FLAVOR PHENOMENOLOGY OF THE QCD AXION AND AXION-LIKE PARTICLES

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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, 2006.04795

"Newton 1665" seminar, Jun 10 2020

MOTIVATION

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

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

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

OUTLINE

- bounds on QCD axion from quark FCNCs
  - minimal axiflavon
- bounds on ALPs from lepton FV
  - proposal for MEGII-fwd
  - several models of LFV ALPs
    - LFV QCD axion, LFV axiflavon, 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 :

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

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

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

  - very puzzling given large CPV phase in the CKM

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

QCD AXION

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

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

  - new ultra-light particle - axion

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

  - obtains mass from QCD anomaly

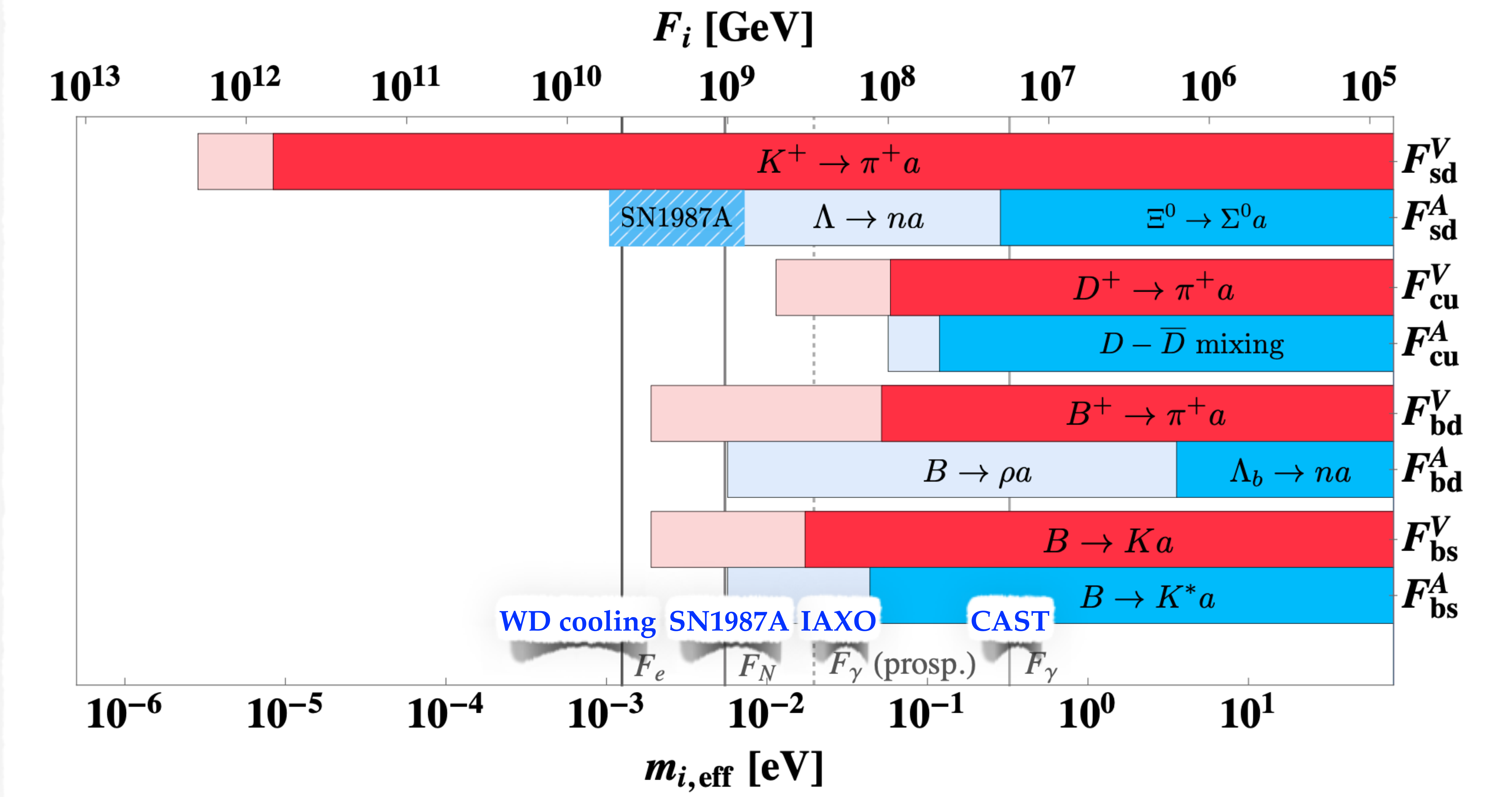
$$m_a = 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

  - viable dark matter candidate (from misalignment mechanism)

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

THE STRONGEST FV CONSTRAINTS

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



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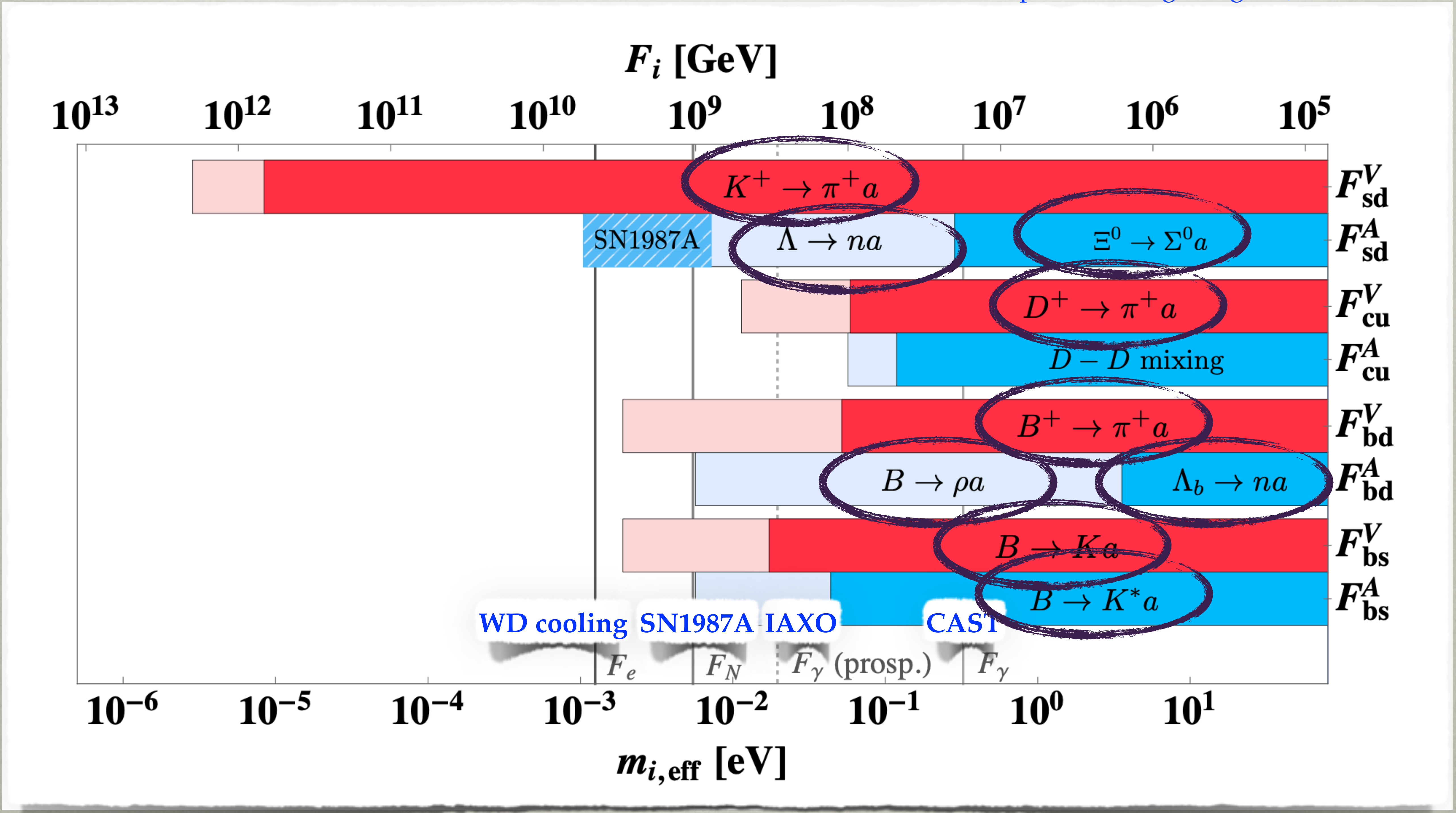
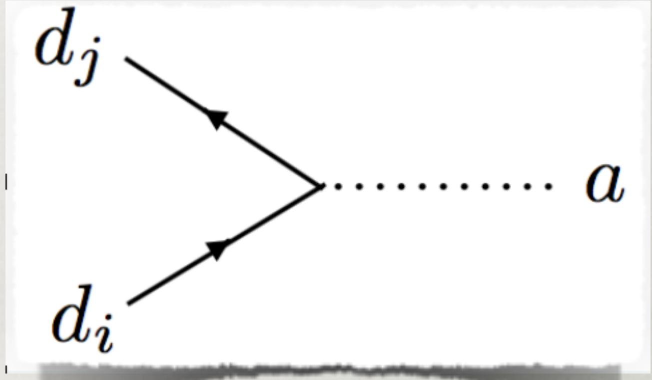


FLAVOR VIOLATING DECAYS



- 2-body meson decays:
  - $P_1 \to P_2 a$ sensitive to F_{ij}^V
    $P_{1,2} = B, D, K, \pi$
    - in principle part of $P_1 \to P_2 \nu\bar{\nu}$, but sometimes $m_{\nu\bar{\nu}} = 0$ bin cut out

      E787&E949, 0709.1000
      CLEO, hep-ex/0106038
      Belle,1702.03224*
      BaBar, 1303.7465
      CLEO, 0806.2112
  - $P_1 \to V_2 a$ sensitive to F_{ij}^A, no exp. searches
    $V_2 = \rho, K^*$
- 2-body hyperon decays, sensitive to F_{ij}^A and F_{ij}^V

  BESS-III, 1612.01775
  - most sensitive $\Xi^0 \to \Sigma^0 a$ (now), $\Lambda \to na$ (future)
- 3-body $K \to \pi\pi a$ decays, sensitive to F_{ij}^A

  E787, hep-ex/0009055
  E391a, 1106.3404

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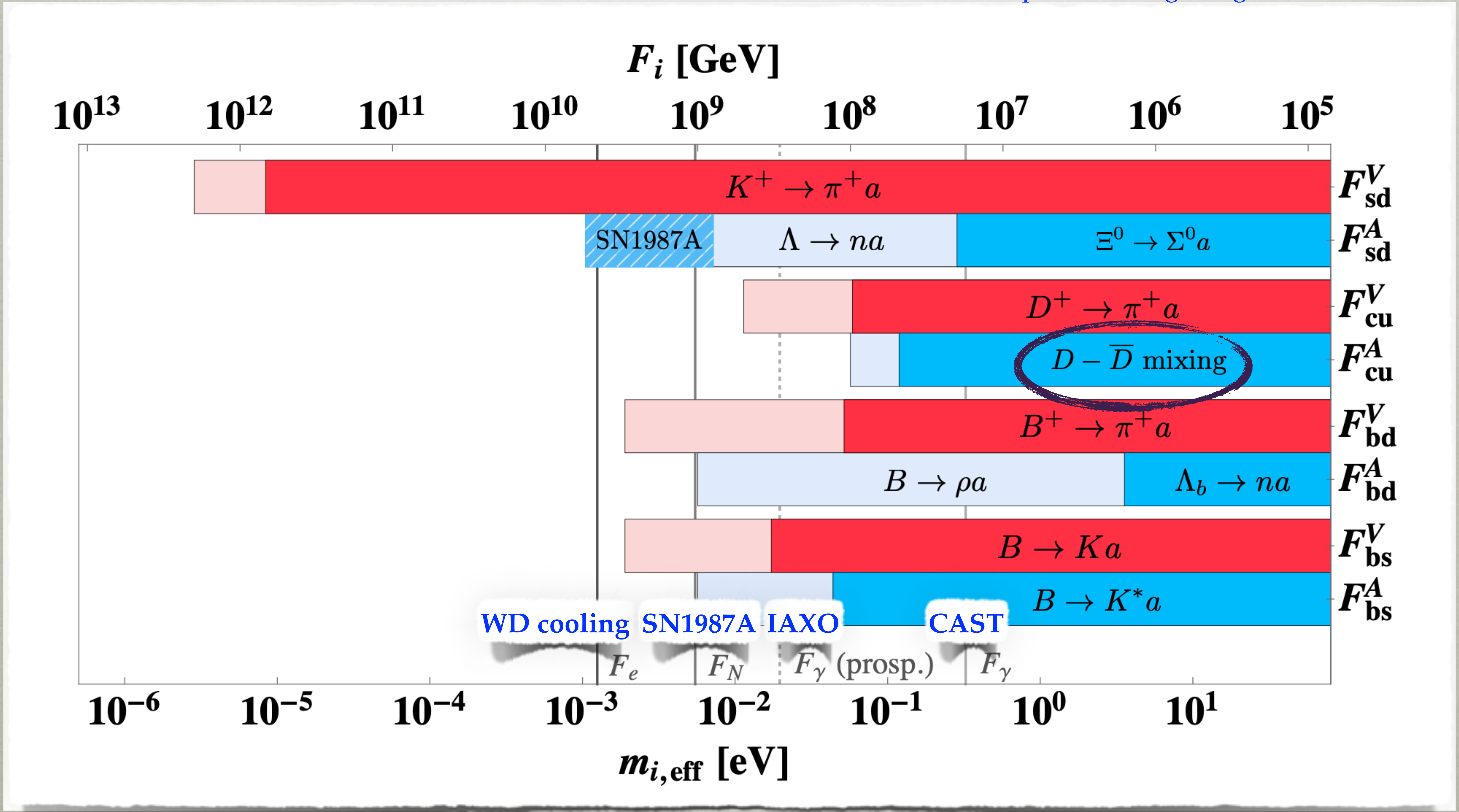
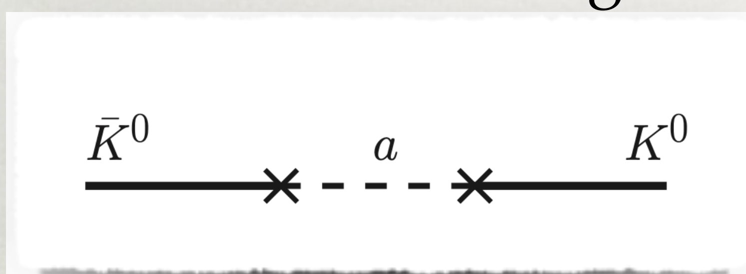
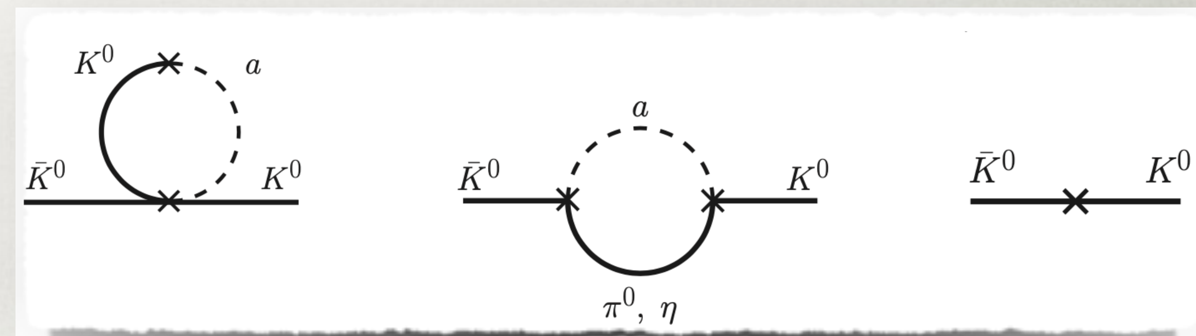


