



The QCD Axion meets Flavor

Robert Ziegler, 15/07/2026, Cluster Assembly 2026, Siegen

based on:

PRD 102 (2020) with Martin Camalich, Pospelov, Vuong, Zupan

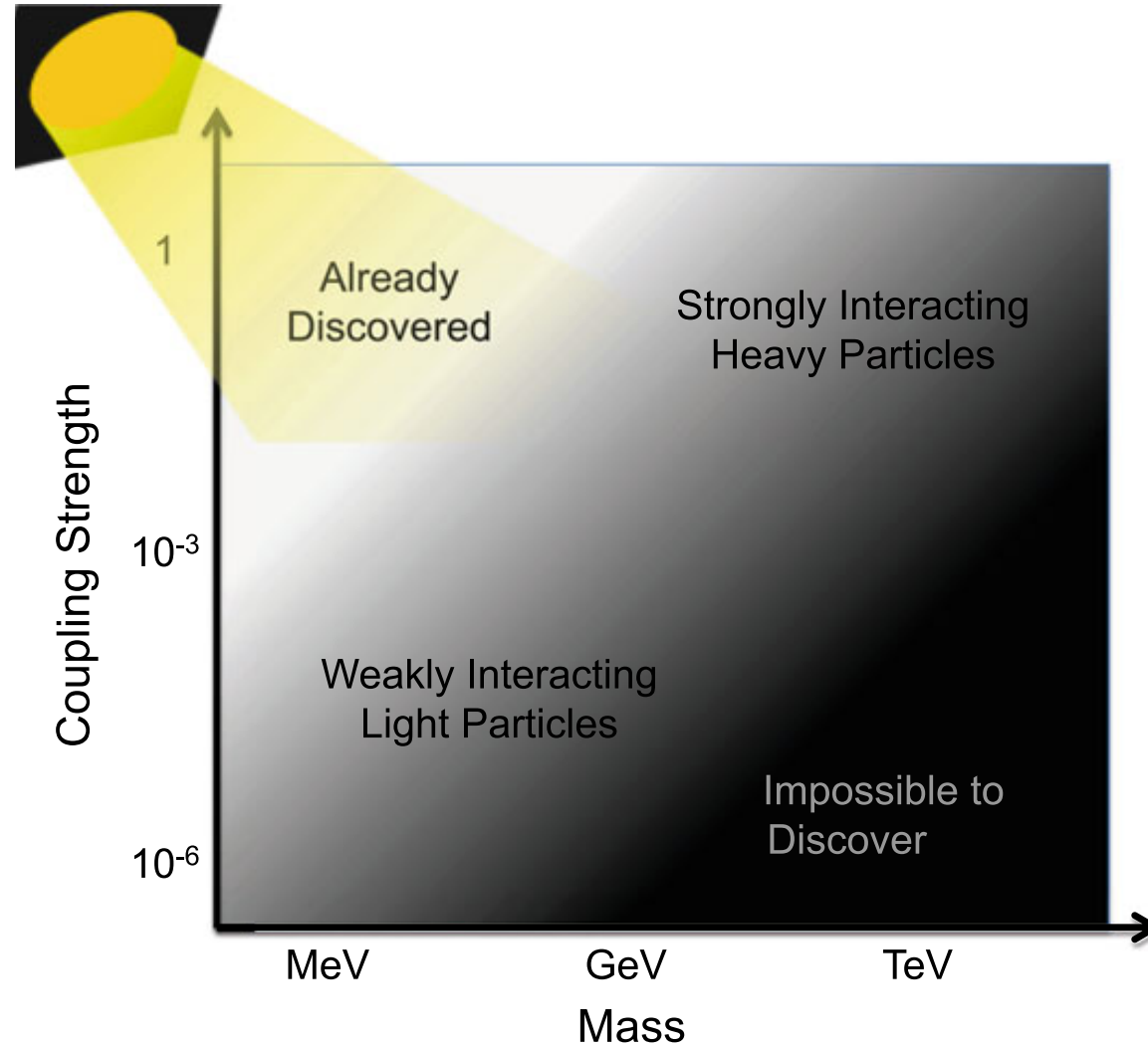
JHEP 09 (2021) with Calibbi, Redigolo, Zupan

PLB 841 (2023) with Badziak, Harigaya

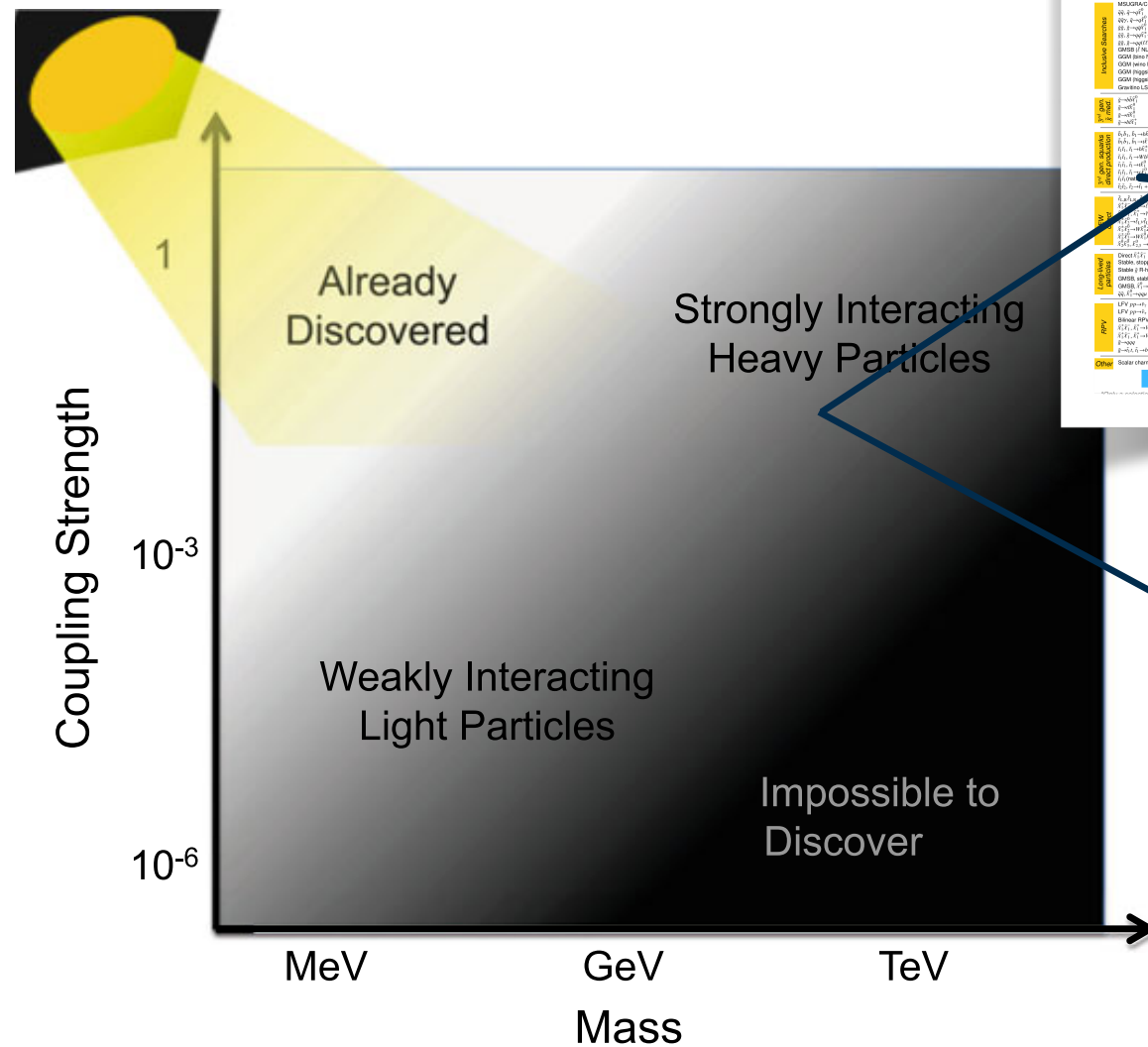
Ann.Rev.Nucl.Part.Sci. 75 (2025) with Martin Camalich

arXiv: 2606.07749 (2026)

Motivation



Motivation



Problem

ATLAS SUSY Searches¹

ATLAS Preliminary

July 2017

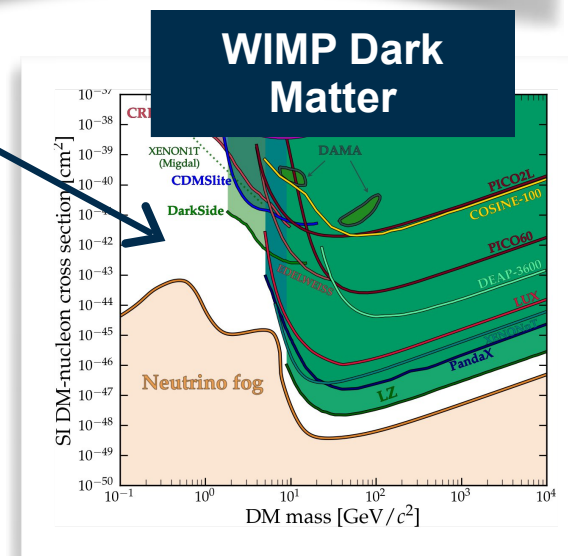
Model

ϵ, μ, τ, ν

Exclusion Model	Model	ϵ, μ, τ, ν	Mass	Type	Search
GMSB/CMSSM	MSSUGRA/CMSSM	0	2.461 TeV	0.15	0.1
	CMSSM (no ν) (compressed)	0	2.461 TeV	0.15	0.1
	$1.0 \times 10^{-12} \times m_{\tilde{g}}^2$	1	0.31 TeV	0.15	0.1
	$1.0 \times 10^{-12} \times m_{\tilde{u}_L}^2$	2	0.31 TeV	0.15	0.1
	$1.0 \times 10^{-12} \times m_{\tilde{u}_R}^2$	3	0.31 TeV	0.15	0.1
	$1.0 \times 10^{-12} \times m_{\tilde{d}_R}^2$	4	0.31 TeV	0.15	0.1
	GMSB/1/16/1	$1.0 \times 10^{-12} \times m_{\tilde{g}}^2$	0.31 TeV	0.15	0.1
	GMSB/1/16/2	$1.0 \times 10^{-12} \times m_{\tilde{u}_L}^2$	0.31 TeV	0.15	0.1
	GMSB/1/16/3	$1.0 \times 10^{-12} \times m_{\tilde{u}_R}^2$	0.31 TeV	0.15	0.1
	GMSB/1/16/4	$1.0 \times 10^{-12} \times m_{\tilde{d}_R}^2$	0.31 TeV	0.15	0.1
GMSB/CMSSM	GMSB/1/16/1	0	2.461 TeV	0.15	0.1
	GMSB/1/16/2	0	2.461 TeV	0.15	0.1
	GMSB/1/16/3	0	2.461 TeV	0.15	0.1
	GMSB/1/16/4	0	2.461 TeV	0.15	0.1
	GMSB/1/16/5	0	2.461 TeV	0.15	0.1
	GMSB/1/16/6	0	2.461 TeV	0.15	0.1
	GMSB/1/16/7	0	2.461 TeV	0.15	0.1
	GMSB/1/16/8	0	2.461 TeV	0.15	0.1
	GMSB/1/16/9	0	2.461 TeV	0.15	0.1
	GMSB/1/16/10	0	2.461 TeV	0.15	0.1
GMSB/CMSSM	GMSB/1/16/1	0	2.461 TeV	0.15	0.1
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	GMSB/1/16/10	0	2.461 TeV	0.15	0.1
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	GMSB/1/16/5	0	2.461 TeV	0.15	0.1
	GMSB/1/16/6	0	2.461 TeV	0.15	0.1
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	GMSB/1/16/8	0	2.461 TeV	0.15	0.1
	GMSB/1/16/9	0	2.461 TeV	0.15	0.1
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GMSB/CMSSM	GMSB/1/16/1	0	2.461 TeV	0.15	0.1
	GMSB/1/16/2	0	2.461 TeV	0.15	0.1
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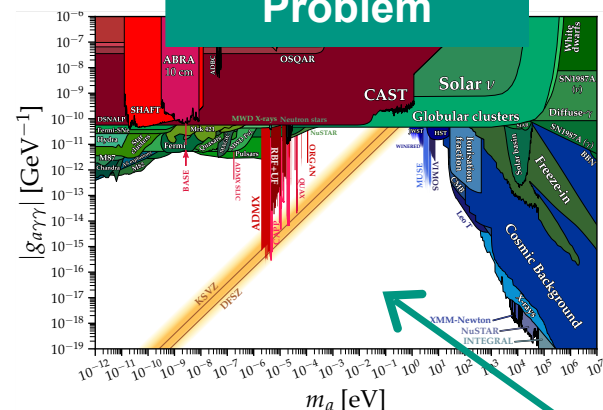
Reference

