Axion-Like particle as Light Dark Matter Portal

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

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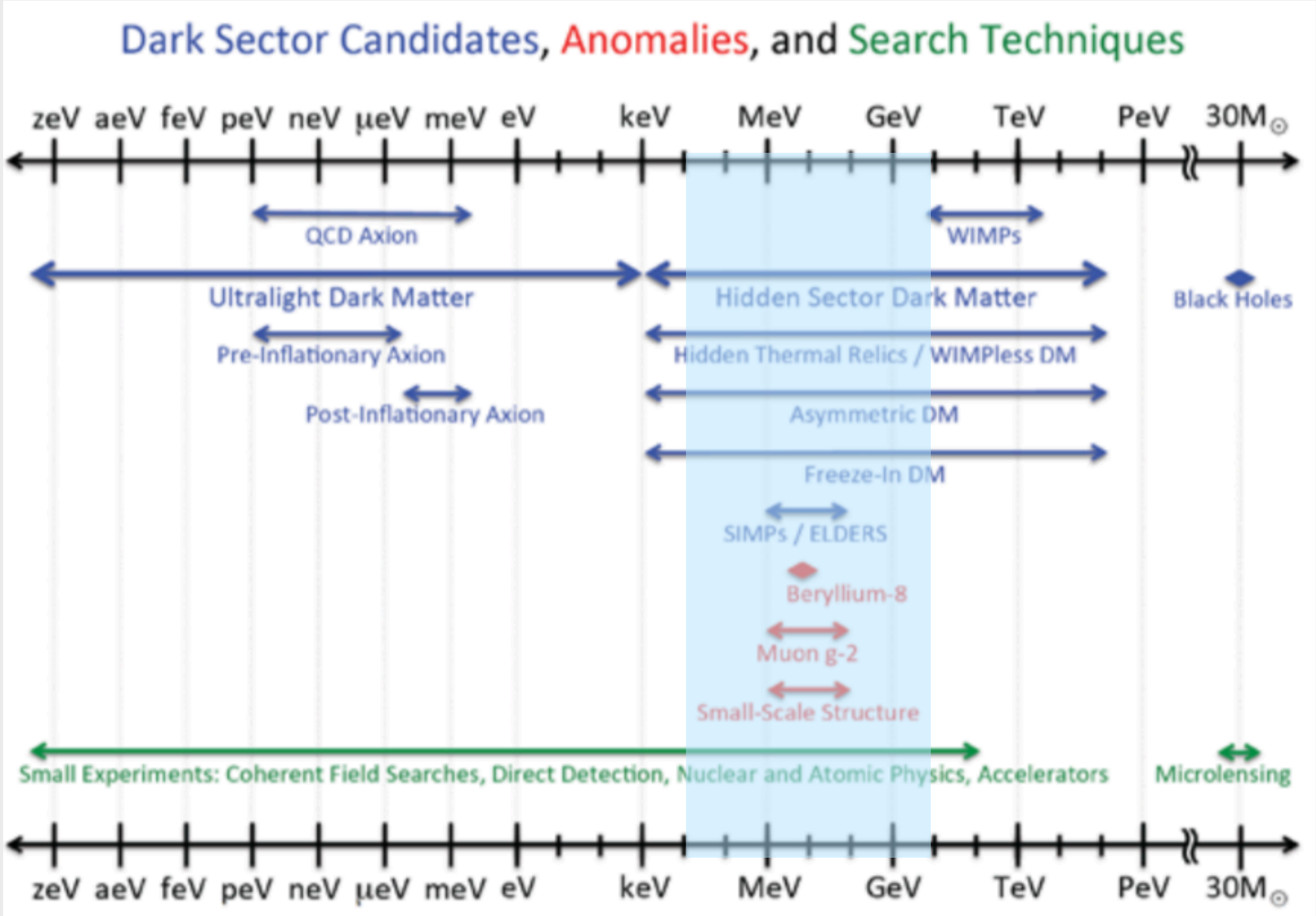

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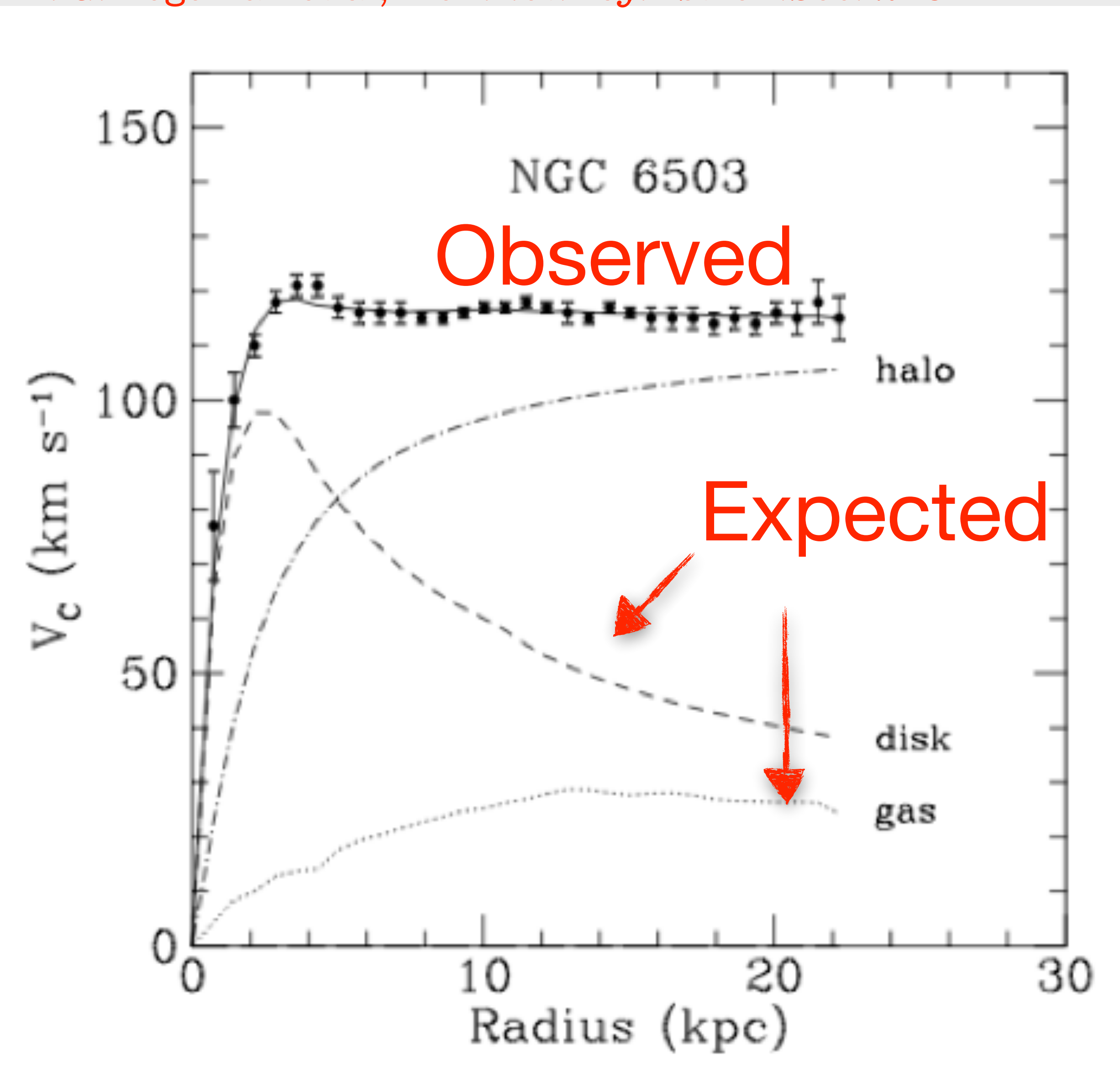
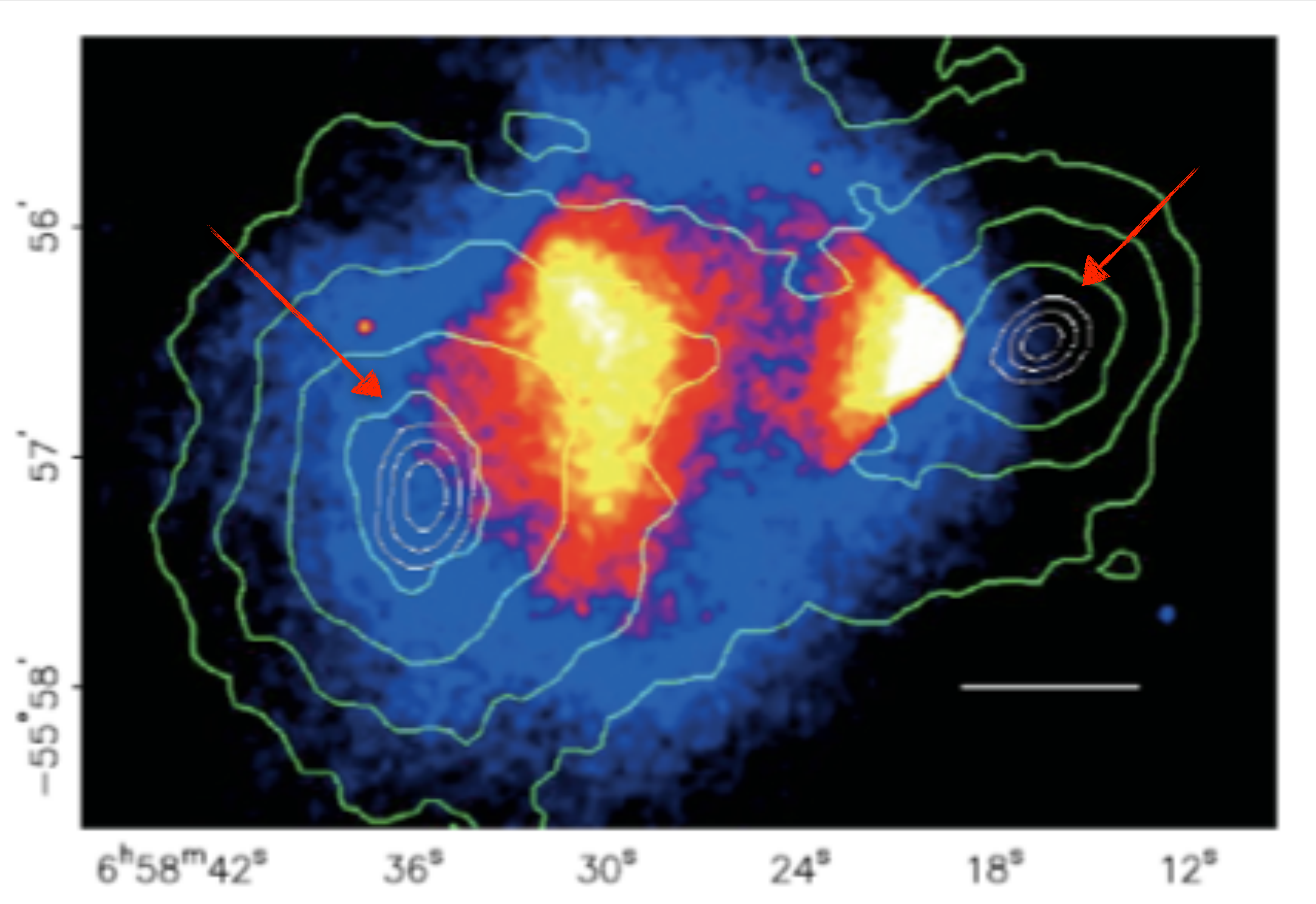
DARK MATTER INTRO

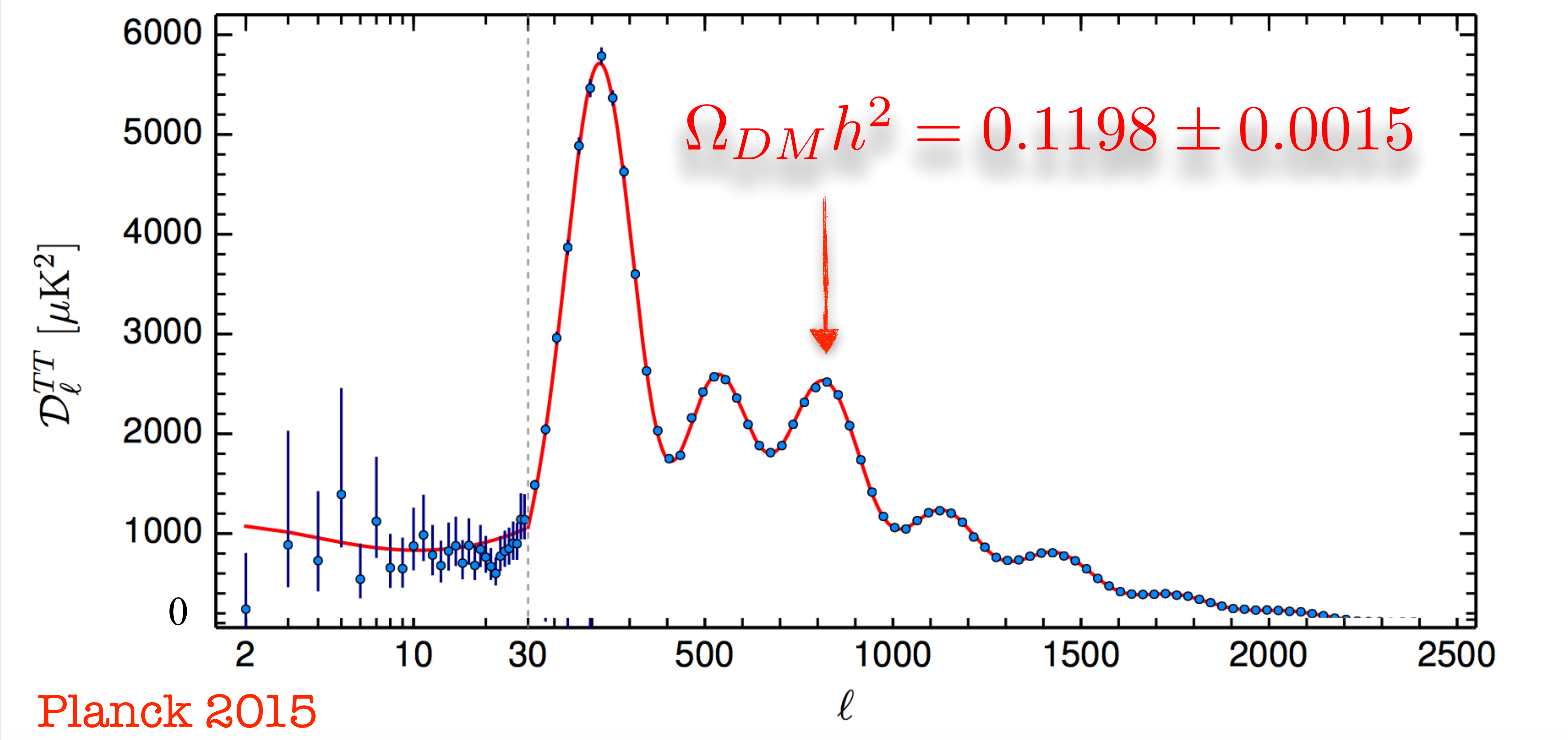
K. G. Begeman et al, Mon.Not.Roy.Astron.Soc. 249



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



Clowe et al, ApJ 648:L109,2006



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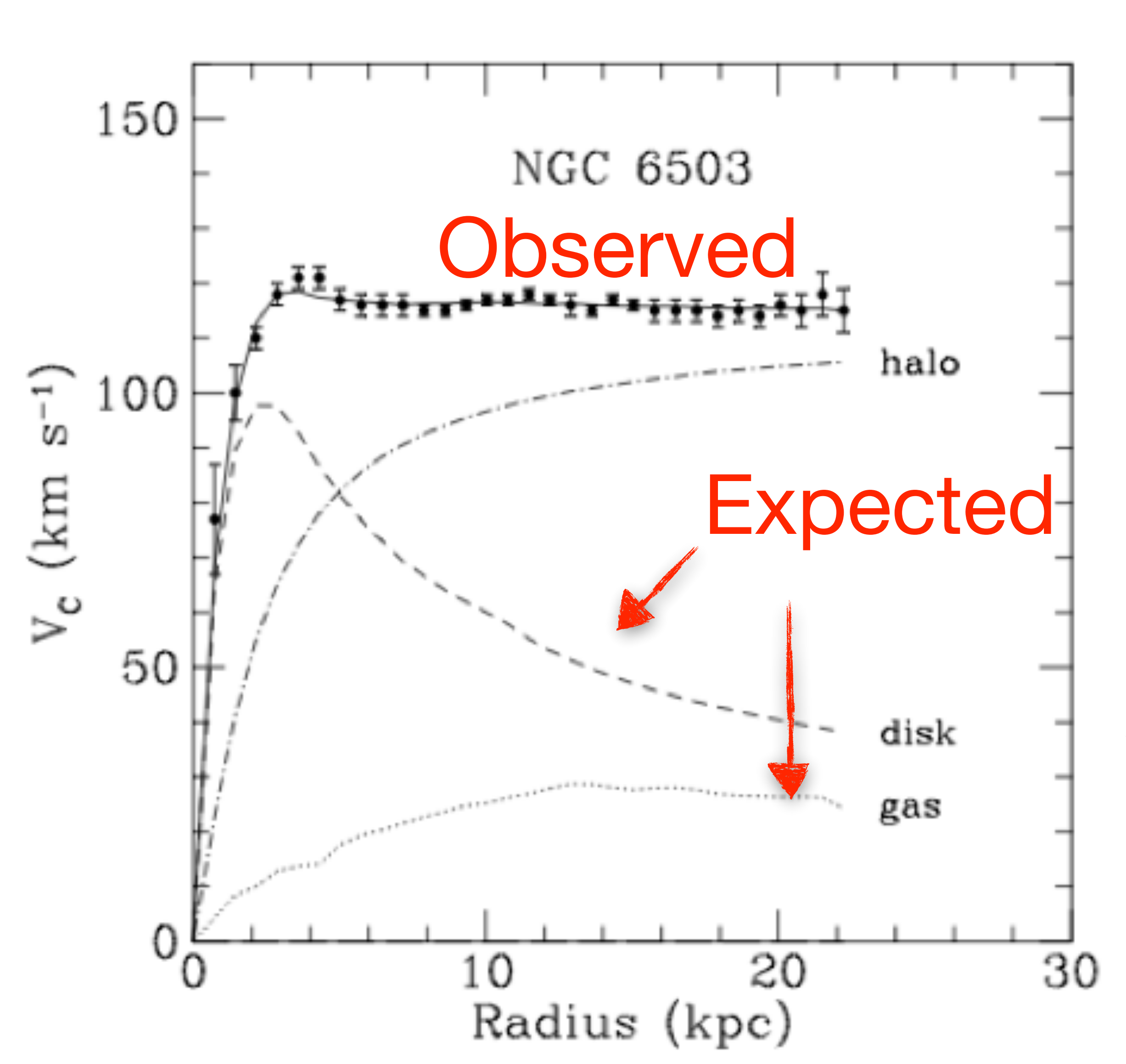

