

# Hidden sectors in kaon decays

Snowmass RPF Spring Meeting  
University of Cincinnati , May 17, 2022

**Kohsaku Tobioka (Tobi)**  
Florida State University, KEK theory center



Contributed paper to RF6

**"*New Physics Searches at Kaon and Hyperon Factories*"** [[arXiv:2201.07805](https://arxiv.org/abs/2201.07805)]

Editors: Evgeni Goudzovski, Diego Redigolo, Jure Zupan, KT  
+60 contributors

# **Community effort between Ex and Th**

## **[mainly on kaon physics, RF6 Dark Sector Studies at High Intensities]**

- Letter of Interest by 4 people  
for new light particles at kaon factories.

**Letter of Interest:  
Probing the Dark Sector at Kaon Factories**

Evgeni Goudzovski<sup>1</sup>, Diego Redigolo<sup>2</sup>, Kohsaku Tobioka<sup>3,4</sup>, and Jure Zupan<sup>5</sup>

- Essential to integrate experimentalists and theorists
- Joined by 60 experts, including people from NA62, KOTO, LHCb, BESIII,  
KLEVER experiments
- Include topics beyond kaon, such as hyperon and BESIII.

# 64 Contributors

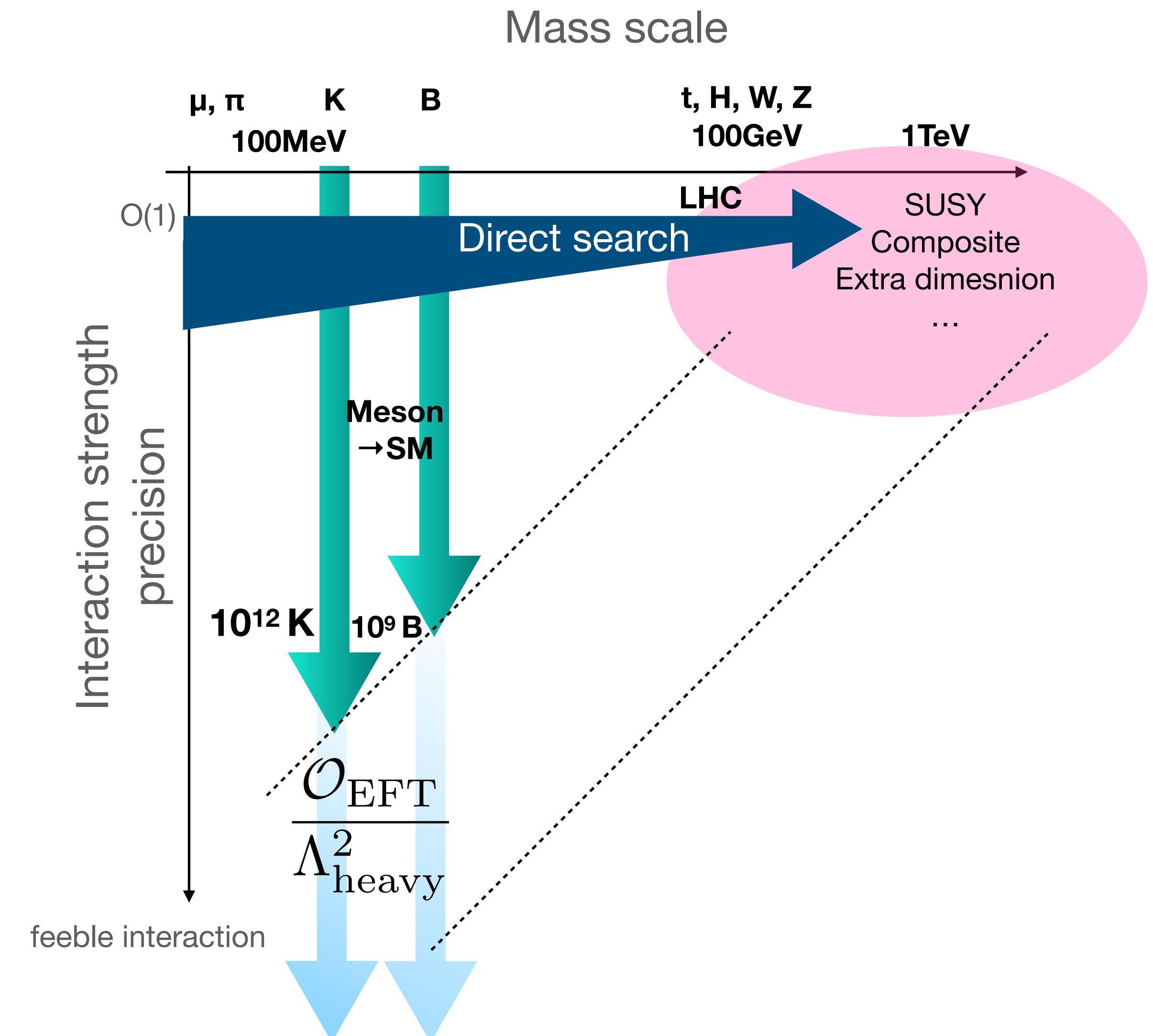
*Editors: Evgeni Goudzovski<sup>1</sup>, Diego Redigolo<sup>2,3</sup>, Kohsaku Tobioka<sup>4,5</sup>, Jure Zupan<sup>6</sup>*

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# Precision Measurements

## As a probe of heavy new physics via EFT

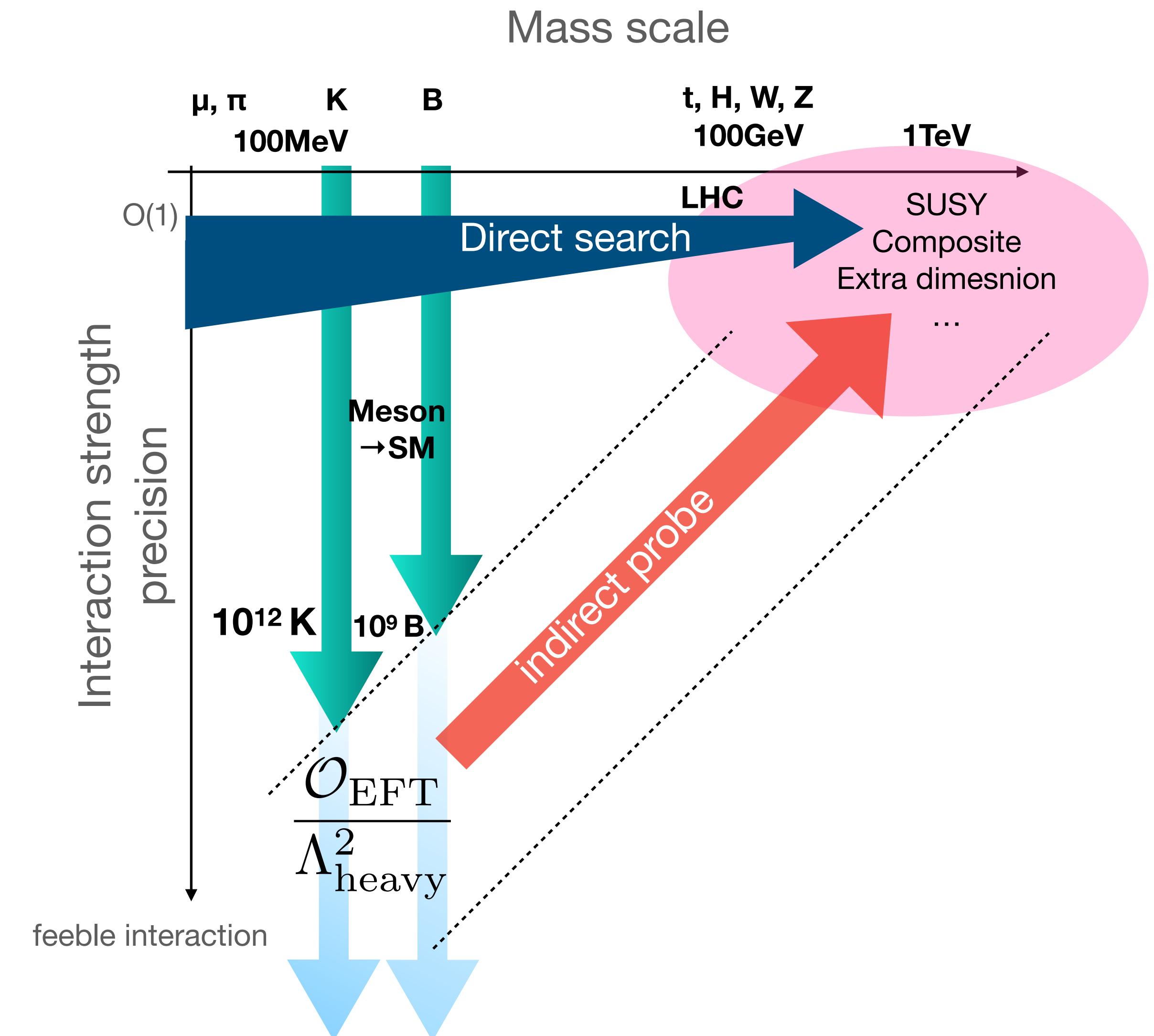
- Many BSM models biased heavy particles above  $\sim$ TeV. Driven by **hierarchy problem & WIMP DM**
- Then, precision measurements, such as meson decay, are to probe the heavy new physics indirectly. **Compatible with EFT approach.**



# Precision Measurements

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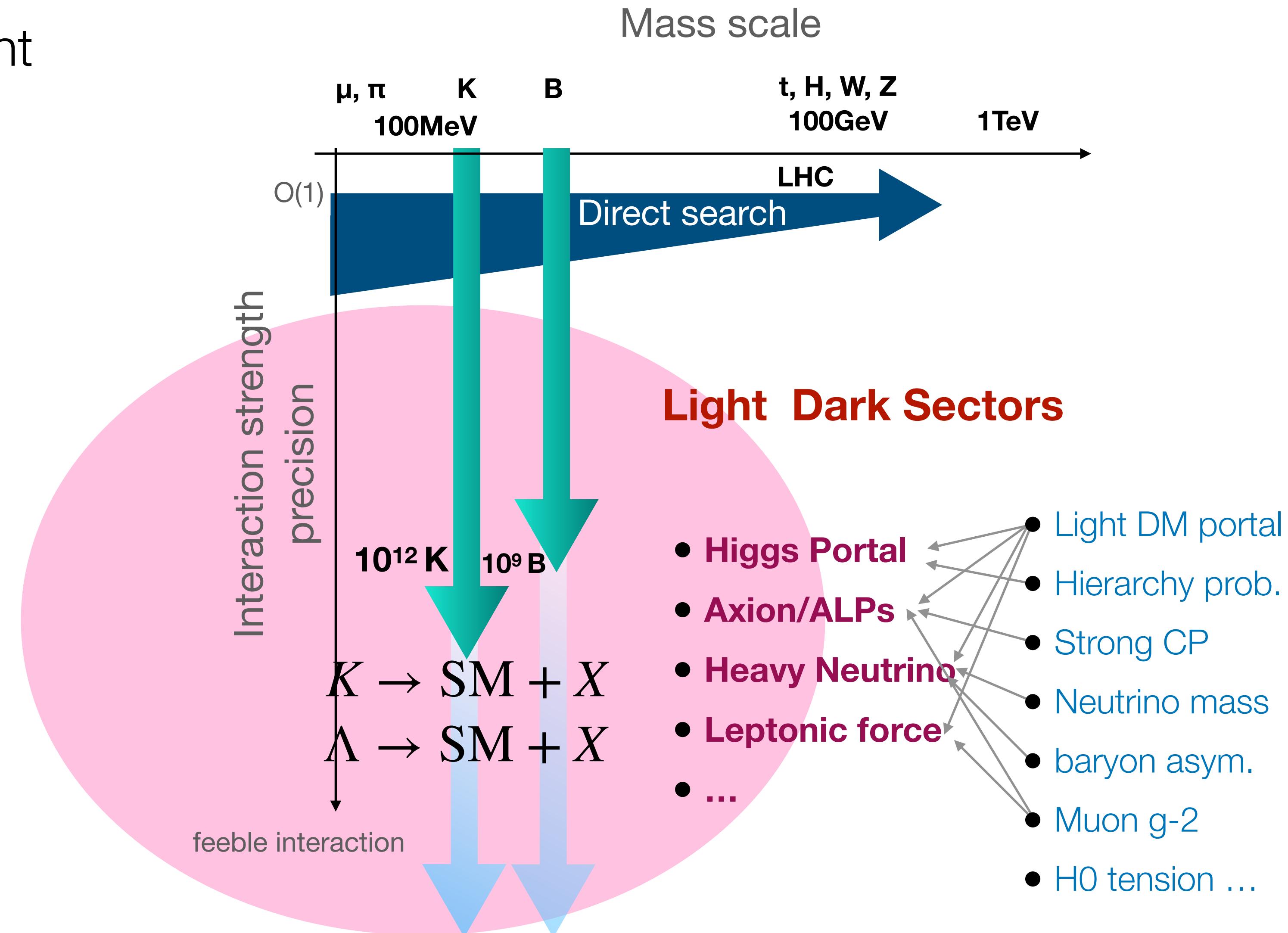
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# Feebly Interacting Light Particles

New DoF. EFT is invalid. Need model-dependent approach.

