EXOTICA FROM KAON DECAYS: THEORY

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Kaons@CERN 2023, Sept 11 2023

The role or rare K decays

In this context Kaon physics plays a unique role:

Unique probe of flavor-symmetry breaking involving light families

The SM (approximate) accidental symmetries imply an extremely strong suppression for $A(s_L \to d_L)_{FCNC}$ [→ $B(K^+ \to \pi^+ \nu\nu)$] and helicity-suppressed amplitudes, such as $A(s_R \to u_L e_R \nu_L)$ [→ $R_{e/\mu}(K)$]

$\oplus$

This talk

Unique probe of possible light, weakly coupled, new dynamics

Not covered in this talk, despite very interesting

Unique probe of some of the fundamental SM parameters

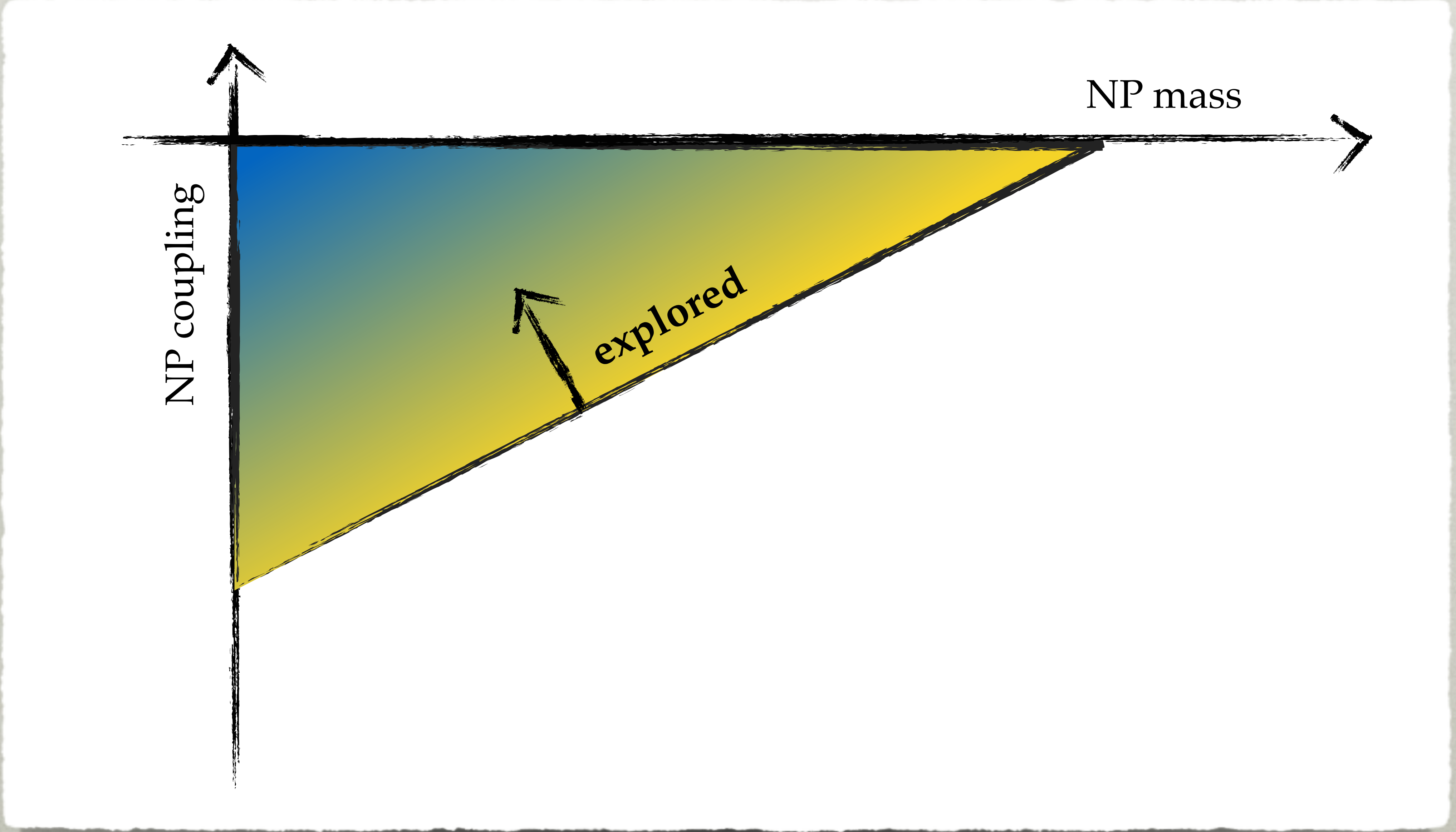
Ideal set-up for the "R&D" of theory tools about non pert. dynamics

OUTLINE

- searching for light new physics
    - increased sensitivity to UV
- rare kaon decays
    - "exotica" may not be so exotic

THE CASE FOR LIGHT NEW PHYSICS SEARCHES

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



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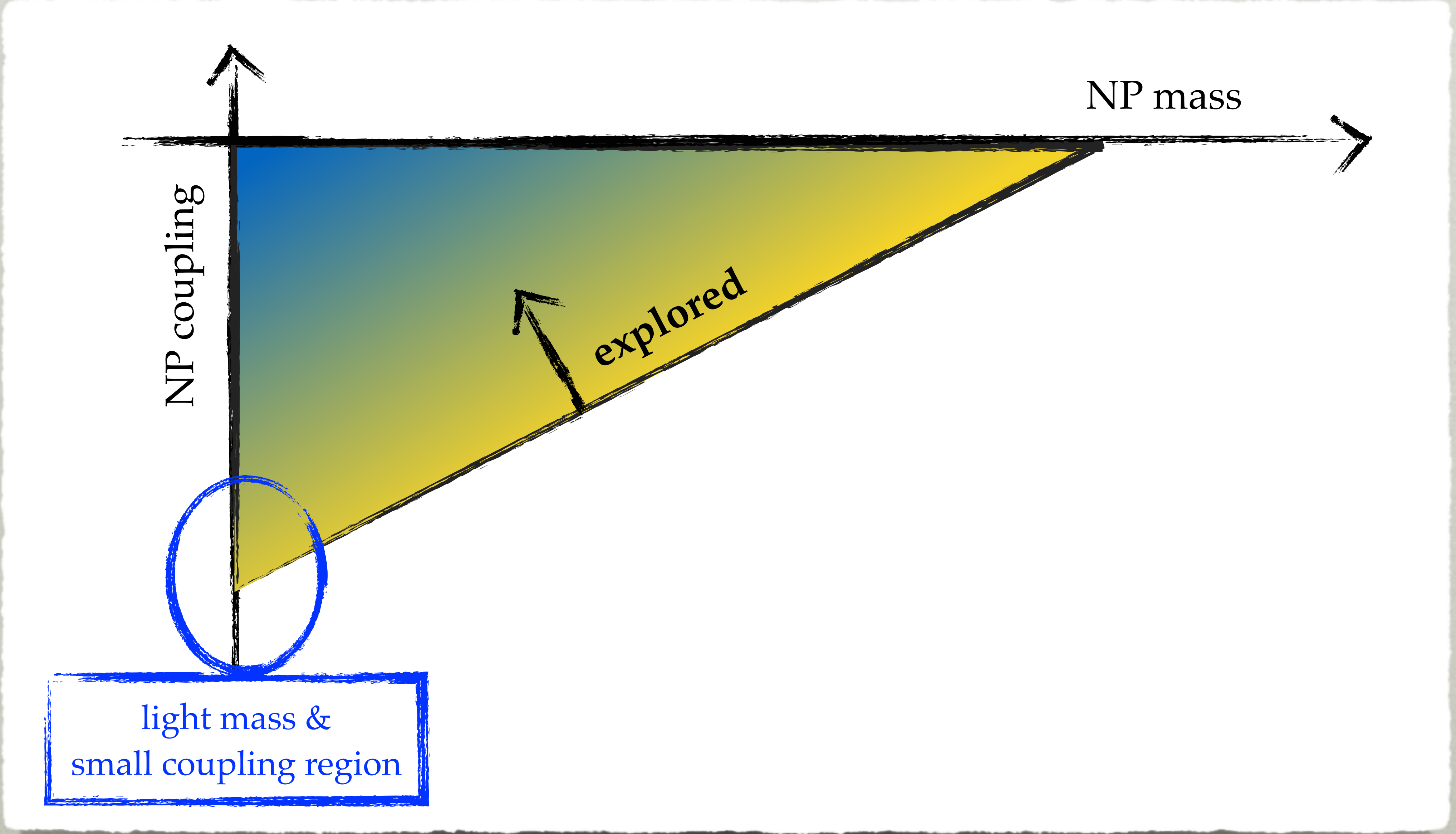

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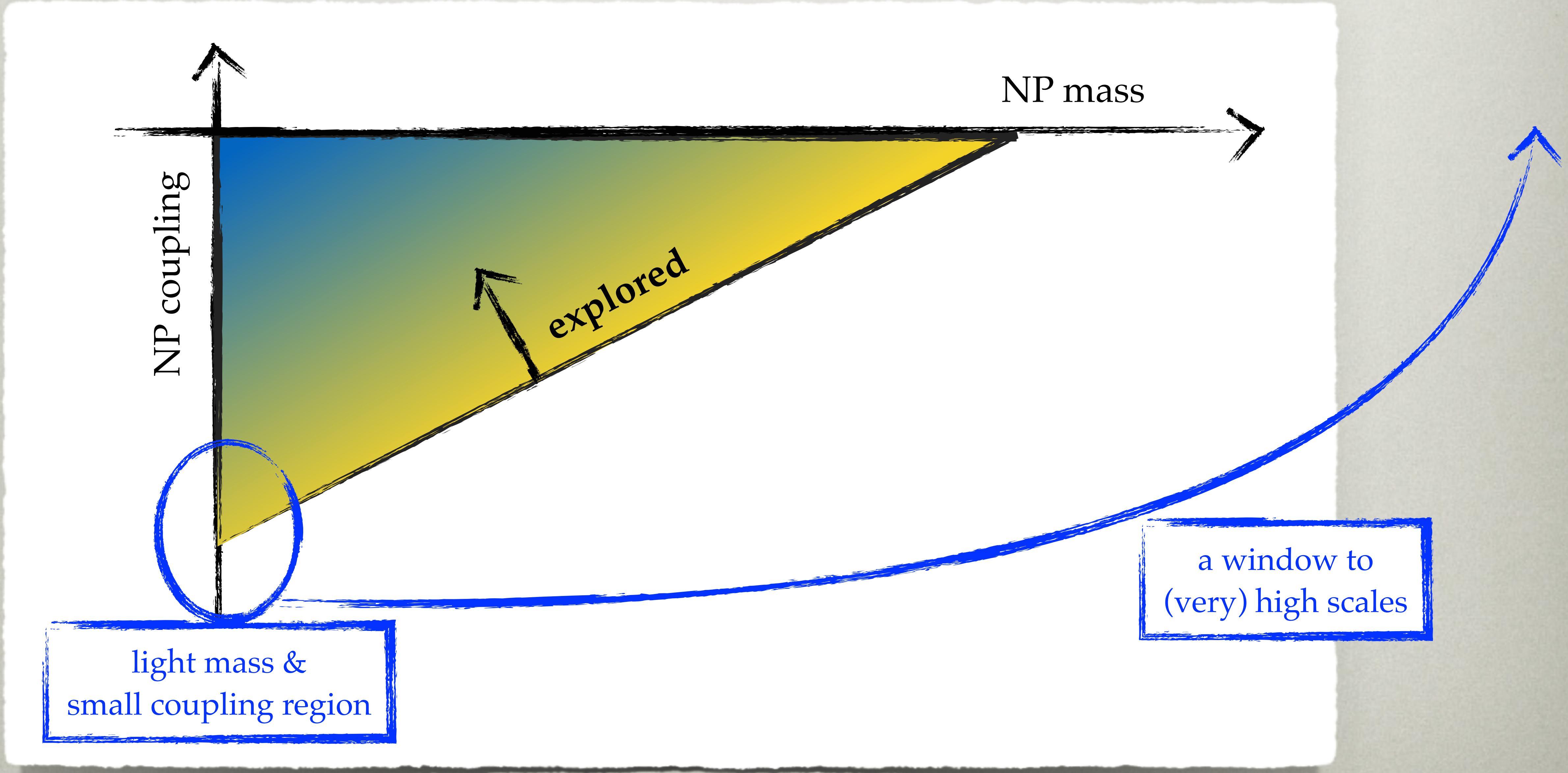
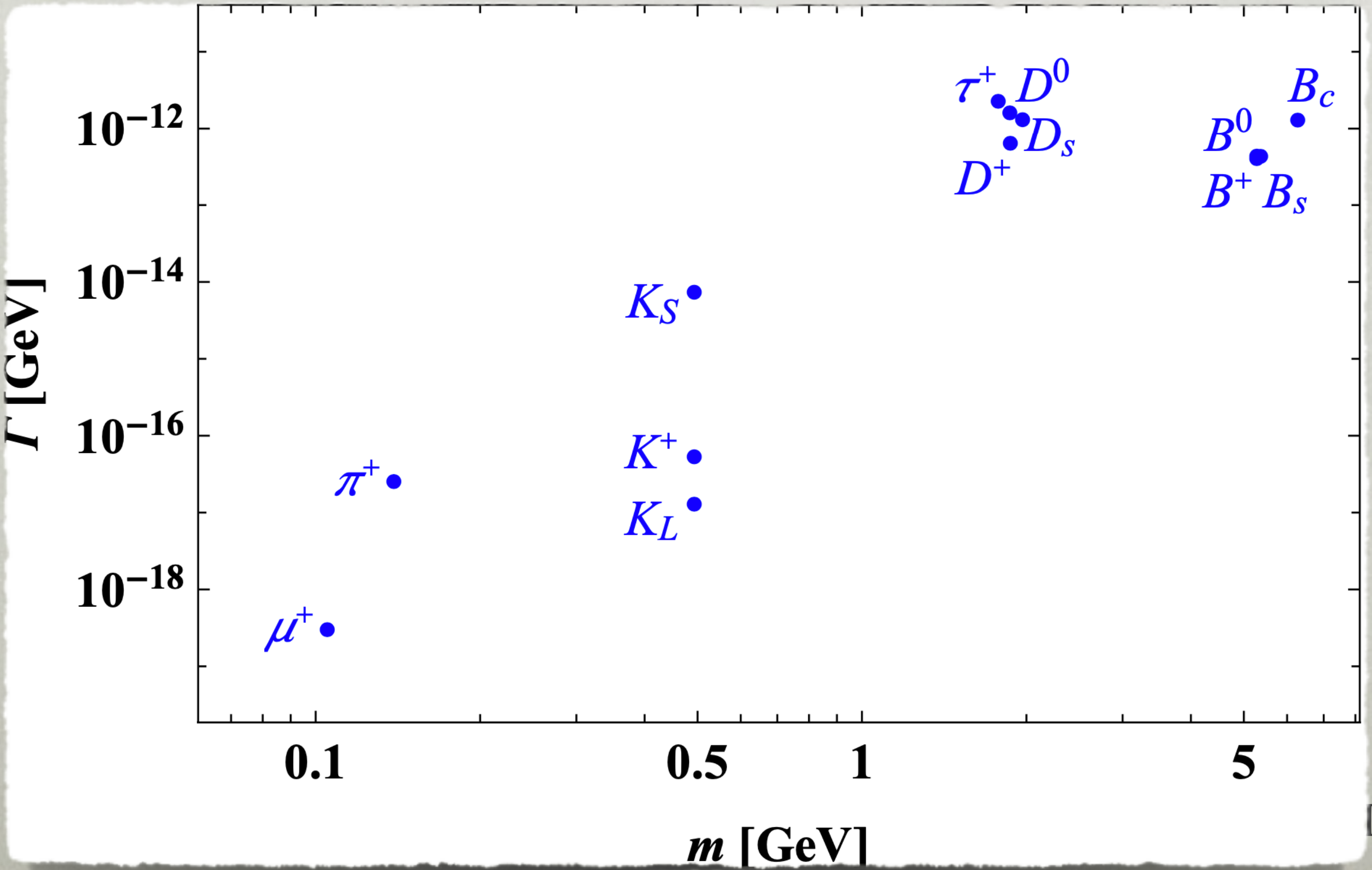


light mass &
small coupling region

a window to
(very) high scales

LOW ENERGY FCNC PROBES

- parametric gain in sensitivity to UV scales
    - SM decay widths small for weak decays $\Gamma \propto m^5/m_W^4$
- if light NP couples through dim 5 ops. supp. by $1/f_a$
    - $\Rightarrow Br(K \to \pi\varphi) \propto (m_W^2/f_a m_K)^2$
    - similar for other mesons, leptons ⇒ which wins depends on flavor and CP structure of the NP



