Searching for new physics at $\mu \to e$ facilities with μ^+ and π^+ decays at rest

(and Other selected topics ...)

Jure Zupan
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Hill, Plestid, JZ, 2310.00043

CLFV Searches with the MU2E Experiment, LNF, June 12, 2025

WHY RARE MUON DECAYS?

- #1: impressive experimental progress expected
- #2: high scales probed
  - especially high, if there is light NP

HIGH SCALES

- muon has a long lifetime
  - SM decay widths are power suppressed $\Gamma_\ell \propto m_\ell^5/m_W^4$
- $\mu \to e\phi$ through dim 5 operator $(\bar{\mu}\gamma^\mu e)\partial_\mu\phi/f$
  - parametrically enhanced sensitivity to new physics
- numerical examples
  - $\mathrm{Br}(\mu \to e\phi) < 50\,\% \Rightarrow f \gtrsim 10^7\,\mathrm{GeV}$
  - $\mathrm{Br}(\mu \to e\phi) < 10^{-18} \Rightarrow f \gtrsim 10^{16}\,\mathrm{GeV}$
- reality: somewhere in-between
  - bounds depend on the final state (ϕ decays)

USING MU2E CALIBRATION DATA

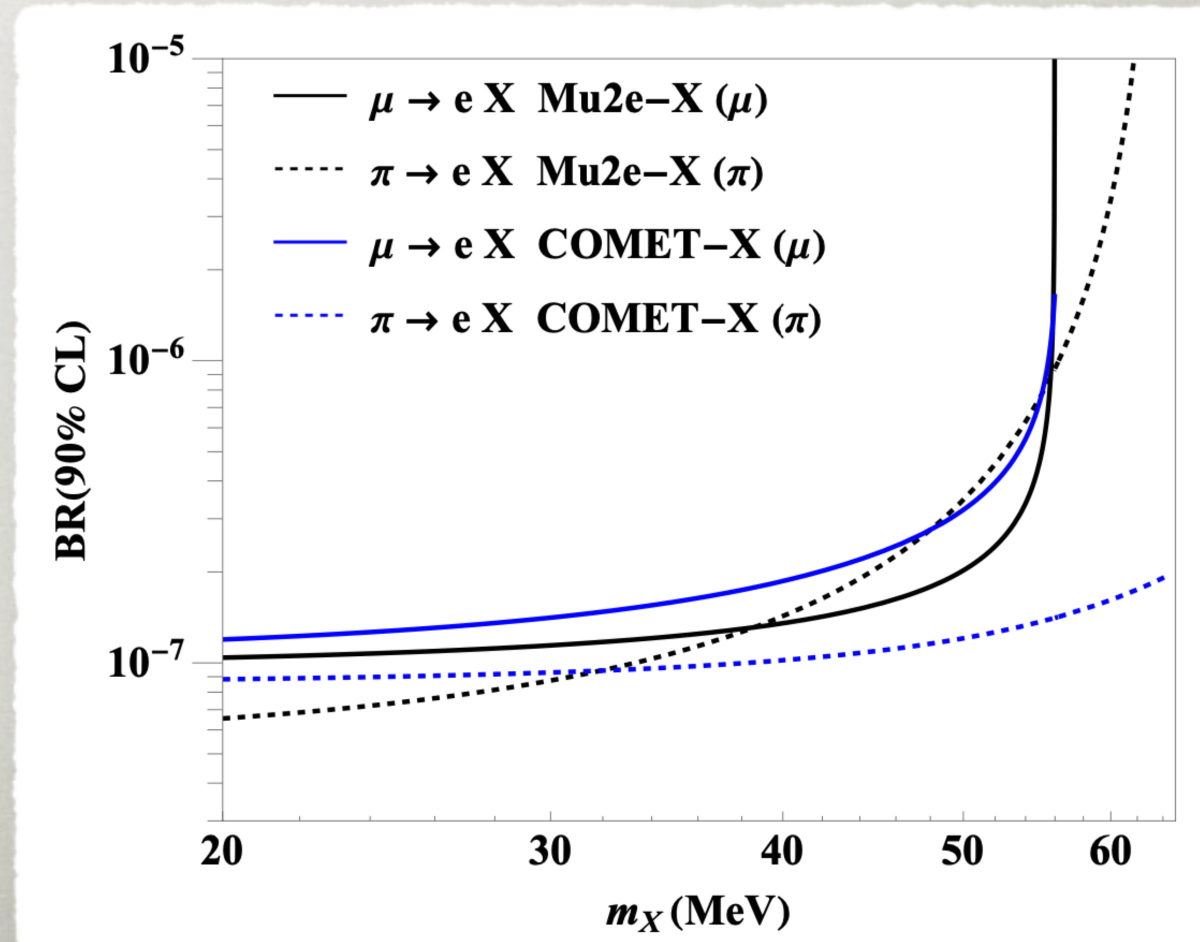
- world leading NP reach possible at Mu2e from a calibration run
  - stopped μ^+ instead of μ^-
  - measure Michel spectrum, operate at <u>1/100th</u> or 1/1000th nominal luminosity

Hill, Plestid, JZ, 2310.00043

Shihua Huang , PhD thesis, Purdue, 2022

- ideal for $\mu \to eX$ and $\pi \to eX$ searches ⇒ Mu2e-X (COMET-X)
  - with 2 weeks of running

Configuration	N_P	B/B_0
Mu2e-X (μ)	3×10^{13}	0.5
Mu2e-X (π)	2×10^{12}	0.76
COMET-X (μ)	1.5×10^{14}	1
COMET-X (π)	9×10^{11}	1



OUTLINE

- light NP and π^+ decays
  - Heavy Neutral Leptons (HNLs)
- light NP and rare μ^+ decays
  - many channels

π^+ AT REST

HEAVY NEUTRAL LEPTONS

Hill, Plestid, JZ, 2310.00043

- one of the three renormalizable portals

$$\mathcal{L} \supset y_N (LH) N + \text{h.c.},$$

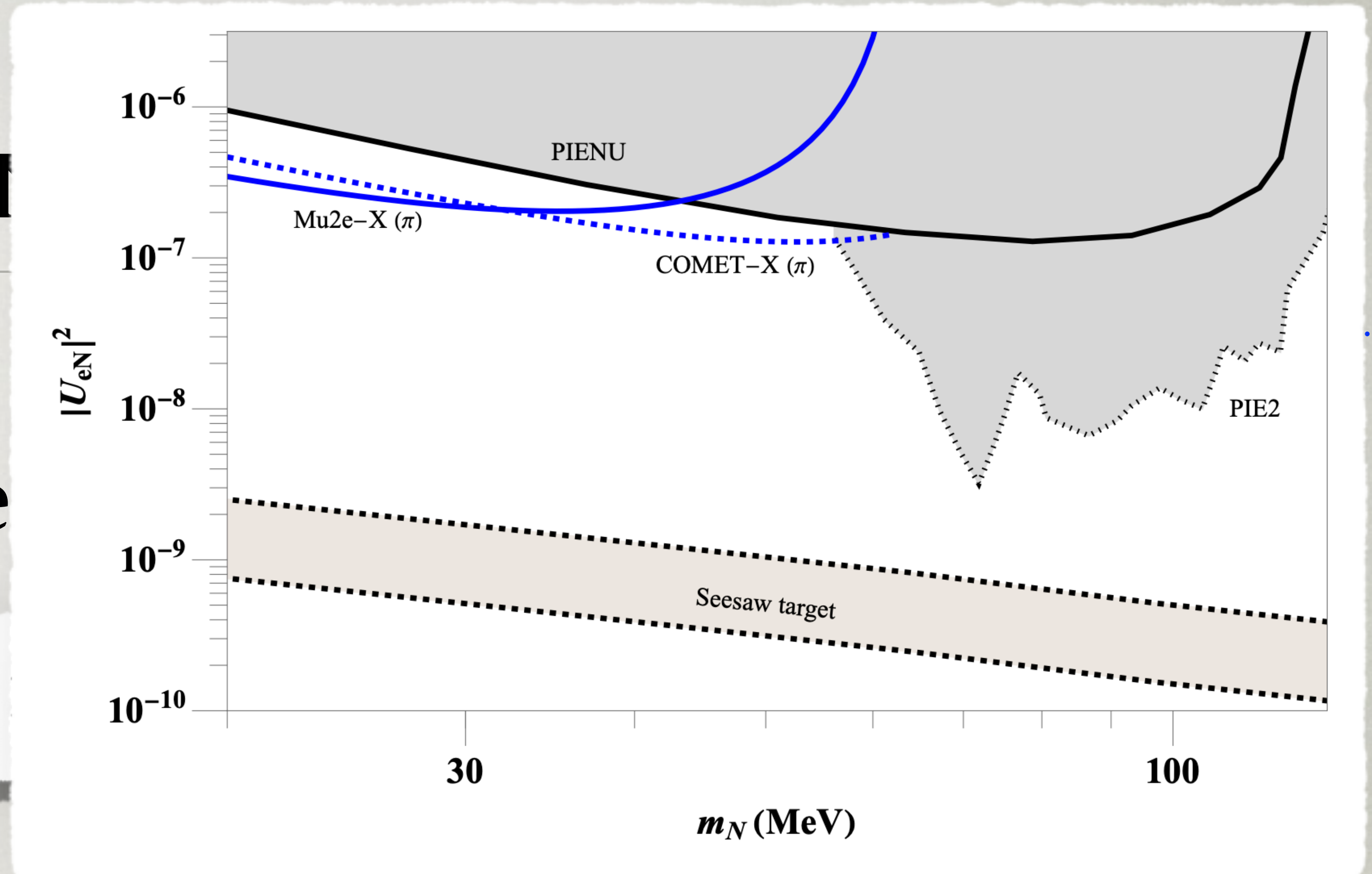
- search for $\pi^+ \to \ell^+ N$ decays
  - $\pi^+ \to e^+ N$, chiral suppression lifted (cf. SM $\pi^+ \to e^+ \nu_e$)
- Mu2e-X can improve on PIENU

HEAVY N

.00043

- one of the

$\mathcal{L}$



- search for $\pi^+ \to \ell^+ N$ decays
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- Mu2e-X can improve on PIENU

μ^+ AT REST

MANY CHANNELS

- muon can only decay to e, γ, inv $\Rightarrow$ a "finite" numb. of differ. observable signatures

MEG-II   MEG, 2005.00339

Mu3e

2306.15631

$e\backslash\gamma$	0	1	2	3	4
1		$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$\dots$	
5	$5e$	$5e\gamma$	$\dots$		
7	$7e$	$\dots$			
$\dots$					

Greljo, Palavrić, Tunja, JZ, work in progress

- other options
  - displaced vertices in $\mu \to 3e$ — Knapen, Opferkuch, Redigolo, Tammaro, 2410.13941
  - $\mu \to 3ea$ — Knapen, Langhoff, Opferkuch, Redigolo, 2311.17915
  - BNV annihilation $\mu^- p \to$ dark sect. — Fox, Hostert, Menzo, Pospelov, JZ, 2407.03450
  - ....

SUPPRESSION SCALES

- assume a single light particle, $\mathrm{BR}(\mu \to eX) \sim 10^{-15}$
  - singlet light scalar S
  - or sterile fermion N

Greljo, Palavric, Tunja, JZ, work in progress

$\mathcal{L}_{\text{eff}} \supset$	$\Lambda \sim$
$\frac{\mathcal{C}_1}{\Lambda}(\bar{\ell}_2 H e_1)\,\mathcal{S}$	$\mathcal{O}(10^{14})$ TeV
$\frac{\mathcal{C}_2}{\Lambda^2}(\bar{\ell}_2 H e_1)\,\mathcal{S}^2$	$\mathcal{O}(10^{4})$ TeV
$\frac{\mathcal{C}_3}{\Lambda^3}(\bar{\ell}_2 H e_1)\,\mathcal{S}^3$	$\mathcal{O}(10)$ TeV
$\frac{\mathcal{C}_4}{\Lambda^4}(\bar{\ell}_2 H e_1)\,\mathcal{S}^4$	$\mathcal{O}(0.8)$ TeV
$\frac{\mathcal{C}_1}{\Lambda^2}(\bar{\ell}_2 \gamma^\mu \ell_1)(\bar{N}\gamma_\mu N)$	$\mathcal{O}(10^{3})$ TeV
$\frac{\mathcal{C}_2}{\Lambda^6}(\bar{\ell}_2 H e_1)(\bar{N}\gamma_\mu N)(\bar{N}\gamma^\mu N)$	$\mathcal{O}(1.1)$ TeV

- a finite number of operators before NP scale becomes uncomfortably low

MODELS

- several concrete models
  - LFV axion-like particle: $\mu \to e\phi_{\text{inv}}$
  - gauged $U(1)_{\mu-e}$: $\mu \to 5e$
  - time dependent $\mu \to e\phi_{\text{inv}}$
  - ...

