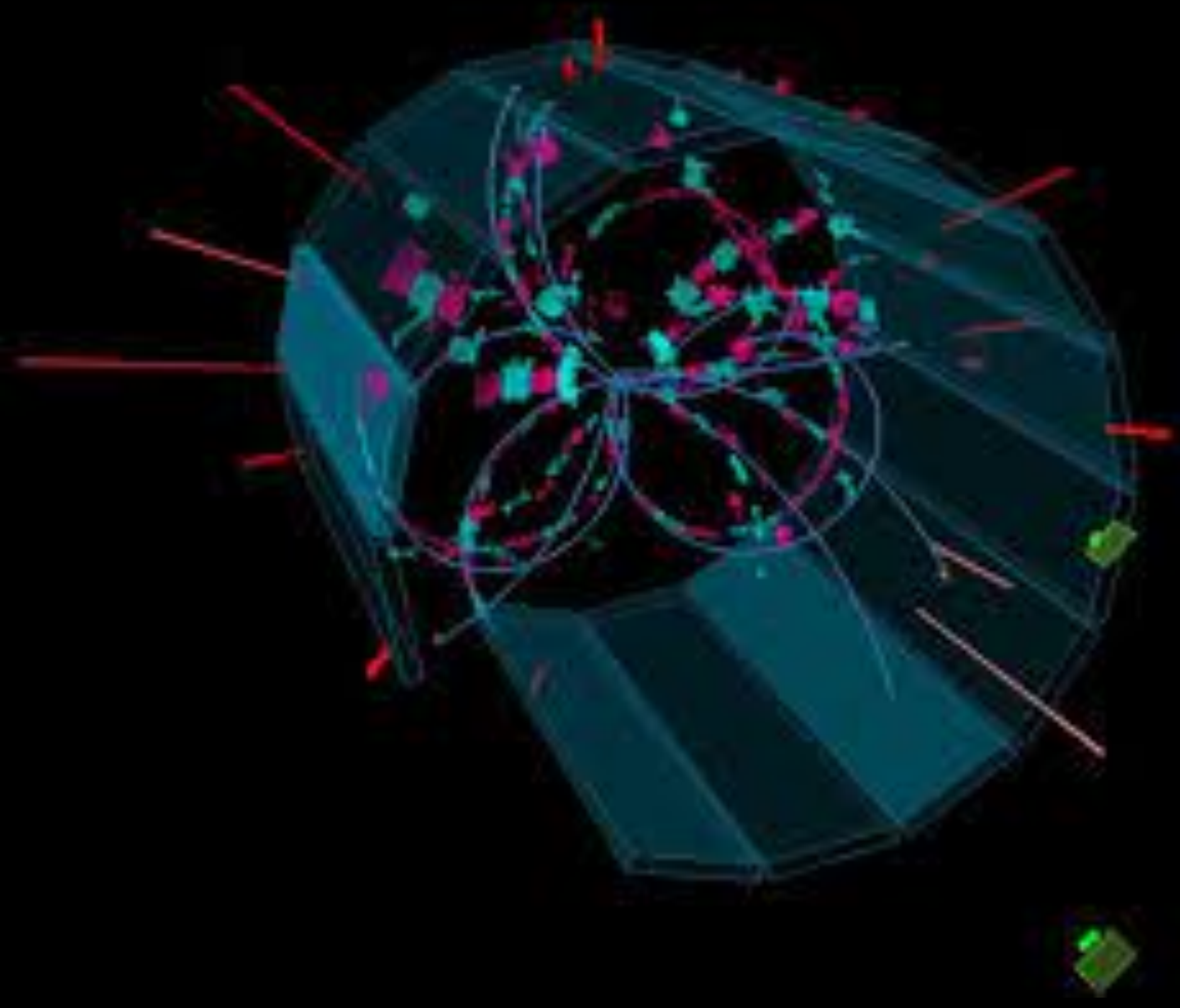
Dark Sectors at Flavor and Neutrino Factories



Pisa
April 2nd 2025

Diego Redigolo
INFN Florence

New search strategies

@ muon factories

arXiv 2006.04795
with L. Calibbi, J. Zupan, R. Ziegler

arXiv 2203.11222
with Y. Jho, S. Knapen

arXiv 2311.17915 and arXiv 2311.17913
with S. Knapen, K. Langhoff, T. Opferkuch

arXiv 2410.13941 with S. Knapen, T. Opferkuch, M. Tammaro

@ neutrino factories

to appear
with M. Borrello, M. Costa

DARK MATTER & NEUTRINOS
as doors to new physics

Overwhelming experimental evidence from experiments

The existence of a cold collisionless fluid is guaranteed by astro and cosmo observables

The existence of a neutrino masses is guaranteed by oscillations exp.

No idea of the fundamental origin of what we see…

What is the dark matter lagrangian?

What dark matter is the origin of neutrino masses?

No guaranteed signal for Dark Matter

Dark Matter can be a singlet of the Standard Model

Dark Matter can be easily be produced non thermally

NO SIGNALS other than Dark Matter gravitational interactions!

No guaranteed signal for Neutrinos

The smallness of Majorana neutrino masses can come from

very heavy steriles   very weakly coupled steriles

$$y_n H L N + M_N N^2$$

SMALL $m_\nu = U^2_{N\nu} M_N$ ⟷ $U_{N\nu} = \frac{y_N v}{M_N}$ SMALL

We might still be lucky…

…and see something

ADVANTAGEOUS PARADIGM FOR ACCELERATORS

The Dark Matter is light thermal relics

For example SM neutrinos are a component of the dark matter today and are easily produced at accelerators while their relic background is difficult to unveil

The neutrino mass comes from inverse seesaw

$$y_n HLN + M_N N\bar{N} + \mu_N N^2$$

SMALL $m_\nu = U^2_{N\nu}\mu_N$ $\xleftrightarrow{\mu_N \ll M_N}$ $U_{N\nu} = \frac{y_N v}{M_N}$ LARGE

THE DARK SECTOR

Accepting the existence of a Standard Model singlet it is useful to develop an EFT approach and explore the possible mediation channels

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

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Lowest dimensional portals $\xrightarrow{\text{Very true}}$ *Largest rates*

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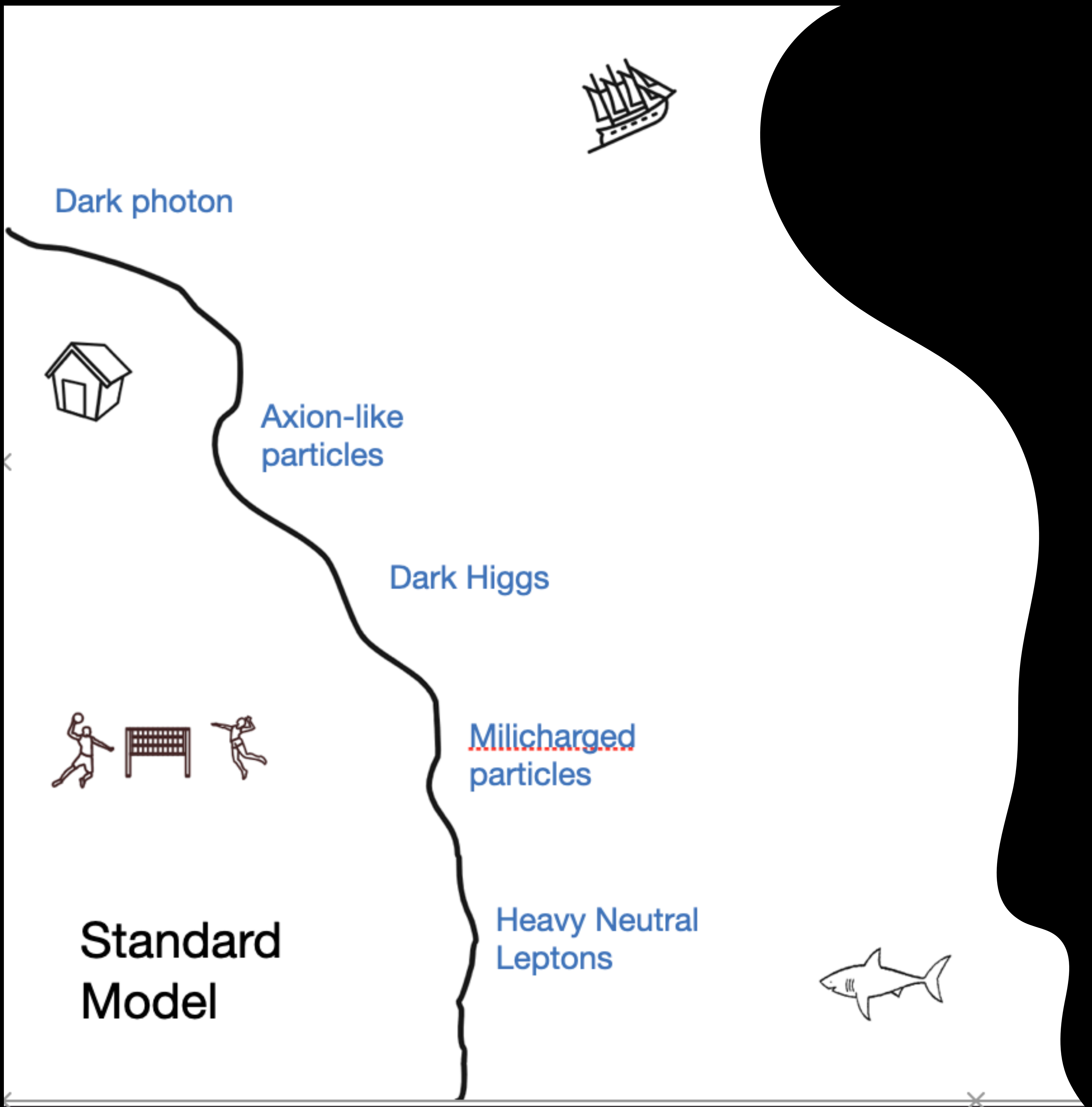
Lowest dimensional portals $\xrightarrow{\text{Very true}}$ *Largest rates*

$\mathcal{O}_{\rm DS} = \{\phi, V, N\}$ *portal mediated by a fundamental particle {scalar, vector, fermion} are the ones with the largest rates*

EXPLORING THE DARK SECTOR LANDSCAPE



$$\mathscr{L}_{\mathrm{ALP}} = \frac{\partial_\mu a}{2f_a}\bar{f}_i C^A_{f_i}\gamma_5 f_i + \frac{g_{a\gamma\gamma}}{4} a F\tilde{F} + \dots$$

ALP couplings @ dimension 5

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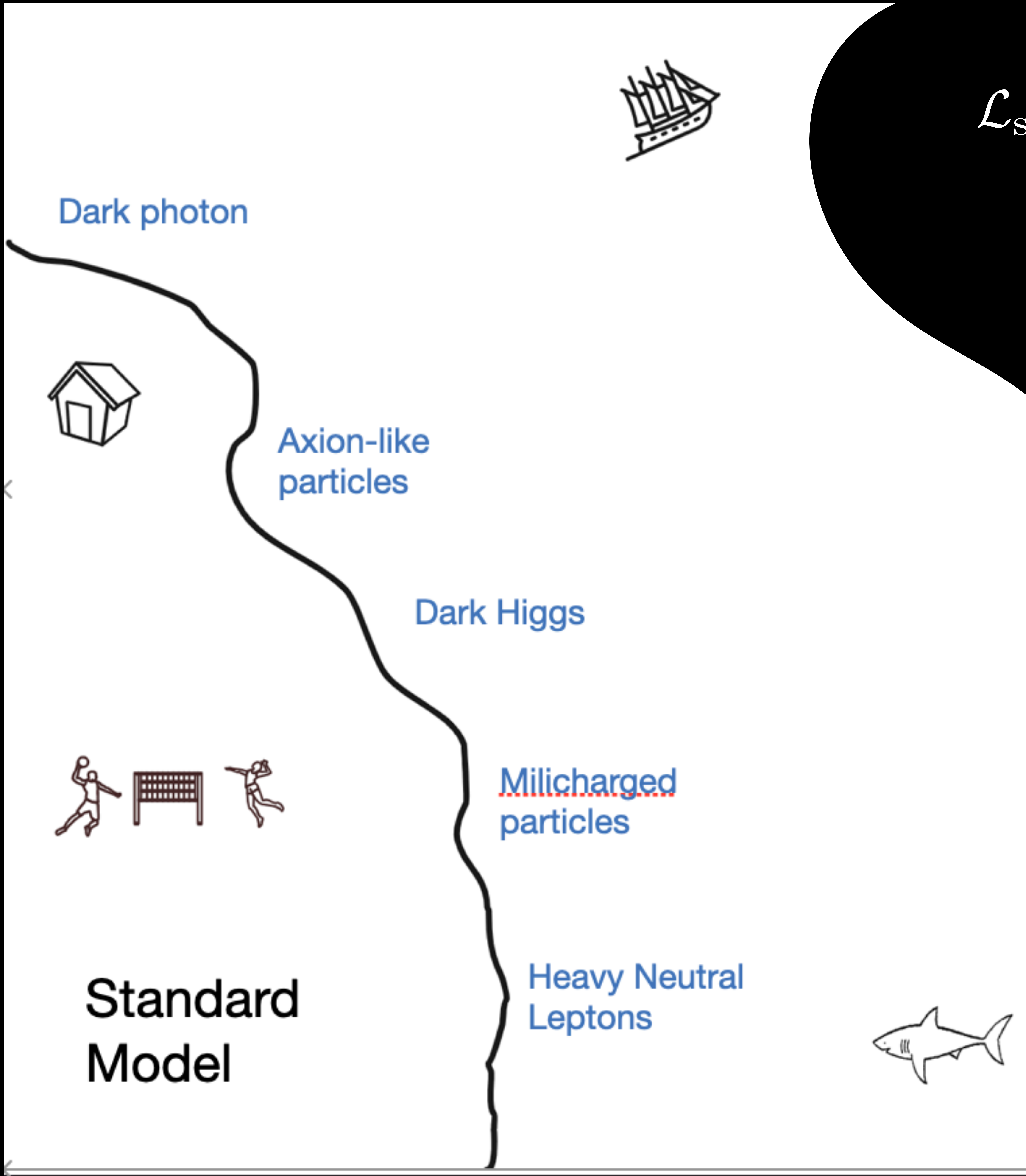

$$\mathcal{L}_{\mathrm{scalar}} = H^\dagger H\left(\kappa S + \lambda S^2\right)$$

- κ *mixing Dark Higgs - SM Higgs*
- λ *SM to double Dark Higgs pairs*

$$\mathscr{L}_{\mathrm{ALP}} = \frac{\partial_\mu a}{2f_a}\bar{f}_i C^A_{f_i}\gamma_5 f_i + \frac{g_{a\gamma\gamma}}{4} aF\tilde{F} + \ldots$$

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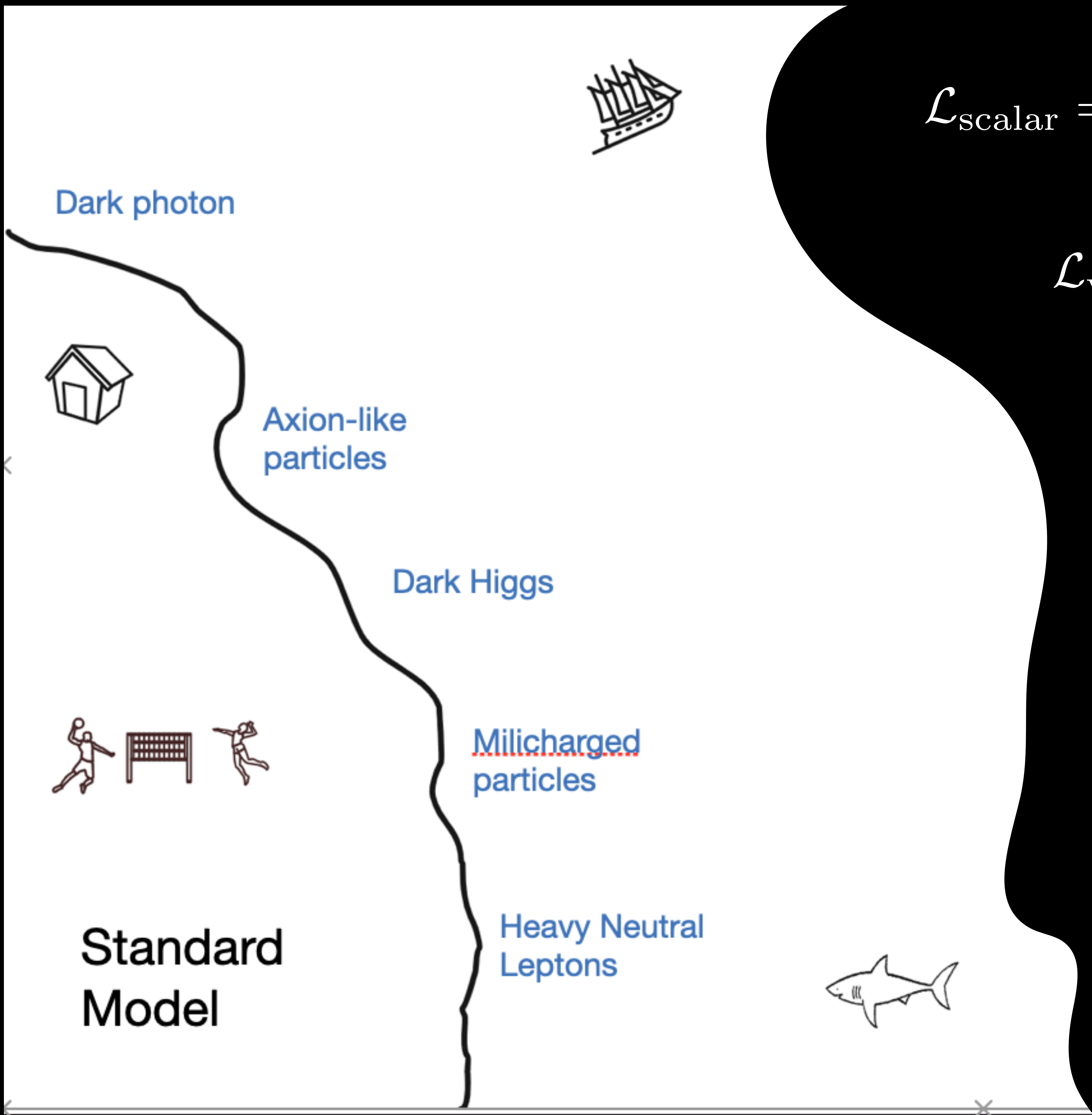

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$$\mathcal{L}_{\text{vector}} = \epsilon B_{\mu\nu} V_{\mu\nu}$$

ϵ mixing Dark photon - photon

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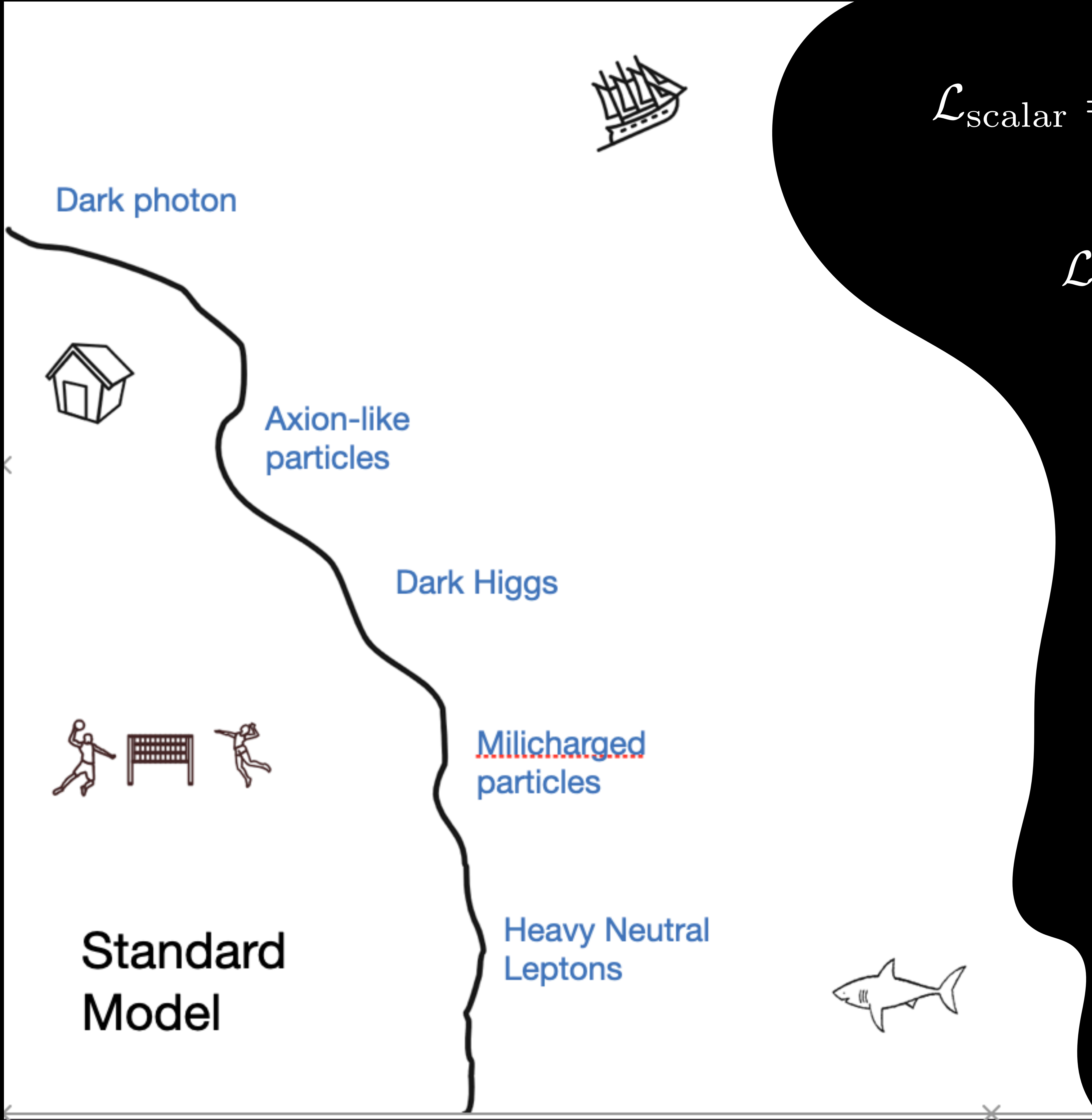

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$$\mathcal{L}_{\rm HNL} = y_N H L N$$

y_N *mixing HNL-neutrino*

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ALP couplings @ dimension 5

Light relic FREEZE-OUT

The existence of the portal drives the dark sector at equilibrium with the visible one

Annihilations into Standard Model set the relic abundance today

↓

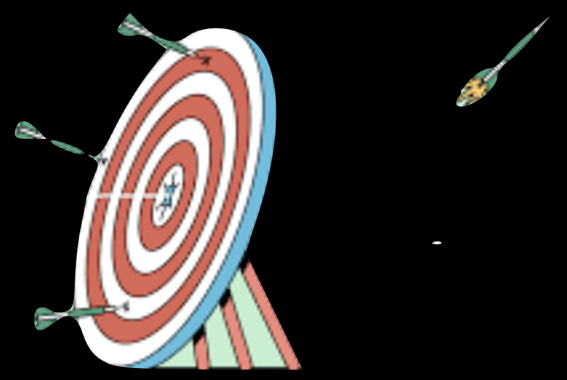
Annihilations need to be strong enough

↓

Lower bound on the interaction strength

↓

Sharp experimental target



If the portal to the dark sector

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

breaks Standard Model accidental symmetries

↓

smaller couplings can be probed @ accelerators

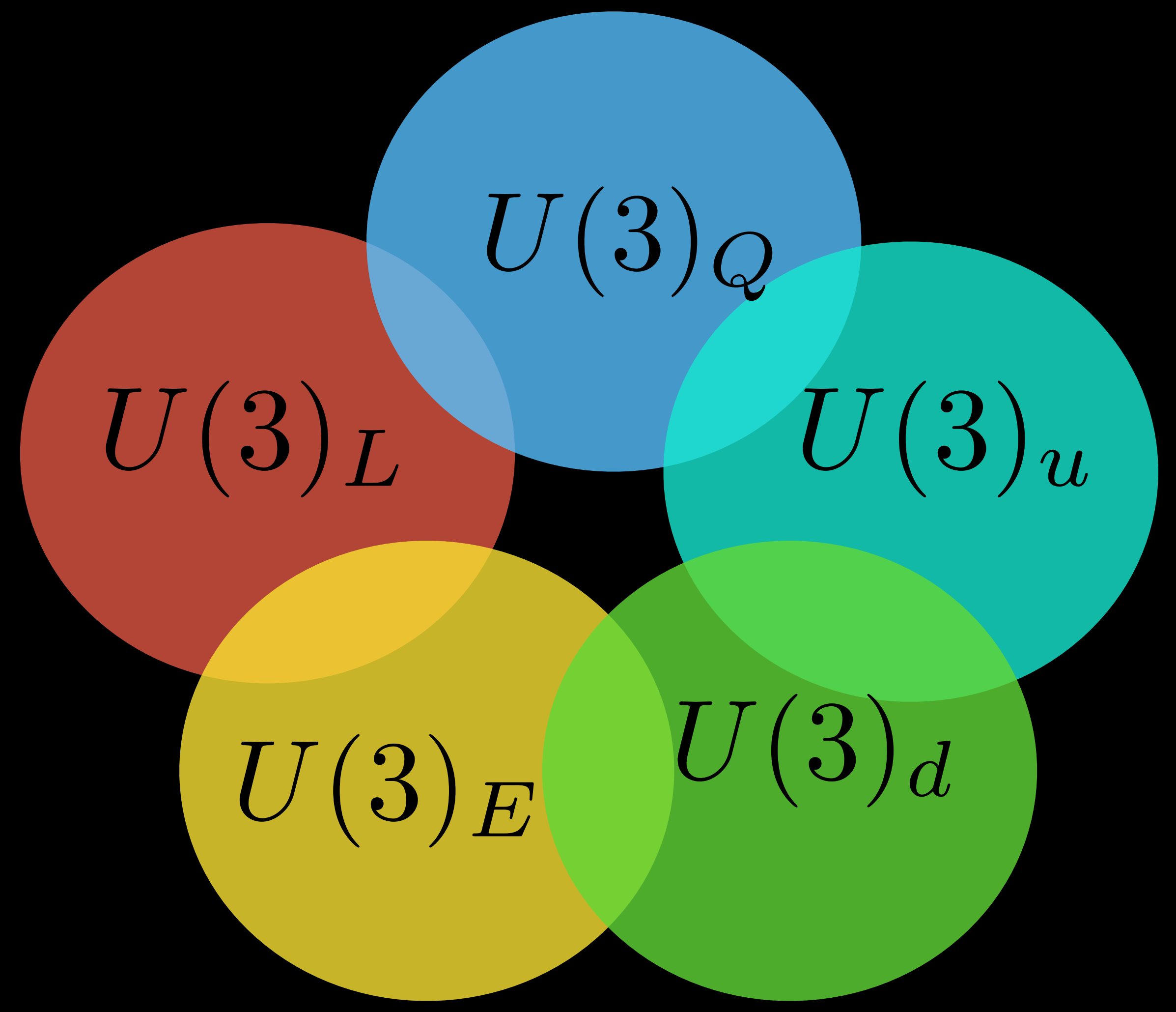
↓

compatible with no thermal contact between the visible and the dark sector

↓

Freeze-in and/or non-thermal production can give a target

Example: Flavor violating axions



Peccei-Quinn charges can be flavor dependent

Q_i, u_i, d_i, E_i, L_i

Calibbi-Goertz-Redigolo-Ziegler-Zupan 2016

Ema-Hamaguchi-Moroi-Nakayama 2016

$$\frac{\partial_\mu a}{2f_a}\bar{f}_i C^A_{f_i}\gamma_5 f_i + \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}_{\mu\nu}$$

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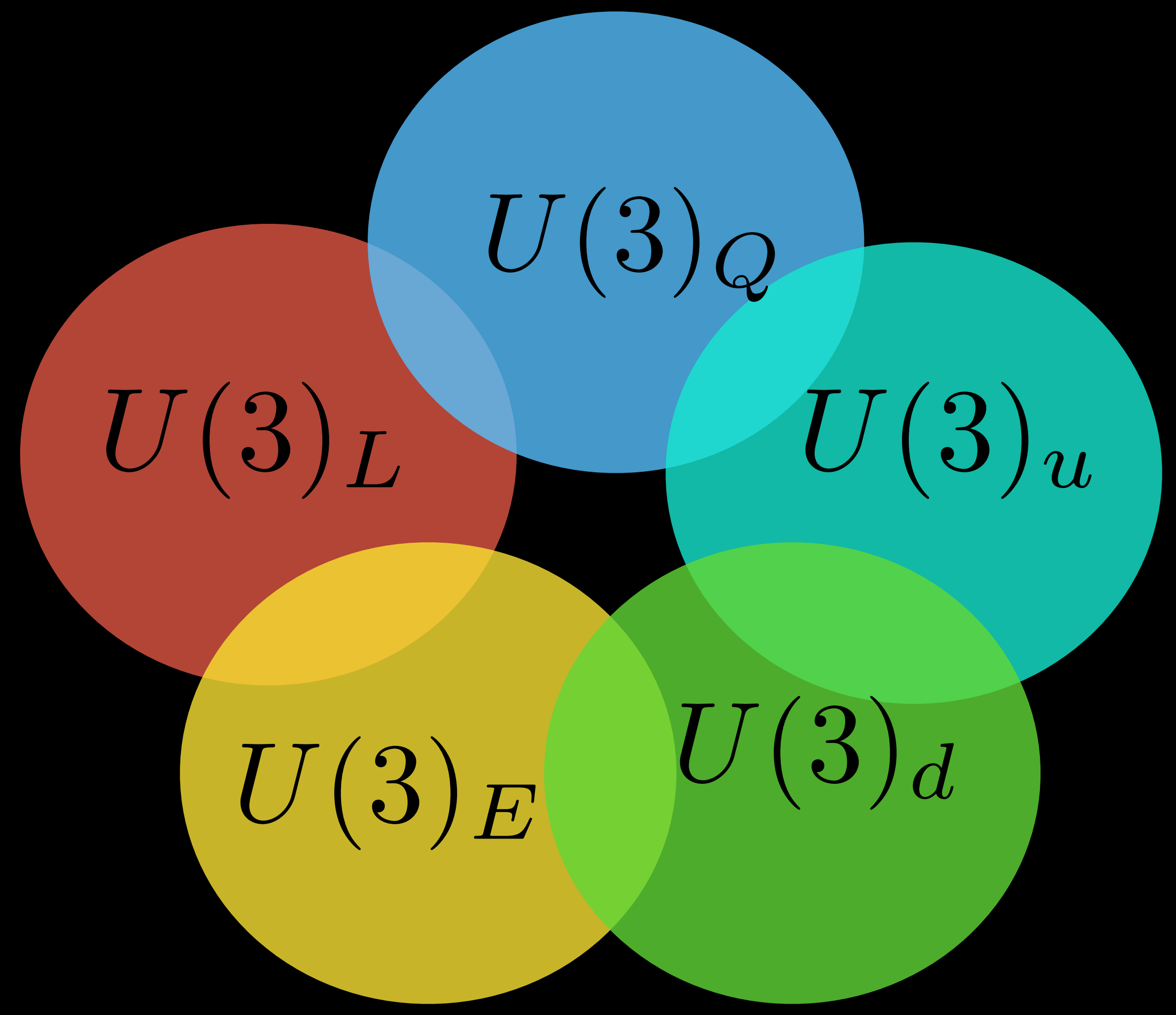

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$$\sum_{i\neq j}\frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu(C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5)f_j$$

Feng-Murayama-Moroi-Shnapka 1998

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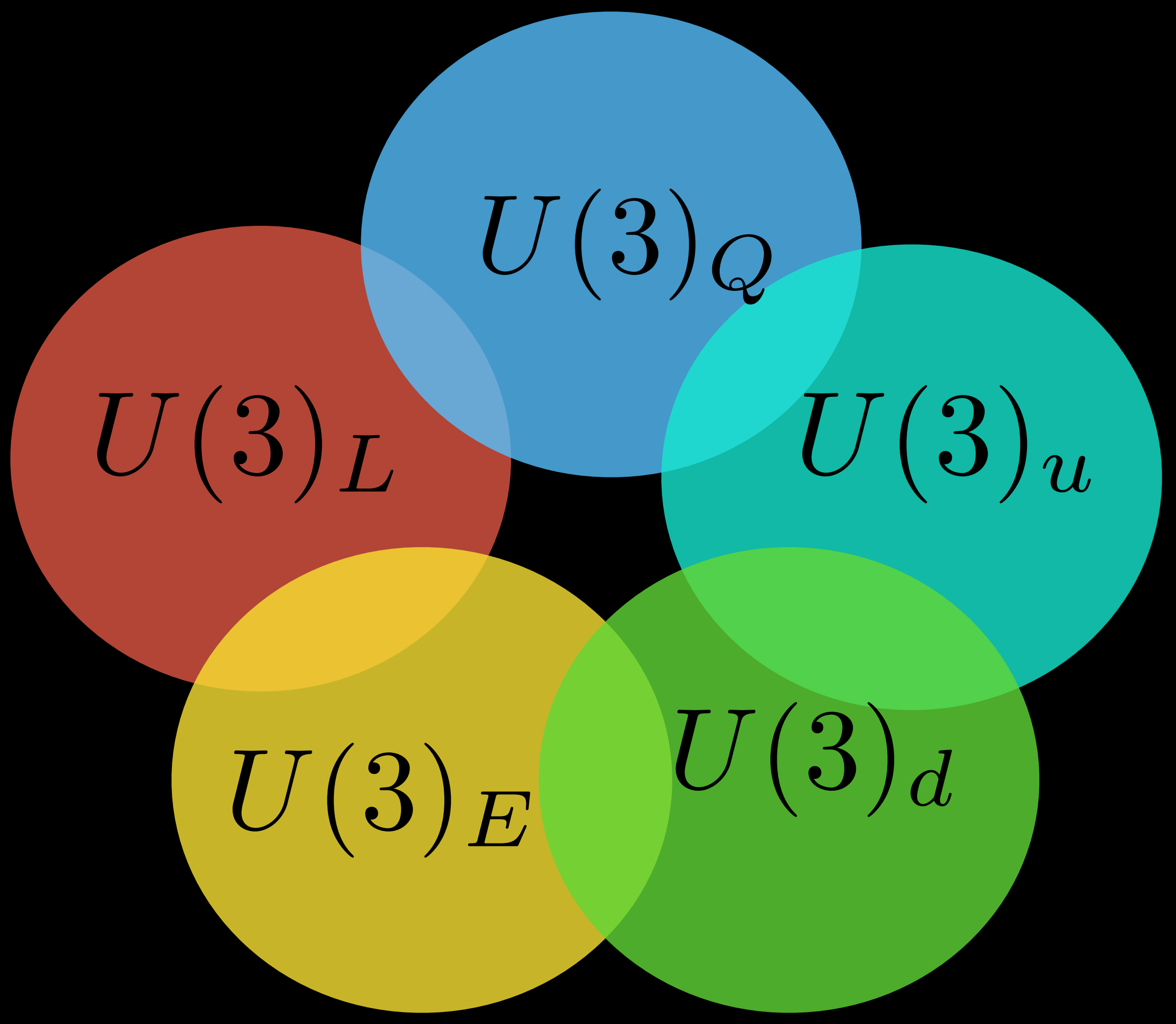