0.1	0.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	3.0	4.0	5.0	10.0	100.0	1000.0	10000.0	100000.0	1000000.0	10000000.0	100000000.0	1000000000.0	10000000000.0	100000000000.0	1000000000000.0	10000000000000.0	100000000000000.0	1000000000000000.0	10000000000000000.0	100000000000000000.0	1000000000000000000.0	10000000000000000000.0	100000000000000000000.0	1000000000000000000000.0	10000000000000000000000.0	100000000000000000000000.0	1000000000000000000000000.0	10000000000000000000000000.0	100000000000000000000000000.0	1000000000000000000000000000.0	10000000000000000000000000000.0	100000000000000000000000000000.0	1000000000000000000000000000000.0	10000000000000000000000000000000.0	100000000000000000000000000000000.0	1000000000000000000000000000000000.0	10000000000000000000000000000000000.0	100000000000000000000000000000000000.0	1000000000000000000000000000000000000.0	10000000000000000000000000000000000000.0	100000000000000000000000000000000000000.0	1000000000000000000000000000000000000000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	100.0	1000.0	1000.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100000000000000000000000000000000
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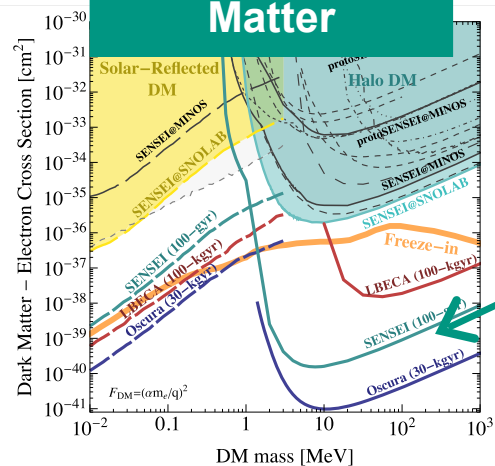


Motivation

Strong CP Problem



Light Dark Matter



Coupling Strength

10^{-3}

10^{-6}

Already Discovered

Weakly Interacting Light Particles

Strongly Interacting Heavy Particles

Impossible to Discover

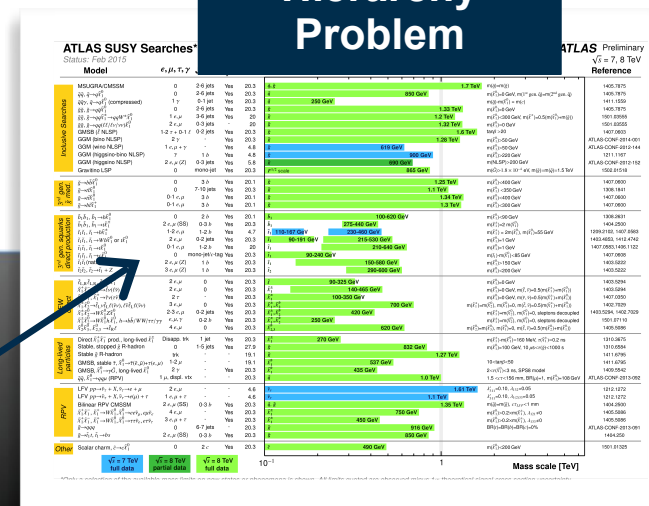
MeV

GeV

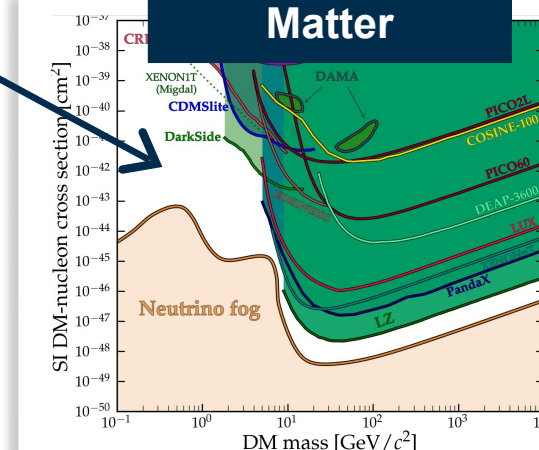
TeV

Mass

Hierarchy Problem

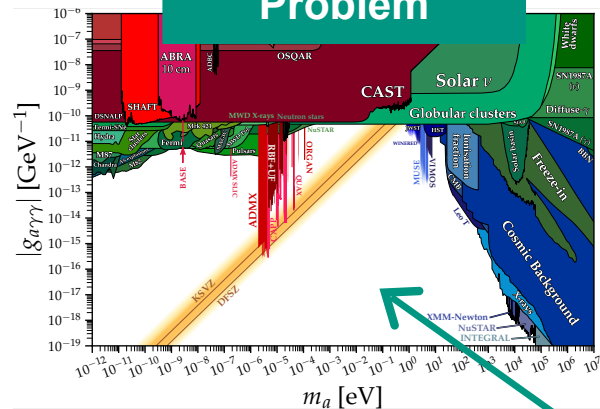


WIMP Dark Matter

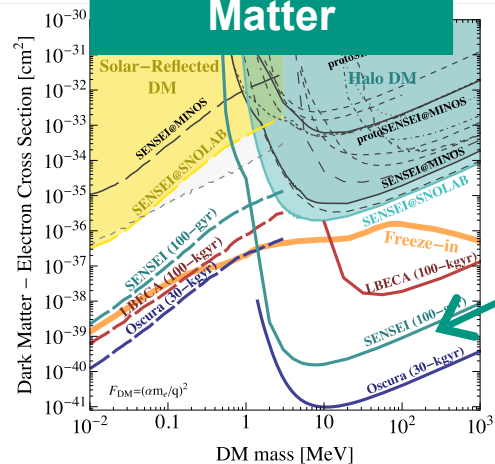


Motivation

Strong CP Problem



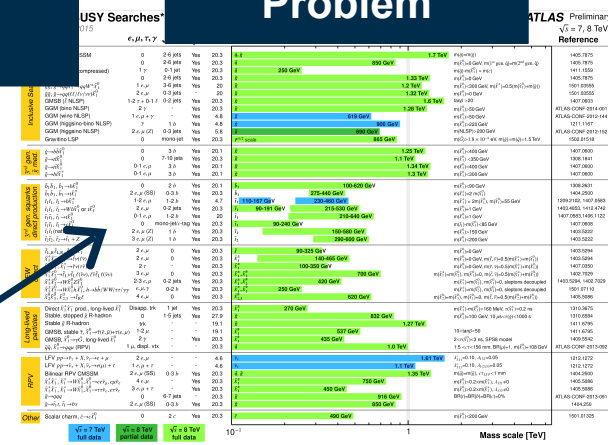
Light Dark Matter



Flavor violation is a problem!

too large FCNCs if suppressed by weak scale

Hierarchy Problem



Coupling Strength

10^{-3}

10^{-6}

Already Discovered

Strongly Interacting Heavy Particles

Weakly Interacting Light Particles

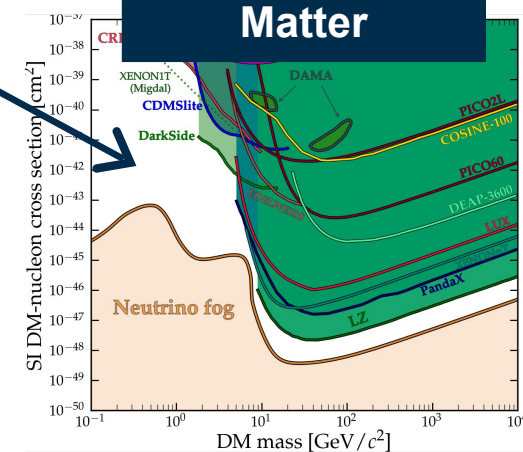
Impossible to Discover

MeV

GeV

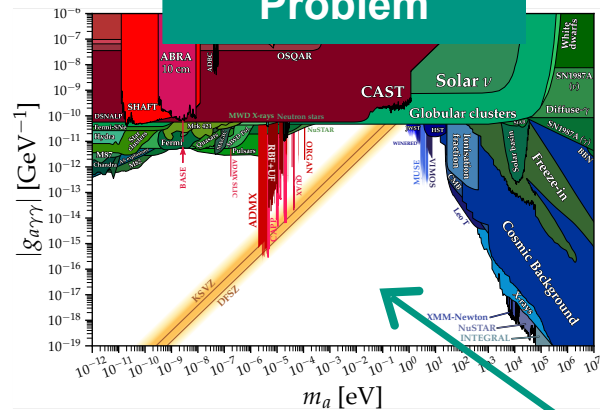
TeV

WIMP Dark Matter

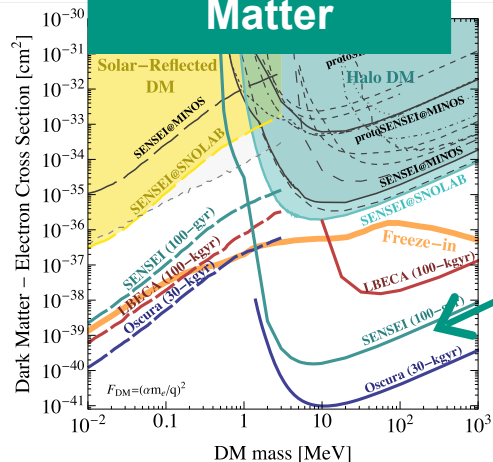


Motivation

Strong CP Problem



Light Dark Matter

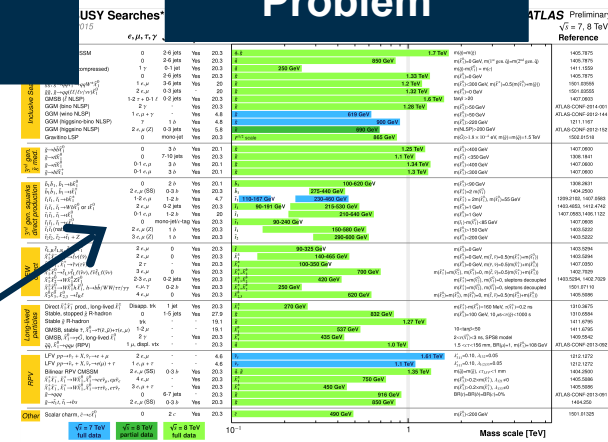


Flavor violation is an opportunity!
allows for light particle production from SM decays

