LIGHT NEW PHYSICS IN MUON DECAYS

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U. of Cincinnati

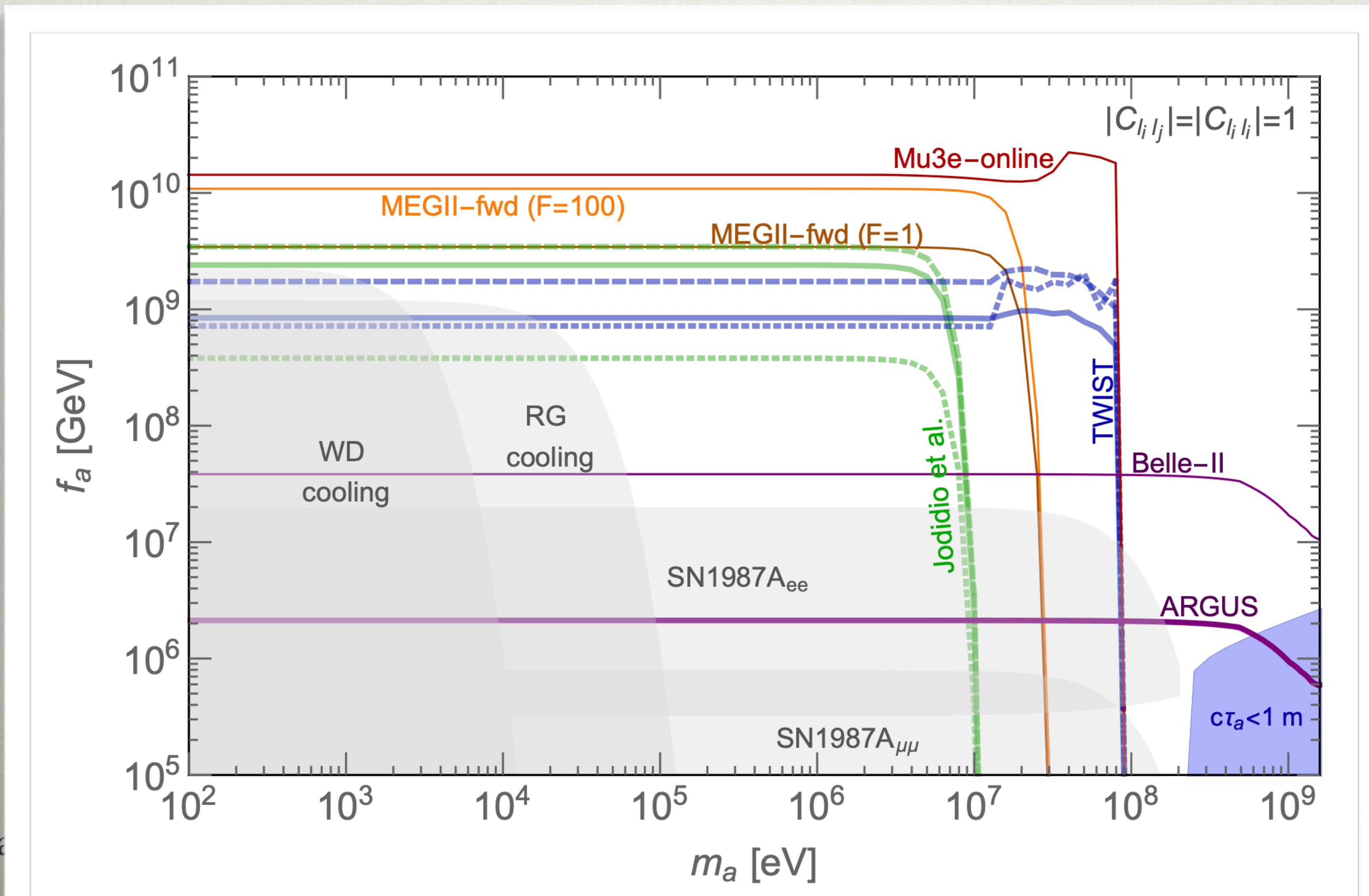
based on Calibbi, Redigolo, Ziegler, JZ, 2006.04795

RF05: CLFV - Muon Decays and Transitions, Jul 2 2020

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

UPSHOT

- $\mu \to e\gamma, \mu \to 3e, \mu \to e$ conv., from dim-6 ops, will reach NP scales of $\sim 10^7 - 10^8$GeV
- $\mu \to ea$ from dim-5 ops., can reach NP scales $\sim 10^{10}$ GeV
  - higher than astrophysics constraints



MOTIVATION FOR AXION-LIKE PARTICLES

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

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$

- our goal: implications of flavor violating couplings
  - do FCNC experiments probe interesting parameter space?
  - possible improvements on search strategies?
  - in many cases FV leptonic couplings highest reach, focus on these

LFV ALPs

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

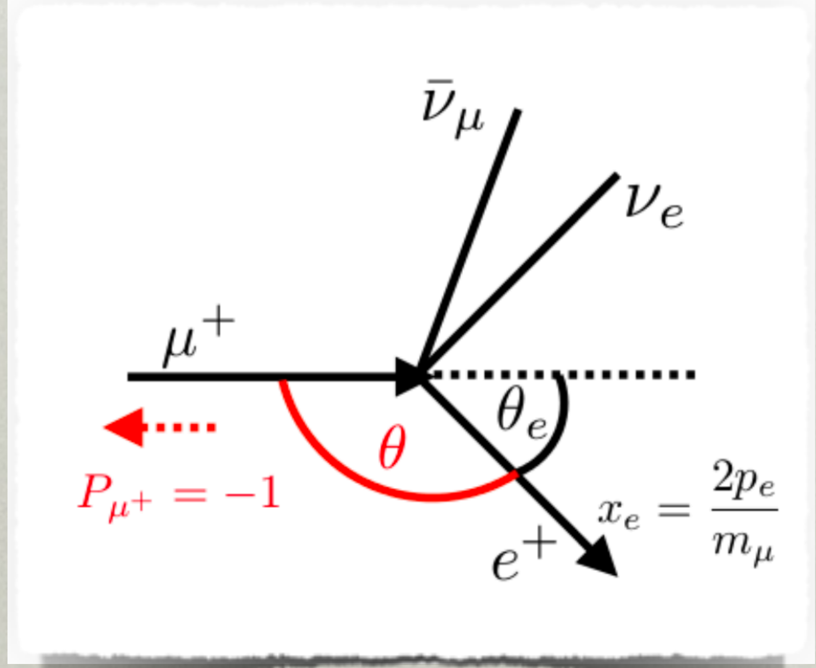
- assume ALP with (predominantly) FV leptonic couplings
  - will allow for varying ALP masses
- main question
  - what does $\mathcal{O}(10^{15} - 10^{17})$ muons at MEG-II, Mu3e, Mu2e buy us?
  - compare with $2 \times 10^7 \mu$ @ Jodidio et al. (1986), and $6 \times 10^8\ \mu$ @ TWIST (2015)

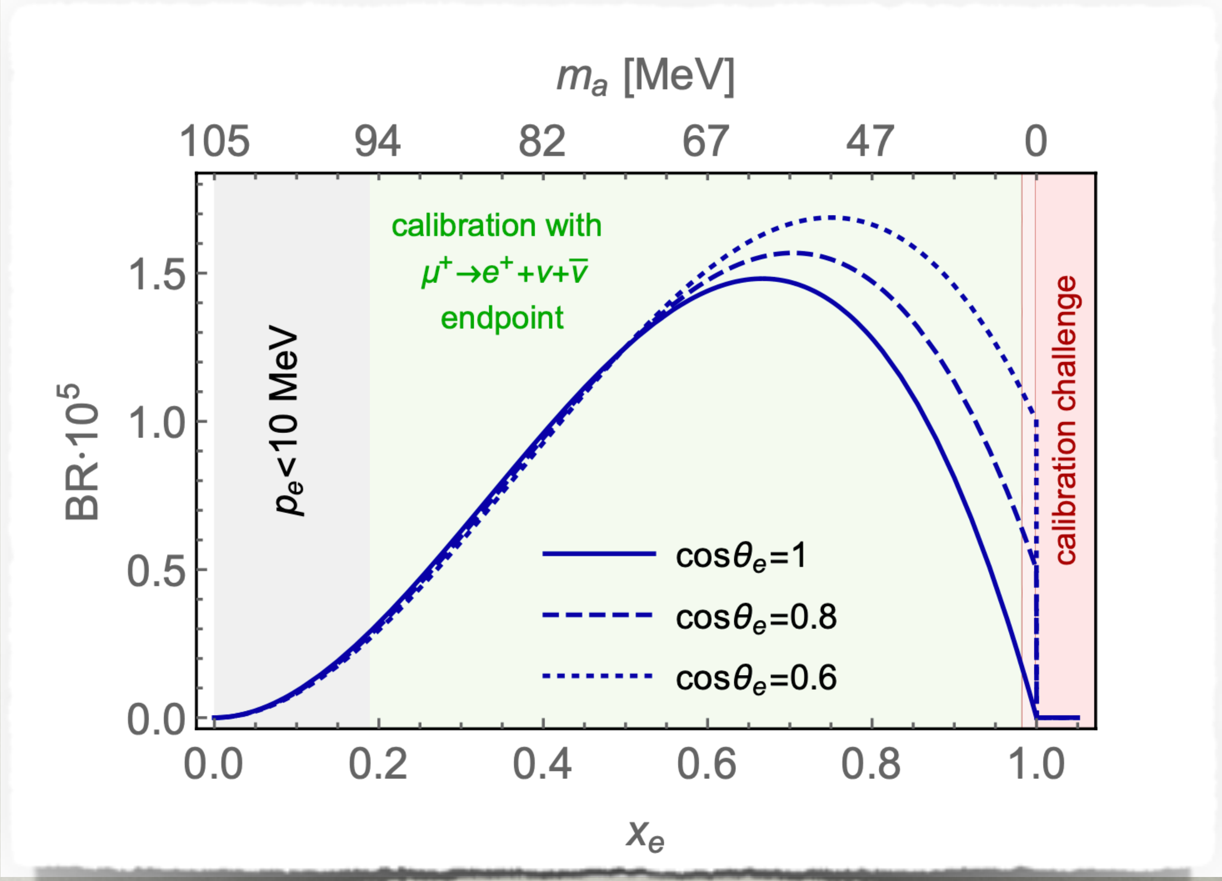
$\mu^+ \to e^+ a$ SEARCHES

- two types of searches for $\mu^+ \to e^+ a$ positron line
- suppress the SM bckg., $\mu \to e\nu\bar{\nu}$

Jodidio et al. 1986

  - use polarized muons $\langle P_\mu \rangle \simeq -1$, in the forward region SM suppressed
  - sensitive only to RH ALP





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

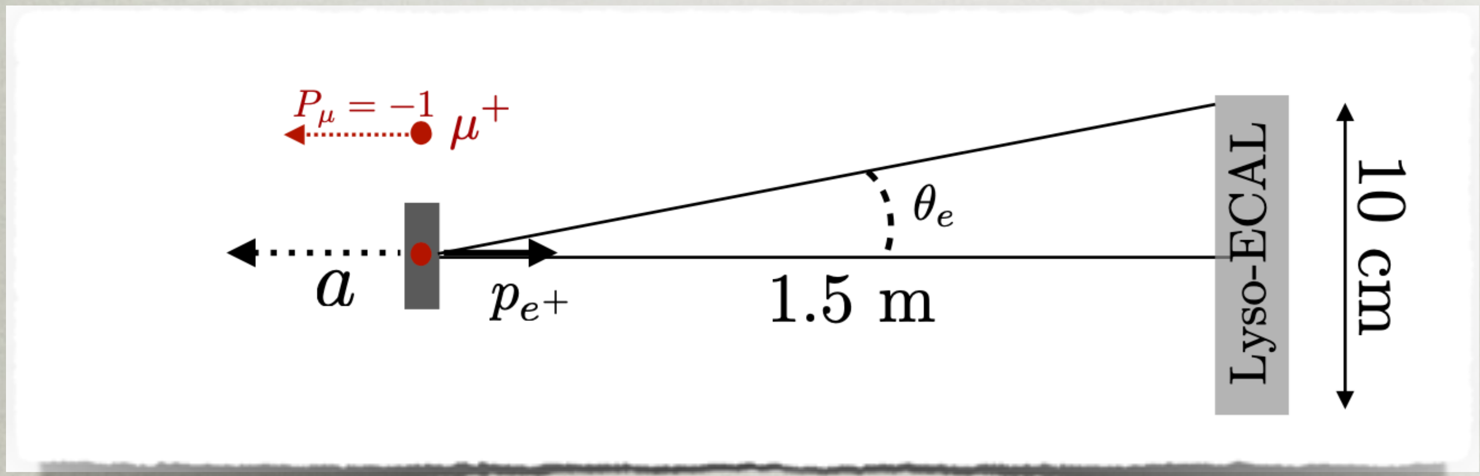
TWIST, 2015

MEGII-fwd

- MEGII is designed to search for $\mu \to e\gamma$
  - could be repurposed for $\mu^+ \to e^+ a$ search ⇒ MEGII-fwd

