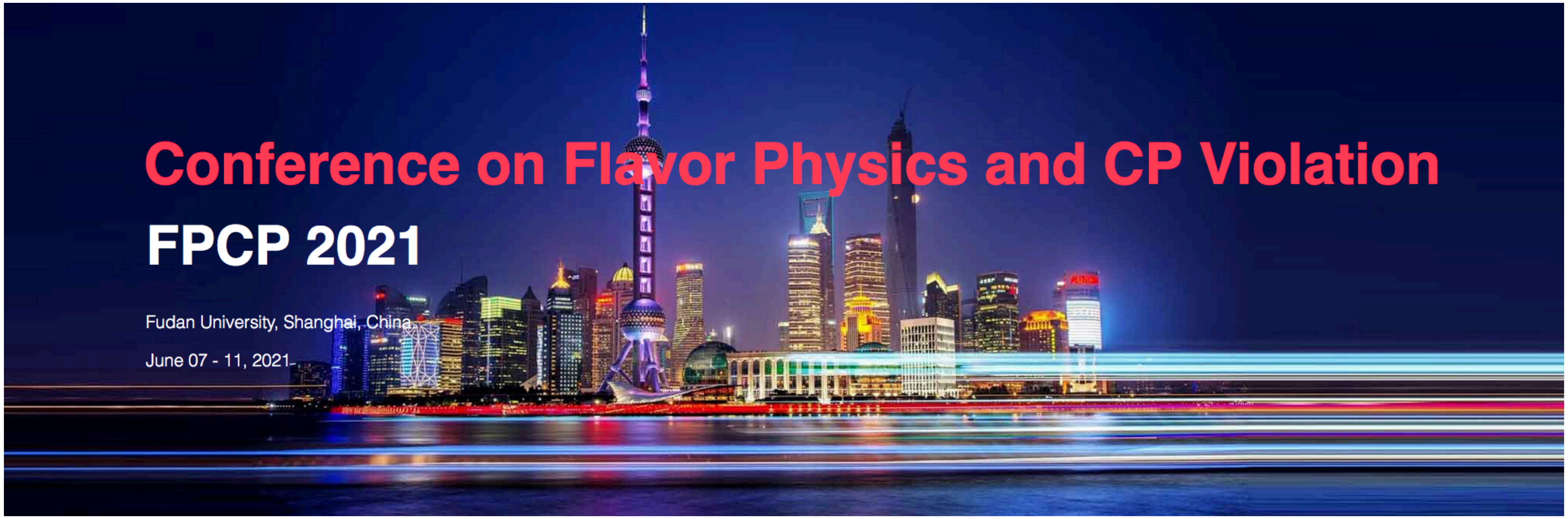
Searching for the QCD Axion at flavor experiments

Robert Ziegler

based on arXiv:2002.04623 & arXiv:2006.04795 & arXiv:2012.11632



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The QCD Axion

★ **Predicted by Peccei-Quinn (PQ) solution to Strong CP Problem**

Goldstone boson of global PQ symmetry that gets mass only through QCD anomaly

[Peccei, Quinn'77, Wilczek '78, Weinberg '78]

