THEORY FRONTIER AND RARE AND PRECISION MEASUREMENTS

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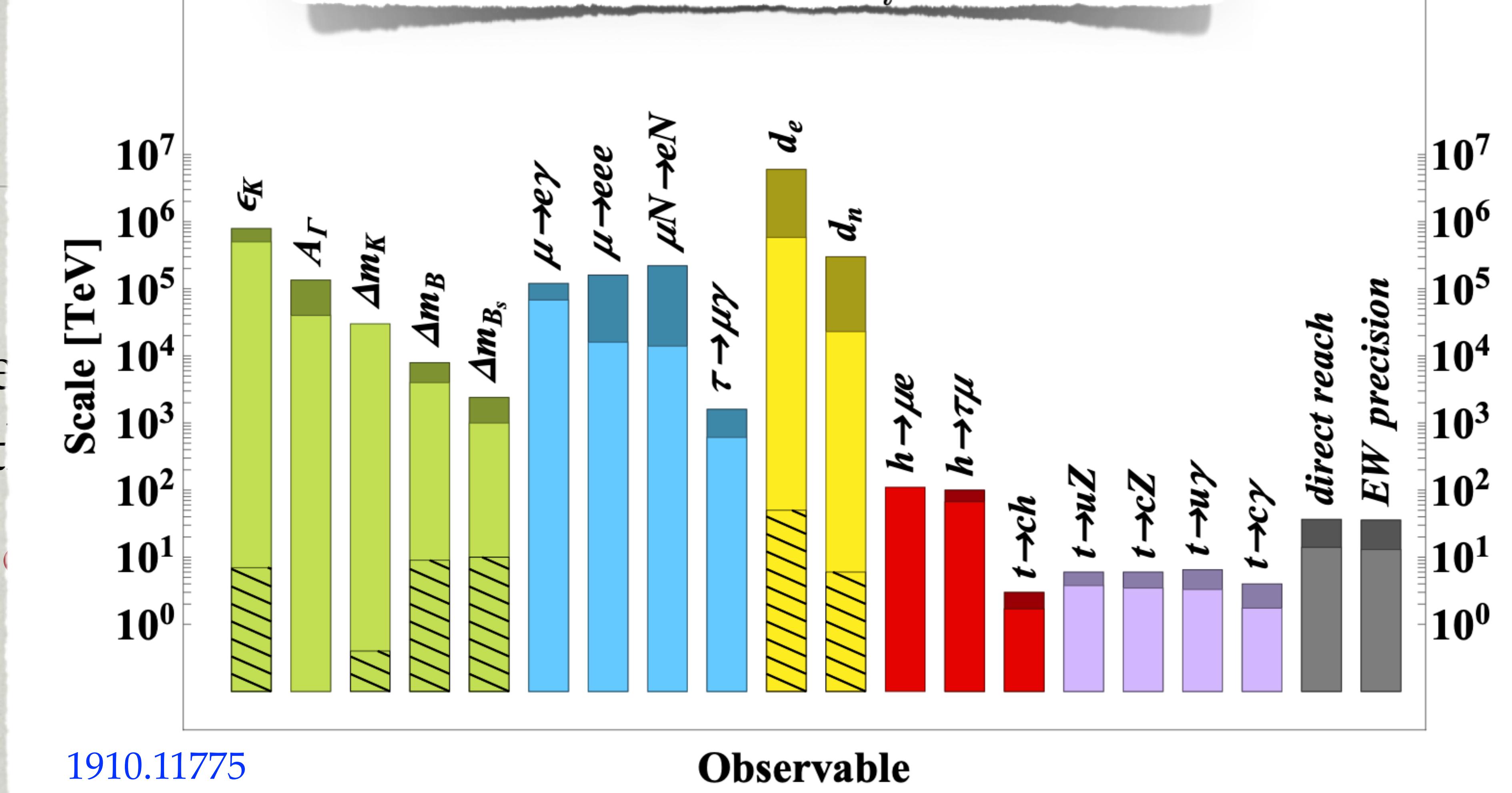
MAIN MESSAGES

- two obvious, yet important statements
  - theory is an essential input for experimental measurements
  - experimental results are essential inputs to theory considerations
- this talk: selected examples of the above interplay

FROM EXPERIMENTS TO PARADIGM SHIFTS

- experimental results can lead to qualitative jumps in theoretical understanding
  - $\delta_{\text{CKM}} \sim \mathcal{O}(1) \Rightarrow$ the strong CP problem, i.e., why $\bar{\theta} \lesssim 10^{-10}$, becomes even more striking
    - is the PMNS phase (and Majorana phases) also $\mathcal{O}(1)$?
  - Higgs discovery $\Rightarrow$no hiding from the hierarchy problem
    - flavor constraints $\Rightarrow$ NP flavor puzzle
    - even if one loop and MFV already being squeezed
    - do we simply live in a fine-tuned world?

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{\rm SM}_{\rm gauge} + \mathcal{L}^{\rm SM}_{\rm Higgs} + \sum_i \frac{1}{\Lambda^{d-4}} \mathcal{C}_i \mathcal{O}_i^{d>4} \,,$$



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  - Higgs discovery ⇒no hiding from the hierarchy problem
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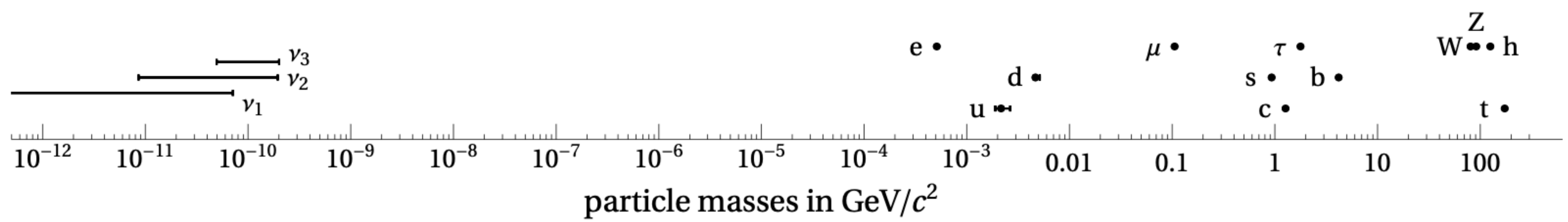
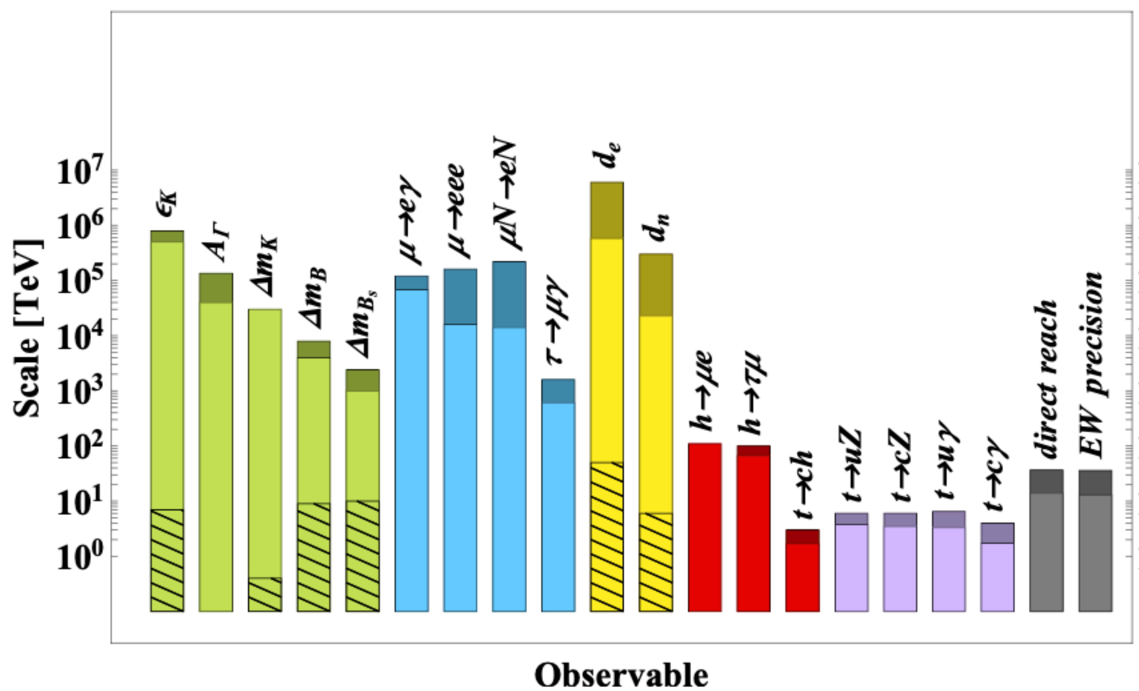
EXPLAINING THE SM HIERARCHIES

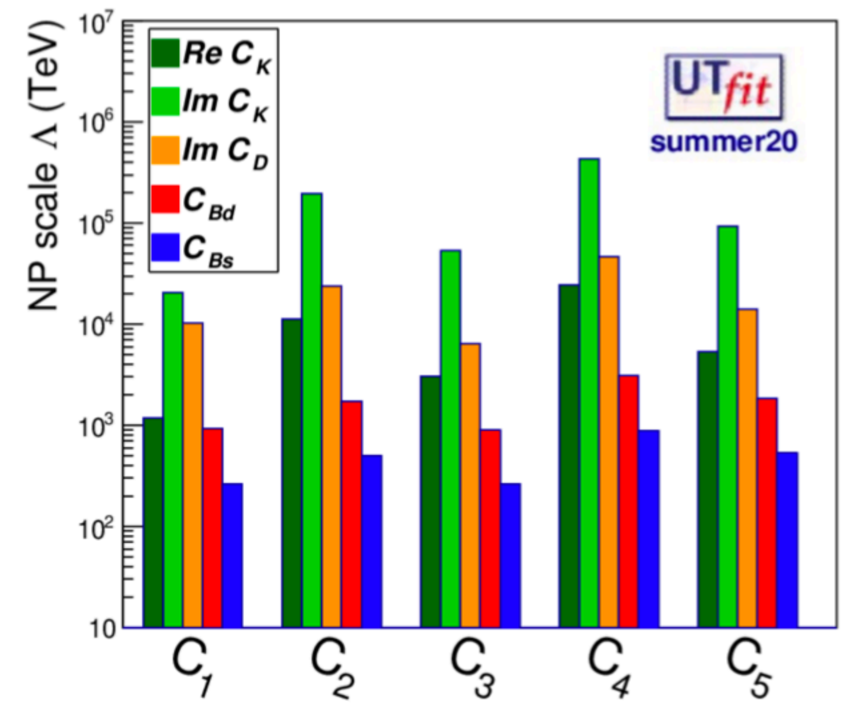


Altmannshofer, JZ, 2203.07726

- is there a dynamical explanation for the pattern of SM fermion masses and mixings?
  - horizontal flavor symmetries
  - warped extra dimensions
  - partial compositness

FLAVOR AS A NEW PHYSICS PROBE





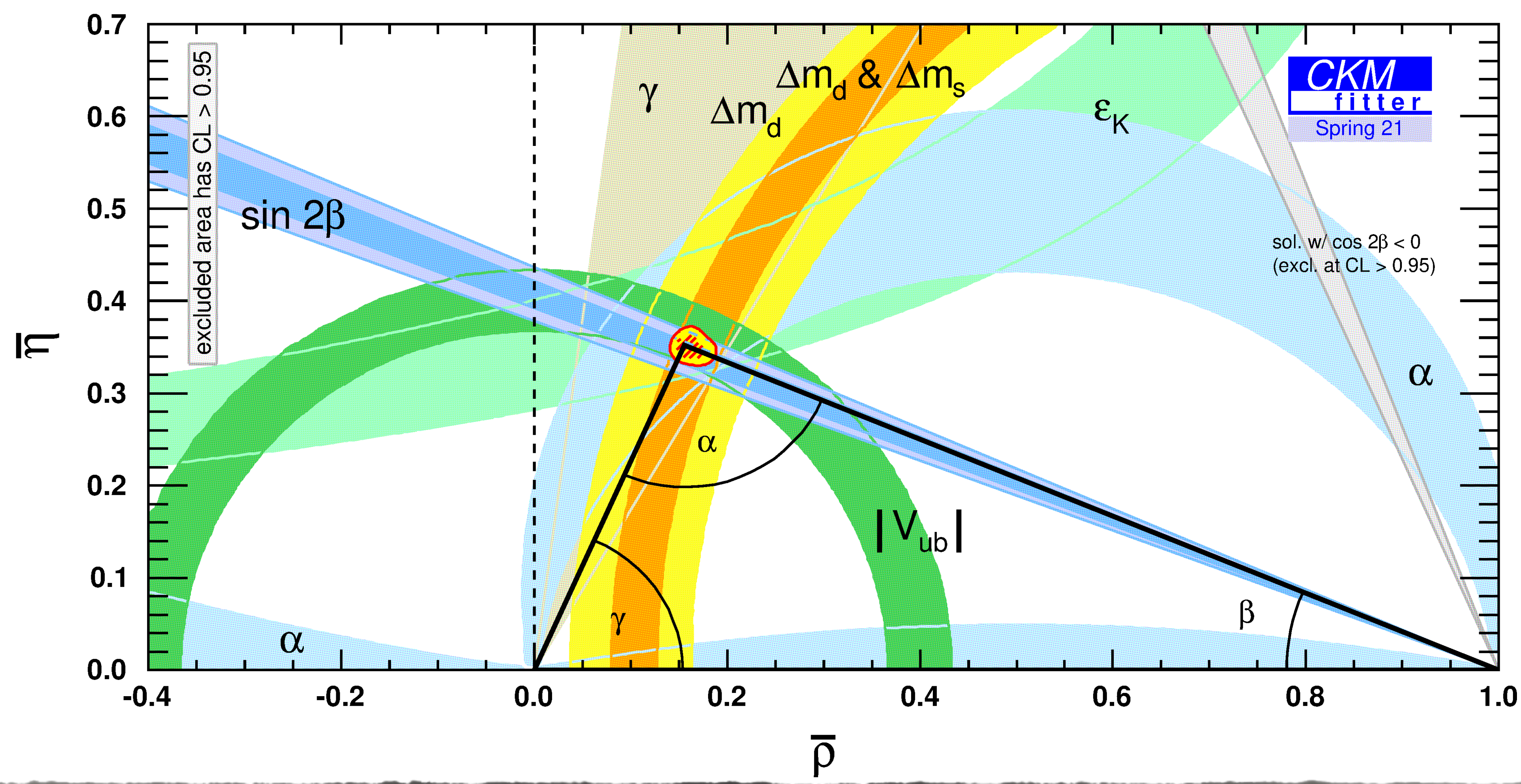
- assuming NP is heavy ⇒ SMEFT
- flavor observables probe very high scales
  - decoupling
  - Minimal Flavor Violation
  - hierarchical new physics flavor couplings

THEORY INPUT

- in many corners of flavor/precision physics theory input indispensible
  - quark flavor transitions involve hadrons/nonperturbative QCD
    - CKM unitarity triangle
    - prediction for $(g-2)_\mu$ in the SM
    - $b \to c\tau\nu$ and $b \to s\mu\mu$ predictions
  - understanding the backgrounds
    - $\mu \to e$ conversion
  - interpretation of experimental results
    - flavor anomalies
  - motivating experimental searches
    - light new physics

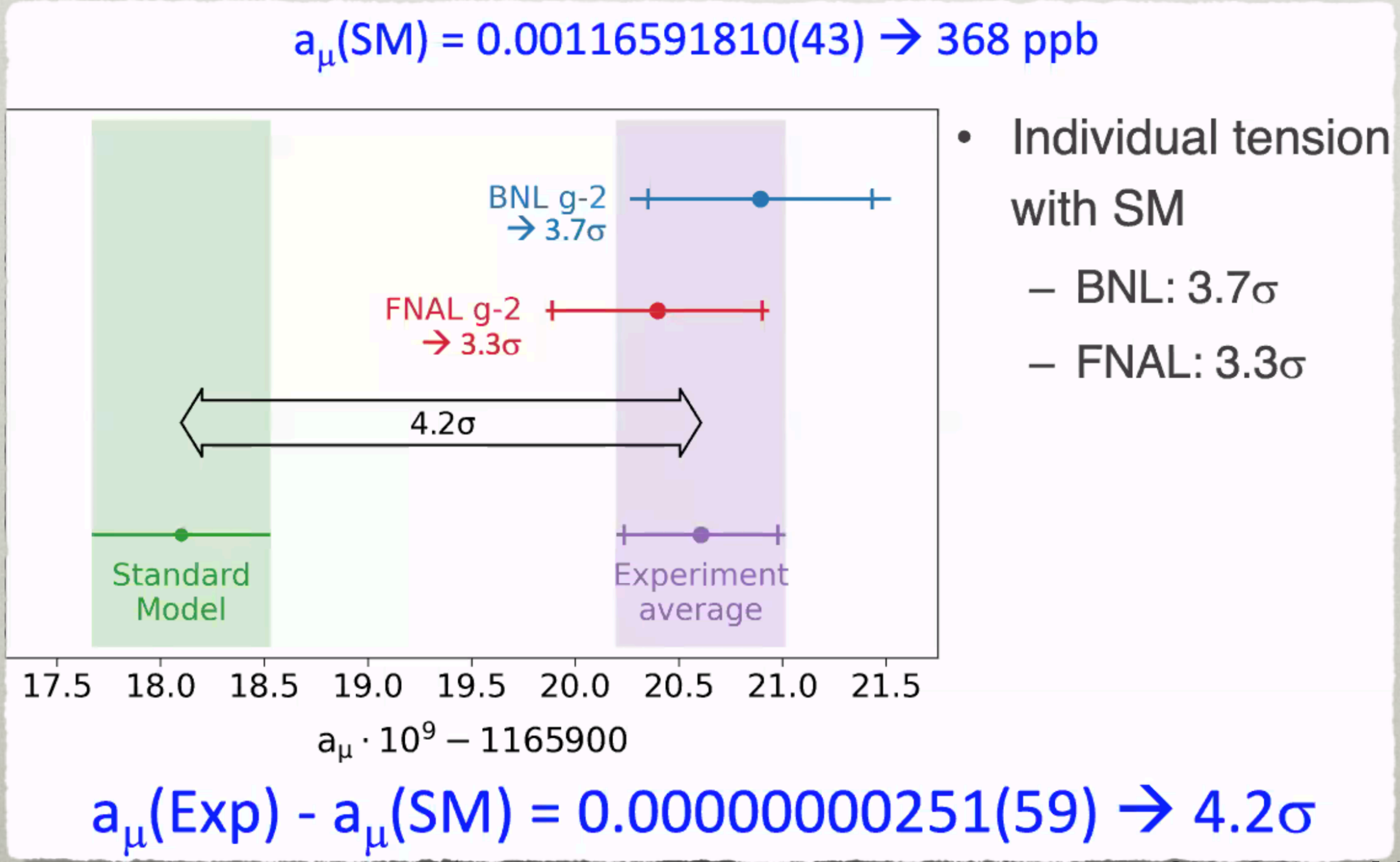
STANDARD CKM UNITARITY TRIANGLE

- every single constraint requires theory inputs or insights
  - lattice QCD, HQET, SCET, SU(2), perturbative QCD & electroweak corrections,...



PREDICTIONS FOR $(g-2)_\mu$ IN THE SM

- searching for NP only if the SM prediction for $(g-2)_\mu$ is understood
  - lattice QCD, dispersion relations

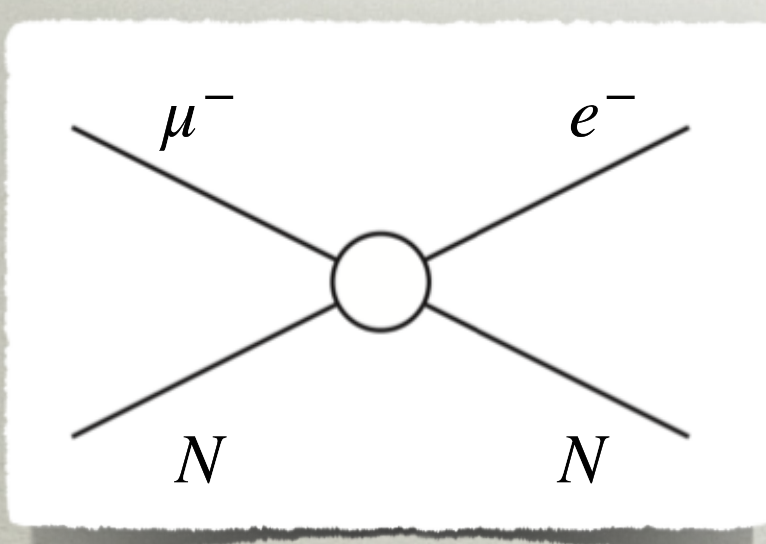


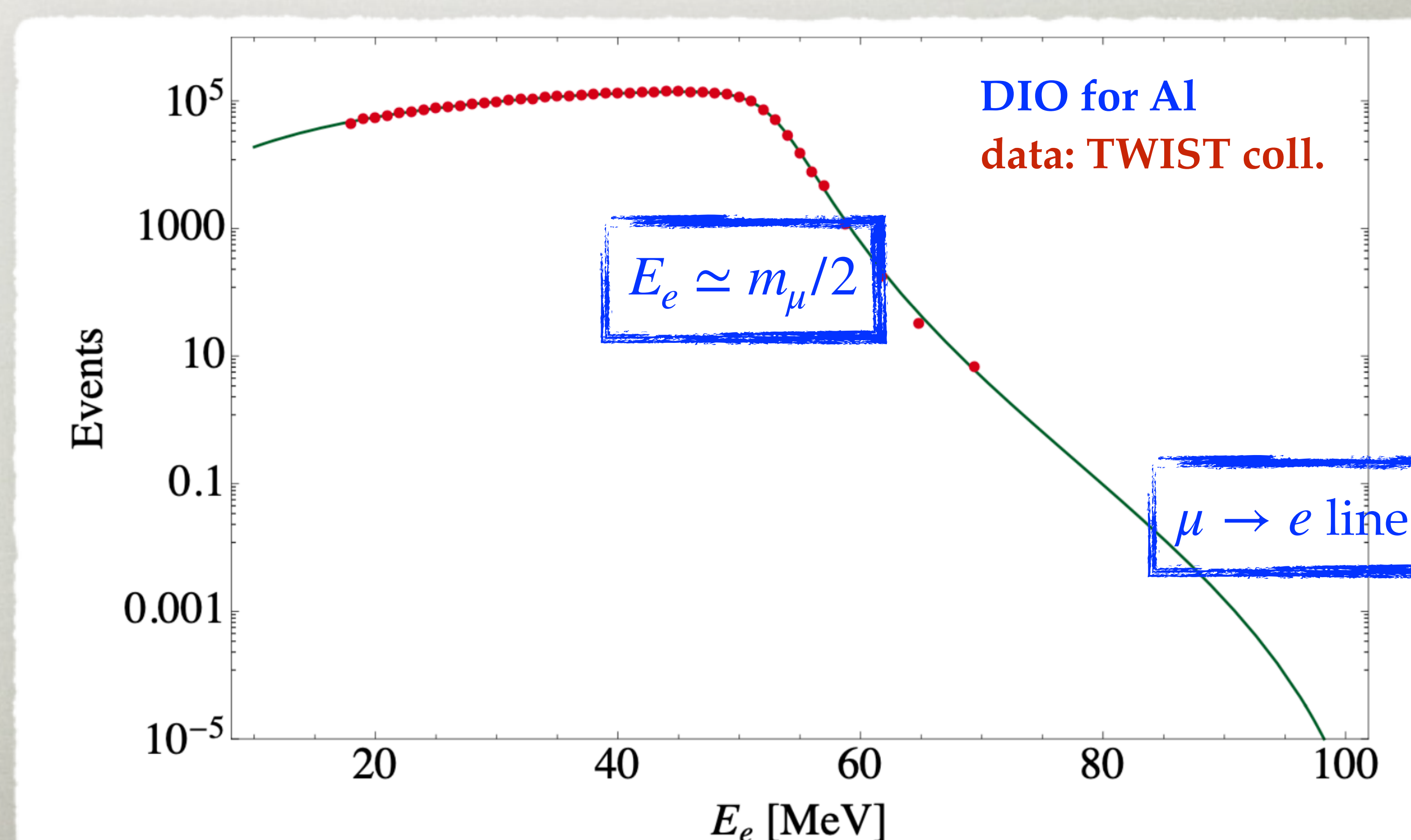
THEORY INPUTS FOR FLAVOR ANOMALIES

- $b \to c\tau\nu$ predictions: HQET, lattice QCD
- $b \to s\mu\mu$
  - the SM corrections to LFUV ratios
    - mass corrections, treatment of QED,...
  - predictions for branching ratios, angular observables