MESON MIXING

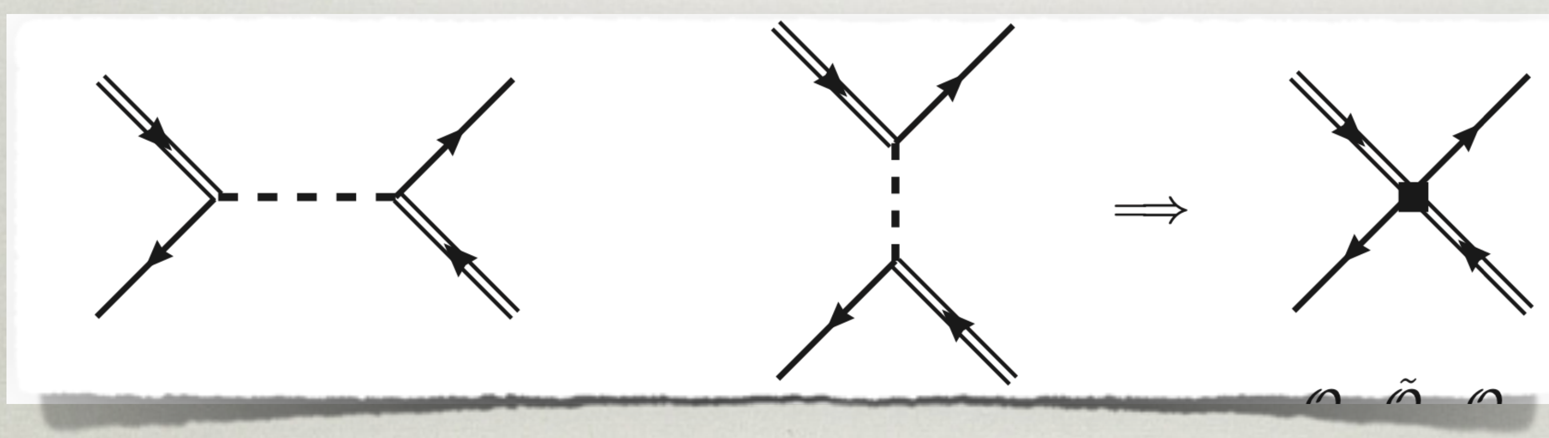
Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

- 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.

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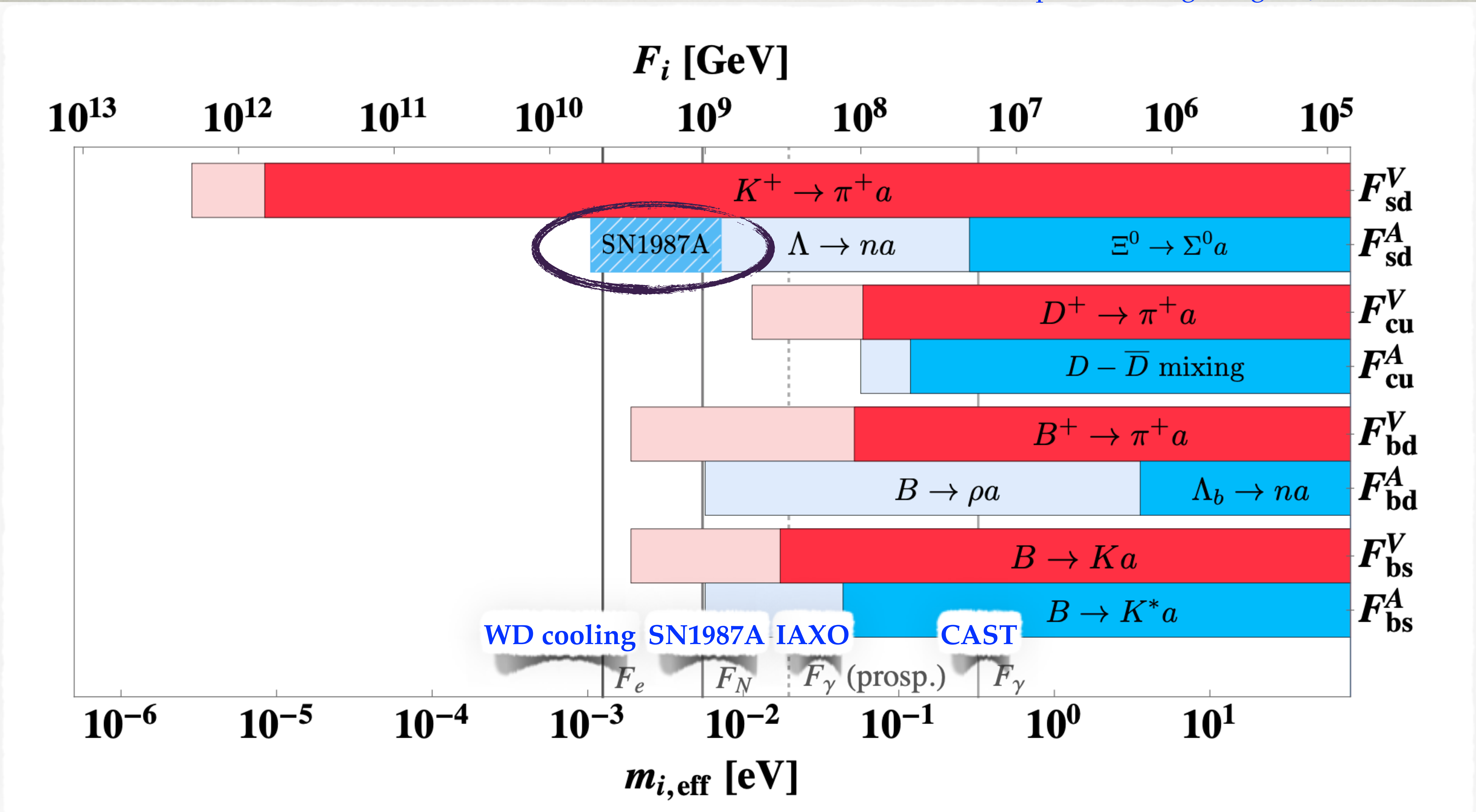
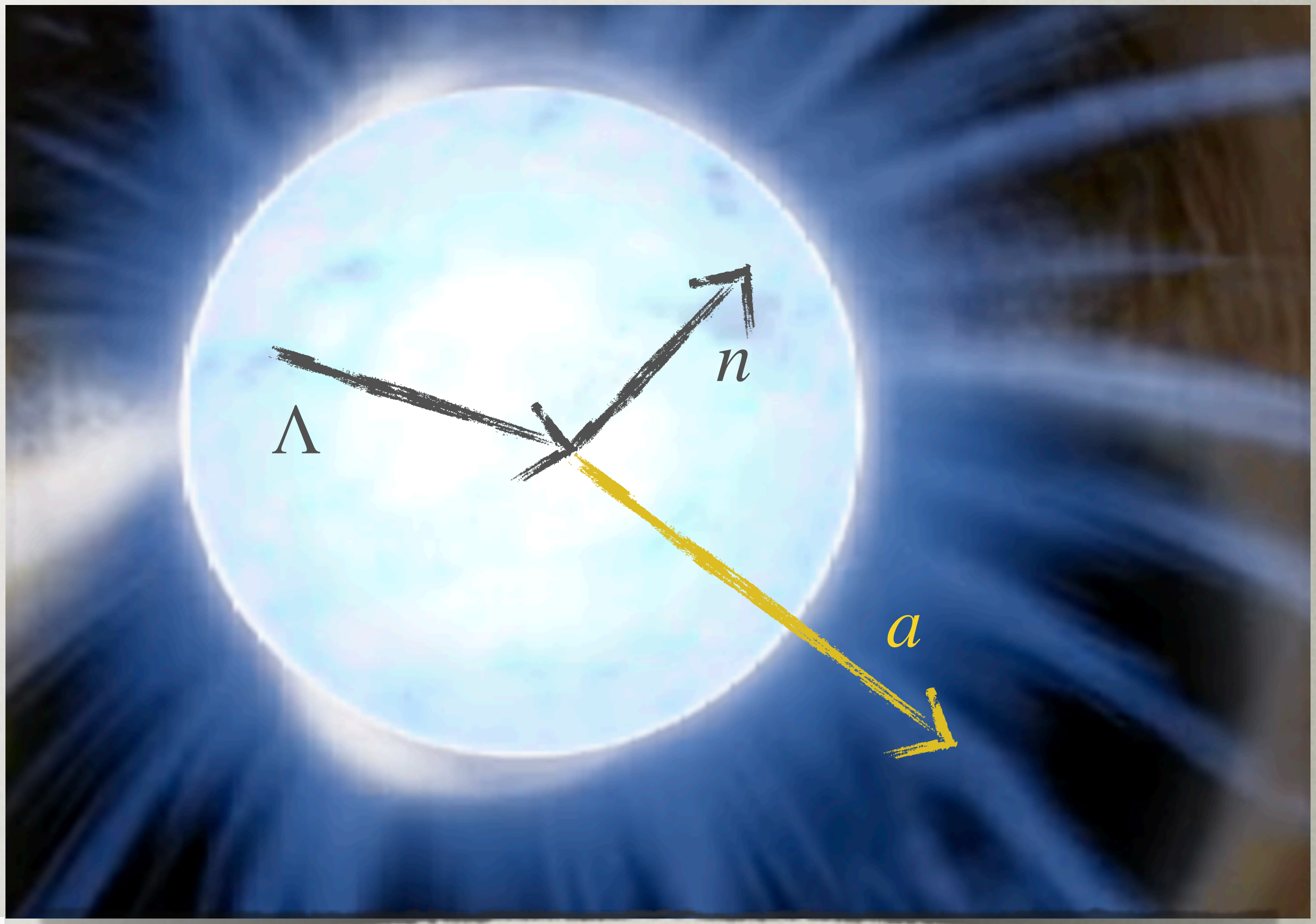


SUPERNOVA BOUNDS

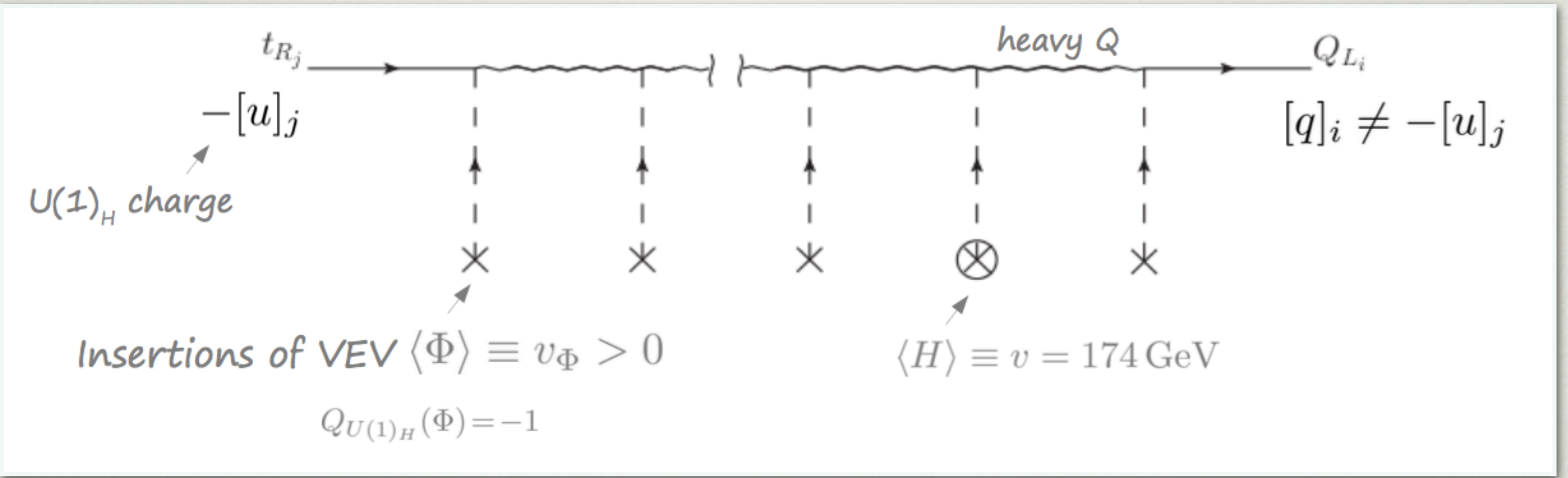


- in neutron star Λ, n, p, e are in equilibrium
- $\Lambda \to na$ decays can cool the proto-neutron star
- Λ, n have the same Fermi energy $\Rightarrow$ at T=0 Pauli blocking forbids $\Lambda \to na$ decays
- at finite temperature volume emission rate (in NR limit)

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

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

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

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

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

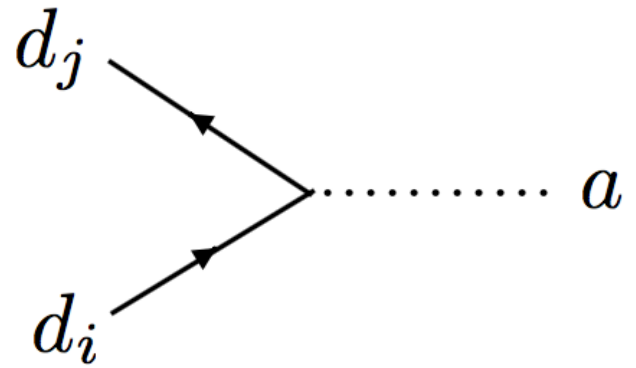
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