LFV ALP

see, e.g., Calibbi, Redigolo, Ziegler, JZ, 2006.04795

AXION LIKE MODELS

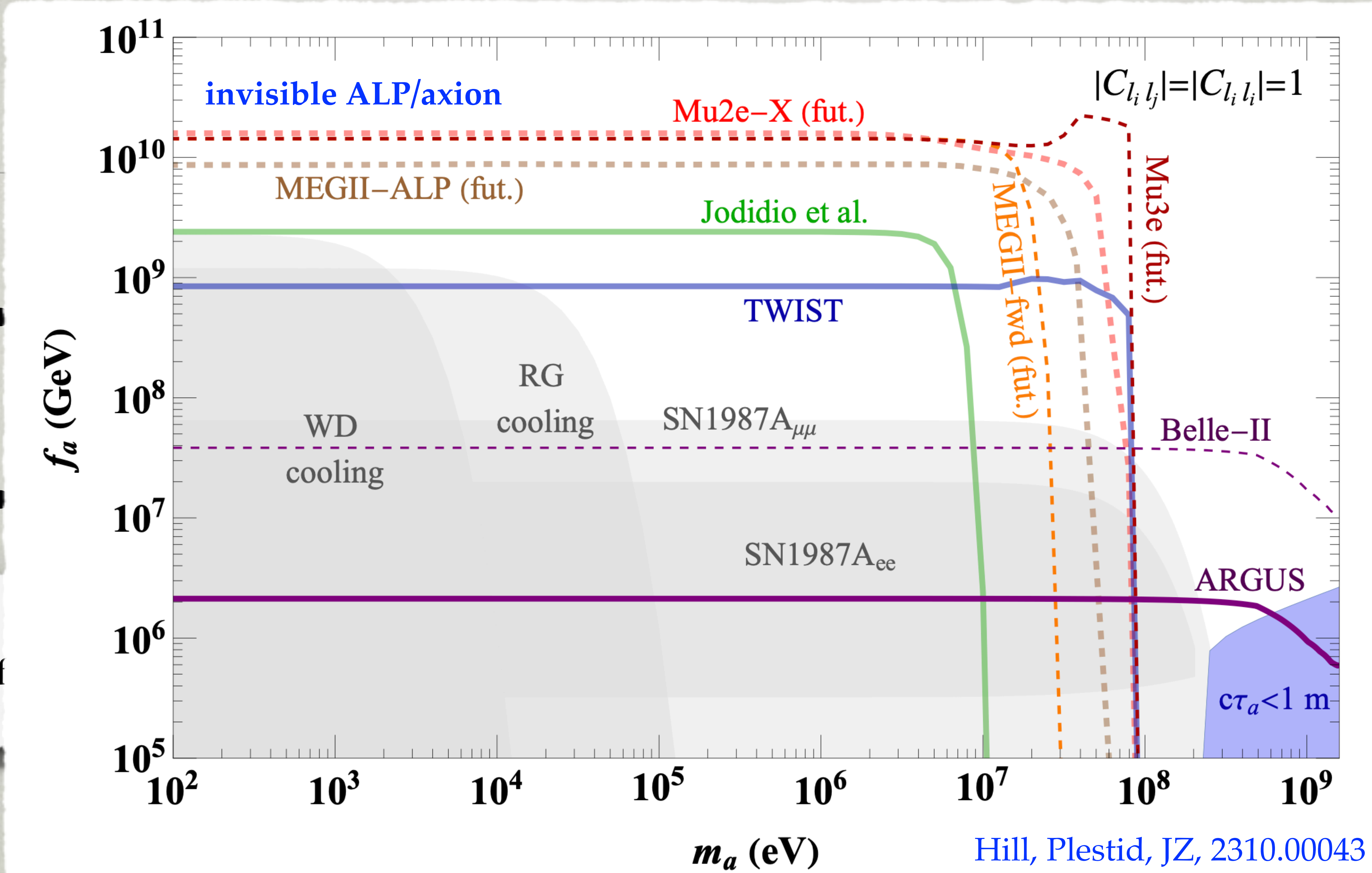
- any spontaneously broken global symmetry ⇒ (p)NGB
  - if "light enough" can be DM
- in general couplings to gluons, photons, SM fermions

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

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

- in general ALPs will have flavor violating couplings
  - here focus on enhanced couplings to leptons

see, e.g., Calibbi, Redigolo, Ziegler, JZ, 2006.04795



Hill, Plestid, JZ, 2310.00043

- in general ALPs will have flavor violating couplings
    - here focus on enhanced couplings to leptons

LFV QCD axion

Calibbi, Redigolo, Ziegler, Zupan, 2006.04795

- 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**

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

$\Rightarrow$ gives lepton FV coupl.s of axion

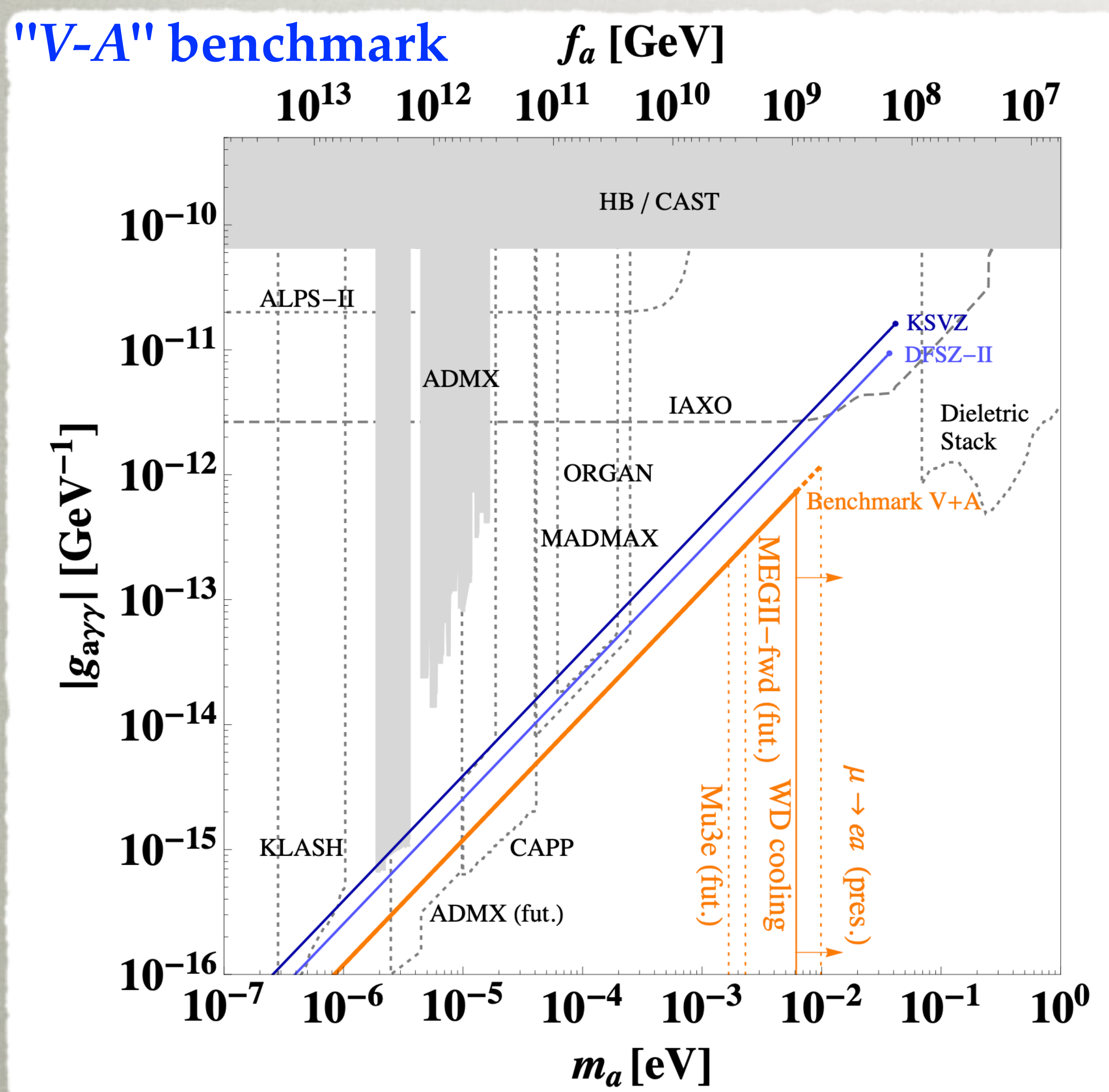
$$y_u = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}, \quad y_d = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

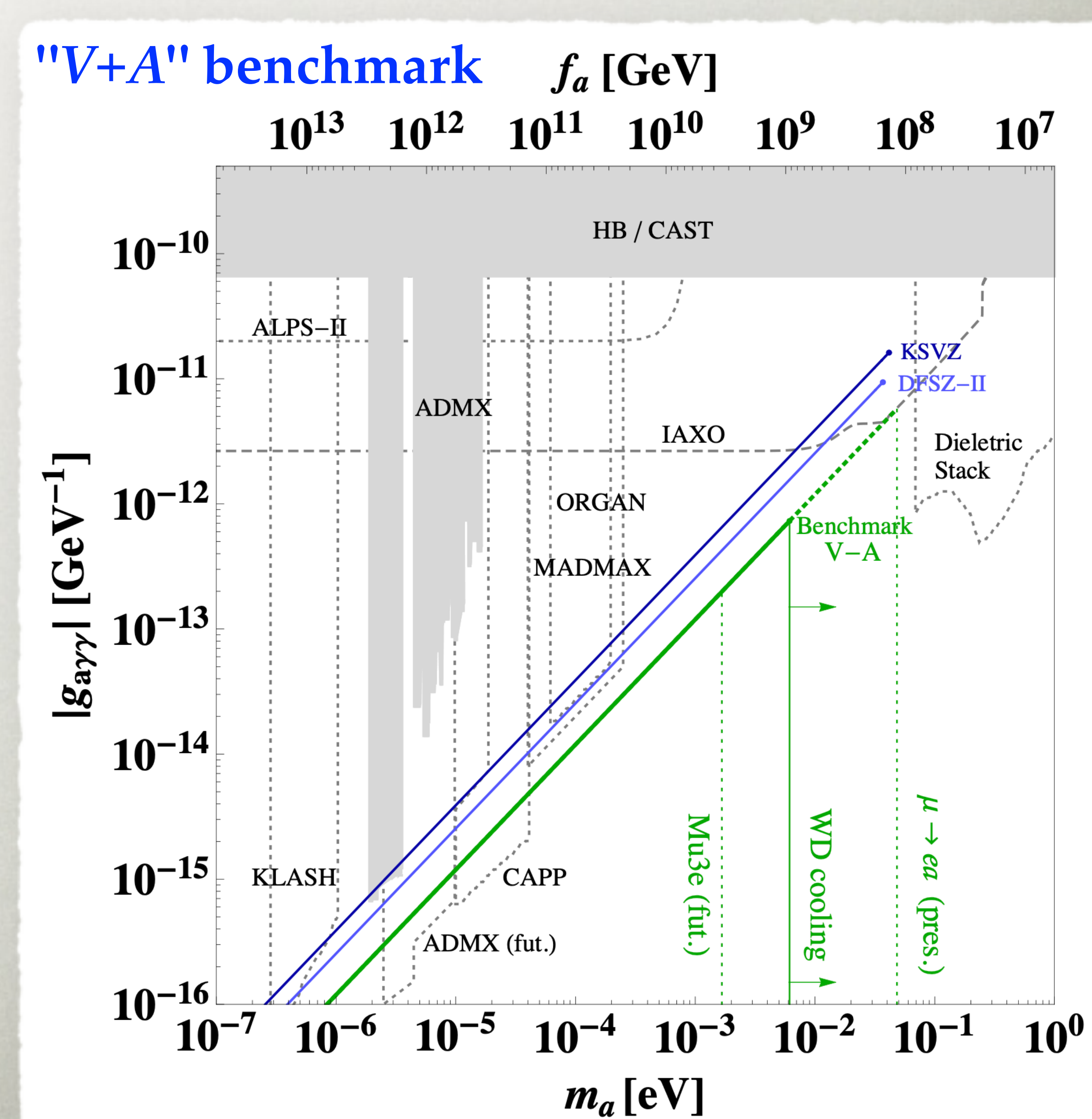
$\Rightarrow$ axion-quark couplings flavor diagonal

- hierarchy of entries external input

LFV QCD axion

- two benchmarks, assume just 1-2 mixing





GAUGED $U(1)_{\mu-e}$

$\mu \to 5e$

- $U(1)_{\mu-e}$ a natural model for $\mu \to 5e$

MEG-II ($\to e\gamma$)   MEG, 2005.00339 ($\to e2\gamma$)

Mu3e ($\to 3e$)

2306.15631 ($\to 5e$)

$e\backslash\gamma$	0	1	2	3	4
1		$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$\dots$	
5	$5e$	$5e\gamma$	$\dots$		
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$\dots$					