Flavor violation is a problem!

too large FCNCs if suppressed by weak scale

Hierarchy Problem



Coupling Strength

10^{-3}

10^{-6}

Already Discovered

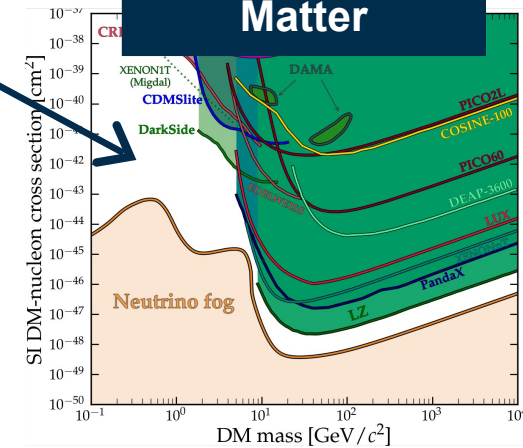
Strongly Interacting Heavy Particles

Weakly Interacting Light Particles

Impossible to Discover

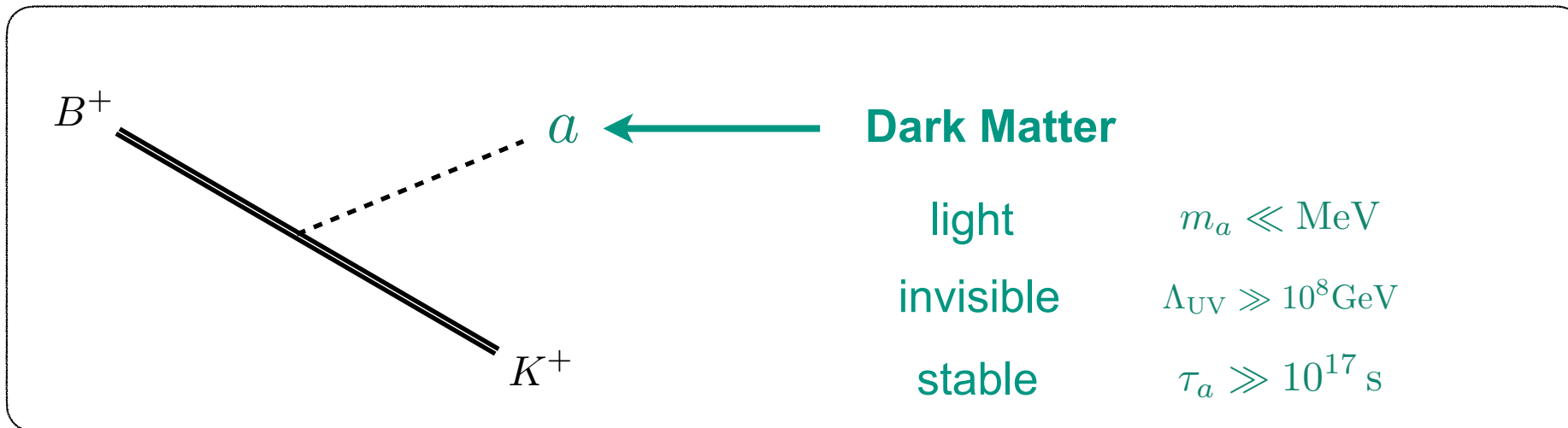
TeV

WIMP Dark Matter



Outline

Flavor-violating two-body decays are great probes of light Dark Matter



Excellent theory motivation:

- QCD axion (produced e.g. via misalignment)
- Axion-like particles (produced e.g. via freeze-in)
- pseudo-Goldstones of global flavor symmetries

Rich phenomenology:

- particle colliders $\rightarrow$ direct searches
- core-collapse supernovae $\rightarrow$ energy loss
- early Universe $\rightarrow$ dark radiation

The QCD Axion

- SM Lagrangian contains topological QCD θ -term, which violates P and CP contributes to neutron EDM, which has stringent upper experimental limit

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

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

Pospelov, Ritz '99; nEDM@PSI '20

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

$$V_\theta \approx -m_\pi^2 f_\pi^2 |\cos \theta/2|$$

...just need to promote θ to scalar field w/o potential

realized if Goldstone boson of new global, anomalous U(1) symmetry $\theta \rightarrow \frac{a(x)}{f_a}$

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

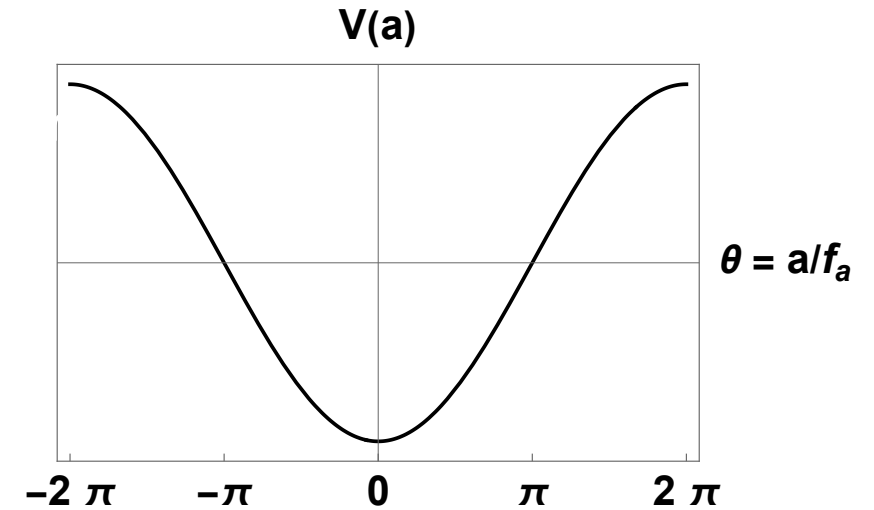
The QCD Axion mass

- Same potential solves Strong CP Problem and generates tiny axion mass

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

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

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

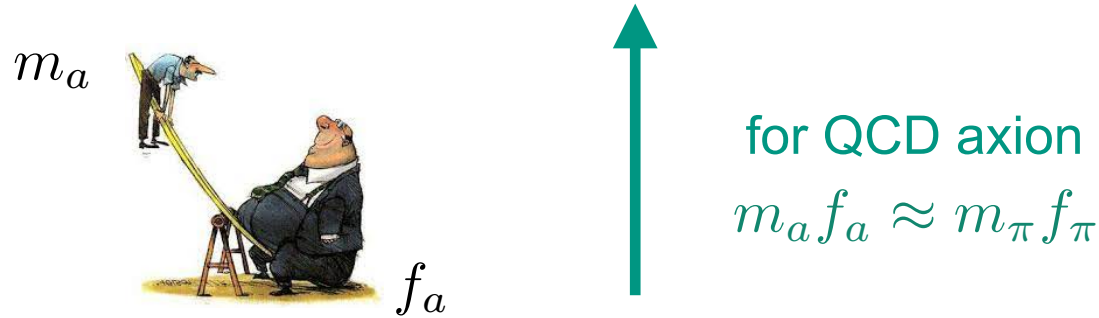


- Generalized to “axion-like” particle (ALP) taking mass as free parameter does usually not solve Strong CP Problem

Axion Dark Matter

- Axions are easily stable on cosmological scales, since very light

$$\Gamma(a \rightarrow \gamma\gamma) \simeq \frac{1}{10^{17}\text{sec}} \left(\frac{m_a}{\text{keV}}\right)^3 \left(\frac{10^8\text{GeV}}{f_a}\right)^2 \simeq \frac{1}{10^{30}\text{sec}} \left(\frac{10^8\text{GeV}}{f_a}\right)^5$$



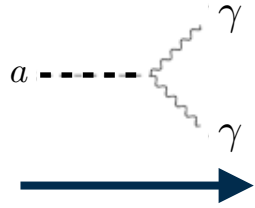
- Can be produced in early Universe in many ways
misalignment, decays of topological defects, thermal freeze-in...

Axion Phenomenology

- Except for gluon couplings, all QCD axion couplings are model-dependent

e.g.

$$\mathcal{L}_a \sim c_\gamma \frac{a(x)}{f_a} \frac{\alpha_{\text{em}}}{4\pi} \tilde{F}_{\mu\nu} F_{\mu\nu}$$



probed by helioscopes & star cooling

$$f_a/c_\gamma \gtrsim 10^7 \text{ GeV} \quad [\text{CAST/HB stars}]$$

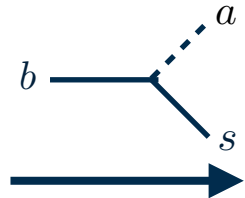
$$\sim 10^8 \text{ GeV} \quad [\text{IAXO}]$$

- Most general axion couplings described by EFT well below PQ breaking scale

Georgi, Kaplan, Randall '86

e.g.

$$\mathcal{L}_a \sim c_{bs} \frac{\partial_\mu a(x)}{f_a} \bar{b} \gamma^\mu s$$



probed by B-factories

$$f_a/c_{bs} \gtrsim 10^8 \text{ GeV} \quad [\text{Belle}]$$

$$\sim 10^9 \text{ GeV} \quad [\text{Belle II}]$$

often *assumed* that flavor violation is absent @tree-level, but well-motivated in many UV theories

Axion Couplings to Photons

- Several contributions to axion-photon coupling

$$g_{a\gamma\gamma} = \frac{\alpha_{\text{em}}}{2\pi f_a} \left[E/N - 2.05(3) + \mathcal{O}(m_a^2/m_f^2) \right]$$

