LIGHT NEW PHYSICS AND RARE TAU DECAYS

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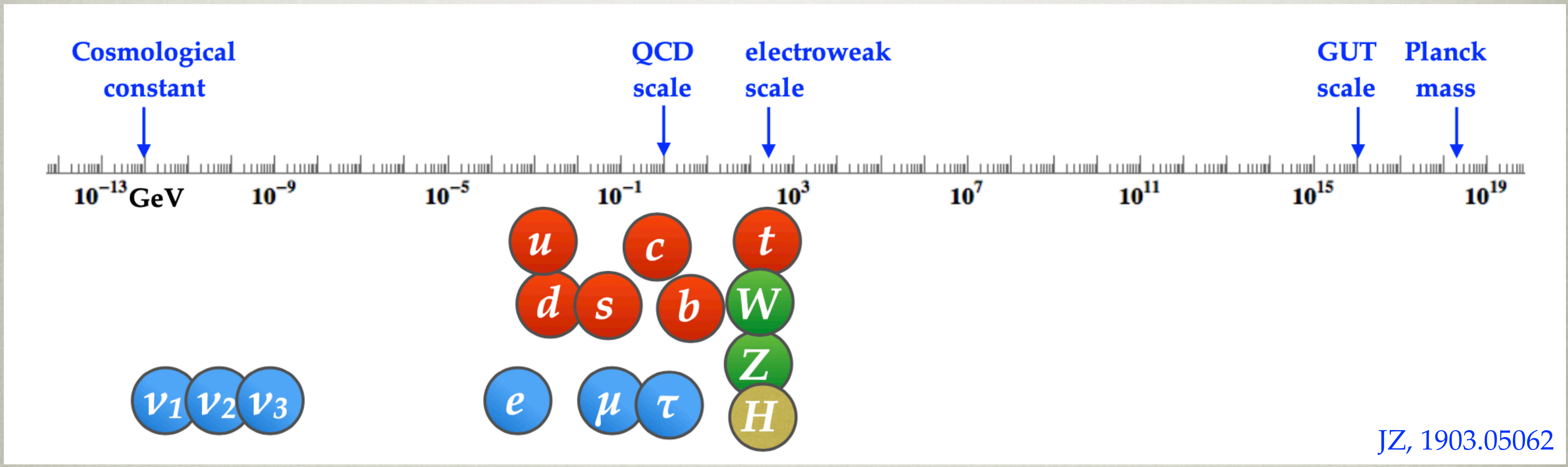
OUTLINE

- why rare tau decays + light new physics?
- light new physics signatures/examples
  - LFV QCD axion/ALPs
  - multi-lepton final states: $\tau \to 5\ell$, $\tau \to 7\ell$,..
  - time dependent tau decays

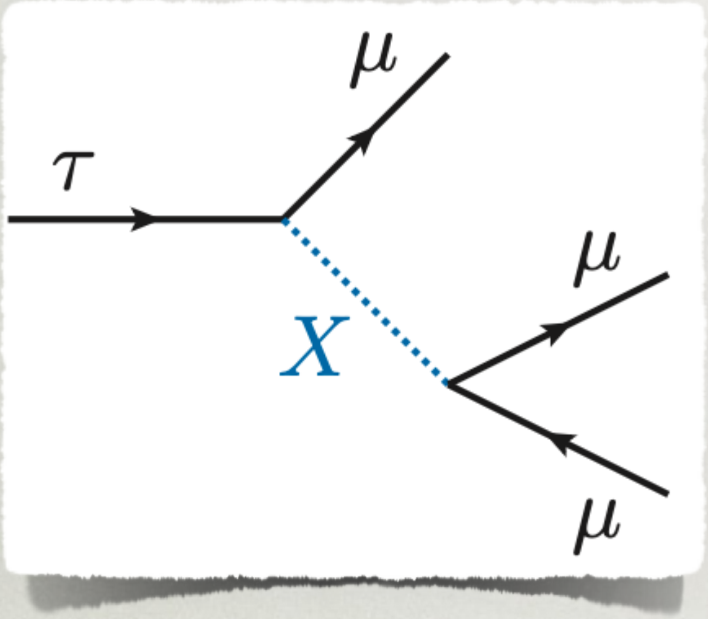
PHYSICS BEYOND THE STANDARD MODEL

- have we discovered all the forces?
- all the particles?



HEAVY VS. LIGHT

- heavy NP integrated out



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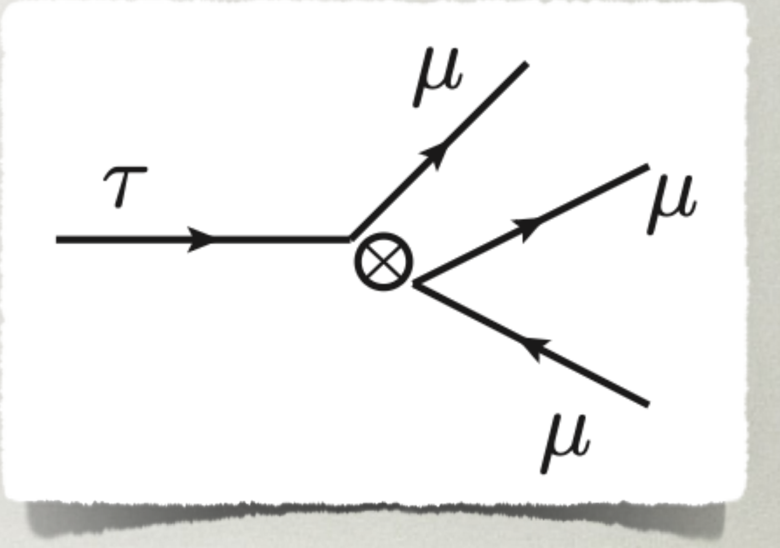
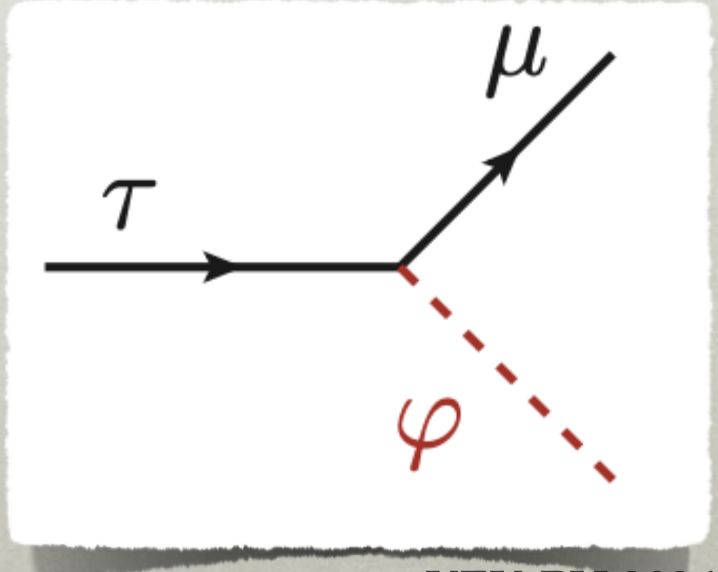


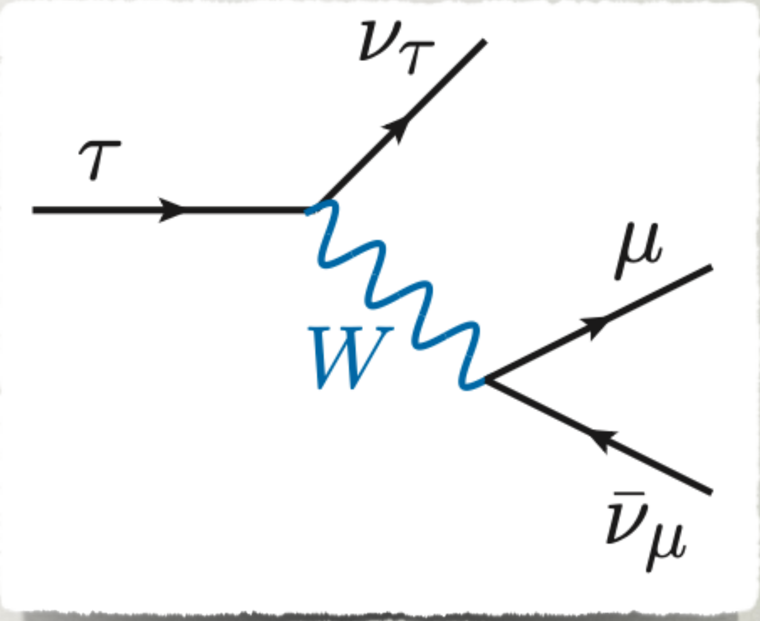
- light NP can be produced in τ decays



DIM. 5 VS DIM. 6

- heavy NP ⇒ dim. 6 SMEFT ops
  - e.g., $\tau \to \mu\gamma$ from $\frac{1}{\Lambda^2}\bar{\tau}_L \sigma^{\mu\nu} \mu H B_{\mu\nu}$
  - or $\tau \to 3\mu$ from $\frac{1}{\Lambda^2}(\bar{\tau}_L \gamma^\mu \mu_L)(\bar{\mu}_L \gamma^\mu \mu_L)$
- light NP ⇒ EFT ops start at dim. 5
  - e.g., $\tau \to \mu\varphi$ from $\frac{1}{\Lambda}\bar{\tau}_L \mu_R H \varphi$
- consequence: for same Br($\tau \to \ldots$) sensitivity
  ⇒ decays to light NP states can probe physics at much higher scales

DIM.5 VS DIM.6



- another ingredient:
  SM tau decay width is small
  $\Gamma_\tau \propto \frac{1}{8\pi}\frac{m_\tau^2}{m_W^4} \ll \frac{1}{8\pi} m_\tau$
- so even $\mathcal{O}(1)$ exotic Br's can probe high scales
  - $\mathrm{Br}(\tau \to \mu\varphi) < 0.5 \Rightarrow \Lambda > 3 \cdot 10^7\,\mathrm{GeV}$ ← **dim 5**
  - compare with $\mathrm{Br}(\tau \to 3\mu) < 0.5 \Rightarrow \Lambda > \mathcal{O}(100\,\mathrm{GeV})$ ← **dim 6**
- upshot: if there are light NP particles
  - a window to physics far in the UV

WHY LIGHT NEW PHYSICS

- how likely is light NP?
- any spontaneously broken global symmetry
  - massless Nambu-Goldstone boson
  - explict breaking ⇒ small mass
  - celebrated example: QCD axion

A FEW EXAMPLES

- light new physics examples
  - LFV QCD axion: $\tau \to \mu a$
  - multi-lepton final states: $\tau \to 5\ell$, $\tau \to 7\ell$,..
  - time dependent $\tau \to \mu\varphi$ decays

Flavor violating QCD axion & ALPs

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

AXION

- 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

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

  - obtains mass from QCD anomaly

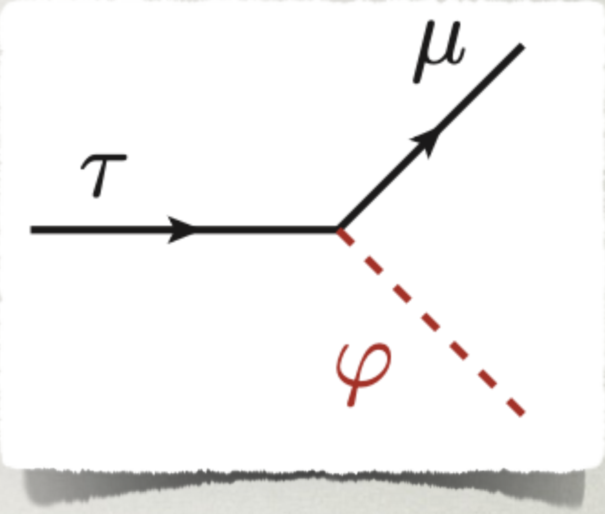
$$m_a = 5.70(7)\,\mu{\rm eV}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)$$

  - viable cold dark matter candidate for (misalignment mech.)

