A viable QCD axion variant in the MeV mass range

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Strong CP problem

QCD allows for a strong CP phase

$$\theta \, G\tilde{G}$$

bounds on neutron EDM $\longrightarrow \quad \theta \lesssim 10^{-10}$

Why is θ so small?

$$\text{Possible explanations} \begin{cases} m_u = 0 \ \ \text{(disfavored by Lattice)} \\ \text{spontaneous } \cancel{CP} \\ \text{anomalous PQ symmetry} \rightarrow \text{axion} \end{cases}$$

The QCD axion

PQ symmetry is spontaneously broken at scale f_a

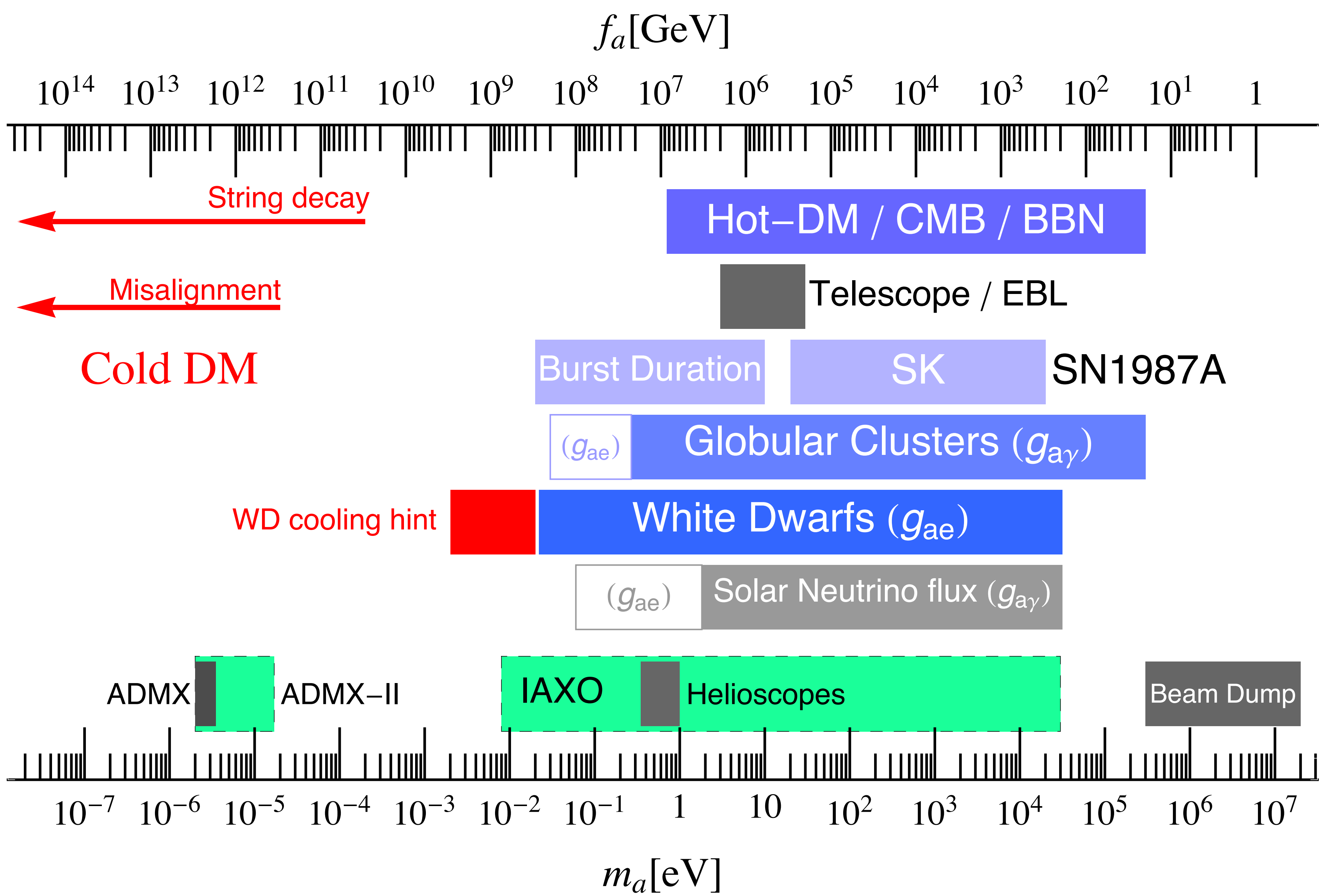
The resulting (pseudo-)Goldstone boson, the axion, has its interactions set by $1/f_a$:

$$\frac{1}{f_a}\,\frac{\alpha_i}{4\pi}\,a\,F_i\tilde{F}_i \qquad , \qquad \frac{1}{f_a}\,\partial_\mu a\,J^\mu$$

Chiral symmetry breaking and QCD non-perturbative effects generate a mass for the axion:

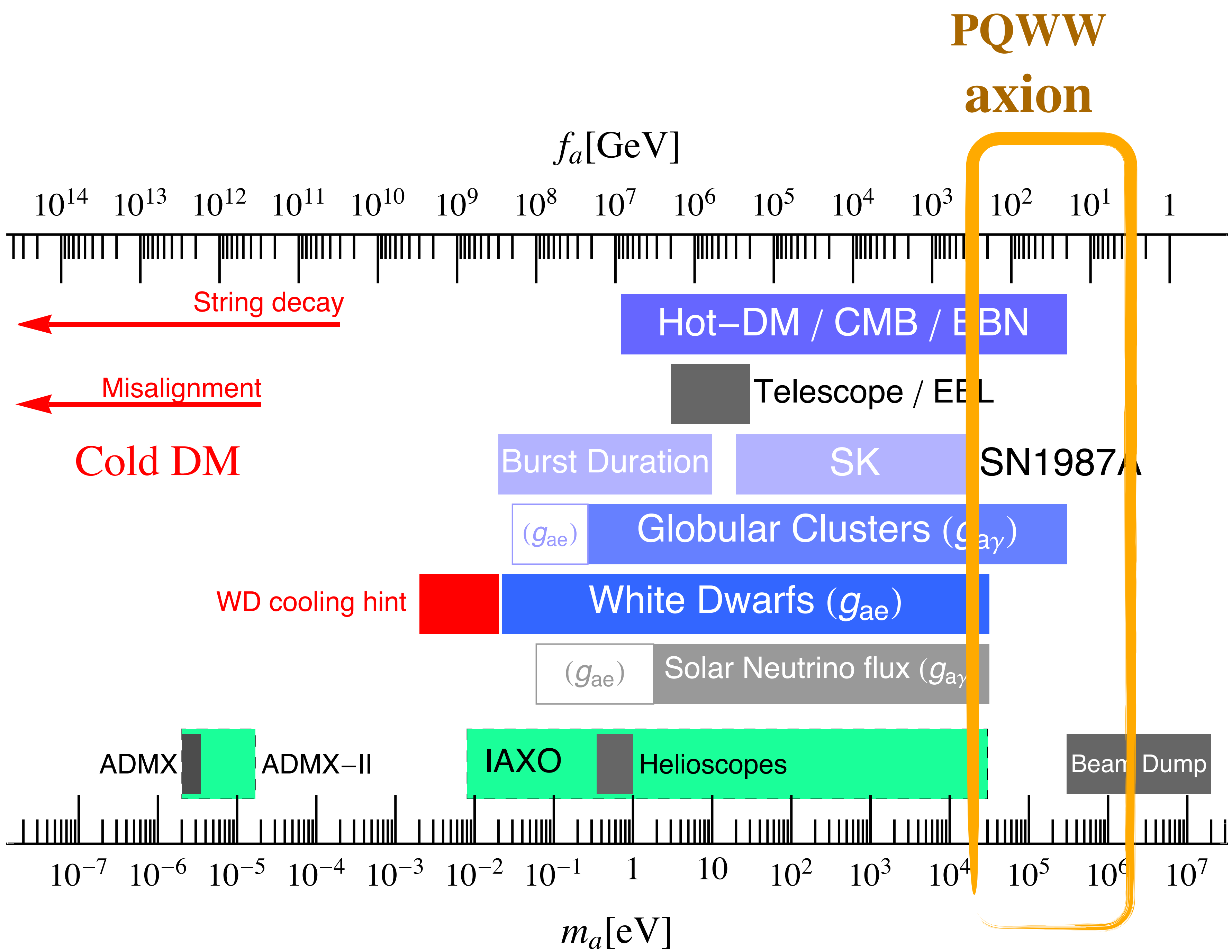
$$m_a \propto \frac{m_\pi f_\pi}{f_a}$$

The QCD axion



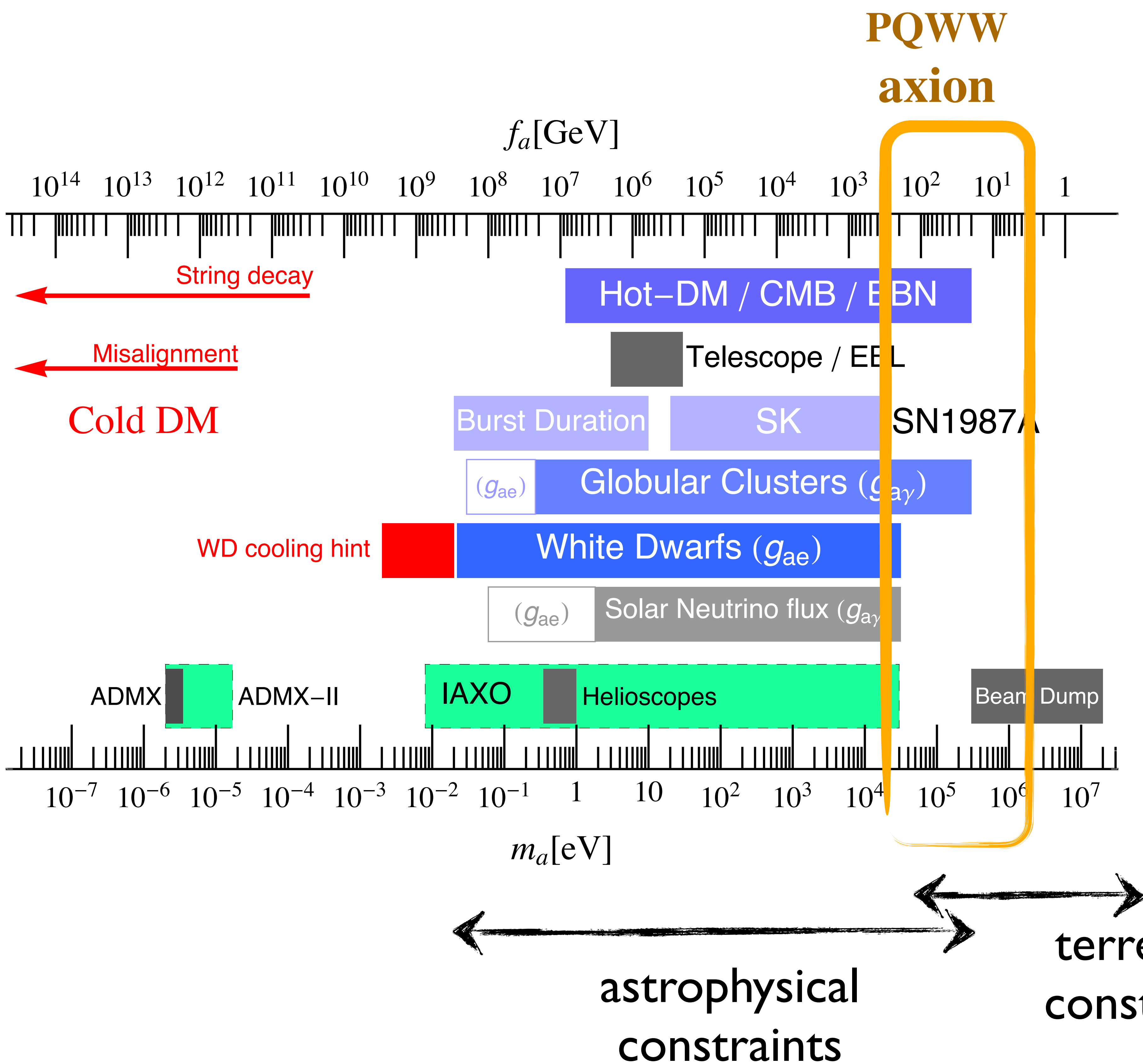
PDG review

The QCD axion



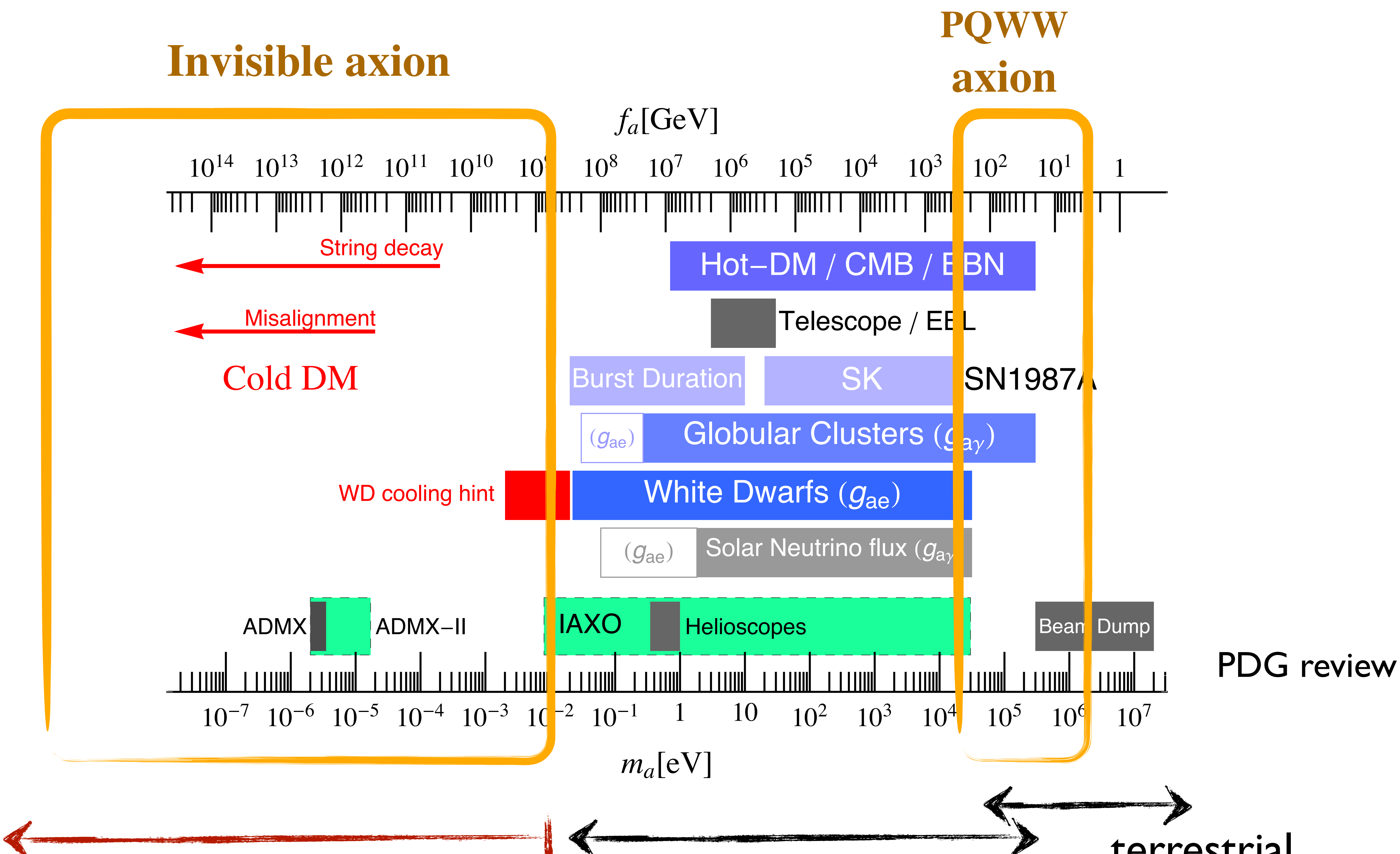
PDG review

The QCD axion



PDG review

The QCD axion



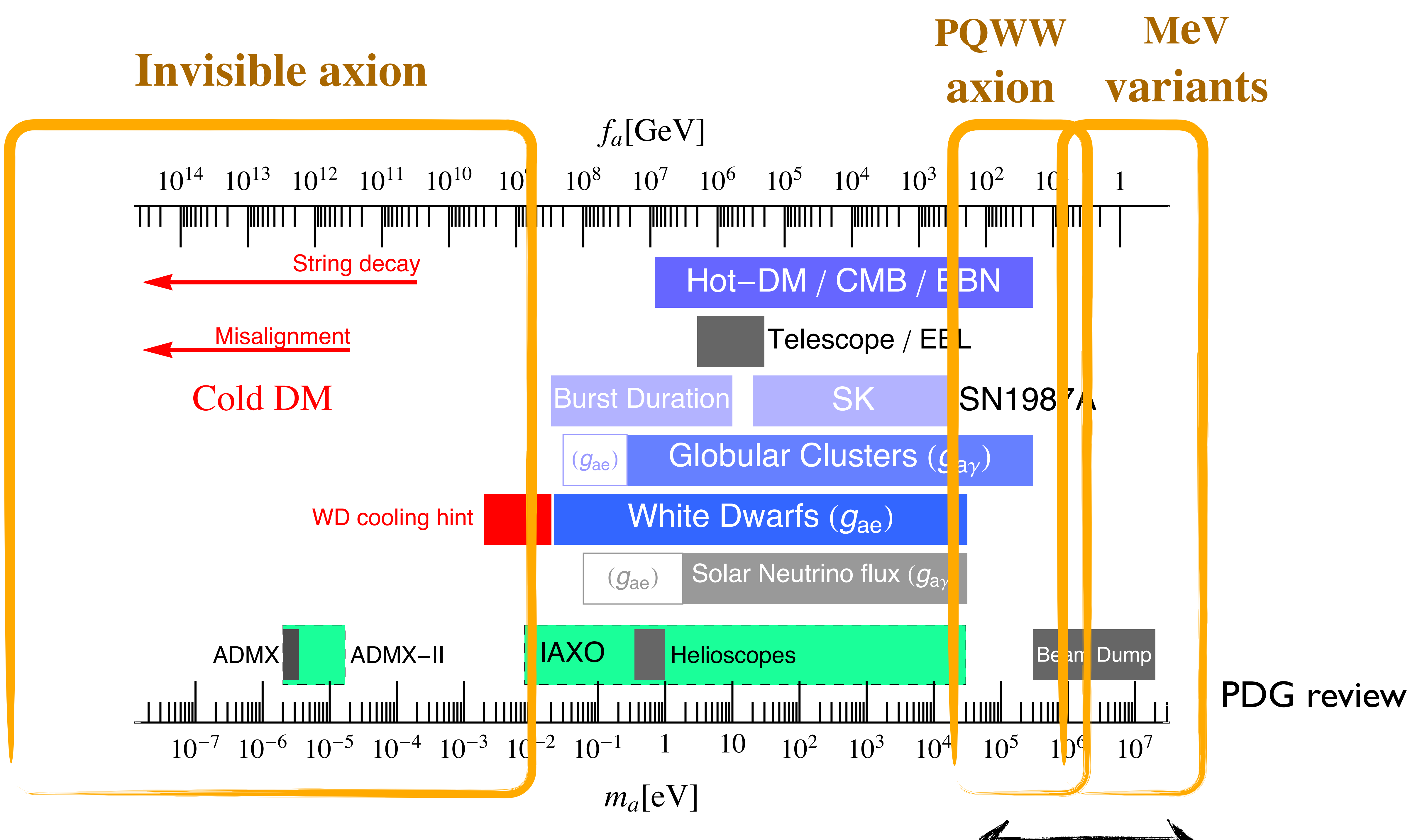
experimental focus

ADMX, CAST, IAXO, PVLS, ALPS-II, CASPEr, ABRACADABRA, ...

astrophysical constraints

terrestrial constraints

The QCD axion



experimental focus

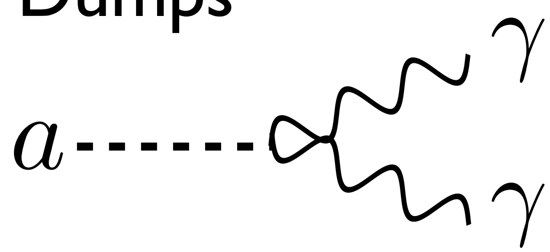
ADMX, CAST, IAXO, PVLS, ALPS-II, CASPEr, ABRACADABRA, ...

astrophysical constraints

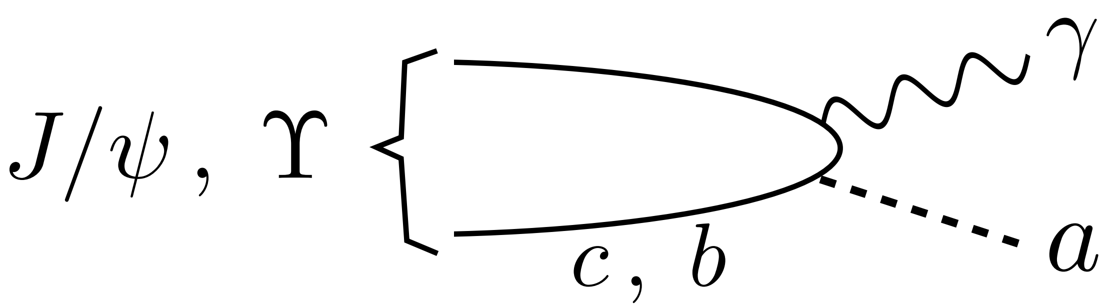
terrestrial constraints

Major constraints on the QCD axion with $\begin{cases} m_a = \mathcal{O}(\mathrm{MeV}) \\ f_a = \mathcal{O}(\mathrm{GeV}) \end{cases}$

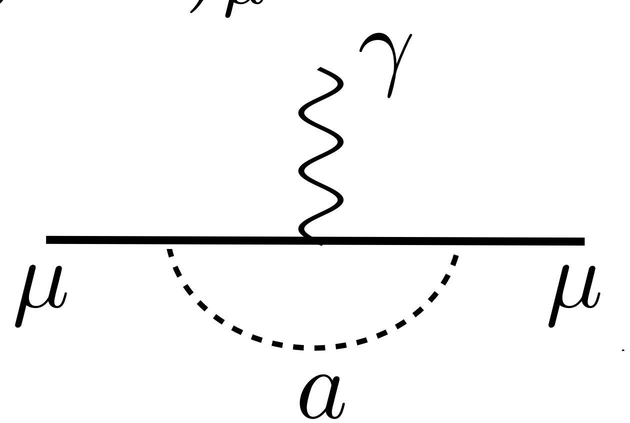
- Beam Dumps



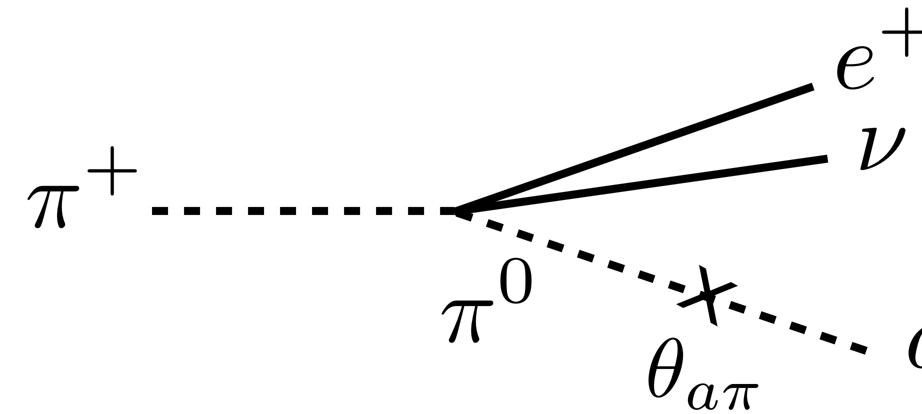
- Quarkonia Decays



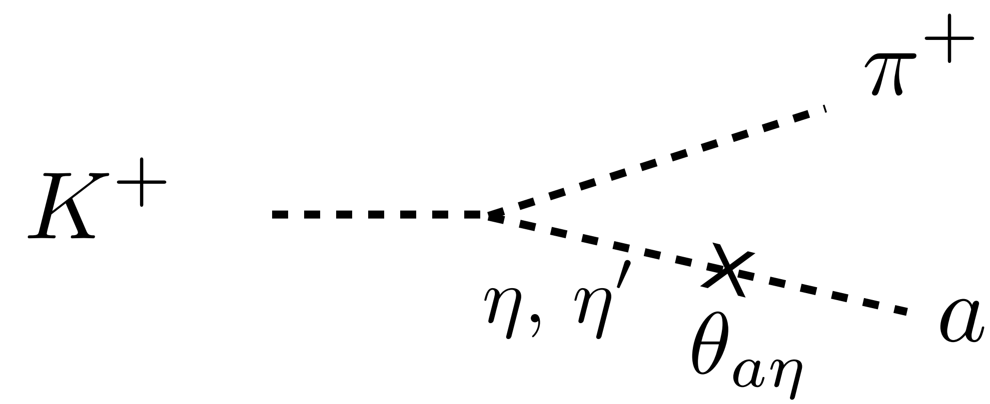
- $(g-2)_\mu$



- Charged Pion Decays



- Charged Kaon Decays



Major constraints on the QCD axion with $\begin{cases} m_a = \mathcal{O}(\mathrm{MeV}) \\ f_a = \mathcal{O}(\mathrm{GeV}) \end{cases}$

