Karlsruhe Institute of Technology

Looking for Axion Dark Matter with Flavor

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KSETA Plenary Workshop 2023

Outline

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Looking for **Axion** Dark Matter with Flavor

- The Strong CP Problem in the Standard Model
- The QCD Axion Solution

Outline

Looking for **Axion Dark Matter** with Flavor

- Axion Stability
- Axion Production in the Early Universe

Outline

Looking for **Axion Dark Matter with Flavor**

- Flavor Symmetries
- Axions with flavor-violating Couplings

Outline

Looking for Axion Dark Matter with Flavor

- in Flavor Factories (Belle II, NA62, Mu3e…)
- in SN1987A
- in the Early Universe

Motivation: SM Failures and Puzzles

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- **Dark Matter**

  astrophysical and cosmological observations require new form of matter contributing to energy density of universe ~5x more than SM baryons

  $$\Omega_{\rm DM} \sim 25\%$$

- **The Strong CP Problem**

  CP violation in strong interactions is found to be tiny (from measurements of neutron electric dipole moment), left unexplained in SM

  $$\theta_{\rm QCD} < 10^{-10}$$

- **The Flavor Problem**

  Fermion masses are small compared to the weak scale (but protected by symmetry against radiative corrections)

  $$\frac{m_e}{v} \sim 10^{-6}$$

The Strong CP Problem

- Gauge and Lorentz symmetries allow "QCD θ-term" in SM Lagrangian, which violates P and CP

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

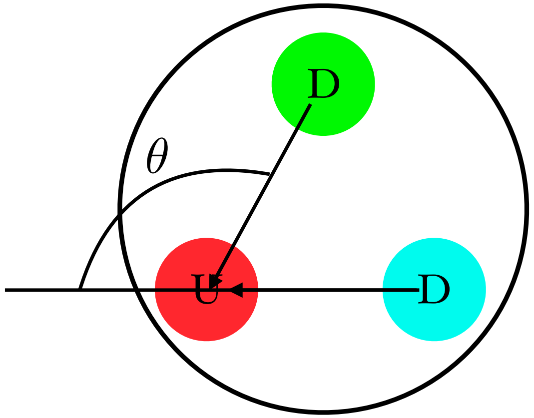
- Total derivative → only non-perturbative effects from instantons: θ is actually angular parameter

$$0 \leq \theta < 2\pi$$

- Contributes to electric dipole moment of neutron, which has stringent upper experimental bound

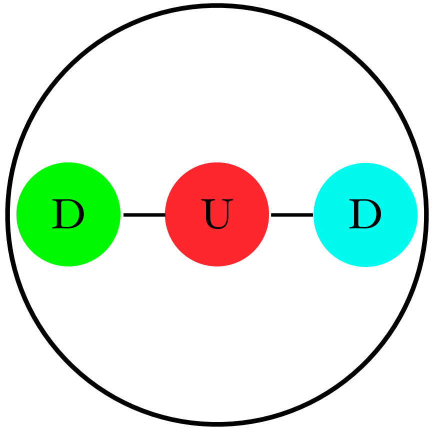
$$|d_n| \approx 2.4\,(1.0) \times 10^{-16} e\,\mathrm{cm} \times \sin\theta \leq 1.8 \times 10^{-26} e\,\mathrm{cm} \rightarrow \theta \leq 10^{-10}$$

Classical Picture

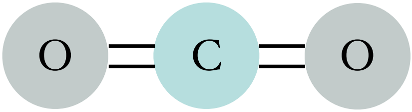


$$|d_n| = \left|\sum q_i \vec{r}\right| \sim e\sqrt{1-\cos\theta}\, r_n \approx 10^{-13} e\,\mathrm{cm}\sqrt{1-\cos\theta}$$

Smallness of nEDM requires almost perfect alignment:



In molecules angle is dynamically adjusted to minimize energy: CO_2-like



The QCD Axion Solution

- QCD generates potential for θ-angle

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

which is minimized for θ = 0!

- θ is constant of nature, but if could promote it to scalar field, would get elegant dynamical explanation for smallness of nEDM

- Need scalar field that ONLY couples as θ-term: Goldstone boson of new global U(1) "Peccei-Quinn" symmetry = **The QCD Axion**

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

The QCD Axion mass

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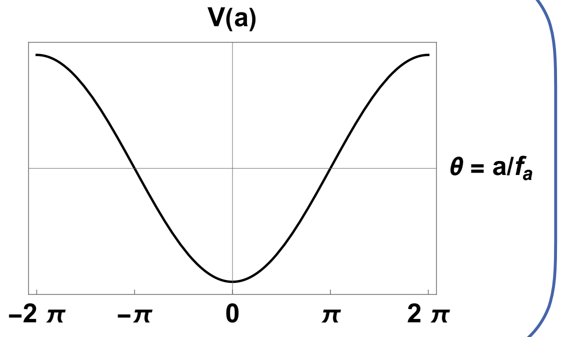
- Axion potential solves Strong CP Problem **and** generates tiny mass



$$V_a \approx -m_\pi^2 f_\pi^2 \, |\cos a(x)/2f_a|$$

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

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

[using chiral perturbation theory]