★ **PQ breaking scale suppresses couplings to SM and sets mass**

To have sufficiently small couplings need PQ breaking above 10^7 GeV

→ QCD axion is essentially massless and stable on cosmological scales

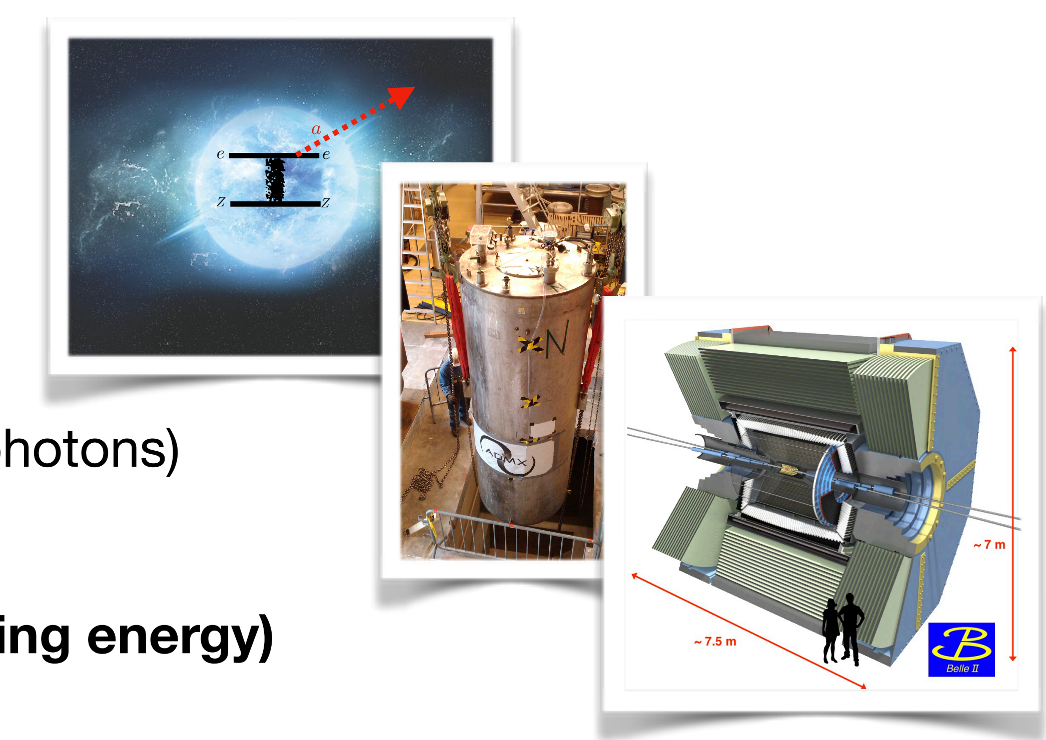
→ Vanilla Dark Matter candidate in vast parts of parameter space

★ **Can be searched for with**

✳ Astrophysics (star cooling via axion emission)

✳ Microwave cavities (DM axion conversion to photons)

✳ **Flavor experiments (rare decays with missing energy)**



Effective Axion Lagrangian

Generic axion interactions described by effective Lagrangian well below PQ breaking scale

[Georgi, Kaplan, Randall '86]

Axion couplings respect shift symmetry except for anomalous couplings to gauge fields