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

  - hierarchy from powers of small parameter ε

SEARCHING FOR AXIFLAVON

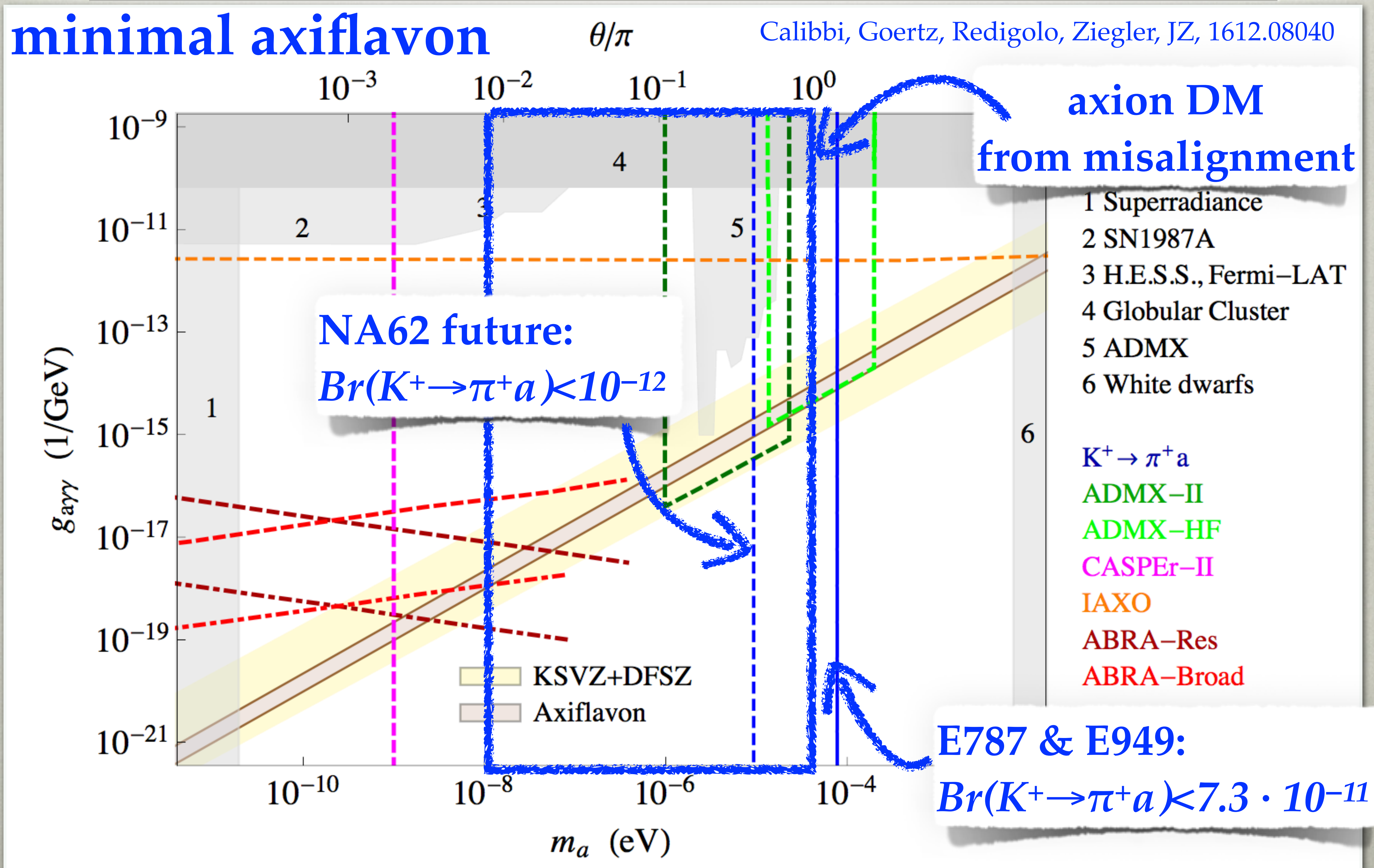
- axiflavon
  - flavor violating couplings to fermions
    - in the minimal FN axiflavon model



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

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

SEARCHING FOR AXIFLAVON



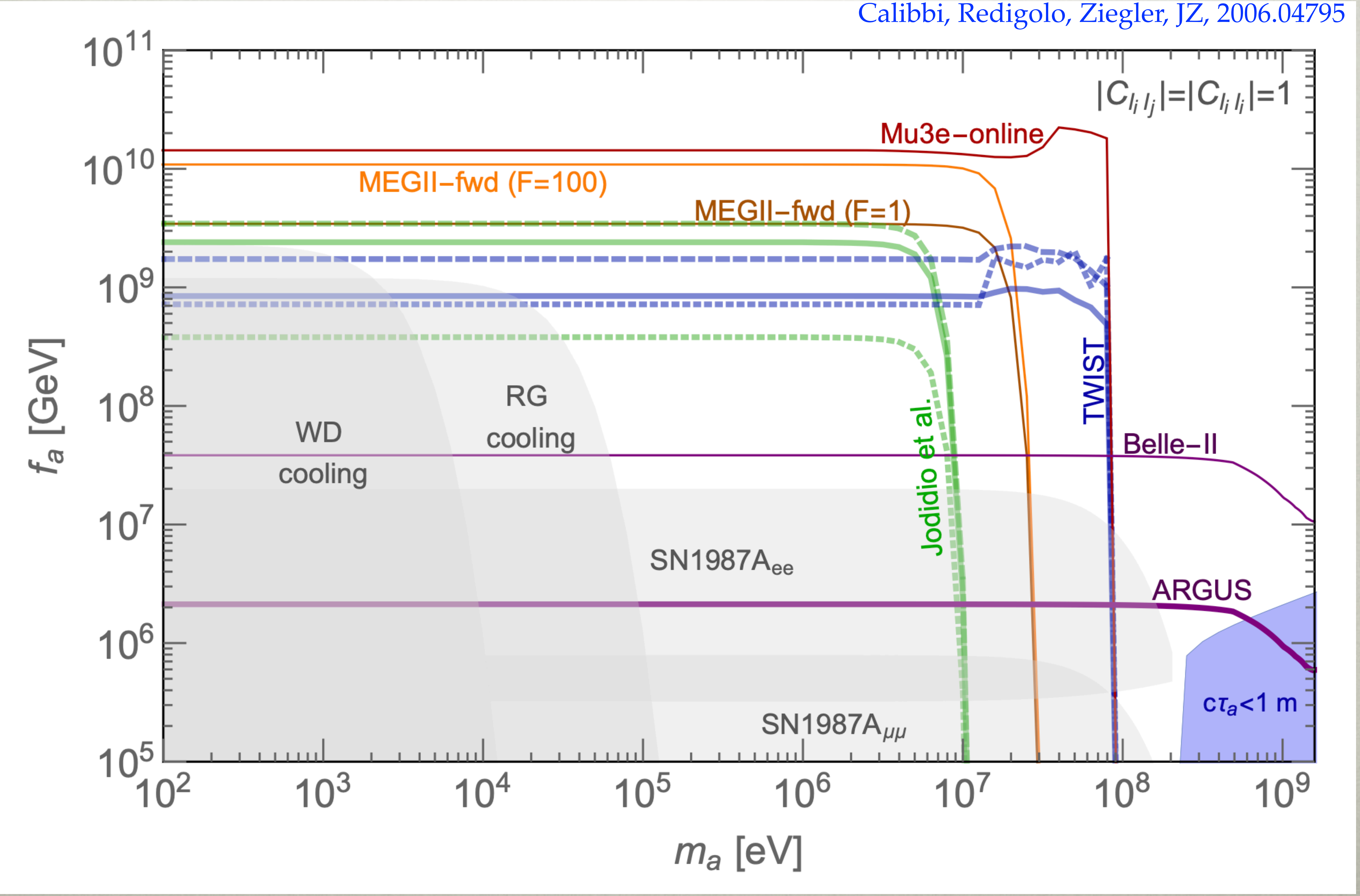
leptonic FCNCs

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 6×10^8 μ @ TWIST (2015)

THE UPSHOT



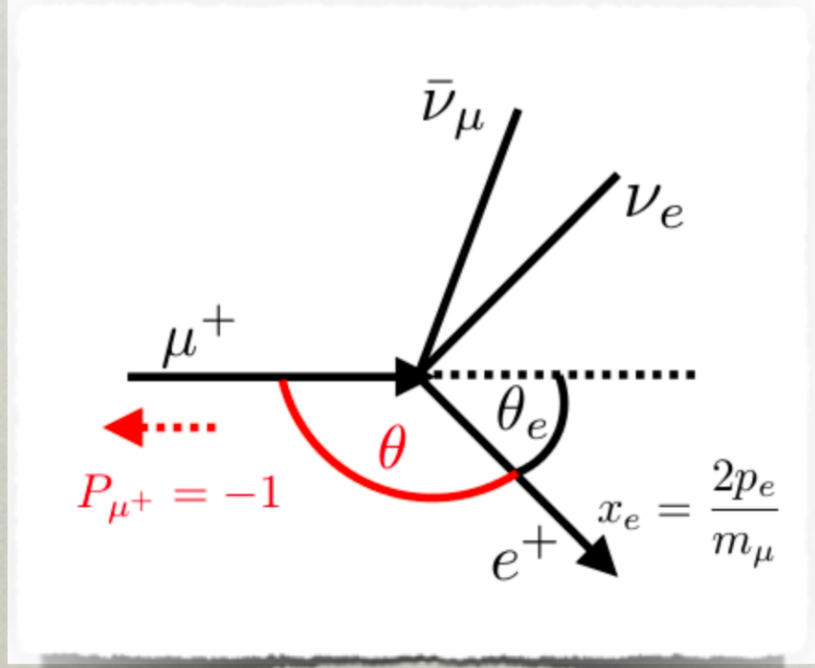
Calibbi, Redigolo, Ziegler, JZ, 2006.04795
$|C_{l_i l_j}|=|C_{l_i l_i}|=1$
Mu3e–online
MEGII–fwd (F=100)
MEGII–fwd (F=1)
TWIST
Belle–II
Jodidio et al.
WD cooling
RG cooling
SN1987A$_{ee}$
SN1987A$_{\mu\mu}$
ARGUS
$c\tau_a$<1 m
f_a [GeV]
m_a [eV]

