

New ideas for Dark Sectors searches

Michele Tammaro

@ WIFAI, 12/11/25



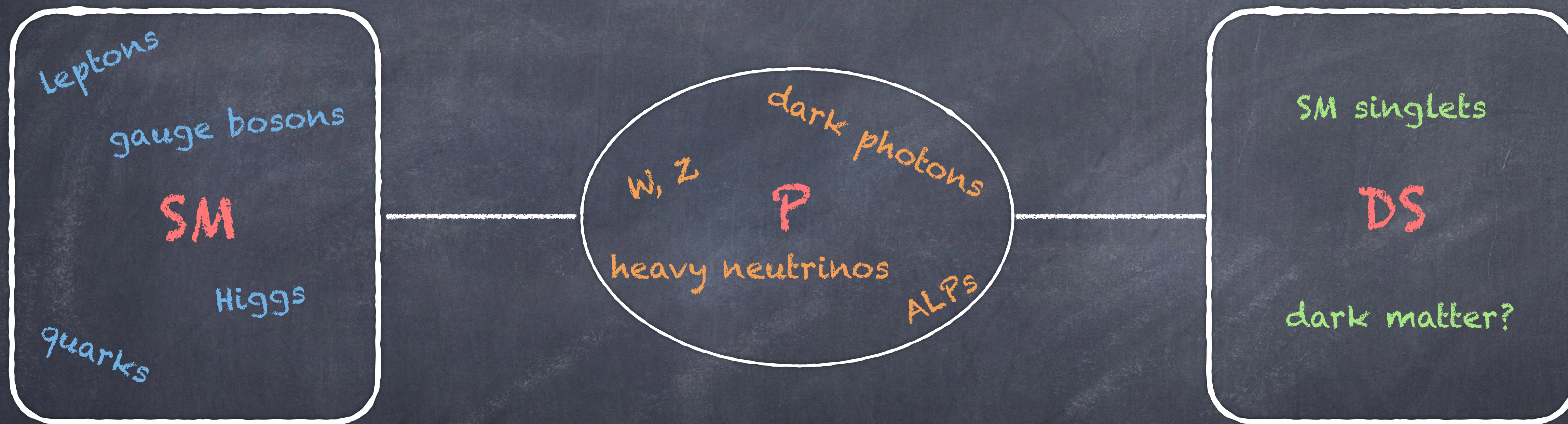
Istituto Nazionale di Fisica Nucleare



The Galileo Galilei Institute for Theoretical Physics

General idea

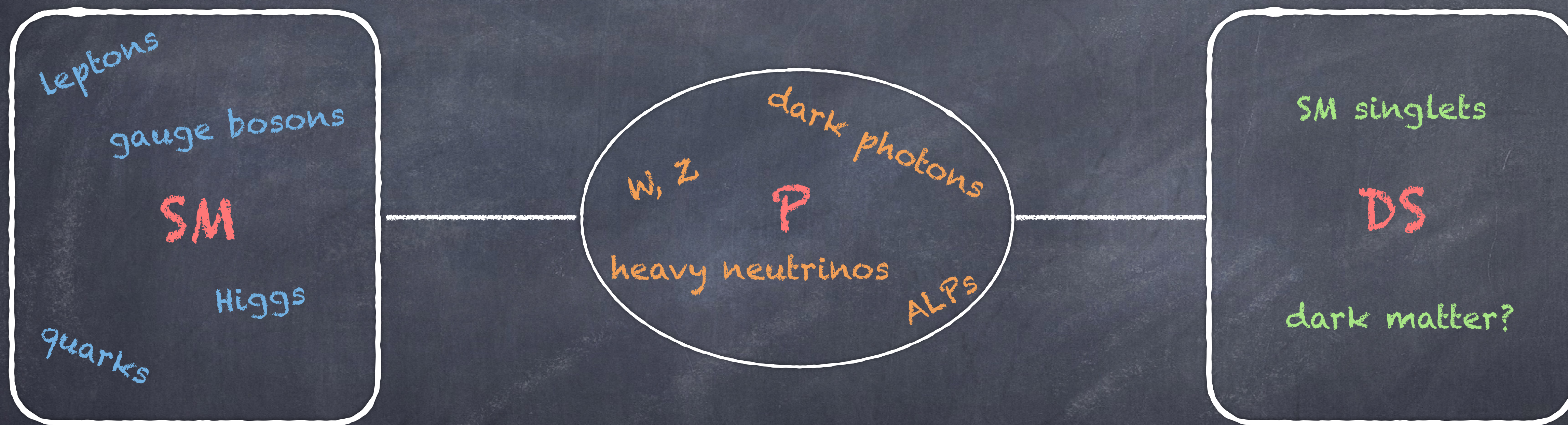
Dark Matter? Gives a clear experimental target...



... but DM can be produced non-thermally

General idea

Physics of Dark Sector? can be simple, or as complicated as the SM

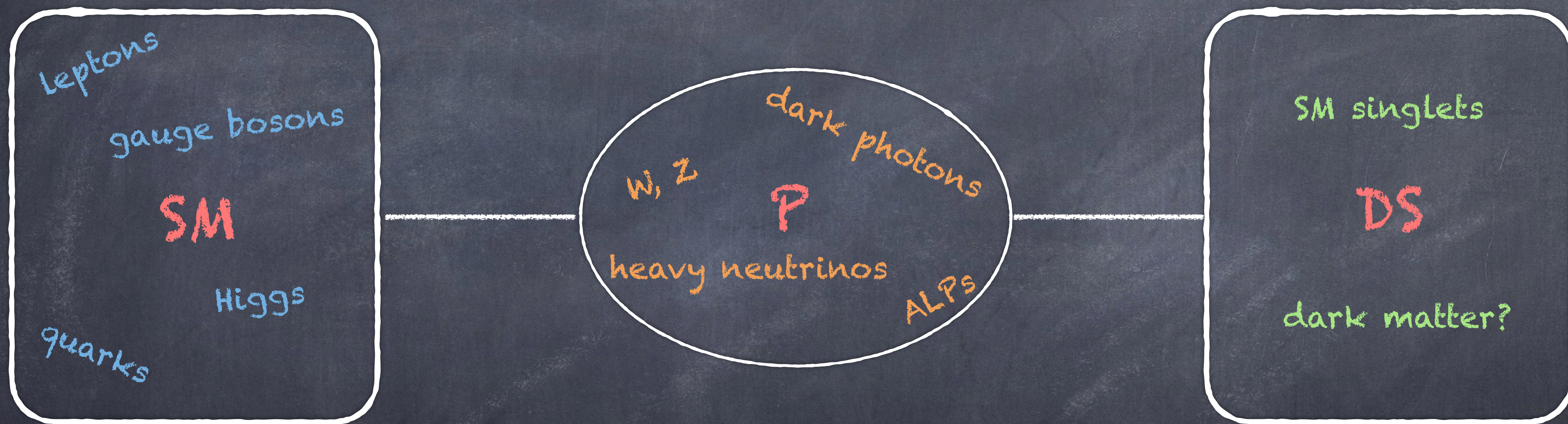


Non-minimal models can disentangle production and decay

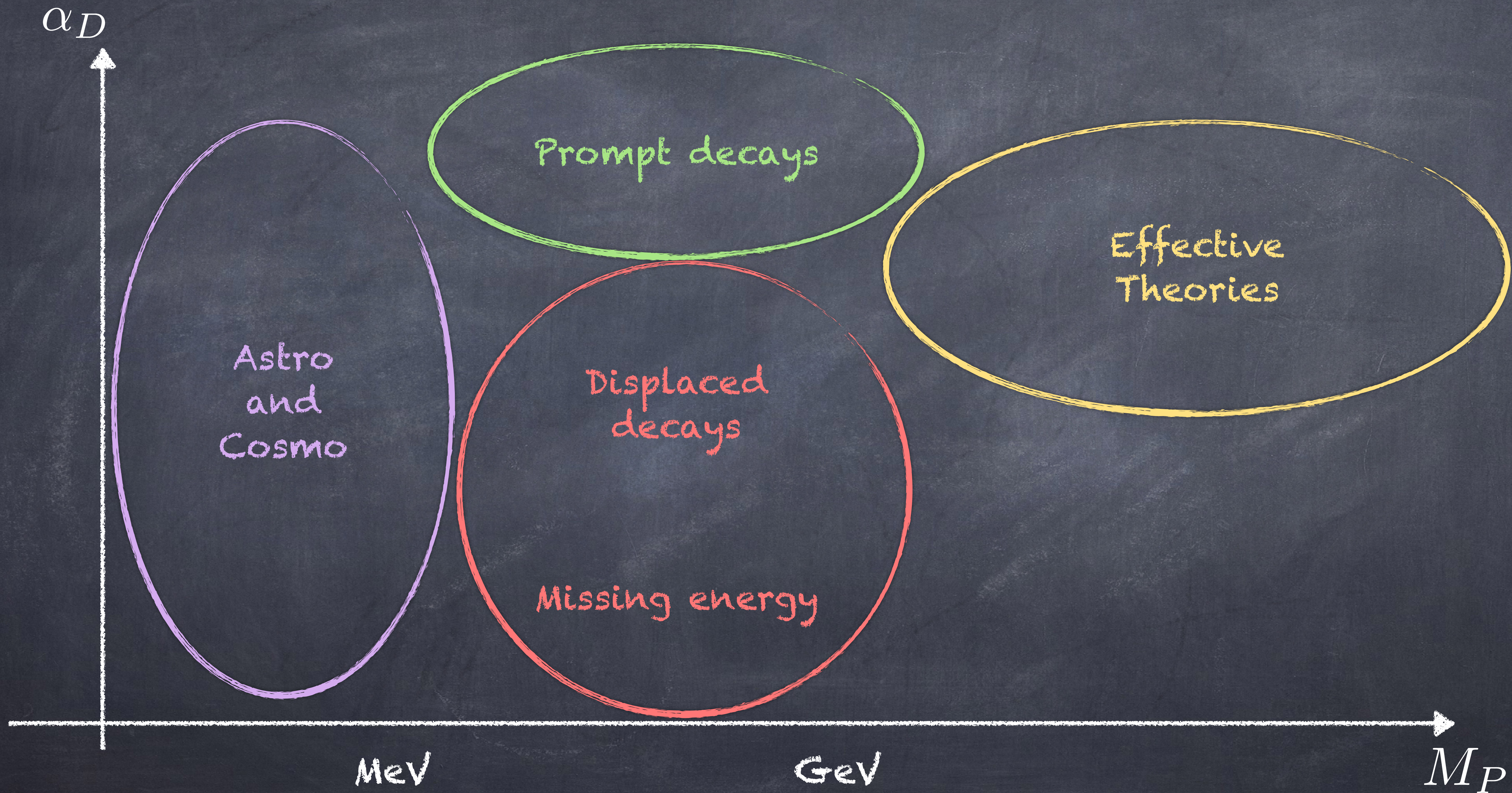
Displaced signatures, missing energy

General idea

Symmetries? NP can naturally break approx/accidental symmetries of the SM



New sources of flavor violation can test very large NP scales



α_D

Heavy NP!

Look for deviations in
precision SM

Or

New types of signatures

Direct production at colliders
(see morning talks)

