# FLAVORFUL DARK SECTORS

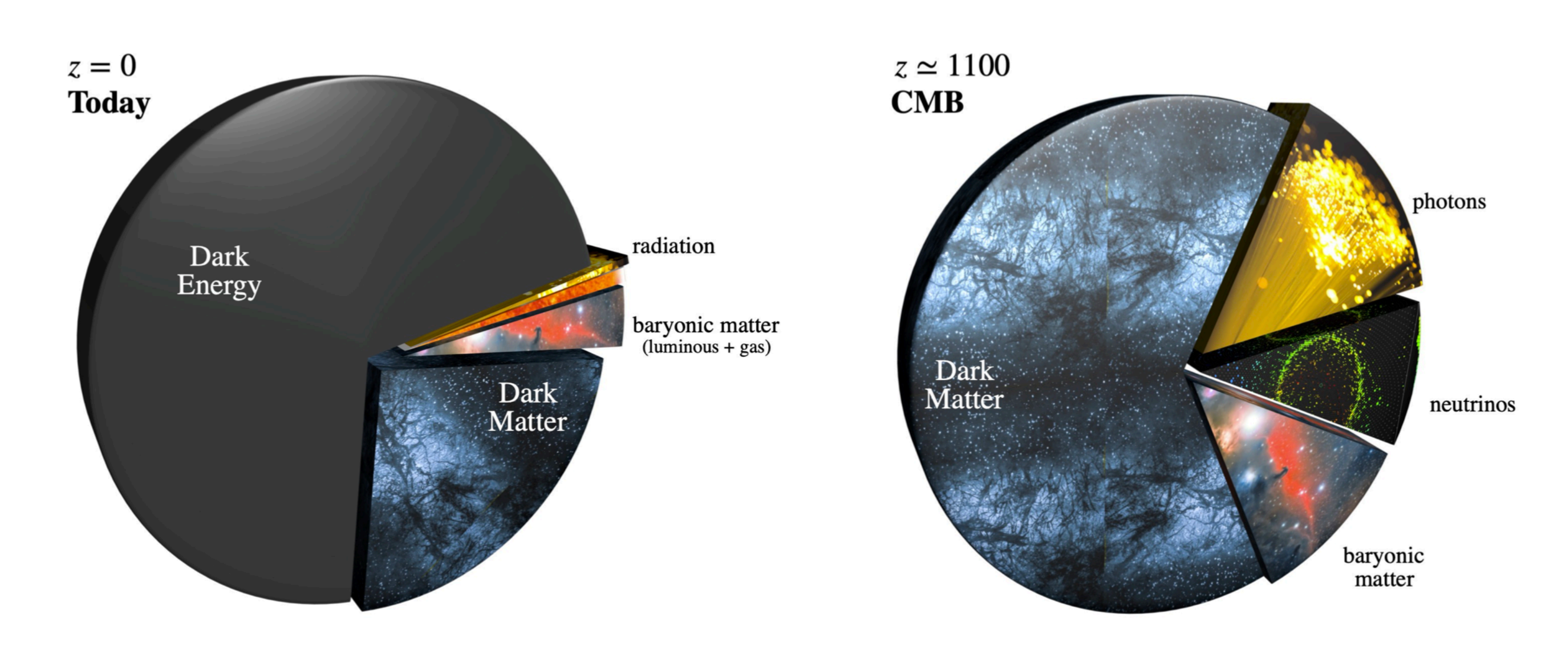
Jure Zupan
U. of Cincinnati

FPCP 2024, Chula U., Bangkok, May 31 2024

see DM review by Cirelli, Strumia, JZ, 2406.nnnn

# DARK MATTER

- overwhelming evidence for DM from gravitational interactions




- good reasons to believe it couples to visible matter
  - relic abundance (freeze-out, freeze-in,...)
- complications/opportunities
  - non-minimal dark sector?
  - flavor violating couplings?

# OUTLINE

- minimal portals to dark sector
    - going beyond minimality
        - flavor violation
        - further exotica
- FCNCs with quarks
- rare muon decays

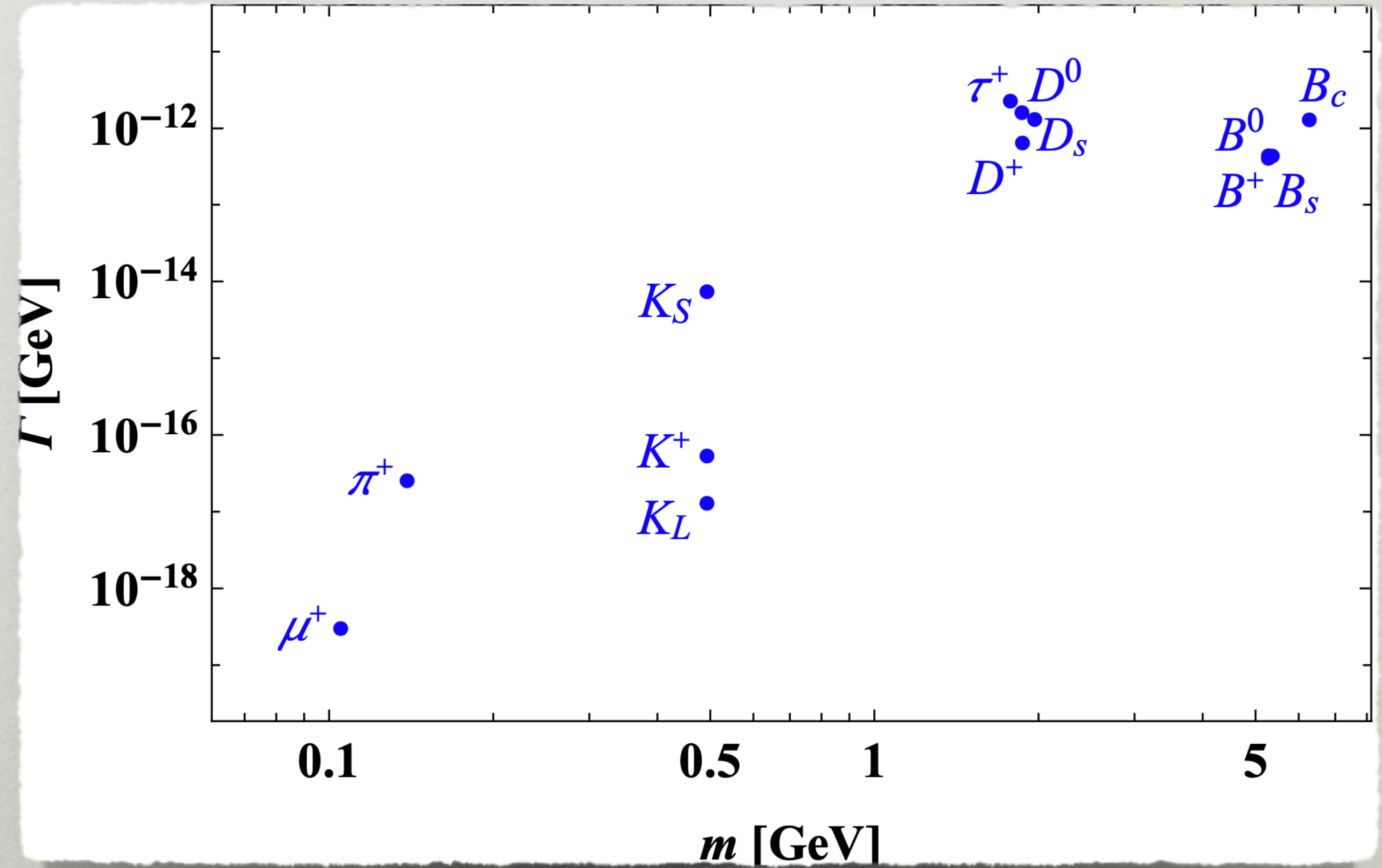
# MINIMAL PORTALS

| Portal | Interactions |
|---|---|
| Dark Photon, $A'_\mu$ | $-\epsilon F'_{\mu\nu} B^{\mu\nu}$ |
| Dark Higgs, $S$ | $(\mu S + \lambda S^2) H^\dagger H$ |
| Heavy Neutral Lepton, $N$ | $y_N LHN$ |
| Axion-like pseudo scalar, $a$ | $aF\tilde{F}/f_a$, $aG\tilde{G}/f_a$, $(\bar{\psi}\gamma^\mu\gamma_5\psi)\partial_\mu a/f_a$ |

- in particular regions of parameter space could be DM
- more generally, can be just mediators to dark sector: DM a different state $\chi$

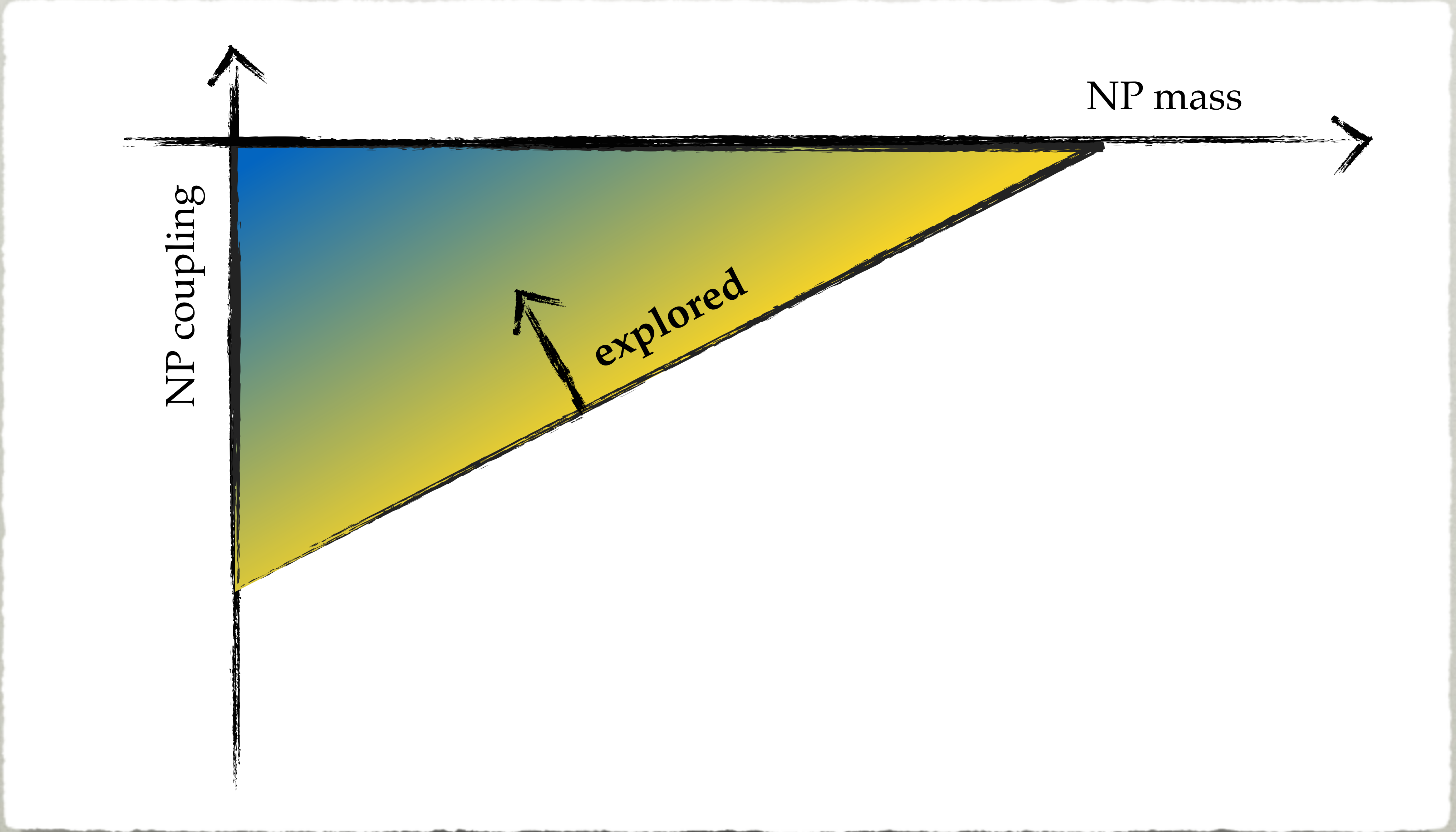
# FLAVOR PORTAL

- mediators can have flavor violating couplings
    - high sensitivity to NP, can be a discovery channel
- example: dim 5 op. $\partial_\alpha \varphi(\bar{e}\gamma^\alpha\gamma_5\mu)/f_a \Rightarrow Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- searching for $K \to \pi X$, $\mu \to eX$, $\pi \to X$ , $B \to KX$,... decays expect to reach very high UV scales



# SEARCHING FOR LIGHT NEW PHYSICS

- heavy new physics only part of the NP parameter space
- light particles: a window to high UV dynamics



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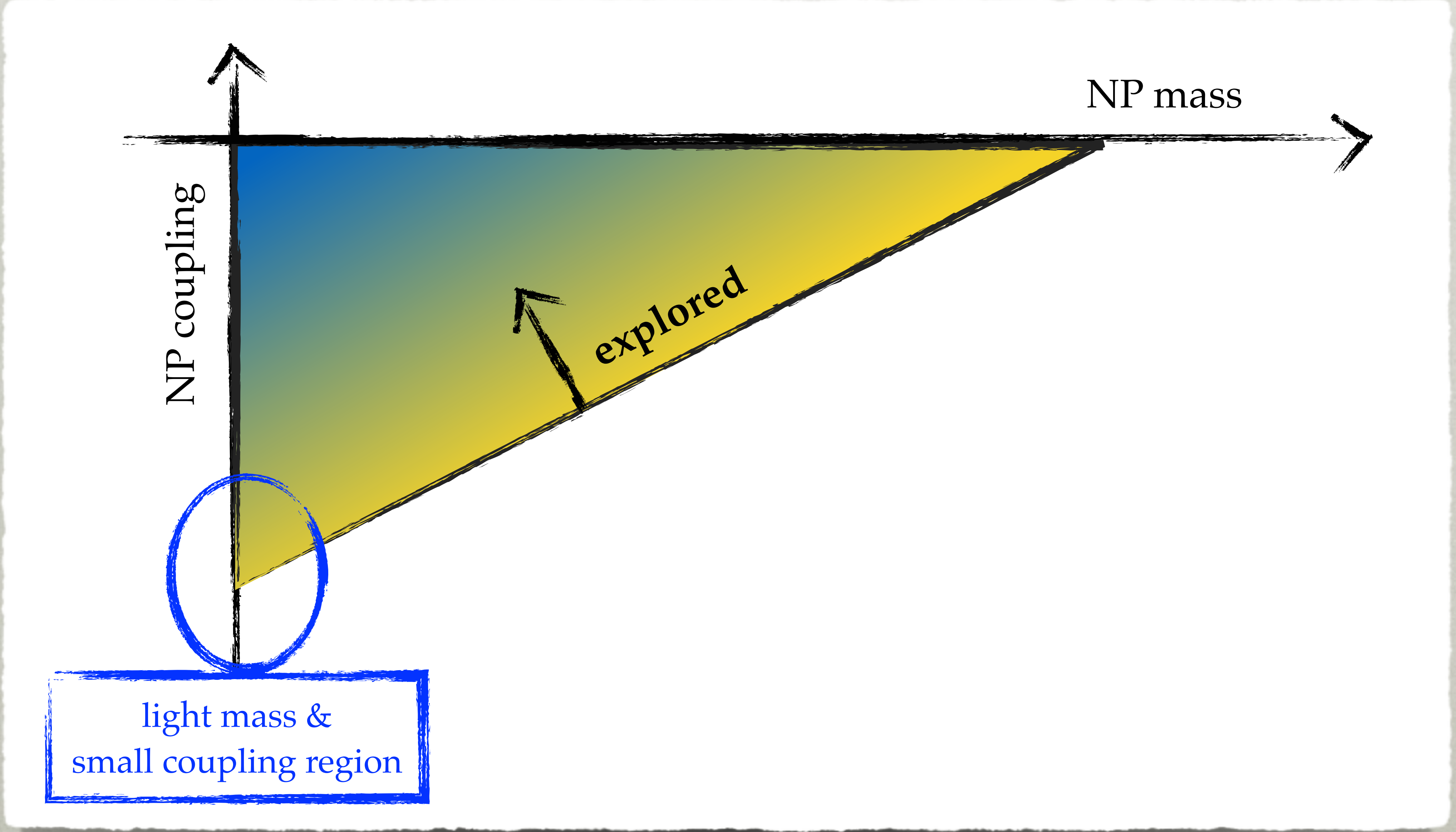