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

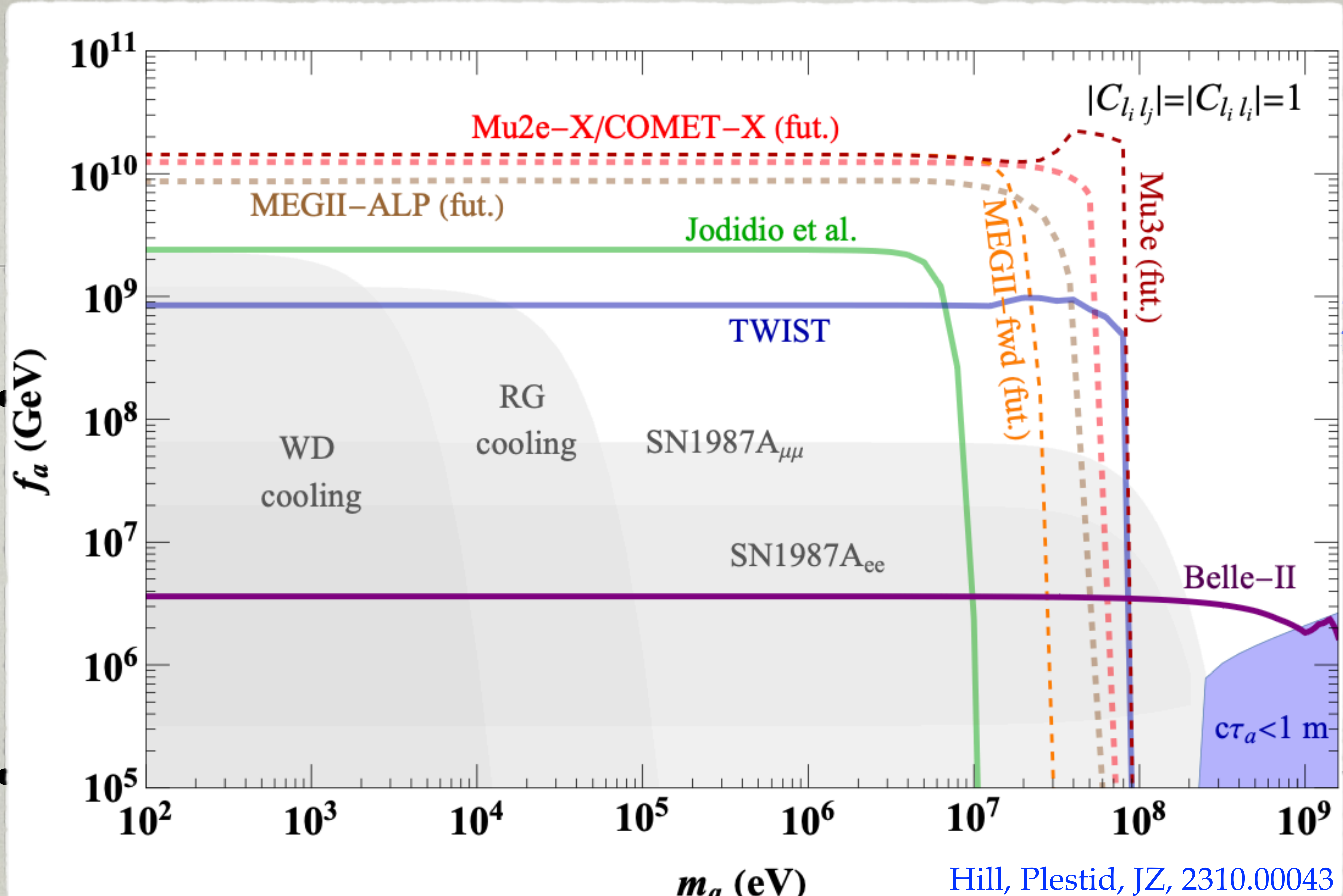
LFV axion

Hill, Plestid, JZ, 2310.00043
Calibbi, Redigolo, Ziegler, JZ, 2006.04795



- flavor violating couplings will induce decays $\tau \to \mu a$, $\tau \to ea$, $\mu \to ea$
  - a essentially massless on collider scales
  - escapes the detector: $\tau \to \ell + \text{inv}$
- which of the decays most sensitive depends on flavor structure
  - for simplicity assume anarchy: $c_{\ell_i \ell_j} = 1$
- tau decays probe: $f_a \ll 10^{12}\text{GeV}$
  - QCD axion that is also a DM candidate would require alternative production mechanisms
  - e.g. kinetic misalignment possible for $f_a \sim 10^8$ GeV

Co, Hall, Harigaya, 1910.14152



, JZ, 2310.00043

; JZ, 2006.04795

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Co, Hall, Harigaya, 1910.14152

LONG LIVED ALPs

Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, 2507.15271

- if the axion-like particles are heavy enough
  - can decade inside detector (including displaced vertices)
  - have large $c\tau$: be searched for in beam dumps
- the interplay is between f_a, m_a and flavor structures
  - three examples
    - LFV: flavor anarchy $\Leftarrow$ all couplings similar
    - LFV: flavor hierarchy $\Leftarrow$ off diagonal suppressed
    - LFC: flavor conservation $\Leftarrow$ only diagonal

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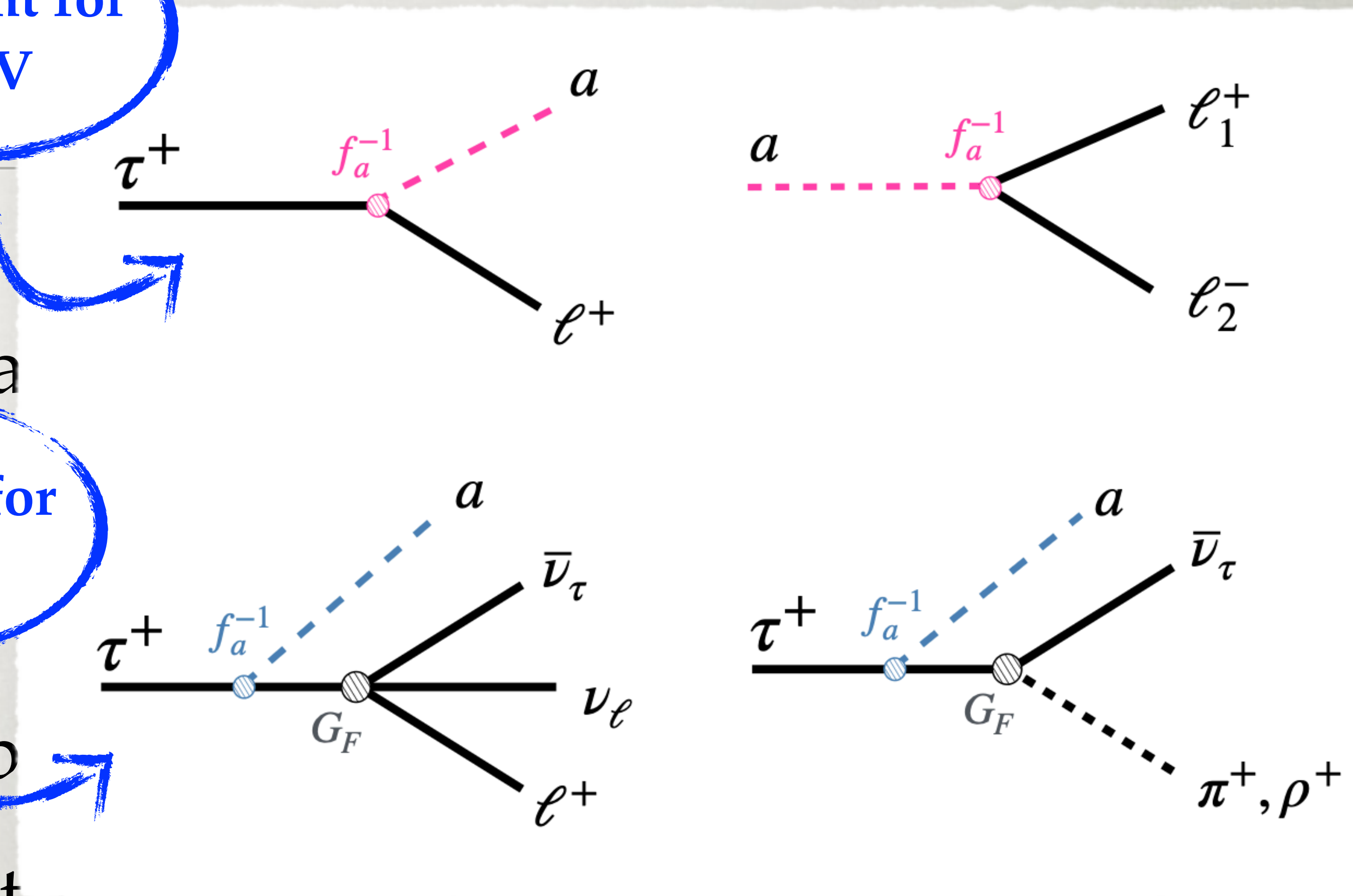