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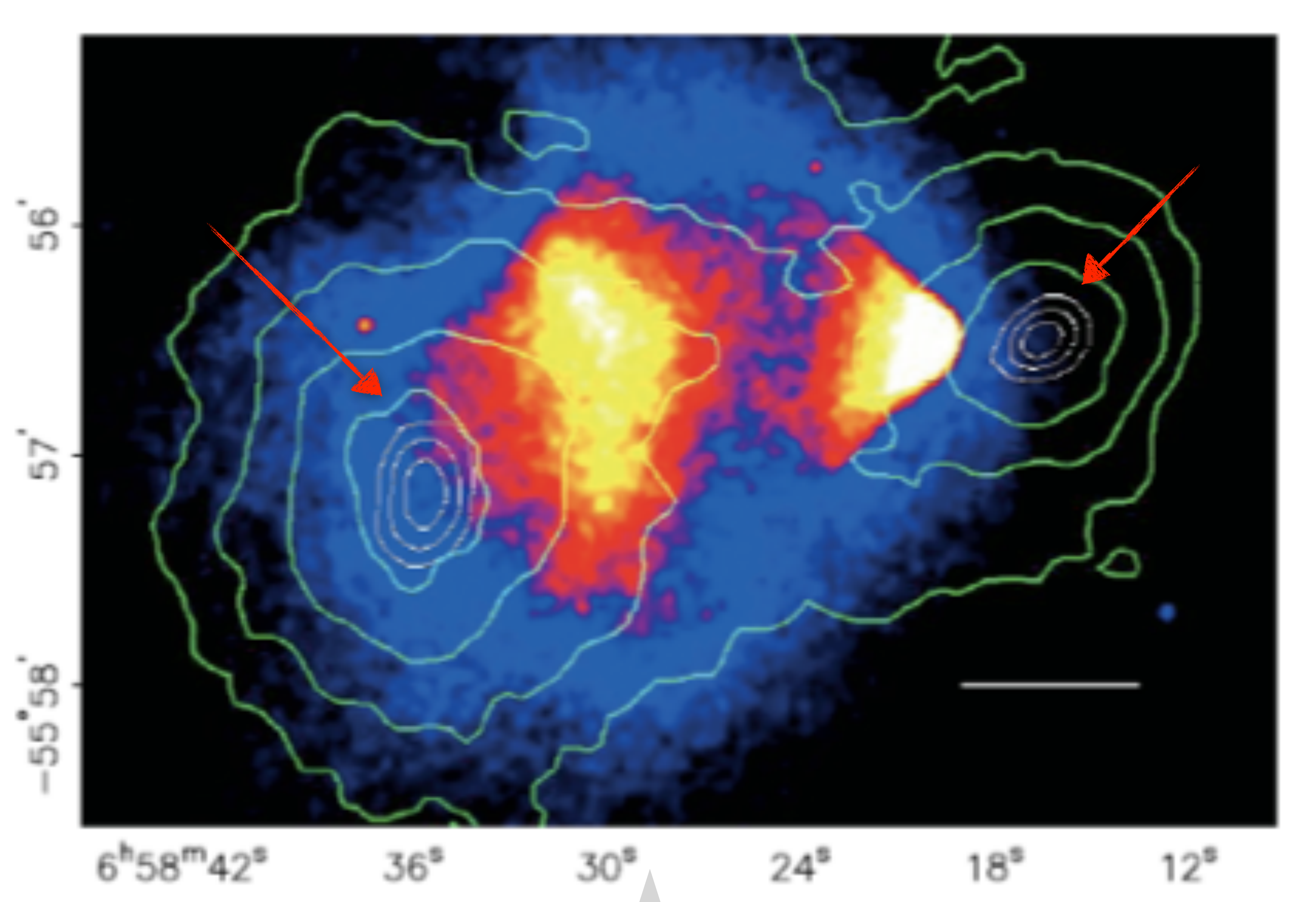

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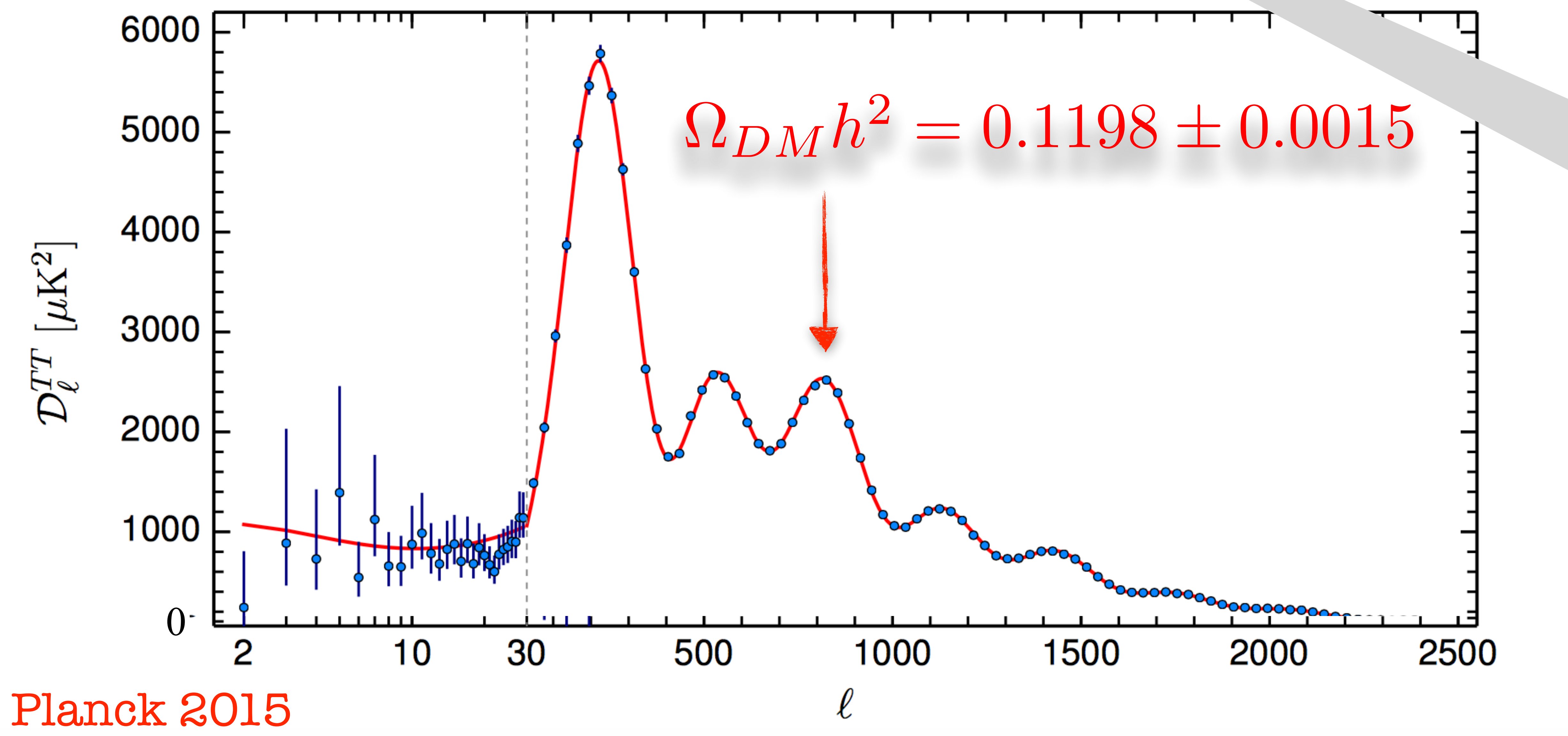


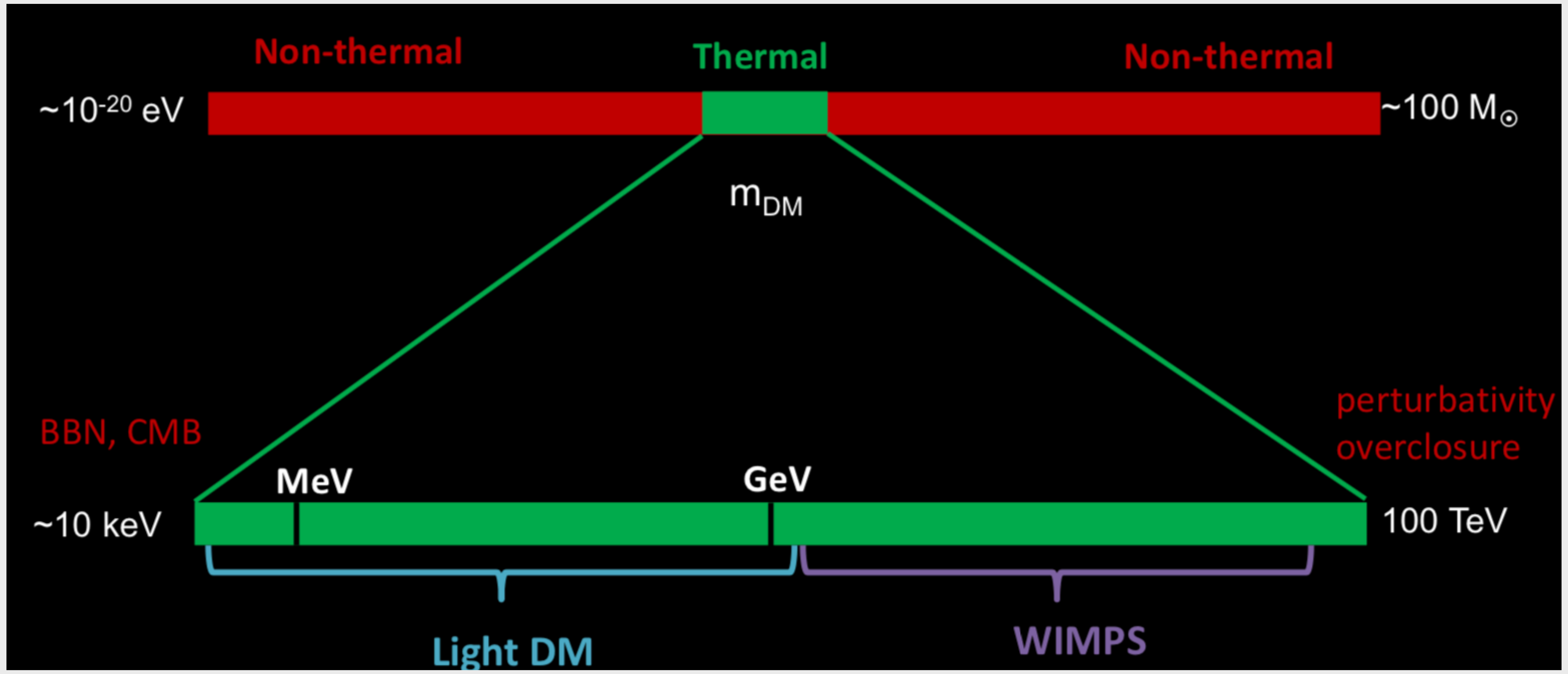
Planck 2015

PROPERTIES
ITS RELIC ABUNDANCE

OPEN QUESTIONS:

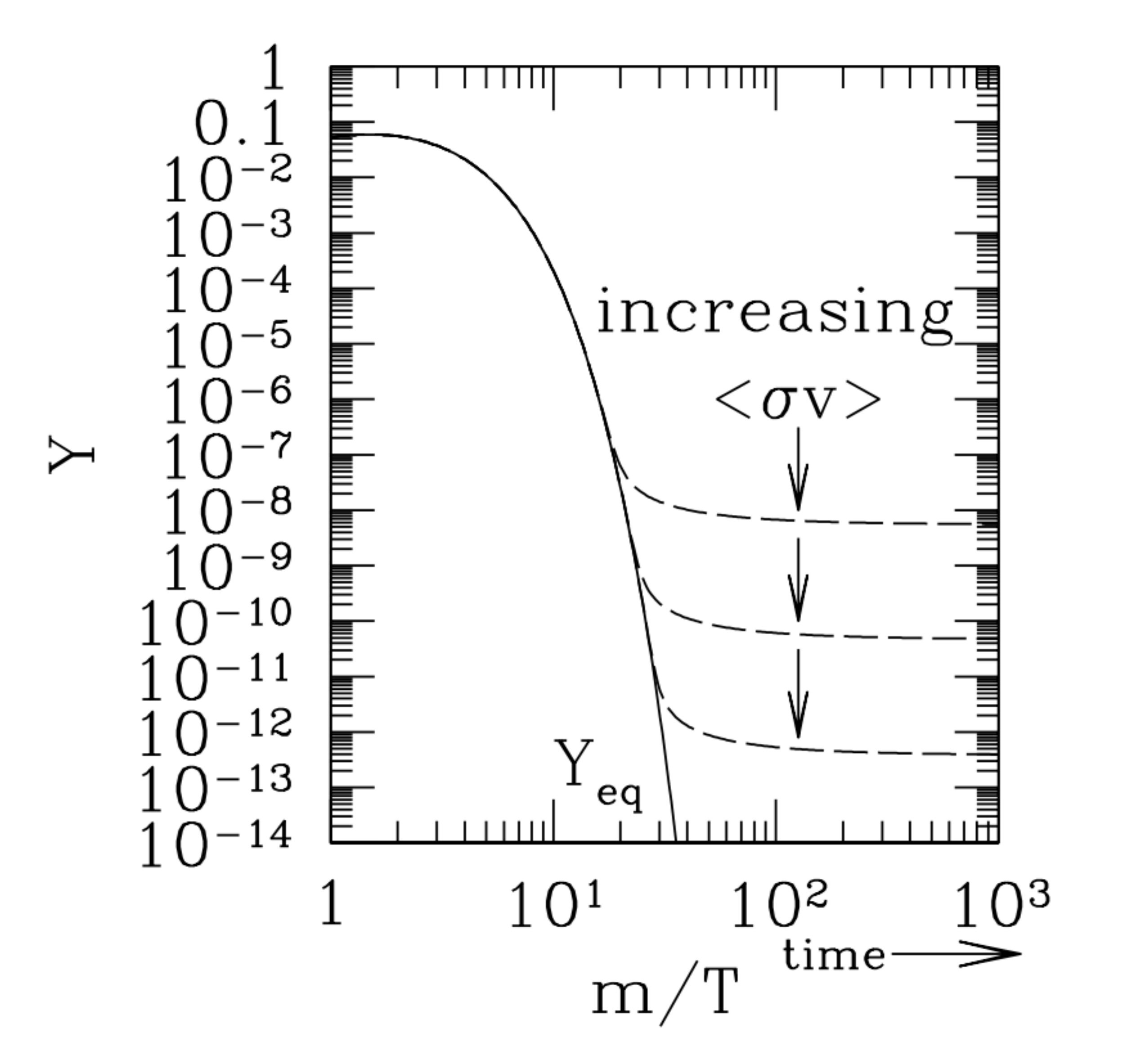
- WHAT IS THE DARK MATTER?
- INTERACTION WITH THE STANDARD MODEL?
- HOW IS THE OBSERVED RELIC ABUNDANCE PRODUCED?
- JUST ONE PARTICLE OR AN ENTIRE DARK SECTOR?
- IS IT A PARTICLE?

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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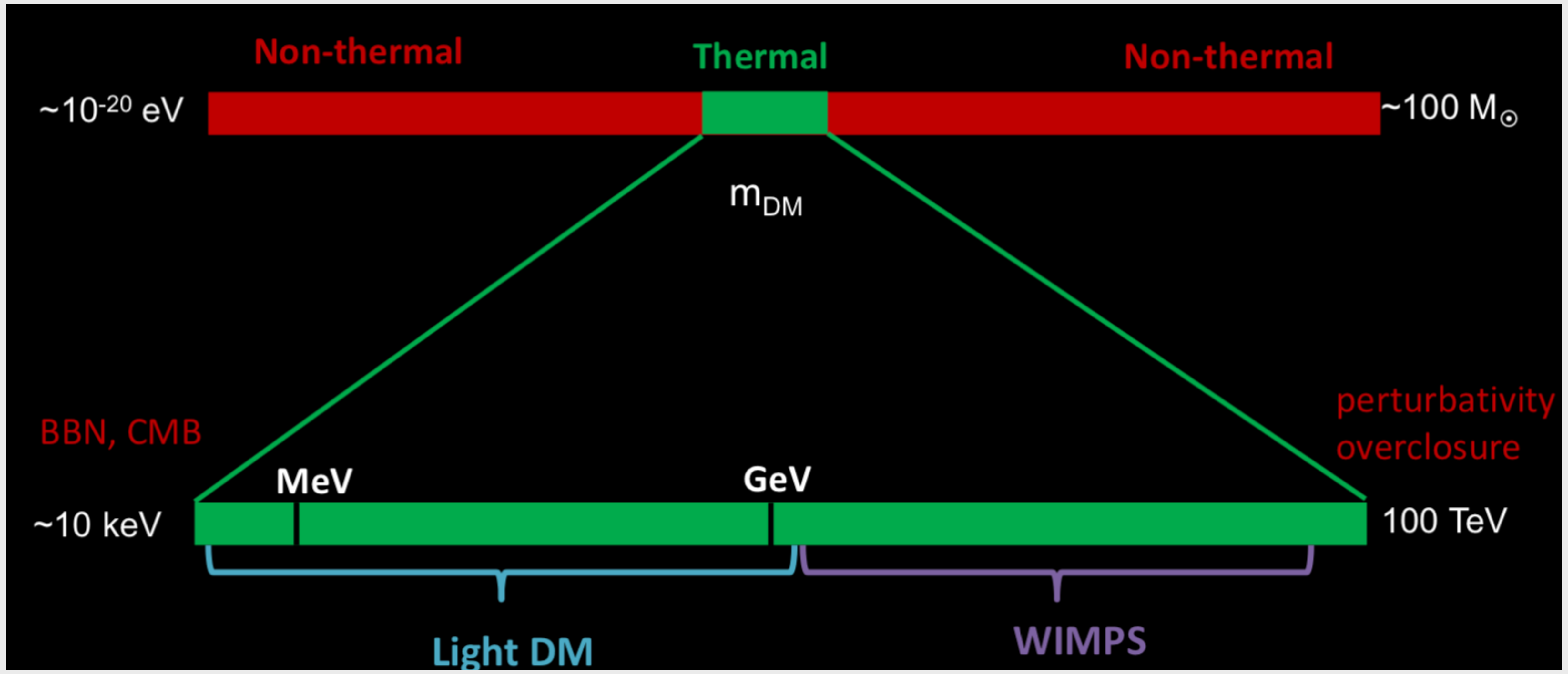
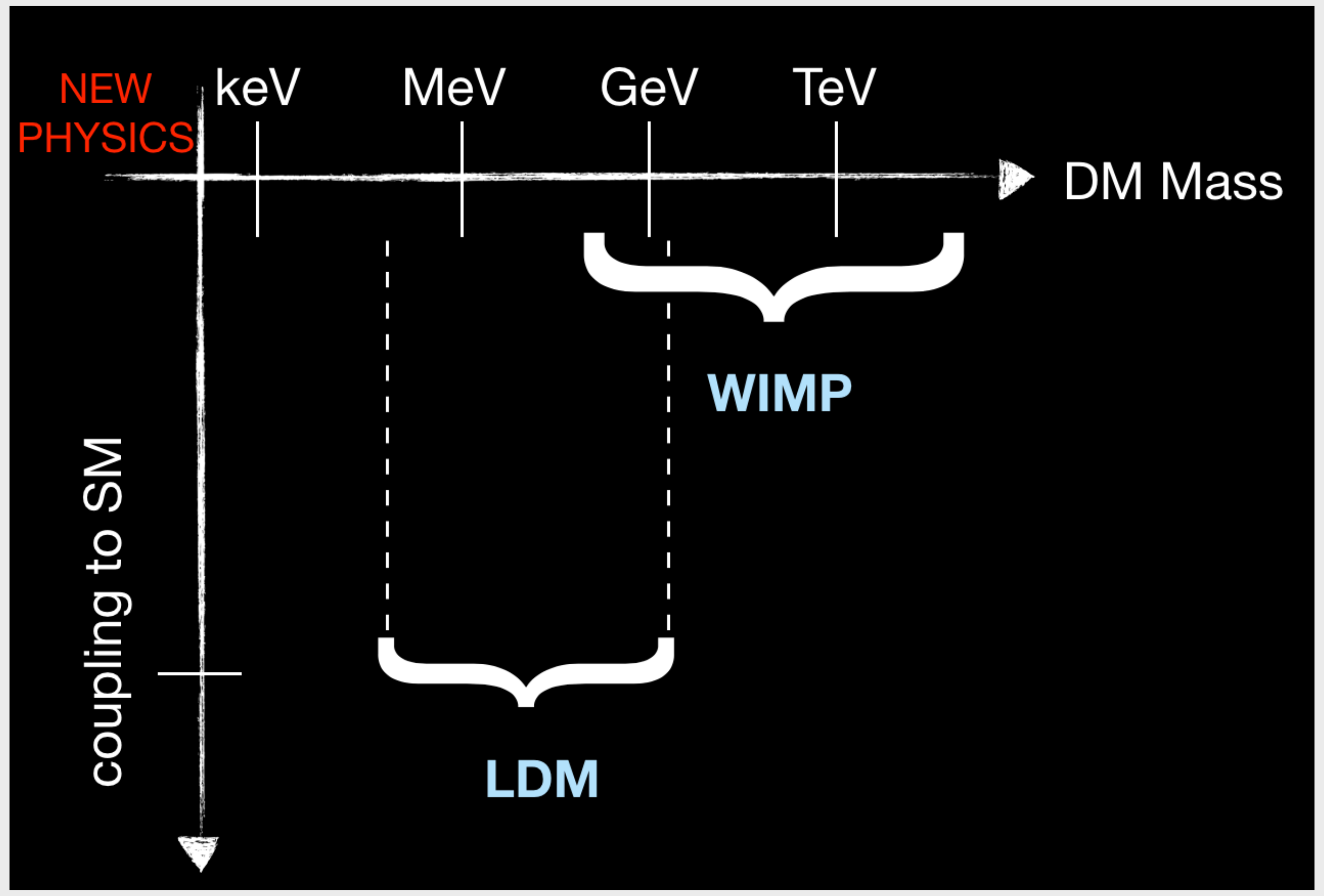


- Weakly Interactive Massive Particle (WIMP):

  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.