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

non-perturbative effects generate axion potential

$$V(a) \sim -m_\pi^2 f_\pi^2 |\cos\frac{a(x)}{f_a}|$$

Solves Strong CP Problem & generates axion mass

$$m_a \approx 5.7\,{\rm eV}\left(\frac{10^6{\rm GeV}}{f_a}\right)$$

gives low-energy axion couplings to photons

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

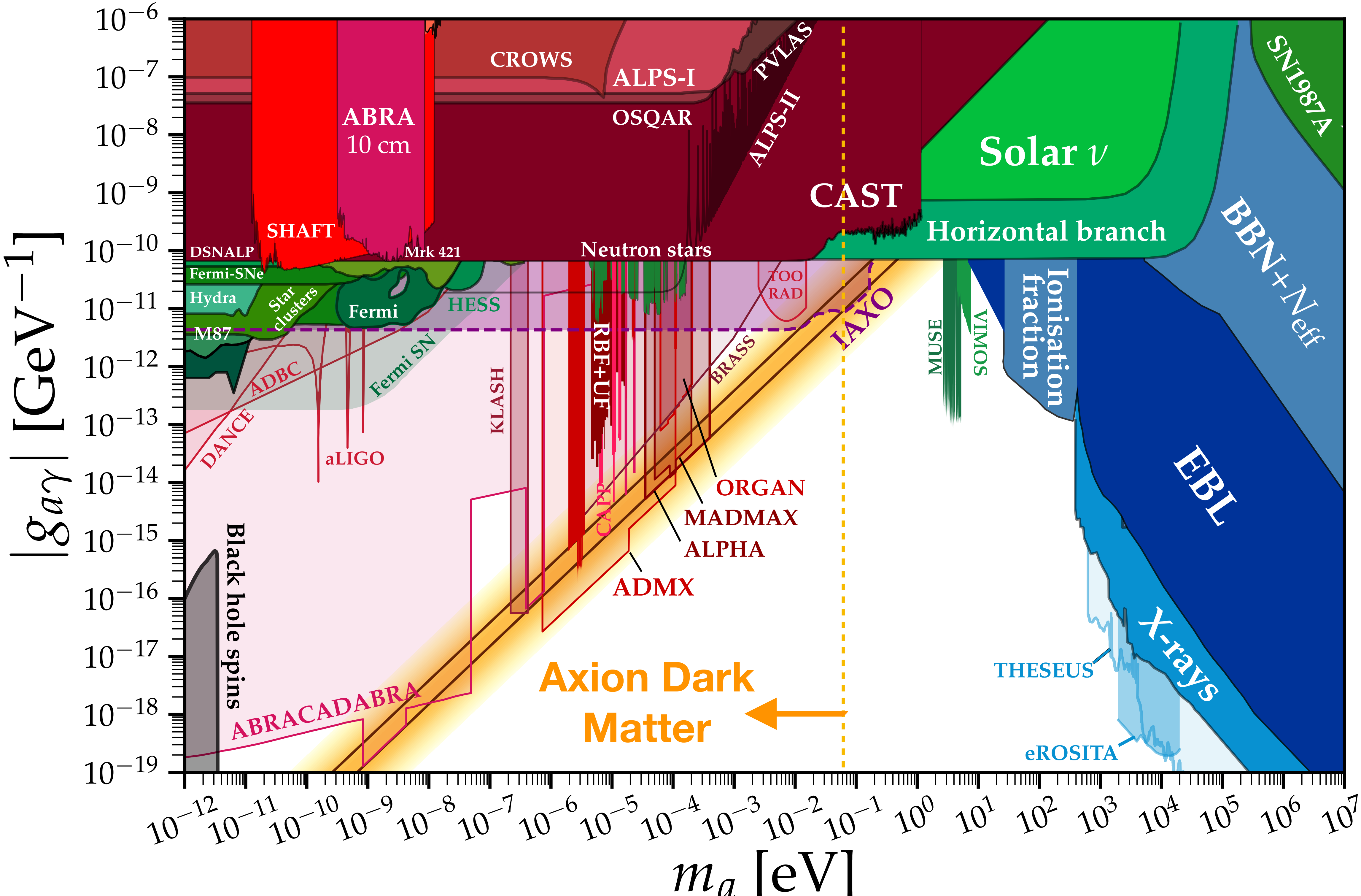
Most common axion search channel

in general described by two hermitian 3x3 matrices in each fermion sector

3 flavor-diagonal couplings: mainly probed by astrophysics

6 flavor-violating couplings: probed by flavor physics

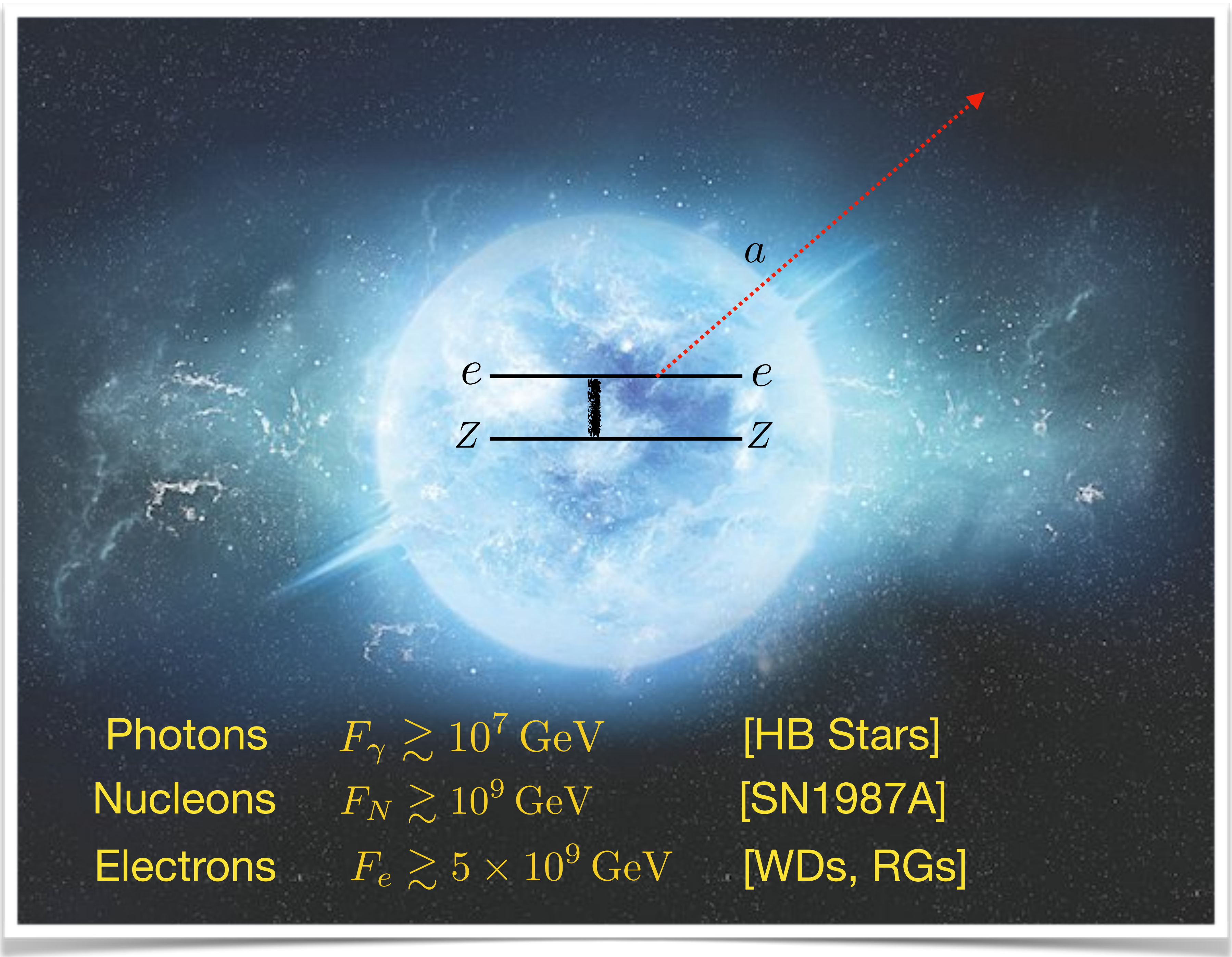
Axion Searches with Photons



from https://cajohare.github.io/AxionLimits

Constraints from Astrophysics

Axion couplings to ordinary matter (e, N, γ) allow to radiate off energy from stellar objects, which can conflict with observations



$F_i \equiv f_a / C_i$

Flavor-violating Couplings

- UV origin: rotate Peccei-Quinn charge matrix to fermion mass basis

$$C^{V,A}_{u_i u_j} \propto \left(V^\dagger_{UL} \mathrm{PQ}_q V_{UL}\right)_{ij} \pm \left(V^\dagger_{UR} \mathrm{PQ}_u V_{UR}\right)_{ij}$$

$$V^\dagger_{UL} Y_u V_{UR} = Y_u^{\mathrm{diag}}$$

- **QCD axion has flavor-violating couplings whenever PQ charges of SM fermions are non-universal** (e.g. in variant DFSZ models)

