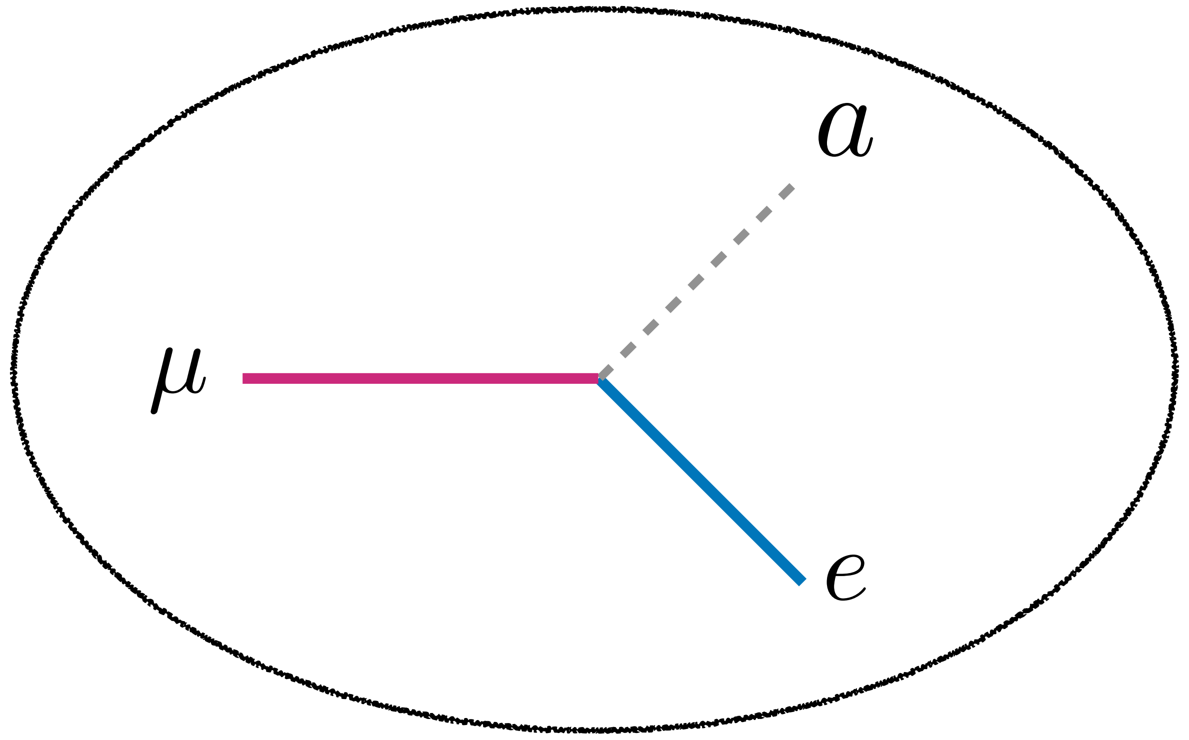
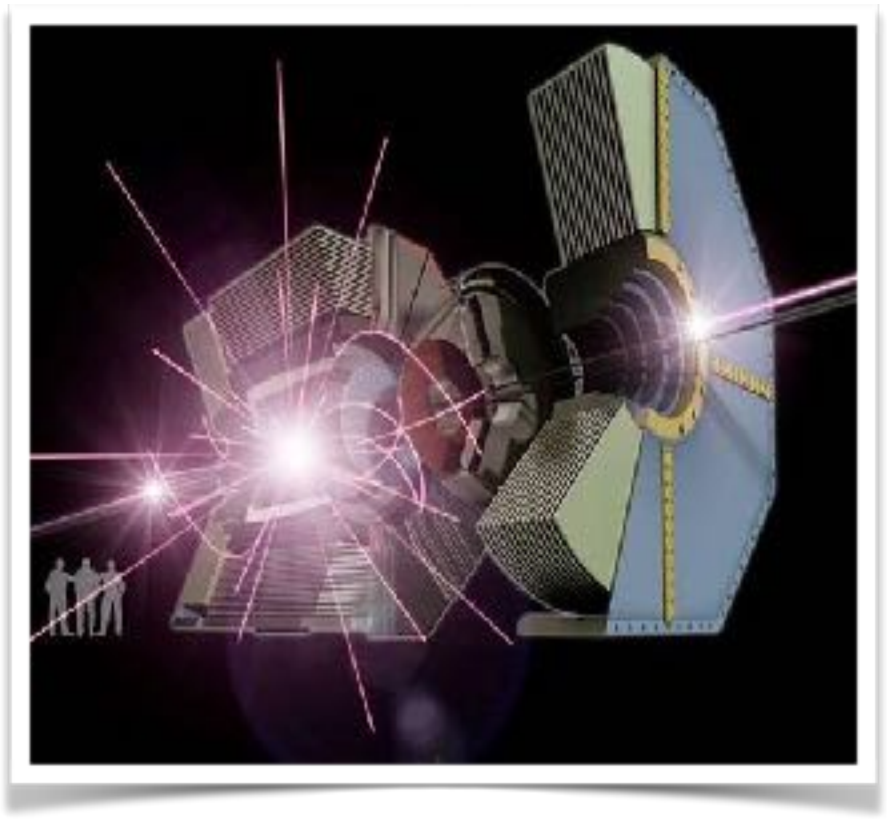
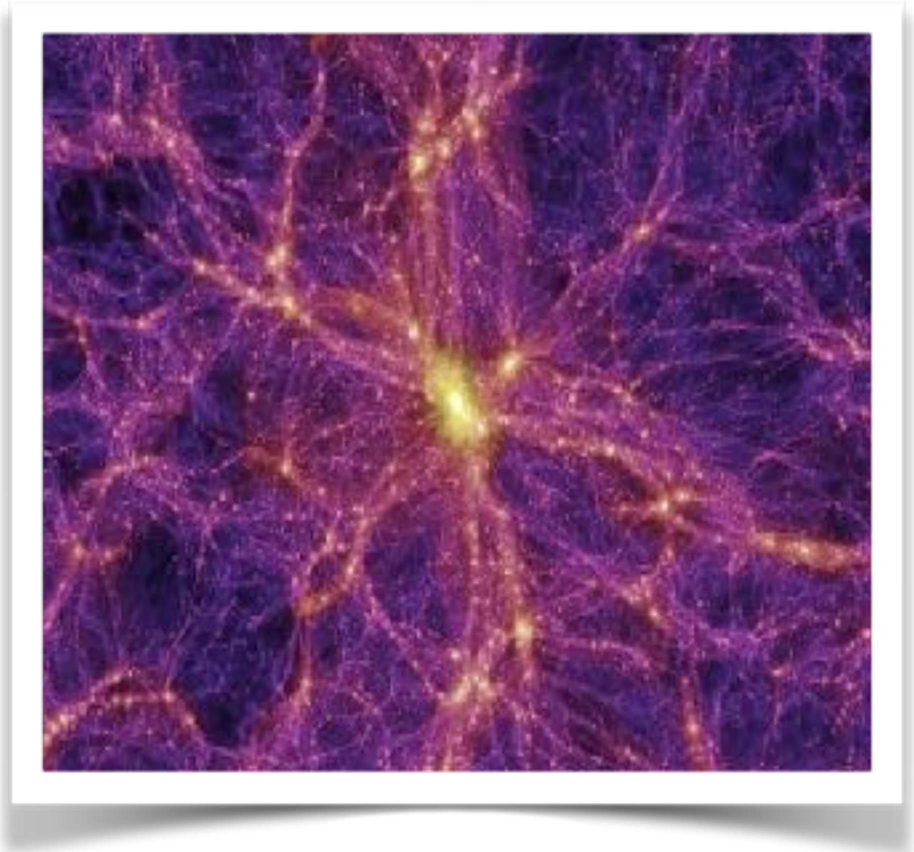
Looking for Axion Dark Matter with Flavor





