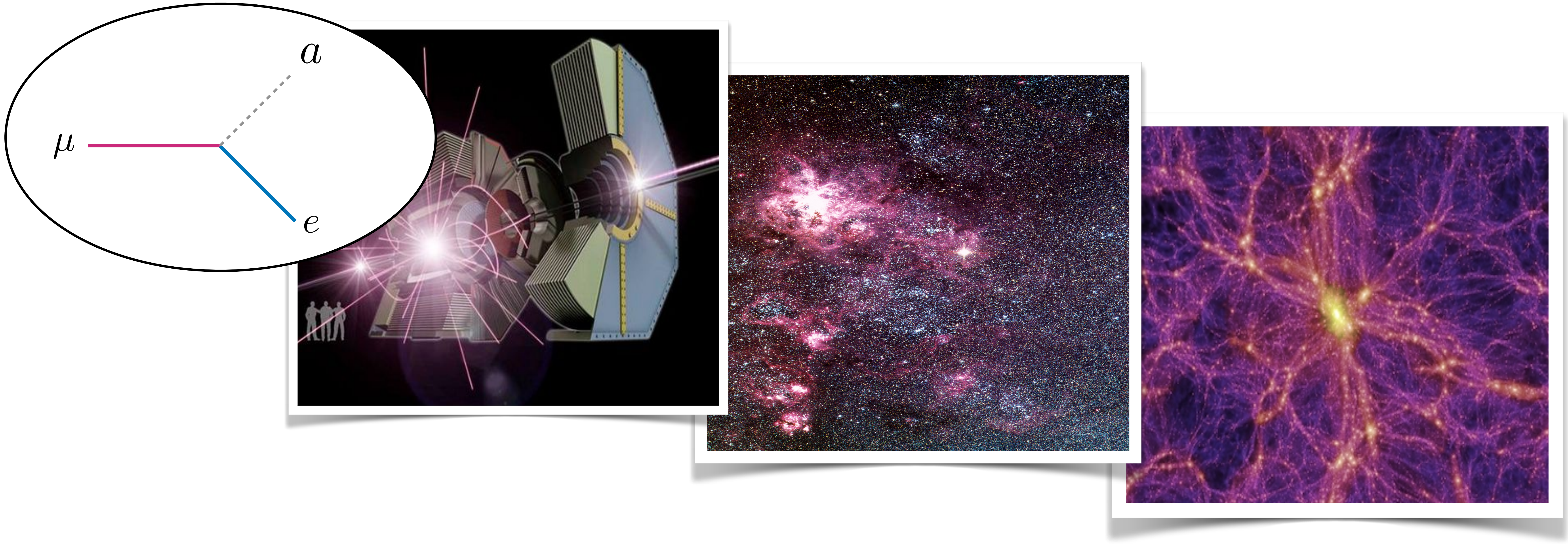
Probing Axion Dark Matter with Flavor Factories

Robert Ziegler



DPG Spring Meeting 2024

based on:
PRD 102 (2020) with Martin Camalich, Pospelov, Vuong, Zupan
JHEP 09 (2021) with Calibbi, Redigolo, Zupan
PLB 841 (2023) with Panci, Redigolo, Schwetz

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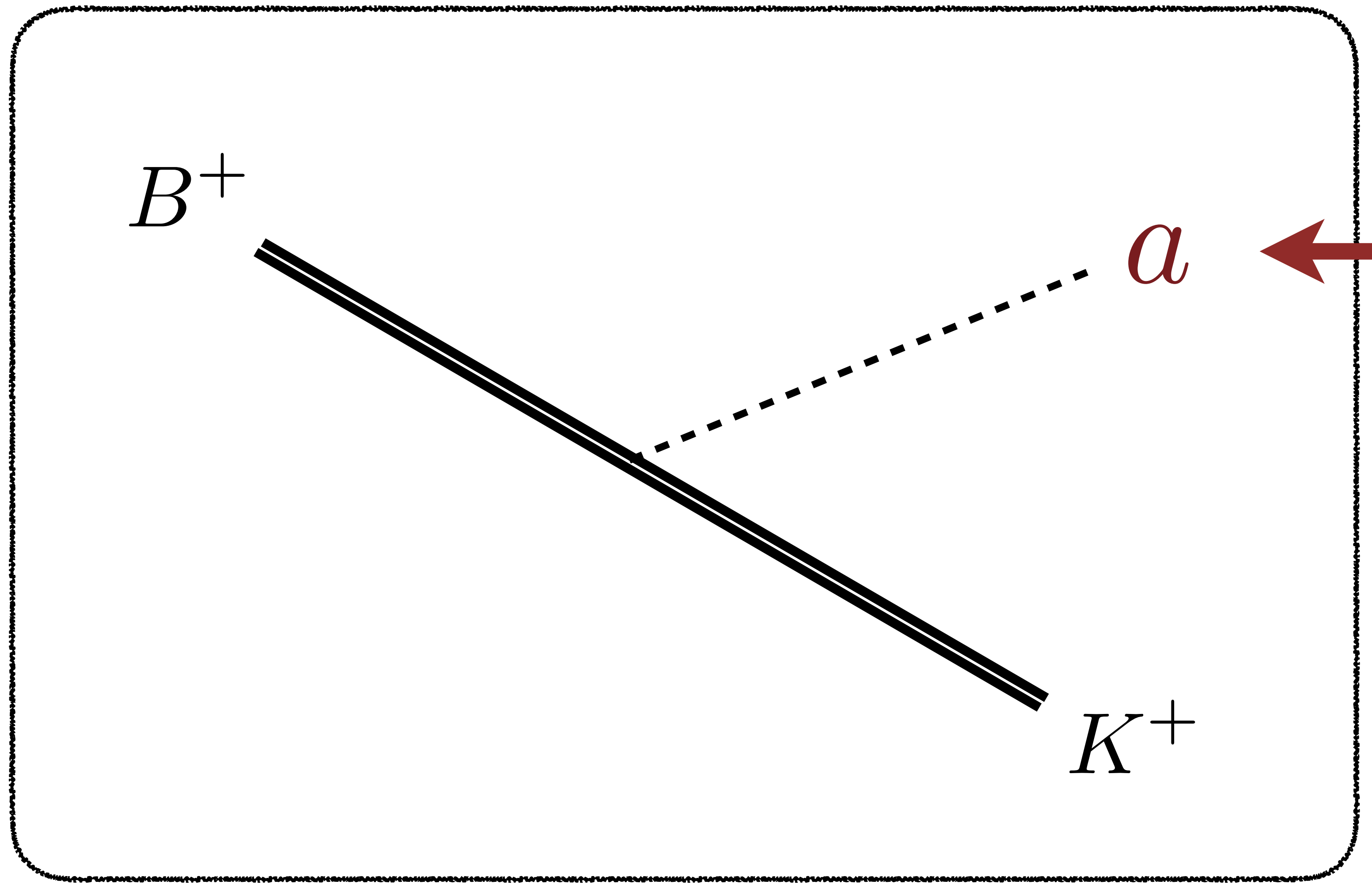
Outline

2-body decays of SM particles with missing energy are excellent probe of new light bosons, which can fully account for observed DM abundance



