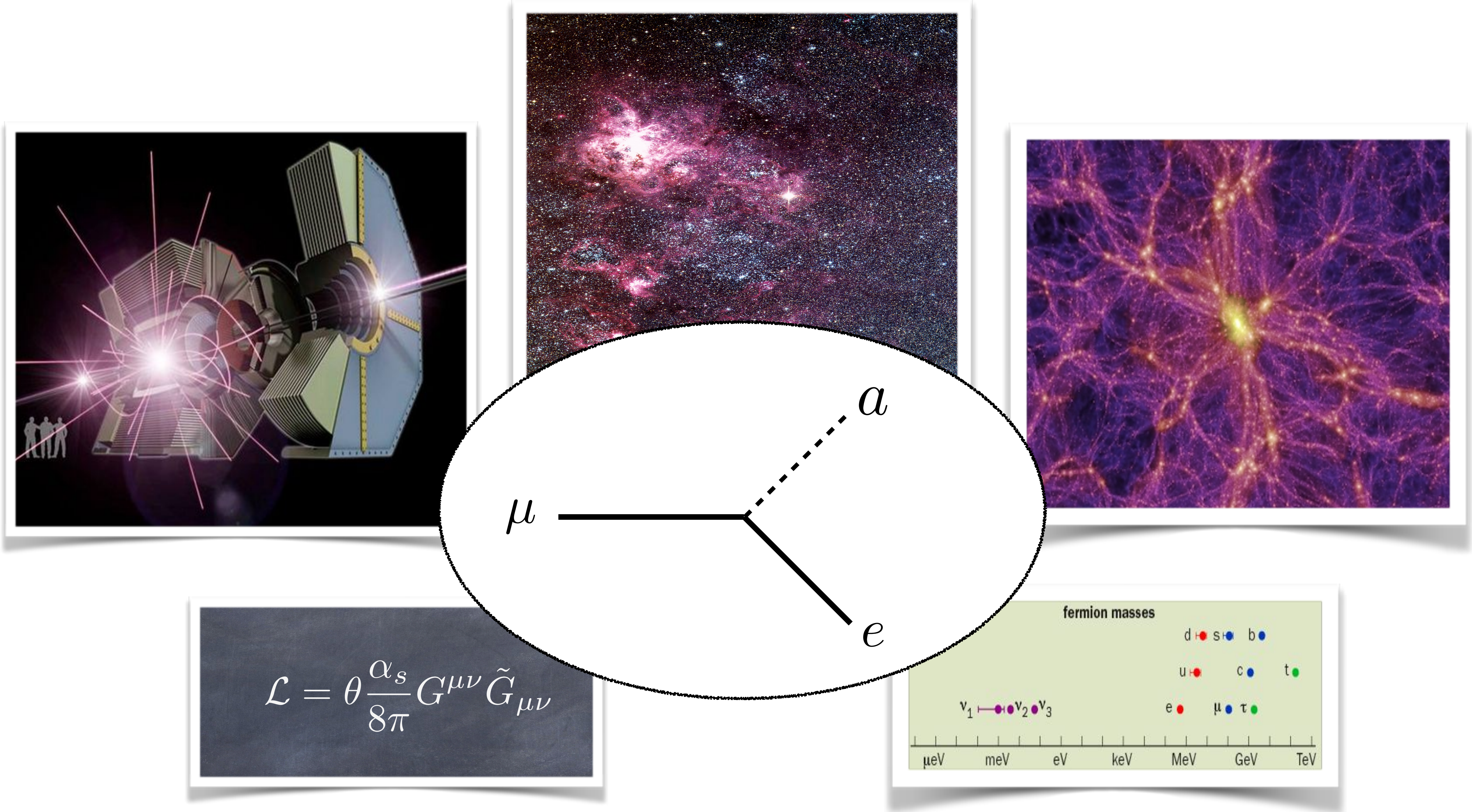
Flavored Axion Dark Matter in the Laboratory, the Stars and the Universe

Robert Ziegler (KIT)



Karlsruher Institut für Technologie

Axions as Dark Matter

The Axion is a very nice Dark Matter Candidate:

