THE QUEST FOR LIGHT NEW PHYSICS

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THE GOAL OF PARTICLE PHYSICS

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$$\mathcal{L} = ?$$

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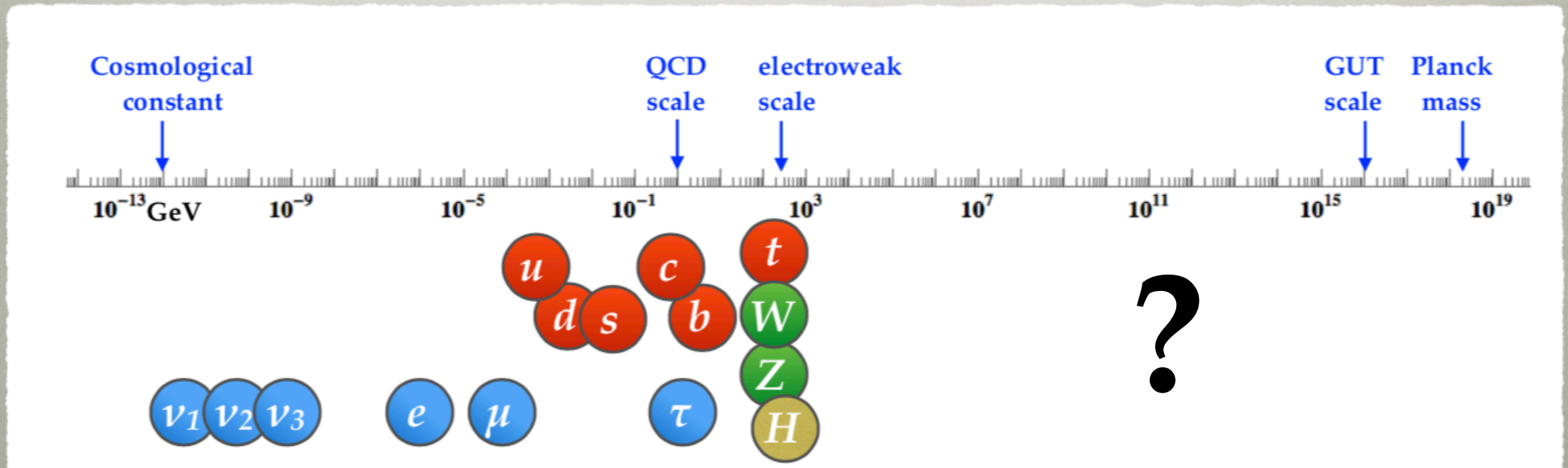
$$\mathcal{L} = \mathcal{L}_{\rm SM} + ?$$

- to answer need to find
  - field content (particles)
  - interactions

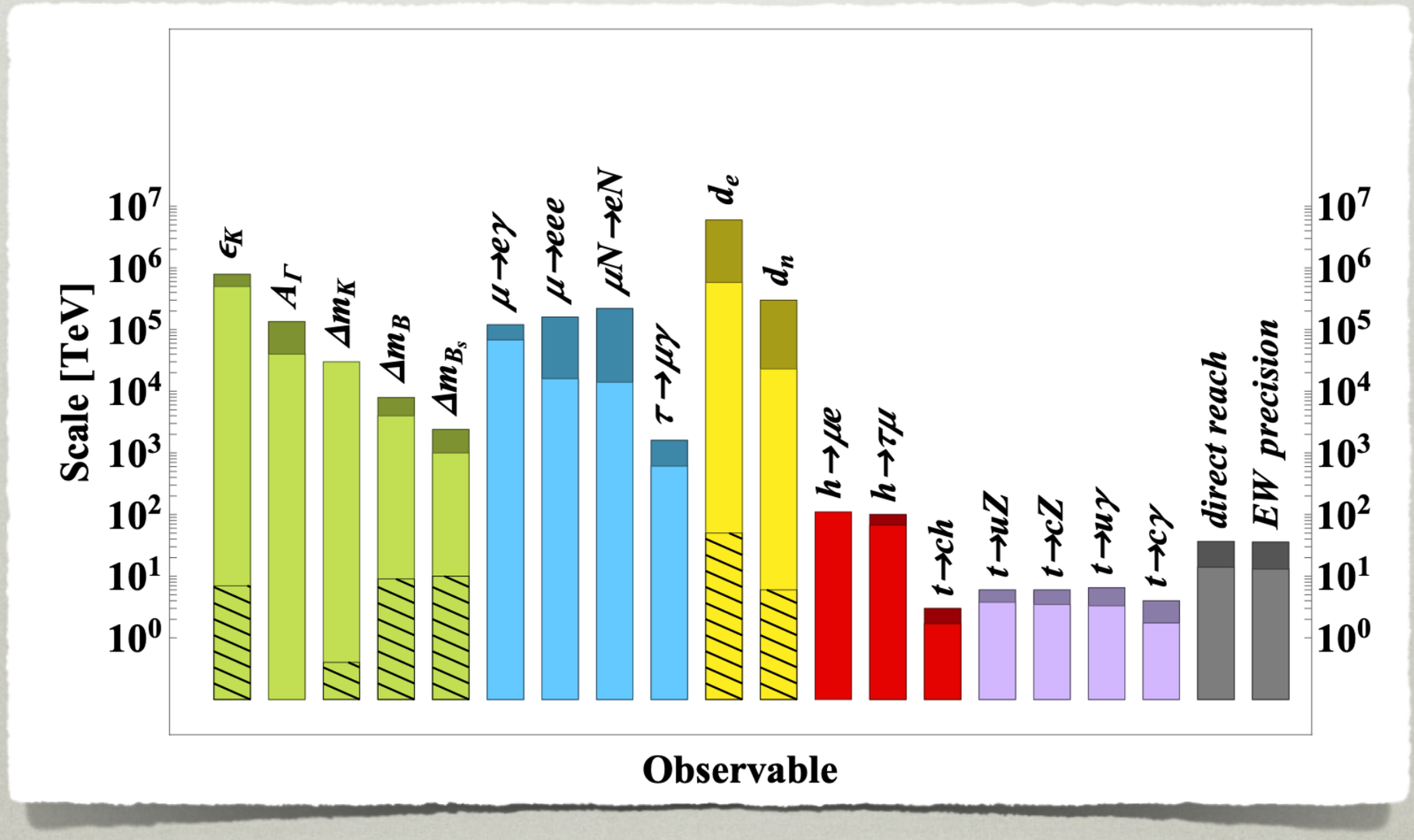
NEW PHYSICS?

- SM is not complete
  - no viable dark matter candidate in the SM
- also other puzzles
  - how tuned is the weak scale (hierarchy problem)
  - baryogenesis
  - any dynamical explanation for flavor structure...



SEARCHING FOR NEW PHYSICS

- direct and indirect probes



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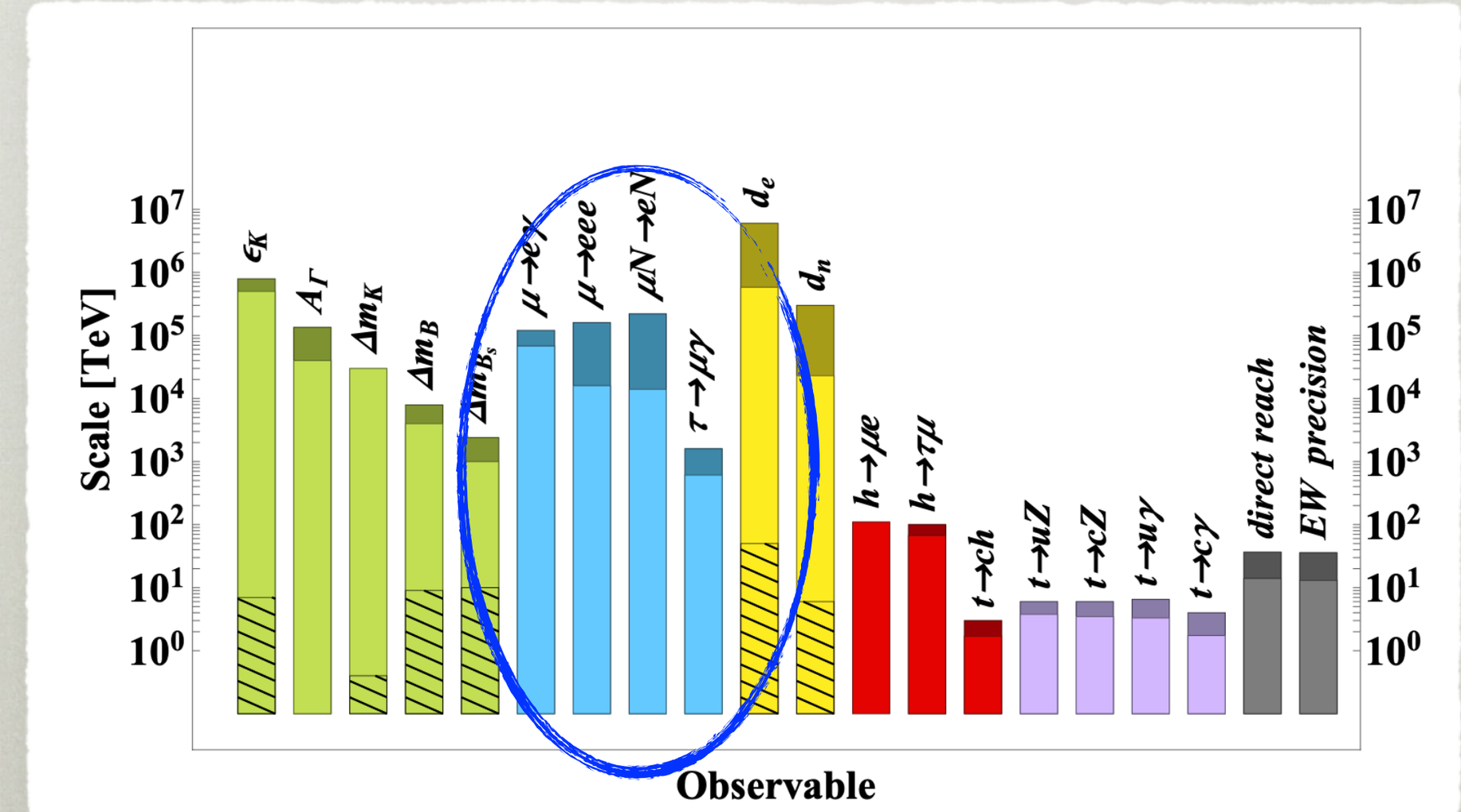


