INT Workshop INT-24-87W
Electroweak and Beyond the Standard Model Physics at the EIC
February 12-16 2024

BSM Searches at the Intensity Frontier — Theoretical Overview

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University of Washington

INSTITUTE for NUCLEAR THEORY

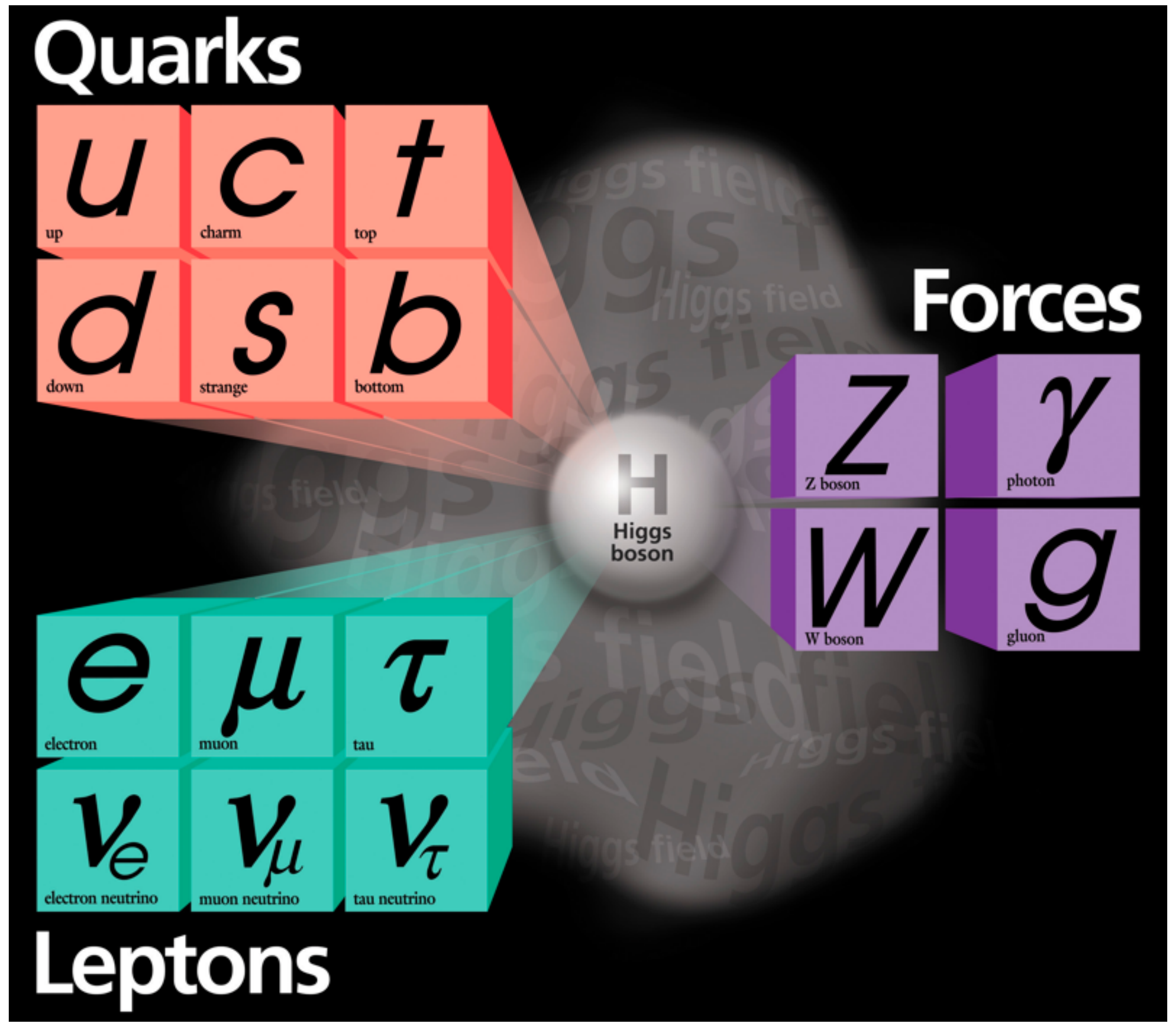
Outline

- The quest for new physics and the intensity frontier
- Beyond the Standard Model searches at the intensity frontier: the landscape
- Outlook: the EIC as an intensity frontier machine

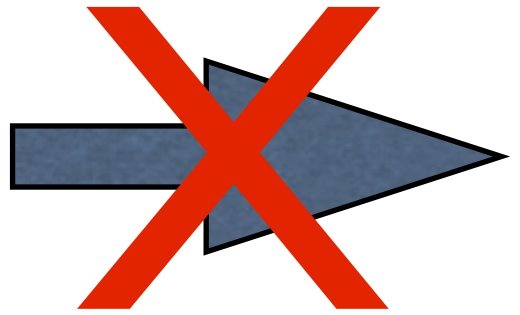
Many thanks to Krishna Kumar and my collaborators!

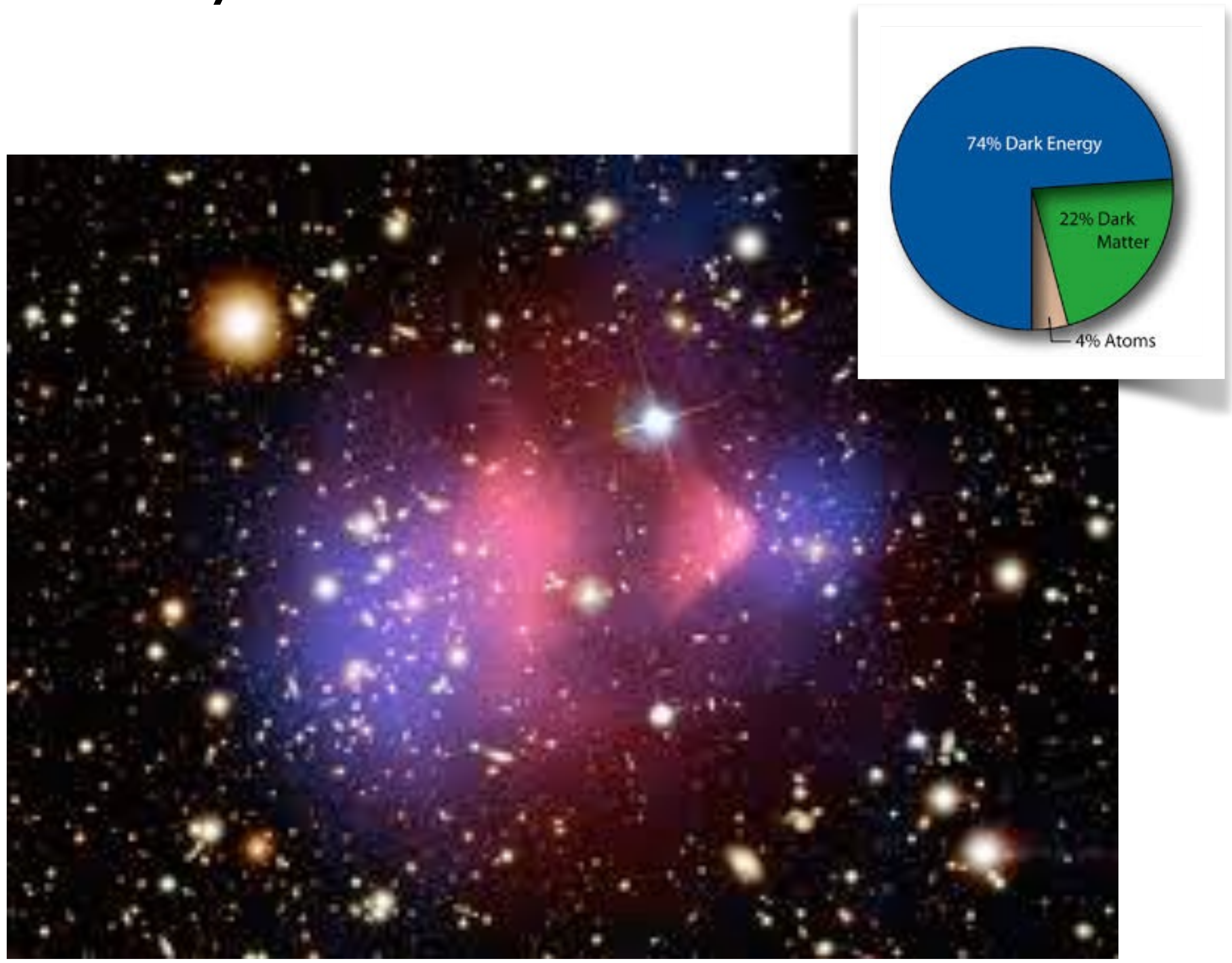
New physics: why?

- The SM is remarkably successful, but it’s not the whole story



Credit: Fermilab





Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

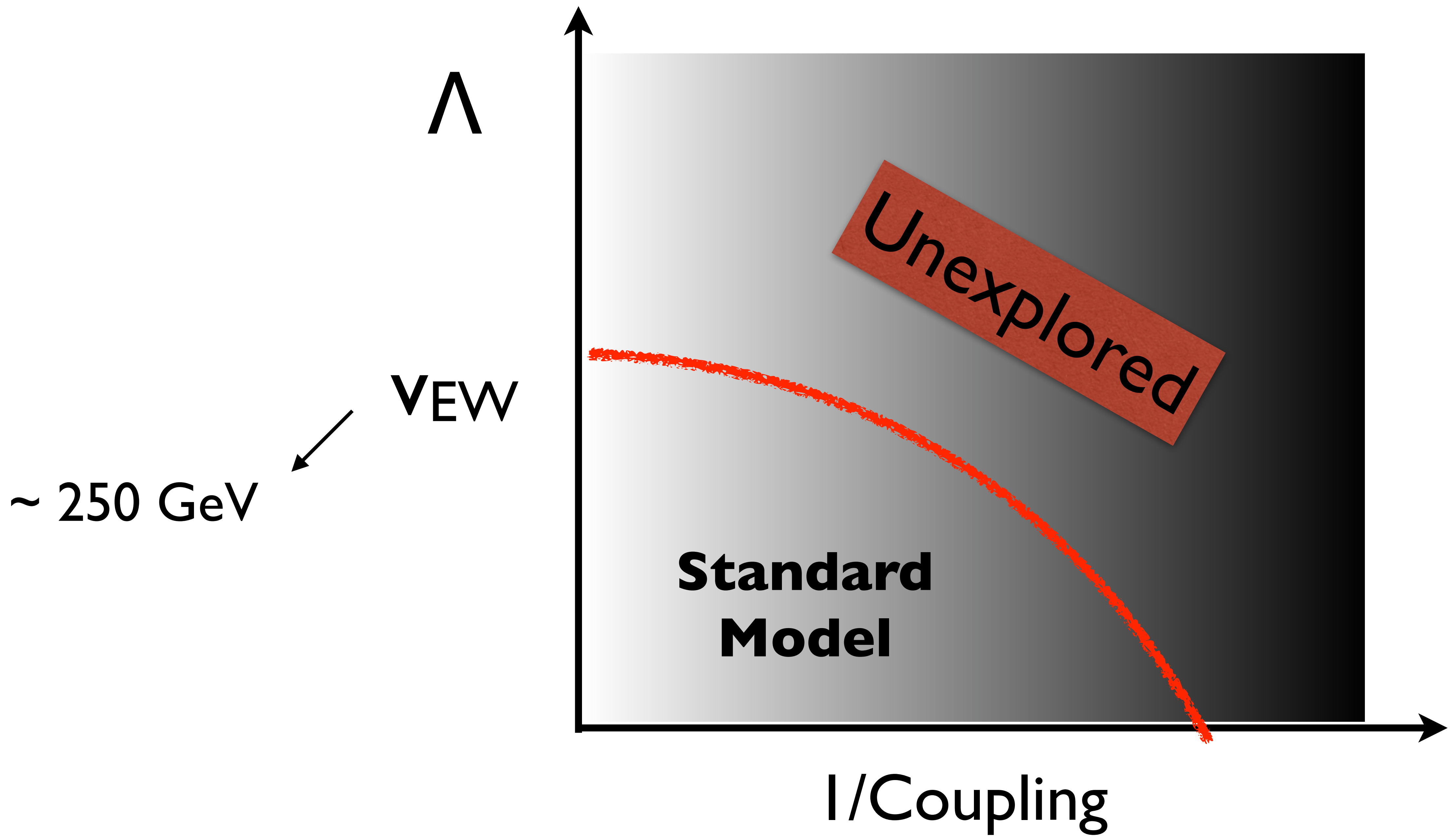
No Baryon Asymmetry, no Dark Matter, no Dark Energy, no Neutrino Mass

Origin of flavor, Strong CP problem, Unification,…

Addressing these puzzles requires new physics

New physics: where?

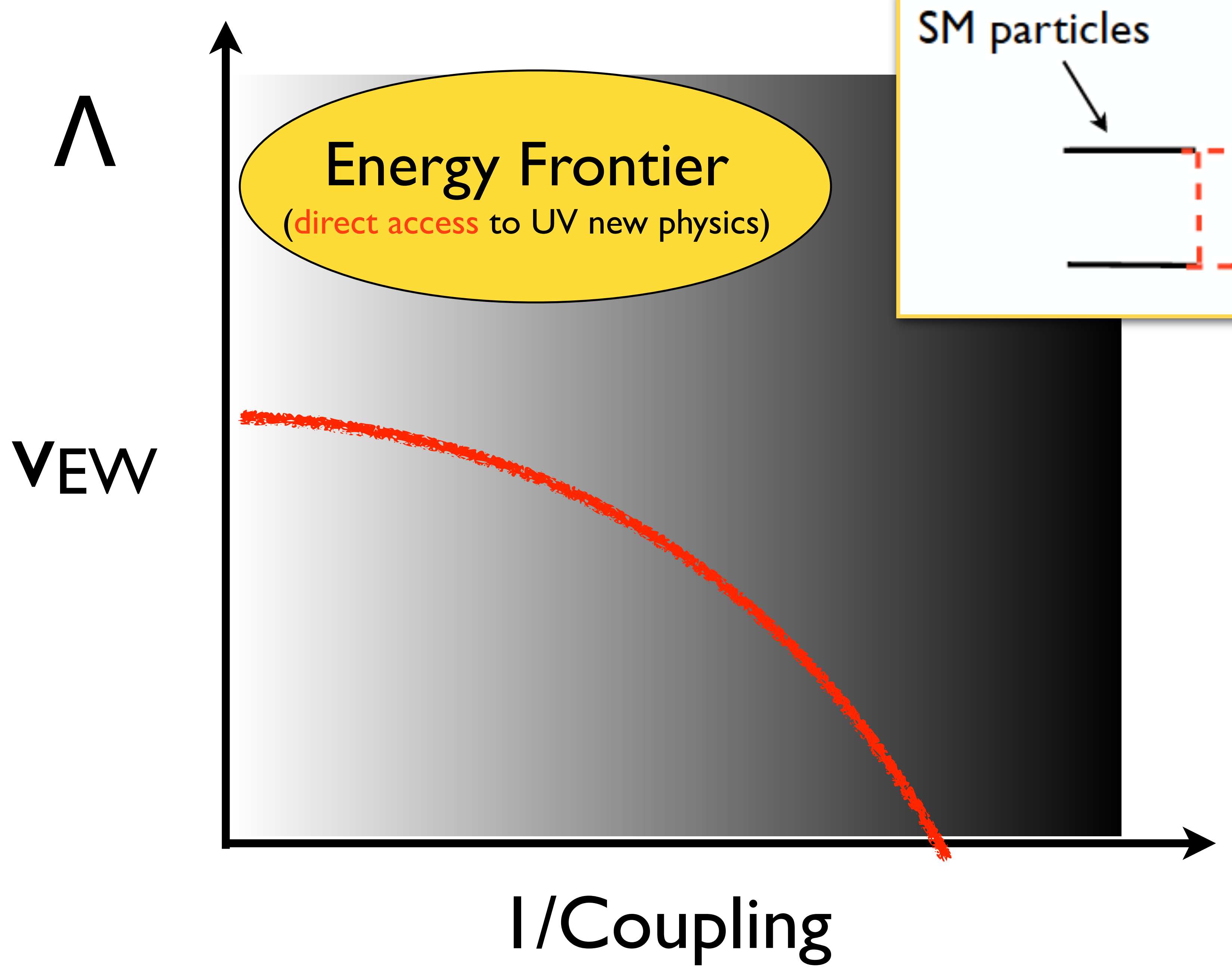
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

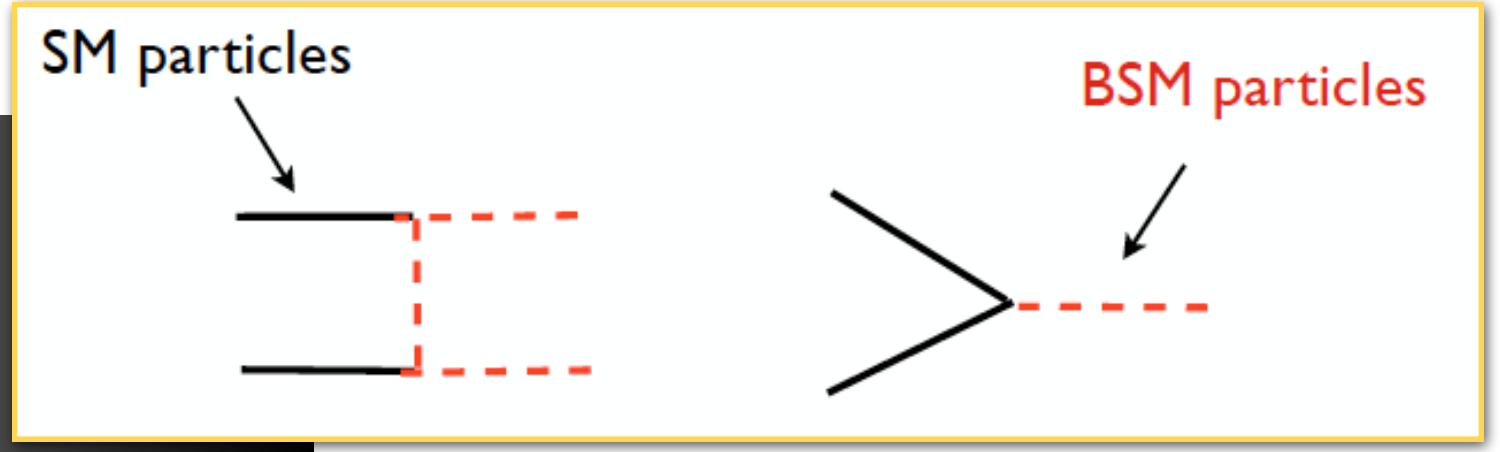


New physics: how?

- Two complementary paths to search for new physics

$$E = mc^2$$





See talk by
Michael Ramsey-Musolf

New physics: how?

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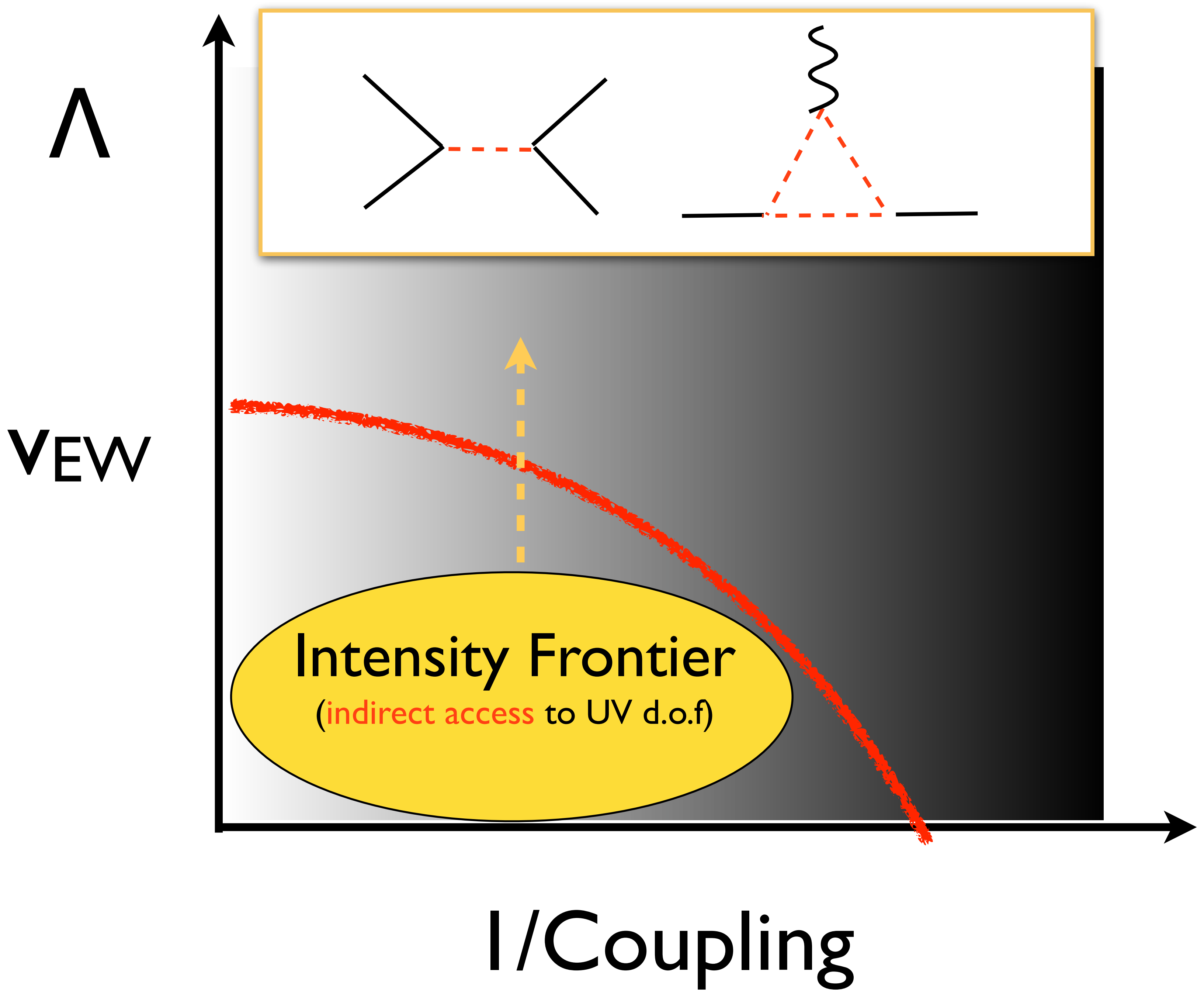
$$\Delta E\,\Delta t \sim h$$



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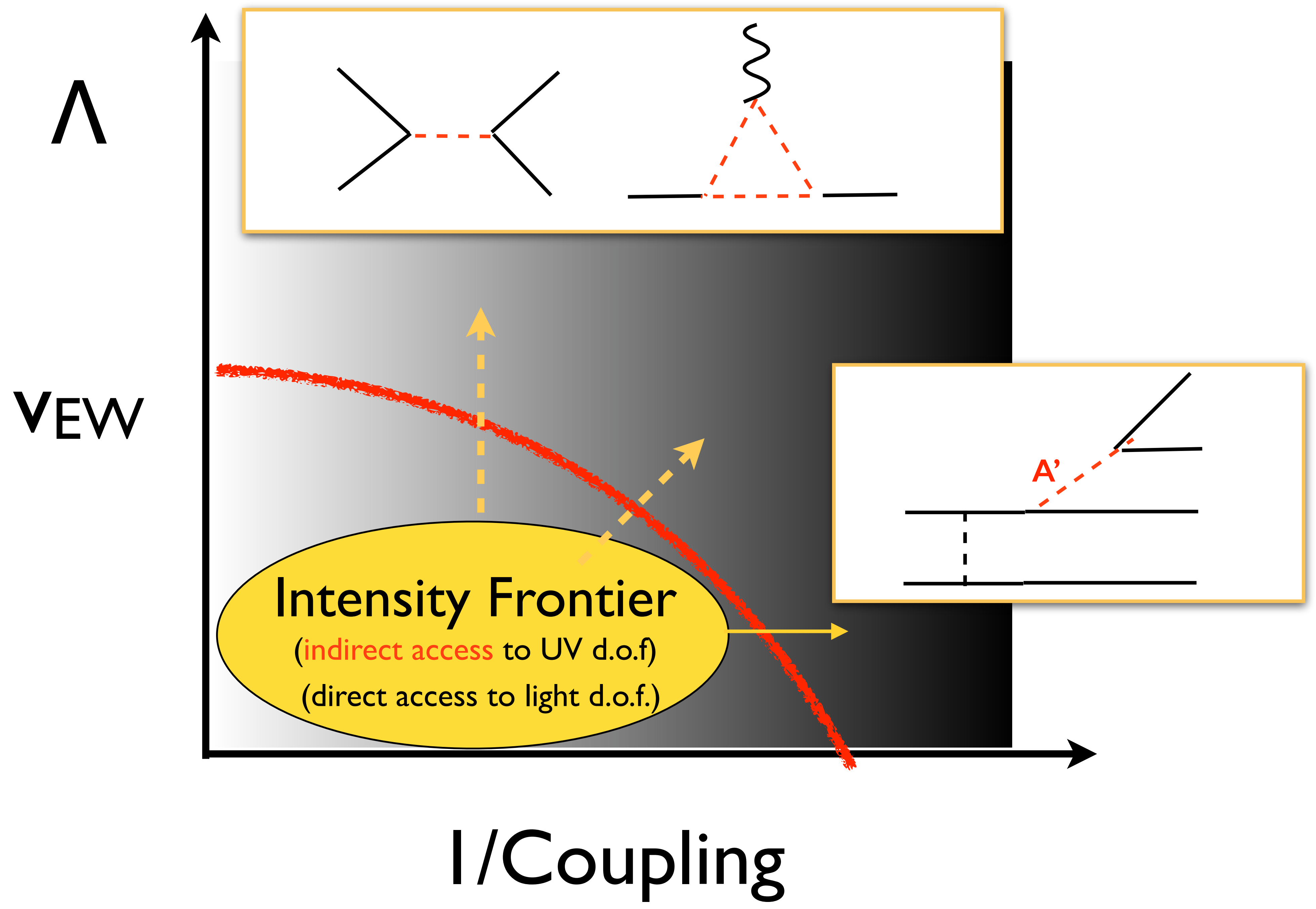
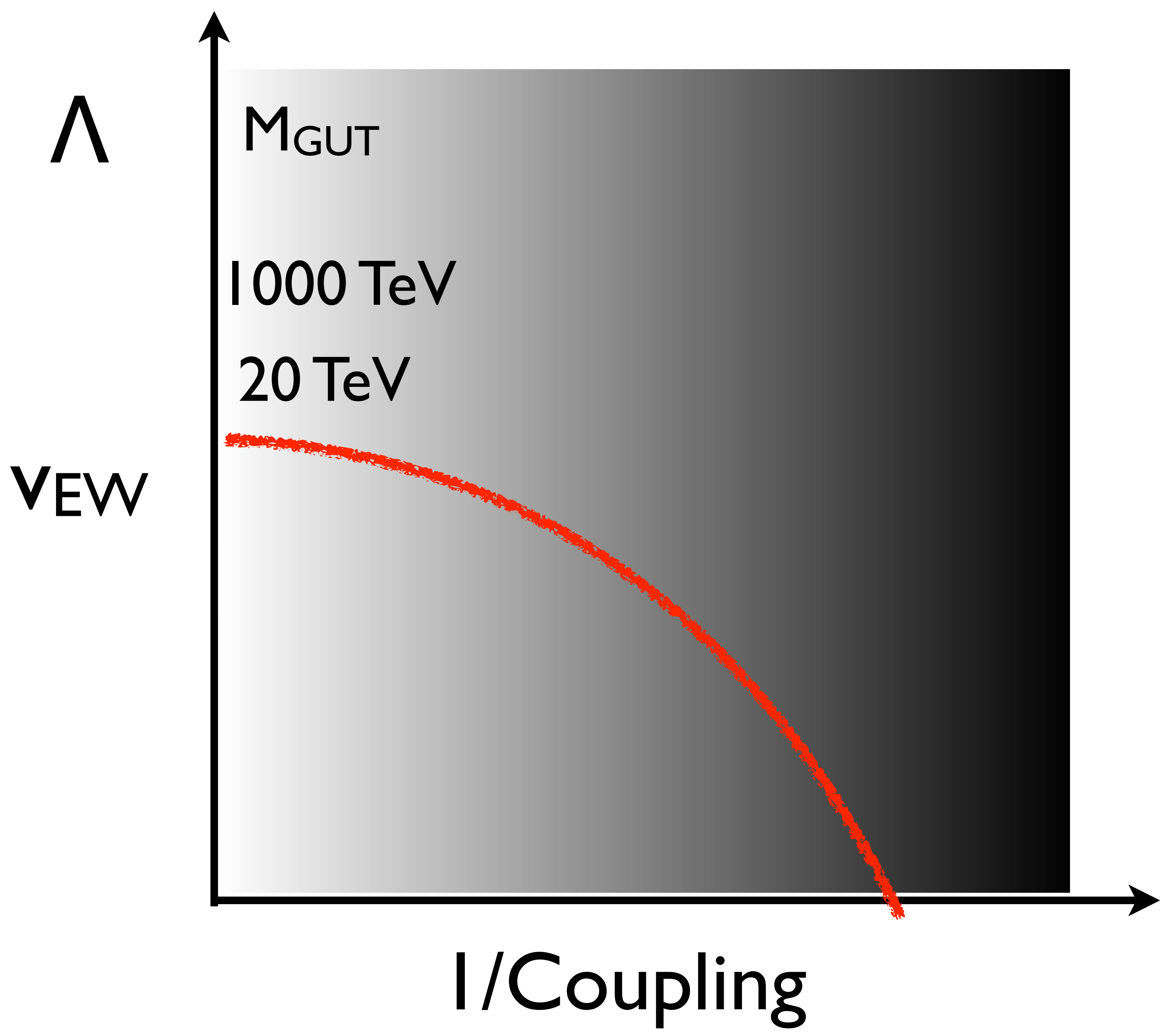