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The hierarchy FLAVOR-DIAGONAL vs FLAVOR-VIOLATING depends on the UV flavor theory

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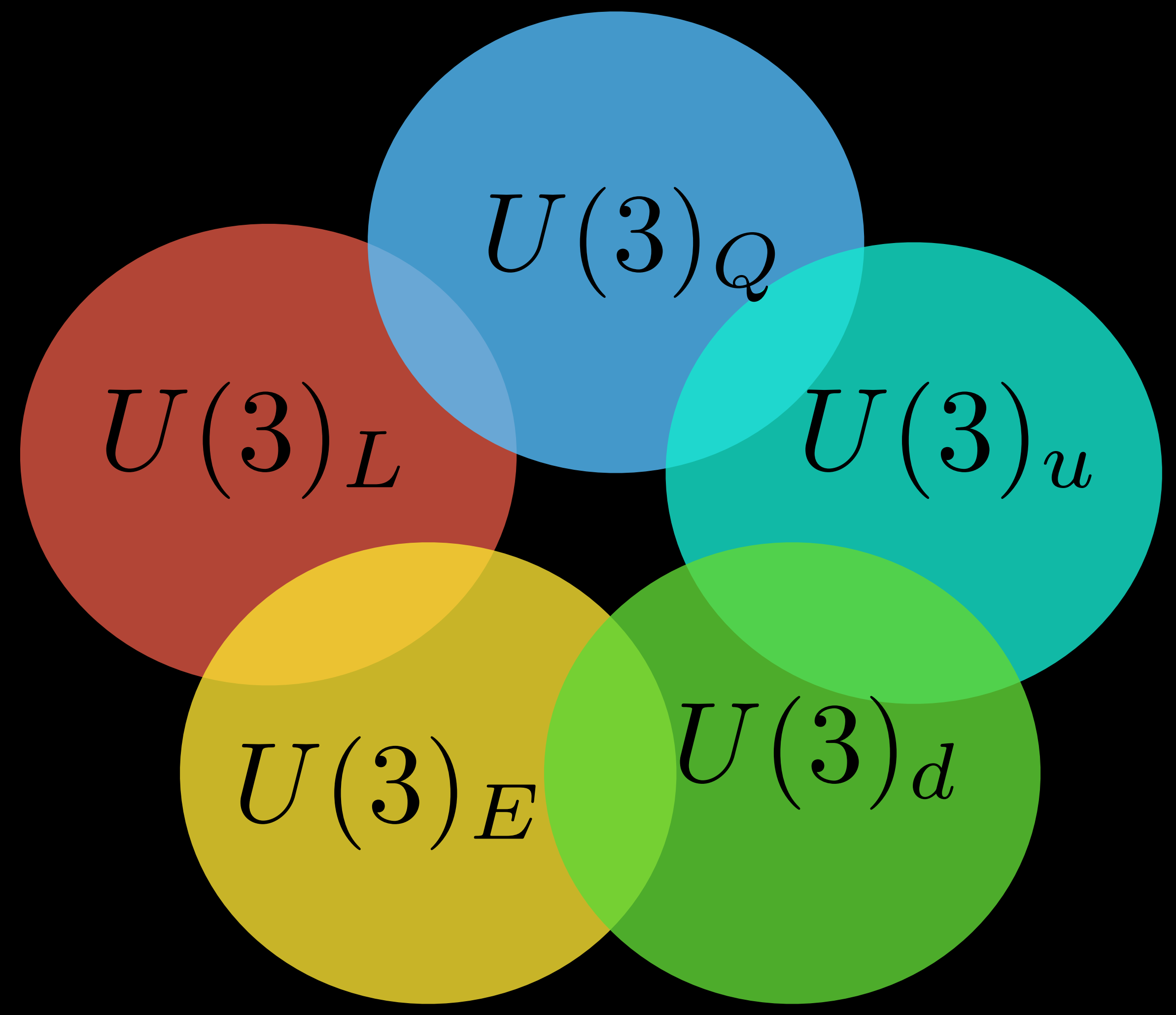

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The hierarchy FLAVOR-DIAGONAL vs FLAVOR-VIOLATING depends on the UV flavor theory

Flavor Anarchy: $C^{A,V}_{ij}(\Lambda_{\rm UV}) \sim \mathcal{O}(1)$

Minimal Flavor Violation: $C^{A,V}_{ij}(\Lambda_{\rm UV}) = 0$

Flavor violating axions freeze-in

The axion abundance is produced through leptonic FV decays

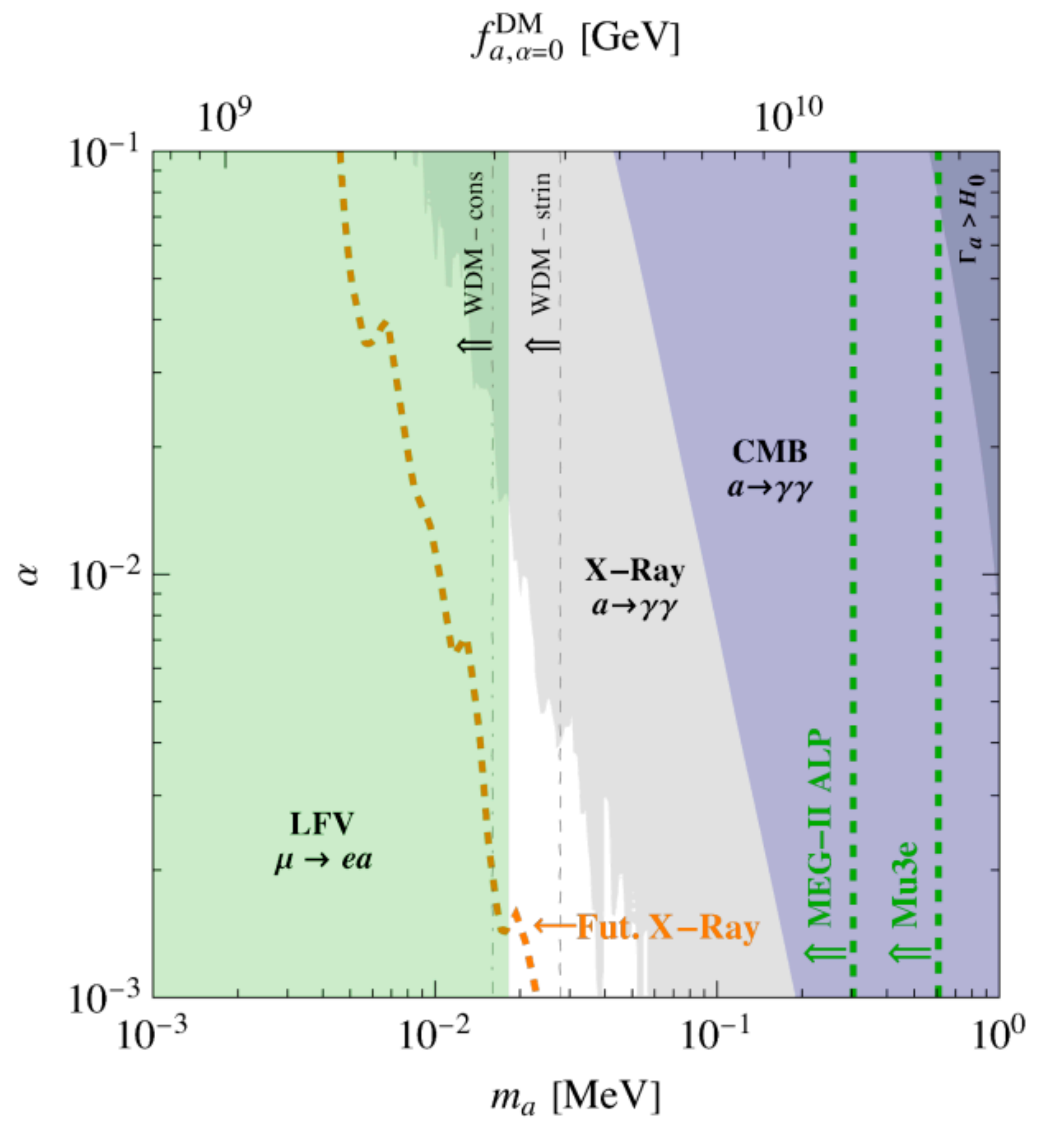
$$\Omega_a h^2|_{\ell_i \to \ell_j a} \approx 0.12 \left(\frac{m_a}{50\,\text{keV}}\right)\left(\frac{m_{\ell_i}}{m_\tau}\right)\left(\frac{5\times 10^9\,\text{GeV}}{f_a/C_{\ell_i\ell_j}}\right)^2\left(\frac{75}{g_*(m_{\ell_i})}\right)^{3/2}$$

$$\tan\alpha \equiv C_{\ell_i}/C_{\ell_i\ell_j}$$

The axion should be long-lived to avoid constraints from gamma-lines

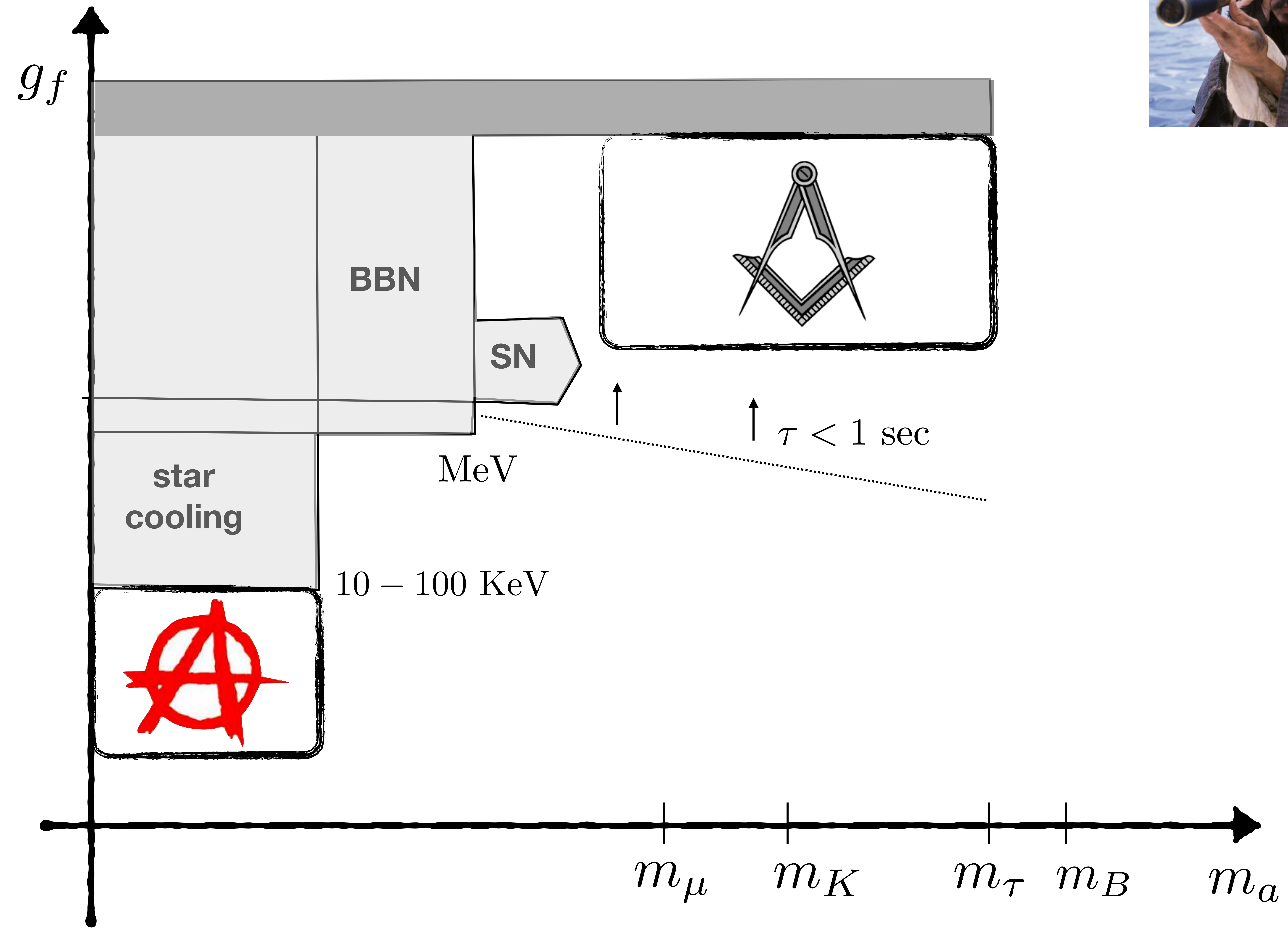
$$\Gamma_{a\to\gamma\gamma} \approx \frac{\alpha_{\rm em}^2}{64\pi^3}\frac{m_a^3}{f_a^2}\left|\sum_i C^A_{\ell_i\ell_i}\frac{m_a^2}{12 m_{\ell_i}^2}\right|^2$$

$$\tau_a^{\gamma\gamma} \gtrsim (10^{26} \to 10^{28})\,\text{sec}$$



This simple DM production mechanism sets a target for LFV experiments

ALP theory landscape



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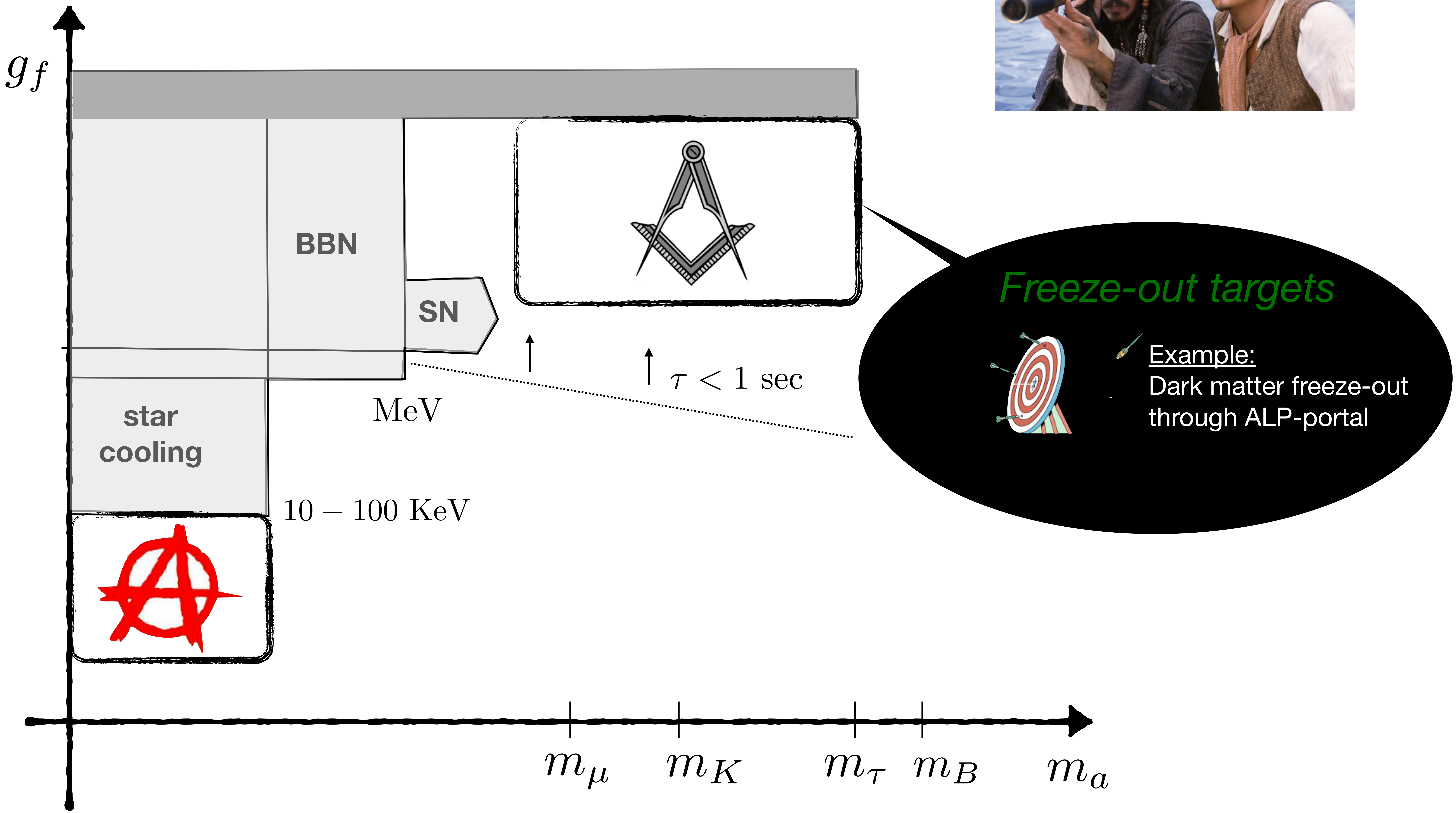

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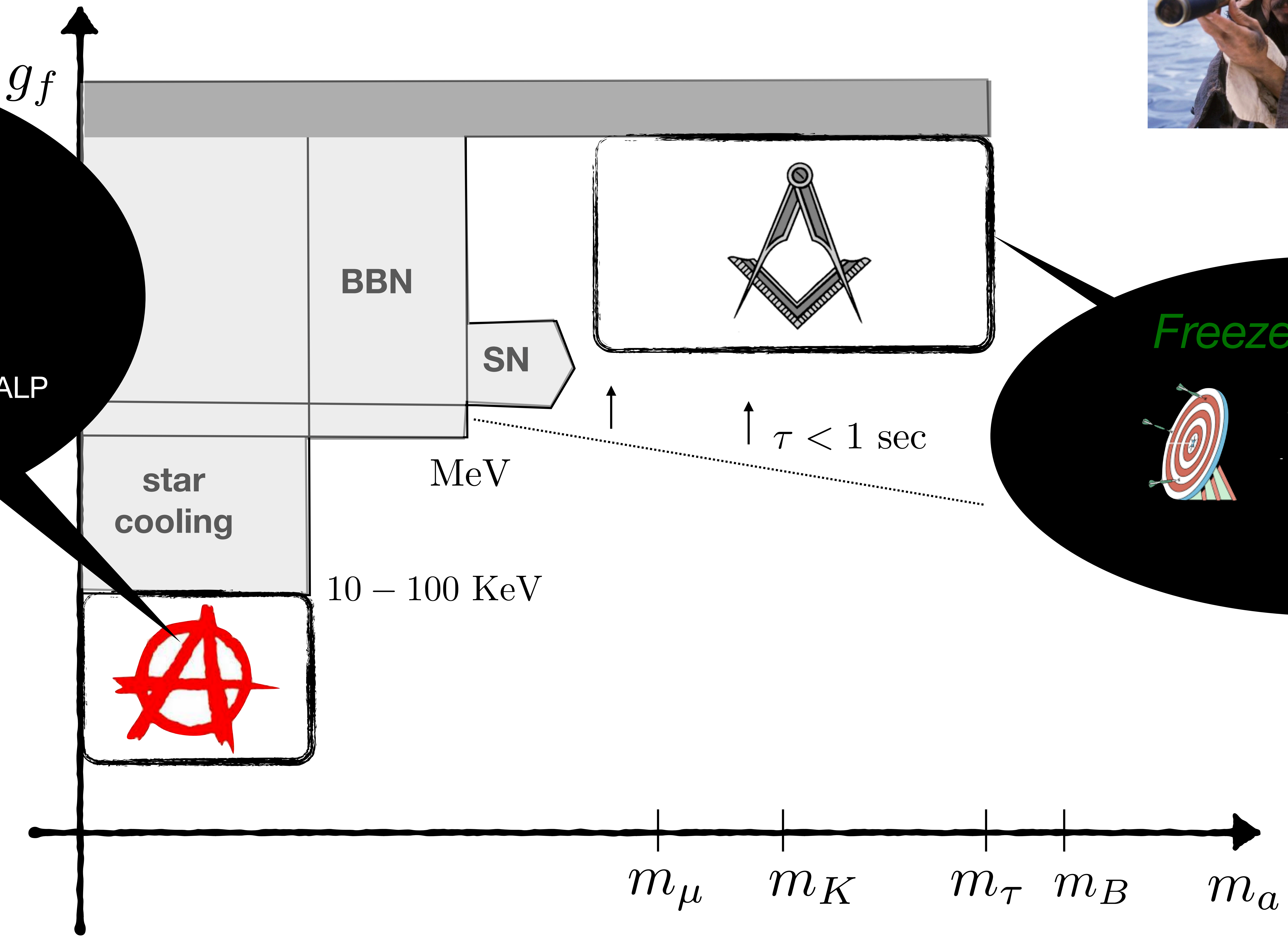


Breaking of SM accidental symmetries

Example:
Lepton flavor violating ALP
Freezing-in

Freeze-out targets

Example:
Dark matter freeze-out through ALP-portal

New ideas to probe dark sectors targets

Triggering data that would otherwise get lost

Example @

Squeezing the data as much as we can

Example @

Triggers

Enormous luminosities poses trigger challenges

We need to know what to look for in advance

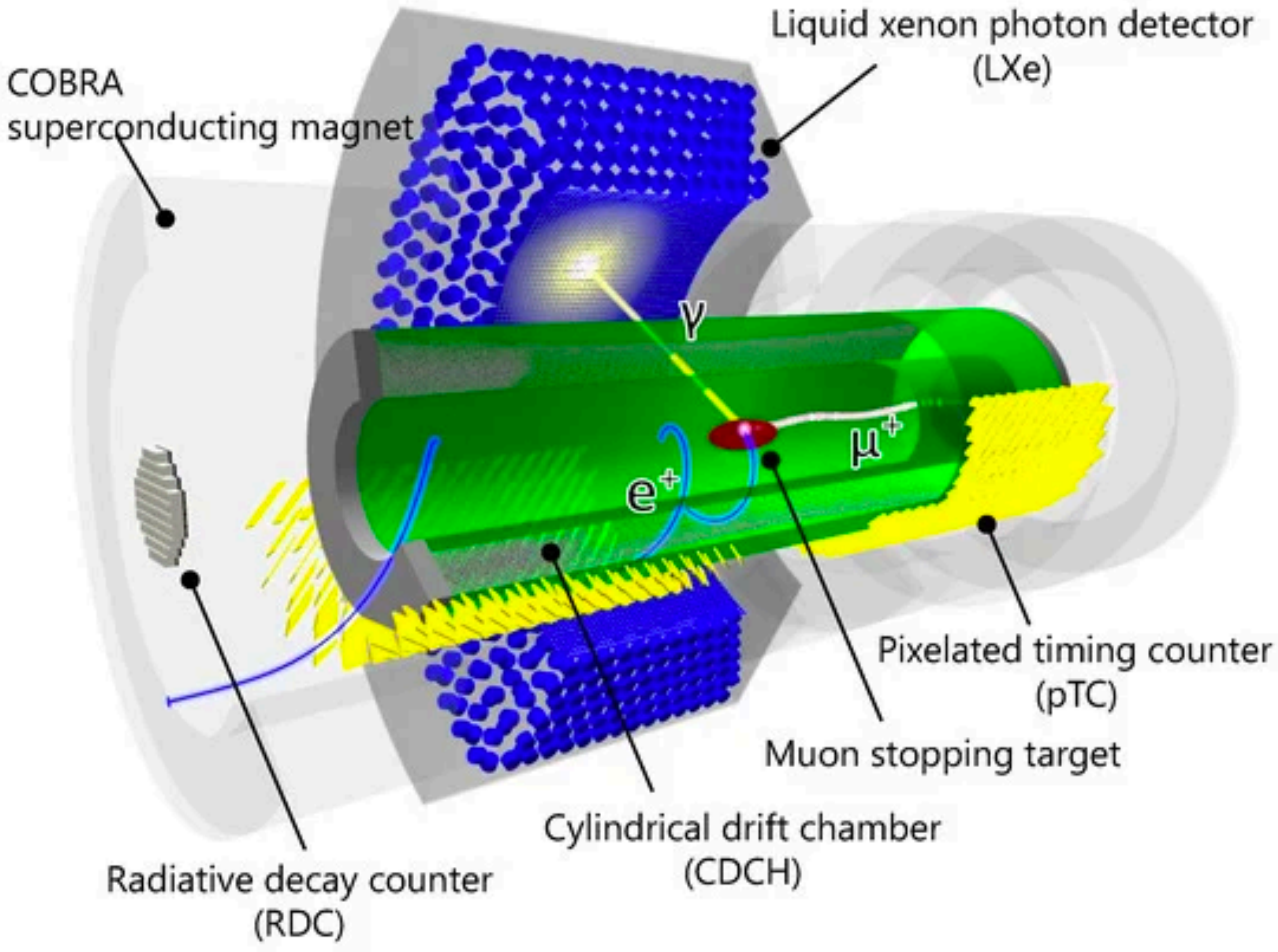
MEG II as an example

see arXiv 2203.11222

with Y. Jho, S. Knapen

MEG II

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ MEG 2016



Trigger level info:

1) Photon energy by liquid Xenon scintillator

2) hit on the timing counter

Offline:

3) full mesure of the positron momentum

Trigger Selection

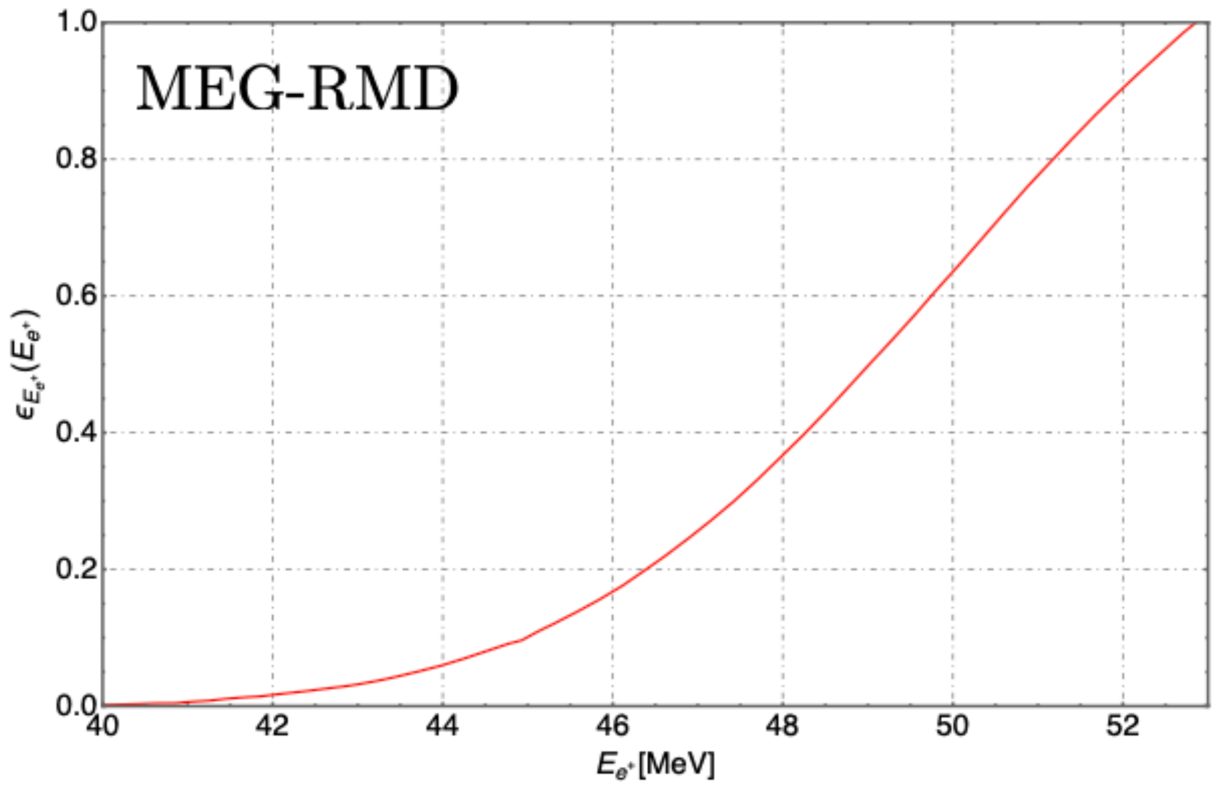
$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ MEG 2016 $\longleftrightarrow$

1) very high intensity
2) very exclusive trigger targeted at $\mu \to e\gamma$

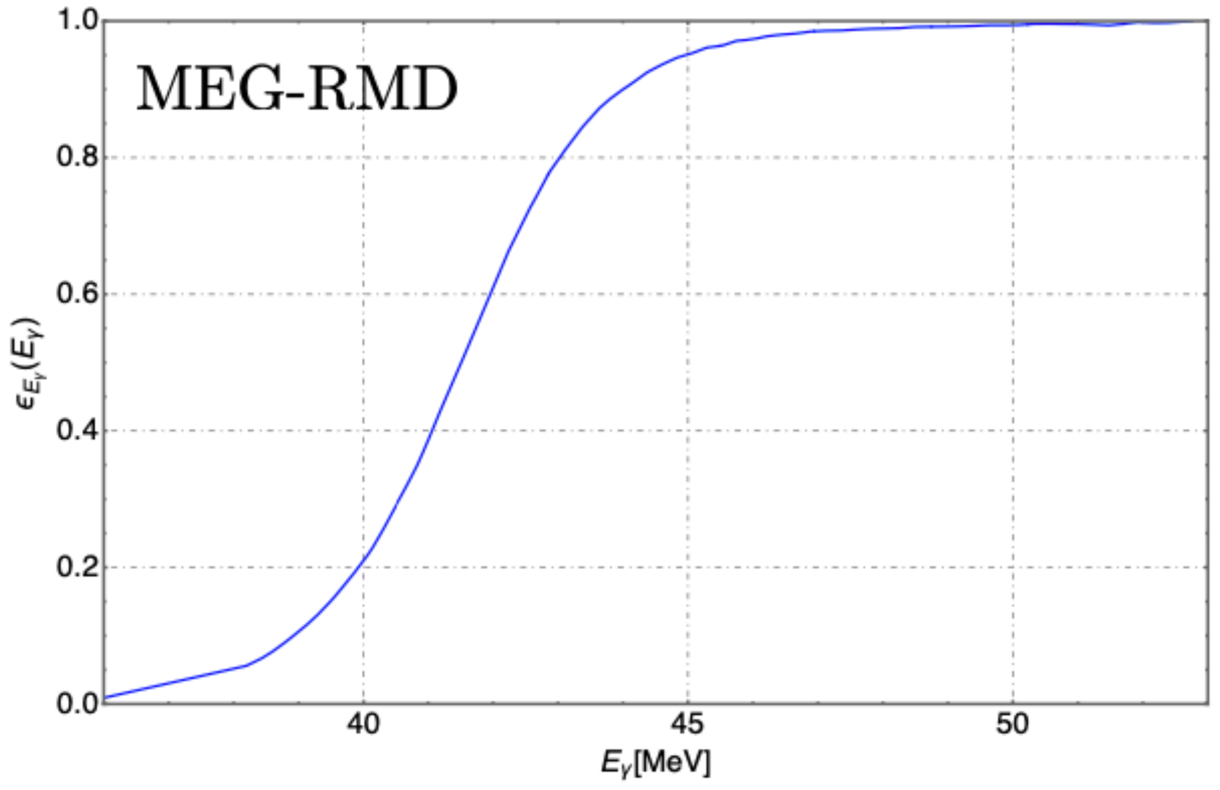
The trigger maximize the efficiency to back to back positron-photon of $E = m_\mu/2$

