# New Physics Searches at Kaon and Hyperon Factories

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based on community report 2201.07805 (editors: Goudzovski, Redigolo, Tobioka, JZ)

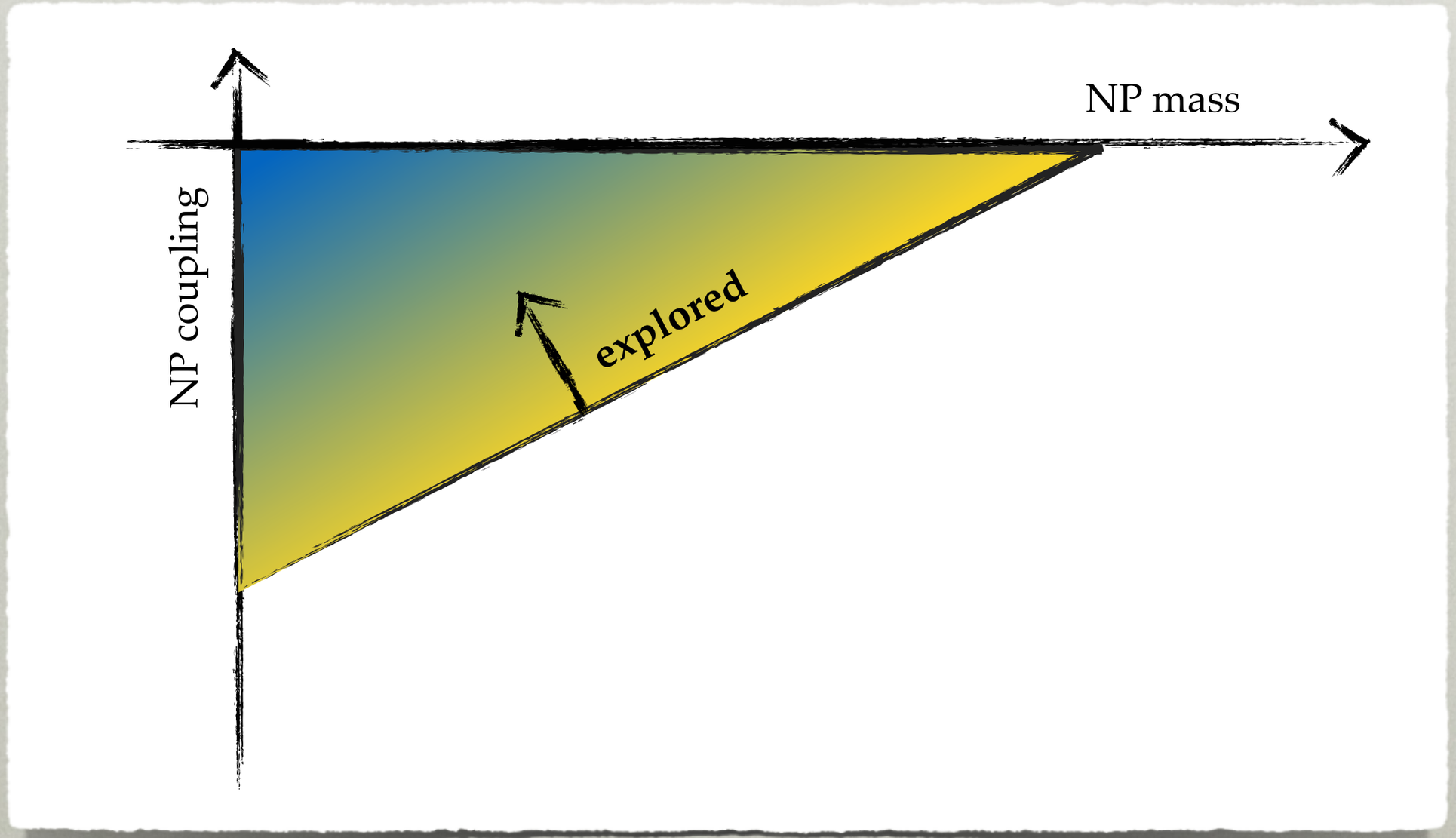
QNP2022, virtual@FSU, Tallahassee, FL, Sep 6 2022,

# MAIN MESSAGES

- NA62, KOTO, KLEVER,... are not single purpose experiments
  - flagship decays: $K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}$ $\Rightarrow$ probe heavy NP
- can also search for light NP: $K \to \pi X_{\rm NP}$
  - $\Rightarrow$ probe even higher scales

# 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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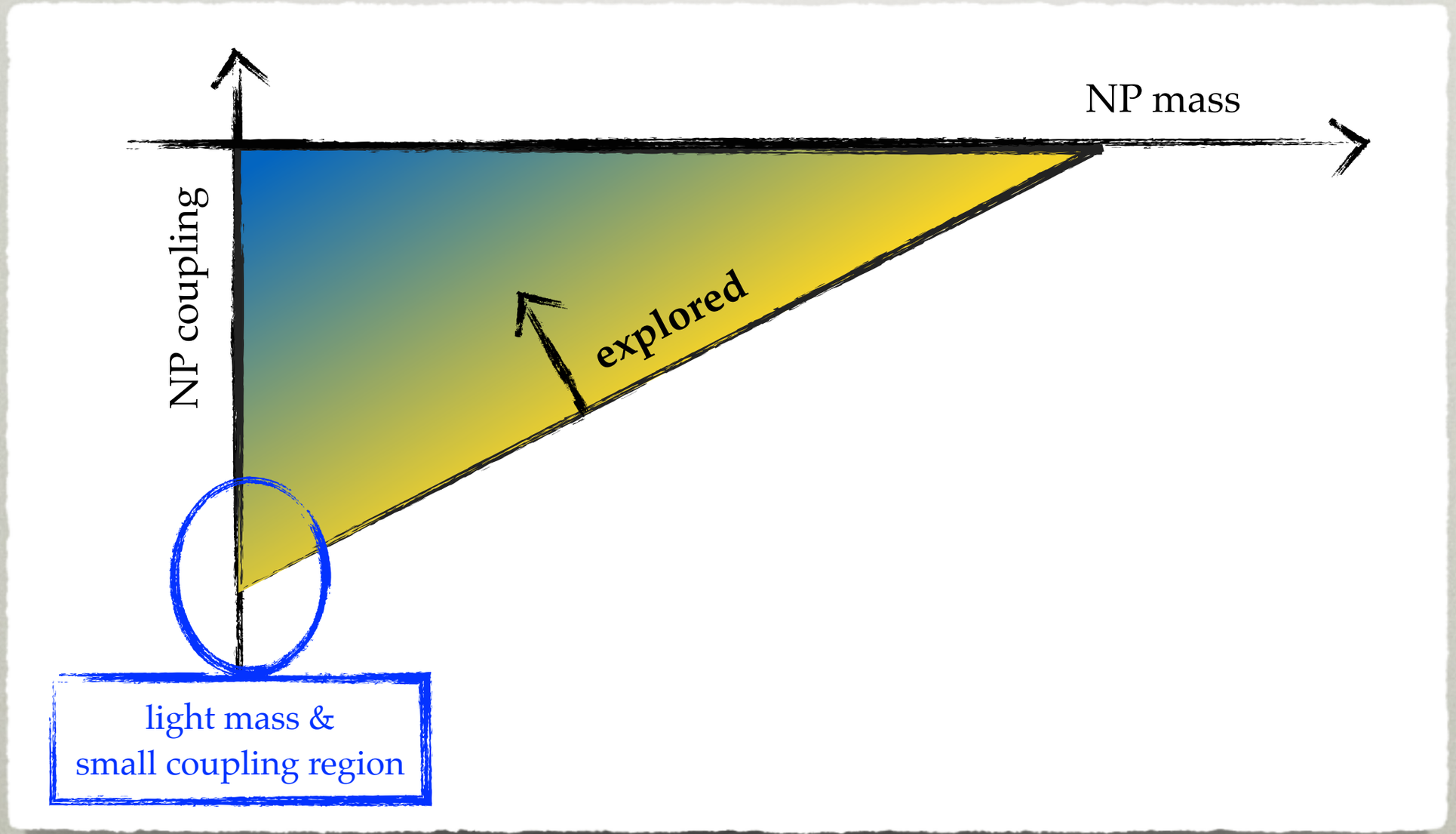