- QCD axion can be generalized to “axion-like particle” (ALP), where mass is free parameter; does usually not solve strong CP

Dark Matter

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- **…is there!** as inferred from CMB and many other observations

  $\rho_{\mathrm{DM,today}} \sim 10^{-6} \mathrm{GeV}/\mathrm{cm}^3$ [much larger in galaxies, since clumps]

- **…is stable** at least compared to lifetime universe (~10^{17} sec), but typically much stronger constraints from e.g. X-ray telescopes

- **…is dark** since constrained from direct searches: sufficiently small couplings to SM, in particular neutral under electromagnetism and QCD

- **…is cold** (= non-relativstic) as required from structure formation

Dark Matter Candidates

- **WIMPs** ("weakly interacting massive particle"), e.g. neutralino [SUSY]
  - masses in GeV-TeV range
  - interactions with SM ~ O(weak force)
  - in thermal contact with SM
  - DM relic abundance produced via "thermal freeze-out"
- **FIMPs** (feebly interacting massive particles), e.g. QCD axion
  - masses << GeV
  - interactions with SM miniscule
  - not in thermal contact with SM
  - relic abundance produced e.g. via "misalignment", "thermal freeze-in", ….

Axion Dark Matter: Stability

Axions are easily stable since Pseudo-Goldstone bosons: $a(x)/f_a$

⟶ light and decoupled from SM particles if PQ broken at large scales

e.g. decay rate to photons:

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

m_a

f_a

natural for **QCD axion** $m_a f_a = m_\pi f_\pi$

Axion Dark Matter: Misalignment

- Axion can behave like classical scalar field; in expanding universe evolution described by same EoM as oscillator with time-dependent friction and mass

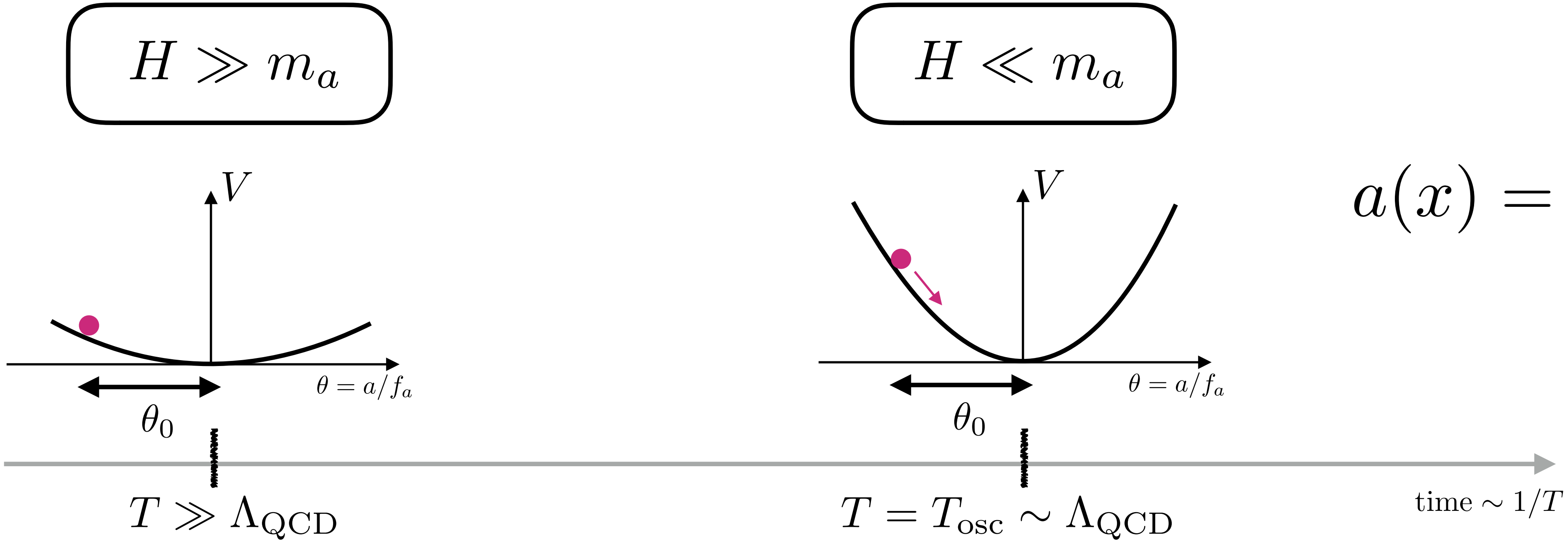
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

Hubble parameter ~T^2

QCD axion mass ~ $\begin{cases} 0 & T \gg \Lambda_{\rm QCD} \\ m_a & T \ll \Lambda_{\rm QCD} \end{cases}$

- In early universe overdamped (constant), start oscillating near T ~ $\Lambda_{\rm QCD}$ energy stored in oscillations behaves exactly as cold dark matter