EM anomaly

$a - \pi^0$ mixing

Meißner et al. '20
Villadoro et al. '15

decoupling fermion contribution

- Present in generic UV models and experimentally easy@Halo- and Helioscopes

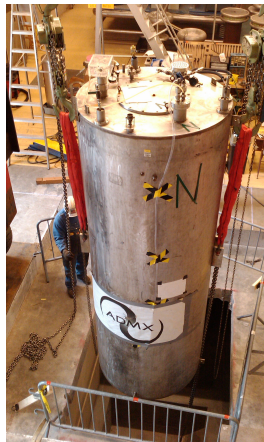
Haloscopes e.g. ADMX

DM axion

$\vec{B} \downarrow$

photon

resonantly detected by
microwave cavity



Helioscopes e.g. CAST

solar photon

$\vec{E} \downarrow$

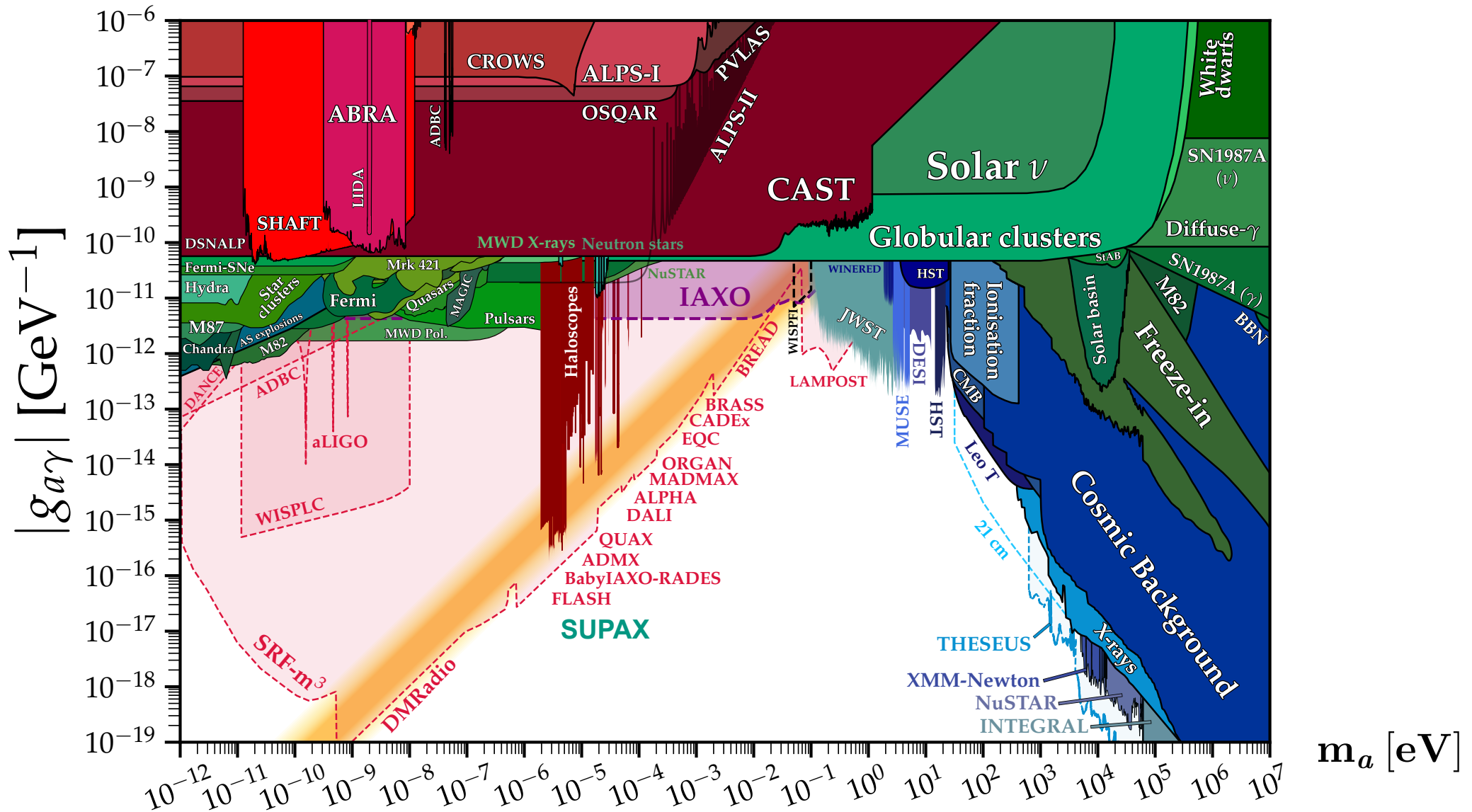
axion

$\vec{B} \downarrow$

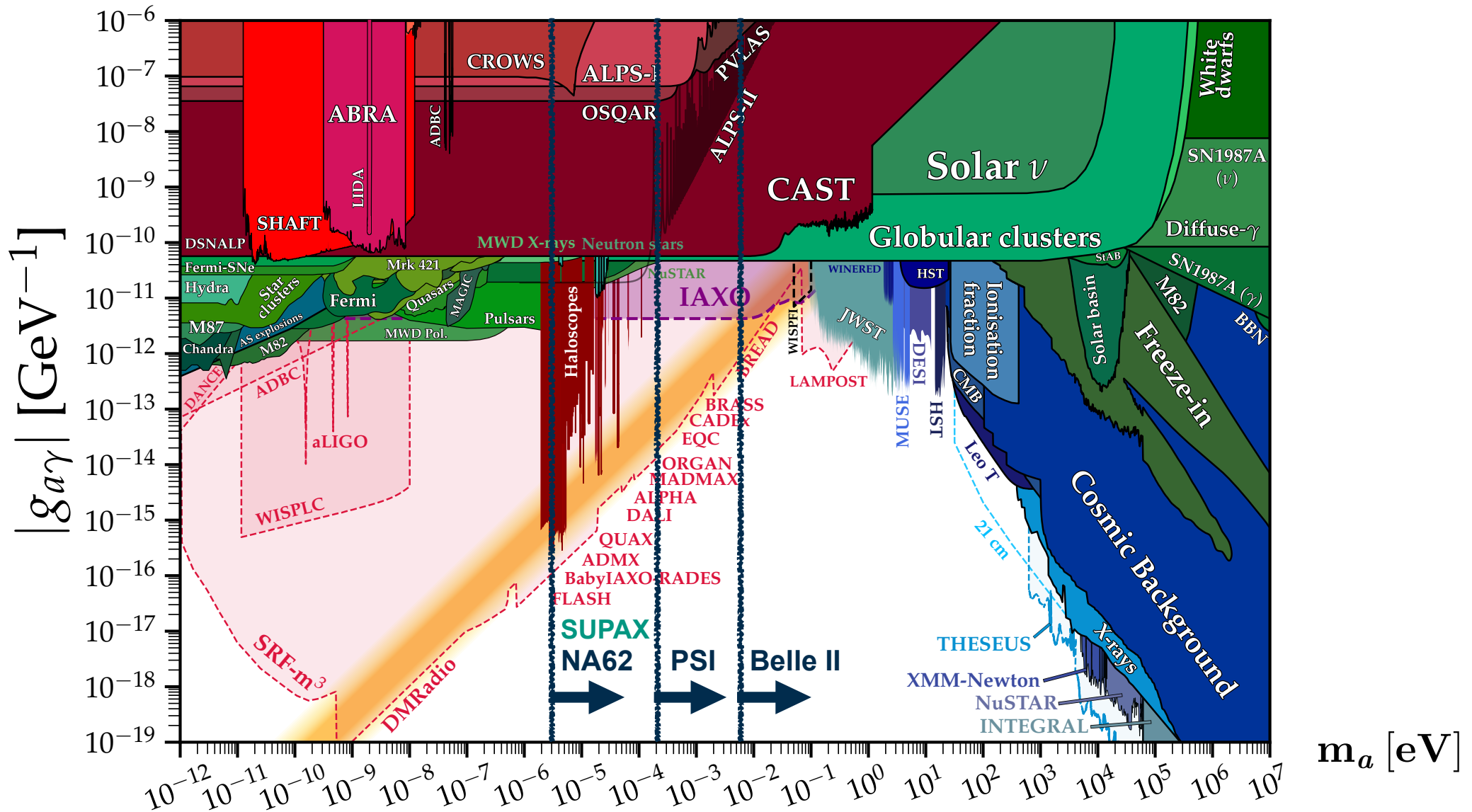
X-ray photon



Photon Phenomenology



Flavor Phenomenology



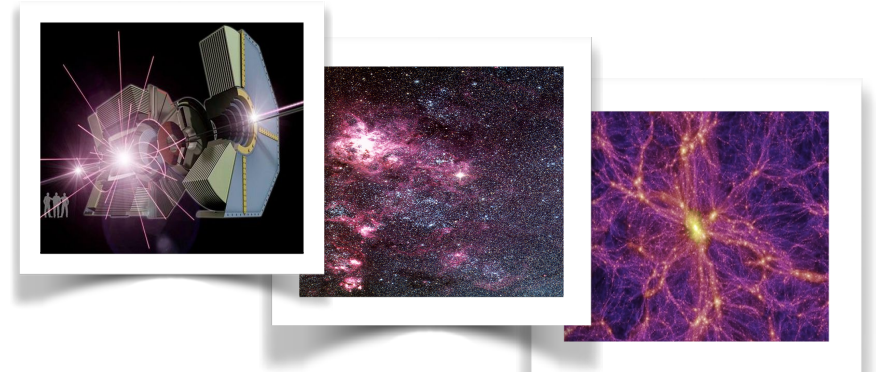
Axion Flavor Phenomenology

- Study 2-body lepton/meson/baryon decays with missing energy

$$\mu \rightarrow ea, \quad \tau \rightarrow ea, \quad K \rightarrow \pi a, \quad \Lambda \rightarrow na, \quad B \rightarrow \rho a, \quad \Lambda_c \rightarrow pa, \quad \dots$$

look like SM decays with neutrino pair, but monochromatic

- Allow for light axion production from tree-level decays of SM particles
 - in particle colliders → **direct searches**
 - in core-collapse supernovae → **energy loss**
 - in the early Universe → **dark radiation**



Origin of Flavor-Violating Couplings

- Fermion couplings determined by PQ charges in fermion mass basis

$$\mathcal{L}_a \supset \frac{\partial_\mu a(x)}{2f_a} \bar{f}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) f_j$$

$$C_{d_i d_j}^{V,A} \propto \left(V_{d_L}^\dagger \underset{\substack{\uparrow \\ \text{diagonal PQ} \\ \text{charge matrices}}}{\text{PQ}_q} V_{d_L} \right)_{ij} \pm \left(V_{d_R}^\dagger \underset{\substack{\uparrow \\ \text{unitary matrices that} \\ \text{diagonalize SM Yukawas}}}{\text{PQ}_d} V_{d_R} \right)_{ij}$$

flavor violation is present at tree-level whenever
fermion charges are not aligned to fermion masses

$$[Y_d Y_d^\dagger, \text{PQ}_q] \neq 0$$

can impose flavor alignment (“Minimal flavor violation”), so that flavor-violation only radiatively induced → loop/CKM suppressed, but constraints from flavor-diagonal pheno typically stronger

- Predicting flavor-violating couplings is difficult: needs theory of flavor

naturally predictive scenarios when PQ = flavor symmetry addressing SM Flavor Puzzle

Axion Production in Flavor Factories

- Explicit searches for 2-body decays are interesting, since probe large UV scales

Light new bosons

dim = 5

$$\frac{\partial_\mu a}{f_a} \bar{b} \gamma^\mu s \xrightarrow{B \rightarrow Ka} f_a \gtrsim 10^5 \text{ TeV}$$
$$\xrightarrow{B_s - \text{mixing}} f_a \gtrsim 800 \text{ TeV}$$

$$\frac{\partial_\mu a}{f_a} \bar{\tau} \gamma^\mu e \xrightarrow{\tau \rightarrow ea} f_a \gtrsim 10^4 \text{ TeV}$$
$$\text{BR} \lesssim 10^{-3}$$

Heavy new dofs (SMEFT)