Flavor Factories

Supernovae



Early Universe

UNI FREIBURG

KIT Karlsruher Institut für Technologie

Outline

- **Introduction**
  - The Strong CP Problem and the QCD Axion
  - Axion Dark Matter
  - Axion Phenomenology

- **Flavored Axion Phenomenology**
  - Precision Flavor Experiments 2002.04623, 2006.04795
  - Flavor Constraints from SN1987A 2012.11632
  - Axion Dark Matter from LFV Decays 2209.03371

The Strong CP Problem

- Gauge and Lorentz invariance allow CP-violating topological term for QCD

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

- Contributes to neutron electric dipole moment that has stringent upper bound

$$d_n \approx 1.3 \times 10^{-26} \left(\frac{\theta}{3 \times 10^{-11}} \right) e\,\mathrm{cm}$$

- Difficult to explain small θ with symmetries or anthropic arguments
  - CP already broken by weak interactions (but radiatively induced θ tiny)
  - θ has not much impact on structure formation in the universe

- Most elegant solution with light new particle: **QCD Axion**

also solutions with heavy new physics: spontaneous P or CP violation

The QCD Axion Solution

- If θ was dynamical field, QCD generates potential with trivial minimum

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

- Realized as Goldstone boson of new global (“Peccei-Quinn”) symmetry that is broken twice: spontaneously & by chiral anomaly Peccei, Quinn ‘77; Wilczek; Weinberg ’78

$$\Pi = e^{i a(x)/V_{\rm PQ}} \quad + \quad \partial_\mu j_a^\mu = N \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}_a^{\mu\nu} \quad = \quad \Delta\mathcal{L} = N \frac{a(x)}{V_{\rm PQ}} \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}_a^{\mu\nu}$$

Goldstone boson **QCD Anomaly** **QCD Axion:** $\theta \rightarrow \frac{a(x)}{V_{\rm PQ}/2N} \Big\} f_a$

Axion mass and Axion-like Particles

- QCD generates tiny axion mass fixed in terms of PQ breaking scale

  can be calculated easily in χPT, after field redefinition that absorbs axion into light quark masses

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

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

- QCD axion can be generalized to "axion-like" particle (ALP)
  - ALP mass is free parameter
  - does not solve strong CP problem [unless more model-building effort]
  - motivated by DM & phenomenology [even @LHC in contrast to QCD axion]

Axion Dark Matter

- ✳ Axions are excellent Dark Matter candidates

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

↓ **light**

naturally for **QCD axion**

$m_a f_a = m_\pi f_\pi$

↓ **decoupled**

stable on cosmological scales

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

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

Axion DM Production

✳ Misalignment

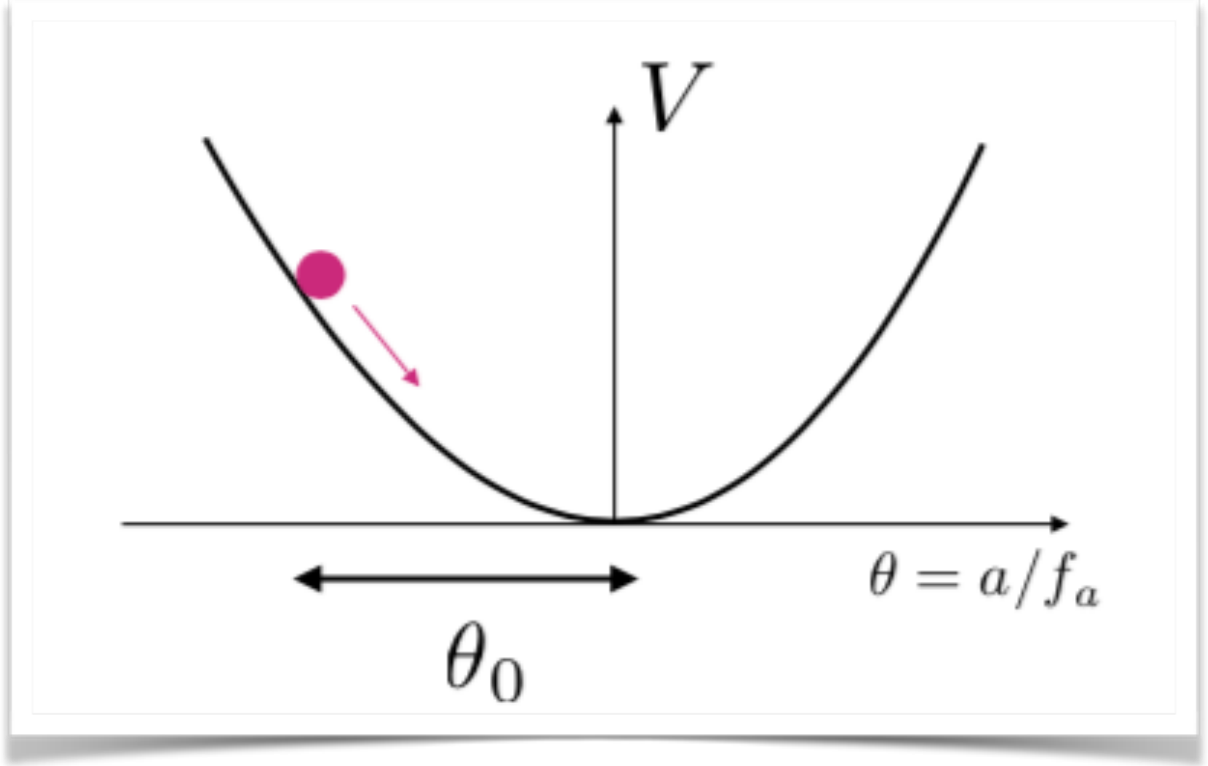
Preskill, Wise, Wilczek / Abbott, Sikivie / Dine, Fischler ’83

EoM of classical scalar field in expanding universe is oscillator with time-dependent friction and mass

$$\boxed{\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0}$$

Energy stored in oscillations behaves like Cold Dark Matter

$$\Omega_a h^2 = 0.25 \times \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^{7/6} \theta_0^2$$