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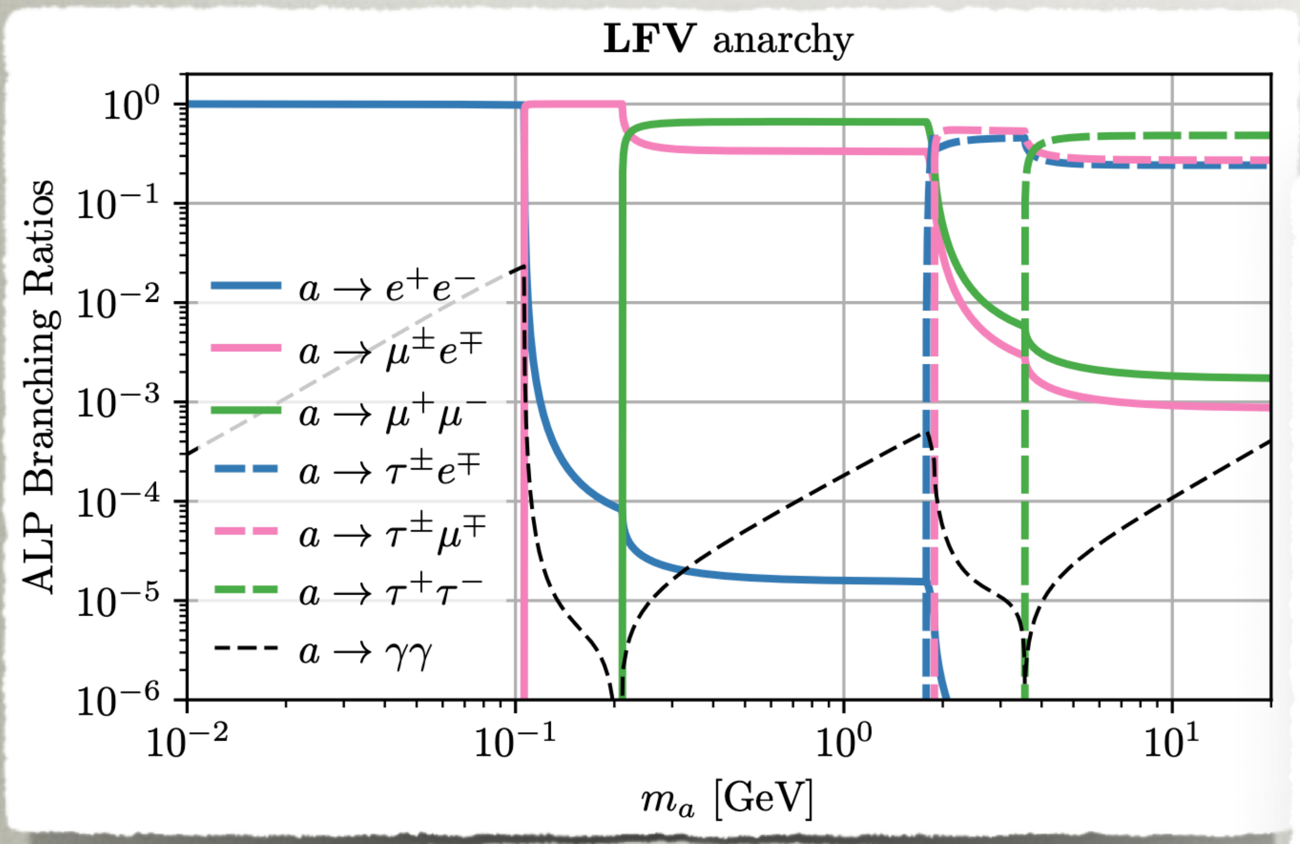
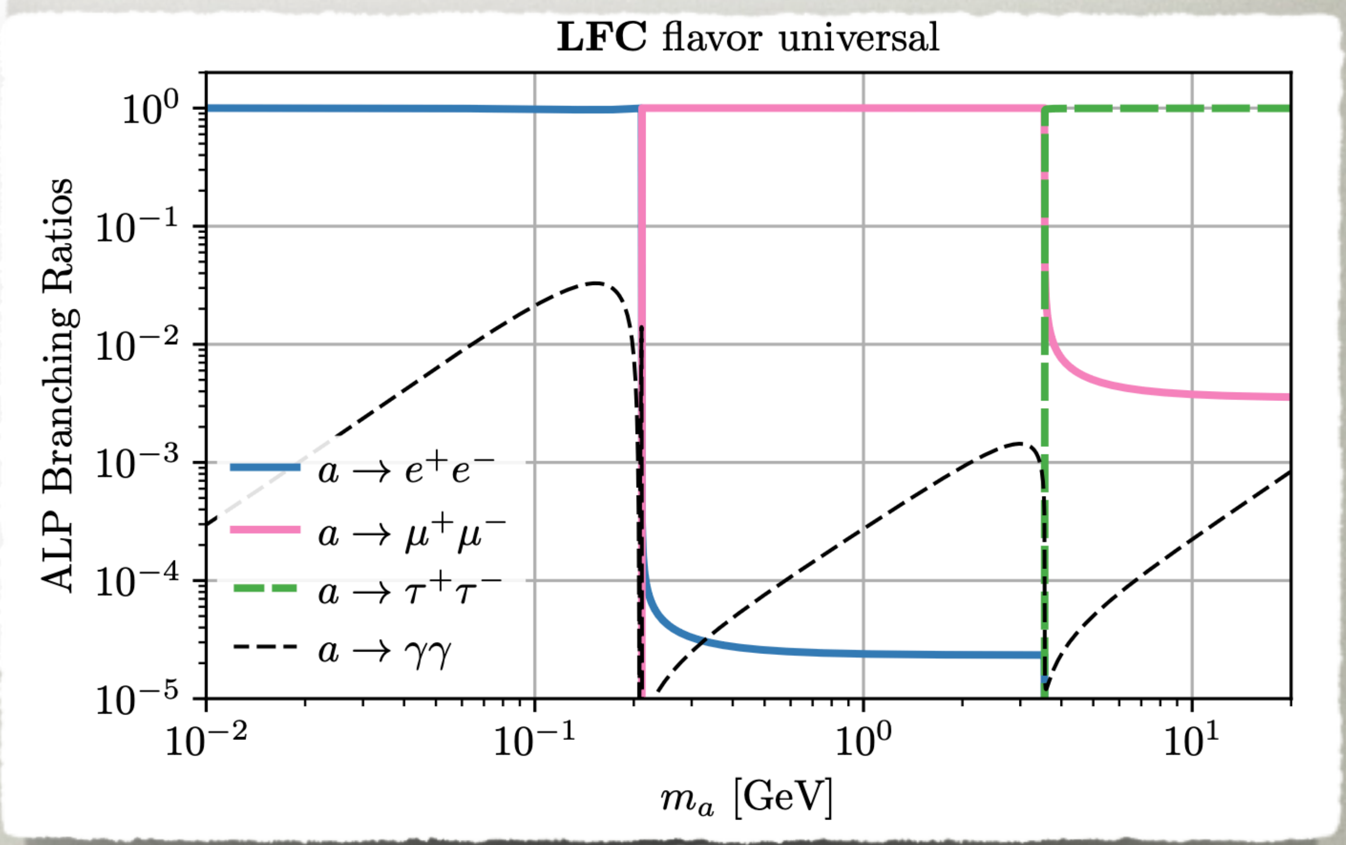
ALP DECAYS

Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, 2507.15271

- which ALP decay channel dominates
  - depends strongly on assumed flavor structure



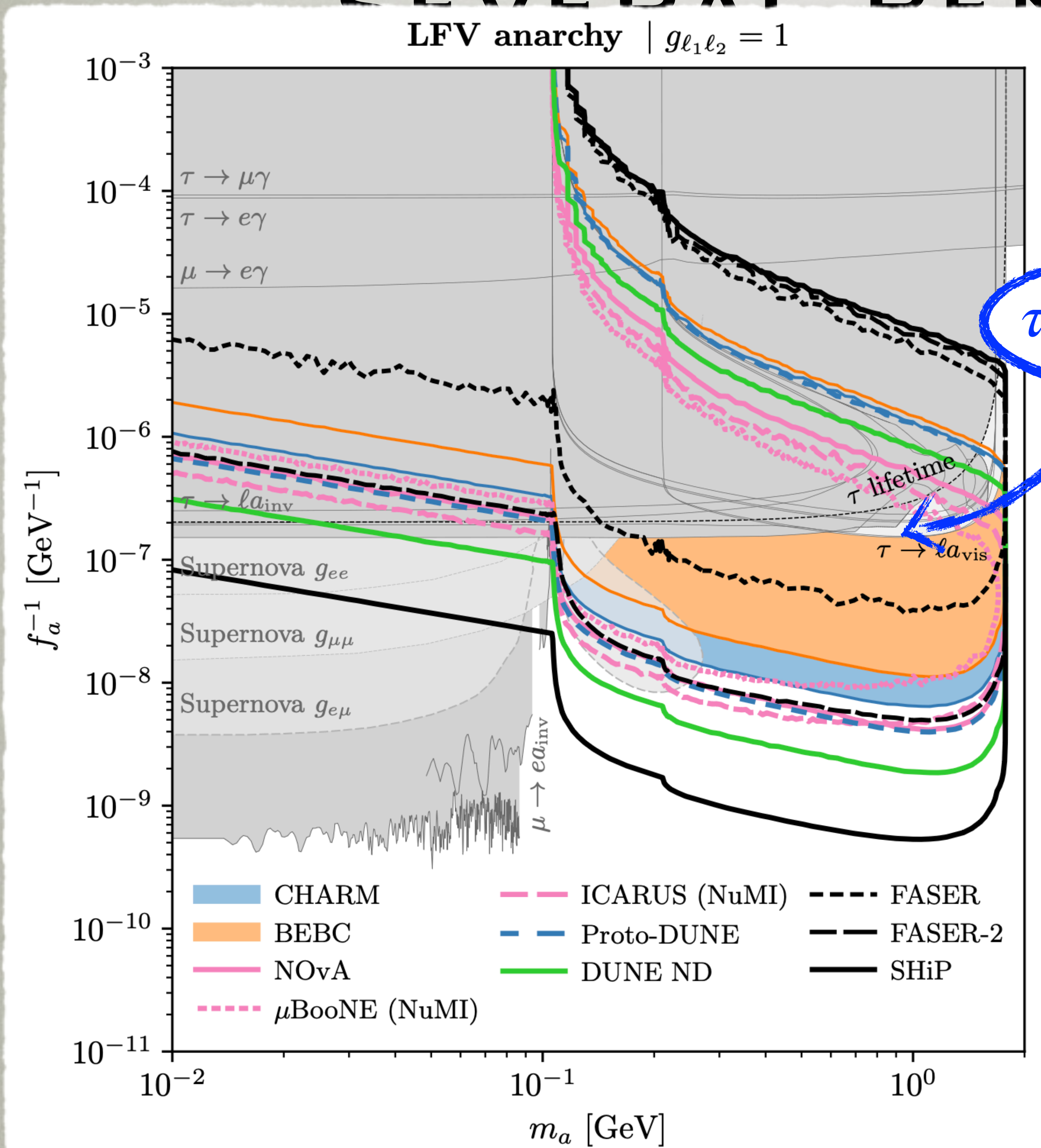


SEVERAL BENCHMARK EXAMPLES

- can Belle-II have the leading sensitivity?
  - depends on the benchmark

Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, 2507.15271

...NCHMARK
...LES



$\tau \to \ell a_{\bf inv}$

...sensitivity?