Goldstone boson of PQ symmetry broken at high scales

stable

$m_a \lll \mathrm{GeV}$

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

decoupled

$f_a \ggg \mathrm{TeV}$

$\Pi = e^{ia(x)/f_a}$

well motivated by strong CP problem: **QCD Axion**

$m_a \sim \Lambda_{\mathrm{QCD}}^2/f_a$

Axion Phenomenology

Most general axion couplings to SM described by EFT below PQ scale

$$\mathcal{L}_{\rm eff} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + C_{a\gamma}\frac{a}{f_a}\frac{\alpha_{\rm em}}{8\pi}F\tilde{F} + C_i\frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu\gamma_5 f_i$$

	$V(a), \pi\pi, NN, \ldots$	$\gamma\gamma$	$ee, \pi\pi, NN, \ldots$
Lab	**nEDM**	**haloscopes, helioscopes**	***e*-helioscopes**
Astro	**SN1987A**	**HB stars**	**SN1987A, WDs, RGs**
Cosmo	**Misalignment**	**Stability**	**Freeze-in**

Flavored Axion Phenomenology

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	$V(a), \pi\pi, NN, \dots$	$\gamma\gamma$	$ee, \pi\pi, NN, \dots$	$\mu e, K\pi, BK, BK^*, \Lambda n, \dots$
Lab	**nEDM**	**haloscopes, helioscopes**	***e*-helioscopes**	**Mu3e, NA62, Belle II**
Astro	**SN1987A**	**HB stars**	**SN1987A, WDs, RGs**	**SN1987A**
Cosmo	**Misalignment**	**Stability**	**Freeze-in**	**Freeze-in**

axion production from SM decays!

Flavor-violating Axion Couplings

- FV couplings determined by PQ charges in fermion mass basis

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

present whenever SM fermions carry PQ charges not aligned to Yukawas

- Decent scenario: PQ = flavor symmetry for Yukawa hierarchies Wilczek '82

$$U(1)_{\mathrm{PQ}} = U(1)_F$$

Calibbi, Goertz, Redigolo, RZ, Zupan '16; Ema et al '16

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

$$U(1)_{\mathrm{PQ}} \subset U(2)_F$$

Linster, RZ '18, Calibbi, Redigolo, RZ, Zupan '20

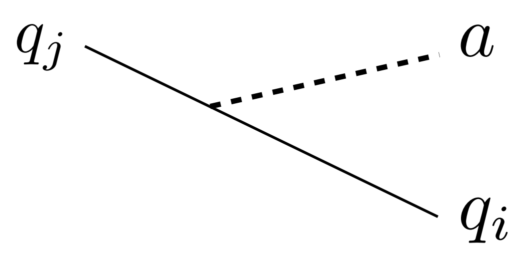
$$C^V_{d_i d_j} \sim (V_{\mathrm{CKM}})_{i3} (V_{\mathrm{CKM}})_{j3}$$