✳ Thermal Freeze-In

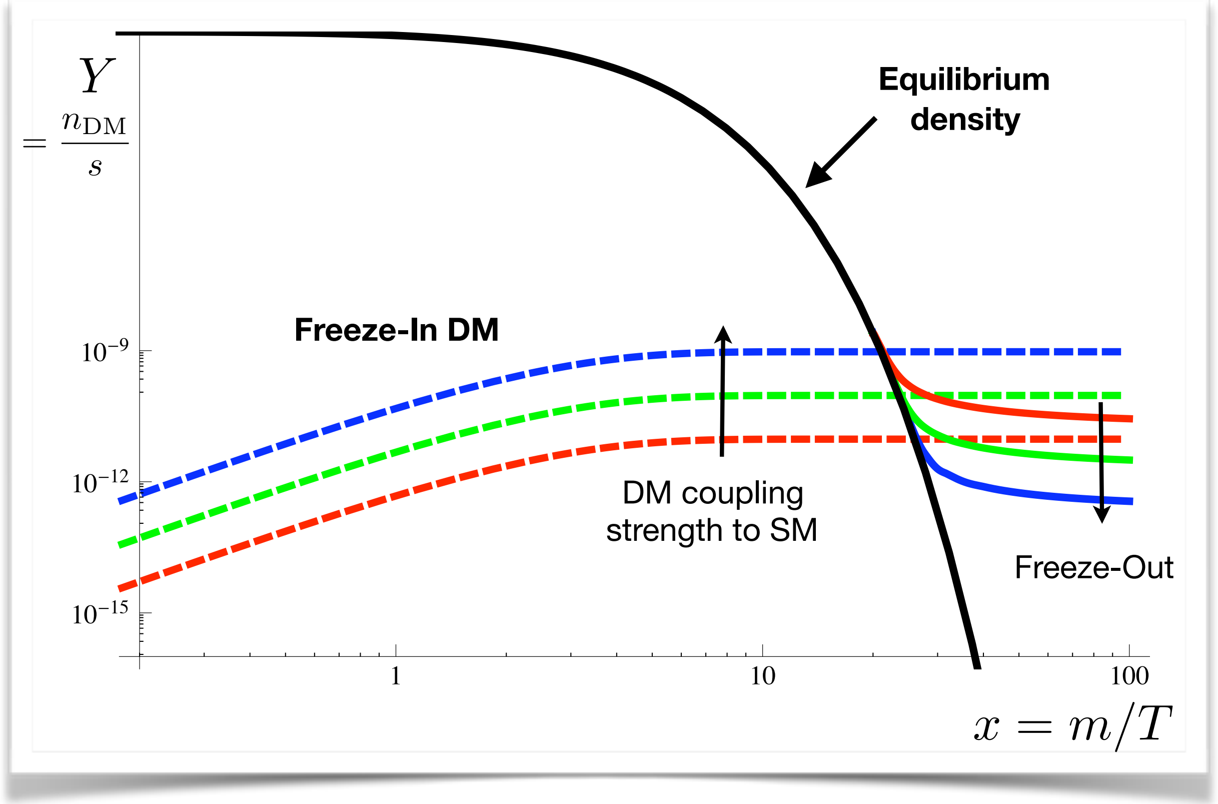
Hall, Jedamzik, March-Russell, West ‘09

DM with coupling to SM so tiny that never in equilibrium

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

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

from decay of particle with mass M



Axion Phenomenology

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

Georgi, Kaplan, Randall ’86

- All terms respect shift symmetry except for anomalous couplings to gauge fields and are suppressed by PQ breaking scale

$$\mathcal{L}_{\text{eff}} = N\frac{a(x)}{\Lambda_{\text{PQ}}}\frac{\alpha_s}{4\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} + E\frac{a(x)}{\Lambda_{\text{PQ}}}\frac{\alpha_{\text{em}}}{4\pi}F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{\partial_\mu a(x)}{\Lambda_{\text{PQ}}}\overline{f}_i\gamma^\mu\left(C_{ij}^V + C_{ij}^A\gamma_5\right)f_j$$

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

✳ Contributions from EM anomaly, axion-pion mixing, fermion loops

$$g_{a\gamma} = \frac{\alpha_{\rm em}}{2\pi f_a}\left[E/N - 1.92(4) + \mathcal{O}(m_a^2/m_f^2)\right]$$