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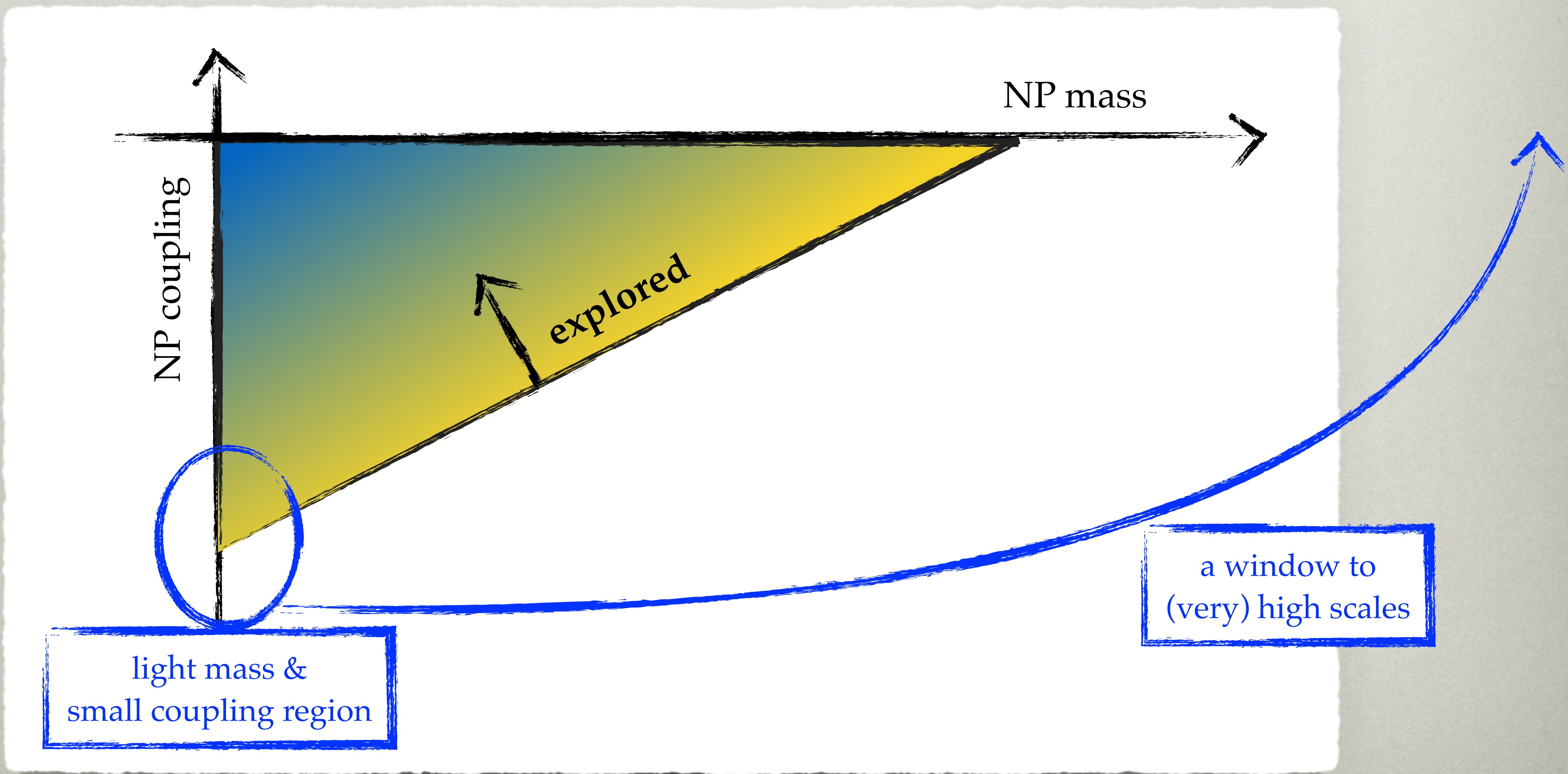
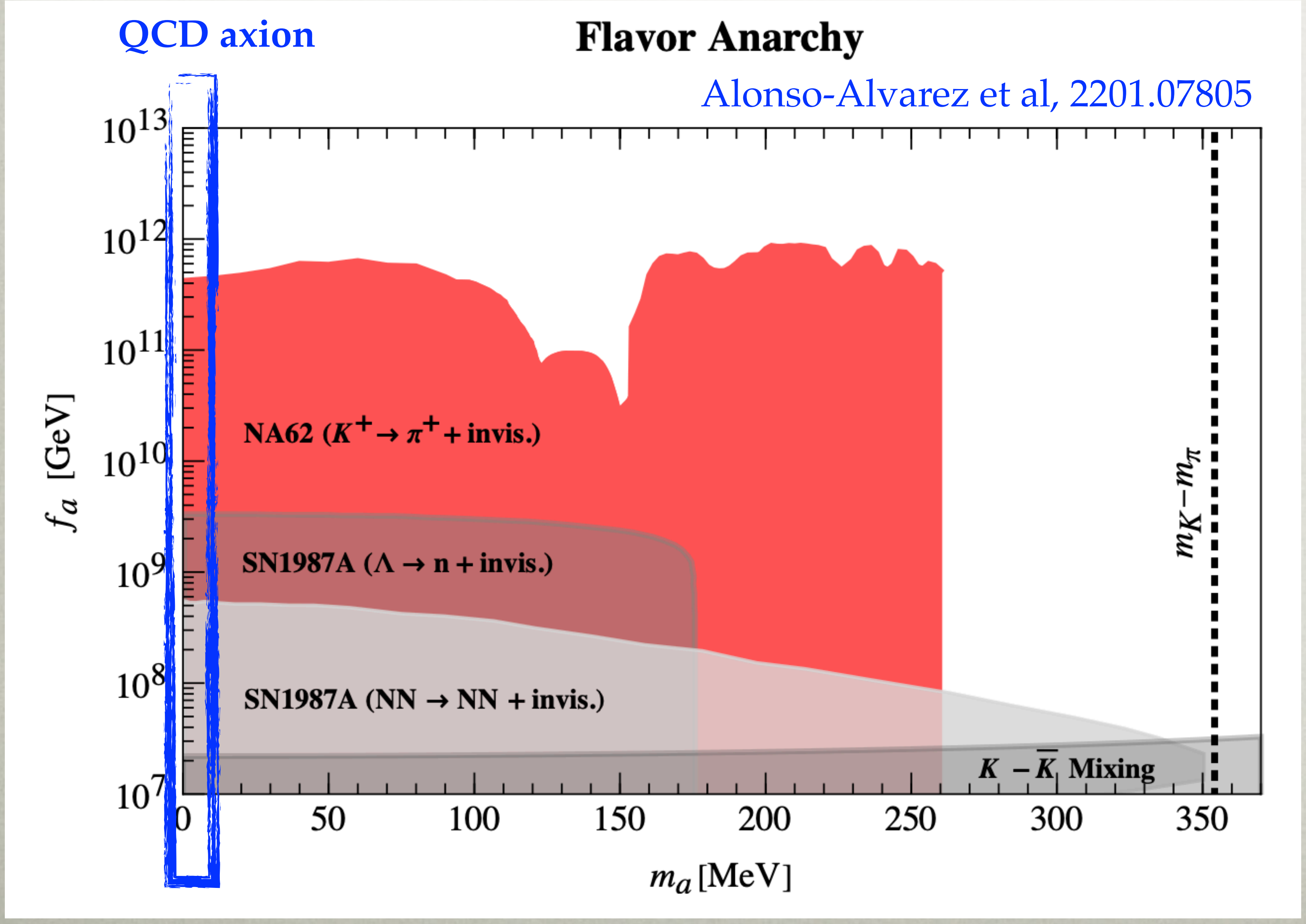


# NEXT SLIDES

- several examples
  - mix of minimal and less minimal dark sectors
- flavorful QCD axion
  - ALP
- heavy neutral leptons
- Higgs-mixed scalar
  - and beyond it...
- flavorful dark photon

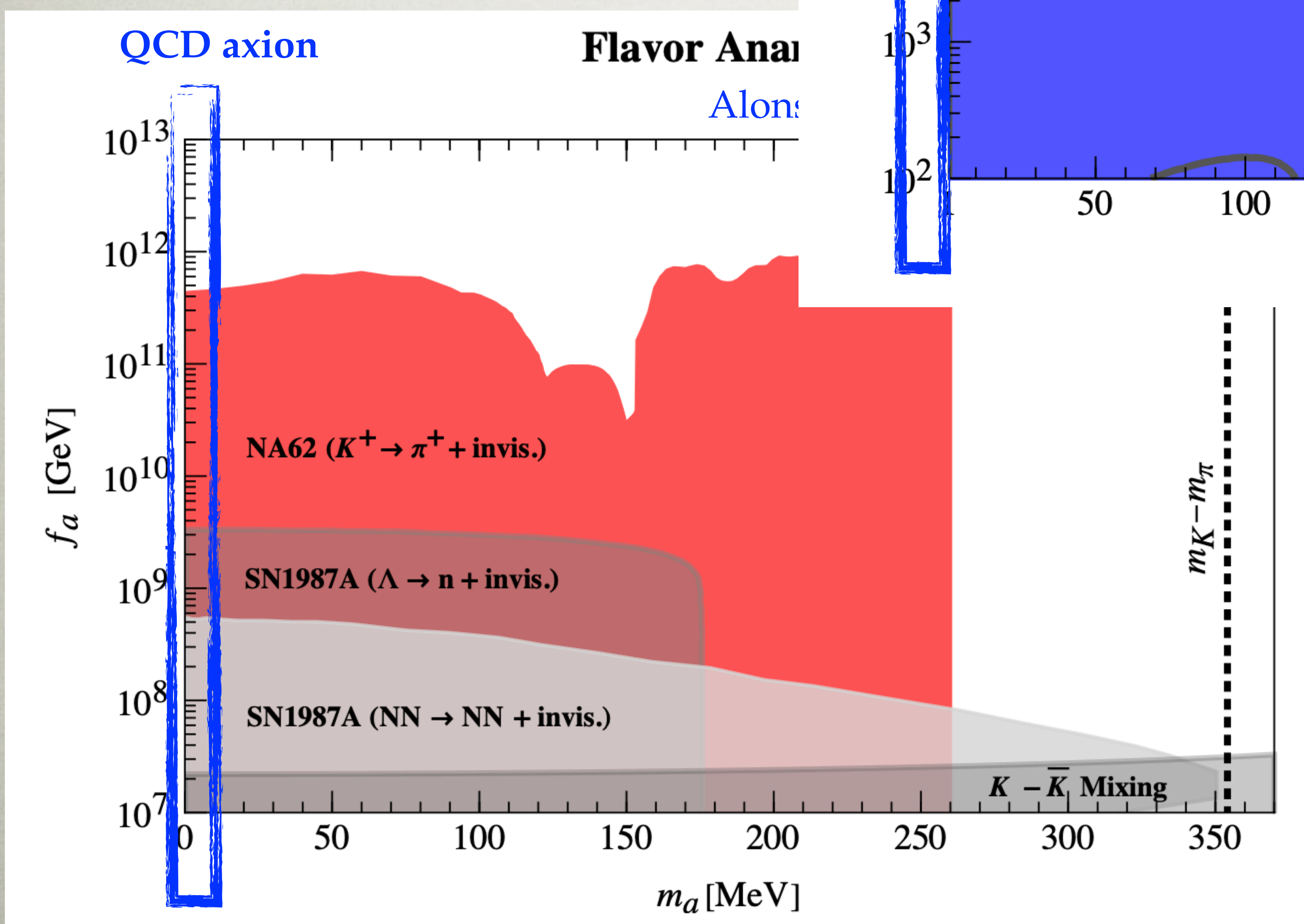
# FLAVORFUL QCD AXION

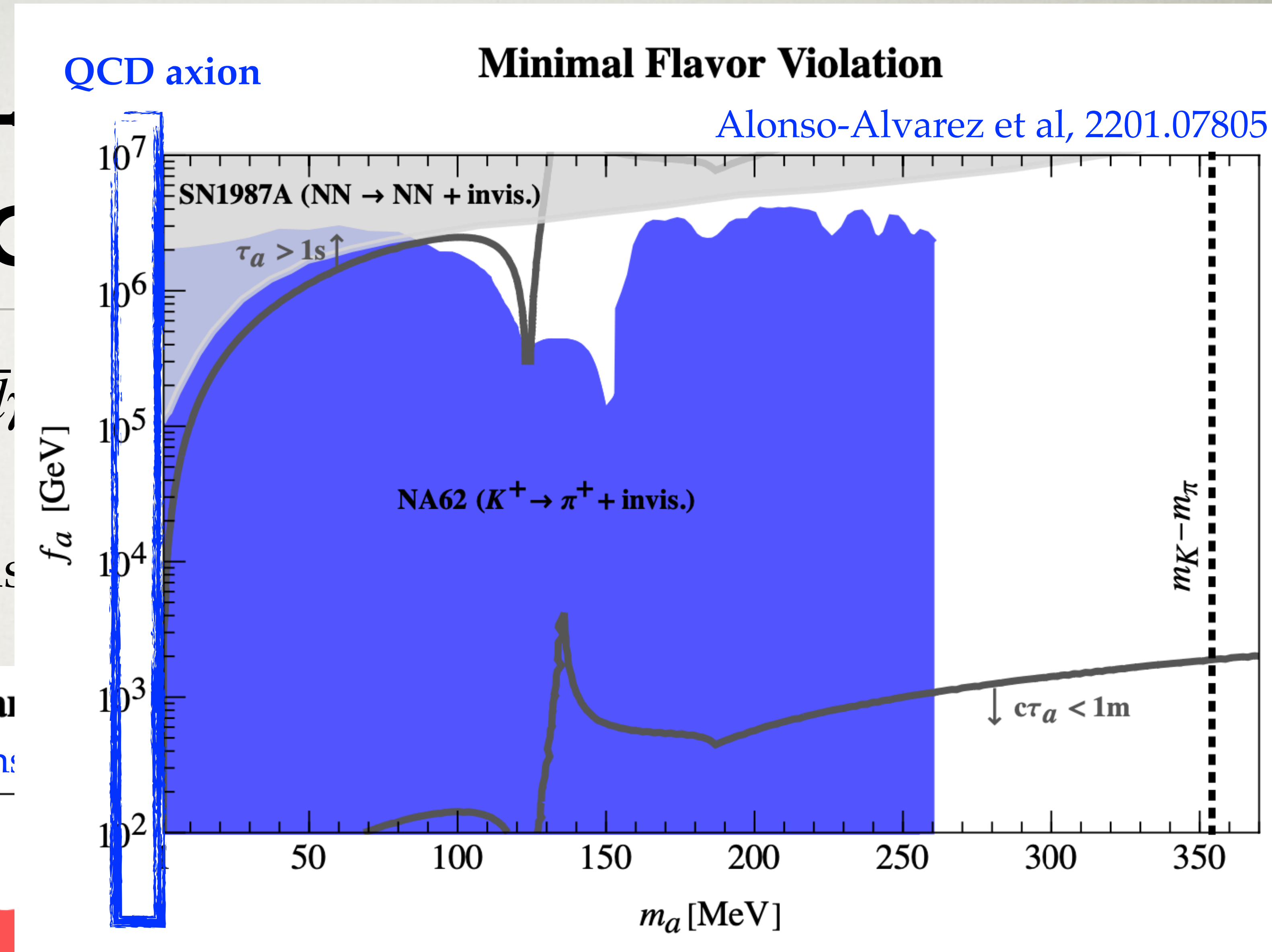
- if QCD axion has $\partial_\mu a(\bar{d}\gamma^\mu\gamma_5 s)/f_a$ coupling $\Rightarrow K^+ \to \pi^+ a$ decay a very sensitive probe
- the reach depends on assumed flavor structure



