Probing Light New Physics at LFV Experiments

Toby Opferkuch

CLFV Searches with the MU2E Experiment

13th of June 2025

INFN

SISSA

Minimal Dark Matter

$$\mathcal{G}_{\mathrm{SM}} \supset \boxed{SU(3)_C} \times \boxed{SU(2)_L \times U(1)_Y}$$

1. Dark matter can be coloured

[See V. de Luca et al. 1801.01135]

QQ or QQQ bound states → Signatures from gQ & $q\bar{q}'Q$ objects

QQ: $SU(3)_C$ octets

QQQ: $SU(3)_C$ fundamental rep.

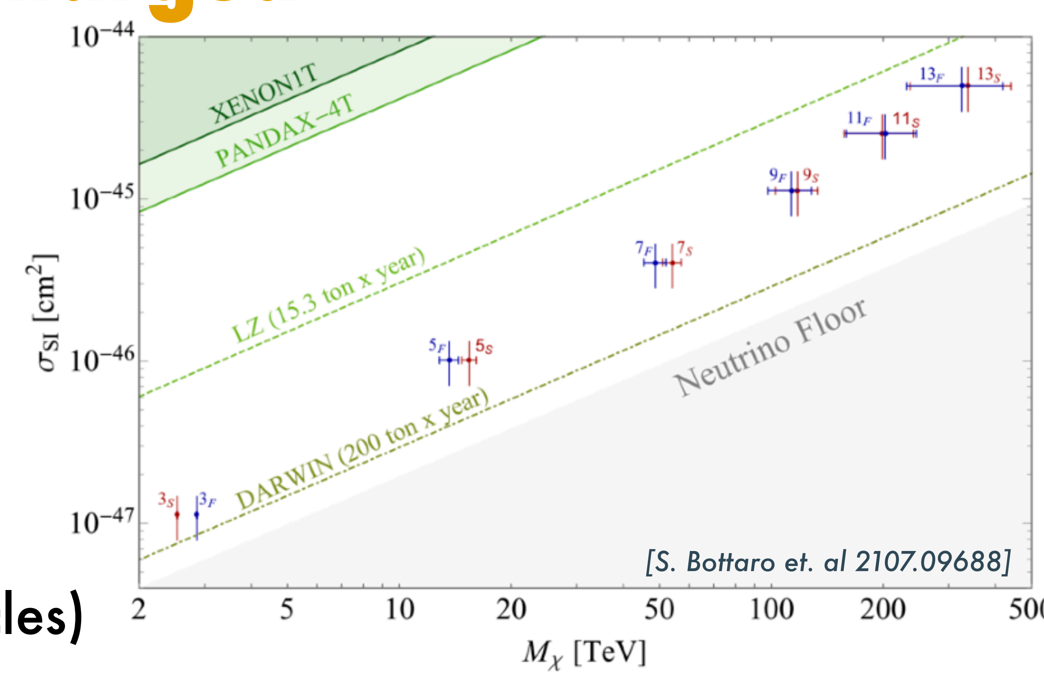
2. Dark matter can be electroweak charged

Finite set of options based on $SU(2)_L$ representations

$Y = 0$ real WIMPS [S. Bottaro et. al 2107.09688]

$Y = 1/2, 1$ complex WIMPS [S. Bottaro et. al 2205.04486]

Includes classic Wino & Higgsino WIMPs (minus SUSY particles)



Minimal Dark Matter

$$\mathcal{G}_{\rm SM} \supset \boxed{SU(3)_C} \times \boxed{SU(2)_L \times U(1)_Y}$$

1. Dark matter can be **colour**

[See V. de Luca et al. 1801.01135]

QQ or QQQ bound stat

$SU(3)_C$ octets $SU(3)_C$ fundamental rep.

2. Dark matter can be **electro**

Finite set of options based on $SU(2)_L$ representa

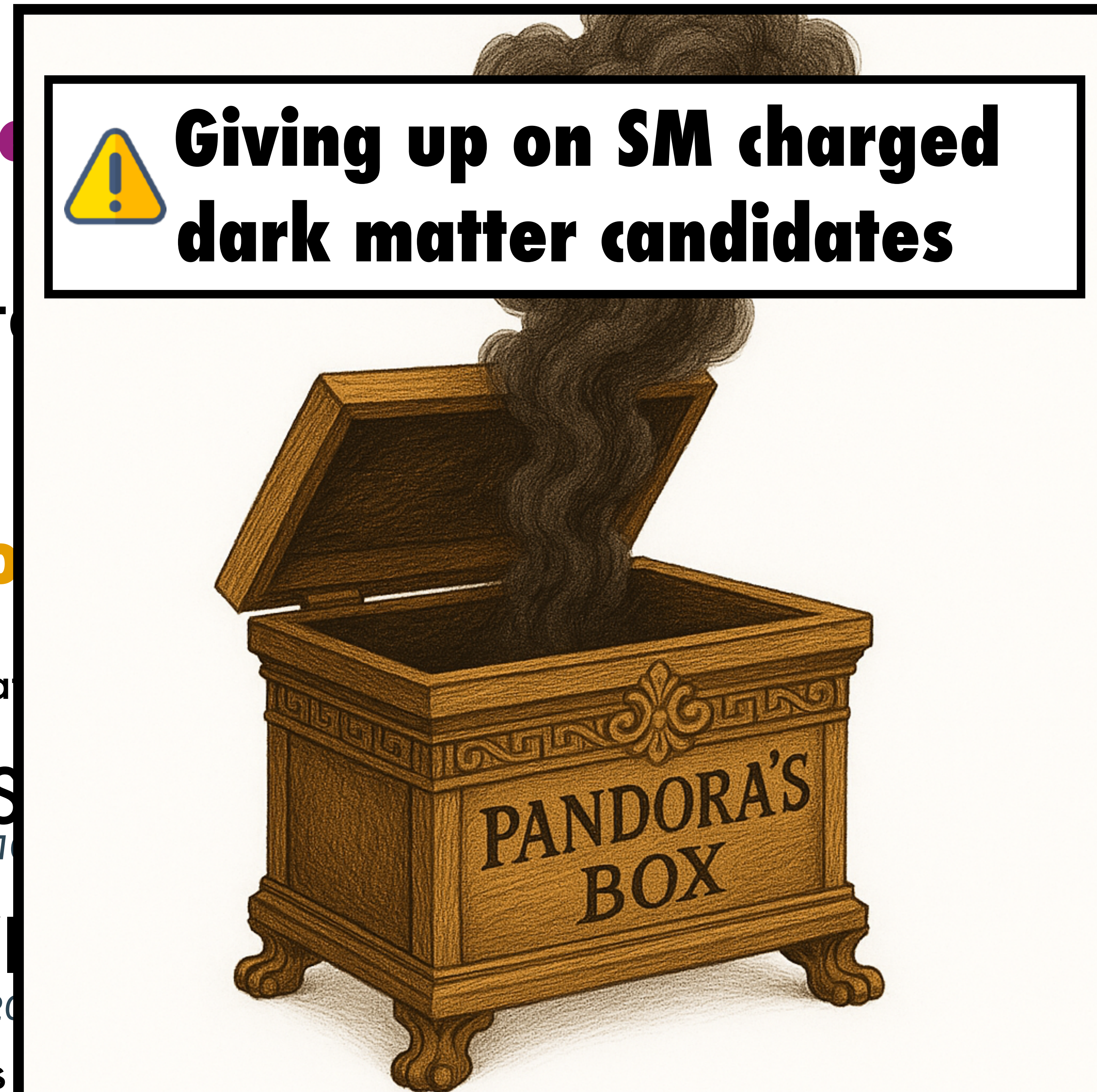
$Y = 0$ real WIMPS

[S. Bottaro et. al 21

$Y = 1/2, 1$ complex WI

[S. Bottaro et. al 22

Includes classic Wino & Higgsino WIMPs (minus



Singlet Dark Matter

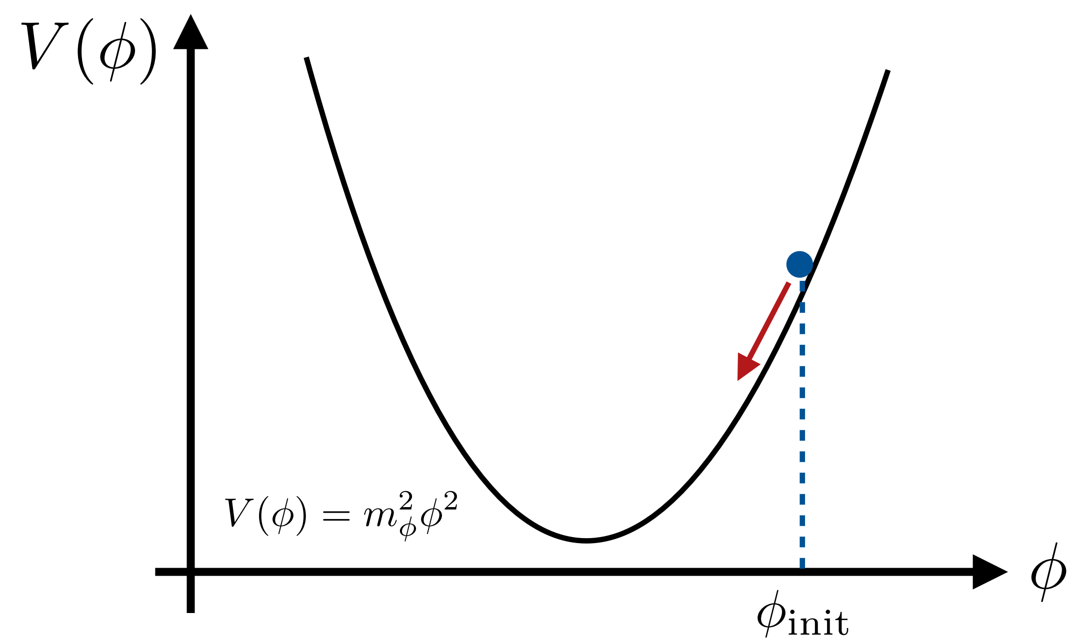
If DM is a SM singlet it need **not interact with the SM**

Ex. Misalignment production:

Consider a free scalar with initial field value $\phi_{\rm init}$

$$\Omega_\phi = 0.12 \left(\frac{\phi_{\rm init}}{2\times 10^{13}\,{\rm GeV}}\right)^2 \left(\frac{m_\phi}{10^{-6}\,{\rm eV}}\right)^{1/2}$$

Scalar must be light for there to be enough DM



Singlet Dark Matter

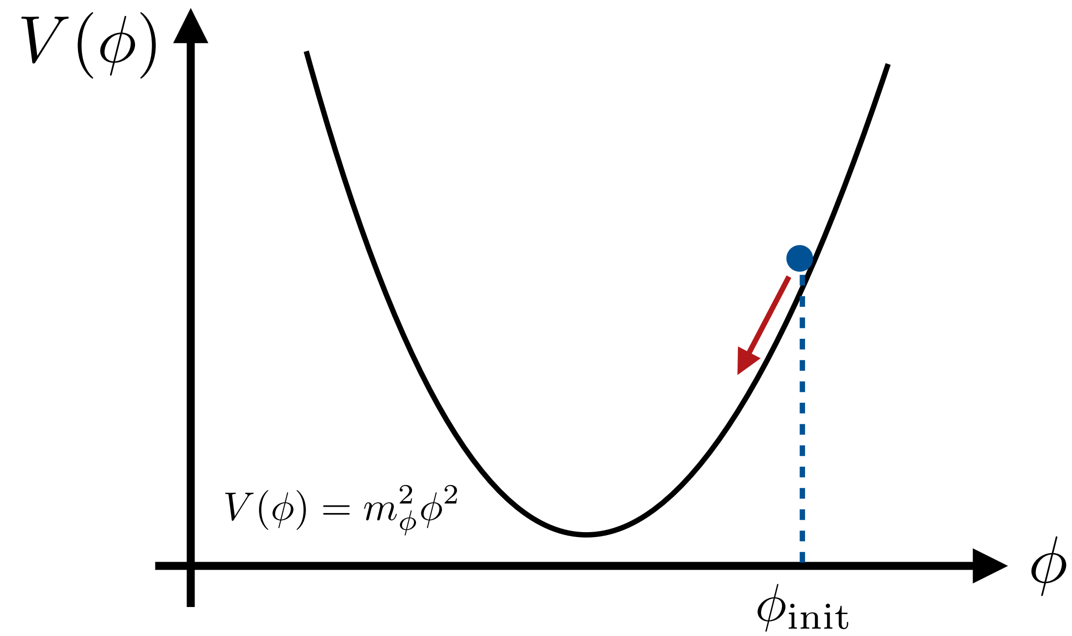
If DM is a SM singlet it need **not interact with the SM**

Ex. Misalignment production:

Consider a free scalar with initial field value $\phi_{\rm init}$

$$\Omega_\phi = 0.12 \left(\frac{\phi_{\rm init}}{2\times 10^{13}\,\mathrm{GeV}}\right)^2 \left(\frac{m_\phi}{10^{-6}\,\mathrm{eV}}\right)^{1/2}$$

Scalar must be light for there to be enough DM



But we might be lucky and observe **light thermal relics!**

Sandbox Studio, Chicago (Ana Kova)

Ex. Neutrinos

Example of a light thermal relic that behaves like dark matter today!

DM may be similar!

But what do we observe?

- ✓ Solar neutrinos
- ✓ Reactor anti-neutrinos
- ✓ Collider neutrinos
- ✗ Cosmic neutrino background

Many Options, Much Fun?

How do I make sense of the landscape of singlet options?

EFT:

$$\mathcal{L}_{\rm portal} \supset \frac{c_n}{\Lambda^{\Delta_{\rm dark}+\Delta_{\rm SM}-4}} \mathcal{O}_{\rm dark}\mathcal{O}_{\rm SM}$$

Any gauge invariant combination of SM fields

Lower dimensional portals

$$\mathcal{O}_{\rm dark} = \{\phi, N, V_\mu, \dots\}$$

Scalar, Fermion, Vector

→ **Largest rates**

Many Options, Much Fun?

How do I make sense of the landscape of singlet options?

EFT:

$$\mathcal{L}_{\rm portal} \supset \frac{c_n}{\Lambda^{\Delta_{\rm dark}+\Delta_{\rm SM}-4}}\mathcal{O}_{\rm dark}\mathcal{O}_{\rm SM}$$

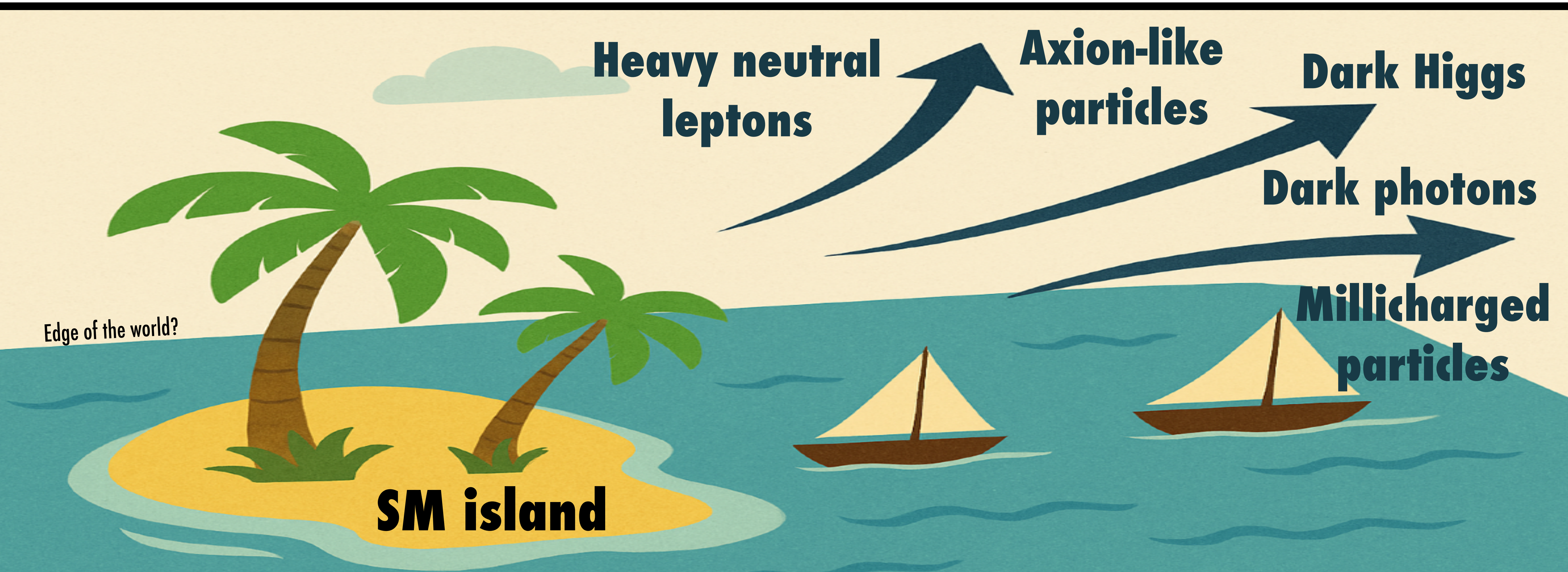
Any gauge invariant combination of SM fields

Lower dimensional portals

$$\mathcal{O}_{\rm dark} = \{\phi, N, V_\mu, \dots\}$$

Scalar, Fermion, Vector

→ **Largest rates**



Dark Sector Thermal History

Portal interaction strength decreasing →

Thermalised [Think WIMPs*]

Decoupled

$\Gamma_{\rm int} \geq H$

$\Gamma_{\rm int} < H$

Dark Sector Thermal History

Portal interaction strength decreasing

Thermalised [Think WIMPs*]

Portal interactions lead to dark sector equilibration with SM

↓

Annihilation rate of DM to SM sets the relic abundance today

↓

Annihilations must be strong enough so that DM does not over close Universe

↓

Lower bound on interaction strength

↓

✓ **Sharp experimental target**

$\Gamma_{\rm int} \geq H$ | $\Gamma_{\rm int} < H$

Decoupled

Dark Sector Thermal History

Portal interaction strength decreasing →

Thermalised [Think WIMPs*]

Portal interactions lead to dark sector equilibration with SM

↓

Annihilation rate of DM to SM sets the relic abundance today

↓

Annihilations must be strong enough so that DM does not over close Universe

↓

Lower bound on interaction strength

↓

✔ **Sharp experimental target**

$\Gamma_{\rm int} \geq H$ | $\Gamma_{\rm int} < H$

Decoupled

Portal interactions insufficient to achieve equilibration with SM

↓

Suppose portal breaks SM accidental symmetries

↓

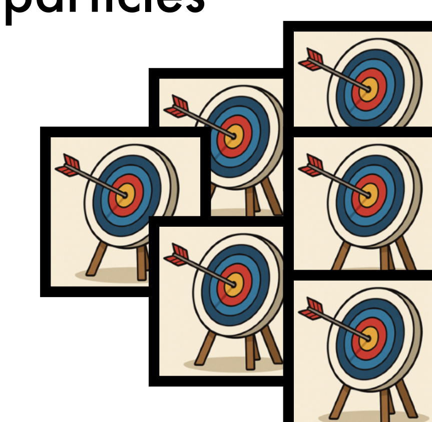
Small coupling leads to freeze-in or non-thermal production

↓

Target becomes rare processes and/or long-lived particles

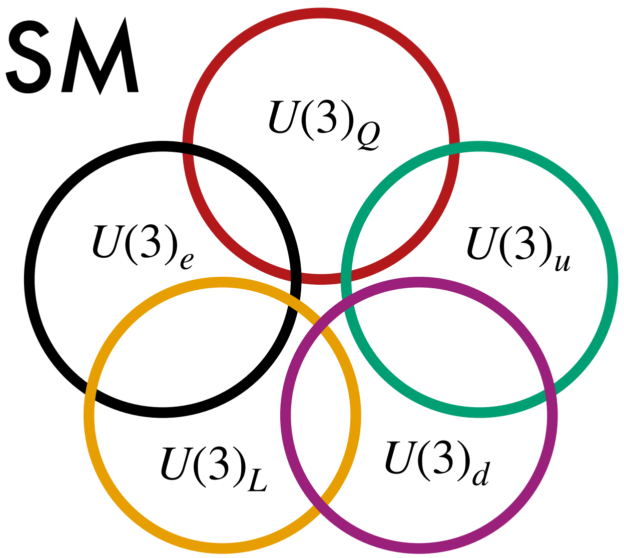
Multiple model dependent targets

[judicious choice important]



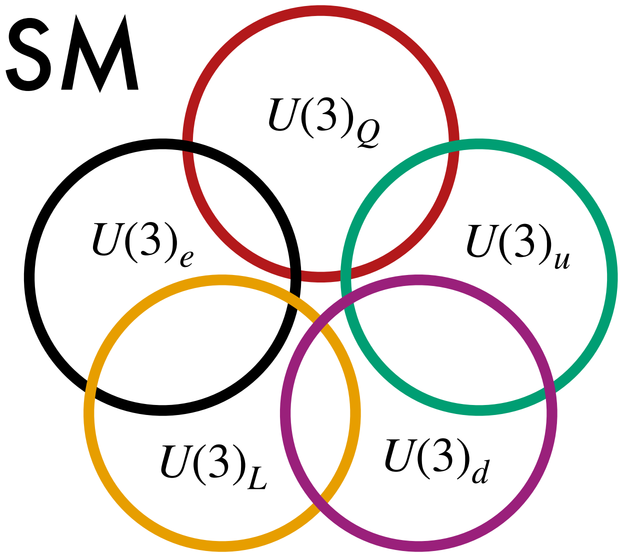
Flavoured Axion-like Portal

Accidental symmetries of the SM might be broken by light new particles feebly coupled to the SM



Flavoured Axion-like Portal

Accidental symmetries of the SM might be broken by light new particles feebly coupled to the SM



Example: Flavour dependent Peccei-Quinn charges

[Calibbi et al 1612.08040]
[Ema et al 1612.05492]

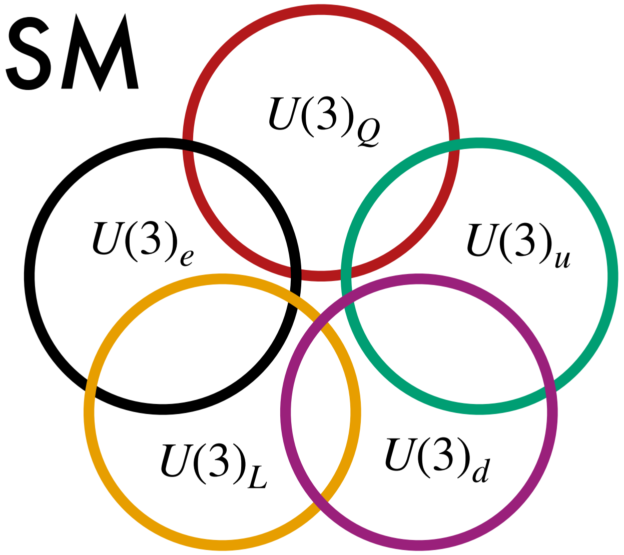
Flavour conserving / **Flavour violating**

$$\mathscr{L} \supset \sum_i \frac{\partial_\mu a}{2f_a}\bar{f}_i C^A_{ii}\gamma_\mu\gamma_5 f_i + \sum_{i\neq j}\frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu\left(C^V_{ij} + C^A_{ij}\gamma_5\right)f_j$$

[Feng et al hep-ph/9709411]

Flavoured Axion-like Portal

Accidental symmetries of the SM might be broken by light new particles feebly coupled to the SM



Example: Flavour dependent Peccei-Quinn charges

[Calibbi et al 1612.08040]
[Ema et al 1612.05492]

Flavour conserving + **Flavour violating**

$$\mathscr{L} \supset \sum_i \frac{\partial_\mu a}{2f_a} \bar{f}_i C^A_{ii} \gamma_\mu \gamma_5 f_i + \sum_{i \neq j} \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu \left(C^V_{ij} + C^A_{ij} \gamma_5 \right) f_j$$

[Feng et al hep-ph/9709411]

Hierarchy between **flavour-conserving** and **flavour-violating** depends on the UV theory

Flavour anarchy: $C^{A,V}_{ij}(\Lambda_{\mathrm{UV}}) \sim \mathcal{O}(1)$

Minimal favour violation: $C^{A,V}_{ij}(\Lambda_{\mathrm{UV}}) = 0$

Where's the Dark Matter?

[Pani, Redigolo, Schwetz & Ziegler 2209.03371]

Lepton flavour violating IR freeze-out dominates over flavour diagonal freeze-in

Flavour diagonal: $\ell\ell \to \gamma a \quad \& \quad \ell\gamma \to \ell a$

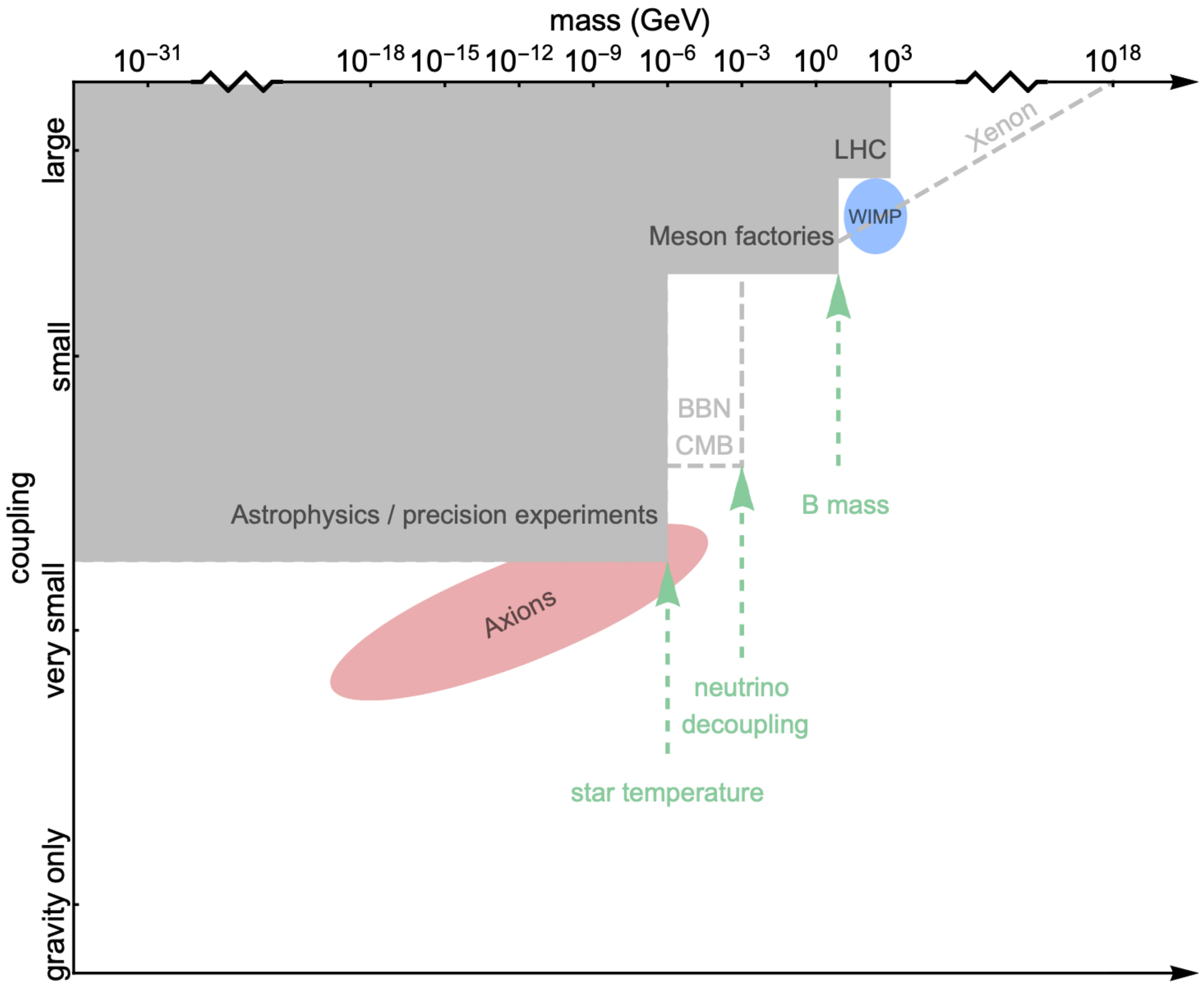
$$\Omega_a h^2|_{\text{scattering}} \approx 9 \times 10^{-4} \left(\frac{m_a}{50\text{ keV}}\right) \left(\frac{5 \times 10^9 \text{GeV}}{f_a/C_{\ell\ell}}\right)^2 \left(\frac{m_\ell}{m_\tau}\right) \left(\frac{75}{g_*(m_\ell)}\right)^{3/2}$$

Flavour violating: $\ell_i \to \ell_j a$

$$\Omega_a h^2|_{\ell_i \to \ell_j a} \approx 0.12 \left(\frac{m_a}{50\,\text{keV}}\right) \left(\frac{m_{\ell_i}}{m_\tau}\right) \left(\frac{5 \times 10^9 \text{GeV}}{f_a/C_{\ell_i\ell_j}}\right)^2 \left(\frac{75}{g_*(m_{\ell_i})}\right)^{3/2}$$

