BSM Physics Across Frontiers

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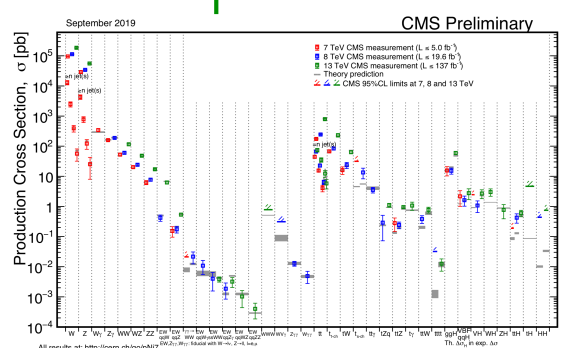
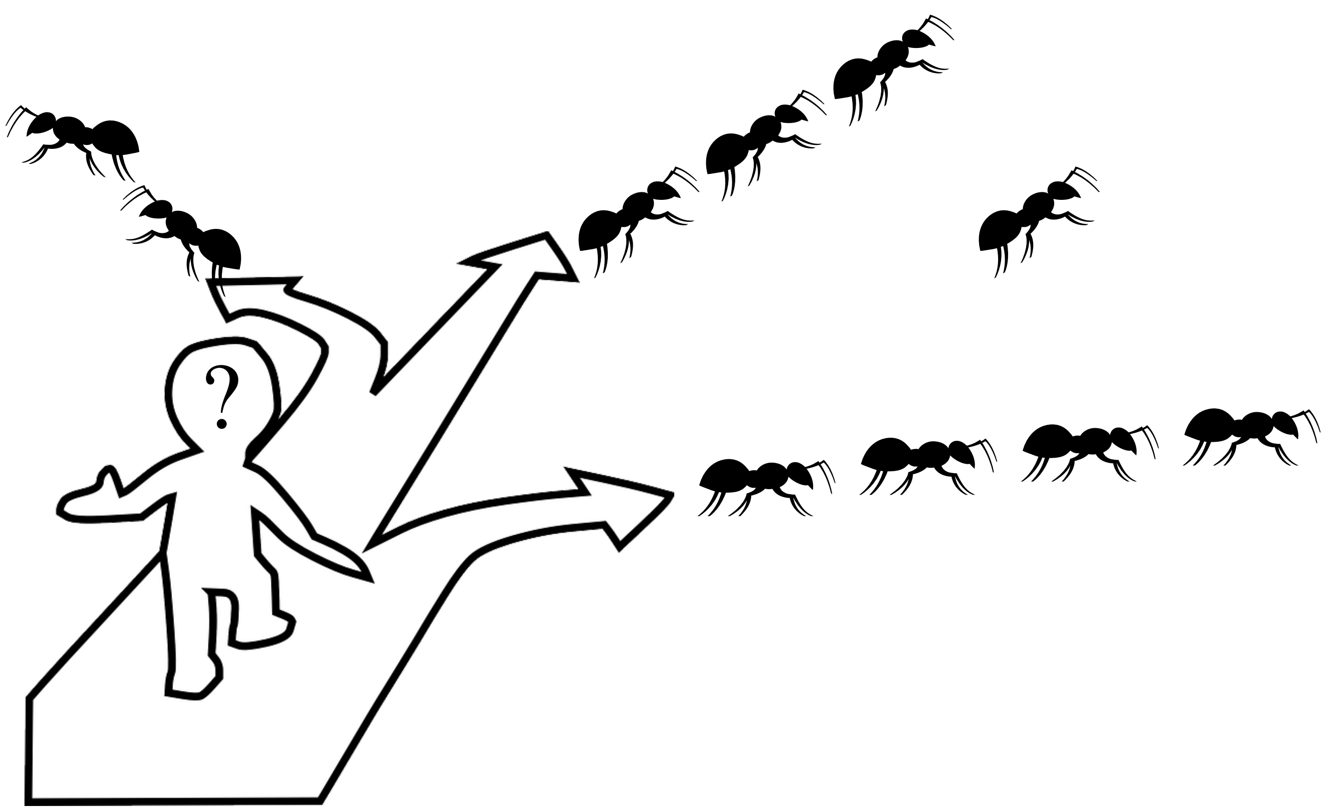
Beyond the SM

Confusing situation?!

1. The SM: Experimental success!





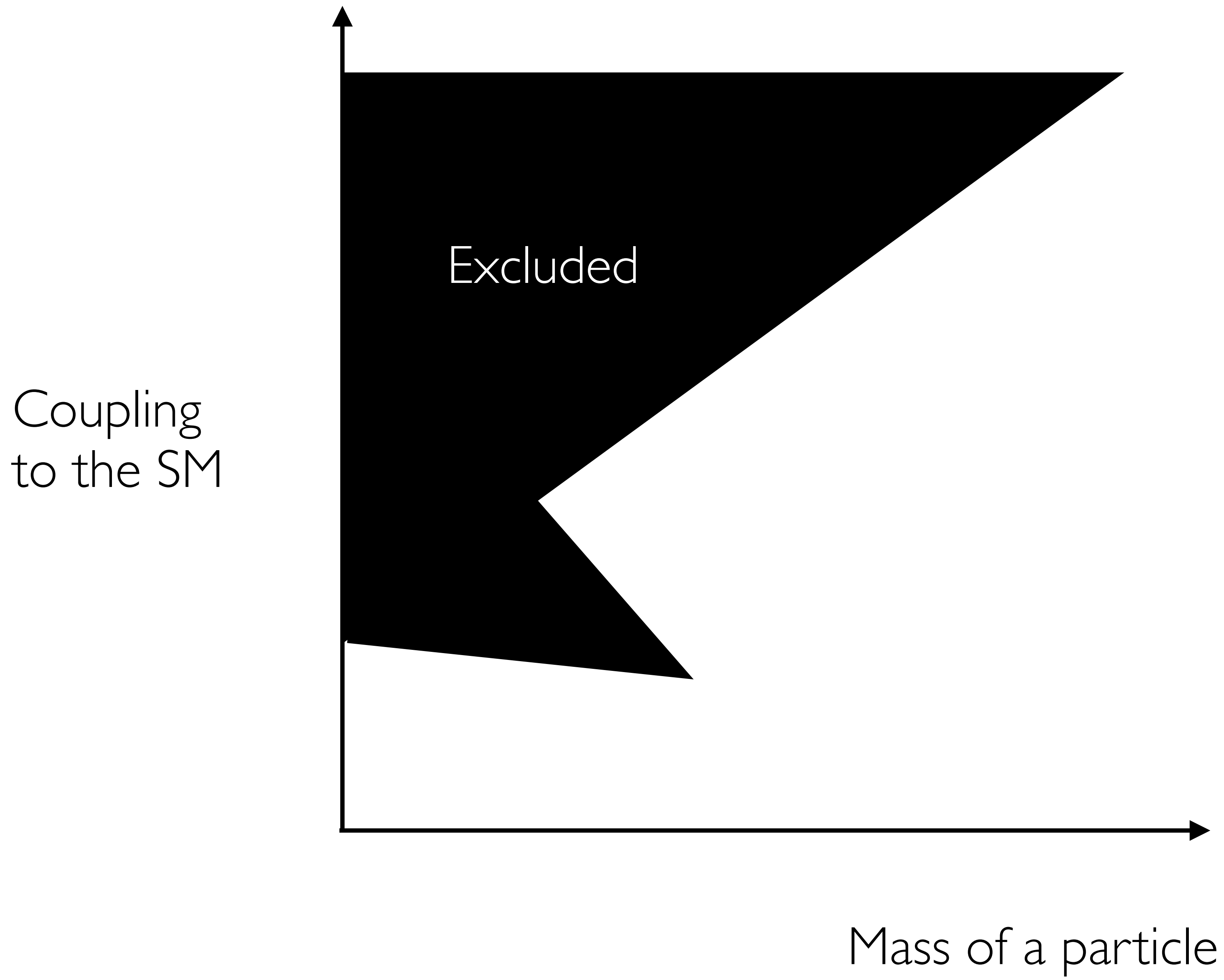
2. Yet, many open questions:

Hierarchy problem
Flavour puzzle
Strong CP problem
Charge quantization

Dark matter
Baryon asymmetry
Neutrino masses

Inflation
Dark energy
Quantum gravity
….

Where could NP particles be?



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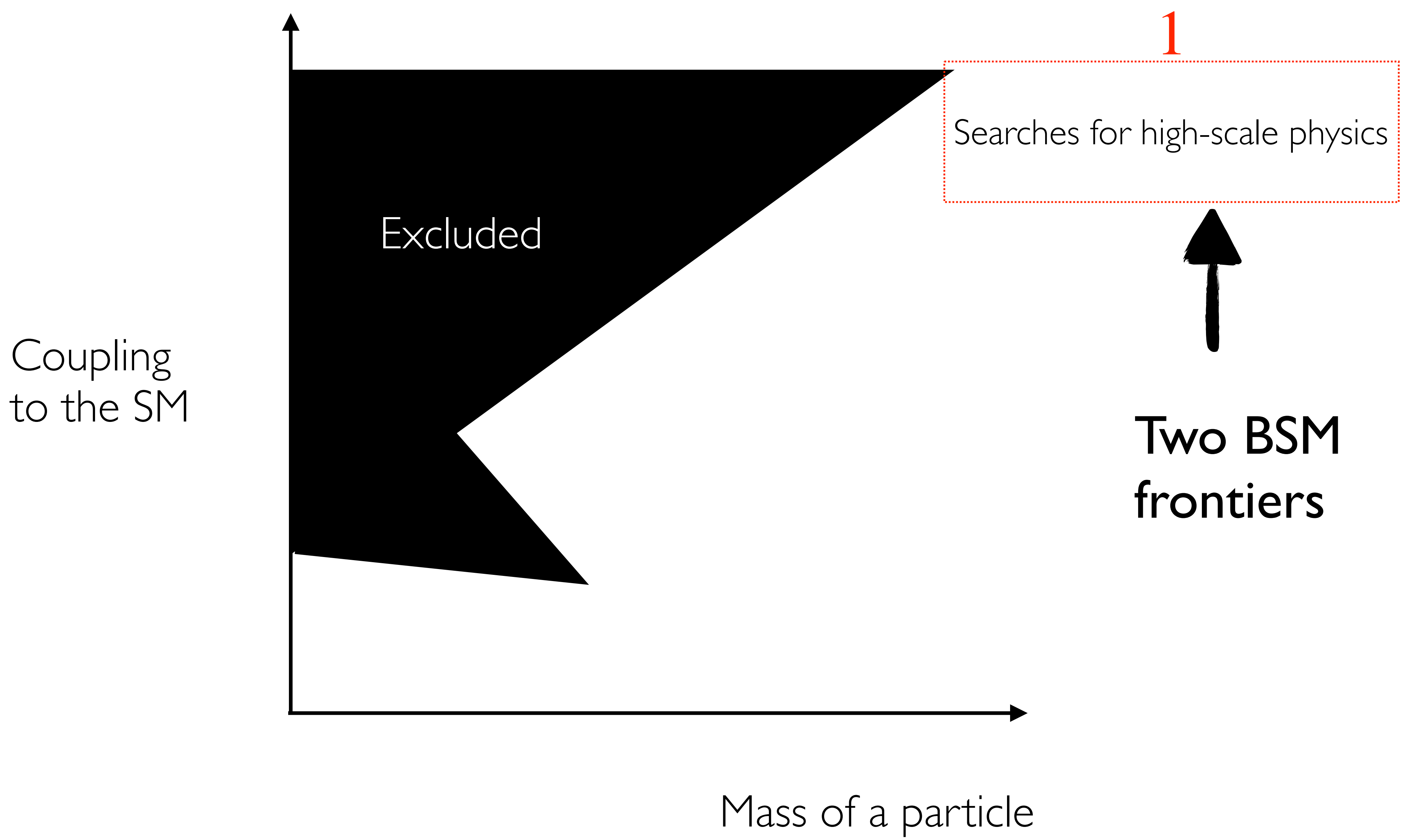

