Searches of Light Dark Matter Portals in PADME

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10 December
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in collaboration with PADME collaboration and G. Corcella, E. Nardi, L. delle Rose, M. Pruna

ALP phenomenology soon in arXiv

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- Dark Sectors and Portals
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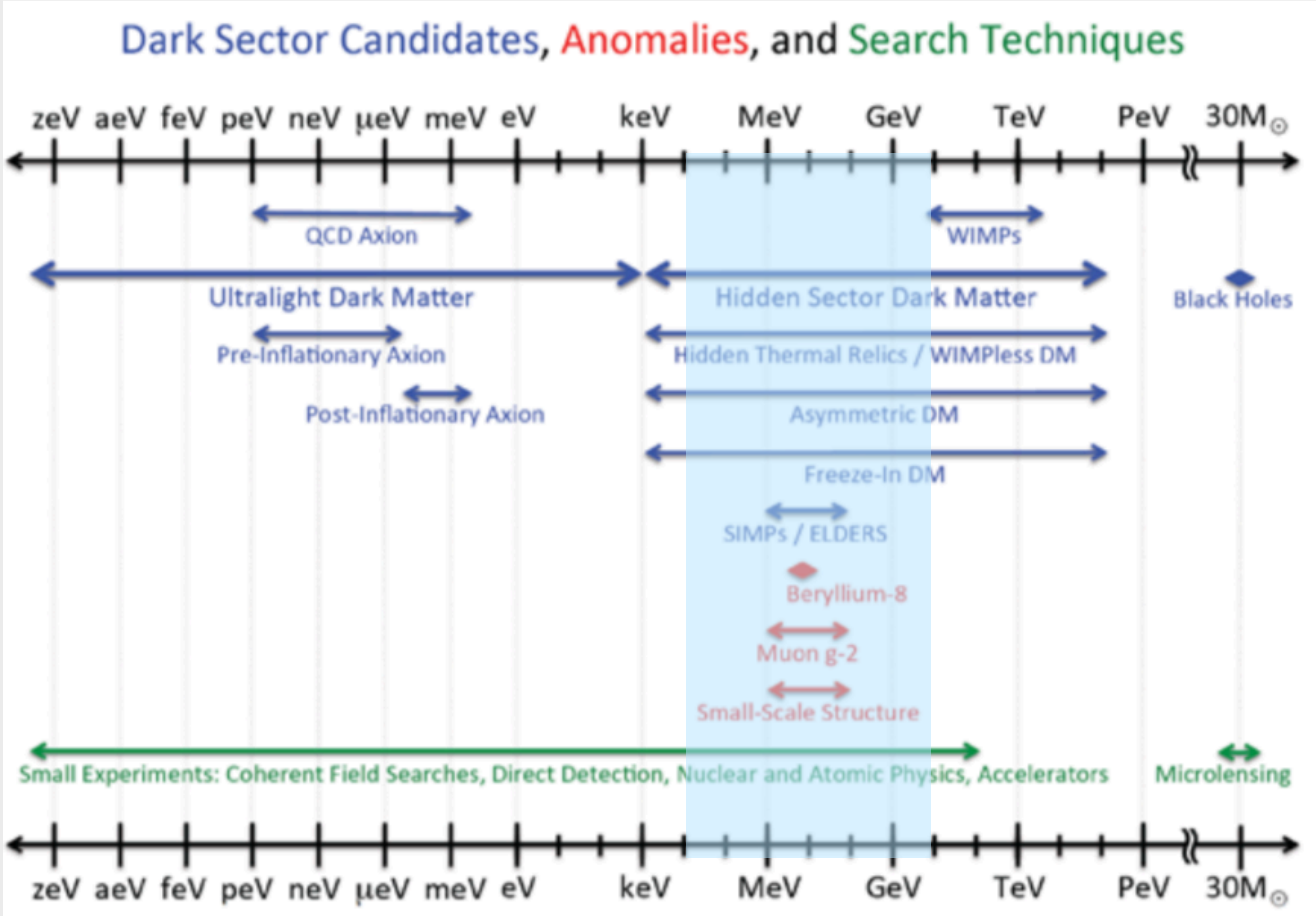

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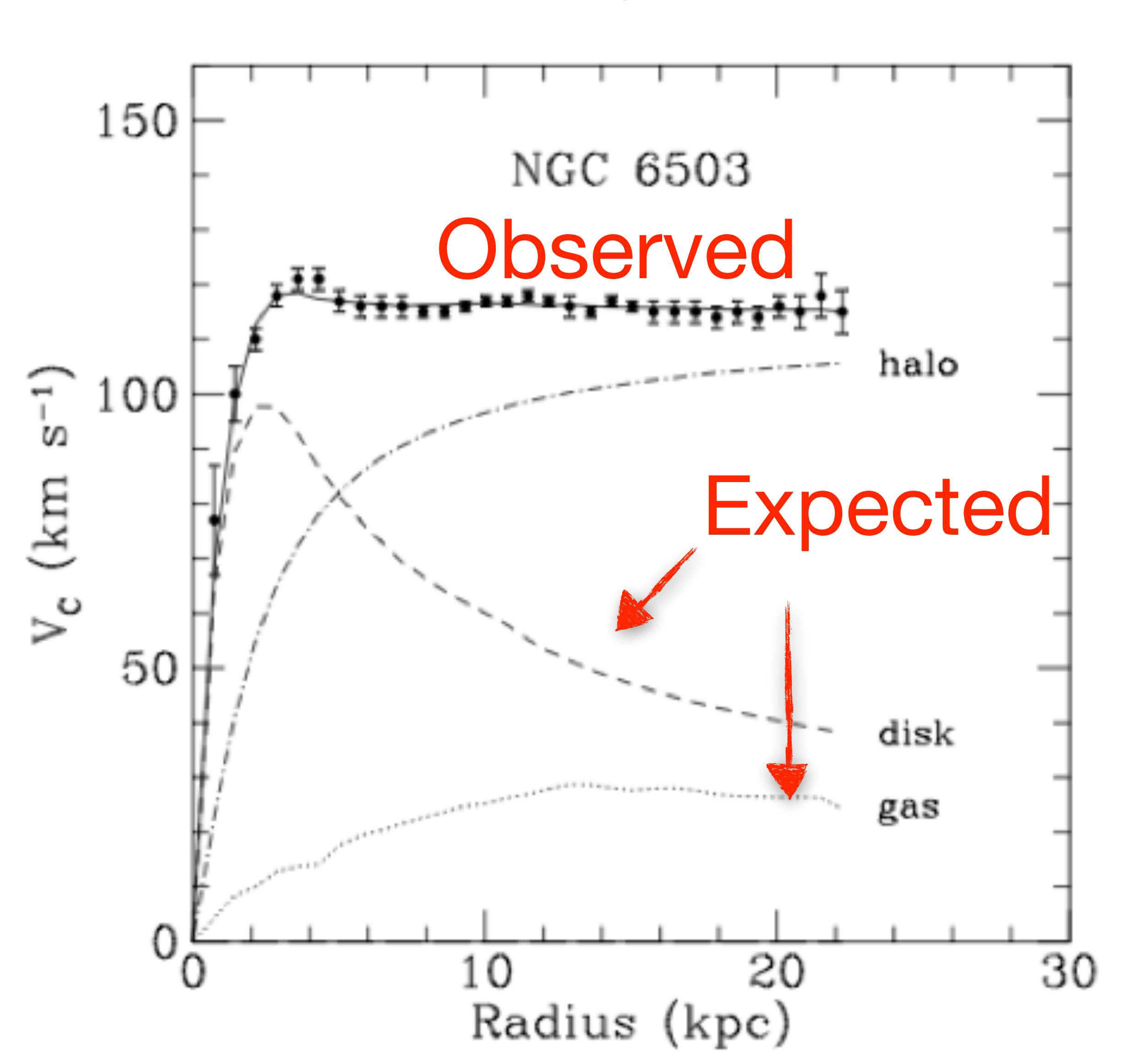
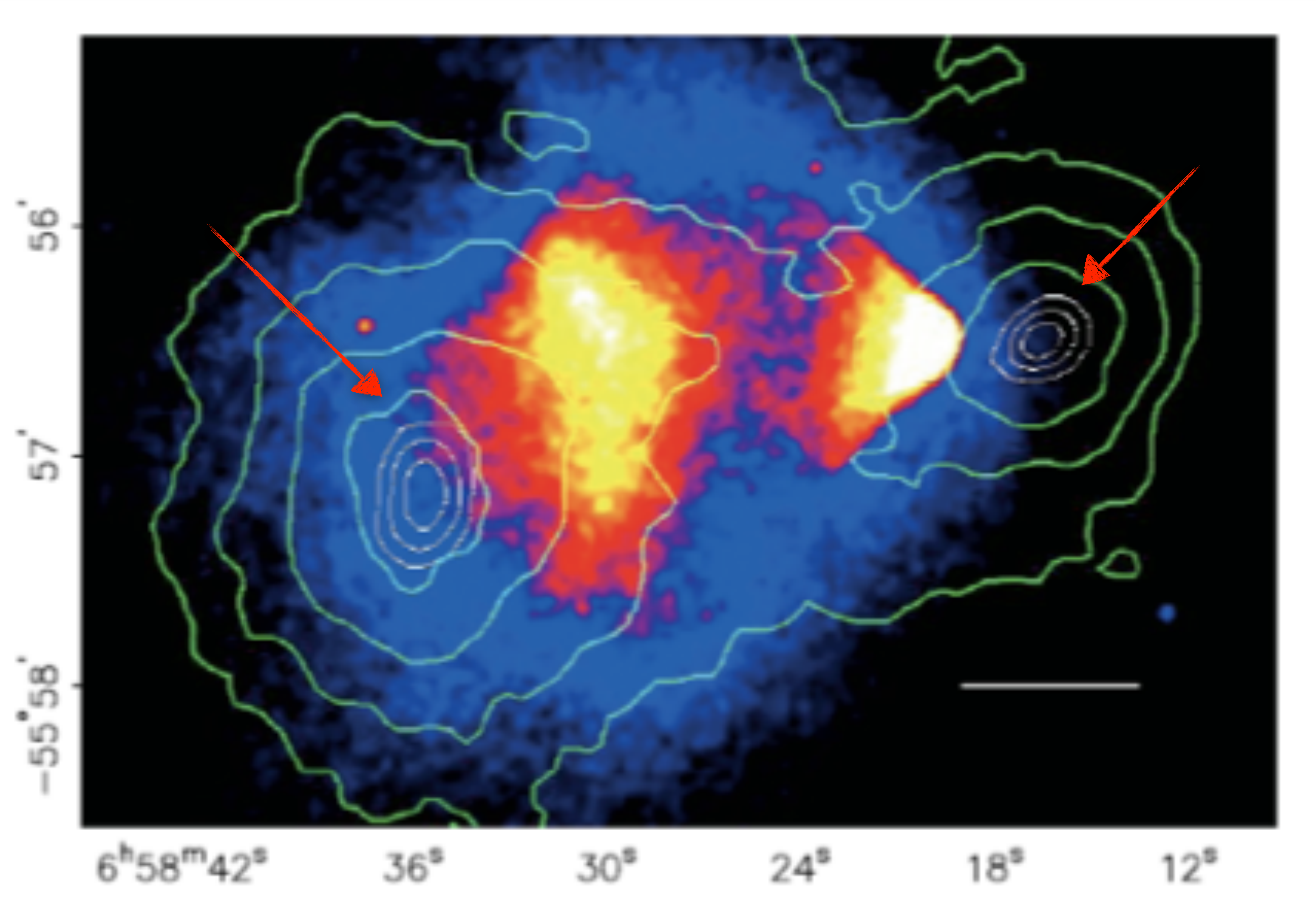
DARK MATTER INTRO

K. G. Begeman et al, Mon.Not.Roy.Astron.Soc. 249



THERE IS EVIDENCE OF DARK MATTER IN A WIDE RANGE OF DISTANCE SCALES: I.E.



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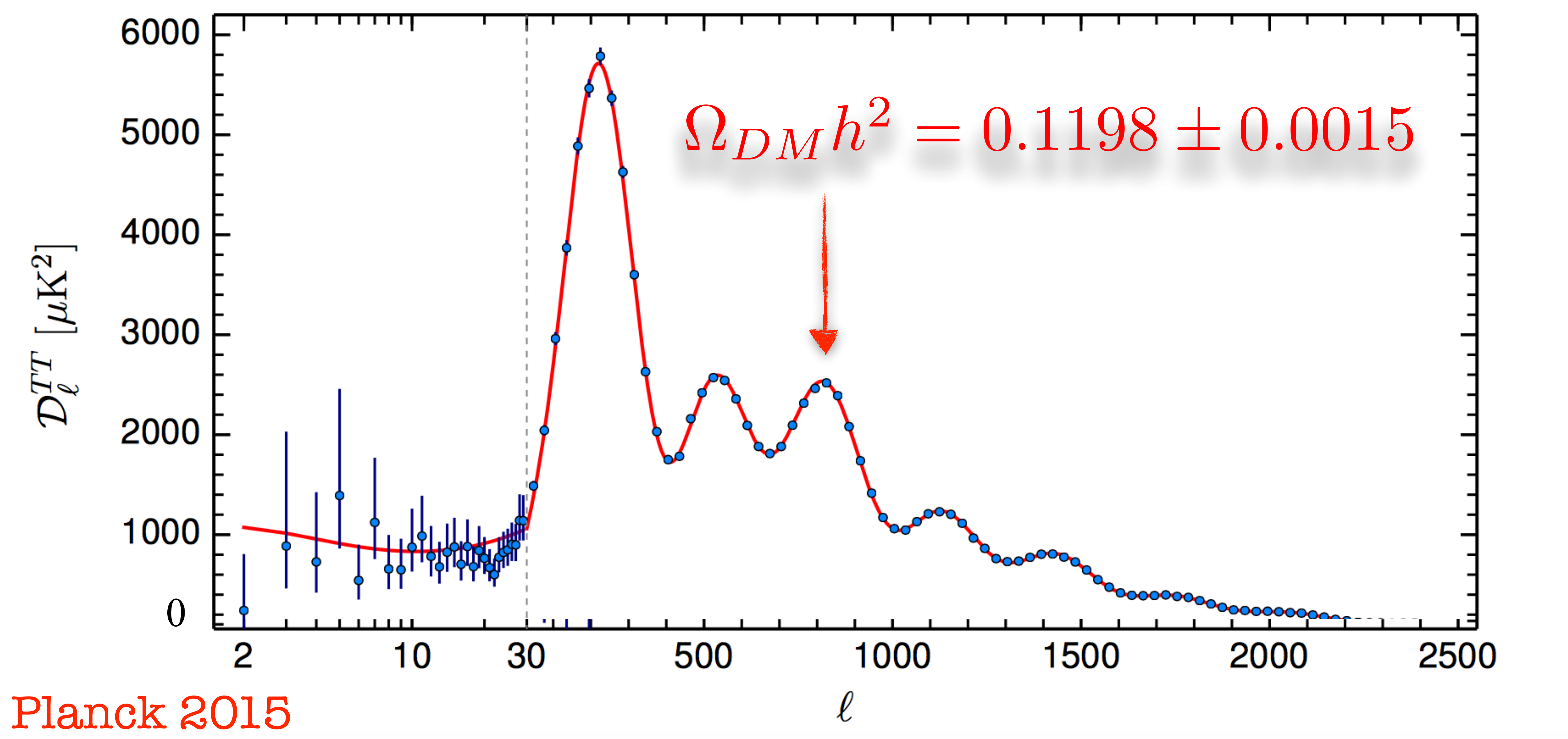

Planck 2015

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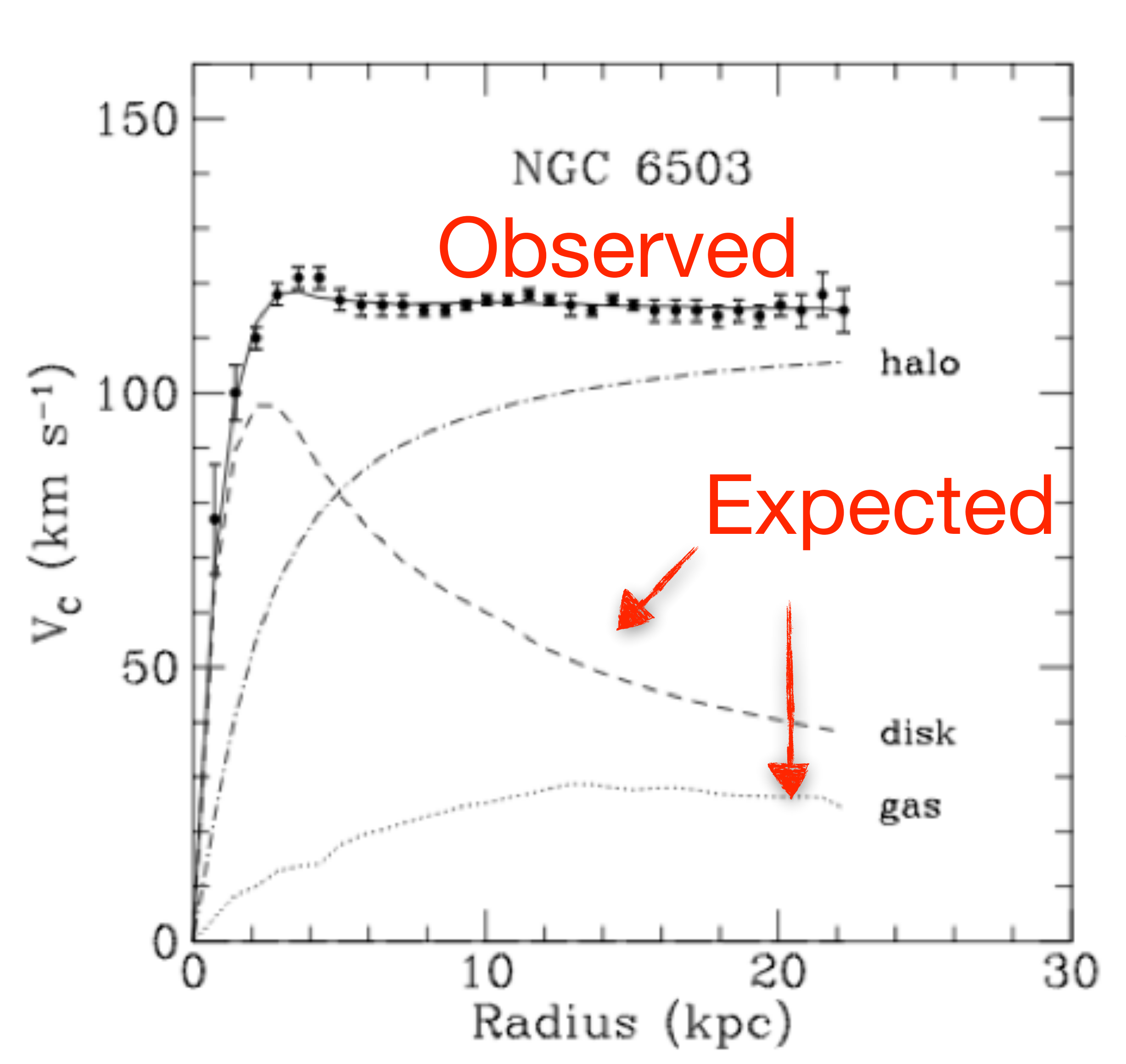

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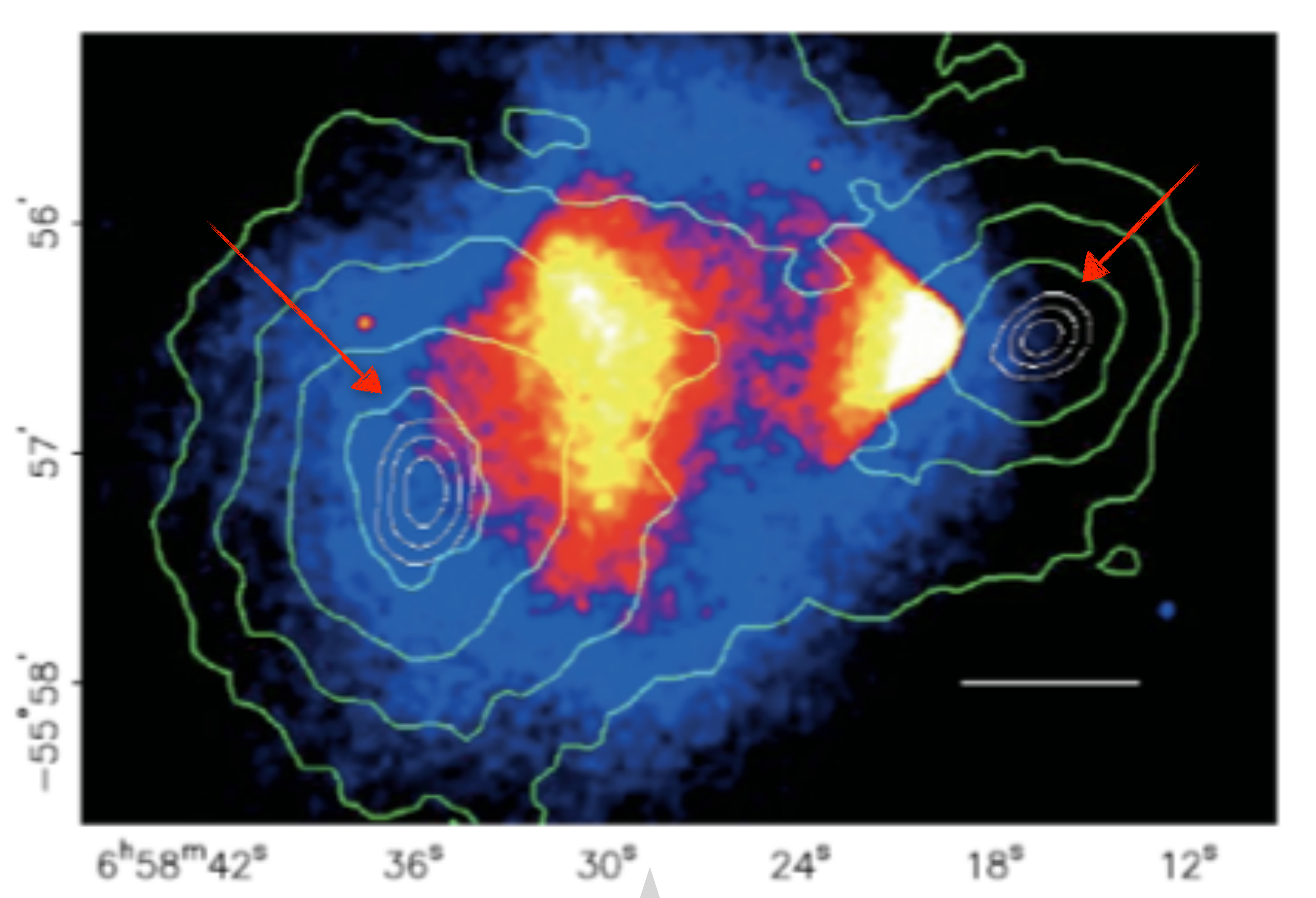

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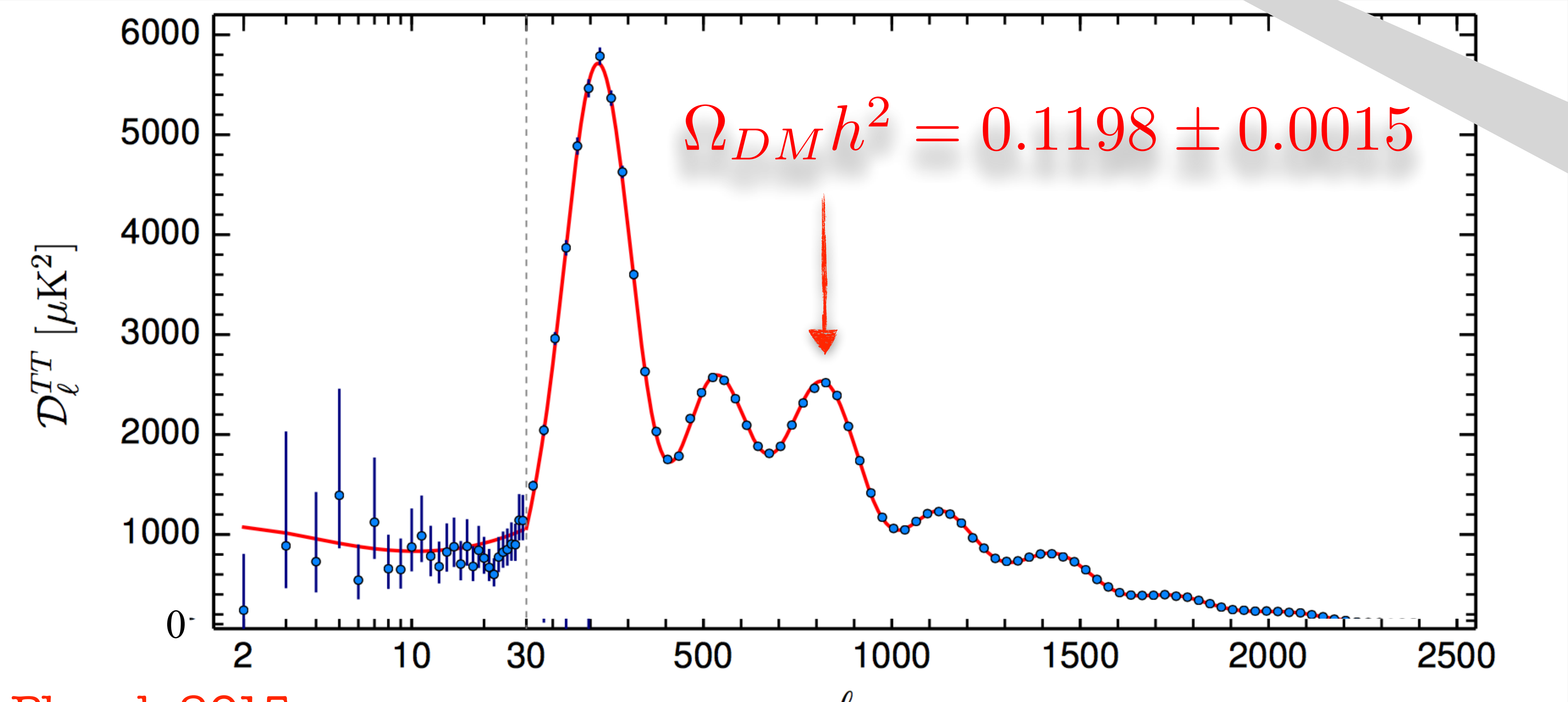


