Axions beyond the QCD axion

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UC Santa Cruz

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The QCD axion. Present and future

Strong CP problem:
why is the QCD $\bar{\theta}$ parameter so small? $\mathcal{L}_{\rm QCD} \supset \theta \frac{g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$

$\bar{\theta} \equiv \theta + \arg(\det(Y_u Y_d))$

QCD axion: elegant way to address this problem.
Dynamical solution to achieve: $\bar{\theta} \lesssim 10^{-10}$ in agreement with neutron EDM constraints

The QCD axion mass is set by its decay constant, f_a: $m_a f_a \sim f_\pi m_\pi$
The generic expectation is that it couples $\sim 1/f_a$

Peccei-Quinn symmetry breaking scale

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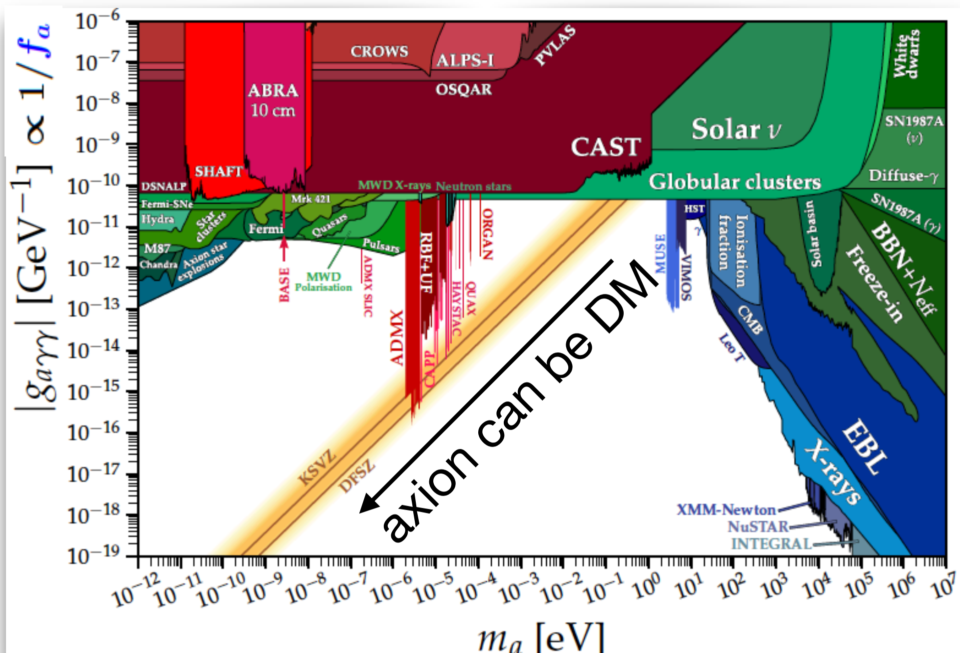
Adams at al., 2203.14923



$f_a \gtrsim \mathcal{O}(10^{11}\text{GeV})$
the QCD axion can easily be DM.
It is more difficult if
$\mathcal{O}(10^8\ \text{GeV}) \lesssim f_a \lesssim \mathcal{O}(10^{11}\ \text{GeV})$

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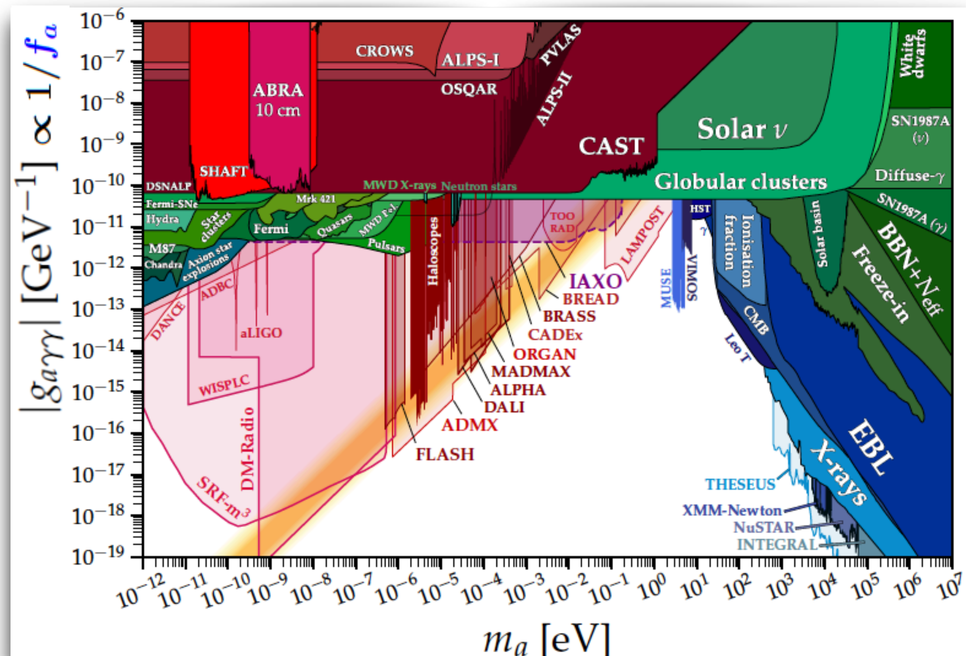

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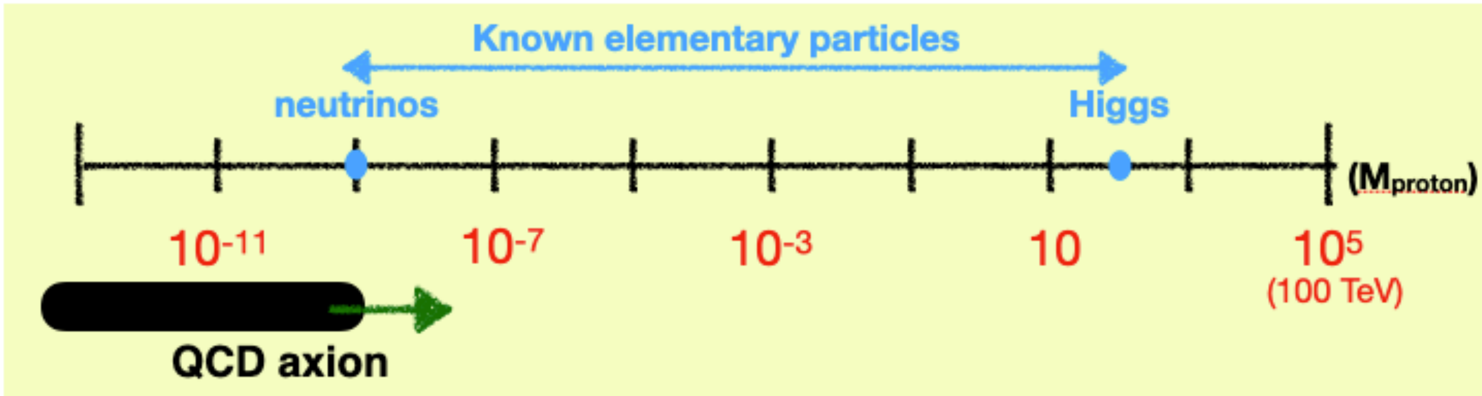
Heavier axions and the strong CP problem



Models where two or more axions naturally cooperate to address the strong CP problem.

(Recent references:
Agrawal, Howe, 1710.04213;
Foster, Kumar, Safdi, Soreq, 2208.10504, …)

(2)

Axion quality problem alleviated for heavy axions

if PQ symmetry broken by dimension D operators at Λ_{UV}:

$$\delta\bar{\theta} \sim \frac{f_a^{D-2}}{m_a^2 \Lambda_{UV}^{D-4}}$$

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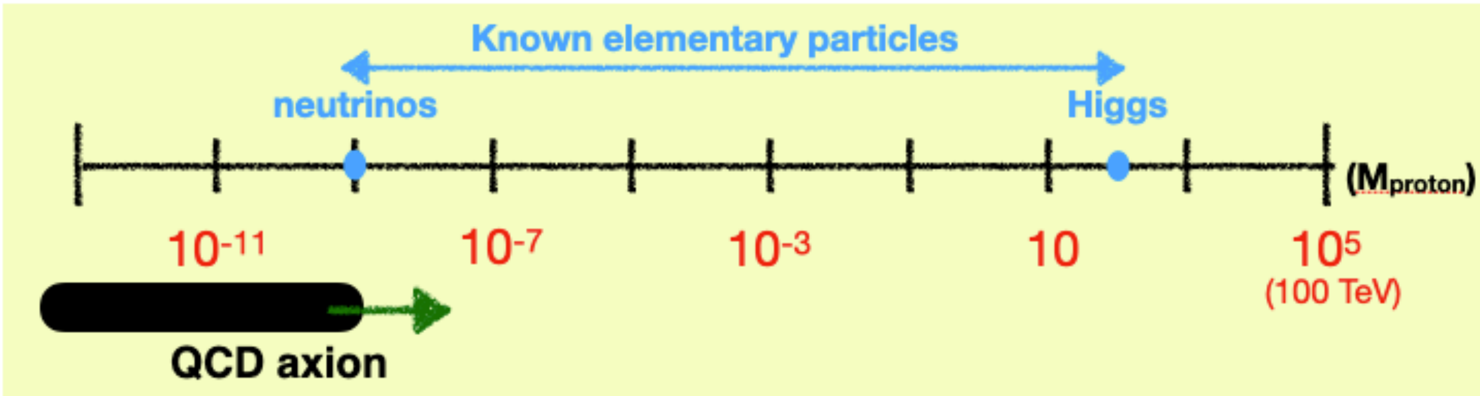

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$$SU(3)\times SU(3)\rightarrow SU(3)_D = SU(3)_c$$

Lot of freedom in the (m_a-f_a) plane.
Also different hierarchies in axion-SM couplings.

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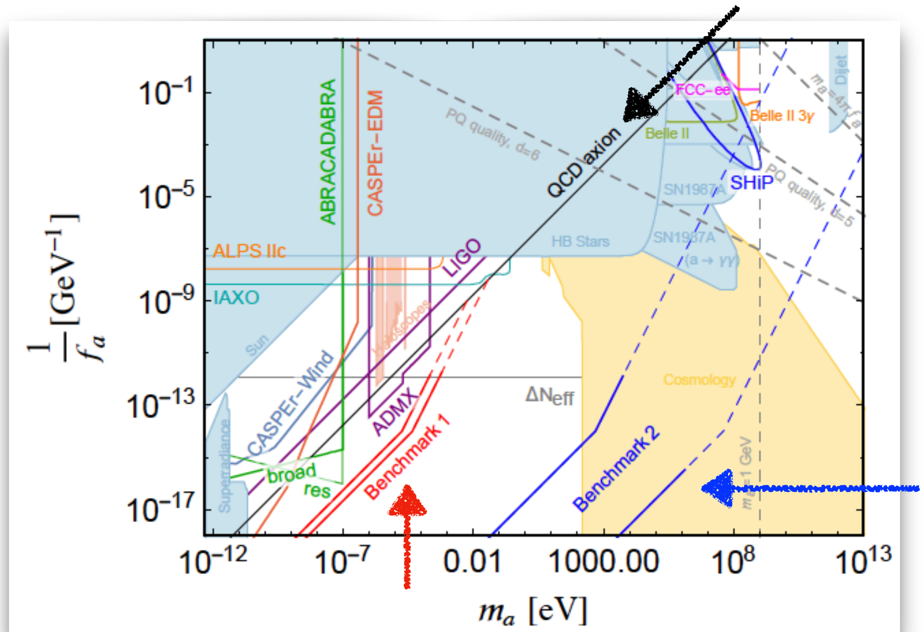

Agrawal, Howe, 1710.04213

For this talk

Variations of the minimal QCD axion:

1) The QCD axion as mediator between the SM and DM, χ: $\frac{c_\chi}{2f_a}\partial_\mu a\ \bar{\chi}\gamma^\mu\gamma_5\chi$

$f_a \lesssim \mathcal{O}(10^{11}\mathrm{GeV})$

Chapter 1.

2) Heavier axions and new phenomenology at meson factories

Chapter 2.

Main references:

1. Dror, SG, Munbodh, 2306.03145 (+ with Knapen, Lin, Munbodh, Suter, 2501.xxxxx)
2. Altmannshofer, Dror, SG, 2209.00665

Chapter 1

The QCD axion as mediator between the SM and DM

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Motivations and model

- If $f_a \lesssim \mathcal{O}(10^{11}\mathrm{GeV})$, typically axions do not constitute a sizable fraction of the DM energy density without additional dynamics beyond the misalignment mechanism ($T_{RH} \lesssim f_a$) or the decay of cosmic defects ($T_{RH} \gtrsim f_a$)
- Experimental program to detect such low f_a axions: upcoming IAXO and ALPS II

Can we still have a connection to DM, even for such lower decay constants?

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A minimal model:

let's take the QCD axion (either KSVZ or DFSZ) and let's couple it to a singlet Dirac fermion DM candidate:

$$\mathcal{L} \supset \frac{c_\chi}{2 f_a} \partial_\mu a \bar{\chi} \gamma^\mu \gamma_5 \chi$$

A small set of free parameters fixes the cosmology of the model: $f_a,\ m_\chi,\ g_{a\chi} \equiv \frac{c_\chi m_\chi}{f_a},\ T_{\rm RH}$

(eventually tanβ in DFSZ)

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Couplings	KSVZ	DFSZ
Gluons	$\frac{\alpha_s}{8\pi f_a}$	
Photons	$-\frac{\alpha}{8\pi f_a}(1.924)$	$\frac{\alpha}{8\pi f_a}\left(\frac{8}{3} - 1.924\right)$
Quarks	Loop suppressed	$\text{up}: \frac{\cos^2\beta}{6f_a},\ \text{down}: \frac{\sin^2\beta}{6f_a}$
Leptons	Loop suppressed	$\text{Type I}: \frac{\sin^2\beta}{6f_a},\ \text{Type II}: -\frac{\cos^2\beta}{6f_a}$

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Bounds from DM self-interaction:

$$c_\chi \frac{m_\chi}{f_a} \equiv g_{a\chi} \lesssim 0.21\left(\frac{m_\chi}{1\ \mathrm{MeV}}\right)^{3/4}$$

$$f_a \gtrsim \begin{cases} 3.9\times 10^8\ \mathrm{GeV} & (\mathrm{KSVZ}) \\ 1.2\times 10^9\ \mathrm{GeV}\ \sin^2\beta & (\mathrm{DFSZ\text{-}I}) \\ 1.2\times 10^9\ \mathrm{GeV}\ \cos^2\beta & (\mathrm{DFSZ\text{-}II}) \end{cases}$$

supernova cooling bounds (axion-nucleon interaction)

cooling bounds on red giant (axion-electron interaction)

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let's couple it to a

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The well - motivated region of QCD axion parameter space is bounded:

$$\mathcal{O}(10^8\ \text{GeV}) \lesssim f_a \lesssim \mathcal{O}(10^{11}\ \text{GeV})$$

astrophysical bounds | subdominant DM component

DM self-interaction:

$$c_\chi \frac{\ldots}{f_a} = g_{a\chi} \lesssim 0.21 \left(\frac{m_\chi}{1\ \text{MeV}}\right)^{3/4}$$

$$f_a \gtrsim \begin{cases} 3.9\times 10^8\ \text{GeV} & \text{(KSVZ)} \\ 1.2\times 10^9\ \text{GeV}\ \sin^2\beta & \text{(DFSZ-I)} \\ 1.2\times 10^9\ \text{GeV}\ \cos^2\beta & \text{(DFSZ-II)} \end{cases}$$

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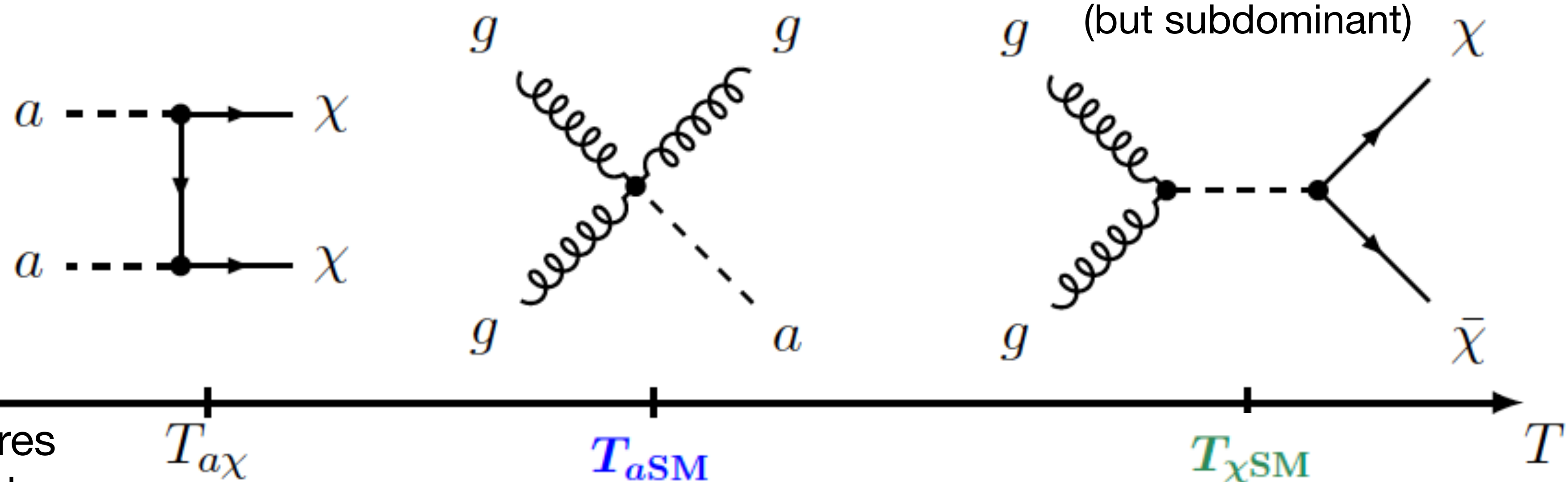
Thermalizations

The thermal history depends on three classes of processes:

also fermion scattering
(but subdominant)



temperatures
only depend on
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(mild)

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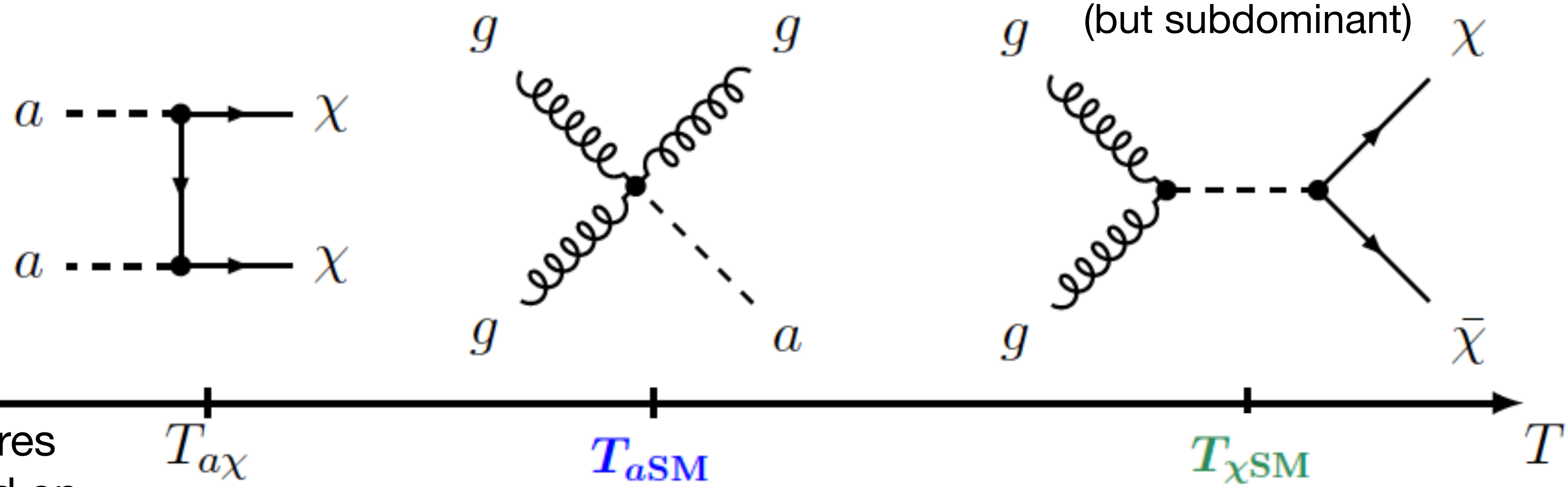

temperatures only depend on $f_a,\ m_\chi,\ g_{a\chi}$ (mild)

$$T_{a\text{SM}} \simeq 2 \times 10^4 \text{GeV} \left(\frac{f_a}{10^9 \text{GeV}} \right)^2$$

$$T_{\chi\text{SM}} \gg T_{a\text{SM}}$$

$$T_{\chi\text{SM}} \simeq 4 \times 10^7 \text{GeV} \left(\frac{f_a}{10^9 \text{GeV}} \right)^2 \left(\frac{1}{g_{a\chi}} \right)^2$$

3 possible hierarchies:

(this is shown in the figure above) → $T_{a\chi} \ll T_{a\text{SM}} \ll T_{\chi\text{SM}}$

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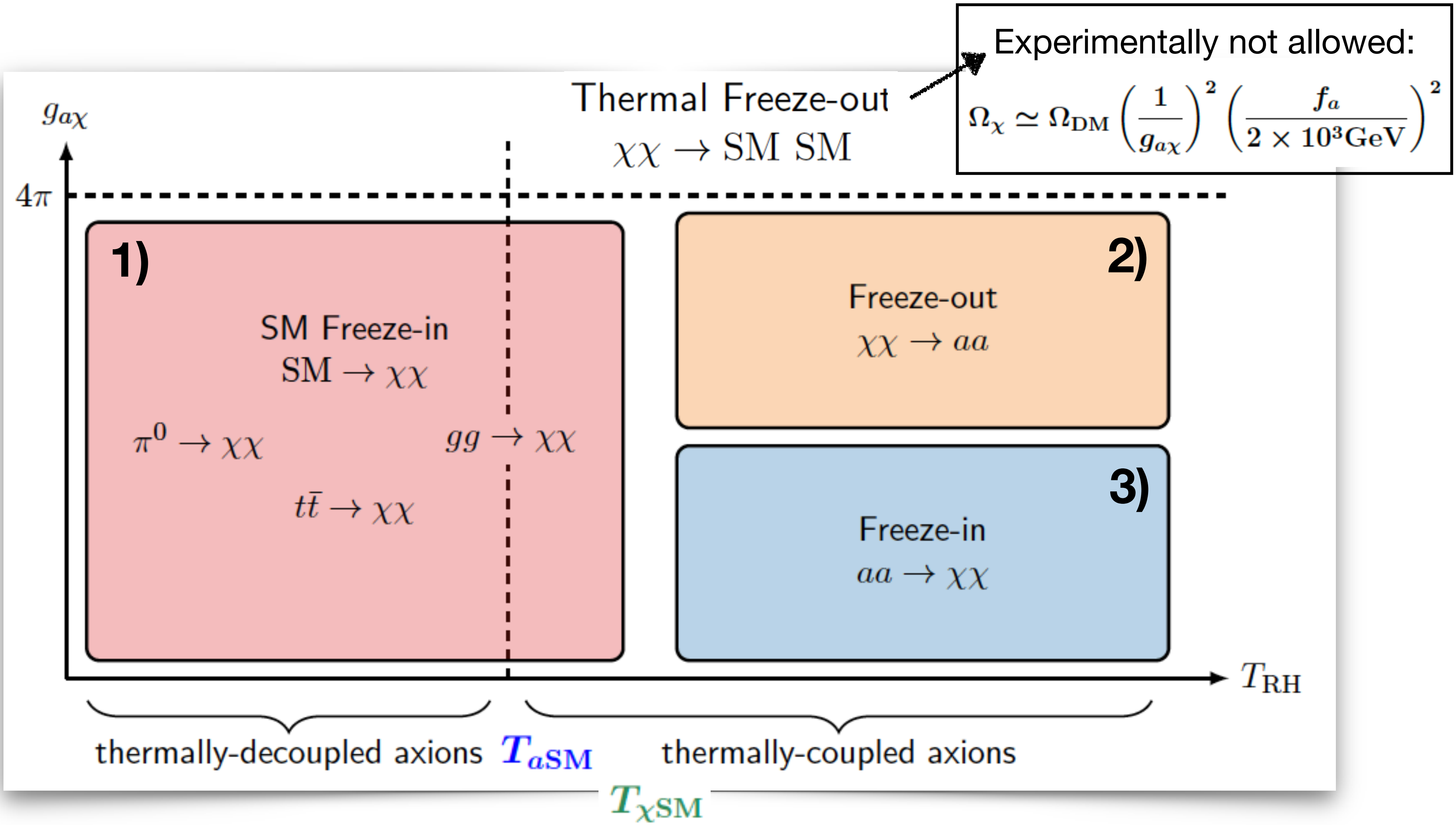
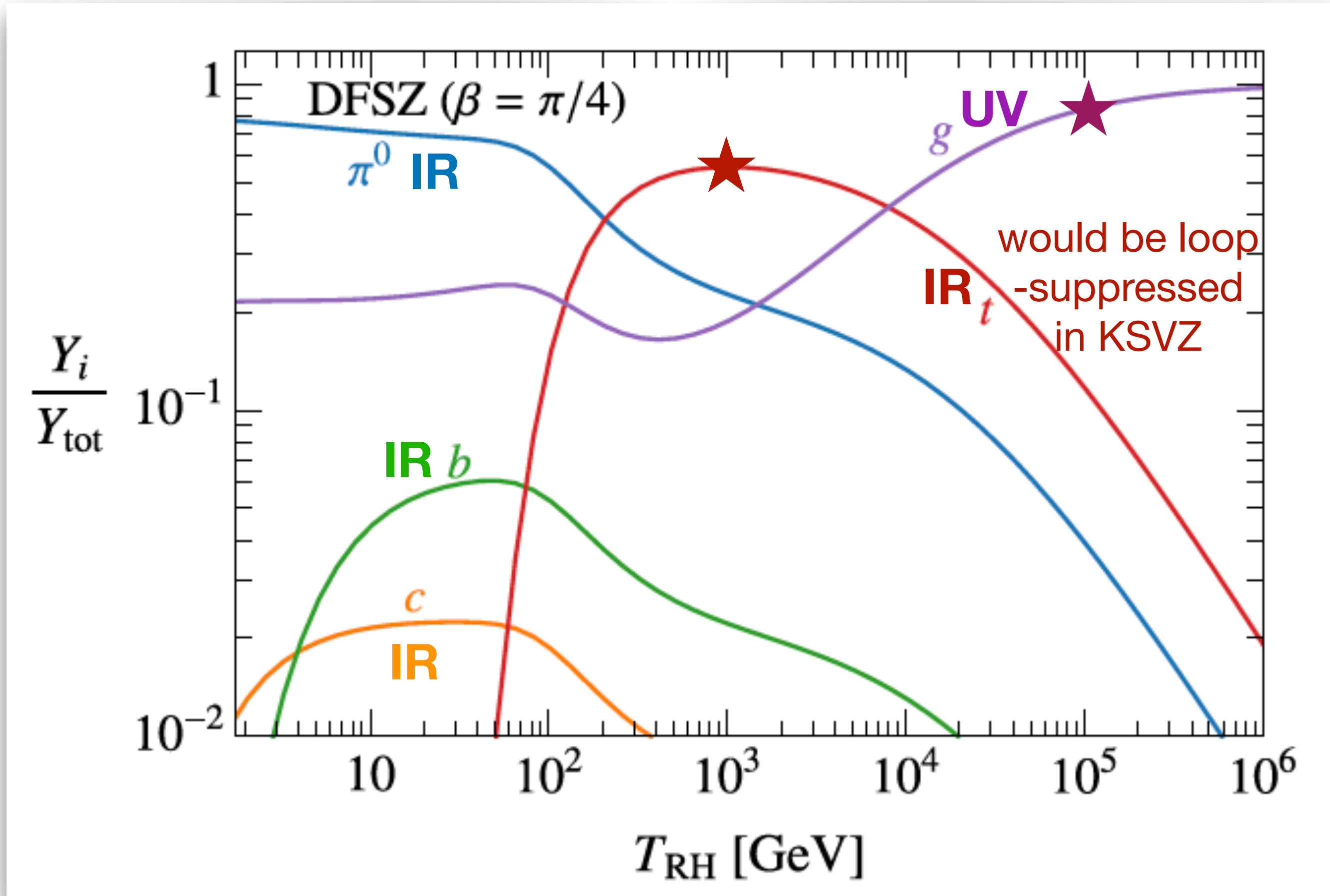
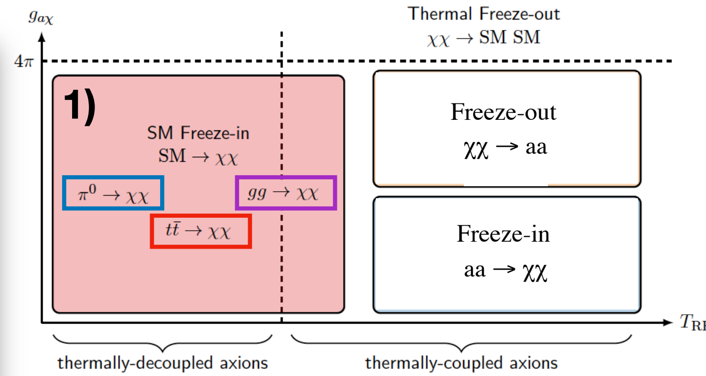
see also Salvio et al., 1310.6982

A bird's-eye view



1) Dark Matter from SM freeze-in





Independent on $f_a,\ g_{a\chi}$

To avoid DM-SM thermalization:

$$T_{RH} < T_{\chi SM} \simeq 4 \times 10^7 \text{GeV} \left(\frac{f_a}{10^9 \text{GeV}}\right)^2 \left(\frac{1}{g_{a\chi}}\right)^2$$

Simplifying assumption:

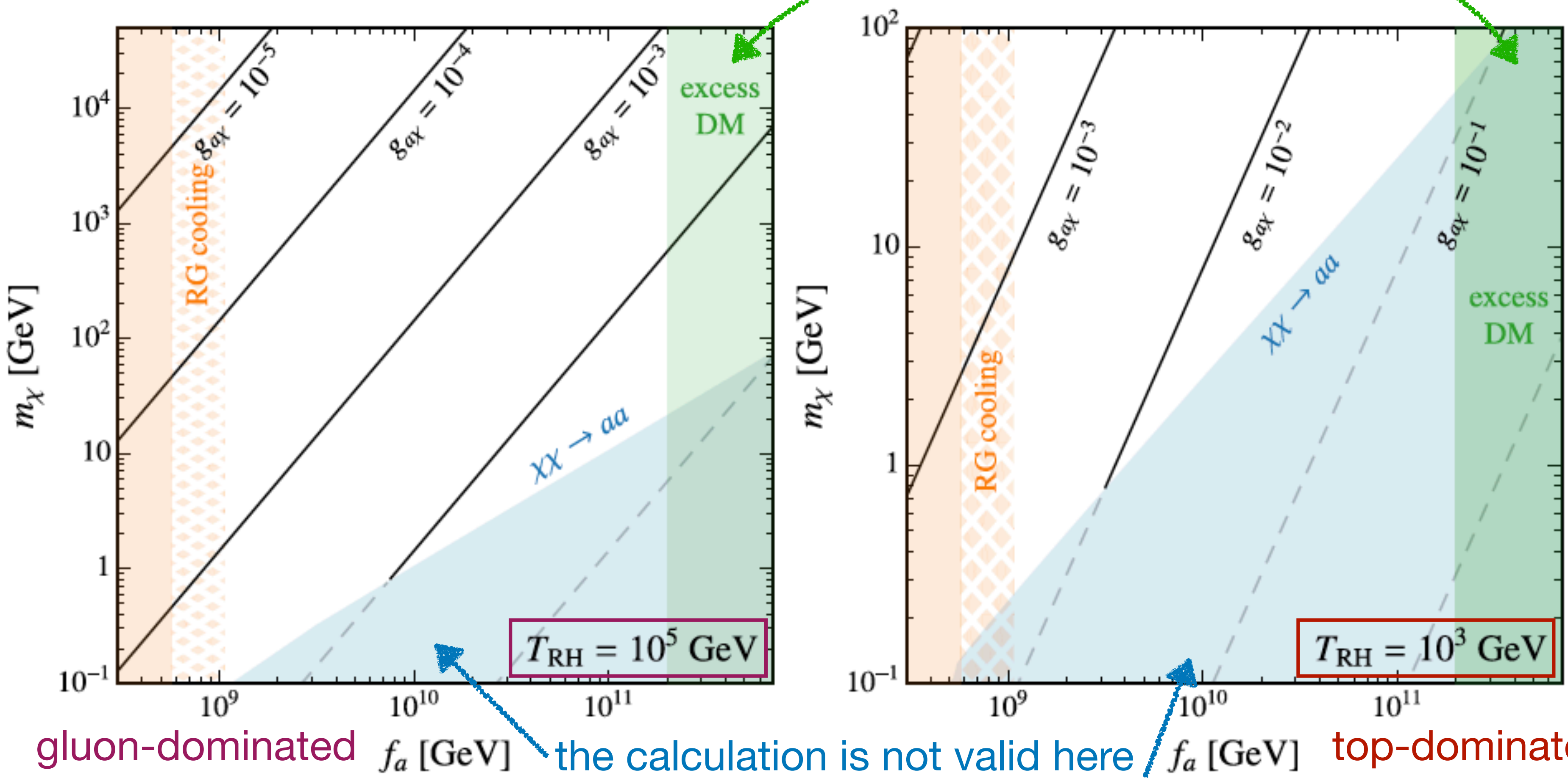
$$T_{RH} < T_{aSM} \simeq 2 \times 10^4 \text{GeV} \left(\frac{f_a}{10^9 \text{GeV}}\right)^2$$

such that the axion does not have a thermal abundance

1) SM freeze-in: the relic abundance

$g_{a\chi}$ needed to get the measured relic abundance

axion is DM here



gluon-dominated

top-dominated

the calculation is not valid here since DM can freeze-out to axions

$$n_\chi \sigma_{\chi\bar{\chi}\to aa} \gtrsim H$$

Decoupled freeze-out regime in Bharucha et al., 2209.03932

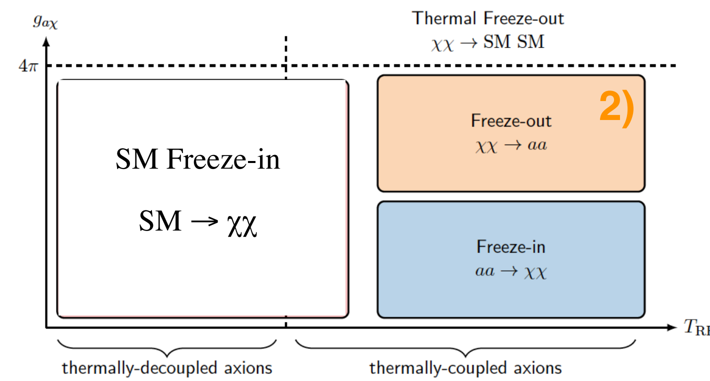
typically not natural regime since $g_{a\chi} \equiv \dfrac{c_\chi m_\chi}{f_a}$

2), 3) Dark Matter from axion freeze-out or freeze-in

No coupling with the SM is necessary

↓

difficult to test experimentally

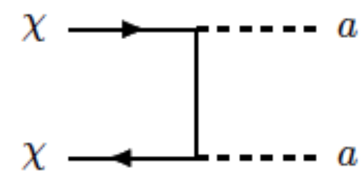


$T_{RH} \gtrsim T_{\chi SM}$ **secluded freeze-out**

2) DM in thermal contact with the SM in the early universe.

$$\frac{\Omega_\chi}{\Omega_{DM}} \sim \left(\frac{m_\chi}{1\text{GeV}}\right)^2 \left(\frac{4.4 \times 10^{-2}}{g_{a\chi}}\right)^4$$

unnatural regime



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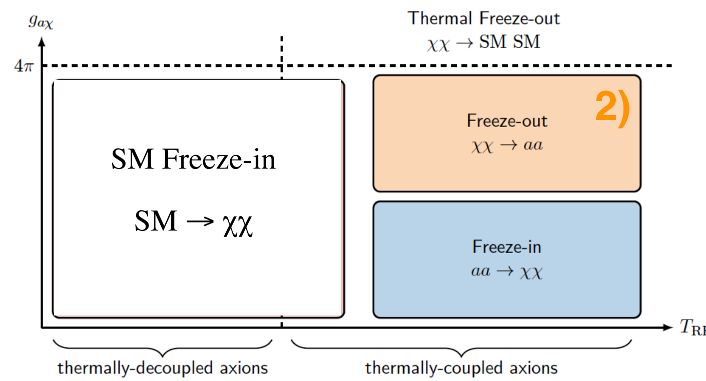

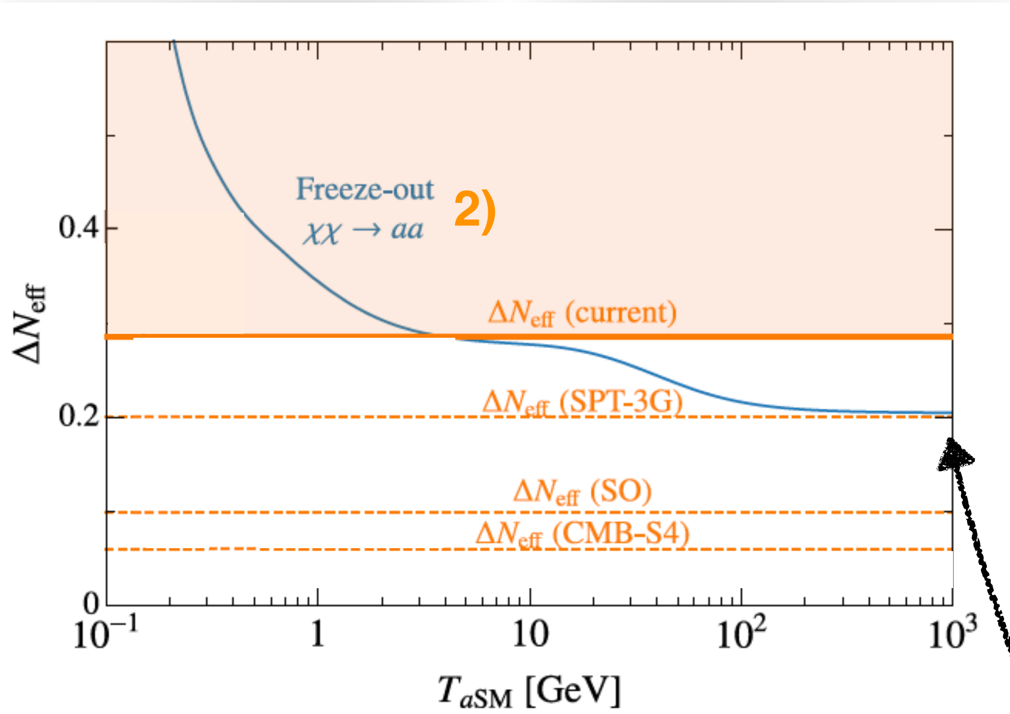

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DM annihilates into QCD axions, which remain relativistic today

→ significant source of dark radiation.

Future experiments will be able to completely probe the freeze-out scenario

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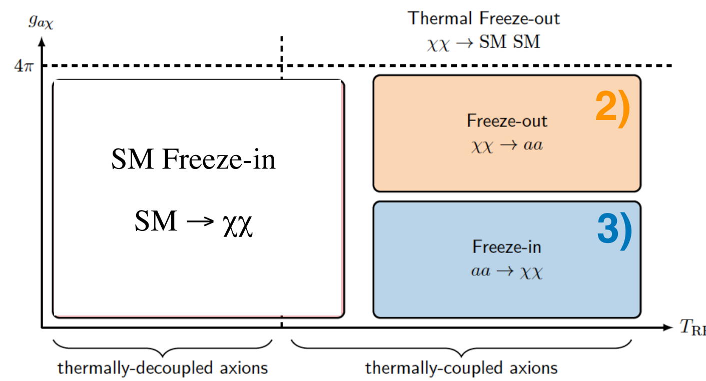

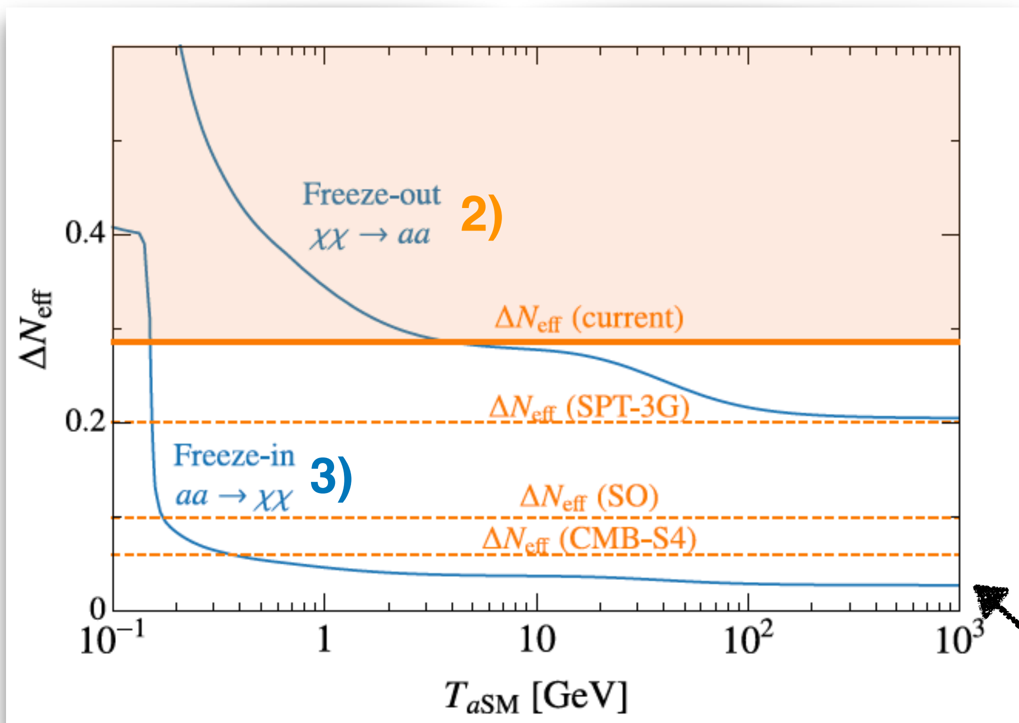

secluded freeze-in

$$T_{aSM} \lesssim T_{RH} \lesssim T_{\chi SM} \text{ and } T_{RH} \gtrsim T_{a\chi}$$

3) axion is thermalized in the early universe

$$\frac{\Omega_\chi}{\Omega_{DM}} \sim \left(\frac{g_{a\chi}}{3 \times 10^{-6}}\right)^4$$

natural regime

The QCD axions will contribute to N_{eff}, but now the DM does not have a sizable energy density → the evolution of the dark sector temperature will be different than in the freeze-out case

The freeze-in scenario is pretty hidden, even to future experiments

Axion mediators beyond the QCD axion

The model we discussed so far is compelling since it is highly predictive and some scenario can be probed in the future. However, no laboratory-based probes

Reason: large f_a that makes the coupling to the SM very small

What if we extend this framework to much heavier axions/axion-like-particles?

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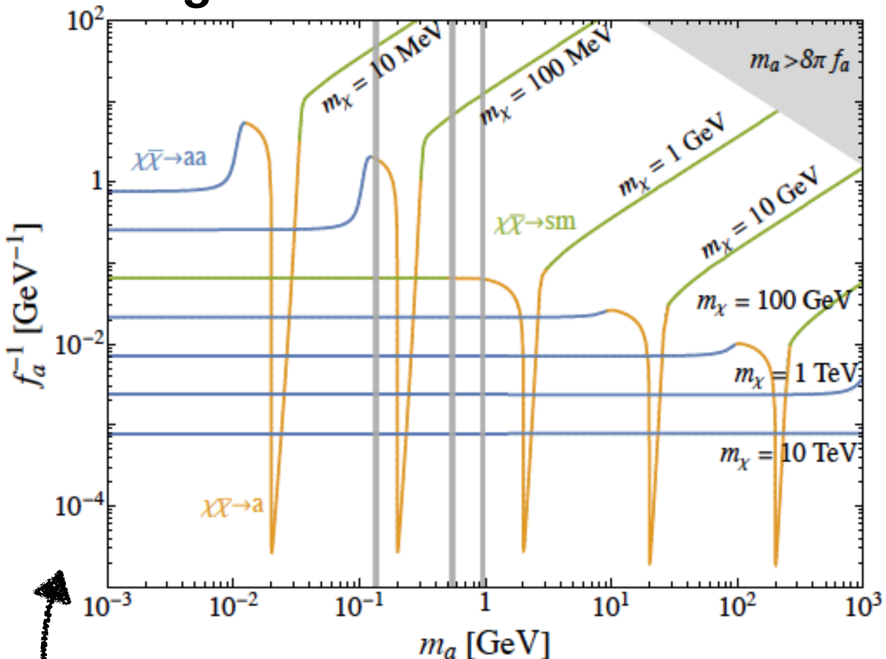
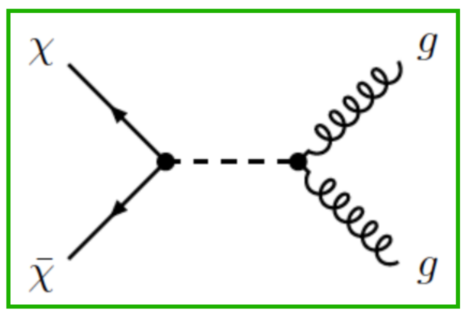
ALP coupled to gluons



$$m_a f_a \neq m_\pi f_\pi$$



SM freeze-out is now a viable model

see e.g., Fitzpatrick et al, 2306.03128 for axion-DM cosmological models with heavier axions

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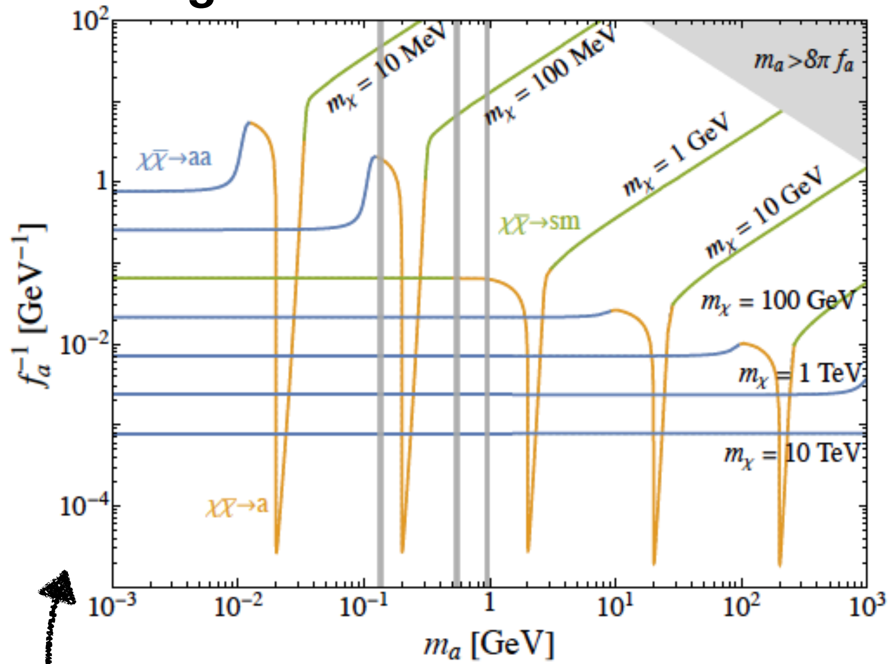
Freeze Out



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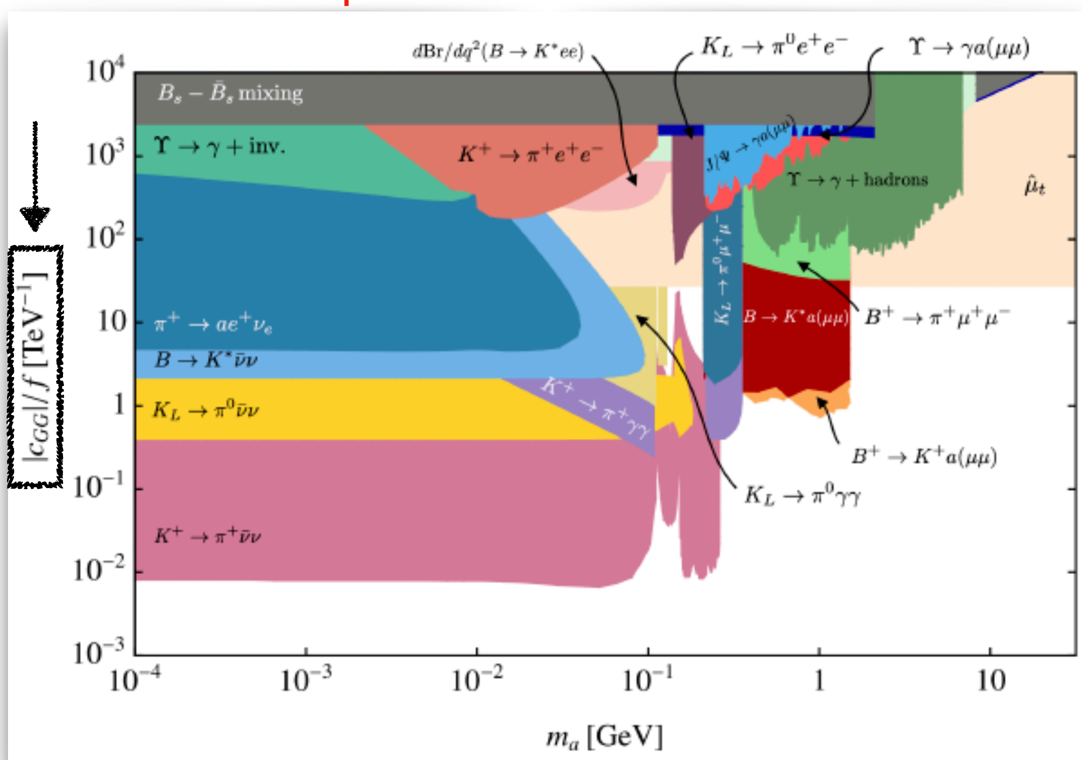
ALPs produced at accelerators



Bauer et al., 2110.10698

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Spin-dependent scattering with nuclei at direct detection experiments

with Knapen, Lin, Munbodh, Suter, 2501.xxxxx

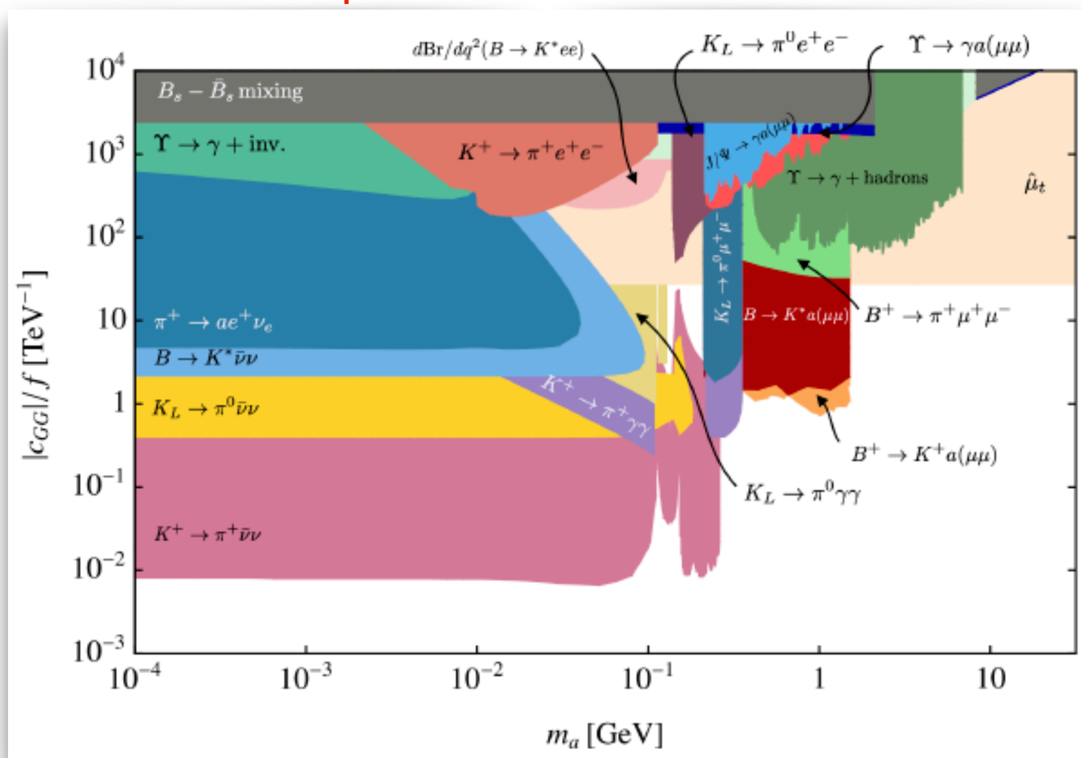
$$\mathcal{H} = -\frac{g_{a\chi} g_n}{m_n m_\chi} \frac{(\bar{q}\cdot\bar{S}_\chi)(\bar{q}\cdot\bar{S}_n)}{\bar{q}^2 + m_a^2} e^{i\bar{q}\bar{r}}$$

g_n is the axion coupling to nuclei:

$$\mathcal{L}_{an} = g_n a \bar{n}\gamma^5 n$$

Computing rates for different materials as a function of the threshold energy, while being consistent with flavor constraints and DM self-interaction constraints

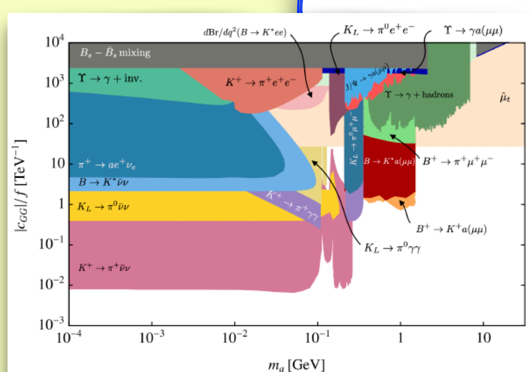
ALPs produced at accelerators



Bauer et al., 2110.10698

Chapter 2

Heavier axions and new phenomenology at meson factories



any new search?

Main reference I will discuss:
Altmannshofer, Dror, SG, 2209.00665

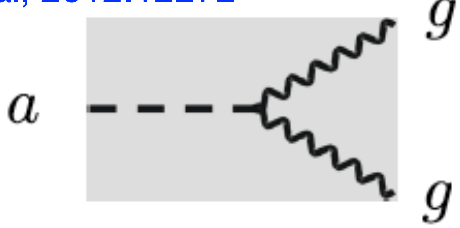
Let’s go back to the EFT for axions

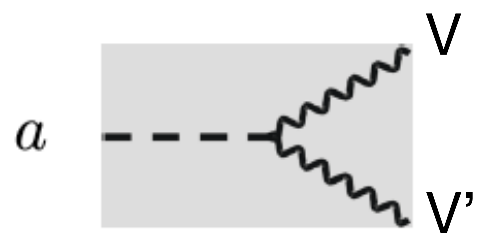
At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

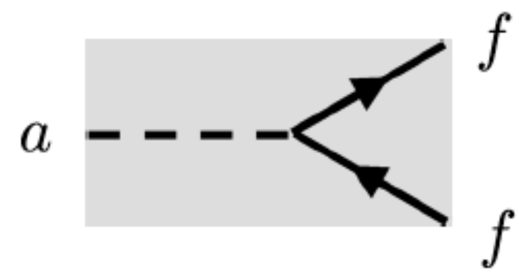
Georgi, Kaplan, Randall 1986

$$\mathcal{L} \supset -\frac{g_{ag}}{4}\, a\, G^{a}_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{g_{aW}}{4}\, a\, W^{a}_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu}\tilde{B}^{\mu\nu} + i g_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$

For the complete one-loop analysis, see
Bonilla et al, 2107.11392
Bauer et al, 2012.12272







Fast progressing number of theory studies + experimental searches

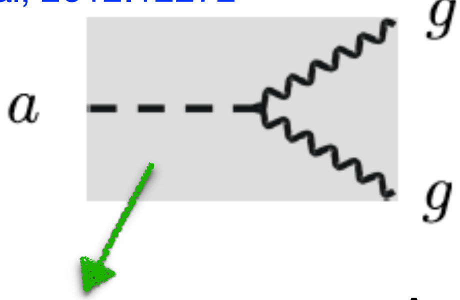
Let's go back to the EFT for axions

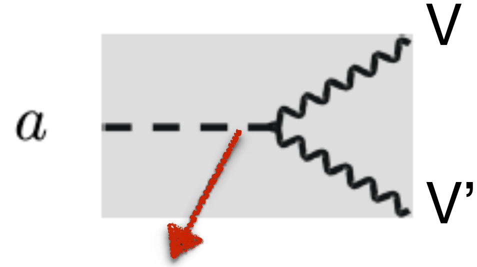
At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

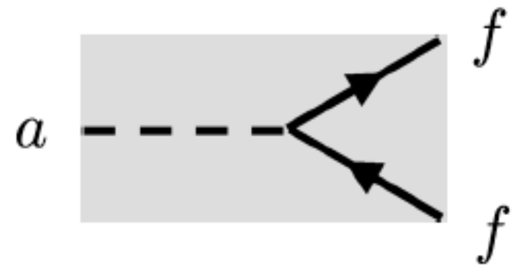
Georgi, Kaplan, Randall 1986

$$\mathcal{L} \supset -\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu}\tilde{B}^{\mu\nu} + i g_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$

For the complete one-loop analysis, see
Bonilla et al, 2107.11392
Bauer et al, 2012.12272







Minimal coupling expected if connection to the strong CP problem.

A axion-photon coupling is generated in the broken phase

$$g_{aB}\cos^2\theta + g_{aW}\sin^2\theta$$

This is the **main coupling** that has been considered for phenomenological studies of axions in the sub-GeV scale.

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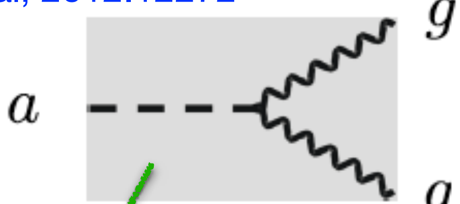

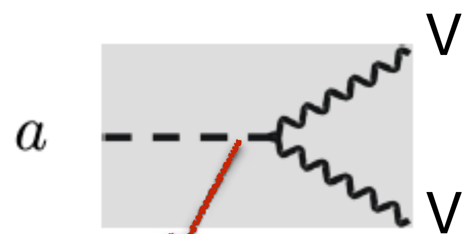

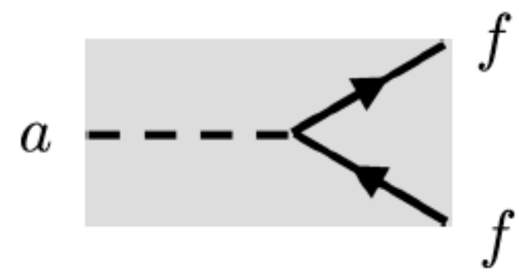

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These are **the least studied couplings**. Nevertheless they are present and sizable even in the minimal DFSZ QCD axion model.

(indeed the most stringent constraint on the DFSZ axion comes from its coupling to electrons (red giant))

Fast progressing number of theory studies + experimental searches

Axion coupling to leptons

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

Altmannshofer, Dror, SG, 2209.00665

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Altmannshofer, Dror, SG, 2209.00665

$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

$$\partial_\mu j^\mu_{\mathrm{PQ}}=g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

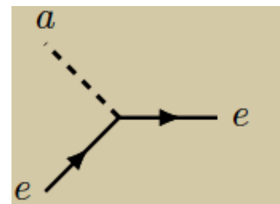
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s_W^2}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$

$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s_W^2)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+$$

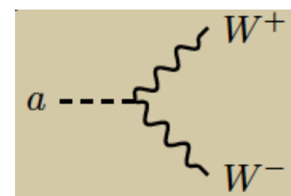
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s_W^2)-g_{\ell\ell}(1-4s_W^2+8s_W^4)+g_\nu}{8s_W^2 c_W^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu$$

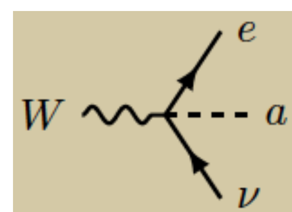
"Standard" vertex



Anomaly terms



Weak vertex



only present if SU(2) (or weak) violation:

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

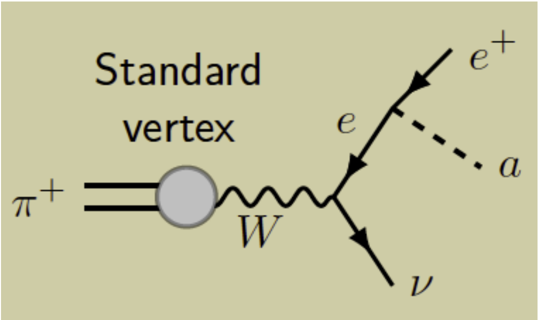
Rate for charged current production

≠ 0 only if weak SU(2) violation

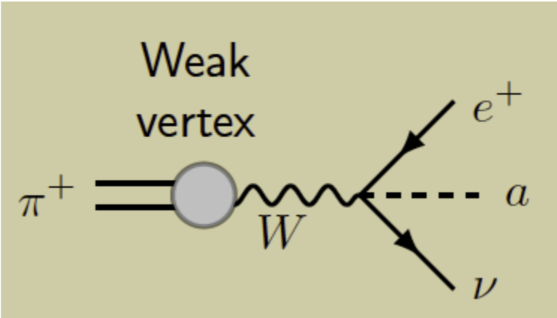
$$\mathrm{BR}(\pi^+ \to e^+ a\nu) = \frac{1}{384\pi^2}\frac{m_\pi^4}{m_e^2 m_\mu^2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^{-2}\Bigg[\overbrace{(g_{ee}-\bar{g}_{ee}+g_\nu)}^{}{}^2 f_0\left(\frac{m_a^2}{m_\pi^2}\right) + \frac{4m_e^2}{m_\pi^2}\left(3(g_{ee})^2 f_3\left(\frac{m_a^2}{m_\pi^2}\right) + 3(\bar{g}_{ee}-g_\nu)^2 f_4\left(\frac{m_a^2}{m_\pi^2}\right) + 2g_{ee}(\bar{g}_{ee}-g_\nu) f_5\left(\frac{m_a^2}{m_\pi^2}\right)\right) + \mathcal{O}\left(\frac{m_e^3}{m_\pi^3}\right)\Bigg]$$

Helicity suppression is lifted only in the case of weak SU(2) violation

Weak preserving models



Weak violating models



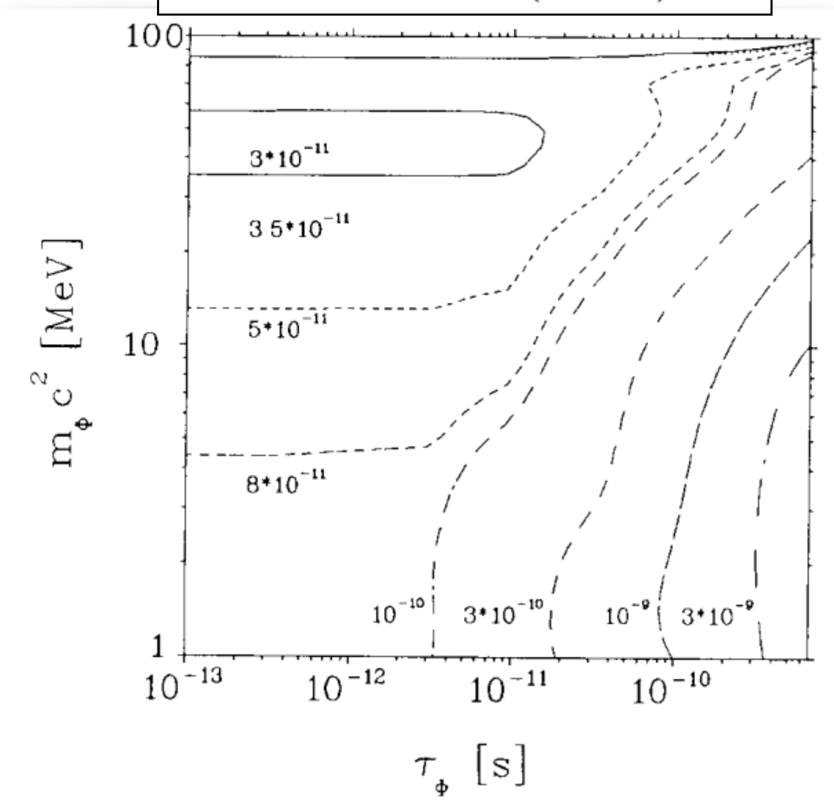
Similar results for $K^+ \to ae^+\nu,\ \ D_s^+ \to ae^+\nu,\ \ B^+ \to ae^+\nu$

The past search for $\pi^+ \to e^+\nu(a \to e^+e^-)$

In the late '80s,
the SINDRUM experiment at PSI:

Almost background free search

$\pi^+ \to \phi e^+\nu \to (e^+e^-)e^+\nu$



Eichler et al. Physics Letters B 175 (1986), no. 1 101–104

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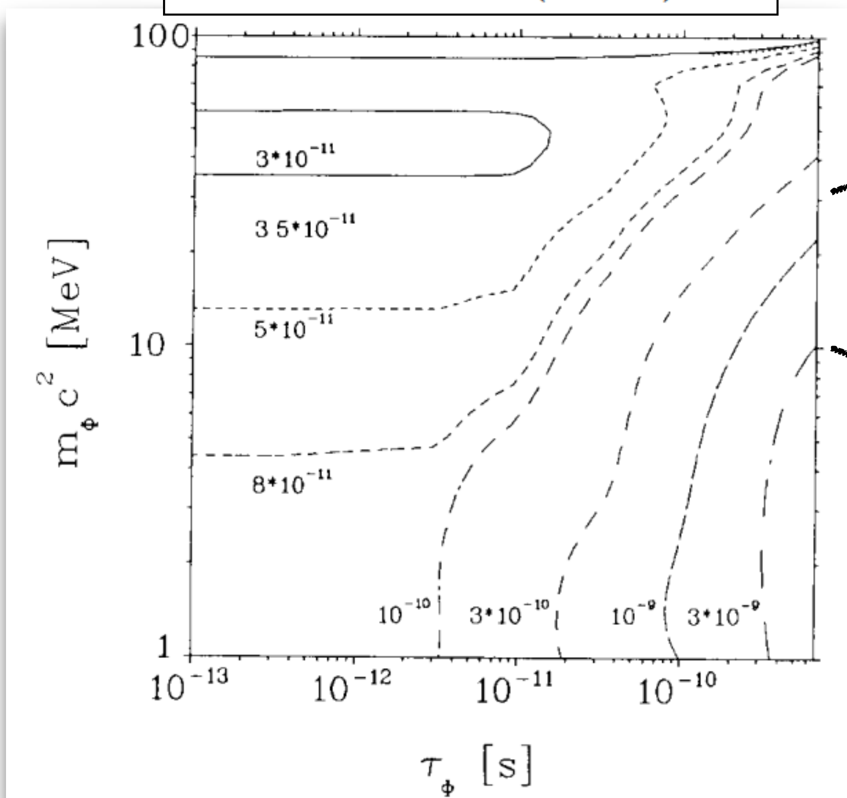

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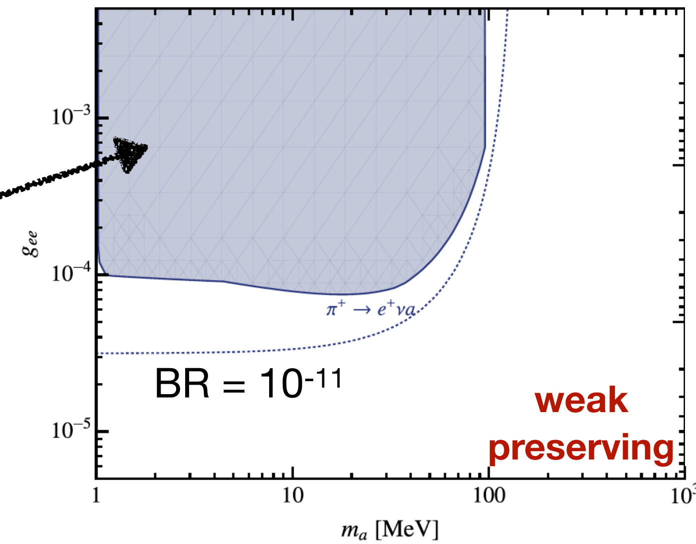
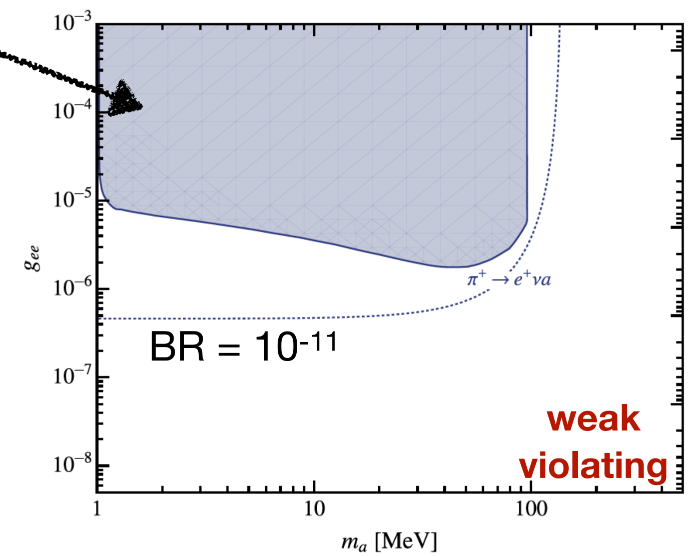
$$f_a \sim m_e/g_{ee}$$





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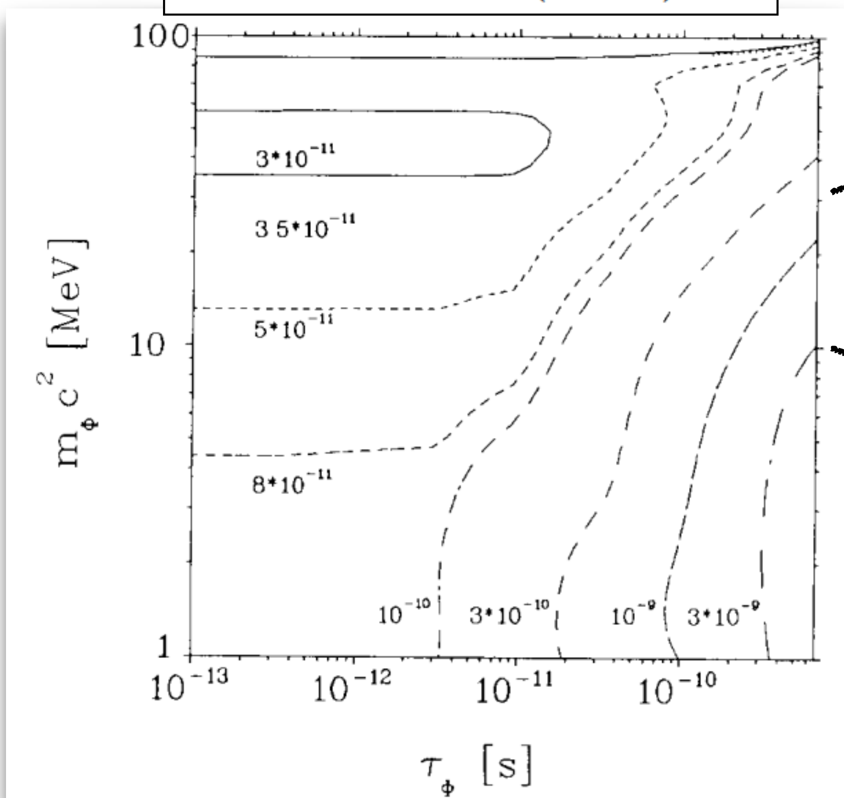

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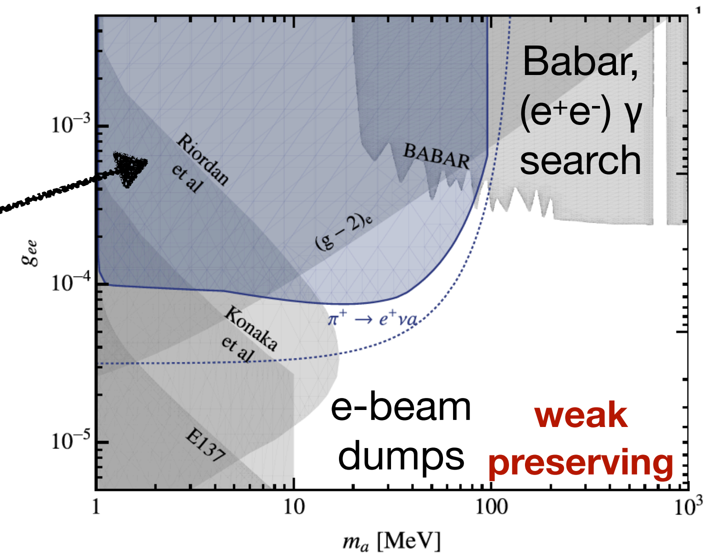
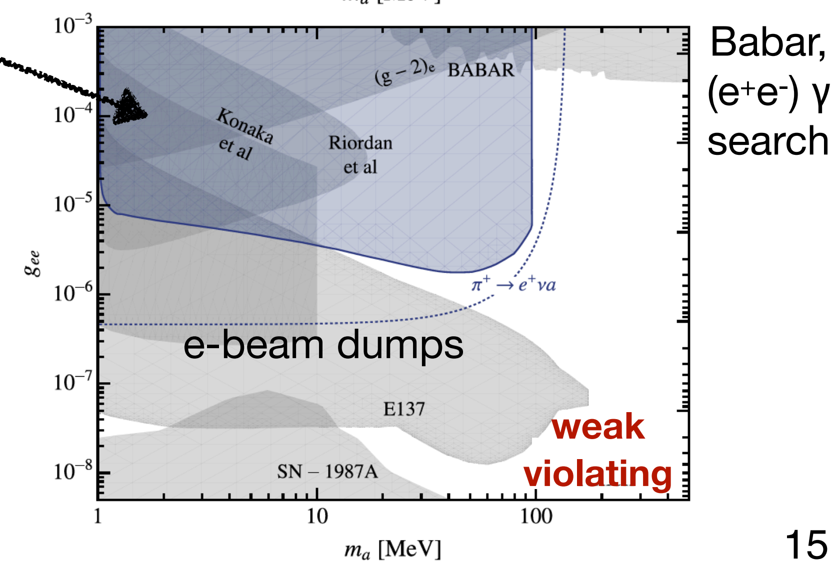
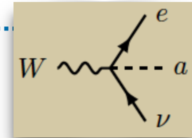




Other charged current decays

Kaon decays

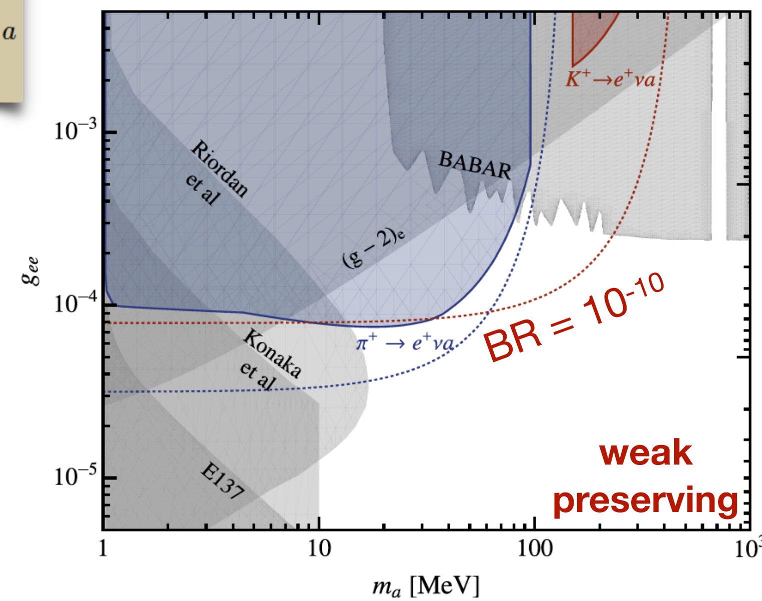


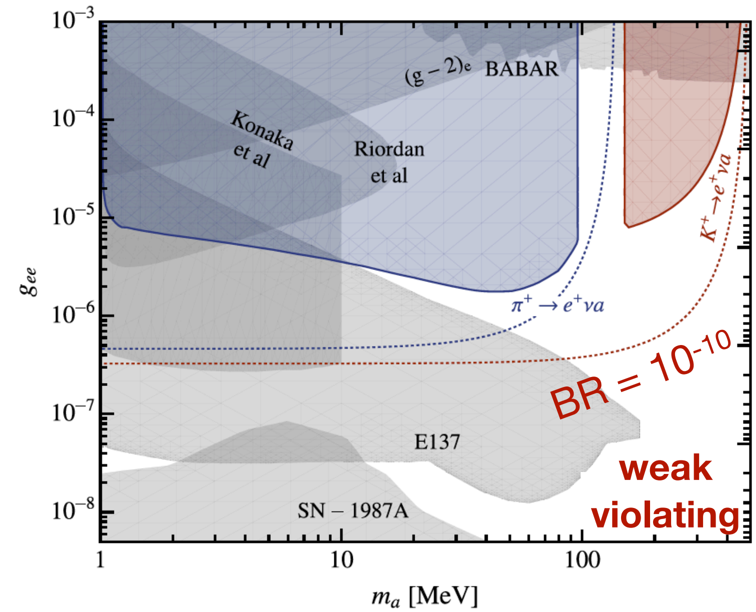
$$\frac{\mathrm{BR}(K^+ \to e^+ \nu a)}{10^{-10}} \simeq \begin{cases} \left(\dfrac{g_{ee}}{3.3\cdot 10^{-7}}\right)^2 & \text{weak violating} \\ \left(\dfrac{g_{ee}}{7.9\cdot 10^{-5}}\right)^2 & \text{weak preserving} \end{cases}$$

hep-ex/0204006, E865 at BNL:

BR measured for $m_{ee} > 150$ MeV

No dedicated search





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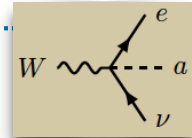

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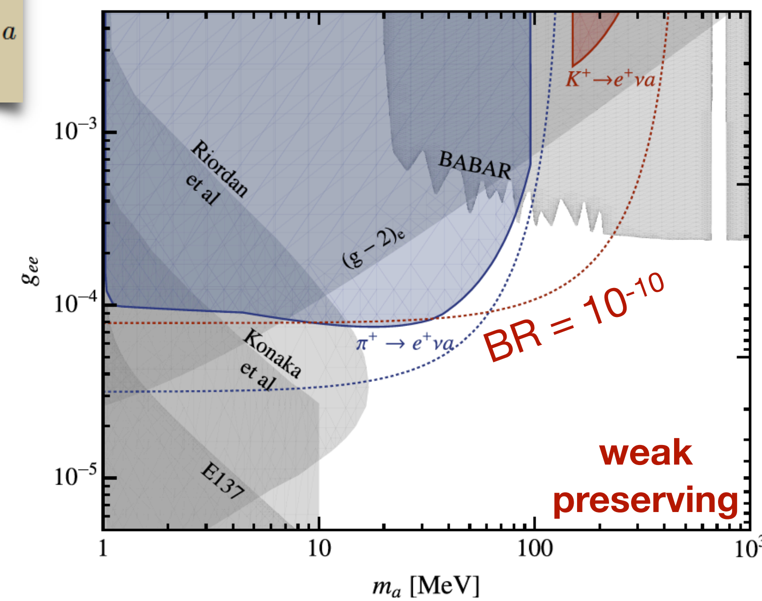


W boson decays

$$\frac{\mathrm{BR}(W^+ \to \ell^+ \nu_\ell a)}{\mathrm{BR}(W^+ \to e^+ \nu)} = \frac{3}{1024\pi^2} \frac{m_W^2}{m_\ell^2} (g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu_\ell})^2$$

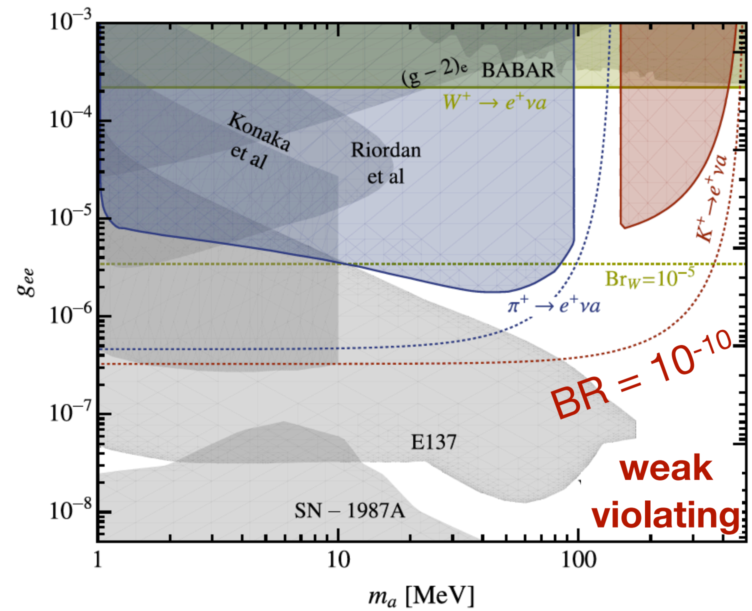
$$\Rightarrow \mathrm{BR}(W^+ \to e^+ \nu_e a) \simeq \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

(only for weak violating)

No dedicated search

We impose:

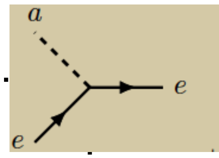
the new width < exp uncertainty on W width



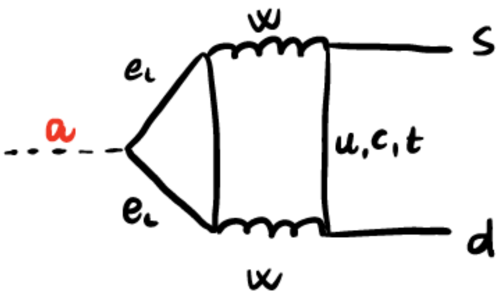
Neutral current decays

Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$K \to \pi a$



1. Axion with LH coupling



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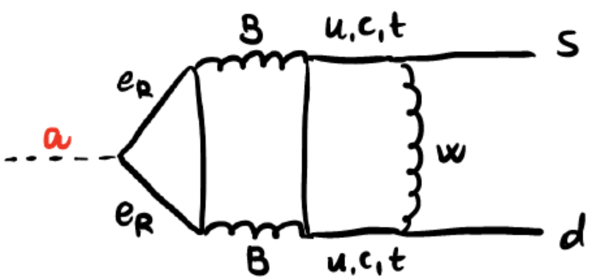

Similar diagrams for $B \to K^{(*)} a$

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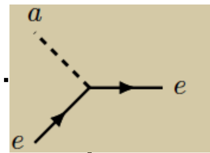

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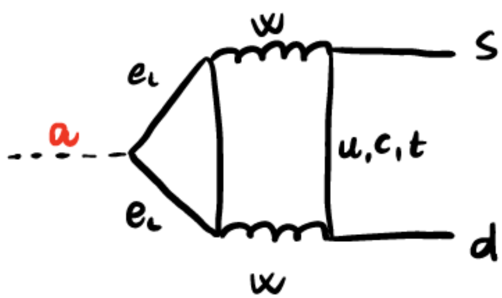

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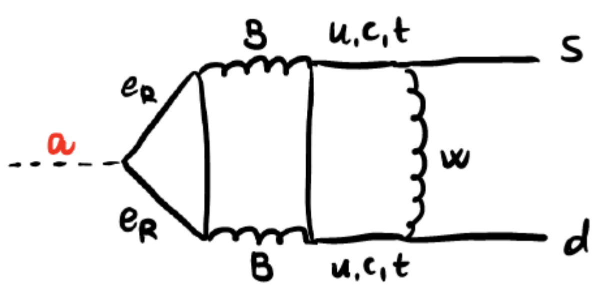

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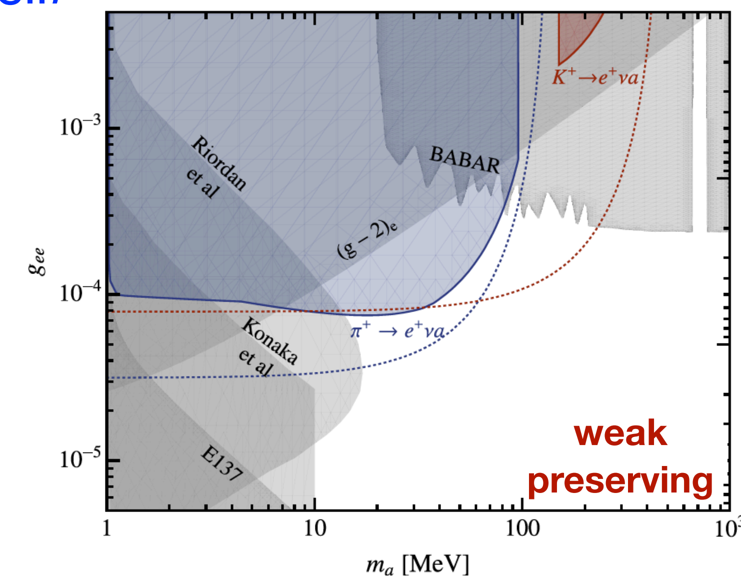

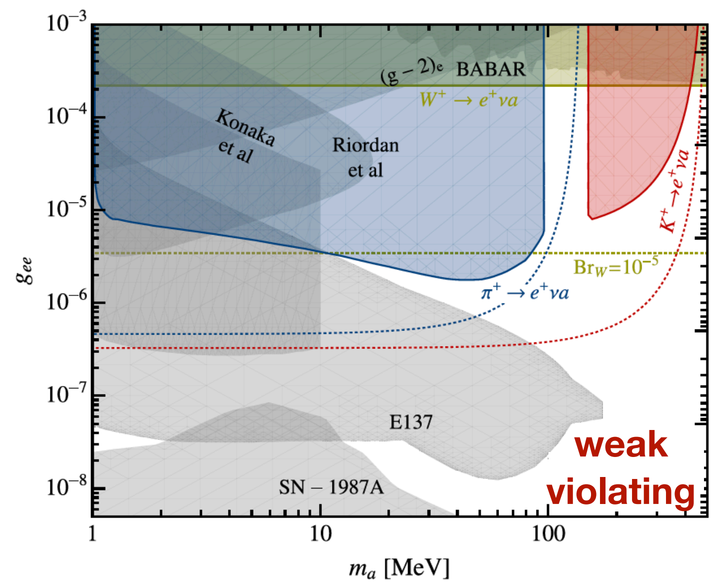

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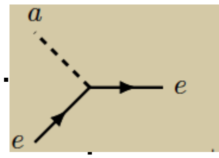

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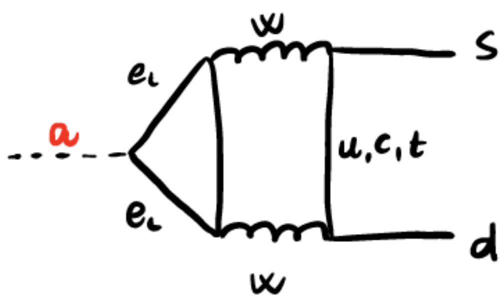

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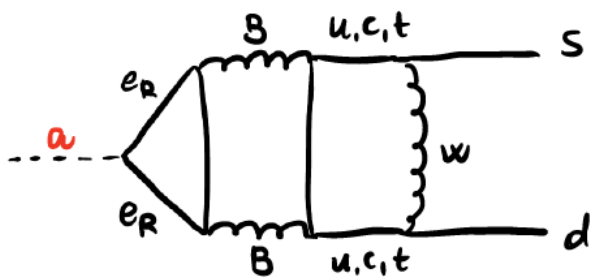

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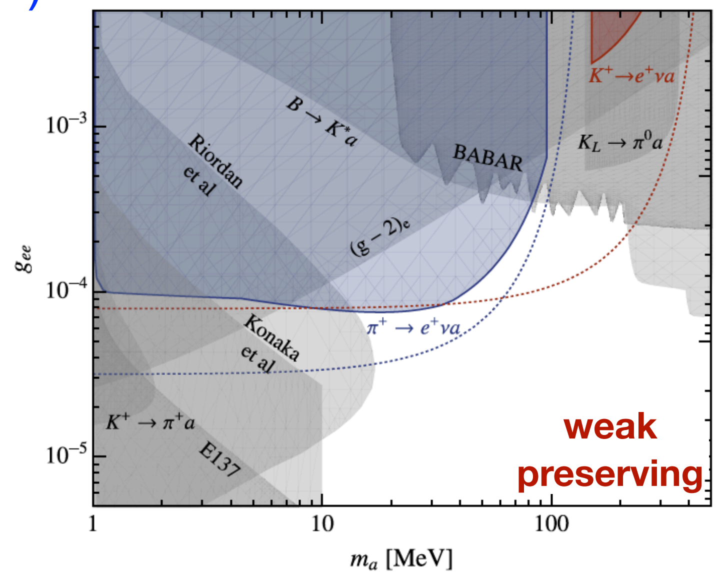

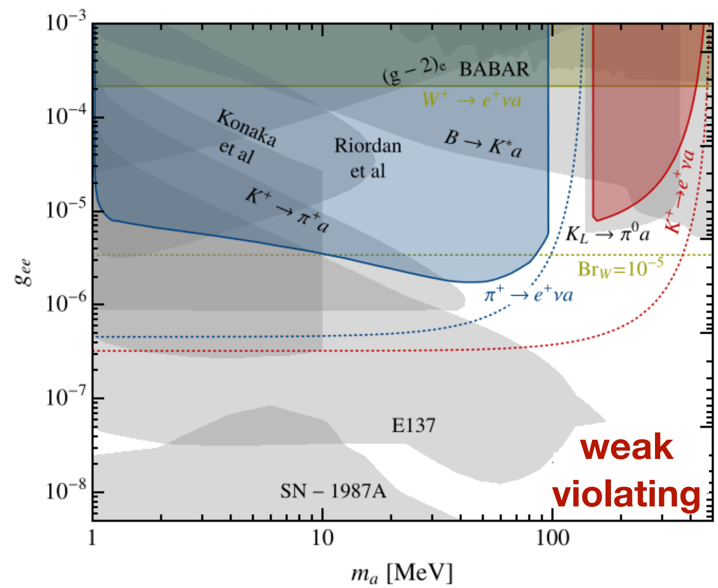

reinterpreting past data (not dedicated searches)

What about the future? Advances in meson factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
Pion-factories	**PIENU experiment** at TRIUMF: ~10^{11} pi^+	**PIONEER experiment** at PSI (phase 1 approved. Data in ~2028(?)): ~10^{12} pi^+
Kaon-factories	**E949** at BNL: ~10^{12} K^+ **E391** at KEK: ~10^{12} K_L	**NA62** at CERN: ~10^{13} K^+ **KOTO** at JPARC: ~10^{14} K_L
B-factories	**LHCb:** more than ~ 5*10^{12} b quarks produced so far; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	**LHCb:** ~30 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced.

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B-factories + LHC, future colliders	**LHCb:** more than ~ $5*10^{12}$ b quarks produced so far; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	**LHCb:** ~30 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced. **Proton fixed target:** 10^8; 10^{13} B

Proton fixed target experiments also produce a huge statistics of mesons.

E.g., DarkQuest (120 GeV protons, $2*10^{18}$ POT); SHiP (400 GeV protons, $2*10^{20}$ POT)

Future axion searches

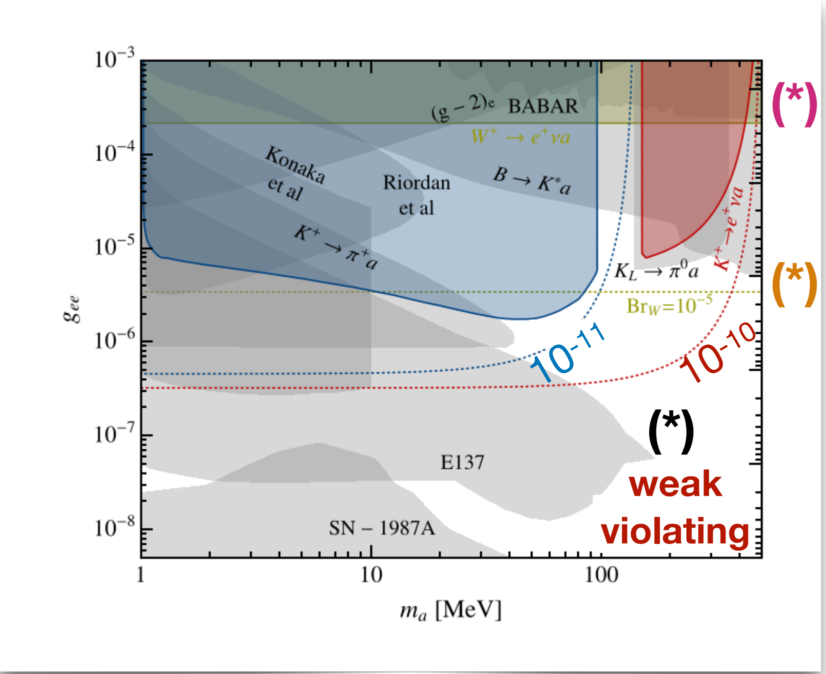
PIONEER is $\mathrm{BR}(\pi^+ \to e^+\nu(a \to e^+e^-)) = 10^{-11}$ reachable?
what about displaced axions?

NA62 is $\mathrm{BR}(K^+ \to e^+\nu(a \to e^+e^-)) = 10^{-10}$ reachable?
what about displaced axions?

Belle-II (*) what about $B^+ \to e^+\nu(a \to e^+e^-)$?

LHC is $\mathrm{BR}(W^+ \to e^+\nu(a \to e^+e^-)) = 10^{-5}$ reachable? (*)

DarkQuest & SHiP Searches for a displaced axion decaying to e^+e^- **(*)**



Conclusions & Outlook

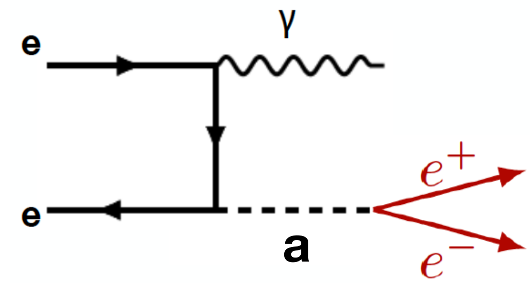
Axions are very well motivated particles beyond the Standard Model.
Large experimental effort to search for the minimal QCD axion.

Axions can
- be a Dark Matter candidate or
- mediate interactions between the Dark Matter and the SM. Several cosmological models and tests with astrophysical and cosmological data

Heavier axions can still address the strong CP problem and lead to new interesting phenomenology for meson factories, LHC, and beam dump experiments.

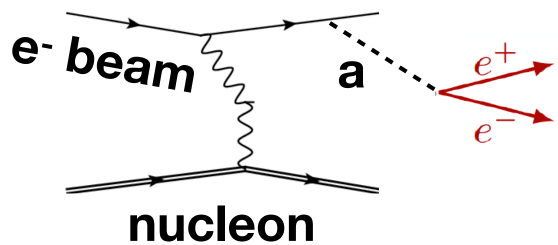
How to search for these axion interactions?

1. Reinterpretation: B- factories direct production (Babar. For prompt axions)

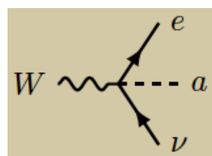


$e^+e^- \rightarrow \gamma\, a \rightarrow \gamma e^+e^-$

2. Direct production at electron beam dump experiments (For displaced axions)



3. W and meson decays through charged currents (LHC, meson factories, proton beam dump experiments. For prompt and displaced axions).

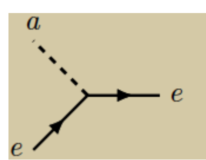


Example: $\pi^+ \rightarrow a e^+ \nu$

NEW

Novel searches can be done in the coming years

4. Meson decays through neutral currents (meson factories, proton beam dump experiments. For prompt and displaced axions).



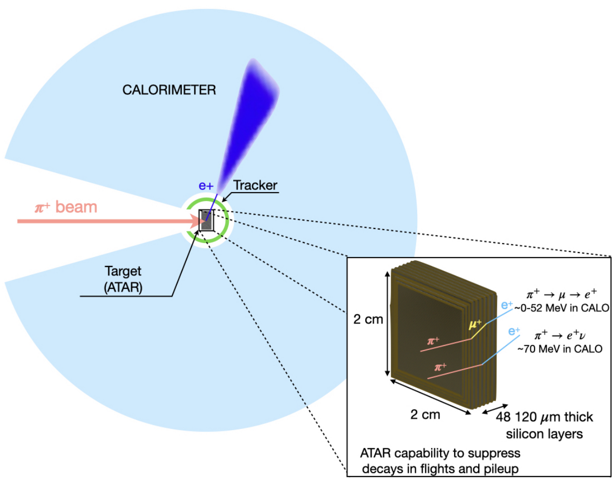
Example: $B \rightarrow K a$

Most studied

The most recent experiments

PIONEER

pion-decay-at rest experiment



Experiment **approved** in summer '22 for **PSI** (Switzerland).

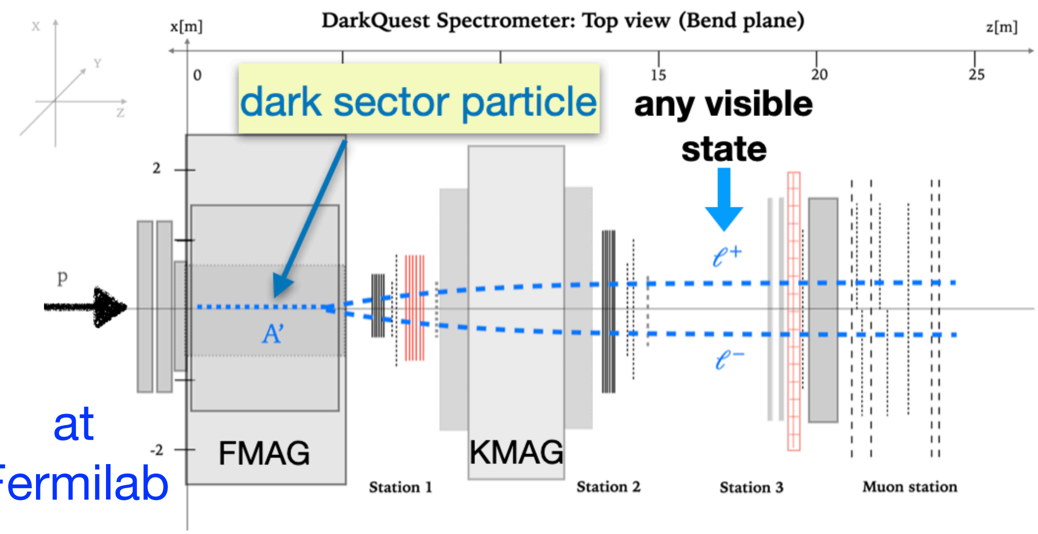
See the proposal:
Altmannshofer et al., 2203.01981

Main physics goals:

most precise measurement of
very rare pion decays

$$\pi^+ \to e^+\nu \qquad \pi^+ \to \pi^0 e^+\nu$$

DarkQuest (upgrade of SpinQuest)



at Fermilab

SpinQuest → **DarkQuest**

Took data last April-June
(only muon signatures)

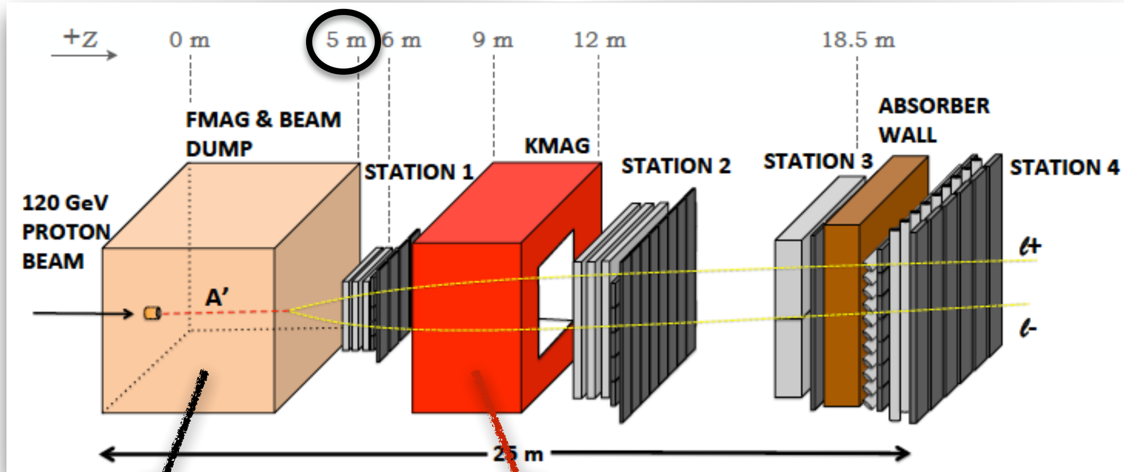
proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)

Initial proposal: Berlin, SG, Schuster, Toro, 1804.00661

August '23:
We got funded!

Similar in scope to the SHiP experiment at CERN

Details on DarkQuest



1. Compact geometry

Sensitivity to (slightly) displaced dark particles with **d > 5m**

FMAG sweeps away soft SM radiation

2. KMAG separating even very forward charged particles ($\Delta p_T \sim 0.4$ GeV)

Identification of very light dark particles/squeezed spectra

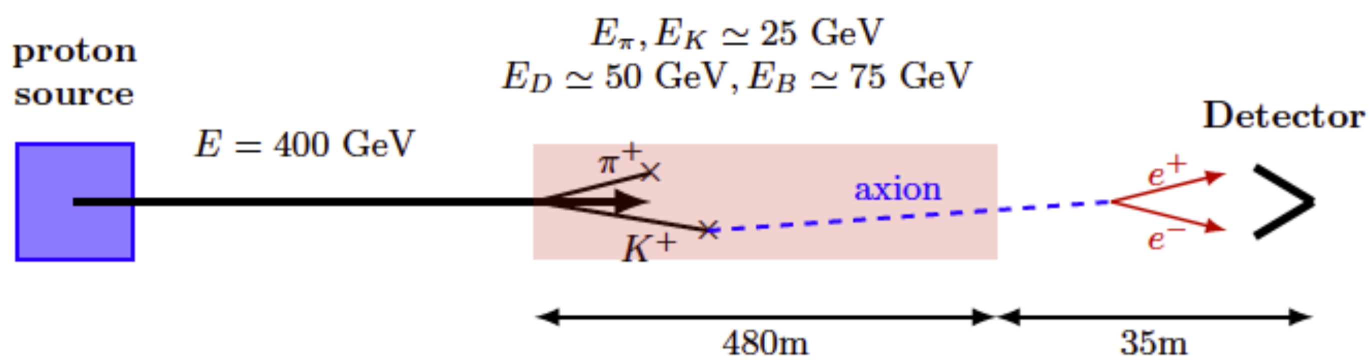
Experiment	Proton energy	POT	Dump	Decay volume
DarkQuest	120GeV	10^{18}	5 m	10 m
CHARM	400GeV	2.4×10^{18}	480 m	35 m
LSND	800MeV	10^{22}	30 m	10 m
NA62-dump	400 GeV	5×10^{19}	100 m	250 m
SHiP	400 GeV	2×10^{20}	30 m	50 m

Past

Proposed

Proton beam dump experiments & axions

CHARM experiment (late 80s at CERN)