Constraints from Flavor Physics

Constrain flavor-violating couplings with SM decays + missing energy

⟶ look like SM decays with final state neutrino pair, but 2-body

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



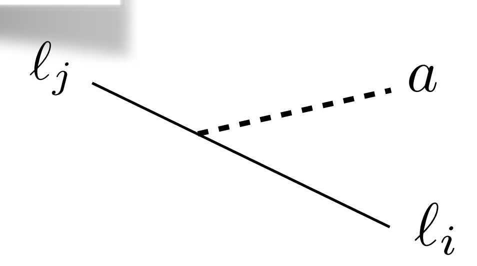
$s \to d$ $\quad c \to u$

$b \to d$ $\quad b \to s$

Quarks

SM background tiny

$\text{BR}(K \to \pi\nu\bar{\nu}) \sim 10^{-10}$



$\tau \to \mu$

$\tau \to e$

$\mu \to e$

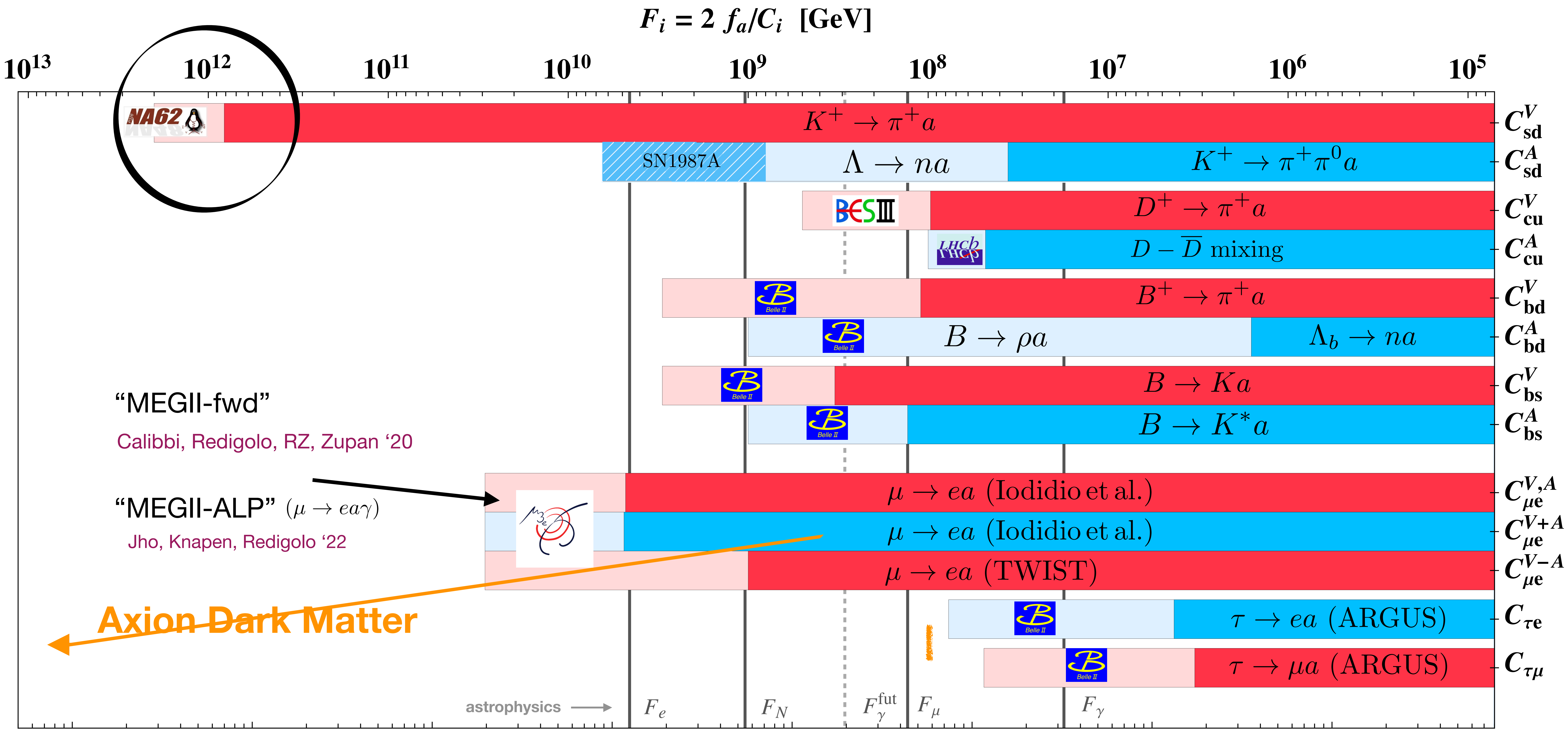
Leptons

SM background huge

