

# Strong CP problem vs flavor experiments

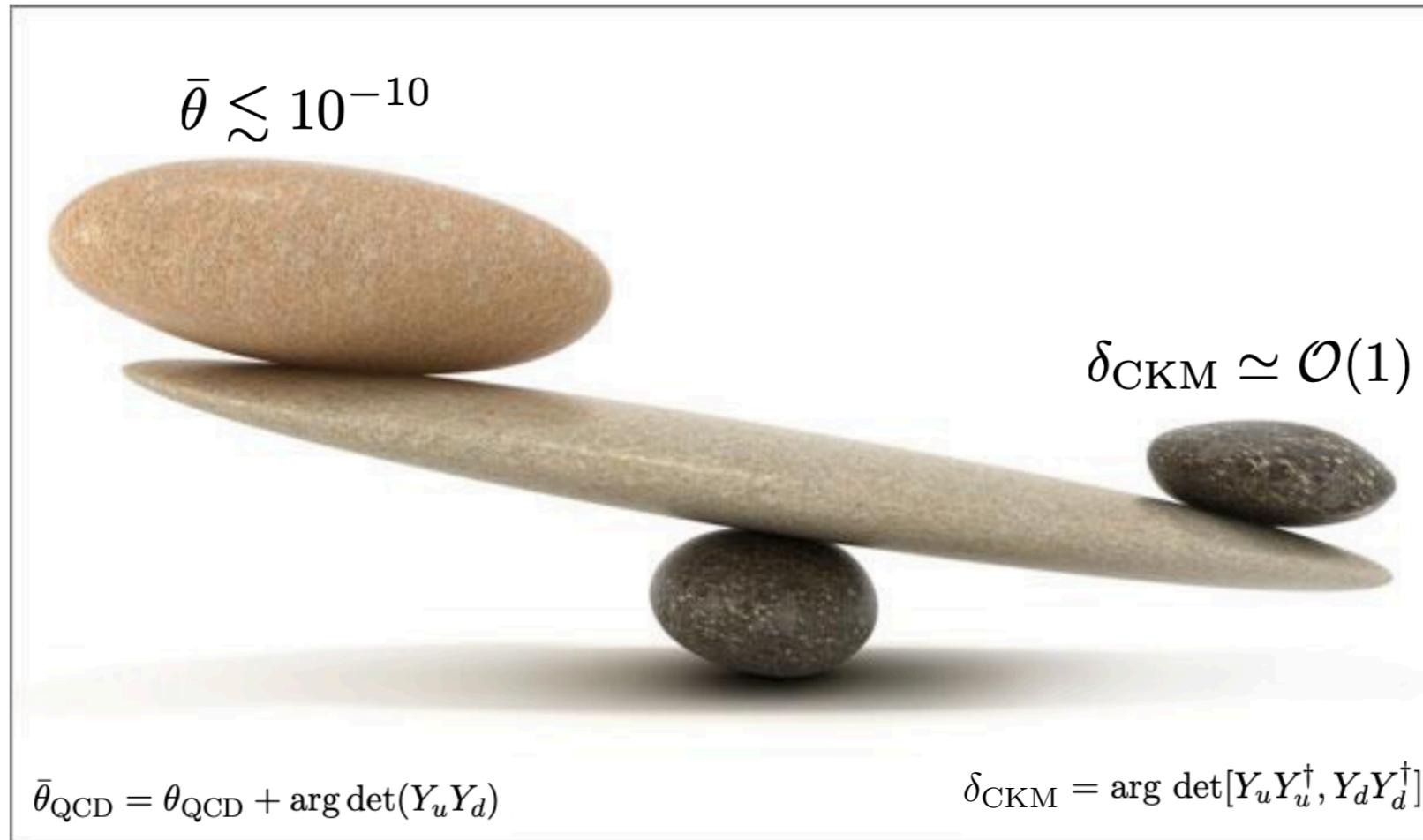
Diego Redigolo

based on [2201.07805](#) review coordinated with *E Goudzovski, K. Tobioka and J. Zupan*  
on [2006.04795 \[hep-ph\]](#) with *L. Calibbi, R. Ziegler, J. Zupan*  
on [2203.11222 \[hep-ph\]](#) with *S. Knapen and Y. Jho*  
+ work in progress...



Istituto Nazionale di Fisica Nucleare  
SEZIONE DI FIRENZE

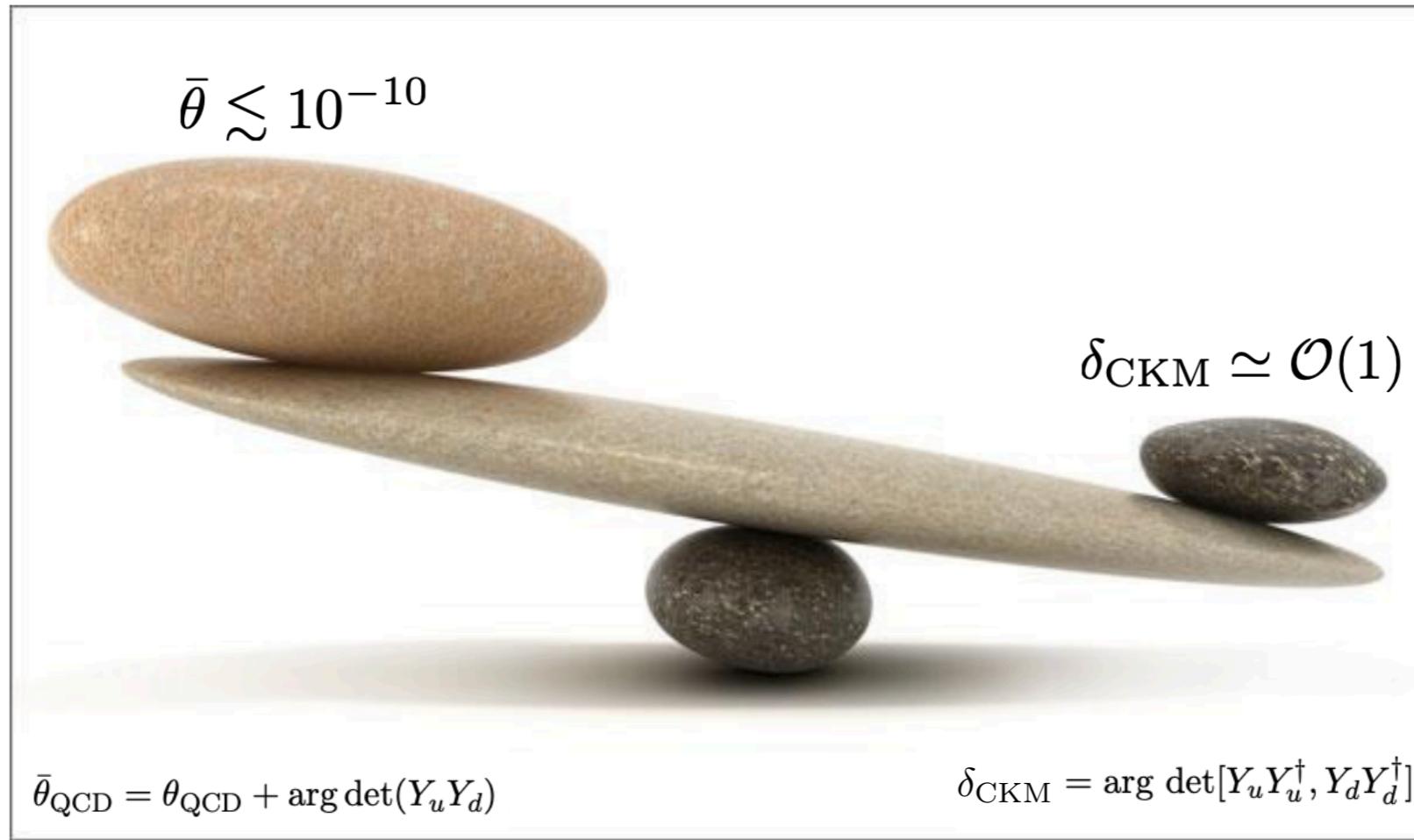
# Strong CP problem & its solutions



**The PQ axion** is the Nambu-Goldstone boson of a spontaneously broken U(1) symmetry  
and stabilizes  $\bar{\theta} = 0$

**The Nelson-Barr** solution sets  $\bar{\theta} = 0$  in the UV and then spontaneously breaks CP in the IR  
generating the CKM phase but not a large  $\bar{\theta}$

# Strong CP and flavor problem might be related?



**The PQ axion** might have something to do with flavor if the PQ symmetry is embedded non-trivially in the (approximate) symmetry of the SM

**In the Nelson-Barr** scheme the challenge is generating the CKM (including the phase) then a full theory of flavor is needed

# Flavor test of Nelson-Barr

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In the Nelson-Barr scheme flavor observable test the indirect effects of the vector-like matter required to implement the mechanism

**Toy example: Bento-Branco-Parada model**

$$\mathcal{L} \supset \mu U \tilde{U} + B_i^u U \tilde{u}_i + \text{h.c.}$$

$$\mathcal{L}_Z^u \supset \frac{m_Z^2}{g_Z \bar{M}^2} \lambda_i^u \lambda_j^{u\dagger} \left( u_{Li} \gamma_\mu u_{Lj}^\dagger \right) Z^\mu, \quad \lambda_i^u = \frac{(B^{u*} V^\dagger Y_u^\dagger)_i}{\bar{M}},$$

*“Spontaneous flavor violation” Egana, Homiller, Meade 2019*

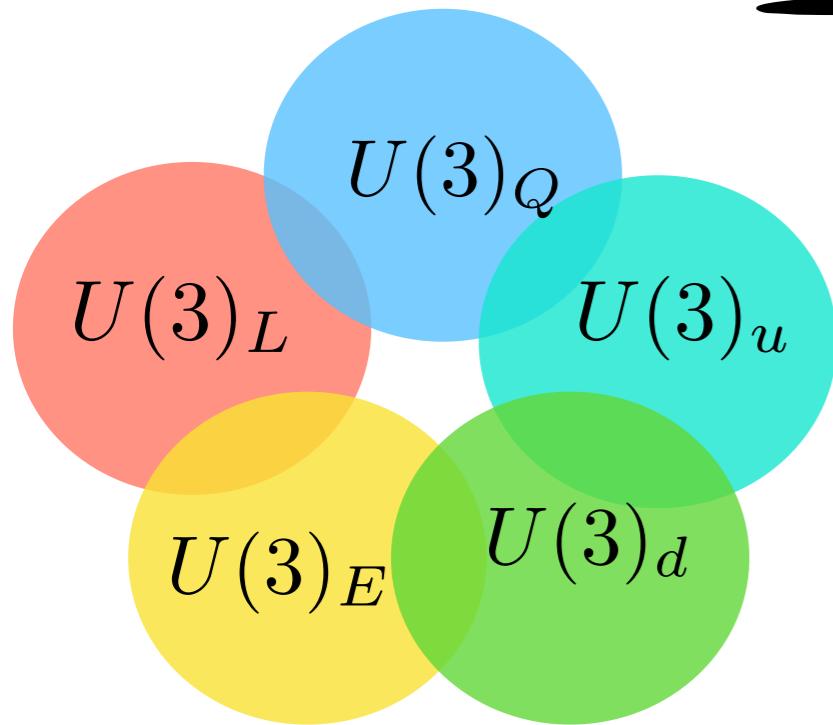
$$\Delta F = 2 \quad \text{Operator} \sim \lambda_i^u \lambda_j^{u\dagger} \frac{v^2}{\bar{M}^2} \longrightarrow \bar{M} > 200 \text{ GeV}$$

$D - \bar{D}$  mixing

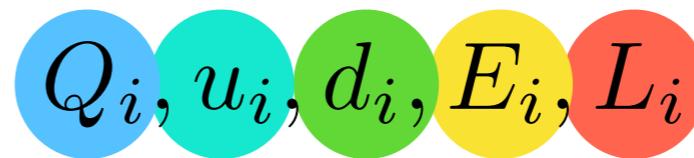
Direct constraints from LHC are stronger!