- Possibility of feebly interacting light particles ( $X$ )  $\in$  light dark sectors, with various motivation  
Light DM, hierarchy problem, strong CP,  $\nu$  mass, baryogenesis,  $(g-2)\mu$  anomaly...
- $X$  can be directly produced, but **EFT approach won't work**



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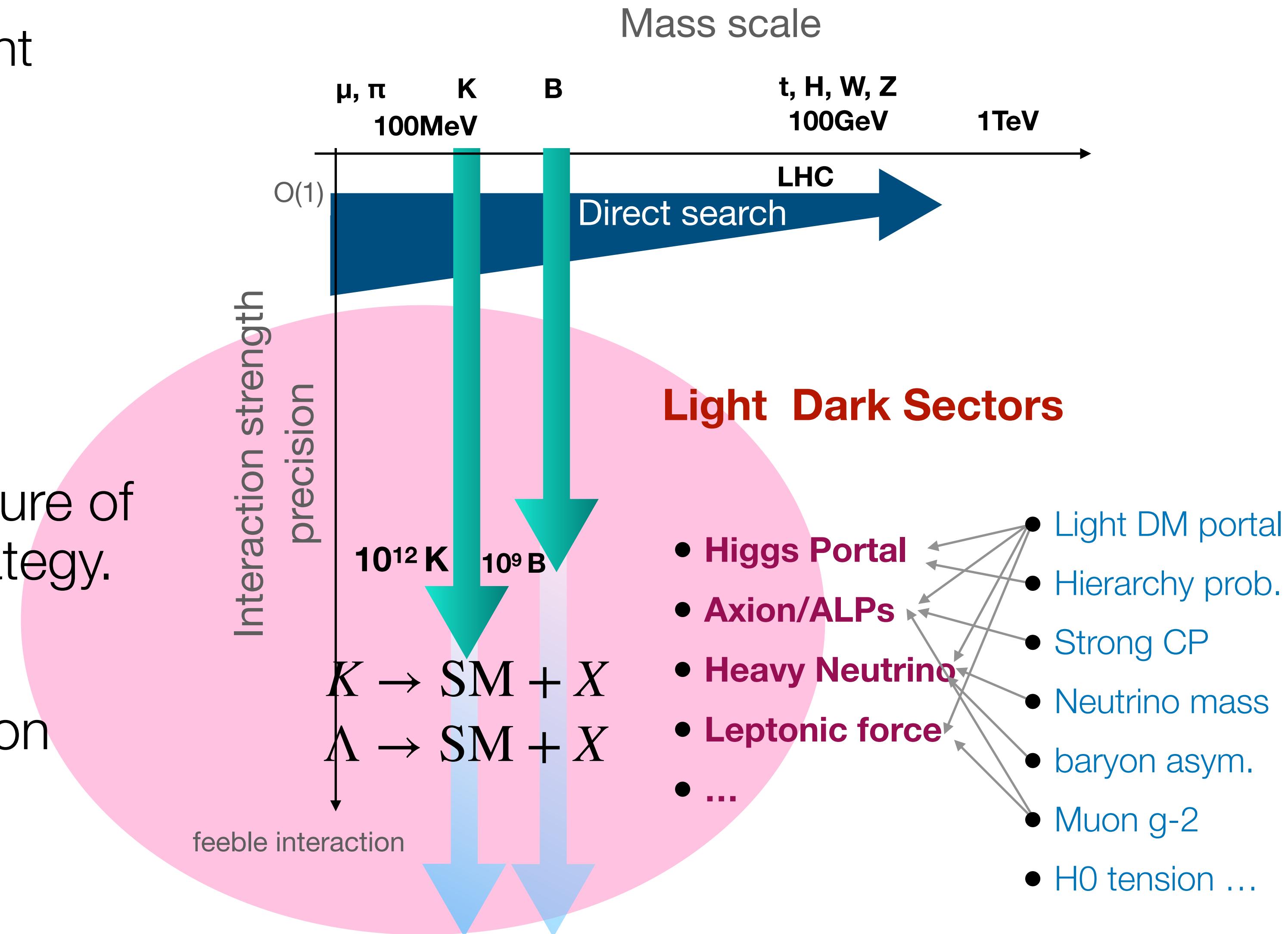
- Possibility of feebly interacting light particles ( $X$ )  $\in$  light dark sectors, with various motivation

Light DM, hierarchy problem, strong CP,  $\nu$  mass, baryogenesis,  $(g-2)\mu$  anomaly...

- $X$  can be directly produced, but **EFT approach won't work**
- Signal strongly depends on nature of  $X$ . Model dependent signal/strategy.
- In each scenario, investigate what is allowed/interesting region  $\Rightarrow$  **target channel and BR**

e.g.  $(g-2)\mu$  anomaly  $\Rightarrow$  BR( $K \rightarrow \mu + \text{inv}$ )

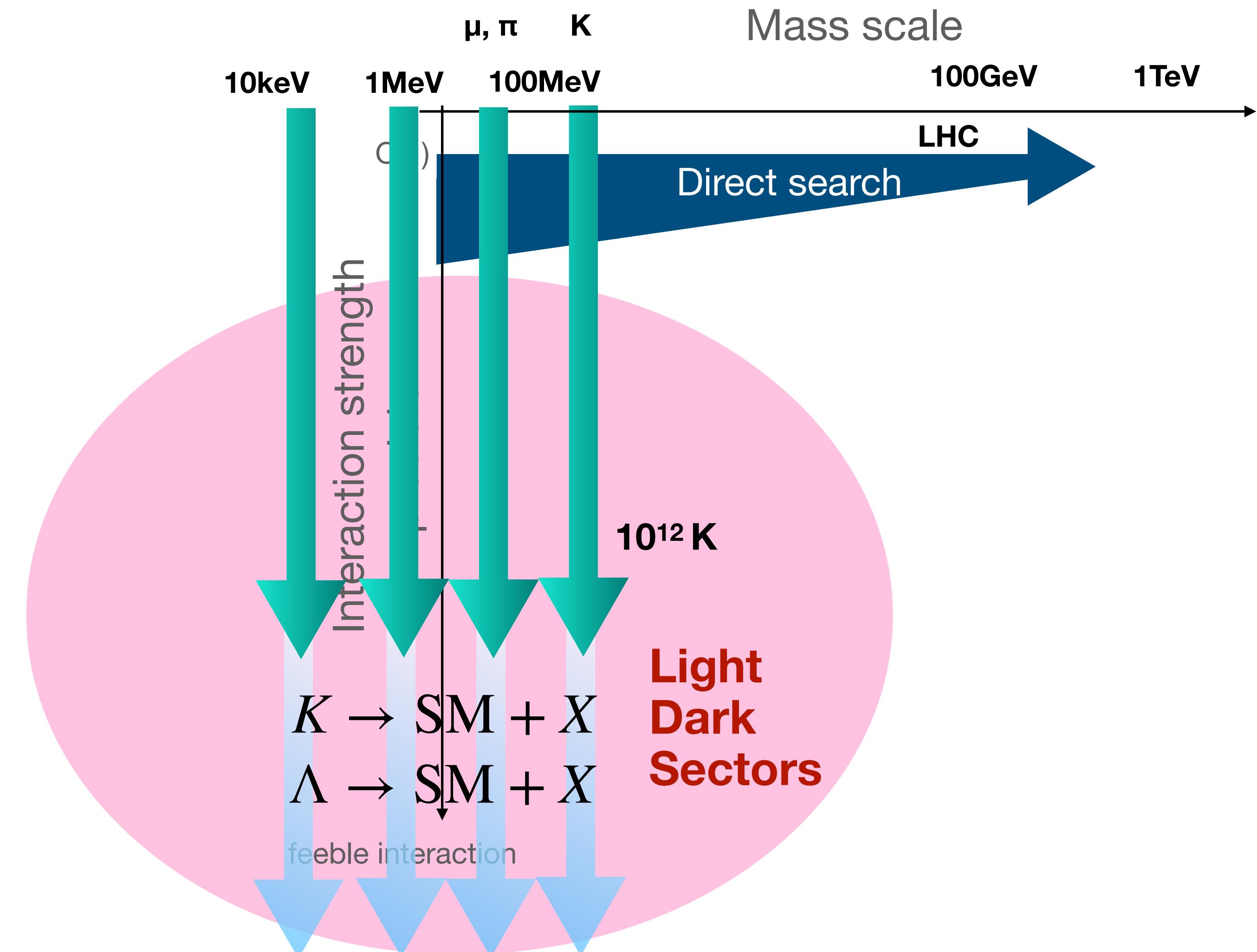
Kohsaku Tobioka, Florida State University



# Why kaon decay for new light particles?

High precision, complementary to astro/cosmology and beam-dump exp.

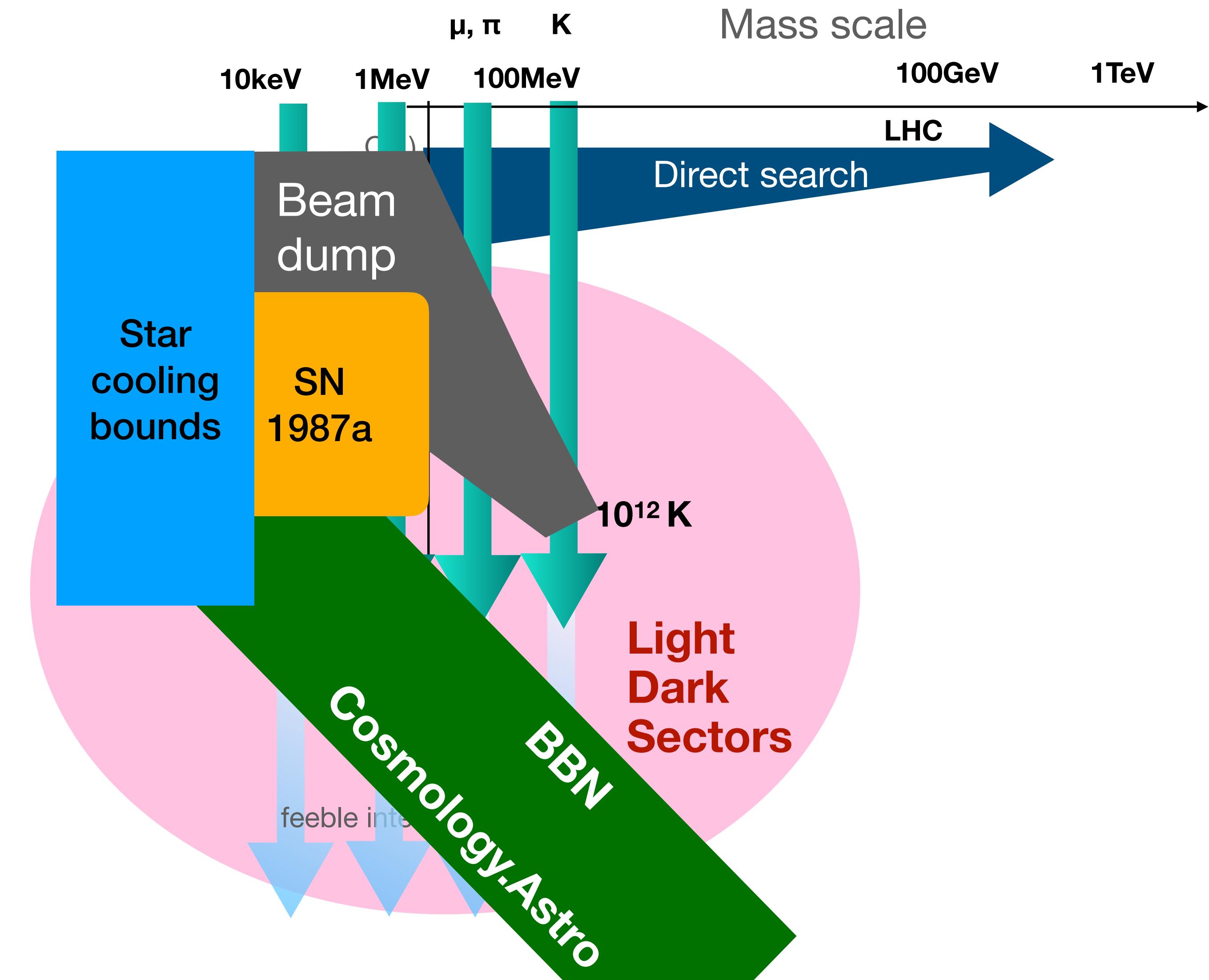
- More kaons (hyperons) from the experiments
- limited decay modes to SM ( $\gamma$ , e,  $\mu$ , maybe  $\pi$ ) for  $m_X < O(100)\text{MeV}$