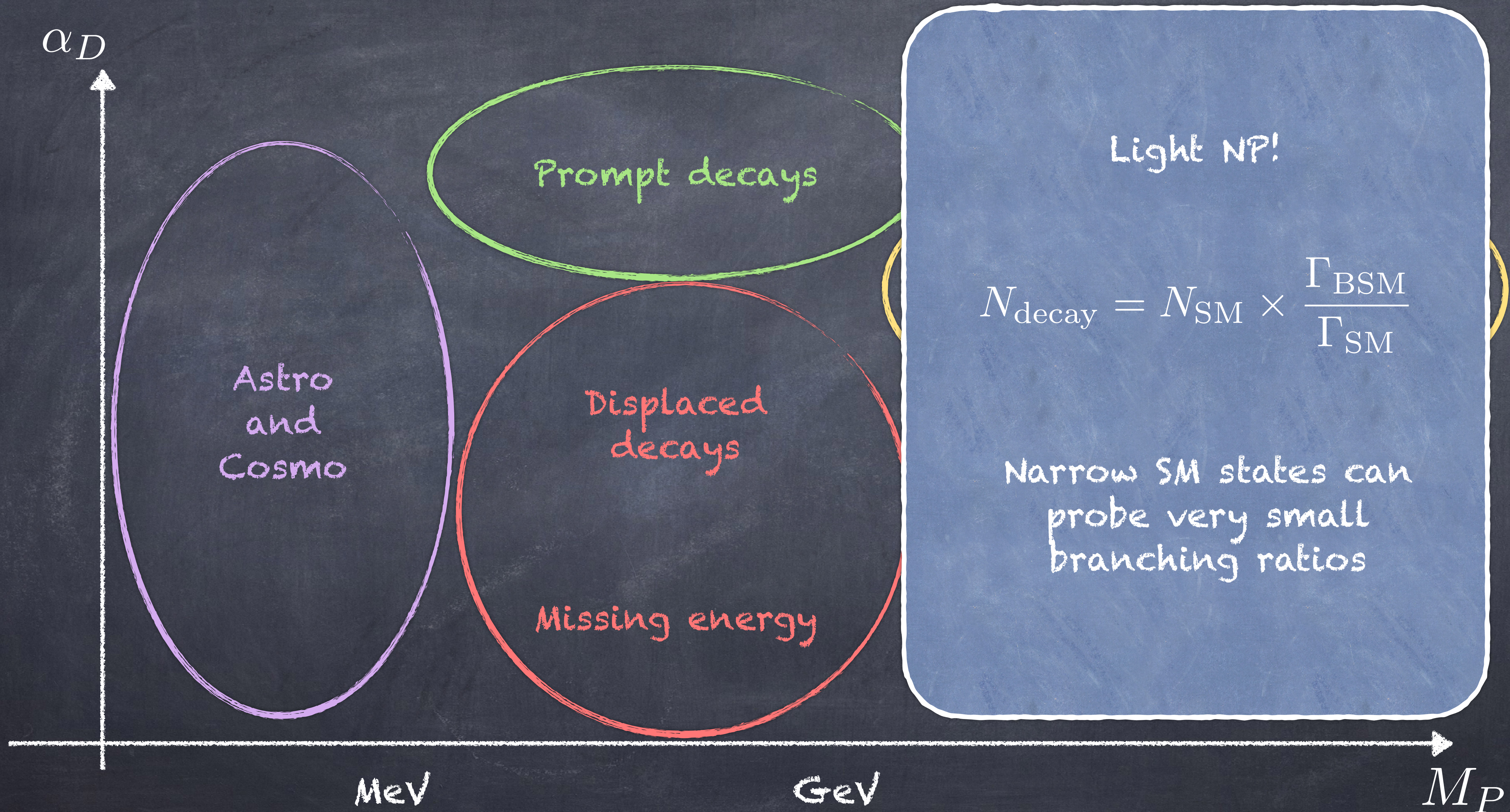
Effective
Theories

Astro
and
Cosmo

MeV

GeV

M_P



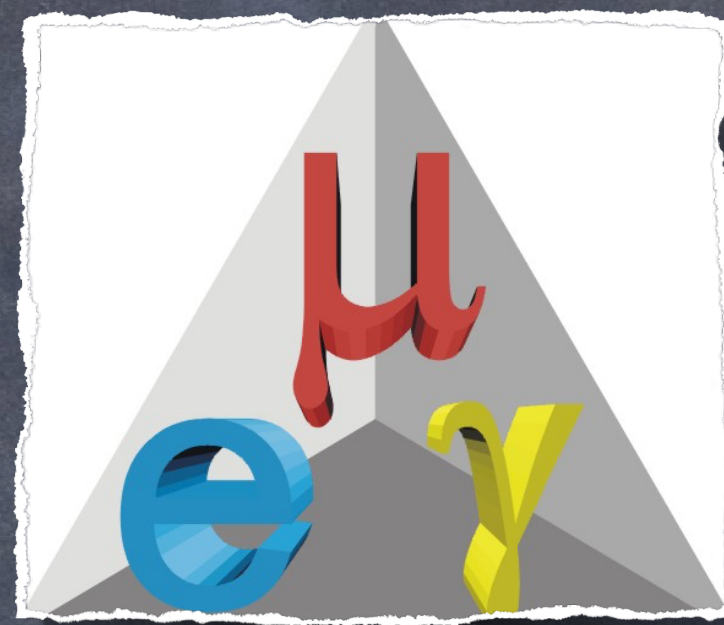
Two new(ish) avenues

Intense muon beams

Mu3e



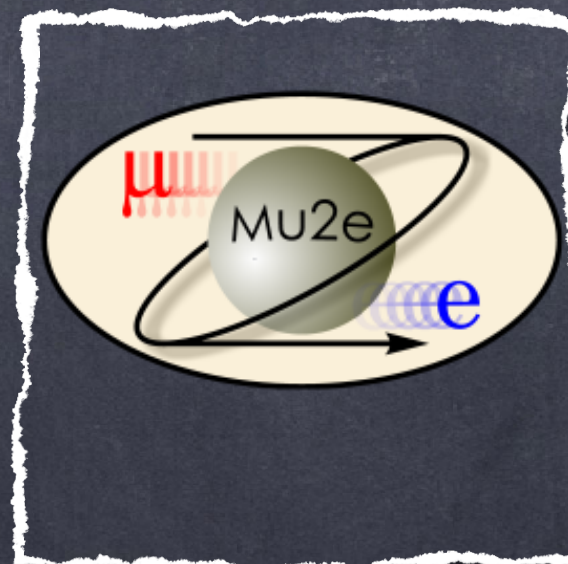
MEG



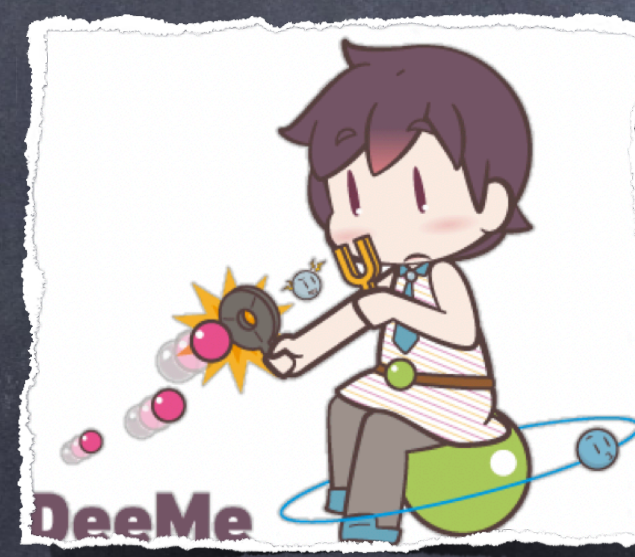
COMET



Mu2e



DeeMe



Intense neutrino beams

DUNE



HyperK



FASER



Find new signatures from motivated models

2026-29



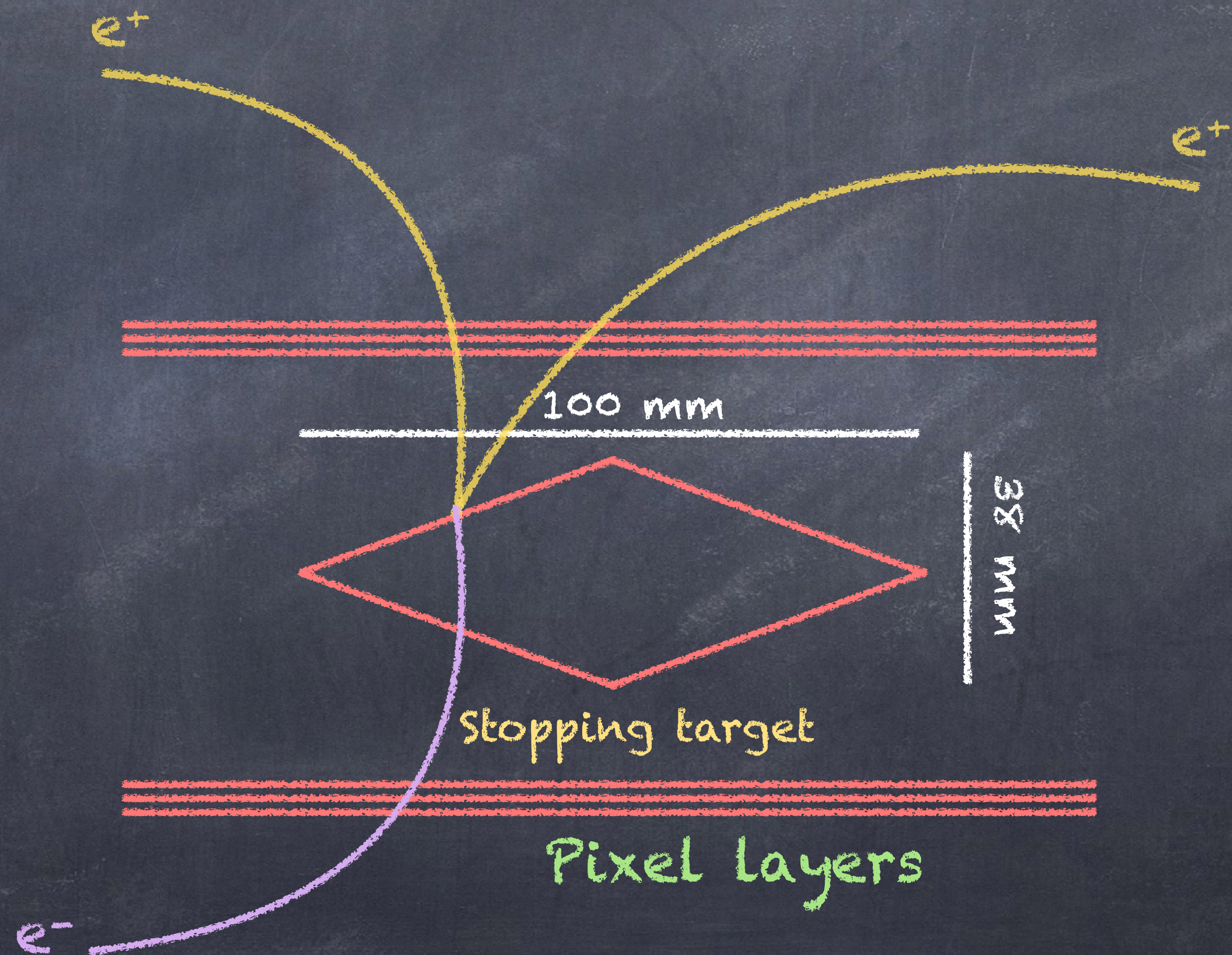
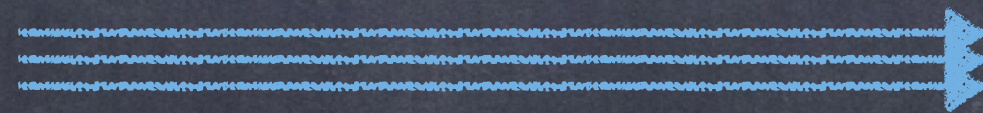
$$N_{\mu} = 2.5 \times 10^{15} - 5 \times 10^{16}$$

Phase I

Phase II

[Mu3e TDR: 2009.11690]

Muon beam



2026-29



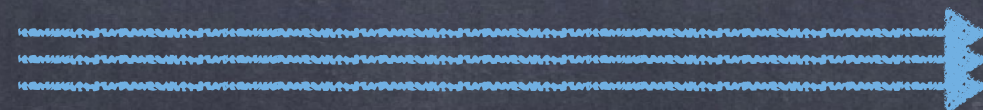
$$N_{\mu} = 2.5 \times 10^{15} - 5 \times 10^{16}$$

Phase I

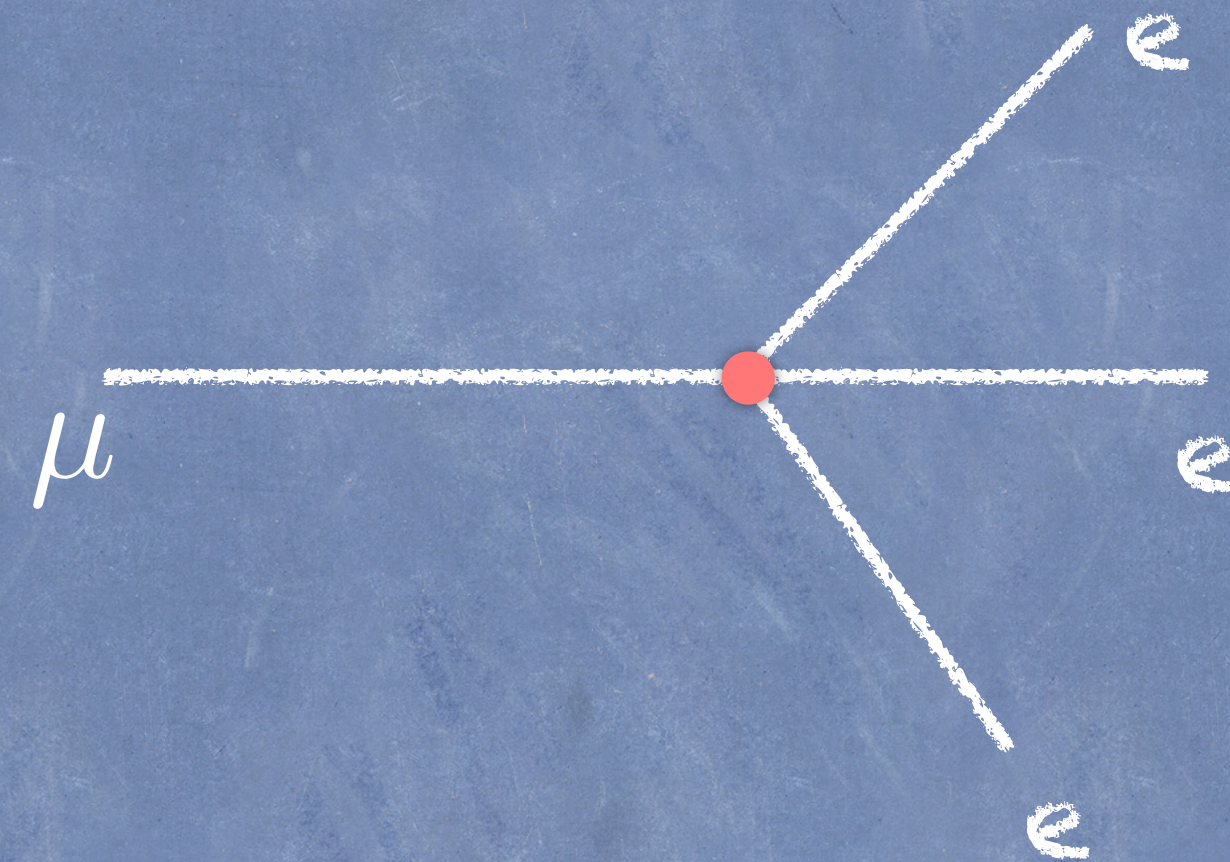
Phase II

[Mu3e TDR: 2009.11690]