Axion Dark Matter: Misalignment



$$a(x) = f_a \theta(x)$$

Energy density depends only on amplitude f_a and initial elongation θ_0

$$\rho_{a,\rm today} \sim 10^{-6} \frac{\rm GeV}{\rm cm^3} \left(\frac{f_a}{10^{12}\,\rm GeV} \right) \theta_0^2$$

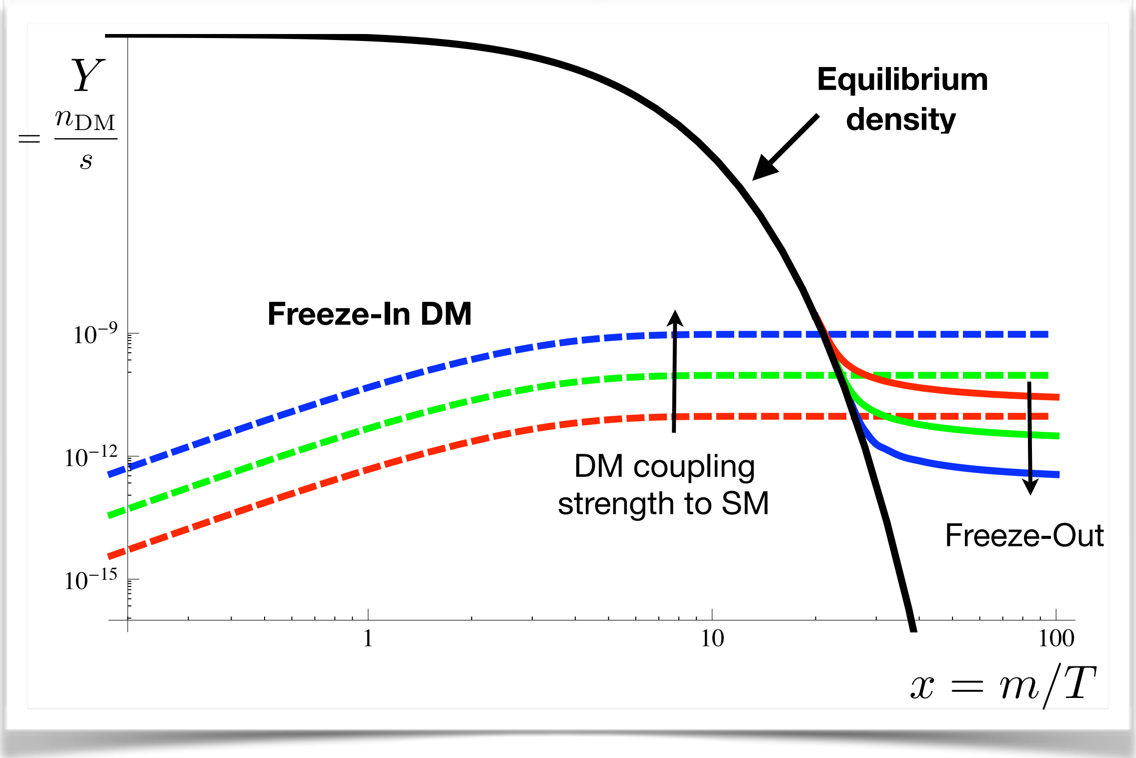
Axion Dark Matter: Freeze-in

DM particle with coupling to SM so tiny that never in equilibrium

DM abundance slowly builds up from SM decays/scattering, until SM particles become non-relativistic

for decay of particle with mass M:

$$\Omega_a h^2 \approx 0.2 \left(\frac{m_a/M}{10^{-3}}\right)\left(\frac{\Gamma_B/M}{10^{-22}}\right)$$



Axion Phenomenology

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Most general axion couplings to SM are described by effective Lagrangian well below breaking scale of PQ symmetry

(needs to respect remnant shift symmetry broken only by axion couplings to gauge bosons)

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

solves Strong CP Problem & generates axion mass

contributes to axion couplings to photons

axion couplings to fermions (**in general flavor-violating**)

Axion Couplings to Photons

- Effective photon coupling slightly model-dependent

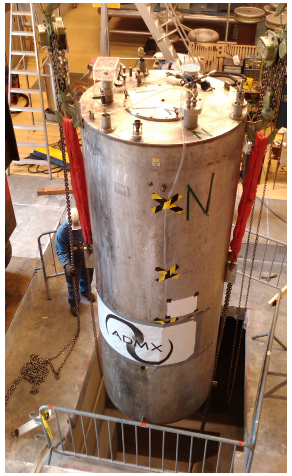
$$g_{a\gamma\gamma} = \frac{\alpha_{\rm em}}{2\pi f_a}\mathcal{O}(1)$$