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High precision, complementary to astro/cosmology and beam-dump exp.

- More kaons (hyperons) from the experiments
- limited decay modes to SM ( $\gamma$ , e,  $\mu$ , maybe  $\pi$ ) for  $m_X < O(100)\text{MeV}$
- Can be long-lived ( $X \sim \text{invisible}$ ), complementary to beam dump experiments and cosmological limit ( $\tau_X > 1\text{sec}$ )
- $m_X \sim O(10\text{-}100)\text{MeV}$  is unique.  
 $m_X < O(1)\text{MeV}$  can be constrained by astrophysics (SN, star cooling)

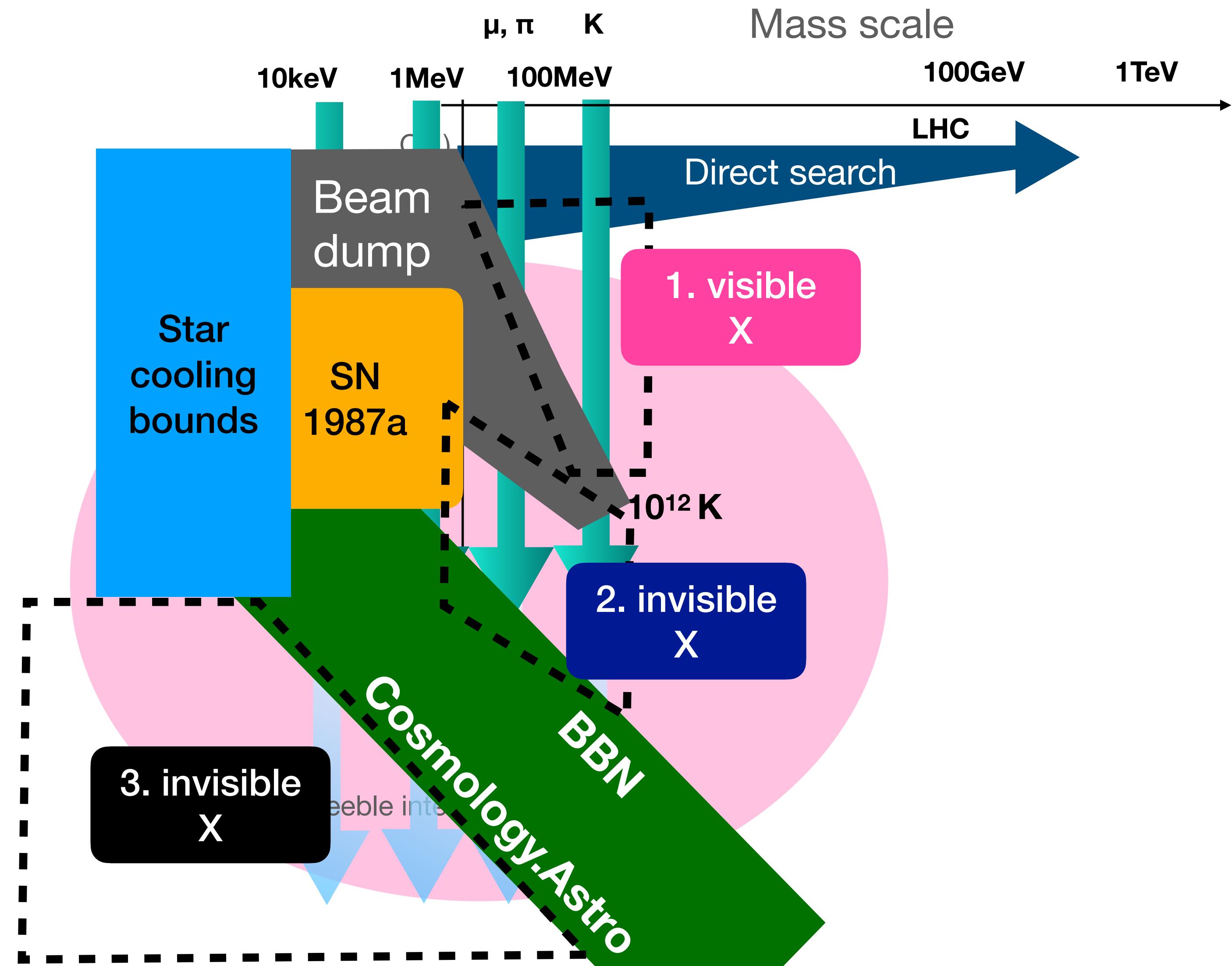


# Why kaon decay for new light particles?

High precision, complementary to astro/cosmology and beam-dump exp.

- **3 Regions** depending on flavor violation of X couplings  
→ enhance  $K/\Lambda \rightarrow \text{SM} + X$ .

1. **visible X** decaying to SM.  
X is flavor conserving.
2. **invisible X** beyond beam-dump.  
Flavor conserving
3. invisible X beyond BBN and cosmology probes.  
X has FV coupling( $\Delta S=1$ ).



# What to look for?

- Study each model  
Motivated parameter space? Other bounds?
- What are the interesting channel?  
Specific target BR?

Repeat, model1, 2, 3...

- Categorize by signature  
[possibly at NA62, KOTO/KLEVER, LHCb, BESIII]

	parent kaon	detectable objects
NA62	K <sup>+</sup>	charged SM, $\gamma$ , missing
KOTO KLEVER	K <sup>L</sup>	$\gamma$ , missing
LHCb	K <sup>S</sup>	charged SM, $\gamma$
BESIII	Hyperon	various objects.

## Section 4,5: Signatures

# Section 2: Models

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 $K \rightarrow \pi + \text{inv}$	✓	✓	—	✓	—	✓	✓	✓	—	—	✓
4.2 $K \rightarrow \pi\pi + \text{inv}$	CP viol.	axial coupl.	—	✓ even massless	—	—	—	—	—	—	—
4.3 $K \rightarrow \pi\gamma + \text{inv}$	possible in extensions	possible in extensions	—	✓ even massless	—	—	—	—	—	—	—
4.4 $K \rightarrow 2\pi\gamma + \text{inv}$	—	—	—	$\pi^0 \rightarrow \gamma A'$	—	—	—	—	—	possible	—
4.5 $K \rightarrow \pi\gamma\gamma$	negligible (✓ dilaton)	✓ prompt	—	—	—	—	—	lifetime loophole	—	—	—
4.6 $K \rightarrow \pi\ell_\alpha\ell_\alpha$	✓ prompt	✓ prompt	—	✓	—	—	—	lifetime loophole	—	—	—
4.7 $K \rightarrow \pi\pi\ell_\alpha\ell_\alpha$	CP viol.	axial coupl. & prompt	—	✓	—	—	—	—	—	—	—
4.8 $K \rightarrow \pi\ell_\alpha\ell_\alpha\ell_\beta\ell_\beta$	—	—	—	—	—	—	—	$A'$ , MeV axion, also $K \rightarrow \pi 2\ell_\alpha 2\ell_\beta \text{inv}$	—	—	—
4.9 $K_L \rightarrow \gamma + \text{inv}$	—	—	—	✓	—	—	—	—	—	—	—
4.10 $K \rightarrow \pi\gamma, 3\gamma$	—	—	—	—	—	—	—	—	—	Lorentz viol.	—
4.11 $K_L \rightarrow \gamma\gamma + \text{inv}$	—	—	—	—	—	—	✓ (Table 2)	—	—	—	—
4.12 $K_{S,L} \rightarrow \ell^+\ell^- + \text{inv}$	—	—	—	—	—	—	possible	possible	—	—	$K_S \rightarrow \mu\mu$
4.12 $K_{S,L} \rightarrow 2\ell 2\gamma$	—	—	—	—	—	—	possible	possible	—	—	—
4.13 $K^0 \rightarrow 4\ell$	—	—	—	—	—	—	possible	possible	—	—	—
4.14 $K^+ \rightarrow \ell^+ + \text{inv}$	—	—	✓	—	✓ ( $X \rightarrow \text{inv}$ )	✓	—	—	—	—	—
4.15 $K^+ \rightarrow 3\ell + \text{inv}$	—	—	possible	—	✓ ( $X \rightarrow \ell\ell$ )	—	—	$U(1) + \text{HNL}$	—	—	—
4.16 $K^+ \rightarrow \ell\gamma\gamma + \text{inv}$	—	—	$K^+ \rightarrow \pi^0\ell^+ N$ ( $m_N \lesssim 20 \text{ MeV}$ )	—	possible ( $X \rightarrow 2\gamma$ )	possible	—	possible	—	—	—
4.17 LFV	—	—	—	—	—	—	—	—	—	FV ALP, $Z'$	FV ALP
4.18 LNV	—	—	✓ ( $K^+ \rightarrow \ell^+ N$ , $N \rightarrow \pi^-\ell^+$ )	—	—	—	—	—	—	—	✓ (Maj. HNL)
4.19 Rare $K_S$ decays	$K_S \rightarrow \pi(\pi)2\ell$	$K_S \rightarrow \pi(\pi)2\ell$ $\rightarrow \pi(\pi)2\gamma$	—	$K_S \rightarrow A'\gamma$ $\rightarrow A'\gamma\pi$	—	—	—	$K_S \rightarrow 4\ell$	—	$K_S \rightarrow 2\gamma + \text{inv}$	$K_S \rightarrow \mu\mu$
4.20 Dark Shower	—	—	—	—	—	—	—	—	—	✓	—
5 Hyperon	$B_1 \rightarrow B_2\varphi$	Table 8	$B_1 \rightarrow B_2 a$	—	Table 1	—	—	—	Table 4	$B \rightarrow \gamma/M + \text{inv}$	—