Greljo, Palavrić, Tunja, JZ, work in progress

Greljo, Palavrić, Tunja, JZ, work in progress

$U(1)_{\mu-e}$

Field	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mu-e}$
ℓ_1	**2**	-1/2	-1
ℓ_2	**2**	-1/2	1
ℓ_3	**2**	-1/2	0
e_1	**1**	-1	-1
e_2	**1**	-1	1
e_3	**1**	-1	0
H	**2**	1/2	0
Φ	**1**	0	2

- add to the SM
  - $U(1)_{\mu-e}$ gauge group
  - a scalar Φ that Higgses it
- SM fermion Yukawas allowed
  - in addition dim-5 FV terms

$$-\mathcal{L}_Y = \hat{y}_{ii}\left(\bar{\ell}_i H e_i\right) + \frac{y_5^{e\mu}}{\Lambda}\Phi^\dagger\left(\bar{\ell}_1 H e_2\right) + \frac{y_5^{\mu e}}{\Lambda}\Phi\left(\bar{\ell}_2 H e_1\right) + \text{h.c.}.$$

- charged lepton mass matrix

$$\mathcal{M} = \frac{v_{\rm EW}}{\sqrt{2}}\begin{pmatrix} \hat{y}_{ee} & y_5^{e\mu}\frac{v_\Phi}{\sqrt{2}\Lambda} & 0 \\ y_5^{\mu e}\frac{v_\Phi}{2\Lambda} & \hat{y}_{\mu\mu} & 0 \\ 0 & 0 & \hat{y}_{\tau\tau} \end{pmatrix}.$$

IN MASS BASIS

- after lepton mass diagonalization

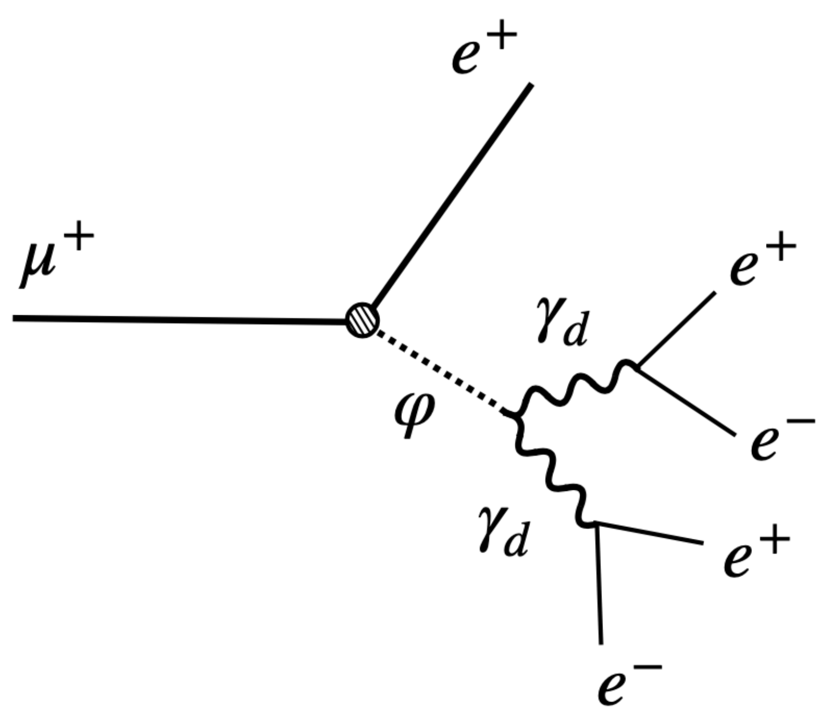
$$\Phi = (v_\Phi + \varphi)/\sqrt{2},$$

$$\mathcal{L}_Y \supset (\bar{\ell}_L y_\varphi e_R)\varphi + \text{h.c.},$$

$$y_\varphi = \begin{pmatrix} \mathcal{O}(y_5^2/\Lambda^2) & \mathcal{O}(y_5/\Lambda) & 0 \\ \mathcal{O}(y_5/\Lambda) & \mathcal{O}(y_5^2/\Lambda^2) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Greljo, Palavrić, Tunja, JZ, work in progress

- diagonal couplings $\varphi\bar{e}e$, $\varphi\bar{\mu}\mu$ are additionally suppressed
- the dominant mode for φ naturally $\varphi \to 2\gamma_d$
    - $\mu \to 5e$ signature

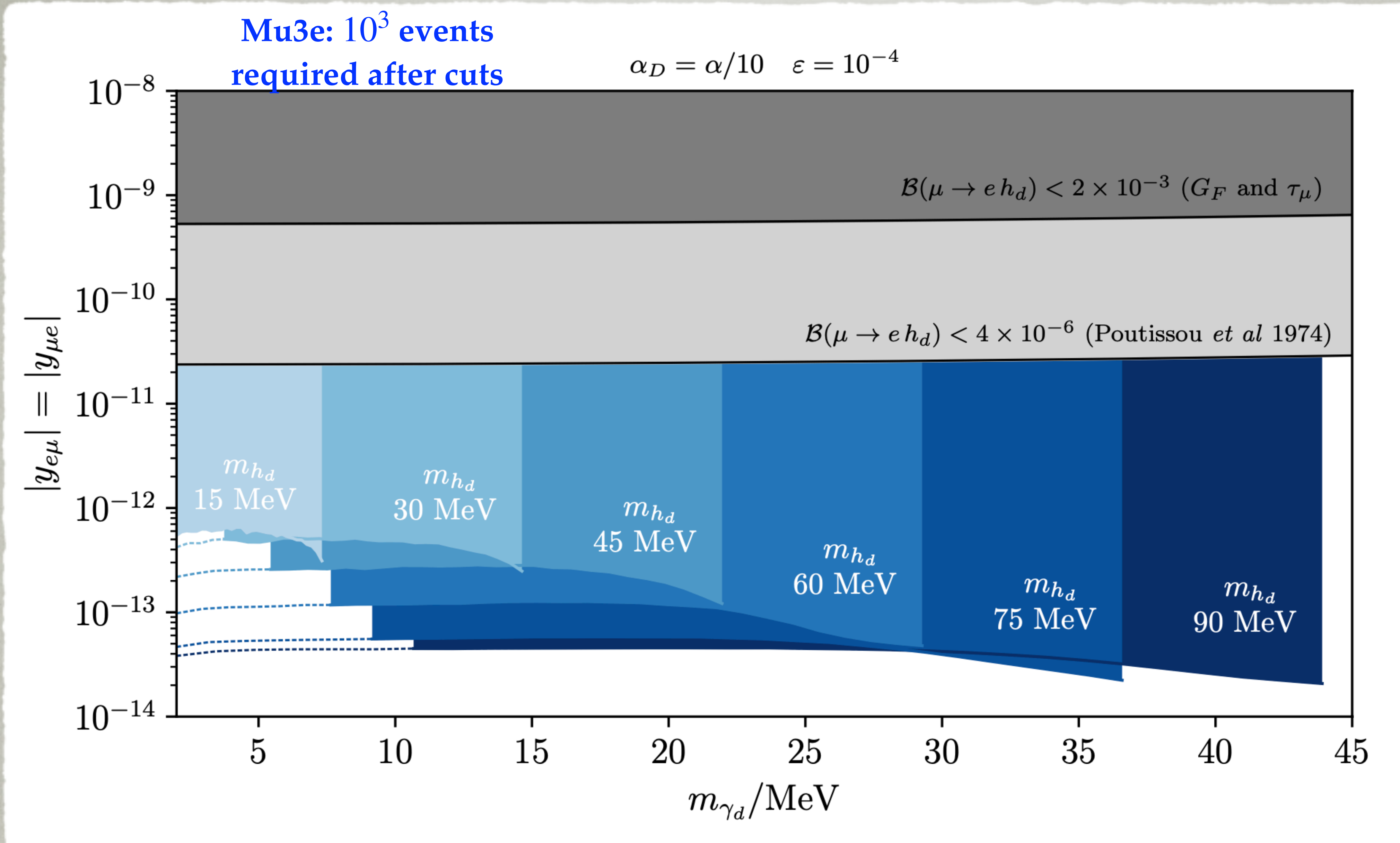


Hostert, Menzo, Pospelov, JZ, 2306.15631

ESTIMATED SENSITIVITY

Hostert, Menzo, Pospelov, JZ, 2306.15631

- for Mu3e: assume $N_\mu = 10^{15}$
- backgrounds
  - intrinsic: $\mu^+ \to 3e^+2e^-2\nu$ suppress to $\mathcal{O}(1)$ evnt level by $E_{\rm miss}$ cuts
  - accidental: simultaneous $\mu \to 3e2\nu$ and $\mu \to e2\nu$ decays with extra e^- from e^+ Bhabha scattering in target
    - $\mathcal{O}(10^3)$ evnts without kinem. cuts
- Mu3e sensivity conservatively set by requiring 10^3 signal evnts. ⇒ $\mathcal{B}(\mu^+ \to e^+ h_d) < 10^{-12}$
  - for $y_5^{e\mu,\mu e} \sim \mathcal{O}(1) \Rightarrow \Lambda \gtrsim 3 \cdot 10^{16}\,\text{GeV}$
- for Mu2e-X this could well still be "zero background" search
  - for O(1) acceptance naively similar sensitivity, $\mathcal{B}(\mu^+ \to e^+ h_d) \sim 10^{-12}$
  - depends on acceptance of relatively soft electrons and positrons



JZ, 2306.15631

s

a e^-

$\mathscr{B}(\mu^+ \to e^+ h_d) < 10$

- for $y_5^{e\mu,\mu e} \sim \mathcal{O}(1) \Rightarrow \Lambda \gtrsim 3 \cdot 10^{16}\,\mathrm{GeV}$
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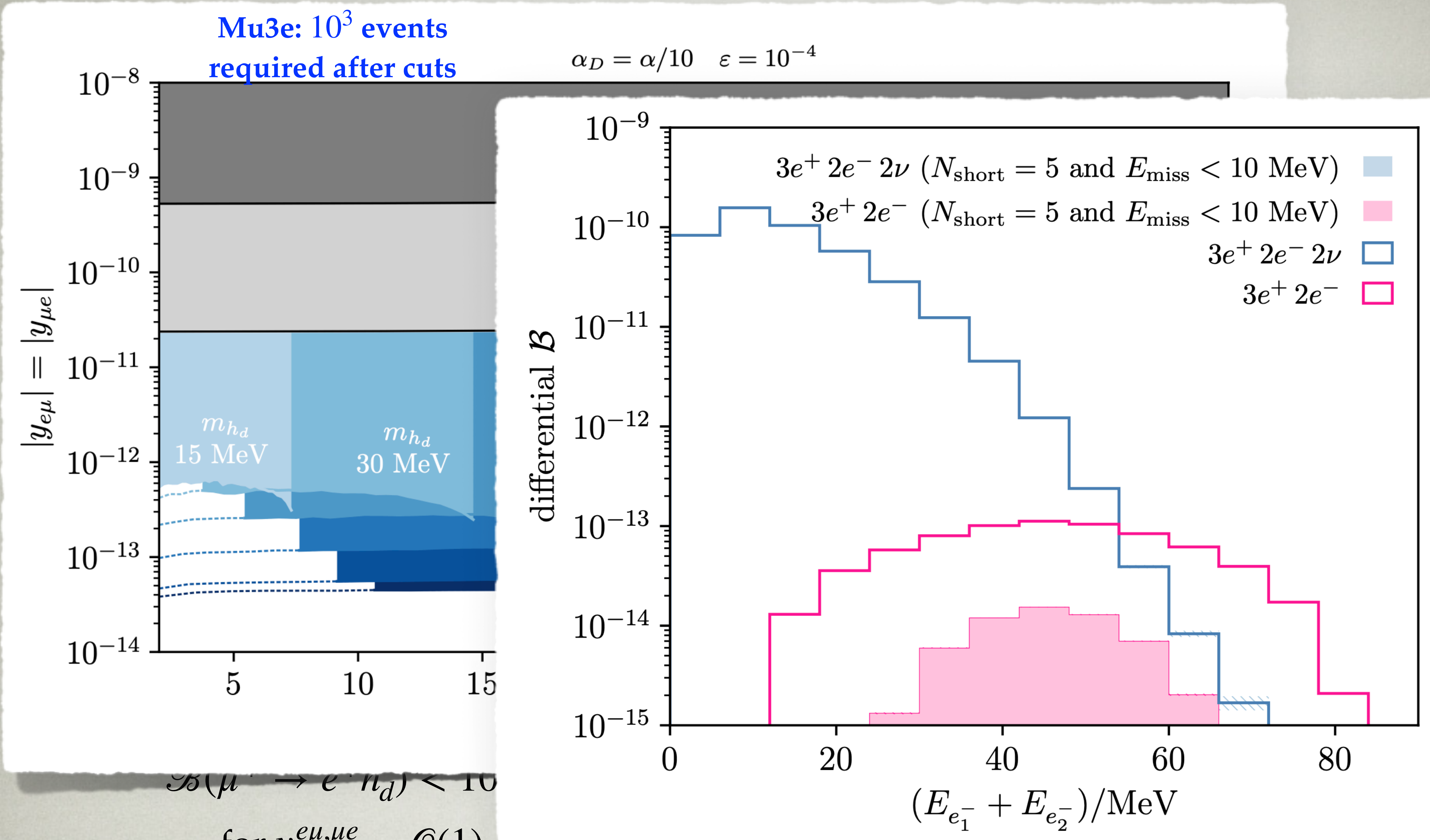