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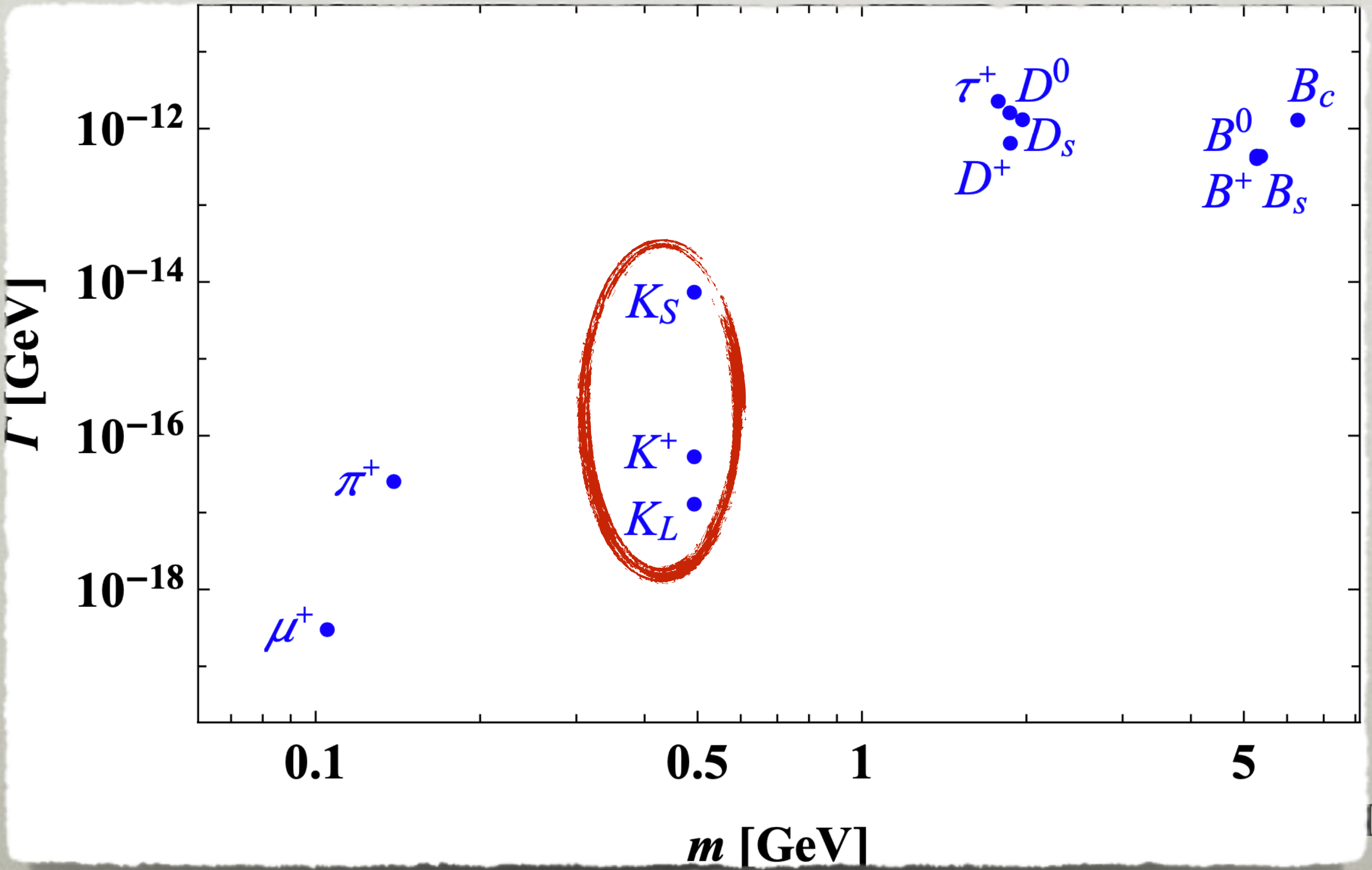


THE REST OF THIS TALK

- searches for light new (pseudo)scalars
  - from rare kaon decays

Alonso-Alvarez et al, 2201.07805

ALPs

- focus on pseudoscalars (ALPs)
- generic in NP scenarios : whenever global U(1) spontaneously broken ⇒ pNGB
    - celebrated example: QCD axion
- in general flavor violating couplings
- from low energy perspective the EFT starts at dim 5

$$\mathcal{L}_{\text{ALP-gauge}} = \frac{N_3 \alpha_s}{8\pi f_a} a G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{N_2 \alpha_2}{8\pi f_a} a W^i_{\mu\nu} \tilde{W}^{i\mu\nu} + \frac{N_1 \alpha_1}{8\pi f_a} a B_{\mu\nu} \tilde{B}^{\mu\nu} \, .$$

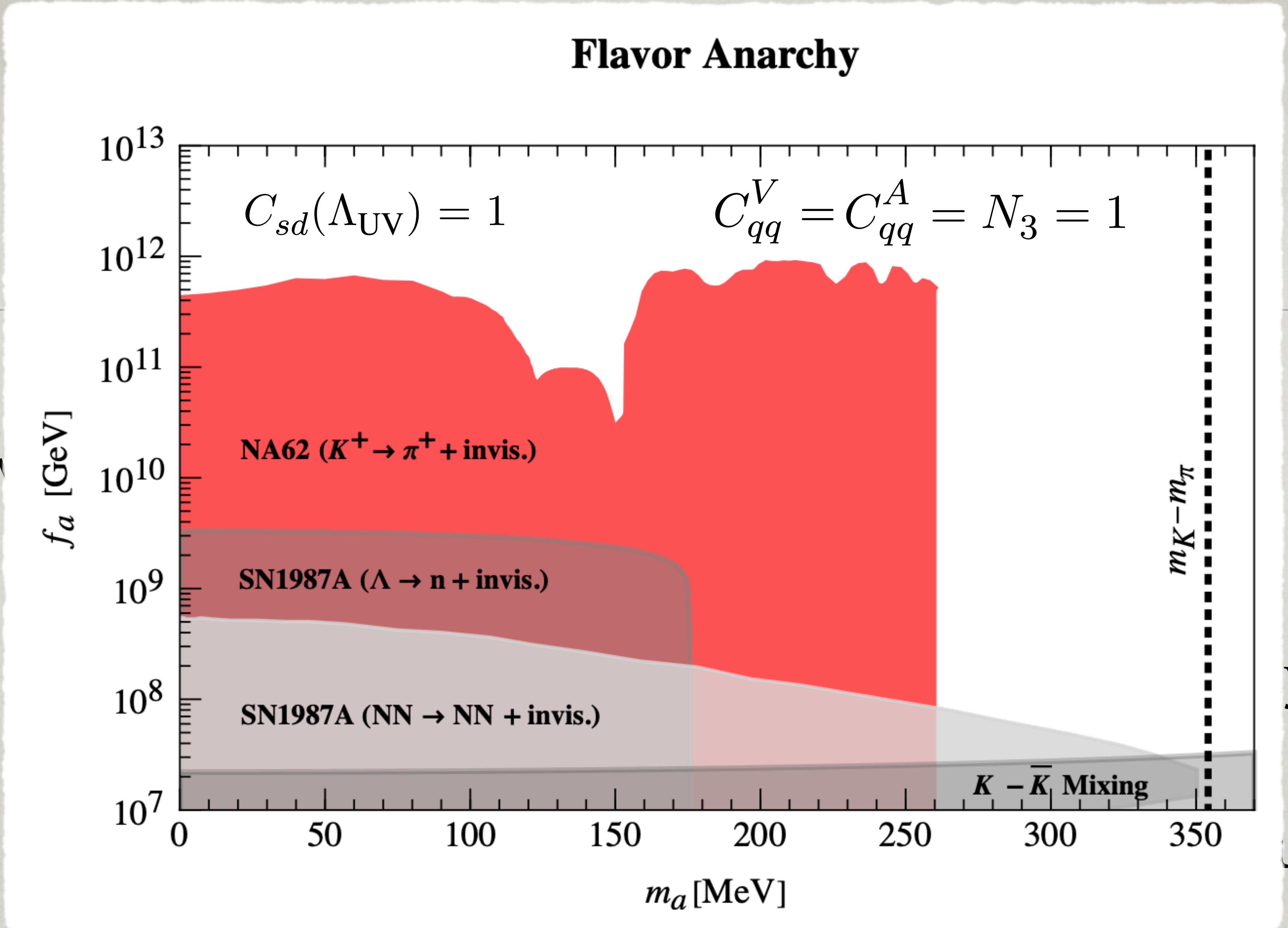
$$\mathcal{L}_{\text{ALP-f}} = \frac{\partial_\mu a}{2 f_a} \, \bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5 \right) f_j \, ,$$

FLAVOR STRUCTURE

- two phenomenologically very different regimes
- if FV in the UV: $C_{ds}^{A,V}(\Lambda_{\rm UV}) \neq 0$
  - very stringent constraints on $f_a \Rightarrow a$ does not decay in the detector
  - $K^+ \to \pi^+ a$ decay results in $K^+ \to \pi^+ +$ inv signature
- if FV only from the SM: $C_{ds}^{A,V}(\Lambda_{\rm UV}) = 0$
  - $s \to da$ coupling from RG $\Rightarrow$ much weaker constraints

$$C_{ds}^{A,V}(M_Z) = \frac{y_t^2}{16\pi^2} V_{td}^* V_{ts} C_{tt}^A \log \frac{\Lambda_{\rm UV}}{M_Z} \simeq 2 \times 10^{-6} C_{tt}^A \log \frac{\Lambda_{\rm UV}}{M_Z}$$

  - a decaying inside detector possible



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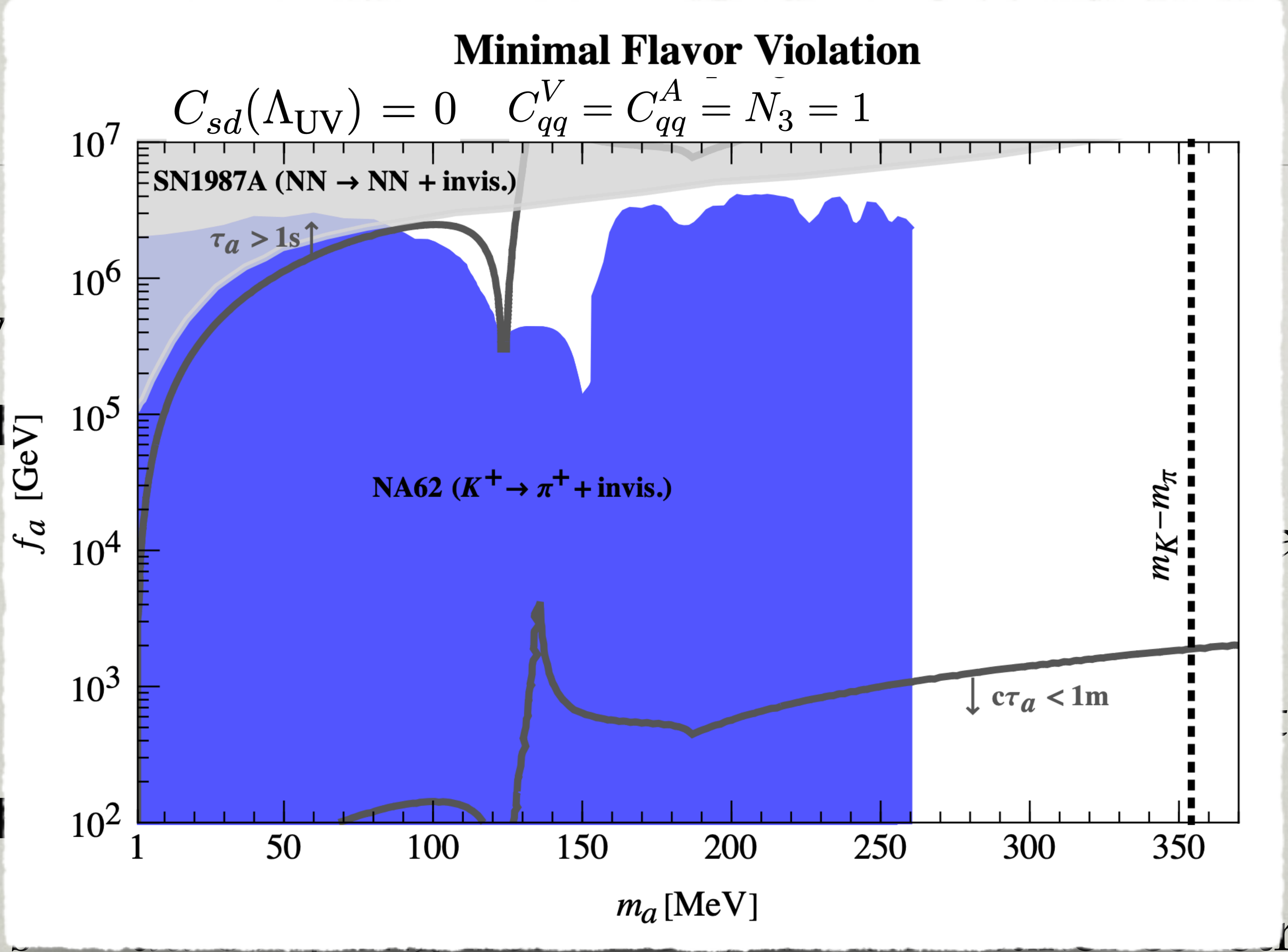

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  - a decaying inside detector possible