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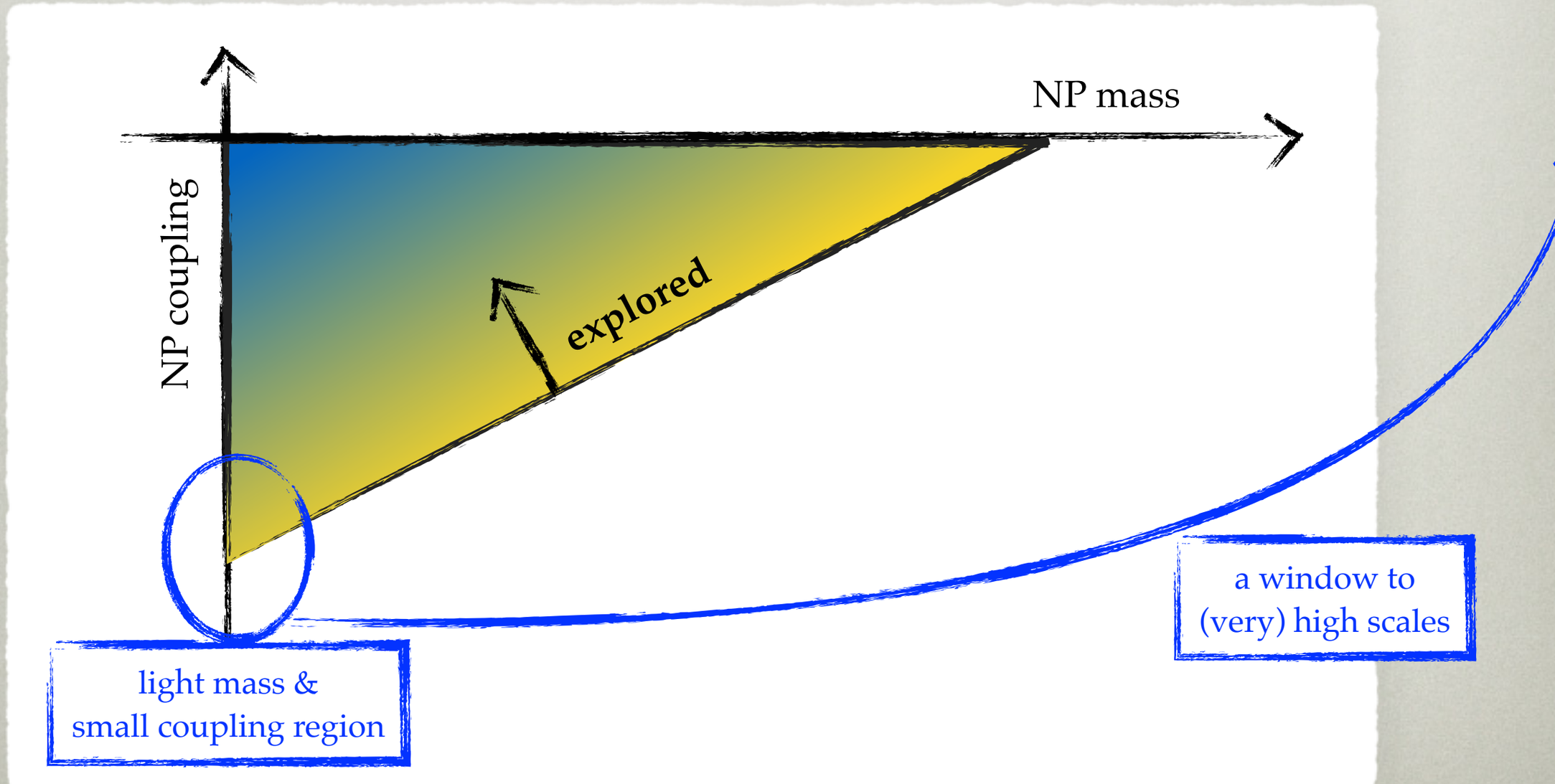


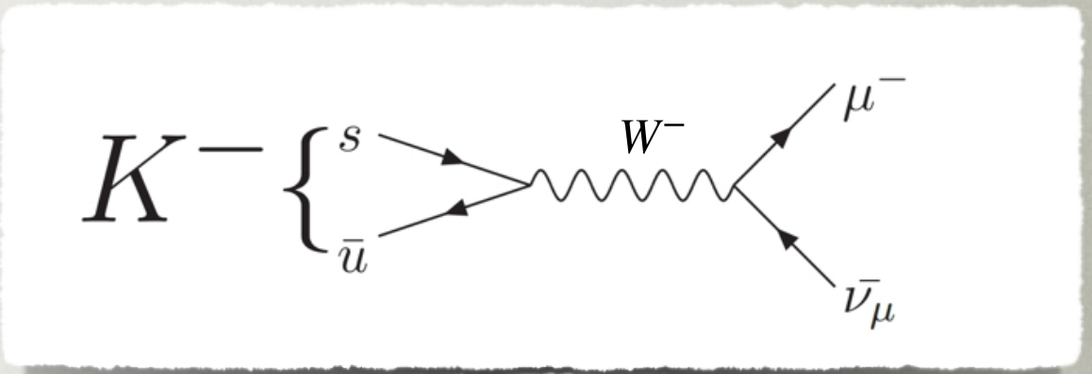
# LIGHT NEW PARTICLES

- how generic are light new particles?
- any spontaneously broken global symmetry
  - $\Rightarrow$ massless Nambu-Goldstone boson

