

SEARCHING FOR AXION LIGHT PARTICLES USING FLAVOR VIOLATING TRANSITIONS

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based on Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623
Calibbi, Redigolo, Ziegler, JZ, 2006.nnnnn

Joint Israel seminar, Jun 3 2020

MOTIVATION

- any spontaneously broken global symmetry \Rightarrow (p)NGB
 - if "light enough" can be DM
- in general couplings to gluons, photons, SM fermions

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G} + \frac{E}{N} \frac{\alpha_{\text{em}}}{8\pi} \frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{f_i f_j}^V + C_{f_i f_j}^A \gamma_5) f_j$$

- our goal: implications of flavor violating couplings
 - do FCNC experiments probe interesting parameter space?
 - possible improvements on search strategies?

NAMING CONVENTION

- a sidenote on the naming used in this talk
 - (QCD) axion - pNGB that obtains mass from (QCD) anomaly
 - any-other-on* - explicit mass term for pNGB that breaks the global symmetry
 - flavon, majoron,...

*almost always: axiflavin/ flaxion is a QCD axion

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axion-like particles
= ALPs

*almost always: axiflavin/ flaxion is a QCD axion

MOTIVATION

- FV couplings of ALPs arise quite generically
- in mass basis ($V_L^{f\dagger} y_f V_R^f = y_f^{\text{diag}}$) the couplings are

$$C_{f_i f_j}^{V,A} = \frac{1}{2N} \left(V_R^{f\dagger} X_{fR} V_R^f \pm V_L^{f\dagger} X_{fL} V_L^f \right)_{ij}$$

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (c_{f_i f_j}^V + c_{f_i f_j}^A \gamma_5) f_j,$$

- FV unless PQ charge matrices $X_{f_{L,R}}$ aligned with $y_f y_f^\dagger, y_f^\dagger y_f$
- note: we will often use

$$F_{f_i f_j}^{V,A} \equiv \frac{2f_a}{c_{f_i f_j}^{V,A}}$$

$$F_{l_i l_j} = \frac{2f_a}{\sqrt{|C_{l_i l_j}^V|^2 + |C_{l_i l_j}^A|^2}}$$

OUTLINE

- bounds on ALPs from quark FCNCs
 - minimal axiflavoron
- bounds on ALPs from lepton FV
 - proposal for MEGII-fwd
 - several models of LFV ALPs
 - LFV QCD axion, LFV axiflavoron, leptonic flavon, majoron

BOUNDS FROM QUARK FCNCs

QCD AXION

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

- in this part will focus on QCD axion with FV couplings to quarks
 - solves the strong CP problem
 - can be a cold DM candidate
 - effectively massless in FV transitions

STRONG CP PROBLEM

- Lorentz and gauge invariance allow a CP violating term in QCD

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

- physically observable is the combination

$$\bar{\theta} \equiv \theta + \arg \det(\mathcal{M}_u \mathcal{M}_d)$$

- experimentally :

$$d_n \approx 4 \times 10^{-16} \bar{\theta} \text{ e cm} \quad \longleftrightarrow \quad |d_n|_{\text{exp}} < 3 \times 10^{-26} \text{ e cm}$$

- why $\bar{\theta}$ so small?

$$\bar{\theta} < 10^{-10}$$

- very puzzling given large CPV phase in the CKM

AXION

- if $\bar{\theta}(x)$ a dynamical field and couples only to $\bar{\theta}G\tilde{G} \Rightarrow$ potential min. at $\bar{\theta}(x) = 0$
- new ultra-light particle - axion

$$F_{f_i f_j}^{V,A} \equiv \frac{2f_a}{C_{f_i f_j}^{V,A}}$$

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G} + \frac{E}{N} \frac{\alpha_{\text{em}}}{8\pi} \frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{f_i f_j}^V + C_{f_i f_j}^A \gamma_5) f_j$$

- obtains mass from QCD anomaly

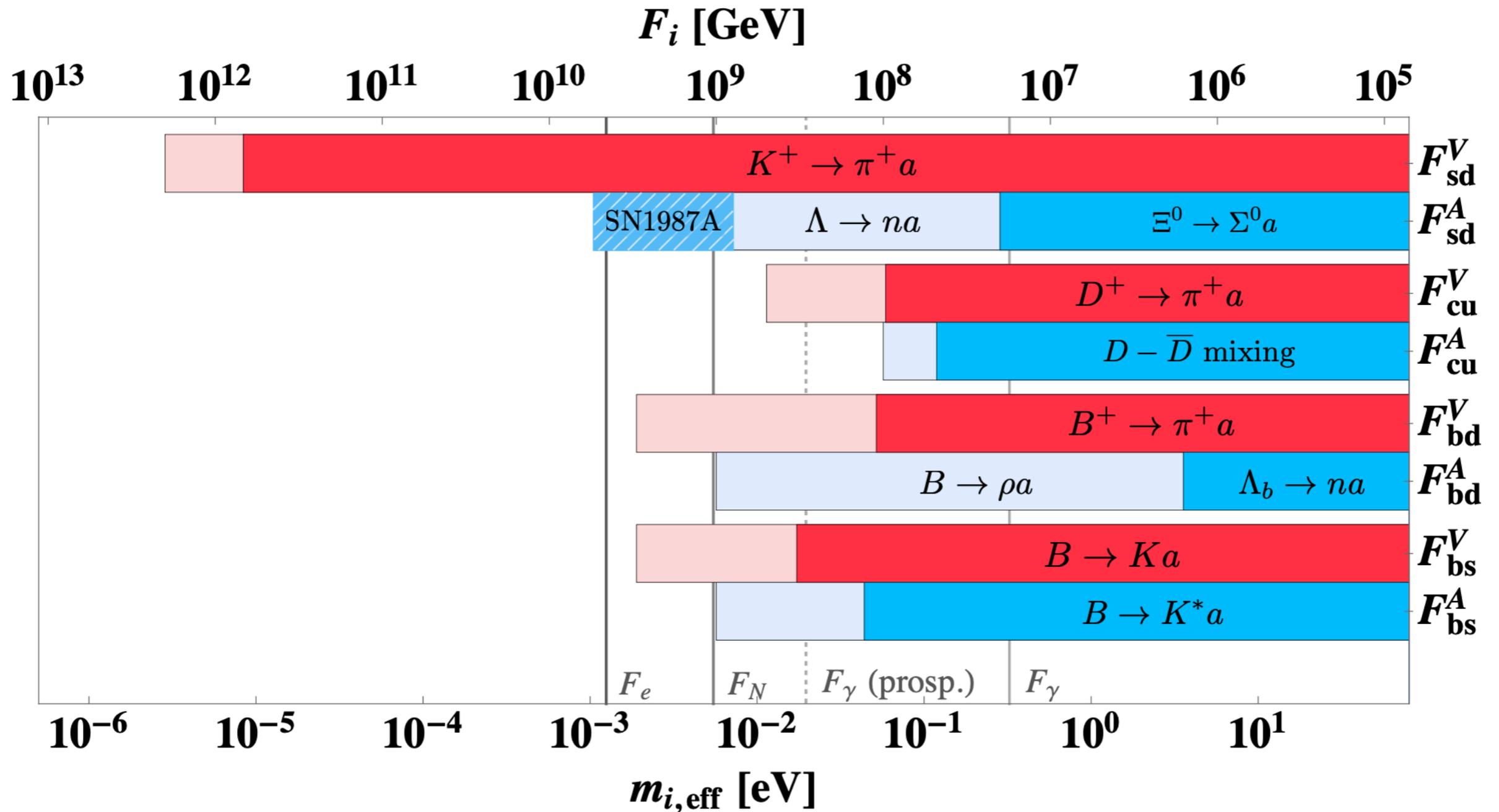
$$m_a = 5.70(7) \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

- viable cold dark matter candidate for

$$10^{-8} \text{ eV} \lesssim m_a \lesssim 10^{-3} \text{ eV}$$

THE STRONGEST FV CONSTRAINTS

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623



FV DECAYS

- 2-body meson decays:

- $P_1 \rightarrow P_2 a$ sensitive to F_{ij}^V

- use exp. searches for $K^+ \rightarrow \pi^+ a, B \rightarrow Ka, B \rightarrow \pi a$
(most stringent: recasts of $B \rightarrow K\nu\bar{\nu}$)

- for $D^+ \rightarrow \pi^+ a$ need to recast $D \rightarrow (\tau \rightarrow \pi\bar{\nu})\nu$

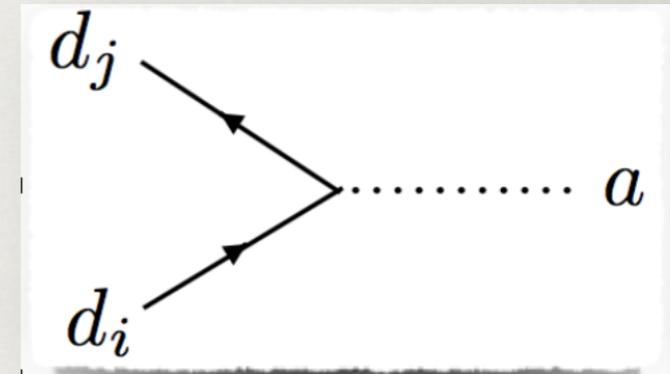
- $P_1 \rightarrow V_2 a$ sensitive to F_{ij}^A , no exp. searches

- 2-body hyperon decays, sensitive to F_{ij}^A and F_{ij}^V

- most sensitive $\Xi^0 \rightarrow \Sigma^0 a$ (now), $\Lambda \rightarrow na$ (future)

- 3-body $K \rightarrow \pi\pi a$ decays, sensitive to F_{ij}^A

- 3-body decays of B, D , could be interesting as well



E787&E949, 0709.1000
CLEO, hep-ex/0106038
Belle, 1702.03224*
BaBar, 1303.7465
CLEO, 0806.2112

BESS-III, 1612.01775

E787, hep-ex/0009055
E391a, 1106.3404

FV DEC

Flavors	Process	F_{ij}^V [GeV]	F_{ij}^A [GeV]
$s \rightarrow d$	$K^+ \rightarrow \pi^+ a$	6.8×10^{11} (2×10^{12})	—
$b \rightarrow s$	$B^{+,0} \rightarrow K^{+,0} a$	3.3×10^8 (3×10^9)	—
$b \rightarrow d$	$B^+ \rightarrow \pi^+ a$	1.1×10^8 (3×10^9)	—
$c \rightarrow u$	$D^+ \rightarrow \pi^+ a$	9.7×10^7 (5×10^8)	—

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FV DEC

Flavors	Process	F_{ij}^V [GeV]	F_{ij}^A [GeV]
	$\Lambda \rightarrow n a$ (decay)	6.9×10^6 (1×10^9)	5.0×10^6 (8×10^8)
$s \rightarrow d$	$\Xi^0 \rightarrow \Sigma^0 a$	1.6×10^7 (2×10^8)	2.0×10^7 (3×10^8)

- 2-body meson decays:

- $P_1 \rightarrow P_2 a$ sensitive to F_{ij}^V

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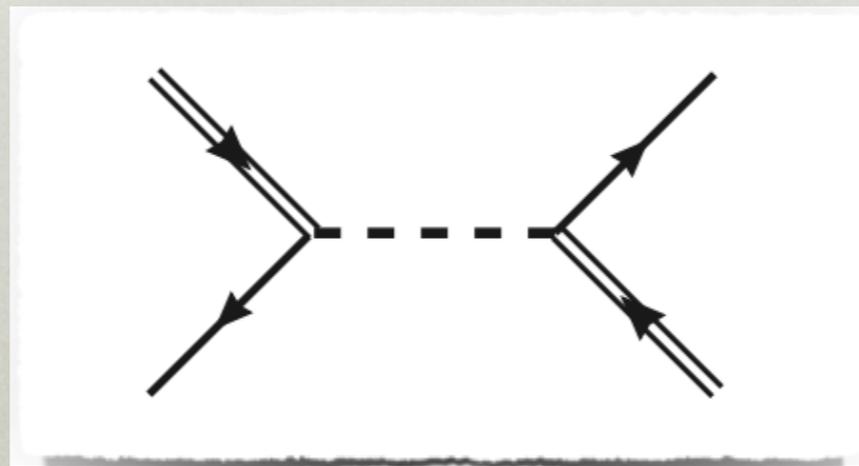
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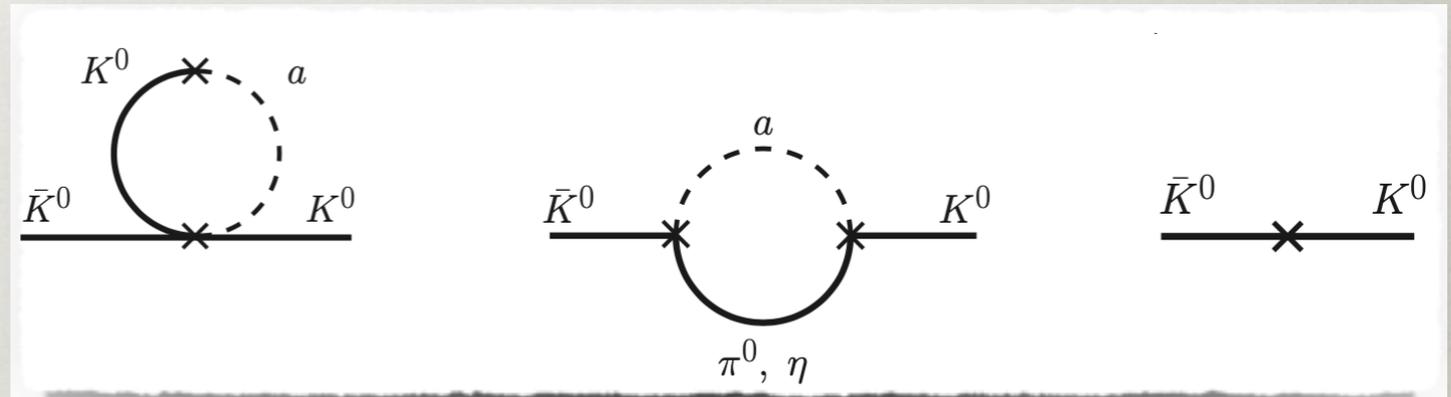
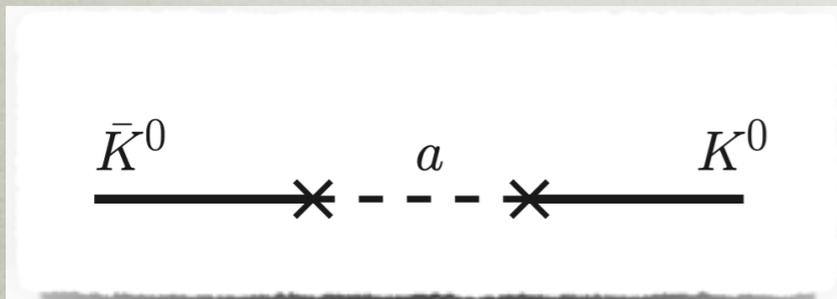
MESON MIXING

- can reliably predict bounds from meson mixing
 - ChPT for $K - \bar{K}$ mixing
 - OPE for $B_q - \bar{B}_q$, $D - \bar{D}$ mixing
- bounds do not depend on ALP decay mode
- but they are UV sensitive
 - there could be cancellations with other dim 6 NP ops.