*Ishiwata, Ligeti, Wise 2015*

# Axions and flavor



→ PQ charges can be flavor dependent



→ Example: Axion + Froggatt-Nielsen

$$\sum_i \frac{\partial_\mu a}{2f_a} \bar{f}_i C_{f_i}^A \gamma_5 f_i$$

diagonal coupling to fermions control astro bounds

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

Flavor violation at dimension 5

Feng-Murayama-Moroi-Shnappa 1998

both axial and vector current are physical!

# Theory disclaimer I

Two basic flavor schemes at the UV cut-off       $\Lambda_{\text{UV}} \sim 4\pi f_a$



**flavor anarchy:**  $C_{ij}^{A,V}(\Lambda_{\text{UV}}) \sim \mathcal{O}(1)$



**MFV:**  $C_{ij}^{A,V}(\Lambda_{\text{UV}}) = 0$        $\left\{ \begin{array}{l} \text{FV generated by SM charged currents} \\ \text{in the quark sector} \\ \\ \text{FV depends on the sterile neutrinos} \\ \text{in the lepton sector} \end{array} \right.$

Ex:  $s \rightarrow d$        $C_{ds} = \frac{y_t^2}{16\pi^2} V_{td} V_{ts} C_{tt} \times \log \sim 10^{-6} C_{tt} \times \log$

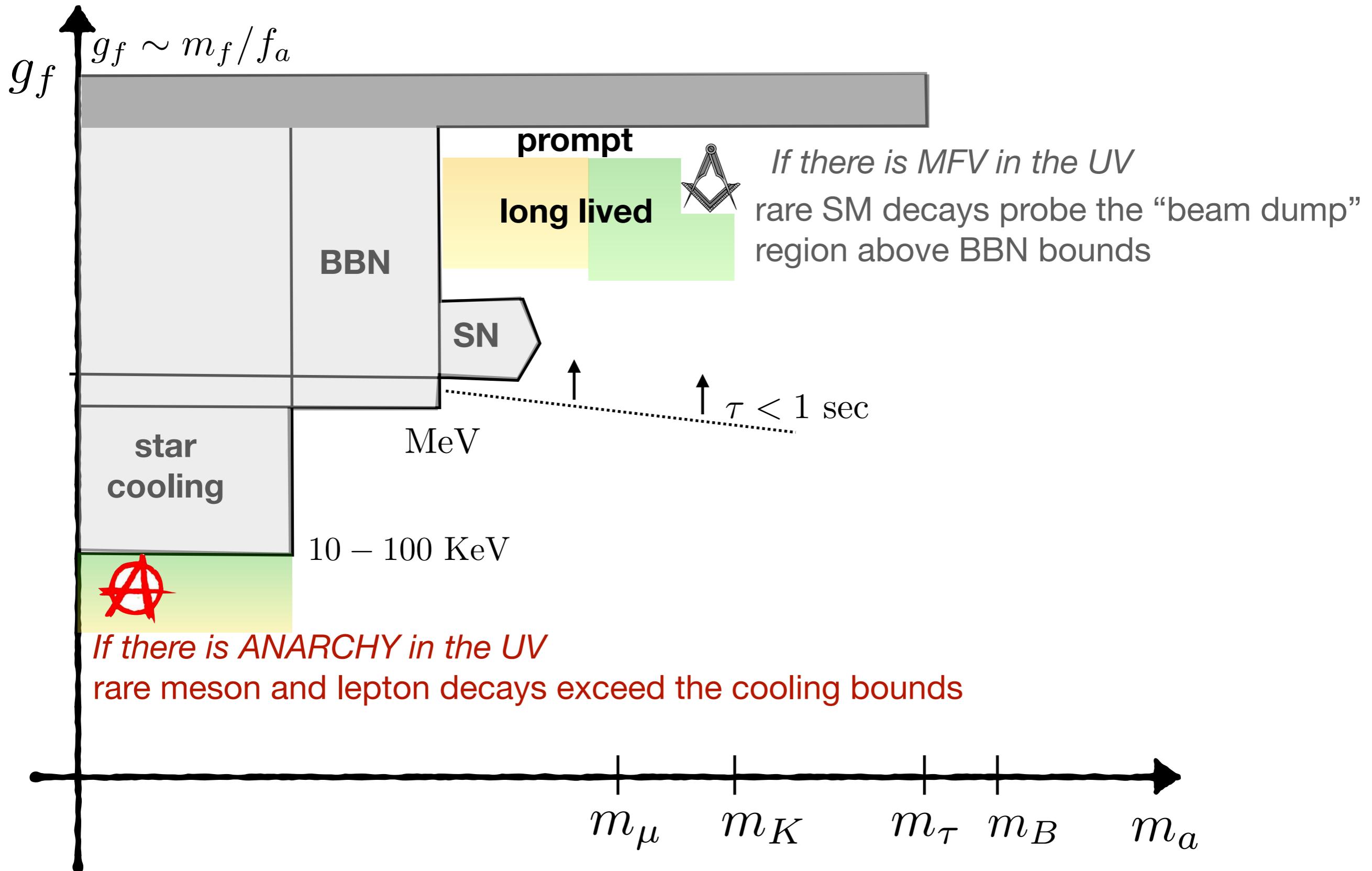
*See Neubert et al. papers for full formulas*

$\mu \rightarrow e$        $C_{\mu e} = \frac{y_{Ne} y_{N\mu}}{16\pi^2} \sim 10^{-2} y_{Ne} y_{N\mu}$

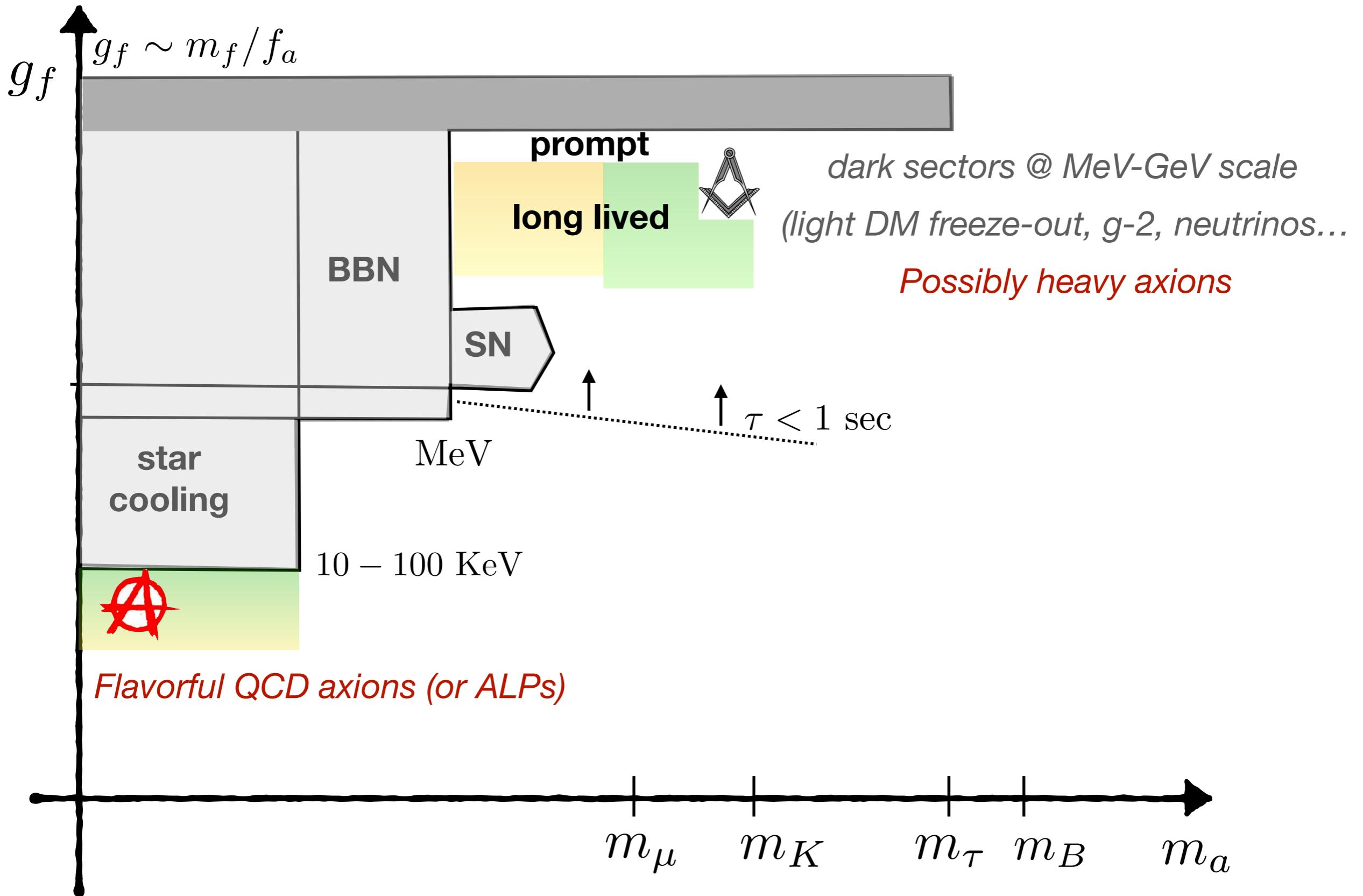
*See C. Garcia-Cely and J. Heeck (2017), J Heeck and H. Patel (2017)*

...