# 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, $N$ | $y_N L H N$ |
| Axion-like pseudo scalar, $a$ | $a F \tilde{F}/f_a$, $a G \tilde{G}/f_a$, $(\bar{\psi}\gamma^\mu\gamma_5\psi)\partial_\mu a/f_a$ |

# LIGHT NEW PHYSICS ⇒ 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
  - $Br(K \to \pi e^- \mu^+) \propto (m_W/\Lambda)^4$

# UPSHOT

- searching for $K \to \pi X$, with X light NP, expect to reach very high UV scales

# EXAMPLE: FLAVOR VIOLATING QCD AXION

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

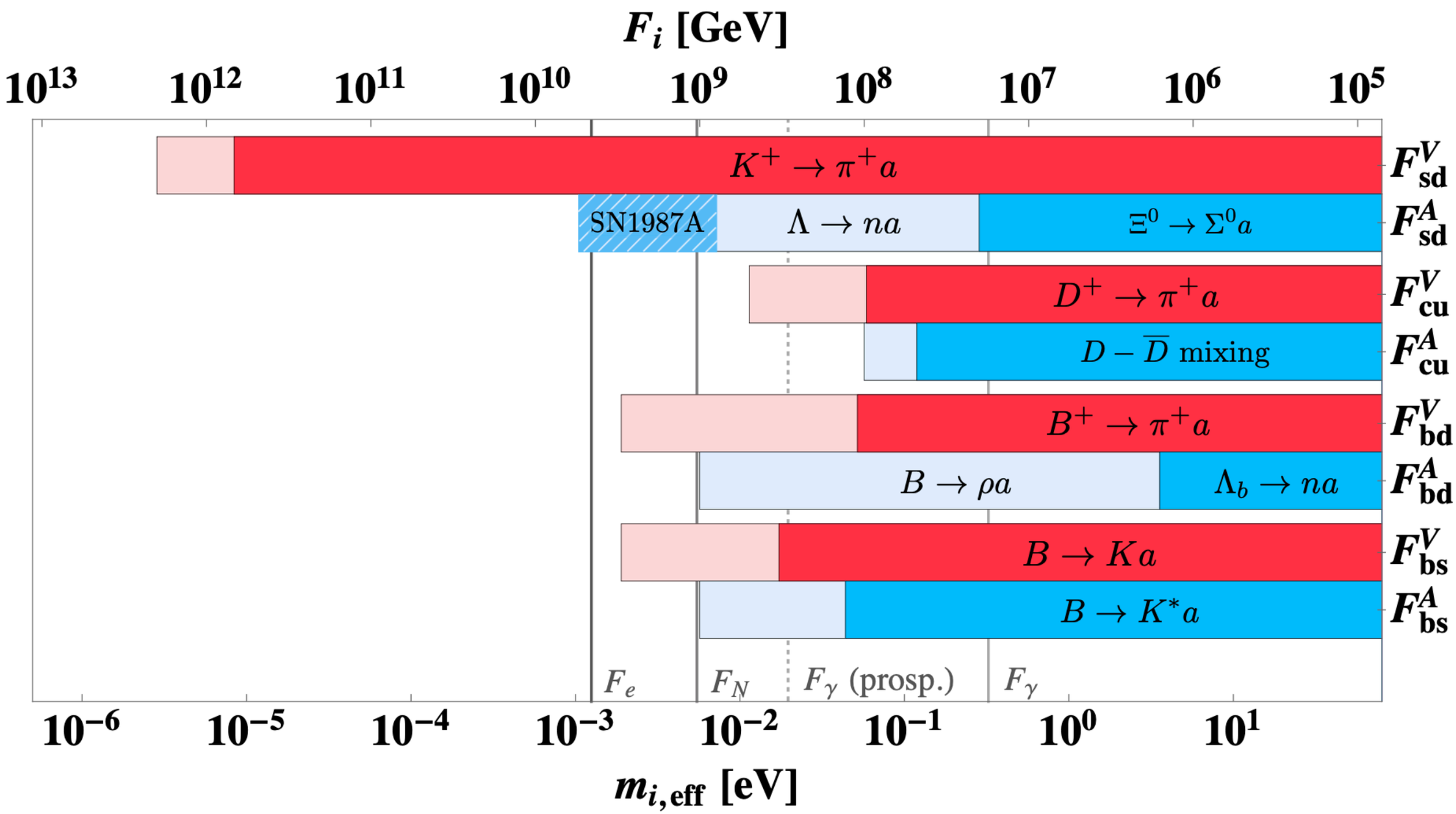
- QCD axion with FV couplings to quarks
  - solves the strong CP problem
  - can be a cold DM candidate
  - effectively massless in FV transitions
- general analysis, allowing for FV couplings as well

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

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

# THE STRONGEST FV CONSTRAINTS

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



# MANY MODES

- many modes / possible NP searches possible at kaon&hyperon factories 2201.07805

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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 | – | – | $K^+ \to \pi^0\ell^+N$ ($m_N \lesssim 20$ 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 | – | – |

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# EXAMPLES

- improved sensitivities expected at next generation of kaon exp.
- $\Rightarrow$ a number of channels and/or models where this translates to a qualitative leap in phenomenology