KAON MIXING

- use ChPT, work to NLO
- at LO, sensitive to F_{ij}^V , at NLO to F_{ij}^A
 - results applicable to other light scalar mediators



$\frac{5}{6}$ in vacuum insertion approx.

$$M_{12}^A = \left(\frac{f_K}{F_{ds}^A}\right)^2 \frac{m_K}{2} \left\{ 1 - \frac{2m_K^2}{f_K^2} (\alpha_0 + 2\alpha_1) + \frac{8}{3} \frac{m_K^2}{16\pi^2 f_K^2} \left(1 - \log\left(\frac{m_K^2}{\mu^2}\right)\right) \right\}.$$

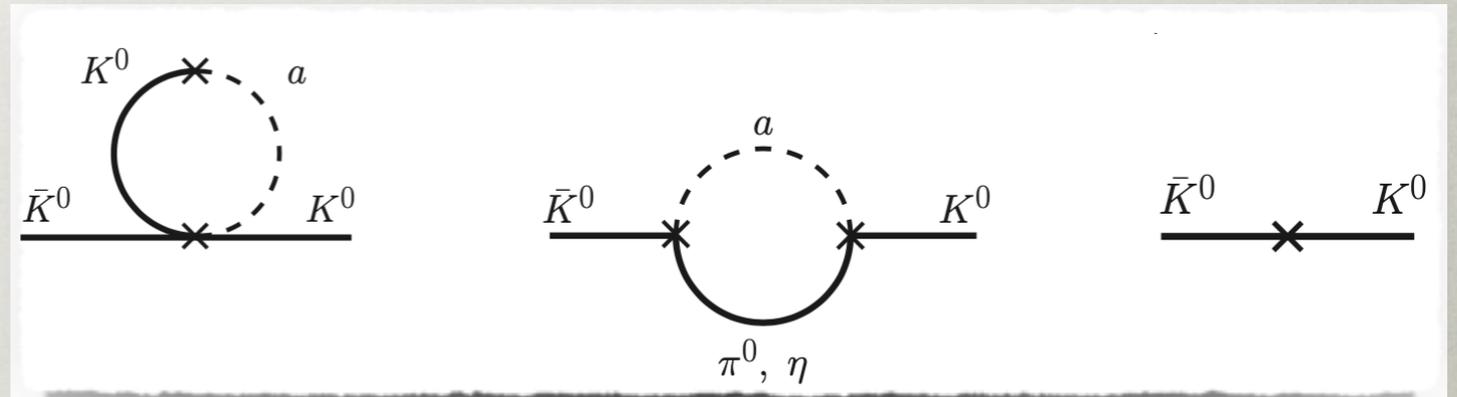
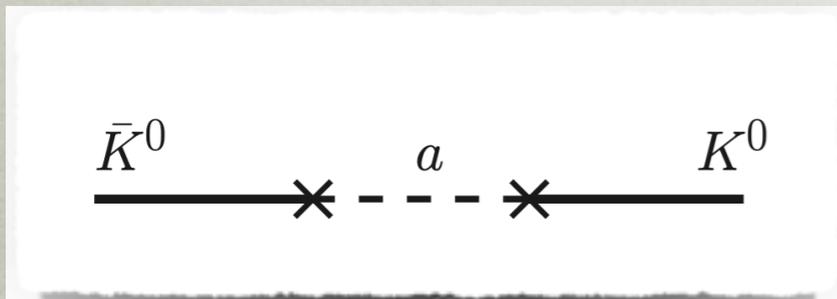
$$M_{12}^V - i\frac{\Gamma_{12}^V}{2} = \left(\frac{f_K}{F_{ds}^V}\right)^2 \frac{m_K}{2} \left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \times \left\{ \frac{m_K^2}{32\pi^2 f_K^2} (I_0(z_\pi) + \frac{1}{3}I_0(z_\eta)) + \frac{2m_K^2}{f_K^2} (\alpha_0 - 2\alpha_1) \right\}.$$

KAON MIXING

Flavors	Process	F_{ij}^V [GeV]	F_{ij}^A [GeV]
$s \rightarrow d$	$K - \bar{K}$ (Δm_K)	$5.1 \times 10^5 \dagger$	2.0×10^6
	(ϵ_K)	$0.9 \times 10^6 \dagger$	4.4×10^7

- use ChPT, work to N²LO
- at LO, sensitive to F_{ij}^V , at NLO to F_{ij}^A

- results applicable to other light scalar mediators



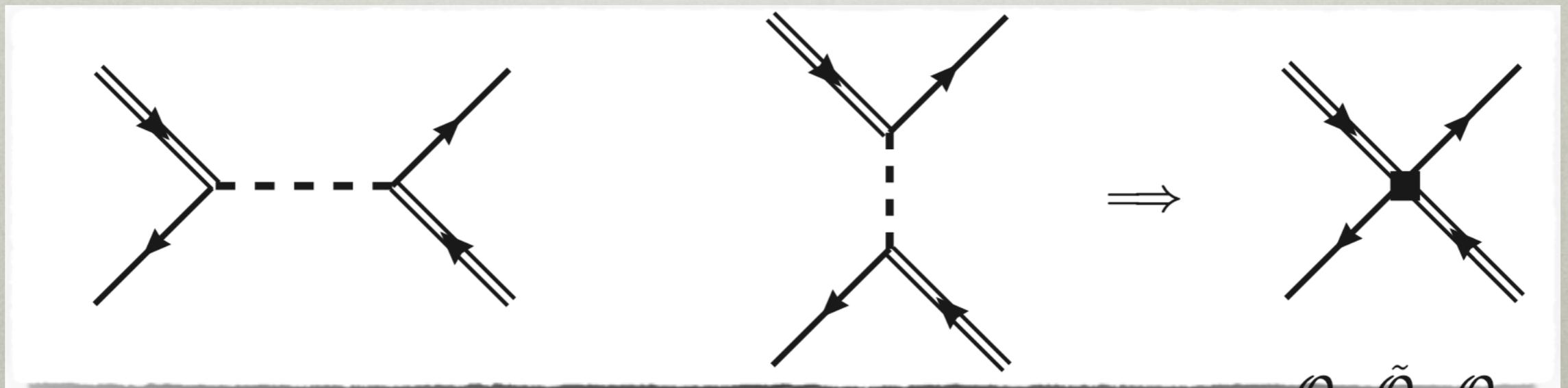
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$$M_{12}^V - i\frac{\Gamma_{12}^V}{2} = \left(\frac{f_K}{F_{ds}^V}\right)^2 \frac{m_K}{2} \left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \times \left\{ \frac{m_K^2}{32\pi^2 f_K^2} (I_0(z_\pi) + \frac{1}{3}I_0(z_\eta)) + \frac{2m_K^2}{f_K^2} (\alpha_0 - 2\alpha_1) \right\}.$$

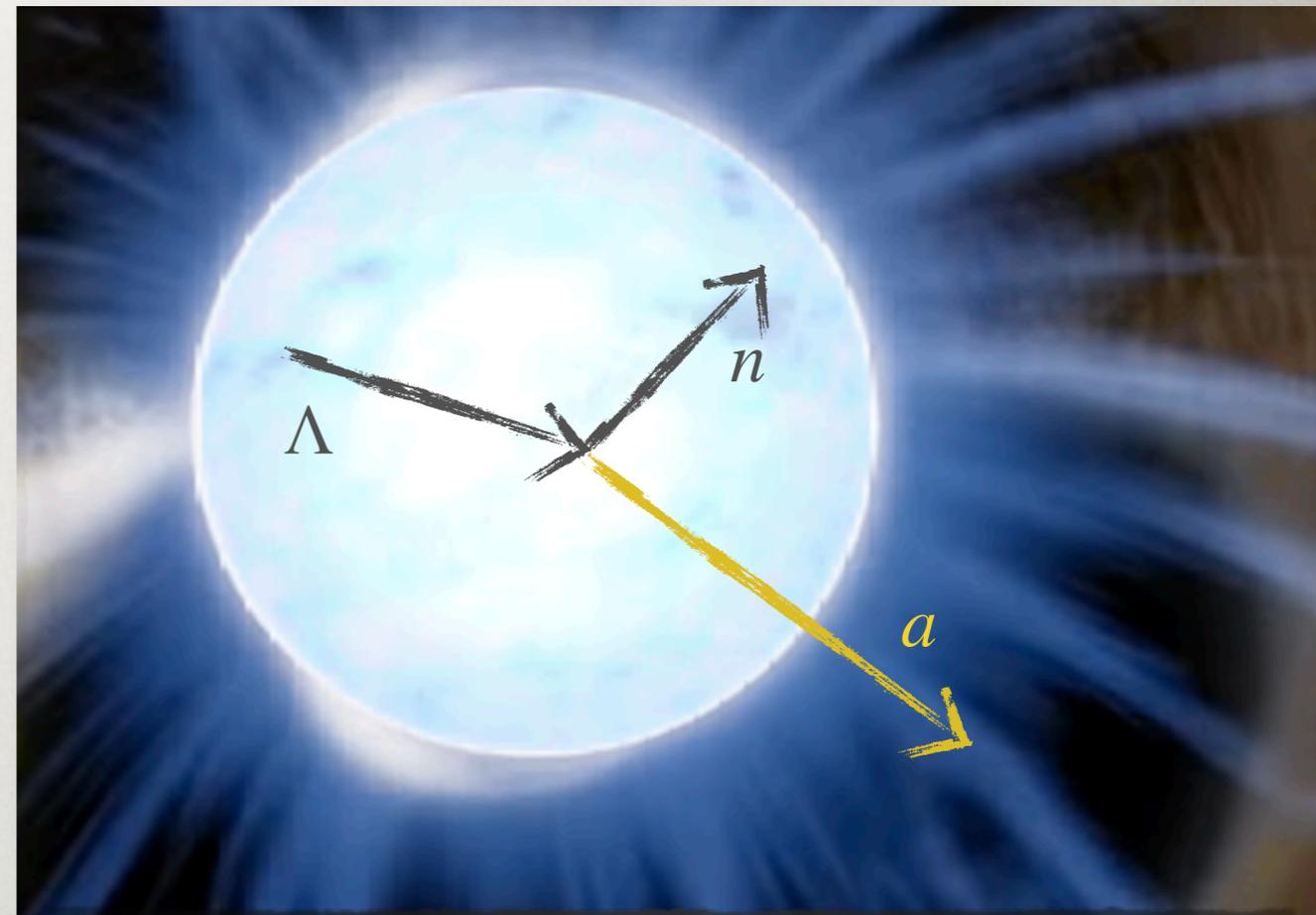
HEAVY MESON MIXING

- since $\Lambda_{\text{QCD}}, m_{u,d,s} \ll m_Q$ can use operator product expansion
- s -channel and t -channel exchanges of the same order
- phenomenologically important for bounding cu - a couplings, otherwise less stringent than decays
- expressions valid for other scalar light mediators