See Galli et al. *JINST 9 (2014)*

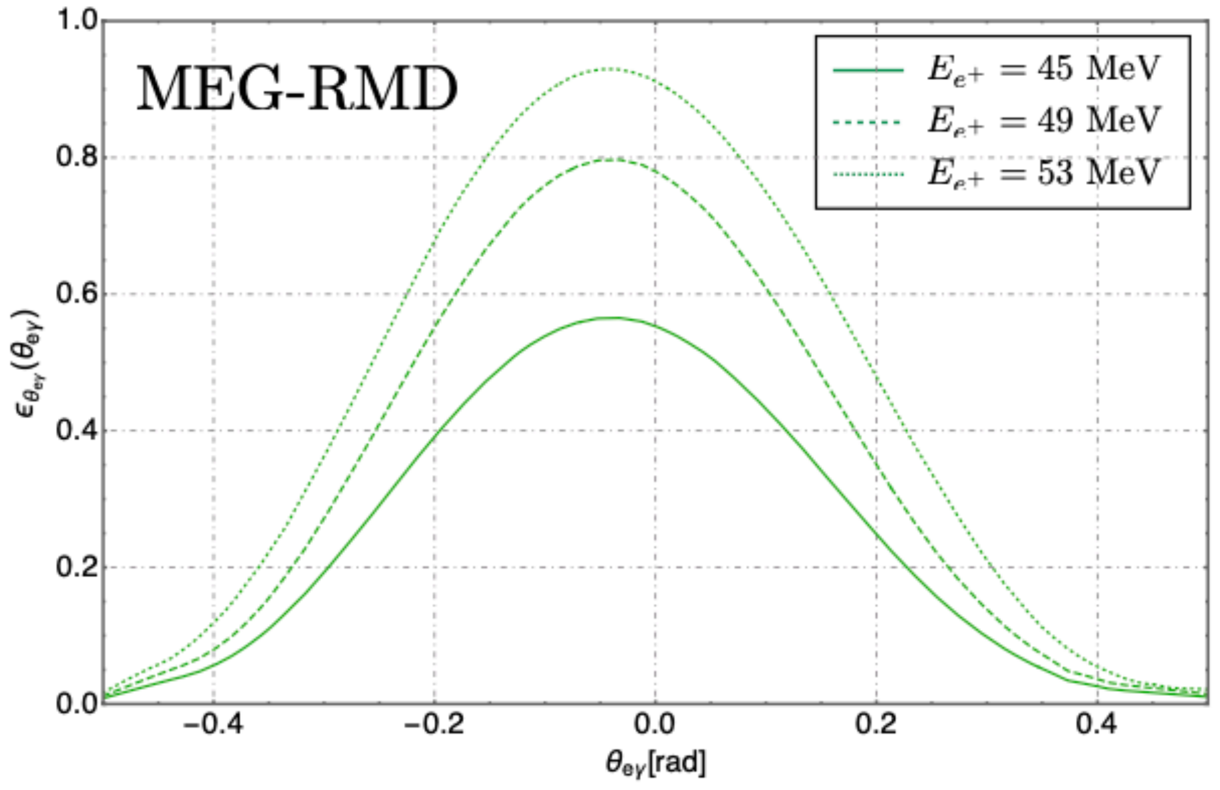
Positron energy >45 MeV hardware



Photon >45 MeV @ trigger level



back to back topology @ trigger level



Taken from *MEG-RMD measurement 1312.3217*

In numbers…

Besides $R_{\mu^+}^{\mathrm{MEG}} = 3 \times 10^7 \mu^+/\mathrm{sec}$ intensity

Very little data can be saved on disk or analysed offline at MEG II

The maximal allowed stream is around 10 Hz

Online the trigger should select 1 "interesting" muon event out of 10^7

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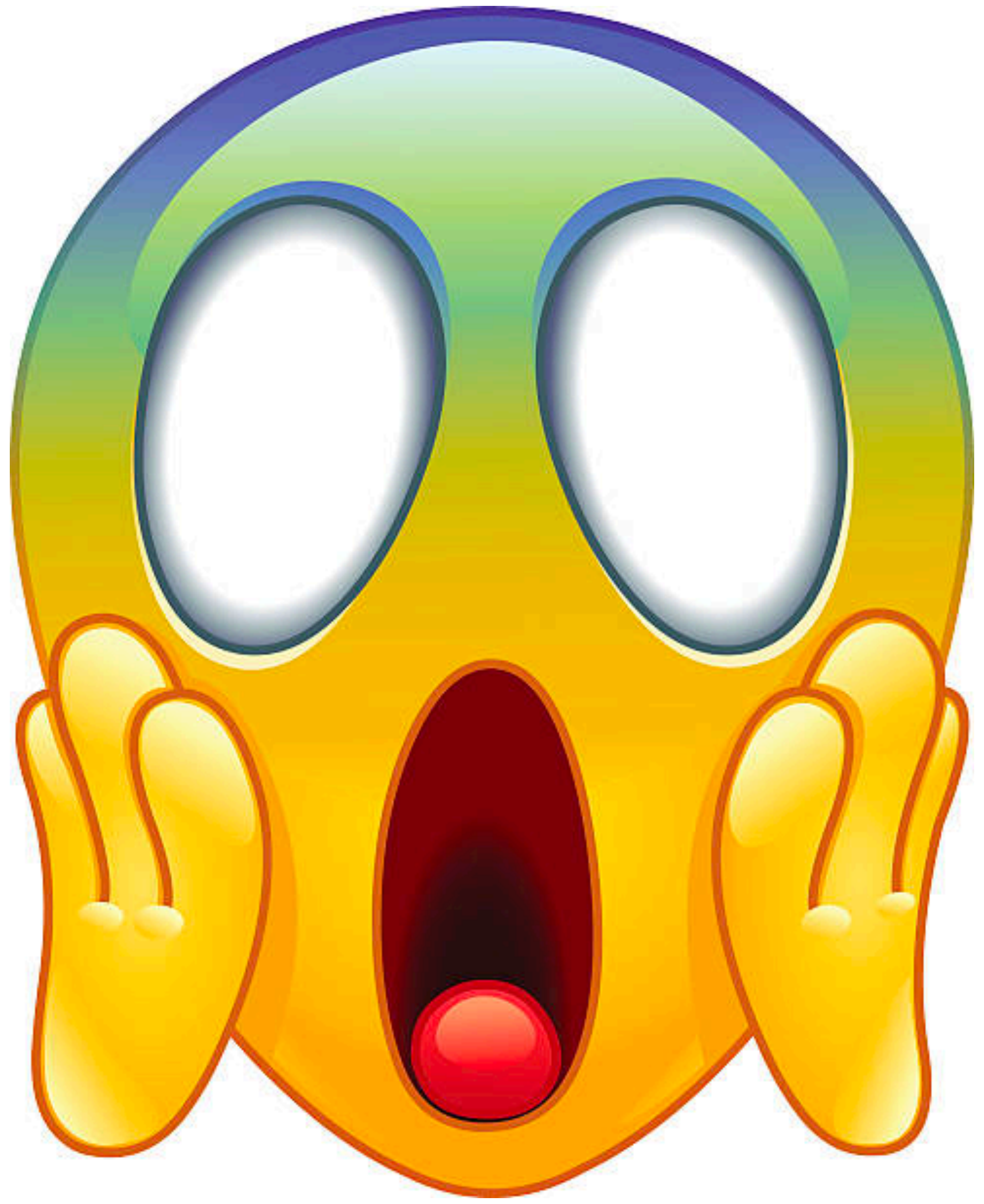
All the rest of the data is lost!

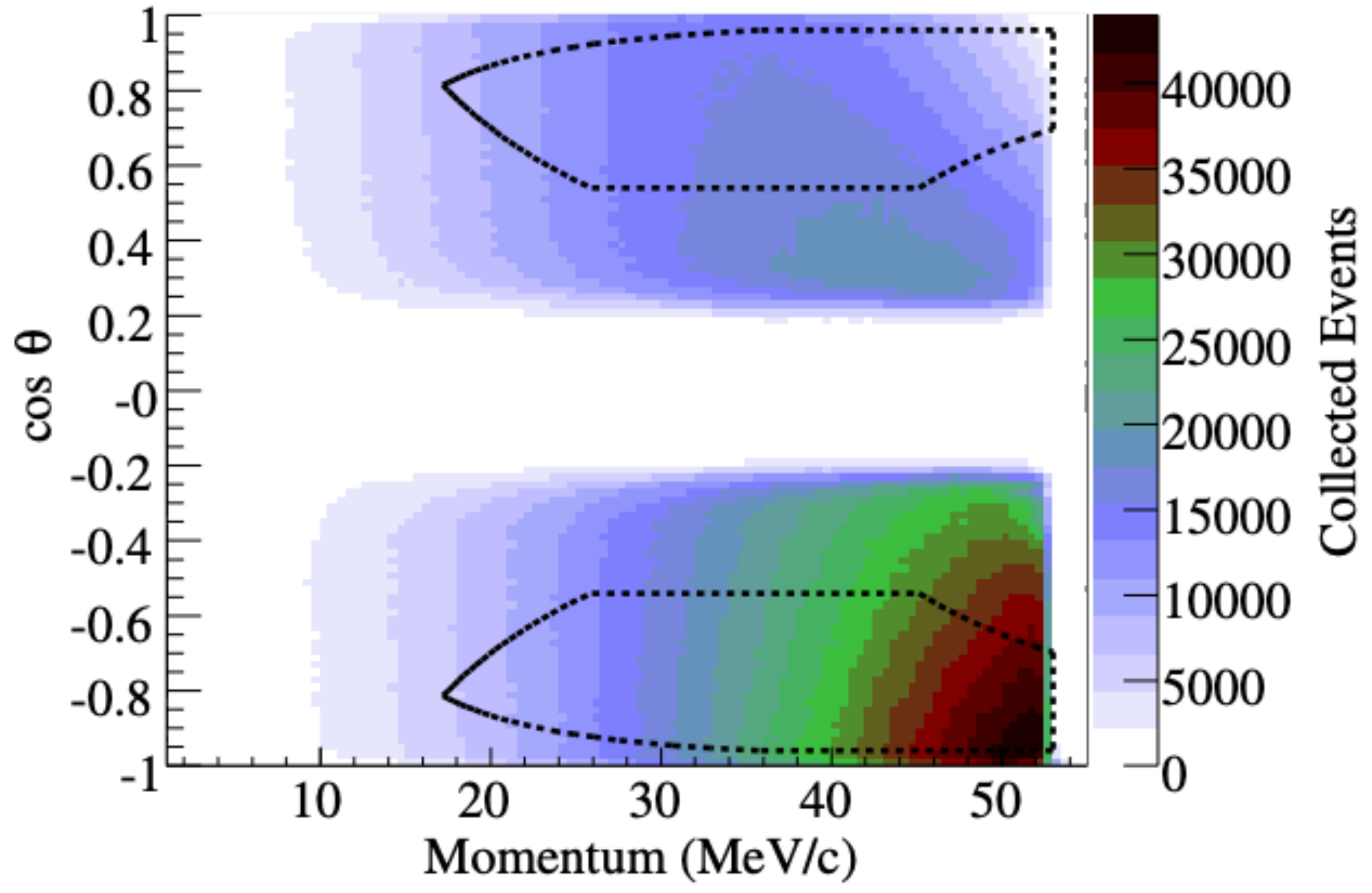


The hunt for rare muon decays with missing energy

$\mu \to ea$

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

See. *TWIST 1409.0638*



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Muon polarization can help discriminating the signal

See *L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795*

bkd suppressed in the fwd region

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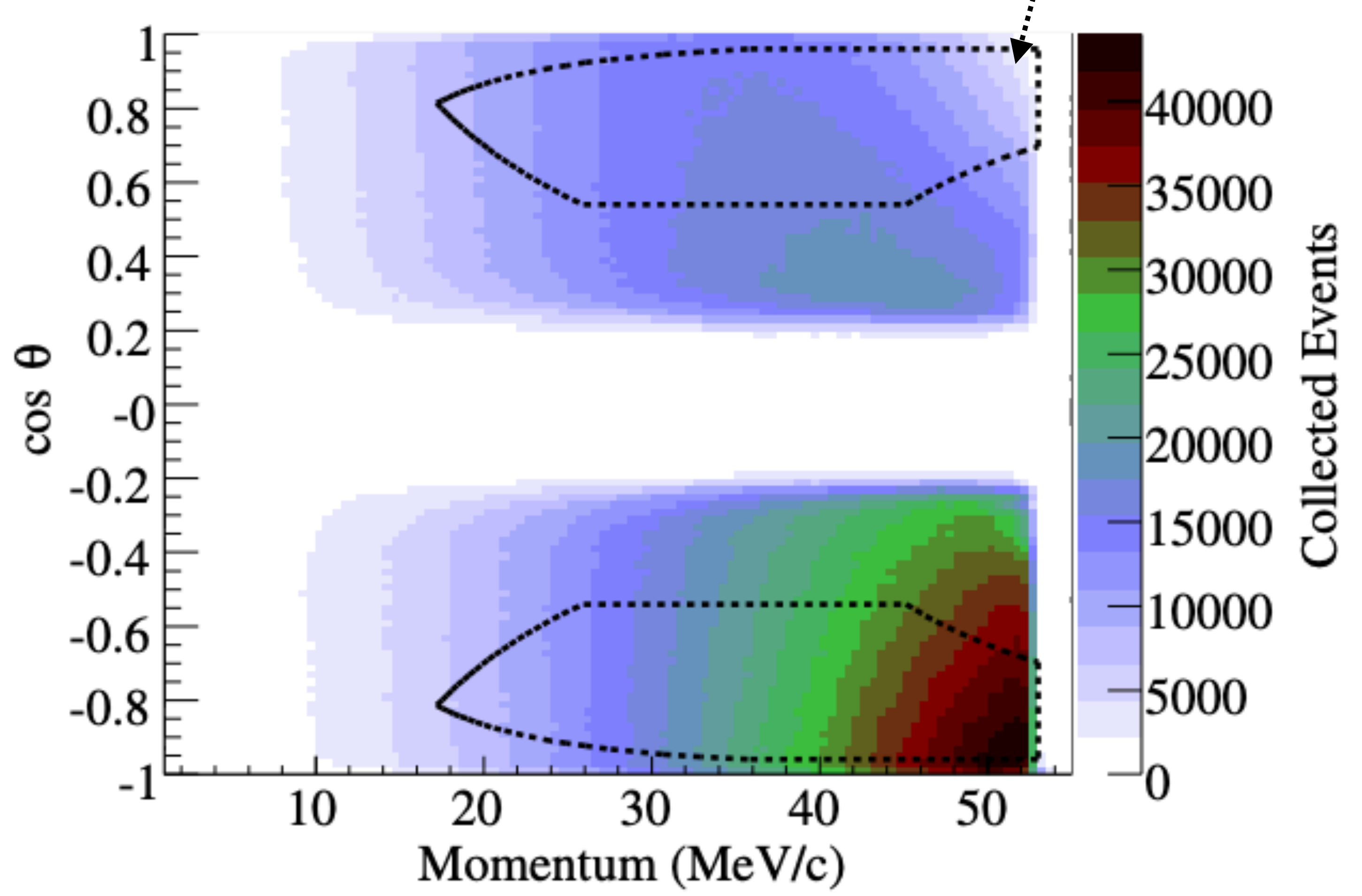

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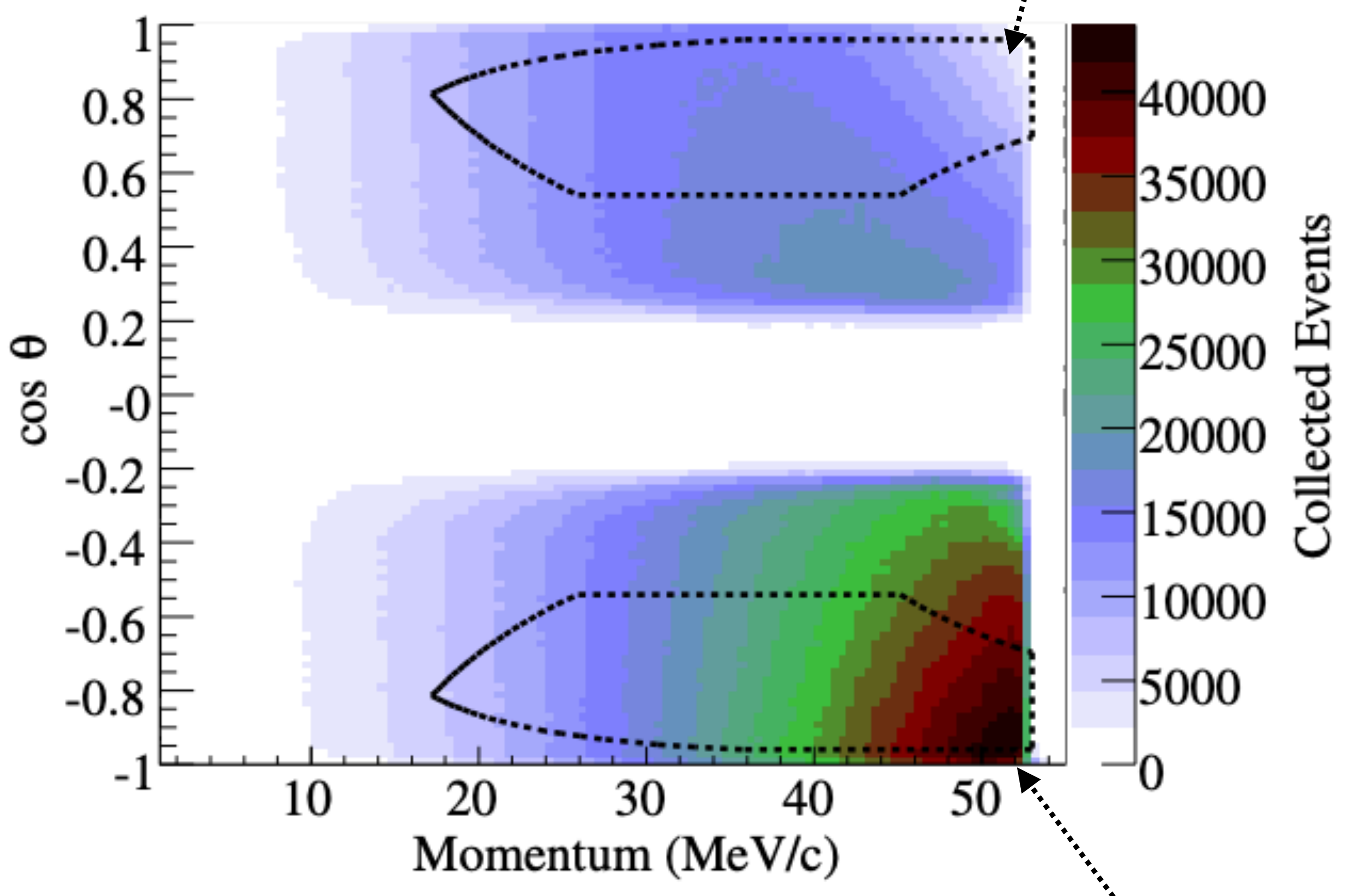

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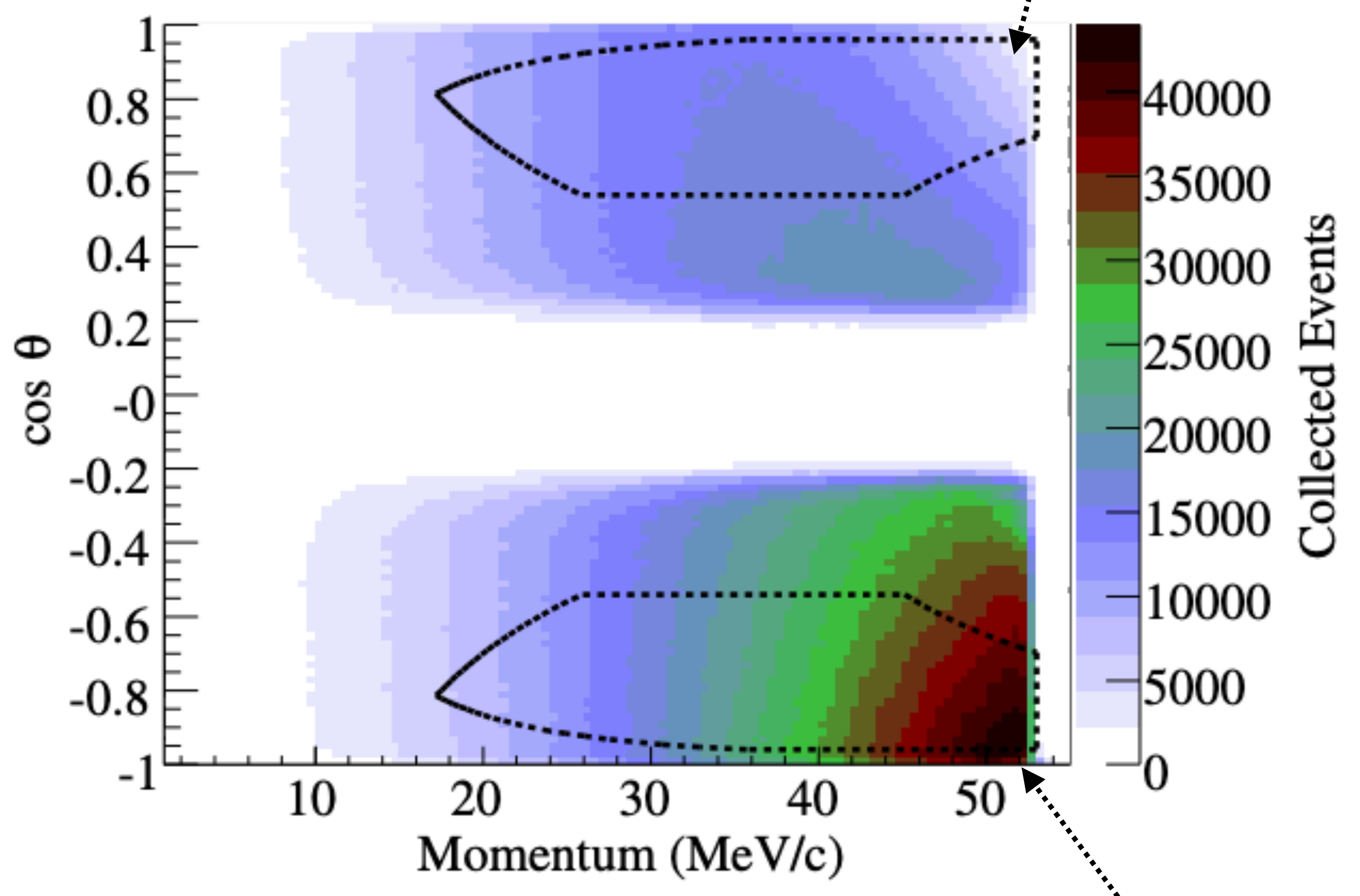

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$$\mu \to e a \gamma$$

The extra photon helps constructing a missing mass distribution which is not used for calibration

The price to pay is a reduced signal partially compensated by the low energy threshold of the detector

See *Jho, Knapen, D.R. 2112.07720*

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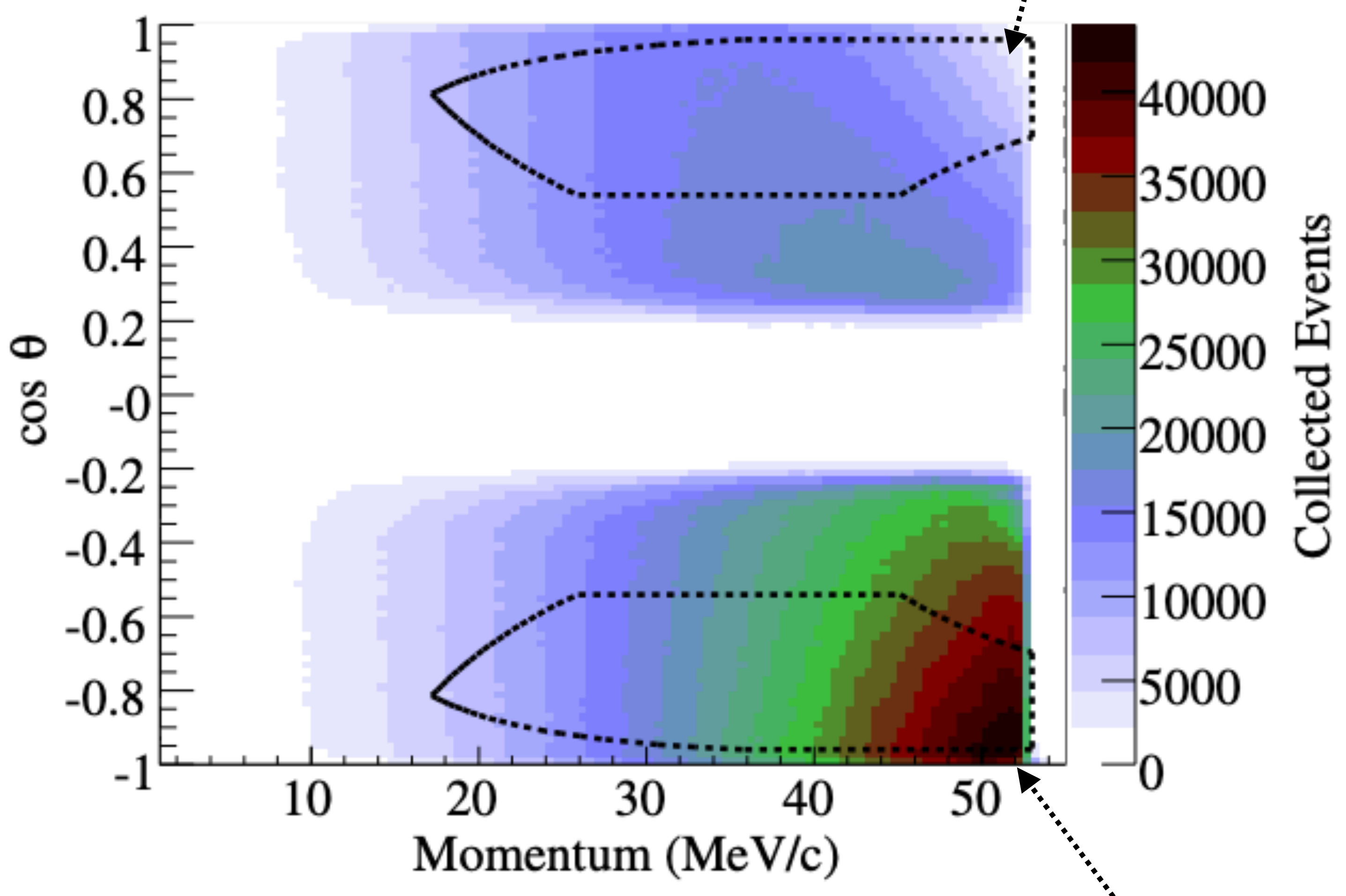

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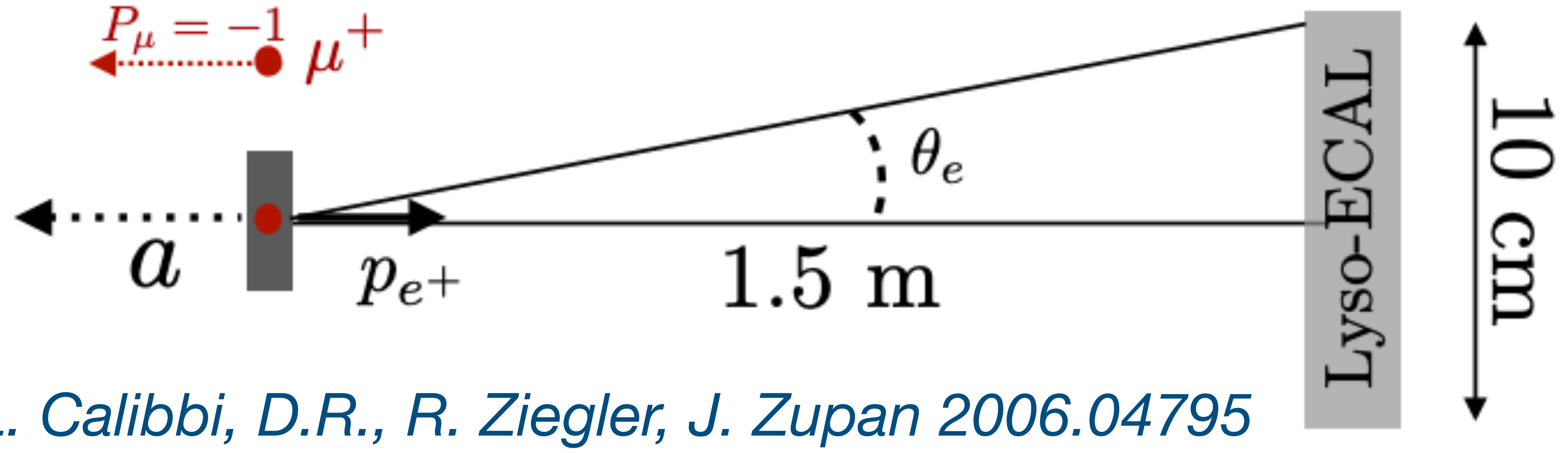
$\mu \to 3ea$

The three electron final state can be seen easily at Mu3e (which hunts for three tracks)

The price to pay is a reduced signal which partially compensated by the low virtuality of the photon

See *Knapen, Langhoff, Opferkuch, D.R., 2311.17915*

Looking forward for right-handed ALPs



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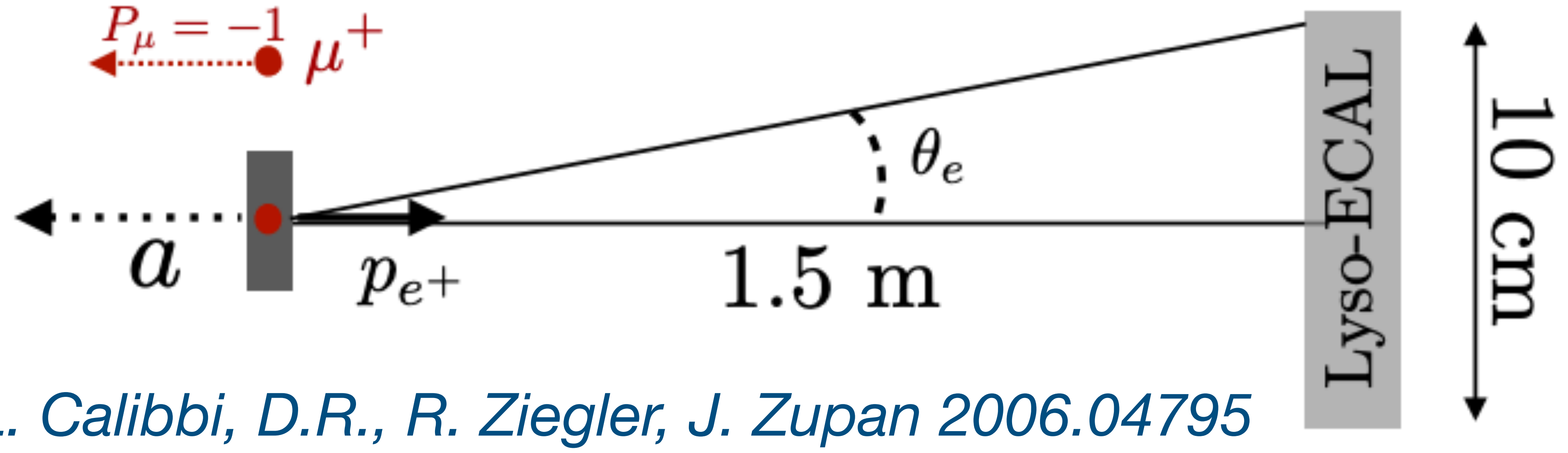

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Background suppression in the fwd direction requires:

1) good momentum resolution $\delta x_e \sim \%$

2) purely polarized muon beam $\delta P_\mu \sim 10^{-2}$

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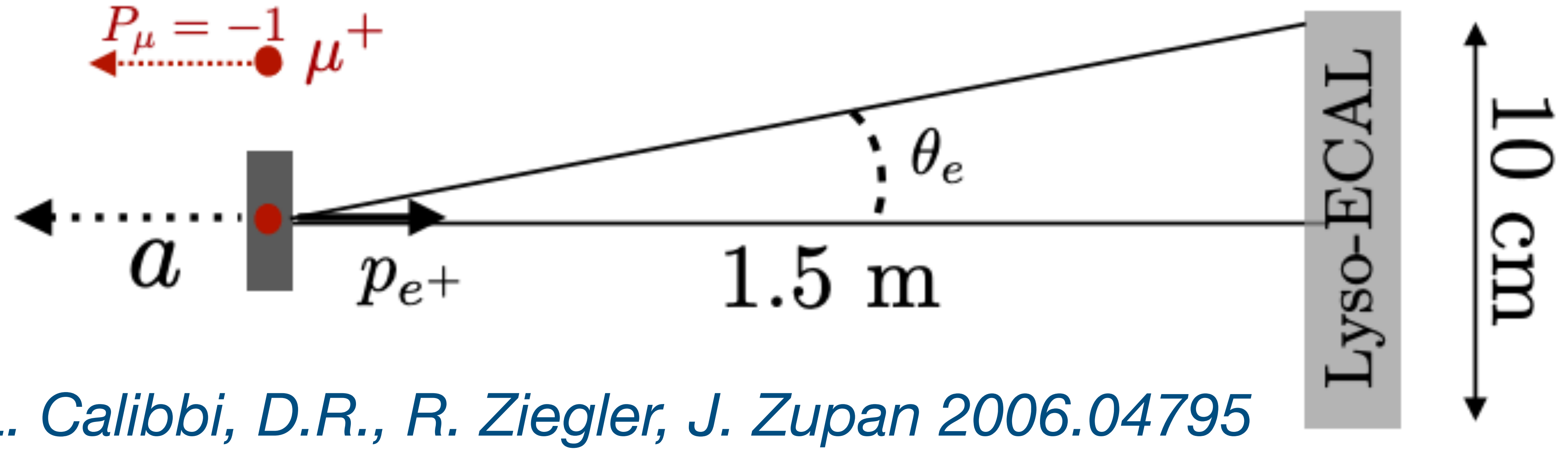

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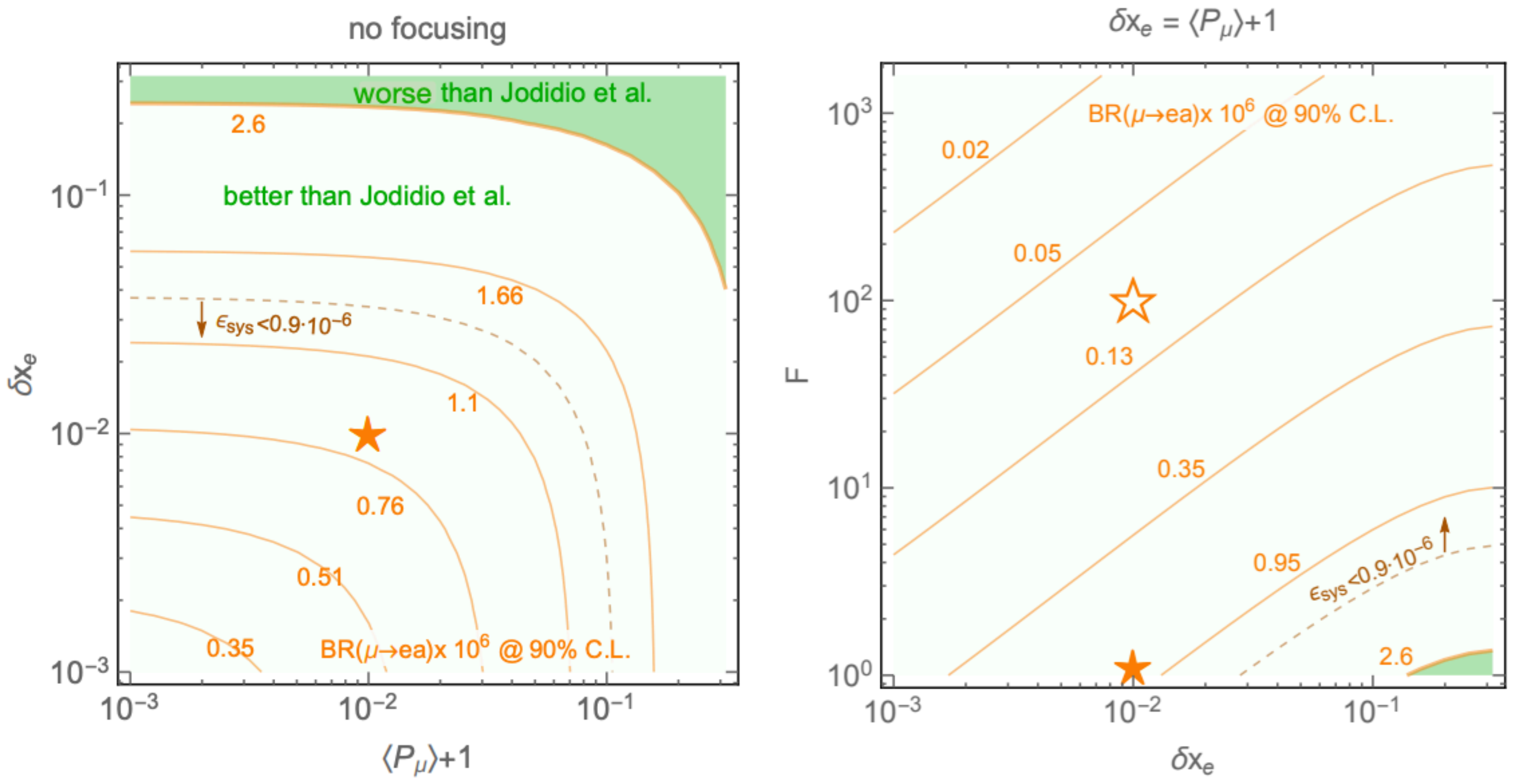