SUMMARY OF CLFV

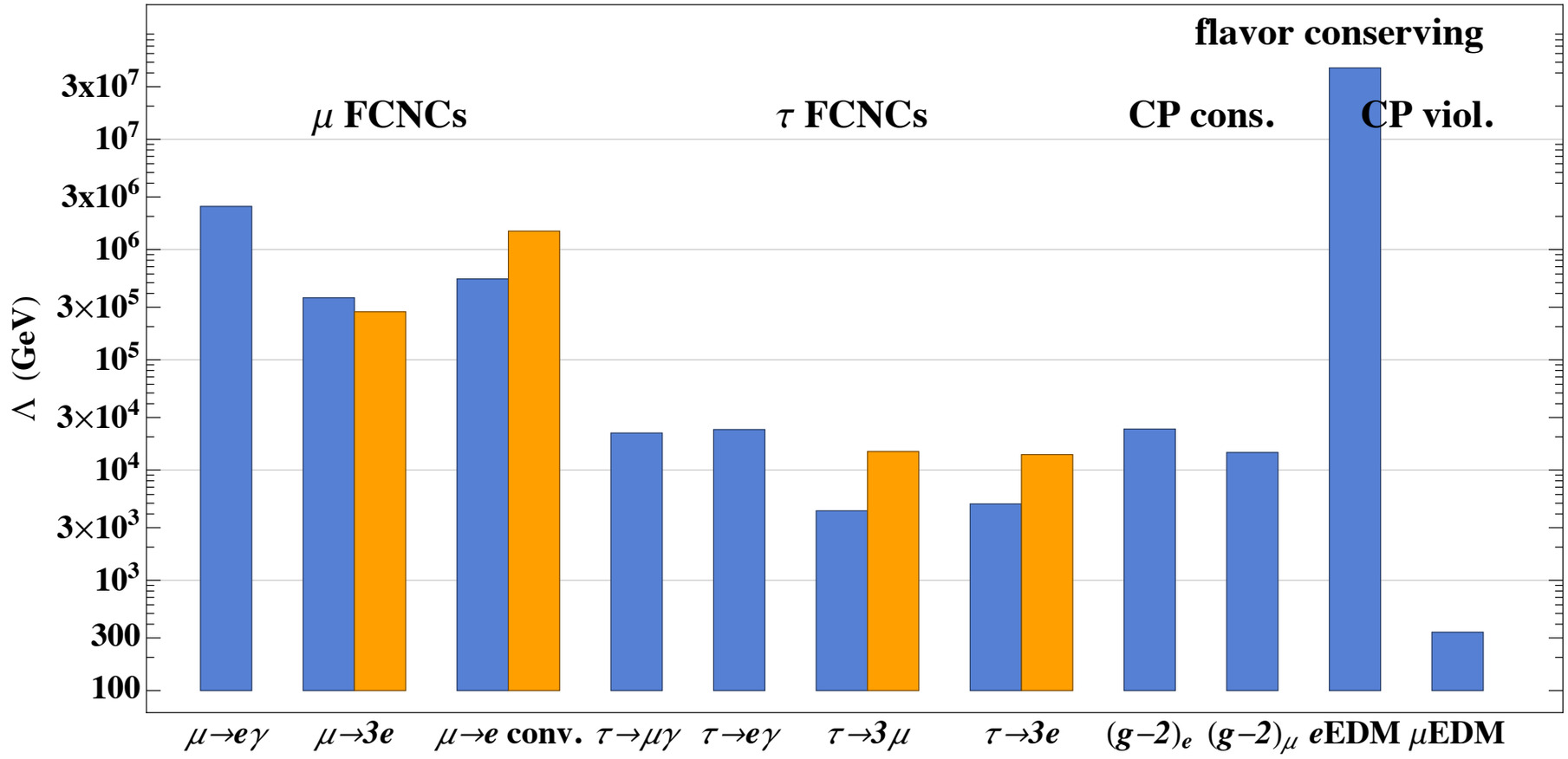
- heavy NP, integrate out
  - matches onto SMEFT
- in the examples switched on only two sets of ops.*

$$\mathcal{L} = \sum_a \frac{C_a}{\Lambda^2} Q_a$$

$$Q_\gamma^{ij} = \frac{e}{8\pi^2} H(\bar{\ell}^i \sigma^{\mu\nu} P_L \ell^j) F_{\mu\nu}$$

$$Q_{4\ \text{ferm.}}^{ijk} = (\bar{\ell}^i \gamma^\mu \ell^j)(\bar{f}^k \gamma_\mu f^k)$$

max. flavor violation ■ **dipole op.** ■ **4–fermion op.**

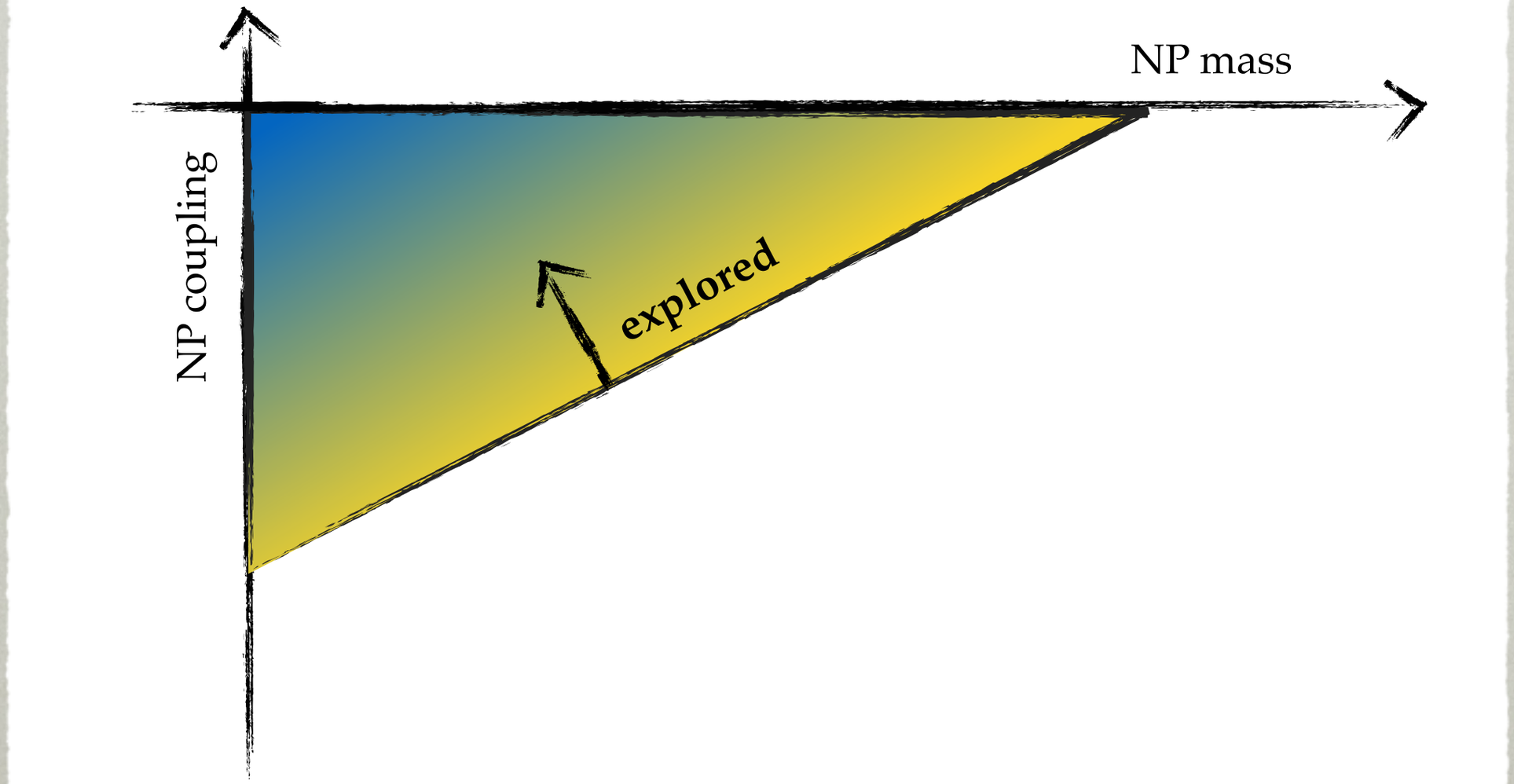


*in bounds either C_a=1 or C_a=i

**$(g\text{-}2)_\mu$ and $(g\text{-}2)_e$ interpreted as bounds

THE LAY OF THE LAND

- explored only part of the NP parameter space
- light particles: a window to high UV dynamics



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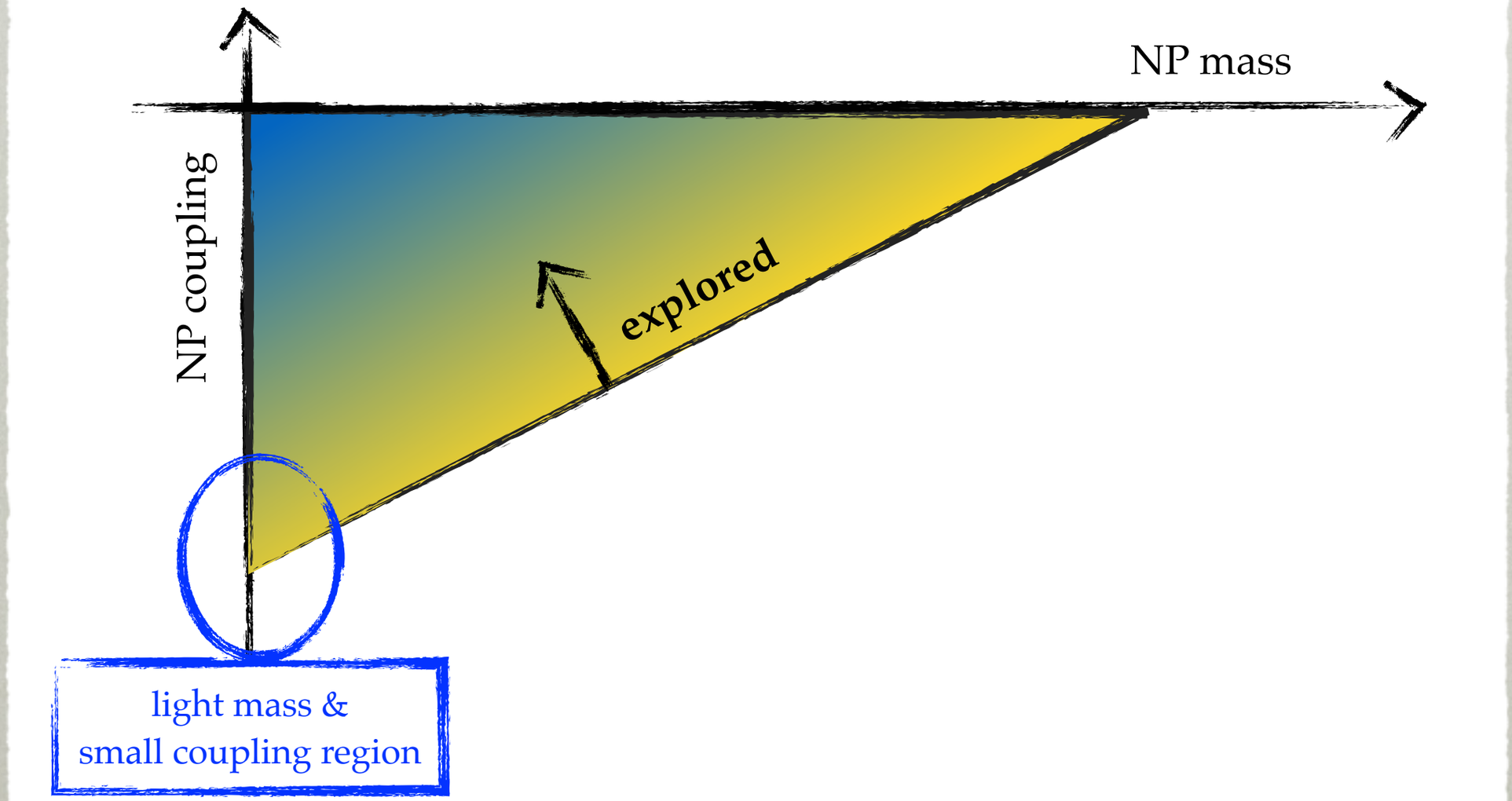