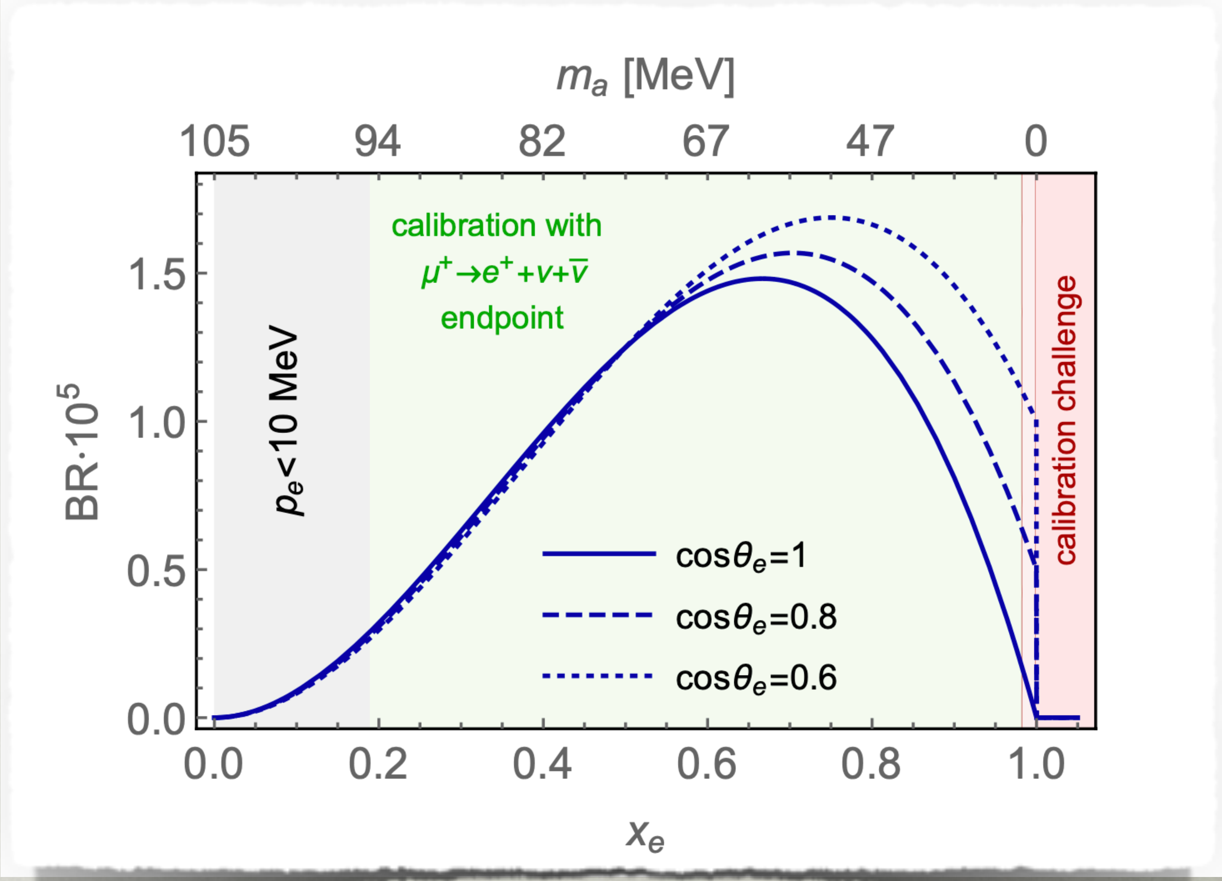
$\mu^+ \to e^+ a$ SEARCHES

- 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

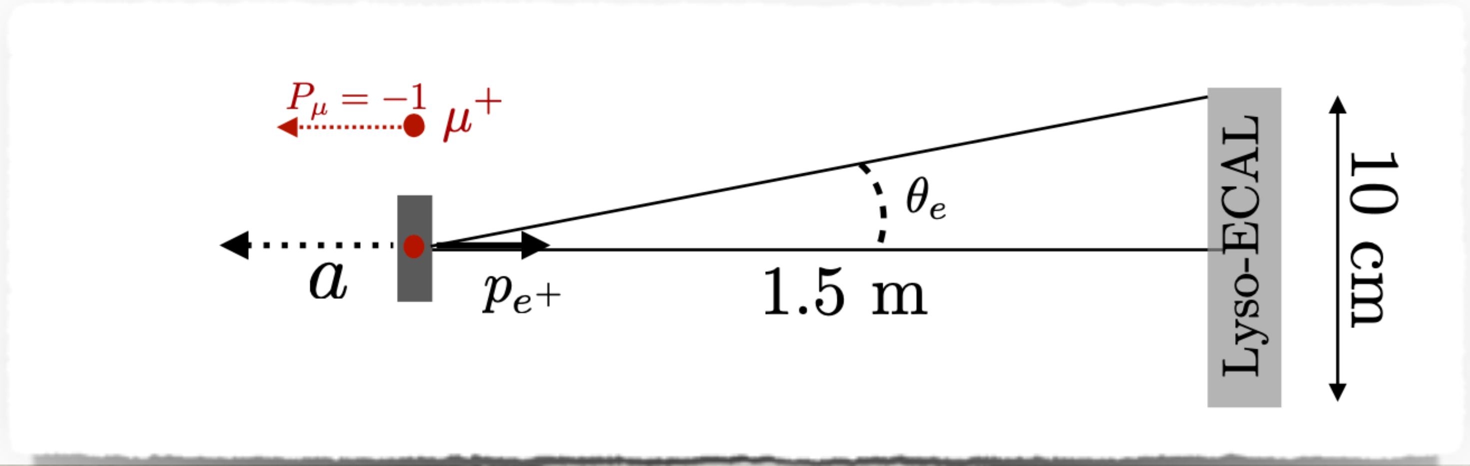
TWIST, 2015

MEGII-fwd

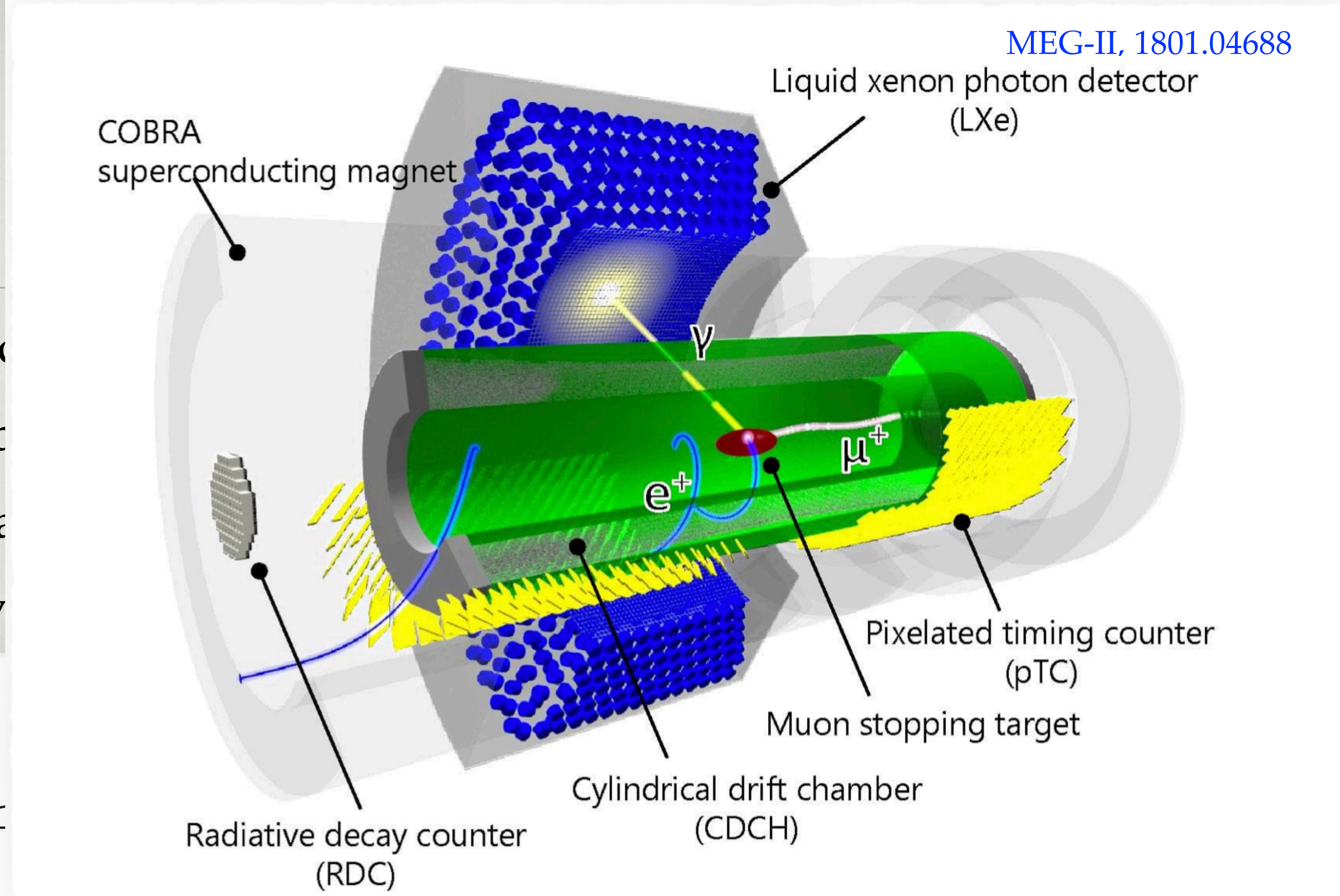
- MEGII is designed to search for $\mu \to e\gamma$
  - could be repurposed for $\mu^+ \to e^+ a$ search ⇒ MEGII-fwd

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

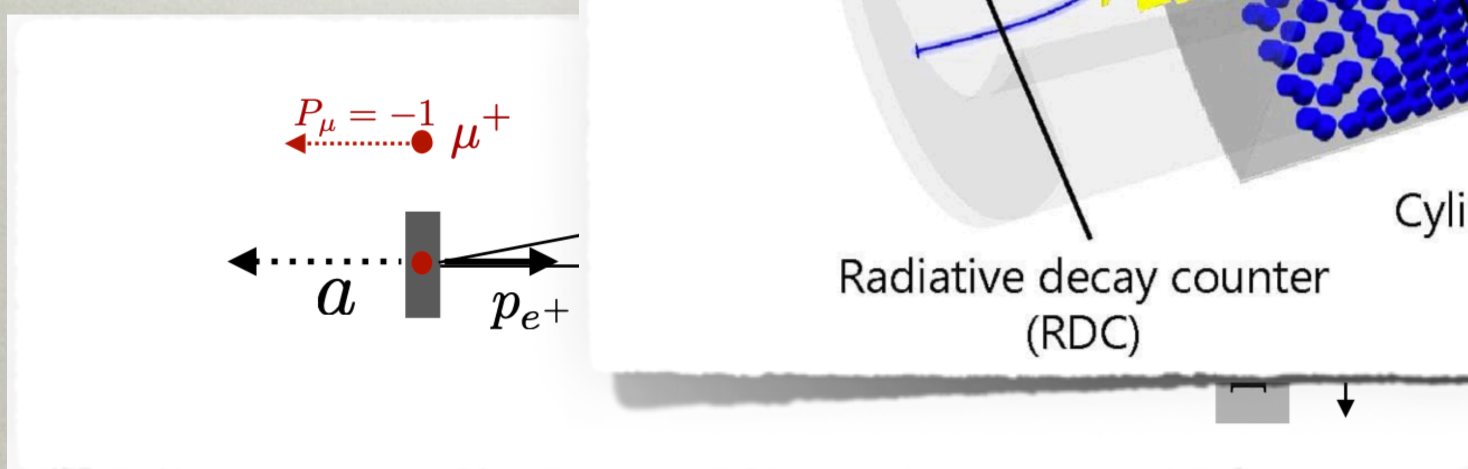
- already has polarized muons
- place a Lyso ECAL downstream



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



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



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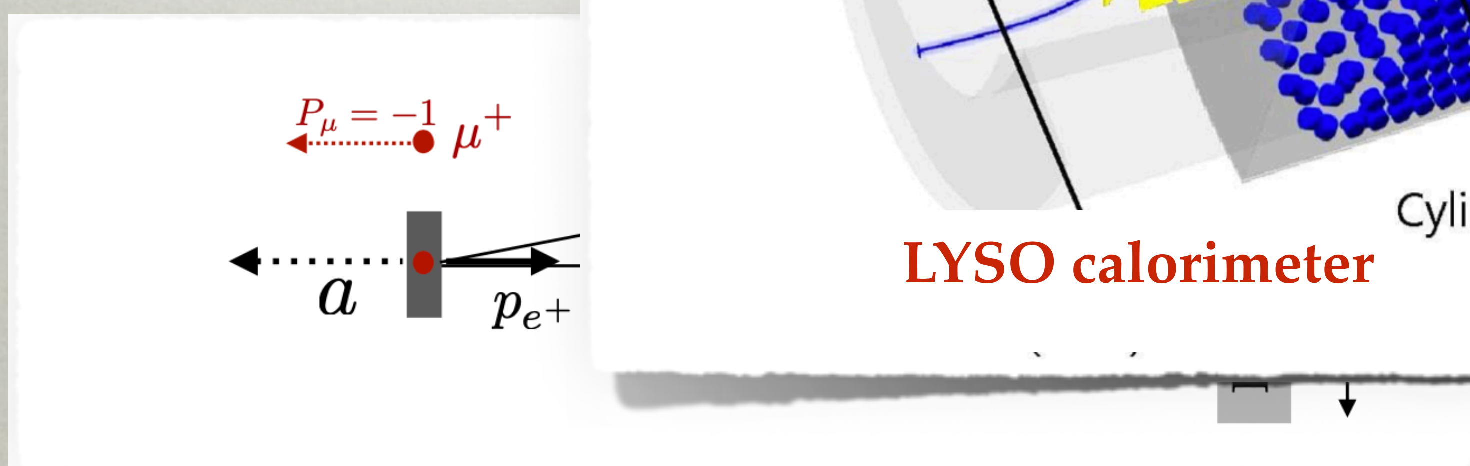

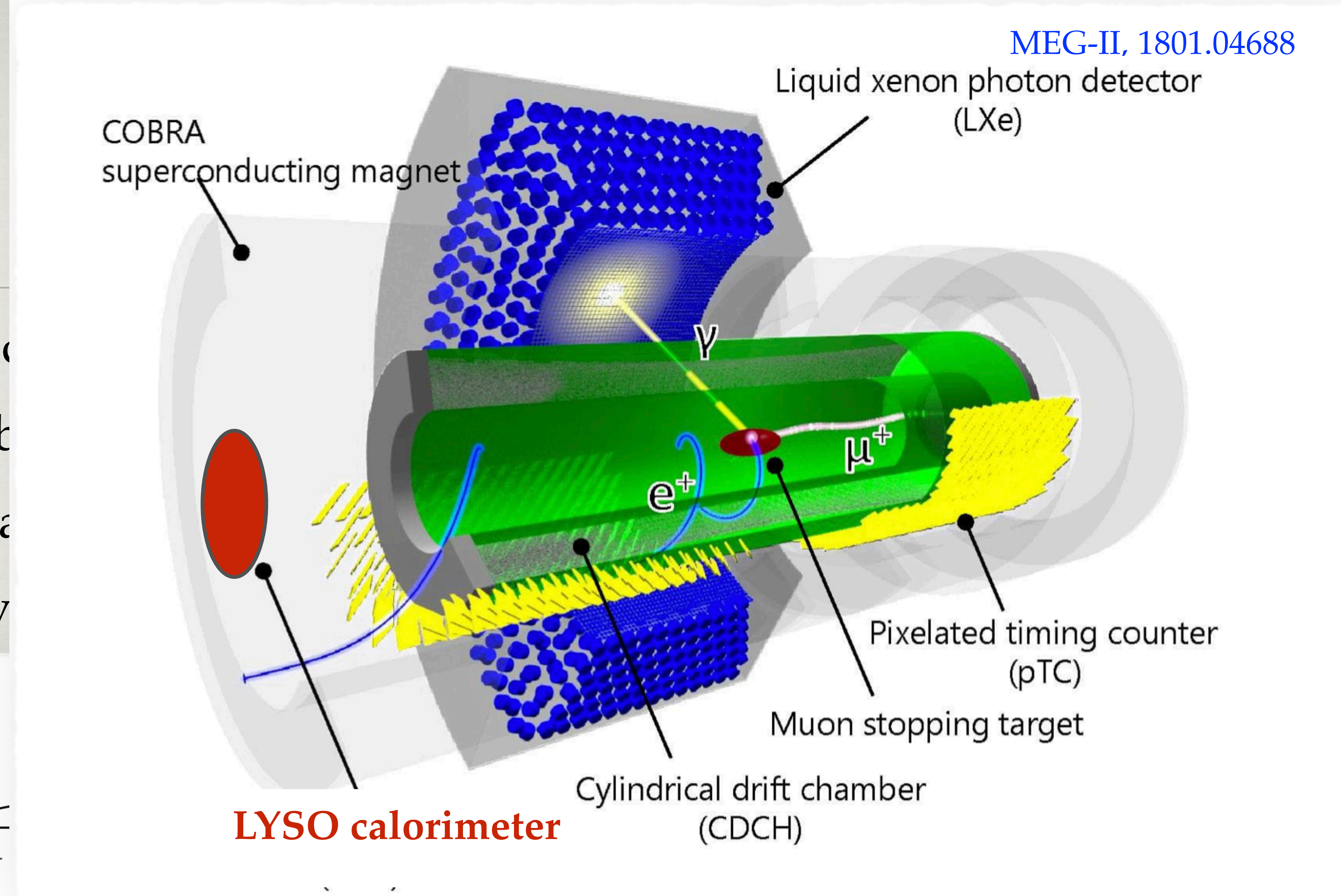

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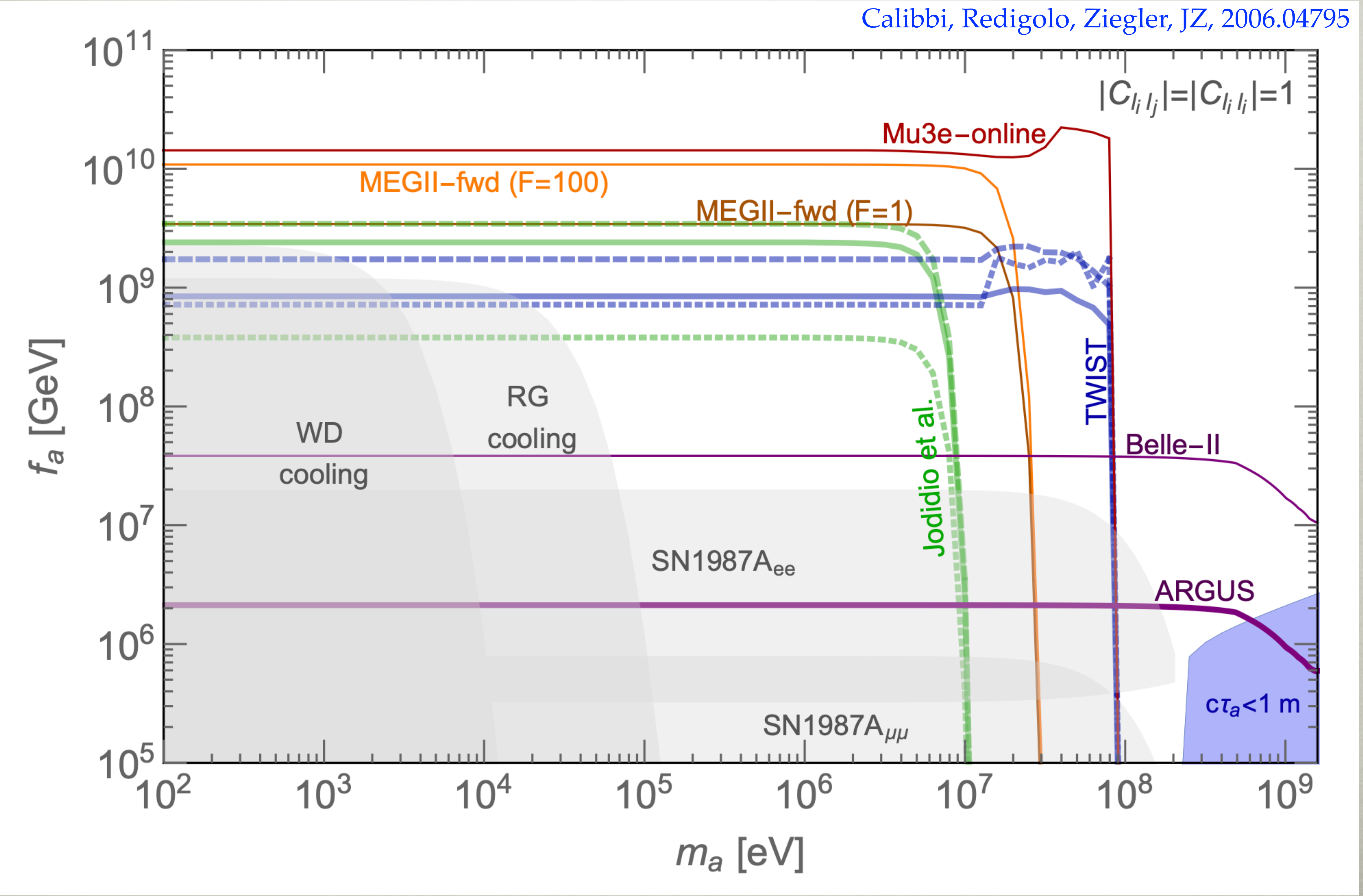