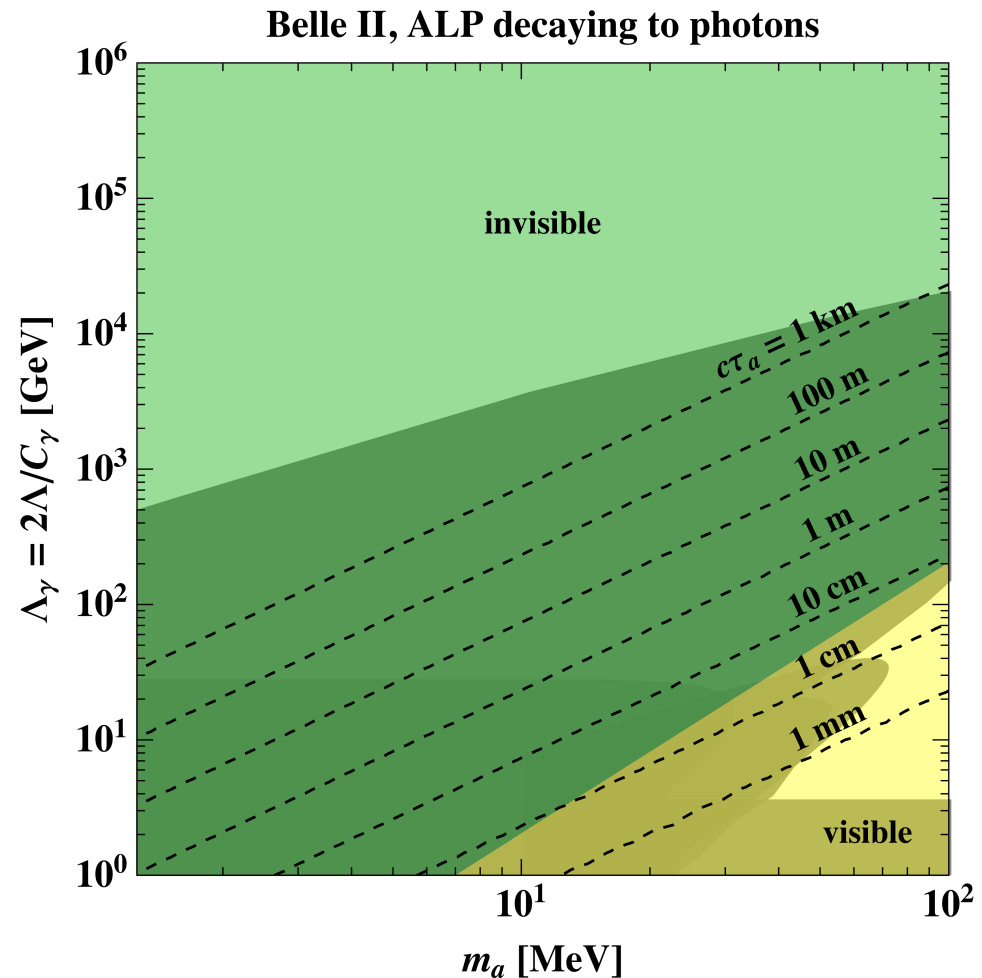
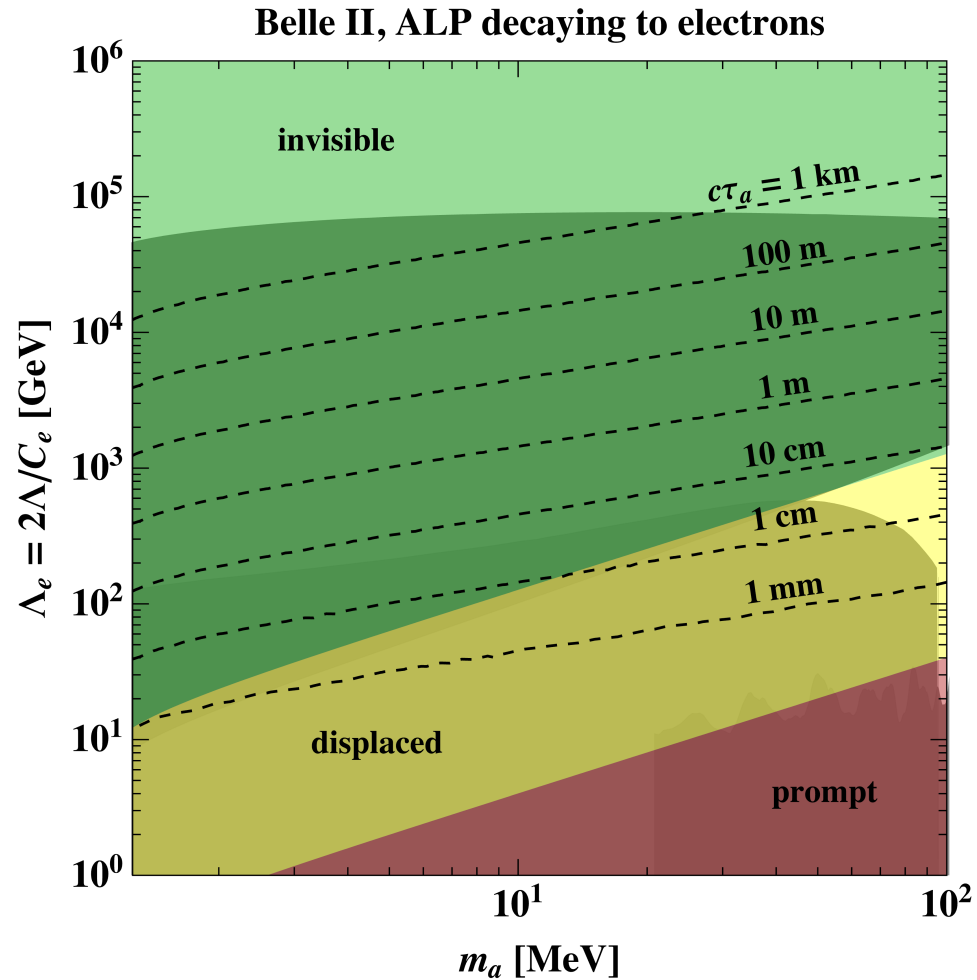
dim = 6

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

$$\frac{1}{\Lambda^2} (\bar{\tau} \gamma^\mu e) (\bar{e} \gamma^\mu e) \xrightarrow{\tau \rightarrow 3e} \Lambda \gtrsim 10 \text{ TeV}$$
$$\text{BR} \lesssim 10^{-8}$$