$\mathscr{B}(\mu^+ \to e^+ h_d) < 10$

- for $y_5^{e\mu,\mu e} \sim \mathcal{O}(1) \Rightarrow \Lambda \gtrsim 5 \cdot 10$ GeV

- for Mu2e-X this could well still be "zero background" search
  - for O(1) acceptance naively similar sensitivity, $\mathscr{B}(\mu^+ \to e^+ h_d) \sim 10^{-12}$
  - depends on acceptance of relatively soft electrons and positrons

TIME DEPENDENT

$$\mu \rightarrow e\phi$$

NON-ABELIAN pNGB

Bigaran, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 2503.07722

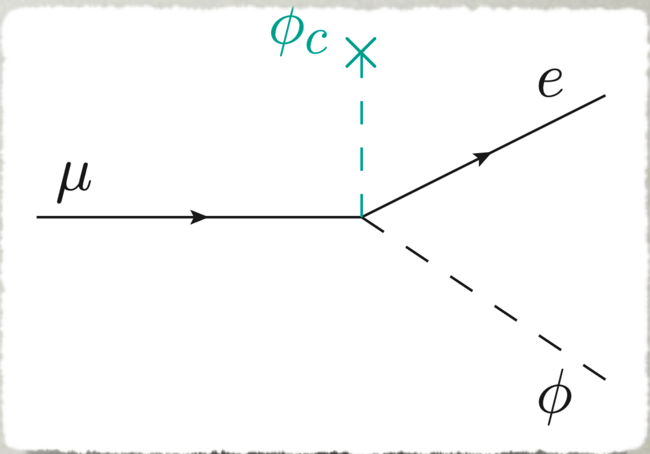
- if DM a non-Abelian pNGB the interactions with the SM of the form

$$\mathcal{L}_{\text{int}} \supset \frac{i\phi_c(\partial_\mu \phi)}{2f^2}\,\bar{\ell}_i\gamma^\mu(C^V_{ij} + C^A_{ij}\gamma_5)\ell_j,$$

  - example in the SM: $\pi^\pm$ interacting with leptons via photon exchange

- classical ϕ background induces time dependent $\mu \to e\phi$ decays

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi}$$



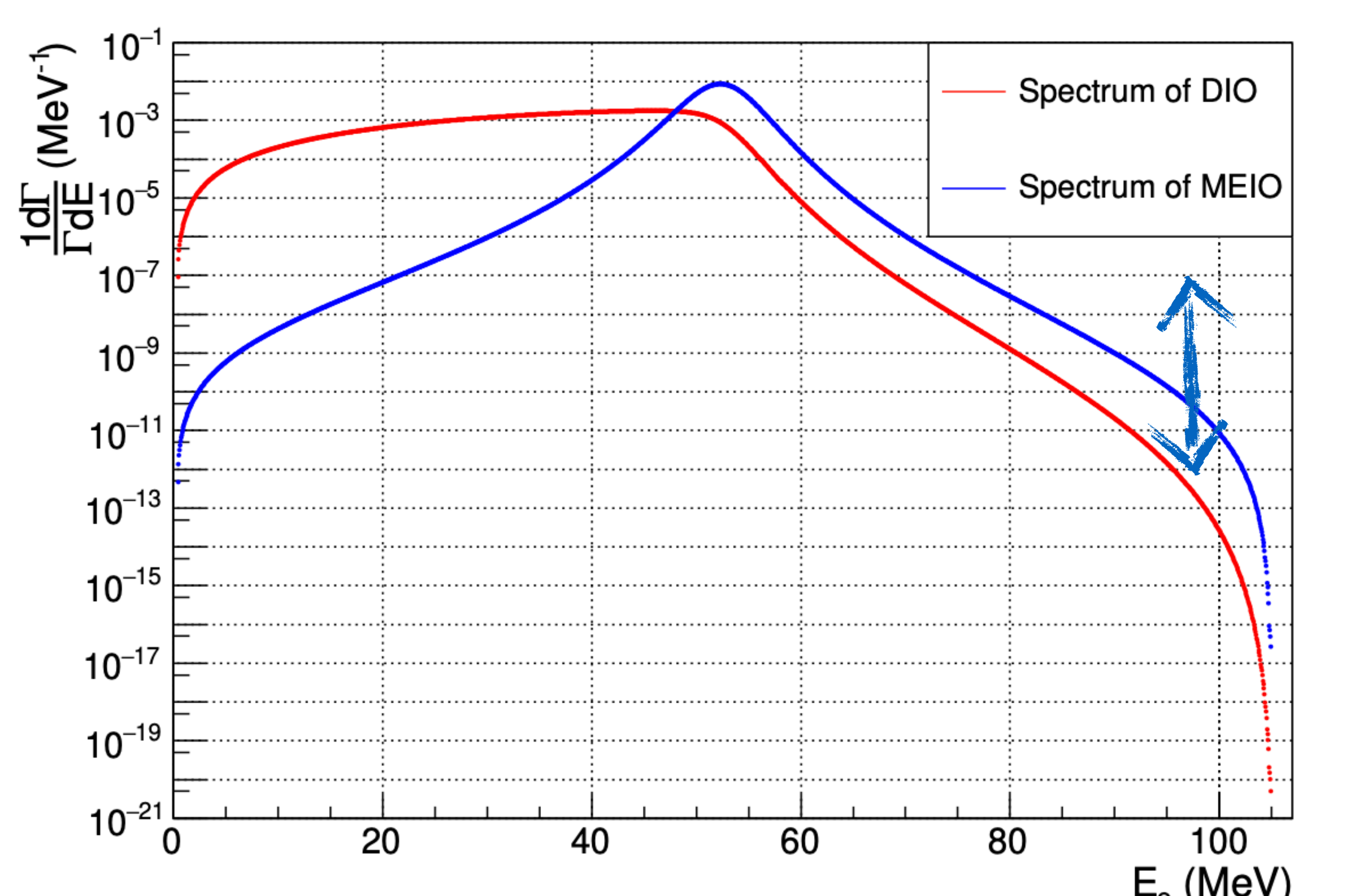
$$\phi_c(t) = \phi_0 \cos(m_\phi t + \delta)$$

  - time dep. searches can be more sensitive ⇔ for systematics dominated searches
  - time dep. a smoking gun signal of DM

TIME DEPENDENT SIGNAL AT MU2E

Bigaran, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 250m.nnnnn

- could search for this with the normal μ^- run of Mu2e
  - search for a small time dependent rate
  - larger acceptance improves the signal
    - how much can one lower the E_e threshold at Mu2e?