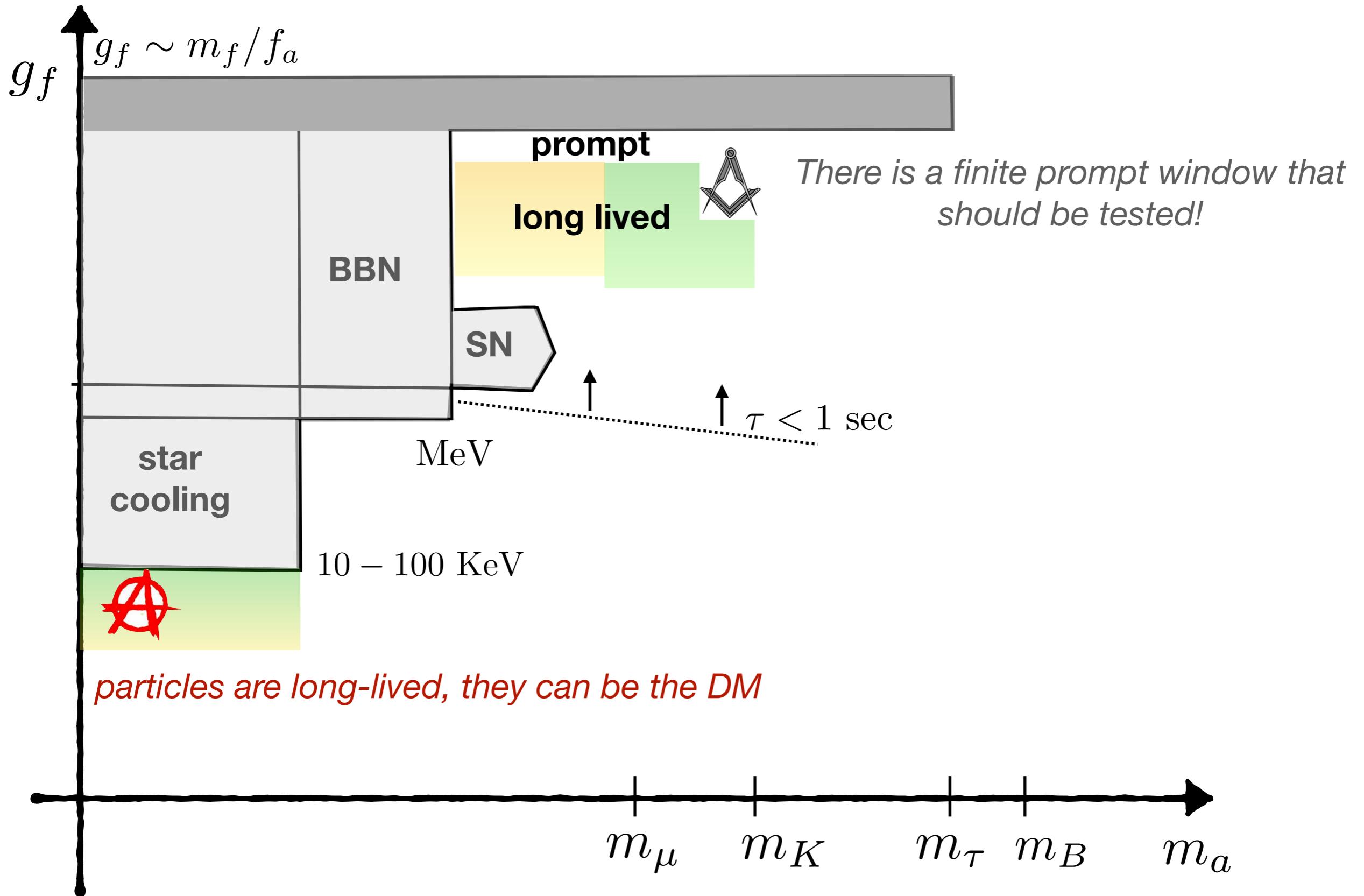
# Theory landscape I



# Theory landscape II



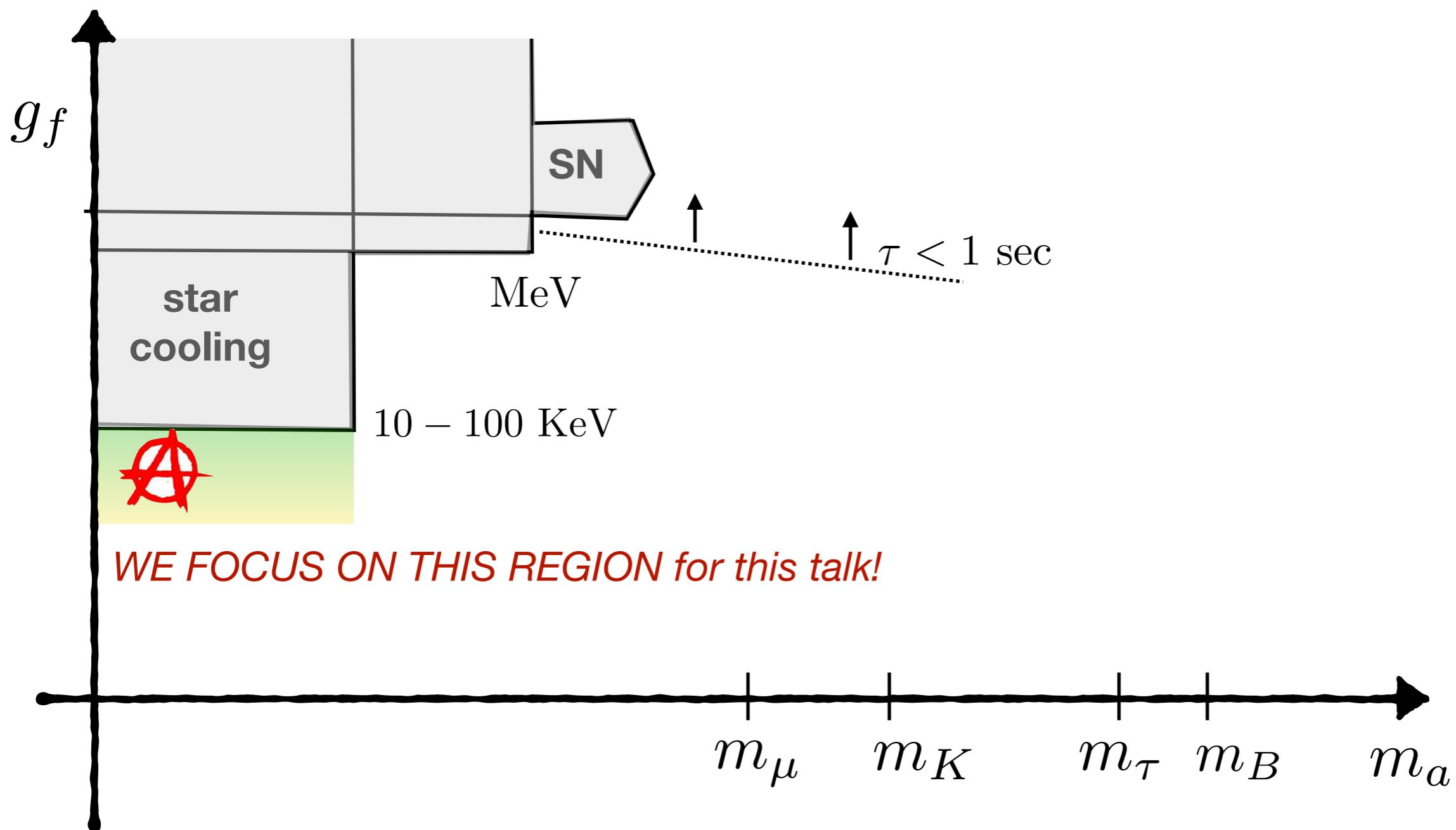
# Theory landscape III



# Theory landscape IV

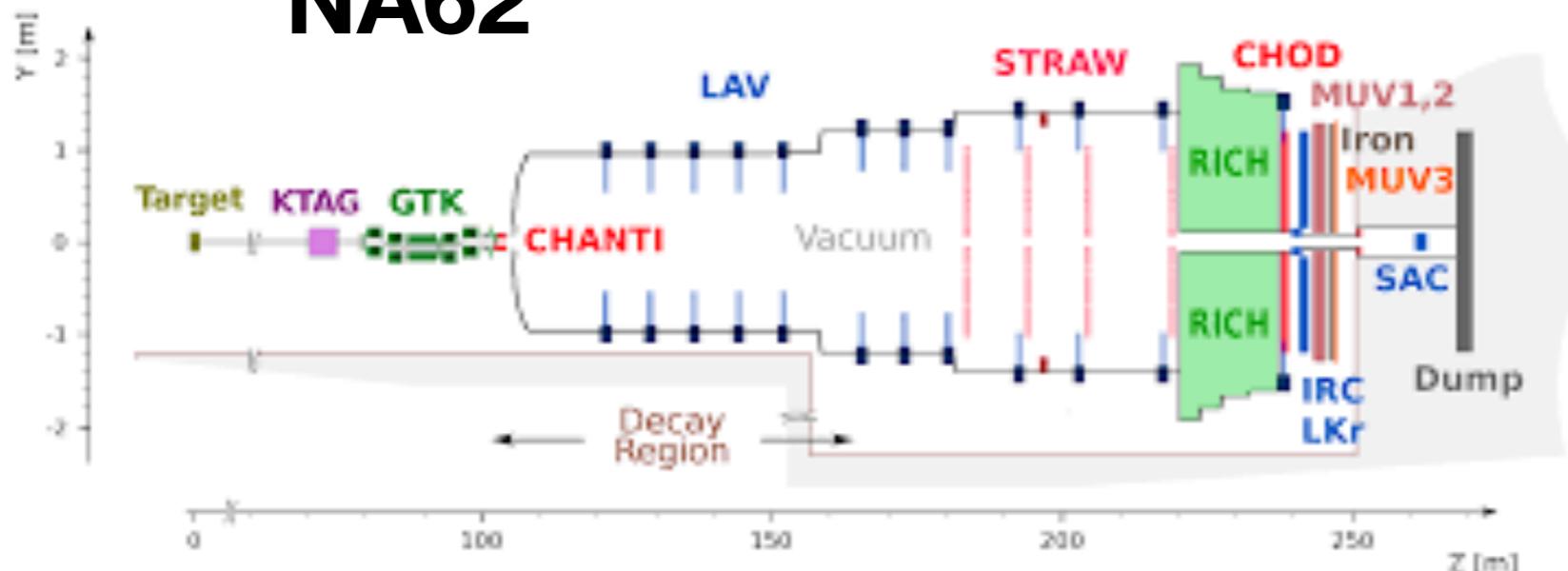
The axion is probably one of our best hopes for new physics