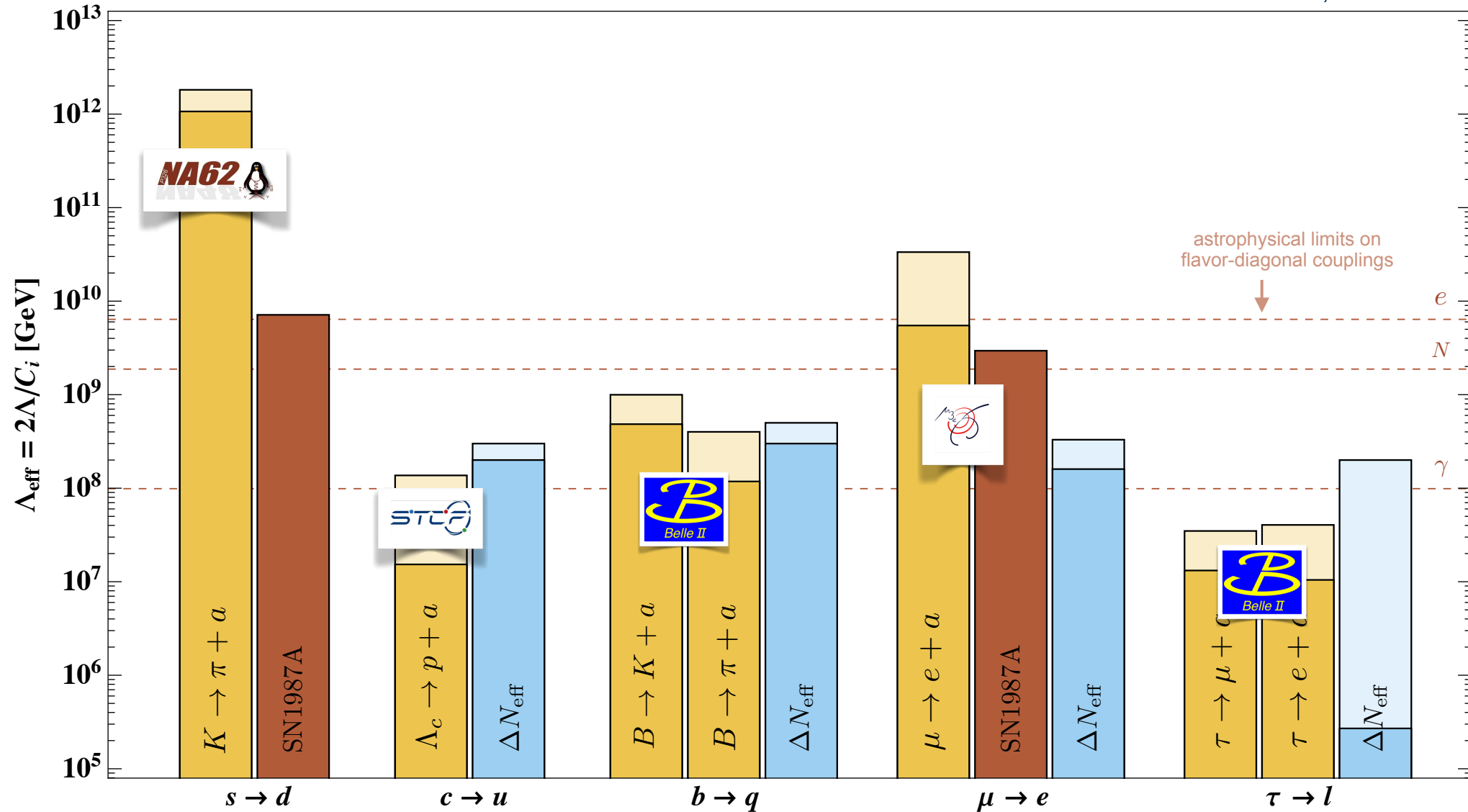
Axion Production in Flavor Factories

- Invisible searches are interesting, since visible decays are very constrained

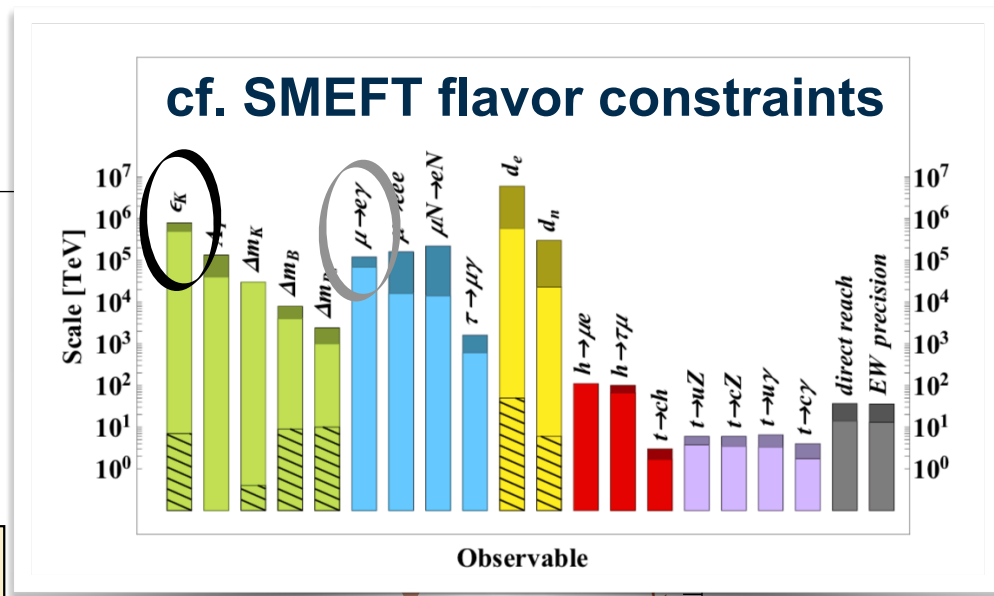
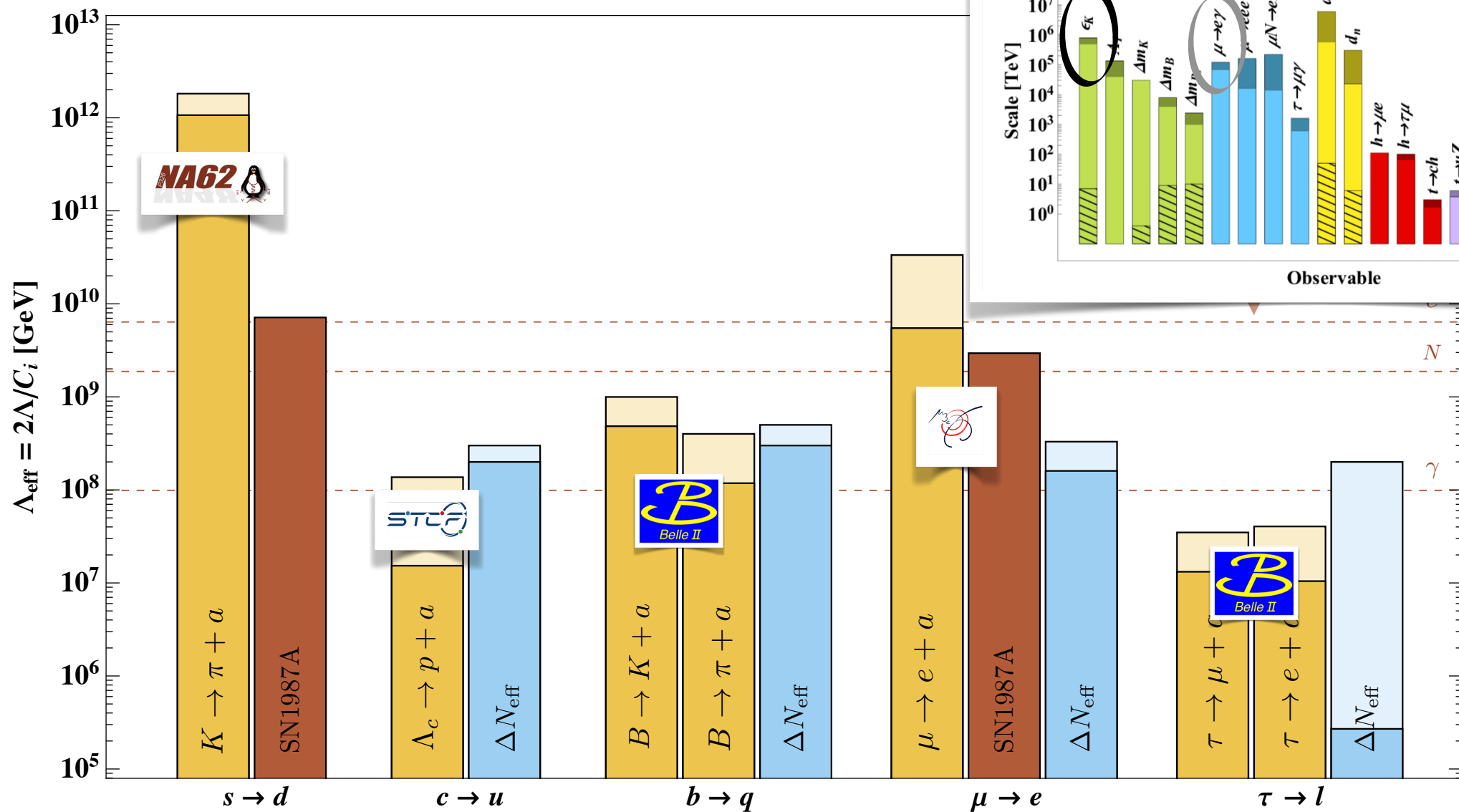


Axion Flavor Phenomenology

RZ, 2606.07749



Axion Flavor Phenomenology



Constraints from Supernova Cooling

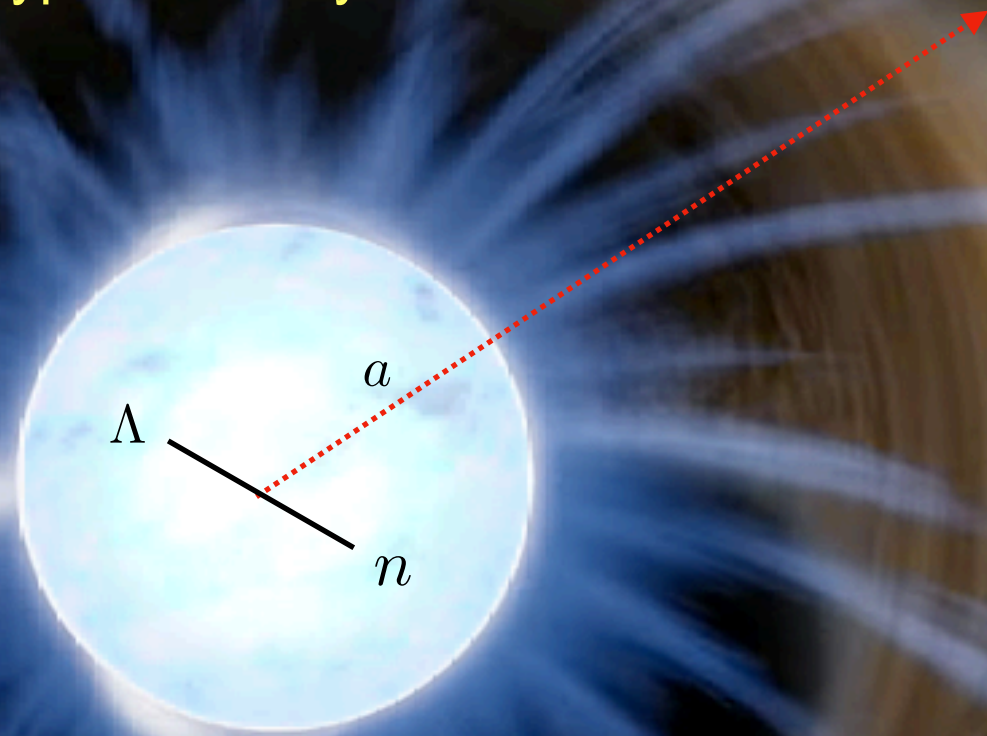
Best handle on axial-vector coupling to s-d from hyperon decays

Many hyperons in hot proto-neutron star formed during core-collapse supernovae [$T \approx 40$ MeV]

Hyperon decays to axions provide extra cooling that would have shorten observed neutrino pulse of SN1987A: limits energy loss rate

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

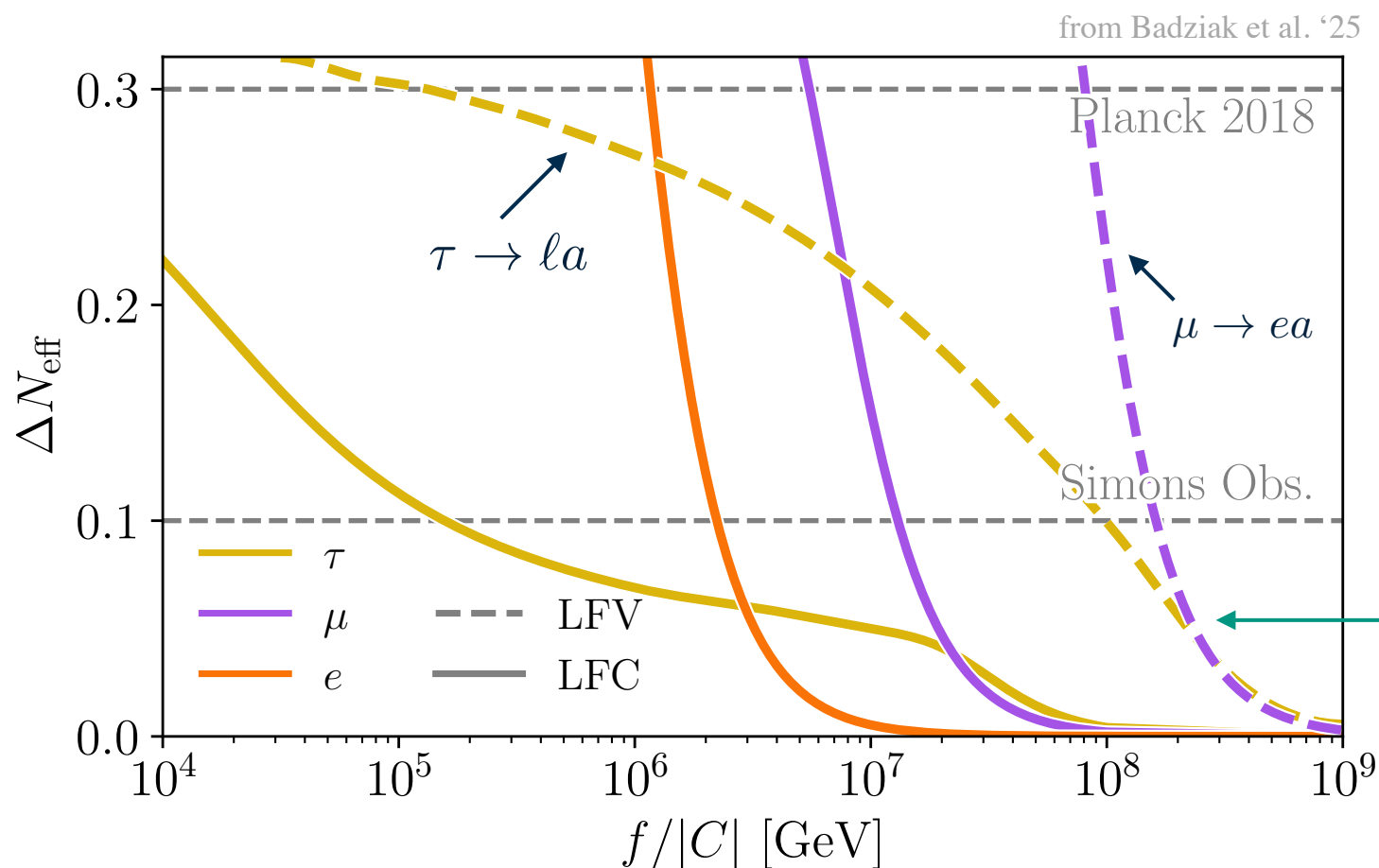
Gives best bound on invisible hyperon decays