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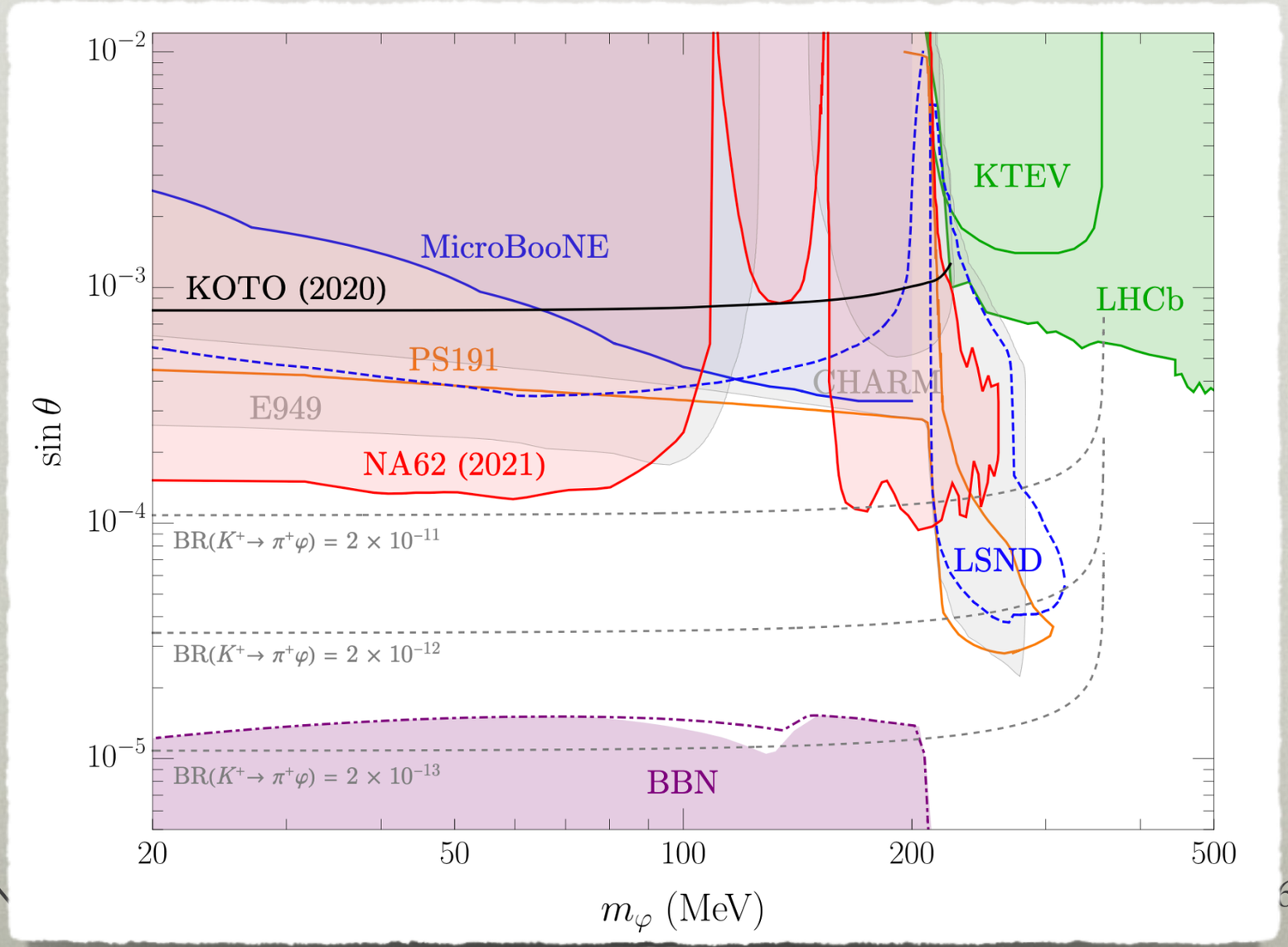
# HIGGS MIXED SCALAR

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



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# PROMPT ALPS

- 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 $K \to \pi a_{\rm inv}$ signature remains

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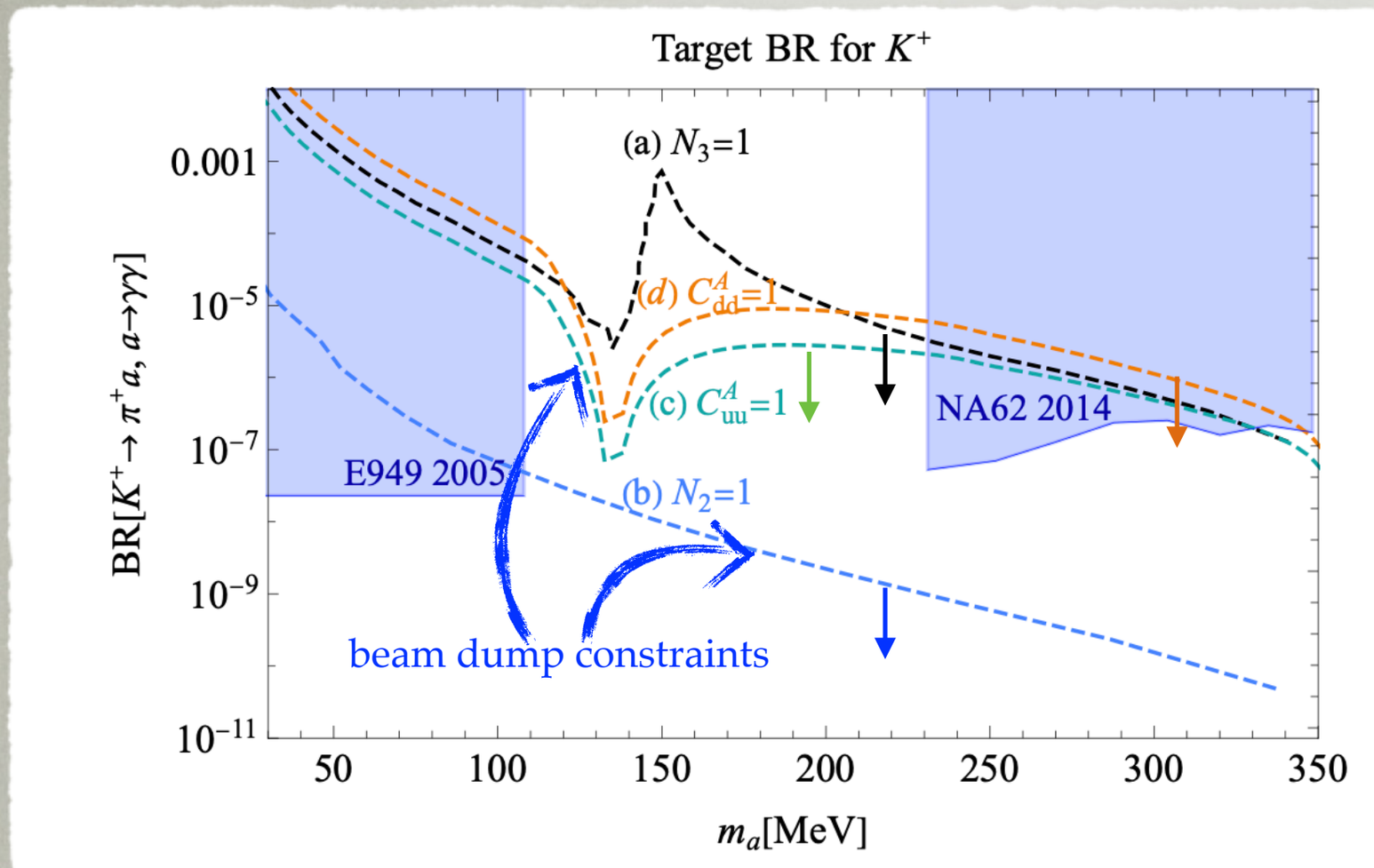