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

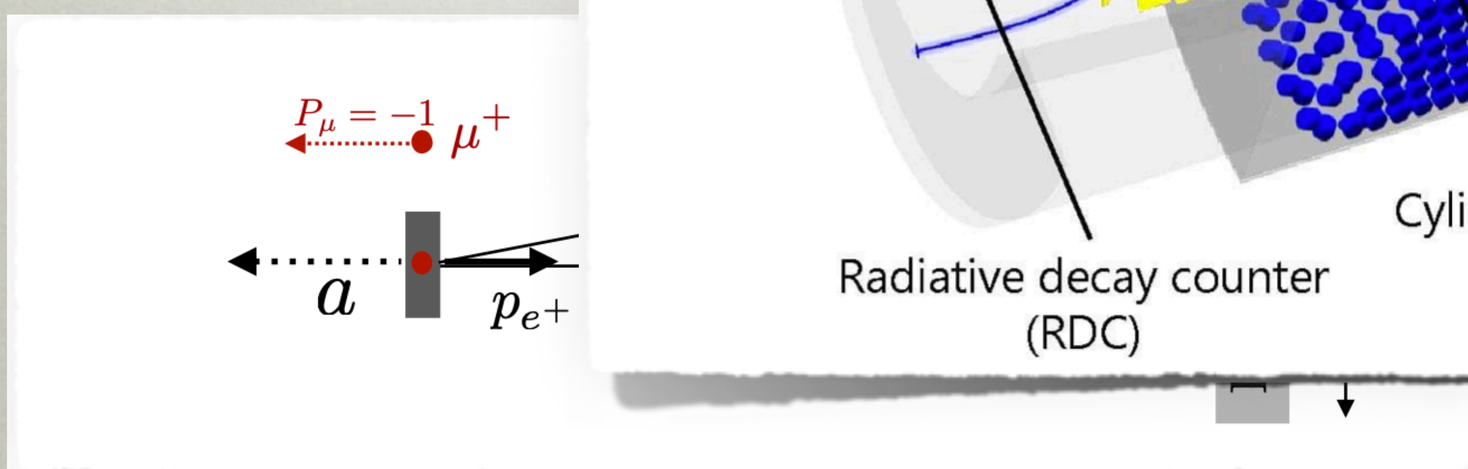
- already has polarized muons
- place a Lyso ECAL downstream

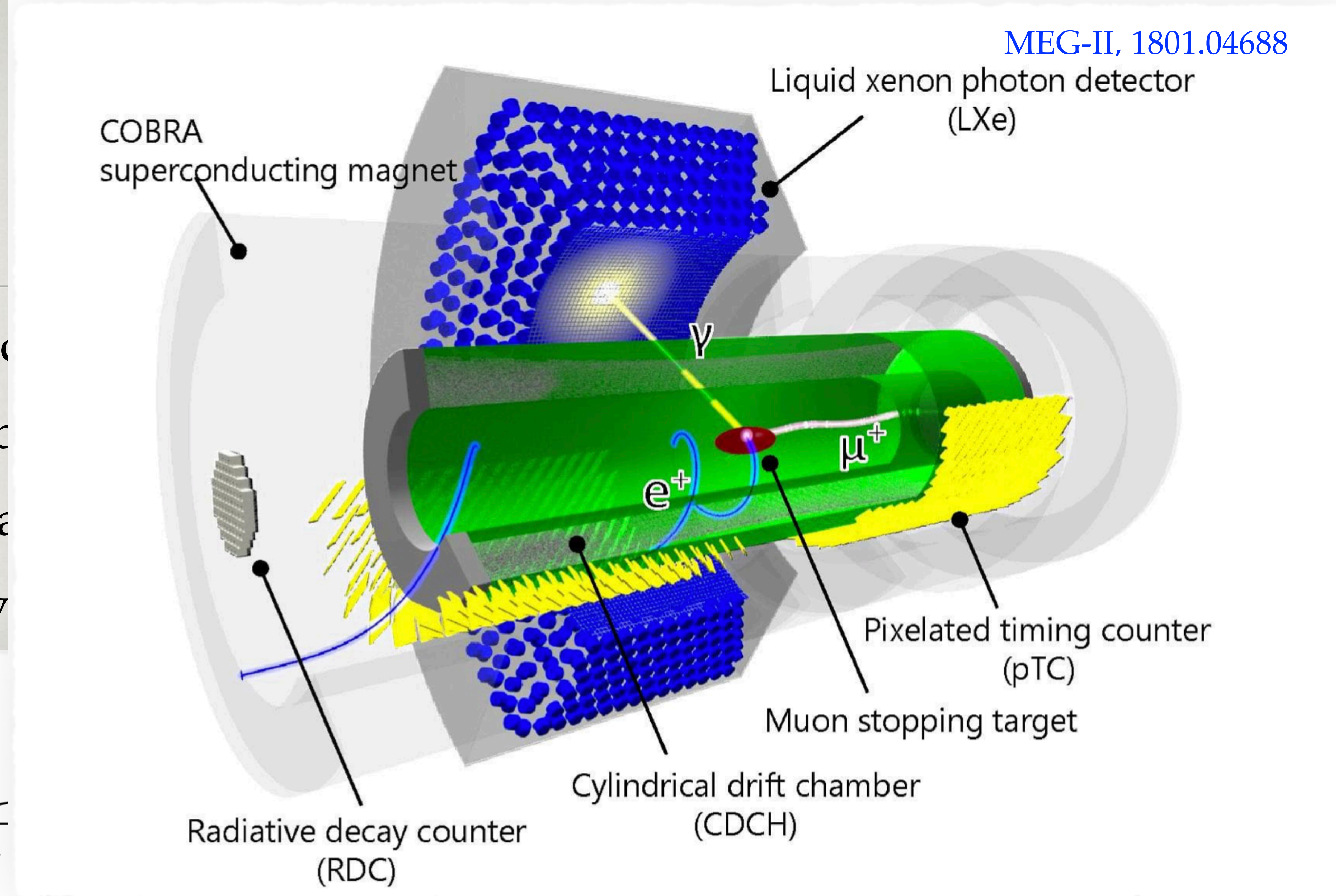


- need to reconfigure the magnetic field
  - most conservative no focusing, F=1
  - possibly more realistic F=100
- interesting reach already with 2weeks of running*

* projections done for $10^8 \mu^+/s$, PSI $\pi E5$ beamline potentially $10^{10} \mu^+/s$ in 2025+

- MEGII is
  - could b
- already ha
- place a Ly





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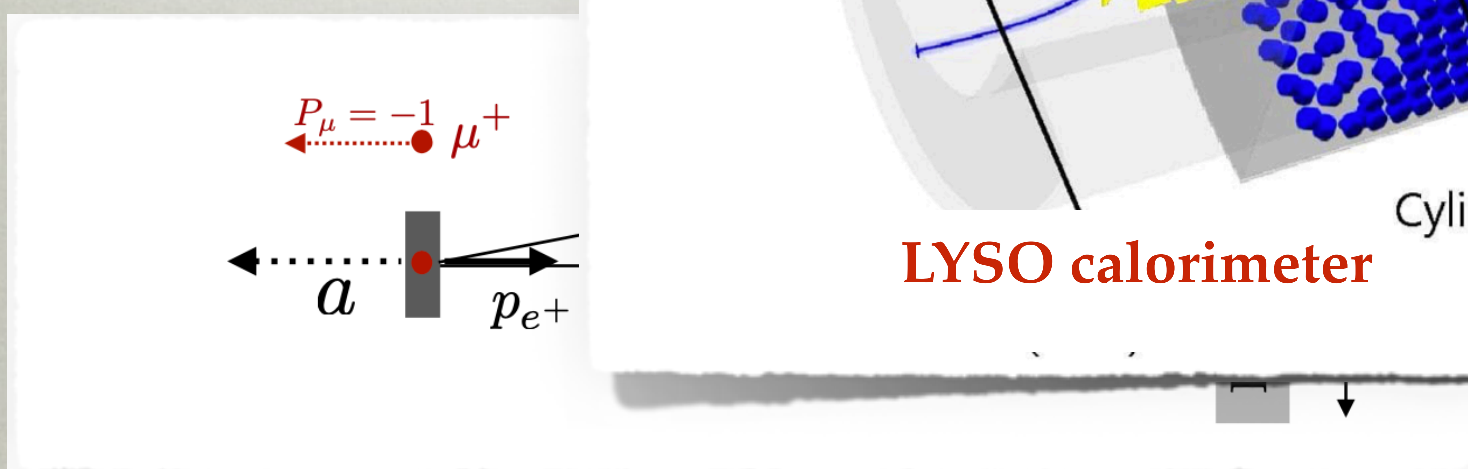