...chmark

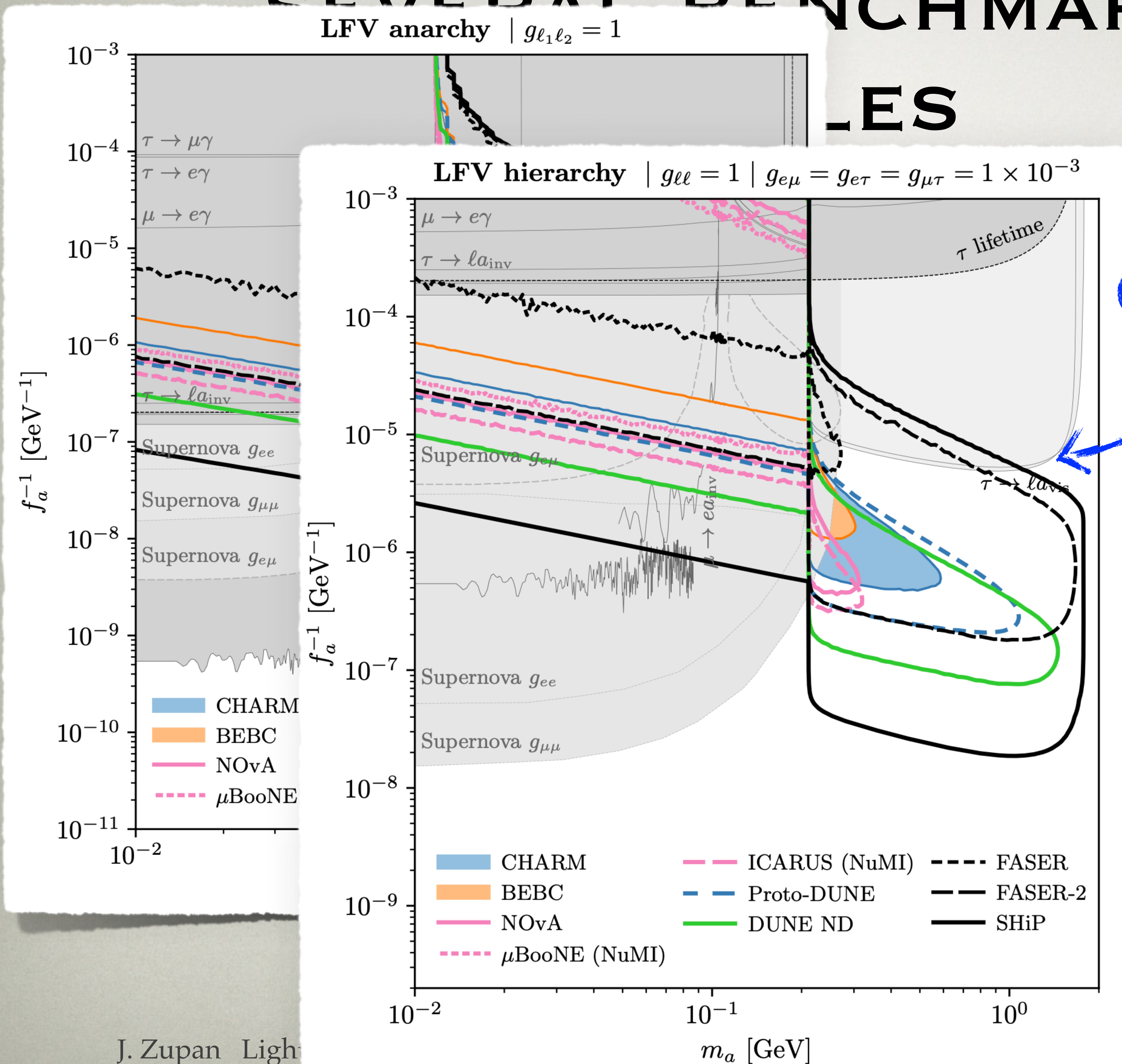
...ma, Fox, Hostert, Menzo, Pospelov, Ray, JZ, 2507.15271

SEVERAL BENCHMARK ...LES

...sitivity?

$\tau \to \ell a_{\rm inv}$

..., Pospelov, Ray, JZ, 2507.15271



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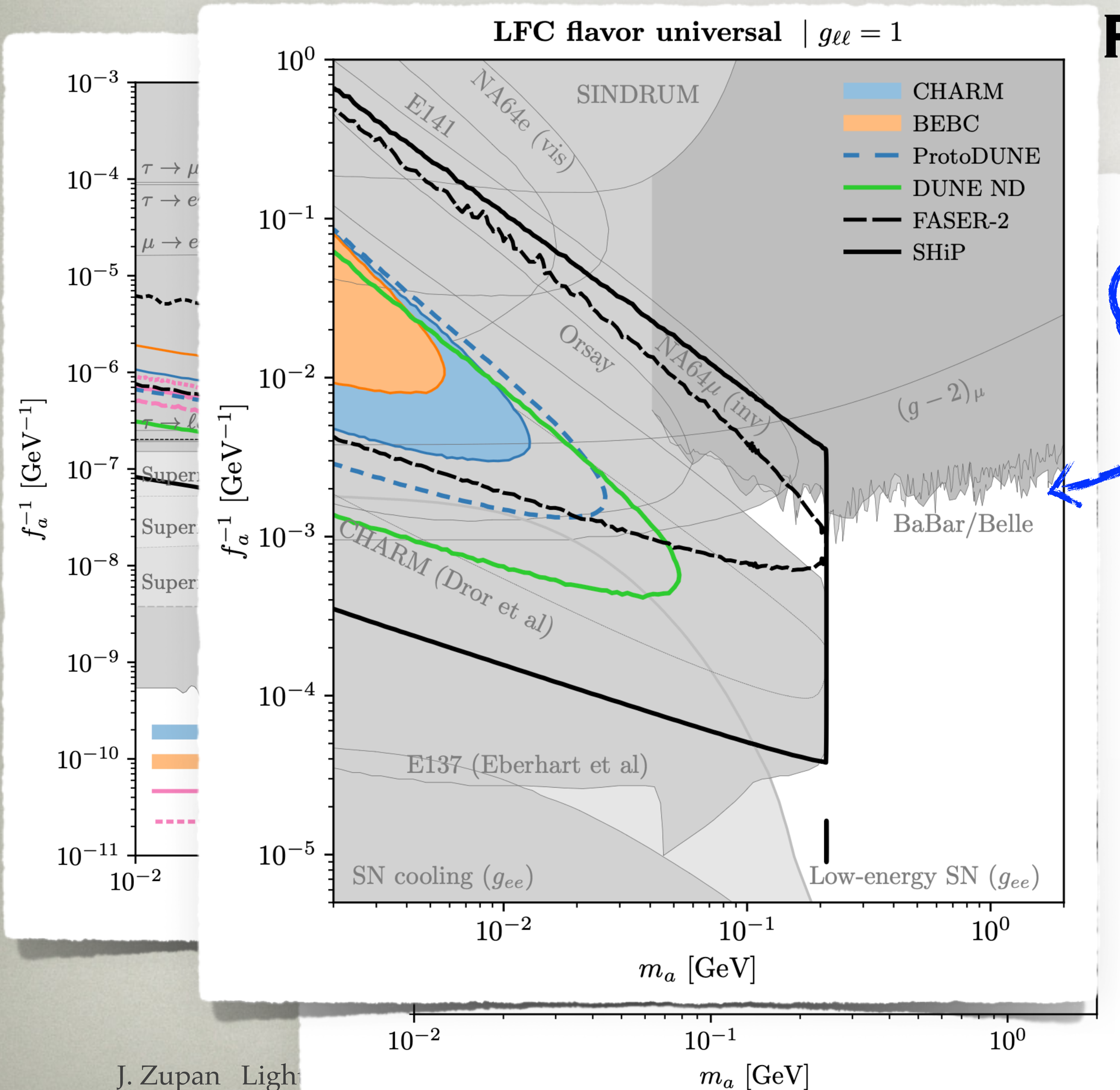


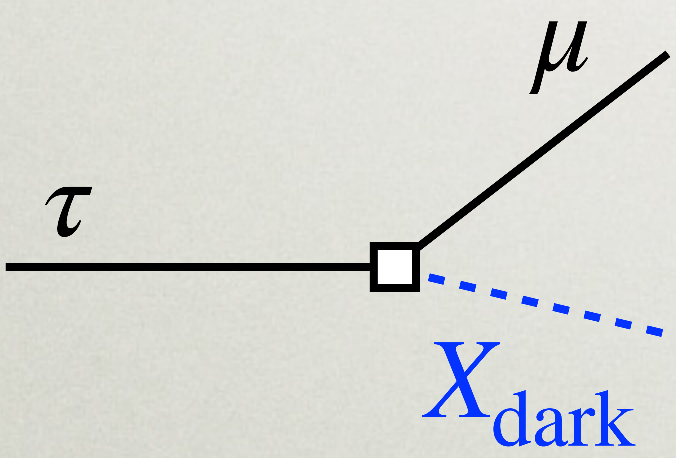
$e^+e^- \to \tau^+\tau^-\phi,$
$\phi \to \ell^+\ell^-$

, Pospelov, Ray, JZ, 2507.15271

MULTI-LEPTON DECAYS

DARK SECTOR SHOWERS

- FCNC tau decay into dark sector: $\tau \to \ell + X_{\rm dark}$
  - a shower in the dark sector
  - lightest dark particles decay back to the SM