# FL
# QC

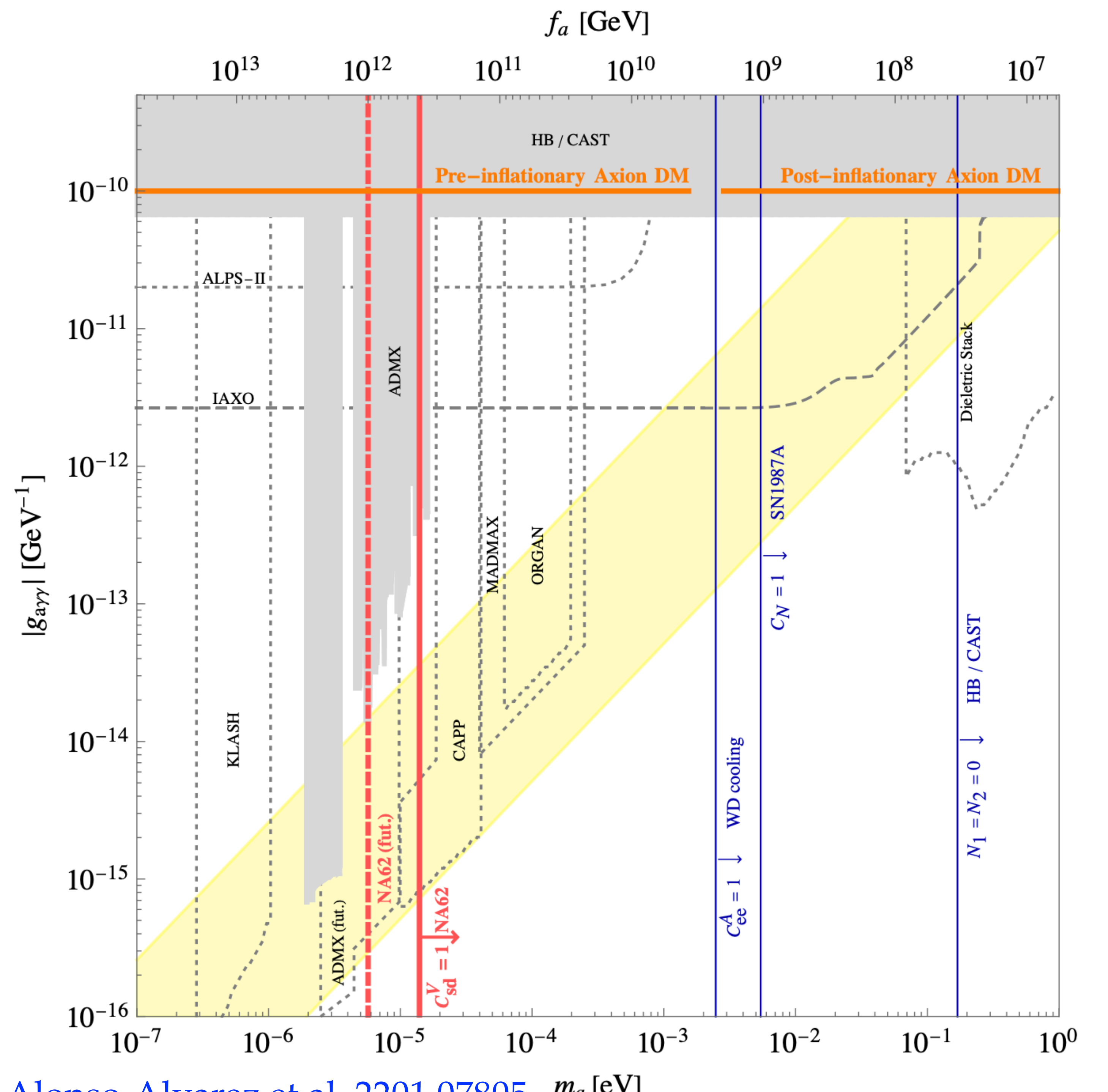
- if QCD axion has $\partial_\mu a(\bar{d}\gamma$ sensitive probe
- the reach depends on as



# FLAVORFUL QCD AXION

- in the usual $g_{a\gamma\gamma} - m_a$ plane
- $K \to \pi a$ can be a discovery channel for anarchic flavor ansatz
- for other flavor structures $B \to \pi a$, $B \to K a$, $D \to \pi a$ can be the discovery channels

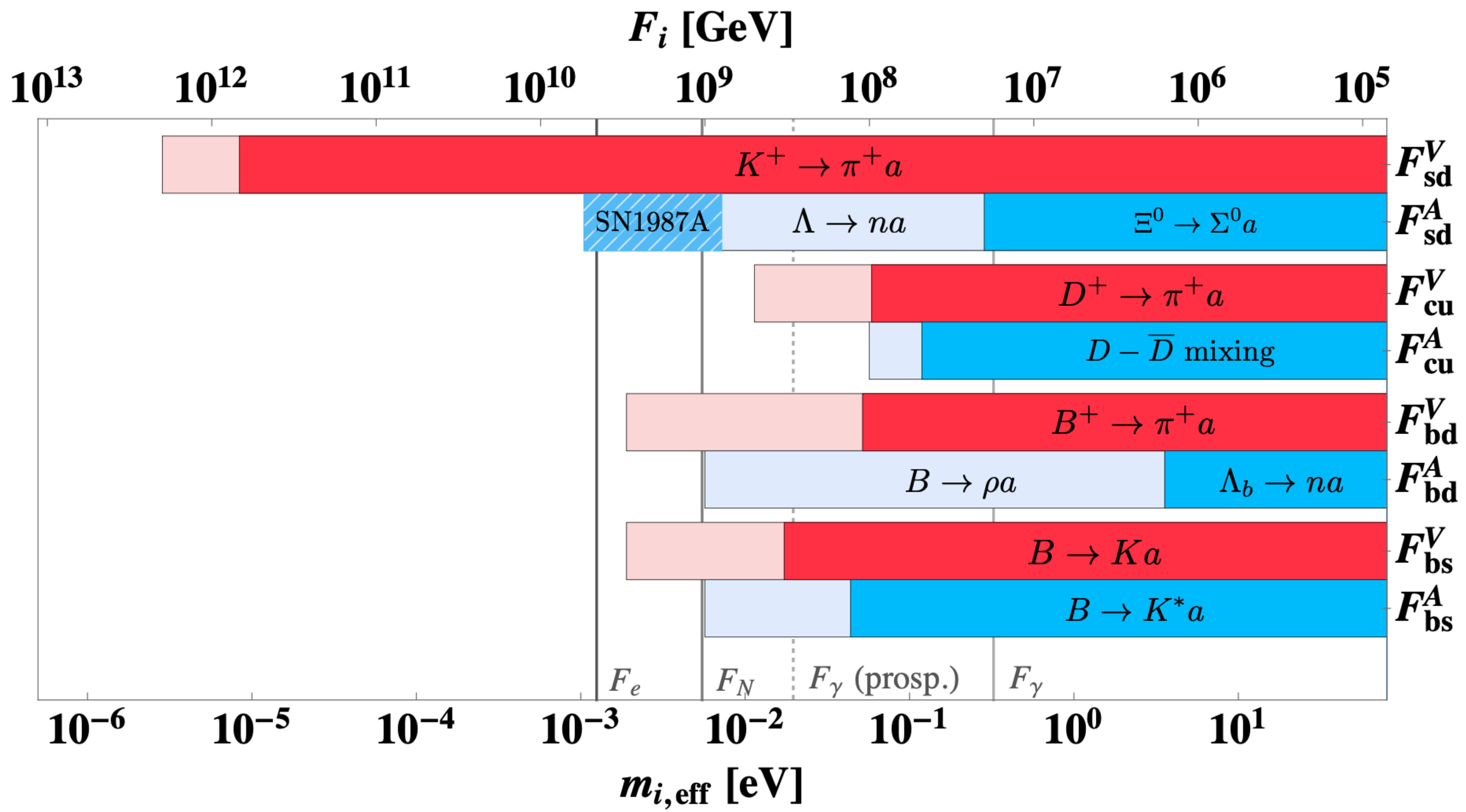



Alonso-Alvarez et al, 2201.07805

# FLAVORFUL AXION PROBES

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

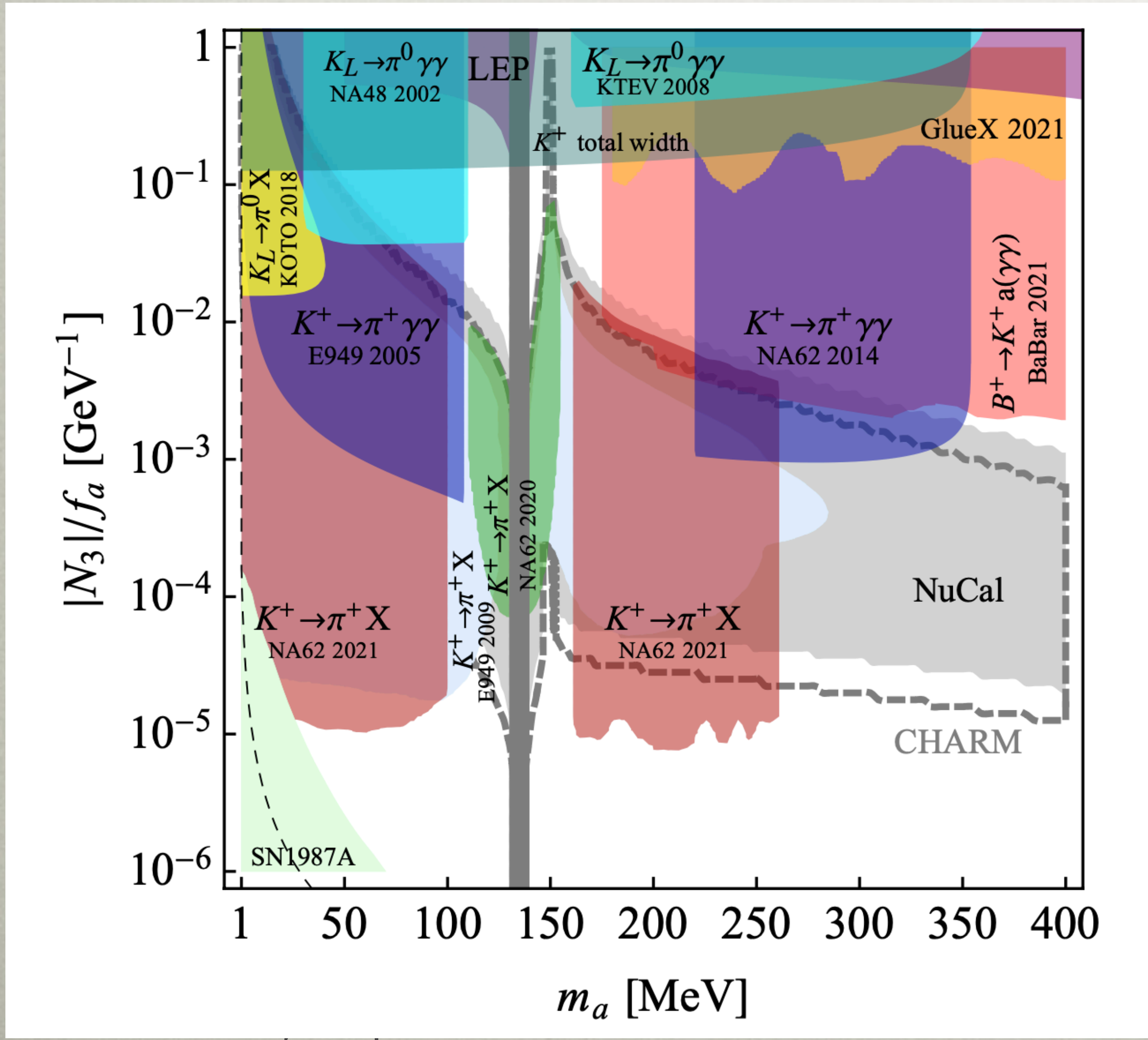
- a rich set of probes of flavorful axion

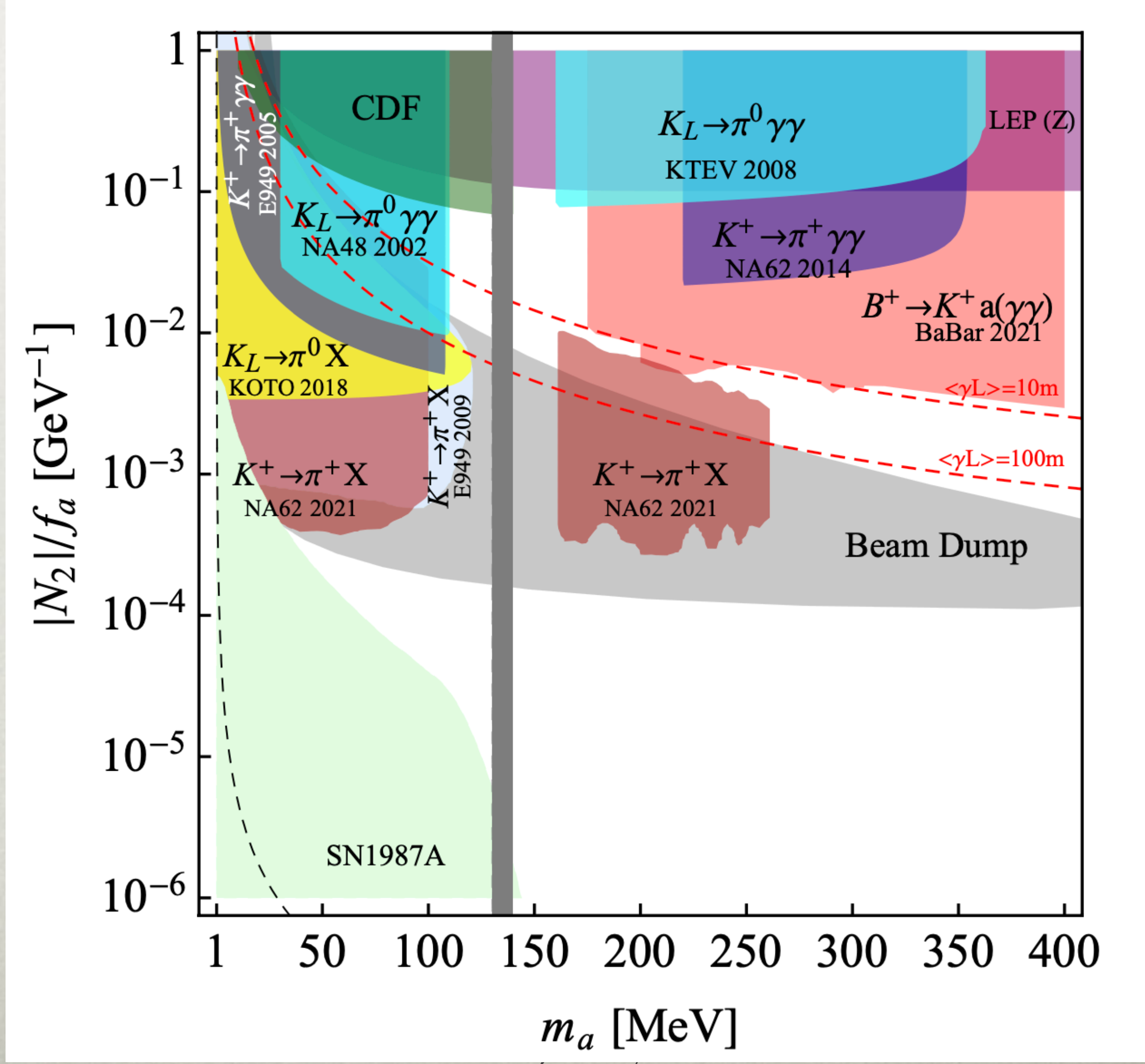


# ALP

Alonso-Alvarez et al, 2201.07805

- if ALP has flavor conserving couplings
  - FCNC transitions ($K \to \pi a$, ...) still possible due to SM CKM
  - ALP decay modes depend on assumed couplings