Calibbi, Redigolo, Ziegler, JZ, 2006.04795
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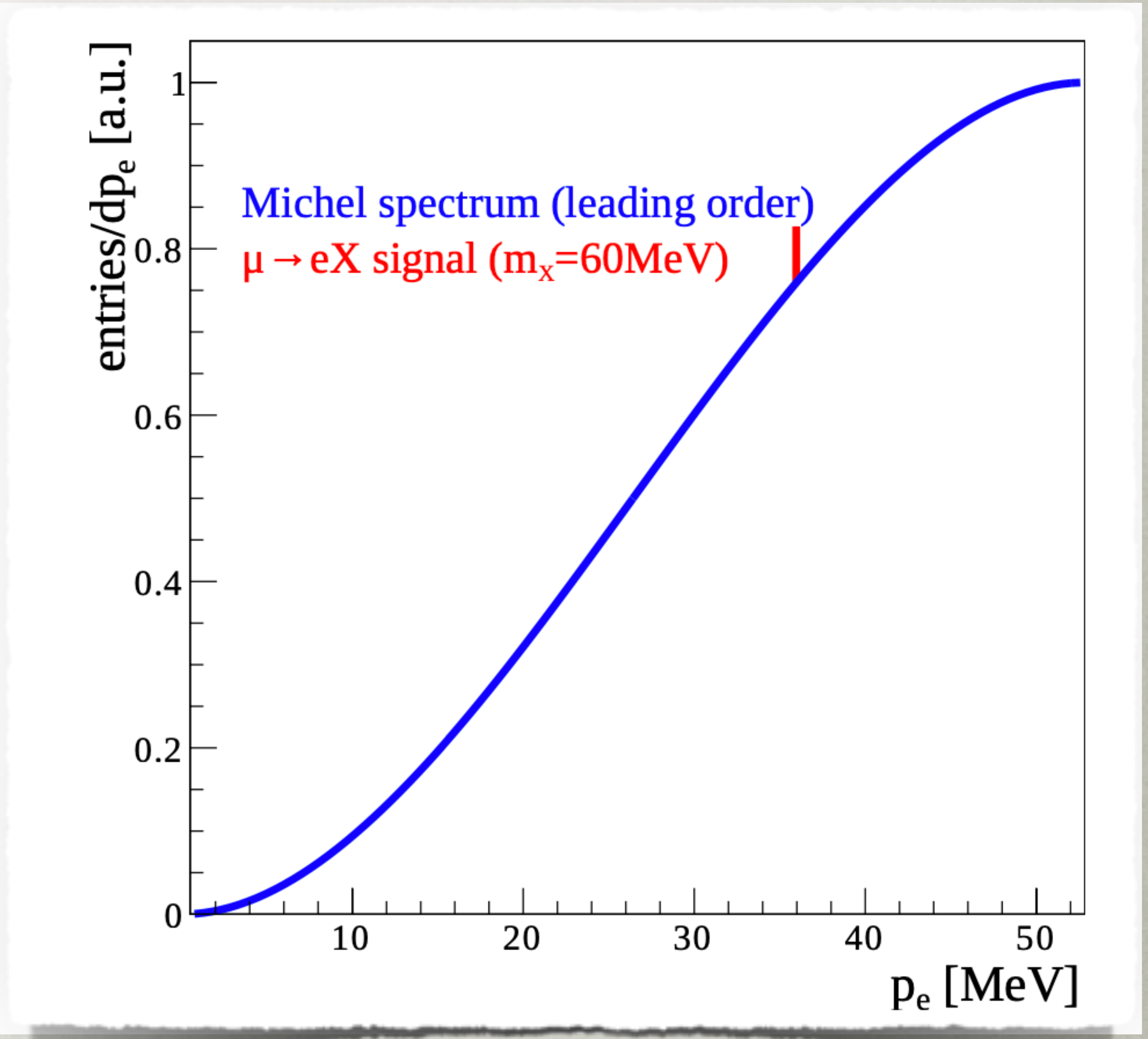
Mu3e-online

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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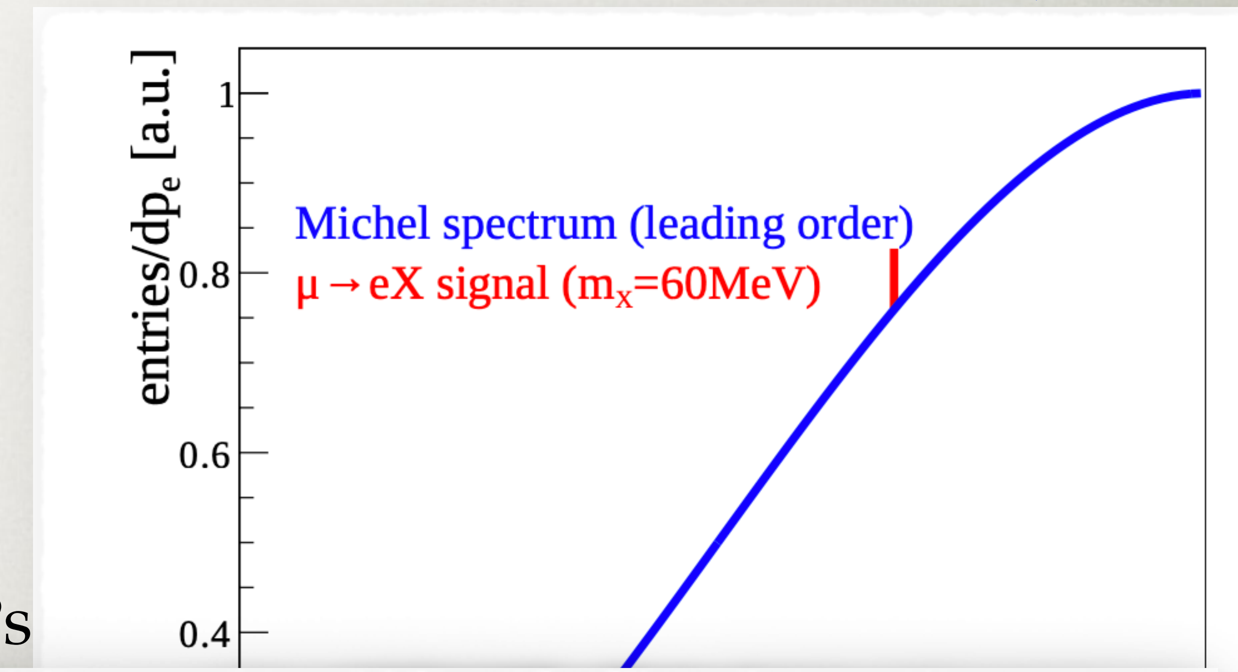
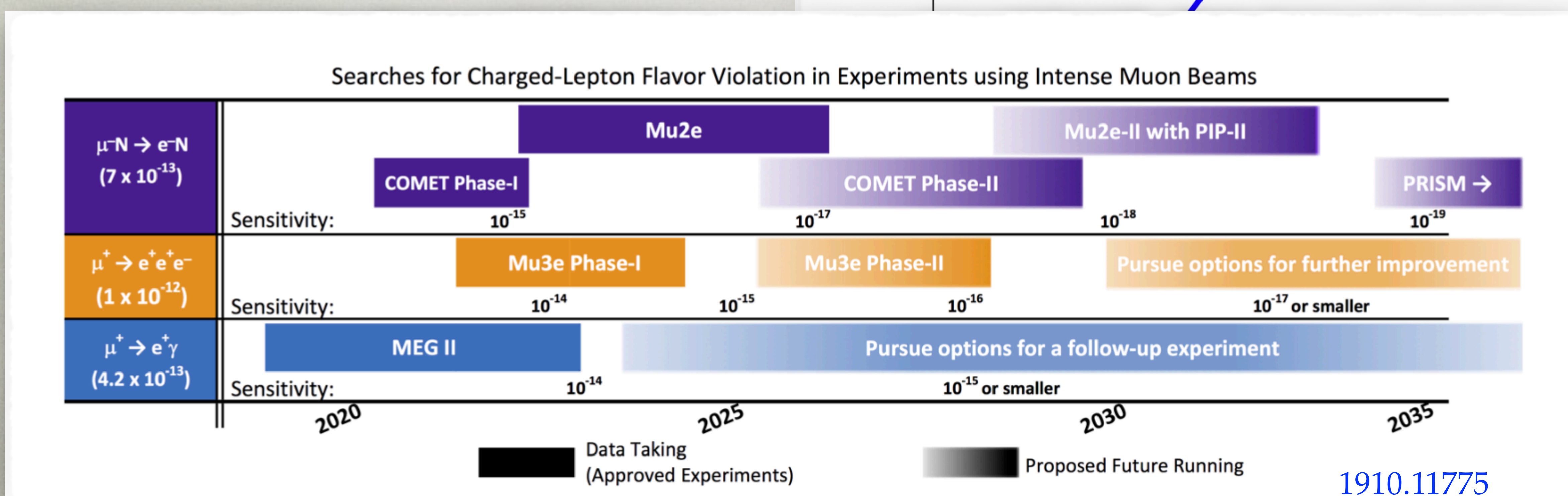




1910.11775

ASTROPHYSICS BOUNDS

Raffelt, Weiss , hep-ph/9410205

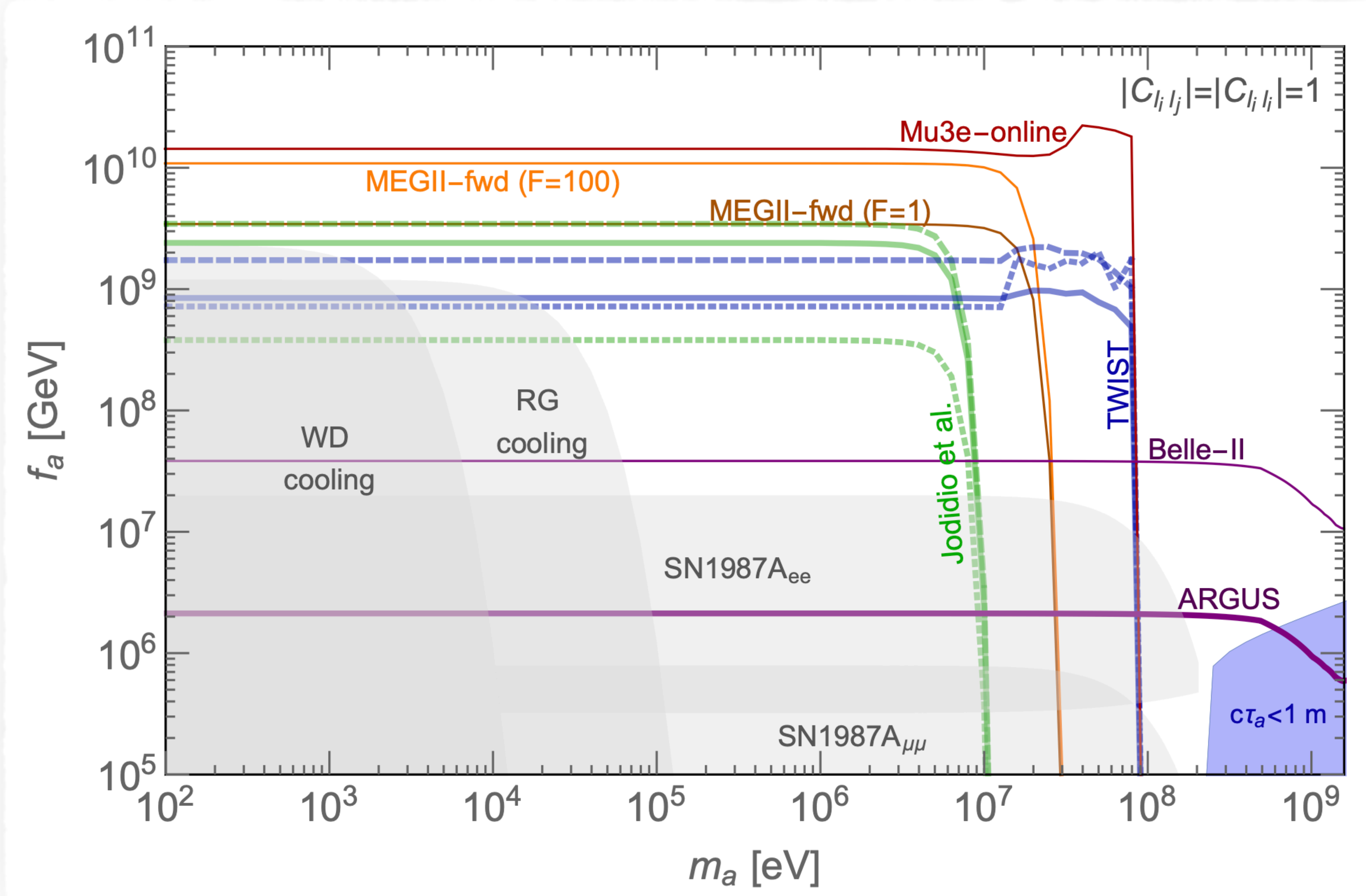
- bounds on massless ALP-electron from red giants and white-dwarf cooling well known
  - due to $e^- + N \to e^- + N + a$
  - we rescale to nonzero ALP masses
- above $m_a \gtrsim 0.1$ MeV SN bounds become important (new!)
- also bounds on couplings to muons, but less severe

Bollig et al., 2005.07141

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

Present best limits				masless ALP
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)

n/9410205



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LFV ALP dark matter

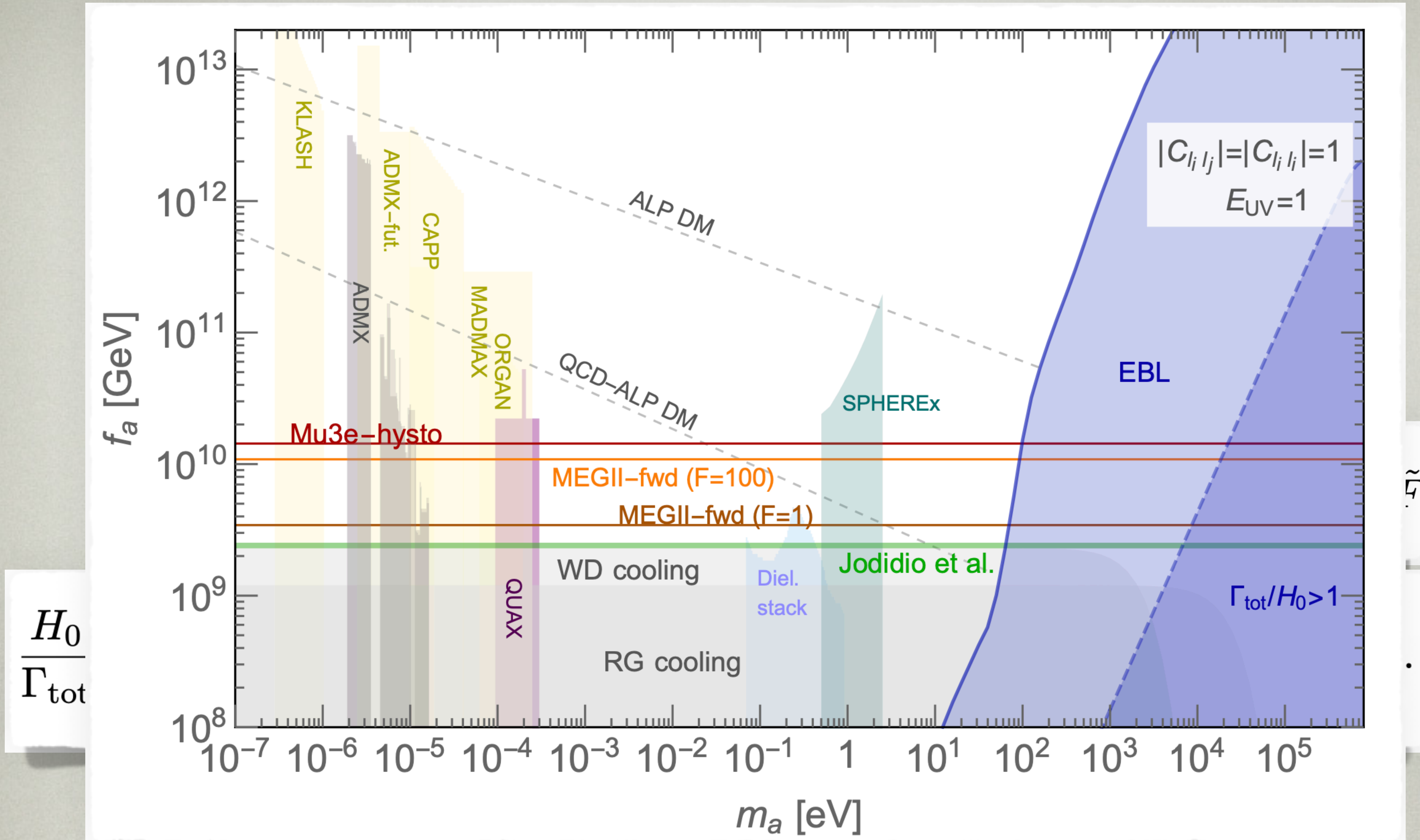
- 0-th order condition for ALP to be a DM: be stable on Hubble time

