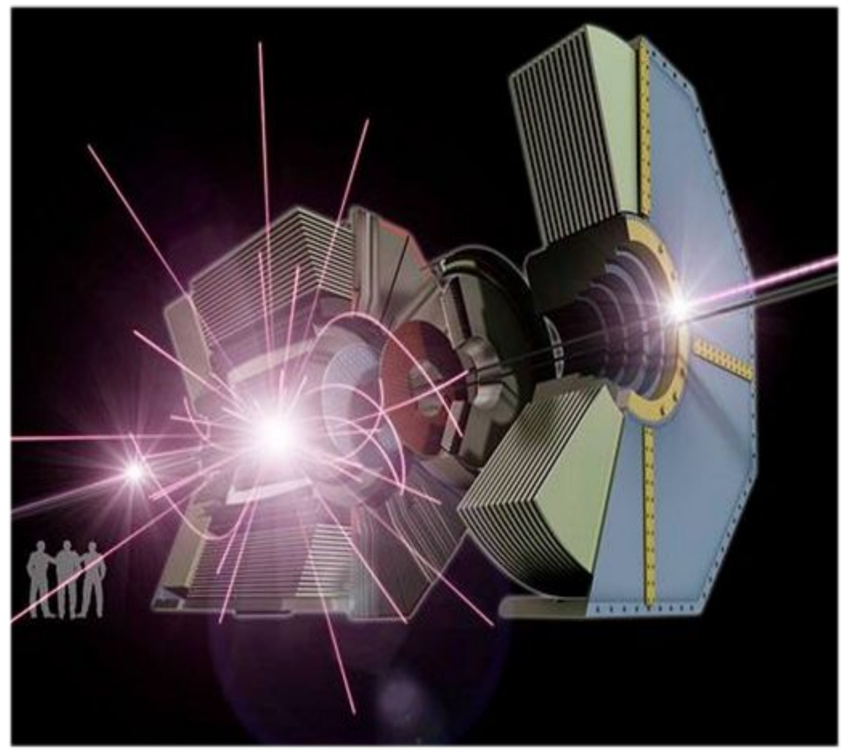
Axions and Flavor

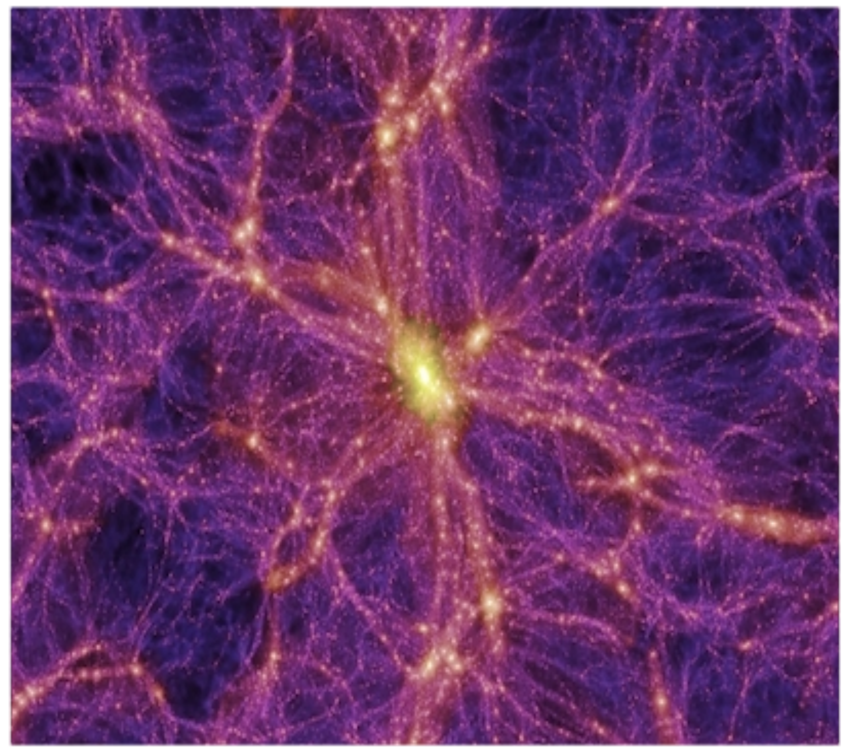
Robert Ziegler (Freiburg/Karlsruhe)

$$\frac{\partial_\mu a}{2f_a}\sum_{i\neq j}\overline{\psi}_i\gamma^\mu\left(C^V_{ij}+C^A_{ij}\gamma_5\right)\psi_j$$



Flavor Factories

Supernovae



Early Universe

UNI FREIBURG

KIT Karlsruher Institut für Technologie

Flavor-violating Axions

Often ignored, but general axion couplings are flavor-violating

$$\mathcal{L}_a = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{a}{f_a}\frac{\alpha_{\rm em}}{8\pi}F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{\partial_\mu a}{2f_a}\sum_i C_i \overline{\psi}_i\gamma^\mu\gamma_5\psi_i \quad + \frac{\partial_\mu a}{2f_a}\sum_{i\neq j}\overline{\psi}_i\gamma^\mu\left(C_{ij}^V + C_{ij}^A\gamma_5\right)\psi_j$$

Enriches phenomenology, but proliferates parameters (+6 in each sector)

Axion production from flavor-violating decays of SM particles

Part 1

Hard to predict unless have model of flavor or pheno motivation [or MFV]

Part 2

Dark Matter Axions

Focus on invisible = Dark Matter axions

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

light

m_a

f_a

naturally for **QCD axion**

$m_a f_a = m_\pi f_\pi$

decoupled

easily **stable on cosmological scales**

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

Axion Production in Flavor Factories

Test flavor-violating couplings searching for **SM decays with missing energy**

Feng, Muroi, Murayama, Schnapka ’98, Björkeroth, Chun, King ‘18

look like meson/lepton decays with neutrino pair, but 2-body

e.g.

$K \to \pi a$	$B \to K^* a$	$\Lambda \to n a$	$\mu \to e a$
$\propto \lvert C^V_{sd}\rvert^2$	$\propto \lvert C^A_{bs}\rvert^2$	$\propto \lvert C^V_{bs}\rvert^2 + \lvert C^A_{bs}\rvert^2$	$\propto \lvert C^V_{\mu e}\rvert^2 + \lvert C^A_{\mu e}\rvert^2$

Quarks SM background tiny $\mathrm{BR}(K \to \pi \nu \bar{\nu}) \sim 10^{-10}$

Experimental searches for 2-body meson decays are rare

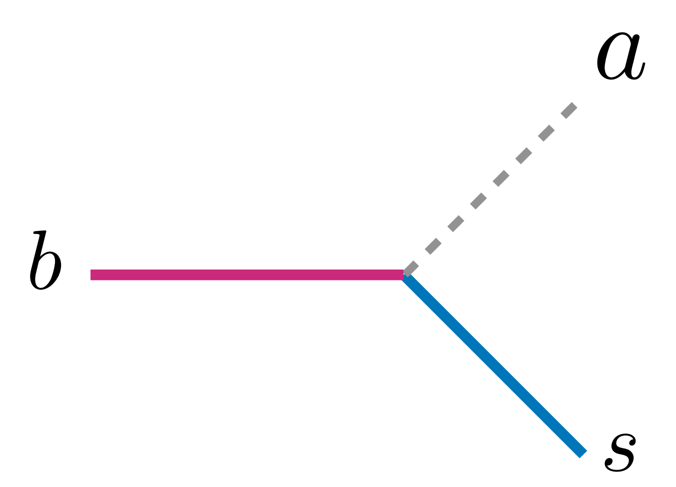
Leptons SM background huge $\mathrm{BR}(\mu \to e \nu \bar{\nu}) = 1$