- Light Dark Matter:

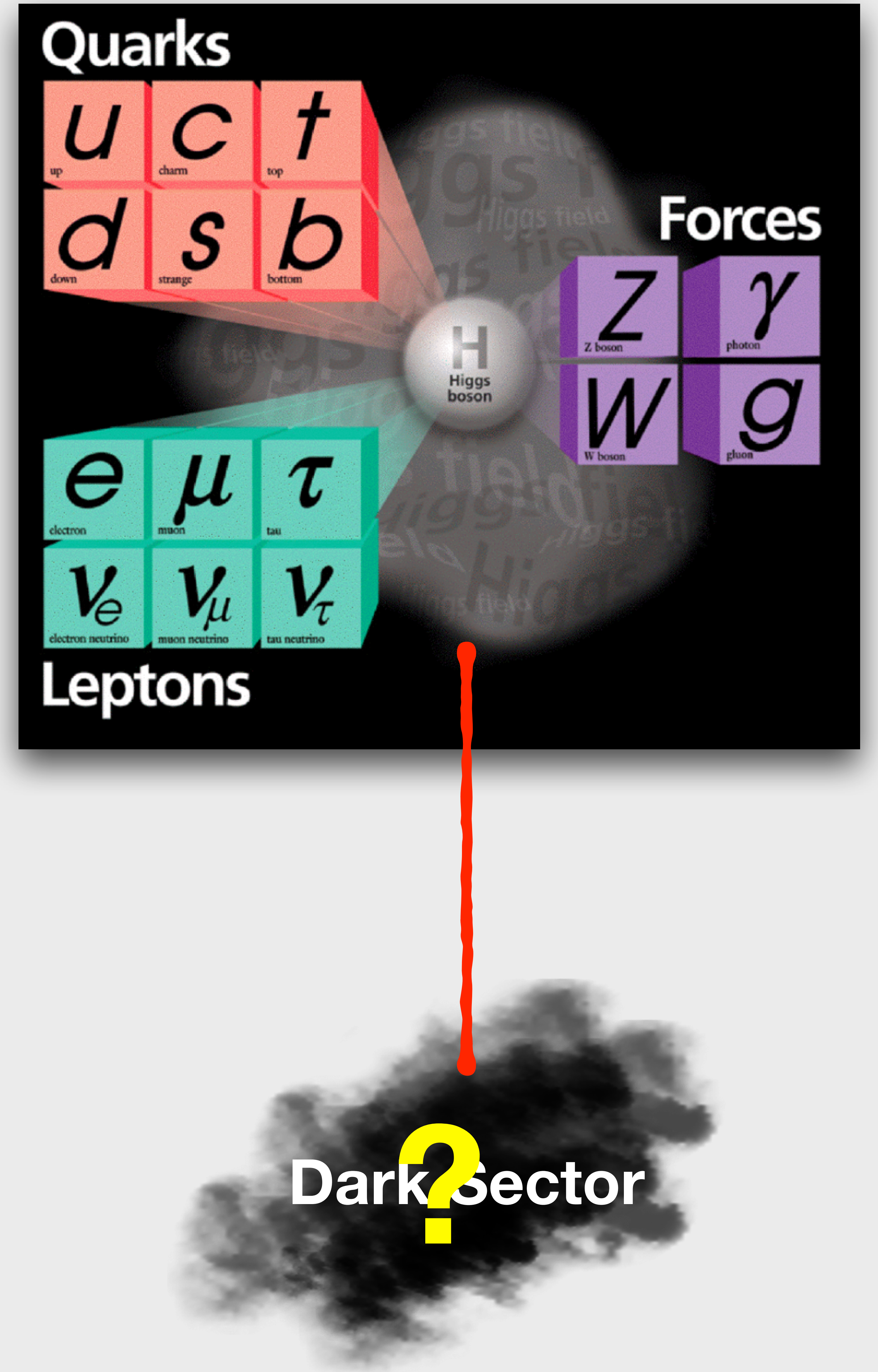
  subGeV masses with very feeble couplings -> *hidden-sector*



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
Dark Photon, A'_μ	$-\frac{\epsilon}{cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
→ Axion-like Particle, a	$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$ $g_{a\psi\psi}\partial_\mu a\bar{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$

$B_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu$ SM hypercharge field strength

$\tilde{F}_{\mu\nu}$ is the dual of $F_{\mu\nu}$

L is a lepton doublet $(1,2,-\frac{1}{2})$

H is the SM Higgs boson $(1,2,+\frac{1}{2})$

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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Ingredients of Minimal Model:

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

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Ingredients of Minimal Model:

- **Dark Sector**: SM gauge symmetries + extra continuous global symmetry $\longrightarrow$ a light, pseudo-scalar particle and derivative coupling with SM particles can be produced: the axion-like particle ALP is a pNGB.

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

- **Portal**: The Portal between visible and invisible sector is allowed by an interaction with photon $\mathscr{L}_{portal} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$ or/and with SM fermions $\mathscr{L}_{portal} = g_{a\psi\psi} \partial_{\mu} a \bar{\psi} \gamma_{\mu} \gamma_5 \psi \to m_e g_{aee} a \bar{\psi} \gamma_5 \psi$.

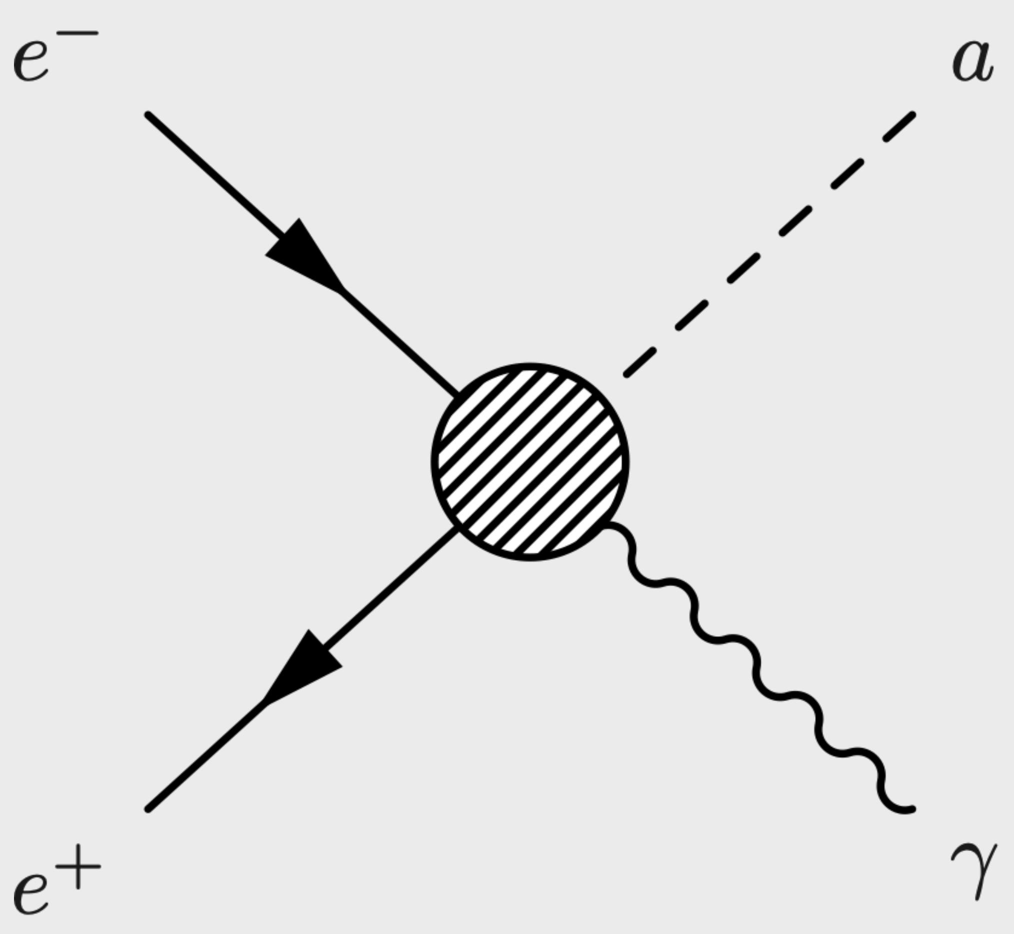
Axion-like Particle Production at accelerators

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

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

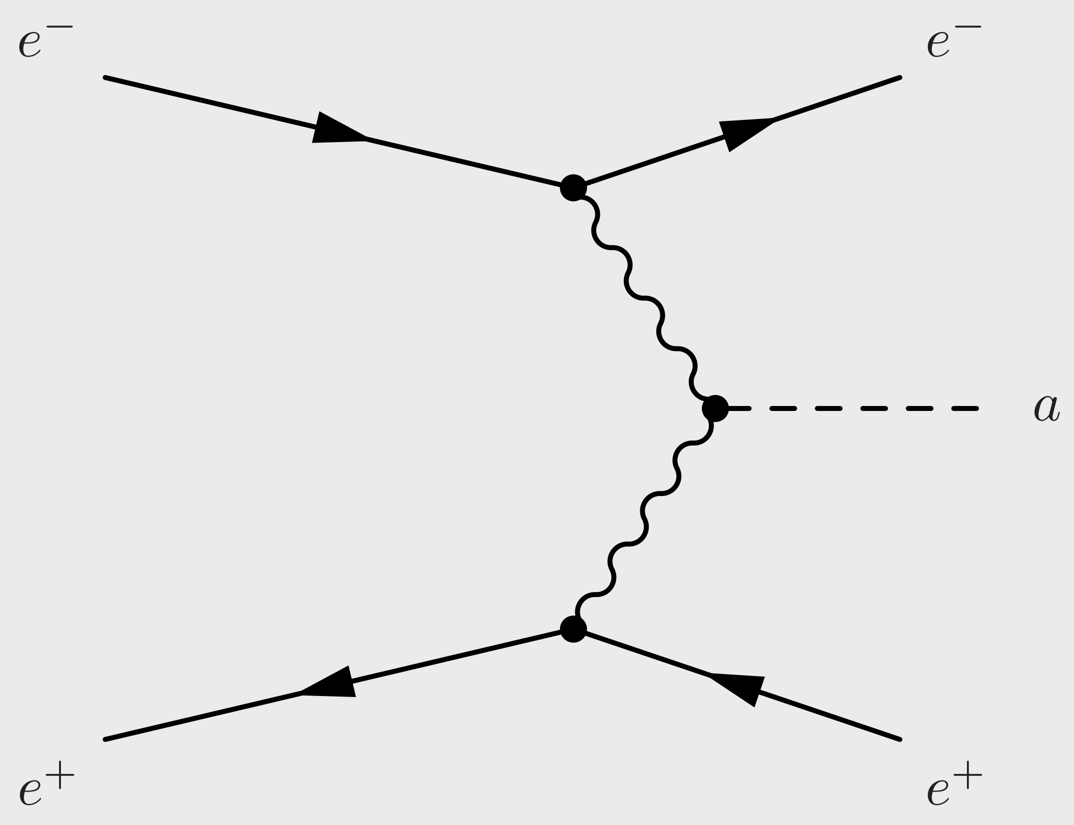
Lepton beam/Collider, e.g. Belle II,…

Annihilation



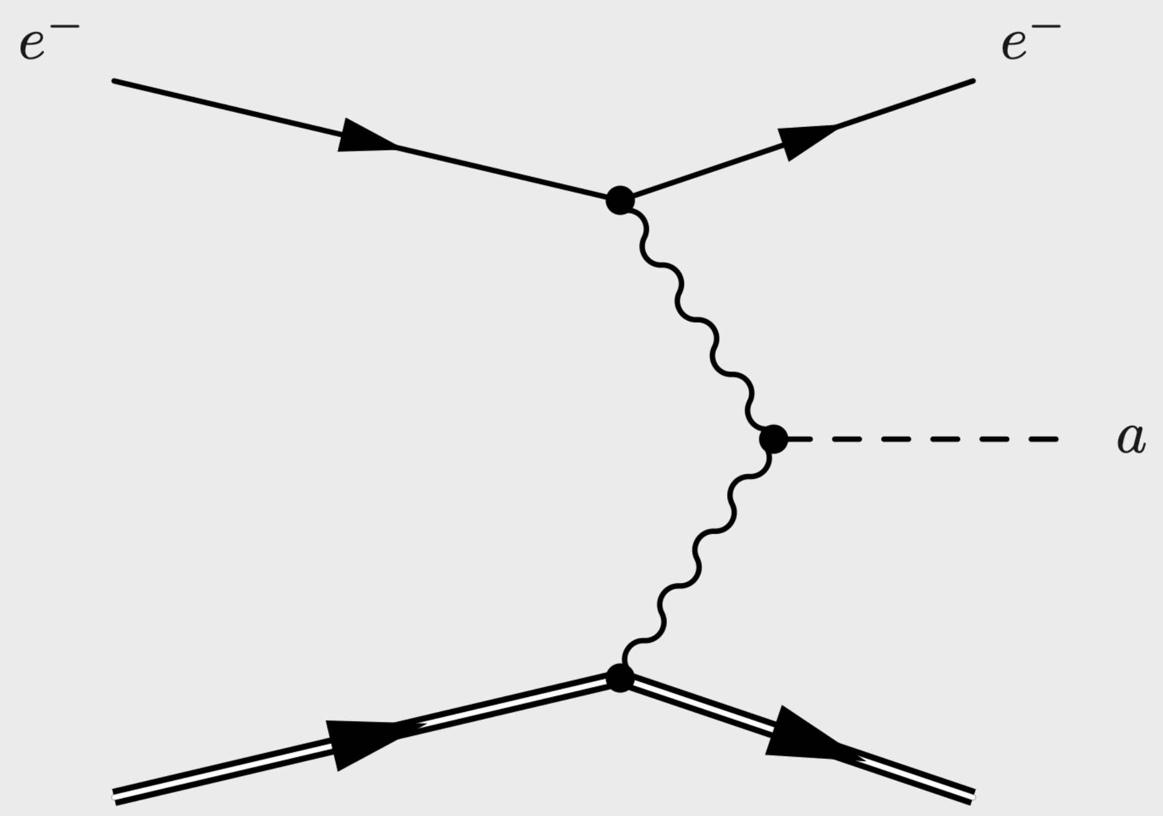
$e^+e^- \to \gamma + a$

Photon Fusion



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

Primakoff effect



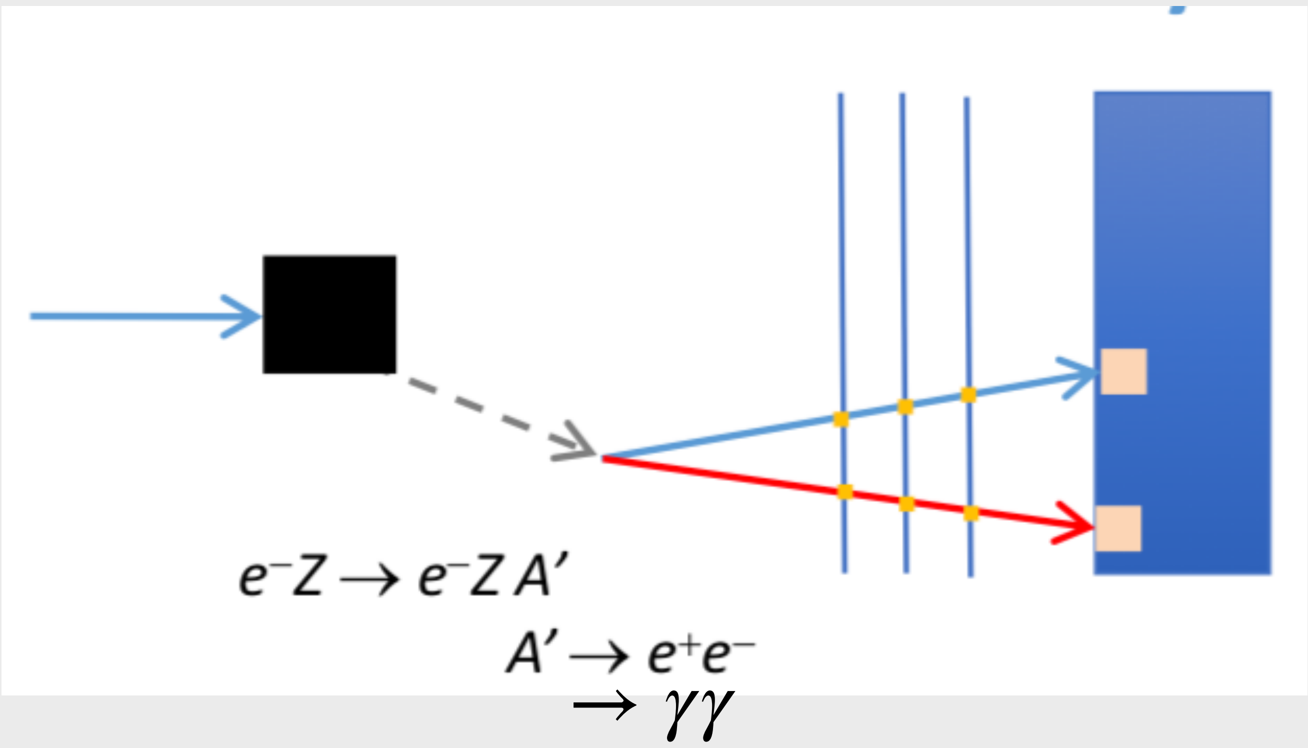
$e^-Z \to e^-Z + a$

TWO POSSIBLE SIGNATURE FOR ALP IN ACCELERATOR:

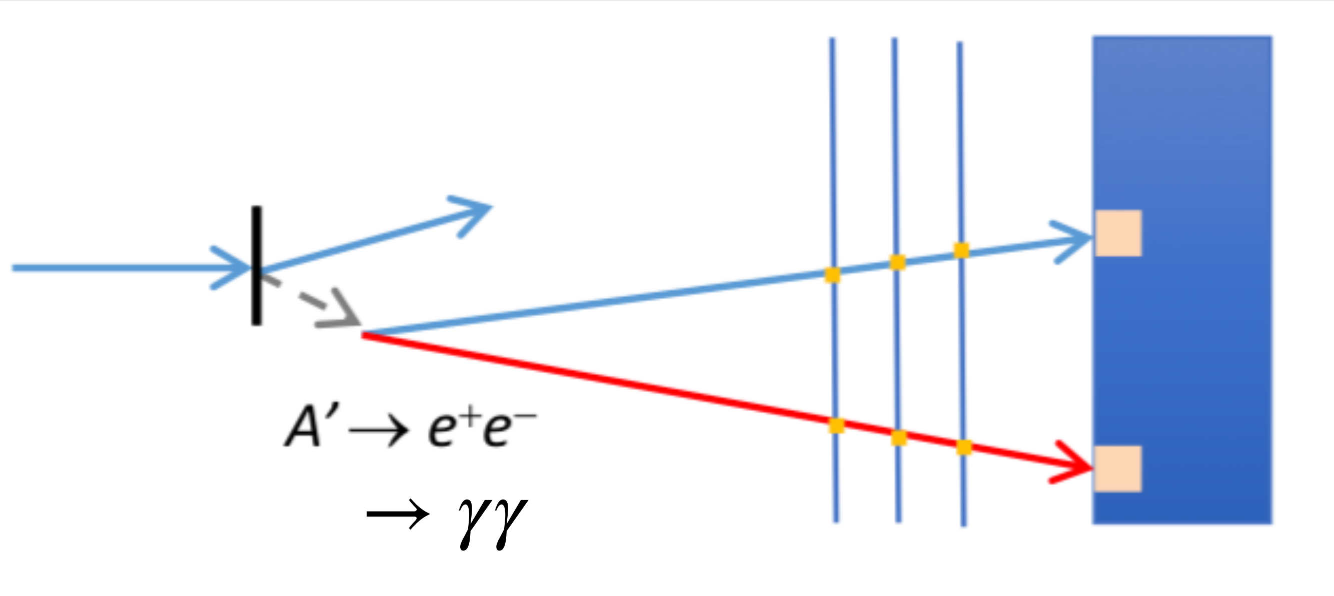
VISIBLE: if $m_a/2 < M_\chi$, $a \to SM\, SM$

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)