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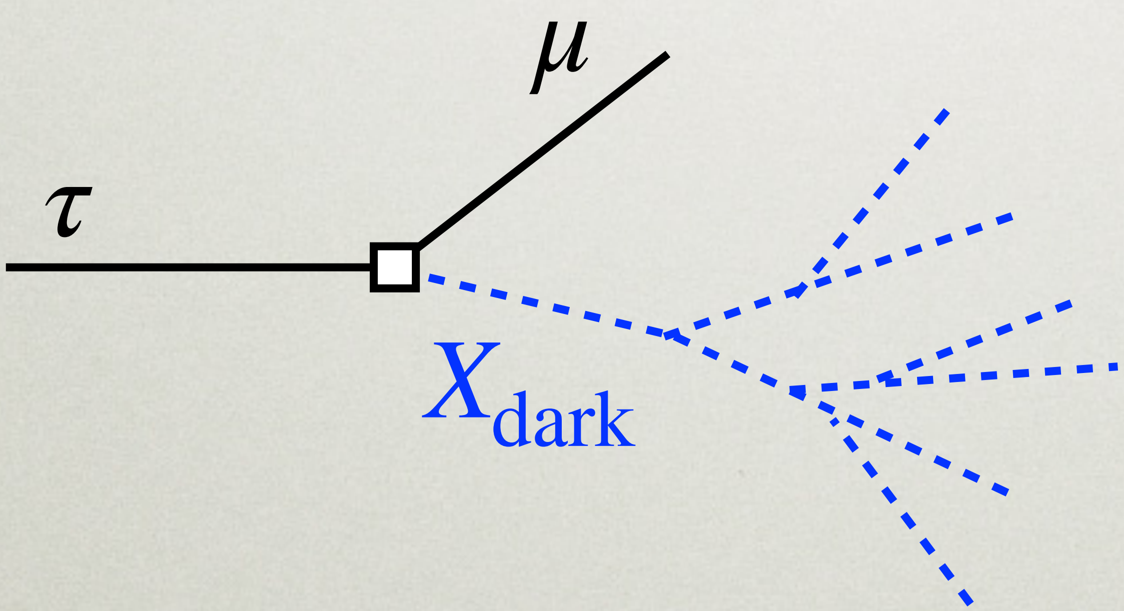

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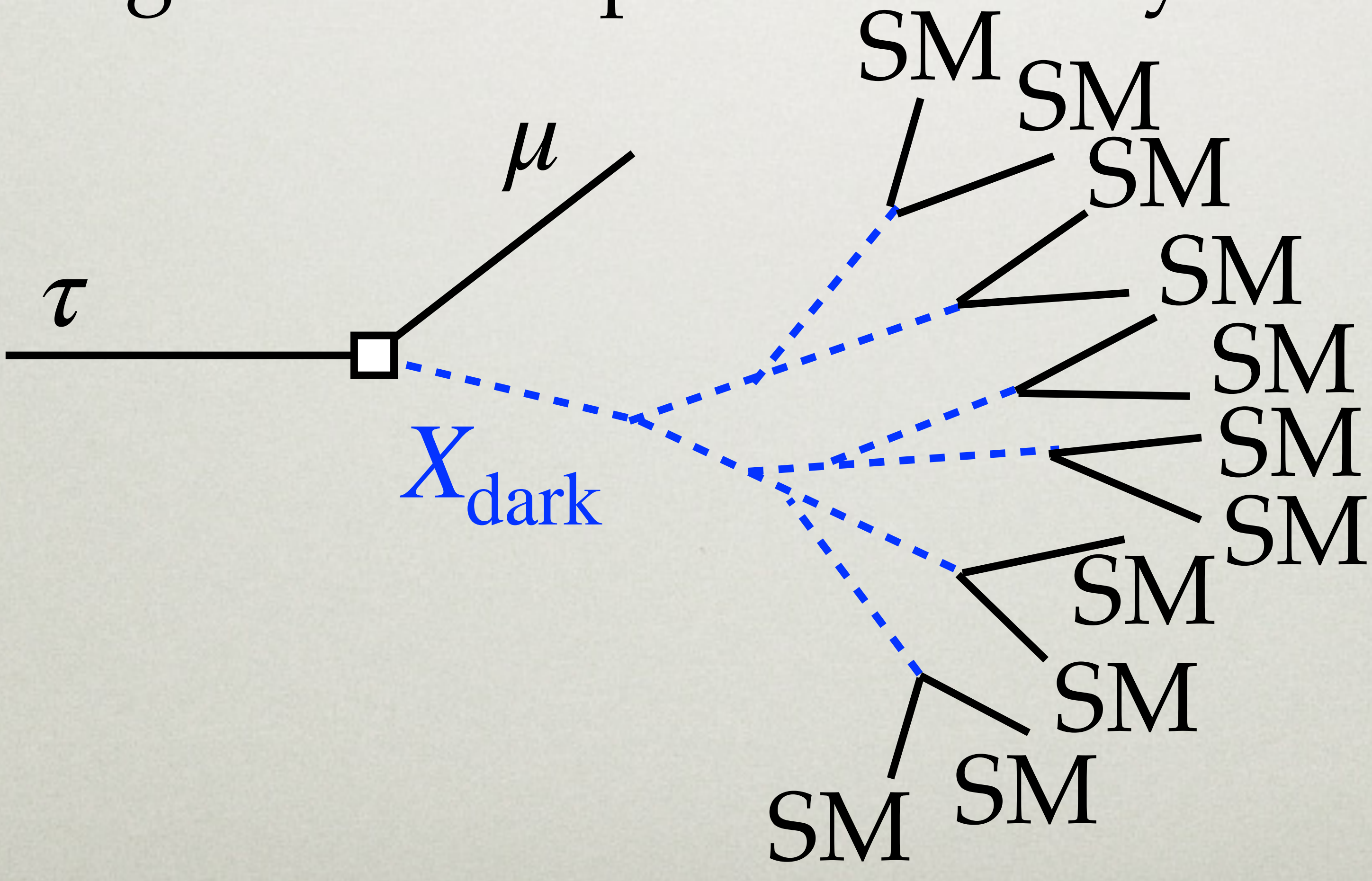
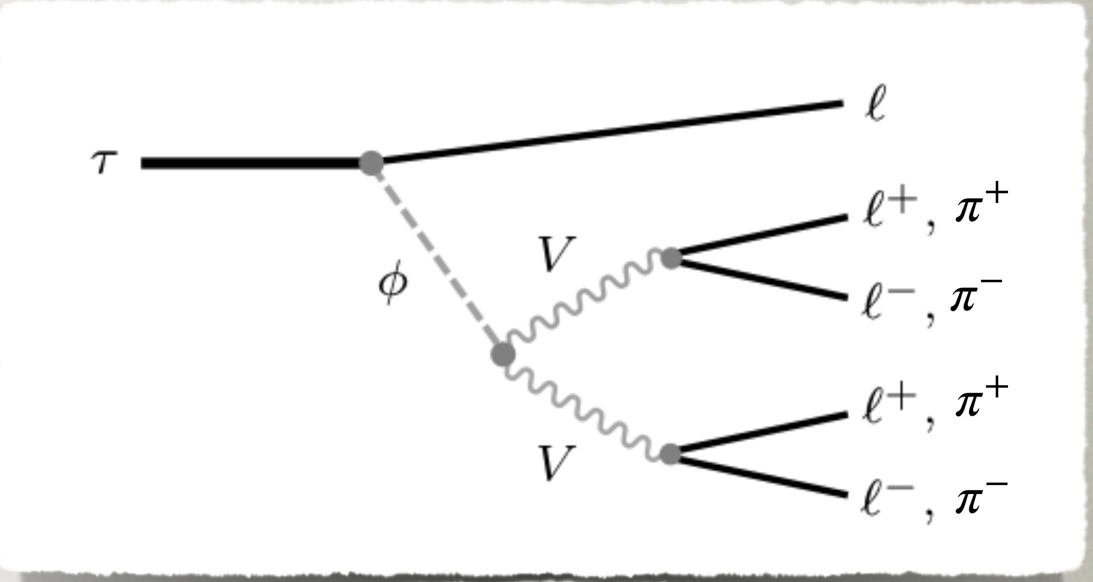


Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, to appear

MANY MODELS...

$\not{E}$	τ decay	Search?	Seclud. $U(1)$ Kinetic mix.	$U(1)_{L_\mu - L_\tau}$ $Q_\Phi^{\mu\tau} = +1$	$U(1)_{L_\mu - L_\tau}$ $Q_\Phi^{\mu\tau} = +2$	$U(1)_{L_\mu + L_e - 2L_\tau}$ $Q_\Phi = +3$	Chiral $U(1)_\mu$	Chiral $U(1)_e$	Flav. prot. scalar
$\not{E} = 0$ leptons	$\tau \to 5\mu$	*	✓		✓	✓	✓		(✓)
	$\tau \to 4\mu\, e$	✗	✓	✓		✓			(✓)
	$\tau \to 3\mu\, 2e$	✗	✓			✓			(✓)
	$\tau \to 2\mu\, 3e$	✗	✓			✓			(✓)
	$\tau \to \mu\, 4e$	✗	✓			✓			(✓)
	$\tau \to 5e$	✗	✓			✓		✓	(✓)
$\not{E} = 0$ hadrons	$\tau \to 3\mu\, 2h$	✗	✓						
	$\tau \to 2\mu\, e\, 2h$	✗	✓						
	$\tau \to \mu\, 2e\, 2h$	✗	✓						
	$\tau \to \mu\, 4h$	✗	✓						
	$\tau \to 3e\, 2h$	✗	✓						
	$\tau \to e\, 4h$	✗	✓						
$\not{E} > 0$	$\tau \to 3\mu\, 2\nu$	✗			✓	✓	(✓)		
	$\tau \to 2\mu\, e\, 2\nu$	[42]		✓		✓			
	$\tau \to \mu\, 2e\, 2\nu$	✗				✓			
	$\tau \to \mu\, 4\nu$	✗			✓	✓	(✓)		
	$\tau \to 3e\, 2\nu$	[42]				✓		(✓)	
	$\tau \to e\, 4\nu$	✗		✓		✓		(✓)	
$\not{E} = 0$ 7 leptons	$\tau \to 7\mu$	✗							✓
	$\tau \to 6\mu\, e$	✗							✓
	$\tau \to 5\mu\, 2e$	✗							✓
	$\tau \to 4\mu\, 3e$	✗							✓
	$\tau \to 3\mu\, 4e$	✗							✓
	$\tau \to 2\mu 5e$	✗							✓
	$\tau \to \mu 6e$	✗							✓
	$\tau \to 7e$	✗							✓

DARK PHOTON + LFV



- dark photon: extend the SM by gauged U(1)'
  - kinetic mixing
    - $\mathscr{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} \Leftarrow$ dark photon V
    - couples to QED current $\propto \varepsilon V_\mu J^\mu_{\rm QED}$
  - U(1)' broken by a vev of $\Phi = (v' + \phi)/\sqrt{2}$
- extend dark photon model by allowing for LFV interactions

