Flavor Phenomenology of the QCD Axion

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Portorož 2019: Precision era in High Energy Physics

The QCD Axion

The Goldstone Boson of a spontaneously broken, global U(1) symmetry that has a QCD anomaly

Dynamical solution to the Strong CP Problem

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

Viable DM candidate in vast parts of parameter space

[Preskill,Wise,Wilczek; Abbott,Sikivie; Dine,Fischler '83]

Maybe the best motivated BSM particle we have

Effective Lagrangian

Axion coupling respects shift symmetry
that is broken only by gauge anomalies

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

anomalous coupling to gluon field strengths

anomalous coupling to EM field strengths

derivative coupling to SM fermions

Effective Lagrangian

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The only contribution to axion potential

$$V_{\rm eff} = -\frac{a(x)}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} \xrightarrow[\text{effects}]{\text{non-PT}} V(a) \sim -m_\pi^2 f_\pi^2 |\cos\frac{a(x)}{f_a}|$$

- has trivial minimum: QCD Θ-term dynamically set to zero
- generates tiny axion mass $m_a \propto m_\pi f_\pi / f_a = 5.7\,\mu{\rm eV}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)$

Effective Lagrangian

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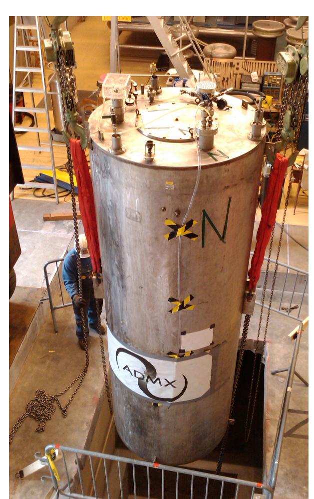
$$\mathcal{L}_{\text{eff}} = N\frac{a(x)}{\Lambda_{\text{PQ}}}\frac{\alpha_s}{4\pi}G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} + E\frac{a(x)}{\Lambda_{\text{PQ}}}\frac{\alpha_{\text{em}}}{4\pi}F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{\partial_\mu a(x)}{\Lambda_{\text{PQ}}}\bar{f}_i\gamma^\mu\left(C_{ij}^V + C_{ij}^A\gamma_5\right)f_j$$

Provides axion couplings to photons:
most common axion search channel

Haloscopes

$a \longrightarrow \gamma$

ADMX



Helioscopes

$\gamma \longrightarrow a \longrightarrow \gamma$

CAST/IAXO

Effective Lagrangian

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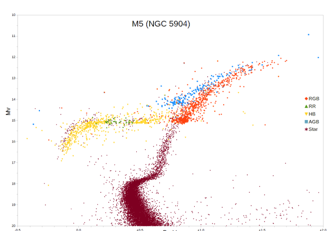
3 + 6 couplings in each fermion sector
(diagonal vector couplings unphysical)

flavor-conserving
constrained mainly by
astrophysics

flavor-violating
constrained mainly by
rare decays

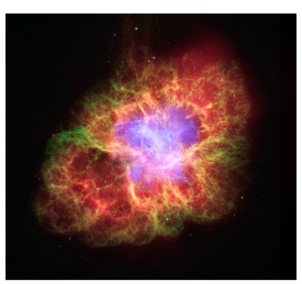
Constraints from Astrophysics

Axion couplings to matter allow to efficiently radiate off energy in astrophysical objects



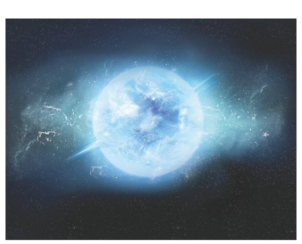
Evolution of Horizontal Branch stars: constrains **photon** couplings