SUPERNOVA BOUNDS

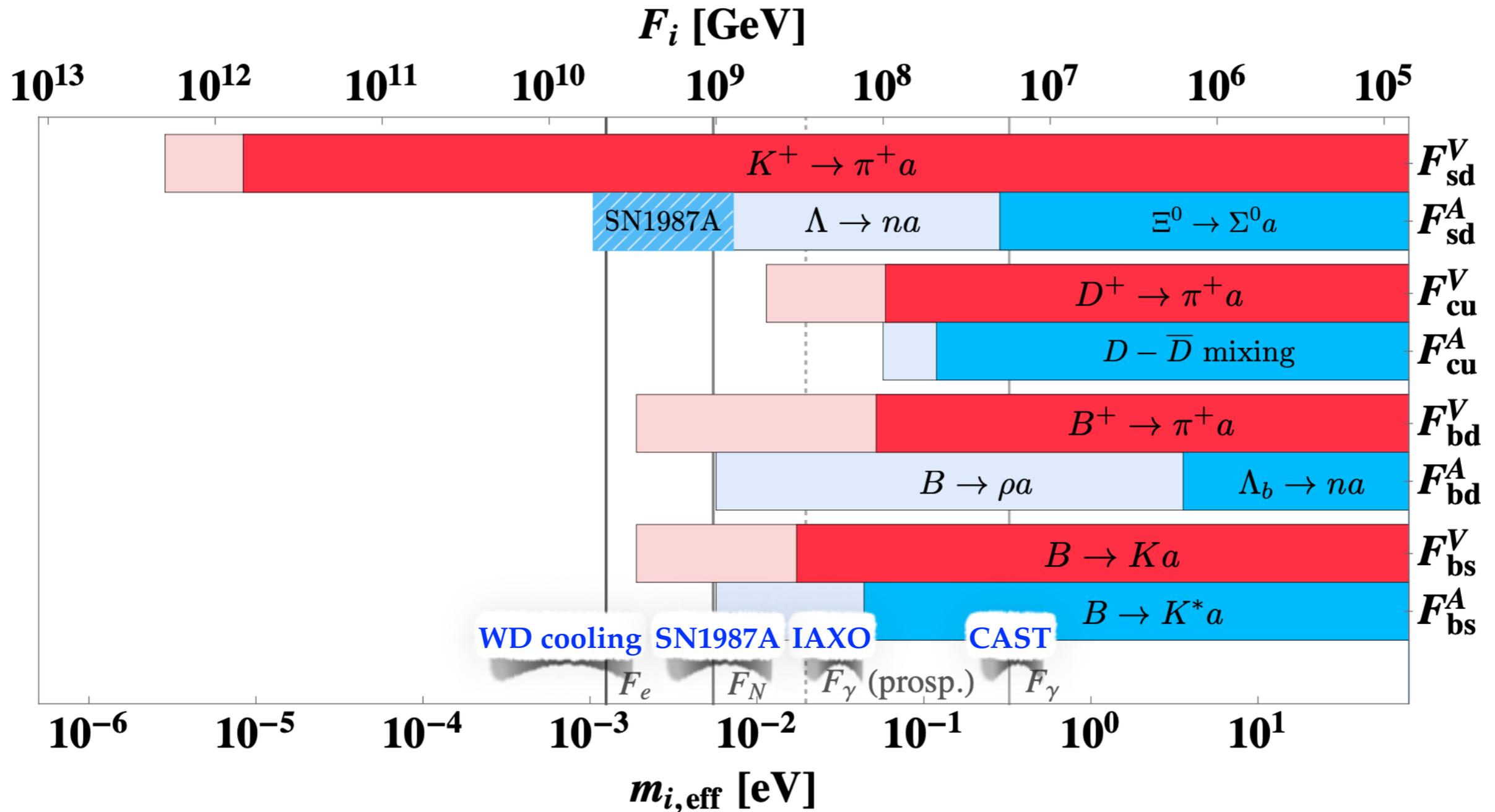
- in neutron star Λ, n, p, e are in equilibrium
- $\Lambda \rightarrow na$ decays can cool the proto-neutron star
- Λ, n have the same Fermi energy \Rightarrow at $T=0$ Pauli blocking forbids $\Lambda \rightarrow na$ decays
- at finite temperature volume emission rate (in NR limit)



$$Q \simeq n_n (m_\Lambda - m_n) \Gamma(\Lambda \rightarrow na) e^{-\frac{m_\Lambda - m_n}{T}},$$

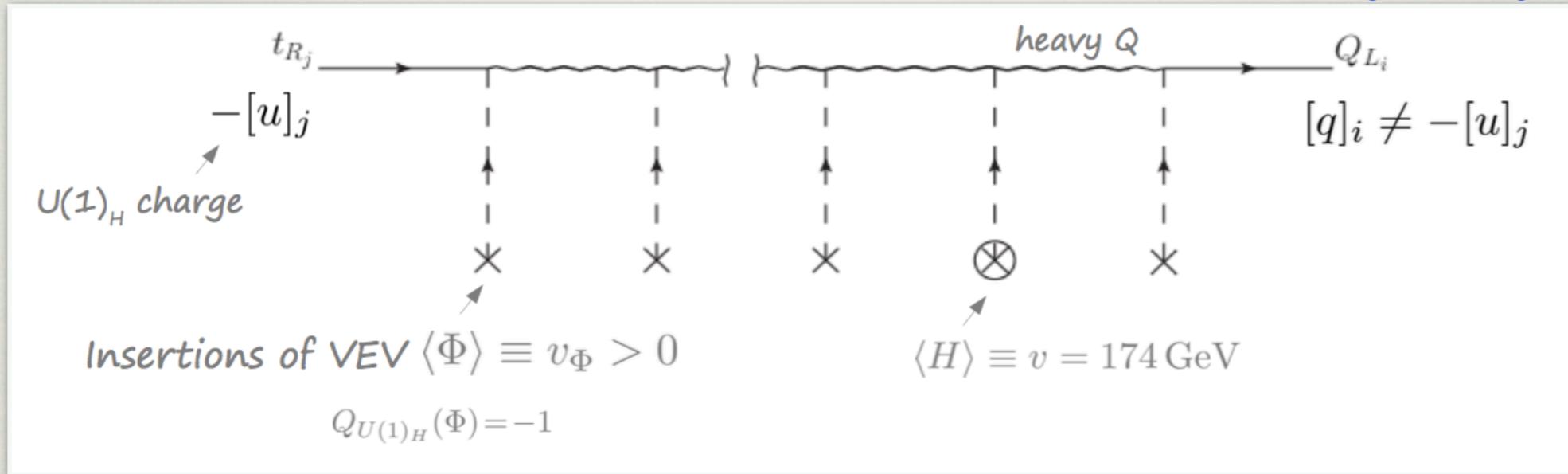
- assuming this is below neutrino emission rate 1sec after the collapse of SN1987A
 - bounds on $|F_{sd}^A|$ and $|F_{sd}^V|$ in the range $10^9 - 10^{10}$ GeV

PROSPECTS



EXPLICIT MODEL - AXIFLAVON

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040



- FN mechanism involves Froggatt, Nielsen, NPB 147, 277 (1979),...
 - vector-like fermions (no QCD anomaly)
 - scalar flavon fields
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

$$\mathcal{L}_{eff} \sim \left(\frac{\phi}{\Lambda_F} \right)^{x_{ij}} h \bar{q}_i u_j$$

$$\epsilon \equiv \frac{\phi}{\Lambda_F}$$

- hierarchy from powers of small parameter ϵ

AXIFLAVON

- ingredients for axion mechanism
 - need a global PQ symmetry that is spontaneously broken
 \Rightarrow Goldstone boson is the axion
 - global symmetry needs to be anomalous under QCD
- flavor symmetries that explain Yukawa hierarchies have a QCD anomaly
- axiflavor mechanism: identify PQ symmetry with FN $U(1)_H$
 - the phase of the flavon is the QCD axion = axiflavor

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{ia(x)/f}$$

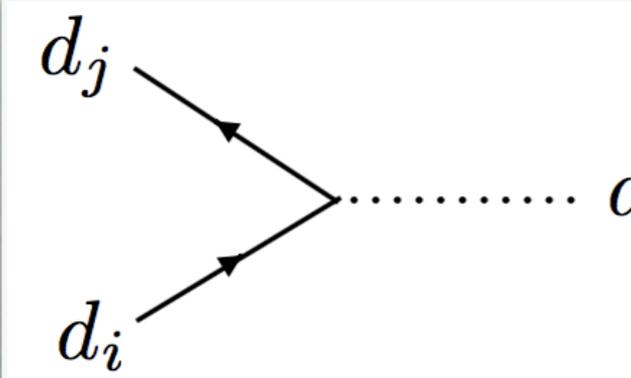
Wilczek, PRL 49, 1549 (1982)

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040

Ema, Hamaguchi, Moroi, Nakayama, 1612.05492

SEARCHING FOR AXIONS/ AXIFLAVONS

- axiflavor
 - flavor violating couplings to fermions
 - in addition to flavor diagonal couplings to electrons, nucleons, couplings to photons, gluons
 - in the minimal FN axiflavor model


$$a \sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu\text{eV}} \frac{\sqrt{m_i m_j}}{10^{12}\text{GeV}}$$