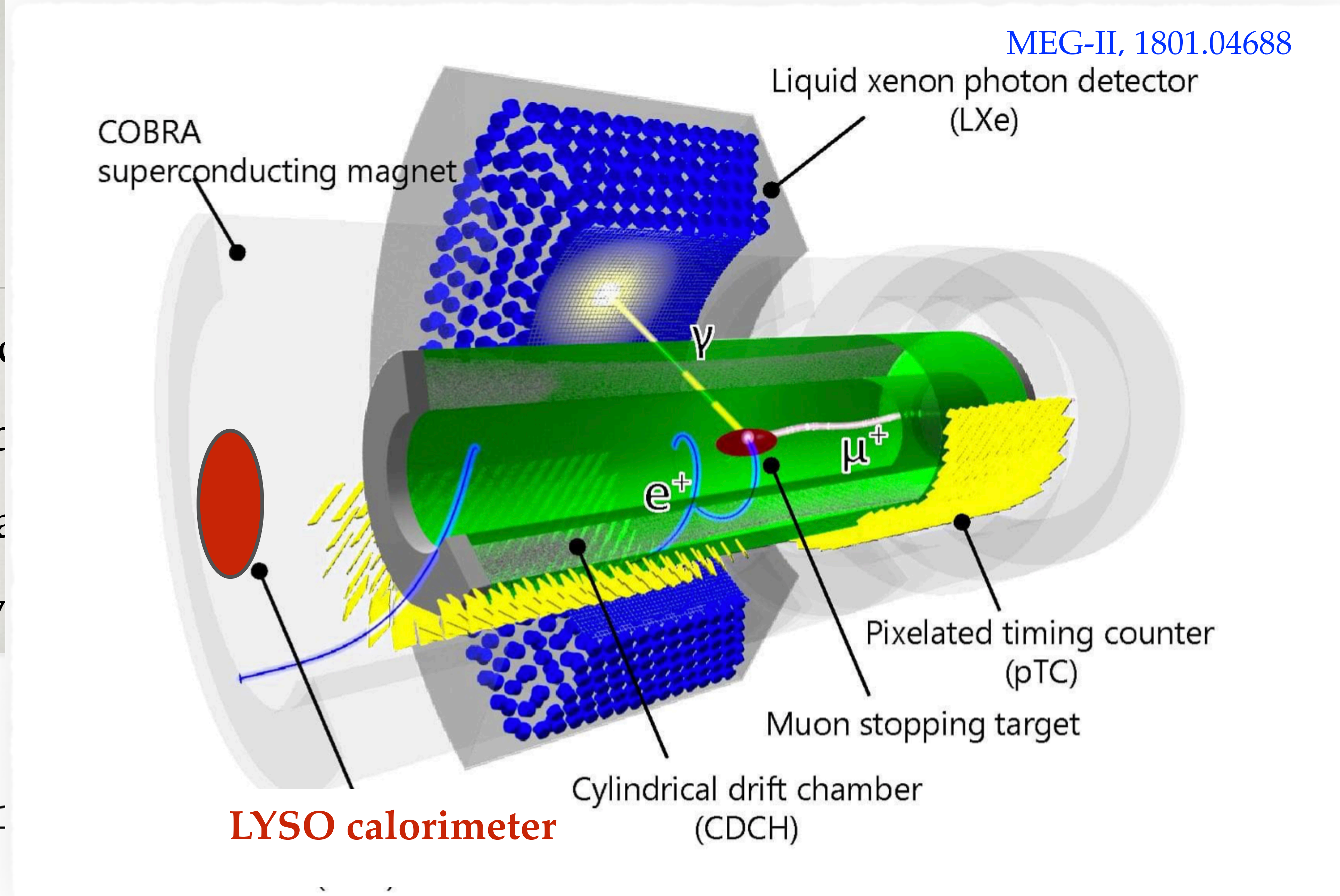

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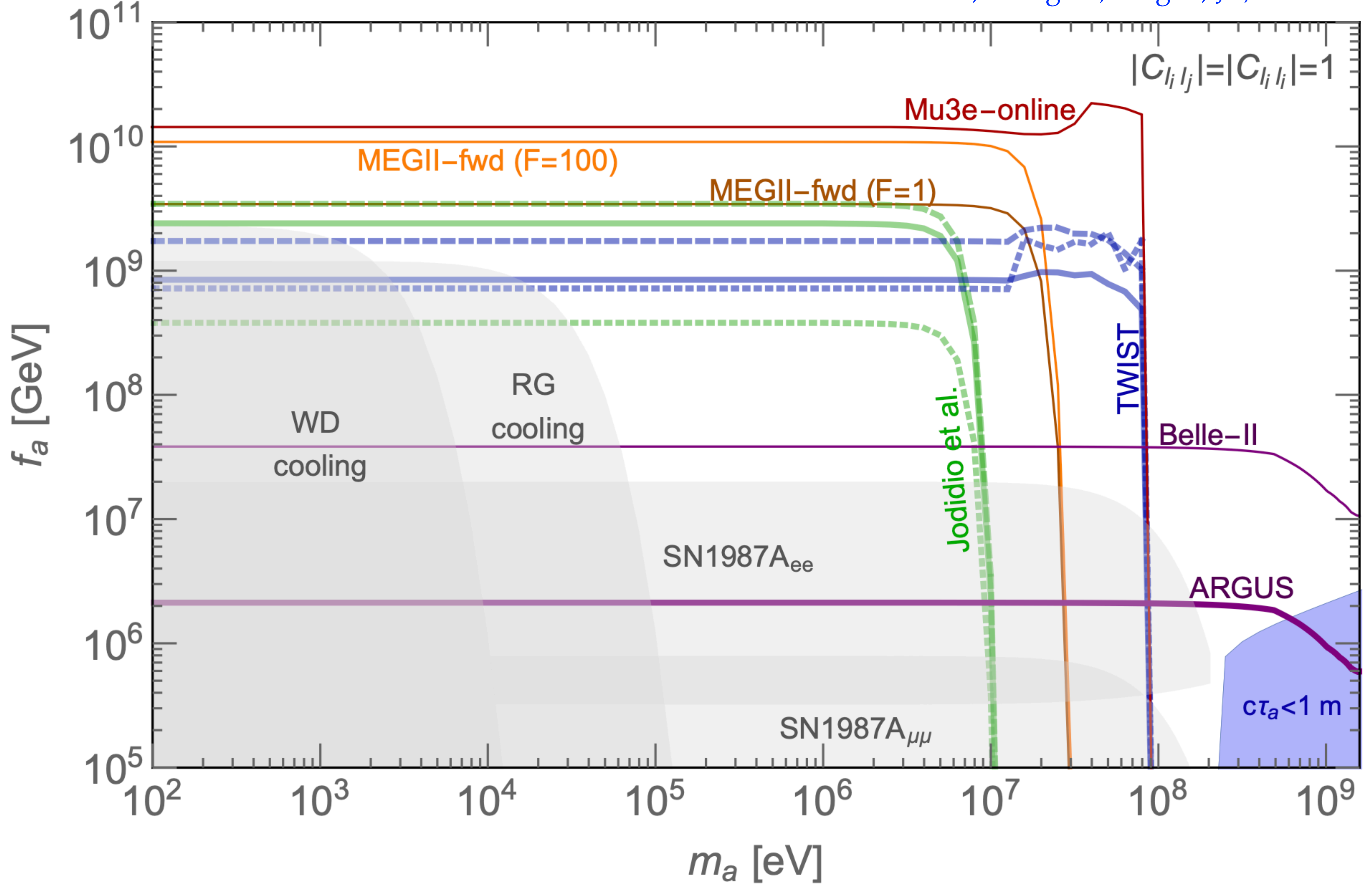
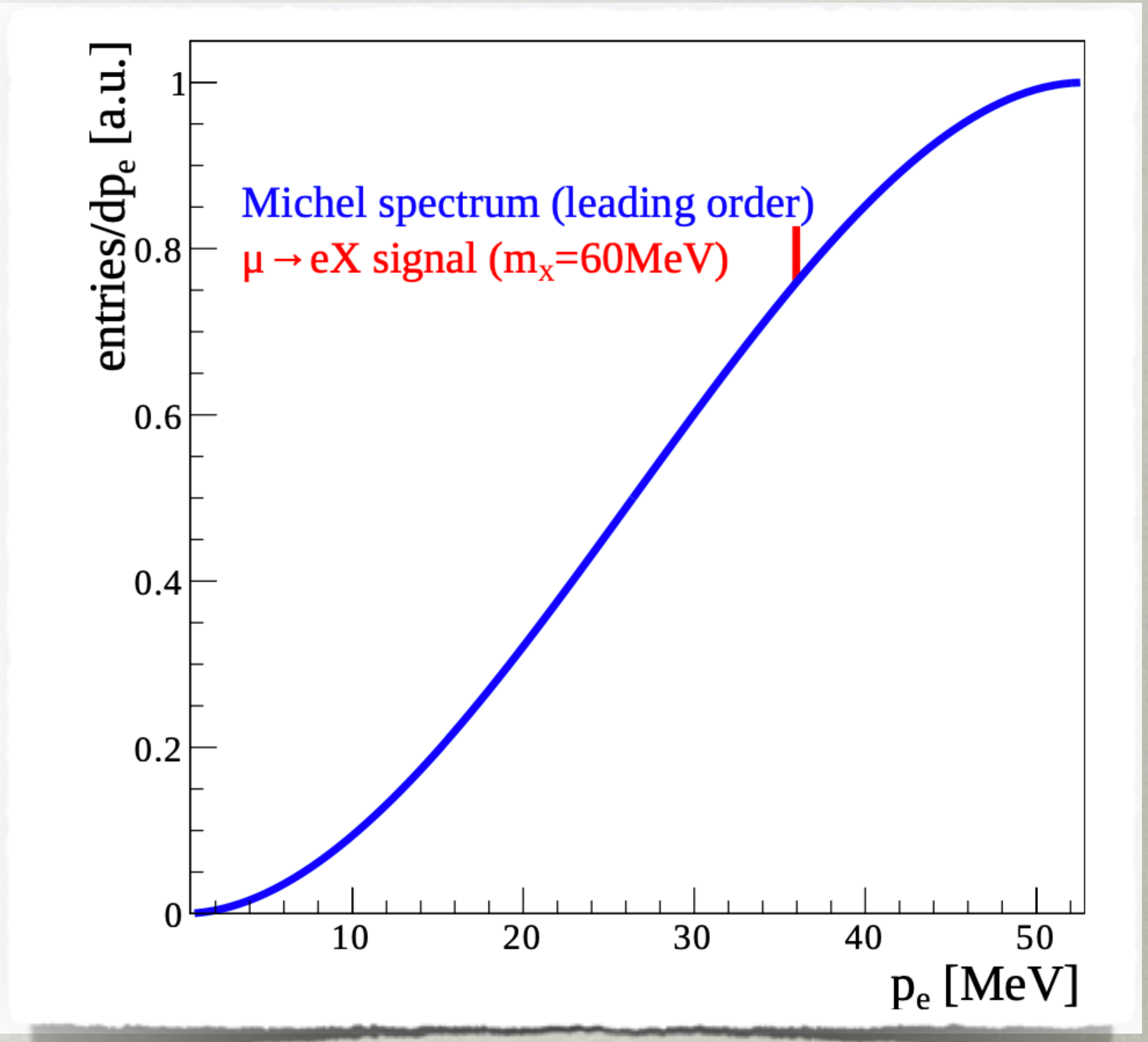


Mu3e-online

A.-K. Perrevoort , PhD thesis
Mu3e, 1812.00741

- 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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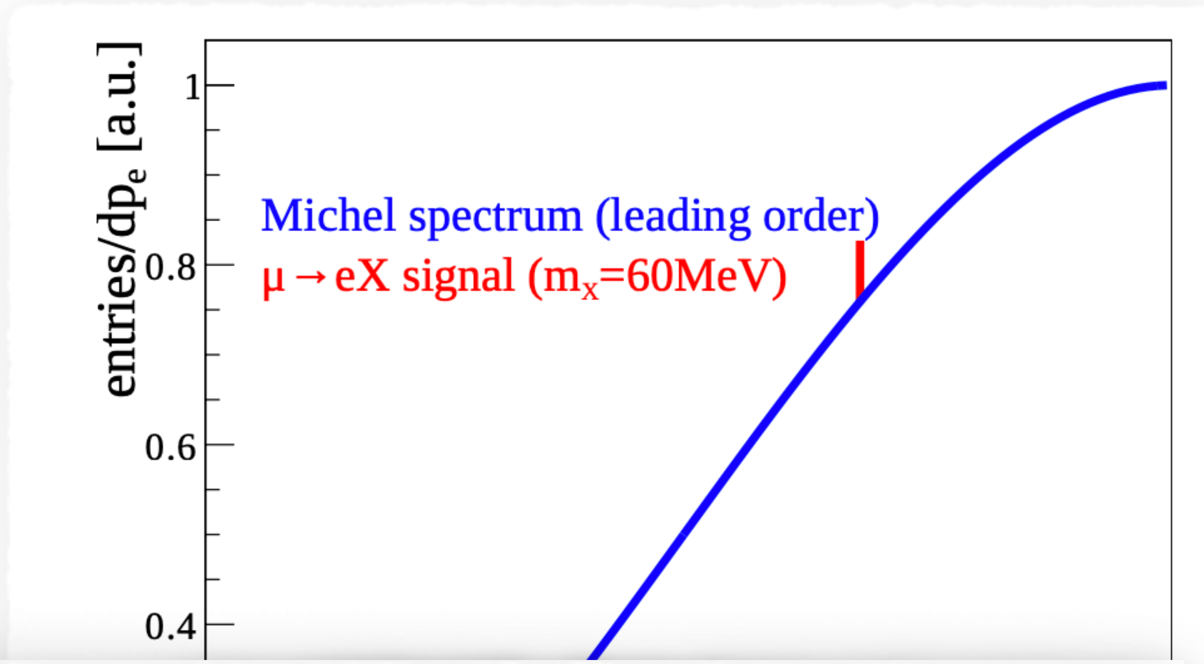
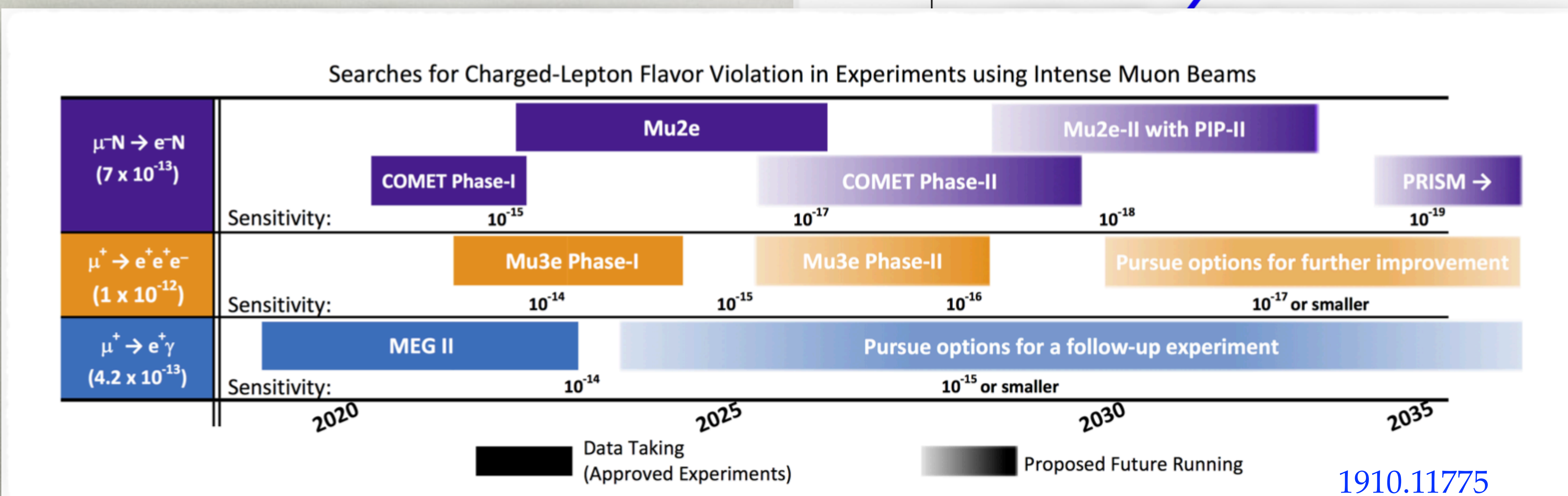