Dark Matter particle

stable

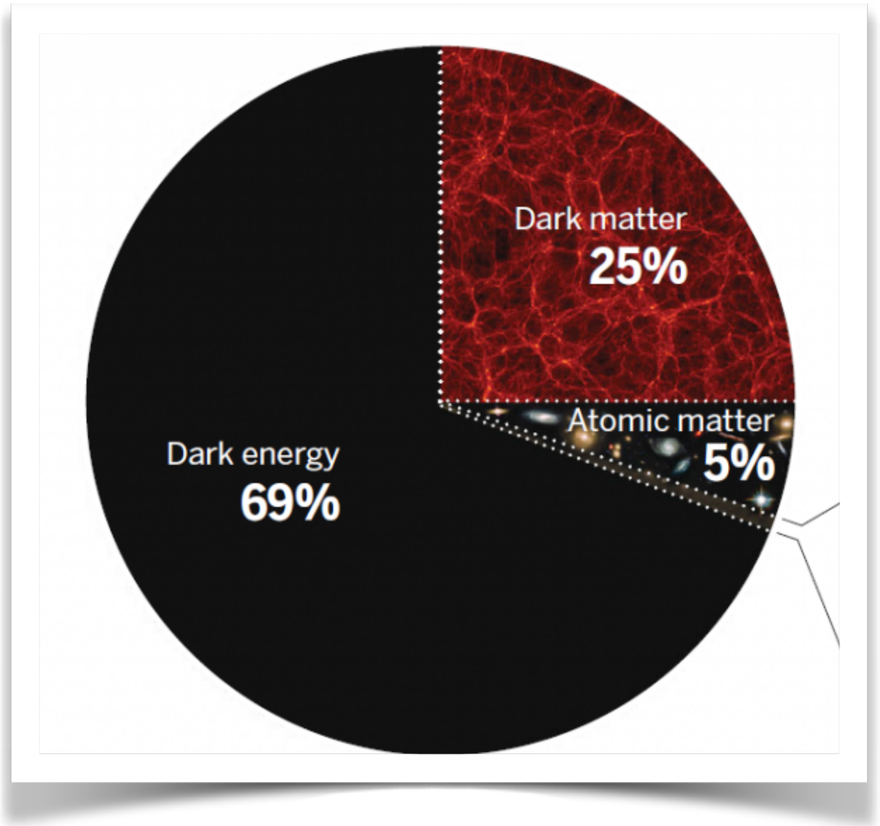
$\tau_a \gg 10^{17}\mathrm{s}$

invisible

$\Lambda_{\mathrm{UV}} \gtrsim 10^9\mathrm{GeV}$

light

$m_a \ll \mathrm{GeV}$



Excellent theory motivation:

- ⋆ QCD Axion produced via misalignment
- ⋆ ALP produced via thermal freeze-in

The Strong CP Problem

- SM contains topological QCD θ-term, which violates P and CP

$$\Delta\mathcal{L}_{\rm SM} = \theta \frac{\alpha_s}{16\pi} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

- Contributes to neutron EDM, which has stringent upper exp. limit

Pospelov, Ritz '99; nEDM@PSI '20

$$|d_n| \approx 2.4(1.0) \times 10^{-26} e\,{\rm cm} \times \left(\frac{\sin\theta}{10^{-10}}\right)$$

difficult to explain small θ with symmetries or anthropic arguments

The QCD Axion Solution

- Non-perturbative QCD generates potential for θ, with trivial minimum

$$V_\theta = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\theta}{2}} \approx -m_\pi^2 f_\pi^2 \left|\cos \theta/2\right|$$

…just need to promote θ to scalar field without potential

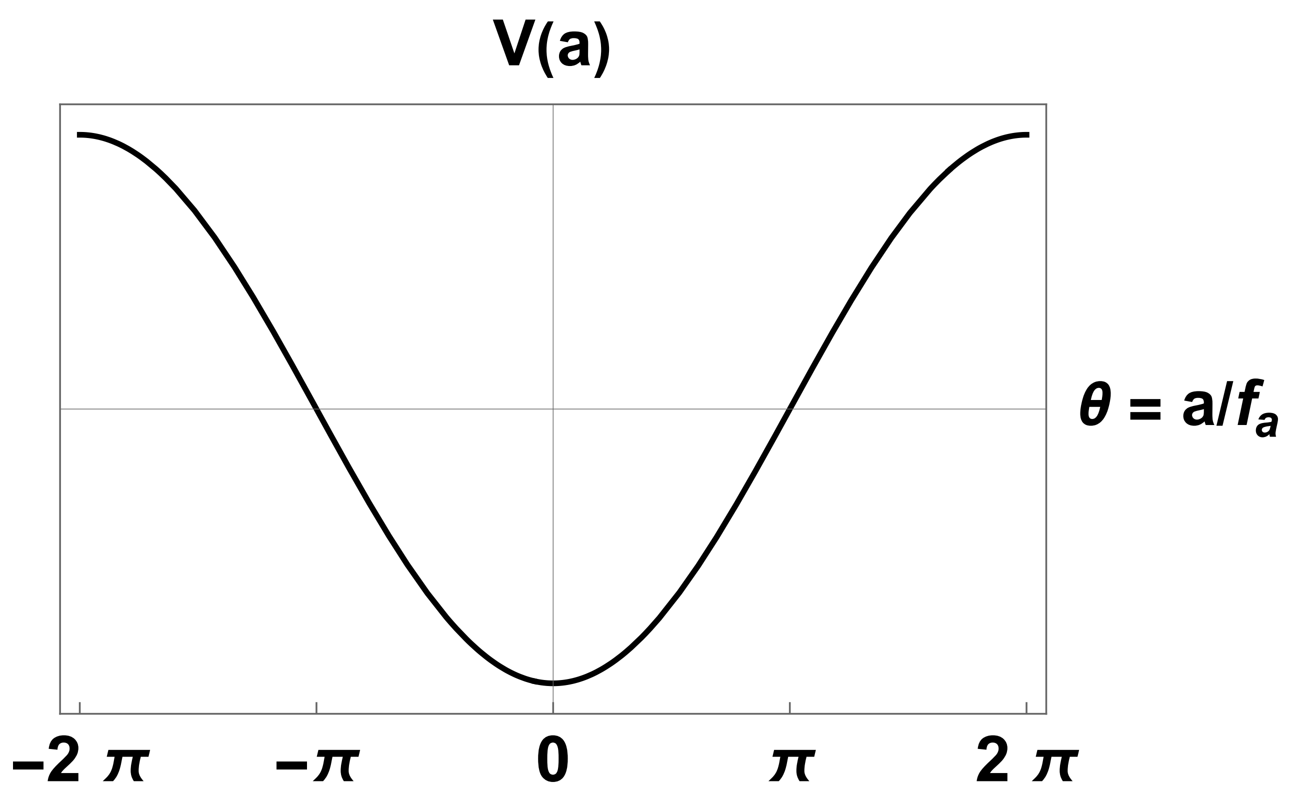
$$\theta \rightarrow \frac{a(x)}{f_a}$$

- Realized if Goldstone boson of new global, anomalous $U(1)_{PQ}$ symmetry

Peccei, Quinn '77; Wilczek; Weinberg '78

The QCD Axion Mass

- Same potential solves Strong CP Problem and generates axion mass



$$\longrightarrow \quad \theta_{\text{eff}} = \langle a(x) \rangle / f_a = 0$$

$$\longrightarrow \quad m_a \approx \frac{m_\pi f_\pi}{f_a} = 5.691(51) \left(\frac{10^9 \text{GeV}}{f_a} \right) \text{meV}$$