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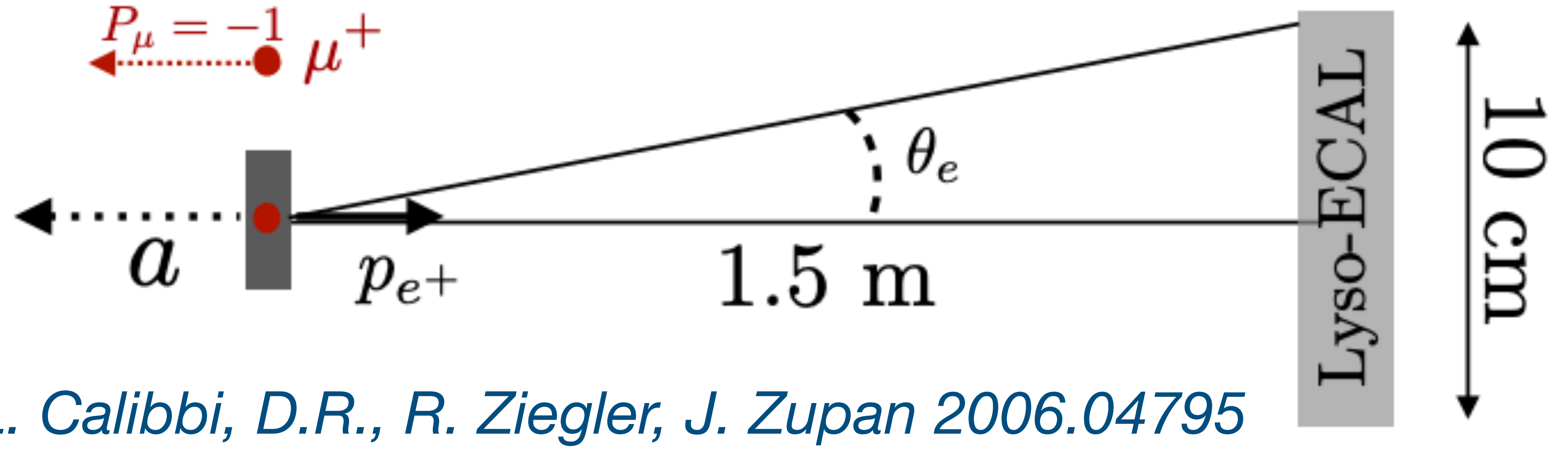

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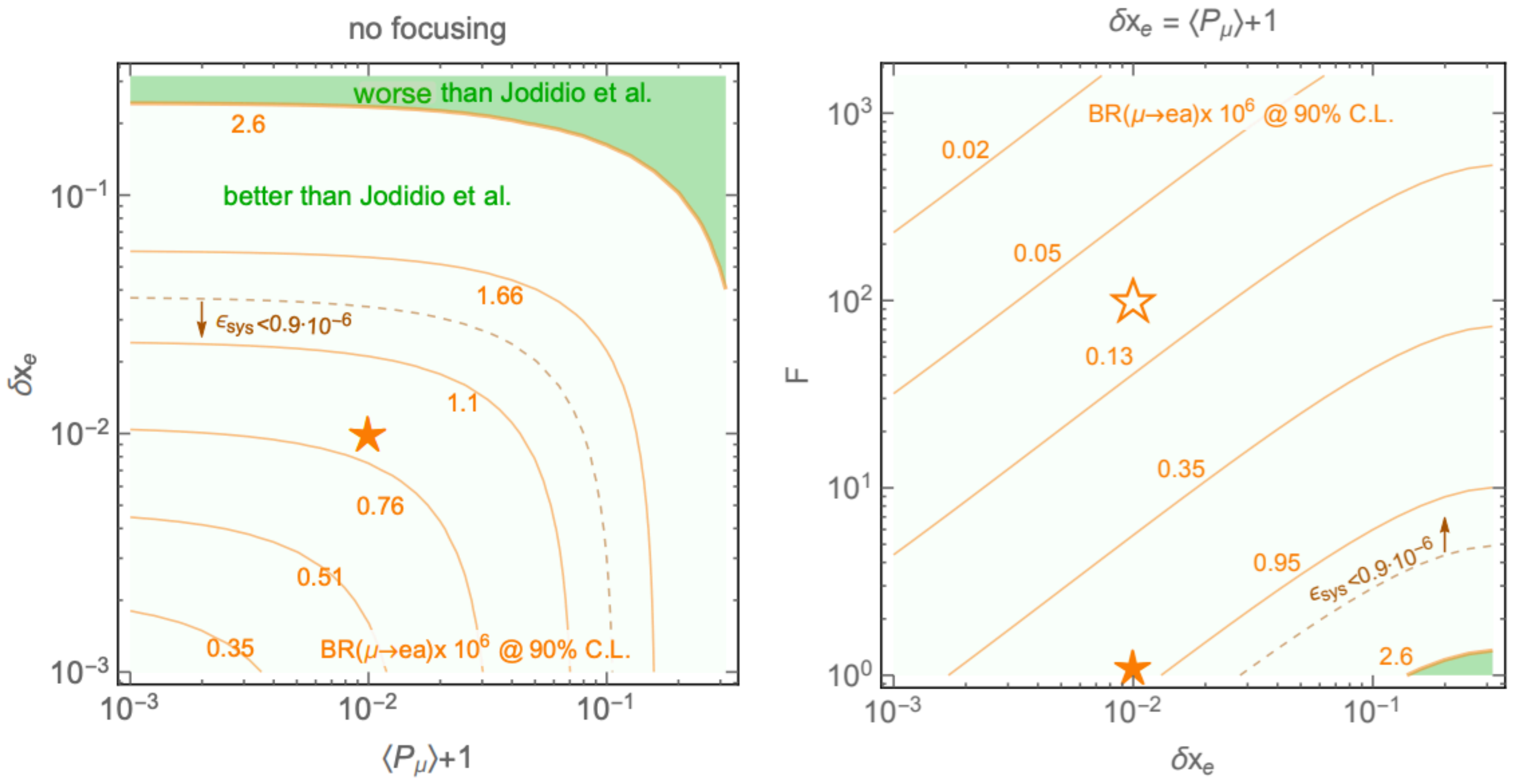

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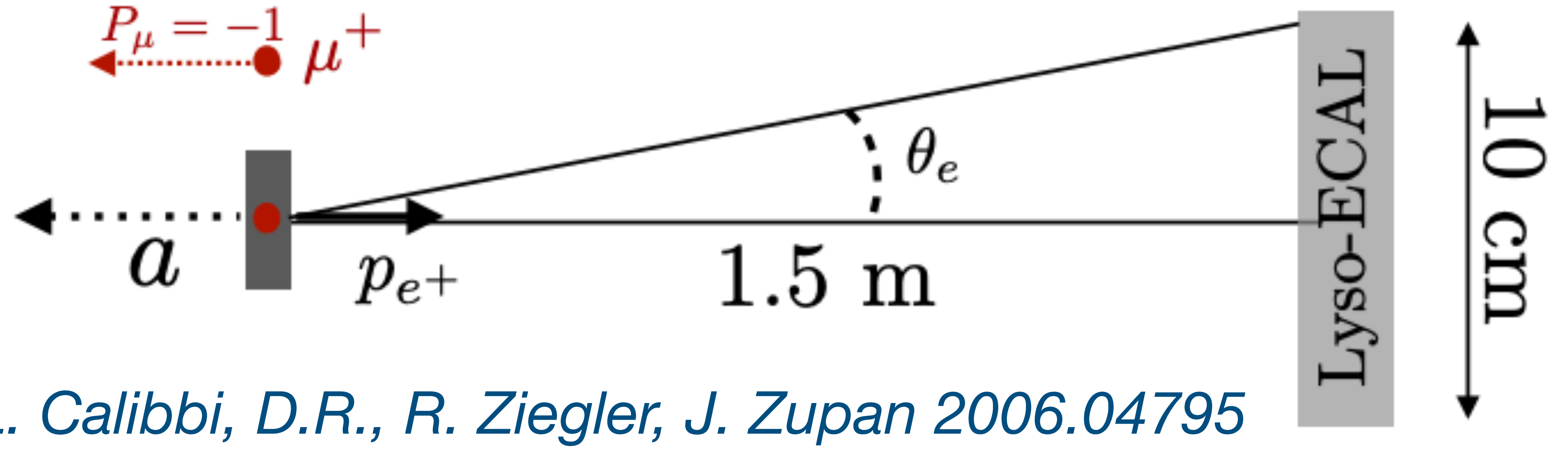
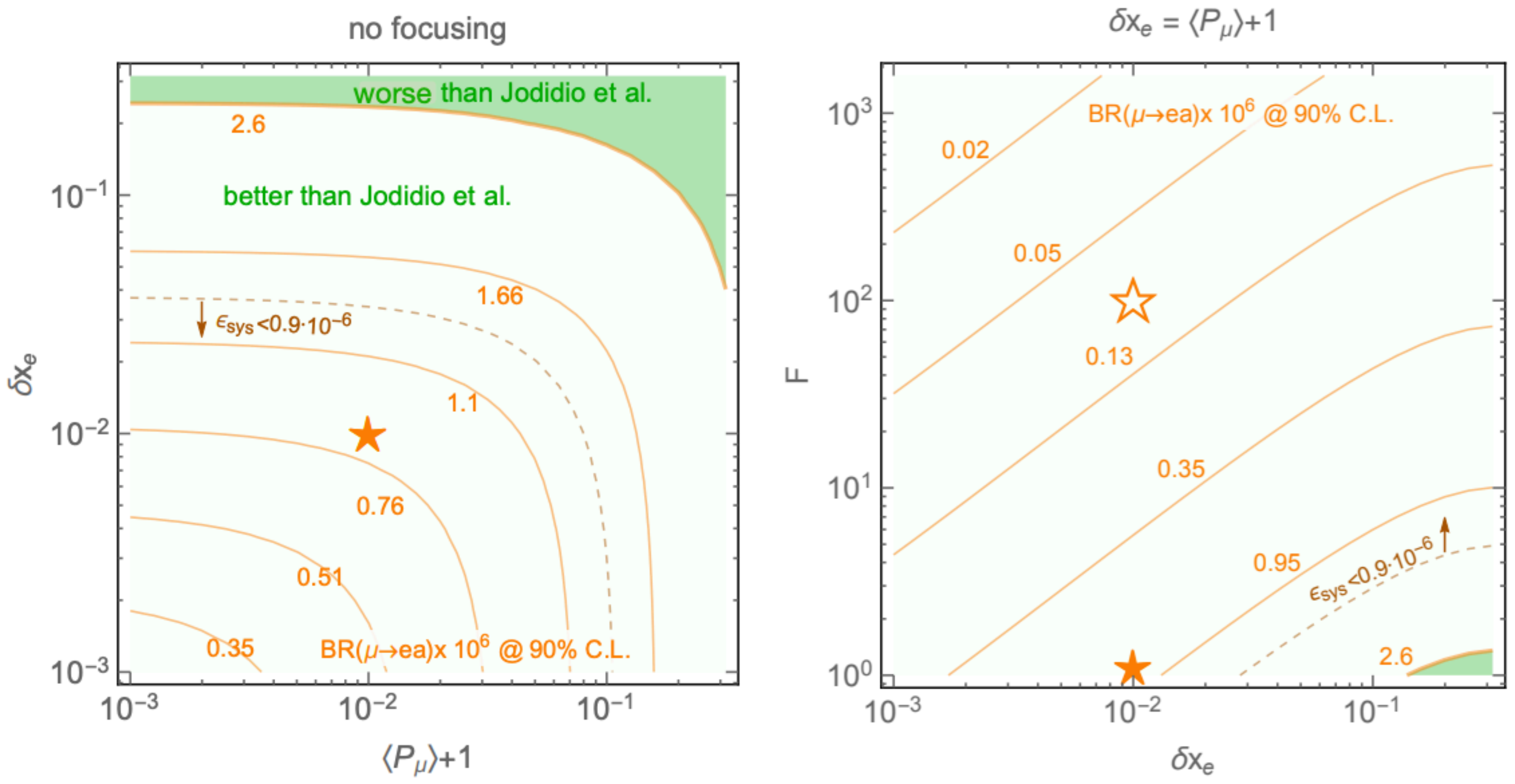
A good signal reach requires further:
- 3) magnetic field focusing F $F \sim 10^2$
- 4) large luminosity $N_\mu \sim 10^{14}\mu^+$
- 5) very low systematics

Looking forward for right-handed ALPs



L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795



Background suppression in the fwd direction requires:
- 1) good momentum resolution $\delta x_e \sim \%$
- 2) purely polarized muon beam $\delta P_\mu \sim 10^{-2}$

A good signal reach requires further:
- 3) magnetic field focusing F $F \sim 10^2$
- 4) large luminosity $N_\mu \sim 10^{14}\mu^+$
- 5) very low systematics

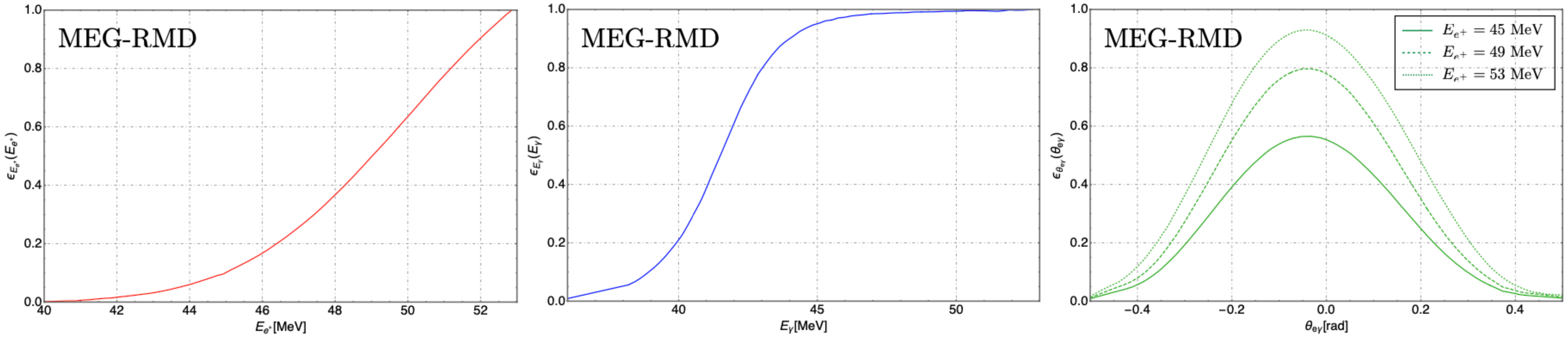
These conditions have been realized before in the Iodidio's exp.

Iodidio et al. (1986)

Can it be done again?

Towards a new data taking strategy

Logic: the trigger requirements are killing the ALP signal



Towards a new data taking strategy

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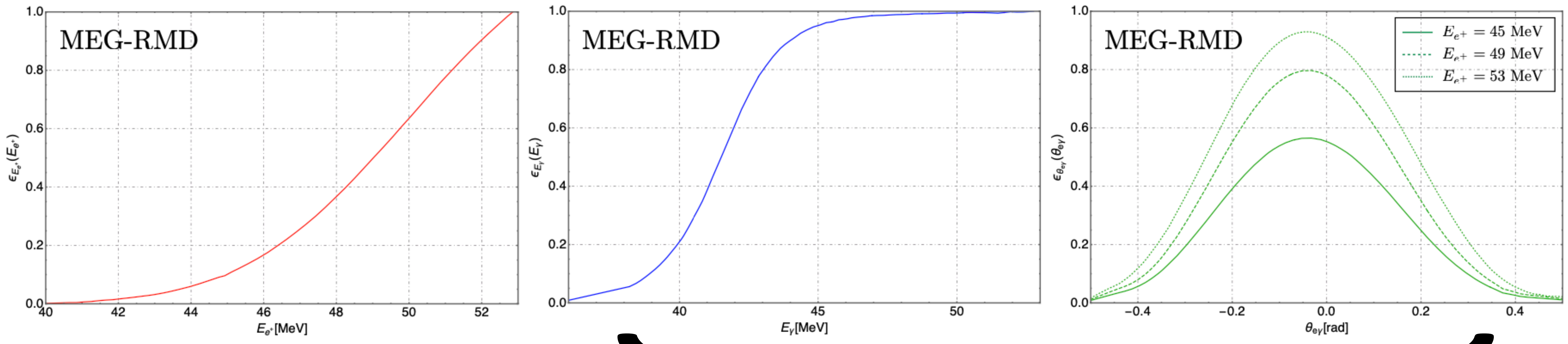
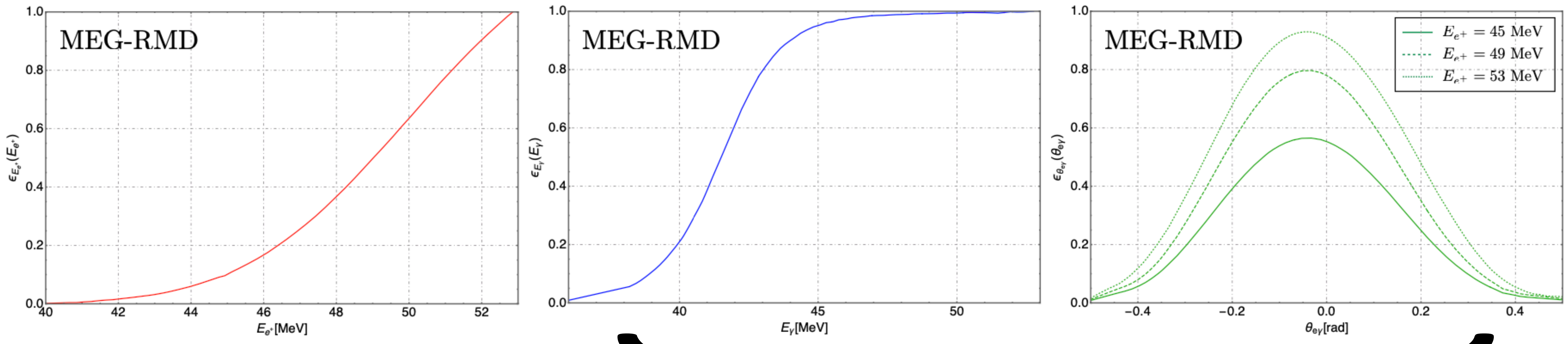


1) Eliminating the matching of the TC hit which assumes back to back topology

2) Lowering the photon trigger threshold reducing the beam intensity

Towards a new data taking strategy

Logic: the trigger requirements are killing the ALP signal



1) Eliminating the matching of the TC hit which assumes back to back topology

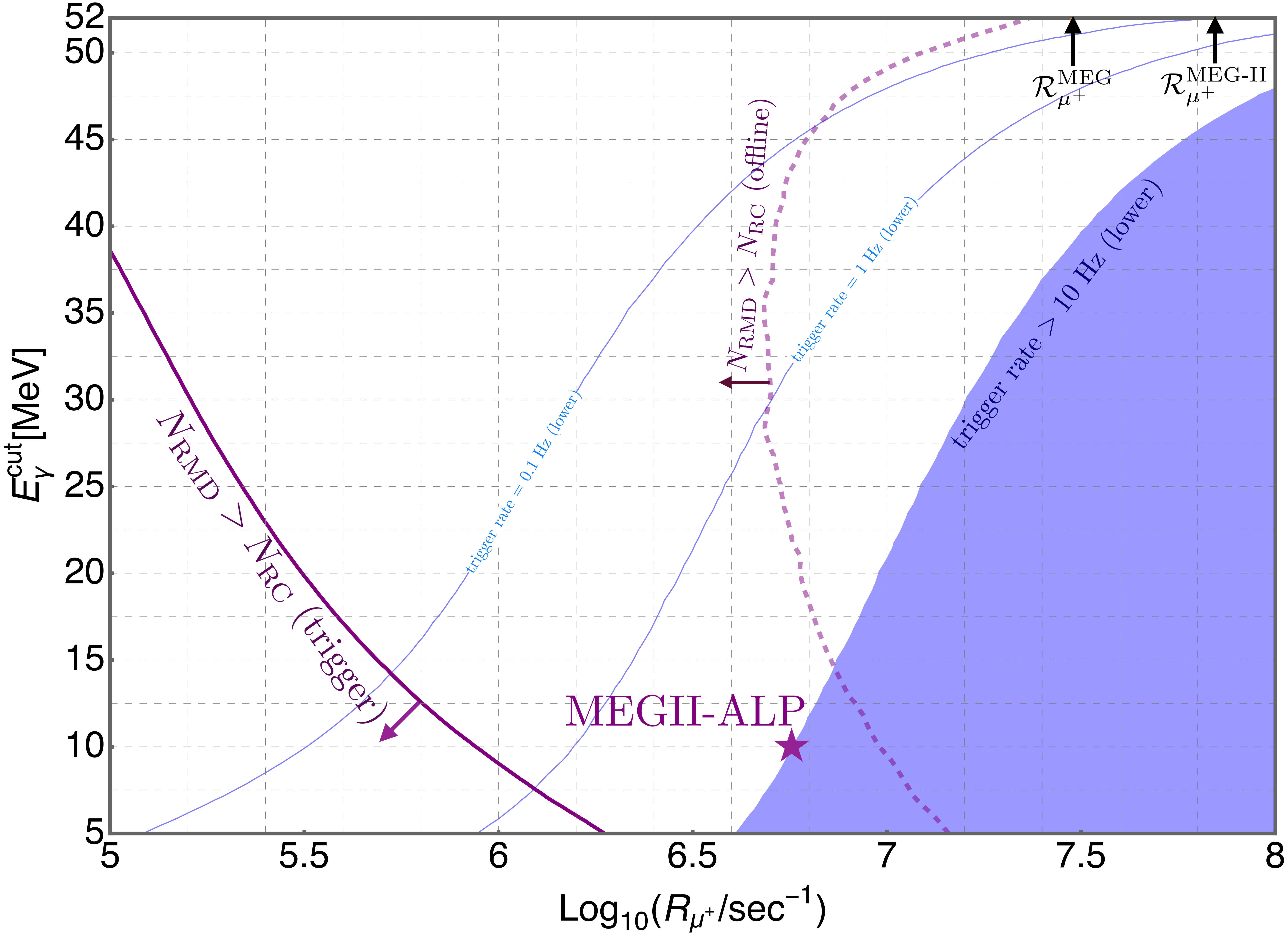
2) Lowering the photon trigger threshold reducing the beam intensity

The RC dominates the trigger rate but it can be suppressed by reducing the intensity

$$\mathrm{RC} \sim R_\mu^2 \quad \mathrm{RMD} \sim R_\mu$$

**many thanks to Luca Galli for teaching us all this!*

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

RMD becomes the dominant bed

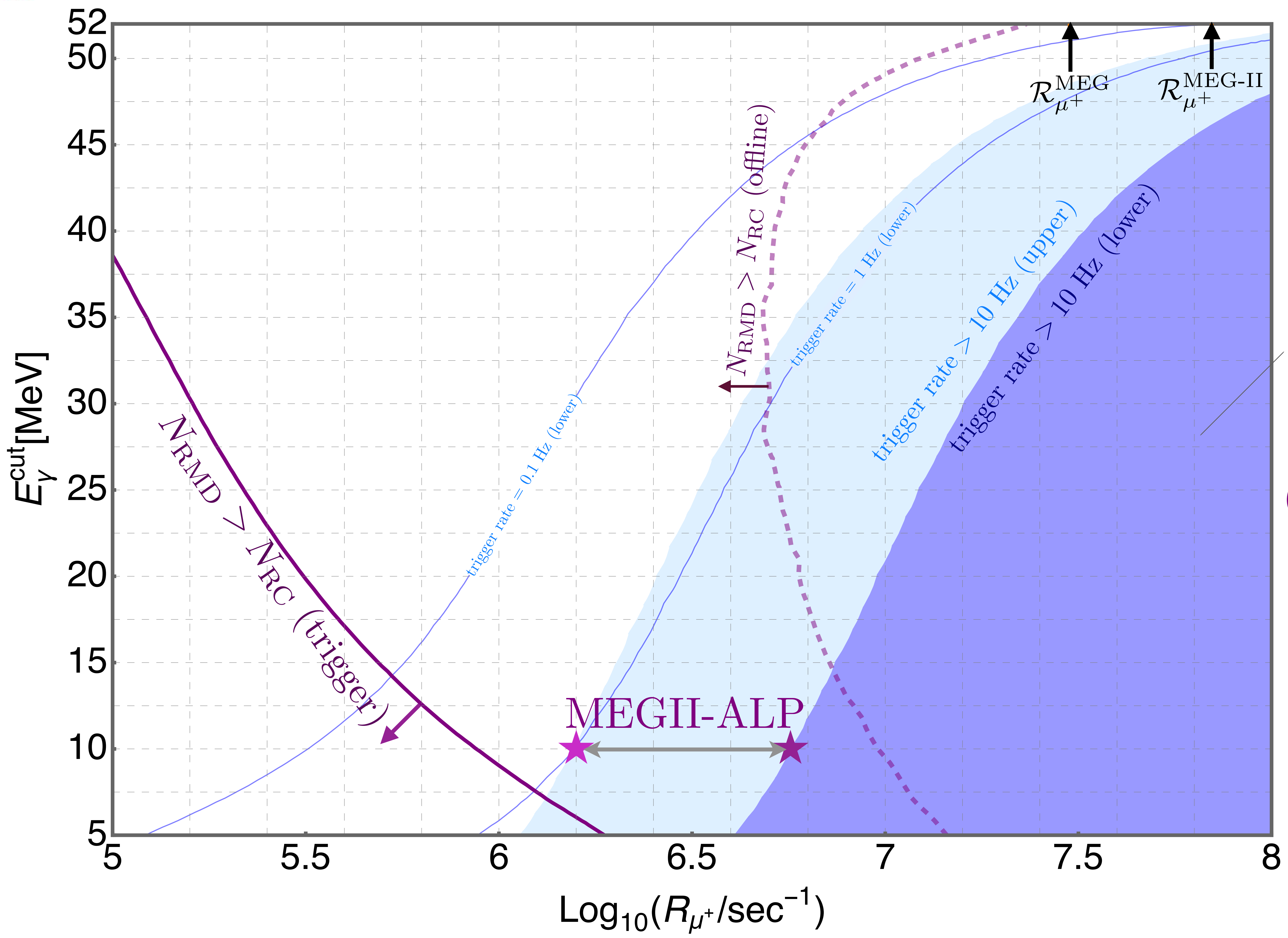
below a certain intensity

(harder to suppress RMD online)

★

Benchmark fixed to the highest intensity for photon energy of 10 MeV given our estimate of the trigger rate

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

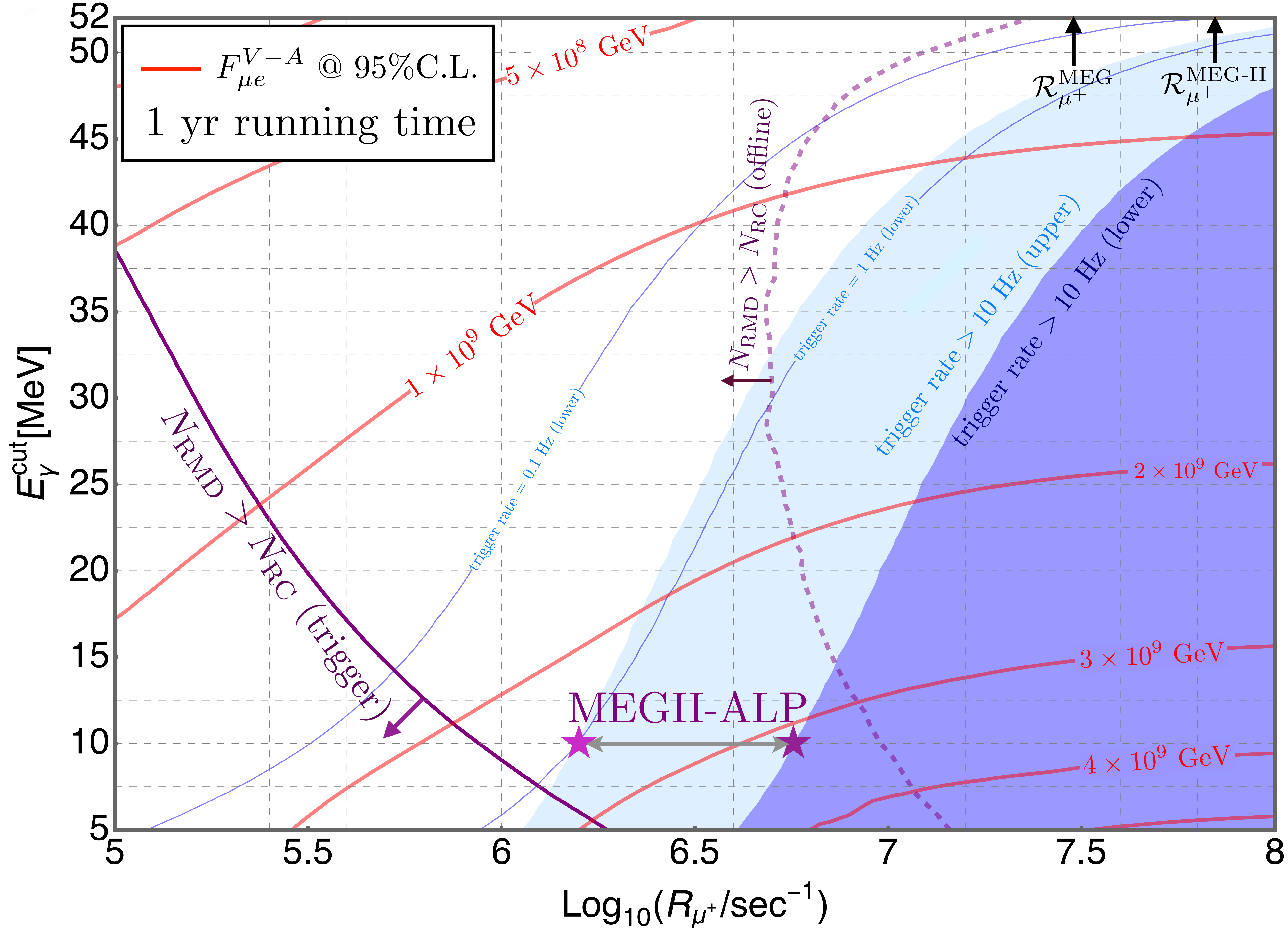
RMD becomes the dominant bed

below a certain intensity

(harder to suppress RMD online)

Uncertainty in trigger rate results in two different benchmark for the same photon energy

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

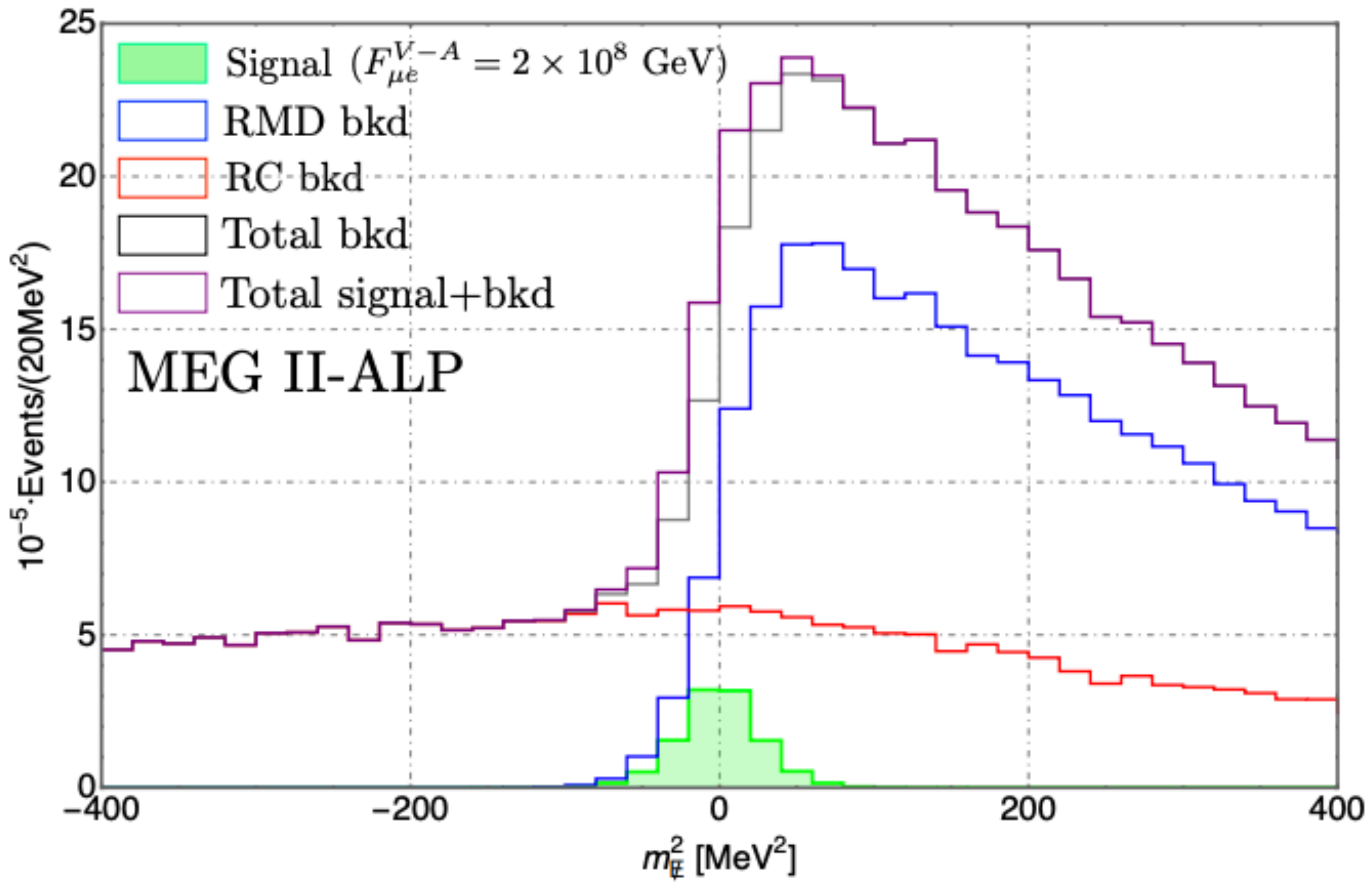
RMD becomes the dominant bkd

below a certain intensity

(harder to suppress RMD online)

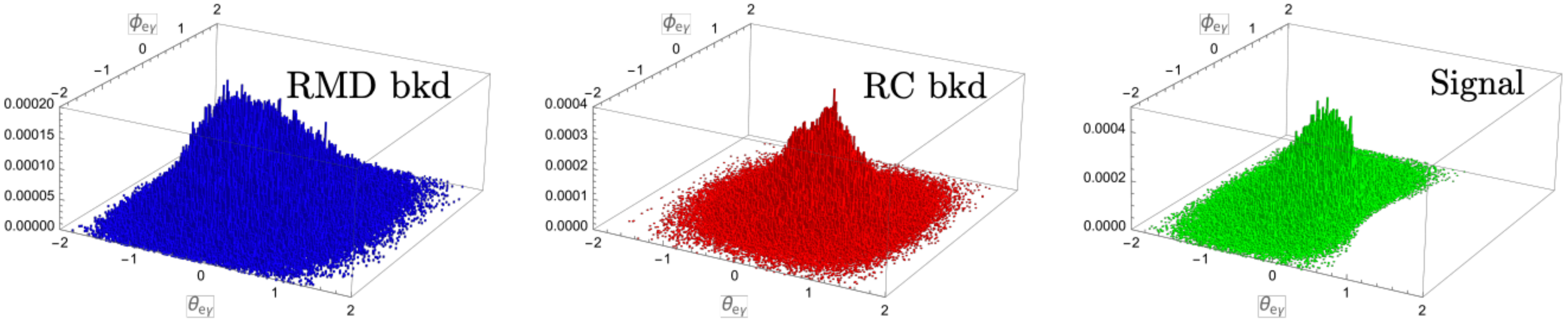
Reach extracted at each point!