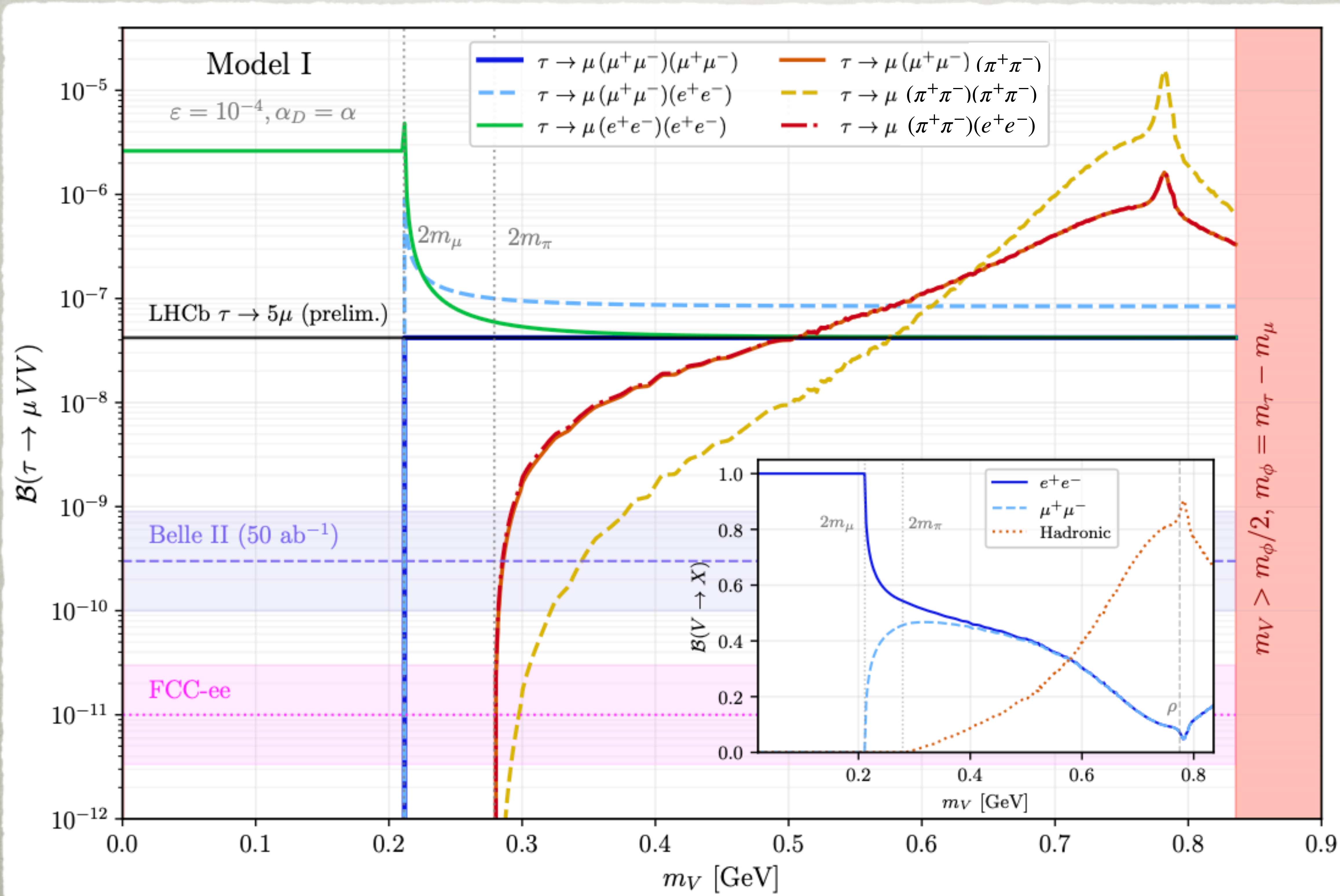
$$-\mathcal{L} \supset \frac{\kappa_{ij}}{\Lambda^2} |\Phi|^2 \bar{L}_i H \ell_{Rj} + \text{h.c.},$$

- leads to $\tau \to 5\mu$, $\tau \to 3\mu 2e$, $\tau \to e4\pi$, ... decays

$$\text{Br}(\tau \to \ell_i \phi) \simeq 10^{-8} \cdot \kappa_{i3}^2 \cdot \left(\frac{10^6\,\text{GeV}}{\Lambda}\right)^4 \cdot \left(\frac{v'}{10\,\text{GeV}}\right)^2$$

Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, to appear

MULTI-LEPTON AND MULTI-HADRON DECAYS

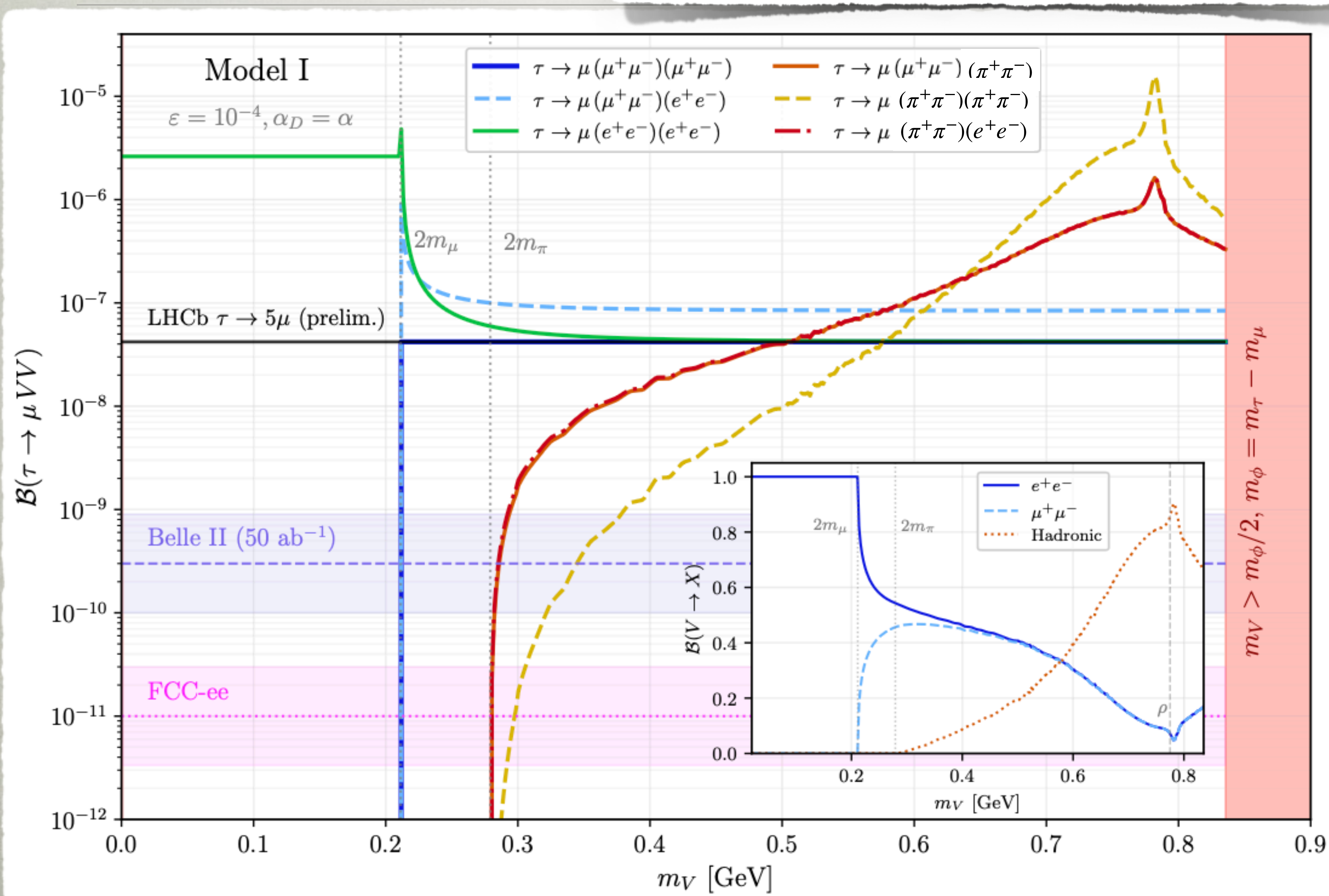


MULTI-L
MULTI-HA

appear

$$c\tau_{A'\to\ell\ell} \simeq 30\,\mu\text{m}\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{300\,\text{MeV}}{m_{A'}}\right),$$

$$c\tau_{\phi\to 2A'} = 109\,\text{fm}\left(\frac{\alpha}{\alpha_d}\right)\left(\frac{1\,\text{GeV}}{m_\phi}\right)^3\left(\frac{m_{A'}}{300\,\text{MeV}}\right)^2$$

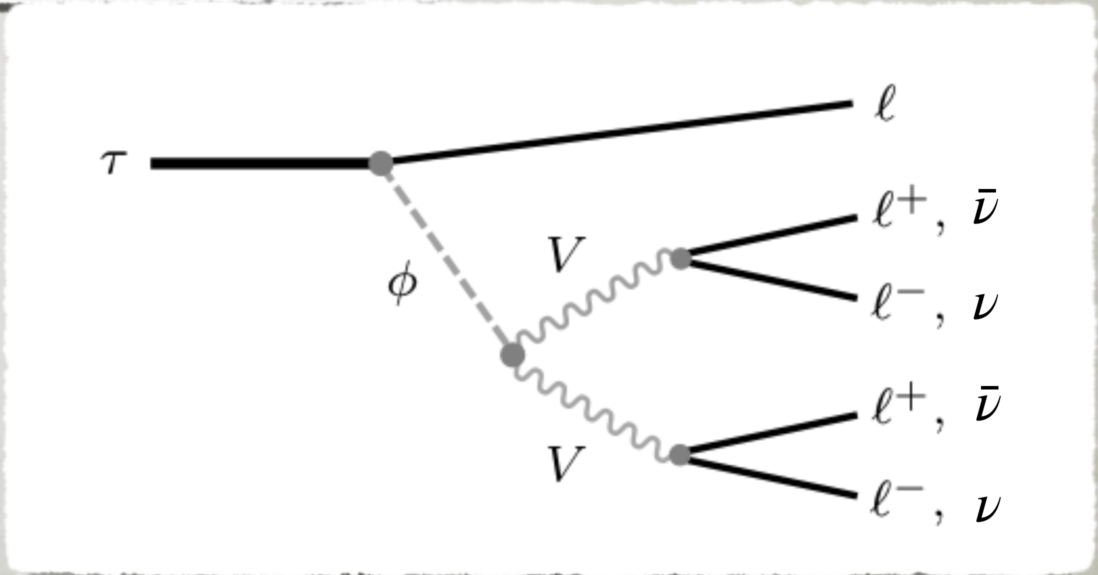


Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, to appear

GAUGED $L_\mu - L_\tau$

- if SM lepton charged under U(1)' the LFV interactions can start at dim-5

$$-\mathcal{L}_{\rm LFV,II} = \frac{\tilde{k}_{ij}}{\Lambda}\Phi \bar{L}_i H \ell_j + \frac{\tilde{k}'_{ij}}{\Lambda}\Phi^* \bar{L}_i H \ell_j + \text{h.c.}$$