- Flavor-violating couplings depend on misalignment between PQ charges and SM Yukawas: *predictions require theory of flavor*

- Motivated and predictive scenarios obtained when $U(1)_{\mathrm{PQ}}$ identified with global flavor symmetry adressing Yukawa hierarchies [Wilczek '82]

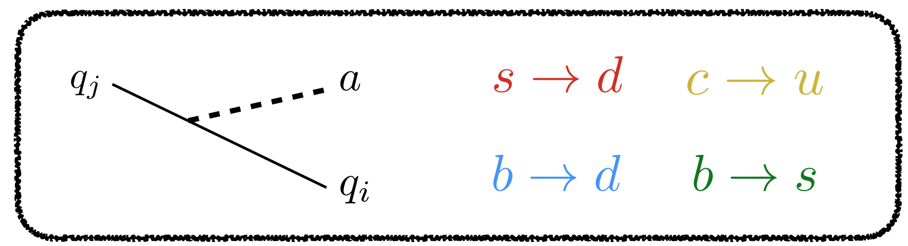
simplest realization: flaxion/axiflavon $U(1)_{\mathrm{Peccei-Quinn}} = U(1)_{\mathrm{Froggatt-Nielsen}}$

[Ema, Hamaguchi, Moroi, Nakayama '16; Calibbi, Goertz, Redigolo, RZ, Zupan '16]

Constraints from Quark Flavor Physics

✳ **Need to constrain 8 effective flavor-violating quark couplings**
neglecting top sector, which gets only weak constraints from top decays

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



✳ **Best probes are hadron decays with invisible final state**
look like highly suppressed SM decays with final state neutrino pair

- ✦ 2-body meson decays $\quad K \xrightarrow{C^V_{sd}} \pi a,\, B \xrightarrow{C^V_{bs}} K a,\, D \xrightarrow{C^V_{cu}} \pi a,\, B \xrightarrow{C^A_{bs}} K^* a, \ldots$
- ✦ 3-body meson decays $\quad K \xrightarrow{C^A_{sd}} \pi \pi a, \ldots$
- ✦ 2-body baryon decays $\quad \Lambda \xrightarrow{C^{V,A}_{sd}} n a,\, \Lambda_b \xrightarrow{C^{V,A}_{bd}} n a, \ldots$