BSM probes @ the Intensity Frontier

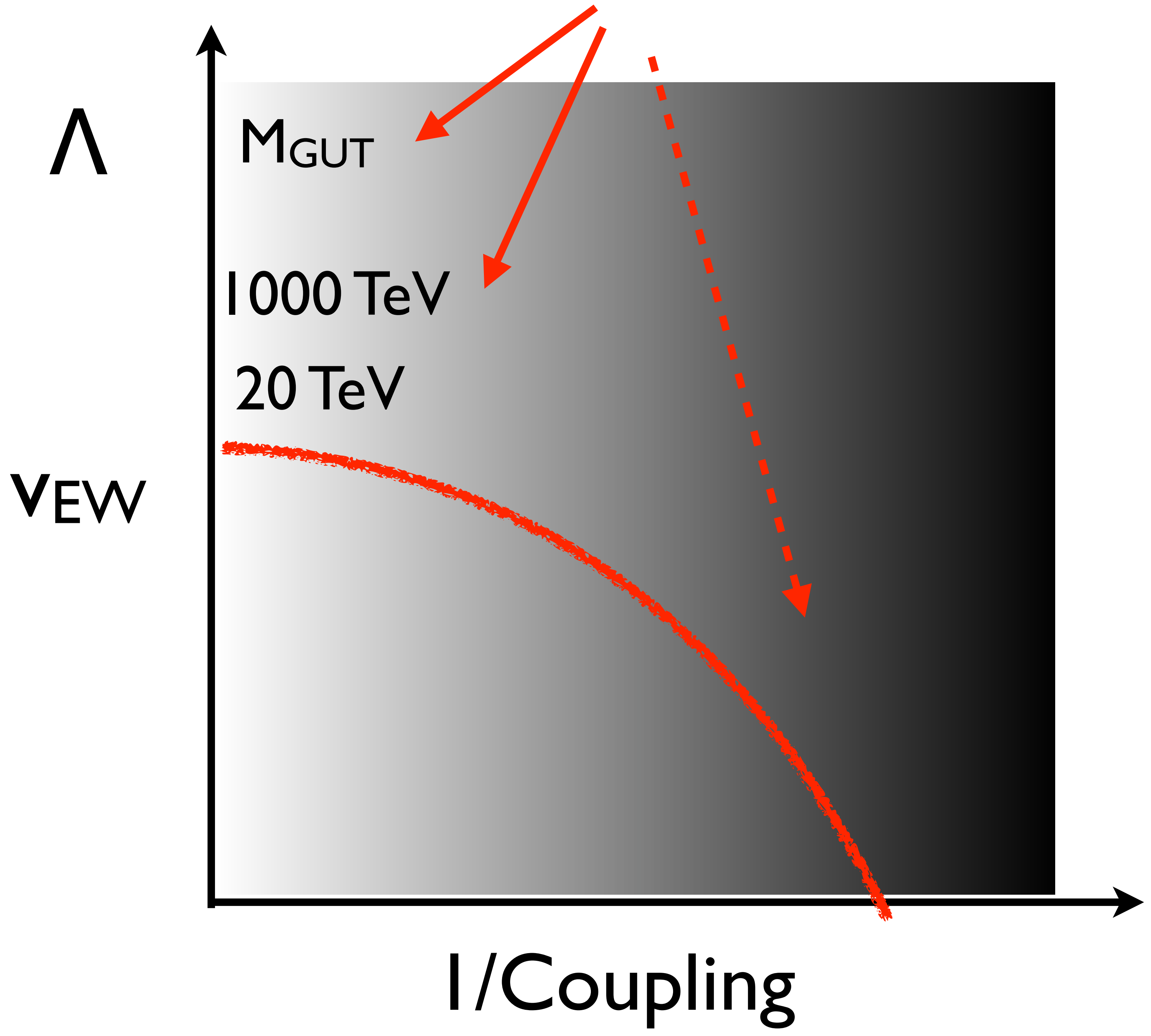
- Three classes, pushing the boundary in qualitatively different ways and at different mass scales



BSM probes @ the Intensity Frontier

- Three classes, pushing the boundary in qualitatively different ways and at different mass scales

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, p decay, EDMs, LFV ($\mu\to e$ conversion, $ep\to\tau X$), …



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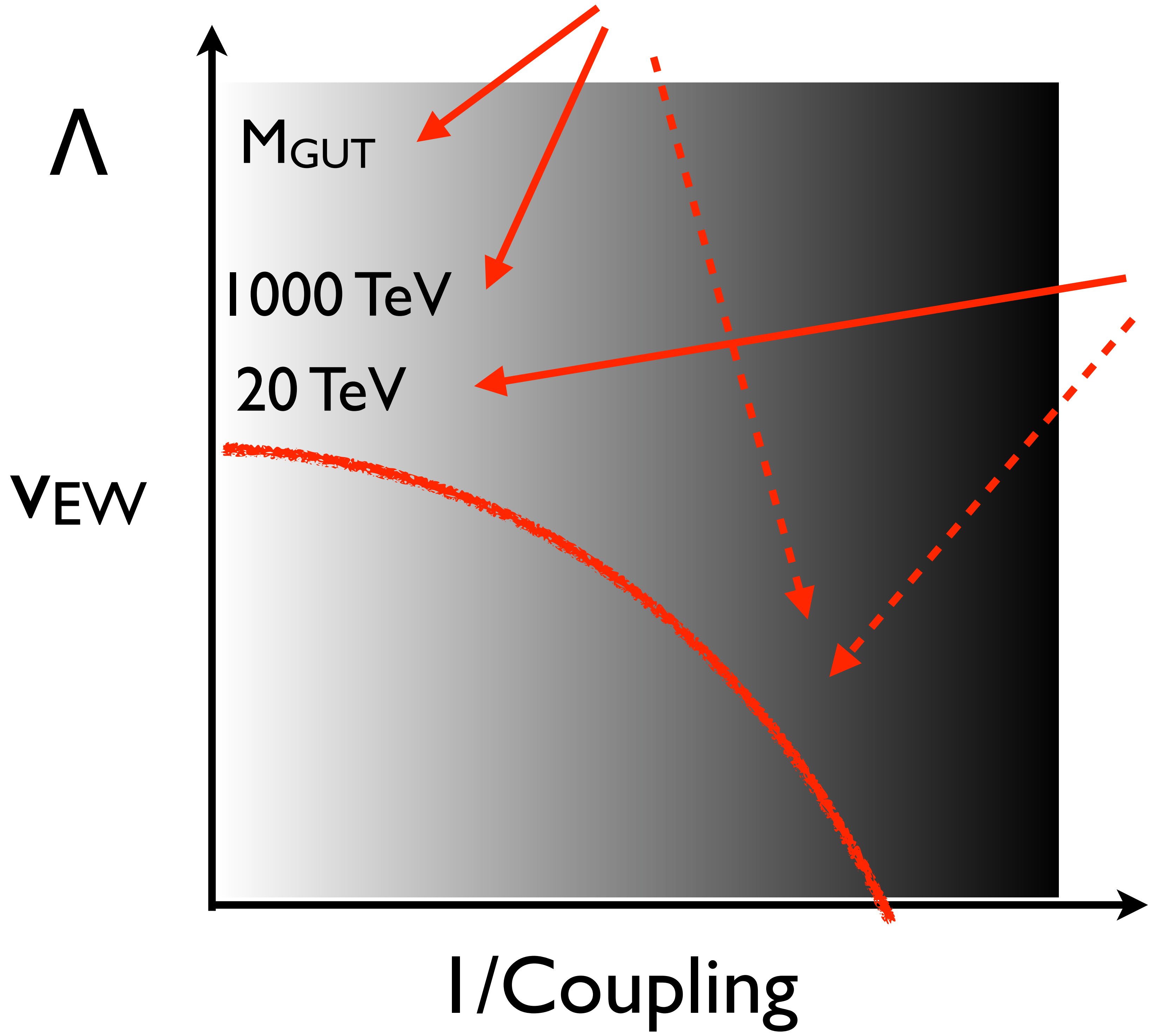

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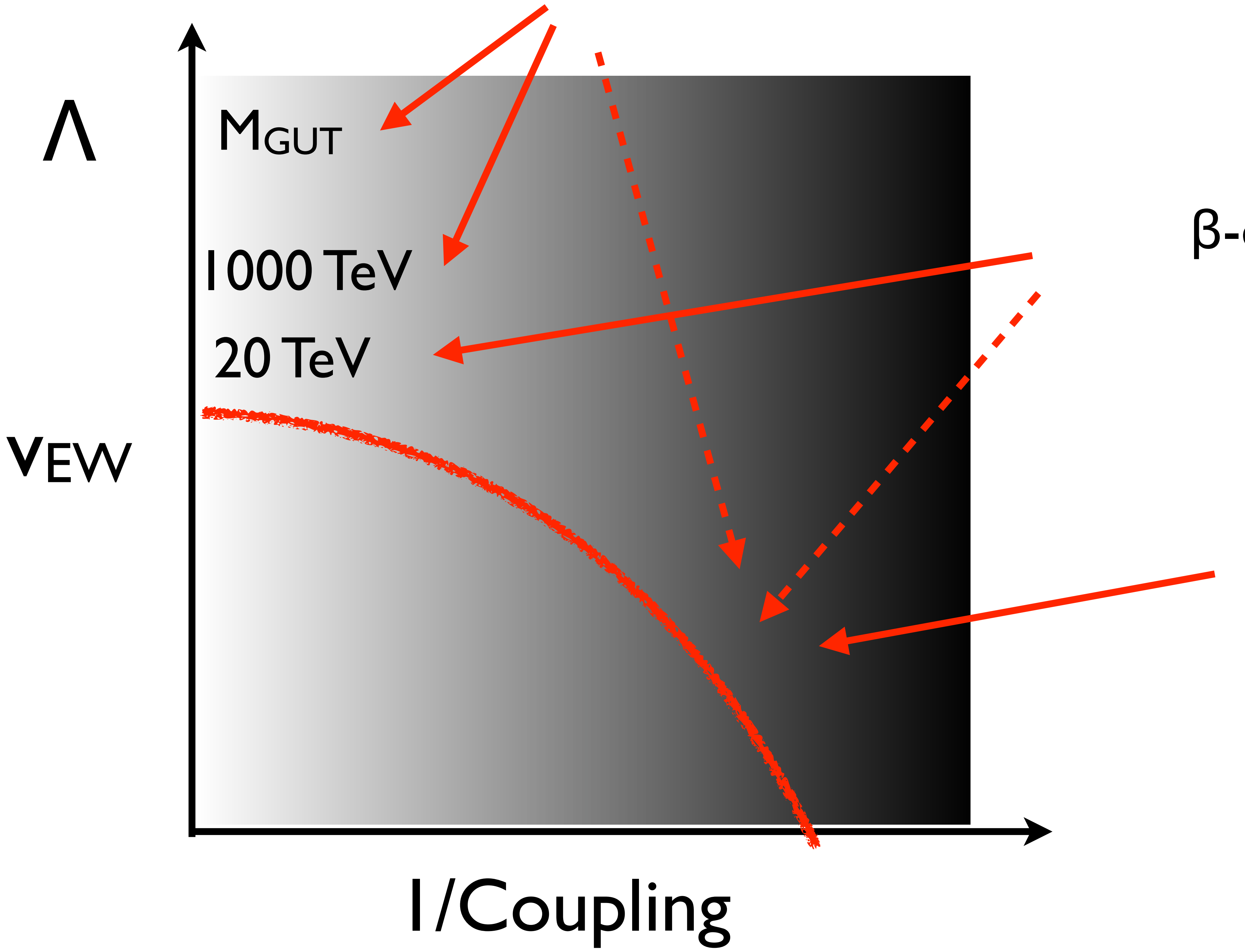

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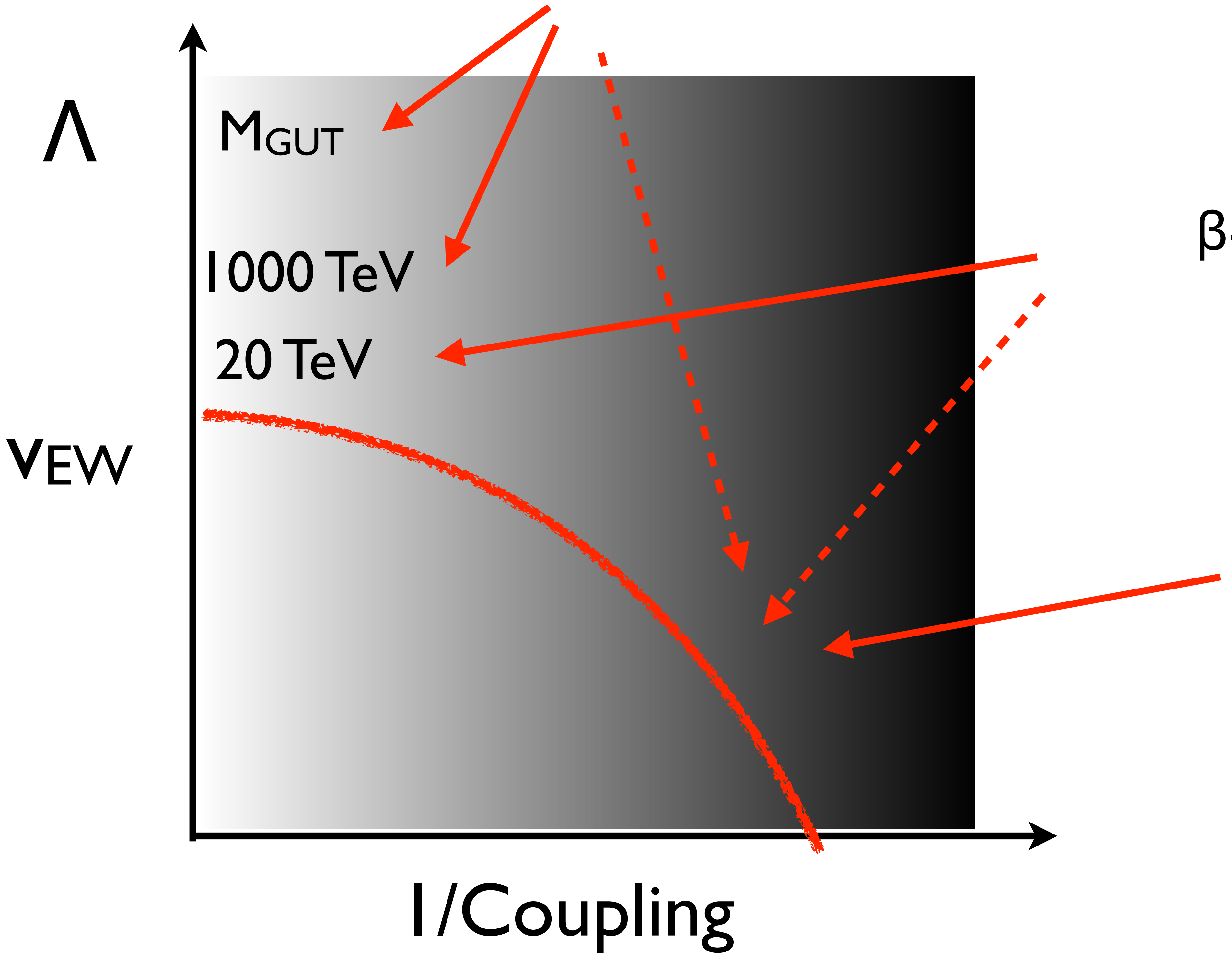

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The EIC can play a role in all three classes

Impact of searches at the Intensity Frontier

- Discovery potential
  - Explore physics that is otherwise difficult / impossible to access: high mass scale; symmetry breaking; ultralight particles
  - A single deviation from SM expectation → new physics!

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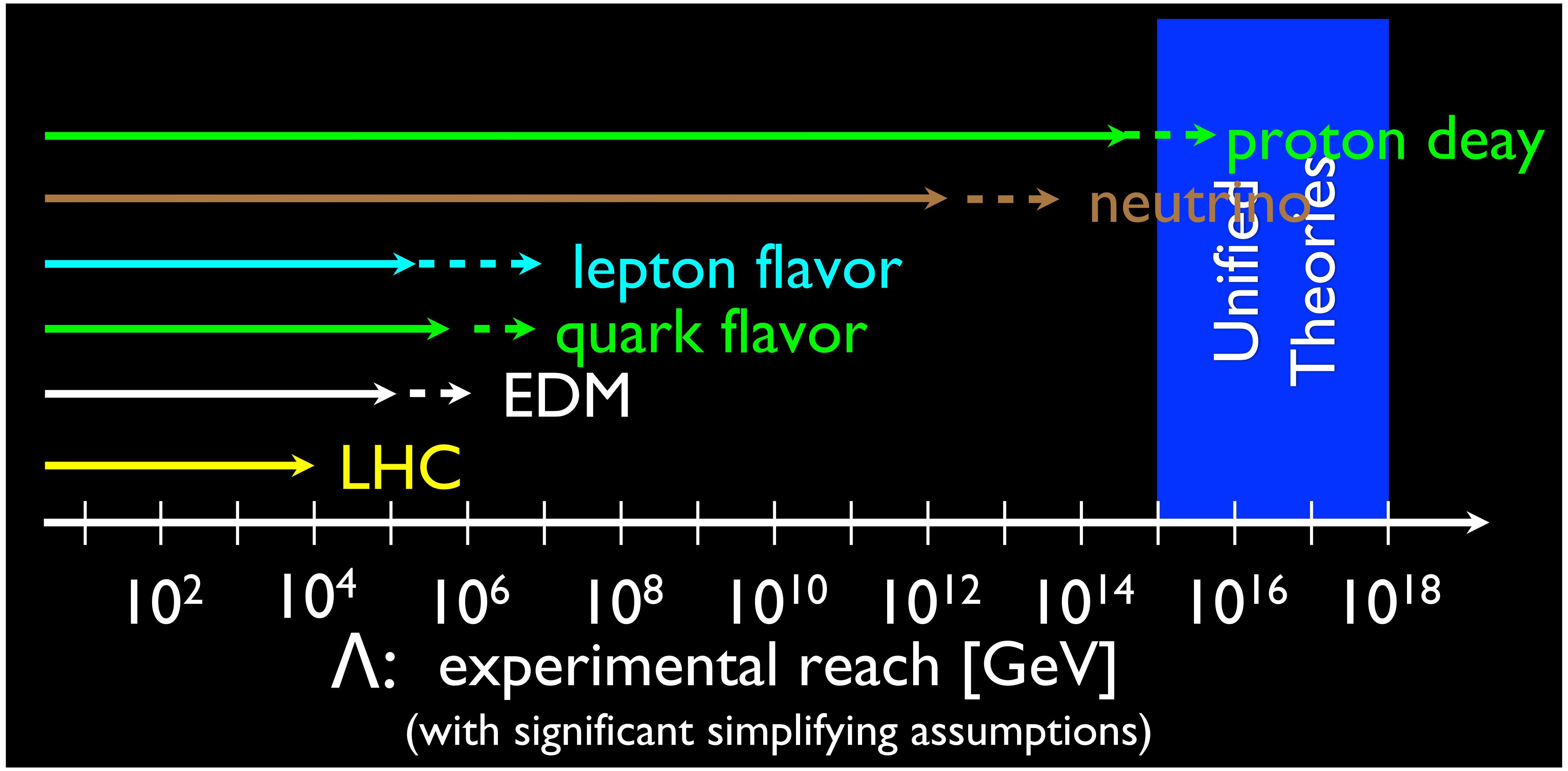
$$\delta M_{\mathrm{BSM}}(\Lambda) = M_{\mathrm{exp}} - M_{\mathrm{SM}}$$

$$\delta M_{\mathrm{BSM}}(\Lambda) \propto 1/\Lambda^2,\ 1/\Lambda^4,\ \ldots$$



From Hitoshi Murayama

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- Diagnosing power when combining multiple probes
  - Multiple EDM searches → underlying sources of CP violation
  - $0\nu\beta\beta$ decay, absolute ν mass measurements, ν oscillations, LFV ($\mu \to e$, $e \to \tau$, …) → origin of neutrino mass
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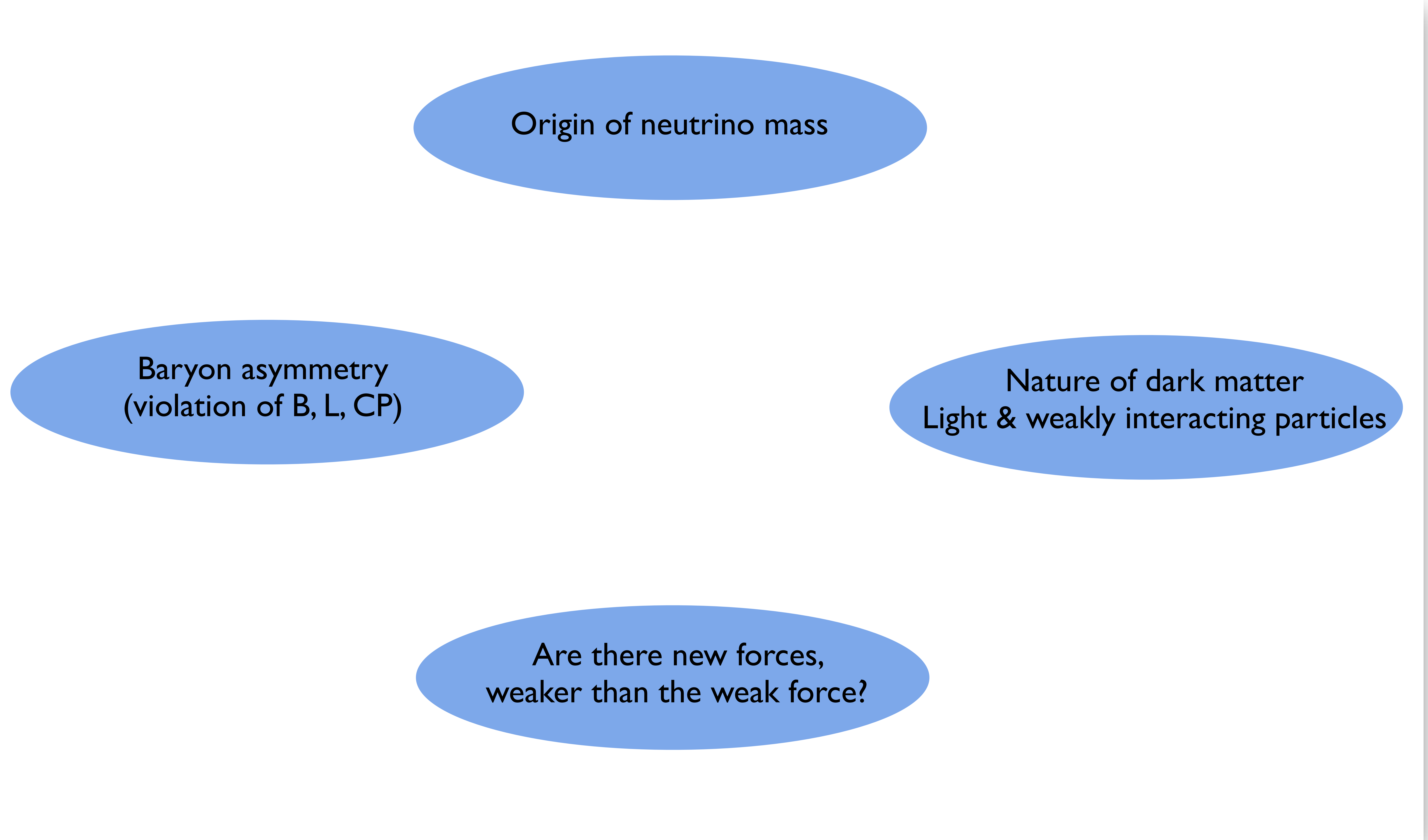
- Connection to open questions

Shedding light on open questions

Intensity Frontier probes cluster around open questions*



Shedding light on open questions

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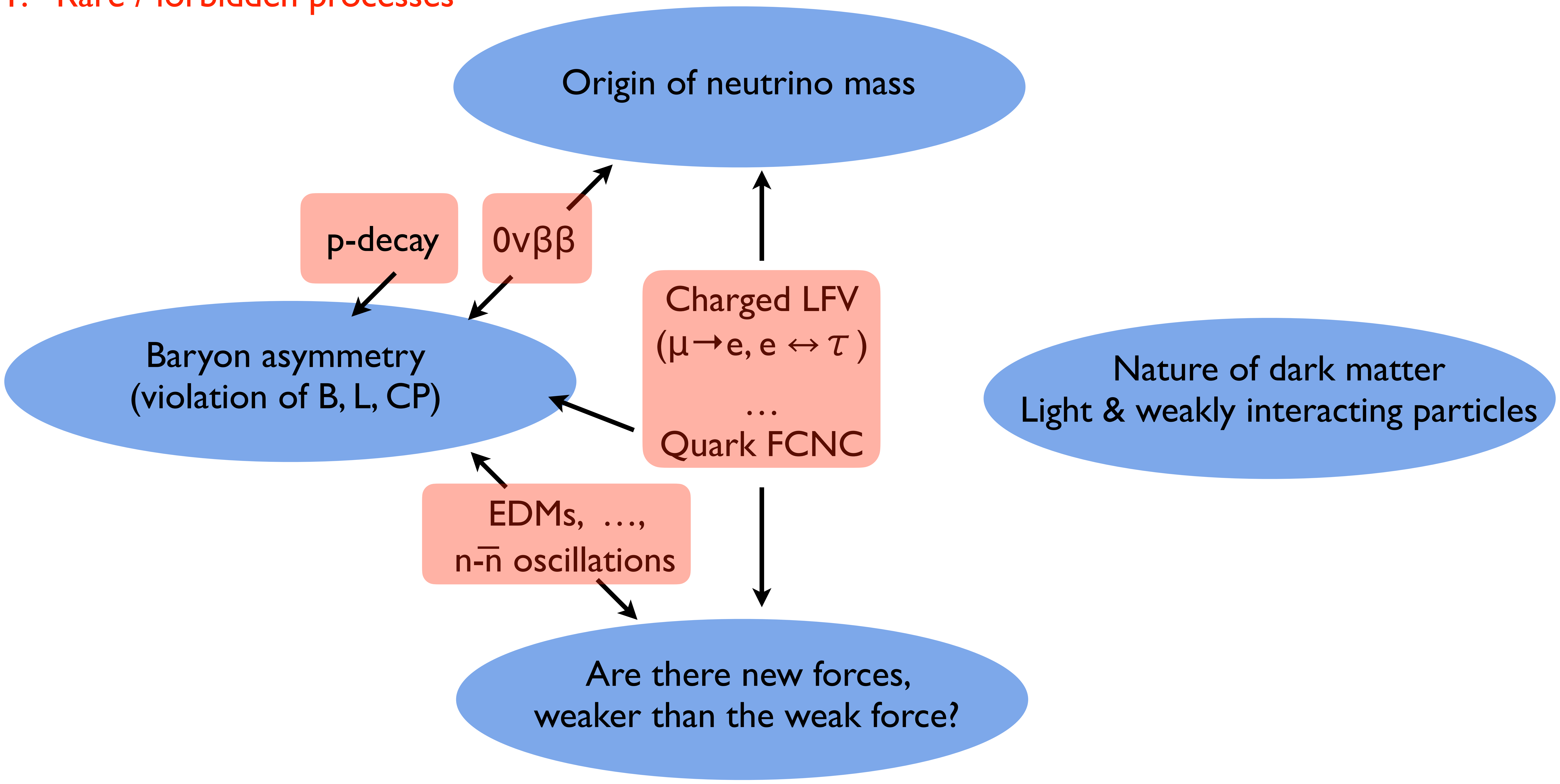
1. Rare / forbidden processes