Experimental searches for 2-body lepton decays are difficult

Meson Decays vs Meson Mixing

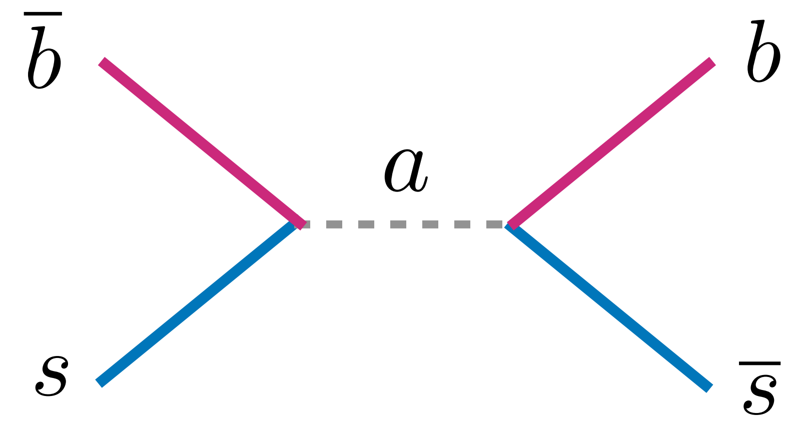
2-body decays probe **LARGE** UV scales

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



and are typically more constraining than meson mixing

$$\frac{\partial_\mu a}{f_a}\bar{b}\gamma^\mu s \xrightarrow{B_s - \mathrm{mixing}} f_a \gtrsim 800\ \mathrm{TeV}$$



in contrast to heavy NP $$\frac{1}{\Lambda^2}\left(\bar{b}\gamma^\mu s\right)\left(\bar{\nu}\gamma_\mu \nu\right) \xrightarrow{B \to K\nu\bar{\nu}} \Lambda \gtrsim 10\,\mathrm{TeV}$$

Constraints on Meson Decays

Experimental constraints on 2-body decays often old / do not exist

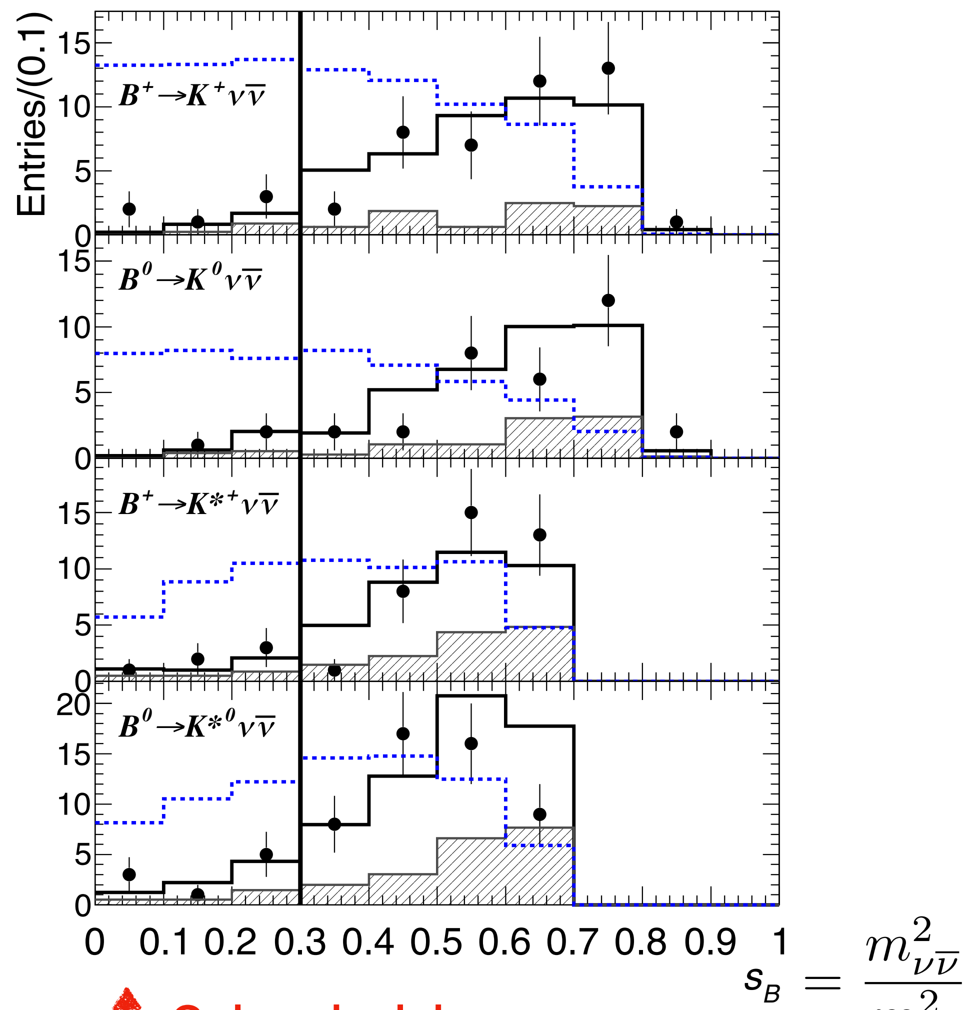
no PDG bound on $D \to \pi a, B \to K^* a, B \to \rho a$

Need to recast experimental data on SM decays in 2-body region

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

	$K \to \pi a$	$D \to \pi a$	$B \to \pi a$	$B \to K a$	
Decay	sd	cu	bd	bs	
$\mathrm{BR}(P_1 \to P_2 + a)_{\mathrm{exp}}$	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]	$\propto \lvert C^V_{ij} \rvert^2$
$\mathrm{BR}(P_1 \to P_2 + \nu\bar{\nu})_{\mathrm{exp}}$	$1.47^{+1.30}_{-0.89} \times 10^{-10}$ [85]	no analysis	0.8×10^{-5} [90]	1.6×10^{-5} [90]	
$\mathrm{BR}(P_1 \to V_2 + a)_{\mathrm{exp}}$	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]	$\propto \lvert C^A_{ij} \rvert^2$
$\mathrm{BR}(P_1 \to V_2 + \nu\bar{\nu})_{\mathrm{exp}}$	4.3×10^{-5} [91]	no analysis	2.8×10^{-5} [90]	2.7×10^{-5} [90]	
			$B \to \rho a$	$B \to K^* a$	

CLEO **Belle** **BaBar**



can recast **CLEO** data on $D \to \tau\nu, \tau \to \pi\nu$ to get bound on $D^+ \to \pi^+ a$ Kamenik, Smith '11