Final reach



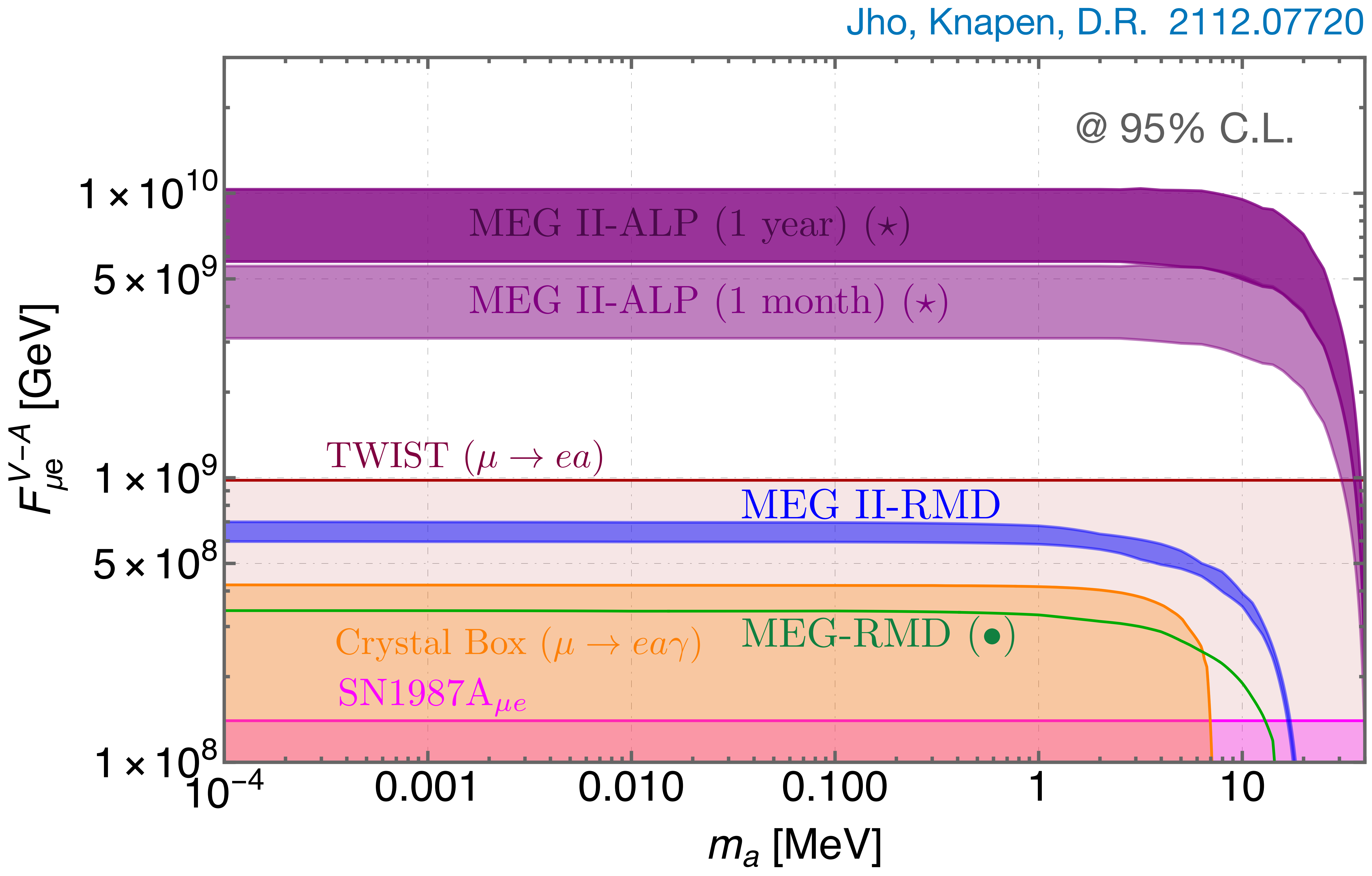
Bump hunt in missing mass*

*for a massless object we are close to a cliff of the bkd (systematics has to be taken into account)



Log-likelihood on angular variables

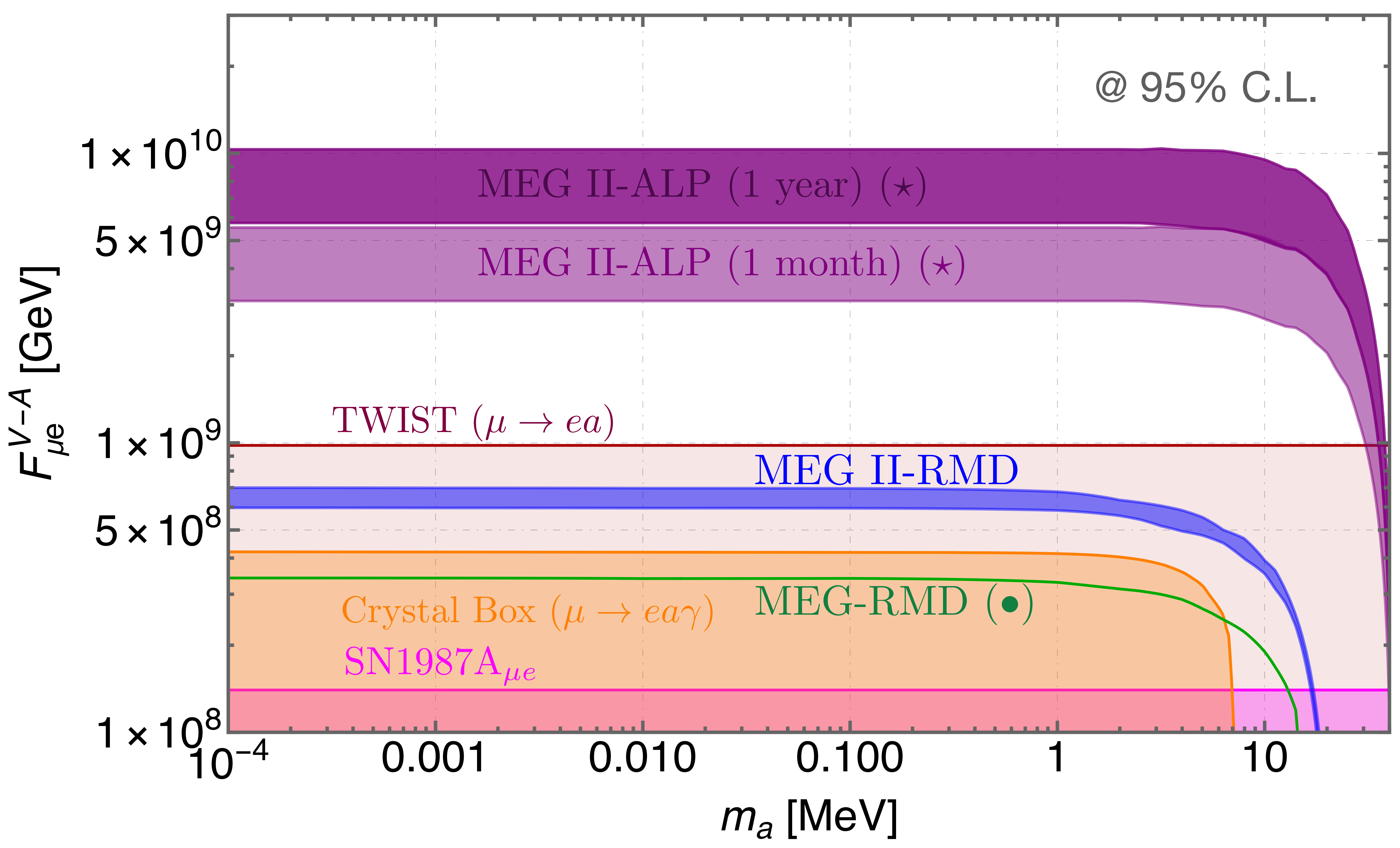
What can we test?



MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

What can we test?

Jho, Knapen, D.R. 2112.07720

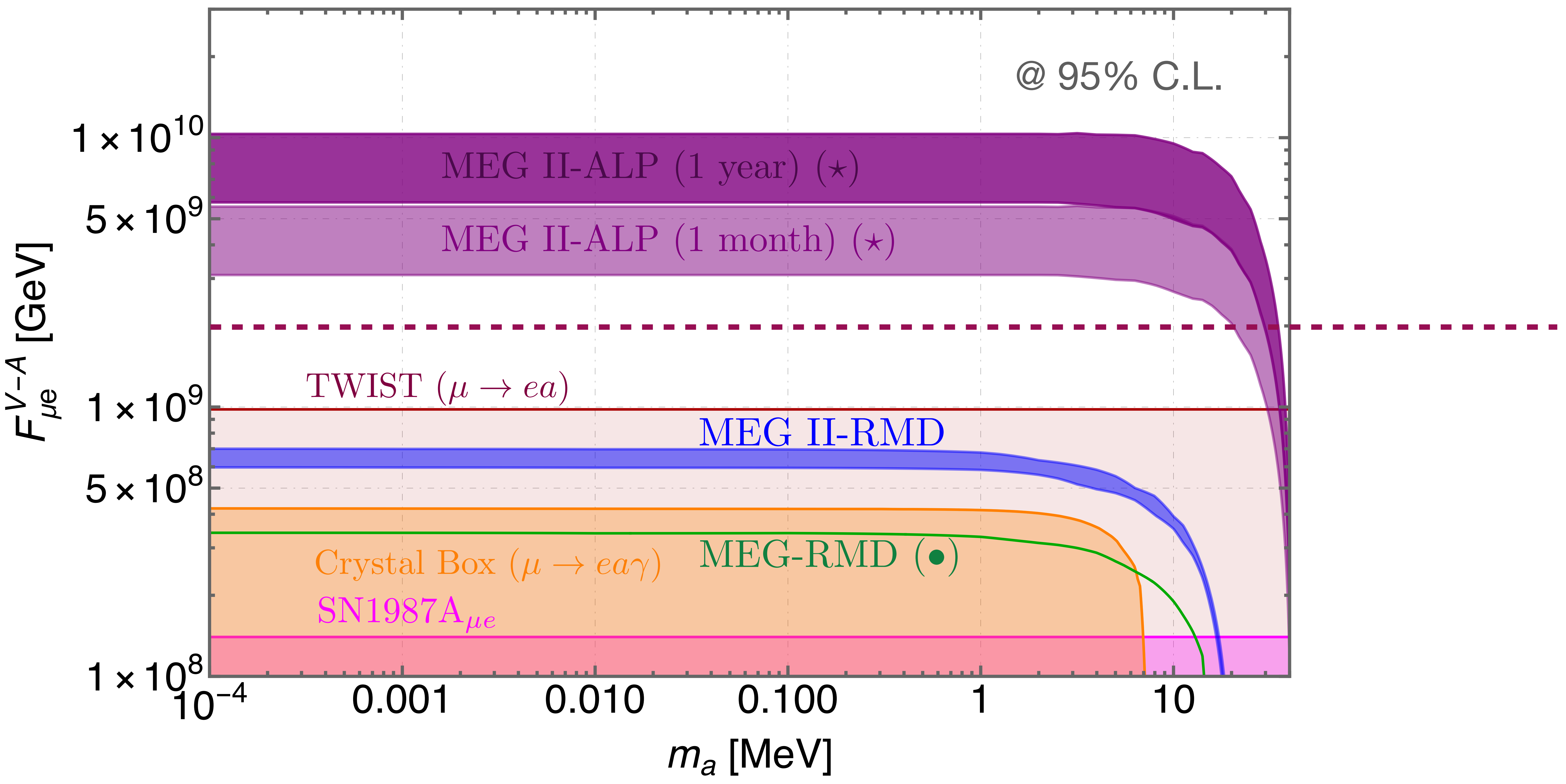


MEG II-ALP can improve on TWIST with only 1 month of data taking*

MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

MEG II RMD data…

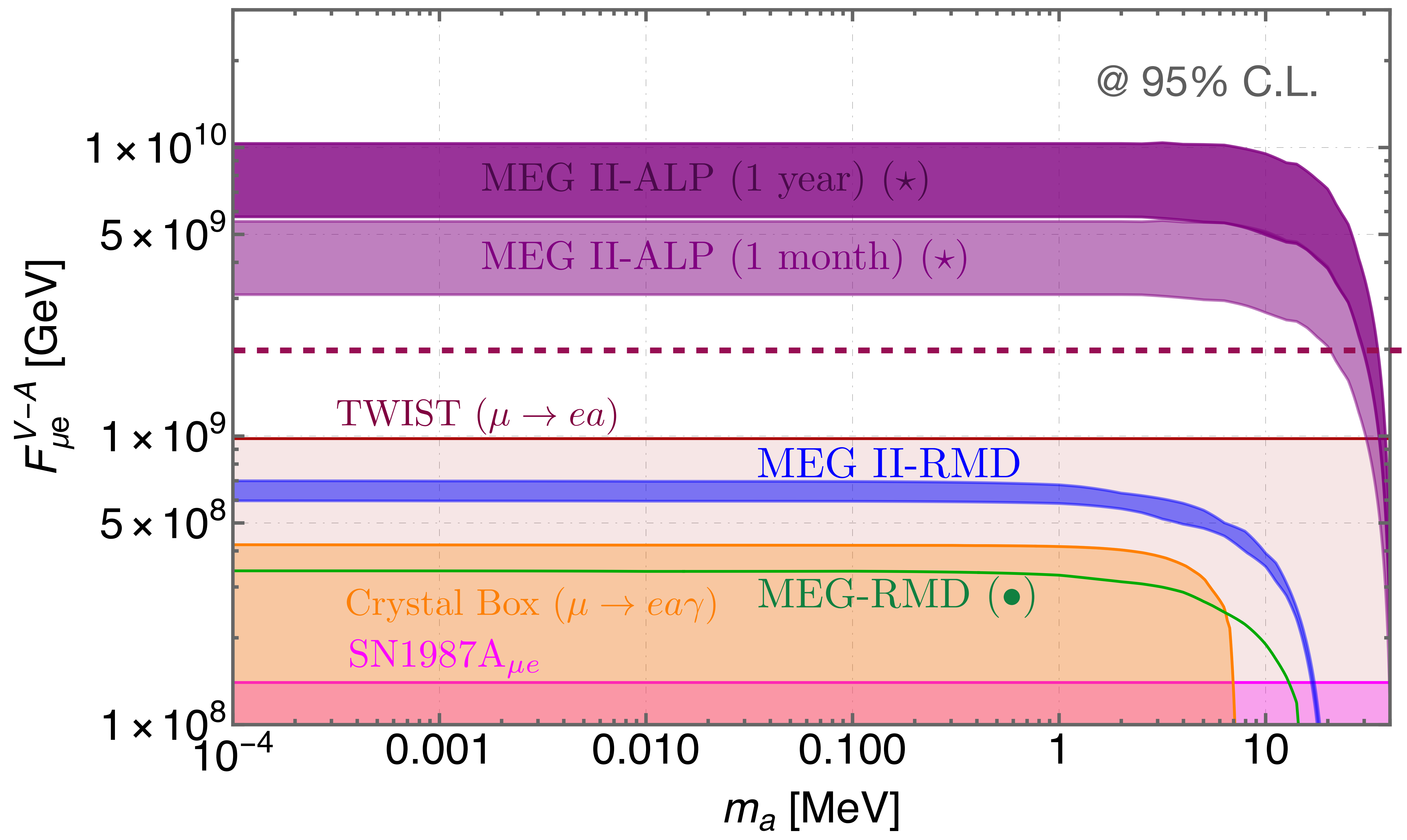
see talk by Elia Gilio Grandoni at WIFAI 2024



MEG-II wil get some new results very soon

MEG II RMD data…

see talk by Elia Gilio Grandoni at WIFAI 2024

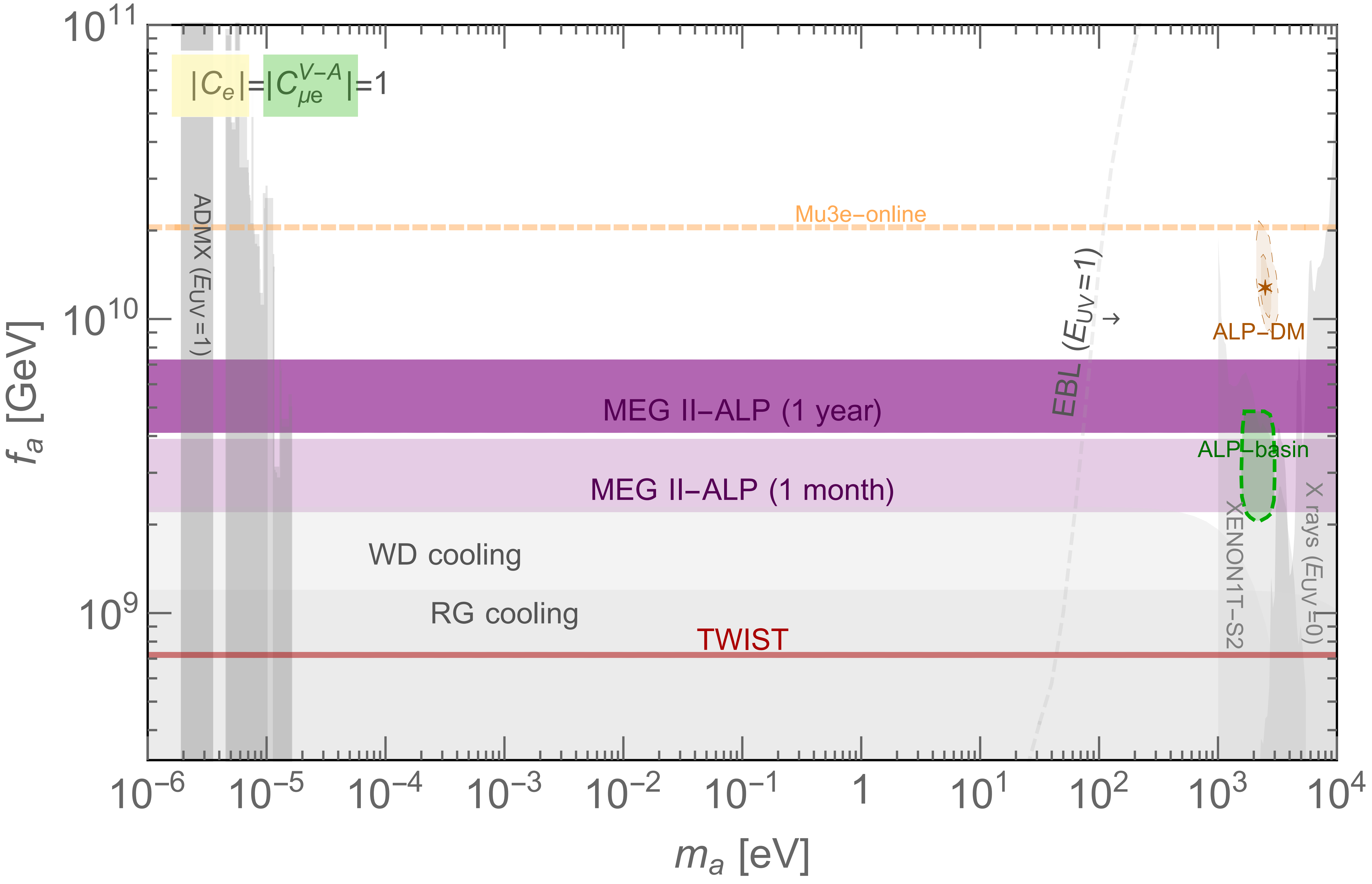


expected reach with 8.7 days of existing data

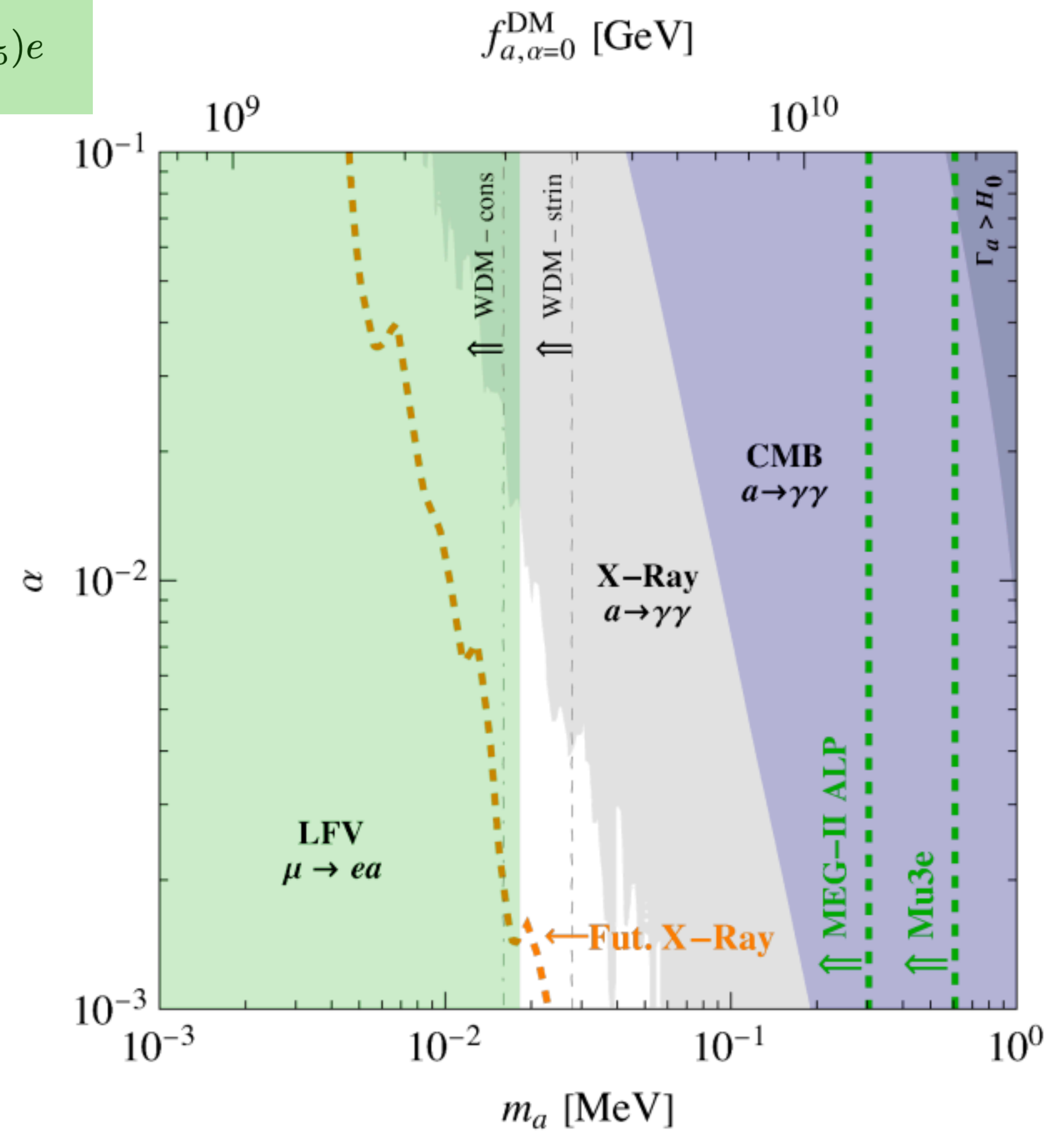
MEG-II wil get some new results very soon

Back to theory

axions coupled to leptons anarchically: *flavor diagonal* $\frac{\partial_\mu a}{f_a}\bar{e}\gamma^\mu\gamma_5 e$ = *flavor off-diagonal* $\frac{\partial_\mu a}{2f_a}\bar{\mu}\gamma^\mu(C^V_{\mu e}+C^A_{\mu e}\gamma_5)e$



Panci, Redigolo, Schwetz Ziegler 2209.03371



Back to theory

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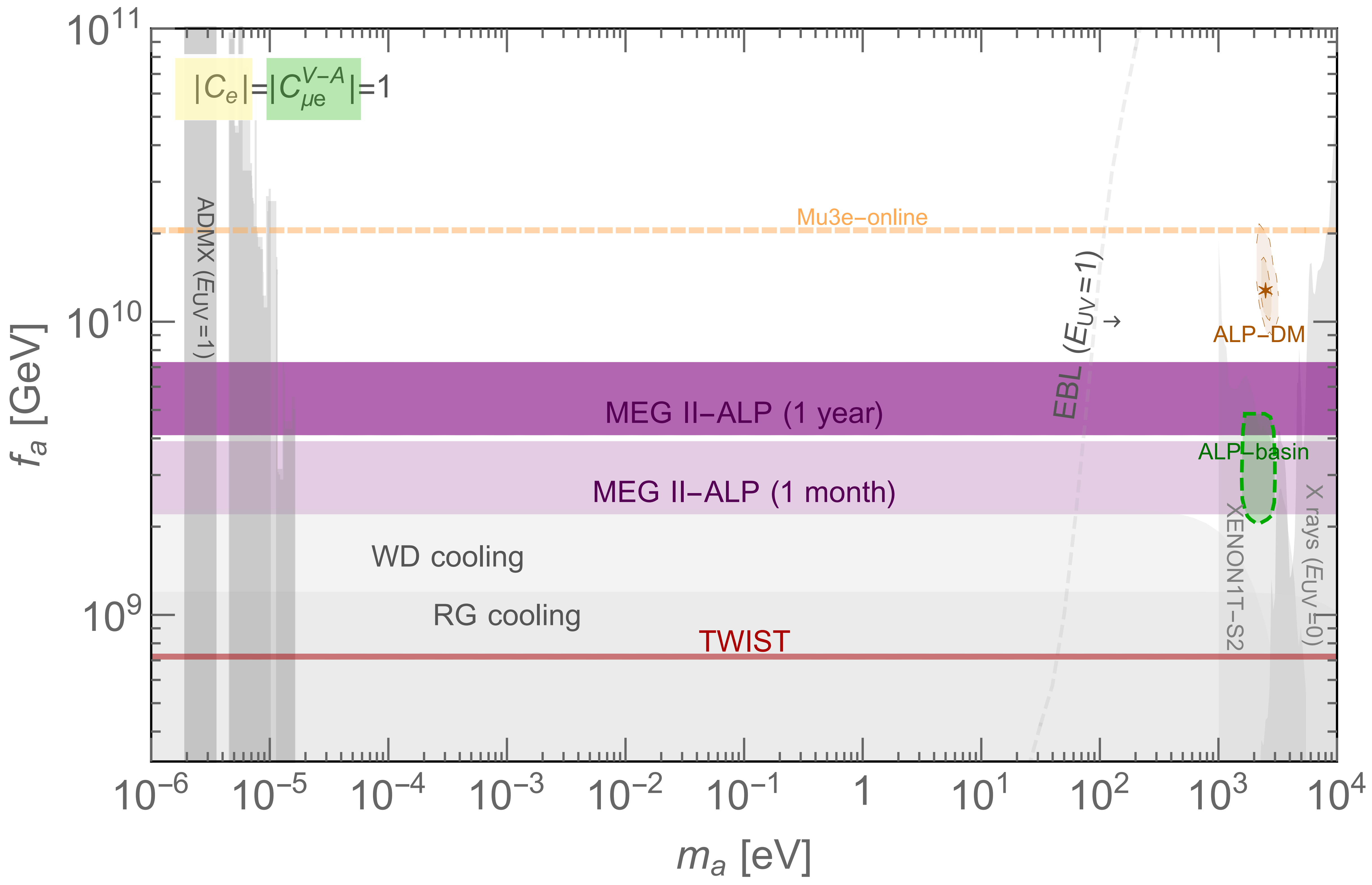
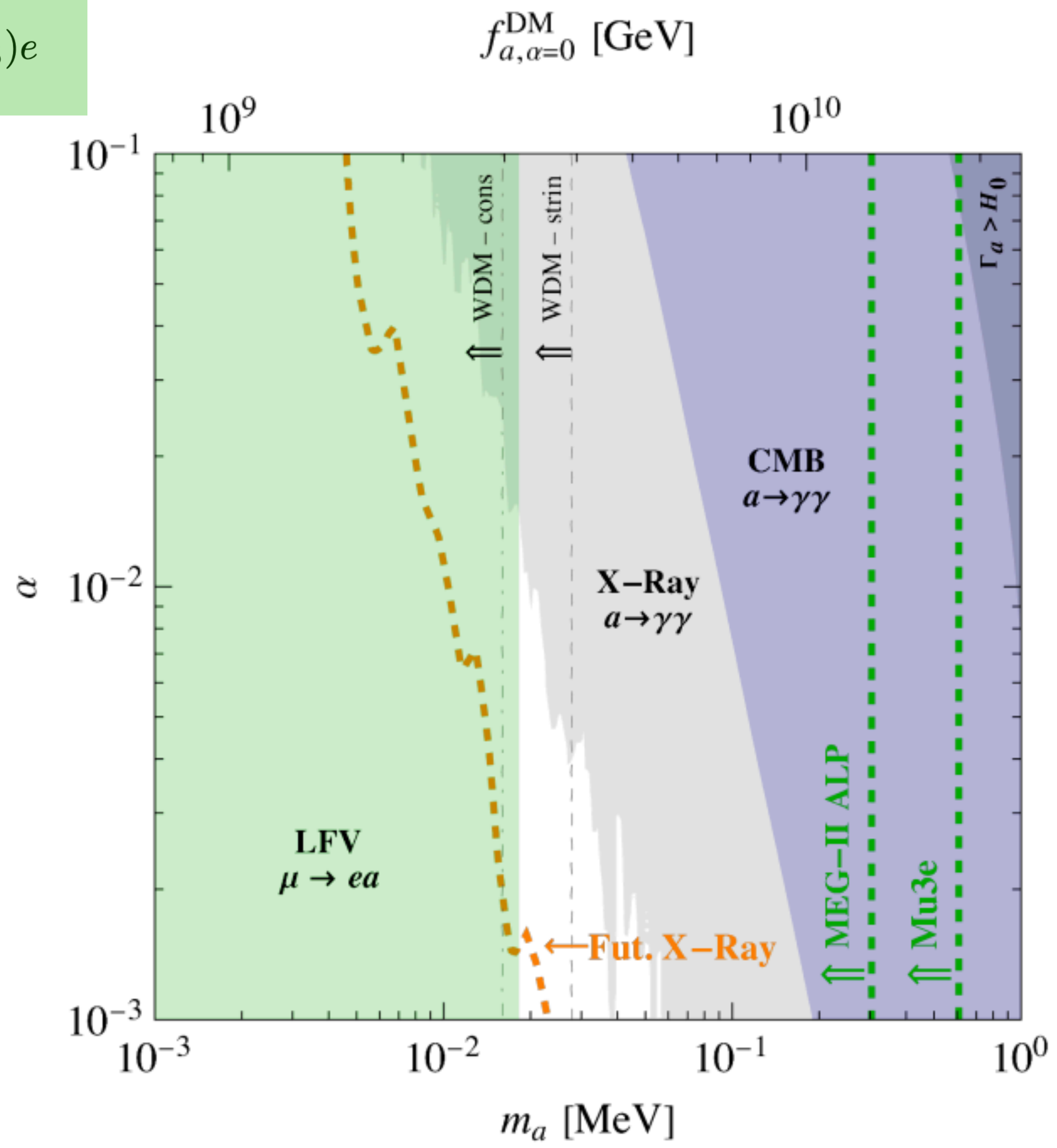
Panci, Redigolo, Schwetz Ziegler 2209.03371



MEG-II can surpass bounds from star cooling!