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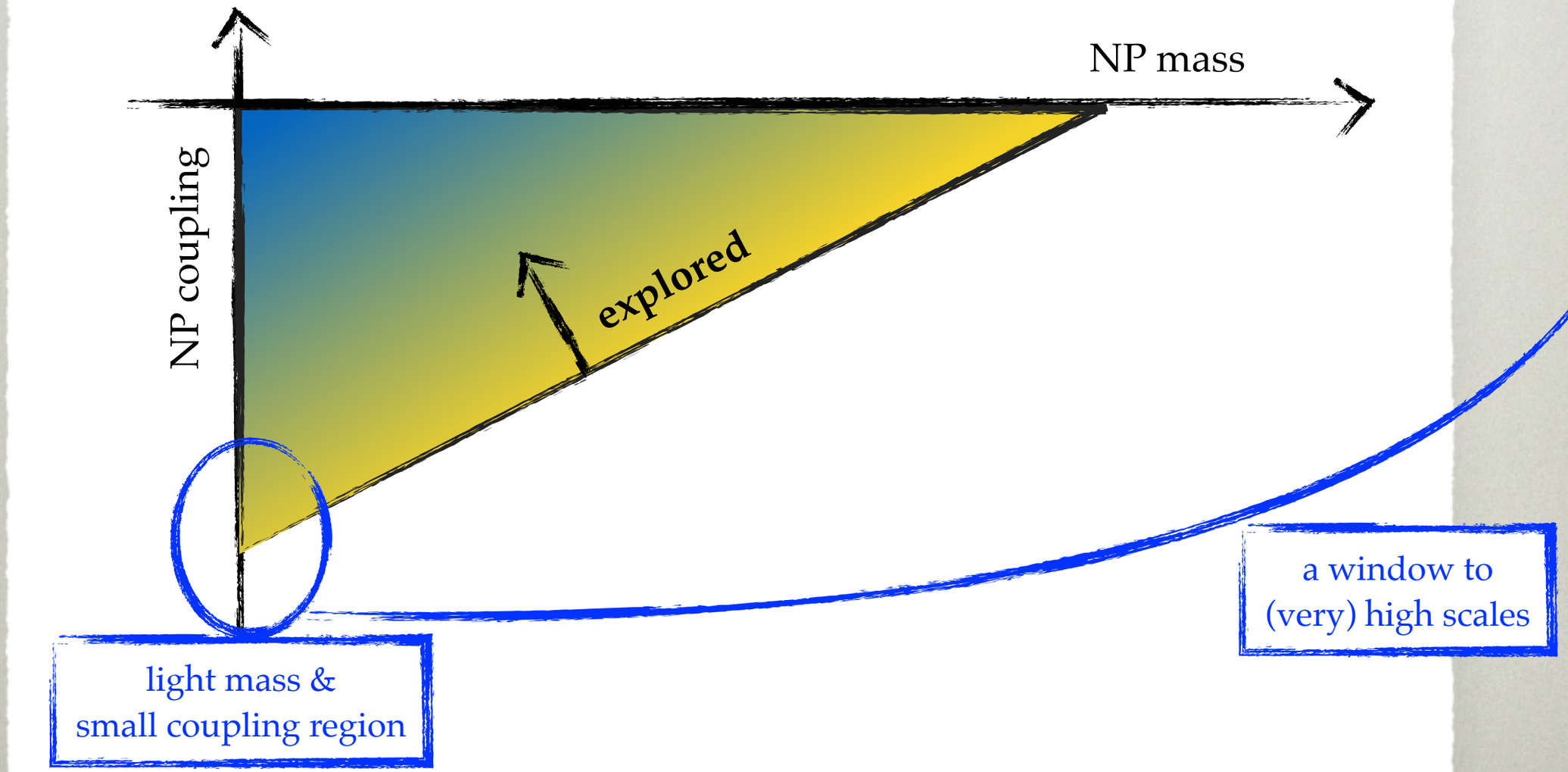
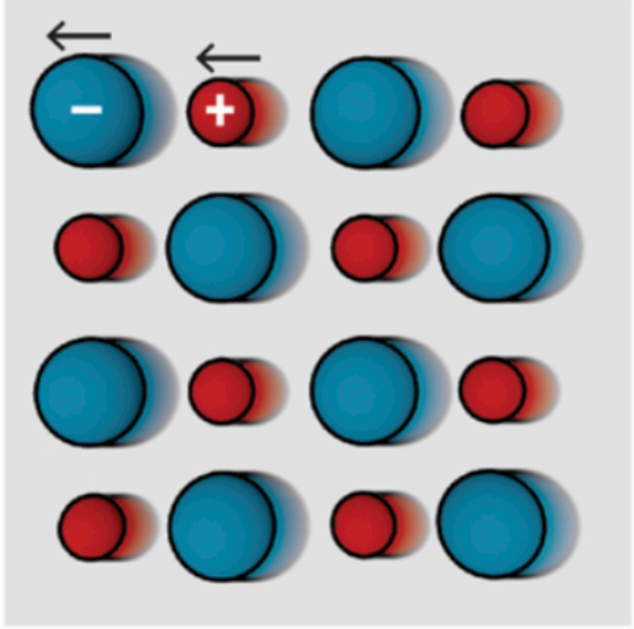


LIGHT NEW PARTICLES

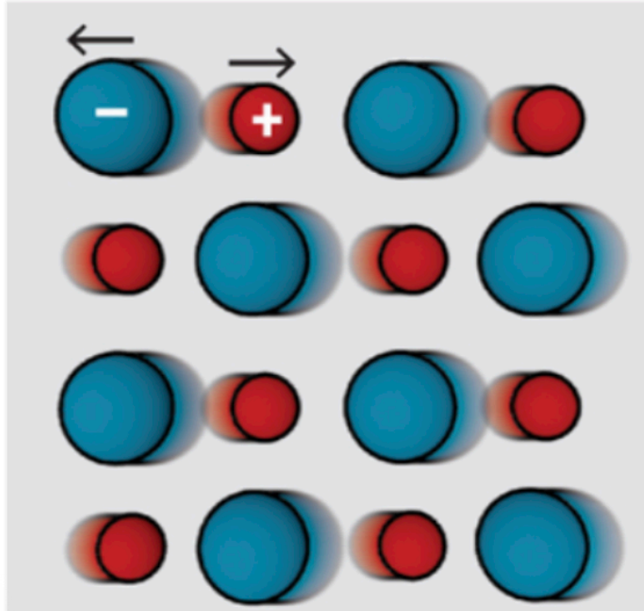
- how generic are light new particles?
- any spontaneously broken global symmetry
  - ⇒ massless Nambu-Goldstone boson

EXAMPLE: PHONONS

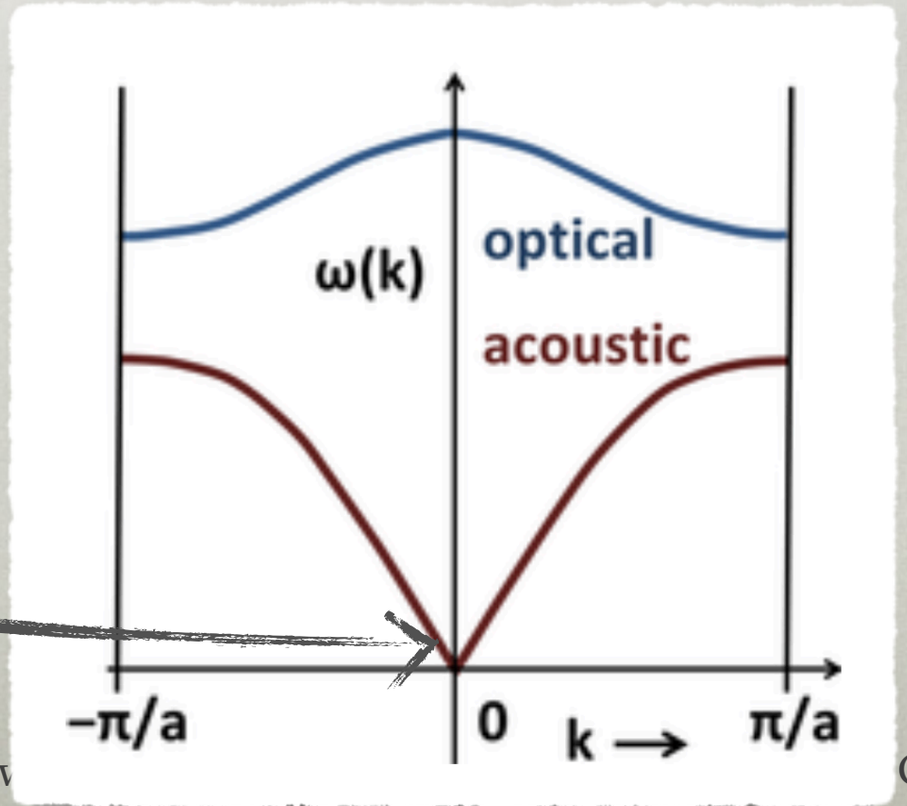
Acoustic Phonons



Optical Phonons



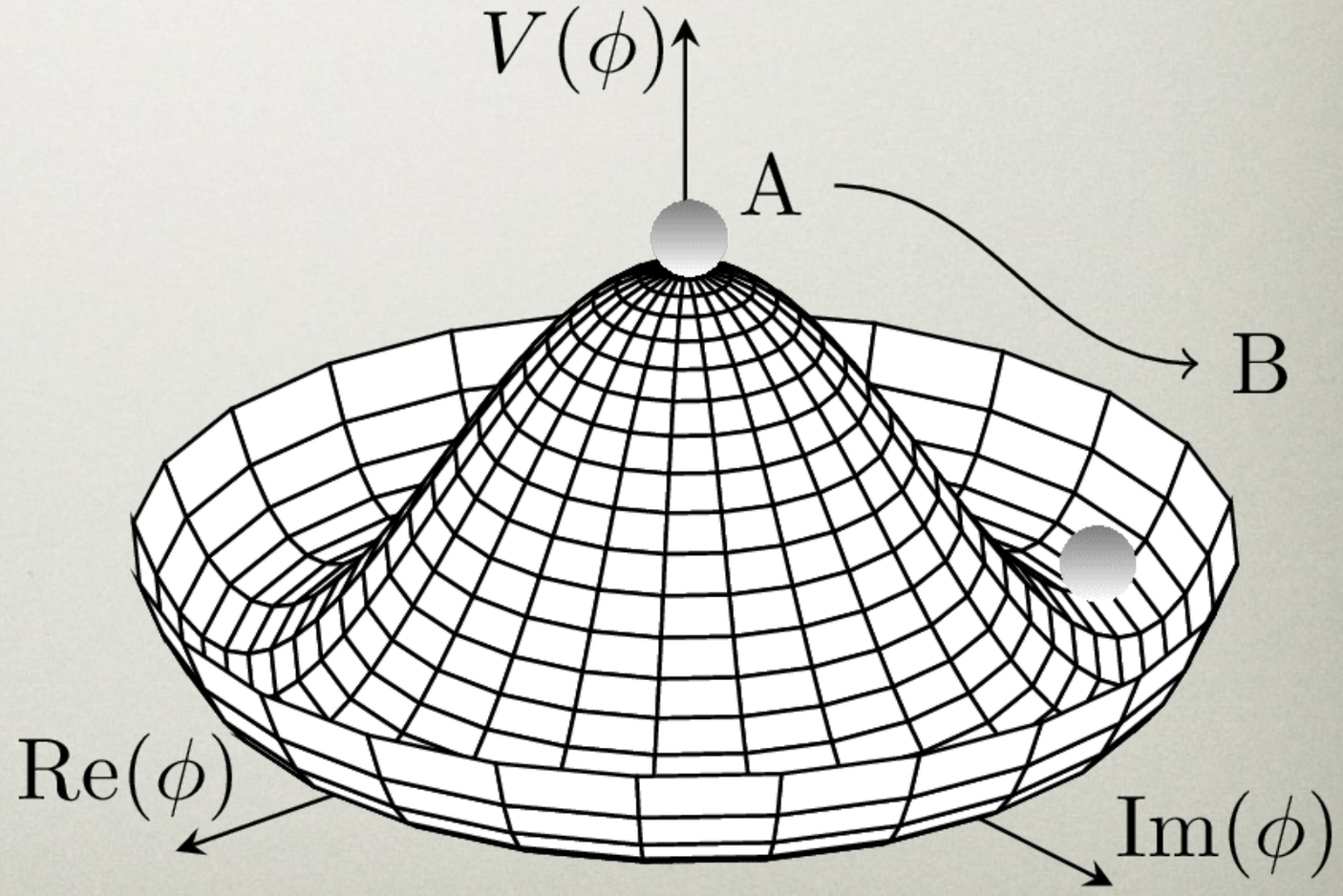
$$\omega = c_s k$$



EXAMPLE: $U(1)$ HIGGS MECHANISM

- a global $U(1)$ spontaneously broken by a scalar vev

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{ia(x)/f}$$



QCD axion

- a celebrated example: QCD axion

STRONG CP PROBLEM

- Lorentz and gauge invariance allow a CP violating term in QCD

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

  - physically observable is the combination

$$\bar{\theta} \equiv \theta + \arg\det(\mathcal{M}_u \mathcal{M}_d)$$

- experimentally :

$$d_n \approx 4 \times 10^{-16} \bar{\theta}\, e\,\mathrm{cm} \quad \Longleftrightarrow \quad |d_n|_{\mathrm{exp}} < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