2201.07805

PROMPT ALPS

- searches for prompt ALPs in $K \to \pi a$
  - either $a \to \gamma\gamma$ or $a \to e^+e^-$
- the bounds depend on what exactly the couplings are
- several examples for $C_{ij}^{V,A}$ at $\mu = \Lambda_{\rm UV} = 4\pi f_a$
  - coupling to only gluons: $N_3 \neq 0$
  - coupling to W, Z only: $N_2 \neq 0$
  - only $C_{uu}^A \neq 0$
  - only $C_{dd}^A \neq 0$

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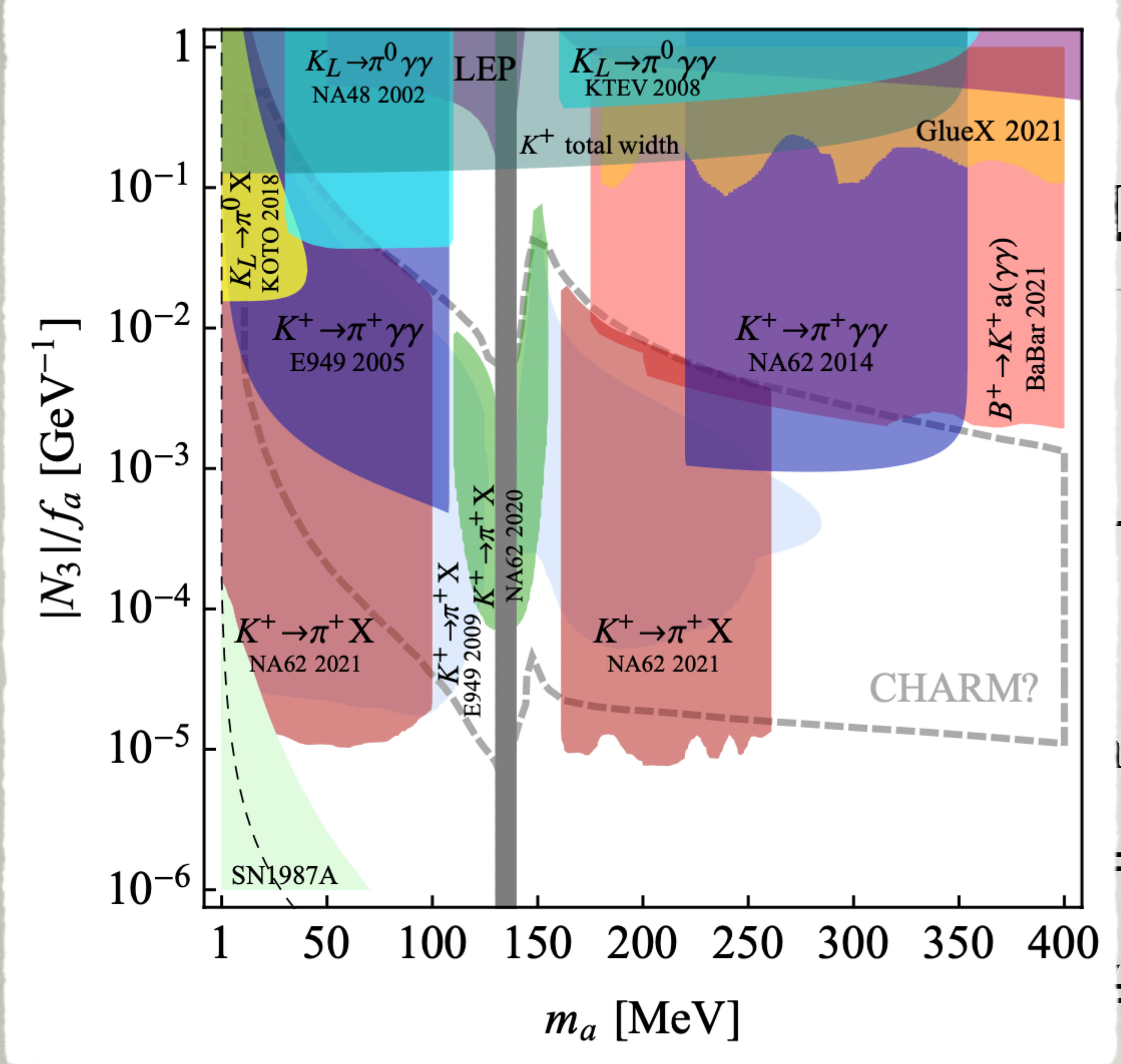
LPS



$\to \pi a$

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$= \Lambda_{\rm UV} = 4\pi f_a$

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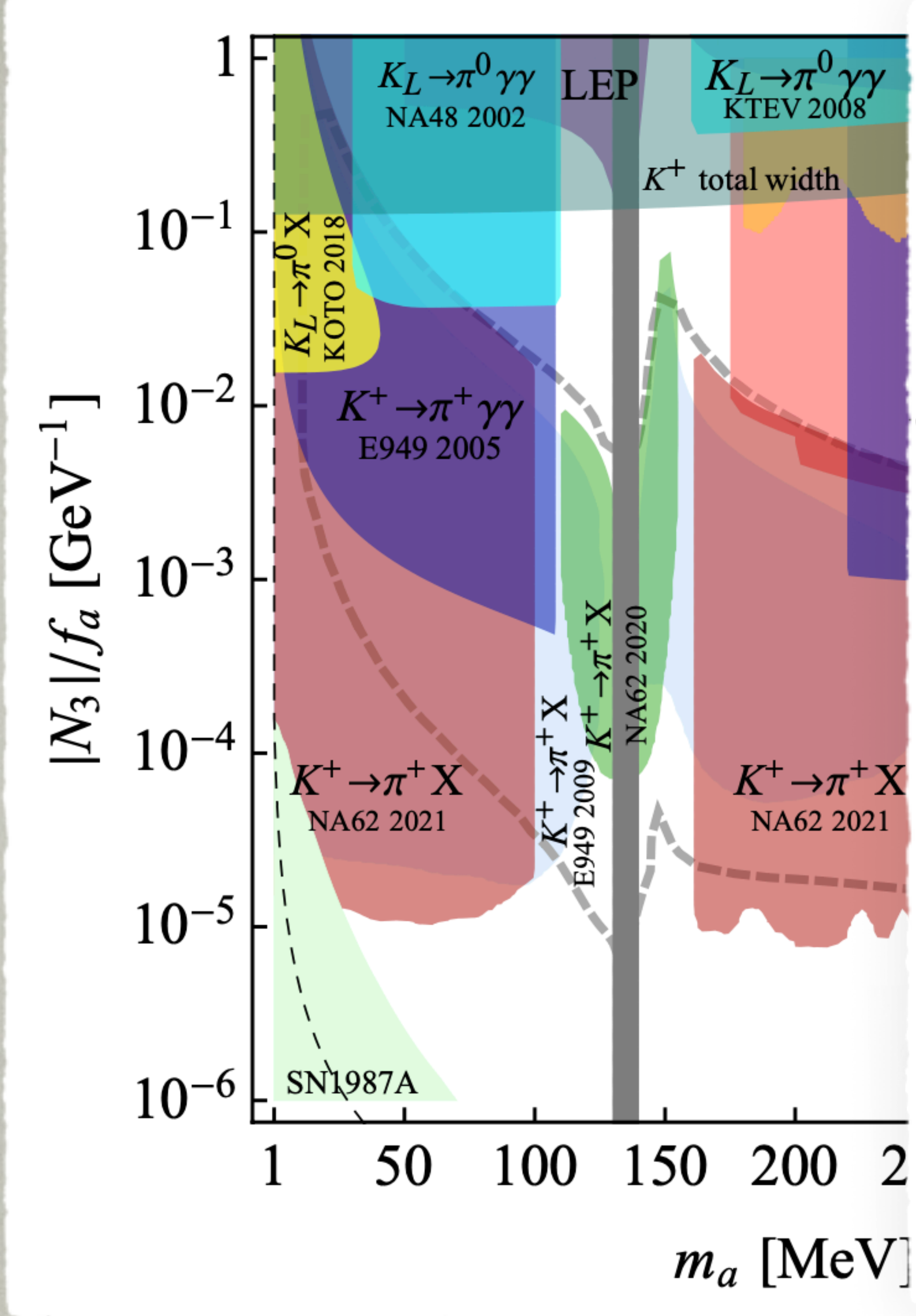

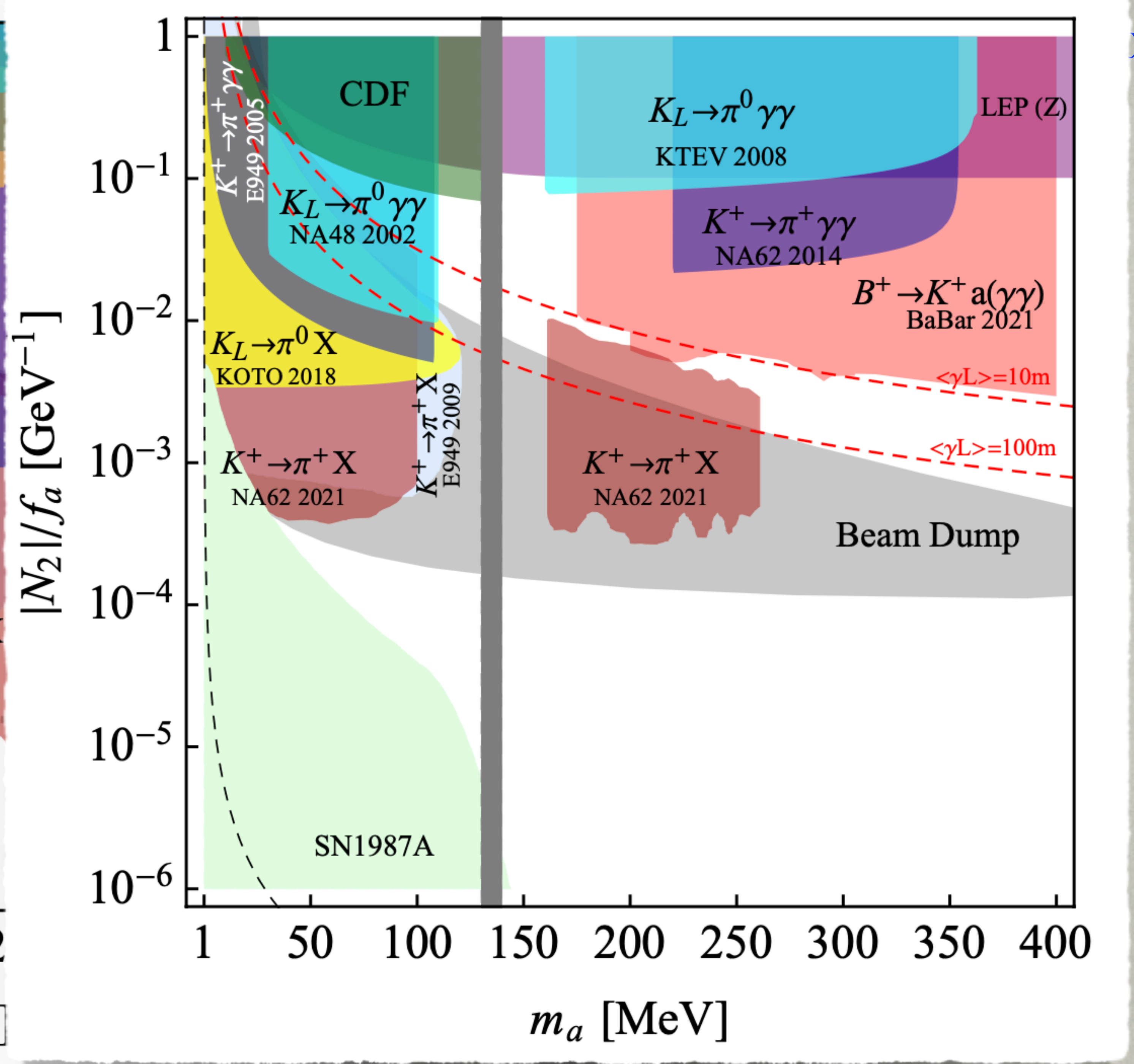

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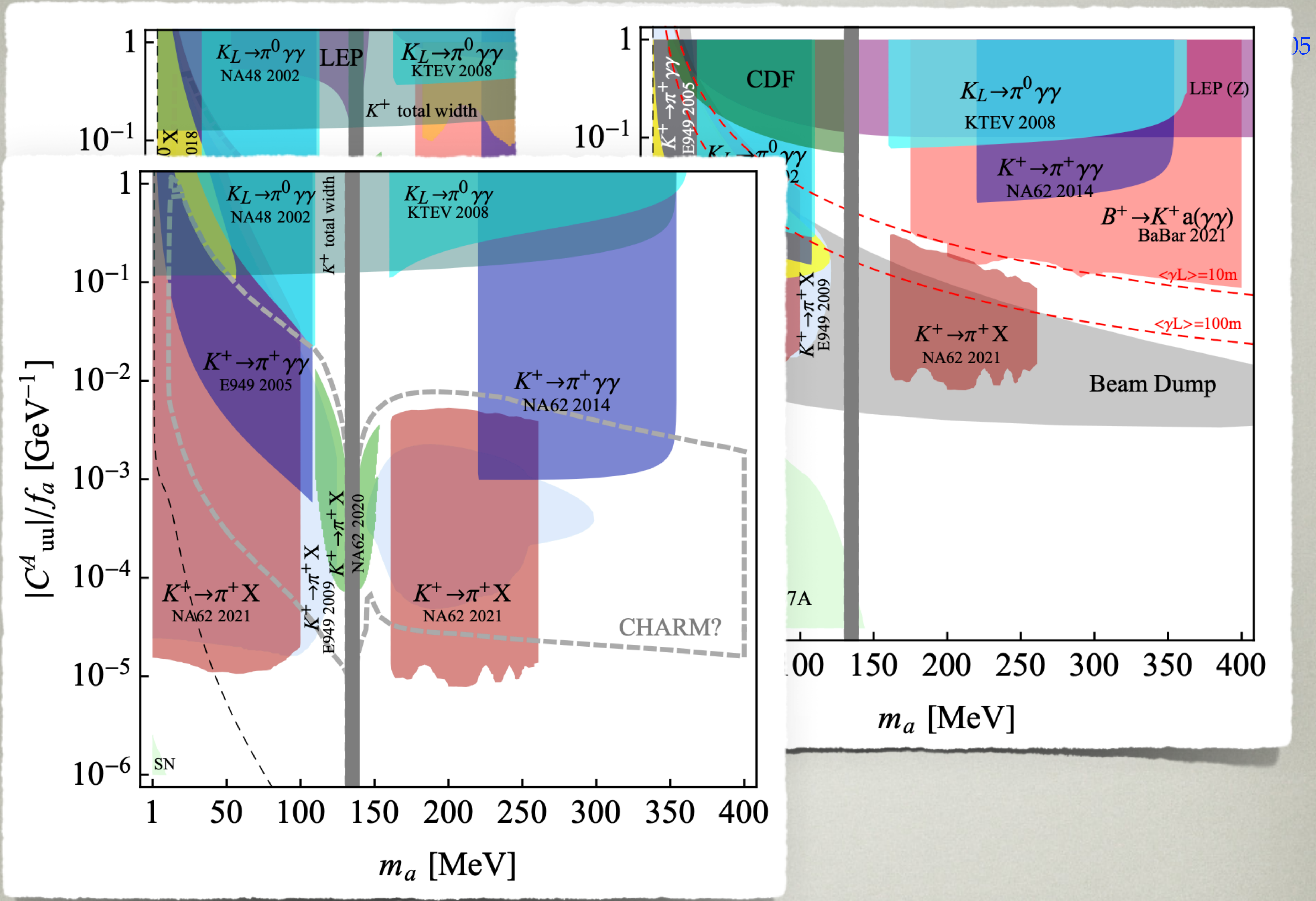