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

Constraints from Dark Radiation

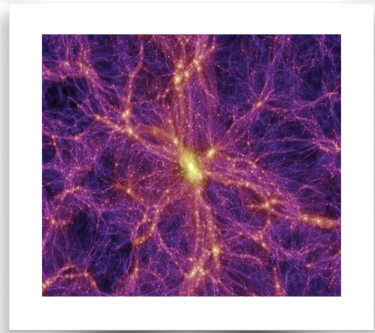
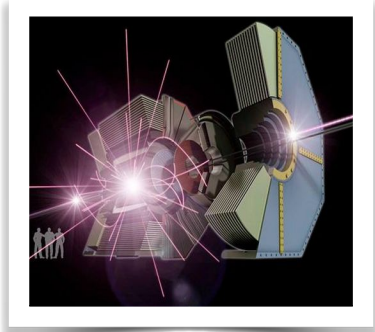
- Flavor-violating SM decays produce hot axions in early universe, which is constrained by limits on Dark Radiation (“ N_{eff} ”) from CMB Baumann et al. '16, D'Eramo, Yun '21



for sufficiently small axion couplings
freeze-in production $\Delta N_{\text{eff}} \propto \Lambda^{-8/3}$

Summary and Outlook

- Light (QCD) axions can be produced in flavor-violating decays, probing UV scales up to 10^{12} GeV (NA62), 10^{10} GeV (Mu3e) or 10^9 GeV (Belle II)
- Collider experiments compete with astrophysics (star cooling) and cosmology (dark radiation)
- More explicit models needed to set experimental targets [connection to SM flavor puzzle]
- Generalize pheno to axion mediators to dark sector [axion becomes long-lived, probe with SHiP/FASER]



Backup slides

Experimental Limits

Present

Decay	90% CL Limit	Experiment
$\text{BR}(K \rightarrow \pi X)$	2.8×10^{-11}	NA62 [129]
$\text{BR}(\Sigma \rightarrow pX)$	3.2×10^{-5}	BESIII [130]
$\text{BR}(D \rightarrow \pi X)$	8.0×10^{-6} [5] _r	CLEO [131]
$\text{BR}(D \rightarrow \omega X)$	1.1×10^{-5}	BESIII [132]
$\text{BR}(\Lambda_c \rightarrow pX)$	8.0×10^{-5}	BESIII [133]
$\text{BR}(B \rightarrow KX)$	3.4×10^{-6}	Belle [134]
$\text{BR}(B \rightarrow K^* X)$	4.2×10^{-5} [135] _r	BaBar [136]
$\text{BR}(B \rightarrow \pi X)$	2.3×10^{-5} [5] _r	BaBar [137]
$\text{BR}(B \rightarrow \rho X)$	3.9×10^{-4} [138] _r	LEP [139]
$\text{BR}(\mu \rightarrow eX)_{\text{iso}}$	2.6×10^{-6}	TRIUMF [17]
$\text{BR}(\mu \rightarrow eX)_{\text{R}}$	2.5×10^{-6} [6] _r	TRIUMF [17]
$\text{BR}(\mu \rightarrow eX)_{\text{L}}$	5.8×10^{-5}	TWIST [140]
$\text{BR}(\tau \rightarrow \mu X)$	2.8×10^{-4}	Belle II [141]
$\text{BR}(\tau \rightarrow eX)$	4.5×10^{-4}	Belle II [141]

Future

Decay	Prosp. Limit	Experiment
$\text{BR}_{\text{proj}}(K \rightarrow \pi X)$	1×10^{-11} [5]	NA62
$\text{BR}_{\text{proj}}(K \rightarrow \pi\pi X)$	7×10^{-7} [5]	E391a
$\text{BR}_{\text{proj}}(\Sigma \rightarrow pX)$	2×10^{-6} [9]	STCF
$\text{BR}_{\text{proj}}(D \rightarrow \pi X)$	1×10^{-5} [9]	STCF
$\text{BR}_{\text{proj}}(\Lambda_c \rightarrow pX)$	1×10^{-6} [9]	STCF
$\text{BR}_{\text{proj}}(B \rightarrow KX)$	8×10^{-7} [9]	Belle II
$\text{BR}_{\text{proj}}(B \rightarrow K^* X)$	4×10^{-6} [9]	Belle II
$\text{BR}_{\text{proj}}(B \rightarrow \pi X)$	2×10^{-6} [9]	Belle II
$\text{BR}_{\text{proj}}(B \rightarrow \rho X)$	3×10^{-6} [9]	Belle II
$\text{BR}_{\text{proj}}(\mu \rightarrow eX)_{\text{iso}}$	7×10^{-8} [6]	MEGII-fwd
$\text{BR}_{\text{proj}}(\mu \rightarrow eX)_{\text{iso,L,R}}$	7×10^{-8} [157]	Mu3e
$\text{BR}_{\text{proj}}(\mu \rightarrow eX)_{\text{iso}}$	1×10^{-7} [158]	Mu2e/COMET-X
$\text{BR}_{\text{proj}}(\tau \rightarrow eX)$	4×10^{-5} [68]	Belle II
$\text{BR}_{\text{proj}}(\tau \rightarrow \mu X)$	3×10^{-5} [68]	Belle II

Limits on QCD axion couplings

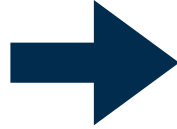
	Λ_{eff}	Experiment	$\Lambda_{\text{eff}}^{\text{proj}}$	Experiment
C_{sd}^V	1.1×10^{12}	NA62	1.8×10^{12}	NA62
C_{sd}^A	2.8×10^7	BESIII	1.1×10^8	STCF
C_{cu}^V	1.5×10^7	BESIII	1.4×10^8	STCF
C_{cu}^A	1.4×10^7	BESIII	1.2×10^8	STCF
C_{bs}^V	4.8×10^8	Belle	1.0×10^9	Belle II
C_{bs}^A	1.4×10^8	BaBar	4.6×10^8	Belle II
C_{bd}^V	1.2×10^8	BaBar	4.0×10^8	Belle II
C_{bd}^A	4.7×10^7	LEP	5.4×10^8	Belle II
$C_{\mu e}^{\text{iso}}$	5.5×10^9	TRIUMF	3.3×10^{10}	Mu3e
$C_{\mu e}^L$	1.2×10^9	TWIST	3.3×10^{10}	Mu3e
$C_{\tau e}$	1.0×10^7	Belle II	4.0×10^7	Belle II
$C_{\tau \mu}$	1.3×10^7	Belle II	3.5×10^7	Belle II

Peccei-Quinn Flavor Models

- Global flavor symmetries models often have QCD anomaly Binetruy, Ramond '94

e.g. single $U(1)_{\text{FN}}$

$$y_{ij}^U \sim \epsilon^{q_i + u_j} \quad y_{ij}^D \sim \epsilon^{q_i + d_j}$$



$$\underbrace{\det m_u \det m_d / v^6}_{\approx 10^{-20}} = \underbrace{[\det a_u \det a_d]}_{\mathcal{O}(1)} \epsilon^{2N} \quad \text{QCD anomaly coefficient}$$

$$\underbrace{\det m_d / \det m_e}_{\approx 0.7} = \underbrace{[\det a_d / \det a_e]}_{\mathcal{O}(1)} \epsilon^{\frac{8}{3}N - E} \quad \text{EM anomaly coefficient}$$

- Fixes flavor-violating couplings up to model-dependent $\mathcal{O}(1)$ coefficients

$$U(1)_{\text{PQ}} = U(1)_F \quad \text{Ema et al. '16} \\ \text{Calibbi, Goertz, Redigolo, RZ, Zupan '16}$$

sizable light
quark transitions

$$C_{d_i d_j}^V \sim (V_{\text{CKM}})_{ij}$$

$$U(1)_{\text{PQ}} \subset U(2)_F \quad \text{Linster, RZ '18} \\ \text{Calibbi, Redigolo, RZ, Zupan '20}$$

suppressed light quark
transitions, but LFV sizable

$$C_{d_i d_j}^V \sim (V_{\text{CKM}})_{i3} (V_{\text{CKM}})_{j3}$$

Flavor Anarchy vs. Minimal Flavor Violation

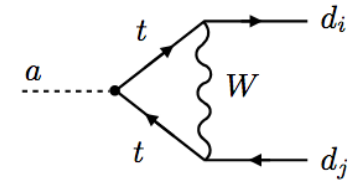
- Always have SM flavor violation from RG running

Choi, Im, Park, Yun '17

Bauer, Neubert, Renner, Schnubel, Thamm '21

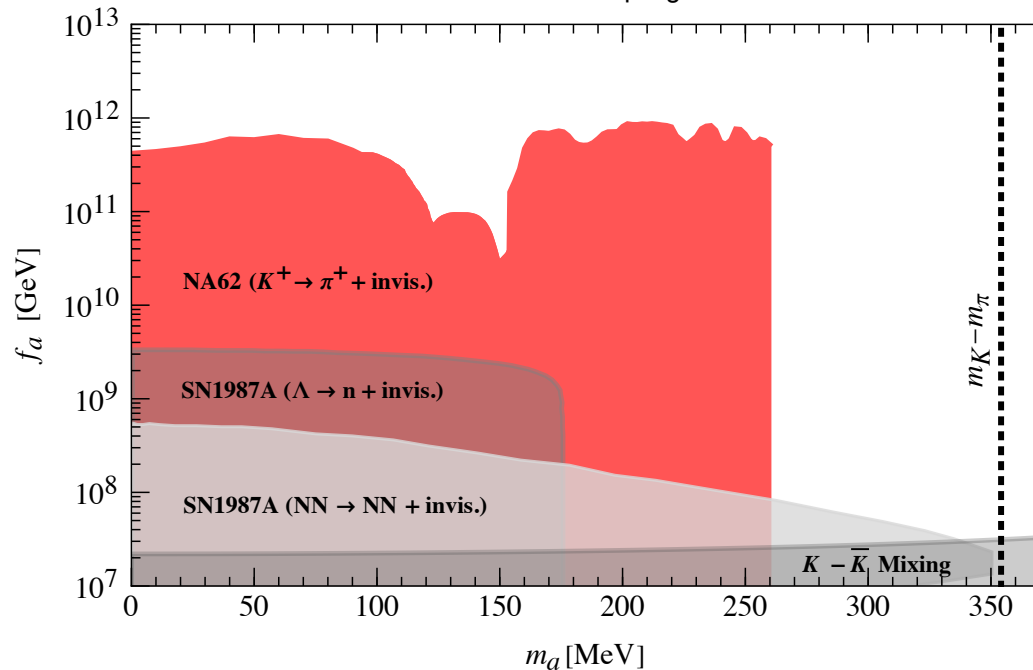
$$C_{sd} \sim \frac{y_t^2 V_{td} V_{ts} C_{tt}}{16\pi^2} \log \sim 10^{-5}$$

for light axions flavor constraints weaker than star cooling constraints from diagonal couplings