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

- assume $a \to \gamma\gamma$ dominates

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

- more strignent bounds from extragalactic background light
- if ALP DM observed in a LFV process $\Rightarrow m_a \lesssim 0.1\ \text{keV}$
  - LFV experiments most sensitive for some m_a
  - need other experiments to confirm it is DM



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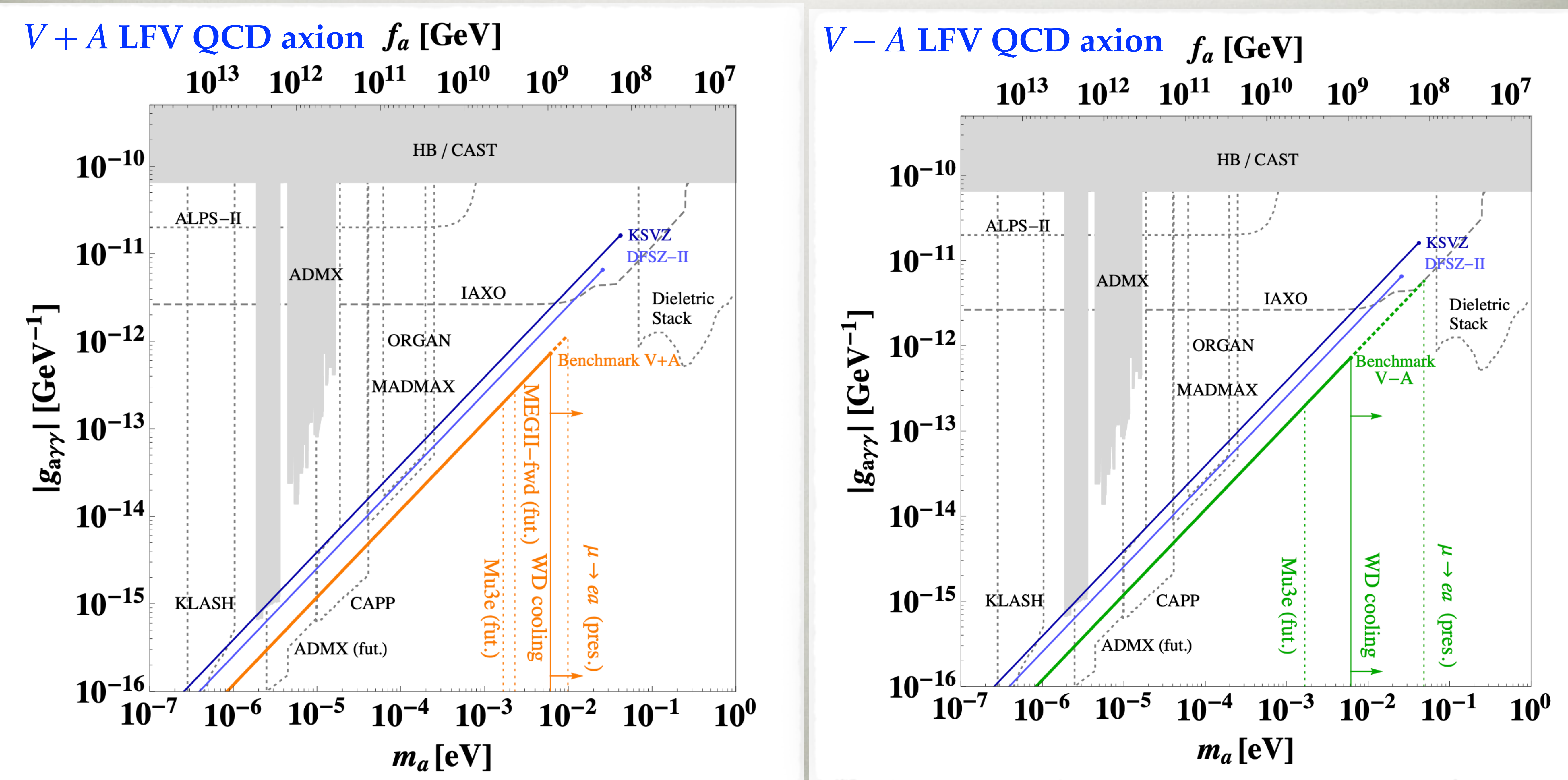
SAMPLE LEPTON FLAVOR VIOLATION ALP MODELS

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

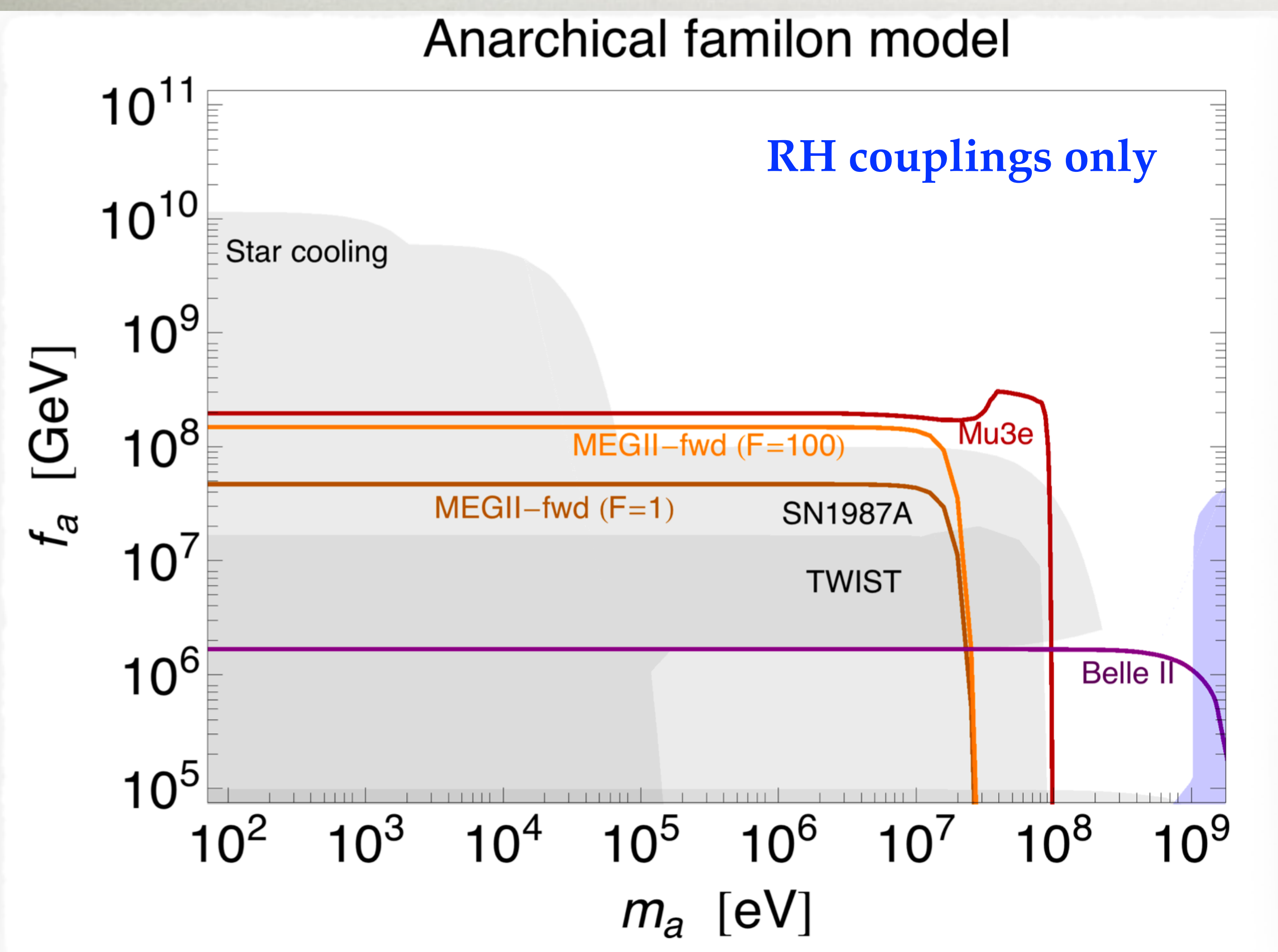
LFV QCD axion

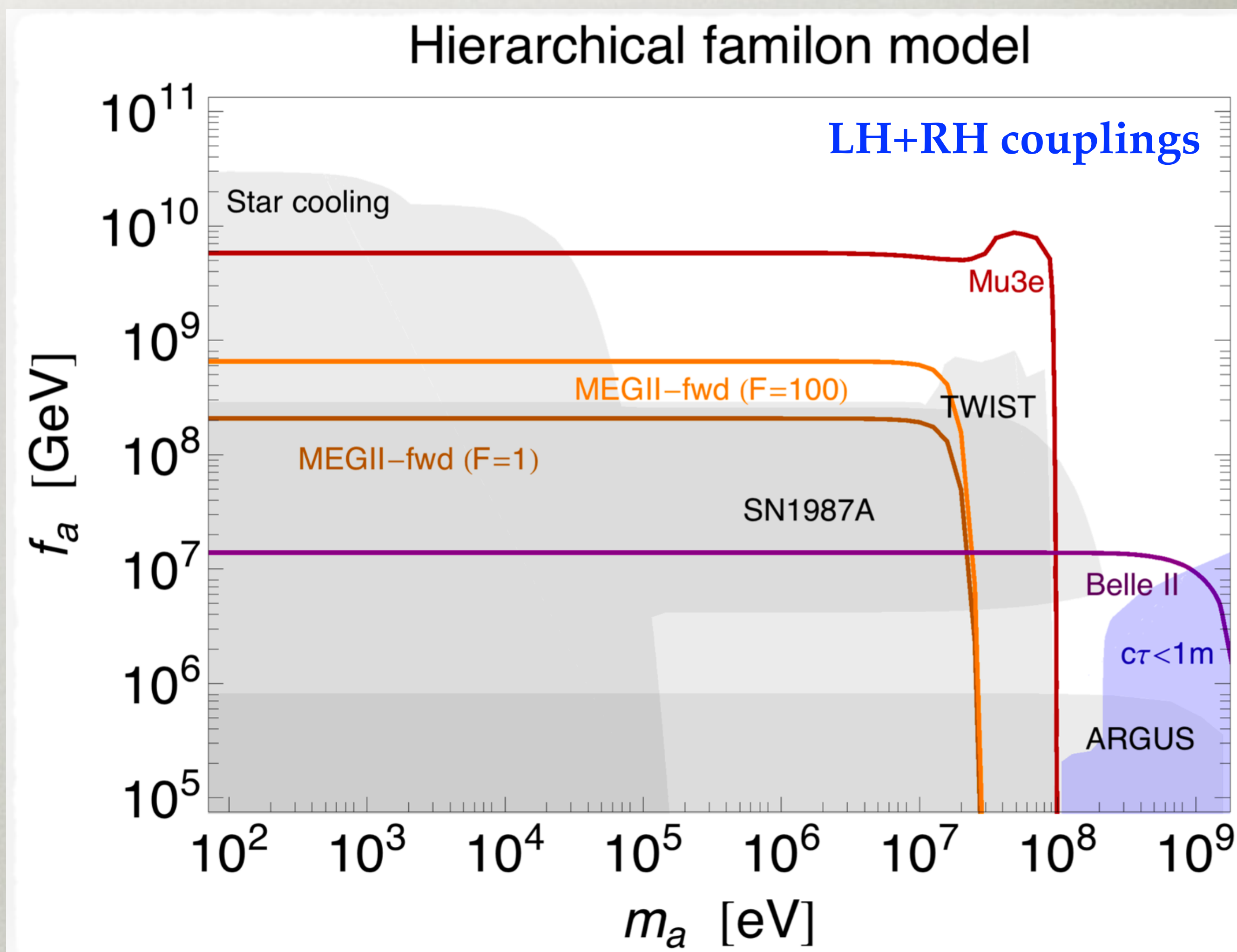
- reach of MEGII-fwd depends on RH couplings



LEPTONIC FAMILON

- reach of MEGII-fwd depends on RH couplings





CONCLUSIONS

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

BACKUP SLIDES

MOTIVATION

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

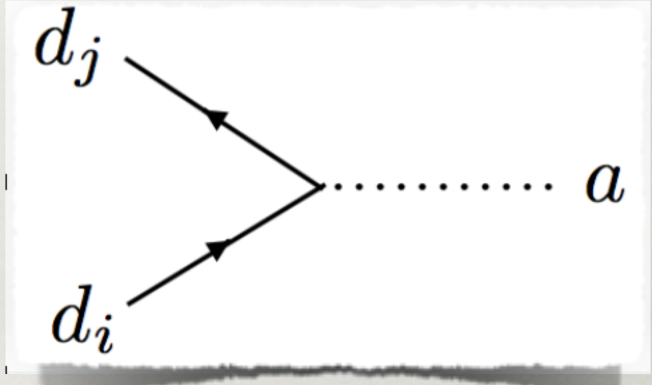
$$C_{f_i f_j}^{V,A} = \frac{1}{2N}\left(V_R^{f\,\dagger} X_{f_R} V_R^f \pm V_L^{f\,\dagger} X_{f_L} V_L^f\right)_{ij}$$

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

- 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

$$F_{f_i f_j}^{V,A} \equiv \frac{2 f_a}{c_{f_i f_j}^{V,A}} \qquad F_{\ell_i \ell_j} = \frac{2 f_a}{\sqrt{|C_{\ell_i \ell_j}^V|^2 + |C_{\ell_i \ell_j}^A|^2}}$$

FV decays



- 2-body meson decays:
  - $P_1 \to P_2 a$ sensitive to F^V_{ij}
    - use exp. searches for $K^+ \to \pi^+ a$, $B \to Ka$, $B \to \pi a$ (most stringent: recasts of $B \to K\nu\bar{\nu}$)
    - for $D^+ \to \pi^+ a$ need to recast $D \to (\tau \to \pi\bar{\nu})\nu$
  - $P_1 \to V_2 a$ sensitive to F^A_{ij}, no exp. searches
- 2-body hyperon decays, sensitive to F^A_{ij} and F^V_{ij}
  - most sensitive $\Xi^0 \to \Sigma^0 a$ (now), $\Lambda \to na$ (future)
- 3-body $K \to \pi\pi a$ decays, sensitive to F^A_{ij}
  - 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^V_{ij} [GeV]	F^A_{ij} [GeV]
$s \to d$	$K^+ \to \pi^+ a$	$\mathbf{6.8 \times 10^{11}}$	$-$
		$(\mathbf{2 \times 10^{12}})$	$-$
$b \to s$	$B^{+,0} \to K^{+,0} a$	$\mathbf{3.3 \times 10^{8}}$	$-$
		$(\mathbf{3 \times 10^{9}})$	$-$
$b \to d$	$B^+ \to \pi^+ a$	$\mathbf{1.1 \times 10^{8}}$	$-$
		$(\mathbf{3 \times 10^{9}})$	$-$
$c \to u$	$D^+ \to \pi^+ a$	$\mathbf{9.7 \times 10^{7}}$	$-$
		$(\mathbf{5 \times 10^{8}})$	$-$