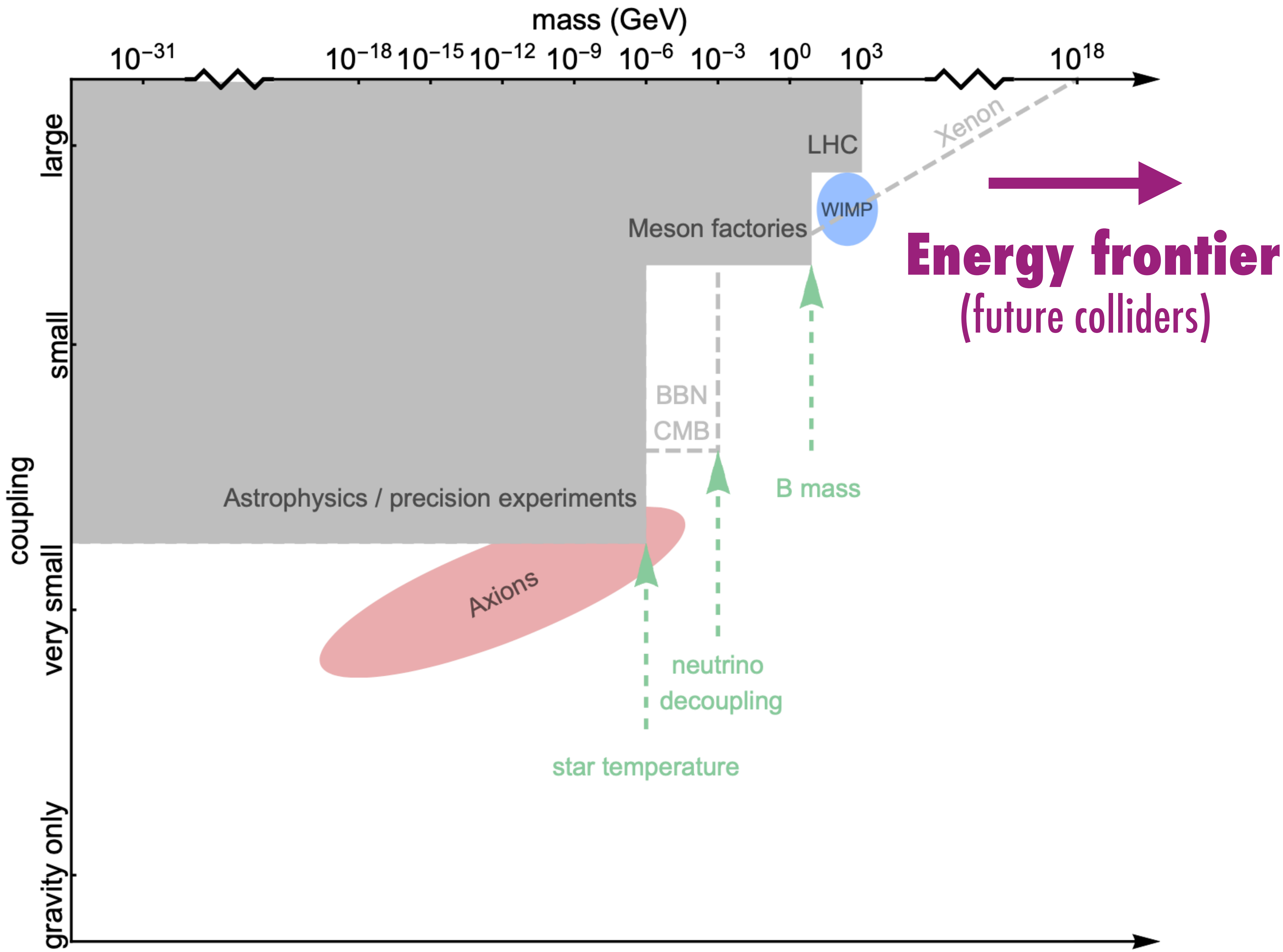
Flavour violating domination also helps suppress $a \to \gamma\gamma$ and $a \to \nu\nu$ (DM stability & indirect detection signals)

New Physics & DM



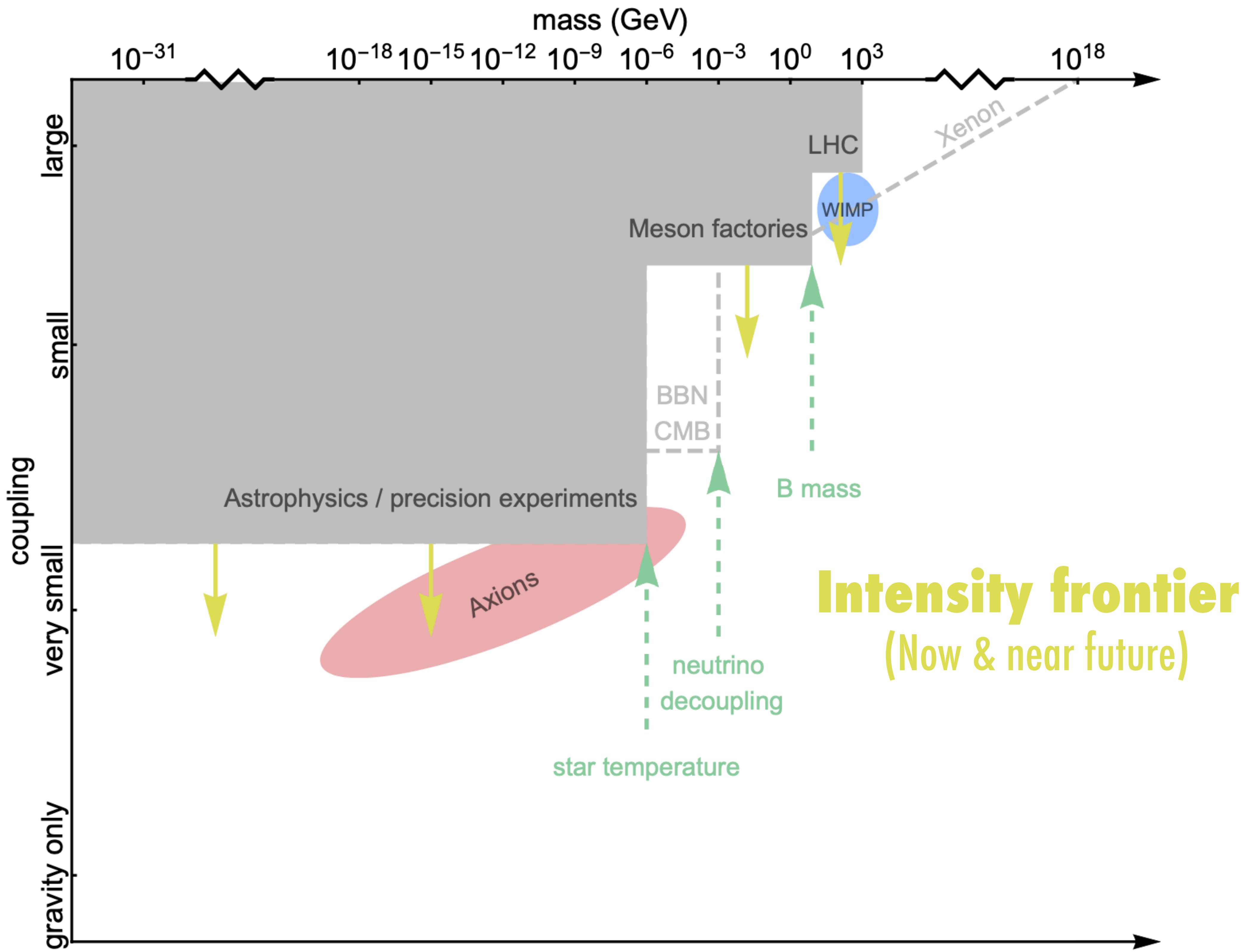
[Slide à la Simon Knapen]

New Physics & DM



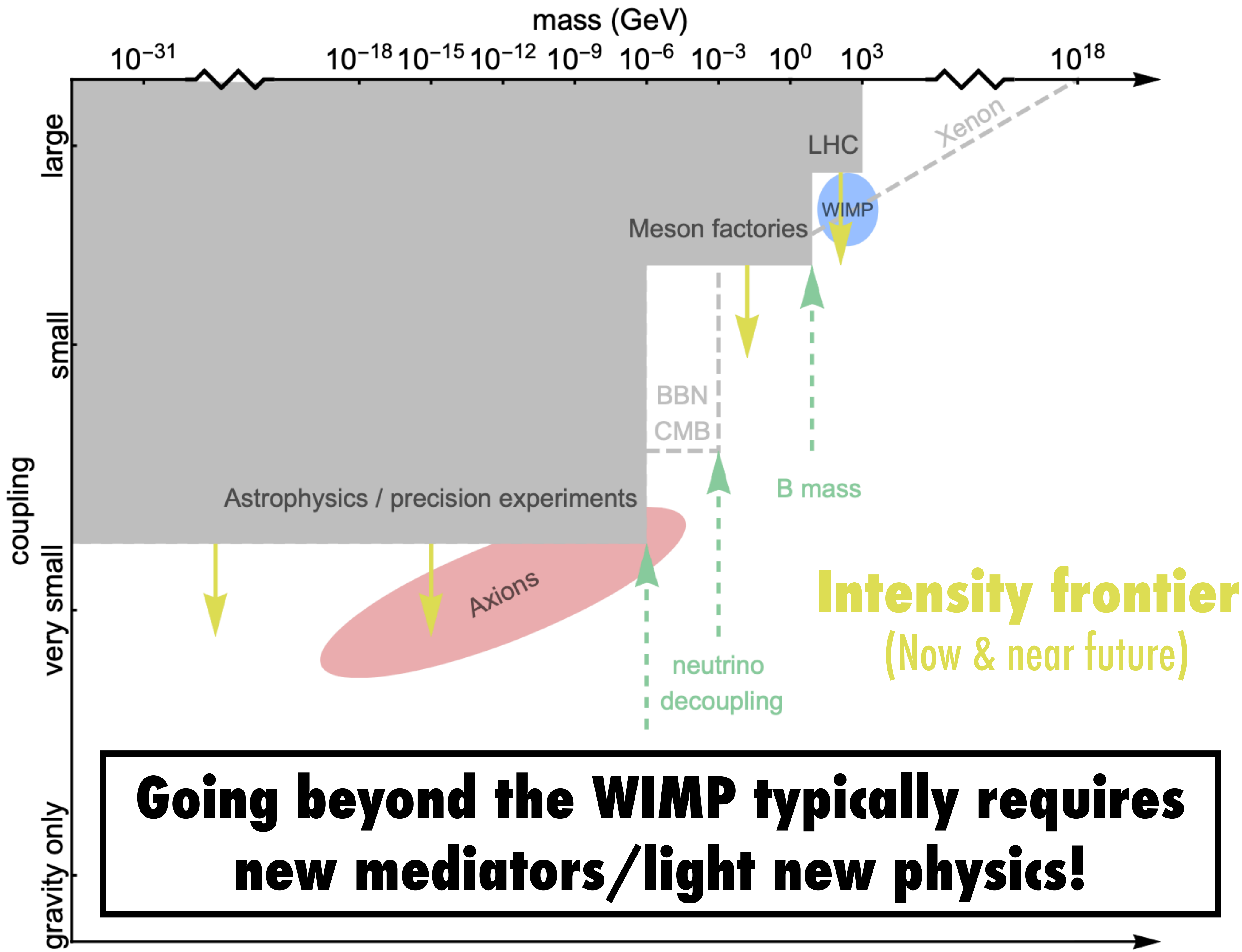
[Slide à la Simon Knapen]

New Physics & DM



[Slide à la Simon Knapen]

New Physics & DM



Going beyond the WIMP typically requires new mediators/light new physics!

[Slide à la Simon Knapen]

Why Muons?

Muons are pretty **special**:

Sensitivity to tiny couplings

$$\mathrm{BR}\left[\mu \to X\right] \sim \frac{\epsilon^2}{8\pi} \boxed{\frac{m_\mu}{\Gamma_\mu}}$$

$\mathcal{O}(10^{17})$

Two-orders of magnitude larger than next best candidate

```
muon = 3.53e+17
tau = 7.84e+11
pion = 5.52e+15
kaon_pm = 9.29e+15
K0_s = 6.77e+13
K0_l = 3.87e+16
B0 = 1.22e+13
```

Why Muons?

Muons are pretty **special**:

Sensitivity to tiny couplings

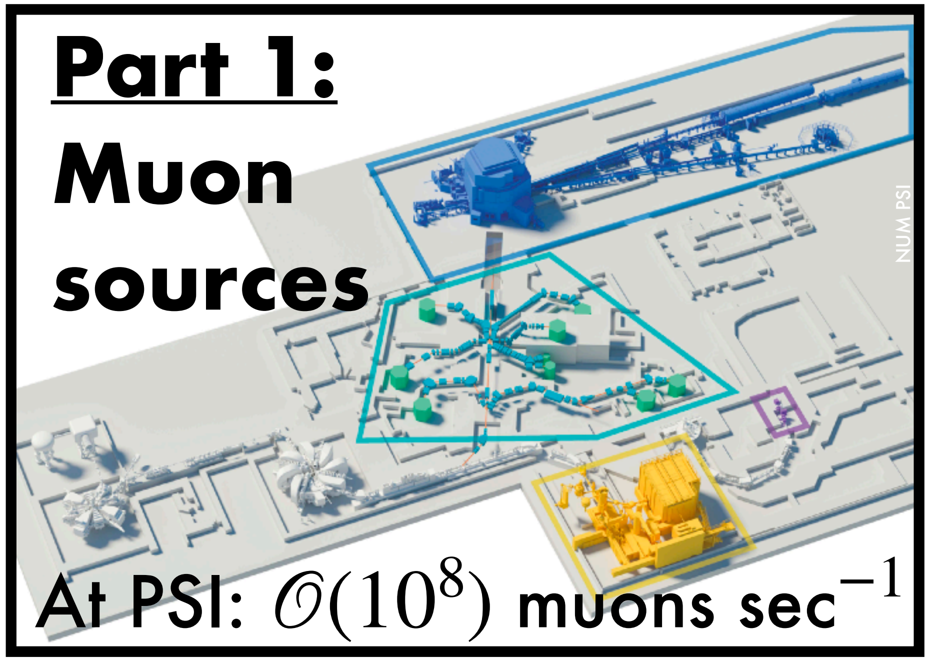
$$\mathrm{BR}\left[\mu \to X\right] \sim \frac{\epsilon^2}{8\pi} \boxed{\frac{m_\mu}{\Gamma_\mu}}$$

$\mathcal{O}(10^{17})$

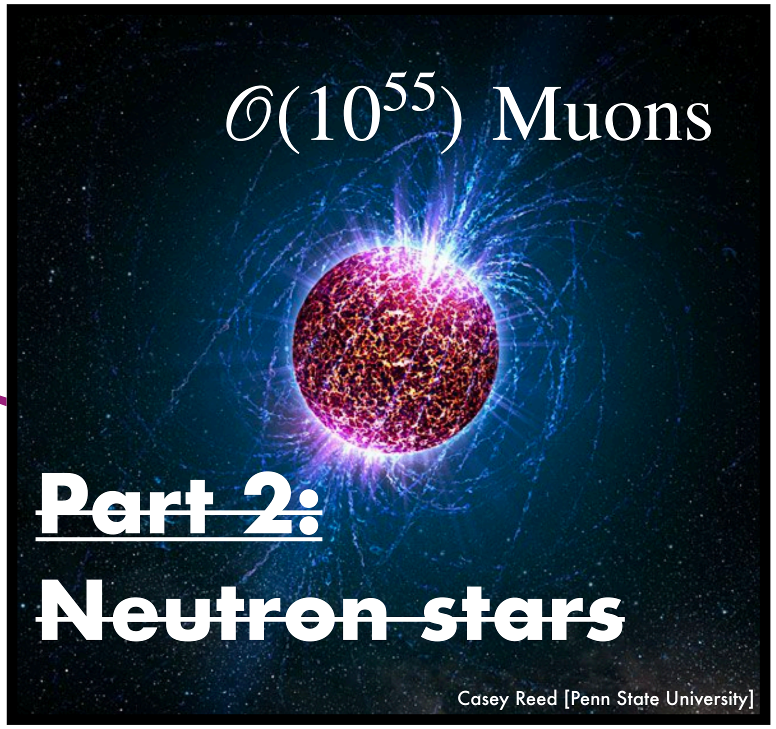
Two-orders of magnitude larger than next best candidate

```
muon = 3.53e+17
tau = 7.84e+11
pion = 5.52e+15
kaon_pm = 9.29e+15
K0_s = 6.77e+13
K0_l = 3.87e+16
B0 = 1.22e+13
```

There are **very many** of them:

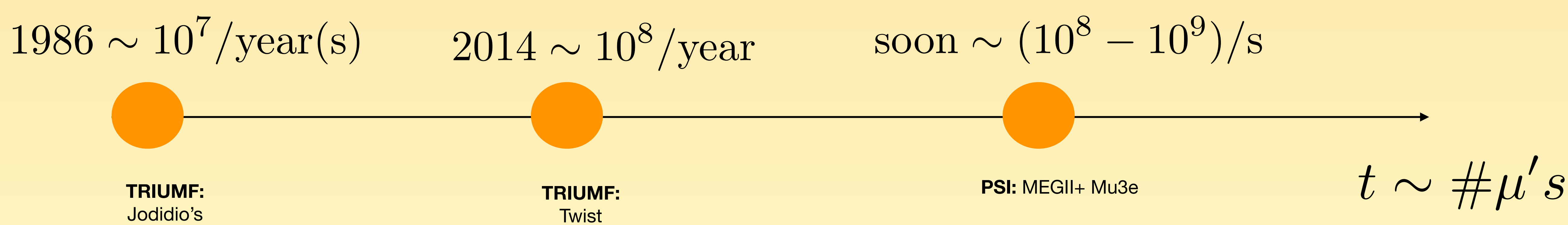


No time today: Ask me offline



Why Muons?

Goal: show how **rare decays of the muon**, usually used to search for heavy new physics, can be used to search for **light new physics**

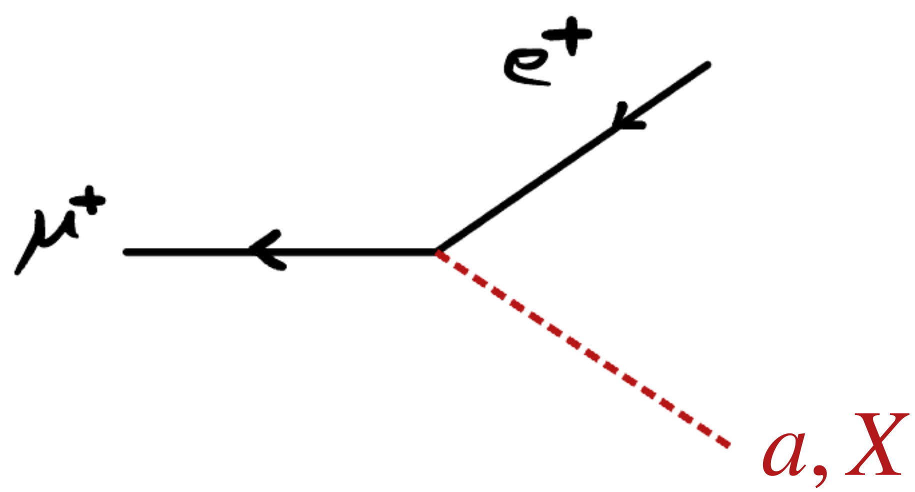


- Motivation hinges on huge amount of upcoming data
- Single purpose detectors where new detection strategies must be established as soon as possible

$\mu \to 3e$	$\mu \to e\gamma$	$(g-2)_\mu$		$\mu N \to eN$	
Mu3e	MEG-II	Muon $g-2$	Mu2e	COMET	DeeMe

What New Physics?

Lepton-flavour Violating

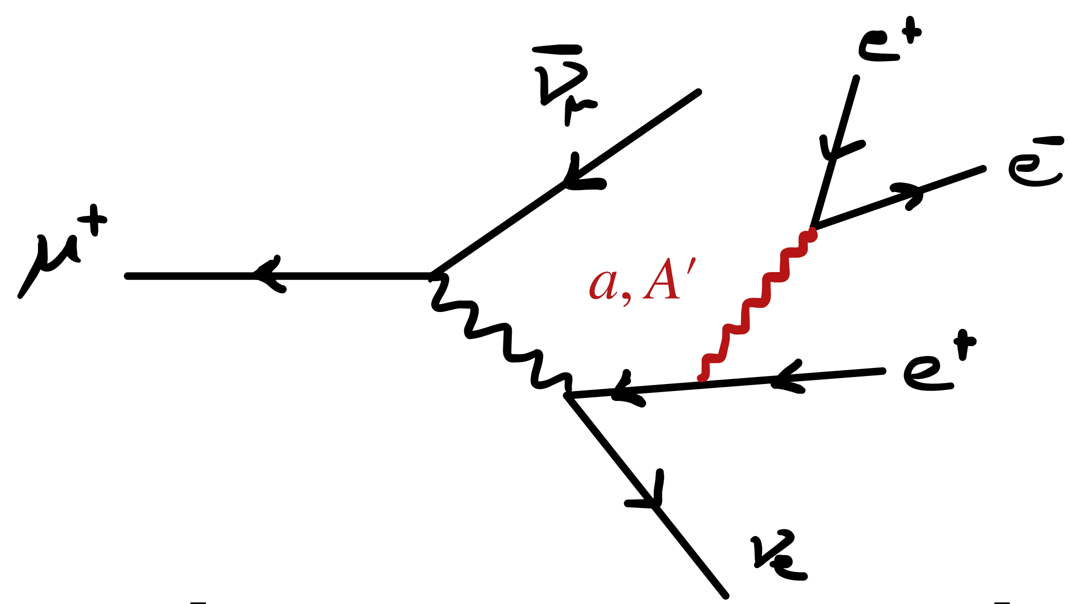


$$\mathcal{L}_{\text{FV}-\text{a}} = \frac{m_\mu}{2f_a}\frac{1}{|C_{e\mu}|}a\bar{\mu}(C^V_{e\mu} + C^A_{e\mu}\gamma_5)e$$

Bump hunt in electron momentum p_e

[Bayes et al (TWIST Collaboration) 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

Lepton-flavour Conserving



$$\mathcal{L}_0 \supset X\left[\bar{\mu}(g^\mu_S + g^\mu_P\gamma_5)\mu + \bar{e}(g^e_S + g^e_P\gamma_5)e\right]$$

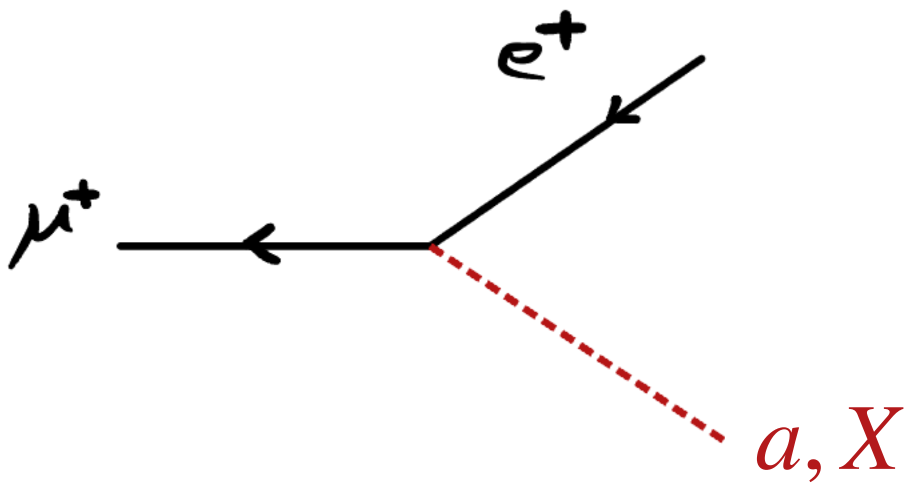
$$\mathcal{L}_1 \supset X^\alpha\left[\bar{\mu}\gamma_\alpha(g^\mu_V + g^\mu_A\gamma_5)\mu + \bar{e}\gamma_\alpha(g^e_V + g^e_A\gamma_5)e\right]$$

Bump hunt in e^+e^--pair invariant mass

[Echenard et al 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

What New Physics?

Lepton-flavour Violating

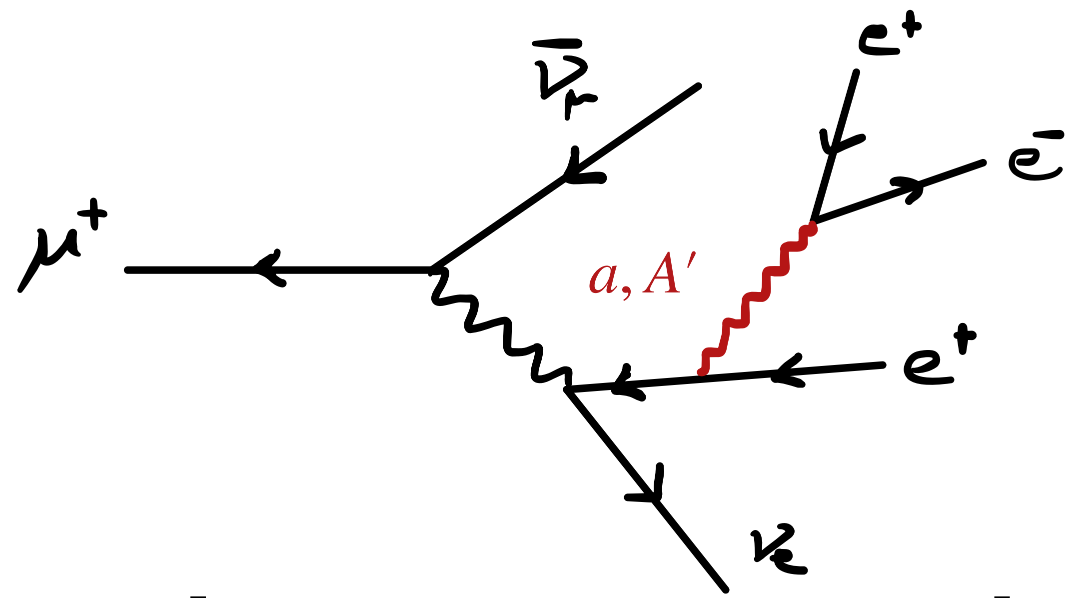


$$\mathscr{L}_{\mathrm{FV-a}} = \frac{m_\mu}{2f_a}\frac{1}{|C_{e\mu}|}a\bar{\mu}(C^V_{e\mu} + C^A_{e\mu}\gamma_5)e$$

Bump hunt in electron momentum p_e

[Bayes et al (TWIST Collaboration) 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

Lepton-flavour Conserving



$$\mathscr{L}_0 \supset X\left[\bar{\mu}(g^\mu_S + g^\mu_P\gamma_5)\mu + \bar{e}(g^e_S + g^e_P\gamma_5)e\right]$$

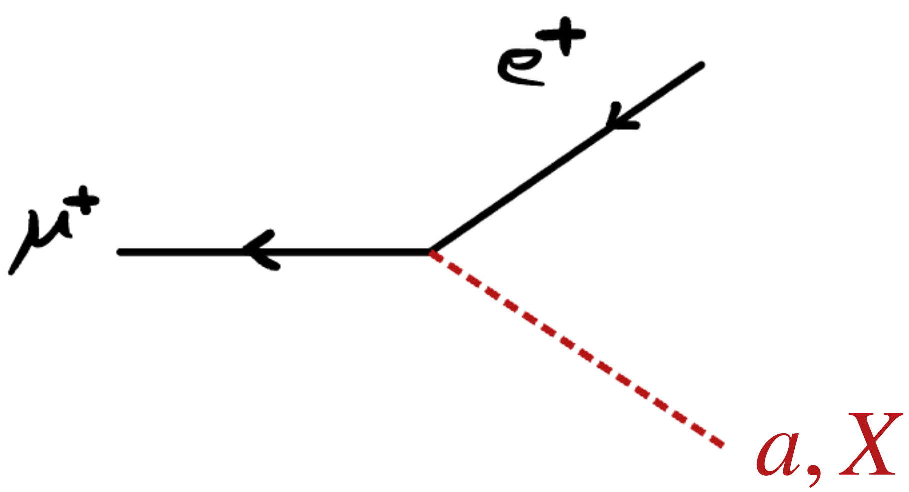
$$\mathscr{L}_1 \supset X^\alpha\left[\bar{\mu}\gamma_\alpha(g^\mu_V + g^\mu_A\gamma_5)\mu + \bar{e}\gamma_\alpha(g^e_V + g^e_A\gamma_5)e\right]$$

Bump hunt in e^+e^--pair invariant mass

[Echenard et al 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

What New Physics?