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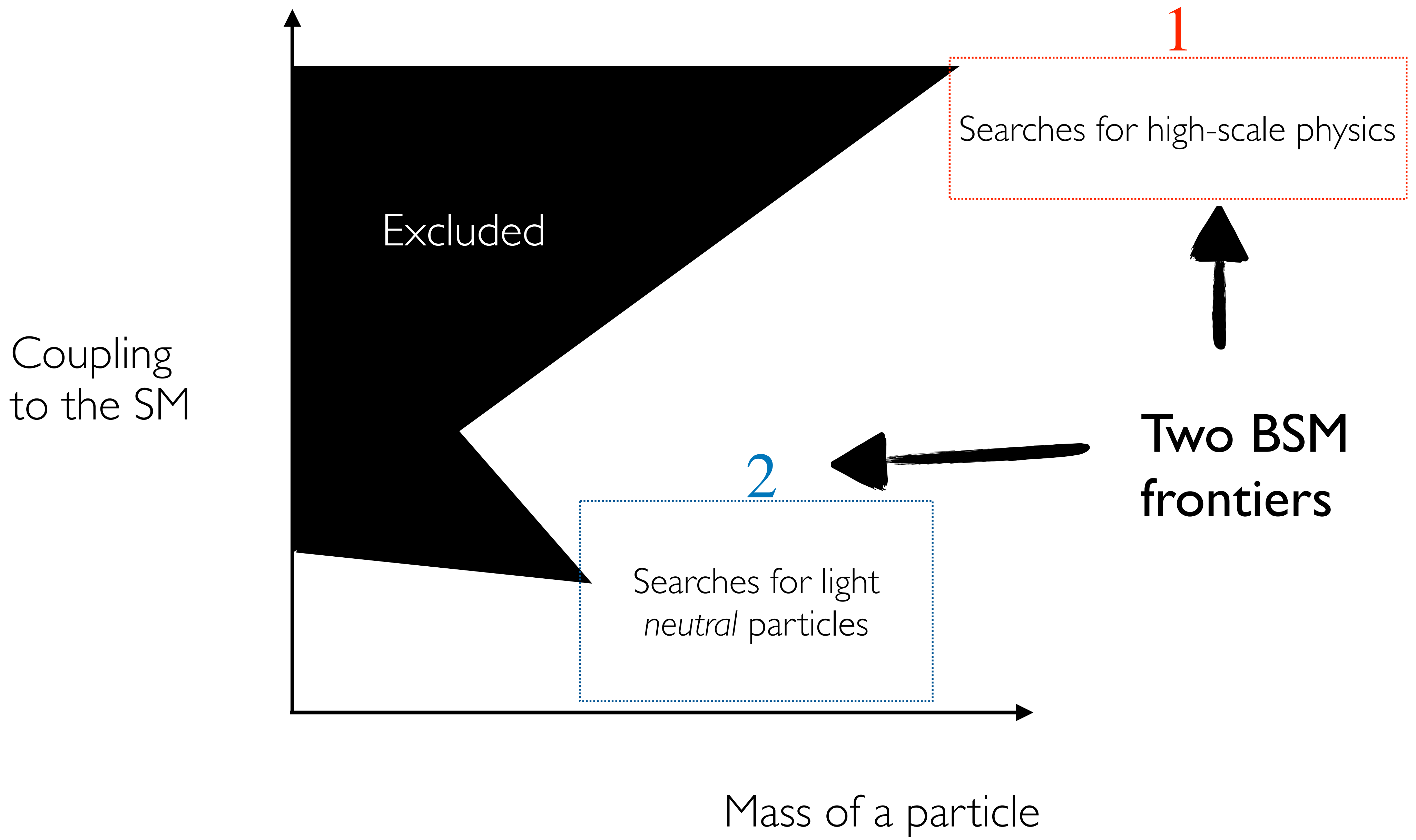
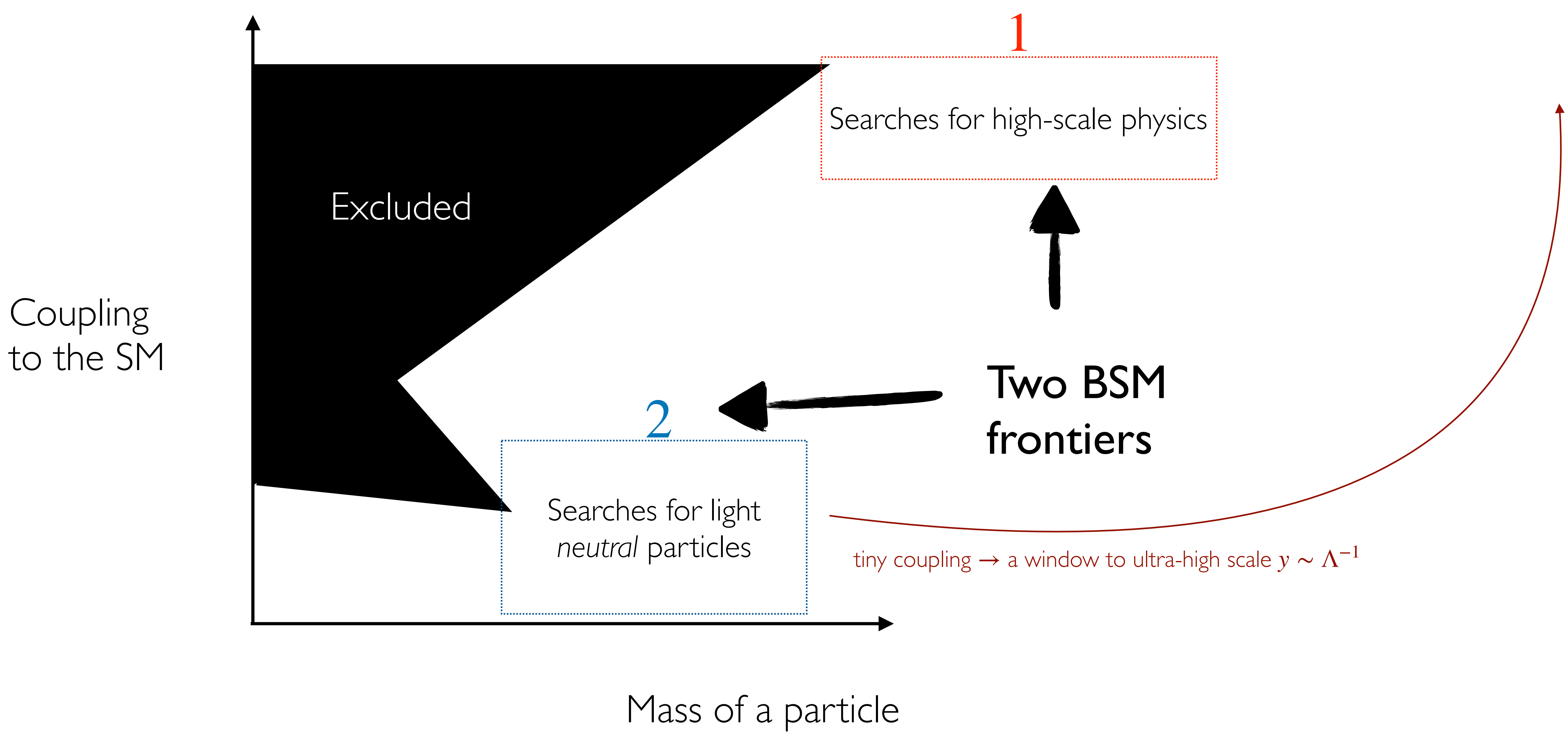


Where could NP particles be?



Outline

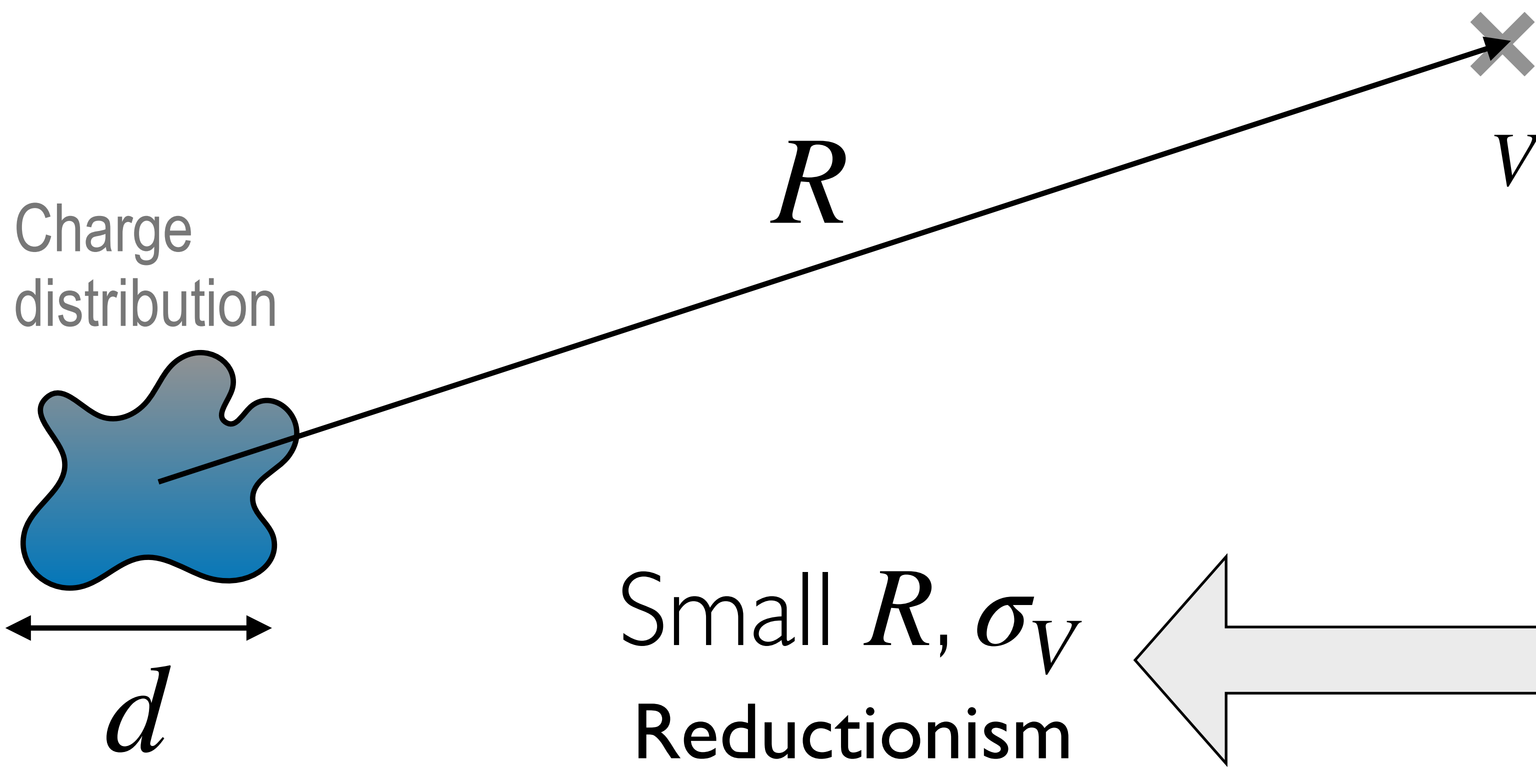
- Taking a step back: *The EFT paradigm*
- Accidental symmetries
- Example: High-multiplicity muon decays

The EFT paradigm

"Physics is the art of approximation"

Effective theories: Electrostatics

- Scale separation $d \ll R$
- Precision/Distance interplay
  [Intensity/Energy frontier]



$$V(R) = C_1 \frac{d}{R} + C_2 \frac{d^2}{R^2} + C_3 \frac{d^3}{R^3} + \ldots$$

Multipole expansion

Small R, σ_V	⟺	Large R, σ_V
Reductionism		**Universality**
[Model discrimination]		[Model independence]
More multipoles, eventually breakdown		Few multipoles