1910.11775

ASTROPHYSICS BOUNDS

Raffelt, Weiss , hep-ph/9410205

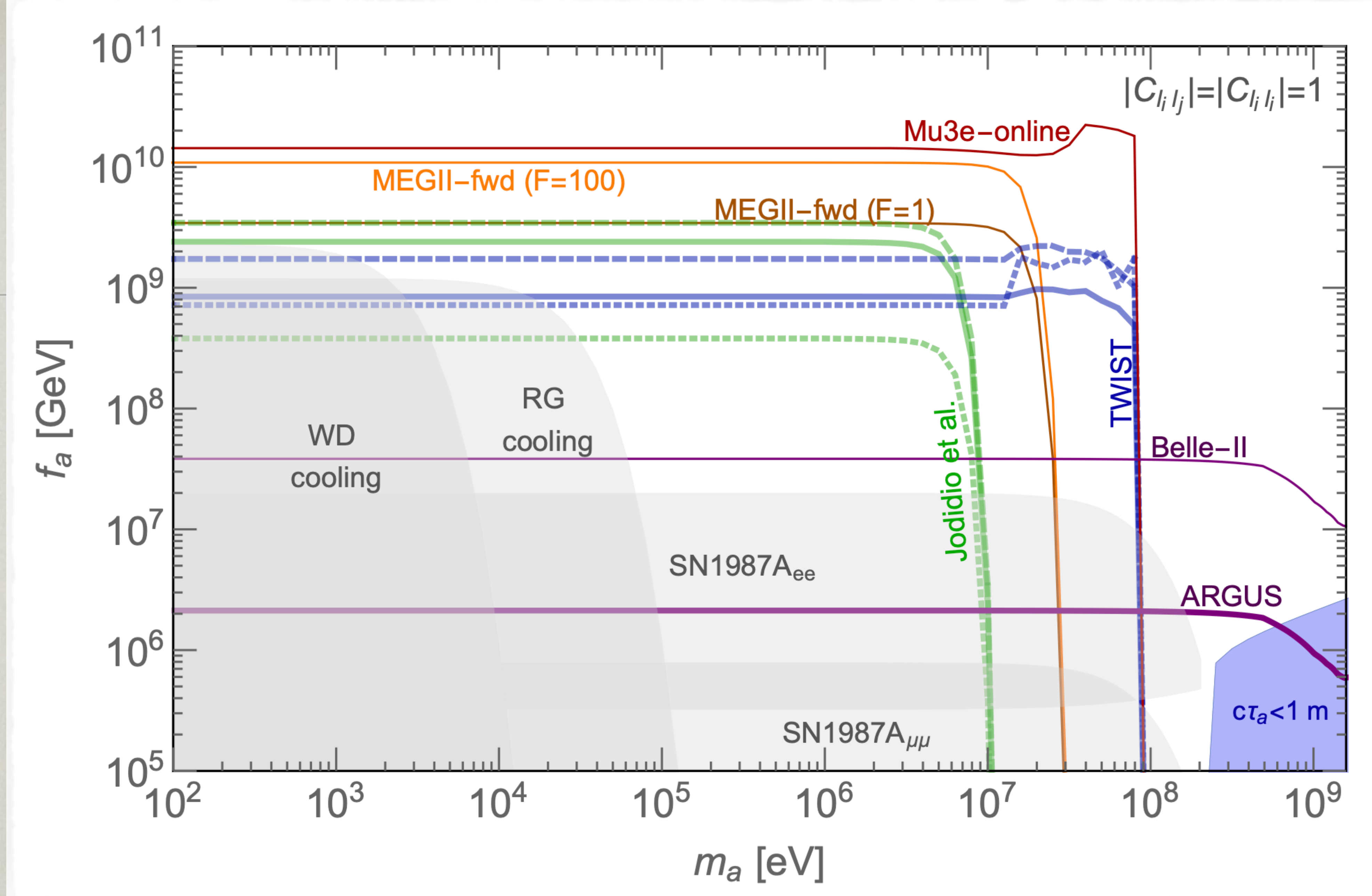
- bounds on massless ALP-electron from red giants and white-dwarf cooling well known
  - due to $e^- + N \to e^- + N + a$
  - we rescale to nonzero ALP masses
- above $m_a \gtrsim 0.1\ \text{MeV}$ SN bounds become important (new!)
- also bounds on couplings to muons, but less severe

Bollig et al., 2005.07141

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

masless ALP

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



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LFV ALP dark matter

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

$$\mathcal{L}_{\text{eff}} = E_{\text{UV}} \frac{\alpha_{\text{em}}}{4\pi} \frac{a}{f_a} F\tilde{F}$$

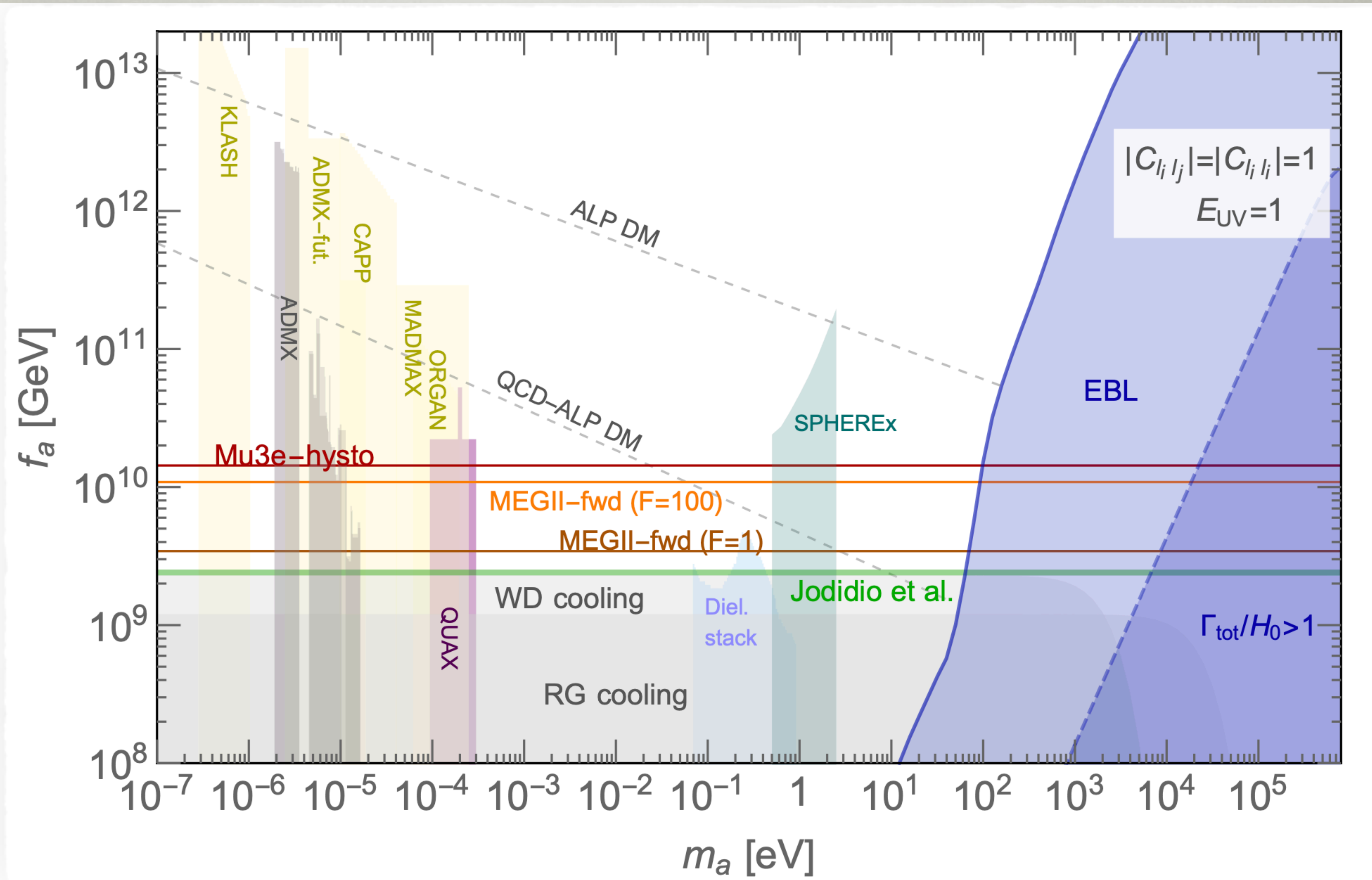
$$\frac{H_0}{\Gamma_{\text{tot}}} = H_0 \tau_a > 1, \quad \text{where} \quad H_0 \tau_a \simeq 5.4 \left(\frac{1}{E_{\text{eff}}^2}\right)^2 \left(\frac{10\ \text{keV}}{m_a}\right)^3 \left(\frac{f_a}{10^{10}\ \text{GeV}}\right)^2 .$$

- more strignent bounds from extragalactic background light
- if ALP DM observed in a LFV process ⇒ for generic coupling to photons: $m_a \lesssim 0.1\ \text{keV}$
  - LFV experiments most sensitive for some m_a
- $a \to \gamma\gamma$ couplings may be suppressed (e.g. majoron)
  - if Xenon1T anomaly persists, MEGII-fwd and Mu3e-online can probe the relevant region

• 0

$$\frac{H_0}{\Gamma_{tot}} = H_0\tau$$

$F\tilde{F}$



• n

• i

p

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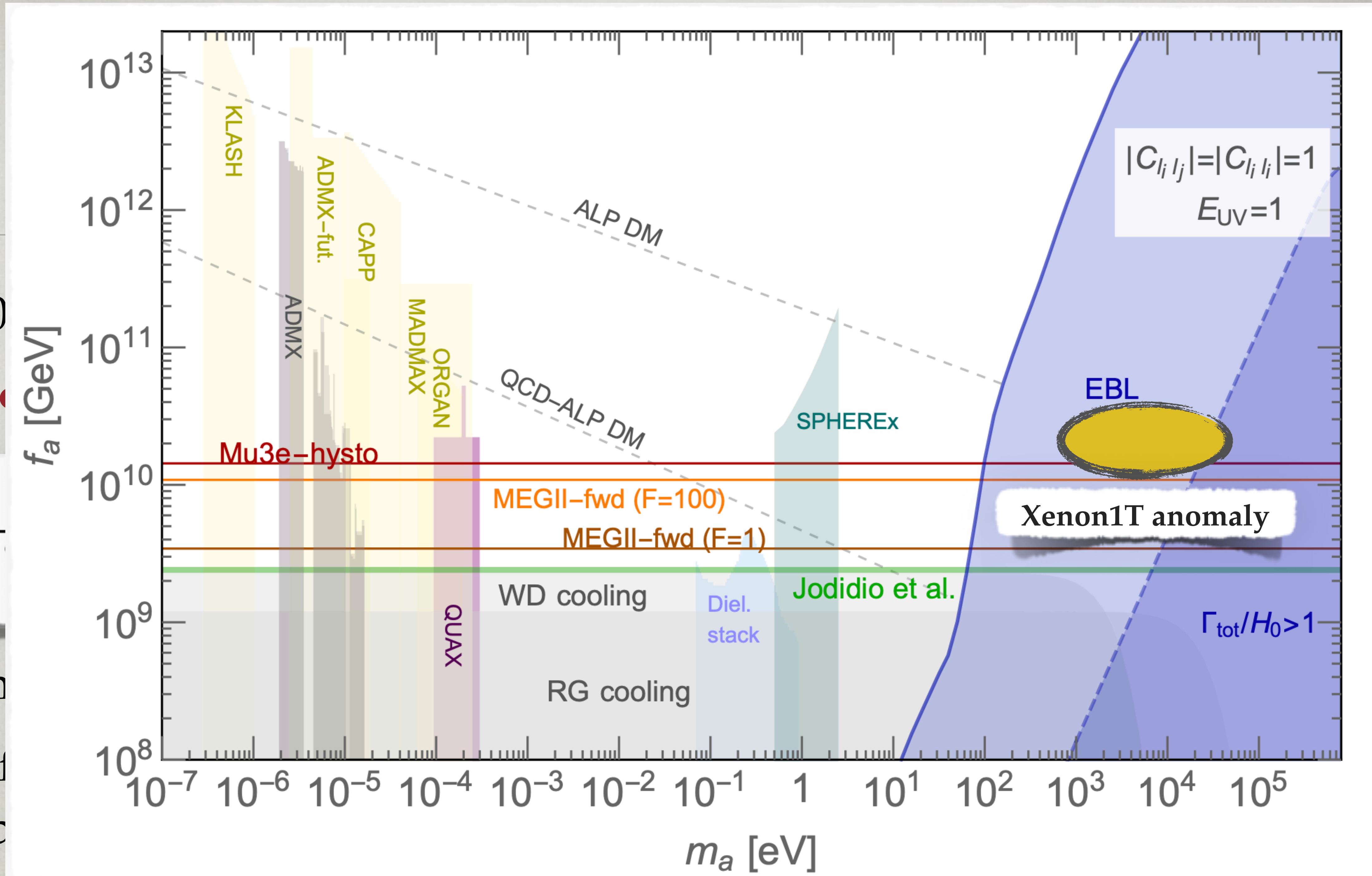