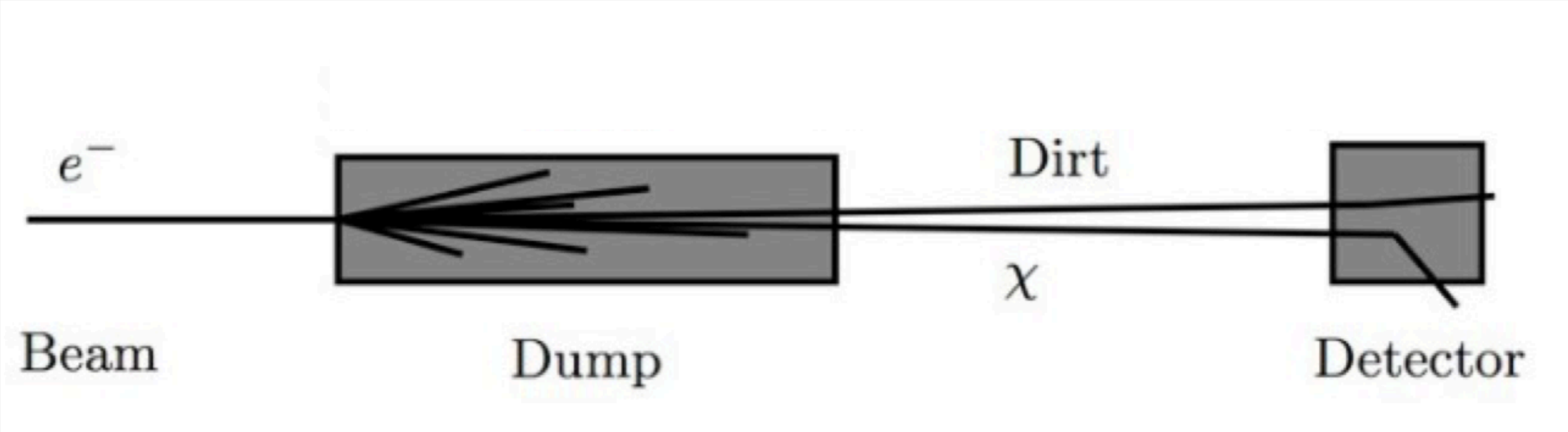


TWO POSSIBLE SIGNATURE FOR ALP IN ACCELERATOR:

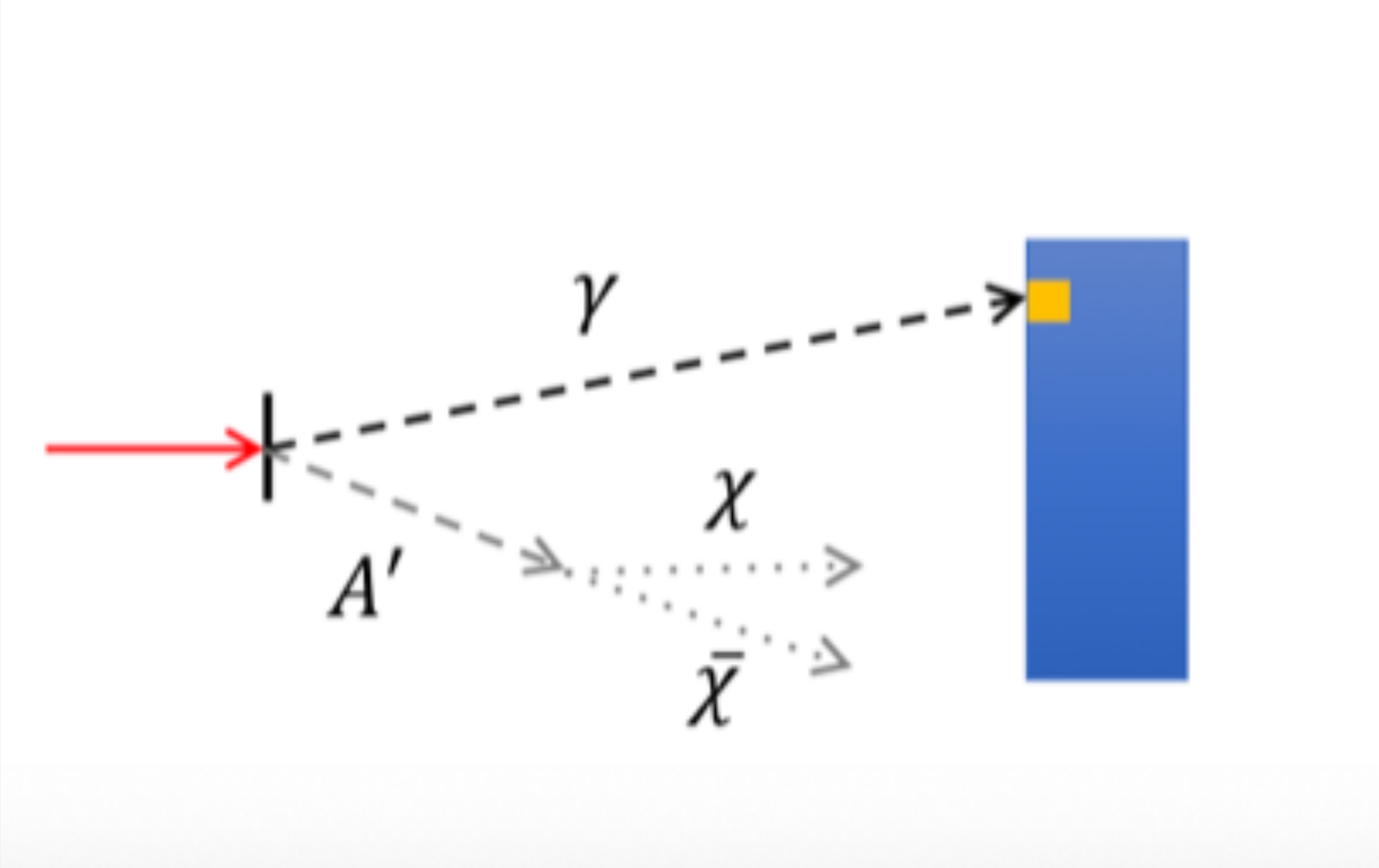
INVISIBLE: long-lived or if $m_a/2 > M_\chi$, $a \to DM\, DM$ with likely $BR \simeq 1$

TECHNIQUES:

1. Dump (bremsstrahlung) + DM scattering



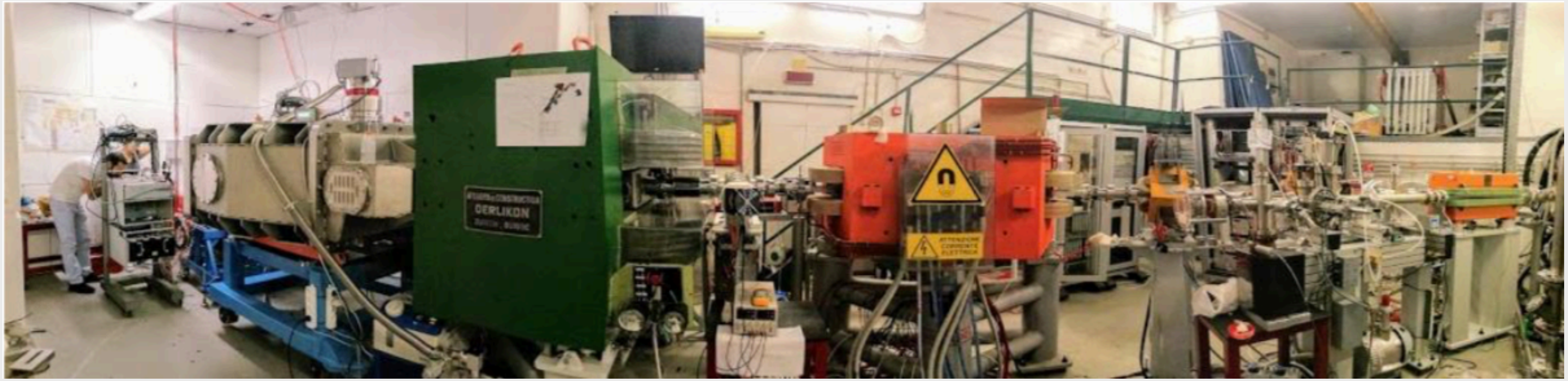
2. missing mass/energy/momentum search (annihilation)

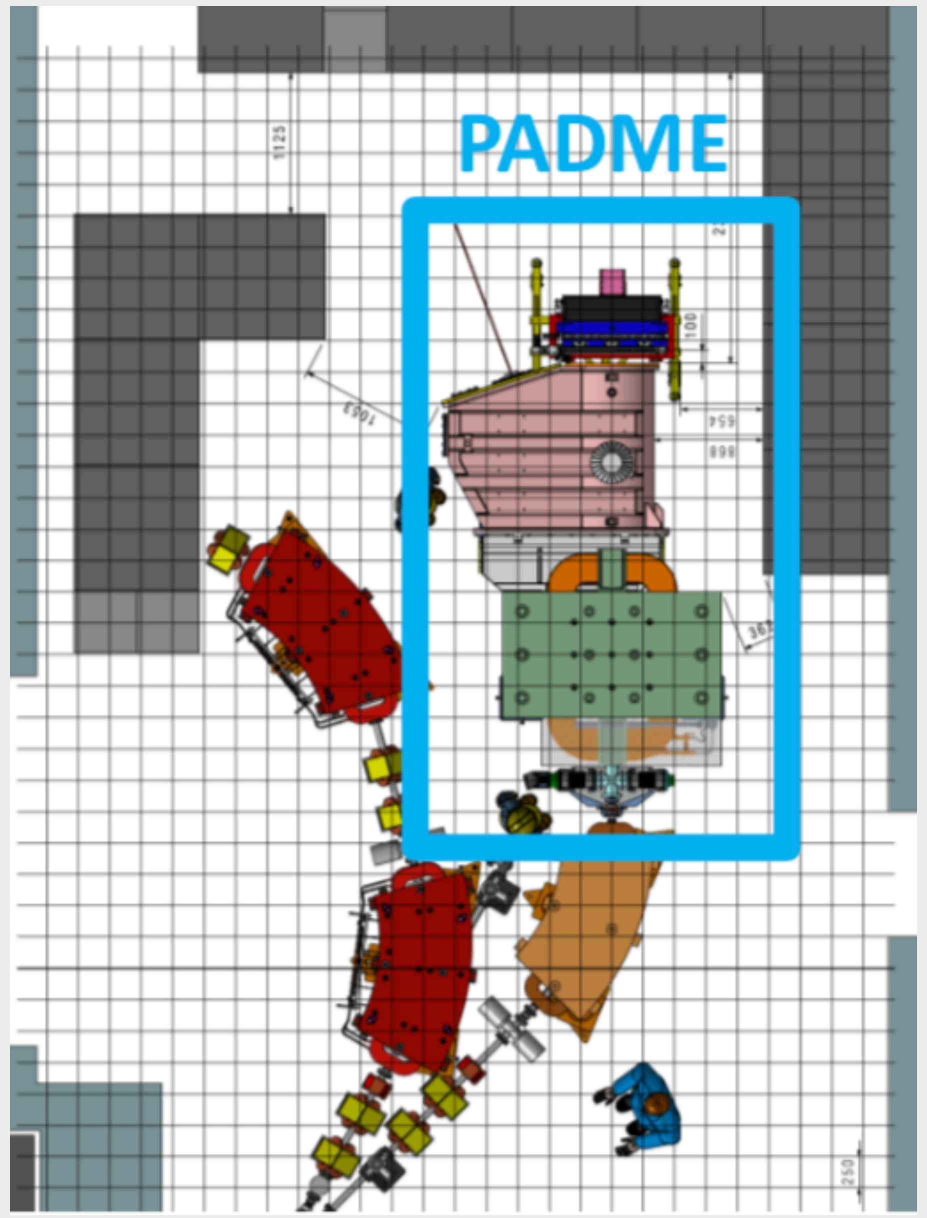


PADME EXPERIMENT

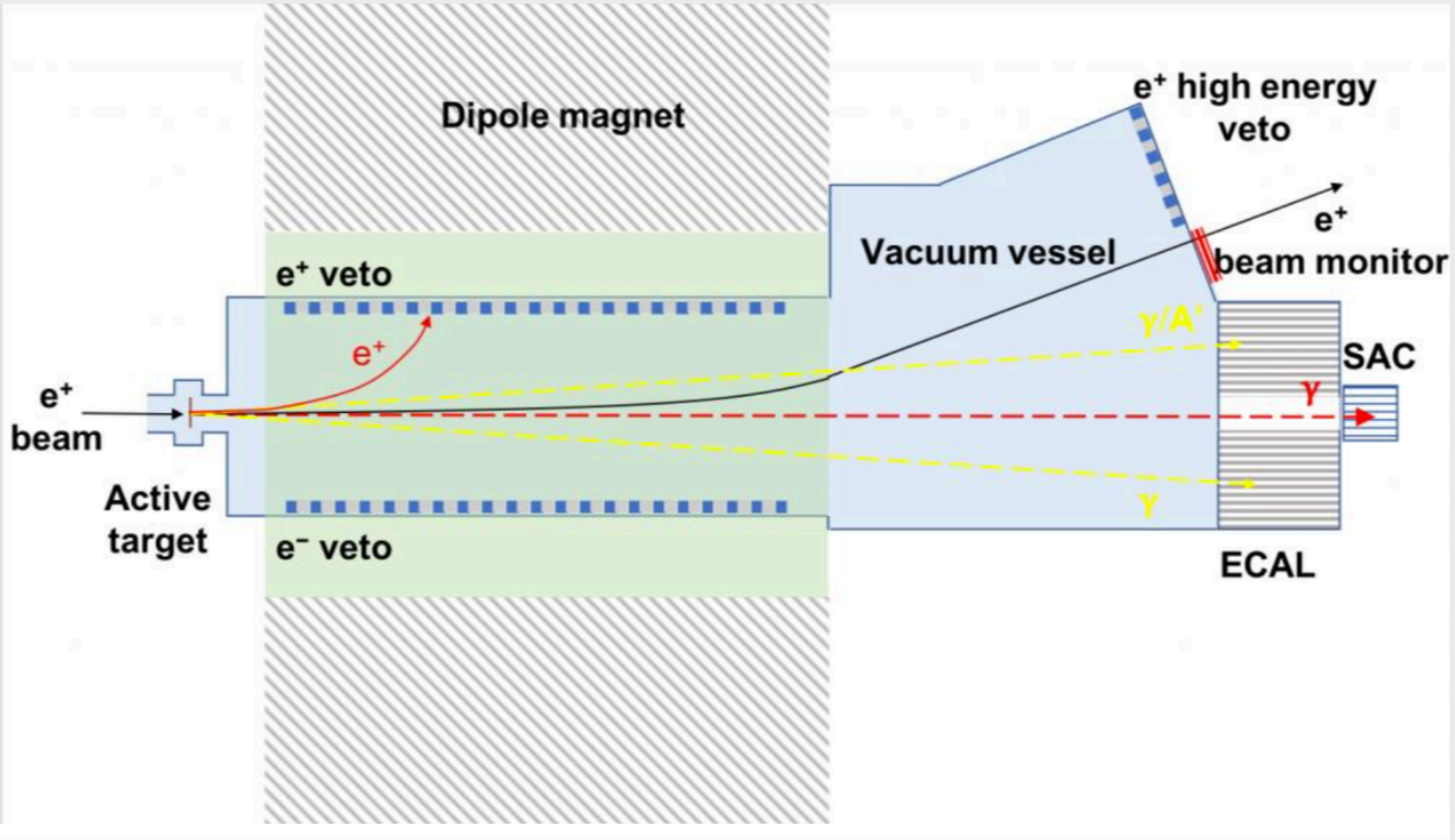
PADME (Positron Annihilation into Dark Matter Experiment) is placed in the Beam Test Facility of the Laboratori Nazionali di Frascati.

~ 4,50 m





Experimental Setup

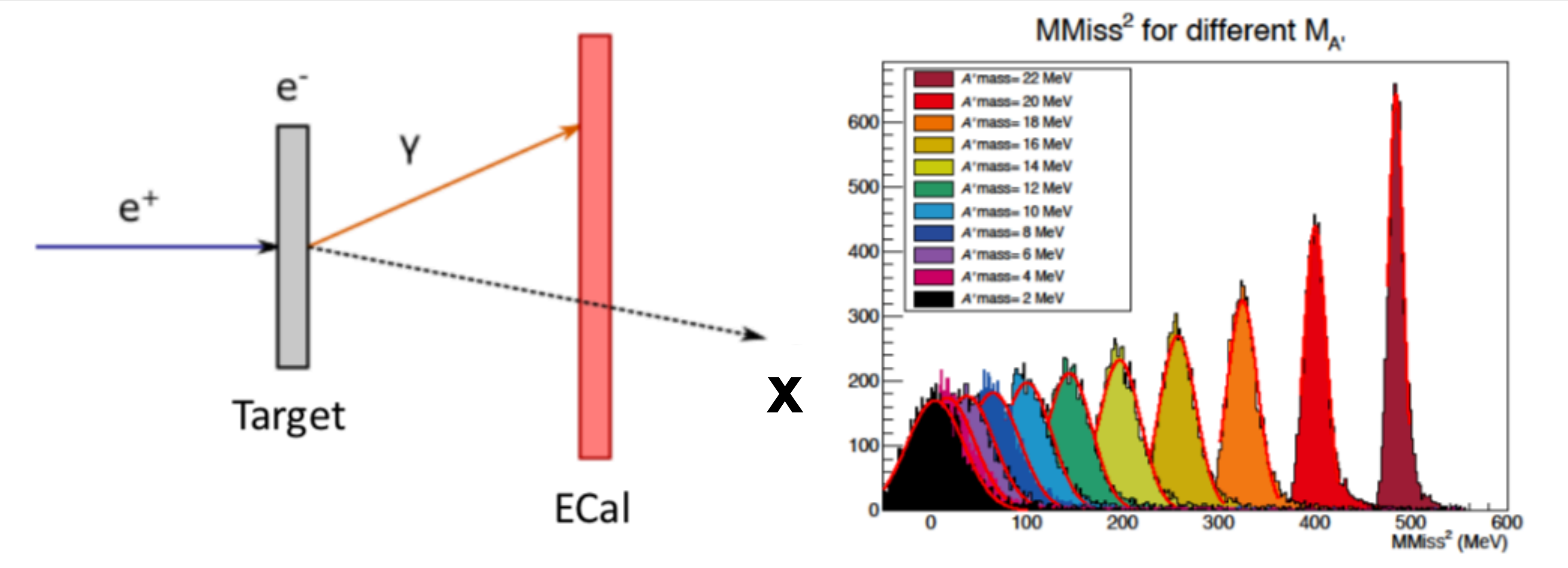


- Beam: e^+ produced at LINAC at 550MeV, multiplicity ~ 20k e^+/bunch, bunch duration 250 ns, frequency 49 Hz.
- Diamond target 100 μm thickness. Active means that we can measure position, size and intensity of incoming beam.
- Dipole magnet of 0.45 T to deflect charged particles out of the vetos and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

How PADME works…

PADME is a fixed target accelerator which looks at the invisible decay of dark photon or ALP through the missing mass technique. Basically the characteristic signature of this reaction is the presence of a narrow resonance emerging over a smooth background in the distribution of the missing mass.