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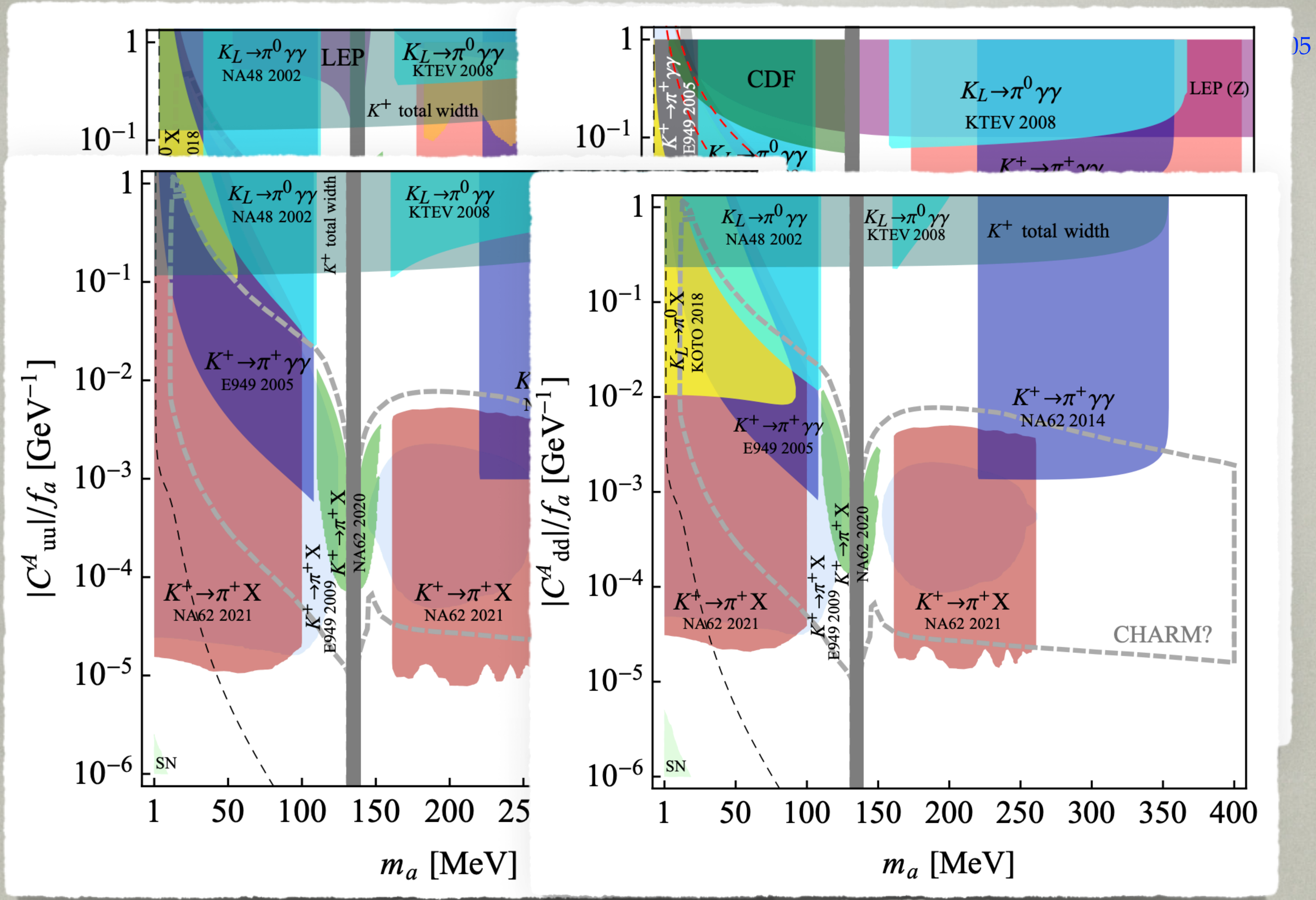

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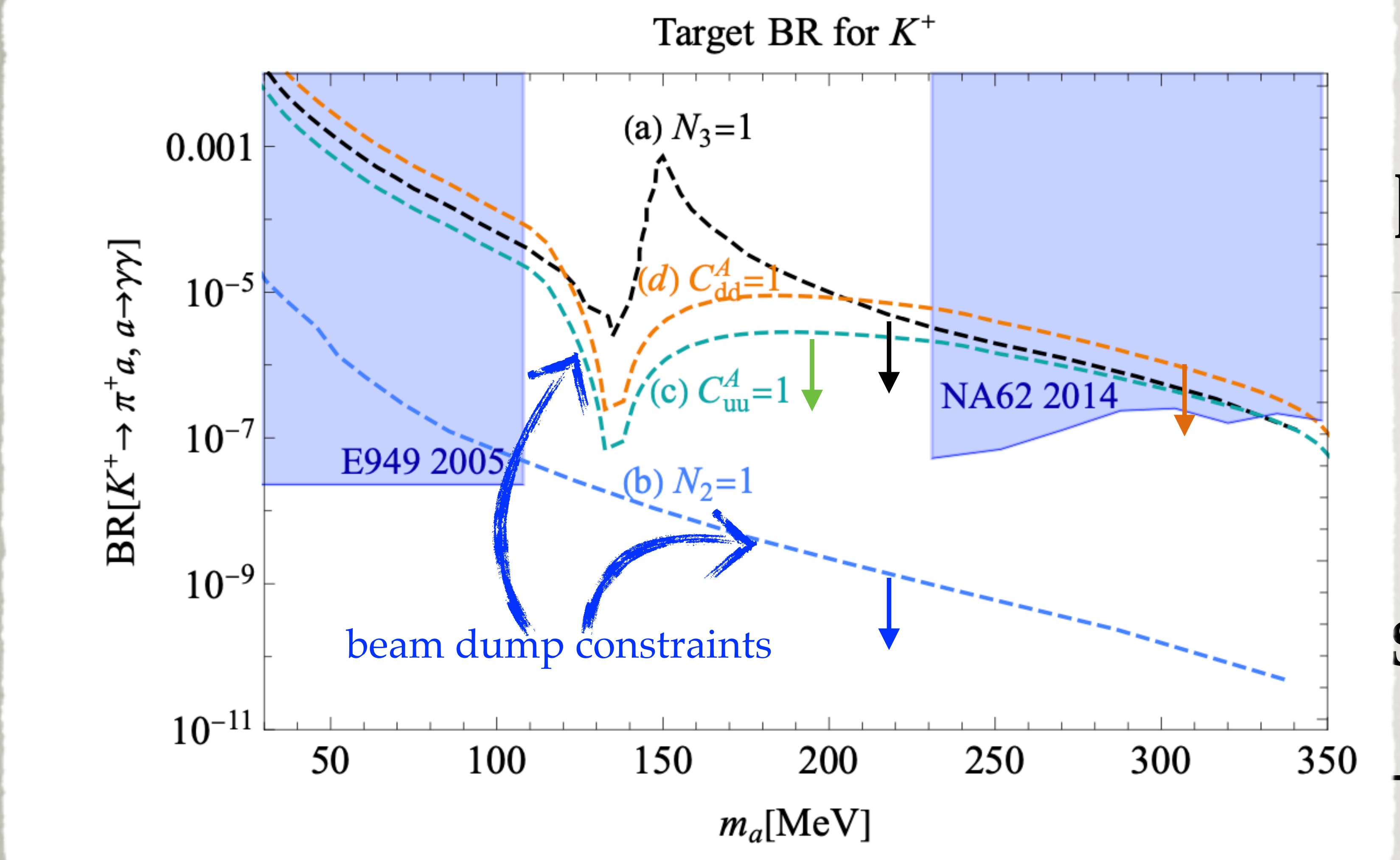
- searches for prompt ALPs in $K \to \pi a$
    - either $a \to \gamma\gamma$ or $a \to e^+e^-$
    - close the gap to constraints from beam dump searches
- $\Rightarrow$ either discovery or only $K \to \pi a_{\text{inv}}$ signature remains



PS

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$^+e^-$

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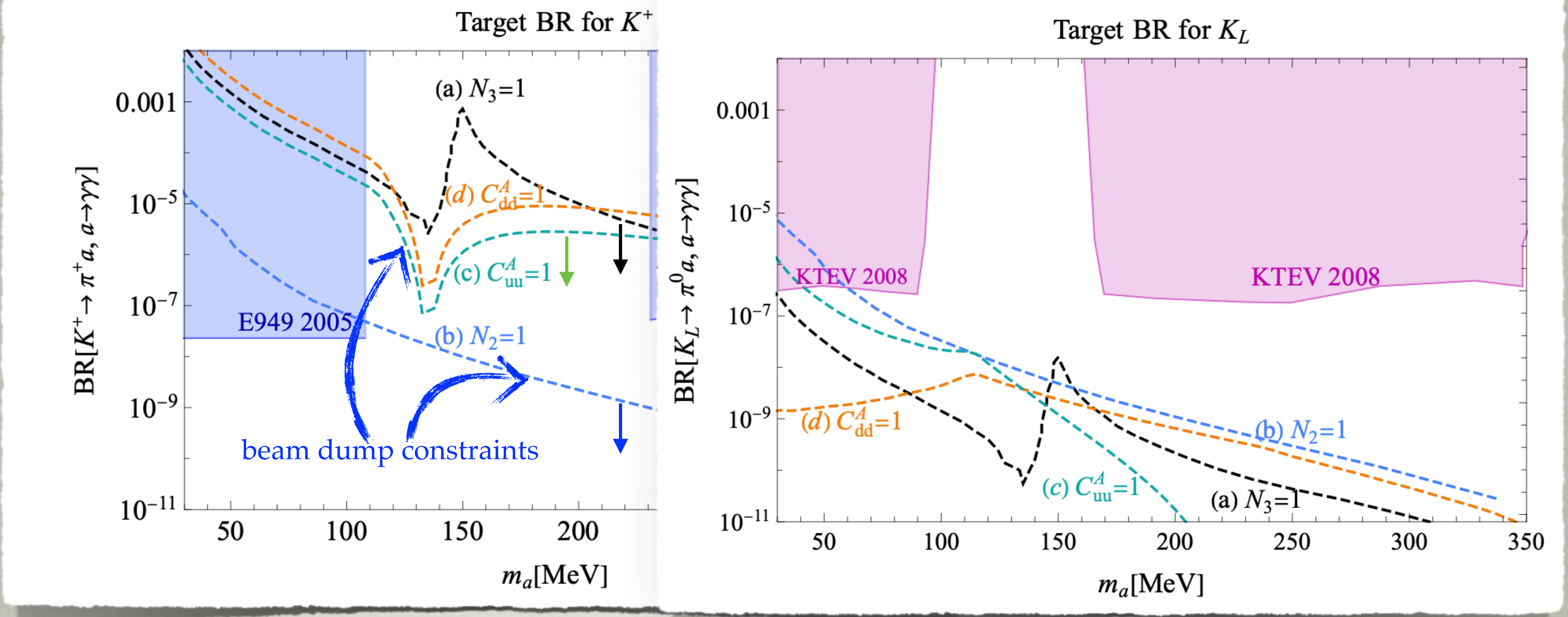

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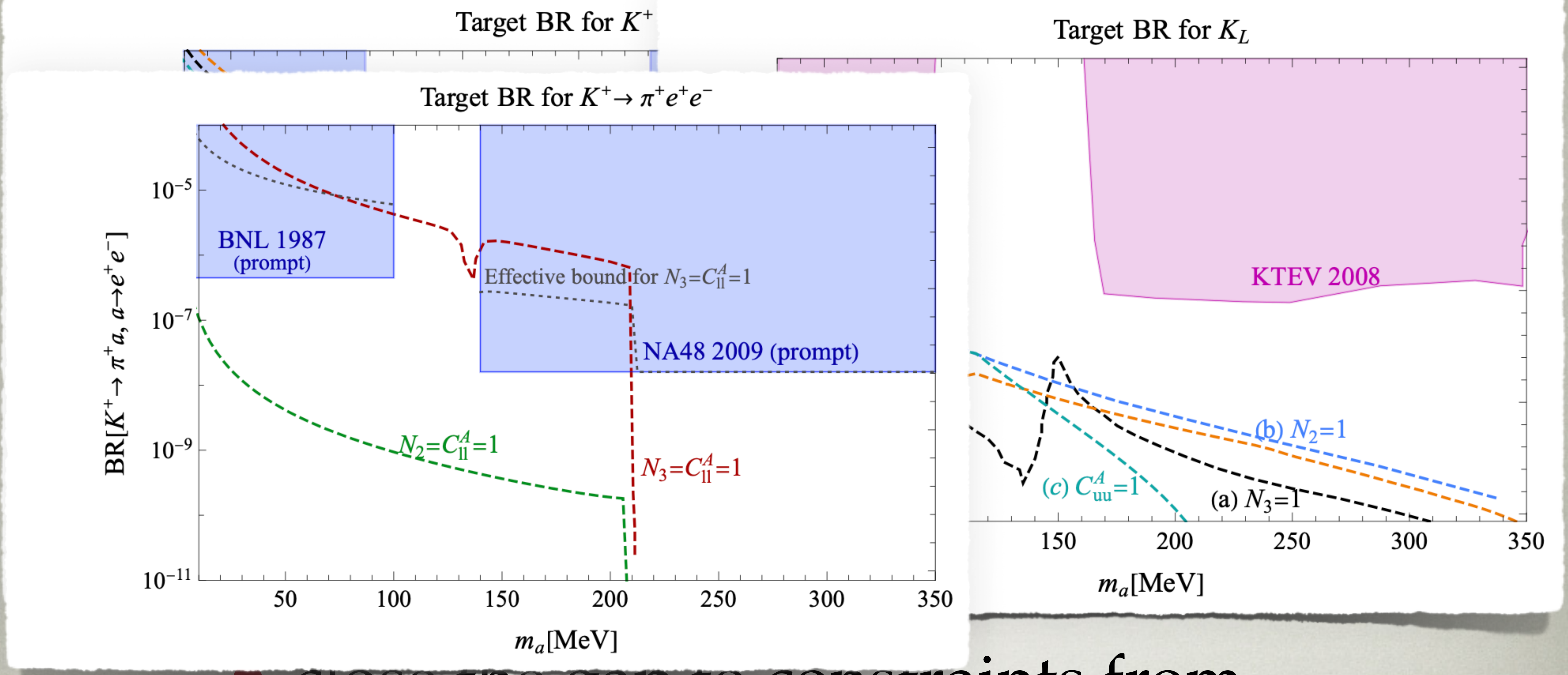