Grilli di Cortona, Hardy, Pardo Vega, Villadoro '15

- Generalized to "axion-like" particle (ALP) taking mass as free parameter

  does usually not solve Strong CP Problem

Axion Dark Matter

- Axion is easily stable on cosmological scales, since Goldstone boson

$$\Gamma(a \to \gamma\gamma) \simeq \frac{1}{10^{19}\mathrm{sec}} \left(\frac{m_a}{\mathrm{keV}}\right)^3 \left(\frac{10^9\mathrm{GeV}}{f_a}\right)^2 \simeq \frac{1}{10^{37}\mathrm{sec}} \left(\frac{10^9\mathrm{GeV}}{f_a}\right)^5$$

for QCD axion

$m_a f_a \approx m_\pi f_\pi$

- Can be produced in early Universe in many ways: misalignment, decays of topological defects, thermal freeze-in, …

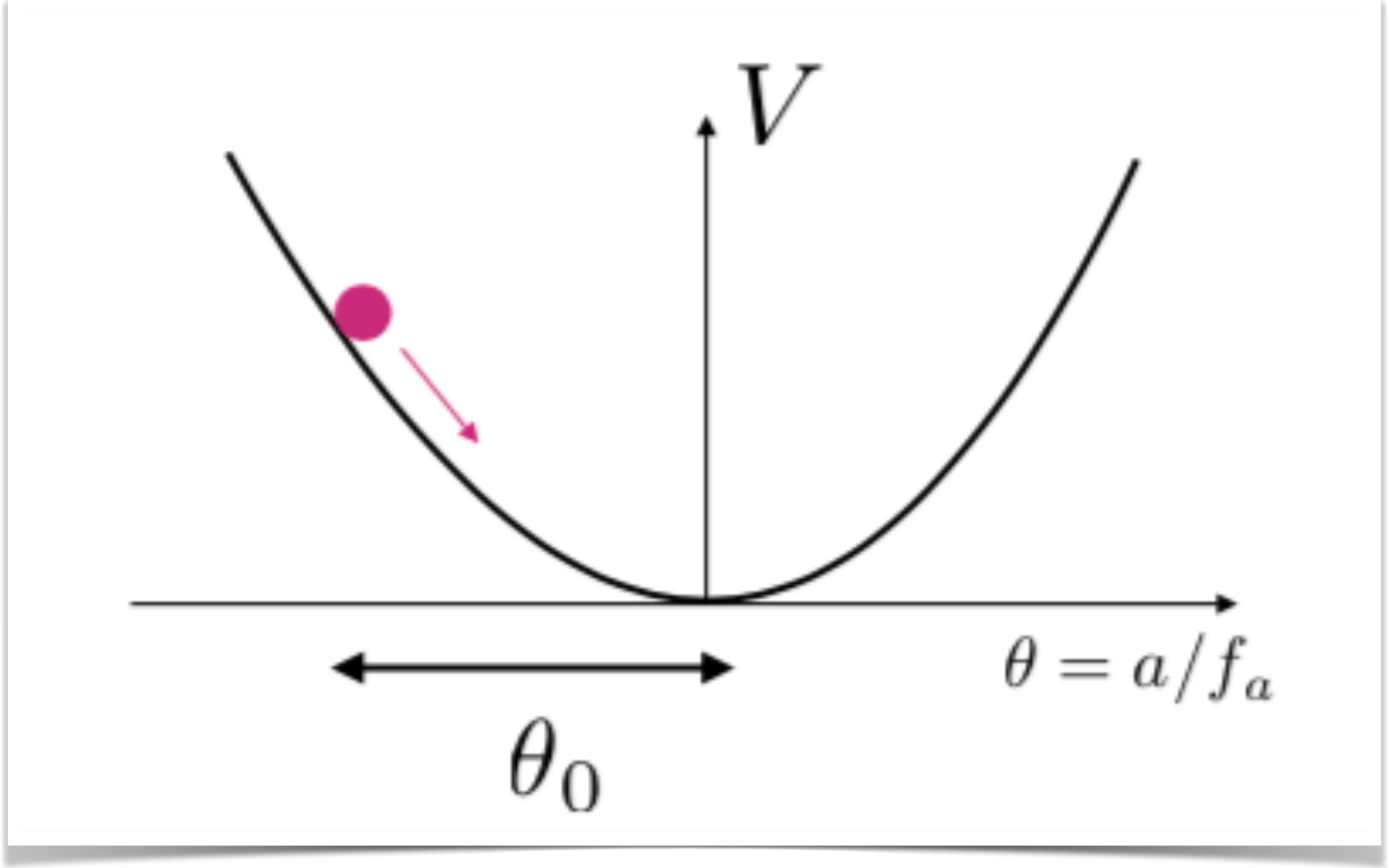
Axion Production: Misalignment

- Evolution of homogenous classical scalar field in expanding universe

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

Hubble friction ~T^2 (↑ $3H\dot{a}$)

thermal mass (↑ m_a^2) $= \begin{cases} 0 & T \gg \Lambda_{QCD} \\ m_a & T \ll \Lambda_{QCD} \end{cases}$



- Energy stored in oscillations behaves just like Cold Dark Matter

$$\Omega_a h^2 = 0.2 \times \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^{7/6} \theta_0^2$$

Preskill, Wise, Wilczek / Abbott, Sikivie / Dine, Fischler ’83

Axion Phenomenology

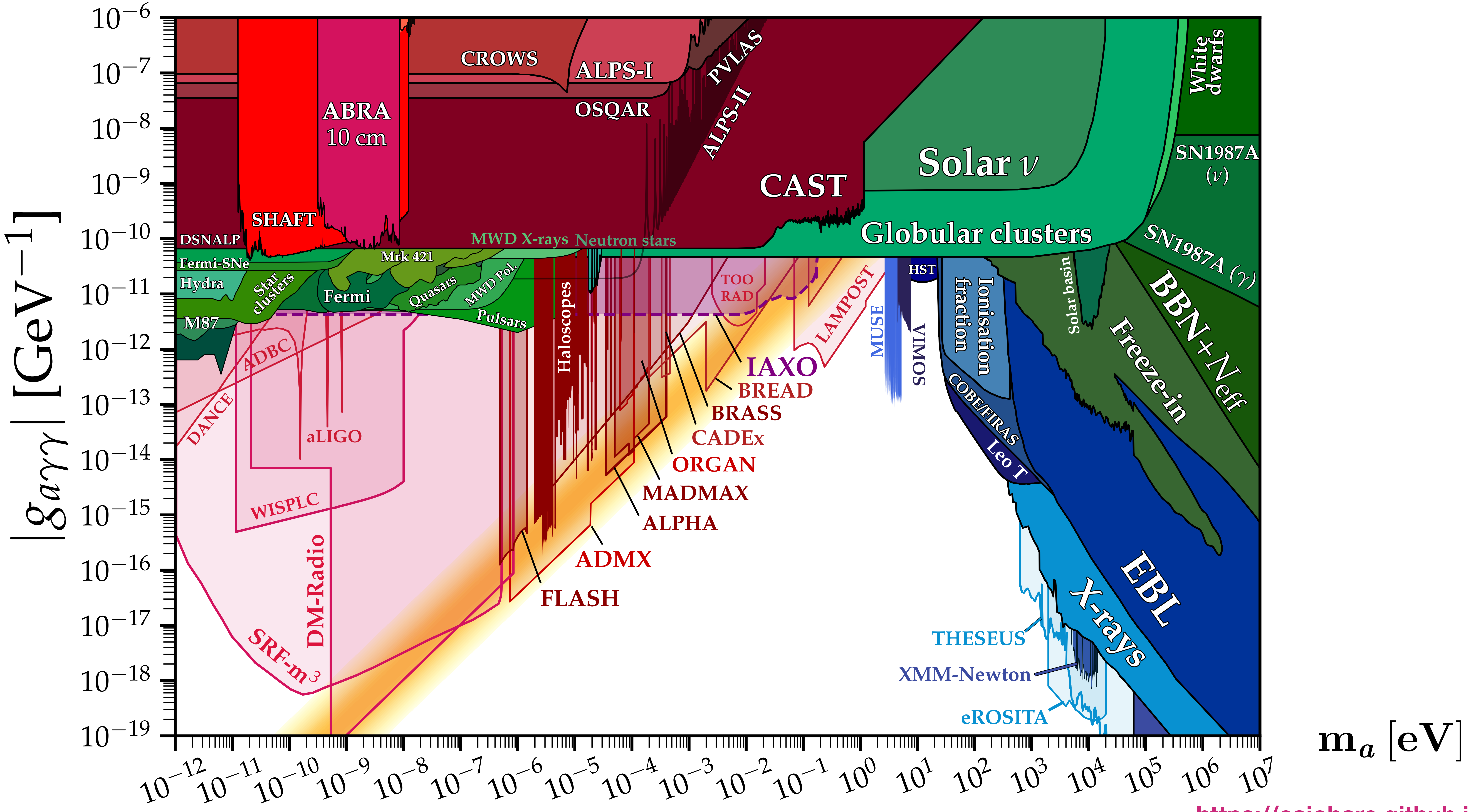
- Most general axion couplings to SM described by EFT well below breaking scale of PQ symmetry