Muon beam



Flavor violation from heavy NP

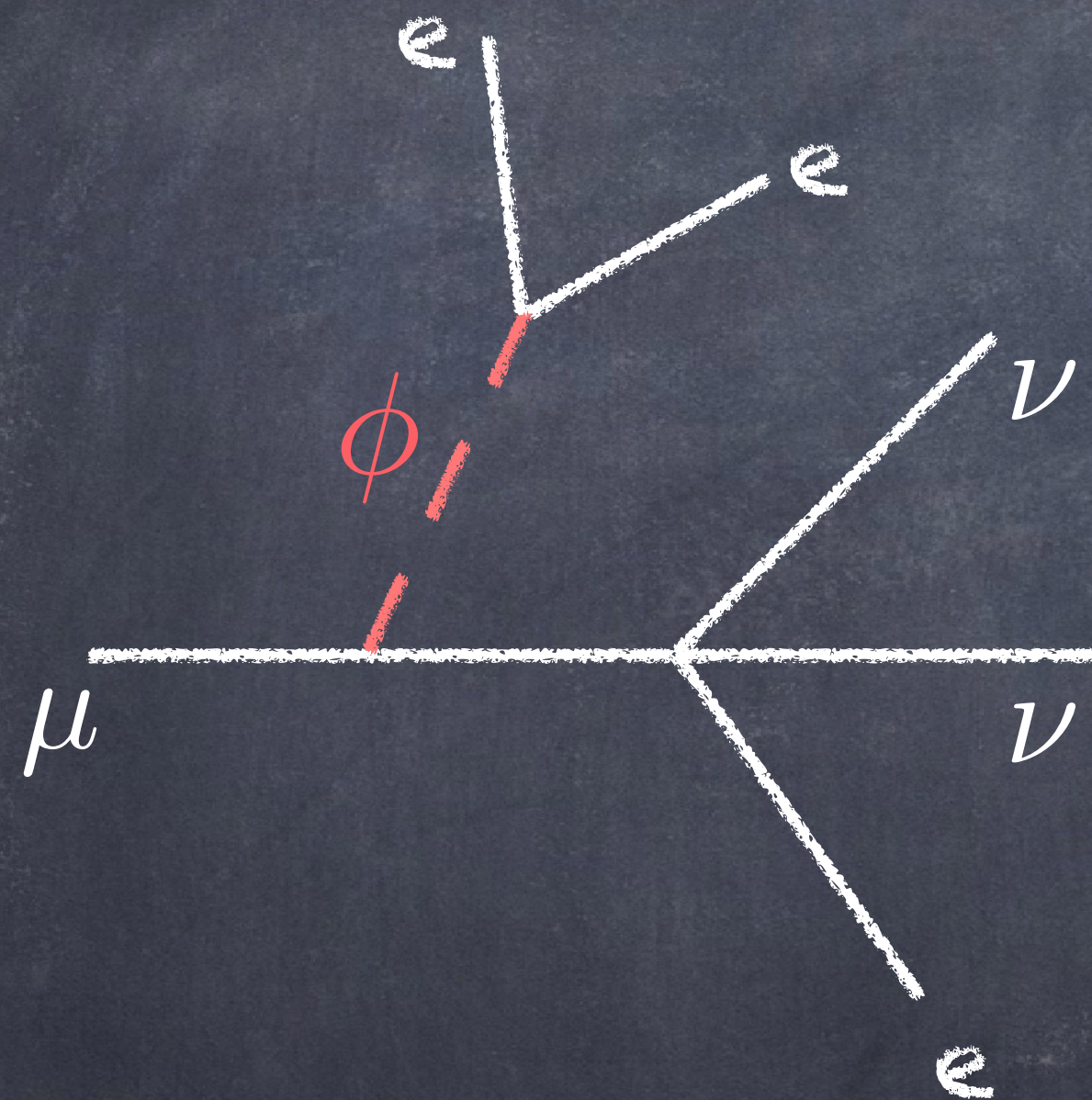


$$\Lambda \geq 10^6 \text{ GeV}$$

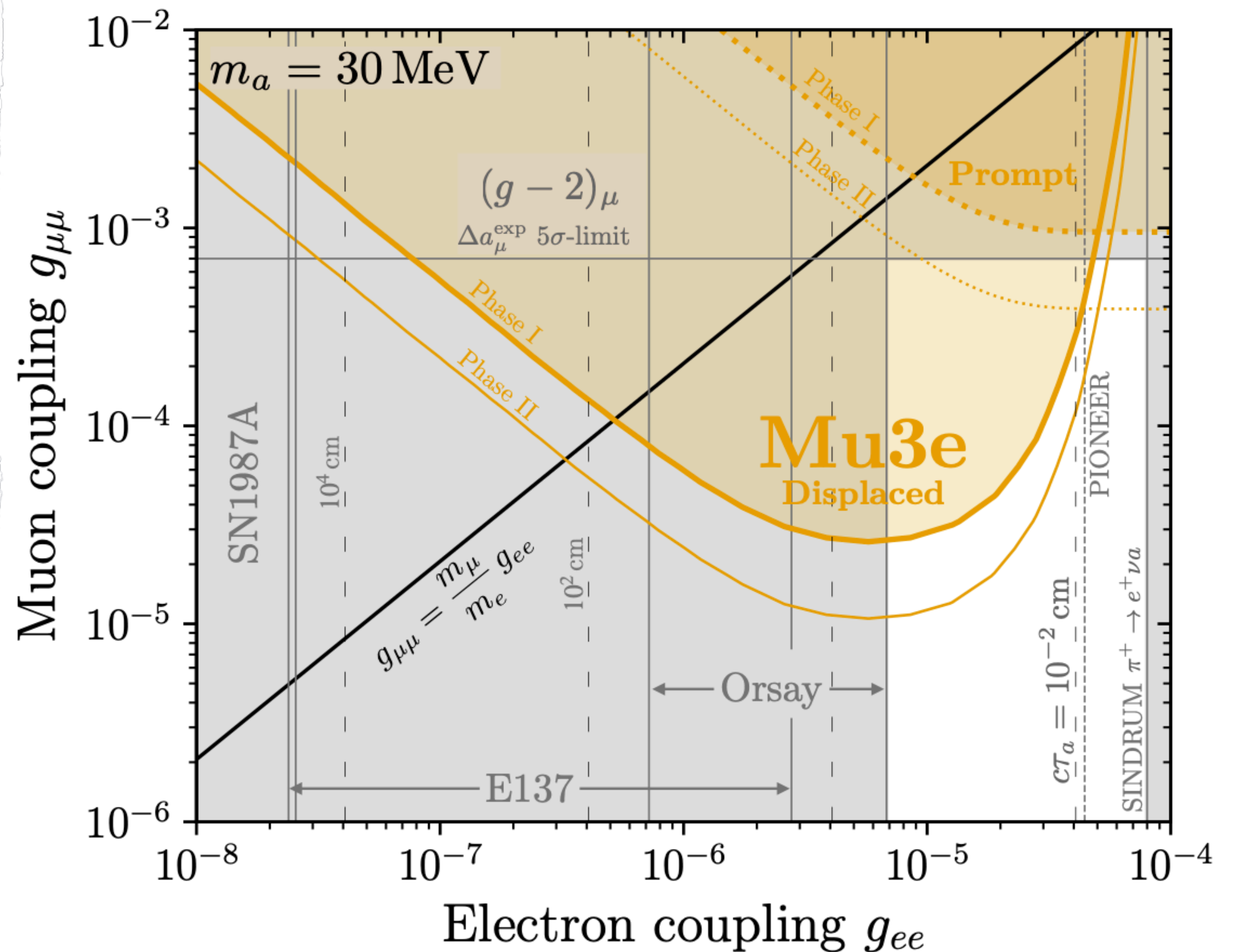
Muon decays

[Knapen, Opferkuch, Redigolo, MT: 2410.13941]

Displaced vertices from Light NP
Light ALPs coupling to leptons



Large improvement over prompts
HI e-beams cannot cover short lifetimes



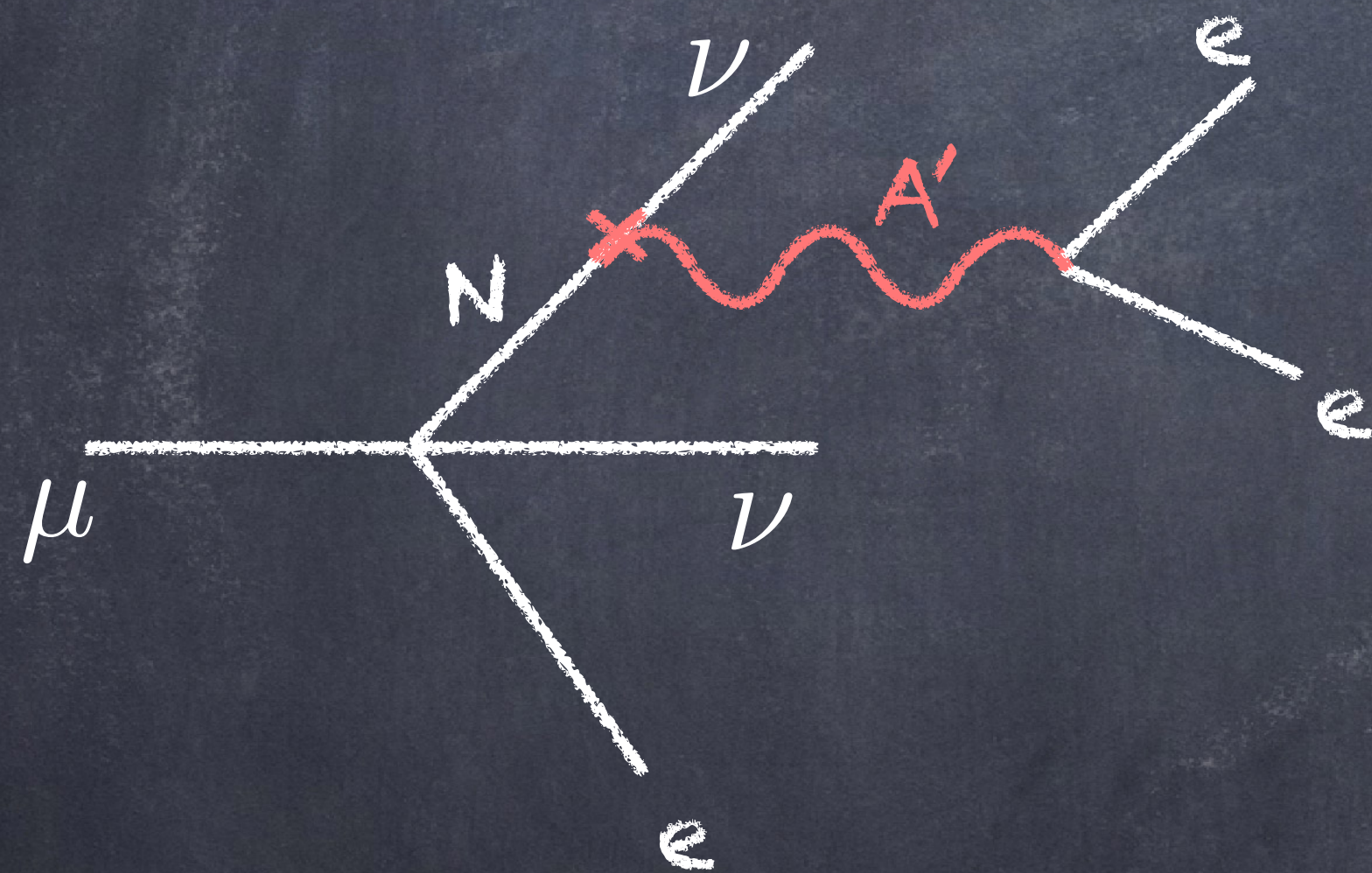
Muon decays

[Knapen, Opferkuch, Redigolo, MT: 2410.13941]