SM background in $\mu \to e$ conversion

- $\mu^- N \to e^- N$ conversion
  - the only intrinsic bckgd is $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ decay in orbit
  - in $\mu^- N \to e^- N$ the e^- is at the kinematical edge of DIO
  - the SM prediction for it essential





INTERPRETATION OF EXPERIMENTAL RESULTS

- example: flavor anomalies point to leptoquarks
  - 3 options if a single LQ dominates in $b \to s\mu\mu$

Hiller, Nisandzic, 1704.05444

Scalar LQ

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
$\tilde{S}_2$	$(3, 2, 1/6)$	C_{RL}	$C'_9 = -C'_{10}$	$R_K < 1,\ R_{K^*} > 1$
S_3	$(\bar{3}, 3, 1/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1.$
S_2	$(3, 2, 7/6)$	C_{LR}	$C_9 = C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	C_{RR}	$C'_9 = C'_{10}$	$R_K \simeq R_{K^*} \simeq 1$

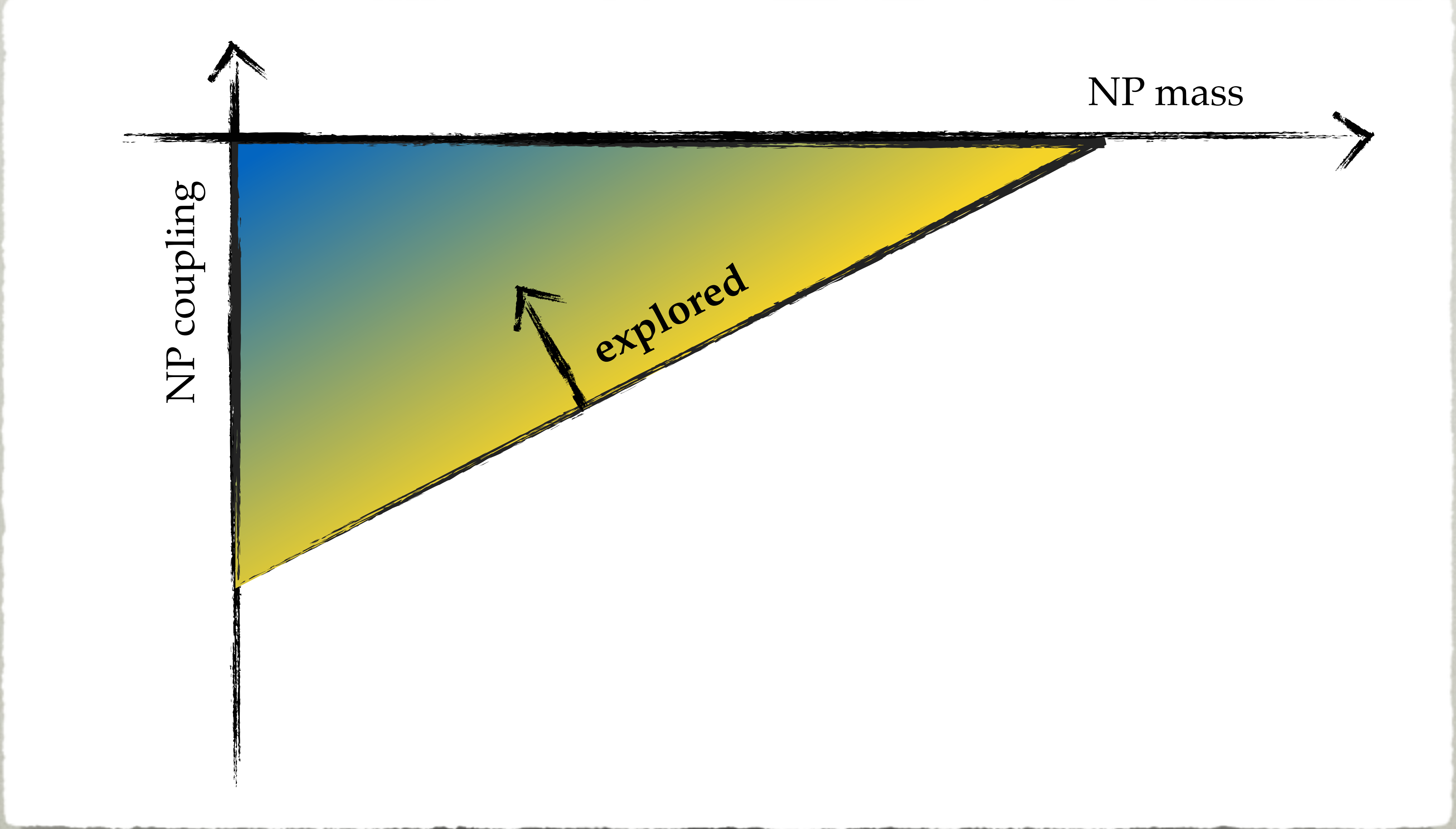
Vector LQ

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
V_1	$(3, 1, 2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
		C_{LR}	$C_9 = +C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_2	$(3, 2, -5/6)$	C_{RL}	$C'_9 = -C'_{10}$	$R_K < 1,\ R_{K^*} > 1$
		C_{RR}	$C'_9 = +C'_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_3	$(3, 3, -2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$

  - motivates new direct searches

THE CASE FOR LIGHT NEW PHYSICS SEARCHES

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



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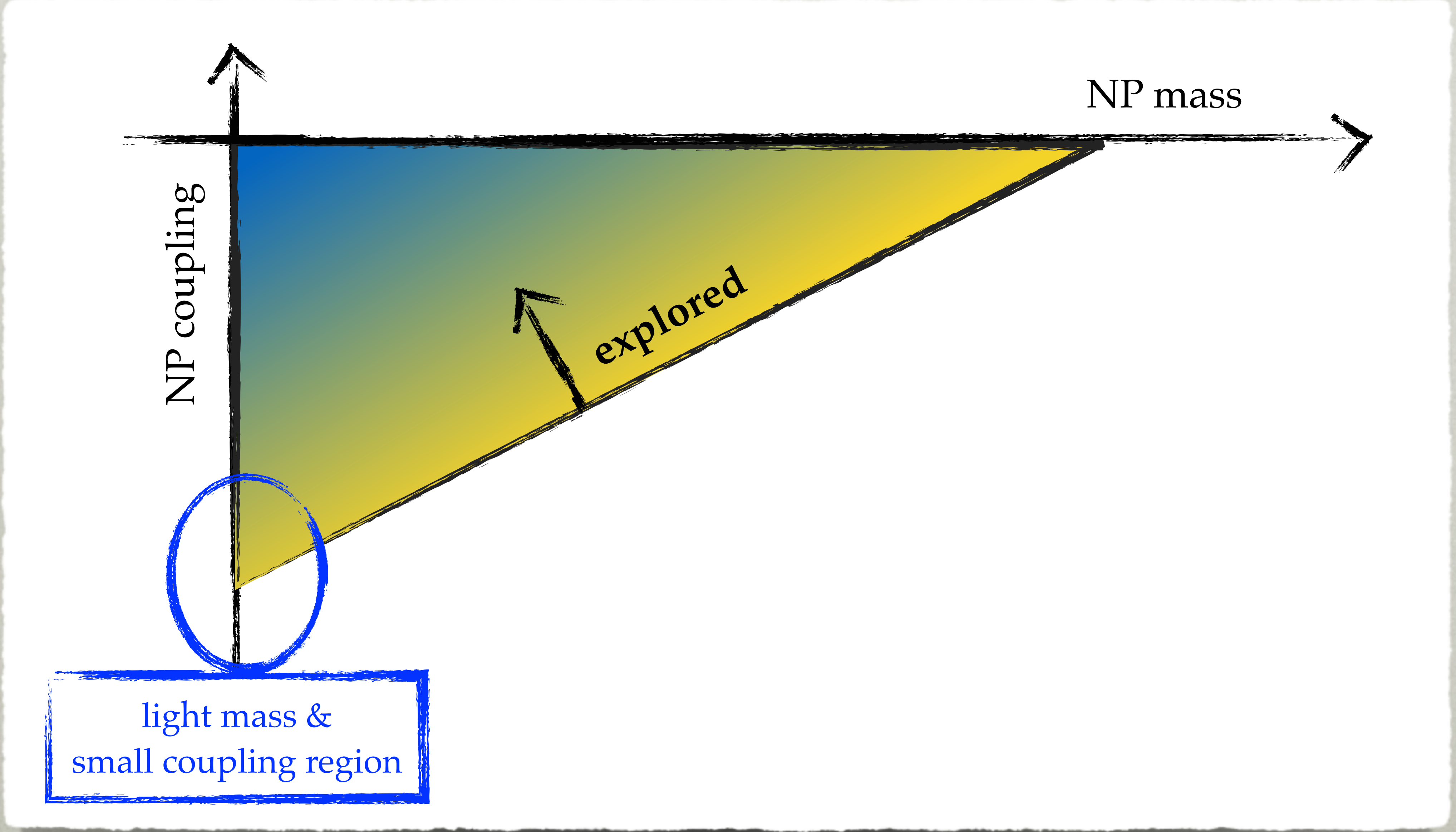

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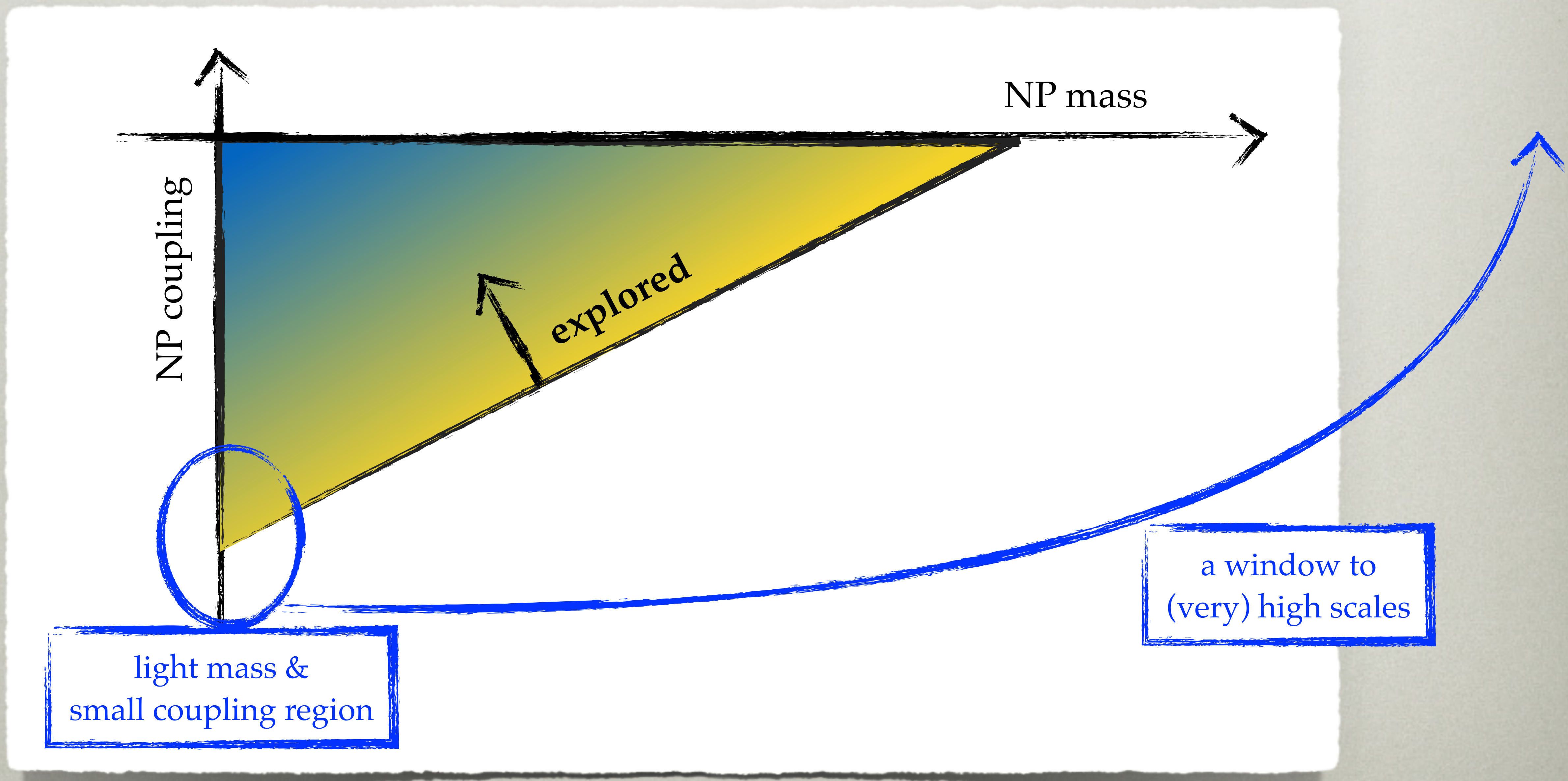


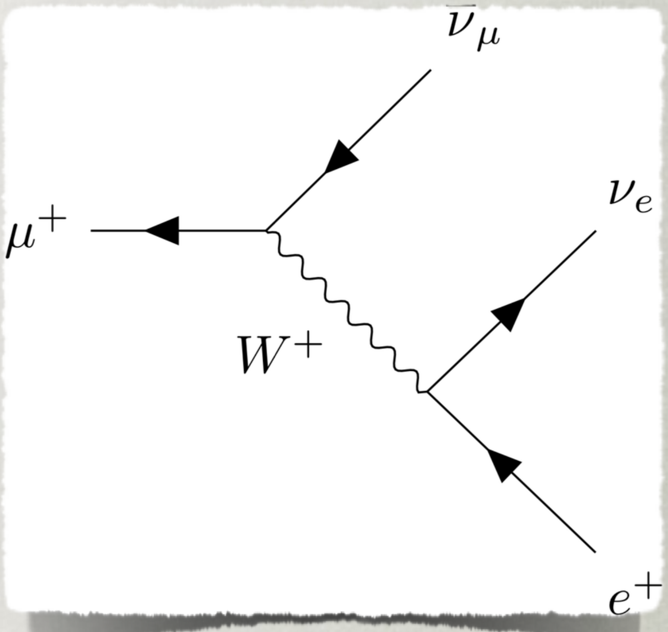
LIGHT NEW PARTICLES

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

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	$y_N LHN$
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 → πX or μ → eX,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops.
  - SM decay width power suppressed: $\Gamma_M \propto m_M^5/m_W^4$
- if through dim 5 op. suppressed by $1/f_a$
  - $\Rightarrow Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
  - similar for dim 4
- no such $1/m_\mu$ or $1/m_K$ enhancement for dim. 6 couplings
  - $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

UPSHOT

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

EXAMPLE: FLAVOR VIOLATING QCD AXION

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

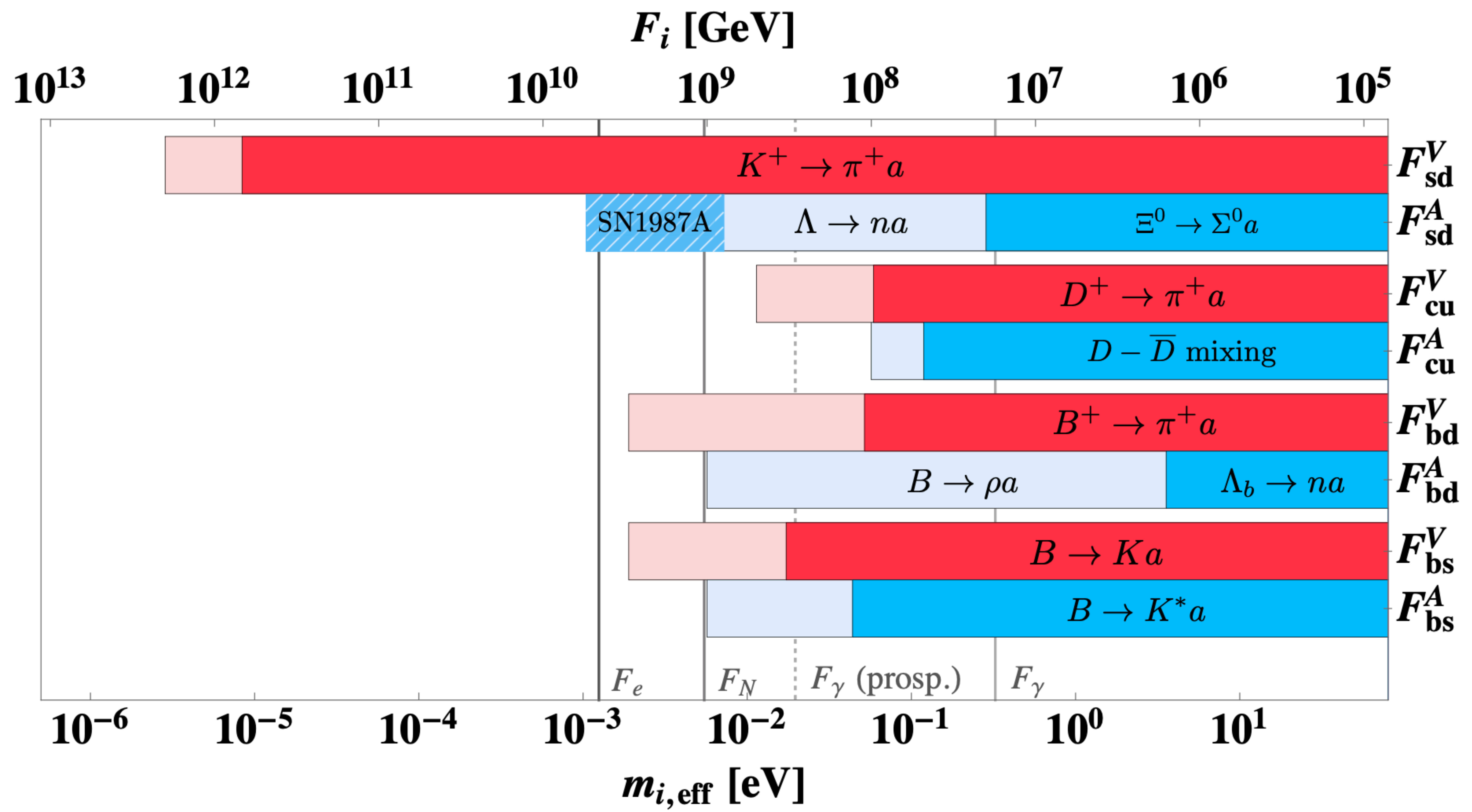
- QCD axion with FV couplings to quarks
  - solves the strong CP problem
  - can be a cold DM candidate
  - effectively massless in FV transitions
- general analysis, allowing for FV couplings as well
  - first focus on quark FV transitions

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

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

THE STRONGEST FV CONSTRAINTS

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



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 $\mu \to ea$

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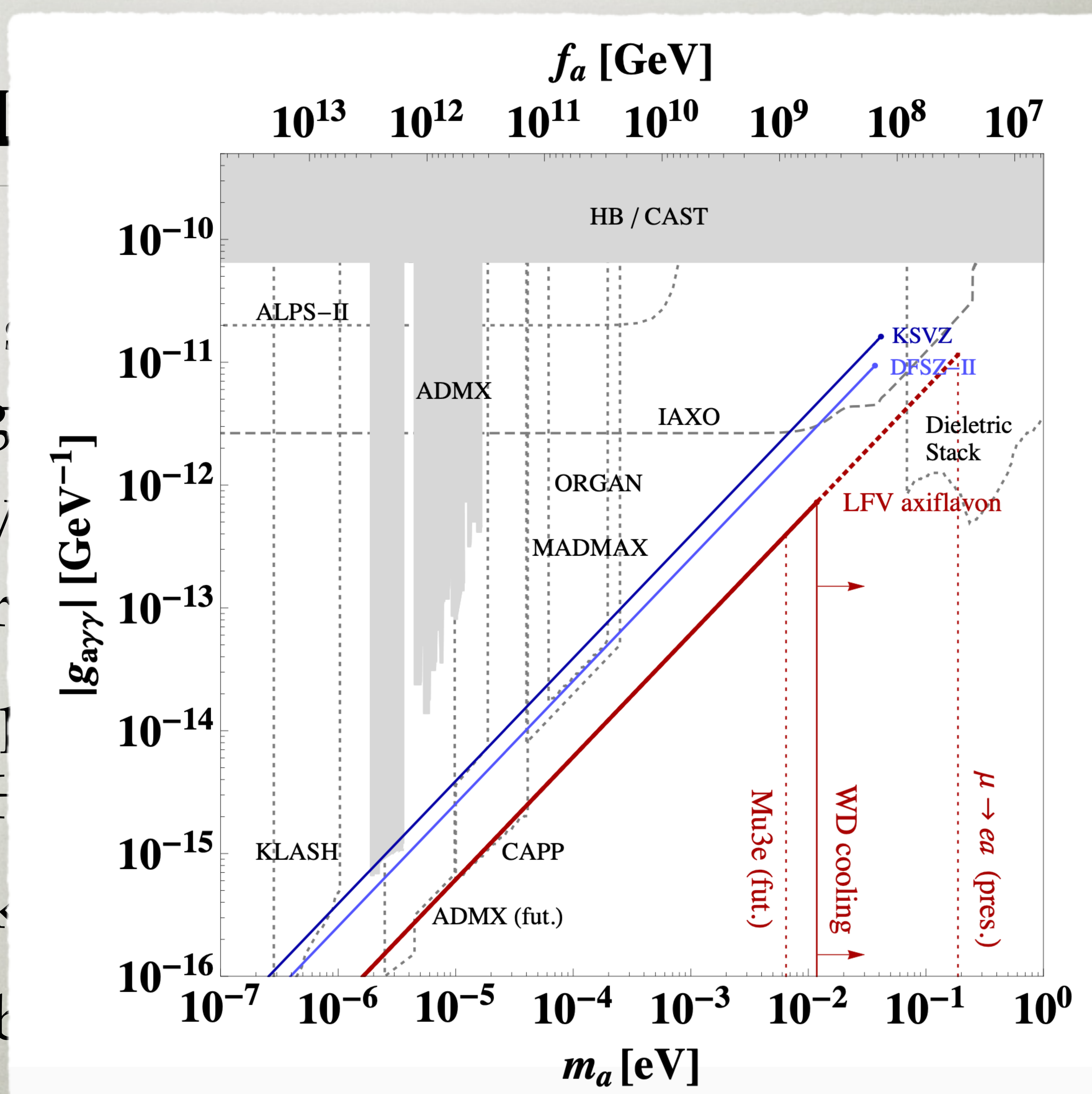


thanks to J. Brod, Z. Ligeti, K. Melnikov

THEORY CROSS-FEED

- tools that were developed for flavor physics find use in other areas
    - SCET first developed for predictions in rare *B* decays
        - now part of standard theory tool-kit for collider physics/ pQCD
        - calculation of indirect DM signal in photon lines
    - HQET and NRQED/NRQCD originate in *B* physics/precision frontier phyics
        - DM relic abundance calculations
        - J/ψ production in *pp* collisions
        - WIMP direct detection scattering rates
    - influenced higher loop perturbative calculations in other areas
        - Laporta algorithm, application of IBP to more cases, loop computations with massive particles in initia/final state

