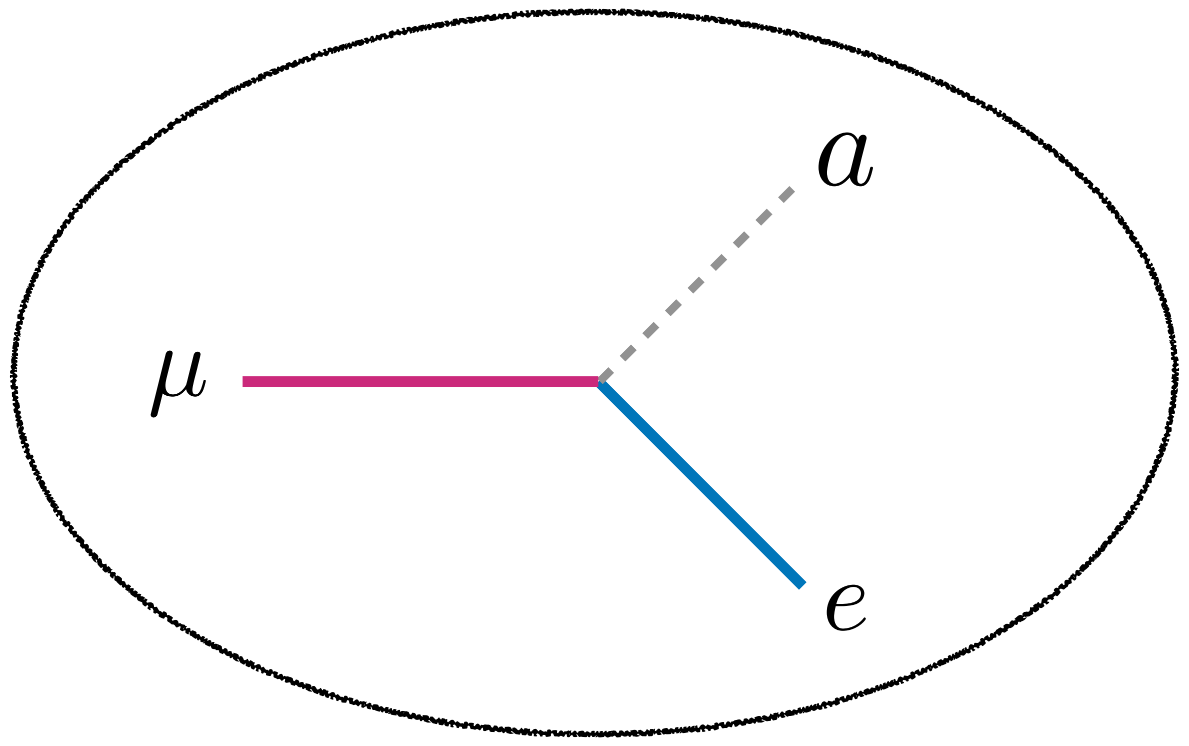
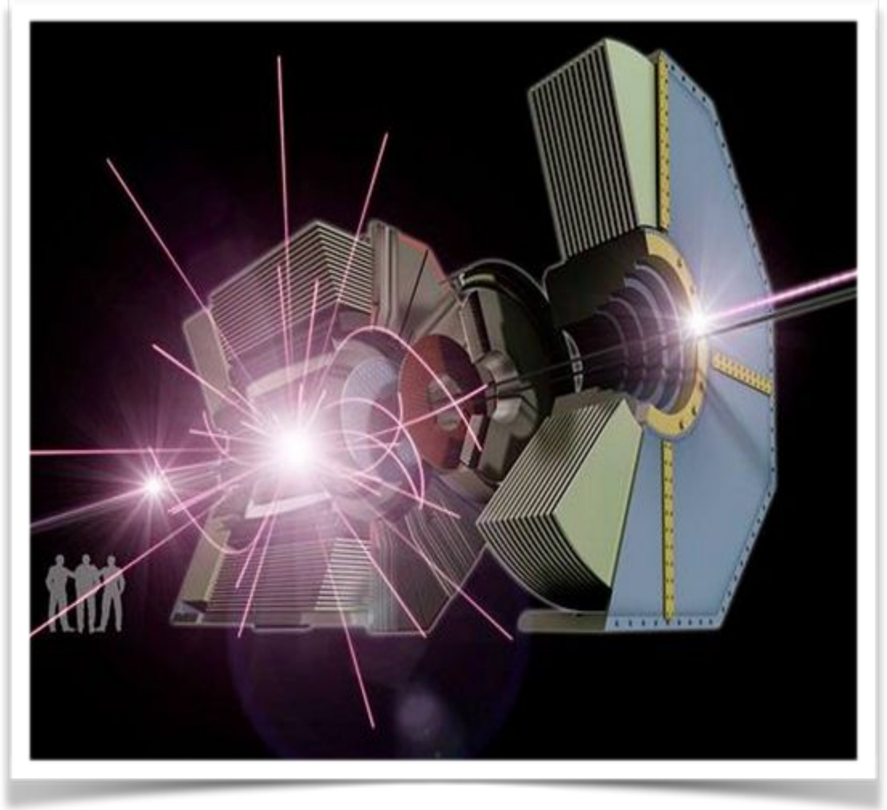
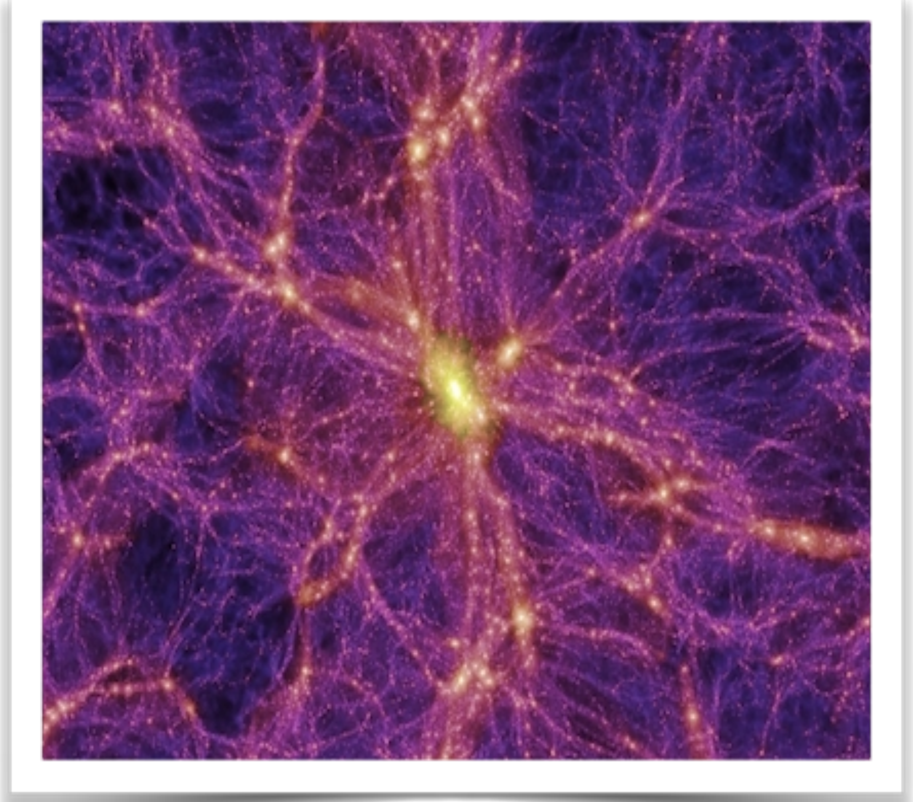
Flavor Probes of Axion Dark Matter