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SAMPLE LEPTON FLAVOR VIOLATING ALP MODELS

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

- possible to have sizeable lepton FV but small or no quark FV
  - LFV QCD axion
    - flavor structure external (by hand)
  - LFV axiflavon
    - PQ symmetry part of $SU(2)_F \times U(1)_F$, for quark FV CKM suppressed, for leptons PMNS mixings ⇒ large
  - leptonic familon
    - U(1) FN separately for quarks and leptons, f_a for quarks larger
  - majoron
    - PNGB due to spontaneous breaking of the lepton number
- relation between flavor conserving and FV probes

LEPTON FLAVOR VIOLATING QCD AXION

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 :

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

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

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

  - very puzzling given large CPV phase in the CKM

QCD AXION

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

- 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

$$F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{c^{V,A}_{f_i f_j}}$$

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

  - obtains mass from QCD anomaly

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

  - viable dark matter candidate (from misalignment mechanism)

$$10^{-8}{\rm eV} \lesssim m_a \lesssim 10^{-4}{\rm eV}$$

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whether FV or not depends on flavor structure of PQ symmetry

  - obtains mass from QCD anomaly

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LFV QCD axion

- DFSZ-like model: 2HDM+S: $X_S = 1, X_{H_2} = 2 + X_{H_1}$
- flavor universal $U(1)_{\rm PQ}$ 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

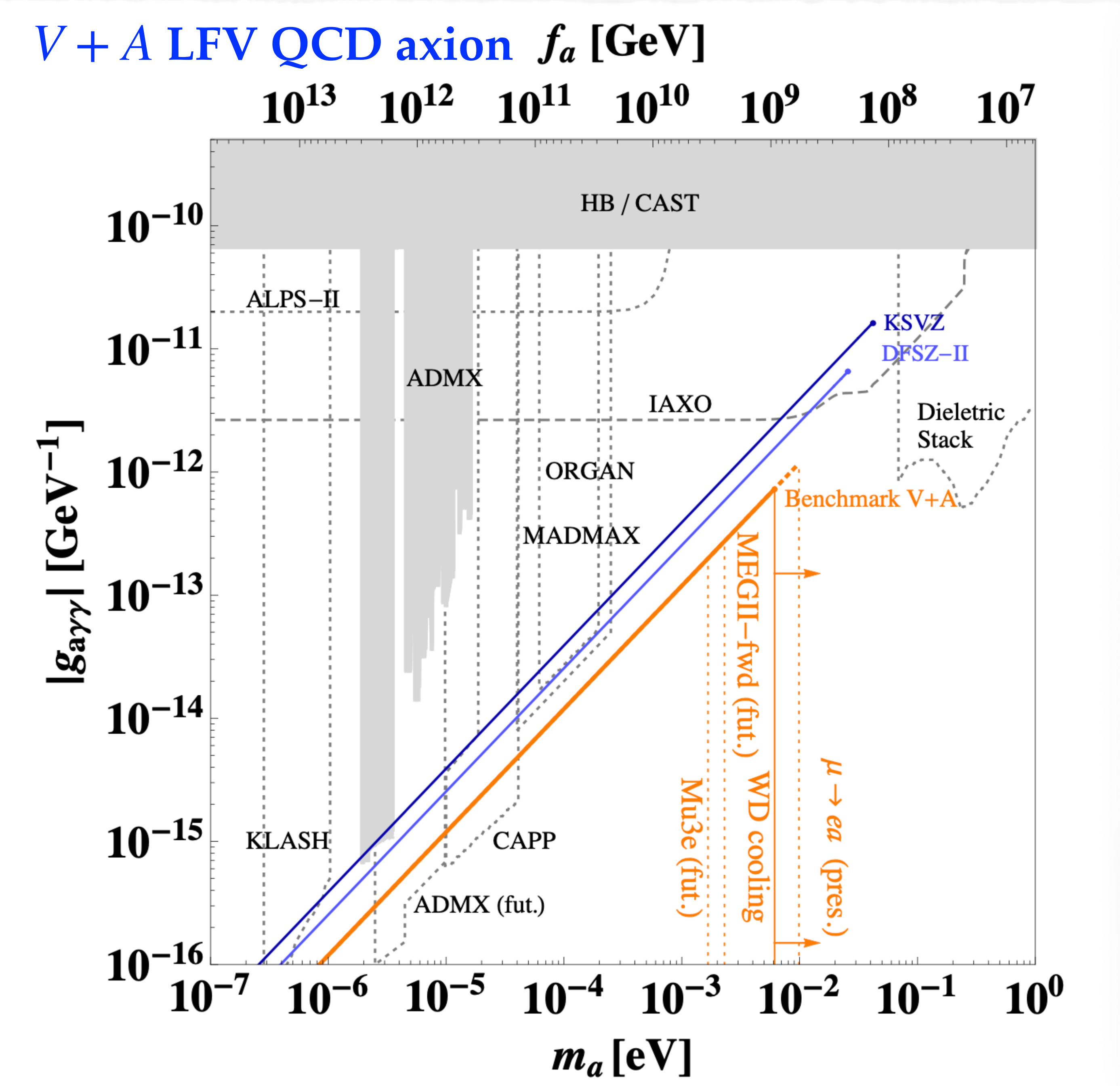
$$y_u = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}, \quad y_d = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

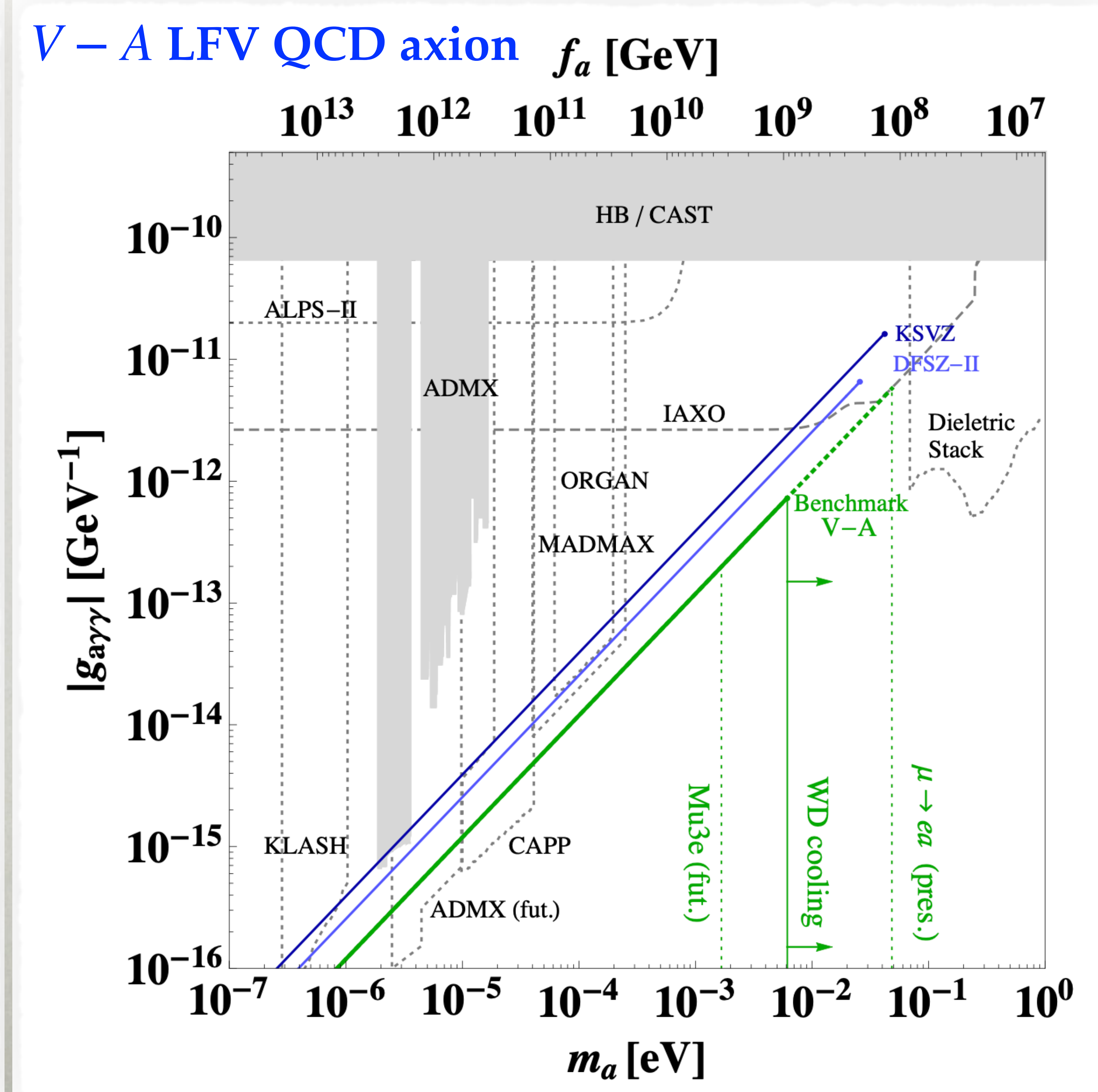
⇒ axion-quark couplings flavor diagonal

- hierarchy of entries external input

LFV QCD axion

- reach of MEGII-fwd depends on RH couplings



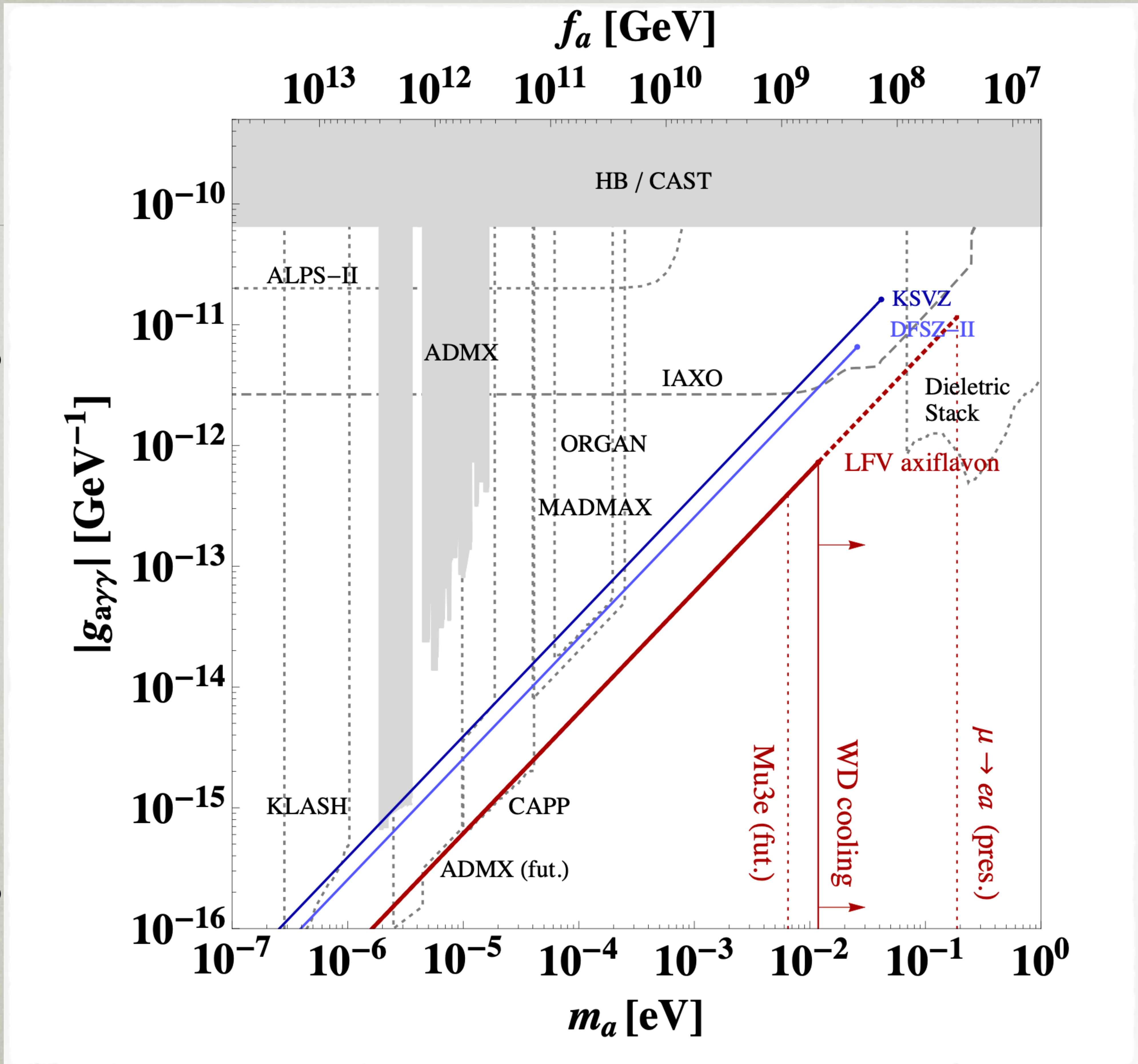


LEPTON FLAVOR VIOLATING AXIFLAVON

LFV axiflavon

Calibbi, Redigolo, Ziegler, JZ, 2006.04795
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 axiflavon, $K \to \pi a$ suppr.
  - the observation mode is $\mu \to ea$



Z, 2006.04795
r, 1805.07341

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- r.