# PS

s in $K \to \pi a$

$^+e^-$

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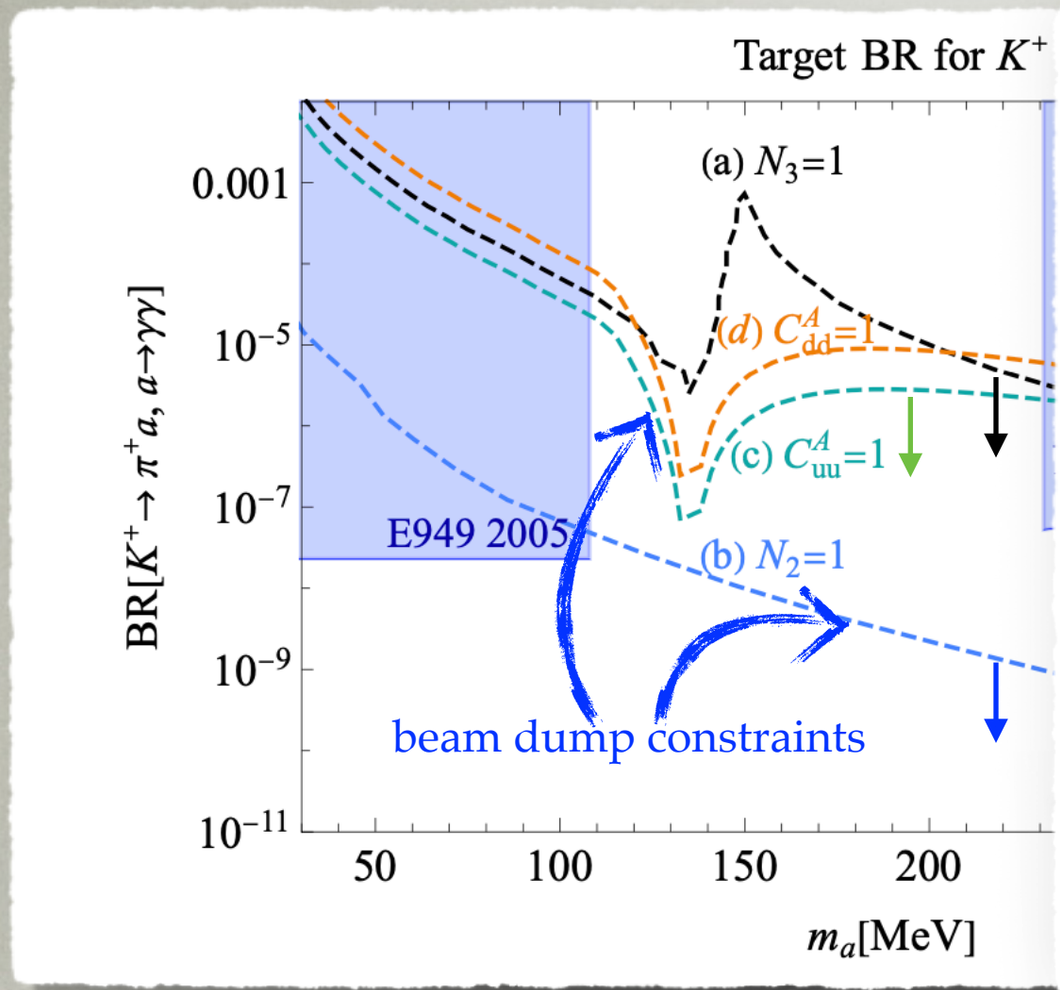


