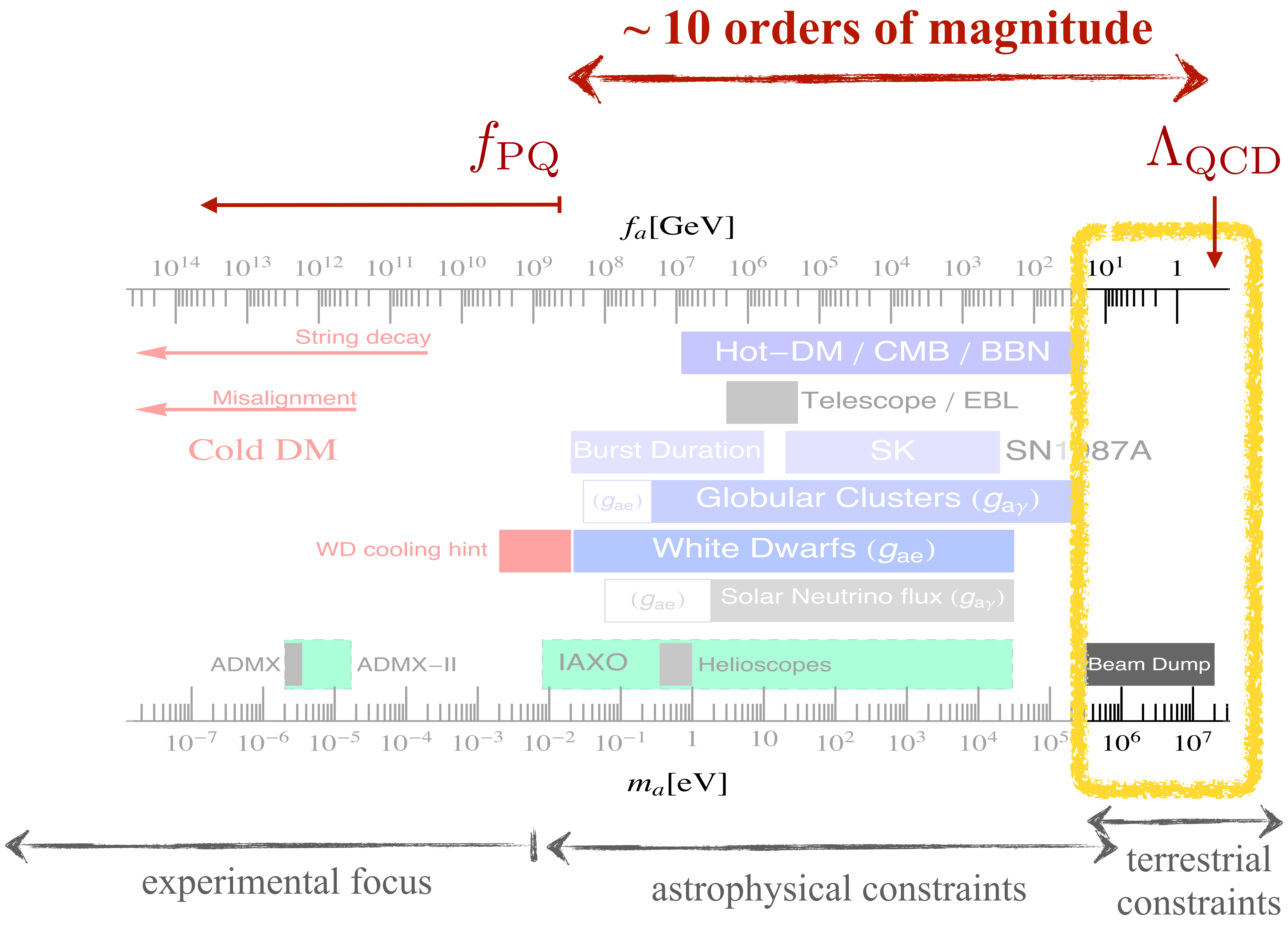

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From this perspective, it is worth considering implementations of the PQ mechanism *closer to* Λ_{QCD}.

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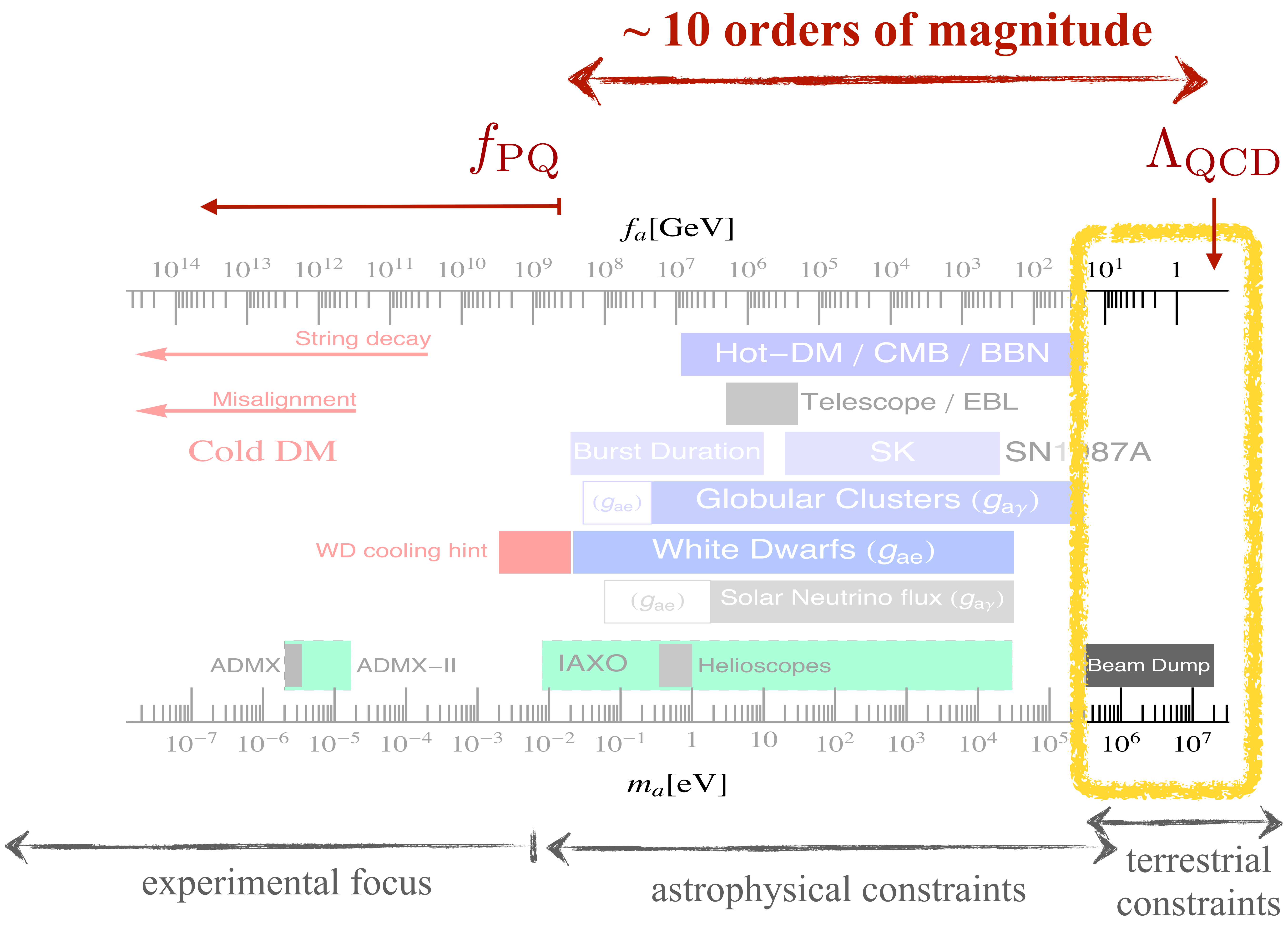

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<u>Consequence</u>: a heavier, less weakly-coupled, and short-lived axion (cannot be dark matter!)

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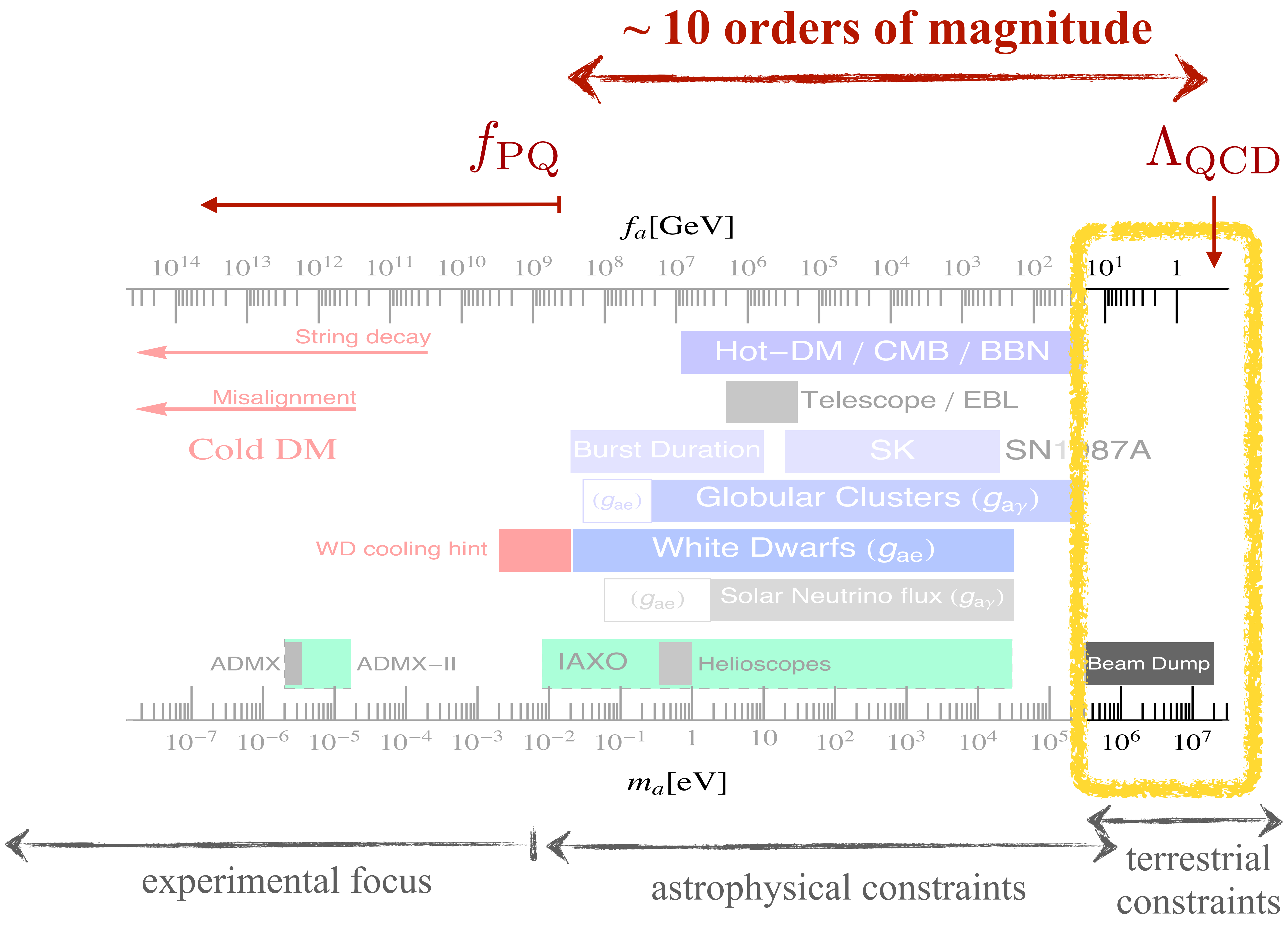

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From this perspective, it is worth considering implementations of the PQ mechanism *closer to* Λ_{QCD}.

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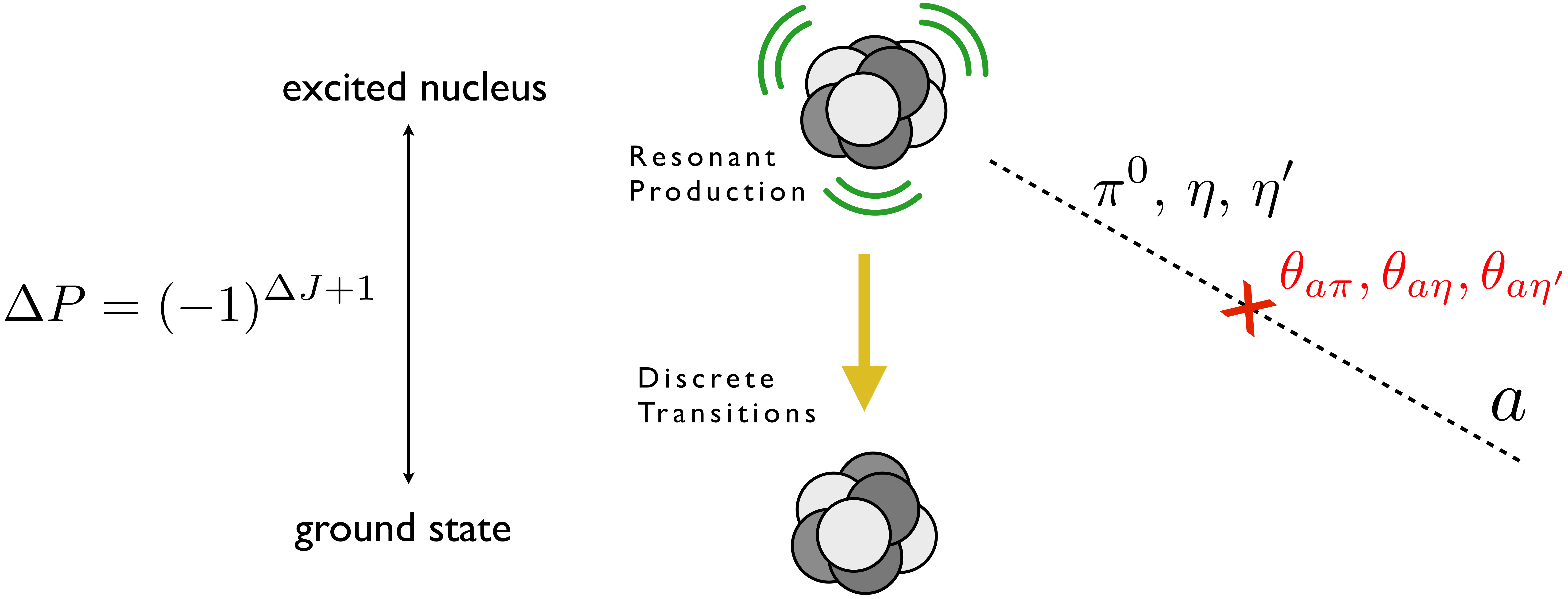
Experimentally viable QCD axion variants in the O(10 MeV) mass range must be:

- piophobic
- electrophilic
- 2nd and 3rd generation-phobic
  (i.e., muon-phobic, charm-phobic, bottom-phobic, etc)

Axion emission in nuclear transitions was one of the first predicted signals of the original axion,

and it was extensively studied and experimentally searched for during the 80s and early 90s…

Emission possible in *magnetic* nuclear transitions with $\Delta E > m_a$



excited nucleus

ground state

$$\Delta P = (-1)^{\Delta J+1}$$

Resonant Production

Discrete Transitions

$\pi^0,\ \eta,\ \eta'$

$\theta_{a\pi},\theta_{a\eta},\theta_{a\eta'}$

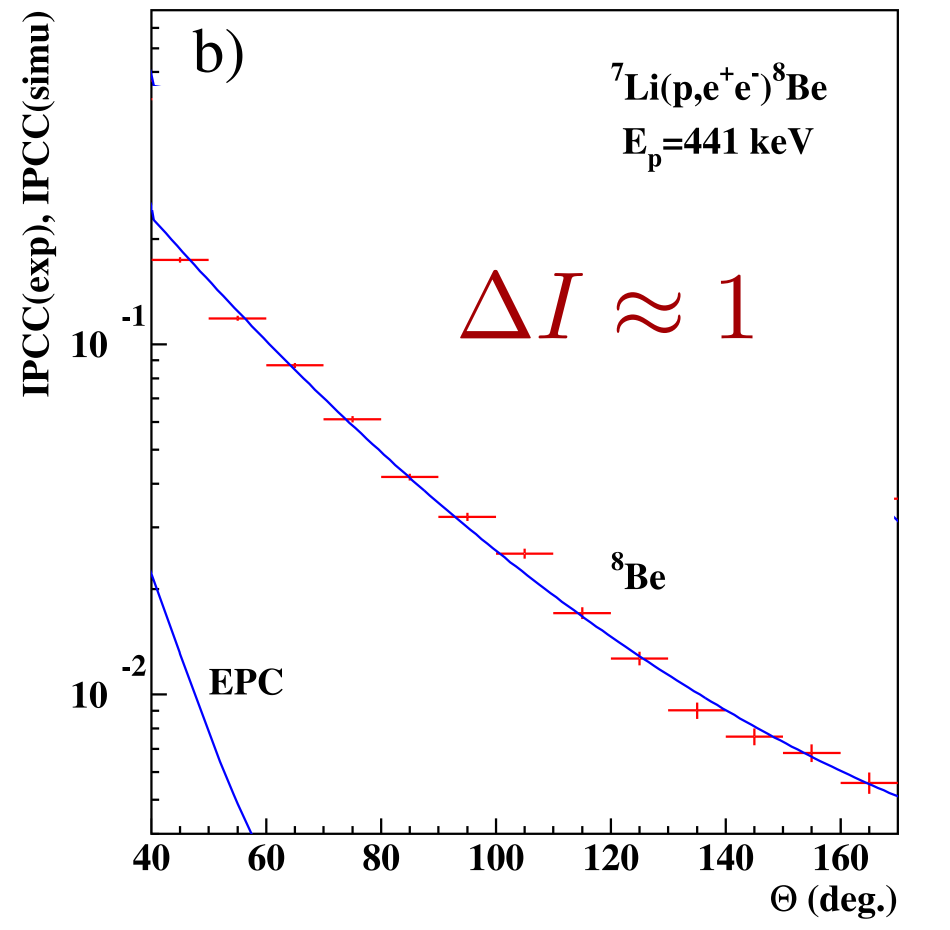
a

adapted from F. Tanedo

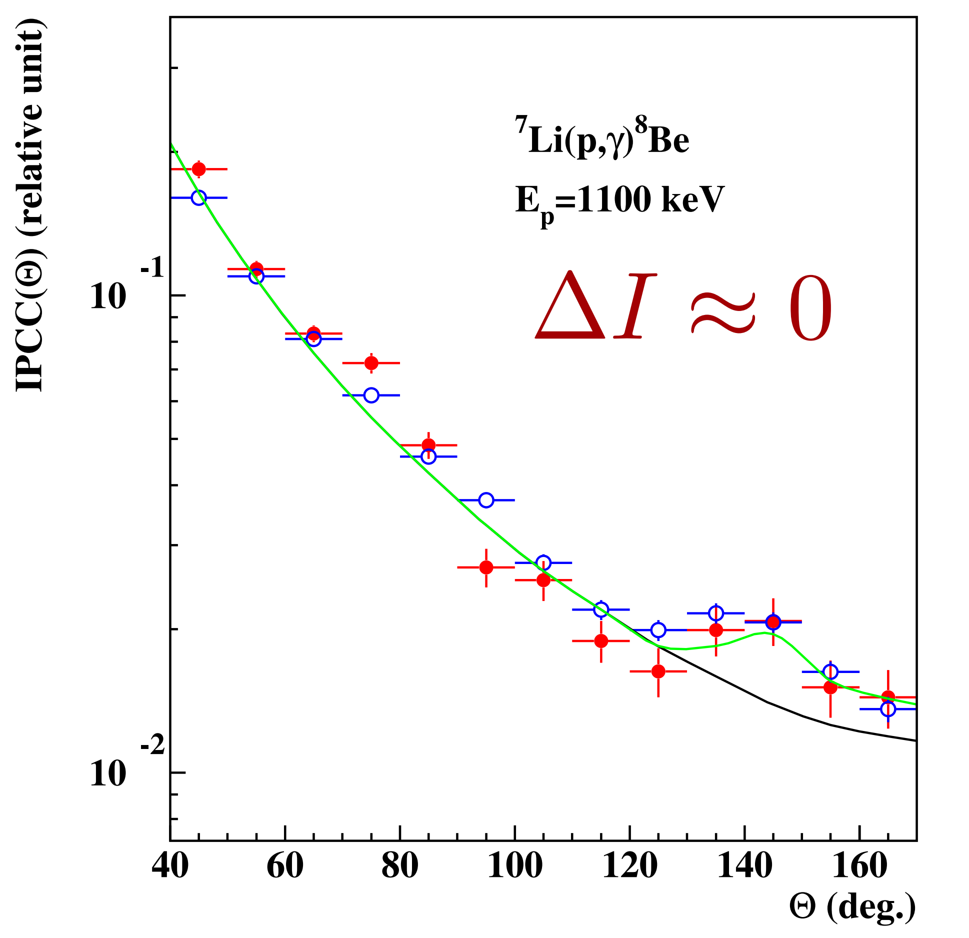
To explain the ^{8}Be and ^{4}He anomalies, the QCD axion must be:

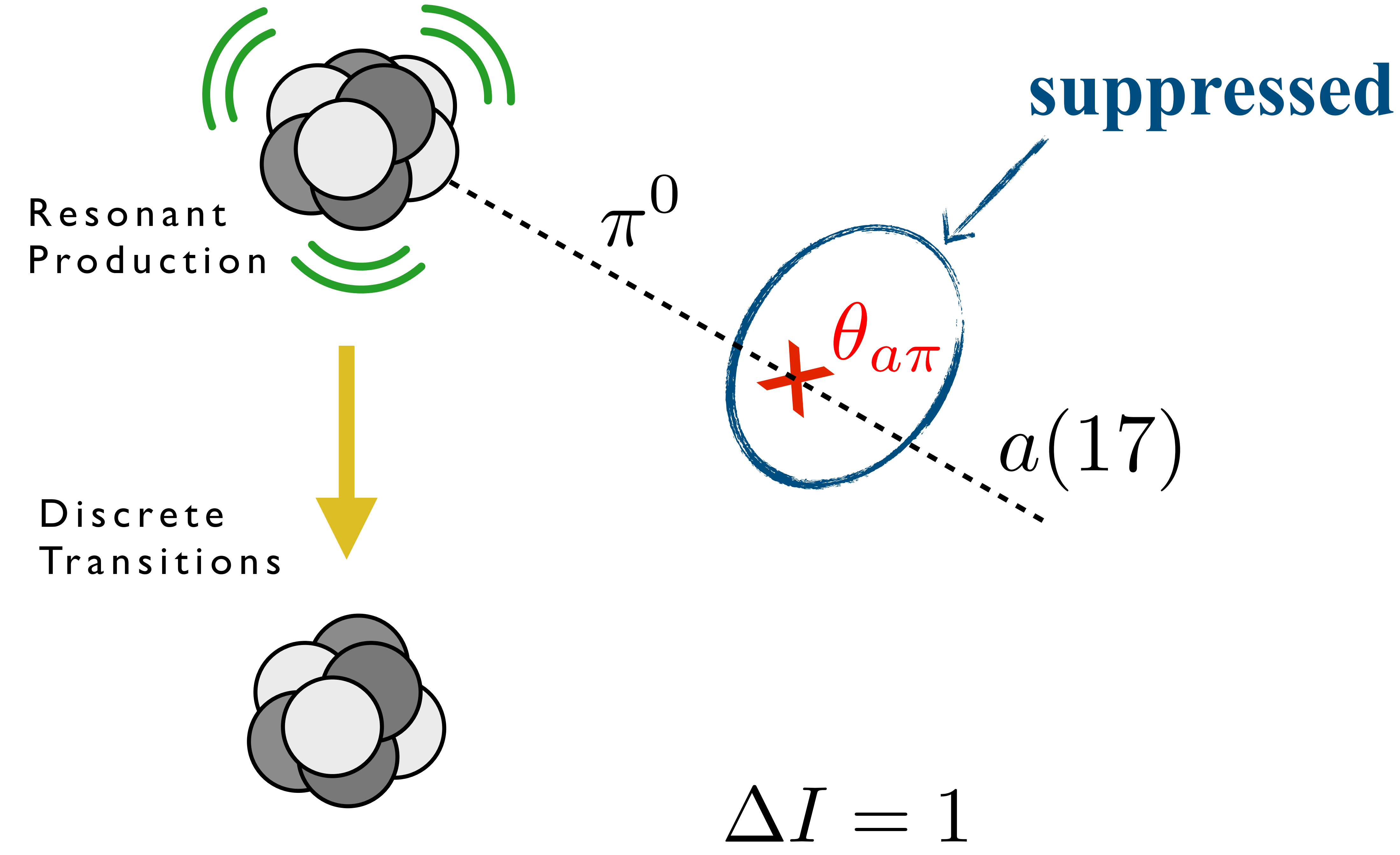
- piophobic (suppressed rate in $\Delta I \approx 1$ transitions)