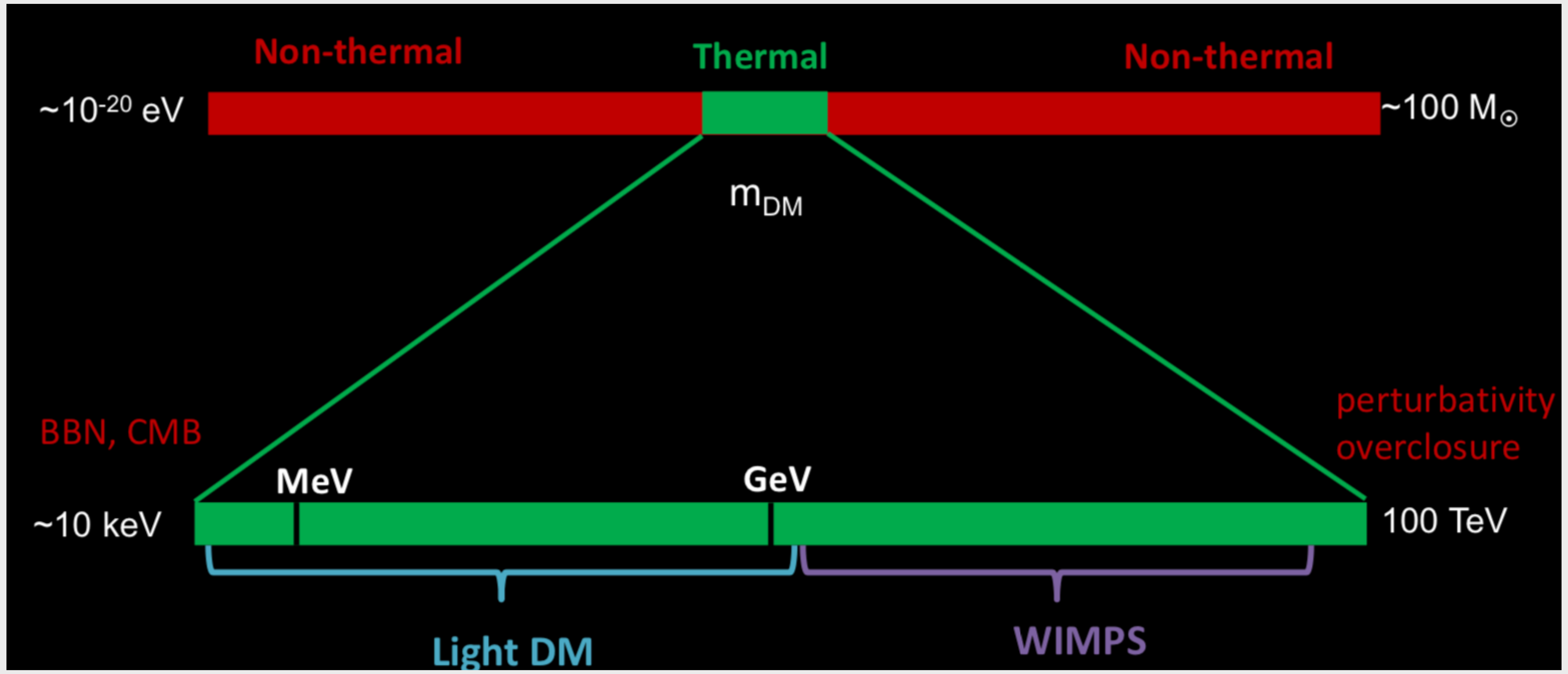
Planck 2015

PROPERTIES
ITS RELIC ABUNDANCE

OPEN QUESTIONS:

- WHAT IS THE DARK MATTER?
- IS IT A PARTICLE?
- HOW IS THE OBSERVED RELIC ABUNDANCE PRODUCED?
- INTERACTION WITH THE STANDARD MODEL?
- JUST ONE PARTICLE OR AN ENTIRE DARK SECTOR?

WHY DARK SECTORS?



- Weakly Interactive Massive Particle (WIMP):

  thermally produced in Early Universe through freeze-out mechanism: at 10GeV-100TeV and annihilation cross-section of electroweak scale, we obtain the observed relic abundance.

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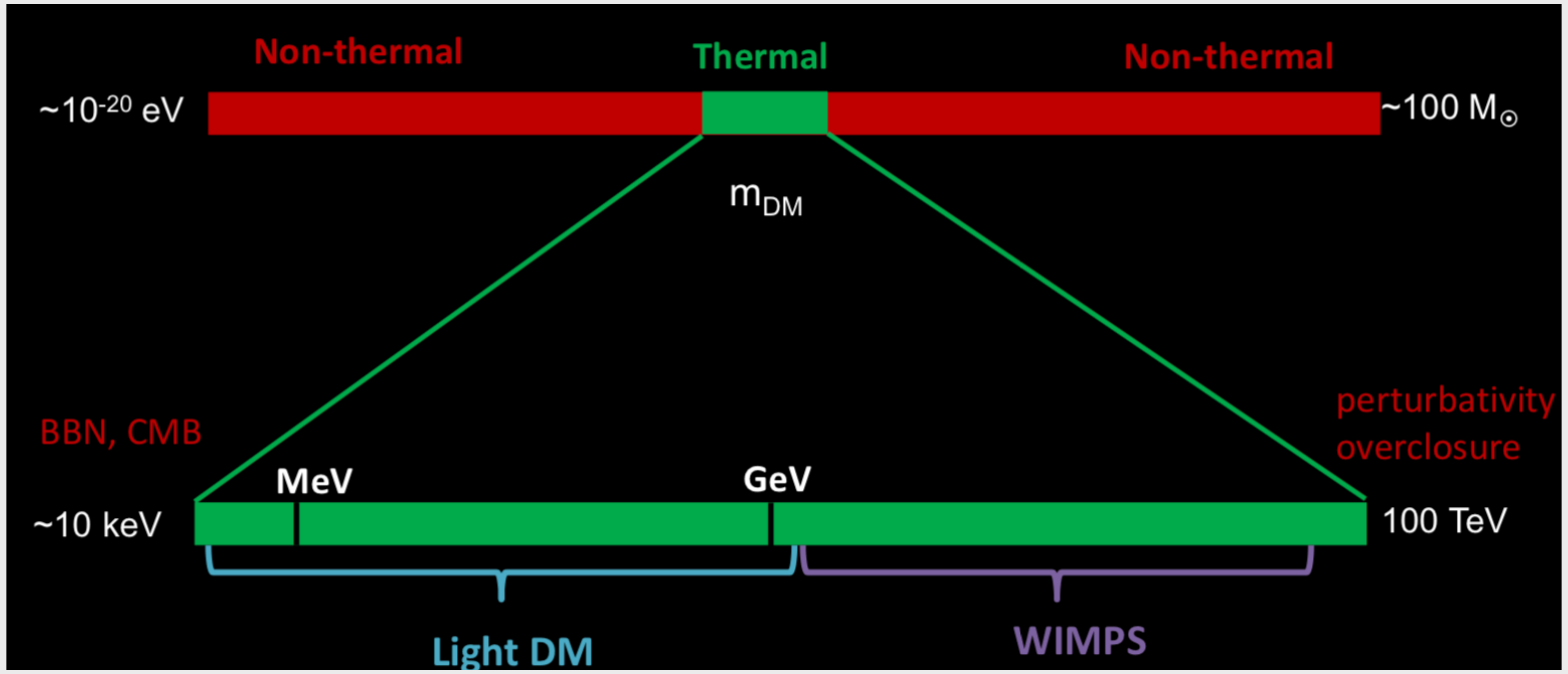

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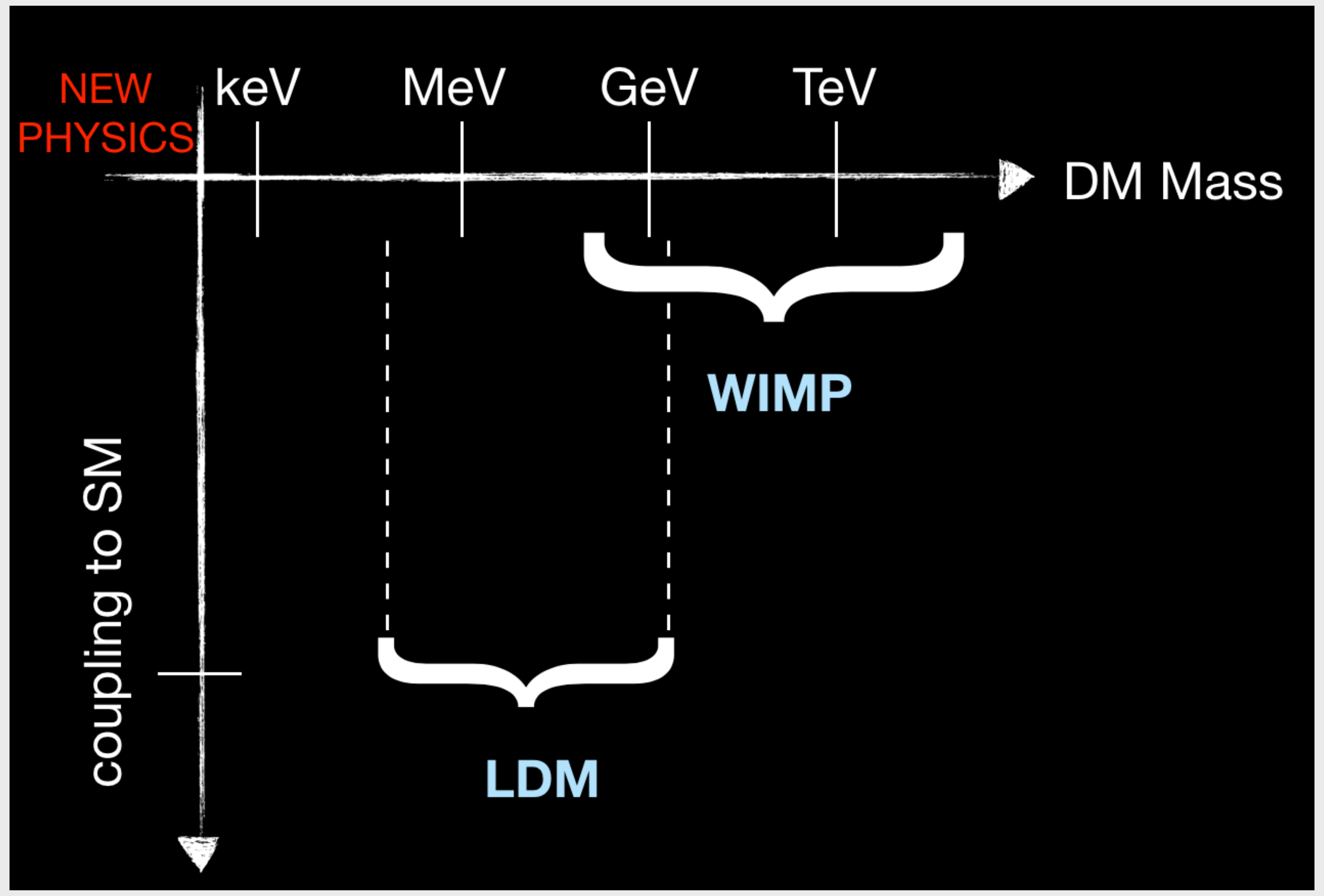
- Light Dark Matter:

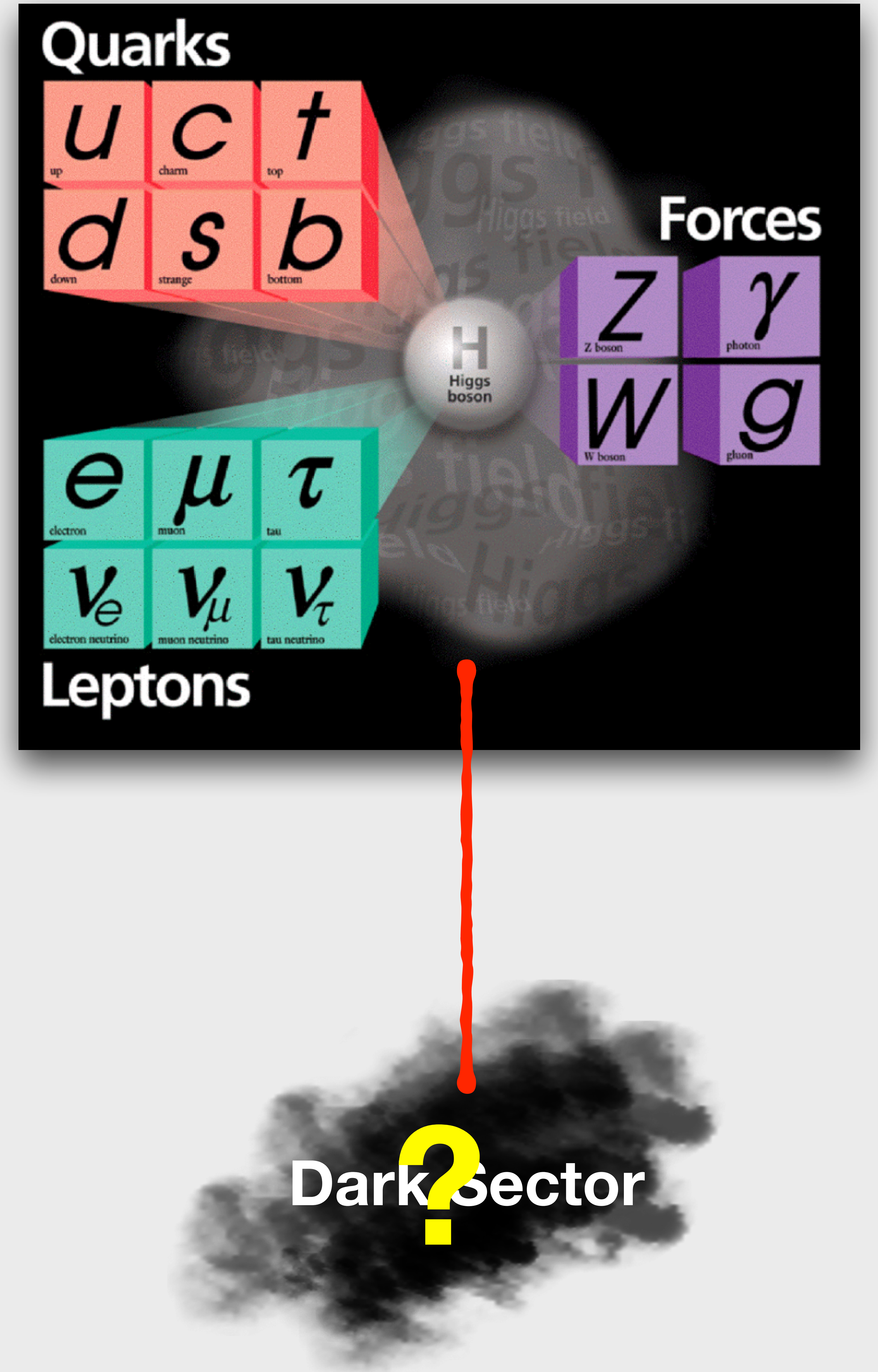
  subGeV masses with very feeble couplings -> *hidden-sector*



WHY DARK SECTORS?

The Standard Model describes the known elementary particle content and three of the four fundamental forces which manage their physics.

- As the Standard Model we can suppose a Dark Sector composed by new particles not charged under SM gauge group and possibly new forces: how is connected with Standard Model?



SIMPLIFIED MODELS

The Simplified Model concept (Abdallah '15, De Simone '16) lies in the description of a model in a simple way, following general prescriptions which summarise the properties of more complete models and EFT theories:

- few and relevant parameters adding in particular the **Portal** particle,
- the new terms in the Lagrangian should be renormalisable, respect the Lorentz invariance, SM gauge invariance and DM stability.
- the Portals (i.e. in the next slides) are representative of a broader class of well-motivated models and can easily be expanded to describe UV-complete theories.

SIMPLIFIED MODEL: LIGHT DARK MATTER PORTAL

Alternatively to WIMP portal, the *hidden-sector portals* are well-motived to explore. Parameter space of hidden-sector are largely invisible to WIMP searches. A high intensity source is necessary to produce LDM portals at a detectable rate: we need high-intensity accelerator beams. The search for new physics in low range of masses and couplings is currently called the *intensity frontier* (Jaeckel et al. 1002.0329, Beacham et al. 1901.09966v2).

Portals for DM at sub-GeV scales are:

	Hidden Sector Portal	Coupling	
[Pospelov, Ritz,Voloshin] [Hooper, Zurek]	Dark Photon, A'_μ	$-\frac{\epsilon}{cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$	$B_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu$ SM hypercharge field strength
[O'Connell, Ramsy-Musolf, Wise]	Scalar Singlet, S	$(\mu S + \lambda S^2)H^\dagger H$	H is the SM Higgs boson $(1,2,+\frac{1}{2})$
[Bertoni, Ipek, Nelson, McKeen] [Bohem, Fayet, Schaeffer]	Sterile Neutrino, N	$y_N LHN$	L is a lepton doublet $(1,2,-\frac{1}{2})$
→	Axion-like particle, a	$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$ $\quad g_{a\psi\psi}\partial_\mu a\bar{\psi}\gamma^\mu\gamma^5\psi$	$\tilde{F}_{\mu\nu}$ is the dual of $F_{\mu\nu}$

Pseudoscalar Portal: Axion-like Particle

$$\mathscr{L}_{pseudoscalar} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mathscr{L}_{portal}$$

Ingredients of Minimal Model:

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- **Dark Sector**: SM gauge symmetries + extra global symmetry

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Motivated by string theories [Arvanitaki 2010, Cicoli 2012],
by addressing open problem as Strong-CP Problem [Peccei&Quinn 1977, Hook 2014, Fukuda et al. 2015]
or Hierarchy Problem [Grahamet al. 2015],
as a possible solution for the muon magnetic moment anomaly [Chang et al. 2001, Marciano et al. 2016]

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$$\mathscr{L}_{DS} = \frac{1}{2}\partial^{\mu}a\partial_{\mu}a - \frac{1}{2}M_a^2a^2 + \mathscr{L}_{dm}$$

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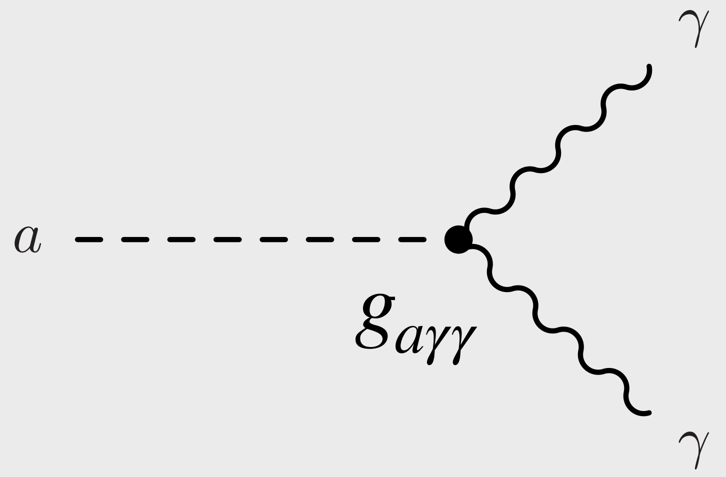
- **Portal**: The Portal between visible and invisible sector is allowed by an interaction with photon ....

$$\mathscr{L}_{portal} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



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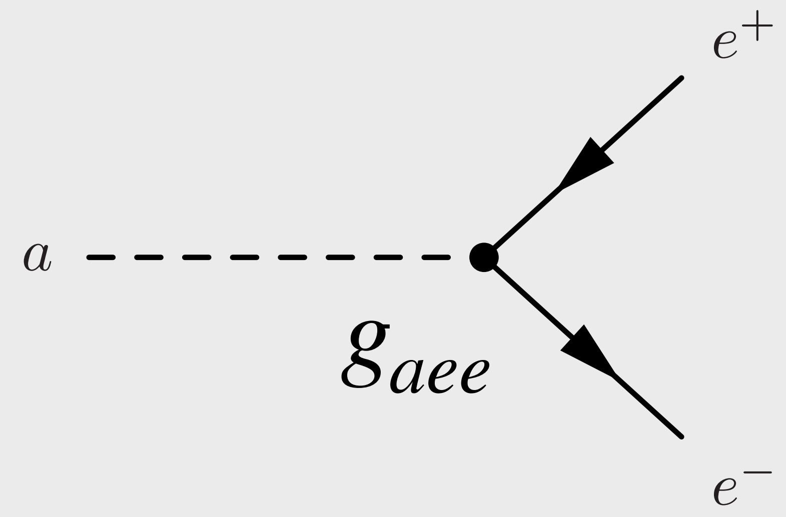
- **Portal**: The Portal between visible and invisible sector is allowed by …. and/or with fermions

$$\mathscr{L}_{portal} = g_{a\psi\psi} \partial_{\mu} a \bar{\psi} \gamma_{\mu} \gamma_5 \psi$$



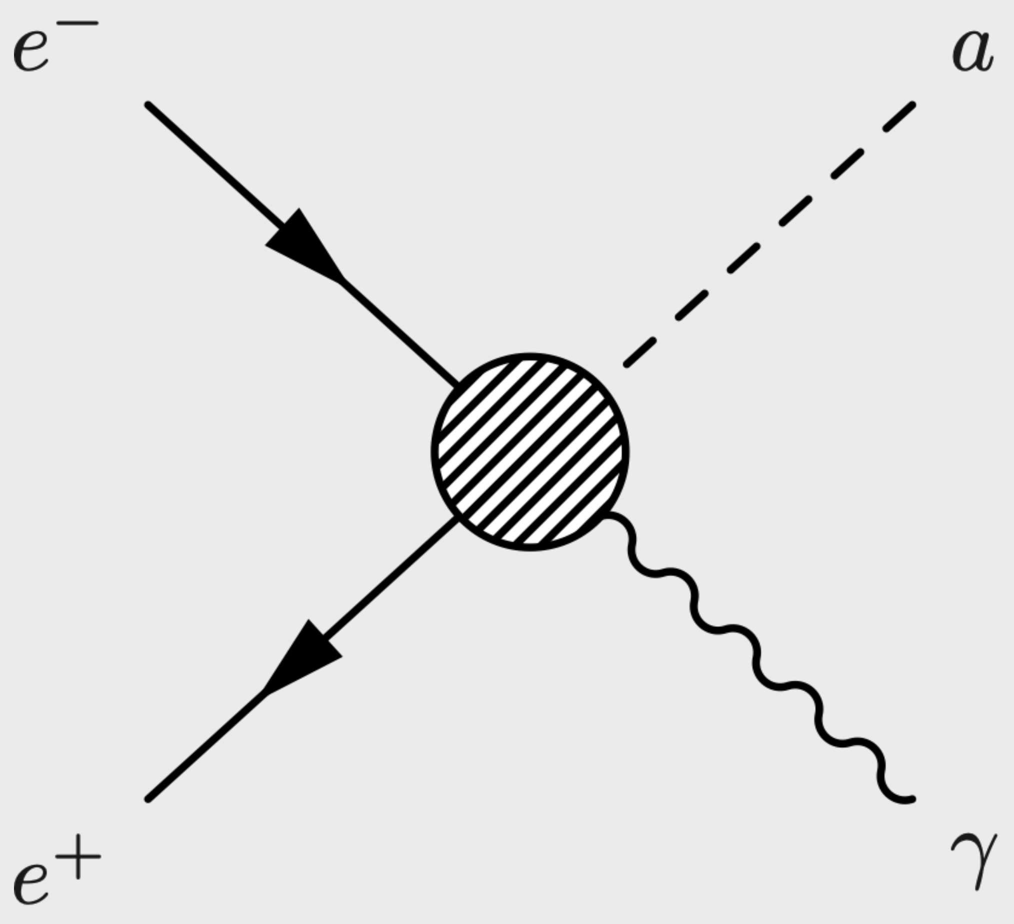
Axion-like Particle Production at accelerators

Increasing interest for experimental searches at accelerators: assuming a leptophilic ALP

⇒ Lepton beam/fixed target, e.g. PADME, BDX,..