- 2-body meson decays:
  - $P_1 \to P_2 a$ sensitive to F^V_{ij}
    - use exp. searches for $K^+ \to \pi^+ a$, $B \to K a$, $B \to \pi a$ (most stringent: recasts of $B \to K \nu \bar{\nu}$)
    - for $D^+ \to \pi^+ a$ need to recast $D \to (\tau \to \pi \bar{\nu})\nu$
  - $P_1 \to V_2 a$ sensitive to F^A_{ij}, no exp. searches

E787&E949, 0709.1000
CLEO, hep-ex/0106038
Belle,1702.03224*
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- 2-body hyperon decays, sensitive to F^A_{ij} and F^V_{ij}
  - most sensitive $\Xi^0 \to \Sigma^0 a$ (now), $\Lambda \to n a$ (future)
- 3-body $K \to \pi \pi a$ decays, sensitive to F^A_{ij}
  - 3-body decays of B, D, could be interesting as well

BESS-III, 1612.01775

E787, hep-ex/0009055
E391a, 1106.3404

FV DEC

Flavors	Process	F^V_{ij} [GeV]	F^A_{ij} [GeV]
	$\Lambda \to n\ a$ (decay)	6.9×10^6 (1×10^9)	5.0×10^6 ($\mathbf{8 \times 10^8}$)
$s \to d$	$\Xi^0 \to \Sigma^0 a$	1.6×10^7 (2×10^8)	$\mathbf{2.0 \times 10^7}$ (3×10^8)

d_i

- 2-body meson decays:
  - $P_1 \to P_2 a$ sensitive to F^V_{ij}
    - use exp. searches for $K^+ \to \pi^+ a$, $B \to Ka$, $B \to \pi a$ (most stringent: recasts of $B \to K\nu\bar{\nu}$)
    - for $D^+ \to \pi^+ a$ need to recast $D \to (\tau \to \pi\bar{\nu})\nu$
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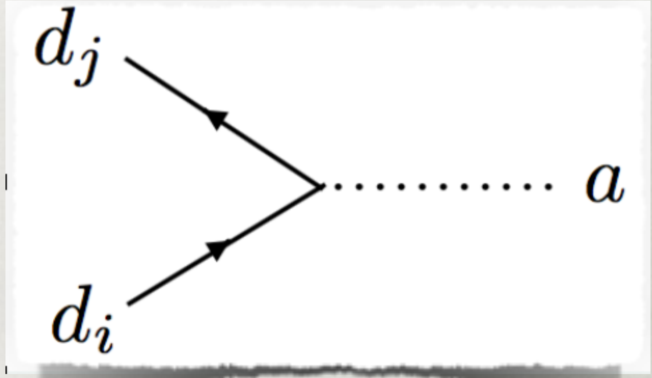
FV decays



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$b \to d$	$B^+ \to \pi^+ a$	$\mathbf{1.1 \times 10^{8}}$	–
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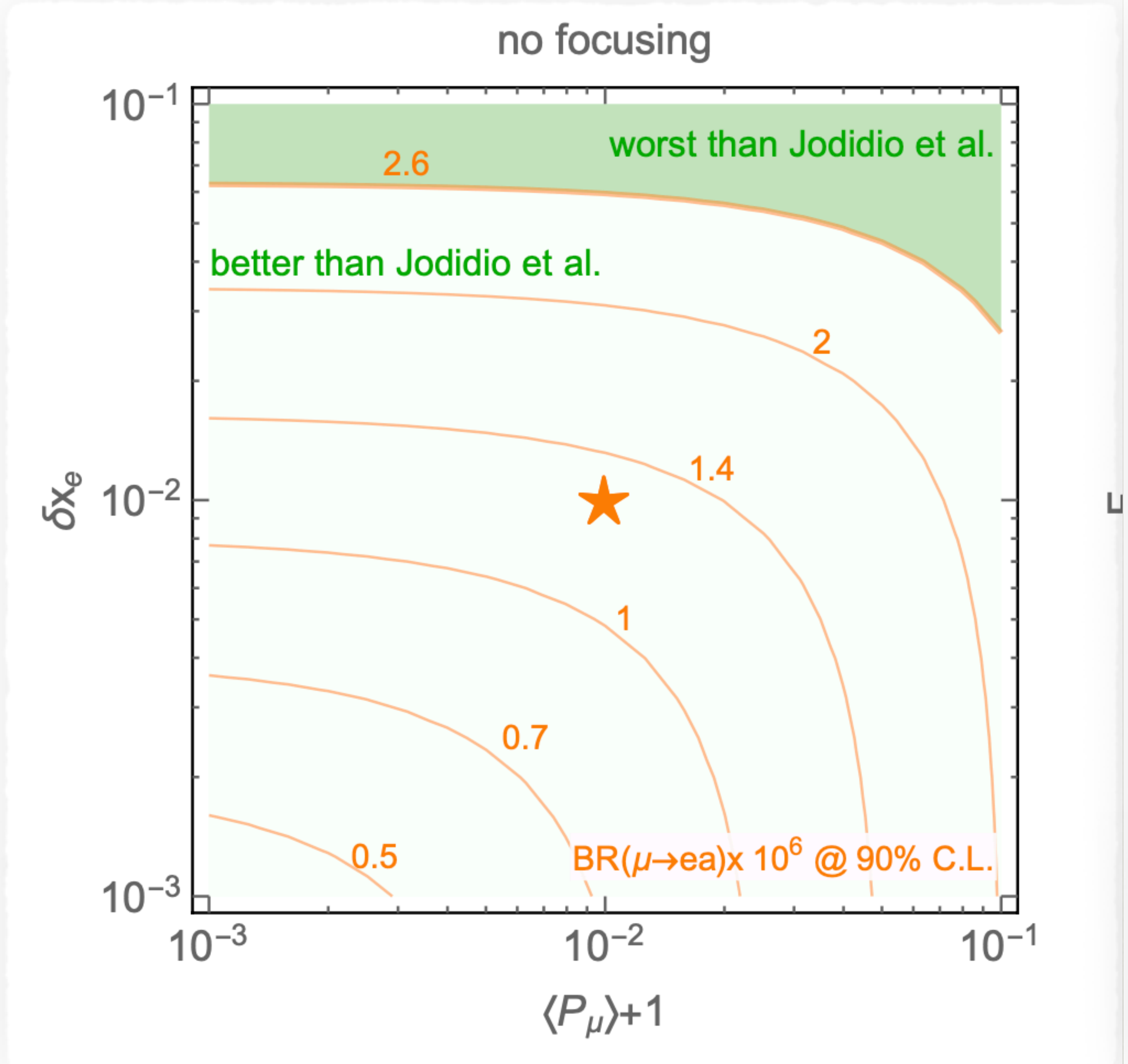
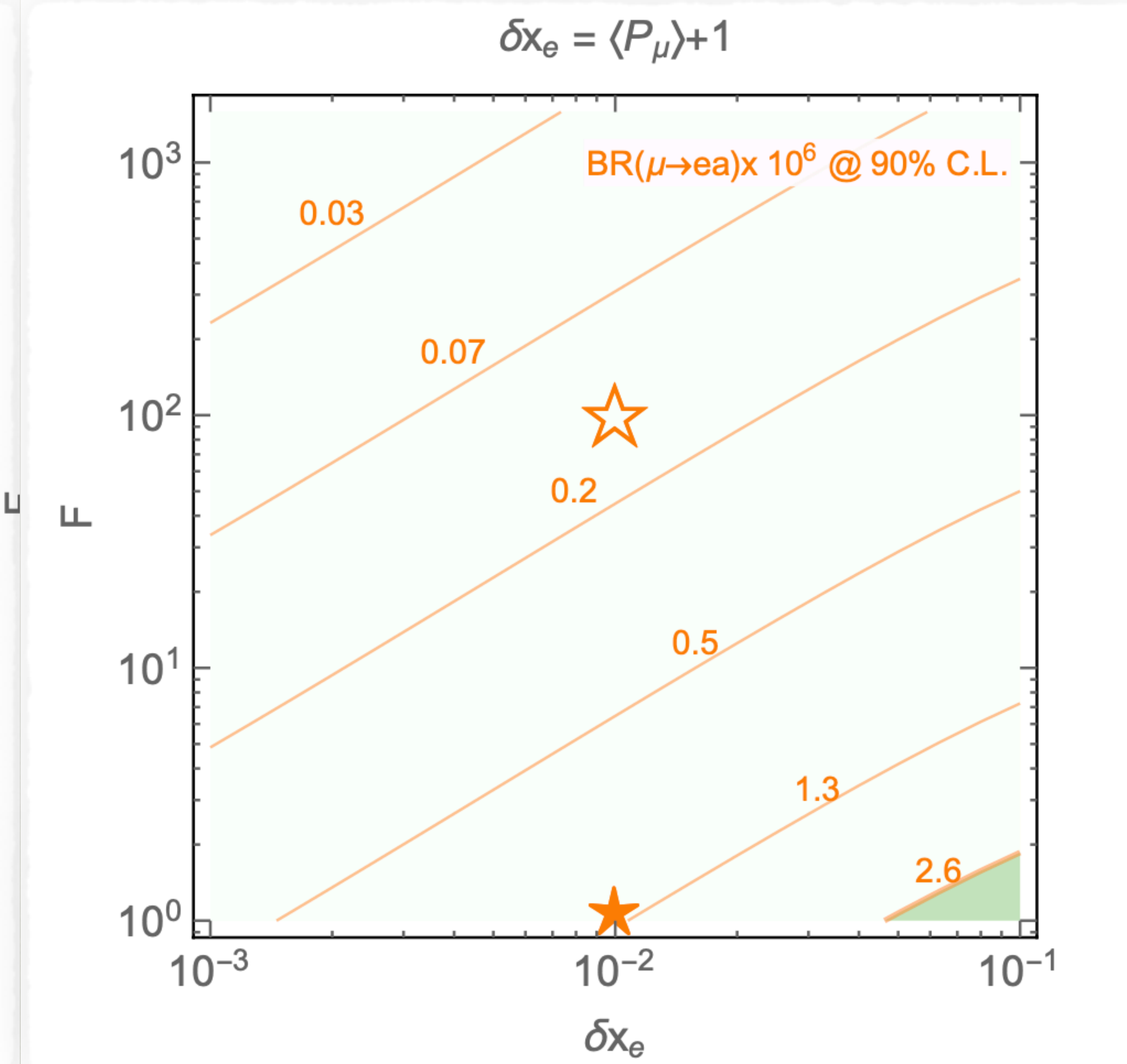

no focusing
worst than Jodidio et al.
better than Jodidio et al.
2.6
2
1.4
1
0.7
0.5
BR(μ→ea)x 10^6 @ 90% C.L.
δx_e
⟨P_μ⟩+1
10^-1
10^-2
10^-3


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*

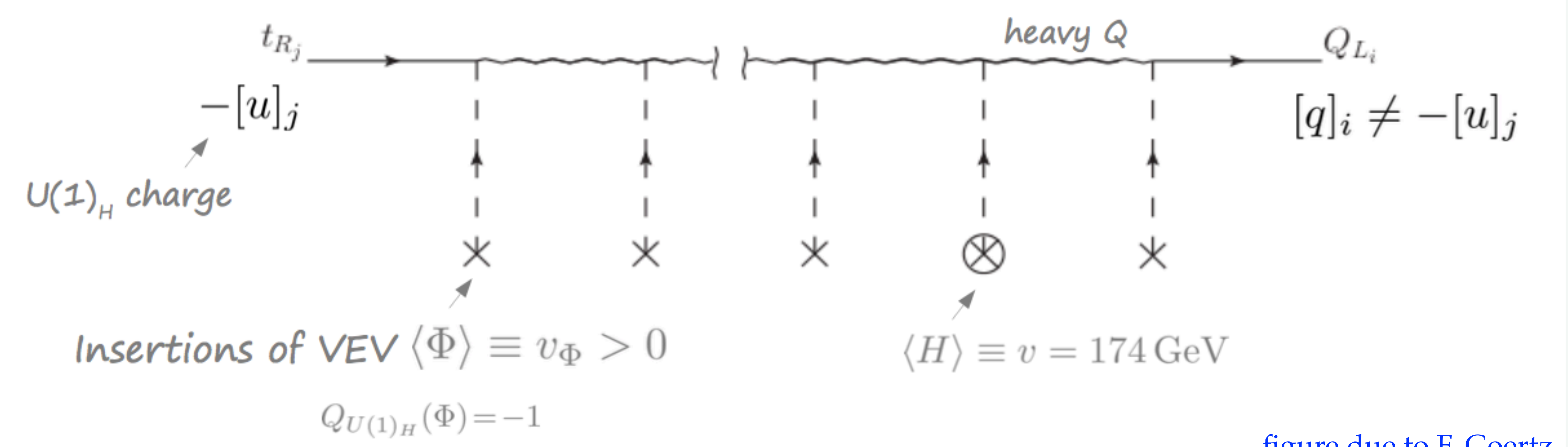
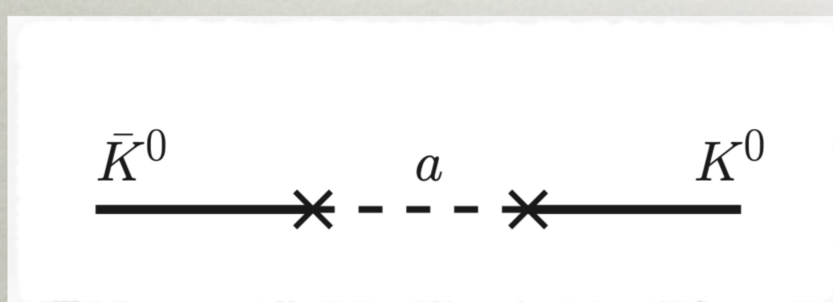
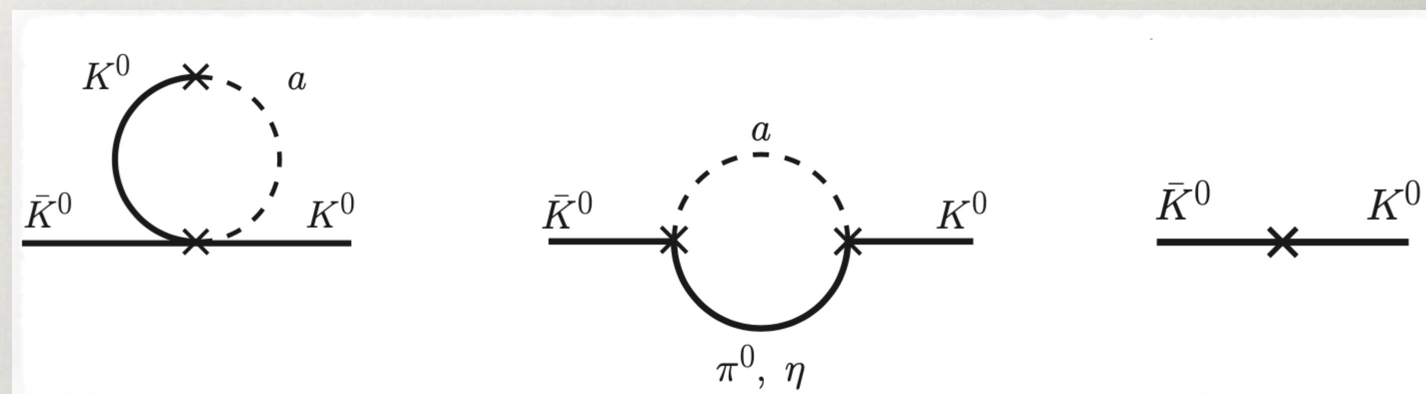


figure due to F. Goertz

KAON MIXING

- use ChPT, work to NLO
- at LO, sensitive to F^V_{ij}, at NLO to F^A_{ij}
  - results applicable to other light scalar mediators