LEPTONIC FAMILON

LEPTONIC FAMILON

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

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

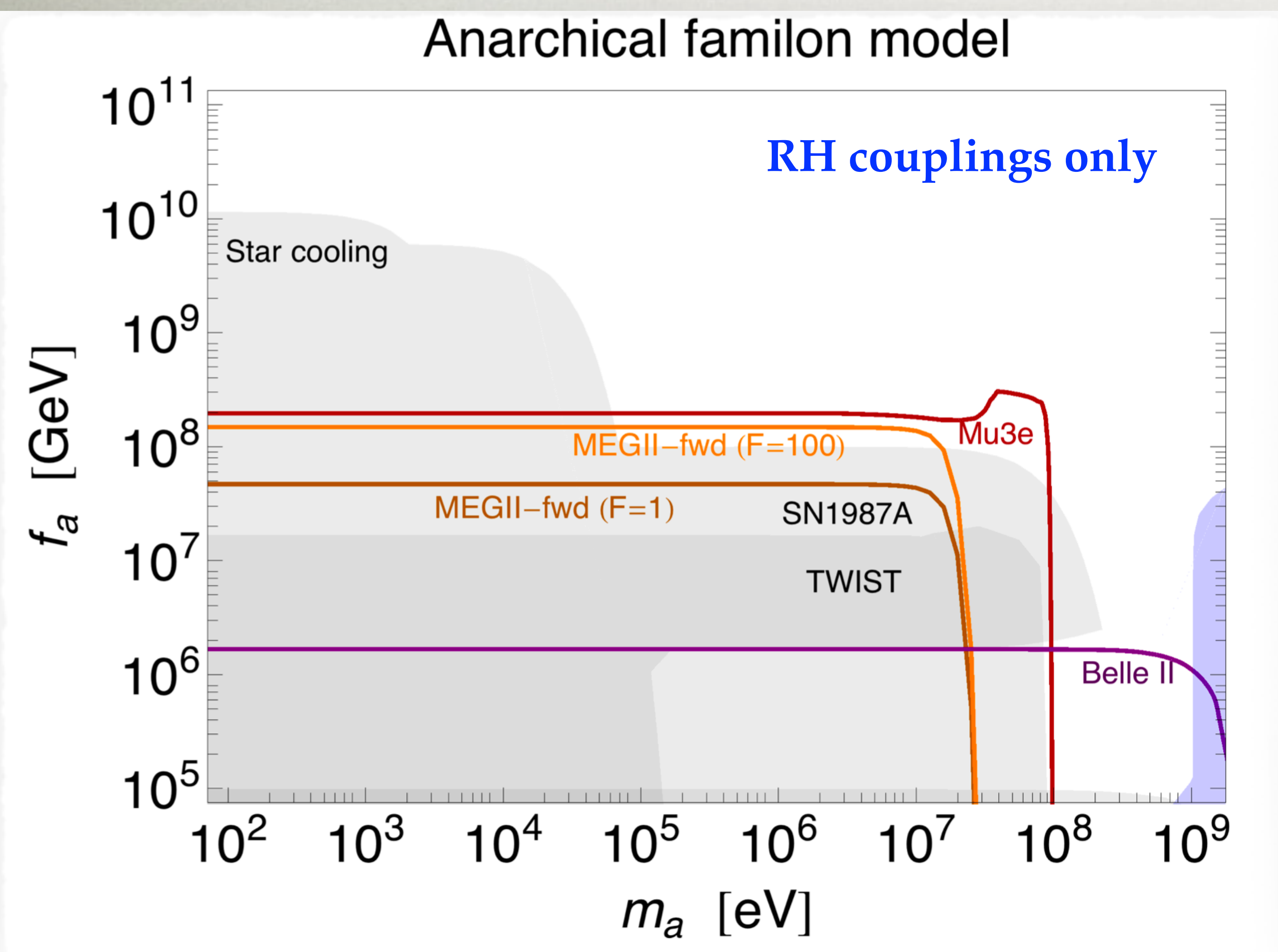
⇒ RH ALP

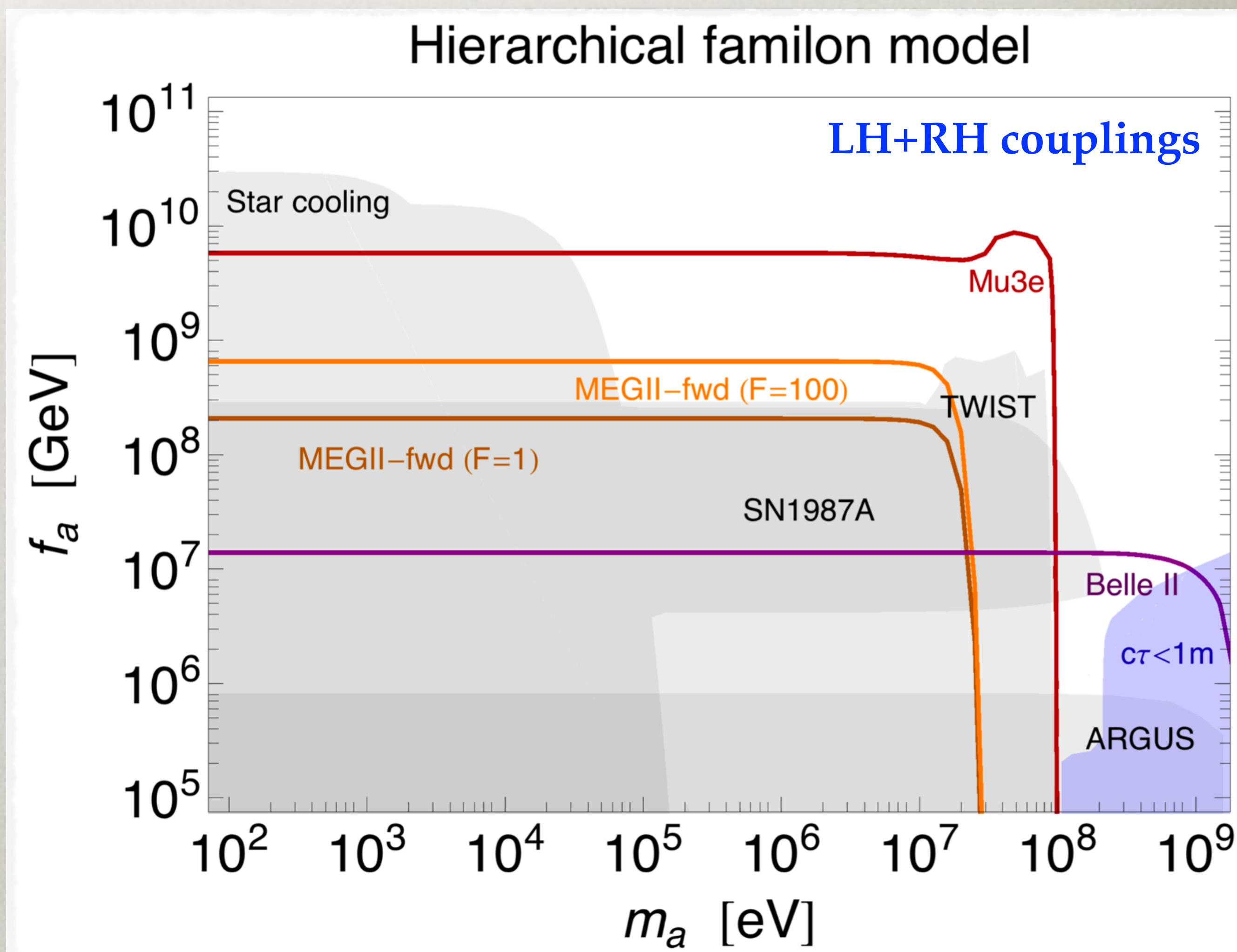
$$([L]_1, [L]_2, [L]_3) = (L+2, L+1, L), \qquad [\texttt{Hierarchy}].$$

⇒ LH and RH couplings

LEPTONIC FAMILON

- reach of MEGII-fwd depends on RH couplings

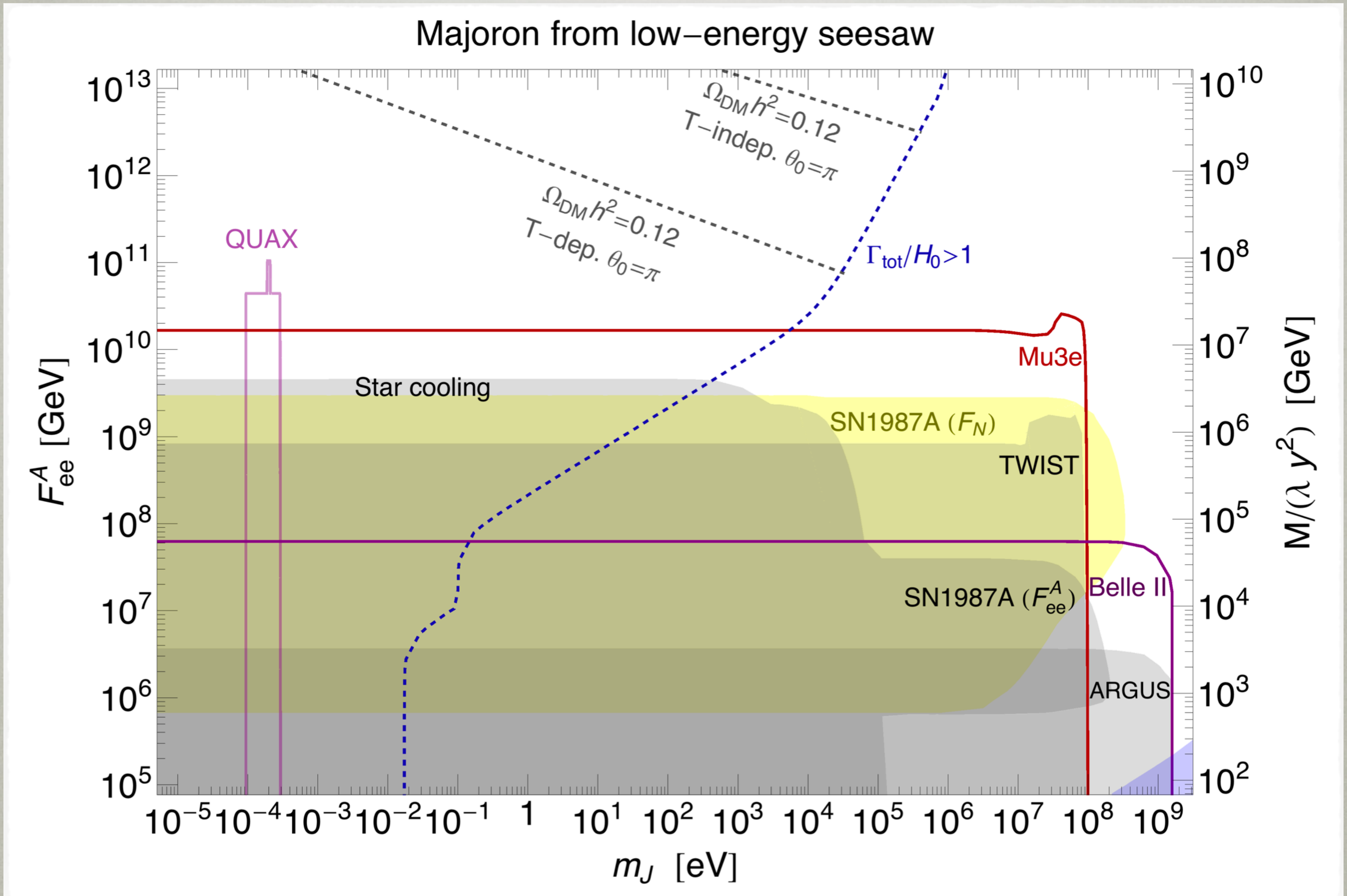




MAJORON

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"