CONCLUSIONS

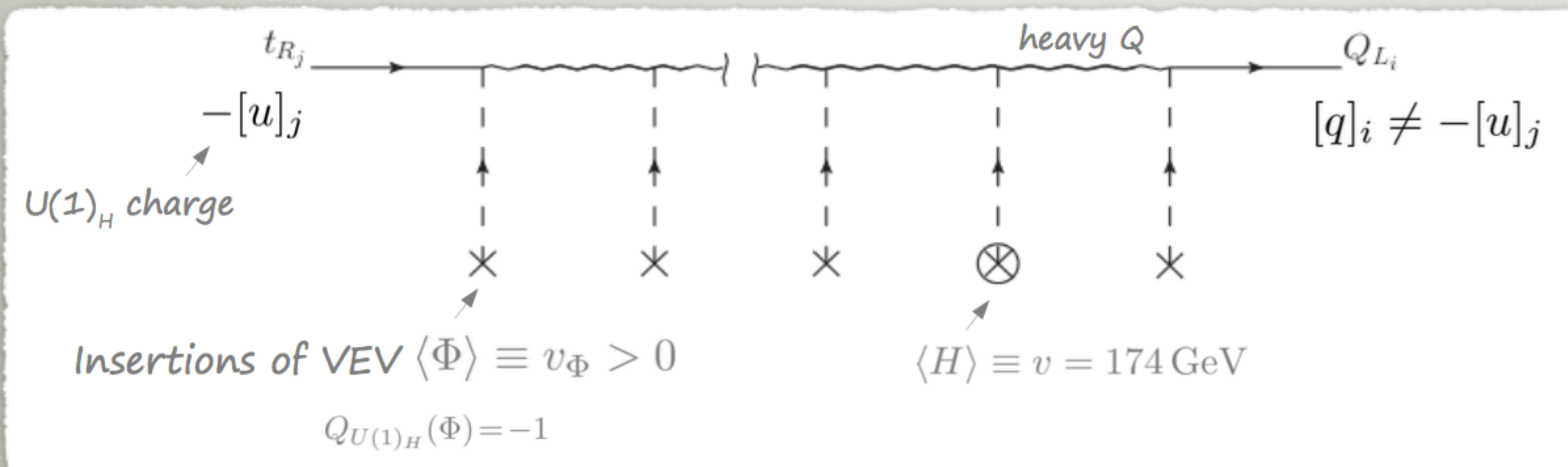
- we are entering a new era of precision measurements: Belle 2, LHCb, muon experiments, dark sector searches, ...
- theory is an integral part of this effort

BACKUP SLIDES

AXIFLAVON

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

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



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

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

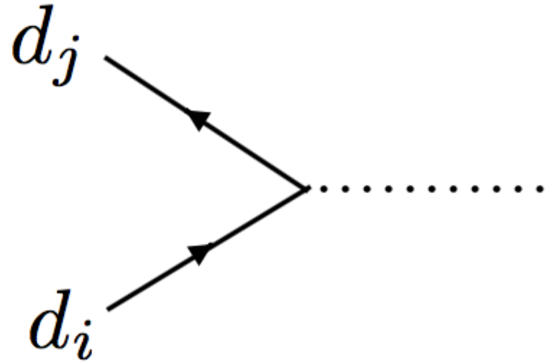
- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
    - the phase of the flavon is the QCD axion = axiflavon

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

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

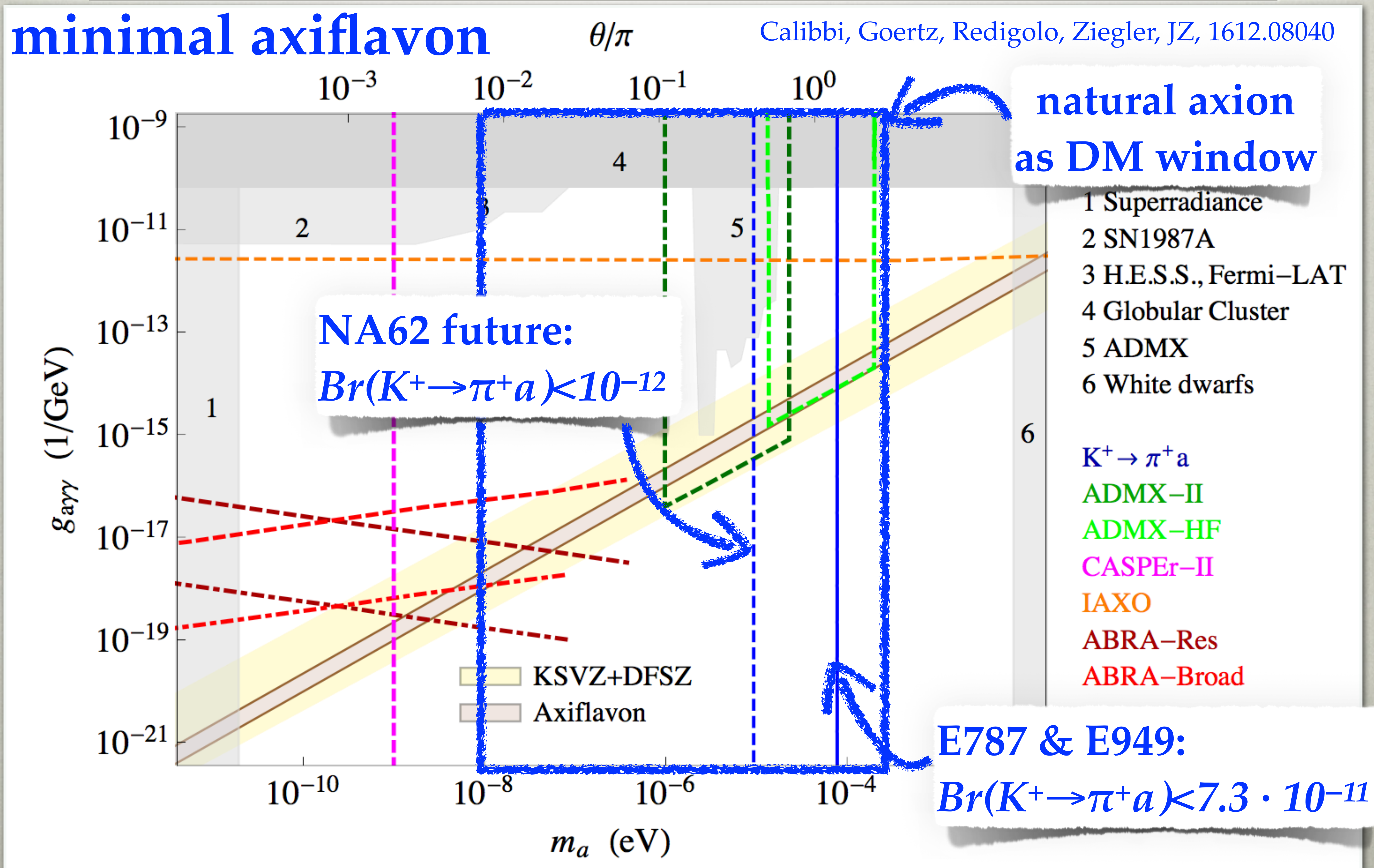
SEARCHING FOR AXIONS/ AXIFLAVONS

- 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



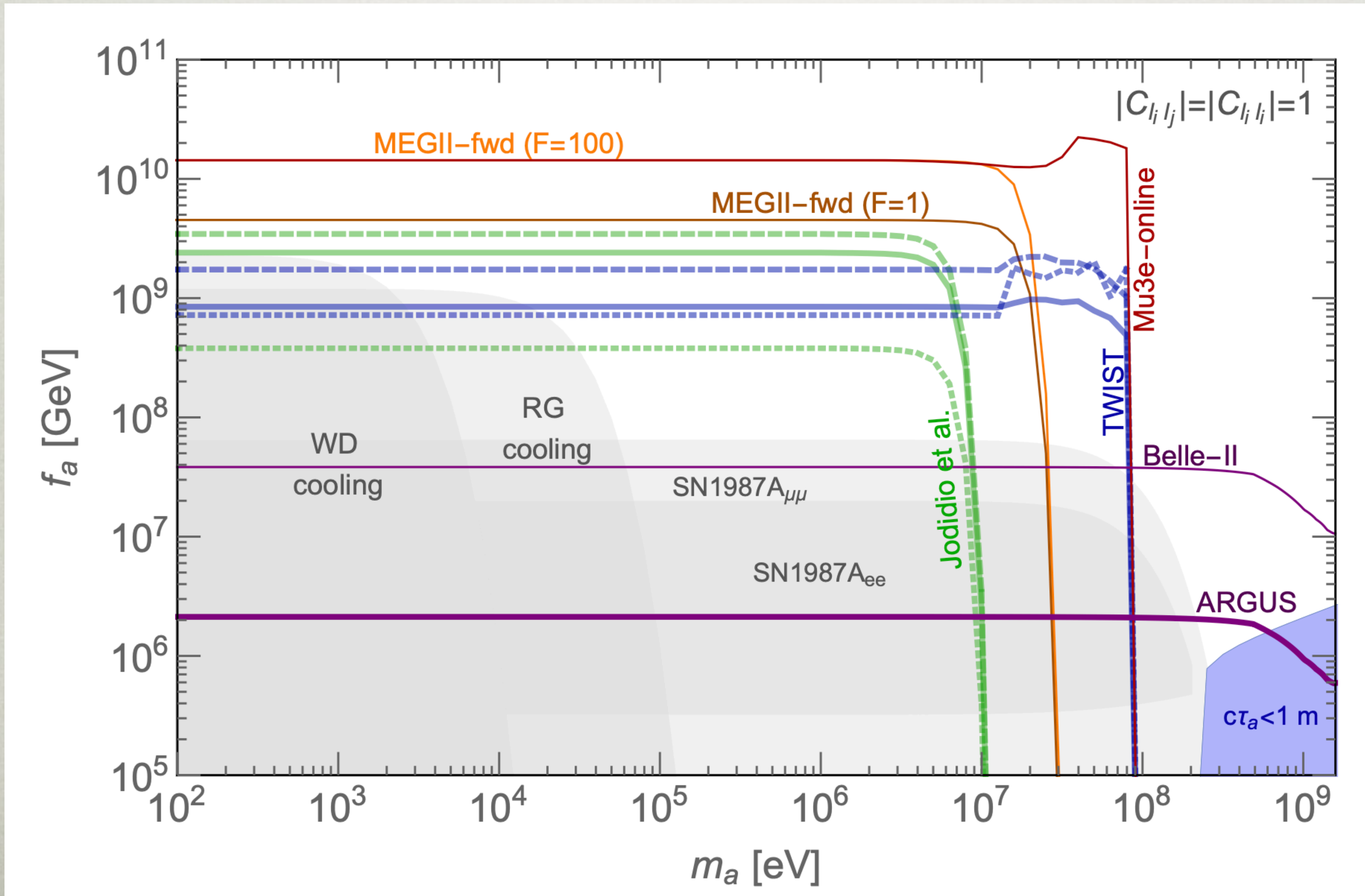
$$\sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu\text{eV}} \frac{\sqrt{m_i m_j}}{10^{12}\text{GeV}}$$

SEARCHING FOR AXIONS/ AXIFLAVONS



MEGII-fwd

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



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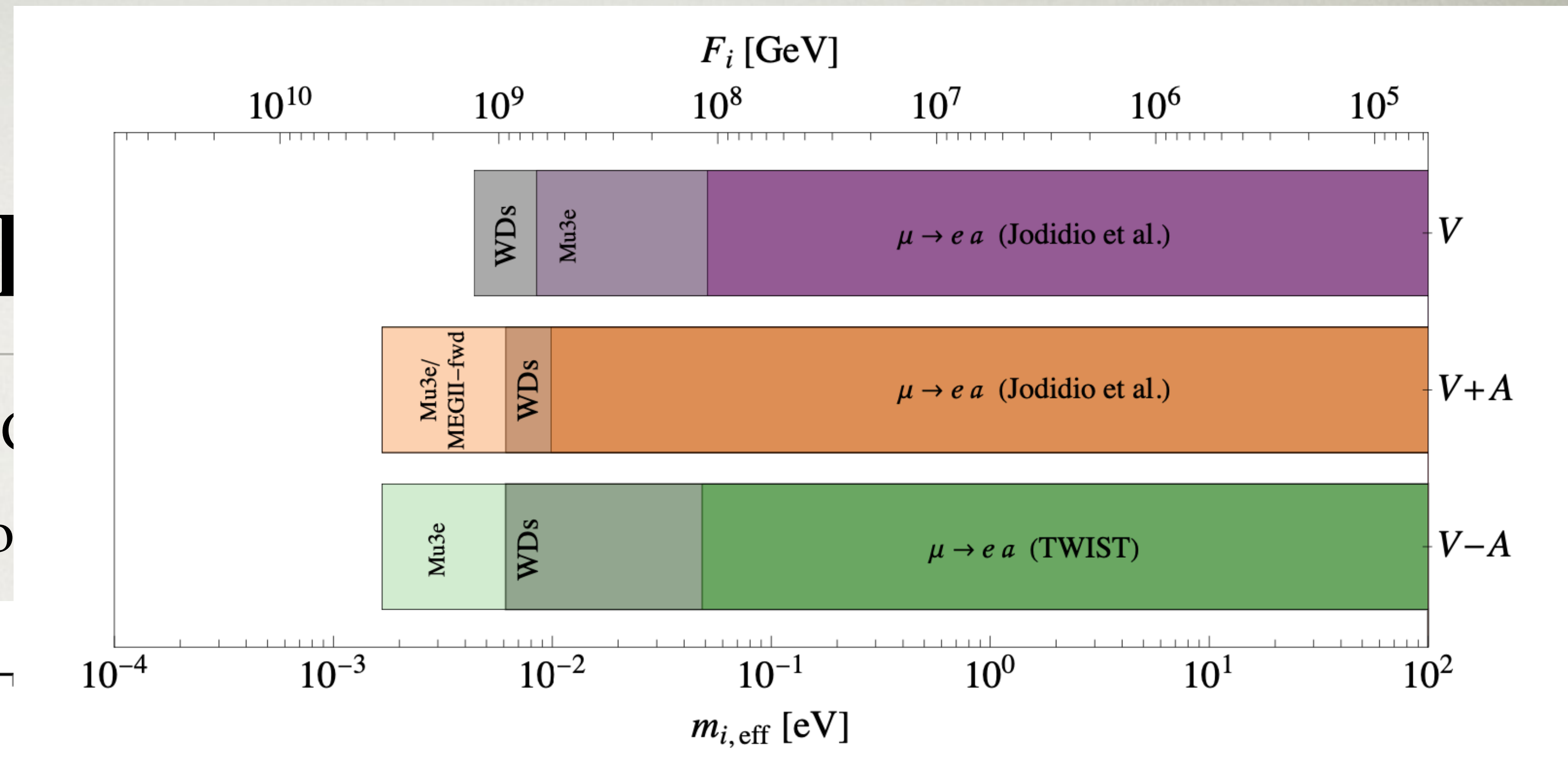

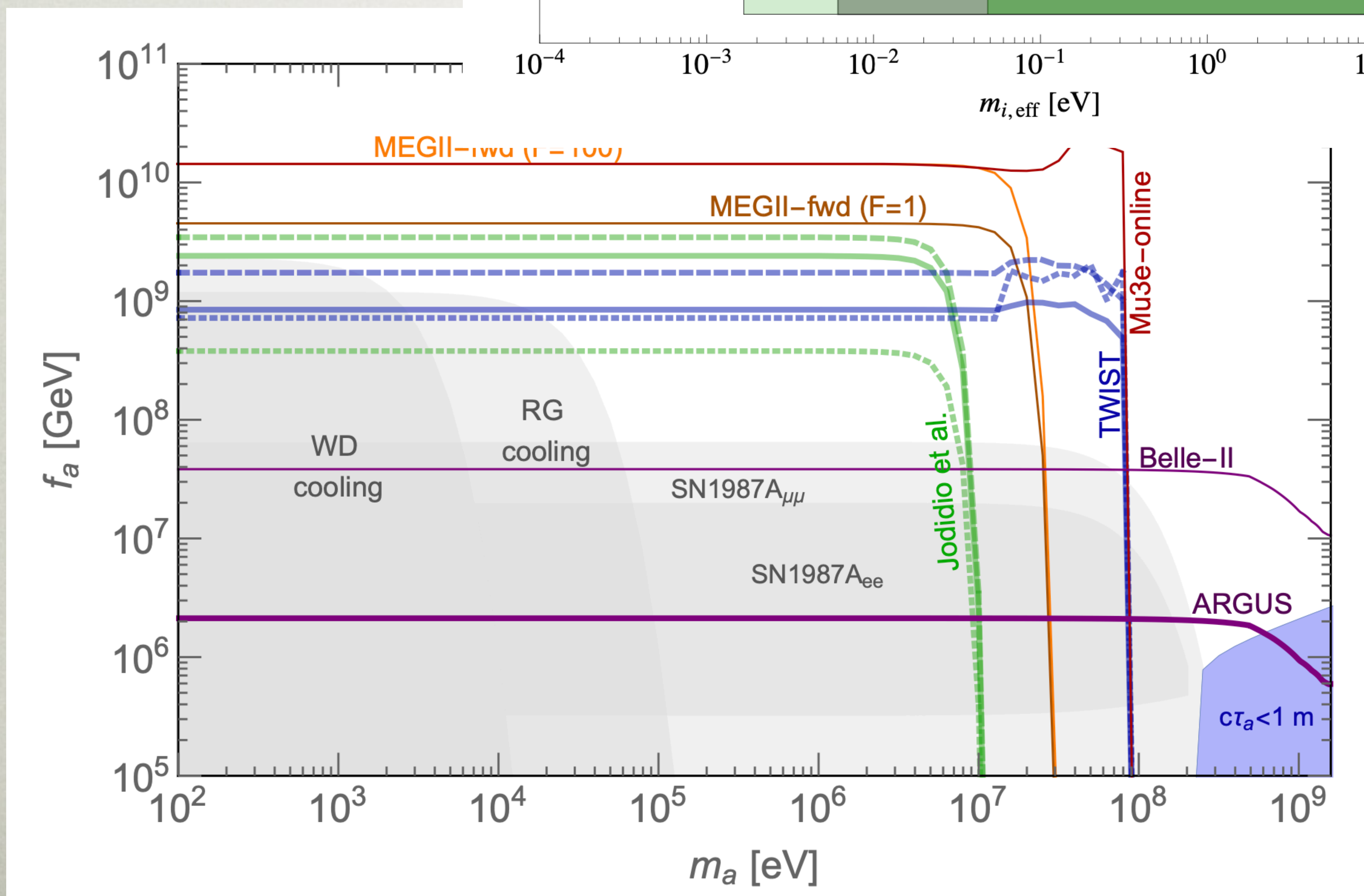

LFV ALP DARK MATTER

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

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

- 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

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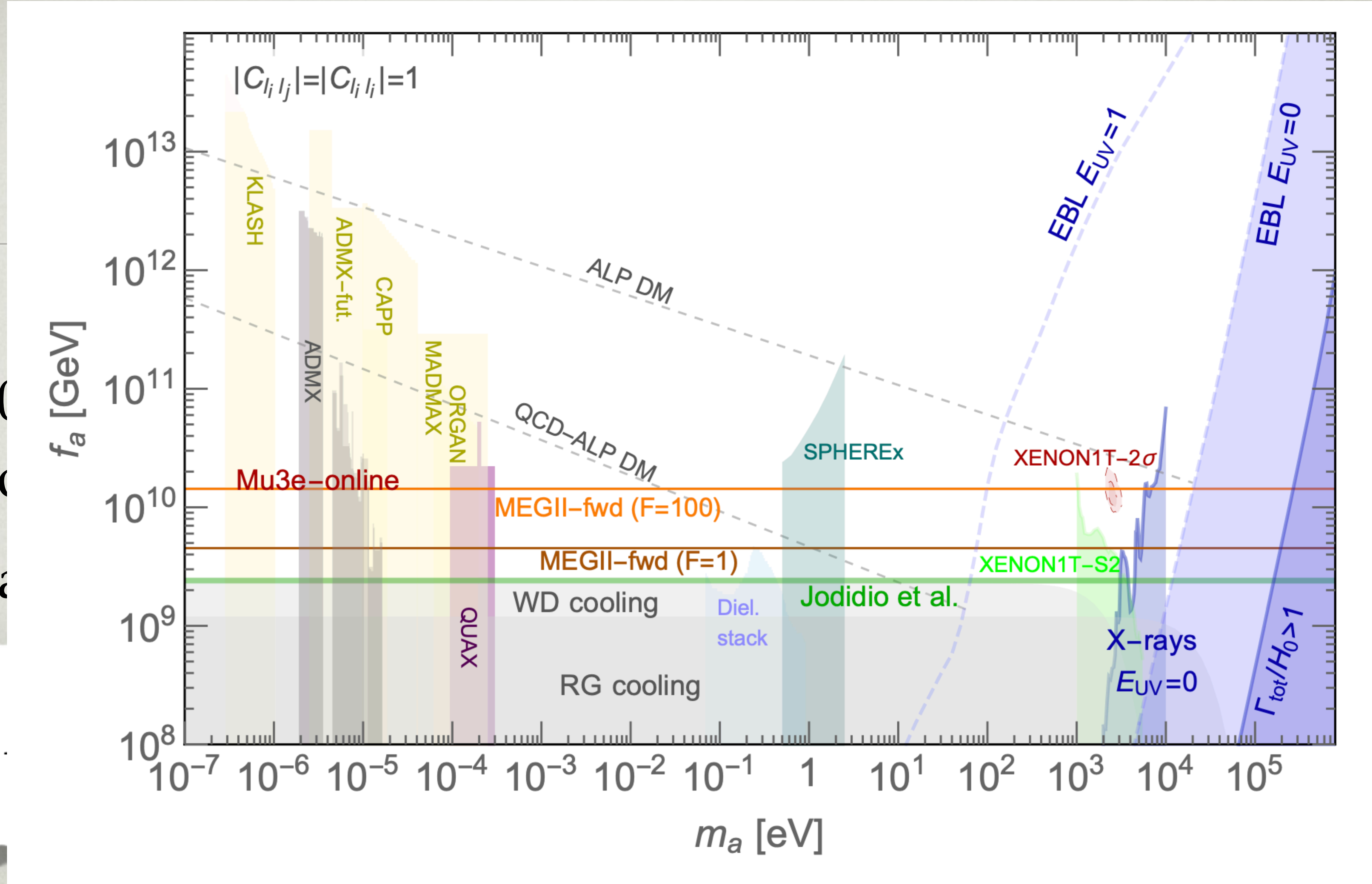
$$\frac{H_0}{\Gamma_{\rm tot}} = \ldots \Big)^2 .$$



• if ALP is observed in a LFV process ⇒ $m_a \lesssim 10$ keV

- LFV experiments most sensitive for some m_a
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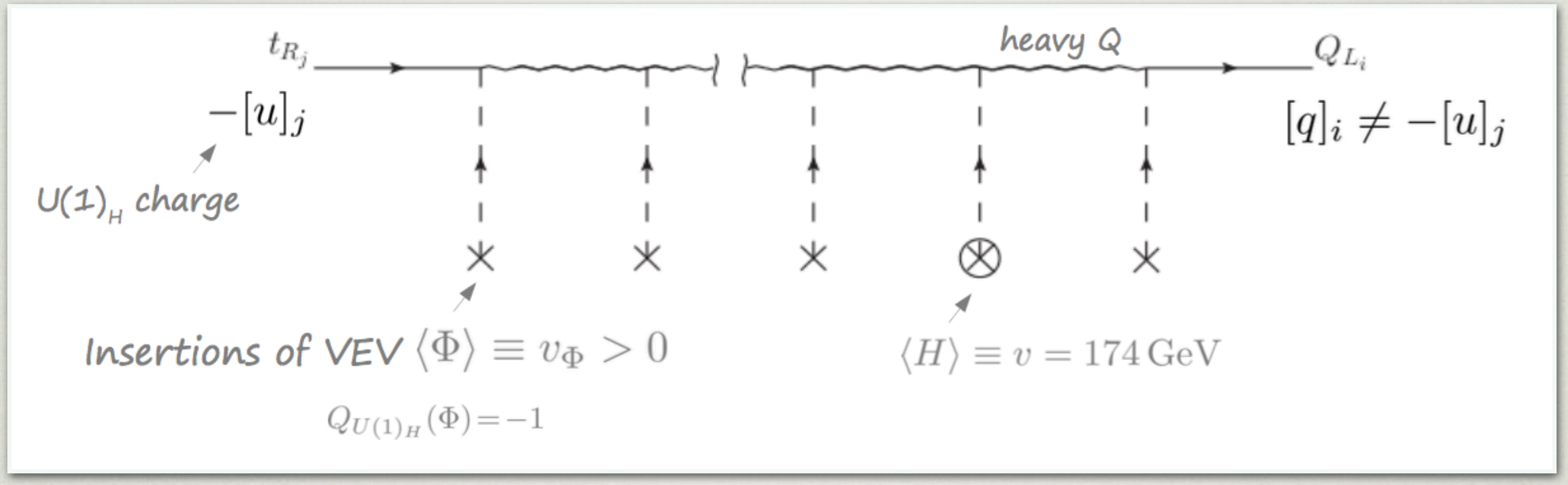
LIGHT NEW PHYSICS ⇒ PROBE OF HIGH SCALES