Lepton-flavour Violating



$$\mathcal{L}_{\text{FV}-\text{a}} = \frac{m_\mu}{2f_a}\frac{1}{|C_{e\mu}|}a\bar{\mu}(C^V_{e\mu} + C^A_{e\mu}\gamma_5)e$$

Bump hunt in electron momentum p_e

[Bayes et al (TWIST Collaboration) 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

For generic model: $\Gamma_{X\to e^+e^-} \approx \frac{g_e^2}{8\pi}m_X$

$$c\tau_X \approx 5\,\text{mm}\left(\frac{10^{-5}}{g_e}\right)^2\left(\frac{10\,\text{MeV}}{m_X}\right)$$

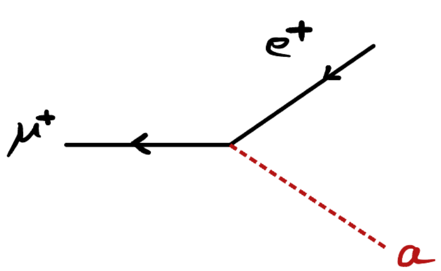
Three possibilities:

1. Long-lived — **Most relevant for DM**
2. Prompt decays
3. Displaced decays

Long-lived Scenario

ALPs long-lived escaping the detector → Rare muon decays with missing energy

1. $\mu \to ea$



TWIST
[TWIST collaboration 1409.0638]

Mu2e
[Hill, et. al 2310.00043]

Mu3e
[Perrevoort et. al (Mu3e Collaboration) 1812.00741]

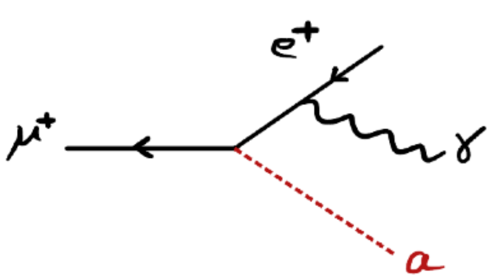
MEG-II
[Jho, et. al 2112.07720]

Ginormous irreducible background from Michel decays $\mu \to e\nu\bar{\nu}$

Muon polarisation can help discriminating signal
[see Calibbi et. al 2006.04795]

[systematics are large for left-handed couplings]

2. $\mu \to ea\gamma$

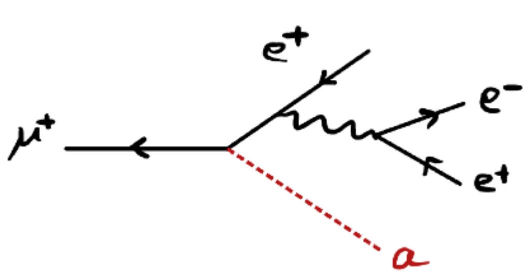


MEG-II
[Jho, et. al 2112.07720]

Require a final state photon to reconstruct missing mass distribution

[reduces signal rate but MEG-II has lower energy thresholds]

3. $\mu \to 3ea$



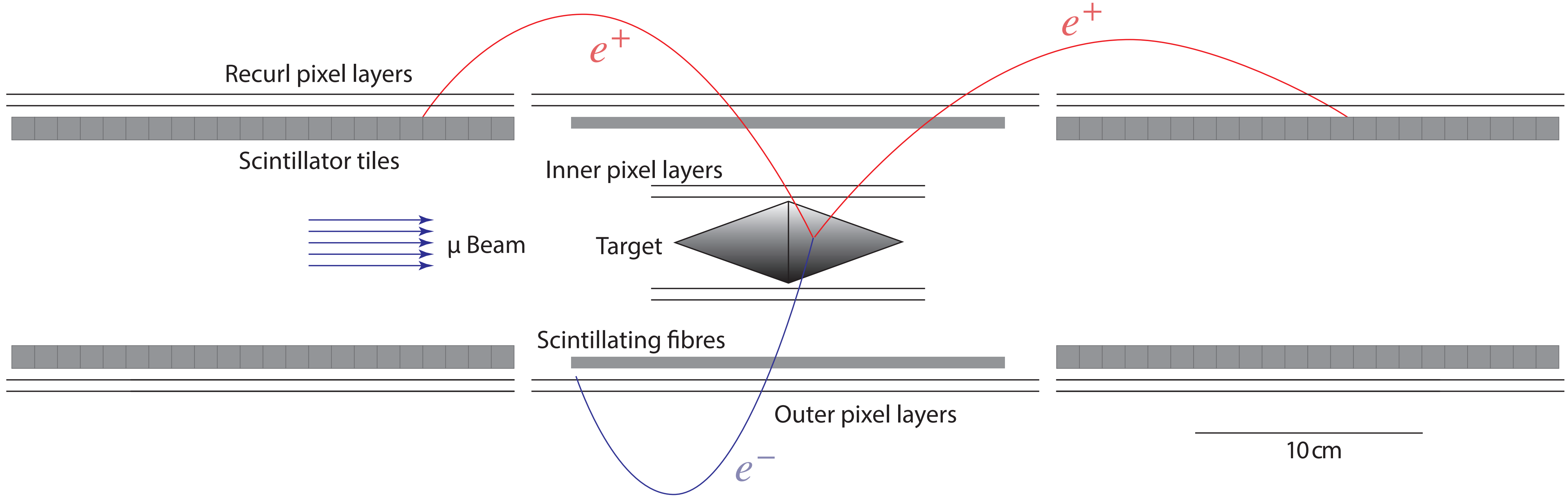
Mu3e
*[Knapen, Langhoff, **Opferkuch** & Redigolo 2311.17915]*

Require a final state photon internally converting to electron-positron pair

Mu3e Experiment

Beautiful **<u>hermetic</u>** detector:

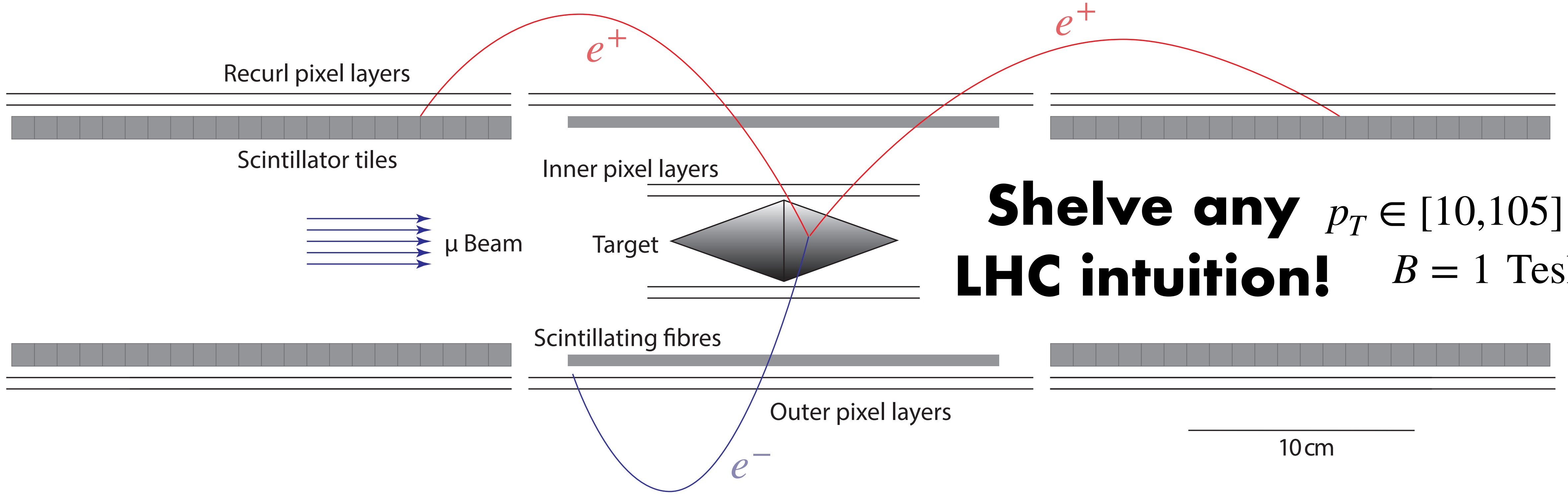
[Technical Design Report (Mu3e Collaboration) 2009.11690]



Mu3e Experiment

Beautiful **hermetic** detector:

[Technical Design Report (Mu3e Collaboration) 2009.11690]



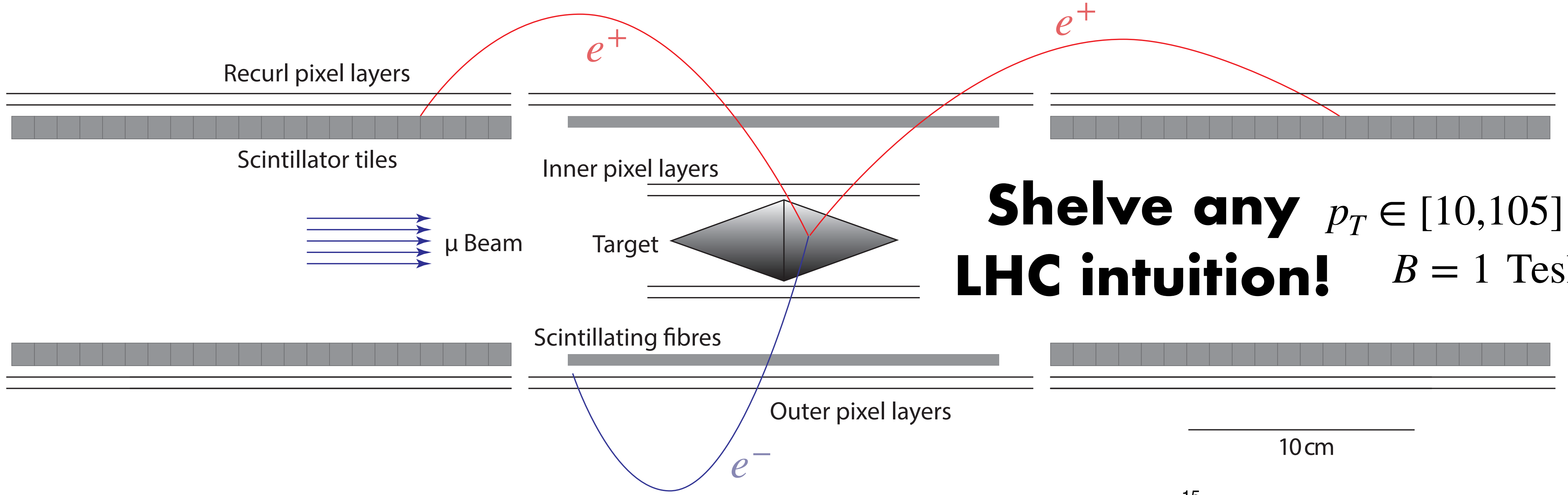
Shelve any LHC intuition!

$p_T \in [10,105]$ MeV

$B = 1$ Tesla

Mu3e Experiment

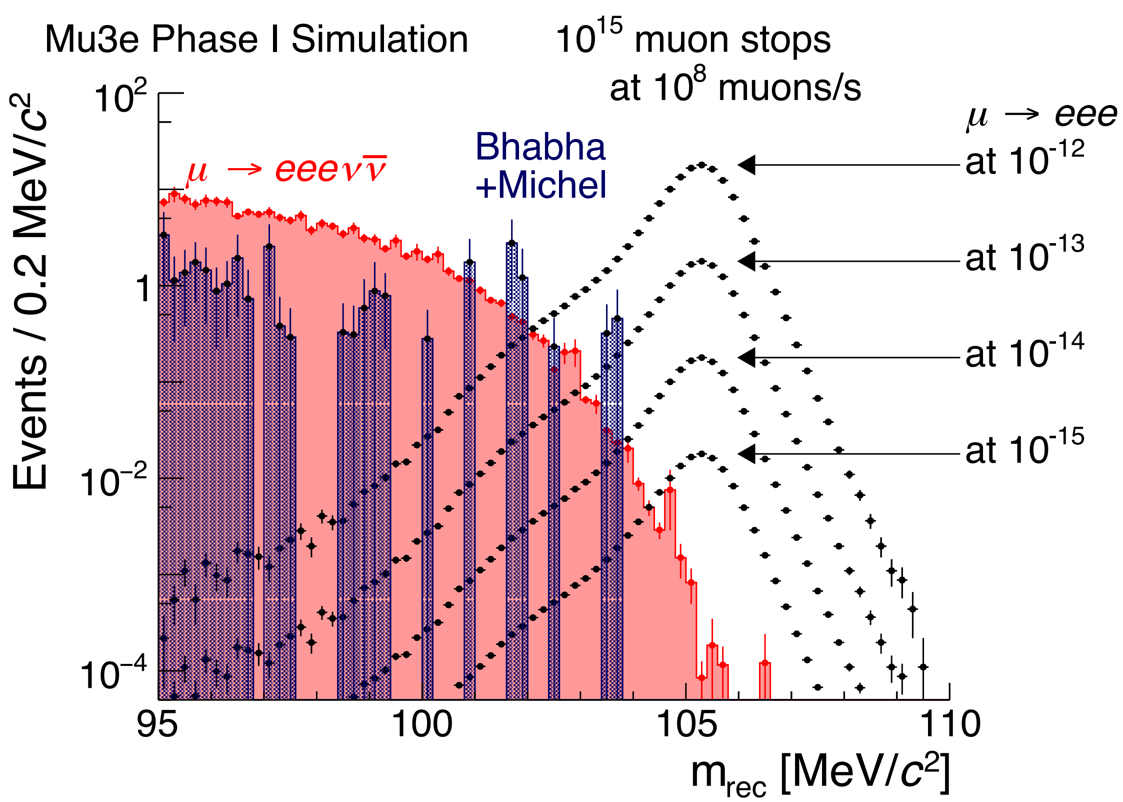
Beautiful **hermetic** detector: *[Technical Design Report (Mu3e Collaboration) 2009.11690]*



Shelve any LHC intuition! $p_T \in [10, 105]$ MeV, $B = 1$ Tesla

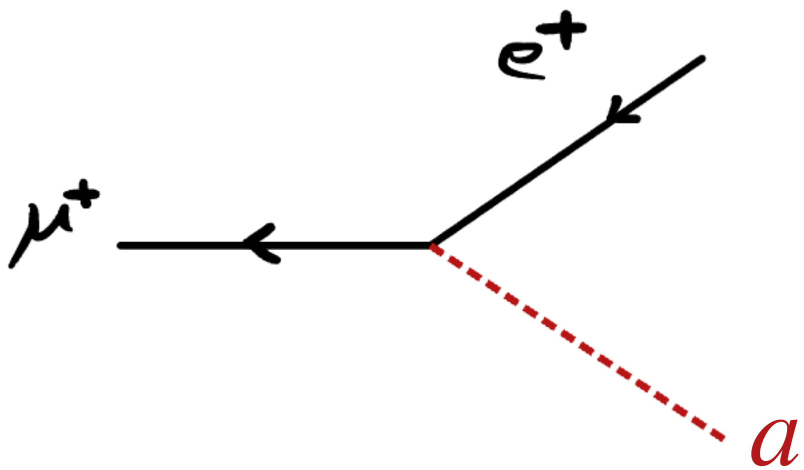
Optimised to detect three $e^\pm$ reconstructing the muon mass

But: All three-$e^\pm$ events saved to tape!



Long-lived Scenario

Lepton-flavour Violating

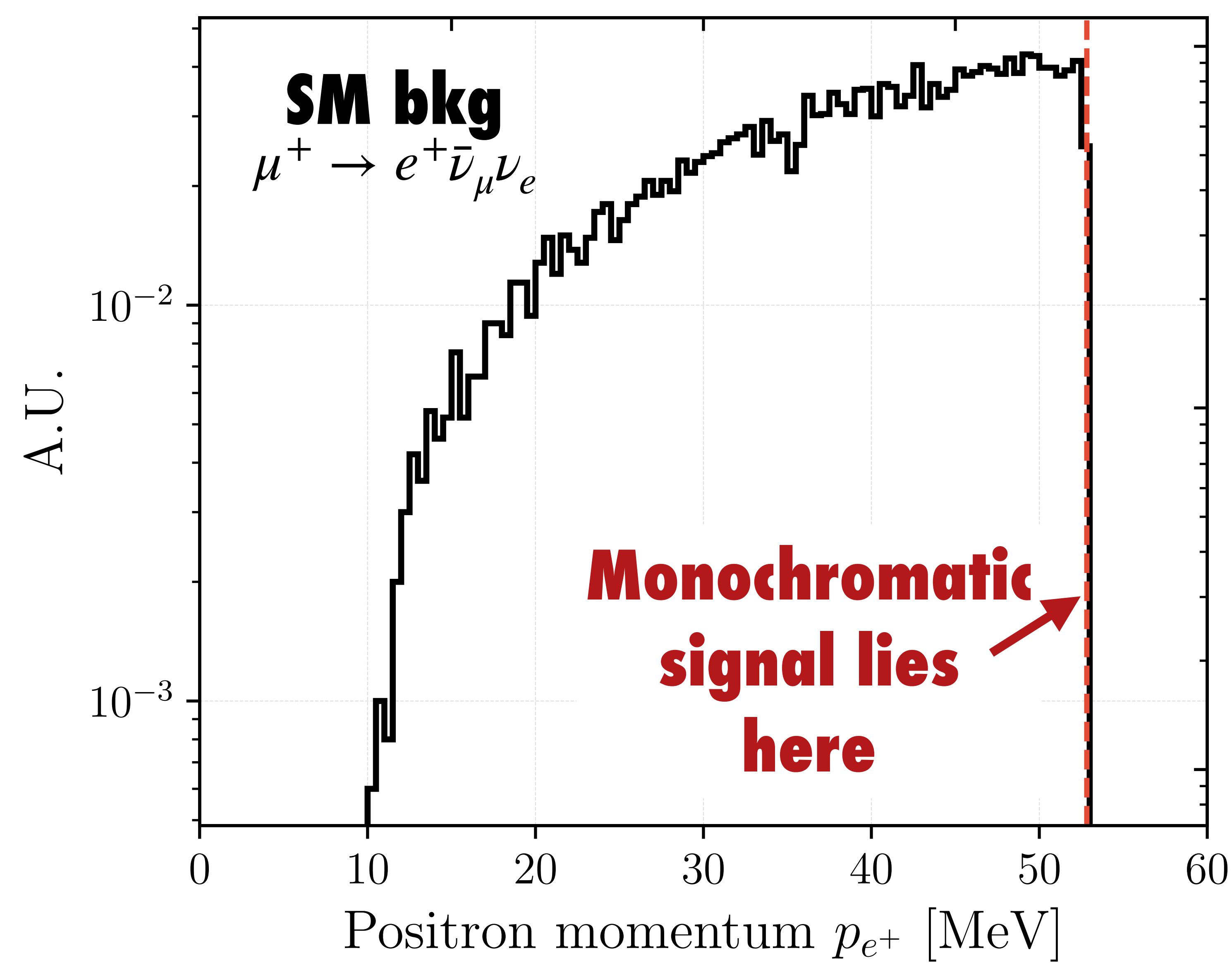


$$\mathscr{L}_{\mathrm{FV-a}} = \frac{m_\mu}{2f_a}\frac{1}{|C_{e\mu}|}a\bar{\mu}(C^V_{e\mu} + C^A_{e\mu}\gamma_5)e$$

Bump hunt in electron momentum p_e

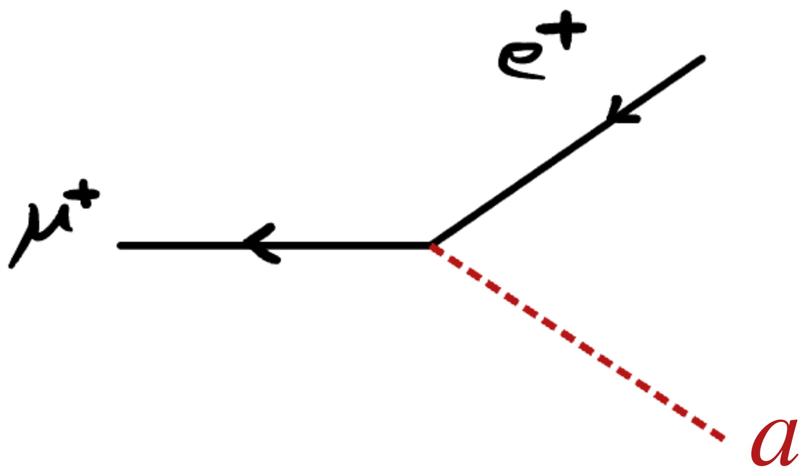
[Bayes et al (TWIST Collaboration) 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

For $m_a \lesssim 25\,\mathrm{MeV}$ calibration challenge as signal lies near the Michel edge



Long-lived Scenario

Lepton-flavour Violating

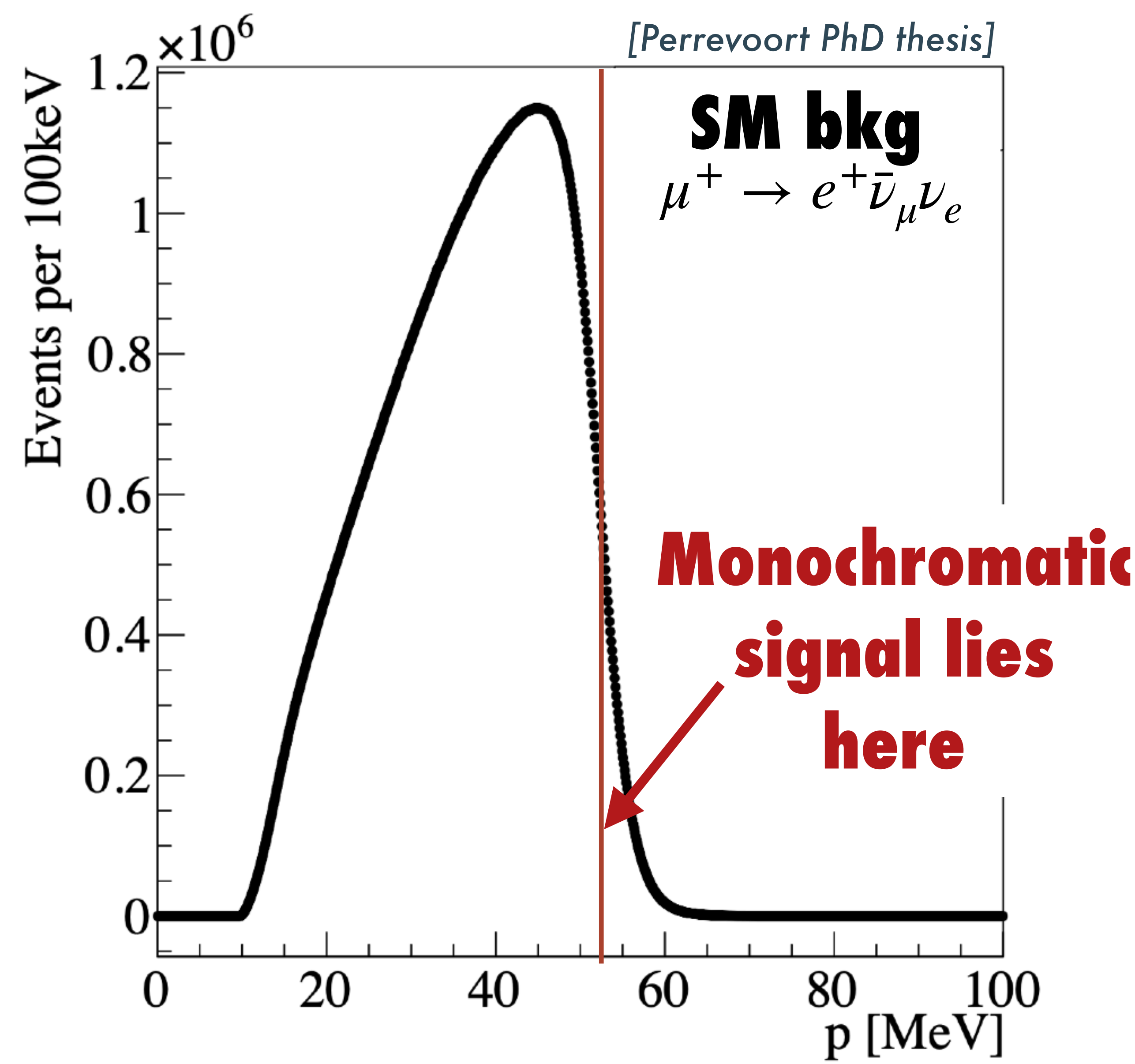


$$\mathscr{L}_{\mathrm{FV-a}} = \frac{m_\mu}{2f_a}\frac{1}{|C_{e\mu}|}a\bar{\mu}(C^V_{e\mu} + C^A_{e\mu}\gamma_5)e$$

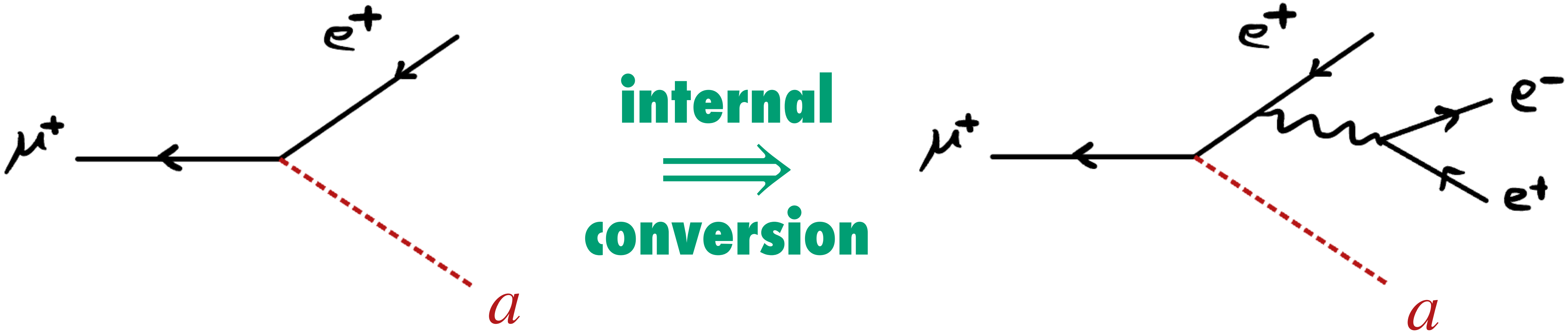
Bump hunt in electron momentum p_e

[Bayes et al (TWIST Collaboration) 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

For $m_a \lesssim 25\,\mathrm{MeV}$ calibration challenge as signal lies near the Michel edge



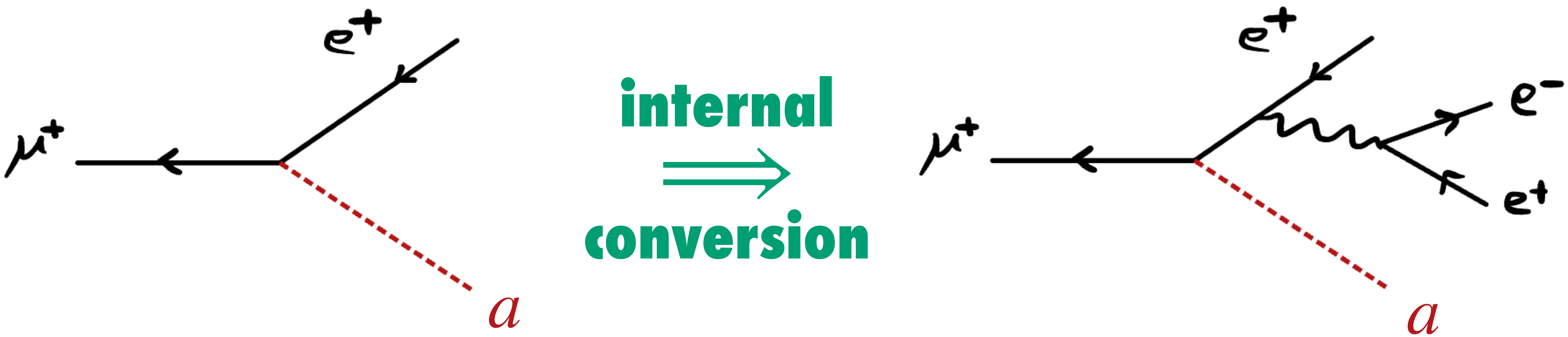
Systematics $\Longrightarrow$ Statistics



"A Robust Search for Lepton Flavour Violating Axions at Mu3e"

*[Knapen, Langhoff, **Opferkuch** & Redigolo 2311.17915]*

Systematics $\Longrightarrow$ Statistics

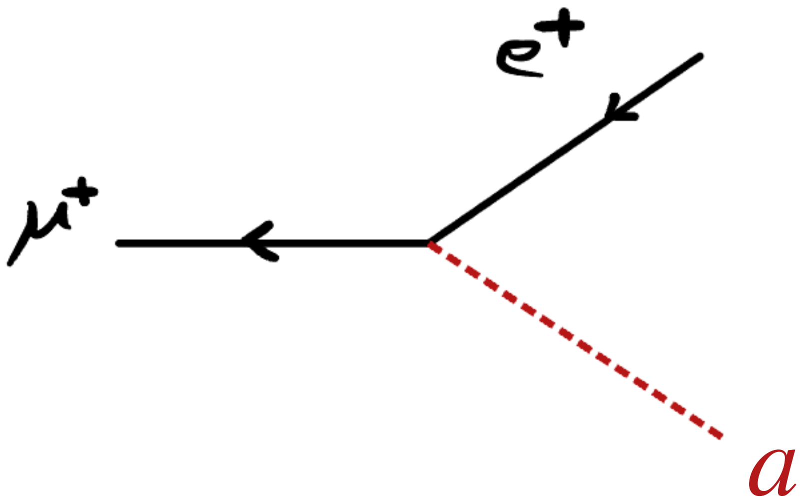


"A Robust Search for Lepton Flavour Violating Axions at Mu3e"
*[Knapen, Langhoff, **Opferkuch** & Redigolo 2311.17915]*

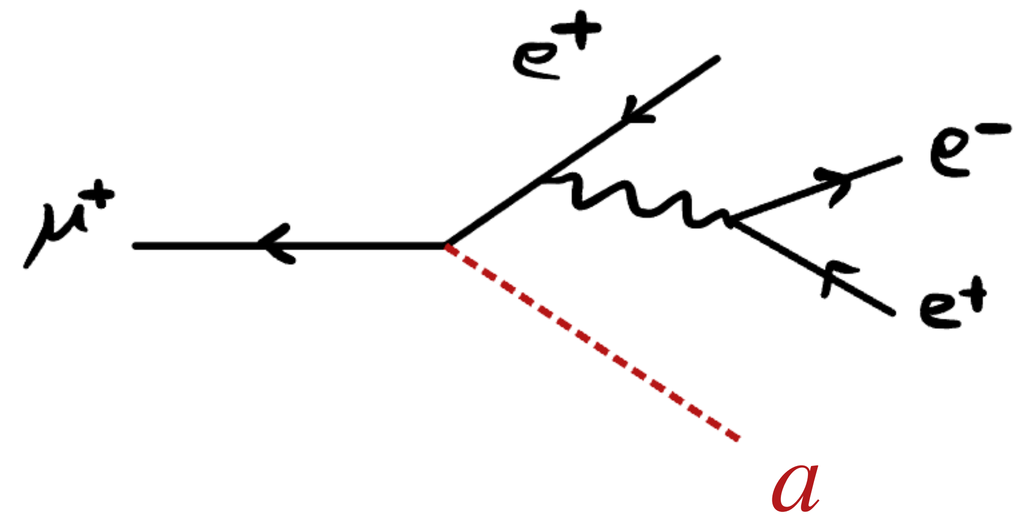
The price to pay:

- Extra factor α^2
- Phase-space suppression
- Additional detector acceptance suppression
  $p_{e^\pm} \geq 10\ \mathrm{MeV}$

Systematics $\Longrightarrow$ Statistics



internal
$\Longrightarrow$
conversion



"A Robust Search for Lepton Flavour Violating Axions at Mu3e"
[Knapen, Langhoff, Opferkuch & Redigolo 2311.17915]

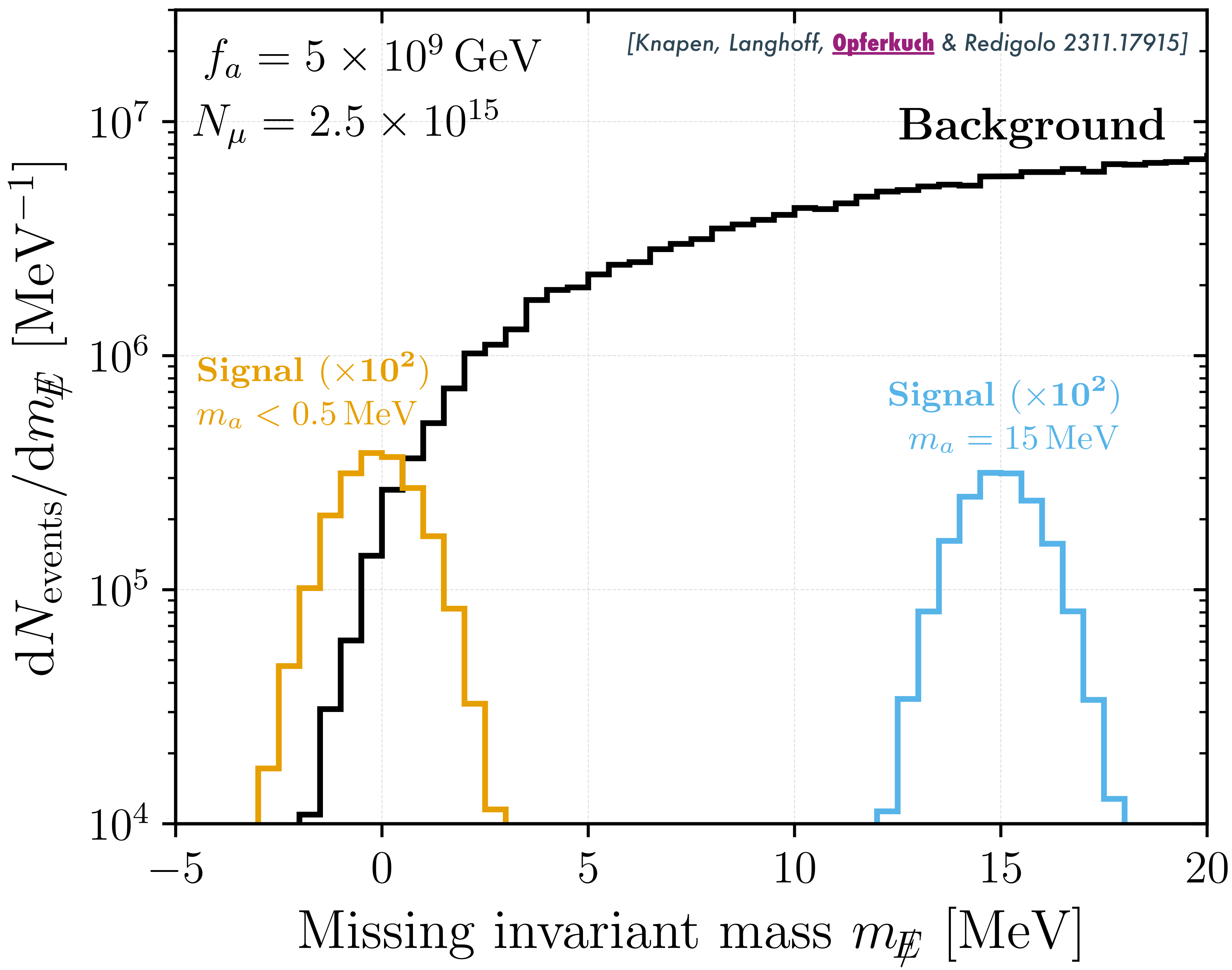
The price to pay:

- Extra factor α^2
- Phase-space suppression
- Additional detector acceptance suppression $p_{e^\pm} \geq 10 \text{ MeV}$

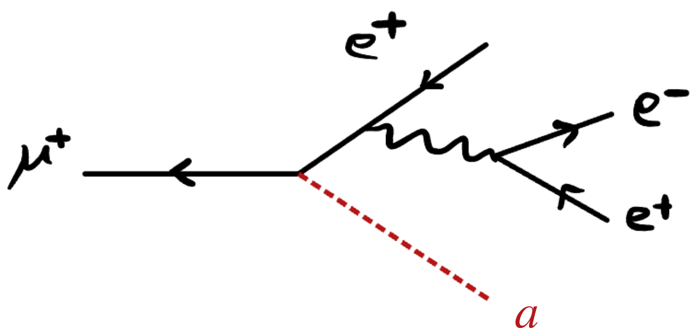
1. $e^\pm$ momenta now lie away from Michel calibration edge!