For generic QCD axions, these constraints are very severe and rule out $m_a > \mathrm{MeV}$

However, a particular realization of MeV axions might still be viable:

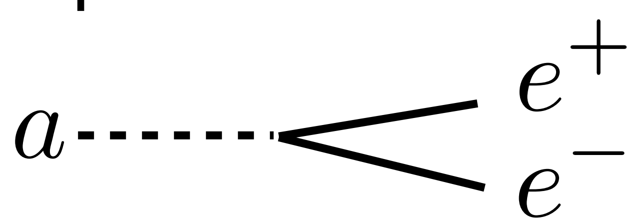
$$2\times \frac{m_u}{f_a}\, a\, \bar{u}\gamma_5 u \quad + \quad 1\times \frac{m_d}{f_a}\, a\, \bar{d}\gamma_5 d \quad + \quad Q_e\times \frac{m_e}{f_a}\, a\, \bar{e}\gamma_5 e$$

and *no further* couplings to $G_{\mu\nu}\tilde{G}^{\mu\nu}$, nor to 2^{nd} and 3^{rd} generations

Major constraints on the QCD axion with $\begin{cases} m_a = \mathcal{O}(\mathrm{MeV}) \\ f_a = \mathcal{O}(\mathrm{GeV}) \end{cases}$

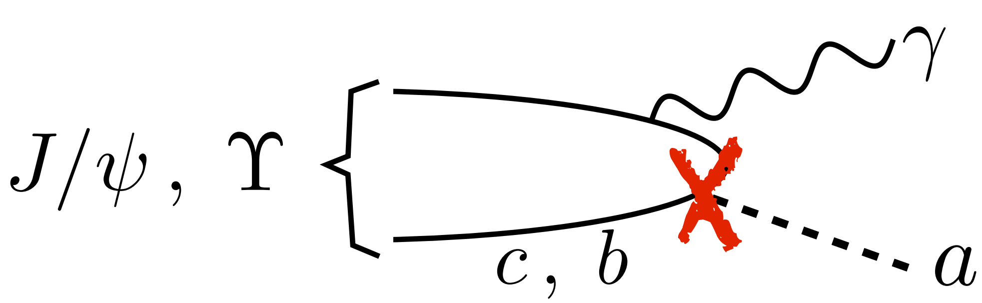
How are constraints avoided?

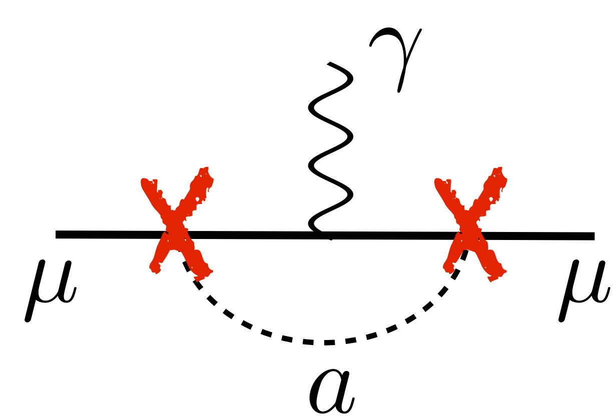
- Beam Dumps



dominant axion decay mode
(lifetime is much shorter)

- Quarkonia Decays, $(g-2)_\mu$



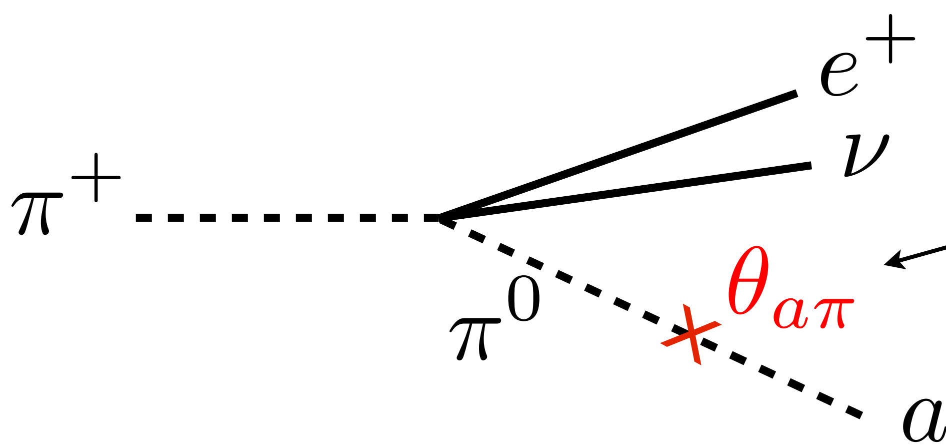


trivially avoided by forbidding couplings to charm, bottom, muon

Major constraints on the QCD axion with $\begin{cases} m_a = \mathcal{O}(\mathrm{MeV}) \\ f_a = \mathcal{O}(\mathrm{GeV}) \end{cases}$

How are constraints avoided?

- Charged Pion Decays



accidental cancellations suppress this mixing angle

very difficult to estimate reliably

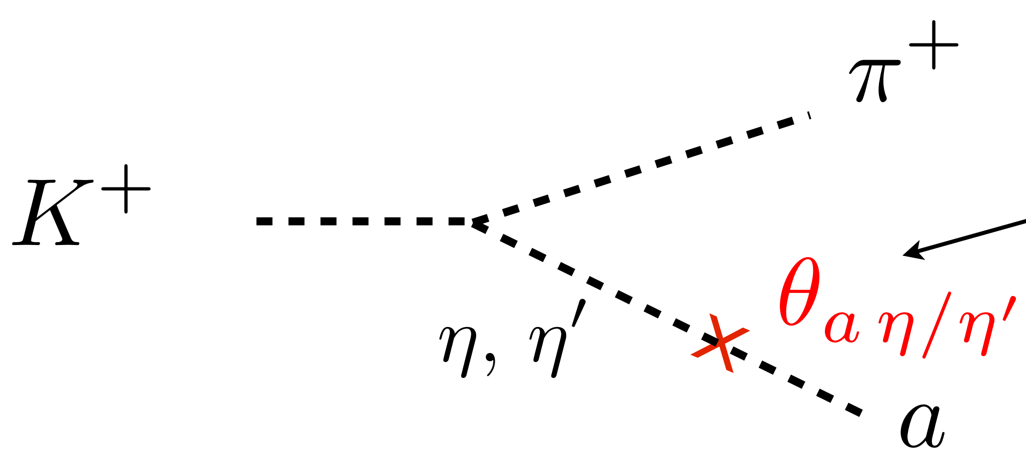
at LO in χPT:
$$\theta_{a\pi}^{\mathrm{LO}} \approx \frac{4}{3}\,\frac{f_\pi}{f_a}\left(\frac{Q_d^{\mathrm{PQ}}(=1)}{Q_u^{\mathrm{PQ}}(=2)} - \frac{m_u}{m_d}\right)$$
$$\approx \frac{(4\ \pm\ 40)\times 10^{-4}}{f_a/\mathrm{GeV}}$$

compatible with bound: $\theta_{a\pi} \lesssim 10^{-4}$

Major constraints on the QCD axion with $\begin{cases} m_a = \mathcal{O}(\mathrm{MeV}) \\ f_a = \mathcal{O}(\mathrm{GeV}) \end{cases}$

How are constraints avoided?

- Charged Kaon Decays



these mixing angles receive large higher order corrections

also very difficult to estimate reliably

at NLO in χPT: $$\theta^{\mathrm{NLO}}_{a\eta/\eta'} \approx \frac{(-2 \pm 3) \times 10^{-3}}{f_a/\mathrm{GeV}}$$

compatible with bound: $$\theta_{a\eta/\eta'} \lesssim 0.4 \times 10^{-3}$$

How to probe this MeV axion?

$$2\times \frac{m_u}{f_a}\, a\, \bar{u}\gamma_5 u \quad + \quad 1\times \frac{m_d}{f_a}\, a\, \bar{d}\gamma_5 d \quad + \quad Q_e\times \frac{m_e}{f_a}\, a\, \bar{e}\gamma_5 e$$

- Via its hadronic couplings

challenging: $\theta_{a\pi}$, $\theta_{a\,\eta}$, $\theta_{a\,\eta'}$ are difficult to estimate reliably

- Via its coupling to the electron $\dfrac{Q_e\, m_e}{f_a}\, a\, \bar{e}\gamma_5 e$

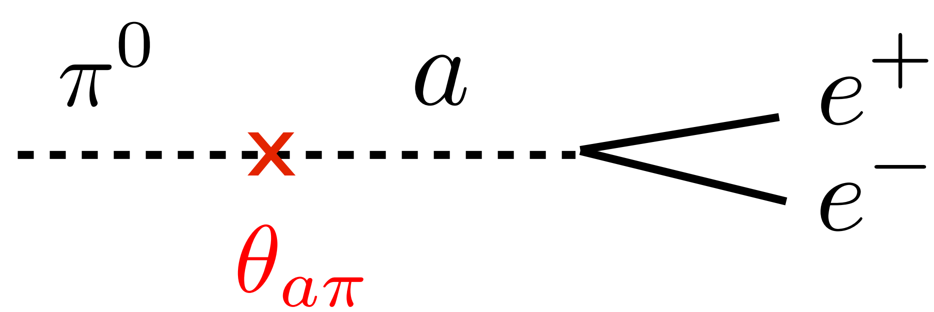
model dependent (Q_e dependence), but calculations are reliable

How to probe this MeV axion?