Georgi, Kaplan, Randall ’86

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

solves Strong CP Problem & generates axion mass	contributes to axion couplings to photons	axion couplings to fermions (**in general flavor-violating**)
probed with oscillating nEDM	probed with Halo- & Helioscopes	**probed with Flavor Factories**

Present Constraints and Prospects: Photons



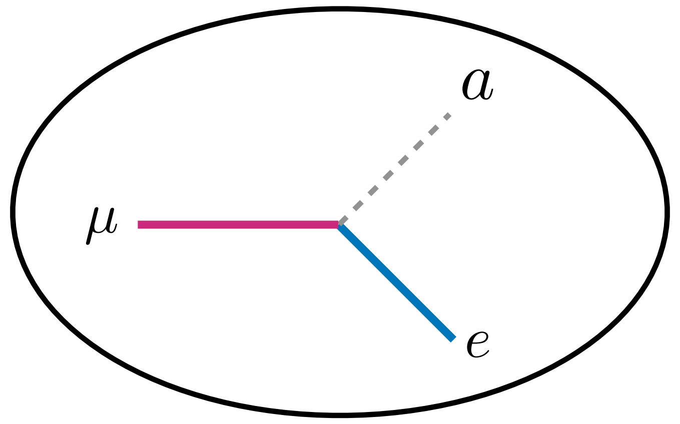
https://cajohare.github.io/AxionLimits

Flavor-violating Axions

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

- Allow axion production from tree-level decays of SM particles

$$\mu \to ea\,, \quad \tau \to ea\,, \quad K \to \pi a\,, \quad \Lambda \to na\,, \quad B \to \rho a\,, \quad \ldots$$



★ particle colliders → **direct searches**

★ core-collapse supernovae → **energy loss**

★ early Universe → **freeze-in DM**

Origin of Flavor-Violating Couplings

- 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 $V^\dagger_{d_L} Y_d V_{d_R} = V_d^{\mathrm{diag}}$

Flavor violation present whenever fermion charges are not aligned to fermion masses

$$\left[Y_d Y_d^\dagger, \mathrm{PQ}_q\right] \neq 0$$

- Predictive when PQ = flavor symmetry addressing SM Flavor Puzzle

Wilczek '82

e.g. $U(1)_{\mathrm{PQ}} = U(1)_F \longrightarrow C^V_{d_i d_j} \sim (V_{\mathrm{CKM}})_{ij}$ predicts sizable light quark transitions

Calibbi, Goertz, Redigolo, RZ, Zupan '16

Axion Production in Flavor Factories

- Study 2-body meson/lepton decays with missing energy
  look like SM decays with neutrino pair, but monochromatic

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

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

- Explicit search interesting, since 2-body decays probe **large UV scales**

Light new bosons

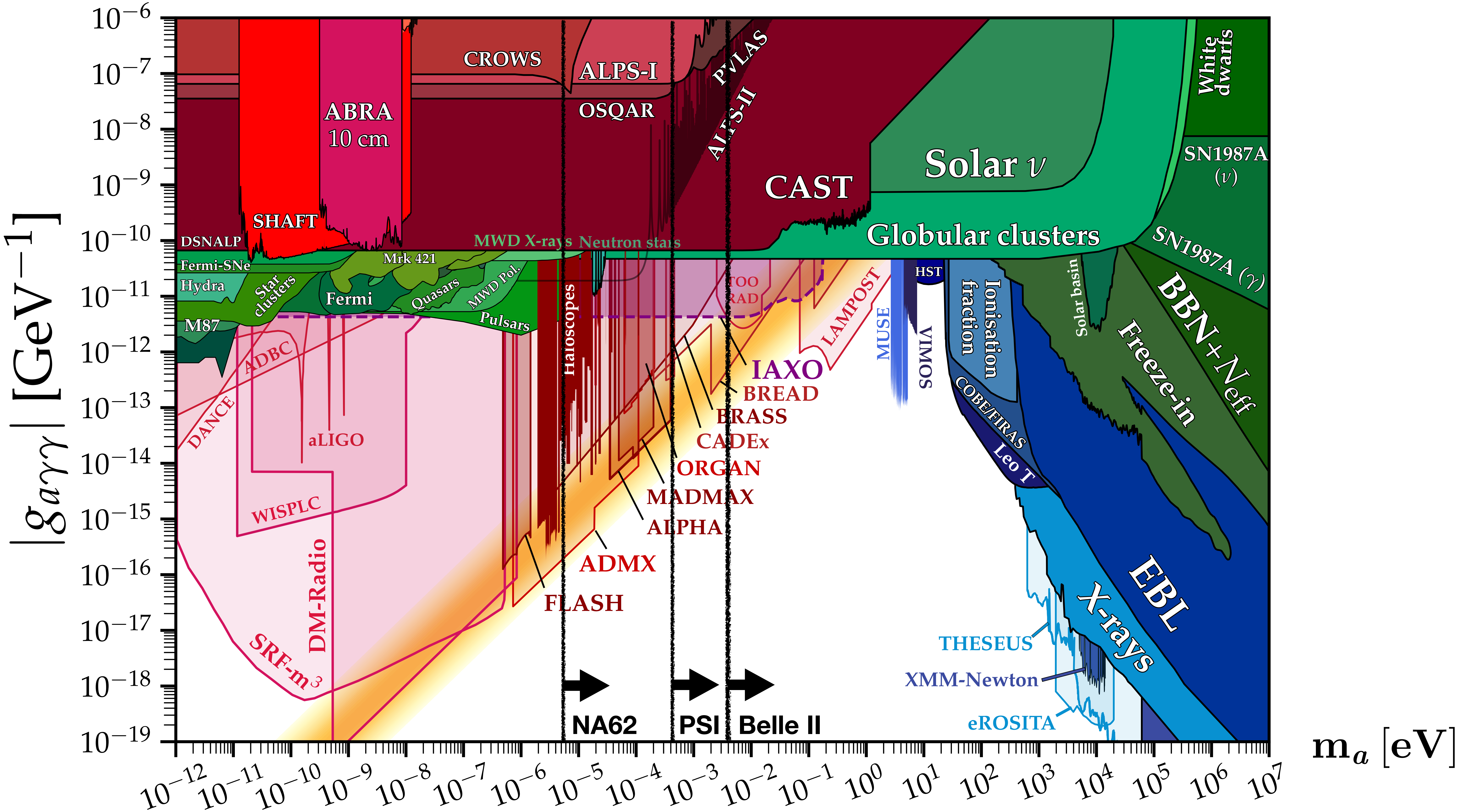
$$\frac{\partial_\mu a}{f_a} \bar{b} \gamma^\mu s \xrightarrow{B \to K a} f_a \gtrsim 10^5 \text{ TeV}$$