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

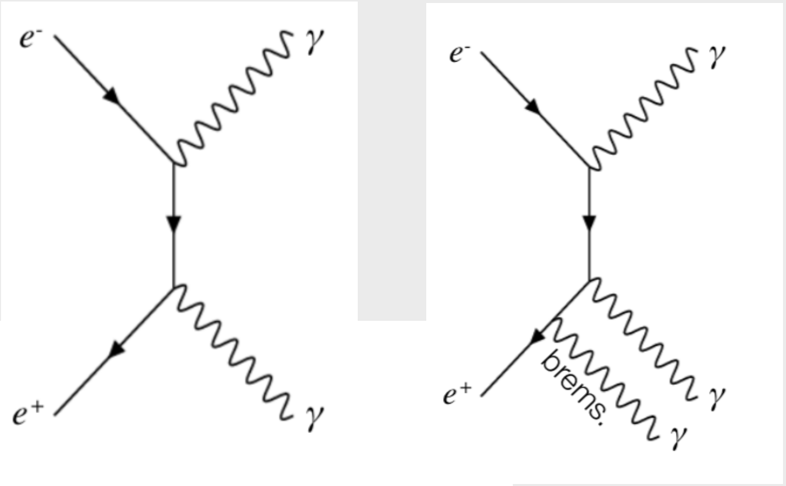


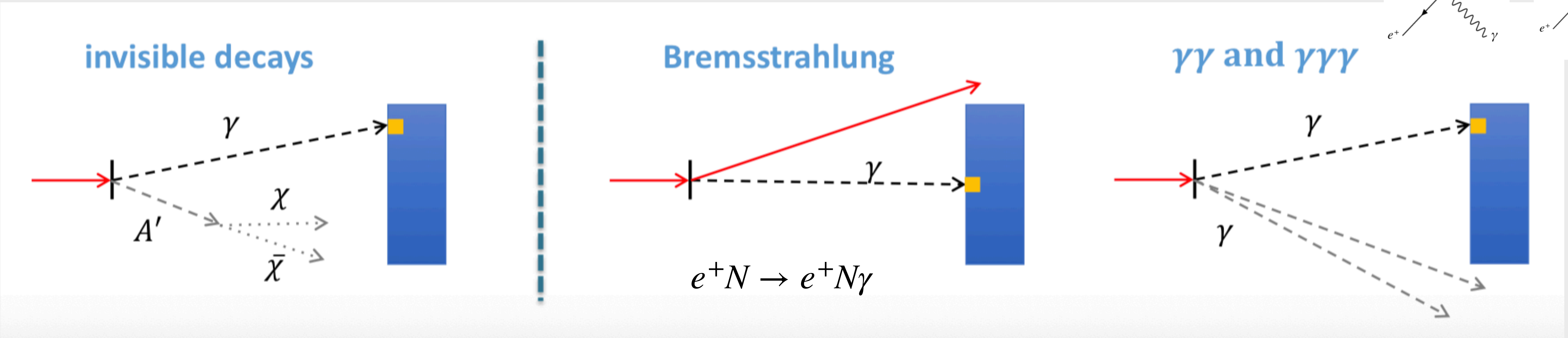
$$M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2$$

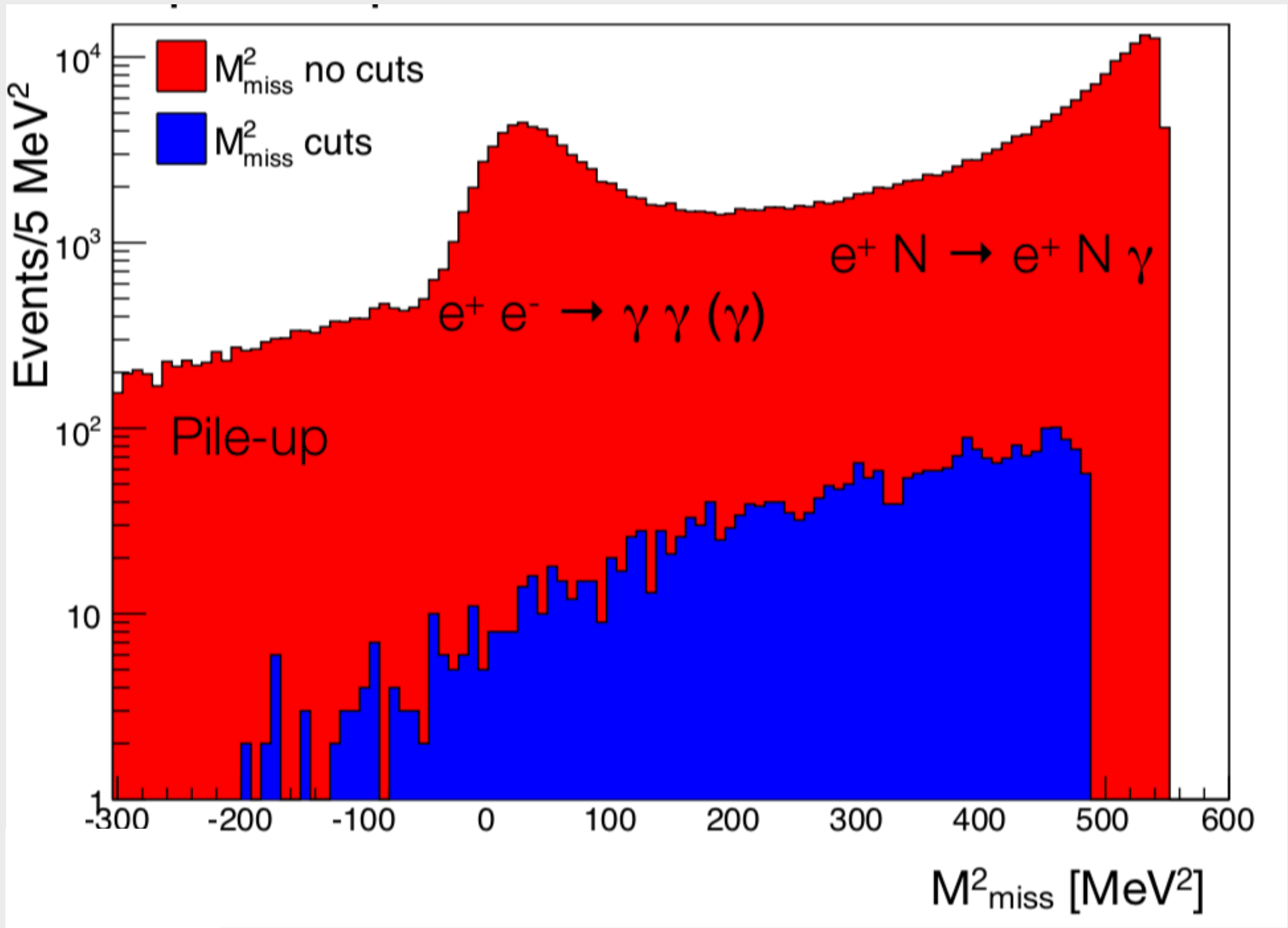
This technique is used in reactions with a well-known initial state and detectors with very good hermeticity that allow to detect all the other particles in the final state.

Model independent experiment. One assumption: *leptophilic dark particles*

Background







WORK IN PROGRESS: IN COLLABORATION WITH MARCO PRUNA, RADIATIVE CORRECTIONS FOR PROCESSES $e^+e^- \to 2\gamma(3\gamma)$ USING ALSO A TOOL CALL RECOLA.

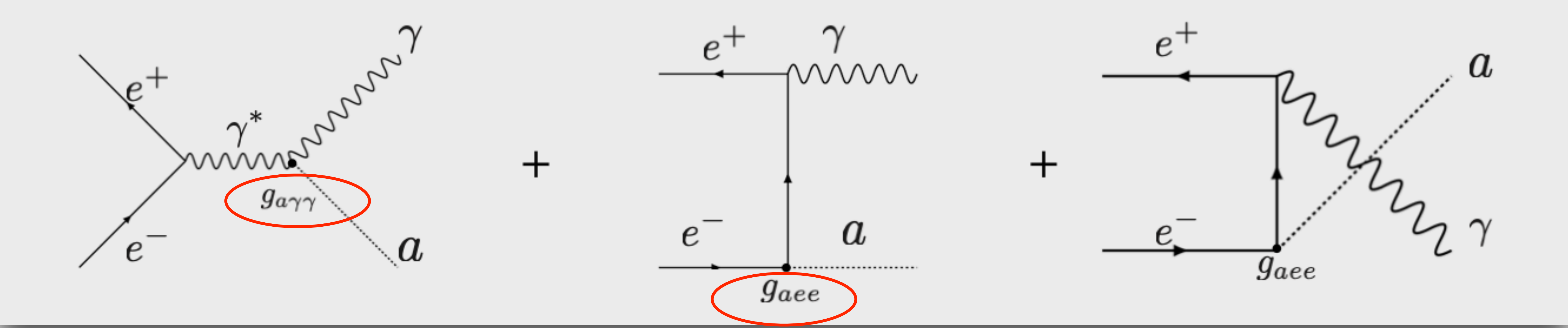
TWO REASONS:

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

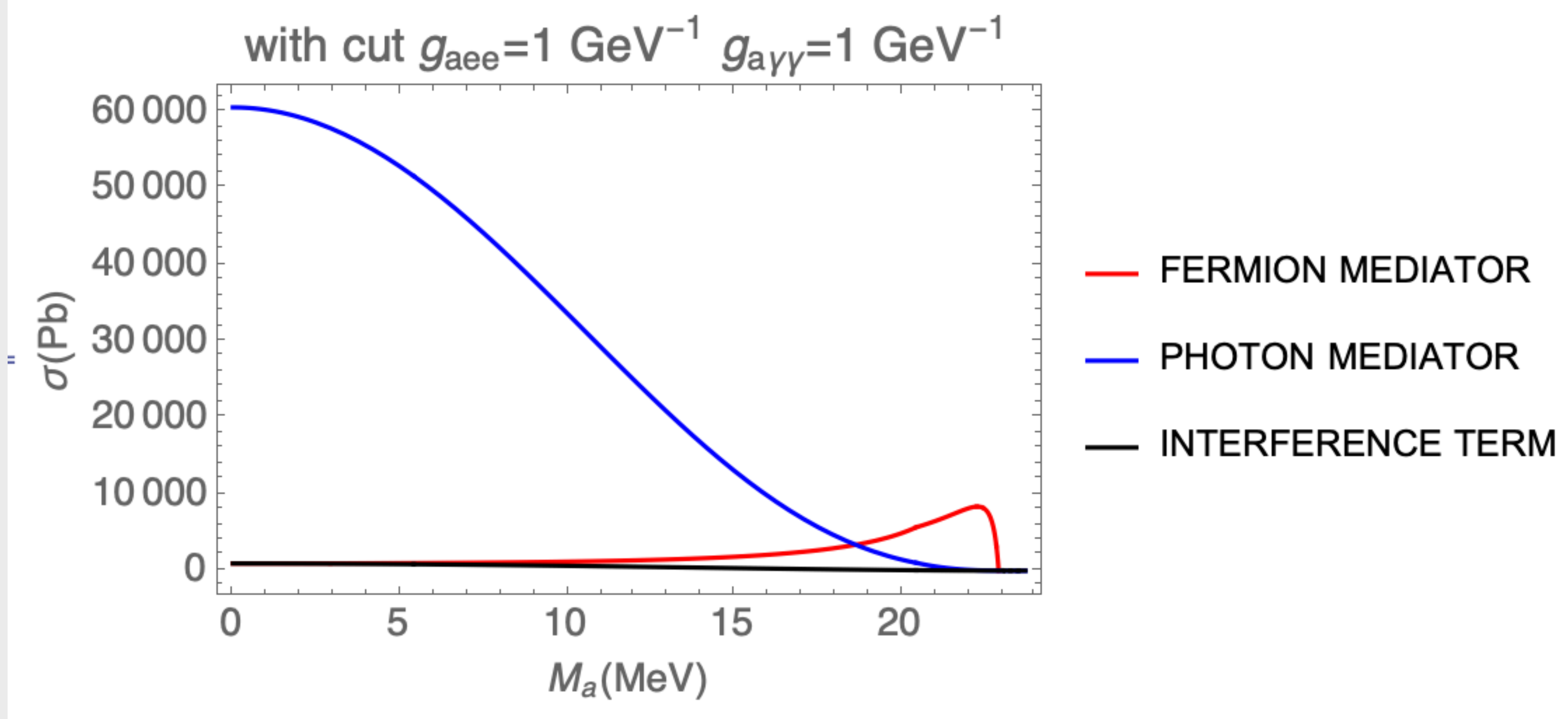
$e^+e^- \to a + \gamma$ in PADME

perche` creo dei cluster e il seed dei cluster e` 20 MeV e aggiungendo gli 8 circostanti (1MeV a cristallo): questo

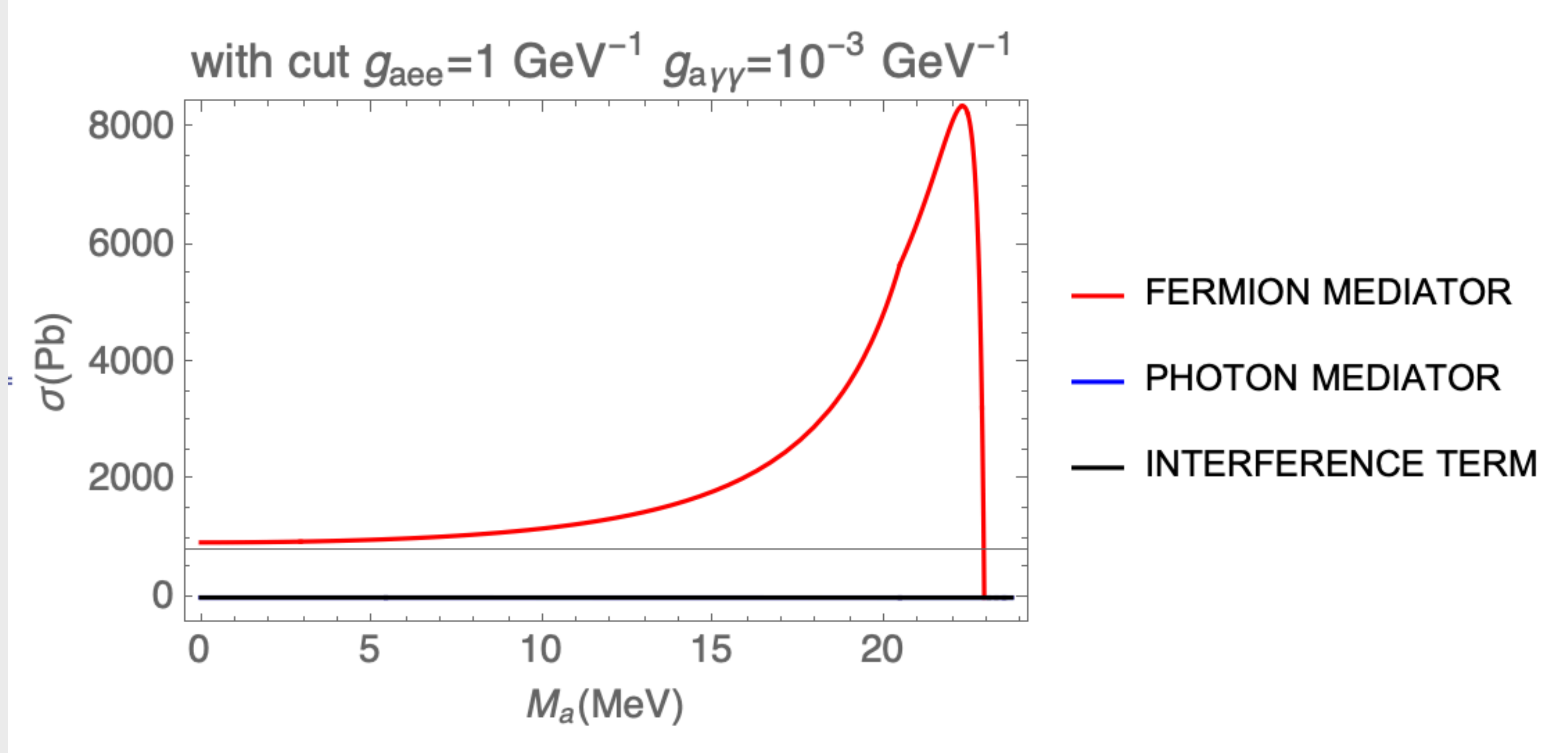
$$\mathscr{L}_{alp} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}M_a{}^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - i g_{aee} m_e a \bar{\psi}\gamma^5\psi + \mathscr{L}_{DM}$$



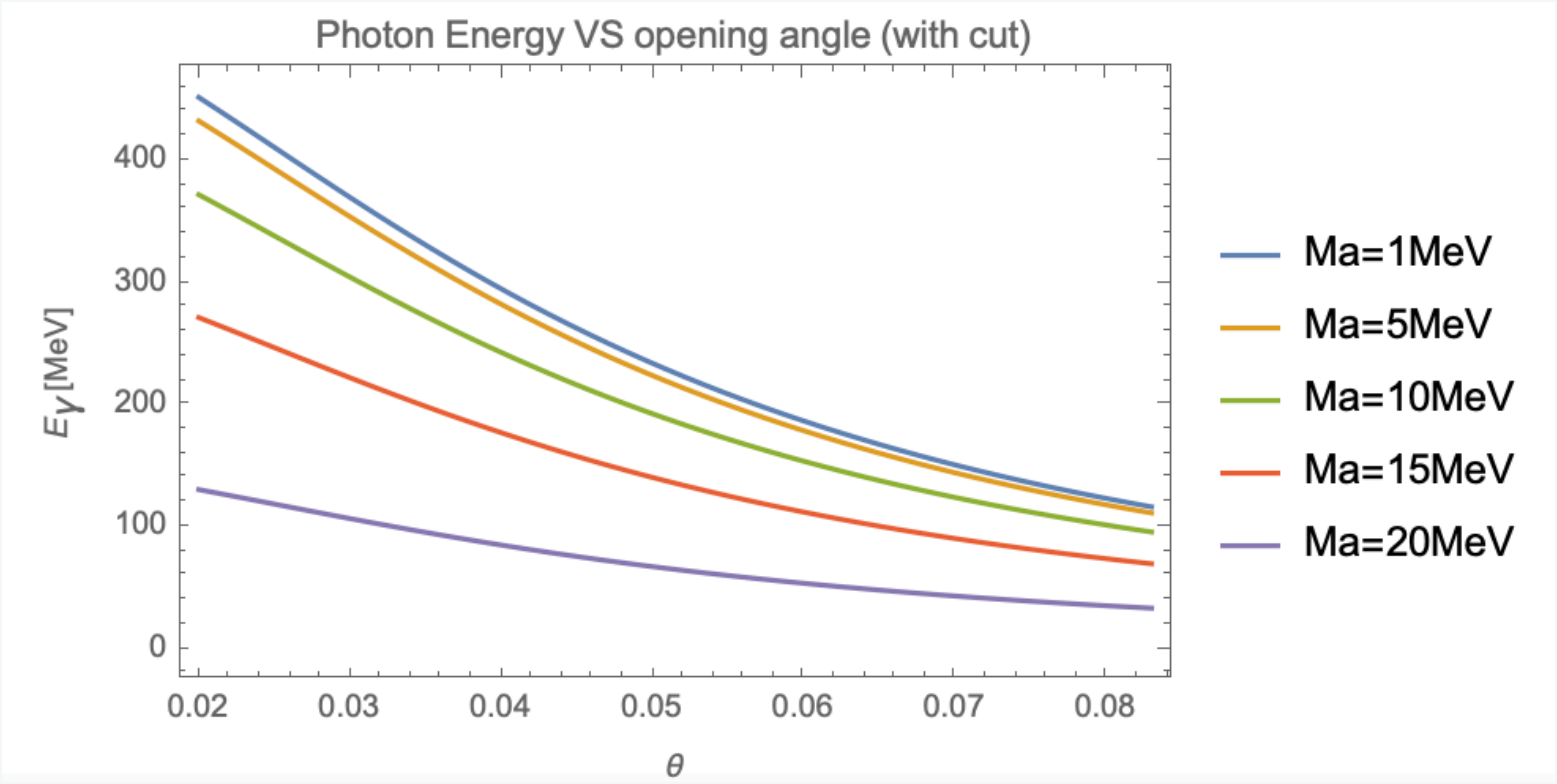
Considering the angular coverage of ECAL ($20 < \theta < 93$ mrad), Energy beam of 550 MeV and photon energy larger than 30 MeV.