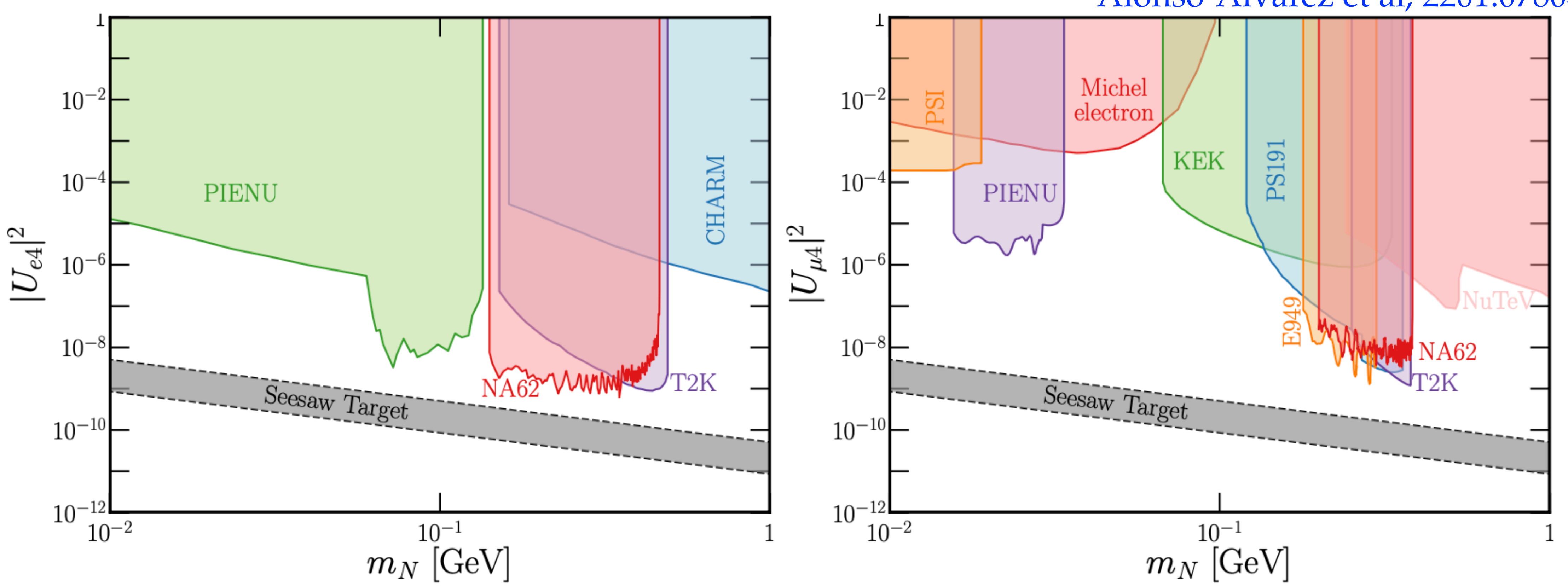


# HEAVY NEUTRAL LEPTON

- heavy neutral leptons from $\pi \to \ell N,\ K \to \ell N$ decays

Alonso-Alvarez et al, 2201.07805




- note: Mu2e and COMET can have best limits with calibration runs

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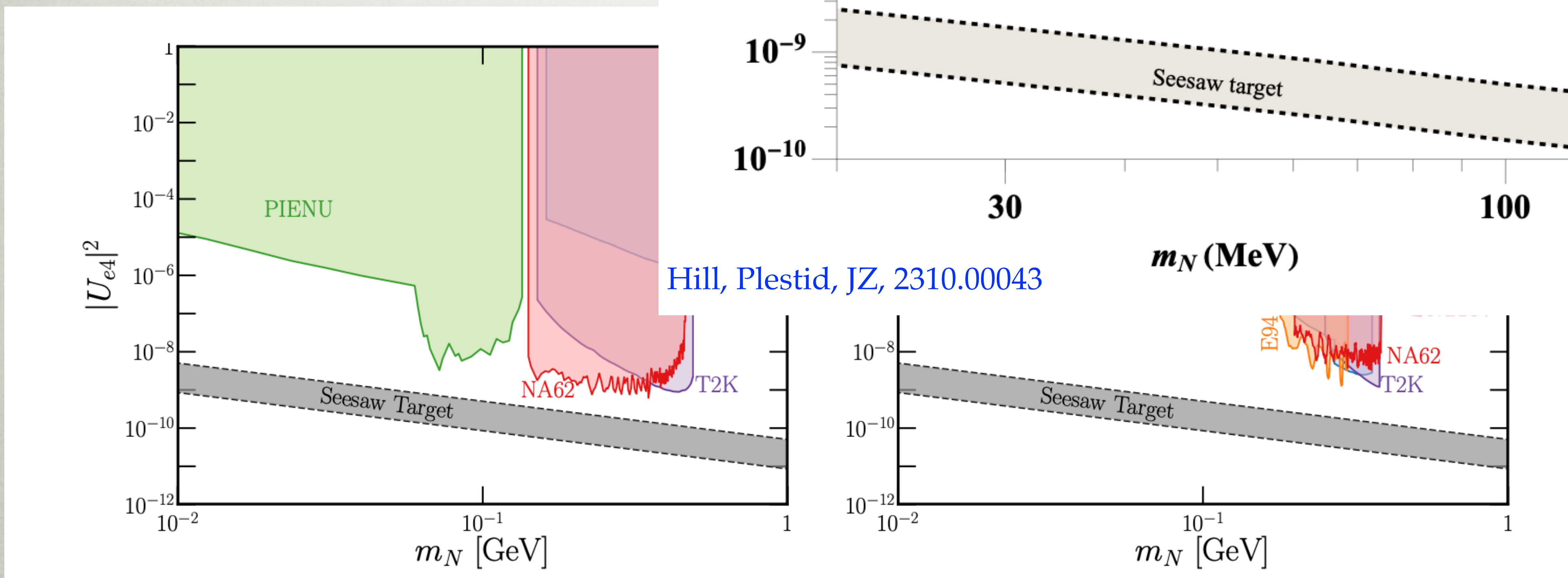
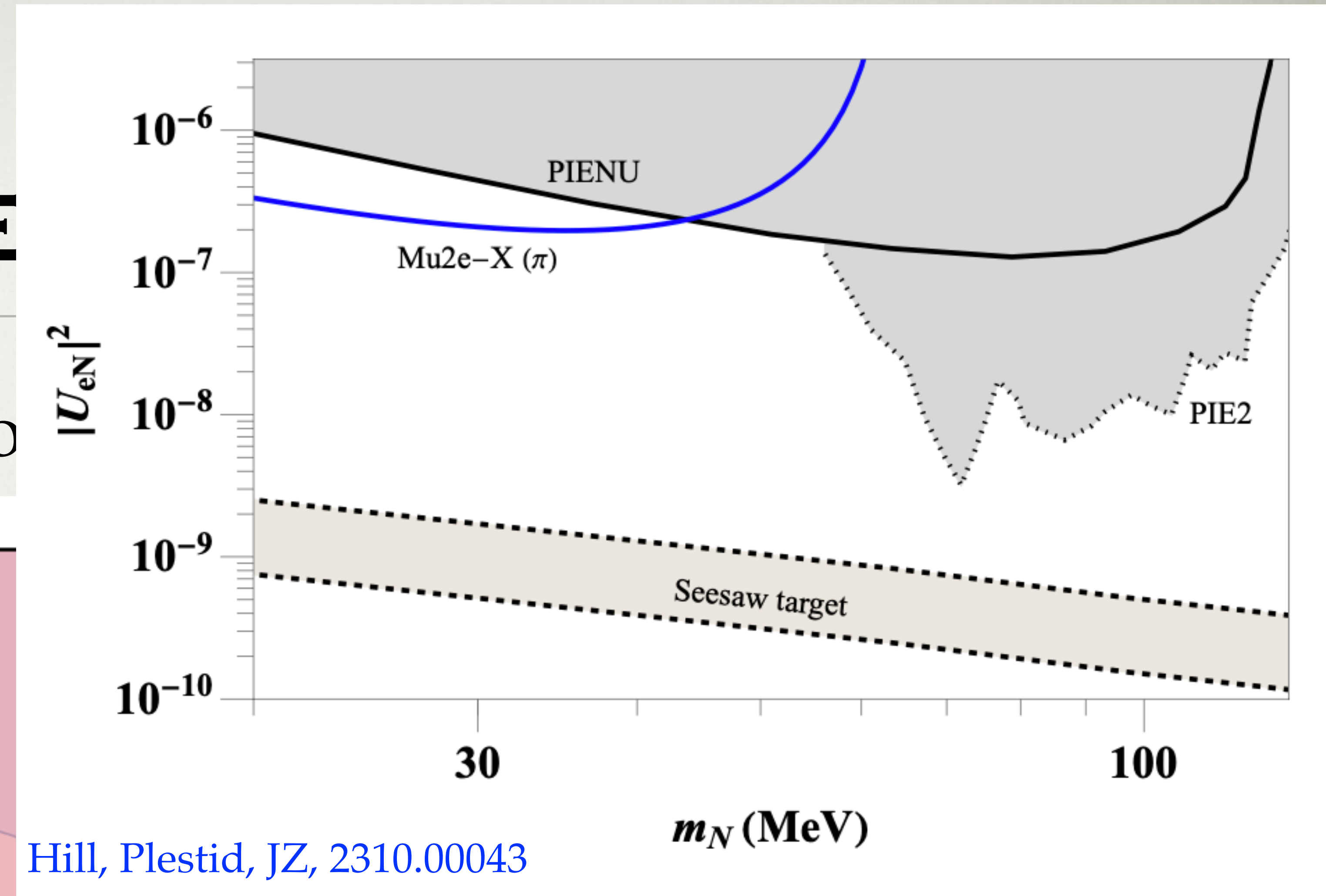








Hill, Plestid, JZ, 2310.00043

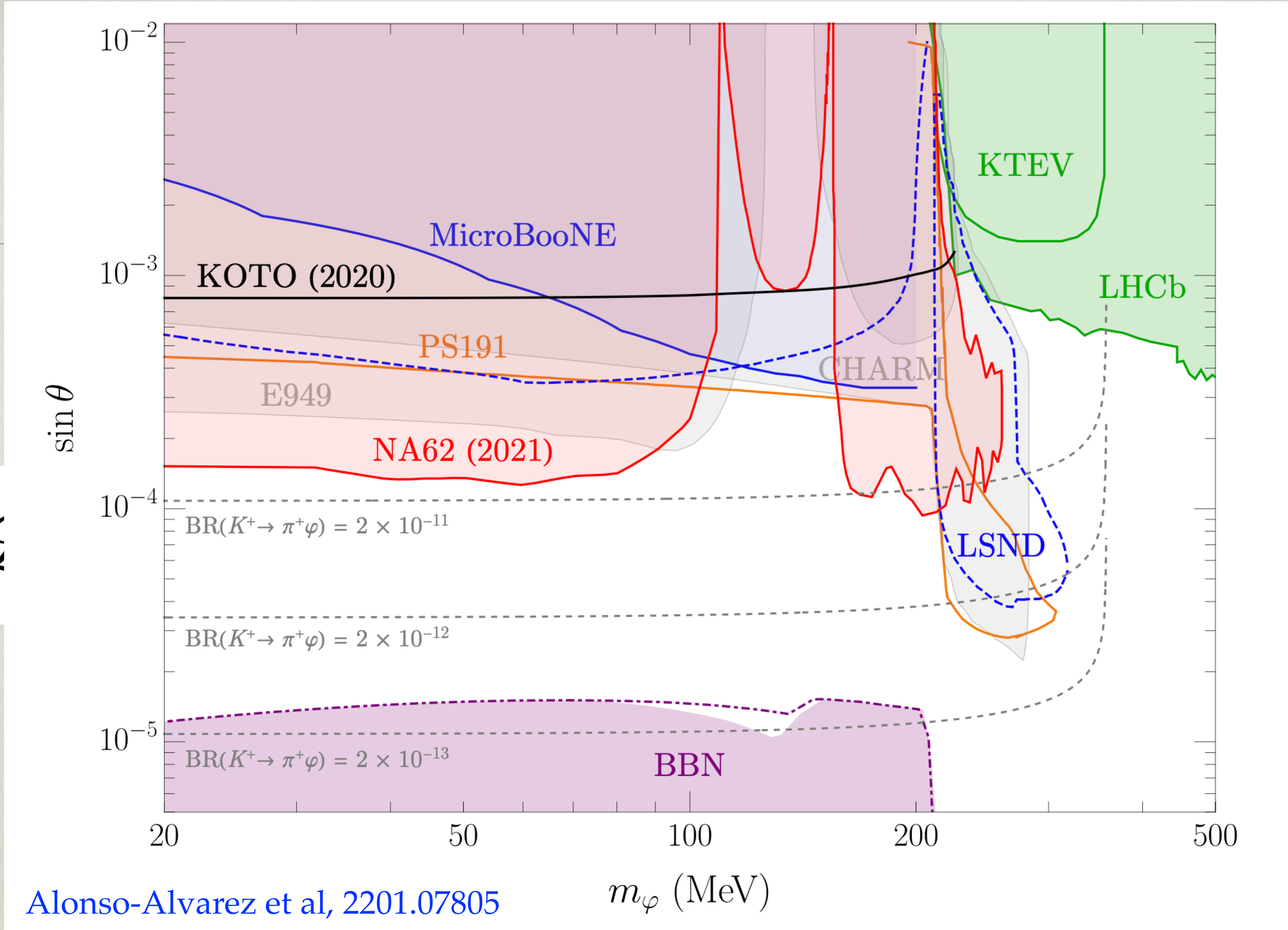
- note: Mu2e and COMET can have best limits with calibration runs

# HIGGS MIXED LIGHT SCALAR

- add a light singlet to the SM

$$\mathscr{L}_{\text{scalar}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\text{DS}} - (\mu S + \lambda_{SH} S^2) H^\dagger H.$$

- after EW symmetry breaking $S$-$H$ mixing
  - $S$ coupl. = $\sin\theta \times H$ coupl.
  - just two parameters: $\sin\theta, m_S$
- with improved kaon program could reach the BBN floor

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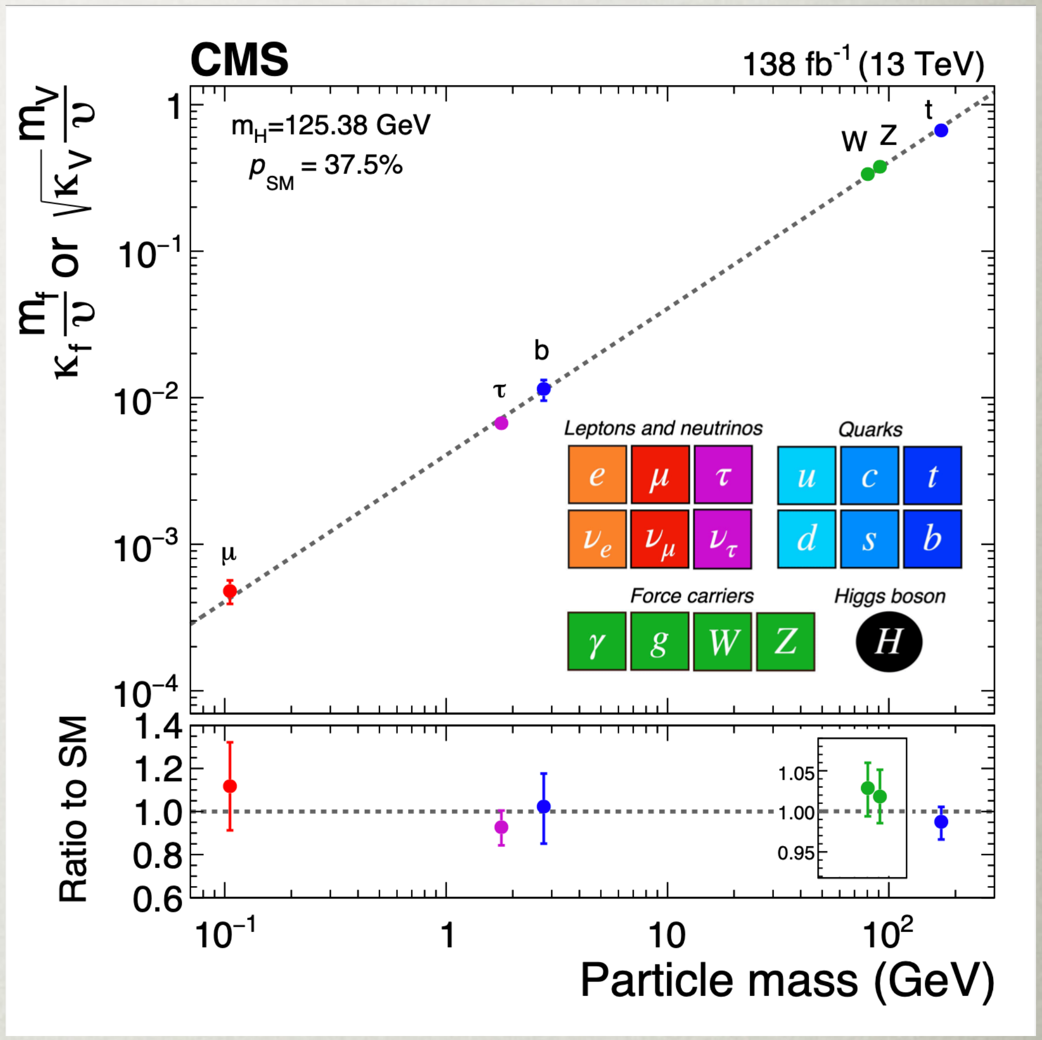
# BEYOND LIGHT HIGGS-MIXED SCALAR

- Higgs-mixed scalar: a strong assumption about light fermion Yukawas
- could be easily changed by NP
  - masses of the first two gen. fermions could have large non-SM contribs.
  - ⇒ coupling of $\varphi$ could largely deviate from the Higgs-mixed scalar limit
- many examples
  - SMEFT+$\varphi$
  - 2HDM+$\varphi$
  - dark dilaton
  - $\varphi$+vectorlike quarks




Delaunay, Kitahara, Soreq, JZ, 2406.nnnnn

# 2HDM+$\varphi$

Delaunay, Kitahara, Soreq, JZ, 2406.nnnnn

- 2HDM in Higgs basis

$$\langle H_1^0\rangle = v/\sqrt{2},\ \langle H_2^0\rangle = 0$$

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$$

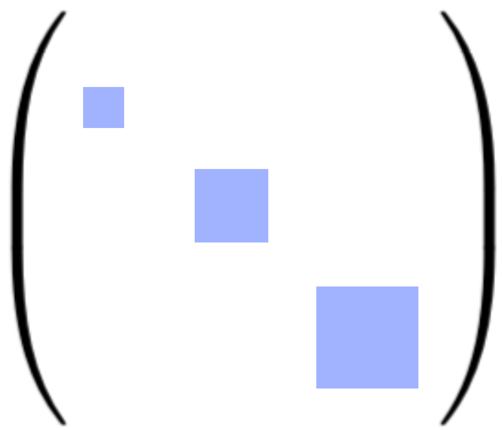
$$V \supset \frac{1}{2}Z_1(H_1^\dagger H_1)^2 + \left\{\frac{1}{2}Z_5(H_1^\dagger H_2)^2 + Z_6(H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.}\right\}.$$