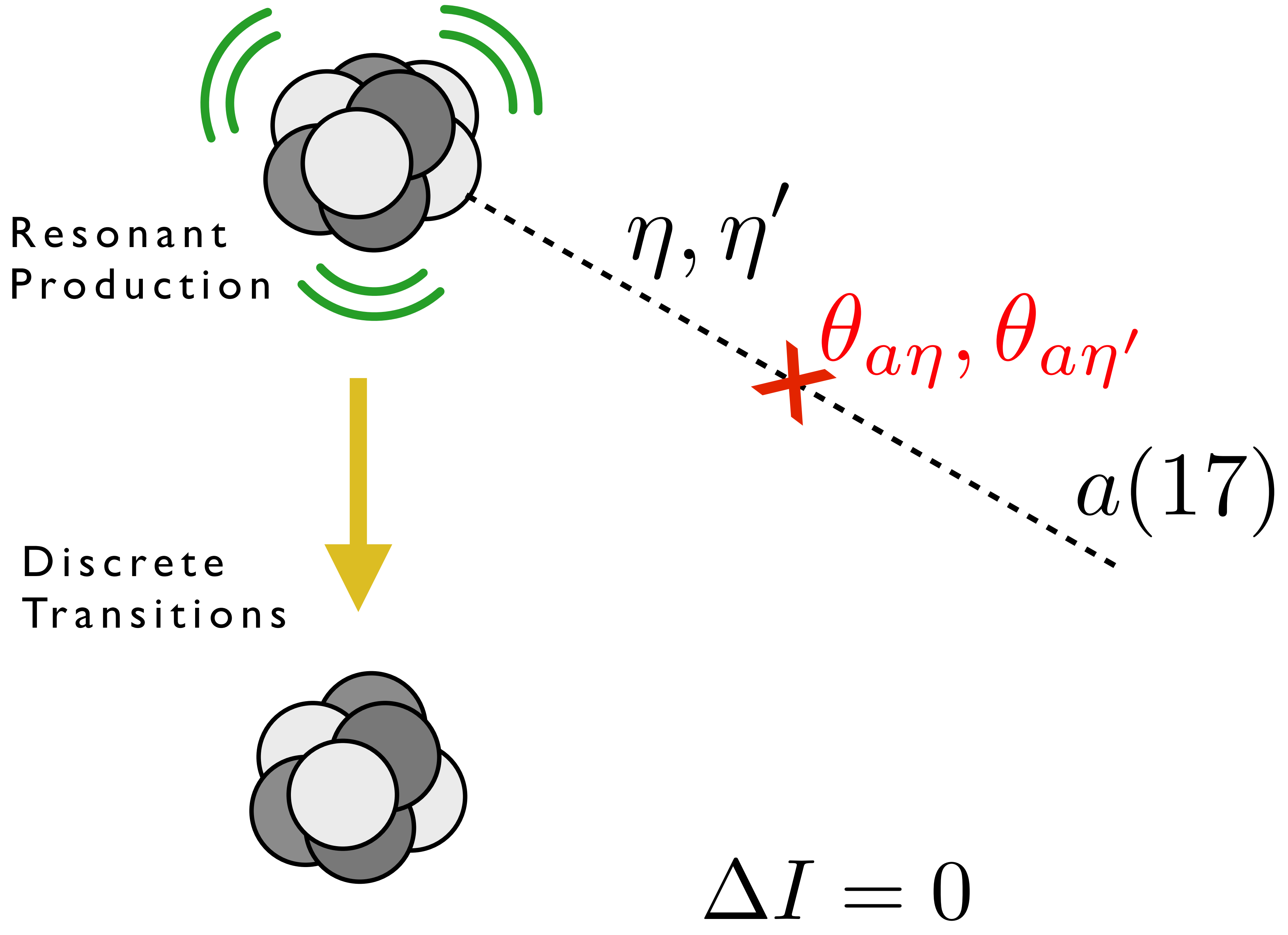
$^{8}\mathrm{Be}^{*}(17.64) \rightarrow {}^{8}\mathrm{Be}(0) + e^{+}e^{-}$



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







To explain the ^{8}Be and ^{4}He anomalies, the QCD axion must be:

- piophobic (suppressed rate in $\Delta I \approx 1$ transitions)
- electrophilic (prompt decay to e^+e^-)

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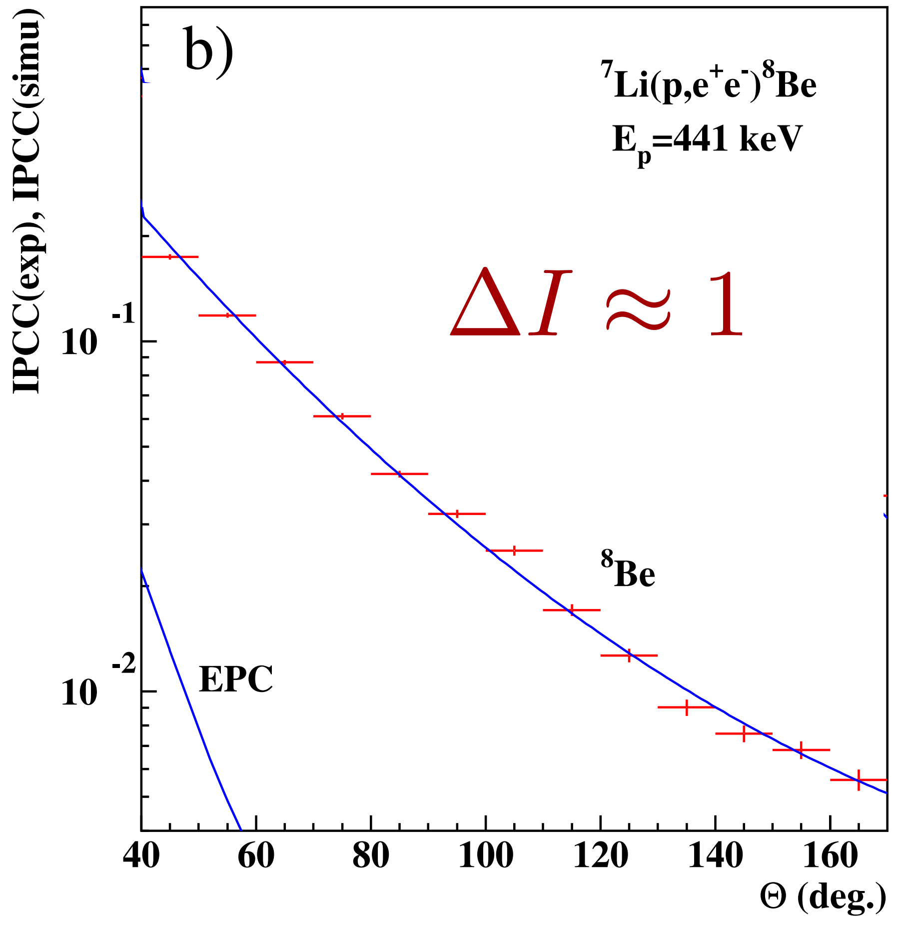

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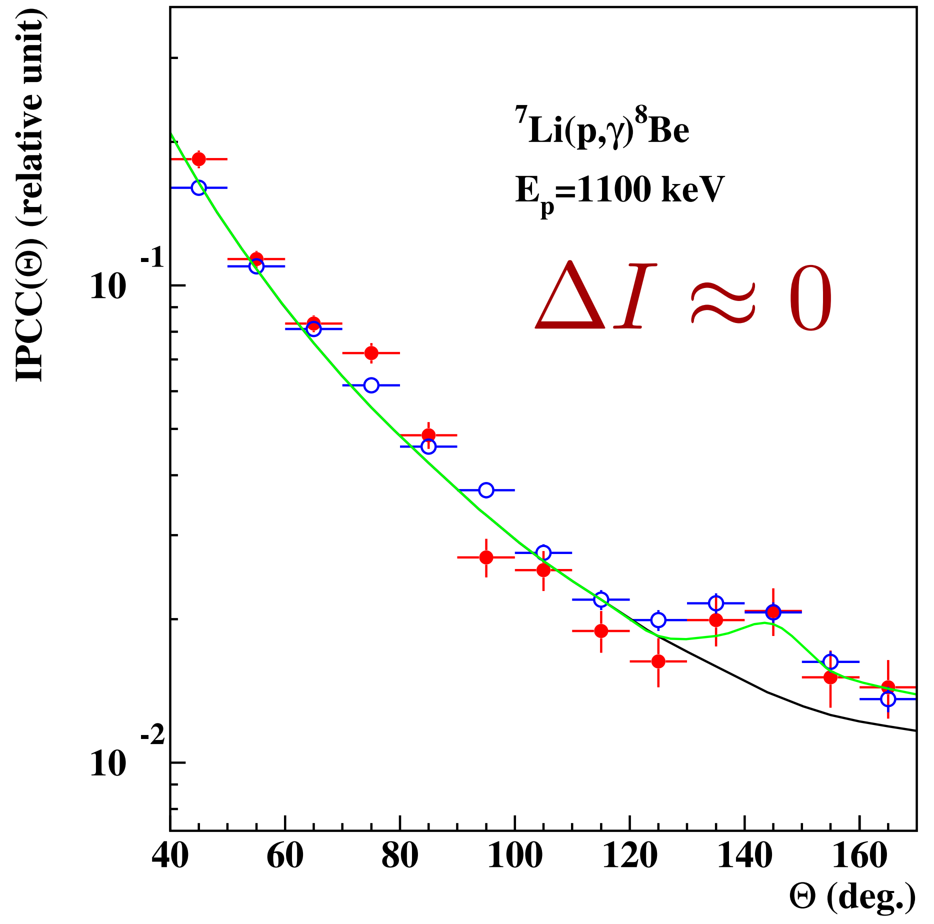

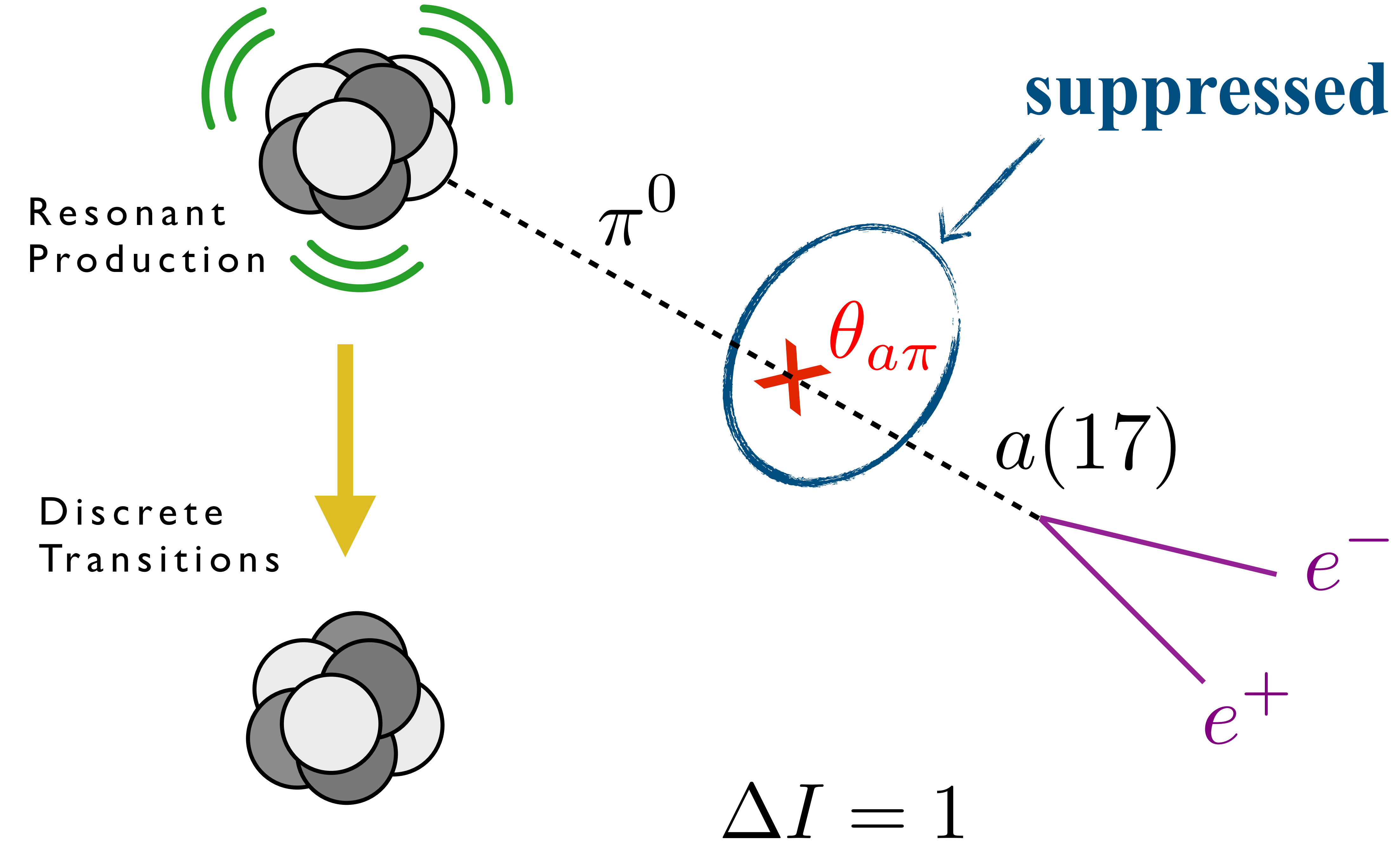

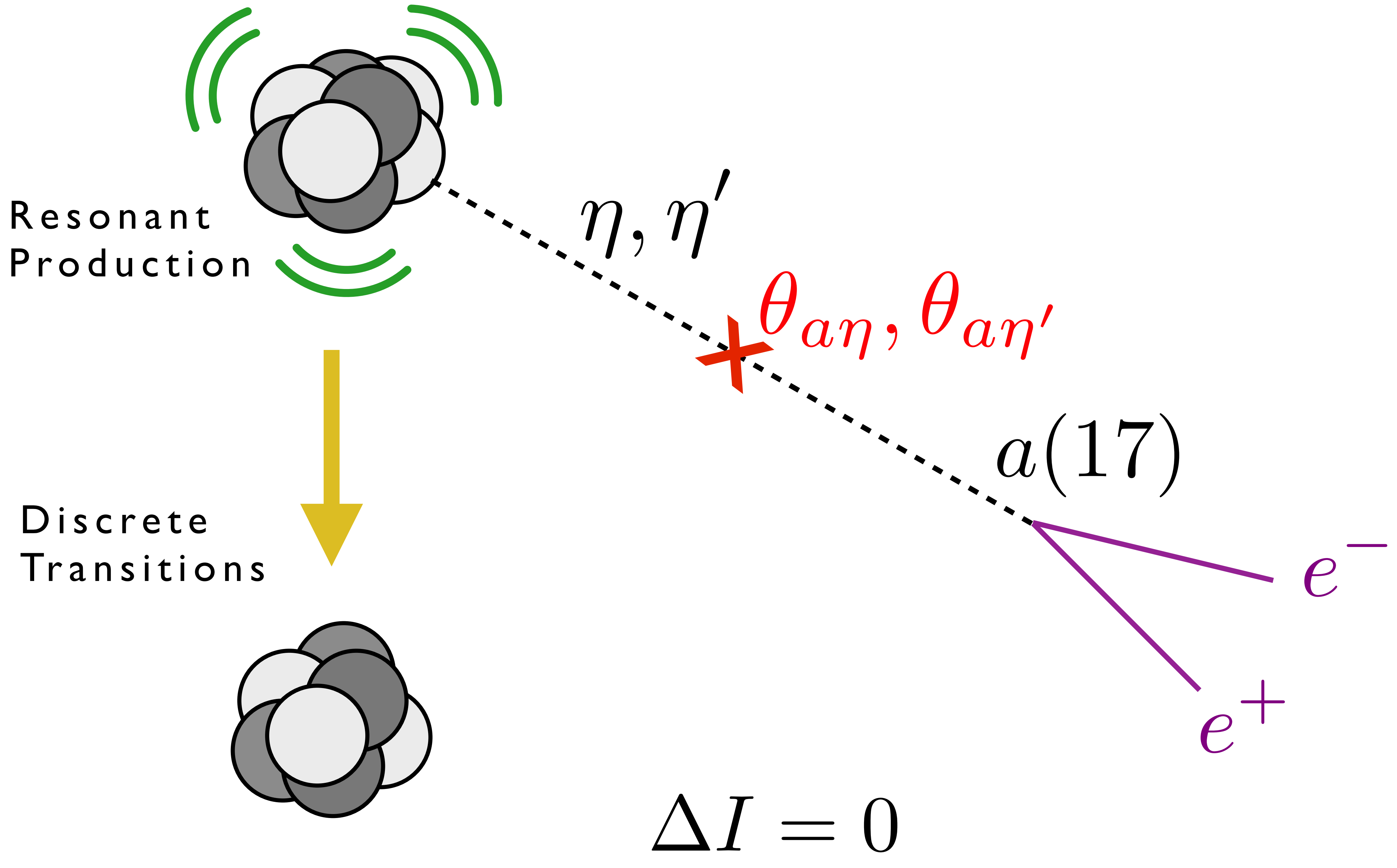

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- piophobic (suppressed rate in $\Delta I \approx 1$ transitions)
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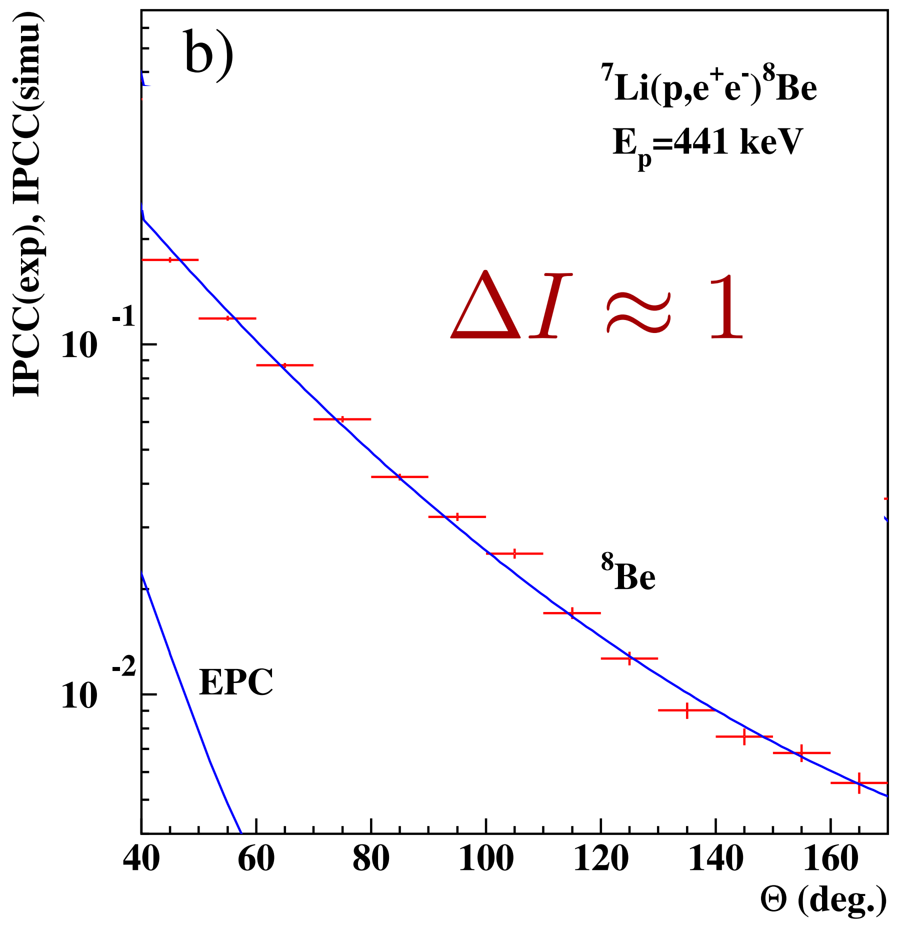
This "*a*(17)" hypothesis naturally explains:

- ^{8}Be anomaly as the M1 transition
  $$^8\mathrm{Be}(18.15) \to {}^8\mathrm{Be}(0) + a(17)$$
- Piophobia implies a suppressed signal in the $\Delta I \approx 1$ transition
  $$^8\mathrm{Be}(17.64) \to {}^8\mathrm{Be}(0) + e^+e^-$$
- ^{4}He anomaly as the M0 ($0^- \to 0^+$) transition
  $$^4\mathrm{He}(21.01) \to {}^4\mathrm{He}(0) + a(17)$$
- The absence of any signal in nuclear transitions/ capture reactions with *electric multipolarity*

$^8\mathrm{Be}^*(17.64) \to {}^8\mathrm{Be}(0) + e^+e^-$



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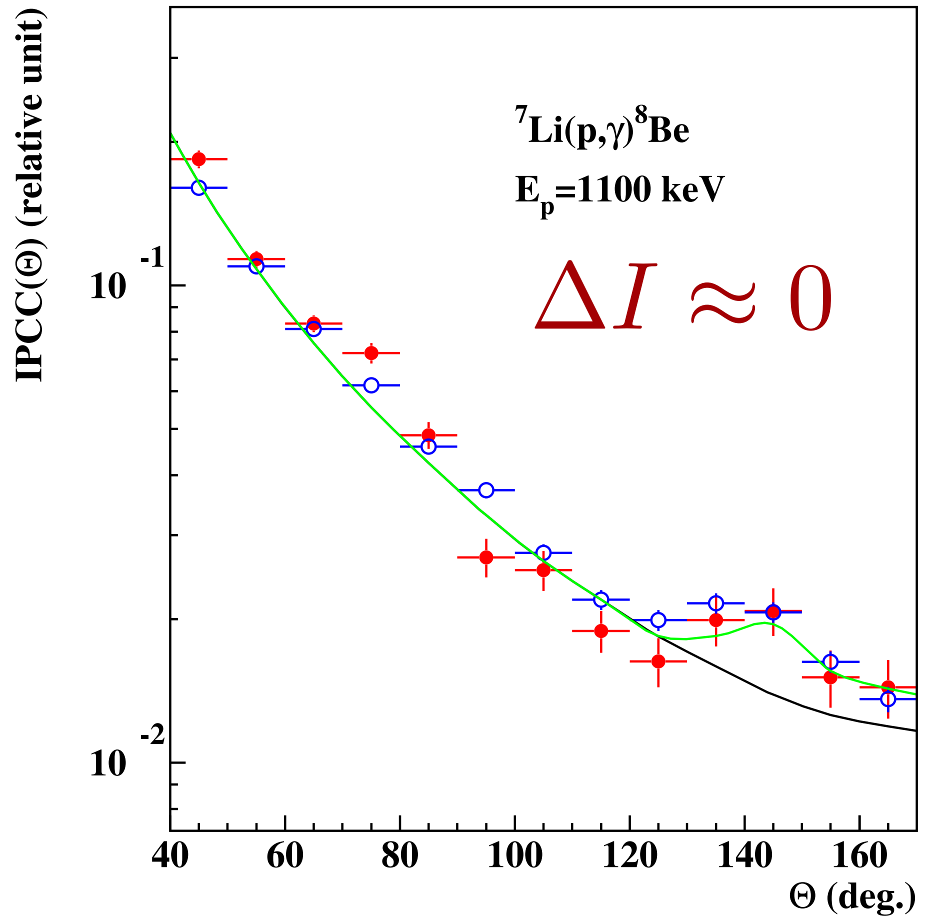
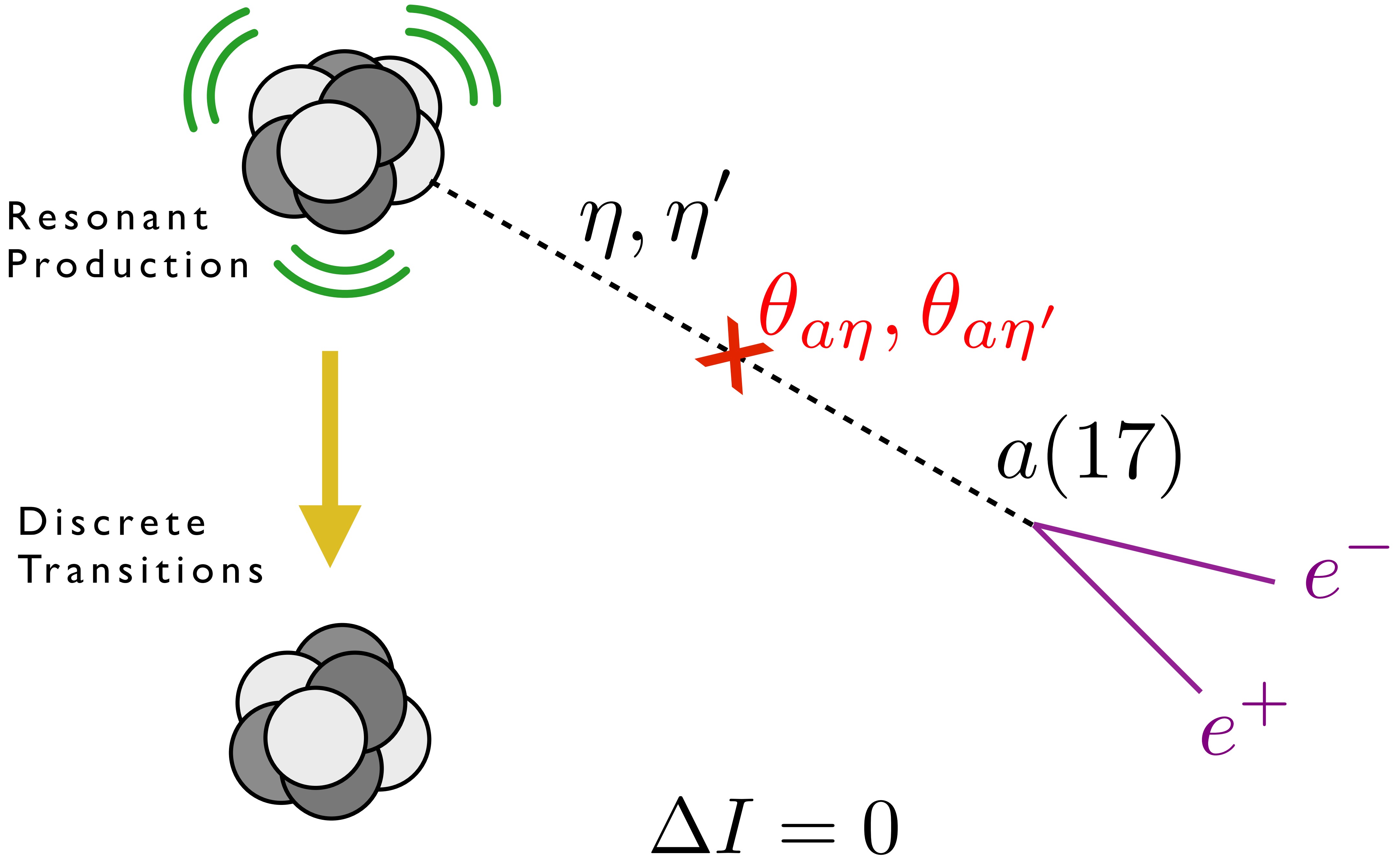
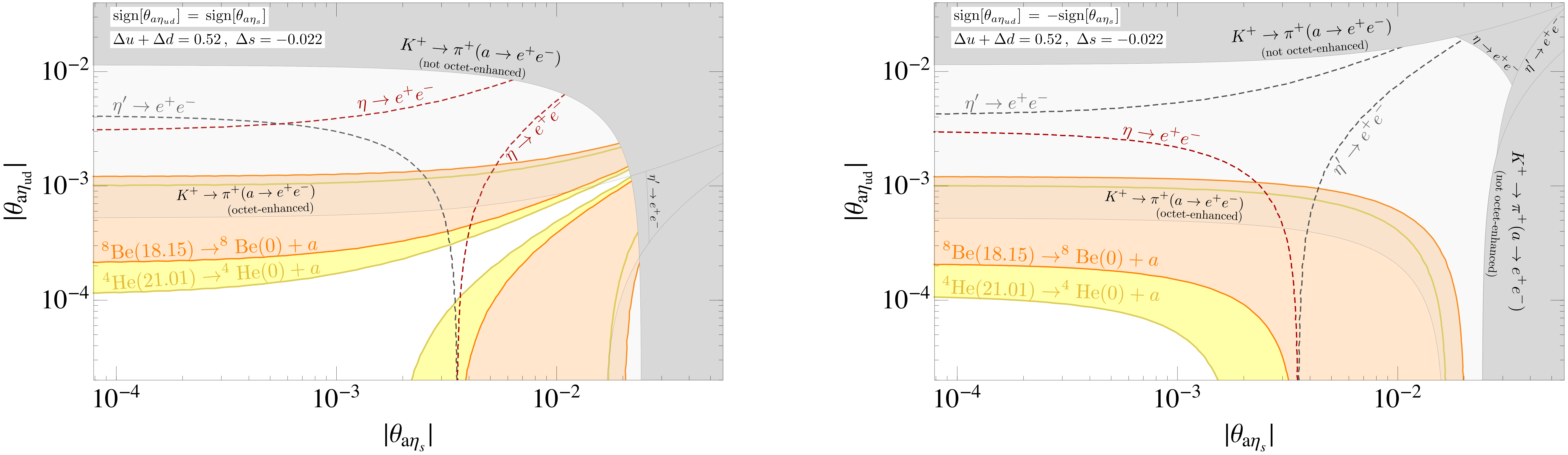