- why $\bar{\theta}$ so small?

$$\bar{\theta} < 10^{-10}$$

  - very puzzling given large CPV phase in the CKM

AXION

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

- if $\bar{\theta}(x)$ a dynamical field and couples only to $\bar{\theta} G\tilde{G}$
  $\Rightarrow$ potential min. at $\bar{\theta}(x) = 0$
  - new ultra-light particle - axion

$$F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{C^{V,A}_{f_i f_j}}$$

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5) f_j$$

- obtains mass from QCD anomaly

$$m_a = 5.70(7)\,\mu{\rm eV}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)$$

- viable cold dark matter candidate for

$$10^{-8}\,{\rm eV} \lesssim m_a \lesssim 10^{-3}\,{\rm eV}$$

PORTALS

Portal	Interactions
Dark Photon, A'_μ	$-\epsilon F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
Axion-like pseudo scalar, a	$aF\tilde{F}/f_a,\ aG\tilde{G}/f_a,\ \left(\bar{\psi}\gamma^\mu\gamma_5\psi\right)\partial_\mu a/f_a$

LIGHT NEW PHYSICS ⇒ PROBE OF HIGH SCALES

- rare decays into a light state, X, e.g., $K \to \pi X$ or $\mu \to eX$,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops
  - the reason is that the SM decay widths are power suppressed $\Gamma_\ell \propto m_\ell^5/m_W^4$
- if light NP couples through dim 4 op with mixing angle $\theta \Rightarrow$ $\Gamma(K \to \pi\varphi) \propto \theta^2 m_K \Rightarrow Br(K \to \pi\varphi) \propto \theta^2 (m_W/m_K)^4$
- if through dim 5 op. suppressed by $1/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- no such $1/m_\mu$ or $1/m_K$ enhancement for dimension 6 couplings $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

UPSHOT

- searching for $K \to \pi X$, $\mu \to e X$, $\tau \to \mu X$ decays expect to reach very high UV scales

EXAMPLES

- two examples
  - flavor violating QCD axion
    - concrete example: axiflavon
  - an axion-like particle (ALP) with lepton flavor violating couplings
  - gauged FN model of flavor
    - light Z'

MOTIVATION FOR LIGHT ALPs

- any spontaneously broken global symmetry ⇒ (p)NGB
  - if "light enough" can be DM
- in general couplings to gluons, photons, SM fermions

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$

$$F^{V,A}_{f_if_j} \equiv \frac{2f_a}{C^{V,A}_{f_if_j}} \qquad F_{\ell_i\ell_j} = \frac{2f_a}{\sqrt{|C^V_{\ell_i\ell_j}|^2 + |C^A_{\ell_i\ell_j}|^2}}$$

- in general ALPs will have flavor violating couplings
  - do FCNC experiments probe interesting parameter space?
  - possible improvements on search strategies?

Flavor violating QCD axion

FLAVOR VIOLATING QCD AXION

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

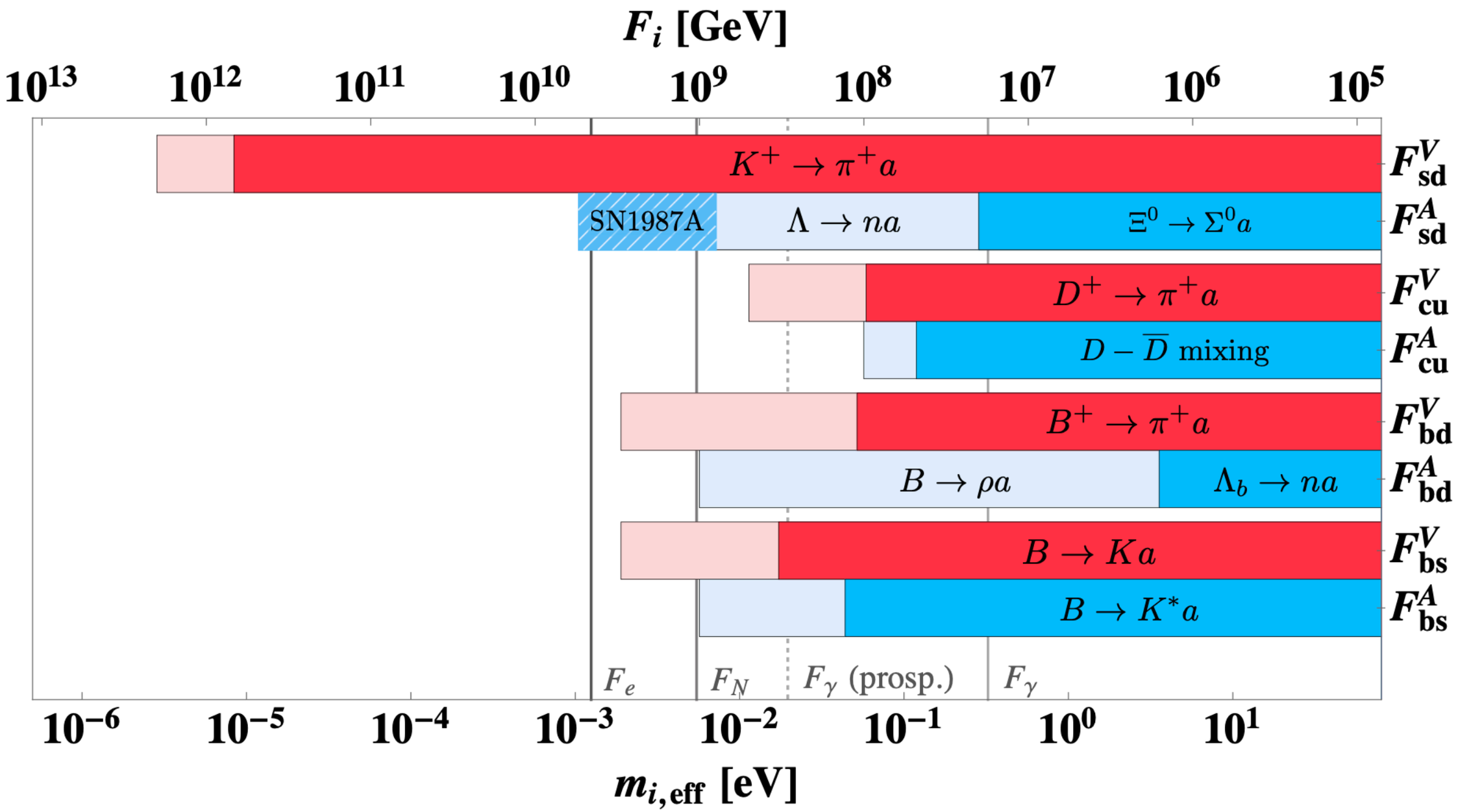
- QCD axion with FV couplings to quarks
  - solves the strong CP problem
  - can be a cold DM candidate
  - effectively massless in FV transitions
- general analysis, allowing for FV couplings as well
  - first focus on quark FV transitions

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$

$$F^{V,A}_{f_if_j} \equiv \frac{2f_a}{C^{V,A}_{f_if_j}}$$

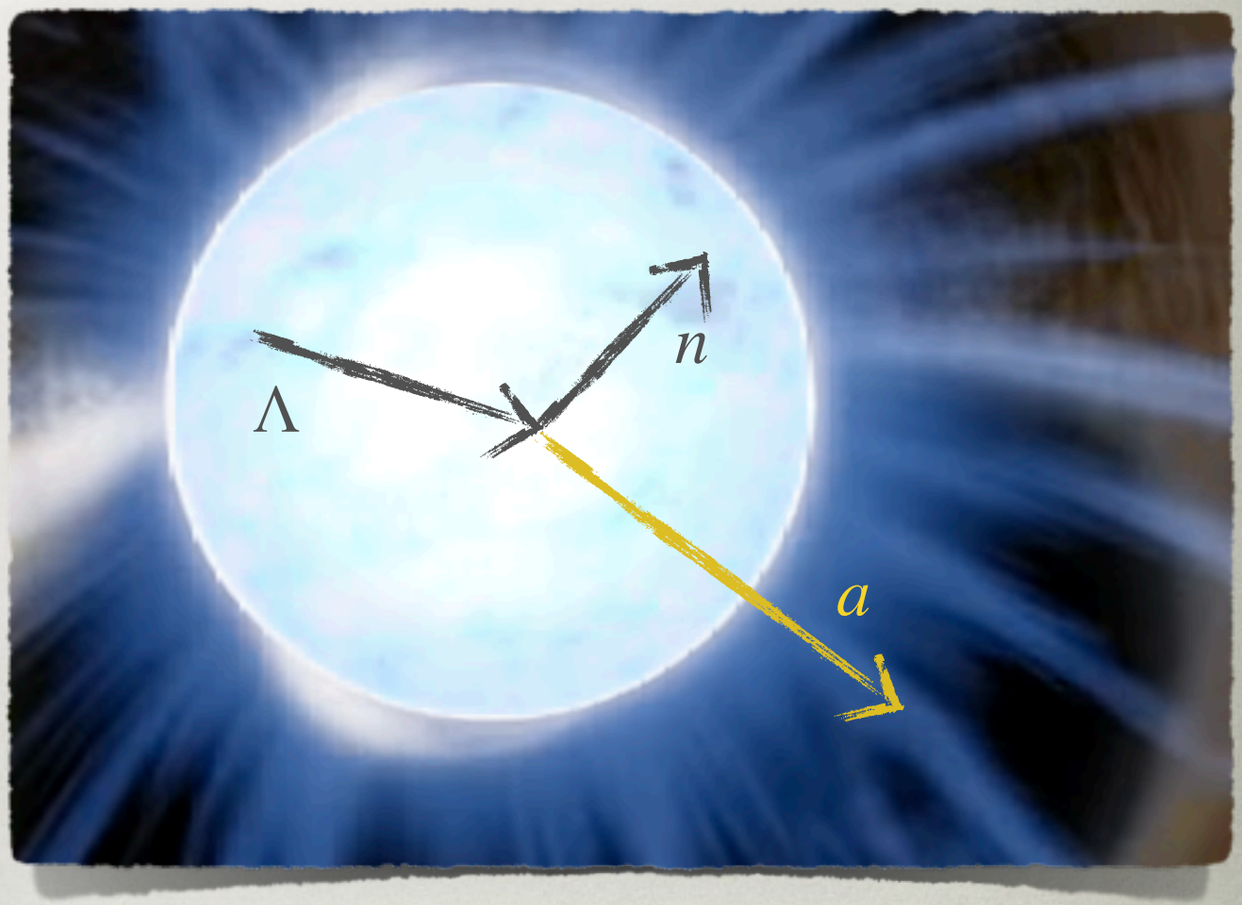
THE STRONGEST FV CONSTRAINTS

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623



SUPERNOVA BOUNDS

- in neutron star Λ, n, p, e are in equilibrium
- $\Lambda \to na$ decays can cool the proto-neutron star
- Λ, n have the same Fermi energy
  $\Rightarrow$ at T=0 Pauli blocking forbids $\Lambda \to na$ decays
- at finite temperature volume emission rate (in NR limit)



$$Q \simeq n_n (m_\Lambda - m_n)\Gamma(\Lambda \to na)\; e^{-\frac{m_\Lambda - m_n}{T}},$$