- 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: 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 θ
  - $\Rightarrow \Gamma(K \to \pi\varphi) \propto \theta^2 m_K \Rightarrow Br(K \to \pi\varphi) \propto \theta^2 (m_W/m_K)^4$
- 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
  - $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

Smolkovic, Tammaro, JZ, 1907.10063

ANOMALY FREE FN MODELS



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

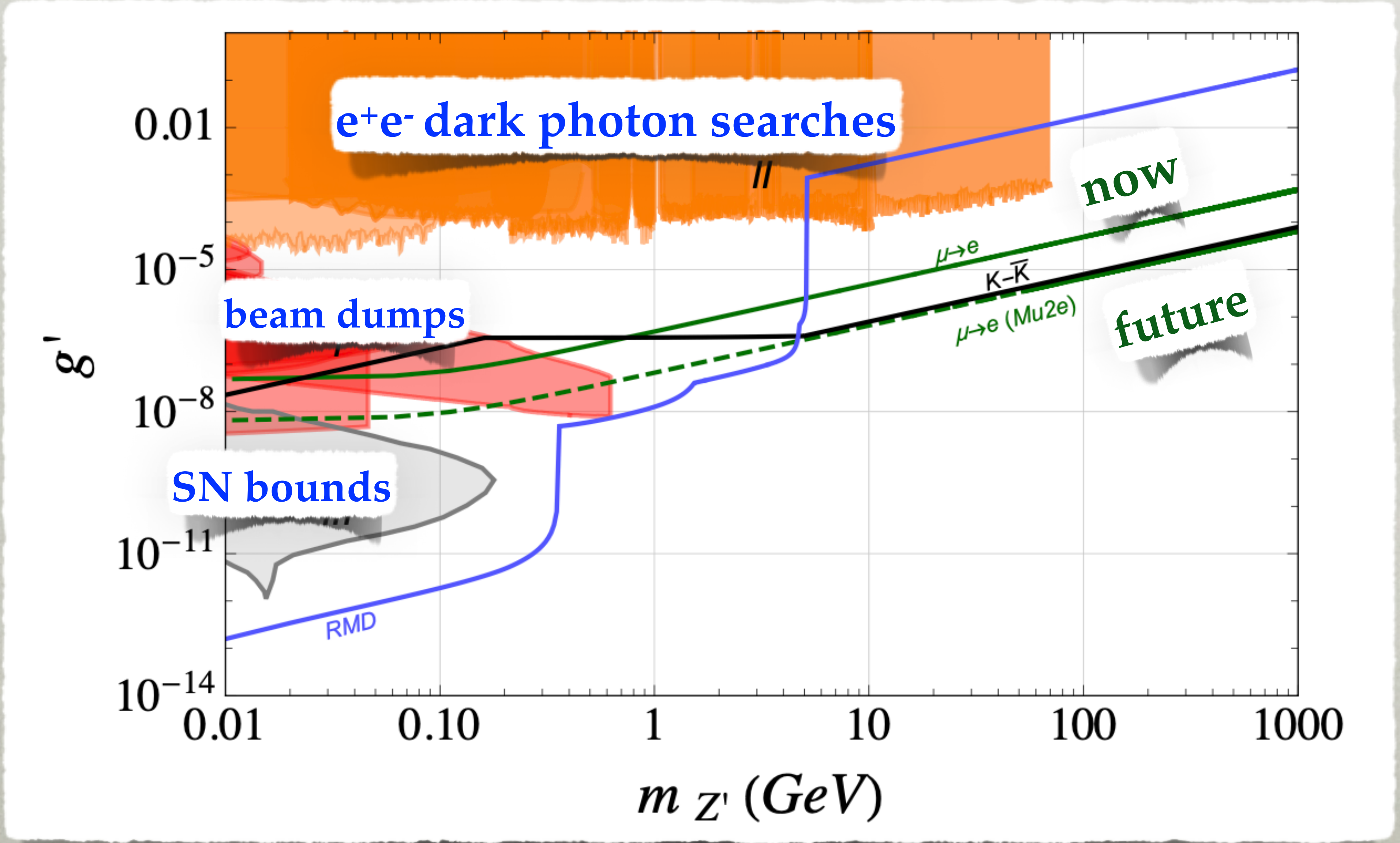
Smolkovic, Tammaro, JZ, 1907.10063

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

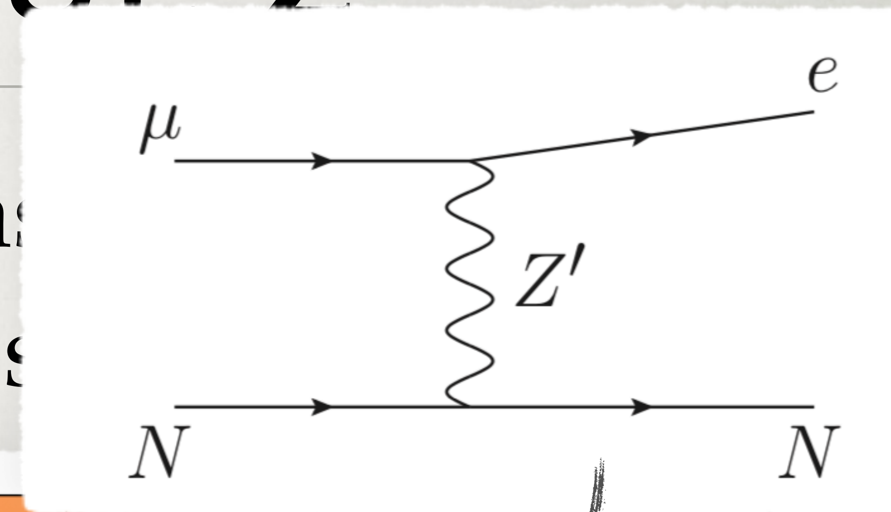
FLAVORFUL Z'

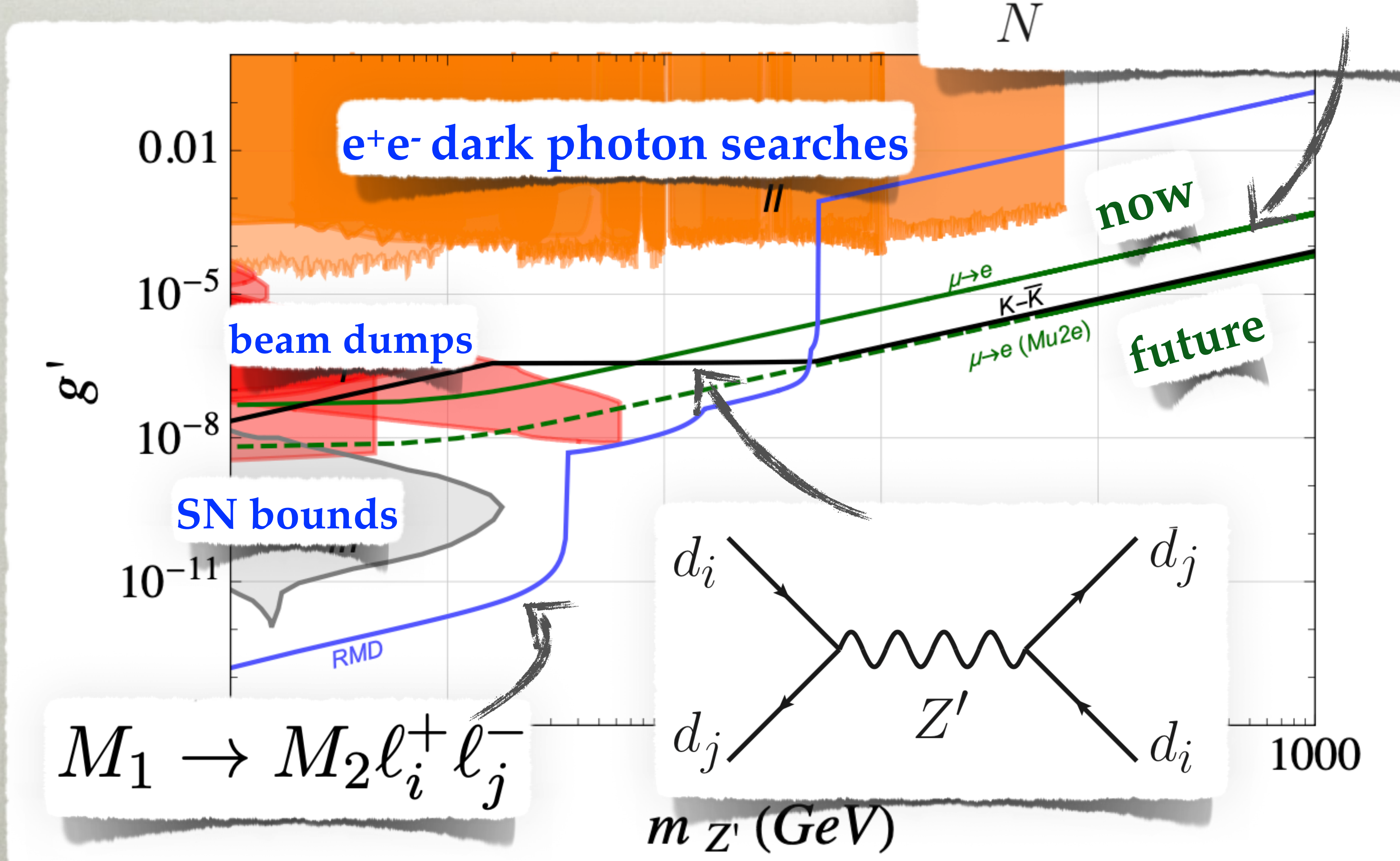
- for $U(1)_{FN}$ benchmark, assuming anarching neutrino mass from Weinber op.



FLAVORFUL Z'

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





LFV QCD axion

- DFSZ-like model: 2HDM+S: $X_S = 1, X_{H_2} = 2 + X_{H_1}$
- flavor universal $U(1)_{\rm PQ}$ charges in quark sector, non-universal in leptonic

Yukawa coupl. to H_1 | Yukawa coupl. to H_2

$$y_e = \begin{pmatrix} 0 & x & x \\ x & 0 & 0 \\ x & 0 & 0 \end{pmatrix}, \quad y_e' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x & x \\ 0 & x & x \end{pmatrix}$$

⇒ gives lepton FV coupl.s of axion

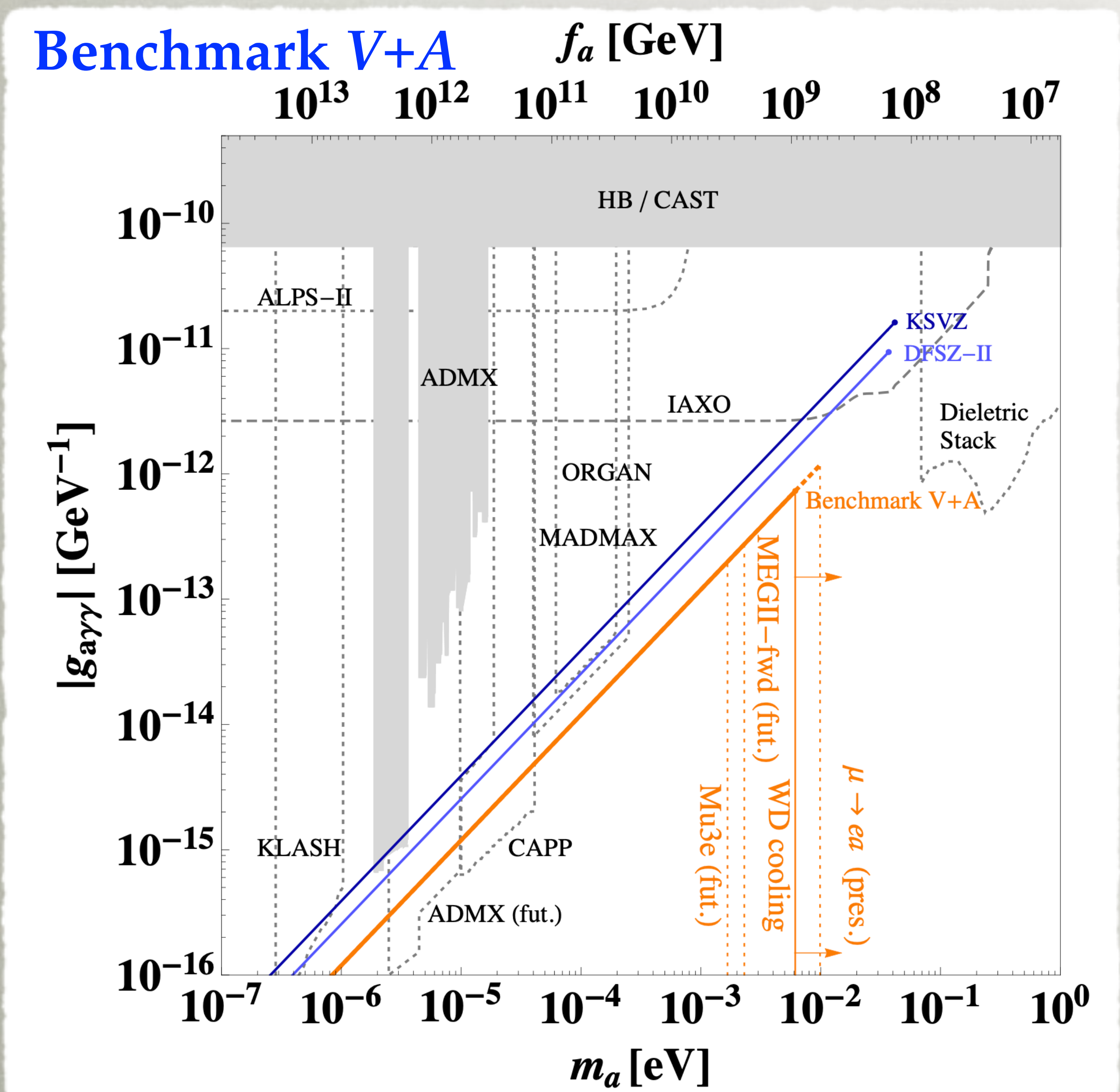
$$y_u = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}, \quad y_d = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

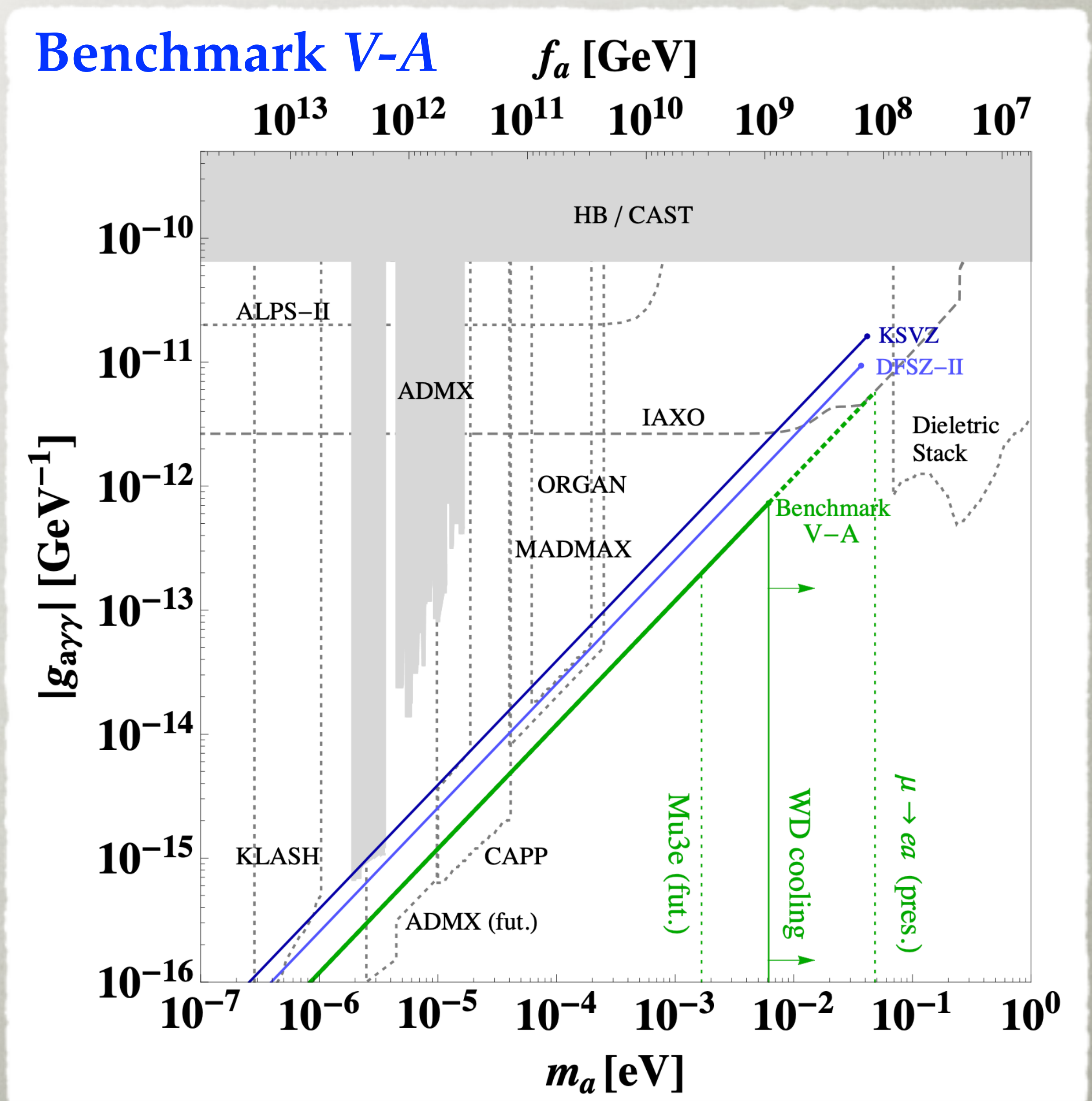
⇒ axion-quark couplings flavor diagonal

- hierarchy of entries external input

LFV QCD axion

- two benchmarks, assume just 1-2 mixing





LEPTONIC FAMILON

- separate Froggatt-Nielsen U(1) for quarks and leptons
  - leptonic f_a scale assumed lighter ⇒ these couplings dominate

$$([L]_1,\, [L]_2,\, [L]_3) \;=\; (L,\, L,\, L), \qquad \texttt{[Pure Anarchy]}\,.$$

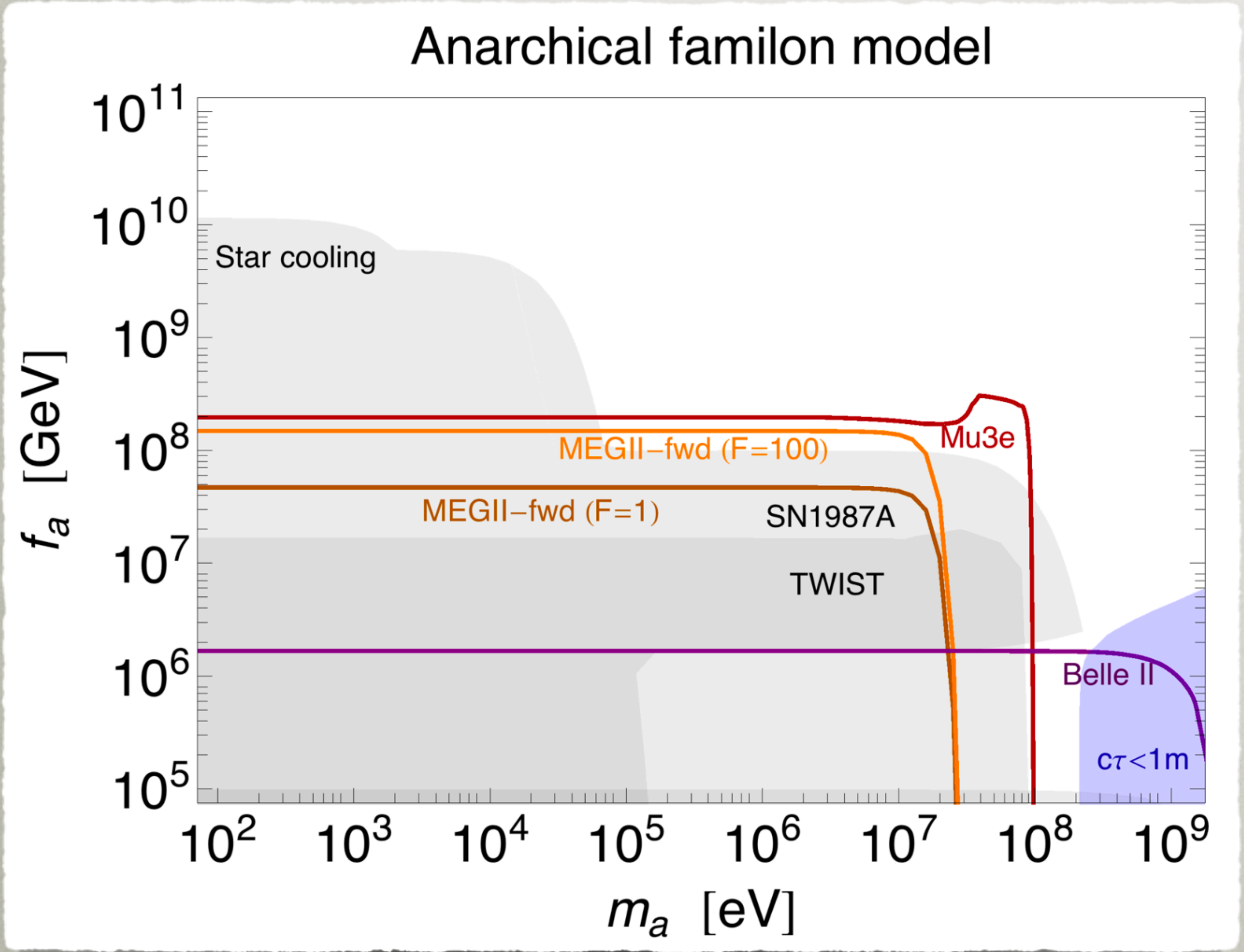
⇒ RH ALP

- two benchmark charge assignments

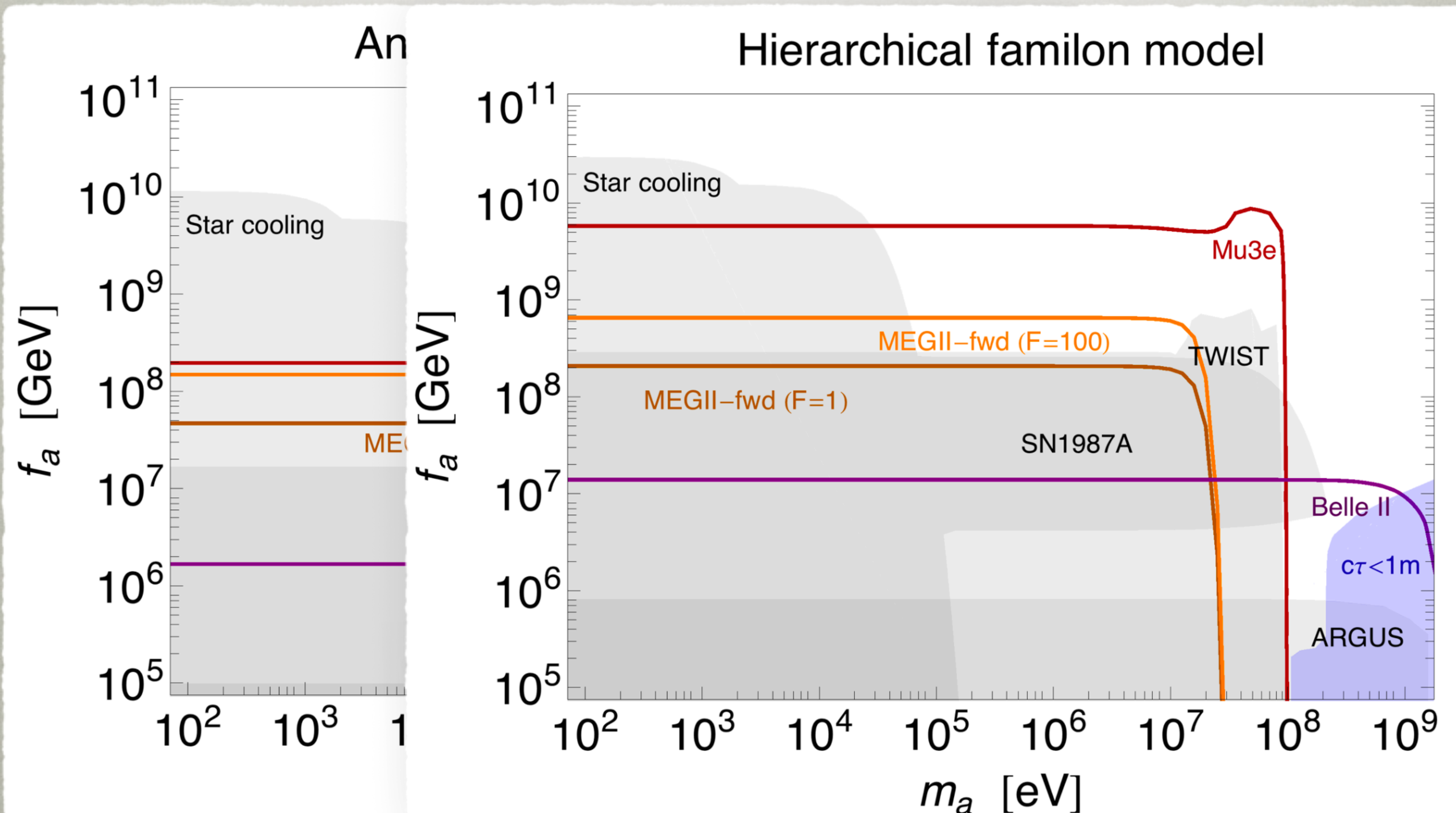
$$([L]_1,\, [L]_2,\, [L]_3) \;=\; (L+2,\, L+1,\, L), \qquad \texttt{[Hierarchy]}\,.$$