$U(1)_{PQ}$  has no reasons to be embedded trivially in the SM flavor group



# Kaon experiments

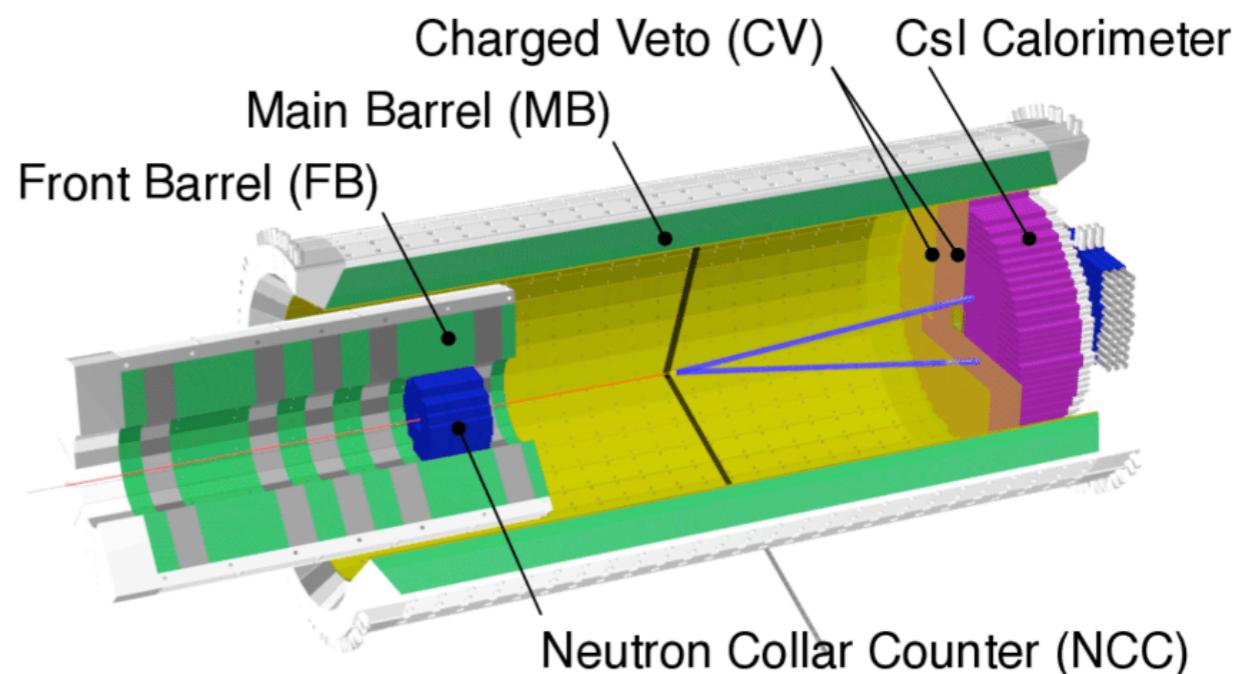
**NA62**



**Target**

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

**KOTO**



**Target**

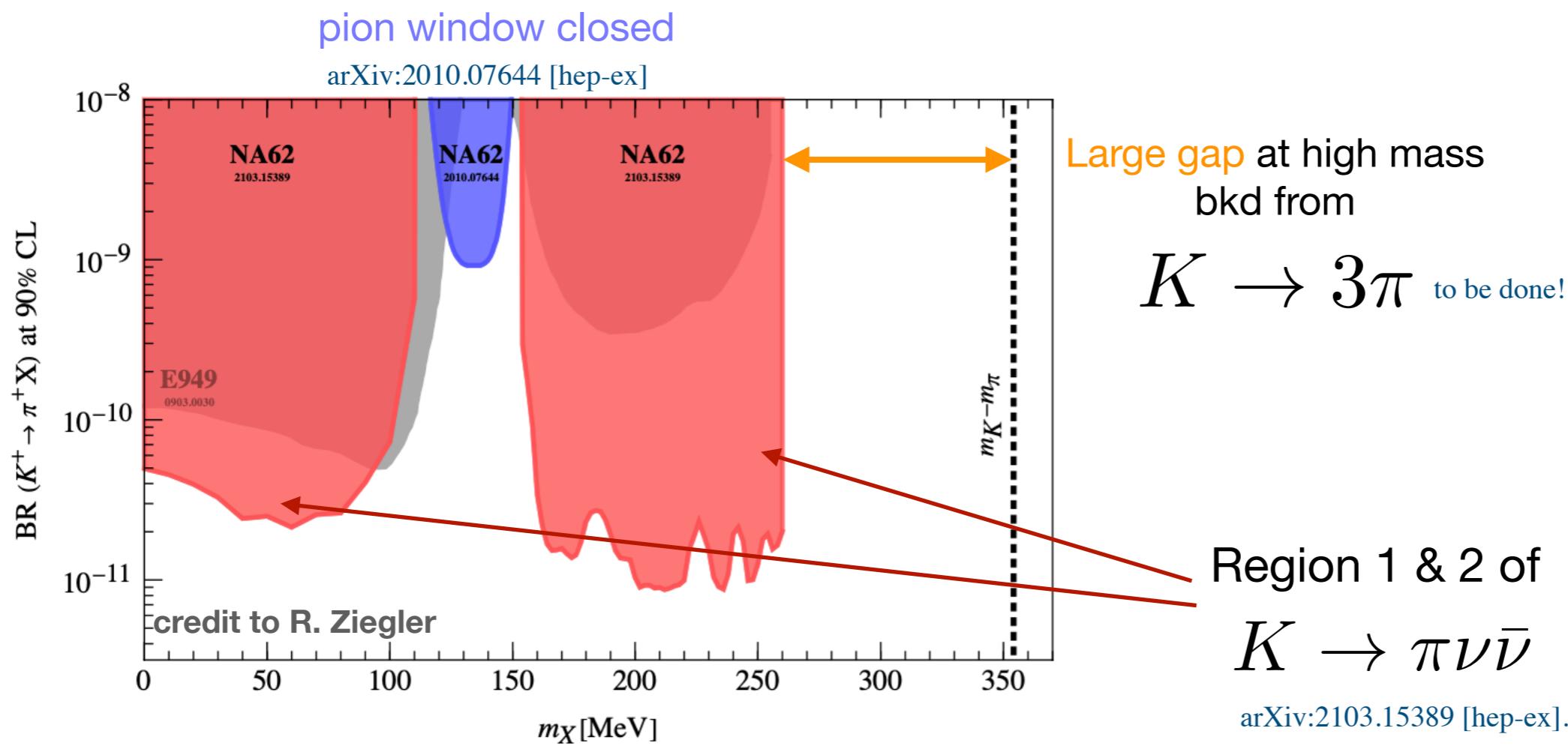
$$K_L \rightarrow \pi_0 \nu \bar{\nu}$$

# Axion @ kaon experiments

Hunting for rare kaon decays involving a light neutral particle

review with *E Goudzovski, K. Tobioka and J. Zupan*

$K \rightarrow \pi a$       } Relatively easy. We can use NA62 data. New analysis are required!  
 $K \rightarrow \pi\pi a$       } *NA62 knows already :)*



# Axion @ kaon experiments

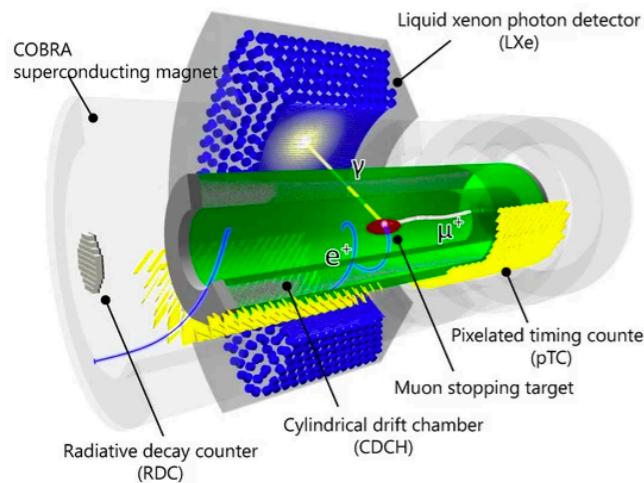
$K_L$  Is generically less powerful than  $K^+$

Unless in setups where the Grossman-Nir bound is violated

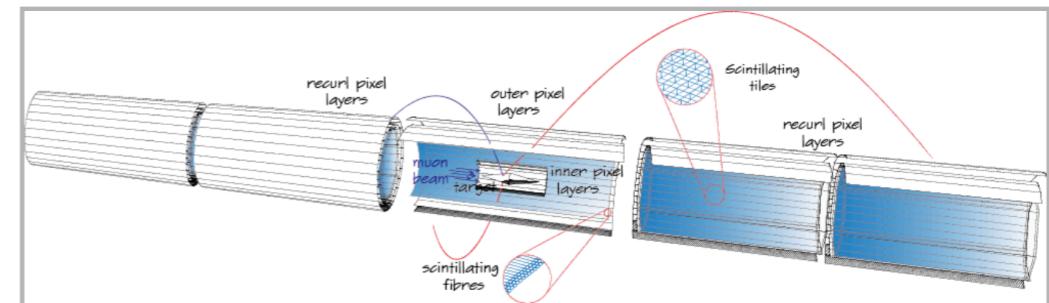
$K_L$ decay	Model	$K_L \rightarrow \gamma\gamma + \text{inv.}$ search strategy	$K^+ \rightarrow \pi^+ + \text{inv.}$ implication	Other predictions
$\rightarrow \pi^0 X$	(d) [244]	current $\pi^0 X$	SM-like	$K^0 - \bar{K}^0$ mixing $X_{1,2}$ at beam-dump
$\Delta I = \frac{3}{2}$ [243]			$\mathcal{B}(K_L \rightarrow \pi^0 X) \leq 51 \mathcal{B}(K^+ \rightarrow \pi^+ X)$	None
$\rightarrow \pi^0 X_1 X_1$	(c) [245]	current $\pi^0 \nu \bar{\nu}$	$\mathcal{B}(K_L \rightarrow \pi^0 X_1 X_1) \sim 4(4\pi)^2 \mathcal{B}(K^+ \rightarrow \pi^+ X_i X_j)$ if $m_{X_i} + m_{X_j} < m_K - m_\pi$	$B \rightarrow K(\pi^0) XX$ (in MFV) $X_2$ at beam dumps
	(e) [244]		SM-like	$K^0 - \bar{K}^0$ mixing $X_2$ at beam-dump
$\rightarrow \gamma\gamma X_1$	(a) [134]	optimize $\gamma\gamma$ selection	$\mathcal{B}(K_L \rightarrow \gamma\gamma X_1) \sim 4(4\pi)^2 \mathcal{B}(K^+ \rightarrow \pi^+ \gamma\gamma X_1)$ $\sim 4(4\pi)^2 \mathcal{B}(K^+ \rightarrow \pi^+ X_1 X_1)$ if $m_{X_i} + m_{X_j} < m_K - m_\pi$	$\mathcal{B}(K_L \rightarrow \pi^0 XX) \sim 10^{-2} \mathcal{B}(K_L \rightarrow \gamma\gamma X)$ $B \rightarrow K(X_2 \rightarrow \gamma\gamma) X_1$ (in MFV) $X_2$ at beam dumps
$\rightarrow \gamma\gamma X_1 X_1$	(a) [245]			
	(b) [245]	optimize $\gamma\gamma$ selection	$\mathcal{B}(K_L \rightarrow \gamma\gamma X_1 X_1) \sim 4(4\pi)^2 \mathcal{B}(K^+ \rightarrow \pi^+ \gamma\gamma X_1 X_1)$ if $m_{X_1} + m_{X_2} < m_K - m_\pi$	$B \rightarrow K(\gamma\gamma) XX$ (in MFV) $X_2$ at beam dumps

# Muon experiments

## MEG II



## Mu3e



$$\mu^+ \rightarrow e^+ e^- e^+$$

Standard signal characterised by **no missing energy**

The challenge is to **increase the luminosity** while suppressing coincidences  
**tightening the kinematic + timing requirements**

# Axion @ muon experiments

## Hunting for rare muon decays involving a light neutral particle

More challenging. New data taking strategies have to be conceived.

$$\mu \rightarrow e a$$

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

Muon polarization can help discriminating the signal

For left-handed couplings the limitation are large systematics

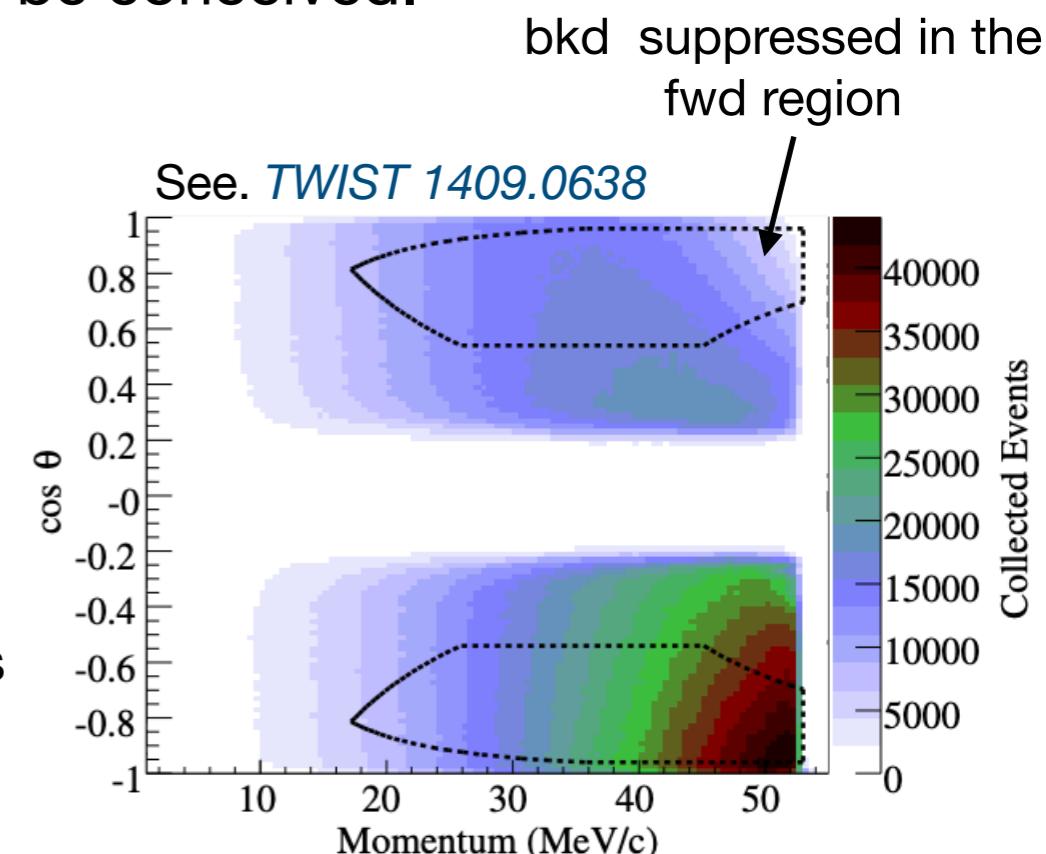
See. [L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795](#)

$$\mu \rightarrow e a \gamma$$

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

The price to pay is a reduced signal by  $\sim \frac{\alpha}{2\pi} \log \frac{2E_\gamma}{m_\mu}$