In our adopted parametrization, the axion nuclear couplings are: $a\,\overline{N}\,i\gamma^5\left(g^{(0)}_{aNN} + g^{(1)}_{aNN}\tau^3\right)N$

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

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



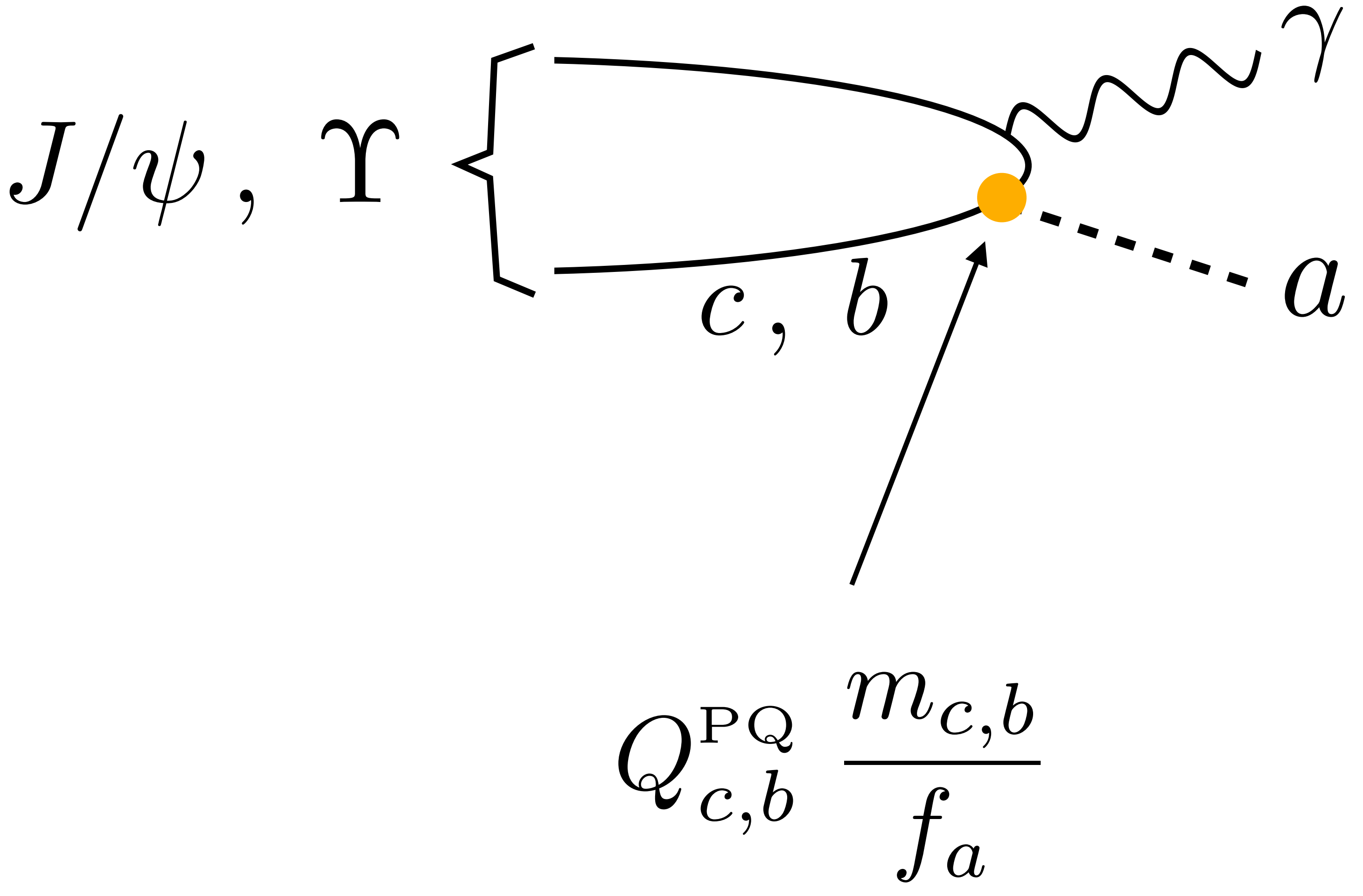
Bands include uncertainties in nuclear matrix elements, nuclear structure parameters, and in $\theta_{a\pi}$ KTeV fit

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

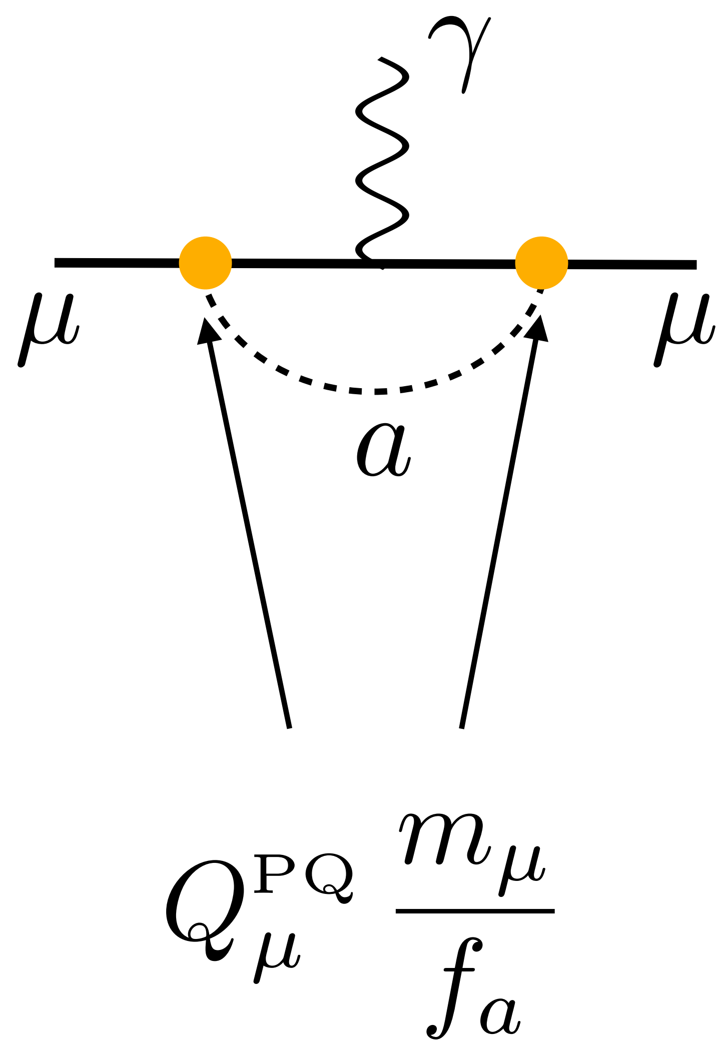
Constraints on $a(17)$

Additional experimental constraints on *a*(17)

Radiative quarkonium decays



Muon's magnetic dipole moment



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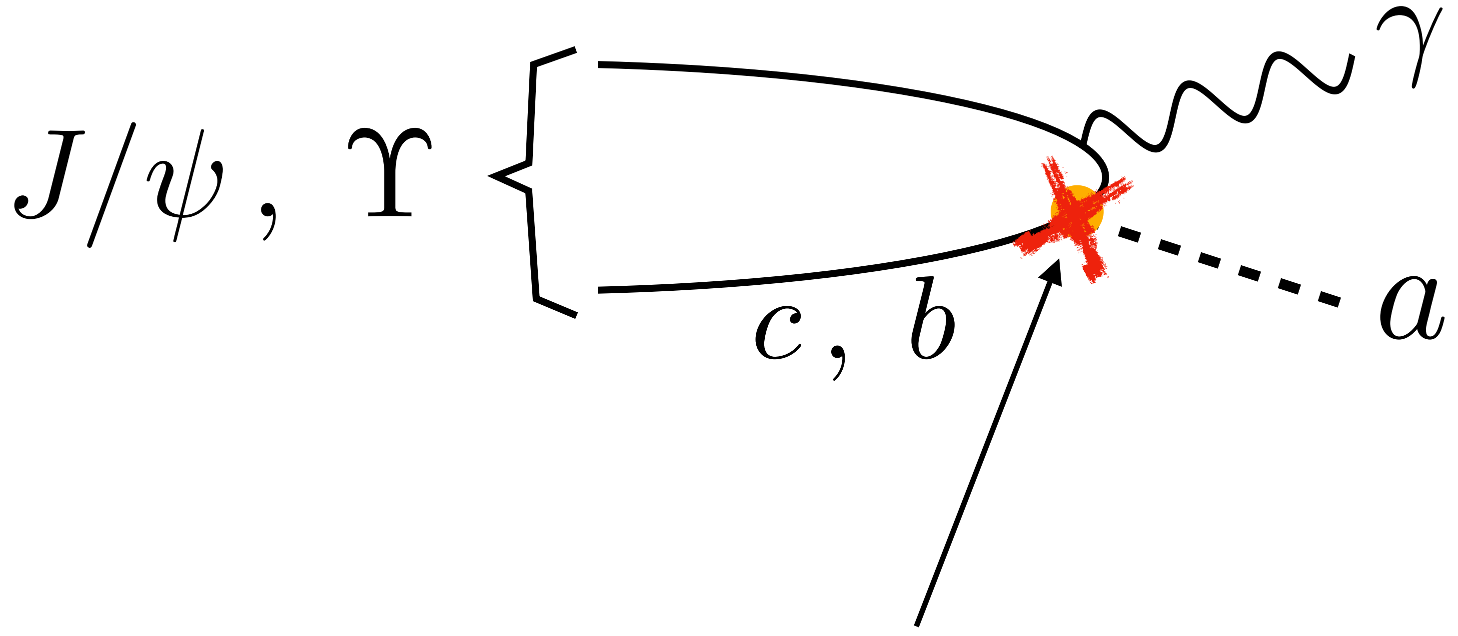

$$Q^{\rm PQ}_{c,b}\ \frac{m_{c,b}}{f_a}$$

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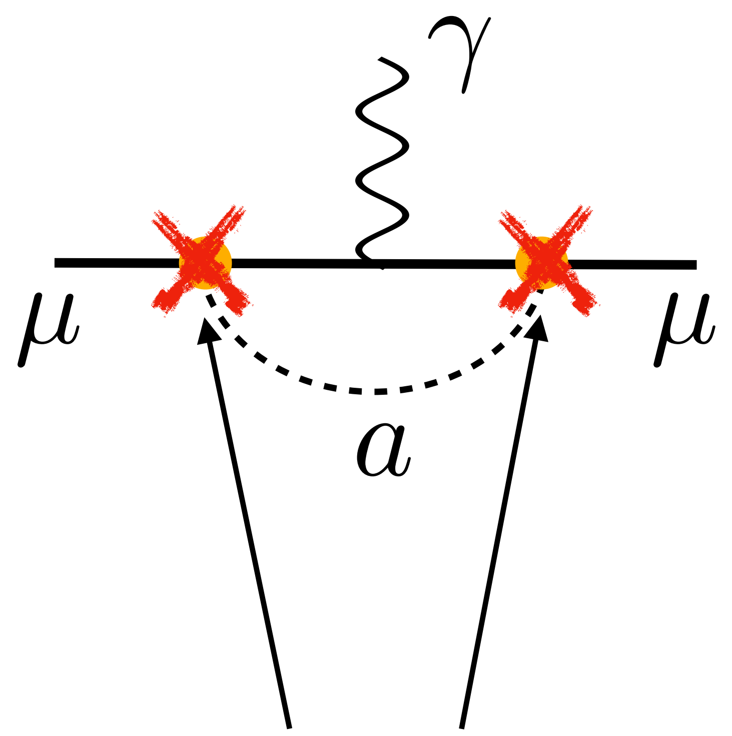


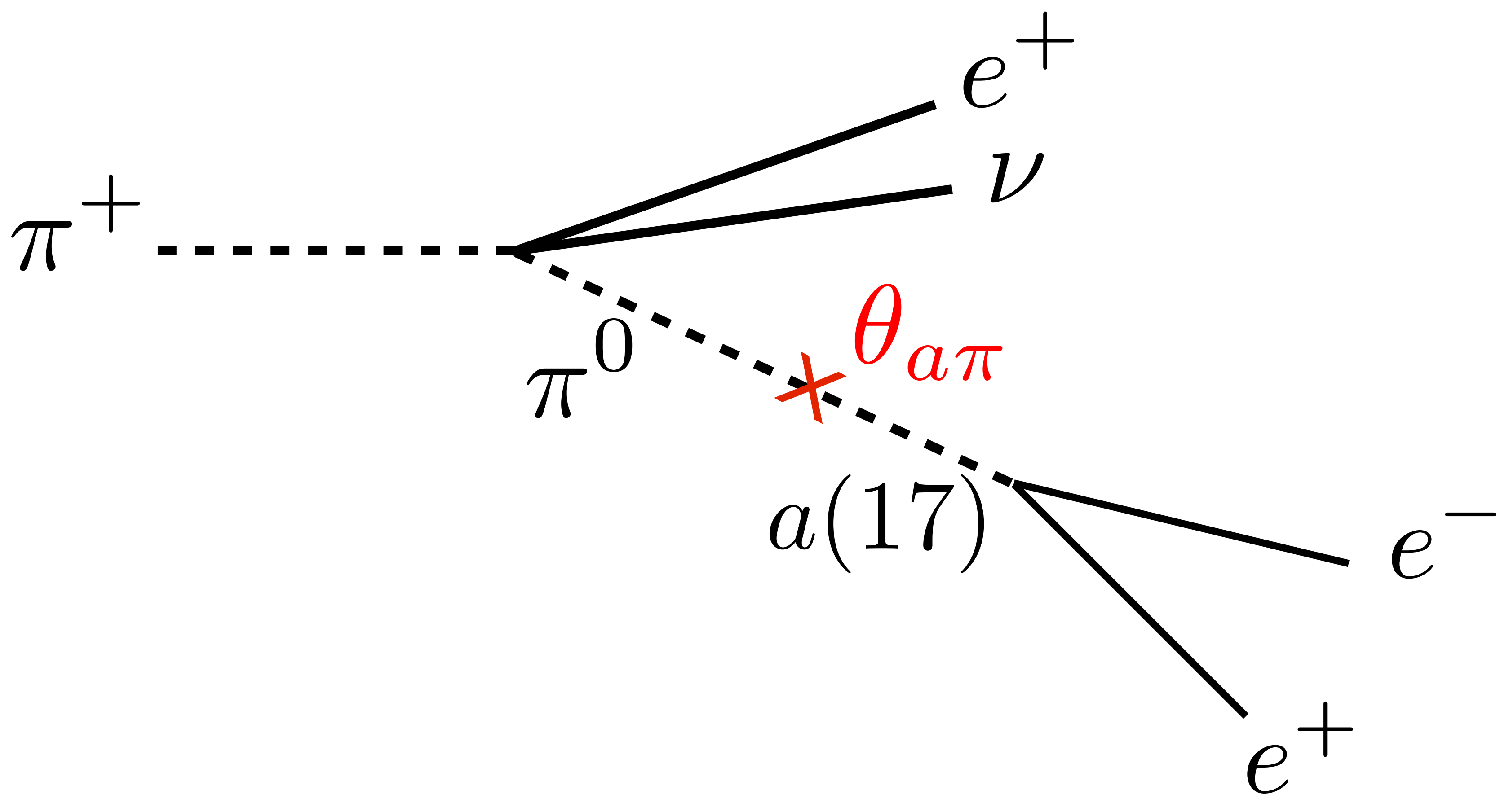
$$Q^{\rm PQ}_{\mu}\ \frac{m_{\mu}}{f_a}$$

These observables are grossly over predicted unless *a*(17) has very suppressed couplings to SM fermions of 2nd and 3rd generations

Additional experimental constraints on *a*(17)

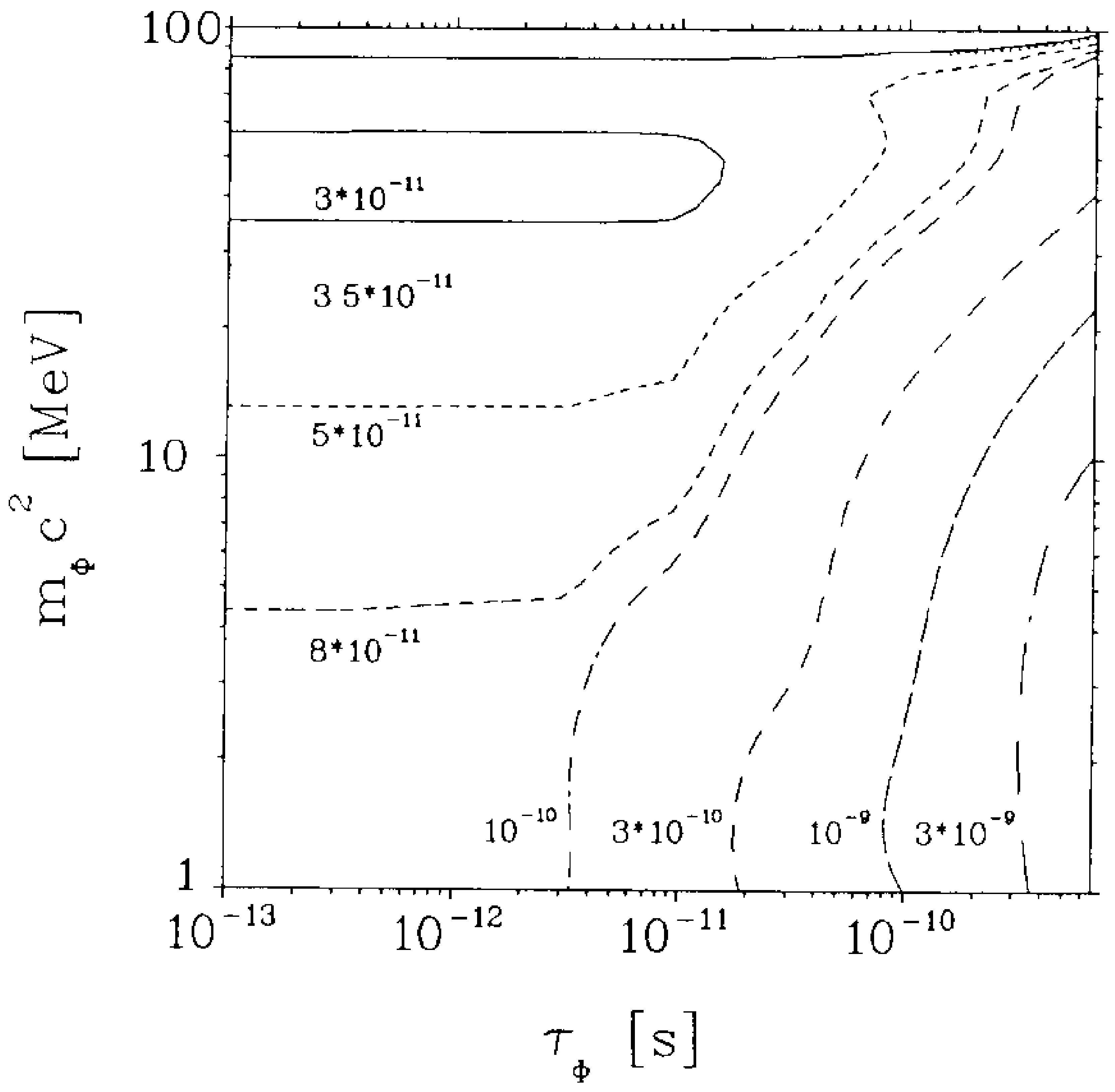
Experimental requirement of *piophobia*

Rare charged pion decays



$$\theta_{a\pi} \lesssim 10^{-4}$$

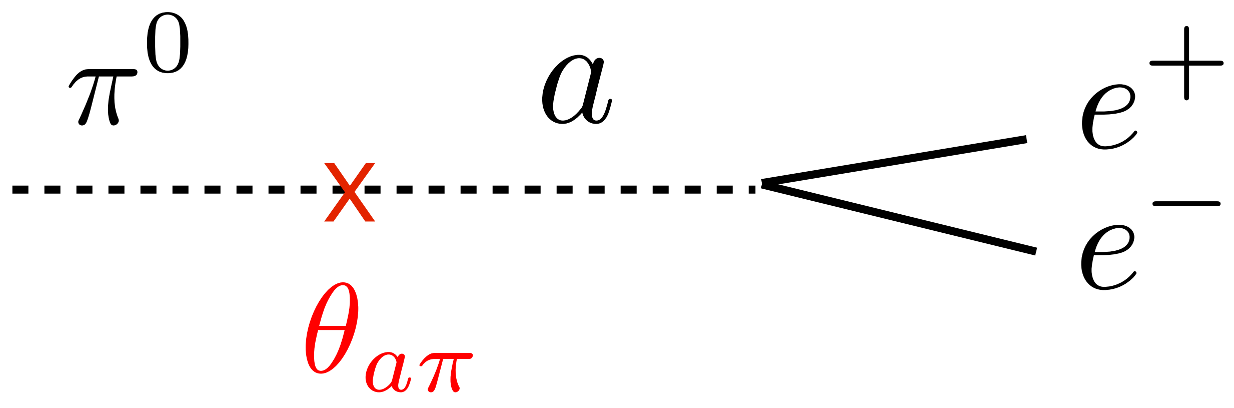
Last looked into in 1986
by the SINDRUM Collaboration