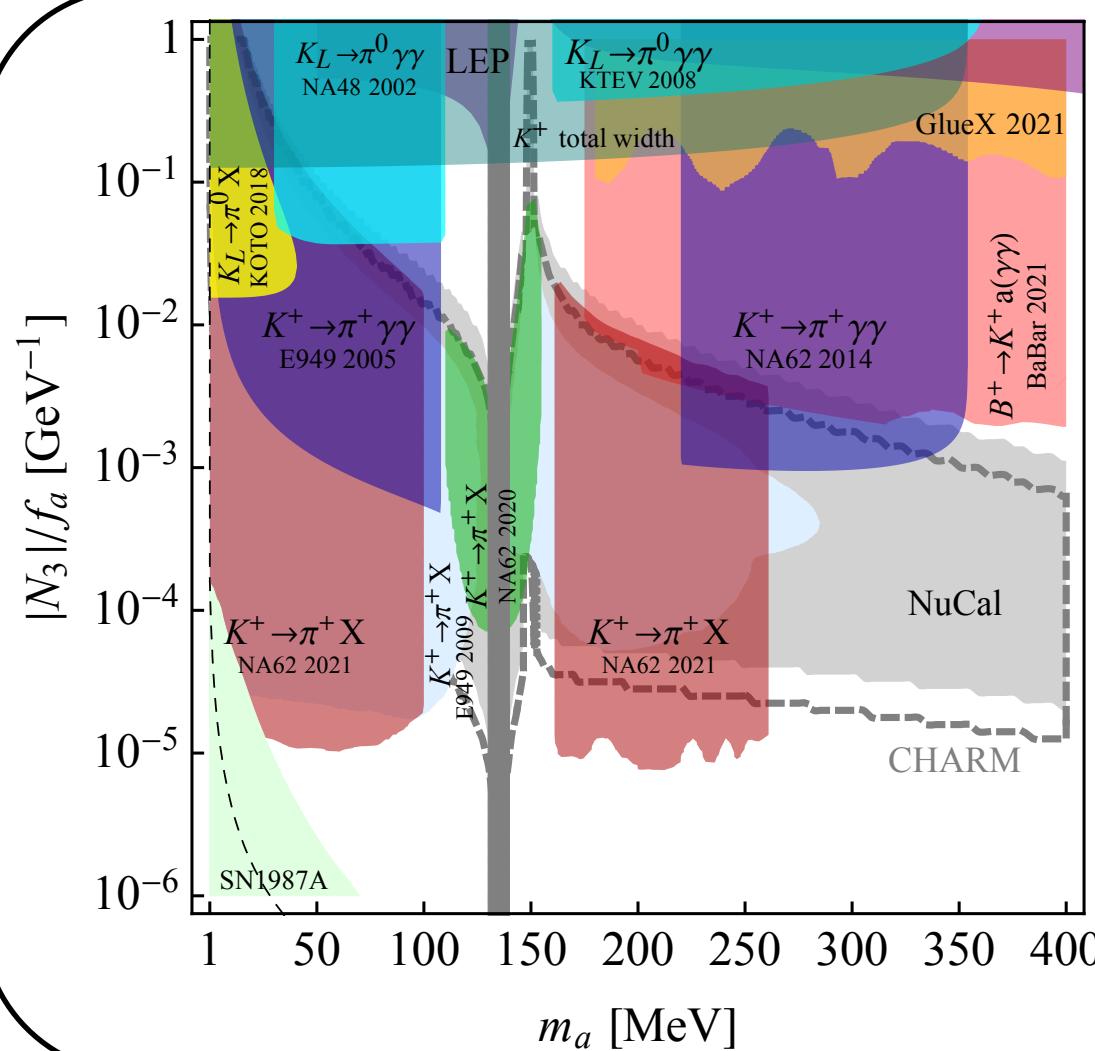
(partially) ongoing

possible, ongoing in similar channel

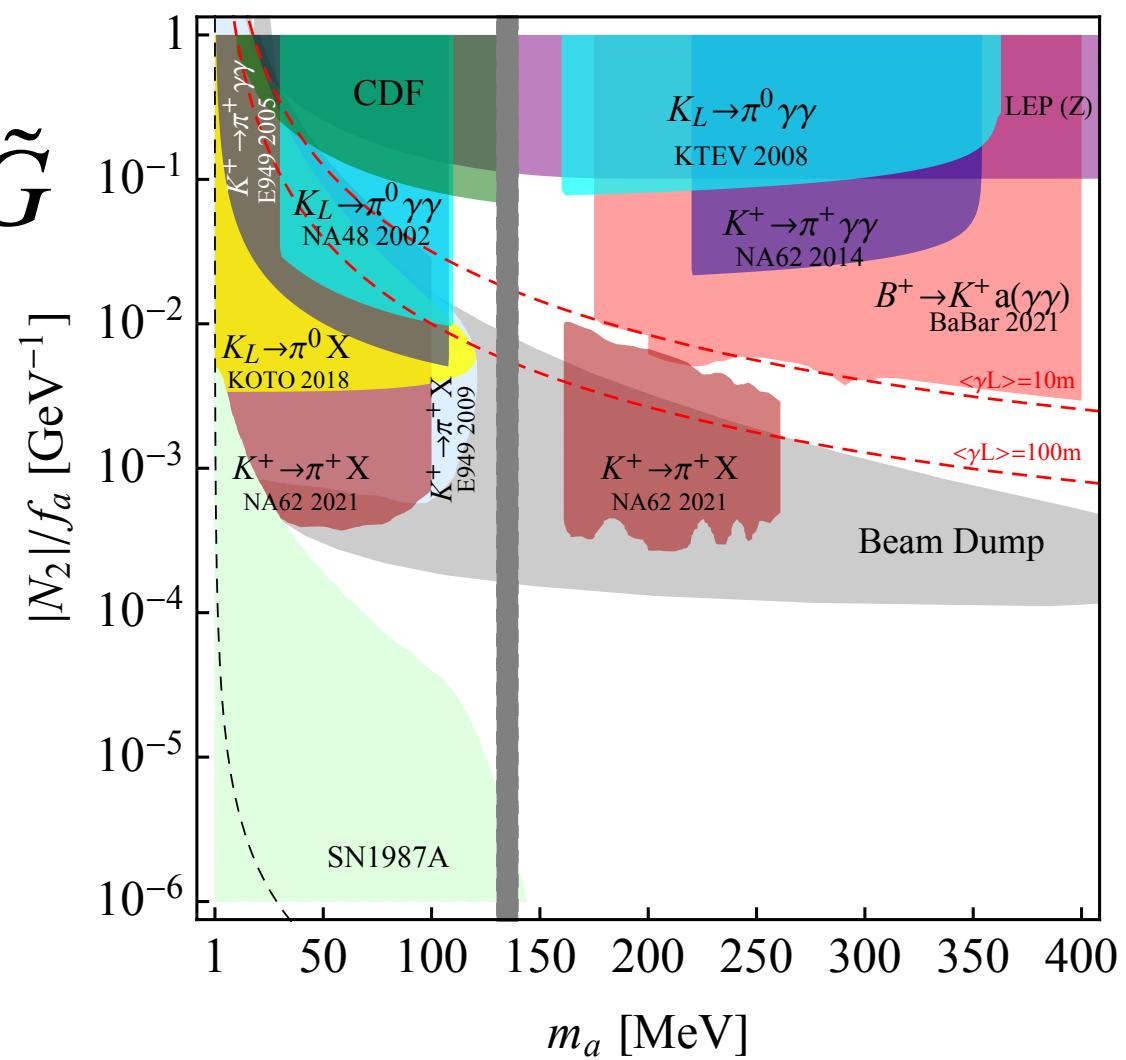
# Examples

# Axion like particles w/o flavor violation

## 1. visible X region

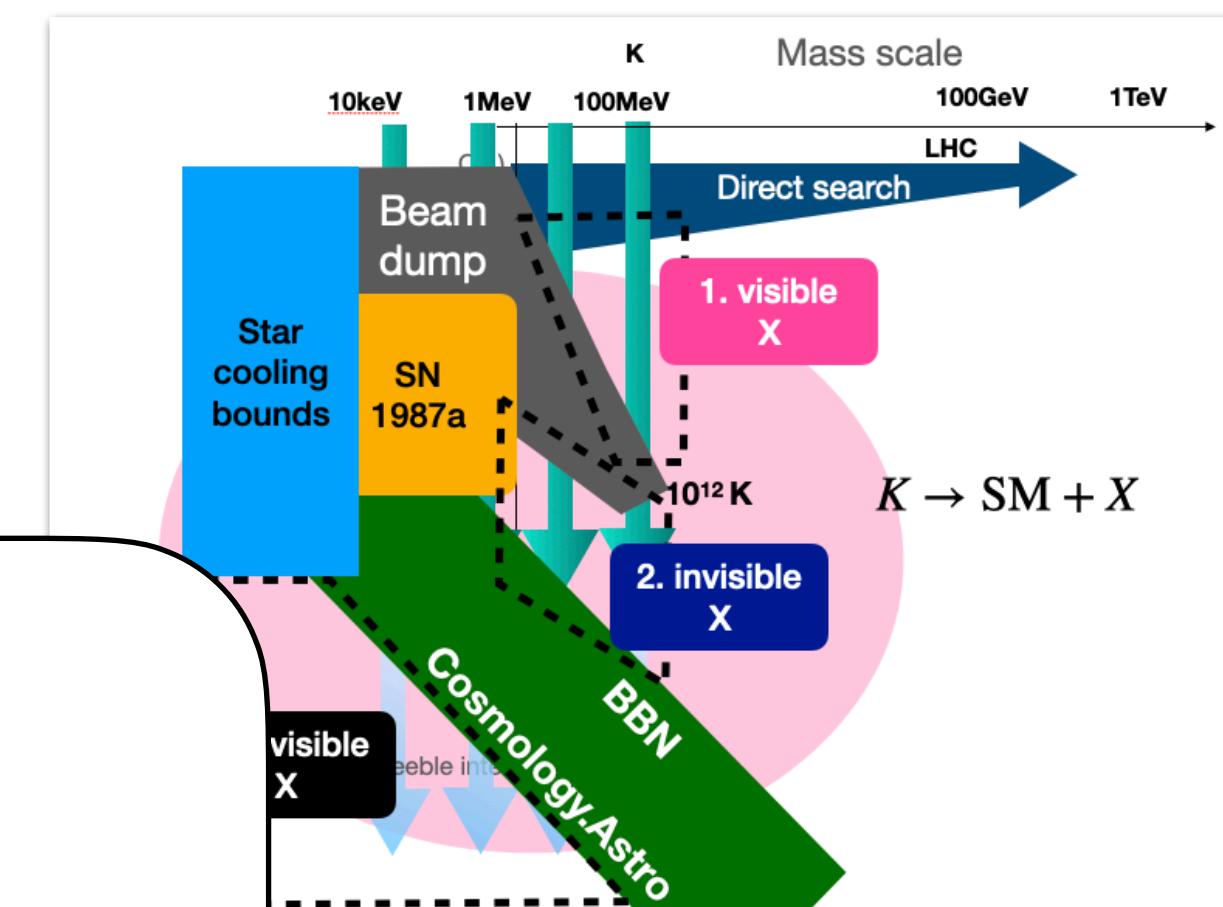


$$(a) \frac{\alpha_s N_3}{8\pi f_a} a G \tilde{G}$$