- low energy see-saw

CONCLUSIONS

- CLFV transitions a powerful tool to search for axion like particles
- advocated for MEGII-fwd phase of MEG-II experiment
  - reach well above previous experiments and above astrophysical bounds
  - complementary in timing to Mu3e-online

BACKUP SLIDES

MOTIVATION

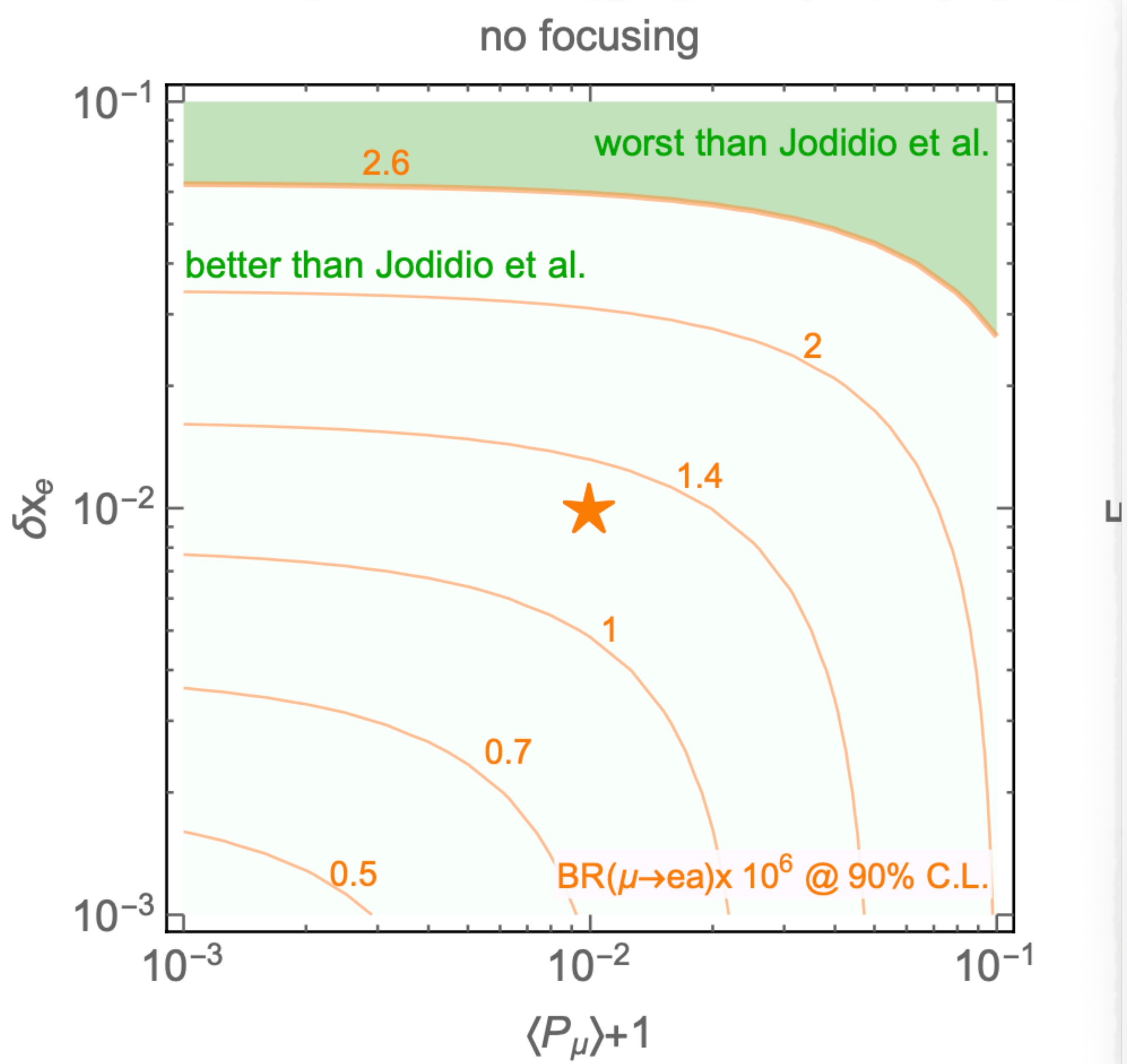
- FV couplings of ALPs arise quite generically
- in mass basis ($V_L^{f\dagger} y_f V_R^f = y_f^{\text{diag}}$) the couplings are

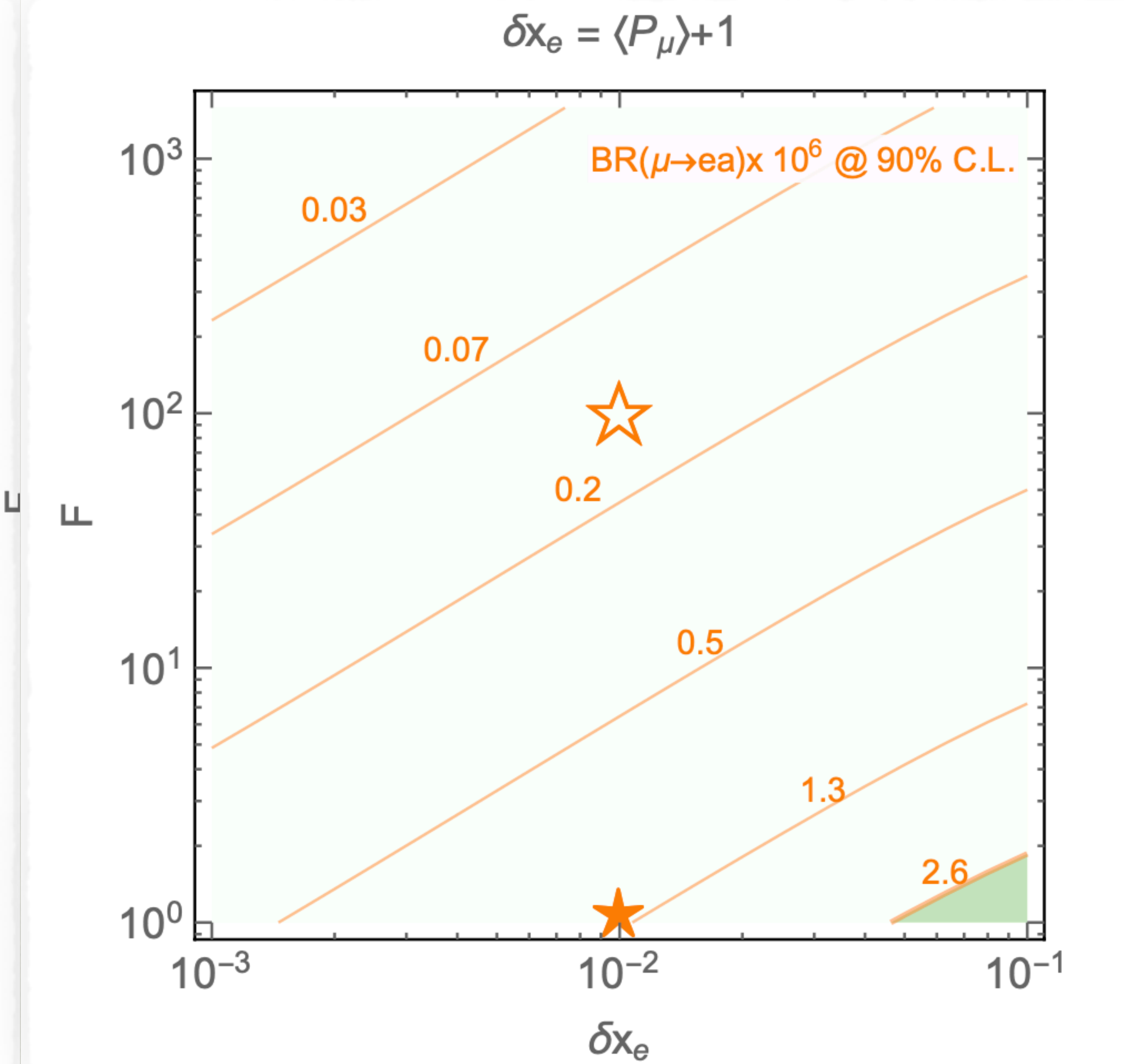
$$C^{V,A}_{f_i f_j} = \frac{1}{2N}\left(V_R^{f\,\dagger} X_{f_R} V_R^f \pm V_L^{f\,\dagger} X_{f_L} V_L^f\right)_{ij}$$

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f_a}\,\bar{f}_i \gamma^\mu \left(c^V_{f_i f_j} + c^A_{f_i f_j}\gamma_5\right) f_j\,,$$

- 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

$$F^{V,A}_{f_i f_j} \equiv \frac{2f_a}{c^{V,A}_{f_i f_j}} \qquad F_{\ell_i \ell_j} = \frac{2f_a}{\sqrt{|C^V_{\ell_i\ell_j}|^2 + |C^A_{\ell_i\ell_j}|^2}}$$


no focusing
worst than Jodidio et al.
better than Jodidio et al.
2.6
2
1.4
1
0.7
0.5
BR(μ→ea)x 10^6 @ 90% C.L.
δx_e
⟨P_μ⟩+1
10^-1
10^-2
10^-3


δx_e = ⟨P_μ⟩+1
BR(μ→ea)x 10^6 @ 90% C.L.
0.03
0.07
0.2
0.5
1.3
2.6
F
δx_e
10^3
10^2
10^1
10^0
10^-3
10^-2
10^-1

EXPLICIT MODEL - AXIFLAVON

Froggatt, Nielsen, NPB 147, 277 (1979),...

- Large hierarchies in quark + lepton masses and in CKM matrix
  - can be addressed via horizontal $U(1)_H$ symmetry
  - SM LH and RH fermions have different $U(1)_H$ charges
  - hierarhical Higgs Yukawas after $U(1)_H$ broken via vev of scalar field, the flavon Φ

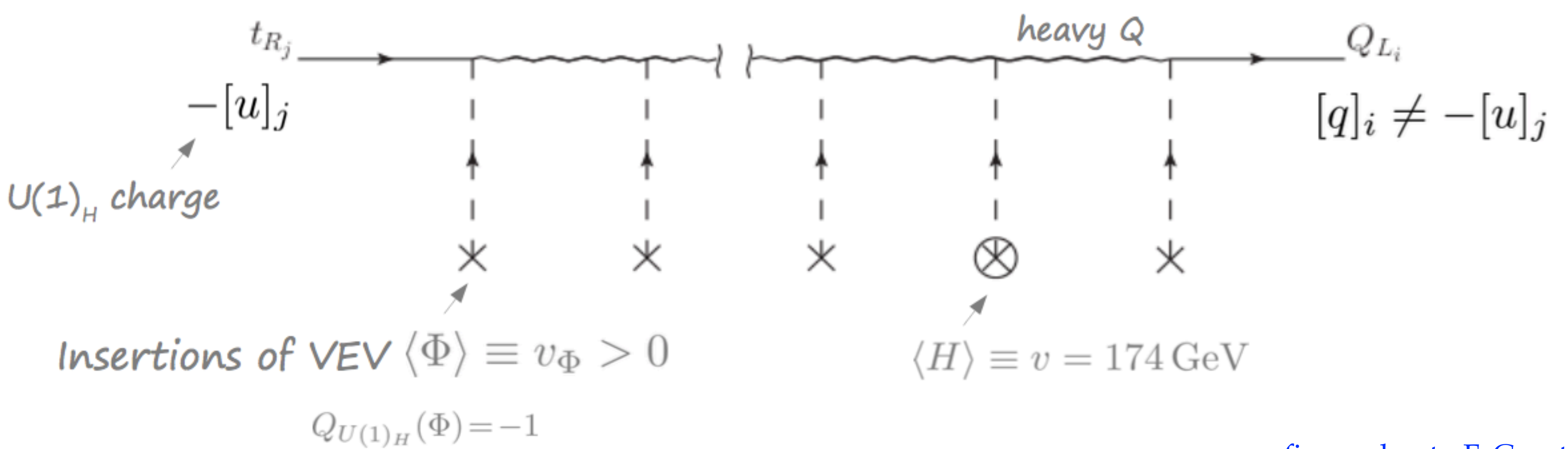


figure due to F. Goertz

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
- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