Robert Ziegler




Flavor Factories

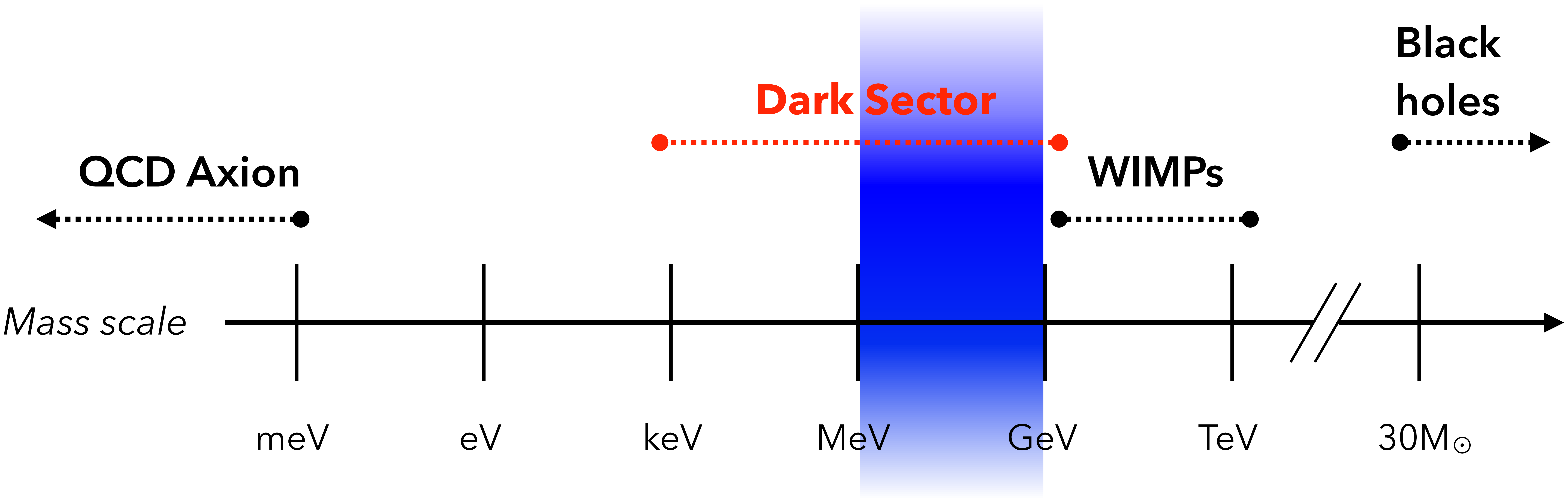

Supernovae


Early Universe

UNI FREIBURG

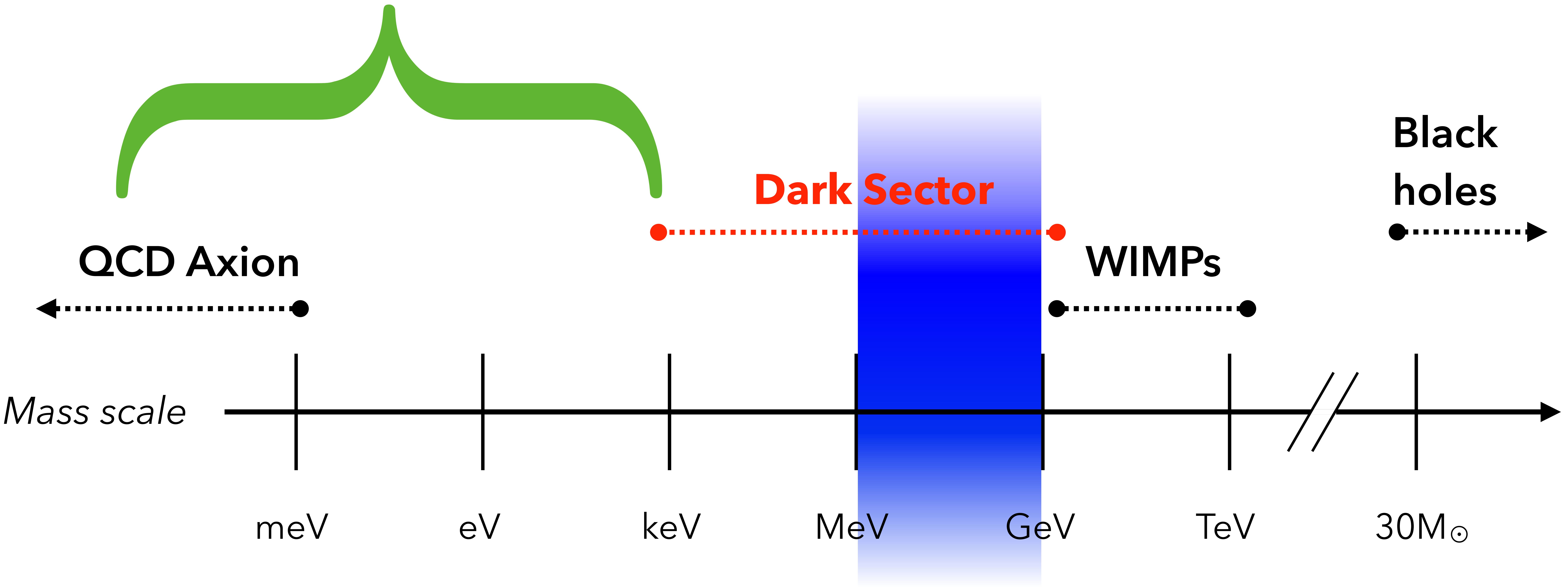
KIT Karlsruher Institut für Technologie

B factories can explore the Dark Sector



B factories can explore the Dark Sector

…and (QCD) Axion Dark Matter!



Axion Dark Matter

- Axions are excellent DM candidates

Pseudo-Goldstone bosons of PQ symmetry **broken at high scales**

light

naturally for **QCD axion**

$m_a f_a = m_\pi f_\pi$

which also solves Strong CP

decoupled

➡ **stable** on cosmological scales

$$1/\Gamma(a \to \gamma\gamma) \simeq 10^{12}\mathrm{yrs} \left(\frac{f_a}{10^9\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{keV}}{m_a}\right)^3$$

- Produced in early universe via misalignment, decays of topological defects, thermal freeze-out, thermal freeze-in, …

see talk by J. Jaeckel

Flavor-violating Axions

- Often ignored, but general axion couplings are flavor-violating!

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

proliferates parameters, but enriches phenomemology

- Allows for axion production from decays of SM particles

e.g. $\mu \to ea$ $\tau \to ea$ $K \to \pi a$ $\Lambda \to na$ $B \to \rho a$ $\cdots$

in precision flavor factories, SN1987A and early universe

↓ **direct searches** ↓ **star cooling** ↓ **freeze-in**

Theoretical Motivation

- Two possible sources of flavor-violating axion couplings

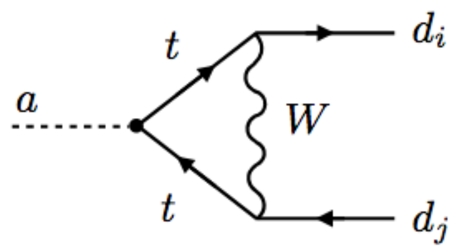
1) Tree-level misalignment of PQ charges and Yukawas $\left[Y_d Y_d^\dagger, \mathrm{PQ}_q\right] \neq 0$

➡ present in non-universal DFSZ models: couplings given by Yukawa misalignment

➡ predictive scenario when PQ = flavor symmetry addressing Yukawa hierarchies

e.g. PQ = FN: $C_{sd} \sim V_{us} \sim 0.2$ Calibbi, Goertz, Redigolo, RZ, Zupan ’16; Ema et al ’16; Wilczek ‘82

2) SM flavor violation from RG running Bauer et al ‘21



$$C_{sd} \sim \frac{y_t^2 V_{td} V_{ts} C_{tt}}{16\pi^2} \log \sim 10^{-5}$$

for light axions flavor constraints weaker than star cooling constraints from diagonal couplings 2201.07805

Axion Production in Flavor Factories

- Test flavor-violating couplings with **SM decays + missing energy**
  look like meson/lepton decays with neutrino pair, but 2-body

Quarks	SM background tiny	$\mathrm{BR}(K \to \pi\nu\bar{\nu}) \sim 10^{-10}$	
Leptons	SM background huge	$\mathrm{BR}(\mu \to e\nu\bar{\nu}) = 1$	[but can profit from polarization]

Experimental analyses of 2-body meson decays are rare ⟶ recast

e.g. no bound on $D \to \pi a, B \to K^* a, B \to \rho a$ no BaBar/Belle bound on $B \to K a, B \to \pi a$