<u>Via its hadronic couplings</u>

Look for other, very sensitive probes of $\theta_{a\pi}\ ,\ \theta_{a\,\eta}\ ,\ \theta_{a\,\eta'}$

E.g.,



"KTeV anomaly":

measurement high relative to theoretical estimates by ~15% (3σ)

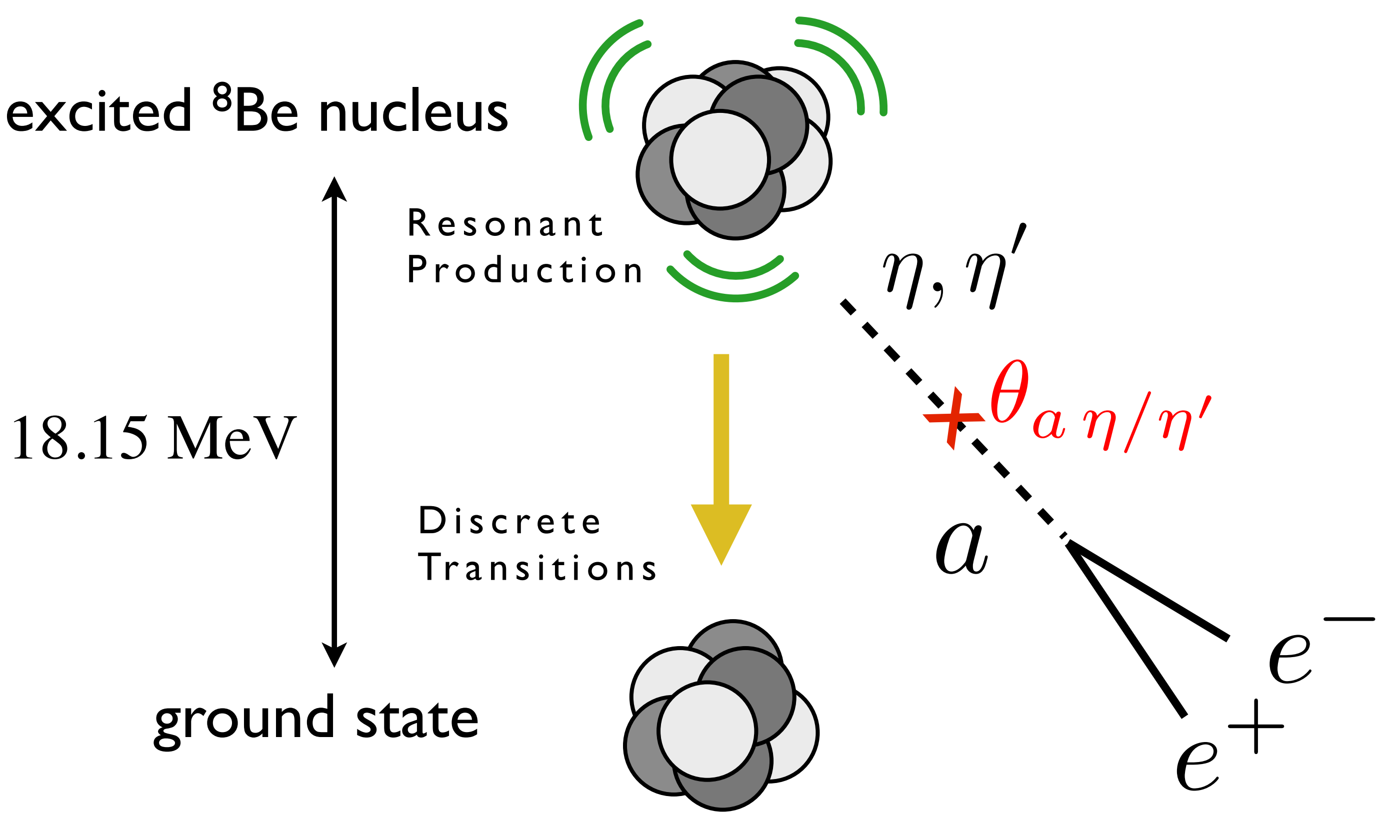
Suggests $\theta_{a\pi} \approx \dfrac{(0.6 \pm 0.2) \times 10^{-4}}{Q_e\ (\mathrm{GeV}/f_a)}$

How to probe this MeV axion?

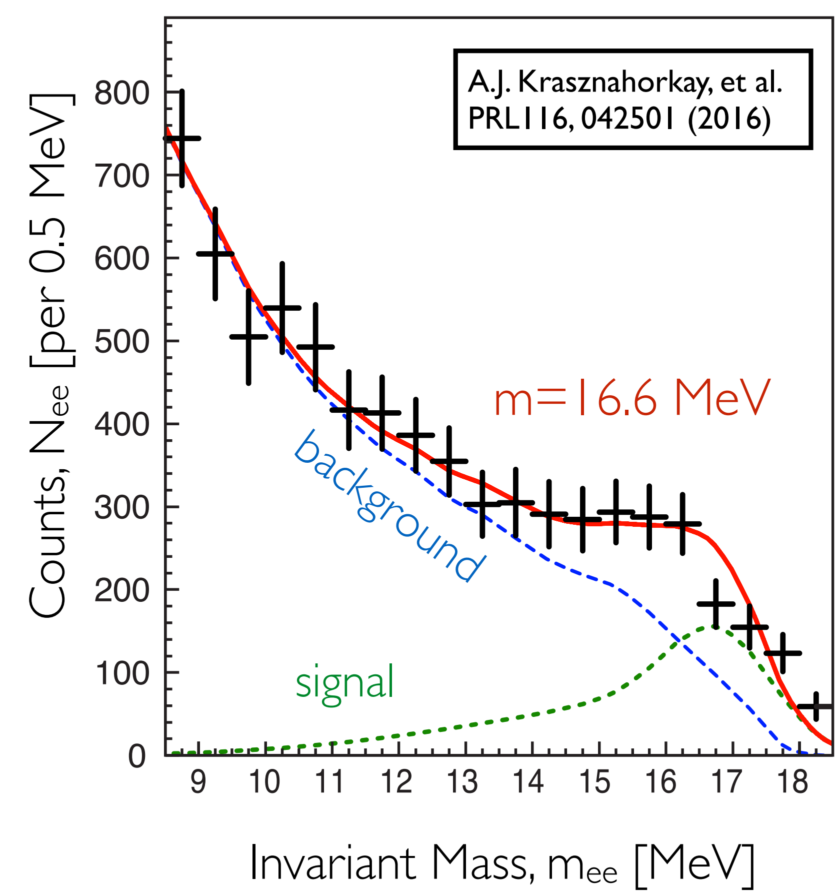
Via its hadronic couplings

Look for other, very sensitive probes of $\theta_{a\pi}$, $\theta_{a\,\eta}$, $\theta_{a\,\eta'}$

" ^{8}Be* anomaly ":



adapted from F. Tanedo



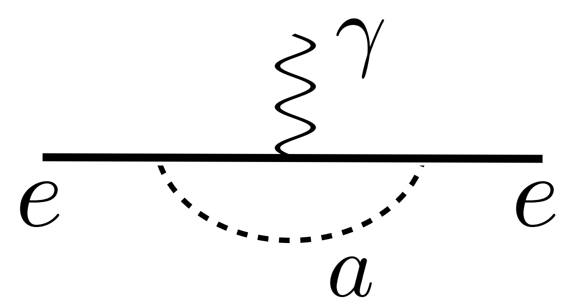
Suggests $m_a \approx (16 \pm 1)\,\mathrm{MeV}$, $\dfrac{1}{\sqrt{3}}\theta_{a\eta} + \dfrac{\sqrt{2}}{\sqrt{3}}\theta_{a\eta'} \approx (0.5 \pm 0.2) \times 10^{-3}$

How to probe this MeV axion?

<u>Via its electron couplings</u>

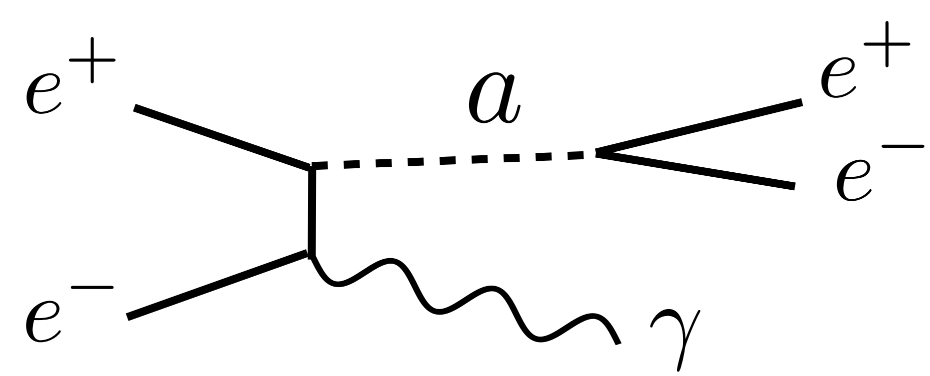
Very similar to light dark photons probes

- $(g-2)_e$

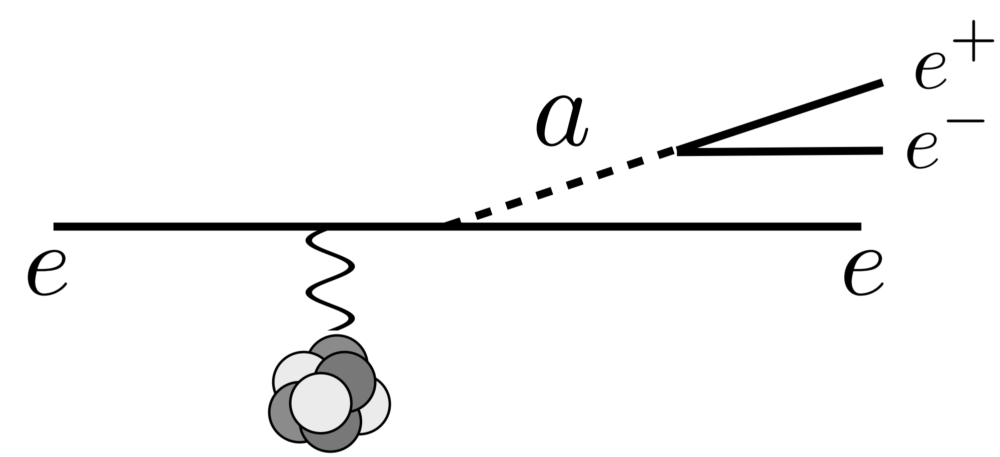


important but model dependent

- e^+e^- colliders



- fixed target experiments

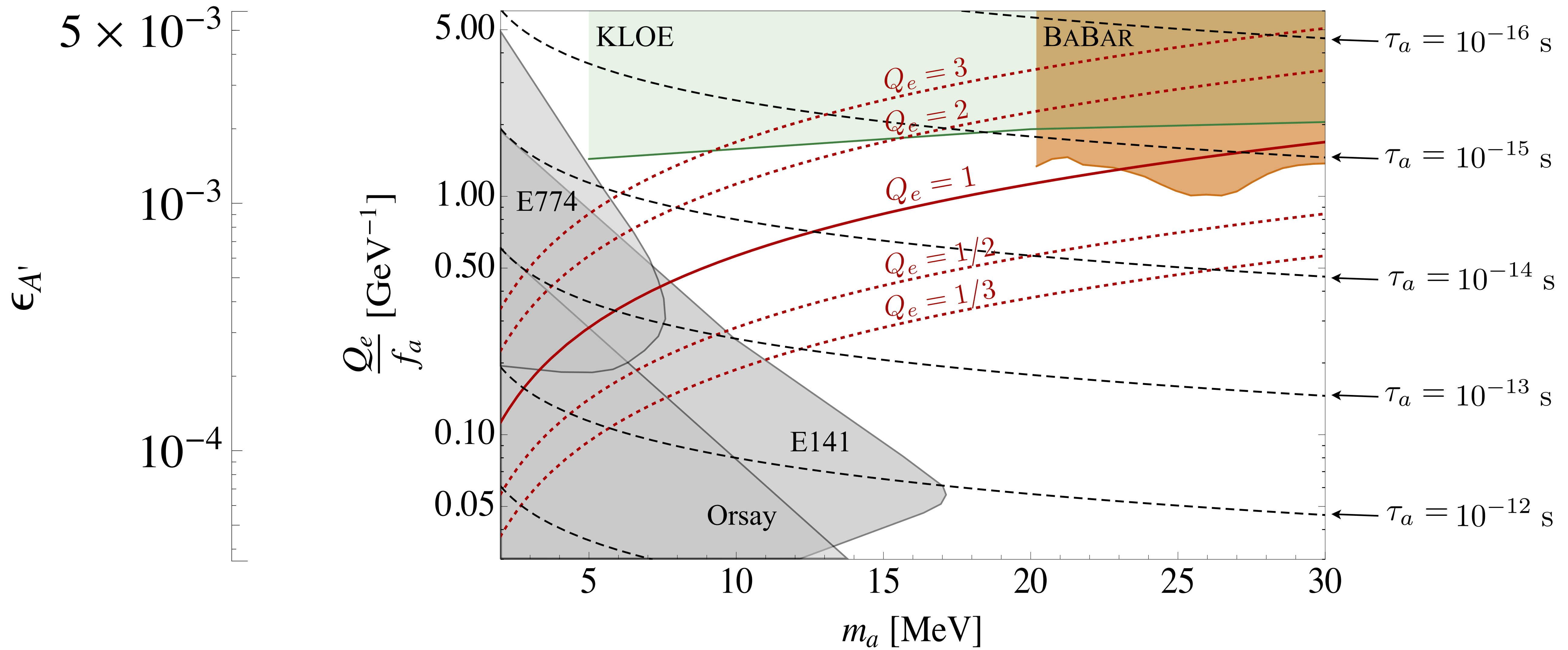


How to probe this MeV axion?