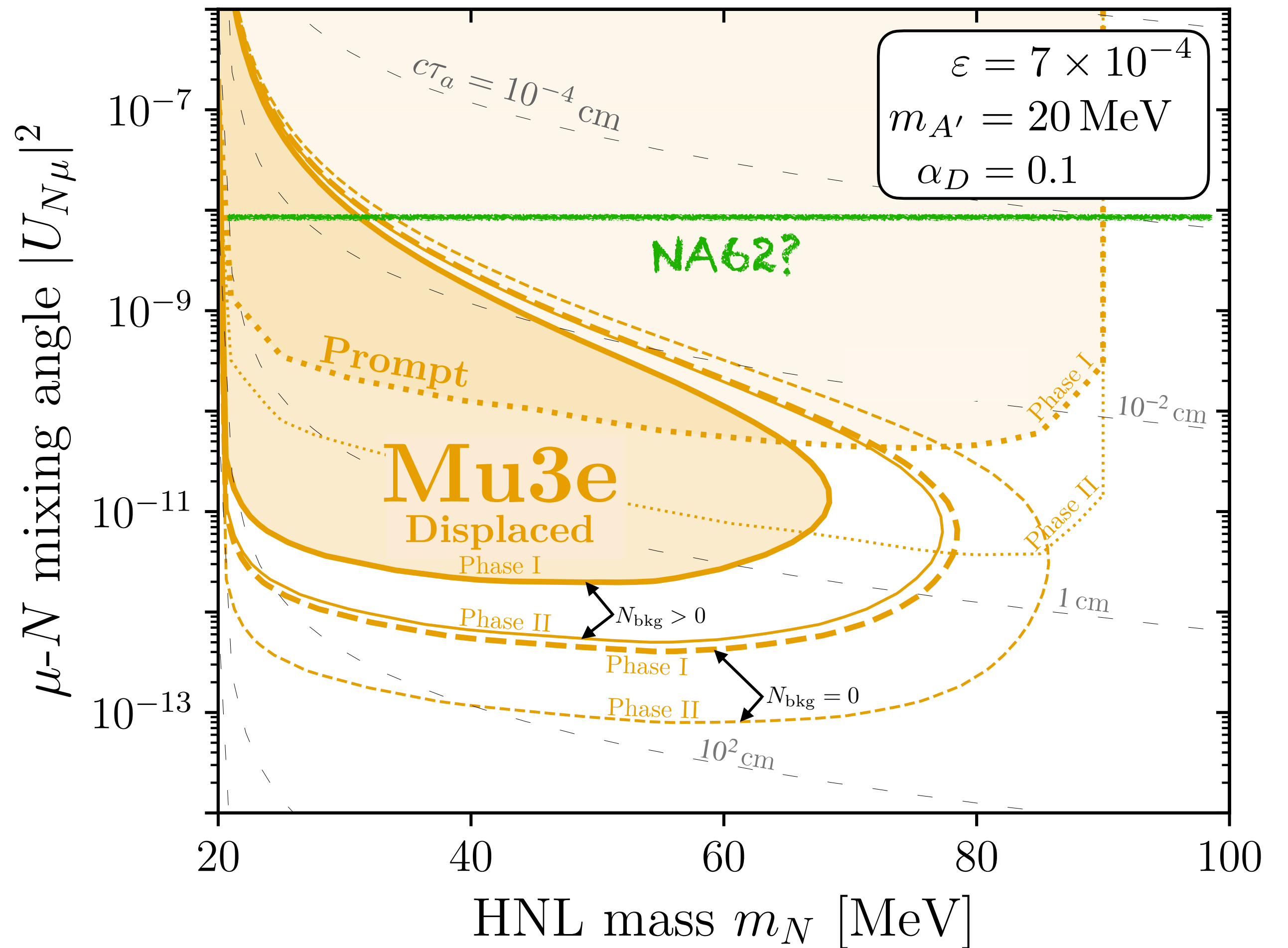
Displaced vertices from Light NP

Heavy Neutral Leptons & Dark Photons

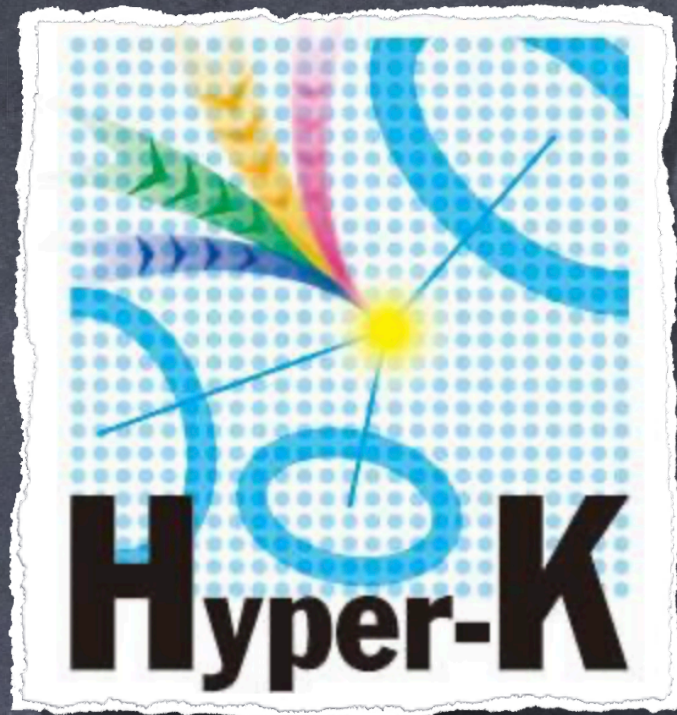
[Ballett, Hostert, Pascoli: 1903.07589]



Lifetime is shorter than naive HNL



2030s



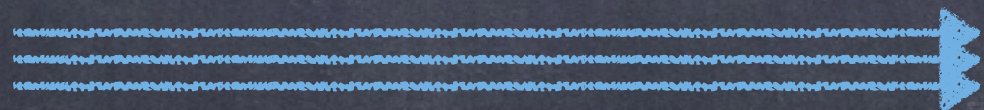
[DUNE TDR: 2002.03005]

[HyperK TDR: 1805.04163]

$$N_{\nu} \sim 10^{18} - 10^{20}$$

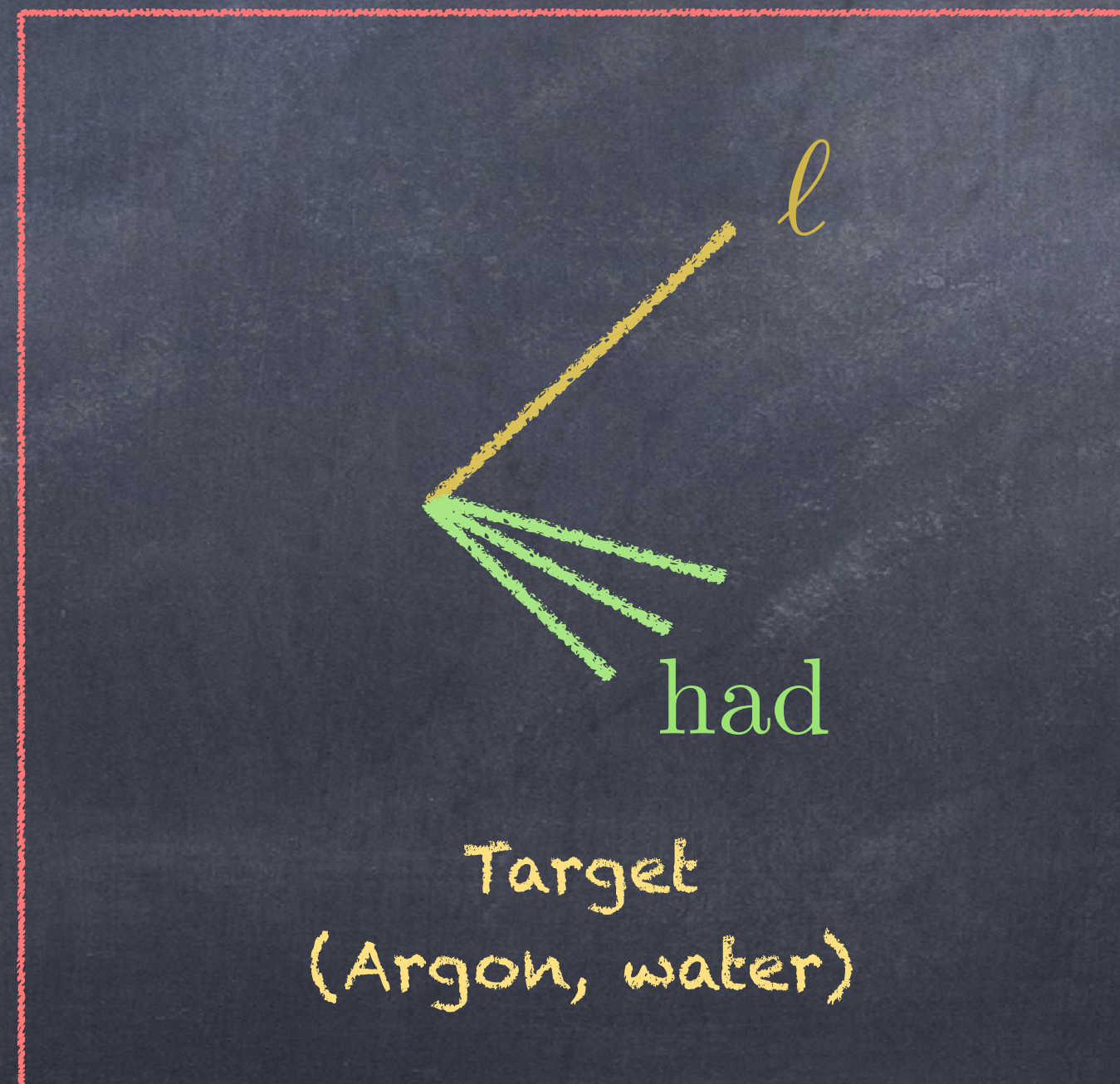
At Near-Detector

Neutrino beam



$$E_{\nu} \sim 1 - 10 \text{ GeV}$$

$O(10) \text{ m}$



Neutrino scattering

[Bansal, Paz, Petrov, MT, Zupan: 2210.05706]

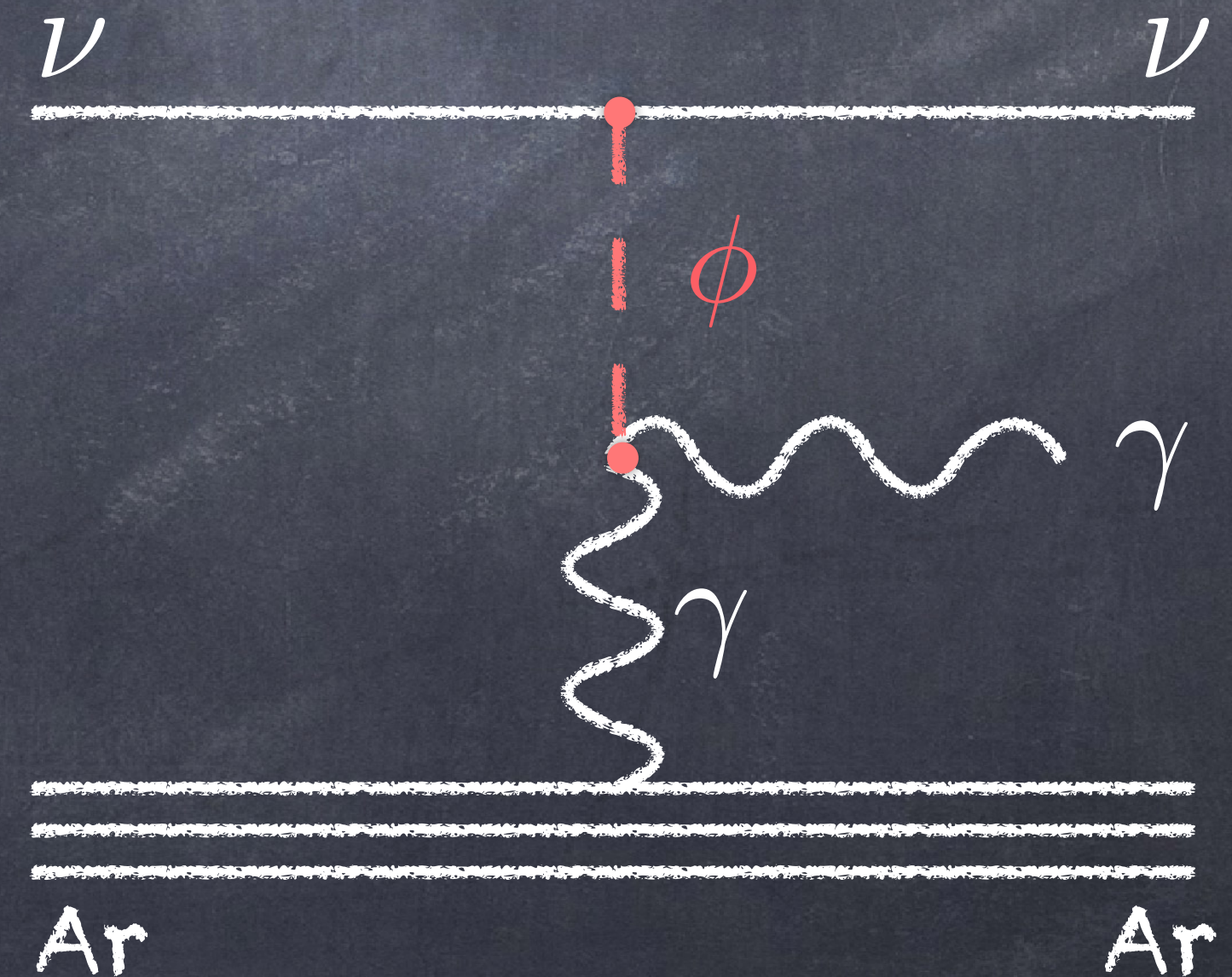
Inverse see saw: small neutrino mass from small breaking of lepton number



Light ALP

pNGB of $U(1)_L$, also known as Majoron

Can couple to F or G



Neutrino scattering

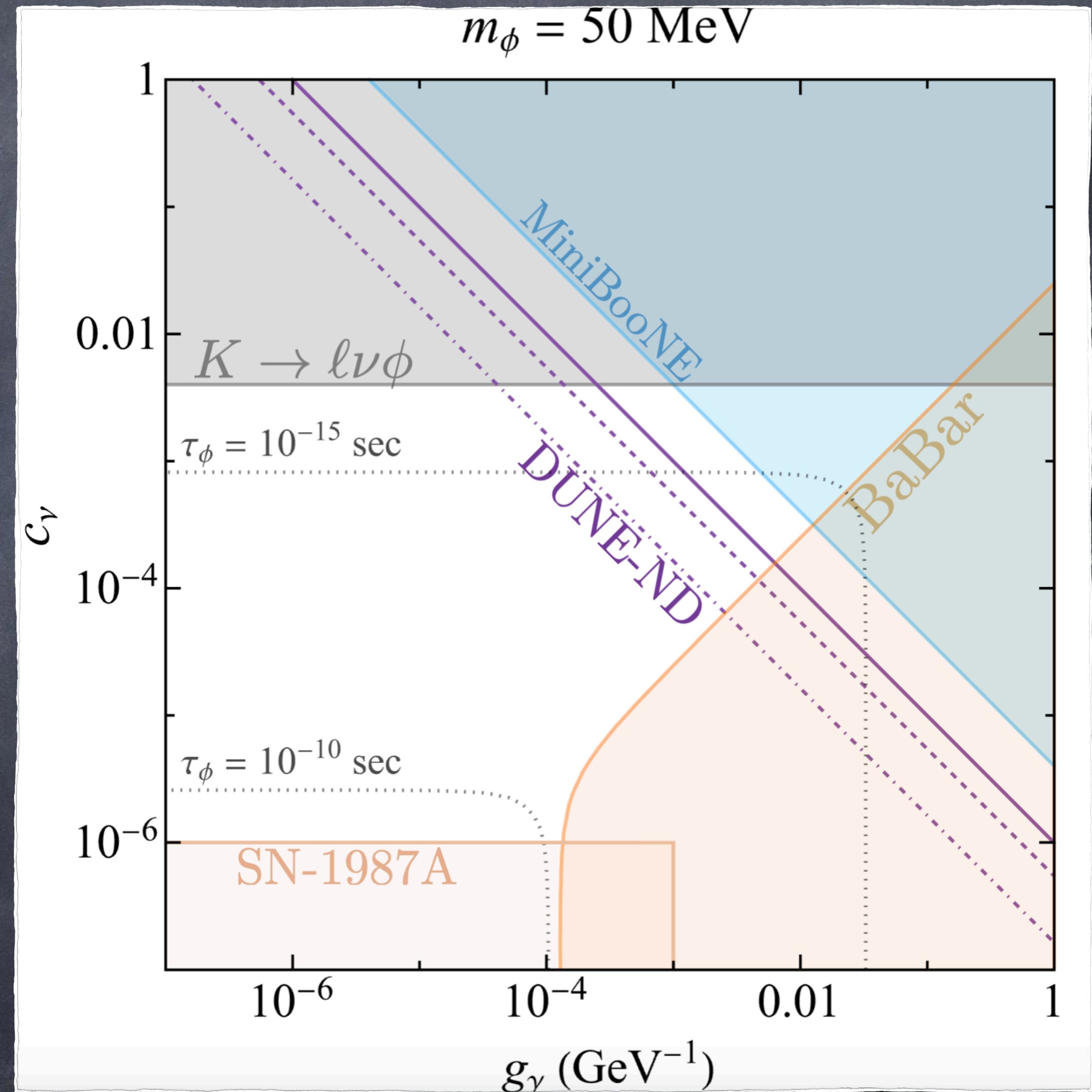
[Carey, Machado, Paz, Petrov, Sousa, MT, Zupan: 2508.16724]