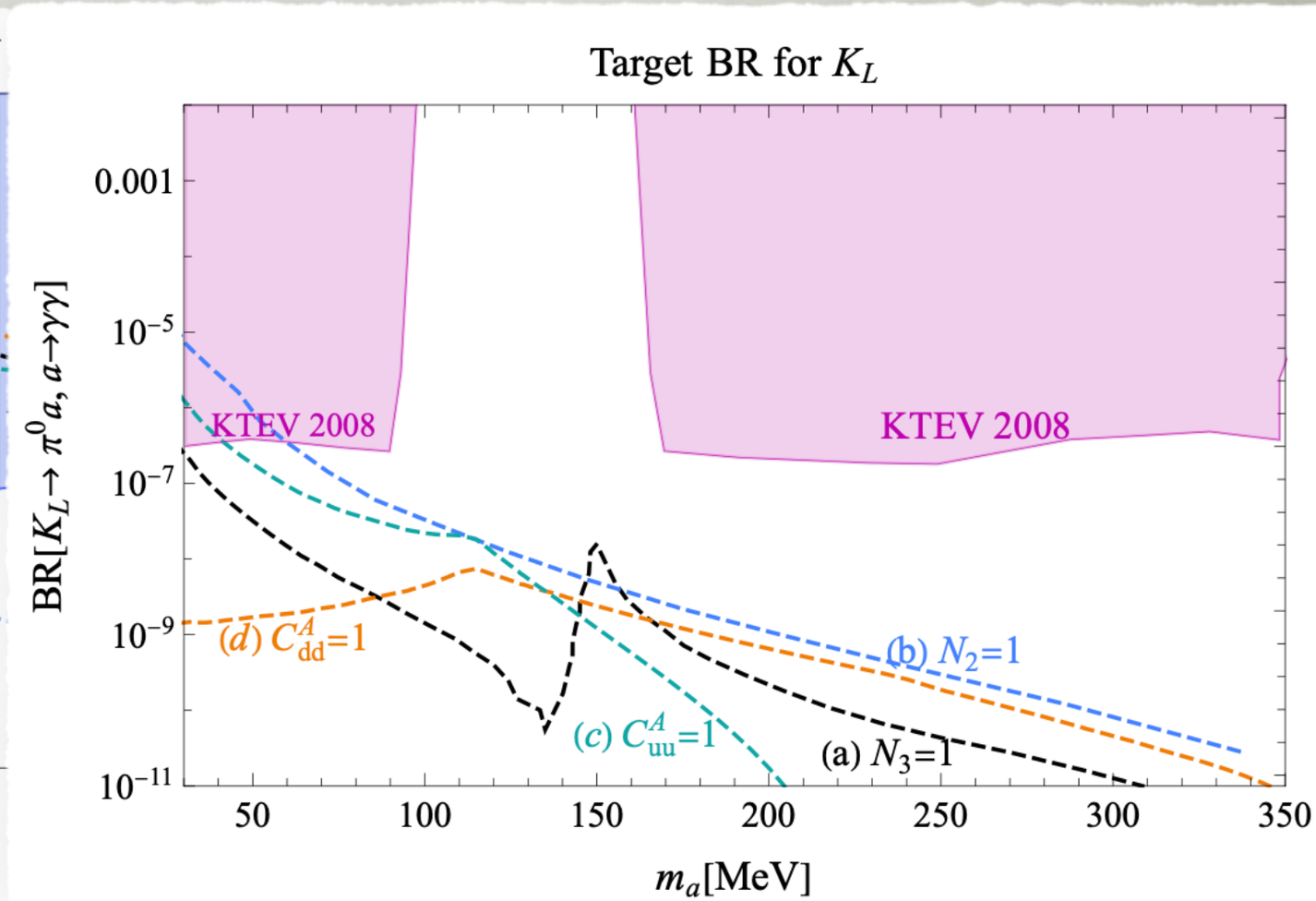


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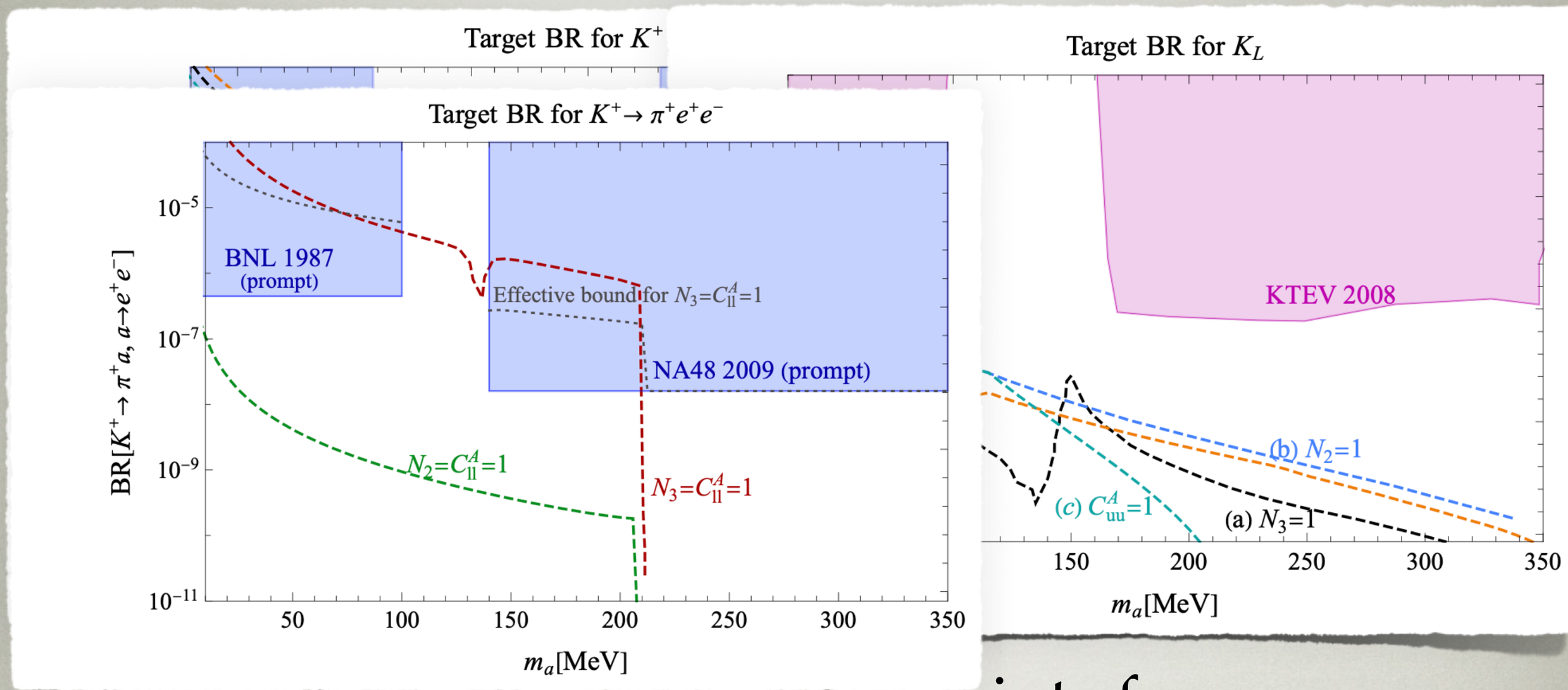


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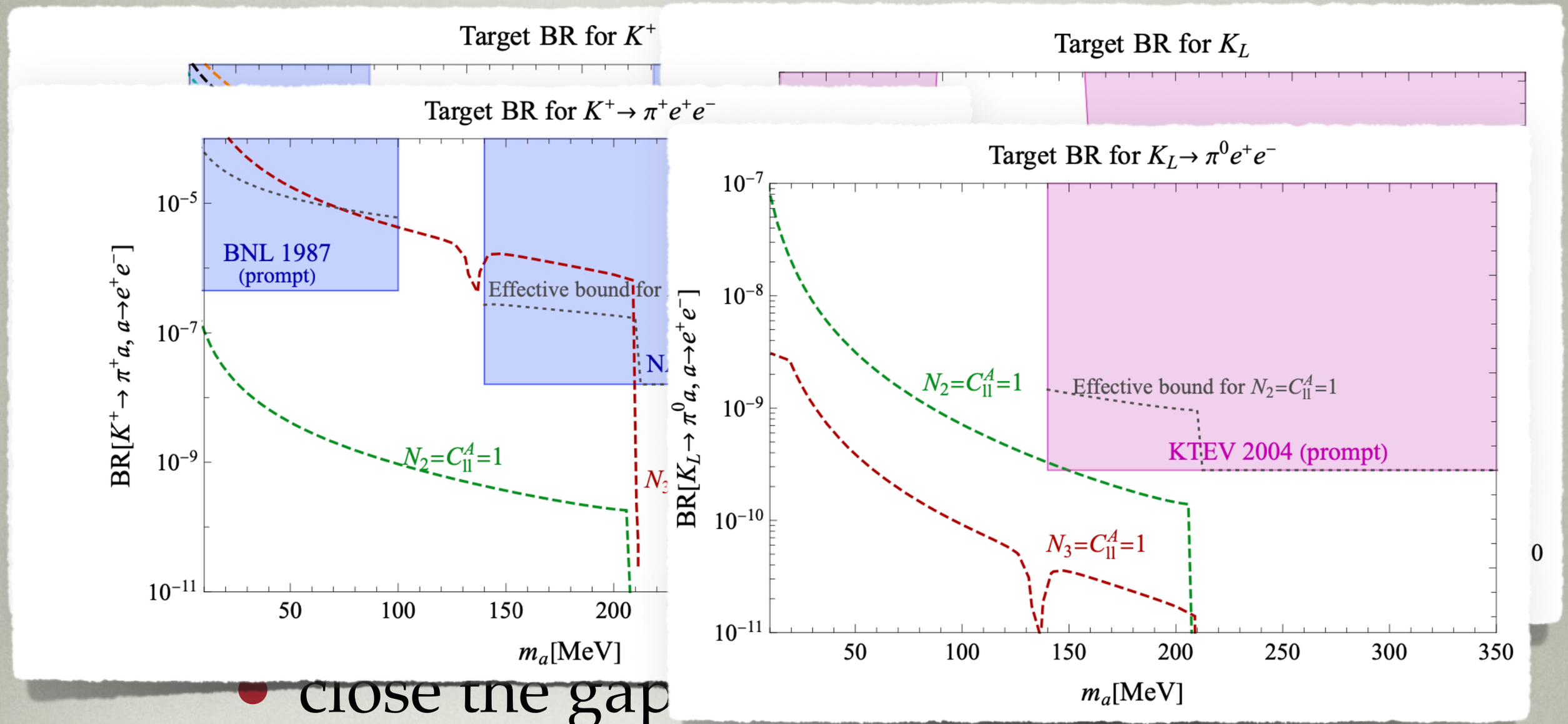