✳ Standard axion search channel, since experimentally easy and generic

Haloscopes
e.g. **ADMX**

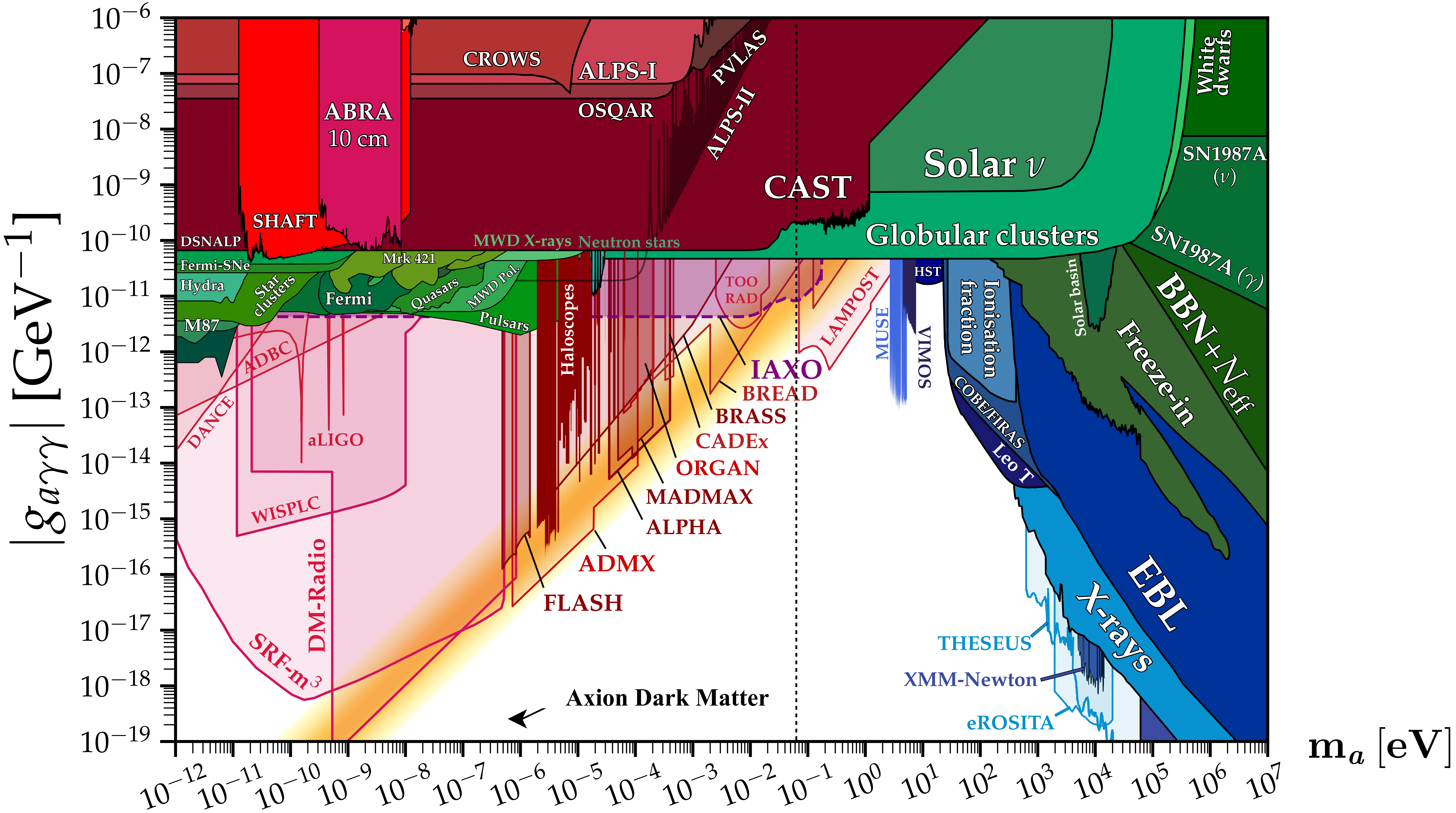
DM axion
$\vec{B}\downarrow$
photon

resonantly detected by
microwave cavity

Helioscopes
e.g. **CAST**

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

Present Constraints and Prospects



Flavor-violating Axions

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

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

proliferates parameters, but enriches phenomemology

- Allows for axion production from decays of SM particles

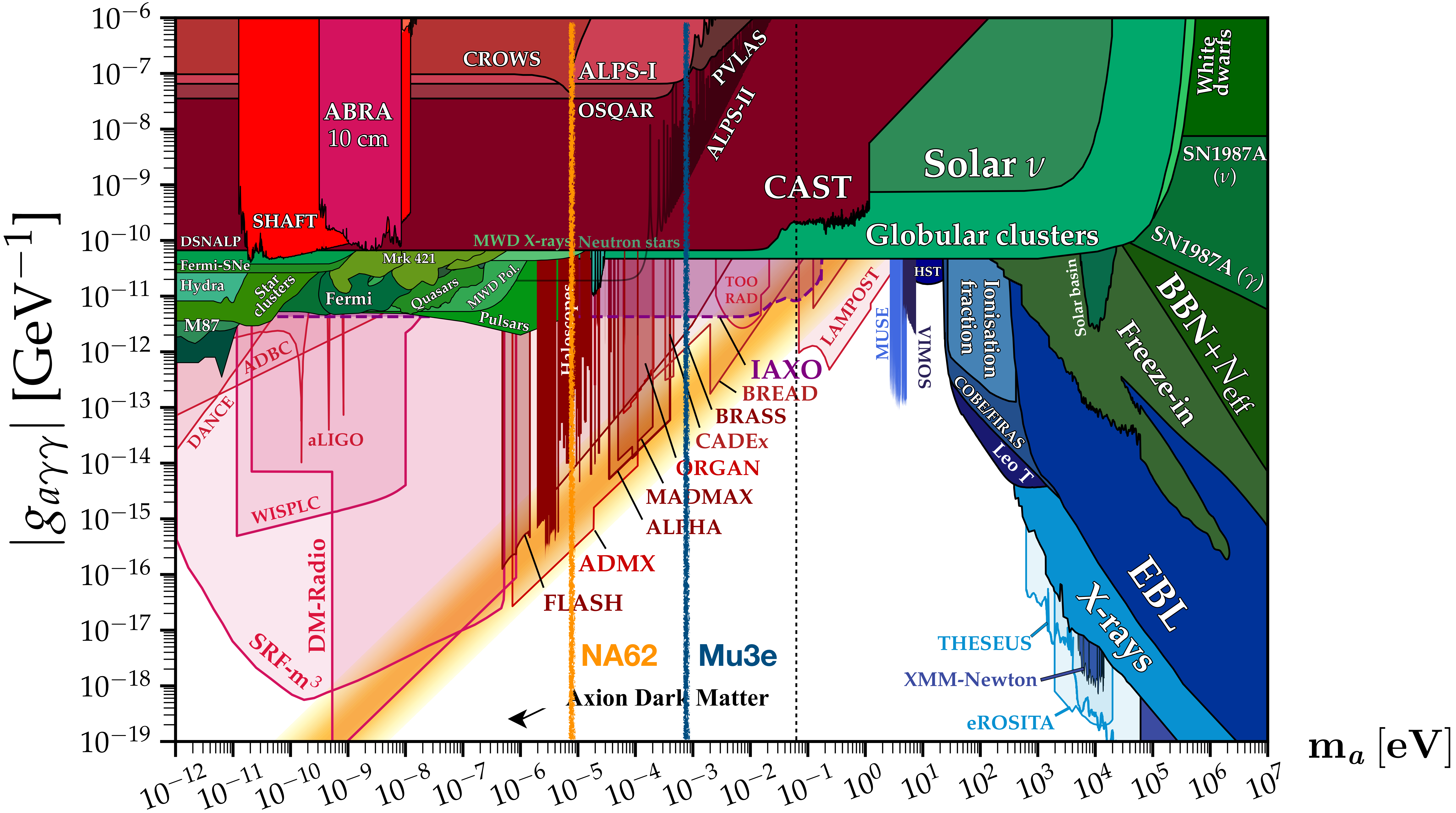
e.g. $\boxed{\mu \to e a}$ $\boxed{\tau \to e a}$ $\boxed{K \to \pi a}$ $\boxed{\Lambda \to n a}$ $\boxed{B \to \rho a}$ $\cdots$

in precision flavor factories, SN1987A and early universe

↓ ↓ ↓

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

Present Constraints and Prospects



Origin of flavor-violating Couplings

- ✳ Fermion couplings determined by PQ charges in fermion mass basis

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

unitary matrices diagonalizing Yukawas

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]

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

Calibbi, Goertz, Redigolo, RZ, Zupan ’16

sizable light quark transitions

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

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

Linster, RZ ’18
Barbieri, RZ ’19
Calibbi, Redigolo, RZ, Zupan ‘20

suppressed light quark transitions, but LFV sizable

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

A realistic U(2) Model of Flavor

- SM fermions in **2+1** of SU(2) and U(1) charges compatible with SU(5)

U(2) forbids most Yukawas but spontaneously broken Barbieri, Dvali, Hall '96

	Fermions				**Scalars**		
$SU(5)$	$\mathbf{10}_a$	$\bar{\mathbf{5}}_a$	$\mathbf{10}_3$	$\bar{\mathbf{5}}_3$	H	ϕ_a	χ
$SU(2)_F$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_F$	1	1	0	1	0	-1	-1
	1st and 2nd generation		**third generation**			**two "flavons"** $\epsilon_\phi \sim 0.03$ $\epsilon_\chi \sim 0.01$	

$$\boxed{m_{\{u,d,e,\nu\}} \sim \begin{pmatrix} 0 & \varepsilon^2 & 0 \\ \varepsilon^2 & \varepsilon^2 & \{\varepsilon, \varepsilon^2, \varepsilon, \varepsilon^2\} \\ 0 & \{\varepsilon, \varepsilon, \varepsilon^2, \varepsilon^2\} & \{1, \varepsilon, \varepsilon, \varepsilon^2\} \end{pmatrix}}$$

$\epsilon \sim V_{cb}$

Linster, RZ '18

- Texture zeros precisely relate masses and mixing angles

$$\boxed{\begin{aligned} |V_{us}| &\approx \left| \sqrt{\frac{m_d}{m_s}} \sqrt{c_{23}^{Rd}} - e^{i(\phi_2-\phi_1)} \sqrt{\frac{m_u}{m_c}} \right| \\ |V_{td}| &\approx \sqrt{\frac{m_d}{m_s}} \sqrt{c_{23}^{Rd}} \left| |V_{cb}| - e^{i\phi_2} \frac{s_{23}^{Rd}}{c_{23}^{Rd}} \frac{m_s}{m_b} \right| \\ |V_{ub}| &\approx \left| \sqrt{\frac{m_u}{m_c}} |V_{cb}| - e^{i\phi_1} \sqrt{\frac{m_d}{m_s}} \sqrt{c_{23}^{Rd}} \frac{s_{23}^{Rd}}{c_{23}^{Rd}} \frac{m_s}{m_b} \right| \end{aligned}}$$

23 mixing angle in RH down sector

free phases

In original U(2) models $s_{23}^{Rd} \sim V_{cb} \longrightarrow |V_{ub}/V_{cb}| \approx \sqrt{m_u/m_c}$

which is off by more than 3σ e.g. Barbieri, RZ '19

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

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

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

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

light NP

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

heavy NP

Constraints from Meson Decays

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

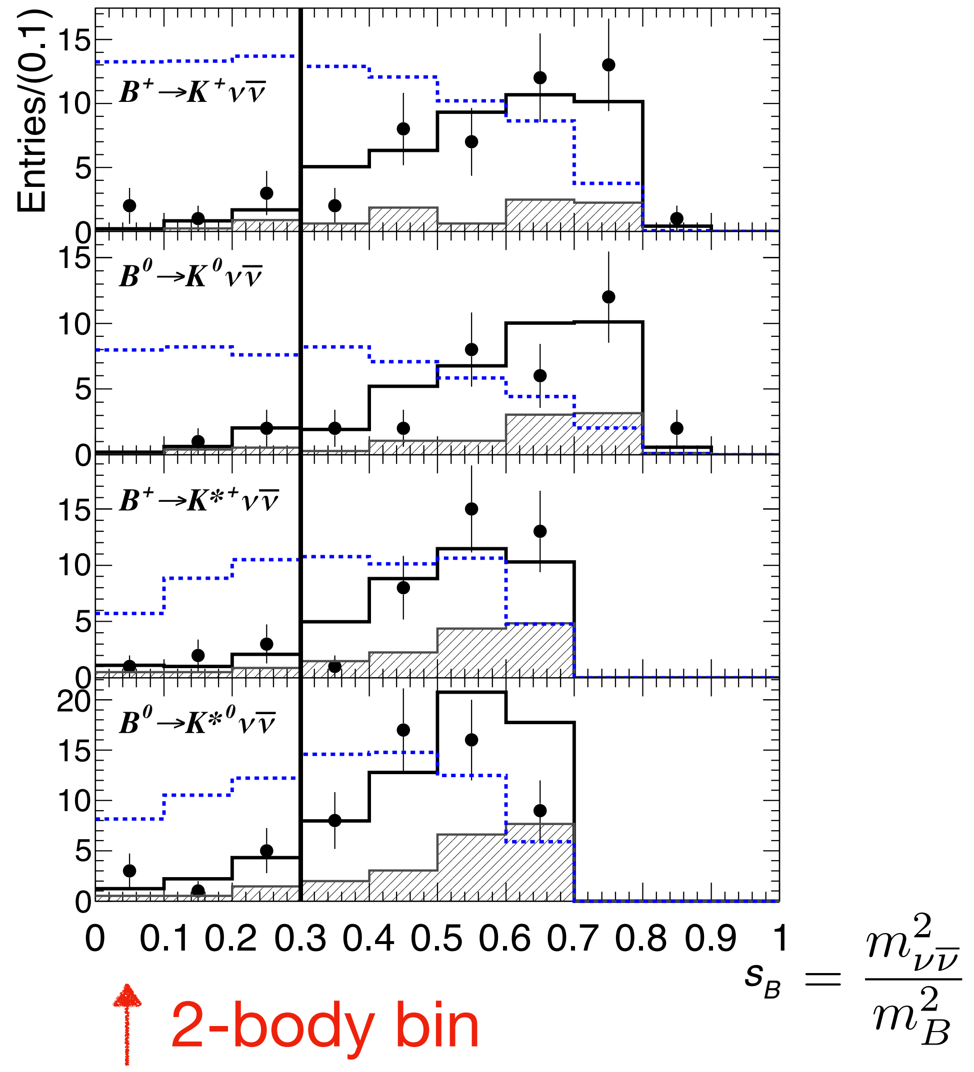
  e.g. no bound on $D \to \pi a, B \to K^* a, B \to \rho a$