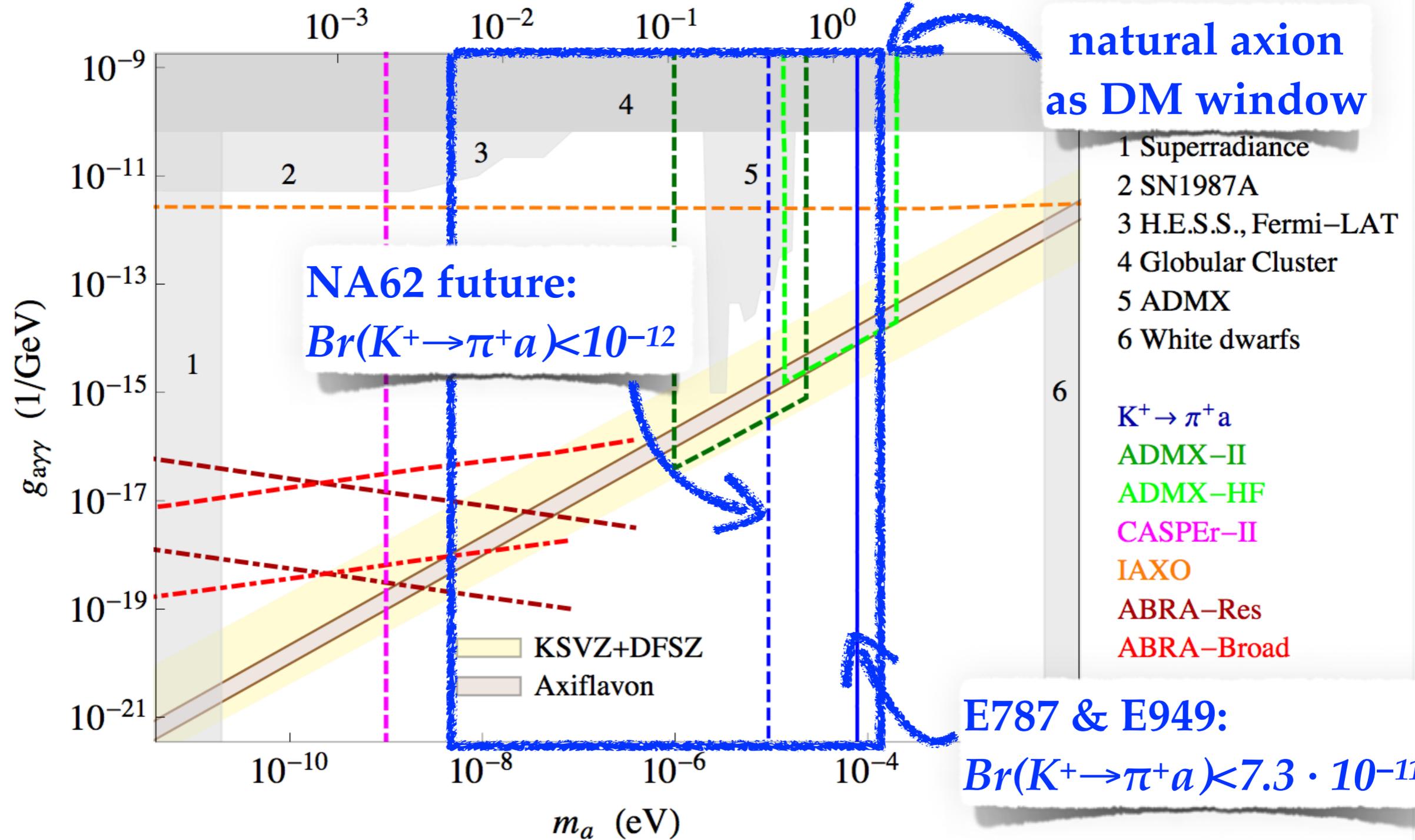
SEARCHING FOR AXIONS/ AXIFLAVONS

minimal axiflavoron

θ/π

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040

natural axion
as DM window



preliminary

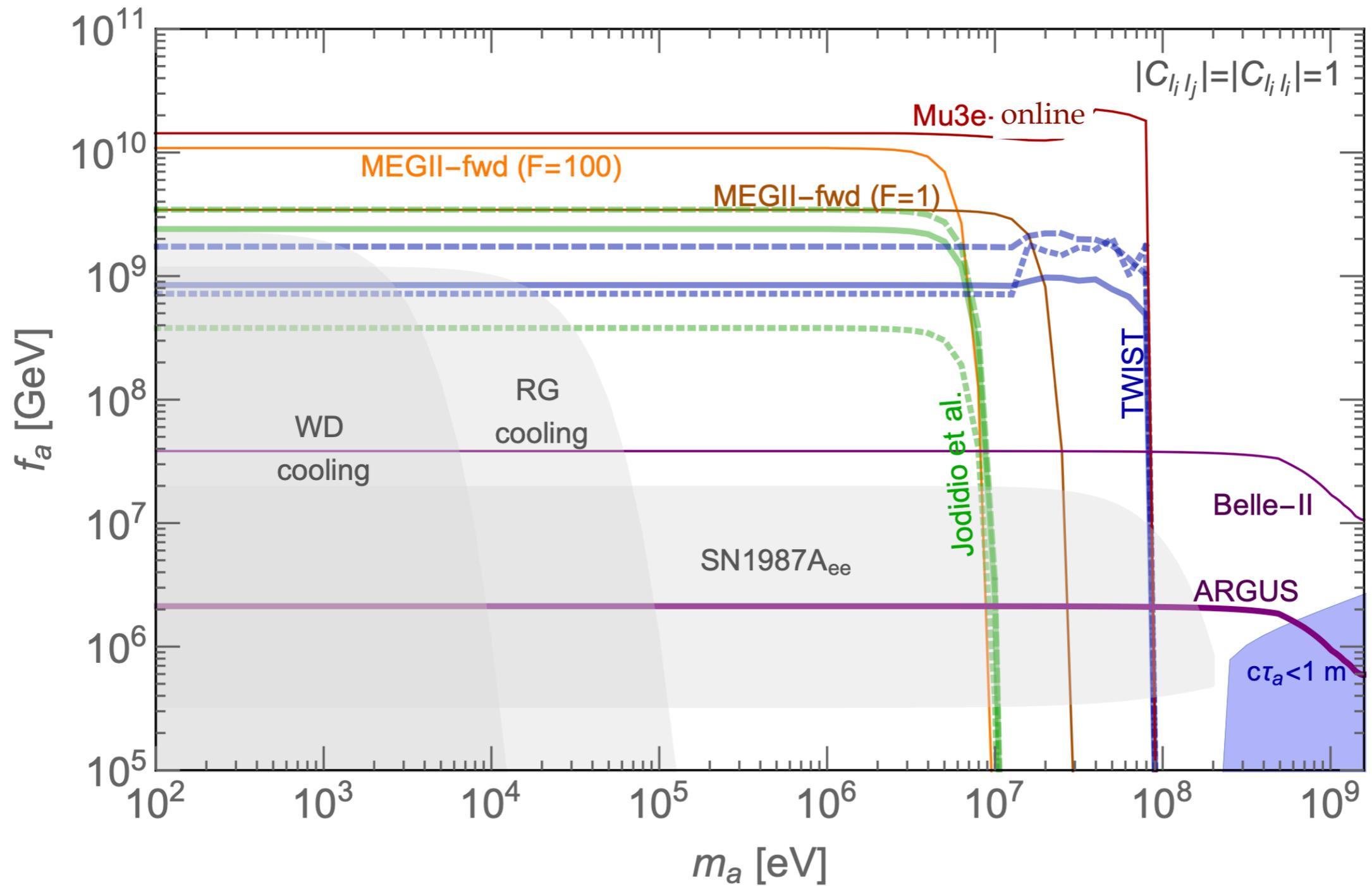
LEPTONIC FCNCS

LFV ALPs

Calibbi, Redigolo, Ziegler, JZ, to appear

- assume ALP with (predominantly) FV leptonic couplings
 - will allow for varying ALP masses
- main question
 - what does $\mathcal{O}(10^{15} - 10^{17})$ muons at MEG-II, Mu3e, Mu2e buy us?
 - compare with $2 \times 10^7 \mu$ @ Jodidio et al. (1986), and $6 \times 10^8 \mu$ @ TWIST (2015)

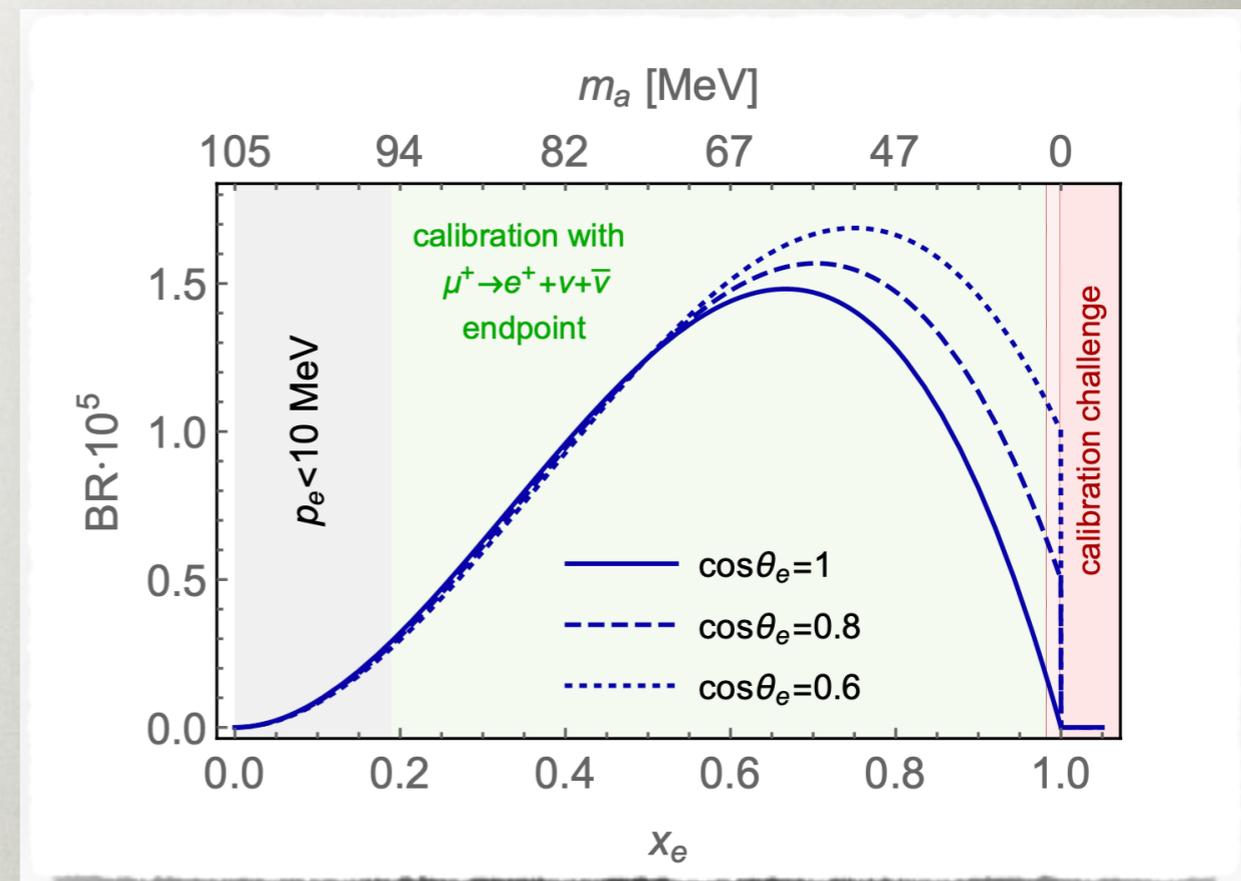
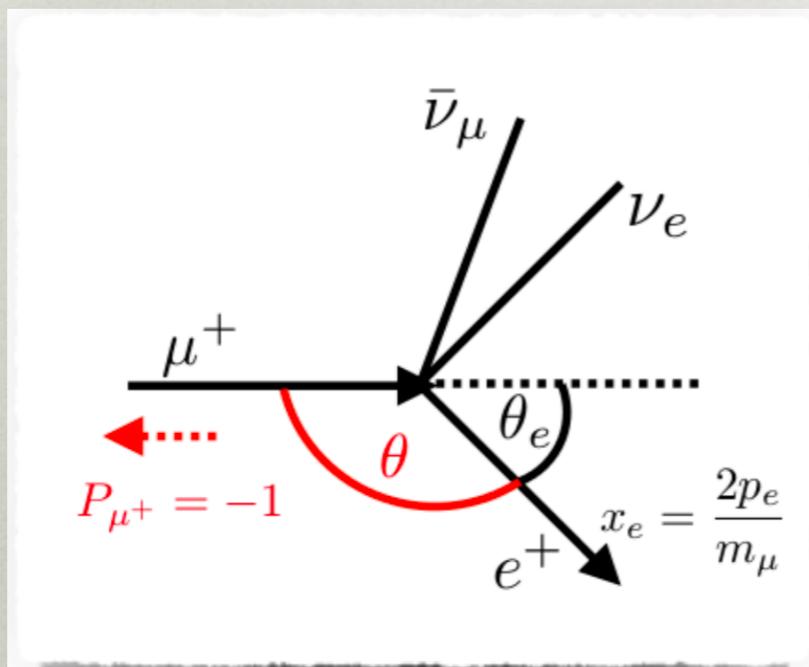
THE UPSHOT



$\mu^+ \rightarrow e^+ a$ SEARCHES

- two types of searches for $\mu^+ \rightarrow e^+ a$ positron line
- suppress the SM bckg., $\mu \rightarrow e \nu \bar{\nu}$
 - use polarized muons $\langle P_\mu \rangle \simeq -1$, in the forward region
SM suppressed
 - sensitive only to RH ALP

Jodidio et al. 1986

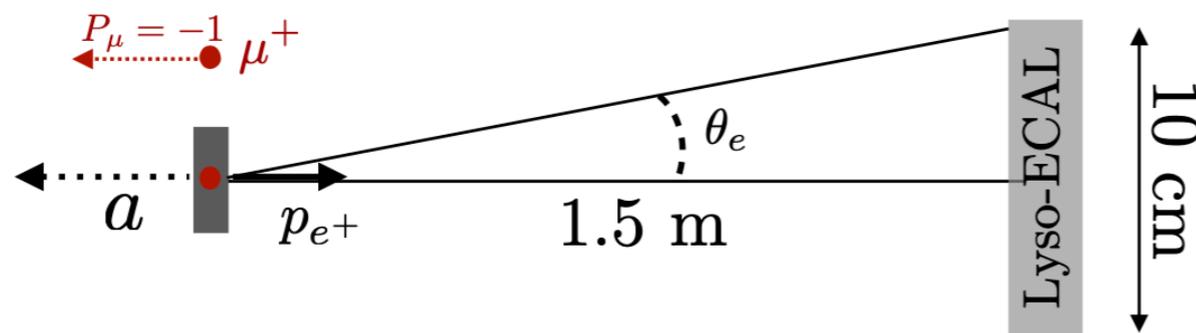


- do not suppress the SM, also sensitive to LH ALP, TWIST

TWIST, 2015

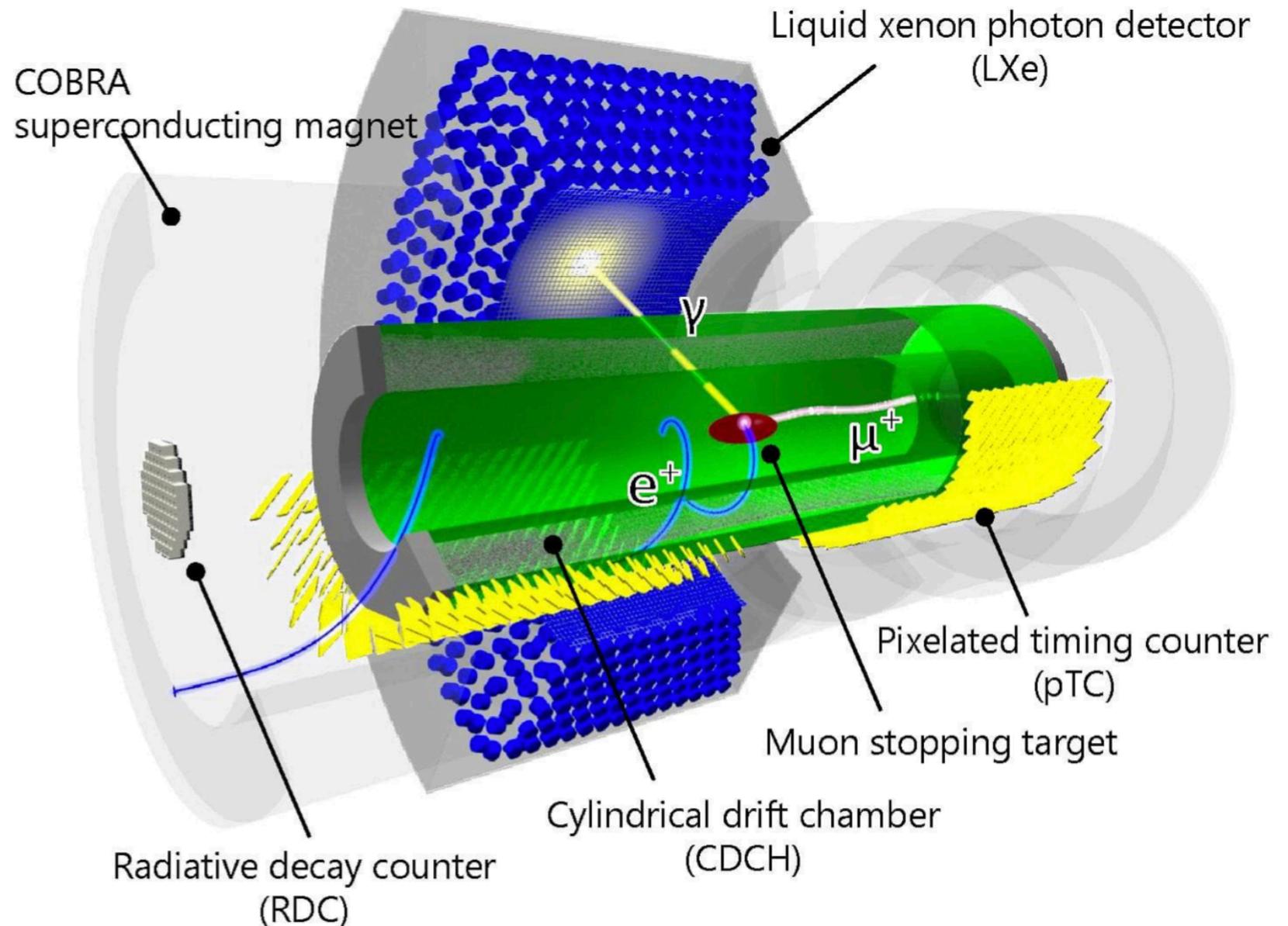
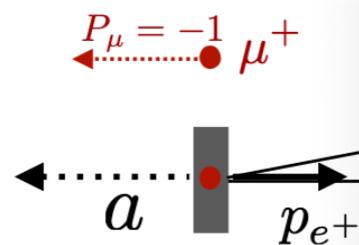
MEGII-FWD