Back to theory

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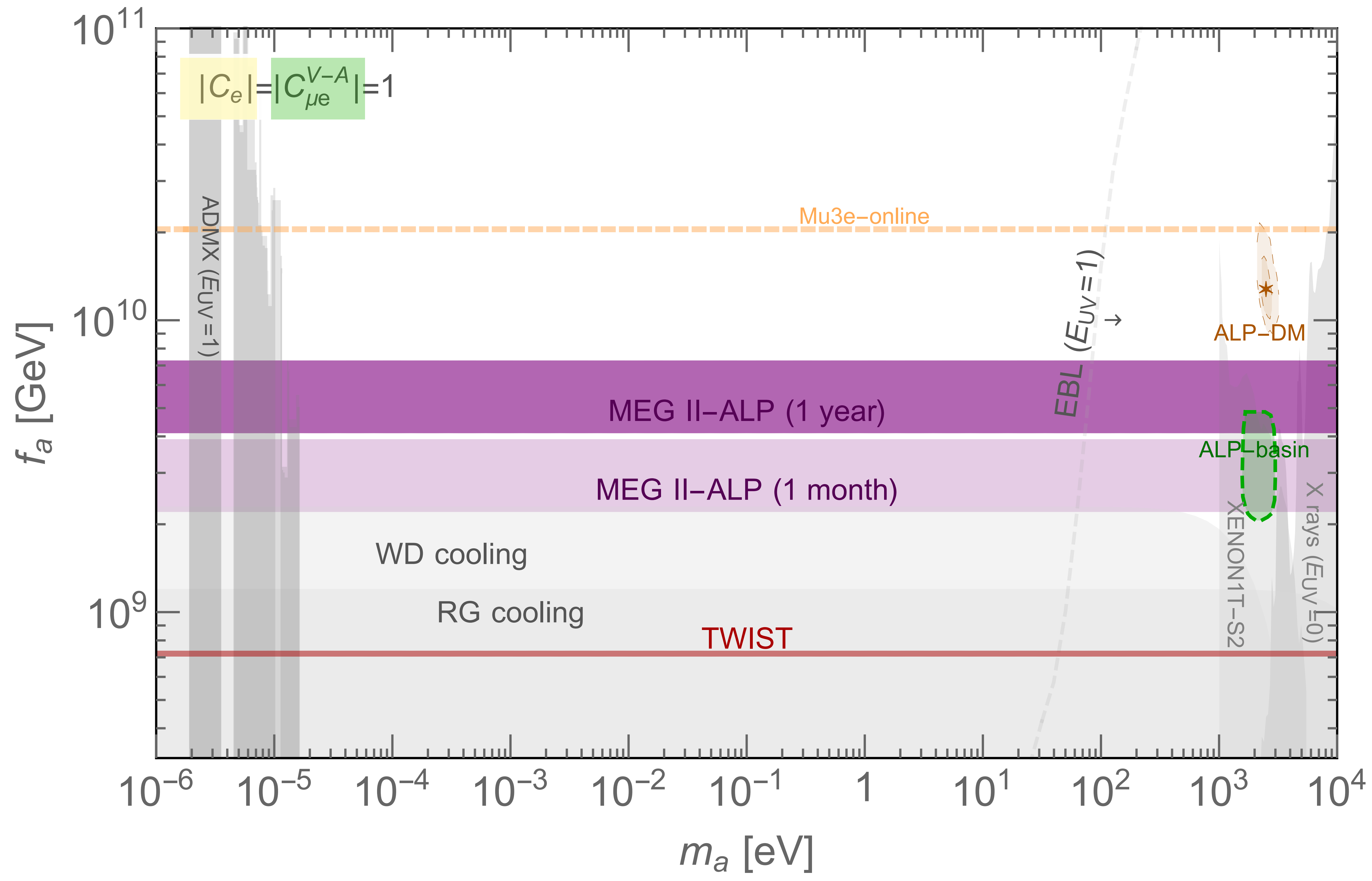
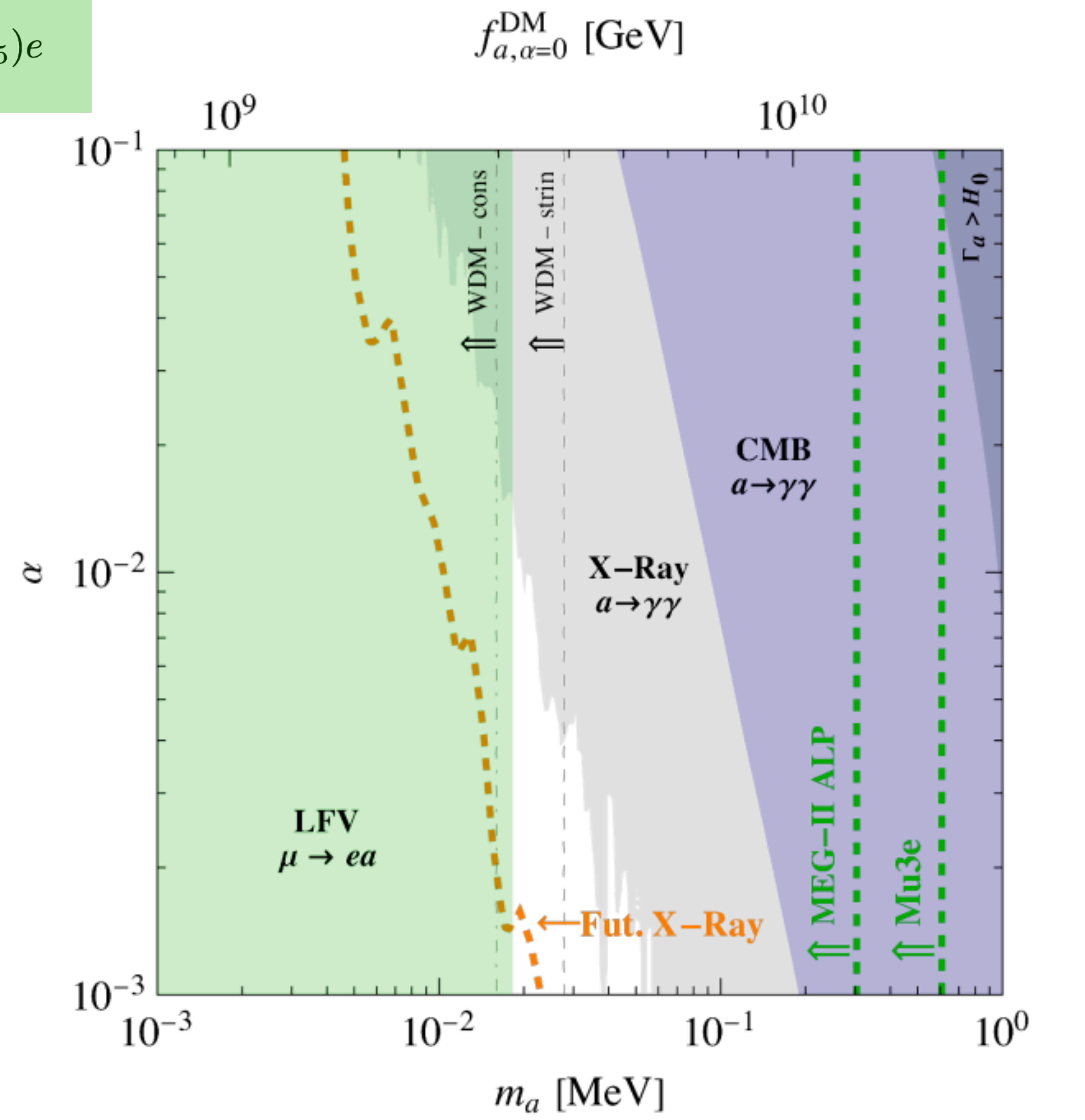
Panci, Redigolo, Schwetz Ziegler 2209.03371



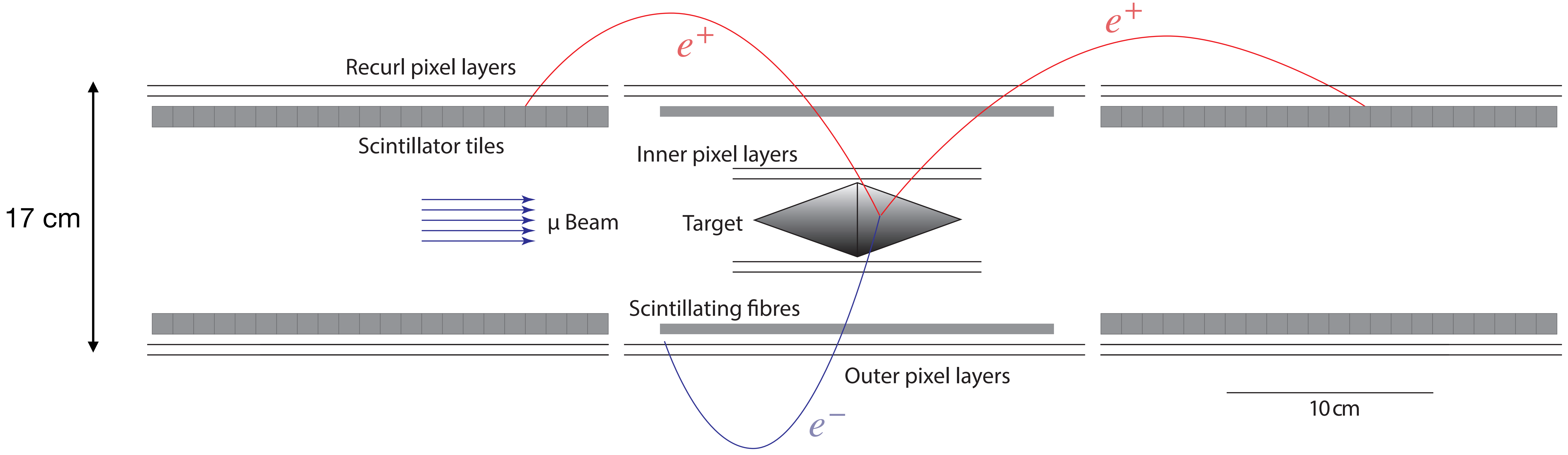


MEG-II can surpass bounds from star cooling!

MEG-II can completely test Freeze-in model based on LFV decays

New searches @ Mu3e

Hermetic detector optimised to detect 3 charged tracks reconstructing the muon mass



$p_T \in [14,105]$ MeV

$B = 1$ Tesla

All the three tracks are save to tape so that missing energy searches can easily done!

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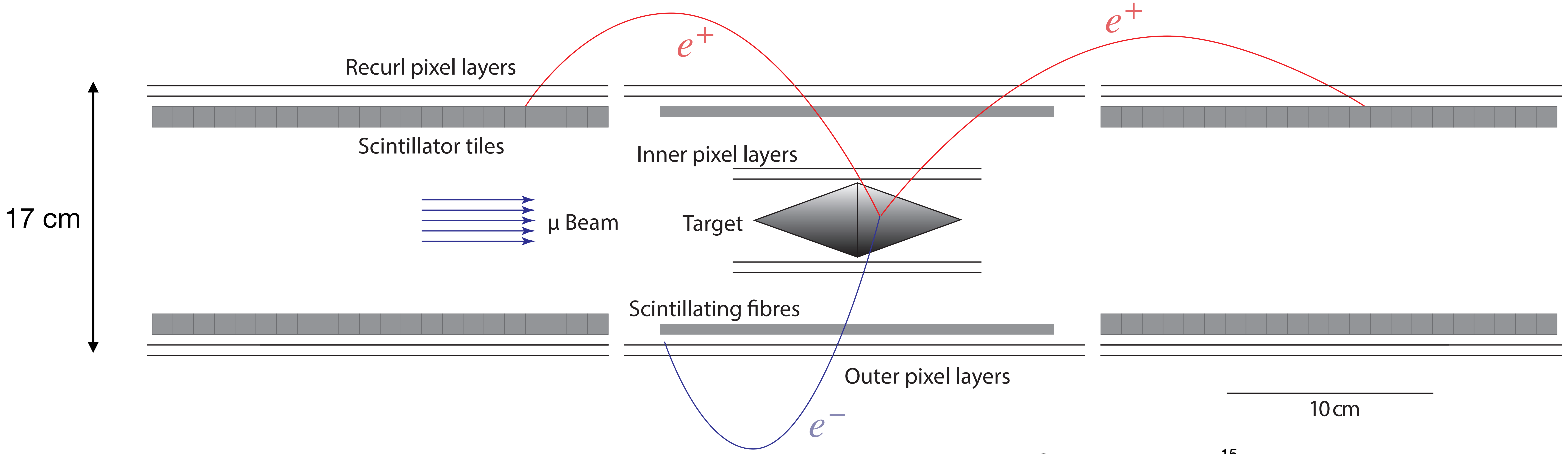

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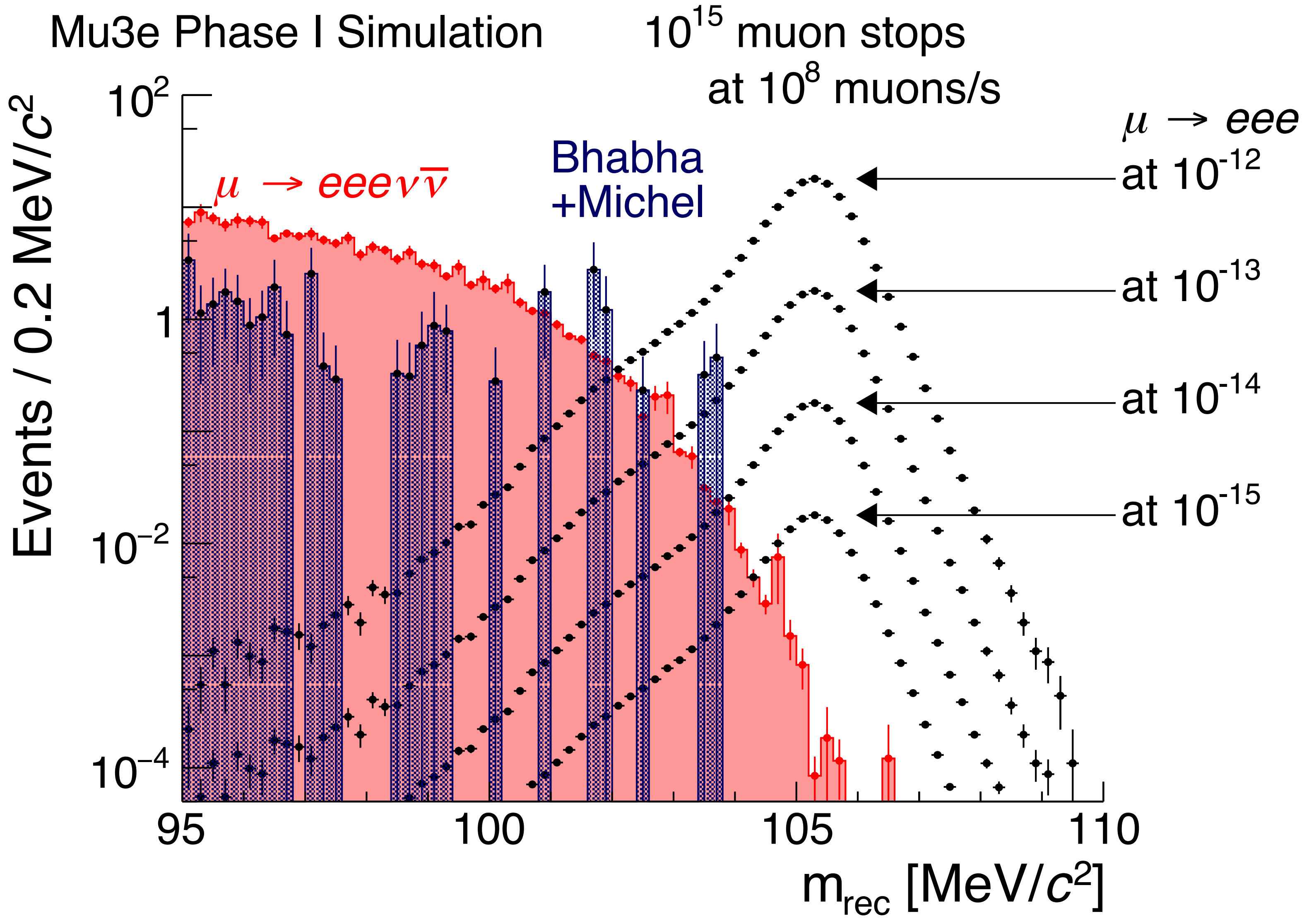
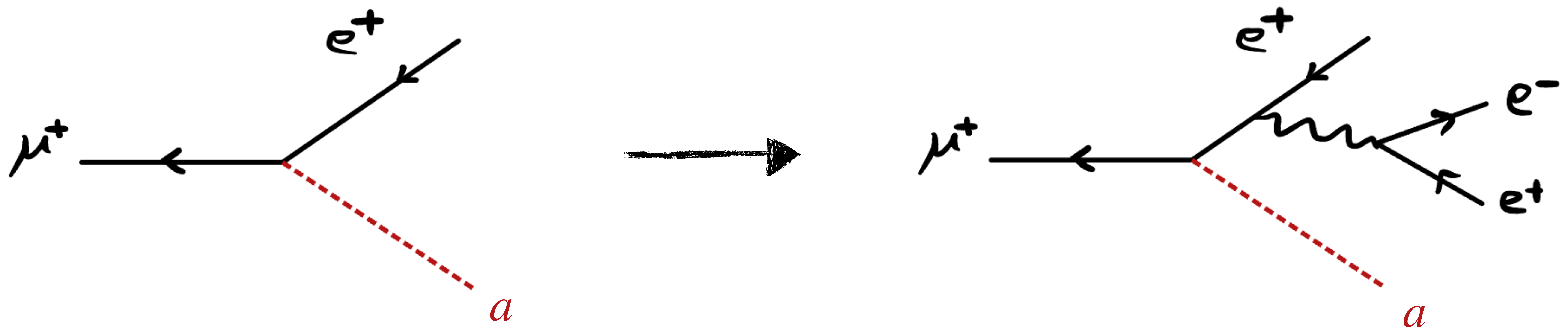


Three tracks + a Flavor violating axion



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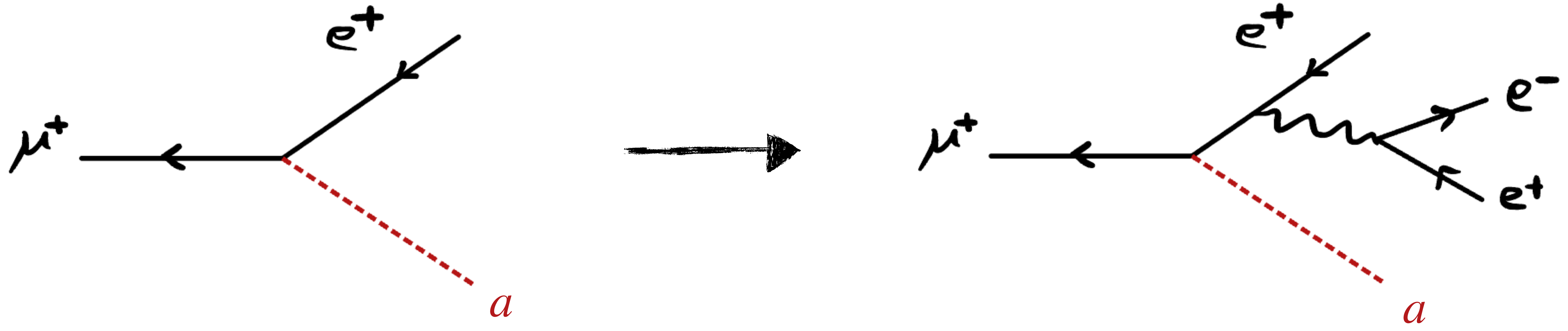
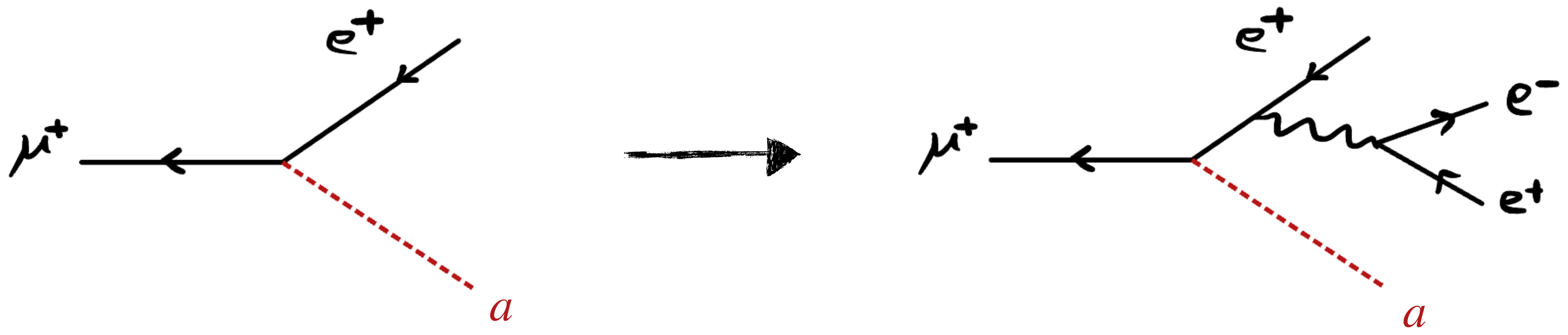


<u>The price to pay:</u>

- Extra factor α^2
- Phase-space suppression limited by the sensitivity of mu3e to low virtuality photons

Three tracks + a Flavor violating axion



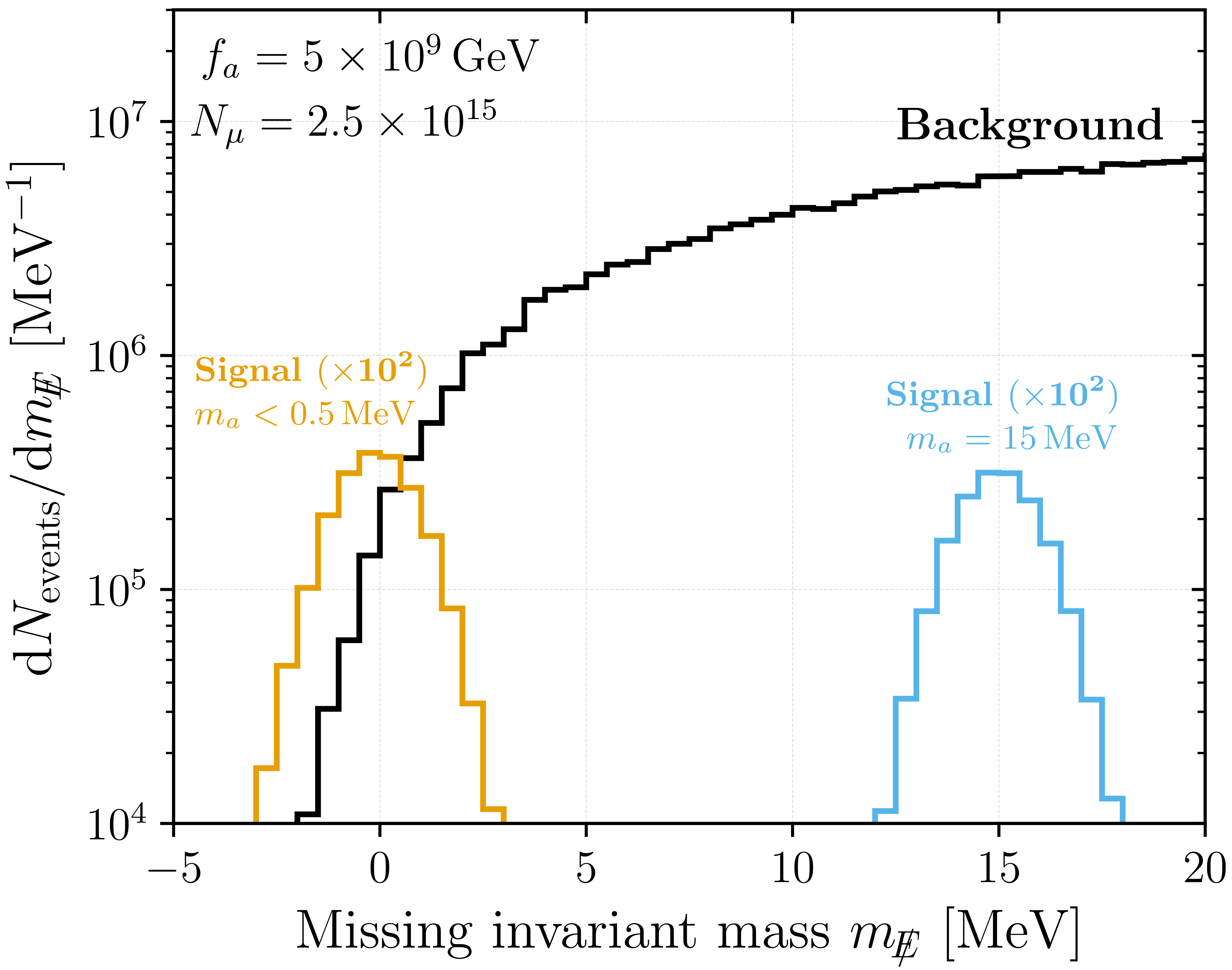
The price to pay:

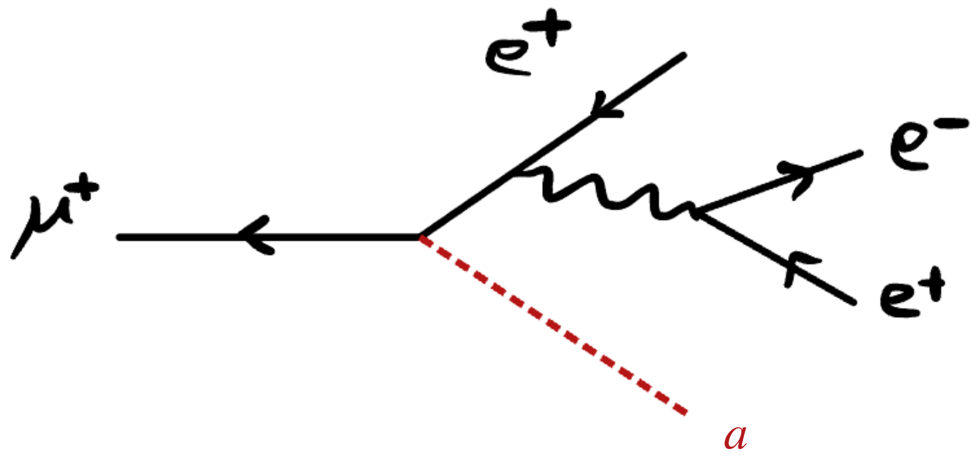
- Extra factor α^2
- Phase-space suppression limited by the sensitivity of mu3e to low virtuality photons

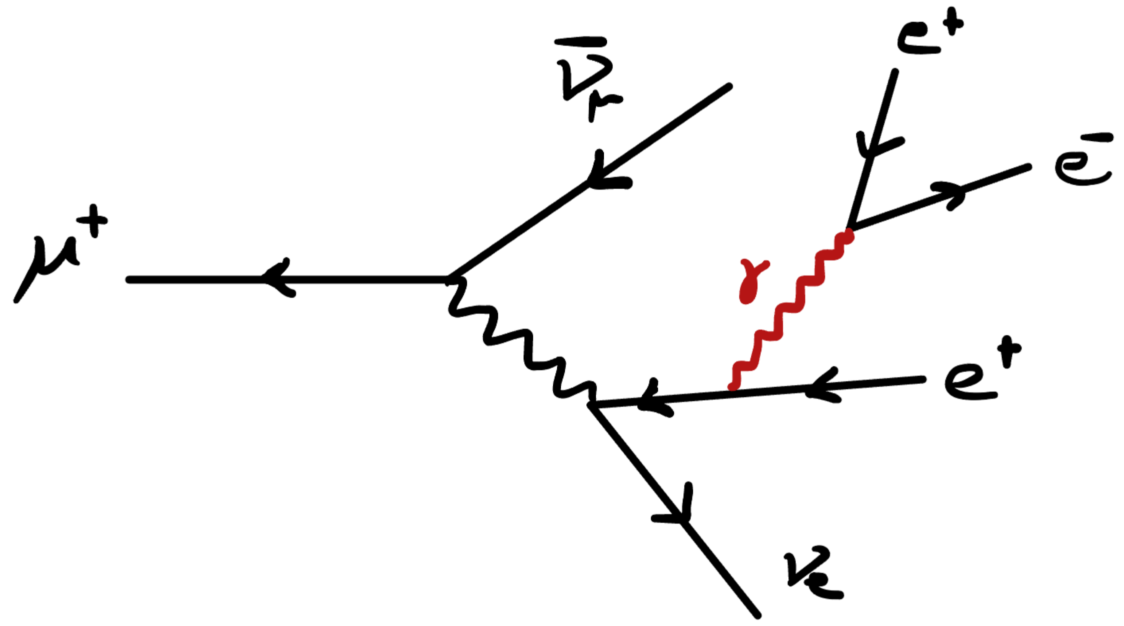
1. $e^\pm$ momenta now lie away from Michel calibration edge!

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

Bump hunt in missing mass

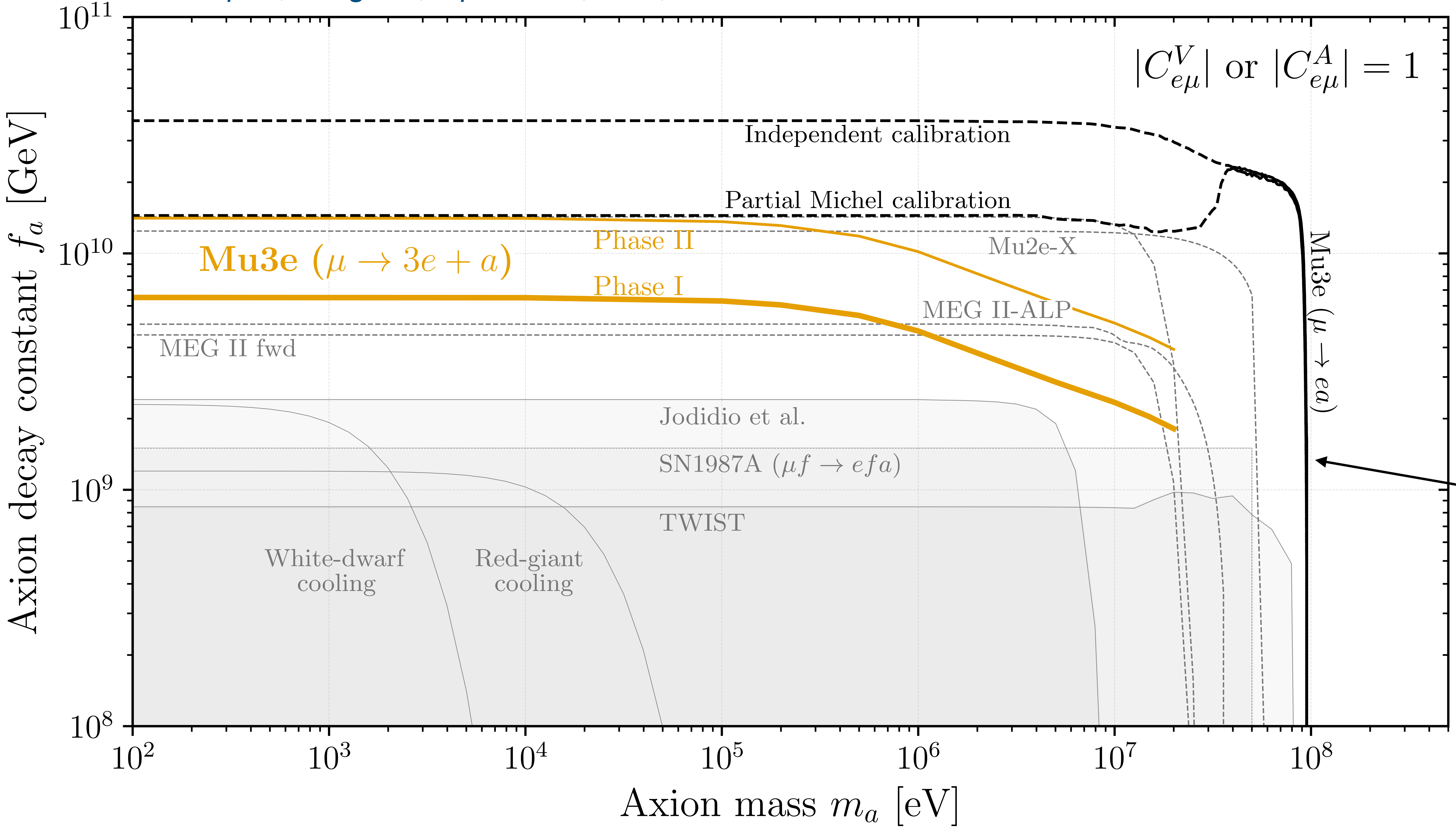






Final Reach

Knapen, Langhoff, Opferkuch, D.R., 2311.17915



Phase I $2.5 \times 10^{15} \mu^+$ stopped muons

Phase II $5.5 \times 10^{16} \mu^+$ stopped muons

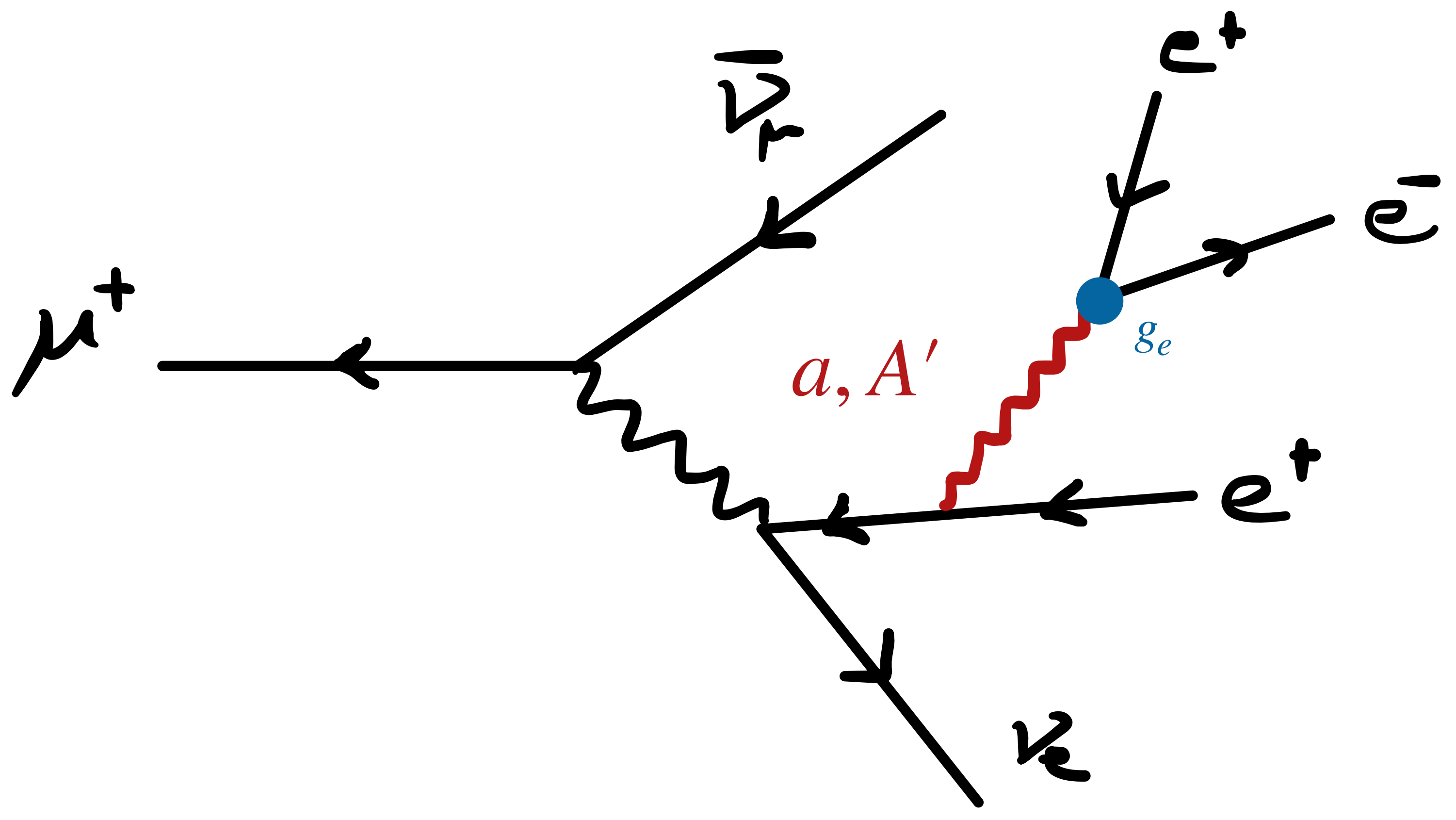
The reach of the two body decay channel should be taken with a grain of salt because it ignores systematic uncertainties