$$\xrightarrow{B_s - \text{mixing}} f_a \gtrsim 800 \text{ TeV}$$

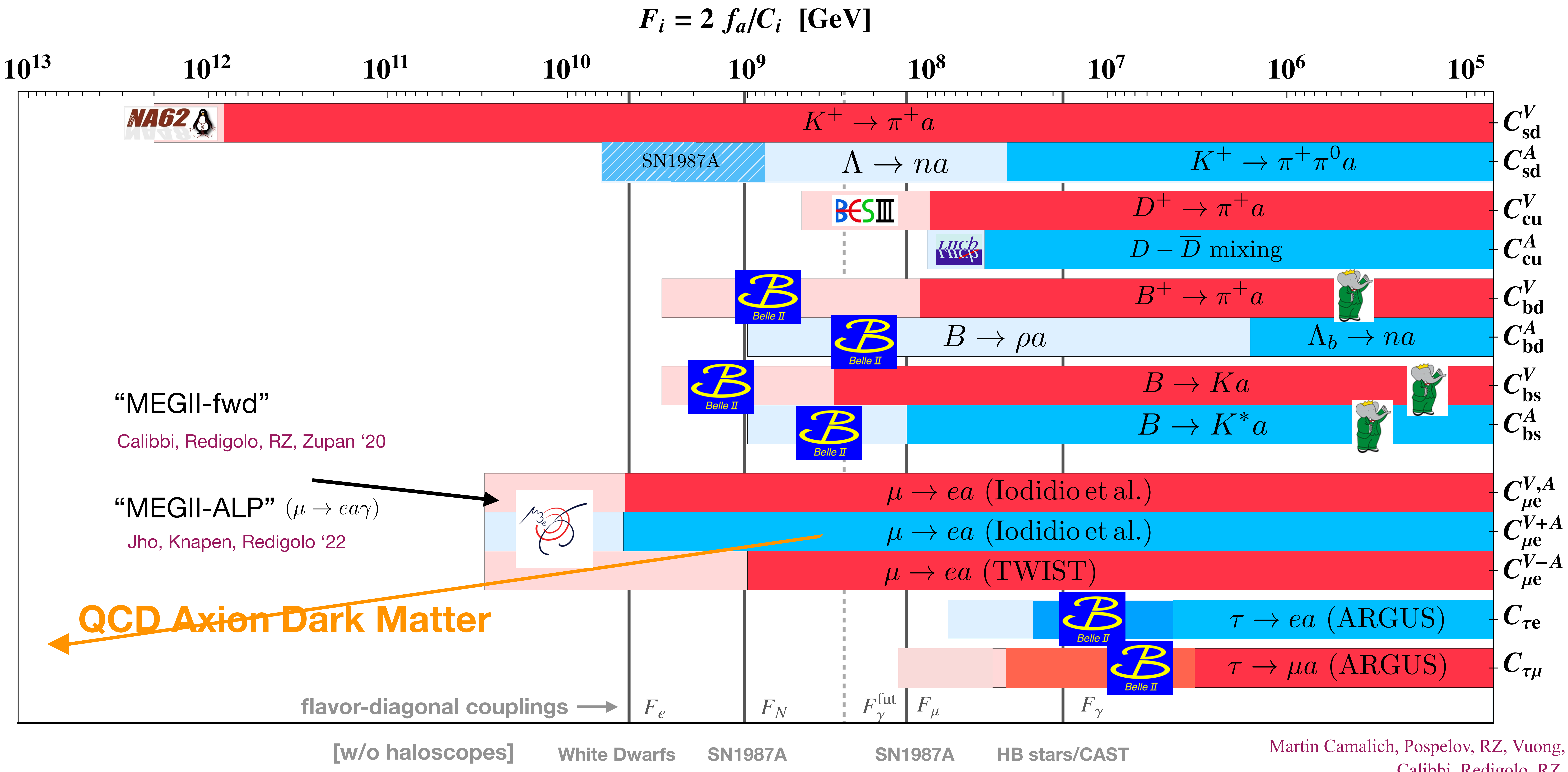
Heavy new dofs (SMEFT)