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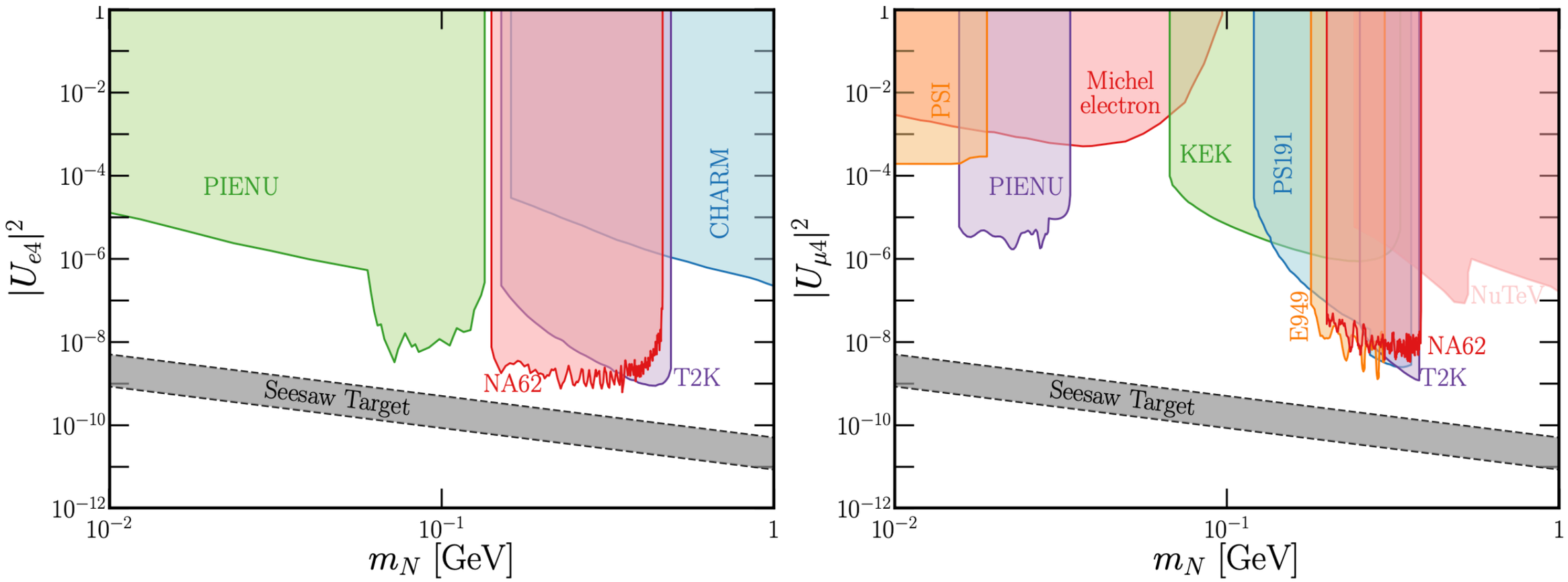
# HEAVY NEUTRINOS

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

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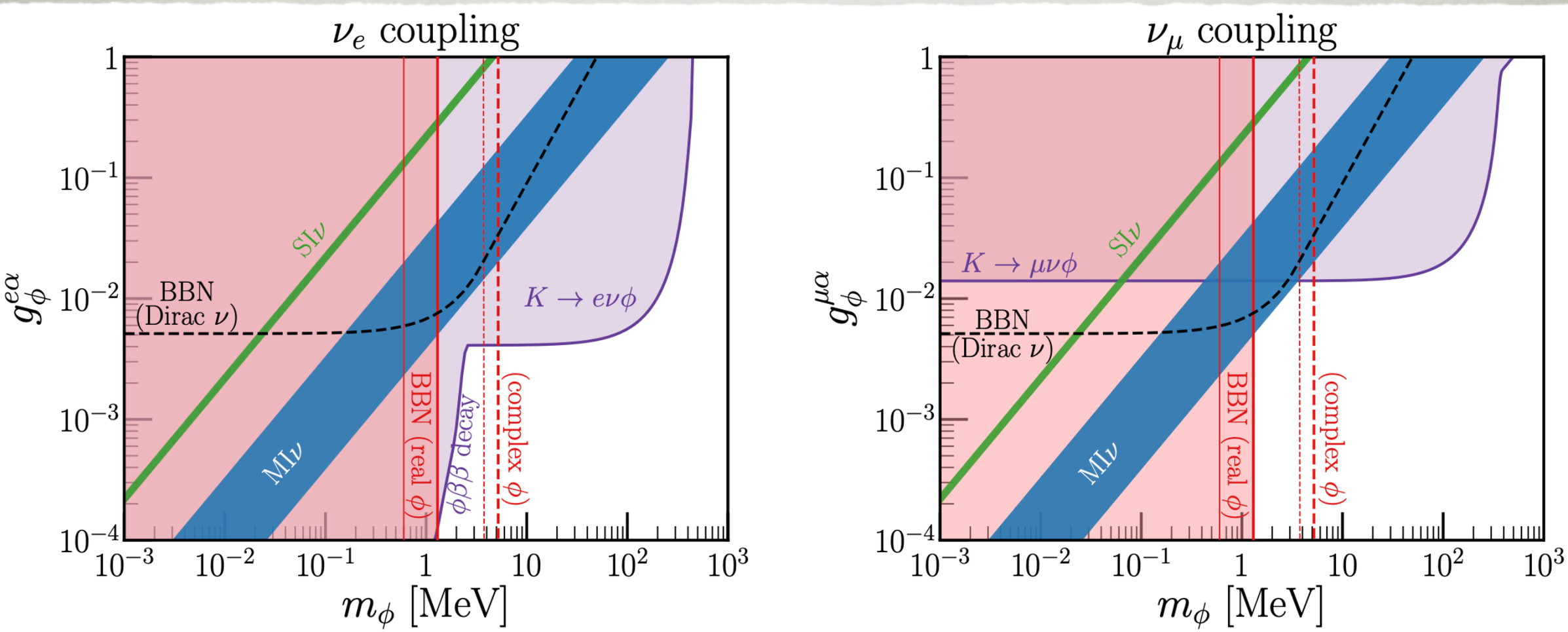
# SELF INTERACTING $\nu$'S