Enhanced Lumi @ mu3e can ameliorate over the MEG II proposal

Three tracks from splitting a dark mediator

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

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



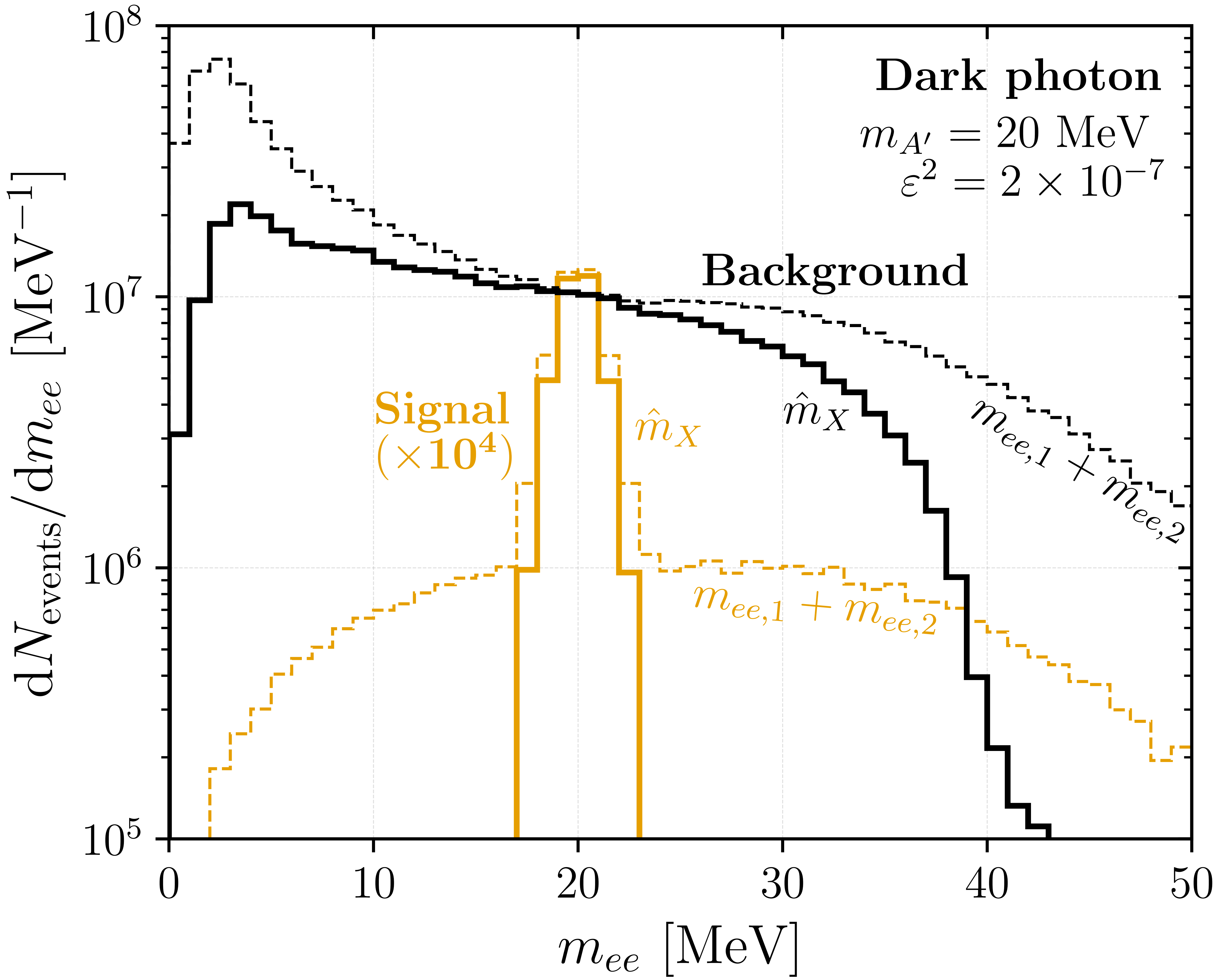
Two possibilities:

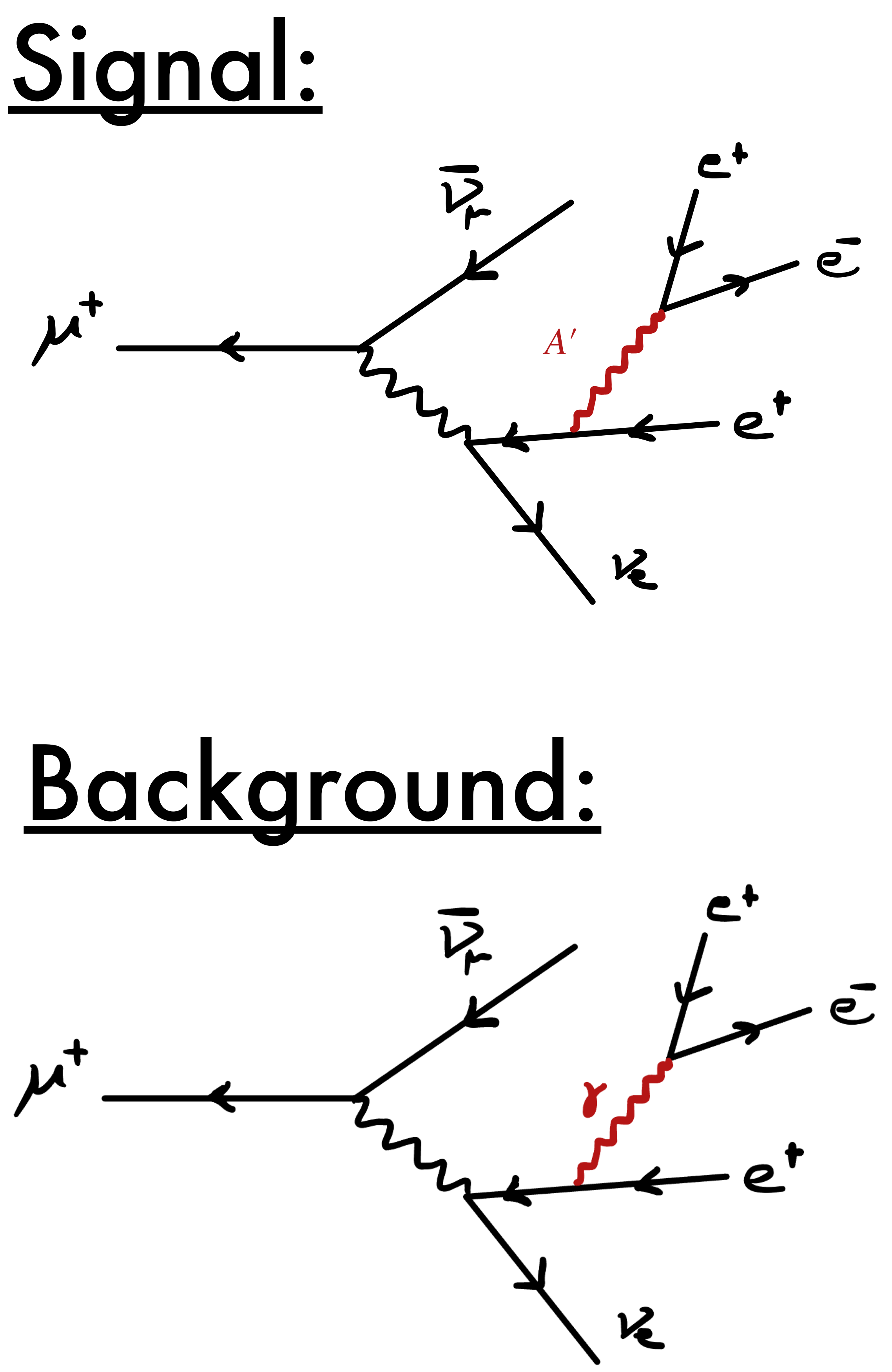
1. Prompt decays *Knapen, Langhoff, Opferkuch, D.R., 2311.17913*

Mu3e event selection requires $d_0 \leq 3$ mm *previous results from [Echenard et al 1411.1770] [Perrevoort et al 1812.00741]*

2. Displaced decays *Knapen, Opferkuch, D.R., Tammaro 2410.13941*

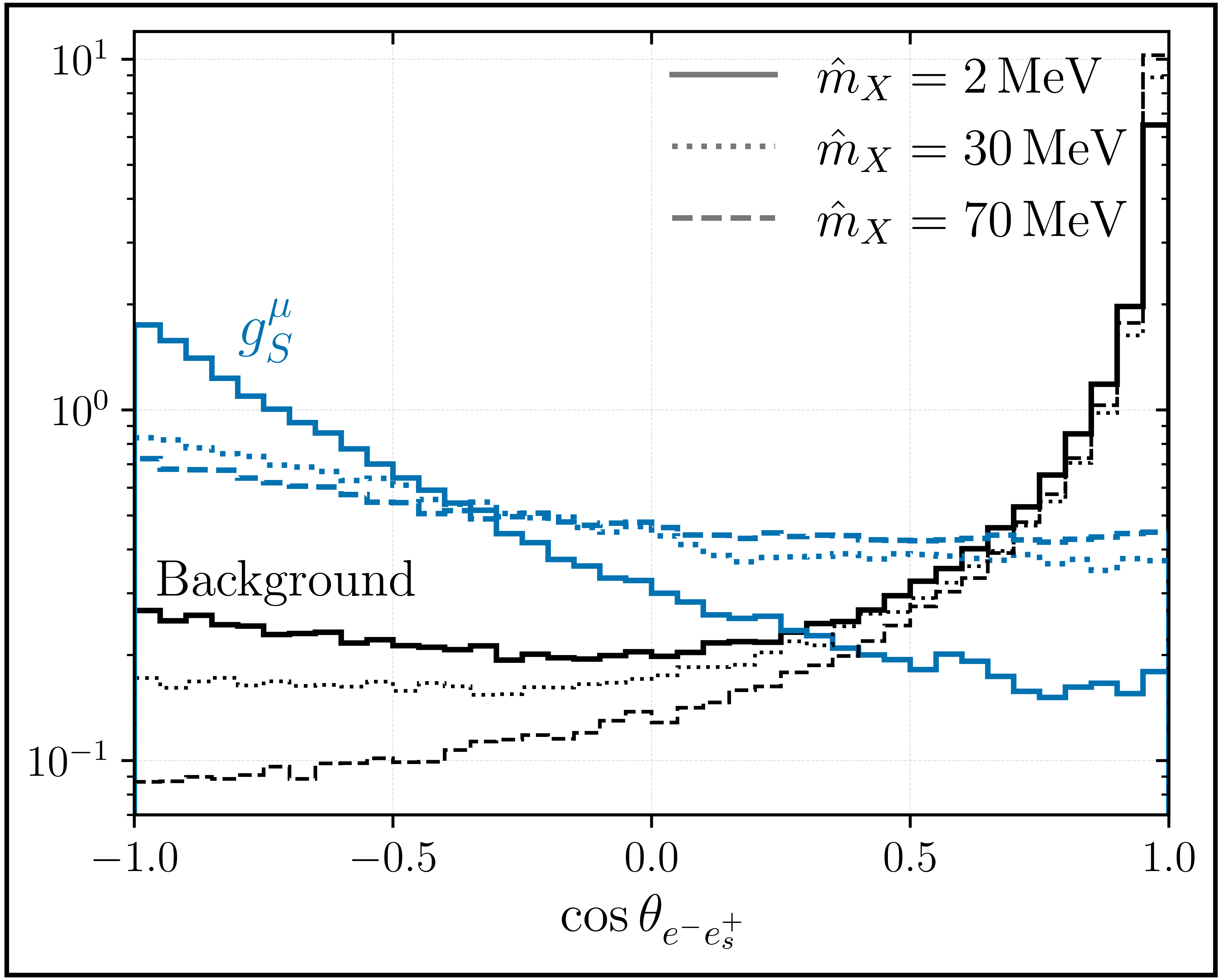
Bump hunt in invariant mass



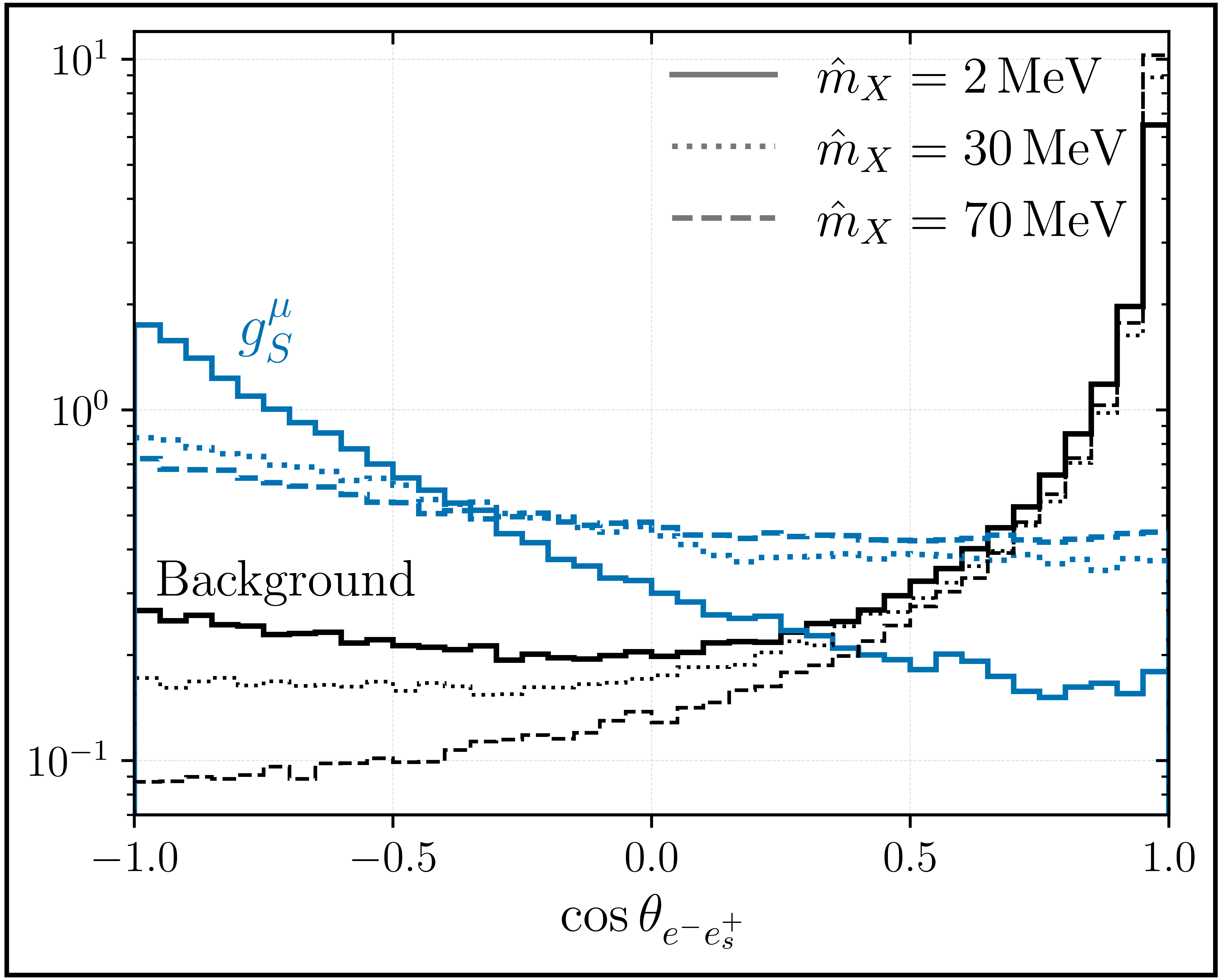


$\hat{m}_X$ is the e^+e^--pair that reconstructs the mass of the hypothetical resonance

Angular correlation



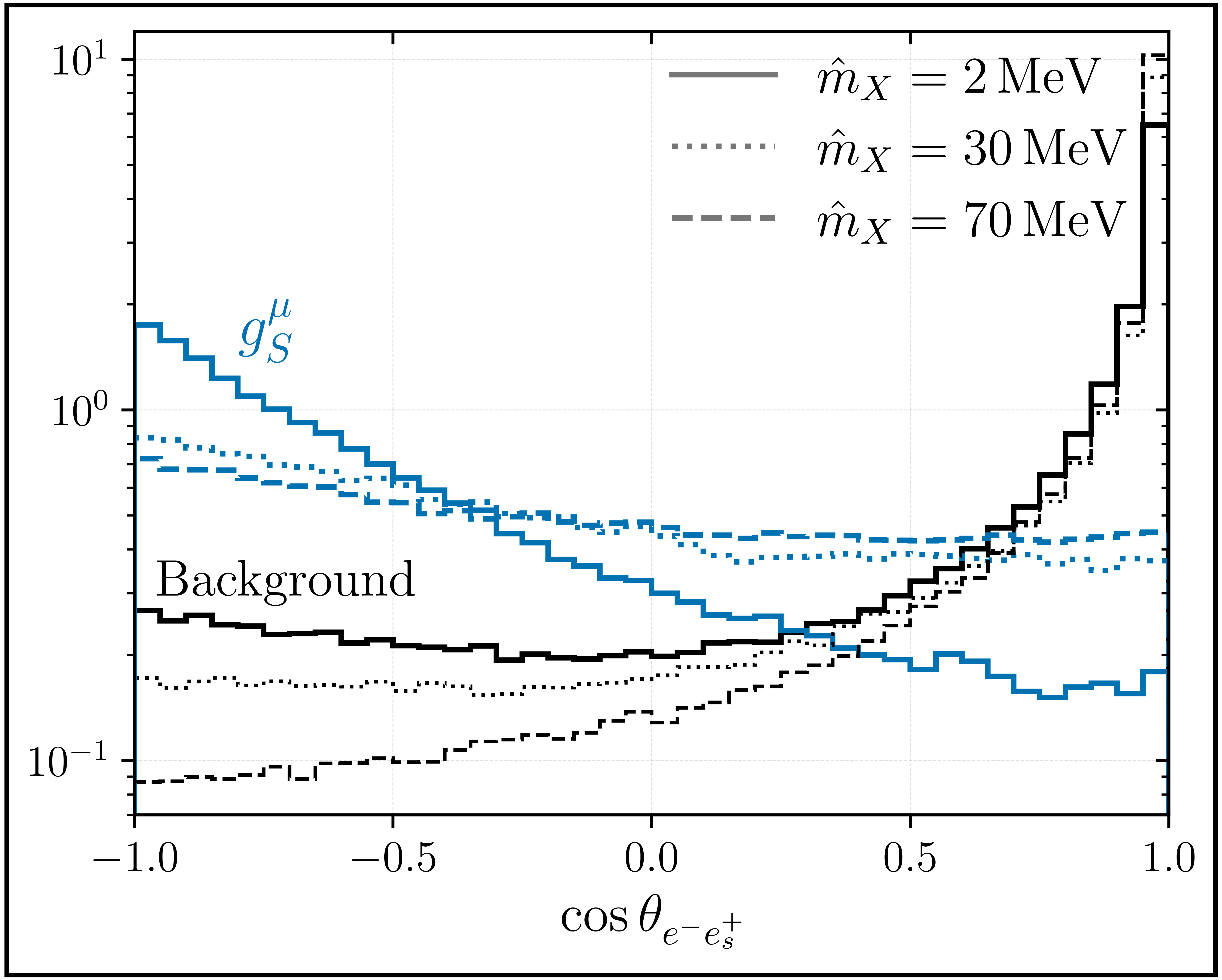
Angular correlation



<u>The off shell SM photon is different from an on shell new resonance</u>

- One particular collinear singularity of the bkd is absent for the signal

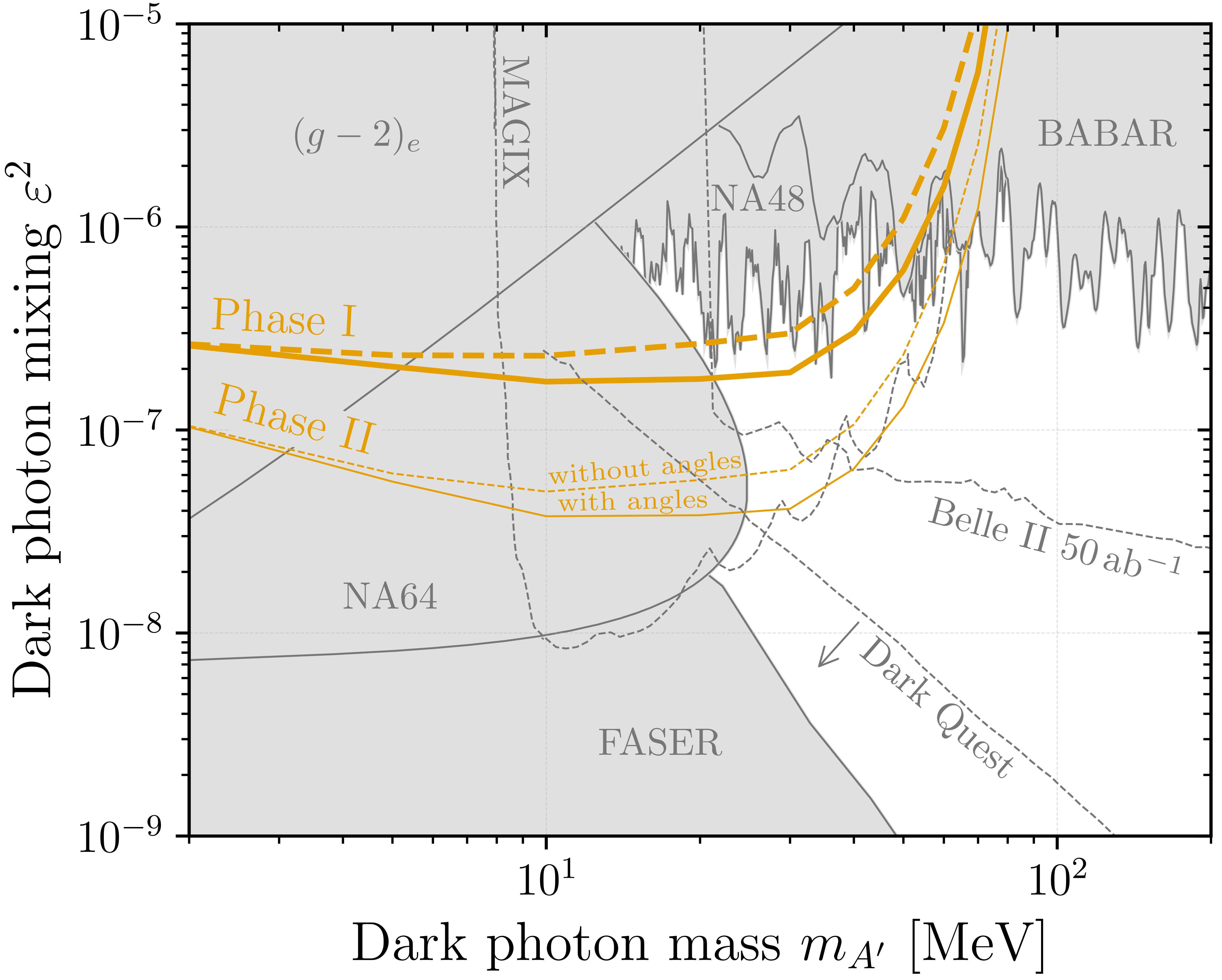
Angular correlation



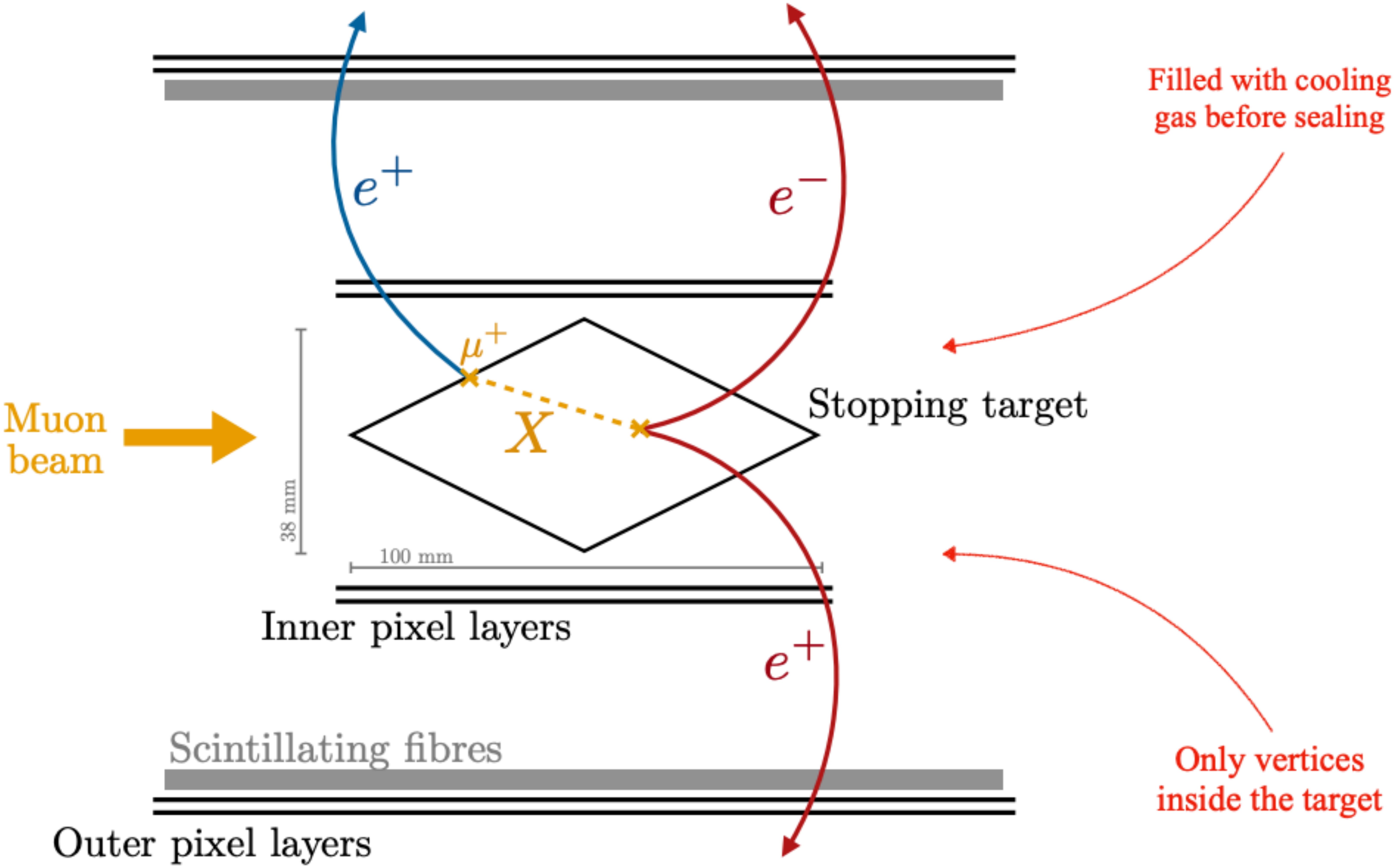
<u>The off shell SM photon is different from an on shell new resonance</u>

- One particular collinear singularity of the bkd is absent for the signal
- Further discrimination can be achieved depending on the coupling structure of the signal

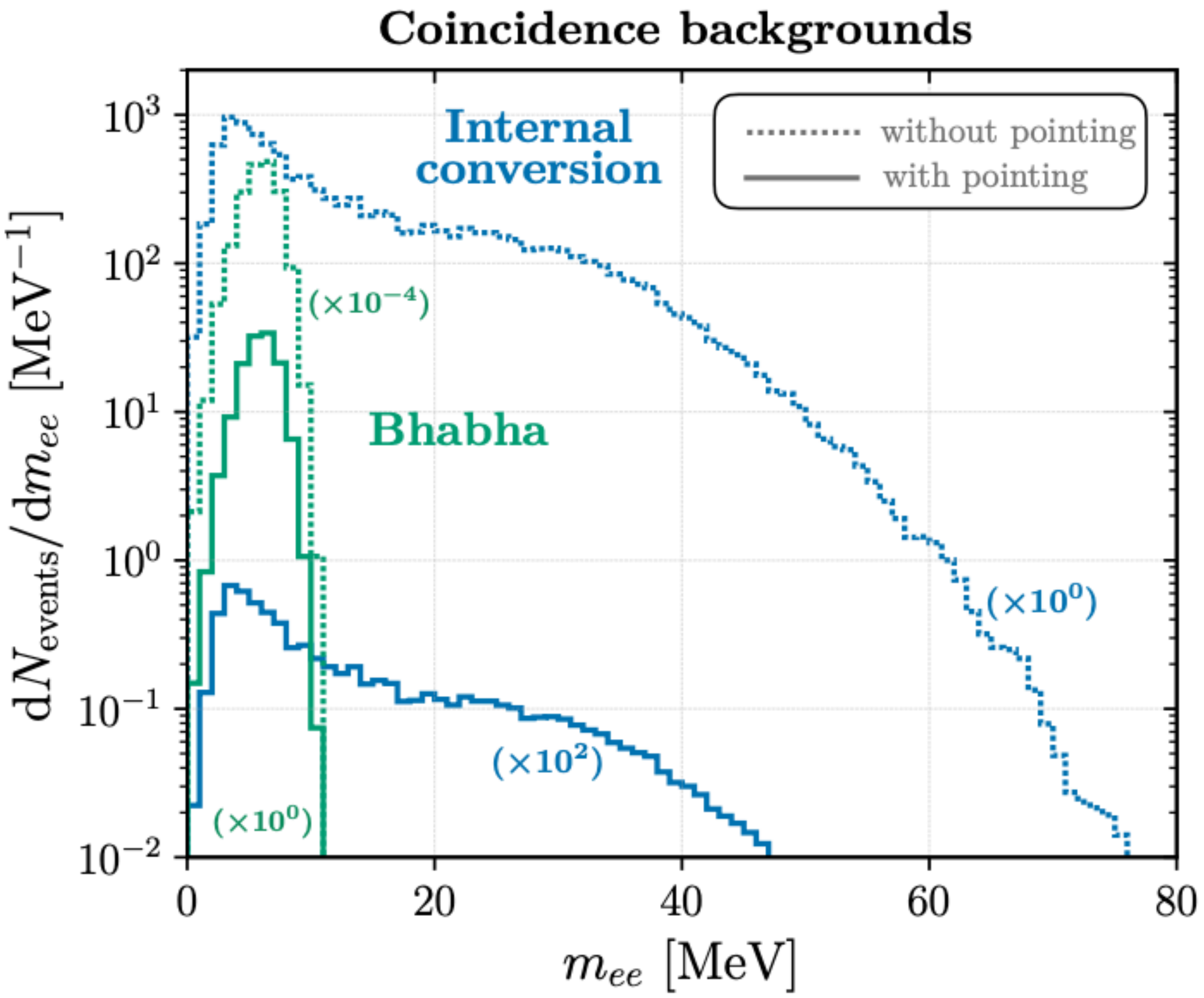
The Dark Photon parameter space



Displaced resonances



Backgrounds



No "neutrinos"