Constraints on Lepton Decays

Can use polarized leptons to suppress SM background

$$\frac{d\Gamma(\mu^+ \to e^+ a)}{d\cos\theta} \propto 1 - 2\cos\theta \frac{C^V_{\mu e} C^A_{\mu e}}{|C^V_{\mu e}|^2 + |C^A_{\mu e}|^2} \quad \longleftrightarrow \quad \frac{d\Gamma_{\rm SM}(\mu^+ \to e^+ a)}{d\cos\theta}\Big|_{E_e = \max} \propto 1 + \cos\theta$$

find strong bounds unless aligned to SM decay (V-A) Iodidio et al. @TRIUMF '86

Can use huge luminosities at modern facilities (PSI)

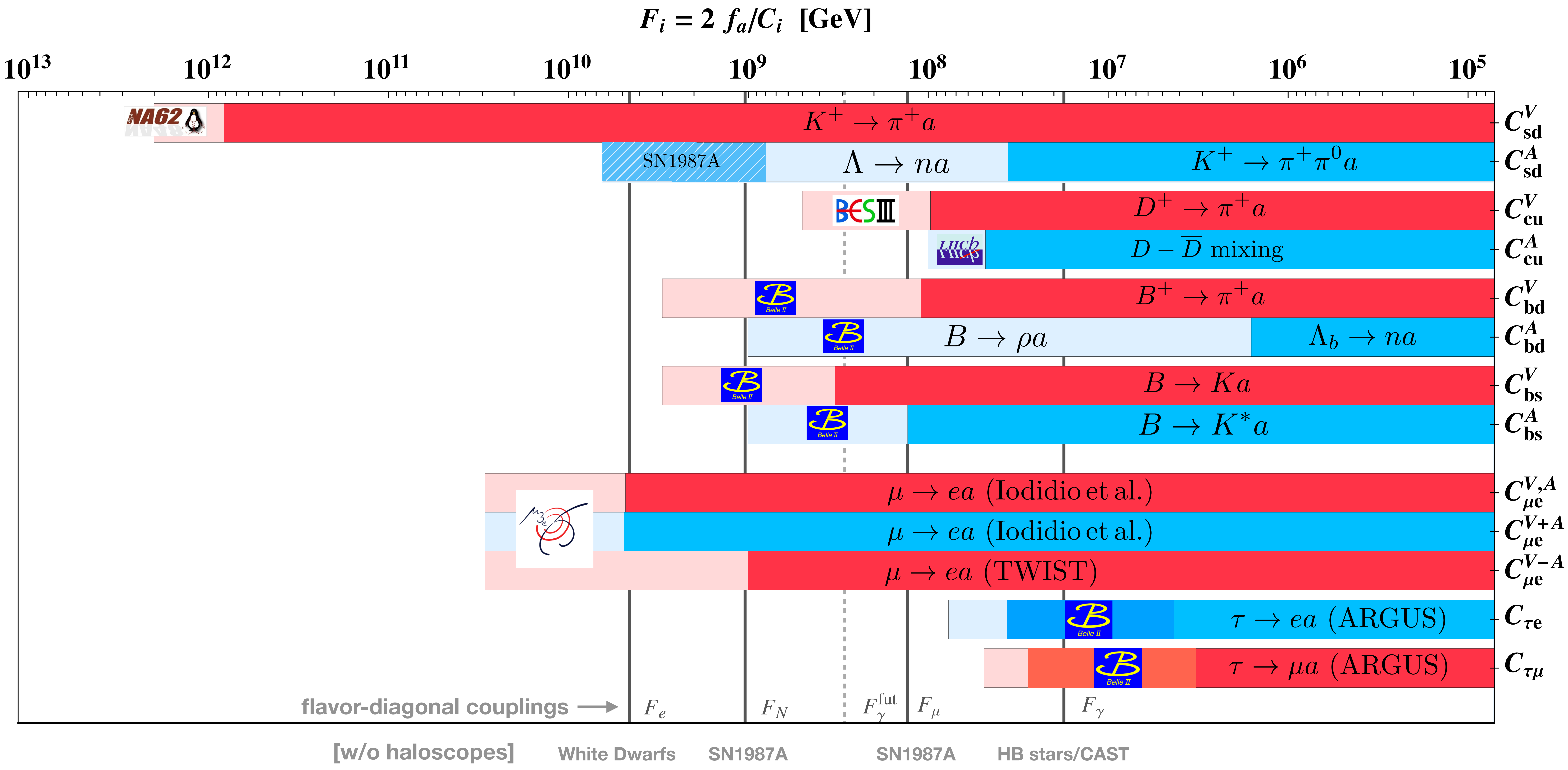
Mu3e plans to measure 2-body on top of SM 3-body decay, but difficult for massless axion when peak = edge of spectrum

for MEG-II only theory proposals:

"MEGII-fwd"
add forward calorimeter
Calibbi, Redigolo, RZ, Zupan '20

"MEGII-ALP" ($\mu \to e a \gamma$)
adjust software triggers
Jho, Knapen, Redigolo '22