Via its electron couplings

Very similar to light dark photons probes

$$\frac{Q_e}{f_a}\, m_e\, a\, \bar{e}\gamma_5 e$$

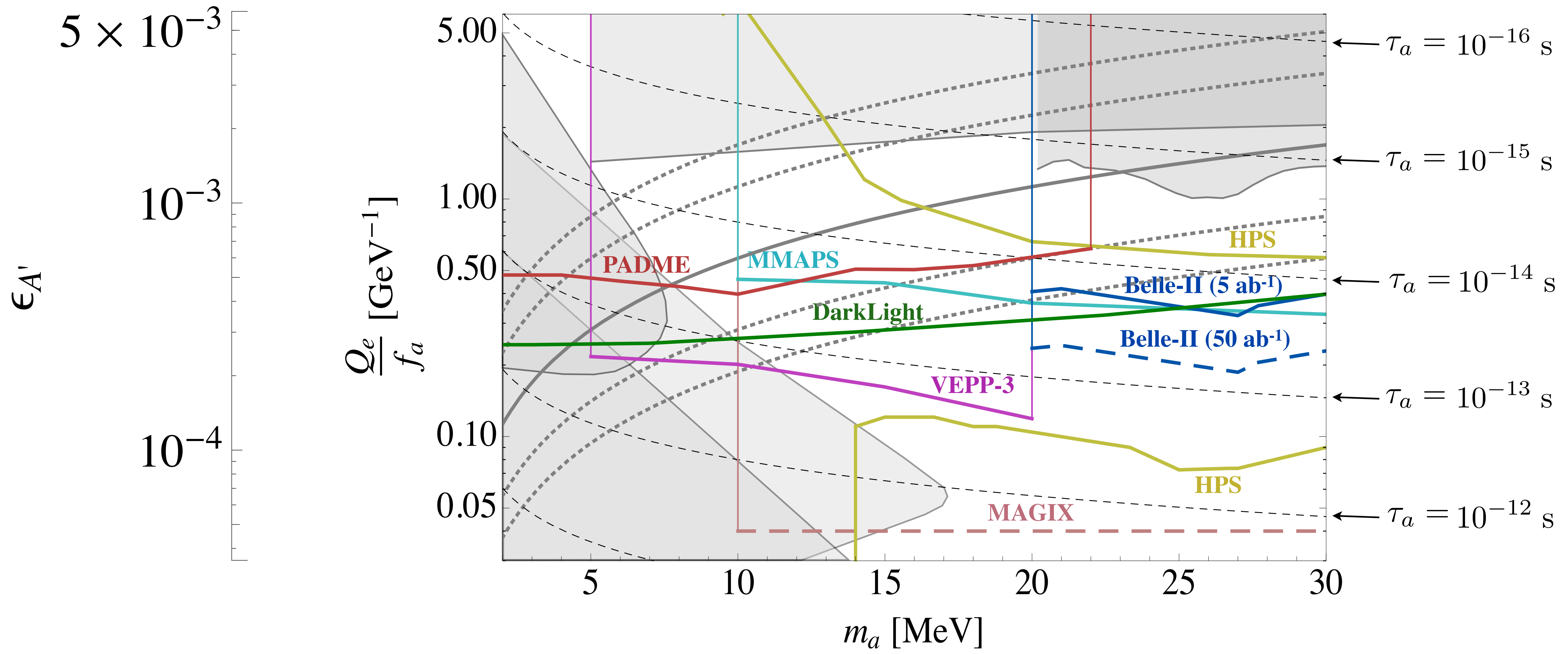


How to probe this MeV axion?

Via its electron couplings

Very similar to light dark photons probes

$$\frac{Q_e}{f_a}\, m_e\, a\, \bar{e}\gamma_5 e$$



New hadronic states at the GeV scale

Since PQ symmetry is being broken at GeV scale,
new light states are needed

$$y_u \, \Phi_u \, uu^c \; + \; y_d \, \Phi_d \, dd^c \; + \; y_e \, \Phi_e \, ee^c \; + \; V(\Phi_u, \Phi_d, \Phi_e)$$

$$\Phi_e = \Phi_{u,d,\mathrm{other}}$$

Enforce via potential $Q_{\Phi_u} = 2 \;,\; Q_{\Phi_d} = 1$

4 new d.o.f. at GeV scale:

$$\underbrace{\phi_u \;,\; \phi_d}_{\text{real scalars}} \qquad\qquad \underbrace{a \;,\; \eta_a}_{\text{pseudoscalars}}$$

Must be EW singlets: couple to fermions via higher dimension operators

New hadronic states at the GeV scale

$\phi_u \; , \; \phi_d$ couple hadronically and could in principle have not been identified if lying in the 1-2 GeV mass range

η_a could hide in 1300-1500 MeV range

- backgrounds from $\eta(1295)$, $\eta(1405)$, $\eta(1475)$
- more extremely, it could be identified with $\eta(1295) \; / \; \eta(1405) \; / \; \eta(1475)$ if broad enough

Completion at the weak scale

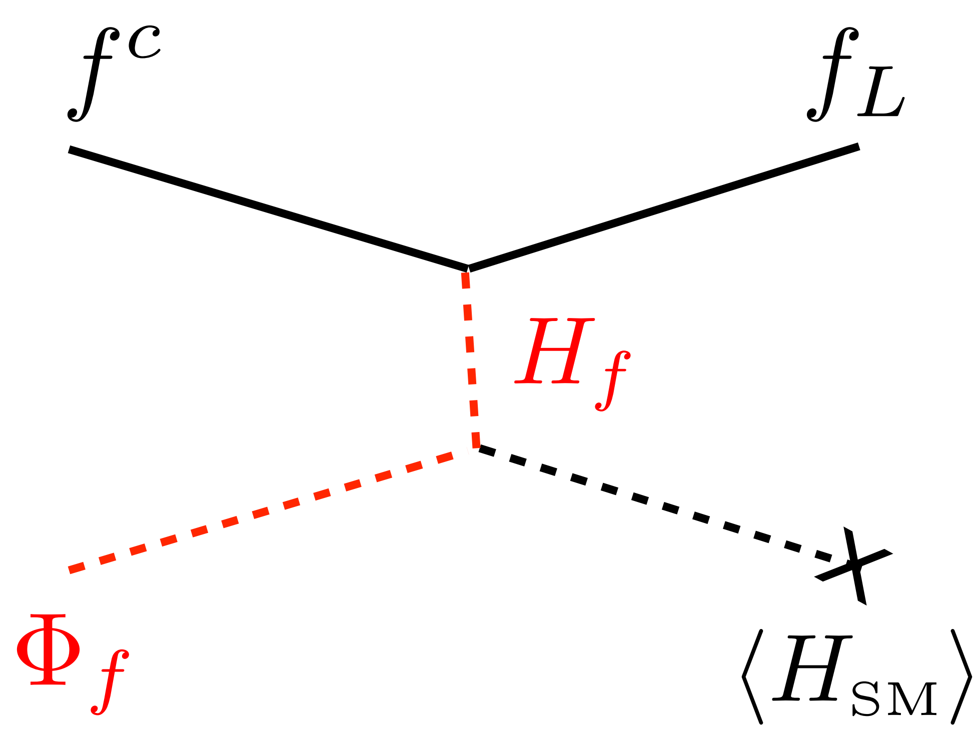
$y_f \, \Phi_f \, f f^c$ is a higher dimensional operator

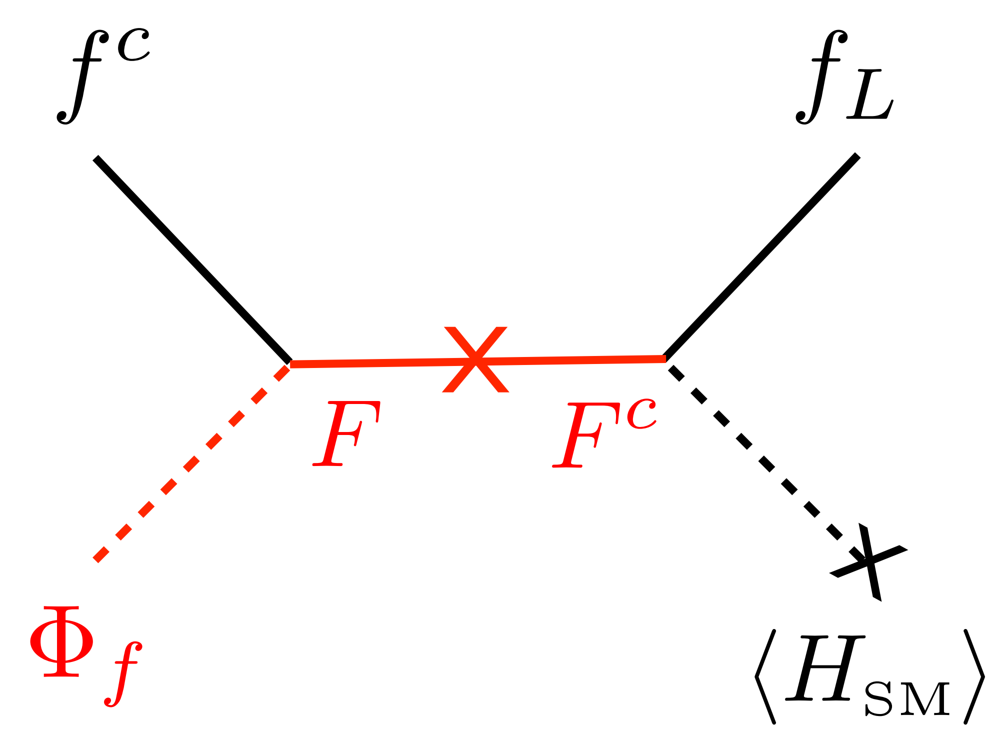
Can be generated by introducing:

- Heavy scalar doublets

or

- Heavy vectorlike fermions





Several interesting signatures at the LHC

Conclusions

For axion variant coupling only to 1st generation with $Q_u = 2\,Q_d$,
$\theta_{a\pi}$, $\theta_{a\eta_0}$ are suppressed, and their estimation unreliable

Cannot claim definitive exclusion from pion/kaon decays

A 16 MeV axion could explain ^{8}Be* and KTeV "anomalies"

This axion variant can be probed in the near future dark photon searches, and by improving sensitivity on rare meson decays

LHC will explore EW completion of such models

Back up slides

Axion-Like Particles, or “ALPs”

ALPs are neutral pseudo-scalars with generic couplings:

$$c_{G\tilde{G}} \frac{a}{f_a} \, G_{\mu\nu}\tilde{G}^{\mu\nu} \quad , \quad c_{F\tilde{F}} \frac{a}{f_a} \, F_{\mu\nu}\tilde{F}^{\mu\nu} \quad , \quad c_f \frac{m_f}{f_a} a \, \bar{f}\gamma_5 f$$

The QCD-axion is a special type of ALP

- It couples to either $G_{\mu\nu}\tilde{G}^{\mu\nu}$ or $\bar{q}\gamma_5 q$, or both
- It is the pseudo-Goldstone boson of a spontaneously broken global symmetry (the Peccei-Quinn symmetry)
- It does not get a potential from non-QCD interactions

$$V(a)_{\text{non-QCD}} = 0$$

The Strong CP problem

The QCD interactions can have CP-violating phases:

$$\frac{\alpha_s}{4\pi}\,\theta_{G\tilde{G}}\,G_{\mu\nu}\tilde{G}^{\mu\nu} \;+\; \sum_q |m_q|\;\bar{q}\,e^{i\gamma_5\theta_q}\,q$$

While many of these phases can be removed by field redefinitions, one linear combination of phases is physical:

$$\theta_{QCD} \;=\; \theta_{G\tilde{G}} \;+\; \sum_q \theta_q$$

θ_{QCD} is know as the strong CP phase

The Strong CP problem

If $\theta_{QCD} \neq 0$, it would induce an EDM for the neutron

$$\frac{|d_n|}{e} \sim \theta_{QCD} \frac{m_u}{M_n^2} < 3 \times 10^{-26}\,\mathrm{cm}$$

$$\Rightarrow \quad \theta_{QCD} \lesssim 10^{-10}$$

The smallness of θ_{QCD} is a puzzle,
because CP is <u>not</u> a symmetry of nature

In fact, the CP-violating phase in the weak sector is large

Is there a dynamical mechanism suppressing θ_{QCD}?