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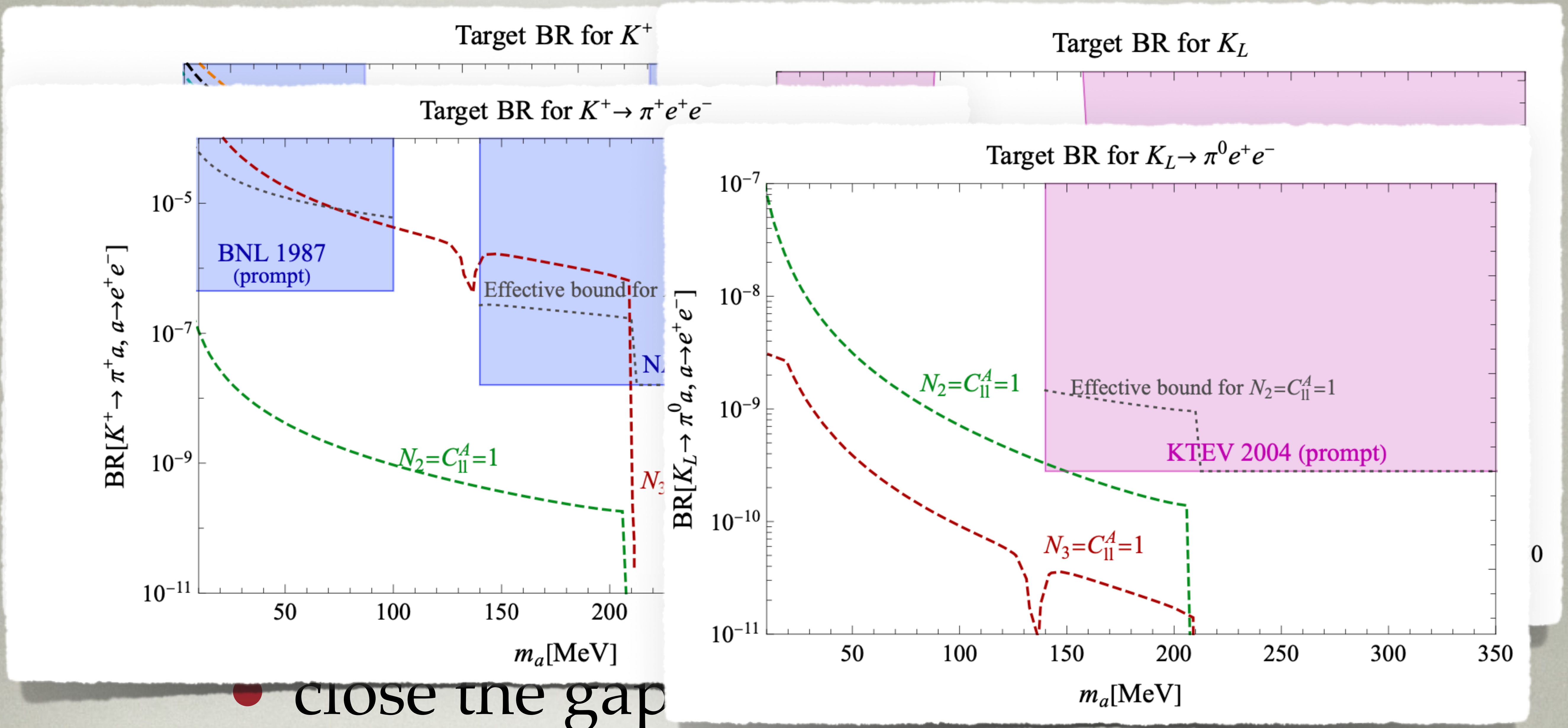

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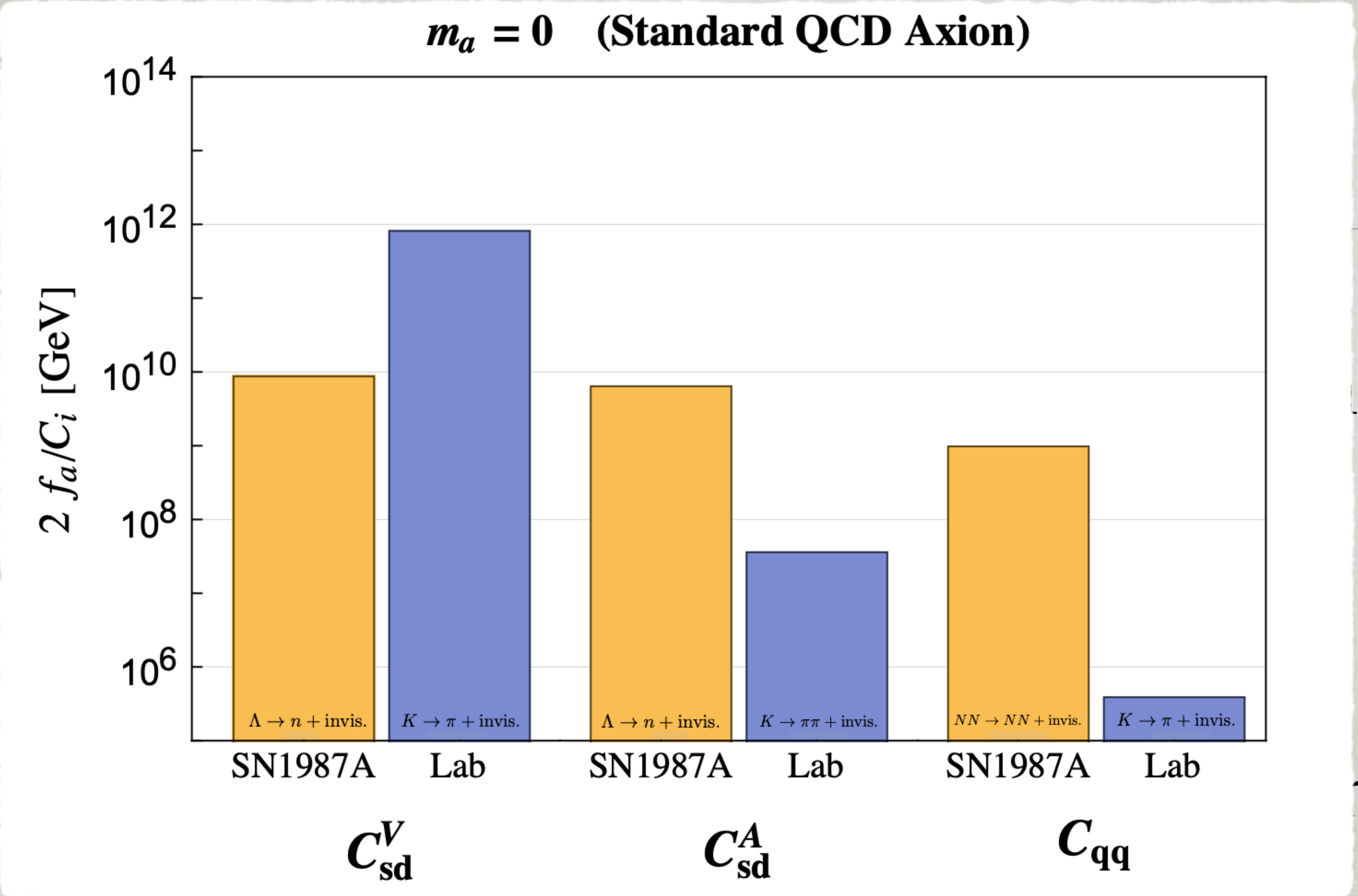
Alonso-Alvarez et al, 2201.07805

FLAVOR VIOLATING QCD AXION

- QCD axion with FV couplings to quarks
  - solves the strong CP problem
  - can be a cold DM candidate
  - effectively massless in FV transitions
- stringent constraints from $K \to \pi a$, $K \to \pi\pi a$ where a invisible
  - can be a discovery mode

Alonso-Alvarez et al, 2201.07805



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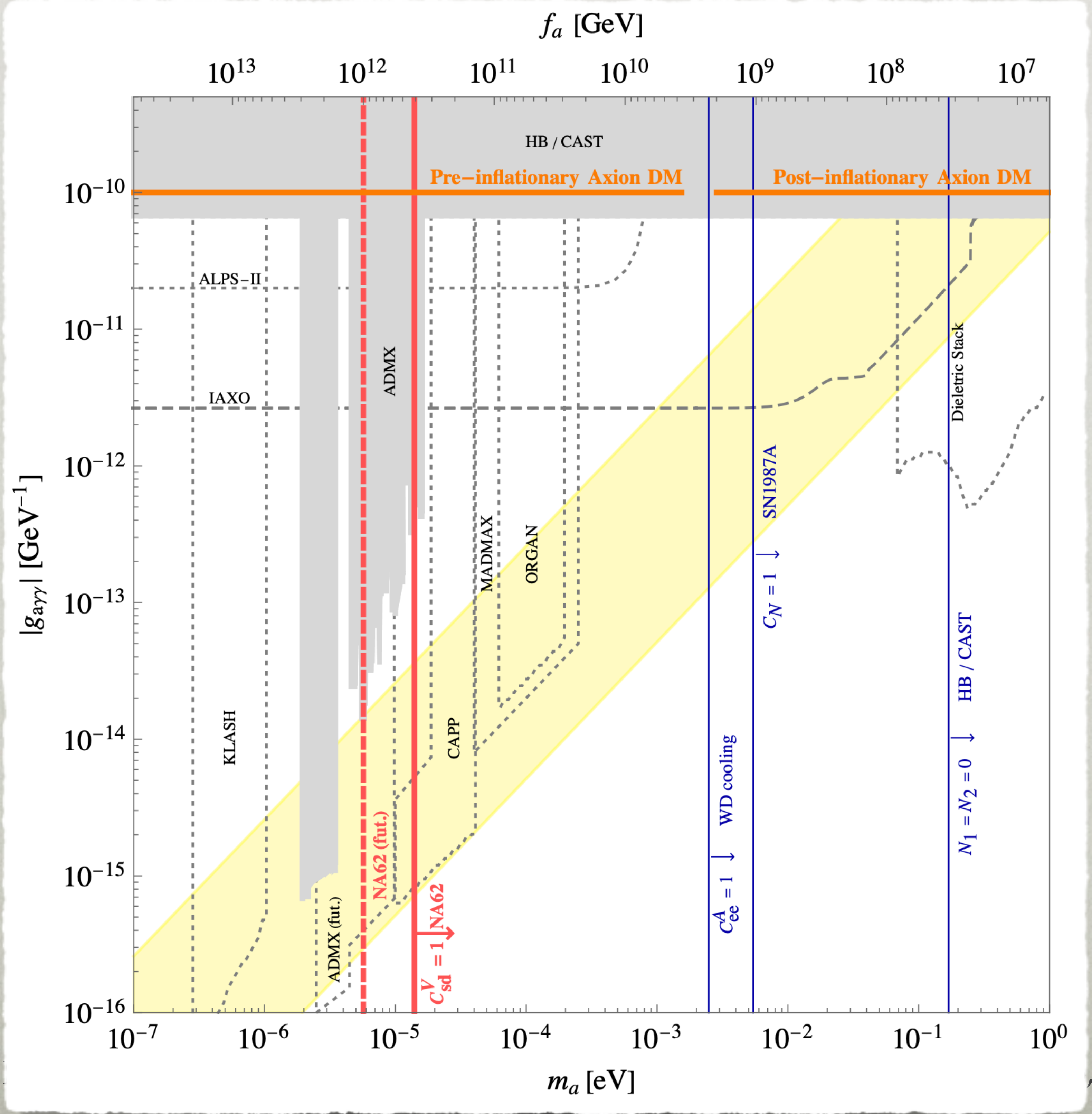
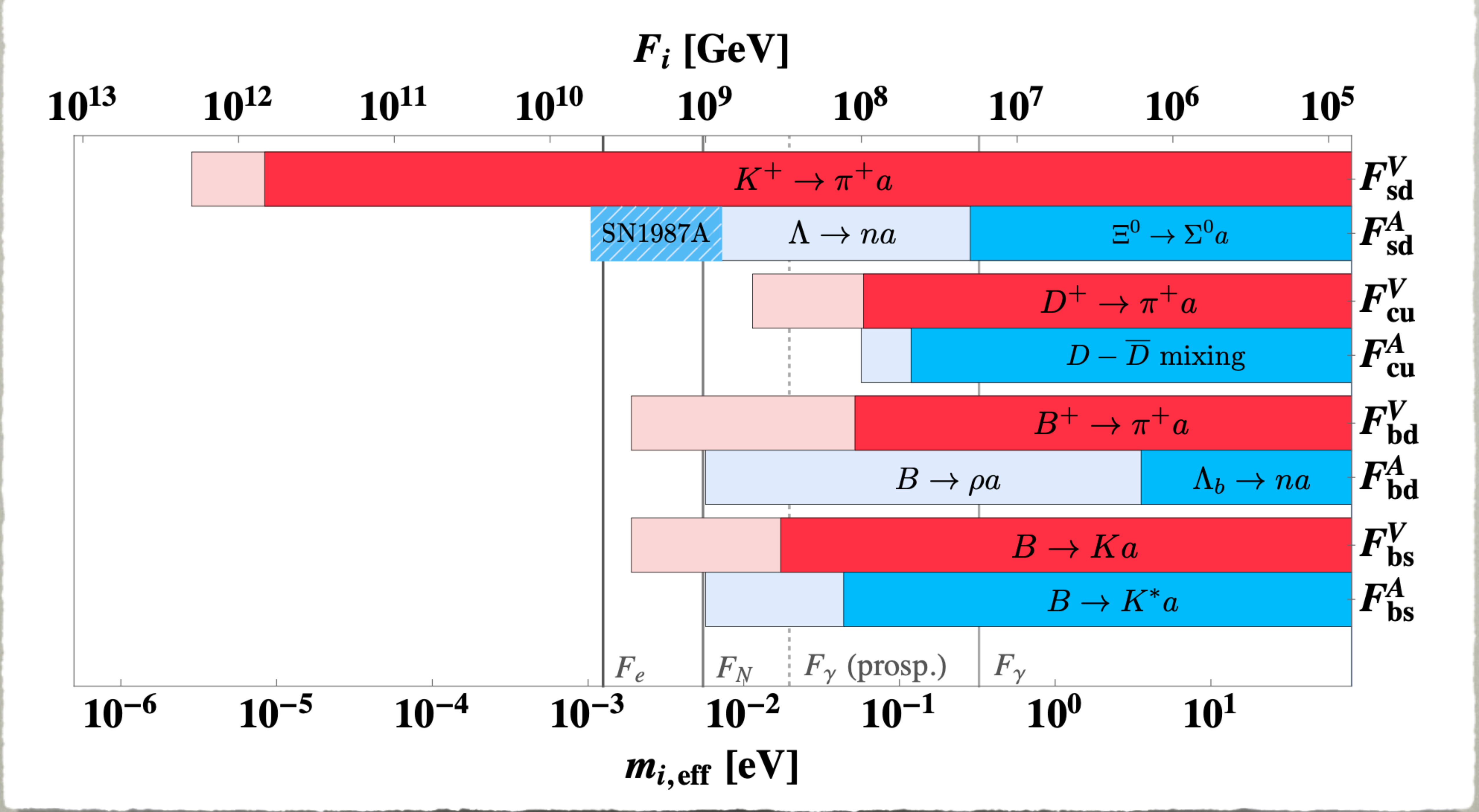