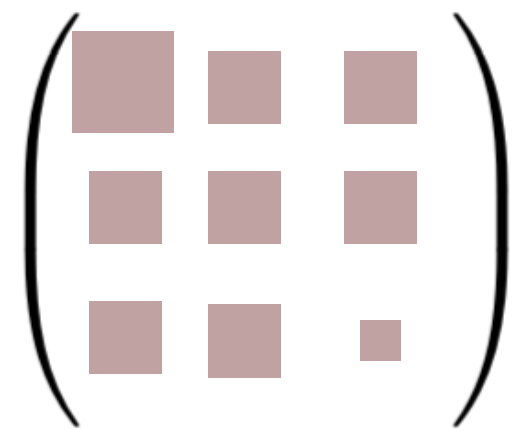
- SM Higgs $h$, heavy Higgs $H$
  - in decoupling limit $m_A^2 + Z_5 v^2 \gg Z_1 v^2$
  - alignment w/o decoupling $|Z_6| \ll 1$
- $\varphi$ small mixing with $h, H$

  $h = \sin\theta_h \varphi + \cdots, \qquad H = \sin\theta_H \varphi + \cdots$
- $\varphi$ coupling to SM fermions
  - $\theta_h \gg \theta_H \Rightarrow$ Higgs-mixed light scalar
  - $\theta_h \ll \theta_H \Rightarrow$ general light scalar

# 2HDM+$\varphi$

JZ, 2406.nnnnn

$\langle H_1^{(}$ $y_h \sim$  sis

$\mathcal{M}_H^2 = \begin{pmatrix} Z \\ Z \end{pmatrix}$ $y_H \sim$ 

$V \supset \frac{1}{2}$ … $_1)(H_1^\dagger H_2) + \text{h.c.}\}.$

Higgs $H$

- in decoupling limit $m_A^2 + Z_5 v^2 \gg Z_1 v^2$
- alignment w/o decoupling $|Z_6| \ll 1$

- $\varphi$ small mixing with $h, H$
  $h = \sin\theta_h \varphi + \cdots, \qquad H = \sin\theta_H \varphi + \cdots$
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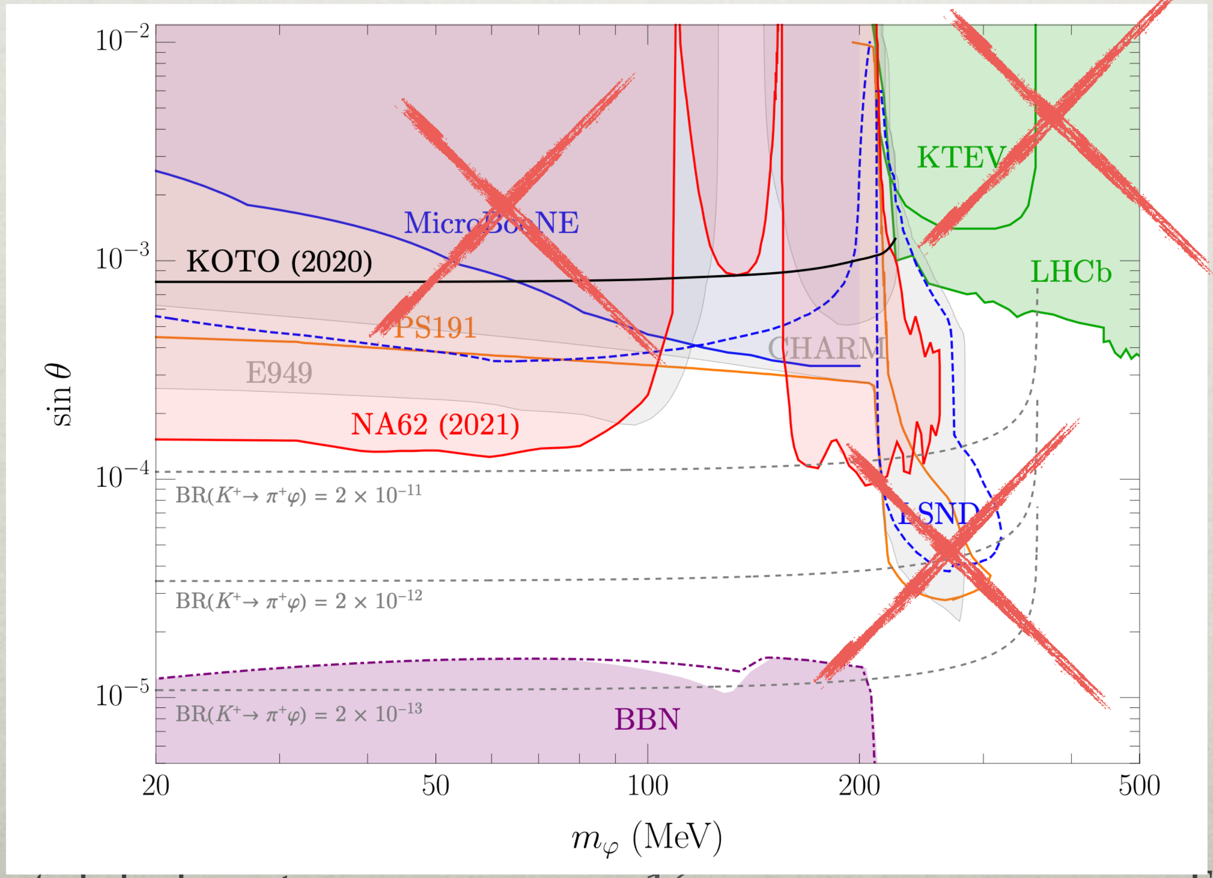
# BEYOND LIGHT HIGGS-MIXED SCALAR

Delaunay, Kitahara, Soreq, JZ, 2406.nnnnn

- phenomenology drastically different
- example: flavor diagonal leptophobic limit
  - only NA62 and KOTO bounds remain

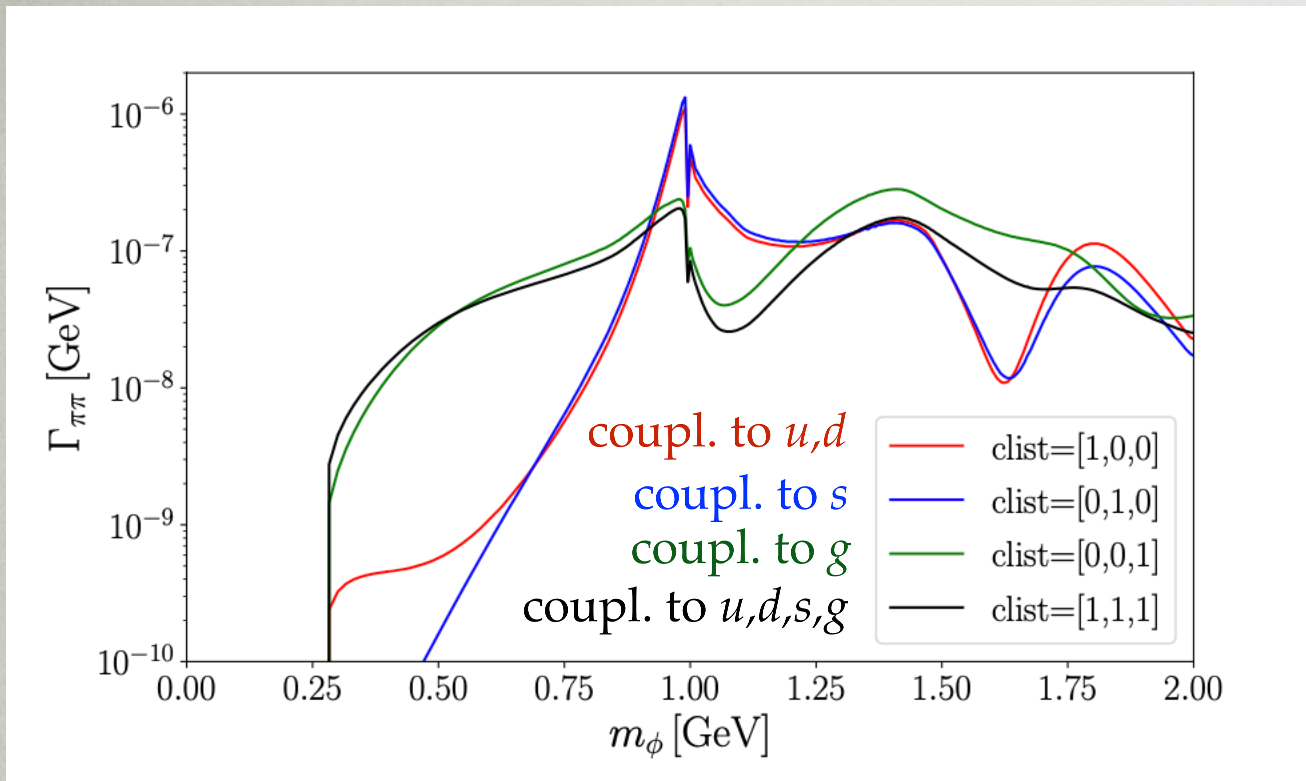


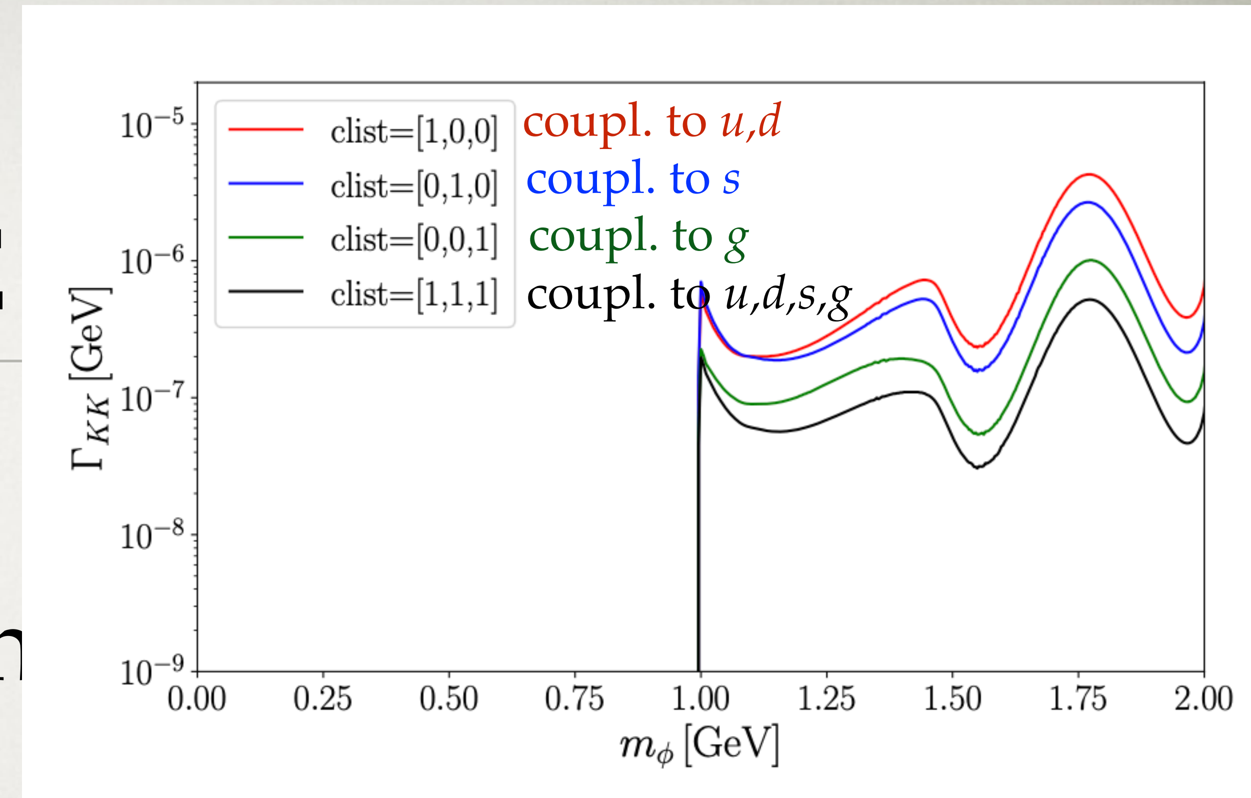

Alonso-Alvarez et al, 2201.07805

# BEYOND LIGHT HIGGS-MIXED SCALAR

- example: flavor aligned leptophobic limit
  - search for narrow peak in $D \to \pi\pi^+\pi^-$, $D \to \pi K^+ K^-$, $D \to \pi\gamma\gamma$
  - similar in $B \to K^{(*)}\varphi$, $B \to \pi\varphi$, $B \to \rho\varphi$, $B_s \to \phi\varphi$,..., with $\varphi \to KK, \pi\pi, \gamma\gamma, ...$
- relative branching ratios depend on values of flavor diagonal couplings

Blackstone, Tarrus Castella, Passemar, JZ, 2406.nnnn

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Blackstone, Tarrus Castella, Passemar, JZ, 2406.nnnn

# DARK PHOTON

- dark photon usually assumed to have only kinetic mixing

$$-\epsilon F'_{\mu\nu} B^{\mu\nu}$$

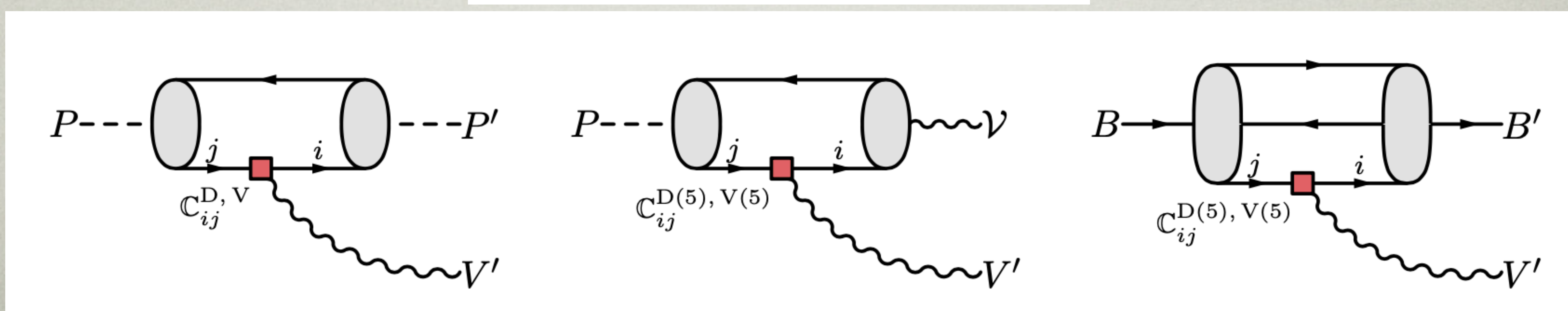
- in general also FV couplings
  - FV vector interactions (e.g. if from horizontal gauge symmetry)

Smolkovic, Tammaro, JZ, 1907.10063
Eguren et al, 2405.00108

$$\frac{m_{V'}}{\Lambda} V'_\mu \bar{f}_i \gamma^\mu \left(\mathbb{C}^{\rm V}_{ij} + \mathbb{C}^{\rm V5}_{ij}\gamma_5\right) f_j$$

  - FV dipole interactions

$$\frac{1}{\Lambda} V'_{\mu\nu} \bar{f}_i \sigma^{\mu\nu} \left(\mathbb{C}^{\rm D}_{ij} + i\mathbb{C}^{\rm D5}_{ij}\gamma_5\right) f_j$$



# DARK PH

- dark photon usually assumed to

$$-\epsilon F'_{\mu\nu} F$$

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$$\frac{1}{\Lambda} V'_{\mu\nu} \bar{f}_i \sigma^{\mu\nu} \left(\mathbb{C}^{D}_{ij} + i\mathbb{C}^{D5}_{ij}\gamma_5\right) f_j$$

| Quark Transition | Hadronic Process |
|---|---|
| $s \to d$ | $K^+ \to \pi^+ + V'$ |
| | $\Sigma^+ \to p + V'$ |
| | $\Xi^- \to \Sigma^- + V'$ |
| | $\Xi^0 \to \Sigma^0 + V'$ |
| | $\Xi^0 \to \Lambda + V'$ |
| | $\Lambda \to n + V'$ |
| $b \to s$ | $B^+ \to K^+ + V'$ |
| | $B \to K^* + V'$ |
| | $\Lambda_b \to \Lambda + V'$ |
| $b \to d$ | $B^+ \to \pi^+ + V'$ |
| | $B \to \rho + V'$ |
| | $\Lambda_b \to n + V'$ |
| $c \to u$ | $D^+ \to \pi^+ + V'$ |
| | $\Lambda_c \to p + V'$ |