Summary of Constraints

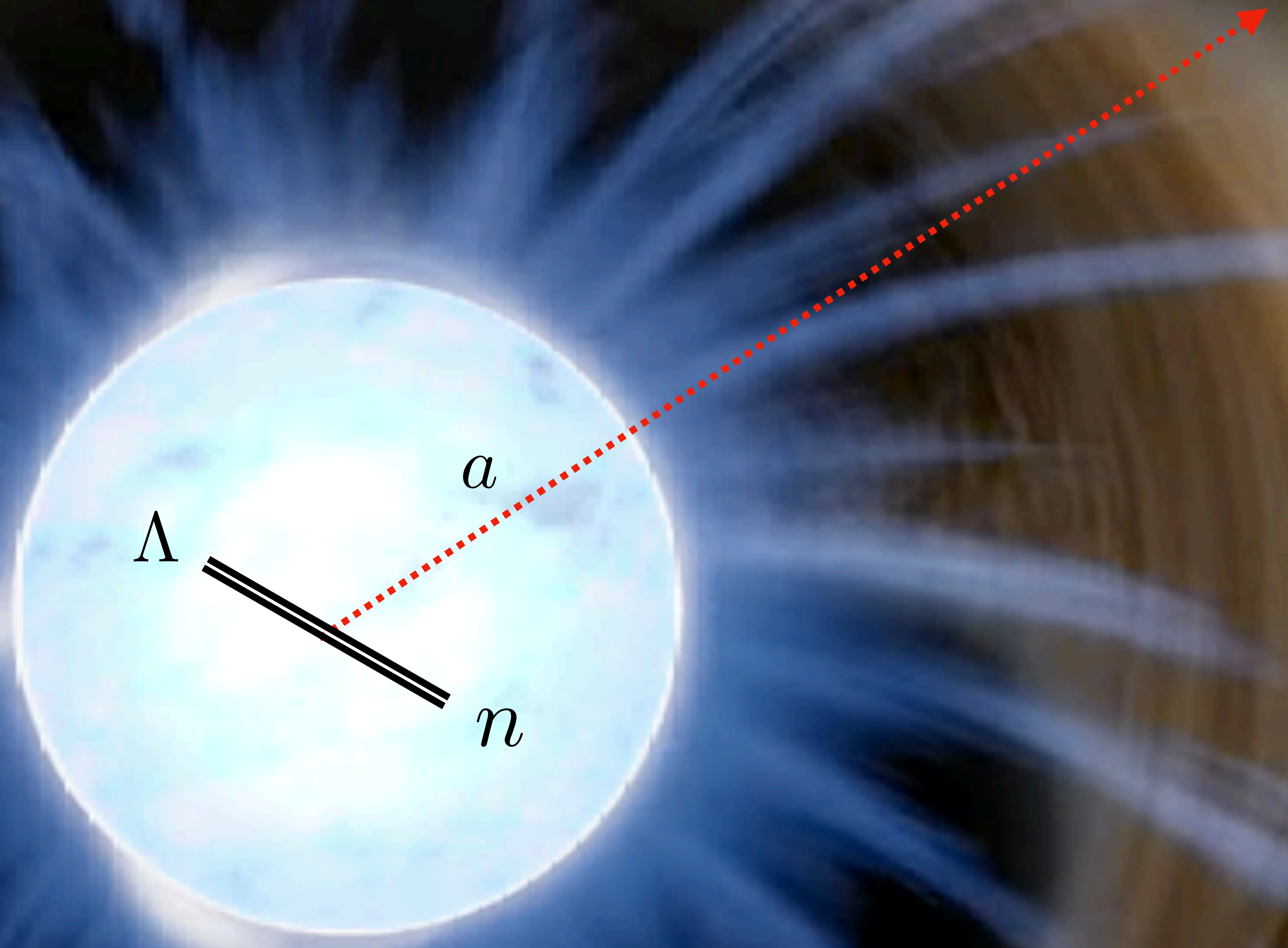


Constraints from SN1987A

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

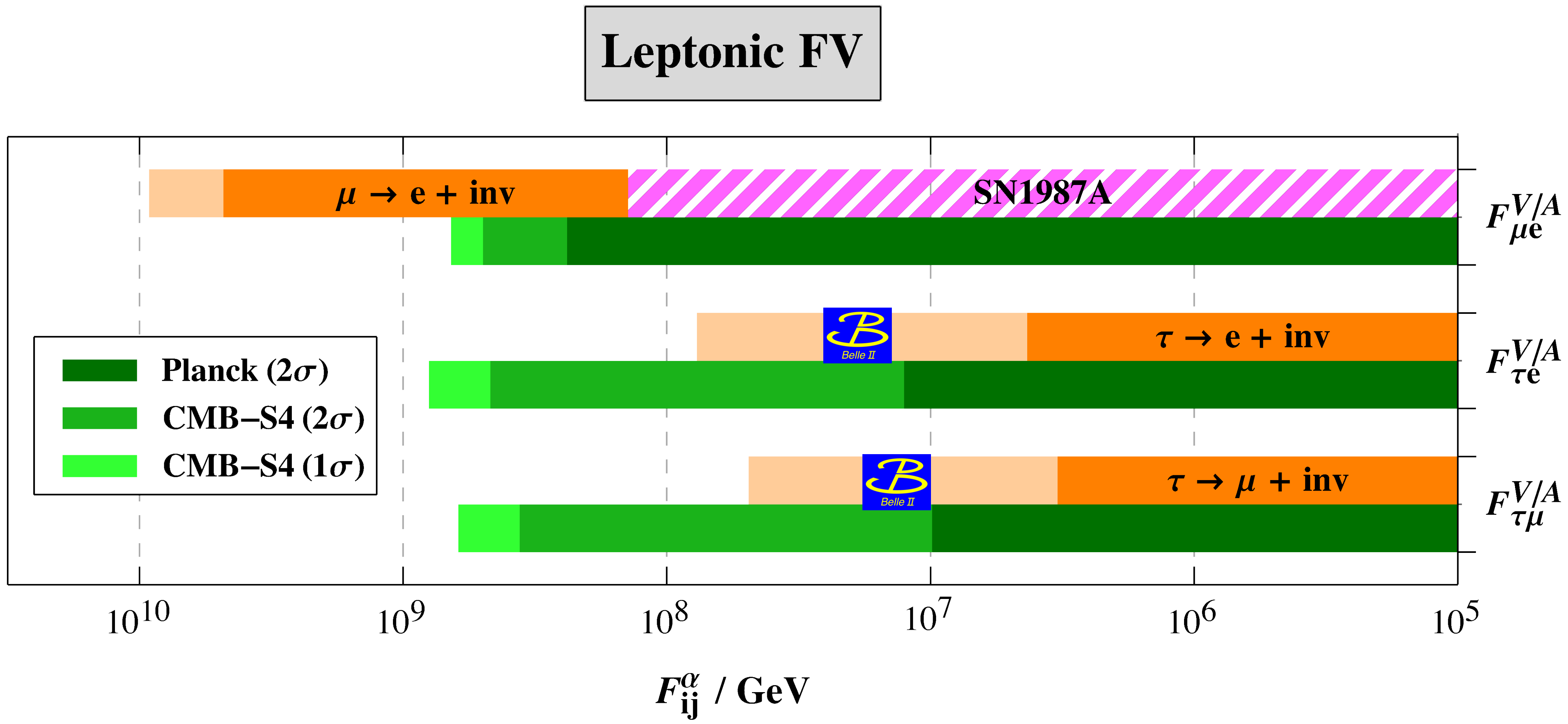
$$\mathrm{BR}(\Lambda \to n a) \lesssim 5.0 \times 10^{-9}$$

[similar for LFV muon decays, but weaker than lab bound]