✳ Bounds from neutral meson mixing typically much less constraining
and moreover meson mixing also sensitive to UV contributions from e.g. axion radial mode

Constraints on Meson Decays

- **Unfortunately experimental bounds often old or even non-existent**
  e.g. no bound on $D^+ \to \pi^+ a, B \to K^* a, B \to \rho a$

- Recast data on SM decays in 2-body region for massless axion

		$K \to \pi a$	$D \to \pi a$	$B \to \pi a$	$B \to K a$
	Decay	sd	cu	bd	bs
$\propto C_{ij}^V$	$\mathrm{BR}(P_1 \to P_2 + a)_{\rm exp}$	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]
	$\mathrm{BR}(P_1 \to P_2 + \nu\bar{\nu})_{\rm exp}$	$1.47^{+1.30}_{-0.89} \times 10^{-10}$ [85]	no analysis	0.8×10^{-5} [90]	1.6×10^{-5} [90]
$\propto C_{ij}^A$	$\mathrm{BR}(P_1 \to V_2 + a)_{\rm exp}$	[redacted]		no analysis	no analysis
	$\mathrm{BR}(P_1 \to V_2 + a)_{\rm recast}$			no data	5.3×10^{-5} [89]
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				$B \to \rho a$	$B \to K^* a$

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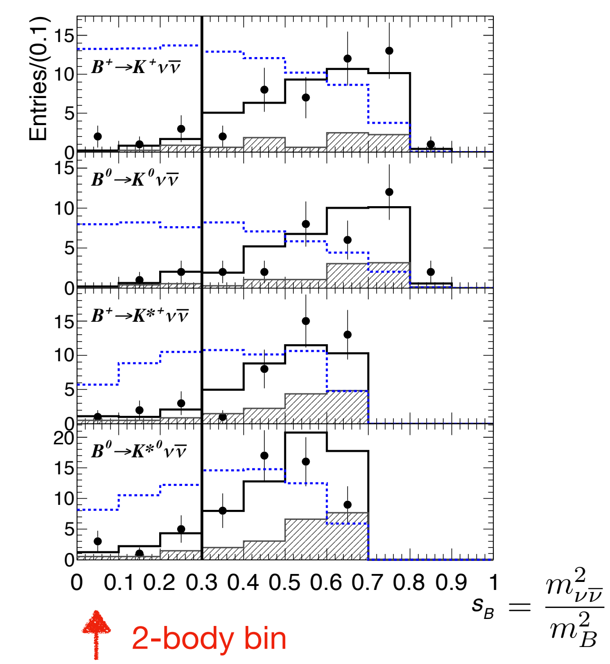
observed + background events



Belle data on B-decays do not admit 2-body recast: take **BaBar** data
e.g. in 1303.3719 2-body region cut out to reject background from radiative decays

Can recast **CLEO** data on $D \to \tau\nu, \tau \to \pi\nu$ to get bound on $D^+ \to \pi^+ a$
[see also Kamenik, Smith ’11]

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	[illegible]	[illegible]	[illegible]	no analysis	no analysis
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	[illegible]	[illegible]	[illegible]	2.8×10^{-5} [90]	2.7×10^{-5} [90]
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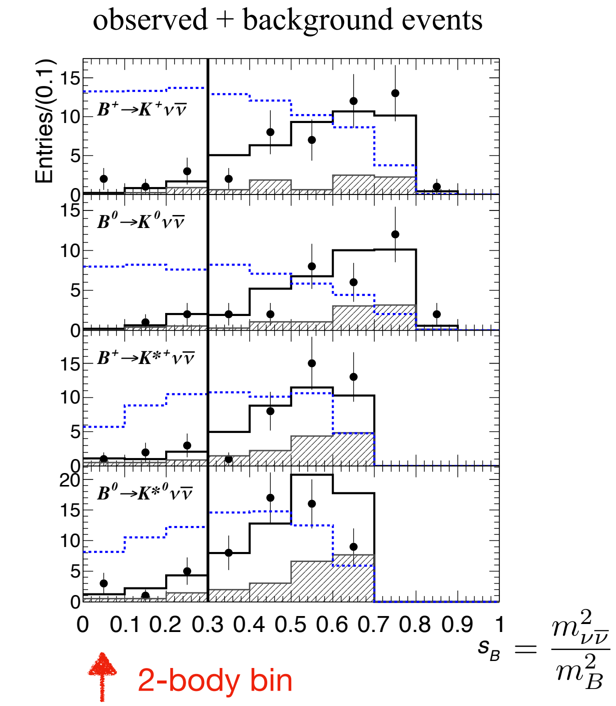
Interesting targets for BES-III and Belle-II