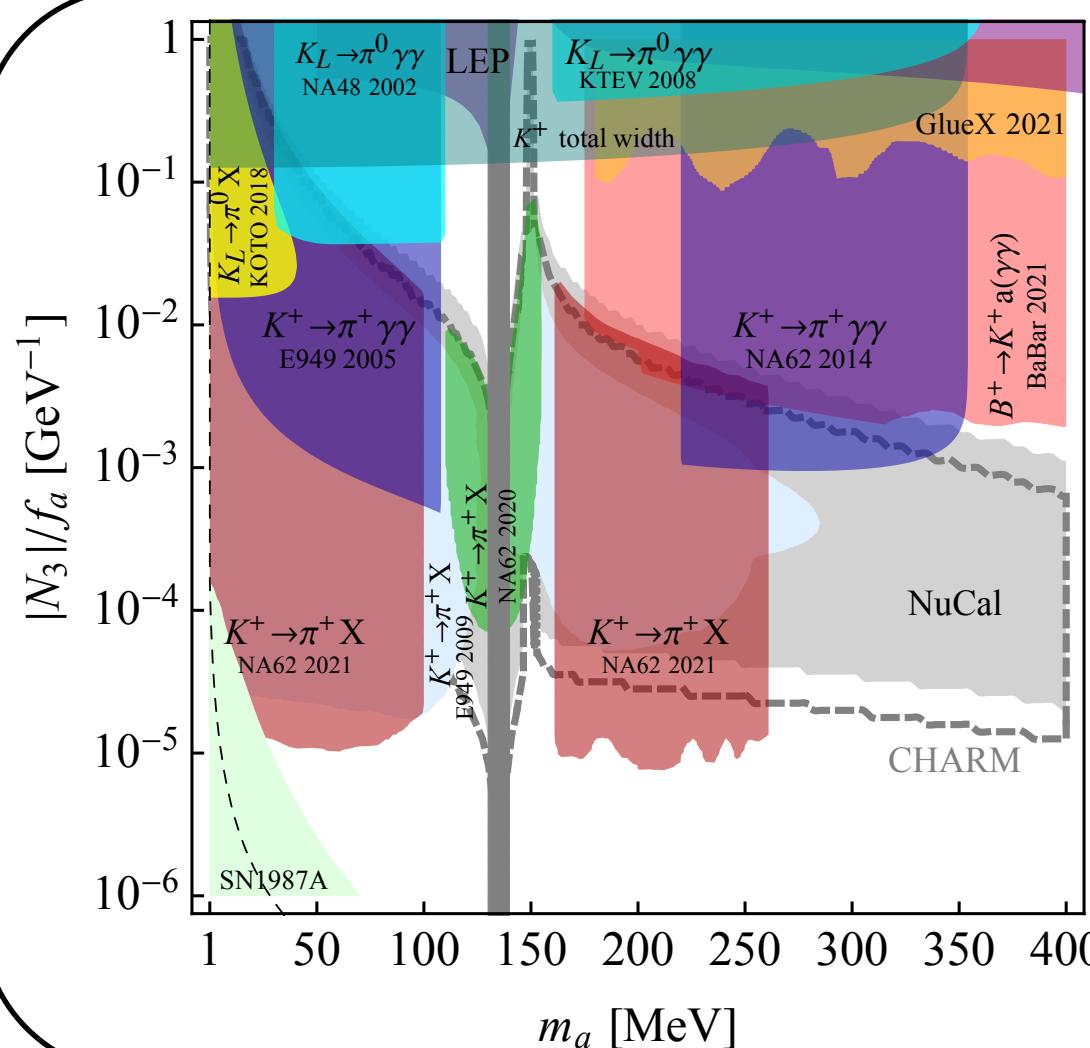
$$(b) \frac{\alpha_2 N_2}{8\pi f_a} a W \tilde{W}$$

+two benchmarks(c,d)

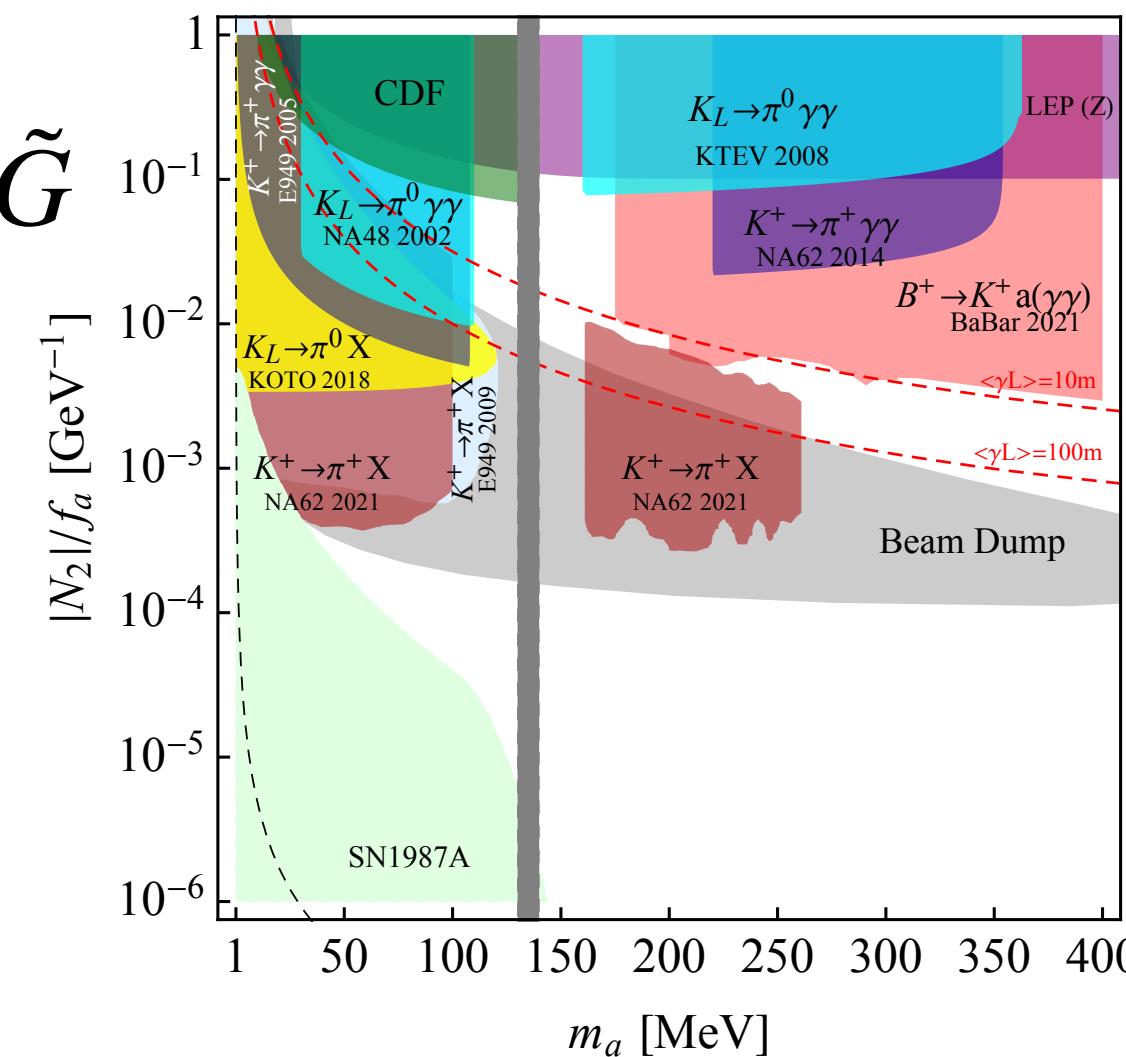


# Axion like particles w/o flavor violation

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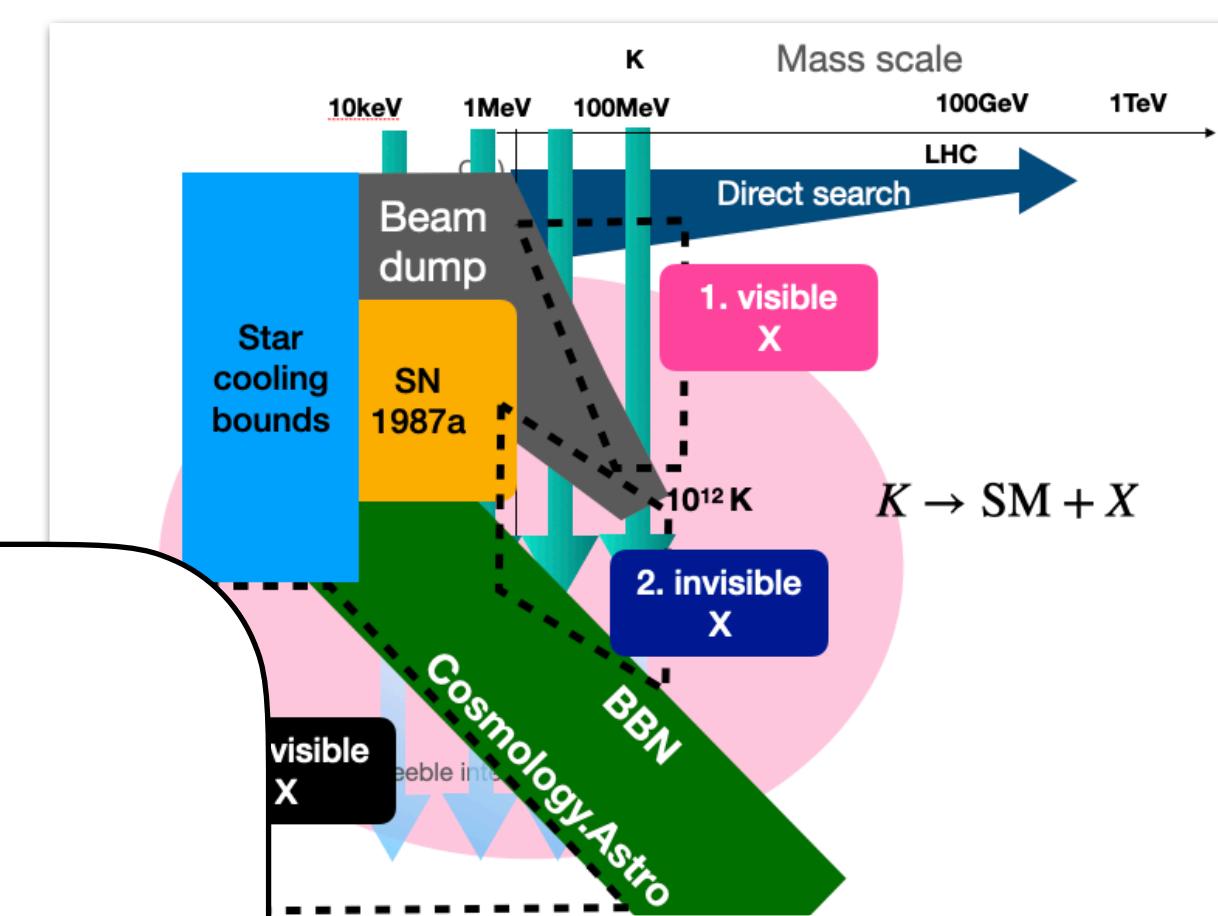