MANY OTHER FV SEARCHES FOR QCD AXION

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



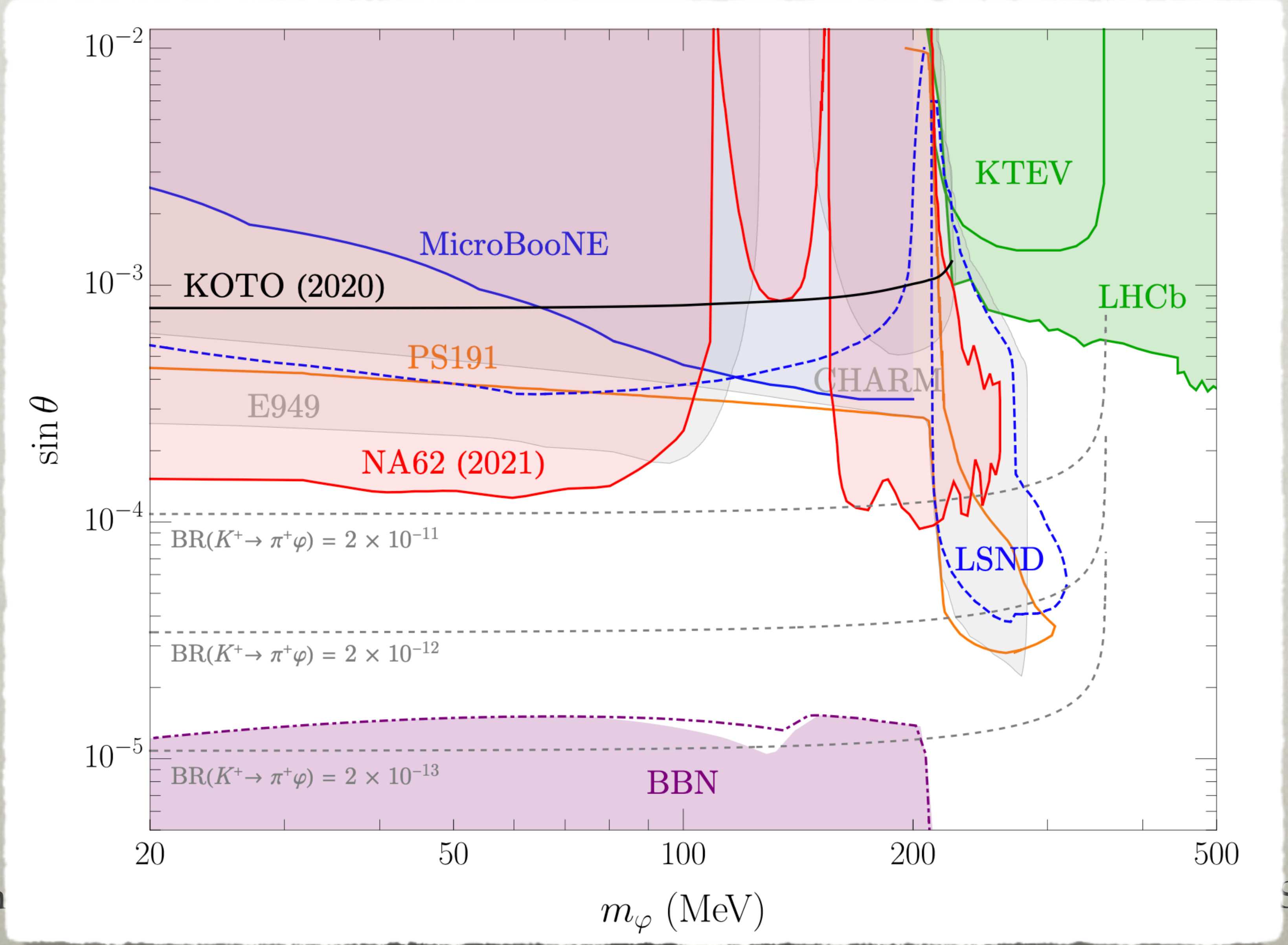
LIGHT SCALARS

- above general analysis valid for pNGBs with pseudoscalar and scalar couplings
  - what changes for scalars with dim-4 couplings?
- usual benchmark: light Higgs mixed scalar
  - couplings to WW, ZZ and fermions are now dim-4
  - proportional to mixing angle $\sin\theta$
- not the most general possibility
  - couplings to the SM fields could be a combination of Higgs mixed scalar and higher dim couplings
  - can be phenomenologically important for couplings to light quarks since Higgs yukawas are very suppressed

2201.07805

HIGGS MIXED SCALAR

- for two to three orders of magnitude larger datasets
  - ⇒ could close the gap for Higgs-mixed scalar all the way to the BBN floor



Delaunay, Kitahara, Redigolo, Soreq, JZ, 2310.nnnnn

Blackstone, Tarrus Castella, Passemar, JZ, 2310.nnnnn

LIGHT SCALAR - MORE GENERALLY

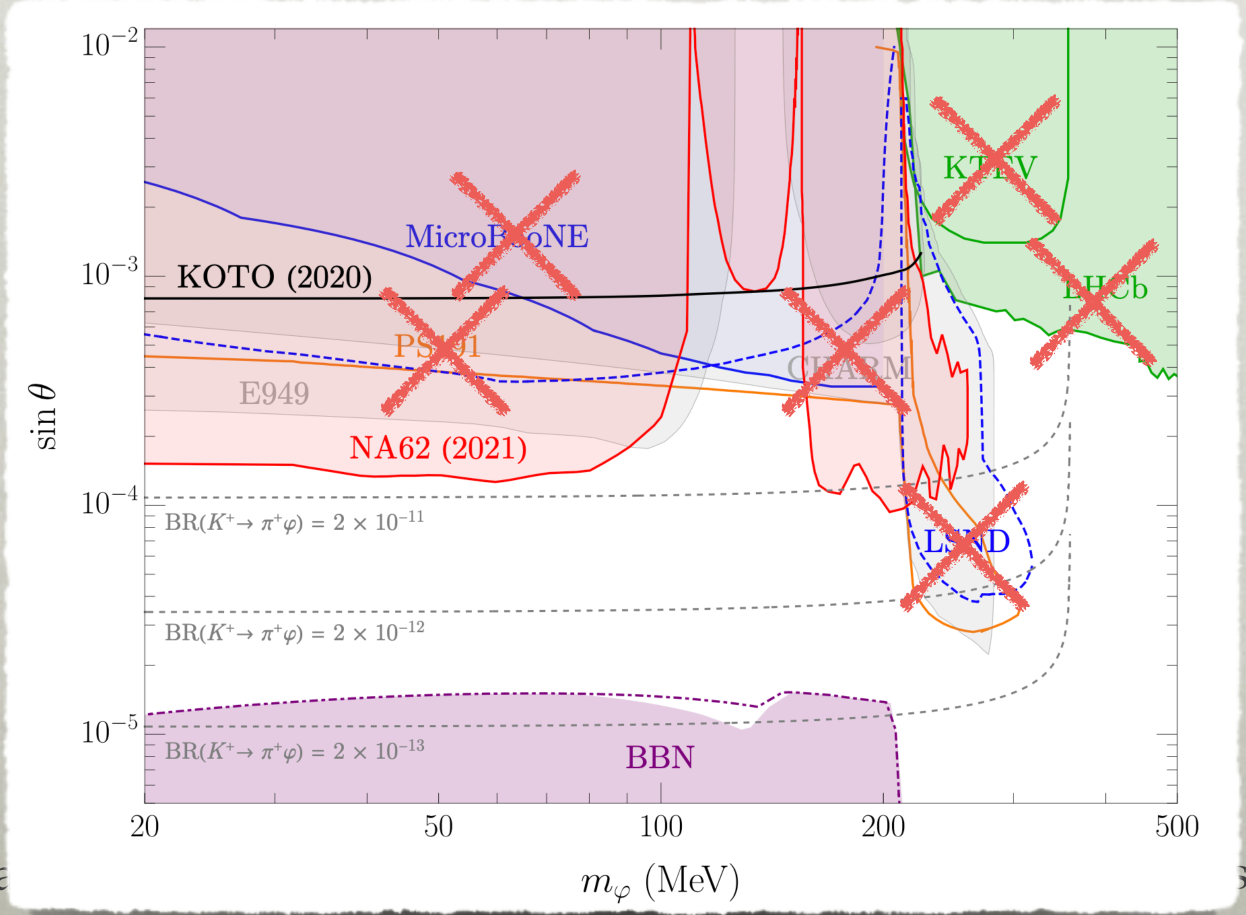
- light Higgs mixed scalar may be a too simplistic model
  - in general one could have the same bottom up approach as for ALPs
- the most general interaction Lagrangian ($\mu = \mu_{\rm EW}$)

$$\mathcal{L}_{\rm int}(\mu \sim m_W) = \frac{\phi}{v}\left[\kappa_g \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{\mu\nu\,a} - \sum_{f,i,j}\left(\kappa_{f_i f_j}\sqrt{m_i m_j}\,\bar{f}_{Li} f_{Rj} + \text{h.c.}\right) + 2\kappa_W m_W^2 W^+_\mu W^{\mu\,-} + \dots\right],$$

  - for Higgs mixed scalar $\kappa_{f_i f_i} = \kappa_W = \sin\theta,\ \kappa_g = \kappa_{f_i f_j} = 0$ (for $i \neq j$)
- two qualitatively different regimes
  - $\kappa_{f_i f_j} \neq 0$ in the UV $\Rightarrow K \to \pi\phi$ probes very high scales
  - FV only from $W^\pm$ loop $\Rightarrow$ similar to Higgs-mixed scalar

PHENO IMPLICATIONS

- the bounds depend heavily on assumed flavor structure
    - also for just flavor diagonal coupl.: $\kappa_{f_i f_j} = 0$ for $i \neq j$
- example: hadro-phylic scalar
    - no $\phi \to \mu^+\mu^- \Rightarrow$ LHCb +KTEV bounds gone
    - no $\phi \to e^+e^- \Rightarrow$ MicroBooNE, LSND, PS191, CHARM bounds gone
    - NA62 and KOTO searches for $K \to \pi +$ inv still apply



MANY OTHER MODELS

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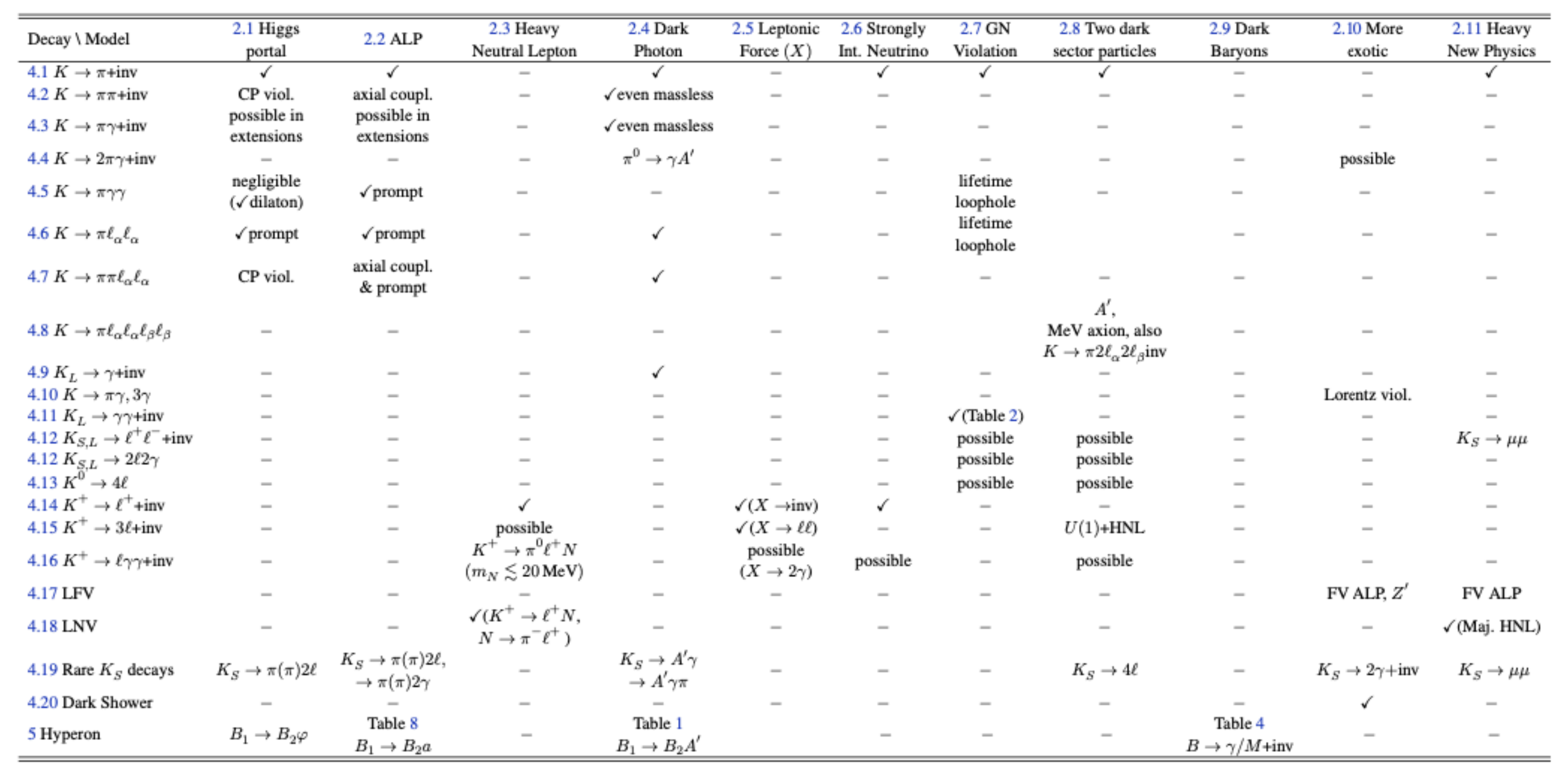
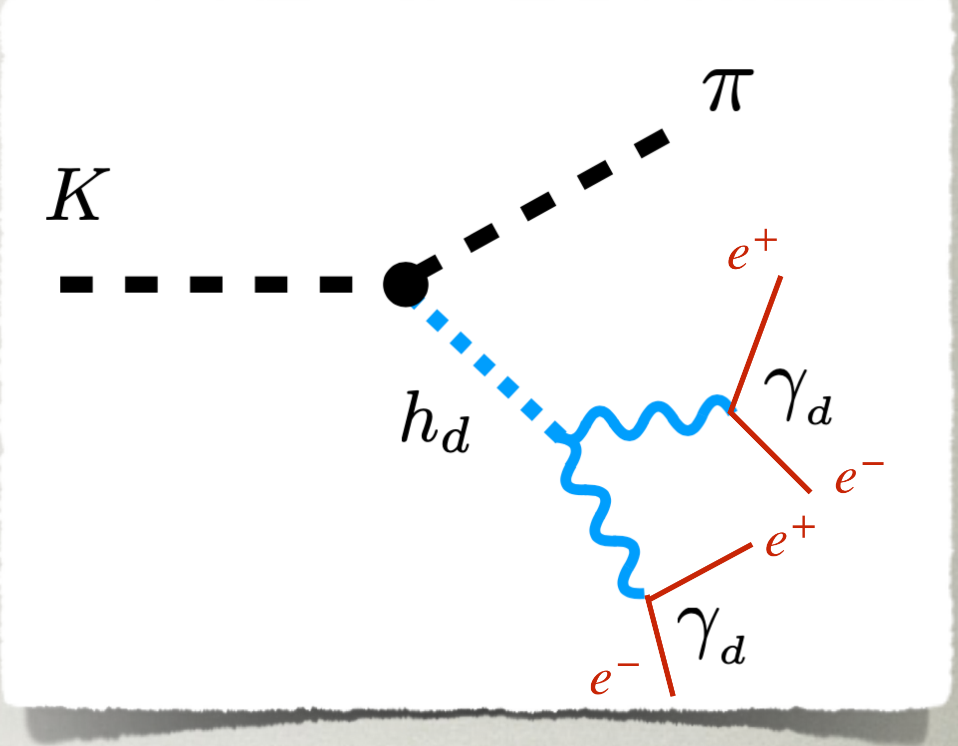