Accidental symmetries

$$V(R) = C_1 \frac{d}{R} + C_2 d \frac{\vec{d}\,\vec{R}}{R^3} + \ldots$$

$$SO(3) \supset SO(2) \supset \ldots$$

Emergent (accidental) symmetries
when truncating the series

Quantum field theory

Quantum Mechanics

$$E \sim p \sim \lambda^{-1}$$

Relativity

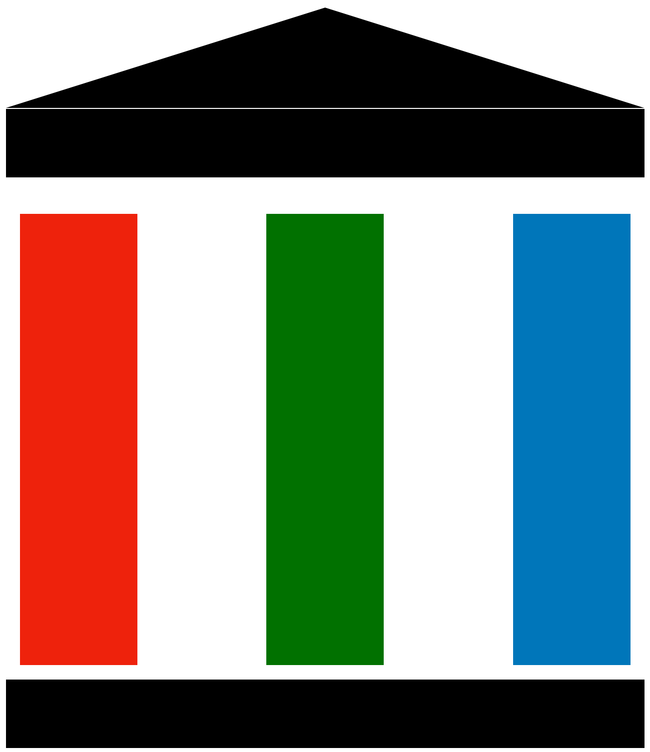
High Energy = Short distance

$\hbar = c = 1$

Wilsonian approach:

Succession of Effective Field Theories

EFT pillars

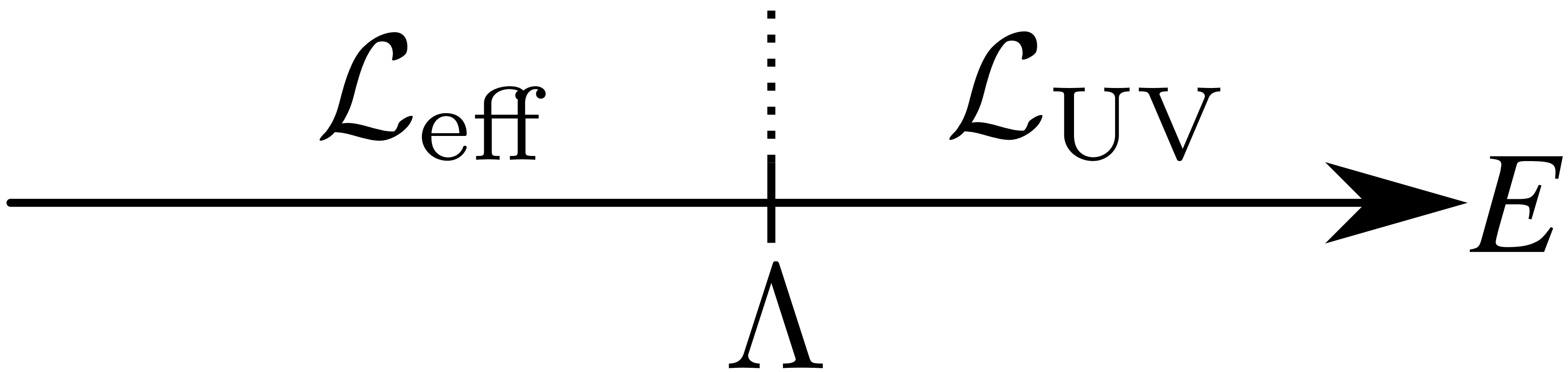


- **Degrees of freedom**
  Drop heavy fields and keep only the light ones. Heavy and light are defined by the **cutoff**.

- **Symmetries**
  Space-time, gauge symmetries. They shape the infinite series of **local** operators of the EFT.

- **Power-counting**
  The expansion parameter gives meaning to the EFT series.

EFT cutoff



cutoff

Infrared,
Long-distance,
Soft

Ultraviolet,
Short-distance,
Hard

EFT matching

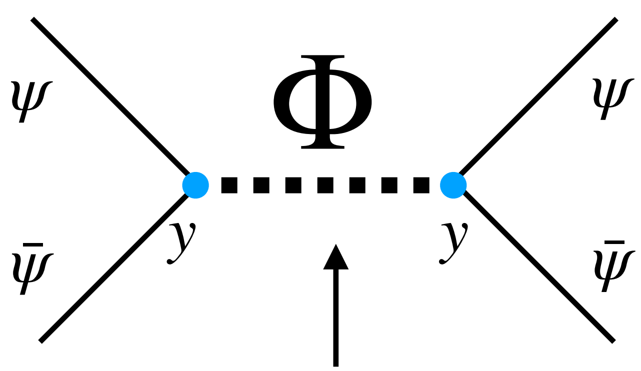
Toy example

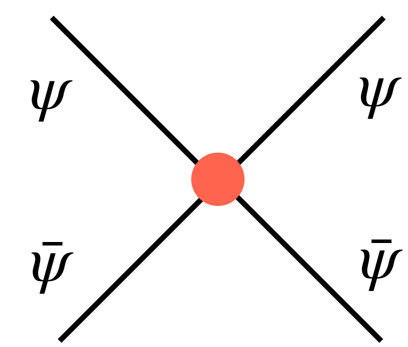
EFT

Consider $M \gg E \gtrsim m$ where E is the collider's energy

$$\mathscr{L}_{\mathrm{UV}} \supset \bar{\psi}\,(iD - m)\,\psi$$
$$+\partial_\mu \Phi\, \partial^\mu \Phi - M^2 \Phi^\dagger \Phi$$
$$-y\,\bar{\psi}\psi\,\Phi$$

$$\mathscr{L}_{\mathrm{eft}} \supset \bar{\psi}\,(iD - m)\,\psi$$
$$-C\,\bar{\psi}\psi\,\bar{\psi}\psi + \dots$$





$+\dots$

$$\langle 0|T\{\Phi(0)\Phi(x)\}|0\rangle = \int \frac{d^4k}{(2\pi)^4} e^{-ikx} \frac{i}{k^2 - M^2} \xrightarrow{k^2 \sim \mathcal{O}(E^2) \ll M^2} -\frac{i}{M^2}\delta^{(4)}(x) + \dots$$

Degrees of freedom (in/out states): only ψ

Local interaction:
The Compton wavelength M^{-1} is very small.
$E \sim M$ needed to probe the inner structure.

EFT: Running

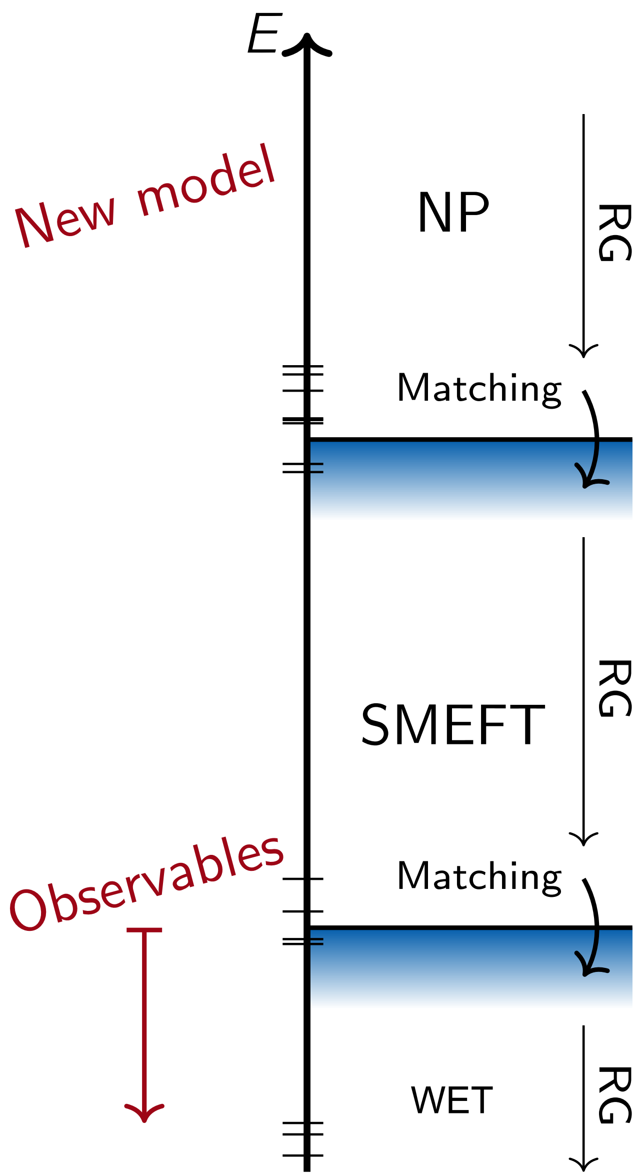
- Large logarithms: The breakdown of the perturbative calculation.
- ***Renormalisation group equation*** is the way out of this disaster.

$$\mathcal{L}^{(6)} = \sum_i C_i Q_i$$

$$\dot{C}_i \equiv 16\pi^2 \mu \frac{\mathrm{d}C_i}{\mathrm{d}\mu} = \gamma_{ij} C_j$$

Anomalous dimension matrix

1308.2627,
1310.4838,
1312.2014,
1709.04486,
1711.05270,
1711.10391,
1710.06445,
1804.05033,
1908.05295,
2010.16341,
2012.08506,
2012.07851,
...



- Operator mixing important in flavor physics

$\mathscr{L}$ = *infinite series*

Theory construction:

1. Space-time & gauge invariance + field content
2. Local Lagrangian = infinite series

Theory parameter (WC)

Local operator
- a monomial in fields and derivatives

$$\mathscr{L}(x) = \sum_{\mathcal{O}}^{\infty} C_{\mathcal{O}}\, \mathcal{O}(x)$$

Dimensionless parameter

Cutoff scale

$$C_{\mathcal{O}} = c_{\mathcal{O}}\, \Lambda_{\mathcal{O}}^{4-[\mathcal{O}]}$$

Physical effects $\sim \left(\frac{E}{\Lambda_{\mathcal{O}}}\right)^{[\mathcal{O}]-4}$

Expansion parameter $= \frac{E}{\Lambda_{\mathcal{O}}}$

- IR relevance: $\mathrm{dim}[\mathcal{O}] \leq 4$
- Irrelevant couplings suppressed by $\Lambda_{\mathcal{O}}^{4-\mathrm{dim}\,\mathcal{O}}$

The Standard Model

Basic notions:

1. "A" quantum field theory

2. Symmetries

$$\underbrace{\text{Poincaré}}_{\text{Spacetime}} + \underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{\text{Gauge}}$$

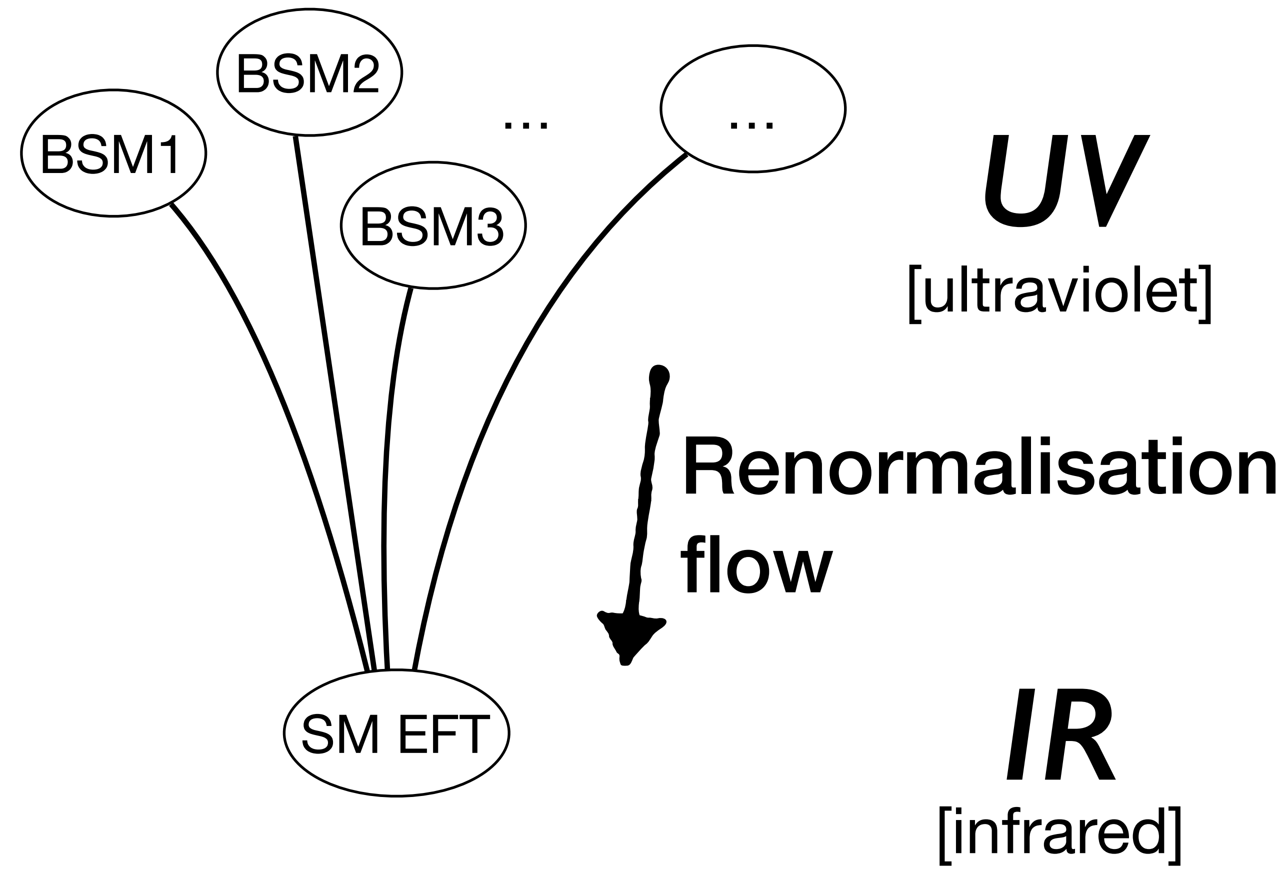
3. Field Content

$$\phi \quad + \quad q_i, \ell_i, u_i, d_i, e_i$$

Flavour $i = 1,2,3$ Complexity!