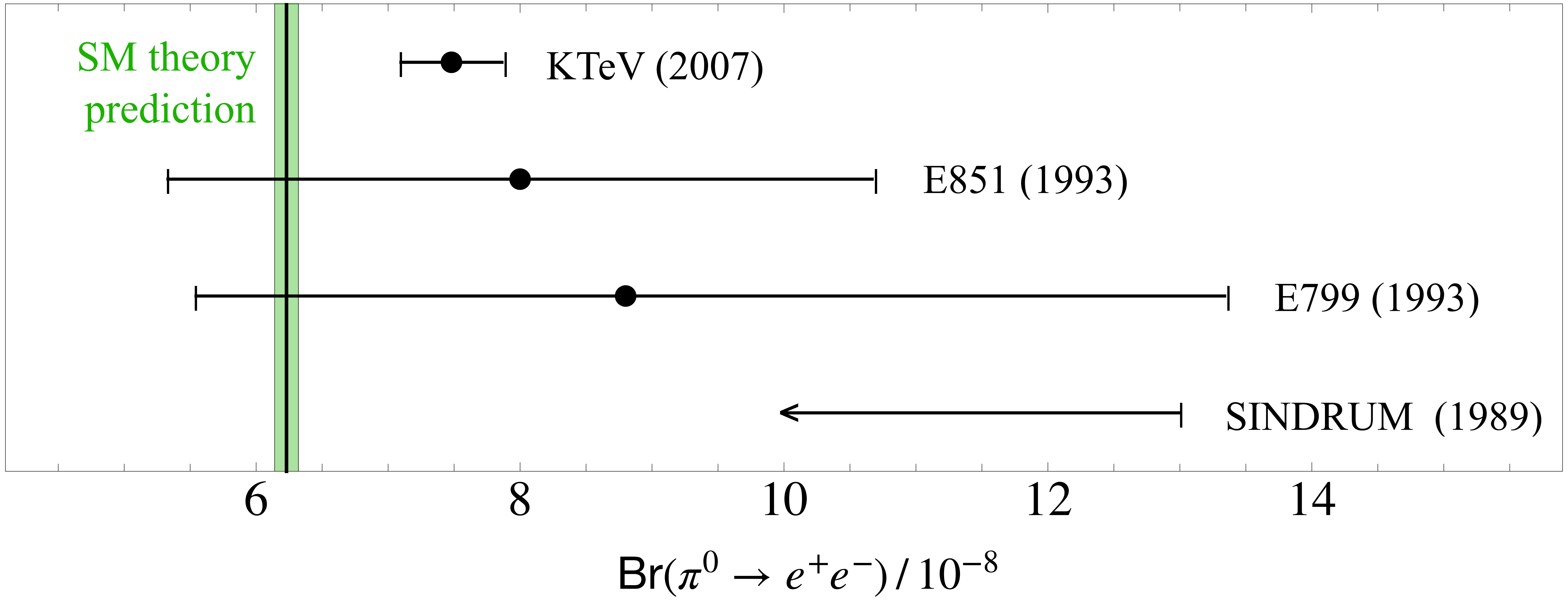


Additional experimental constraints on $a(17)$

Experimental preference for *piophobia*

Rare neutral pion decay





A piophobic $a(17)$ could explain KTeV measurement of $\Gamma(\pi^0 \to e^+e^-)$,

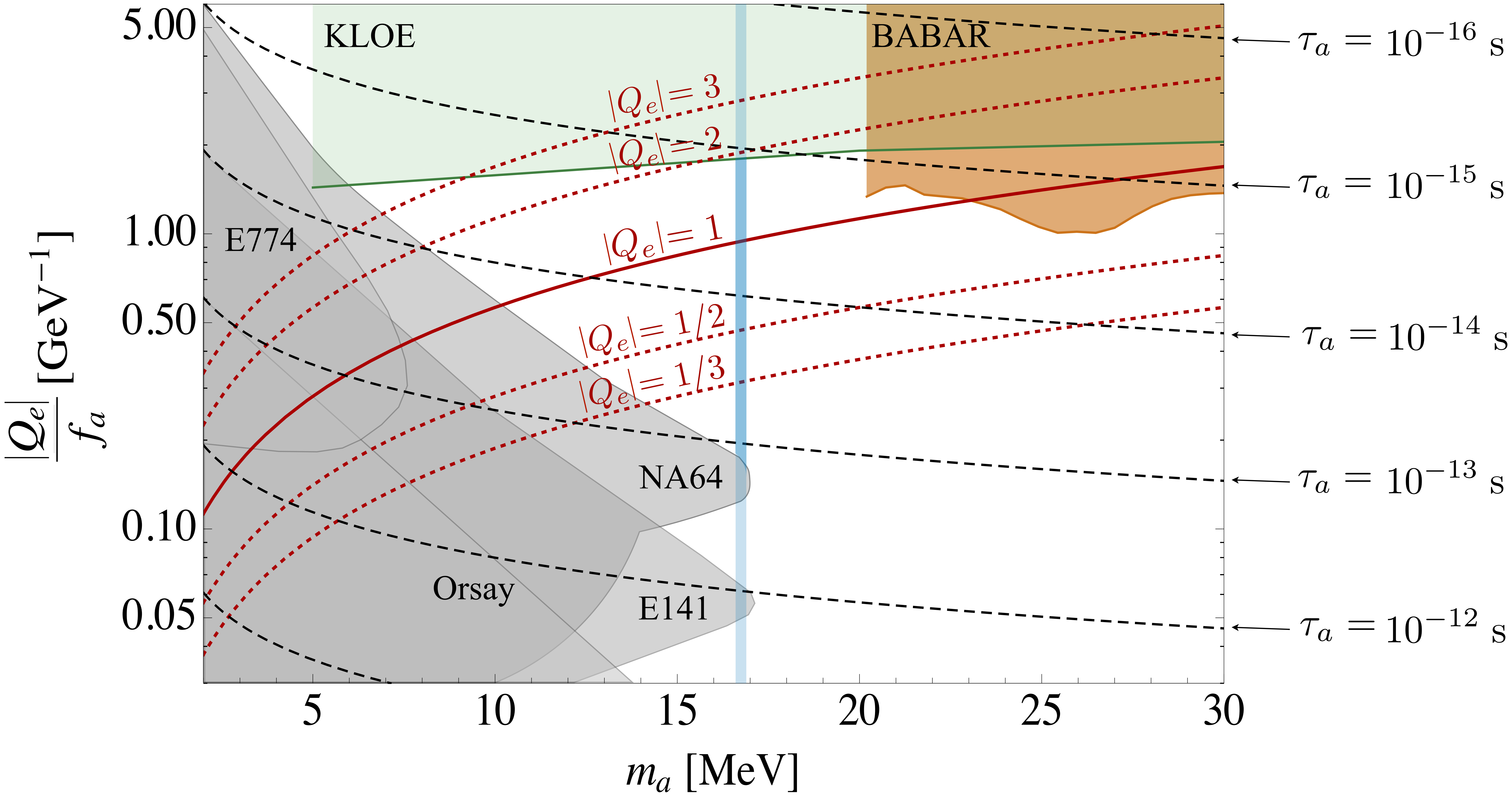
which is ~ 15% higher than SM expectation (~ $2 - 3\sigma$ discrepancy)

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

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

Additional experimental constraints on $a(17)$

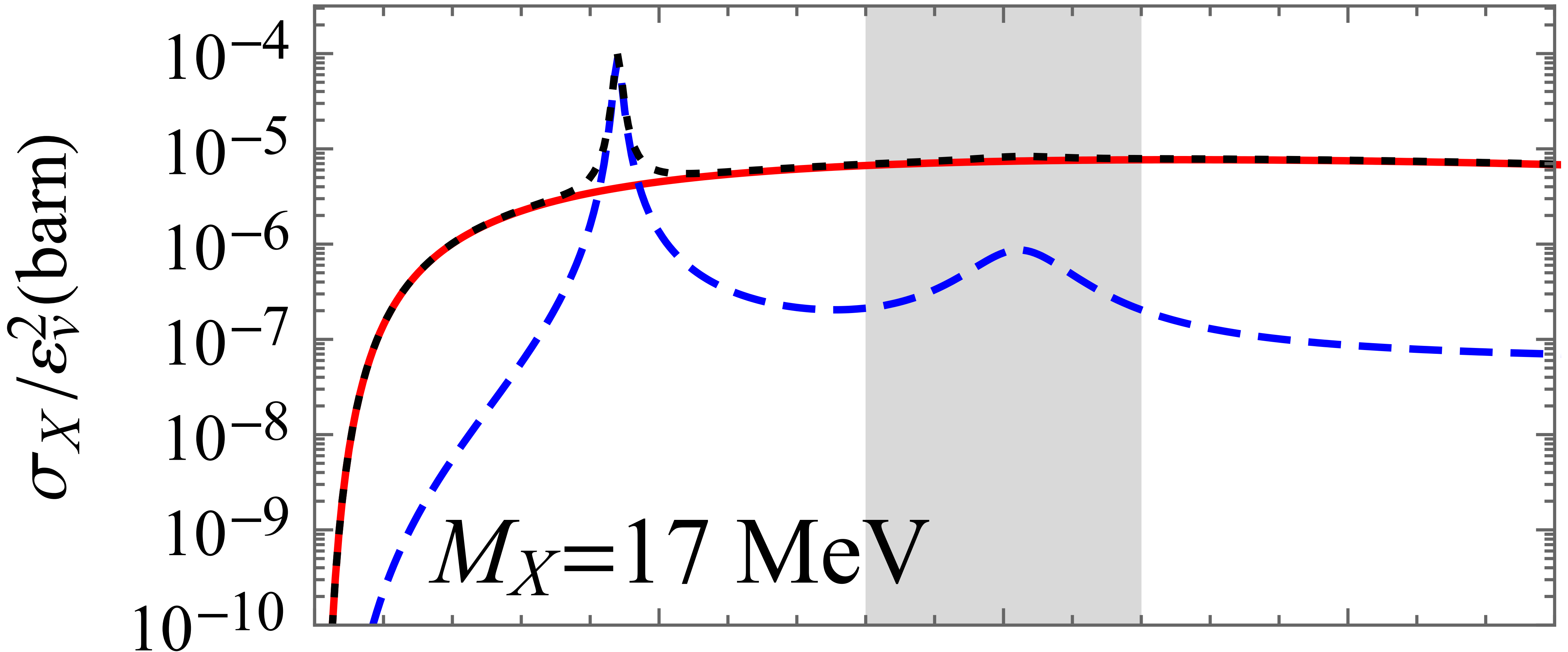
Electronic coupling of $a(17)$, $Q_e^{\mathrm{PQ}}\dfrac{m_e}{f_a}\,a\,\bar{e}\,i\gamma_5\,e$, is constrained to $1/5 \lesssim Q_e^{\mathrm{PQ}} \lesssim 2$



Potential channels for exclusion and/or discovery

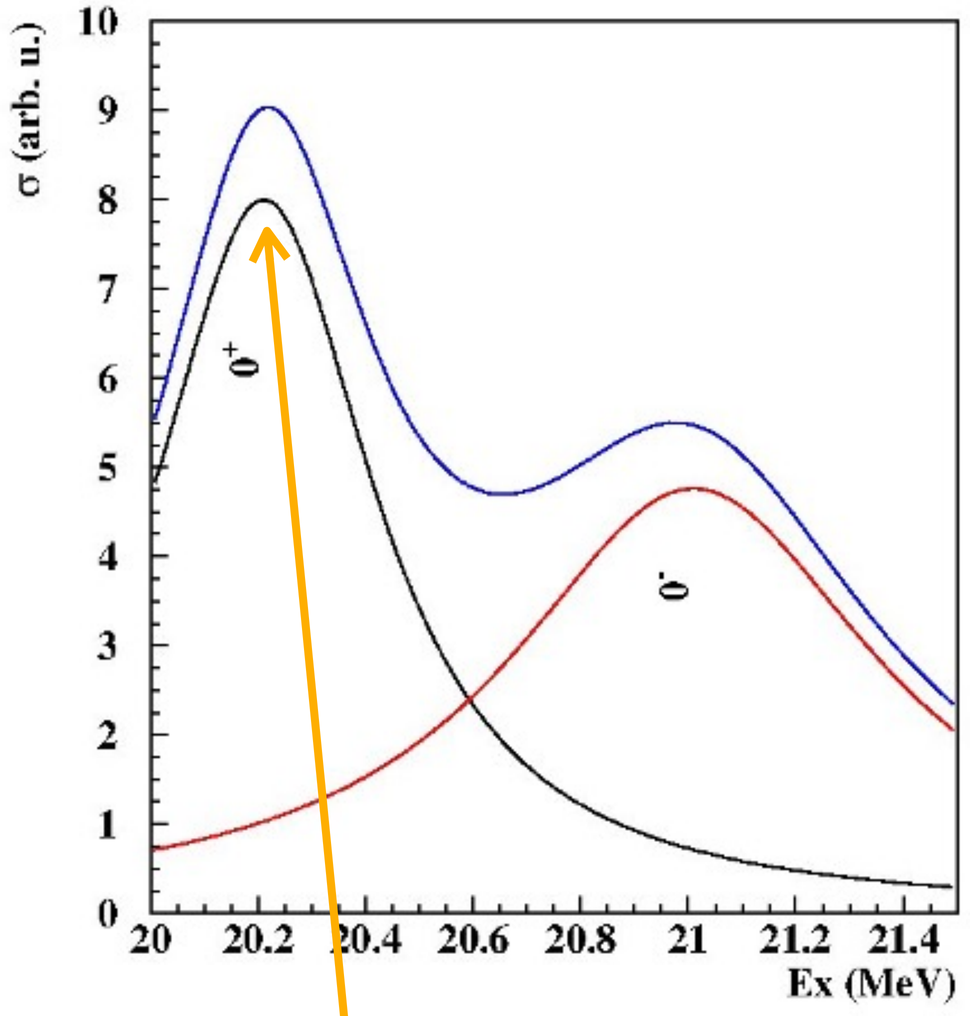
Signals that are NOT predicted by *a*(17) hypothesis

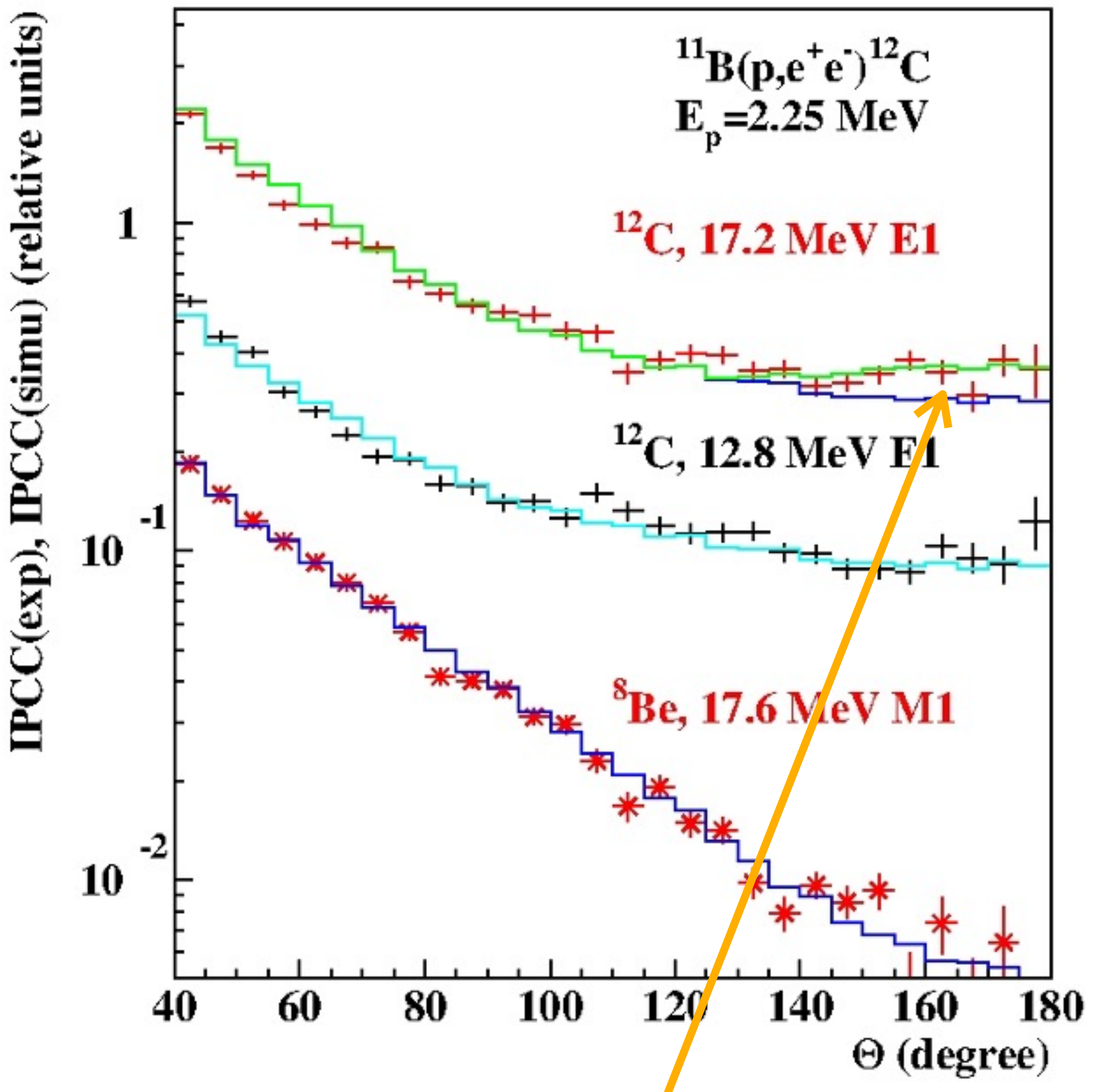
a(17) is not emitted in transitions/capture reactions with electric multipolarity



Zhang and Miller, PLB **813** (2021)

No Bremsstrahlung radiation





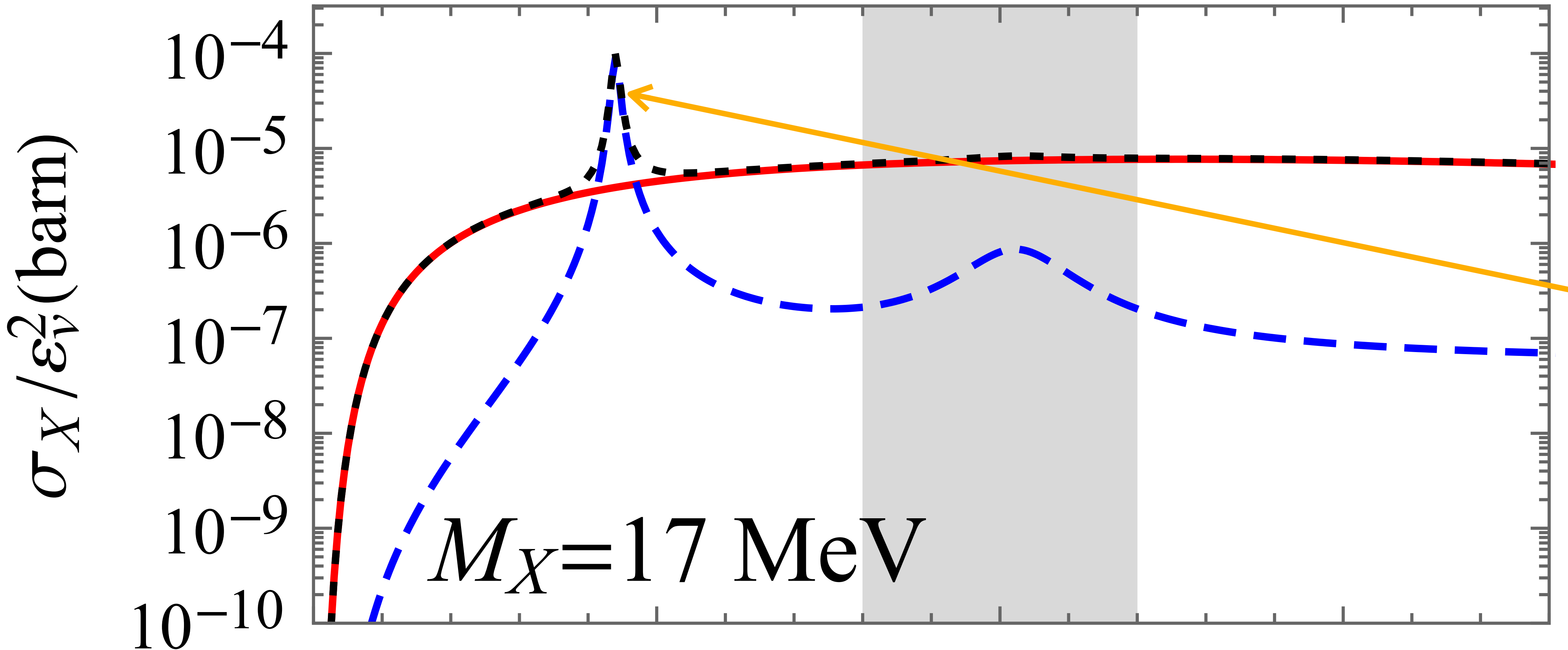
A. Krasznahorkay's talk on Monday

No $^4\mathrm{He}(20.49) \to {}^4\mathrm{He}(0) + a(17)$ $(0^+ \to 0^+)$ transition

No $^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C}(0) + a(17)$ E1 transition

Signals that are NOT predicted by $a(17)$ hypothesis

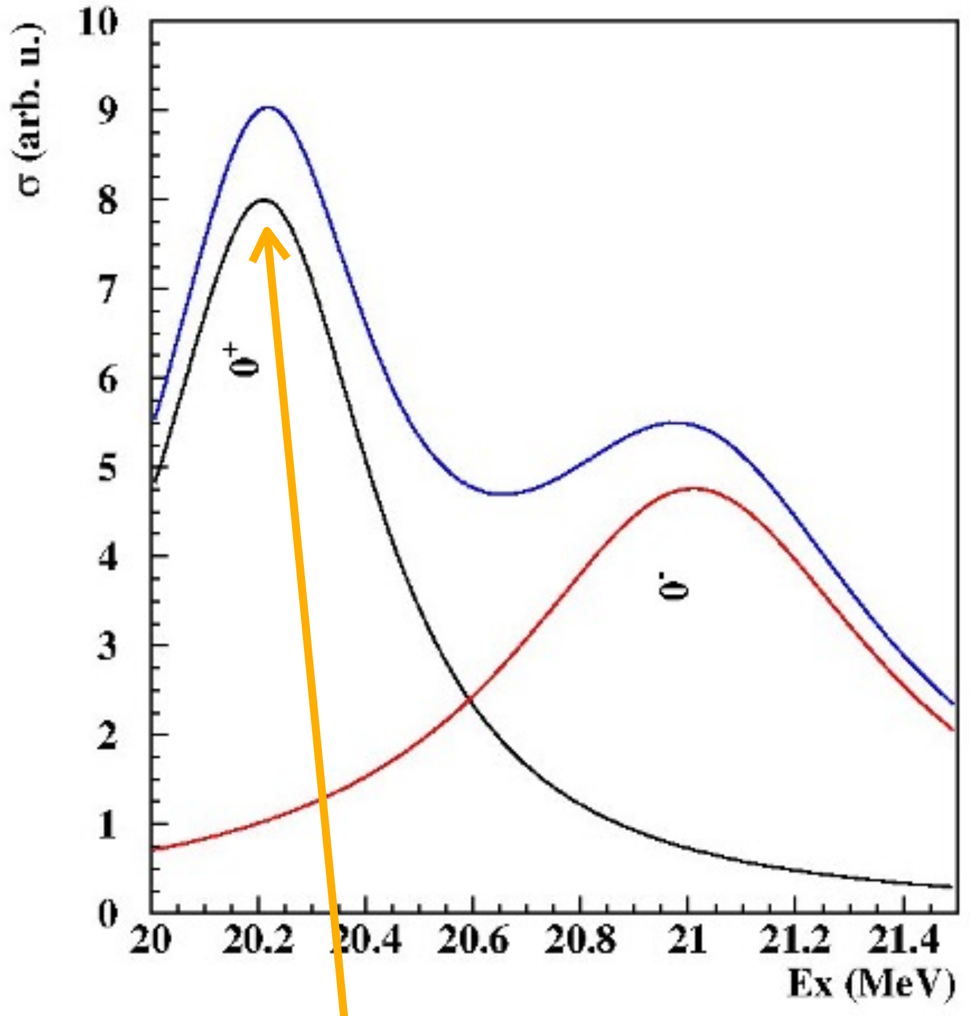
$a(17)$ emission is suppressed in isovector magnetic transitions