⇒ LH and RH couplings

LEPTONIC FAMILON

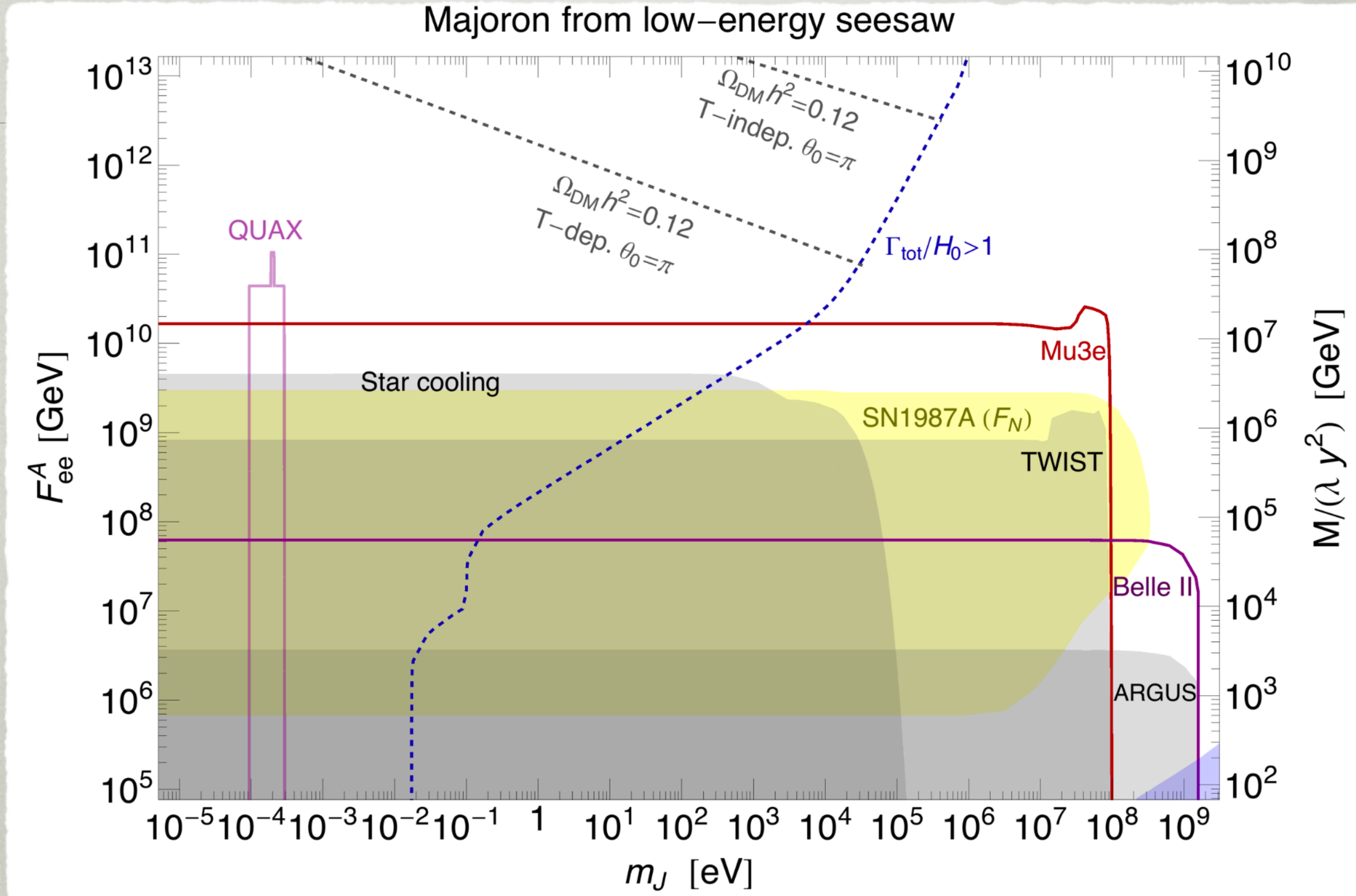


LEPTONIC FAMILON



MAJORON

- majoron- PNGB due to spontaneous breaking of the lepton number
- neutrino masses $m_\nu \propto y_\nu y_\nu^T v^2/m_N$
- majoron couplings, $C_{ij} \propto y_\nu y_\nu^\dagger$
- if m_ν suppressed by global U(1)
  - $\Rightarrow$ majoron observable
  - "low energy see-saw"

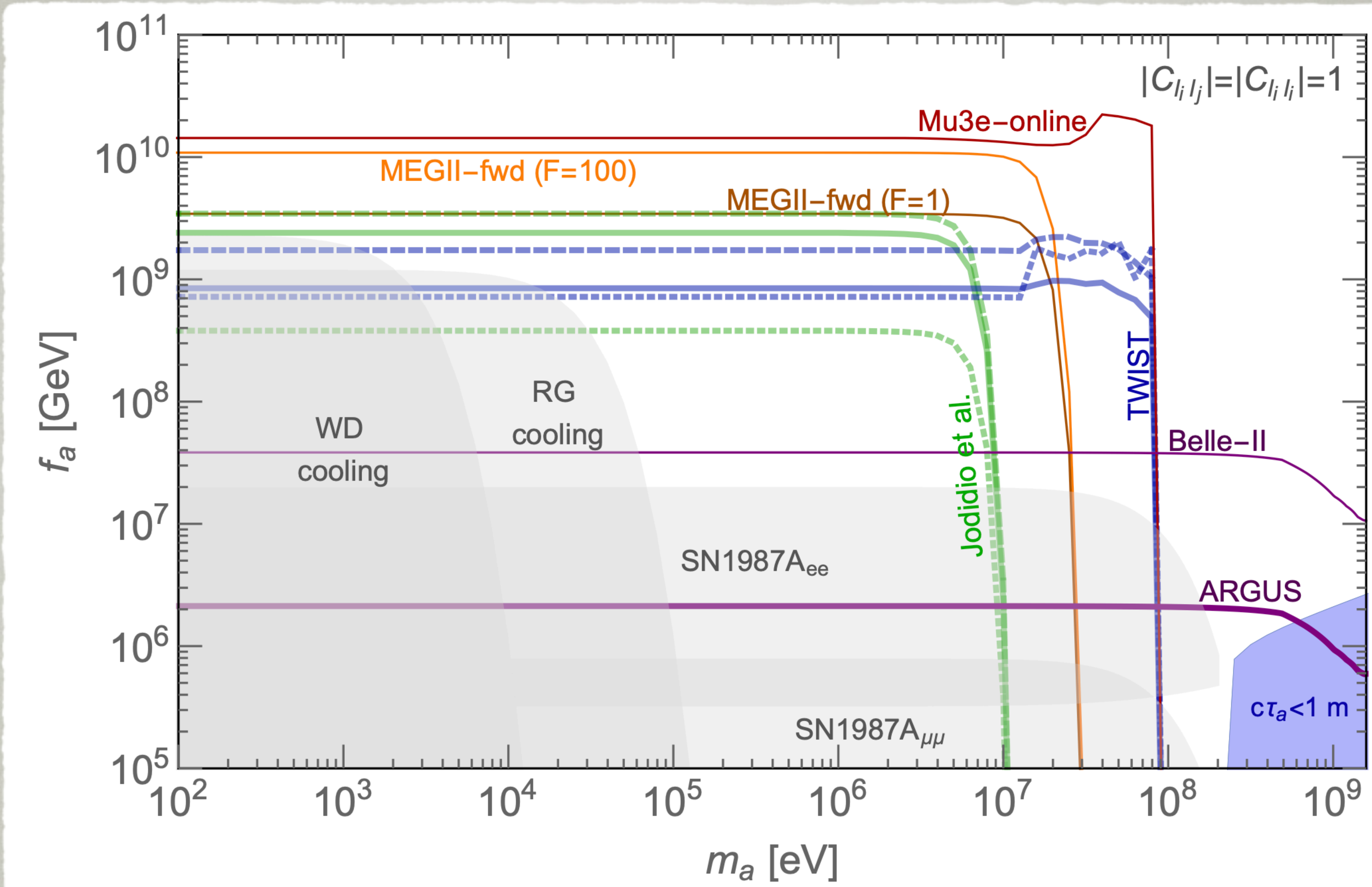


- "low energy see-saw"

ASTROPHYSICS BOUNDS

Raffelt, Weiss , hep-ph/9410205

- bounds on massless ALP-electron from red giants and white-dwarf cooling well known
  - due to $e^- + N \to e^- + N + a$
  - rescaled to nonzero ALP masses
- above $m_a \gtrsim 0.1$ MeV SN bounds become important
- also bounds on couplings to muons, but less severe



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- also bounds on couplings to muons, but less severe

CONNECTION TO BARYOGENESIS

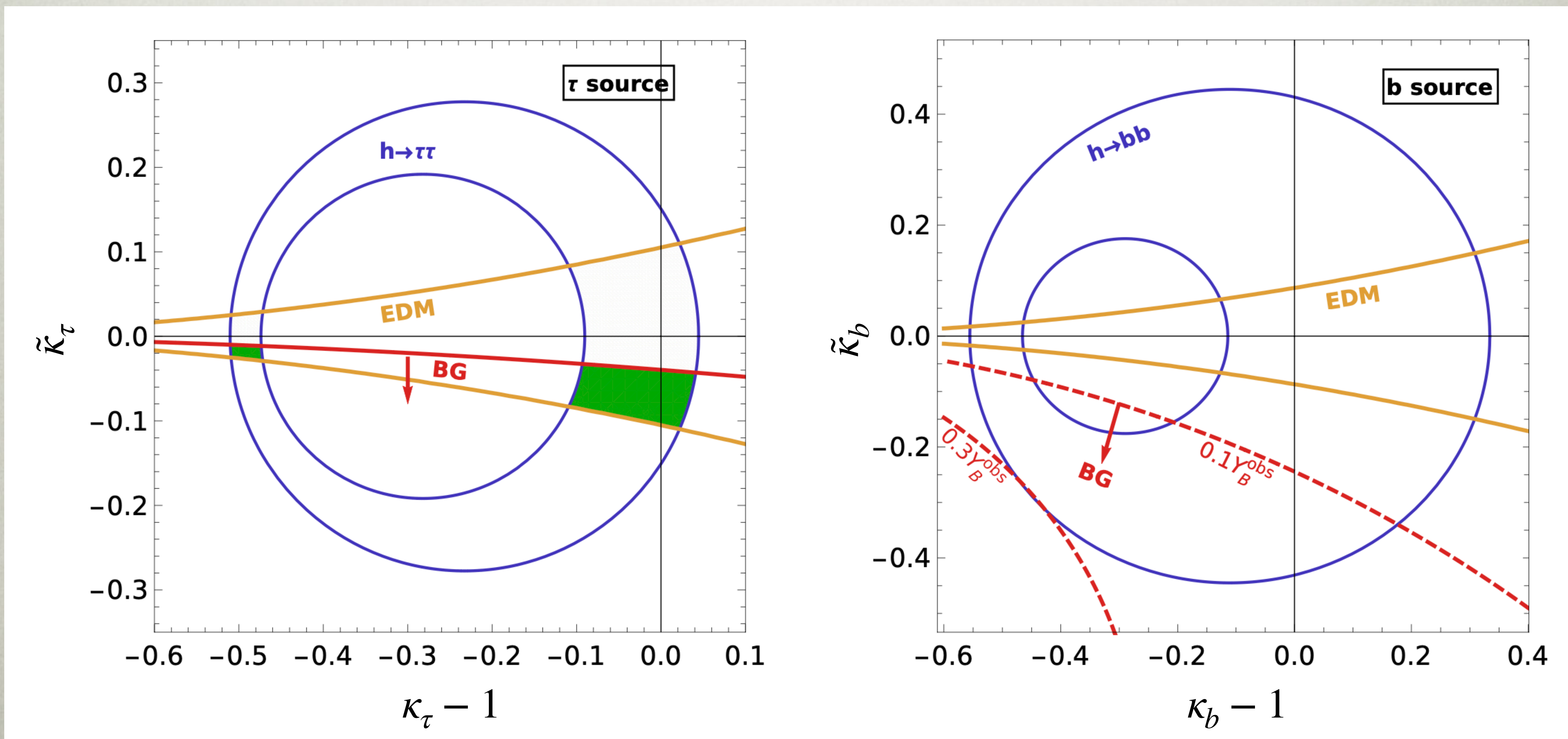
Fuchs, Losada, Nir, Viernik, 1911.08495, 2003.00099

- if EW baryogenesis assumed to be dominated by dim 6 Yukawas
  - $\Rightarrow$ lower limit on CPV Yukawas, κ_f
- additional assumptions:
  - there are additional d.o.f.s that give strongly first-order EWPT
  - these do not change SM fermion interact. in the bubble wall
  - no other (relevant) sources of CPV
- tau $\tilde{\kappa}_\tau \neq 0$ can explain EWBG, but not top or bottom
  - reduced wash-out since no strong sphalerons for tau lepton
  - large lepton diffusion coeffs. lead to efficient diffusion of baryon assmymetry intto the broke phase
  - overcompensate the smaller τ-Yukawa coupling

CONNECTION TO BARYOGENESIS

Fuchs, Losada, Nir, Viernik, 2003.00099

- $\tilde{\kappa}_\tau \sim 0.01 - 0.1$ required for successful EWBG
- corresponds to $\Lambda/\sqrt{\lambda'_{\tau\tau}} \lesssim 18\ \text{TeV}\sqrt{0.01/\tilde{\kappa}_\tau}$

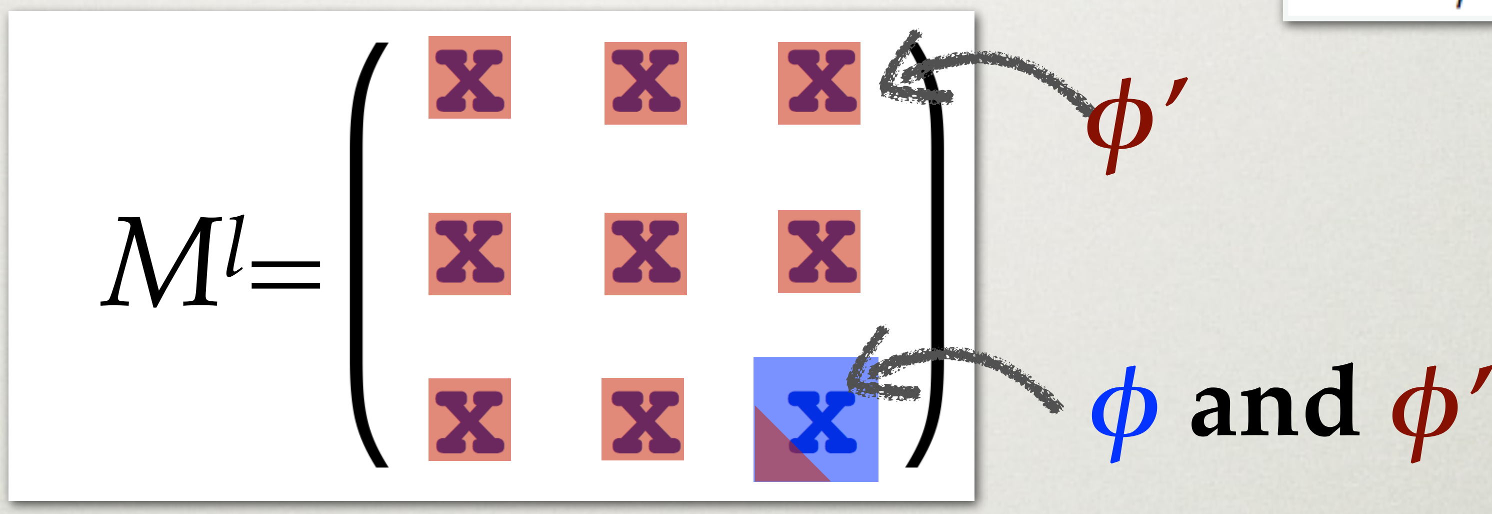


Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

2HDM example: sequestered mass generation

- two Higgs doublets, neutral compts: ϕ, ϕ',vevs v, v'
  - ϕ couples to 3rd family, ϕ' to all three

$$\tan\beta = v/v'$$

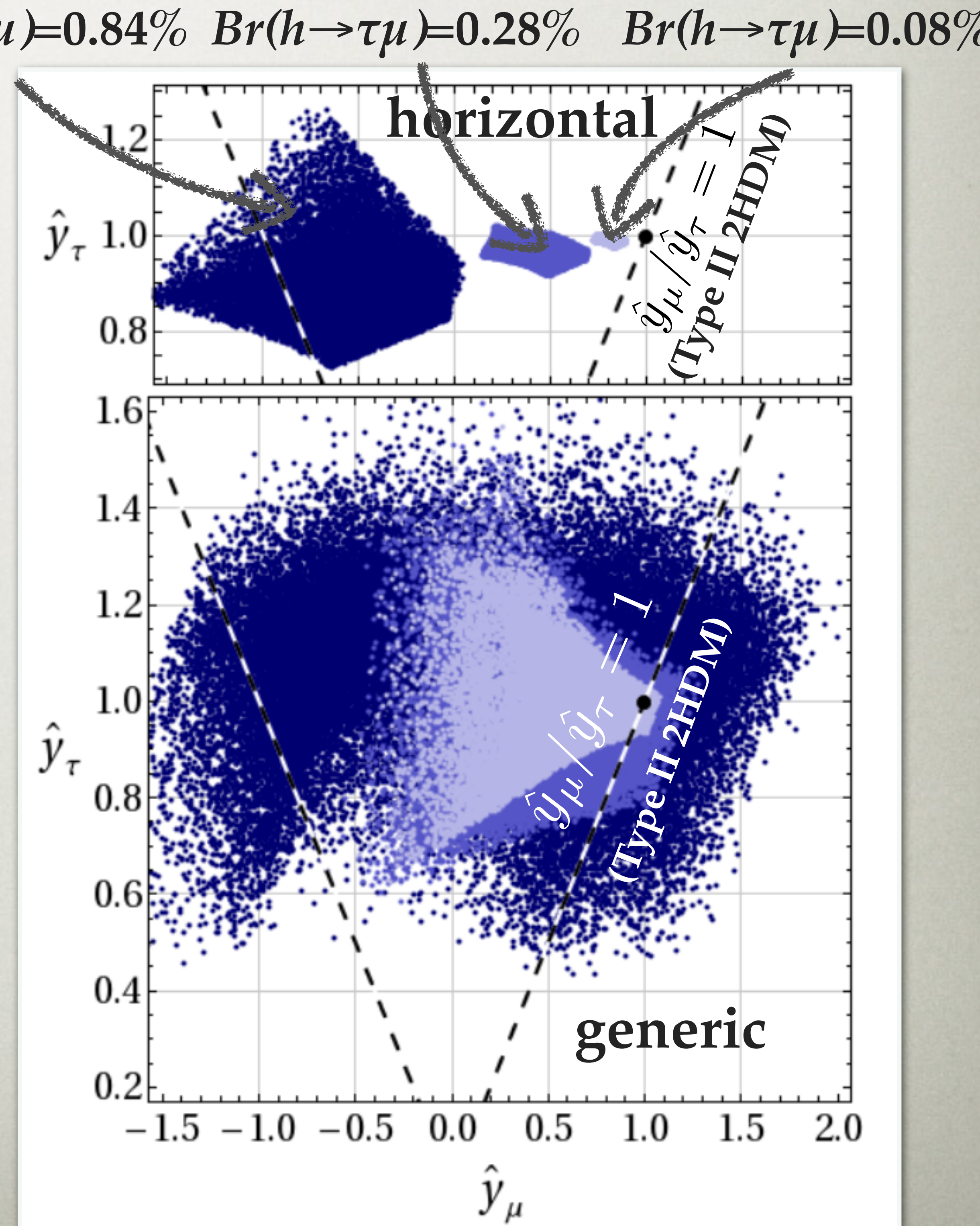


  - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- consider two flavor structures for ϕ' contribs. to M^l
  - *"horizontal"*: only off-diagonal entries nonzero
  - *"generic"*: all m_{ij}' nonzero

DIAGONAL YUKAWAS

- scanning over mass matrix entries and imposing:
  - that m_μ, m_τ are eigenvalues
  - the heavy Higgs xsec bounds
- ratios $\kappa_\mu < 1$ and $\kappa_\mu/\kappa_\tau < 1$ favored
- sizeable flavor violating $Br(h \to \tau\mu)$

CMS: $Br(h \to \tau\mu) < 0.15\,\%$



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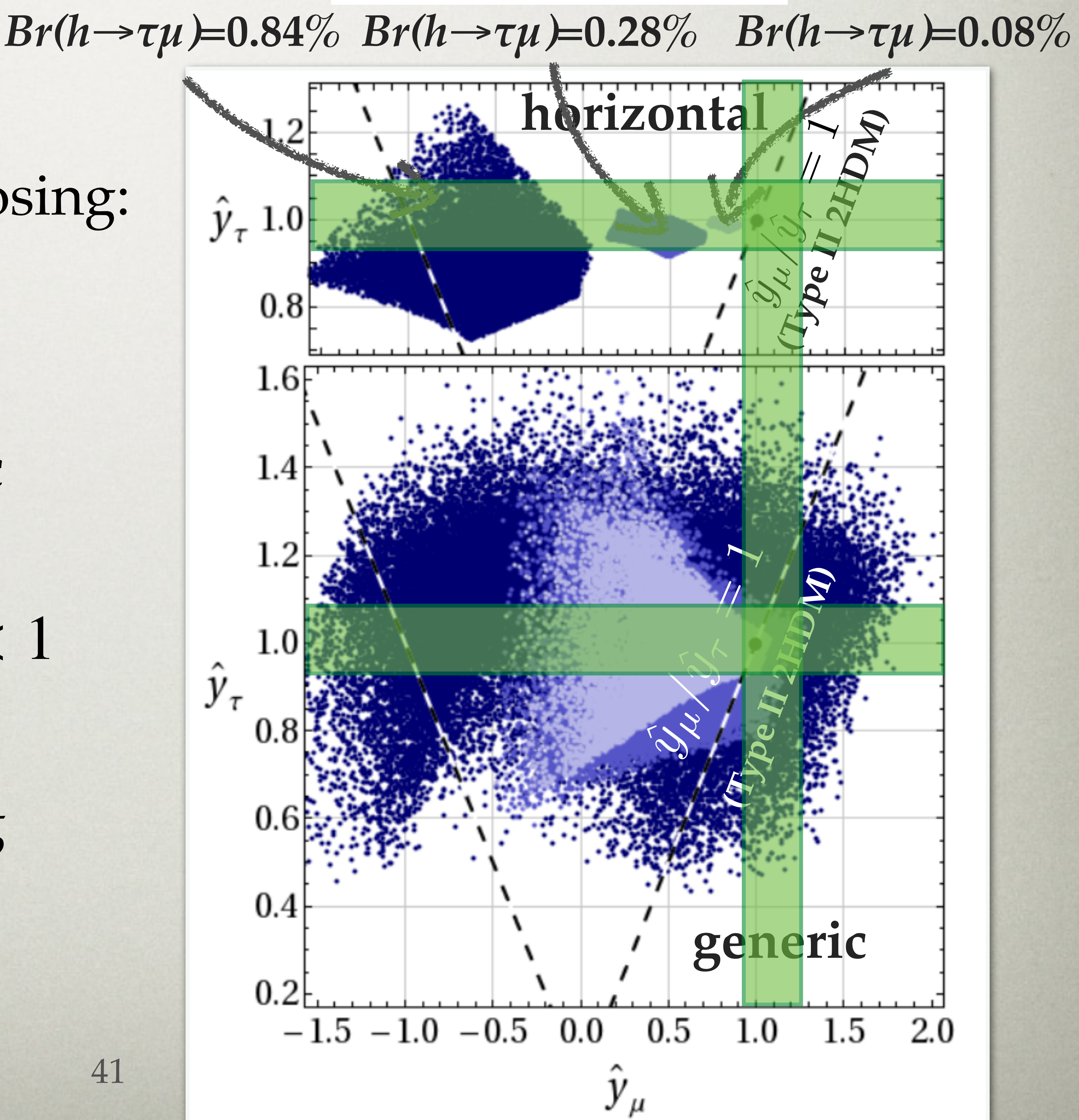


MAGNETIC AND ELECTRIC DIPOLE MOMENTS

- two flavor diagonal dimension 5 operators

$$\mathcal{L}_{\rm eff} \supset -\frac{e a_\ell}{4 m_\ell}\left(\bar{\ell}\sigma^{\mu\nu}\ell\right)F_{\mu\nu} - \frac{d_\ell}{2}\left(\bar{\ell}\sigma^{\mu\nu}i\gamma_5\ell\right)F_{\mu\nu}$$

- anomalous magnetic moment $(g-2)_\ell = 2a_\ell$
  - CP conserving
  - SM value nonzero
- electric dipole moment d_ℓ
  - CP violating
  - SM value highly suppressed

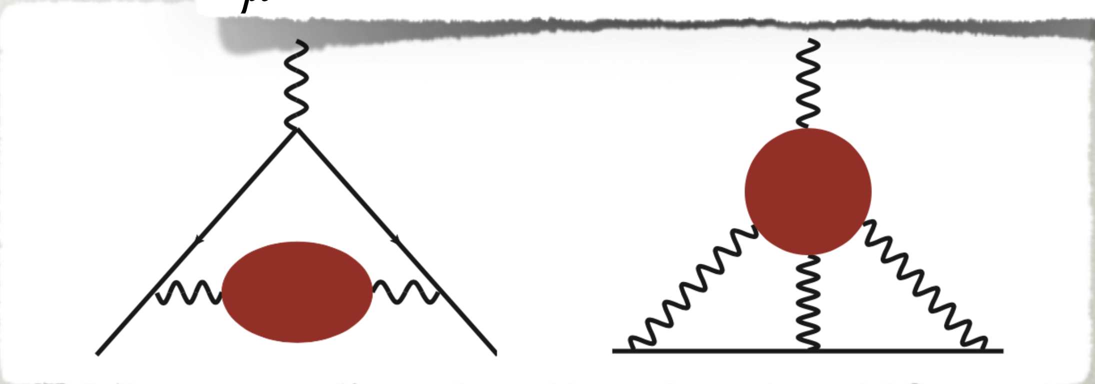
POSSIBLE DEVIATION IN $(g-2)_\mu$

- the value of $(g-2)_\mu$ from g-2 coll.