4. Renormalisability

$\dim \mathcal{O} \leq 4$ *The IR relevant terms in an EFT expansion



- SM fields & symmetries
- Scale separation $\Lambda_{\rm Q} \gg v_{\rm EW}$
- Higher-dimensional operators encode short-distance physics:

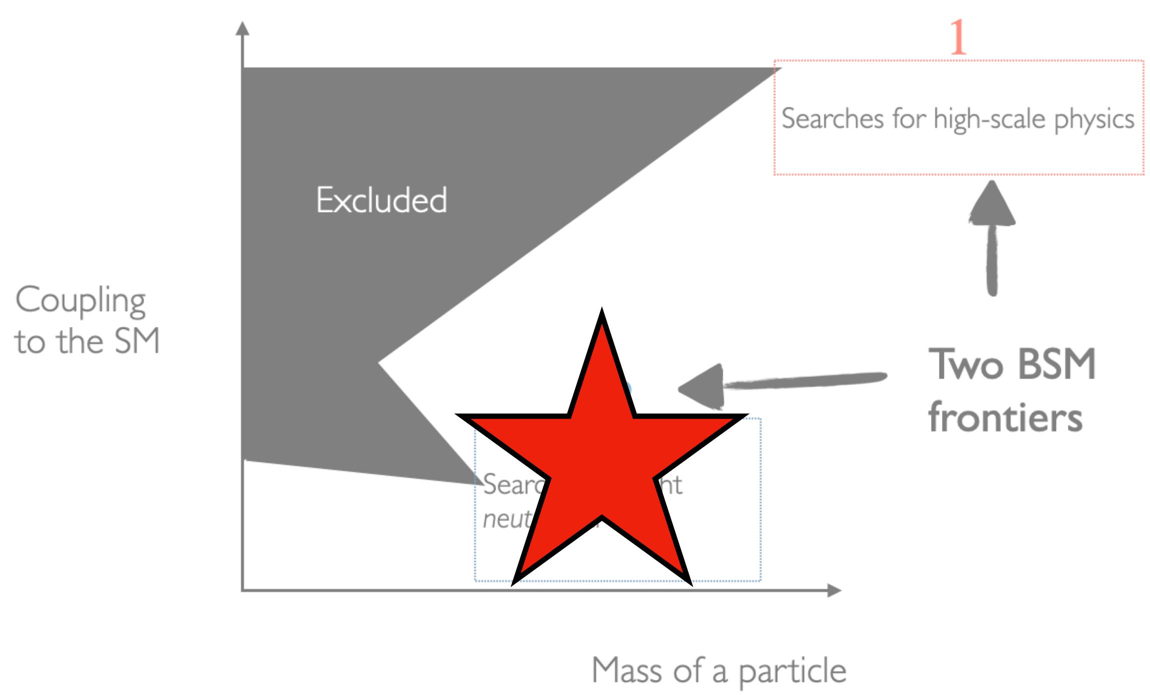
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_{\mathcal{O}>4}^{\infty} \frac{c_{\mathcal{O}}}{\Lambda_{\mathcal{O}}^{[\mathcal{O}]-4}} \mathcal{O}$$

Feeble Interacting Particle EFTs

- Another direction
  Add light, electrically neutral particle interacting weakly with the SM

- Motivation for the light Universe: Dark sector, pNGBs, etc…

- Add a degree of freedom and construct an EFT



ALP	Dark higgs
Dark photon	HNL

Common choices
pseudoscalar, scalar, vector, fermion

Accidental symmetries

Symmetries

- Spacetime and gauge symmetries are due to redundancies (physics is independent of parameterizations)

- **Global symmetries** play a crucial role to learn about the UV

  Accidental = As a result of truncating the series at low energies

  (quantum gravity breaks global symmetries)

- Exact or approximate symmetries $\Longrightarrow$ Selection rules

  Spurion: a parameter can always be assigned a symmetry representation

  Observable's dependence on such params dictated by ***symmetry covariance***

$\mathscr{L}_4^{SM}$: *Accidental symmetries*

$\mathscr{L}_4^{SM}$ sans Yukawa: $U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{H} U + \bar{q} \hat{Y}^d H D + \bar{l} \hat{Y}^e H E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

↓

$\mathscr{L}_4^{SM}$: $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Prediction: No proton decay nor cLFV

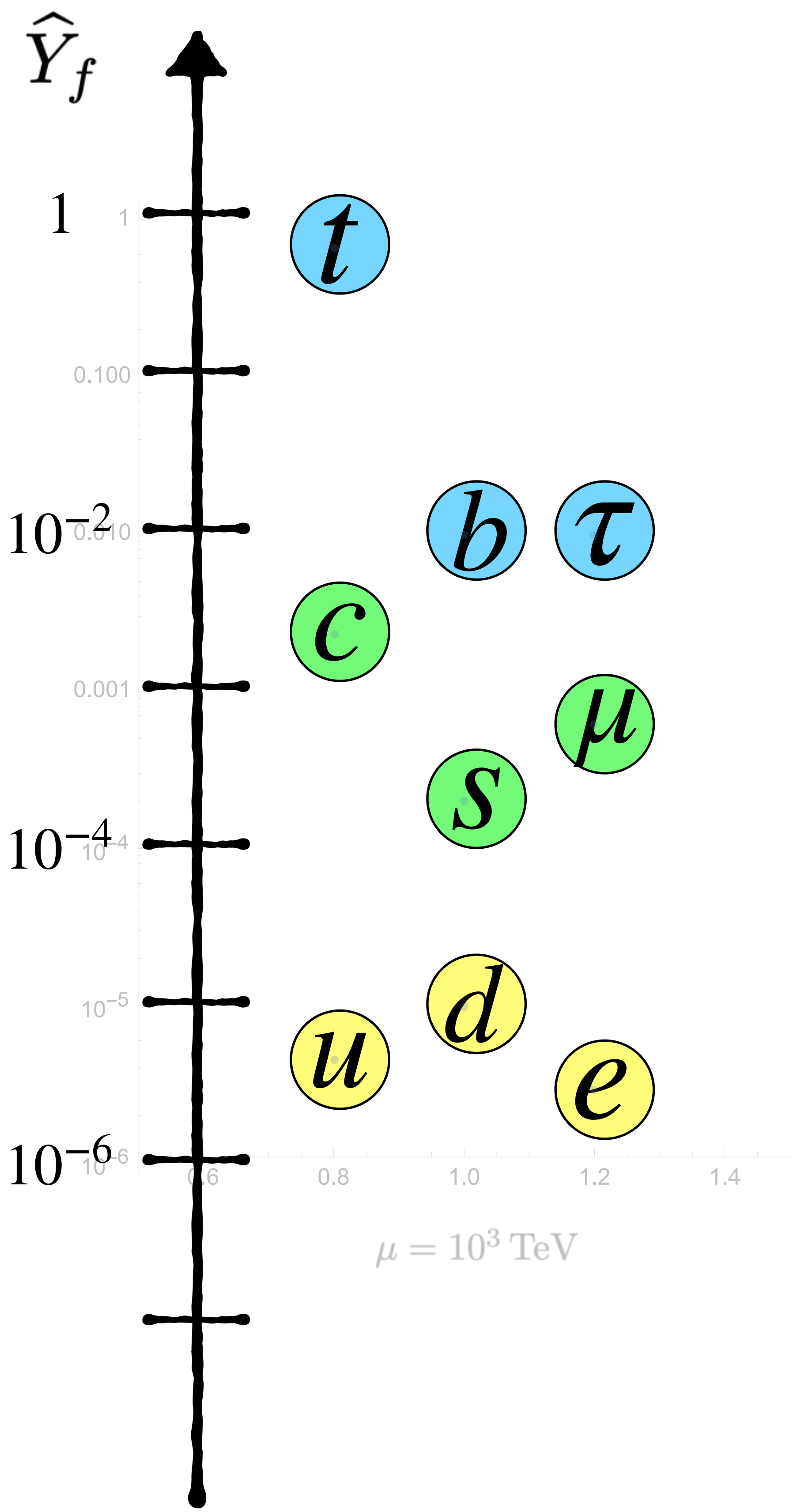
Experiment: $\tau_p \gtrsim 10^{34}$ years, $BR(\mu \to e\gamma) \lesssim 10^{-13}, \ldots$

- Λ_{NP}^{-1} truncation at the $[\mathscr{L}^{\text{SMEFT}}] \leq 4 \Longrightarrow$ **Exact** accidental symmetries
- Peculiar observed values of $Y^{u,d,e} \Longrightarrow$ **Approximate** accidental symmetries

  [Mass hierarchy & CKM alignment] [Quark flavour, CP, LFU, etc]

The Flavour Puzzle

Empirical



?

$$V_{\rm CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{pmatrix}$$

$$-\mathcal{L}_{\rm SM} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

SVD: $Y_f = L_f \widehat{Y}_f R_f^\dagger$

$$V_{\rm CKM} = L_u^\dagger L_d$$

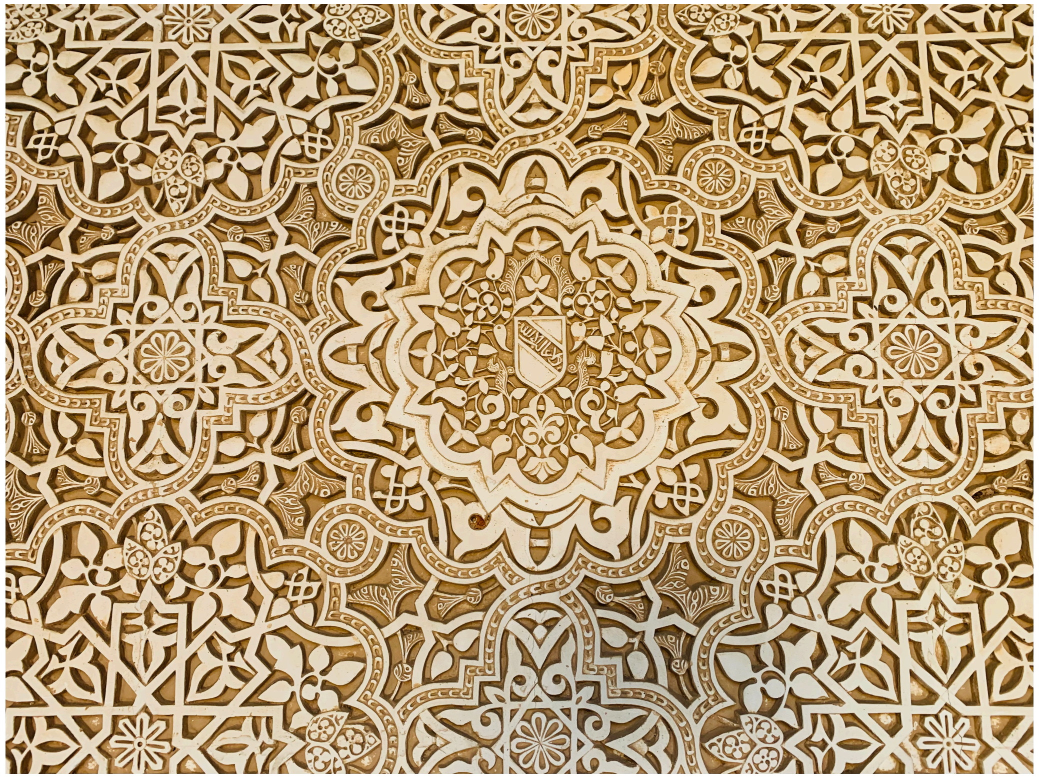
- Enter the theory in the same way. **Why hierarchies???**