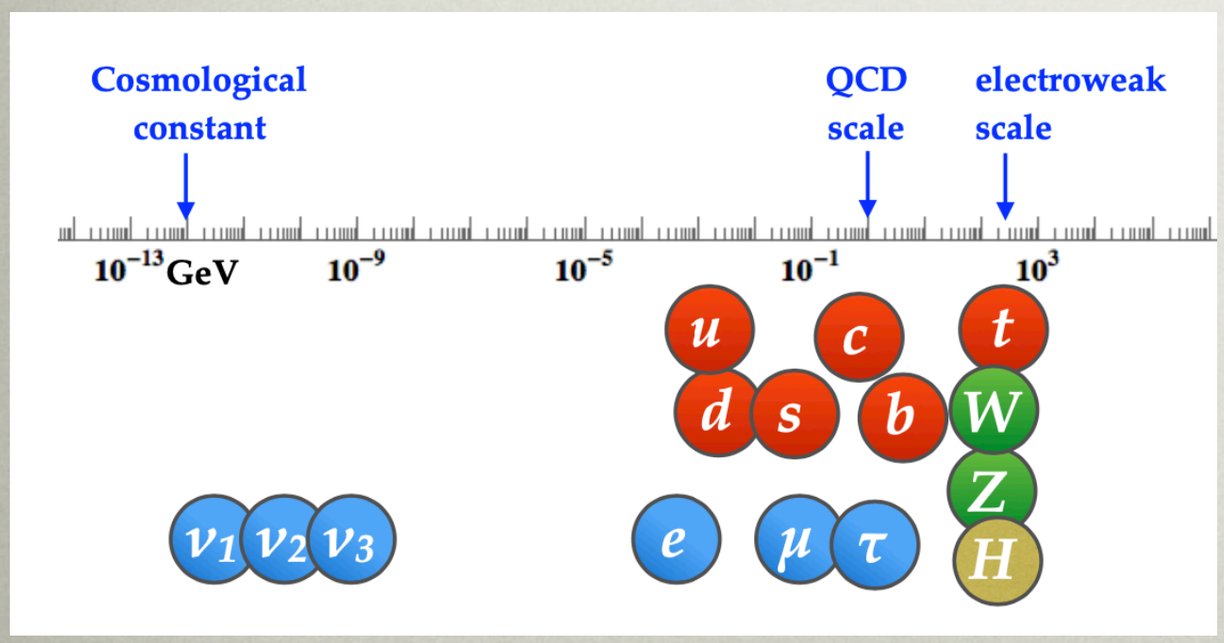
see also Camalich et al, 2012.11632

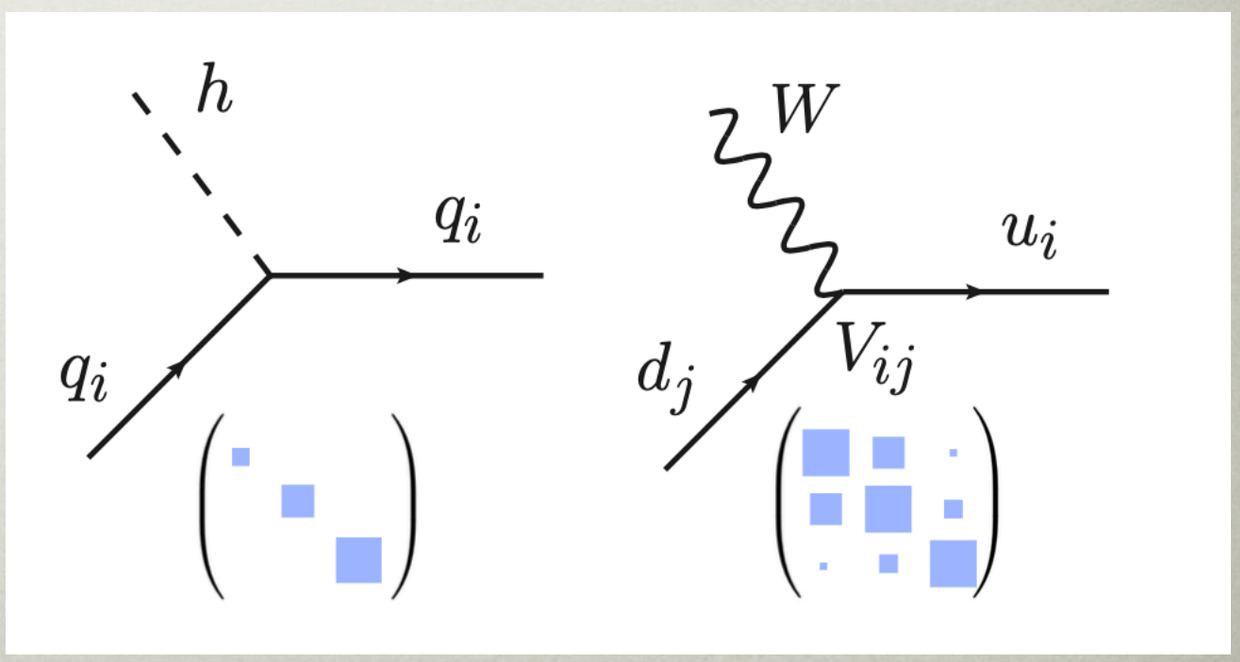
- assuming this is below neutrino emission rate 1sec after the collapse of SN1987A
  - bounds on $|F^A_{sd}|$ and $|F^V_{sd}|$ in the range $10^9 - 10^{10}$ GeV

AXIFLAVON

STANDARD MODEL FLAVOR PUZZLE

- are flavor violating couplings of QCD axion motivated?
- could be related to the solution of the standard model flavor puzzle
  - why SM fermion masses so hierarchical?
  - why CKM matrix hierarchical, any pattern in PMNS?

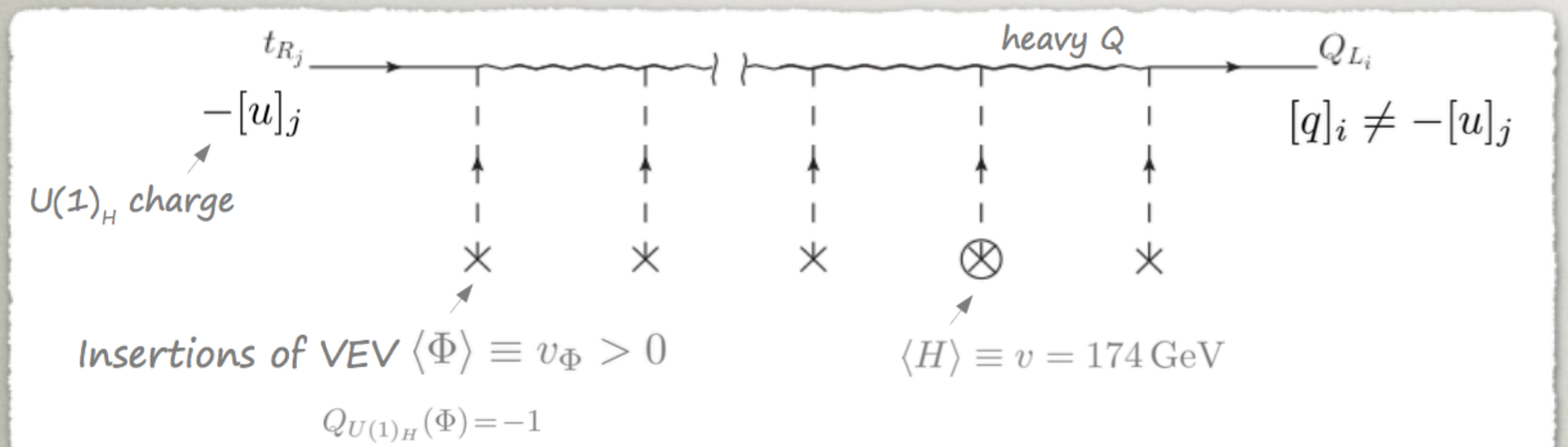




AXIFLAVON

- flavor symmetries that explain Yukawa hierarchies have a QCD anomaly
  - example FN models of flavor

Froggatt, Nielsen, NPB 147, 277 (1979),...



$$\mathcal{L}_{eff} \sim \left(\frac{\phi}{\Lambda_F}\right)^{x_{ij}} h\,\bar{q}_i u_j$$

$$\epsilon \equiv \frac{\phi}{\Lambda_F}$$

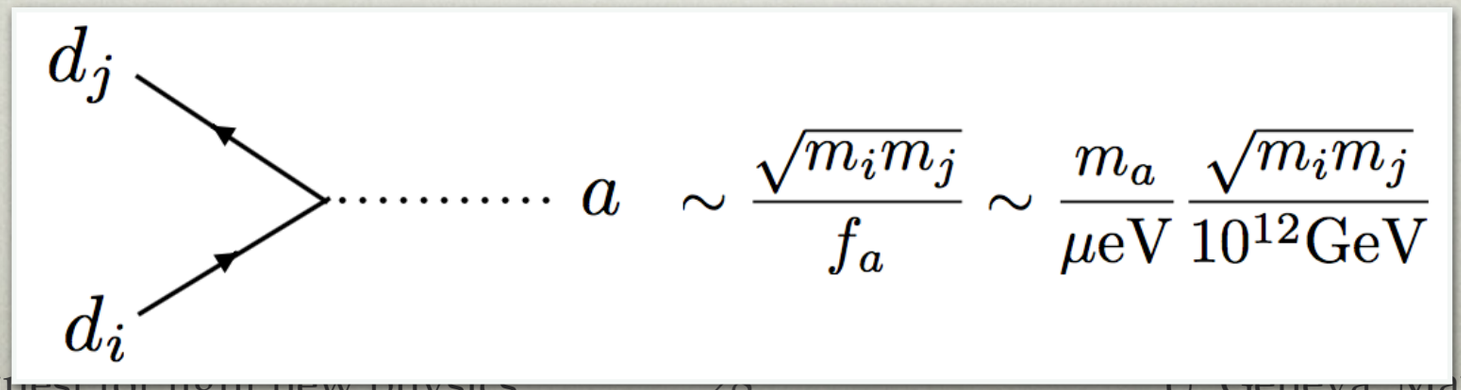
- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{i a(x)/f}$$

Wilczek, PRL 49, 1549 (1982)
Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Ema, Hamaguchi, Moroi, Nakayama, 1612.05492

SEARCHING FOR AXIONS/ AXIFLAVONS

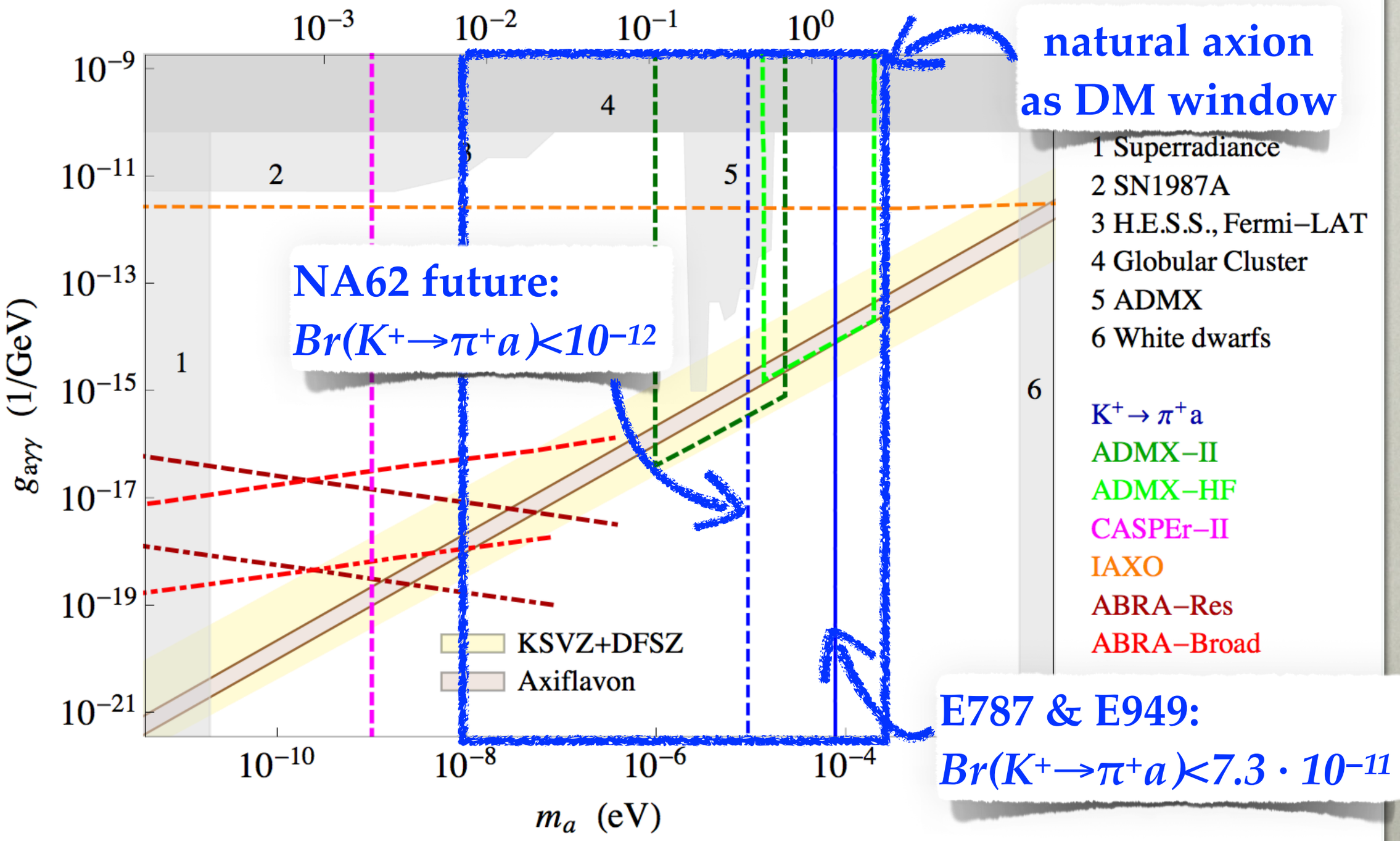
- axion searches use
  - couplings to photons (haloscopos, helioscopes,...)
  - couplings to gluons (CASPEr)
  - flavor diagonal couplings to electrons, nucleons (astrophysical bounds)
- axiflavon
  - in additon flavor violating couplings to fermions
  - in the minimal FN axiflavon model