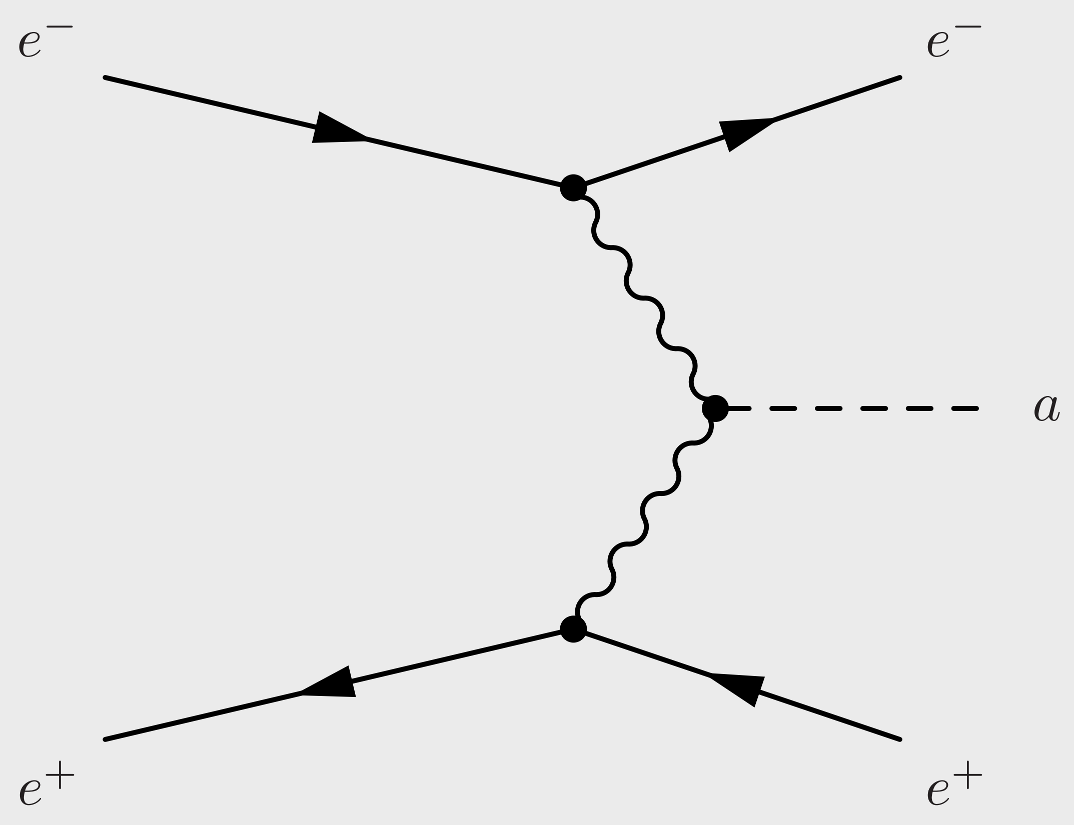
Lepton beam/Collider, e.g. Belle II, Babar, KLOE,..

Annihilation



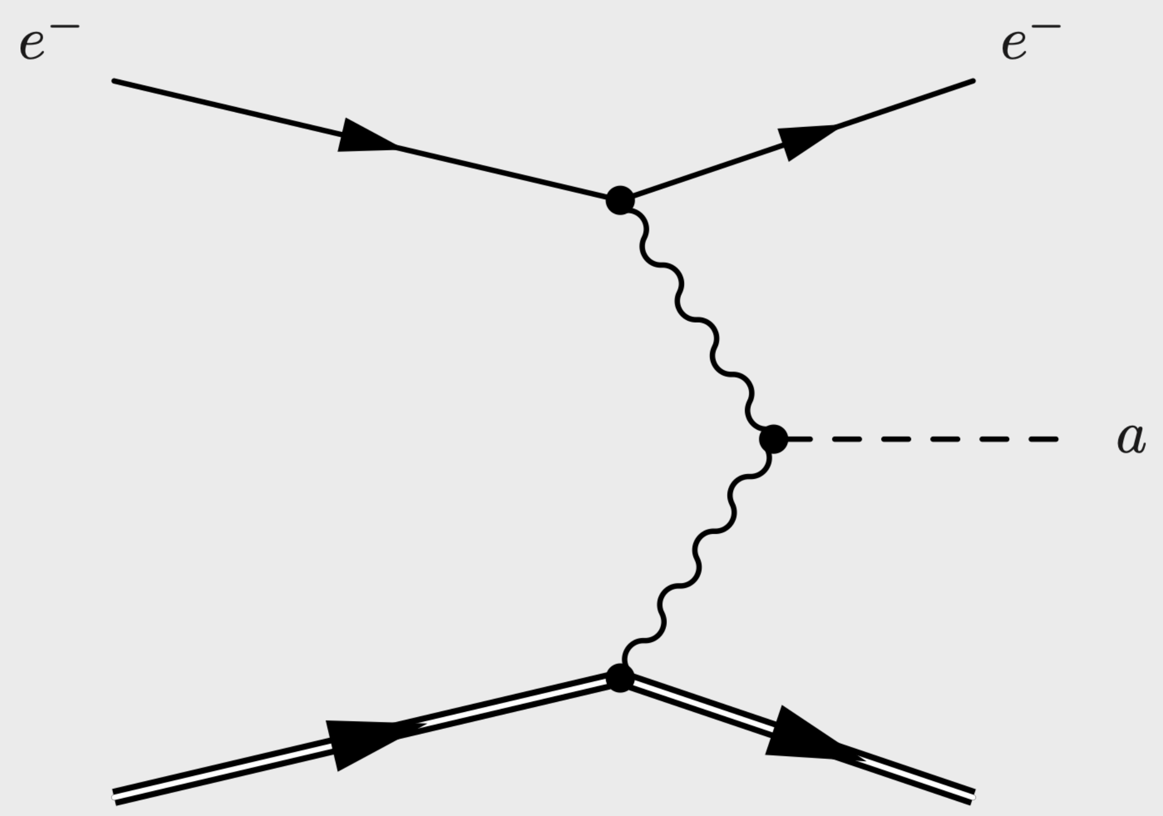
$e^+e^- \to \gamma + a$

Photon Fusion



$e^+e^- \to e^+e^- + a$

Primakoff effect



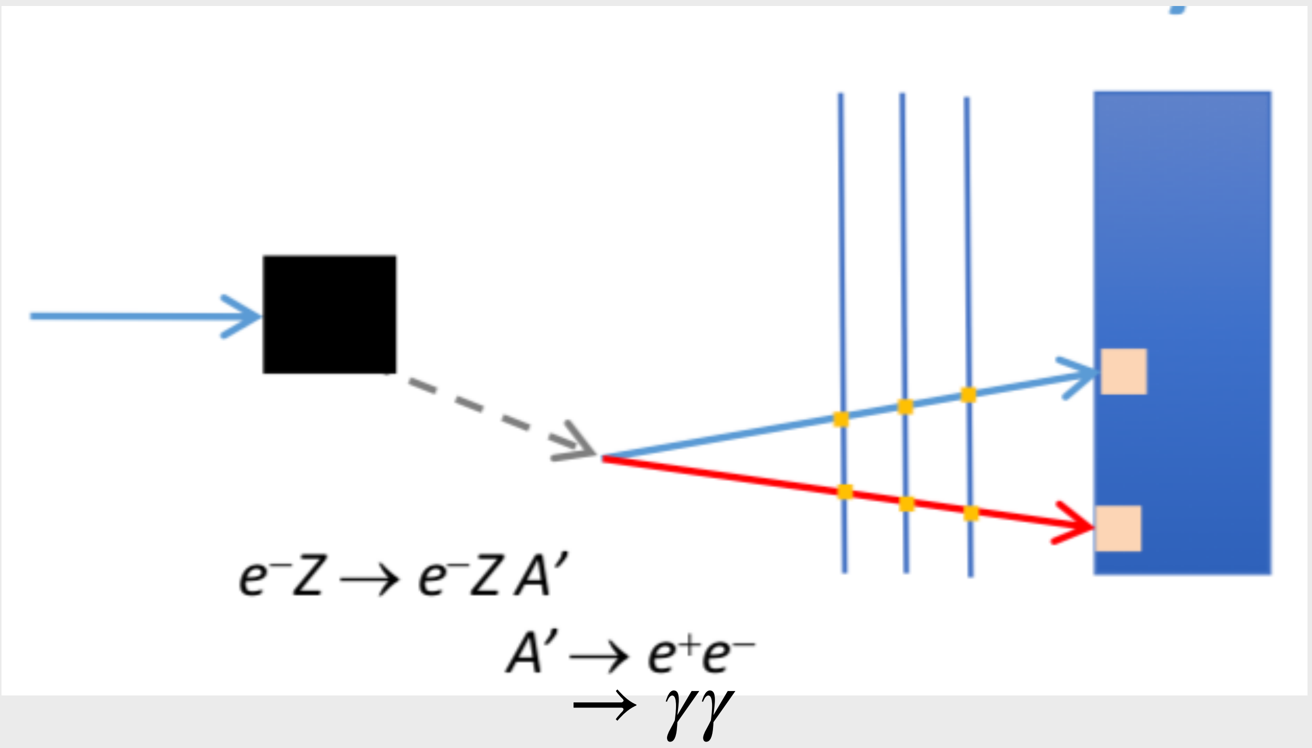
$e^-Z \to e^-Z + a$

TWO POSSIBLE SIGNATURES FOR ALP IN ACCELERATOR:

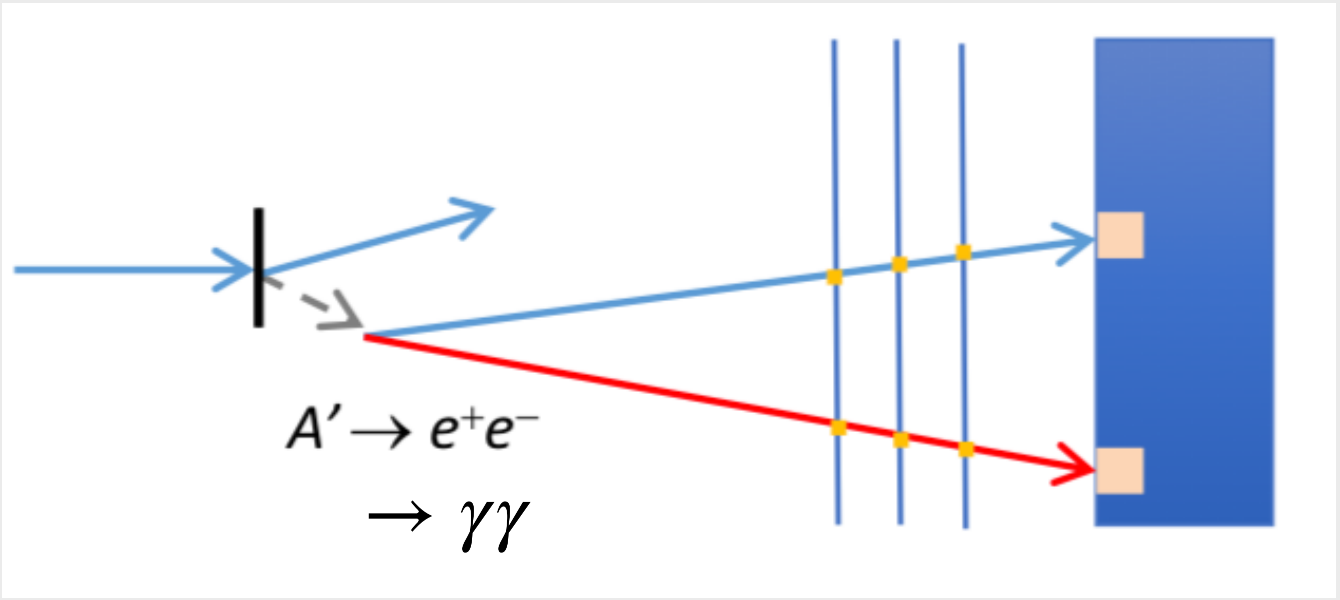
VISIBLE: if $m_a/2 < M_\chi$, $a \rightarrow SM\,SM$

TECHNIQUES:

1. Beam dump (Primakoff effect) using a very intense electron beam + an high Z target + shield for SM absorption



2. thin fixed target (annihilation)

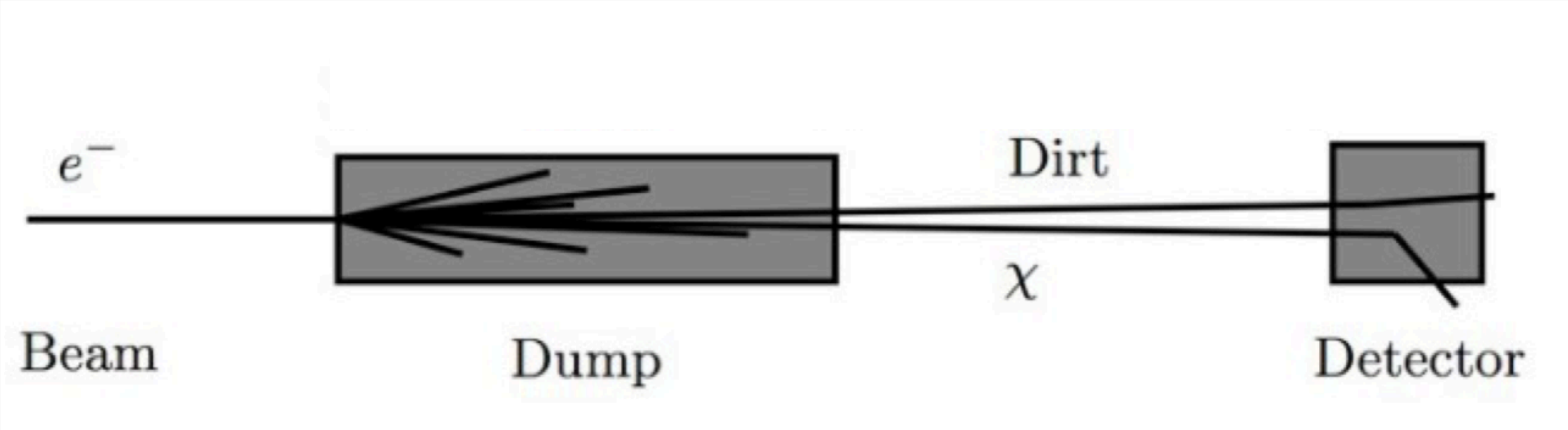


TWO POSSIBLE SIGNATURE FOR ALP IN ACCELERATOR:

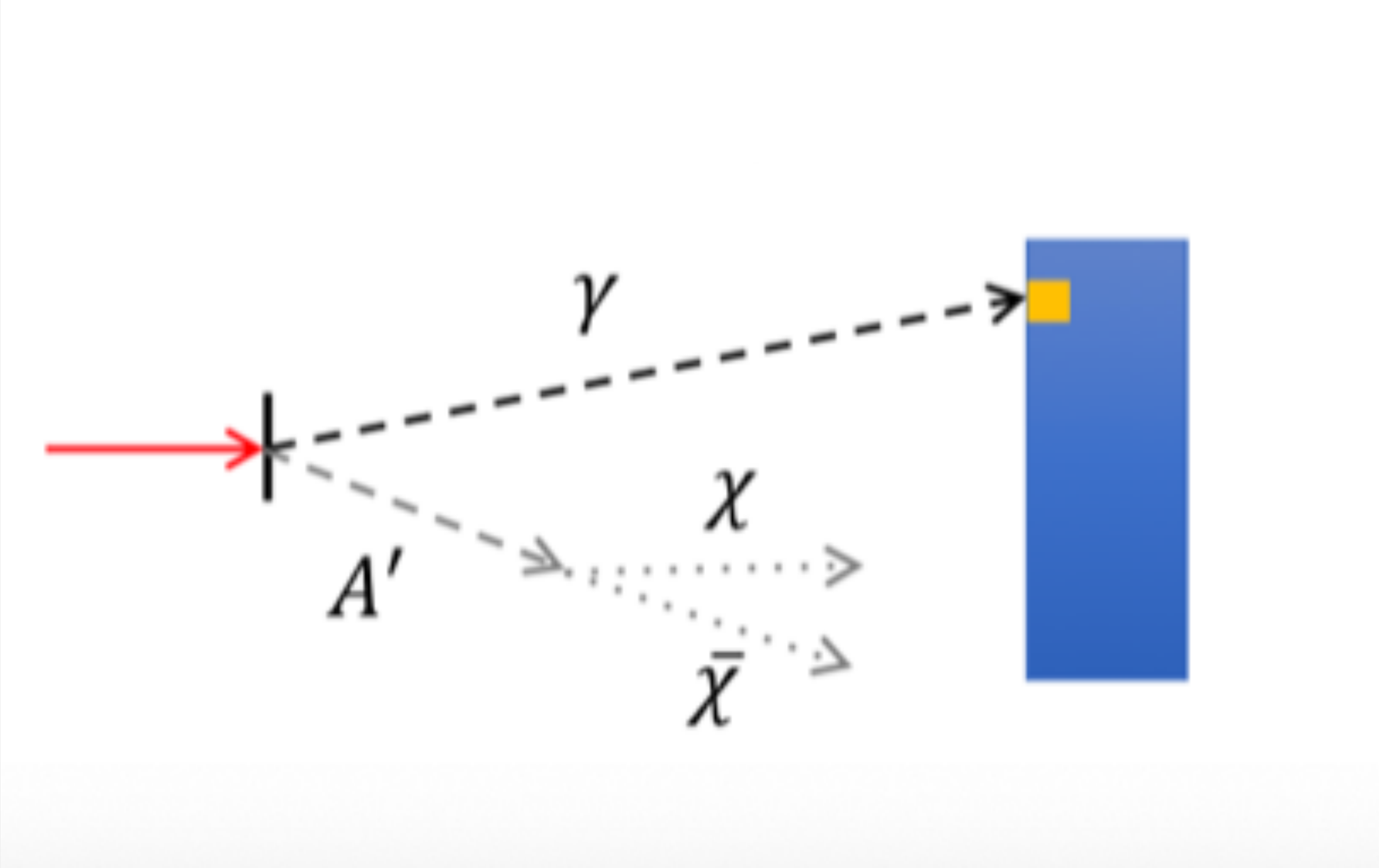
INVISIBLE: long-lived or if $m_a/2 > M_\chi$, $a \rightarrow DM\,DM$ with likely $BR \simeq 1$

TECHNIQUES:

1. Dump (bremsstrahlung) + DM scattering

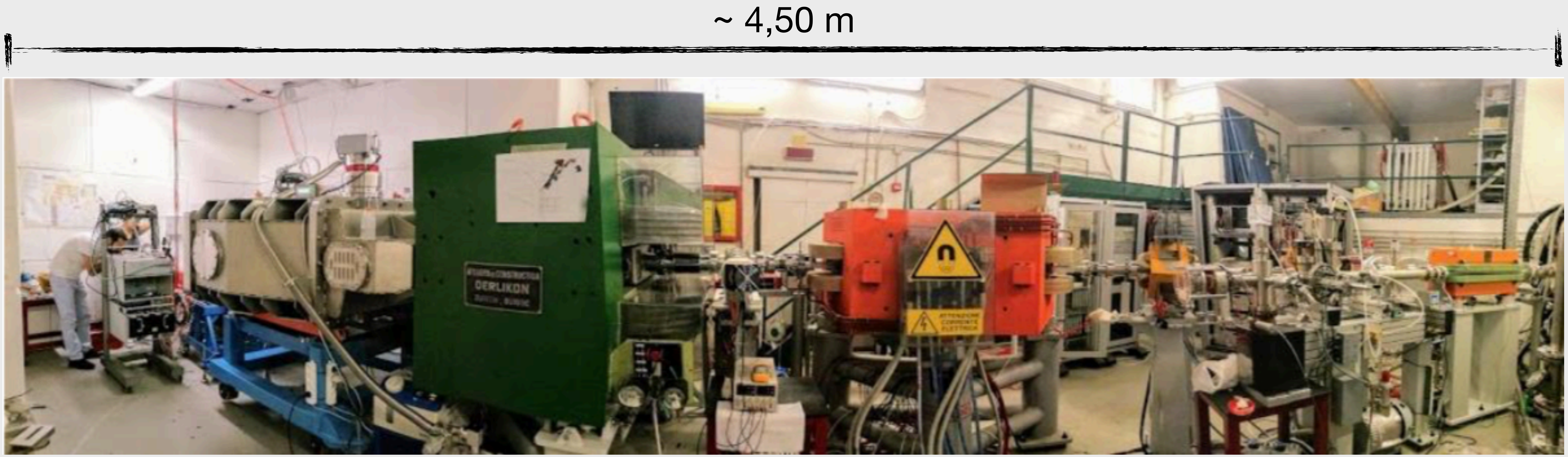


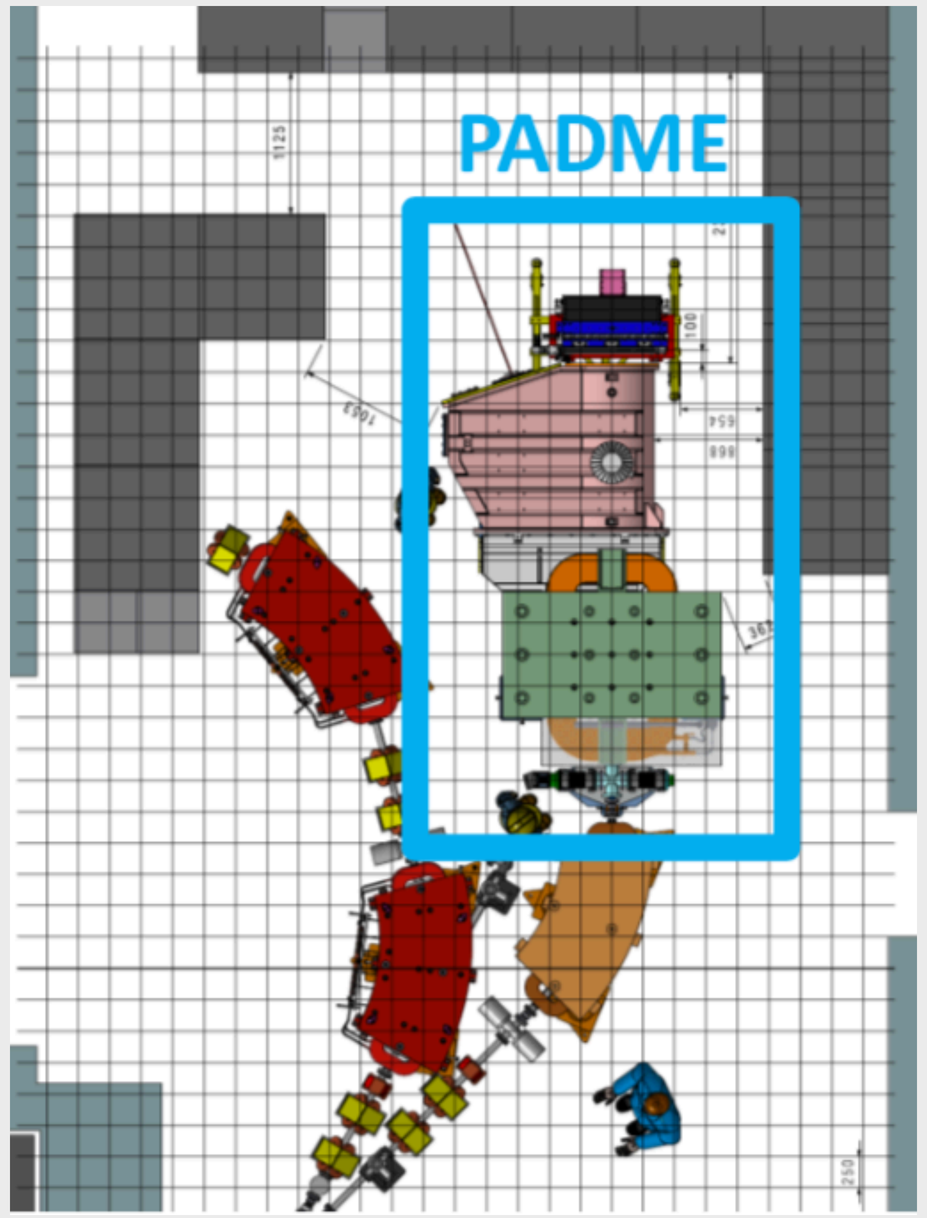
2. missing mass/energy/momentum search (annihilation)



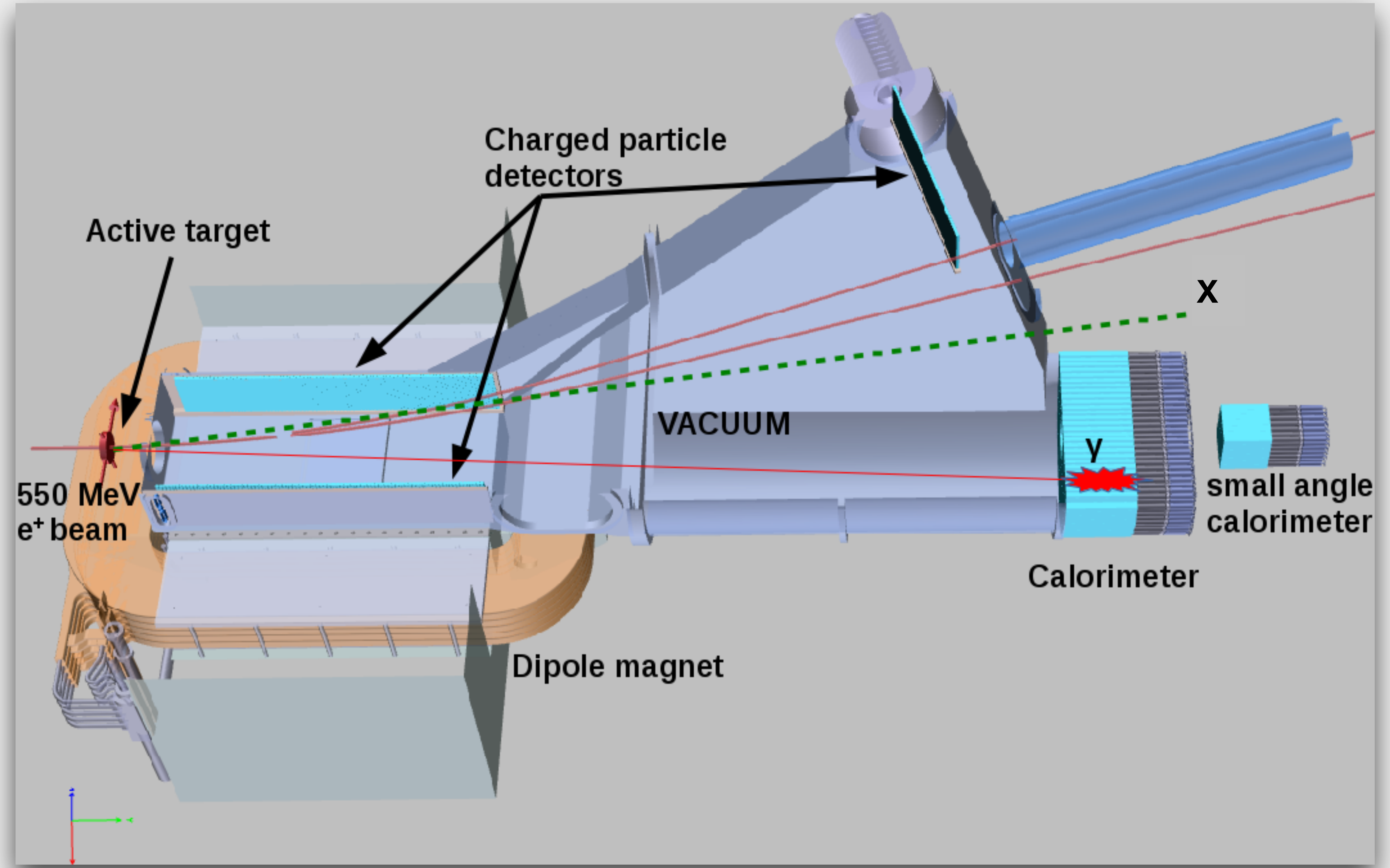
PADME EXPERIMENT

PADME (Positron Annihilation into Dark Matter Experiment) is placed in the Beam Test Facility of the Laboratori Nazionali di Frascati.