See. [S. Knapen and Y. Jho 2203.11222](#)



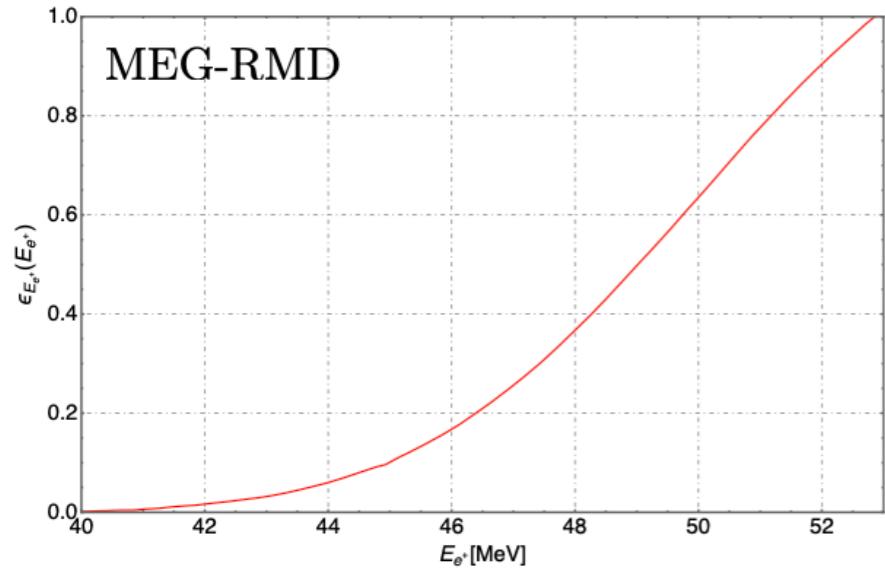
# What MEG can teach us?

$\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$  MEG 2016  $\longleftrightarrow$  1) very high intensity  
2) very exclusive trigger targeted at  $\mu \rightarrow e\gamma$

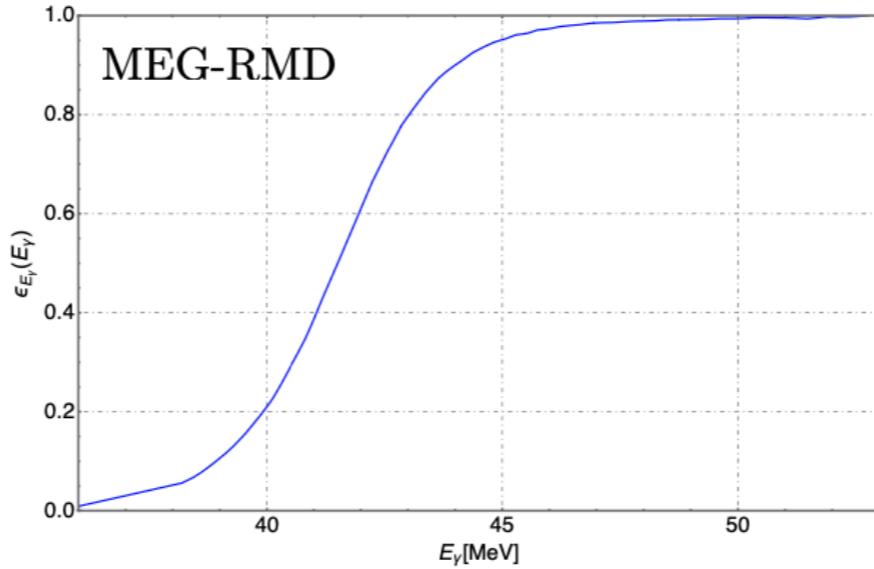
The trigger maximize the efficiency to back to back positron-photon of  $E = m_\mu/2$

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

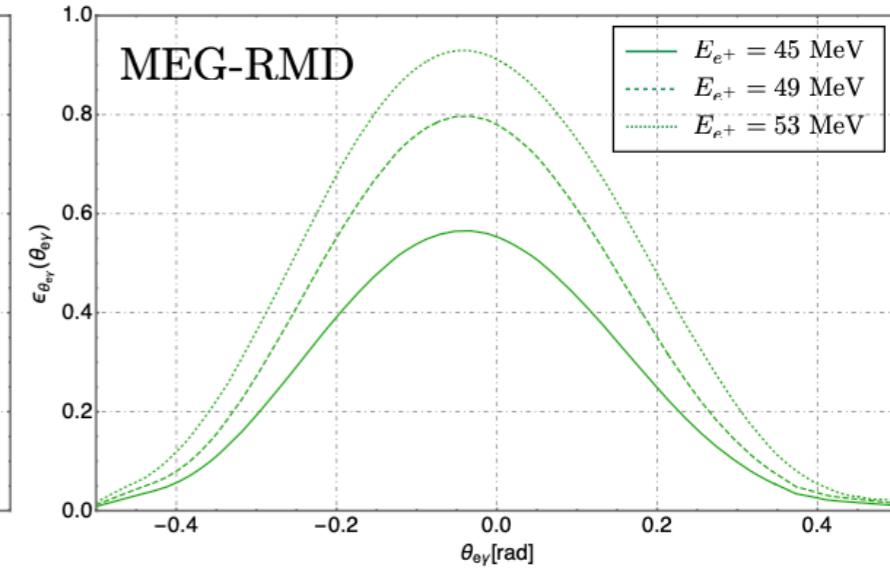
Positron energy >45 MeV @ hardware level



Photon >45 MeV @ trigger level



back to back topology @ trigger level



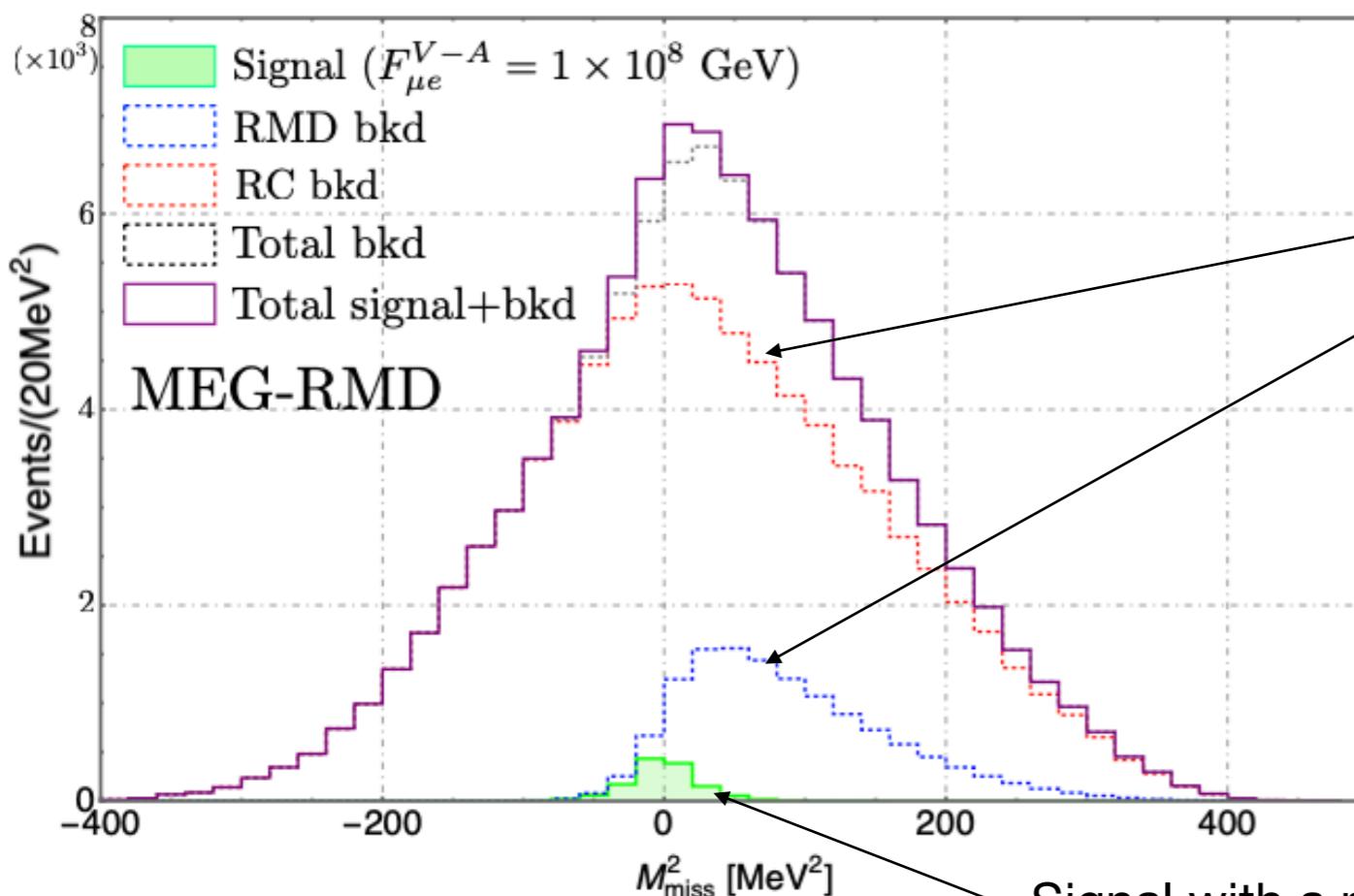
Taken from *MEG-RMD measurement 1312.3217*

# Recasting MEG-RMD results

MEG-RMD search [1312.3217](#)  $N_\mu = 1.8 \times 10^{14}$  collected in 2009-2010

The goal was to observe the RMD  $\mu \rightarrow e\nu\bar{\nu}\gamma$

over the bkd of random coincidences (RC): pileup of  $\mu \rightarrow e\nu\bar{\nu}\gamma + \mu \rightarrow e\nu\bar{\nu}$



missing mass distribution of the bkd  
obtained with an home brew MC  
normalized to the offline number of RMD  
and RC events observed.