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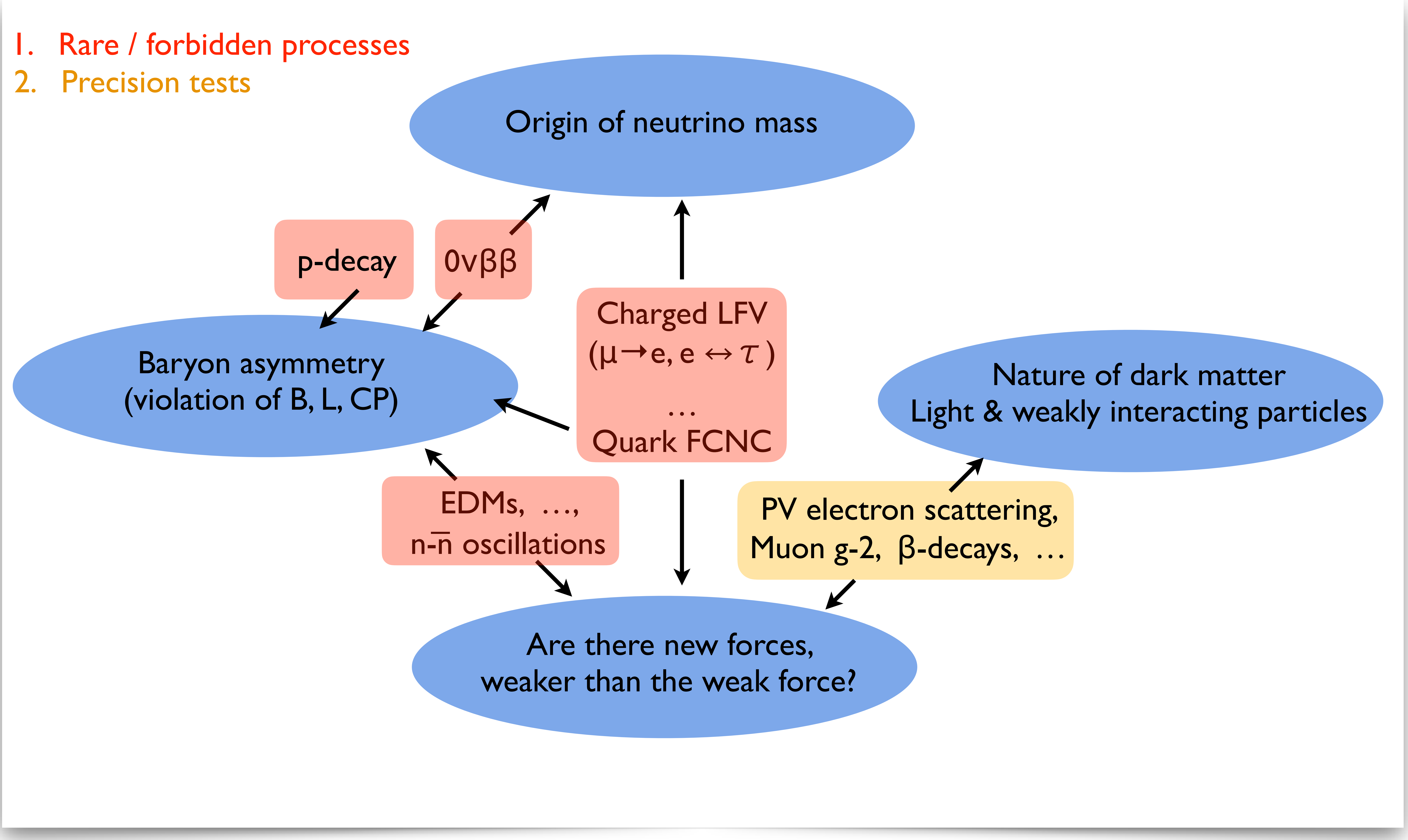

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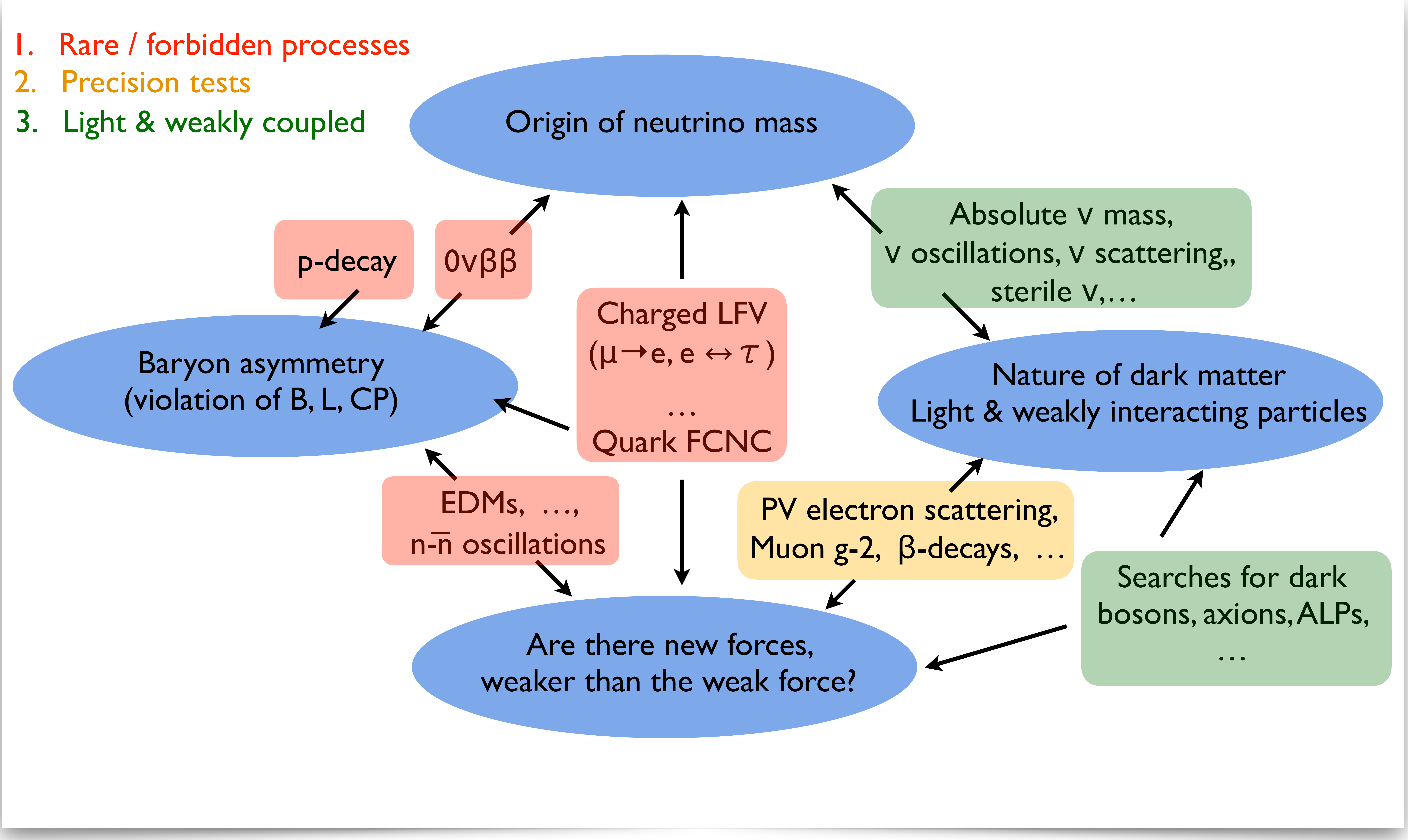

The Intensity Frontier in NP and HEP

- IF in the 2023 NSAC Long Range Plan (NP)

"Fundamental Symmetries, Neutrons, and Neutrinos"

- Searches for rare / SM-forbidden processes:
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    - LFV in muon (Mu2e) and tau decays (Belle-II)
    - Flavor physics: Belle-II, LHCb
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    - High-Luminosity LHC (ATLAS, CMS)
    - Higgs factory
    - …
- Search / characterization of light weakly coupled particles
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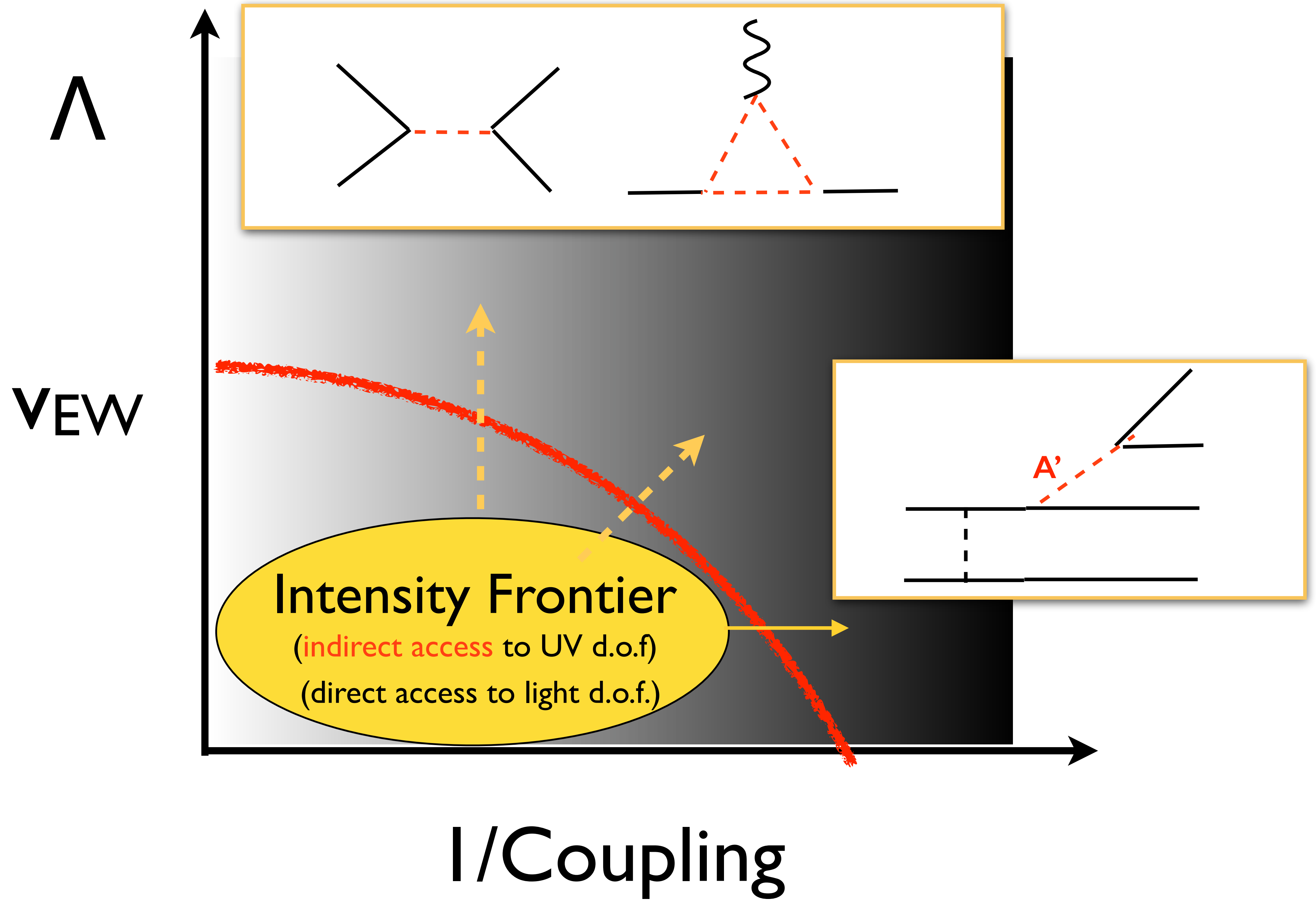
In the rest of this talk: selected IF probes (with emphasis on NP and an eye towards the EIC)

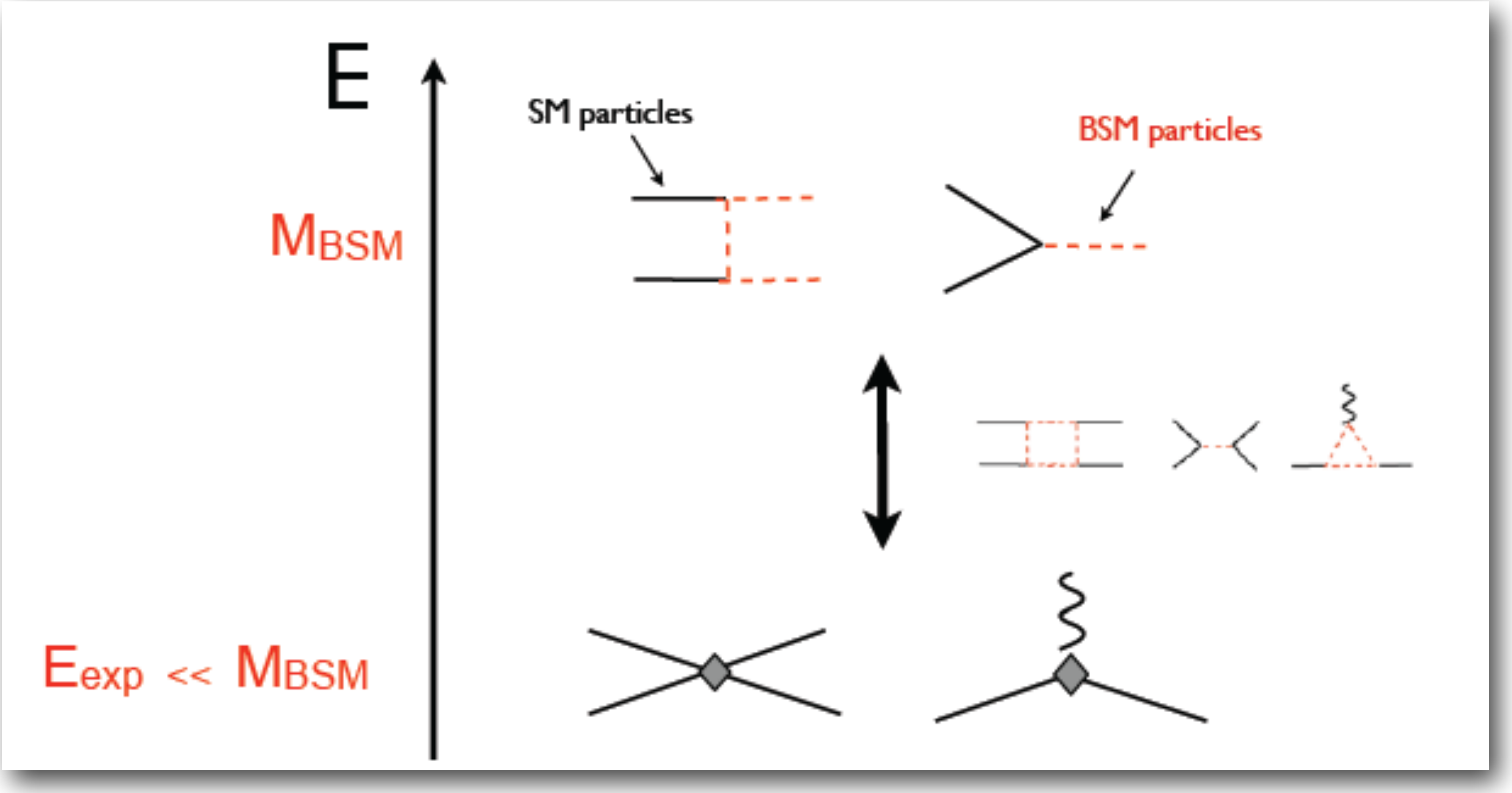
Interlude: theory framework



To motivate and analyze intensity frontier searches,
fairly general EFT-based theory framework(s) have emerged,
encompassing many underlying models

UV: the Standard Model Effective Field Theory

Heavy new particles affect low-energy physics through local operators
suppressed by inverse powers of heavy scale



Appelquist-Carazzone 1975, Weinberg 1979, Wilczek-Zee1979, Buchmuller-Wyler 1986, ...

[$\Lambda \leftrightarrow M_{BSM}$]

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

$\Delta L=2$

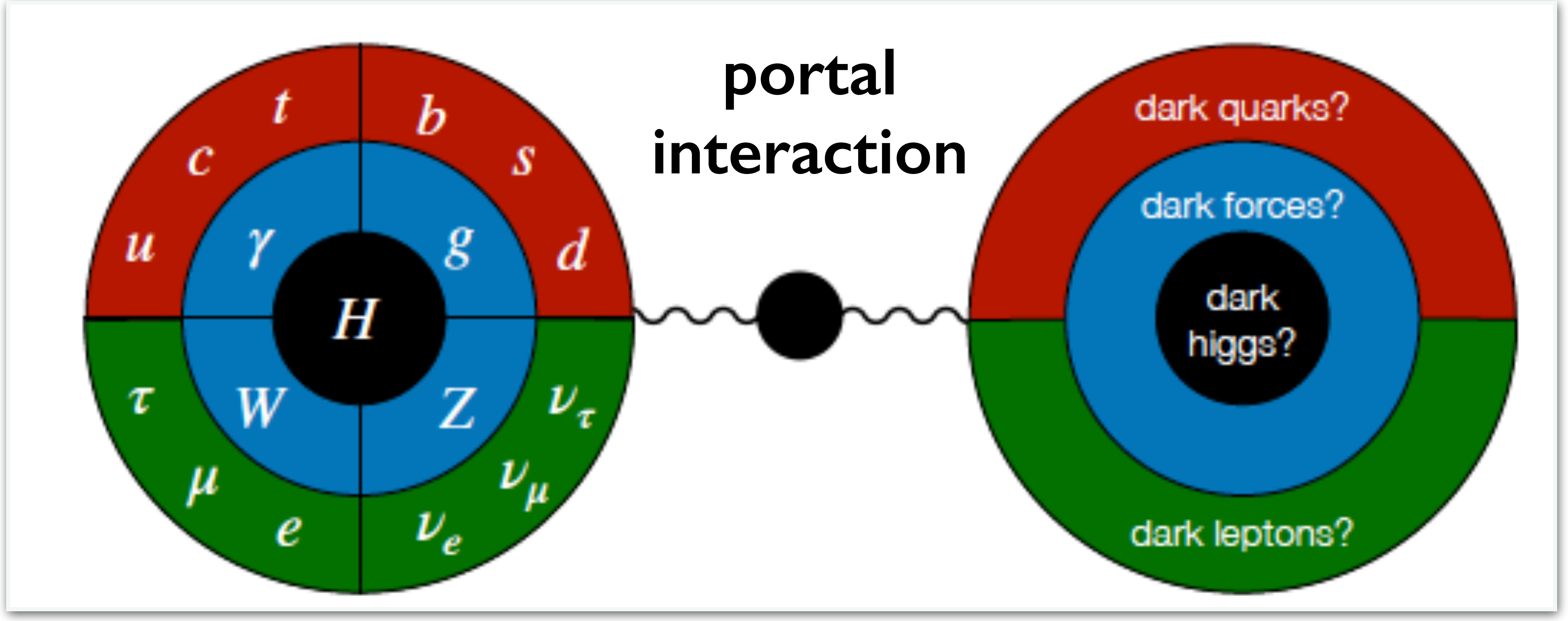
$\Delta B=\Delta L=1$, LFV, CPV, qFCNC, CC . NC, …

Full theory ← Simplified model ← SMEFT → LEFT→ hadronic EFT, LQCD, …

See talk by Radja Boughezal

Light, weakly coupled new physics: portals

"Portals": dominant interactions through which the SM and dark sector couple
(↔ lowest dimensional SM singlet operators)



Credit: Stefania Gori

$$\mathcal{L} \sim O_{\text{portals}} + O\left(\frac{1}{\Lambda}\right)$$

$$O_{\text{Vector}} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$$

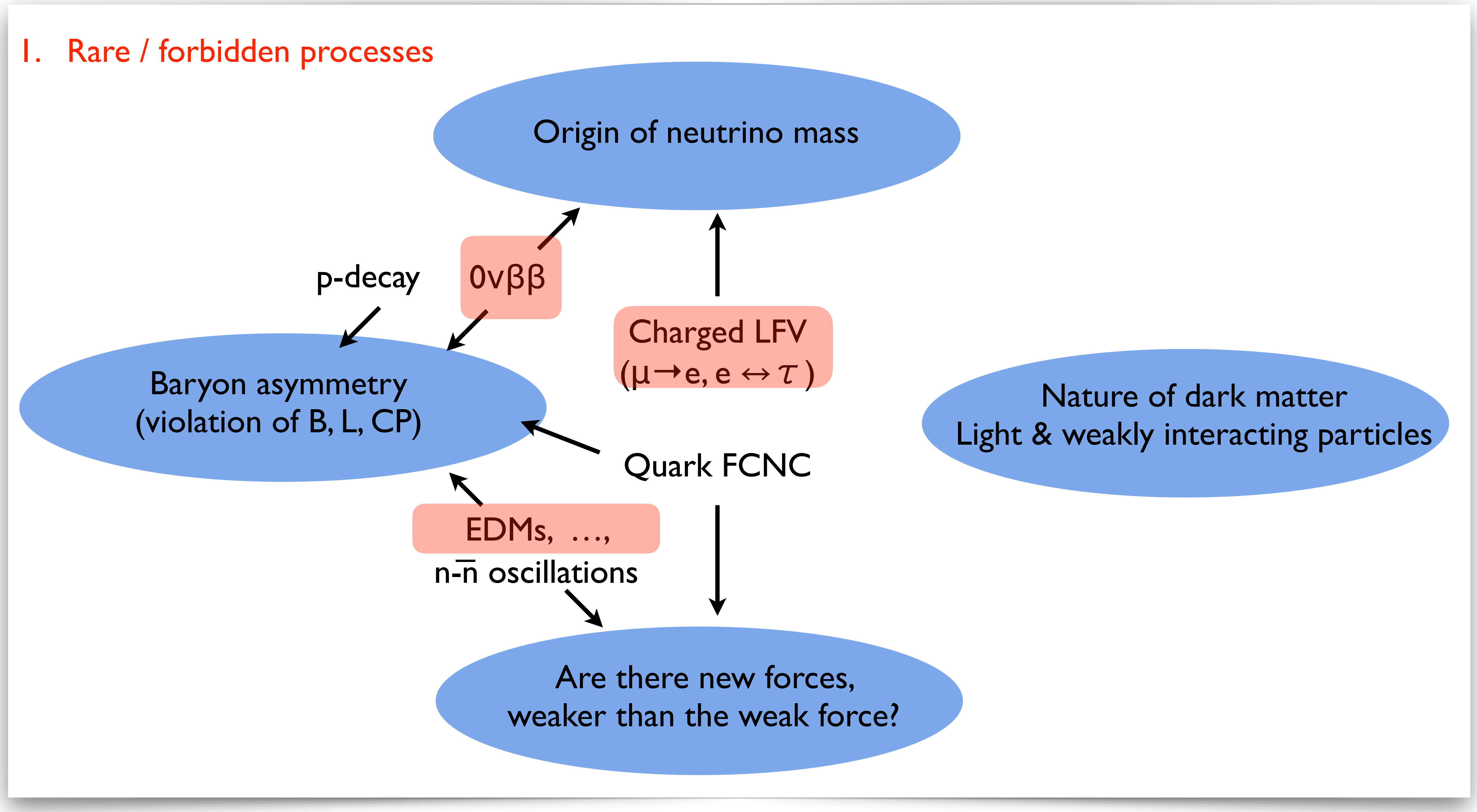
$$O_{\text{Neutrino}} = -Y_N^{ij} \bar{L}_i H N_j$$

$$O_{\text{Higgs}} = -H^\dagger H \left(A\, S + \lambda\, S^2\right)$$

Leading axion interactions appear at O(1/Λ):

$$aF\tilde{F}/f_a \,, aG\tilde{G}/f_a \,, \bar{\psi}\gamma^\mu\gamma_5\psi\, \partial_\mu a/f_a$$

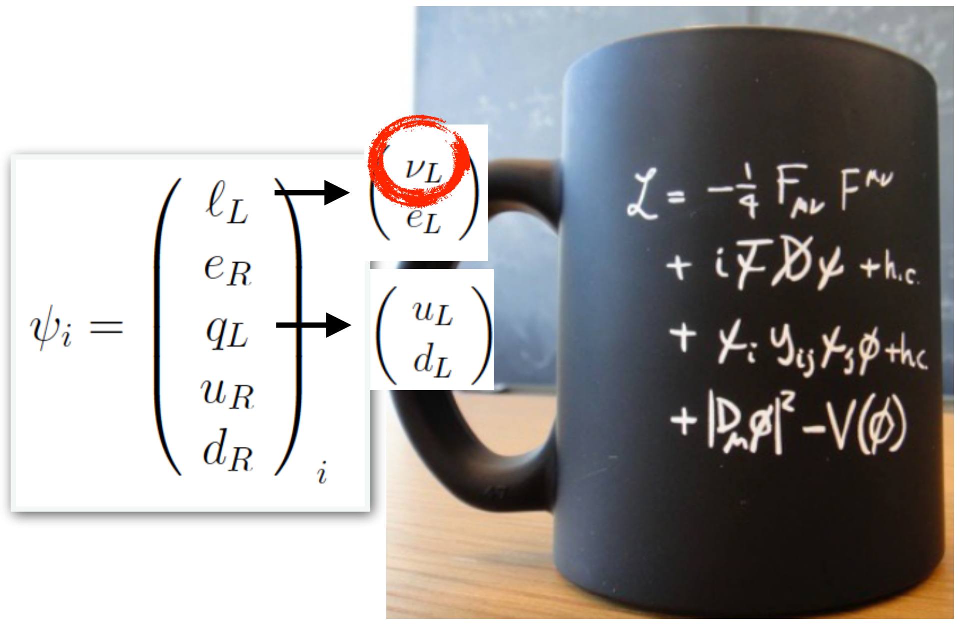
Rare / forbidden processes



Neutrino mass & new physics

- Massive neutrinos provide the only laboratory-based evidence of physics beyond the Standard Model
- Lorentz invariance ⇒ two options for massive neutrinos: Dirac or Majorana

The Standard Model



→ ?