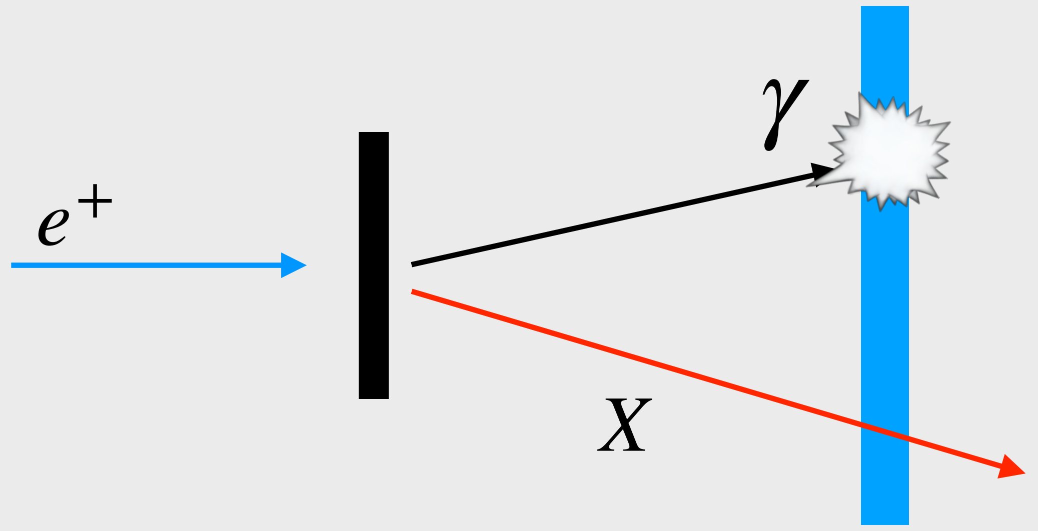
Experimental Setup



- **Beam:** e^+ produced at LINAC at 550MeV, multiplicity ~ 20k e^+/bunch, bunch duration 250 ns, frequency 49 Hz.
- Diamond active **target** 100 μm thickness. Active means that we can measure position, size and intensity of incoming beam.
- Dipole **magnet** of 0.45 T to deflect charged particles out calorimeter
- Plastic scintillators **veto** system + high energy positron veto in order to detect charged particles bent by magnet;
- The **vacuum** to minimise the unwanted interactions of primary and secondary particles
- Electromagnetic calorimeter (**ECAL**) composed of 616 BGO crystals
- Small angle calorimeter (**SAC**) composed of 25 PbF_2 crystals

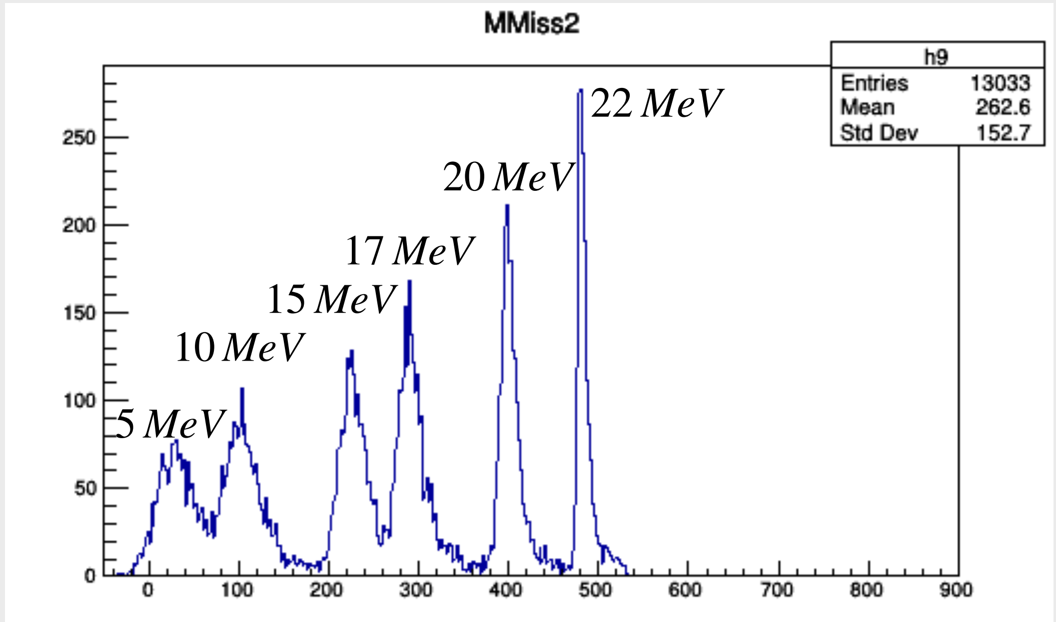
How PADME works…

PADME is a fixed target experiment which looks at the invisible decay of *dark photon* or *ALP* through the missing mass technique:



$$e^+e^- \rightarrow \gamma + X$$

- well-known initial state and detectors with very good hermeticity that allow to detect all the other particles in the final state.

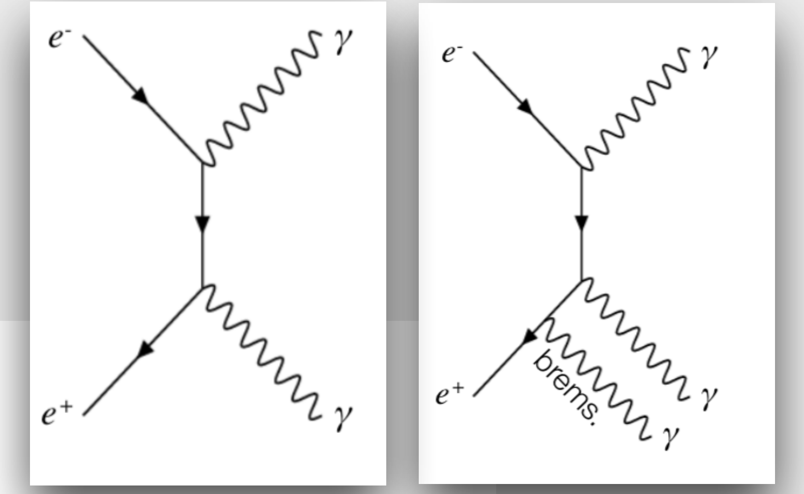


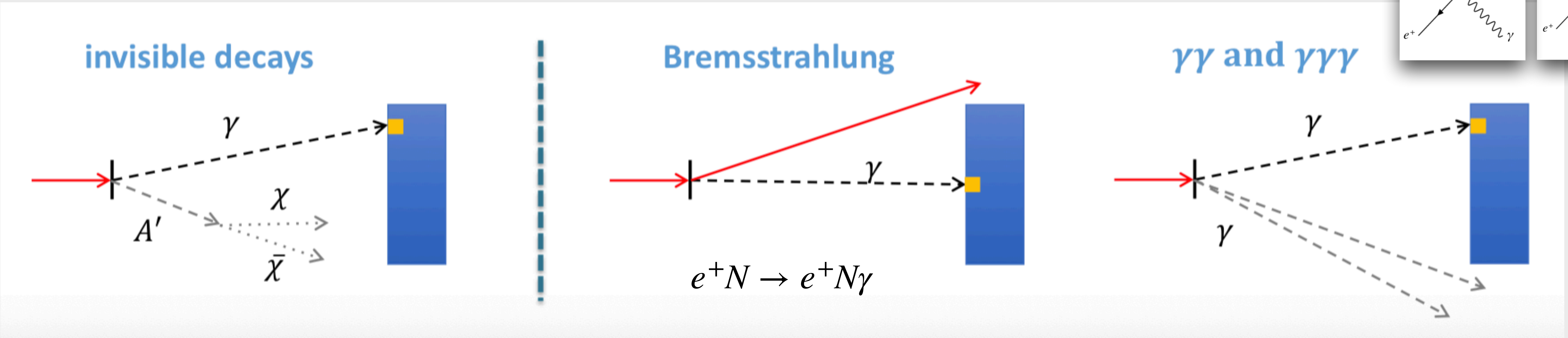
$$M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2$$

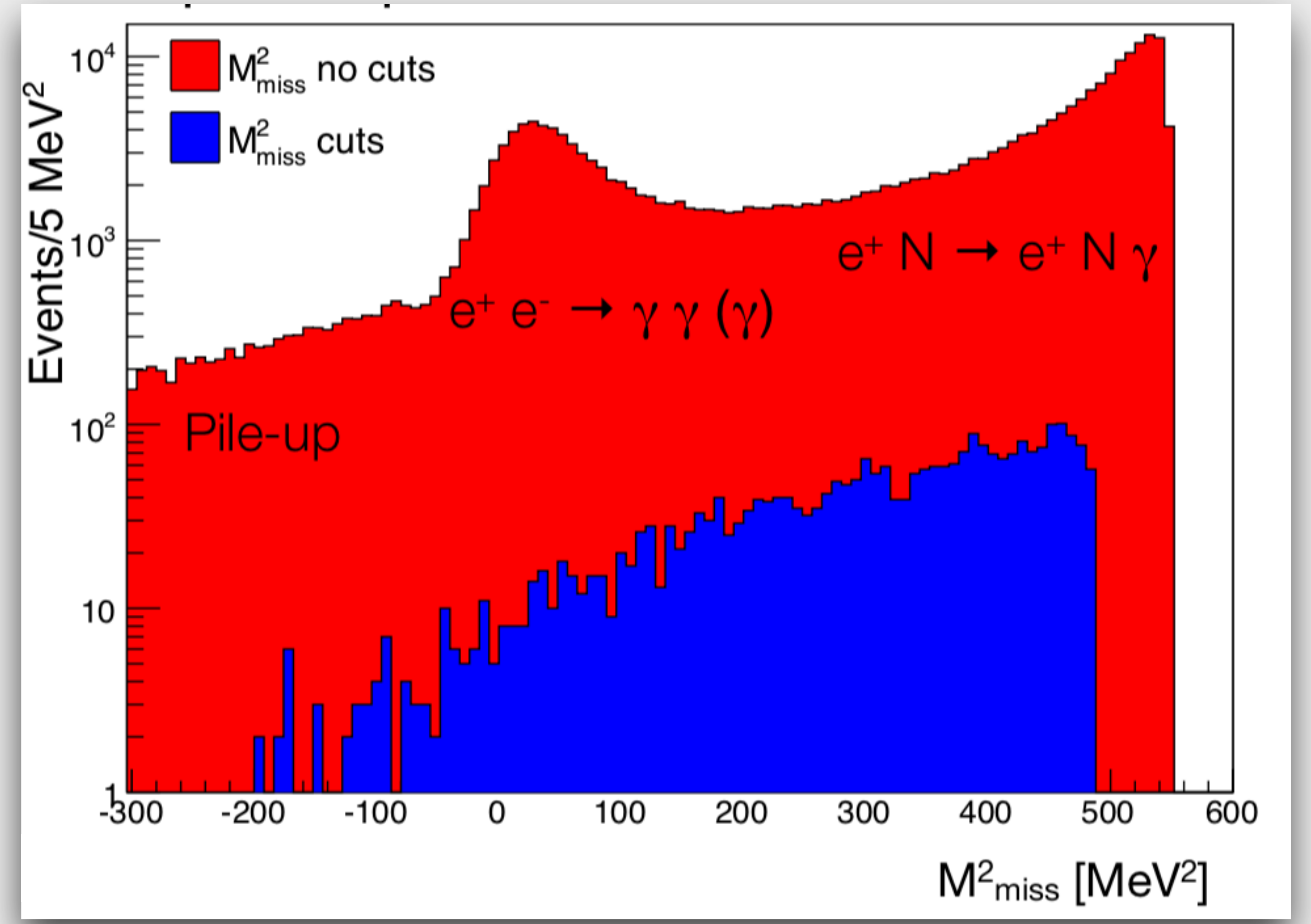
- basically the characteristic signature of this process is the presence of a peak emerging over a smooth background in the distribution of the missing mass.

One assumption: *leptophilic dark particles*

Background

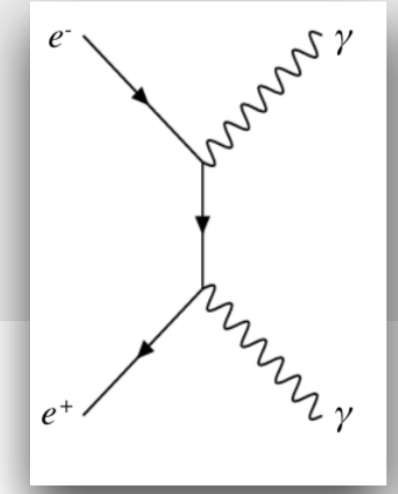


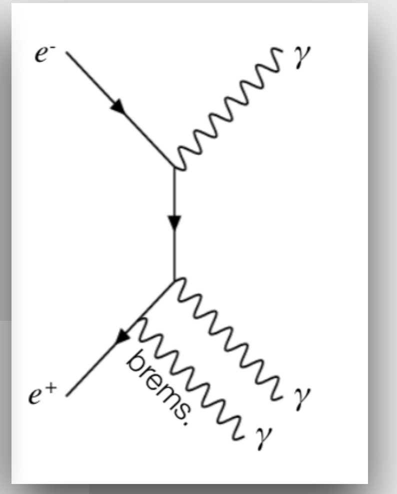


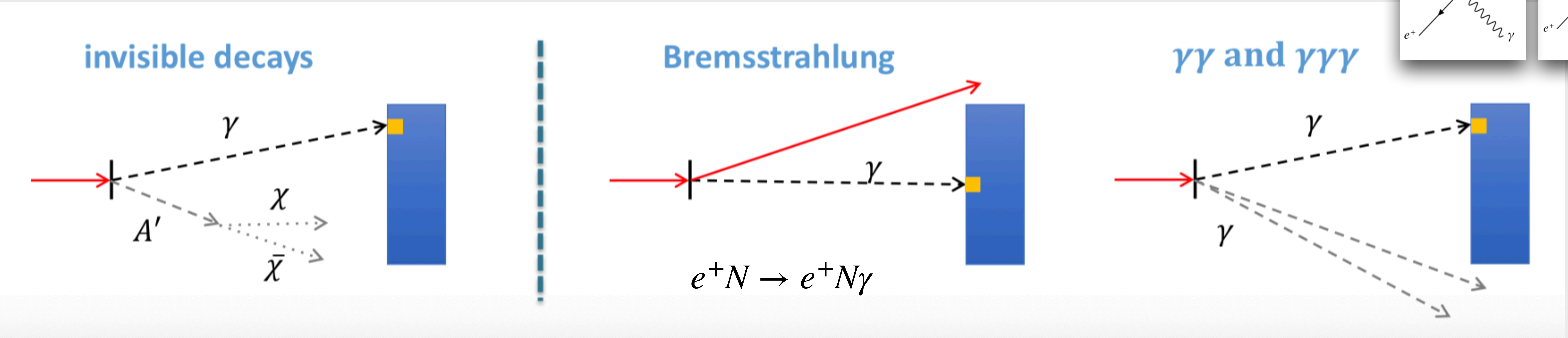


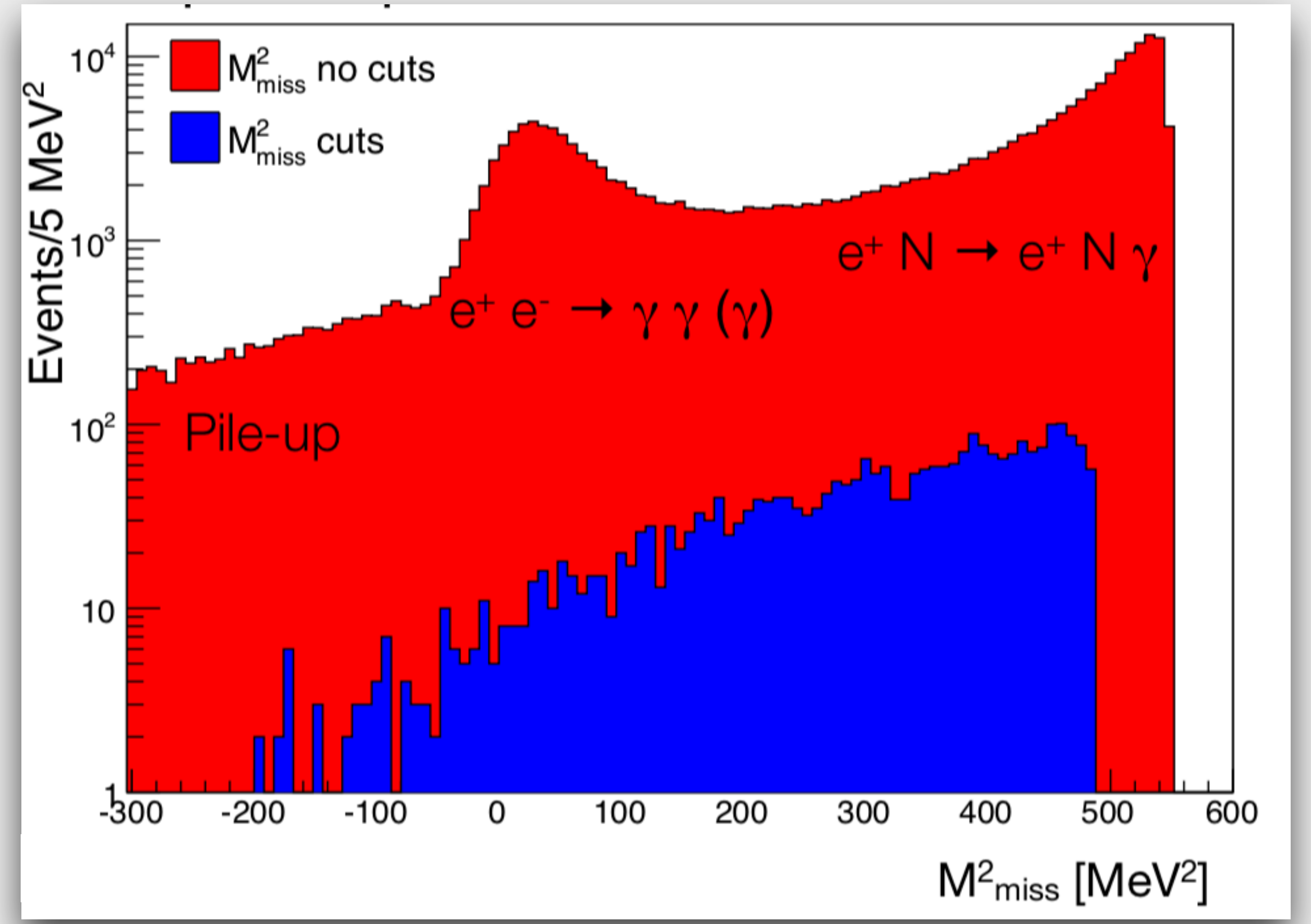
Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+ + N \to e^+ N \gamma$	4000 mb	$E\gamma > 1$MeV
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma > 1$MeV
$e^+e^- \to e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma > 1$MeV

Background









WORK IN PROGRESS ⚠️:

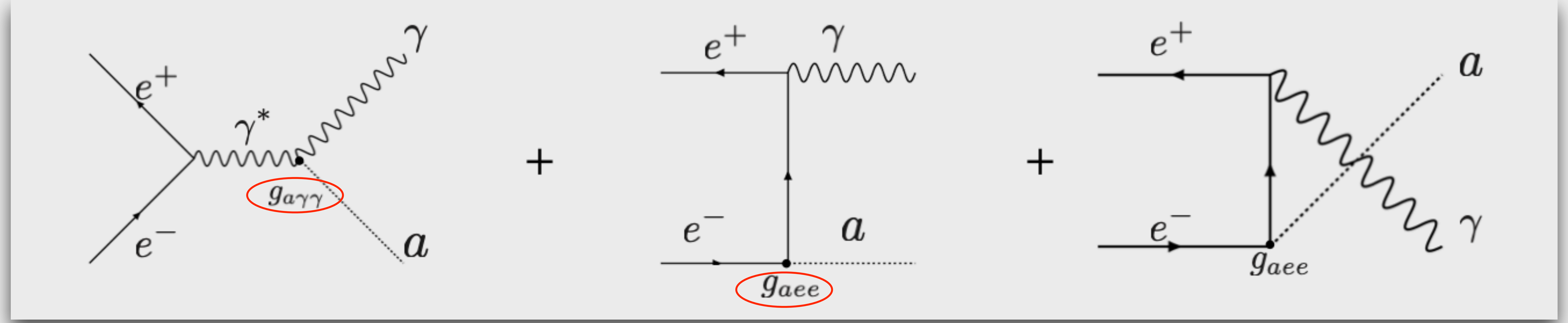
IN COLLABORATION WITH *MARCO PRUNA*, RADIATIVE CORRECTIONS FOR PROCESSES $e^+e^- \rightarrow 2\gamma, 3\gamma, 4\gamma$ USING ALSO A TOOL CALL RECOLA.