Signal with a rate with mu polarisation See. [MEG 1510.04743](#)

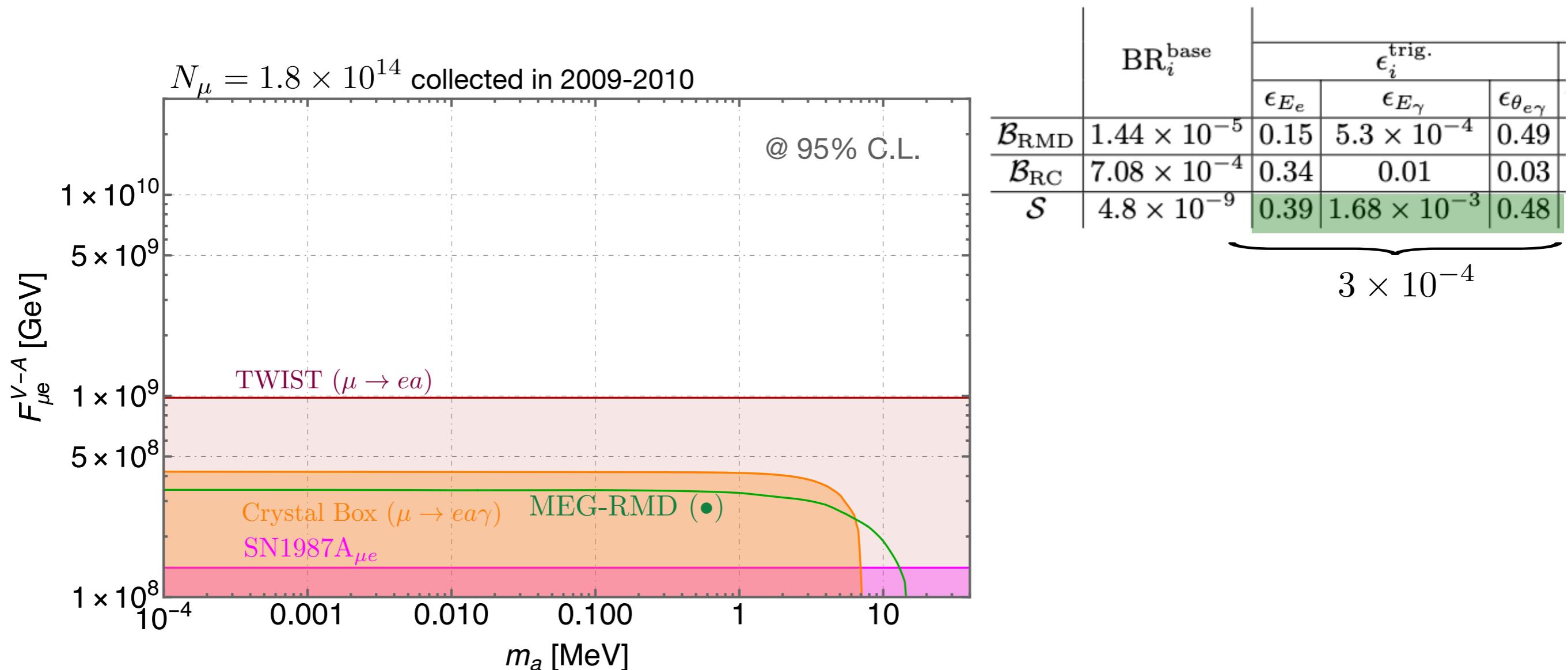
We account for detector smearing

See. [MEG 2005.00339](#)

# Recasting MEG-RMD results

The topology is already close to back to back at trigger level

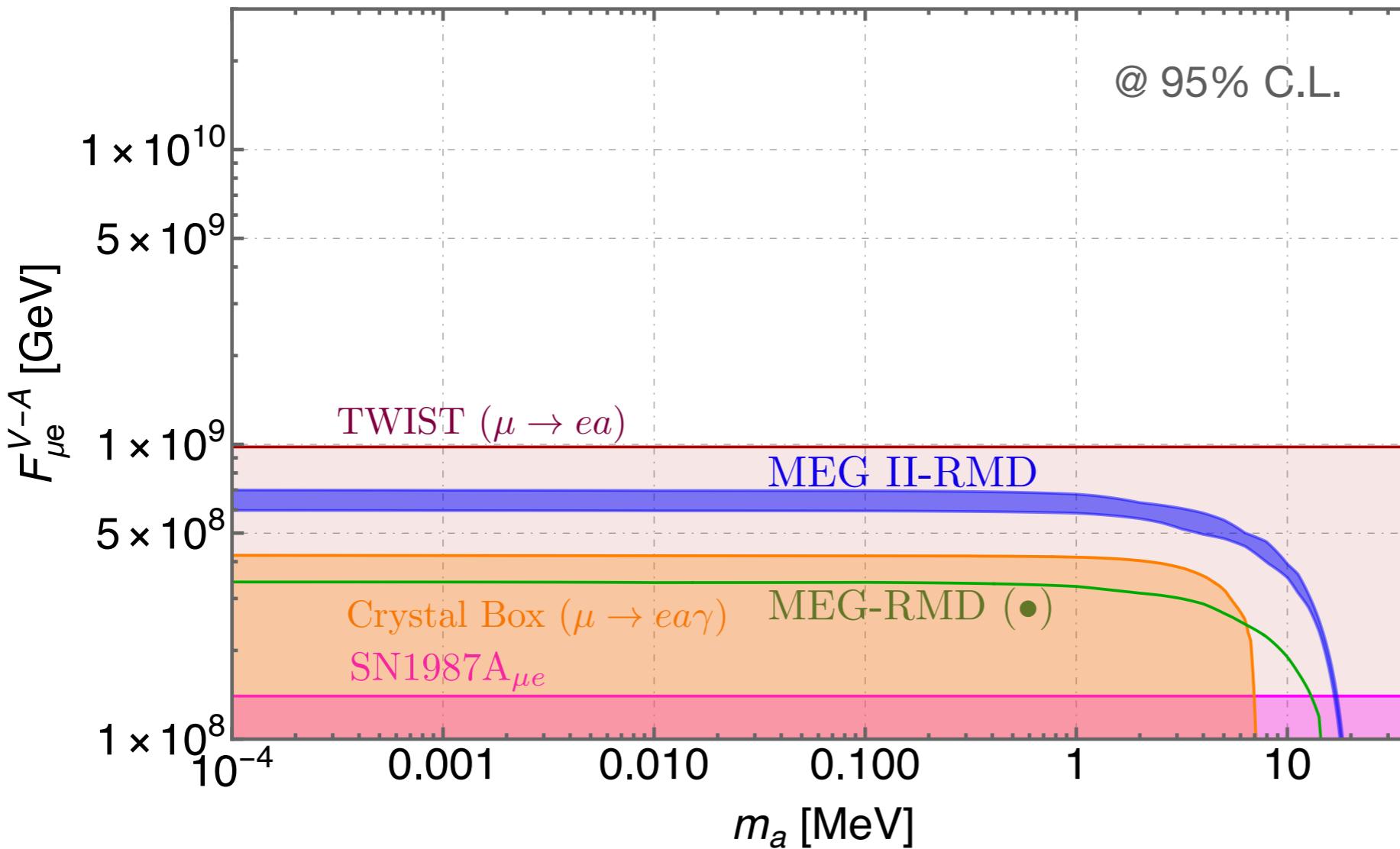
Very low signal efficiency for  $\mu \rightarrow ea\gamma$  limits the MEG reach



# What about MEG II?

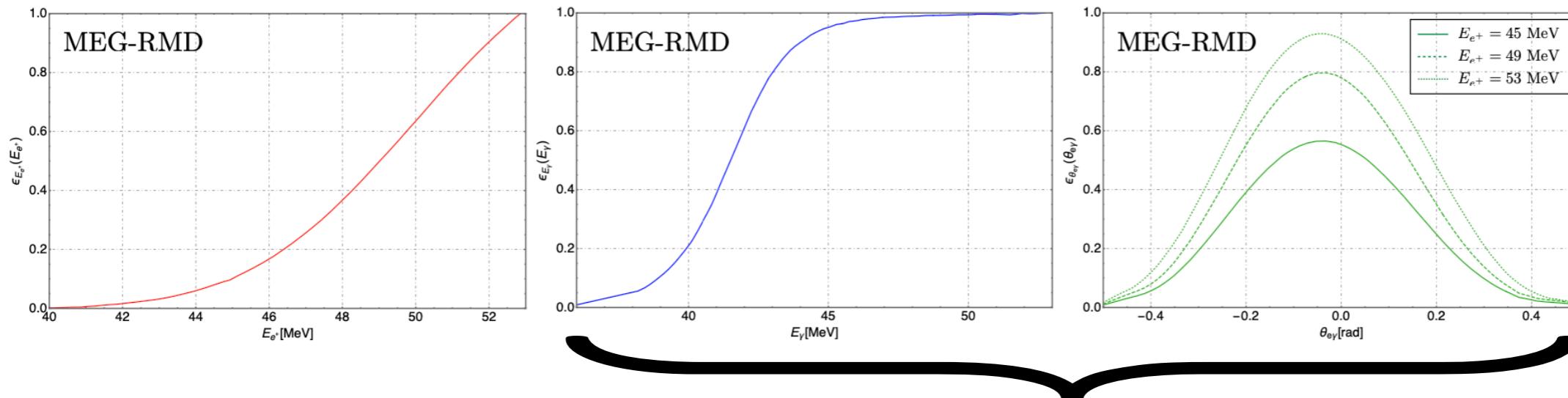
Keeping the same analysis as the MEG-RMD one but accounting for:

- 1) larger luminosity  $N_\mu = 1.8 \times 10^{15} \mu^+$
- 2) Improved energy and angular resolution (See [MEG II 1801.04688](#))
- 3) Reduced RC background by 50% after installation of radiative decay counter



# Towards a new data taking strategy I

Logic: the trigger requirements are killing the ALP signal



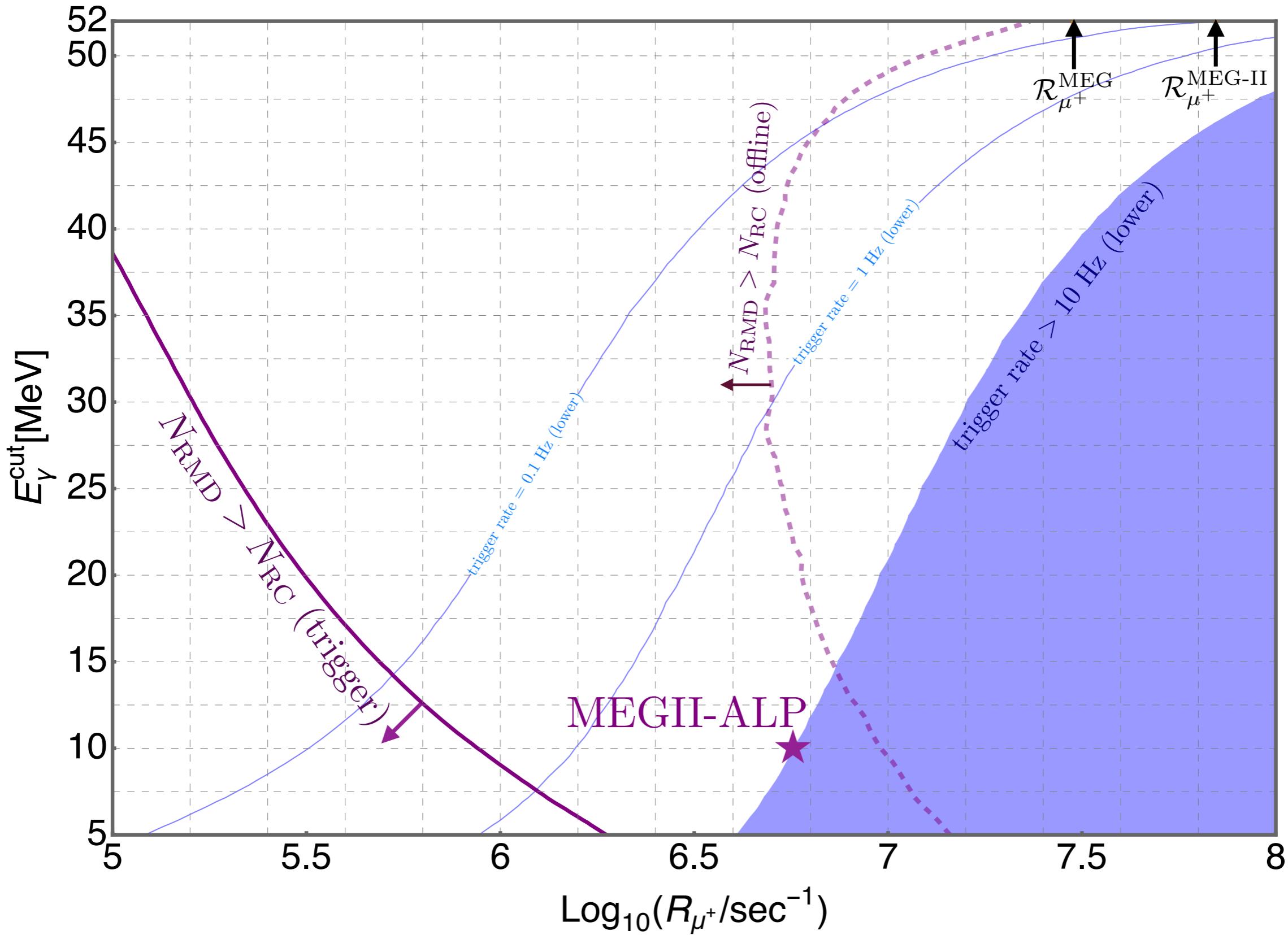
- 1) Eliminate matching of timing counter hit which assumes back to back topology
- 2) Lower photon trigger threshold by reducing the beam intensity