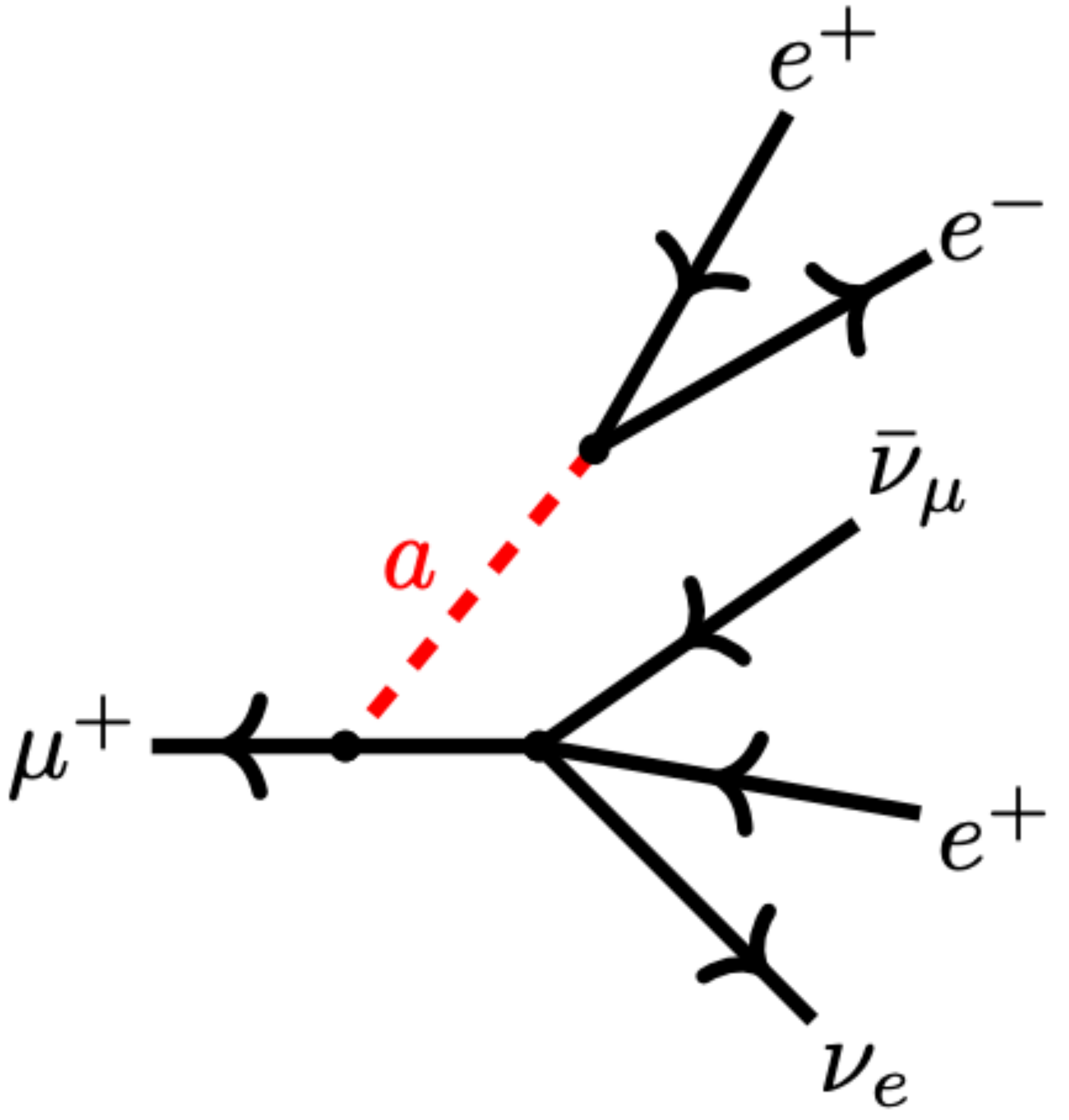
$$p^{\mu}_{\not{E}} = 0$$

"neutrinos"

$$p^2_{\not{E}} > 0$$

Lepton flavor conserving ALP

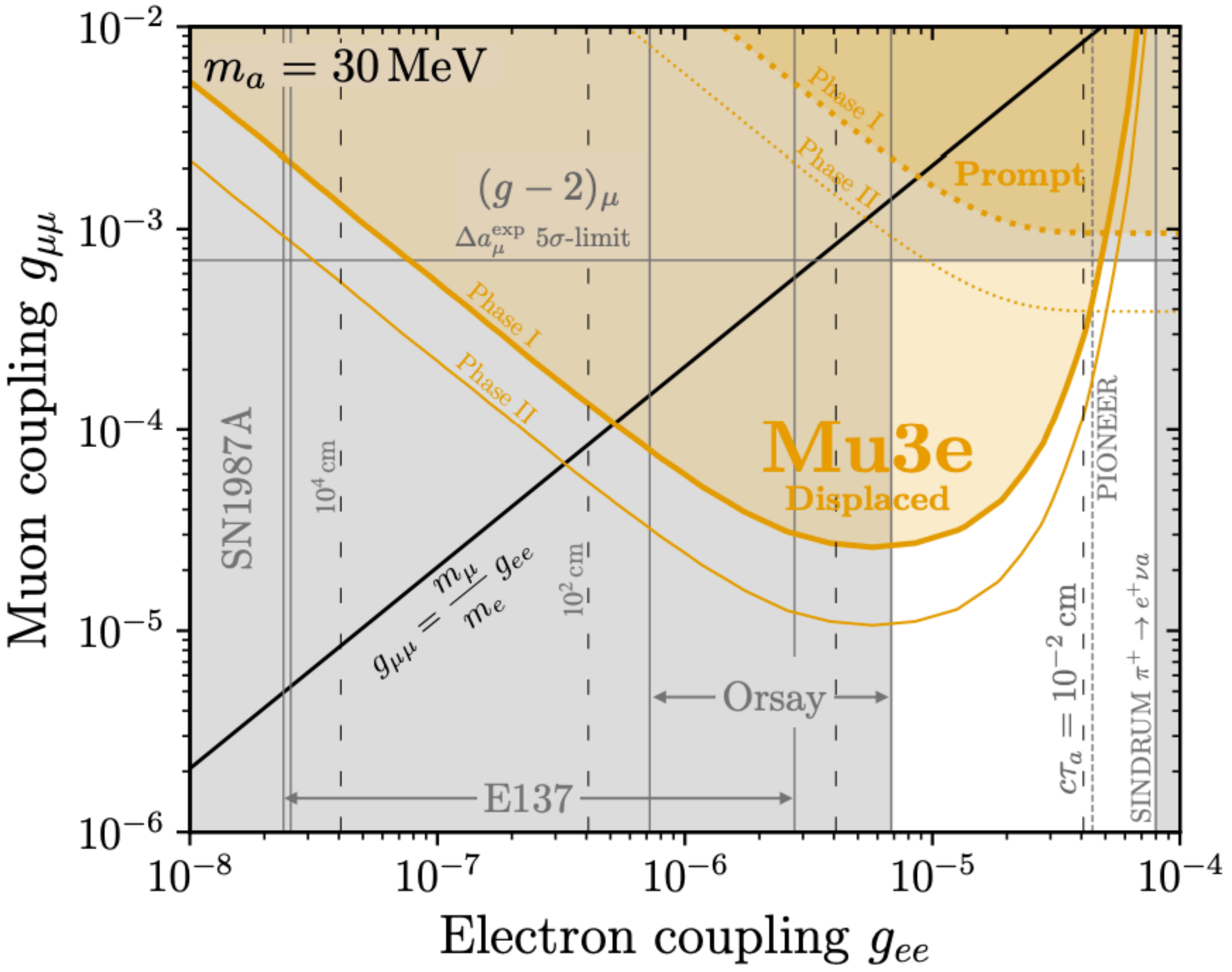
$$\mathcal{L}_a = g_{\mu\mu} a \bar{\mu} \gamma_5 \mu + g_{ee} a \bar{e} \gamma_5 e$$



✔ Pointing

✘ Mass reconstruction

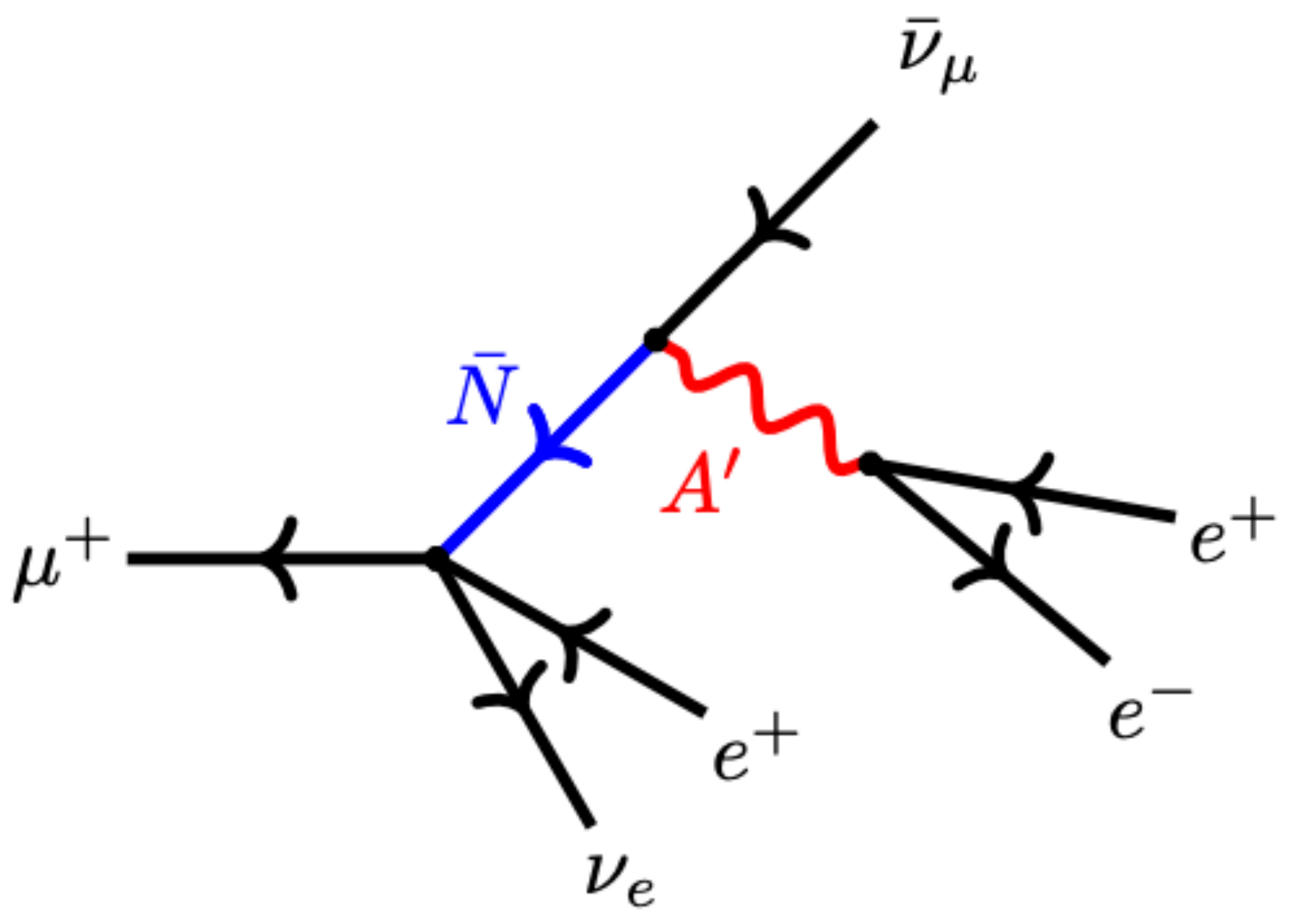
6



short-baseline high intensity flavor experiments can win over beam dumps for short displacements!

Light steriles + dark photon

$$2m_e < m_{A'} < m_N < m_\mu$$



✗ Pointing

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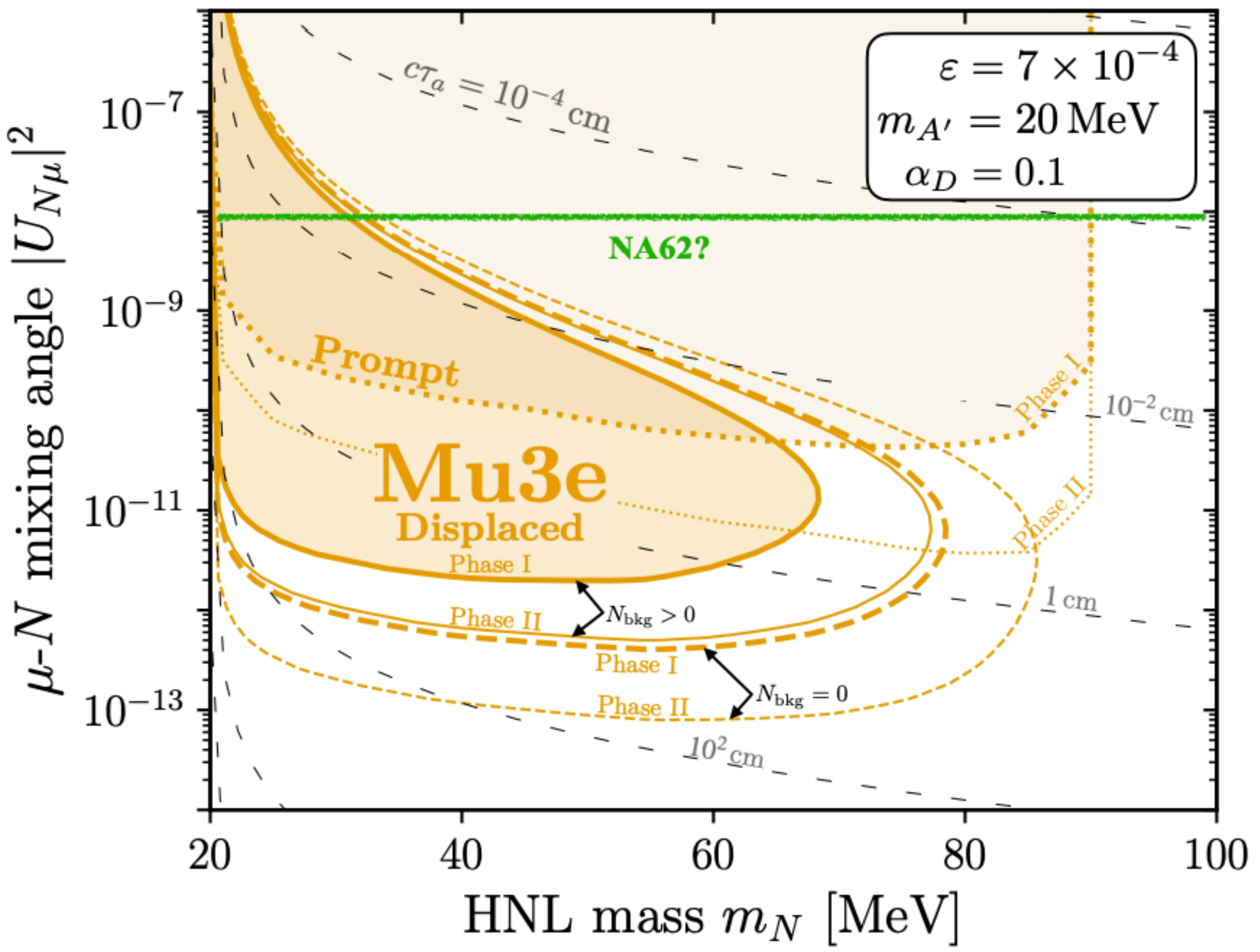


if the signal contains a lot of missing energy flavor factories can significantly extend the reach

We might still be lucky…

…and see something

ADVANTAGEOUS PARADIGM FOR ACCELERATORS

The Dark Matter is light thermal relics

For example SM neutrinos are a component of the dark matter today and are easily produced at accelerators while their relic background is difficult to unveil

The neutrino mass comes from inverse seesaw

$$y_n H L N + M_N N \bar{N} + \mu_N N^2$$

SMALL $m_\nu = U^2_{N\nu} \mu_N$ $\quad \xleftrightarrow{\mu_N \ll M_N} \quad$ $U_{N\nu} = \dfrac{y_N v}{M_N}$ LARGE

What if neutrino are composite?

to appear with M. Costa and M. Borrello

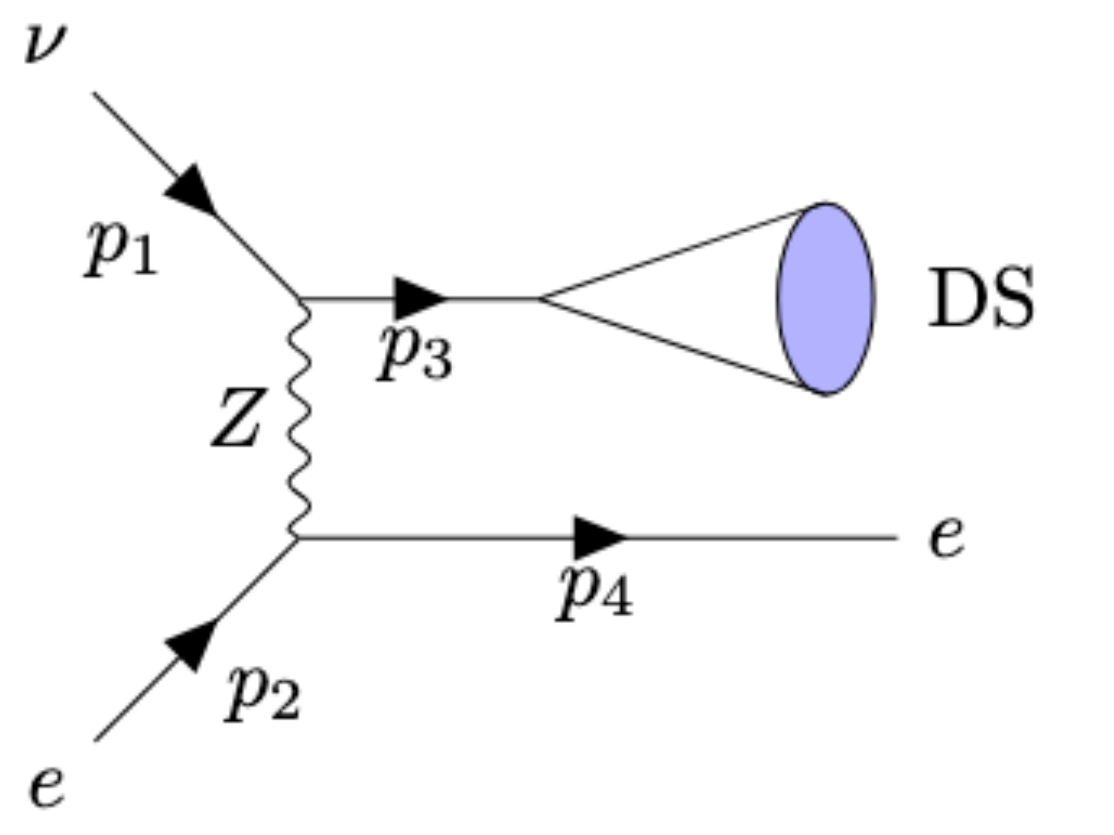
$$\Delta\mathcal{L}_N = \frac{y_\mu H L_\mu \mathcal{O}_N}{\Lambda_{\mathrm{UV}}^{\Delta_N - 3/2}}$$

the sterile neutrino gets replaced by an operator dimension Δ_N

$\Delta_N \geq 7$: dark-jet on detector scales

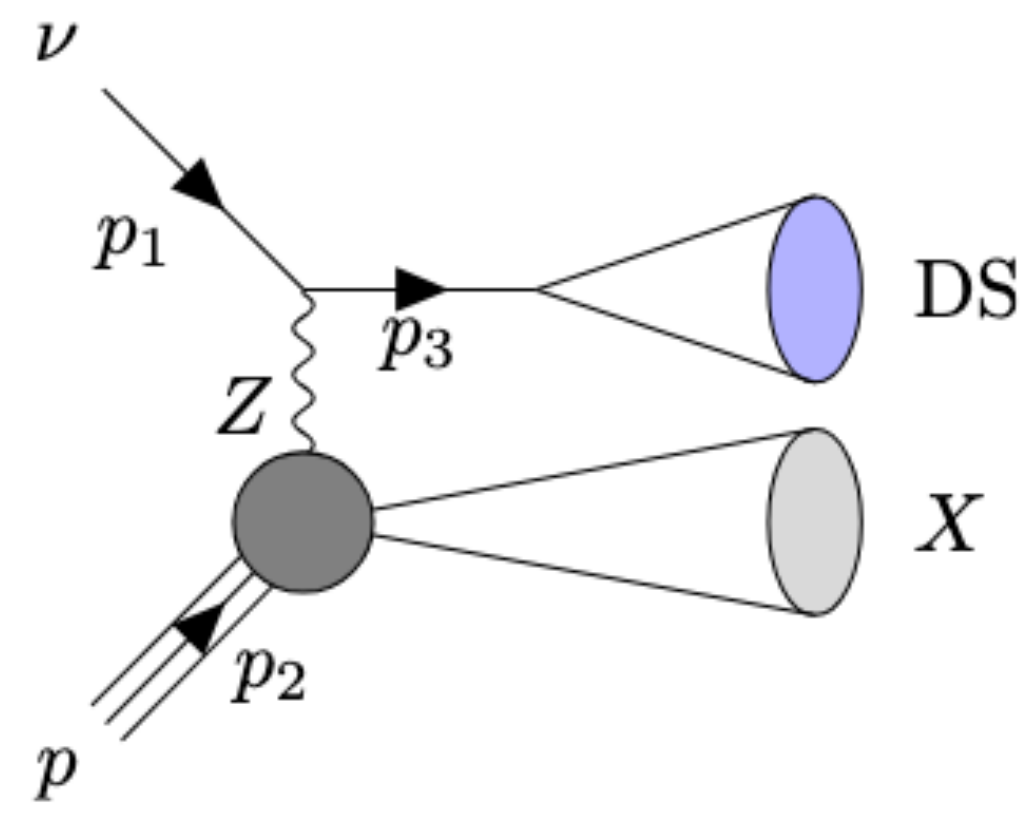
New processe in neutral currents

Neutrino disintegration into a dark-jet



$e - \nu$

DIS scattering

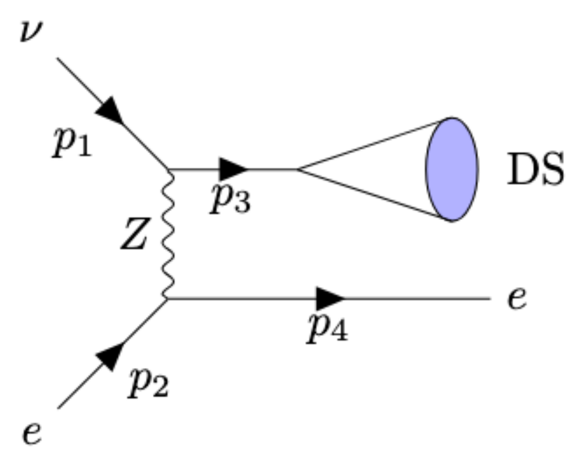


$e - N$

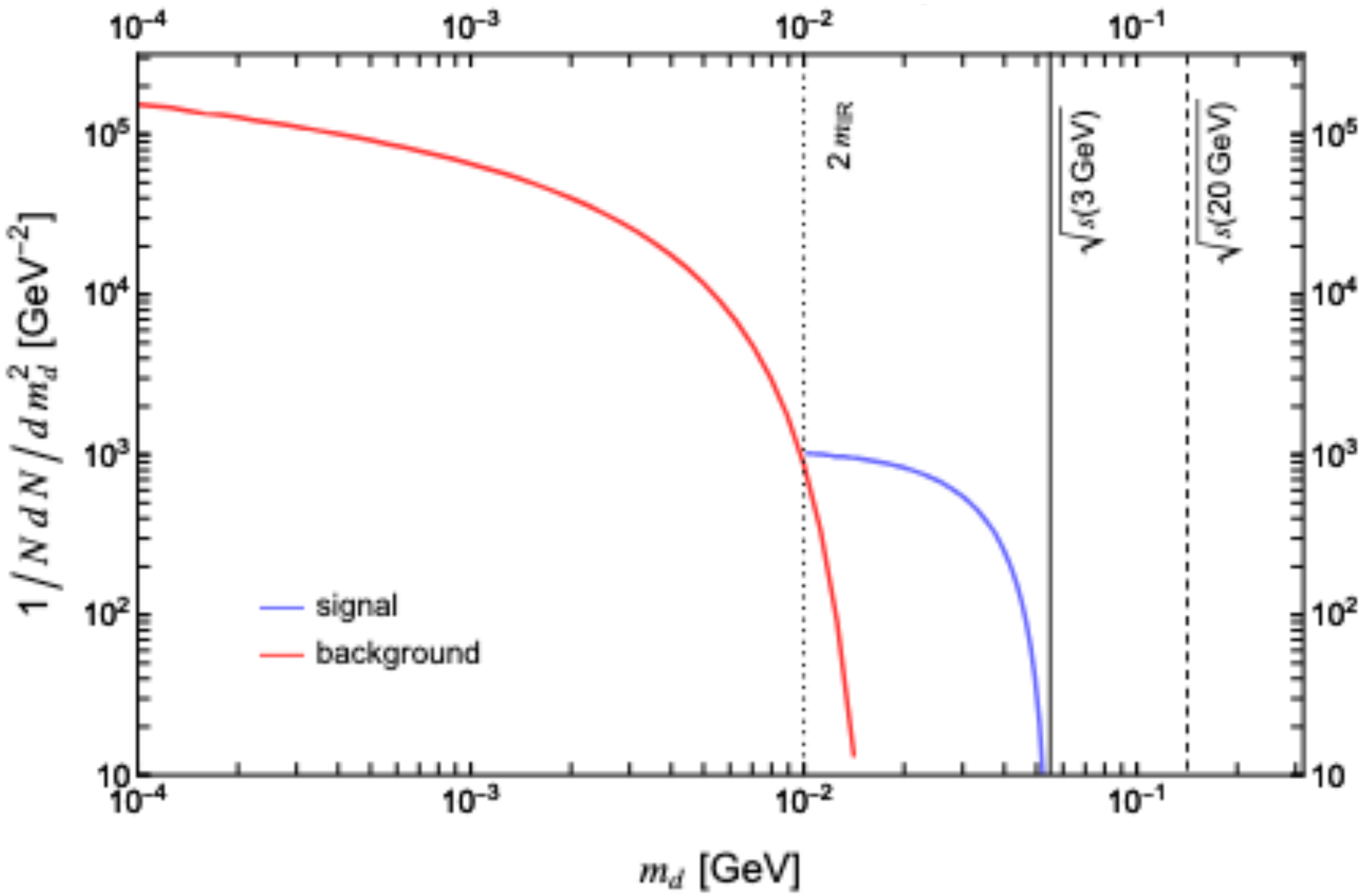
2-DIS scattering

Distinguishing from the background

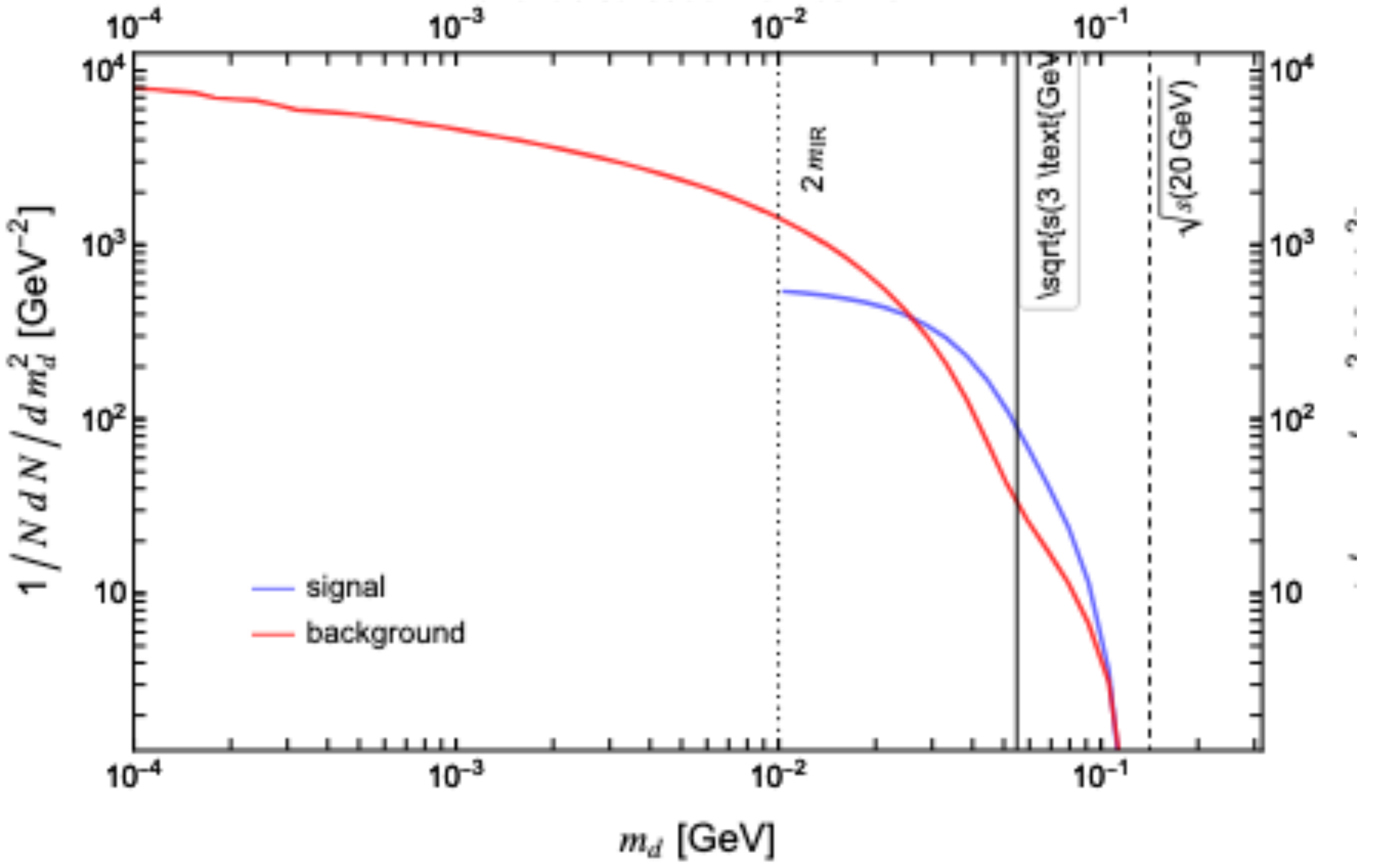
Example: electron recoil



NARROW INCOMING NEUTRINO FLUX

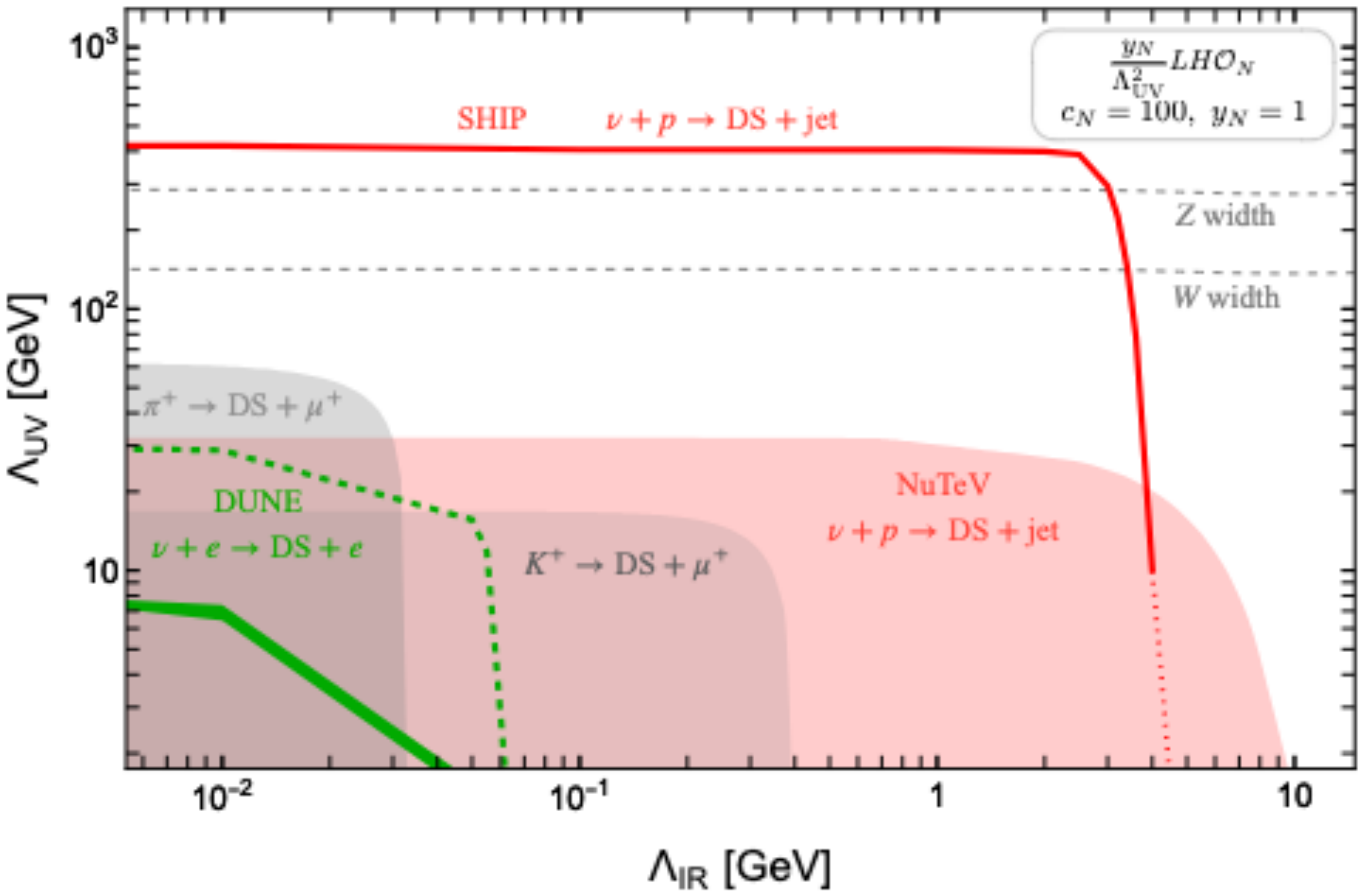


WIDE NEUTRINO FLUX (AS PLANNED @ DUNE)



high missing mass tail in neutrino scattering!

Summary



$\nu - N$ recoils enhanced @ high missing mass

Novel constraint from existing NuTeV data

Expected reach at SHIP surpasses EW invisible BR

Electron recoil subdominant because $s = m_e E_\nu$ is small

Dark Sectors at Flavor Factories

LFV ALP @ MEG II & Mu3e

breaking SM accidental symm.

New resonances in muon decays

Standard freeze-out targets

Direct probe of neutrino compositeness

Thanks…