TWO REASONS:

1. PERFORMING A GOOD ANALYSIS FOR INVISIBLE DECAY,
2. MAKE A MEASURE OF PHYSICS WITH ELEVATED PRECISION.

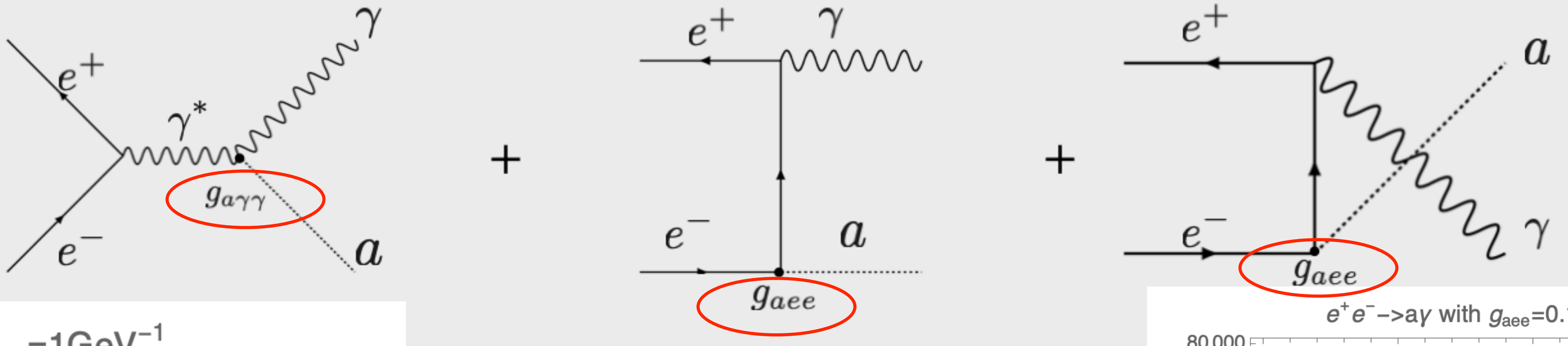
$e^+e^- \to a + \gamma$ in PADME

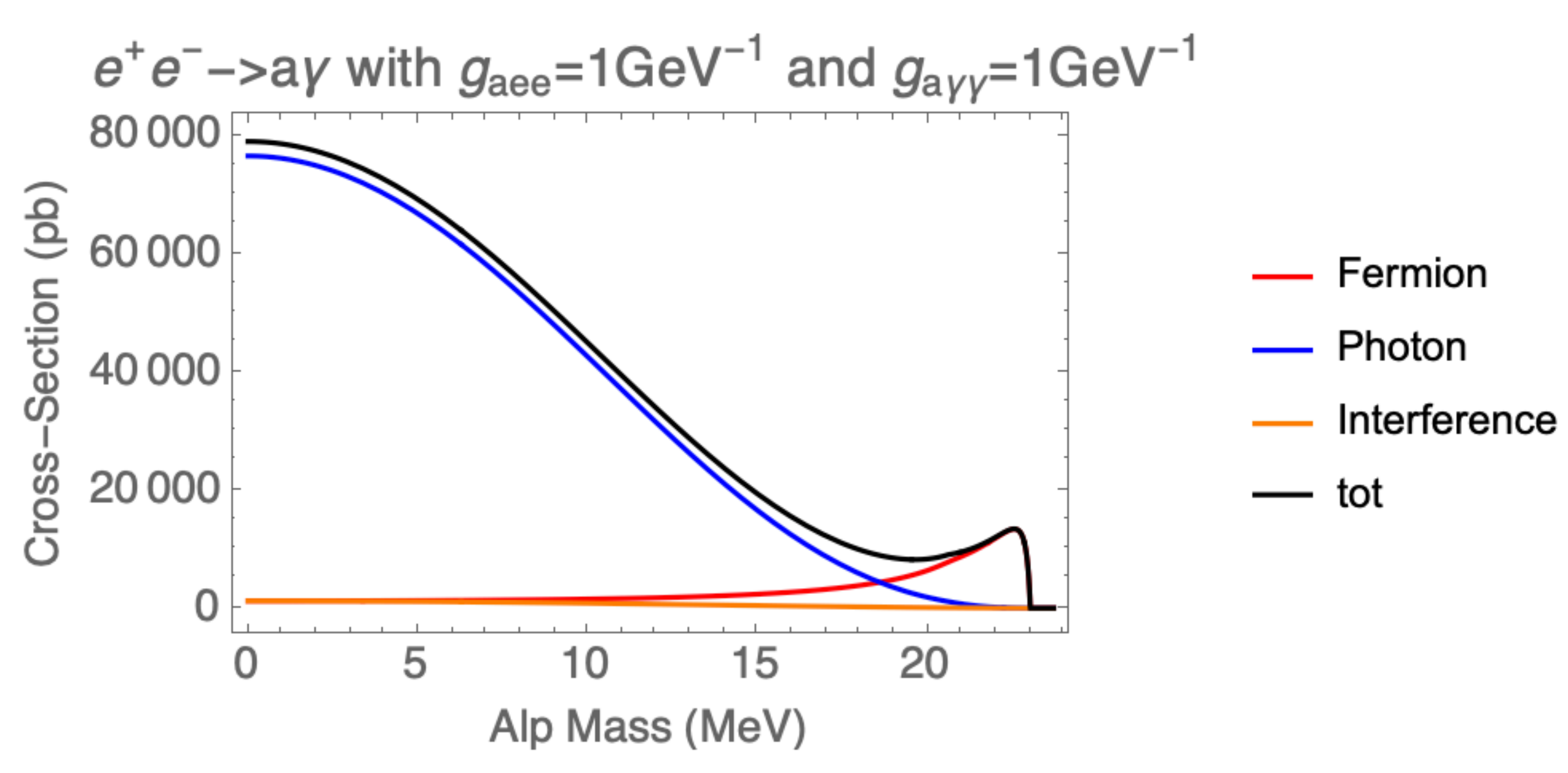
$$\mathcal{L}_{alp} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}M_a{}^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - i g_{aee} m_e \bar{a} \bar{e} \gamma^5 e + \mathcal{L}_{DM}$$

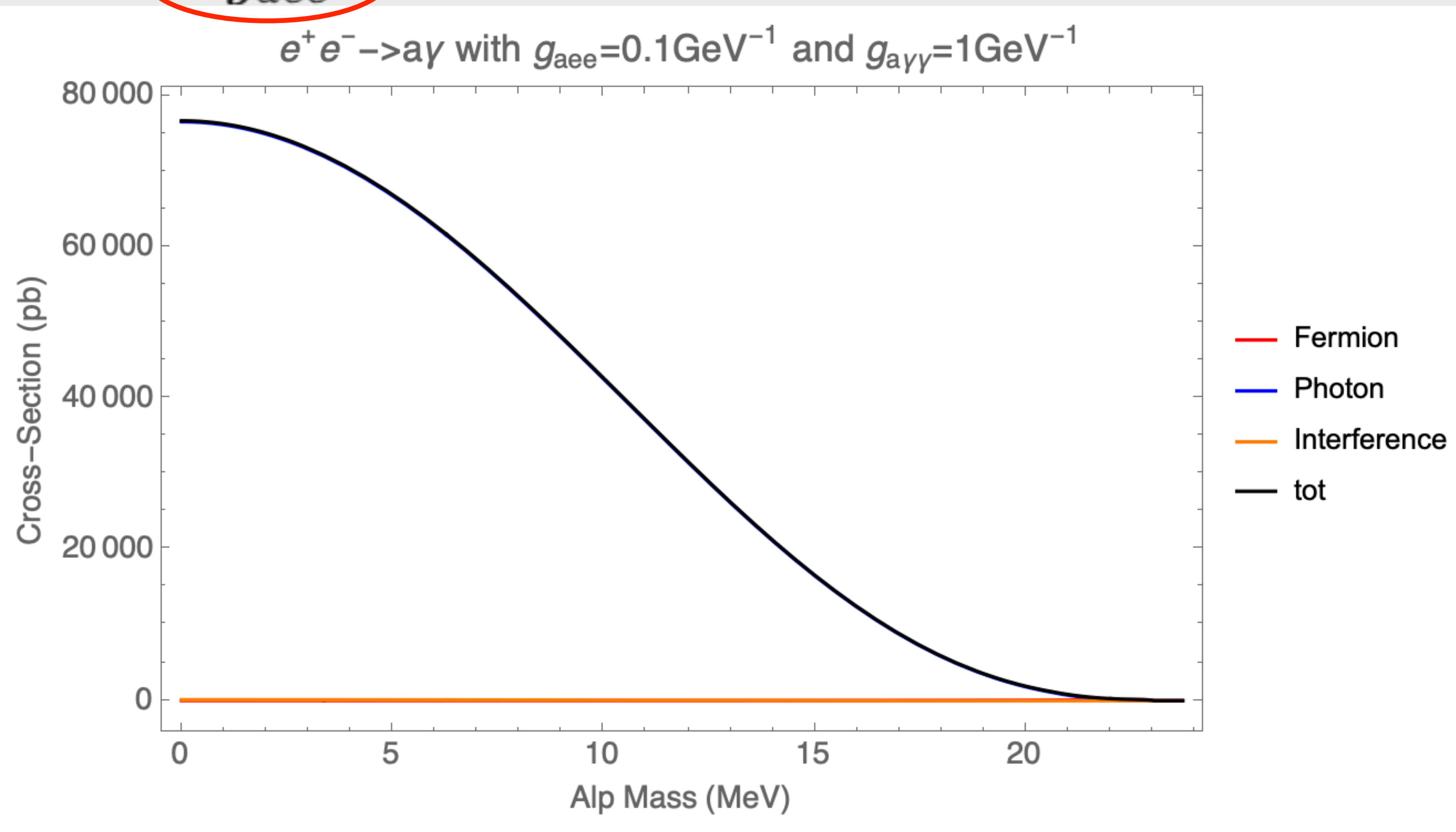


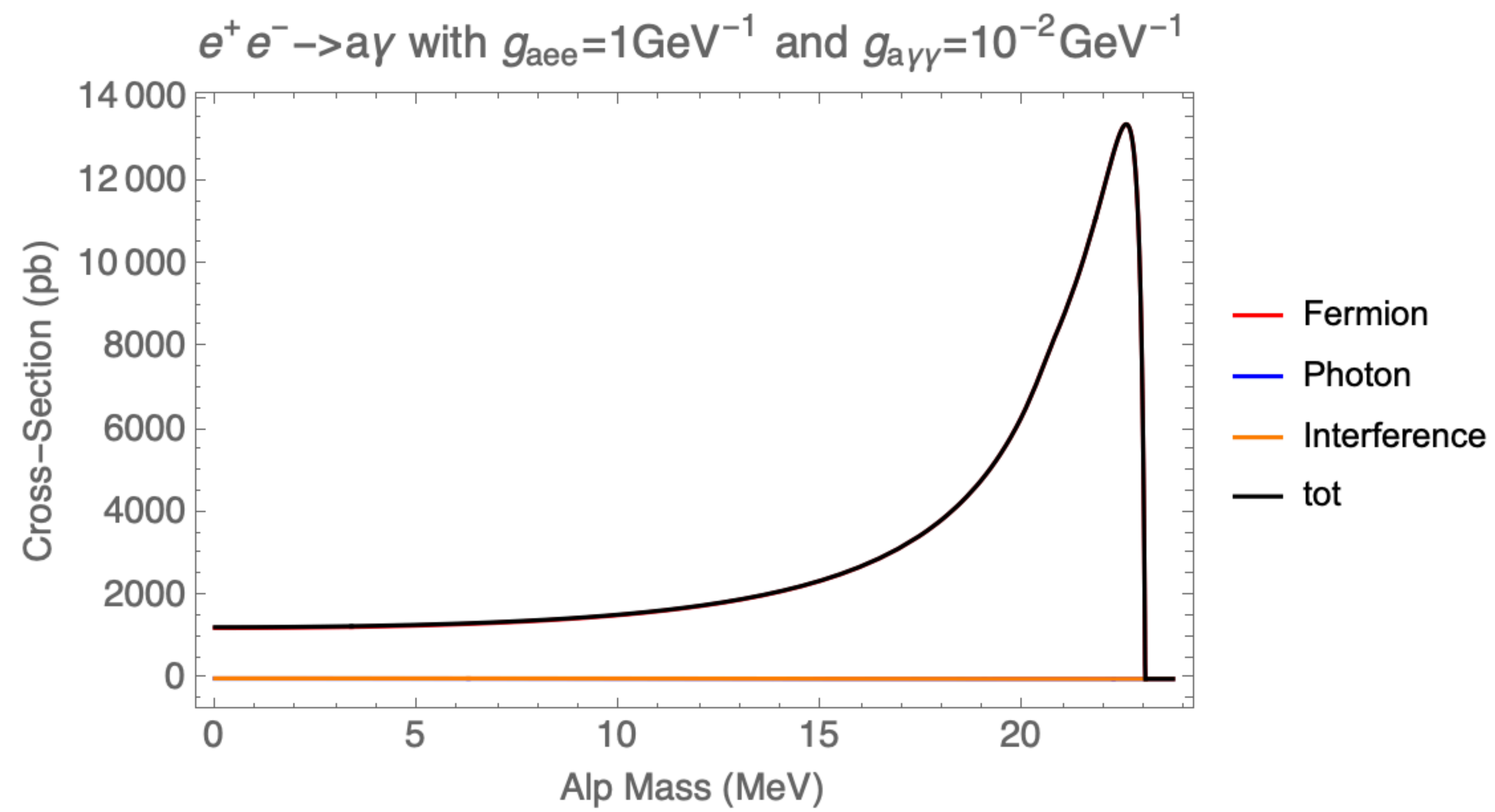
$e^+e^- \to a + \gamma$ in PADME

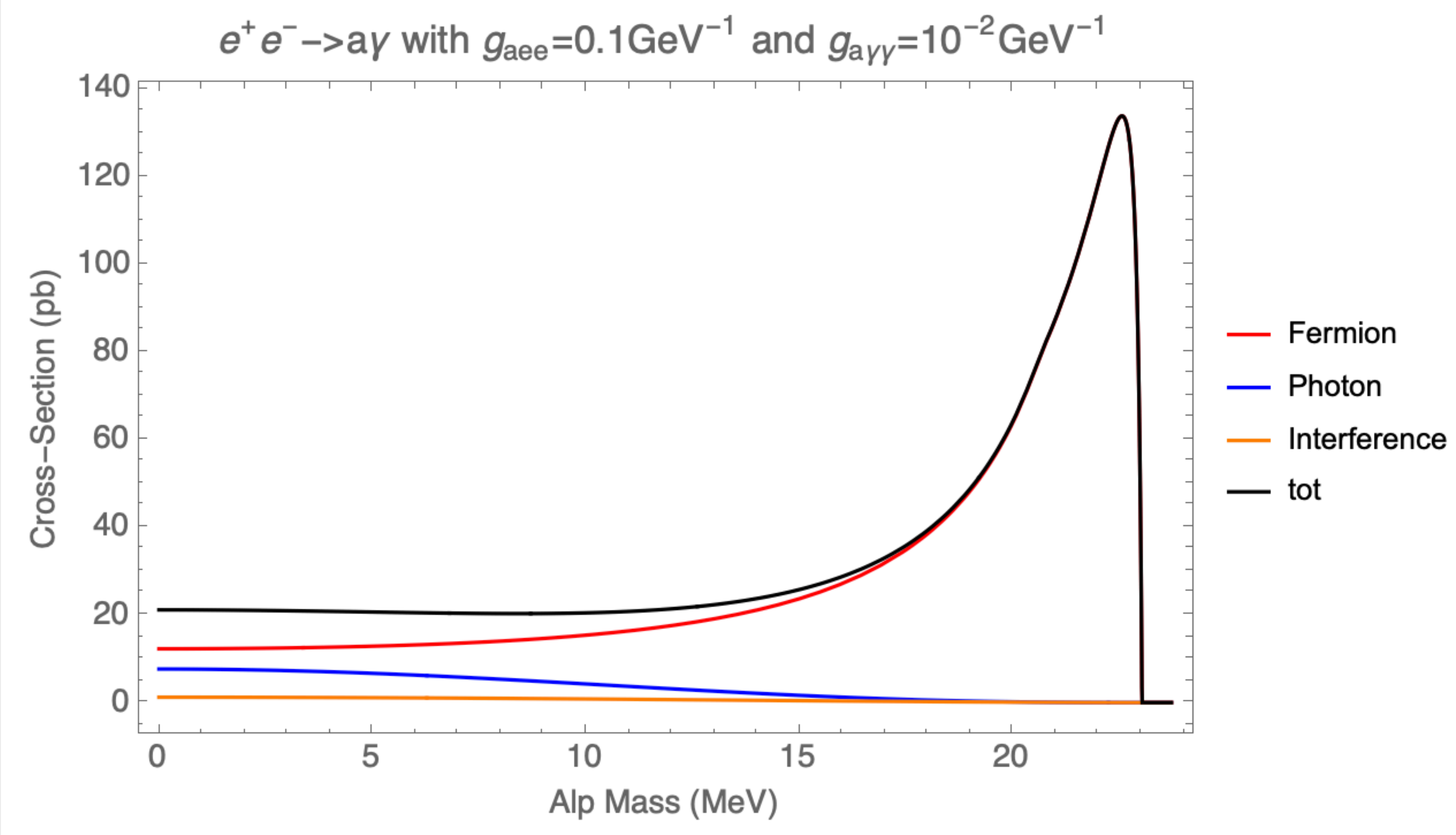
- **angular coverage of ECAL ($15 < \theta < 84$ mrad),**
- **Energy beam of 550 MeV**
- **photon energy larger than ~ 30 MeV.**











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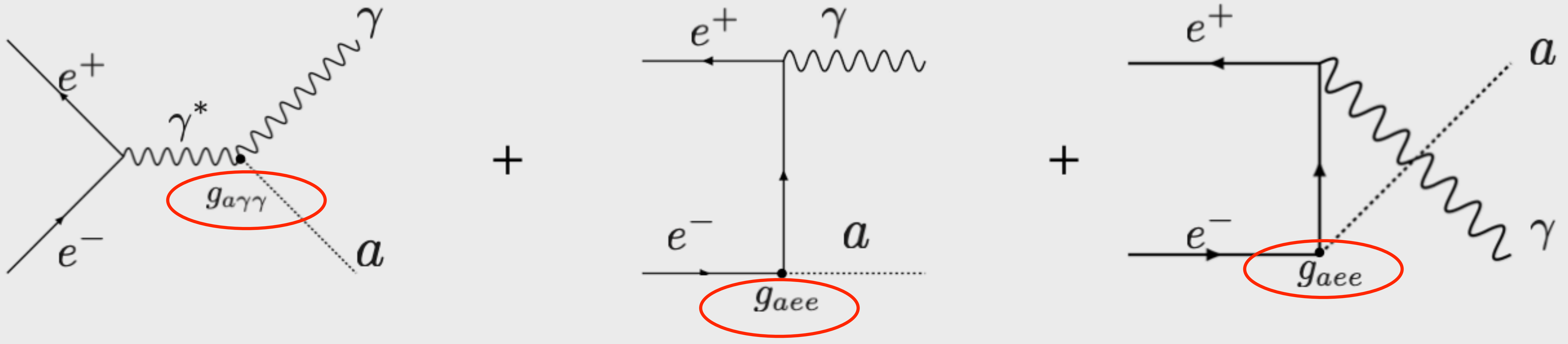
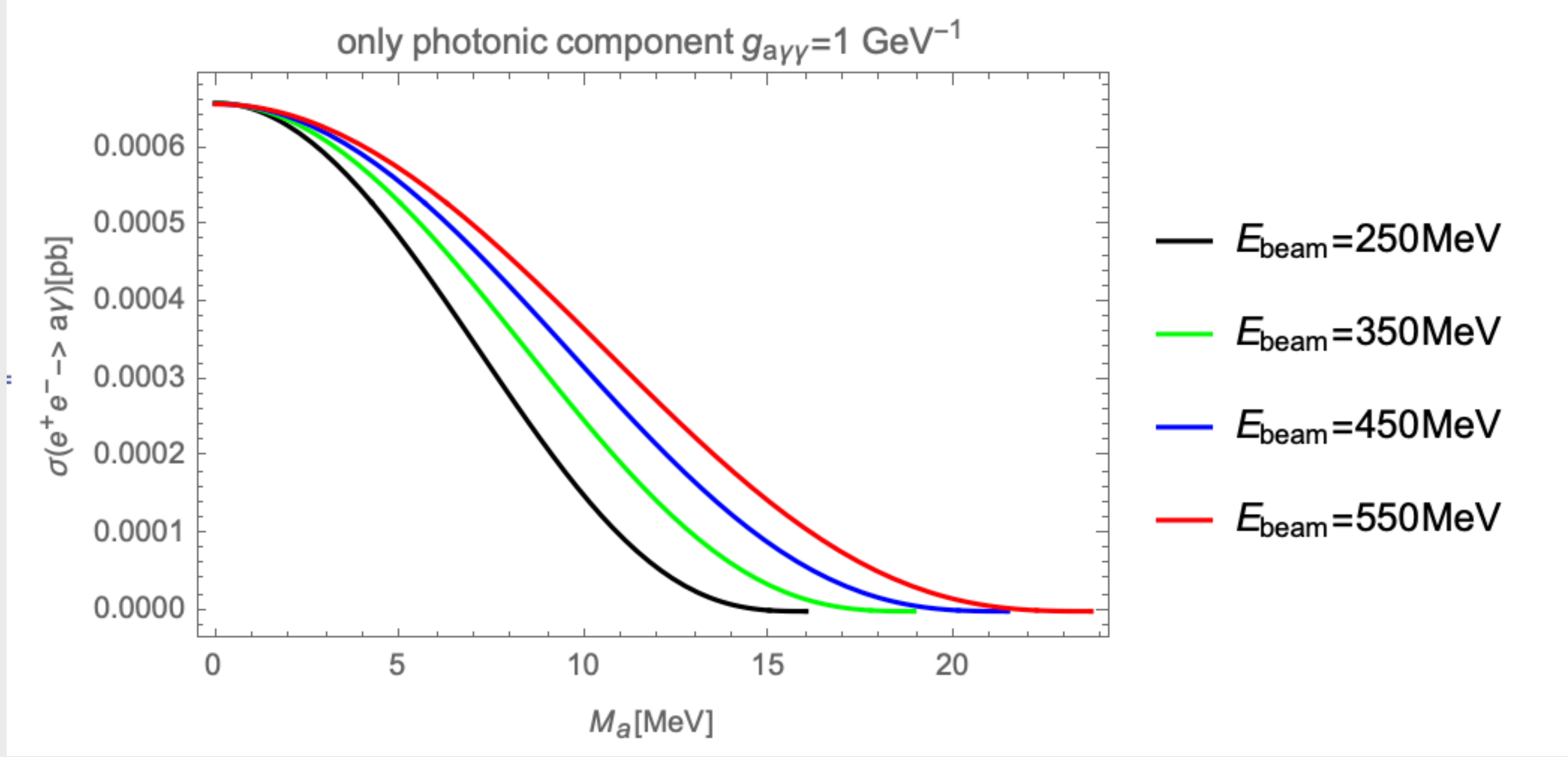
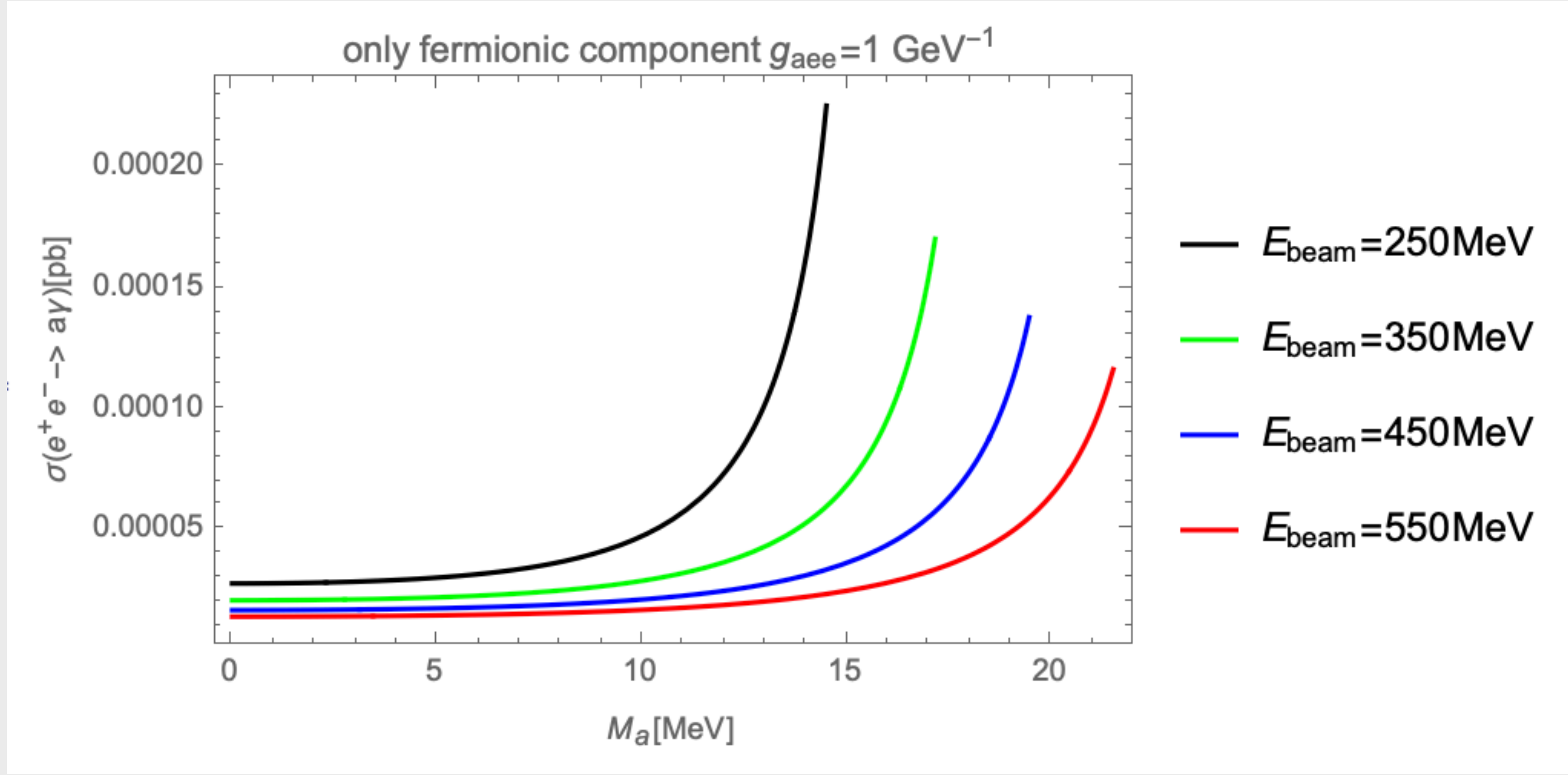