2. Analysis can be done offline leading to improved event reconstruction

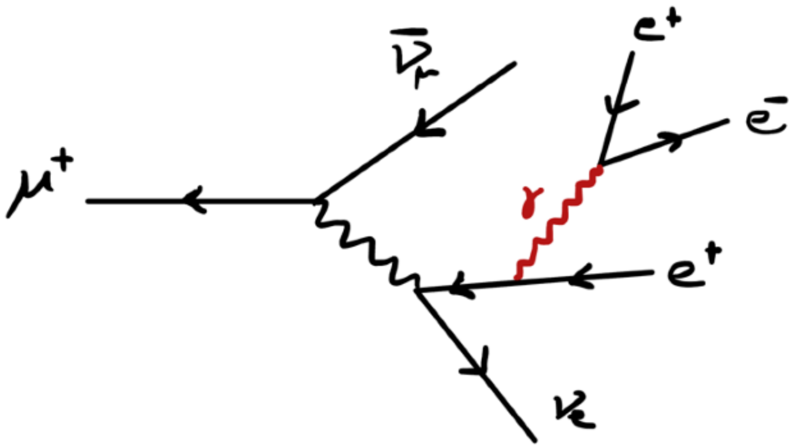
Search Strategy



Signal:



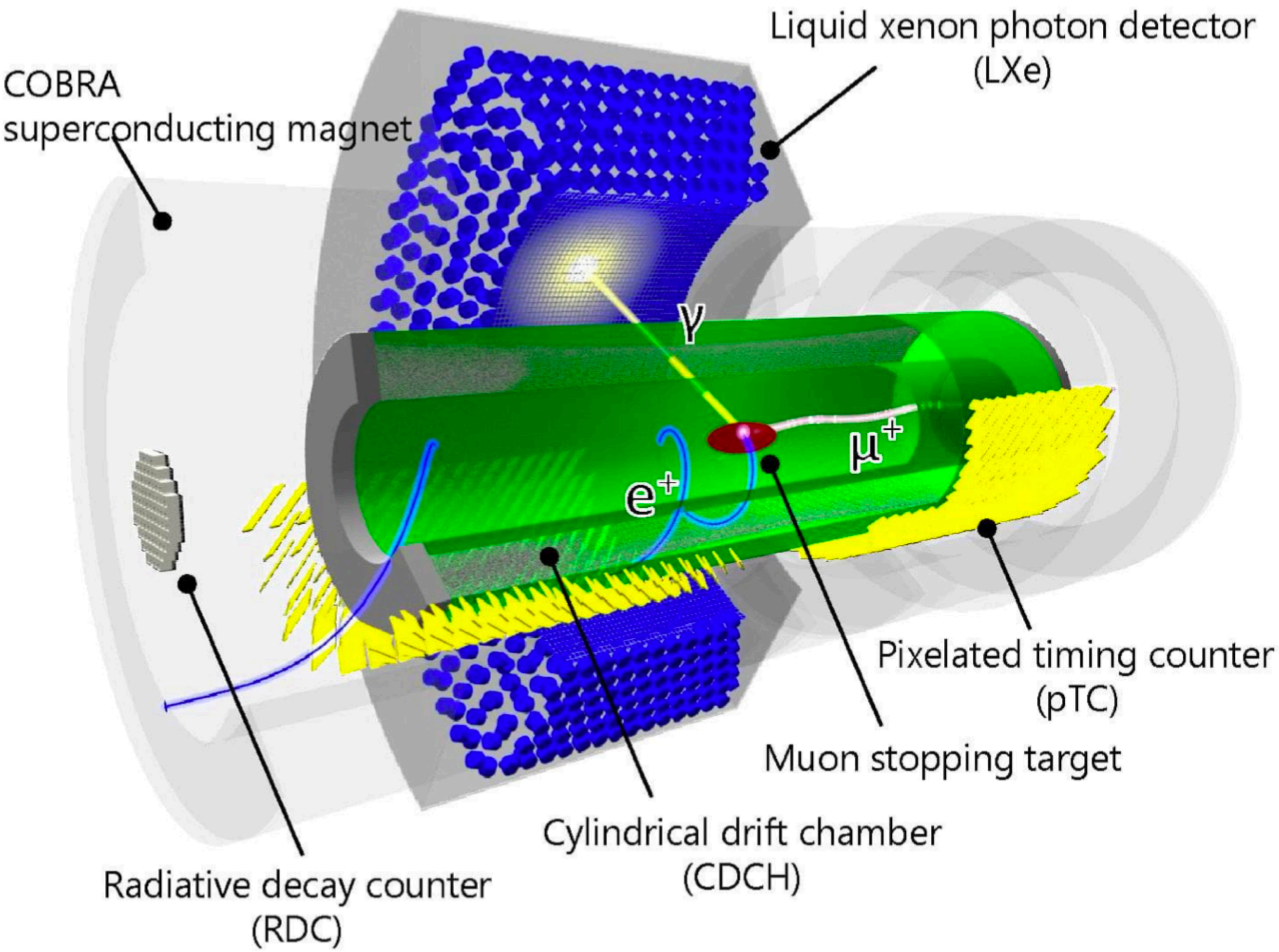
Background:



Small missing mass requires collinear neutrinos

MEG-II Experiment

Not a **hermetic** detector:



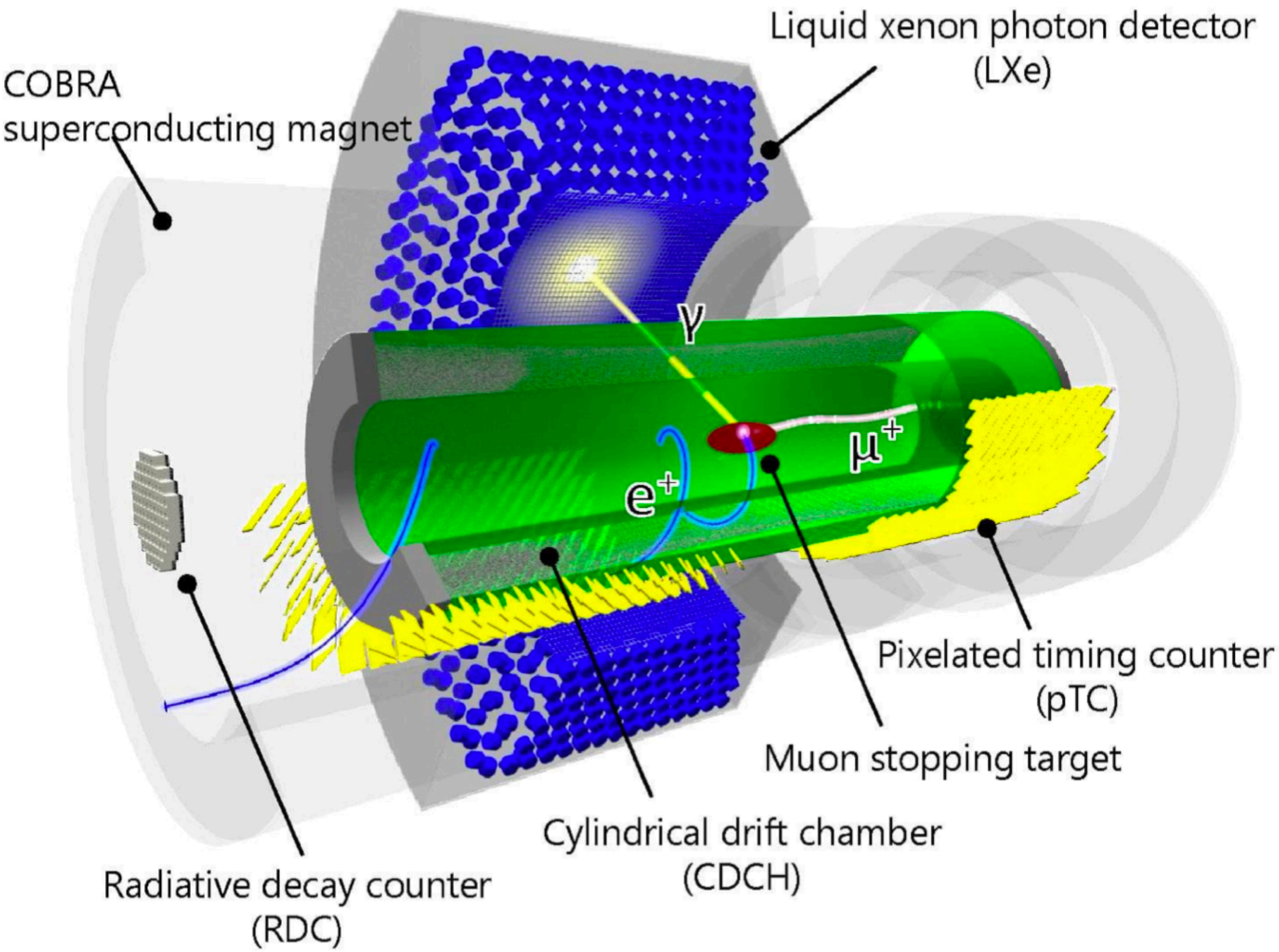
Detector geometry and trigger assume:

- e^+ and γ back-to-back
- $E_{e^+} \simeq m_\mu/2$

e.g. B-field is non-uniform designed to sweep soft e^+ away from tracker

MEG-II Experiment

Not a **hermetic** detector:



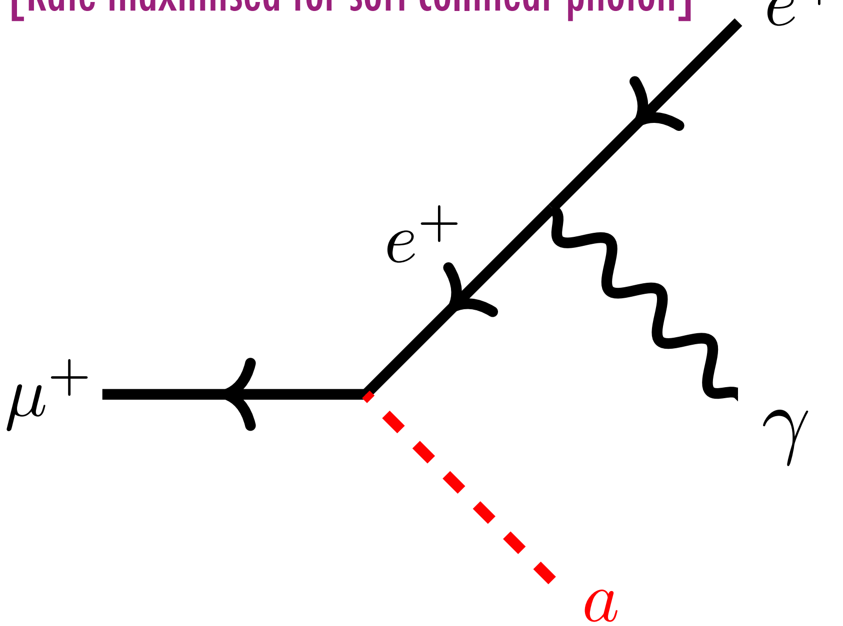
Detector geometry and trigger assume:

- e^+ and γ back-to-back
- $E_{e^+} \simeq m_\mu/2$

e.g. B-field is non-uniform designed to sweep soft e⁺ away from tracker

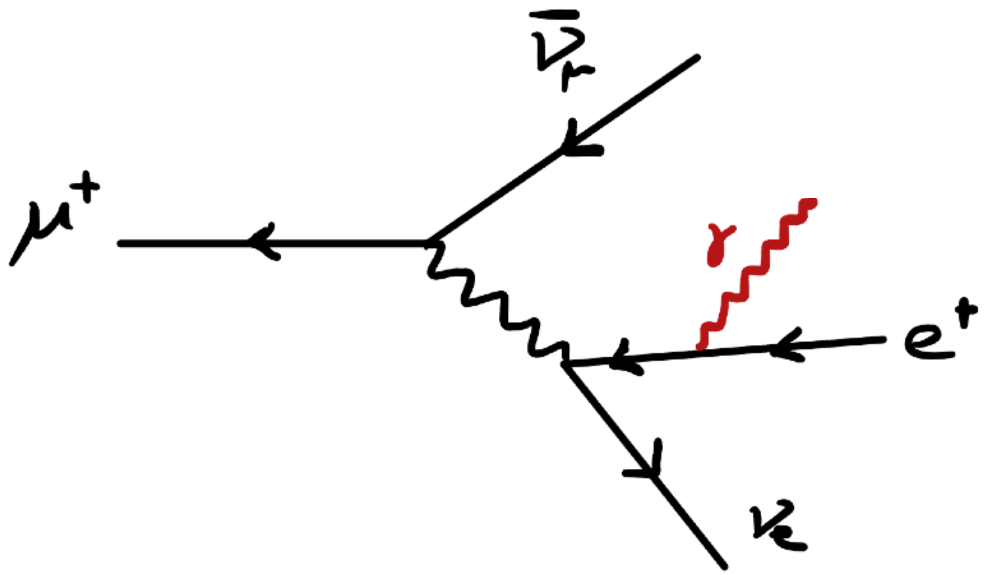
ALP Signal

[Rate maximised for soft collinear photon]



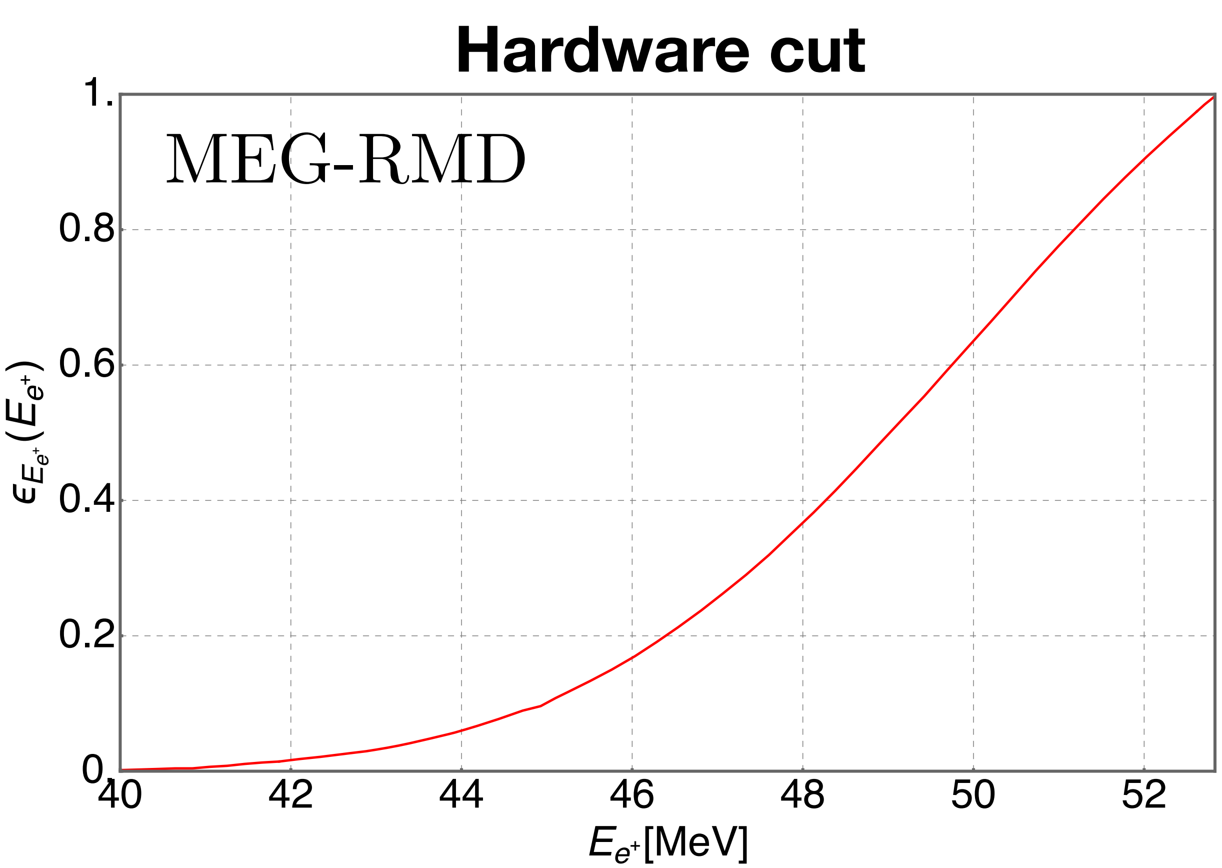
MEG Triggers

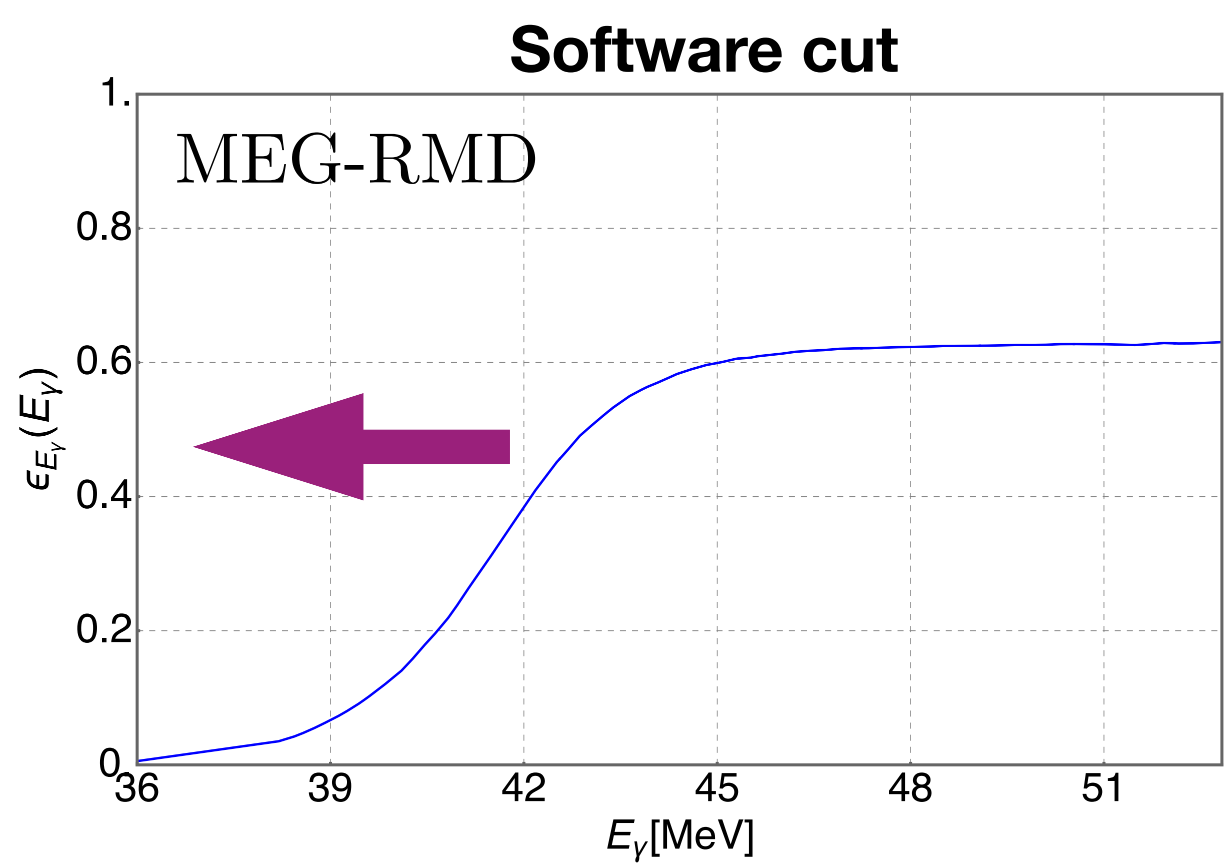
Extremely oversimplified



Triggers from radiative muon decay search (RMD) [MEG Collaboration 1312.3217]

1. Remove back-to-back requirement
2. Reduce $E_\gamma^{\rm cut}$ by lowering beam intensity

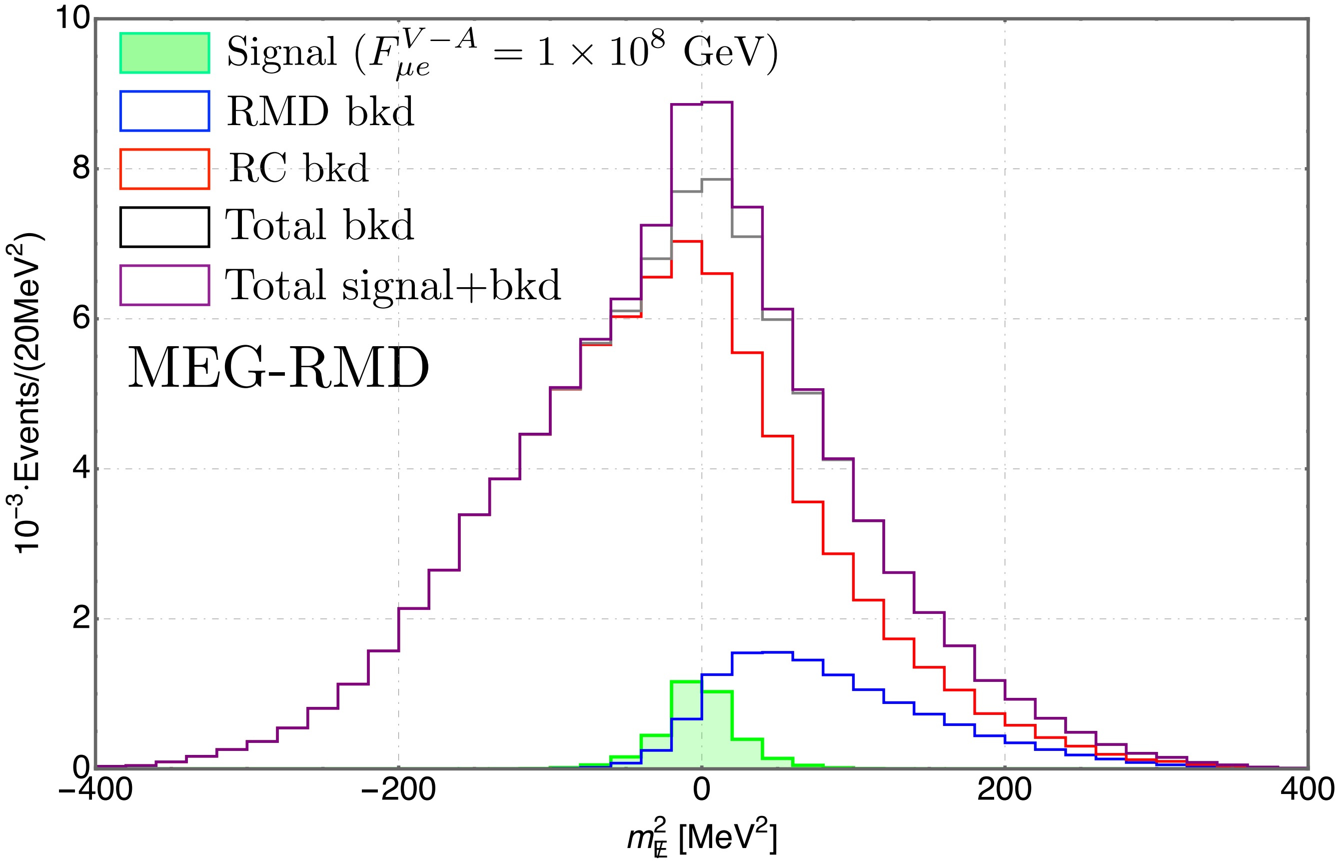




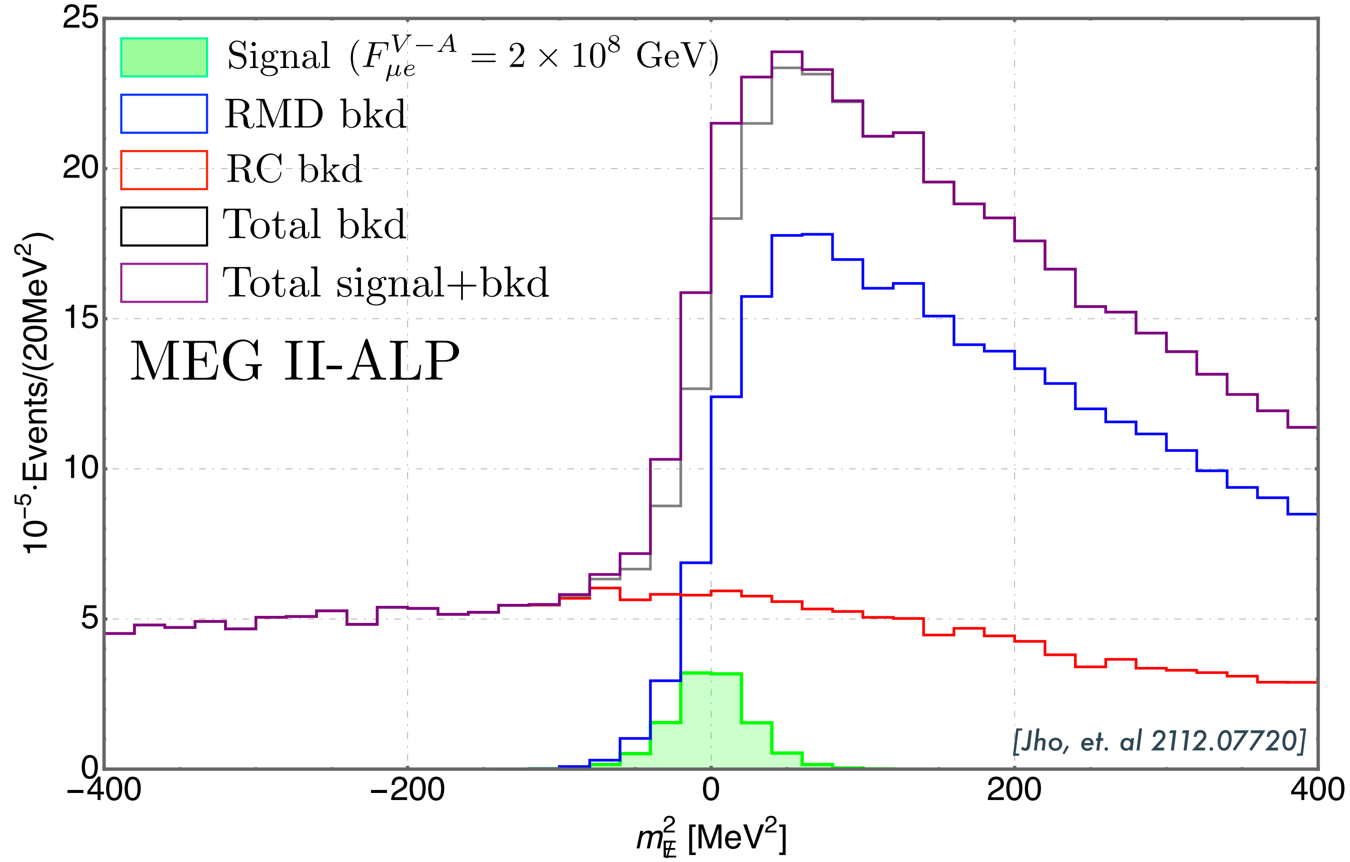
Missing Mass at MEG-II

Can reconstruct the missing invariant mass from the $e + \gamma$

Parasitic on normal MEG II run



Dedicated low intensity run



A low intensity run (1/50 of normal) is better because:

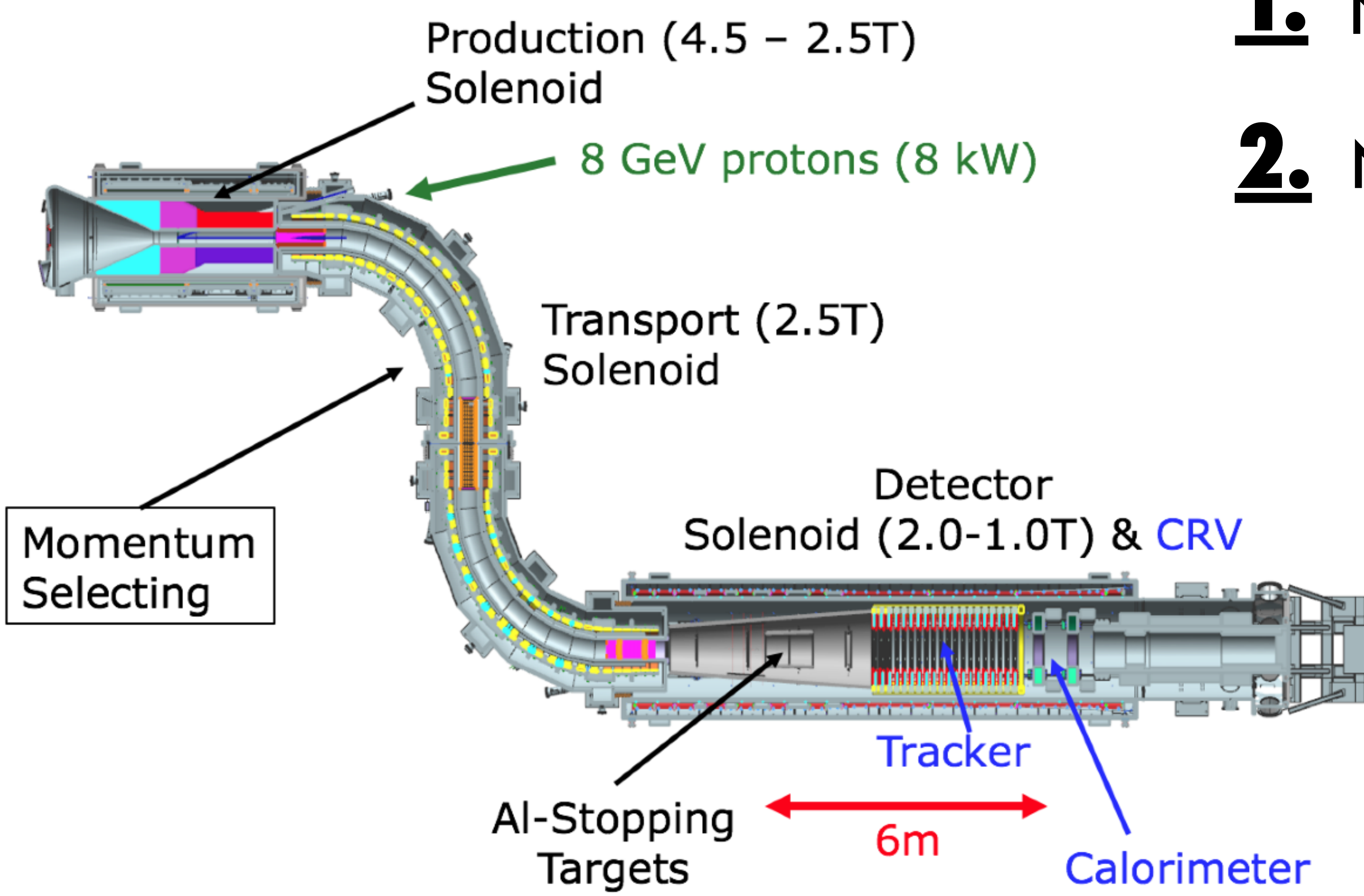
- Allows for looser cut on photon energy
- Reduced background from coinciding decays

RMD $\propto R_{\mu^+}$

RC $\propto R_{\mu^+}^2$

LFV ALPs at Mu2e

Beyond the flagship search:



What's required for $\mu \to ea$?