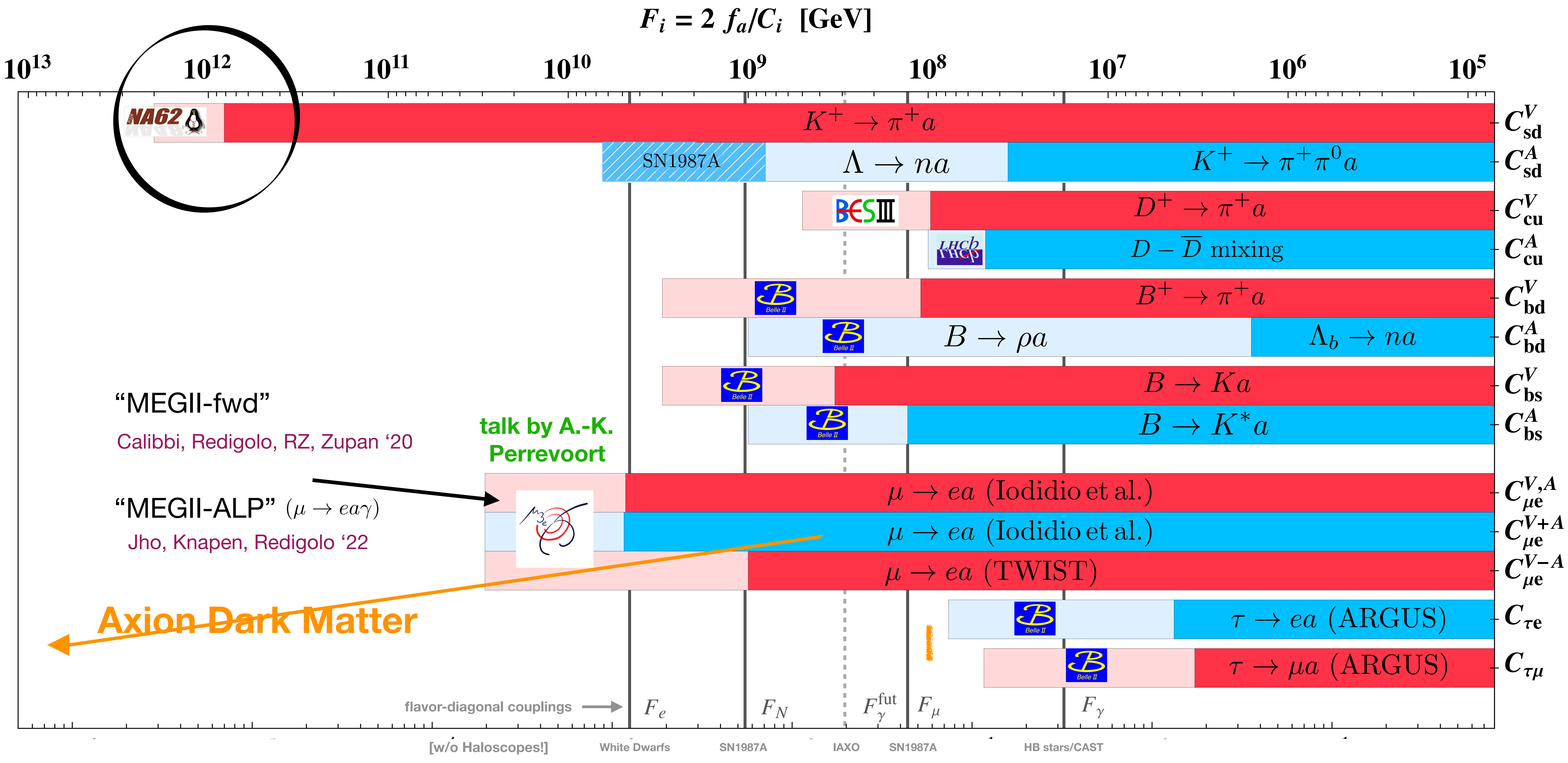
- 2-body decays probe **LARGE** NP scales [and typically more constraining than meson mixing]

$$\frac{\partial_\mu a}{f_a} \bar{b}\gamma^\mu s \xrightarrow{B \to K a} f_a \gtrsim 10^5 \text{ TeV}$$

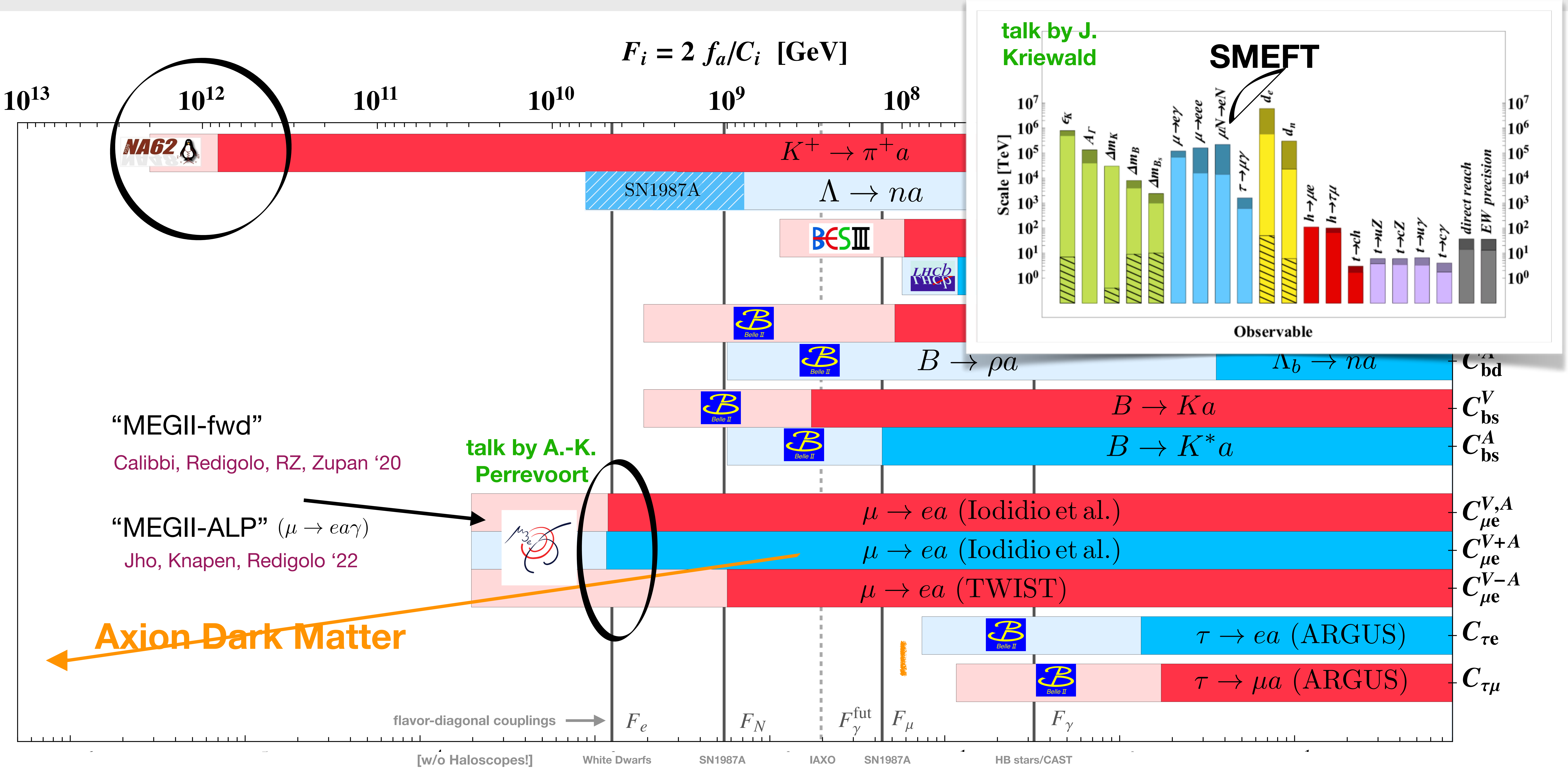
$$\xrightarrow{B_s - \text{mixing}} f_a \gtrsim 200 \text{ TeV}$$

$$\frac{1}{\Lambda^2}\left(\bar{b}\gamma^\mu s\right)\left(\bar{\nu}\gamma_\mu \nu\right) \xrightarrow{B \to K\nu\bar{\nu}} \Lambda \gtrsim 10 \text{ TeV}$$