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-10}$$

$$a_\mu^{\rm SM} = 116591810(43) \times 10^{-10}$$

- the SM theory error dominated by hadronic uncert.



QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)

The muon g-2 theory initiative, 2006.04822

IF NEW PHYSICS...

- $(g-2)_\mu$ showing 4.2σ deviation from the SM
    - in SMEFT from dim6 operator

$$\mathcal{L} \supset -\frac{\sqrt{2} e\, v}{(4\pi\Lambda_{ij})^2}\, \bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu} + \text{h.c.}\ ,$$

$$(g-2)_\mu \Rightarrow \Lambda_{22} \sim 15\,\text{TeV}$$

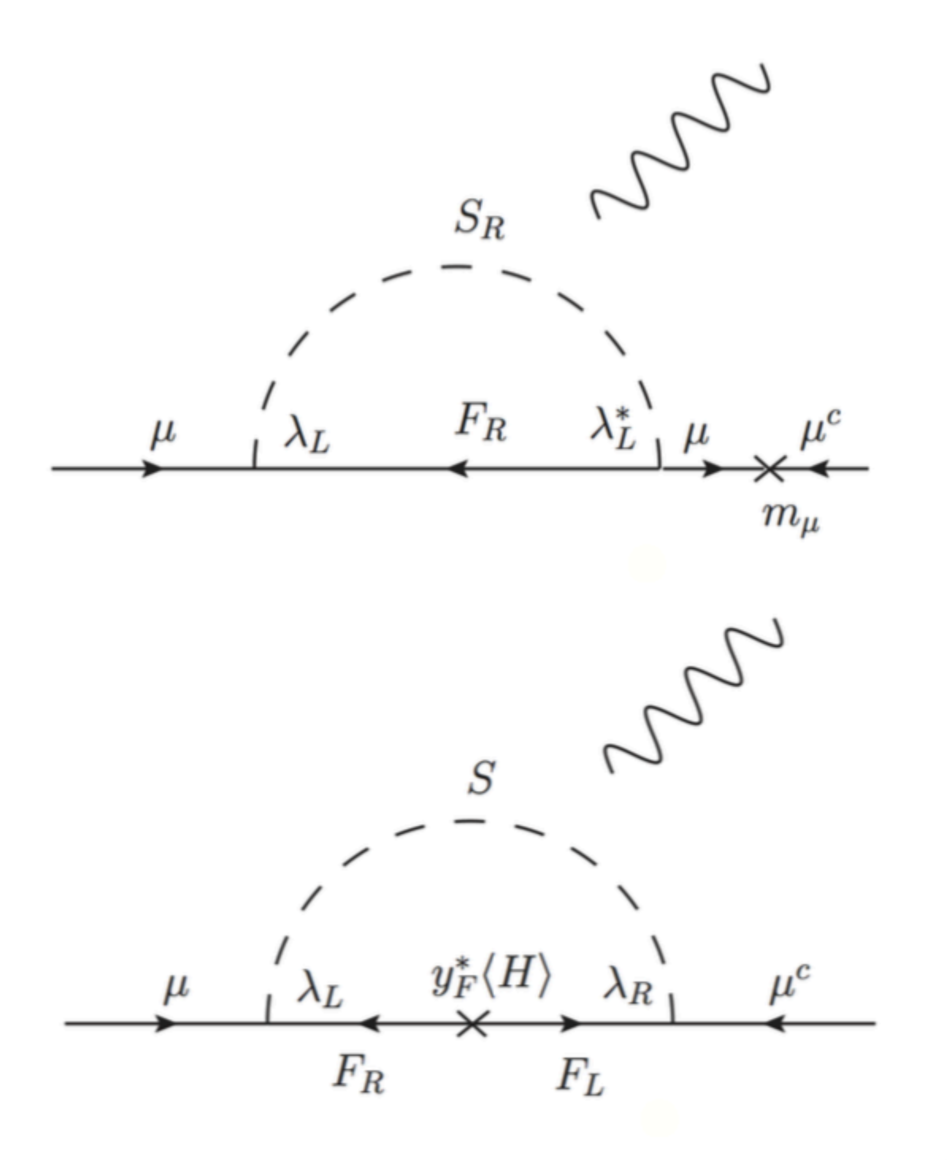
- note: any flavor violation needs to be highly suppressed $\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\text{TeV}$ Greljo, Stangl, Thomsen, 2103.13991
- a possible (natural) solution - a symmetry
    - a phenomenologically viable example: $L_\mu - L_\tau$

$(g-2)_\mu$ NEW PHYSICS MODELS

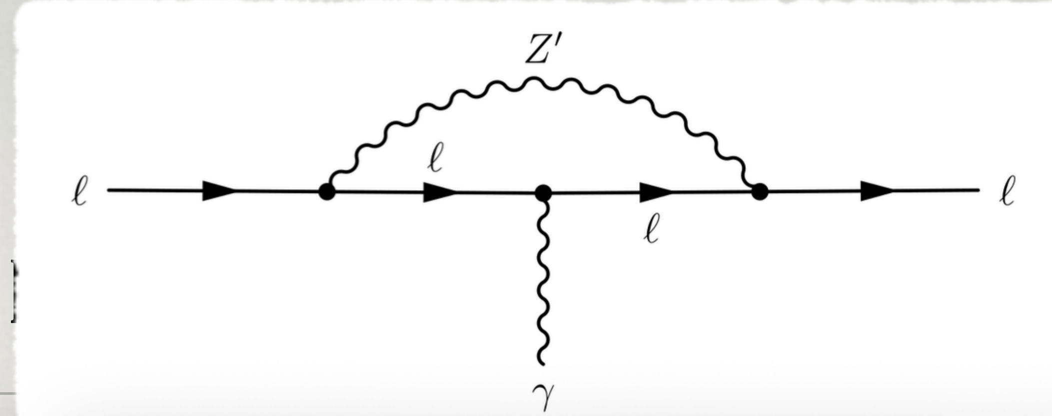
$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-10}$

$$\frac{e}{8\pi^2}(\bar\mu\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

- NP models of two types
- chirality flip on SM fermion leg
  - NP need to be light, example: Z' from $L_\mu - L_\tau$
- chirality flip can be on the NP fermion leg
  - NP can be much heavier
  - example: minimal models with DM

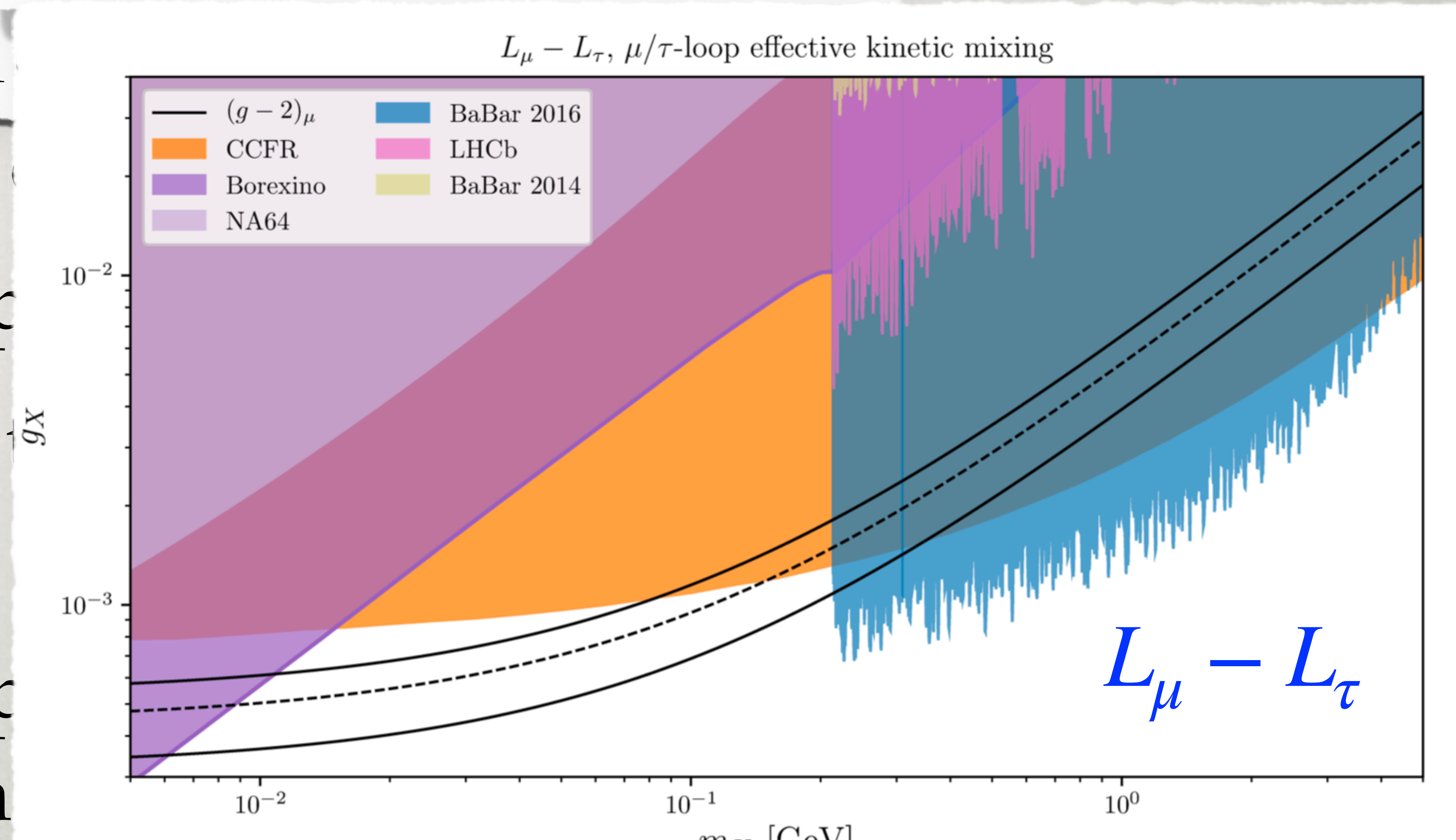


$(g-2)_\mu$ ... ODELS

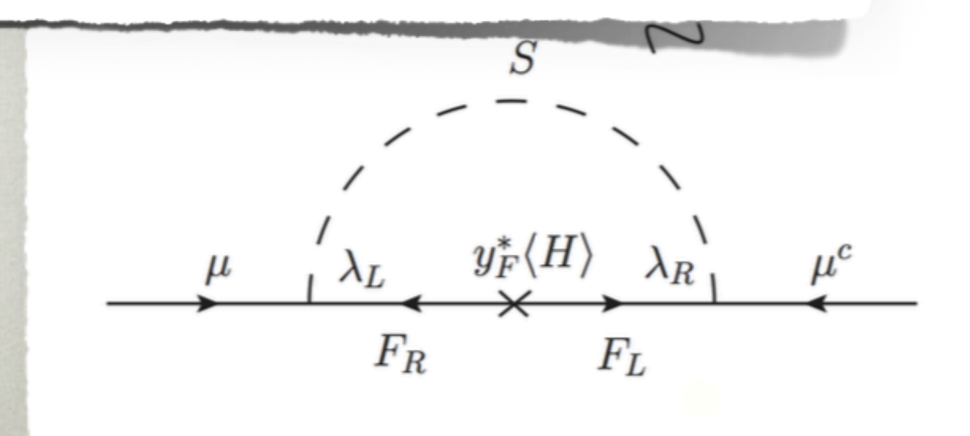


$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251$ ...

- NP models ...
- chirality flip ...
  - NP need ...
    example: ...
- chirality flip ...
  NP fermion ...
  - NP can be much heavier
  - example: minimal models with DM



Greljo et al, 2203.13731



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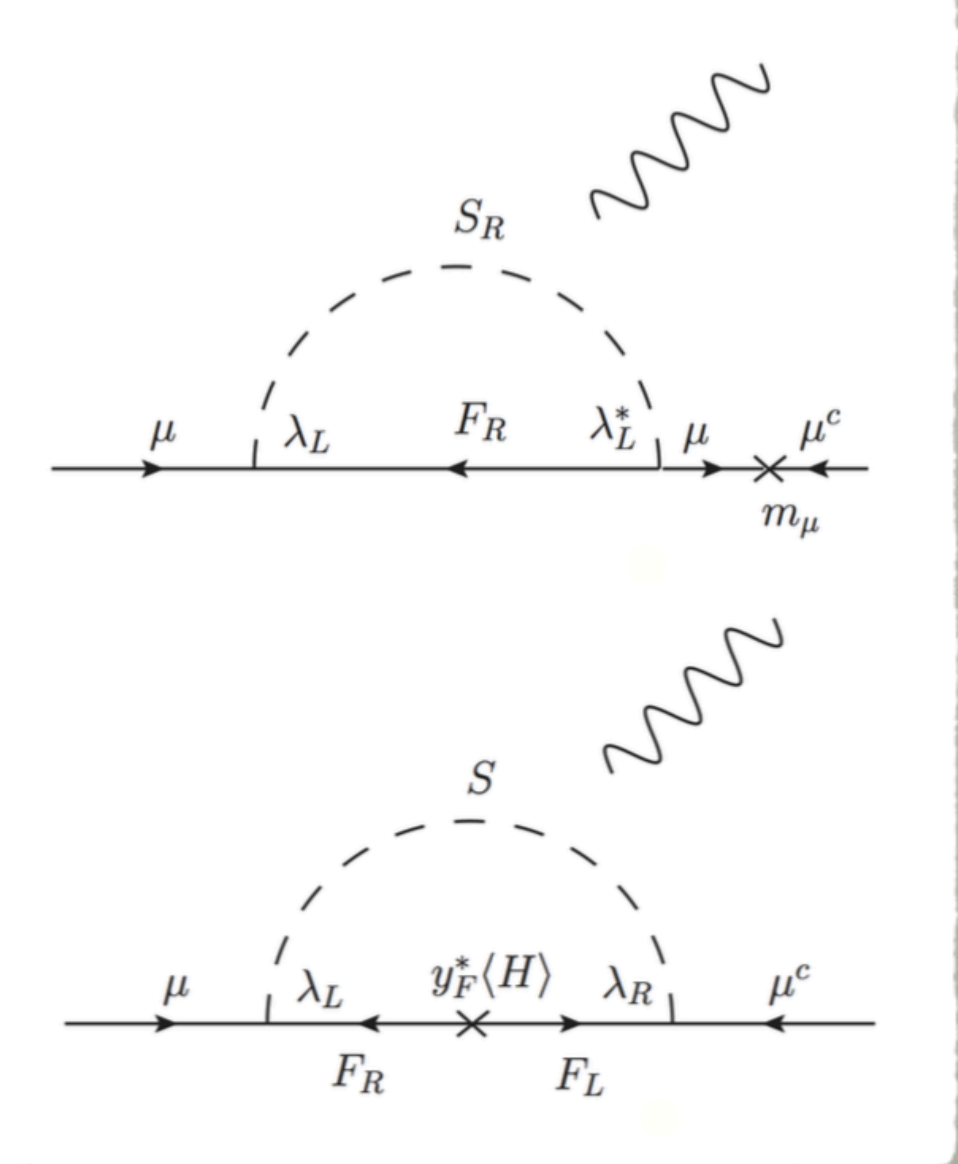

$(g-2)_\mu$ NEW PHYSICS MODELS

exp SM 251(59) $\times 10^{-10}$

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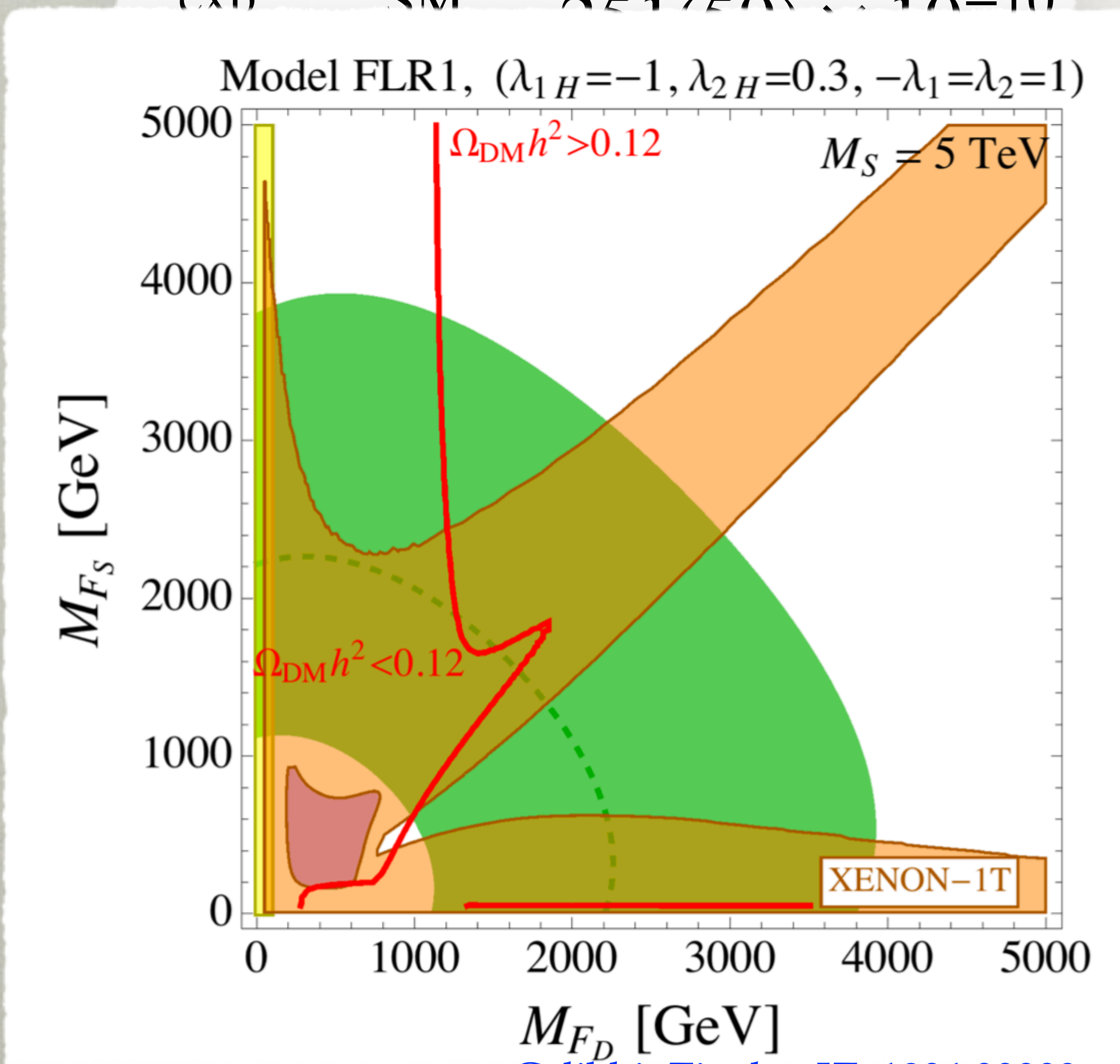
ion leg