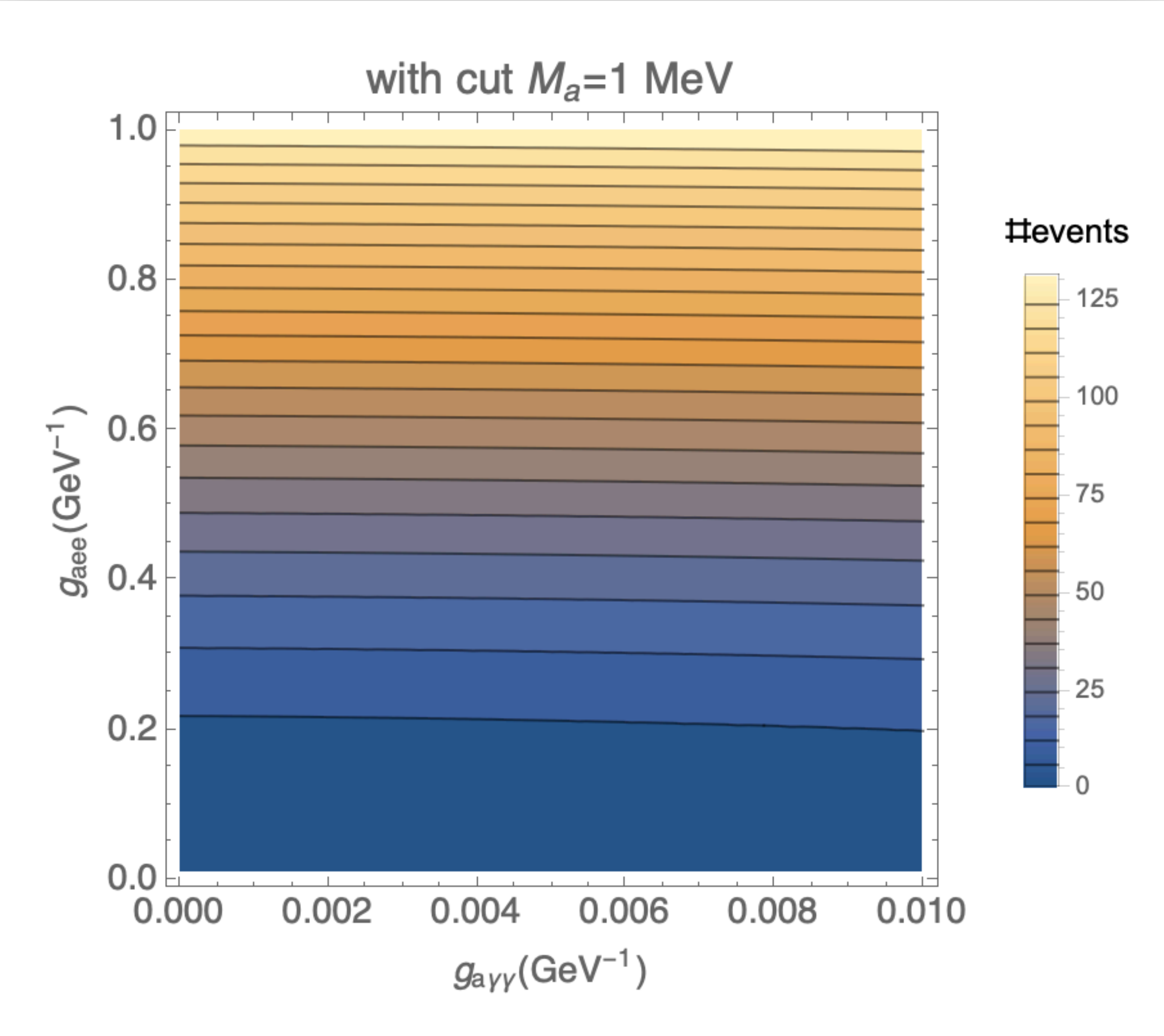
Number of events of $e^+e^- \to \gamma + a$ in PADME

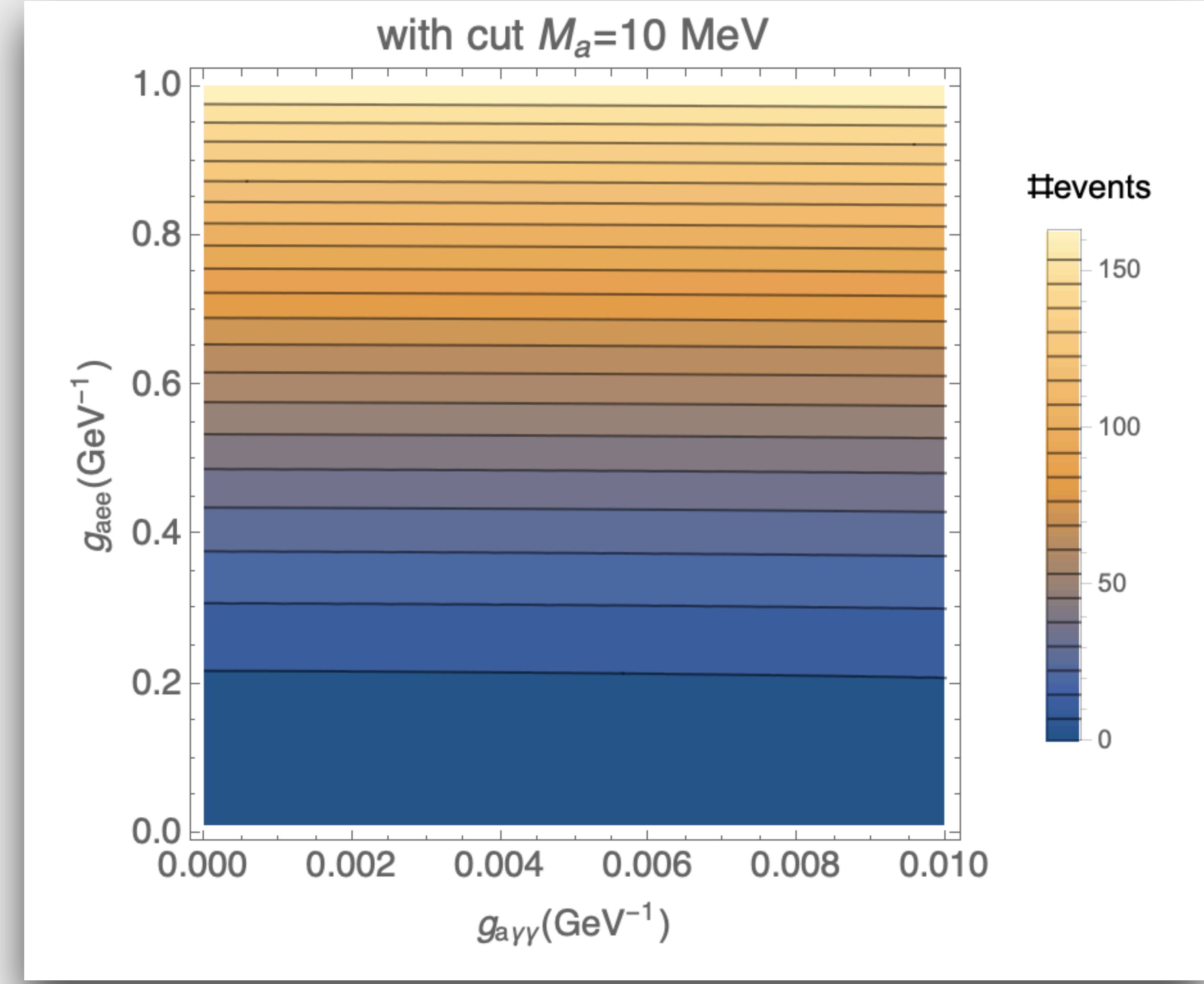
diamond density 3.5 g/cm^3

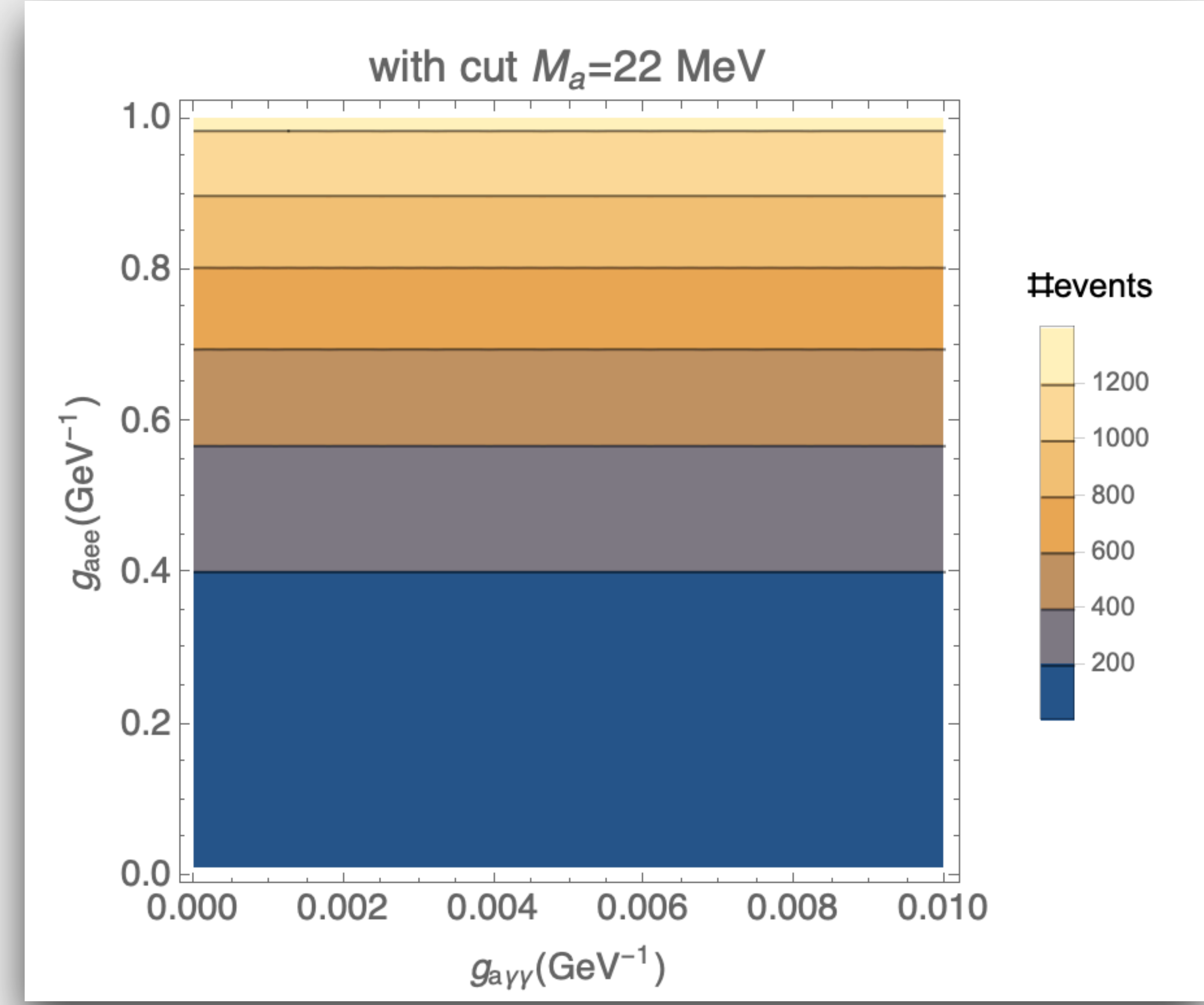
$$N_{events} = 10^{13} N_e \sigma_{e^+e^- \to a\gamma} = 6 d_{target} N_A \frac{\rho}{A} \sigma_{e^+e^- \to a\gamma}$$

$\#_{tot}$ of e$^-$ on target per unit surface area

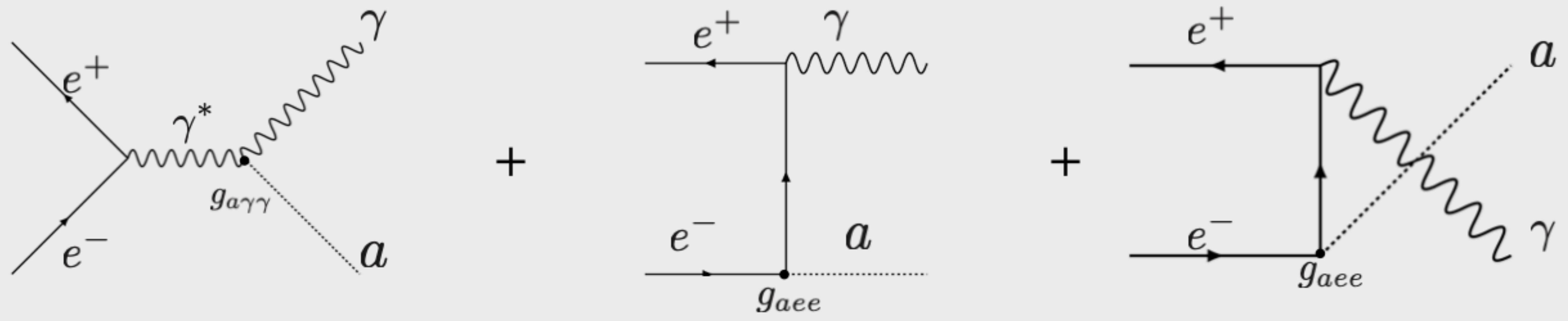
atomic mass = 12 g/mol

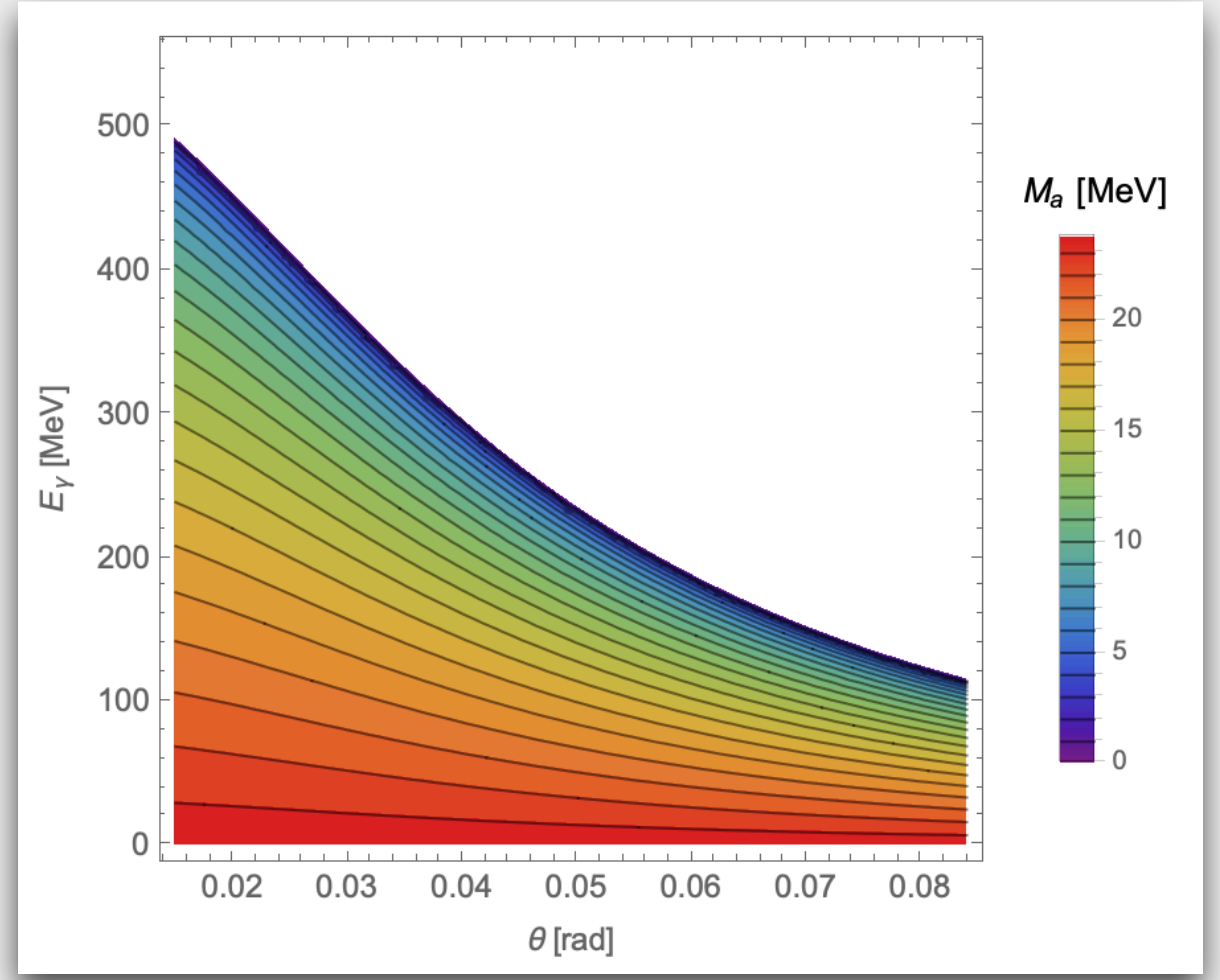






$e^+e^- \to a + \gamma$ in PADME





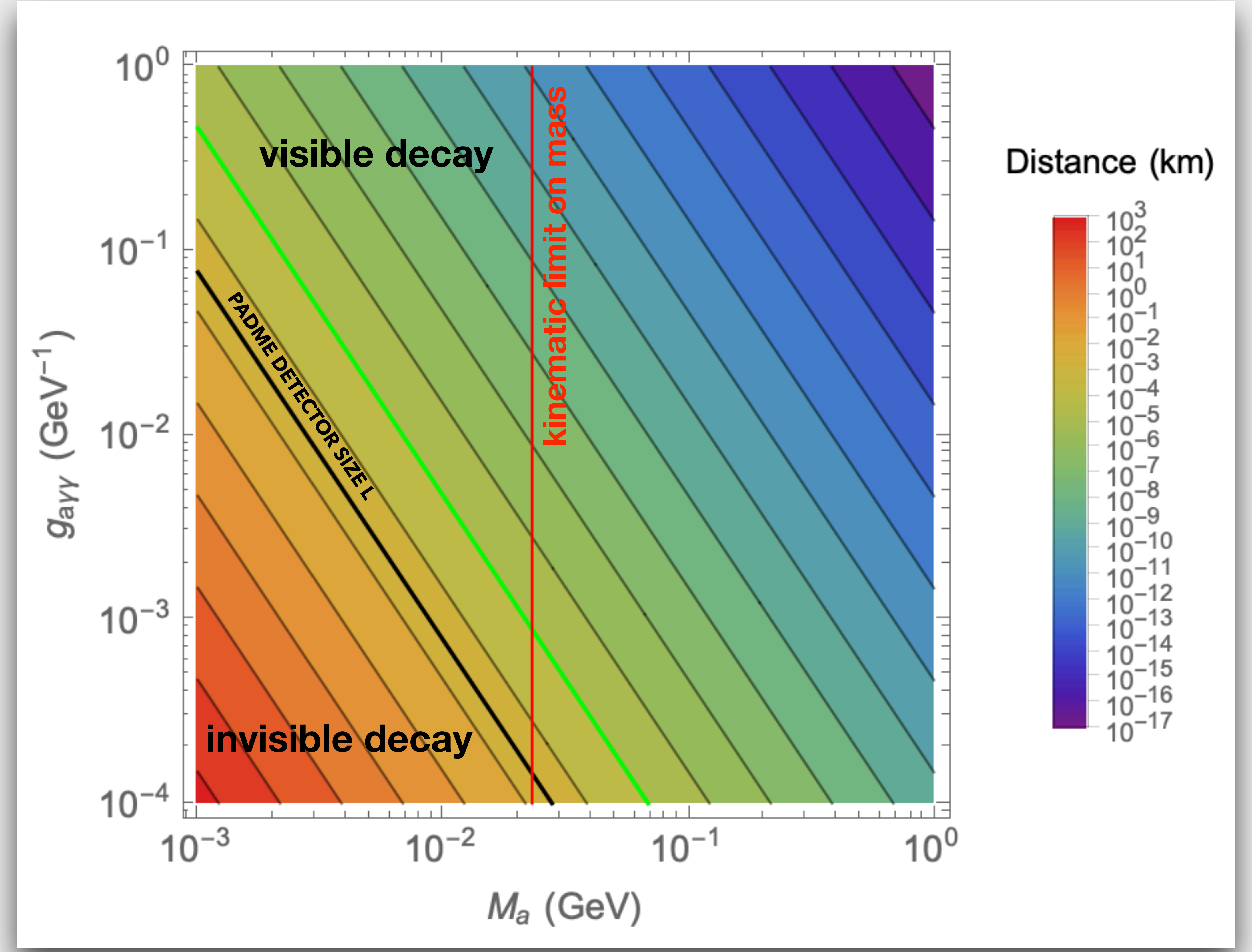
WHAT ABOUT VISIBLE DECAYS OF ALPS IN PADME?