Summary of present and future Constraints



Summary of present and future Constraints

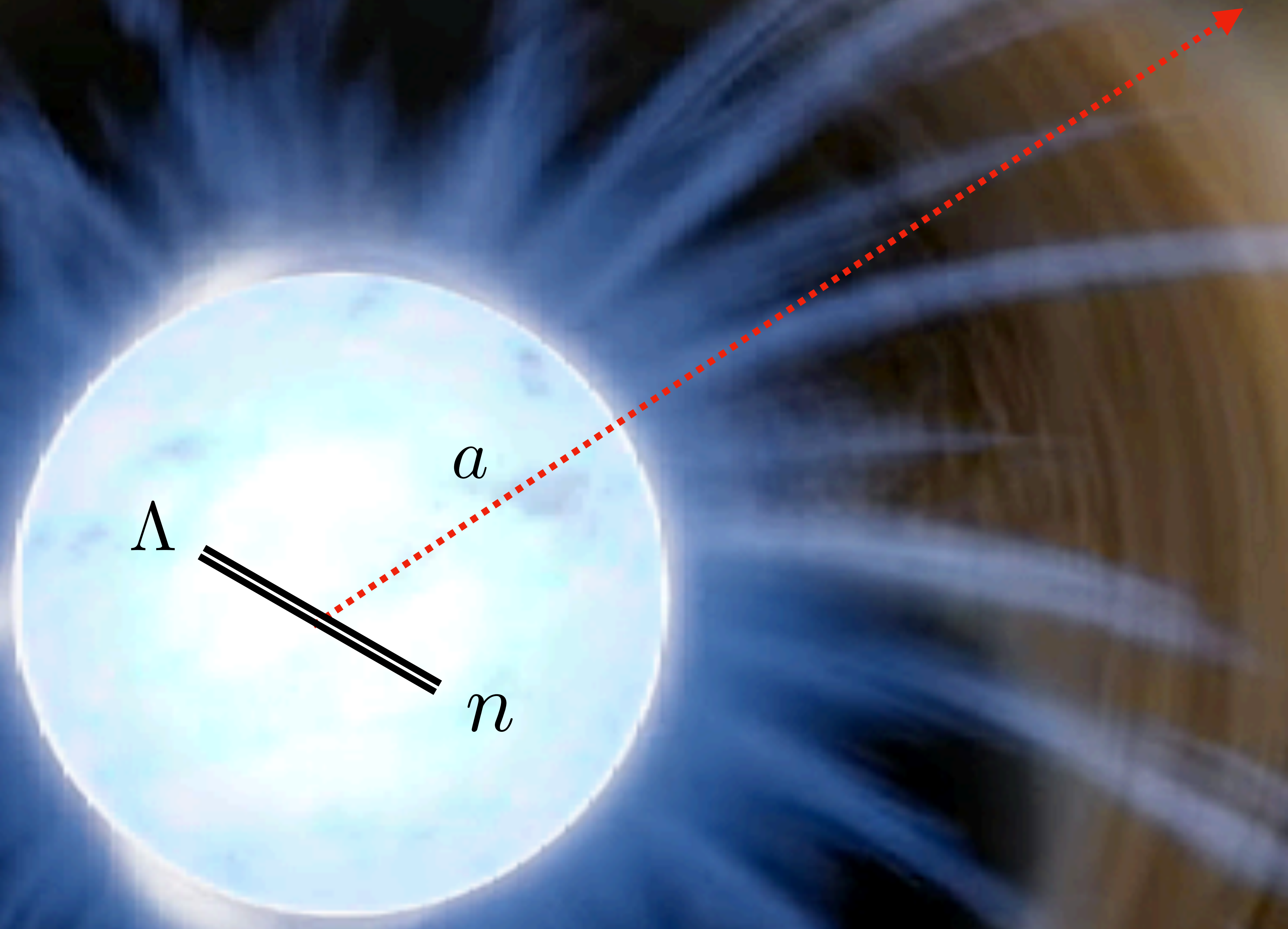


Constraints from SN1987A

Best handle on axial-vector coupling to s-d from hyperon decays

Many hyperons in hot proto-neutron star formed during core-collapse supernovae [T ≈ 40 MeV]

Hyperon decays to axions provide extra cooling which would have shorten observed neutrino pulse of SN1987A: limits energy loss rate



$$L_a \simeq \int_{\mathrm{PNS}} n_n (m_\Lambda - m_n) \Gamma(\Lambda \to n a) e^{-\frac{m_\Lambda - m_n}{T}} dV \leq 10^{52} \mathrm{erg/s}$$

Gives best bound on invisible hyperon decays:

[can do same for LFV muon decays, but weaker than lab bound]

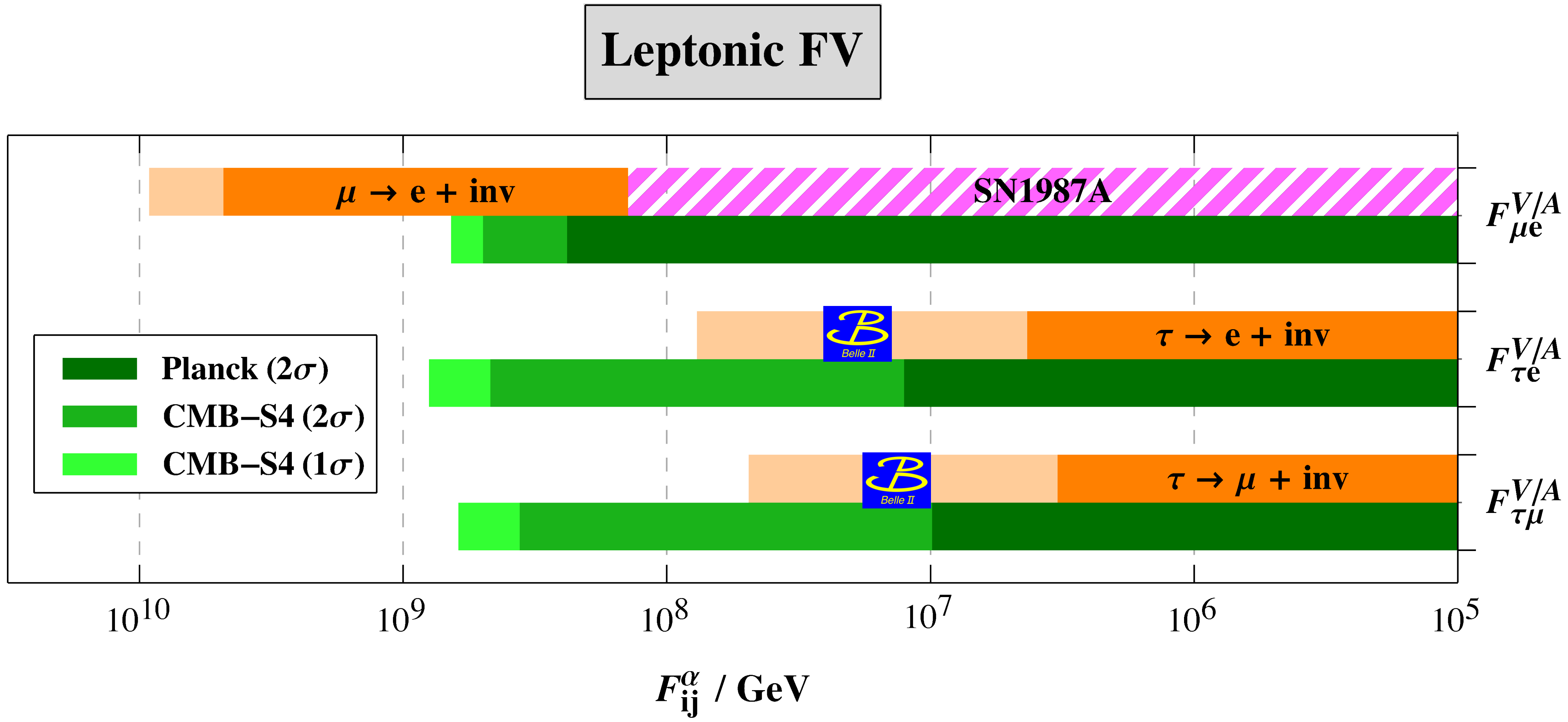
$$\mathrm{BR}(\Lambda \to n a) \lesssim 5.0 \times 10^{-9}$$

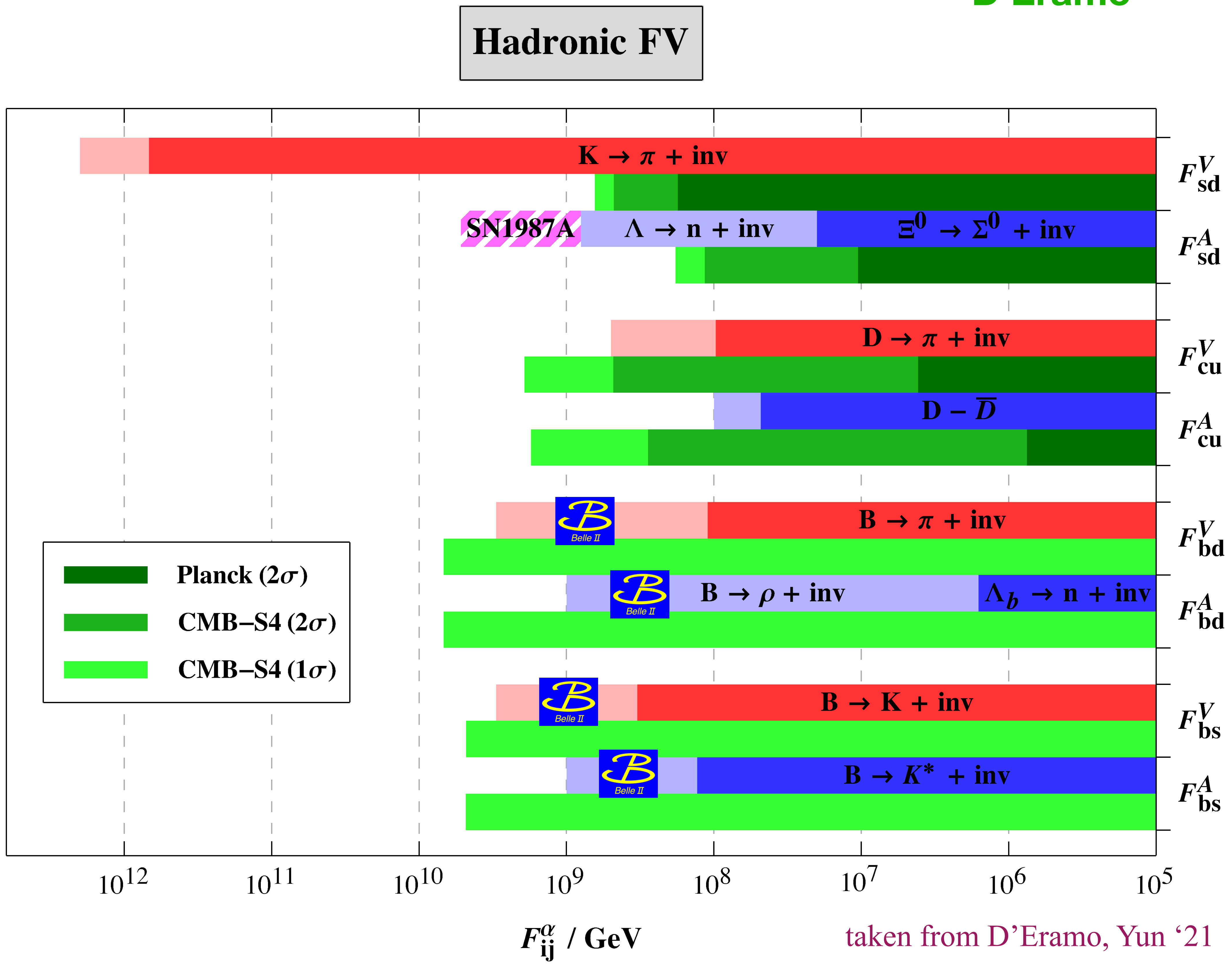
Martin Camalich, Terol-Calvo, Tolos, RZ ‘20