⇒ No neutrino mass

ΔL= 0

$$\mathcal{L}_D \sim \bar{\nu}_R \, M_D \, \nu_L$$

Conserves L=L_e+L_μ+L_τ

ΔL=2

$$\mathcal{L}_M \sim \nu_L^T \, C M_M \, \nu_L$$

Violates L (ΔL=2)

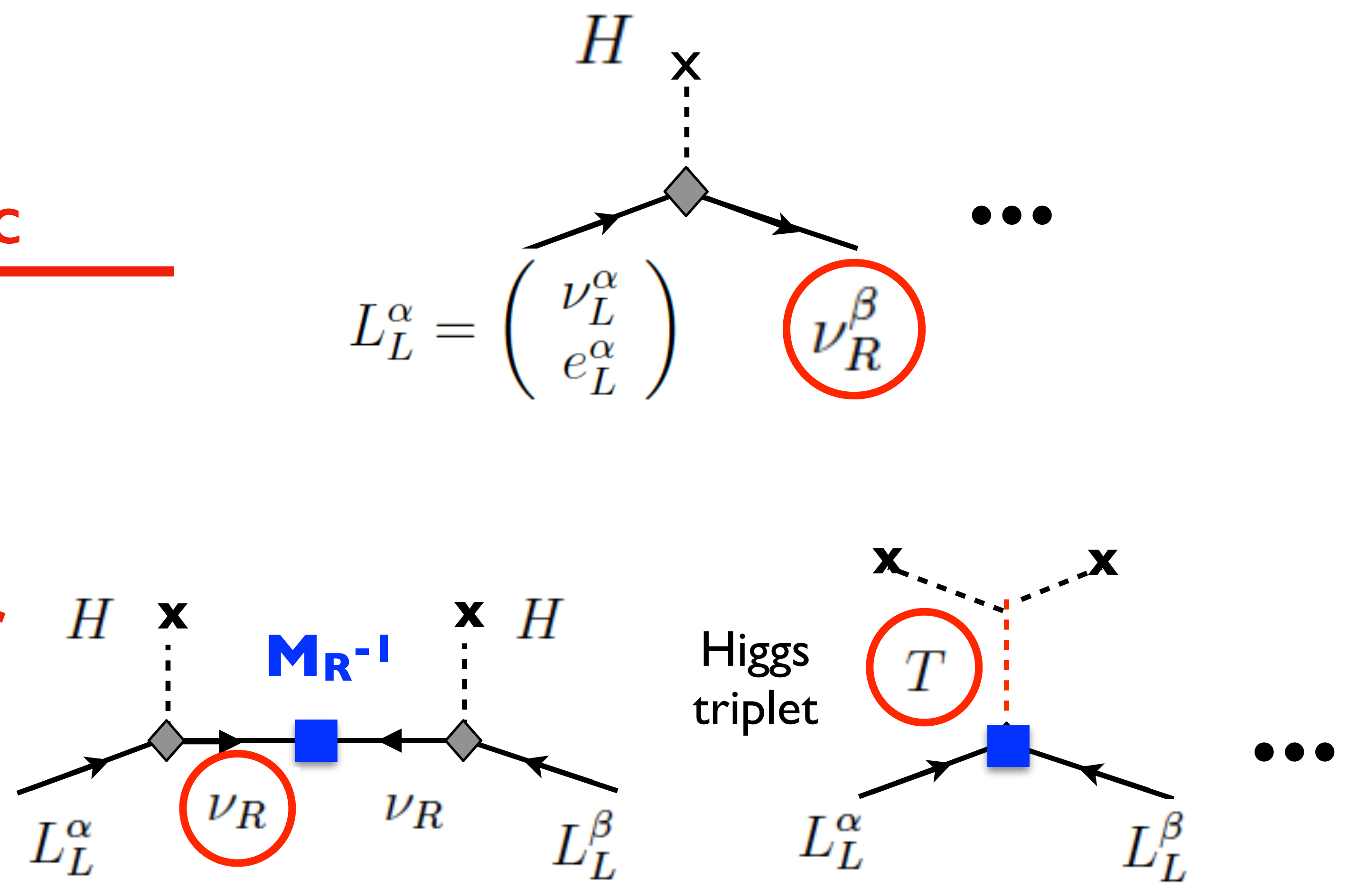
Neutrino mass & new physics

- Massive neutrinos provide the only laboratory-based evidence of physics beyond the Standard Model
- Lorentz invariance ⇒ two options for massive neutrinos: Dirac or Majorana
- In both cases ν mass requires introducing new degrees of freedom & interactions

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}} + \ldots$$

Dirac

Majorana



Is Lepton Number violated?

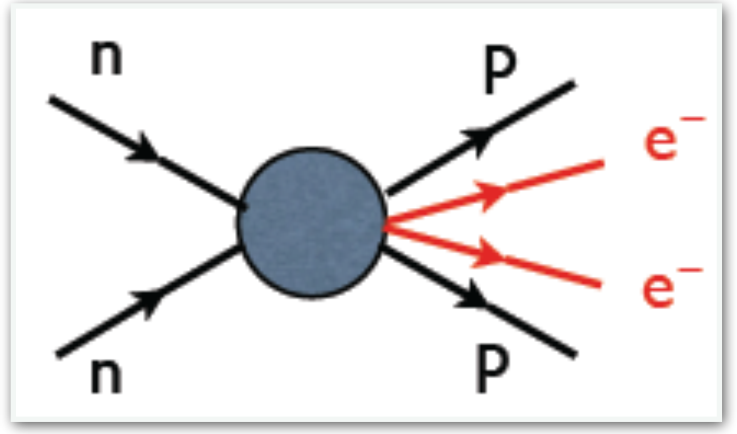
→ 0νββ

What are the sources and mediators of lepton family violation?

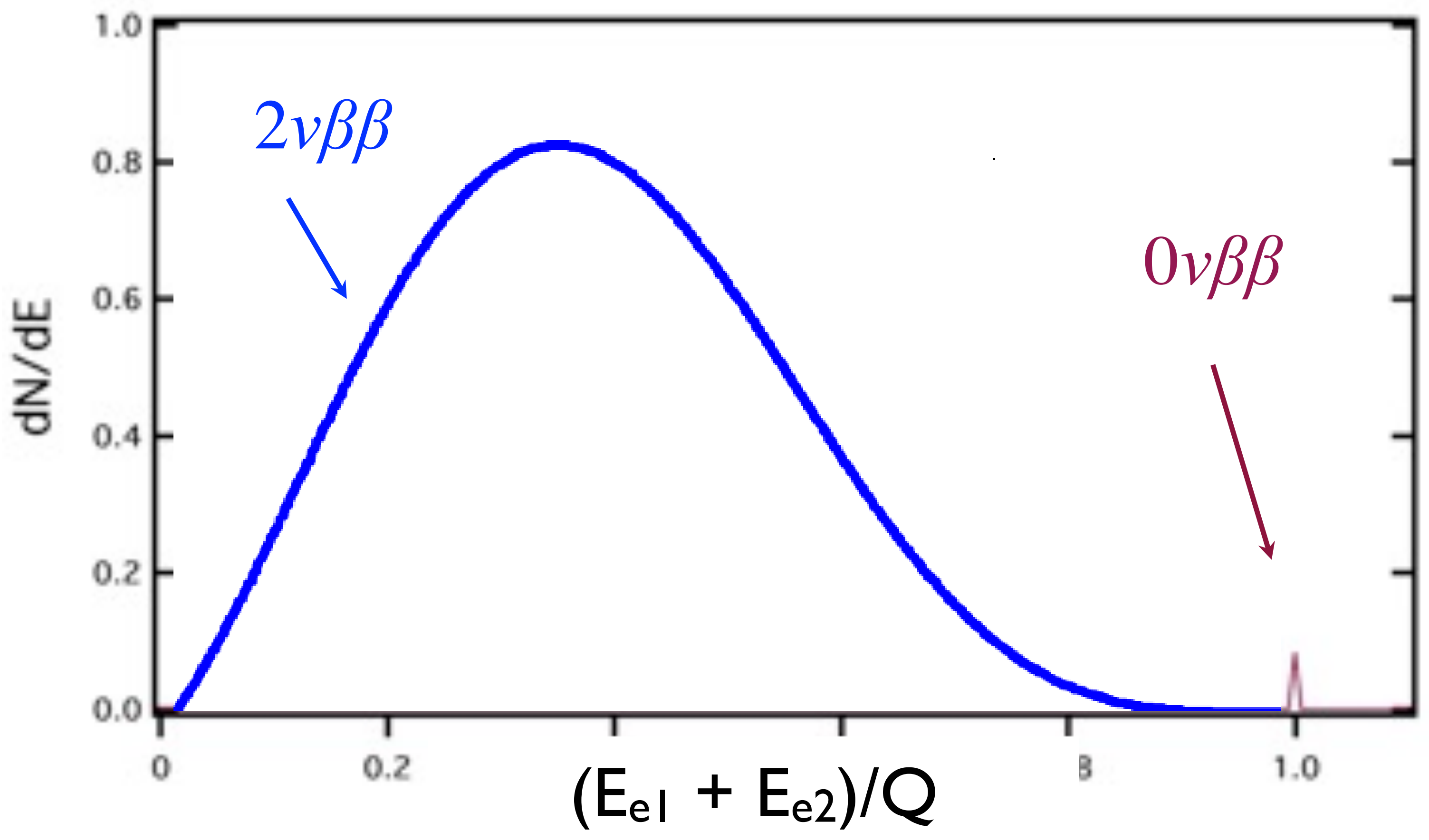
→ Charged Lepton Flavor Violation

0νββ decay: significance

$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$



ΔL=2



Potentially observable only in certain even-even nuclei (^{76}Ge, ^{100}Mo, ^{136}Xe, …) for which single beta decay is energetically forbidden

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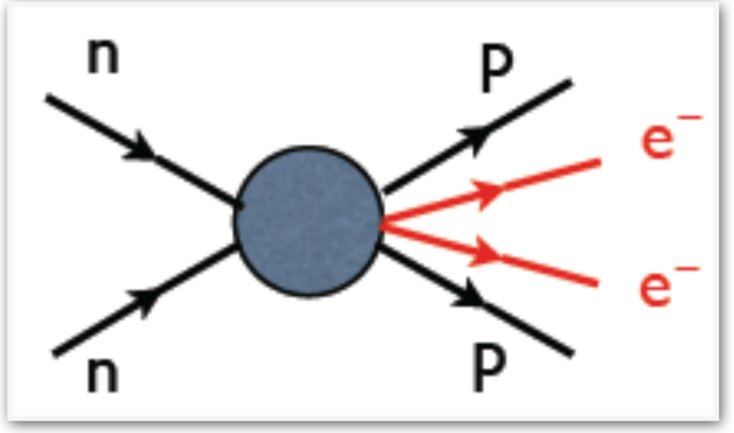

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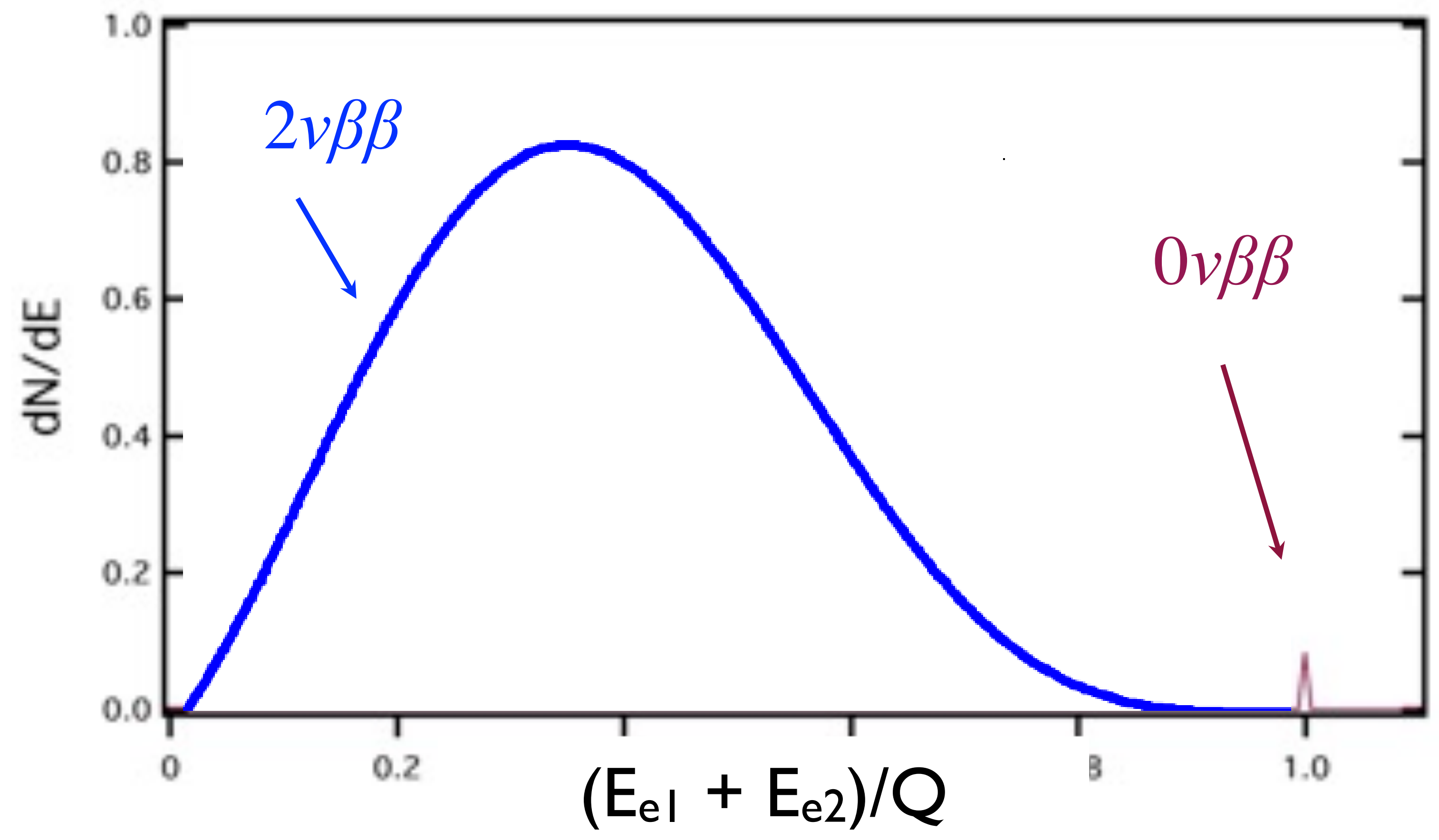

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Observation ⇒ BSM physics

(B-L conserved in the the SM)

Shed light on the physics responsible for tiny but non-zero neutrino mass

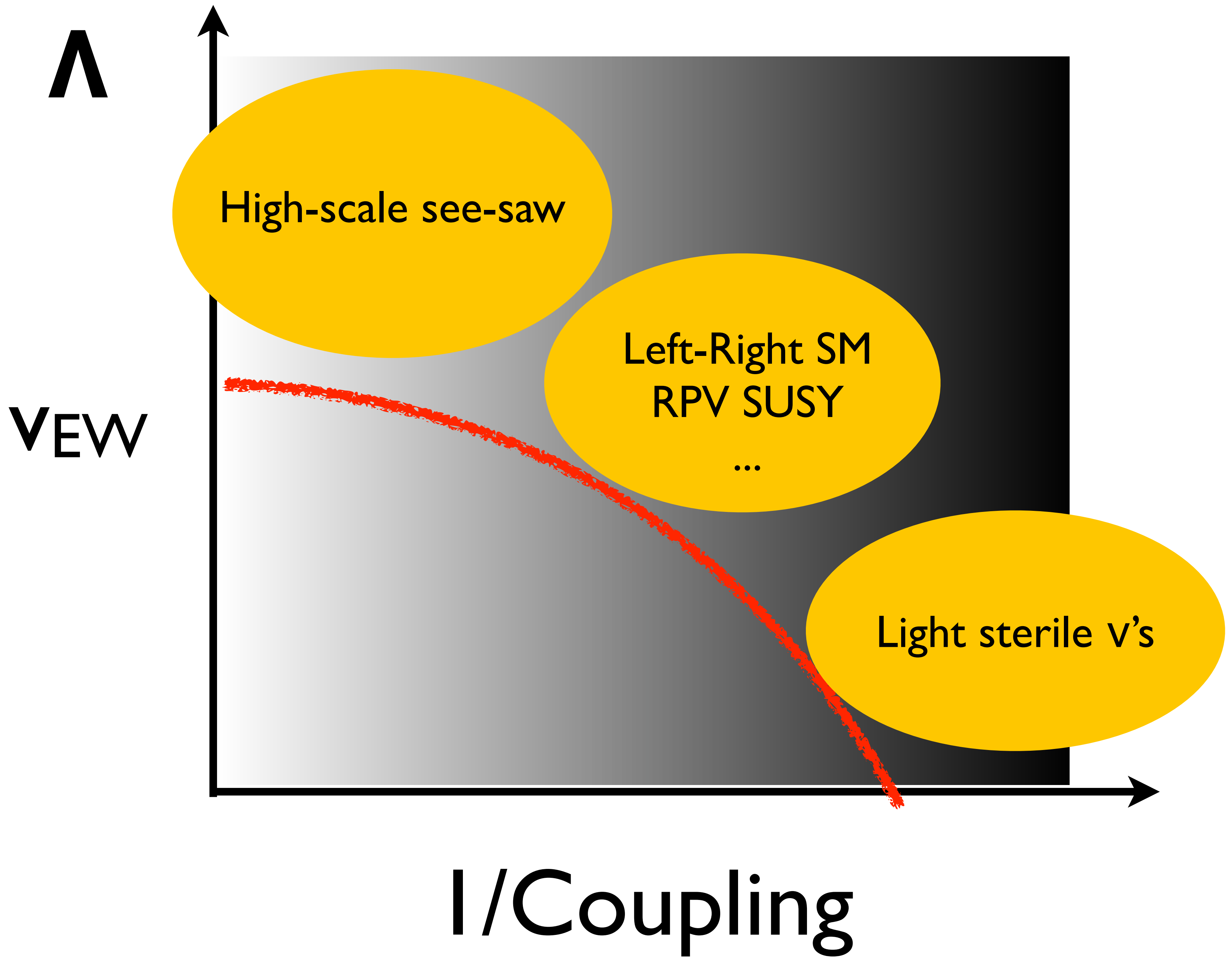
&

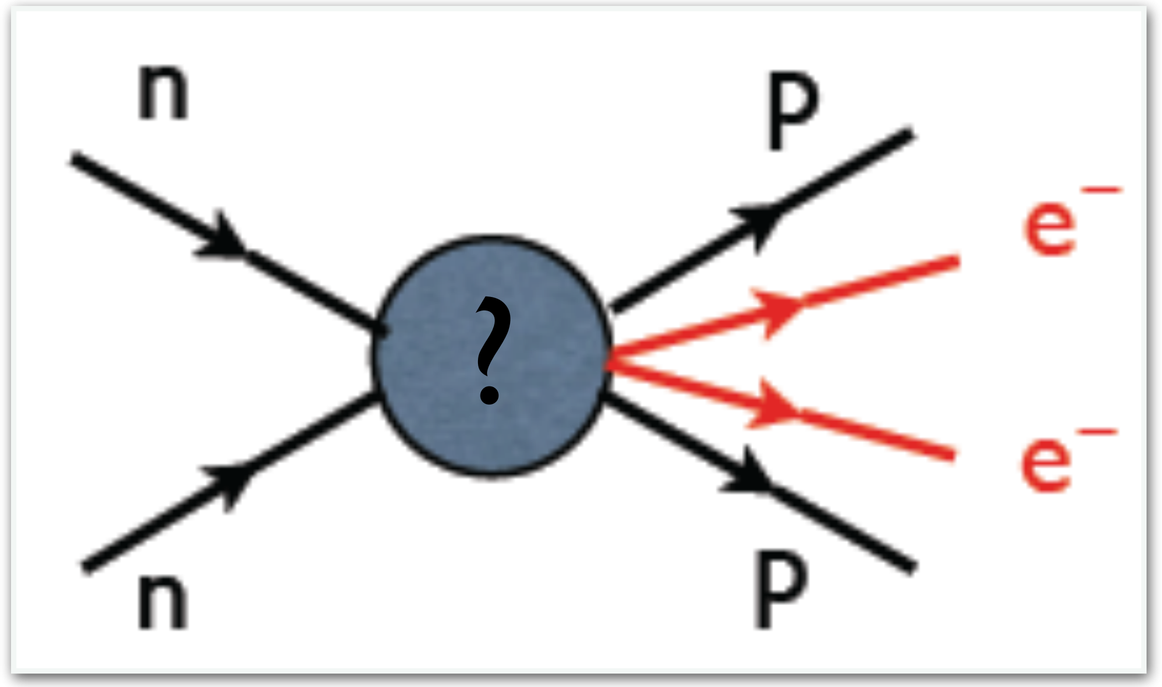
Demonstrate Majorana nature of neutrinos (neutrino=antineutrino)

This 'matter-creating' process points to elegant mechanisms for generating the matter-antimatter asymmetry in the universe (leptogenesis)

0νββ decay: discovery potential

- Ton-scale 0νββ searches [$T_{1/2} \sim 10^{27\text{-}28}$ yr] can discover LNV from a broad variety of mechanisms and mass scales





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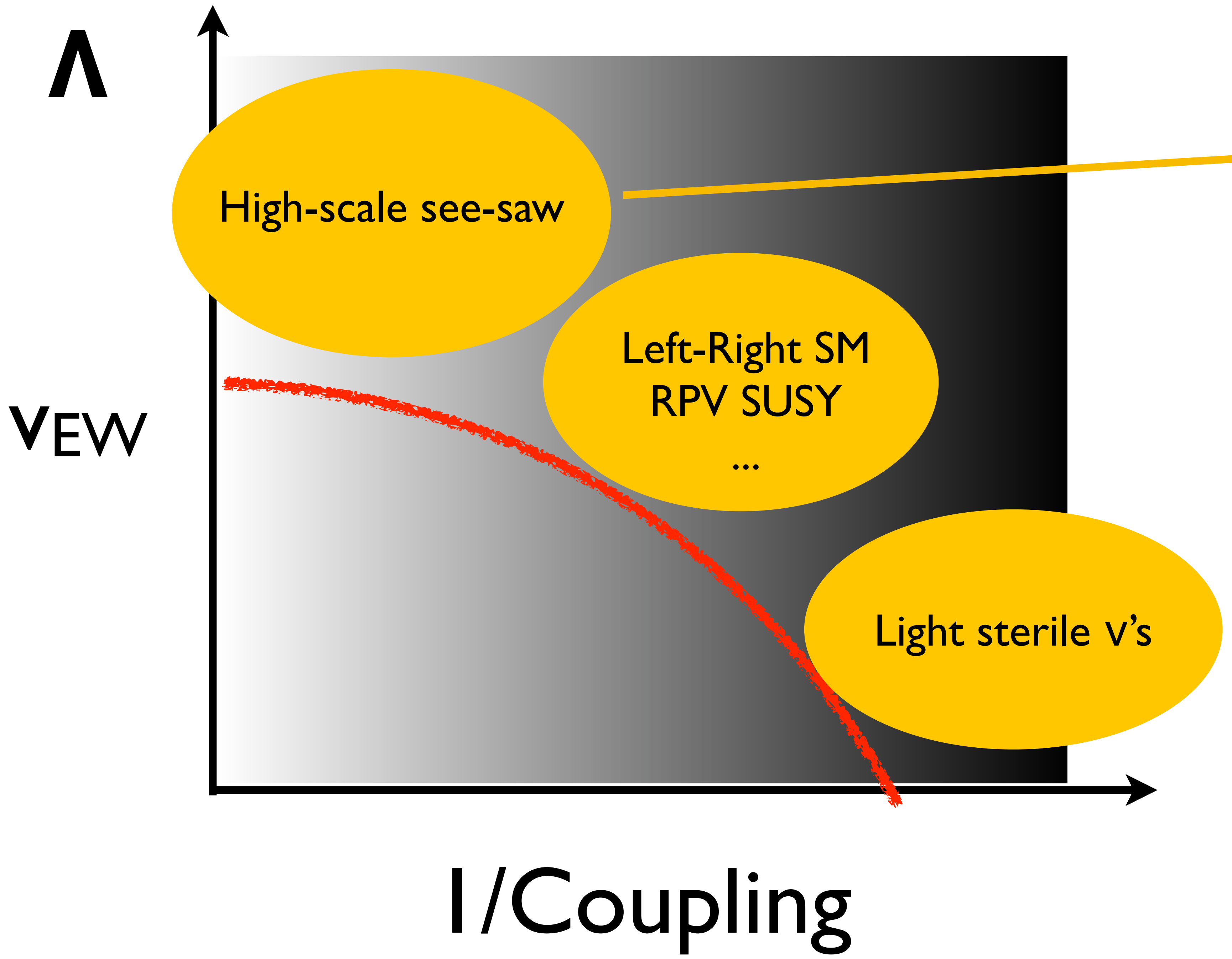
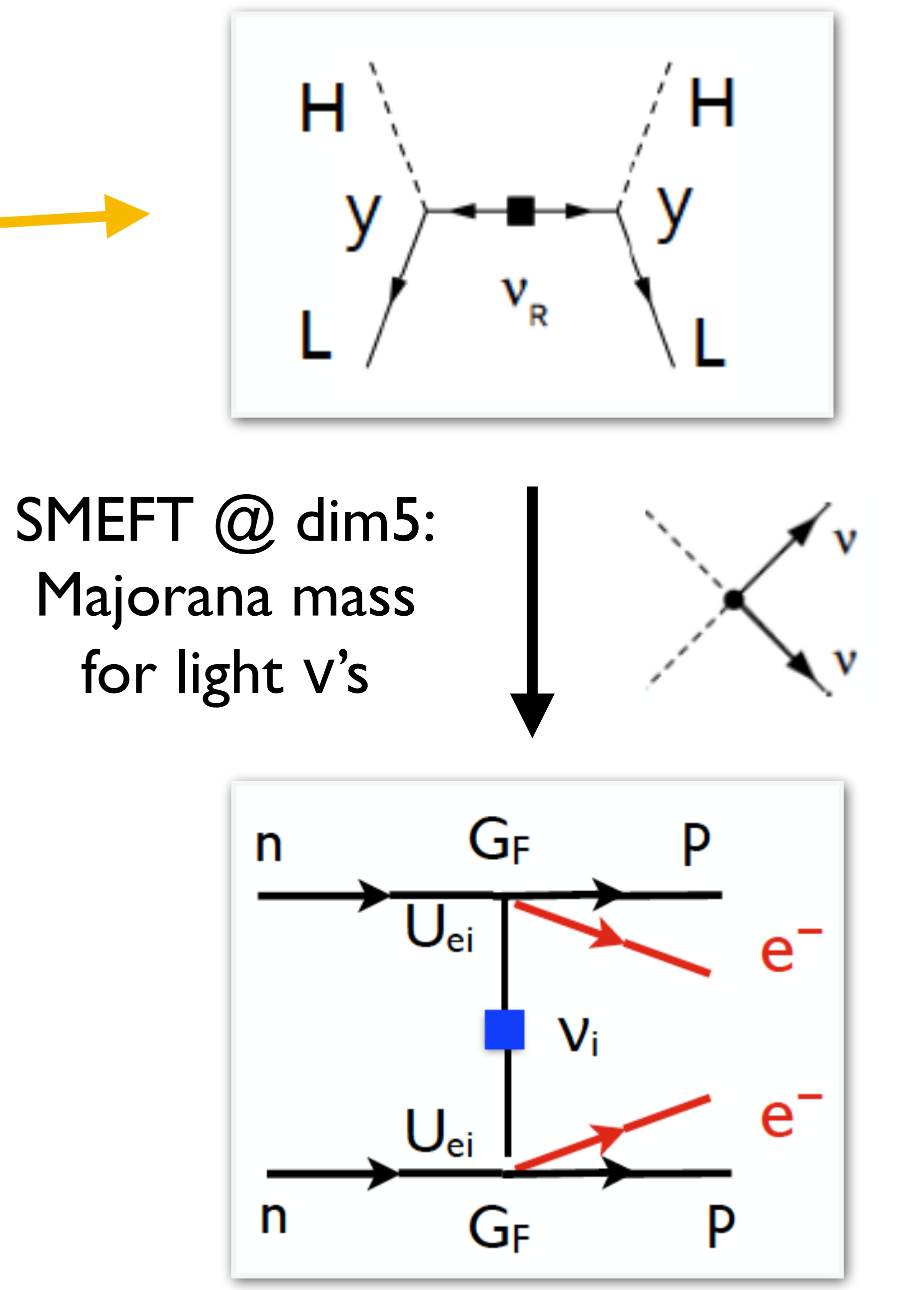
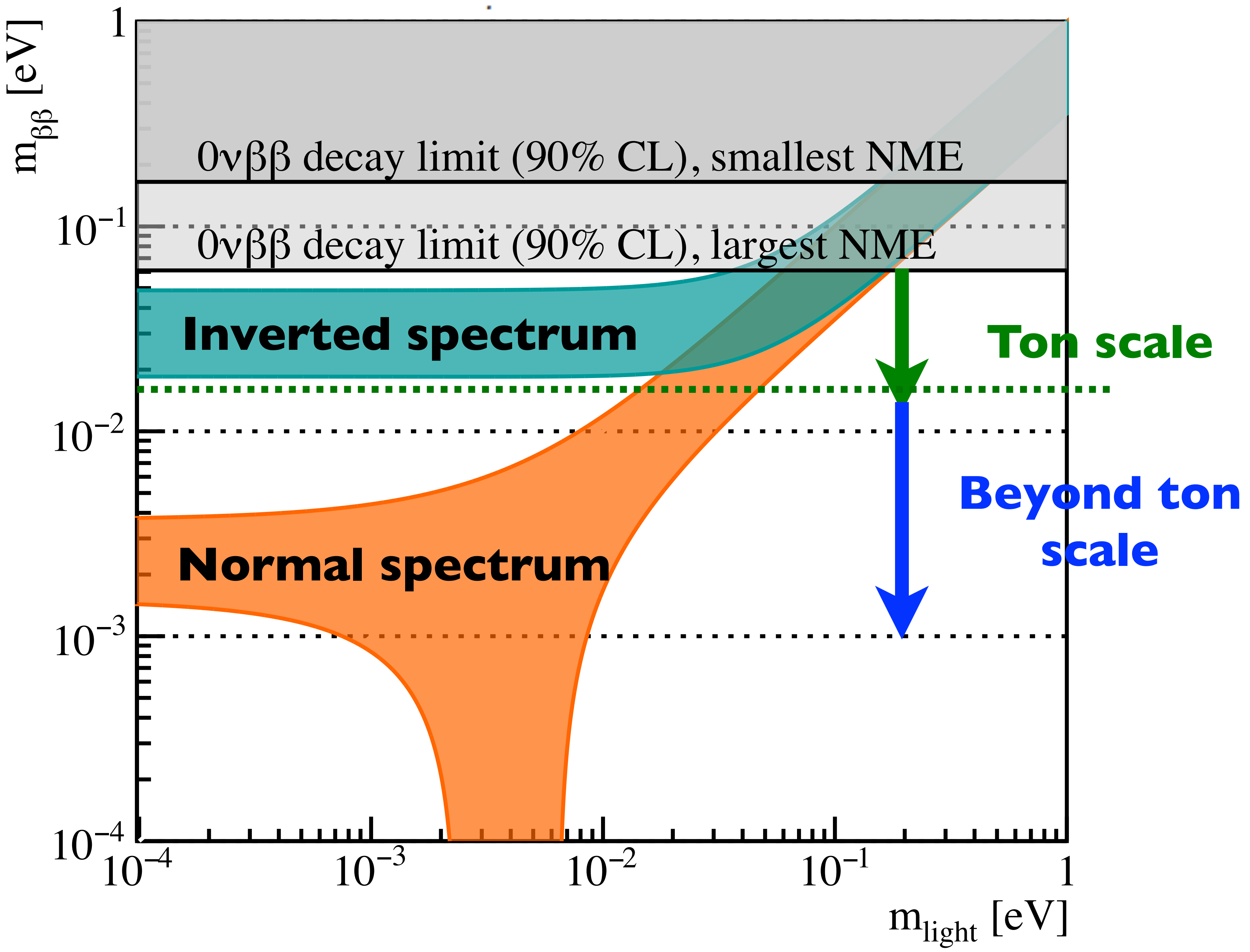