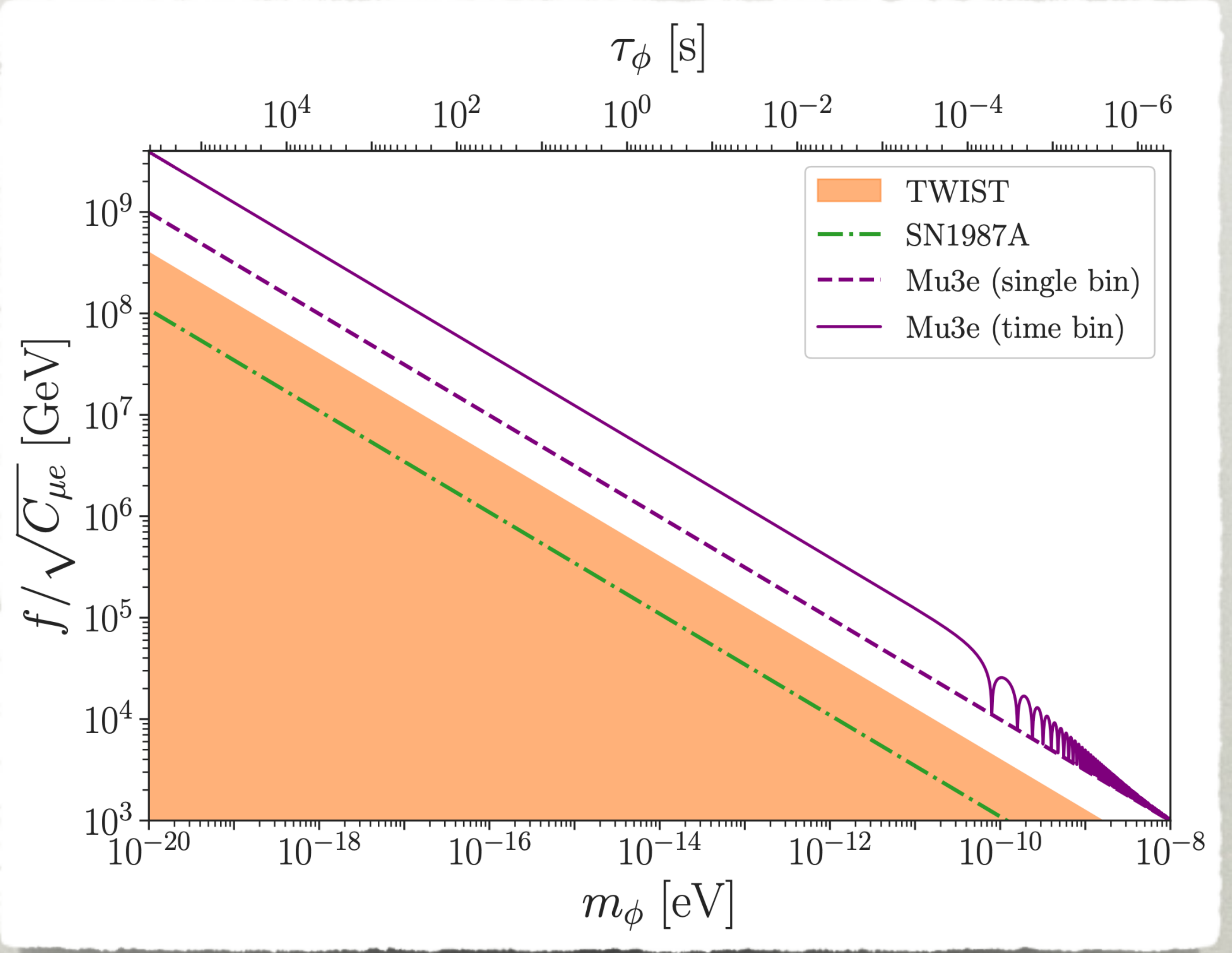


Xing et al, 2209.12802

NON-ABELIAN pNGB

Bigaran, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 2503.07722

- worked out the results for $\mu \to e\phi$ decays in Mu3e experiment

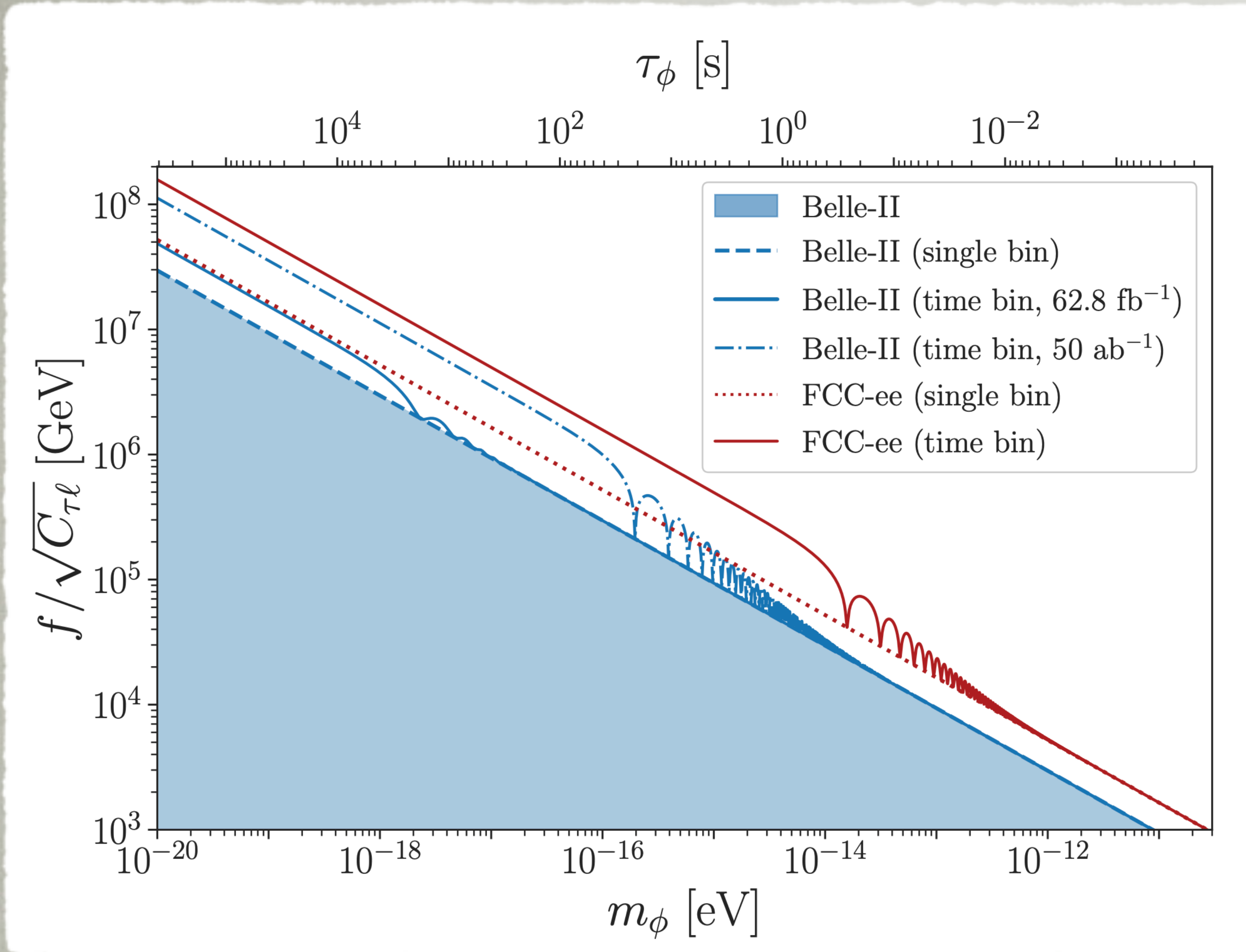


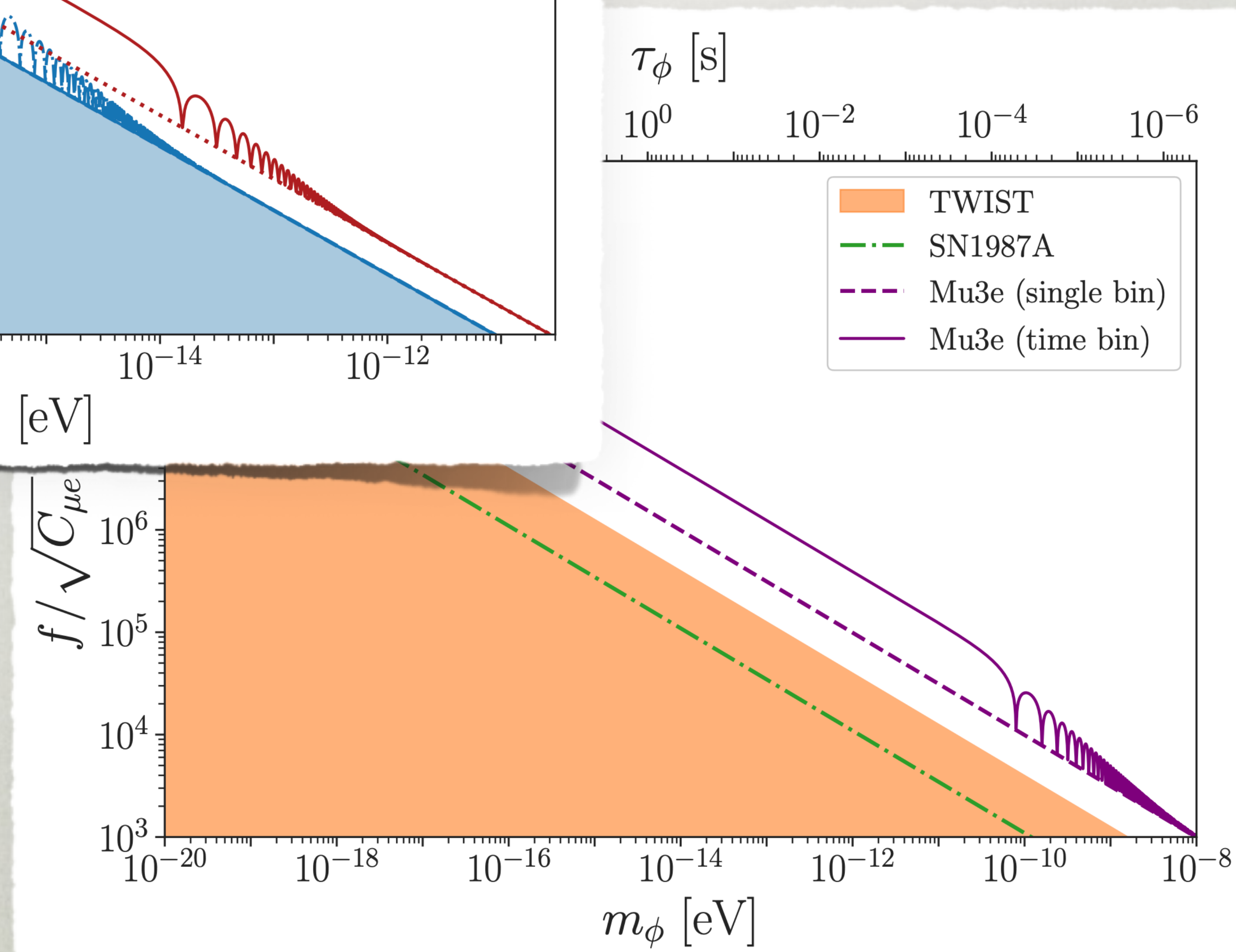
- can also do time dep. $\tau \to \ell\phi$ search at Belle II

N PNGB

Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 2503.07722

$e\phi$ decays in Mu3e





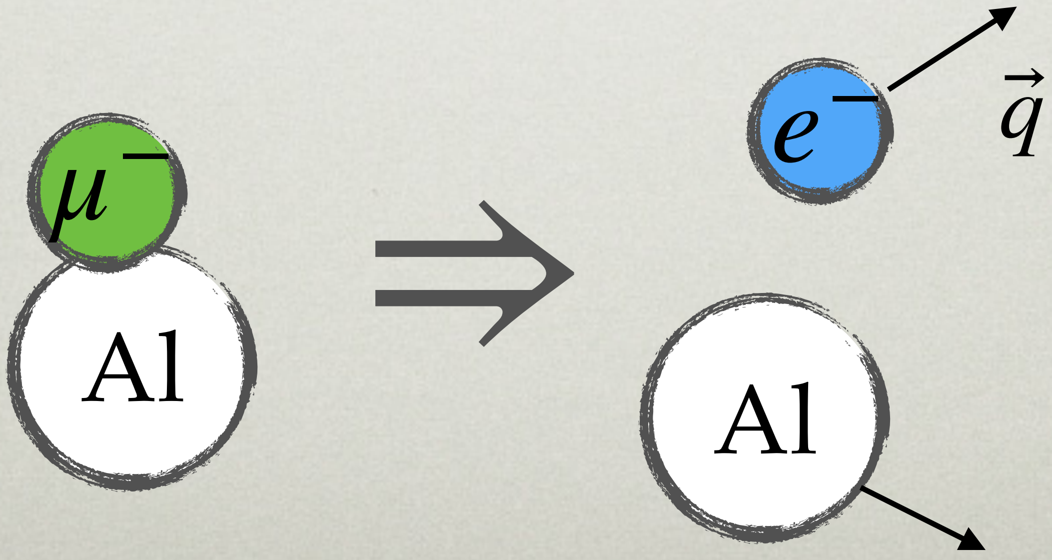
- can also do time dep. $\tau \to \ell\phi$ search at Belle II

BONUS:
EFT BASED $\mu \to e$ PREDICTIONS

$\mu \to e$ KINEMATICS

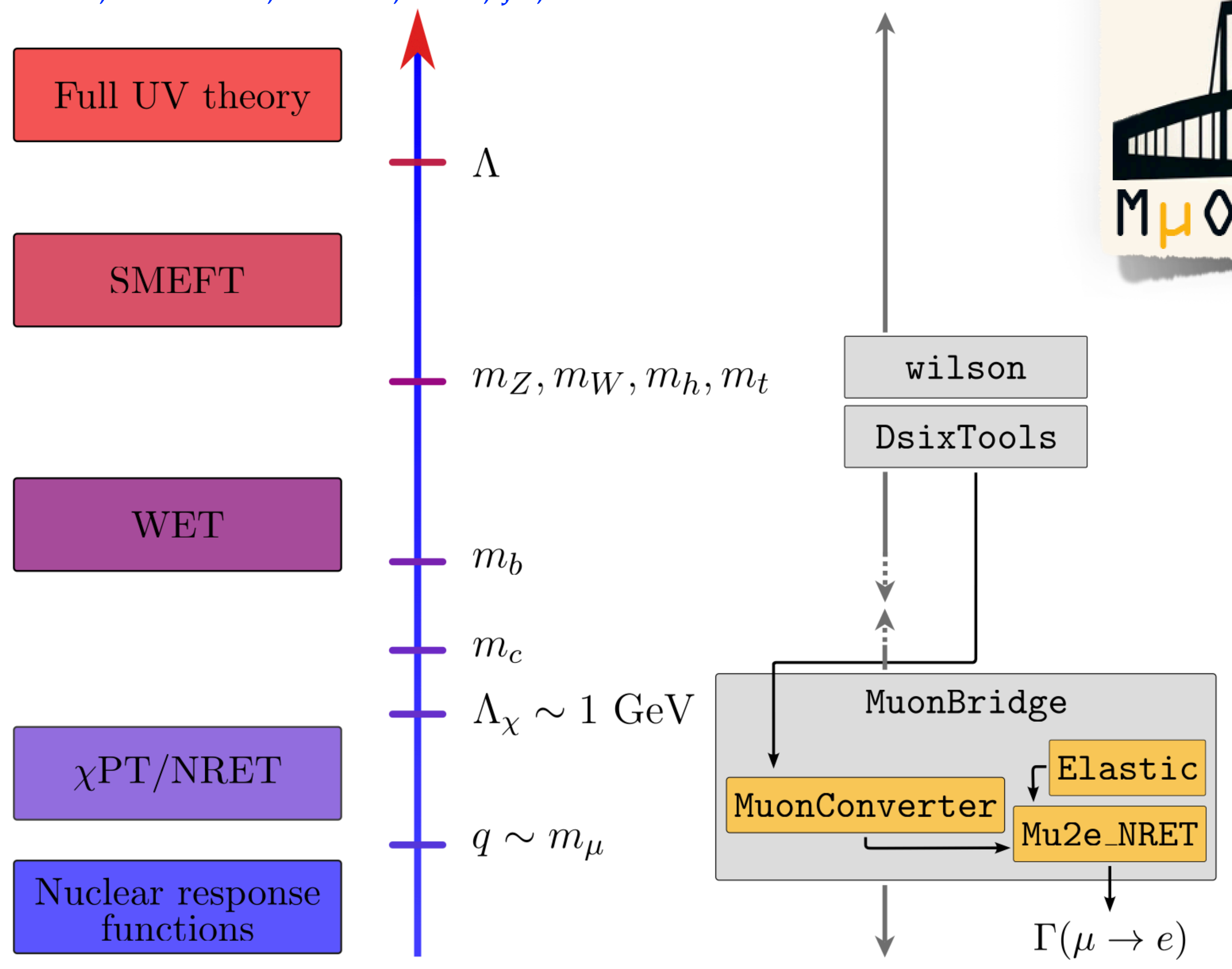
Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- initial state: μ^- in 1s orbital
- final state: relativistic e^- with three momentum
  - $E_\mu^{\text{bind}} \ll m_\mu$ (for ^{27}Al $E_\mu^{\text{bind}} \simeq 0.463\,\text{MeV}$) $\Rightarrow |\vec{q}| \sim \mathcal{O}(100\,\text{MeV})$



TOWER OF EFTS ⇒ MUONBRIDGE CODE

Haxton, McElvain, Menzo, Rule, JZ, 2406.13818



Haxton, McElvain, Ramsey-Mussolf, Rule, 2208.07945
Haxton, McElvain, Rule, 2109.13503
Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