SEARCHING FOR AXIONS/ AXIFLAVONS

minimal axiflavon

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040



natural axion as DM window

NA62 future:
$Br(K^+ \to \pi^+ a) < 10^{-12}$

E787 & E949:
$Br(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$

LEPTON FLAVOR VIOLATING ALPS

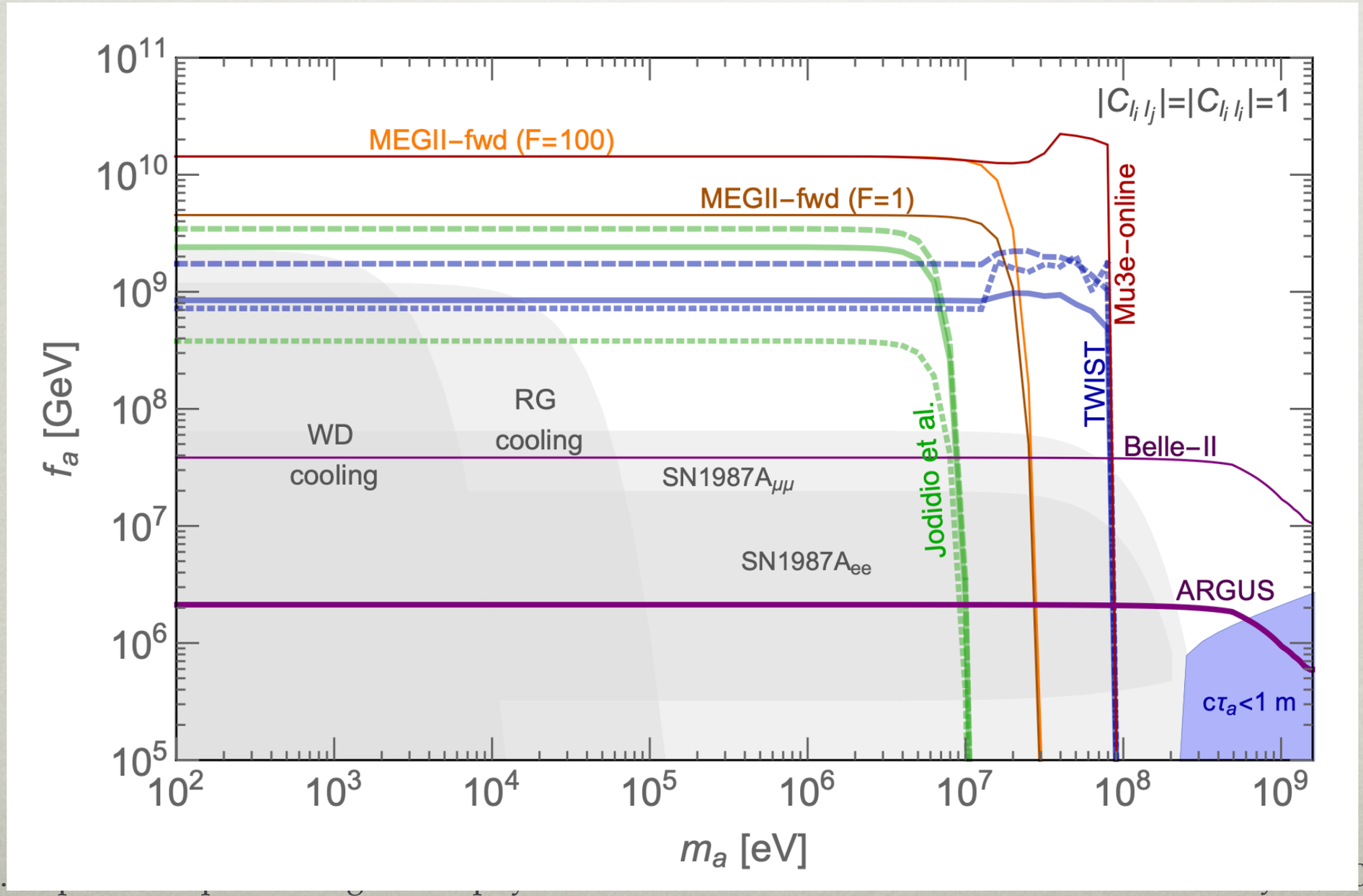
LFV ALPs

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

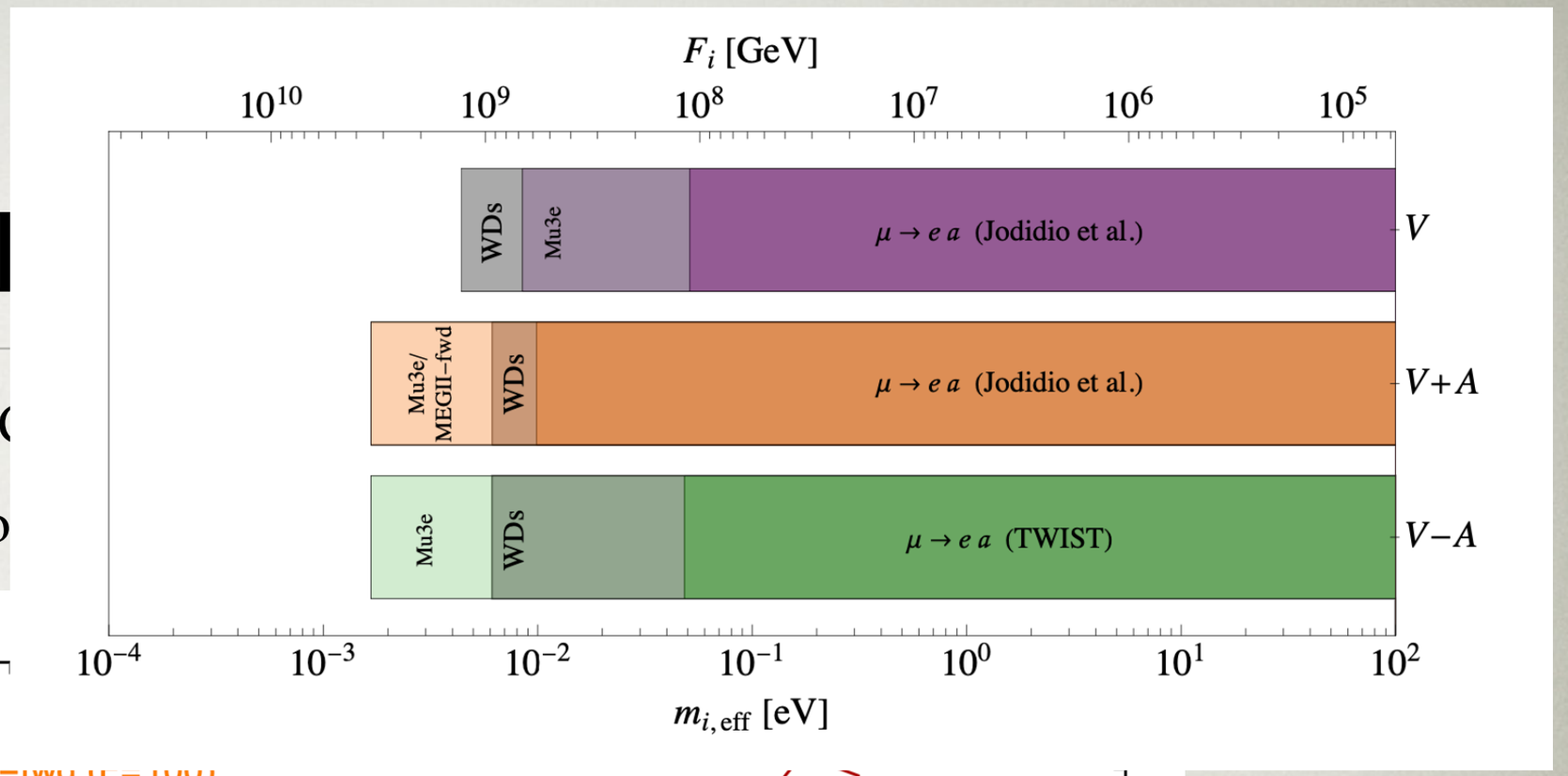
- an example of large, quite untapped, experimental potential
- consider ALP with flavor violating couplings to muons and electrons, $\mu \to ea$
  - $\mathcal{O}(10^{15} - 10^{17})$ muons available at MEG-II ($\mu \to e\gamma$), Mu3e ($\mu \to eee$), Mu2e ($\mu N \to eN$)
  - compare with present bounds using $2 \times 10^7 \mu$ @ Jodidio et al. (1986), and 6×10^8 μ @ TWIST (2015)