[Hill, Plestid & Zupan 2310.00043]

1. Need μ^+ and π^+ (modify transport solenoid)

2. Need reduced intensity proton beam

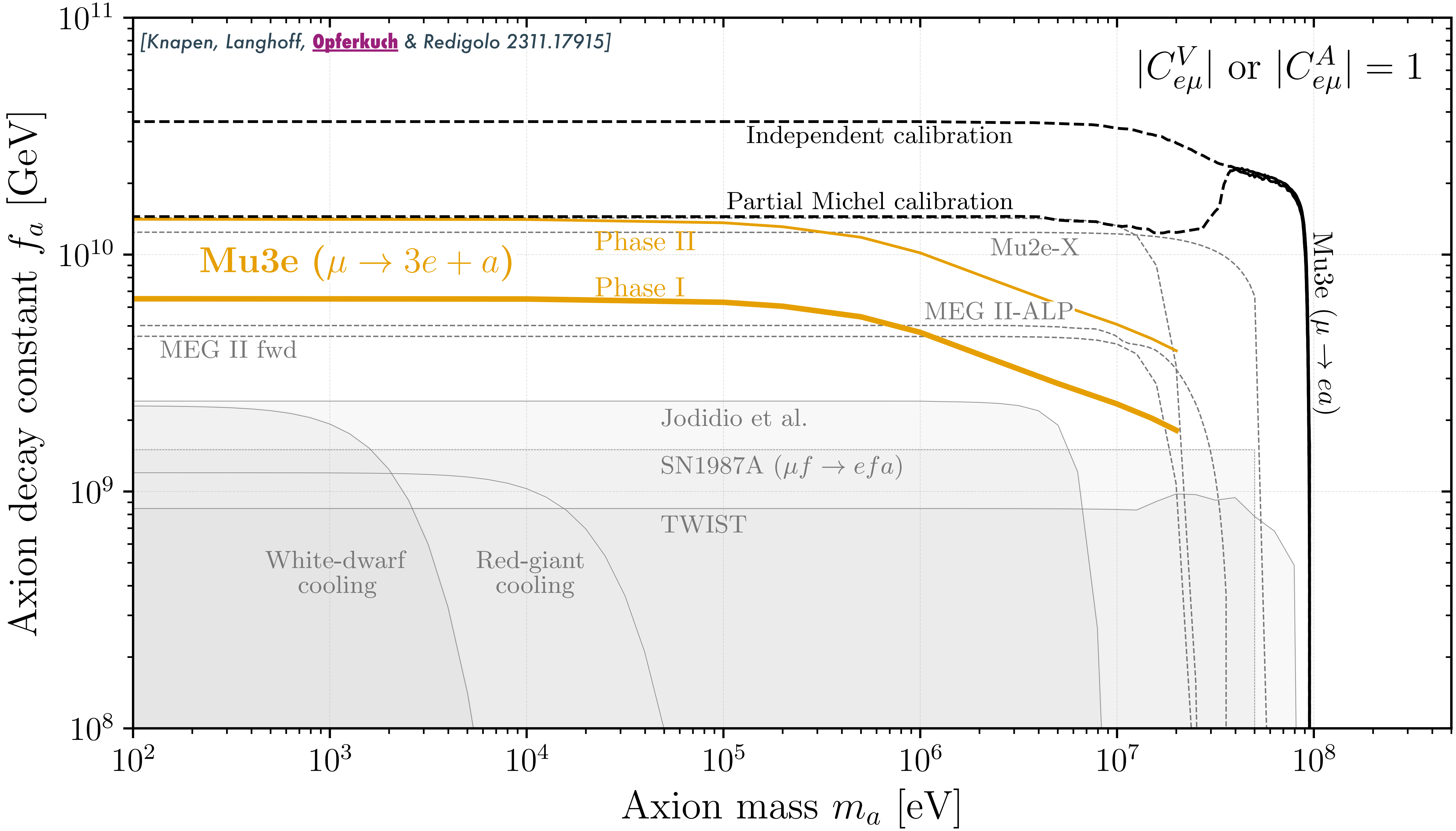
Michel background overwhelms detector

Degraded energy resolution

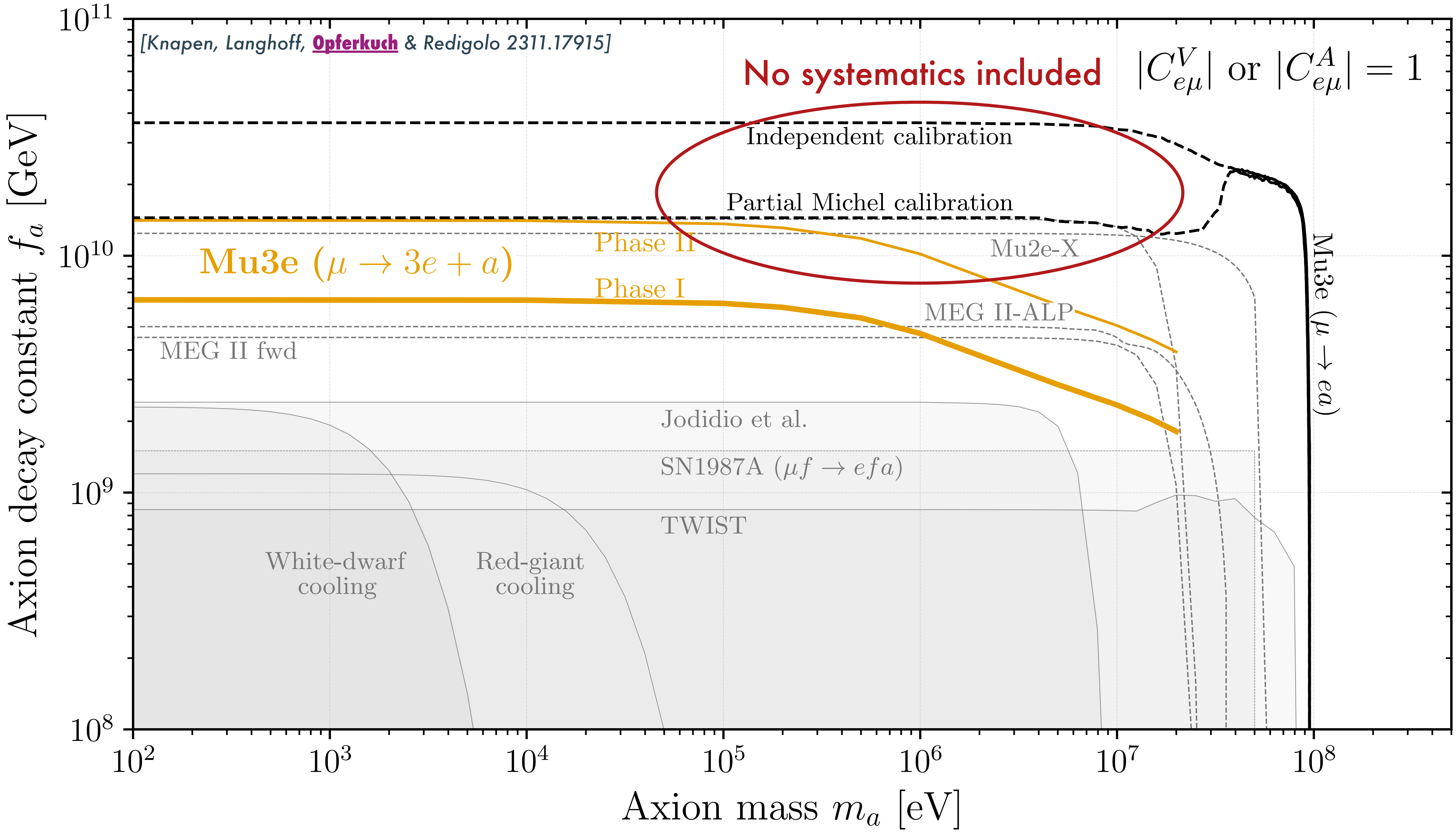
But for $m_a \lesssim 20\,\mathrm{MeV}$ calibration challenge as for Mu3e

Can a similar approach to **Mu3e** be implemented?

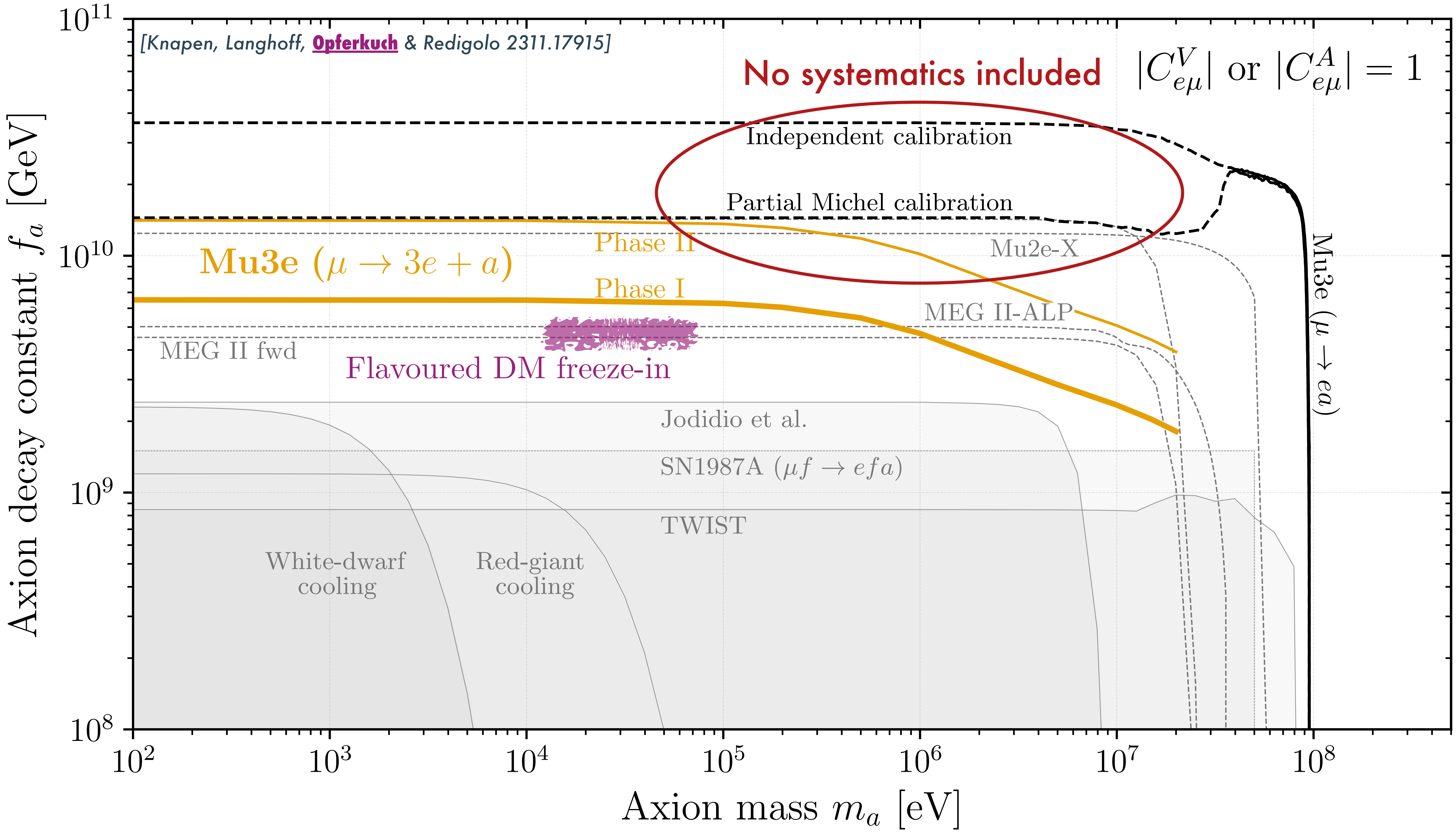
Final Reach Long-lived ALP



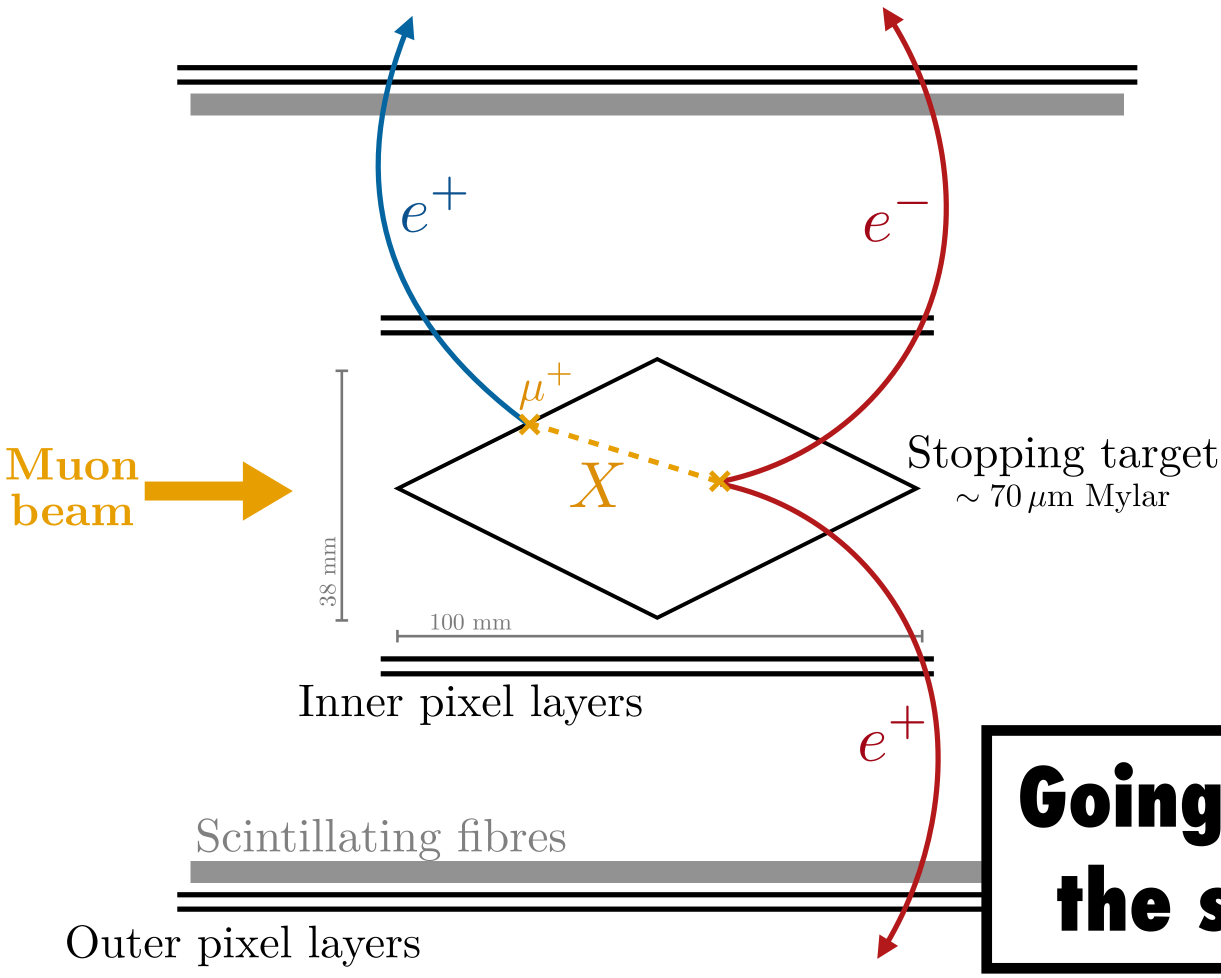
Final Reach Long-lived ALP



Final Reach Long-lived ALP

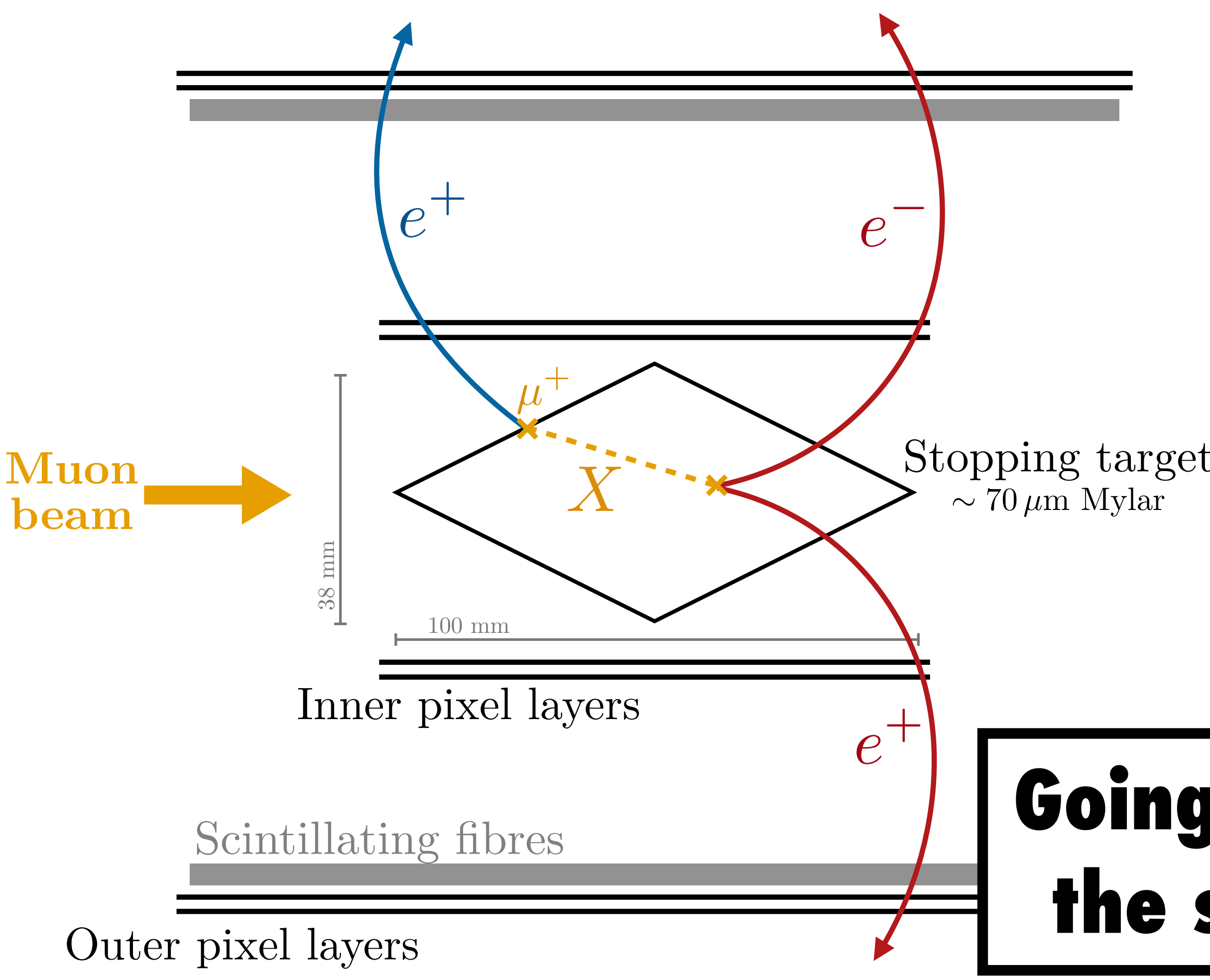


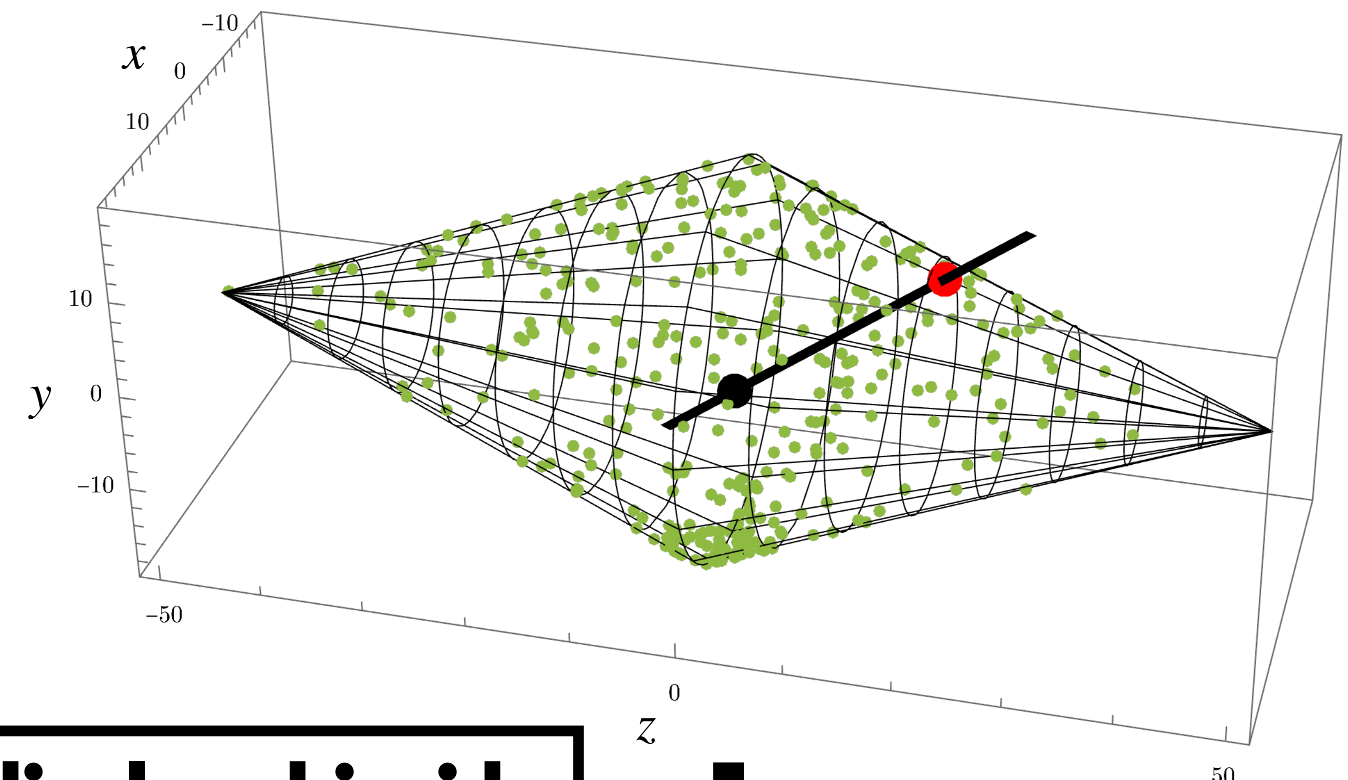
Going Displaced at Mu3e



Going displaced inside the stopping target!

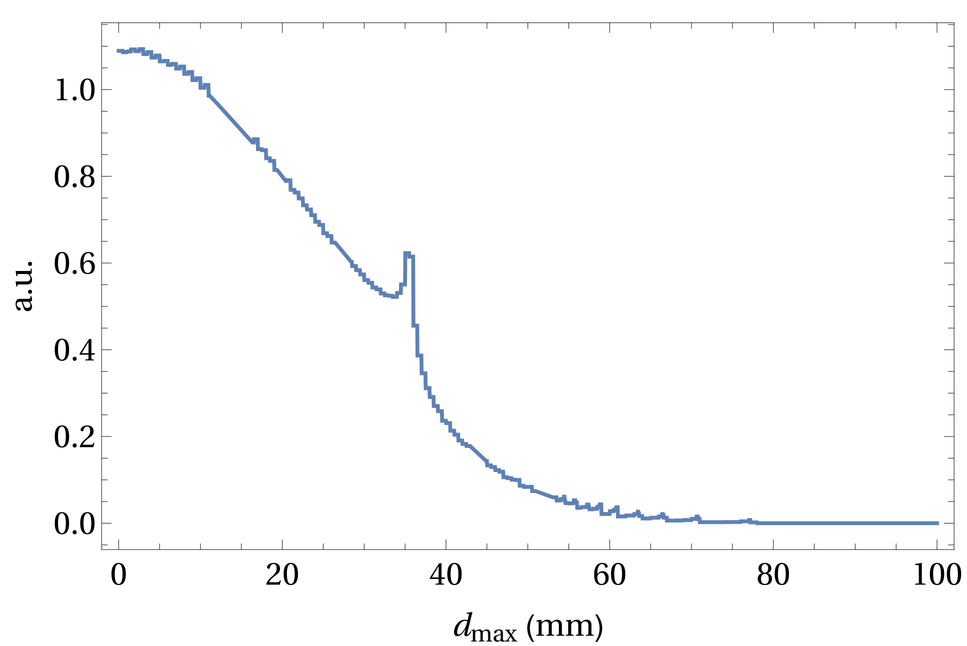
Going Displaced at Mu3e



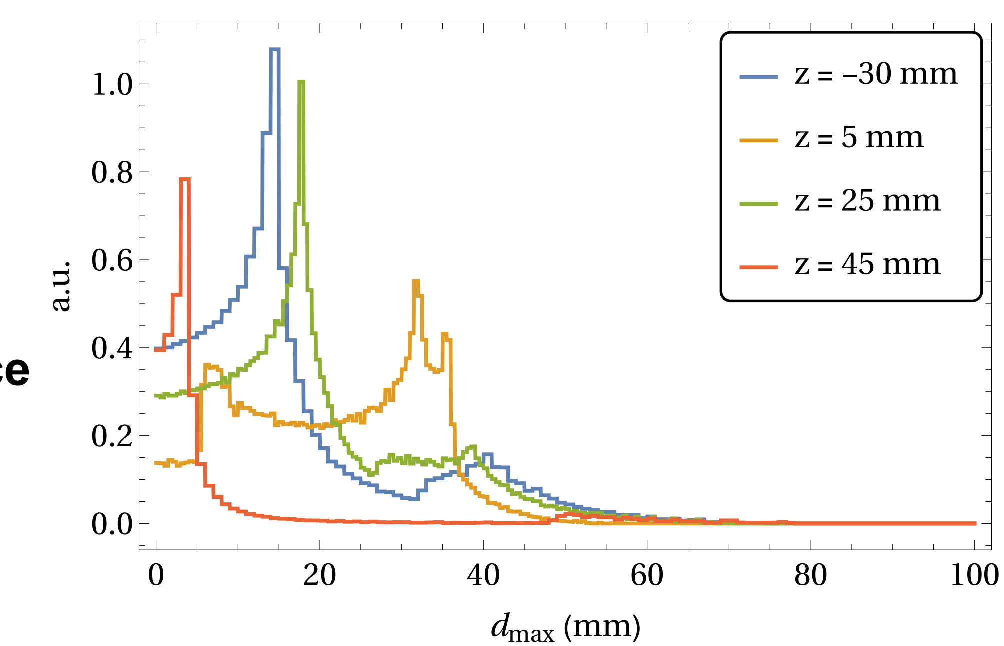


Going displaced inside the stopping target!