Patterns <> Symmetries

Selection rules

- Flavour patterns observed in the Yukawa sector
$\Longrightarrow$ *Approximate flavour symmetries in the SM*

Bottom-up:
The largest spurion $y_t = Y^u_{33} \sim 1$ breaks
$U(3)_q \times U(3)_u \to U(2)^2 \times U(1)$, etc…



Alhambra of **Granada**

1 Important to understand the SM phenomenology:

- *isospin, SU(3), heavy-quark symmetries, GIM, …*

2 Stringent tests of the SM
— a window to new physics.

SMEFT dim-6 violation

Antusch, AG, Stefanek, Thomsen; 2311.09288

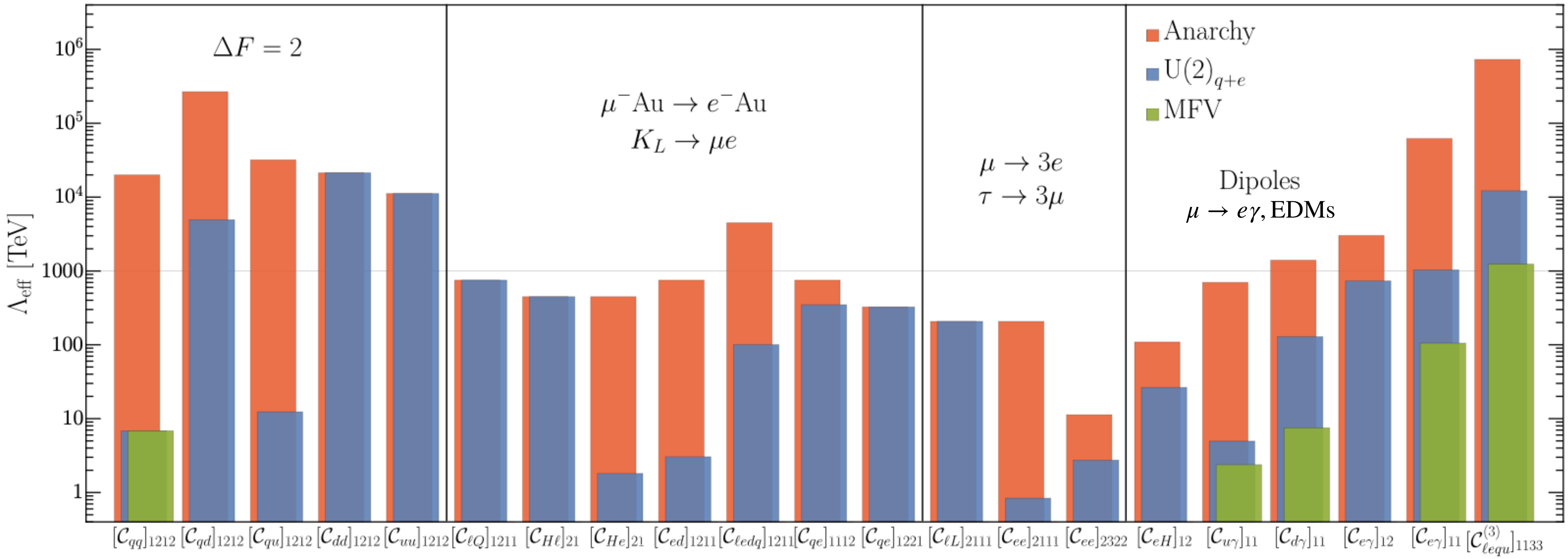


FIG. 1. Comparative constraints on SMEFT operators from flavor and CP violation: Minimally-broken $\mathrm{U}(2)_{q+e}$ (Blue), MFV (Green), Flavor Anarchy (Red). Here, $Q = q, u, d$ and $L = \ell, e$. See Section 3 for details.

- SMEFT as a proxy for short-distance physics:
  $\Longrightarrow$ Violation of accidental symmetries sets stringent limits on NP!
- The new physics flavor puzzle!

Froggatt-Nielsen ALP

- FN model to explain the SM flavor puzzle

$$-\mathcal{L} \supset \sum_{f,F} \left[x_{ij}^{f} \left(\frac{\Phi}{M}\right)^{n_{ij}^{f}} + x_{ij}^{f\prime} \left(\frac{\Phi^*}{M}\right)^{n_{ij}^{f\prime}} \right] \bar{F}_{L,i} H f_{R,j}$$

- Flavor dependent charges

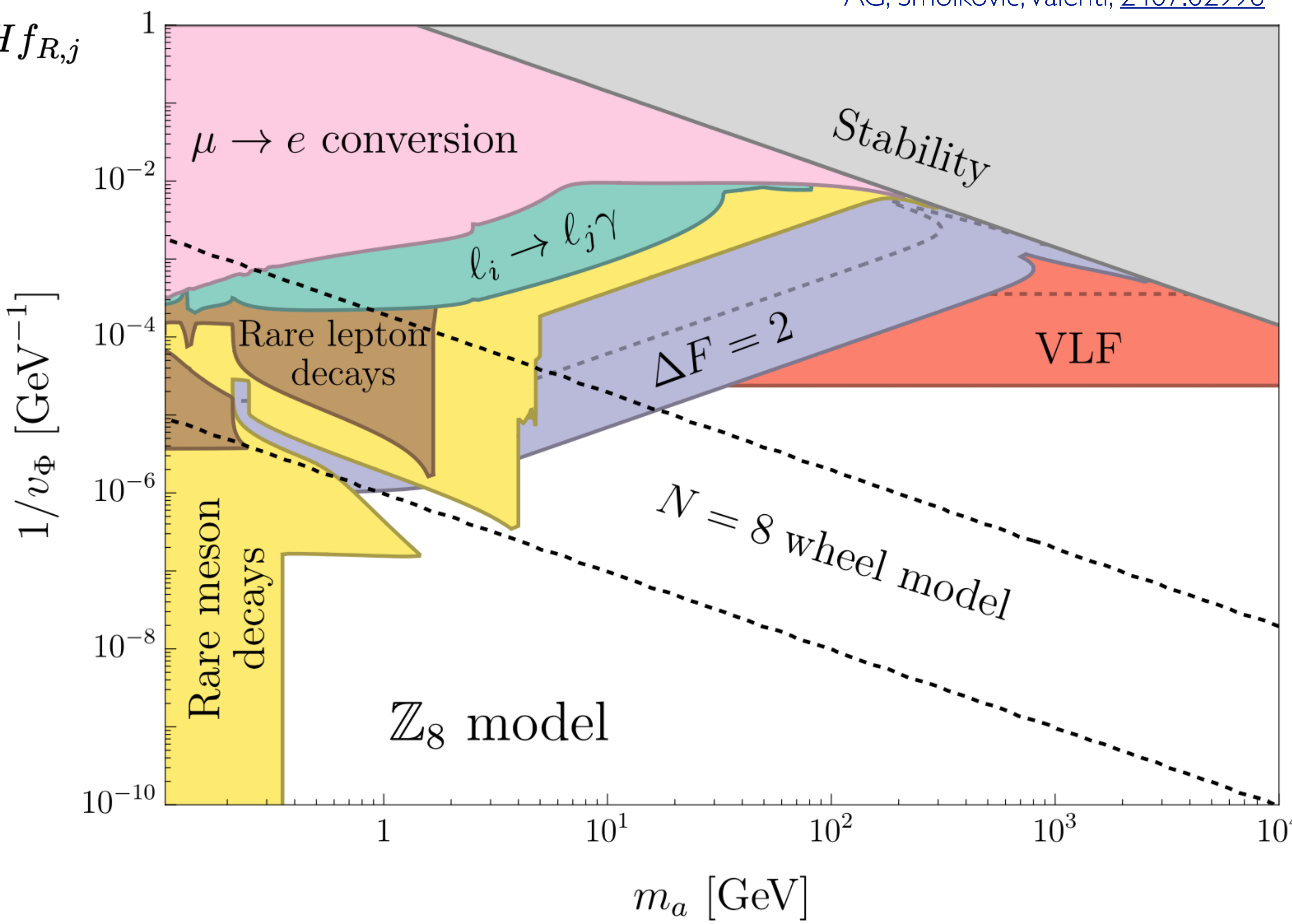
- Small parameter v_Φ / M

- There is a light pNGB

$$\Phi = \left(\frac{v_\Phi + \rho}{\sqrt{2}}\right) e^{ia/v_\Phi}$$

ALP

AG, Smolkovic, Valenti; 2407.02998



High-multiplicity muon decays

High-Multiplicity Muon Decays

AG, Palavric, Tunja, Zupan; wip

$$\mu \to (2k+1)\, e + m\, \gamma$$

w/ or w/o INV

$$k, m \in \mathbb{Z}_{\geq 0}$$

- MEG II and Mu3e
- ***What*** can we learn from this?

High-Multiplicity Muon Decays

AG, Palavric, Tunja, Zupan; wip

Golden modes (GM)

High-multiplicity (HM)

$e\backslash\gamma$	0	1	2	3	4
1	e+INV	$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$\dots$	
5	$5e$	$5e\gamma$	$\dots$		
7	$7e$	$\dots$			
$\dots$					

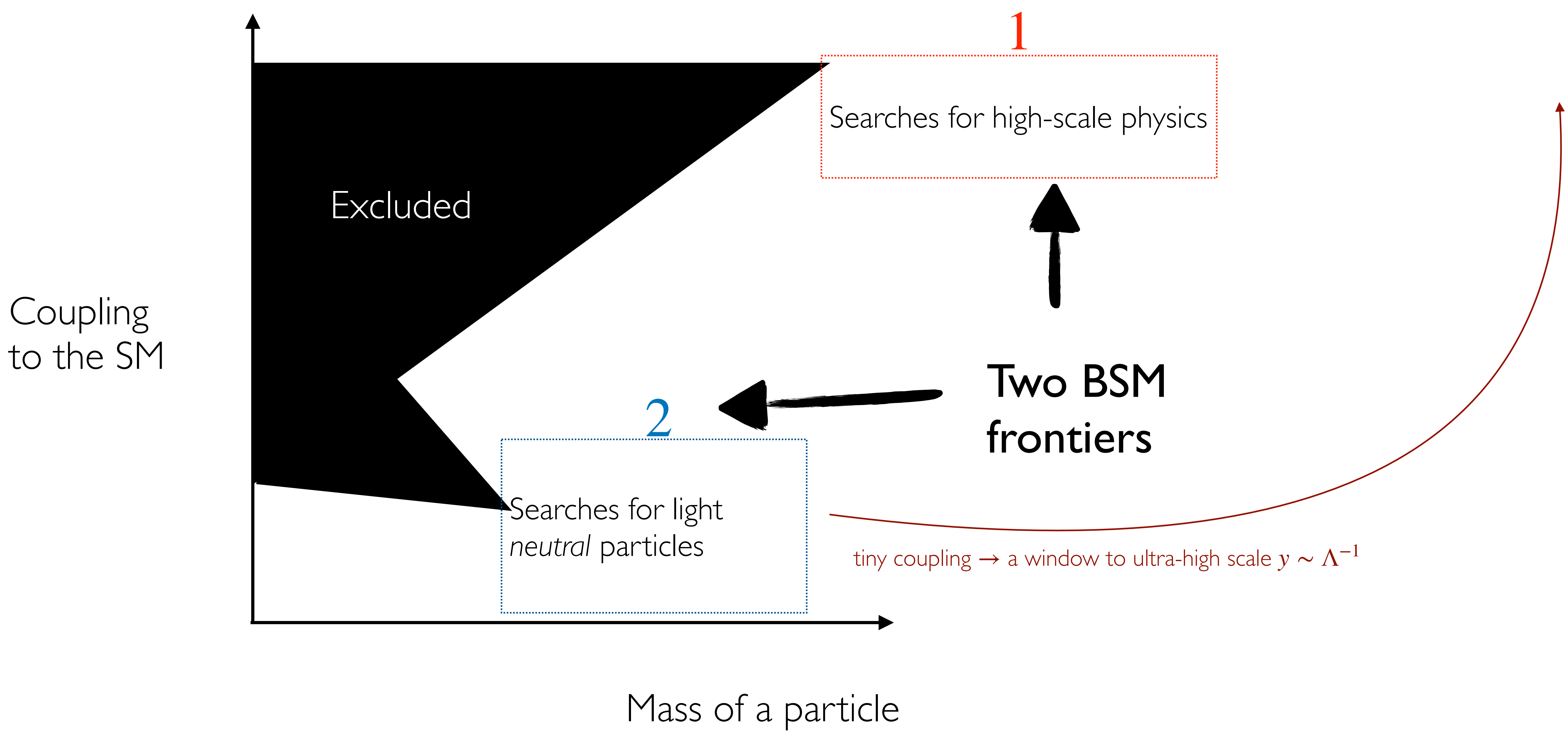
- QED radiation from the golden modes => suppressed HM
- We are after BSM models in which
  HM branching ratios are dominant or at least comparable to GM