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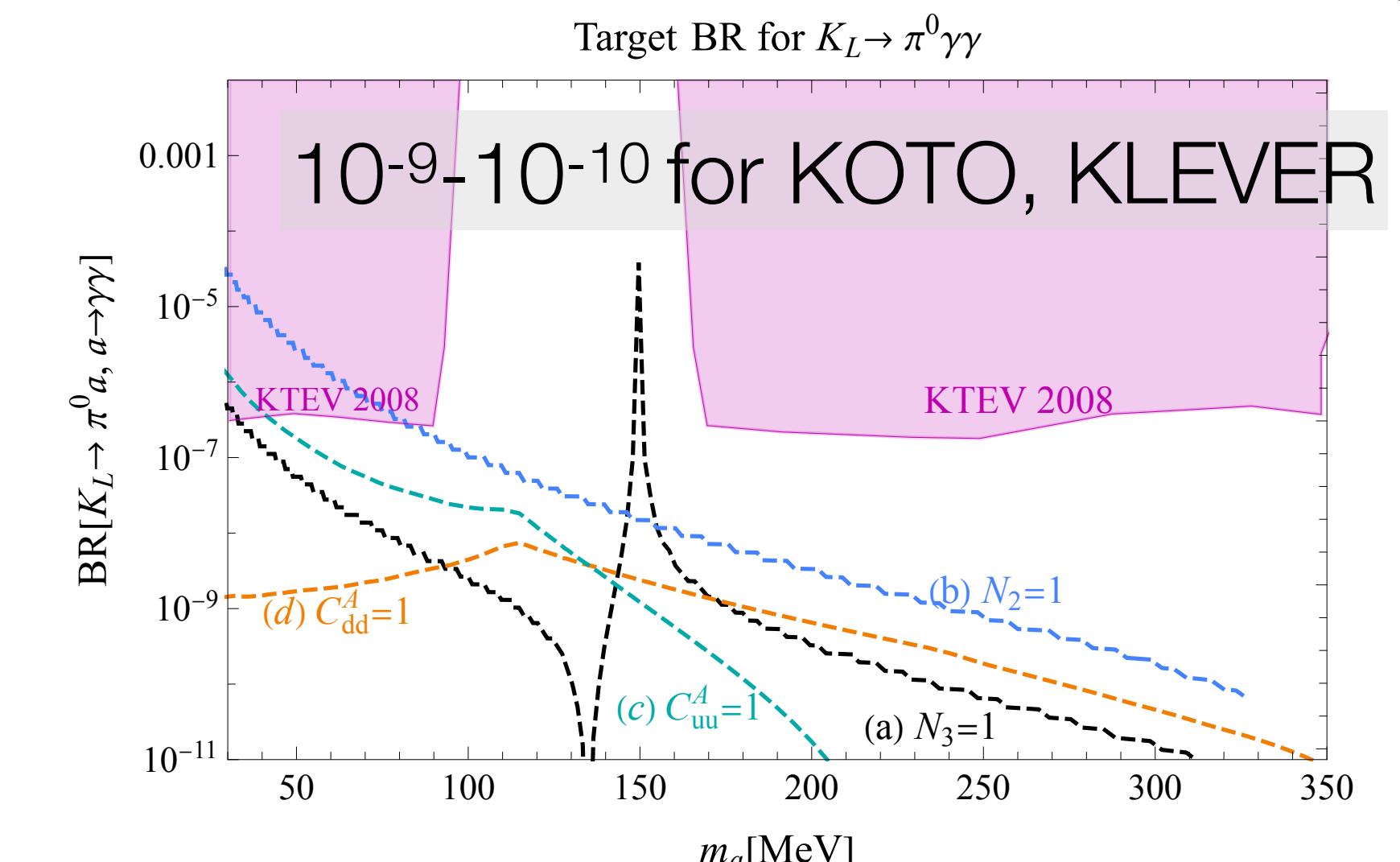
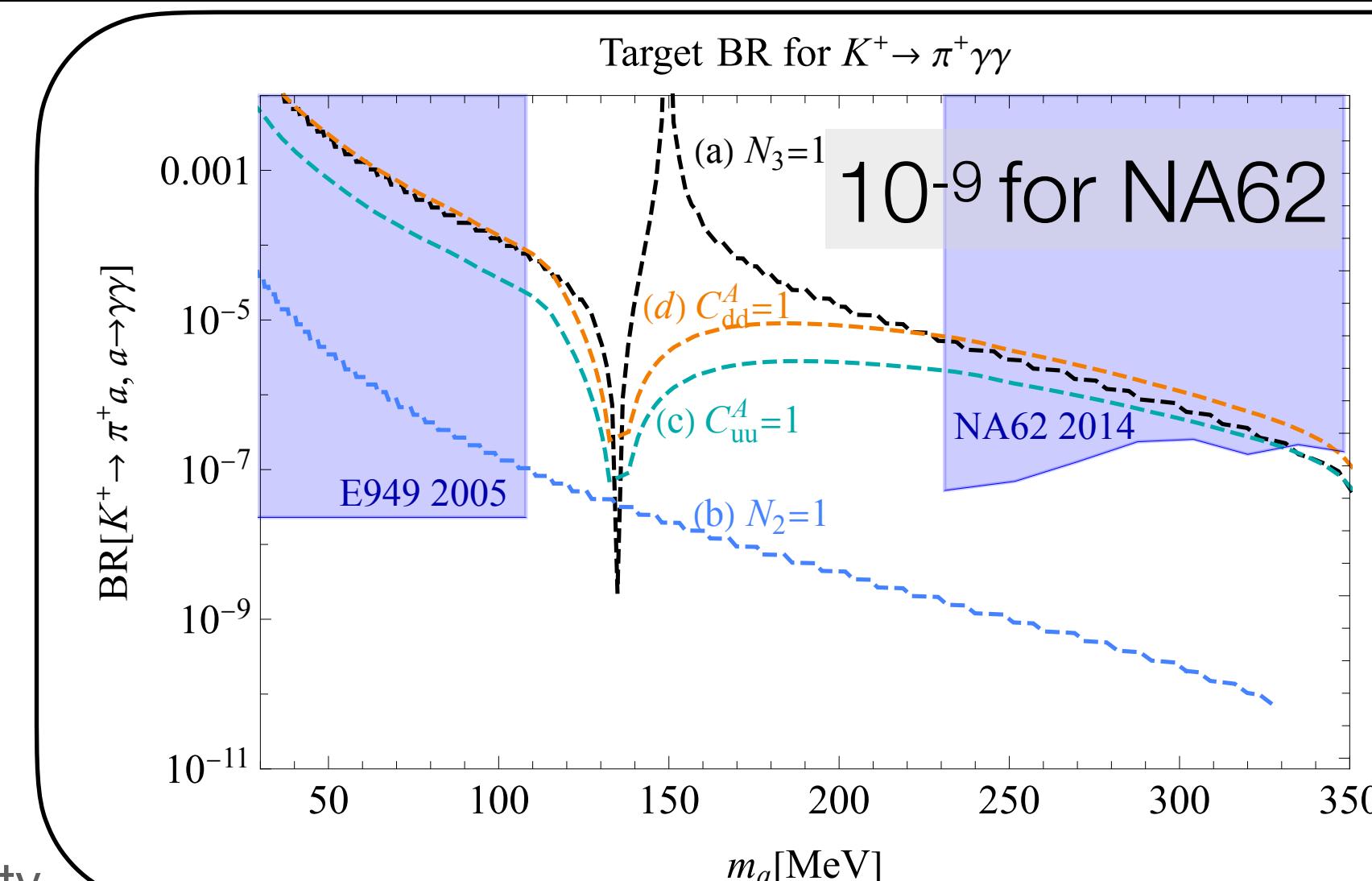
$$(b) \frac{\alpha_2 N_2}{8\pi f_a} a W \tilde{W}$$

+two benchmarks(c,d)



Target BR( $K \rightarrow \pi \gamma \gamma$ )  
set by beam dump exp.

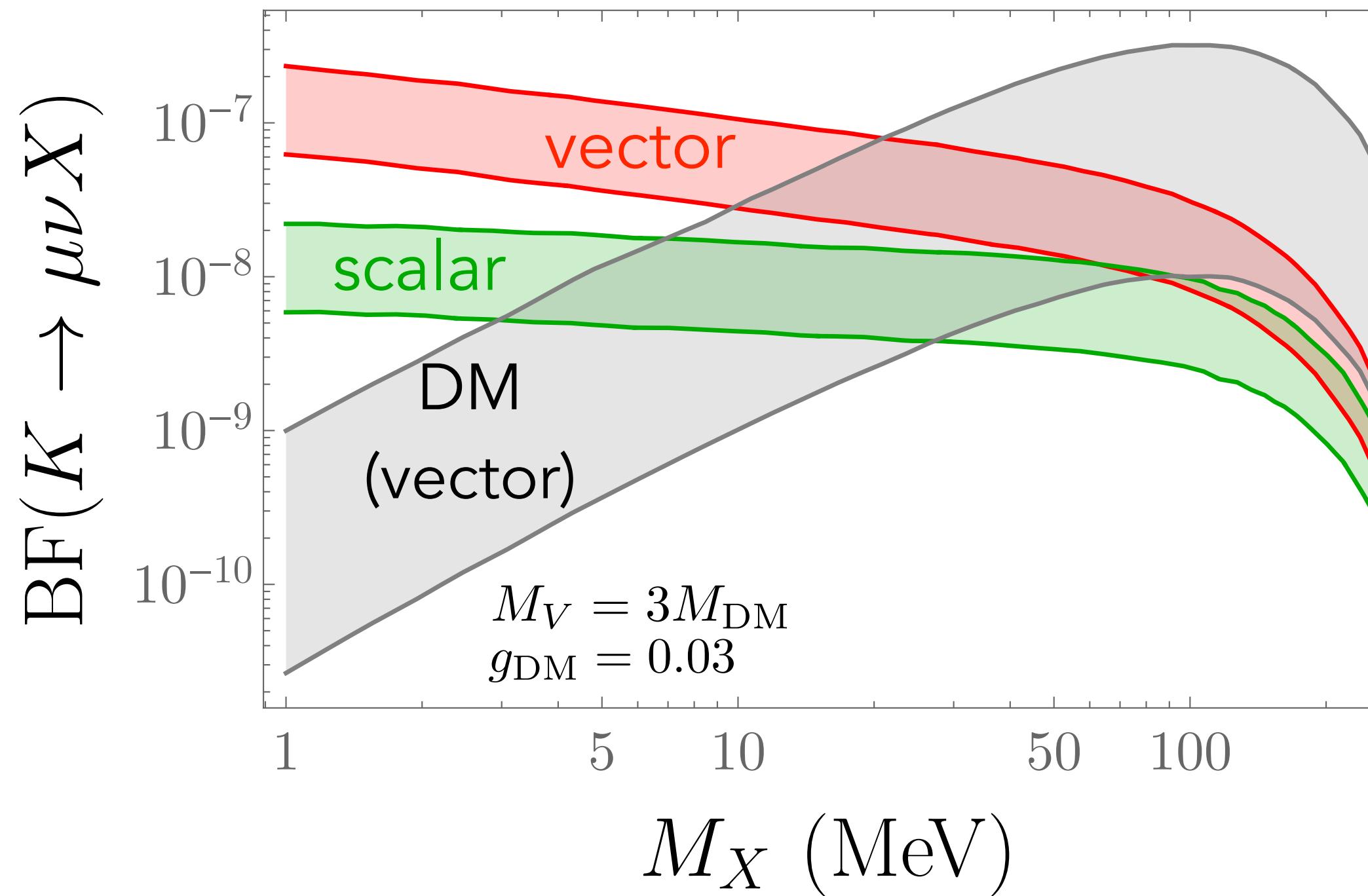
Similar study for  $K \rightarrow \pi^{+/-}$



# Leptonic force, Heavy Neutral Lepton, Higgs Portal

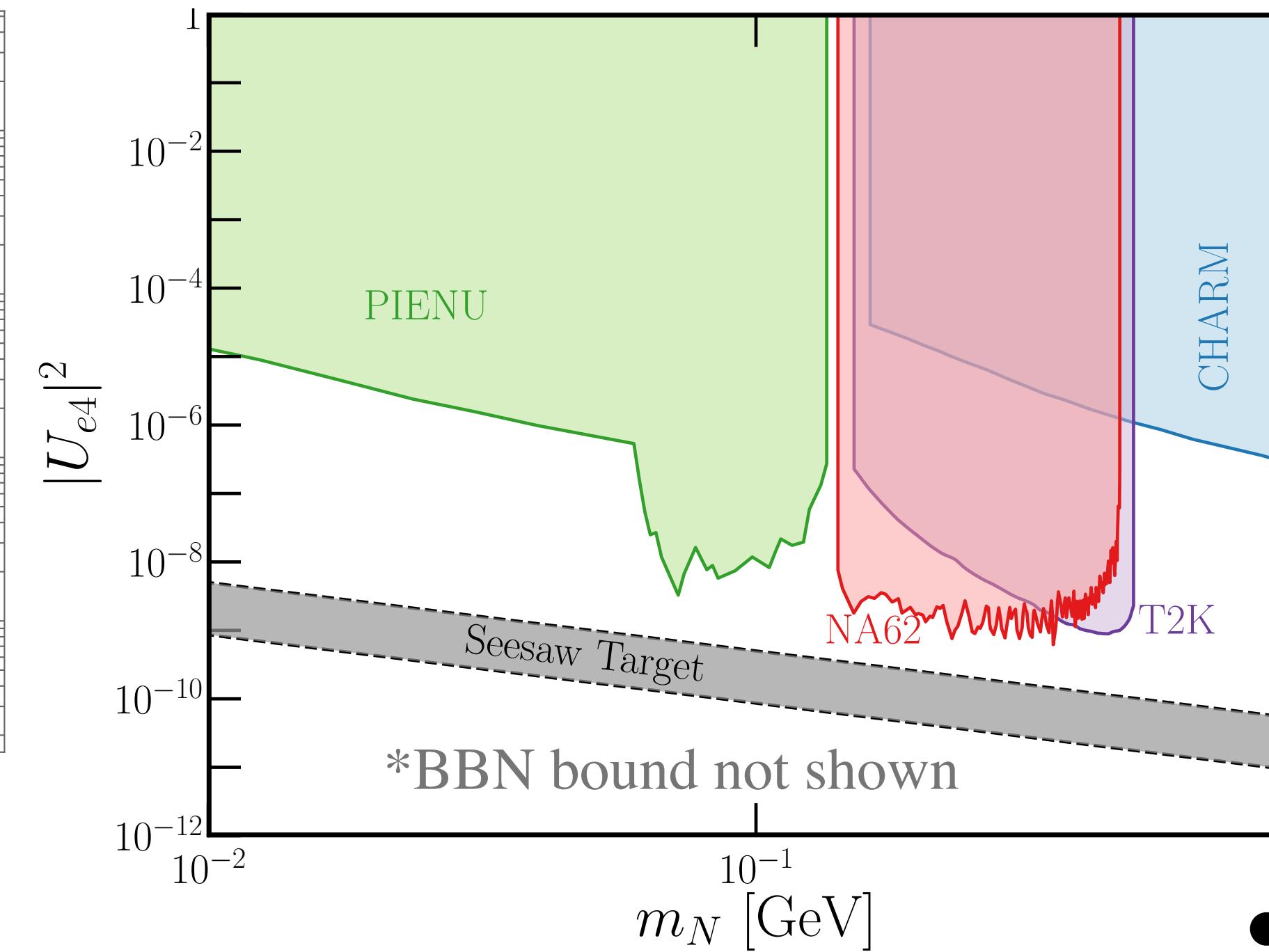
## 2. Invisible X region

- Leptonic force  
g-2 target, light DM (H0 problem)