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

Present Constraints and Prospects: Flavor

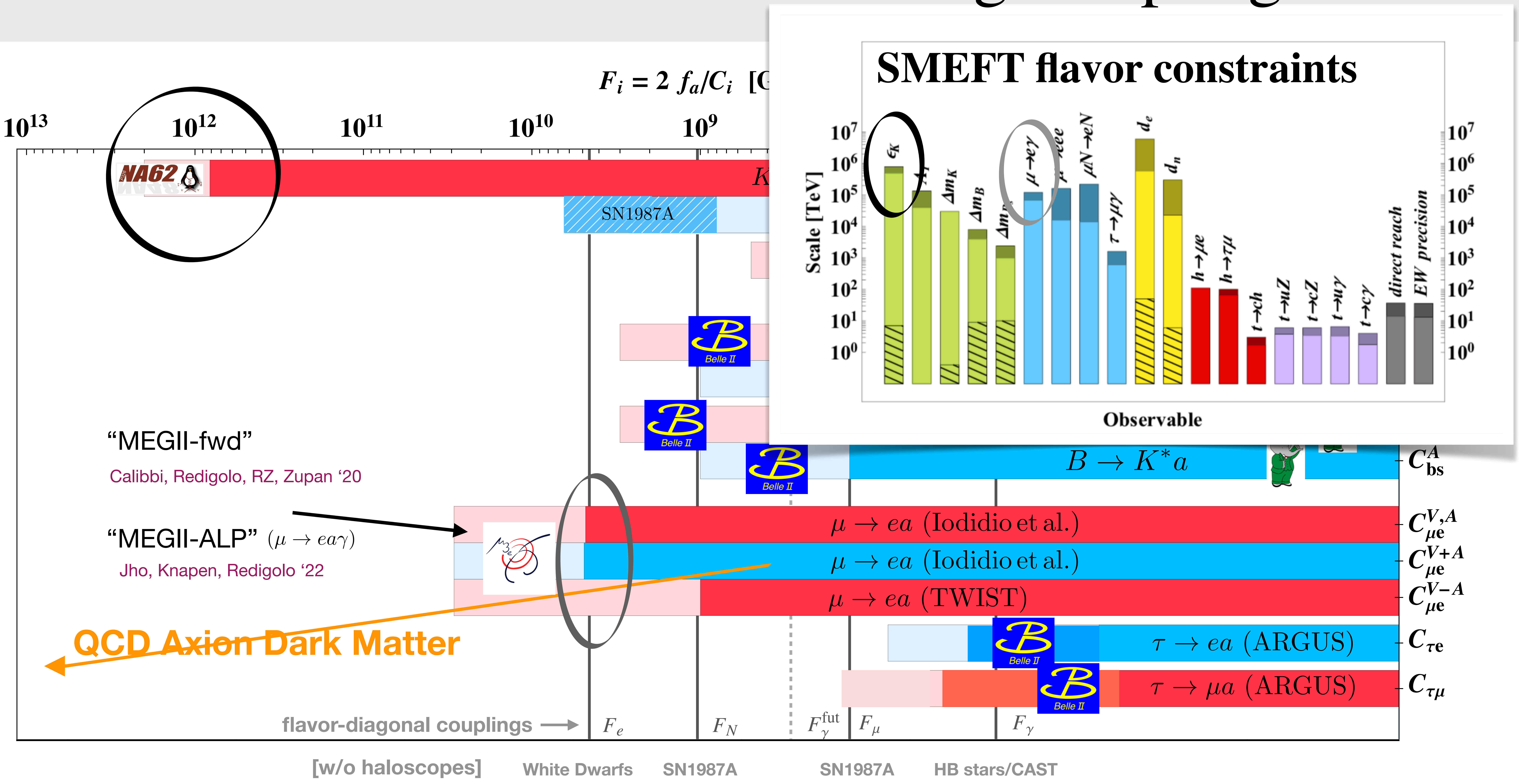


Constraints on Flavor-violating Couplings



Martin Camalich, Pospelov, RZ, Vuong, Zupan '20
Calibbi, Redigolo, RZ, Zupan '21

Constraints on Flavor-violating Couplings

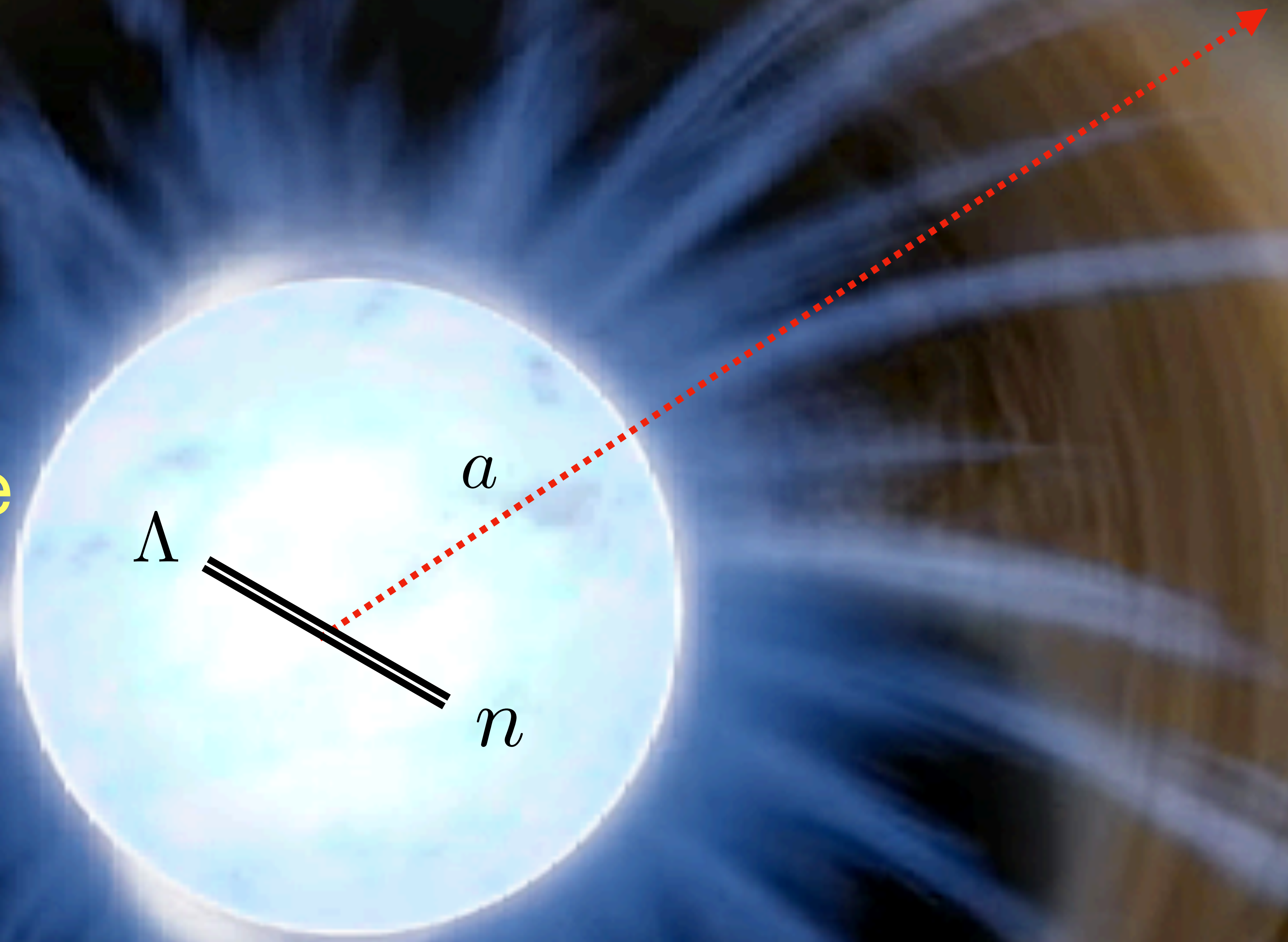


Constraints from SN1987A

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 that would have shorten observed neutrino pulse of SN1987A: limits energy loss rate