Monophoton signal at DUNE/HyperK
(with no hadronic activity)

Main bkg from electrons in the
final state



Possible to discriminate from
photons with ML

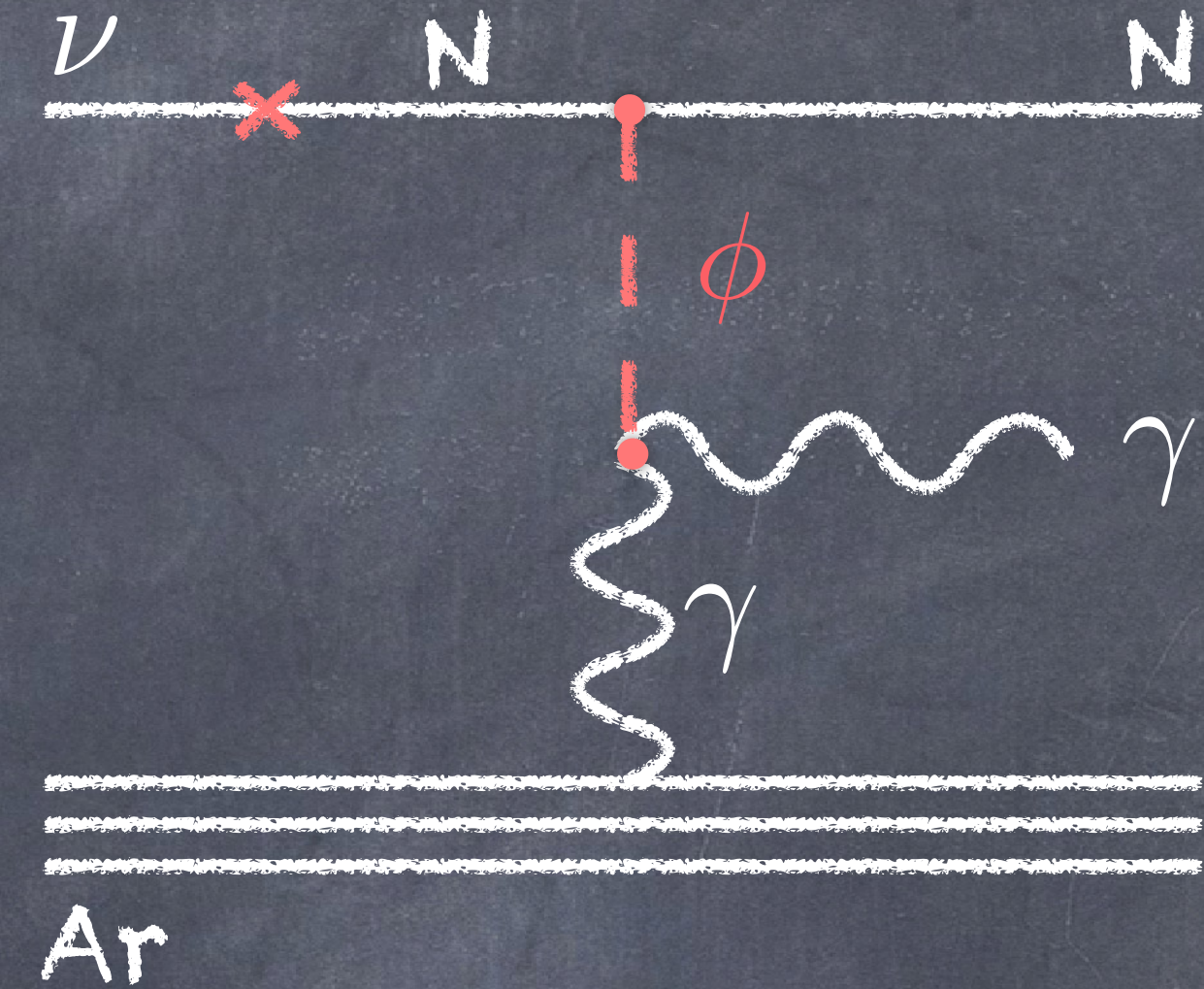


Neutrino scattering (WIP-1)

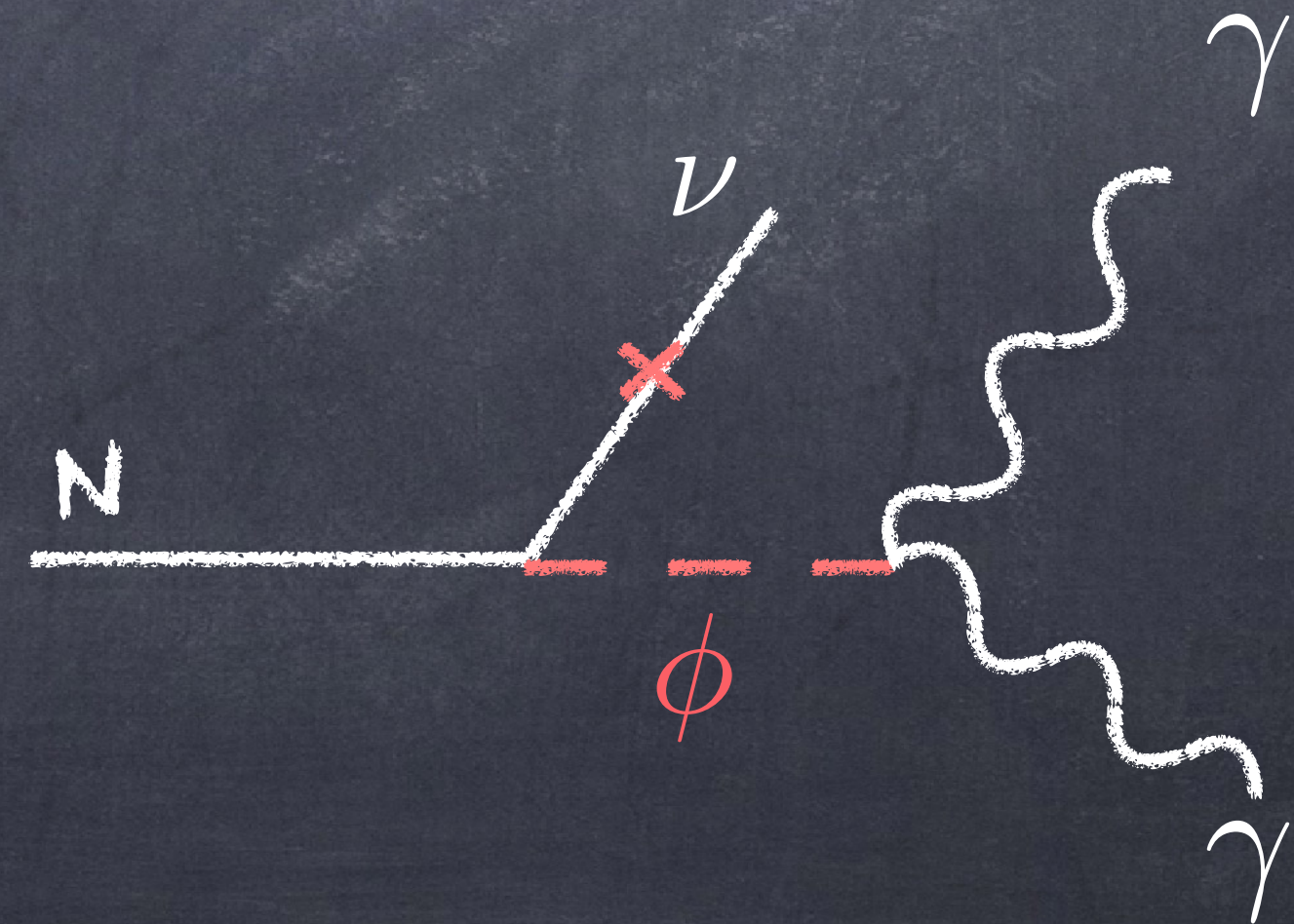
[Carey, MT, Zupan: 25xx.xxxxxx]

ISS includes heavy neutrinos

Coupling to Majoron unrestricted



Bkg-free search of displaced
multi-photon



Neutrino scattering (WIP-2)

[Borrello, Costa, Redigolo, MT: 25xx.xxxxxx]

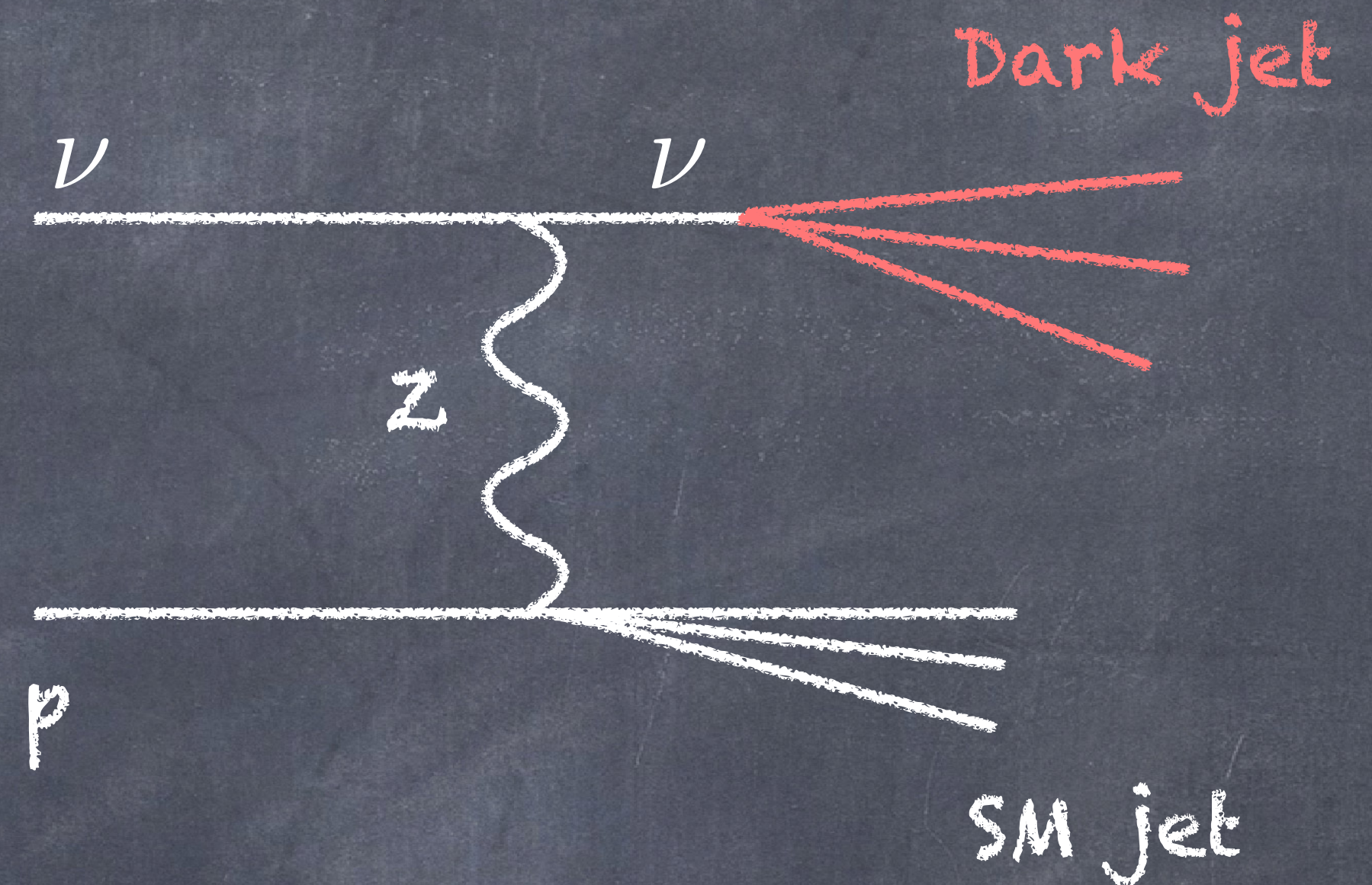
Models of 'composite' neutrino

Strongly coupled Dark Sector

$$\frac{y_\ell}{\Lambda_{UV}^{\Delta_N - 3/2}} H L O_N$$

High dim. Portal $\rightarrow$ Energy matters

$$E_\nu \sim 10^2 - 10^3 \text{ GeV}$$



Neutrino scattering (WIP-2)