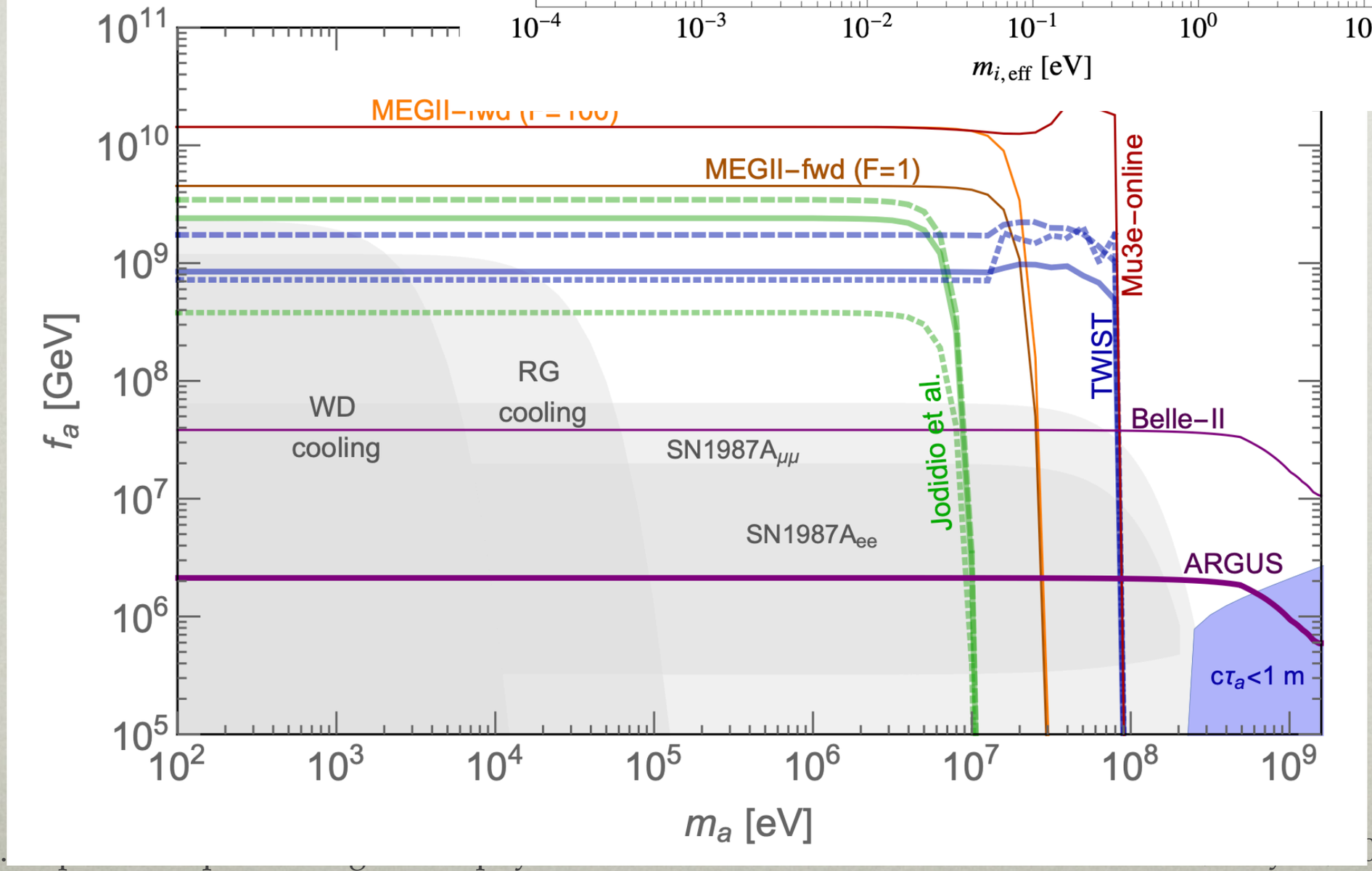
MEGII-FWD

- could repurpose MEG II (→ MEGII-fwd) Calibbi, Redigolo, Ziegler, JZ, 2006.04795
  - with two weeks of running already very stringent constraints possible



- could repurpose ME
  - with two weeks o



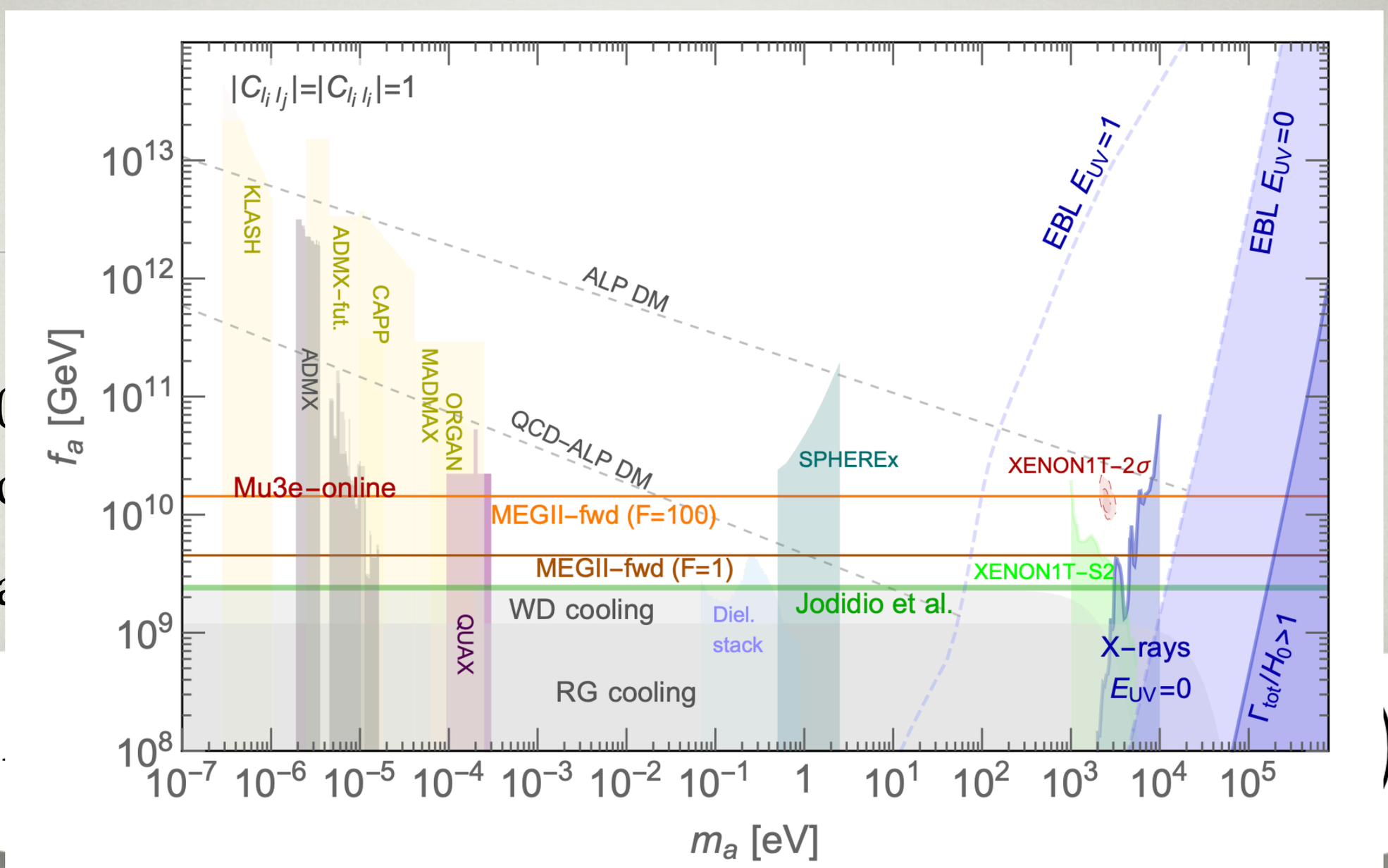


LFV ALP DARK MATTER

- 0-th order condition for ALP to be a DM: be stable on Hubble time
- assume $a \to \gamma\gamma$ dominates

$$\frac{H_0}{\Gamma_{\rm tot}} = H_0\tau_a > 1, \quad \text{where} \quad H_0\tau_a \simeq 5.4 \left(\frac{1}{E_{\rm eff}^2}\right)^2 \left(\frac{10\ {\rm keV}}{m_a}\right)^3 \left(\frac{f_a}{10^{10}\ {\rm GeV}}\right)^2 .$$

- if ALP is observed in a LFV process $\Rightarrow m_a \lesssim 10$ keV
  - LFV experiments most sensitive for some m_a
  - need other experiments to confirm it is DM



$$\frac{H_0}{\Gamma_{\rm tot}} = \left(\right)^2 .$$

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LFV AXIFLAVON

Calibbi, Redigolo, Ziegler, JZ, 2006.04795
see also, Linster, Ziegler, 1805.07341

- the PQ symmetry is part of $SU(2)_F \times U(1)_F$ flavor group
  - all FV couplings need to go through 3rd generation
  - for leptons 1-2 and 1-3 mixings are larger (in LH sector to reproduce PMNS matrix)
- $\Rightarrow$ unlike minimal axiflavon, $K \to \pi a$ suppr.
  - the observation mode is $\mu \to e a$

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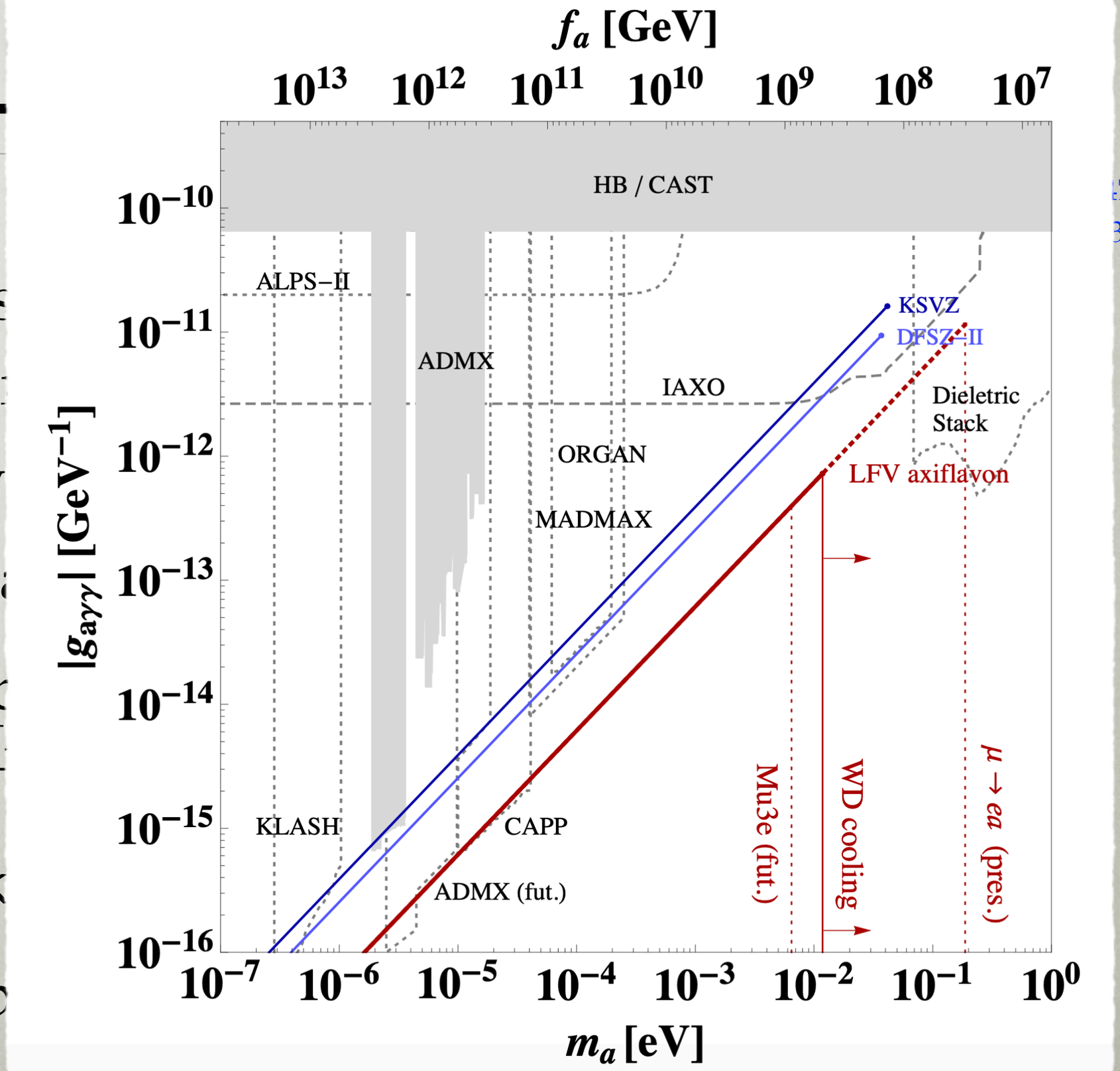