L_τ

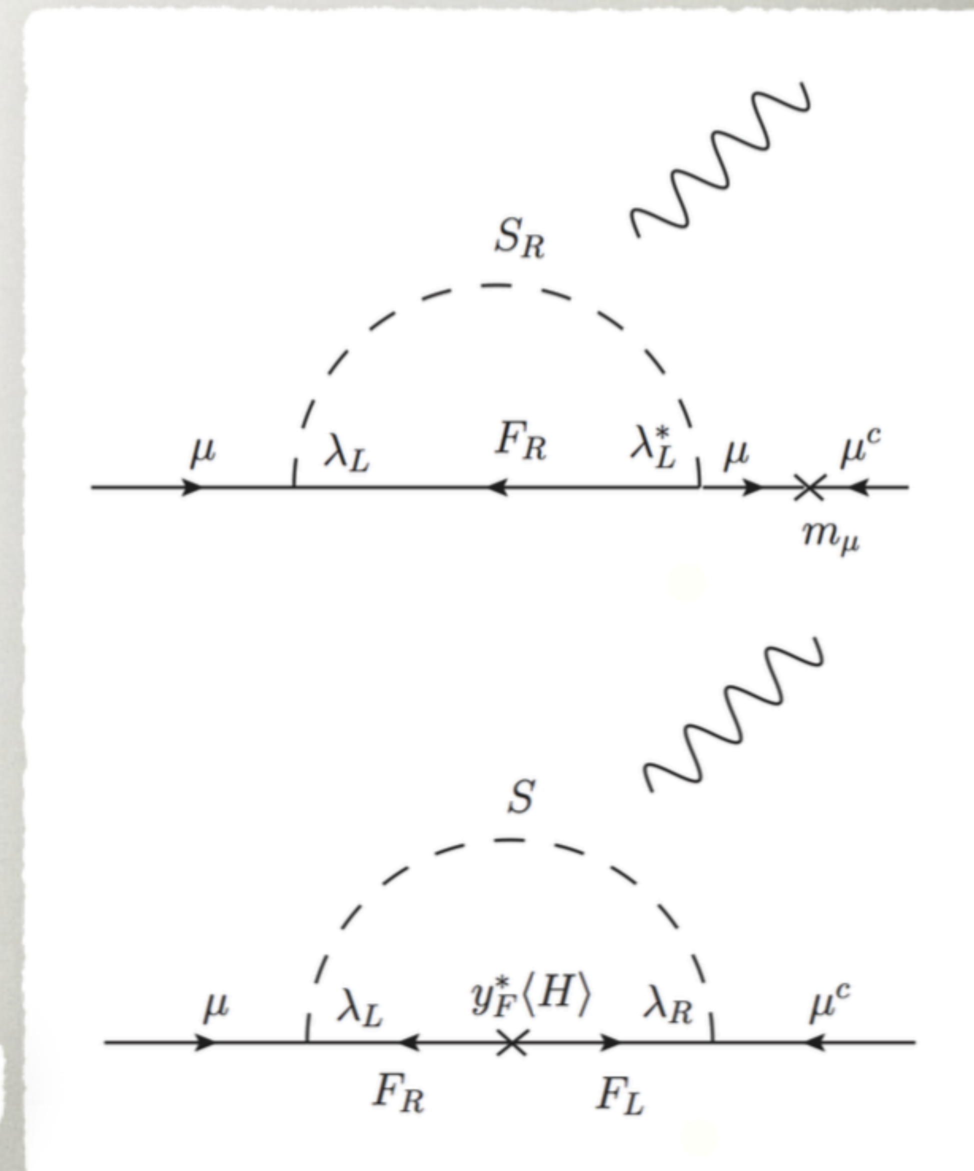
e

er

dels



Calibbi, Ziegler, JZ, 1804.00009

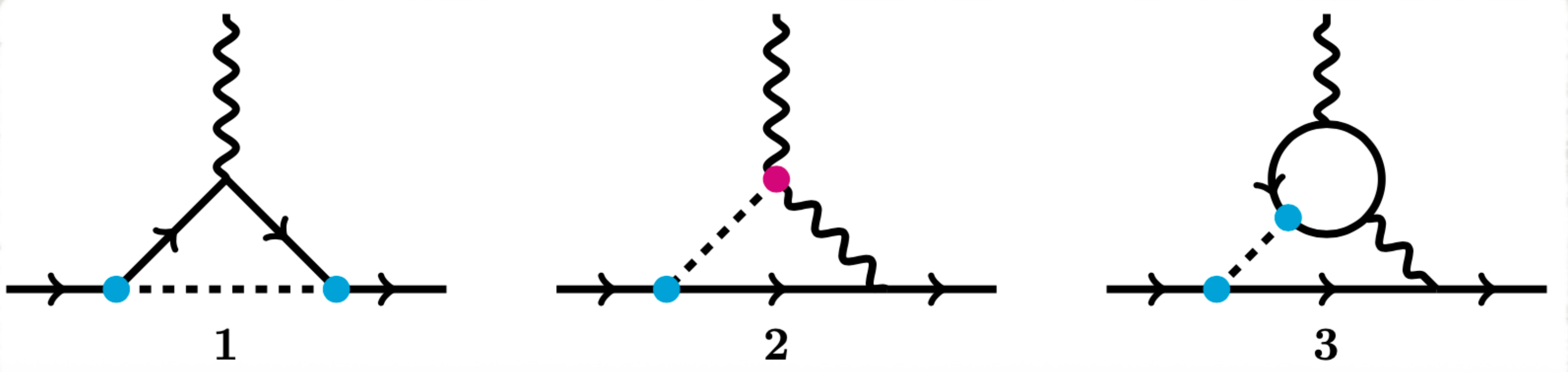


$F_S \equiv F_R \sim 1_0, \quad F_D \equiv F_L \sim 2_{-1/2}, \quad F_D^c \equiv F_L^c \sim 2^*_{1/2}, \quad S \equiv S_R \sim 2_{1/2},$

Buen-Abad, Fan, Reece, Sun, 2104.03267

FLAVOR DIAGONAL ALP?

- ALP coupling to muons gives wrong sign contrib. to Δa_μ

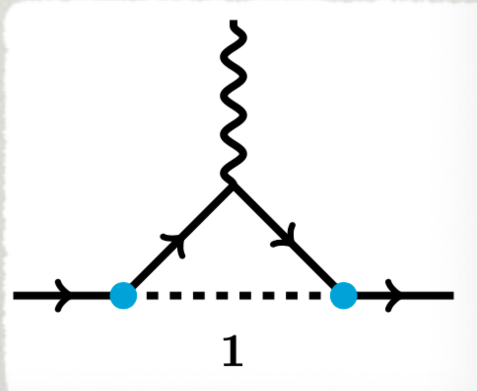


$$\Delta a_\mu^{(1)} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \quad \Delta a_\mu^{(2)} \propto -\frac{c_{\mu\mu}c_{\gamma\gamma}\alpha}{16\pi^3}, \quad \Delta a_\mu^{(3)} \propto -\frac{c_{\mu\mu}c_{ii}\alpha}{16\pi^3},$$

  - need to compensate with $aF\tilde{F}$ coupling at 1-loop, and with 2-loop contribs
  - the scale required to explain Δa_μ anomaly low, $f_a \sim 100\,\mathrm{GeV}$
  - difficult model building
- note: at the same order, $1/f_a^2$, expect other contribs. to a_μ from UV

FLAVOR

- ALP coupling to muon



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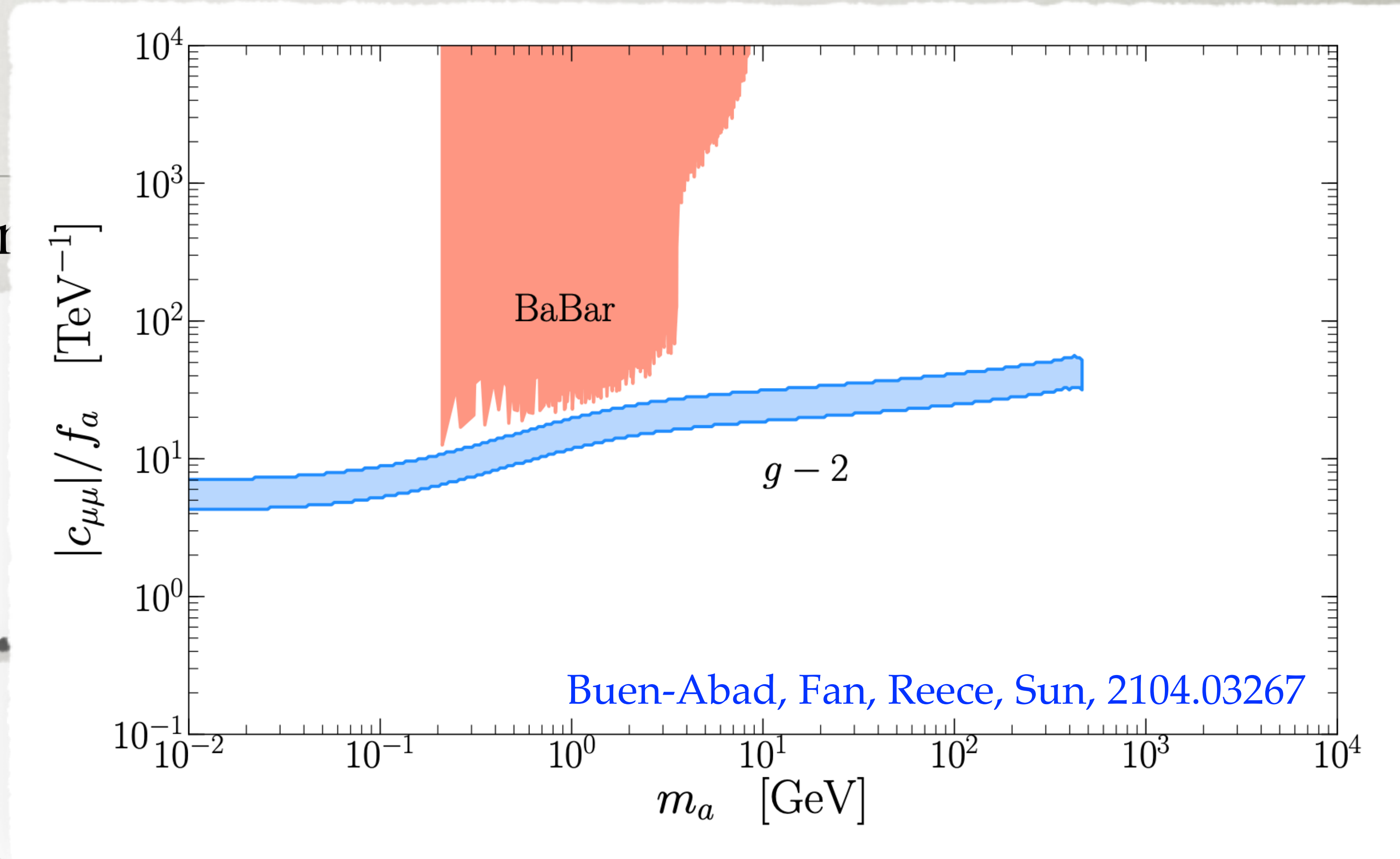

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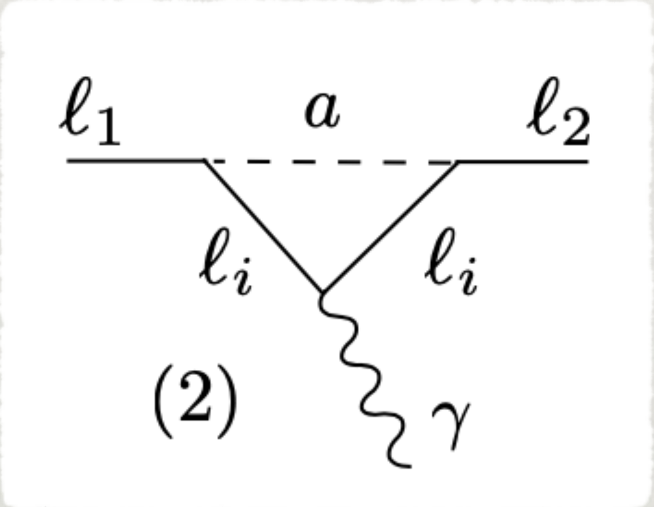
Bauer, Neubert, Renner, Schnubel, Thamm, 1908.00008

FLAVOR VIOLATING ALP FOR $(g-2)_\mu$

- FV coupling $c^A_{e\mu}$ gives the right sign of Δa_μ for $m_a > m_\mu$

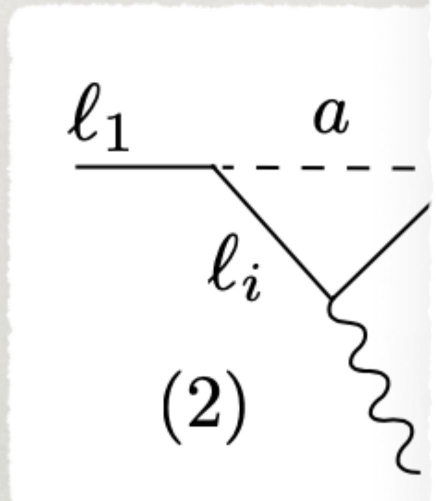


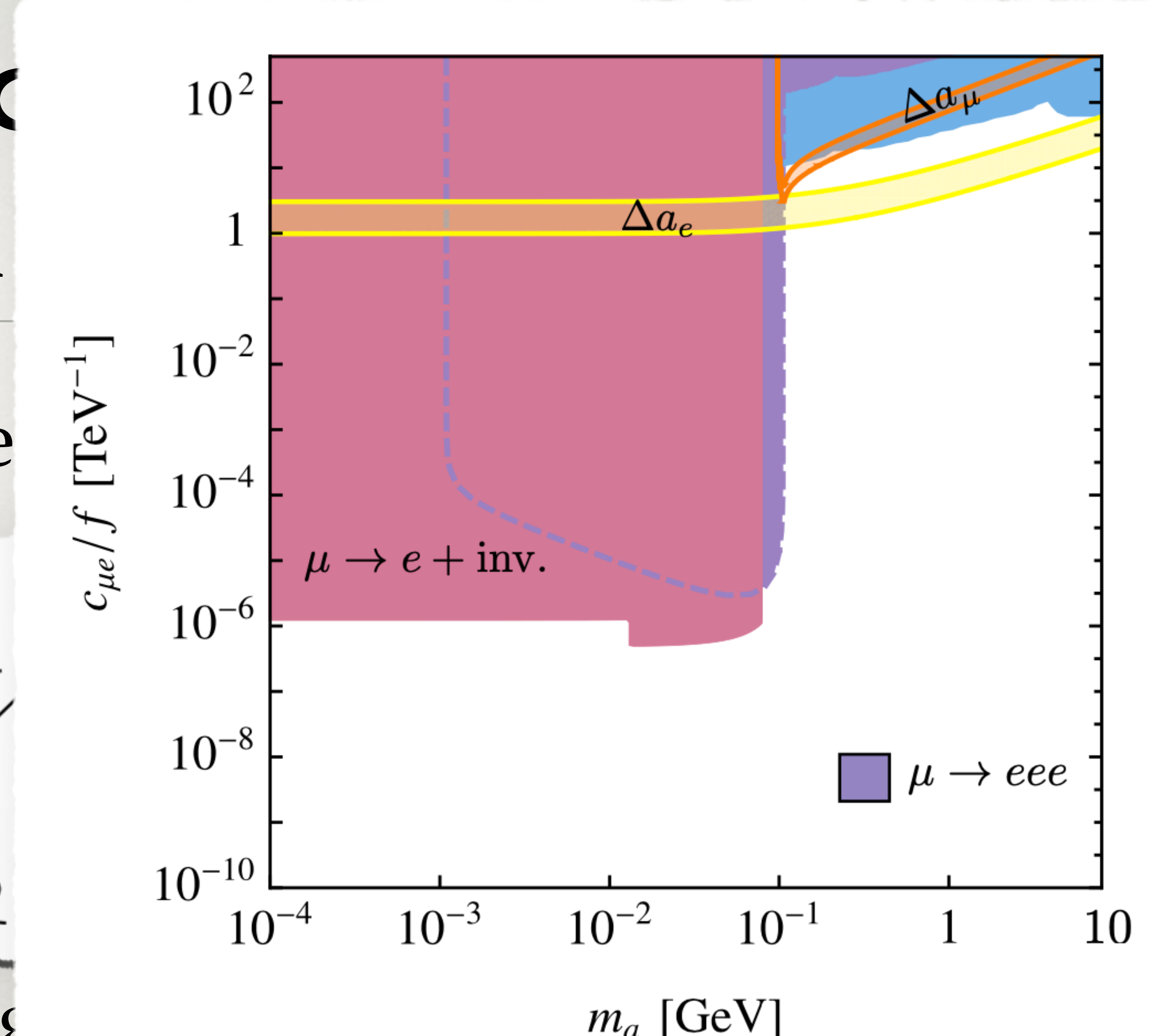
- same model building challenge: low f_a
- a possible way out: couple μ off-diagonally to heavy vector-like fermions E_i, L_i
  - chirality flip from internal E_i, L_i line $\Rightarrow$ higher $f_a \gtrsim 1$ TeV

Brdar, Jana, Kubo, Lindner, 2104.03282

FLAVOR VIO
FOR

- FV coupling $c^A_{e\mu}$ give
$m_a > m_\mu$





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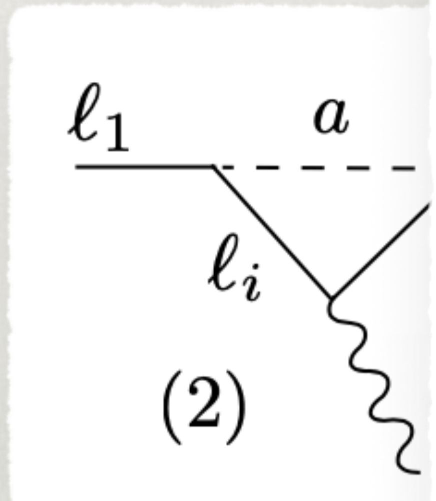

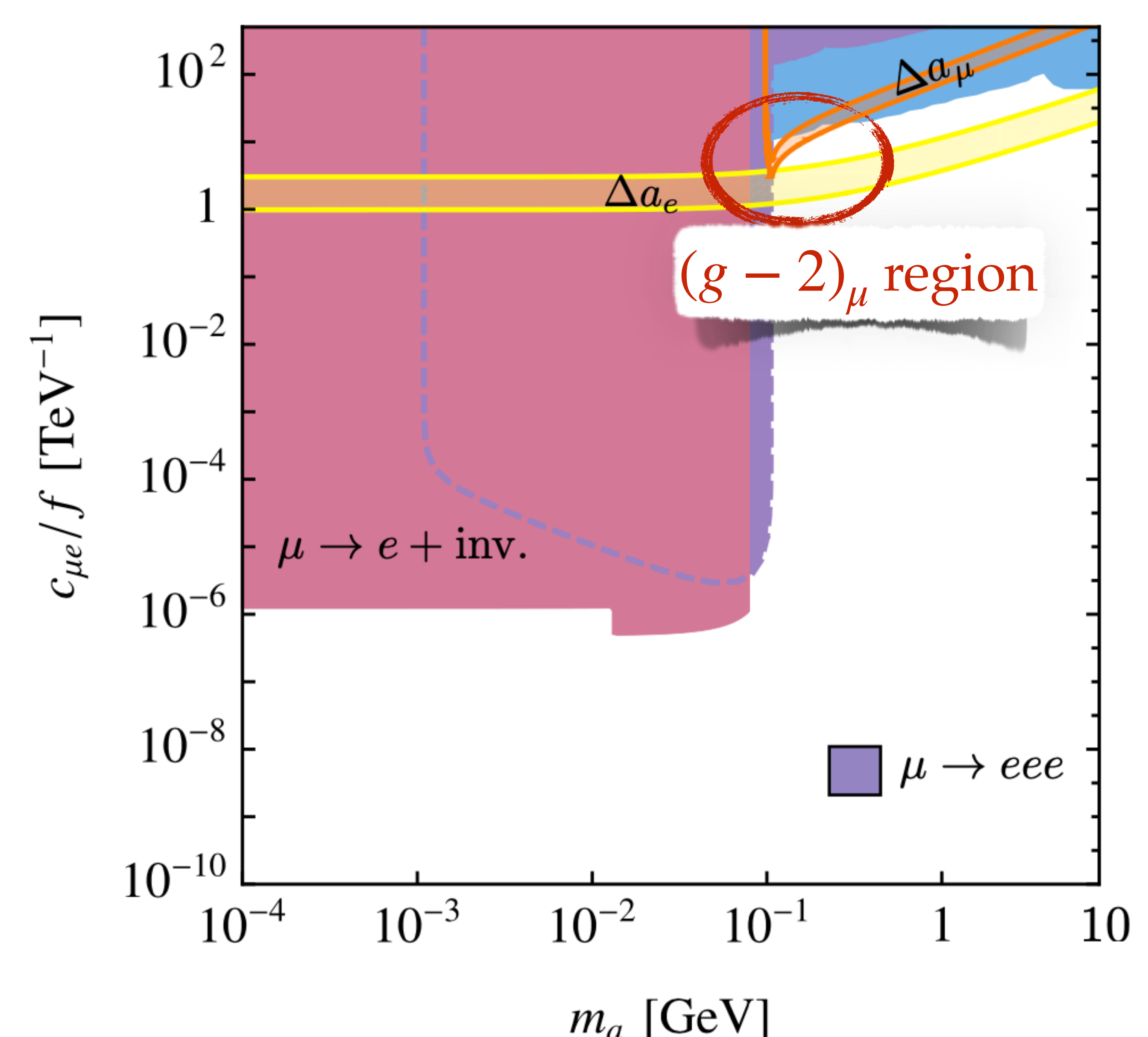

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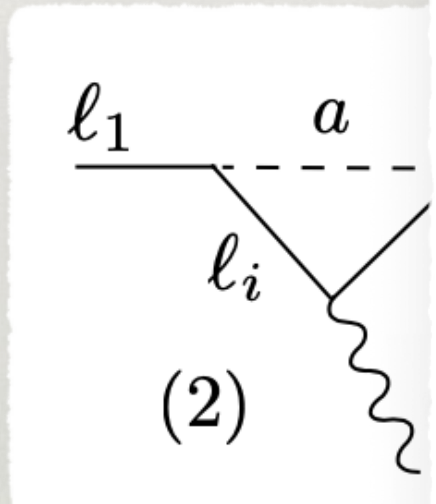
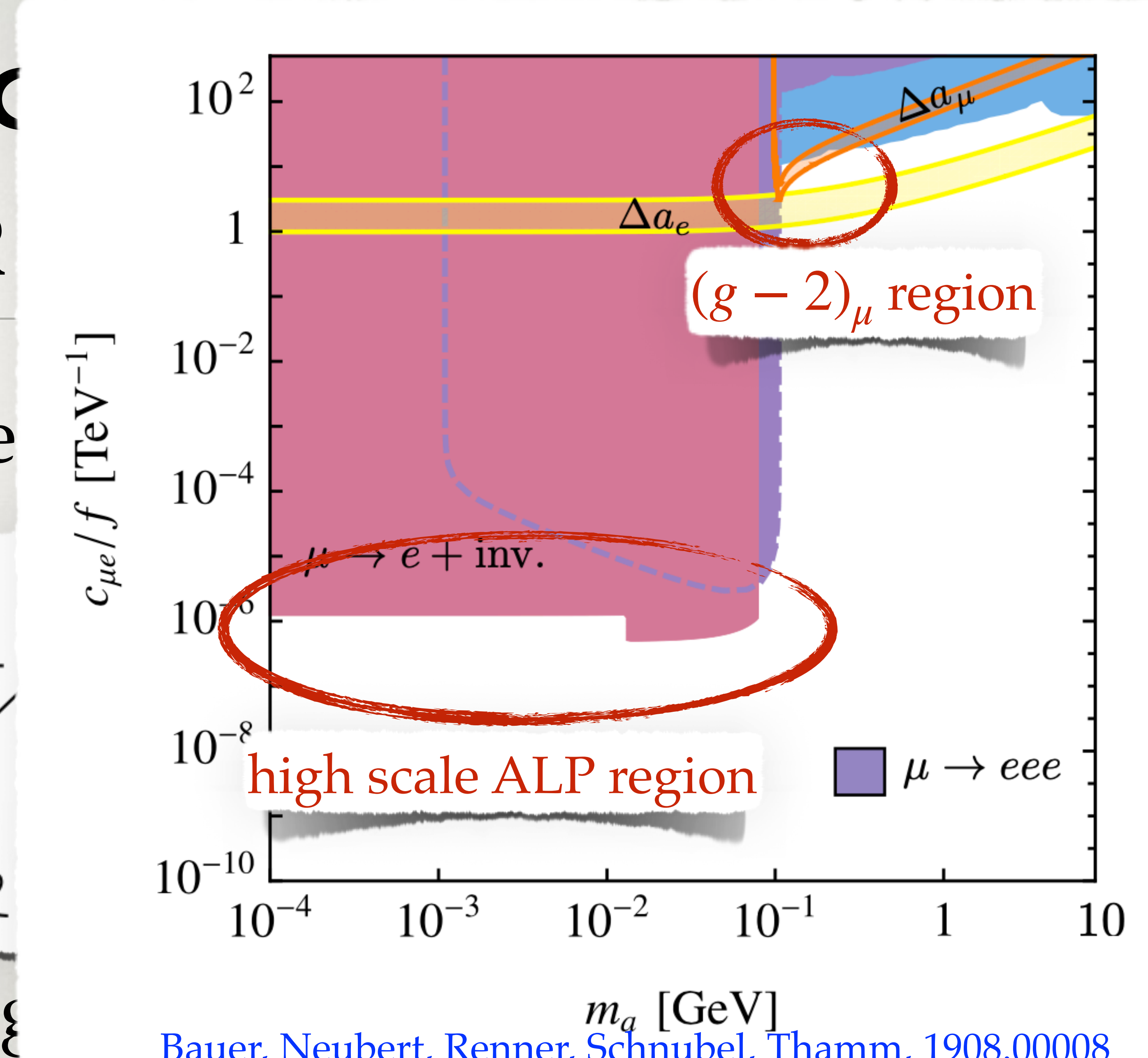
Brdar, Jana, Kubo, Lindner, 2104.03282