The Peccei-Quinn solution of the Strong CP problem

In the PQ mechanism, θ_{QCD} is promoted to a dynamical field

$$\theta_{QCD} \;\rightarrow\; \frac{a}{f_a}$$ (f_a is the axion's decay constant)

QCD non-perturbative effects + chiral symmetry breaking generate a periodic potential for the axion:

$$V(a) = -\,\#\, m_\pi^2\, f_\pi^2\, \cos\!\left(\frac{a}{f_a}\right)$$

O(1) model dependent coefficient

$V(a)$ is minimized at $\langle a \rangle = 0$

$$\Rightarrow\; d_n \;\propto\; \langle a \rangle \;=\; 0$$

Useful Formulas

coupling to electron: $$\frac{Q_e}{f_a}\, m_e\, a\, \bar{e}\gamma_5 e$$

m_a - f_a relation: $$m_a = \underbrace{|Q_u + Q_d|}_{\text{2+1}} \frac{\sqrt{m_u m_d}}{m_u + m_d}\, \frac{m_\pi\, f_\pi}{f_a}$$

lifetime: $$\tau_a^{-1} = \frac{1}{8\pi}\left(\frac{Q_e}{f_a} m_e\right)^2 m_a$$

isotropic decay in axion's rest frame

analogous coupling in dark photon case: $$\epsilon_{A'} \simeq \frac{m_e}{\sqrt{2}\, e}\, \frac{Q_e}{f_a}$$

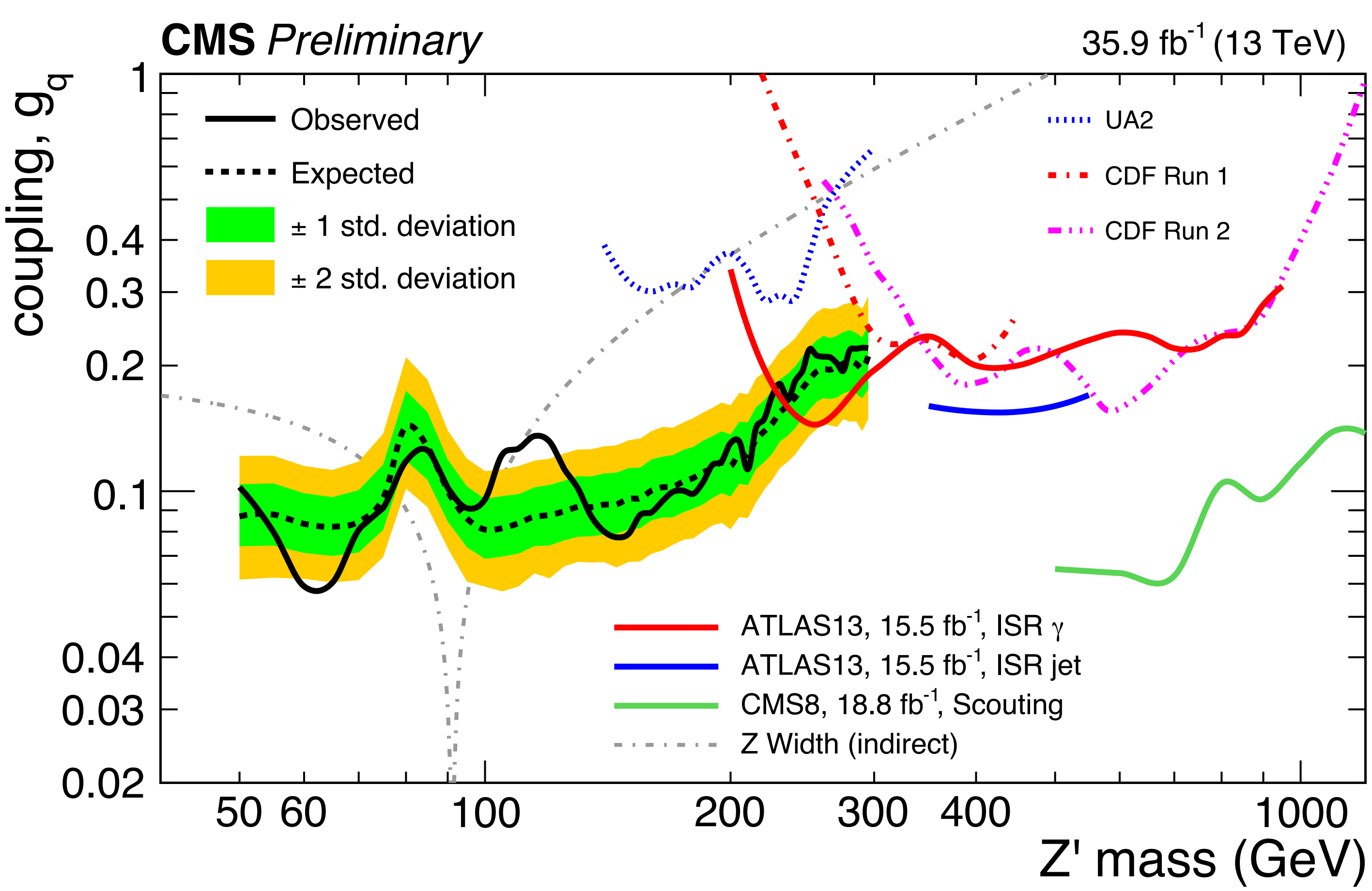
Completion at the weak scale

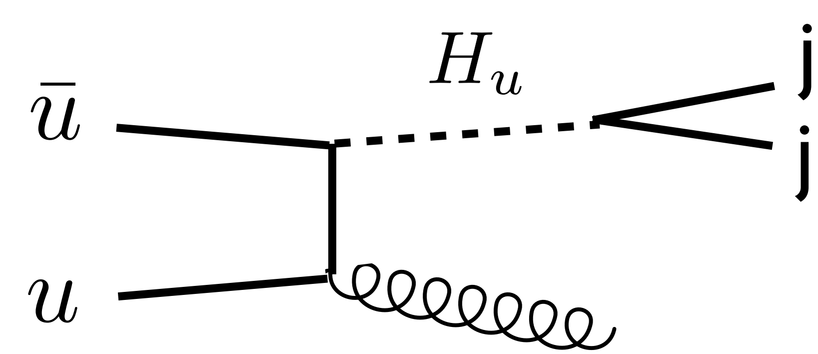
2 new doublets $H_u \quad , \quad H_d$

$$y_u H_u u u^c + M_{H_u}^2 |H_u|^2 + A_u \Phi_u H_{\rm SM}^* H_u + (u \to d)$$

Integrate out H_u :

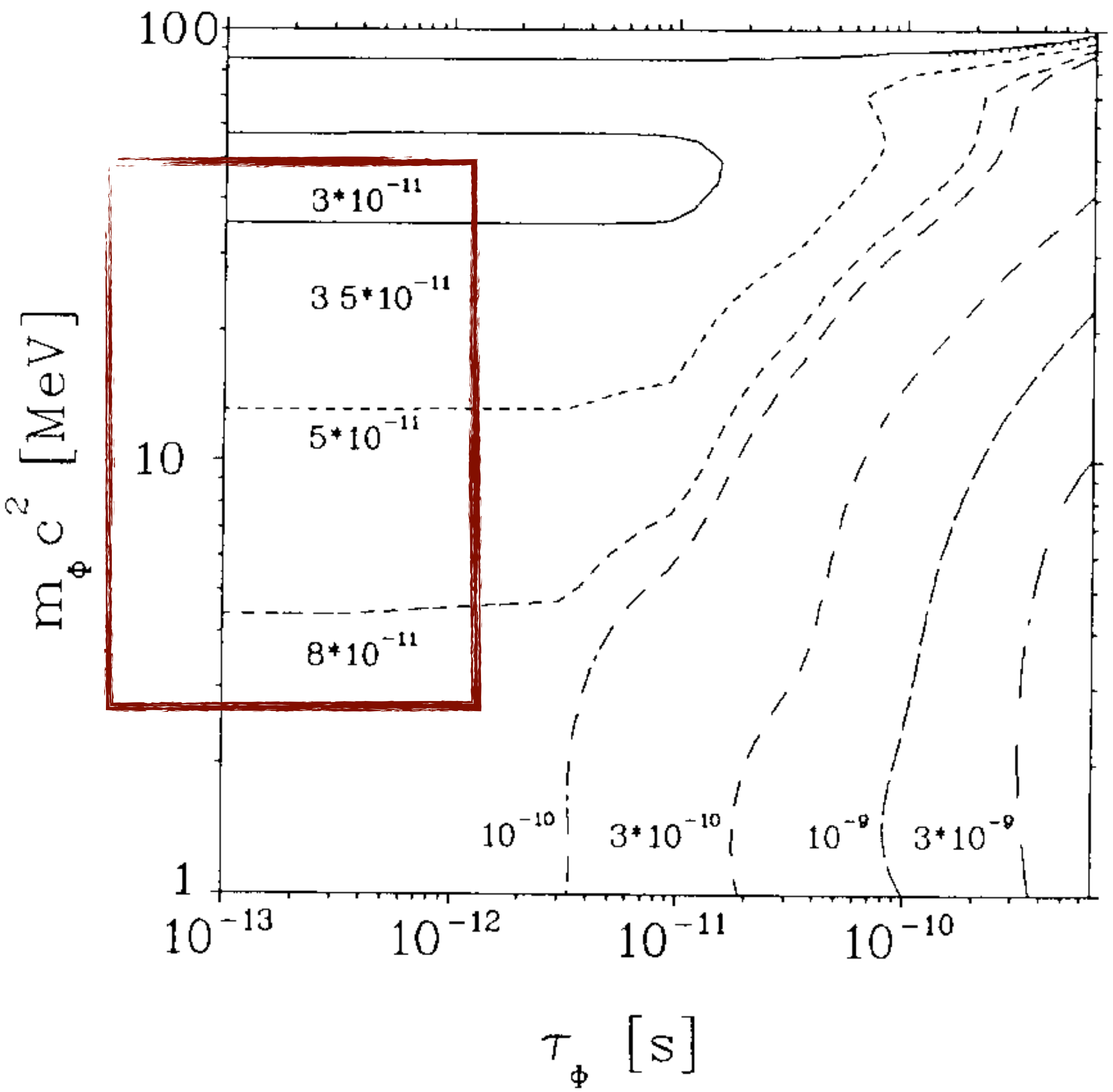
$$y_u' \Phi_u \, u u^c \; = \; \left(y_u \frac{A_u v}{M_{H_u}^2} \right) \Phi_u \, u u^c \; + \; (u \to d)$$





$$\pi^{\pm} \to a\, e^{\pm} \nu$$

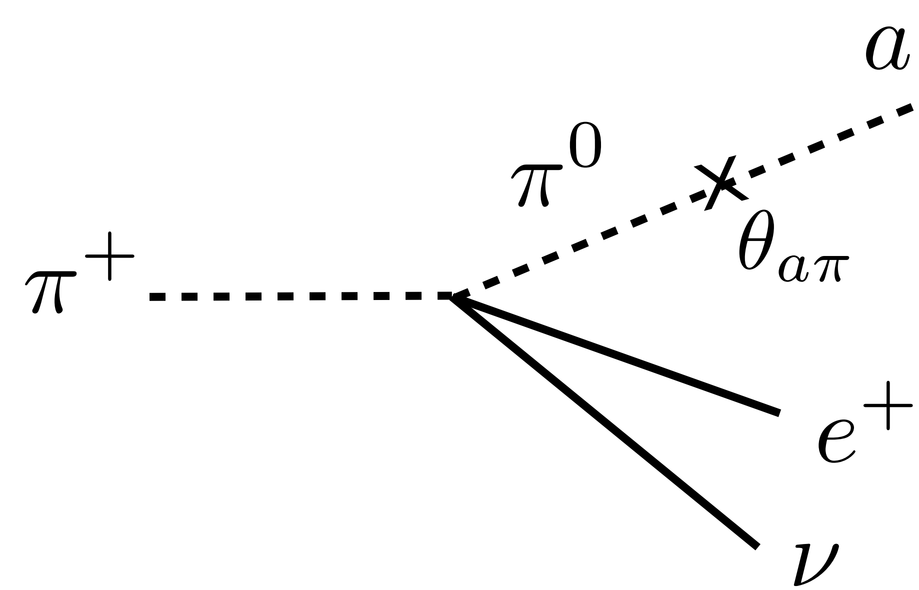
SINDRUM collaboration
(Eichler *et al.* 1986)