- MEGII could be repurposed for $\mu^+ \rightarrow e^+ a$ search
⇒ MEGII-fwd
- already has polarized muons
- place a Lyso ECAL downstream



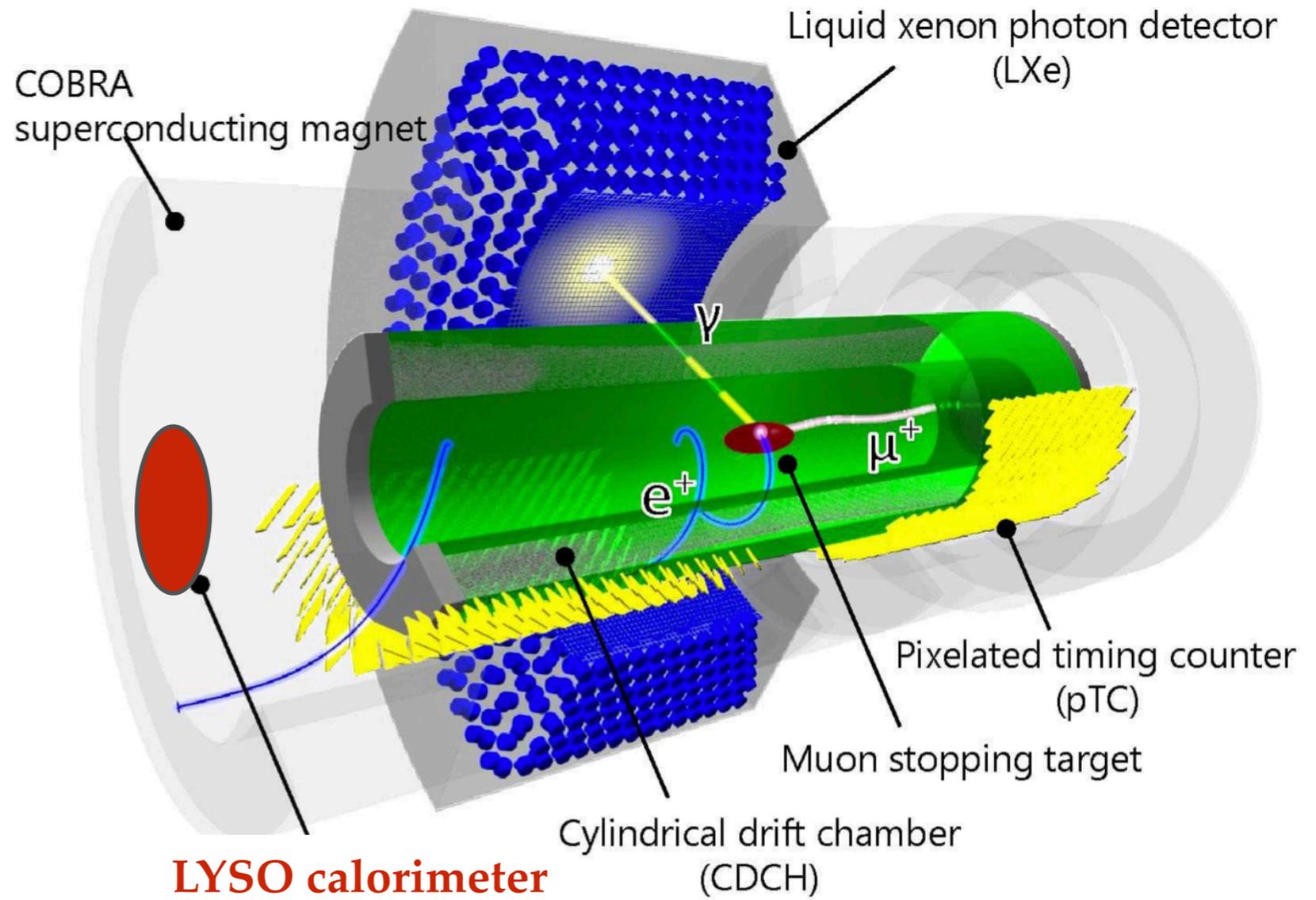
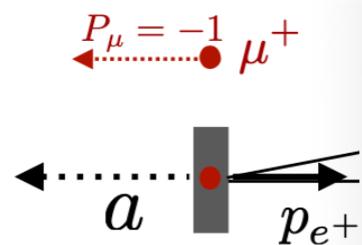
- need to reconfigure the magnetic field
 - most conservative no focusing, $F=1$
 - possibly more realistic $F=100$
- interesting reach already with 2 weeks of running

- MEGII co
- ⇒ MEGII
- already h
- place a Ly

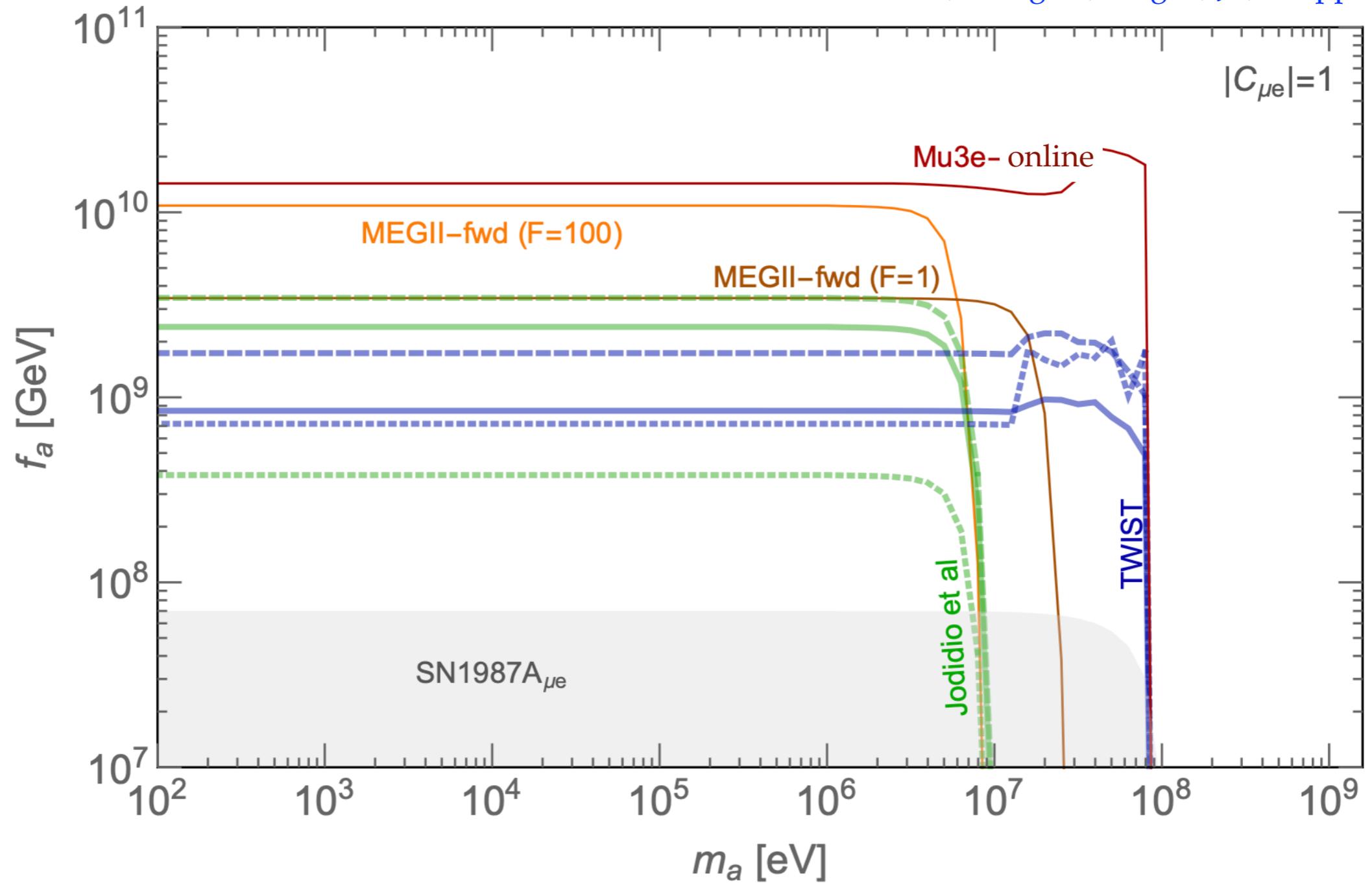


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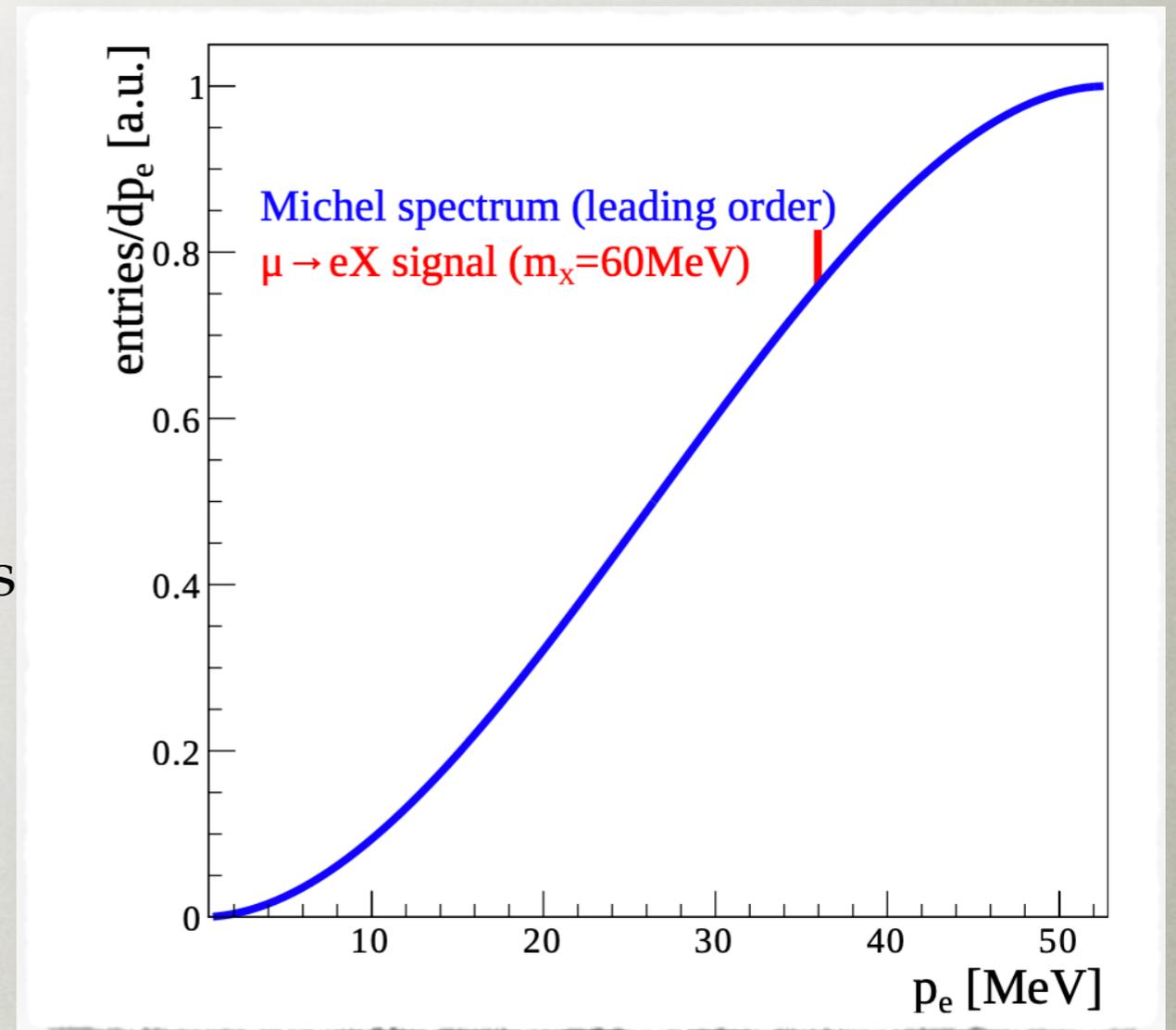
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Mu3e-online