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[see also Kamenik, Smith '11]

Light vs. Heavy New Physics

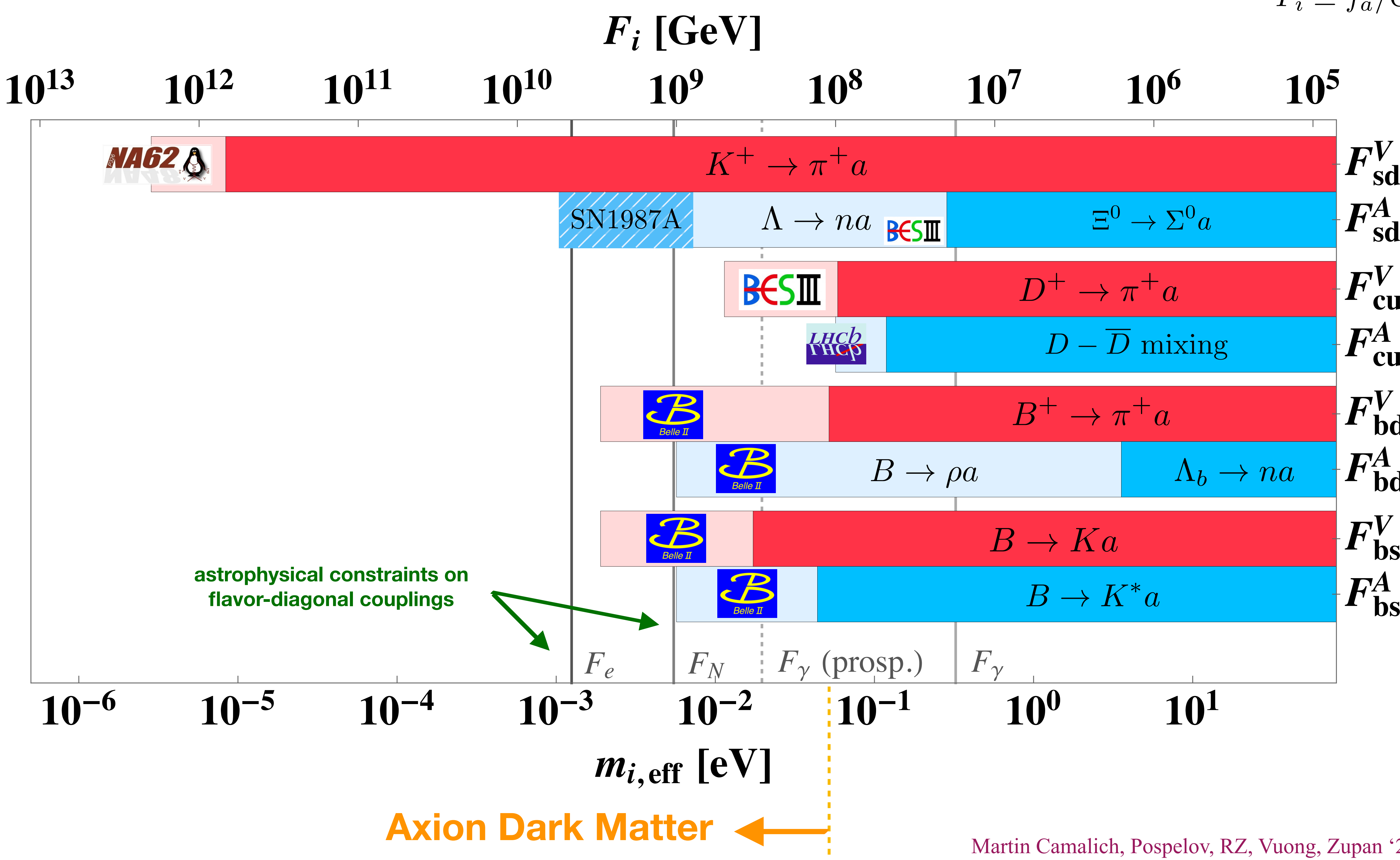
Looking for 2-body decays gives **sensitivity to much higher NP scales** than looking for deviations from SM 3-body decay