$$m_a < \frac{3 \cdot 10^{-1}\,\mathrm{eV}}{C_\gamma}$$



Supernova neutrino burst duration: constrains **nucleon** couplings

$$m_a < \frac{4 \cdot 10^{-3}\,\mathrm{eV}}{|C_N|}$$



White Dwarf cooling: constrains **electron** couplings

$$m_a < \frac{3 \cdot 10^{-3}\,\mathrm{eV}}{|C_e|}$$

Constraints from Flavor Physics

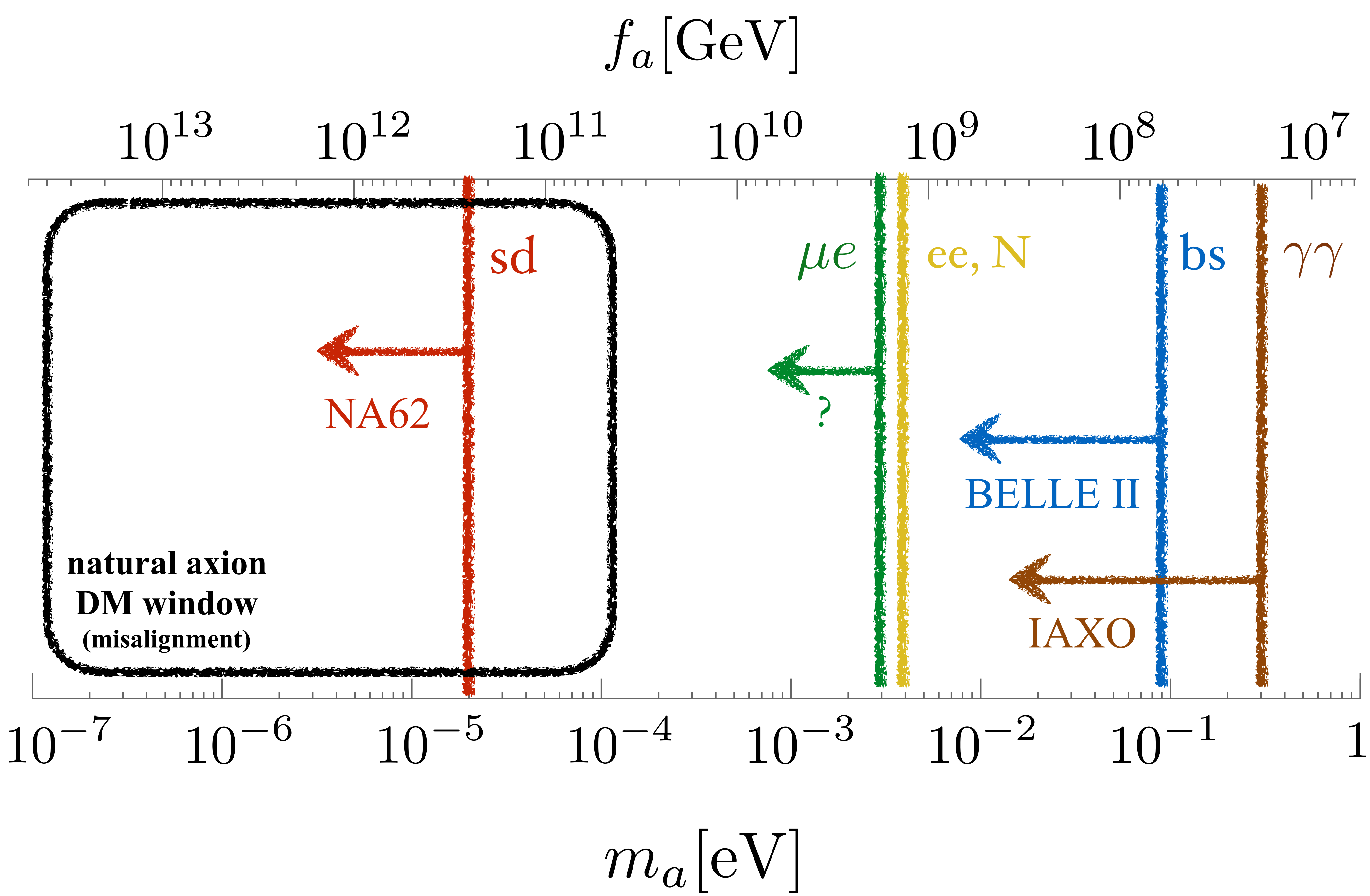
Flavor-violating axion couplings allow for rare decays with **invisible & massless final state**