A.-K. Perrevoort, PhD thesis

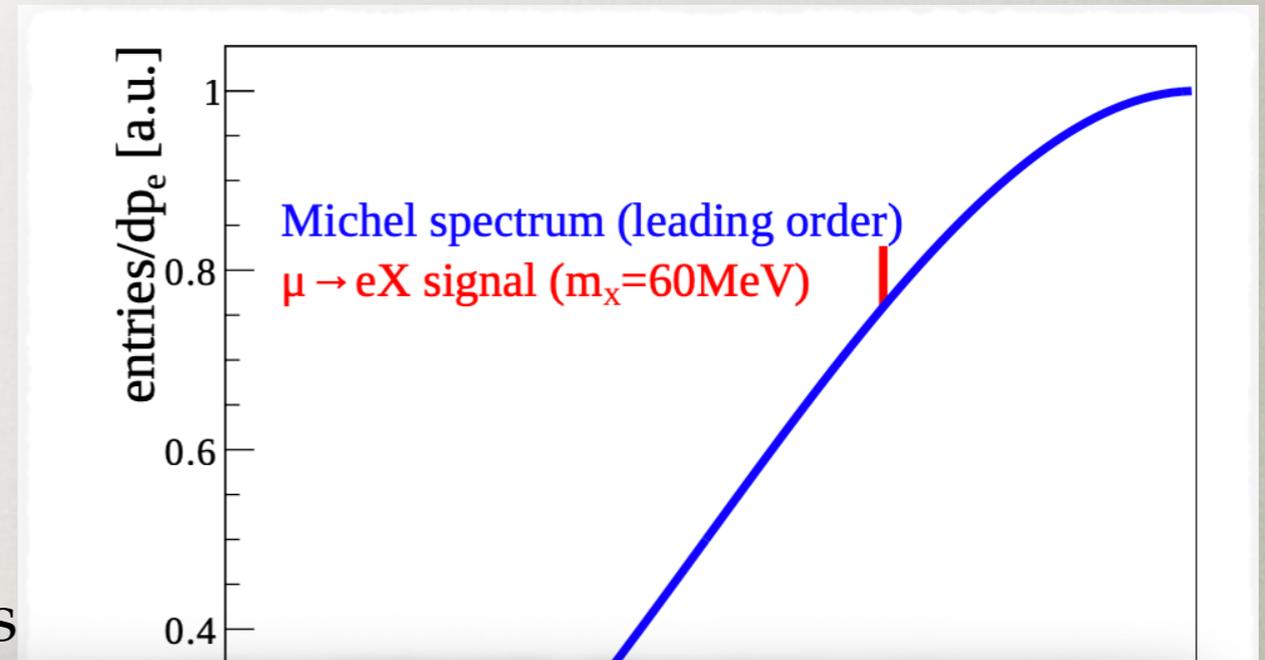
- Mu3e-online: a dedicated search strategy at Mu3e
- online event reconstruction with fgpa's
 - p_e^μ on tape from reduced info ("short tracks"=4 hits in 4 layers)
- bump hunt on Michel spectrum
 - sensitive to both LH and RH ALPs



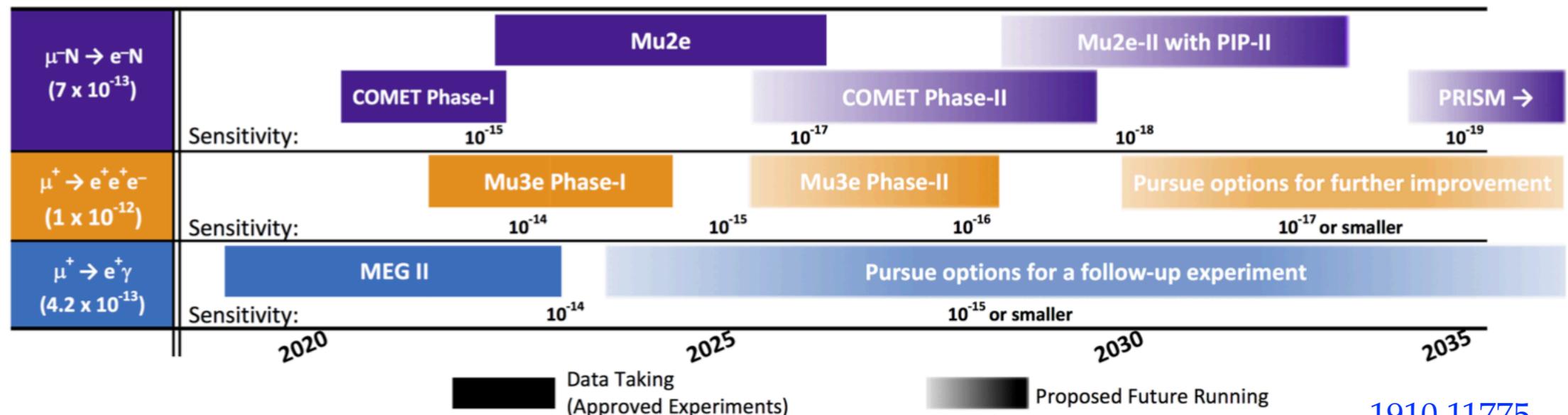
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Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams



1910.11775

ALPs IN TAU DECAYS

- for $\tau \rightarrow \ell a$ the challenge is the extra missing energy
 - $e^+e^- \rightarrow \tau^+(\rightarrow \ell^+a)\tau^-(\rightarrow \rho^-\nu_\tau)$
- can only boost to pseudo-rest frame of tau
- current bound from ARGUS 1995

$$\text{BR}(\tau \rightarrow \mu a) < 4.5 \times 10^{-3} \quad (95\% \text{ C.L.}) \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 3.3 \times 10^6 \text{ GeV} .$$

ARGUS, 1995

$$\text{Belle (1/ab) prospect: } \text{BR}(\tau \rightarrow \mu a) < 1.1 \times 10^{-4} \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 2.1 \times 10^7 \text{ GeV} .$$

Belle, 2017

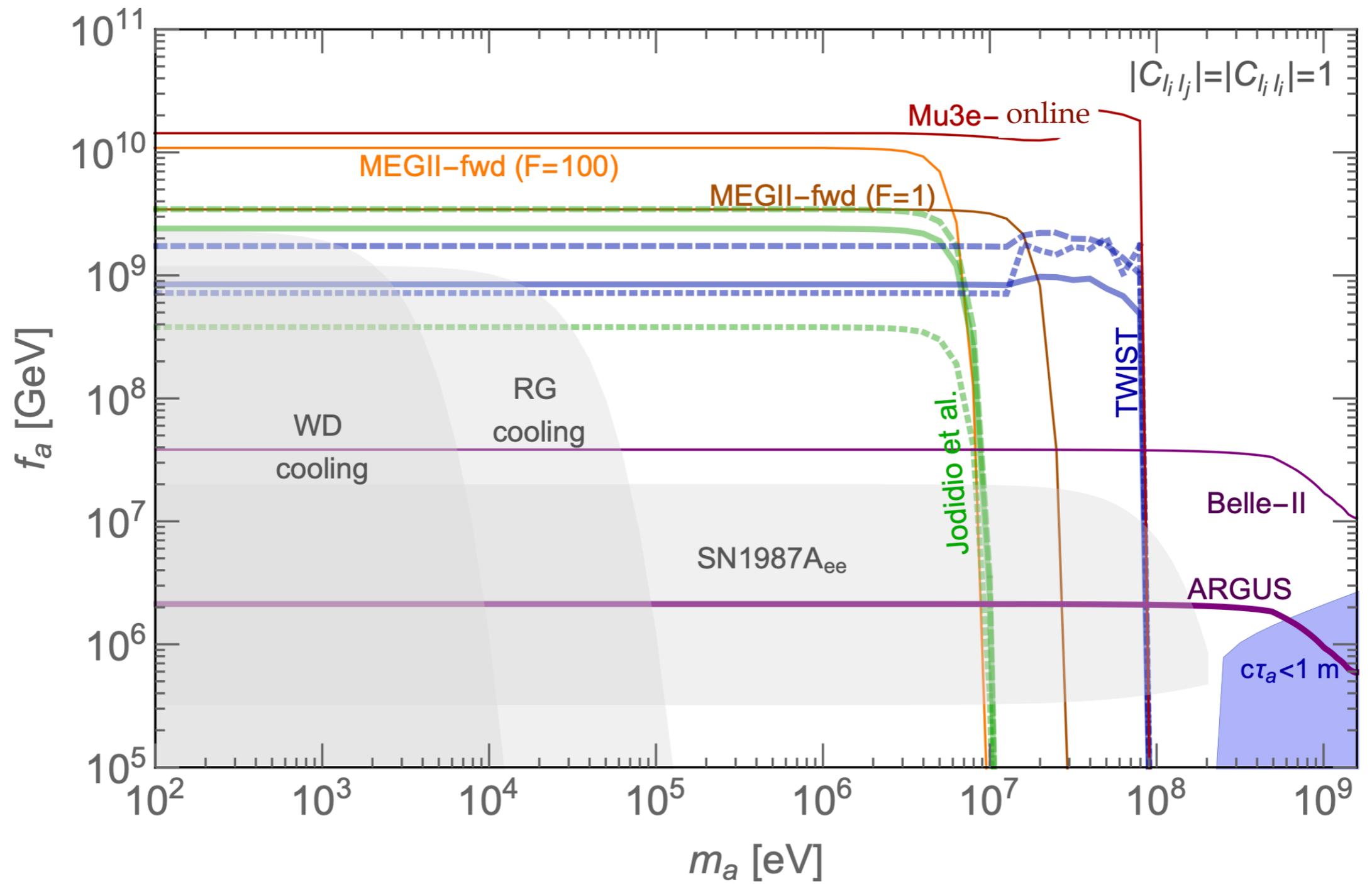
$$\text{Belle-II (50/ab) prospect: } \text{BR}(\tau \rightarrow \mu a) < 1.4 \times 10^{-5} \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 5.6 \times 10^7 \text{ GeV} .$$

our naive rescaling

ASTROPHYSICS BOUNDS

Raffelt, Weiss , [hep-ph/9410205](#)

- bounds on massless ALP-electron from red giants and white-dwarf cooling well known
 - due to $e^- + N \rightarrow e^- + N + a$
 - we rescale to nonzero ALP masses
- above $m_a \gtrsim 0.1$ MeV SN bounds become important (new!)
- also bounds on couplings to muons, but less severe



05

ASTROPHYSICS BOUNDS

Raffelt, Weiss, hep-ph/9410205

- bounds on massless ALP-electron from red giants and white-dwarf cooling well known
 - due to $e^- + N \rightarrow e^- + N + a$
 - we rescale to nonzero ALP masses
- above $m_a \gtrsim 0.1$ MeV SN bounds become important (new!)
- also bounds on couplings to muons, but less severe

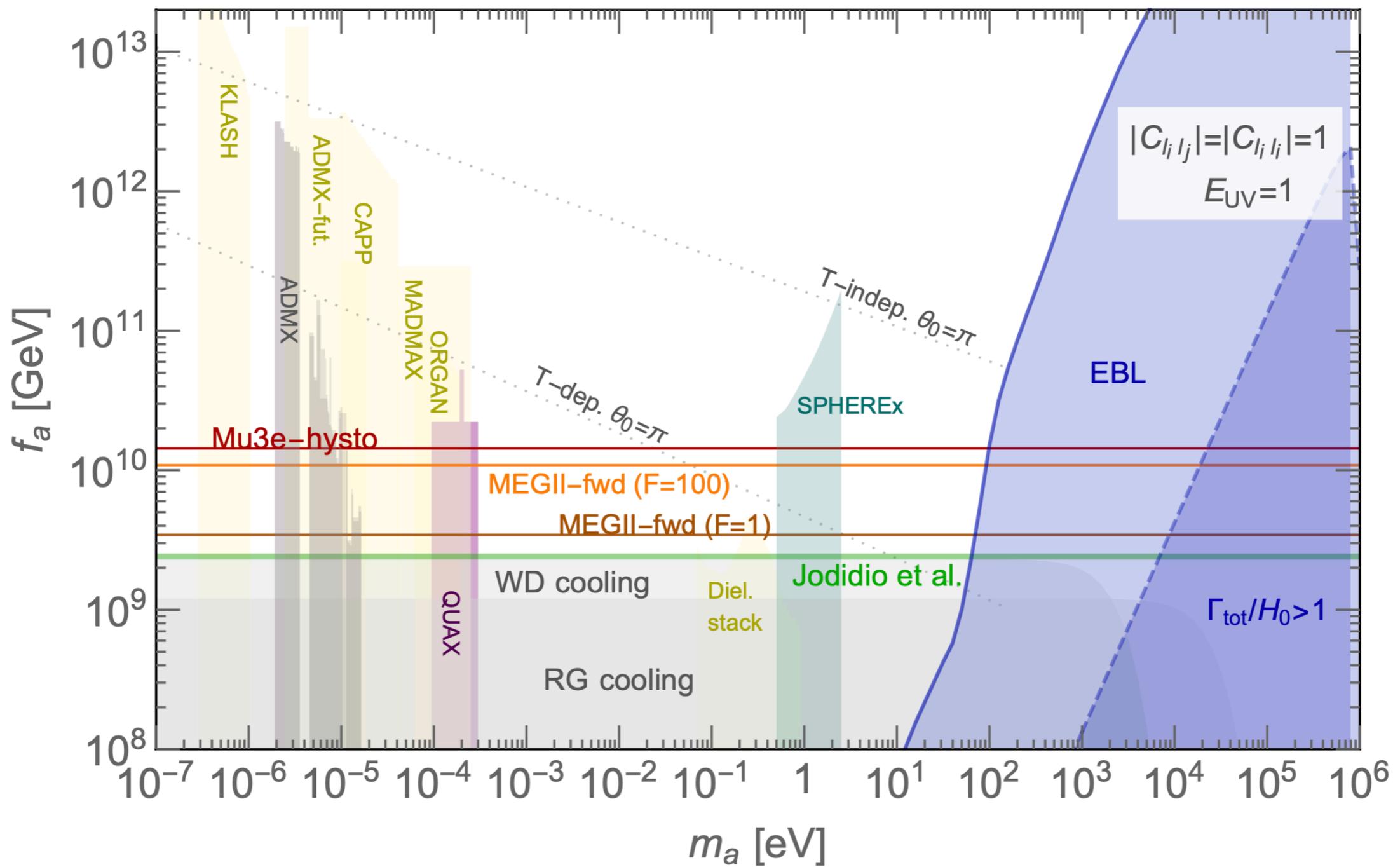
Process	BR Limit	Present best limits		Experiment
		Decay constant	Bound (GeV)	
Star cooling	–	F_{ee}^A	4.6×10^9	WDs [44]
	–	$F_{\mu\mu}^A$	1.6×10^6	SN $_{\mu\mu}$ [45]
	4×10^{-3}	$F_{\mu e}$	1.4×10^8	SN $_{\mu e}$ (Sec. 6.1)