Constraints from Cosmology

- Flavor-violating SM decays produce hot axions in early universe very light axions constrained by bounds on Dark Radiation from CMB

talk by F. D'Eramo





taken from D'Eramo, Yun '21

Belle-II will compete with future CMB telescopes

Axion Dark Matter from SM Decays

- Use flavor-violating decays as main production of axion Dark Matter

LFV: 2209.03371, with P. Panci, D. Redigolo, T. Schwetz

abundance fixes decay rate: **get explicit targets for exp. searches**

DM Abundance

$$\Omega_a h^2 \propto m_a \Gamma(\ell_i \to \ell_j a) \propto m_a \frac{C_{ij}^2}{f_a^2} = \mathbf{0.12}$$

gives viable axion mass window

$$m_a^{\min} < m_a < m_a^{\max}$$

lab constraints & Warm Dark Matter ($m_a^{\min}$)

kinematic threshold ($m_a^{\max}$)

DM Stability

$$\Gamma(a \to \gamma\gamma) \propto \frac{m_a^3}{f_a^2} \left| E + N + C_{ii} \frac{m_a^2}{12 m_{\ell_i}^2} \right|^2 \lesssim \frac{\mathbf{1}}{\mathbf{10^{28} sec}}$$

X-ray telescopes

need anomaly-free PQ and light axion/heavy lepton/small diagonal coupling

Explicit LFV Scenarios

- Give leptons traceless PQ charges (two generations for simplicity)

$$\mathrm{PQ}_e = \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix}$$

rotation → in 1-2 plane

$$C^V_{e_i e_j} = C^A_{e_i e_j} = \begin{pmatrix} s_\alpha & c_\alpha & 0 \\ c_\alpha & -s_\alpha & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- Axion relic abundance dominantly arises from LFV decays (for small T_R)

$$\Omega h^2|_{\mu\to ea} \approx 0.19 \left(\frac{m_a}{20\,\mathrm{keV}}\right)\left(\frac{10^9\mathrm{GeV}}{f_a/\cos\alpha}\right)^2$$

IR freeze-in from LFV decays

IR freeze-in of $\mu\gamma \to ea$ $\quad \alpha_{\rm em}$

UV freeze-in of $\mu h \to ea$ $\quad \frac{m_\mu T_R}{3\pi^3 v^2}$

$\Big\} \times \Omega h^2|_{\mu\to ea}$

Misalignment reduced by $\frac{T_R}{T^{\rm std}_{\rm osc}}$ (matter domination)

- DM lifetime

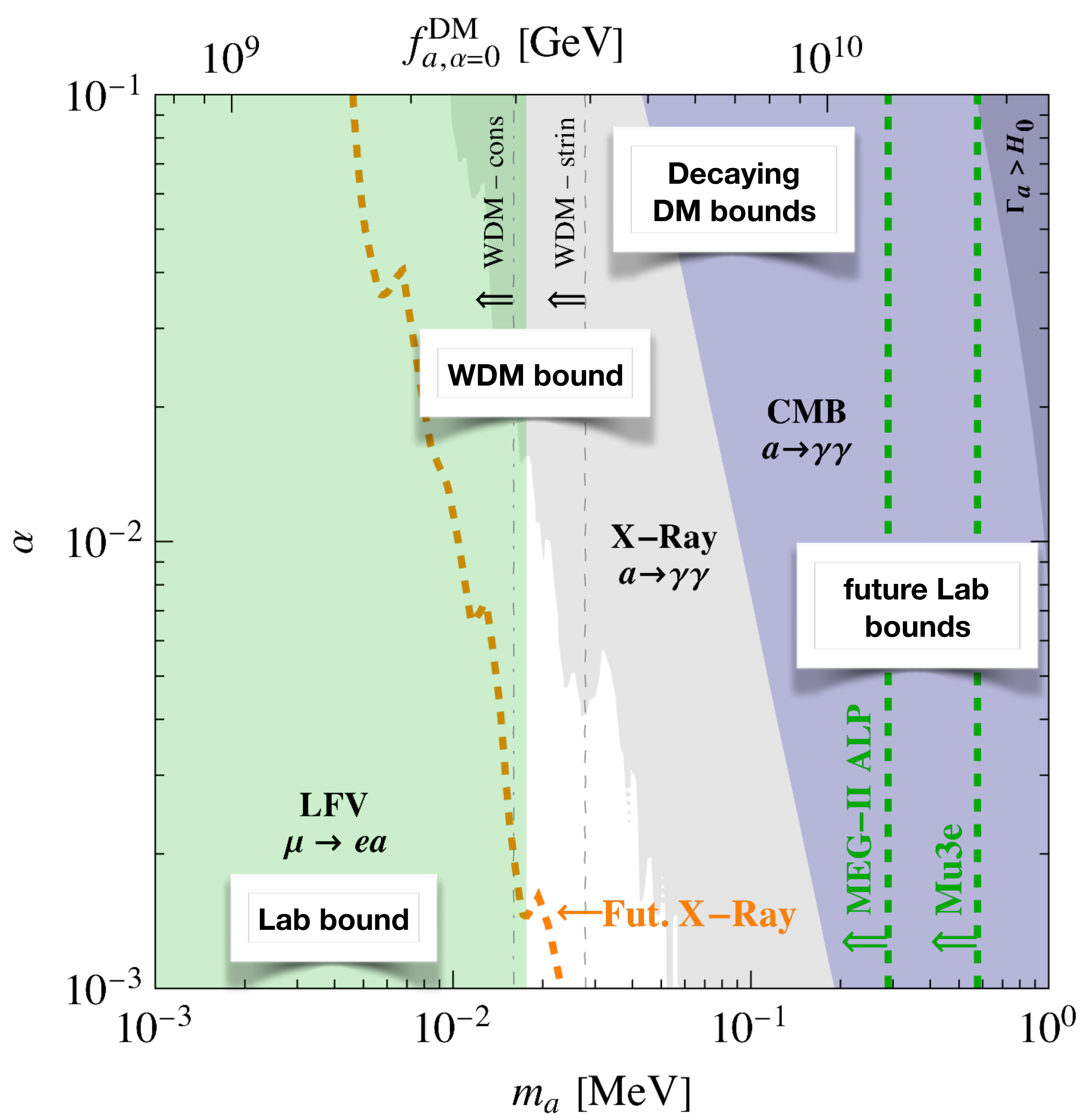
$$\tau_a = 10^{20}\mathrm{sec}\left(\frac{60\,\mathrm{keV}}{m_a}\right)^7\left(\frac{f_a/\sin\alpha}{10^9\mathrm{GeV}}\right)^2$$