- 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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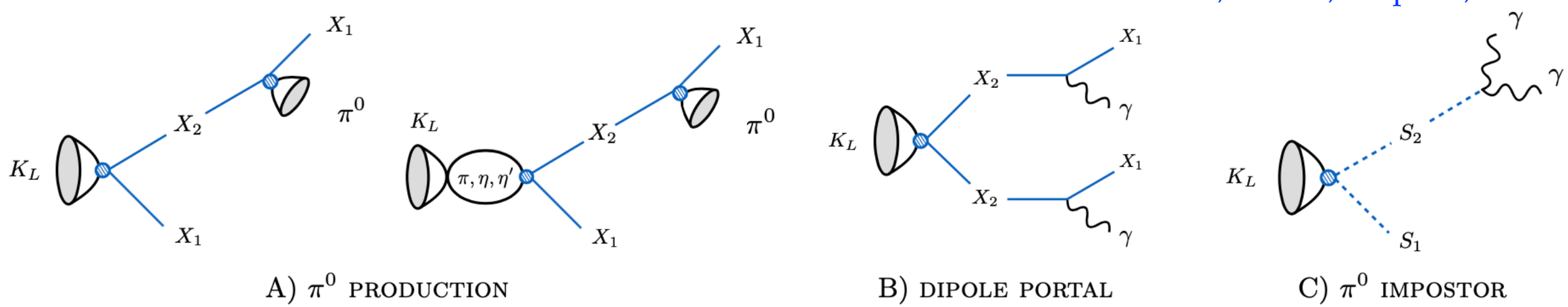


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# HYPERONS

- exp. limits on rare hyperon decays are less stringent.
- but, hyperons probe different couplings than $K \to \pi$
  - e.g., $B_1 \to B_2 X_{\rm inv}$ (vs. $K \to \pi X_{\rm inv}$) probes
    - CP violating (vs. CP conserv.) coupl. of Higgs mixed scalar model ($X_{\rm inv} = \varphi$)
    - axial (vs. vectorial) couplings for ALPs ($X_{\rm inv} = a$)
  - can search for decays kinematically forbidden for kaons
    - example: $B \to \gamma B_{\rm dark}$ or $B \to M B_{\rm dark}$ in dark baryon models

Geng et al, 2112.11979

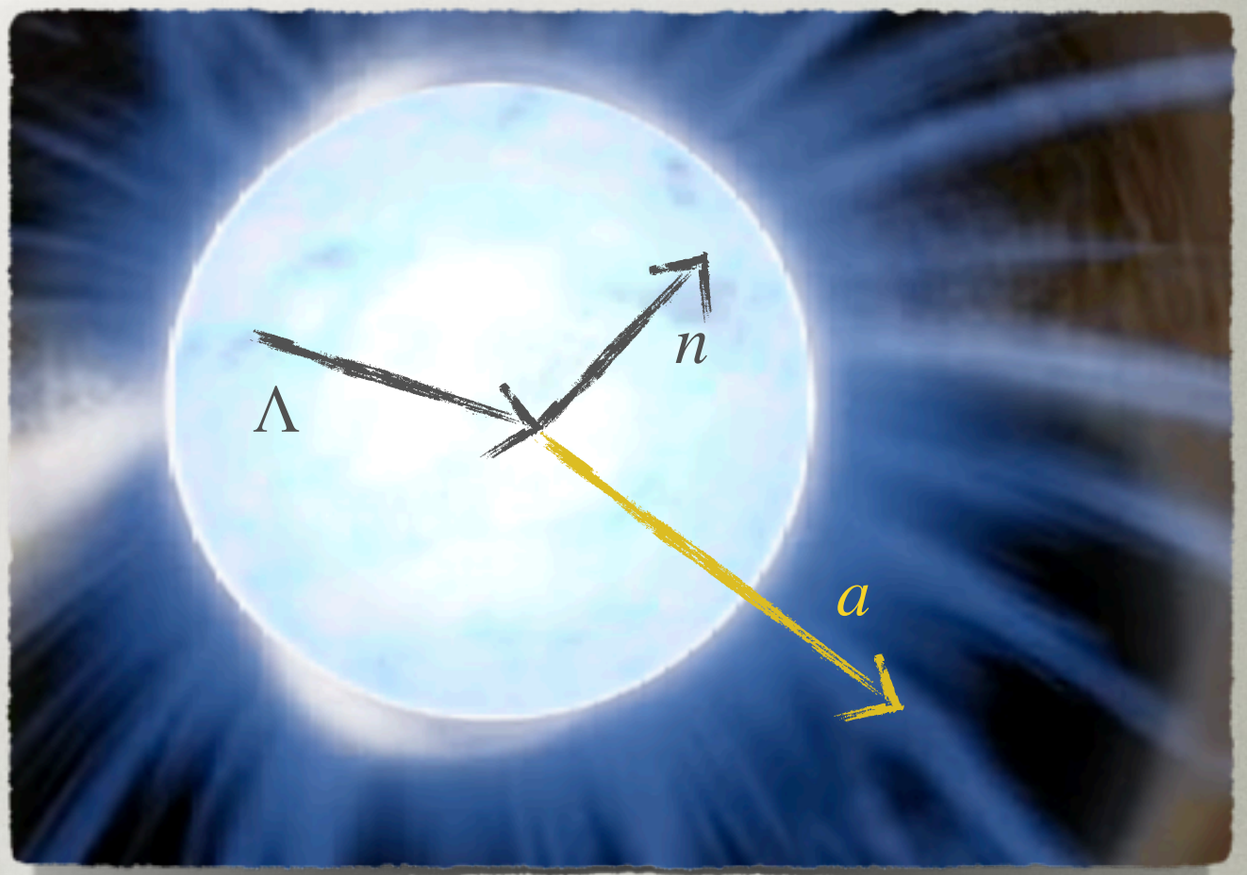
# CONCLUSIONS

- rare kaon and hyperon decays: many interesting channels for light NP searches
- a clear set of targets for the next generation of experiments

# BACKUP SLIDES

# SUPERNOVA BOUNDS

- in neutron star $\Lambda$, $n$, $p$, $e$ are in equilibrium
- $\Lambda \to na$ decays can cool the proto-neutron star
- $\Lambda$, $n$ 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)




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

see also Camalich et al, 2012.11632

- 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