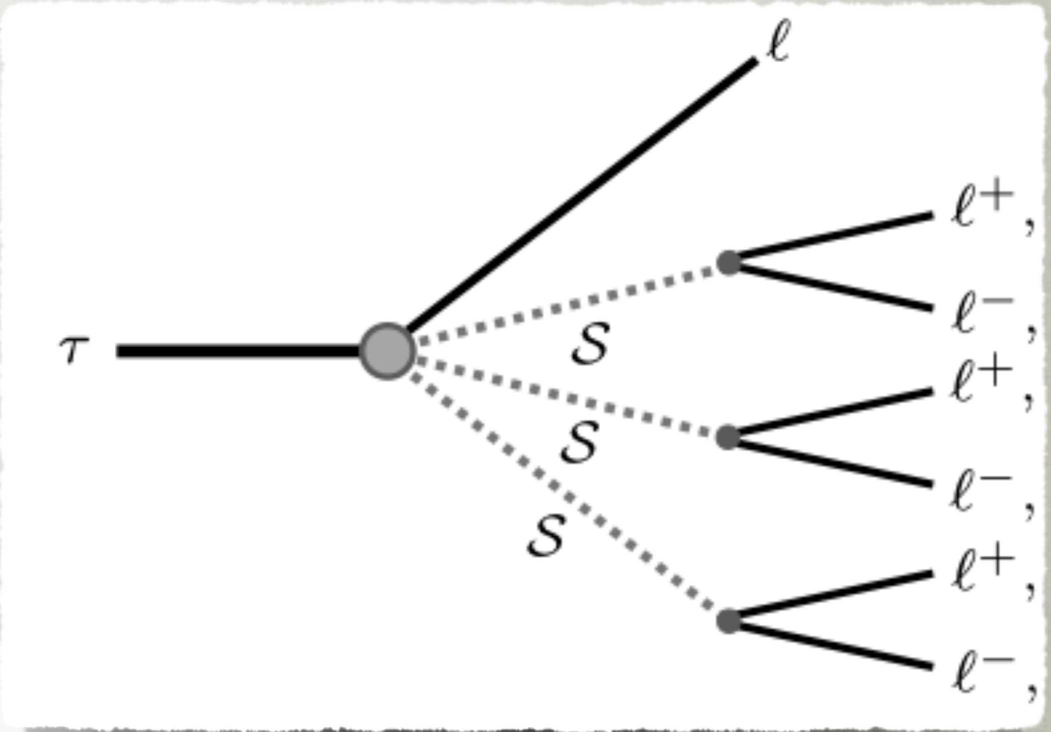
- example: $U(1)' = L_\mu - L_\tau$
- two benchmarks:
  - $[\Phi]_{L_\mu - L_\tau} = 2 \Rightarrow \tau \to \mu\phi$
  - $[\Phi]_{L_\mu - L_\tau} = 1 \Rightarrow \tau \to e\phi$
- Z' decays also to neutrinos

$$\frac{\Gamma(\tau \to \ell + 4\mu)}{\Gamma(\tau \to \ell + 2\mu + 2\nu)} \simeq 0.5, \quad \ell = e, \mu,$$

- parametrically higher scales probed

$$\text{Br}(\tau \to \ell_i \phi) \simeq 10^{-8} \cdot \kappa_{i3}^2 \cdot \left(\frac{10^{11}\,\text{GeV}}{\Lambda_5}\right)^2$$

FLAVOR PROTECTED SCALAR



- global $U(1)^3_\ell \equiv U(1)_e \times U(1)_\mu \times U(1)_\tau$ broken by two spurions
  - $[\varepsilon_\tau]_{L_\tau} = -\frac{1}{3},\ [\varepsilon_\mu]_{L_\mu} = -1$
  - leading couplings to SM leptons

$$\mathcal{L} \supset \frac{\mathcal{C}^{(3)}_{\mathcal{S}}}{\Lambda^3}\,\bar{\ell}_2 H e_3\,\mathcal{S}^3 + \frac{\mathcal{C}_{\mu\mathcal{S}}}{\Lambda}\bar{\ell}_2 H e_2 \mathcal{S} + \frac{\mathcal{C}_{e\mathcal{S}}}{\Lambda}\bar{\ell}_1 H e_1 \mathcal{S} + \text{h.c.}\,.$$

  - suppressed by only linear powers of spurions

$$\mathcal{C}^{(3)}_{\mathcal{S}} \sim \mathcal{O}(\varepsilon_\mu) \qquad \mathcal{C}_{\mu\mathcal{S}} \sim \mathcal{C}_{e\mathcal{S}} \sim \mathcal{O}(\varepsilon_\tau)$$

- for $\varepsilon_\tau \ll m_\tau/(4\pi\Lambda)$ the $\tau \to \ell S$ and $\tau \to \ell 2S$ are parametrically suppressed
  - the leading exotic LFV decay is $\tau \to 7\ell$ and not $\tau \to 5\ell$ or $\tau \to 3\ell$

Ema, Fox, Hostert, Menzo, Pospelov, Ray, JZ, to appear

OTHER COMMENTS

- higher dim. FCNC operators may induce other decays not just taus
- depends on the UV theory/flavor structure
  - e.g.: in dark photon +FCNCs
  - both couplings to quarks and leptons allowed by U(1)'

$$-\mathcal{L} \supset \frac{\kappa_{ij}}{\Lambda^2} |\Phi|^2 \bar{L}_i H \ell_{Rj} + \text{h.c.},$$

$$-\mathcal{L} \supset \frac{\kappa^u_{ij}}{\Lambda^2} |\Phi|^2 \bar{Q}_i H u_{Rj} + \frac{\kappa^d_{ij}}{\Lambda^2} |\Phi|^2 \bar{Q}_i \tilde{H} d_{Rj} + \text{h.c.},$$

  - in principle also $\mu \to 5e$, $B \to K4\ell$, $D \to \pi 4\ell$, ... signatures

Greljo, Palavric, Tunja, JZ, 2510.08674

- in other models, however, only tau decays
  - e.g. in flavor protected scalar, only $\tau \to$ multi lepton decays
  - same for $L_\mu - L_\tau$ model

TIME DEPENDENT

$$\tau \to \ell\phi$$

NON-ABELIAN PNGB

Bigaran, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 2503.07722

- if DM a non-Abelian pNGB the interactions with the SM of the form

$$\mathcal{L}_{\rm int} \supset \frac{i\phi\,(\partial_\mu \phi)}{2f^2}\,\bar{\ell}_i \gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5)\ell_j,$$

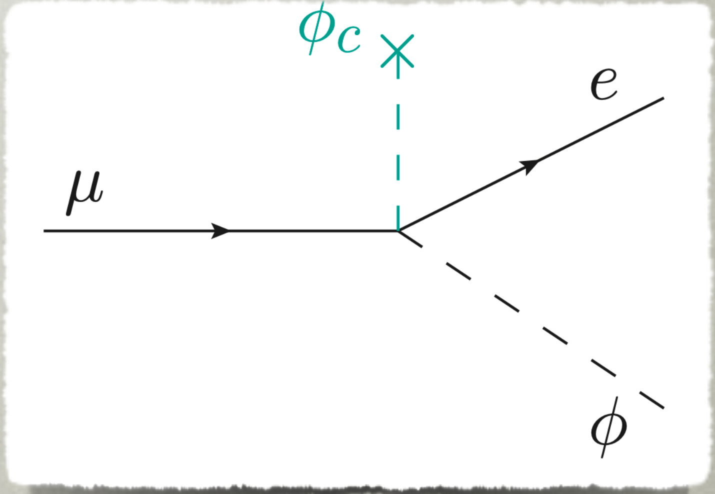
  - an example in the SM: $\pi^\pm$ interacting with electrons/positrons via photon exchange

- classical ϕ background induces time dependent $\mu \to e\phi$ decays

$$\phi_c(t) = \phi_0 \cos(m_\phi t + \delta),$$

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \simeq 2.5\,\text{TeV}\left(\frac{10^{-15}\,\text{eV}}{m_\phi}\right)$$

  - time dep. searches can be more sensitive ⇔ for systematics dominated searches
  - time dep. a smoking gun signal of DM



TIME DEPENDENT SEARCHES

Bigaran, Fox, Gouttenoire, Harnik, Krnjaic, Menzo, JZ, 2503.07722

- coherency over $\mathcal{O}(v^{-2}) \sim 10^6$ oscillations
- as an example assume continuous data taking and using χ^2 test on Asimov test
  - in exp. searches could do Lomb-Scargle periodogram
  - examples for Mu3e ($\mu \to e\phi$) and Belle-II ($\tau \to \ell\phi$)