Isotropic decays

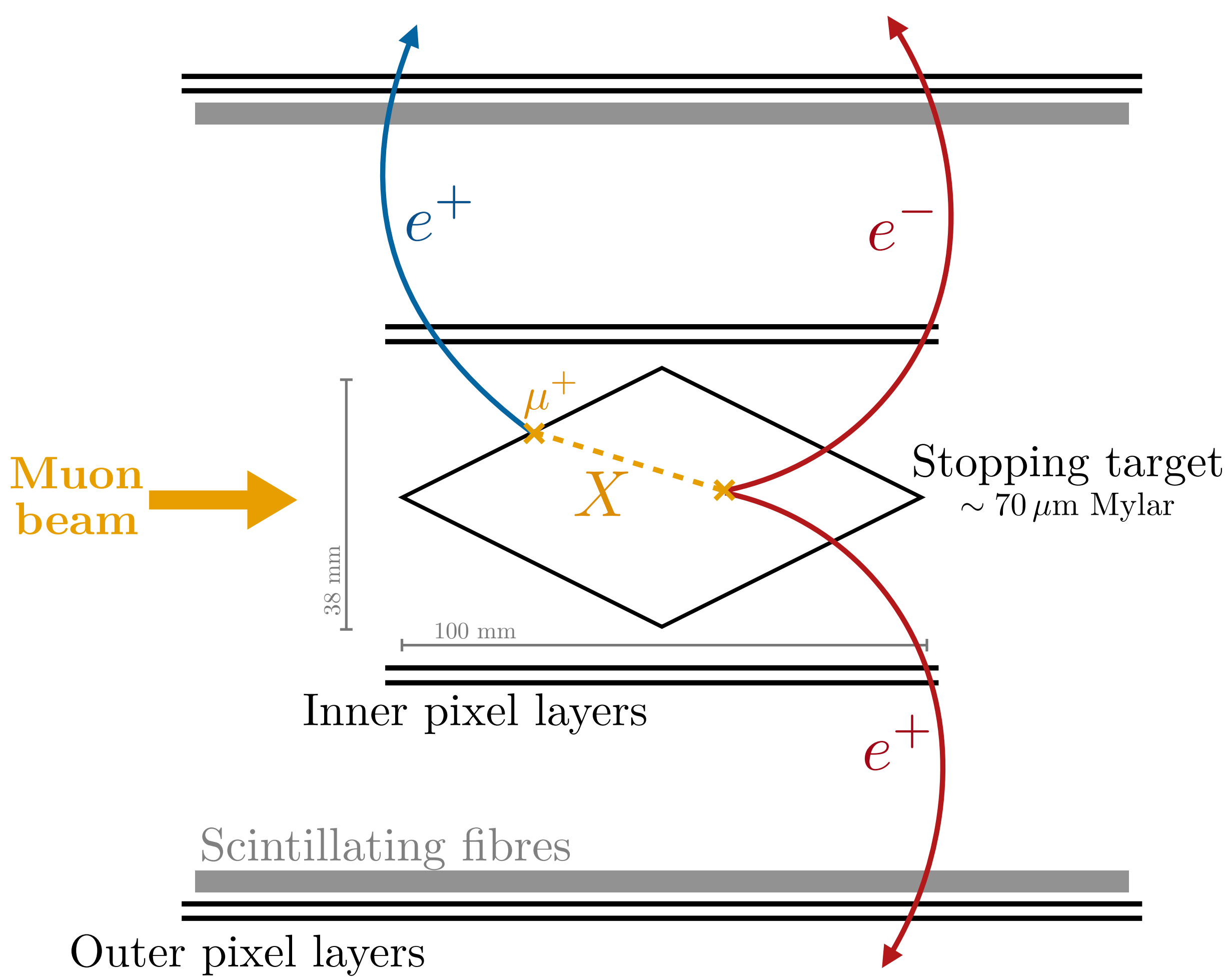


z-dependence stopped muons



Backgrounds

1. Require e^+ pointing to muon decaying on stopping target



2. Require e^+-e^- pair reconstructed to decay inside target (With at least 3mm displacement)

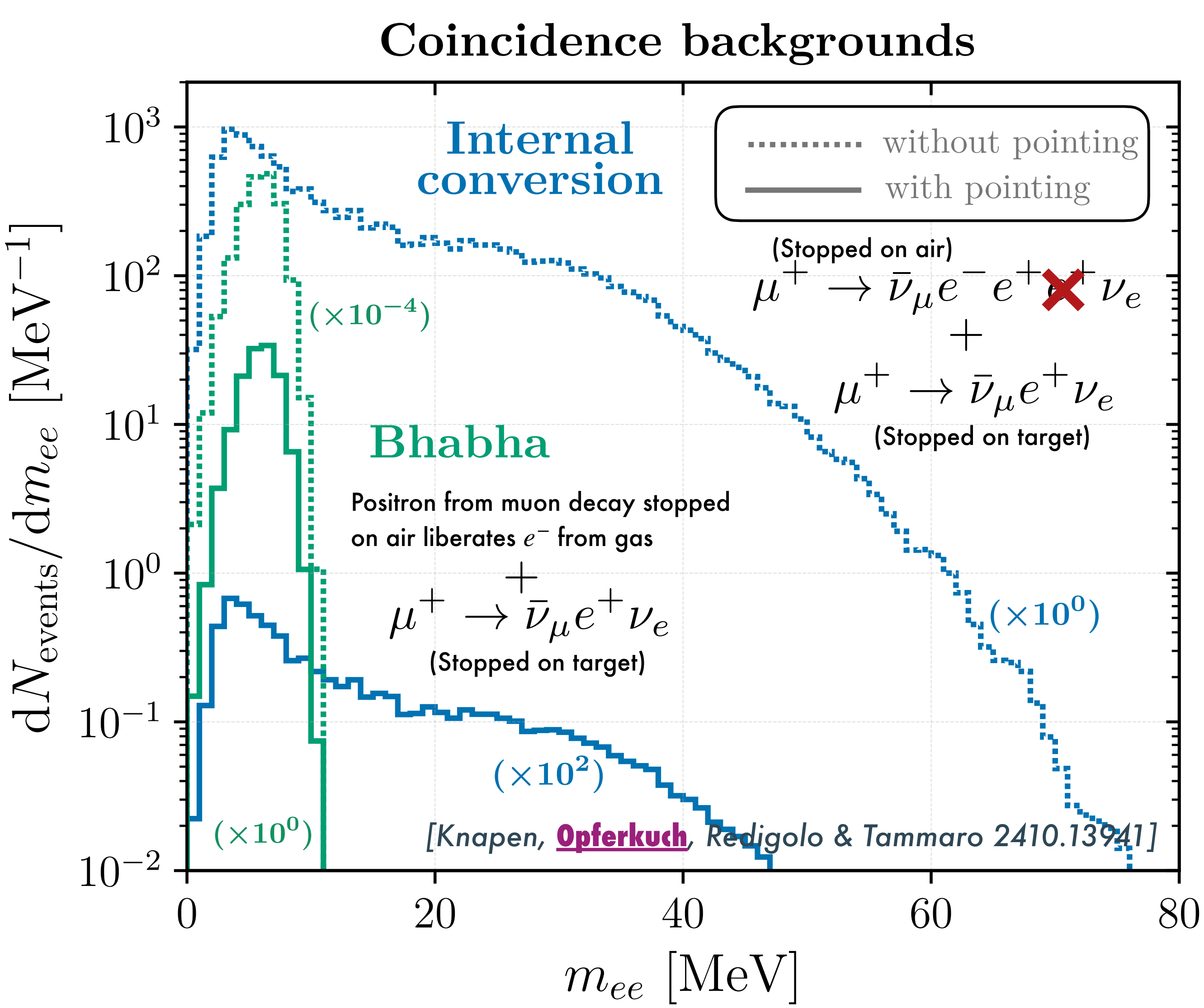
3. (optional) Require e^+-e^- pair to point to muon decay on surface

4. Insist $p^\mu_{\rm miss} = 0$ or $p^2_{\rm miss} > 0$

Without ν's With ν's

Backgrounds

1. Require e^+ pointing to muon decaying on stopping target



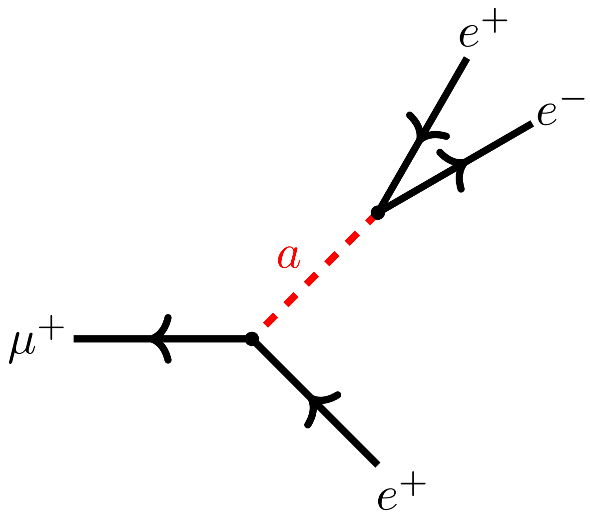
2. Require e^+-e^- pair reconstructed to decay inside target (With at least 3mm displacement)

3. (optional) Require e^+-e^- pair to point to muon decay on surface

4. Insist $p^\mu_{\text{miss}} = 0$ or $p^2_{\text{miss}} > 0$

Without ν's With ν's

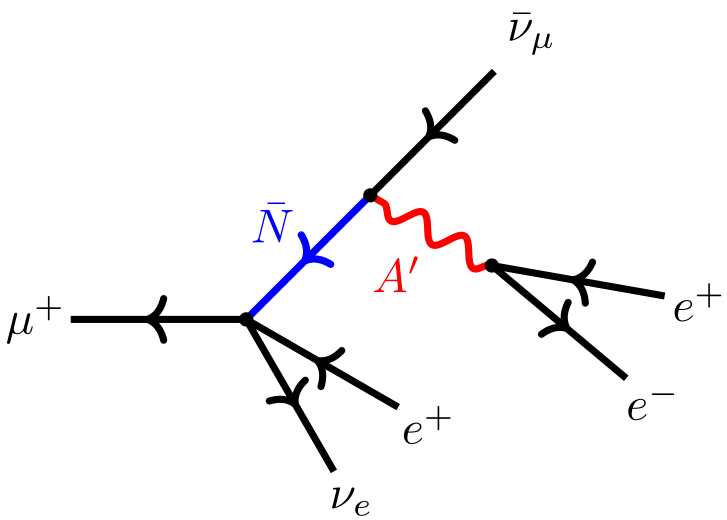
Production Modes



1. Two-body: Ex. LFV ALP

✓ **Mass reconstruction**

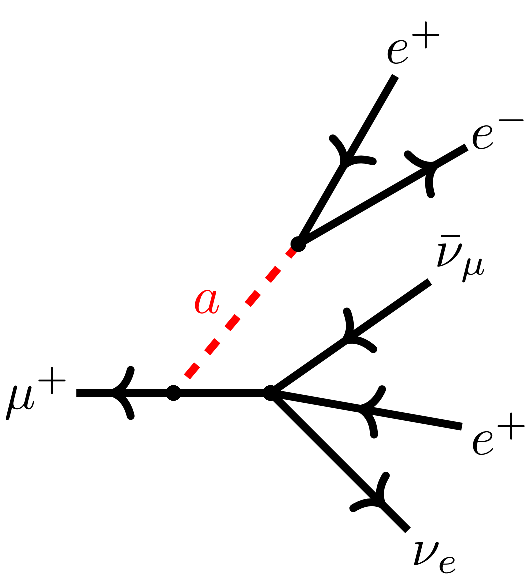
✓ **Pointing**



2. Three-body: Ex. HNL with dark photon

✗ **Mass reconstruction**

✗ **Pointing**



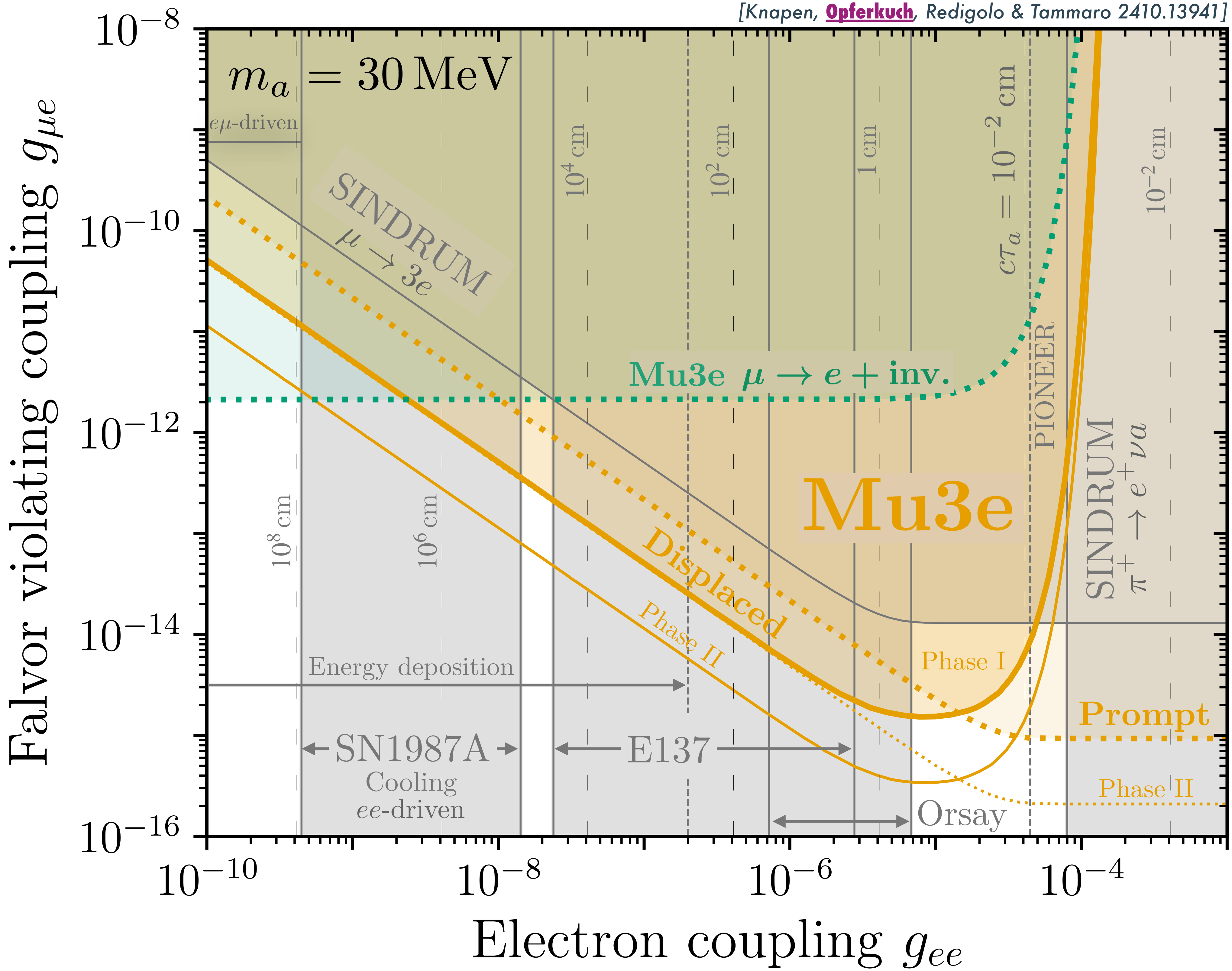
3. Four-body: Ex. LFC ALP

✗ **Mass reconstruction**

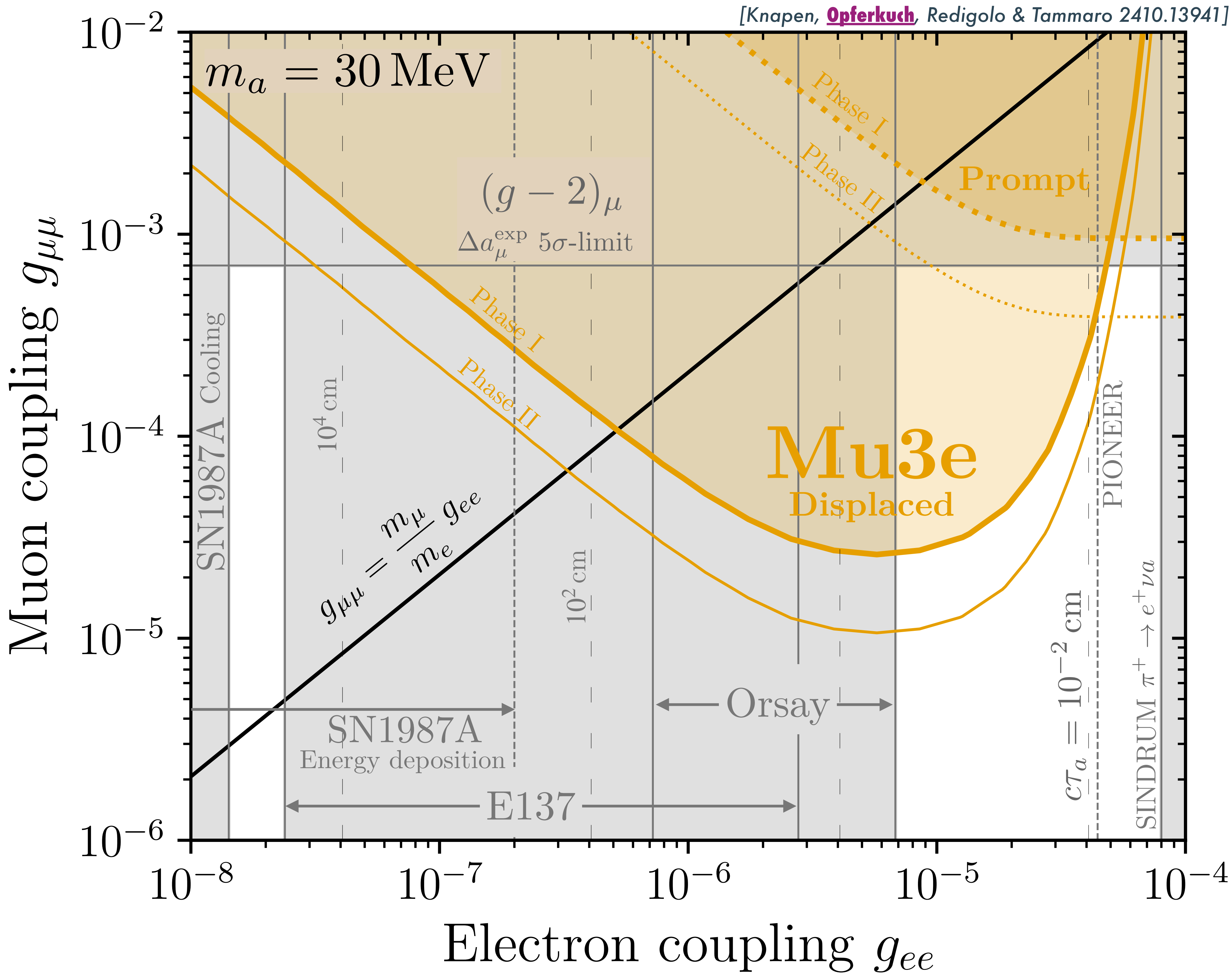
✓ **Pointing**

Lepton Flavour Violating ALP

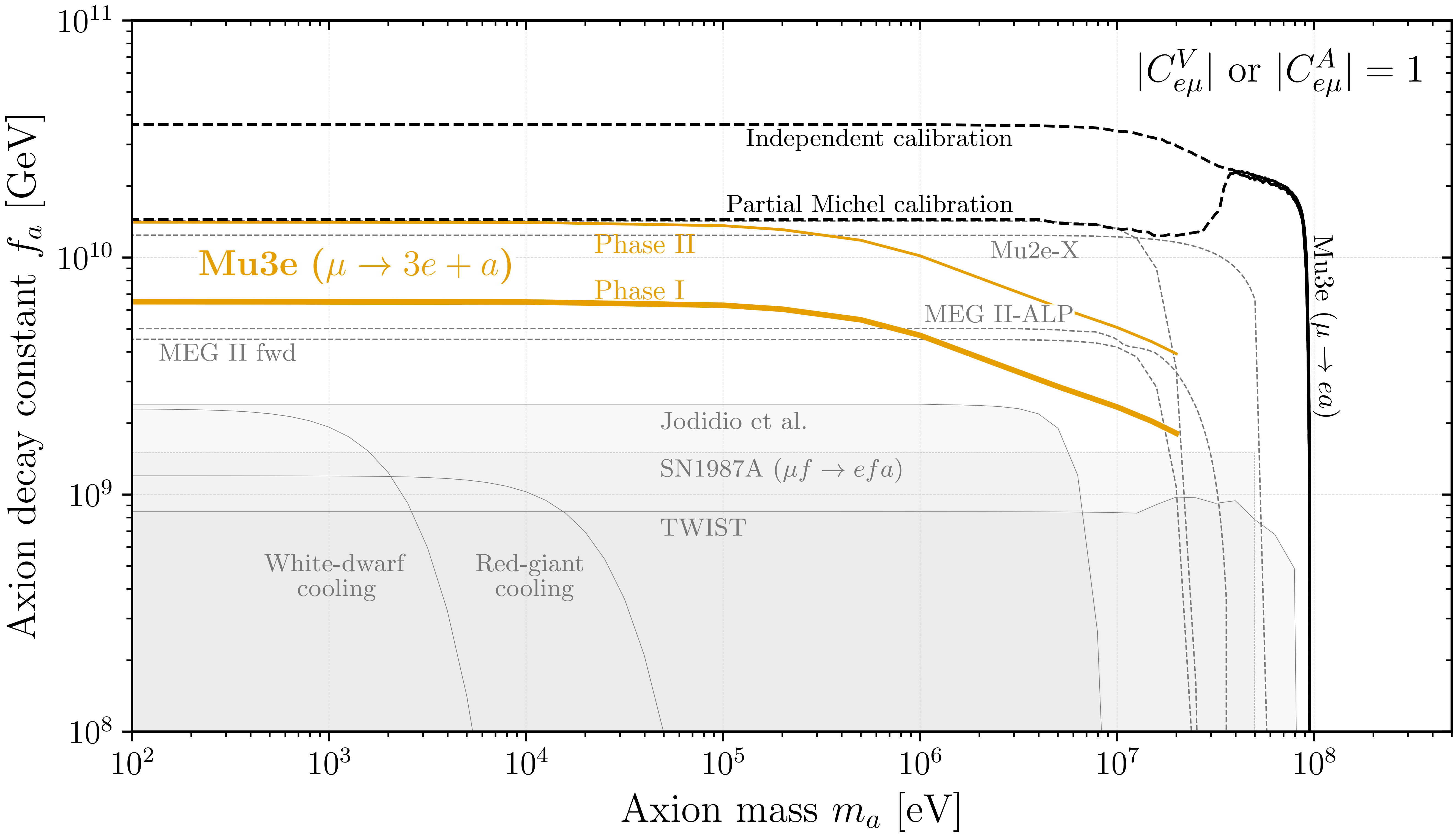
[Knapen, Opferkuch, Redigolo & Tammaro 2410.13941]



Lepton Flavour Conserving ALP



Take Home Message

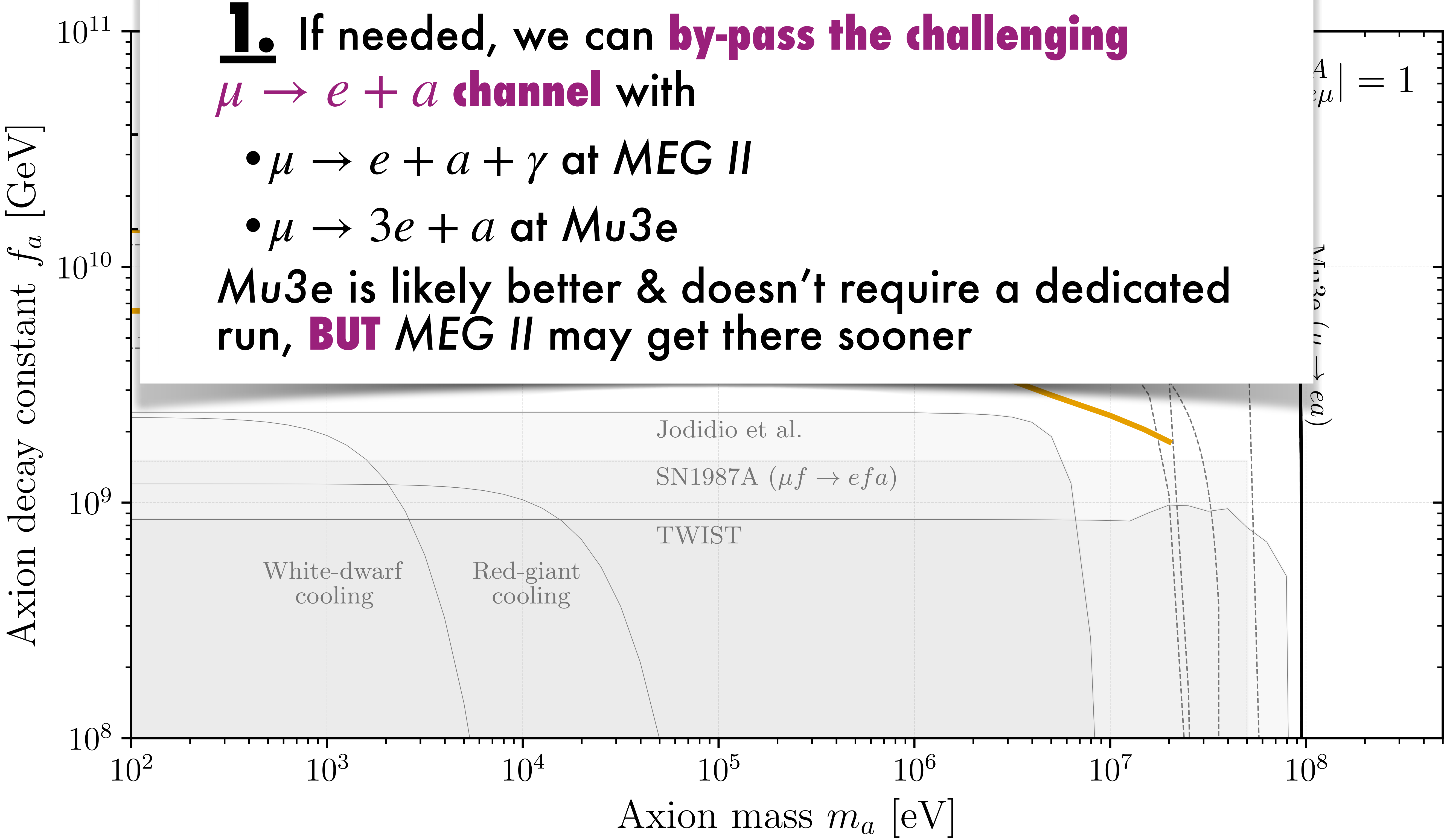


Take Home Message

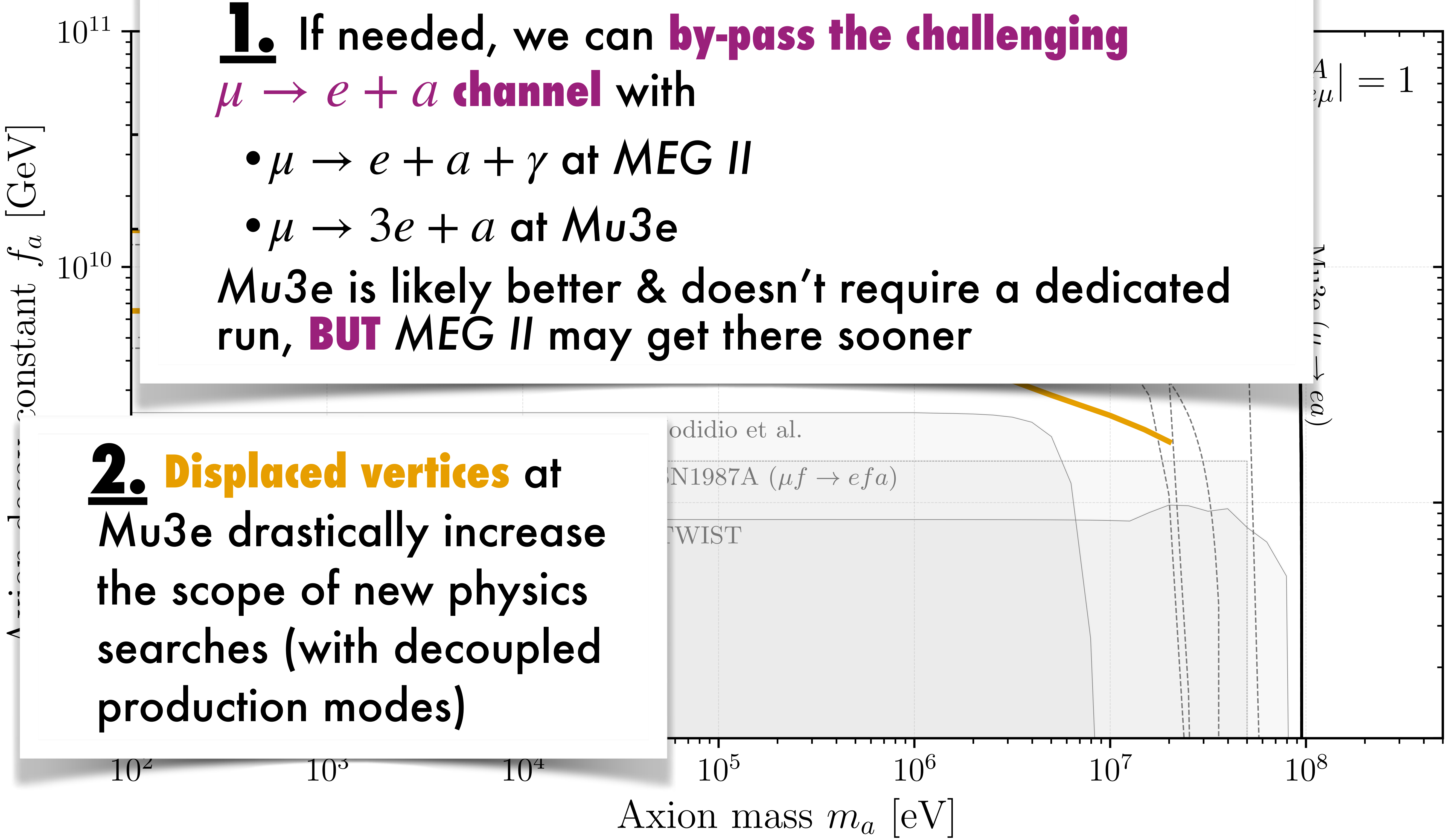
1. If needed, we can **by-pass the challenging $\mu \to e + a$ channel** with

- $\mu \to e + a + \gamma$ at *MEG II*
- $\mu \to 3e + a$ at *Mu3e*

Mu3e is likely better & doesn't require a dedicated run, **BUT** *MEG II* may get there sooner



Take Home Message



1. If needed, we can **by-pass the challenging $\mu \to e + a$ channel** with

- $\mu \to e + a + \gamma$ at *MEG II*
- $\mu \to 3e + a$ at *Mu3e*

Mu3e is likely better & doesn't require a dedicated run, **BUT** *MEG II* may get there sooner

2. **Displaced vertices** at Mu3e drastically increase the scope of new physics searches (with decoupled production modes)