Decay \ Model	2.1 Higgs portal	2.2 ALP	2.3 Heavy Neutral Lepton	2.4 Dark Photon	2.5 Leptonic Force (X)	2.6 Strongly Int. Neutrino	2.7 GN Violation	2.8 Two dark sector particles	2.9 Dark Baryons	2.10 More exotic	2.11 Heavy New Physics
4.1 $K \to \pi$+inv	✓	✓	–	✓	–	✓	✓	✓	–	–	✓
4.2 $K \to \pi\pi$+inv	CP viol.	axial coupl.	–	✓even massless	–	–	–	–	–	–	–
4.3 $K \to \pi\gamma$+inv	possible in extensions	possible in extensions	–	✓even massless	–	–	–	–	–	–	–
4.4 $K \to 2\pi\gamma$+inv	–	–	–	$\pi^0 \to \gamma A'$	–	–	–	–	–	possible	–
4.5 $K \to \pi\gamma\gamma$	negligible (✓dilaton)	✓prompt	–	–	–	–	lifetime loophole	–	–	–	–
4.6 $K \to \pi\ell_\alpha\ell_\alpha$	✓prompt	✓prompt	–	✓	–	–	lifetime loophole		–	–	–
4.7 $K \to \pi\pi\ell_\alpha\ell_\alpha$	CP viol.	axial coupl. & prompt	–	✓	–	–	–	–	–	–	–
4.8 $K \to \pi\ell_\alpha\ell_\alpha\ell_\beta\ell_\beta$	–	–	–	–	–	–		A', MeV axion, also $K \to \pi 2\ell_\alpha 2\ell_\beta$inv	–	–	–
4.9 $K_L \to \gamma$+inv	–	–	–	✓	–	–	–	–	–	–	–
4.10 $K \to \pi\gamma, 3\gamma$	–	–	–	–	–	–	–	–	–	Lorentz viol.	–
4.11 $K_L \to \gamma\gamma$+inv	–	–	–	–	–	–	✓(Table 2)	–	–	–	–
4.12 $K_{S,L} \to \ell^+\ell^-$+inv	–	–	–	–	–	–	possible	possible	–	–	$K_S \to \mu\mu$
4.12 $K_{S,L} \to 2\ell 2\gamma$	–	–	–	–	–	–	possible	possible	–	–	–
4.13 $K^0 \to 4\ell$	–	–	–	–	–	–	possible	possible	–	–	–
4.14 $K^+ \to \ell^+$+inv	–	–	✓	–	✓$(X \to$inv$)$	✓	–	–	–	–	–
4.15 $K^+ \to 3\ell$+inv	–	–	possible	–	✓$(X \to \ell\ell)$	–	–	$U(1)$+HNL	–	–	–
4.16 $K^+ \to \ell\gamma\gamma$+inv	–	–	$K^+ \to \pi^0\ell^+ N$ $(m_N \lesssim 20\,\text{MeV})$	–	possible $(X \to 2\gamma)$	possible	–	possible	–	–	–
4.17 LFV	–	–	–	–	–	–	–	–	–	FV ALP, Z'	FV ALP
4.18 LNV	–	–	✓$(K^+ \to \ell^+ N,$ $N \to \pi^-\ell^+)$	–	–	–	–	–	–	–	✓(Maj. HNL)
4.19 Rare K_S decays	$K_S \to \pi(\pi)2\ell$	$K_S \to \pi(\pi)2\ell,$ $\to \pi(\pi)2\gamma$	–	$K_S \to A'\gamma$ $\to A'\gamma\pi$	–	–	–	$K_S \to 4\ell$	–	$K_S \to 2\gamma$+inv	$K_S \to \mu\mu$
4.20 Dark Shower	–	–	–	–	–	–	–	–	–	✓	–
5 Hyperon	$B_1 \to B_2\varphi$	Table 8 $B_1 \to B_2 a$	–	Table 1 $B_1 \to B_2 A'$		–	–	–	Table 4 $B \to \gamma/M$+inv	–	–

"EXOTICA": HIGGSED U(1)'

- even not very exotic models can lead to nontrivial experimental signatures
- case in point light higgsed U(1)'
  - induces $K \to \pi + 2(e^+e^-)$
  - current NA62 bound $Br(K^+ \to \pi^+ 4e) < 1.4 \times 10^{-8}$
  - FV from dim-5 operator $\mathscr{L}_{\text{int}} \supset \frac{c}{\Lambda} H\bar{s}_L d_R \phi \Rightarrow \Lambda \gtrsim 5 \times 10^{13}\,\text{GeV}$



Hostert, Pospelov, 2012.02142

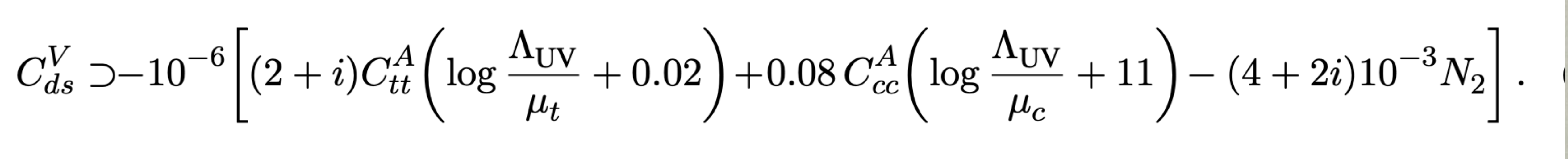
CONCLUSIONS

- rare kaon processes: if ∃ light NP ⇒ parametrically enhanced sensitivity to UV
- "exotica":
  - many possible signatures
  - many well motivated models

BACKUP SLIDES

FV FROM RUNNING

- numerical solution to RG running



$$C^{V}_{ds} \supset -10^{-6}\left[(2+i)C^{A}_{tt}\left(\log\frac{\Lambda_{\mathrm{UV}}}{\mu_t}+0.02\right)+0.08\,C^{A}_{cc}\left(\log\frac{\Lambda_{\mathrm{UV}}}{\mu_c}+11\right)-(4+2i)10^{-3}N_2\right].$$

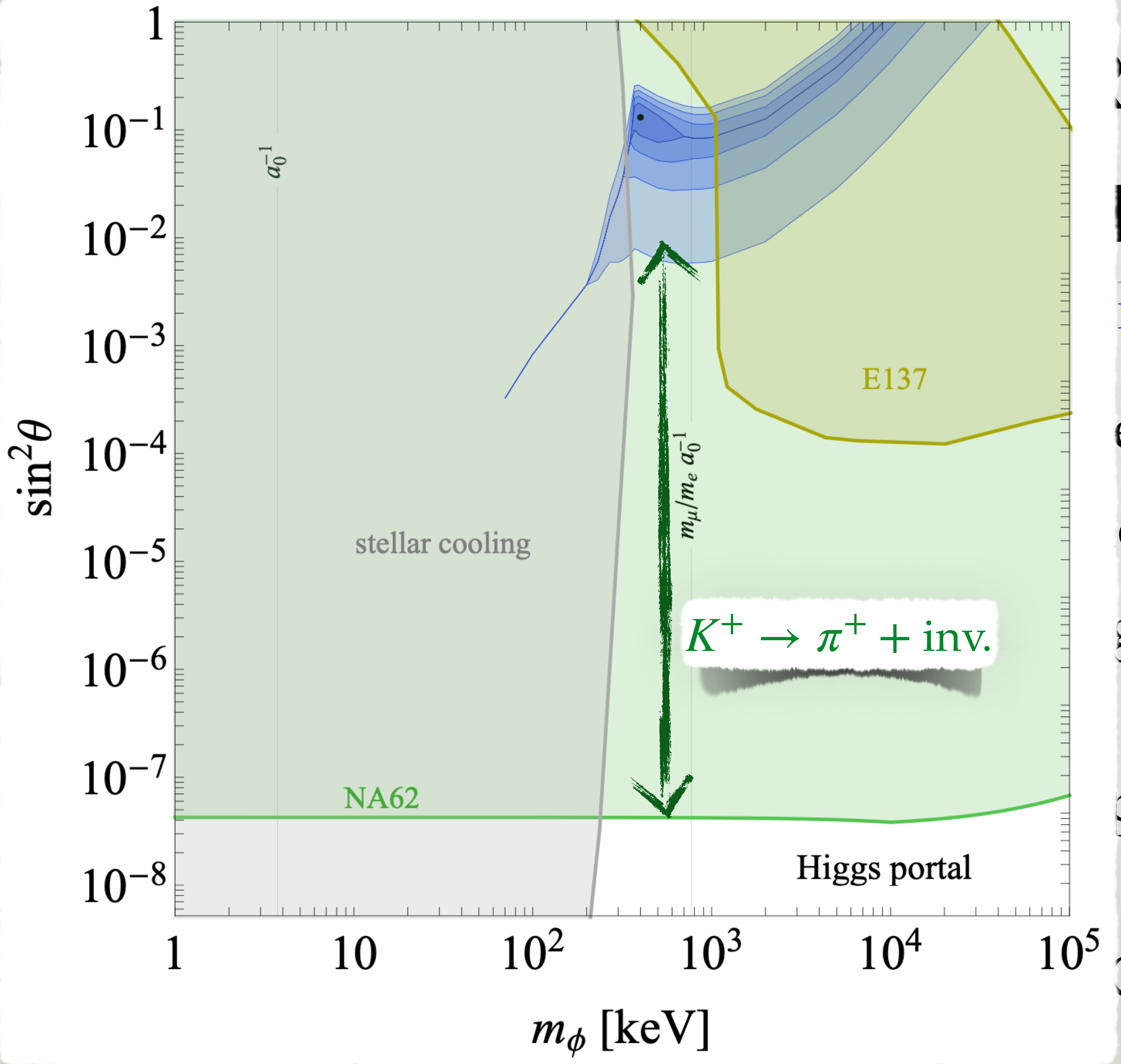
PROTON CHARGE RADIUS PUZZLE+

Delaunay, Karr, Kitahara, Koelemeij, Soreq, JZ, 2210.10056

- important to stress how sensitive are rare kaon decays
- compare with sensitivity of spectroscopic probes
  - hydrogen/deuterium+muonic hydrogen/deuterium data
- several ~3σ anomalies in obs. related to proton charge radius and mass
  - exp+th errors under-appreciated? ⇒ CODATA 2018
  - NP? : global analysis of SM + light scalar ⇒ consistent description
    - light Higgs mixed scalar excluded by NA62 $K^+ \to \pi^+ + \text{inv}$ search

RGE
LE+

Kitahara, Koelemeij, Soreq, JZ, 2210.10056



e kaon decays

c probes

gen/deuterium

proton charge

CODATA 2018

- NP? : global analysis of SM + light scalar ⇒ consistent description
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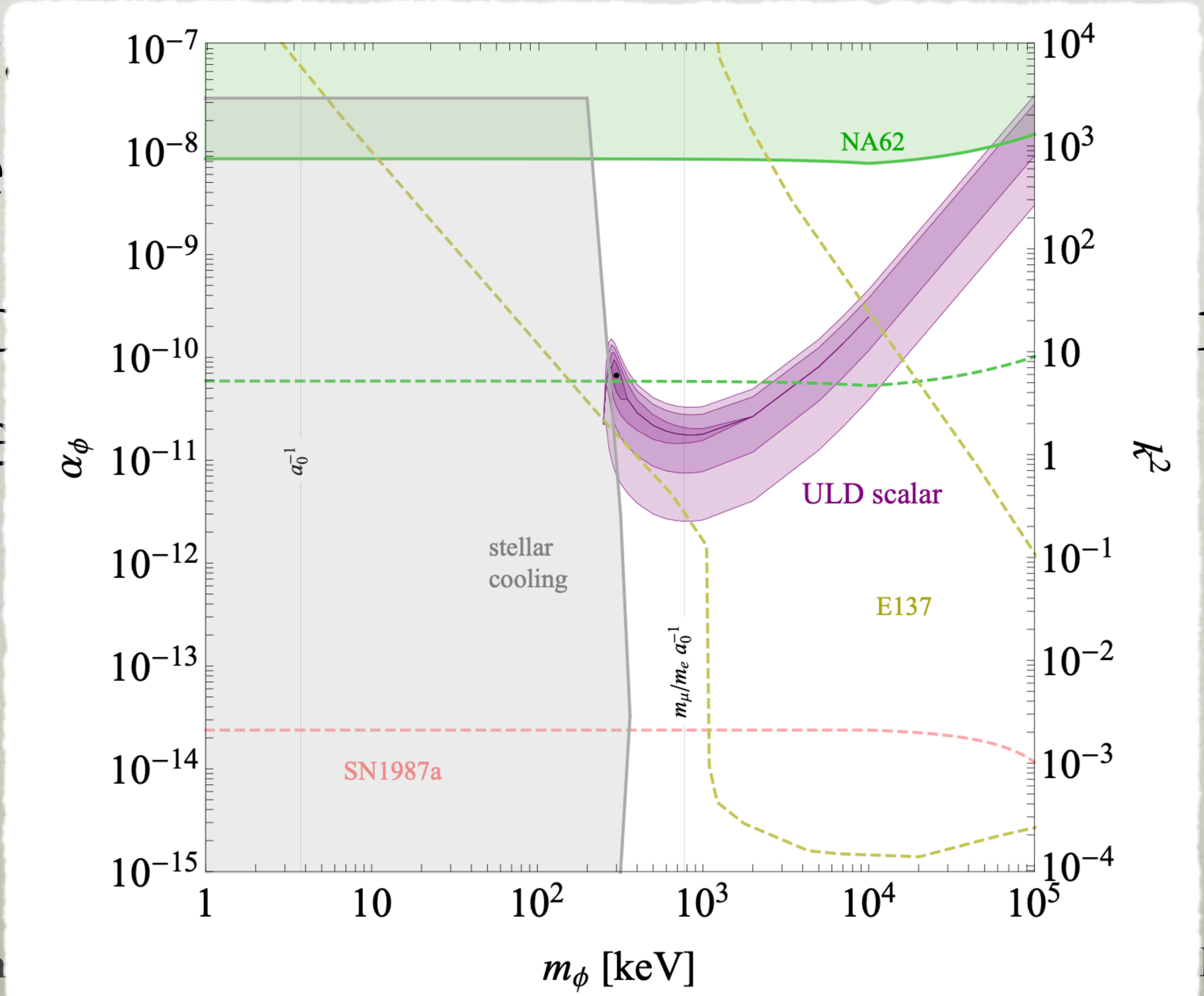
PROTON CHARGE RADIUS PUZZLE+