Warm DM bound: $m_a \gtrsim 20\,\mathrm{keV}$

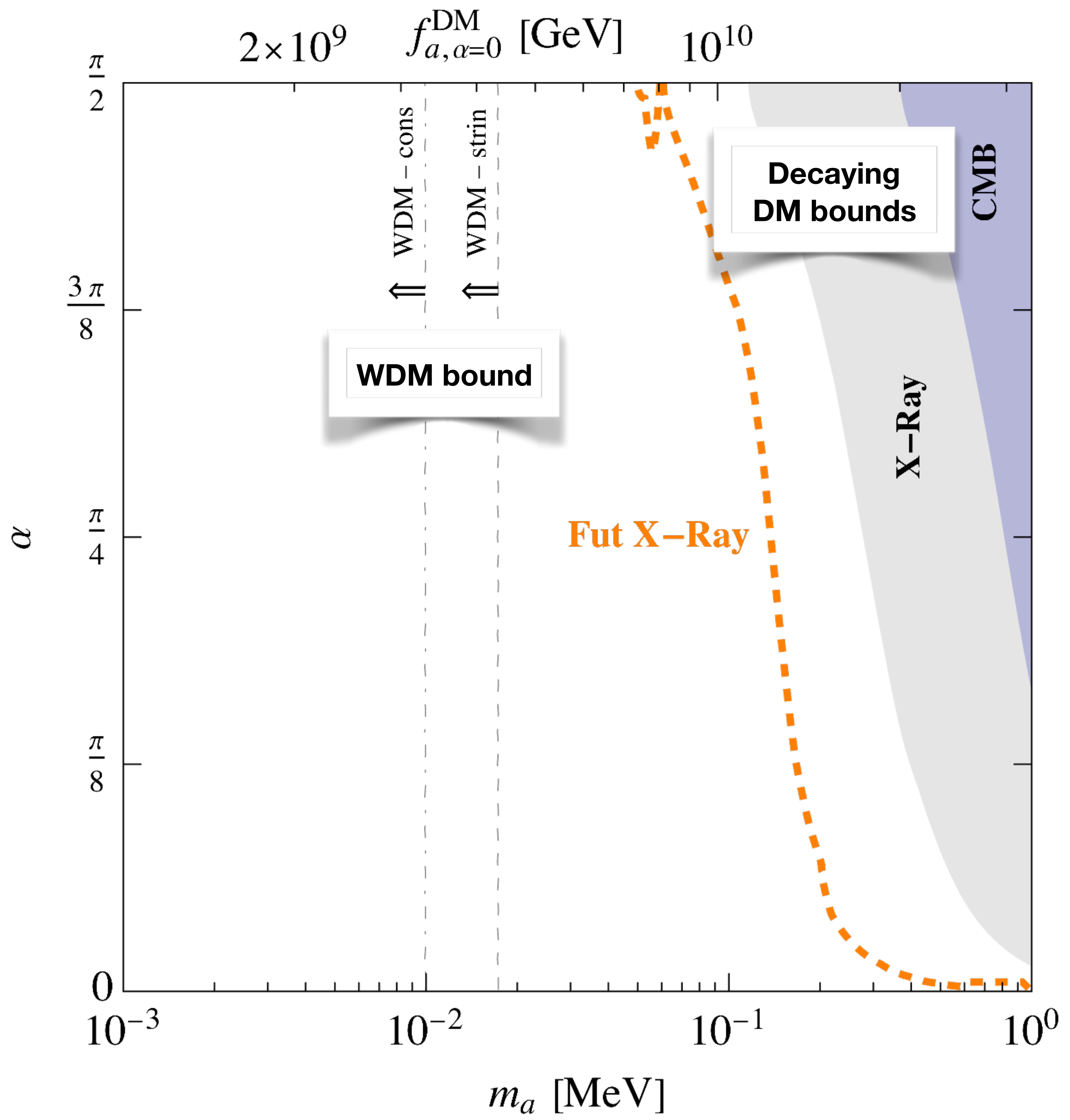
D'Eramo, Lenoci '20, Ballesteros et al '20, Decant et al '21

Results

μe-Scenario



$\tau\mu$-Scenario



Summary

DM Axions with flavor-violating couplings can be produced by SM decays

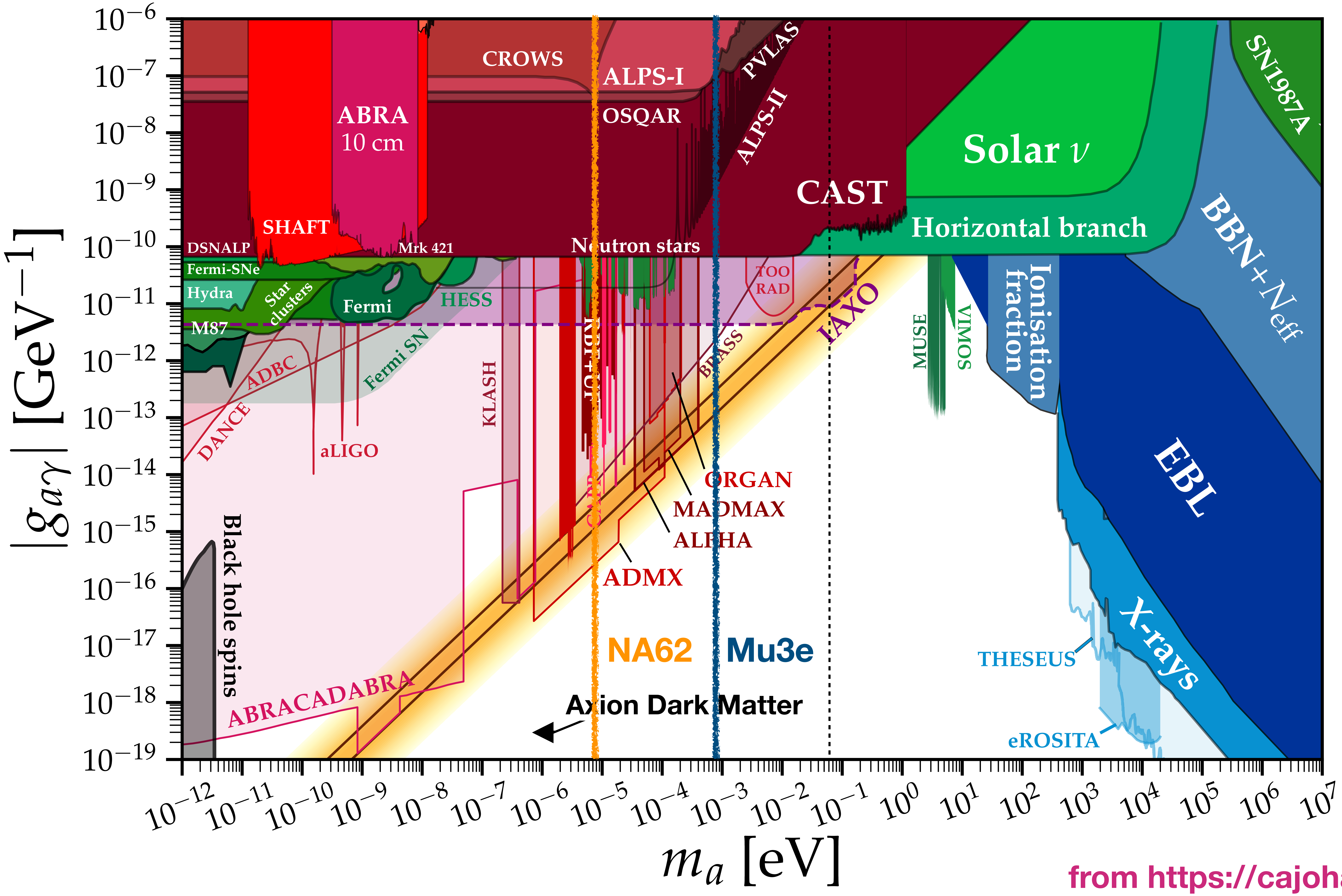
- ★ **in precision flavor experiments**, probing decay constants up to 10^{12} GeV (NA62) or 10^{10} GeV (Mu3e) or 10^{8} GeV (B-factories)

- ★ **in SN1987A** from decays of moderately heavy flavors, contributing to energy loss and providing strongest bounds on hyperons decays

- ★ **in the early universe**, giving observed DM abundance via freeze-in: very simple class of DM models that can be tested at flavor factories such as Mu3e and MEG-II [quark case in progress]