LFV ALP DARK MATTER

- 0-th order condition for ALP to be a DM: be stable on Hubble time
- assume $a \rightarrow \gamma\gamma$ dominates

$$\frac{H_0}{\Gamma_{\text{tot}}} = H_0\tau_a > 1, \quad \text{where} \quad H_0\tau_a \simeq 5.4 \left(\frac{1}{E_{\text{eff}}^2} \right)^2 \left(\frac{10 \text{ keV}}{m_a} \right)^3 \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^2.$$

- if ALP is observed in a LFV process $\Rightarrow m_a \lesssim 10 \text{ keV}$
 - LFV experiments most sensitive for some m_a
 - need other experiments to confirm it is DM



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SAMPLE LFV ALP MODELS

-
- show several examples of LFV ALP
 - LFV QCD axion
 - LFV axiflavoron
 - leptonic familon
 - majoron

LFV QCD AXION

- DFSZ-like model: 2HDM+S: $X_S = 1, X_{H_2} = 2 + X_{H_1}$
- flavor universal $U(1)_{PQ}$ charges in quark sector, non-universal in leptonic

Yukawa coupl. to H_1

Yukawa coupl. to H_2

$$y_e = \begin{pmatrix} 0 & x & x \\ x & 0 & 0 \\ x & 0 & 0 \end{pmatrix}, \quad y'_e = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x & x \\ 0 & x & x \end{pmatrix}$$

⇒ gives lepton FV coupl.s of axion

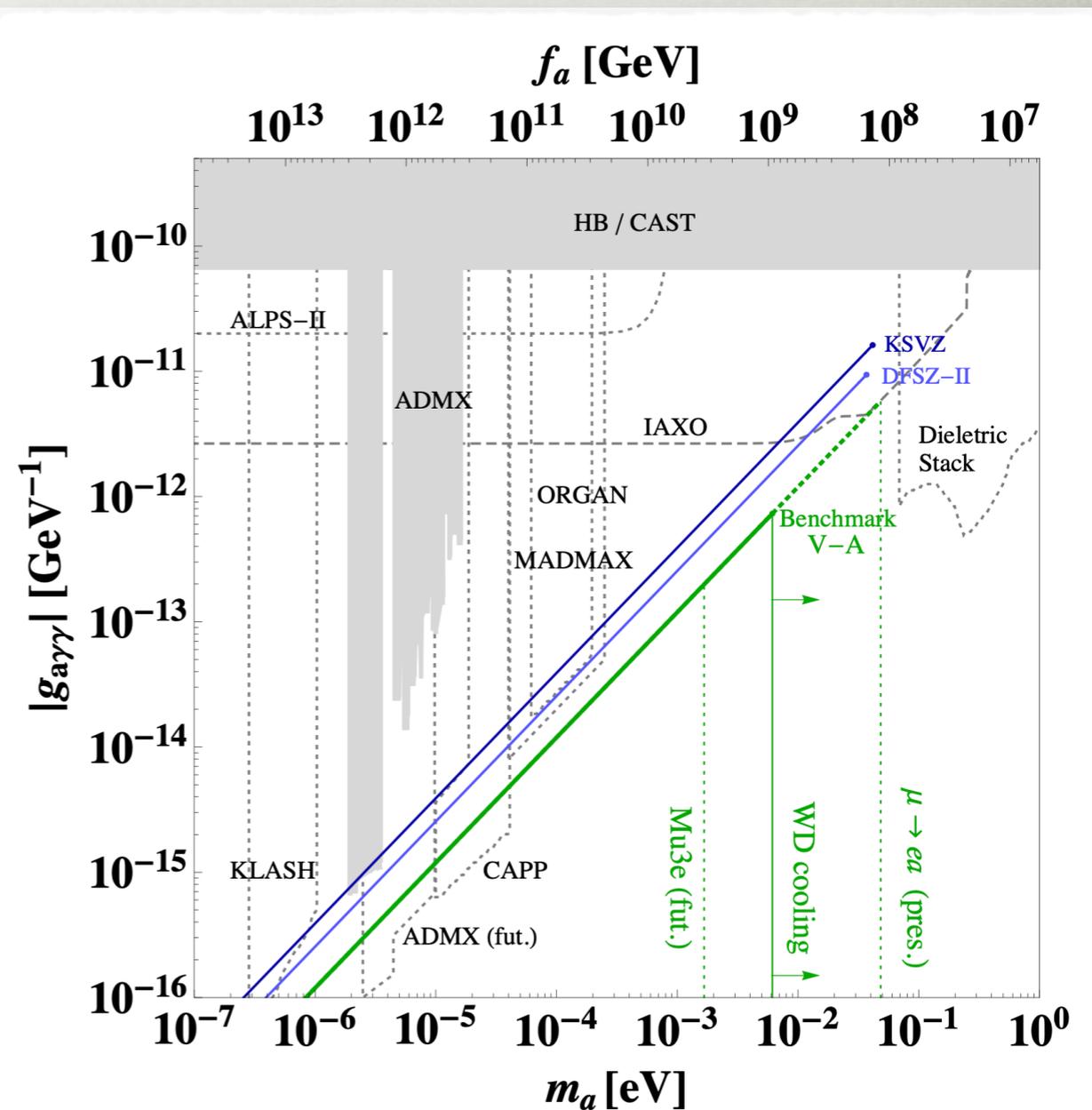
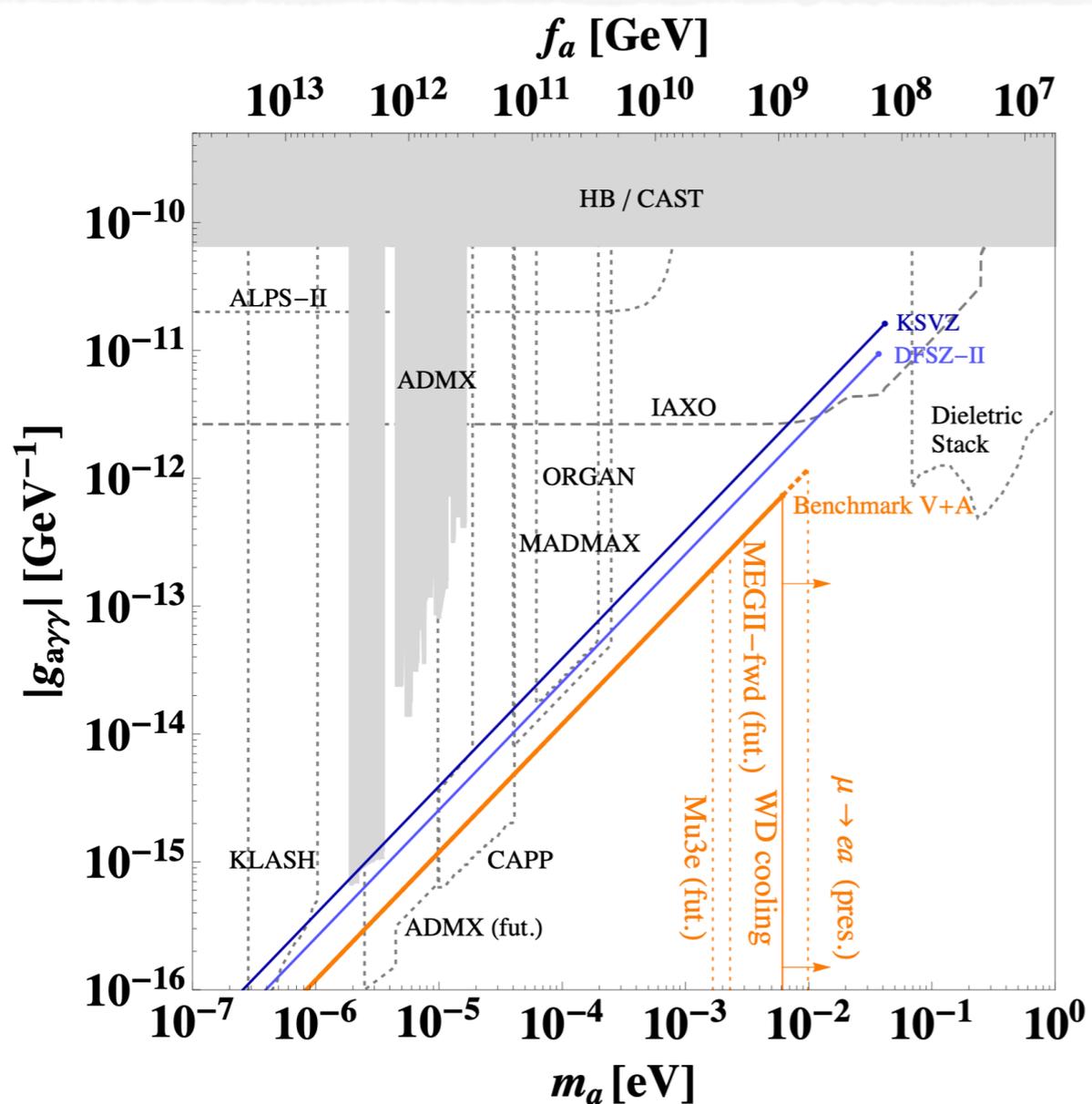
$$y_u = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}, \quad y_d = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

⇒ axion-quark couplings flavor diagonal

- hierarchy of entries external input

LFV QCD AXION

- two benchmarks, assume just 1-2 mixing

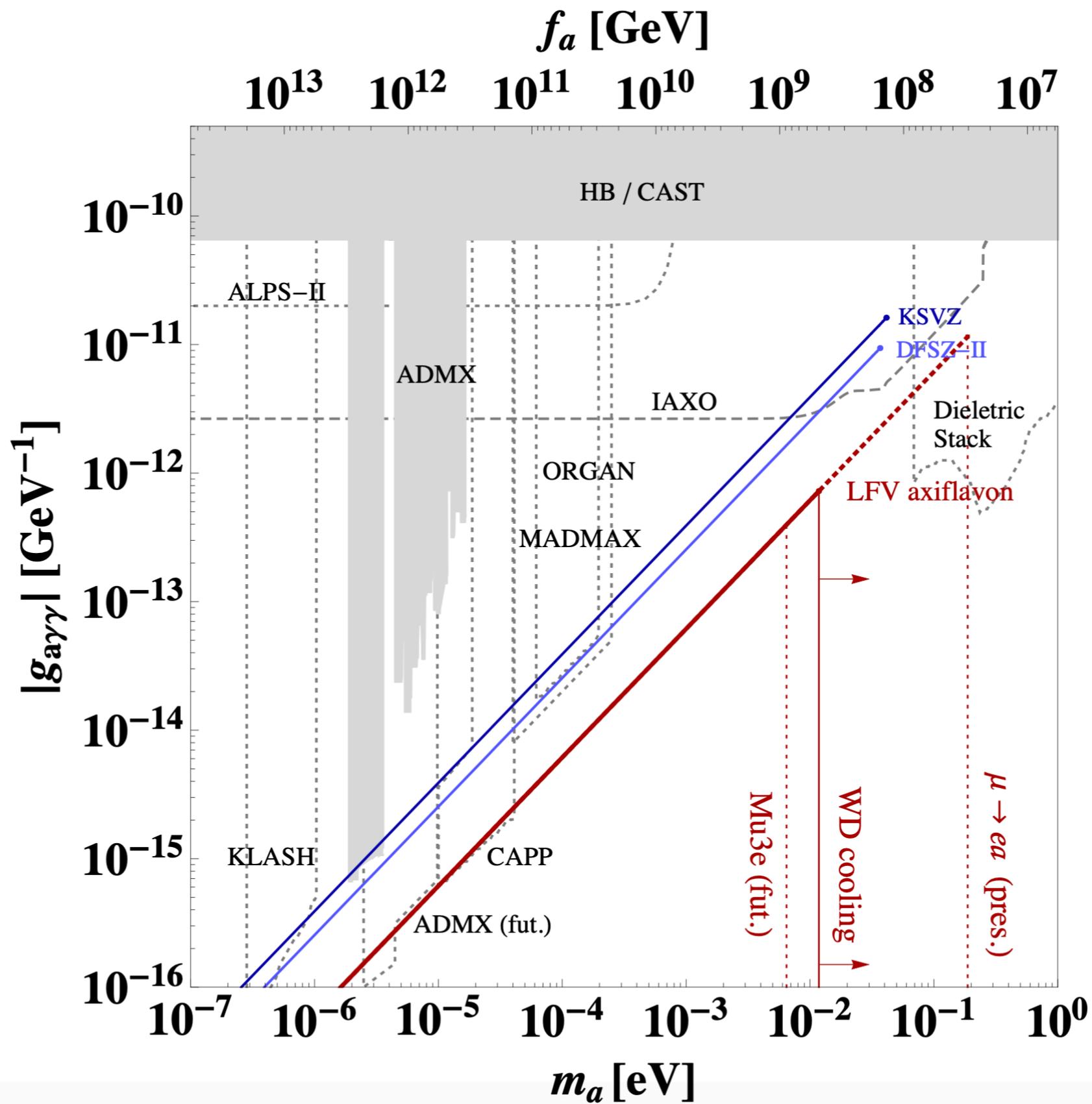


LFV AXIFLAVON

Calibbi, Redigolo, Ziegler, JZ, to appear
see also, Linster, Ziegler, 1805.07341

- the PQ symmetry is part of $SU(2)_F \times U(1)_F$ flavor group
 - all FV couplings need to go through 3rd generation
 - for leptons 1-2 and 1-3 mixings are larger (in LH sector to reproduce PMNS matrix)
- \Rightarrow unlike minimal axiflavor, $K \rightarrow \pi a$ suppr.
 - the observation mode is $\mu \rightarrow ea$

- the
- fla
-
-
-
-



c, JZ, to appear
ler, 1805.07341

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(x)

Dr.