- Standard axion search channel, since experimentally easy and generic

Haloscopes
e.g. **ADMX**

DM axion
$\vec{B}$ ↓
photon

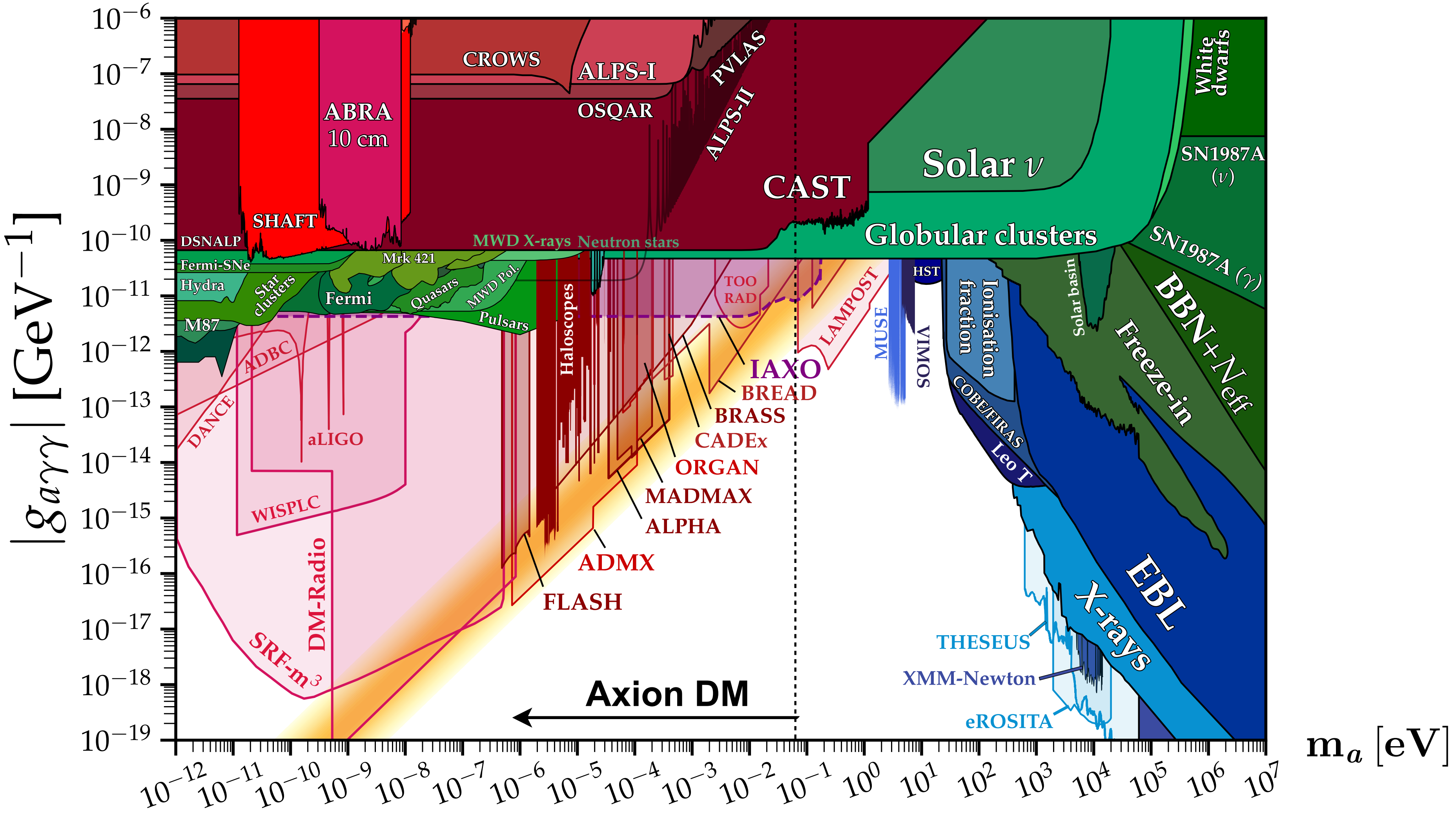
resonantly detected
by microwave cavity



Helioscopes
e.g. **CAST**

solar photon
$\vec{E}$ ↓
axion
$\vec{B}$ ↓
X-ray photon

Experimental Constraints and Prospects

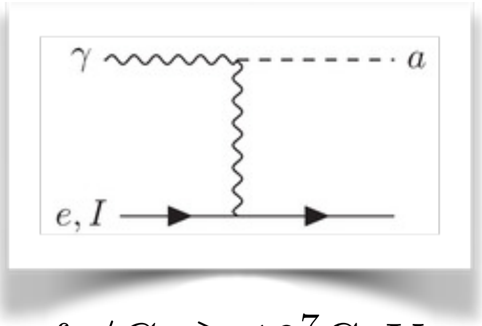


Star Cooling Constraints

- Since axion is essentially **massless**, can be produced in stellar plasmas by couplings to ordinary matter (γ, e, N) [T_{sun} ~ keV, T_{SN1987A} ~ 40 MeV]