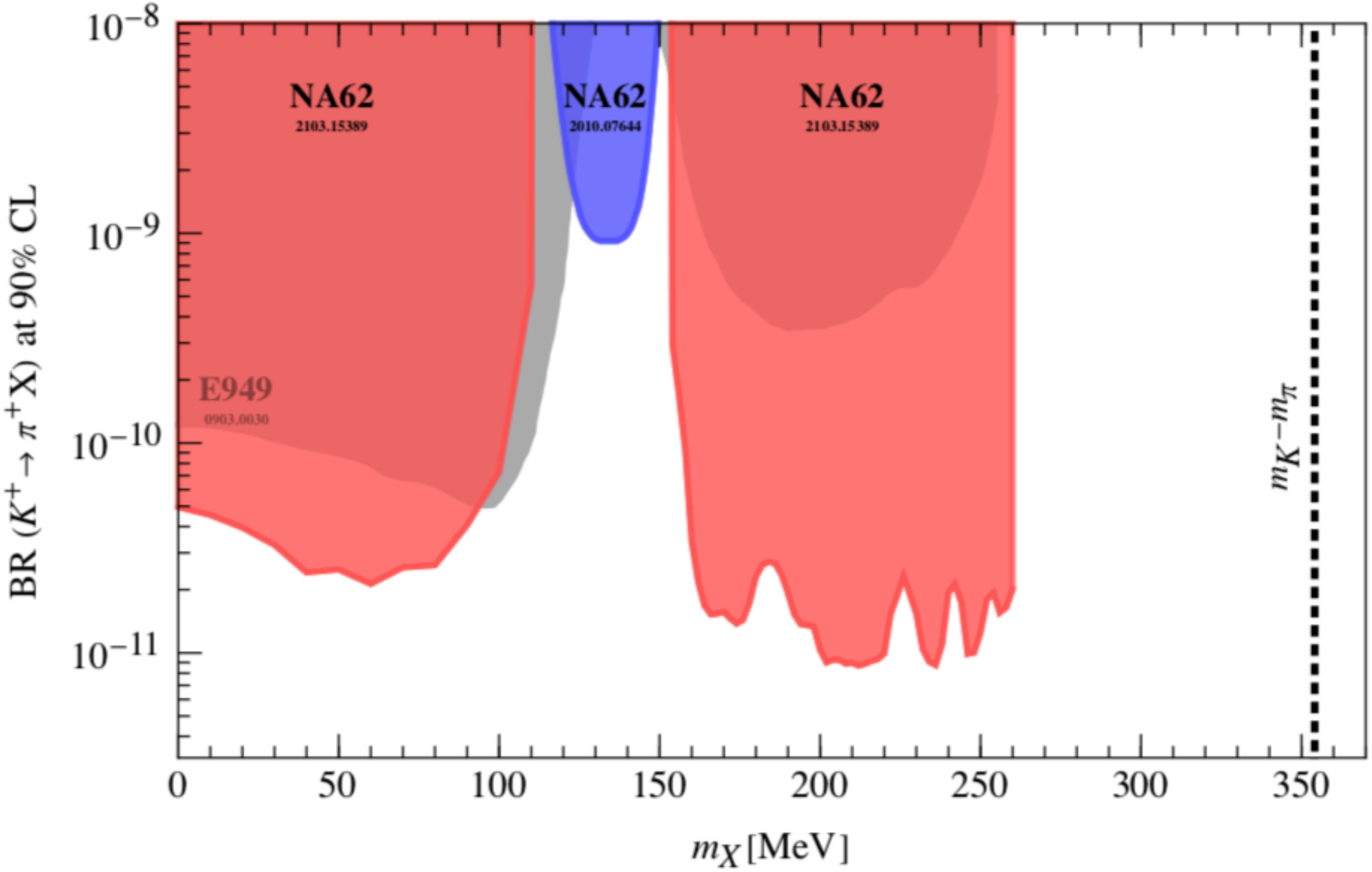
Backup

Flavor Constraints in the Axion Plane



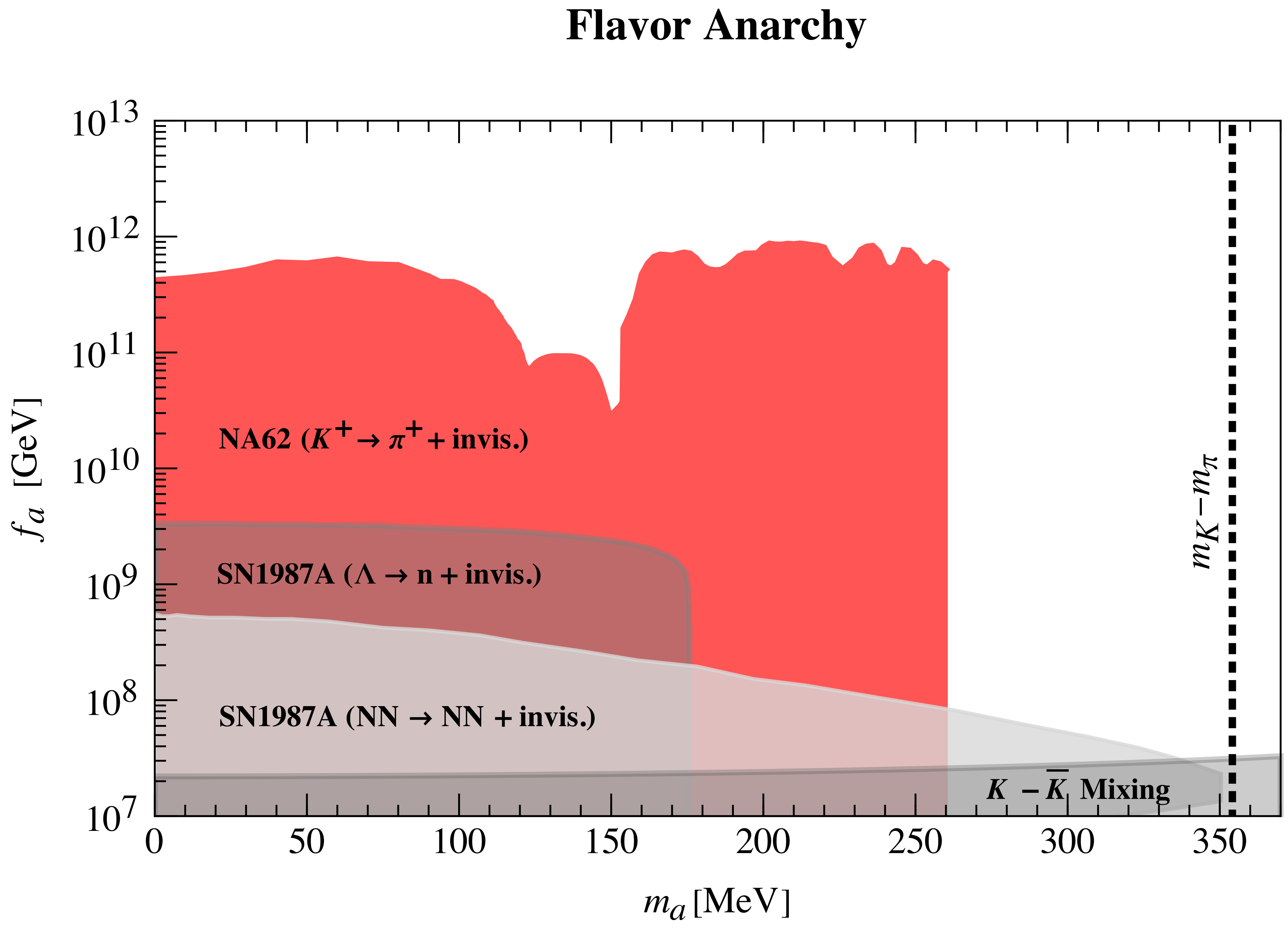
from https://cajohare.github.io/AxionLimits