- ✳ 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	
$\mathrm{BR}(P_1 \to P_2 + a)_{\rm exp}$	7.3×10^{-11} [85]	no analysis	4.9×10^{-5} [86]	4.9×10^{-5} [86]	
$\mathrm{BR}(P_1 \to P_2 + a)_{\rm recast}$	no need	8.0×10^{-6} [87]	2.3×10^{-5} [88]	7.1×10^{-6} [89]	$\propto C^V_{ij}$
$\mathrm{BR}(P_1 \to P_2 + \nu\overline{\nu})_{\rm exp}$	$1.47^{+1.30}_{-0.89} \times 10^{-10}$ [85]	no analysis	0.8×10^{-5} [90]	1.6×10^{-5} [90]	
$\mathrm{BR}(P_1 \to V_2 + a)_{\rm exp}$	3.8×10^{-5} [91]	no analysis	no analysis	no analysis	
$\mathrm{BR}(P_1 \to V_2 + a)_{\rm recast}$	no need	no data	no data	5.3×10^{-5} [89]	$\propto C^A_{ij}$
$\mathrm{BR}(P_1 \to V_2 + \nu\overline{\nu})_{\rm exp}$	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**

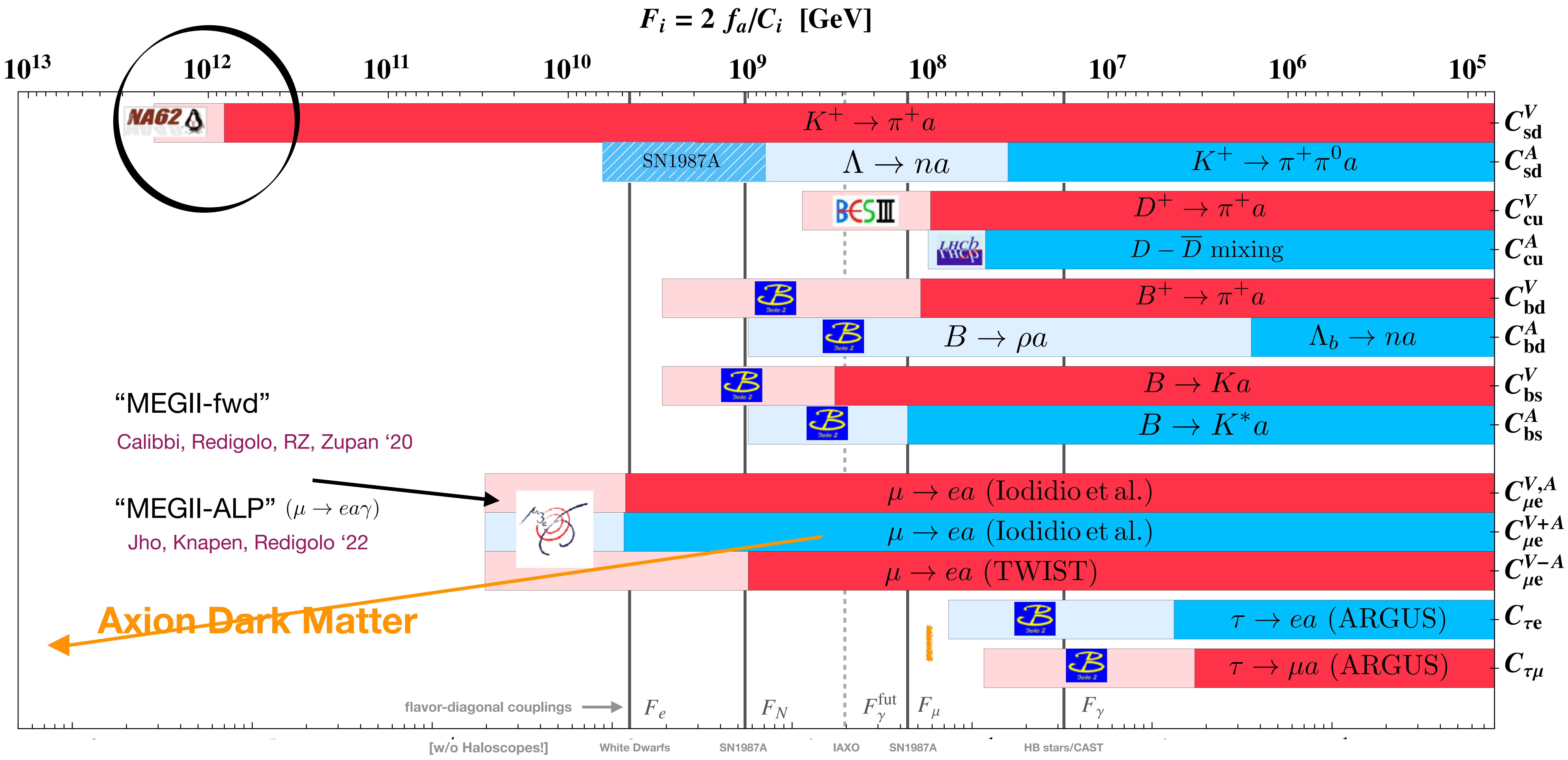


↑ 2-body bin

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

Summary of present and future Constraints



“MEGII-fwd”