but considering current coupling constraints →



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



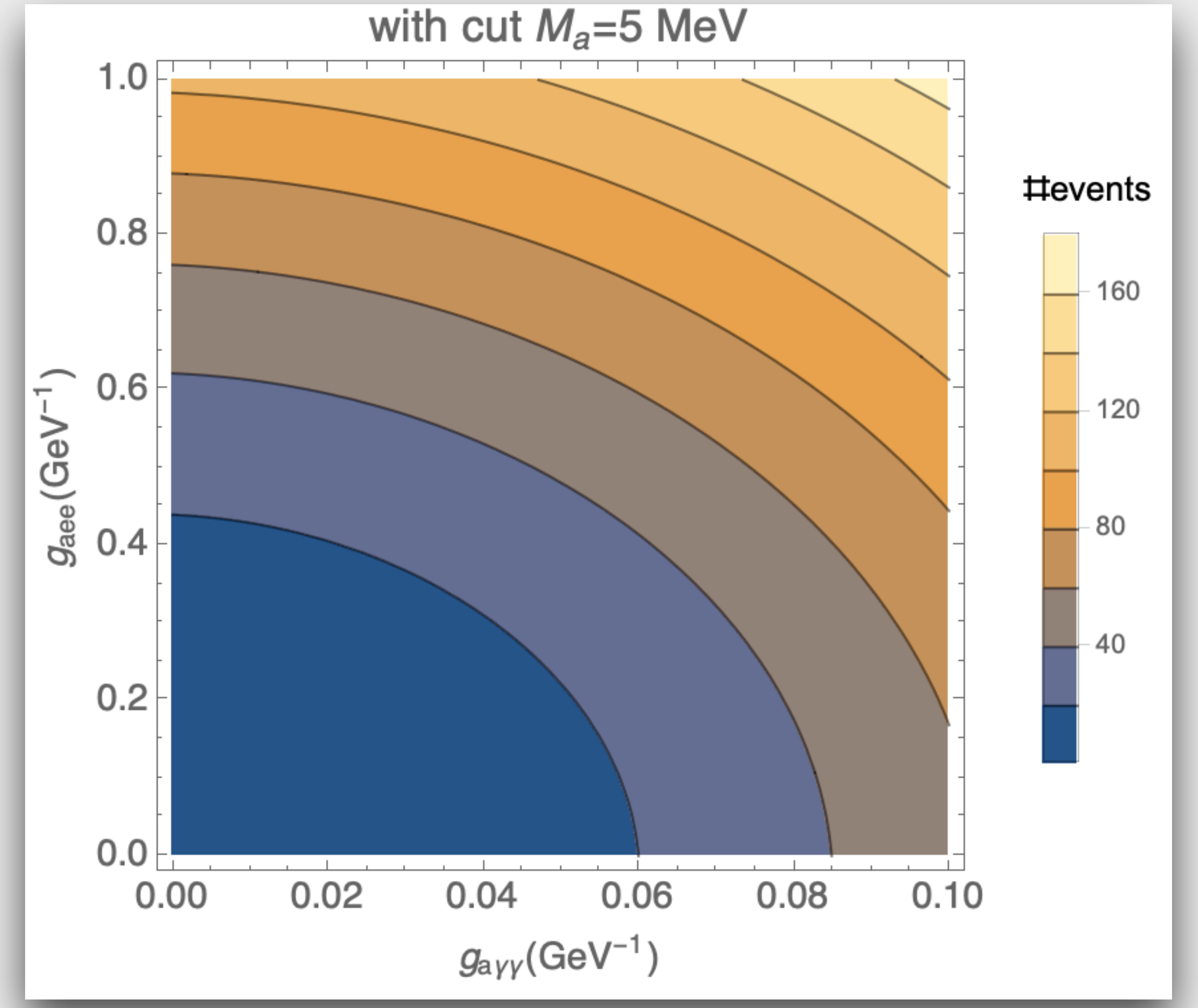
Number of events of $e^+e^- \rightarrow \gamma + a$ in PADME

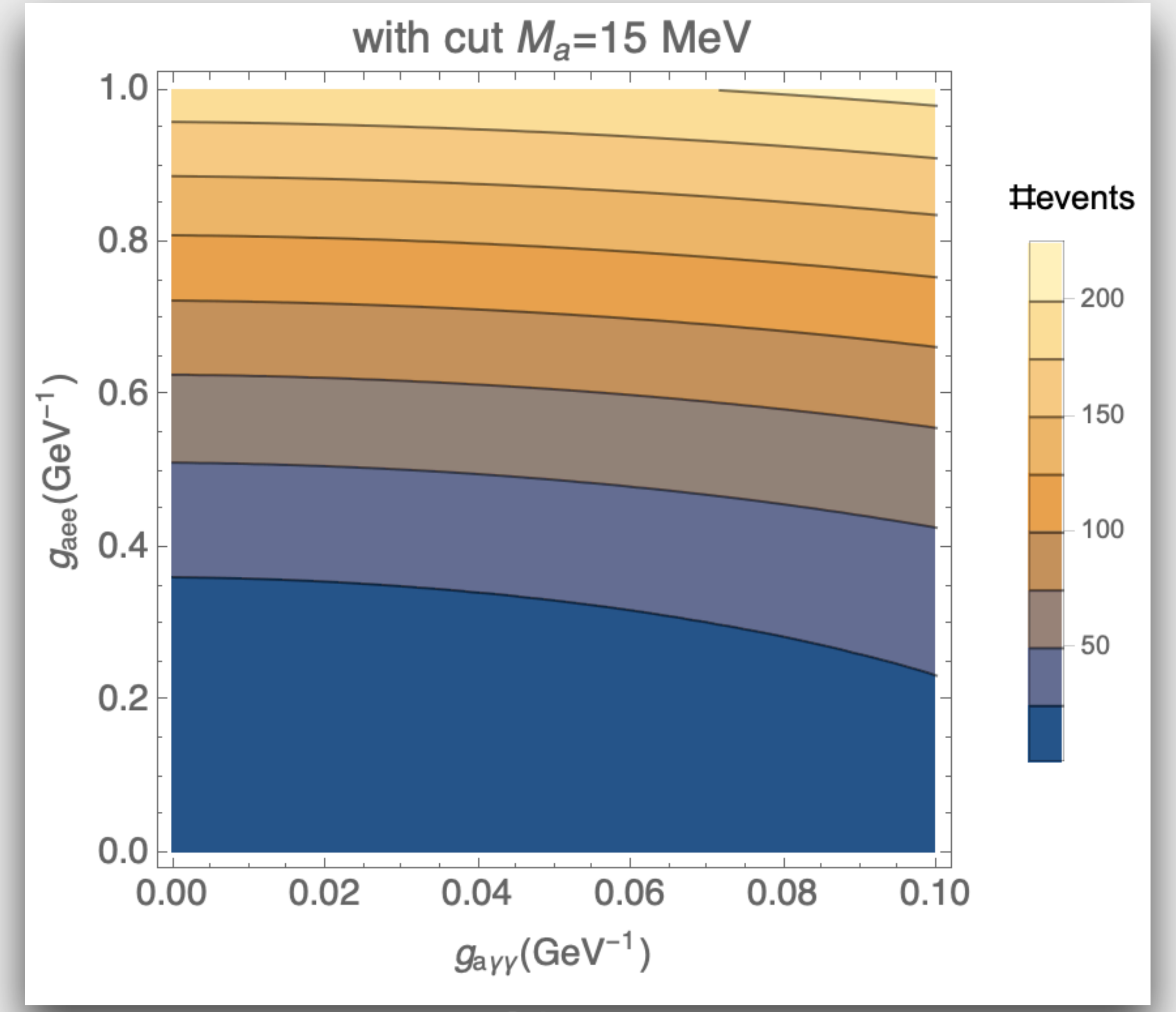
$$N_{events} = 10^{13} N_e \sigma_{e^+e^- \rightarrow a\gamma} = 6 d_{target} N_A \frac{\rho}{A} \sigma_{e^+e^- \rightarrow a\gamma}$$

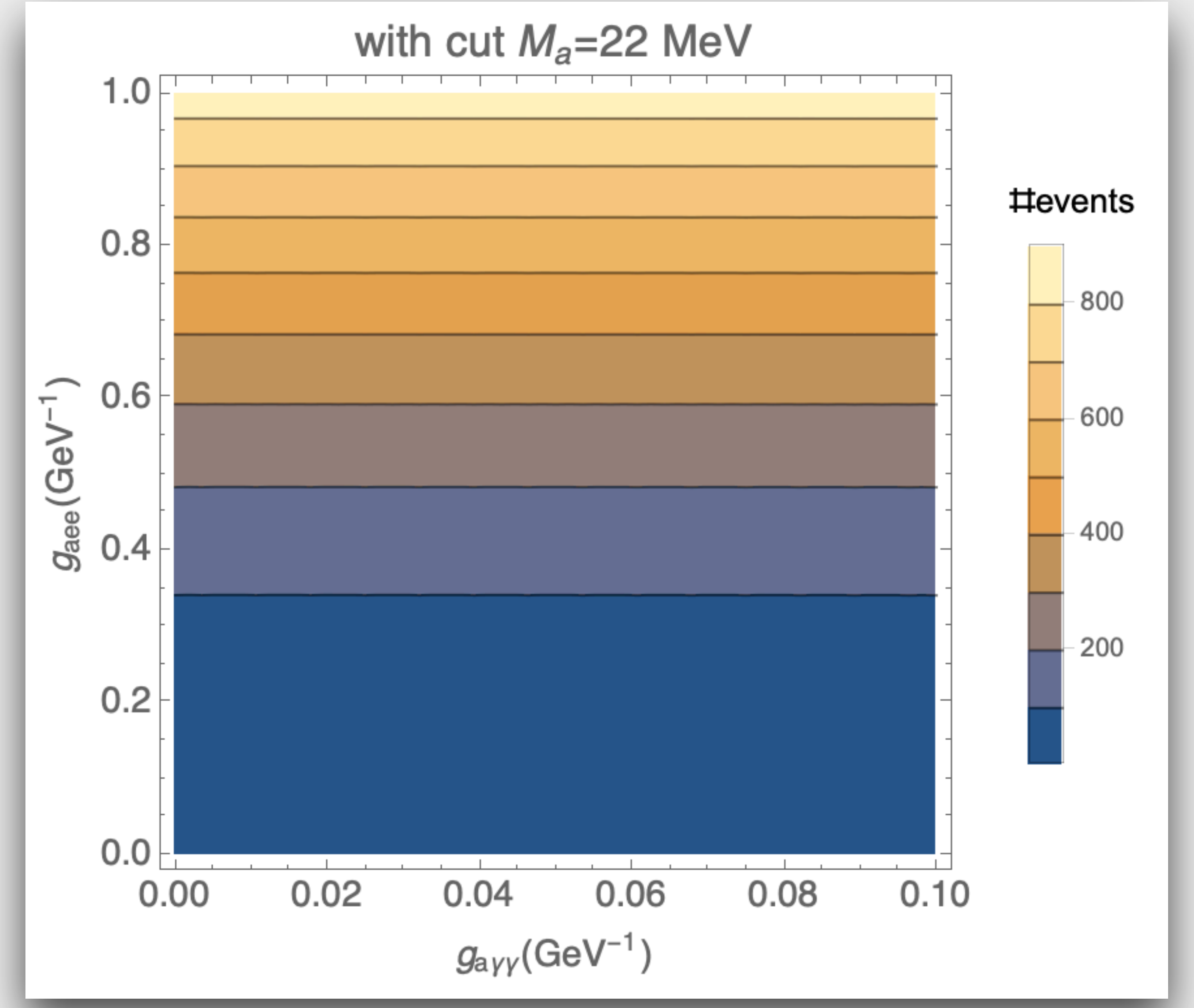
diamond density 3.5 g/cm^3

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

atomic mass = 12 g/mol







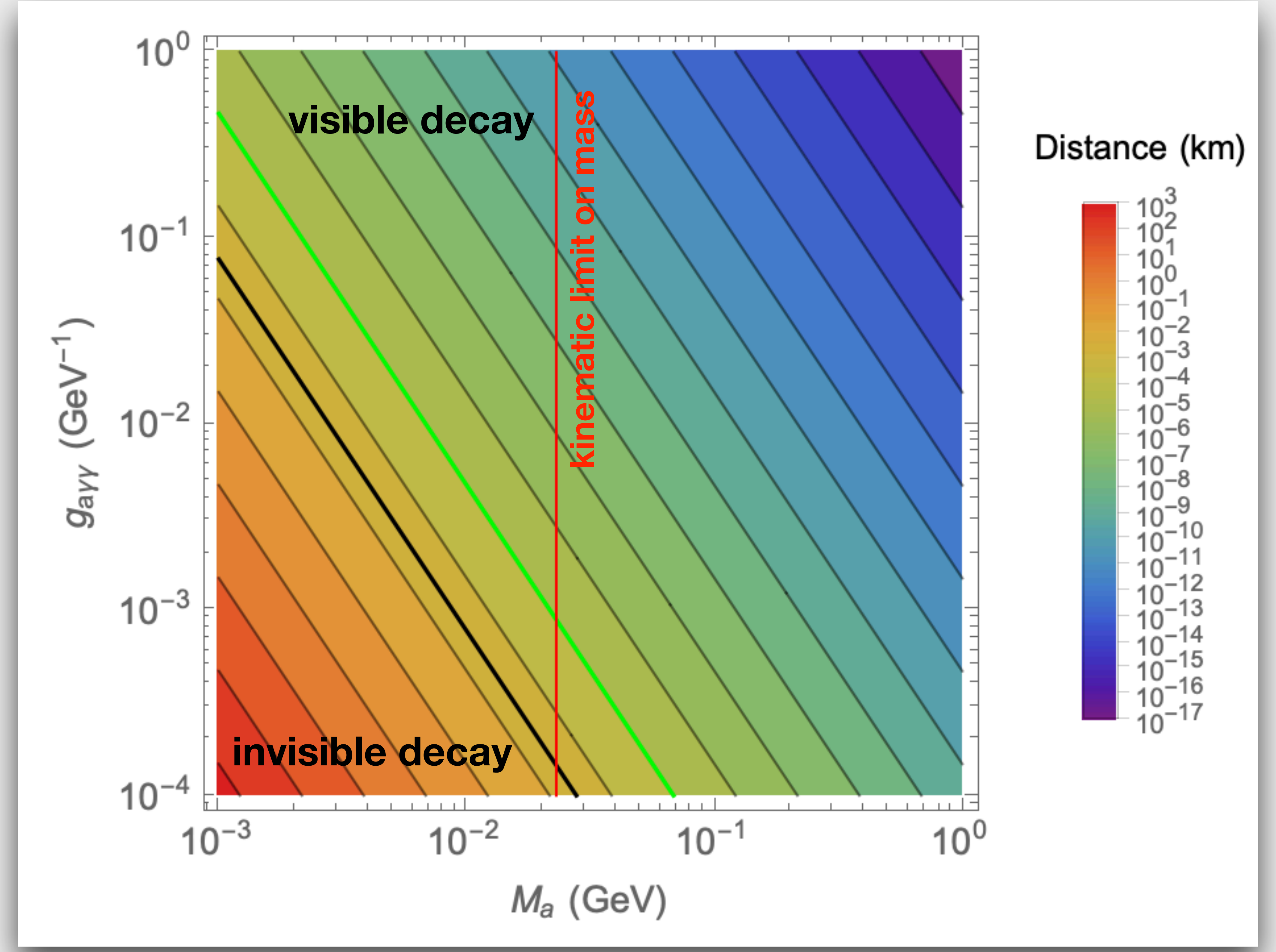
WHAT ABOUT VISIBLE DECAYS OF ALPS IN PADME?

It depends in 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**



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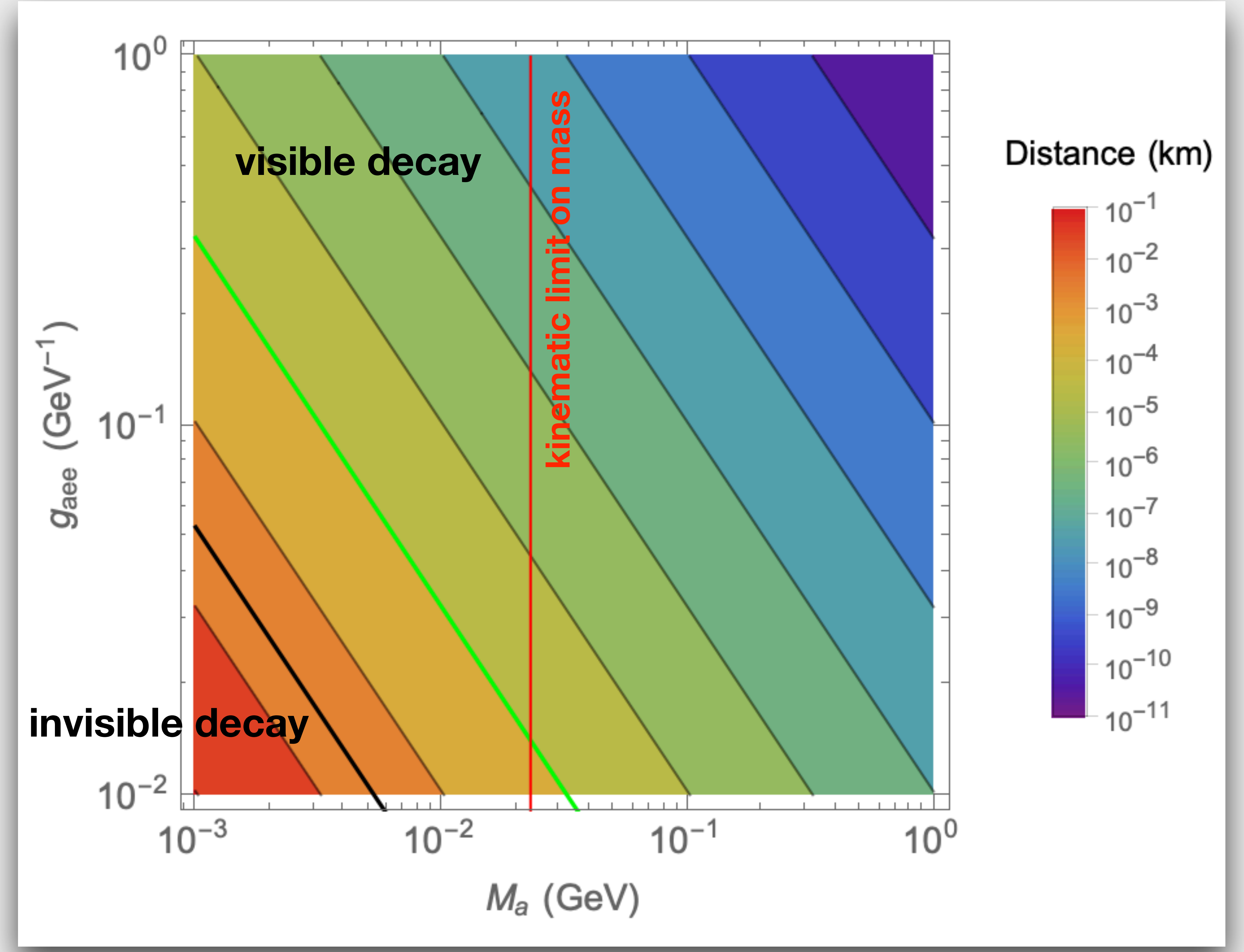
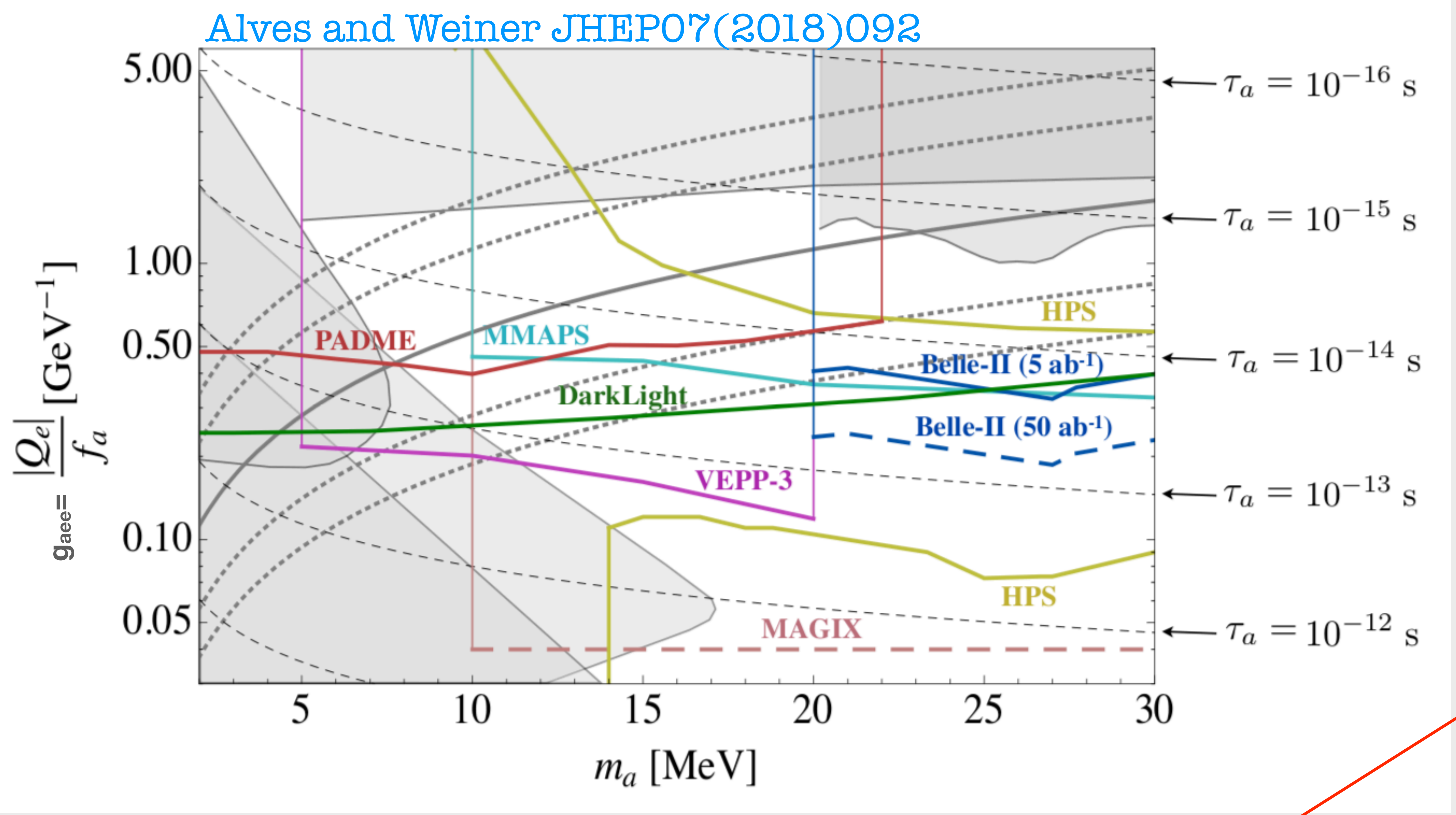