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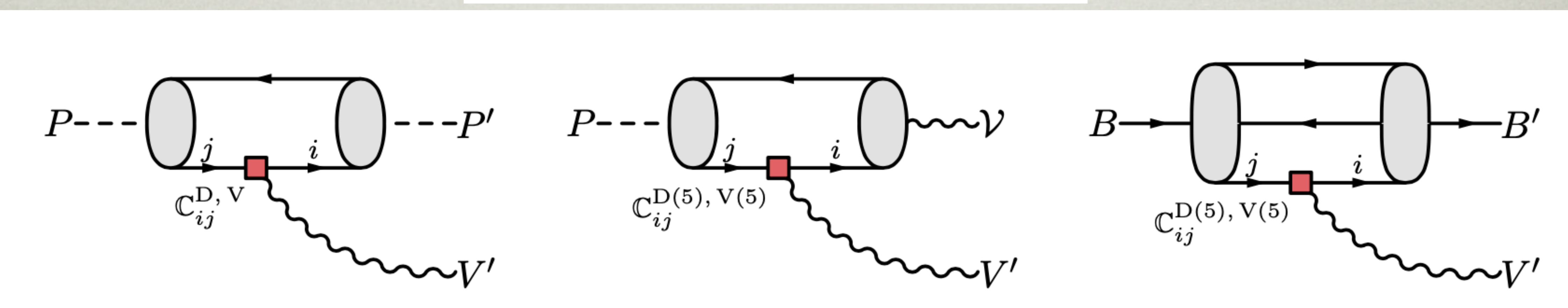

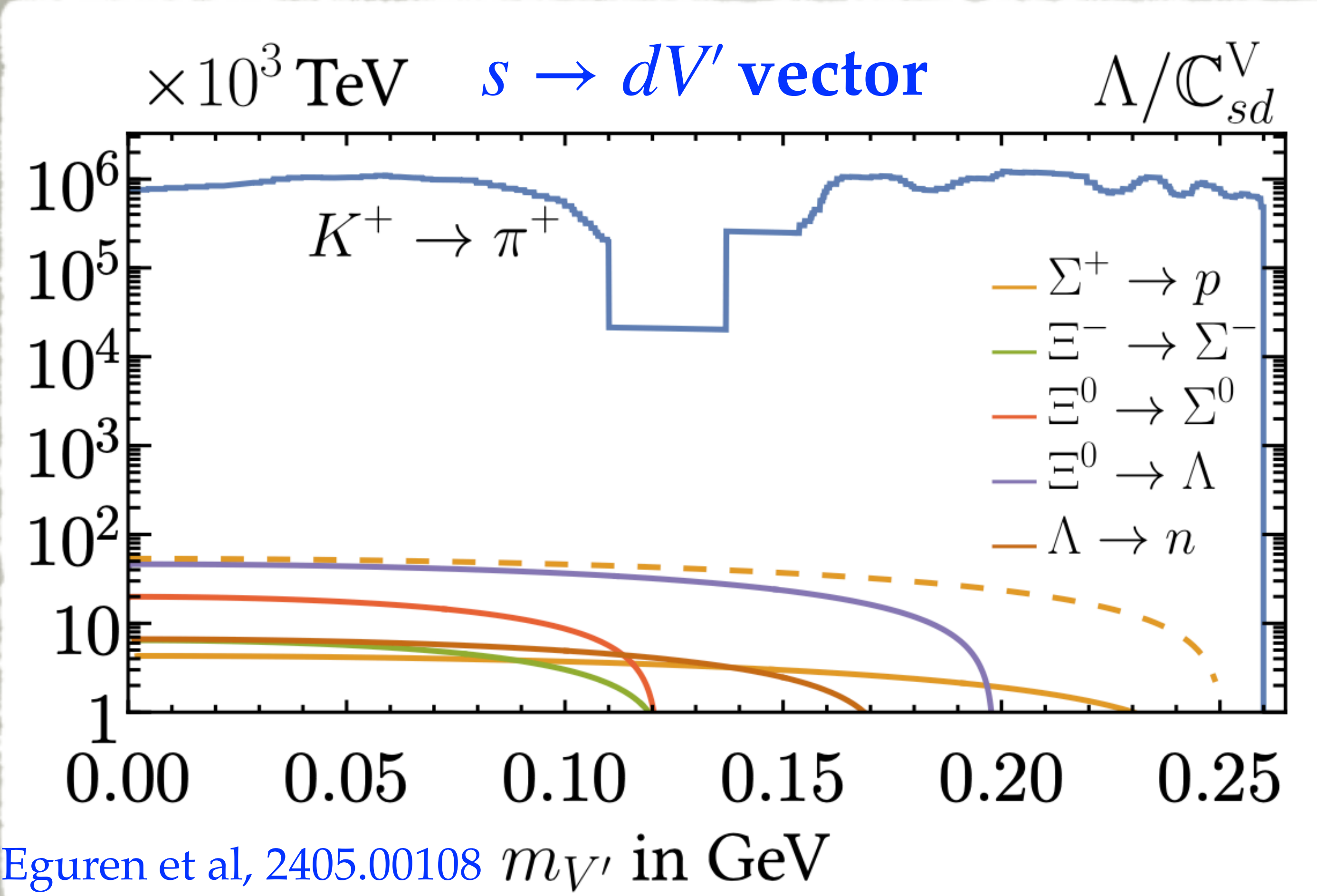

Eguren et al, 2405.00108

| Quark Transition | Hadronic Process |
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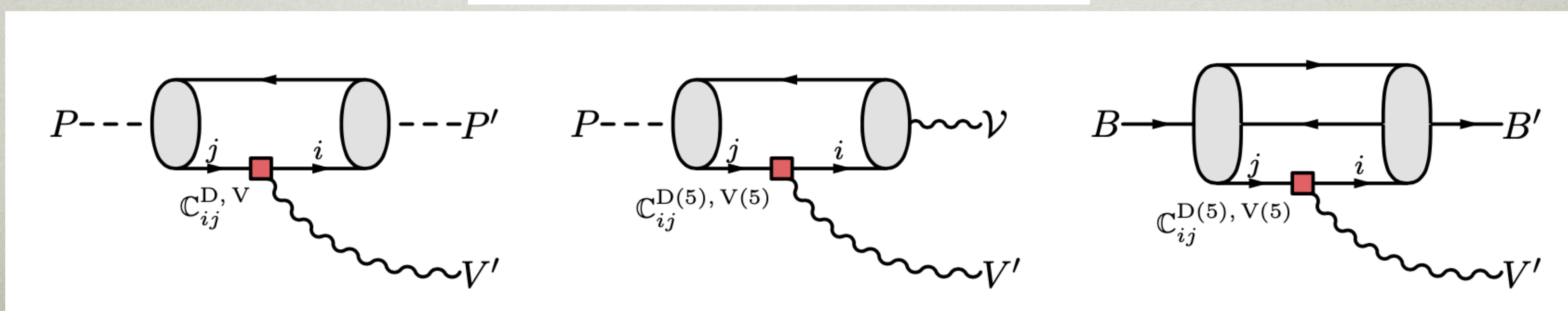
| $s \to d$ | $K^+ \to \pi^+ + V'$ <br> $\Sigma^+ \to p + V'$ <br> $\Xi^- \to \Sigma^- + V'$ <br> $\Xi^0 \to \Sigma^0 + V'$ <br> $\Xi^0 \to \Lambda + V'$ <br> $\Lambda \to n + V'$ |
| $b \to s$ | $B^+ \to K^+ + V'$ <br> $B \to K^* + V'$ <br> $\Lambda_b \to \Lambda + V'$ |
| $b \to d$ | $B^+ \to \pi^+ + V'$ <br> $B \to \rho + V'$ <br> $\Lambda_b \to n + V'$ |
| $c \to u$ | $D^+ \to \pi^+ + V'$ <br> $\Lambda_c \to p + V'$ |

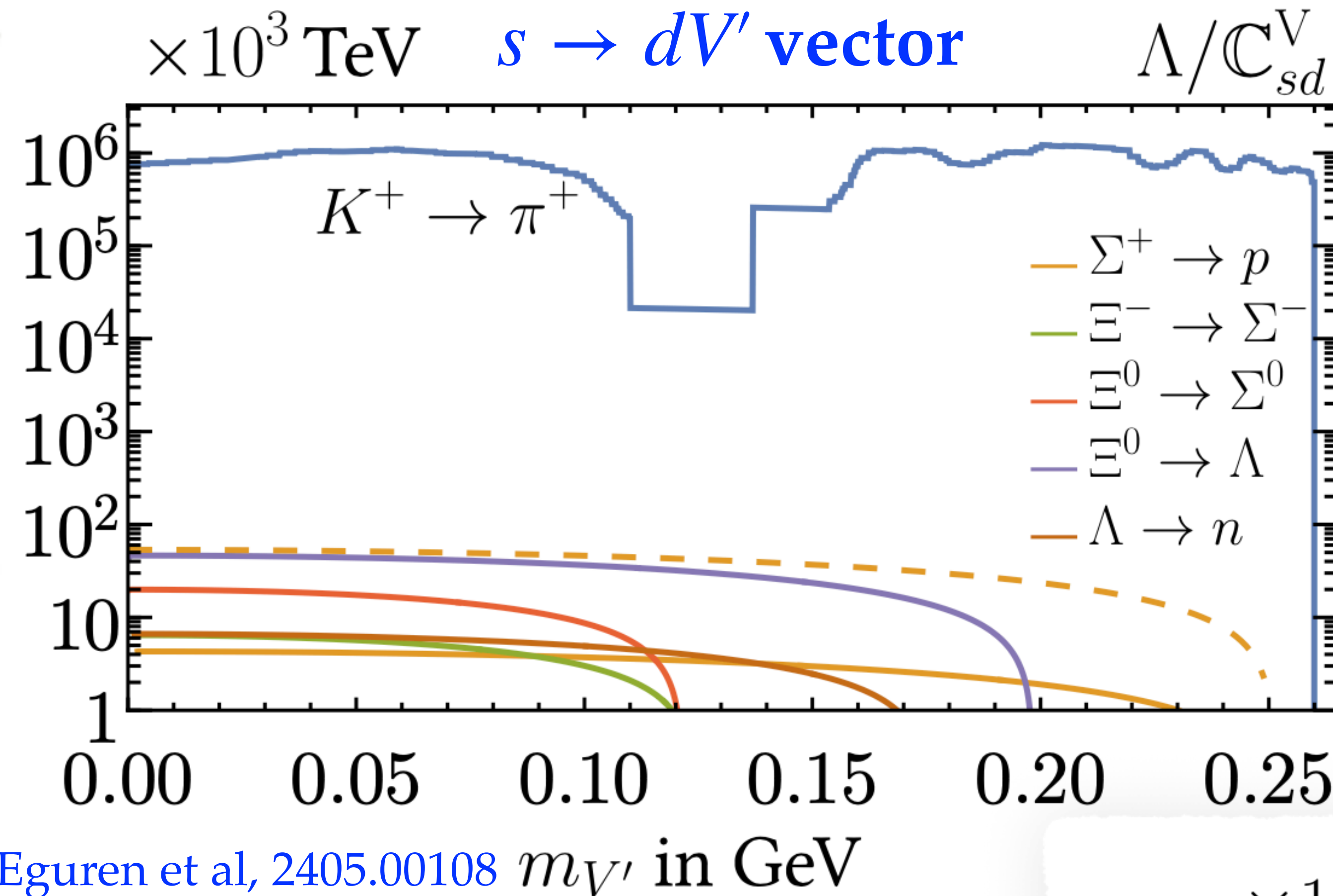
- FV vector interactions (e.g.

$$\frac{m_{V'}}{\Lambda} V'_\mu \bar{f}_i \gamma^\mu \left(\mathbb{C}^{V}_{ij}\right.$$

- FV dipole interactions

$$\frac{1}{\Lambda} V'_{\mu\nu} \bar{f}_i \sigma^{\mu\nu} \left(\mathbb{C}^{D}_{ij} + i\mathbb{C}^{D5}_{ij}\gamma_5\right) f_j$$





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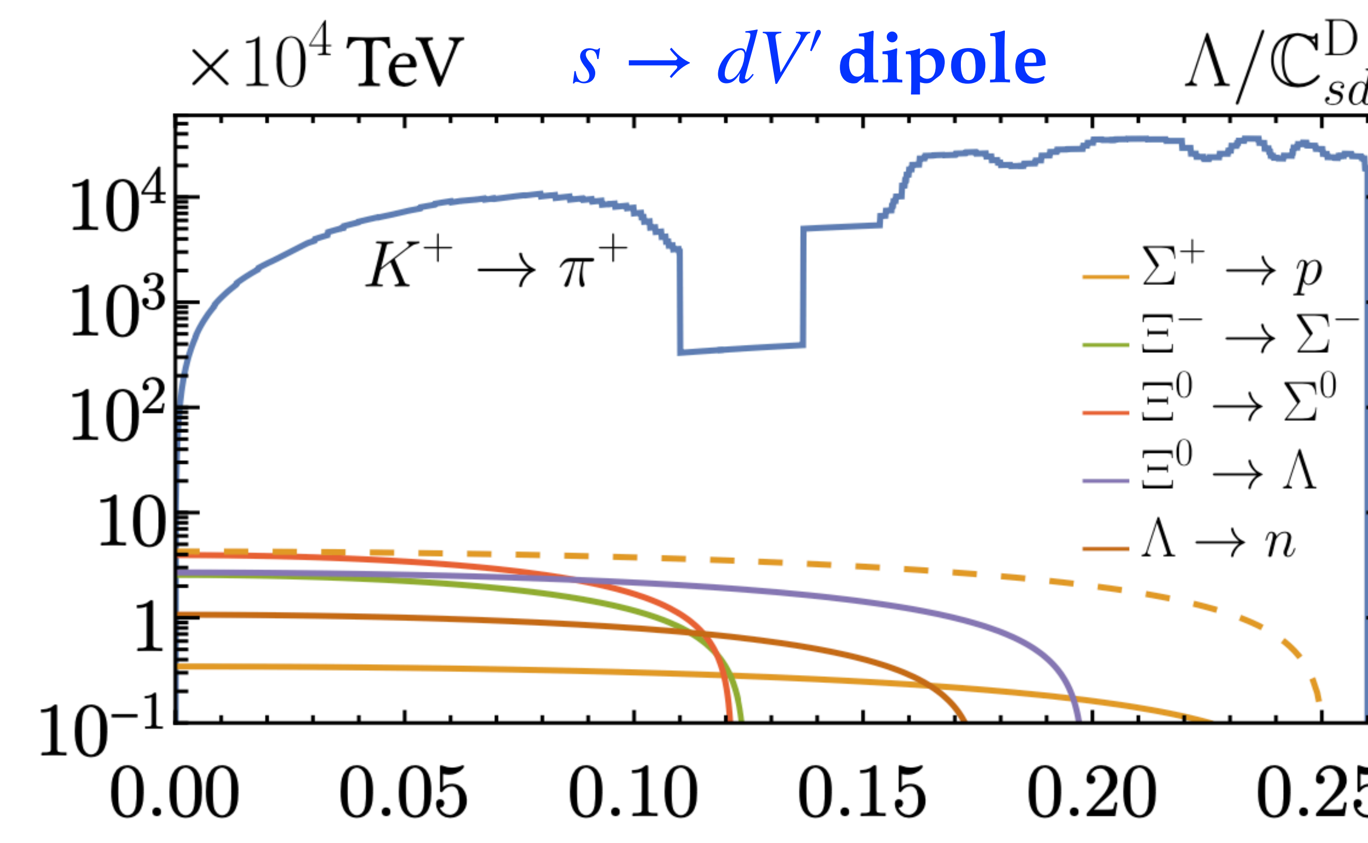