Bounds from NA62

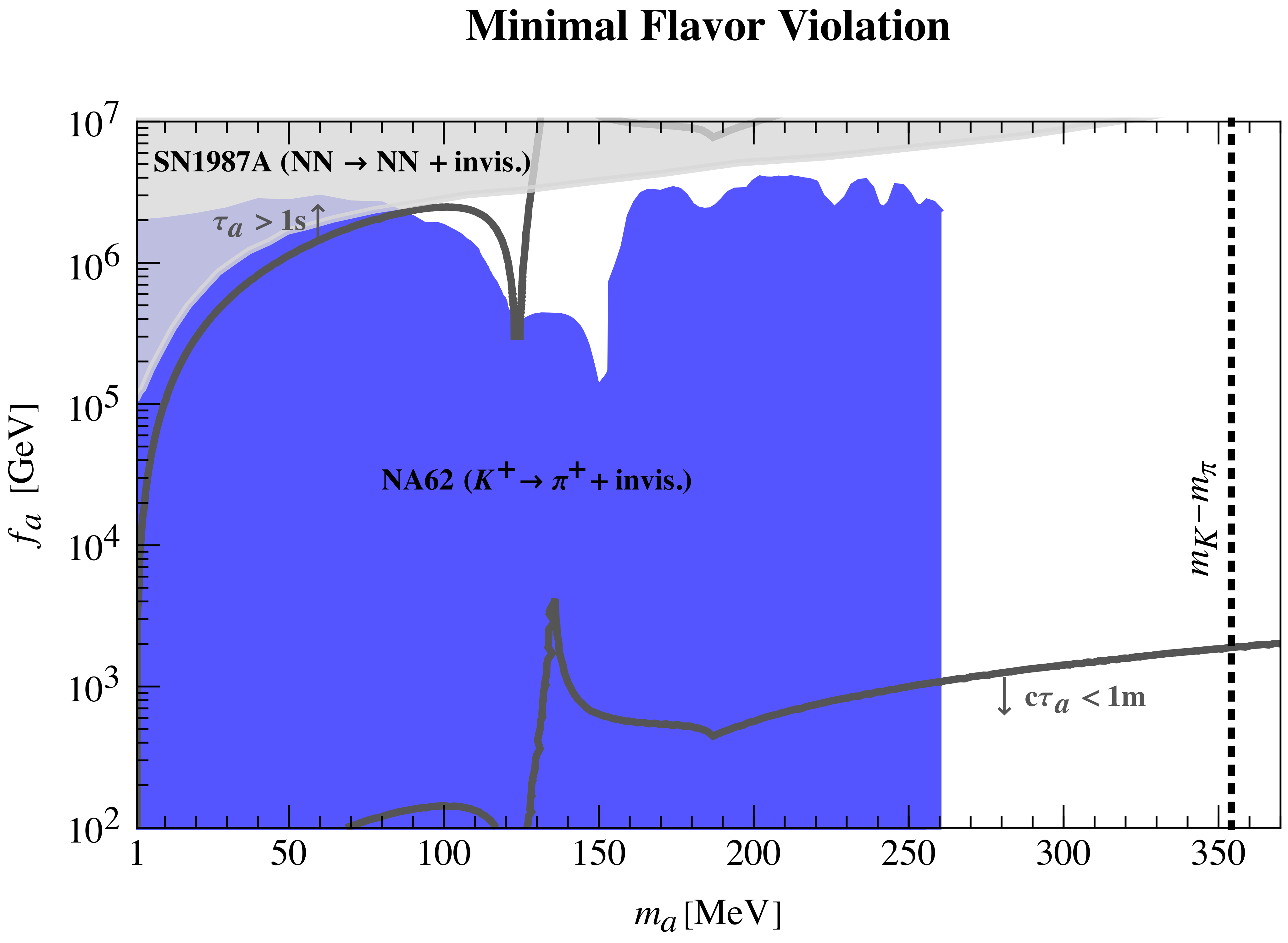


from arXiv: 2201.07805

Flavor Anarchy vs. MFV



all axion UV couplings = 1



all flavor-diagonal UV couplings = 1

from arXiv: 2201.07805

Lepton Sector Bounds

Present best limits				
Process	BR Limit	Decay constant	Bound (GeV)	Experiment
Star cooling	–	F_{ee}^A	4.6×10^9	WDs [44]
	–	$F_{\mu\mu}^A$	1.3×10^8	SN1987A$_{\mu\mu}$ [45, 46]
	4×10^{-3}	$F_{\mu e}$	1.4×10^8	SN1987A$_{\mu e}$ (Sec. 6.1)
$\mu \to e\, a$	$2.6 \times 10^{-6*}$	$F_{\mu e}$ (V or A)	4.8×10^9	Jodidio at al. [9]
$\mu \to e\, a$	$2.5 \times 10^{-6*}$	$F_{\mu e}$ ($V + A$)	4.9×10^9	Jodidio et al. [9]
$\mu \to e\, a$	$5.8 \times 10^{-5*}$	$F_{\mu e}$ ($V - A$)	1.0×10^9	TWIST [10]
$\mu \to e\, a\, \gamma$	$1.1 \times 10^{-9*}$	$F_{\mu e}$	$5.1 \times 10^{8\#}$	Crystal Box [47]
$\tau \to e\, a$	$2.7 \times 10^{-3**}$	$F_{\tau e}$	4.3×10^6	ARGUS [43]
$\tau \to \mu\, a$	$4.5 \times 10^{-3**}$	$F_{\tau\mu}$	3.3×10^6	ARGUS [43]

Expected future sensitivities				
Process	BR Sens.	Decay constant	Sens. (GeV)	Experiment
$\mu \to e\, a$	$7.2 \times 10^{-7*}$	$F_{\mu e}$ (V or A)	9.2×10^9	MEGII-fwd*
$\mu \to e\, a$	$7.2 \times 10^{-8*}$	$F_{\mu e}$ (V or A)	2.9×10^{10}	MEGII-fwd**
$\mu \to e\, a$	$7.3 \times 10^{-8*}$	$F_{\mu e}$ (V or A)	2.9×10^{10}	Mu3e [42]
$\tau \to e\, a$	$8.3 \times 10^{-6**}$	$F_{\tau e}$	7.7×10^7	Belle II
$\tau \to \mu\, a$	$2.0 \times 10^{-5**}$	$F_{\tau\mu}$	4.9×10^7	Belle II

from arXiv: 2006.04795

Constraints from Meson Decays

- Experimental bounds often old or non-existent

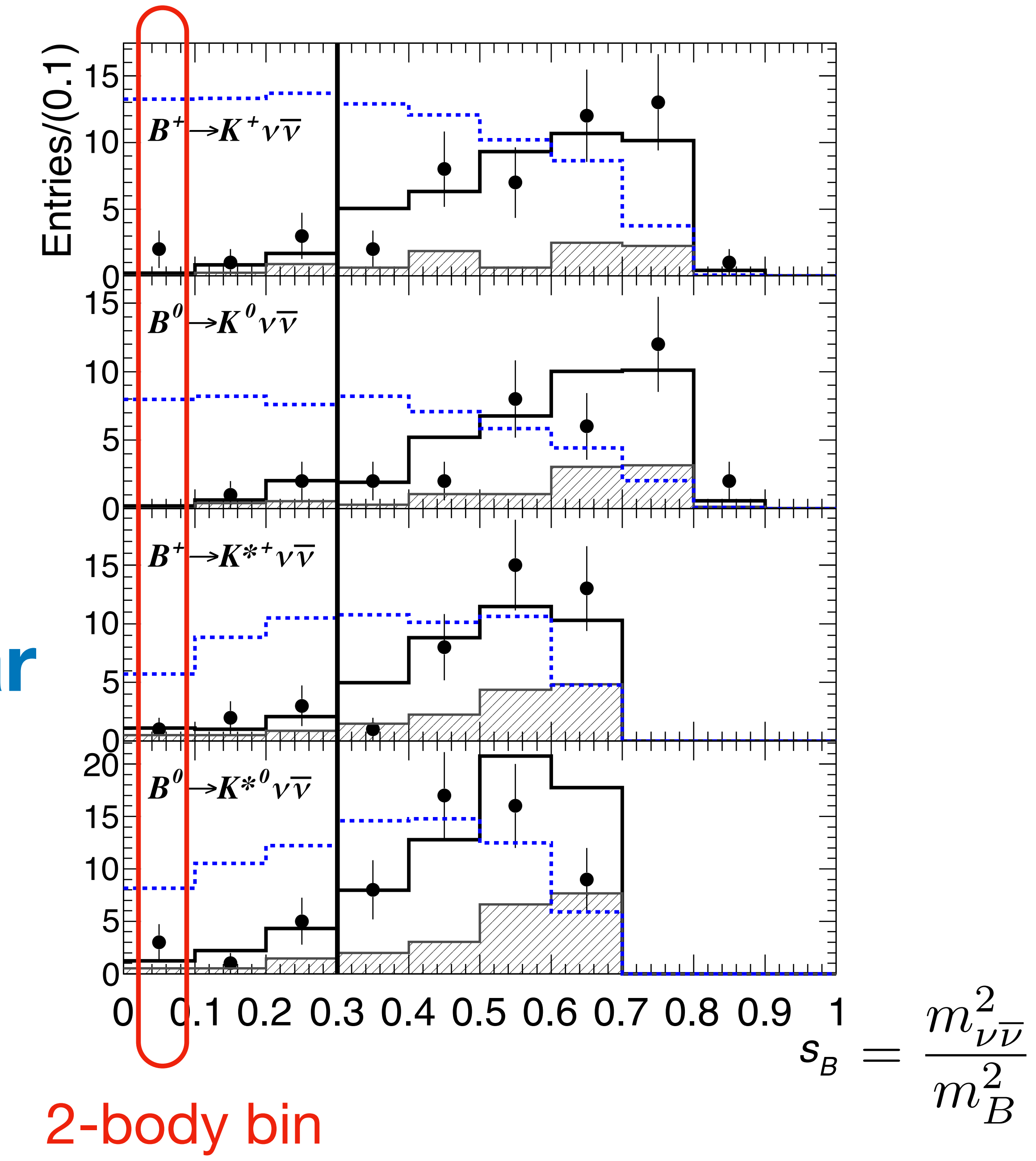
  e.g. no bound in PDG on $D^+ \to \pi^+ a, B \to K^* a, B \to \rho a$

- Need to recast data for SM decays in 2-body region

  Martin Camalich, Pospelov, Vuong, RZ, Zupan ‘20

		$K \to \pi a$	$D \to \pi a$	$B \to \pi a$	$B \to K a$
	Decay	sd	cu	bd	bs
$\propto C_{ij}^V$	$\mathrm{BR}(P_1 \to P_2 + a)_{\mathrm{exp}}$	7.3×10^{-11} [85]	no analysis	4.9×10^{-5} [86]	4.9×10^{-5} [86]
	$\mathrm{BR}(P_1 \to P_2 + a)_{\mathrm{recast}}$	no need	8.0×10^{-6} [87]	2.3×10^{-5} [88]	7.1×10^{-6} [89]
	$\mathrm{BR}(P_1 \to P_2 + \nu\bar{\nu})_{\mathrm{exp}}$	$1.47^{+1.30}_{-0.89} \times 10^{-10}$ [85]	no analysis	0.8×10^{-5} [90]	1.6×10^{-5} [90]
$\propto C_{ij}^A$	$\mathrm{BR}(P_1 \to V_2 + a)_{\mathrm{exp}}$	3.8×10^{-5} [91]	no analysis	no analysis	no analysis
	$\mathrm{BR}(P_1 \to V_2 + a)_{\mathrm{recast}}$	no need	no data	no data	5.3×10^{-5} [89]
	$\mathrm{BR}(P_1 \to V_2 + \nu\bar{\nu})_{\mathrm{exp}}$	4.3×10^{-5} [91]	no analysis	2.8×10^{-5} [90]	2.7×10^{-5} [90]
		$K \to \pi\pi a$	$D \to \pi\pi a$	$B \to \rho a$	$B \to K^* a$

BaBar
Belle



e.g. recast **CLEO** data on $D \to \tau\nu, \tau \to \pi\nu$ to get bound on $D^+ \to \pi^+ a$

Kamenik, Smith ‘11