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

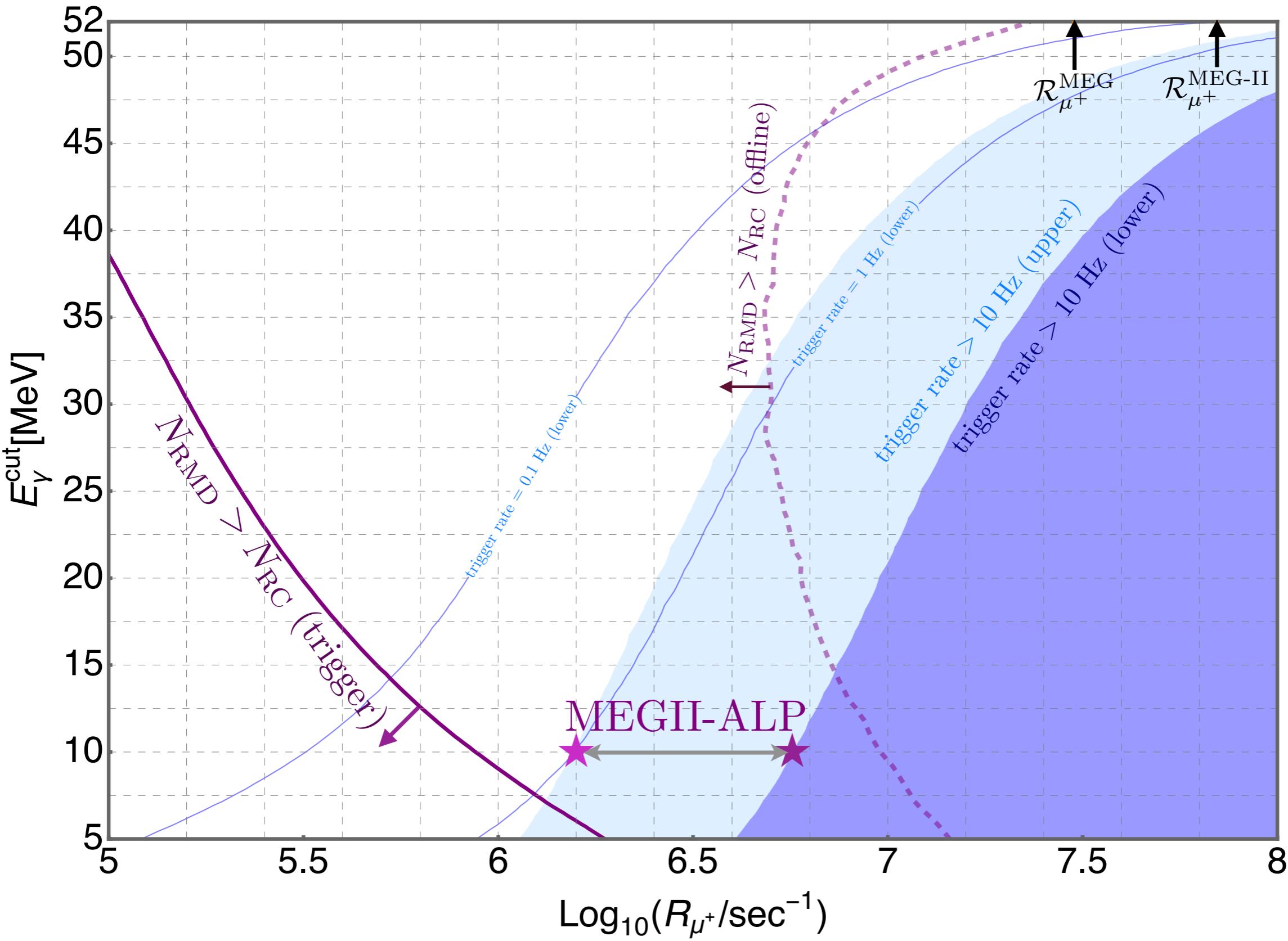
$$\text{RC} \sim R_\mu^2$$

$$\text{RMD} \sim R_\mu$$

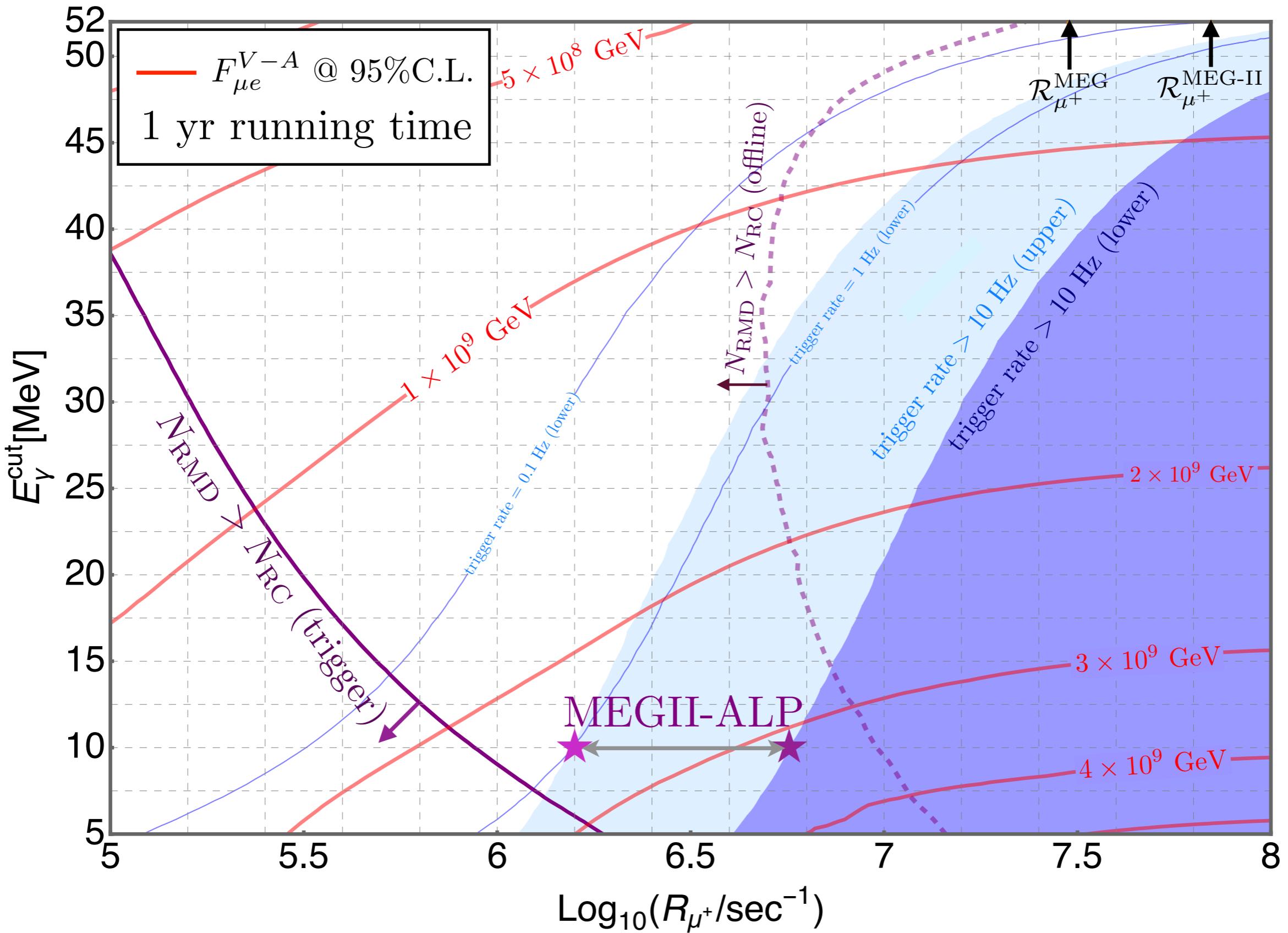
# Towards a new data taking strategy II



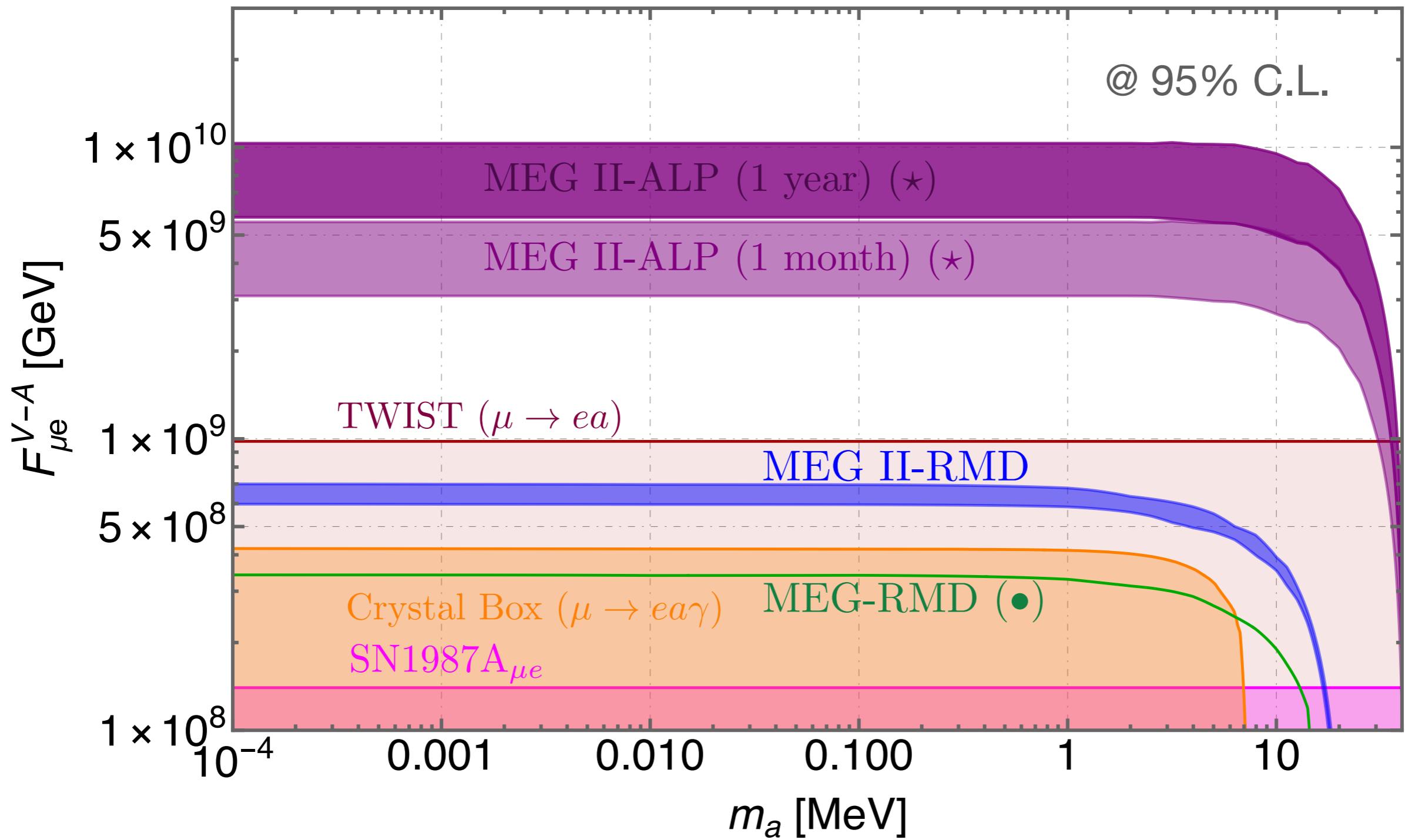
# Towards a new data taking strategy II



# Towards a new data taking strategy III



# Expected sensitivity

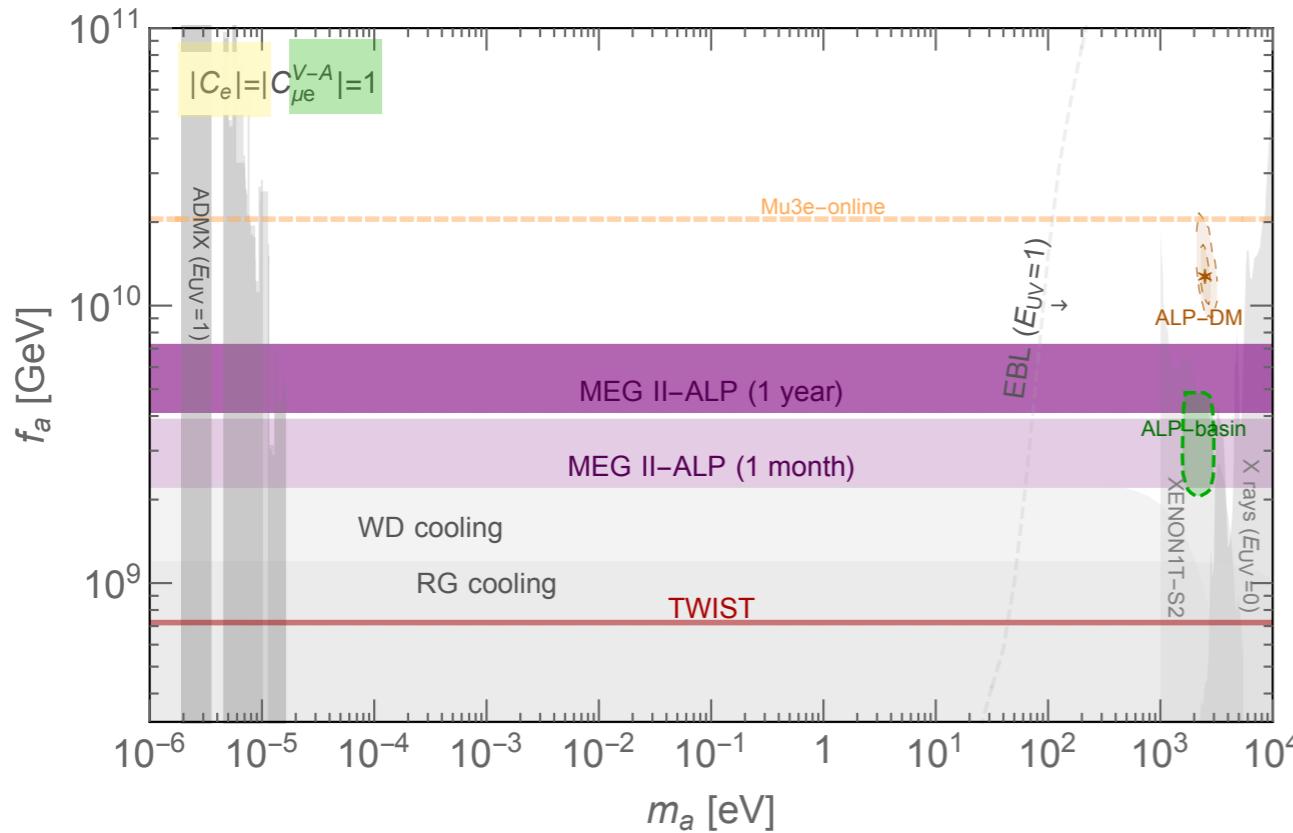


# Back to theory land

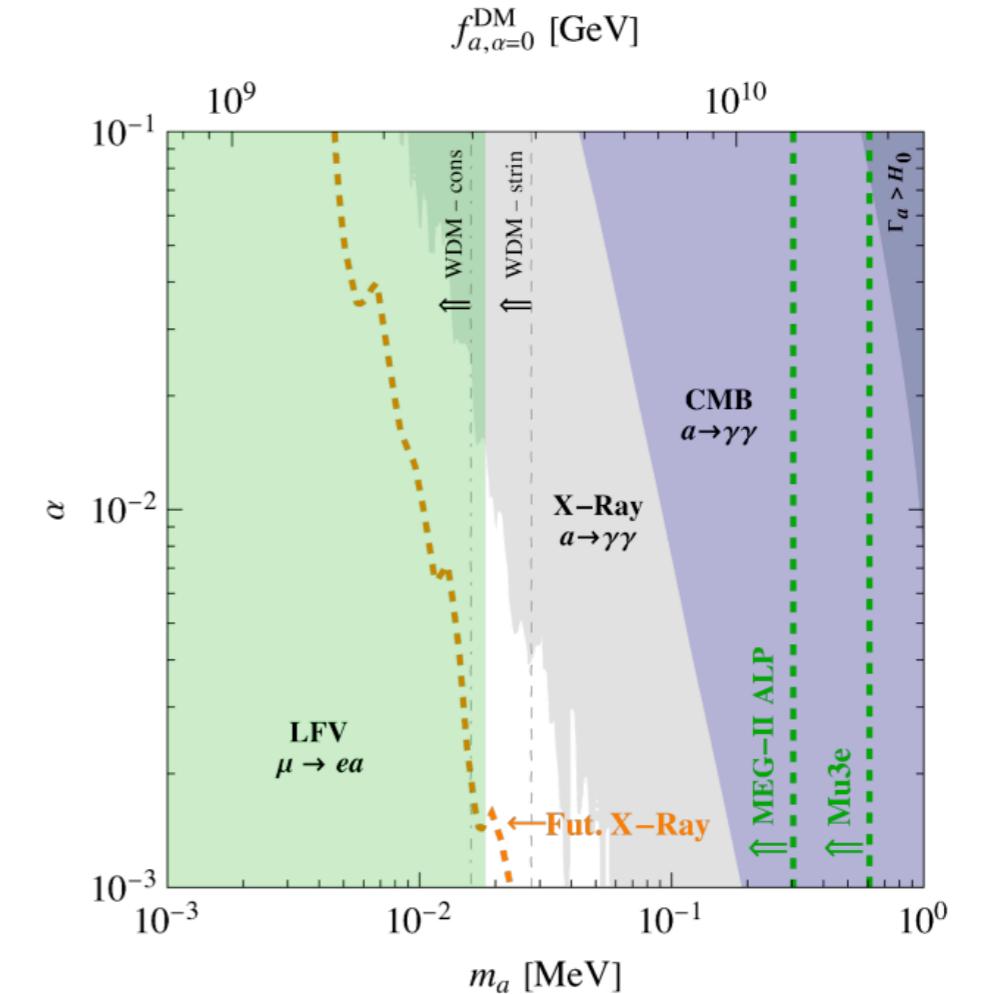
axions coupled to leptons anarchically: *flavor diagonal* = *flavor off-diagonal*