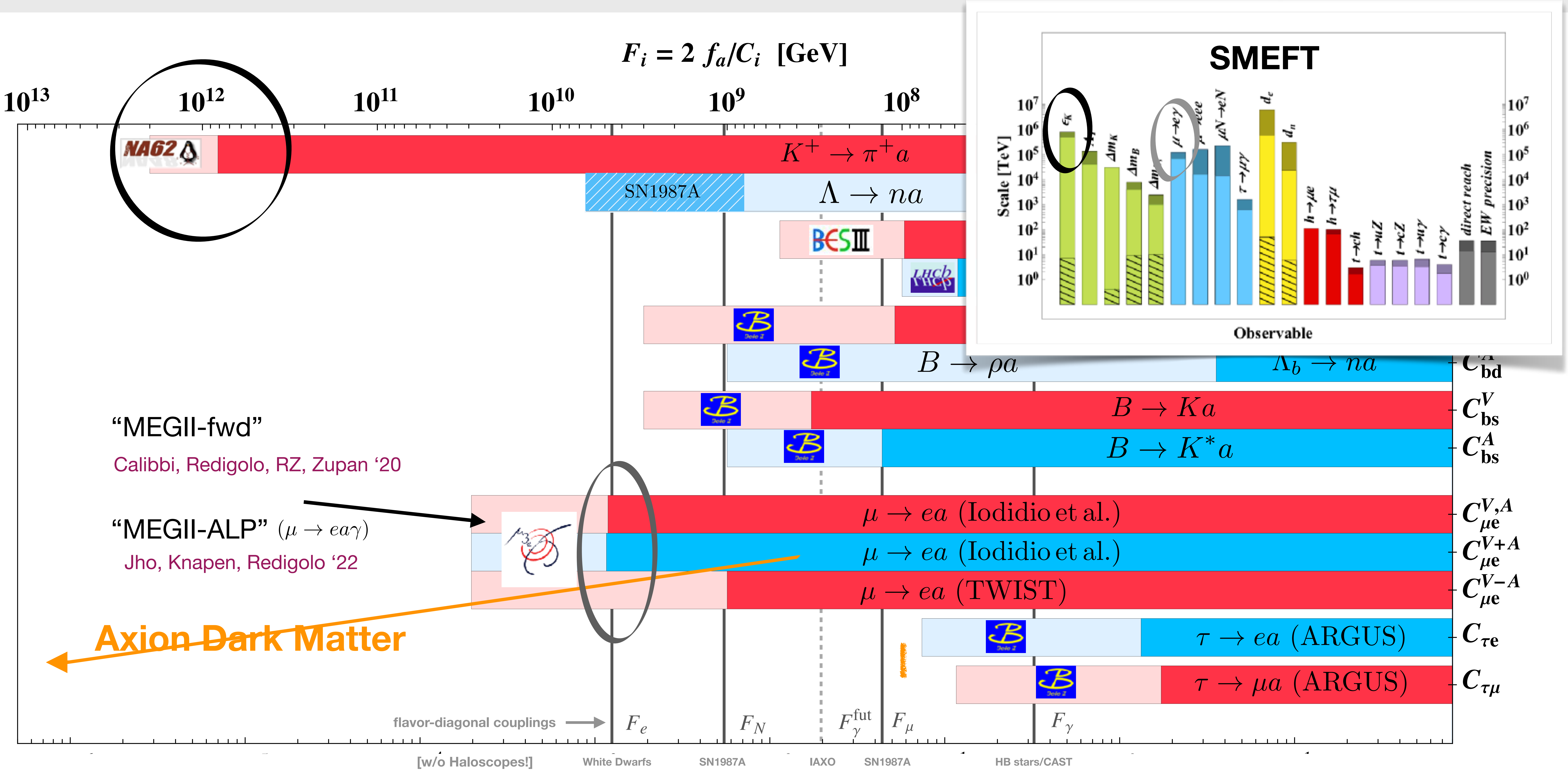
Calibbi, Redigolo, RZ, Zupan ‘20

“MEGII-ALP” $(\mu \to e a \gamma)$

Jho, Knapen, Redigolo ‘22

Axion Dark Matter

Summary of present and future Constraints



“MEGII-fwd”

Calibbi, Redigolo, RZ, Zupan ‘20

“MEGII-ALP” $(\mu \to ea\gamma)$

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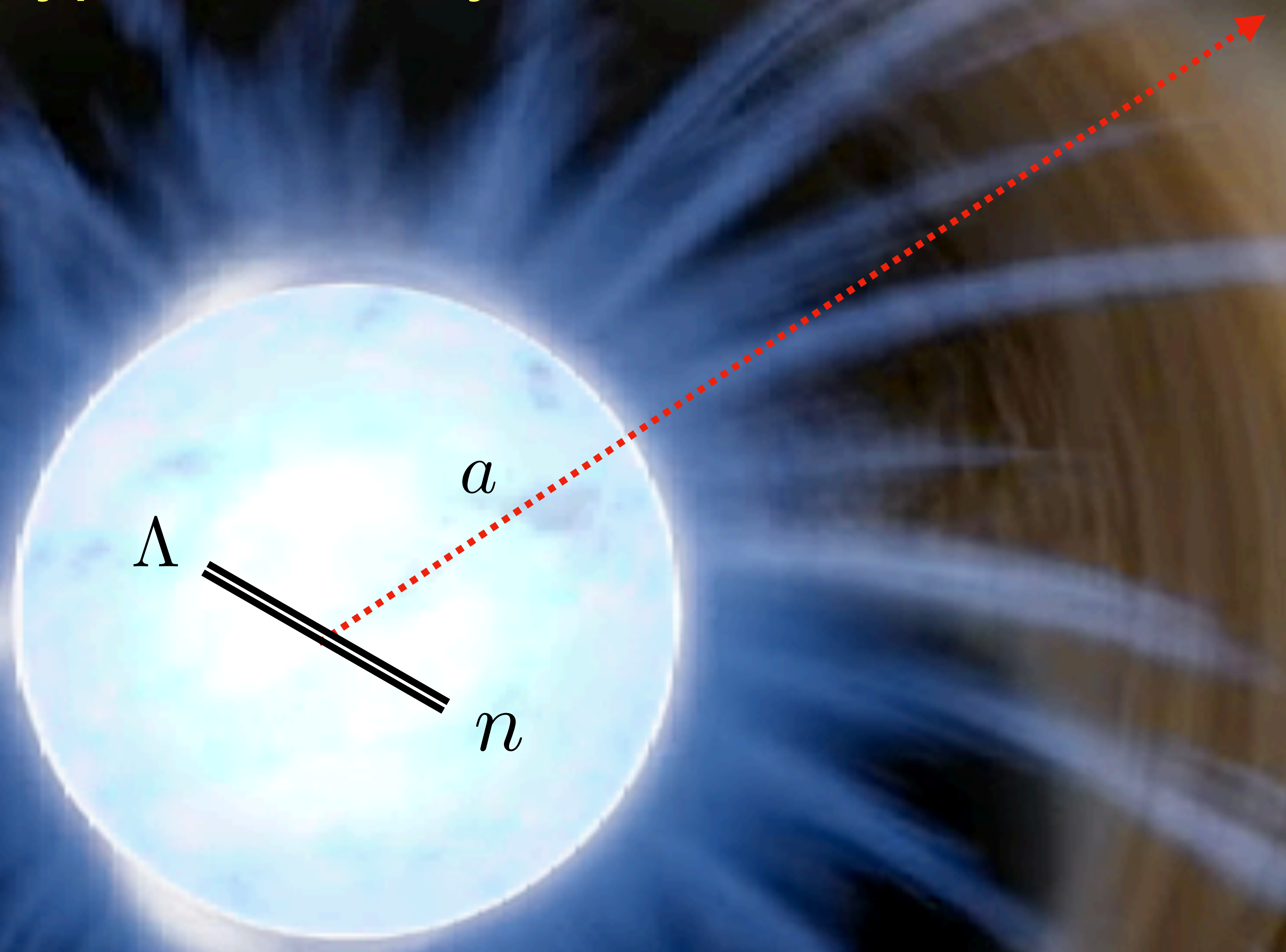
Axion Dark Matter

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



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

Gives best bound on invisible hyperon decays:

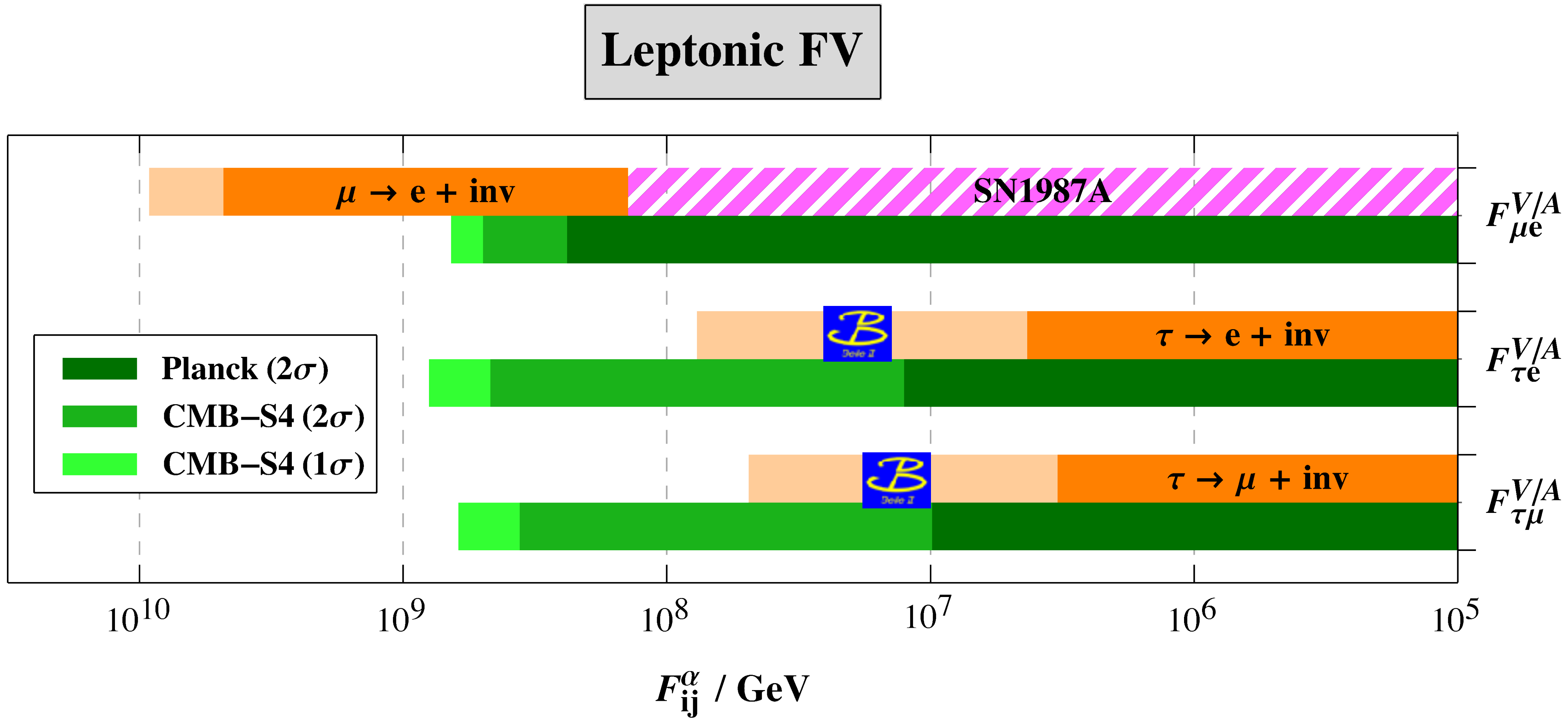
$$\boxed{{\rm BR}(\Lambda \to na) \lesssim 5.0 \times 10^{-9}}$$

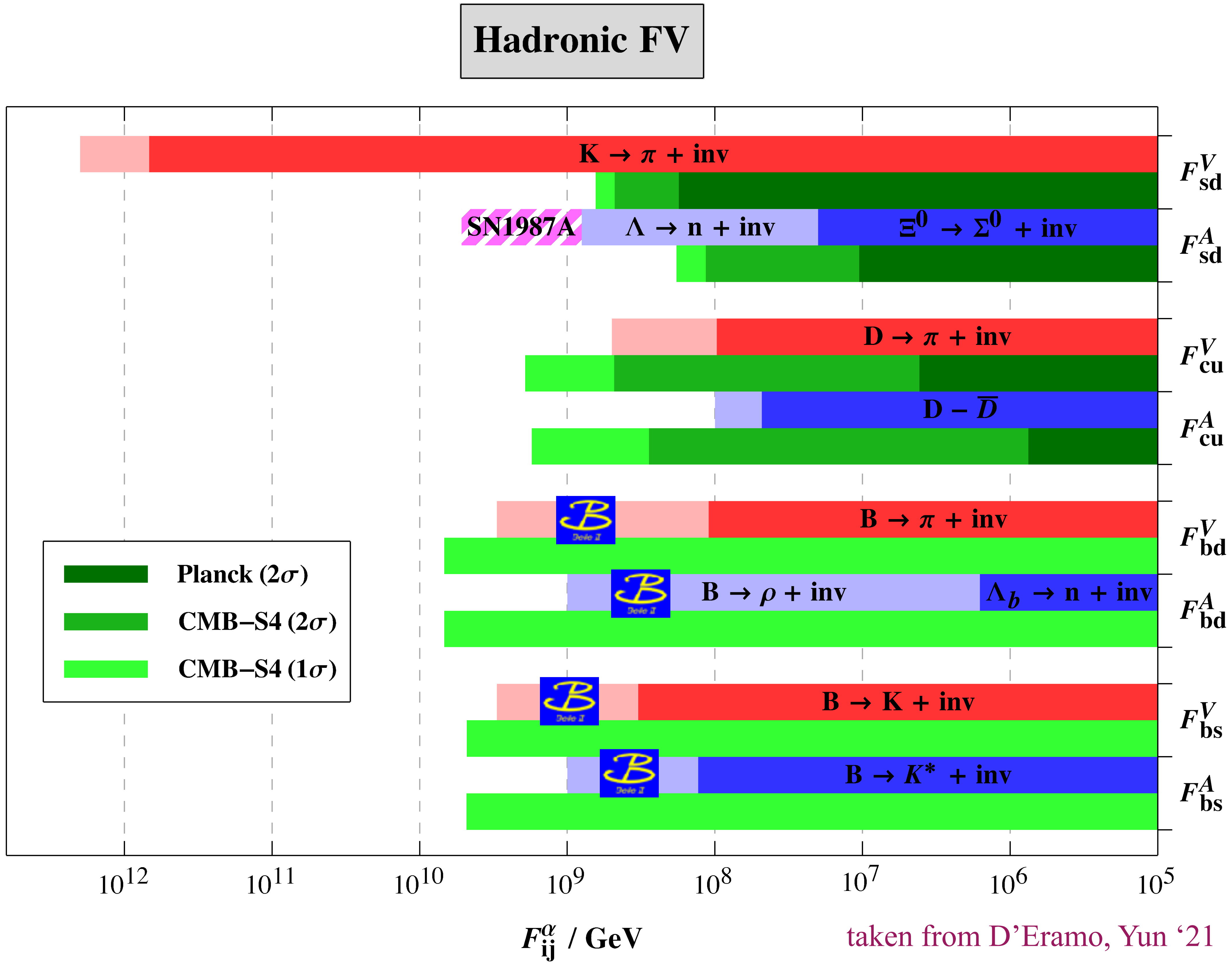
[similar for LFV muon decays, but weaker than lab bound]

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

Constraints from Cosmology

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





taken from D'Eramo, Yun '21

→ Belle-II competes with future CMB telescopes

Axion Dark Matter from SM Decays

- Use flavor-violating decays as main 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

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

→ requires axion mass in suitable window

(lab searches / WDM vs. kinematic threshold)