$\text{BR}(\mu \to e\nu\bar{\nu}) = 1$

2-body decays probe much larger UV scales than 3-body decays

Constraints from Flavor Physics



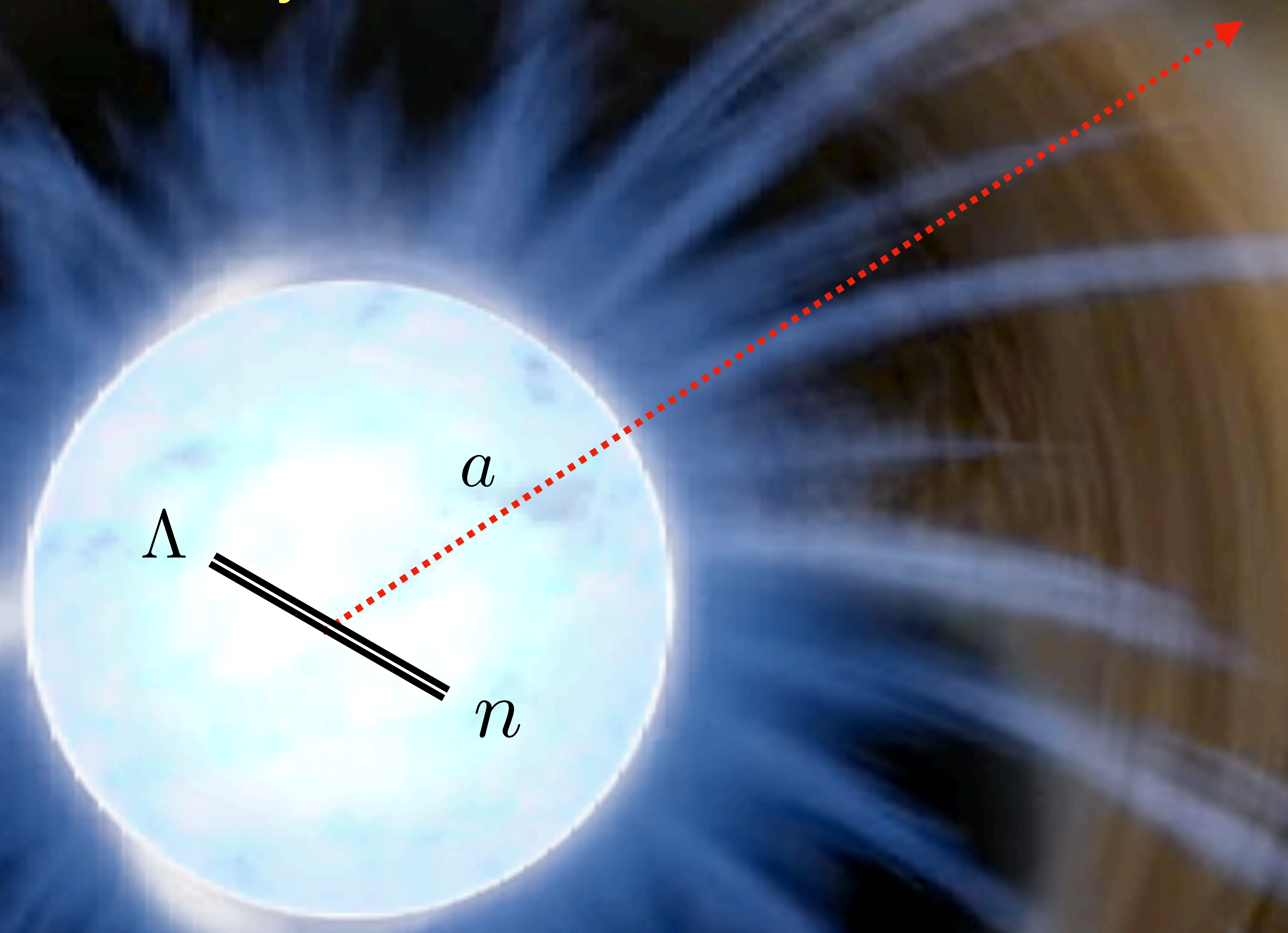
Calibbi, Redigolo, RZ, Zupan '20 Martin Camalich, Pospelov, RZ, Vuong, Zupan '20

Constraints from Astrophysics

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



Estimate energy loss rate per volume:

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

Gives model-indep. bound on invisible hyperon decays:

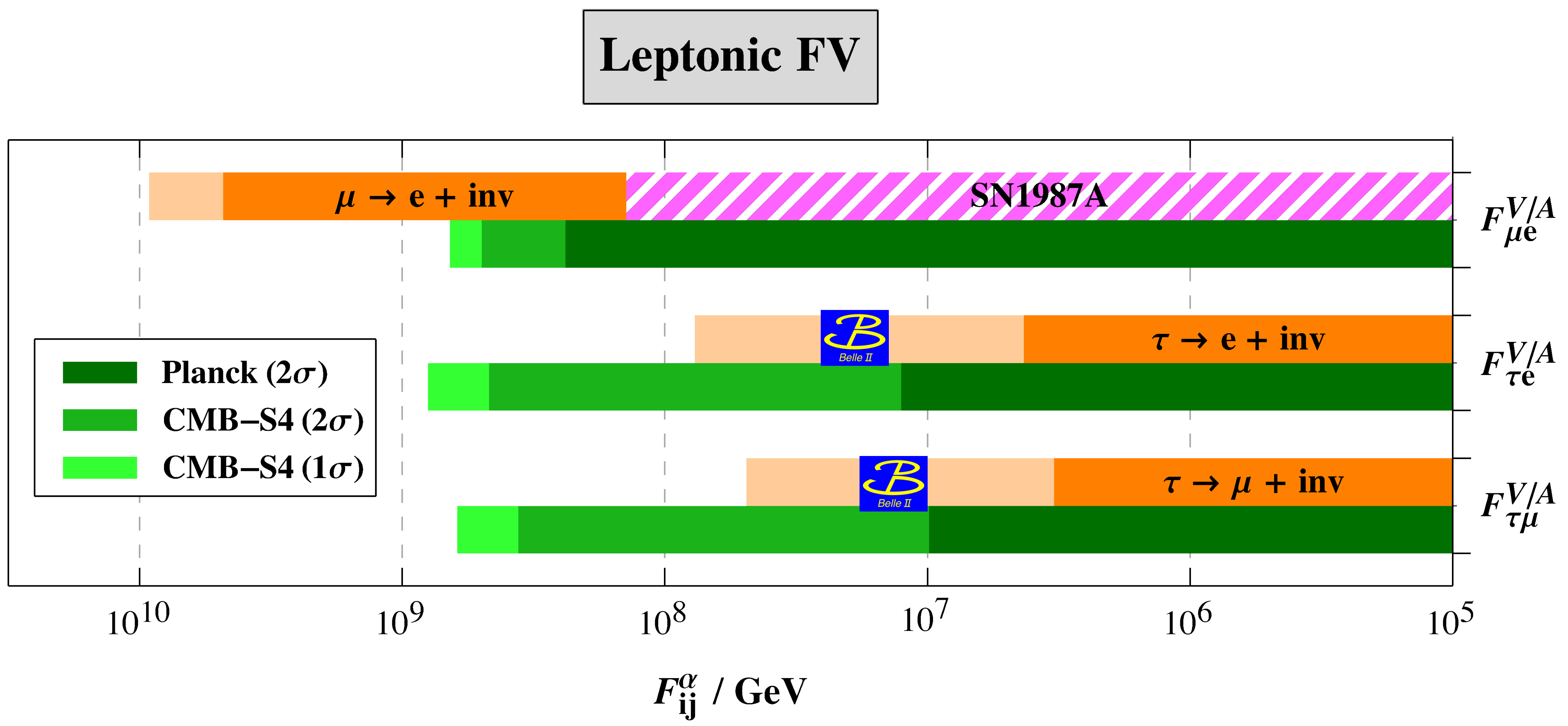
$$\mathrm{BR}(\Lambda \to nX^0) \lesssim 5.0 \times 10^{-9}$$