$$\tau_a < 10^{-13}\,\mathrm{s} \;\; \text{for} \;\; m_a > 3\,\mathrm{MeV}$$

$$\mathrm{BR}(\pi^{\pm} \to e^{\pm}\nu\,(a \to \; e^{+}e^{-}))$$

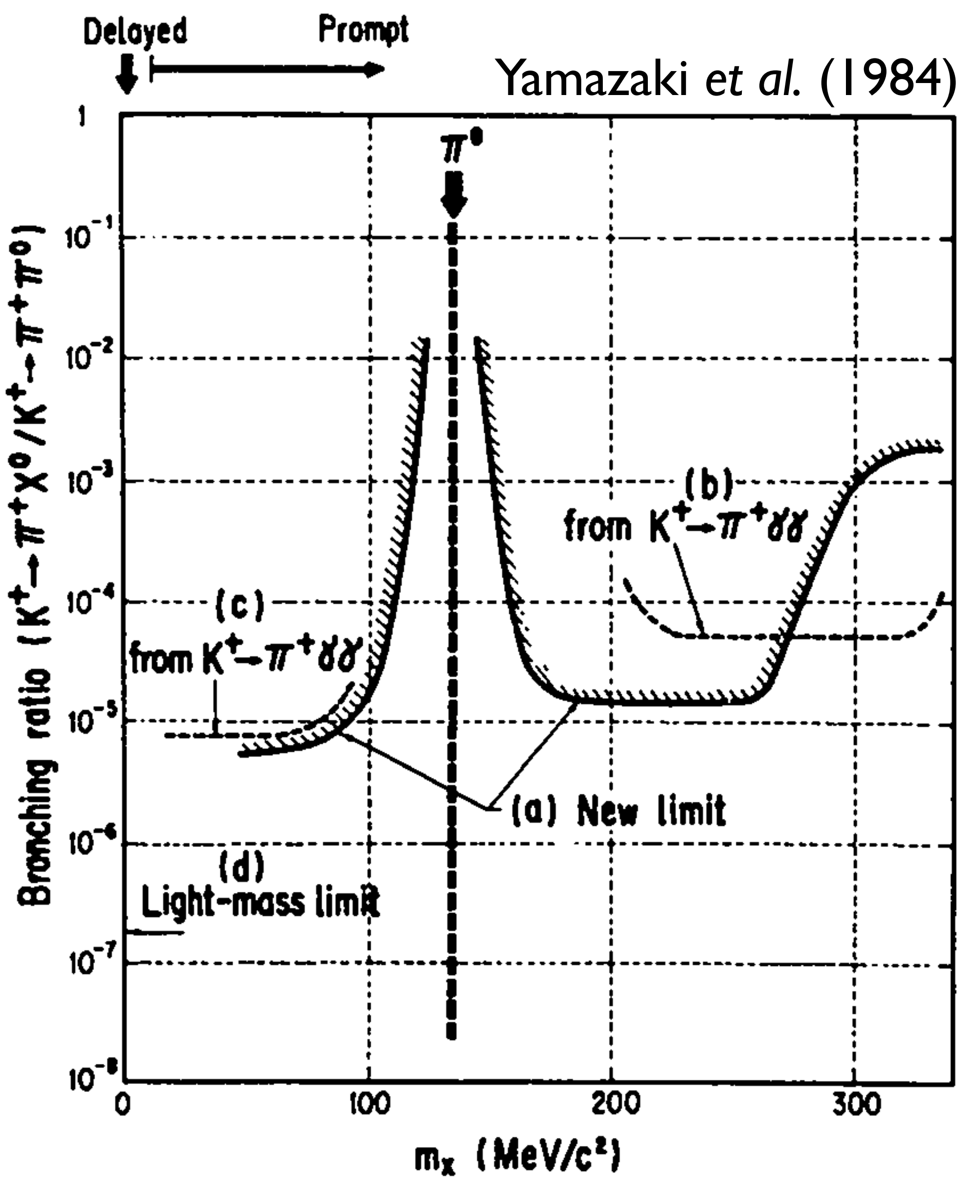
$$\lesssim (0.4 - 0.8) \times 10^{-10}$$

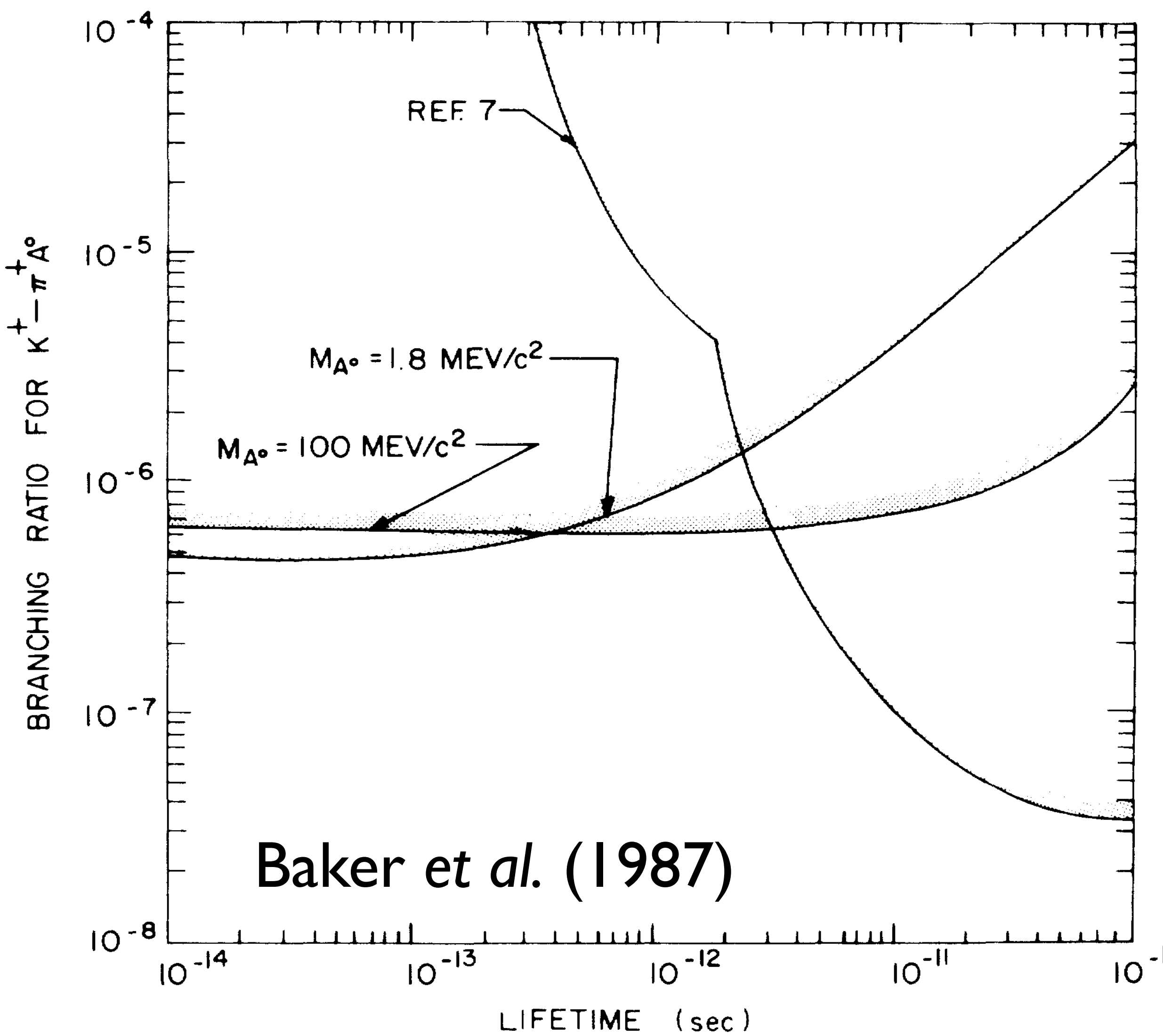


$$\theta_{a\pi} \lesssim 0.5 \times 10^{-4}$$

$$K^{\pm} \to \pi^{\pm}(a \to e^{+}e^{-})$$

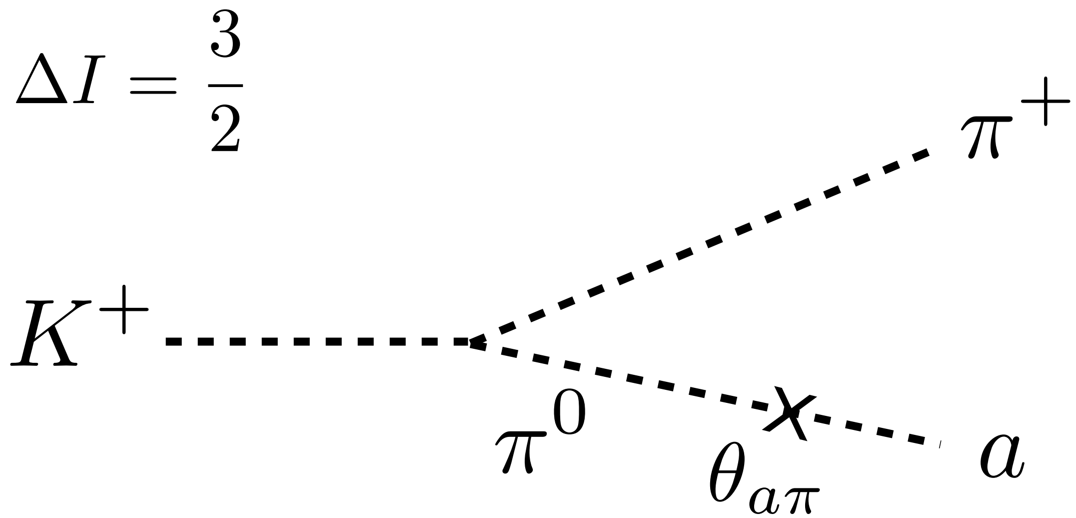
Only 2 experiments (in the 80's) searched for this decay in the $m_{ee} < m_{\pi}$ region





$$\mathrm{BR}(K^{\pm} \to \pi^{\pm}(a \to e^{+}e^{-})) \lesssim 10^{-5} - 10^{-6}$$