[Borrello, Costa, Redigolo, MT: 25xx.xxxxx]

Models of 'composite' neutrino

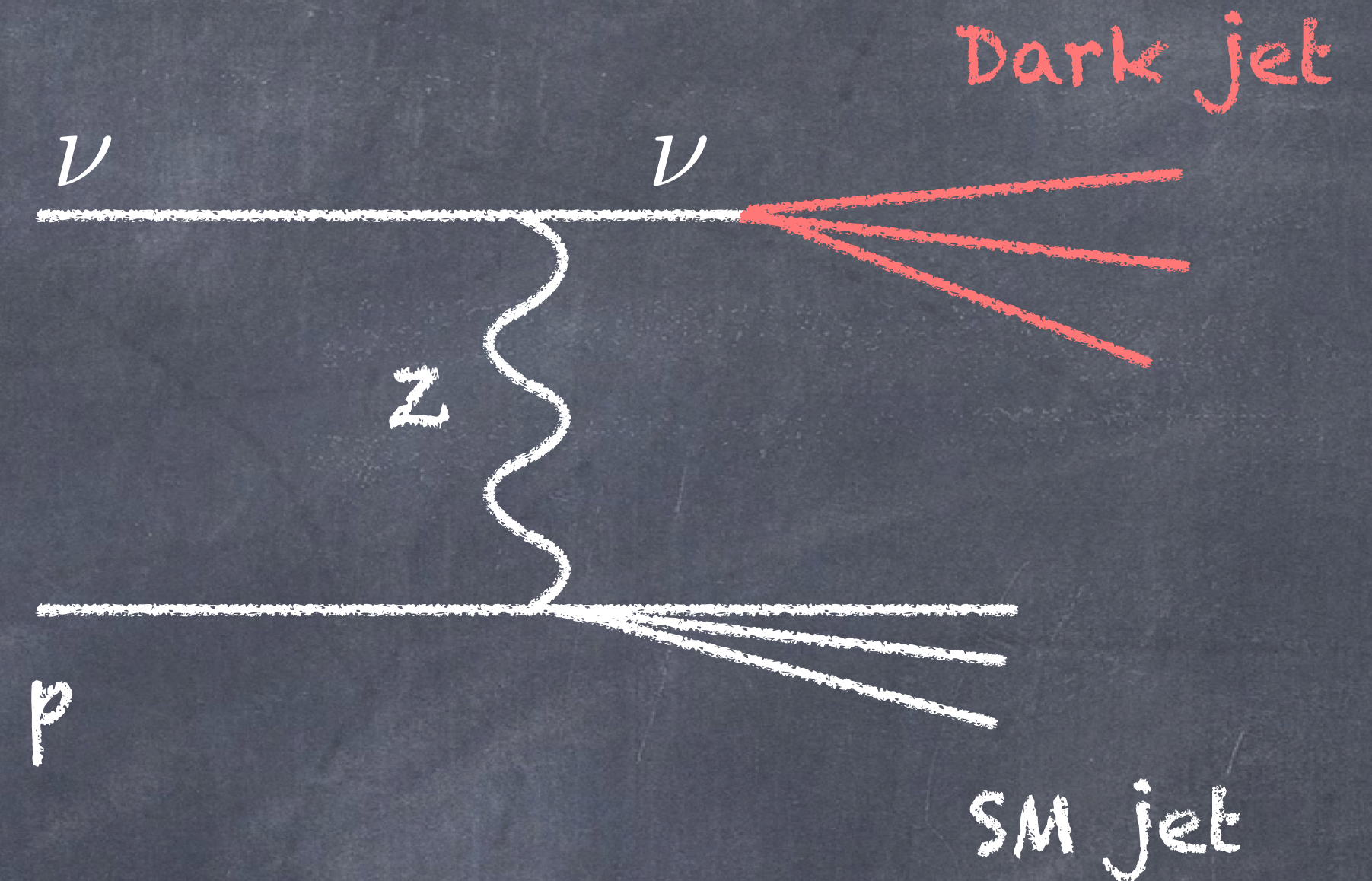
Strongly coupled Dark Sector

$$\frac{y_\ell}{\Lambda_{UV}^{\Delta_N - 3/2}} H L O_N$$

High dim. Portal $\rightarrow$ Energy matters

Enhancement of Neutral
Currents from 'invisible jets'

[Borrello, Costa, Redigolo: 2507.12527]



Dark jet fragments can decay
back to SM

Semi-visible jets!

See Borrello's talk later today!

Take home message

- High-Intensity experiments have much to offer to DS searches

Let's dig into new experiments in the near future

- Look for new ways to probe New Physics

No data wasting!

- Synergy between theory and experiment can only benefit us

Like this Workshop!

Backups

Flavorful Axion

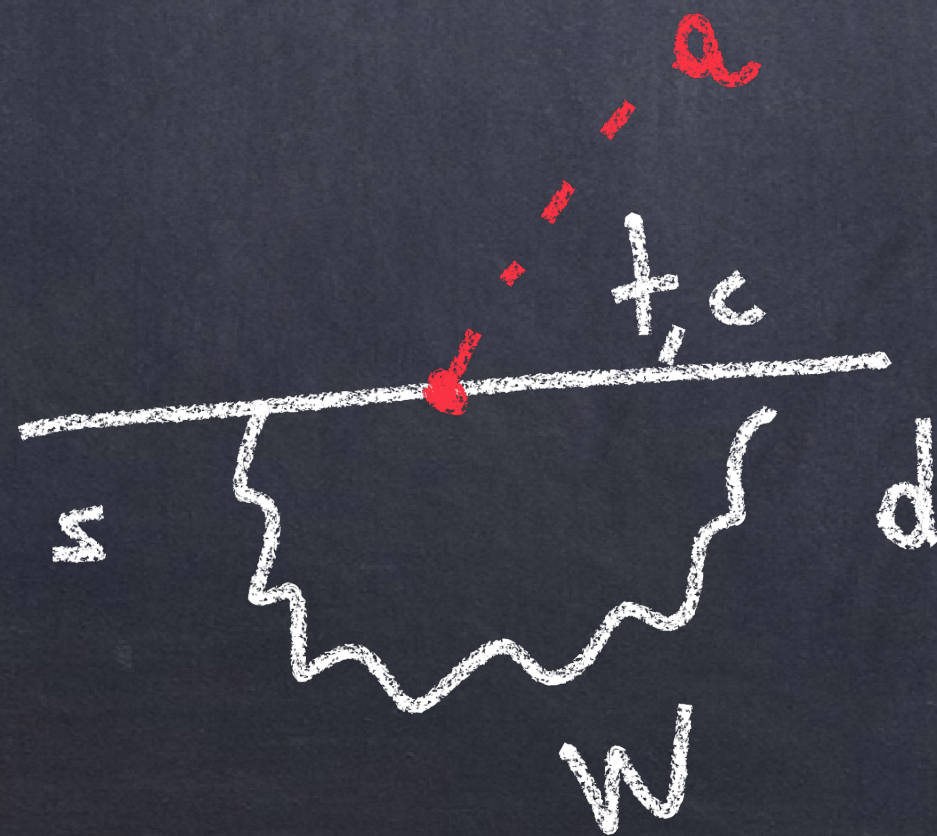
$$\frac{\partial_\mu a}{f_a} \bar{s} \gamma^\mu (C_{sd}^V + \gamma_5 C_{sd}^A) d$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ a) \sim 0.1 \left(\frac{10^7 \text{ GeV}}{f_a} \right)^2 (C_{sd}^{V,A})^2$$

Minimal Flavor Violation

[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

$$C_{sd}^{V,A}(\mu) \sim \mathcal{O}(10^{-6}) \times \log \left(\frac{\Lambda_{\text{UV}}}{\mu} \right) C_{qq,W}(\Lambda_{\text{UV}})$$



$$U(1)_{\text{PQ}} \times \mathcal{G}_{\text{flavor}}$$

Observed $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \nu)$

For $f_a \gtrsim 10^{6-7} \text{ GeV}$

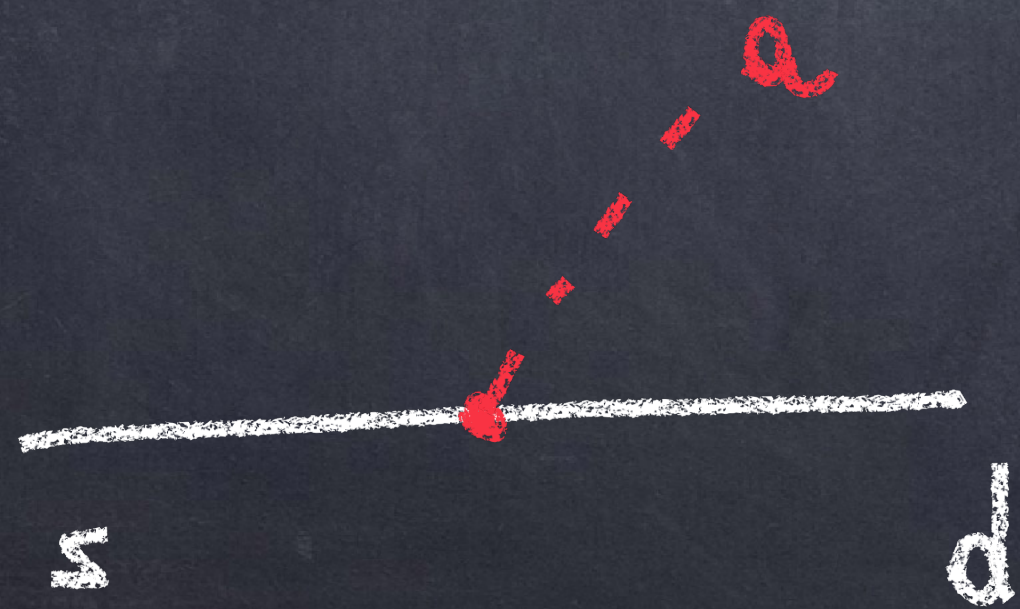
Flavorful Axion

$$\frac{\partial_\mu a}{f_a} \bar{s} \gamma^\mu (C_{sd}^V + \gamma_5 C_{sd}^A) d$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ a) \sim 0.1 \left(\frac{10^7 \text{ GeV}}{f_a} \right)^2 (C_{sd}^{V,A})^2$$

Flavor anarchy

$$C_{sd}^{V,A}(\mu_c) \sim C_{sd}^{V,A}(\Lambda_{\text{UV}}) \sim \mathcal{O}(1)$$



$$U(1)_{\text{PQ}} \supseteq \mathcal{G}_{\text{flavor}}$$

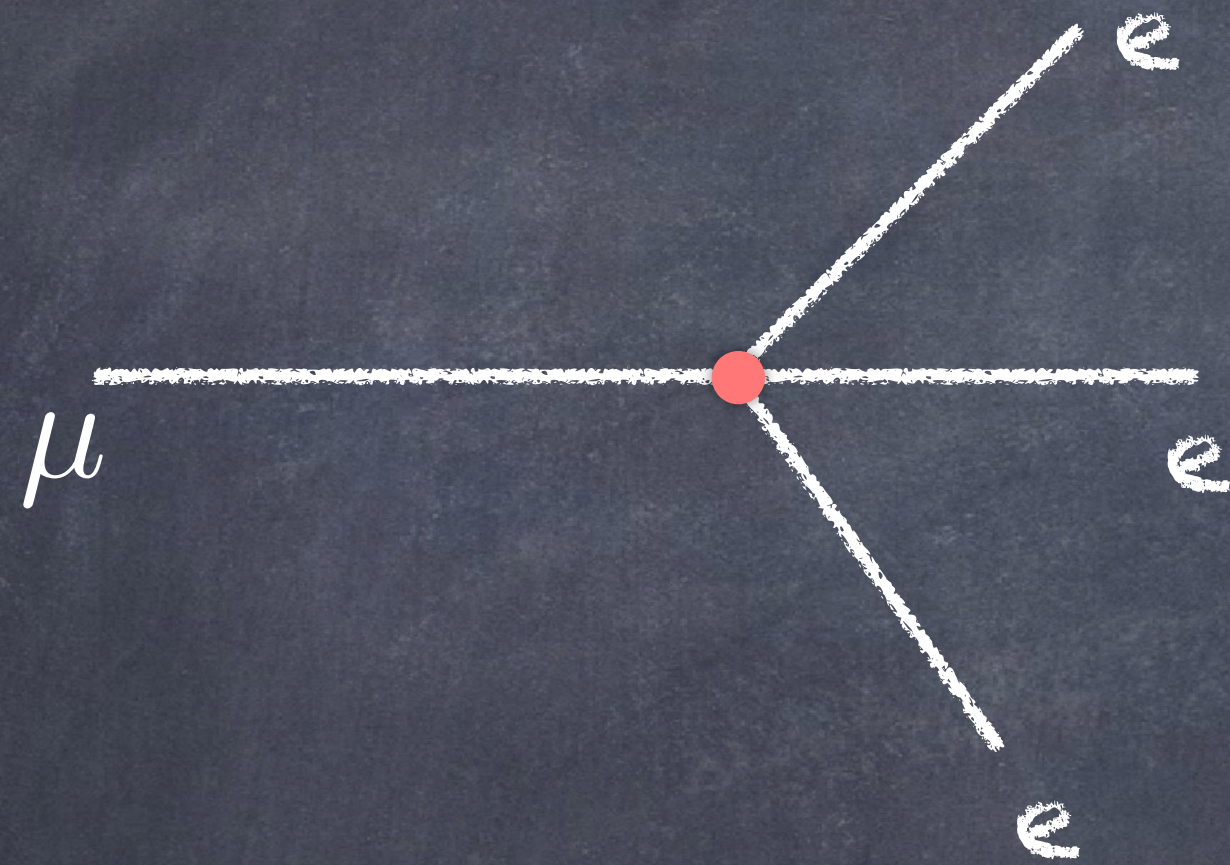
Observed $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \nu)$