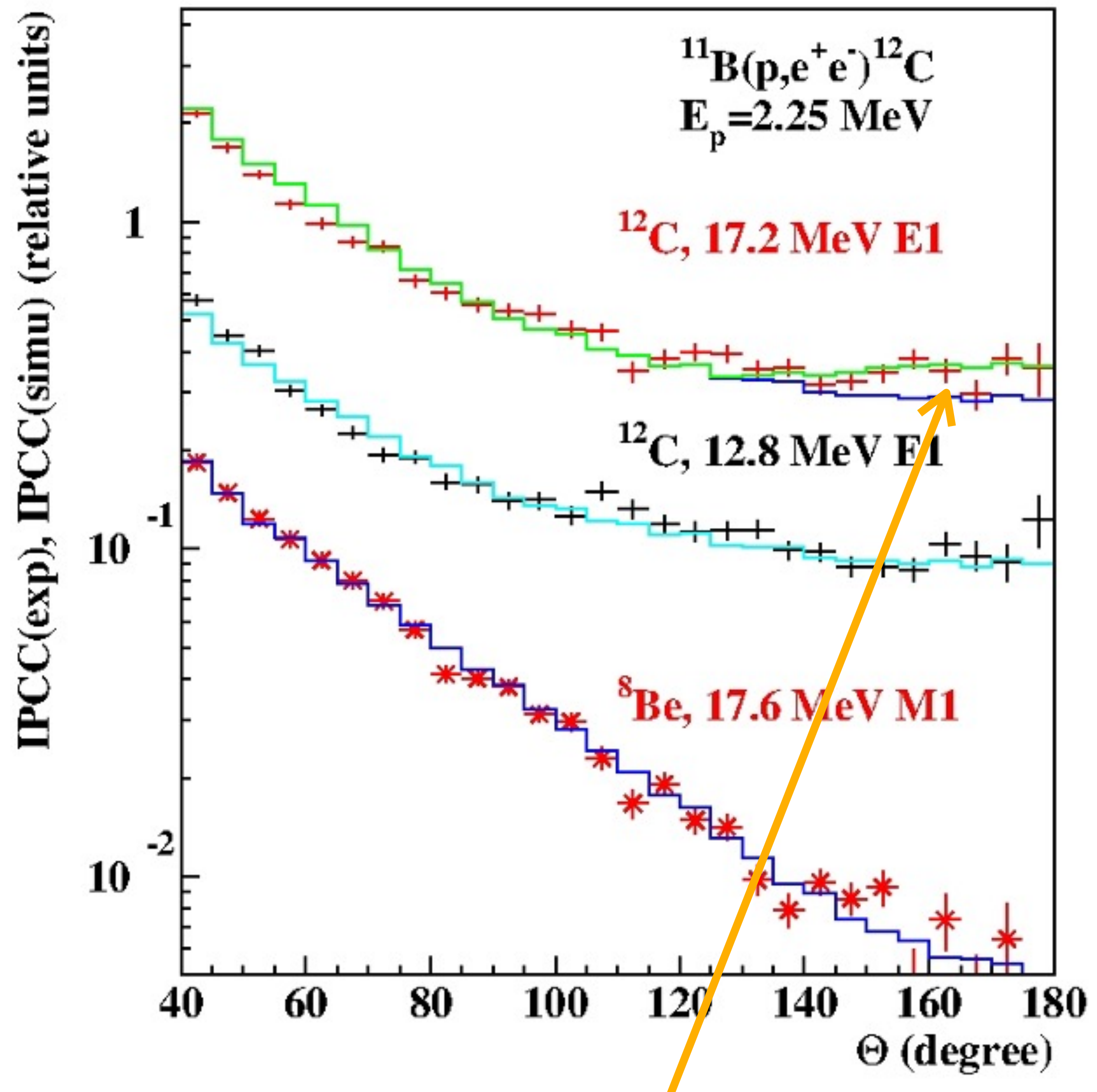


Zhang and Miller, PLB **813** (2021)

No Bremsstrahlung radiation

Suppressed *isovector* M1 transitions





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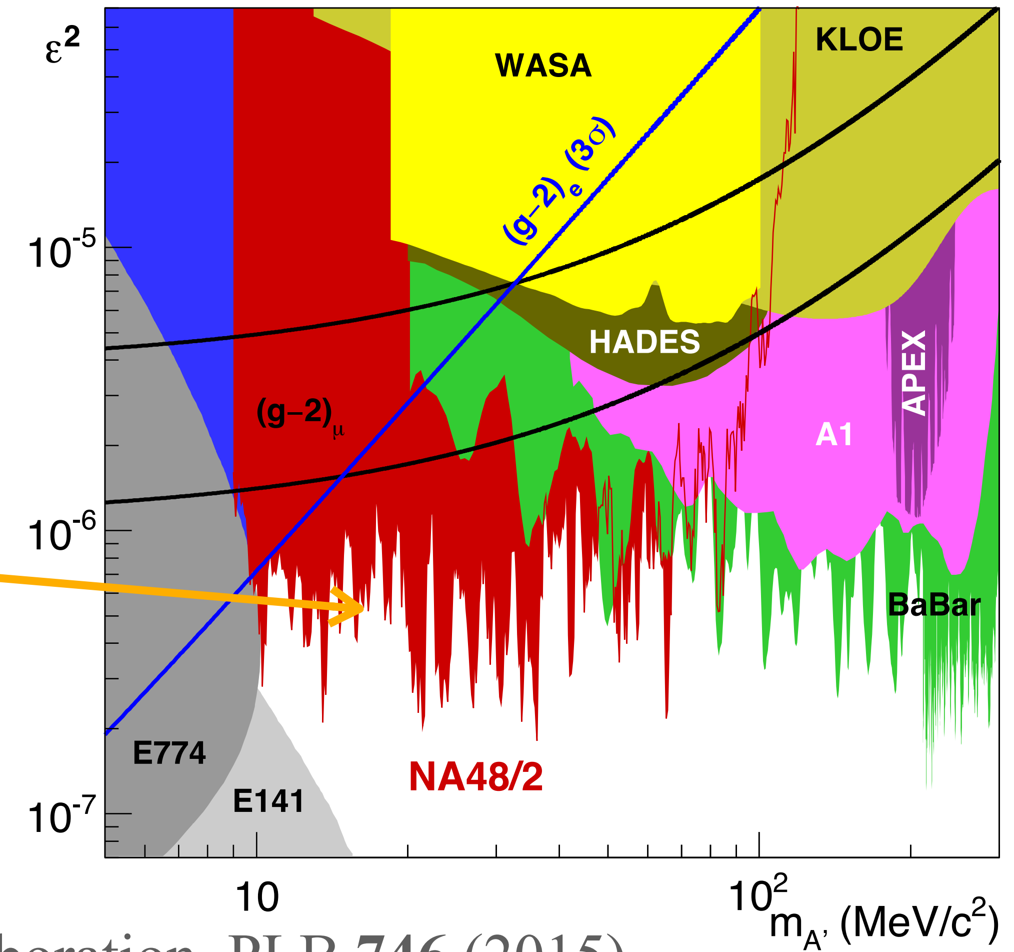
No $^4\mathrm{He}(20.49) \rightarrow {}^4\mathrm{He}(0) + a(17)$ $(0^+ \rightarrow 0^+)$ transition

No $^{12}\mathrm{C}(17.2) \rightarrow {}^{12}\mathrm{C}(0) + a(17)$ E1 transition

Signals that are NOT predicted by $a(17)$ hypothesis

$\pi^0 \to \gamma\, a$ decay is forbidden

NA48/2 limits not relevant to $a(17)$ parameter space



NA48/2 Collaboration, PLB **746** (2015)

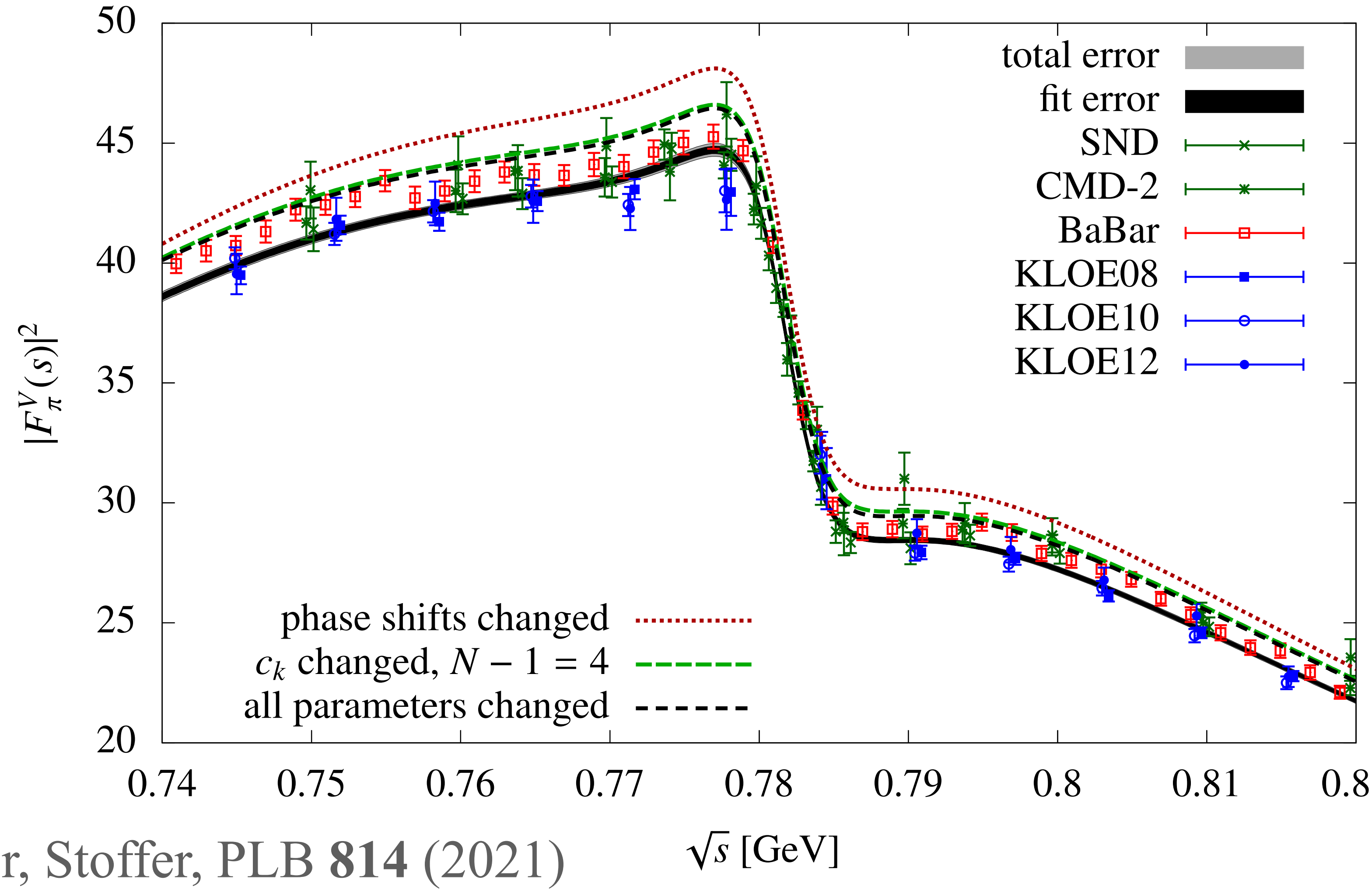
$a(17) \to \gamma\gamma$ is highly suppressed

No 17 MeV $\gamma\gamma$ resonance expected

$$\mathrm{Br}(a \to \gamma\gamma) \;\approx\; 10^{-7} \times \frac{1}{(q^e_{\mathrm{PQ}})^2} \left(\frac{\theta_{a\pi} + \frac{5}{3}\,\theta_{a\eta_{ud}} + \frac{\sqrt{2}}{3}\,\theta_{a\eta_s}}{10^{-3}} \right)^2$$

No contribution to $\Delta(g\text{-}2)_\mu$

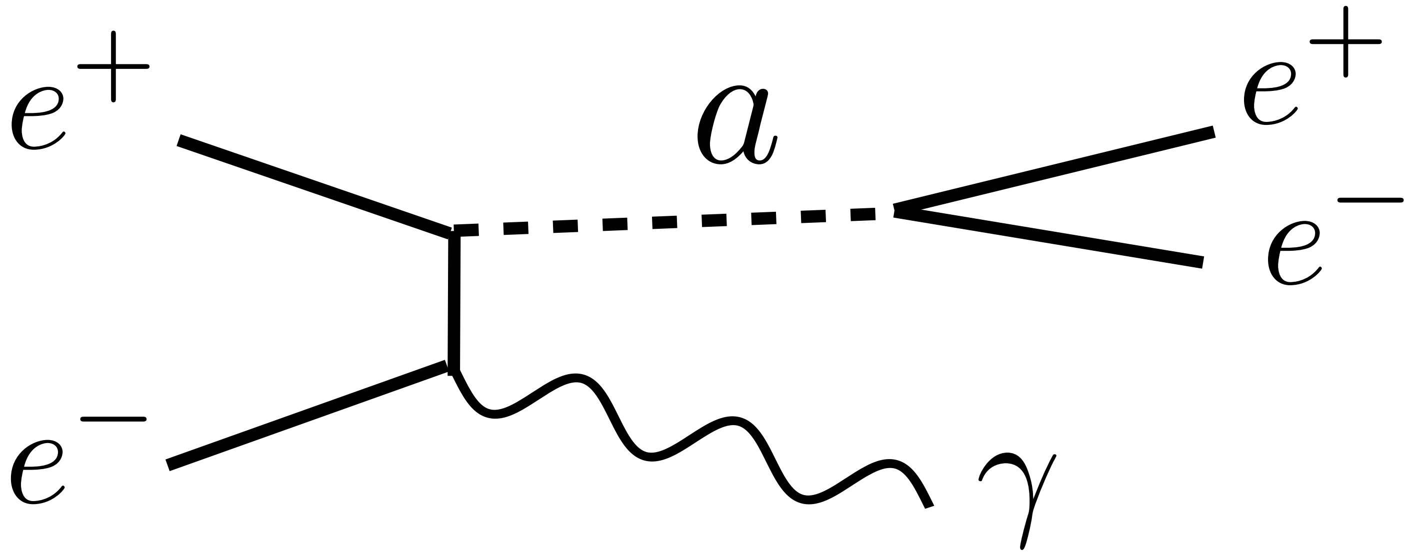
Only $(g-2)_\mu$ relevance to that I could conceive of is
if the GeV-scale PQ sector affected the extraction of
$\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$ below $\sqrt{s} = 1$ GeV
(a few % change could reconcile the observation and SM prediction of $(g-2)_\mu$)



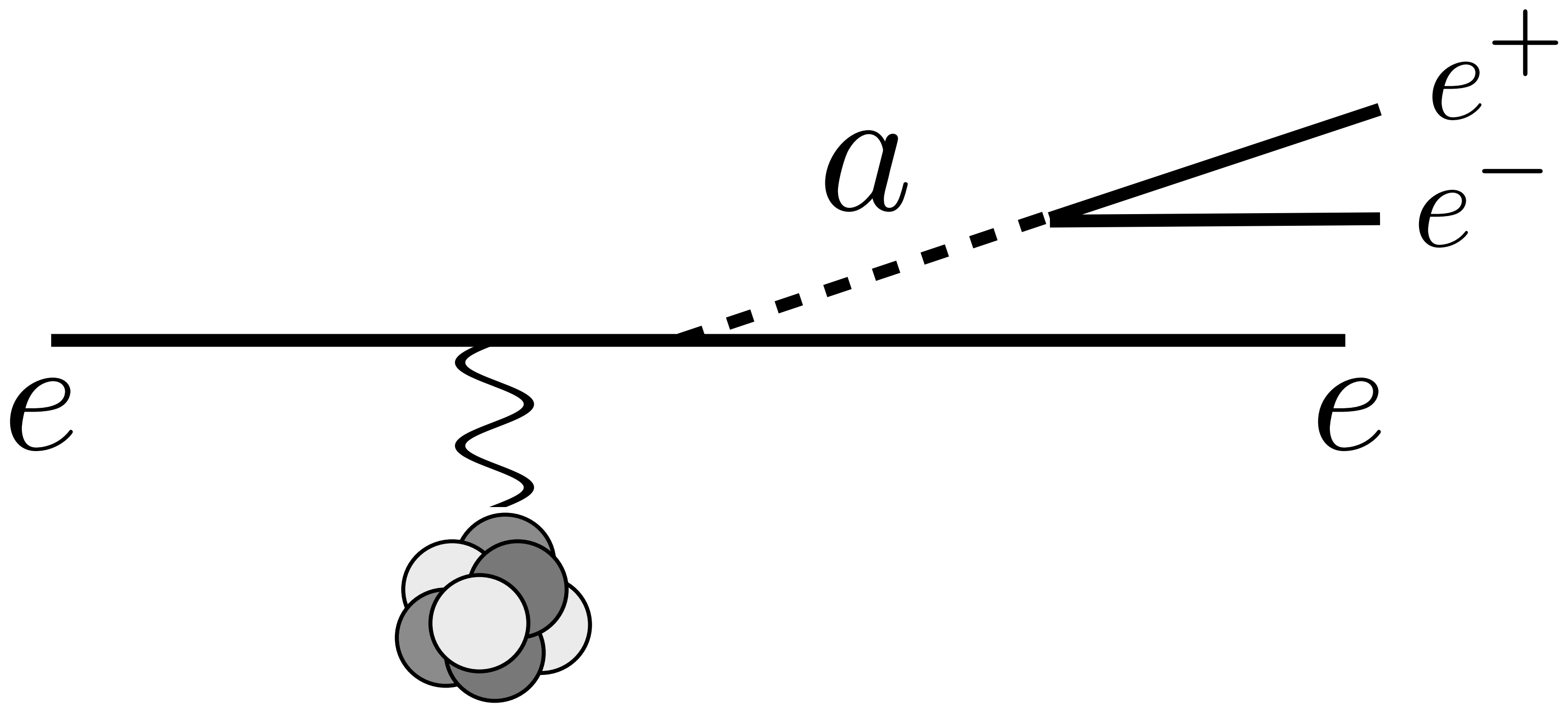
Colangelo, Hoferichter, Stoffer, PLB **814** (2021)

a(17) electronic couplings

Dark-photon searches will also probe *a*(17) through analogous productions processes



PADME, Belle II



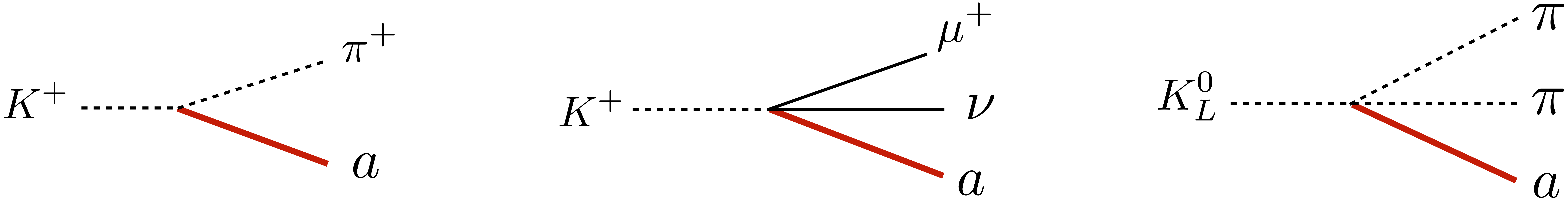
NA64, DarkLight, HPS, MAGIX, …

$a(17)$ signals in Kaon decays

"Standard" axionic Kaon decays

$$K^+ \to \pi^+ a,\ \ K_{L,S} \to \pi^0 a,\ \ K^+ \to \ell^+ \nu\, a,\ \ K^+ \to \pi^+ \pi^0 a,\ \ K_L \to \pi\pi a,\ \ K_L(\to a^*) \to e^+ e^-$$

Most promising channels with Br $\sim 10^{-6} - 10^{-9}$



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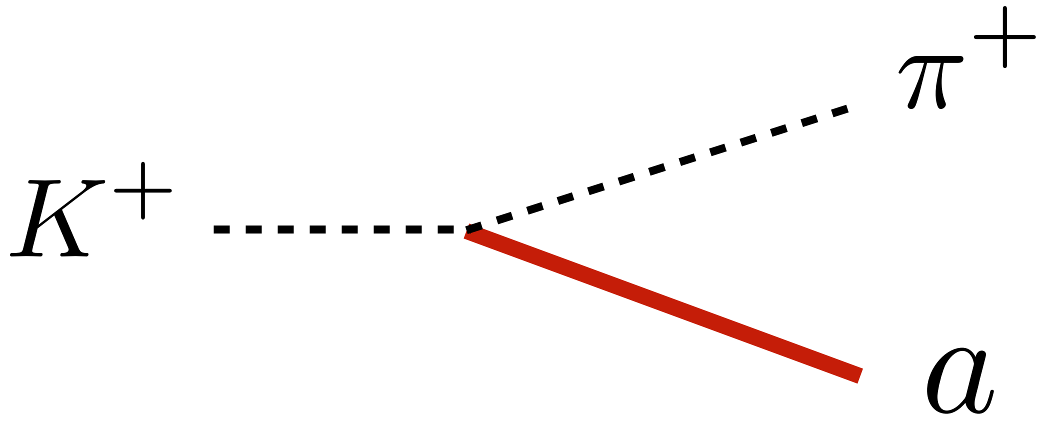
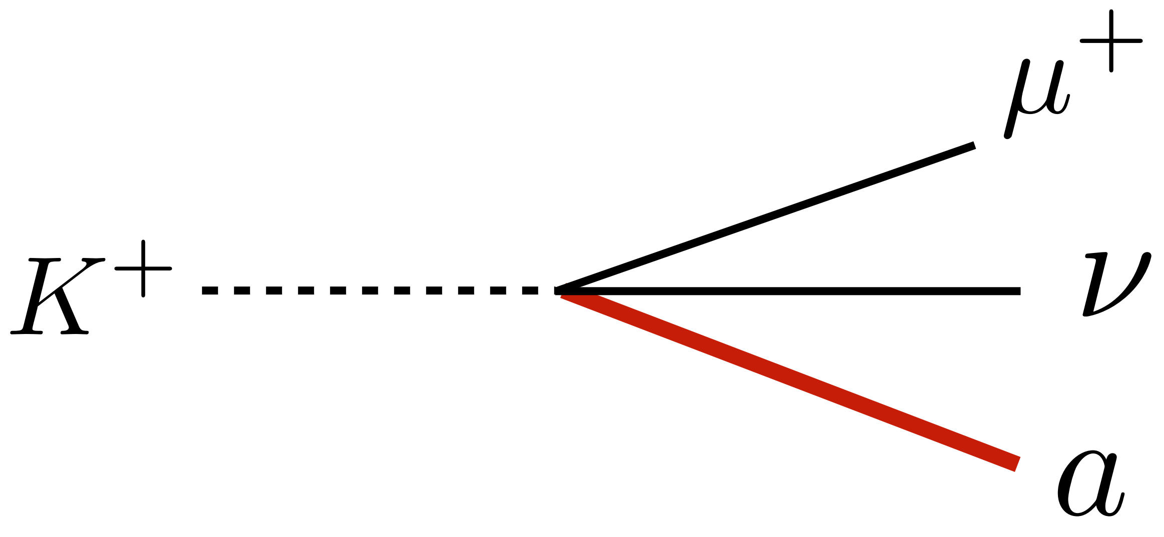
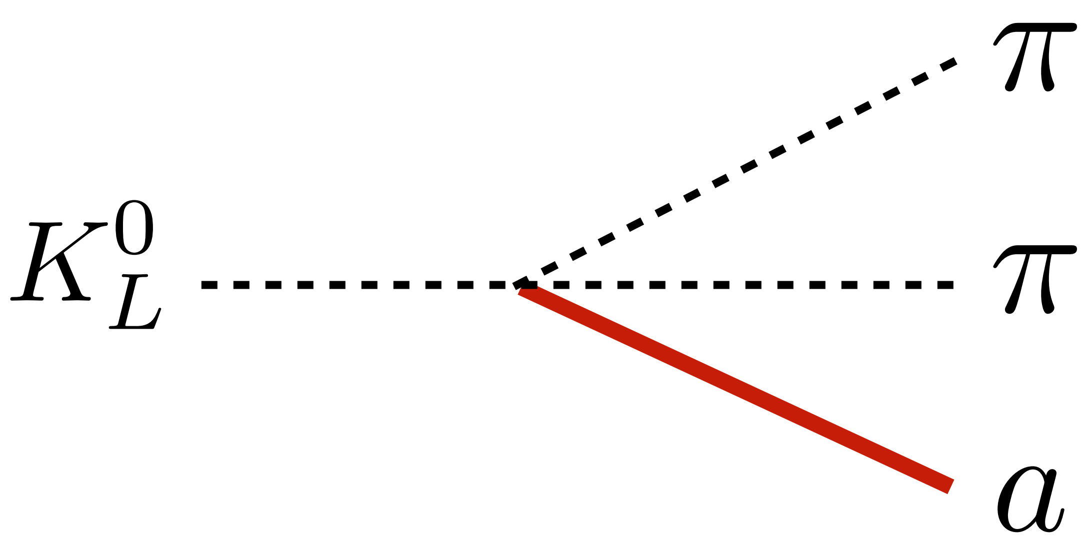
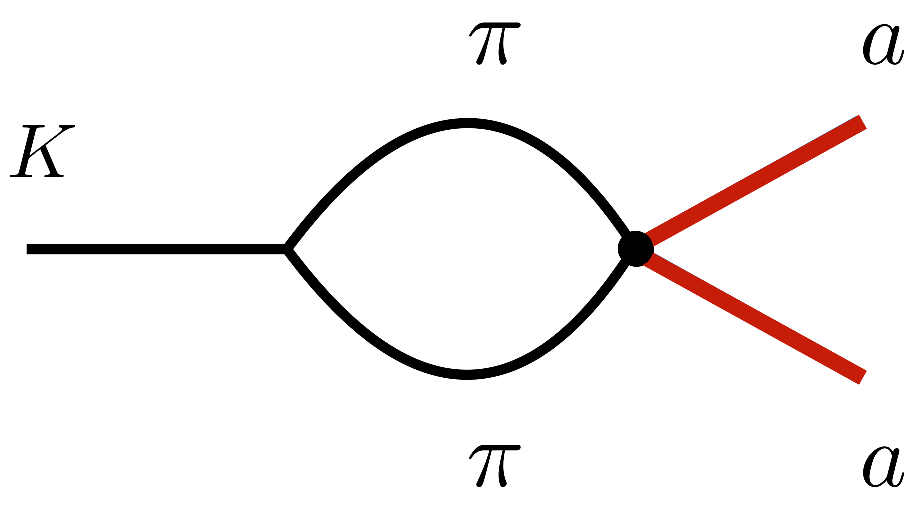