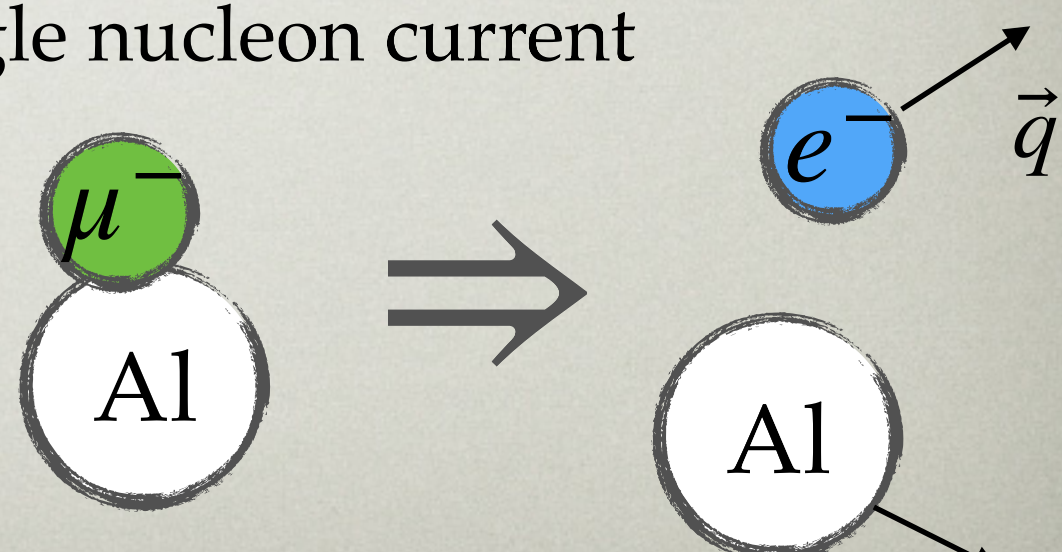
NON-RELATIV. EXPANSION

- a hierarchy of small parameters

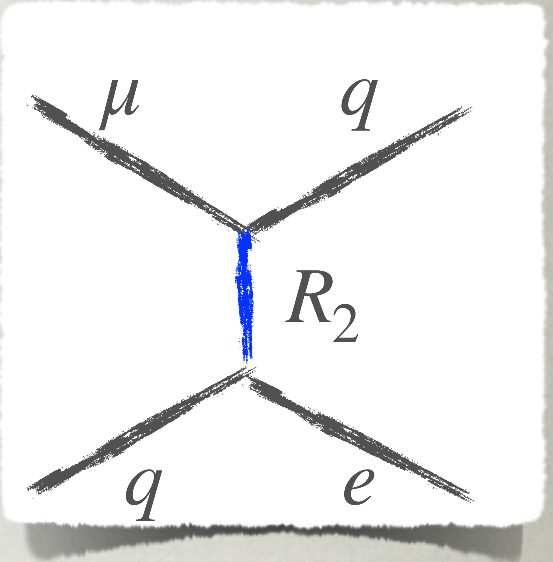
$$y \equiv \left(\frac{qb}{2}\right)^2 > |\vec{v}_N| > |\vec{v}_\mu| > |\vec{v}_T|$$

$b \sim$ nuclear size	$\vec{v}_N = (\vec{k}_1 + \vec{k}_2)/2$ average nucleon velocity	bound muon velocity	velocity of outgoing target nucleus

- $y \sim 0.2 - 0.5 \Rightarrow$ nuclear scales are being probed
- Chiral EFT: interactions with single nucleon current dominate
- can expand in v_N and v_μ
  - we keep $\mathcal{O}(v_N)$, $\mathcal{O}(v_\mu)$ terms



LEPTOQUARK EXAMPLE



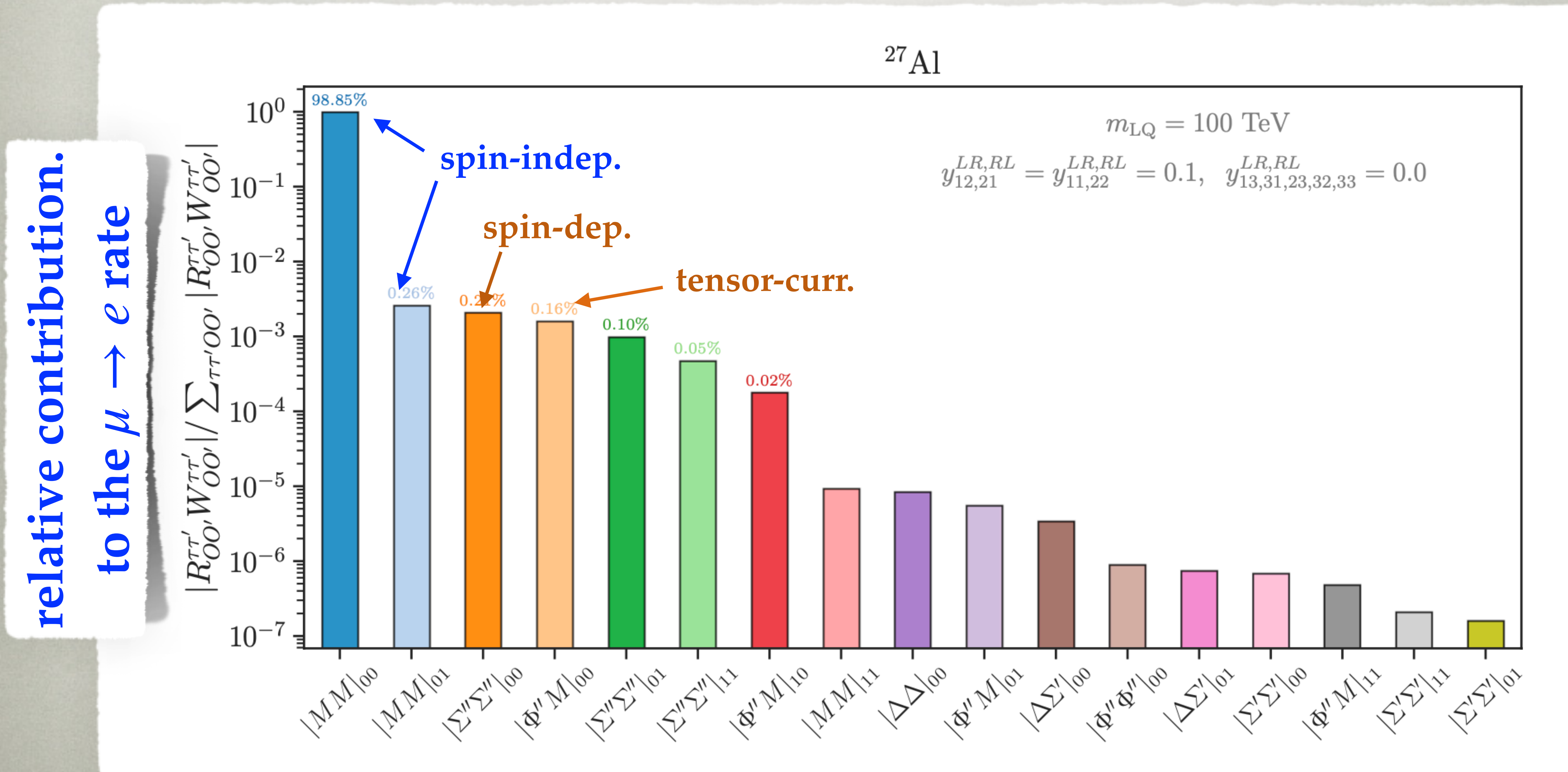
- scalar leptoquark R_2 in the $(3, 2, 7/6)$ of the SM gauge group

$$\mathcal{L} \supset y_{2\,ij}^{RL}\, \bar{u}_R^i R_2 L_L^j + y_{2\,ij}^{LR}\, \bar{e}_R^i R_2^* Q_L^j + \text{h.c.},$$

- integrating out $R_2 \Rightarrow$ generates all 10 dim 6 ops in WET
  - including tensor currents
  - these have coherently enhanced contribs. at subleading powers in v_N, $v_\mu \Rightarrow$ kept in **MuonBridge**

DIFFERENT CONTRIBS.

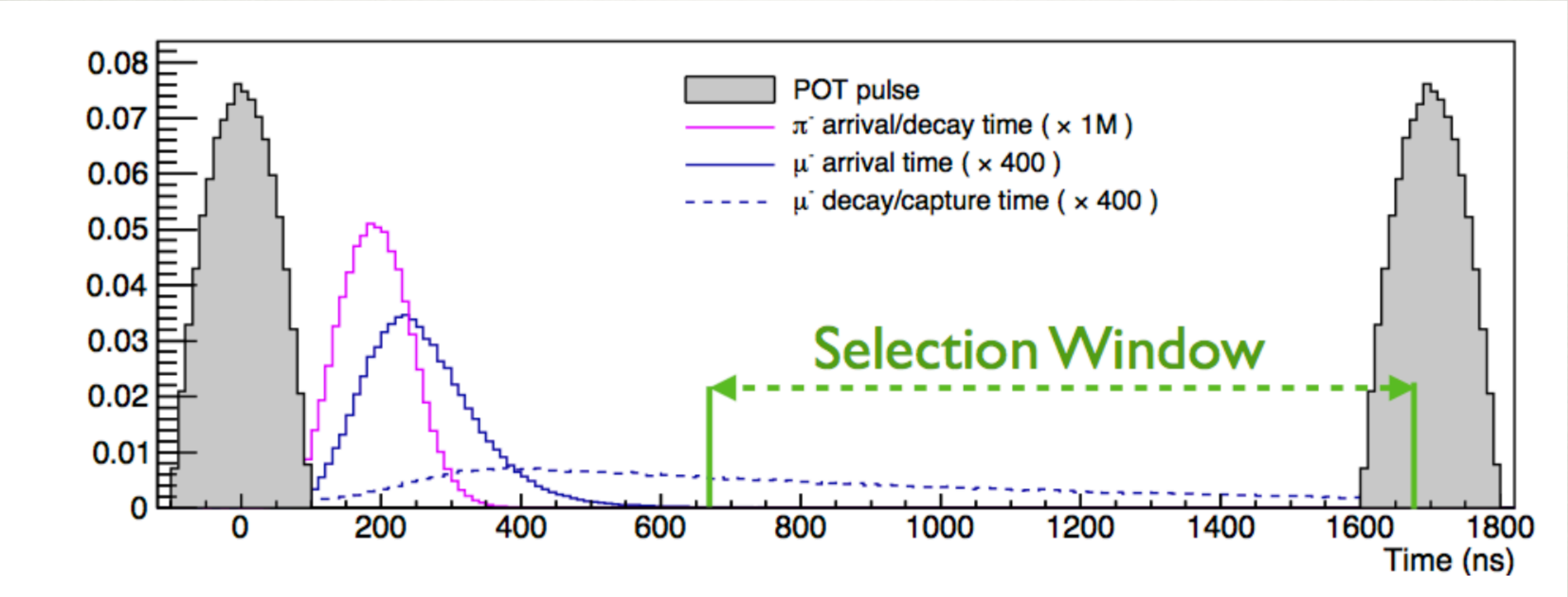
- typical point in the parameter space is dominated by spin independent contrib.