For $f_a \gtrsim 10^{12} \text{ GeV}$

Muon decays

[Redigolo, MT, Tesi: 2408.00847]

FV from heavy mediator

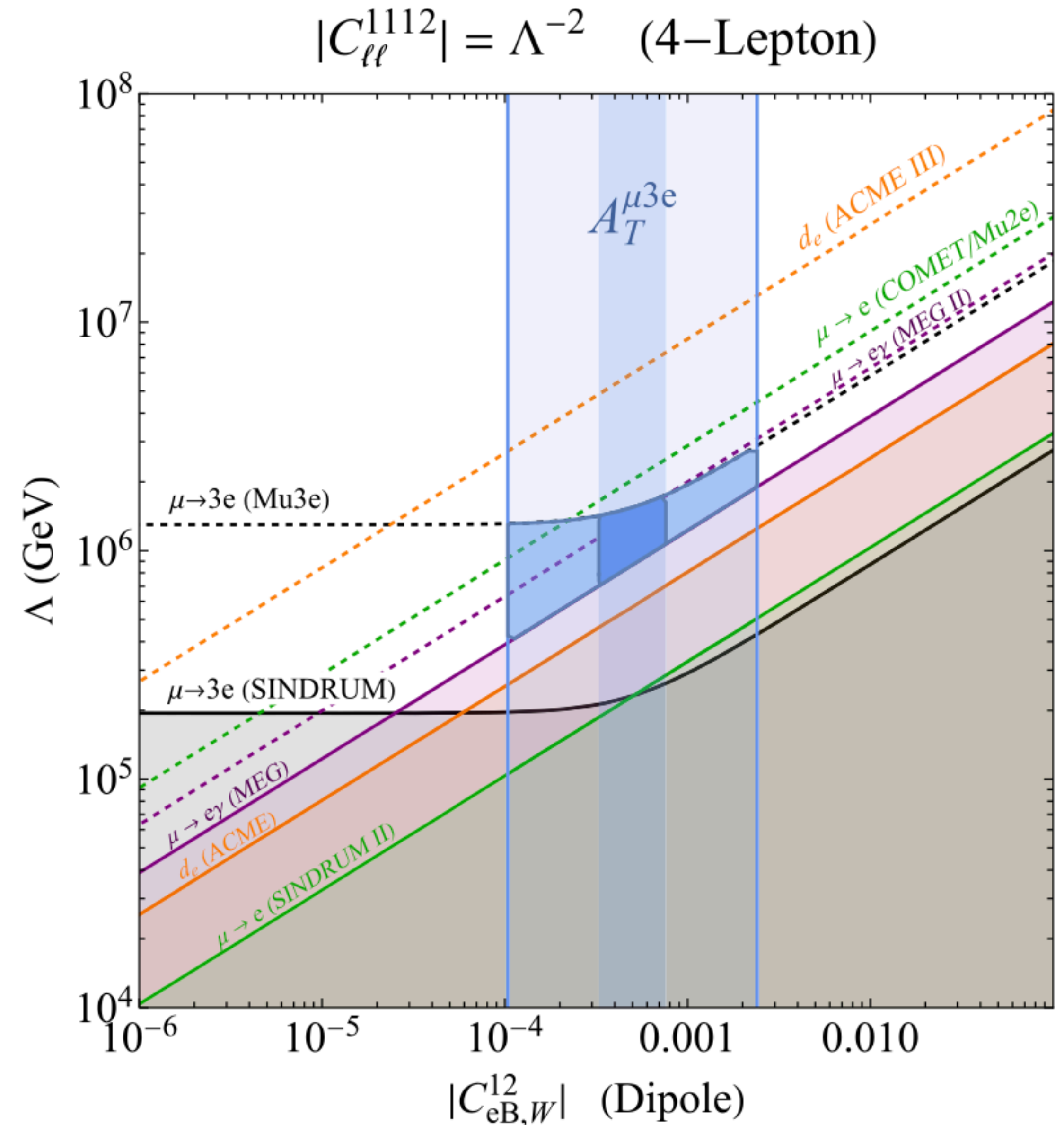


Dipole

$$\frac{C_{eB}^{rs}}{\Lambda^2} (\bar{L}_r \sigma_{\mu\nu} e_s) H B^{\mu\nu}$$

4-Leptons

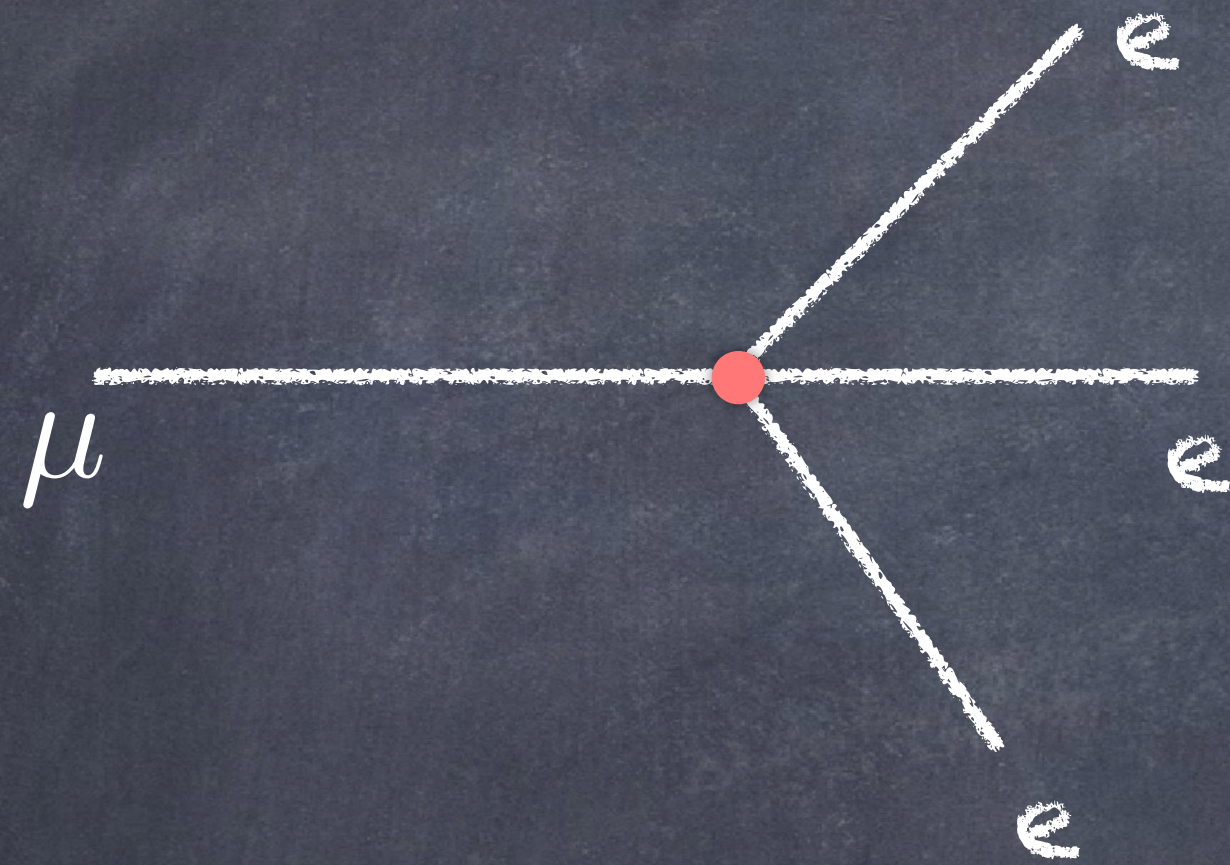
$$\frac{C_{\ell\ell}^{rs}}{\Lambda^2} (\bar{L}_r \gamma_\mu L_s) (\bar{L}_p \gamma^\mu L_q)$$