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

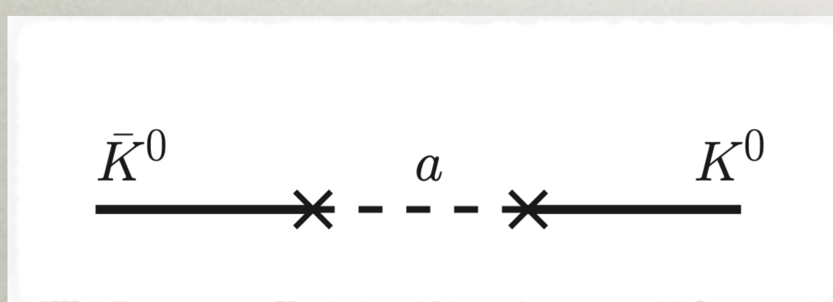
$$M_{12}^A = \left(\frac{f_K}{F_{ds}^A}\right)^2 \frac{m_K}{2} \left\{1 - \frac{2m_K^2}{f_K^2}(\alpha_0 + 2\alpha_1) + \frac{8}{3}\frac{m_K^2}{16\pi^2 f_K^2}\left(1 - \log\left(\frac{m_K^2}{\mu^2}\right)\right)\right\}.$$

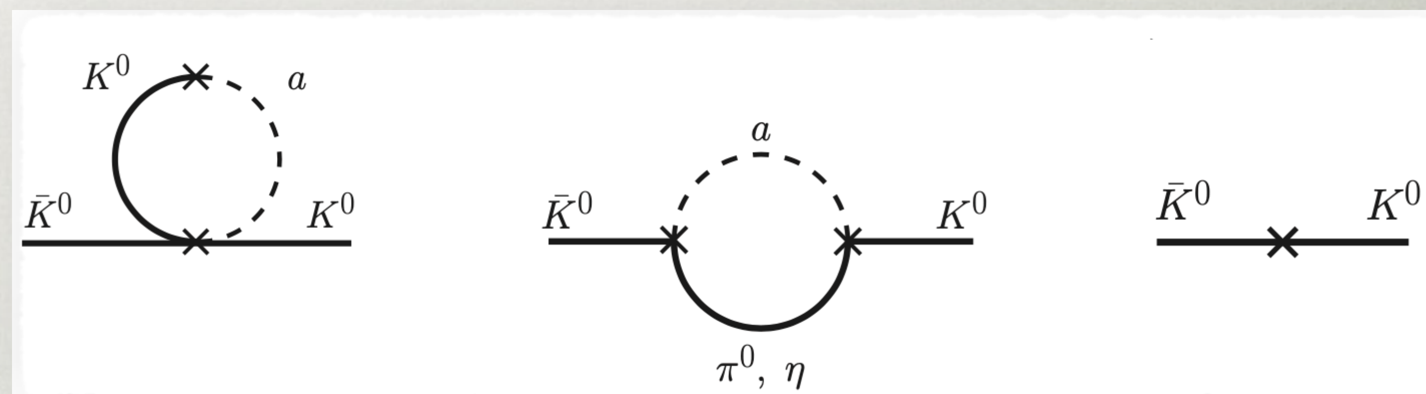
$$M_{12}^V - i\frac{\Gamma_{12}^V}{2} = \left(\frac{f_K}{F_{ds}^V}\right)^2 \frac{m_K}{2}\left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \times \times\left\{\frac{m_K^2}{32\pi^2 f_K^2}\left(I_0(z_\pi) + \tfrac{1}{3}I_0(z_\eta)\right) + \frac{2m_K^2}{f_K^2}(\alpha_0 - 2\alpha_1)\right\}.$$

KAON MIXING

Flavors	Process	F^V_{ij} [GeV]	F^A_{ij} [GeV]
$s \to d$	$K - \overline{K}$ (Δm_K)	5.1×10^5 †	2.0×10^6
	(ϵ_K)	0.9×10^6 †	$\mathbf{4.4 \times 10^7}$

- use ChPT, work to N
- at LO, sensitive to F^V_{ij}, at NLO to F^A_{ij}
  - results applicable to other light scalar mediators





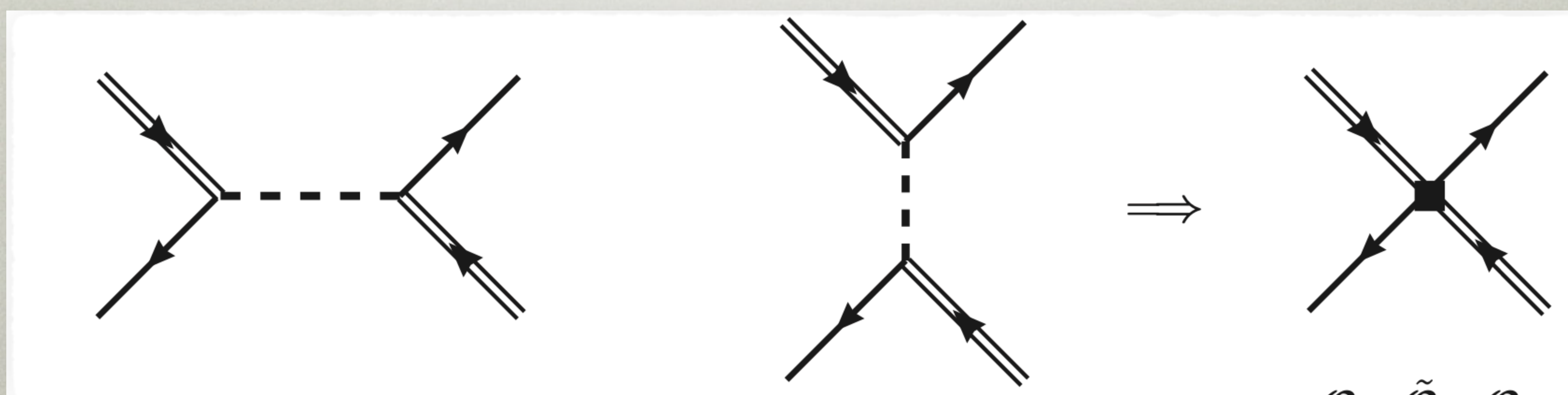
$\frac{5}{6}$ in vacuum insertion approx.

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

$$M^V_{12} - i\frac{\Gamma^V_{12}}{2} = \left(\frac{f_K}{F^V_{ds}}\right)^2 \frac{m_K}{2}\left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \times \times\left\{\frac{m_K^2}{32\pi^2 f_K^2}\left(I_0(z_\pi) + \tfrac{1}{3}I_0(z_\eta)\right) + \frac{2m_K^2}{f_K^2}(\alpha_0 - 2\alpha_1)\right\}.$$

HEAVY MESON MIXING

- since $\Lambda_{\rm QCD}, m_{u,d,s} \ll m_Q$ 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



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

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

ARGUS, 1995

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

Belle, 2017

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

our naive rescaling

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

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

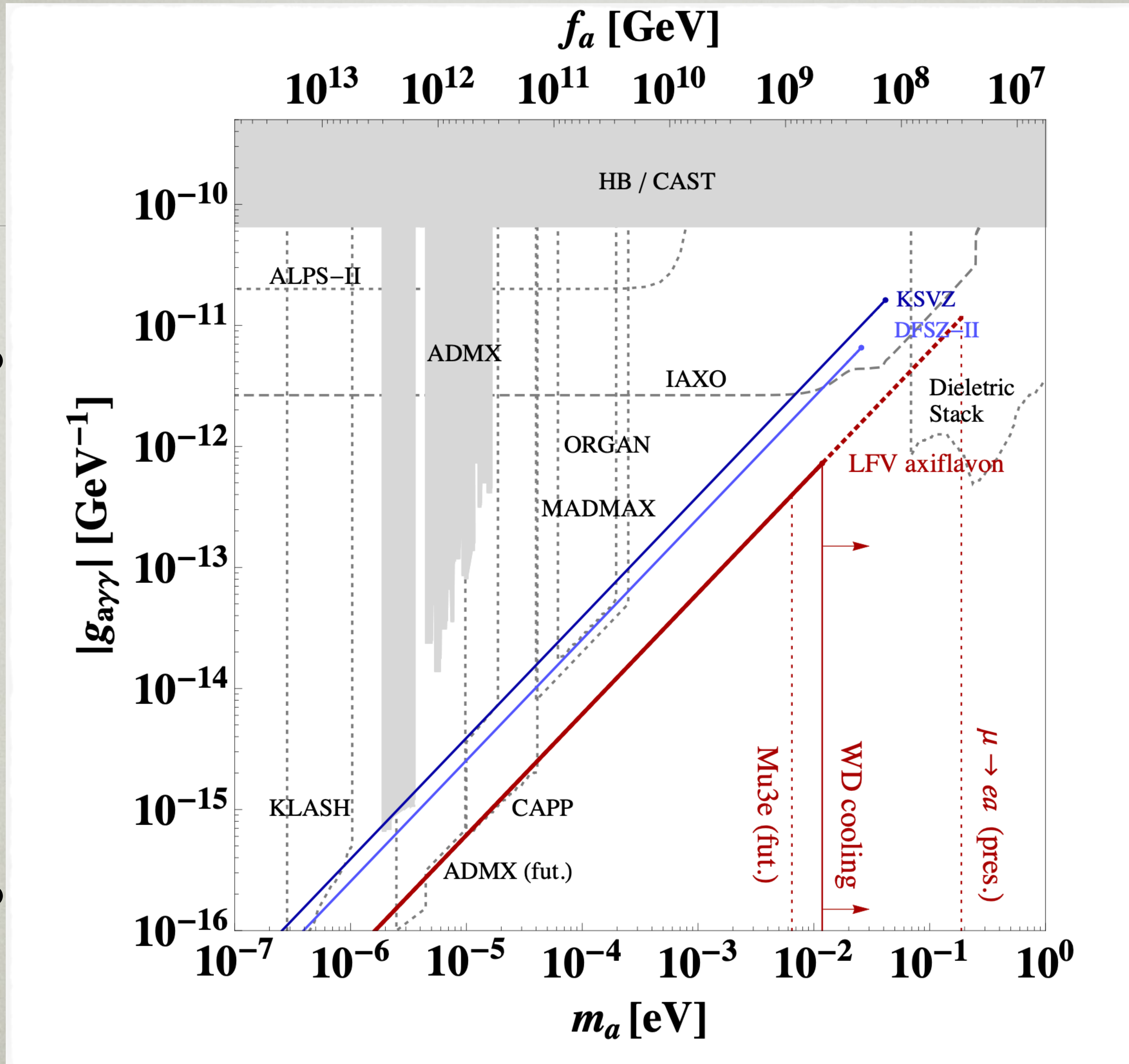
⇒ axion-quark couplings flavor diagonal

- hierarchy of entries external input

LFV 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

•

• r.

LEPTONIC FAMILON

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

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

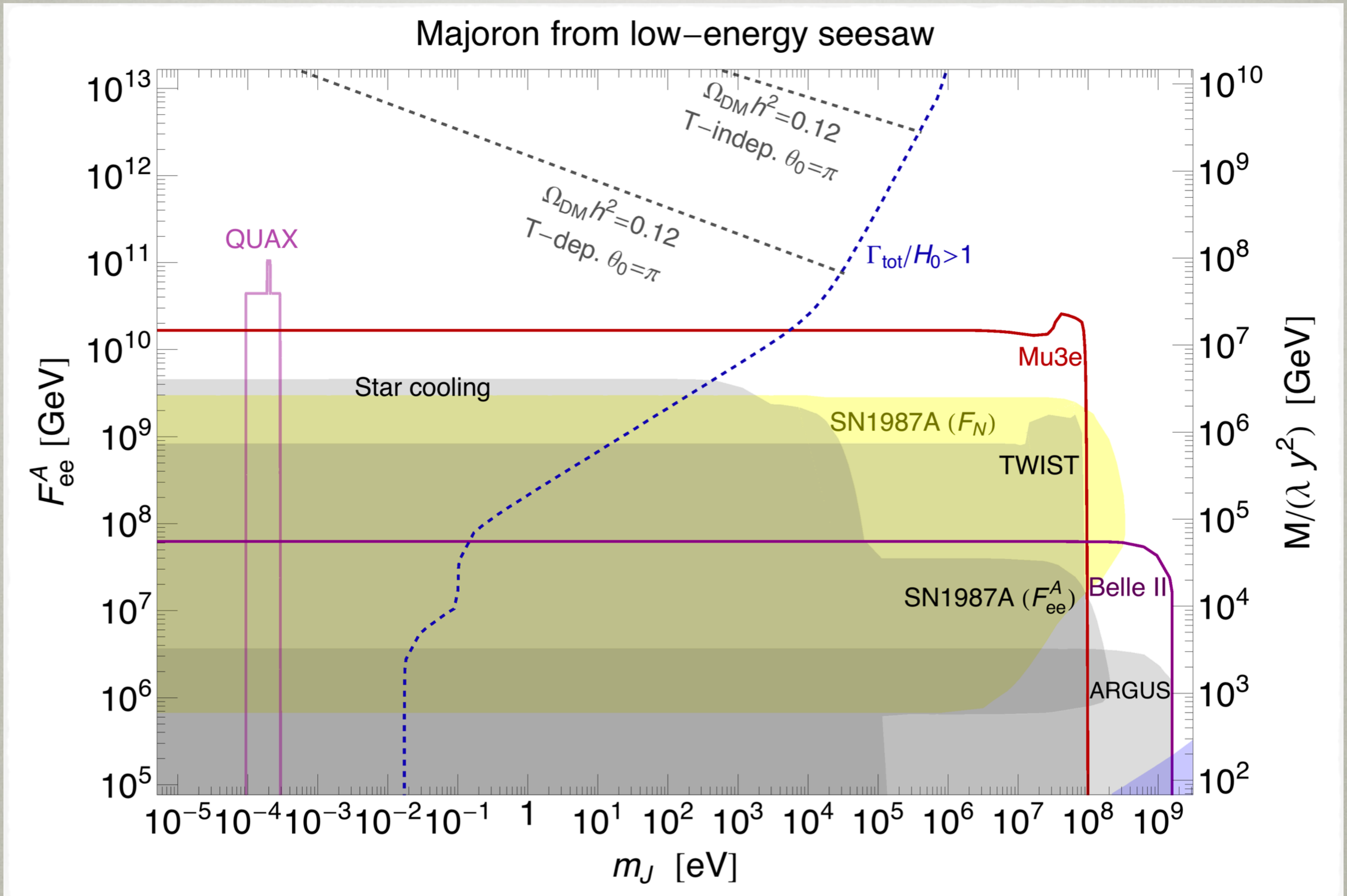
⇒ RH ALP

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

⇒ LH and RH couplings

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