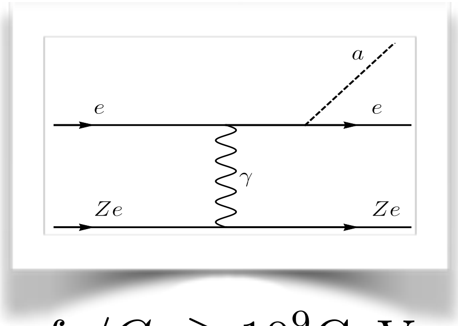
- Since axion is essentially **stable**, once produced it escapes from star carrying away energy: strongly constrained by standard stellar evolution

Horizontal Branch stars



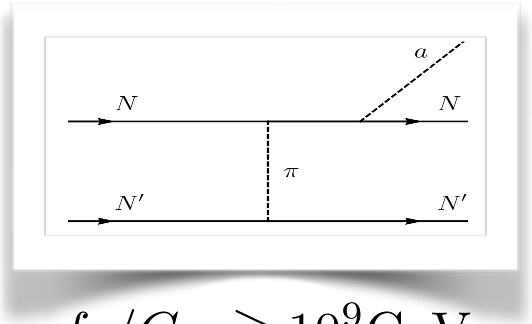
$f_a/C_\gamma \gtrsim 10^7\,\text{GeV}$

Red Giants/White Dwarfs



$f_a/C_e \gtrsim 10^9\,\text{GeV}$

SN1987A (Proto-Neutron star)



$f_a/C_N \gtrsim 10^9\,\text{GeV}$

Flavor-violating Axions

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

$$\mathcal{L}_a^{\text{eff}} = \frac{\partial_\mu a}{2 f_a} C_i \overline{f}_i \gamma^\mu \gamma_5 f_i \quad \longrightarrow \quad \mathcal{L}_a^{\text{eff}} = \frac{\partial_\mu a}{2 f_a} \overline{f}_i \gamma^\mu \left(C_{ij}^V + C_{ij}^A \gamma_5 \right) f_j$$

- Allow for axion production from decays of SM particles

$$\mu \to e a\,, \quad \tau \to e a\,, \quad K \to \pi a\,, \quad \Lambda \to n a\,, \quad B \to \rho a\,, \quad \ldots$$

relevant for **1) direct searches** **2) star cooling** **3) early universe**

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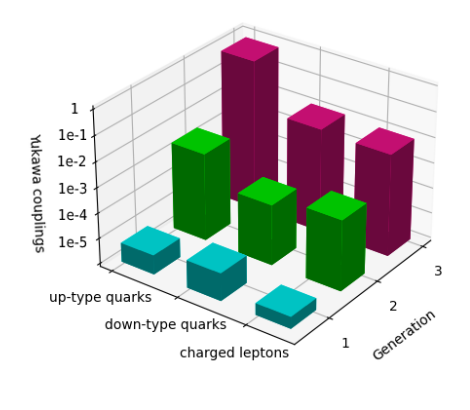
Relation to SM Flavor Puzzle

- SM fermion masses and quark mixing angles are very hierarchical



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

Small Yukawa couplings can be put in by hand, but would like to explain more fundamentally, e.g. by ratios of mass scales and couplings of O(1)

Flavor Symmetries

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- Forbid most Yukawa couplings by new flavor-dependent global symmetry acting on SM fermions (“Froggatt-Nielsen”)
- Symmetry is spontaneously broken by ”flavon": Yukawa couplings arise from higher-dimensional operators involving suitable powers of flavon

$$\mathcal{L}_{\rm eff} = \lambda_{ij} \bar{q}_{L,i} u_{R,j} H \left(\frac{\Phi}{M}\right)^{X_i^q + X_j^u}$$

$$\langle \Phi \rangle = \epsilon M$$

$$Y_{ij}^u = \lambda_{ij} \epsilon^{X_i^q + X_j^u}$$

By choosing suitable charges can reproduce all Yukawa hierarchies

- Flavor symmetry can be *identified* with Peccei-Quinn symmetry: determine flavor-violating axion couplings: e.g. $C^V_{d_i d_j} \sim (V_{\rm CKM})_{ij}$

Calibbi, Goertz, Redigolo, RZ, Zupan ’16

Axion Production in Flavor Factories

- Probe FV couplings in **meson/lepton decays with missing energy** look like SM decays with neutrino pair, but 2-body