For example heavy ν_R exchange



Only low-E remnant of LNV
is the neutrino mass

$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2 \sim (v^2/\Lambda)^2$



Falsifiable correlations with other neutrino mass probes

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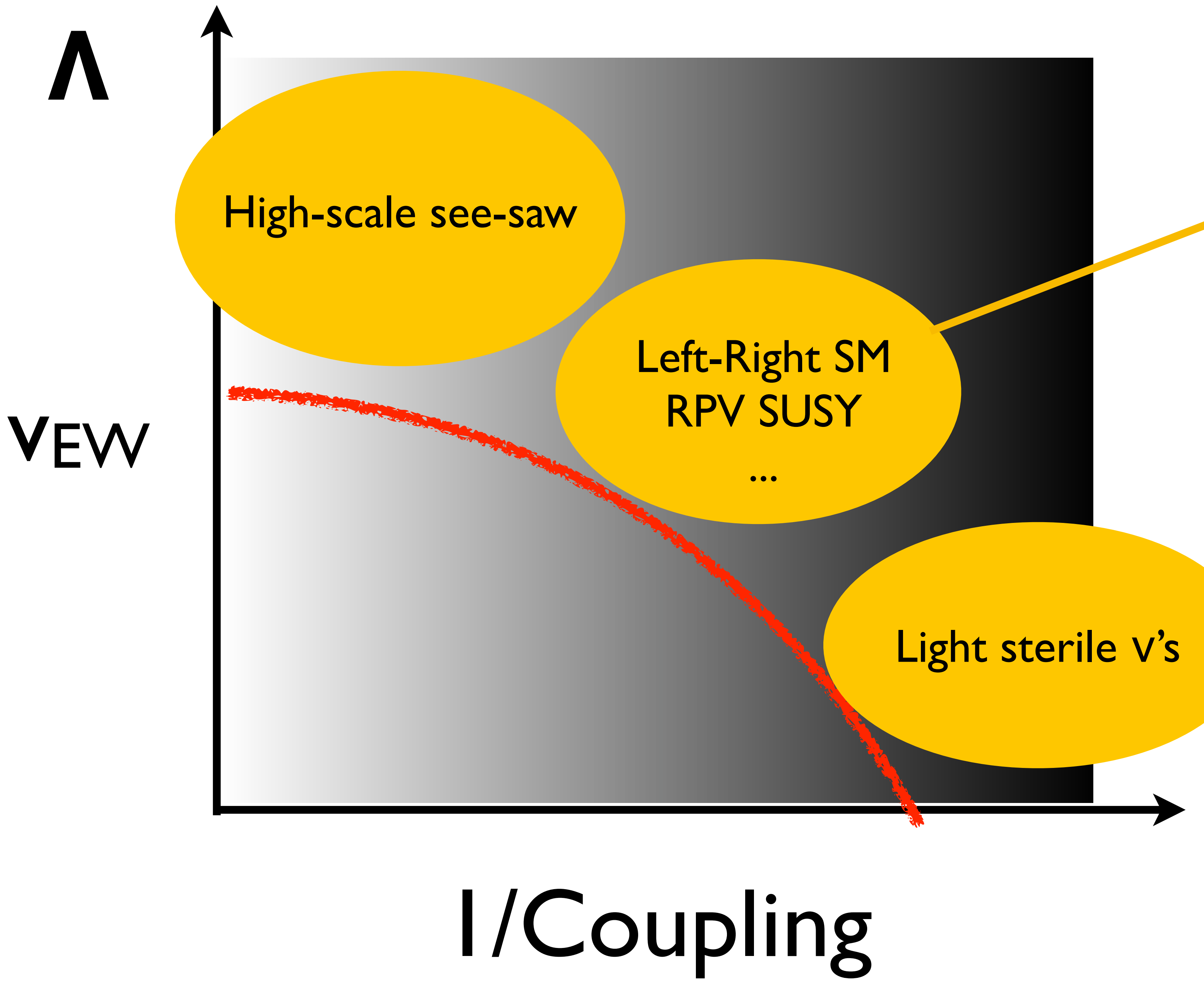
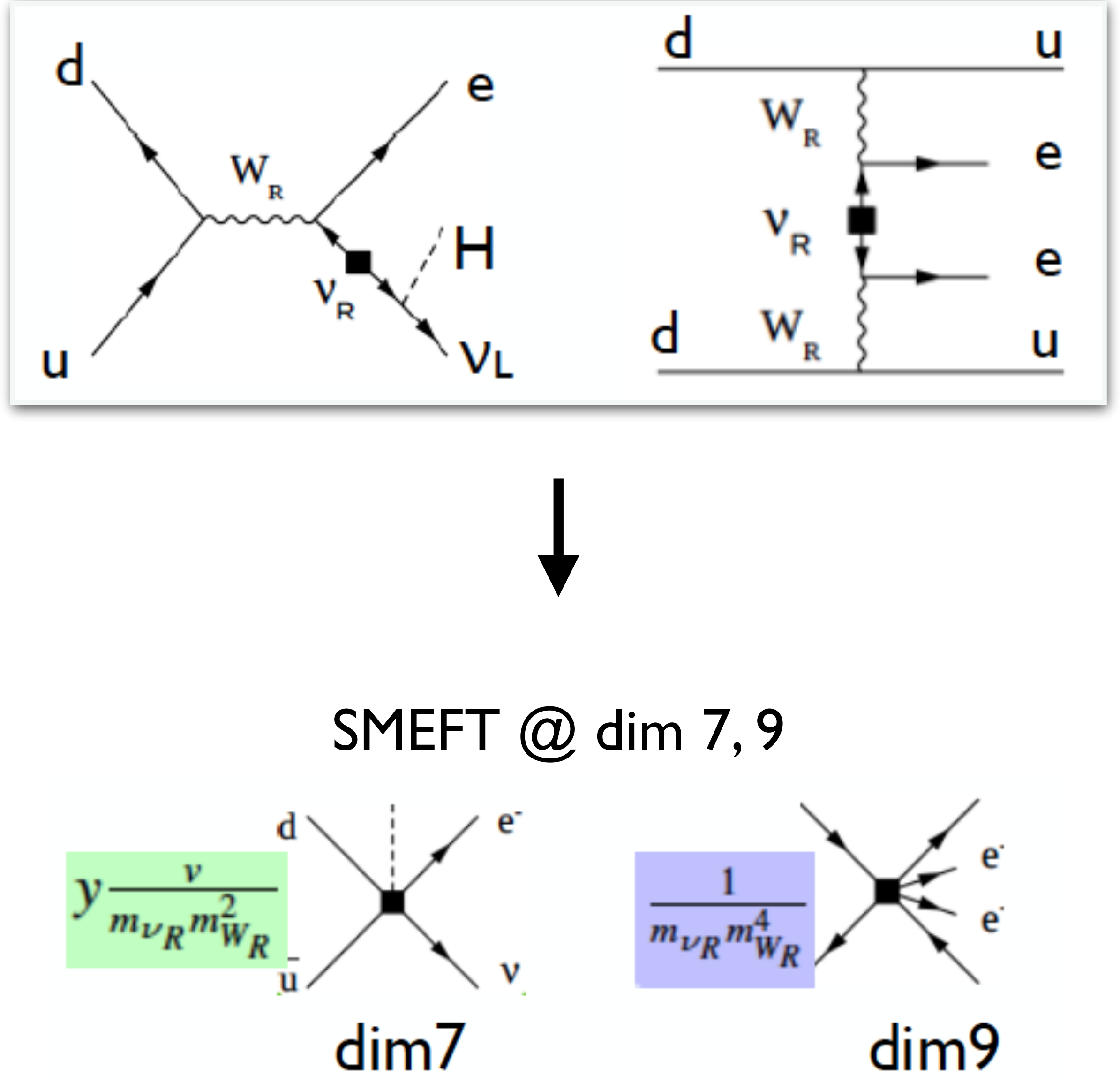
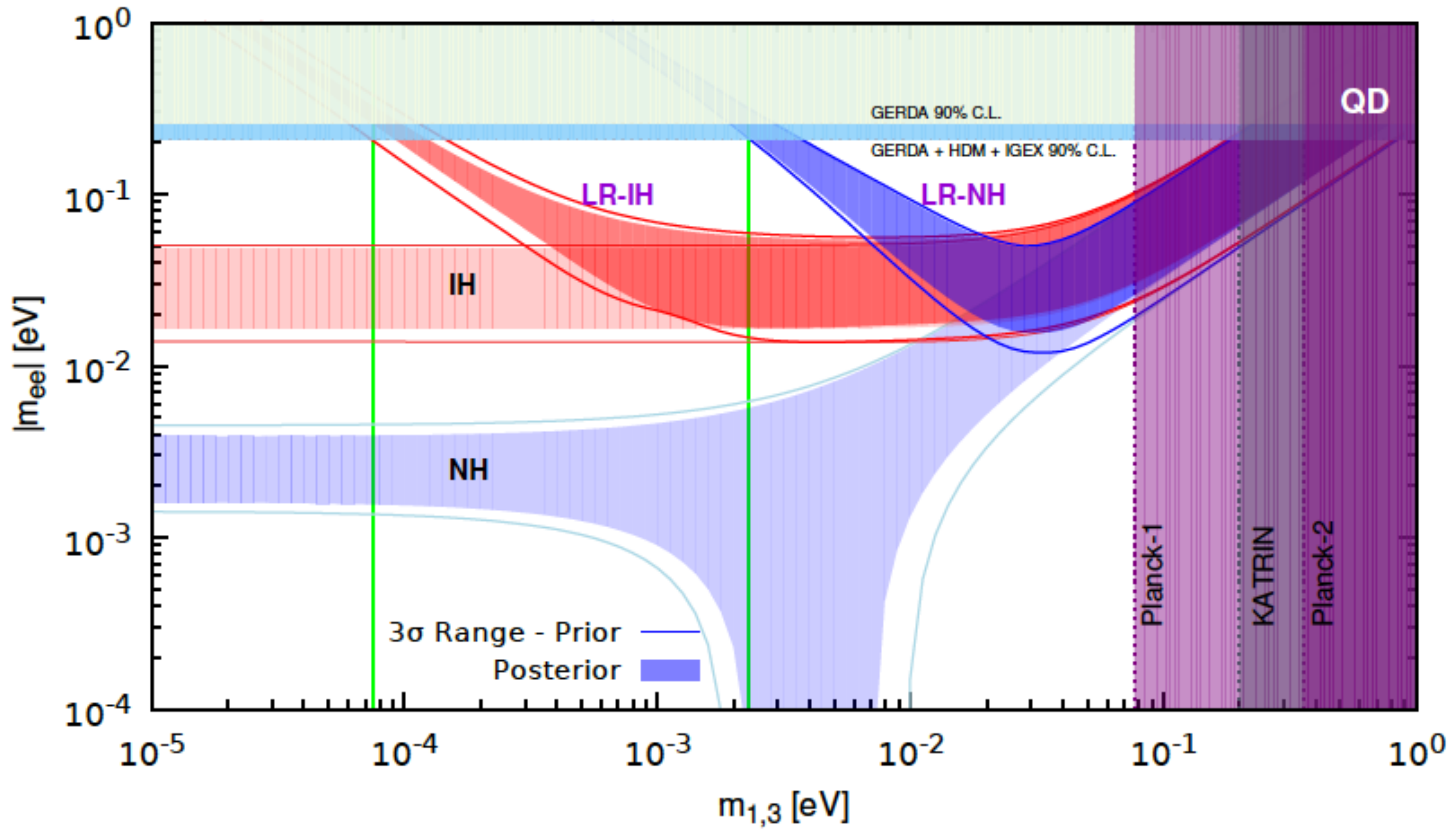




Example: LRSM with type-II seesaw



Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522
Ge-Lindner-Patra 1508.07286
Li, Ramsey-Musolf, Vasquez 2009.01257
...

Contributions to 0νββ *not directly related to the exchange of light neutrinos*,
within reach of planned experiments & possibly correlated with signal at LHC in pp → ee jj

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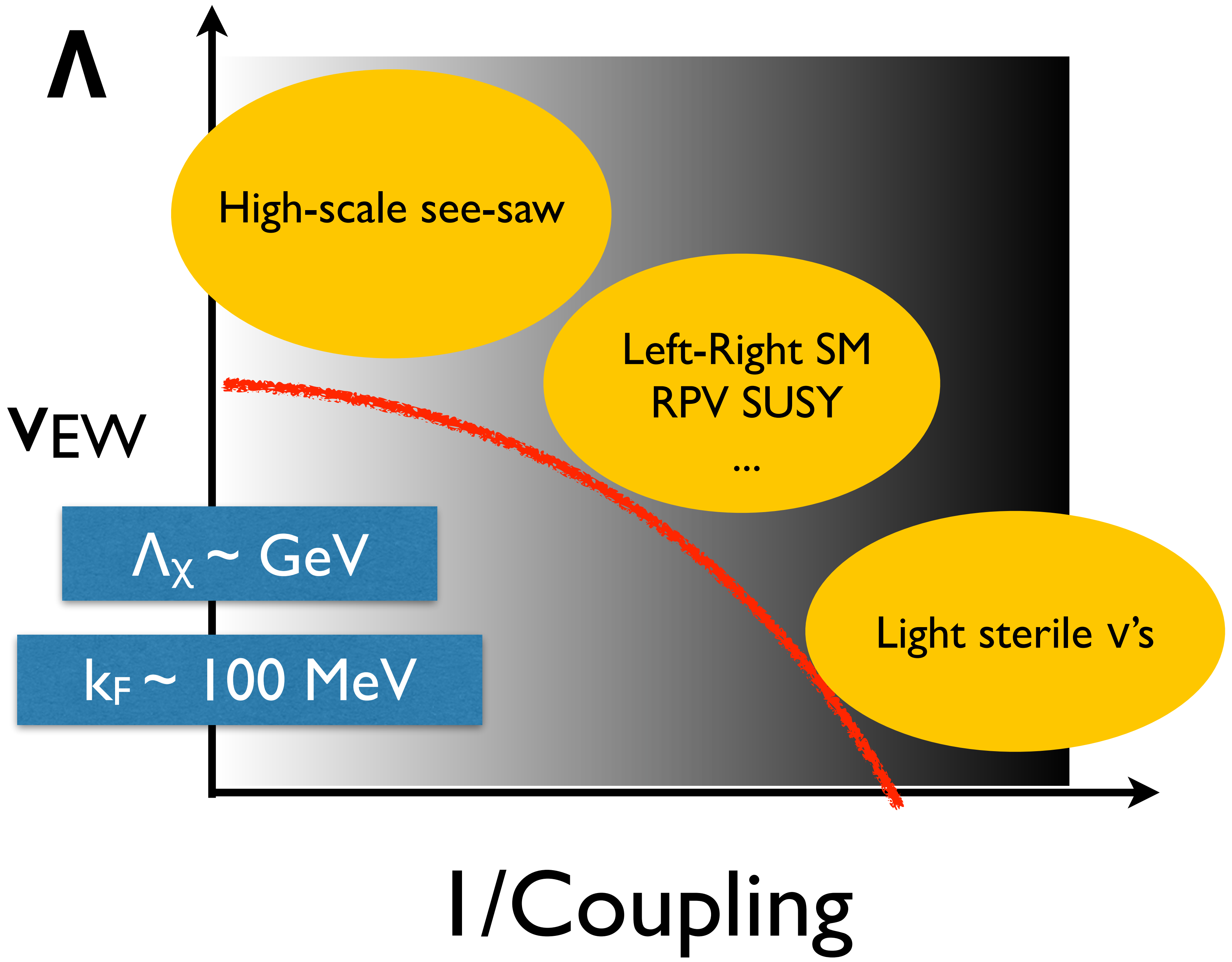


- Connecting sources of LNV to nuclei is a multi-scale problem! Best tackled through EFT to achieve controlled uncertainty
- Theory advances require synergy of phenomenology, EFT, Lattice QCD, and first-principles nuclear structure

SMEFT LEFT Chiral EFT

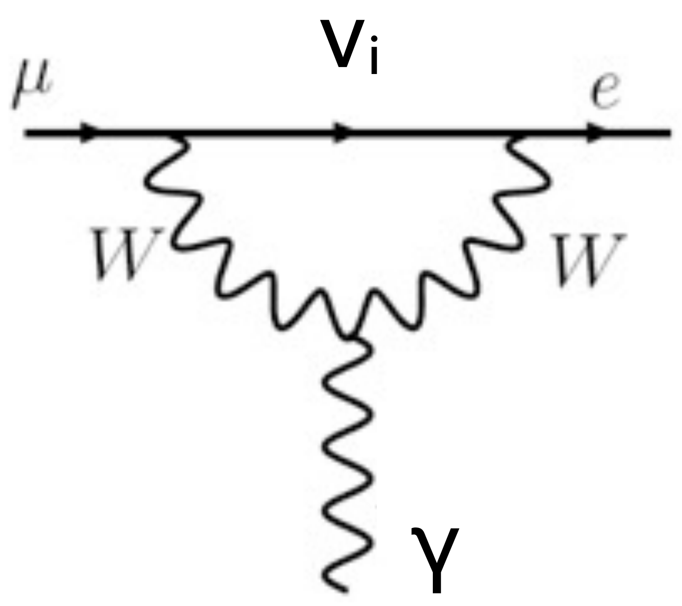
$$T_{1/2} \propto (m_W/\Lambda)^A \ (\Lambda_X/m_W)^B \ (k_F/\Lambda_X)^C$$

White paper 2203. 21169 and refs therein

- Exciting prospects due to planned ton-scale experiments

Charged LFV and new physics

- ν oscillations ⇒ $L_{e,\mu,\tau}$ not conserved. However, in SM + massive ν, Charged-LFV decays are suppressed to unobservable level

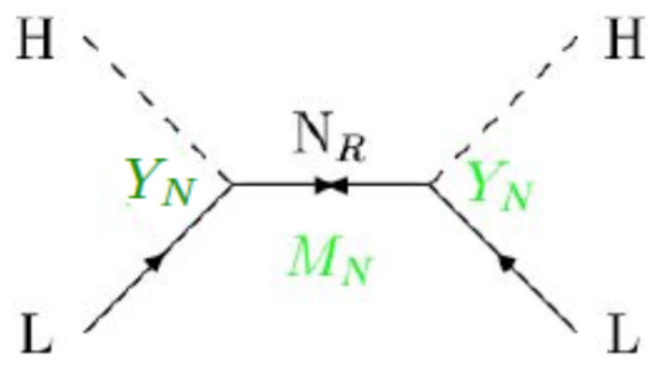


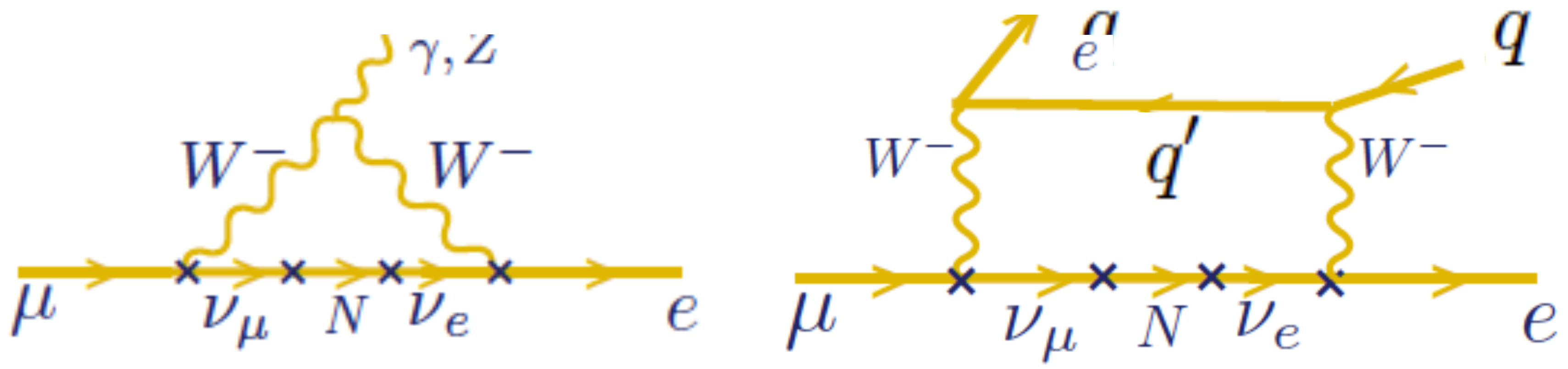
$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}}$$

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

Petcov '77, Marciano-Sanda '77, Shrock '77…

Ex: Type-I seesaw

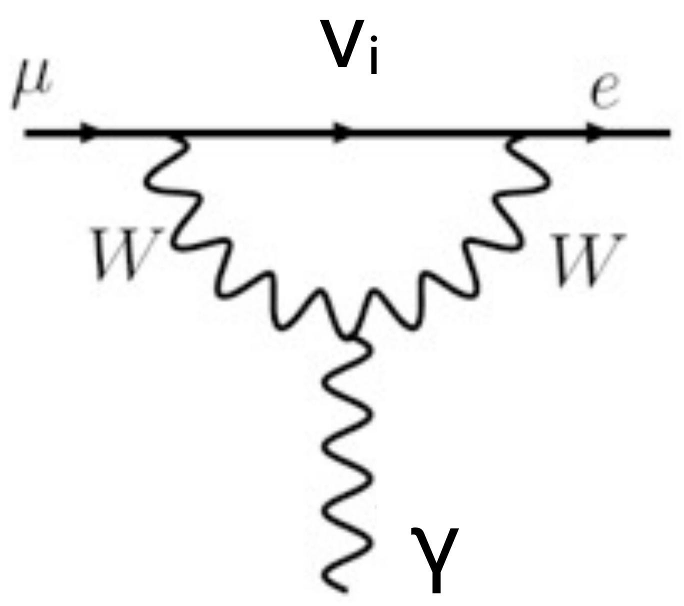




- Observation of CLFV processes would unambiguously indicate new physics, related to the origin of leptonic 'flavor' & possibly neutrino mass

Charged LFV and new physics

- ν oscillations ⇒ $L_{e,\mu,\tau}$ not conserved. However, in SM + massive ν, Charged-LFV decays are suppressed to unobservable level



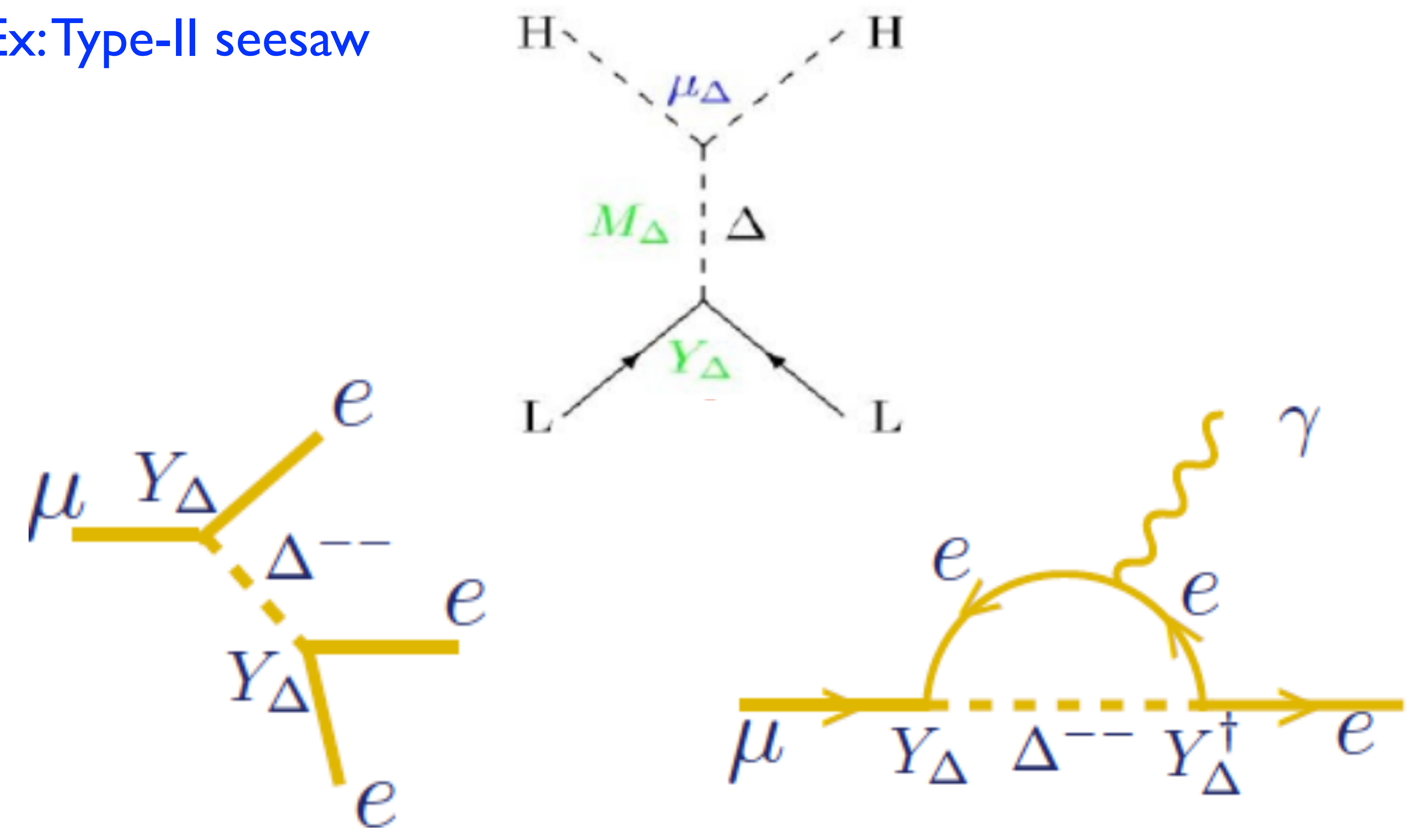
$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}}$$