Take Home Message

1. If needed, we can **by-pass the challenging $\mu \to e + a$ channel** with

- $\mu \to e + a + \gamma$ at *MEG II*
- $\mu \to 3e + a$ at *Mu3e*

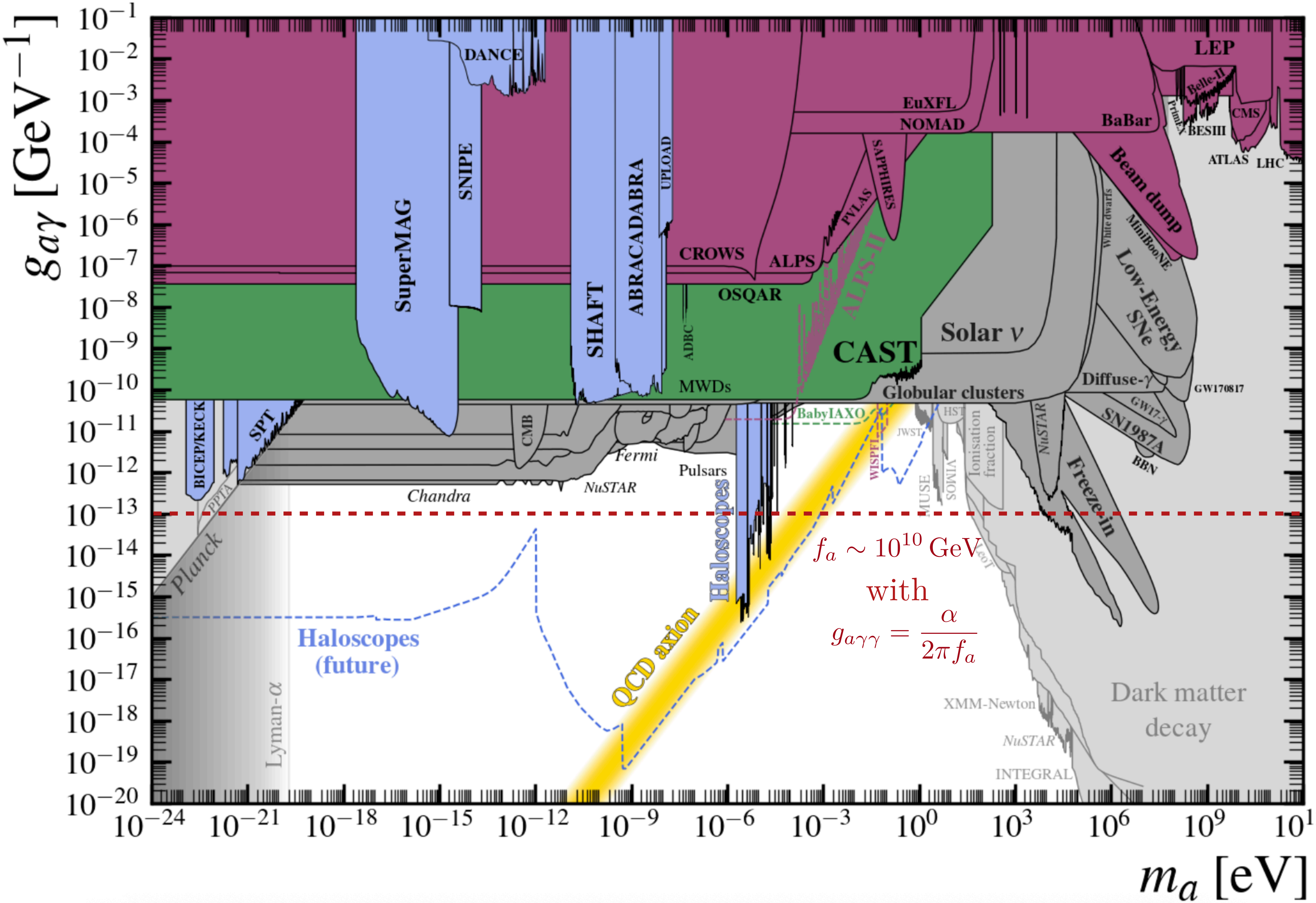
Mu3e is likely better & doesn't require a dedicated run, **BUT** *MEG II* may get there sooner

2. **Displaced vertices** at Mu3e drastically increase the scope of new physics searches (with decoupled production modes)

3. What can be done at **Mu2e** using **dedicated runs**:

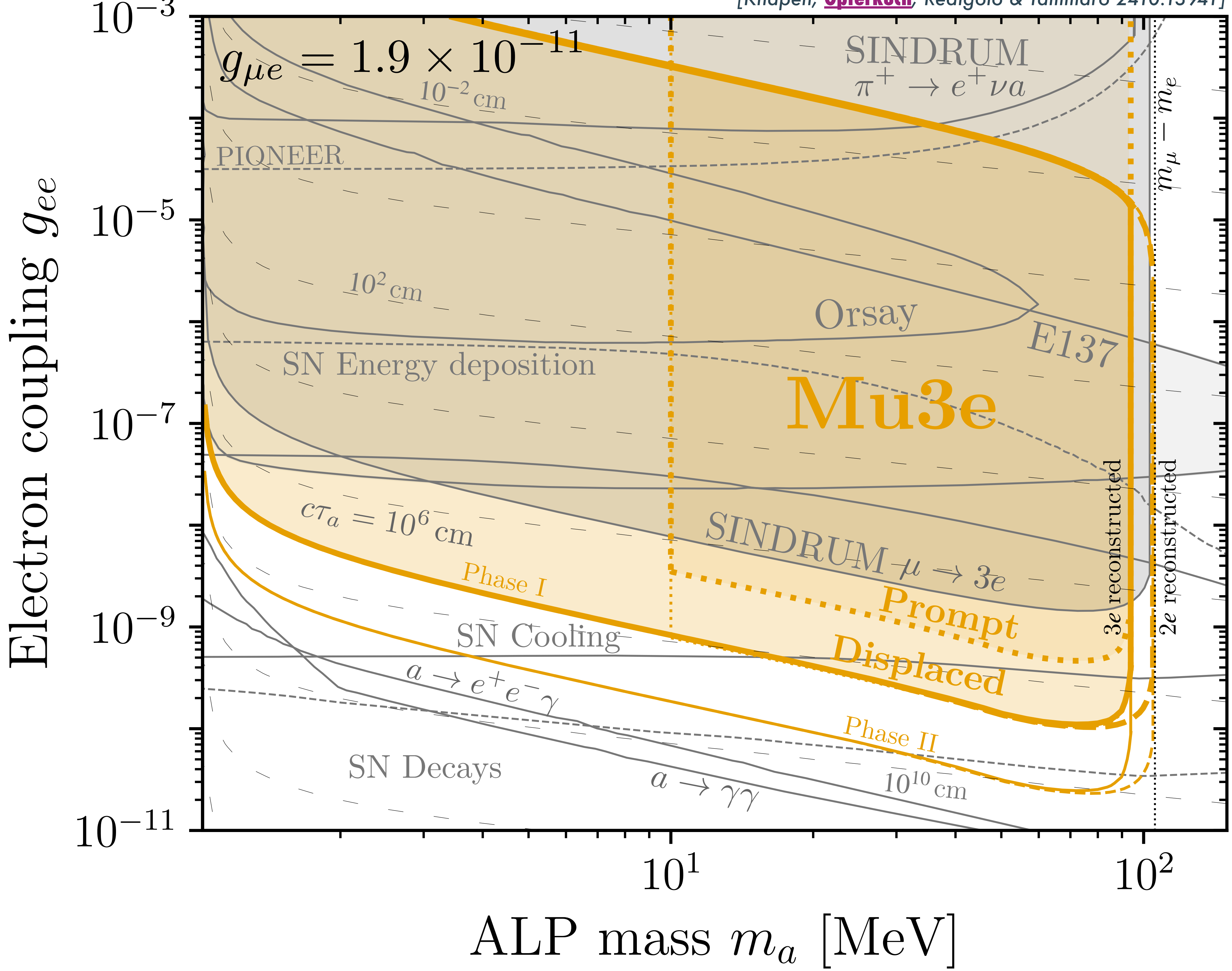
- $\mu \to e + a + ?$
- Displaced vertices?
- Prompt ALP decay searches?
- Something **even better?**

Questions?

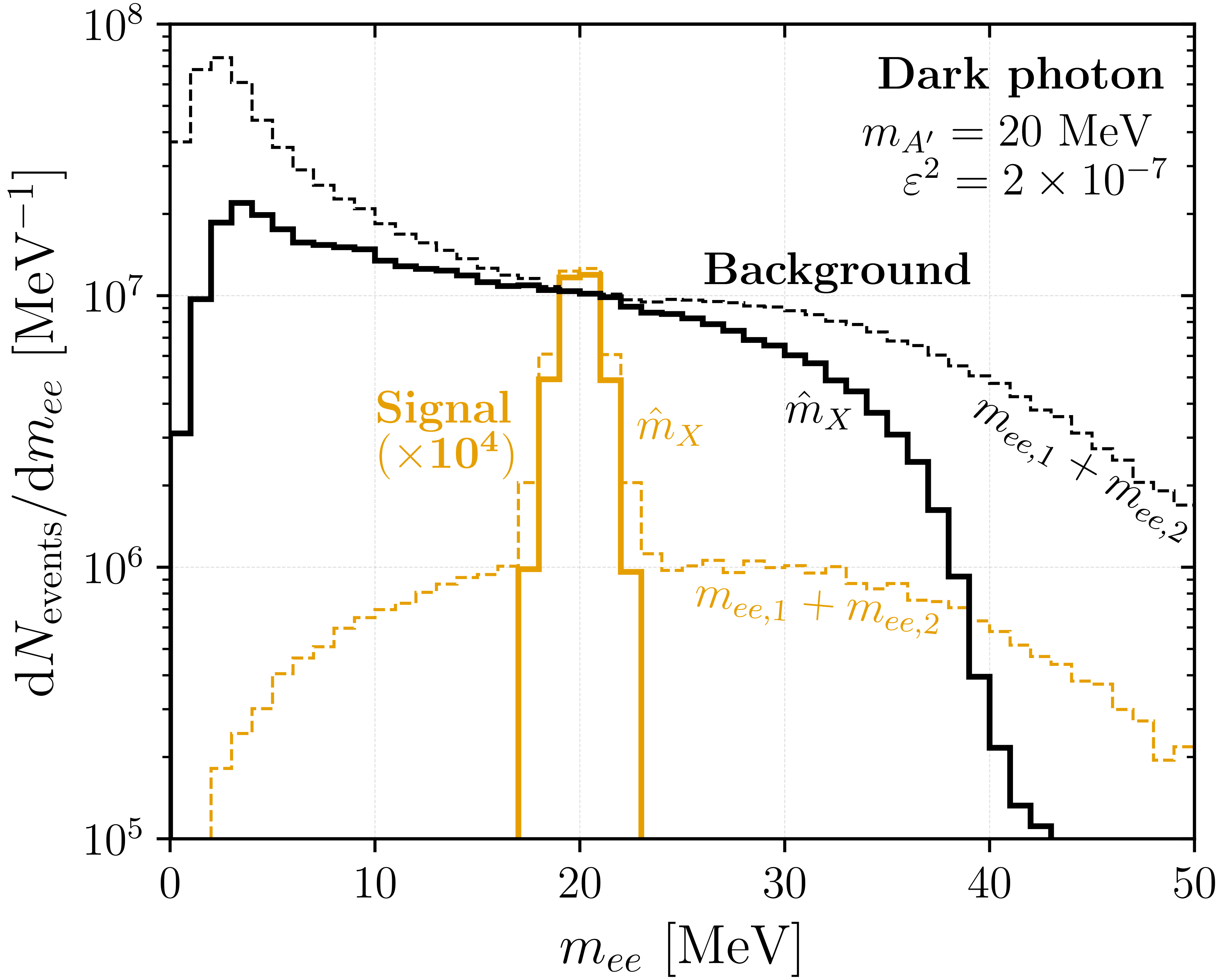

$g_{a\gamma}$ [GeV^{-1}]
m_a [eV]
DANCE
SuperMAG
SNIPE
SHAFT
ABRACADABRA
UPLOAD
CROWS
ALPS
OSQAR
EuXFL
NOMAD
SAPPHIRES
PVLAS
ALPS-II
BaBar
LEP
Belle-II
PrimEx
BESIII
CMS
ATLAS
LHC
Beam dump
MiniBooNE
White dwarfs
Low-Energy SNe
Solar ν
CAST
ADBC
MWDs
Globular clusters
Diffuse-γ
GW170817
GW17-γ
SN1987A
BBN
Freeze-in
NuSTAR
BabyIAXO
HST
JWST
WISPFI
MUSE
VIMOS
SOMIA
Ionisation fraction
BICEP/KECK
SPT
PPTA
CMB
Fermi
Pulsars
NuSTAR
Chandra
Planck
Haloscopes
Haloscopes (future)
Lyman-α
QCD axion
$f_a \sim 10^{10}$ GeV
with
$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}$
Dark matter decay
XMM-Newton
NuSTAR
INTEGRAL

Lepton Flavour Violating ALP

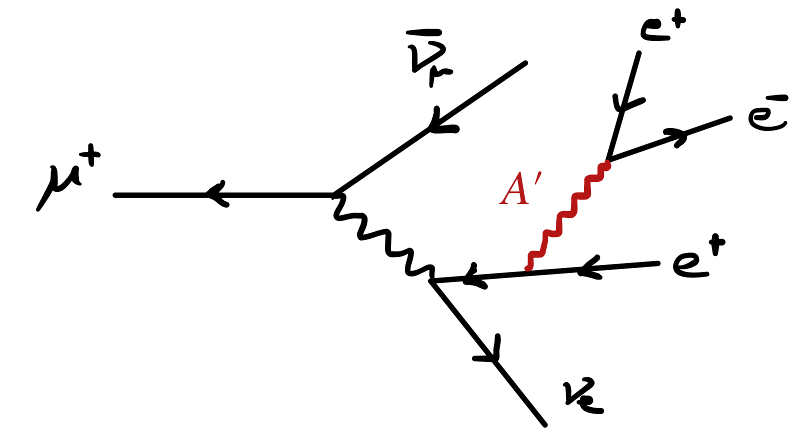
[Knapen, Opferkuch, Redigolo & Tammaro 2410.13941]



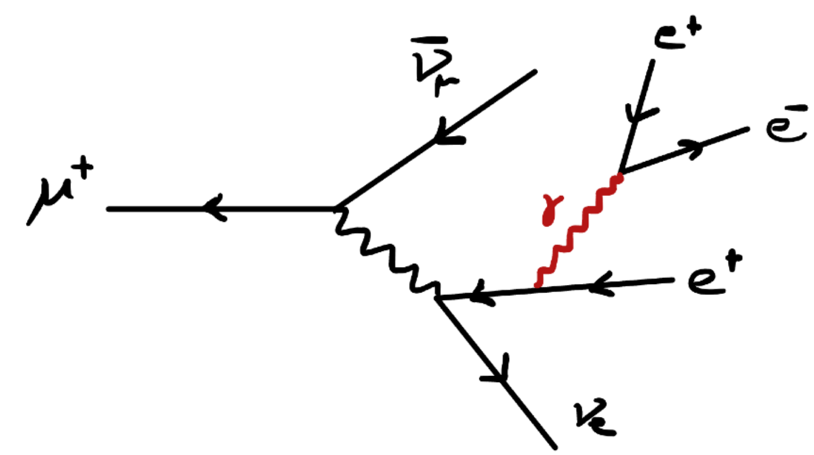
Search Strategy



Signal:

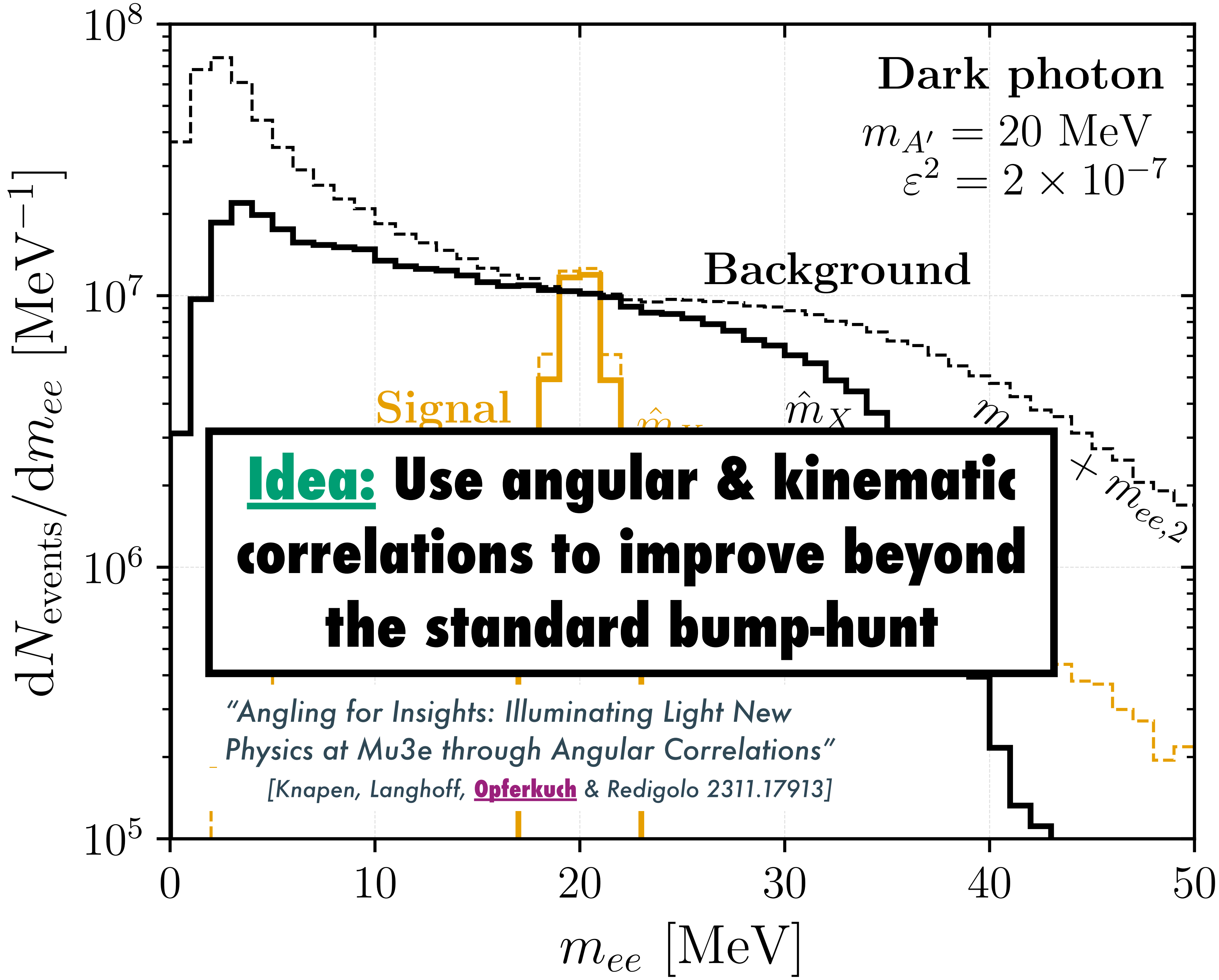


Background:



$\hat{m}_X$ is the e^+e^--pair that reconstructs the mass of the hypothesised resonance

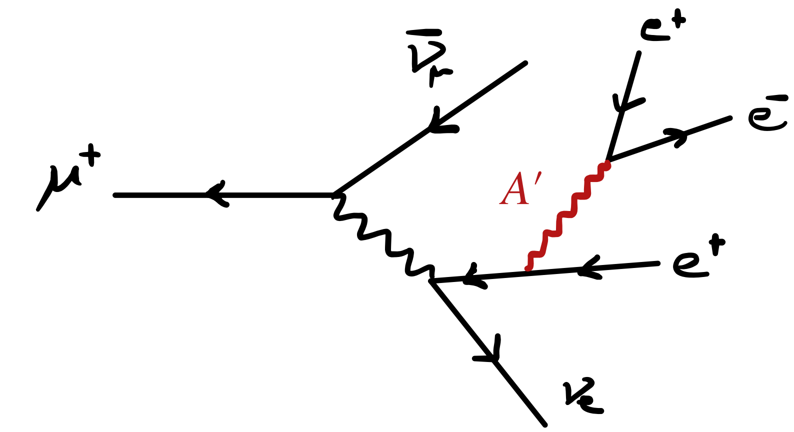
Search Strategy



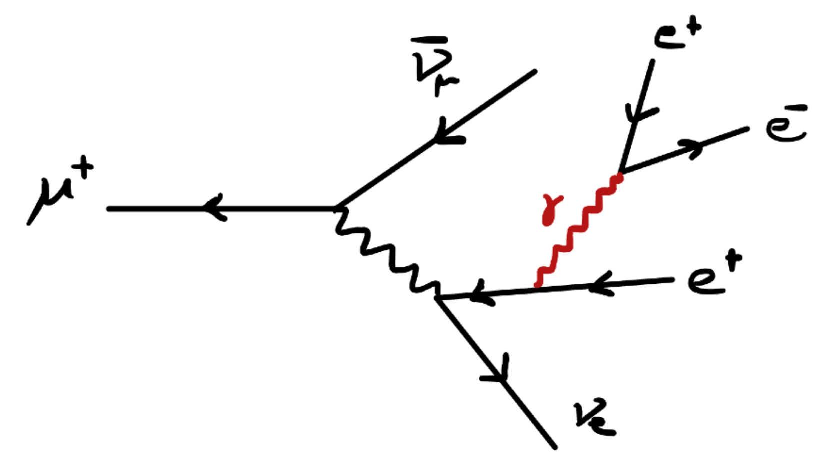
Idea: Use angular & kinematic correlations to improve beyond the standard bump-hunt

"Angling for Insights: Illuminating Light New Physics at Mu3e through Angular Correlations"
[Knapen, Langhoff, **Opferkuch** & Redigolo 2311.17913]

Signal:



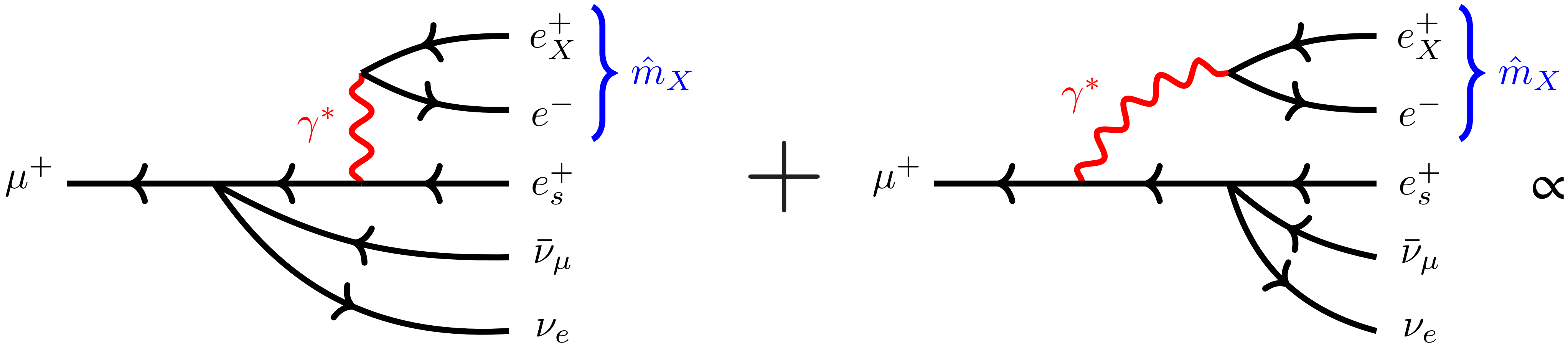
Background:



$\hat{m}_X$ is the e^+e^--pair that reconstructs the mass of the hypothesised resonance

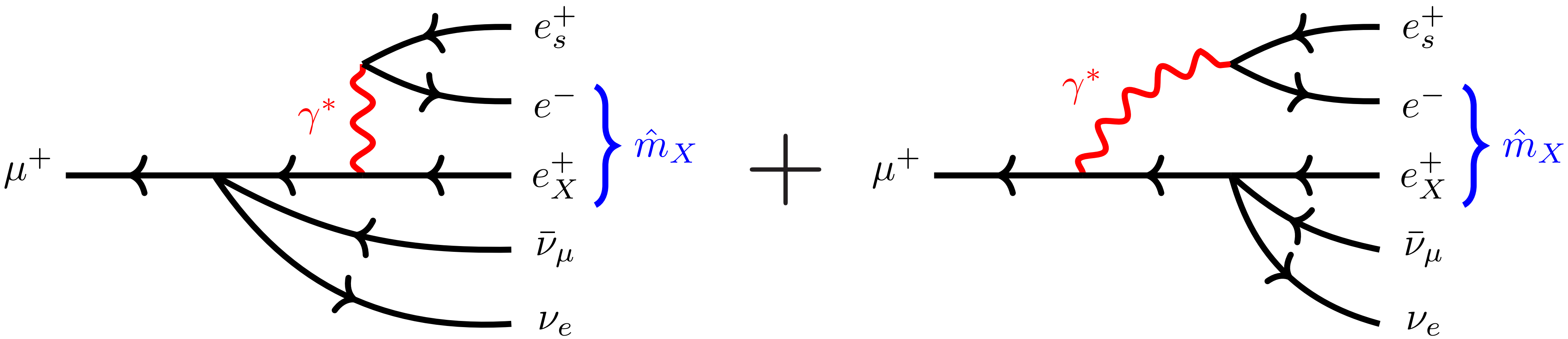
Background Combinatorics

Correct pair for m_X



$$\propto \frac{1}{p_{e^-} \cdot p_{e_X^+}} \sim \frac{1}{m_X^2}$$

Incorrect pair for m_X

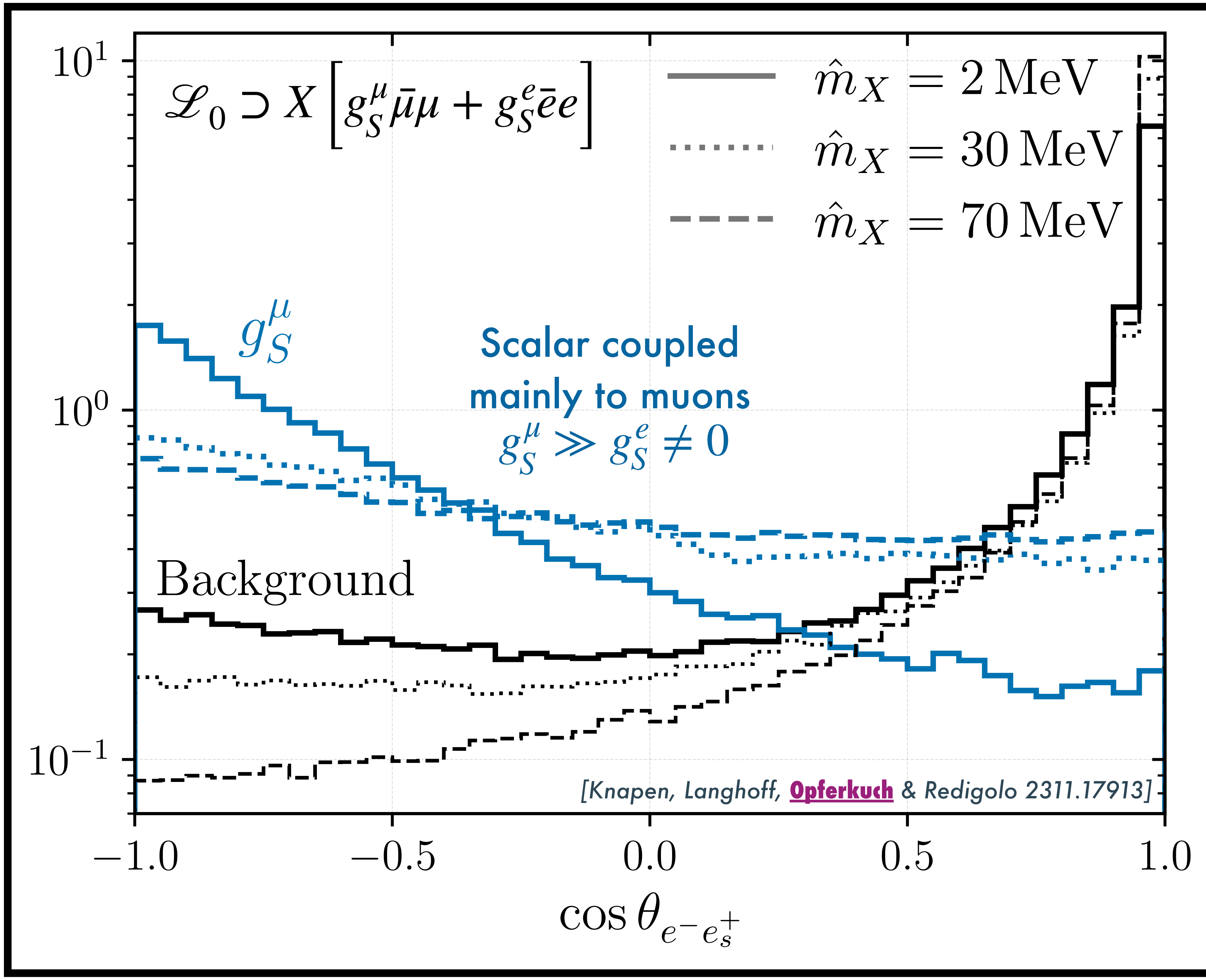


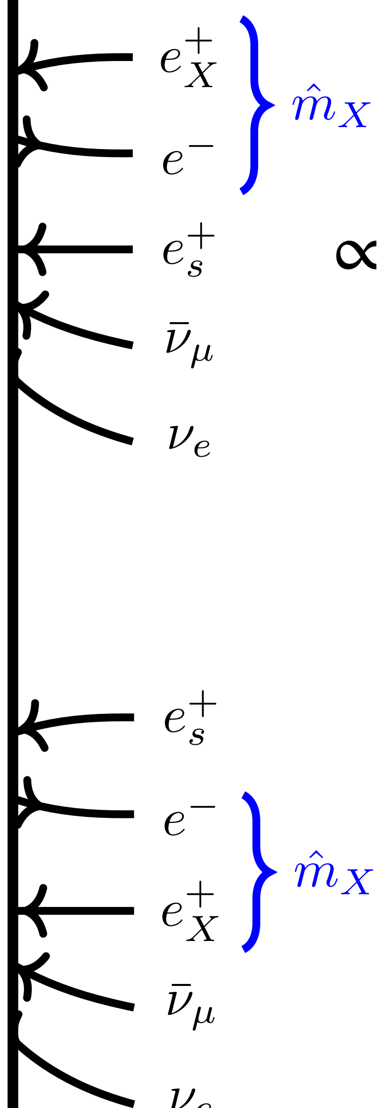
$$\propto \frac{1}{p_{e^-} \cdot p_{e_s^+}}$$

$$\sim \frac{1}{E_e \text{-} E_{e_s^+}(1 - \cos\theta_{e^- e_s^+})}$$

Collinear singularity for background only!