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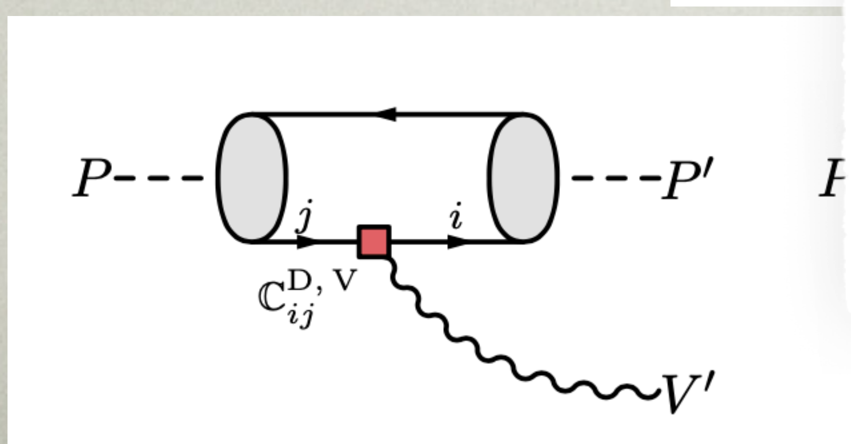
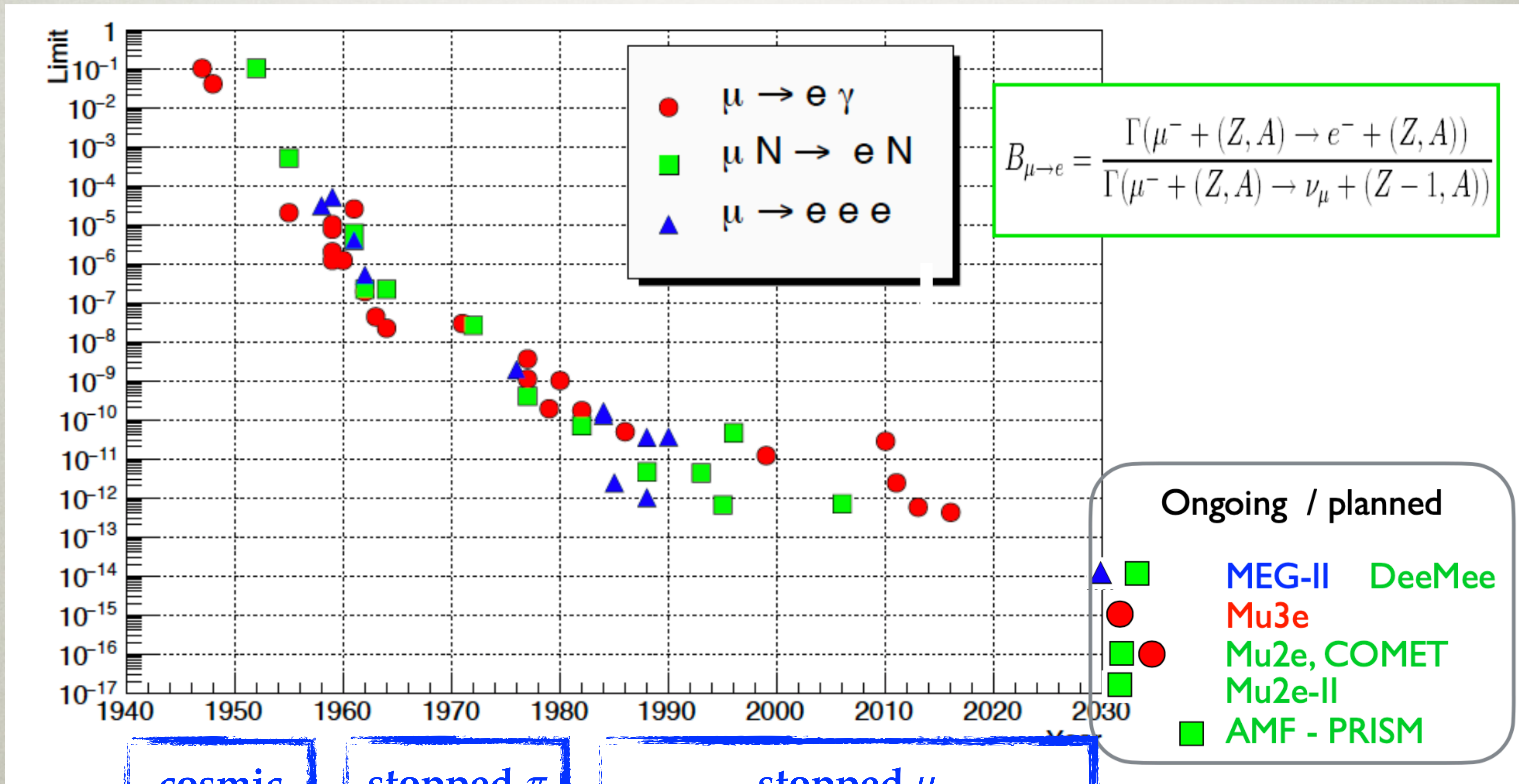


# RARE MUON TRANSITIONS

# EXPERIMENTAL PROGRESS

- steady experimental progress since 1940s




$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

cosmic rays

stopped $\pi$ beams

stopped $\mu$ beams

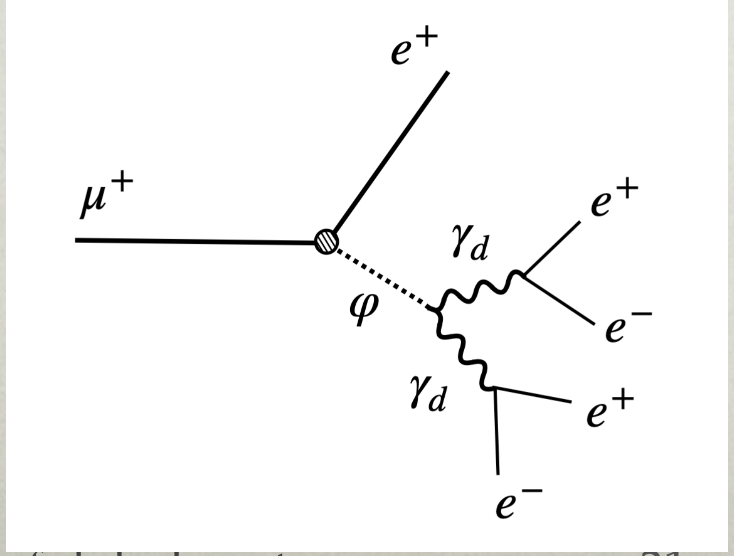
# $\mu \to 5e$

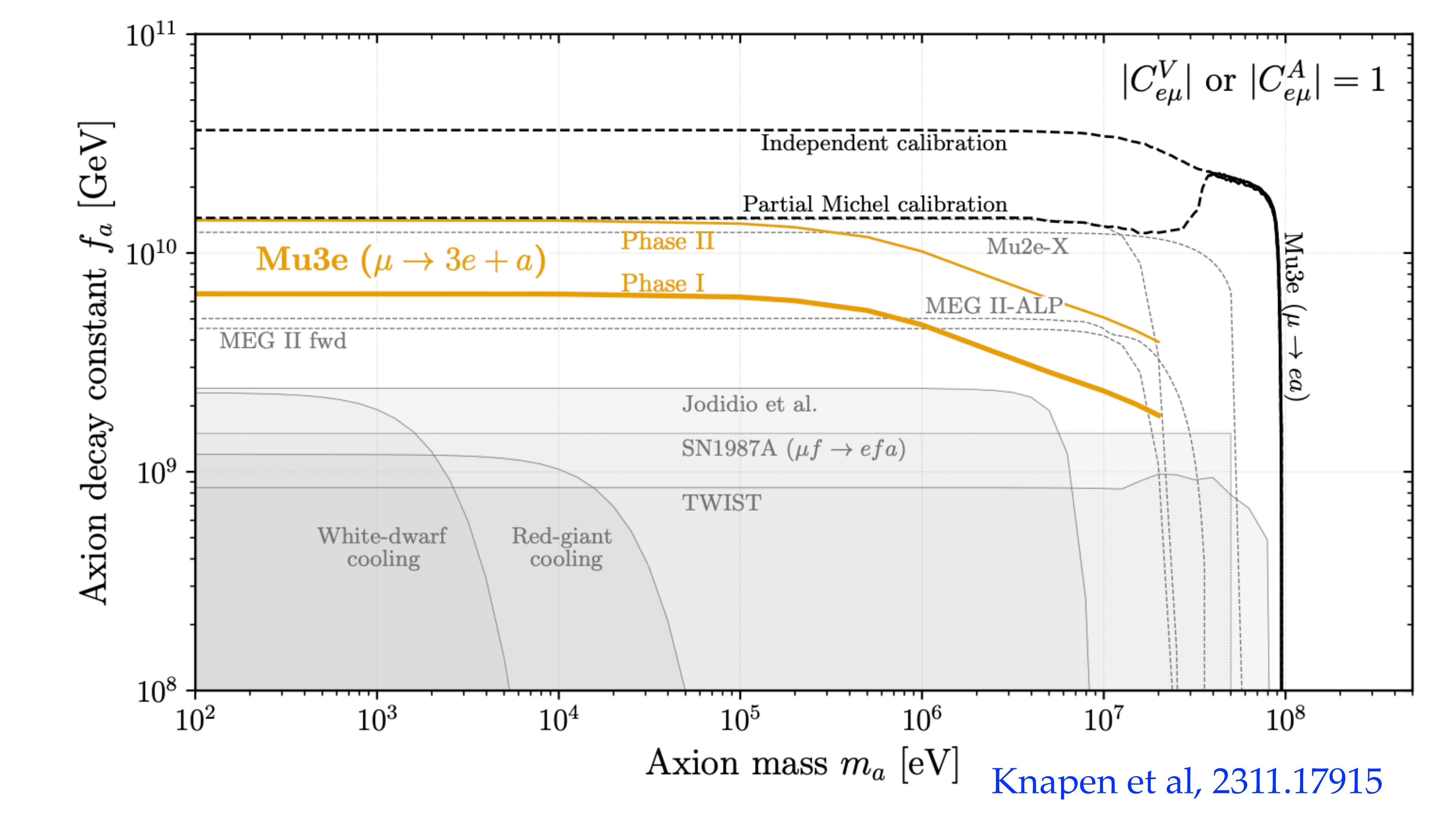
- if $\frac{m_\mu}{\Lambda}\phi(\bar{e}\mu)$ coupling ⇒ mediates $\mu \to e\varphi$
  - if $\varphi$ QCD axion ⇒ escapes the detector $\mu \to e + \text{inv}$
    - MEG-II, Mu3e, Mu2e-X, COMET-X can search for it

see also talk by Michael Schmidt on Monday

  - if $\varphi$ can decay ⇒ sensitivity to even higher scales
    - example: $\mu \to 5e$ can probe $f_a \gtrsim 10^{13}$GeV

Hostert, Menzo, Pospelov, JZ, 2306.15631






Knapen et al, 2311.17915

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l Schmidt on Monday

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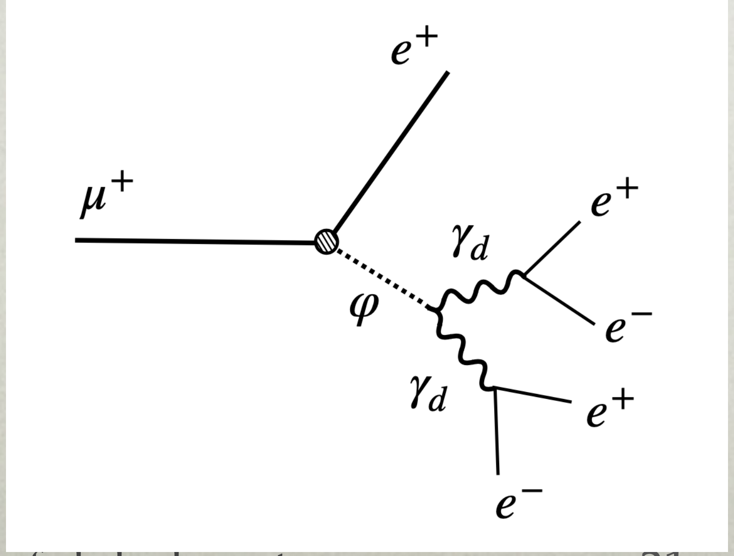

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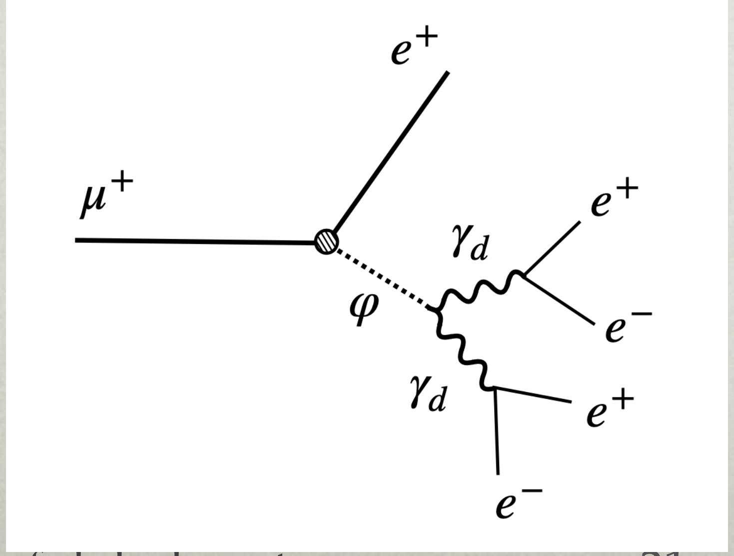
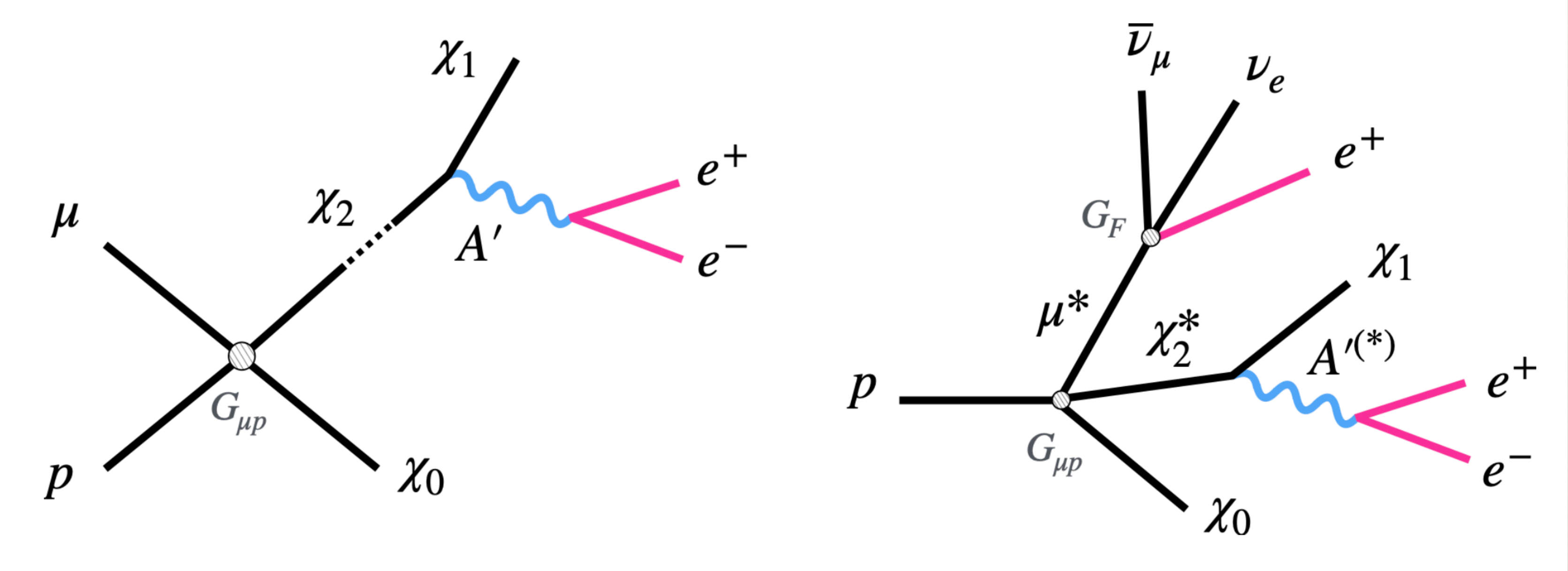


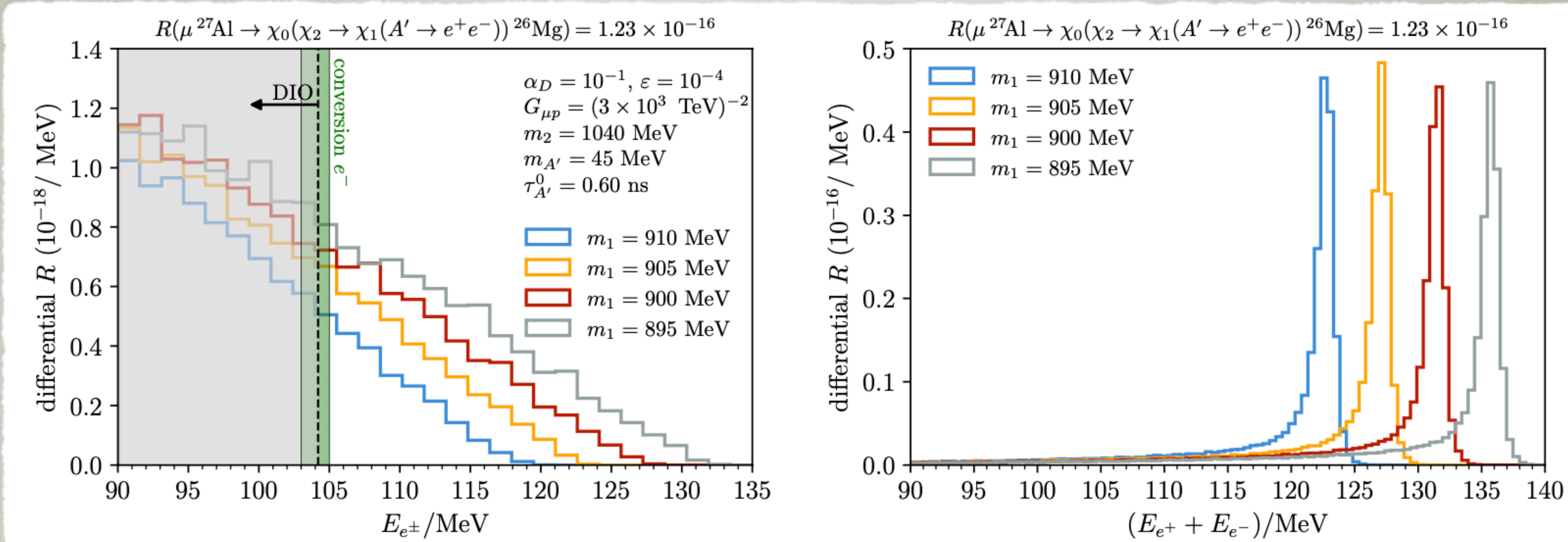
# BARYON NUMBER VIOLATION IN $\mu \to e$