It depends on the ALP decay length relative to the size of the detector

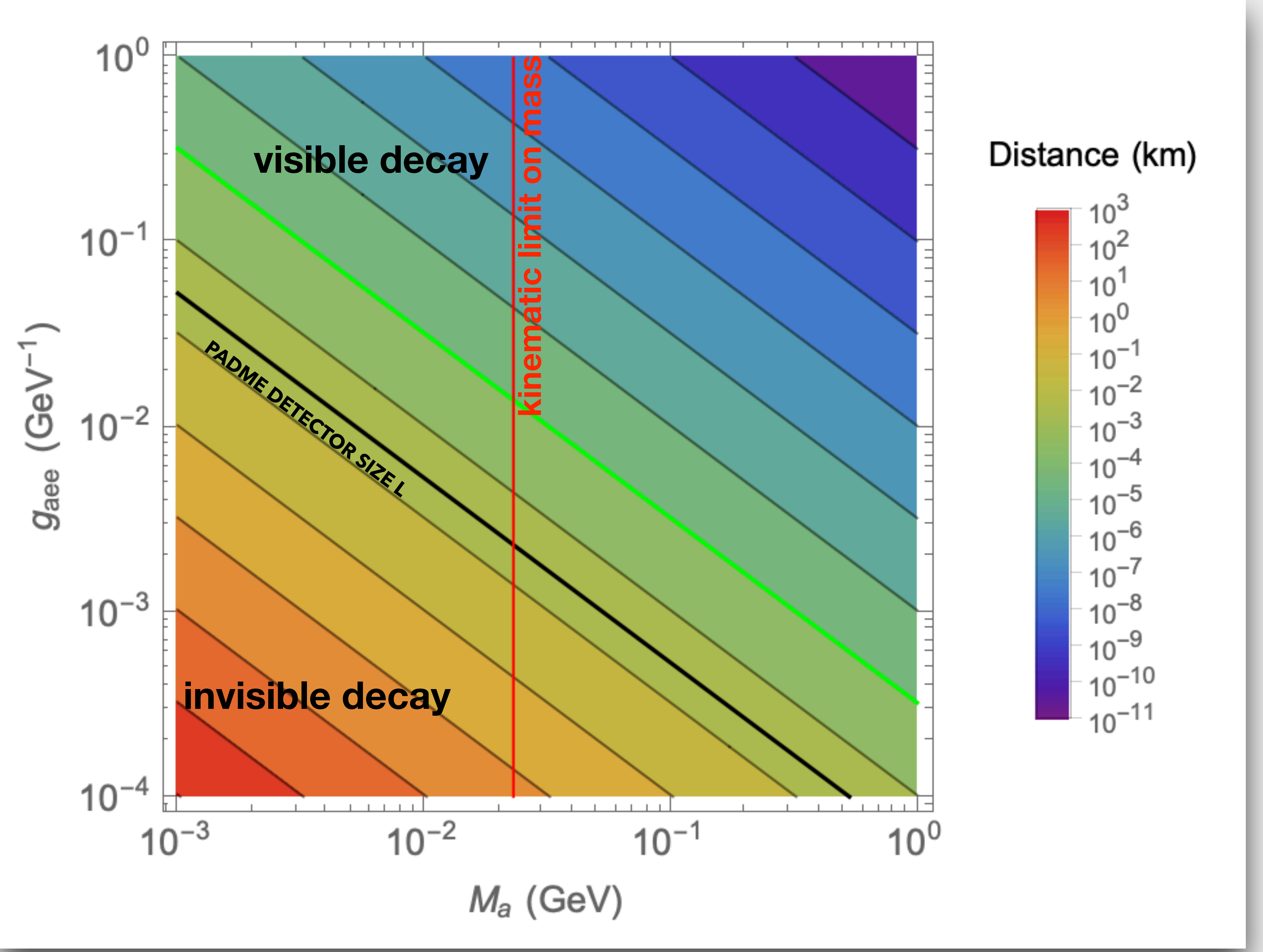
$$L_{a\to\gamma\gamma} = \frac{64\pi c E_a \hbar}{g_{a\gamma\gamma}^2 M_a^4}$$

$$L_{a\to e^+e^-} \simeq \frac{8\pi c E_a \hbar}{g_{aee}^2 M_a^2 M_e^2}$$

$E_a = 550$ **MeV**

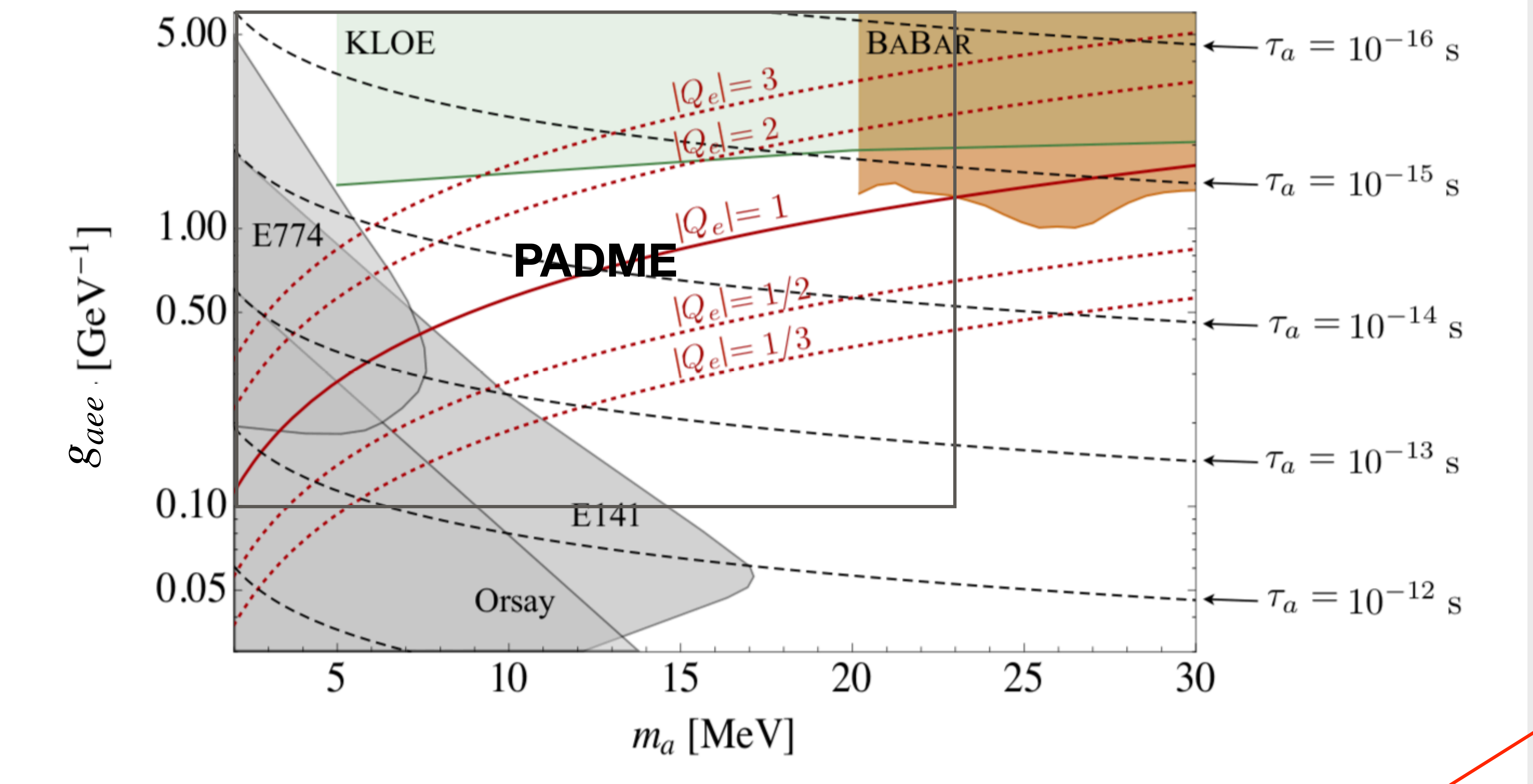


$E_a = 550$ **MeV**



CURRENT CONSTRAINTS

Alves and Weiner JHEP07(2018)092



FUTURE PADME RESULTS ARE <u>NOT A RECAST</u> OF DARK PHOTON MEASUREMENTS, BUT IT IS EXPLORING DIRECTLY THESE REGIONS

$$\frac{d\sigma}{d\cos\theta} = \frac{(1+\cos^2\theta)\pi\,\alpha^2\,\epsilon^2}{2\,\sin^2\theta\,E^2_{\text{beam}}}, \tag{3.2}$$

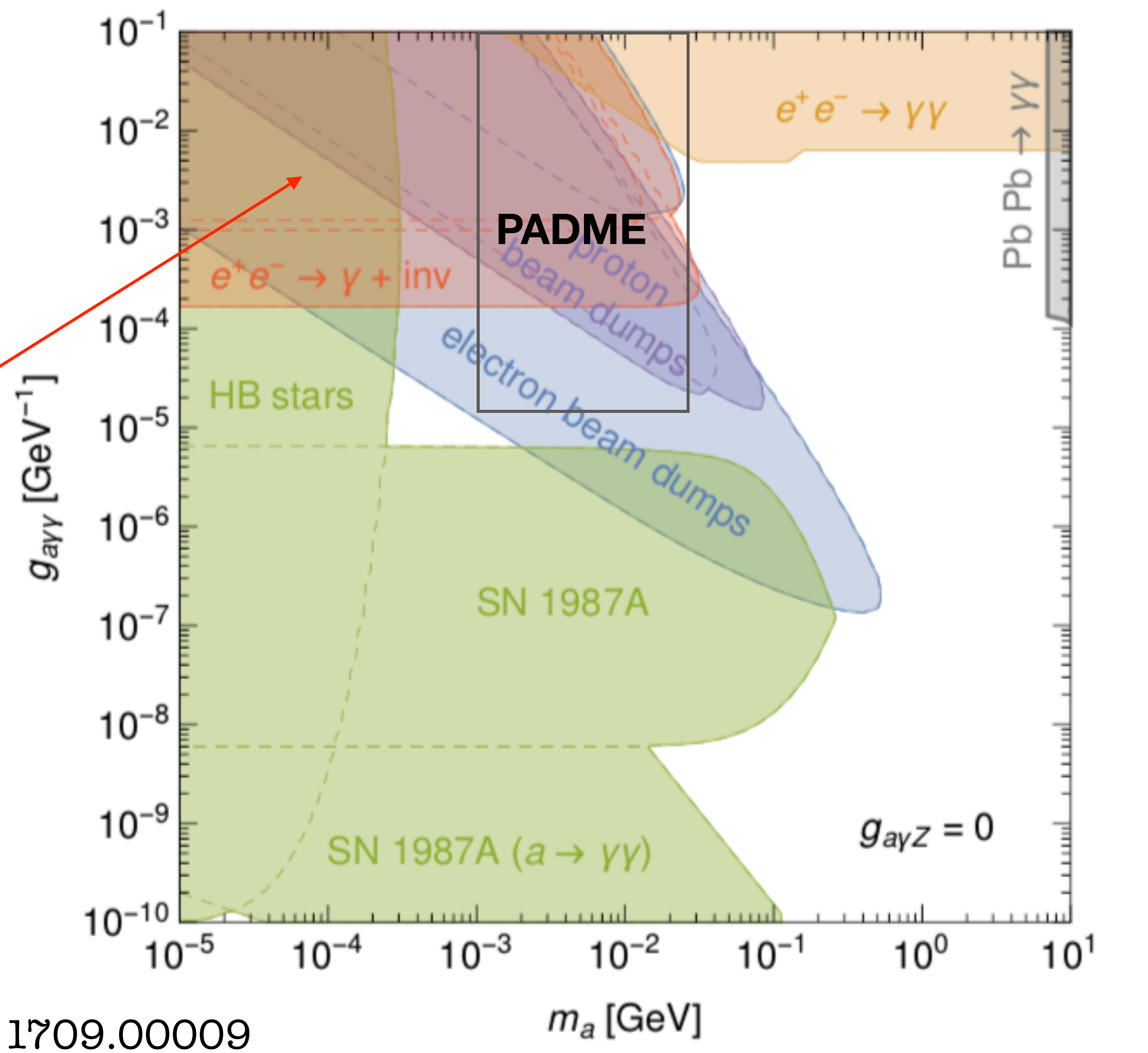
where ϵ denotes the kinetic mixing parameter.[7] To convert a bound on ϵ for Dark Photons into a bound on $g_{a\gamma\gamma}$ for ALPs we therefore have to correct for the fact that the geometric acceptance will be very different in the two cases.

The BaBar analysis considers $-0.6 < \cos\theta < 0.6$ for $m_{A'} > 5.5$ GeV and $-0.4 < \cos\theta < 0.6$ for $m_{A'} < 5.5$ GeV. By integrating the respective differential cross sections for ALP production and Dark Photon production over these ranges we obtain the fiducial cross section including geometric acceptance. Using these numbers, we can translate bounds on Dark Photons into the ALP parameter space under the assumption that all other selection cuts have the same efficiency for the two models. For very small masses of the invisibly decaying particle, we find that the translation is given by

RECAST

$$g_{a\gamma\gamma} = 1.8\times10^{-4}\,\text{GeV}^{-1}\left(\frac{\epsilon}{10^{-3}}\right). \tag{3.3}$$

Repeating this calculation for finite ALP masses and taking into account the probability that the ALP decays before leaving the detector (see above) using a detector length of $L_D = 275$ cm [59], we can then reinterpret the full BaBar bound in the context of ALPs.

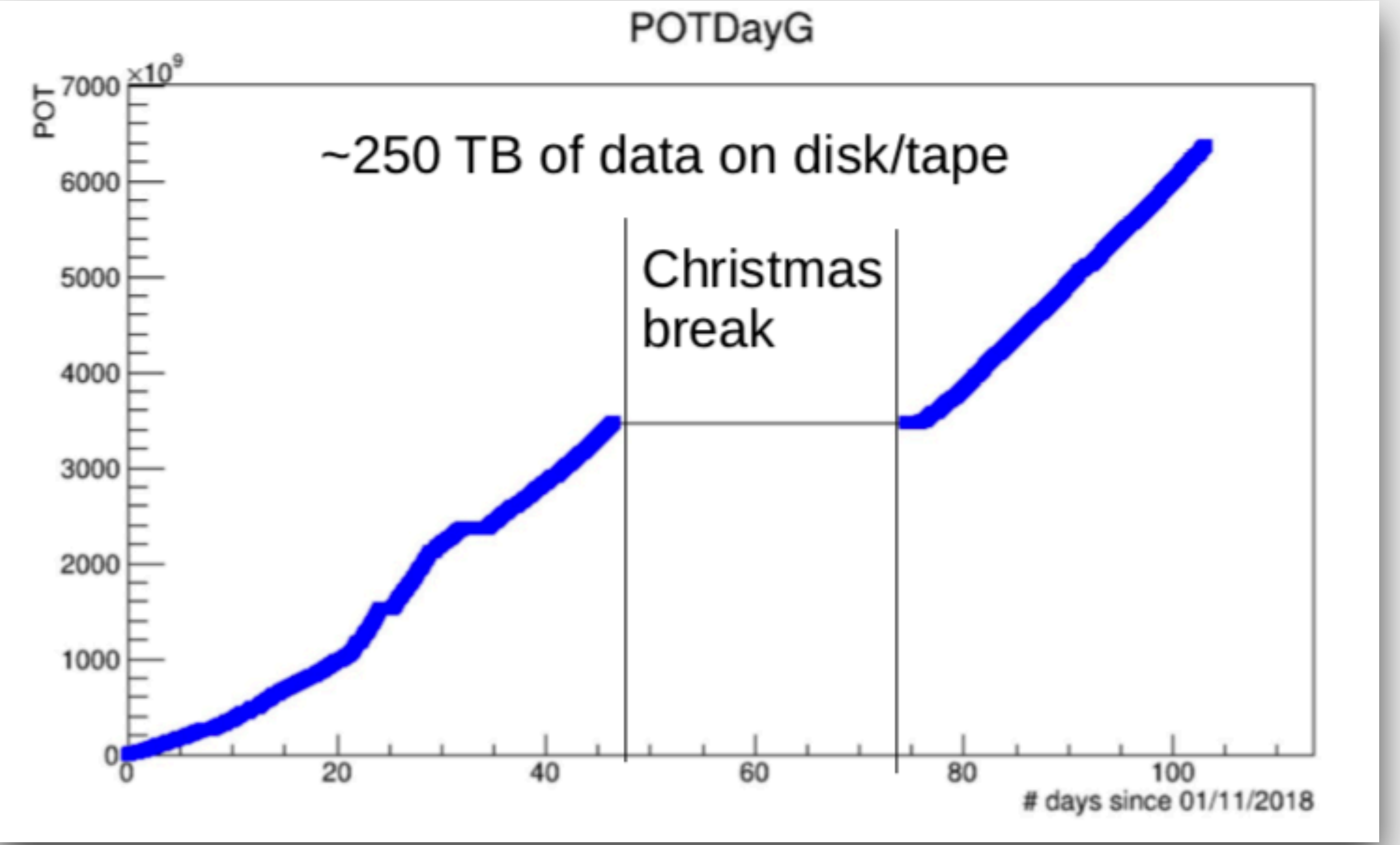


1709.00009

CURRENT STATUS OF PADME

PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th

- $\sim 7 \times 10^{12}$ positrons on target recorded
- Data quality and detector calibration in progress



In July Run-2 was where:

- few days of data
- detector performance/calibration check

Next:

− Finalise detector absolute calibration

− Measure physics signals (bremsstrahlung and annihilation) from data − Minimise beam background along the beam line

– Collecting the 10^{13} PoT that we want to reach.

Conclusion

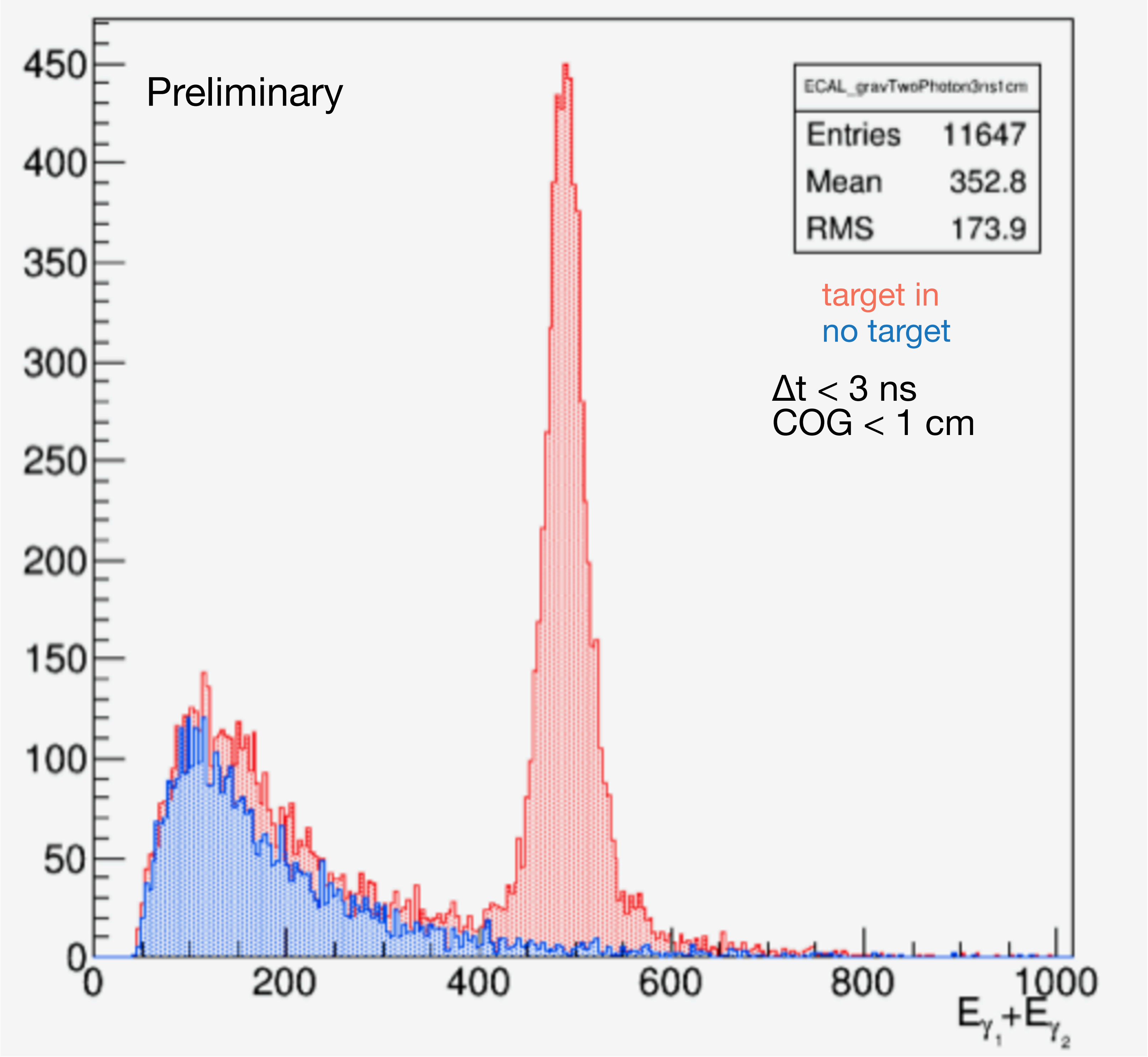
- Not only WIMP searches, but also Light Dark Matter is really interesting.
- *Intensity Frontier* experiment are increasing the interest.
- PADME is a promising (from data analysis ongoing and the detector performance reaching design parameters) and simple experiment which can look at new physics. In particular, not only dark photon, but ALP parameter space is testable with an interesting phenomenology to study.
- Complete analysis of background for a good analysis of parameter space.
- Other phenomenology is going to study: probing the anomaly at *17 MeV* observed in ATOMKI experiment [1504.01527].

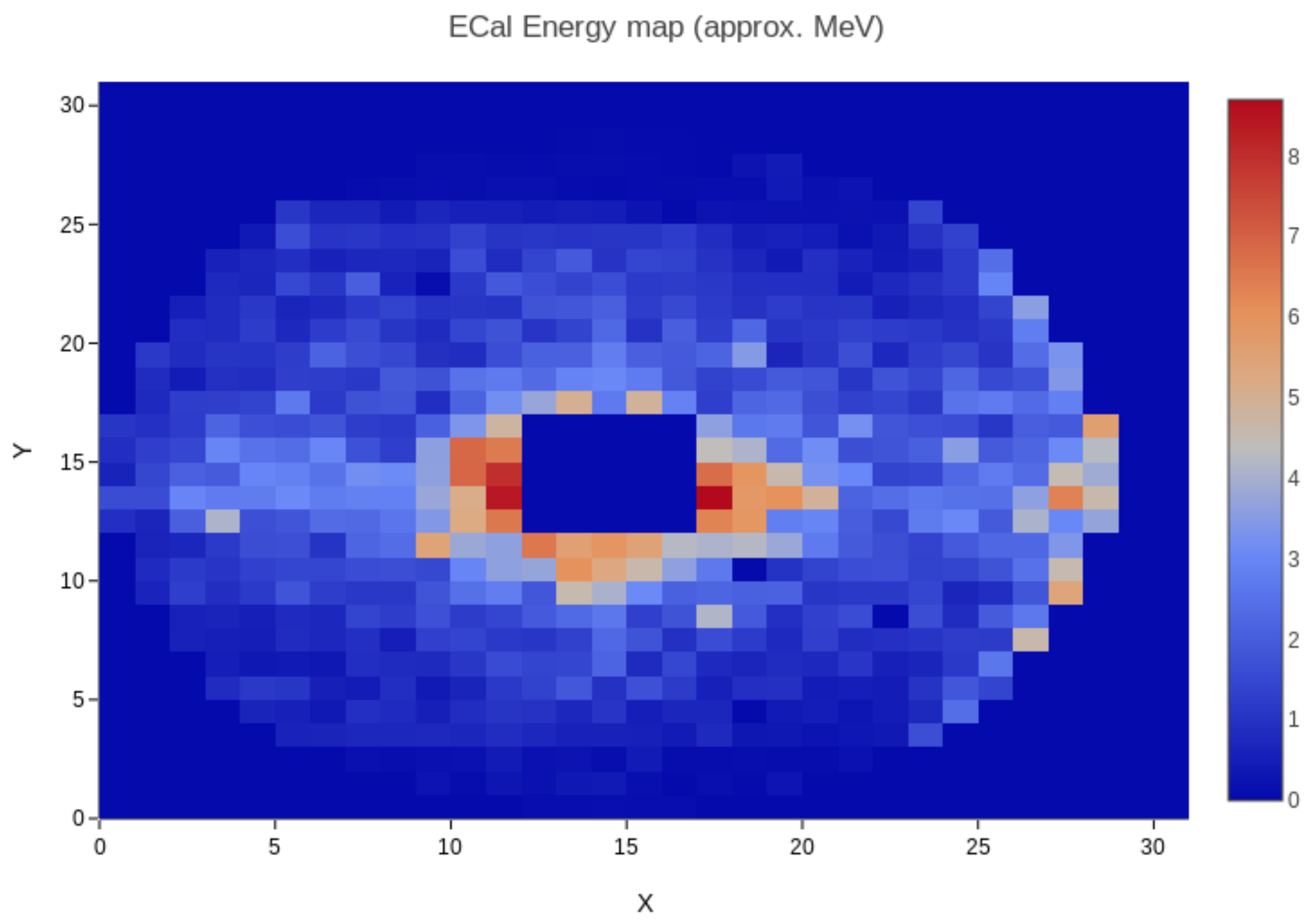
BACKUP SLIDES

PADME

P. Albicocco, F. Bossi, B. Buonomo, R. De Sangro, D. Domenici, G. Finocchiaro, L.G. Foggetta, A. Ghigo, F. Giacchino, P. Gianotti, A. Loreti, I. Sarra, B. Sciascia, T. Spadaro, E. Spiriti, E. Vilucchi, A.P. Caricato, F. Gontad, M. Martino, I. Oceano, F. Oliva, S. Spagnolo, C. Cesarotti, A. Frankenthal, J. Alexander, G. Chiodini, F. Ferrarotto, E. Leonardi, E. Long, F. Safai Tehrani, P. Valente, S. Fiore, G. Georgiev, V. Kozhuharov, B. Liberti, C. Taruggi, G.C.Organtini, G. Piperno, M. Raggi, L. Tsankov, S. Ivanov, S. Ivanov, R. Simeonov

from Venelin Kozhuharov, LDMA 2019





BACKUP SLIDES

Vector Portal: Dark Photon

$$\mathscr{L}_{vector} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mathscr{L}_{portal}$$

Ingredients of Minimal Model:

Vector Portal: Dark Photon

$$\mathscr{L}_{vector} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mathscr{L}_{portal}$$

Ingredients of Minimal Model:

- Dark Sector: SM gauge symmetries + extra gauge symmetry of BSM: $SM \times U(1)'$. As QED, A'_μ is the new gauge field of $U(1)'$ group so-called "dark photon", $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength and the dark matter.

  - If $U(1)'$ is unbroken the dark photon is massless and the dark matter is millicharged $|Q_\chi| = |\epsilon g_D e|$ [JHEP**0703**(2007)120].

  - If $U(1)'$ is broken by a Higgs-like mechanism, the dark photon acquires mass and the Lagrangian of the dark sector is

$\mathscr{L}_{DS} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2}m^2_{A'}(A'_\mu)^2 + \bar{\chi}(i\not{D} - M_\chi)\chi$ **(fermionic DM) or** $+ (D^\mu\phi)^*(D_\mu\phi) - m^2_\phi|\phi|^2$ **(scalar DM)**

with $D_\mu = \partial_\mu - ig_D A'_\mu$.

Vector Portal: Dark Photon

$$\mathscr{L}_{vector} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mathscr{L}_{portal}$$

Ingredients of Minimal Model:

- Dark Sector: SM gauge symmetries + extra gauge symmetry of BSM: $SM \times U(1)'$. As QED, A'_μ is the new gauge field of $U(1)'$ group so-called "dark photon", $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength and the dark matter.