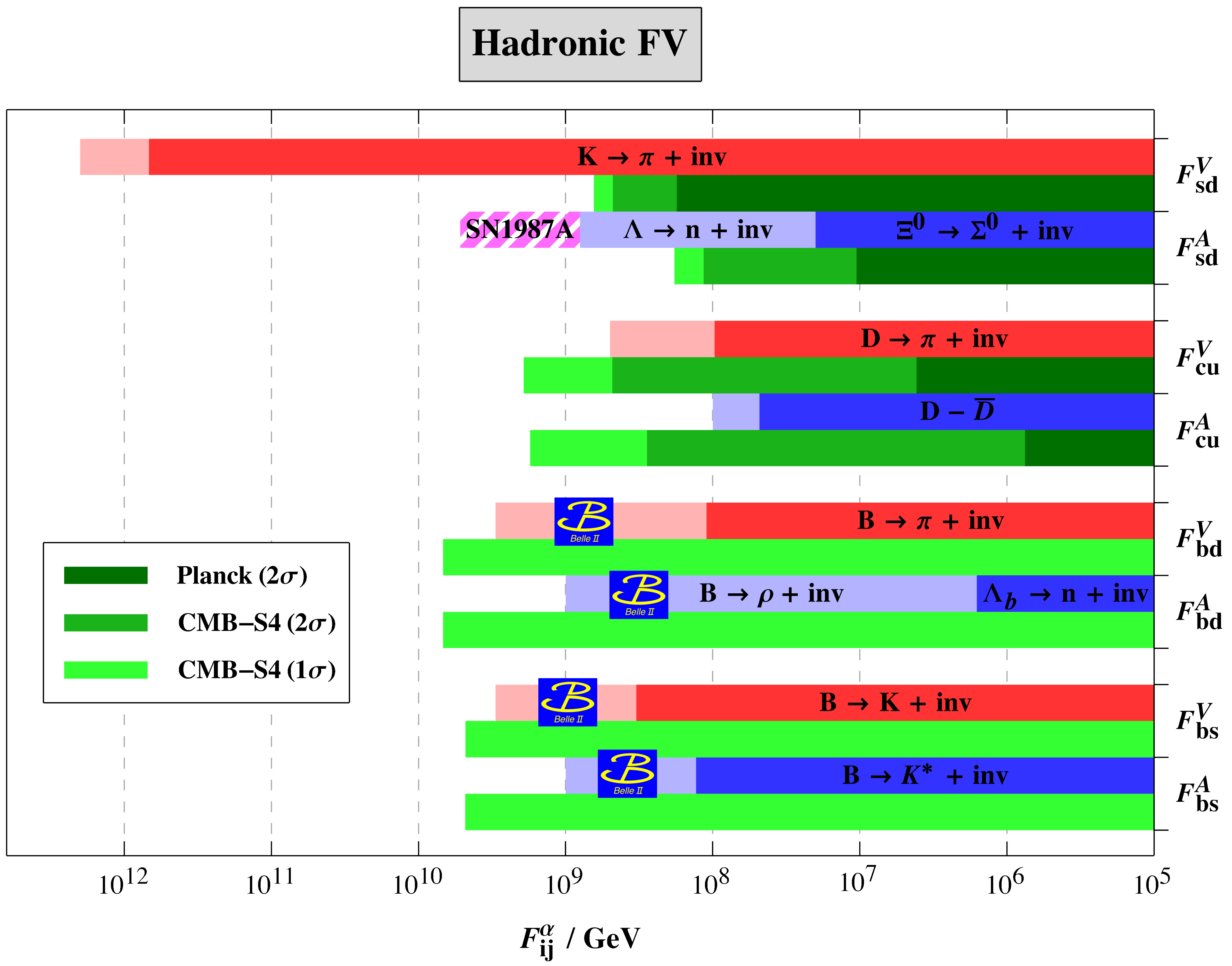
Martin Camalich, Terol-Calvo, Tolos, RZ ‘20

Constraints from Cosmology

Flavor-violating SM decays can produce axions in early universe

very light axions constrained by bounds on Dark Radiation from CMB D'Eramo, Yun '21





→ Belle-II will compete with future CMB telescopes

A simple Model of LFV ALP DM

- Freeze-in production of ALP DM from LFV decays of SM leptons

to appear, with D. Redigolo, P. Panci, T. Schwetz

Charge right-handed SM leptons under PQ as (1,-1,0) in flavor space —in mass basis / for 1-2 rotation→

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

- ALP decays suppressed if sufficiently light (no EM anomaly)

$$\Gamma_{a\to\gamma\gamma} = \sin^2\alpha \frac{\alpha_{\rm em}^2}{64\pi^3}\frac{m_a^3}{f_a^2}\frac{m_a^4}{144 m_e^4}$$

($m_a \ll m_e$)