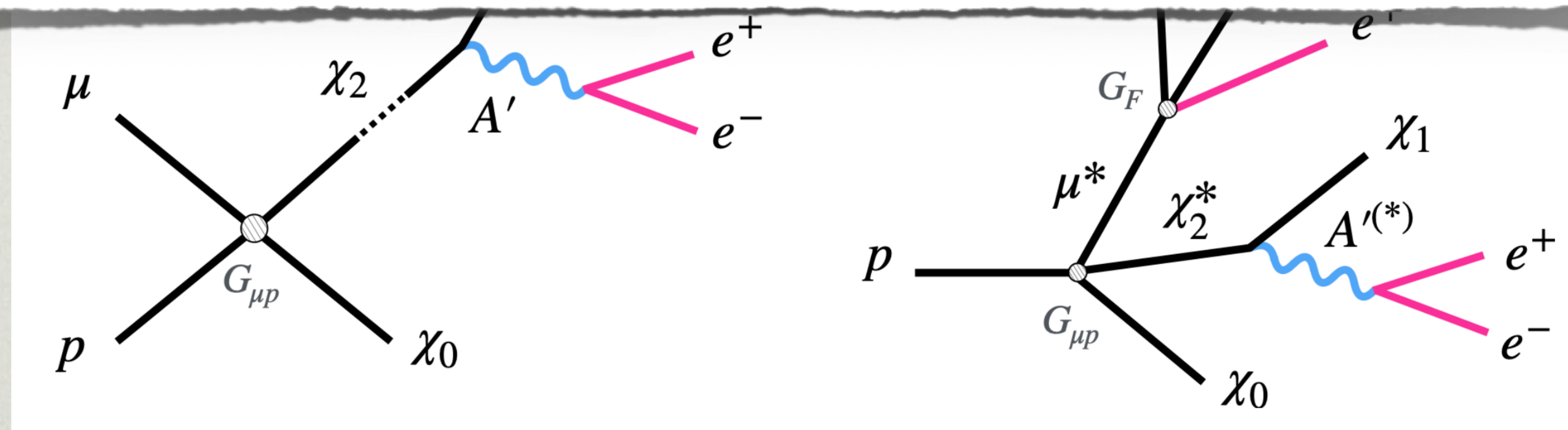
Fox, Hostert, Menzo, Pospelov, JZ, 2406.nnnnn

- one can also search for more exotic signatures
- BNV transition $\mu^- p \to e^- X$ annihilation




  - baryon no. violation only apparent, dark sector states carry baryon no.
- many constraints: proton decay, neutron star stability,....
- possible to have transitions with electrons above the $\mu \to e$ endpoint




- baryon no. violation only apparent, dark sector states carry baryon no.

- many constraints: proton decay, neutron star stability,....
- possible to have transitions with electrons above the $\mu \to e$ endpoint

# CONCLUSIONS

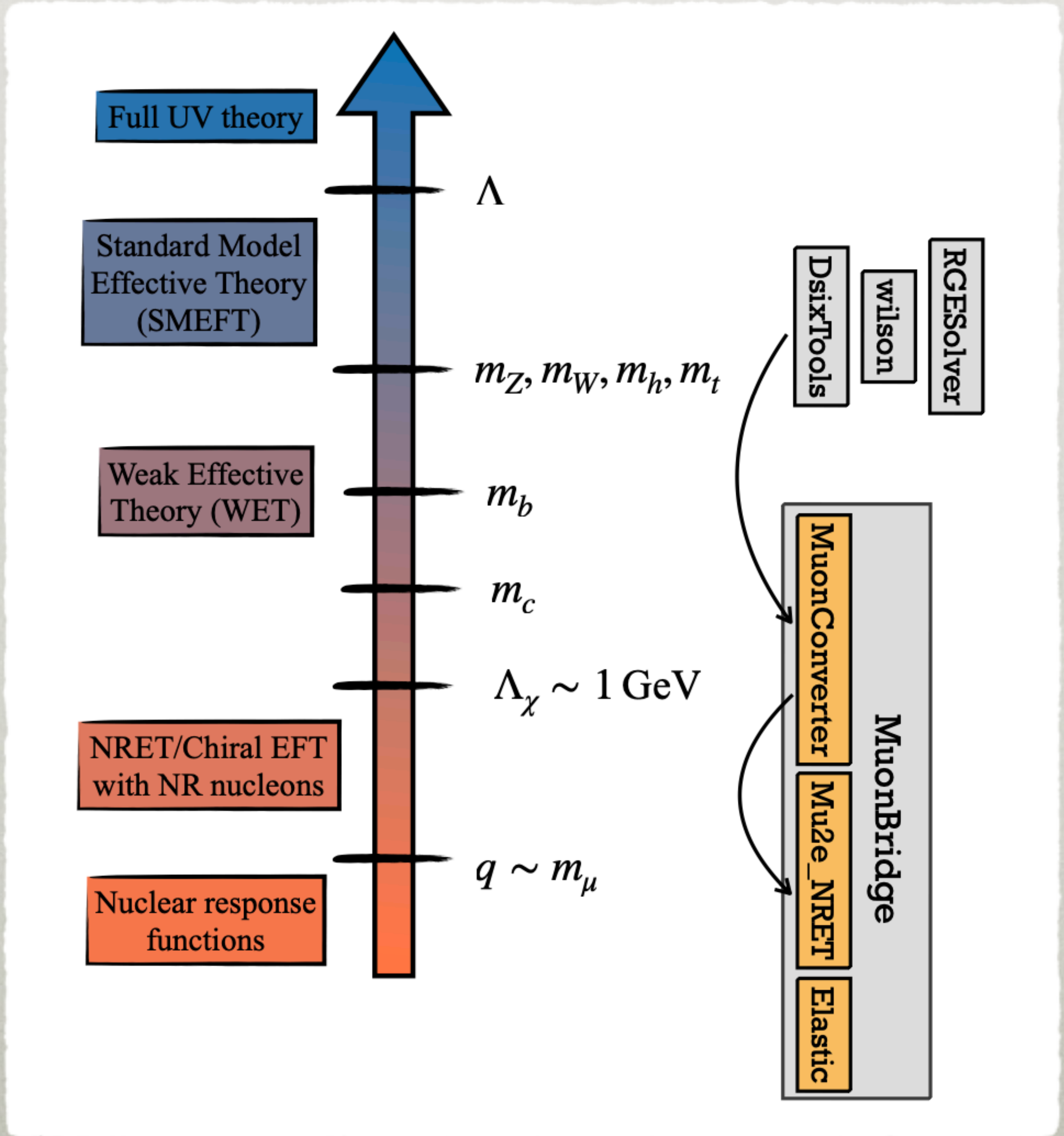
- flavor physics a sensitive probe of UV physics
- parametrically enhanced sensitivity, if decays to light states
  - can probe QCD axion + many more

# BACKUP SLIDES

# LIGHT NEW PHYSICS ⇒ PROBE OF HIGH SCALES

- rare decays into a light state, X, e.g., $K \to \pi X$ or $\mu \to eX$,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops
  - the reason is that the SM decay widths are power suppressed $\Gamma_\ell \propto m_\ell^5/m_W^4$
- if light NP couples through dim 4 op with mixing angle $\theta \Rightarrow$ $\Gamma(K \to \pi\varphi) \propto \theta^2 m_K \Rightarrow Br(K \to \pi\varphi) \propto \theta^2 (m_W/m_K)^4$
- if through dim 5 op. suppressed by $1/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- no such $1/m_\mu$ or $1/m_K$ enhancement for dimension 6 couplings $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

# TOWER OF EFTs FOR $\mu \to e$

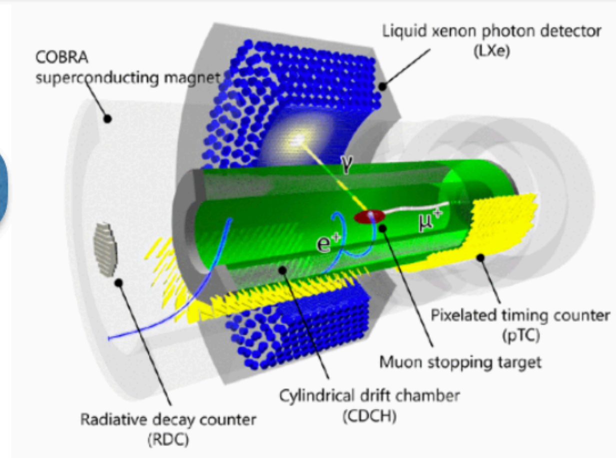


talk by Toshiyuki Iwamoto @ FPCP2020

# cLFV experiments in the world

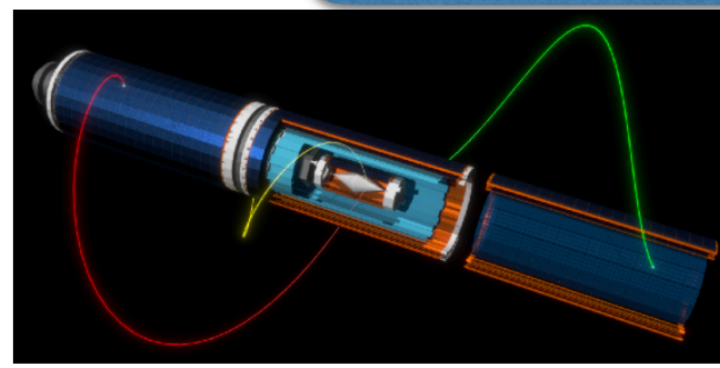
## MEG II

$\mu^+ \to e^+\gamma$




## Mu3e

$\mu^+ \to e^+e^+e^-$



Coincidence measurement: DC beam needed to minimize backgrounds from accidental coincidences

BKG $\propto$ (Rate)$^2$

PSI

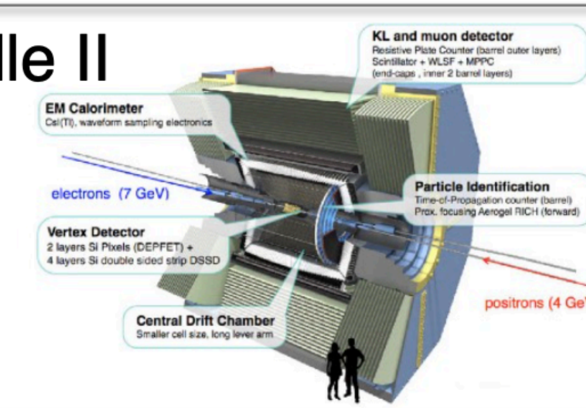
CERN

LHCb/ATLAS/CMS

$\tau \to 3\mu$, $\tau \to \mu\gamma$

KEK

Belle II

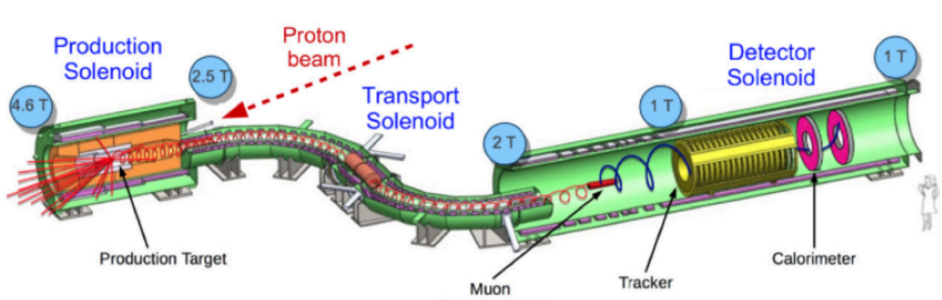



Fermilab

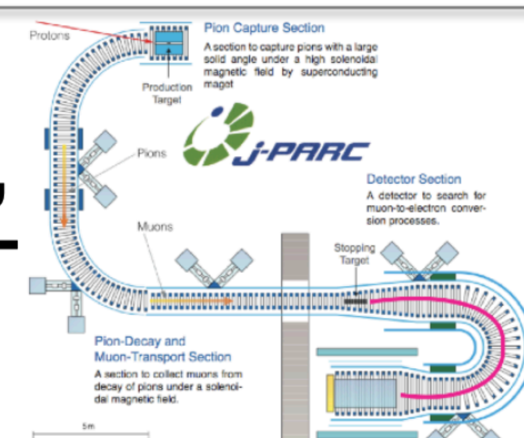
$\mu^- N \to e^- N$

J-PARC

## Mu2e




## DeeMe, COMET




Single $e^-$ measurement: pulsed beam needed

Many pion-induced backgrounds after proton pulse

wait it out with 26 ns lifetime

# COMPLEMENTARY PROBES

| | | | |
|---|---|---|---|
| **4-leptons operators** | | **Dipole operators** | |
| $Q_{\ell\ell}$ | $(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$ | $Q_{eW}$ | $(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$ |
| $Q_{ee}$ | $(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$ | $Q_{eB}$ | $(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$ |
| $Q_{\ell e}$ | $(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$ | | |
| **2-lepton 2-quark operators** | | | |
| $Q^{(1)}_{\ell q}$ | $(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$ | $Q_{\ell u}$ | $(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$ |
| $Q^{(3)}_{\ell q}$ | $(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$ | $Q_{eu}$ | $(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$ |
| $Q_{eq}$ | $(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$ | $Q_{\ell edq}$ | $(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$ |
| $Q_{\ell d}$ | $(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$ | $Q^{(1)}_{\ell equ}$ | $(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$ |
| $Q_{ed}$ | $(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$ | $Q^{(3)}_{\ell equ}$ | $(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$ |
| **Lepton-Higgs operators** | | | |
| $Q^{(1)}_{\Phi\ell}$ | $(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$ | $Q^{(3)}_{\Phi\ell}$ | $(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$ |
| $Q_{\Phi e}$ | $(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$ | $Q_{e\Phi 3}$ | $(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$ |

**probed by**

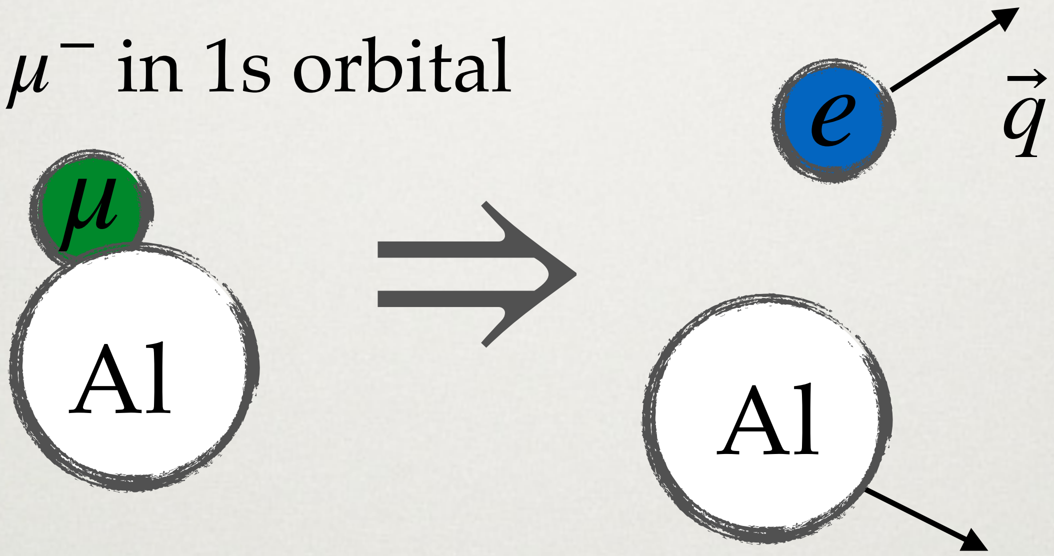
$\mu \to e\gamma$

$\mu \to 3e$

$\mu \to e$

# $\mu \to e$ CONVERSION

- initial state: $\mu^-$ in 1s orbital




- a theory challenge: predictions require nuclear physics
- there is a small parameter $|\vec{q}| \sim \mathcal{O}(100\,\mathrm{MeV}) \ll m_N$
  - can use EFT techniques (non-relativistic EFT / chiral EFT)
  - **MuonBridge** code

Haxton, McElvain, Menzo, Rule, JZ, 2406.nnnn

# LFV QCD axion

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