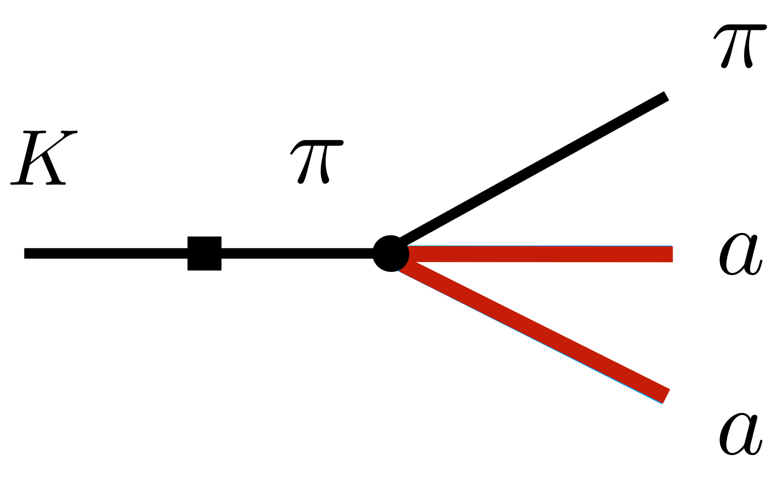


"Exotic" multi-axionic Kaon decays

(Hostert and Pospelov, arXiv:2012.02142)



$$\mathcal{B}(K_{S,L} \to aa) \simeq \begin{cases} 2.6 \times 10^{-7} & \text{for } K_S, \\ 7.2 \times 10^{-10} & \text{for } K_L. \end{cases}$$

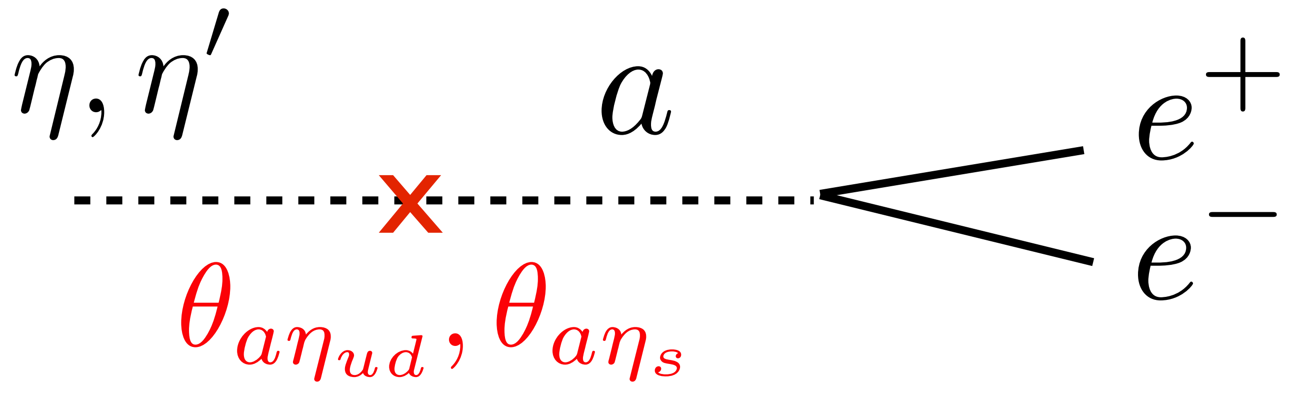


$$\mathcal{B}(K_L \to \pi^0 aa) \simeq 7 \times 10^{-5}$$

$$\mathcal{B}(K^+ \to \pi^+ aa) \simeq 1.7 \times 10^{-5}$$

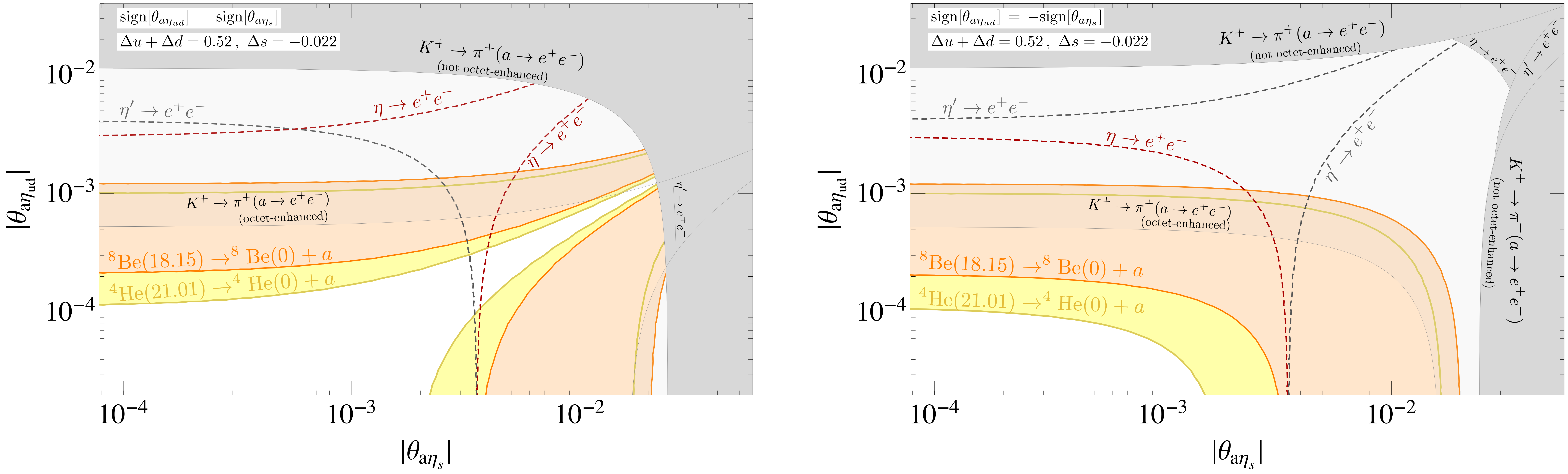
$a(17)$ signals in η and η' decays

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



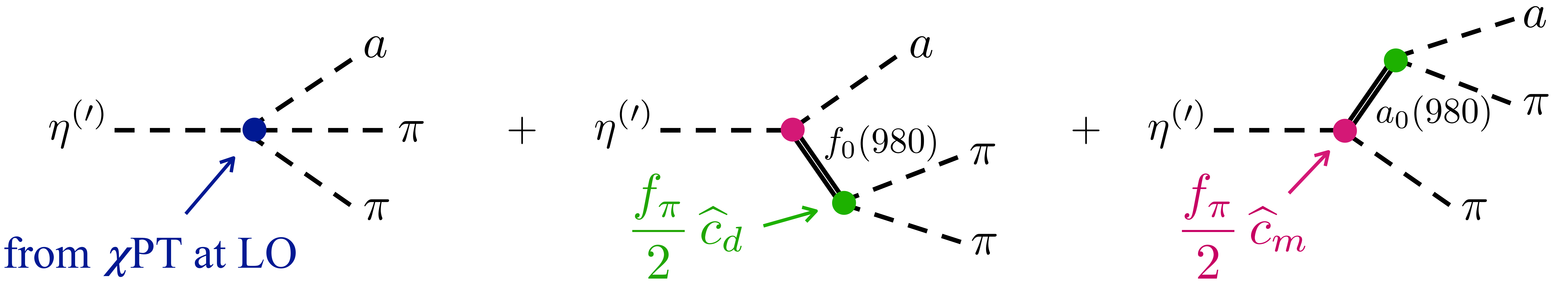
$$\mathrm{Br}(\eta \to e^+e^-)_{\mathrm{exp}} < 7\times 10^{-7}$$
$$\mathrm{Br}(\eta \to e^+e^-)_{\mathrm{SM}} \approx (4.6-5.4)\times 10^{-9}$$

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



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

$a(17)$ signals in η and η' decays



from χPT at LO

$\frac{f_\pi}{2}\,\widehat{c}_d$

$\frac{f_\pi}{2}\,\widehat{c}_m$

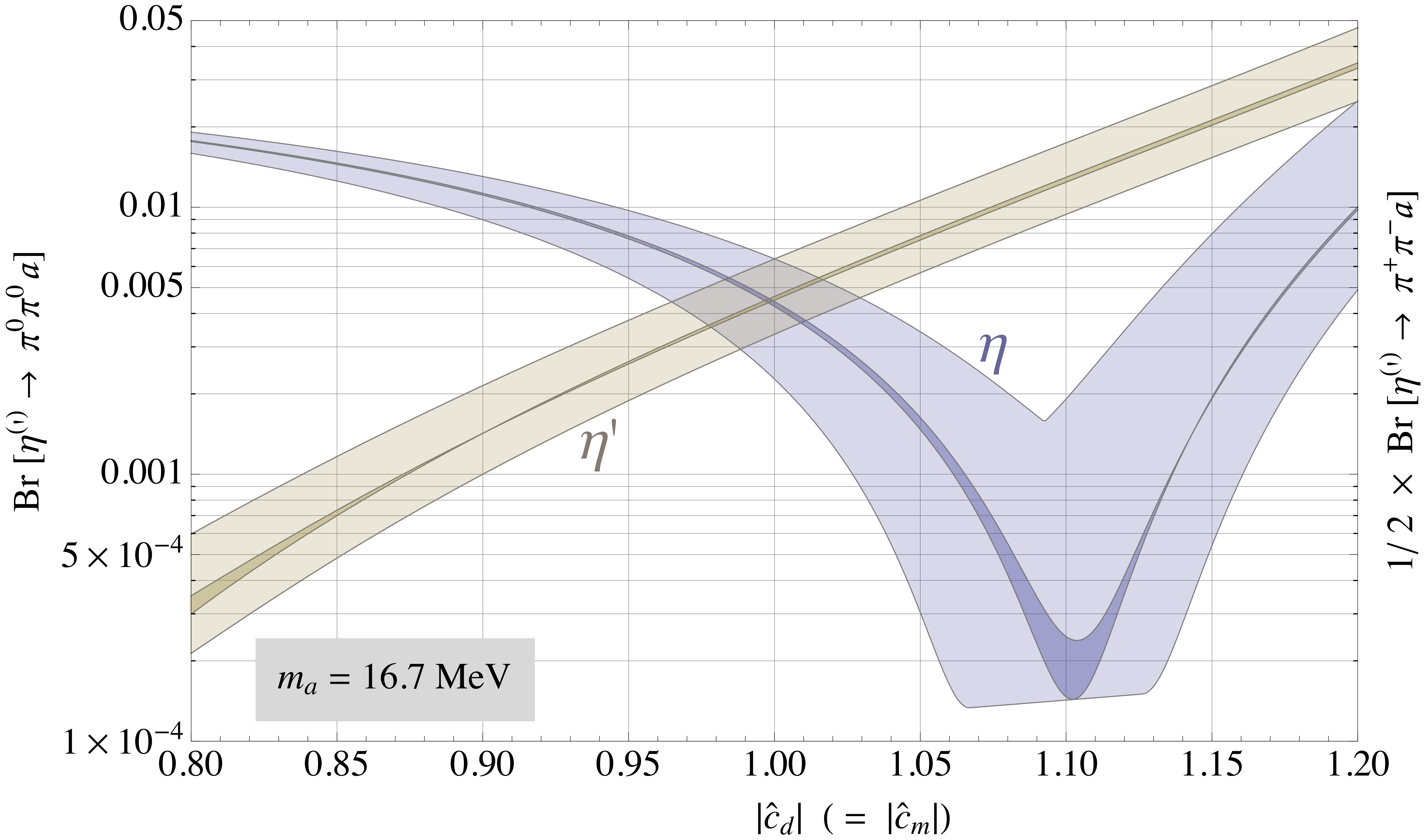
Estimated in the framework of *Resonance Chiral Theory* (RχT), a “UV completion” of χPT which incorporates the low-lying QCD resonances and extends the principle of vector meson dominance

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

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

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

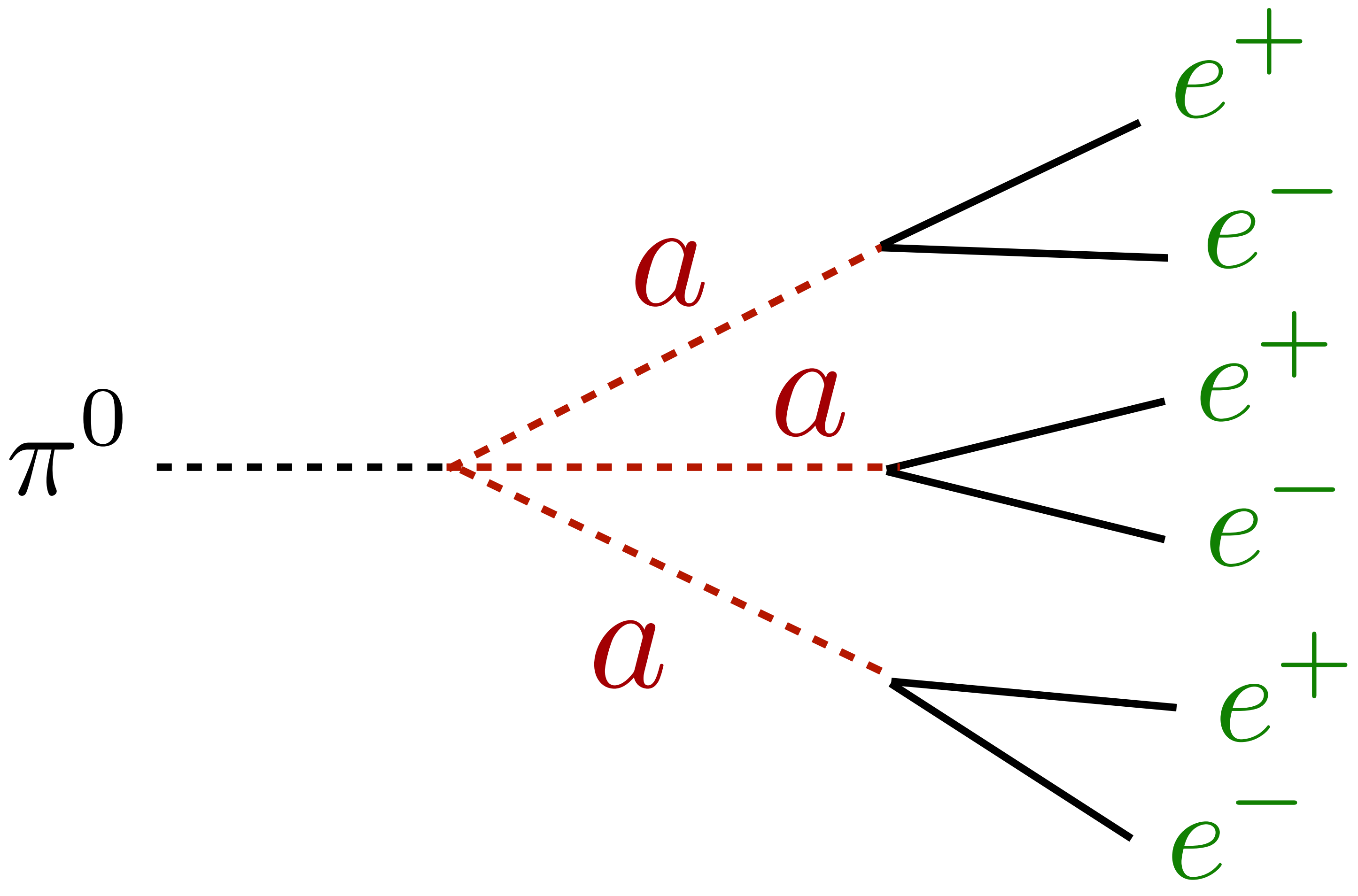
Pich, hep-ph/0205030



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

Nonetheless, within reach of future η-factories (JLab, REDTOP)

$a(17)$ signals in exotic π^0 decays



$$\mathrm{Br}\left[\pi^0 \to 3\, a(17)\right] \simeq 10^{-3}$$

(Hostert and Pospelov, arXiv:2012.02142)

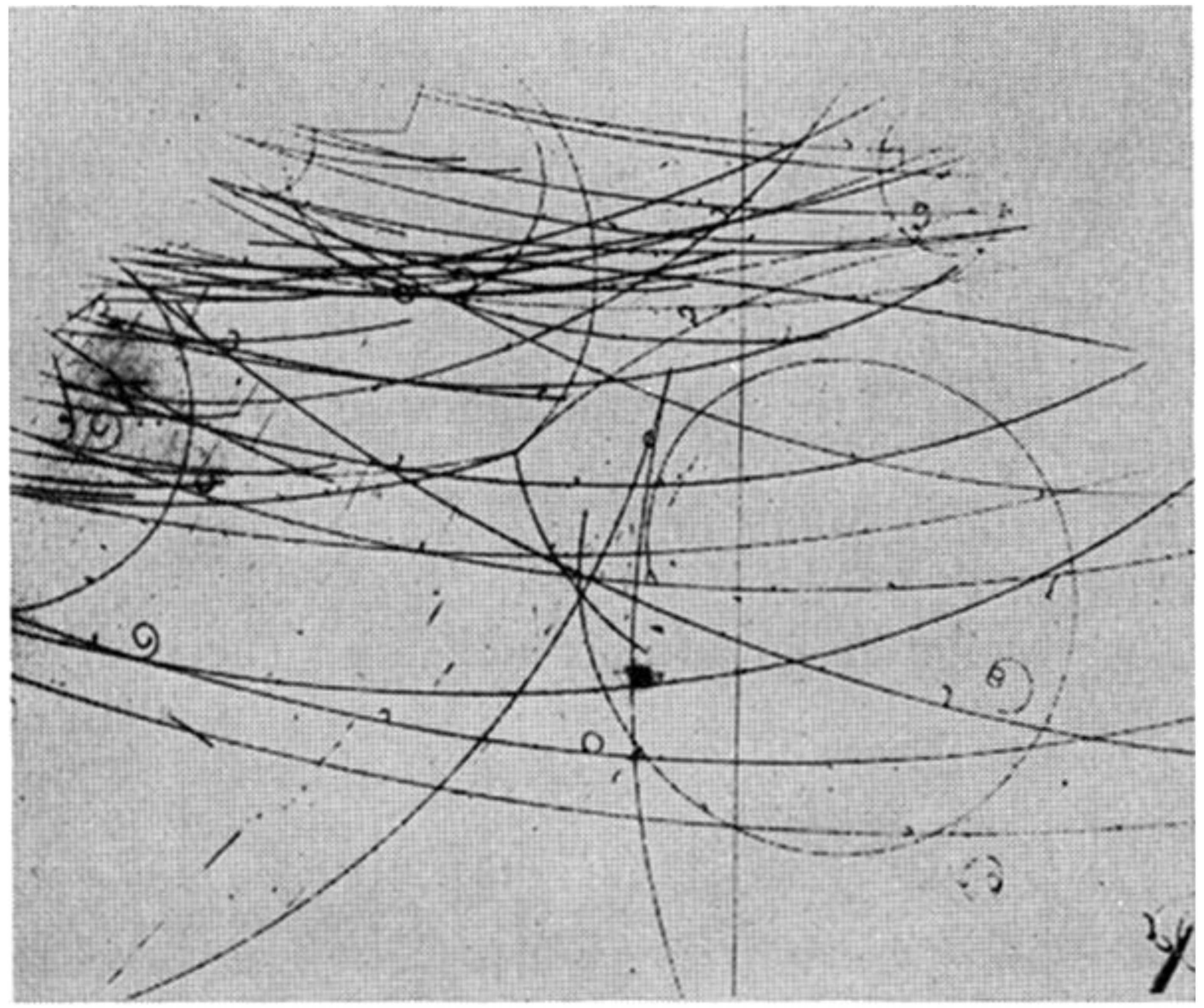


FIG. 1. Photograph of a typical double internal conversion.

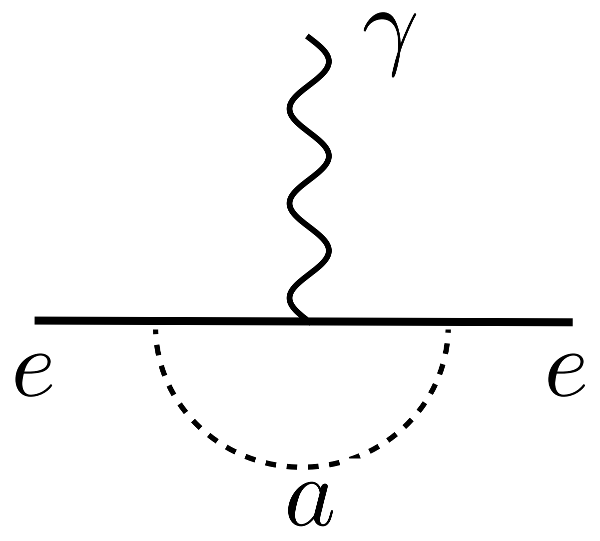
Samios *et al.*, *Phys. Rev.* **126**, 1844 (1962)

Factor of ~30 higher than the pion double-Dalitz decay, $\pi^0 \to 2\,(\gamma^* \to e^+e^-)$, measured in 1962 in bubble chamber pictures, with a sample of 8 million neutral pions.