$K \to \pi a$ (E787+E949, '08) $\qquad m_a < \dfrac{2 \cdot 10^{-5}\,\mathrm{eV}}{|C^V_{sd}|}$ $\xrightarrow{\times 1/8}$ **NA62**

$\mu \to e a \gamma$ (Crystal Box, '88) $\qquad m_a < \dfrac{3 \cdot 10^{-3}\,\mathrm{eV}}{|C_{\mu e}|}$ $\xrightarrow{?}$ **MEG, Mu3e**

$B \to K a$ (CLEO, '01) $\qquad m_a < \dfrac{9 \cdot 10^{-2}\,\mathrm{eV}}{|C^V_{bs}|}$ $\xrightarrow{\times 1/10}$ **BELLE II**

Present and Future Constraints



(for $C_i = 1$)

Origin of Axion-Fermion Couplings

Axion couples to PQ current: in fermion mass basis given by PQ charges folded with unitary rotations

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

diagonal PQ charge matrix of LH quarks

unitary rotations that diagonalize Yukawas

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

Induce flavor-violating couplings whenever SM fermions carry non-universal PQ charges

- e.g. non-universal DFSZ models; size given by (free) rotation angles
  Celis, Fuentes-Martin, Serodio '14; di Luzio, Mescia, Nardi, Panci, RZ '17, ...
- very predictive framework: PQ = FN ("axiflavon"/"flaxion")
  Calibbi, Goertz, Redigolo, RZ, Zupan '16 / Ema et al. '16 Wilczek '82

Model-Independent Bounds

$$\mathcal{L}_{\text{eff}} = \frac{\partial_\mu a}{F^V_{ij}} \bar{f}_i \gamma^\mu f_j + \frac{\partial_\mu a}{F^A_{ij}} \bar{f}_i \gamma^\mu \gamma_5 f_j$$

Feng, Moroi, Murayama, Schnapka '97

Björkeroth, Chun, King '18

	$F^V_{q_1 q_2}$ [GeV]	$F^A_{q_1 q_2}$ [GeV]
sd	$6.9 \cdot 10^{11}$	$2.3 \cdot 10^{6}$
cu	$3.3 \cdot 10^{5}$	$2.4 \cdot 10^{6}$
bd	$1.0 \cdot 10^{8}$	$1.4 \cdot 10^{6}$
bs	$1.2 \cdot 10^{8}$	$3.0 \cdot 10^{5}$