BSM from GM

Golden Modes:

- $\mu \to e\gamma, \mu \to 3e, \mu \to e + \mathrm{inv}$

offer excellent prospects to discover NP of both 1 and 2 scenarios



BSM from GM

Calibbi, Signorelli; 1709.00294

Scenario 1:

SMEFT at $\dim[\mathcal{O}] = 6$

$$\Lambda \gtrsim \sqrt{C} \times 4\pi \times 10^4\,\text{TeV}$$

Expectation

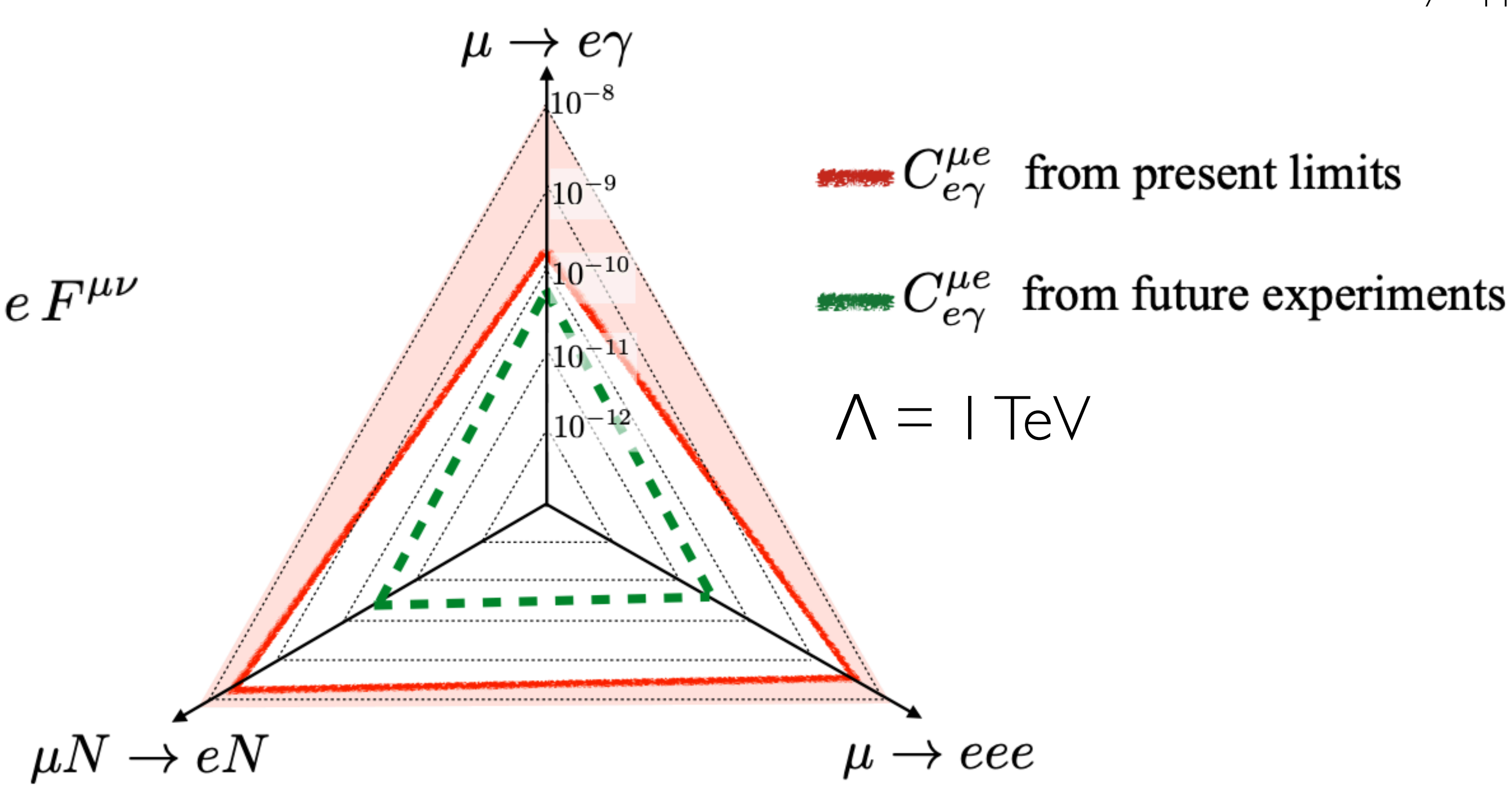
Loop-generated: $C \sim 1/(4\pi)^2$

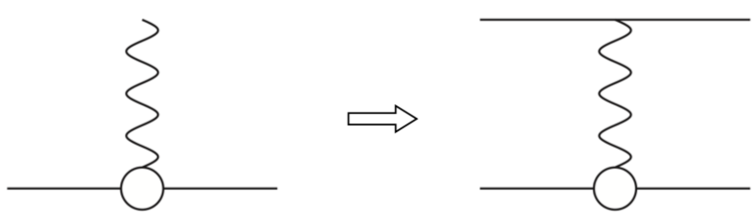
+ chirality suppressed: $C \sim \sqrt{y_\mu y_e}/(4\pi)^2$

Still $\gtrsim 100\,\text{TeV}$

The NP flavor puzzle!

$$\mathscr{L} \supset + \frac{C_{e\gamma}^{\mu e}}{\Lambda^2} \frac{v}{\sqrt{2}} \bar{\mu}\, \sigma_{\mu\nu} P_R\, e\, F^{\mu\nu}$$





*Similarly, bounds on 4F ops from $\mu \to 3e$ is $\gtrsim 100\,\text{TeV}$

BSM from GM

Scenario 2:

Axion-like particles

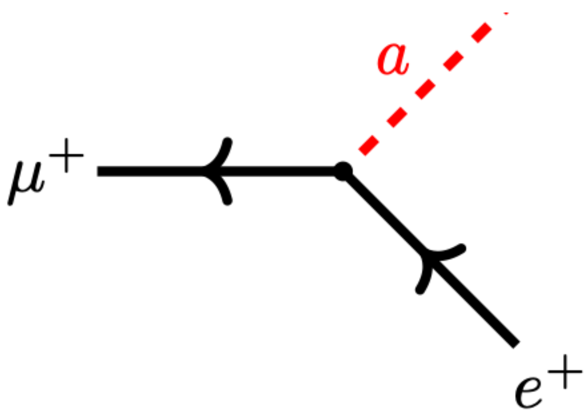
$m_a < 105$ MeV

$\mu \to e + \text{inv}$

$$\mathscr{L} \supset \frac{\partial_\mu a}{2f_a} \bar{\ell}_i \gamma^\mu \left[C^V_{ij} + C^A_{ij}\gamma_5\right] \ell_j$$

Flavor anarchy → Long lived a

$C^{V,A}_{ij} \sim \mathcal{O}(1)$



- The Michel decay positron energy spectrum
- Since small m_a values are natural, the endpoint of the spectrum is of special importance.
- SM precision calculation crucial! Signer et al; 2211.01040

MEG II: $\mathcal{B} < 10^{-6}$

Mu3e: $\mathcal{B} < 10^{-8}$

Great potential to probe ***huge*** scales: $C^{V,A}_{ij} \sim \mathcal{O}(1)$ ➞ $f_a \gtrsim 10^{10}\,\text{GeV}$

BSM from GM

Scenario 2:

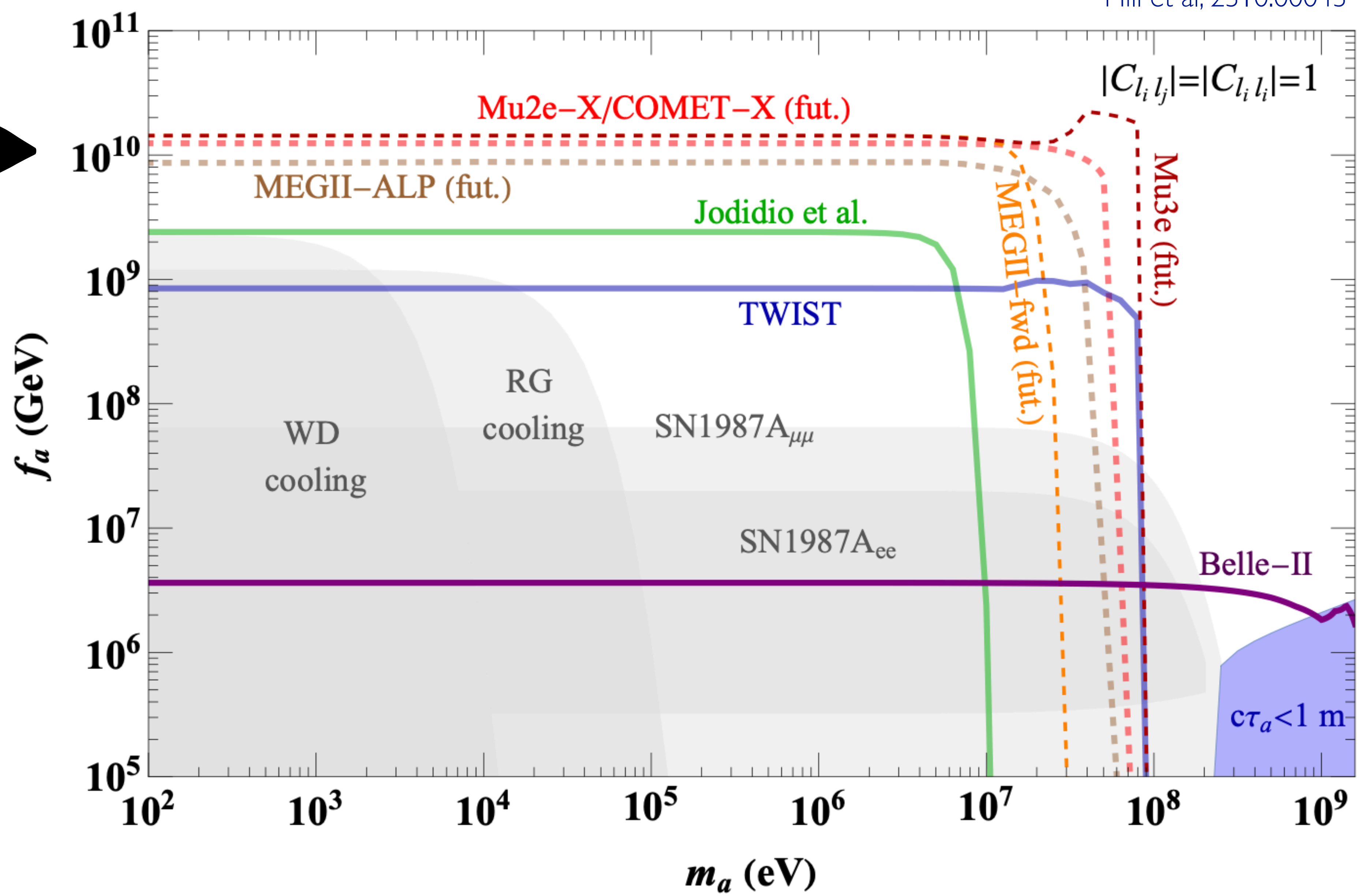
Axion-like particles
$m_a < 105$ MeV

$$\mu \to e + \text{inv}$$

$$\mathscr{L} \supset \frac{\partial_\mu a}{2f_a}\bar{\ell}_i\gamma^\mu\left[C^V_{ij} + C^A_{ij}\gamma_5\right]\ell_j$$