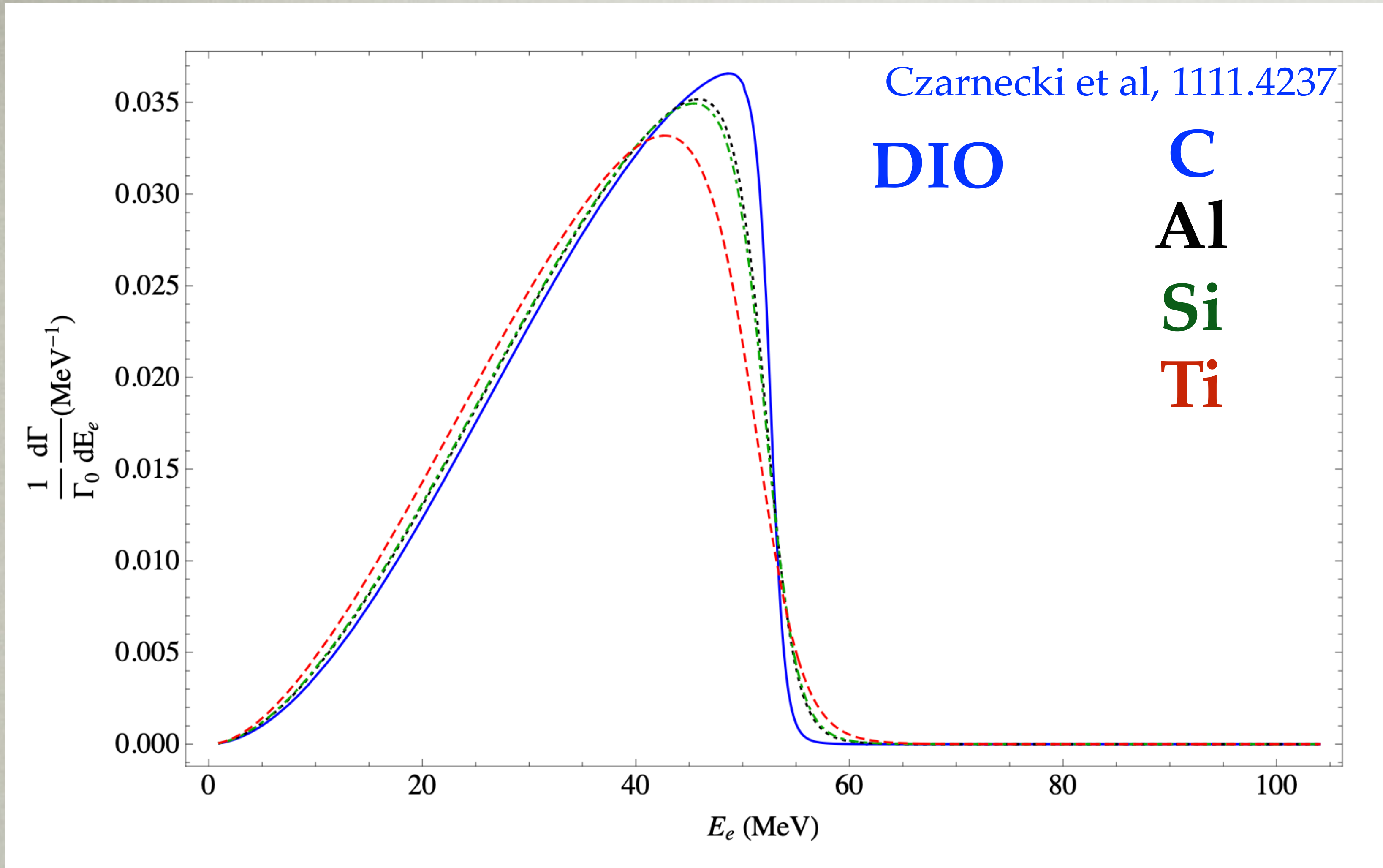
CONCLUSIONS

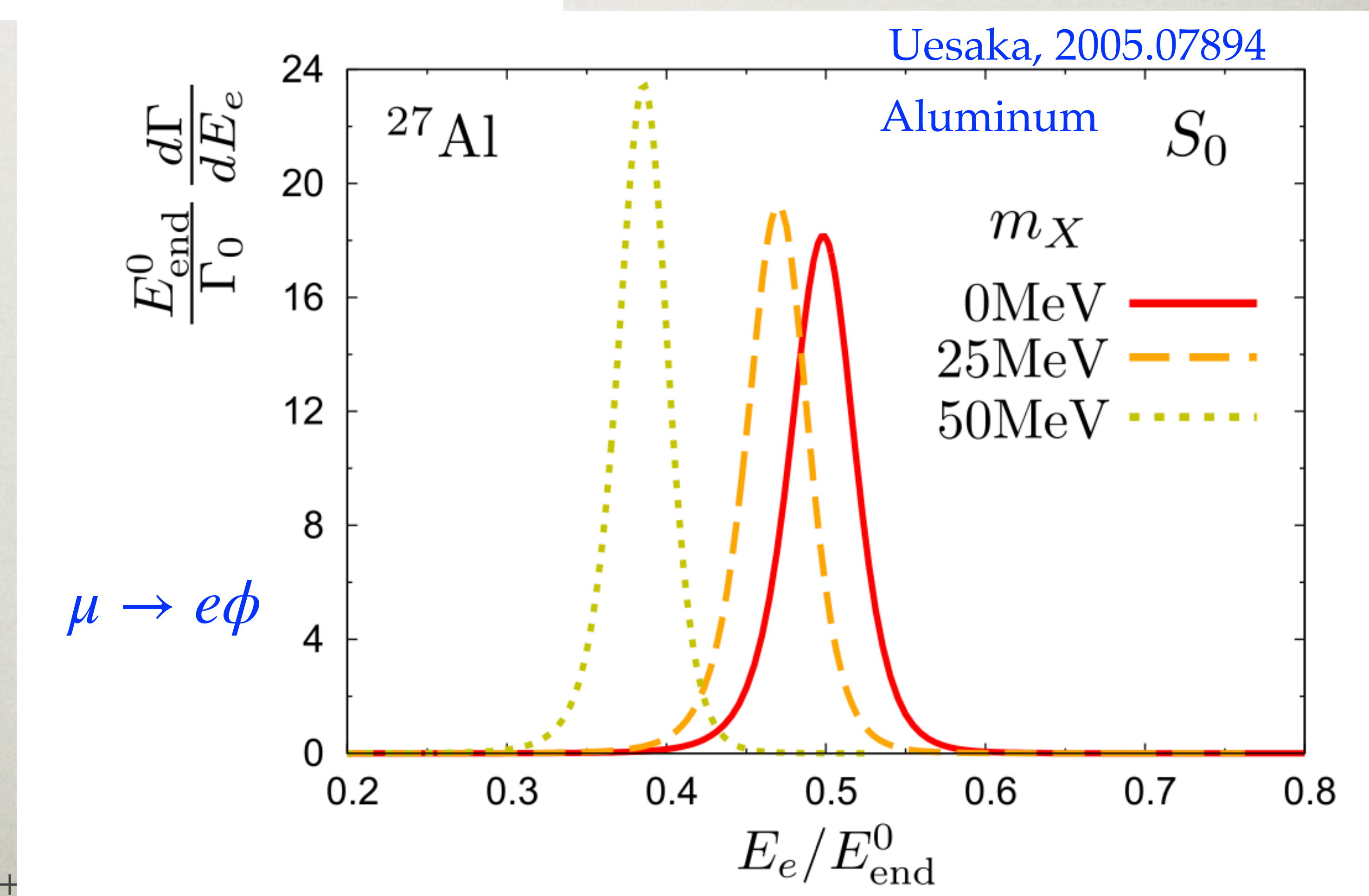
- light new physics can be a window to very high scales
- rare π^+ decays at Mu2e
  - search for heavy neutral leptons
- rare muon decays at Mu2e
  - μ^+ run
    - QCD axion $\Rightarrow \mu \to e\phi_{\text{inv}}$
    - $U(1)_{\mu-e} \Rightarrow \mu \to 5e$
    - ....
  - nominal μ^- run
    - time dependent $\mu \to e\phi_{\text{inv}}$

BACKUP SLIDES



POT pulse
π⁻ arrival/decay time (× 1M)
μ⁻ arrival time (× 400)
μ⁻ decay/capture time (× 400)
Selection Window
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)


Czarnecki et al, 1111.4237
DIO
C
Al
Si
Ti
$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e}$(MeV^{-1})
E_e (MeV)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100


Uesaka, 2005.07894
^{27}Al
Aluminum
S_0
m_X
0MeV
25MeV
50MeV
$\mu \to e\phi$
$\frac{E^0_{\rm end}}{\Gamma_0}\frac{d\Gamma}{dE_e}$
$E_e/E^0_{\rm end}$
24
20
16
12
8
4
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8

ALP two-photon decays

MEG, 2005.00339

- heavier ALP can decay via $a \to 2\gamma$
  - the corresponding decay width still large

$$c\tau_a \approx 2.3\,\mathrm{m}\left(\frac{f_a}{100\,\mathrm{GeV}}\right)^2\left(\frac{50\,\mathrm{MeV}}{m_a}\right)^3\left(\frac{1}{|C_{\gamma\gamma}^{\mathrm{eff}}|}\right)^2$$

- MEG search: $Br(\mu \to e(\phi \to 2\gamma)) < \mathcal{O}(10^{-11})$
  - would imply $F_{\mu e} \gtrsim \mathcal{O}(10^{12}\,\mathrm{GeV})$
- excluded by beam-dump searches
  - unless $c\tau_a \lesssim 1\,\mathrm{mm}$
  - hard to imagine one can write a viable UV model

Al

, 2005.00339

- he
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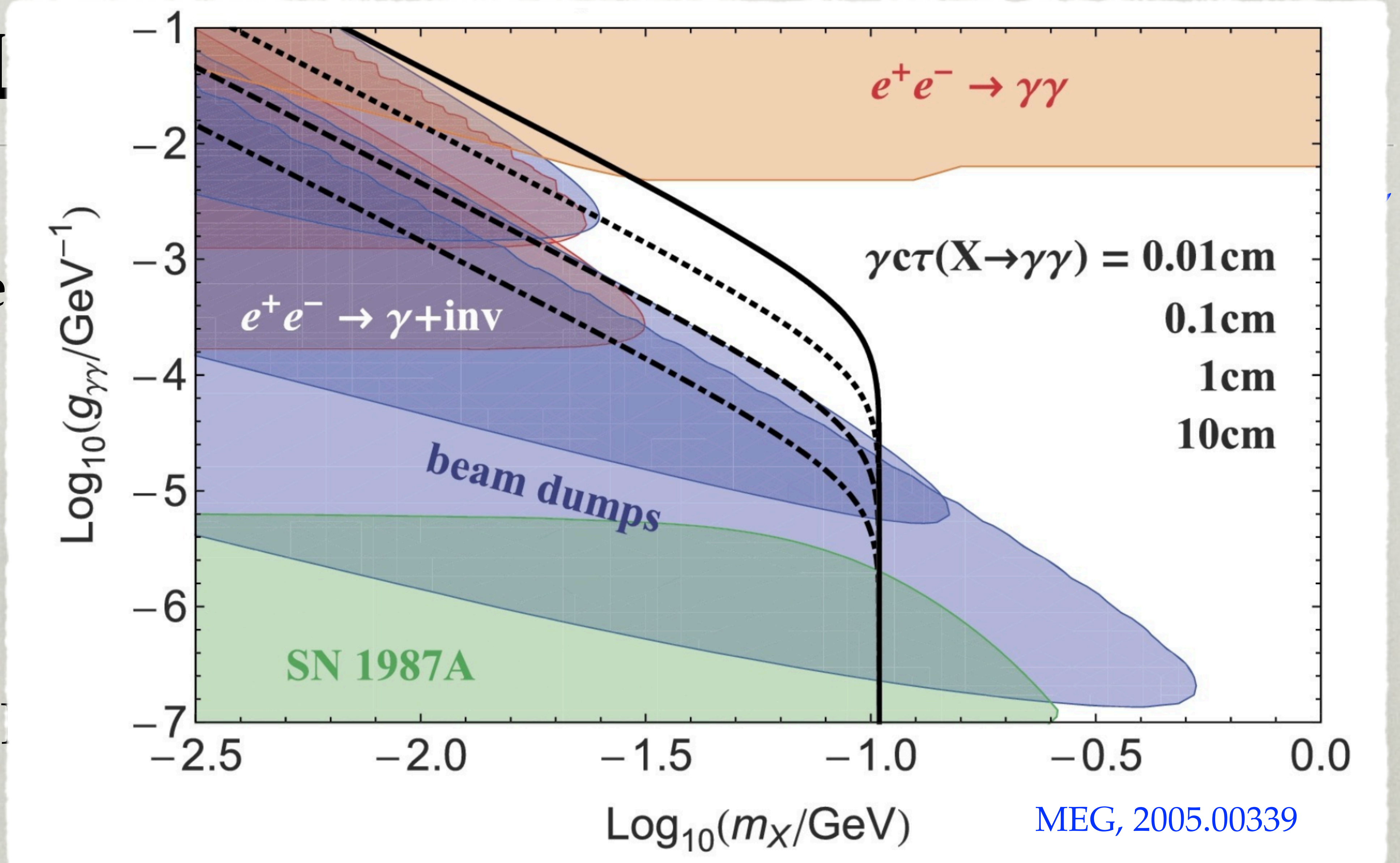

MEG, 2005.00339

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  - unless $c\tau_a \lesssim 1\,\mathrm{mm}$
  - hard to imagine one can write a viable UV model