DM Stability

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

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

- Several contributions to axion relic abundance

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

IR freeze-in of lepton decays

$$\left.\begin{array}{ll} \text{IR freeze-in of } \mu\gamma\to ea & \alpha_{\mathrm{em}} \\ \text{UV freeze-in of } \mu h\to ea & \dfrac{m_\mu T_R}{3\pi^3 v^2} \end{array}\right\} \times \Omega h^2|_{\mu\to ea}$$

take small T_R , which also suppresses misalignment

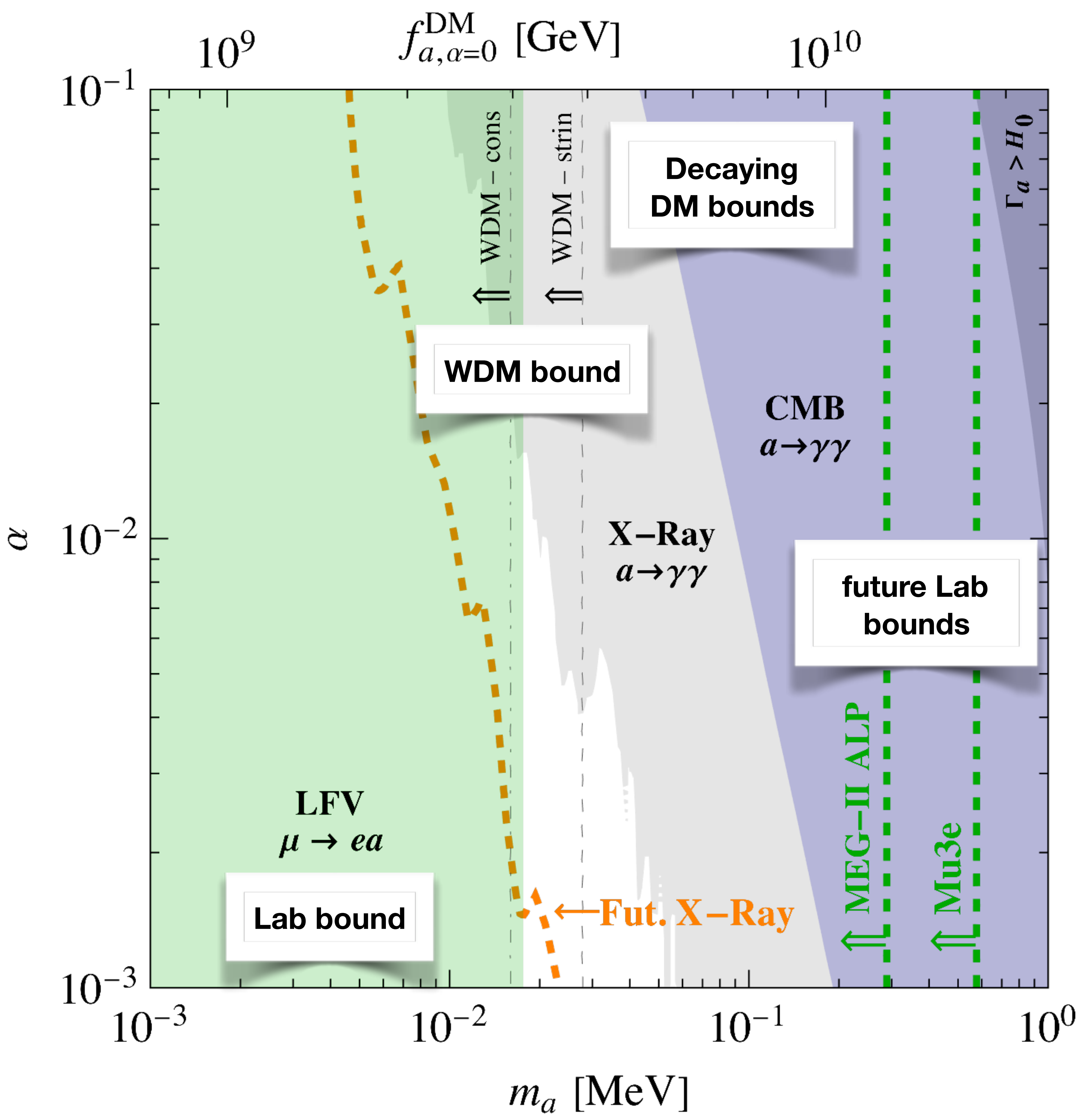
- DM lifetime $\tau_a = 10^{20}\mathrm{sec}\left(\frac{60\,\mathrm{keV}}{m_a}\right)^7\left(\frac{f_a/\sin\alpha}{10^9\mathrm{GeV}}\right)^2$

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

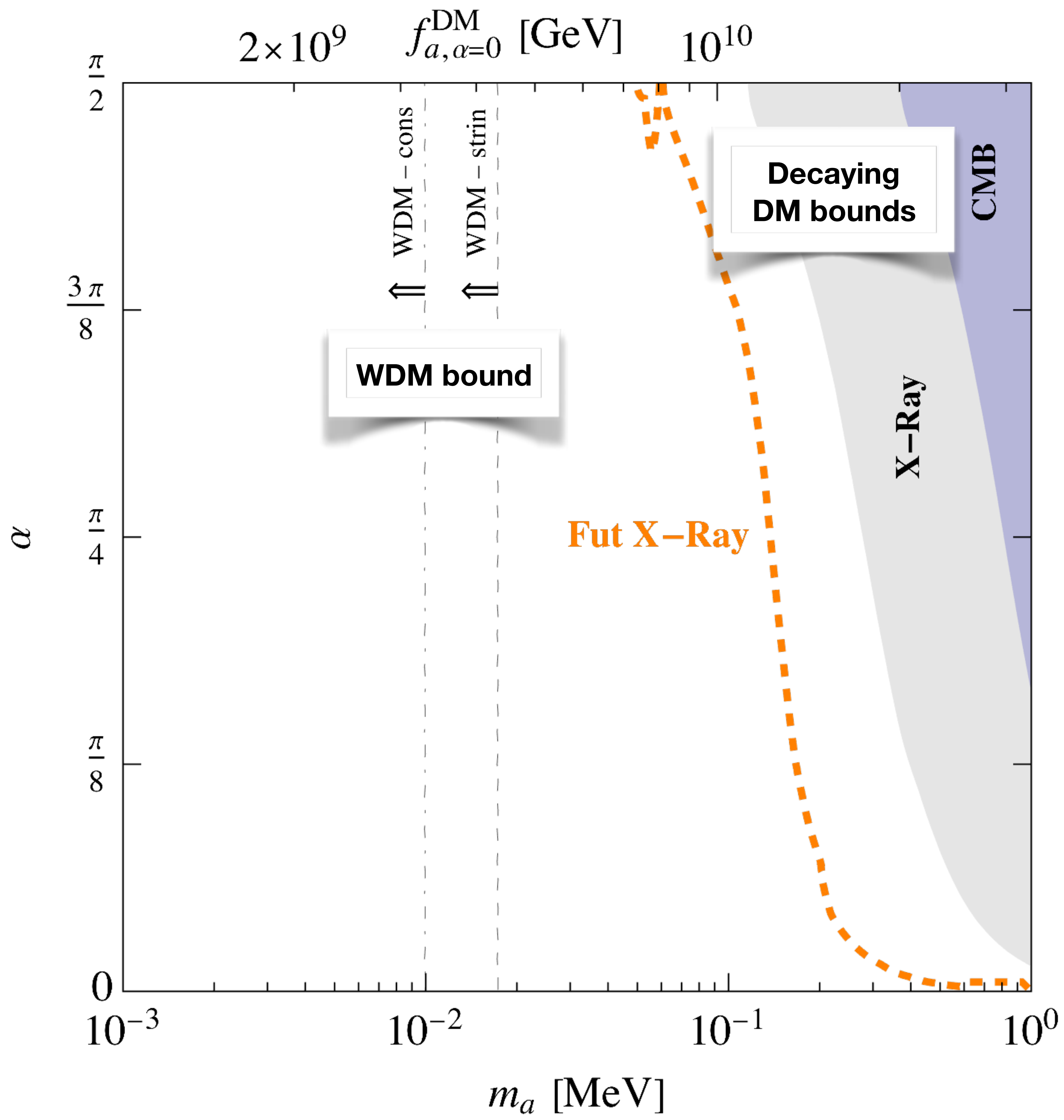
D'Eramo, Lenoci '20, Ballesteros et al '20, Decant et al '21

Results

μe-Scenario



τμ-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]