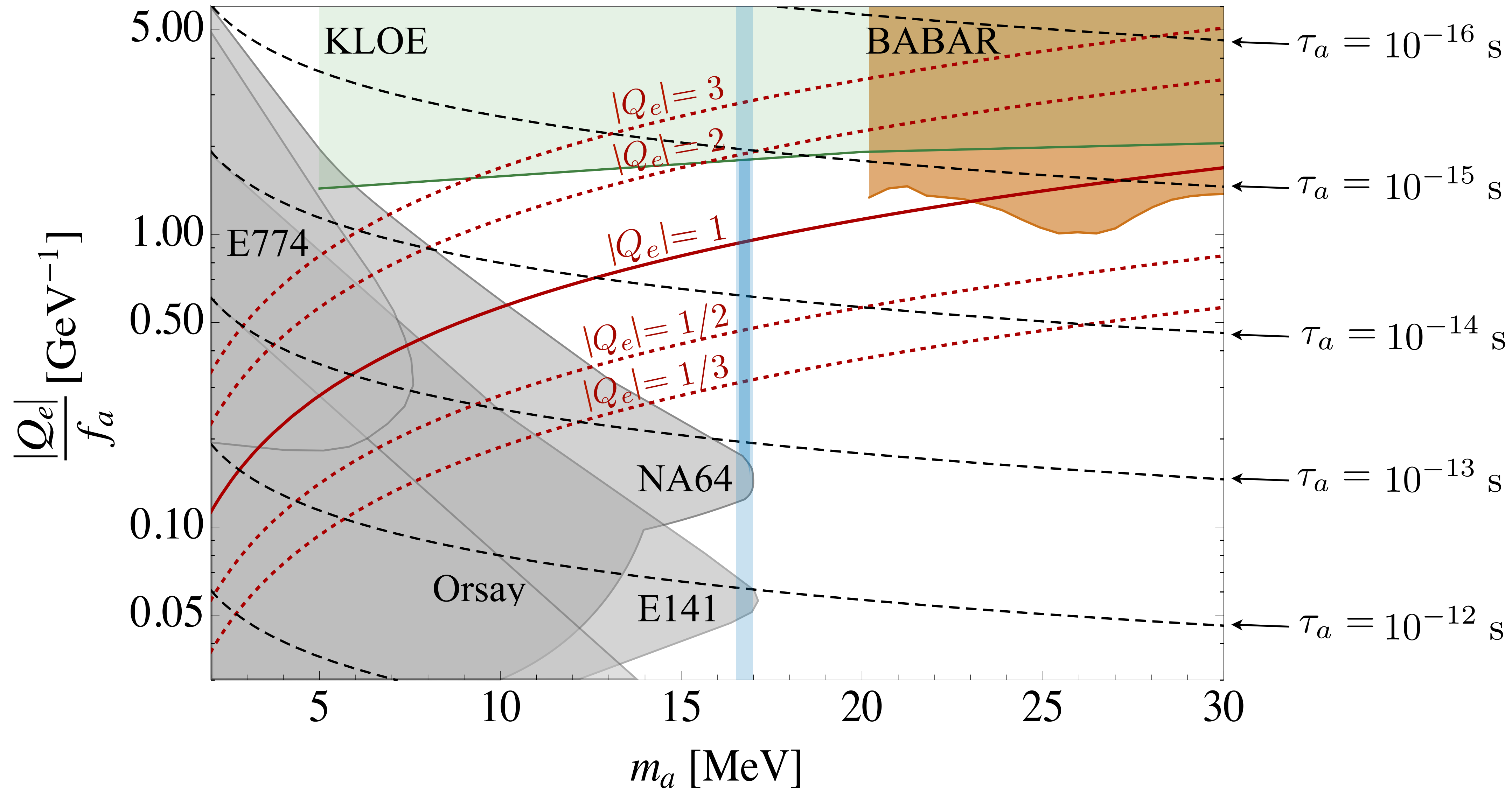
Unclear whether this is definitively excluded, but could be searched for in dedicated analysis of experiments with large π^0 samples (from K, τ, ϕ decays; π^- capture; neutrino experiments; etc)

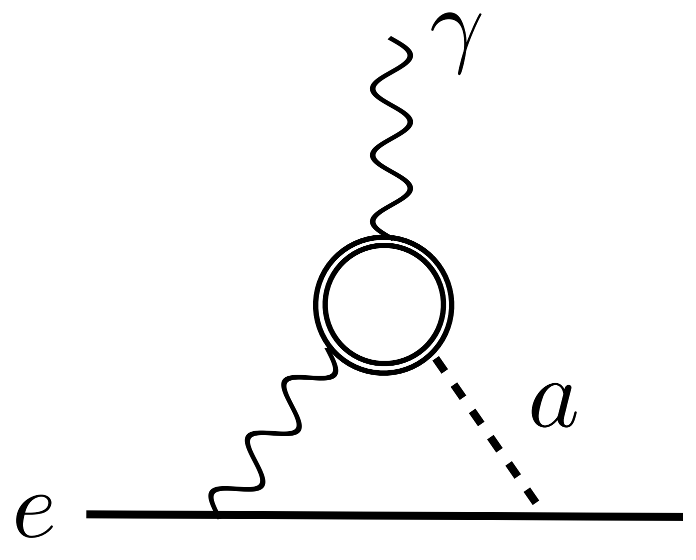
$a(17)$ contributions to $(g-2)_e$

Alves, Weiner, *JHEP* **07**, 092 (2018)
Liu *et al.*, *JHEP* **05**, 138 (2021)



always negative and proportional to $|Q_e^{\mathrm{PQ}}|^2$



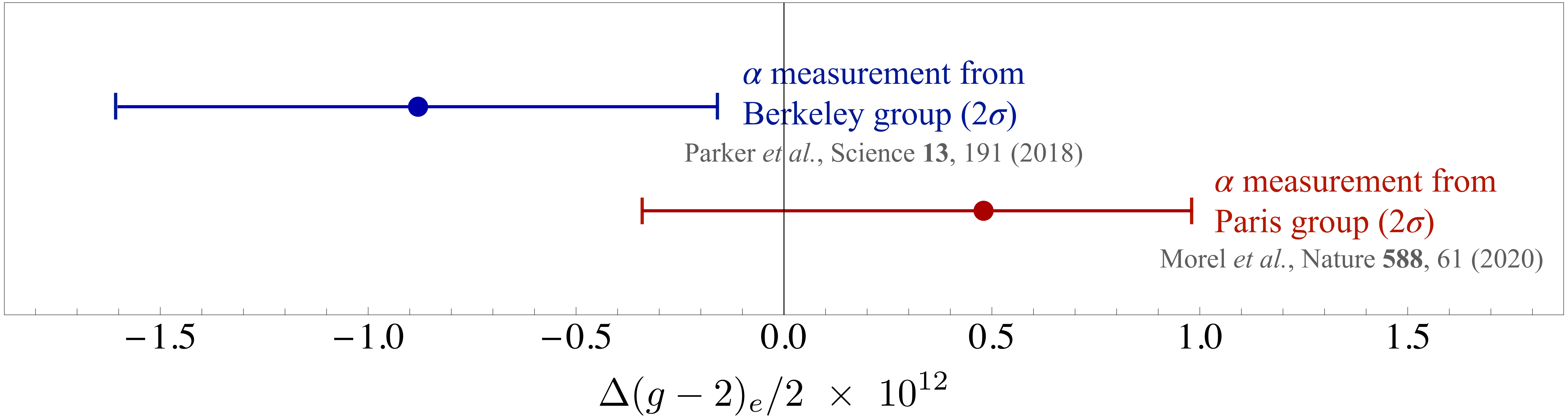


sign proportional to $Q_e^{\mathrm{PQ}} \times g_{a\gamma\gamma} \;=\; Q_e^{\mathrm{PQ}} \times \dfrac{\alpha}{4\pi f_\pi}\underbrace{\left(\theta_{a\pi} + \frac{5}{3}\,\theta_{a\eta_{ud}} + \frac{\sqrt{2}}{3}\,\theta_{a\eta_s}\right)}$

For the range of $a(17)$ isoscalar couplings favored by the ^{8}Be and ^{4}He anomalies, these two contributions are comparable and can significantly interfere

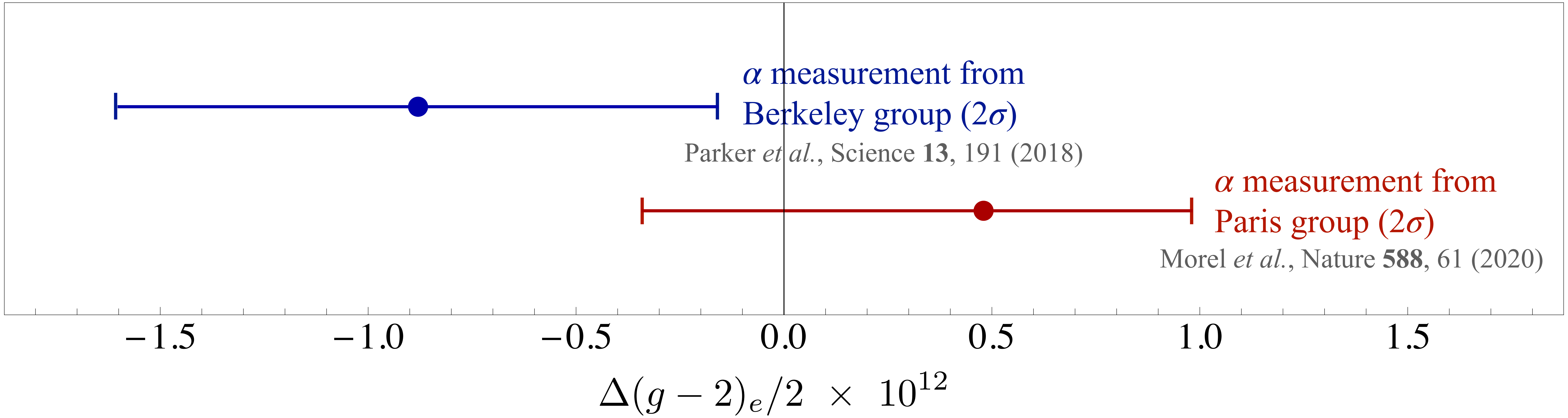
$a(17)$ contributions to $(g-2)_e$

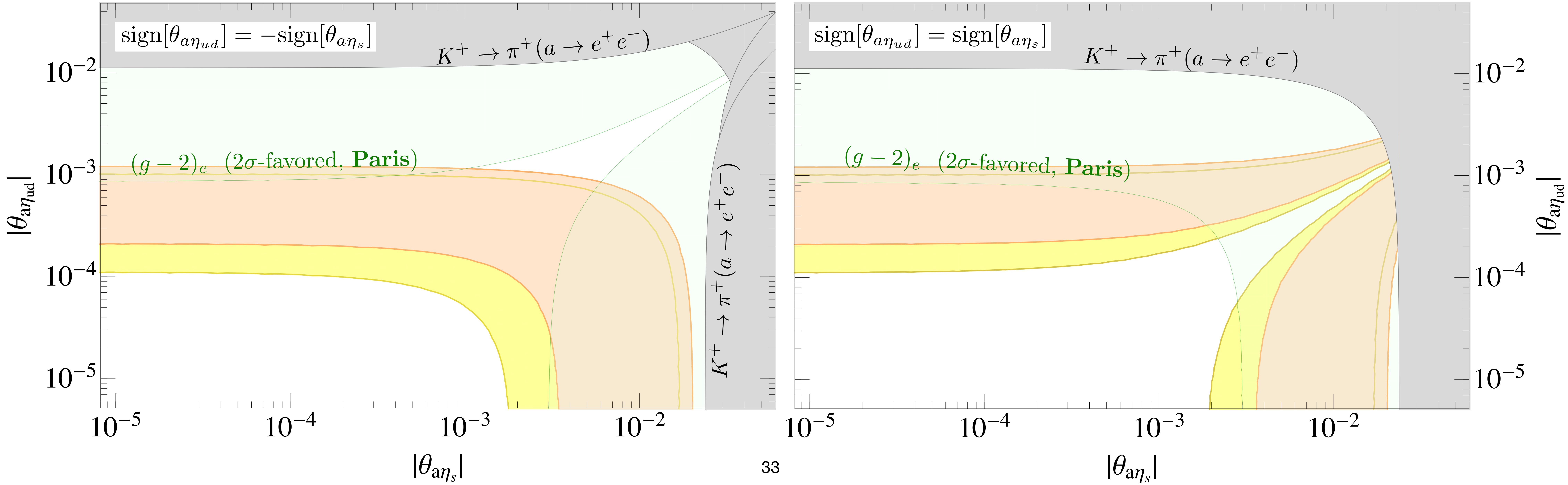
Current experimental range for $(g-2)_e$ is ambiguous



$a(17)$ contributions to $(g-2)_e$

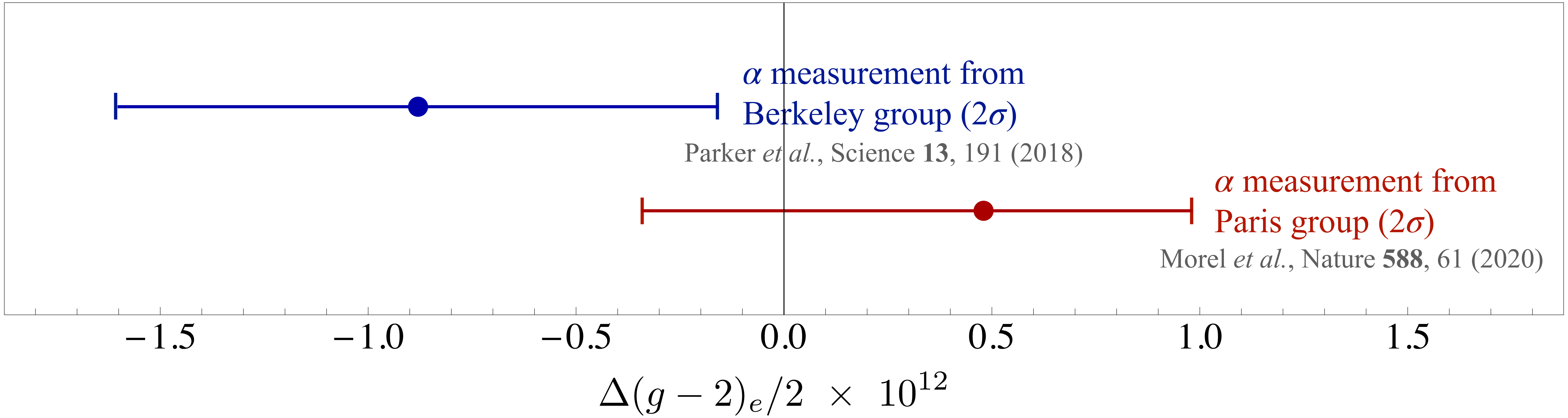
Current experimental range for $(g-2)_e$ is ambiguous

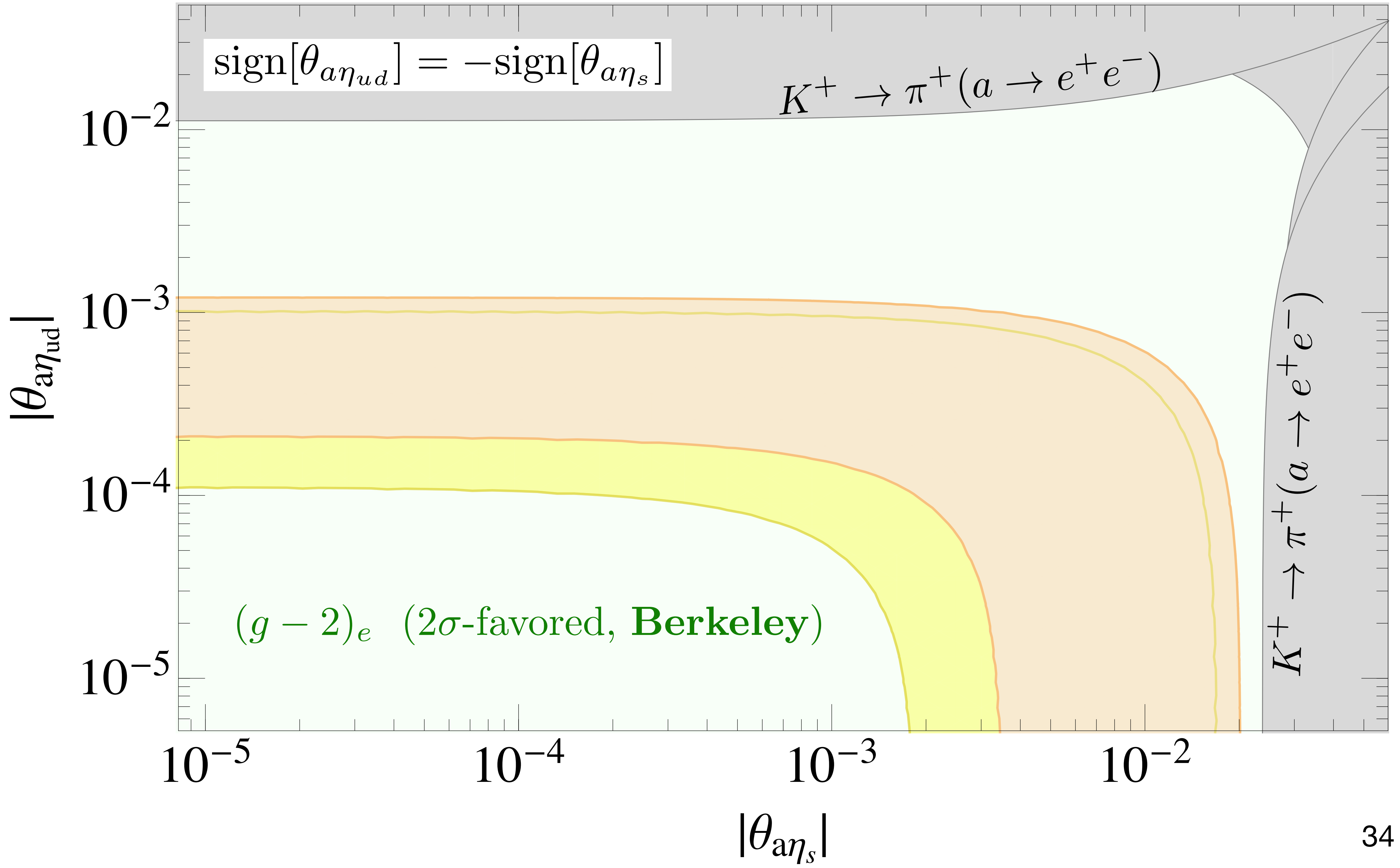


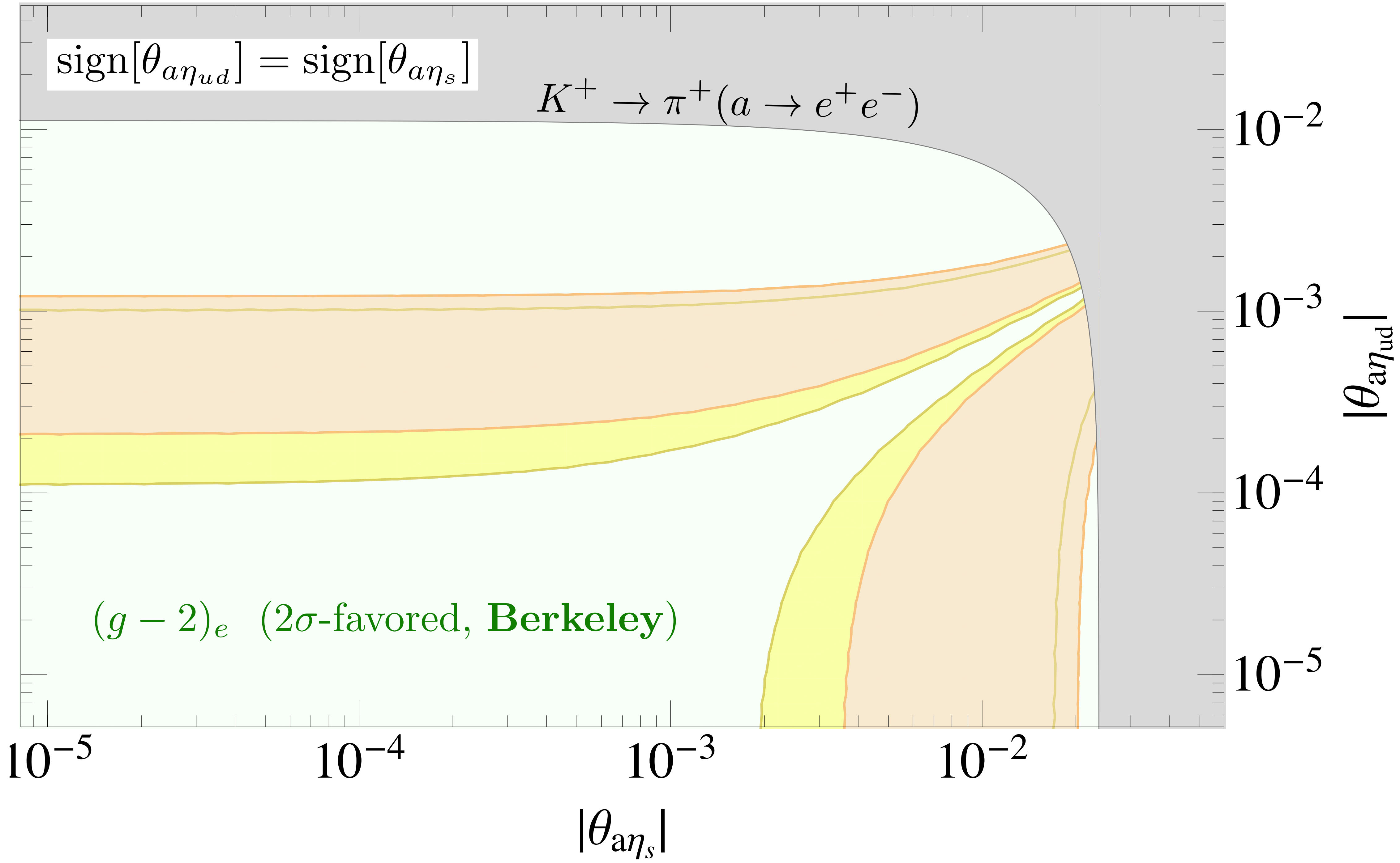


$a(17)$ contributions to $(g-2)_e$

Current experimental range for $(g-2)_e$ is ambiguous







Take away

The QCD axion interpretation of the ~~X17~~ a(17) boson 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 can be probed in upcoming meson factories

Back-up Slides

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

$$\mathcal{L}_{\rm PQSM} \supset \left(m_u\, e^{i\, q^u_{\rm PQ}\, a/f_a}\right) u u^c + \left(m_d\, e^{i\, q^d_{\rm PQ}\, a/f_a}\right) d d^c + \left(m_s\, e^{i\, \overset{\to 0}{\cancel{q^s_{\rm PQ}}}\, a/f_a}\right) s s^c$$

It follows from LO χPT:

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

$\Rightarrow$ accidental cancellation if $\dfrac{q^u_{\rm PQ}}{q^d_{\rm PQ}} = 2$

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

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

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

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

- The axion must 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)

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

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

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

- 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):

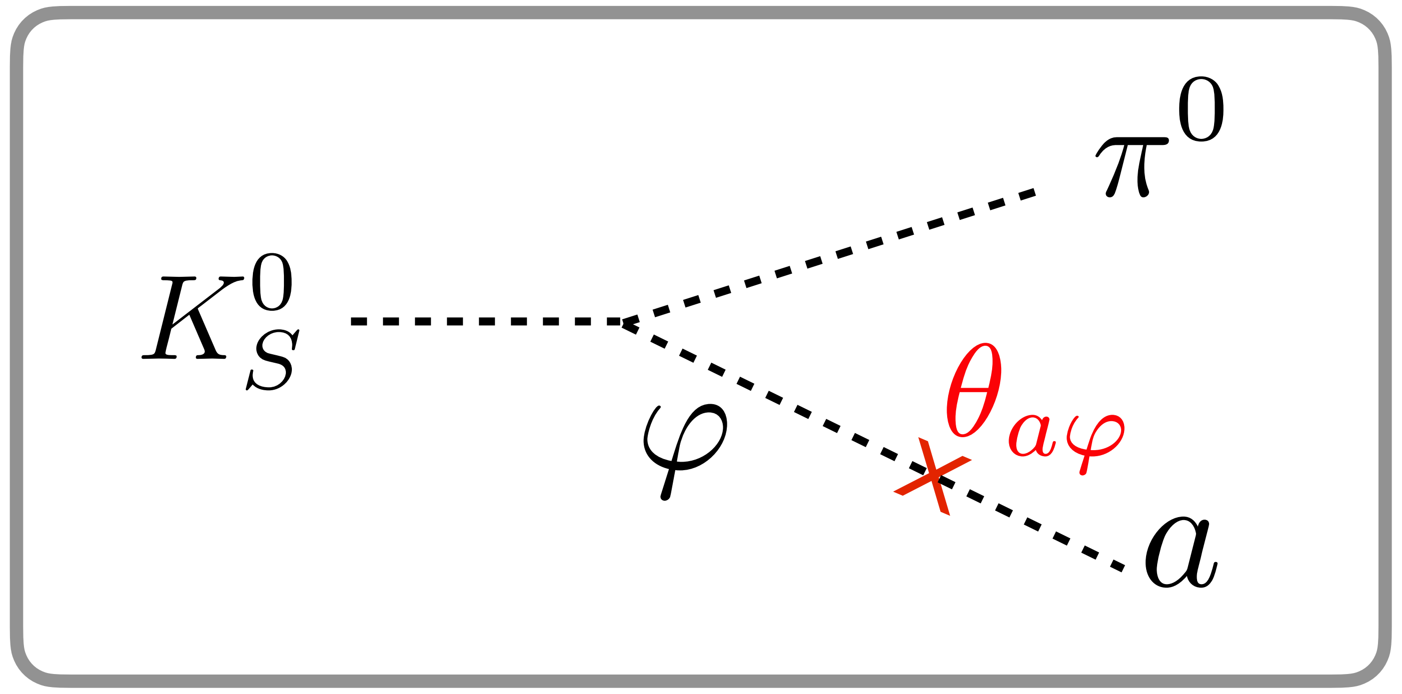
$$J_\mu^{a_{\rm phys}} \equiv f_a\, \partial_\mu a_{\rm phys} \equiv \frac{f_a}{f_\pi}\left(f_\pi\, \partial_\mu a + \theta_{a\pi}\, J_{5\,\mu}^{(3)} + \theta_{a\eta_{ud}}\, J_{5\,\mu}^{(ud)} + \theta_{a\eta_s}\, J_{5\,\mu}^{(s)}\right),$$