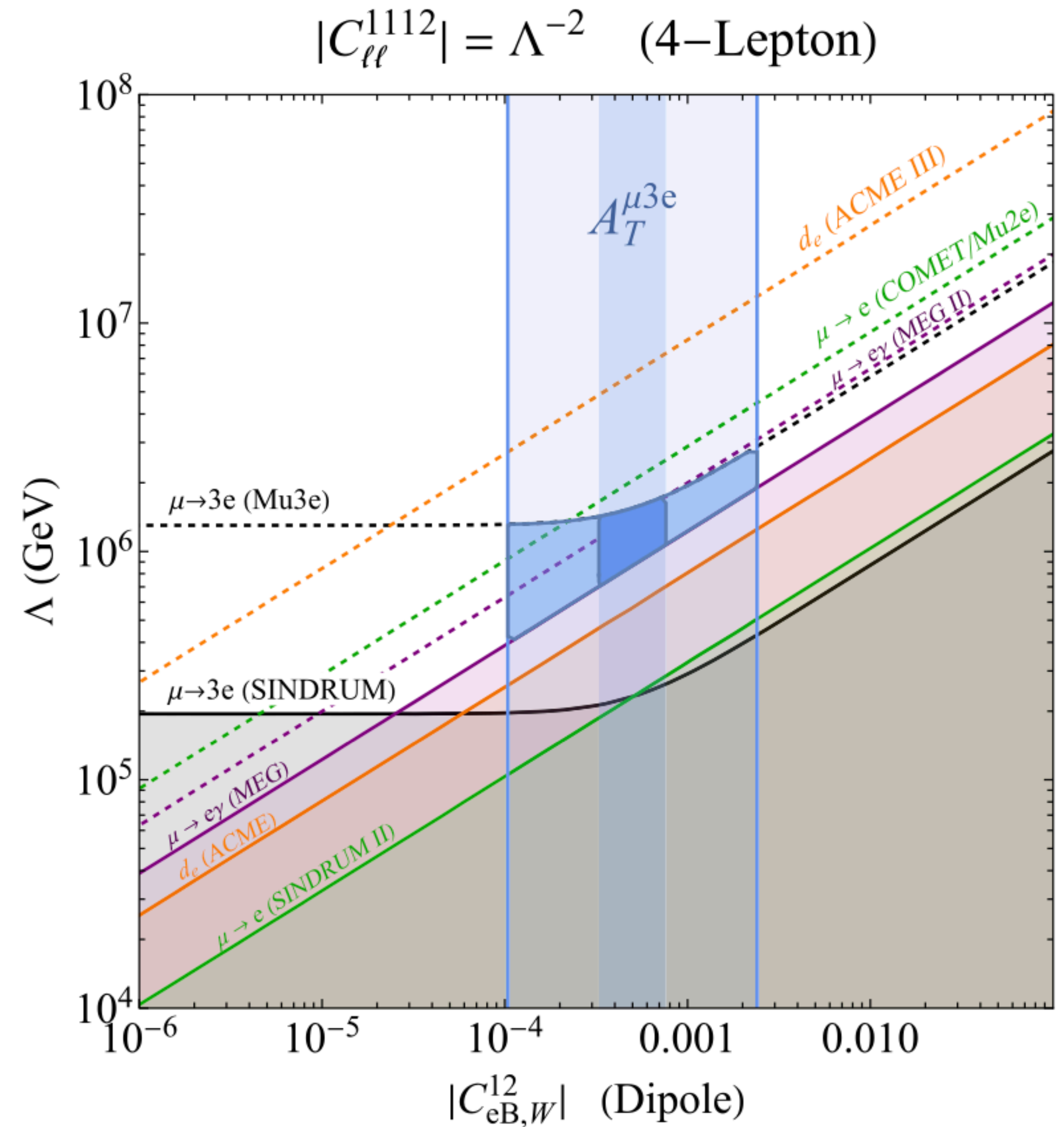
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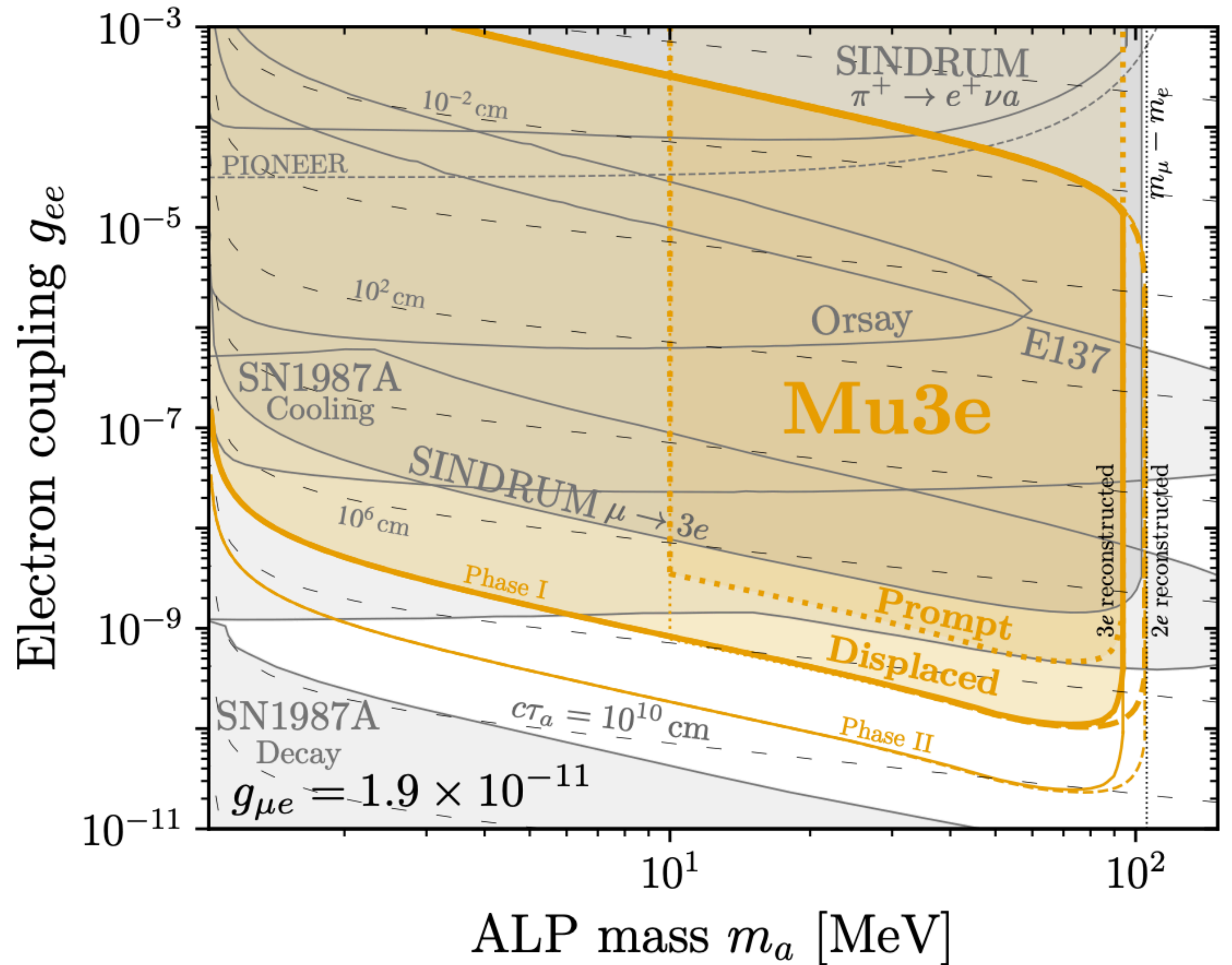
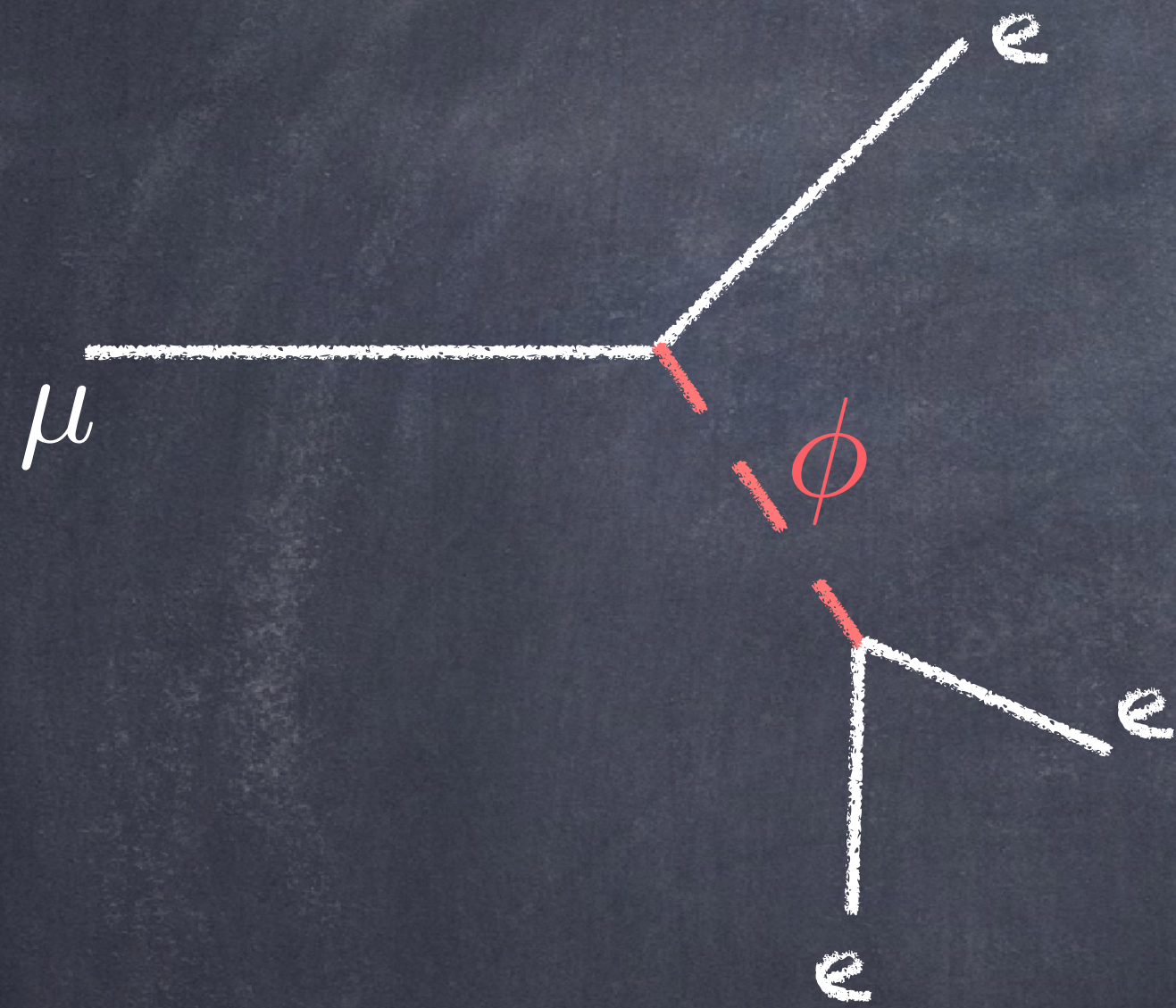


Mu3e can also probe CP violation!

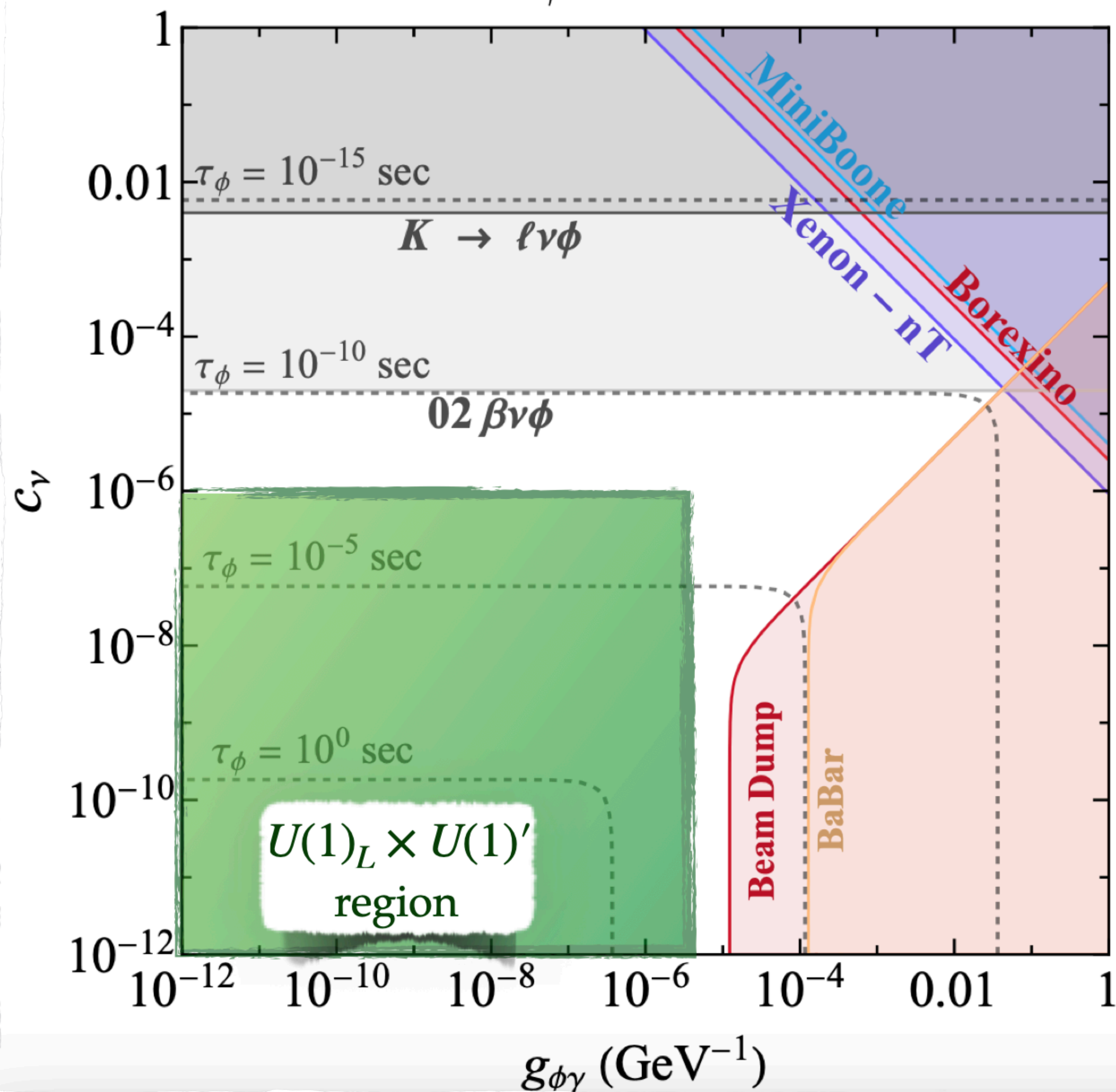


Muon decays

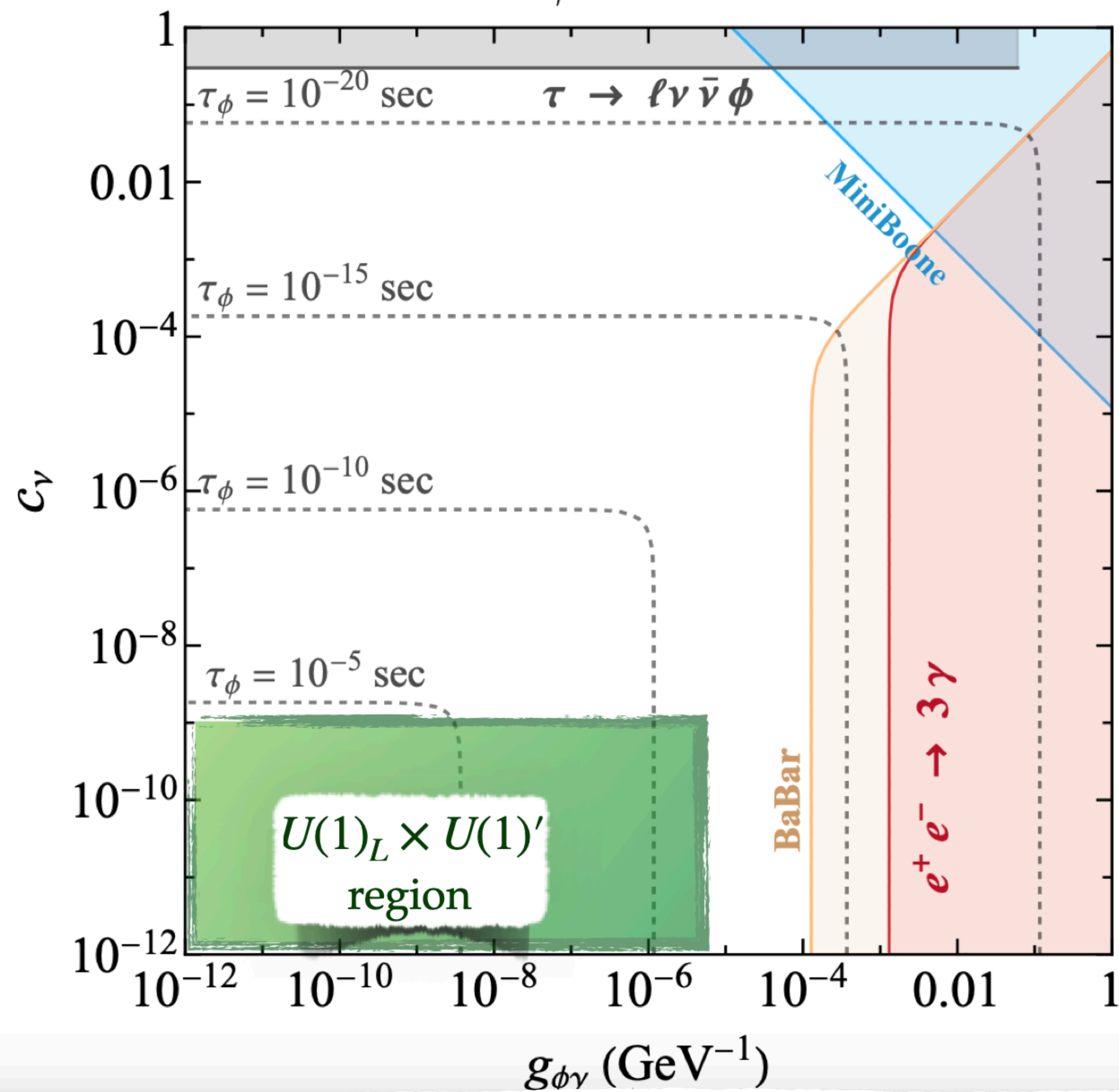
[Knapen, Opferkuch, Redigolo, MT: 2410.13941]



$m_\phi = 1 \text{ MeV}$



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Neutrino scattering

[Carey, Machado, Paz, Petrov, Sousa, MT, Zupan: 2508.16724]