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}$$

Petcov '77, Marciano-Sanda '77, Shrock '77…

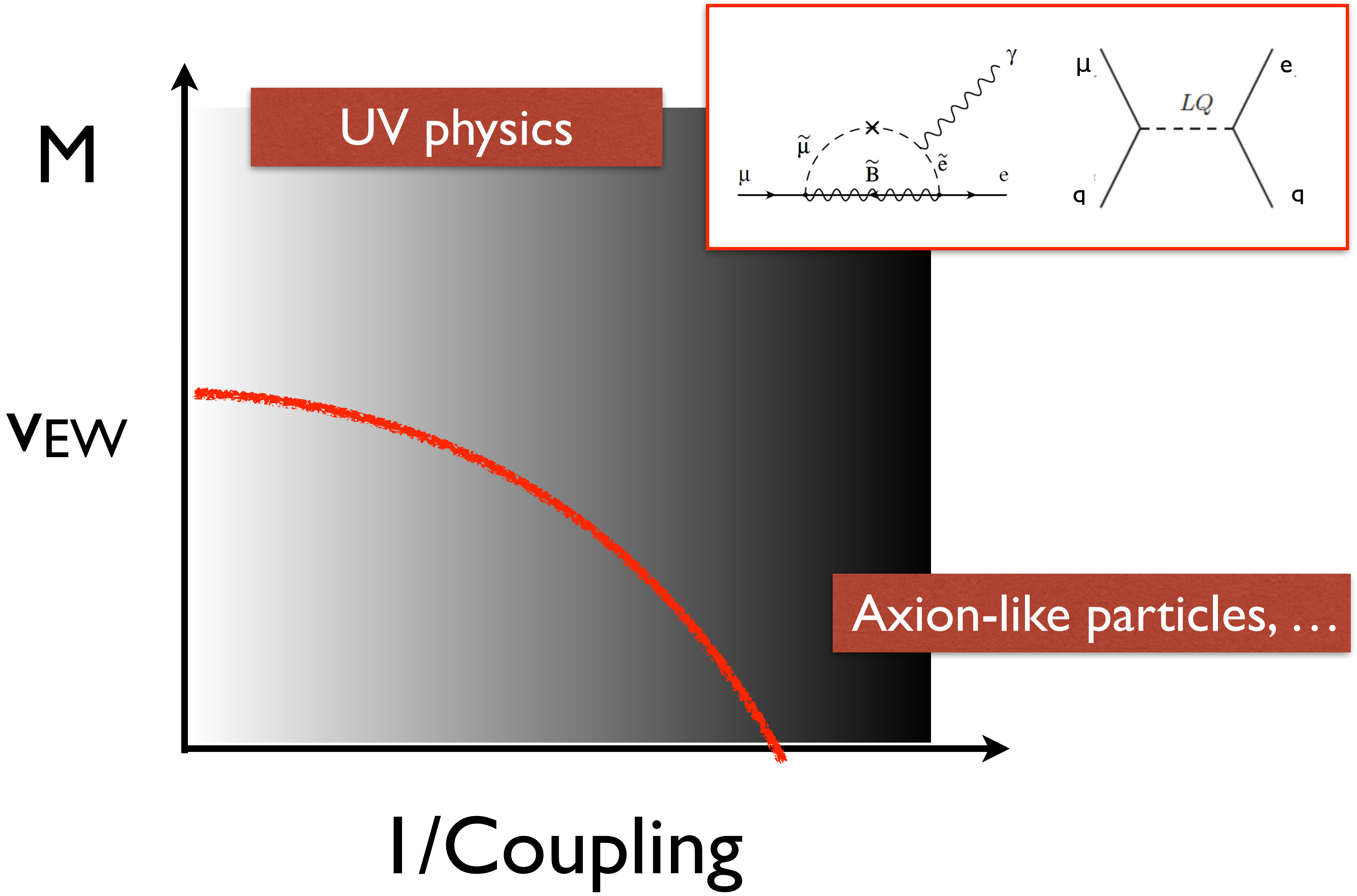
- Observation of CLFV processes would unambiguously indicate new physics, related to the origin of leptonic 'flavor' & possibly neutrino mass

Ex: Type-II seesaw



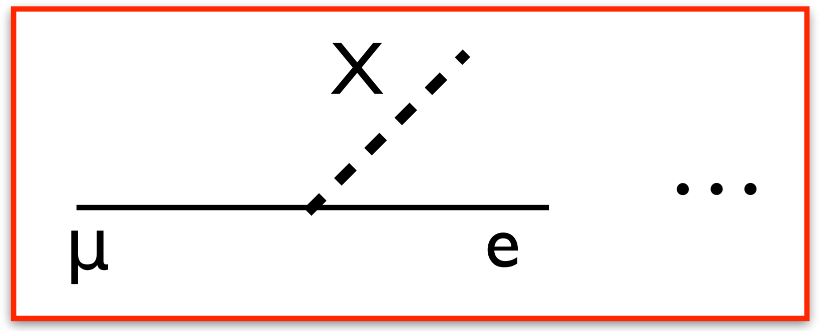
CLFV physics reach

- LFV processes are sensitive to broad spectrum of new physics: both heavy and light + weakly coupled



→ $$\mathcal{L}_{\rm SMEFT} \supset \sum_n \frac{C_n}{\Lambda^2} O_n^{\rm LFV} + \ldots$$

$\Lambda/\sqrt{C}$ up to ~ $10^{4\text{-}5}$ TeV



$$\mathcal{L}_{\rm portals} \supset \frac{1}{F^{\Gamma}_{\alpha\beta}} \partial_\mu a \, \bar{\ell}_\alpha \Gamma^\mu \ell_\beta + \ldots$$

$F_{\alpha\beta}$ up to ~ 10^9 TeV

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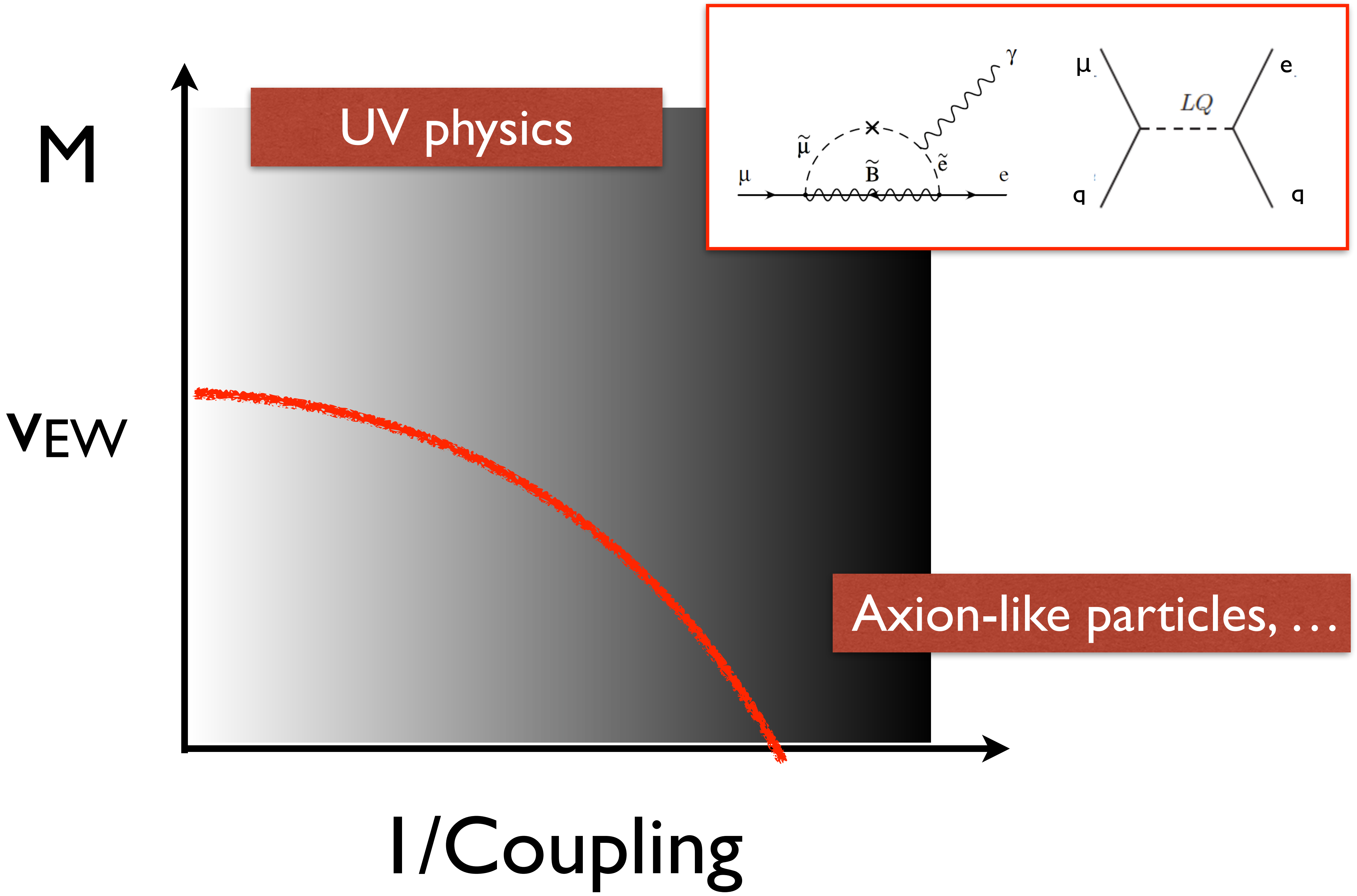

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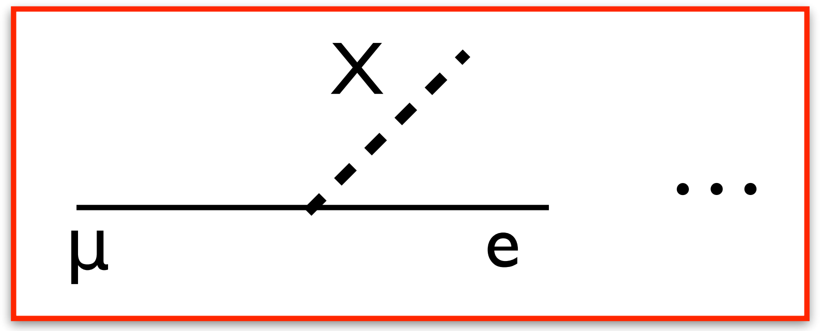

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$F_{\alpha\beta}$ up to ~ 10^9 TeV

We can probe LFV dynamics through a combination of low-energy and collider searches

LFV probes across energy scales

- Decays of μ, τ (and mesons)

(K → πμe; B → Kμτ, Kμe; B_s → μτ, μe, quarkonia , …)

$$\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z)$$ μ → e a

$$\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \to \ell\, Y \qquad Y = P, S, V, P\bar{P}, \ldots$$

BR~ 10^{-13} (BR~ 10^{-6})

BR~ 10^{-8}

- Collider processes:

LHC

$$pp \to R \to \ell_\alpha \bar{\ell}_\beta + X \qquad R = Z', h, \tilde{\nu}, \ldots.$$
$$pp \to \ell_\alpha \bar{\ell}_\beta + X$$

HERA,
EIC

$$ep \to \ell + X$$

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- Collid

Given the relatively low energy, the discovery potential and diagnosing power of the EIC can be studied in the context of the SMEFT** & portals

** See talk by Emanuele Mereghetti

LHC

HERA,
EIC

$$e\,p \to \ell + X$$

CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{vC_D^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\sigma_{\mu\nu}\ell^\beta + \sum_{\tilde{\Gamma}}\frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\tilde{\Gamma}\ell^\beta\bar{\ell}\tilde{\Gamma}\ell + \sum_{\Gamma}\frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\Gamma\ell^\beta\bar{q}\Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}}\partial_\mu a\,\bar{\ell}^\alpha\Gamma^\mu\ell^\beta$$

Each model generates a specific pattern of operators
→ multiple CLFV measurements needed to extract the underlying physics

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- New physics mass scale probed through any process

$$BR_{\alpha\to\beta} \sim (v_{ew}/\Lambda)^4 * |(C_n)^{\alpha\beta}|^2$$

μ-e sector:	$\Lambda/\sqrt{C} \sim 10^{4\text{-}5}$ TeV	(Muon decays)
τ-μ(e) sector:	$\Lambda/\sqrt{C} \sim 10^{2}$ TeV	(Tau decays)

CLFV phenomenology

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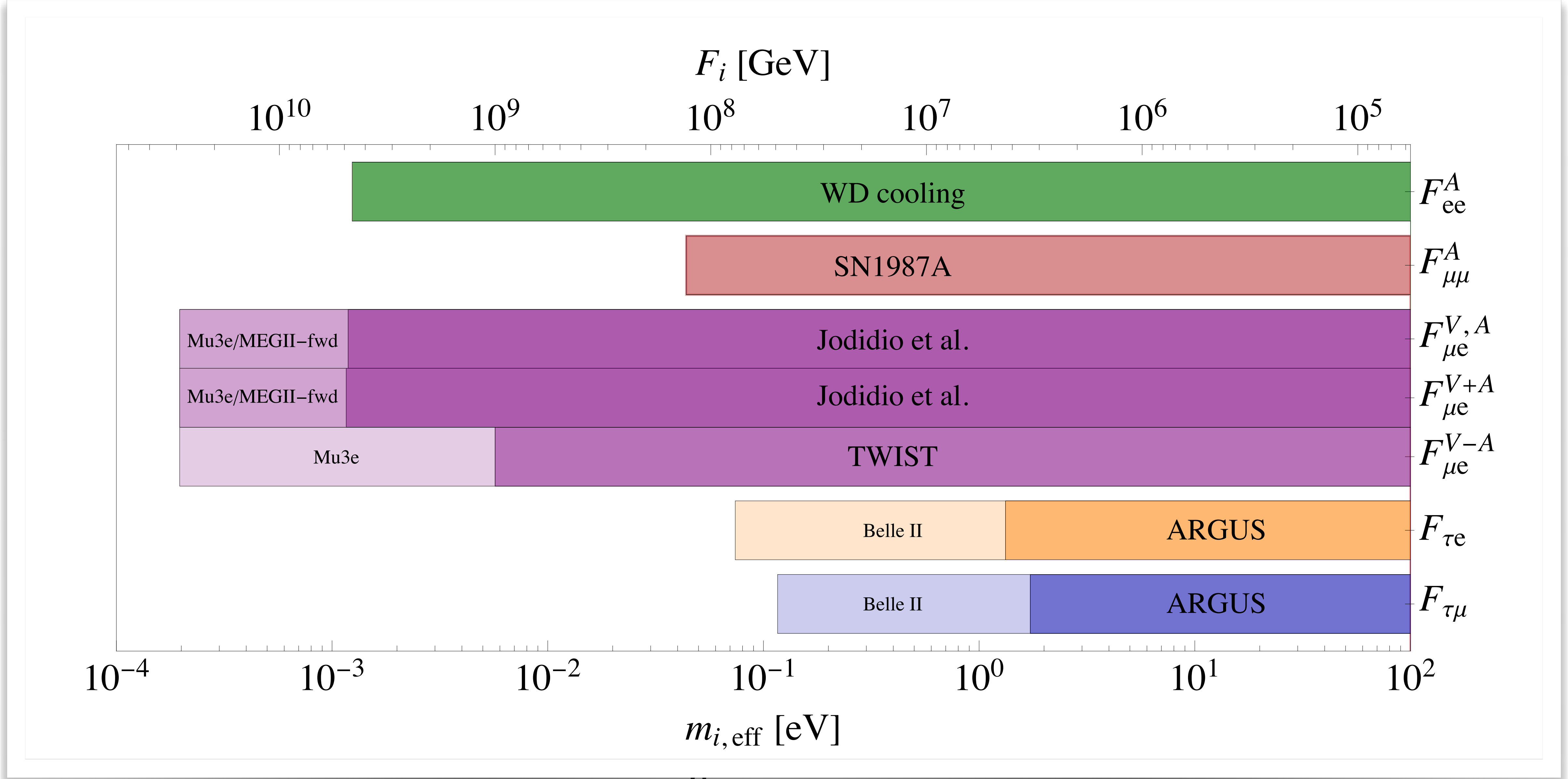
$BR(l_\alpha \to l_\beta\, a) \sim ((v_{ew})^2/(m_a F_{\alpha\beta}))^2$



Calibbi-Redigolo-Ziegler-Zupan
2006.04795

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- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through $\mu \to 3e$ versus $\mu \to e\gamma$ versus $\mu \to e$ conversion (and similarly for $\tau \to e,\mu$) ⇒ Mediators, mechanism

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- Flavor structure of couplings ($[C_D]^{e\mu}$ vs $[C_D]^{\tau\mu}$…) through $\mu \to e$ versus $\tau \to \mu$ versus $\tau \to e$ ⇒ Sources of flavor breaking

CLFV phenomenology

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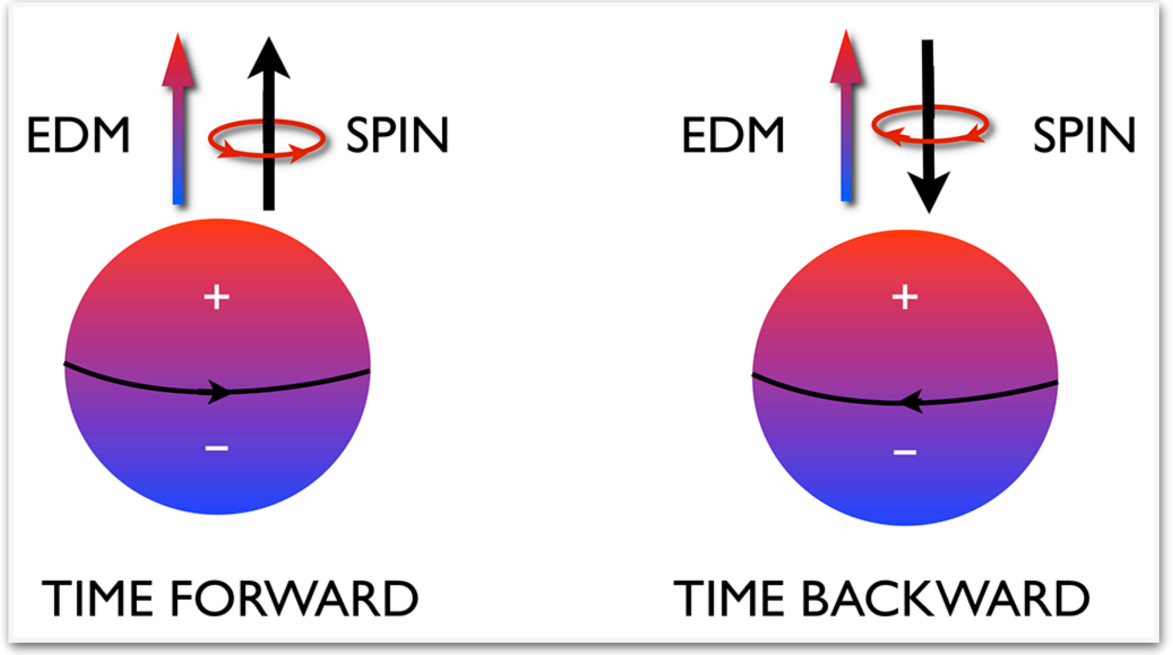
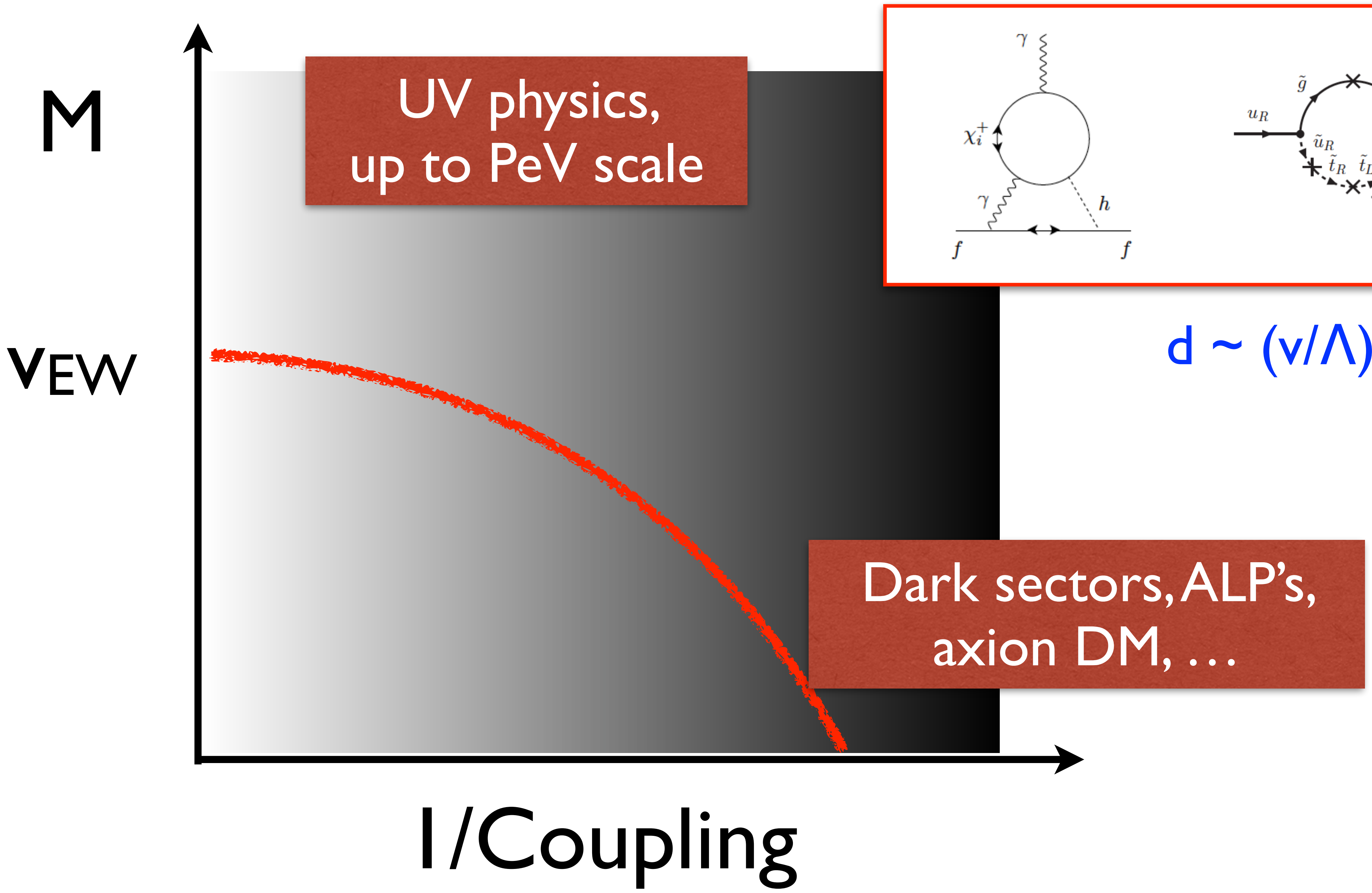
Plurality of searches is essential. The EIC can play an important role

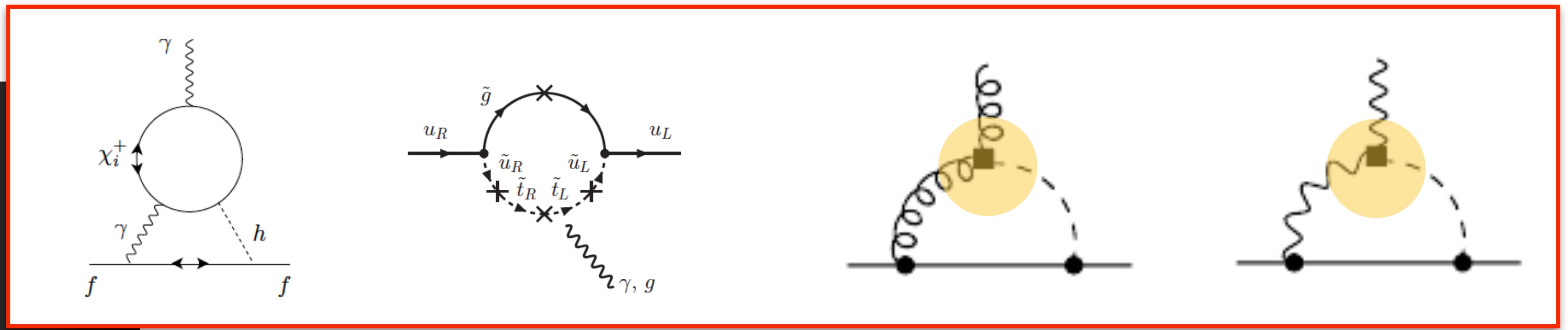
EDMs and new sources of CP violation

White paper 2203.08103 and refs therein

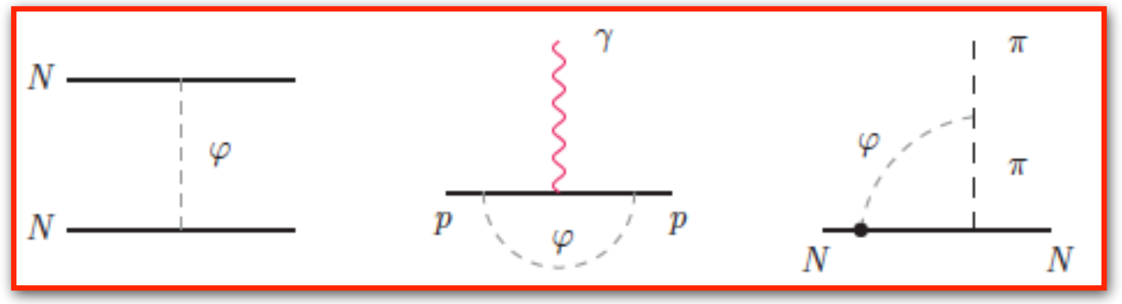


- Probe P *and* T symmetry violation (CP) in flavor diagonal transitions:
  - Highly suppressed in Standard Model (CKM phase)
  - A non-zero EDM would imply new physics or a tiny QCD θ-term ($< 10^{-10}$). Multiple measurements (n, p, atoms, molecules) can disentangle the two effects
  - Sensitive to broad spectrum of new physics (Higgs sector, SUSY, ALPs…) & baryogengesis mechanisms





$d \sim (v/\Lambda)^2 \; 10^{-22}$ e cm $\rightarrow$ $\Lambda \sim 10^3$ TeV

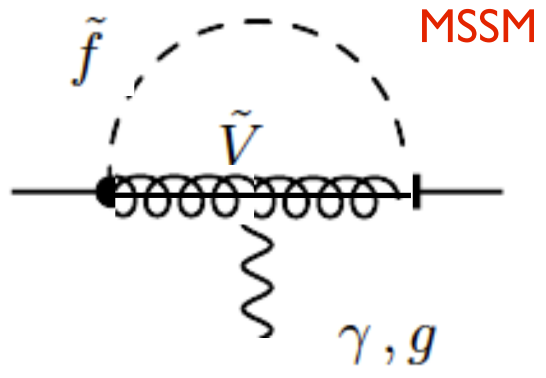


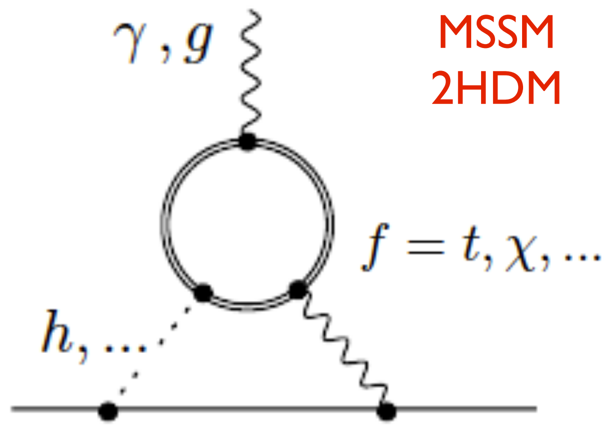
Theoretical challenges & opportunities

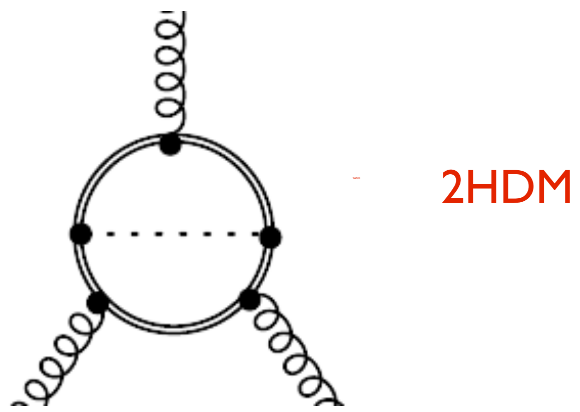
White paper 2203.08103 and refs therein

M

Λ







...