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

Wilczek, PRL 49, 1549 (1982)
Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Ema, Hamaguchi, Moroi, Nakayama, 1612.05492

ALPs in tau decays

- for $\tau \to \ell a$ the challenge is the extra missing energy
  - $e^+e^- \to \tau^+(\to \ell^+ a)\tau^-(\to \rho^0\pi^-\nu_\tau)$
- can only boost to pseudo-rest frame of tau
- current bound from ARGUS 1995

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

ARGUS, 1995

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

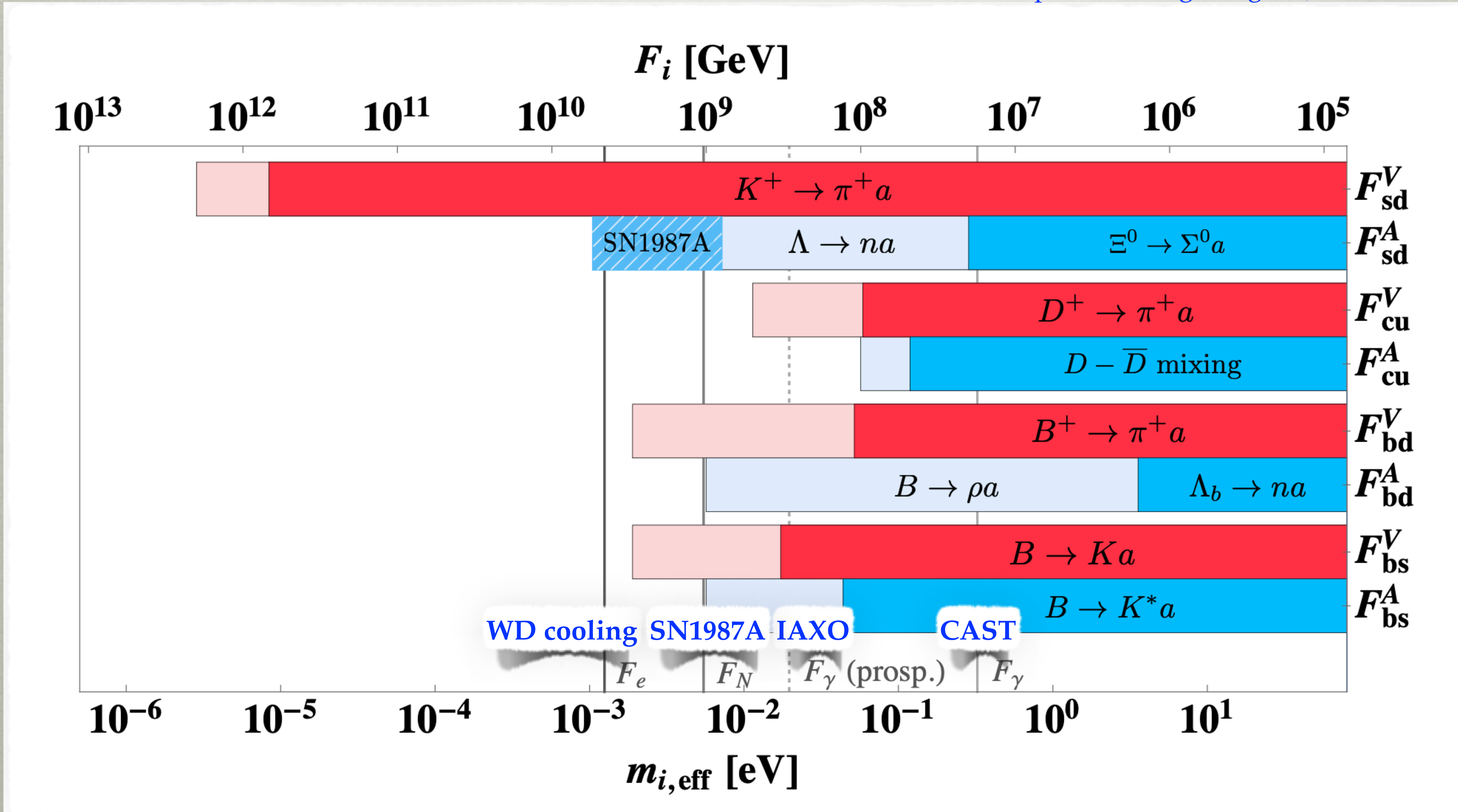
Belle, 2017

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

our naive rescaling

THE STRONGEST FV CONSTRAINTS

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



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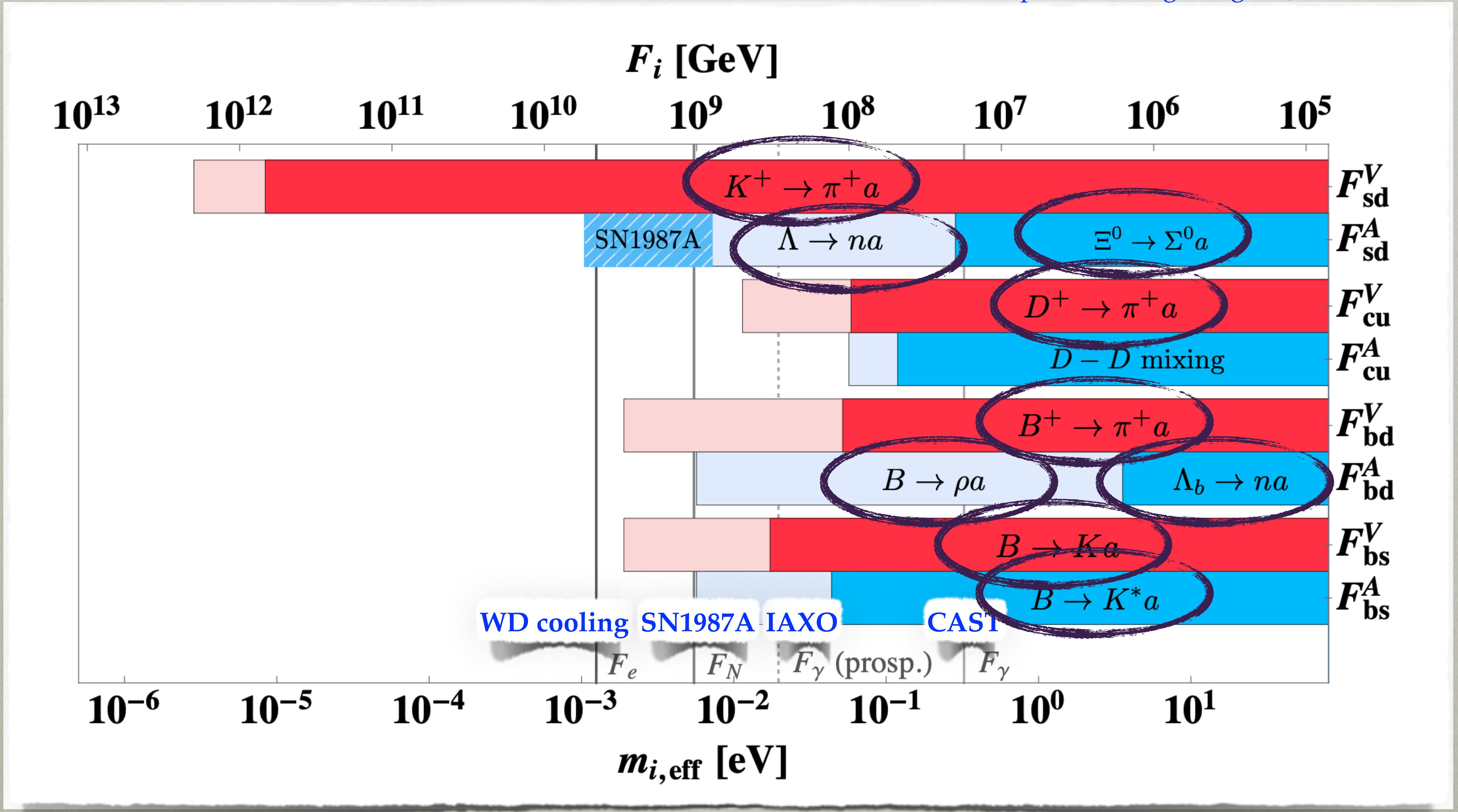
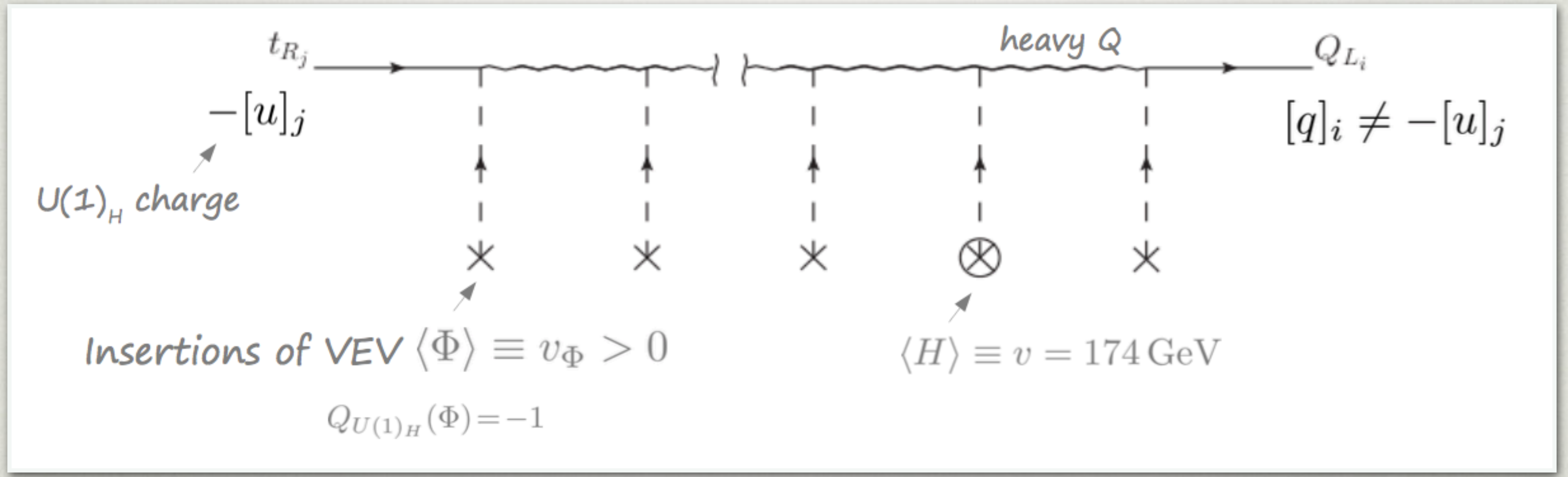


EXPLICIT MODEL - AXIFLAVON



Froggatt, Nielsen, NPB 147, 277 (1979),...

- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

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

Wilczek, PRL 49, 1549 (1982)

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040

Ema, Hamaguchi, Moroi, Nakayama, 1612.05492

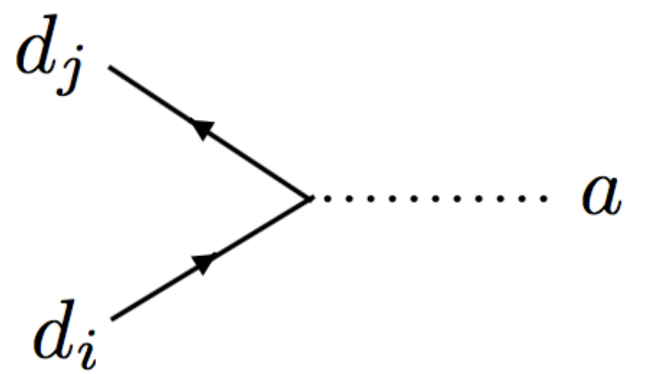
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

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

  - hierarchy from powers of small parameter ε

SEARCHING FOR AXIFLAVON

- axiflavon
  - flavor violating couplings to fermions
    - in the minimal FN axiflavon model



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

  - in addition to flavor diagonal couplings to electrons, nucleons, couplings to photons, gluons

SEARCHING FOR AXIFLAVON