$B \to K a$	$B \to K \nu \overline{\nu}$
$\frac{\partial_\mu a}{f_a} \bar{b} \gamma^\mu s$	$\frac{1}{\Lambda^2} \left(\bar{b} \gamma^\mu s \right) \left(\overline{\nu} \gamma_\mu \nu \right)$
↓ $\Gamma \propto M_B^3 / f_a^2$	↓ $\Gamma \propto M_B^5 / \Lambda^4$
$f_a \gtrsim 3 \times 10^5 \, \mathrm{TeV}$	$\Lambda \gtrsim 10 \, \mathrm{TeV}$

(moreover heavy NP typically stronger constrained by mixing than decays)

Present Constraints & Prospects

$F_i \equiv f_a / C_i$



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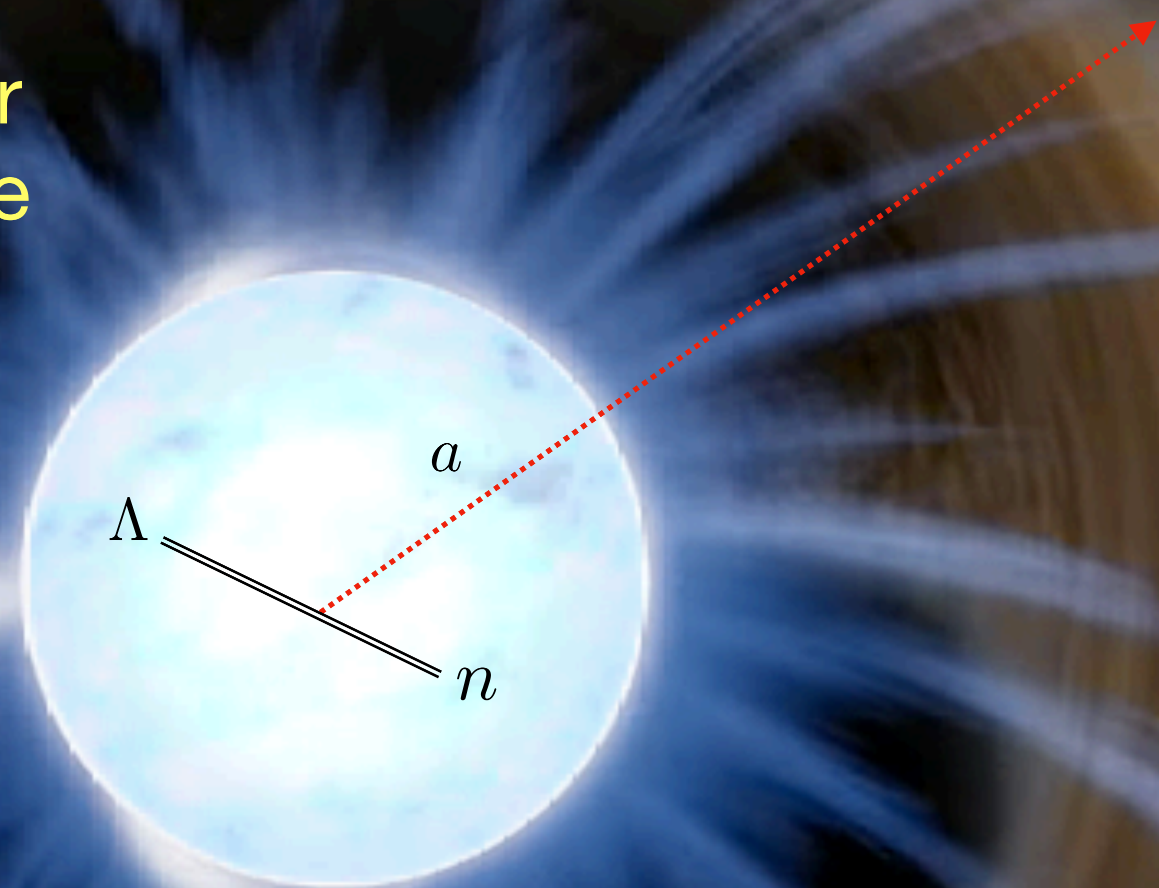
Flavor Physics with SN1987A

Best handle on axial-vector coupling 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 shortened observed neutrino pulse of SN1987A