v_{ew}

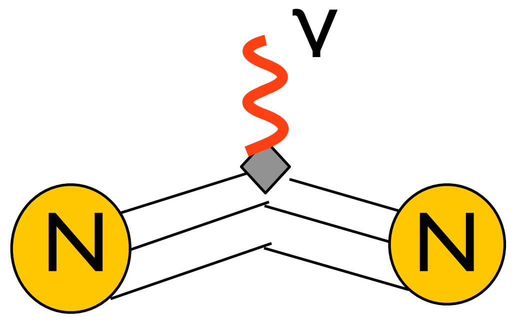
$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

$$d_W \sim \frac{1}{\Lambda^2}$$

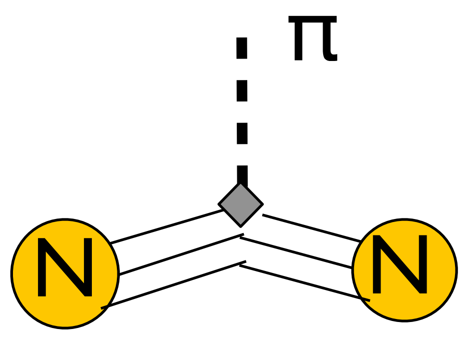
$$d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

Λ_χ

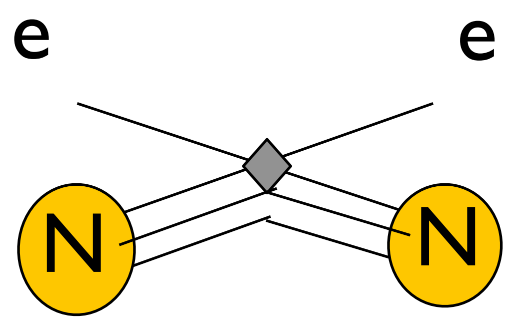
Electron and Nucleon EDMs



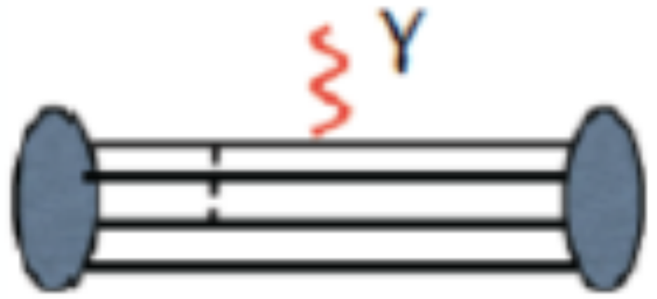
CP-odd πN couplings



Short-range 4N and 2N2e coupling



m_π



Theoretical challenges & opportunities

White paper 2203.08103 and refs therein

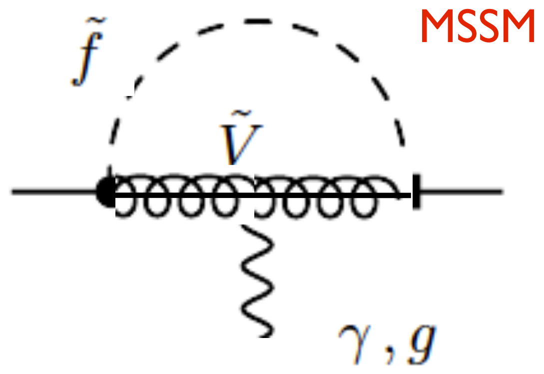
M

Λ

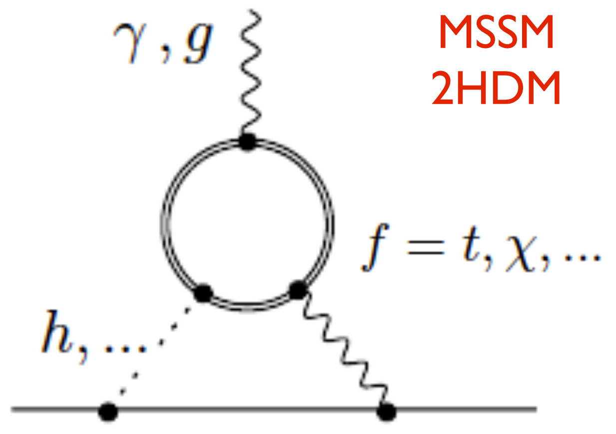
v_{ew}

Λ_χ

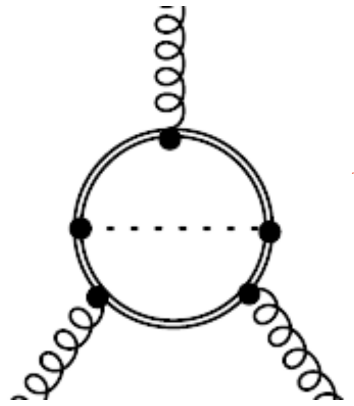
m_π



MSSM



MSSM
2HDM



2HDM

...

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$$d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

Lattice QCD   QCD sum rules

μ=2GeV

$$d_n = -(1.5 \pm 0.7) \cdot 10^{-3} \; \bar{\theta} \, e \, \mathrm{fm}$$
$$-(0.20 \pm 0.01) d_u \; + \; (0.78 \pm 0.03) d_d \; + \; (0.0027 \pm 0.016) d_s$$
$$-(0.55 \pm 0.28) e\tilde{d}_u \; - \; (1.1 \pm 0.55) e\tilde{d}_d \; + \; (50 \pm 40) \, \mathrm{MeV} \, e \, \tilde{d}_G$$

UNCERTAINTY SCOREBOARD:
Proton: same as neutron. Nuclei: worse.
Hard to assess relative reach of various EDMs & to disentangle underlying physics in case of discovery

Theoretical challenges & opportunities

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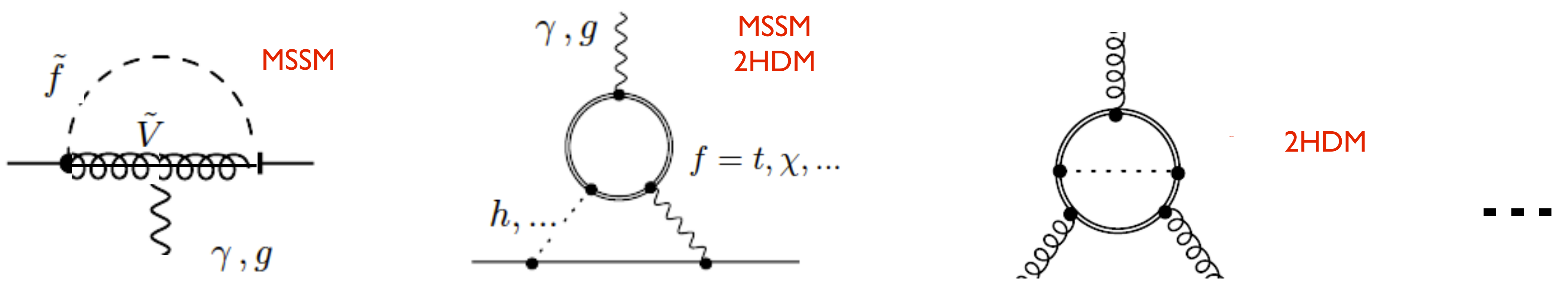

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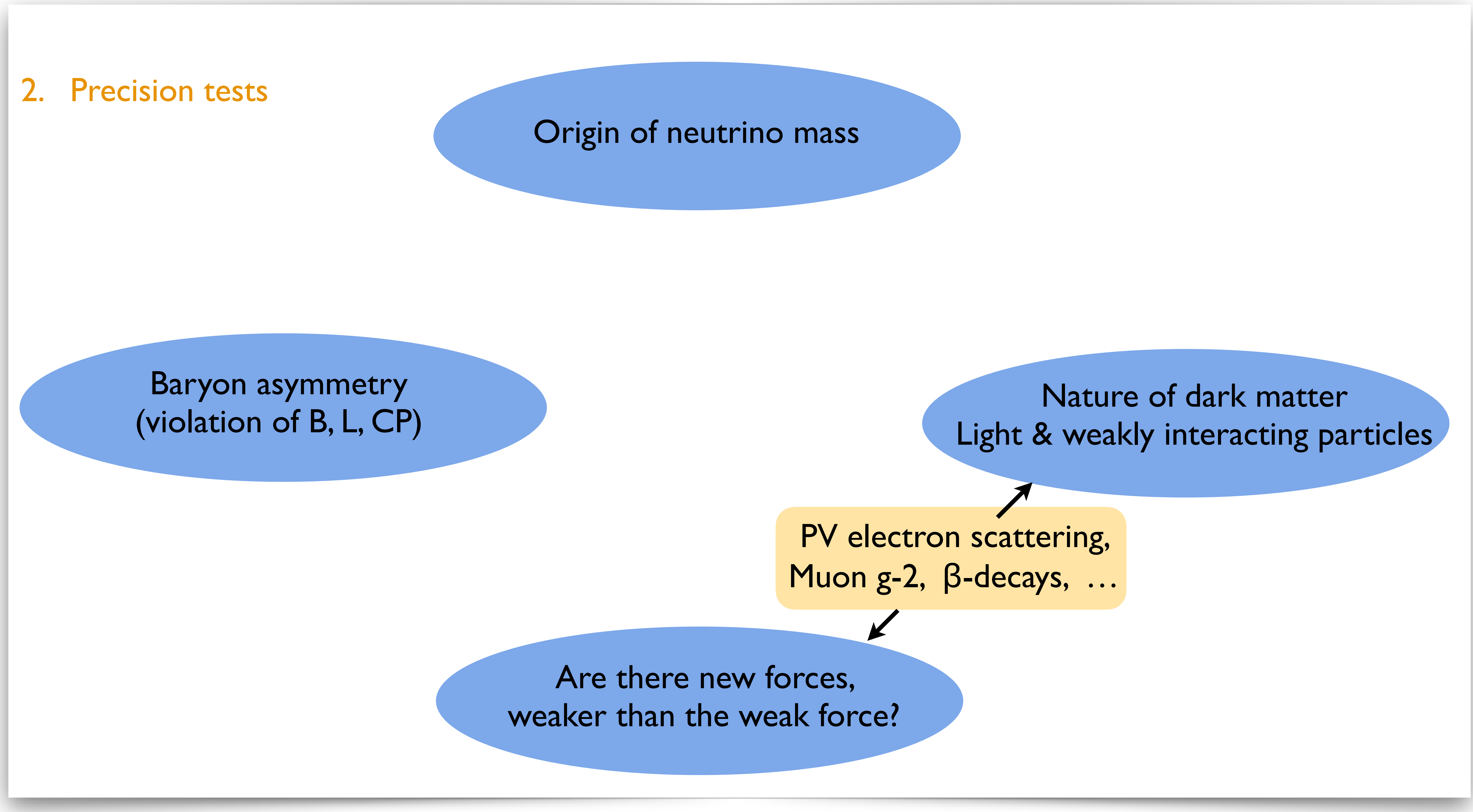
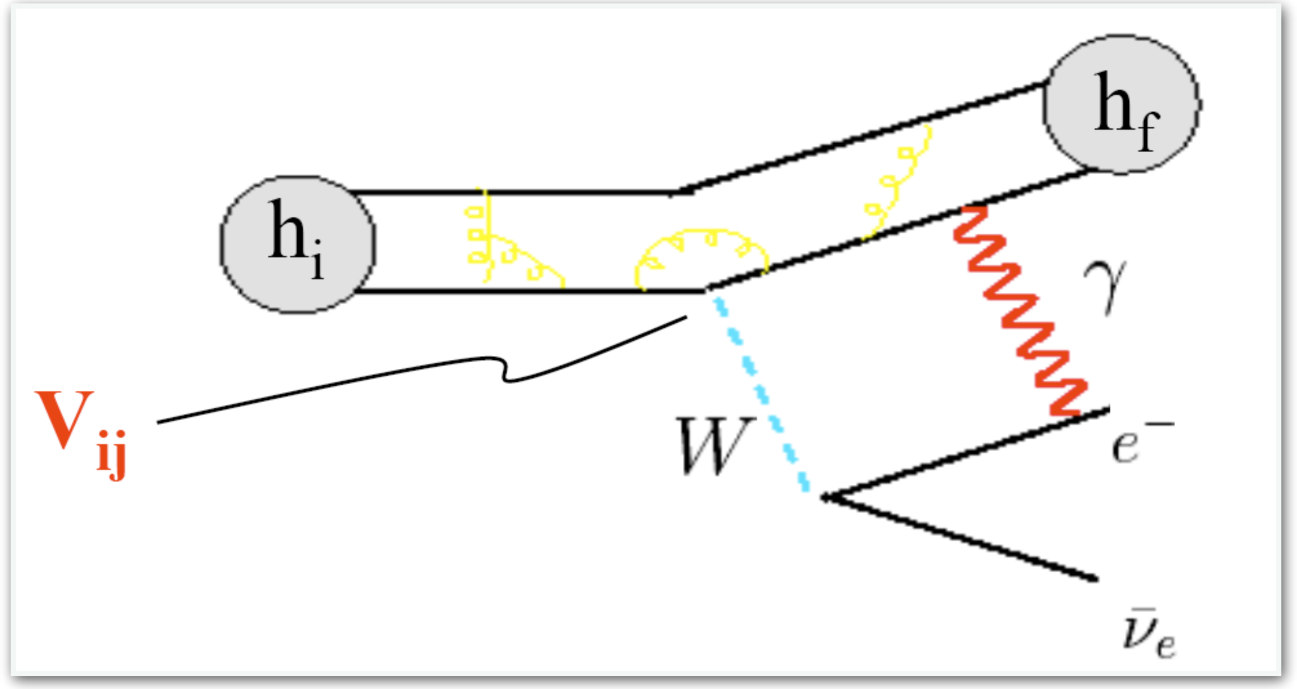
Opportunity for lattice QCD & EIC spin physics

Precision tests

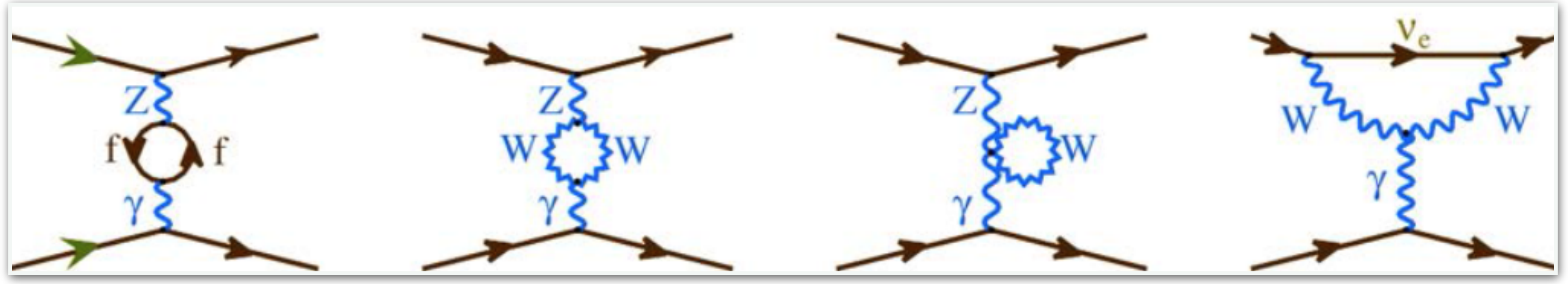


Precision probes of weak interactions

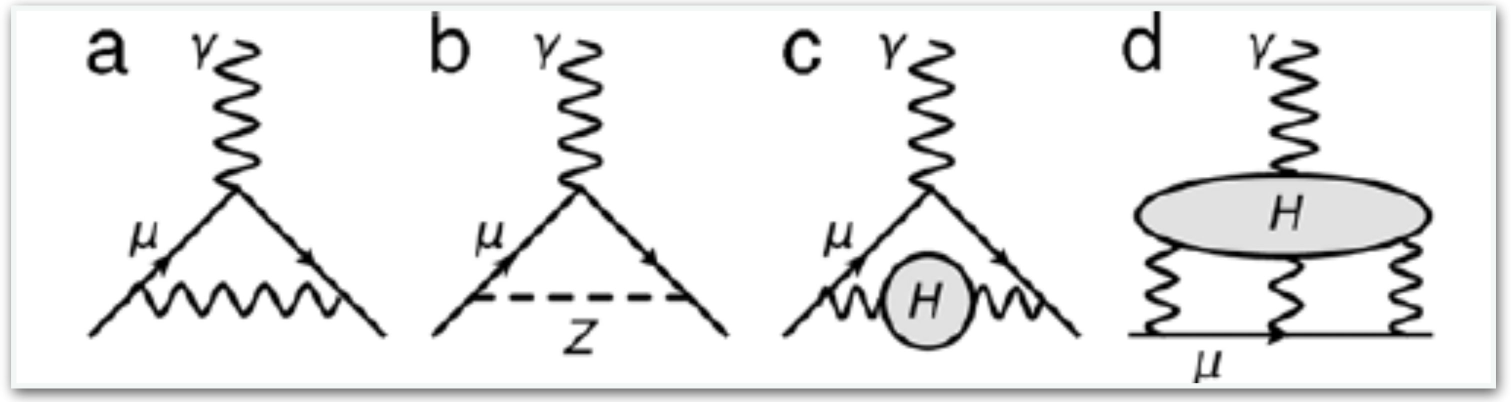
- Beta decays and parity-violating electron scattering (PVES) have played a central role in establishing the Standard Model
- Today, with precision approaching the 0.1% level or better (together with the muon g-2 at the <ppm level!) they probe quantum effects in the Standard Model at unprecedented levels
- "Broad band" sensitivity to new physics, both heavy and light



β decay



Radiative corrections to electron scattering



Representative diagrams for muon g-2

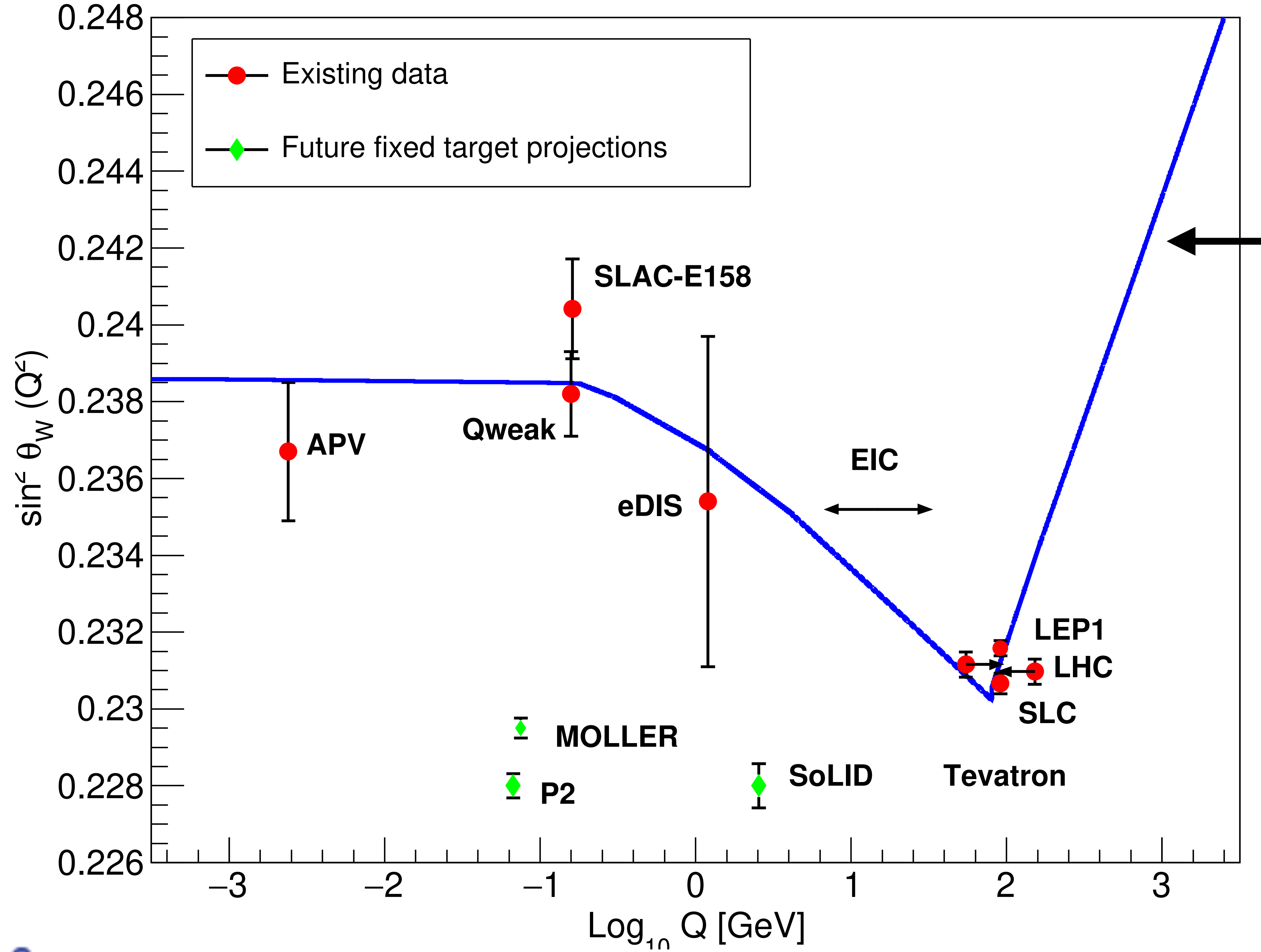
PVES and the weak mixing angle θ_W

$A_{PV}=(\sigma_R-\sigma_L)/(\sigma_R+\sigma_L)$

↕

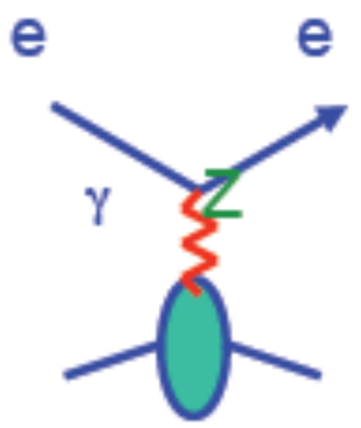
Generated by γ-Z interference

Access to
$\theta_W = \mathrm{ArcTan}(g_1/g_2)$

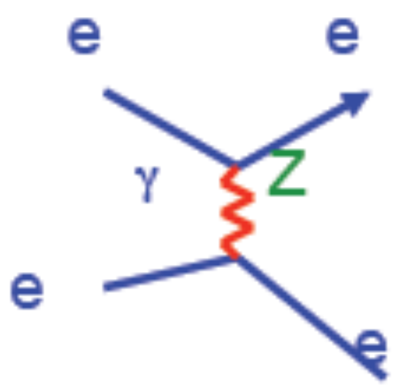


SM prediction: relating EW measurements at Q~100 GeV to low-energy

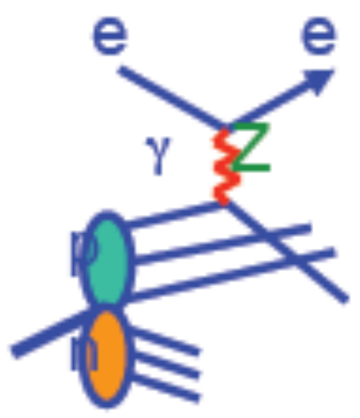
Erler & Ferro-Hernandez, 1712.09146 and references therein



ep (Q-Weak, P-2)



Purely leptonic (MOLLER):
will reach level of Z-pole measurements



e-DIS (SoLID)

Complementarity with LHC (Λ~10 TeV) + sensitivity to low-scale new physics (Z', …)

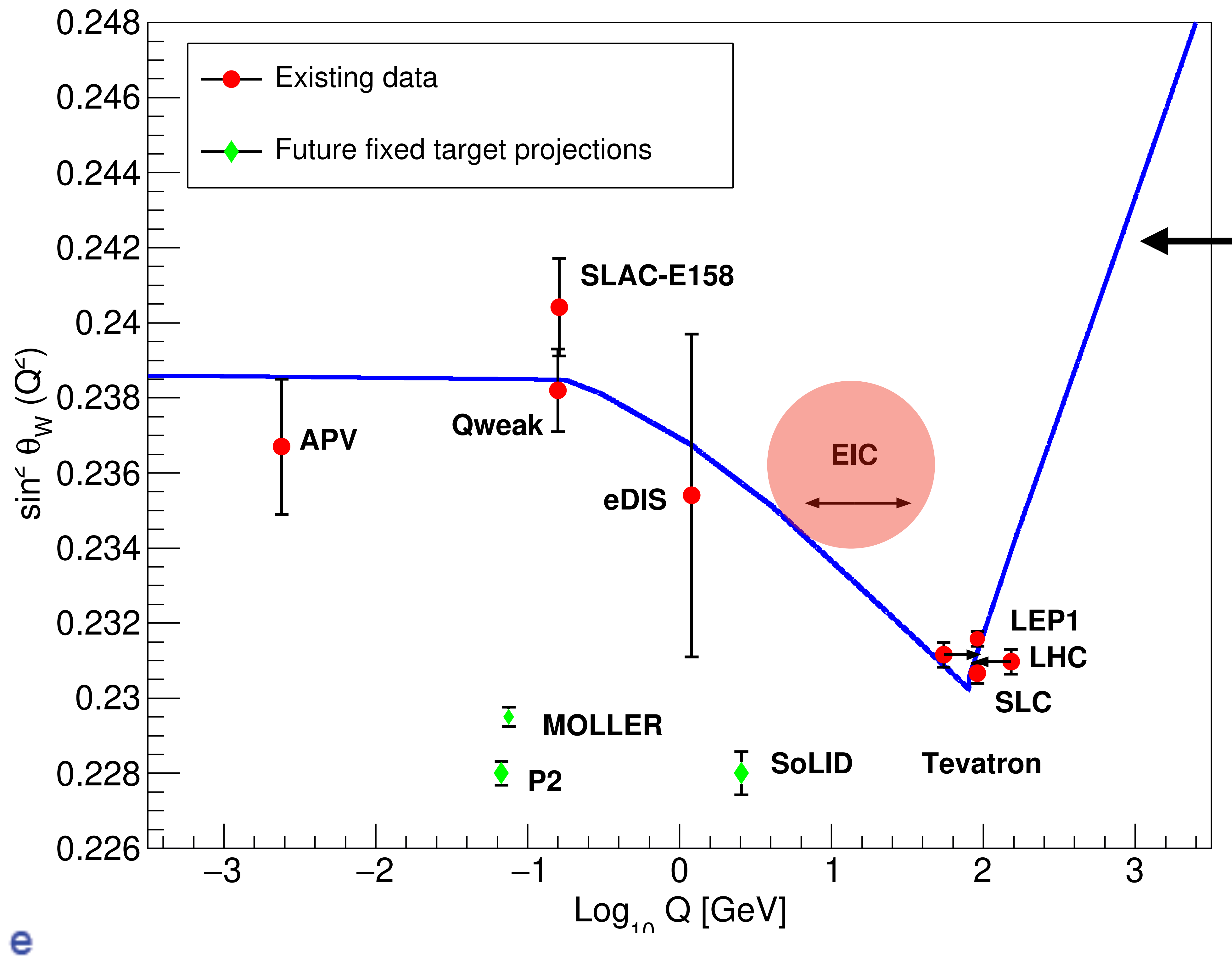
PVES and the weak mixing angle θ_W

$A_{PV}=(\sigma_R-\sigma_L)/(\sigma_R+\sigma_L)$

↕

Generated by γ-Z interference

Access to
$\theta_W = \mathrm{ArcTan}(g_1/g_2)$



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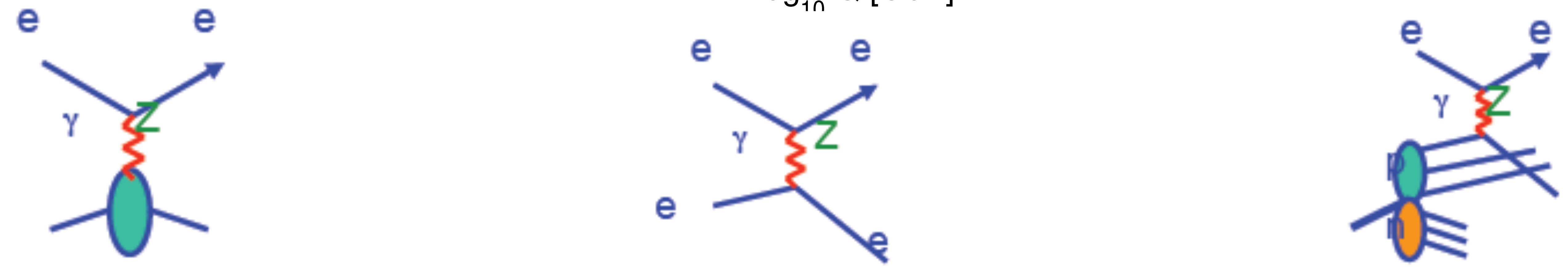


ep (Q-Weak, P-2)