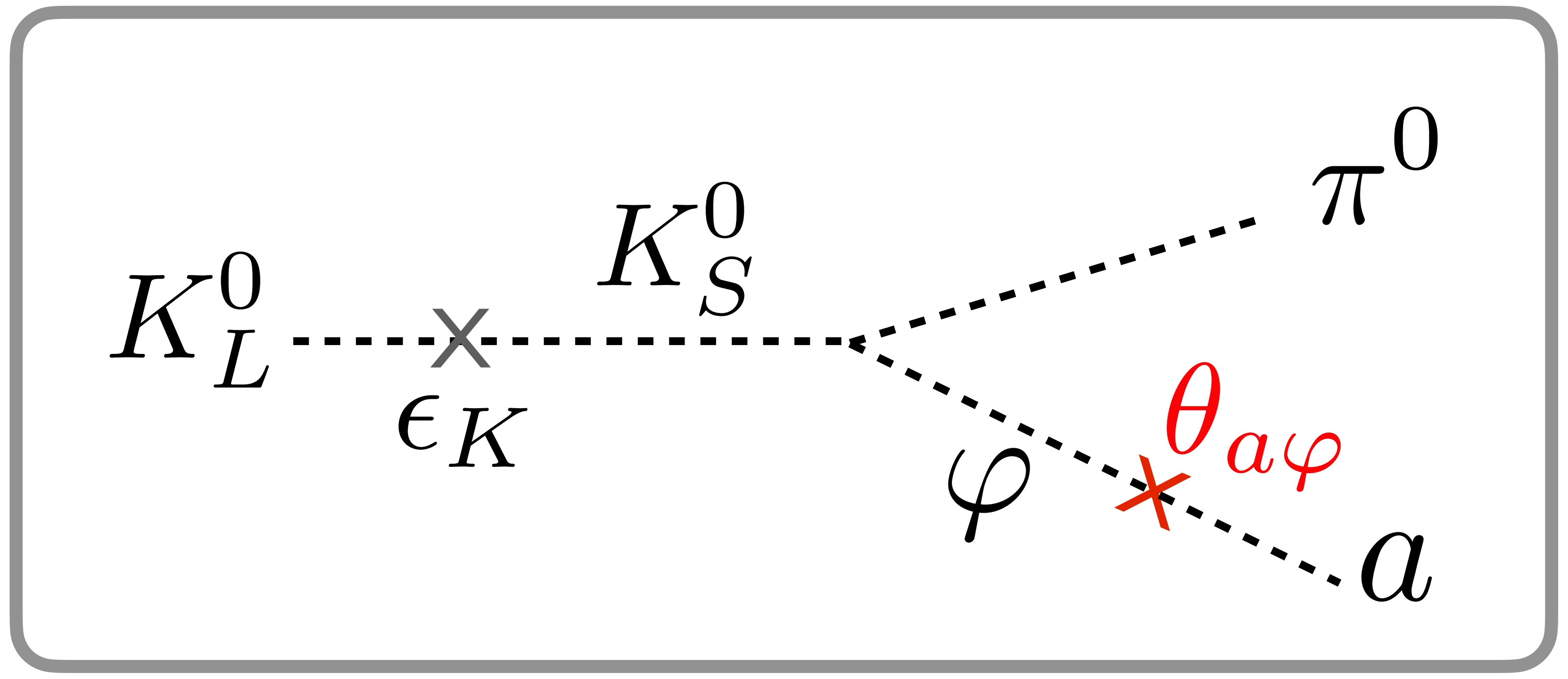
$$\begin{aligned} J_{5\,\mu}^{(3)} &\equiv \frac{\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d}{2} \equiv f_\pi\, \partial_\mu \pi_3\,, \\ J_{5\,\mu}^{(ud)} &\equiv \frac{\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d}{2} \equiv f_\pi\, \partial_\mu \eta_{ud}\,, \\ J_{5\,\mu}^{(s)} &\equiv \frac{\bar{s}\gamma_\mu\gamma_5 s}{\sqrt{2}} \equiv f_\pi\, \partial_\mu \eta_s\,. \end{aligned}$$

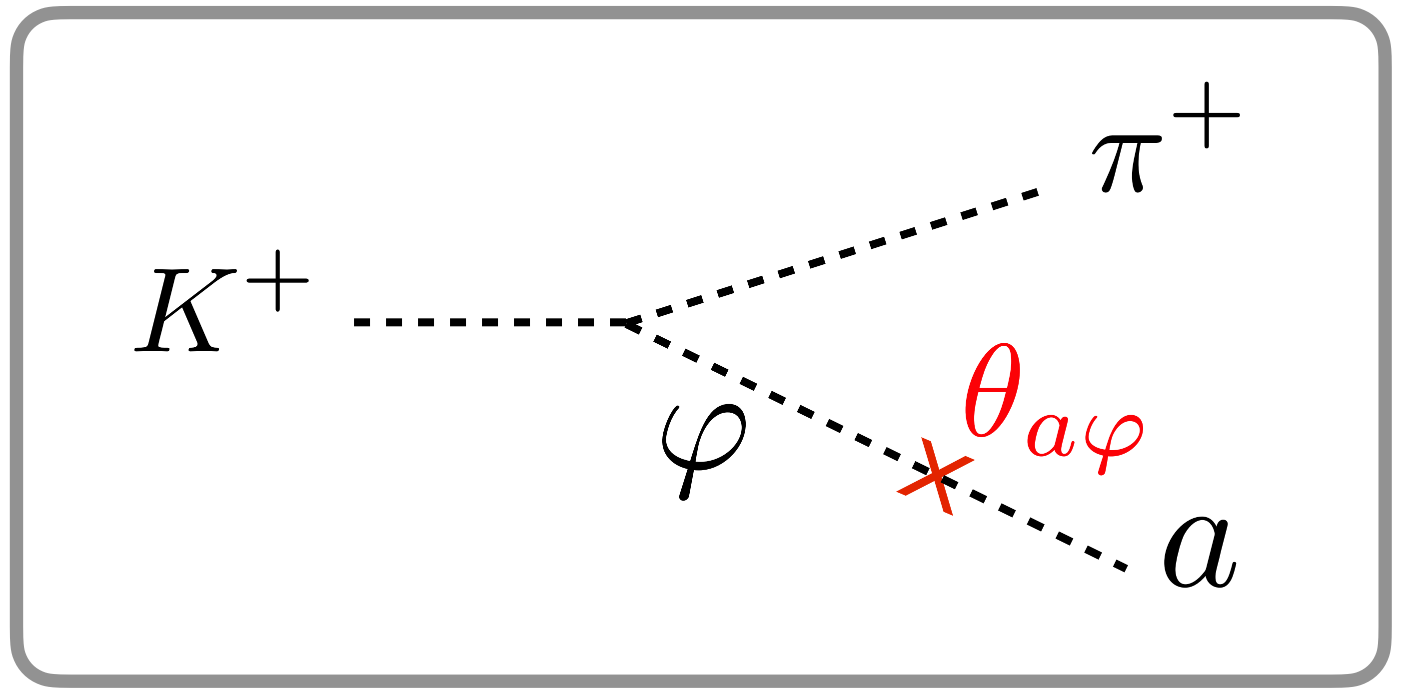
The d.o.f.'s $a,\, \pi_3,\, \eta_{ud},\, \eta_s$ mix amongst themselves to yield the mass eigenstates $a_{\rm phys},\, \pi^0,\, \eta,\, \eta'$

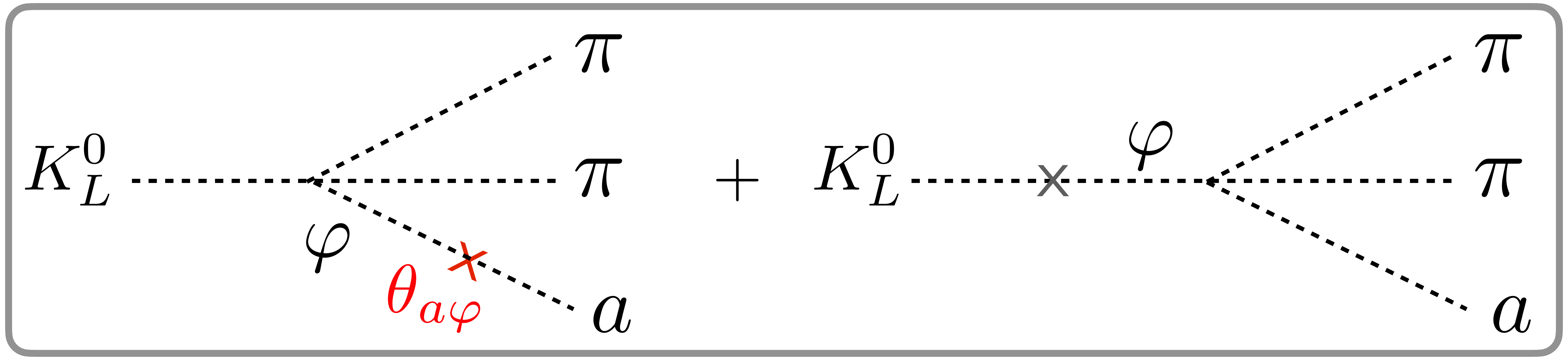
Axionic Kaon decays follow from SM amplitudes weighted by axion-meson mixing angles

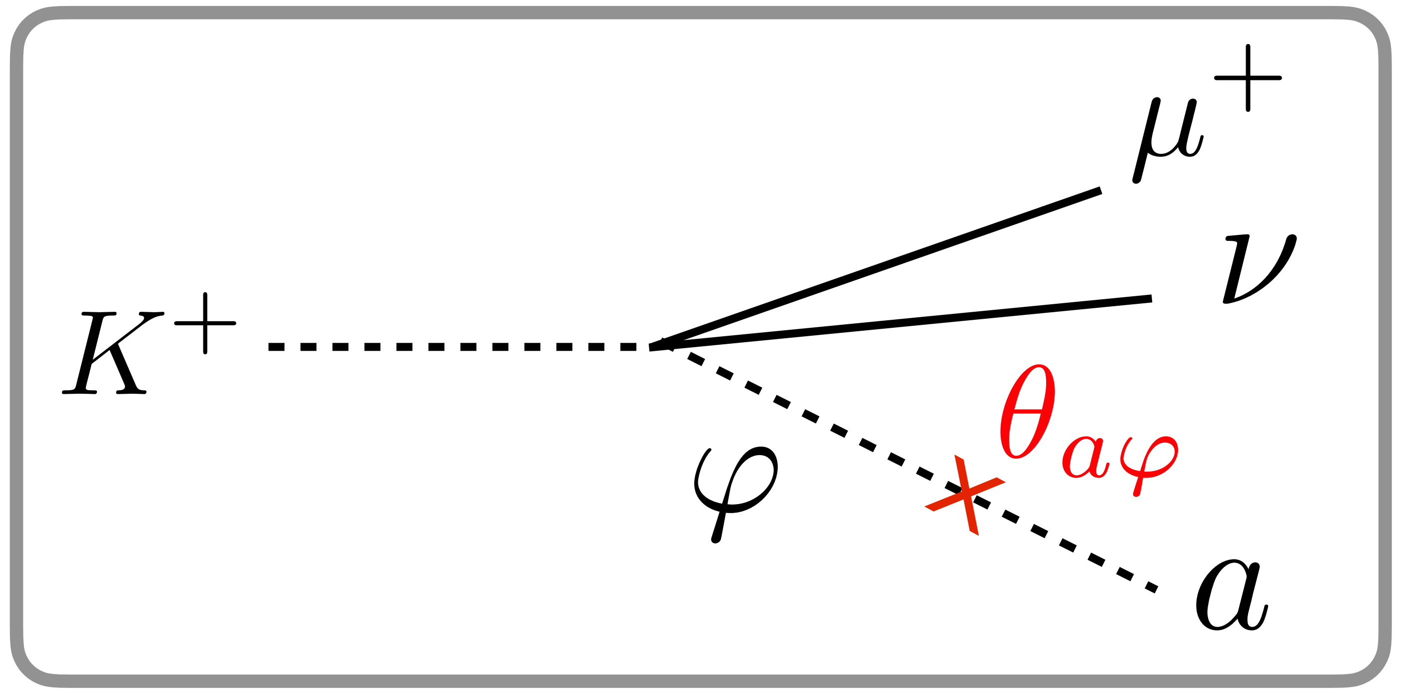
$$\varphi \equiv \pi^0,\ \eta_{ud}\ ,\ \eta_s$$

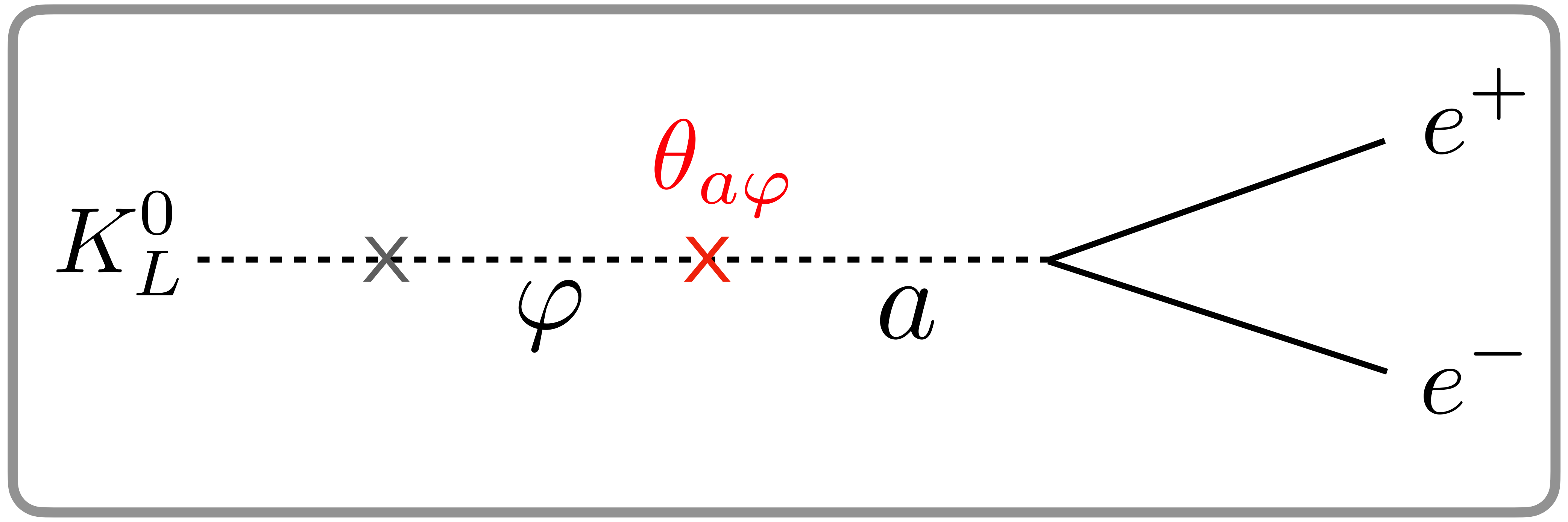










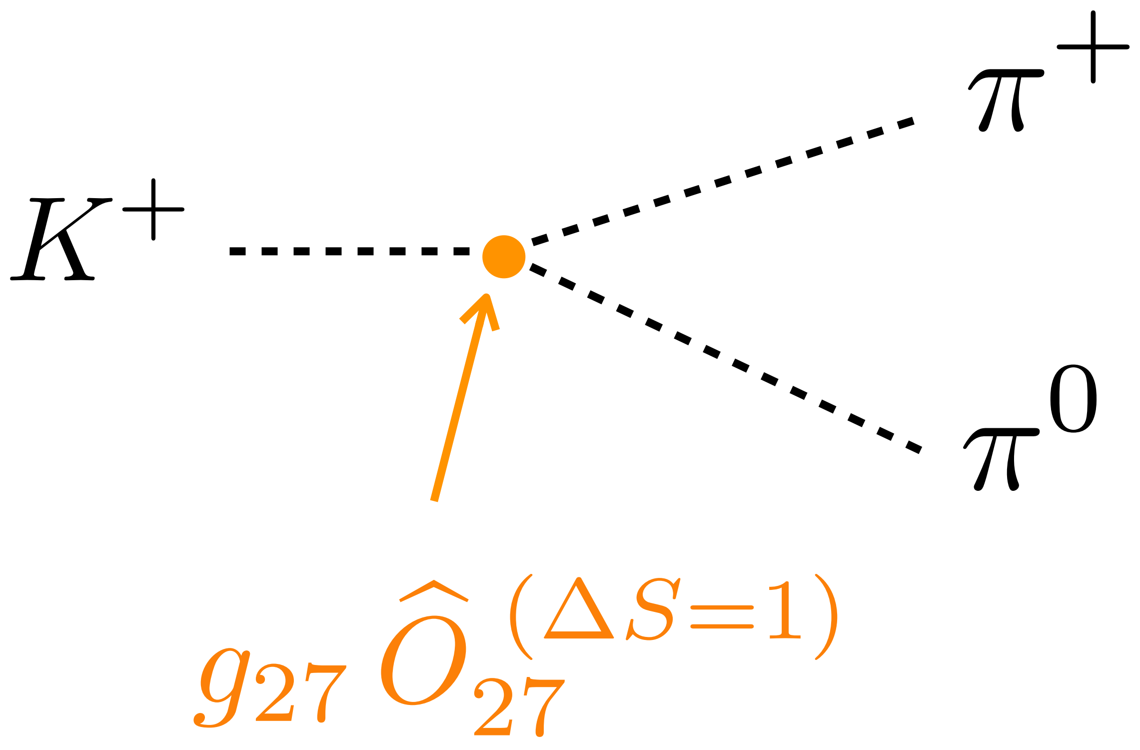


<u>Subtlety</u>: *octet enhancement*

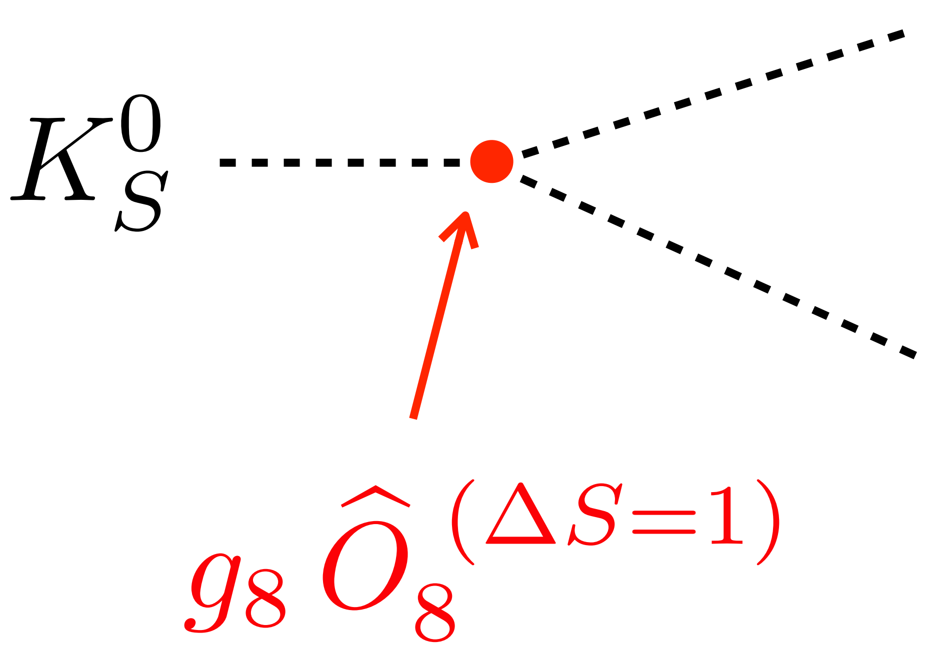
In the SM, there are large disparities between the hadronic widths of different Kaon states,

e.g.,

$\Gamma_{K^+} \sim \mathcal{O}(10^{-8})\,\mathrm{eV}$



$\Gamma_{K_S} \sim \mathcal{O}(10^{-5})\,\mathrm{eV}$



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,

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

standard implementation

or

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

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

New hadronic states at the GeV scale

Since PQ symmetry is broken at the GeV scale, new states are needed:

$$\underset{\substack{\uparrow \\ q_{\rm PQ}^{\Phi_u} = 2}}{}\qquad \underset{\substack{\uparrow \\ q_{\rm PQ}^{\Phi_d} = 1}}{}$$

$$\boxed{y_u\, \underset{\substack{\uparrow \\ q_{\rm PQ}^{\Phi_u} = 2}}{\Phi_u}\, u u^c \;+\; y_d\, \underset{\substack{\uparrow \\ q_{\rm PQ}^{\Phi_d} = 1}}{\Phi_d}\, d d^c \;+\; y_e\, \Phi_e\, e e^c \;+\; V(\Phi_u\,, \Phi_d\,, \Phi_e)}$$

PQ charges and PQ breaking are enforced via potential:

$$\Phi_u \;=\; \left(\frac{f_u}{\sqrt{2}} + \frac{\varphi_u}{\sqrt{2}}\right)\, \mathrm{Exp}\, i \left(q_{\rm PQ}^{\Phi_u} \frac{a}{f_a} \;+\; \frac{q_{\rm PQ}^{\Phi_d}}{\tan\beta_{\rm PQ}} \frac{\eta_{\rm PQ}}{f_a} \right)$$

$$\Phi_d \;=\; \left(\frac{f_d}{\sqrt{2}} + \frac{\varphi_d}{\sqrt{2}}\right)\, \mathrm{Exp}\, i \left(q_{\rm PQ}^{\Phi_d} \frac{a}{f_a} \;-\; q_{\rm PQ}^{\Phi_u} \tan\beta_{\rm PQ} \frac{\eta_{\rm PQ}}{f_a} \right)$$

$$\tan\beta_{\rm PQ} \;\equiv\; f_u / f_d \qquad\qquad f_a^2 \;\equiv\; (q_{\rm PQ}^{\Phi_u})^2\, f_u^2 \;+\; (q_{\rm PQ}^{\Phi_d})^2\, f_d^2$$

New hadronic states at the GeV scale

4 new d.o.f. at GeV scale

$$\underbrace{\varphi_u\ ,\varphi_d}_{\text{scalars}} \qquad\qquad \underbrace{a\ ,\eta_{\rm PQ}}_{\text{pseudoscalars}}$$

(must be EW singlets, and therefore couple to fermions via higher dimensional operators)

$\varphi_u\ ,\varphi_d$ couple hadronically and could in principle have not been identified if lying in the mass range of ~ 500 MeV − 2 GeV

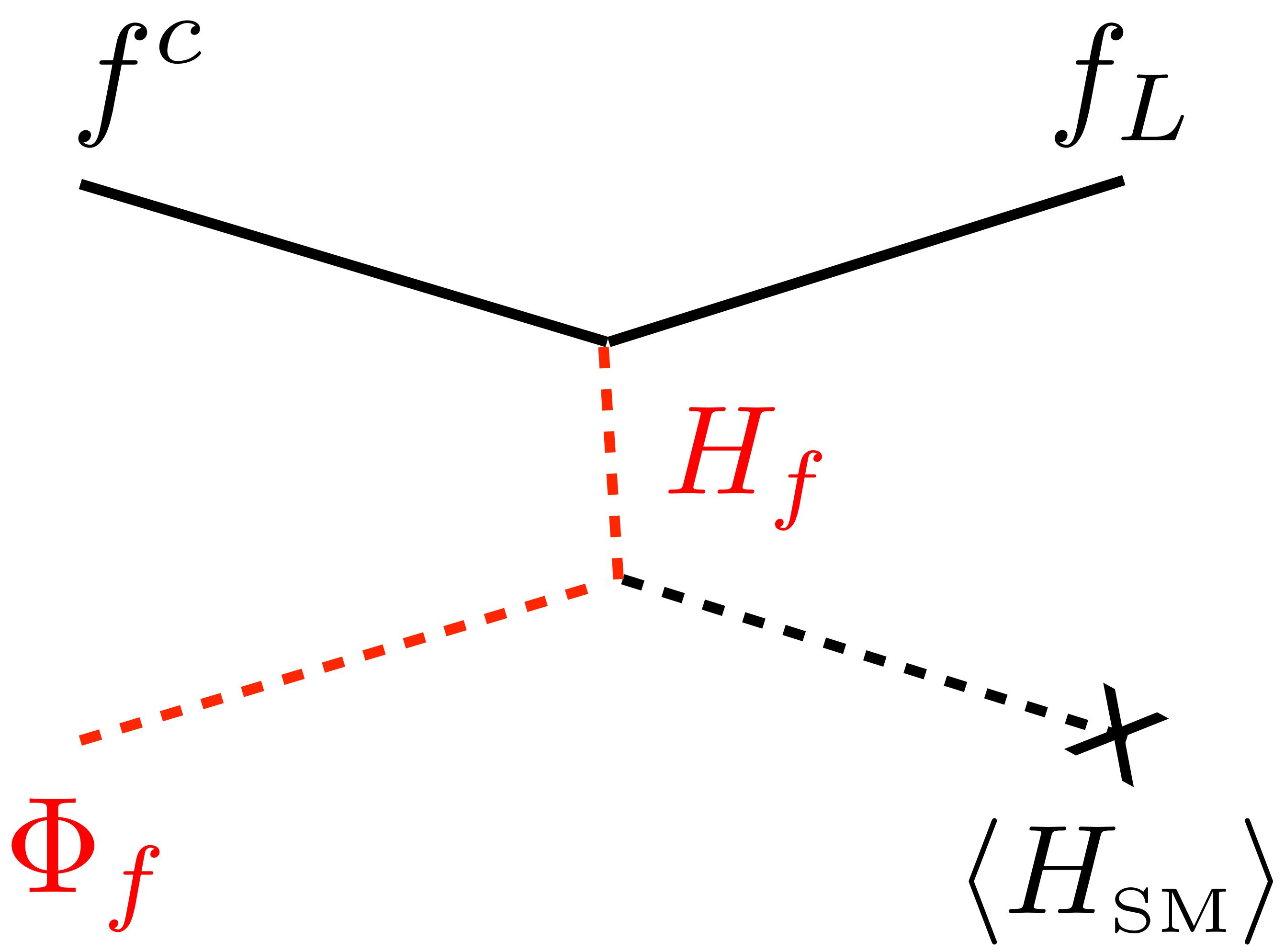
$$\eta_{\rm PQ}\ \text{could hide in 1300 − 1500 MeV mass range}\ \left\{\begin{array}{l}\text{backgrounds from } \eta(1295)\ /\ \eta(1405)\ /\ \eta(1475) \\[1ex] \text{more dramatically, it could be identified with} \\ \eta(1295)\ /\ \eta(1405)\ /\ \eta(1475)\ \text{if broad enough}\end{array}\right.$$

Completion at the weak scale

$y_f\, \Phi_f\, f\, f^c$ is a higher dimensional operator

Can be generated by introducing:

- Heavy scalar doublets:



- Heavy vectorlike fermions: