

“New” searches for Flavored Axions

Diego Redigolo



“New” Targets & “New” Experiments



“New”

=

old but with a twist

Deviating from
vanilla axion scenario

=

Enlarging purposes
of Flavor Experiments

“vanilla” axion

$$\frac{\alpha_s}{8\pi} \frac{Na}{f_a} G\tilde{G}$$

solves SM issues

$$\theta_{\text{QCD}} = \left\langle \frac{a}{f_a} \right\rangle \simeq 0$$
$$\Omega h^2 \simeq 0.2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1.18} \theta^2$$

gives exp. target

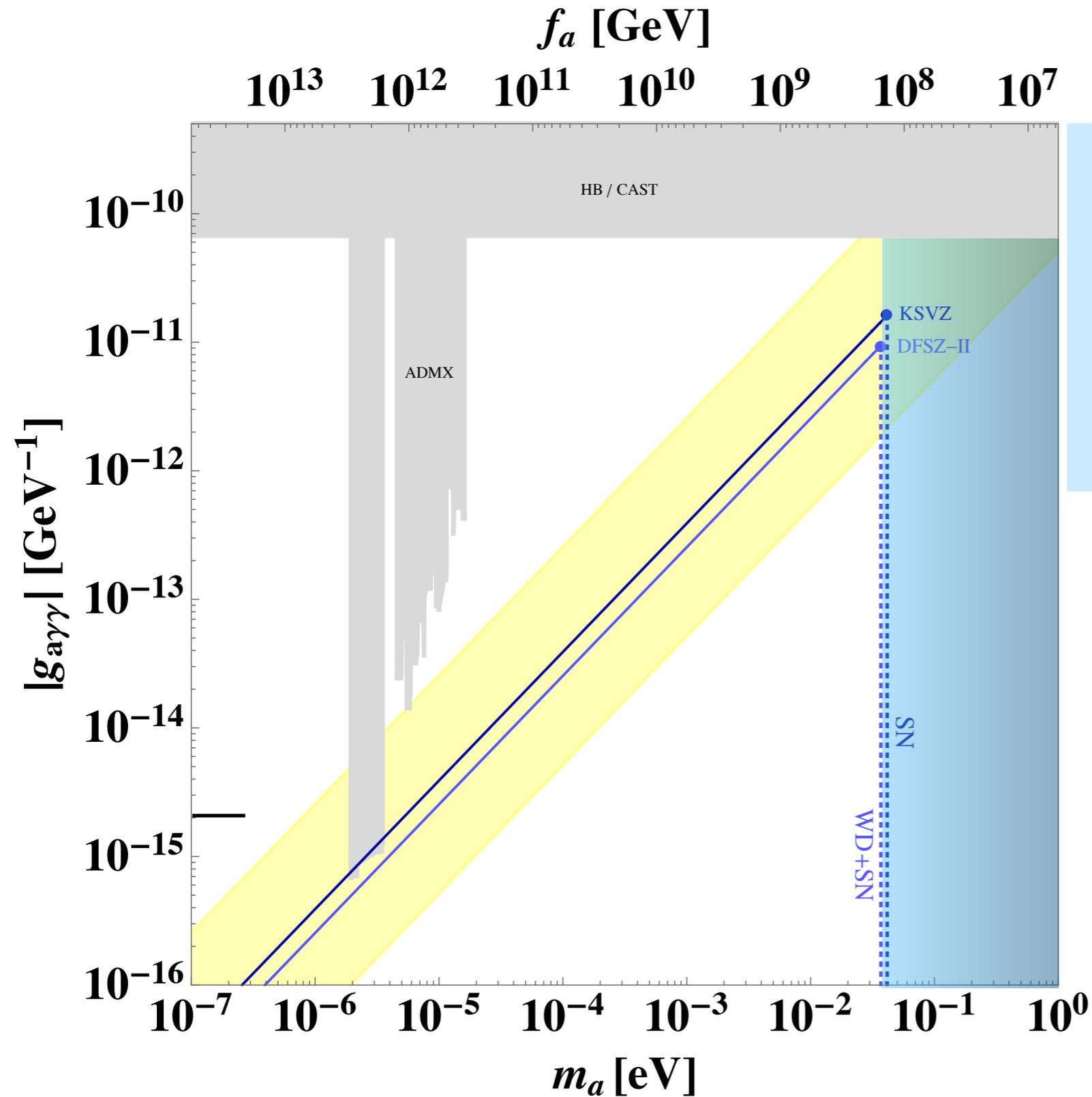
$$m_a \simeq \Lambda_{\text{QCD}}^2 / f_a$$
$$g_{a\gamma\gamma} = \frac{\alpha_{\text{em}}}{2\pi f_a} \left(\frac{E}{N} - 1.92 \right)$$

More/other issues?



More targets?

QCD axion parameter space

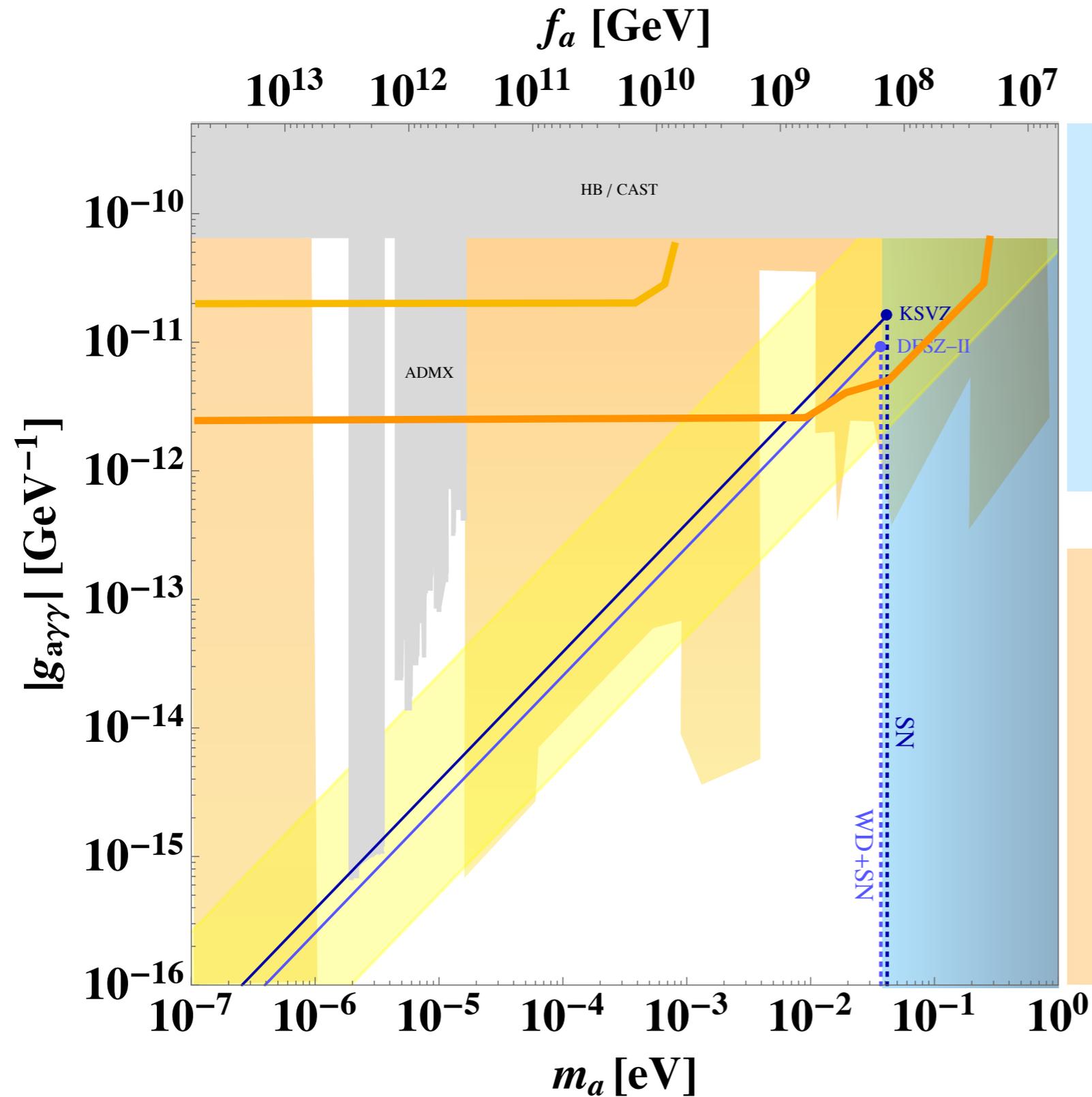


Heaviest possible axion mass set by the cooling of astro objects

- axion flux from supernova 1987A
- white dwarf cooling

$$(g_{NN}\bar{N}\gamma^\mu\gamma_5N + g_{ee}\bar{e}\gamma^\mu\gamma_5e)\partial_\mu a$$

QCD axion parameter space



Heaviest possible axion mass set by the cooling of astro objects

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$$(g_{NN}\bar{N}\gamma^\mu\gamma_5N + g_{ee}\bar{e}\gamma^\mu\gamma_5e)\partial_\mu a$$

Photon coupling gives further/future experimental handles

$$g_{a\gamma\gamma} \frac{aE \cdot B}{f_a}$$

Flavored Axions

controls the astro bounds

$$\sum_i \frac{\partial_\mu a}{2f_a} \bar{f}_i C_{f_i}^A \gamma_5 f_i$$

new opportunities here?

$$+ \sum_{i \neq j} \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{f_i f_j}^V + C_{f_i f_j}^A \gamma_5) f_j$$

Feng-Murayama-Moroi-Shnapka 1998

$$[C_f^V, M_f] \neq 0 \quad \text{Flavor Violating Vector (FVV) current}$$

$$[C^A, M_f] \neq 0 \quad \text{Flavor Violating Axial (FVA) current}$$

Given a set of PQ charges: X_L, X_R

$$C_{ij}^{V,A} = \frac{1}{2N} \left(V_R^\dagger X_R V_R \pm V_L^\dagger X_L V_L \right)_{ij}$$

A theory of flavor is needed
to get V_L, V_R

Ema-Hamaguchi-Moroi-Nakayama '16

Calibbi-Goertz-Redigolo-Ziegler-Zupan '16

Plan

■ FV in the quark sector

$$K \rightarrow \pi a$$

Axiflavoron vs Axion

Experimental status

Future improvements...

■ FV in the lepton sector

$$\mu \rightarrow e a$$

MEGII-fwd concept

Experimental status

LFV Axions

Future improvements...

Disclaimer

We focus on axions directly related to SM issues:

$$\theta_{\text{QCD}} = \left\langle \frac{a}{f_a} \right\rangle \simeq 0$$
$$\Omega h^2 \simeq 0.2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1.18} \theta^2$$

We focus on long-lived signal

$$c\tau_a \gg L_{\text{detector}}$$

We focus on very light masses

$$m_a \ll \Delta m|_{\text{exp}}$$

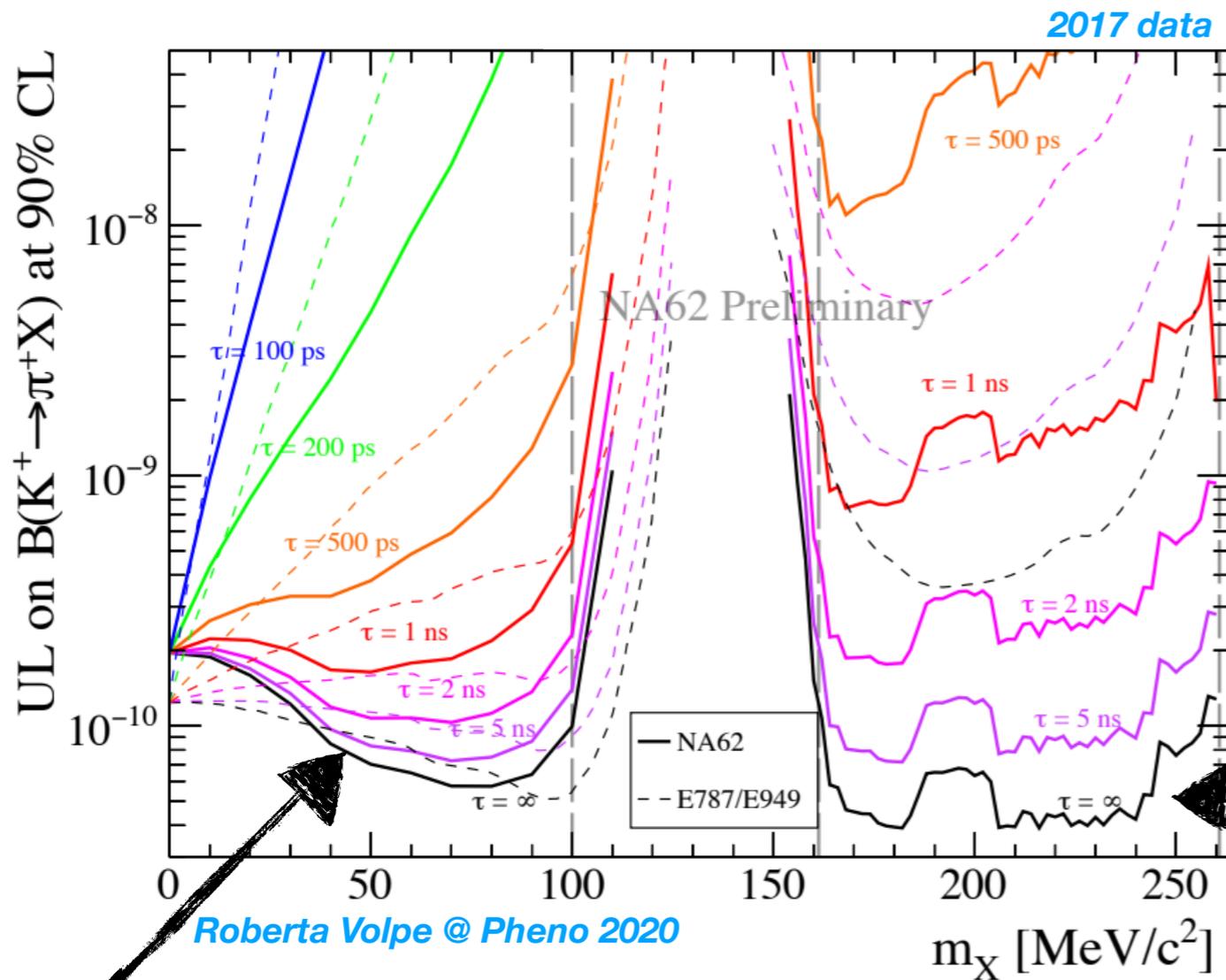
PROMPT/DISPLACED ALPs are possible?

$$\frac{1}{f_a} \partial_\mu a J_{\text{SM}}^\mu \quad \mathbf{vs} \quad \frac{1}{g_\star^2 f_a^2} J_{\text{SM}}^2$$

to be explored...

Status of $K \rightarrow \pi X$

NA62 results based on $\sim 2 \times 10^{12} K^+$



KOTO data on

$$K_L \rightarrow \pi^0 X$$

are typically not competitive

- Grossmann-Nir bound
- experimental challenges

at high masses

1 order of magnitude improvement
w.r.t the previous bound

at low mass the bound is comparable to

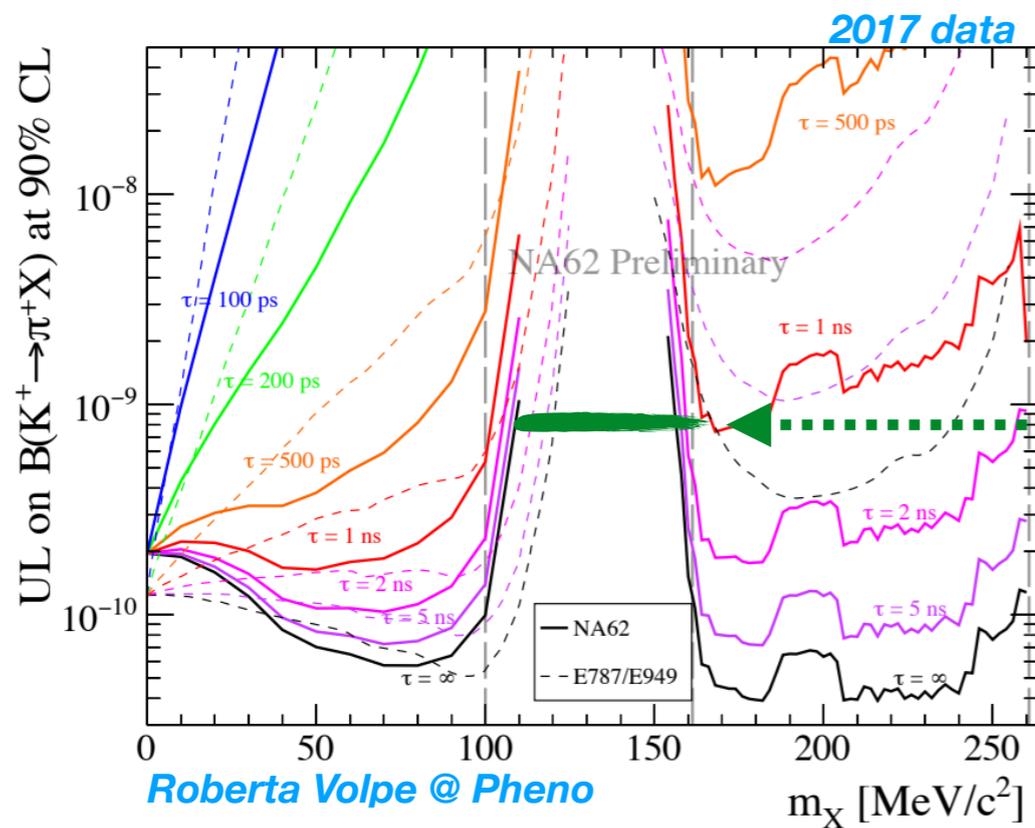
$$BR(K^+ \rightarrow \pi^+ a) < 7.3 \cdot 10^{-11}$$

E787+E949

Roberta Volpe @ Pheno 2020

Status of $K \rightarrow \pi X$

Is there a GAP at $m_a \simeq m_{\pi^0}$?



The gap for $m_a \simeq m_{\pi^0}$ can be covered already!

$$\text{BR}(\pi^0 \rightarrow \text{invisible}) \leq 4.4 \times 10^{-9} \quad \text{at 90\% C.L.}$$

Roberta Volpe @ Pheno 2020

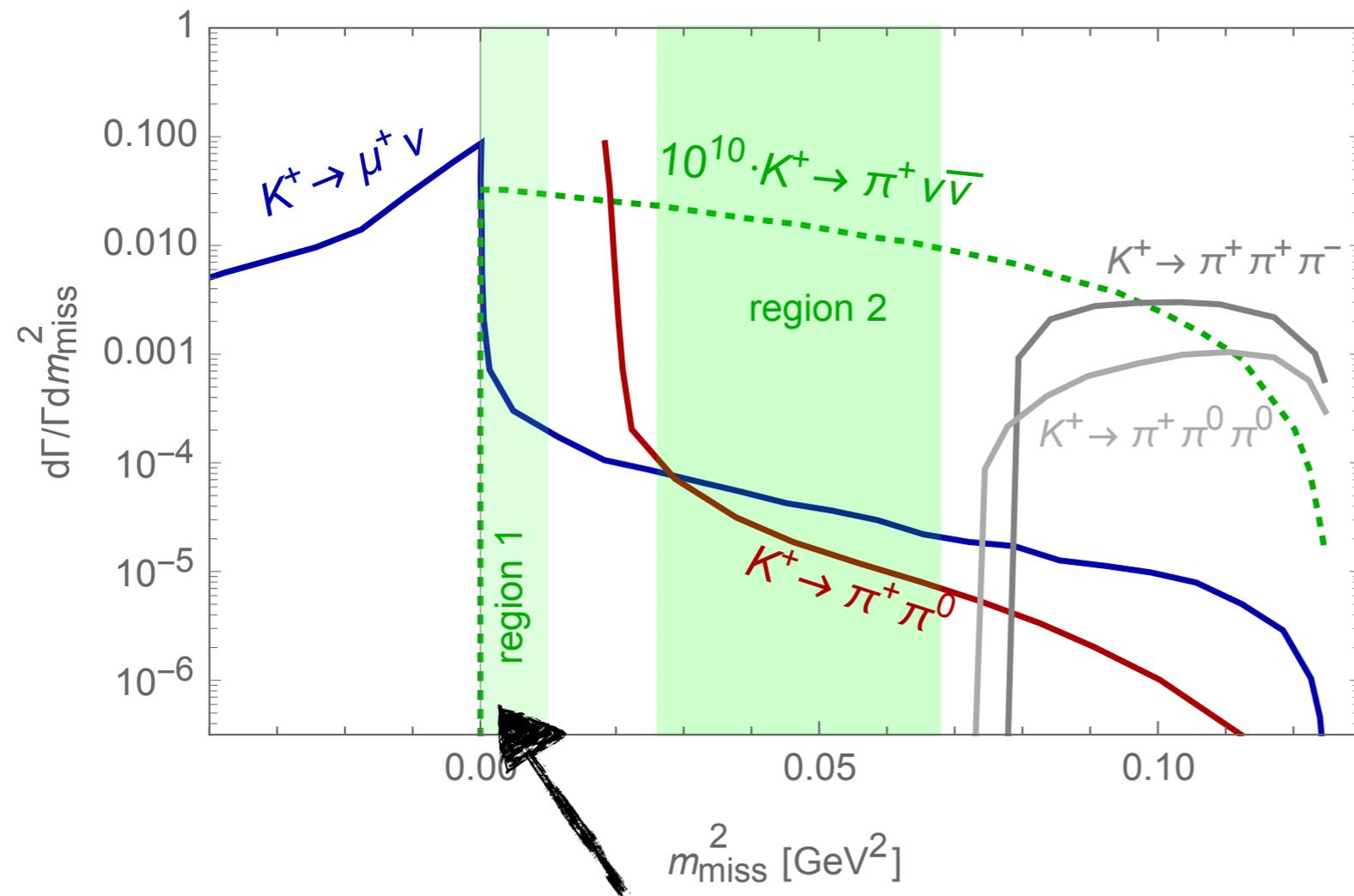
$$\text{BR}(K^+ \rightarrow \pi^+ a) \lesssim 8.8 \times 10^{-10}$$

$$m_a \simeq m_{\pi^0}$$

Prospects of $K \rightarrow \pi X$

$K^+ \rightarrow \pi^+ a$ gives a peak at $m_{\text{miss}}^2 = 0$ for $m_a \ll \Delta m_{\text{miss}} \sim 30 \text{ MeV}$

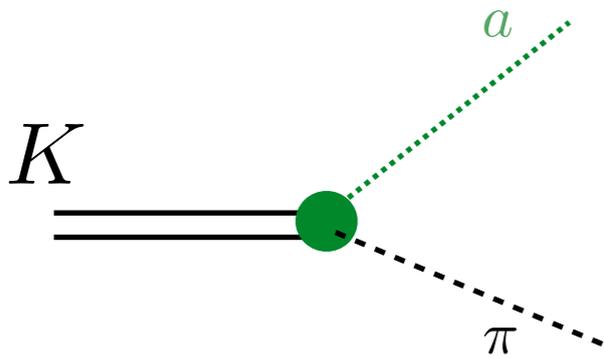
where $m_{\text{miss}}^2 = (P_K - P_\pi)^2$



**NA62 will collect
~10 times more data!**

enlarging region 1 to low missing mass will give a factor of ~2 more signal events

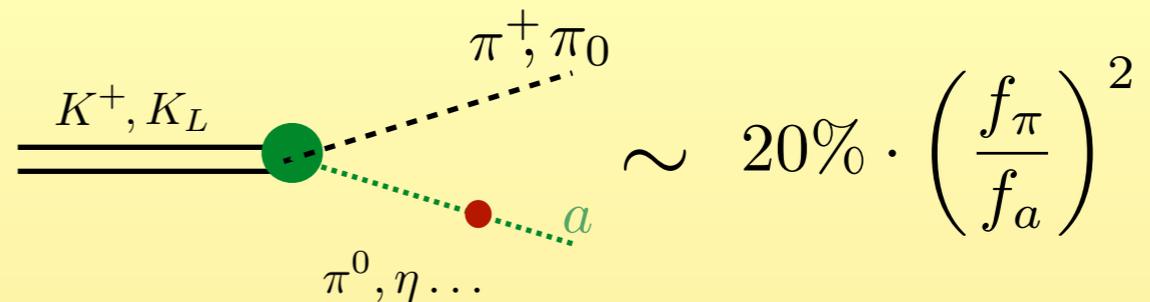
Axiflavoron vs Axion



Depending on the couplings of the axion to the SM
 $\Gamma(K \rightarrow \pi a)$ changes dramatically

Vanilla axion

$$\frac{\alpha_s}{8\pi} \frac{Na}{f_a} G\tilde{G}$$



$$\sim 20\% \cdot \left(\frac{f_\pi}{f_a}\right)^2$$

$$\text{BR}(K^+ \rightarrow \pi^+ a) < 7.3 \cdot 10^{-11} \quad \longleftrightarrow \quad f_a \gtrsim 5 \cdot 10^4 \text{ GeV} \quad \xleftrightarrow{m_a \simeq \Lambda_{\text{QCD}}^2/f_a} \quad m_a \lesssim 0.1 \text{ KeV}$$

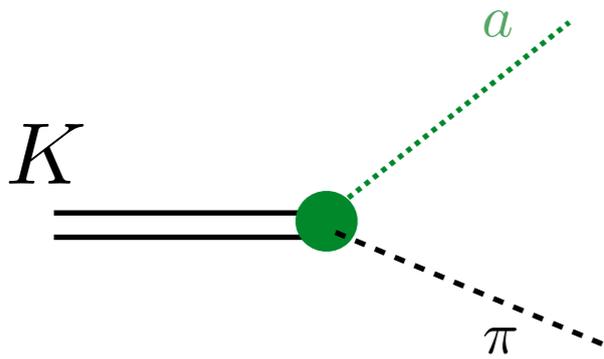
E787+E949

superseded by supernova bound

$$L_a^{\text{SN}} \lesssim 2 \cdot 10^{52} \frac{\text{erg}}{\text{s}} \quad \longleftrightarrow \quad f_a \gtrsim 10^8 \text{ GeV} \quad \xleftrightarrow{m_a \simeq \Lambda_{\text{QCD}}^2/f_a} \quad m_a \lesssim 0.054 \text{ eV}$$

Raffelt bound '90

Axiflavoron vs Axion



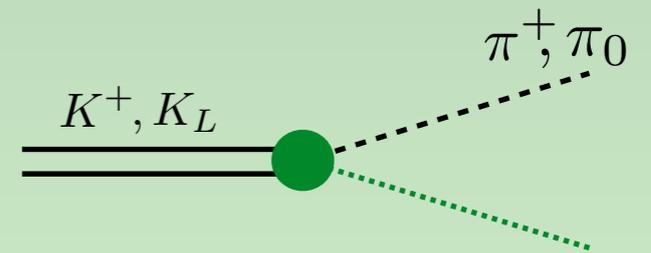
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Axiflavoron

$$\sum_{i \neq j} \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{f_i f_j}^V + C_{f_i f_j}^A \gamma_5) f_j$$

Ema-Hamaguchi-Moroi-Nakayama '16

Calibbi-Goertz-Redigolo-Ziegler-Zupan '16



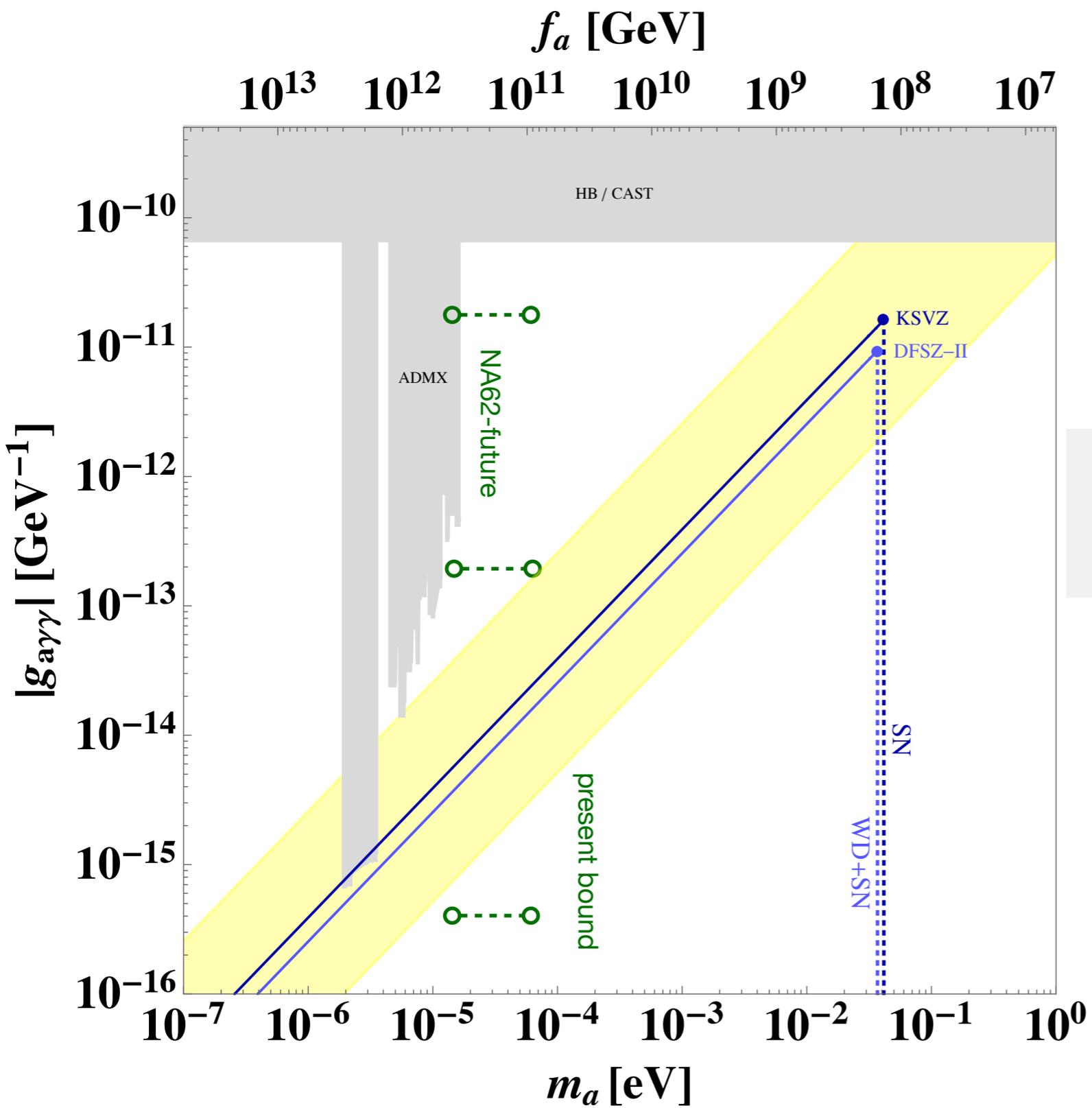
$$\text{BR}(K^+ \rightarrow \pi^+ a) \simeq 268 \left(\frac{5 \cdot 10^4 C^V}{f_a} \right)^2 \longleftrightarrow f_a \gtrsim 7.5 \cdot 10^{10} \text{ GeV} \xleftrightarrow{m_a \simeq \Lambda_{\text{QCD}}^2 / f_a} m_a \lesssim 76 \mu\text{eV}$$

stronger than the supernova bound for $C_V \sim 1$

$$L_a^{\text{SN}} \lesssim 2 \cdot 10^{52} \frac{\text{erg}}{\text{s}} \longleftrightarrow f_a \gtrsim 10^8 \text{ GeV} \xleftrightarrow{m_a \simeq \Lambda_{\text{QCD}}^2 / f_a} m_a \lesssim 0.054 \text{ eV}$$

Raffelt bound '90

Summary

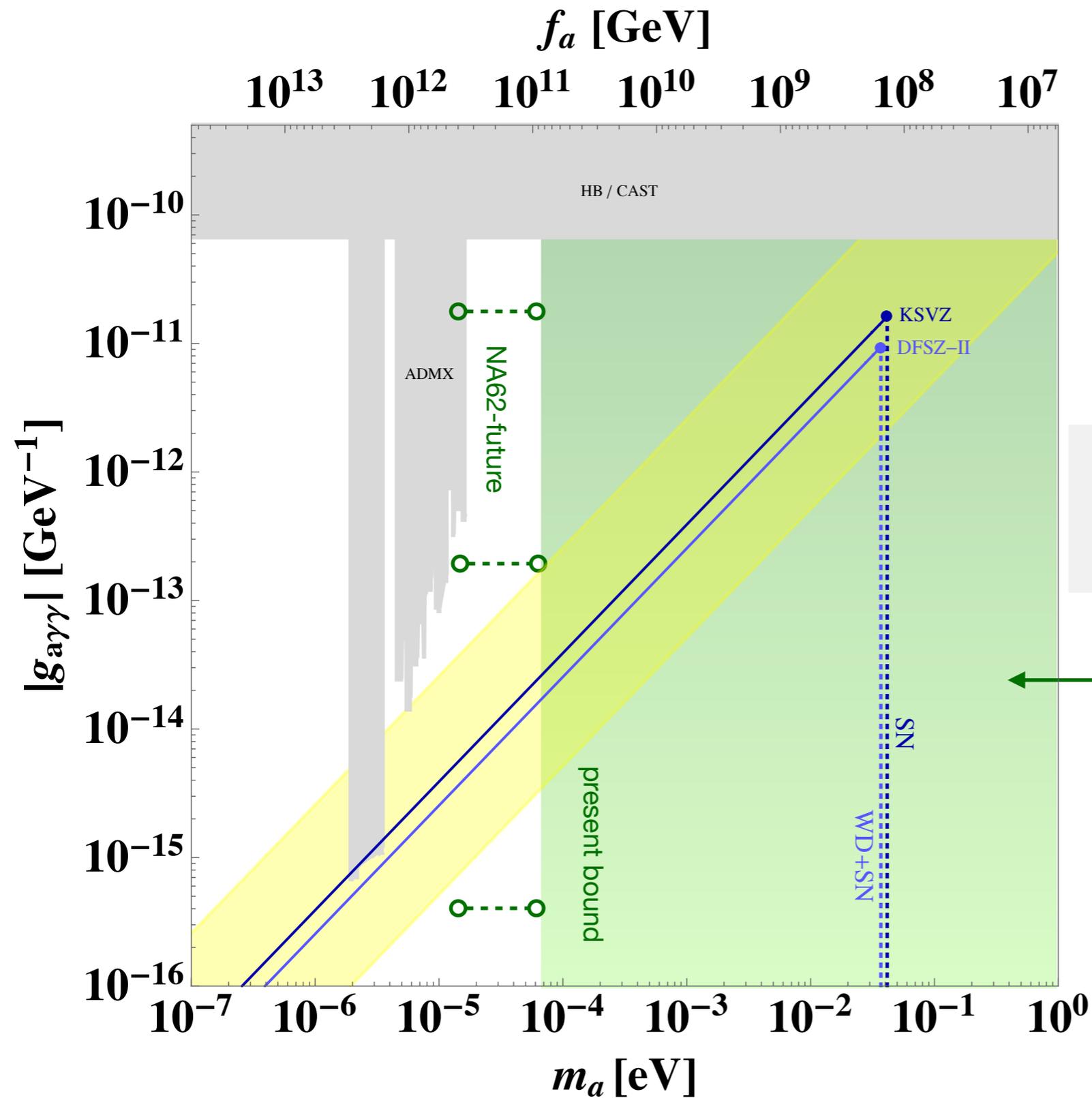


Flavor Violating Vector (FVV) current

- Max axion mass set by flavor bounds

- Lower bound depends on the texture of the PQ charges

Summary



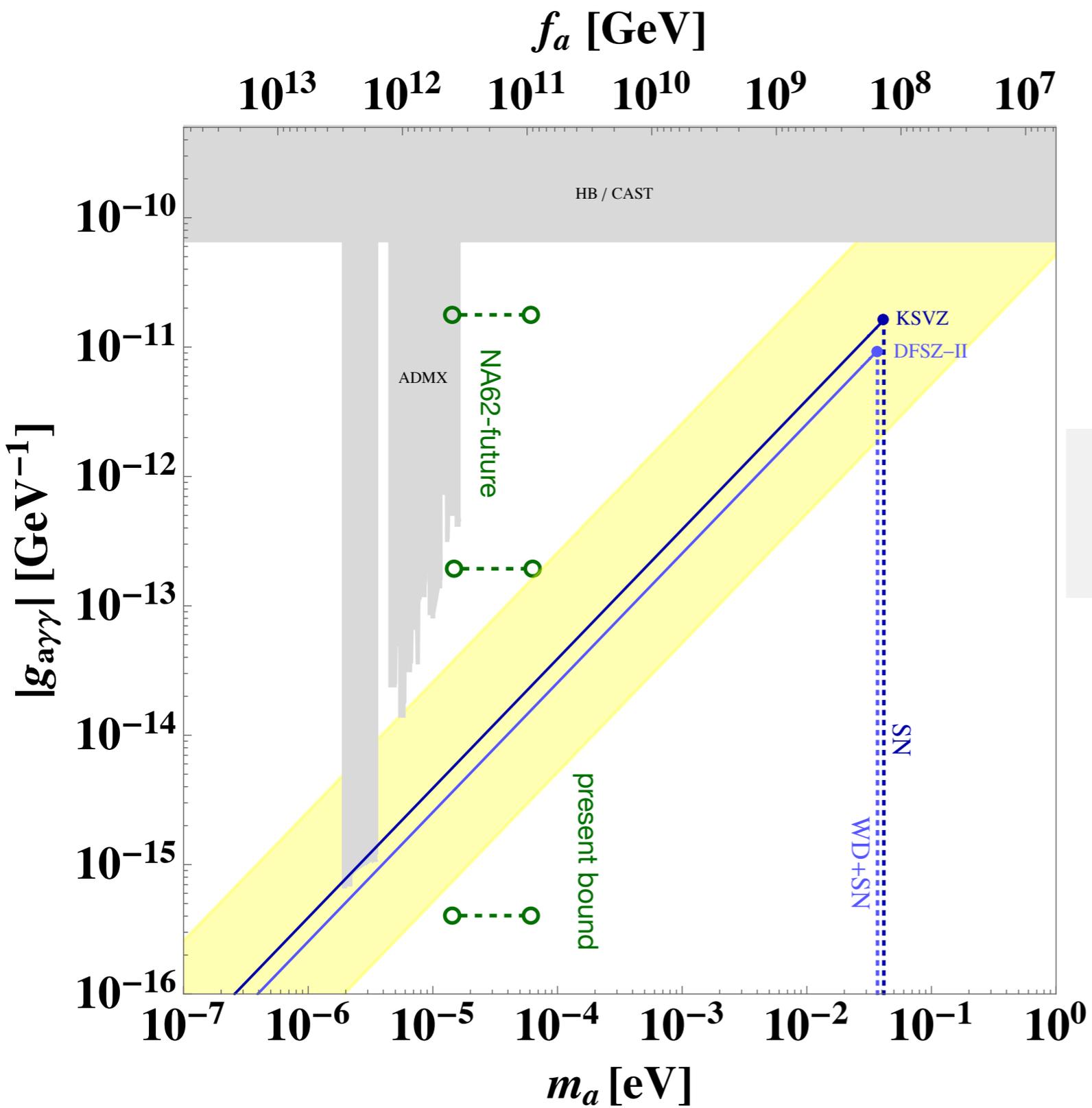
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• $U(1)_{\text{PQ}} = U(1)_{\text{FN}}$

Summary

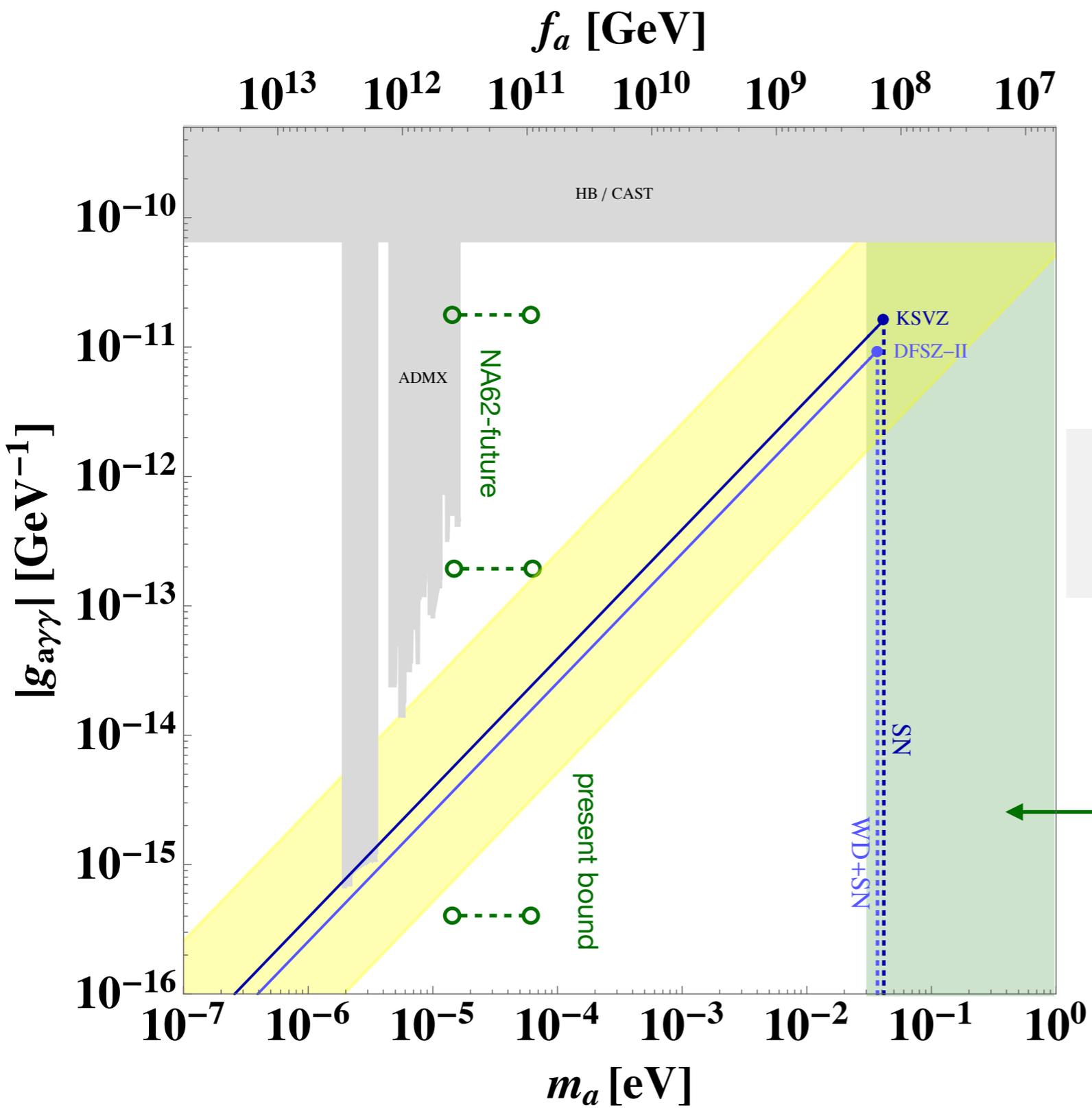


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Flavor Violating Vector (FVV) current

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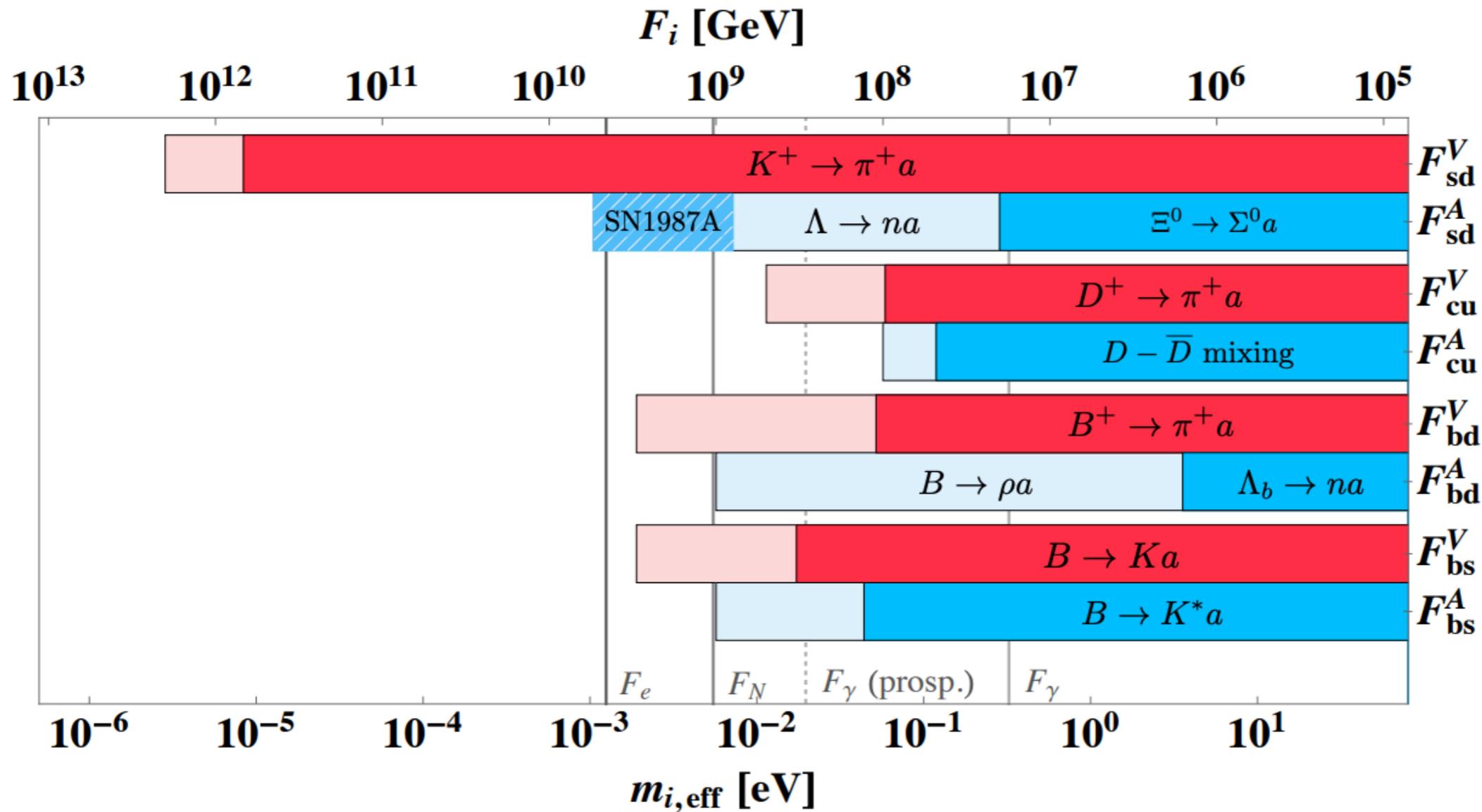
- $U(1)_{PQ} \supset U(2)_{FN}$

Linster-Ziegler 2018

Experimental status beyond $K \rightarrow \pi X$

Camalich-Pospelov-Vuong-Ziegler-Zupan

depending on the flavor transition different mesonic decay channels should be explored!



Future improvements

$K^+ \rightarrow \pi^+ a$ probes **Flavor Violating Vector (FVV) current**

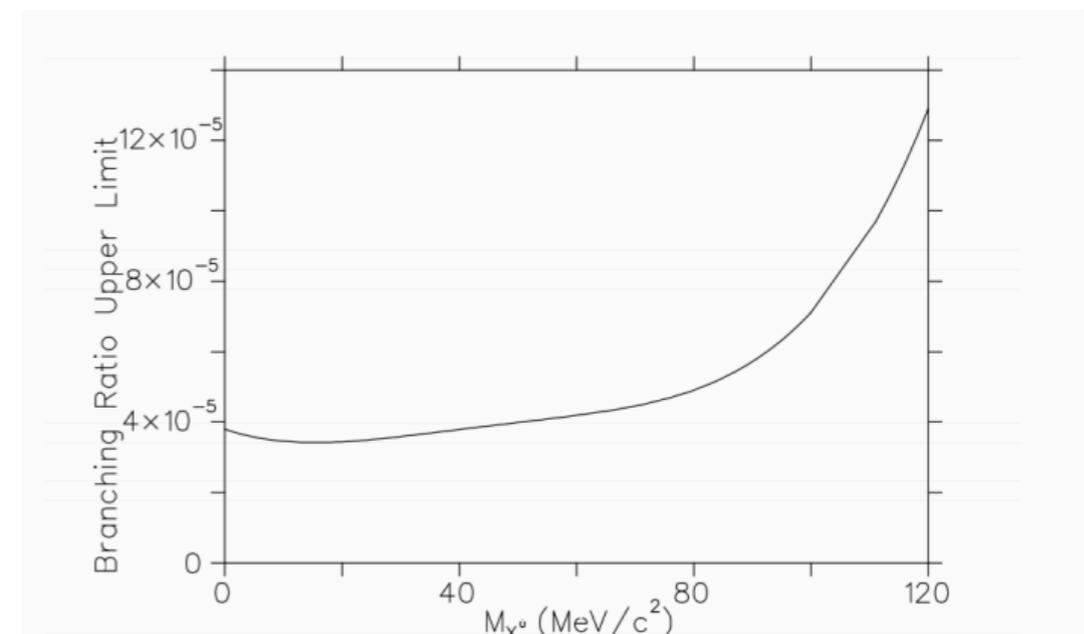
- $q_\mu \langle K^+(p') | \bar{s} \gamma^\mu d | \pi^+(p) \rangle = (m_K^2 - m_\pi^2) f_+(0)$
- $\langle K^+(p') | \bar{s} \gamma^\mu \gamma_5 d | \pi^+(p) \rangle = 0$ because QCD preserves parity!

3 body $K^+ \rightarrow \pi^+ \pi^0 a$ probes **Flavor Violating Axial (FVA) current**

present bound given by E787 with $\sim 10^8 K^+$

Designing a search at NA62

work in progress with Prisco LoChiatto



Status of $\mu^+ \rightarrow e^+ a$

Main player: $\mu^+ \rightarrow e^+ a$ or $\mu^+ \rightarrow e^+ a \gamma$

Irreducible SM background: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
BR $\sim 100\%$

or $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$

background
suppressed as much
as the signal!



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background
suppressed as much
as the signal!



Hunting for a positron line on the top of the Michel spectrum @ muon factories

1986 $\sim 10^7$ /year(s)

2014 $\sim 10^8$ /year

soon $\sim (10^8 - 10^9)$ /s

●
TRIUMF:
Jodidio's

●
TRIUMF:
Twist

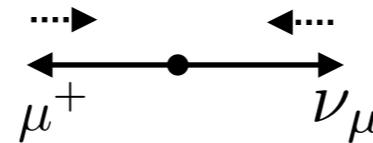
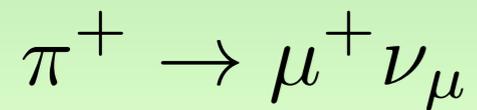
●
PSI: MEGII+ Mu3e

$t \sim \#\mu's$

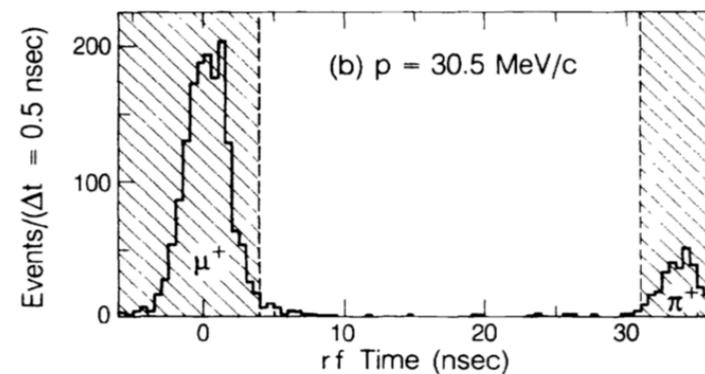
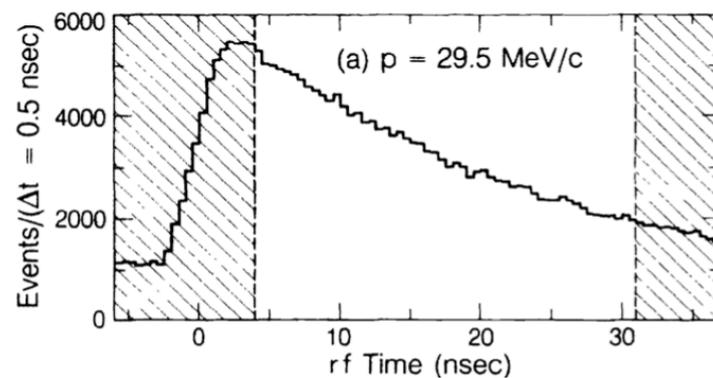
extra handle on the background

Iodidio et al. @ TRIUMF 1988

The muon are highly polarized



- They are produced by pion @ rest



polarization purity
augmented with a cut
on the t.o.f.

- Strong magnetic field parallel to the beam to suppress spin-orbit in muonium

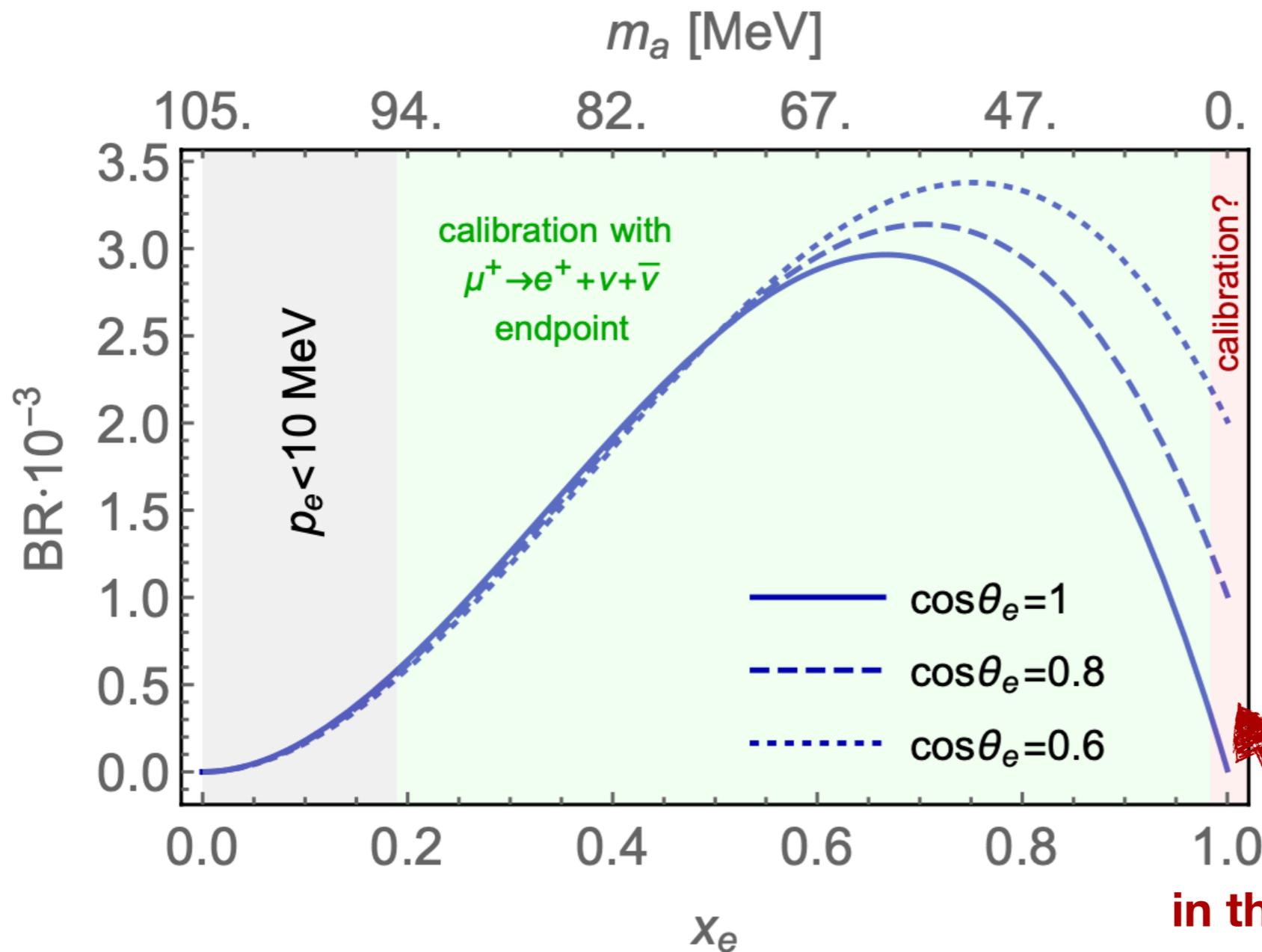
Using polarization to suppress the background?



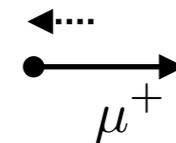
the forward direction

$$\frac{d^2\Gamma(\mu \rightarrow e \nu \bar{\nu})}{dx_e d \cos \theta_e} \simeq \Gamma_\mu ((3 - 2x_e) + P(2x_e - 1) \cos \theta) x_e^2$$

$$x_e = \frac{2E_e}{m_\mu}$$



the bkd goes to zero in the “forward” direction (the direction opposite to the muon polarization)

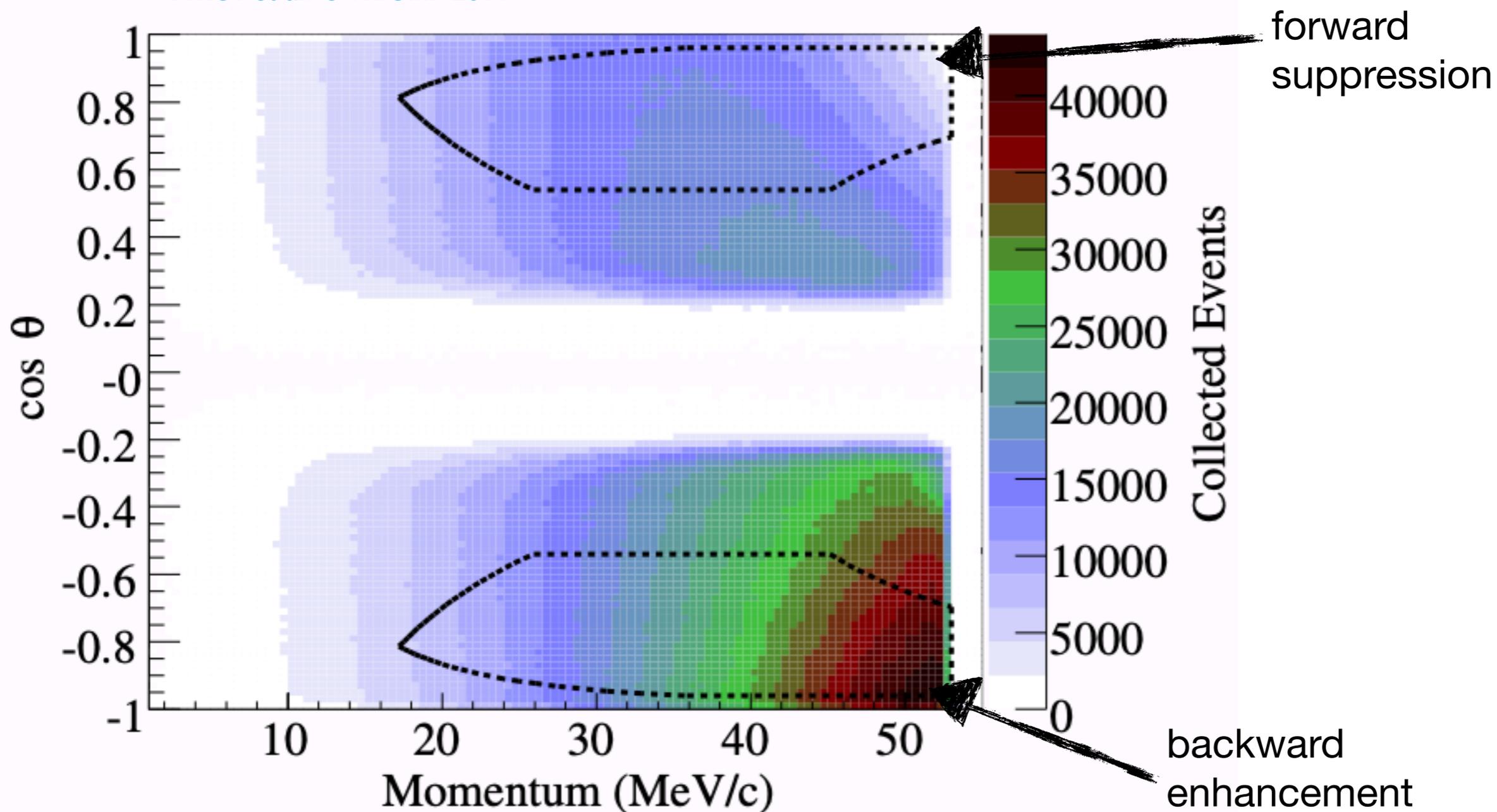


$\Delta\theta = 10^{-3}$ angular res.

in the massless case

bkd suppression in data

TWIST et al. @ TRIUMF 2014

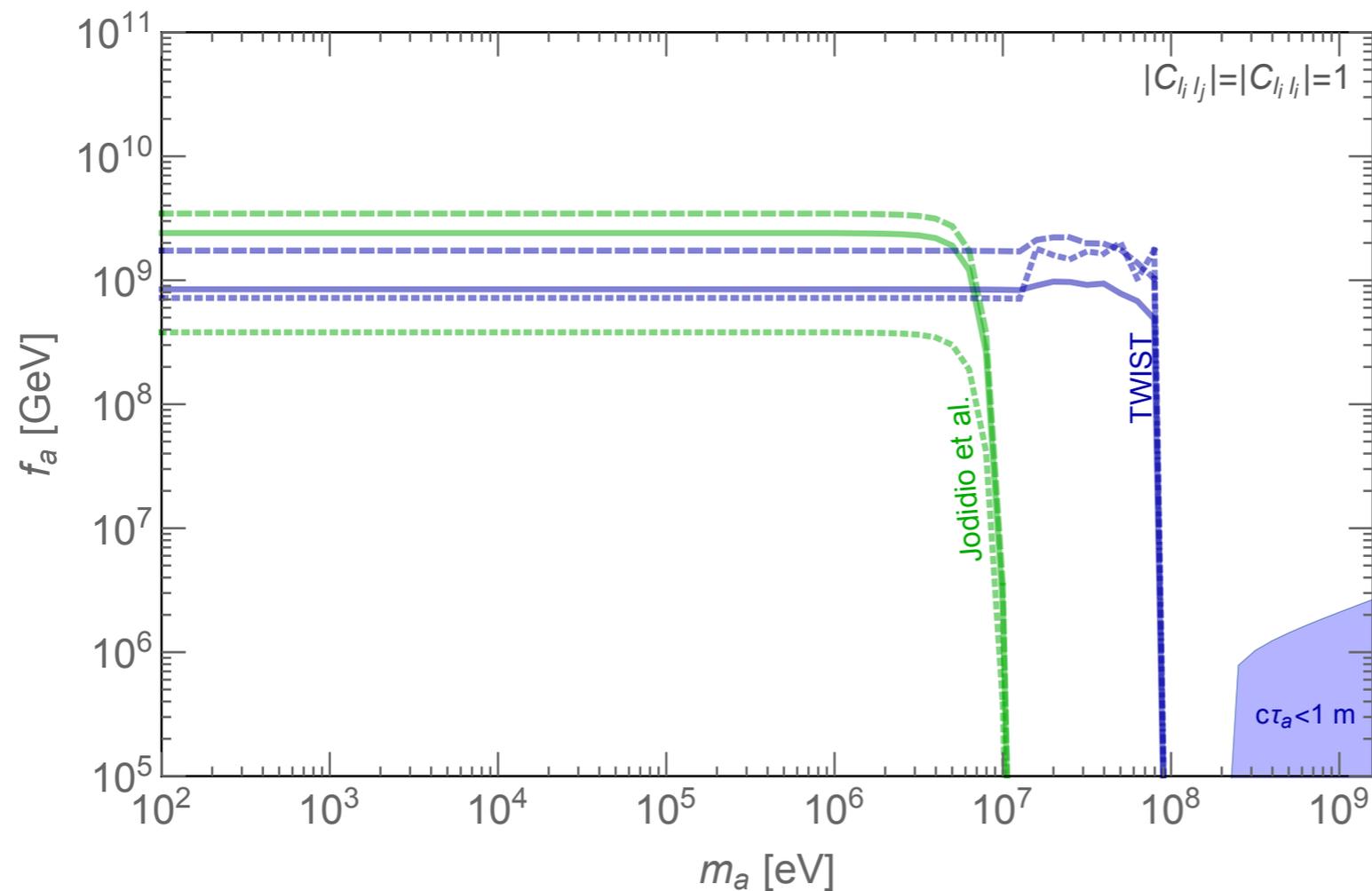


background suppression in TWIST data where the muons are typically polarized at $\sim 90\%$

signal from LFV axions

$$\frac{d\Gamma(l_i \rightarrow l_j a)}{d\cos\theta} = \frac{m_{l_i}^3}{32\pi F_{l_i l_j}^2} \left(1 - \frac{m_a^2}{m_{l_i}^2}\right)^2 \left[1 + 2P_{l_i} \cos\theta \frac{C_{l_i l_j}^V C_{l_i l_j}^A}{(C_{l_i l_j}^V)^2 + (C_{l_i l_j}^A)^2} \right]$$

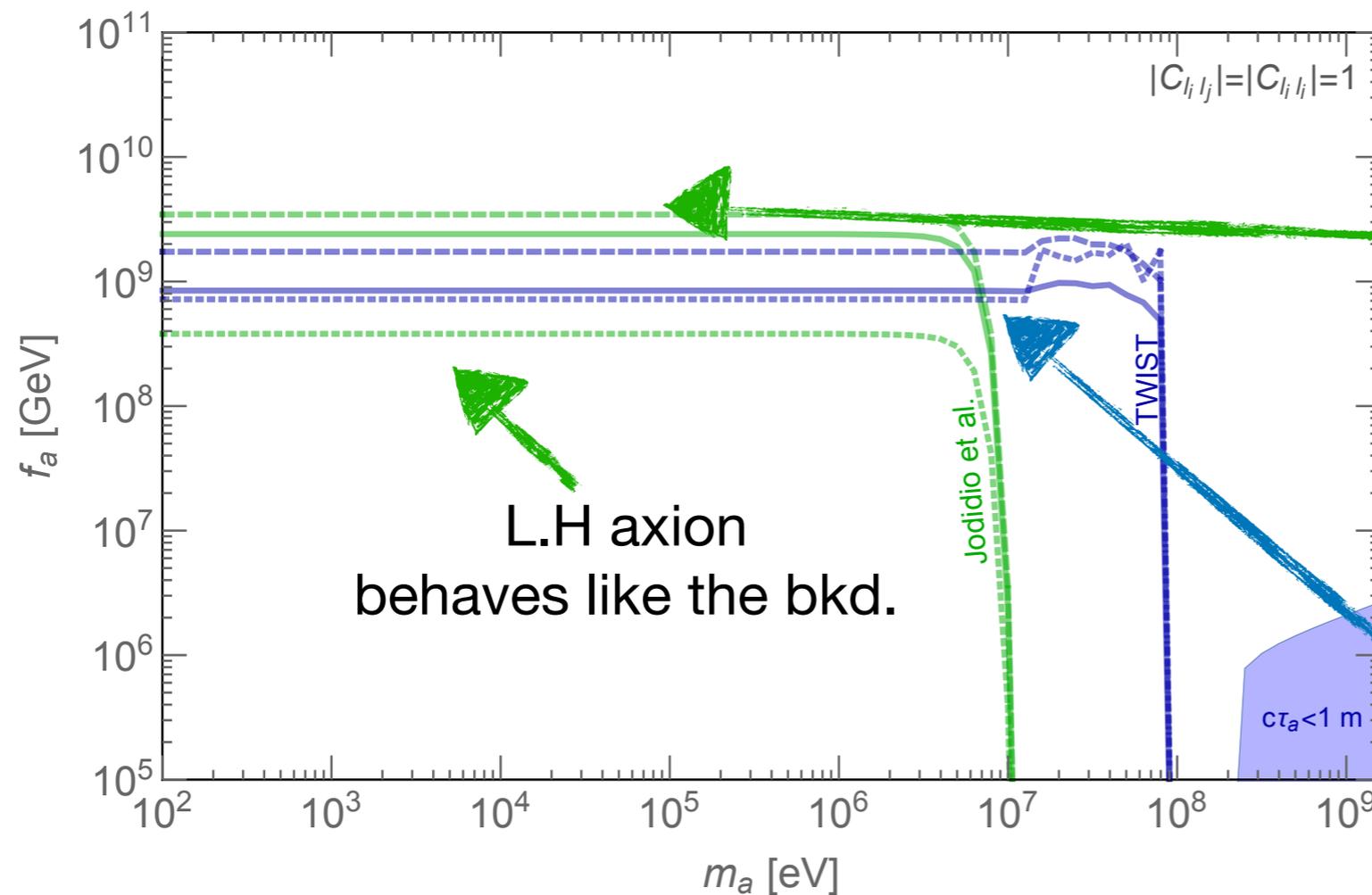
The signal angular distribution depends on the chiral structure of the couplings



signal from LFV axions

$$\frac{d\Gamma(l_i \rightarrow l_j a)}{d\cos\theta} = \frac{m_{l_i}^3}{32\pi F_{l_i l_j}^2} \left(1 - \frac{m_a^2}{m_{l_i}^2}\right)^2 \left[1 + 2P_{l_i} \cos\theta \frac{C_{l_i l_j}^V C_{l_i l_j}^A}{(C_{l_i l_j}^V)^2 + (C_{l_i l_j}^A)^2} \right]$$

The signal angular distribution depends on the chiral structure of the couplings



The Jodidio et al. exp. still gives the best bound as long as the axion has a R.H coupling to the SM

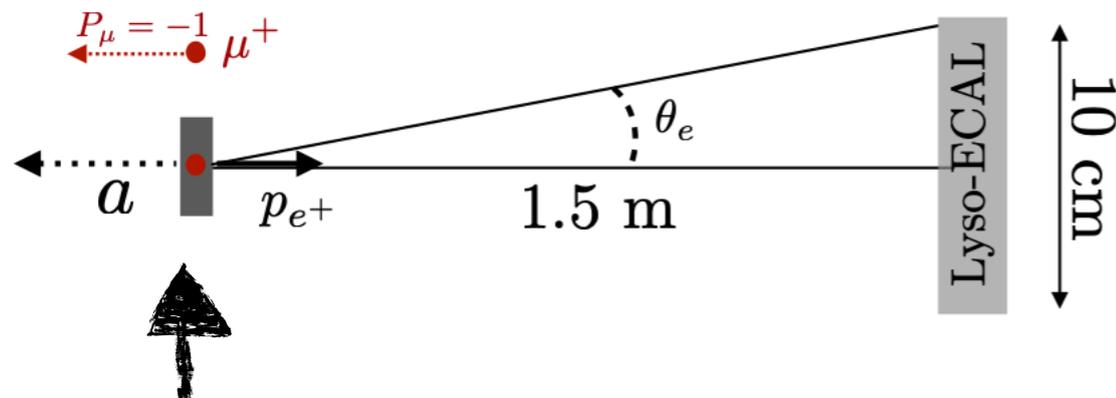
TWIST has the best limit on purely L.H axions!

MEGII-forward

Can we achieve a Jodidio's setup @ MEGII?

MEGII has an extra calorimeter used to calibrate the instrument for $\mu \rightarrow e\gamma$

thanks to Angela Papa and Giovanni Signorelli

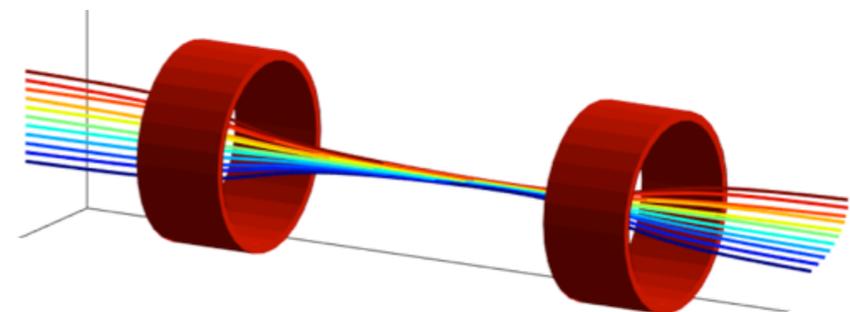


1.5 m from the target
ECAL 10 cm of diameter

muon stopping point

Solenoid lens to increase the signal acceptance!

$$a_{\text{eff}} \sim F a_{\text{geo}}$$

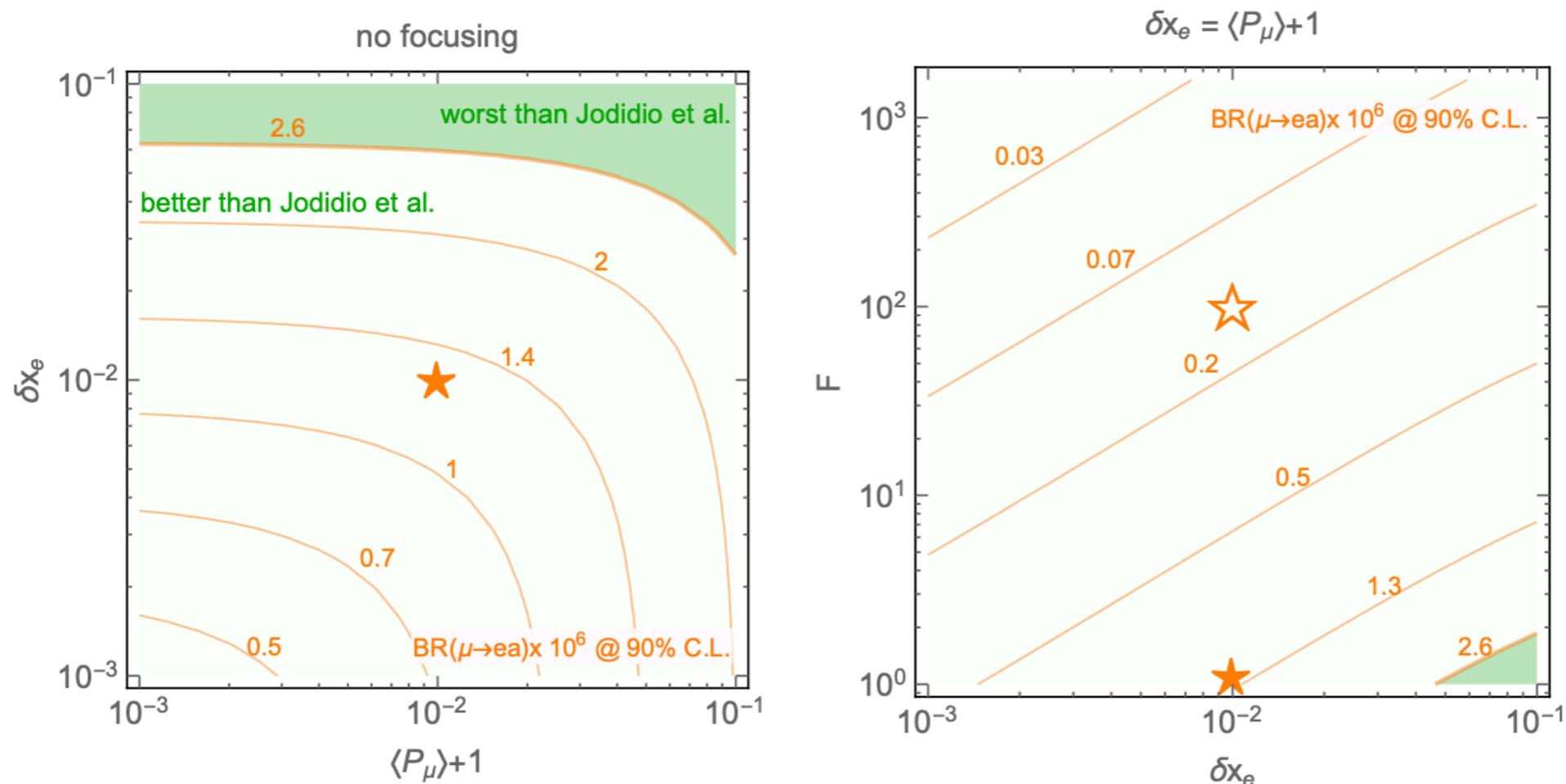


MEGII-forward projections

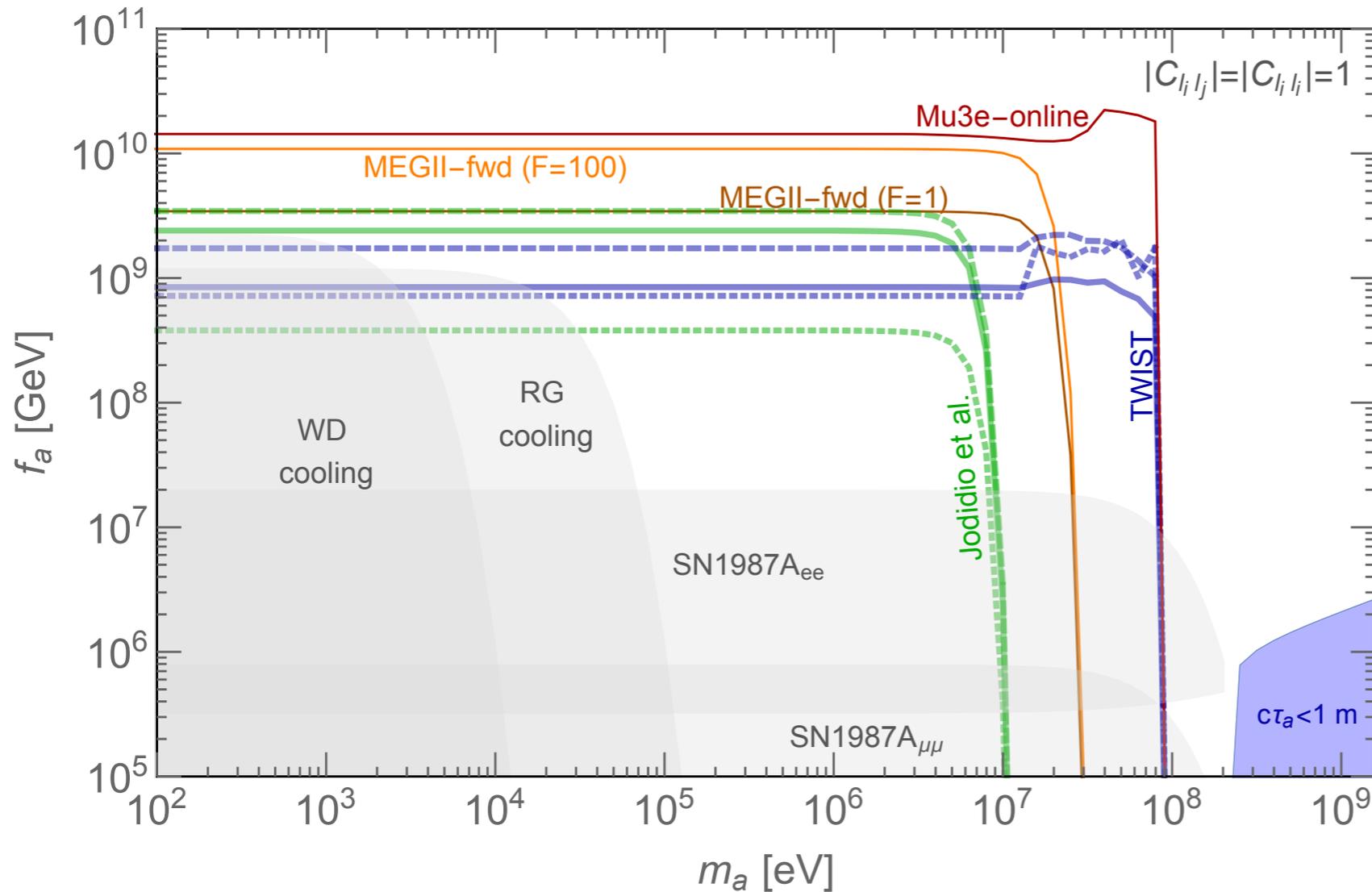
We take the analytical expression for the background B_{truth}

We smear it with the experimental momentum resolution δx B_{reco}

We compute the sensitivity after cutting around $x = 1 \pm \delta x$



Future of $\mu^+ \rightarrow e^+ a$

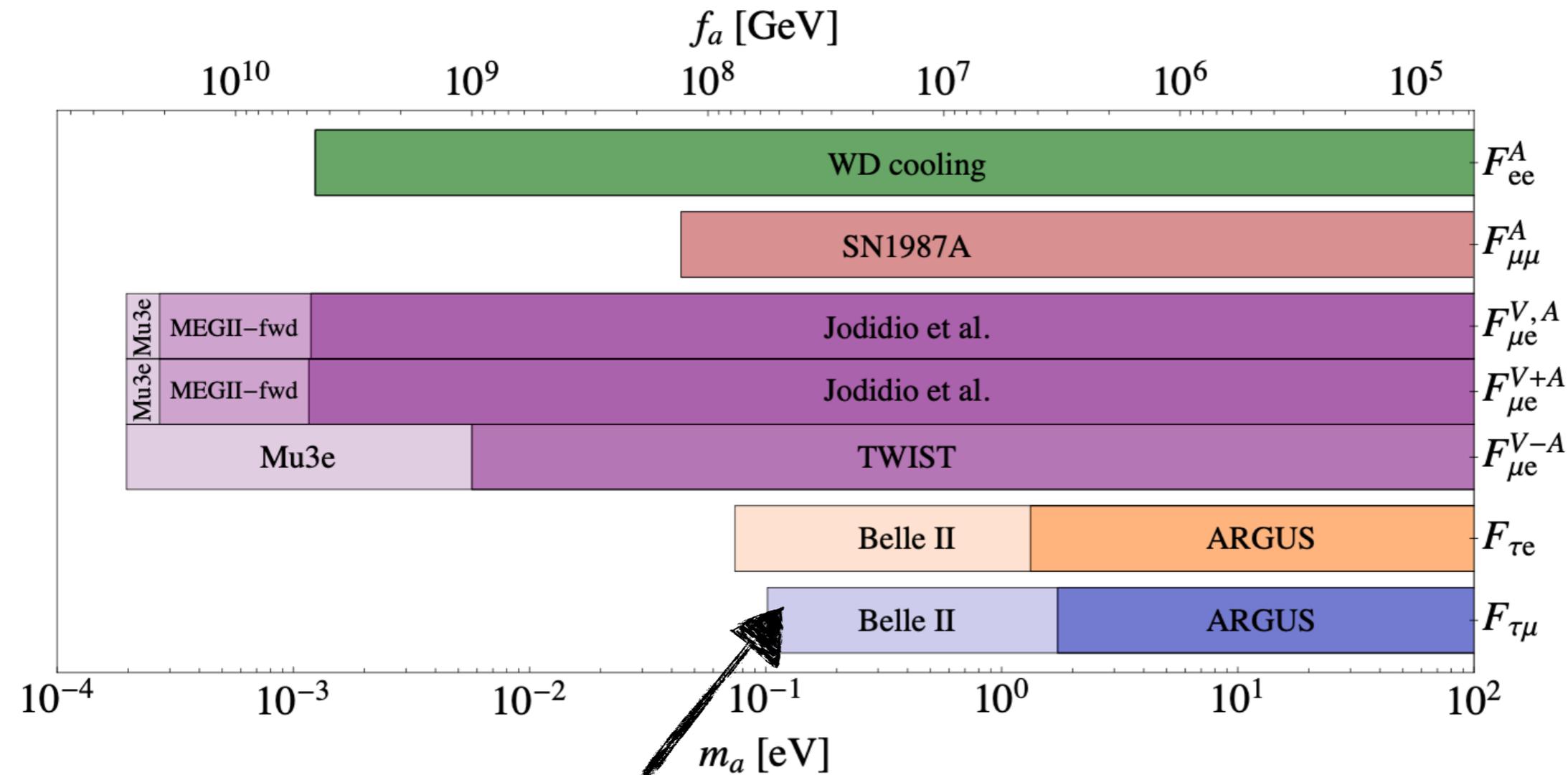


Ground based LFV experiments can beat astrophysical limits

Our projection of MEGII-fwd is competitive with the one of Mu3e and deserves further studies given the timescale of the 2 experiments!

on going discussion with Angela Papa...

Experimental status of LFV



Bounds on LFV tau decays can be improved by optimizing the analysis:

- Optimizing the reconstruction of the tau rest frame
- Using polarization information

work in progress with Aleks Smolkovic and J. Zupan

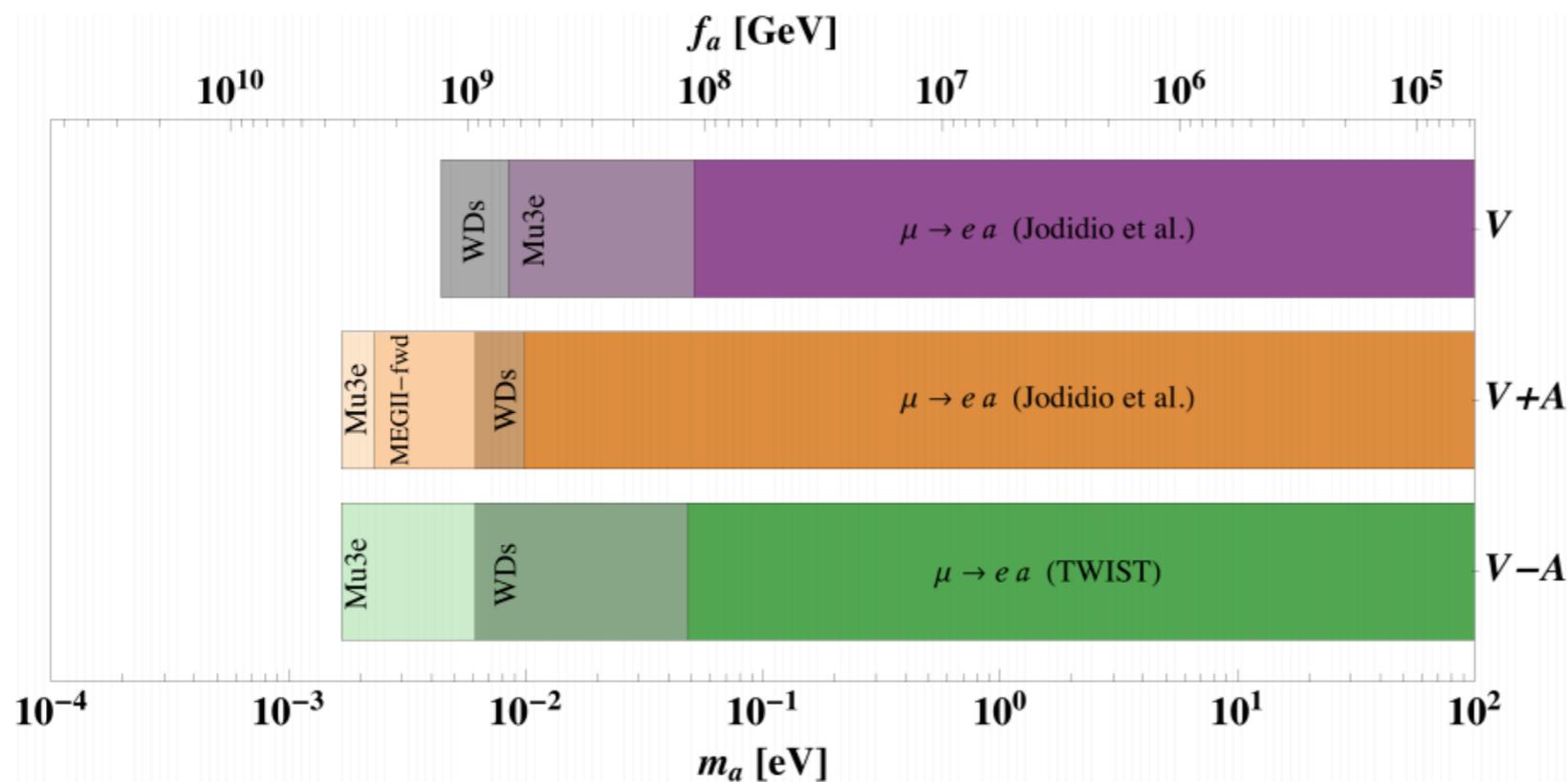
LFV axions-I

Are there well-motivated axions with lepton-flavour-violating couplings?

- *DFSZ-axion (2 Higgs doublet model+1 singlet)*

$$\mathcal{L} = y_{1a}^e \bar{\ell}_{L1} e_{Ra} \tilde{H}_1 + y_{a1}^e \bar{\ell}_{La} e_{R1} \tilde{H}_1 + y_{ab}^e \bar{\ell}_{La} e_{Rb} \tilde{H}_2 .$$

the Yukawas are generically not diagonal in the mass basis!



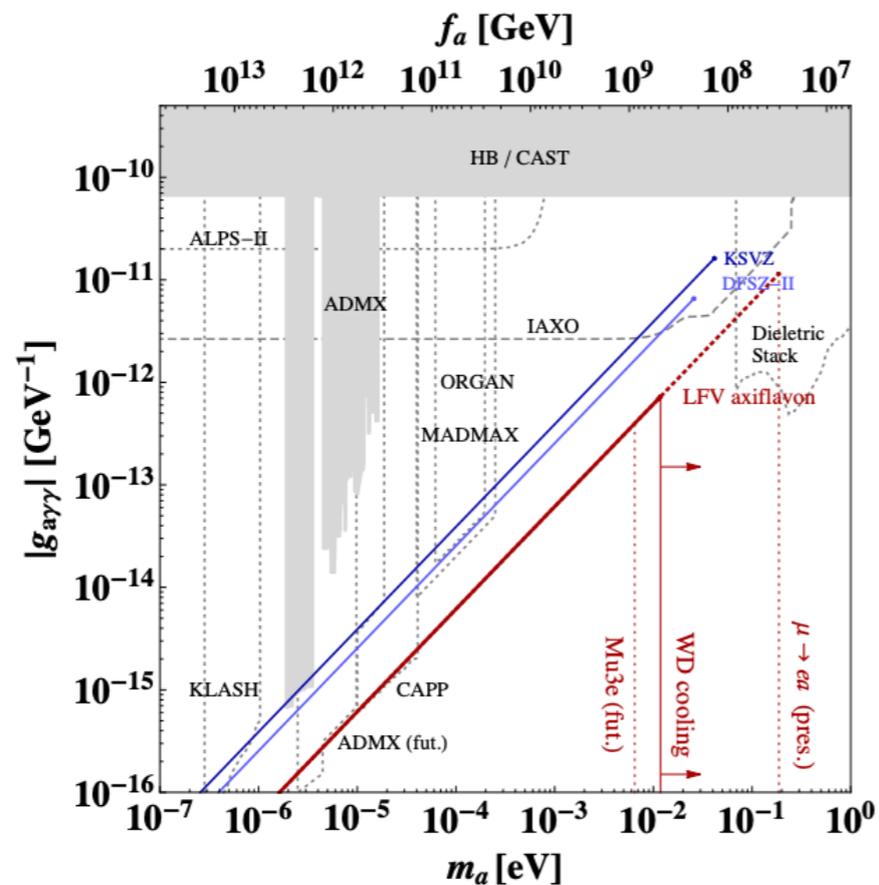
LFV axions-II

Are there well-motivated axions with lepton-flavour-violating couplings?

■ LFV Axiflavoron

If $K^+ \rightarrow \pi^+ a$ is suppressed by a $U(2)$ flavor symmetry

$\mu^+ \rightarrow e^+ a$ can become the dominant discovery channel!