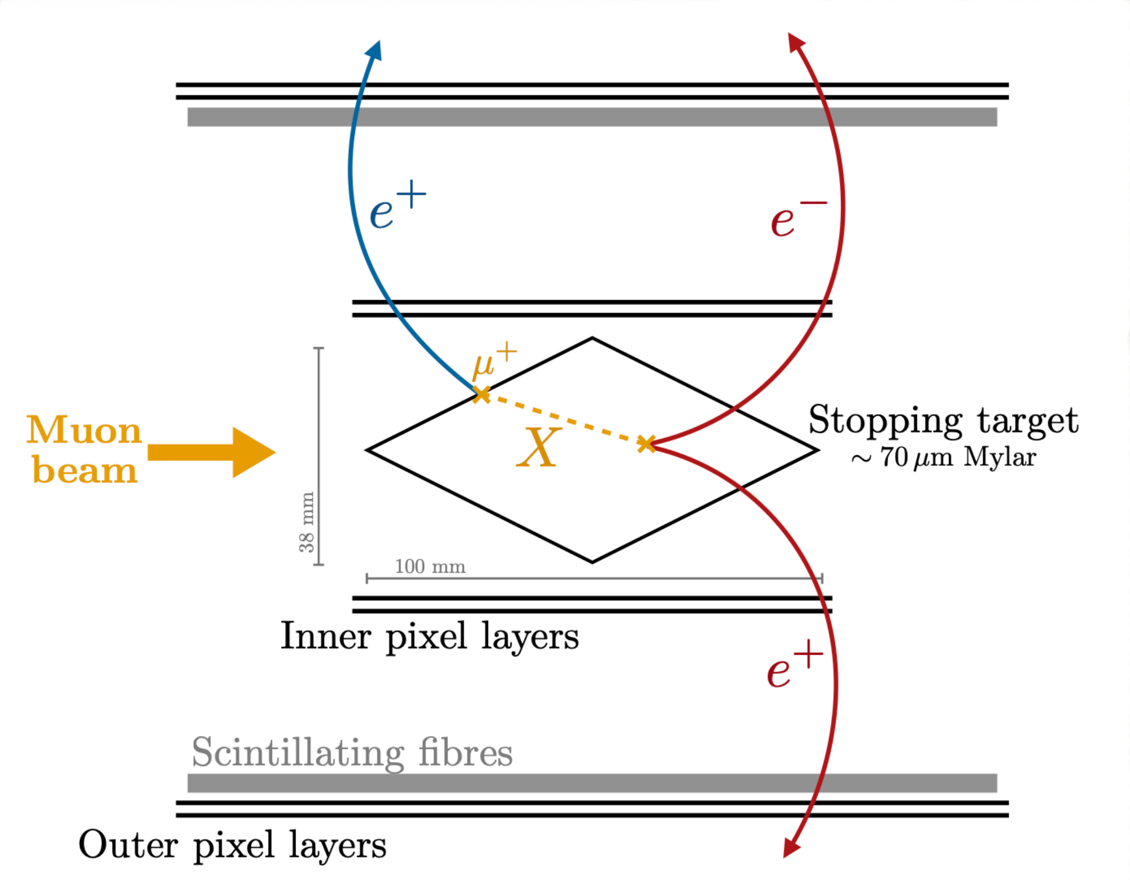
DECAYS TO ELECTRONS

Knapen, Opferkuch, Redigolo, Tammaro, 2410.13941

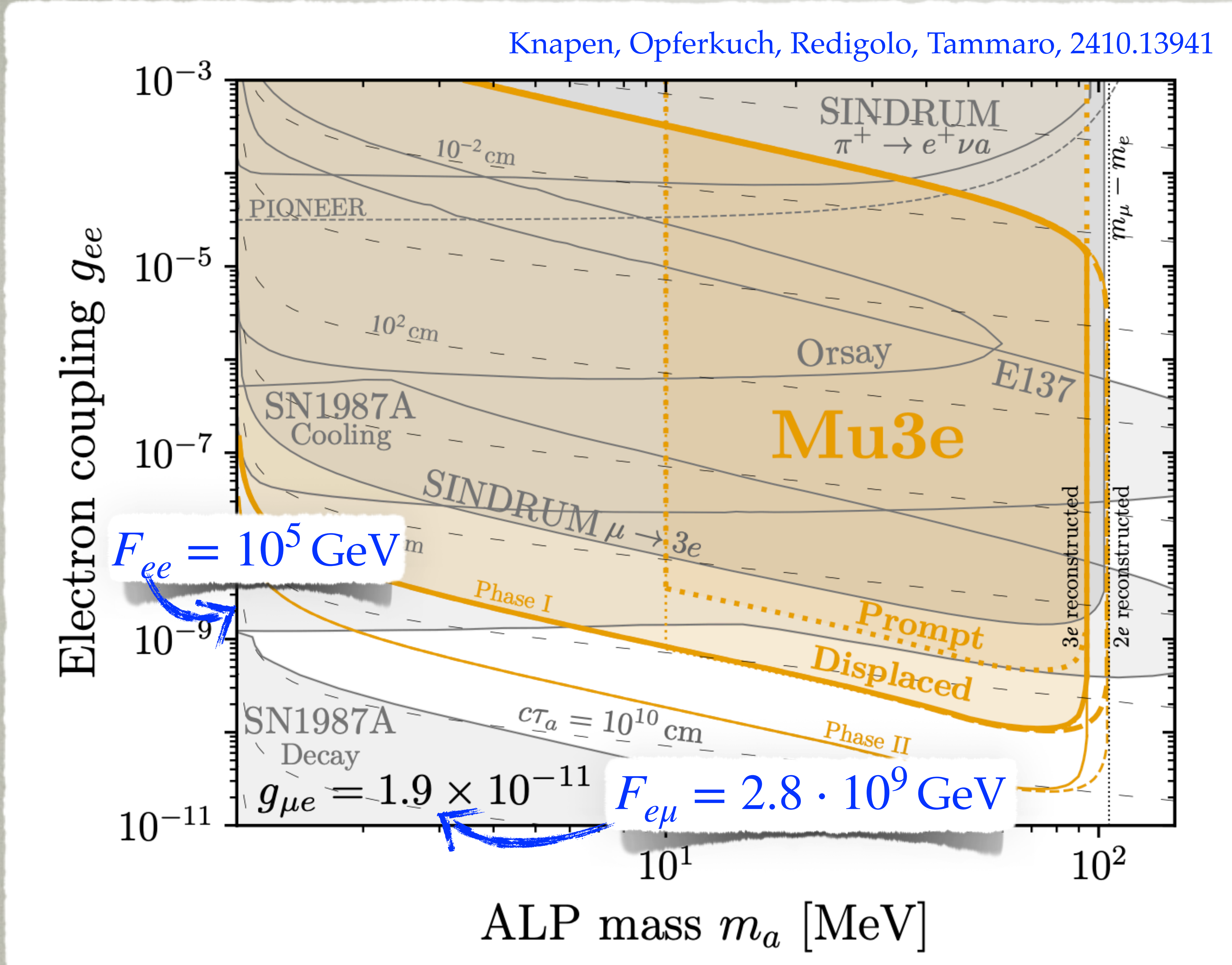
- for $a \to e^+e^-$ typically shorter $c\tau_a$ than for $a \to 2\gamma$

$$c\tau_a \approx 1.9\,\mathrm{m}\left(\frac{f_a}{\mathrm{TeV}}\right)^2\left(\frac{10\,\mathrm{MeV}}{m_a}\right)\left(\frac{1}{C^A_{ee}}\right)^2,$$

- displaced vertex
- can search for it a Mu3e



- large hierarchy $F_{ee} \gg F_{\mu e}$ needed



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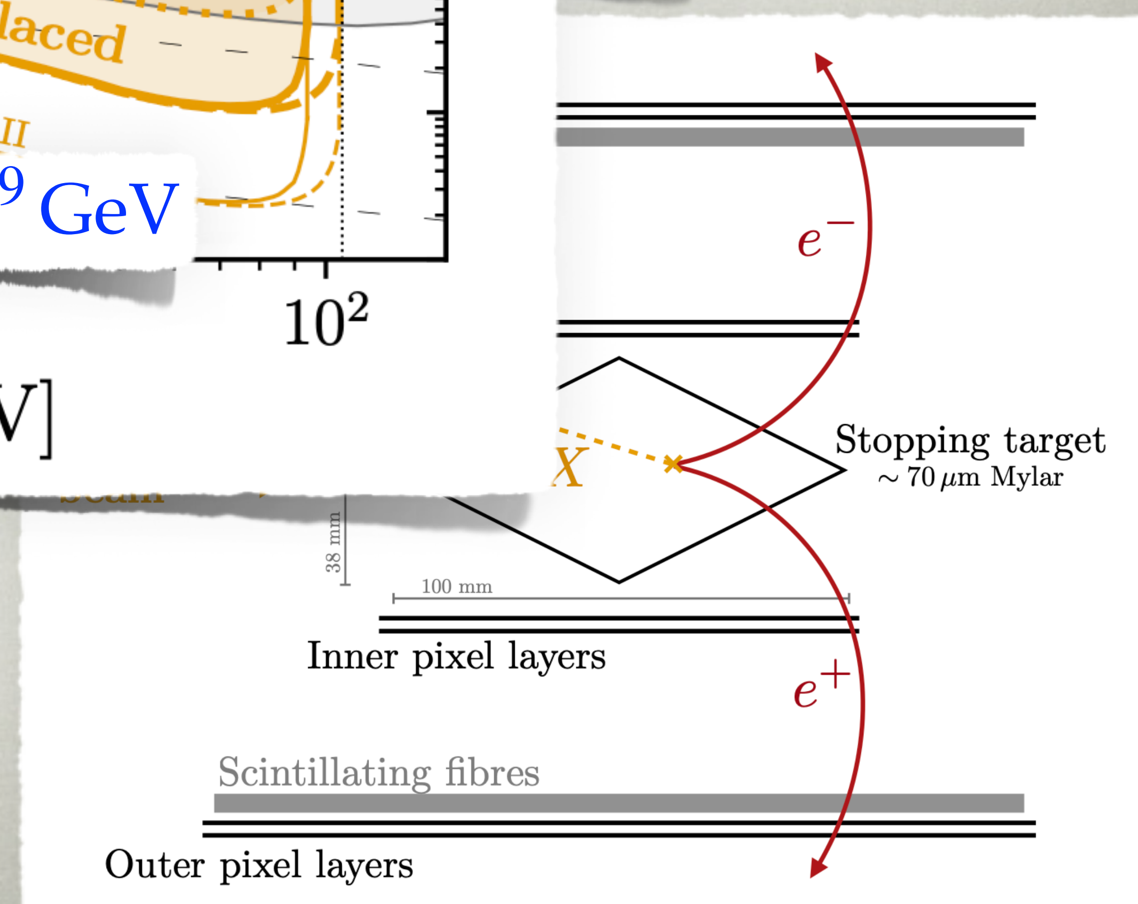
$)^2$,



- large hierarchy $F_{ee} \gg F_{\mu e}$ needed

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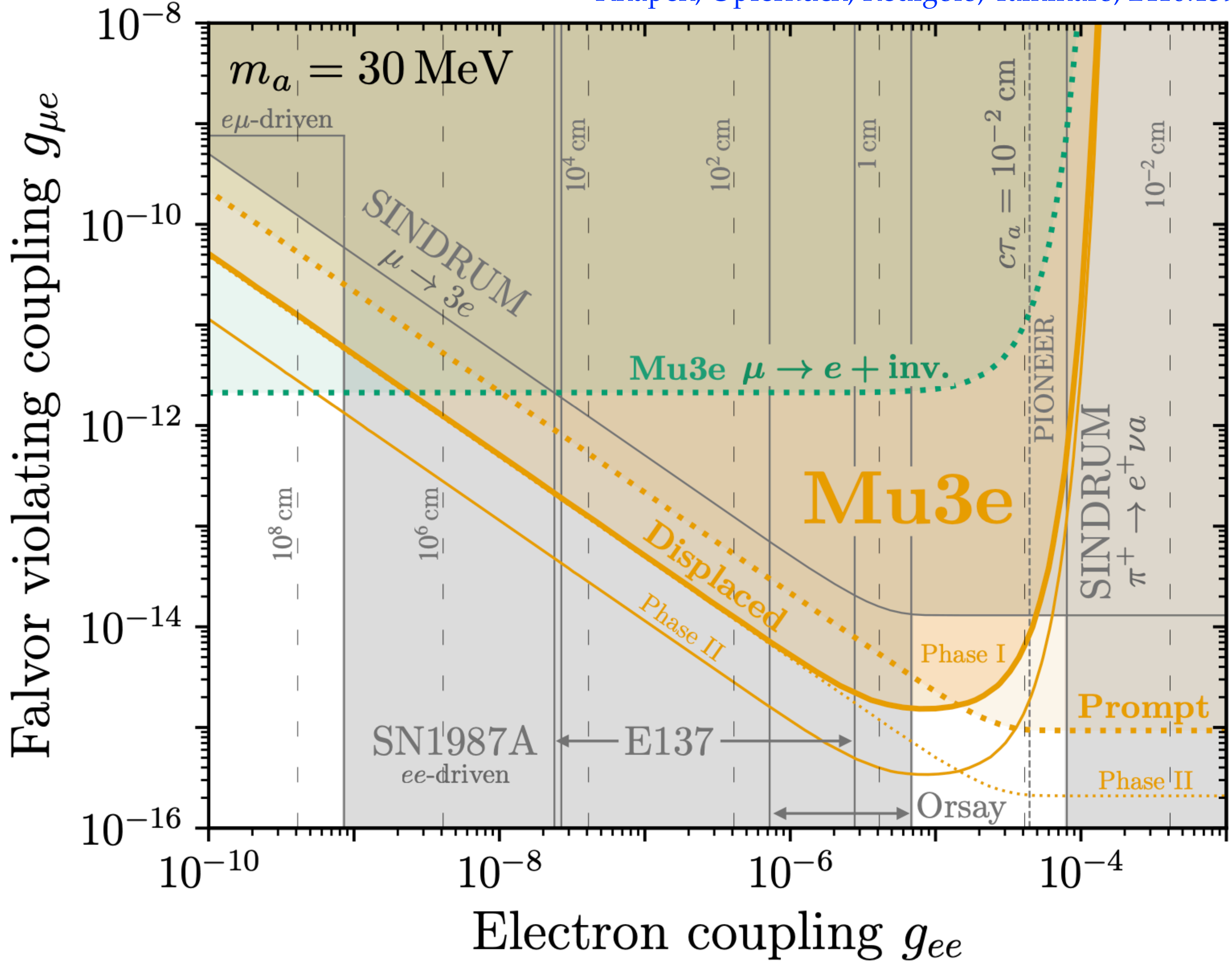

TIME DEPENDENT SIGNAL AT MU2E

Bigaran, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 250m.nnnnn

- could search for this with the normal μ^- run of Mu2e
  - search for a small time dependent rate
  - larger acceptance improves the signal
    - how much can one lower the E_e threshold at Mu2e?