Great potential to probe ***huge*** scales

Hill et al; 2310.00043



BSM from GM

Scenario 2:

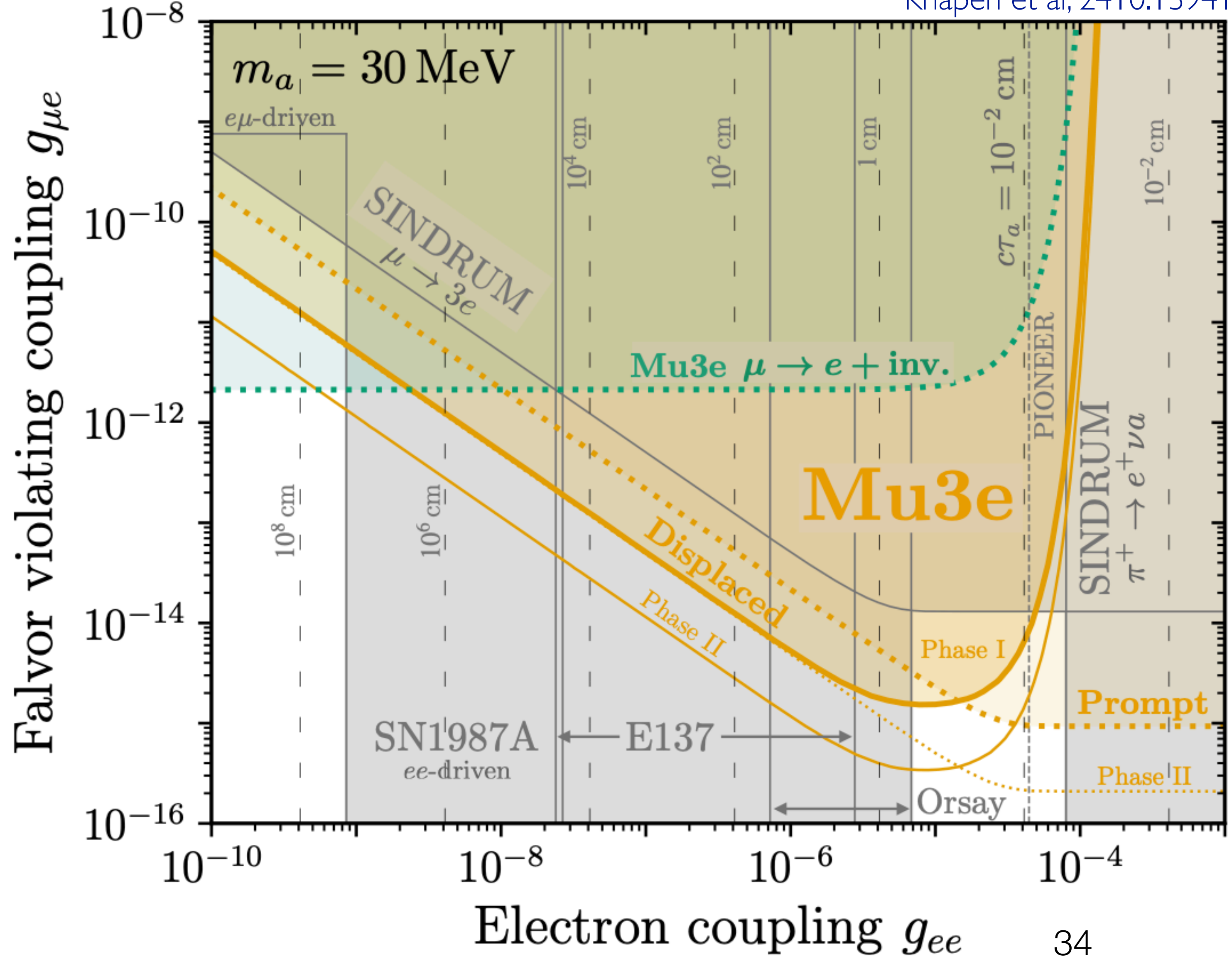
Axion-like particles
$m_a < 105$ MeV

$$\mu \to e + (e^+e^-)$$

$$\ell_a \simeq 2\,\text{cm}\left(\frac{|\boldsymbol{p}_a|}{40\,\text{MeV}}\right)\left(\frac{10^{-5}}{g_{ee}}\right)^2\left(\frac{10\,\text{MeV}}{m_a}\right)^2$$

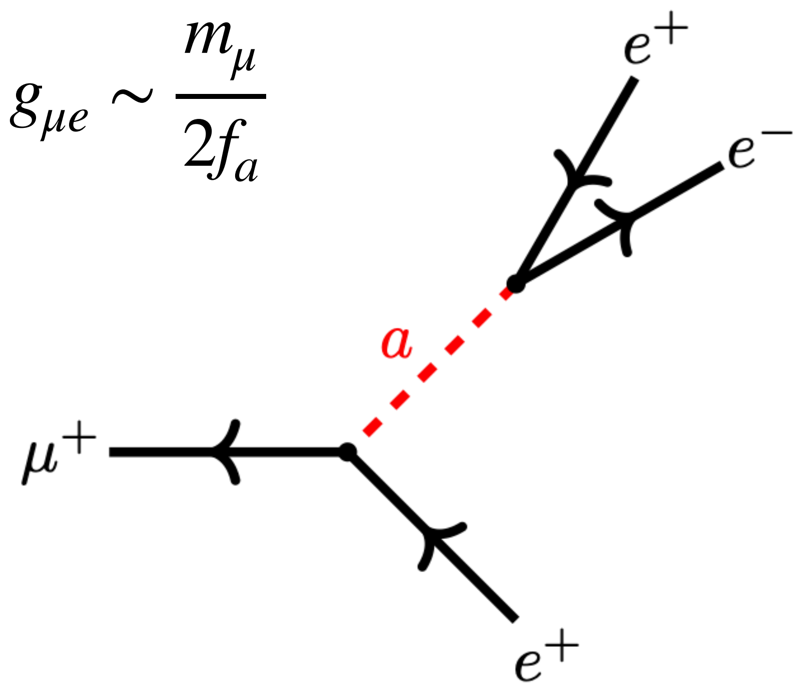
$$\mathcal{L}_a = g_{\mu\mu} i a \bar{\mu}\gamma_5\mu + g_{ee} i a \bar{e}\gamma_5 e + g_{\mu e} i a \bar{\mu}\gamma_5 e$$

Knapen et al; 2410.13941



Previous slide

$$g_{\mu e} \sim \frac{m_\mu}{2f_a}$$

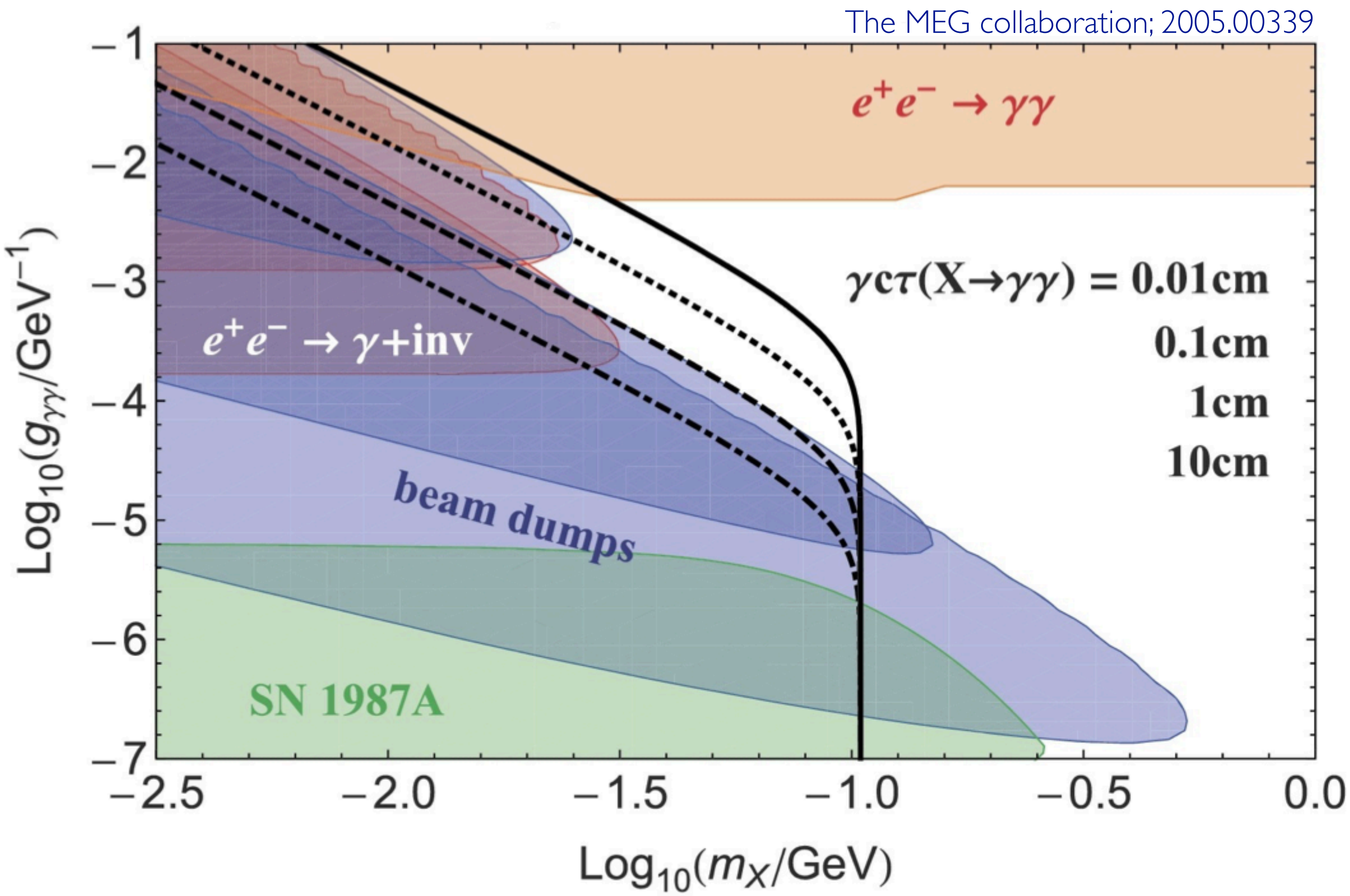


Lesson: $g_{\mu e} \ll g_{ee}$

$\Longrightarrow$LFC $U(1)_e \times U(1)_\mu$

Towards HM decays: MEG search

$$\mu^+ \to e^+X, X \to \gamma\gamma$$

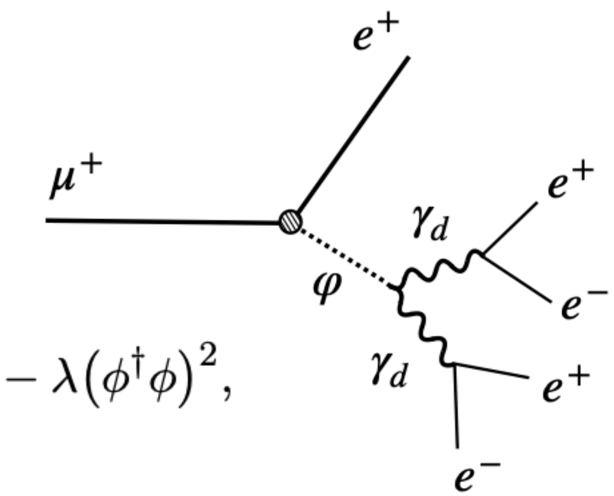


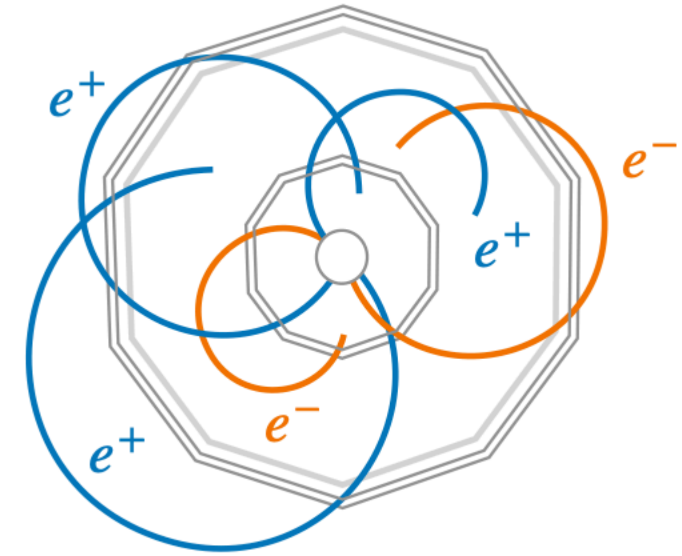
Axion-like particle X decaying to diphoton