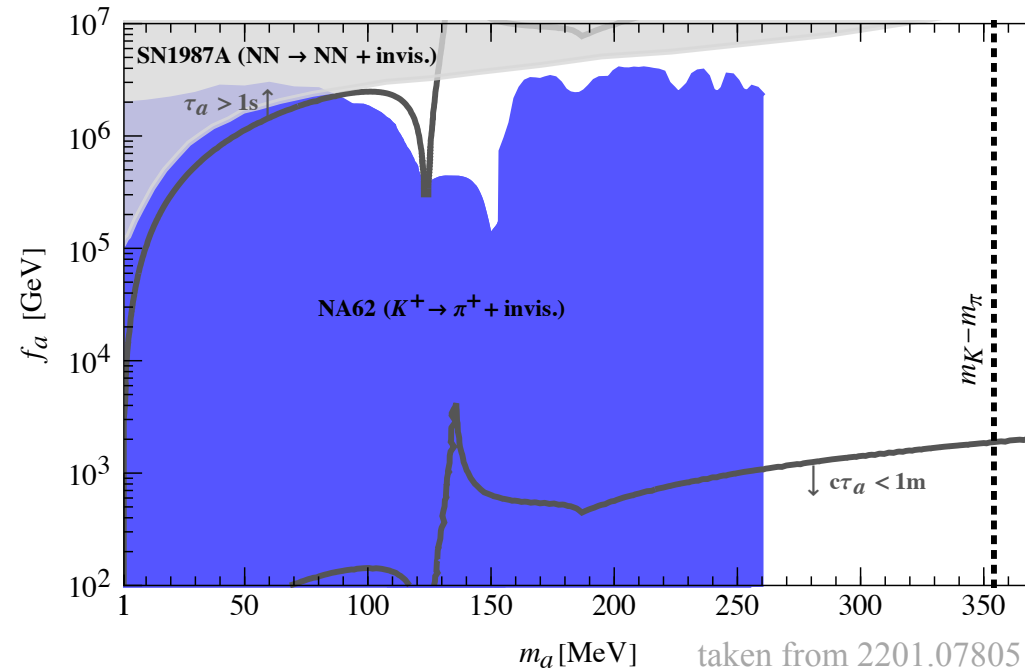
Flavor Anarchy

all axion UV couplings = 1



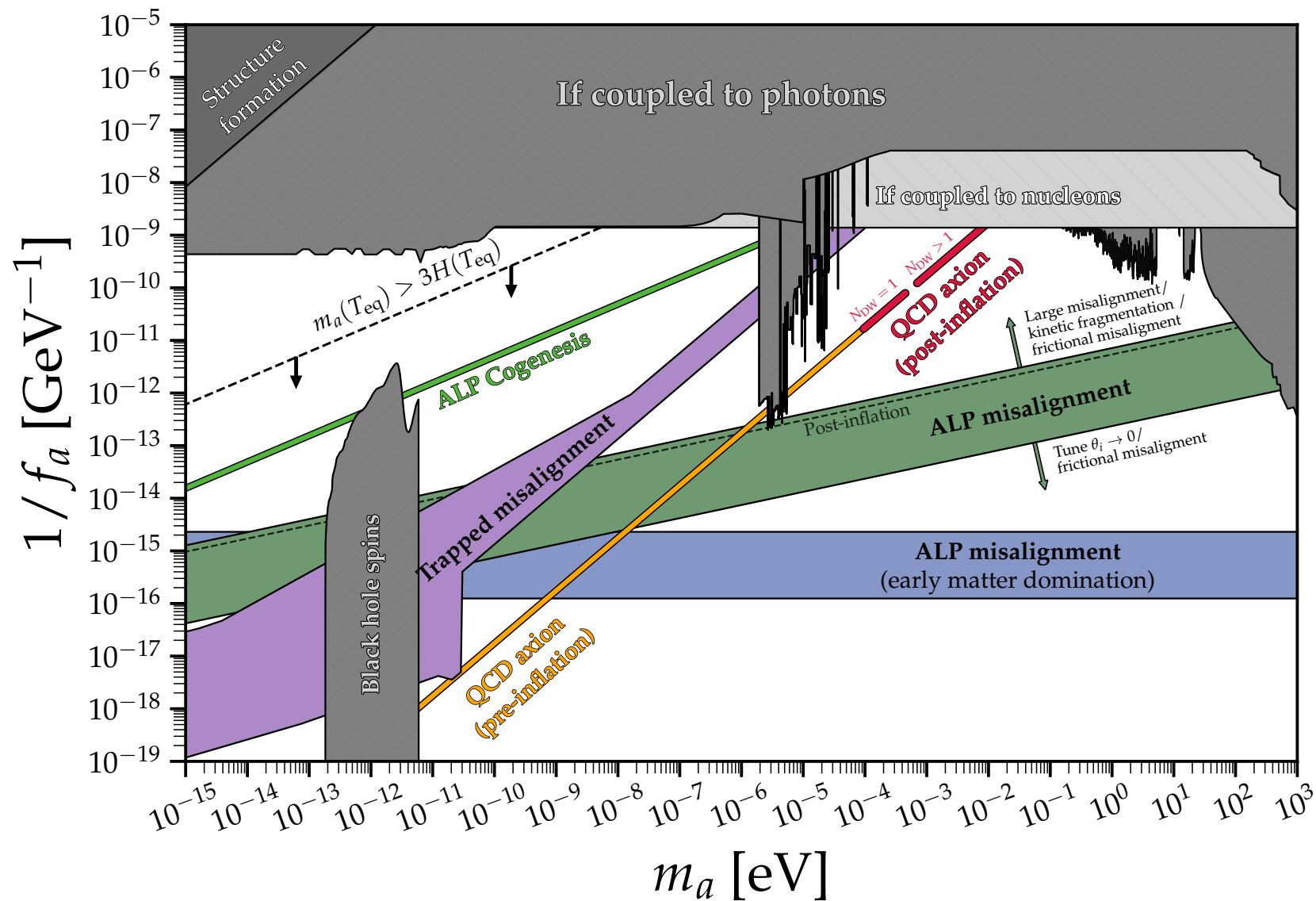
Minimal Flavor Violation

all flavor-diagonal UV couplings = 1



taken from 2201.07805

Axion Dark Matter Scenarios



Axion DM Production: Misalignment

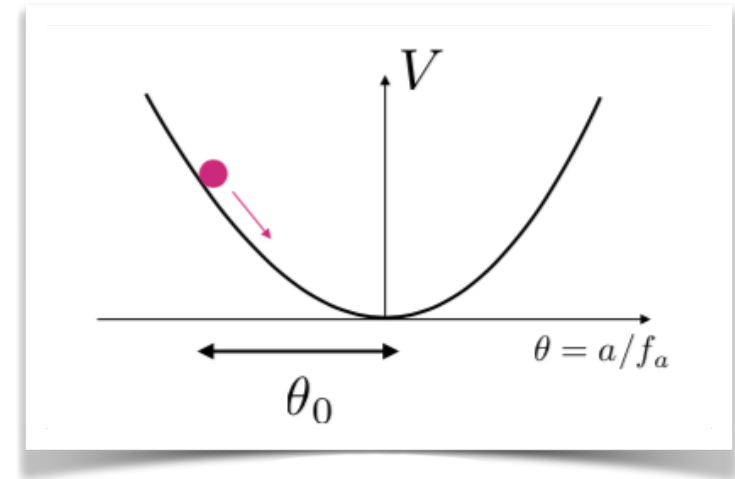
- Evolution of homogenous classical scalar field in expanding universe

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

↑ ↑

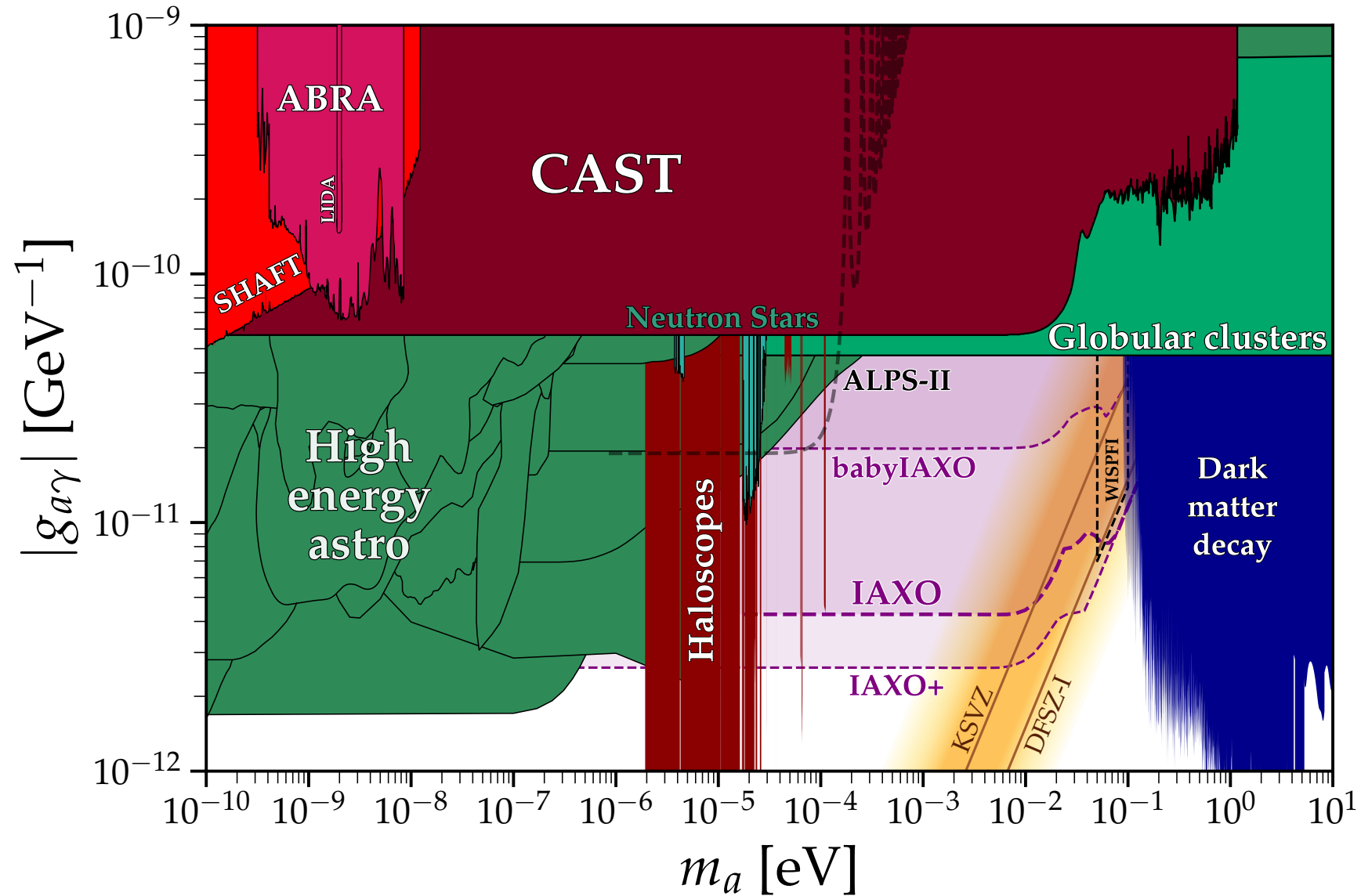
Hubble for QCD axion
friction $\sim T^2$ T-dependent

$$= \begin{cases} 0 & T \gg \Lambda_{\text{QCD}} \\ m_a & T \ll \Lambda_{\text{QCD}} \end{cases}$$



- Energy stored in oscillations behaves just like Cold Dark Matter for $f_a \gtrsim 10^8 \text{ GeV}$

Axion Helioscopes



Axion Haloscopes