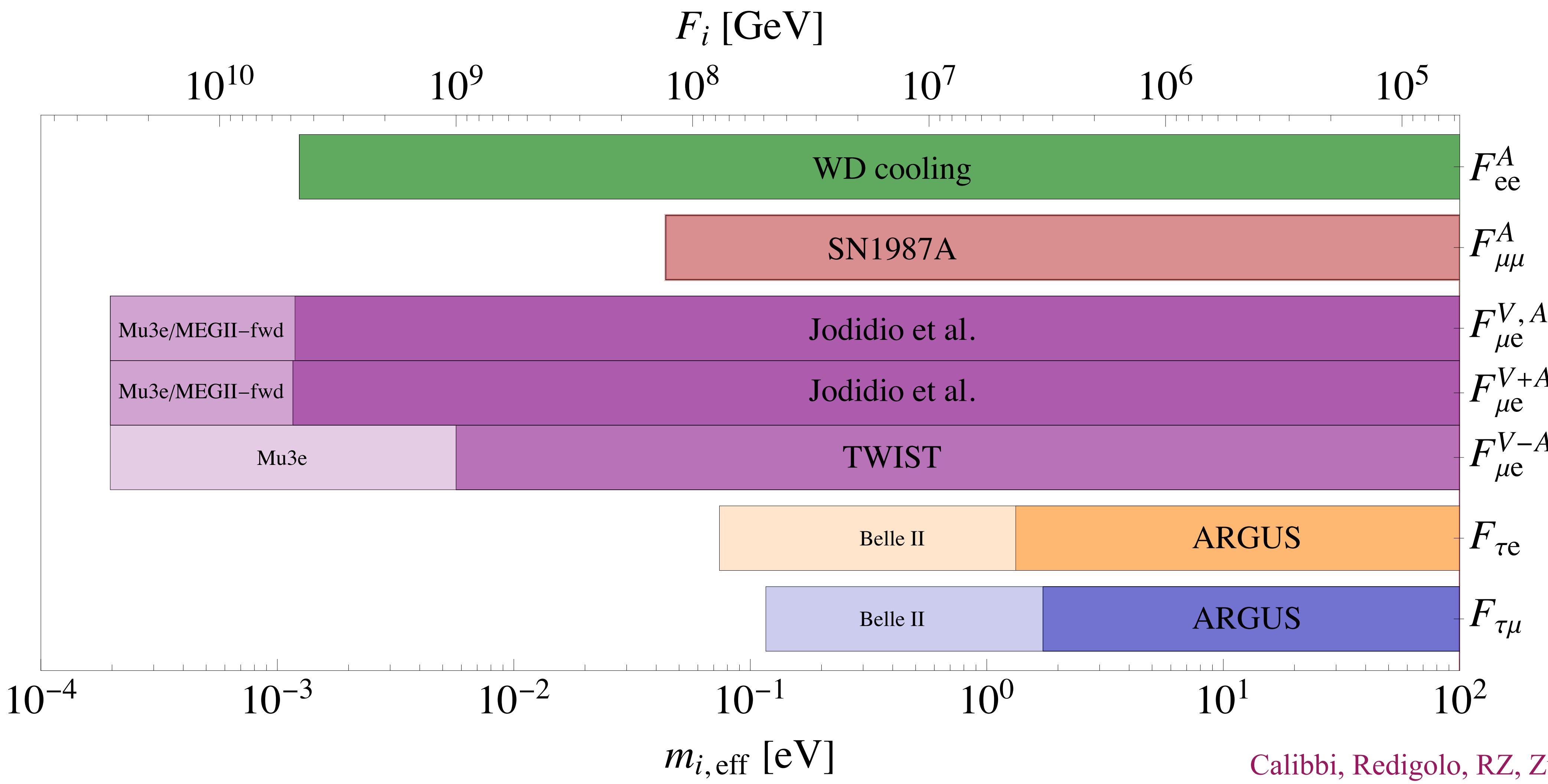
Constrain energy loss rate in axions

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

Gives best bound on invisible hyperon decays! $(\mathrm{BR} \lesssim 10^{-8}, \mathrm{BR}_{\mathrm{lab}} \lesssim 10^{-2})$

Constraints from Lepton Flavor Physics

- LFV decays with axions difficult since same signature as SM decay



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- Very intense muon beams available at PSI could help to improve existing bounds at Mu3e or MEG-II (+EM calorimeter in fwd direction)

Summary

- ★ The QCD axion can have large flavor-violating couplings which would contribute to 2-body meson decays with missing energy
- ★ Without flavor suppression strongest bound on axion decay constant is of order 10^{12} GeV and comes from NA62
- ★ 2-body decays are interesting experimental target since can probe higher NP scales than deviations from SM 3-body decays
- ★ Full data set of Belle II and BES-III could provide bounds of order 10^{9} GeV on flavor-violating axion coupling to b/c-quarks
- ★ Constraints on hyperon decays to invisible particles from SN1987A outclass lab bound by six orders of magnitude