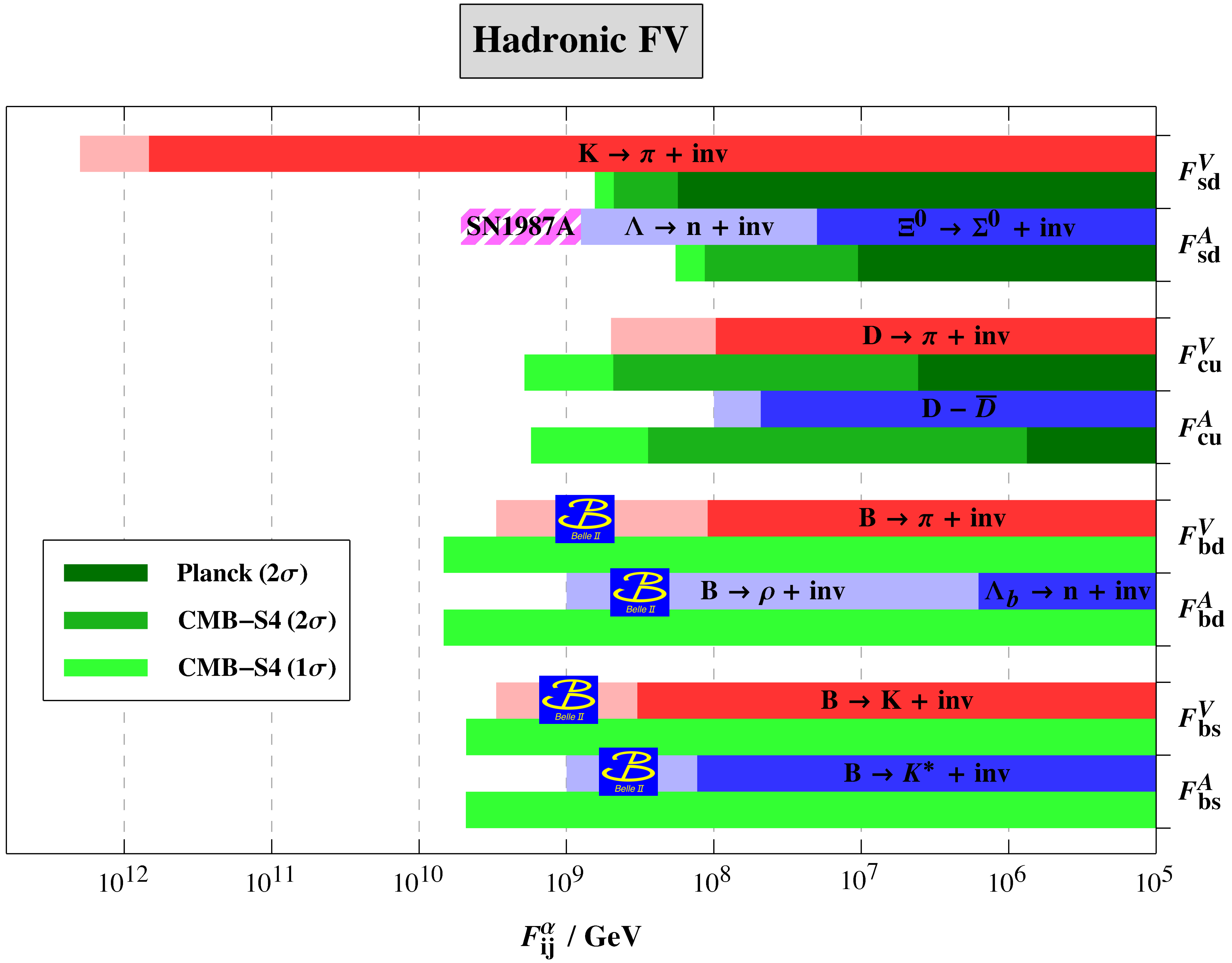
Martin Camalich, Terol-Calvo, Tolos, RZ '20

Constraints from Cosmology

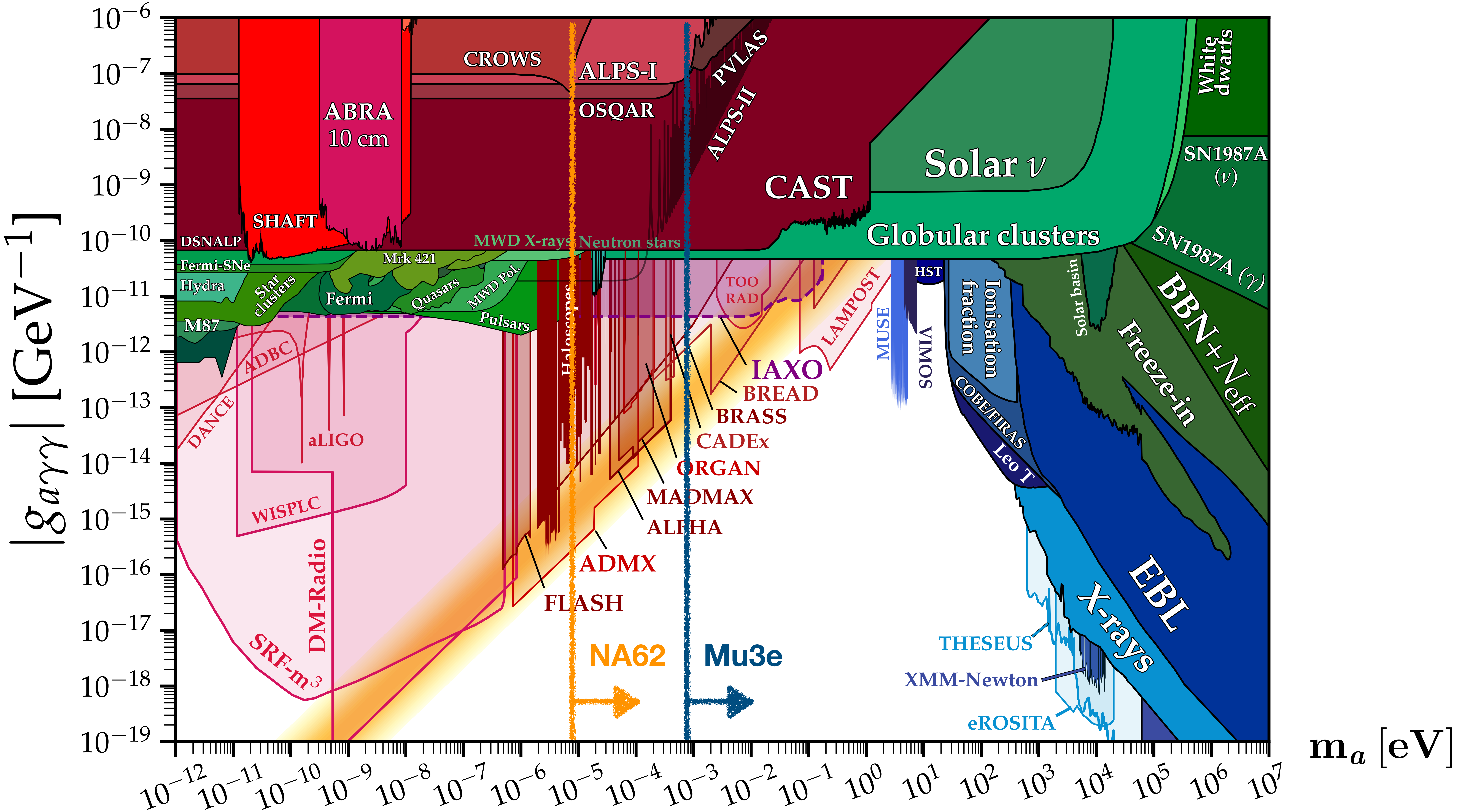
Flavor-violating SM decays produce hot axions in early universe, which are constrained by bounds on Dark Radiation from CMB D'Eramo, Yun '21



Belle-II competes with future CMB telescopes



Constraints for O(1) Flavor Violation



UV Motivation

Fermion couplings determined by PQ charges in fermion mass basis

$$C^{V,A}_{d_i d_j} \propto \left(V^\dagger_{d_L} \mathrm{PQ}_q V_{d_L}\right)_{ij} \pm \left(V^\dagger_{d_R} \mathrm{PQ}_u V_{d_R}\right)_{ij}$$

← unitary matrices diagonalizing Yukawas

Flavor violation expected **if fermions carry non-universal PQ charges**

Usual DFSZ and KSVZ models are MFV: just RG induced flavor violation

→ **astro beat flavor bounds**

Non-MFV models:

- non-universal DFSZ
- KSVZ + mixing

} motivated by e.g. $N_{DW} = 1$ or avoiding astro bounds

- Peccei-Quinn = Froggatt-Nielsen } allows parametric prediction of FV couplings

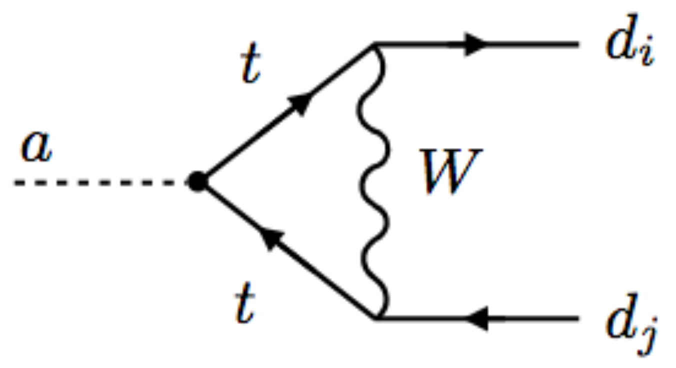
Flavor Anarchy vs. MFV

Always have SM flavor violation from RG running

Choi, Im, Park, Yun'17
Bauer, Neubert, Renner, Schnubel, Thamm '21

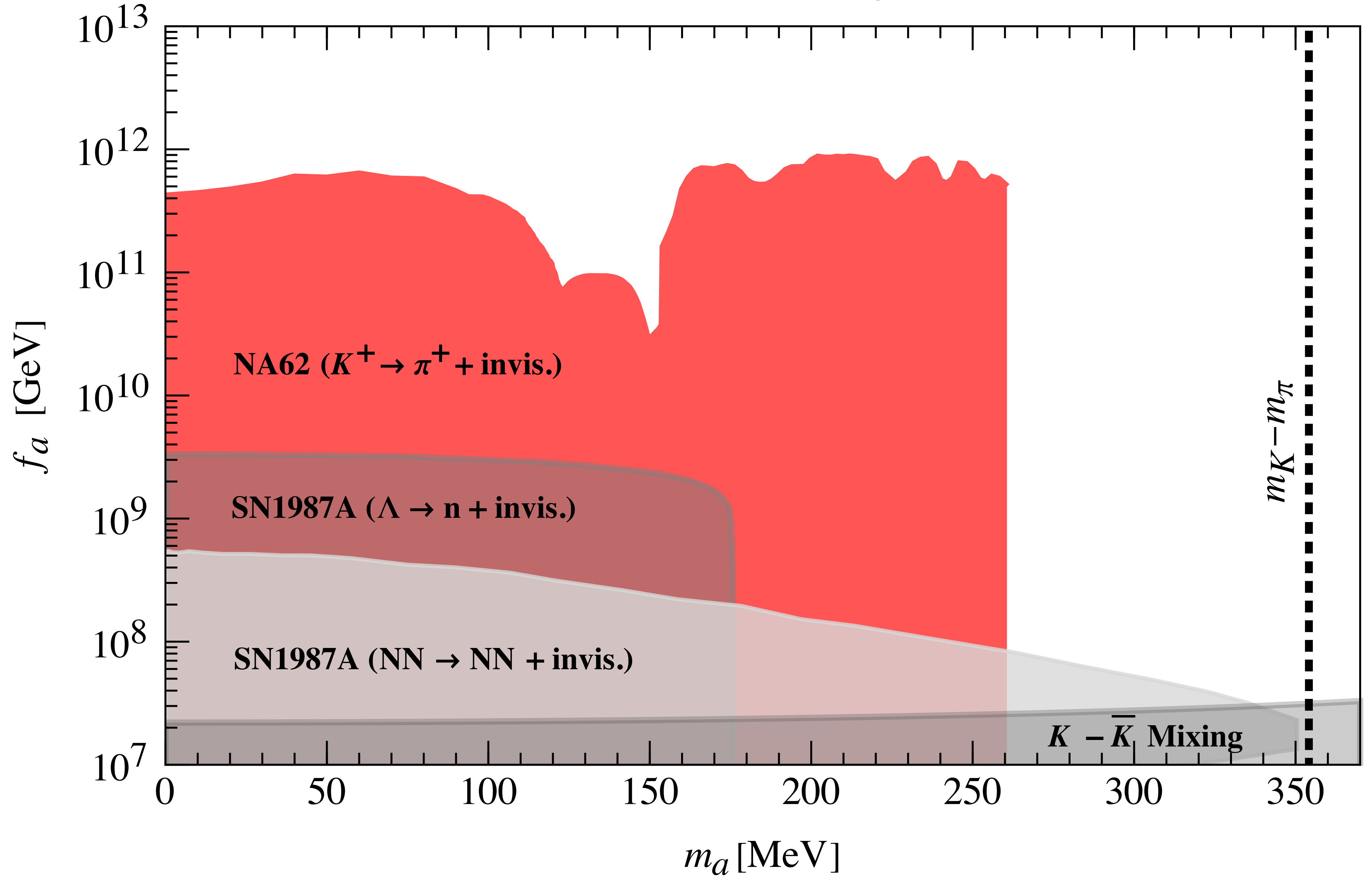
$$C_{sd} \sim \frac{y_t^2 V_{td} V_{ts} C_{tt}}{16\pi^2} \log \sim 10^{-5}$$