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

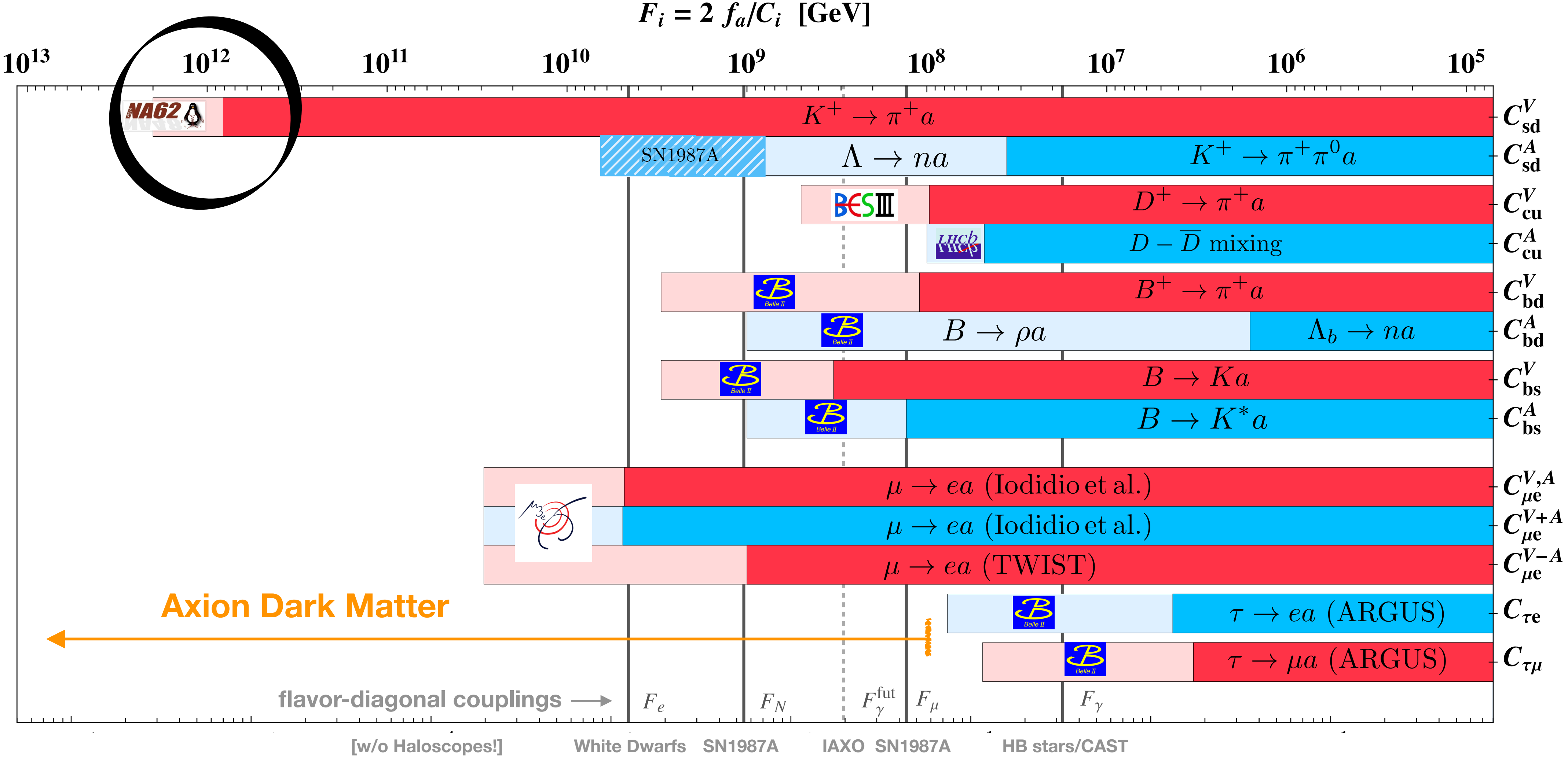
Leptons: SM background huge $\mathrm{BR}(\mu \to e\nu\overline{\nu}) = 1$

- Experimental constraints on 2-body decays are often old or do not even exist, but can recast experimental data on SM decays in 2-body region