- possible to (almost) evade NA62 $K^+ \to \pi^+ + \text{inv}.$ bound

Delaunay, Karr, Kitahara, Koelemeij, Soreq, JZ, 2210.10056



- sc … + dark
  se

- nc … ngs, still
  ve … $\pi + \text{inv}$

ULD SCALAR

- ULD scalar couples only to *u*, *e*, *μ* and a dark sector

$$\mathcal{L}_\phi = k\frac{m_\ell}{v}\phi\bar{\ell}\ell + k\frac{m_u}{v}\phi\bar{u}u + y_\chi\phi\bar{\chi}\chi\,,$$

- couplings to nucleons

$$\mathcal{L}_{\text{eff}} = g_\ell\phi\bar{\ell}\ell + g_N\phi\bar{N}N$$

$$g_\ell = k\frac{m_\ell}{v}\,, \qquad g_N = k\frac{\kappa'_N m_N}{v}\,,$$

$$\kappa'_p \simeq 0.018(5) \qquad \kappa'_n \simeq 0.016(5)$$

ULD SCALAR

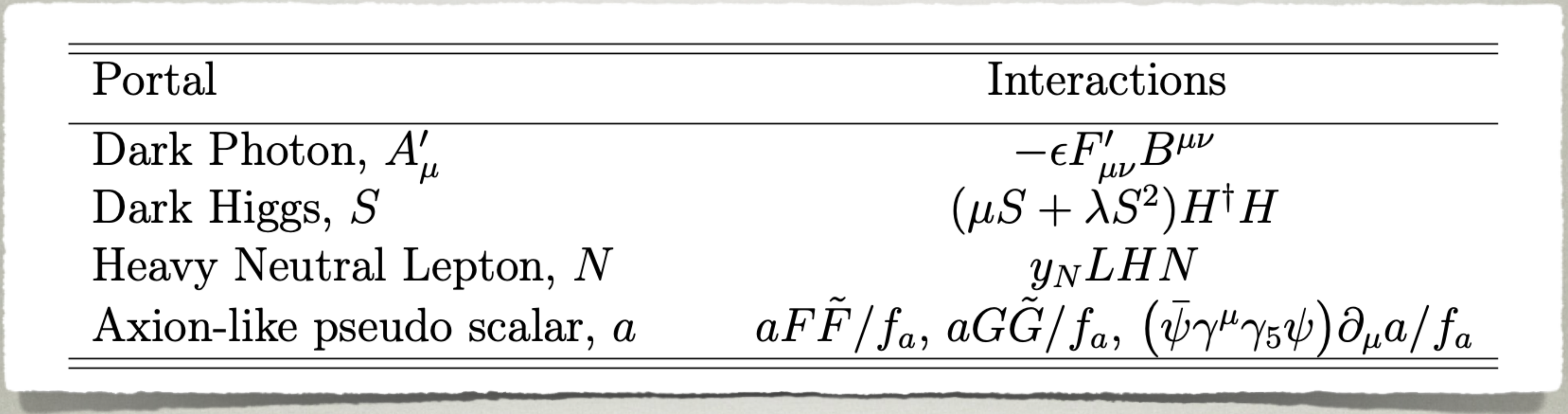
- if these couplings are due to dim 5 ops

$$\mathcal{L}_\phi = \frac{y'_\ell}{\Lambda}\phi\,\bar{L}_\ell H \ell_R + \frac{y'_u}{\Lambda}\phi\,\bar{Q}_u \tilde{H} u_R + \text{h.c.}\,,$$

- for numerical expediency assume $y'_{\ell,u} = A \times m_{\ell,u}/v$
- the anomaly requires rougly

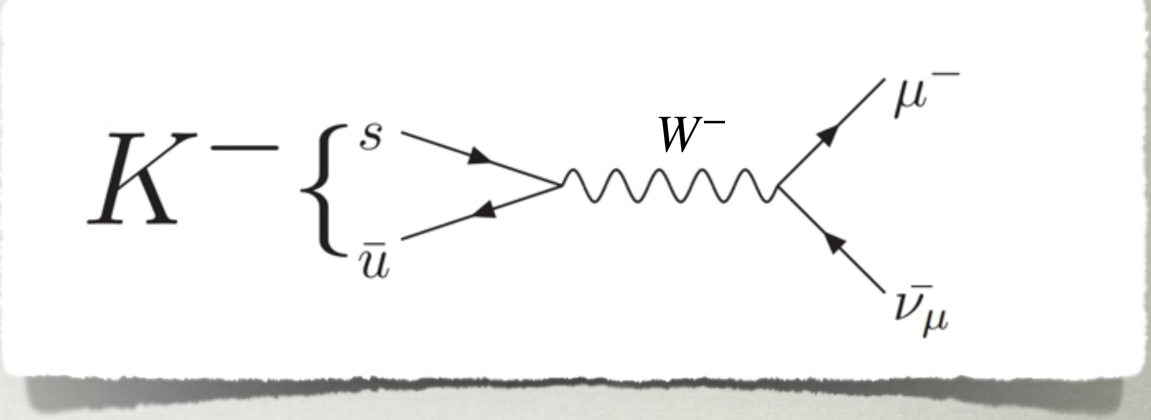
$$A \simeq 100 \times (\Lambda/10\,\text{TeV})$$

PORTALS



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

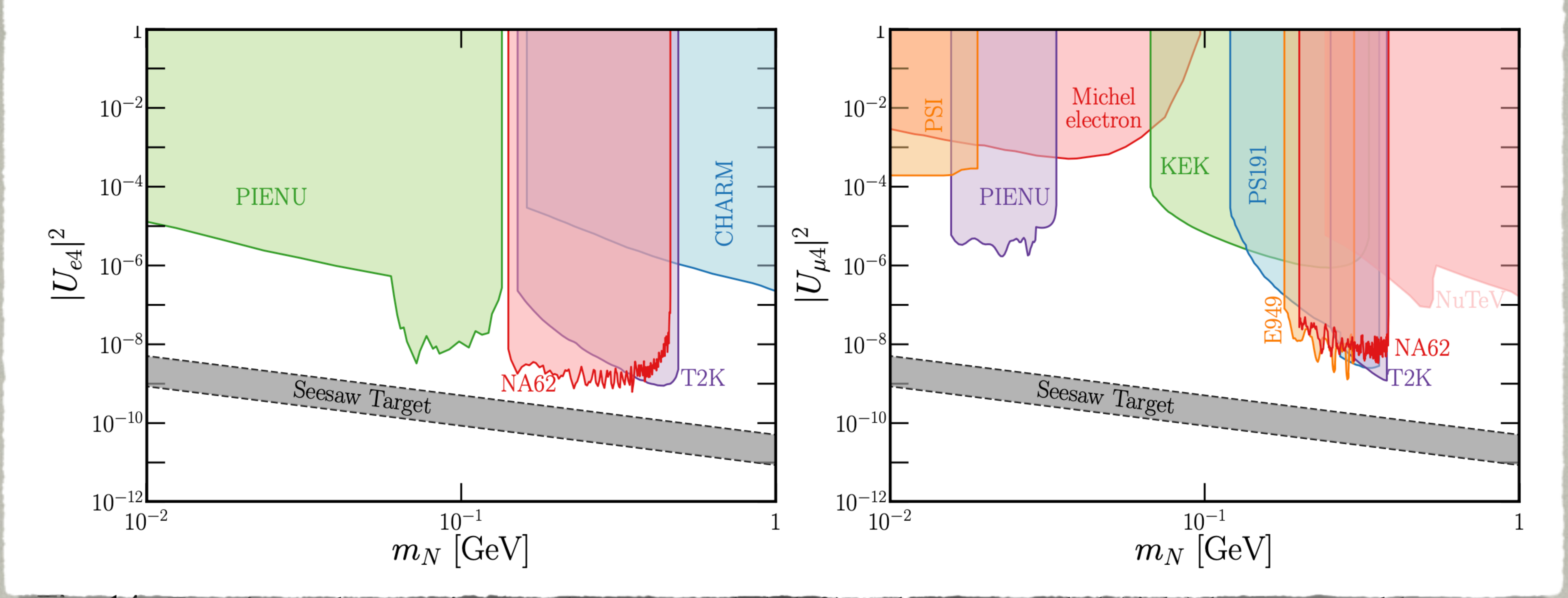
LIGHT NEW PHYSICS $\Rightarrow$ PROBE OF HIGH SCALES



- rare decays into a light state, X, e.g., $K \to \pi X$,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops.
  - SM decay width power suppressed: $\Gamma_K \propto m_K^5/m_W^4$
- if through dim 5 op. suppressed by $1/f_a$
  - $\Rightarrow Br(K \to \pi\varphi) \propto (m_W^2/f_a m_K)^2$
  - similar for dim 4
- no such $1/m_K$ enhancement for dim. 6 couplings
  - $Br(K \to \pi e^- \mu^+) \propto (m_W/\Lambda)^4$

HEAVY NEUTRINOS

- two orders improvement in $Br(K^+ \to \ell^+ N)$
  - start probing minimal see-saw neutrino mass models
  - for O(100 MeV) sterile neutrino masses



- start probing minimal see-saw neutrino mass models
- for O(100 MeV) sterile neutrino masses

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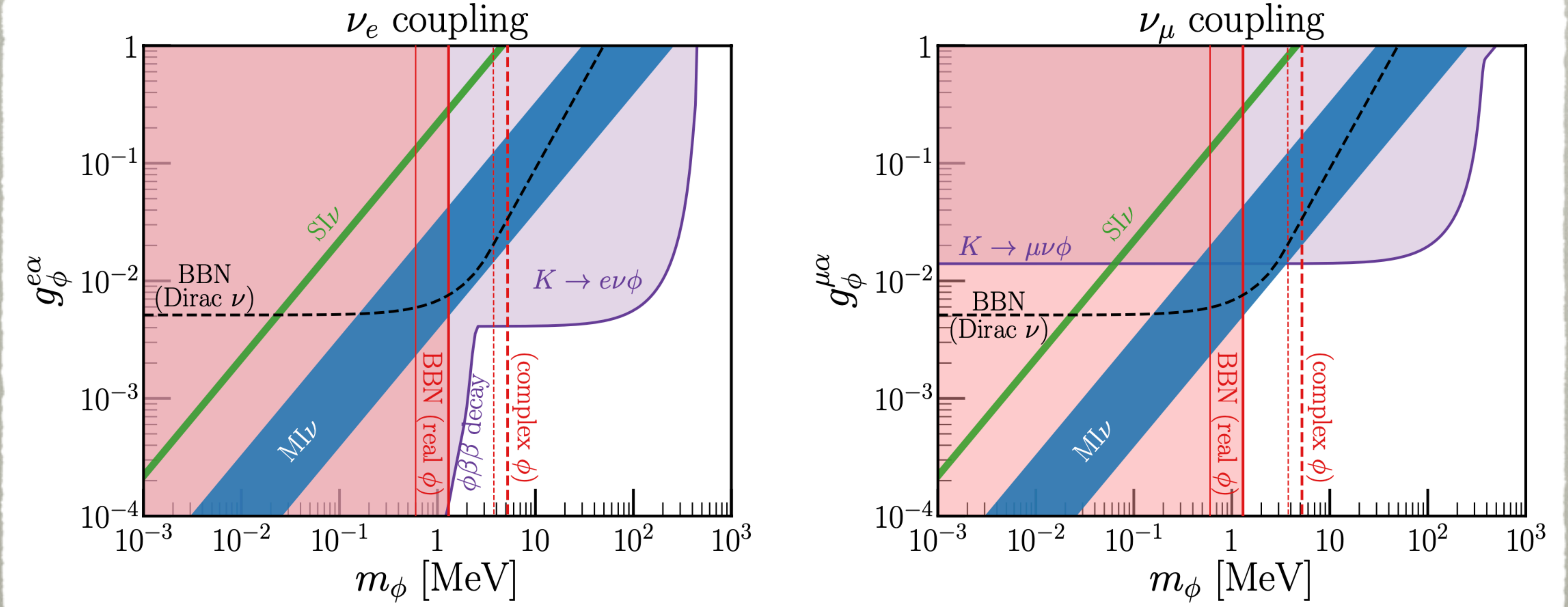
SELF INTERACTING ν'S

- order of magnitude improvement on $Br(K^+ \to \mu^+ \nu X_{\rm inv})$
- probe fully self-interacting $\nu_{e,\mu}$ explanation of Hubble tension



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K_L DECAYS

- $K_L \to \pi^0 X_{\rm NP}$ from $s \to d X_{\rm NP}$ less sensitive than $K^+ \to \pi^+ X_{\rm NP}$
- still, many K_L decays with leading sensitivity to NP
  - $K_L \to \pi^0 \nu\bar{\nu}$ theoretically the cleanest SM prediction
    - will provide higher sensitivity to heavy NP than $K^+ \to \pi^+ \nu\bar{\nu}$
  - K_L decays can probe Grossman-Nir violating models
    - subleading constr. from K^+ decays

Hostert, Kaneta, Pospelov, 2005.07102

Gori, Perez, Tobioka, 2005.05170

Ziegler, Zupan, Zwicky, 2005.00451

Egana-Ugrinovic, Homiller, Meade, 1911.10203; Kitahara, Okui, Perez, Soreq, Tobioka, 1909.11111;
Liu, McGinnis, Wagner, Wang, 2001.06522; Liao, Wang, Yao, Zhang, 2005.00753

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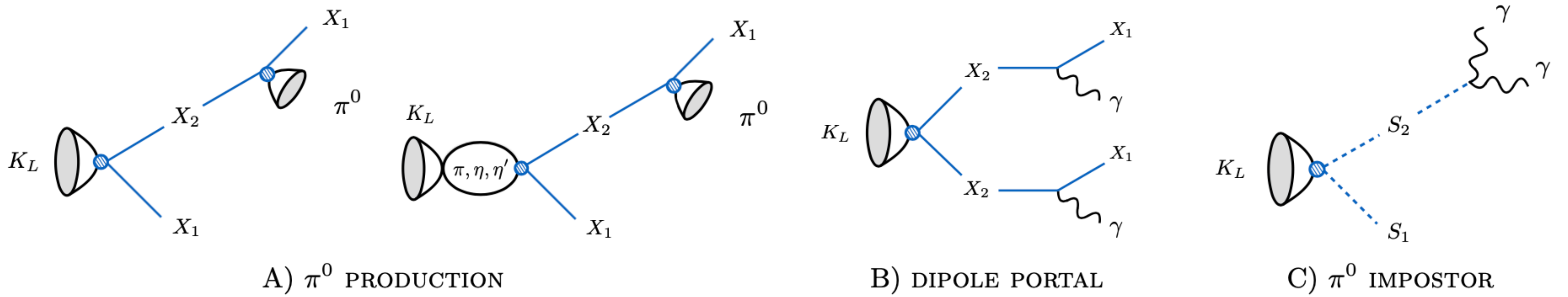

A) π^0 PRODUCTION B) DIPOLE PORTAL C) π^0 IMPOSTOR

Hostert, Kaneta, Pospelov, 2005.07102

- $K_L \to \pi^0 X_{\rm NP}$ from $s \to dX_{\rm NP}$ less sensitive than $K^+ \to \pi^+ X_{\rm NP}$
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