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

Gives best bound on invisible hyperon decays

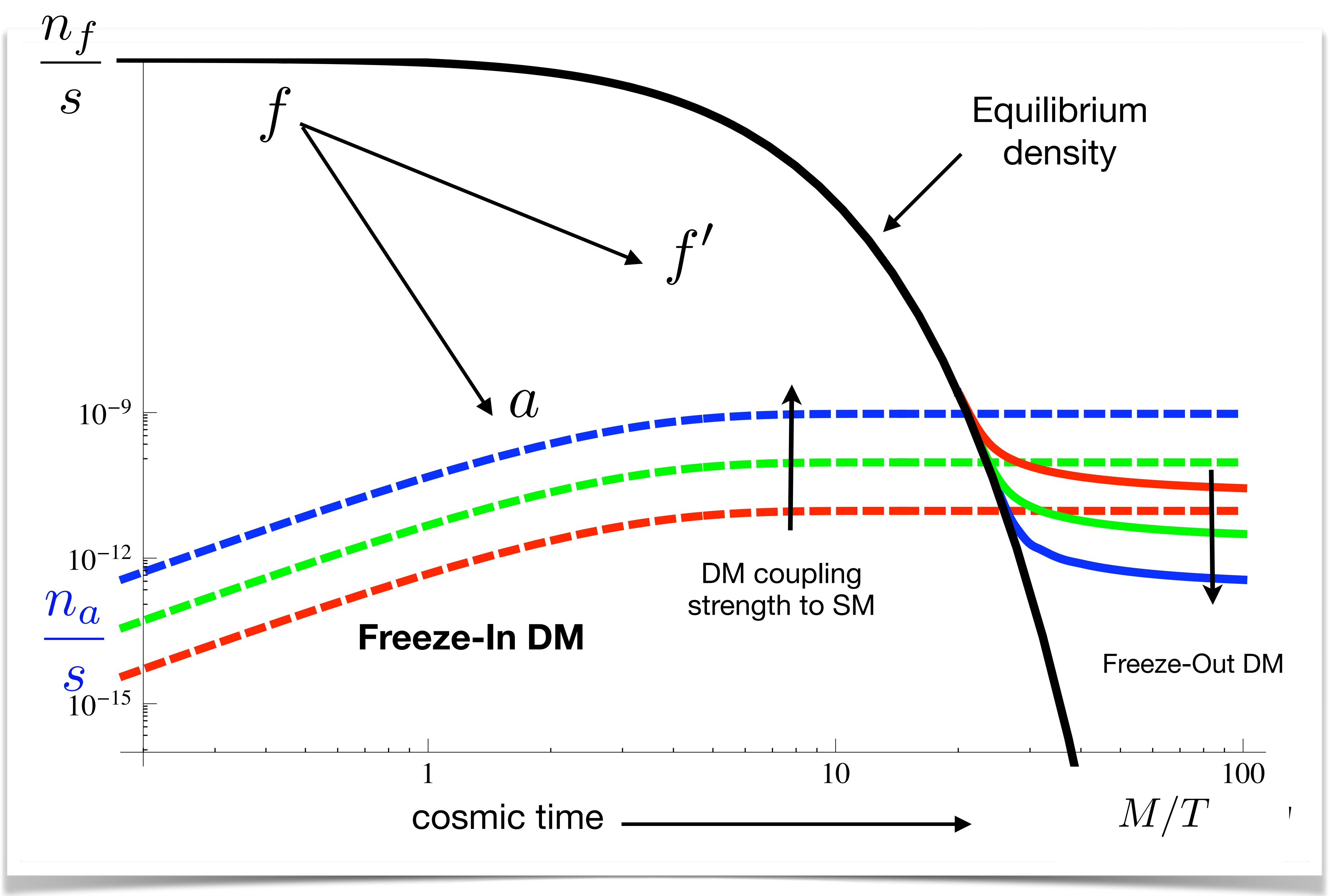
$$\mathrm{BR}(\Lambda \to na) \lesssim 5.0 \times 10^{-9}$$

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

Axion DM Production: Thermal Freeze-In

- DM has couplings to SM so tiny that never in thermal equilibrium

  Continuously produced from SM decays (and scattering), until SM particles become non-relativistic



for decay of SM particle *f* with mass M

- DM abundance determined by product of DM mass & decay rate

$$\Omega_a h^2 \approx 0.2 \left(\frac{m_a/M}{10^{-3}}\right)\left(\frac{\Gamma_{f\to f'a}/M}{10^{-22}}\right)$$

Hall, Jedamzik, March-Russell, West '09

ALP Dark Matter from SM Decays

- Use flavor-violating SM decays for freeze-in production of ALP DM

Panci, Redigolo, Schwetz, RZ ‘23

DM abundance fixes decay rate

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

→ requires ALP mass in suitable window

(lab searches vs. kinematic threshold)

DM stability is challenging

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

X-ray telescopes

→ requires suppressed photon coupling

(anomaly-free, coupling/mass hierarchy)

Benchmark Models

- Simple ALP DM models with 3 parameters for given flavor transition

e.g. "μe-Scenario"

$$\mathcal{L}_a = \frac{\partial_\mu a}{2 f_a} \begin{pmatrix} \bar{e} \\ \bar{\mu} \end{pmatrix}^T \begin{pmatrix} \sin\alpha & \cos\alpha \\ \cos\alpha & -\sin\alpha \end{pmatrix} \gamma^\mu \gamma_5 \begin{pmatrix} e \\ \mu \end{pmatrix} - \frac{1}{2} m_a^2 a^2$$

overall coupling | relative coupling | ALP mass

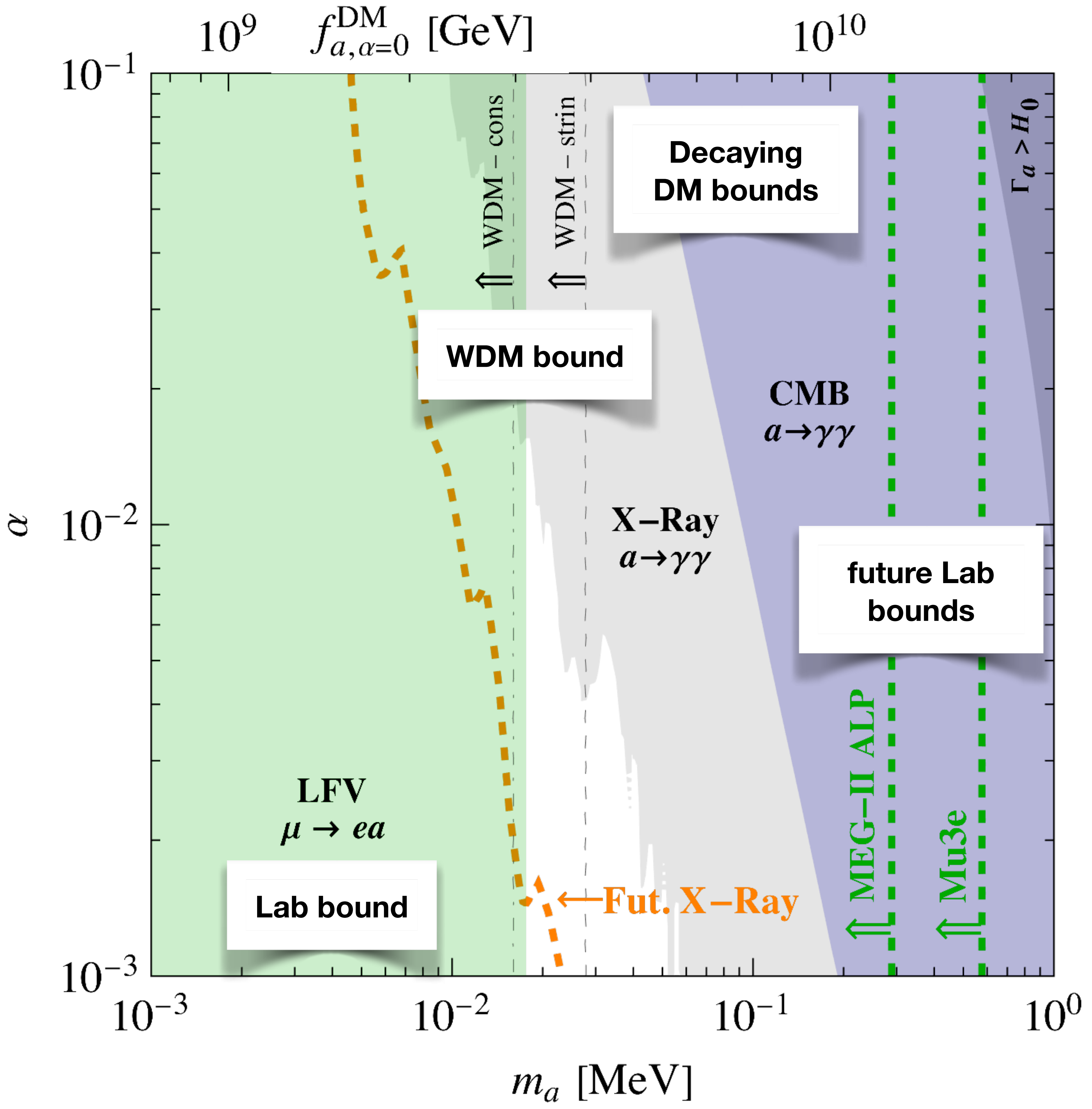
$$\Gamma(\mu \to e a) \propto \frac{\cos^2\alpha}{f_a^2}$$ → bounded by flavor factories and structure formation ("Warm DM")

$$\Gamma(a \to \gamma\gamma) \propto \frac{\sin^2\alpha}{f_a^2} \frac{m_a^7}{m_e^4}$$ → bounded by X-ray telescopes