FLAVOR VI… FOR…

- FV coupling $c^{A}_{e\mu}$ give… $m_a > m_\mu$





Bauer, Neubert, Renner, Schnubel, Thamm, 1908.00008

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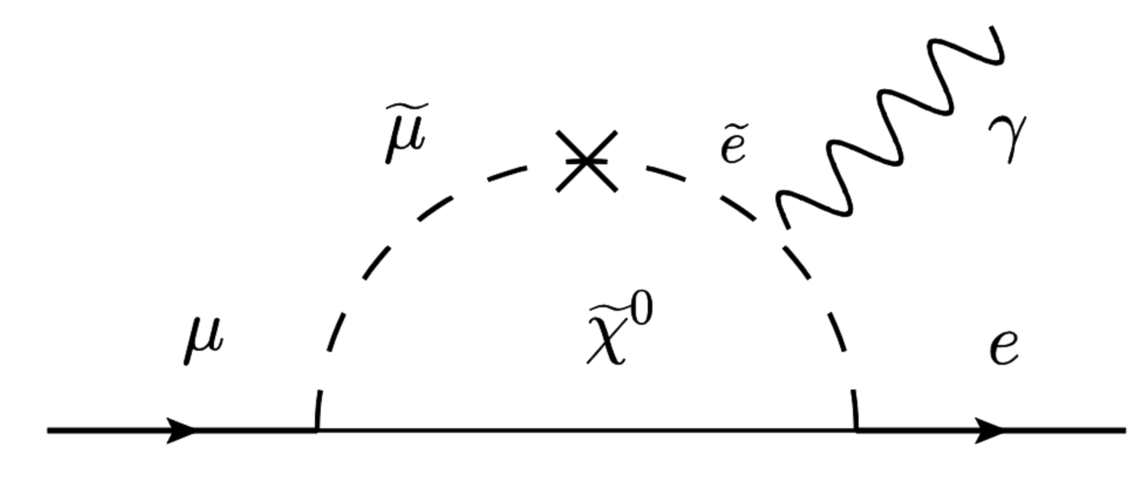
Brdar, Jana, Kubo, Lindner, 2104.03282

SUPERSYMMETRIC SEE-SAW

- the dominant LFV contribution comes from dipole operators ("photon penguin")



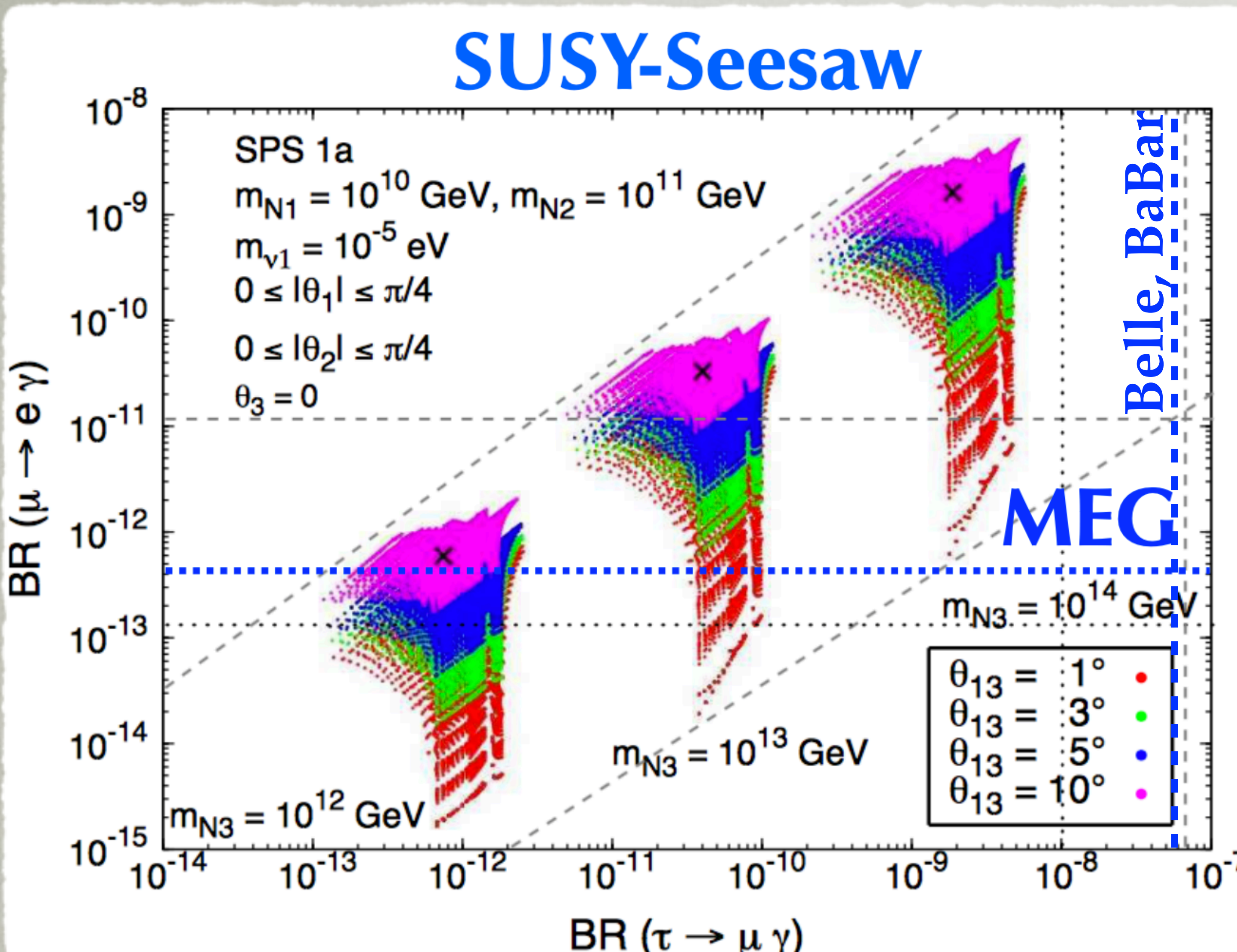
- the $\ell_j \to 3\ell_i$ are thus given by

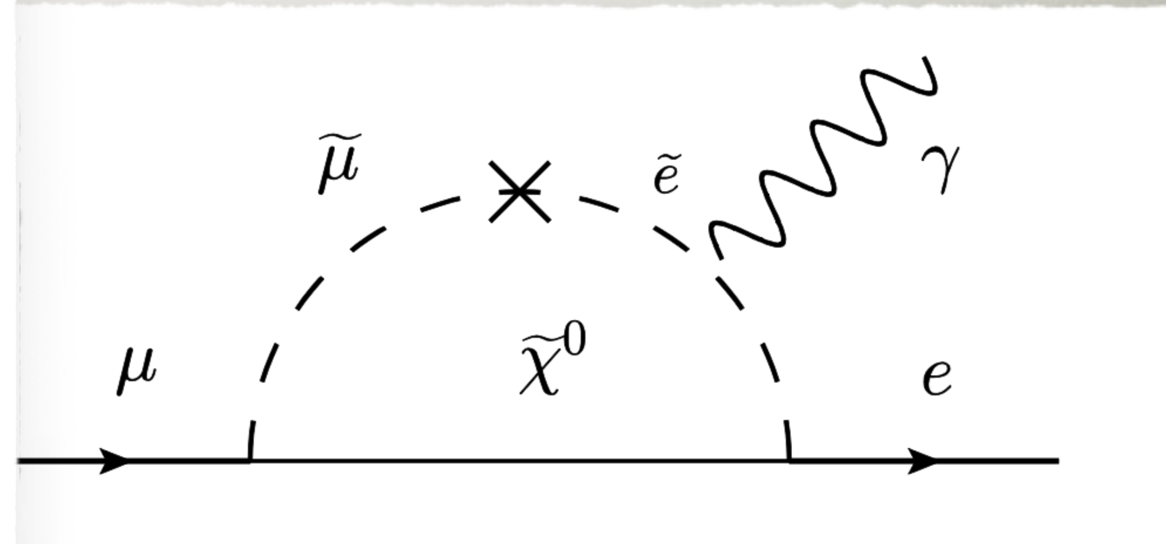
Antusch et al., hep-ph/0607263

$$\mathrm{BR}(l_j \to 3 l_i) = \frac{\alpha}{3\pi}\left(\log\frac{m_{l_j}^2}{m_{l_i}^2} - \frac{11}{4}\right) \times \mathrm{BR}(l_j \to l_i\,\gamma)\,,$$

- because of restricted flavor structure there is also a relation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$

METRIC
AW





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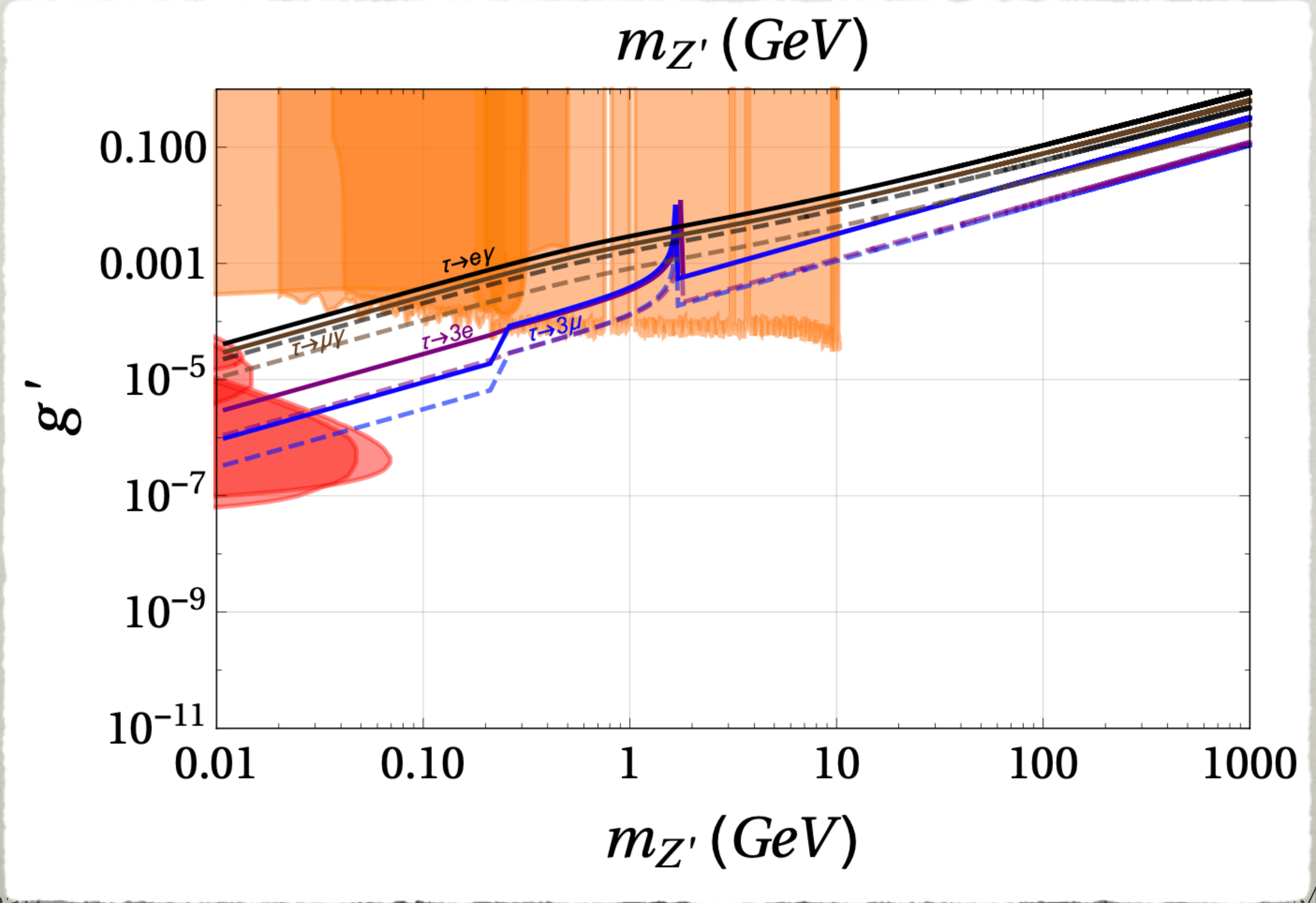
- because of restricted flavor structure there is also a relation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$

TAU DECAYS

- in this model tau decays less sensitive as discovery tool
- but essential to be measured in order to confirm the model



RARE MESON DECAYS

- so far a focus on LFV transitions with μ, τ in the initial state
- another possibility, use meson decays
  - $K^+ \to \pi^+\mu^+e^-,\ B^+ \to K^+\mu^+e^-, \ldots$
- an example already shown is Z' in $U(1)_{\rm FN}$
  - if tree-level mediator off-shell⇒ meson mixing or LFV FCNCs more constrained
  - for on-shell Z' on the other hand $M_i \to M_j Z'$ gives the leading constraints
  - note: Z' may decay through flavor conserving mode, so searches such as $B \to K\mu^+\mu^-$ also relevant

RA

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- another
  - $K^+ \rightarrow$
- an examp
  - if tree-
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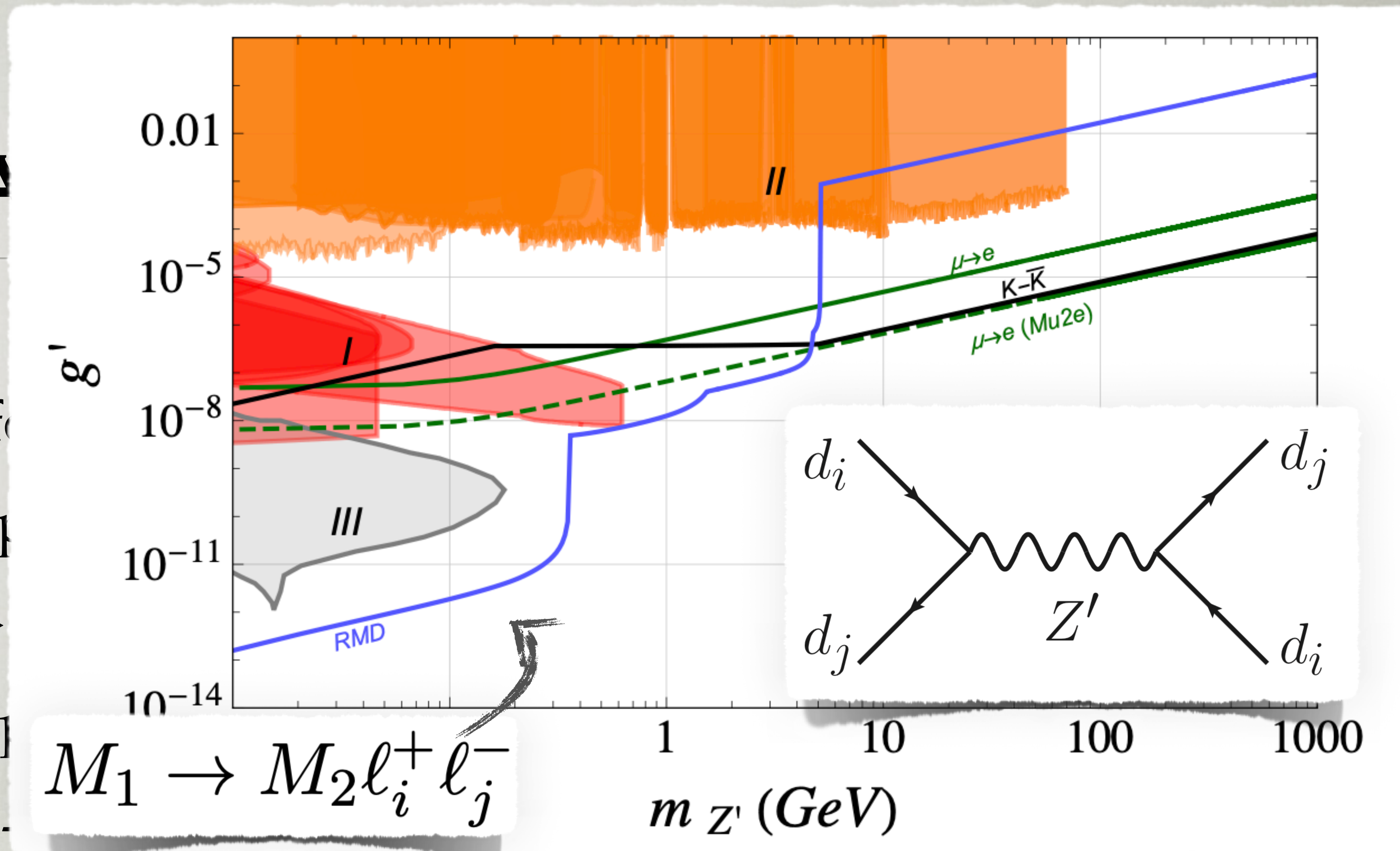
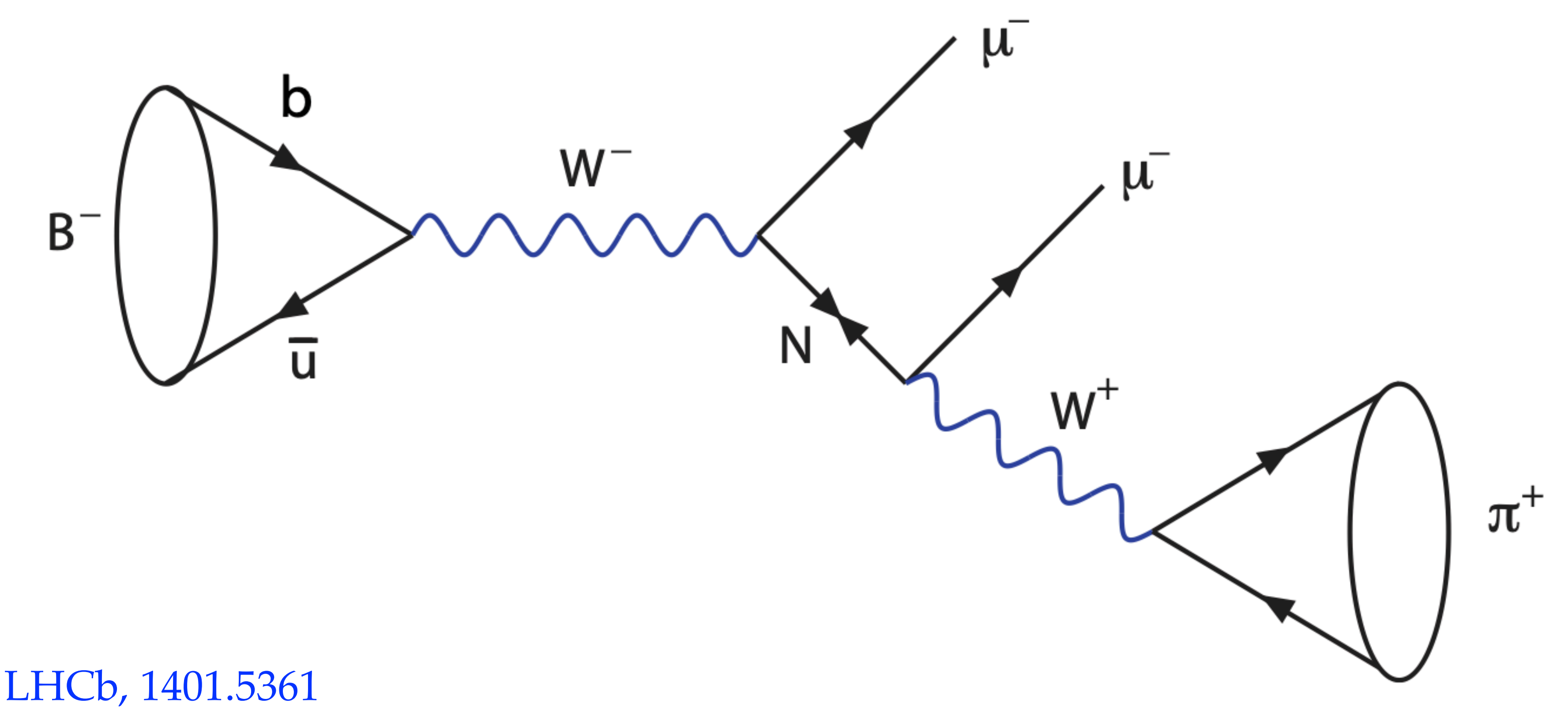


MAJORANA NEUTRINOS

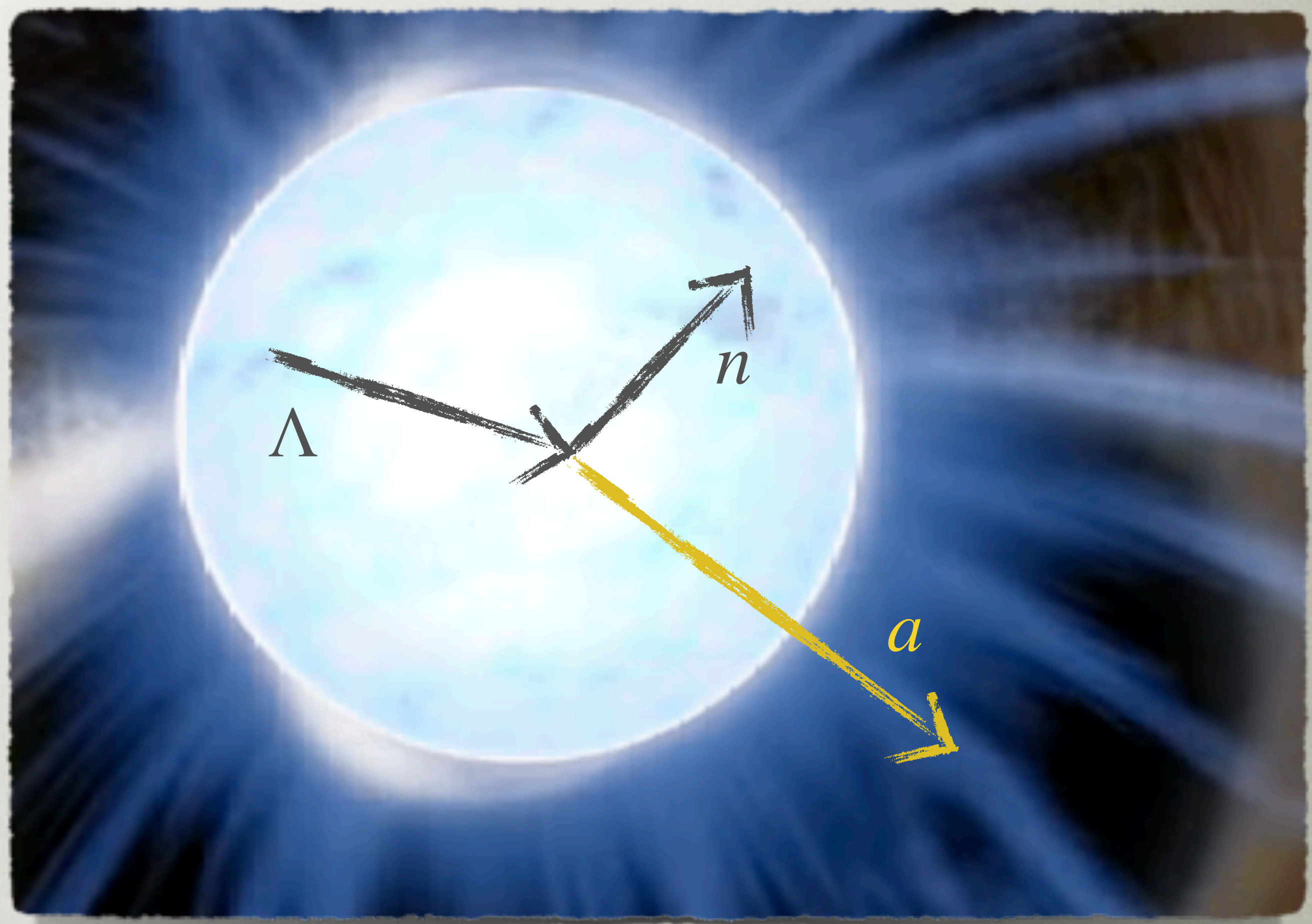
- if neutrinos Majorana fermions then lepton number violating decays possible
- leptons can be of same flavor, $B^- \to \pi^+\mu^-\mu^-$, or different flavor, $B^- \to \pi^+\mu^-e^-$,$B^- \to \pi^+\mu^-\tau^-$, ...



LHCb, 1401.5361

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