Towards HM decays: $5e$

Dark photon model

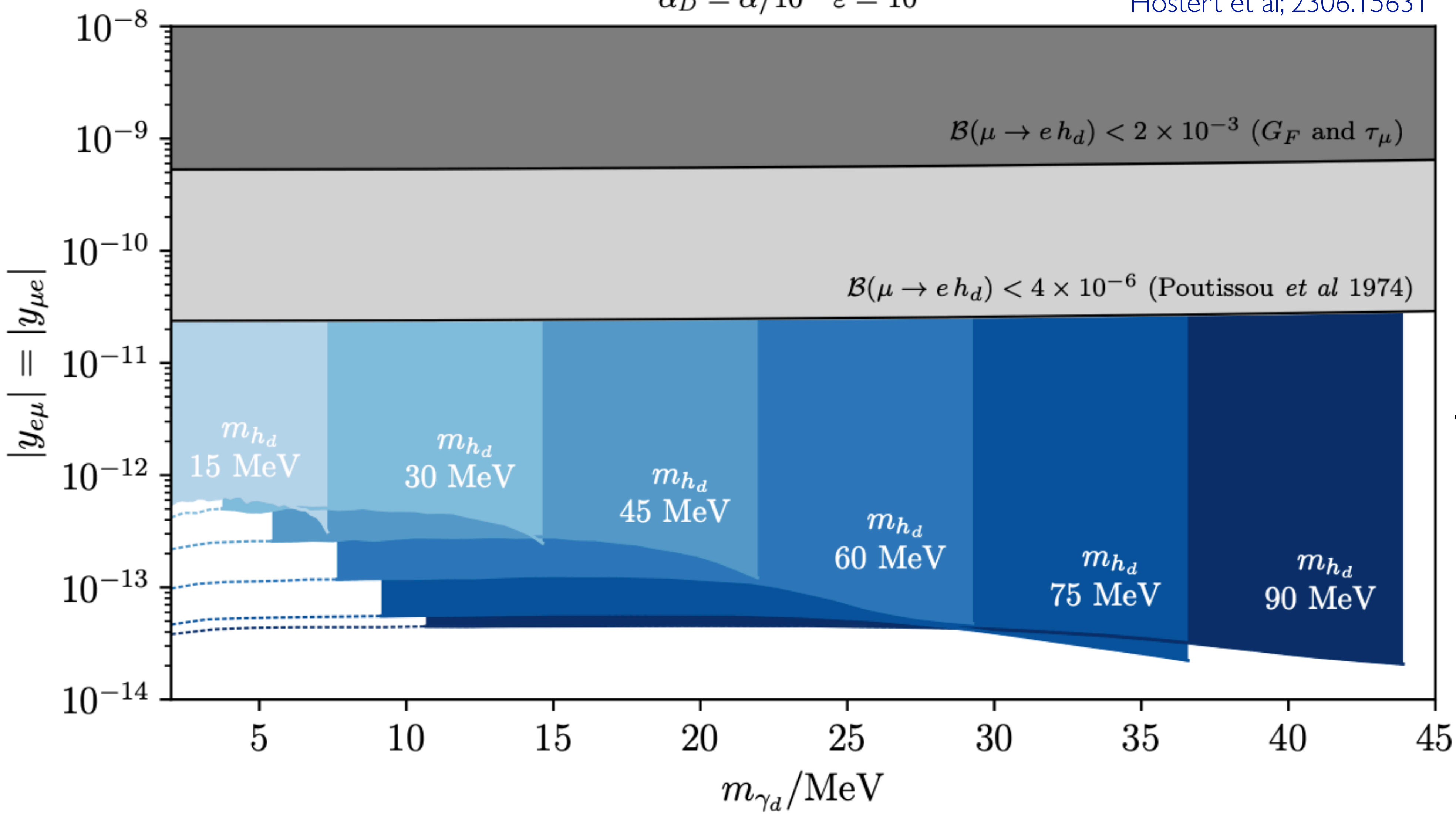
$$\mathscr{L}_{\rm DS} = (D_\mu\phi)^\dagger D^\mu\phi - \frac{1}{4}F_d^{\mu\nu}F_{d\,\mu\nu} - \frac{\varepsilon}{2}F_d^{\mu\nu}F_{\mu\nu} - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2,$$





$\alpha_D = \alpha/10 \quad \varepsilon = 10^{-4}$

Hostert et al; 2306.15631



$$\mathscr{L} \supset -\,y_{ij}\bar{\ell}_{Li}\ell_{Rj}h_d$$

Cascade $1 \to 2$ decays

$\Longrightarrow$ probe high scales!

HM decays: EFT argument

$e\backslash\gamma$	0	1	2	3	4
1	e	$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$\ldots$	
5	$5e$	$5e\gamma$	$\ldots$		
7	$7e$	$\ldots$			
$\ldots$					

AG, Palavric, Tunja, Zupan; wip

SMEFT contributes at higher EFT orders!

$5e$

$$\mathcal{L}^{\mu\to 5e}_{\rm SMEFT} \supset \frac{\mathcal{C}^{(1)}_{10}}{\Lambda^6}(\bar\ell\gamma^\mu\ell)^2(\bar\ell\, H\, e) + \frac{\mathcal{C}^{(2)}_{10}}{\Lambda^6}(\bar e\gamma^\mu e)^2(\bar\ell\, H\, e) + \frac{\mathcal{C}^{(3)}_{10}}{\Lambda^6}(\bar\ell\gamma^\mu\ell)(\bar e\gamma_\mu e)(\bar\ell\, H\, e) + \text{h.c.}.$$

$$C \sim \mathcal{O}(1), BR \sim 10^{-15} \implies$$

$$\Lambda \sim 50\,\text{GeV}$$

$3e\gamma$

$$\mathcal{L}^{\mu\to 3e\gamma}_{\rm SMEFT} \supset \frac{\mathcal{C}_8}{\Lambda^4}(\bar\ell\gamma^\mu\ell)(\bar\ell\gamma^\nu\ell)B_{\mu\nu}$$

$$C \sim \mathcal{O}(1), BR \sim 10^{-15} \implies$$

$$\Lambda \sim 200\,\text{GeV}$$

$e3\gamma$

$$\mathcal{L}^{\mu\to 3e2\gamma}_{\rm SMEFT} \supset \frac{\mathcal{C}''_8}{\Lambda^4}(\bar\ell\gamma^\mu \overleftrightarrow{D}^\nu\ell)(\bar\ell\gamma_\mu \overleftrightarrow{D}_\nu\ell),$$

$$C \sim \mathcal{O}(1), BR \sim 10^{-15} \implies$$

$$\Lambda \sim 100\,\text{GeV}$$

$\implies$ UV completions $\lesssim$ EW scale

$\implies$ new light neutral particles

Motivation: dark sectors!

HM decays: 1-particle EFT

AG, Palavric, Tunja, Zupan; wip

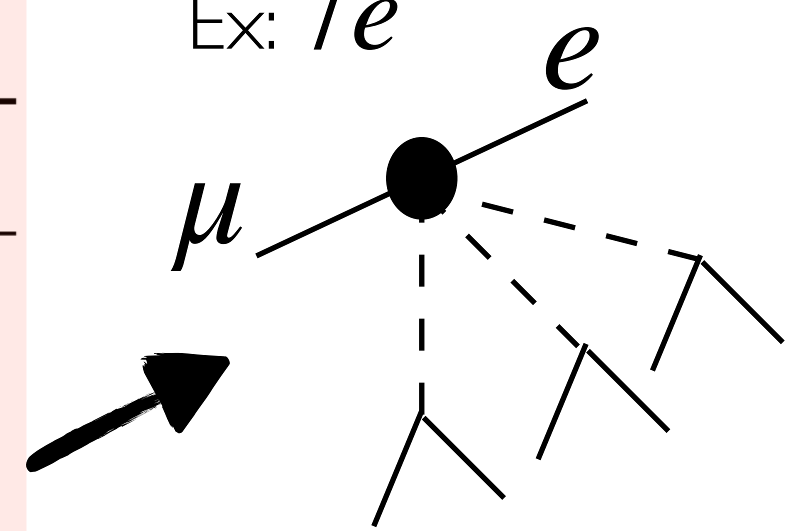
- Systematic approach
  - Consider single field on-shell in muon decays!
  - Build a systematic EFT

High-scales!

$\mathcal{L}_{\text{eff}} \supset$	$\Lambda \sim$
$\frac{\mathcal{C}_1}{\Lambda}(\bar{\ell}_2 H e_1)\,\mathcal{S}$	$\mathcal{O}(10^{14})$ TeV
$\frac{\mathcal{C}_2}{\Lambda^2}(\bar{\ell}_2 H e_1)\,\mathcal{S}^2$	$\mathcal{O}(10^{4})$ TeV
$\frac{\mathcal{C}_3}{\Lambda^3}(\bar{\ell}_2 H e_1)\,\mathcal{S}^3$	$\mathcal{O}(10)$ TeV
$\frac{\mathcal{C}_4}{\Lambda^4}(\bar{\ell}_2 H e_1)\,\mathcal{S}^4$	$\mathcal{O}(800)$ GeV
$\frac{\mathcal{C}_1}{\Lambda^2}(\bar{\ell}_2\gamma^\mu \ell_1)(\bar{N}\gamma_\mu N)$	$\mathcal{O}(10^{3})$ TeV

TABLE III. Overview of the single-field effective interactions and the corresponding estimates on the scales assuming $\mathrm{BR}(\mu \to eX) \sim 10^{-15}$, where $X = \mathcal{S}, N$.

Ex: $7e$



+ ALP + dark photon

HM decays: 1-particle EFT

- *What* can be the on-shell state? AG, Palavric, Tunja, Zupan; wip

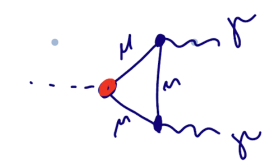
ALP

$a \to ee$

$a \to \gamma\gamma$

Dark higgs (scalar)

$s \to ee$

$s \to \gamma\gamma$ 

Dark photon

$X_\mu \to ee$

HNL

$N_2 \to N_1 ee$

$N \to \nu\gamma$

$N \to \nu X_\mu$

Various bounds from beam dumps and colliders, however, still available parameter space to allow for prompt (or displaced) decays!

Lesson: $g_{\mu e} \ll g_{ee}$

Prompt decays

$\Longrightarrow$LFC $U(1)_e \times U(1)_\mu$

High-Multiplicity Muon Decays

AG, Palavric, Tunja, Zupan; wip

Golden modes (GM)

High-multiplicity (HM)

$e \backslash \gamma$	0	1	2	3	4
1	e+INV	$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$\ldots$	
5	$5e$	$5e\gamma$	$\ldots$		
7	$7e$	$\ldots$			
$\ldots$					

Work in progress:

- Define benchmark models to populate this table
- Provide MG5 implementation for MC studies of signal efficiency

Conclusions

- EFTs provide a platform to systematically explore BSM physics
- Testing accidental symmetries seems a good strategy
- LFV High-multiplicity muon decays sensitive to new light particles
- The most interesting cases involve intermediate on-shell particles

Prompt decays of X	$\Longrightarrow$	Approximate $U(1)_e \times U(1)_\mu$

- Cascade $1 \to 2$ decays predict sizeable BR probing indirectly high-scale NP
- Plenty of new models and topologies for exploration

Alhambra of Granada

Thank you

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