CURRENT CONSTRAINTS FOR INVISIBLE DECAY



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

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

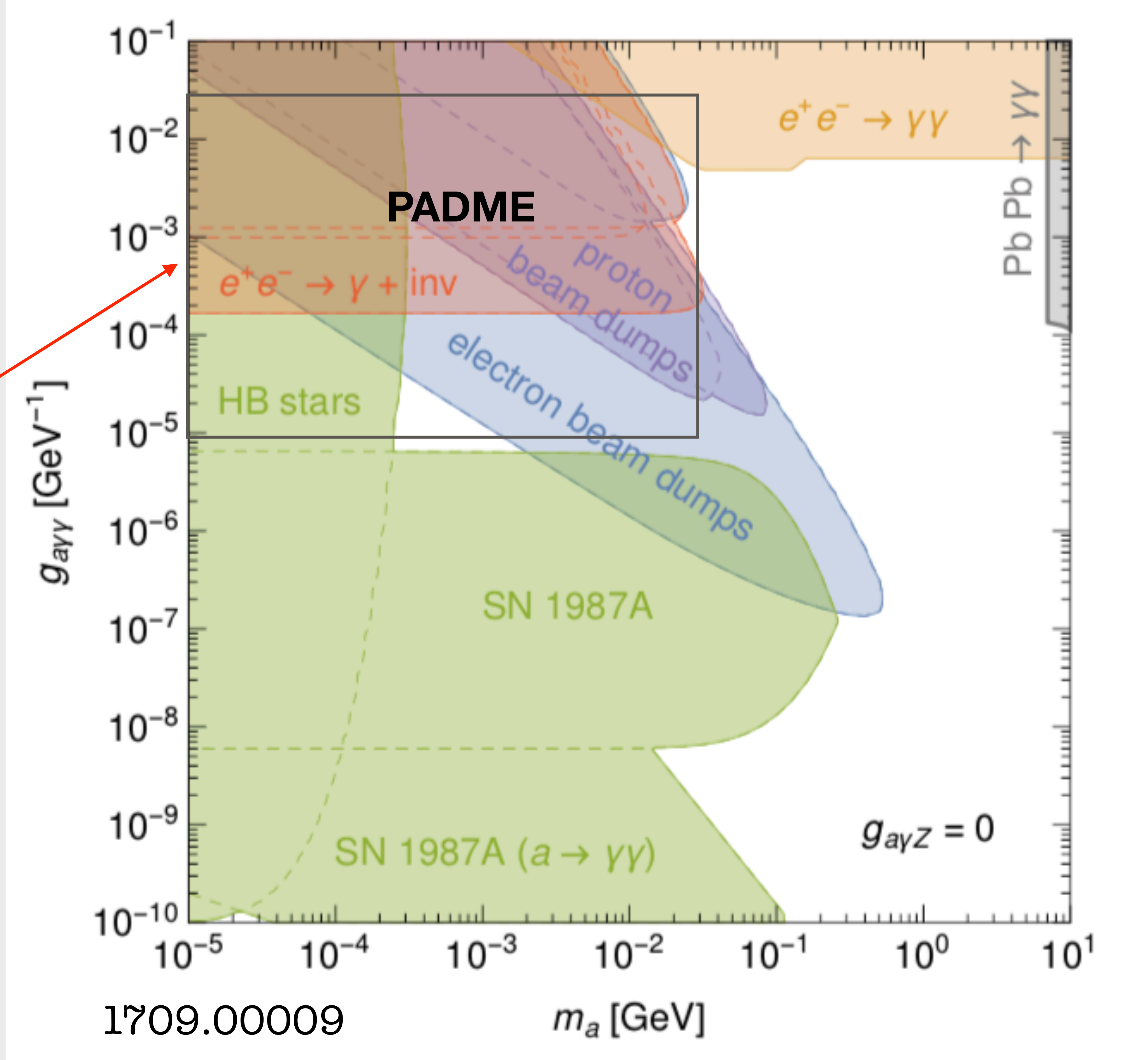
where ϵ denotes the kinetic mixing parameter.[7] To convert a bound on ϵ for Dark Photons into a bound on $g_{a\gamma\gamma}$ for ALPs we therefore have to correct for the fact that the geometric acceptance will be very different in the two cases.

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

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

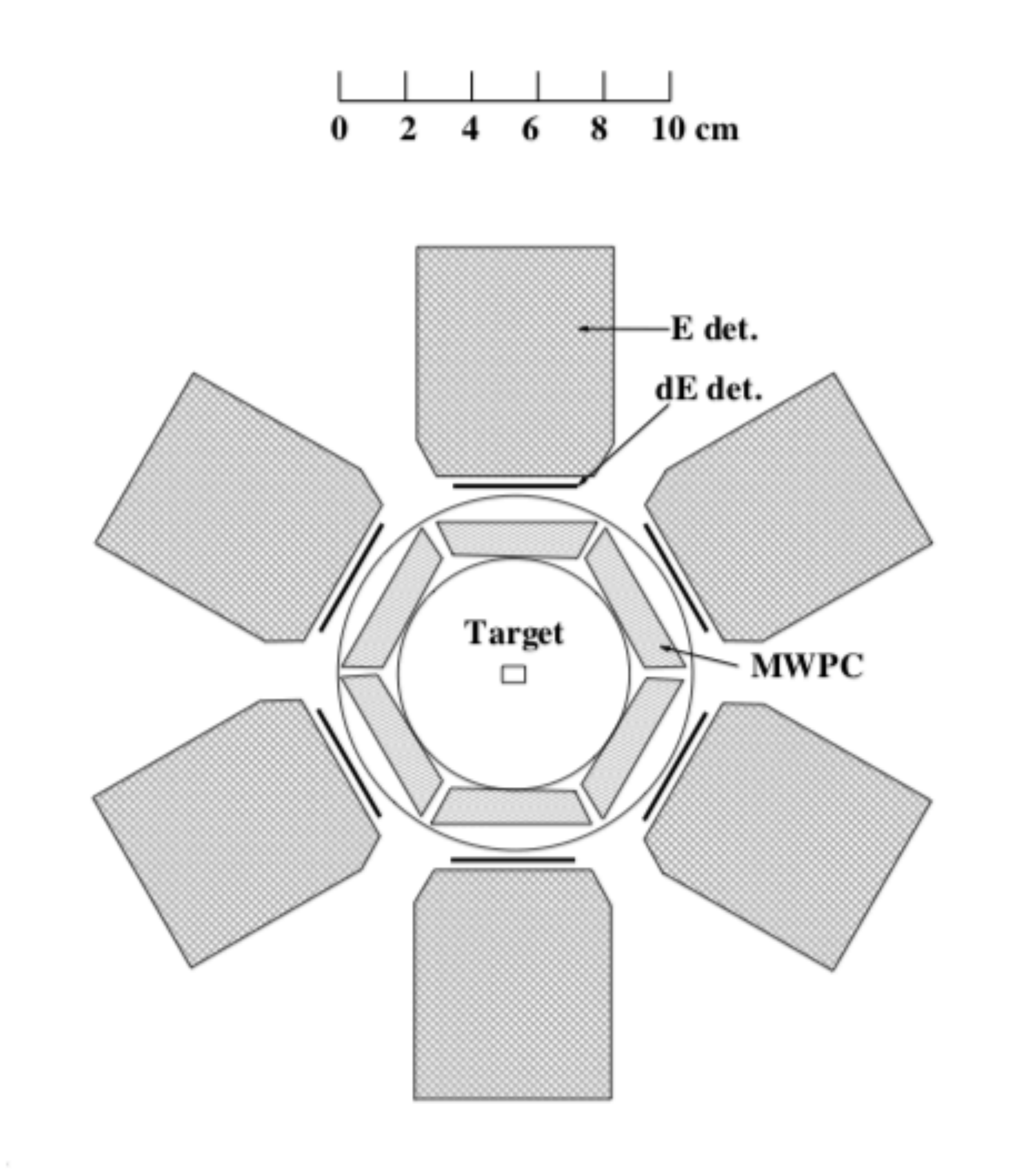
Repeating this calculation for finite ALP masses and taking into account the probability that the ALP decays before leaving the detector (see above) using a detector length of $L_D = 275$ cm [59], we can then reinterpret the full BaBar bound in the context of ALPs.

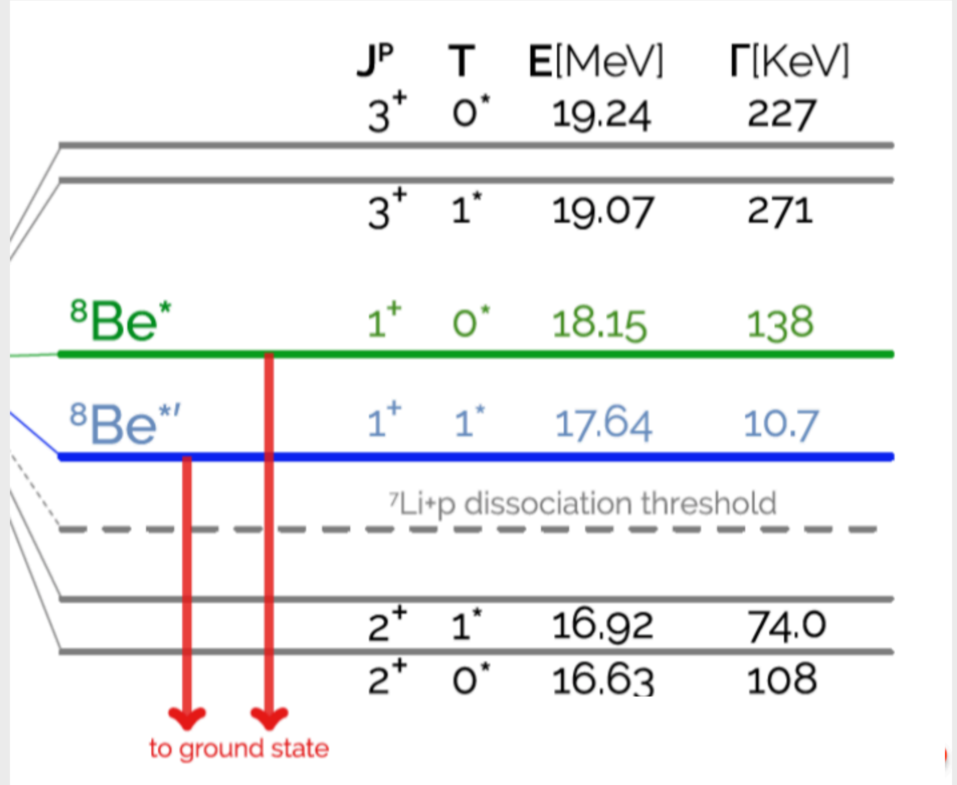
RECAST

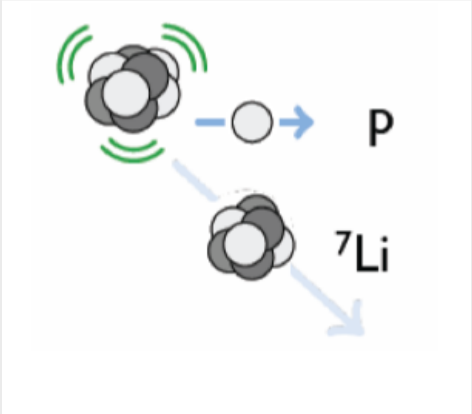


BERYLLIUM (&HELIUM) ANOMALY: EXISTENCE OF NEW PARTICLE AT 17 MEV?

The ATMOKI collaboration [1504.01527] has found "something", let's say anomaly, on angular correlation distribution of e^+e^- internal pair creation (IPC) process of Beryllium 8: $^8Be* \rightarrow Be\, e^+e^-$

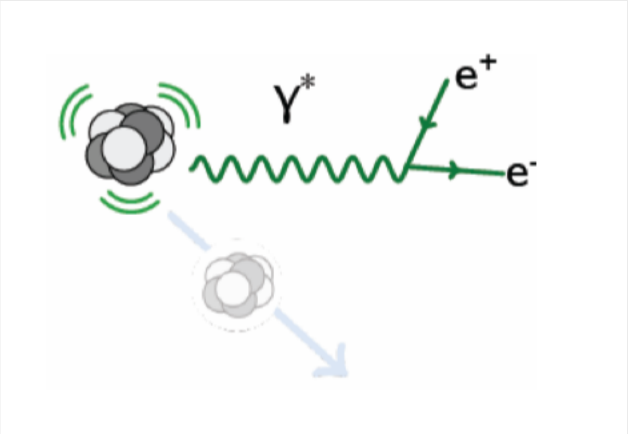






BR~1

BR~10^{-5}



BR~10^{-8}

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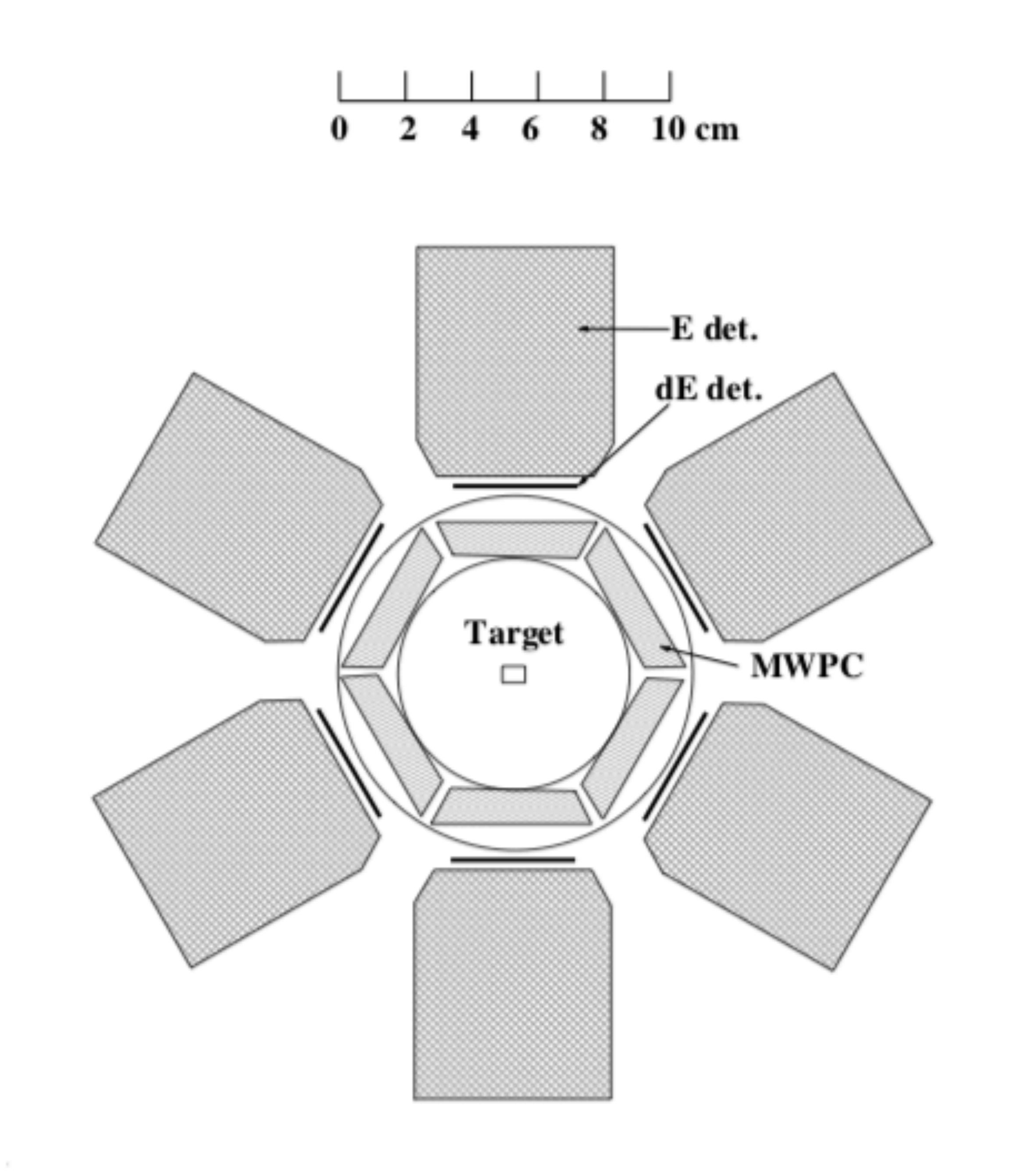
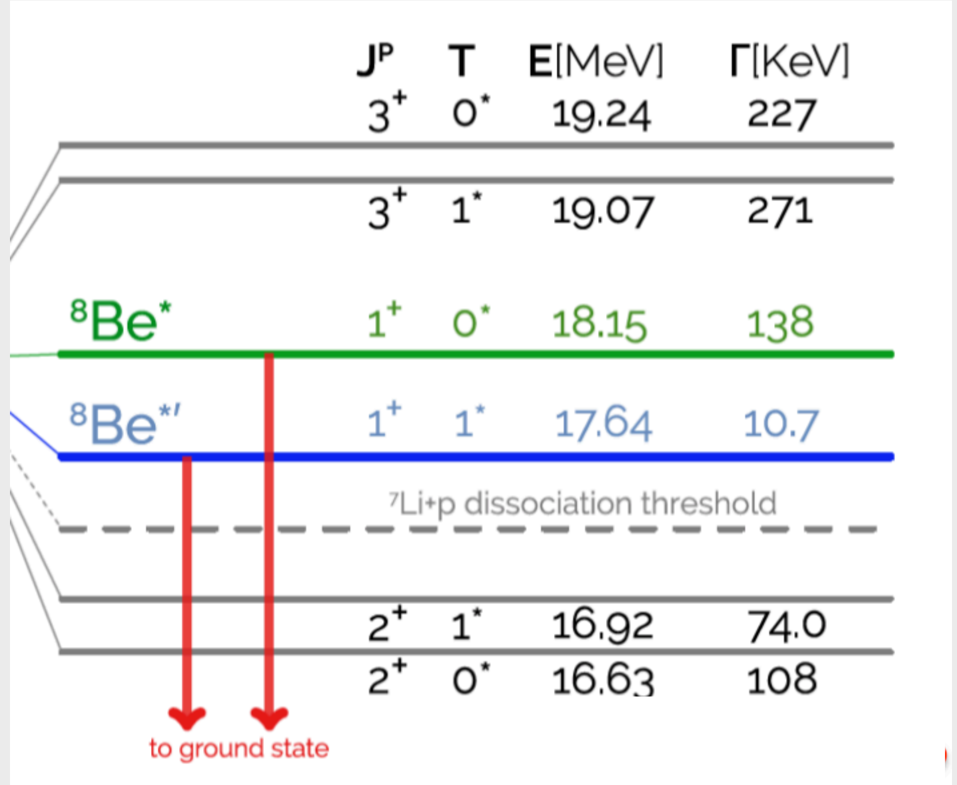
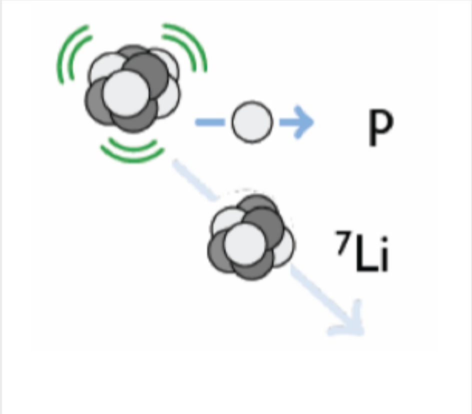
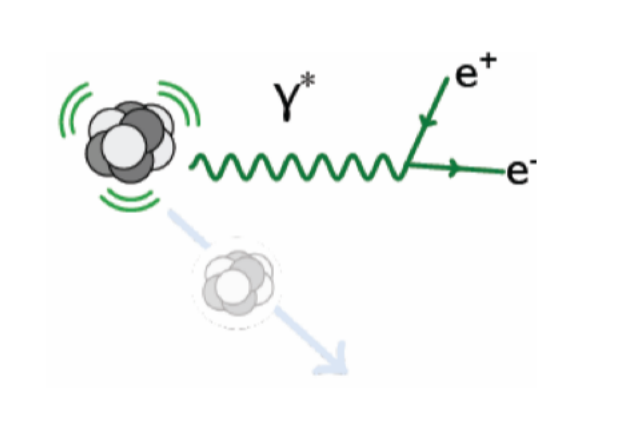
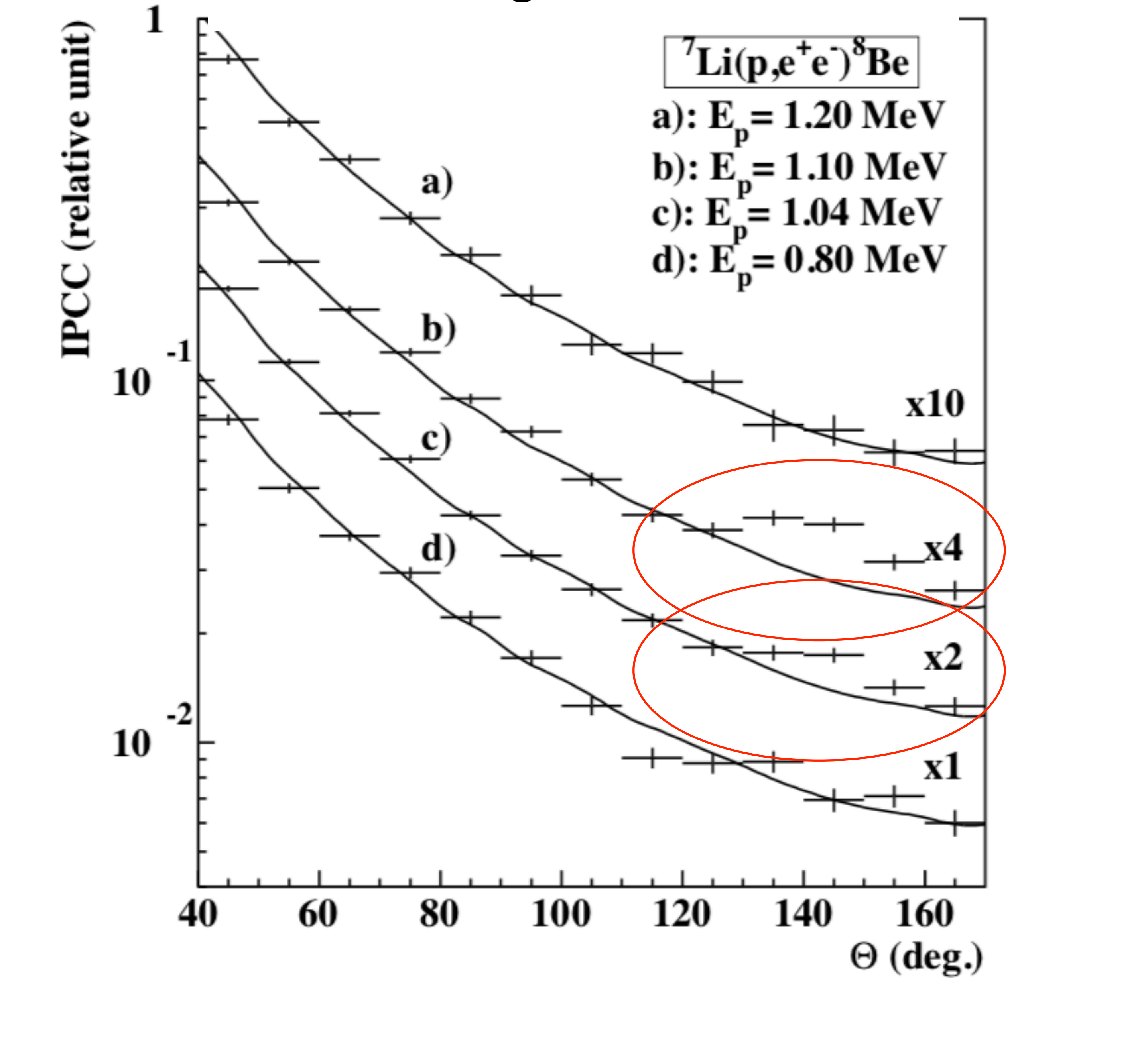