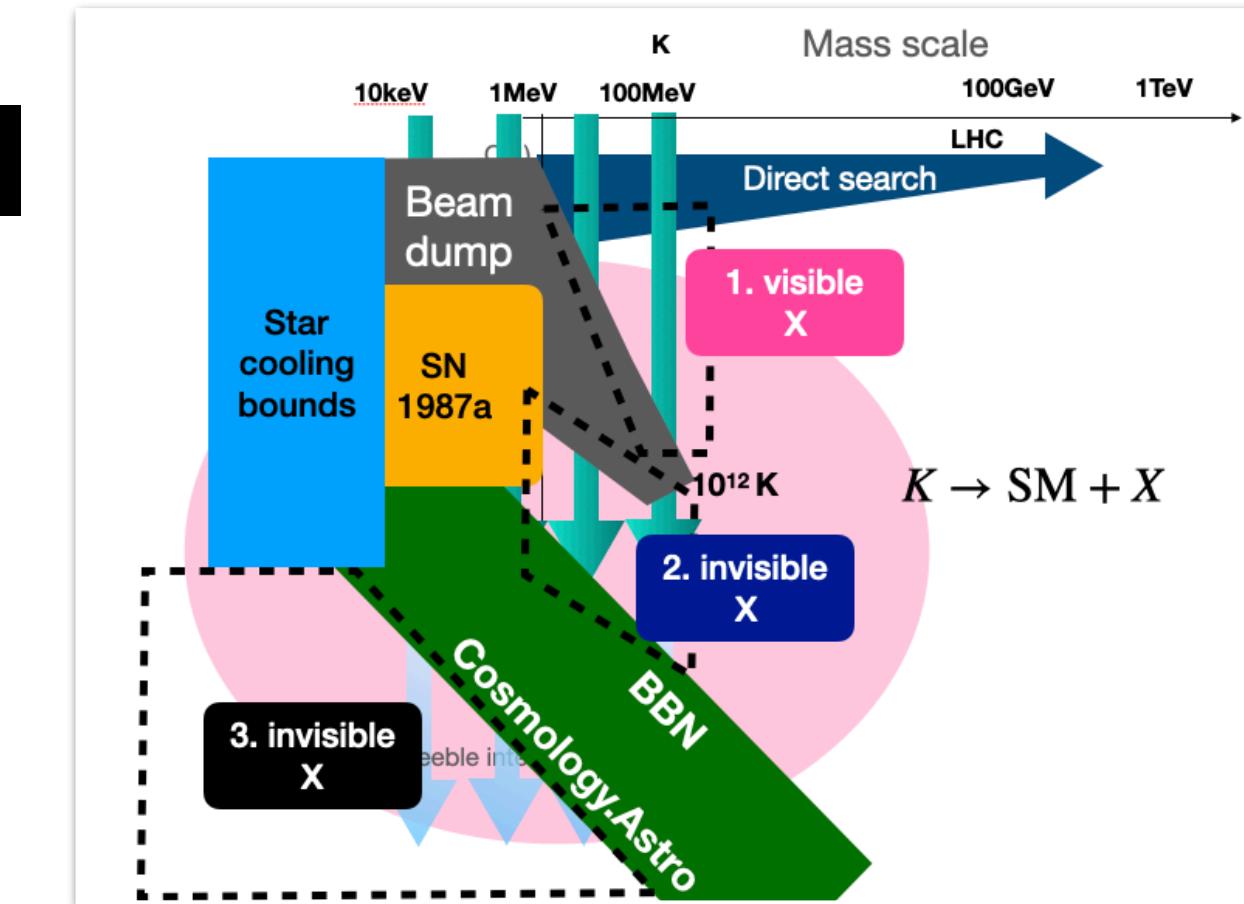


- $\text{BR}(K^+ \rightarrow \mu^+ \nu X) \sim 10^{-9} (10^{-7})$   
[currently  $10^{-7}$ ]

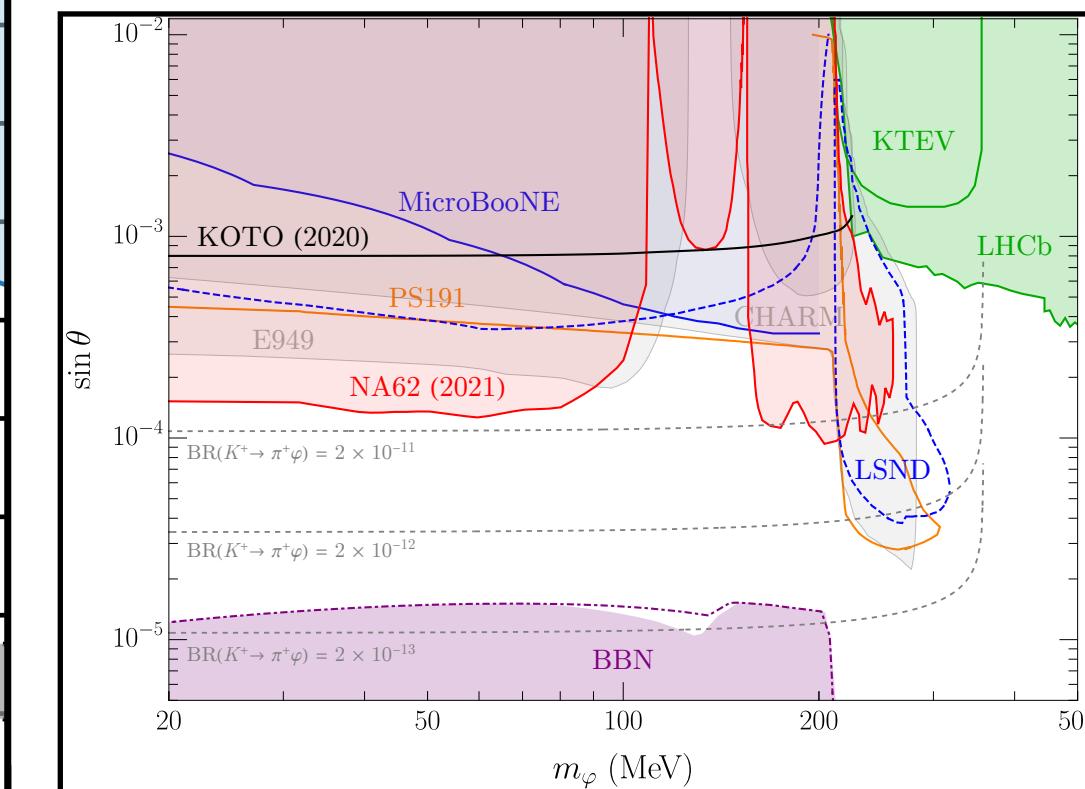
- HNL. neutrino mass  
with type I seesaw



- $\text{BR}(K^+ \rightarrow e^+ X) \sim 10^{-10}$   
[currently  $10^{-9}$ ]