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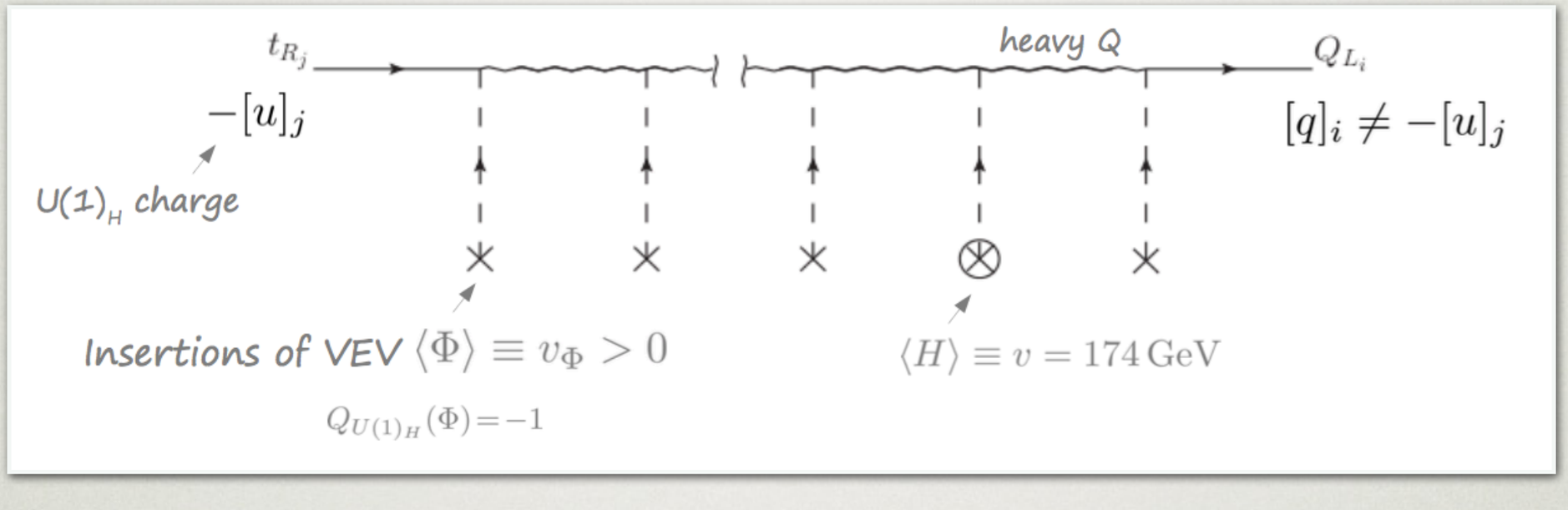
GAUGED FN MODEL EXAMPLE

ANOMALY FREE FN MODELS



- inverted FN mechanism ⇒ non-anomalous $U(1)_{\rm FN}$
  - vector-like fermions all charged under $U(1)_{\rm FN}$ (no anomaly)
  - chiral fields not charged under $U(1)_{\rm FN}$ (in the middle of the chain)
  - a concrete realization of the "clockwork" mechanism
- $U(1)_{\rm FN}$ can be gauged

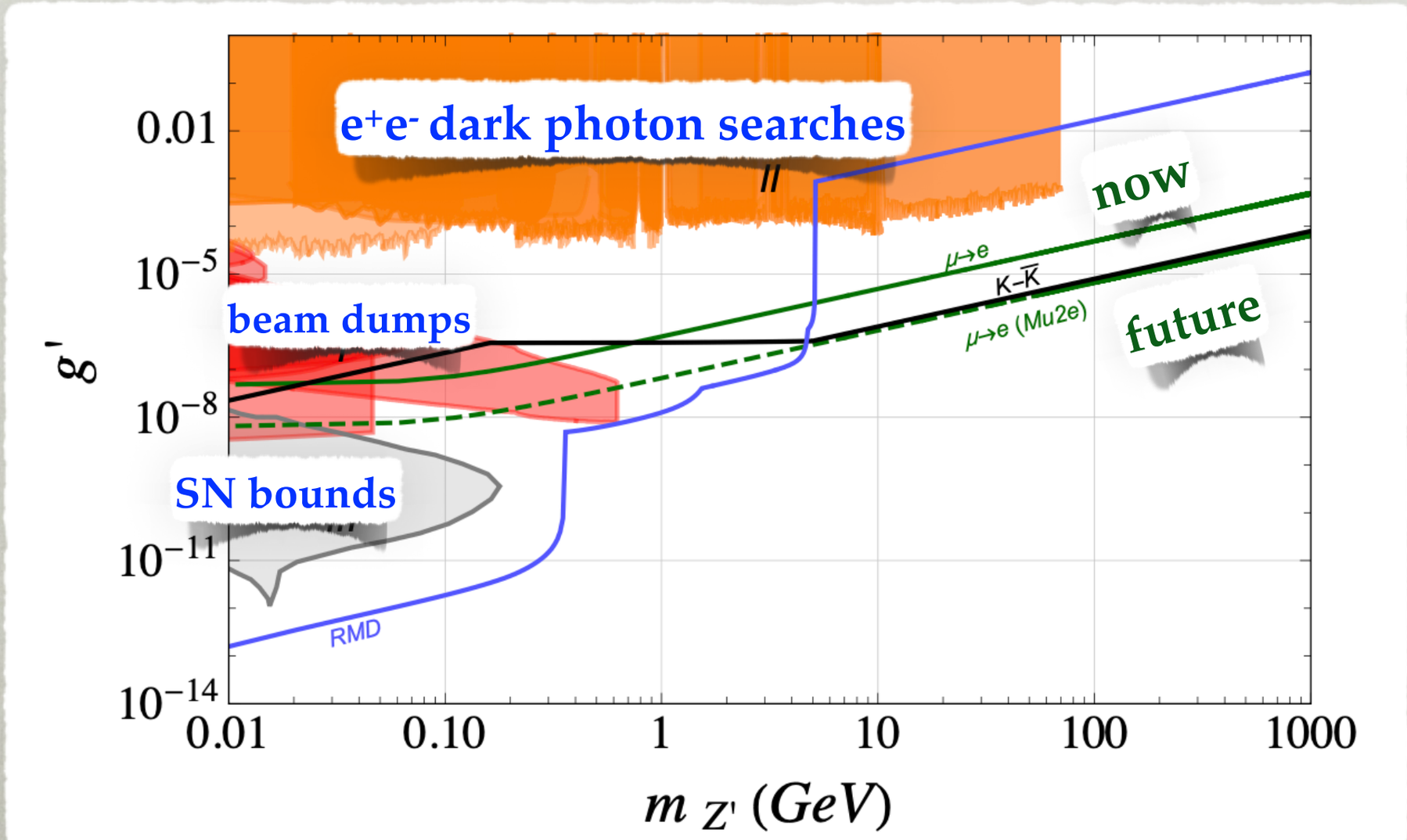
Smolkovic, Tammaro, JZ, 1907.10063

EXPERIMENTAL SEARCHES

- how to observe experimentally?
- search in FCNCs
  - $K - \bar{K}$, $B - \bar{B}$ mixing, etc.
    - exchanges of flavons, heavy vector-like fermions, flavorful Z' s
    - for $\mathcal{O}(1)$ couplings masses $\gtrsim 10^7$ GeV
- for small $U(1)_{FN}$ gauge couplings Z' can be light
  - can also search for it directly: beam dumps, e^+e^- colliders, astrophysics

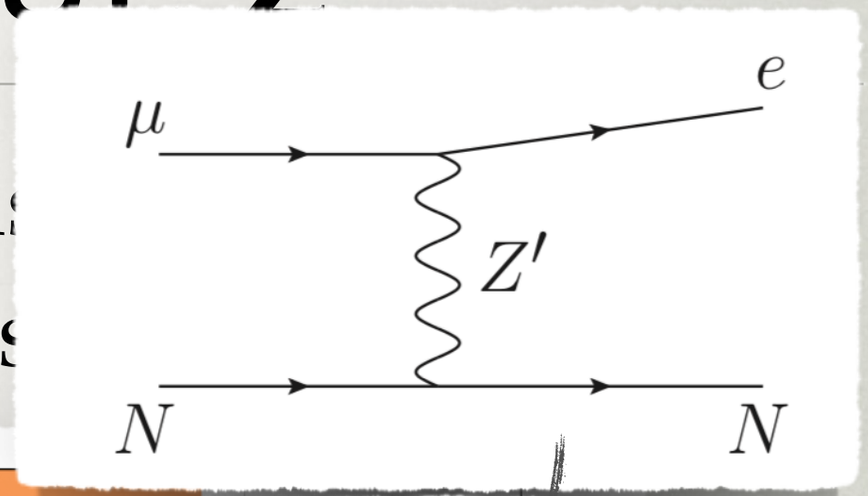
FLAVORFUL Z'

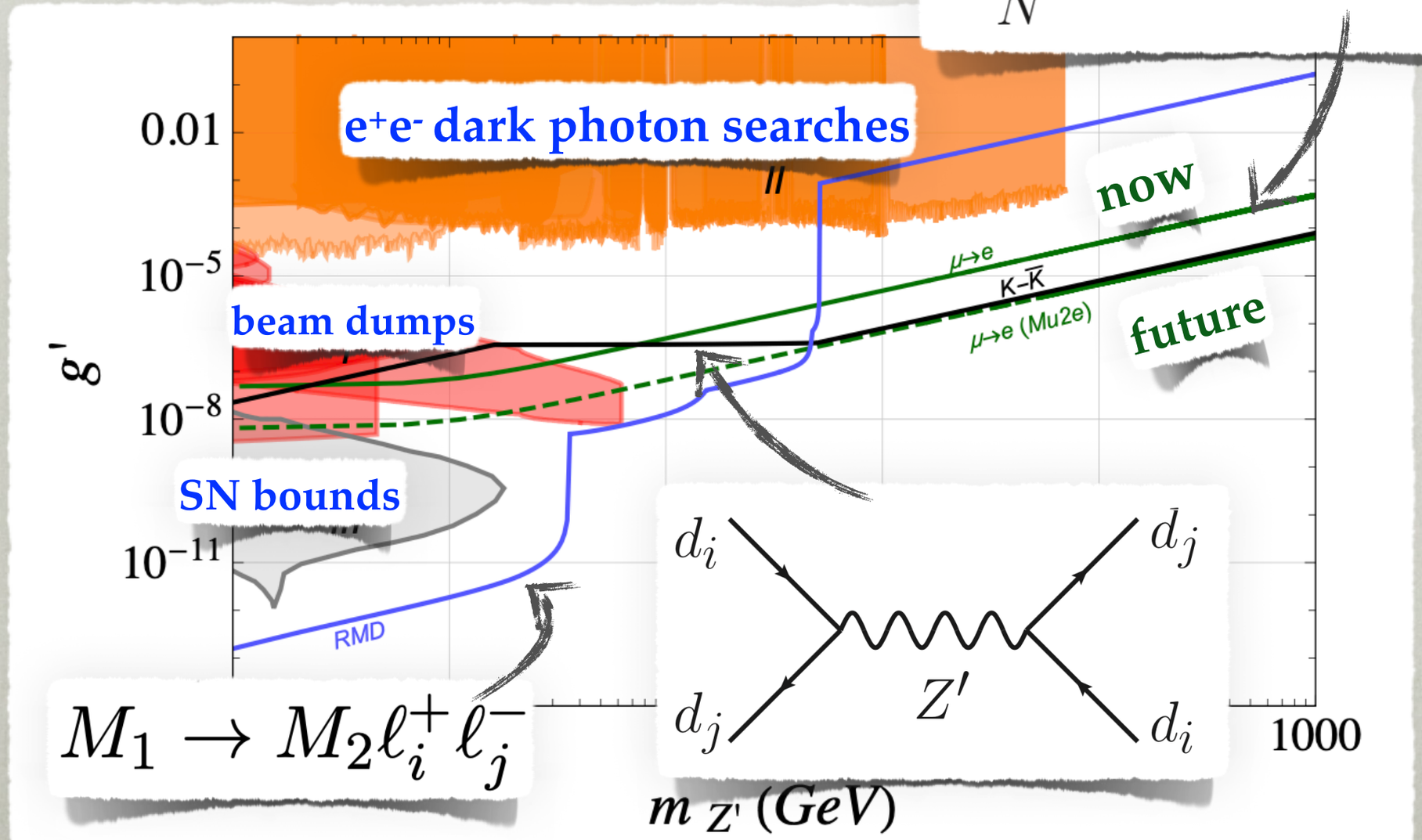
- for $U(1)_{FN}$ benchmark, assuming anarching neutrino mass from Weinber op.



FLAVORFUL Z'

- for $U(1)_{FN}$ benchmark, a
  anarching neutrino mass





CONCLUDING REMARKS

- FV decays to light new physics give us access to physics at very high scales
- shown several examples
  - could even discover a QCD axion through FV processes

BACKUP SLIDES