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



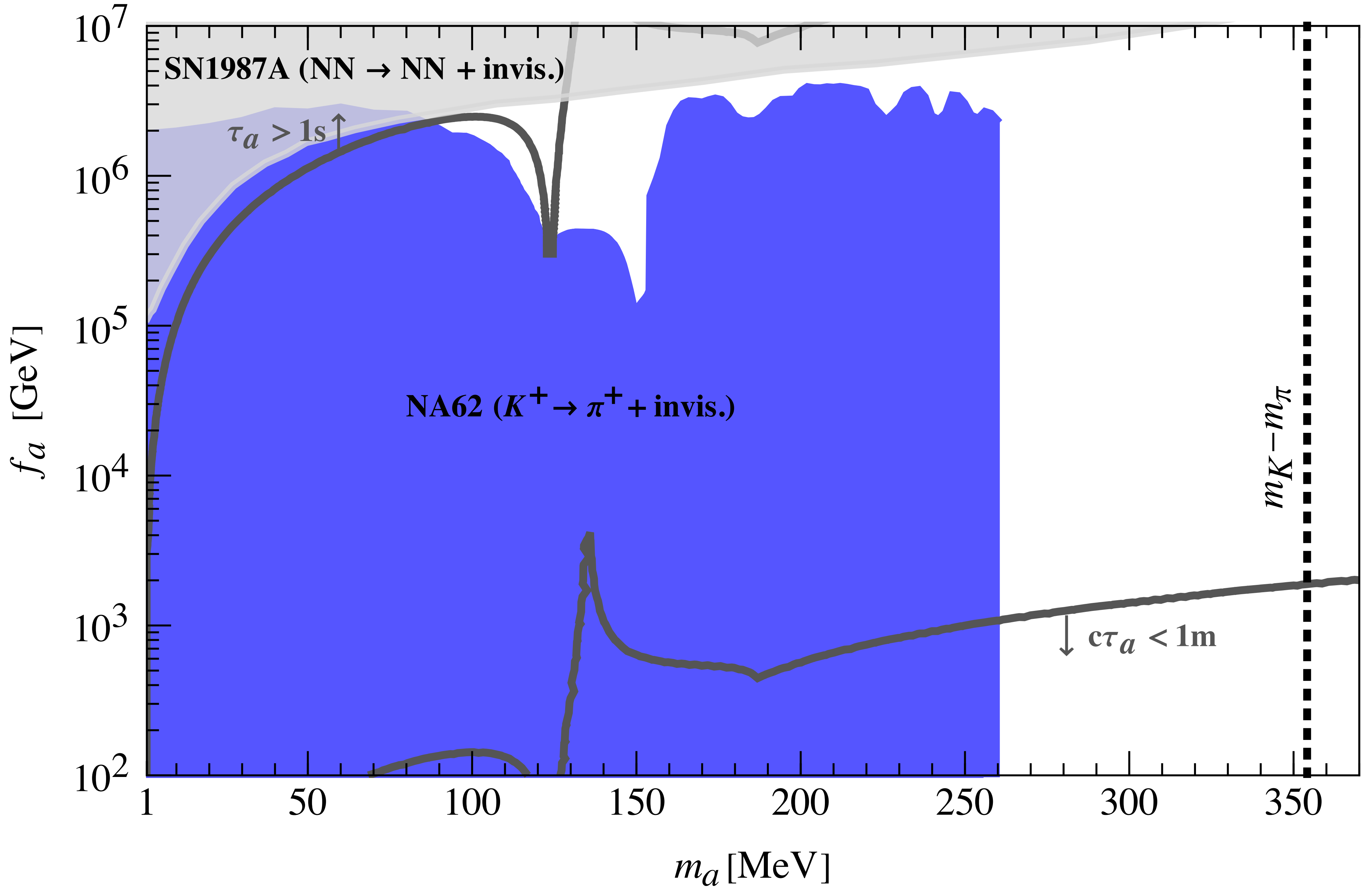
Flavor Anarchy

all axion UV couplings = 1



Minimal Flavor Violation

all flavor-diagonal UV couplings = 1



from 2201.07805

Non-universal DFSZ Models

Flavor non-universality required by $N_{DW} = 1$ or to avoid astro bounds

e.g. SN1987A bound on C_N

$$\left.\begin{aligned} C_p + C_n &= 0.50(C_u + C_d - 1) + \delta_{s,c,b,t} \\ C_p - C_n &= 1.26(C_u - C_d - \frac{1-z}{1+z}) \end{aligned}\right\} \ll 1$$

when $C_u = 2/3, C_d = 1/3$

z: $m_u/m_d \approx 1/2$

<u>can be realized in:</u>

2HDM models with 2+1 flavor structure: $N_{DW} = 1$, tuning $v_u^2/v_d^2 \approx 1/2$

di Luzio, Mescia, Nardi, Panci, RZ '18

3HDM models with 2+1 flavor structure: $N_{DW} = 1$, same tuning for $C_e \approx 0$

Björkeroth, di Luzio, Mescia, Nardi, Panci, RZ '19

3HDM models with 1+2 flavor structure: $N_{DW} = 3$, without tuning $v_{u,d} \ll v_{SM}$

Badziak, Harigaya '23

PQ Flavor Models

Predictive when PQ = flavor symmetry addressing SM Flavor Puzzle

[Davidson, Wali; Berezhiani; Wilczek]

Often automatically anomalous

$$\underbrace{\det m_u \det m_d / v^6}_{\approx 10^{-20}} = [\underbrace{\det a_u \det a_d}_{\mathcal{O}(1)}]\, \epsilon^{2N}$$

QCD anomaly coefficient

$$\underbrace{\det m_d / \det m_e}_{\approx 0.7} = [\underbrace{\det a_d / \det a_e}_{\mathcal{O}(1)}]\, \epsilon^{\frac{8}{3}N - E}$$

EM anomaly coefficient

e.g. single $U(1)_F$ Binetruy, Ramond '94

$$y^U_{ij} \sim \epsilon^{q_i + u_j} \qquad y^D_{ij} \sim \epsilon^{q_i + d_j}$$

Fixes flavor-violating couplings up to model-dependent O(1) coefficients

$U(1)_{\rm PQ} = U(1)_F$ — Ema et al. '16; Calibbi, Goertz, Redigolo, RZ, Zupan '16

sizable light quark transitions

$$C^V_{d_i d_j} \sim (V_{\rm CKM})_{ij}$$

= generic expectation

$U(1)_{\rm PQ} \subset U(2)_F$ — Linster, RZ '18; Calibbi, Redigolo, RZ, Zupan '20

suppressed light quark transitions, but LFV sizable

$$C^V_{d_i d_j} \sim (V_{\rm CKM})_{i3} (V_{\rm CKM})_{j3}$$

= FCNC suppression in SUSY U(2)

Barbieri et al '95

ALP Dark Matter from SM Decays

Use flavor-violating decays as freeze-in production of axion Dark Matter abundance fixes decay rate: **get explicit targets for exp. searches**

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

DM Abundance

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

→ requires ALP mass in suitable window

(lab searches / WDM vs. kinematic threshold)

DM Stability

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

X-ray telescopes

→ requires suppressed photon coupling

(anomaly-free PQ, coupling hierarchy or heavy leptons)

Explicit LFV Scenarios

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

$$\mathrm{PQ}_e = \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix} \xrightarrow[\text{in 1-2 plane}]{\text{rotation}} C^V_{e_ie_j} = C^A_{e_ie_j} = \begin{pmatrix} s_\alpha & c_\alpha & 0 \\ c_\alpha & -s_\alpha & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