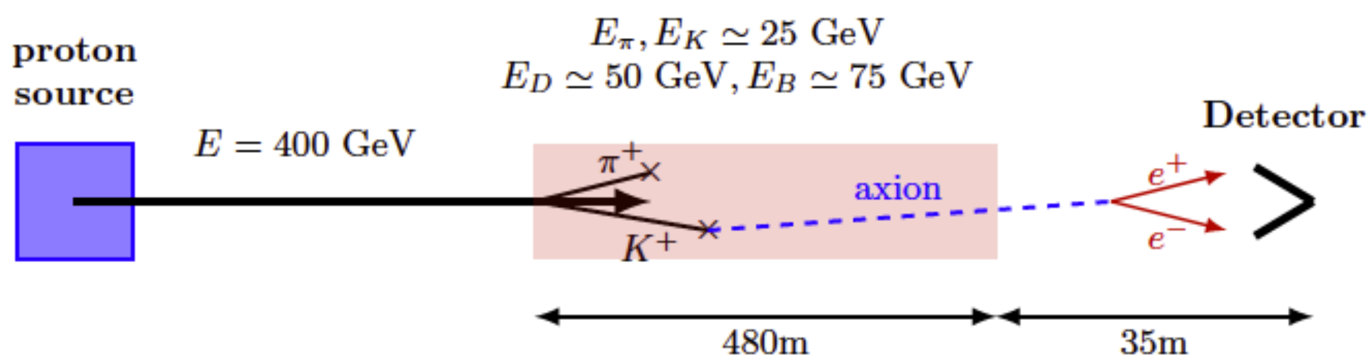
Past proton beam dump experiments produced unprecedented amounts of mesons.
For example, the CHARM experiment collected **~10^{20} pions**

Several studies for axions (or other dark sector particle) production at past proton beam dump experiments: $K \to \pi a$ or $B \to K a$

However, charged current production has been neglected ($K^+ \to a\, e^+ \nu$, …)

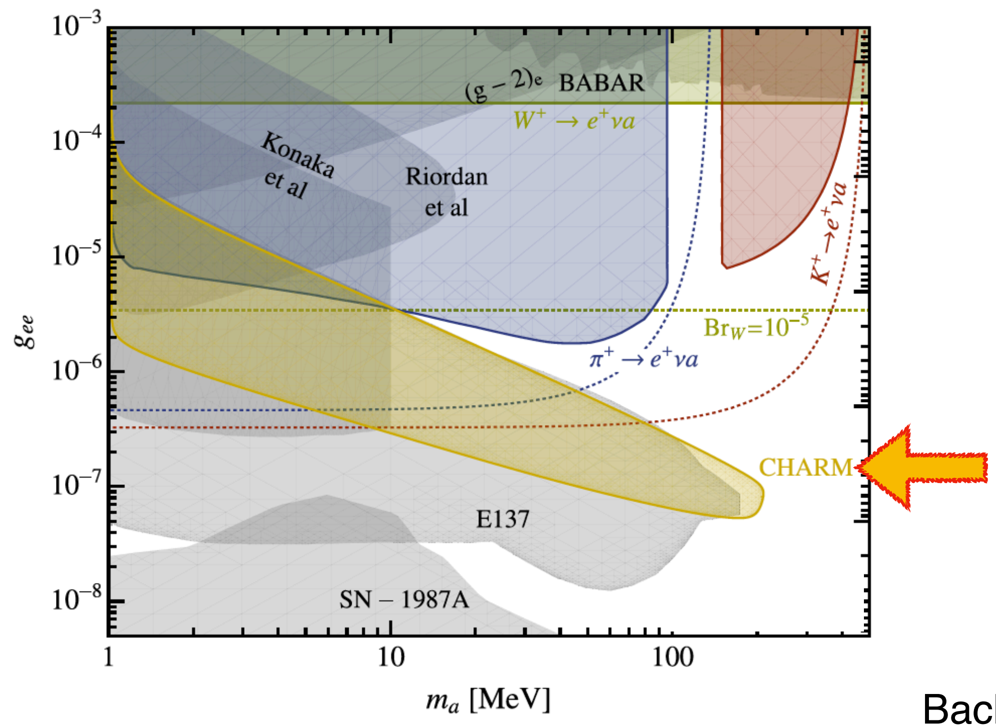
Proton beam dump experiments & axions

CHARM experiment (late 80s at CERN)



New in our study:

- First use of D, D_s, B_c mesons
- Introduction of charged current meson decays

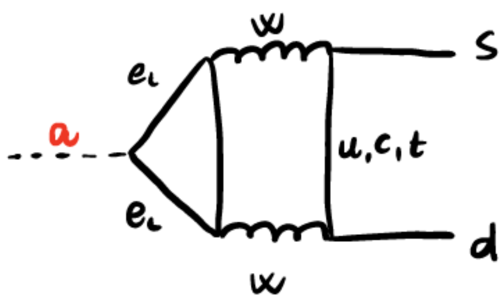


Neutral current decays

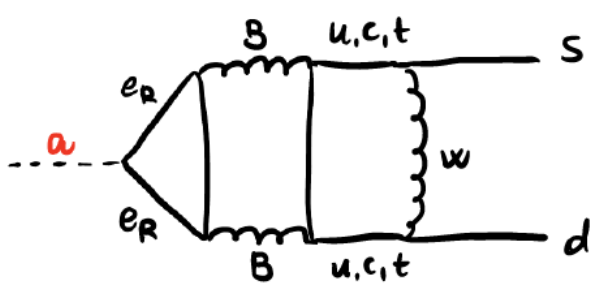
Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$K \to \pi a$

1. Axion with LH coupling



2. Axion with RH coupling



Similar diagrams for $B \to K^{(*)} a$

They arise from the anomaly terms induced at loop level

$$-\frac{g_{aW}}{4}\, a\, W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu} \tilde{B}^{\mu\nu}$$

1. The sum of these diagrams is finite

$$\mathcal{L} \supset \frac{\partial_\mu a}{m_\ell} g_{d_i d_j} (\bar{d}_i \gamma^\mu P_L d_j) \ + \ \text{h.c.}$$

$$g_{d_i d_j} \simeq -\frac{g^2}{16\pi^2} V^*_{ti} V_{tj} \Big[\frac{g^2}{16\pi^2} \frac{3}{8} \overset{\textbf{1.}}{(g_{ee} - \bar{g}_{ee} - g_{\nu_e}) F(x_t)} + \underset{\textbf{2.}}{\frac{g'^4}{(16\pi^2)^2} \frac{17}{96} (g_{ee} + \bar{g}_{ee}) \frac{m_t^2}{m_W^2} \log^2\left(\frac{\Lambda^2}{m_t^2}\right)} \Big]$$

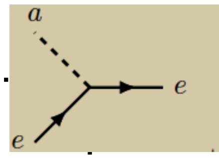
2. Log divergent

$$\Gamma(K^+ \to \pi^+ a) \ \propto \ |g_{asd}|^2$$
$$\Gamma(K_L \to \pi^0 a) \ \propto \ \text{Im}(g_{asd})^2$$

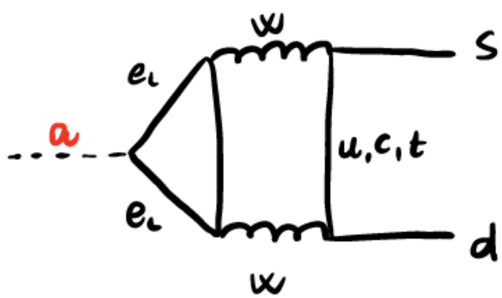
Neutral current decays

Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

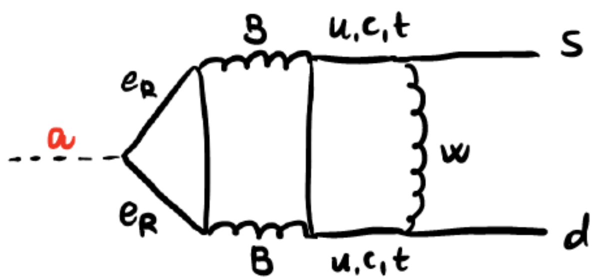
$K \to \pi a$



1. Axion with LH coupling



2. Axion with RH coupling



Similar diagrams for $B \to K^{(*)} a$

Main bounds: reinterpreting past data

NA62, 2103.15389: $K^+ \to \pi^+ + (a \to \text{ invisible})$

KTeV, 0309072: $K_L \to \pi^0 (a \to e^+ e^-)$
m_{ee} in (140, 363) MeV

777 @ BNL, Phys. Rev. Lett. 59 (1987) 2832–2835:
$K^+ \to \pi^+ (a \to e^+ e^-)$ $m_a < 100$ MeV

see also Alves, Weiner, 1710.03764

LHCb, 1501.03038: $B^0 \to K^{(*)0} (a \to e^+ e^-)$

Example of weak violating axions

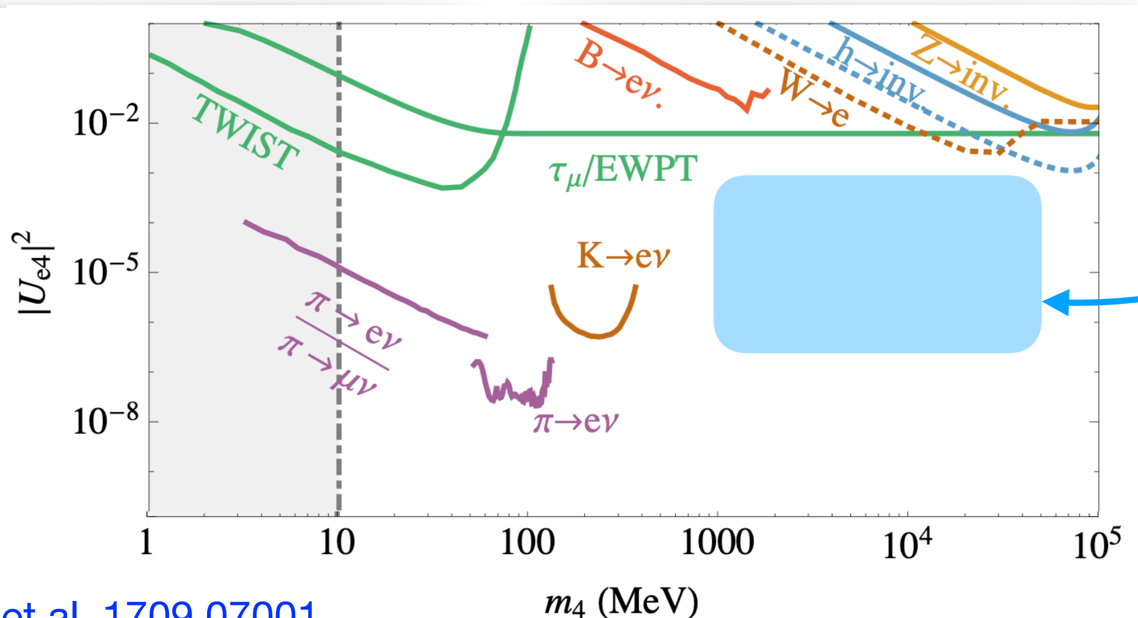
$$\mathcal{L} \supset -yHLN^c - Me^{ia/f_a}NN^c + \text{h.c.}$$

N (with Dirac partner N^c) charged under PQ

After EWSB, sterile neutrinos and SM neutrinos mix and

$$\Rightarrow \mathcal{L} \supset \frac{\theta^2}{f_a}\partial_\mu a(\bar{\nu}_e\gamma^\mu P_L \nu_e) \Rightarrow \begin{cases} g_\nu = \frac{2\theta^2 m_e}{f_a} = 1.0\times 10^{-5}\left(\frac{\theta}{0.1}\right)^2\left(\frac{\text{GeV}}{f_a}\right) \\ g_{ee} = \bar{g}_{ee} = 0 \end{cases}$$

$\theta^2 =$



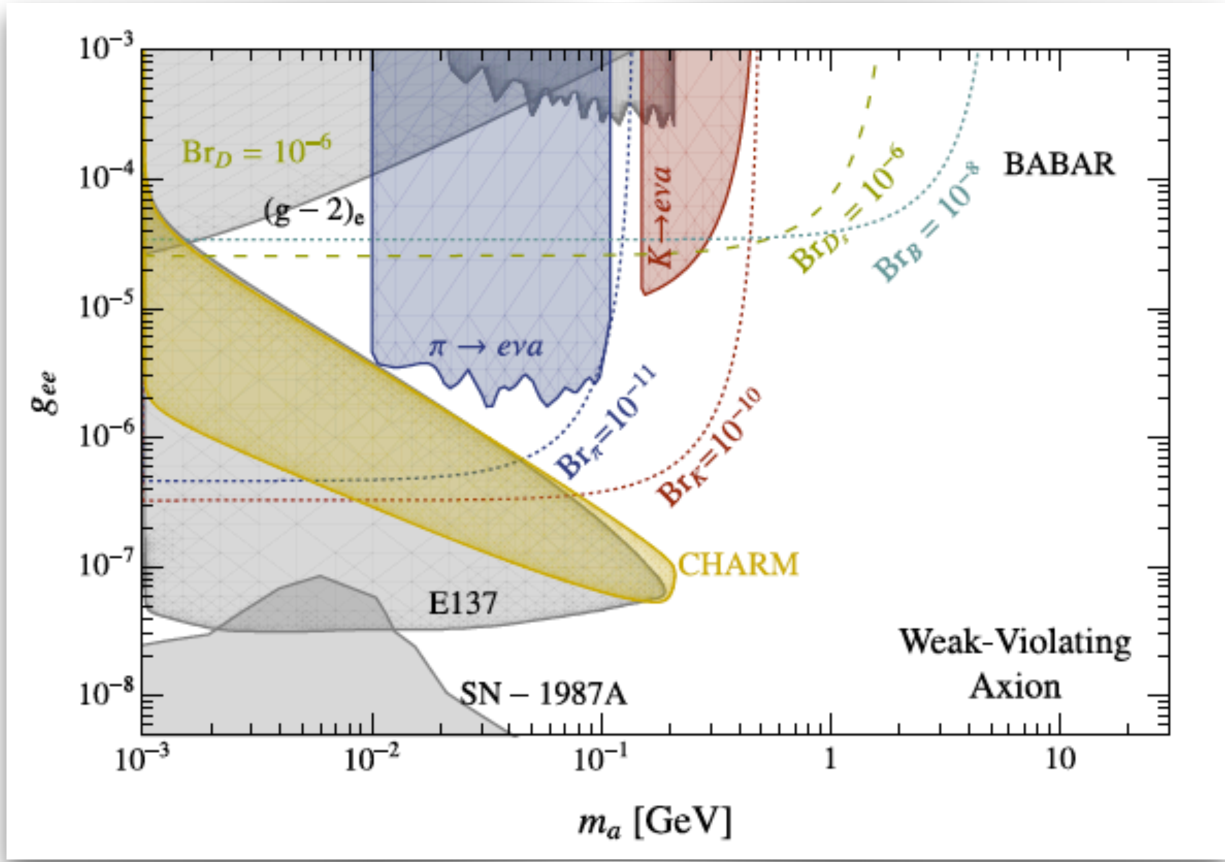
Batell, et al, 1709.07001

additional constraints from visibly decaying HNL (less robust)

Similar construction for vector-like leptons charged under PQ:

$\bar{g}_{ee} - g_{ee} \neq 0, \quad g_{\nu_e} = 0$

Charged current heavy meson decays



Lepton-coupled axion lifetime