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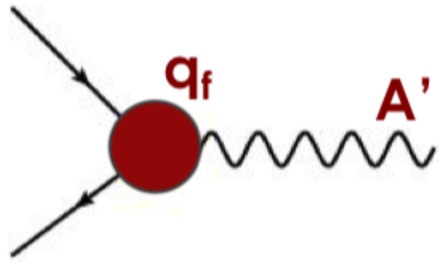
with $D_\mu = \partial_\mu - ig_D A'_\mu$.

- Portal: The Portal between visible and invisible sector is allowed by a kinetic mixing term (B. Holdom Phys.Lett. B166 (1986) 196) between the QED photon and the dark photon (after the EW symmetry breaking):

$$\mathscr{L}_{portal} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

Here ϵ is a new dimensionless parameter and represents the kinetic mixing between the dark-photon and pairs of charged SM particles $\epsilon e A'_\mu J^\mu_{em}$



Millicharged DP

$$\begin{pmatrix} A_\mu^{\gamma'} \\ A_\mu^{\gamma} \\ Z_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_\epsilon) & \sin(\theta_\epsilon) \\ 0 & -\sin(\theta_\epsilon) & \cos(\theta_\epsilon) \end{pmatrix} \begin{pmatrix} 1 & \epsilon & 0 \\ 0 & \sqrt{1-\epsilon^2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} B'_\mu \\ B_\mu \\ W^3_\mu \end{pmatrix}$$

$$\partial_\mu + igT_3W_{3\mu} + ig_Y\frac{Y}{2}B_{Y\mu} + ig'Q'B'_\mu$$

$$\begin{aligned} D_\mu = \partial_\mu \; & + \; ig(T^1W^1_\mu + T^2W^2_\mu) \\ & + \; iA^\gamma_\mu\left(\frac{eQ\cos(\theta_\epsilon)}{\cos\theta_W\sqrt{1-\epsilon^2}} - \frac{g'Q'\epsilon\cos\theta_\epsilon}{\sqrt{1-\epsilon^2}}\right) \\ & + \; iZ_\mu\left(gT^3\cos\theta_\epsilon - g_Y\frac{Y}{2}\frac{\sin\theta_\epsilon}{\sqrt{1-\epsilon^2}} + \frac{g'Q'\epsilon\sin\theta_\epsilon}{\sqrt{1-\epsilon^2}}\right) \\ & + \; iA^{\gamma'}_\mu g'Q', \end{aligned}$$

Q' couples to the photon field A_μ with charge

$$Q_{em} = (Q_{SM} - g'Q'\,\epsilon/g_Y)e' \text{ with } e' = g_Y\cos\theta_\epsilon/\sqrt{1-\epsilon^2}$$

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TWO U(1)'S AND ϵ CHARGE SHIFTS

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If new particles are gauged by a new U(1) then their electromagnetic charges may be shifted by a calculable amount.

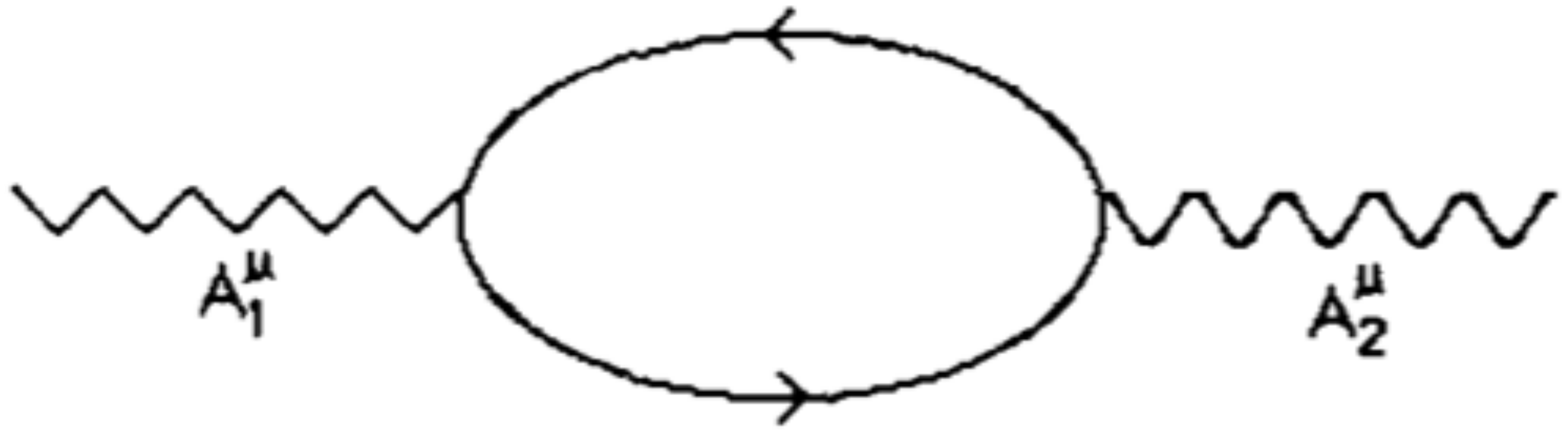
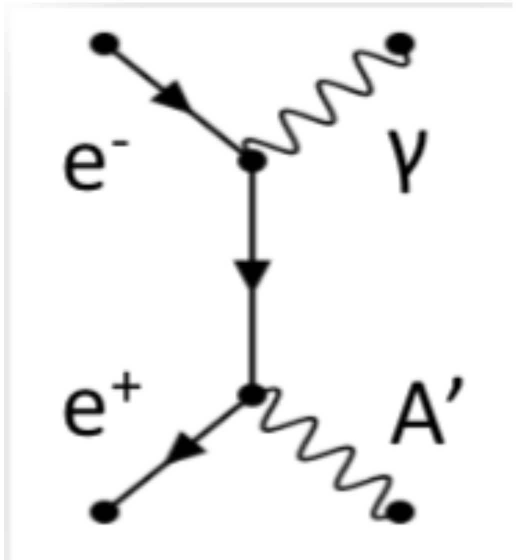


Fig. 1.

Here ε is a priori a free parameter, though it often arises from loops of heavy states charged under both groups, so it is generically expected to be small, $\varepsilon \sim 10^{-3}$ or smaller.

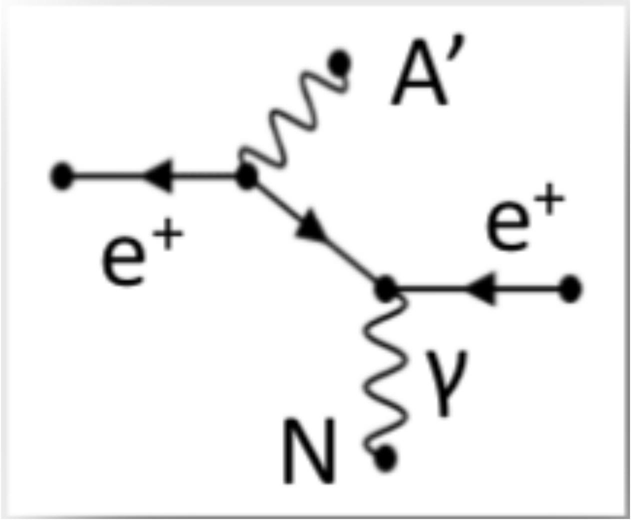
DARK PHOTON PRODUCTION IN e+ AND e- PROCESSES:

- ANNIHILATION: $e^+e^- \rightarrow \gamma A'$



✓

- BREMSSTRAHLUNG: $e^-Z \rightarrow e^-ZA'$



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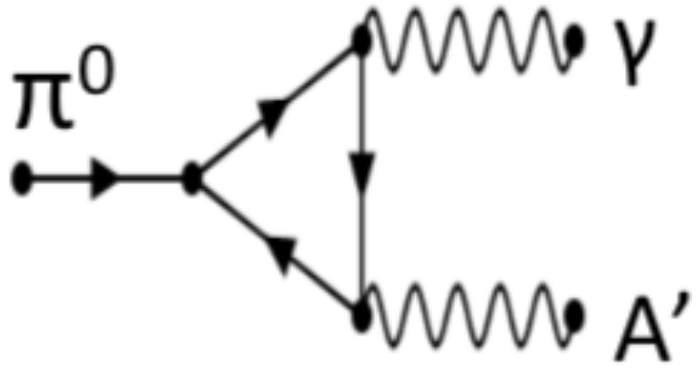
- MESON DECAY: $\pi^0/\eta/\eta' \rightarrow \gamma A'$

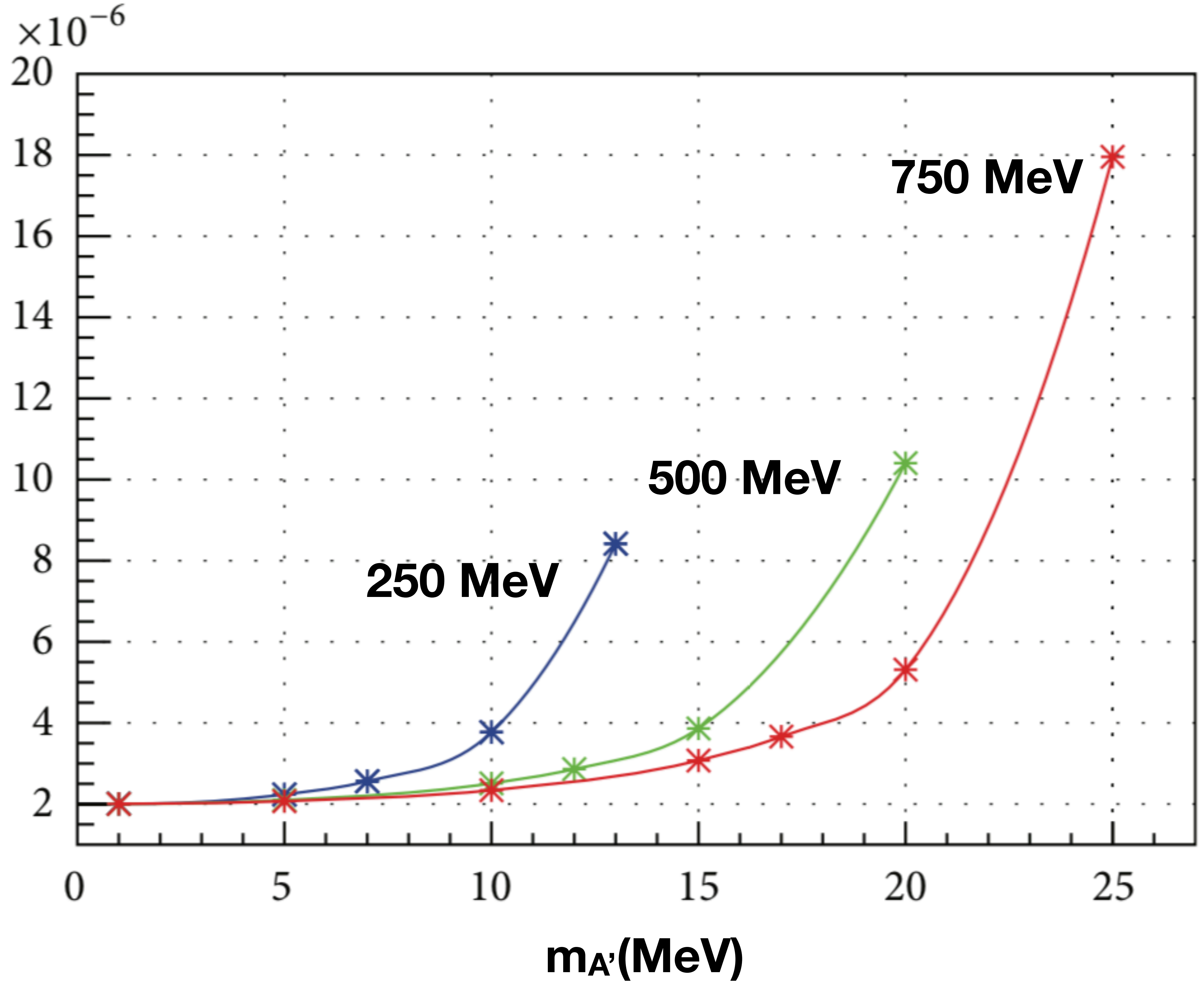


✗

Dark Photon in PADME

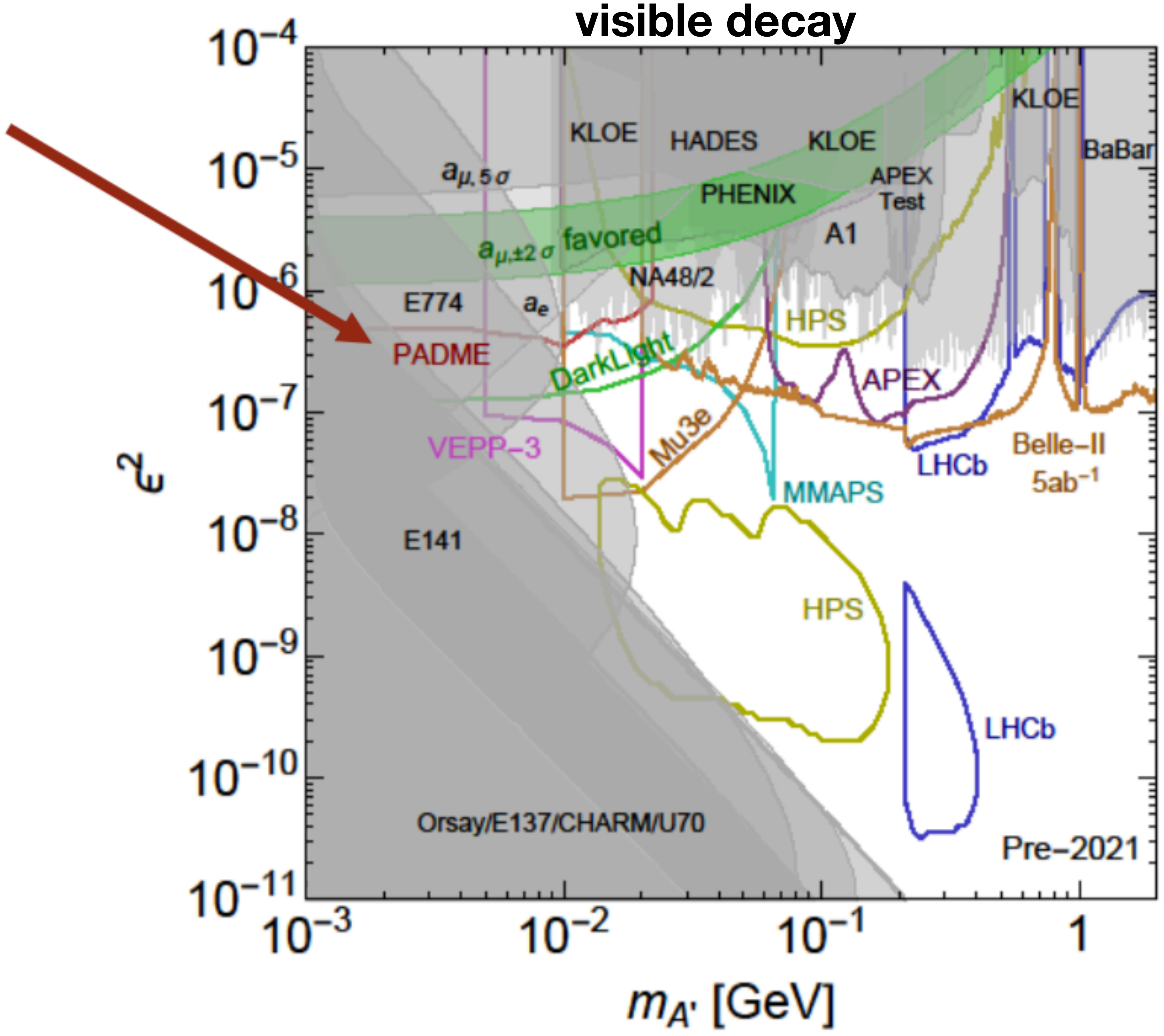
$$\frac{\sigma(e^+e^- \to A'\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \epsilon^2\delta$$

Cross-section enhancement with the approach of the production threshold

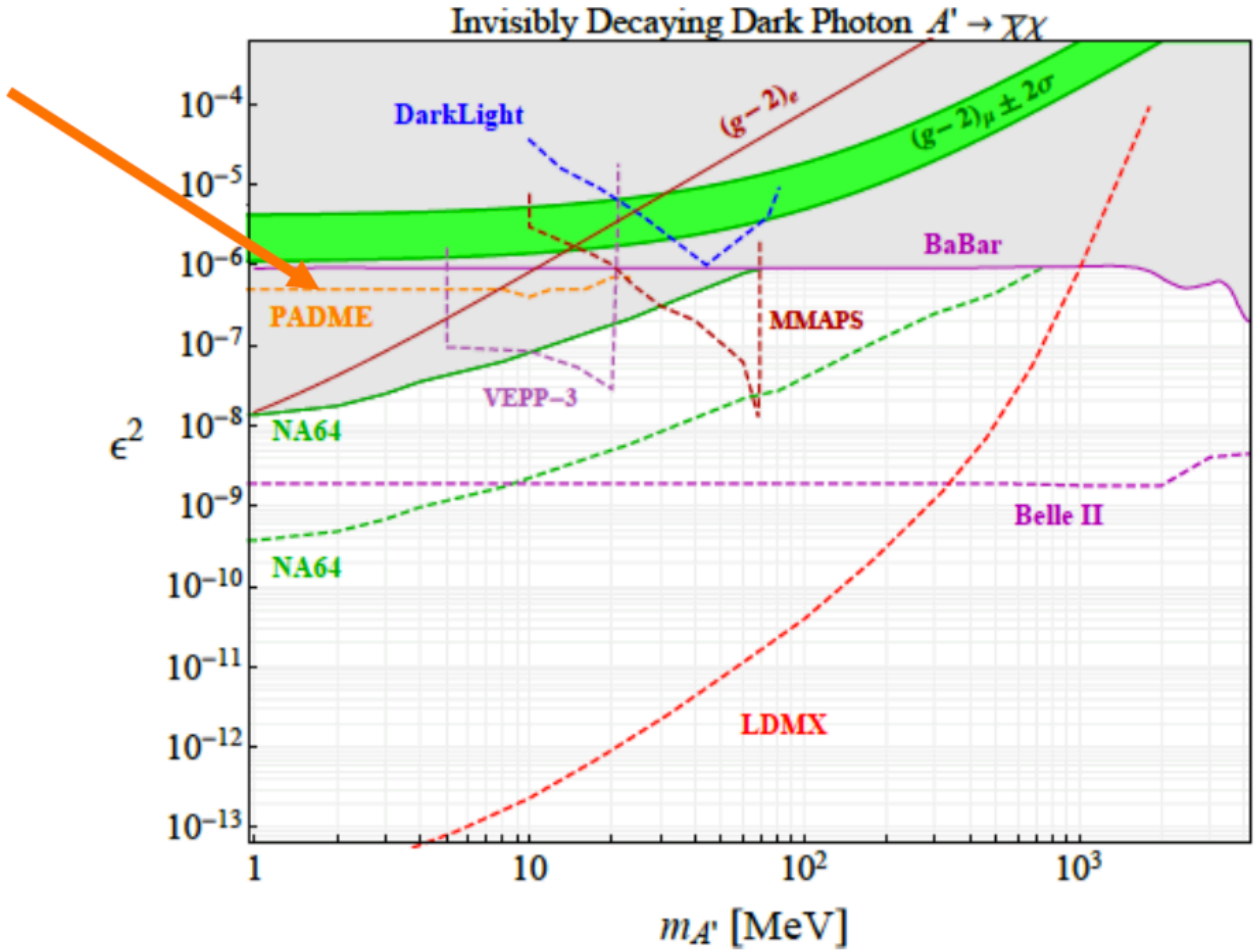


Dark Photon in PADME

visible decay



$g_D=0.5$
$m_{A'}=3m_X$



$e^+e^- \to a + \gamma$ in PADME

$$\sigma = \alpha\, g^2_{a\gamma\gamma} \frac{(s+2m_e^2)(s-m_a^2)^3}{24\,\beta\, s^4} + \alpha\, g^2_{aee} m_e^2 \frac{-2m_a^2\,\beta\, s + (s^2 + m_a^4 - 4m_a^2 m_e^2)\log\frac{1+\beta}{1-\beta}}{2(s-m_a^2)s^2\beta^2}$$

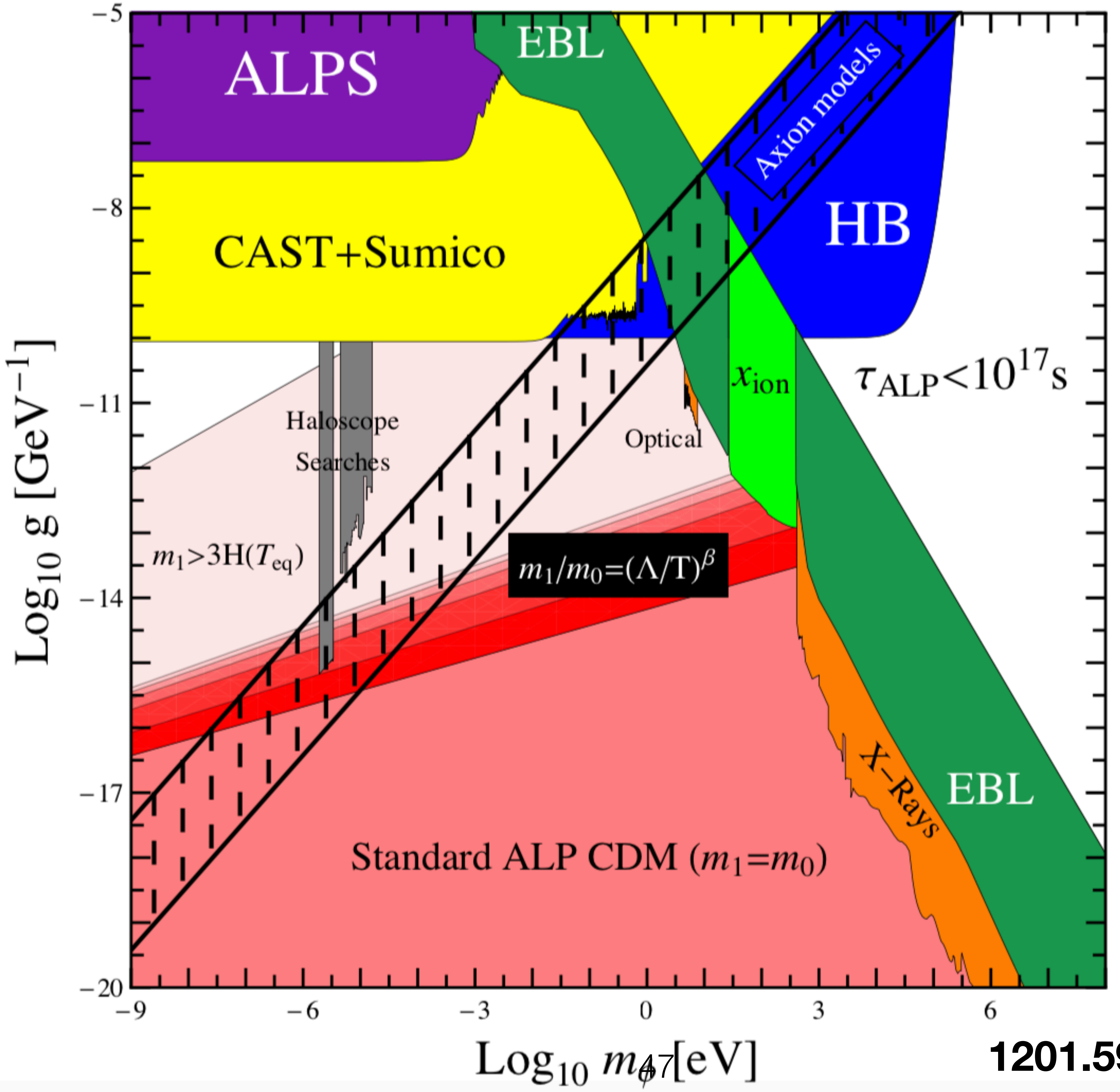
$$+\ \alpha\, g_{a\gamma\gamma}\, g_{aee}\, m_e^2 \frac{(s-m_a^2)^2}{2\,\beta^2\, s^3} \log\frac{1+\beta}{1-\beta}$$

with $\beta = \sqrt{1 - \frac{4m_e^2}{s}}$.

Haloscopes: exploiting their coupling to photons utilizing microwave cavities. A resonator convert axion in photons resonant at the frequency corresponding to the energy of the produced photons. Since the energy of outgoing photons is equal to the energy of the incoming axions, the natural window is in the 1-100 μeV.

Light-shining-through-walls experiment: strong magnetic fields are used to induce photon-ALP oscillations in incoming laser light

Helioscopes: same of light-shining-through-wall experiments but searching for solar ALPs or HPs. So they exploit the photons interactions the electromagnetic fields of electrons and ions in the plasma



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