3 parameters: α, f_a, m_a

- ALP relic abundance mainly from lepton decays for small T_R

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

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

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

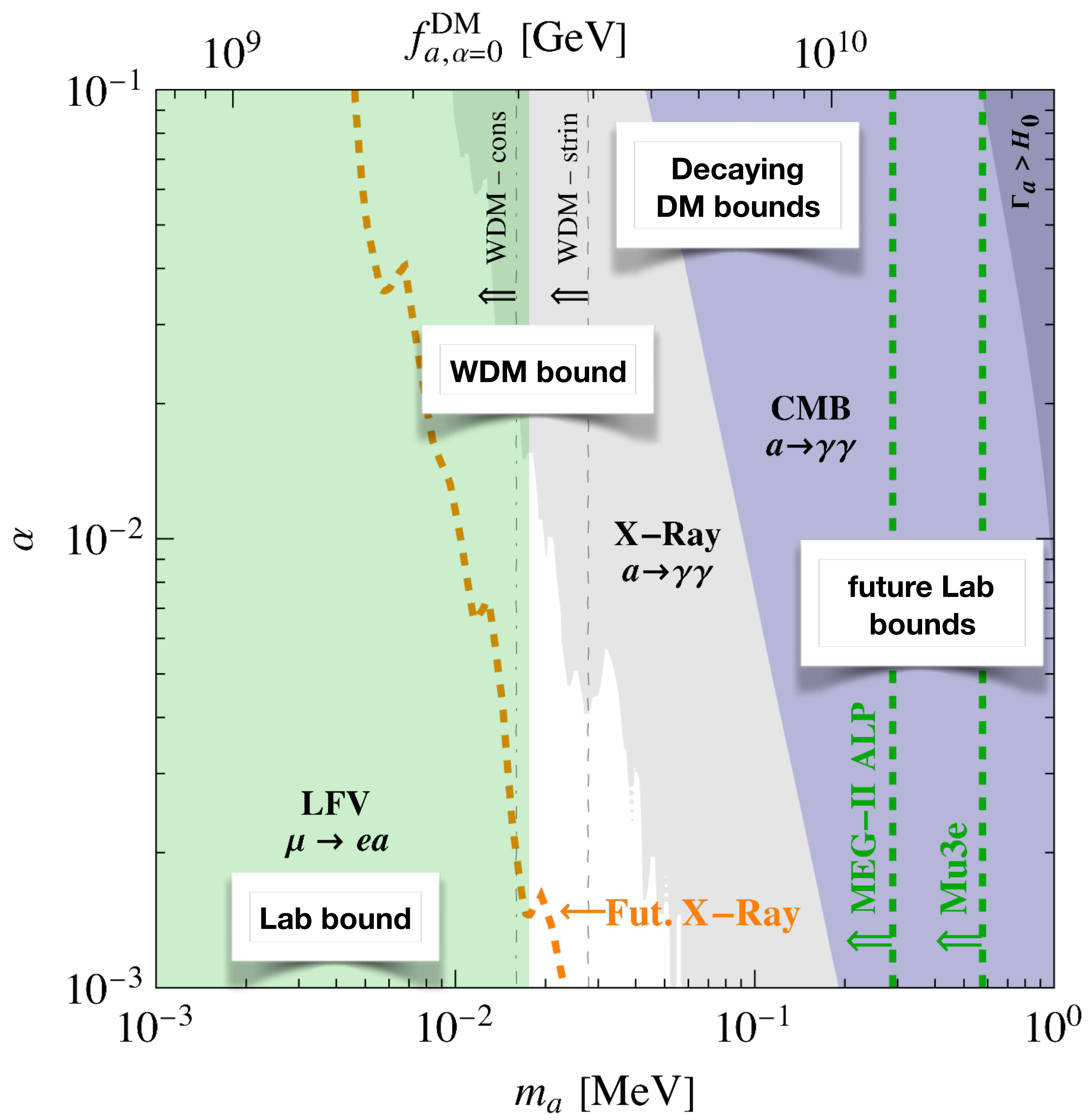
$\Big\} \times \Omega h^2|_{\mu\to ea}$

Misalignment $\quad \Omega h^2|_{\rm mis} \approx 0.04\,(f_a\theta_0/10^{10}\,\mathrm{GeV})^2 \times \frac{m_\mu T_R}{3\pi^3 v^2}$

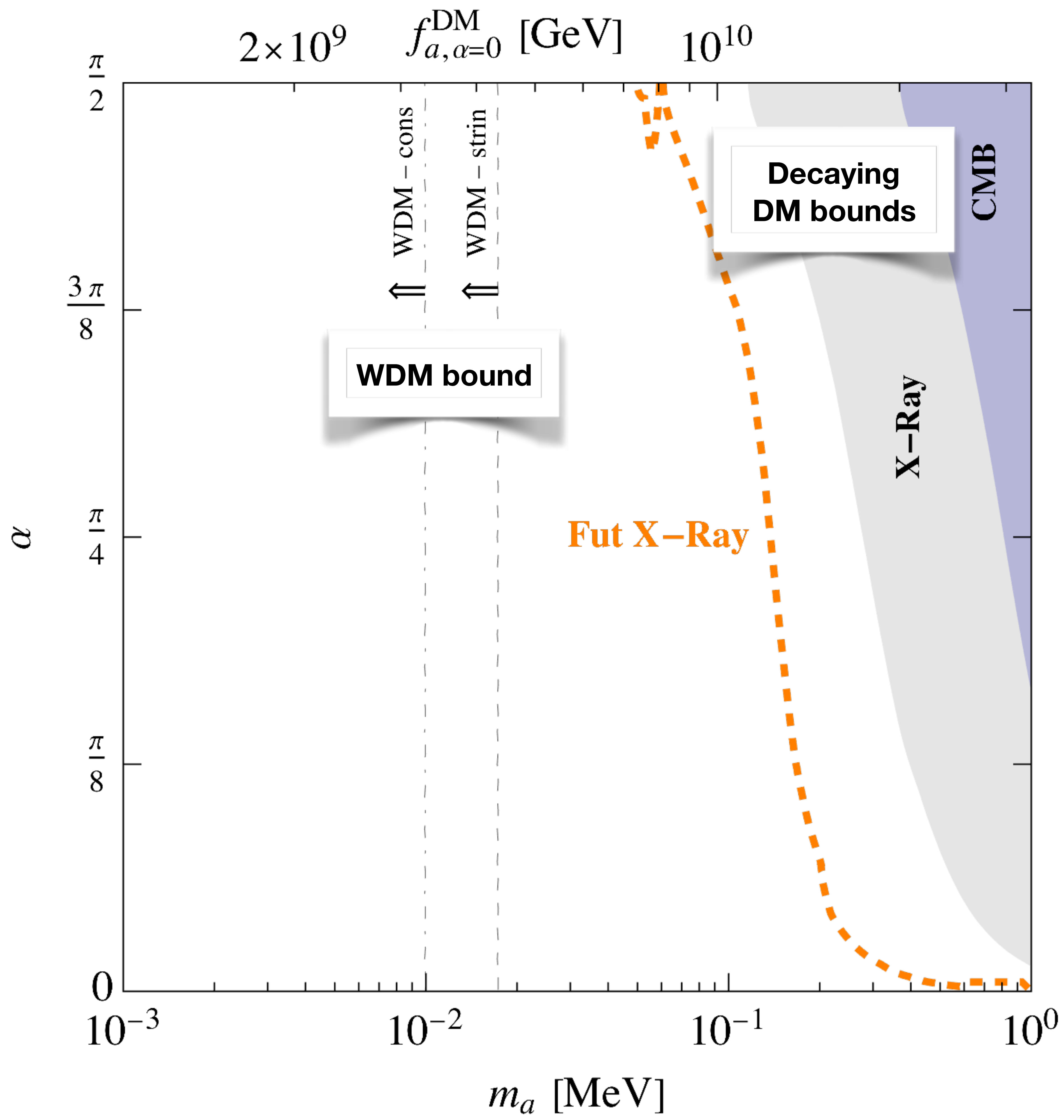
- DM lifetime $\tau_a = 10^{20}\mathrm{sec}\left(\frac{60\,\mathrm{keV}}{m_a}\right)^7\left(\frac{f_a/\sin\alpha}{10^9\,\mathrm{GeV}}\right)^2$ / Warm DM bound $m_a \gtrsim 20\,\mathrm{keV}$

Numerical Results

μe-Scenario



$\tau\mu$-Scenario



Summary

Invisible Axions with flavor-violating couplings can be produced by decays of SM particles, which is relevant

- ★ **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

and arise naturally when PQ is flavor symmetry explaining Yukawa hierarchies, or in non-universal DFSZ models with $N_{DW} = 1$ and/or $C_N << 1$