LEPTONIC FAMILON

- separate Froggatt-Nielsen U(1) for quarks and leptons
 - leptonic f_a scale assumed lighter \Rightarrow these couplings dominate
 - familon mass a free parameter
- two benchmark charge assignments

$$([L]_1, [L]_2, [L]_3) = (L, L, L), \quad [\text{Pure Anarchy}].$$

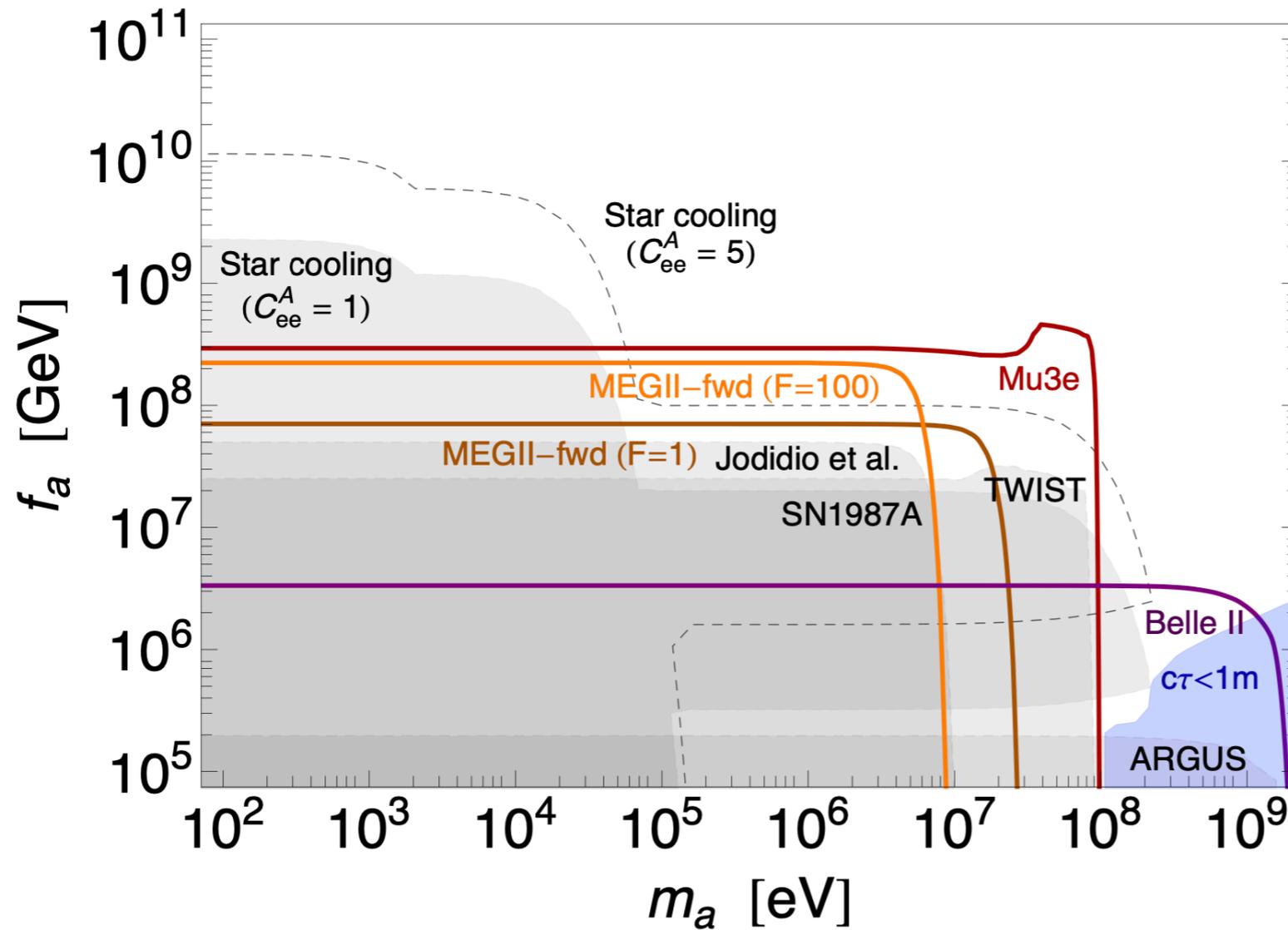
\Rightarrow RH ALP

$$([L]_1, [L]_2, [L]_3) = (L + 2, L + 1, L), \quad [\text{Hierarchy}].$$

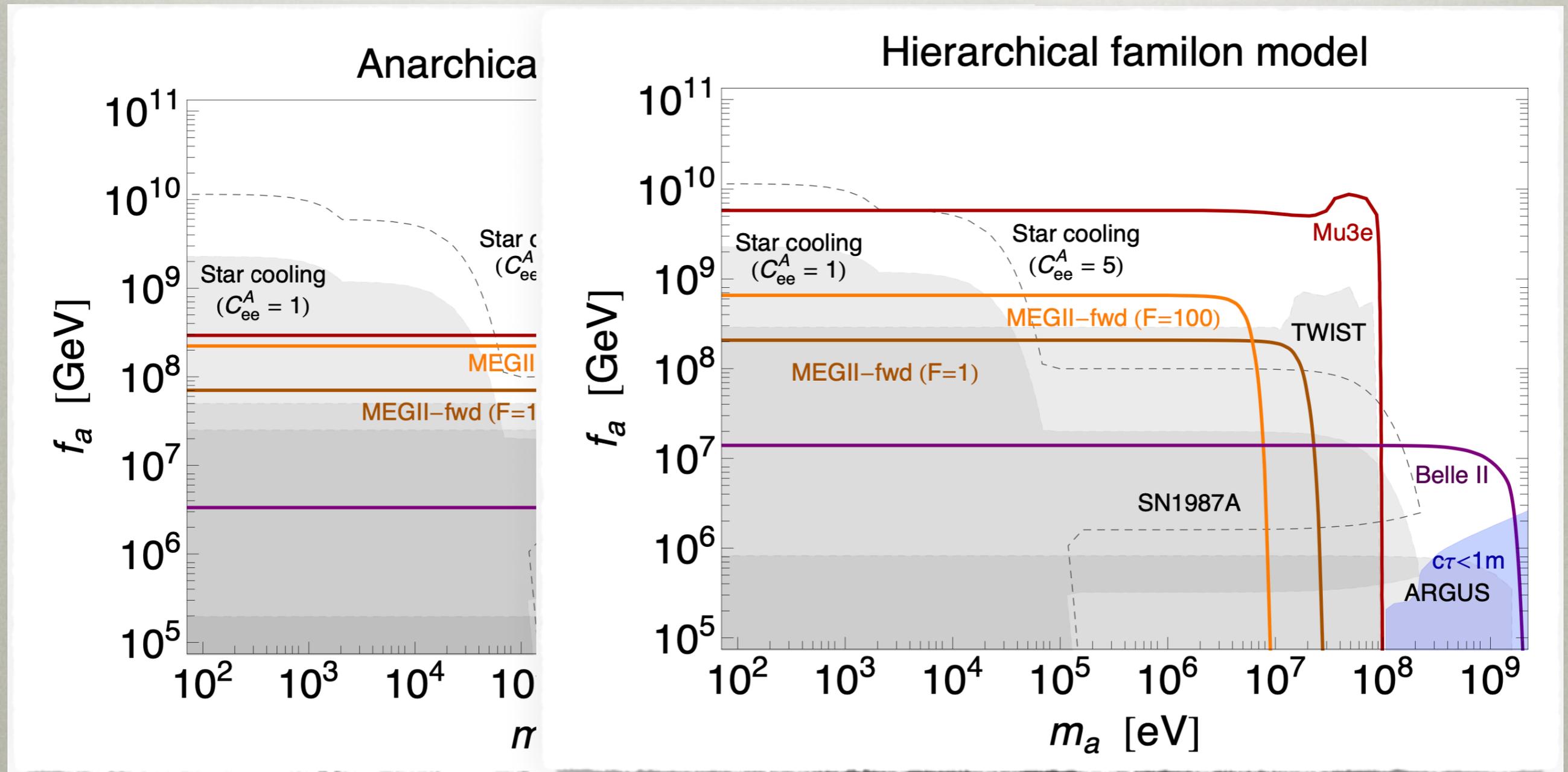
\Rightarrow LH and
RH couplings

LEPTONIC FAMILON

Anarchical familon model



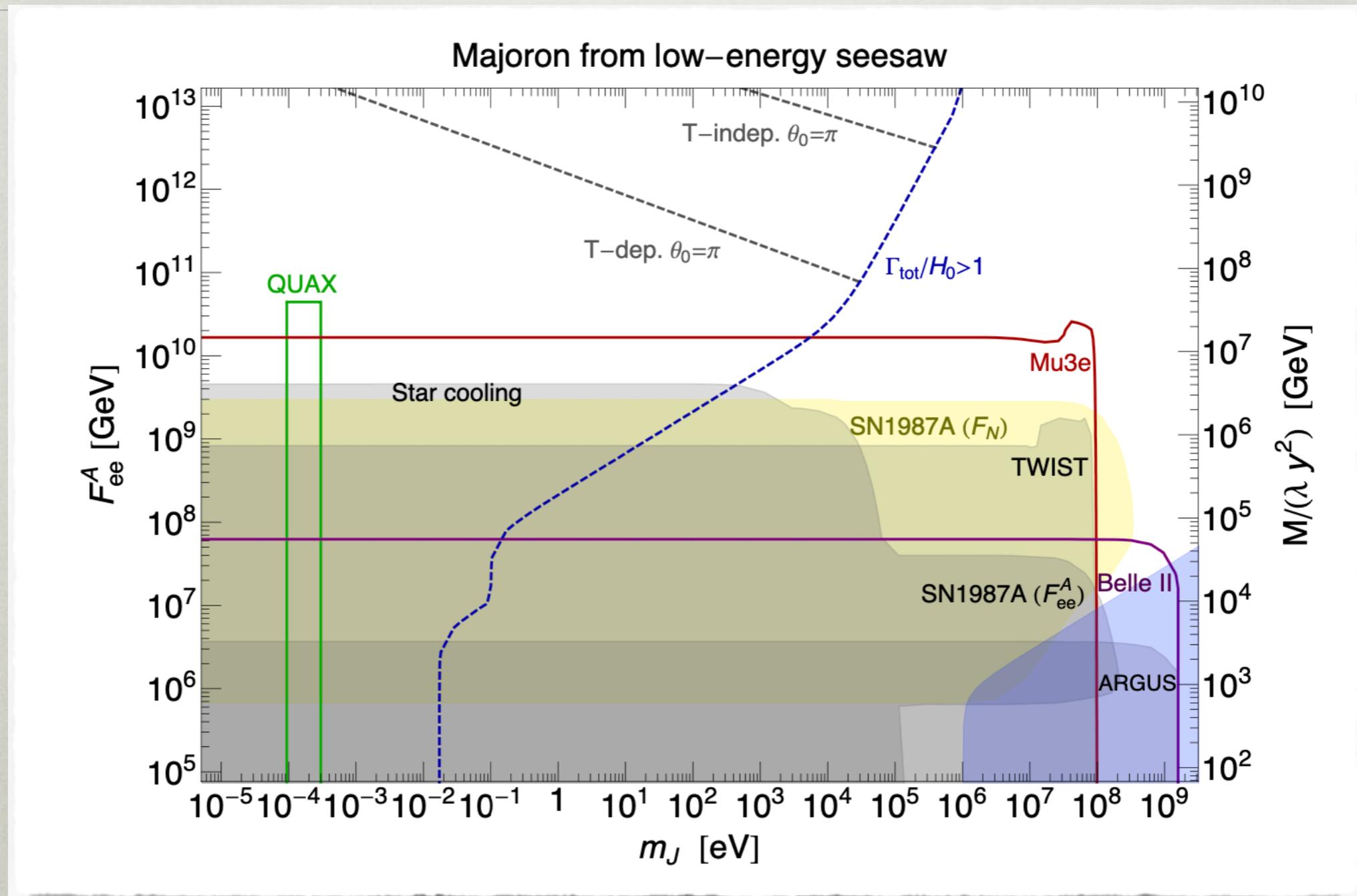
LEPTONIC FAMILON



MAJORON

- majoron- PNGB due to spontaneous breaking of the lepton number
- neutrino masses $m_\nu \propto y_\nu y_\nu^T v^2 / m_N$
- majoron couplings, $C_{ij} \propto y_\nu y_\nu^\dagger$
- if m_ν suppressed by global U(1)
 - \Rightarrow majoron observable
 - "low energy see-saw"

MAJORON



- "low energy see-saw"

CONCLUSIONS

- FCNCs a powerful tool to search for axion like particles
- many transitions were not systematically included in BSM searches
 - $B \rightarrow K^{(*)}a, D \rightarrow \pi a, \Lambda \rightarrow na, \dots$
- advocated for MEGII-fwd phase of MEG-II experiment
 - reach well above previous experiments and above astrophysics bounds

BACKUP SLIDES