Background Combinatorics





$$\propto \frac{1}{p_{e^-}\cdot p_{e_X^+}} \sim \frac{1}{m_X^2}$$

$$\propto \frac{1}{p_{e^-}\cdot p_{e_s^+}}$$

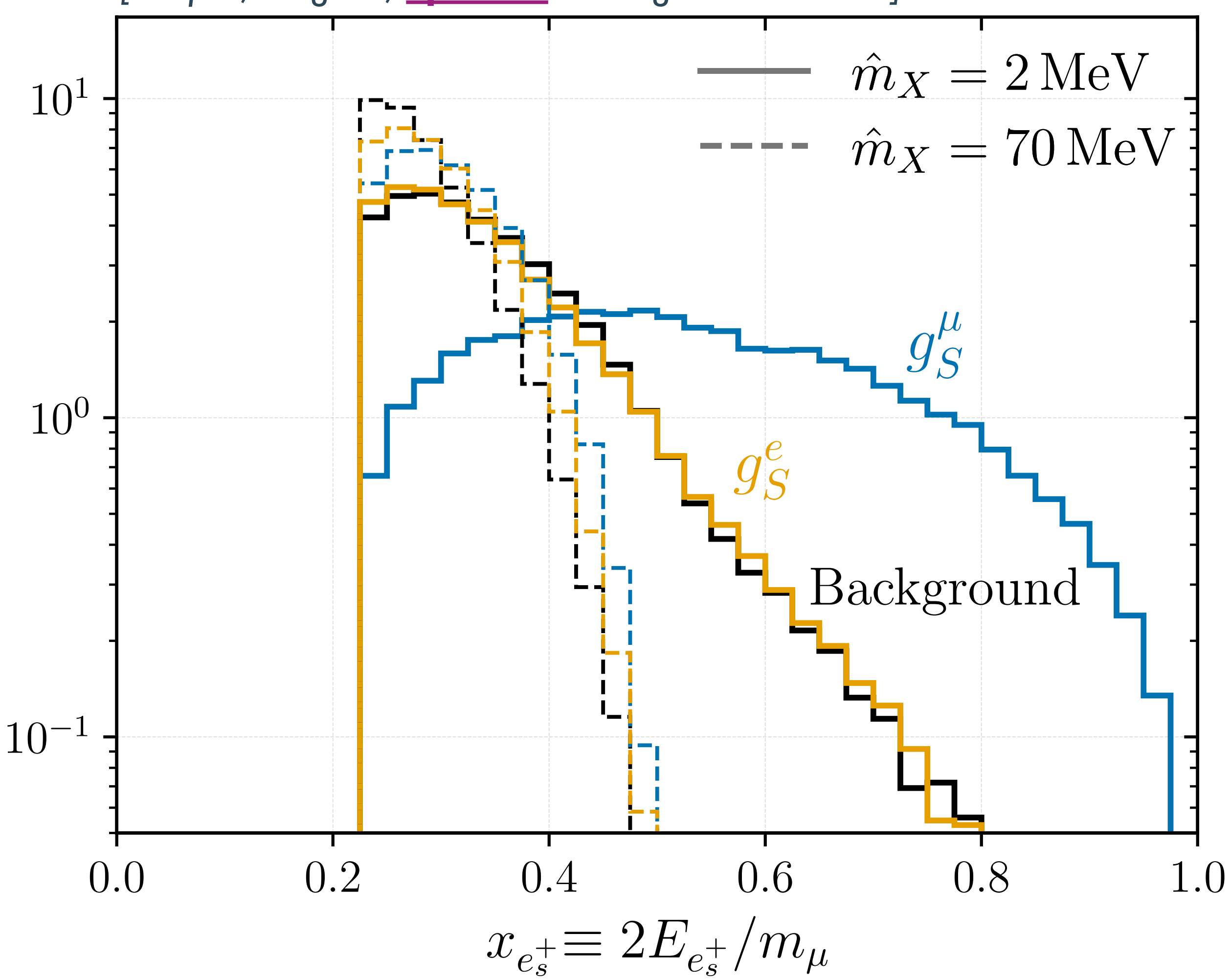
$$\sim \frac{1}{E_{e^-}E_{e_s^+}(1-\cos\theta_{e^-e_s^+})}$$

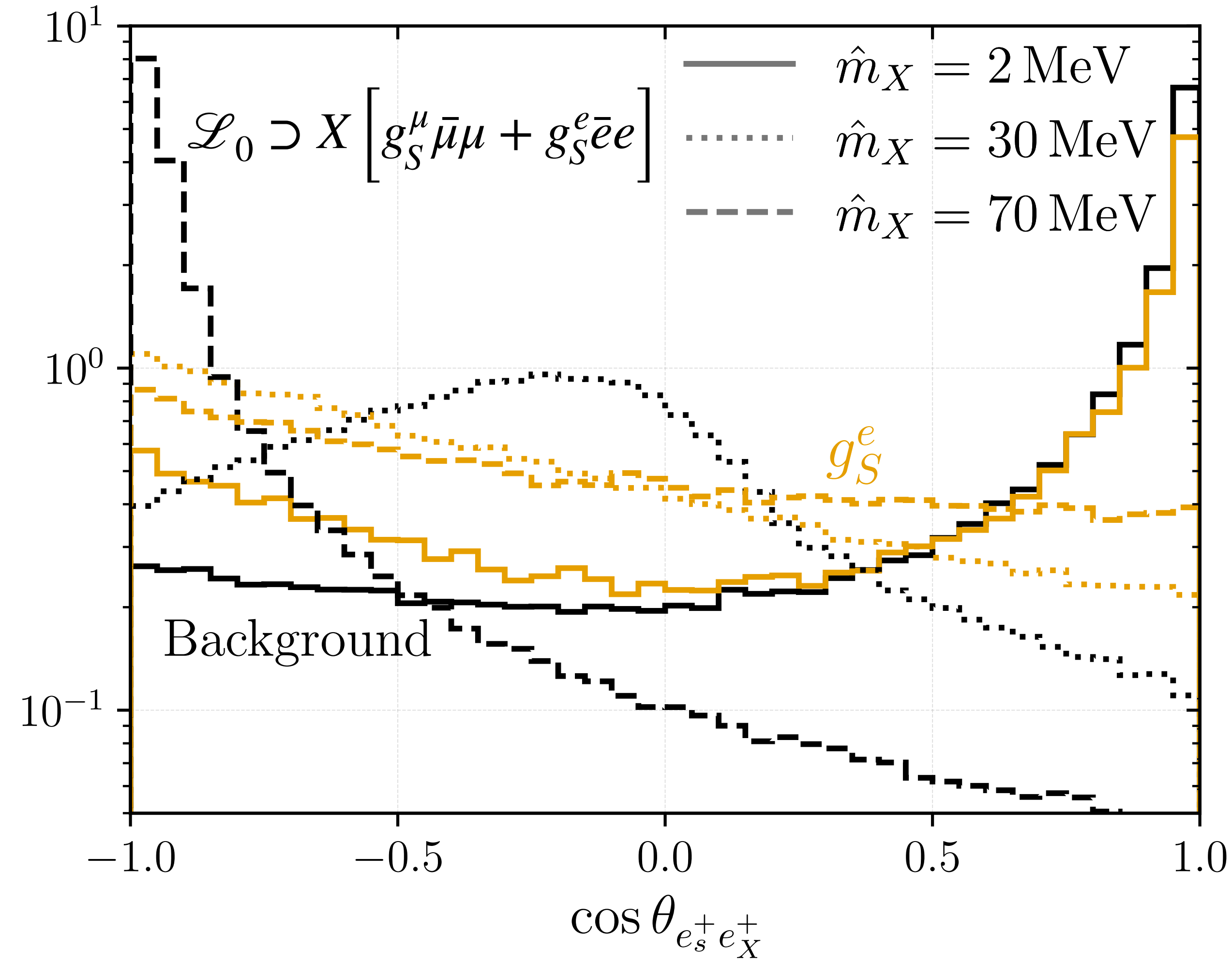
Collinear singularity for background only!

Kinematic Correlations

Two additional model-dependent discriminating variables

[Knapen, Langhoff, **Opferkuch** & Redigolo 2311.17913]

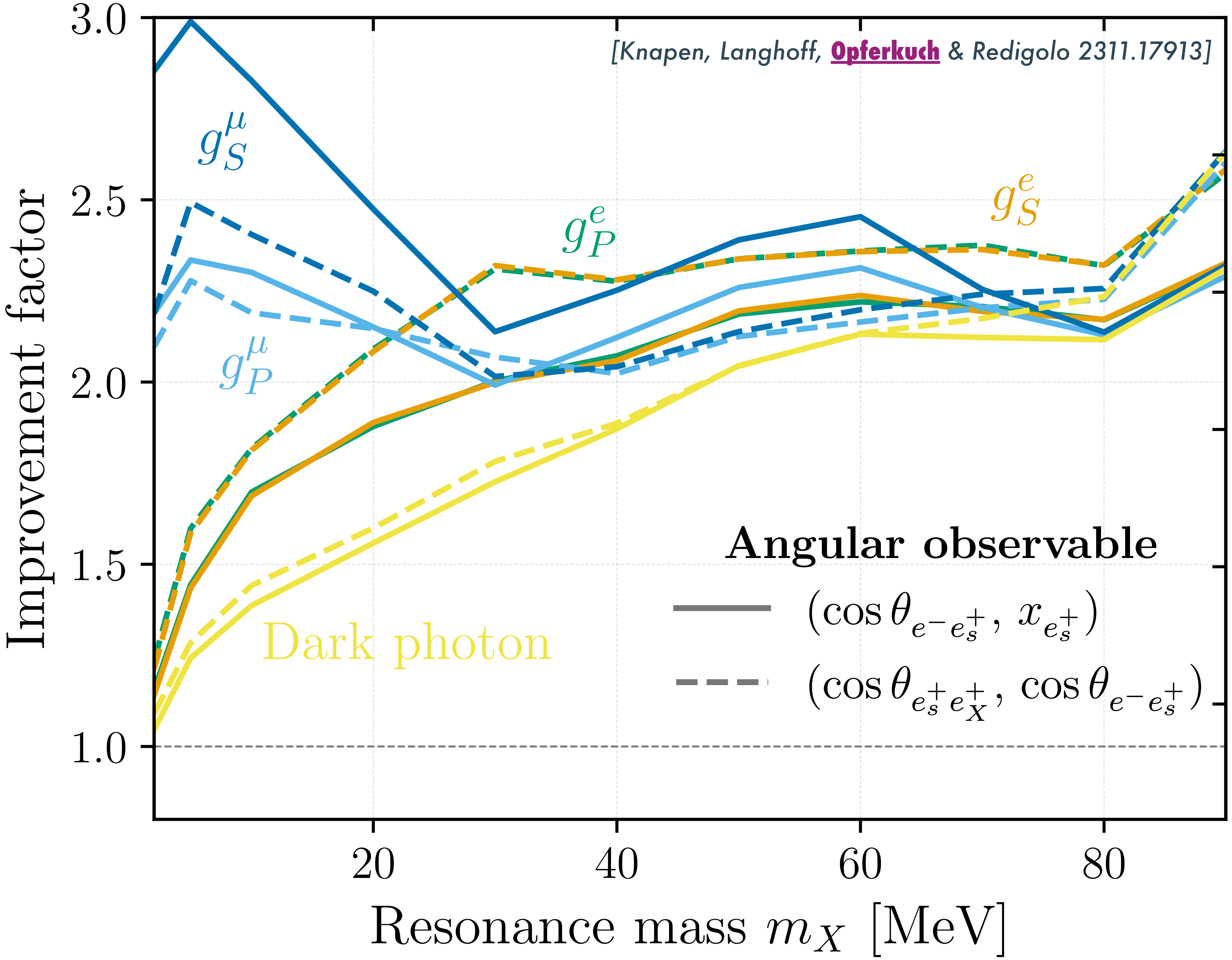




Dominant muon coupling behaves differently

Kinematic Correlations

Limited by MC statistics to binning in 2 variables only



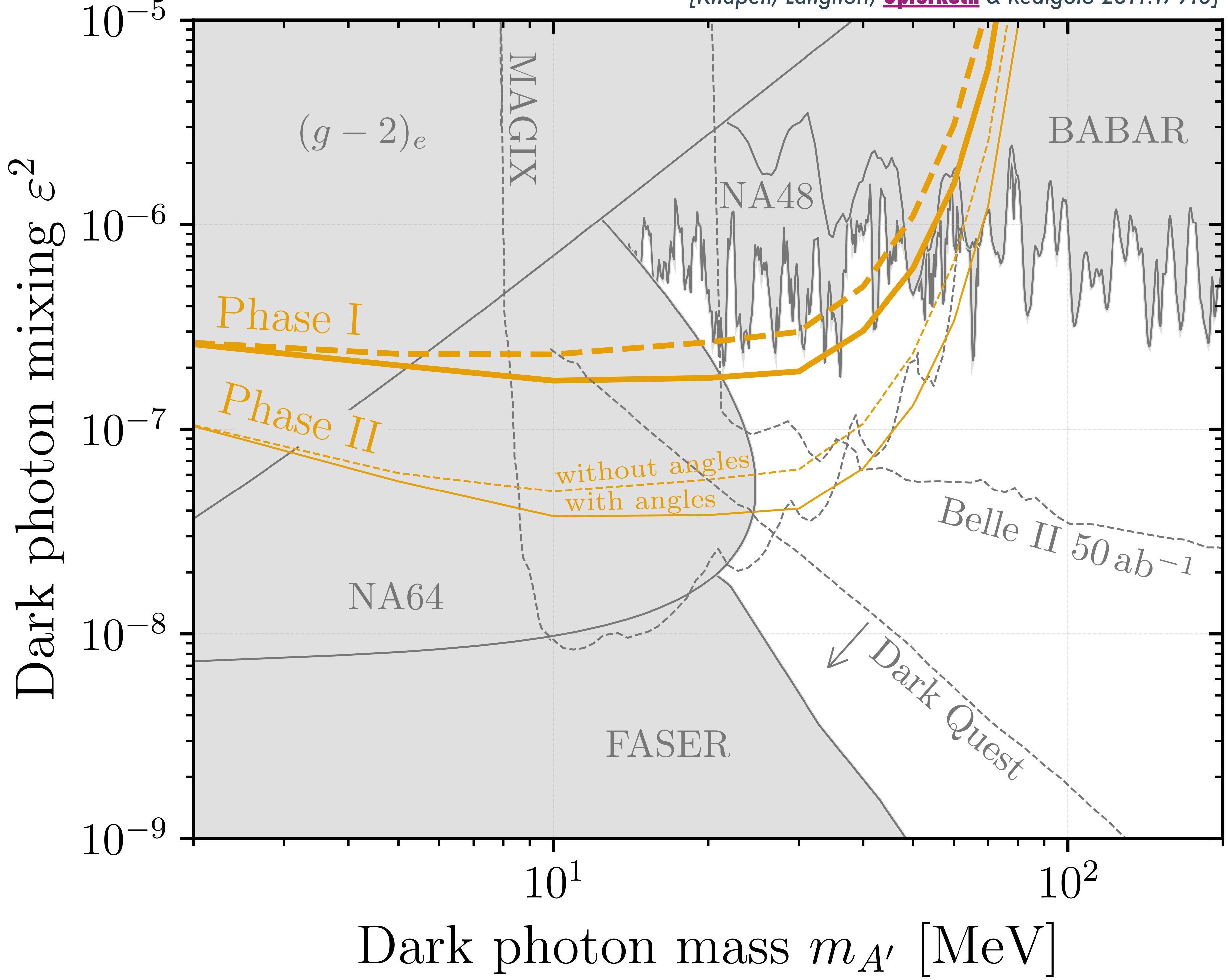
Include parity-odd couplings:

$$\mathscr{L}_0 \supset X\Big[g_S^\mu\,\bar{\mu}\mu + g_P^\mu\,\bar{\mu}\gamma_5\mu + g_S^e\,\bar{e}e + g_P^e\,\bar{e}\gamma_5 e\Big]$$

Mu3e can extract full kinematic information using a data driven background estimate

Example 1: Dark Photon

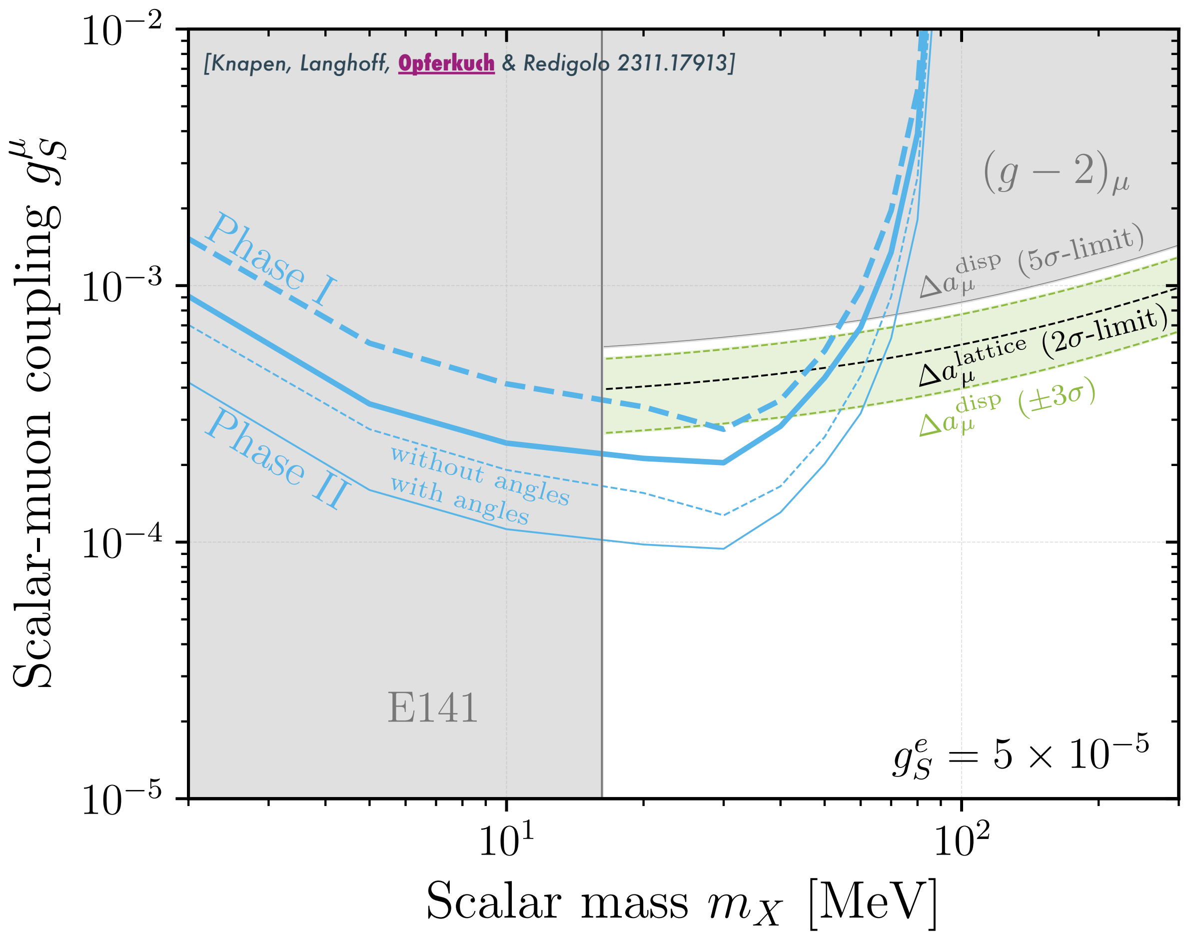
[Knapen, Langhoff, Opferkuch & Redigolo 2311.17913]



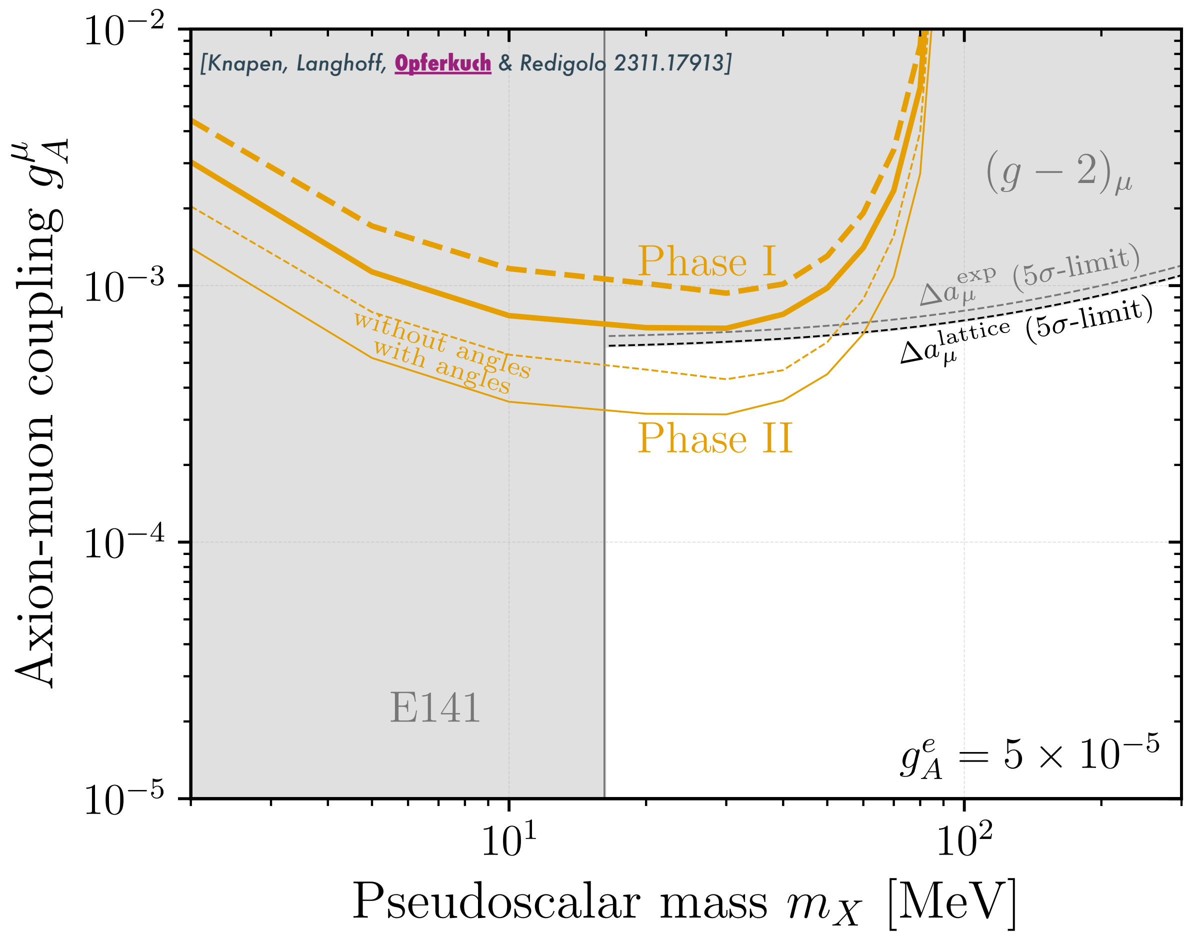
[Echenard et al 1411.1770]
[Perrevoort et al (Mu3e Collaboration) 1812.00741]

Example 2: Scalar Coupling to Muons

Scalar



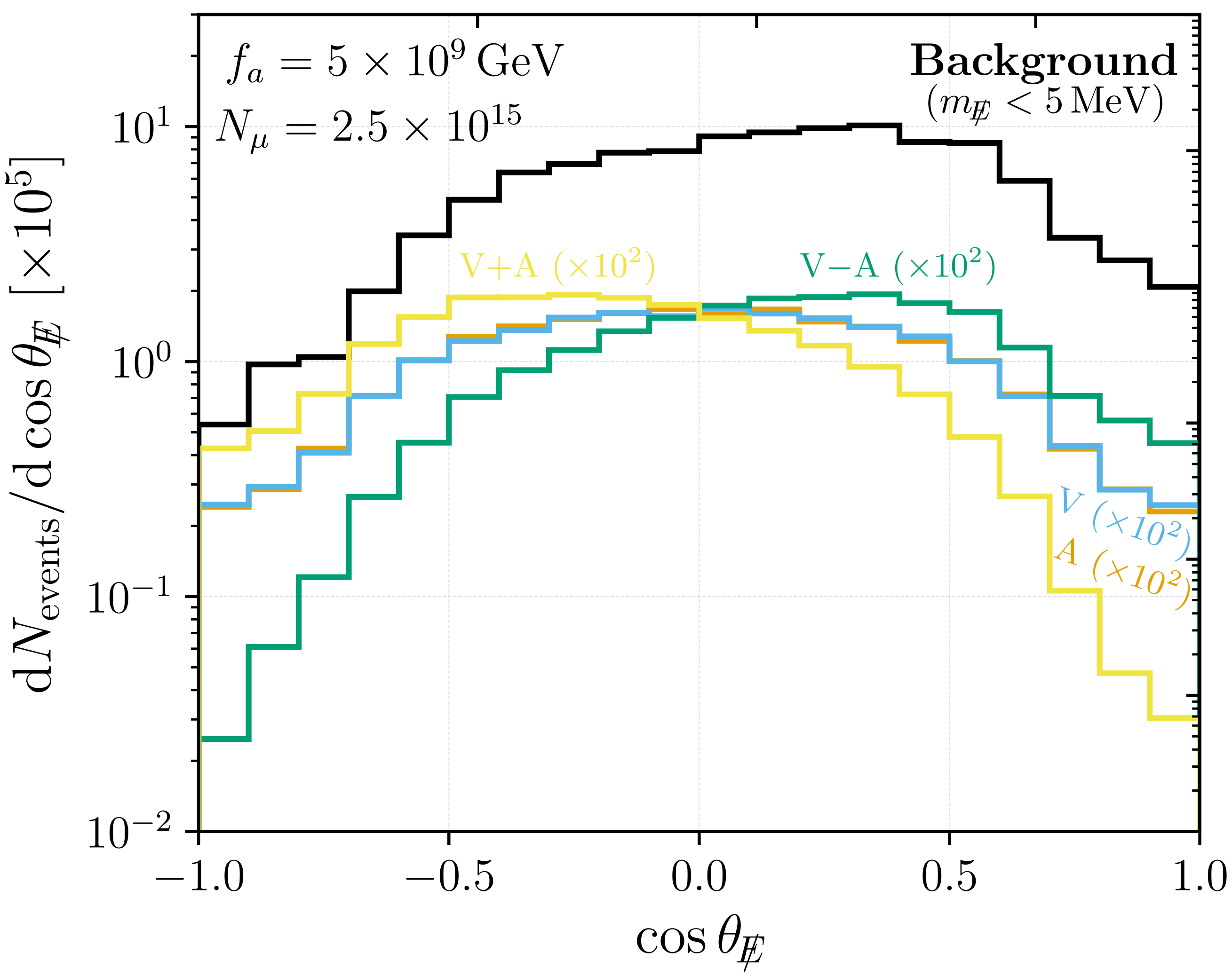
Pseudoscalar

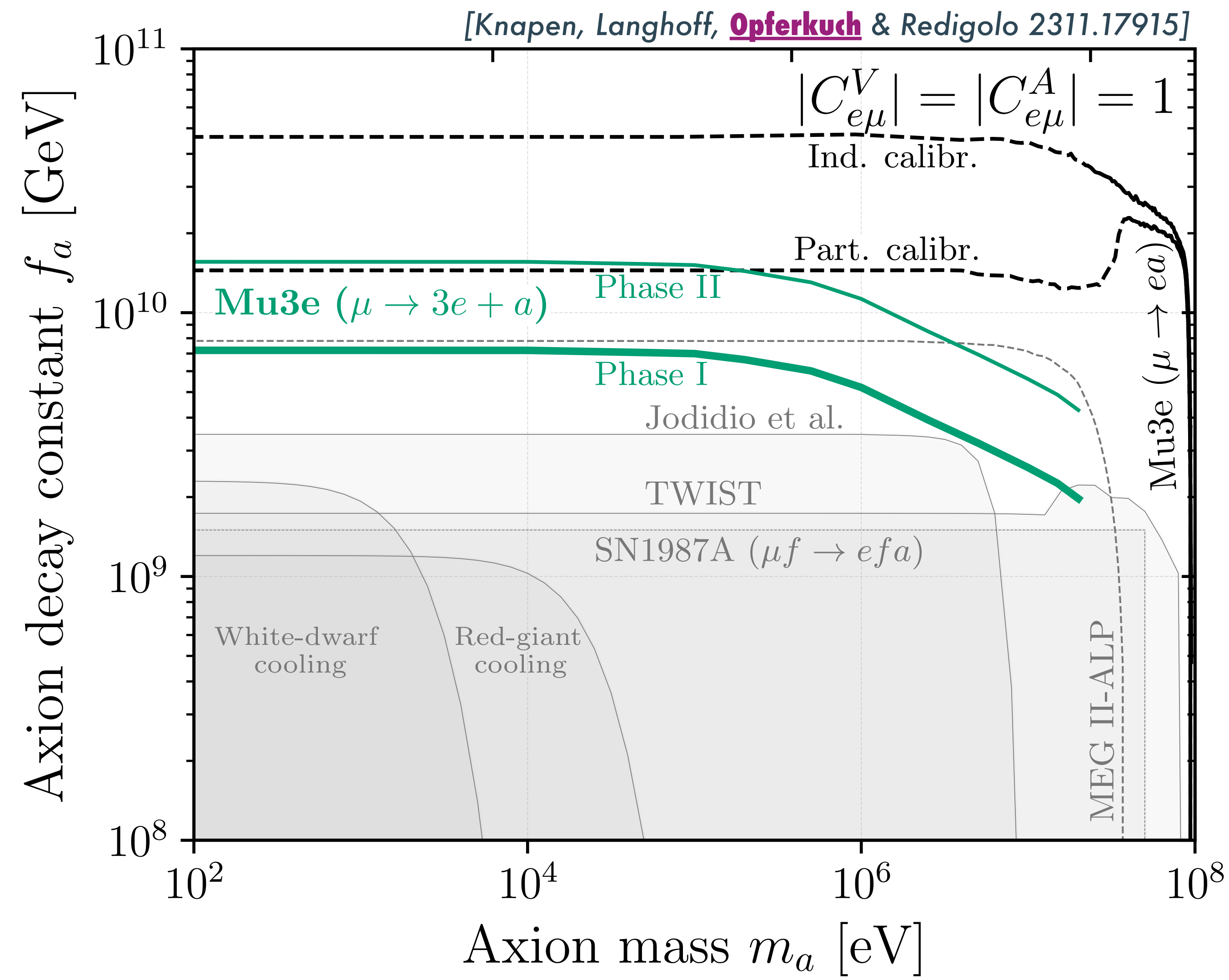


Other models investigated (Mu3e not competitive):

- Scalars coupled only to electrons
- Scalars with mass hierarchical couplings
- $L_\mu - L_e$ (also twisted)

Angular Observables





Small improvement for right-handed currents