*Panci, Redigolo, Schwetz Ziegler 2209.03371*

*S. Knapen and Y. Jho 2203.11222*



**MEG-II can surpass bounds  
from star cooling!**

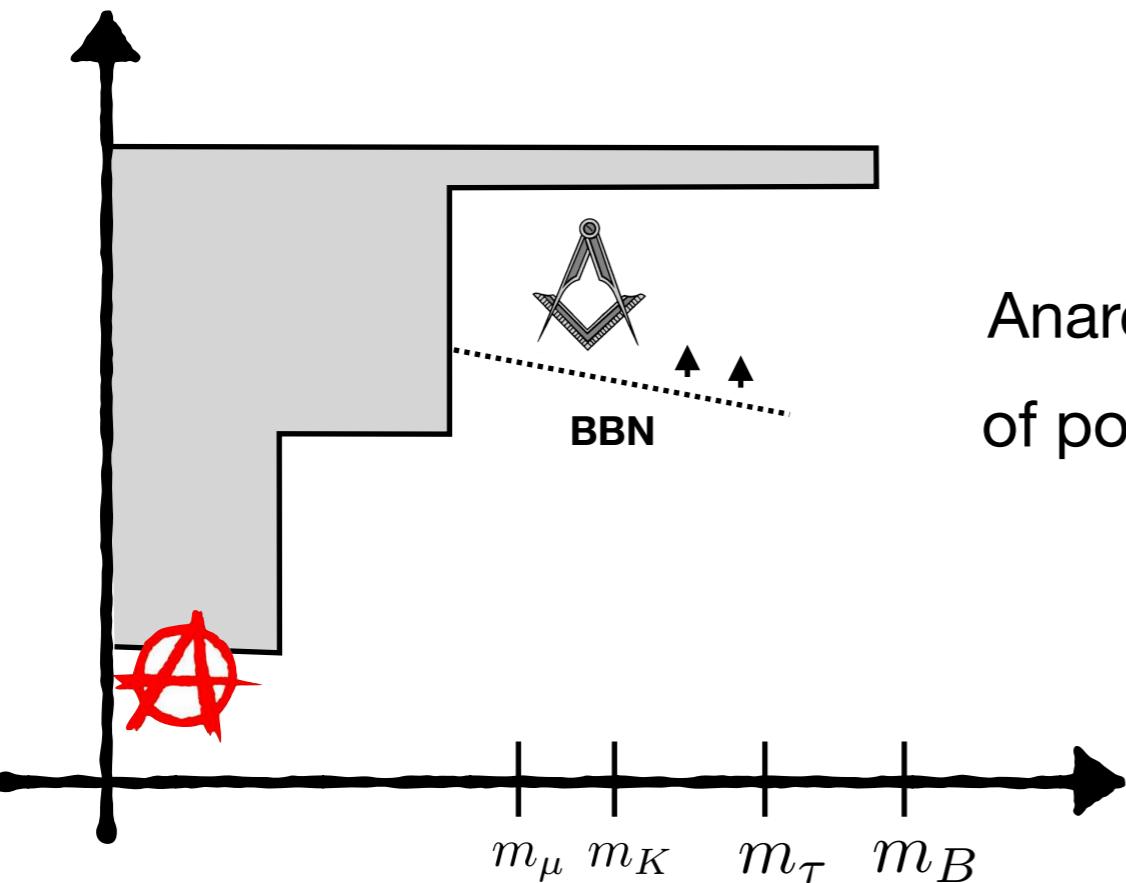


**MEG-II can completely test  
Freeze-in model based on LFV decays**

# Summary

Solutions of the strong CP problems might be related to flavor

The question for the PQ axion is how PQ is embedded in the SM flavor group



Anarchy vs MFV gives a guidance in the landscape of possible flavoured axions

 For anarchic axions flavor exp. test new physics @  $10^{10}$  GeV

New searches & new triggers are required!