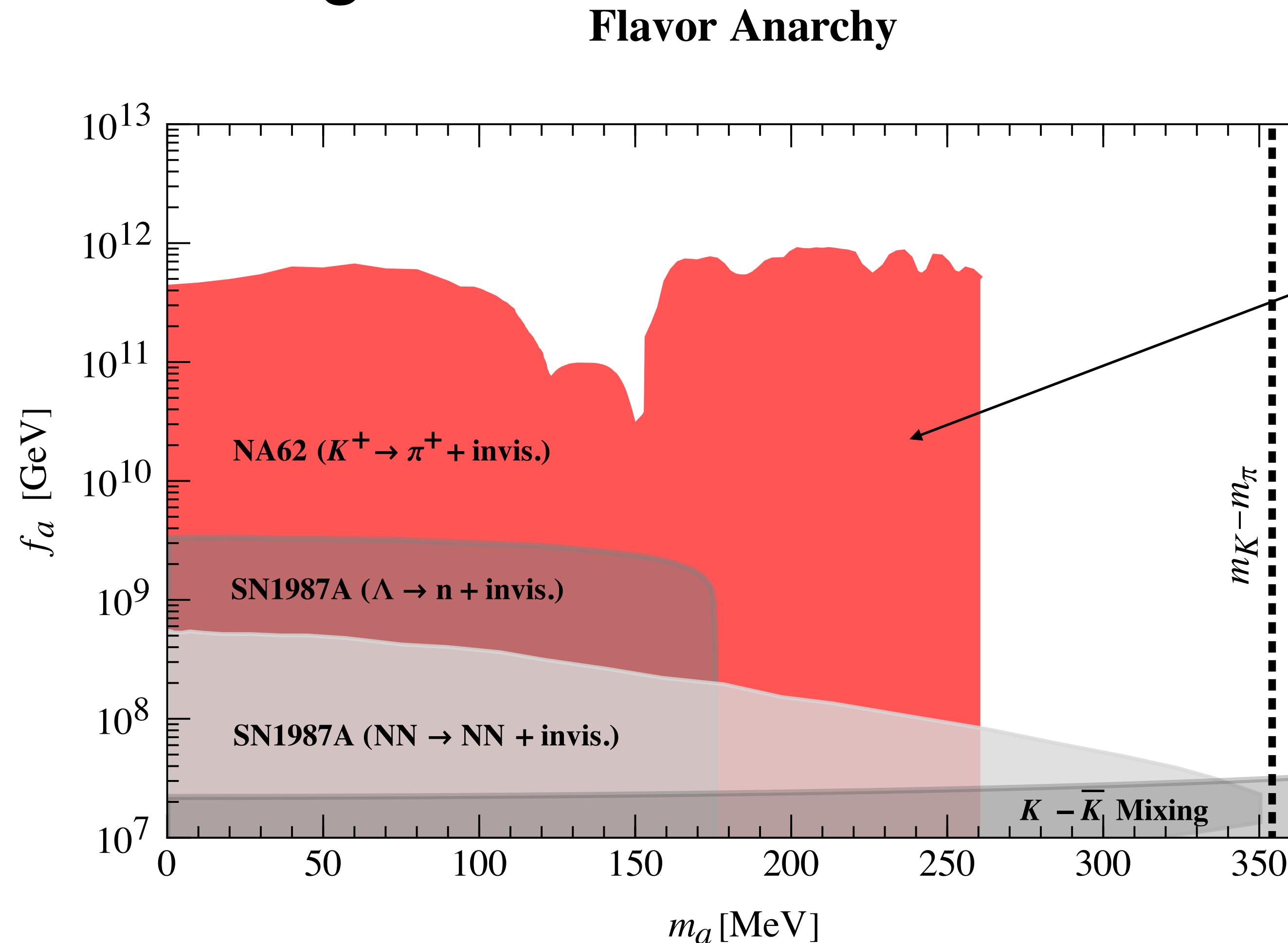
- Higgs portal  
vs BBN



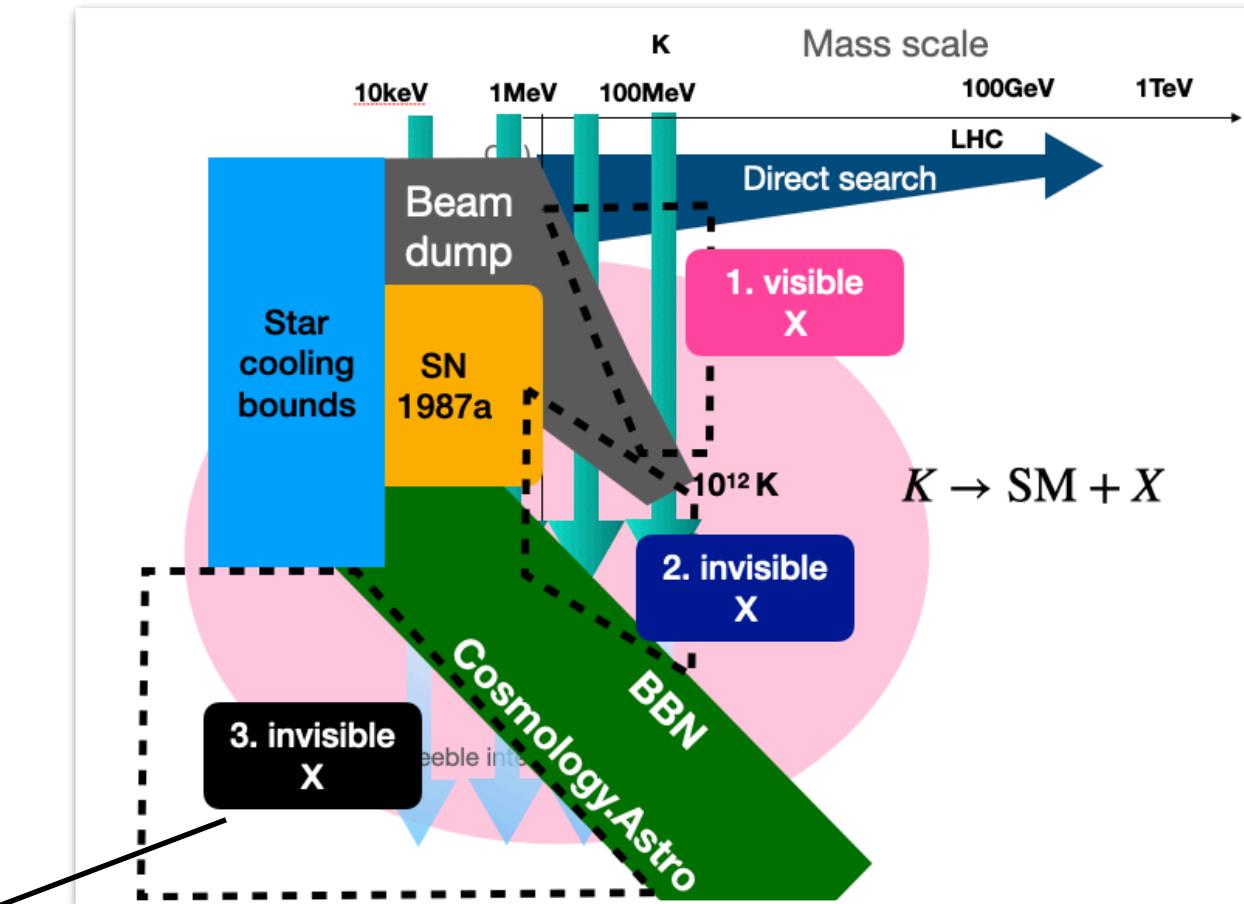
- $\text{BR}(K^+(K_L) \rightarrow \pi^+(\pi^0)X) > 10^{-10} (-9)$   
[kaon>beam dump exp]

# QCD axion w/ flavor violation

## 3. invisible X region



- QCD axion with generic quark coupling,  $K \rightarrow \pi X(\text{inv})$  is the best probe >> SN, BBN
- Improve as much as possible.



# Dark photon w/ $\Delta S=1$ dipole operator

## Signatures across $K^+$ , $K_L$ , and hyperons

- Beyond kinetic mixing, UV physics can generate dipole operator w/  $s \rightarrow d$

$$\mathcal{L}_{\text{dim-5}} = \frac{1}{\Lambda} \bar{\psi}_i \sigma^{\mu\nu} \left( \mathbb{D}_M^{ij} + i \mathbb{D}_E^{ij} \gamma_5 \right) \psi_j F'_{\mu\nu}$$

allowed by kaon mixing (allowed by SN for  $m_{A'} < 1 \text{ MeV}$ )

Kaons		Hyperons	
Decay mode	Max branching ratio	Decay mode	Max branching ratio
$K^+ \rightarrow \pi^+ \pi^0 A'$	$1.3 \times 10^{-7}$ ( $7.8 \times 10^{-11}$ )	$\Lambda \rightarrow n A'$	$1.4 \times 10^{-5}$ ( $8.0 \times 10^{-9}$ )
$K^+ \rightarrow \pi^+ \gamma A'$	$3.2 \times 10^{-8}$ ( $1.9 \times 10^{-11}$ )	$\Sigma^+ \rightarrow p A'$	$8.3 \times 10^{-7}$ ( $4.9 \times 10^{-10}$ )
$K_L \rightarrow \pi^0 \gamma A'$	$5.9 \times 10^{-8}$ ( $3.4 \times 10^{-11}$ )	$\Xi^0 \rightarrow \Sigma^0 A'$	$5.2 \times 10^{-6}$ ( $3.0 \times 10^{-9}$ )
$K_L \rightarrow \pi^+ \pi^- A'$	$5.6 \times 10^{-7}$ ( $3.2 \times 10^{-10}$ )	$\Xi^0 \rightarrow \Lambda A'$	$2.4 \times 10^{-6}$ ( $1.4 \times 10^{-9}$ )
$K_L \rightarrow \gamma A'$	$6.8 \times 10^{-5}$ ( $4.0 \times 10^{-8}$ )	$\Xi^- \rightarrow \Sigma^- A'$	$6.1 \times 10^{-6}$ ( $3.6 \times 10^{-9}$ )
$K_L \rightarrow \text{inv.}$	$1 \times 10^{-4}$ ( $6.5 \times 10^{-10}$ )	$\Omega^- \rightarrow \Sigma^- A'$	$6.1 \times 10^{-5}$ ( $3.6 \times 10^{-8}$ )

Table 1: Upper bounds on the branching ratios for different radiative kaon and hyperon decay channels using the maximal  $s \rightarrow d A'$  dipole transition allowed by  $\Delta M_K$  from kaon mixing. If the stronger SN constraints apply, the maximal branching ratios are those listed in the parentheses. For the hadronic inputs we have used [190].

# Summary

- Light new particles are interesting physics cases.
- Precision measurements → EFT → New Physics, won't work for light particles.  
Model dependent approach needed.
- Kaon/hyperon is unique playground complementary to astrophysics, cosmology, and beam-dump experiments.
- The contributed paper gives comprehensive overview between models and signatures.
- The paper will serve as input for planning current and future strategies for the kaon/Hyperon experiment.

**Thank you!**

# What to look for?

Can be more efficient than case-by-case

Model1	common prediction	$X \rightarrow \text{inv}$	(Model1,2)
Model2	$K \rightarrow \pi X$	$X \rightarrow \gamma\gamma$	(Model1, 3)
Model3 ...			

	parent kaon	detectable objects	$X \rightarrow \text{inv}$ (Higgs portal, ALP, dark)	$X \rightarrow \gamma\gamma$ (ALP)	Only $K^0 \rightarrow \pi X$	...
NA62	$K^+$	charged SM, $\gamma$	ongoing	possible	NA	
KOTO	$K^0 L$	$\gamma$	ongoing	possible	possible	
LHCb	$K^0 S$	charged SM, $\gamma$	possible?	possible?	possible	
...	Hyperon	...				

# (Proposed) Channel → Models to be probed

Model ↓

Possible signatures

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4.1 $K \rightarrow \pi + \text{inv}$	✓	✓	—	✓	—	✓	✓	✓	—	—	✓
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4.3 $K \rightarrow \pi\gamma + \text{inv}$	possible in extensions	possible in extensions	—	✓ even massless	—	—	—	—	—	—	—
4.4 $K \rightarrow 2\pi\gamma + \text{inv}$	—	—	—	$\pi^0 \rightarrow \gamma A'$	—	—	—	—	—	possible	—
4.5 $K \rightarrow \pi\gamma\gamma$	negligible (✓ dilaton)	✓ prompt	—	—	—	—	—	lifetime loophole	—	—	—
4.6 $K \rightarrow \pi\ell_\alpha\ell_\alpha$	✓ prompt	✓ prompt	—	✓	—	—	—	lifetime loophole	—	—	—
4.7 $K \rightarrow \pi\pi\ell_\alpha\ell_\alpha$	CP viol.	axial coupl. & prompt	—	✓	—	—	—	—	—	—	—
4.8 $K \rightarrow \pi\ell_\alpha\ell_\alpha\ell_\beta\ell_\beta$	—	—	—	—	—	—	—	$A'$ , MeV axion, also $K \rightarrow \pi 2\ell_\alpha 2\ell_\beta \text{inv}$	—	—	—
4.9 $K_L \rightarrow \gamma + \text{inv}$	—	—	—	✓	—	—	—	—	—	—	—
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4.12 $K_{S,L} \rightarrow \ell^+\ell^- + \text{inv}$	—	—	—	—	—	—	possible	possible	—	—	$K_S \rightarrow \mu\mu$
4.12 $K_{S,L} \rightarrow 2\ell 2\gamma$	—	—	—	—	—	—	possible	possible	—	—	—
4.13 $K^0 \rightarrow 4\ell$	—	—	—	—	—	—	possible	possible	—	—	—
4.14 $K^+ \rightarrow \ell^+ + \text{inv}$	—	—	✓	—	✓ ( $X \rightarrow \text{inv}$ )	✓	—	—	—	—	—
4.15 $K^+ \rightarrow 3\ell + \text{inv}$	—	—	possible	—	✓ ( $X \rightarrow \ell\ell$ )	—	—	$U(1)+\text{HNL}$	—	—	—
4.16 $K^+ \rightarrow \ell\gamma\gamma + \text{inv}$	—	—	$K^+ \rightarrow \pi^0\ell^+ N$ ( $m_N \lesssim 20 \text{ MeV}$ )	—	possible ( $X \rightarrow 2\gamma$ )	possible	—	possible	—	—	—
4.17 LFV	—	—	—	—	—	—	—	—	—	FV ALP, $Z'$	FV ALP
4.18 LNV	—	—	✓ ( $K^+ \rightarrow \ell^+ N$ , $N \rightarrow \pi^-\ell^+$ )	—	—	—	—	—	—	—	✓ (Maj. HNL)
4.19 Rare $K_S$ decays	$K_S \rightarrow \pi(\pi)2\ell$ $\rightarrow \pi(\pi)2\gamma$	$K_S \rightarrow \pi(\pi)2\ell$ $\rightarrow \pi(\pi)2\gamma$	—	$K_S \rightarrow A'\gamma$ $\rightarrow A'\gamma\pi$	—	—	—	$K_S \rightarrow 4\ell$	—	$K_S \rightarrow 2\gamma + \text{inv}$	$K_S \rightarrow \mu\mu$
4.20 Dark Shower	—	—	—	—	—	—	—	—	—	✓	—
5 Hyperon	$B_1 \rightarrow B_2\varphi$	Table 8	$B_1 \rightarrow B_2a$	—	Table 1	—	—	—	Table 4	$B \rightarrow \gamma/M + \text{inv}$	—

ongoing

possible

maybe future

difficult

unknown