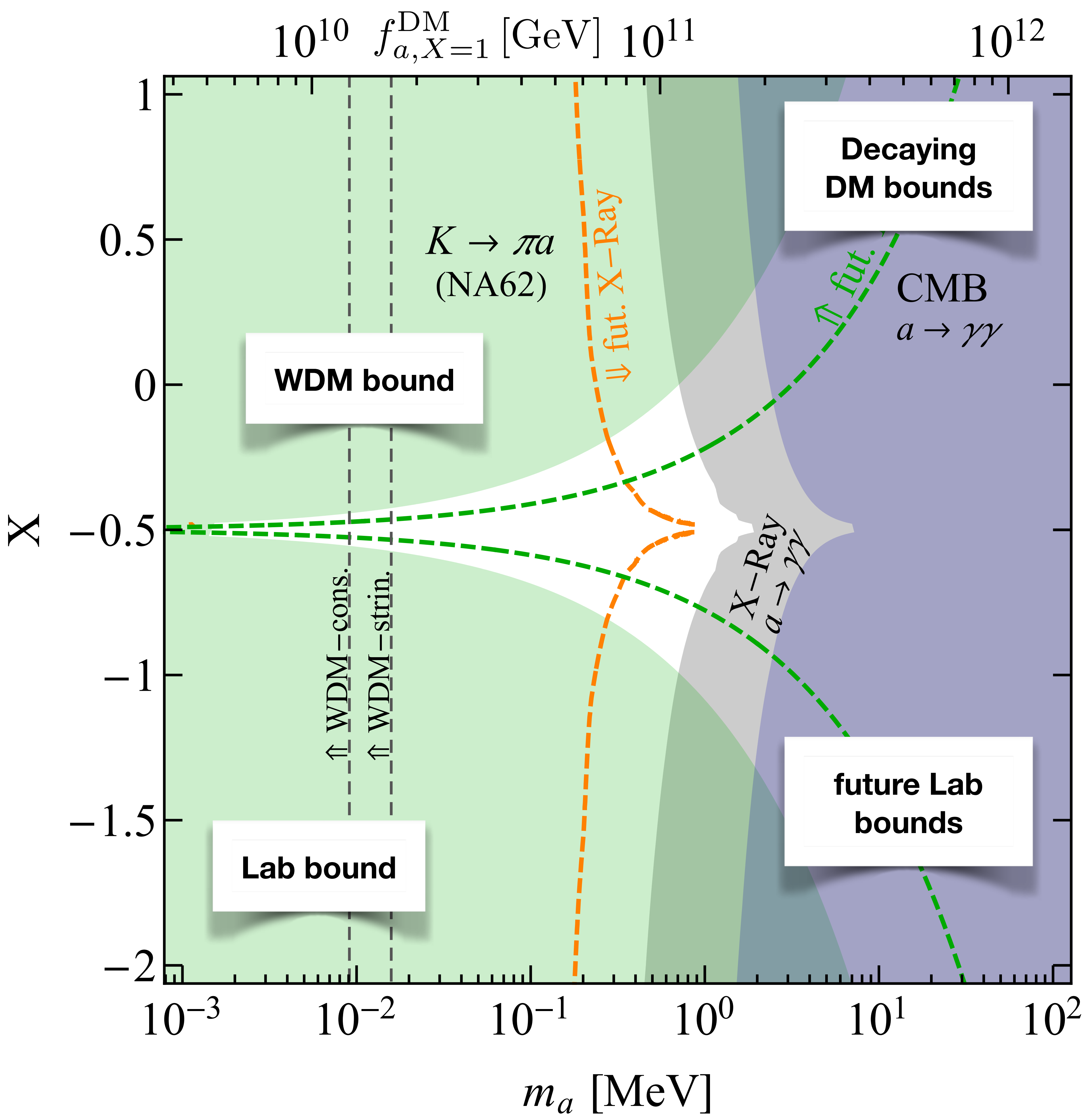
[alternatively fix flavor rotation by CKM and PQ_q = diag (X,-1-X,1): "CKM-Scenario"]

Benchmark Models

μe-Scenario

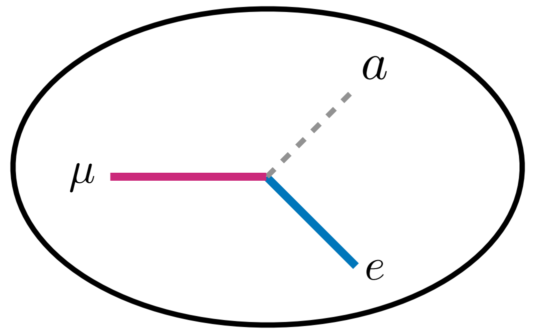


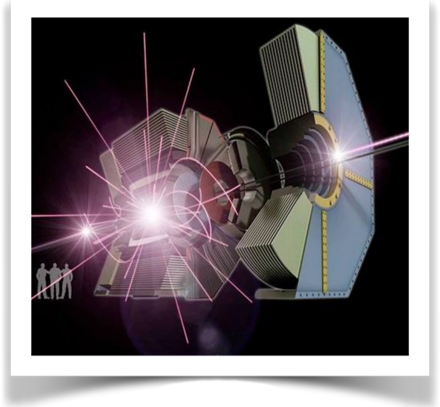
CKM-Scenario



Summary

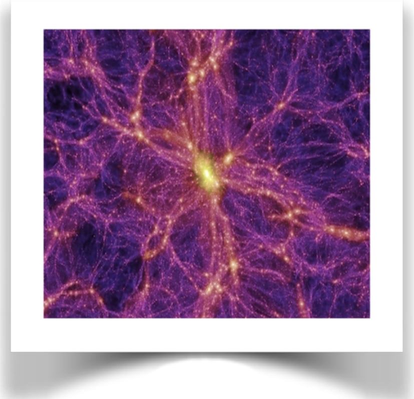
DM Axions can be produced by flavor-violating SM decays





in Flavor Factories, probing decay constants up to 10^{12} GeV (NA62) or 10^{10} GeV (Mu3e) or 10^{8} GeV (B-factories) with 2-body decays

in SN1987A from decays of moderately heavy flavors, contributing to energy loss and providing strongest bounds on hyperon decays



in the early Universe, giving observed DM abundance via freeze-in: very simple class of DM models that can be tested at PSI and NA62