Meson decays to PS + axion

Neutral Meson Mixing

E787 + E949 '07 $\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$

no dedicated search $\mathrm{BR}(D^+ \to \pi^+ a) < 1$

CLEO '01 $\mathrm{BR}(B^+ \to K^+/\pi^+ a) < 4.9 \cdot 10^{-5}$

$$\Delta M_K \approx \frac{f_K^2 M_K}{(F^A_{sd})^2}$$

Plenty of Room for Improvement

- recast $D \to \tau\nu, \tau \to \pi\nu$ CLEO '08

  $\mathrm{BR}(D^+ \to \pi^+ a) < 1.3 \cdot 10^{-4}$ $F_{cu}^V \times 100$

Camalich, Vuong, RZ, Zupan, in progress

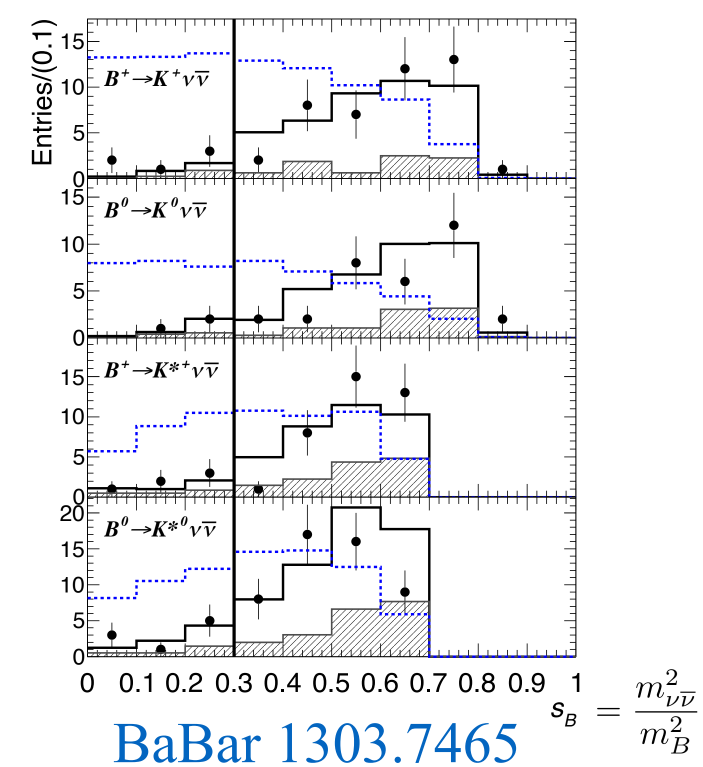
see also Kamenik, Smith '11

- recast $B \to K/K^*\nu\bar{\nu}$ BaBar '13

  $\mathrm{BR}(B \to Ka) < 1.6 \cdot 10^{-5}$

  $\mathrm{BR}(B \to K^*a) < 1.0 \cdot 10^{-4}$ $F_{bs}^A \times 1000$

  (Belle cuts away $m^2_{\nu\bar{\nu}} = m_a^2 \approx 0$ region)



BaBar 1303.7465

- Many interesting channels for Belle II

  $B \to Ka, B \to K^*a, B \to \pi a, B \to \rho a, \ldots$ $F_{bs,bd} \times (10 \div 50)$

Summary

- Precision flavor experiments allow to look for QCD axion complementarily to usual axion searches
- Flavor-violating axion couplings are generic and sizable whenever SM fermions have non-universal PQ charges
- NA62 will test PQ breaking scales up to 10^{12} GeV!
- Interesting prospects also for Belle II using 2-body phase space region in $B \to (K/\pi/K^*/\rho)\,\nu\bar{\nu}$ samples

Backup

Axion Models

Specify **anomalous** breaking of PQ (**fermion sector**)
& **spontaneous** breaking of PQ (**scalar sector**)

$$U(1)_{\rm PQ} \times SU(3)_c^2$$

SM fermions → 2Higgs: **PQWW** [Peccei, Quinn, Wilczek, Weinberg '78]

SM fermions → 2Higgs+Singlet: **DFSZ** [Dine, Fischler, Srednicki, Zhitnitsky '80]

BSM fermions → Higgs+Singlet: **KSVZ** [Kim, Shifman, Vainshtein, Zakharov '80]