Purely leptonic (MOLLER): will reach level of Z-pole measurements

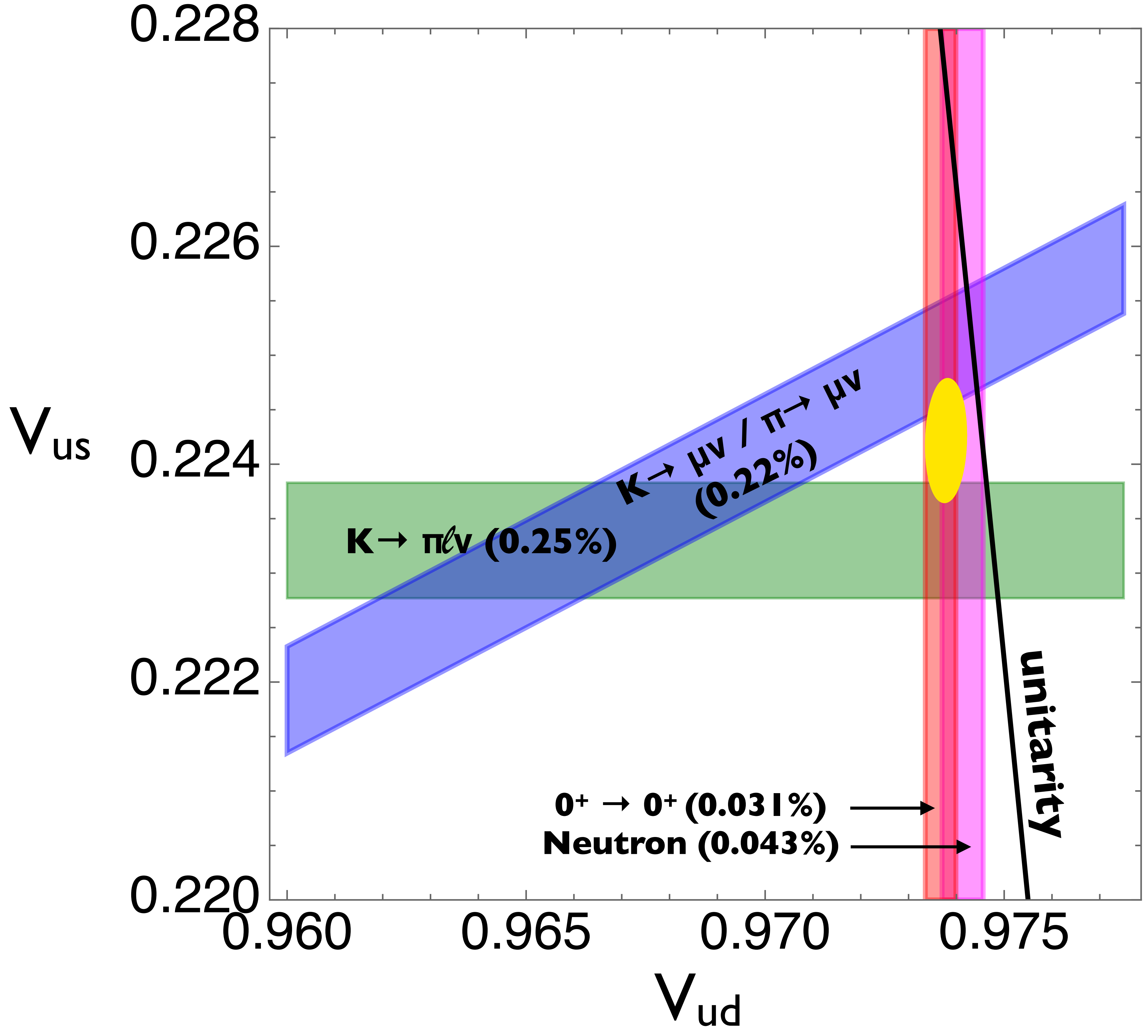
e-DIS (SoLID)

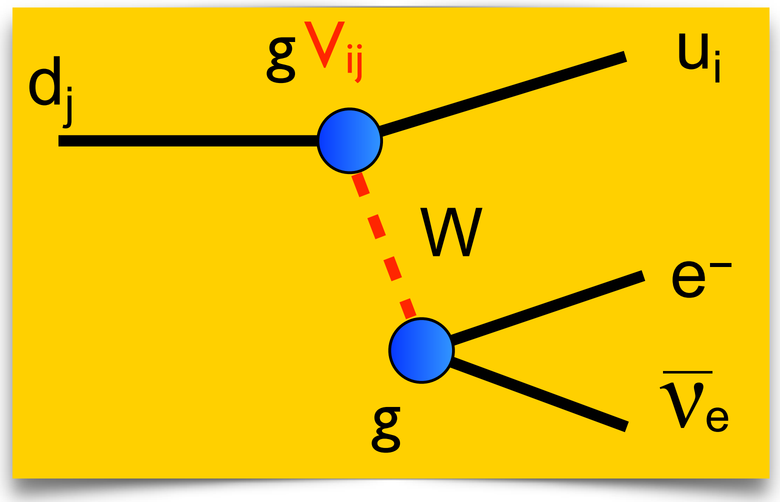
Complementarity with LHC (Λ~10 TeV) + sensitivity to low-scale new physics (Z', ...)

β decays and CKM unitarity

$\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = -15(5)\times 10^{-4}$

VC-Crivellin-Hoferichter-Moulson 2208.11707
and references therein





- Two ~3σ ‘anomalies’

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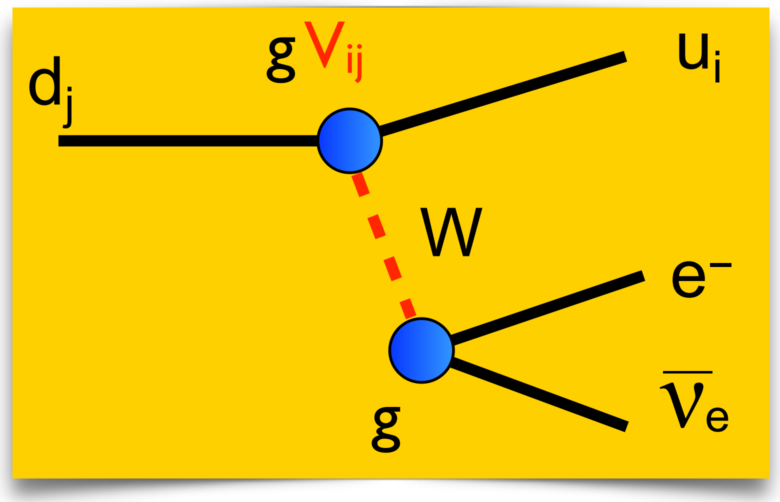

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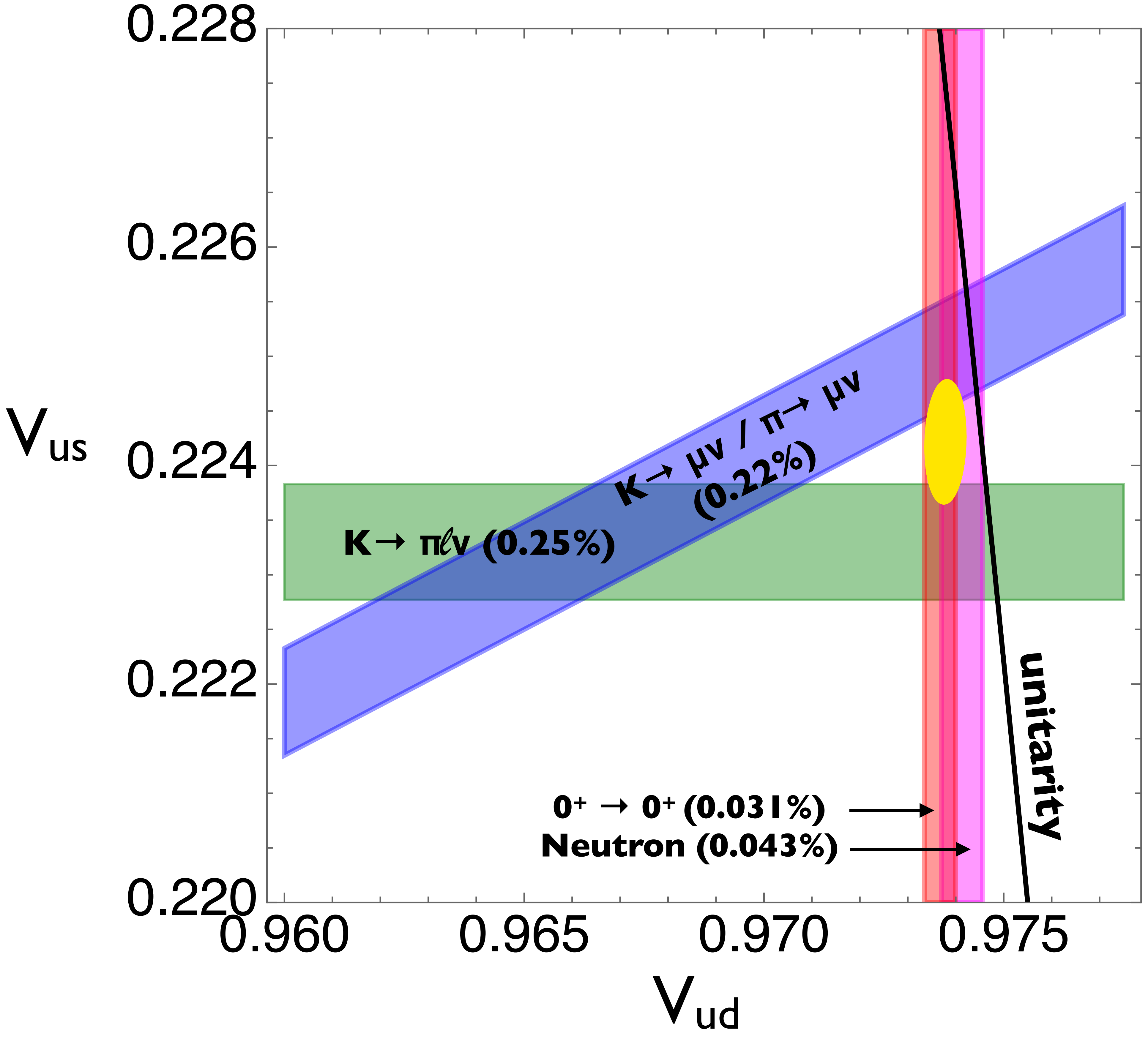

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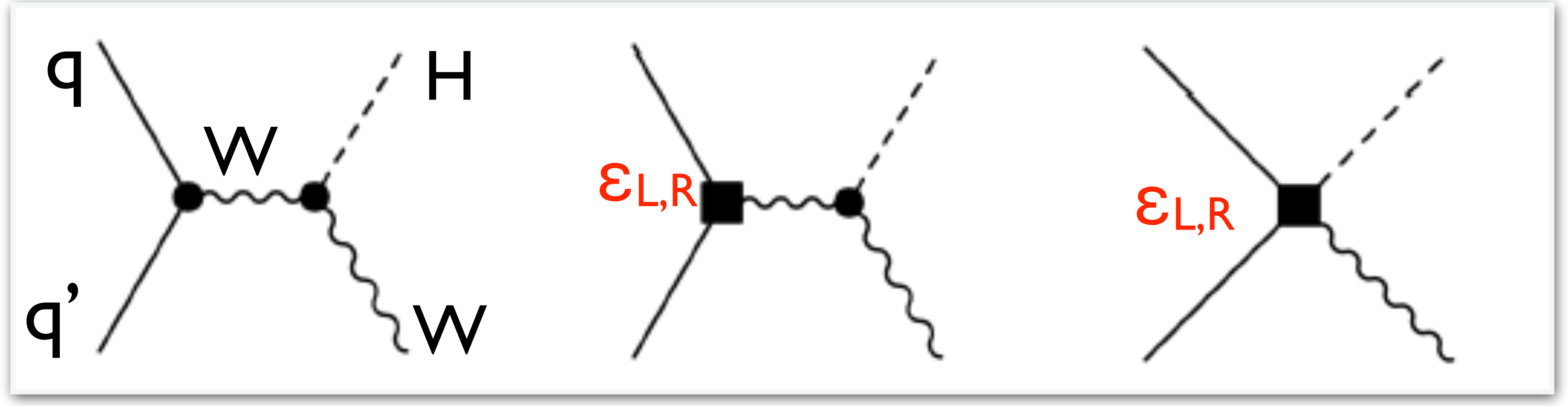
- At face value point toward vertex corrections with Λ~10 TeV (hard to probe even at the HI-LUMI LHC). Δ_{CKM} is a full-fledged precision EW observable and should be included in global fits.

VC, Dekens, de Vries, Mereghetti, Tong, 2311.00021



Alioli, VC, Dekens, deVries, Mereghetti 1703.04751

β decays and CKM unitarity

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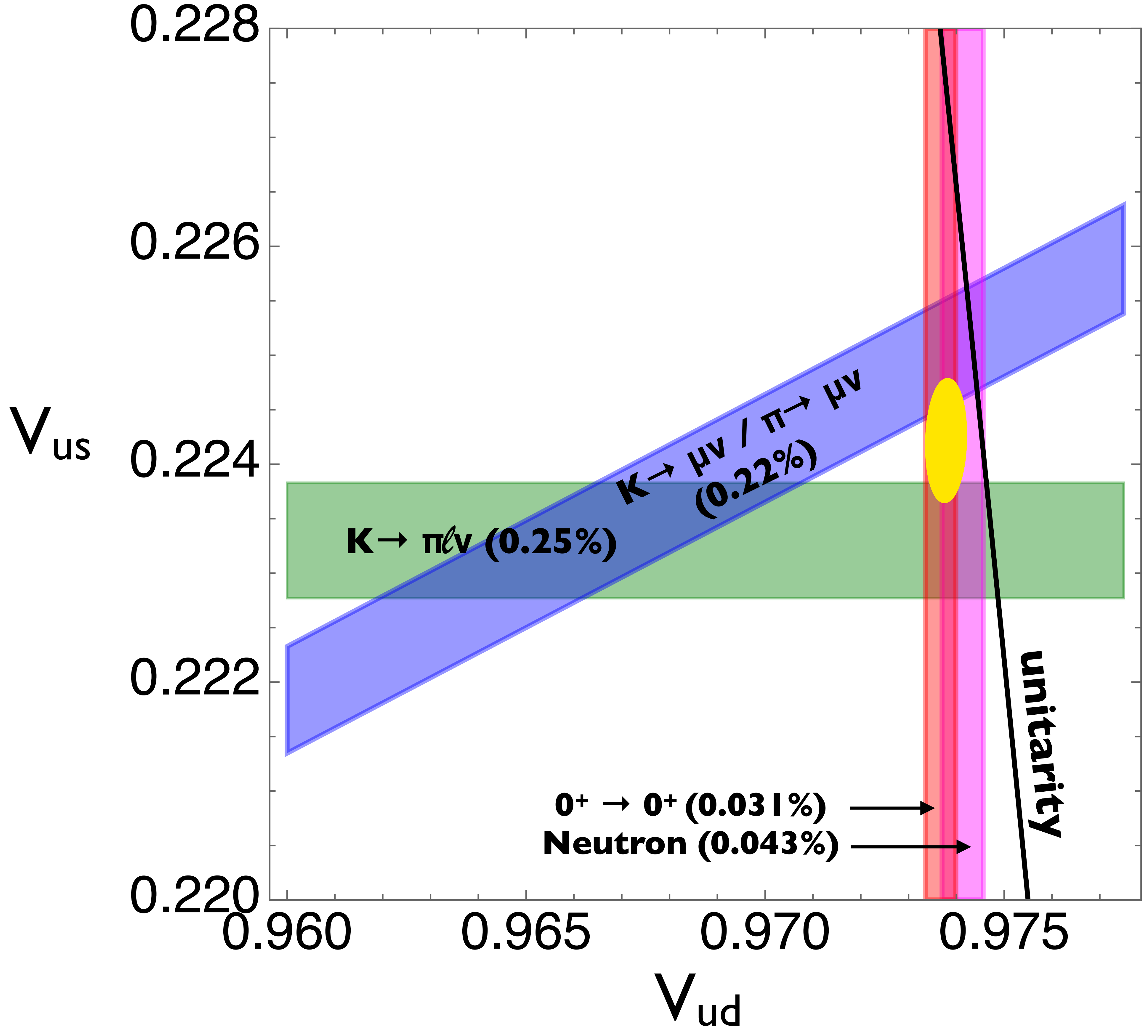

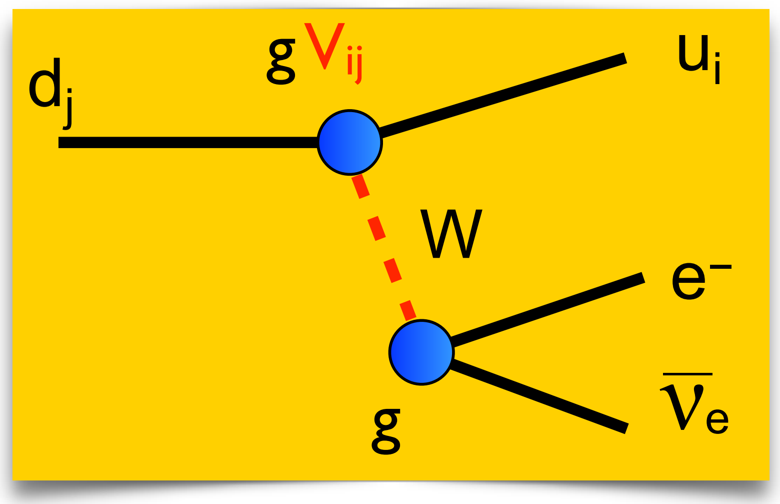

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  VC, Dekens, de Vries, Mereghetti, Tong, 2311.00021
- Theory opportunities: rad. corr. to neutron (lattice QCD+QED) and nuclear decays (EFT + ab initio n.s.)
- Experimental opportunities in neutron decay, $0^+ \to 0^+$, π & K decays, all with clear target goals. EIC?

The Intensity Frontier and the EIC

- IF in the 2023 NSAC Long Range Plan (NP)
  - Searches for rare / SM-forbidden processes:
    - LNV: $0\nu\beta\beta$
    - EDMs: neutron, nuclei
  - Precision measurements of SM-allowed processes:
    - Muon g-2
    - Weak charged current (mesons, neutron, nuclei)
    - Weak neutral current (PVES)
  - Search / characterization of light weakly coupled particles
    - Absolute neutrino mass
    - Sterile neutrinos
    - Neutrino scattering

The EIC not on the map yet.

- IF in the 2023 P5 report (HEP)** (my very rough 'binning')
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The EIC not on the map yet. But can directly or indirectly lead to advances in several areas.

The Intensity Frontier and the EIC

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    - LNV: $0\nu\beta\beta$ $e^- p \to \mu^+ X$ $e^- p \to \tau^+ X$?
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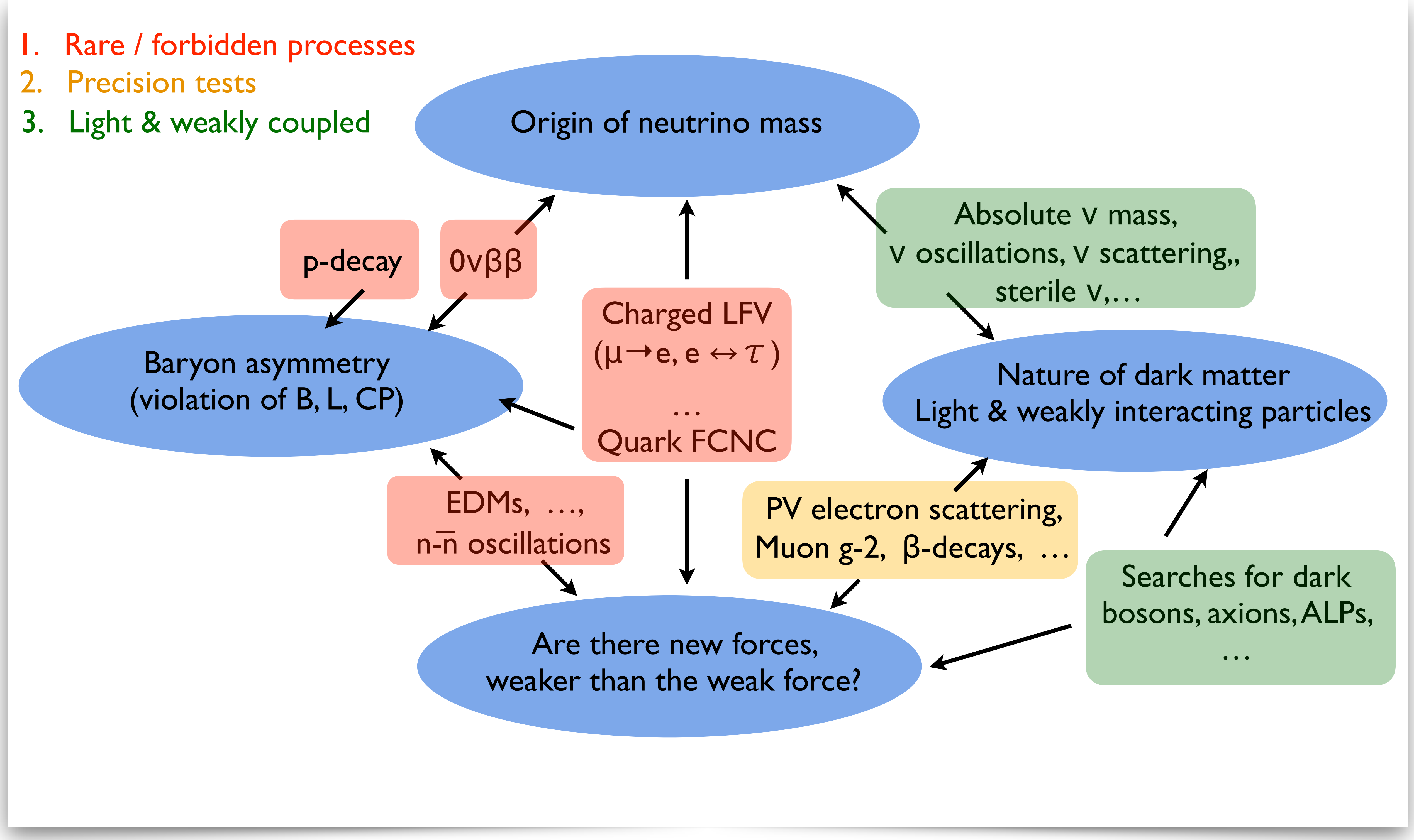
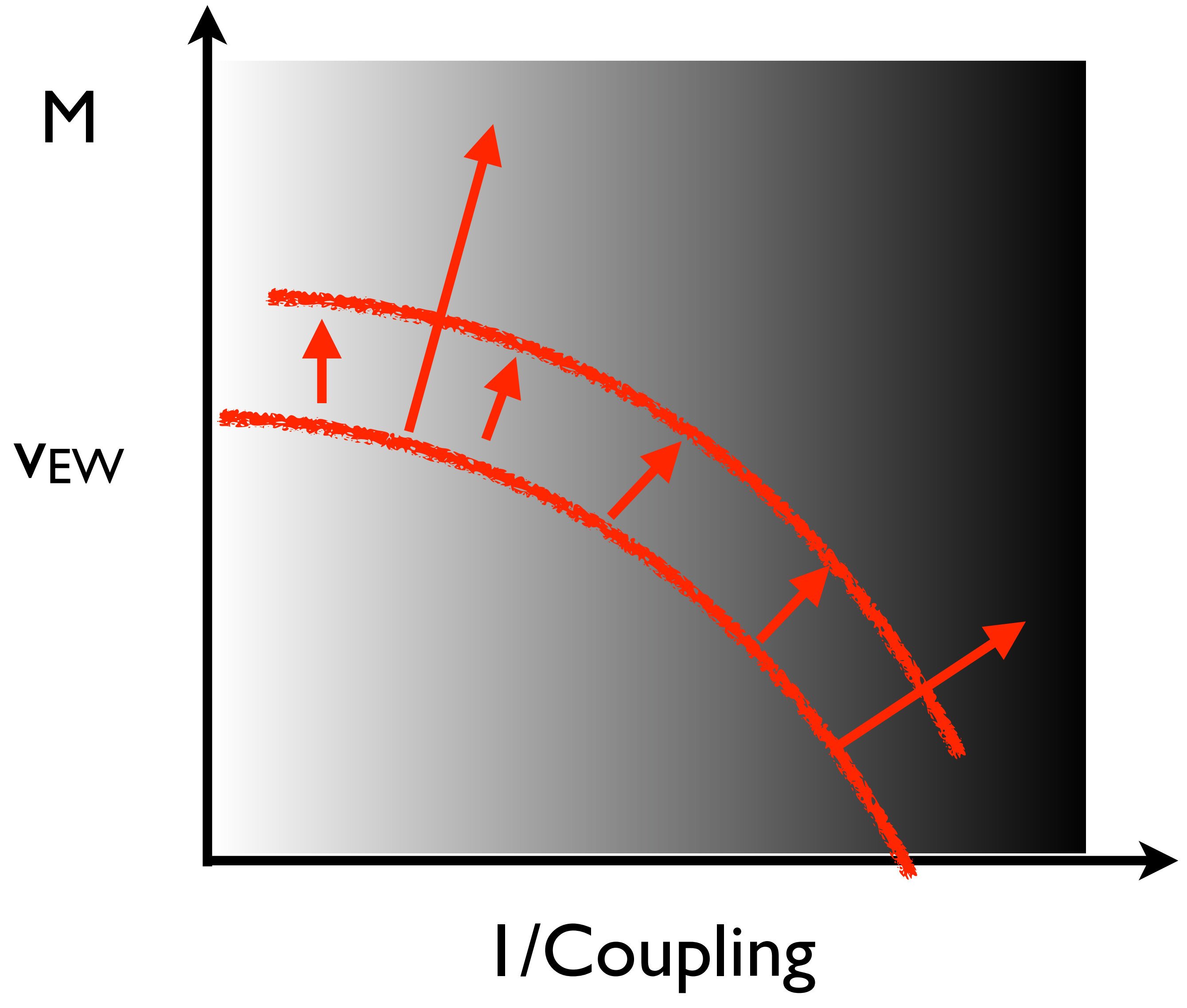
Concluding comments

- Experiments at the Intensity Frontier are exploring uncharted territory in the search for new physics, in a complementary way to other frontiers





- Vibrant experimental program probes BSM physics related to "big questions"

- The EIC can and should play a role in this exciting area