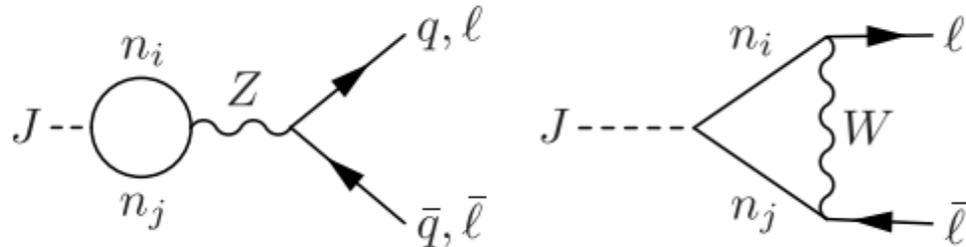


LFV axions-III

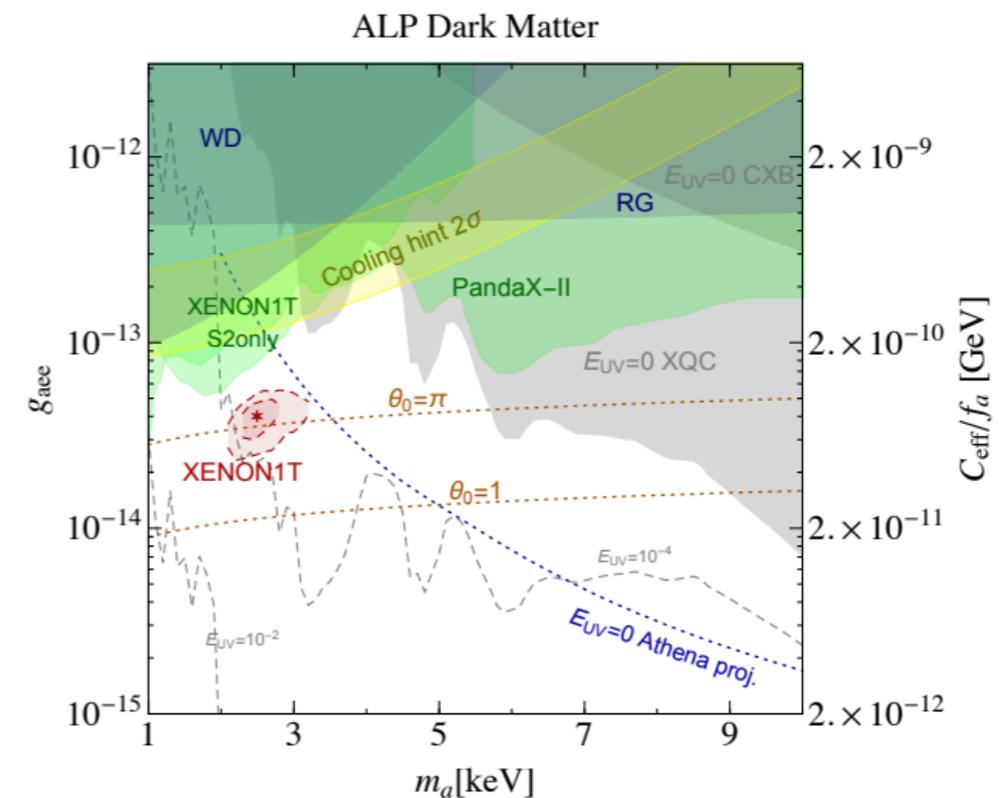
Are there well-motivated axions with lepton-flavour-violating couplings?

Majoron

its an axion-like particle getting its coupling to the SM through a sterile loop



since it is automatically photophobic and it can be DM it is a natural candidate to explain the Xenon-anomaly!

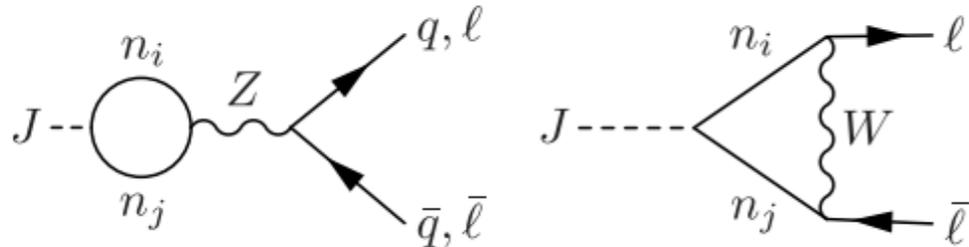


LFV axions-III

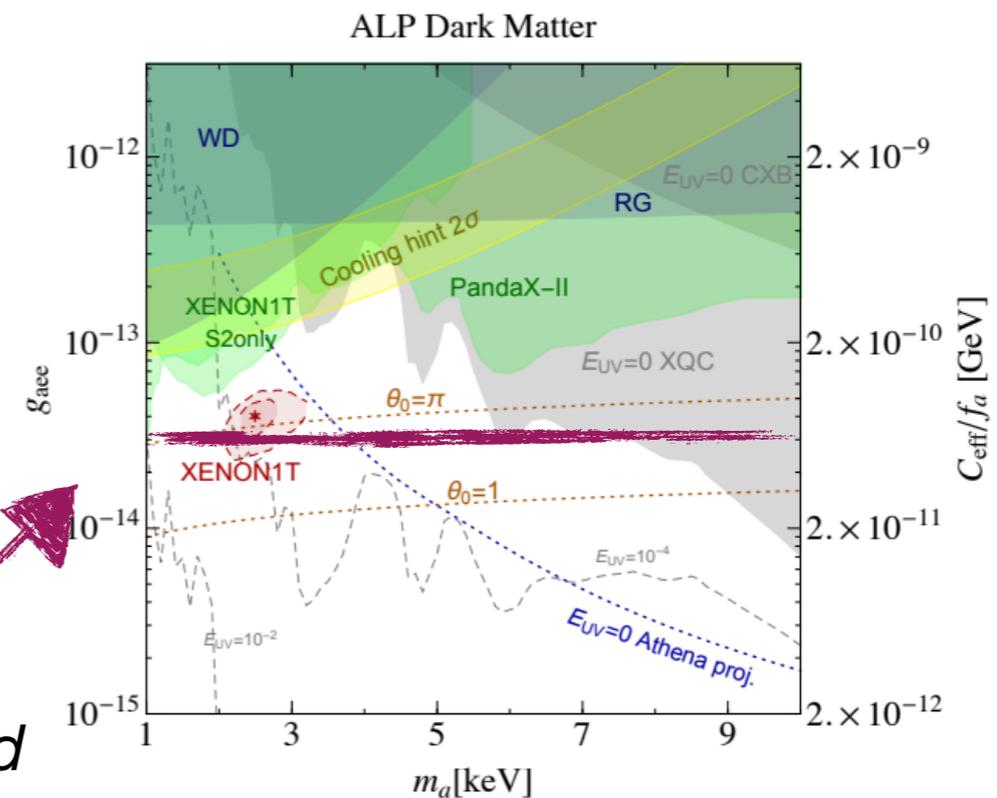
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signal at $\mu^+ \rightarrow e^+ a$ expected

Future improvements

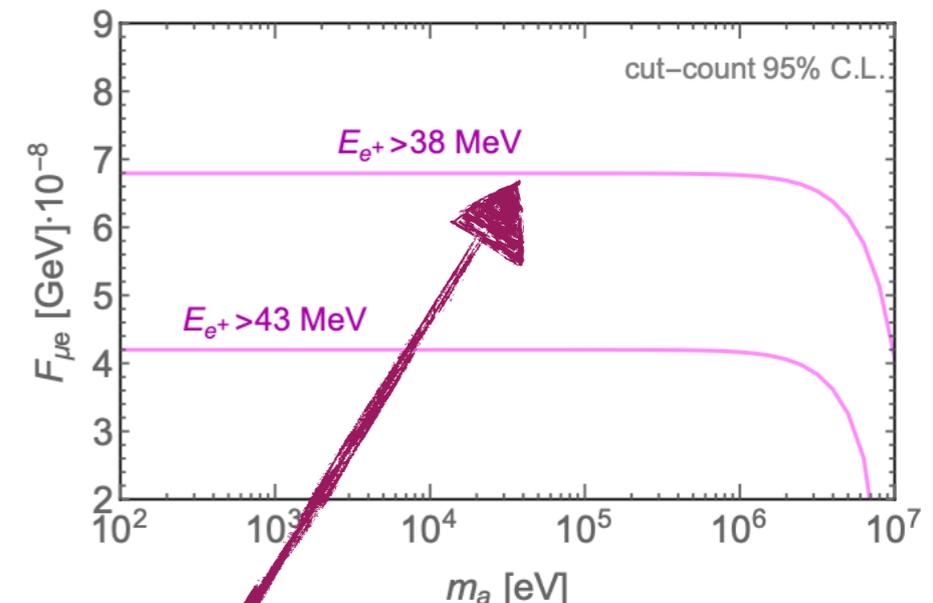
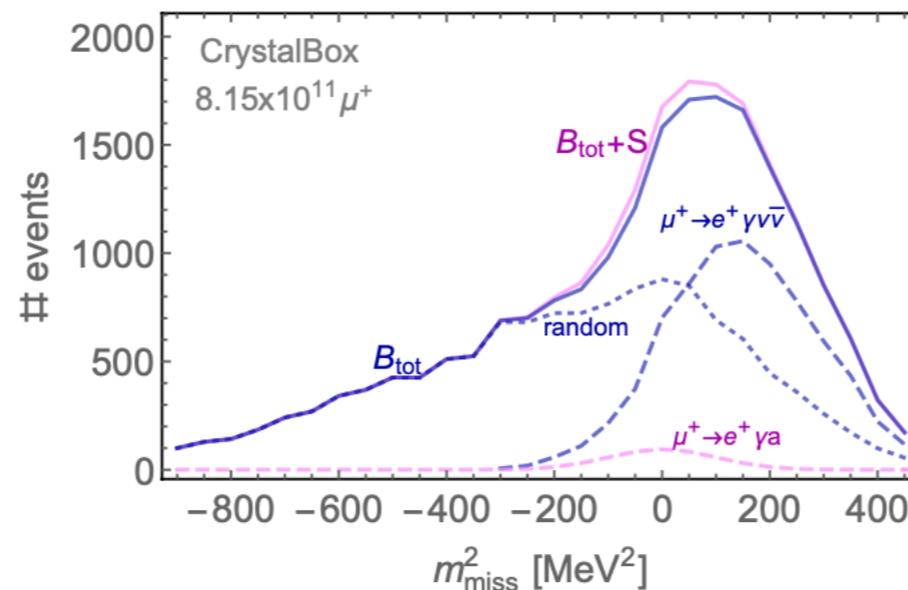
Can we do better in $\mu^+ \rightarrow e^+ a \gamma$?

This observable is less sensitive to the chirality of the axion coupling

CRISTAL BOX

$$\sim 8 \times 10^{11} \mu^+$$

$$E_{\gamma,e} > 38 \text{ MeV}$$



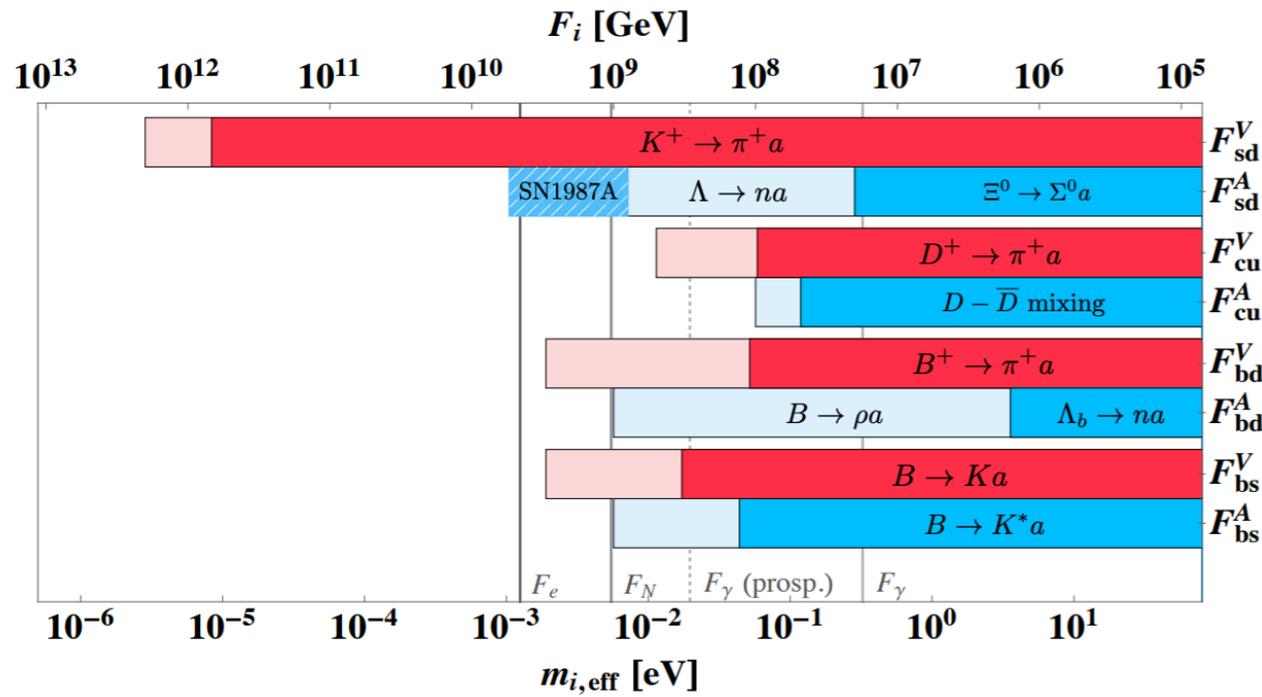
MEGII can dramatically improve on this reach if it can trigger on this!

trigger design on the basis of CRISTAL BOX: Can we reduce the rate to 200 Hz?

Summary

Flavored axions are well motivated “new” targets

which can be hunted in a plethora of new exp. searches



IN THE QUARK SECTOR

IN THE LEPTON SECTOR