$$K^{\pm} \to \pi^{\pm}(a \to e^+e^-)$$

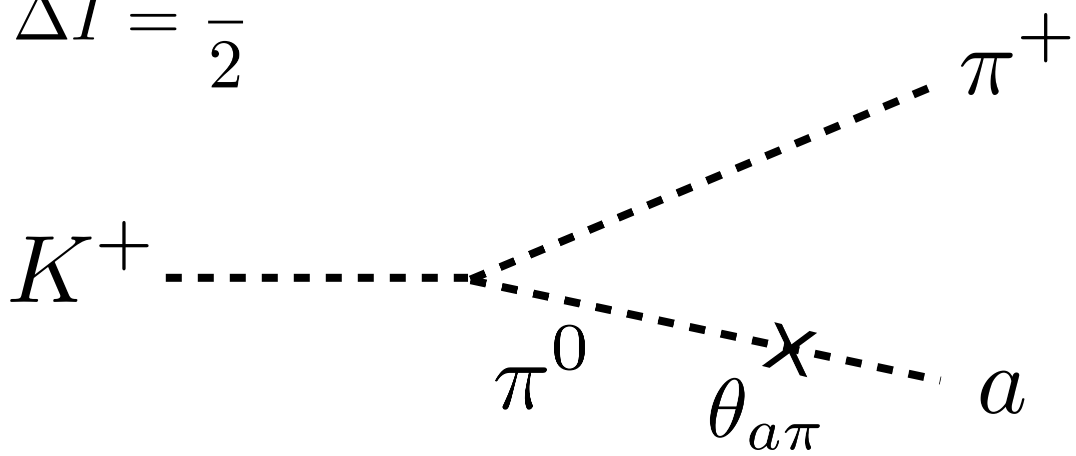


$$\frac{\Gamma(K^+ \to \pi^+ a)}{\Gamma(K^+ \to \pi^+\pi^0)} = \theta_{a\pi}^2$$

$$\Rightarrow \theta_{a\pi} \lesssim (1-3) \times 10^{-3}$$

$$K^{\pm} \to \pi^{\pm}(a \to e^+e^-)$$

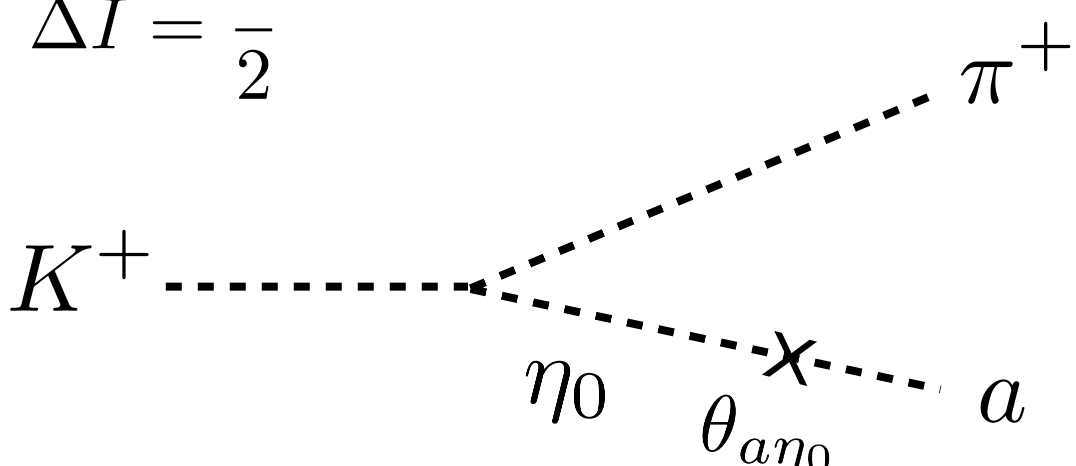
$\Delta I = \frac{3}{2}$



$$\frac{\Gamma(K^+ \to \pi^+ a)}{\Gamma(K^+ \to \pi^+\pi^0)} = \theta_{a\pi}^2$$

$$\Rightarrow \theta_{a\pi} \lesssim (1-3) \times 10^{-3}$$

$\Delta I = \frac{1}{2}$



$$\frac{\Gamma(K^+ \to \pi^+ a)}{\Gamma(K^0 \to \pi^+\pi^-)} = \frac{2\theta_{a\eta_0}^2}{\kappa^2}$$

corrects for strong $\pi\pi$ final state interactions; $\kappa^2 \sim 3$ for $\eta \to 3\pi$

isoscalar $\frac{1}{\sqrt{3}}\eta + \frac{\sqrt{2}}{\sqrt{3}}\eta'$

$$\Rightarrow \theta_{a\eta_0} \lesssim (1-4) \times 10^{-4}$$

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

Convention for couplings

PQ current

$$J_\mu^{PQ} = f_a \partial_\mu a + Q_u \, \bar{u}\gamma_\mu\gamma_5 u + Q_d \, \bar{d}\gamma_\mu\gamma_5 d$$

$$\Downarrow$$

Axion as a phase of the quark masses

$$m_u \, e^{i\, Q_u a/f_a} \, uu^c \;+\; m_d \, e^{i\, Q_d a/f_a} \, dd^c \;+\; m_s \, ss^c$$

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

Effective Chiral Lagrangian Framework

$$\mathcal{L}_\chi^{(0)} = \frac{f_\pi^2}{4}\,\mathrm{Tr}[\partial_\mu U^\dagger\,\partial^\mu U] + \frac{f_\pi^2}{2} B\,\mathrm{Tr}[M_q(a)U + U^\dagger M_q^\dagger(a)] - \frac{1}{2}M_0^2\eta'^{\,2}$$

$$M_q(a) \equiv \begin{bmatrix} m_u\, e^{i\,\frac{Q_u a}{f_a}} & & \\ & m_d\, e^{i\,\frac{Q_d a}{f_a}} & \\ & & m_s \end{bmatrix}$$

$$U \equiv \exp\frac{i\sqrt{2}}{f_\pi}\begin{bmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta'}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta'}{\sqrt{3}} & \overline{K}^0 \\ K^- & K^0 & -2\frac{\eta}{\sqrt{6}} + \frac{\eta'}{\sqrt{3}} \end{bmatrix}$$

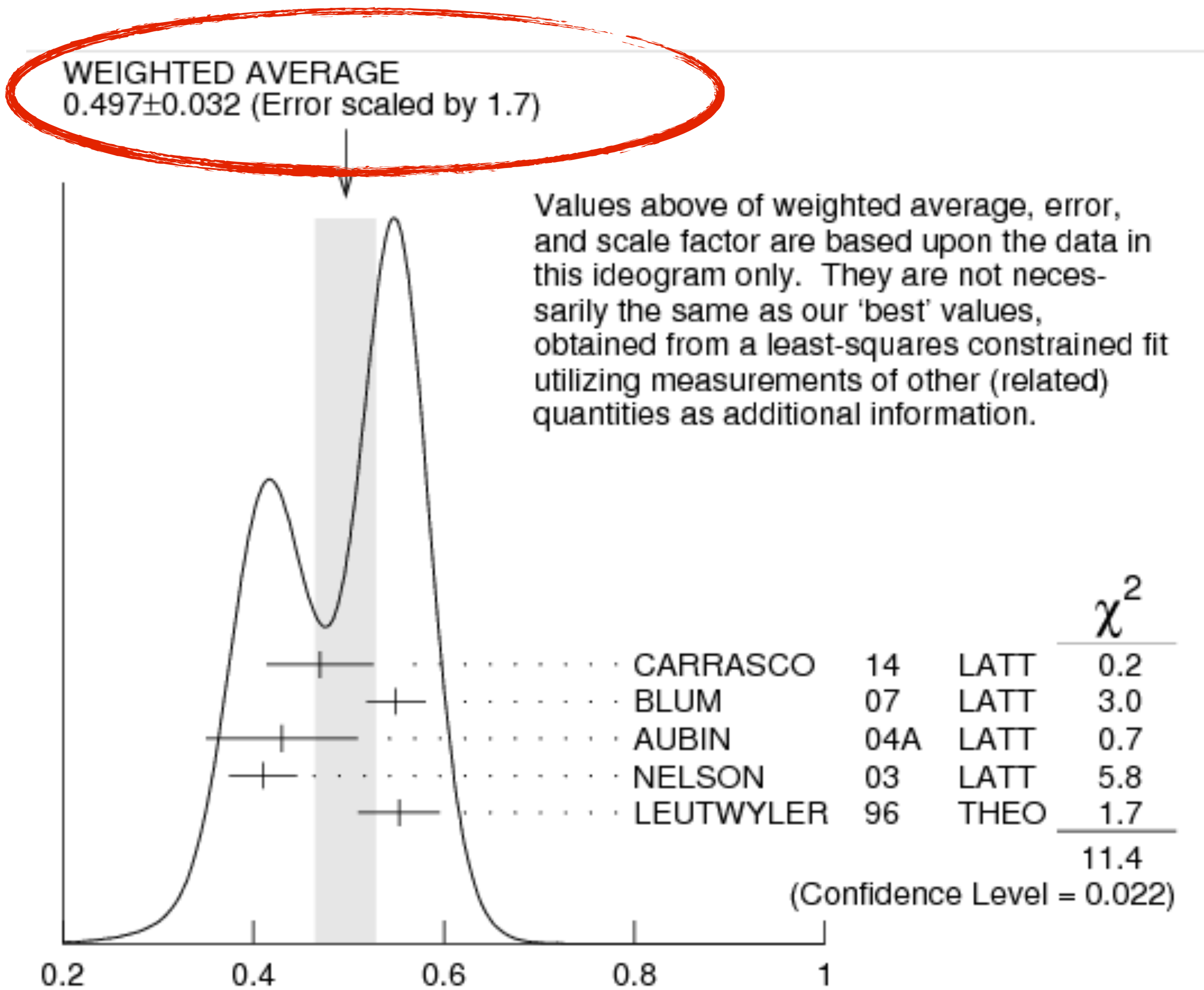
Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

$$\theta_{a\pi}^{(0)} \simeq -\frac{(Q_u m_u - Q_d m_d)}{m_u + m_d}\frac{f_\pi}{f_a}$$

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

$$\theta^{(0)}_{a\pi} \simeq -\frac{(Q_u m_u - Q_d m_d)}{m_u + m_d}\frac{f_\pi}{f_a}$$

Accidental suppression of $\theta^{(0)}_{a\pi}$ if $Q_u = 2\ ,\ Q_d = 1$



PDG 2016

$$\theta^{(0)}_{a\pi} \simeq \frac{4}{3}\frac{f_\pi}{f_a}\left(0.5 - \frac{m_u}{m_d}\right)$$

$$\sim \frac{0.4\times 10^{-3}}{f_a/\mathrm{GeV}}$$

for PDG's central value of $\dfrac{m_u}{m_d} = 0.497$

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

$$\theta^{(0)}_{a\eta_0} \simeq -\left(\frac{1}{4} + \frac{3}{2}\frac{m_K^2}{M_0^2}\right)\frac{(Q_u m_u + Q_d m_d)}{m_u + m_d}\,\frac{m_\pi^2}{m_K^2}\,\frac{f_\pi}{f_a}$$

$$\Rightarrow \qquad \theta^{(0)}_{a\eta_0} \sim \frac{-0.5\times 10^{-2}}{f_a/\mathrm{GeV}}$$

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

$$\theta_{a\eta_0}^{(0)} \simeq -\left(\frac{1}{4} + \frac{3}{2}\frac{m_K^2}{M_0^2}\right)\frac{(Q_u m_u + Q_d m_d)}{m_u + m_d}\frac{m_\pi^2}{m_K^2}\frac{f_\pi}{f_a}$$

$$\Rightarrow \qquad \theta_{a\eta_0}^{(0)} \sim \frac{-0.5 \times 10^{-2}}{f_a/\mathrm{GeV}}$$

These estimates are unreliable

Contributions from 2nd order chiral expansion
can be as large as 1st order

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

E.g., operators such as $\left\{ \begin{array}{l} L_5 \, \mathrm{Tr} \left[\, \partial^\mu (2BM_q \, U) \, \partial_\mu U^\dagger \, U + \mathrm{h.c.} \, \right] \\ L_8 \, \mathrm{Tr} \left[\, (2BM_q) \, U \, (2BM_q) \, U + \mathrm{h.c.} \, \right] \end{array} \right.$

give corrections to $\theta_{a\eta_0}^{(0)}$ of order:

$$\frac{32 m_K^2}{f_\pi^2} \, L_i \;\sim\; \mathcal{O}(10^3) \, L_i \;\sim\; \mathcal{O}(1)$$

and partially cancel $\theta_{a\eta_0}^{(0)}$ to 1 part in 3:

$$\theta_{a\eta_0} \;\approx\; \frac{\theta_{a\eta_0}^{(0)}}{3} \approx \; \frac{-1.7 \times 10^{-3}}{f_a/\mathrm{GeV}}$$

Estimating $\theta_{a\pi}$, $\theta_{a\eta_0}$

There are many other, less constrained operators in the $\mathcal{O}(p^4)$ expansion of the Chiral Lagrangian, such as

$$L_7\,\mathrm{Tr}\,[\,(2BM_q)U - U^\dagger(2BM_q)]^2$$

$$L_{18}\,\mathrm{Tr}\,[U^\dagger\partial^\mu U]\,\mathrm{Tr}\,[\,\partial_\mu(2BM_q)U - \partial_\mu U^\dagger(2BM_q)^\dagger]$$

...

which also contribute to $\theta_{a\eta_0}$. These contributions can be just as large as 1st order if L_7, L_{18}, *etc*., are of similar size as L_5 , L_8 .

In principle, these various contributions could partially cancel.

constraint from *(g-2)$_e$* is very model dependent:

f_a suggests new dynamics at GeV scale and extra states contributing to *(g-2)$_e$*