ALP is VERY stable →

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

- Freeze-in via μ-decays gives DM abundance for suitable m_a and f_a

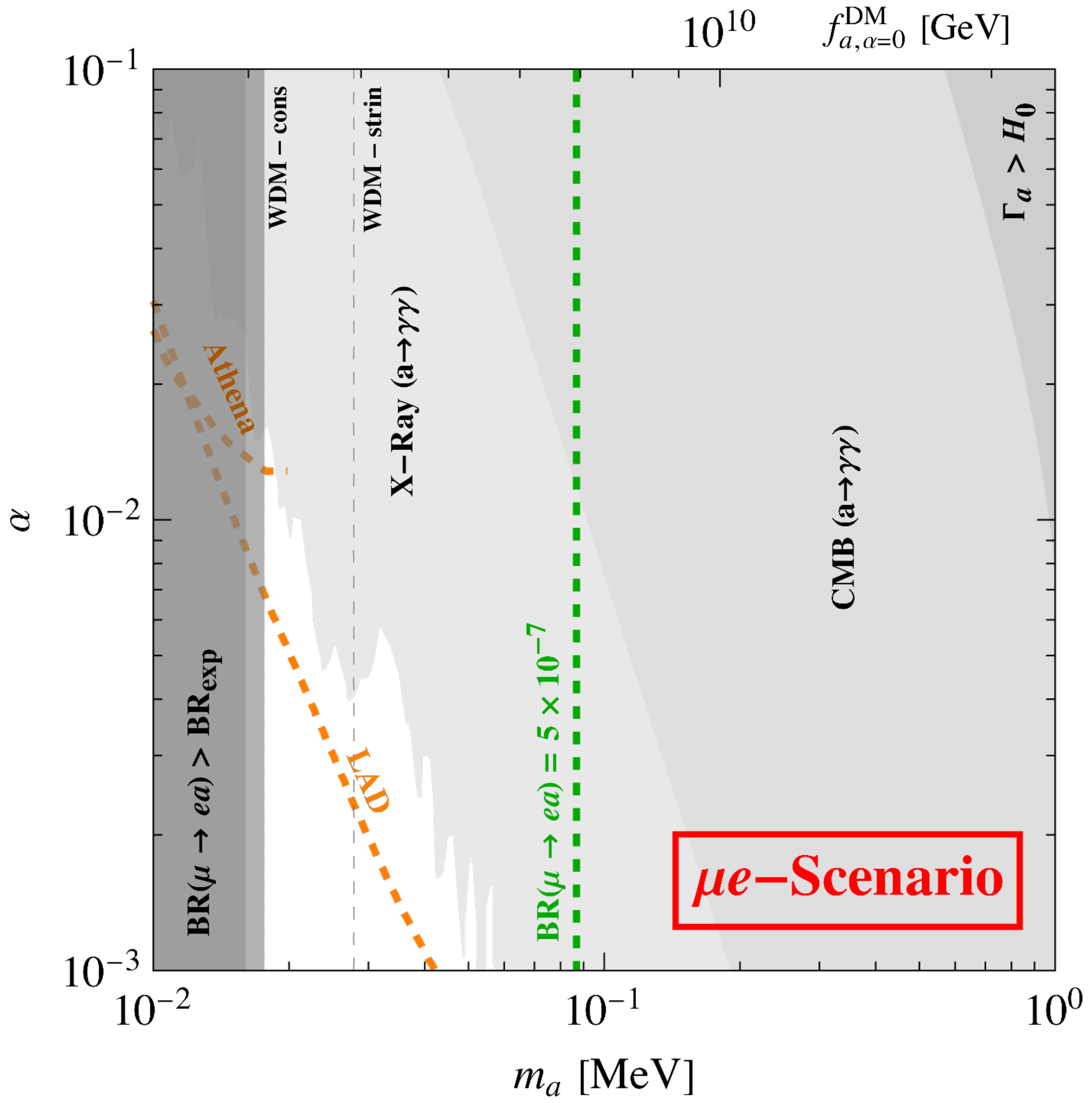
$$\Omega_a h^2|_{\ell_i\to\ell_j a} \approx 4.4\times 10^{27}\frac{\Gamma(\ell_i\to\ell_j a)}{g_*^{3/2}(m_{\ell_i})}\frac{m_a}{m_{\ell_i}^2}$$

$\Gamma \propto m_{\ell_i}^3 \cos^2\alpha / f_a^2$ →

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

ALP Dark Matter from LFV Decays

Get 2d parameter space subject to flavor & cosmology constraints



Axion searches at Mu3e look for same LFV decay that has produced DM in early universe

Summary

- QCD axions with flavor-violating couplings can be searched for by precision flavor experiments, probing decay constants of 10^{12} GeV

- SN1987A gives best constraints on flavor-violating hyperon decays to invisibles

- LFV decays of SM leptons can yield axion DM via thermal freeze-in: simple class of DM models that can be tested at Mu3e and MEG-II