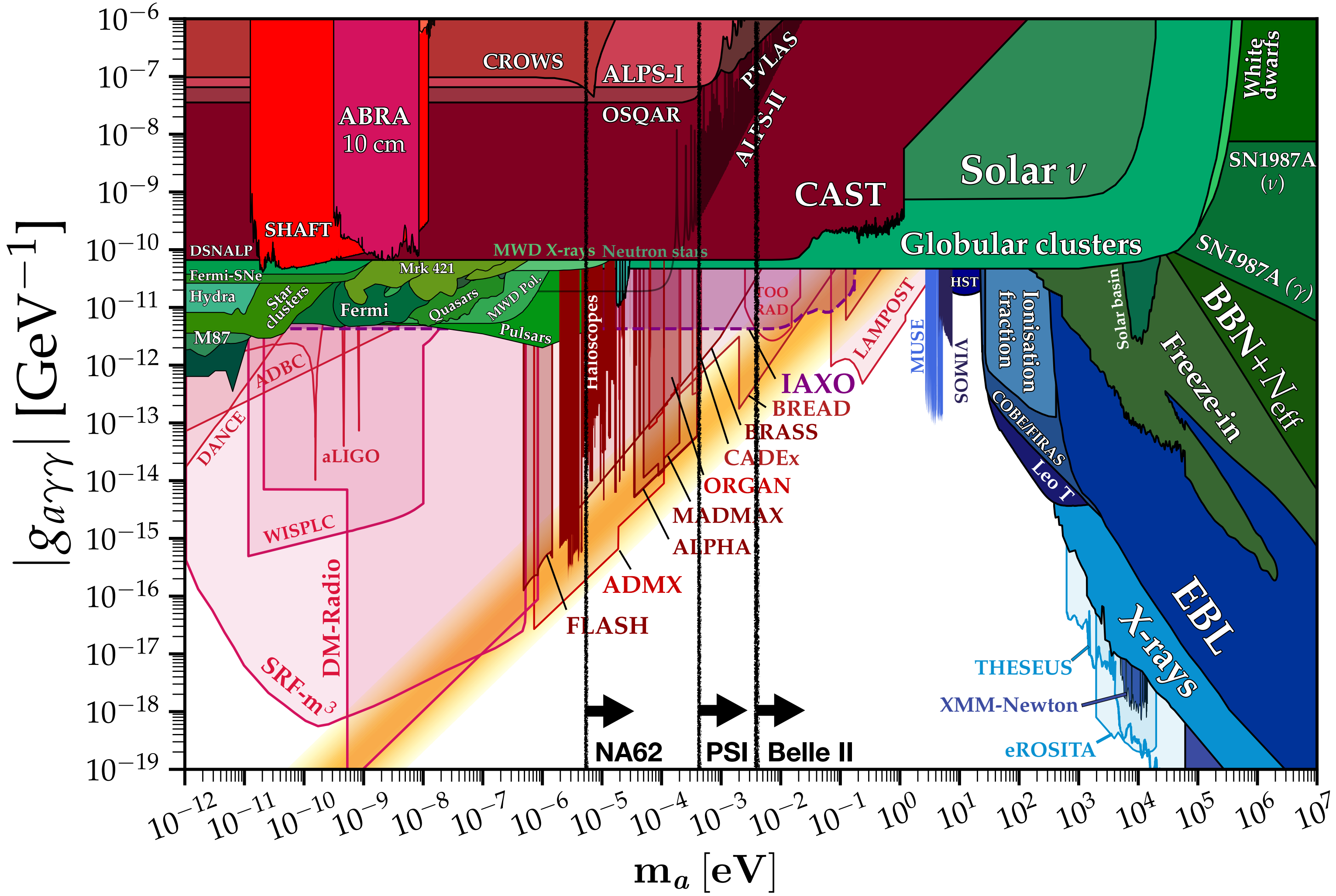
e.g. no bound on $D \to \pi a$, but can recast CLEO data on $D \to \tau\nu, \tau \to \pi\nu$

Present and Future Constraints

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



Present and Future Constraints

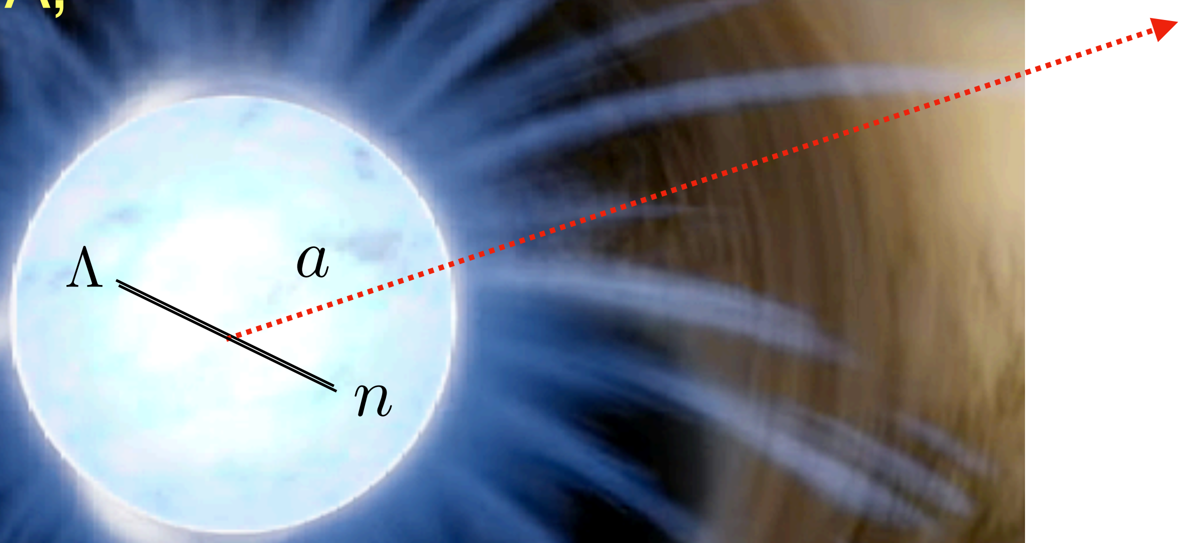


Axion Production in SN1987A

Best handle on axial-vector coupling to s-d from hyperon decays in SN1987A, which are limited by constraints on energy loss rate

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

- n_n: nuclear density
- $(m_\Lambda - m_n)$: axion energy
- $\Gamma(\Lambda \to na)$: decay rate
- $e^{-\frac{m_\Lambda - m_n}{T}}$: Boltzmann suppression
- dV: volume integral



Gives very strong bound on hyperon decays to invisible particles:

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

Axion Production in the early Universe

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

Panci, Redigolo, Schwetz, RZ '22

- Freeze-in abundance fixes decay rate: get targets for exp. searches

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

→ requires ALP mass in suitable window

(lab searches vs. kinematic threshold)

Main challenge is DM stability:
requires suppressed photon coupling

$$\Gamma(a \to \gamma\gamma) \lesssim \frac{\mathbf{1}}{\mathbf{10^{28} sec}}$$

(X-ray telescopes)

Lepton-flavor-violating (LFV) Model

- Take 2-generation model for leptons

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

depending on 3 parameters: α, f_a, m_a

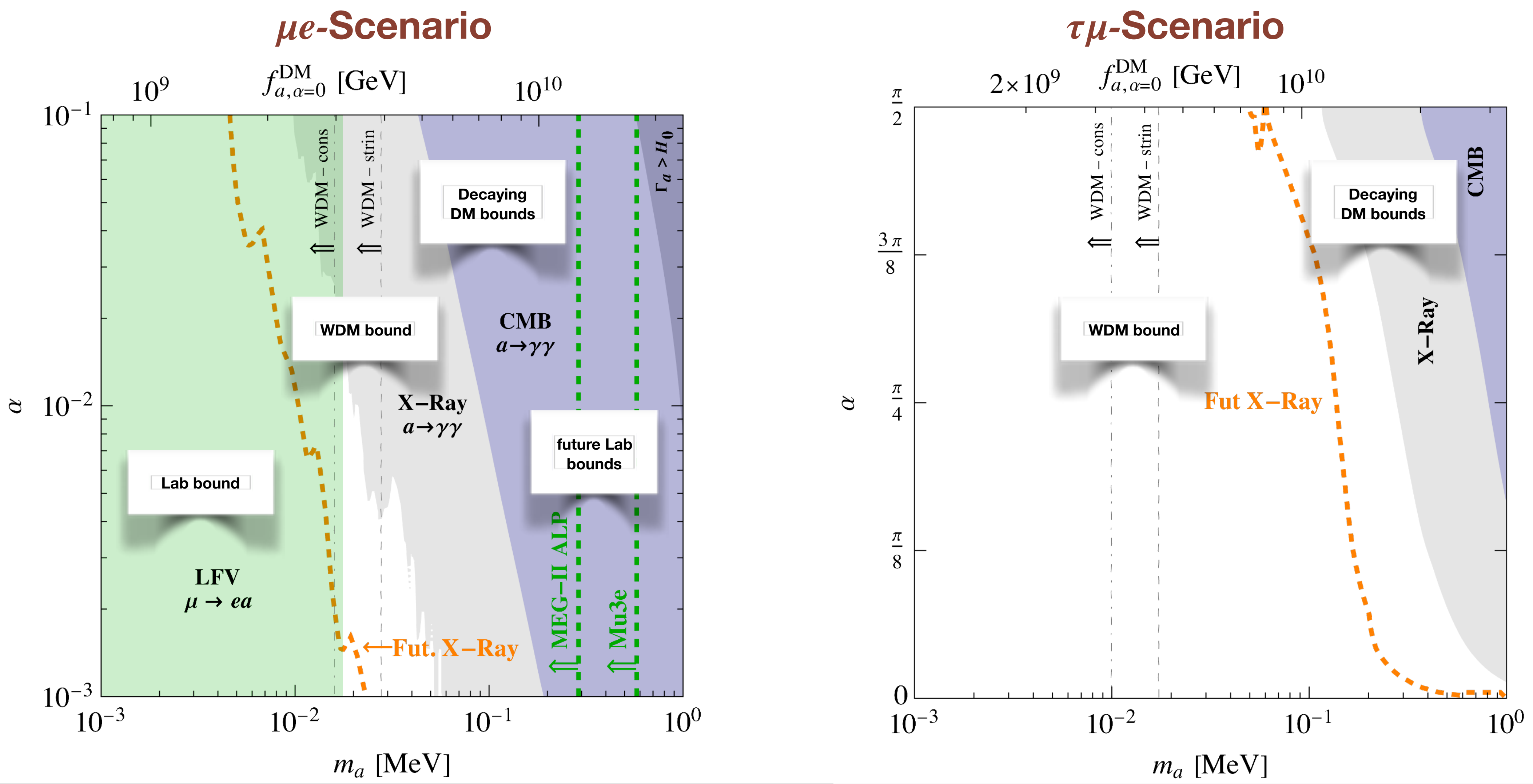
(α, f_a: ALP couplings to leptons; m_a: ALP mass)

- LFV decays give ALP DM abundance, diagonal couplings control lifetime

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

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

Numerical Results



Summary

Axions are very light BSM particles with tiny couplings to the Standard Model, which are well-motivated by **Dark Matter** and the **Strong CP Problem** (small nEDM)

Axion Dark Matter with **flavor-violating couplings** can be produced by SM decays

- **in precision flavor experiments**, probing decay constants up to 10^{12} GeV
- **in SN1987A** from decays of moderately heavy flavors, contributing to energy loss
- **in the early universe**, giving observed DM abundance via freeze-in