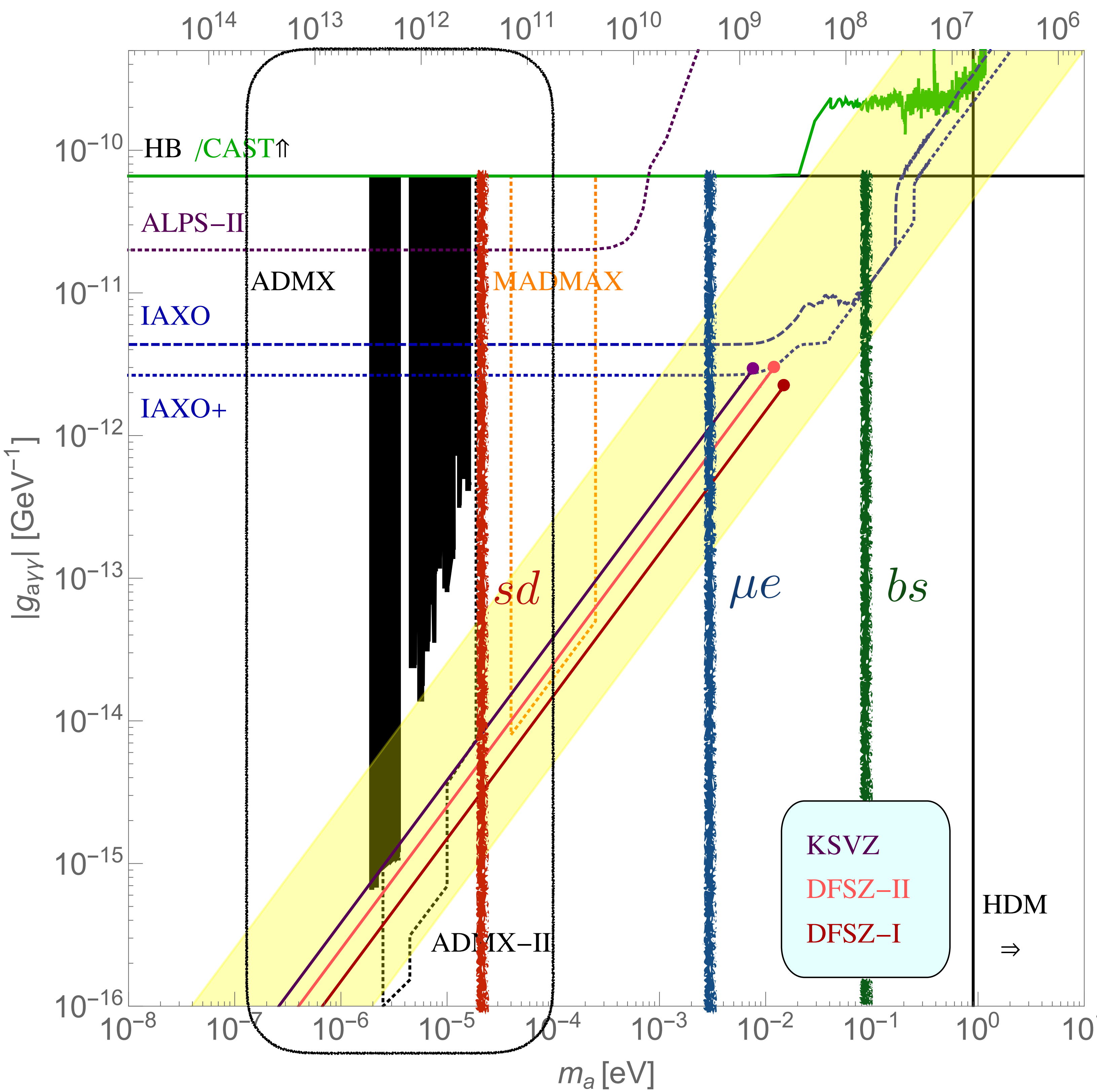
excluded

$J/\psi \to \gamma a$

see however 1710.03764

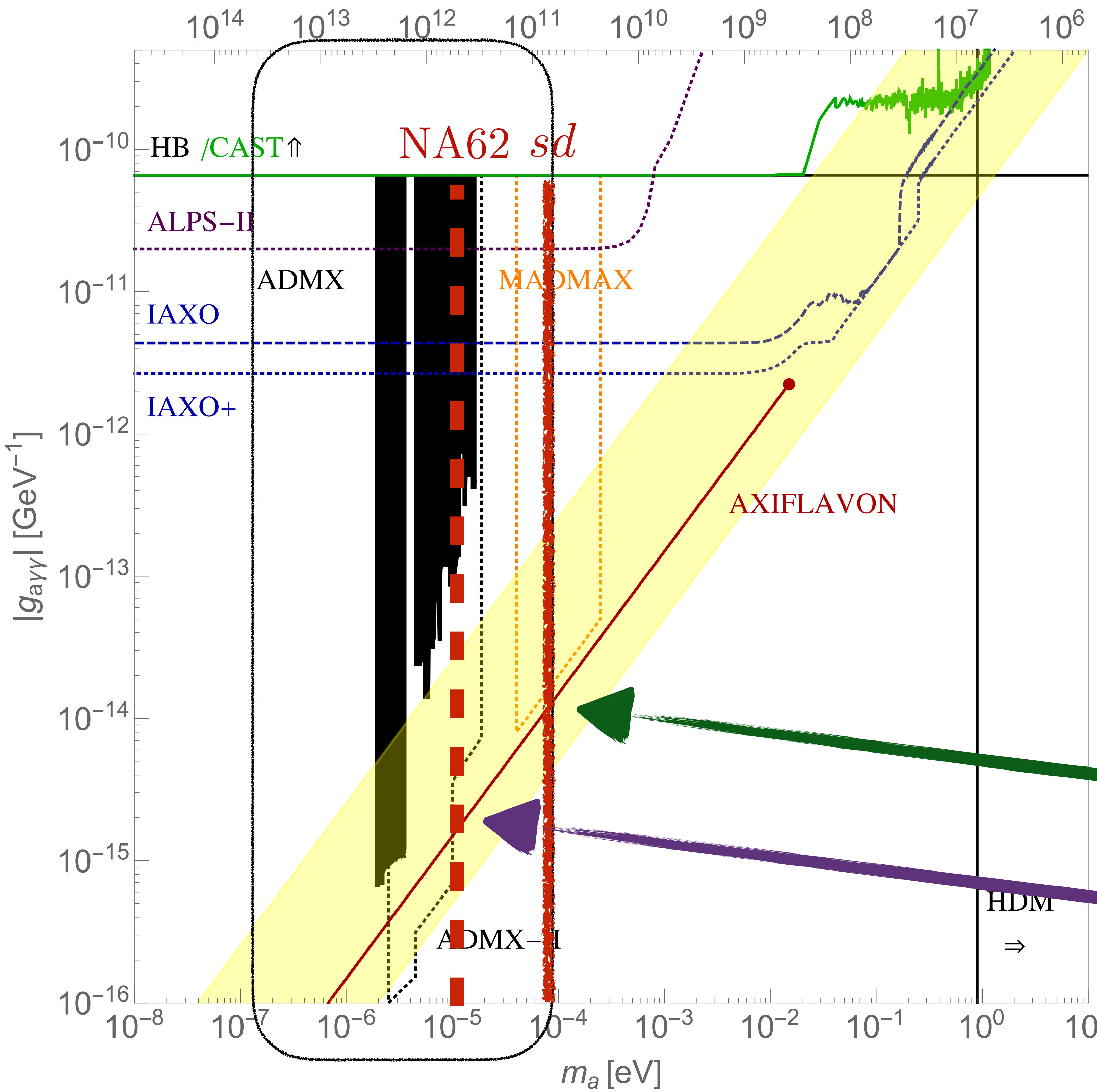
DFSZ, KSVZ: $\langle \text{Singlet} \rangle \gg v$: "Invisible" axion models

Flavor Constraints



(for $C_{i\neq j} = 1$)

The Axiflavon



Natural axion DM window testable at NA62 (and ADMX-II)

Present bound from E787+E949

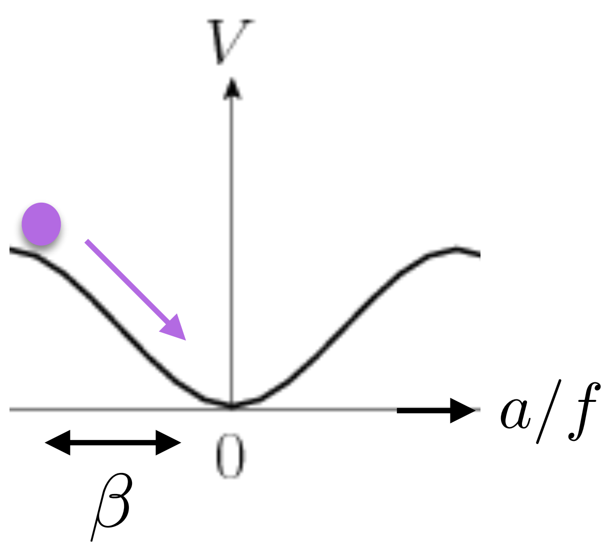
Expected future bound from NA62

Axions as Dark Matter

[axion essentially stable for $m_a \lesssim 20\,\text{eV}$]

When PQ breaking before inflation axion can be dark matter through "misalignment mechanism"

At QCD phase transition axion starts oscillating around minimum: energy stored in oscillations contributes to DM energy density



$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{10^{-5}\text{eV}}{m_a}\right)^{1.18} \beta^2$$

Correct abundance for
$10^{-7}\,\text{eV} \lesssim m_a \lesssim 10^{-4}\,\text{eV}$