T IES

Menzo, JZ, 2503.07722

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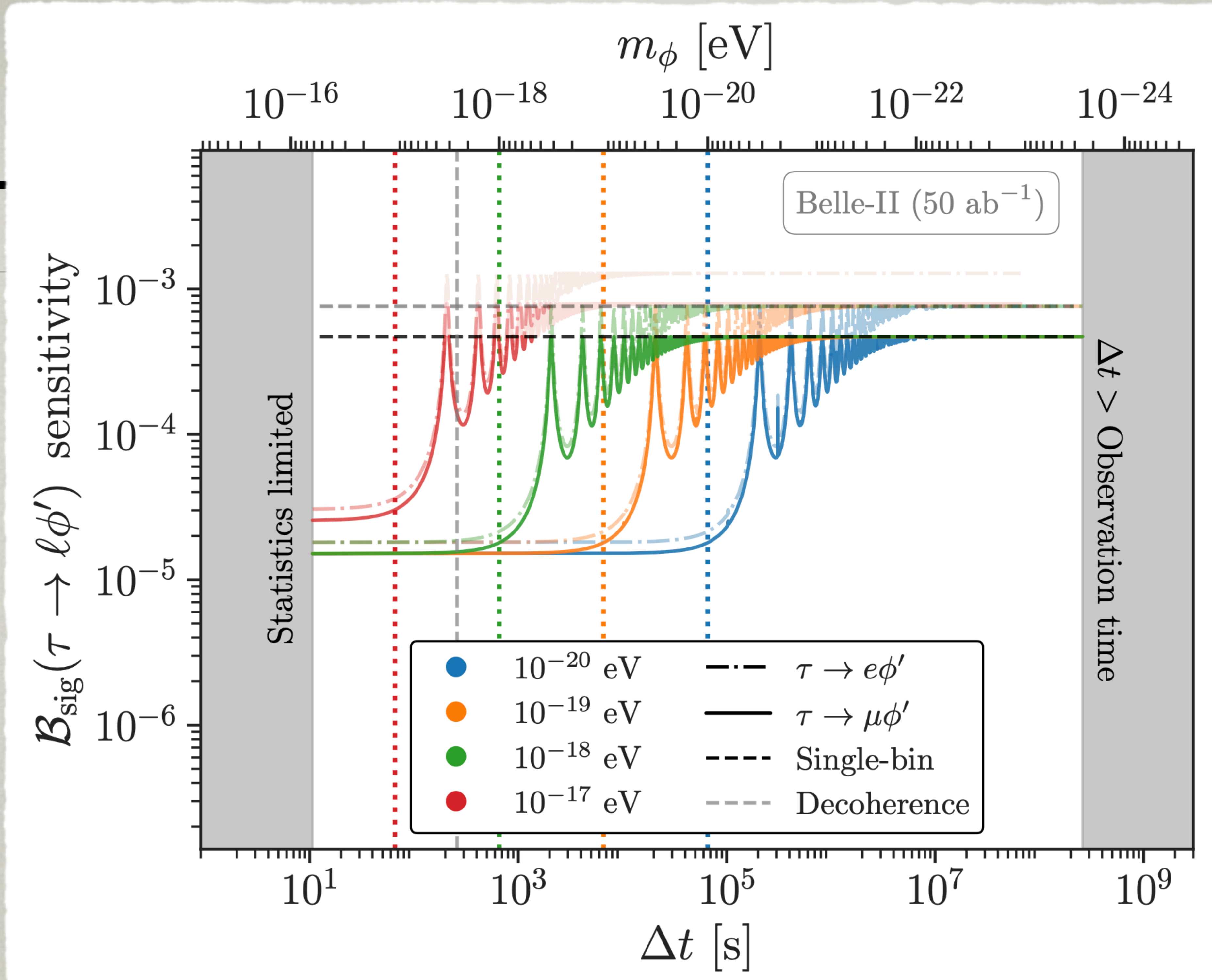
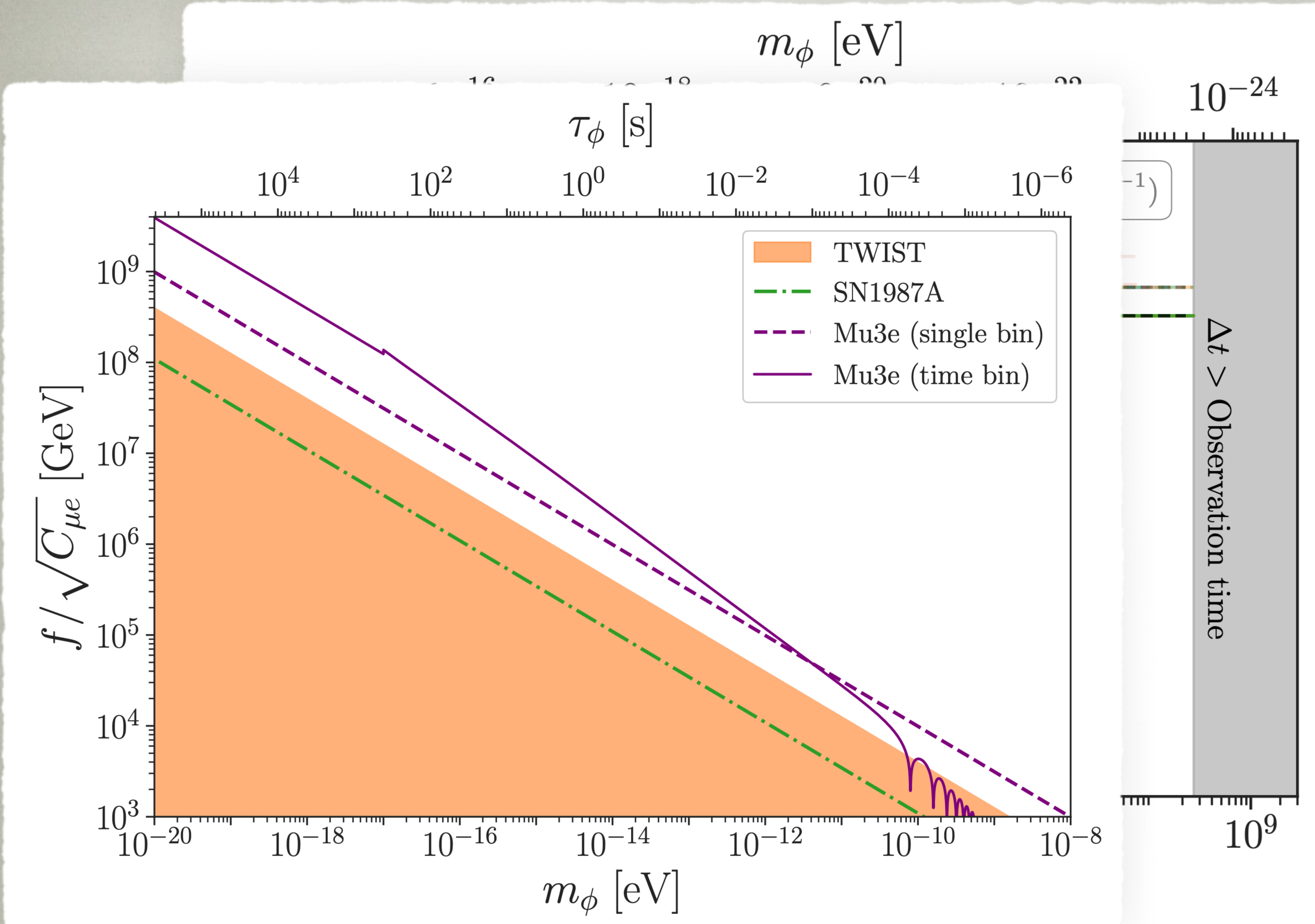


- examples for Mu3e ($\mu \to e\phi$) and Belle-II ($\tau \to \ell\phi$)



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Menzo, JZ, 2503.07722

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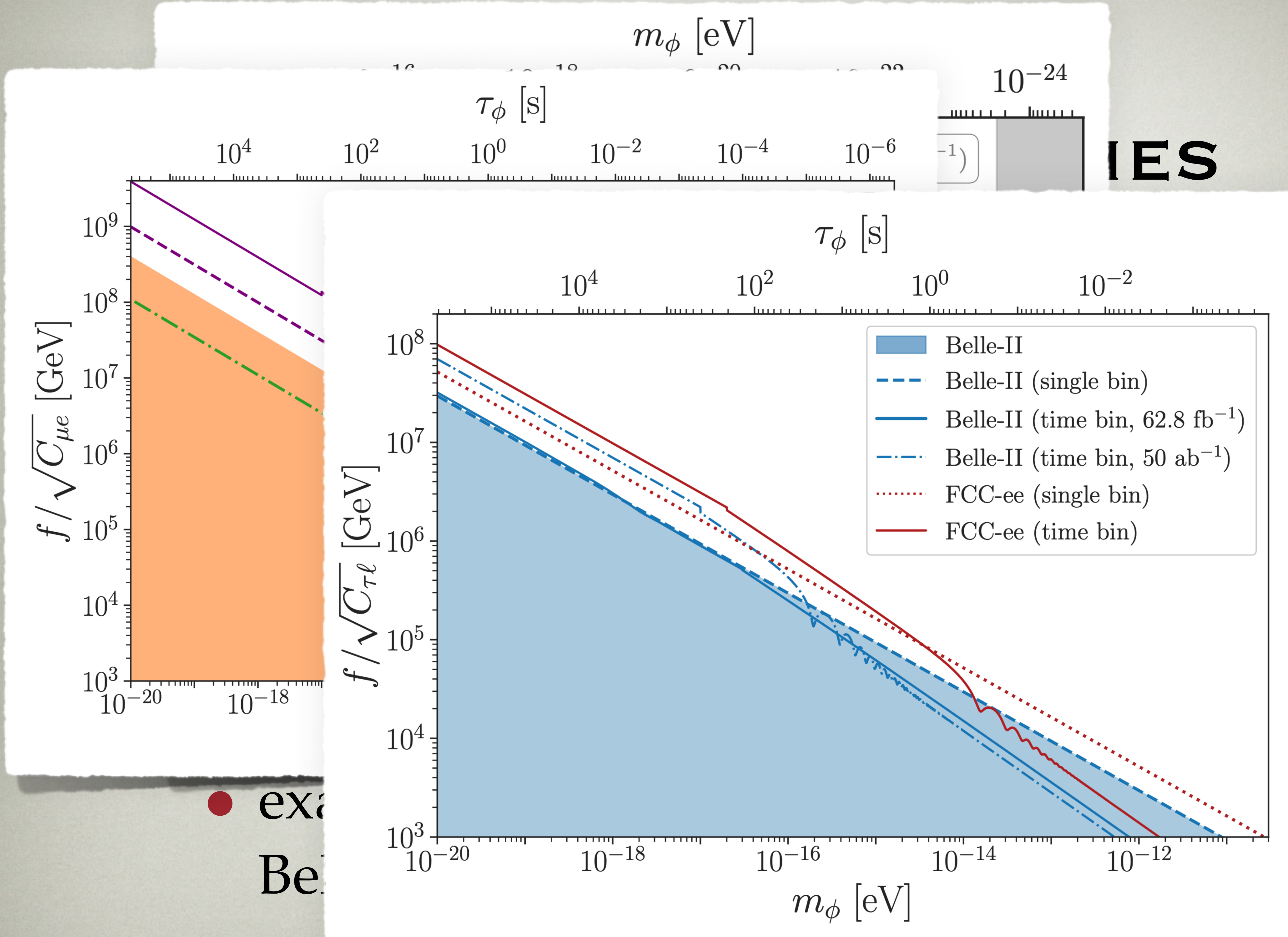

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CONCLUSIONS

- light new physis in rare tau decays can probe very high new physics scales
- presented several models that would lead to $\tau \to 5\ell$ and $\tau \to 7\ell$ signatures
- ultra light dark matter can lead to time dependent tau and muon decays

BACKUP SLIDES