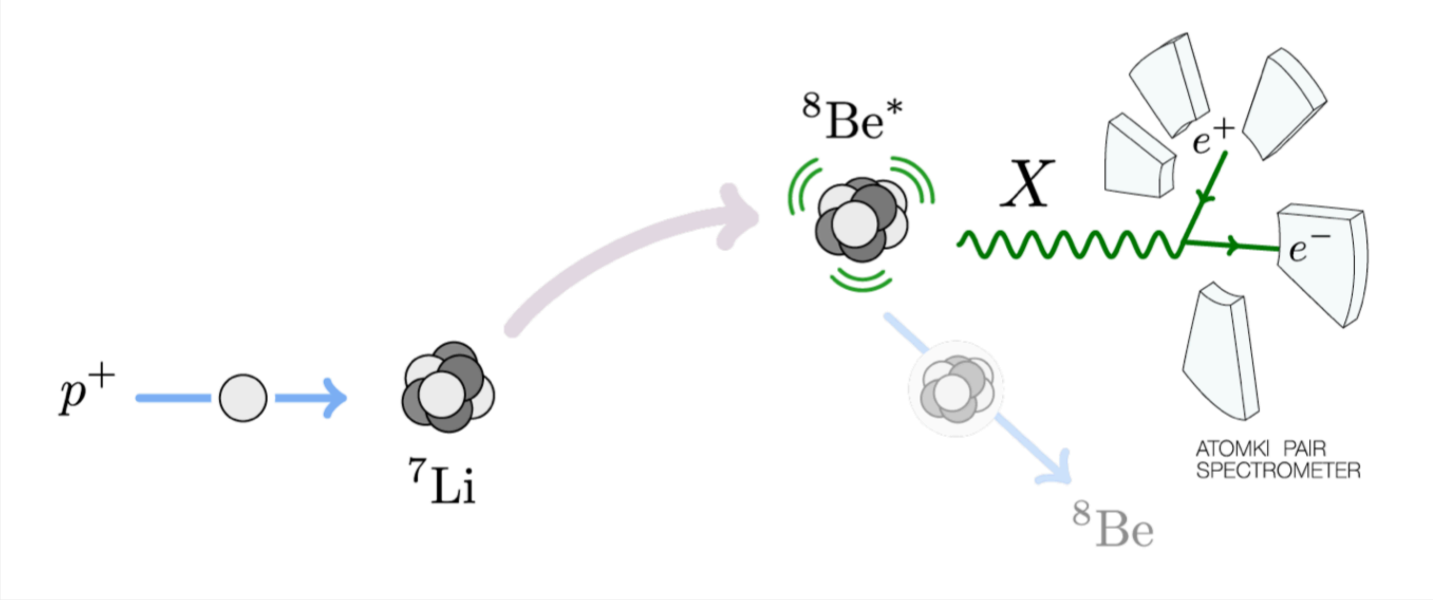






For e^+e^- produced by a virtual photon, $dN/d\theta$ is sharply peaked at low θ and is expected to be a monotonically decreasing function of θ



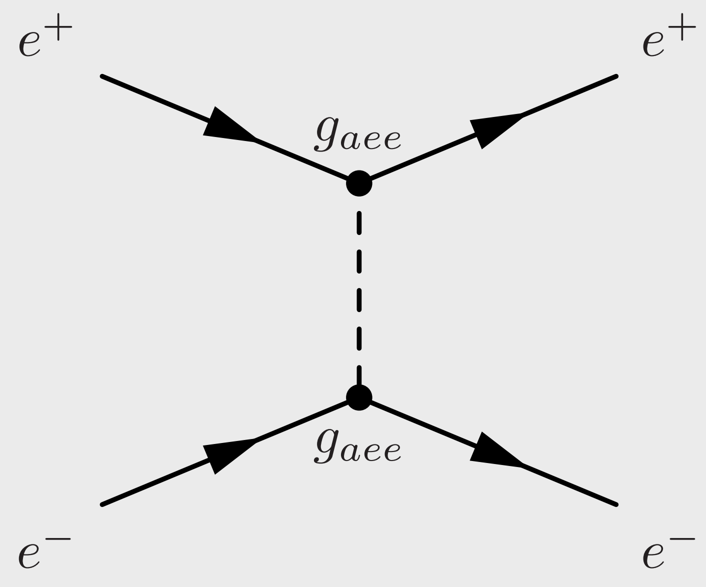


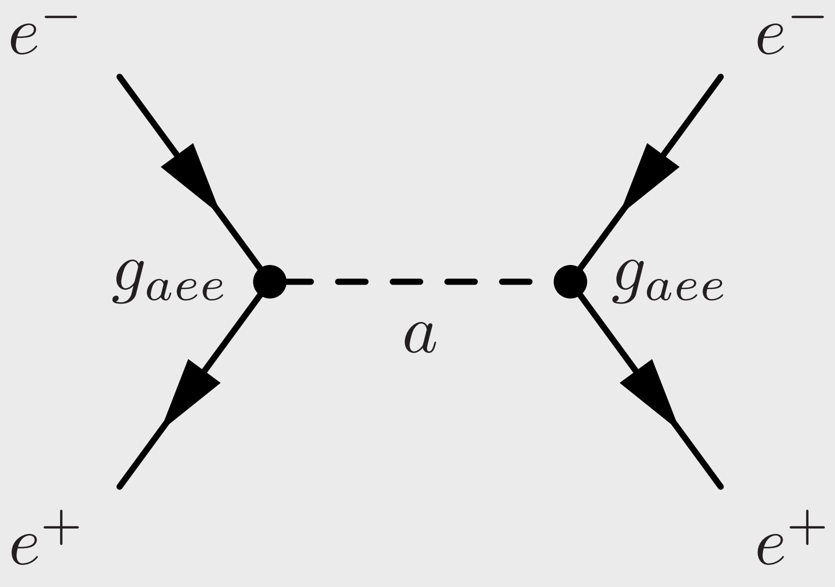
[Feng et al. ’16,’17]

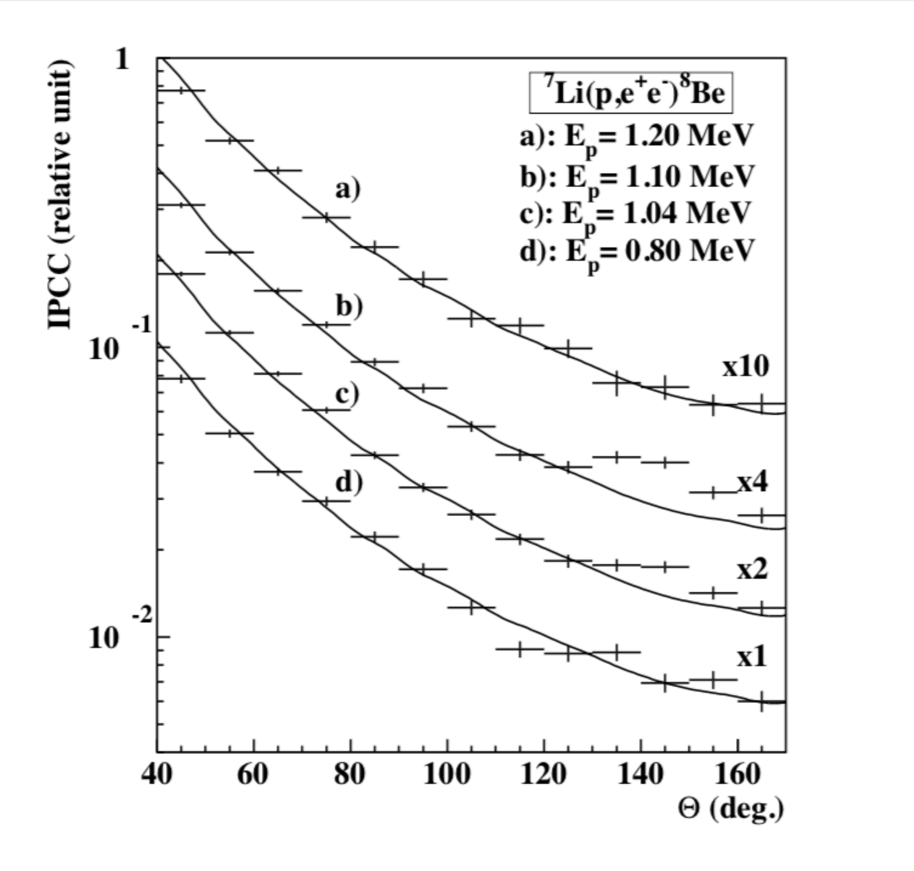
BERYLLIUM (&HELIUM) ANOMALY: EXISTENCE OF NEW PARTICLE AT 17 MEV?

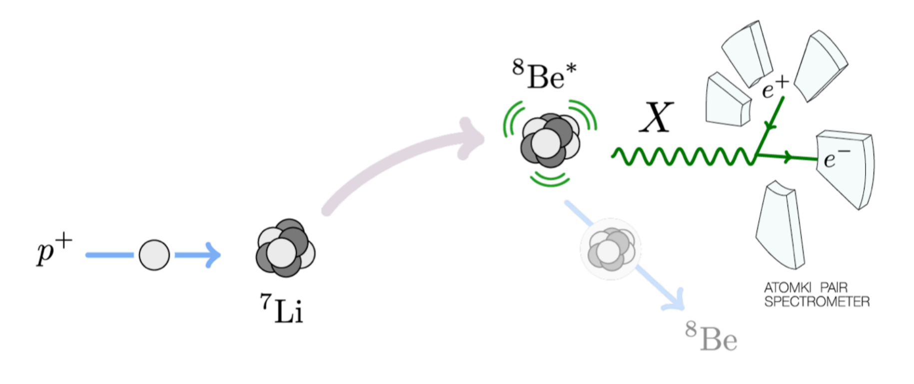
Anomaly observed in excited $^{8}B_{e}$ nuclear decays by Atomki collaboration is particularly relevant for PADME because it could be involved by a new particle at $M_a \sim 17\,MeV$ so really in a parameter space that PADME are testing.

Exploiting the process $e^-e^+ \rightarrow X \rightarrow e^-e^+$ where X = ALP



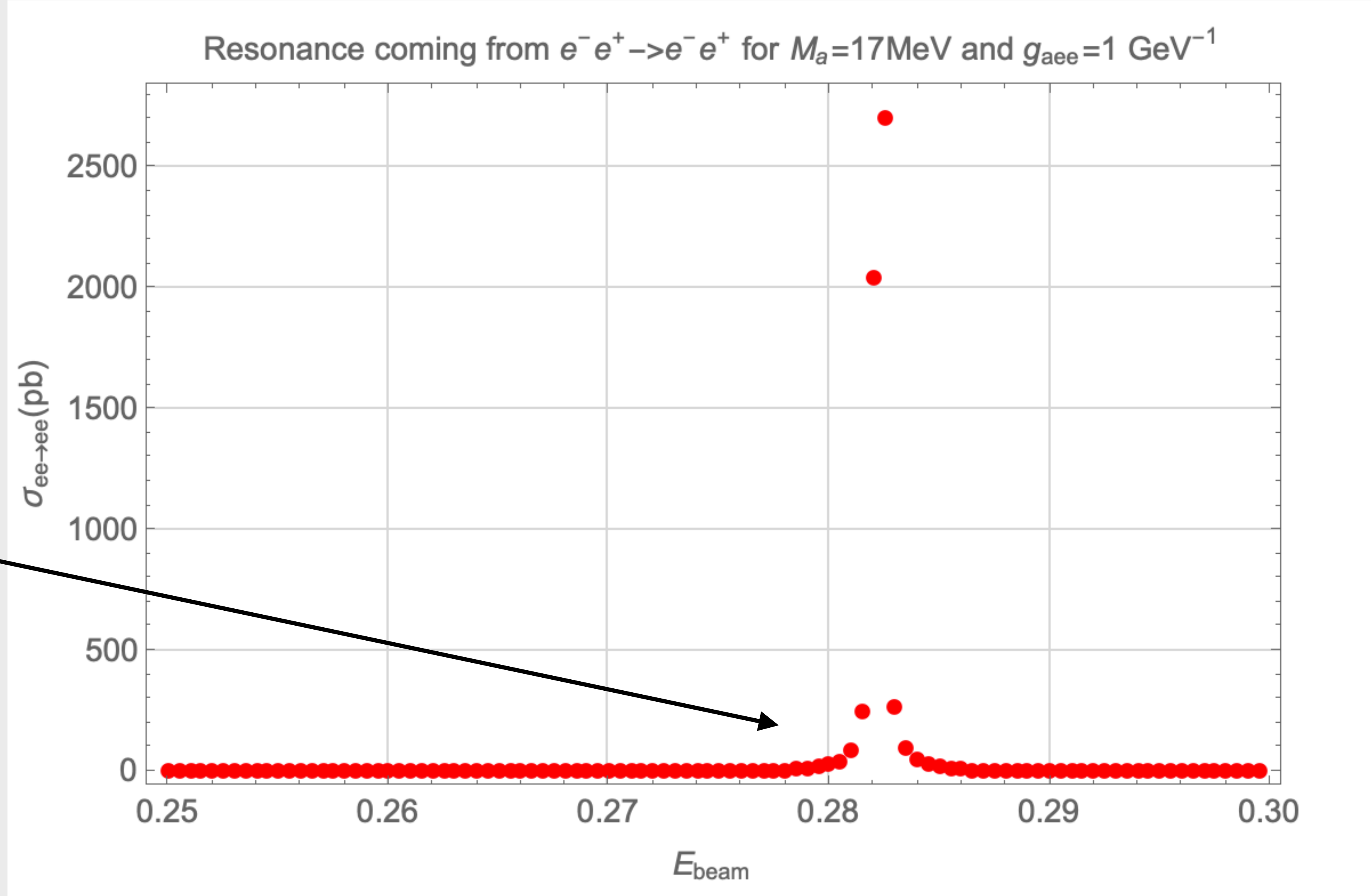






Following the [Nardi et al. '18], and using the narrow width approximation, the cross-section can be written:

$$\sigma_{res} = \sigma_{peak}\frac{\Gamma^2_{ee}/4}{(\sqrt{s} - Ma)^2 + \Gamma^2_{ee}/4} \rightarrow E_{beam} \simeq 0.282268 \text{ at } M_a = 17MeV$$



How many event we have with a thin target of PADME?
And how reduce the background (Bhabha)?

WORK IN PROGRESS

Conclusion

- Not only WIMP searches, but also Light Dark Matter is really interesting.
- *Intensity Frontier* experiment are increasing the interest.
- PADME is a promising 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 exclusion plot.
- Beryllium anomaly in thin target.

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

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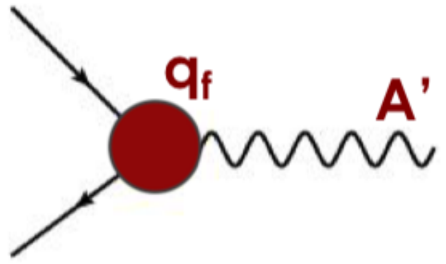
- Portal: The Portal between visible and invisible sector is allowed by a kinetic mixing term (B. Holdom Phys.Lett. B166 (1986) 196) between the QED photon and the dark photon (after the EW symmetry breaking):

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

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

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

$$\partial_\mu + igT_3 W_{3\mu} + ig_Y \frac{Y}{2} B_{Y\mu} + ig'Q'B'_\mu$$

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

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.

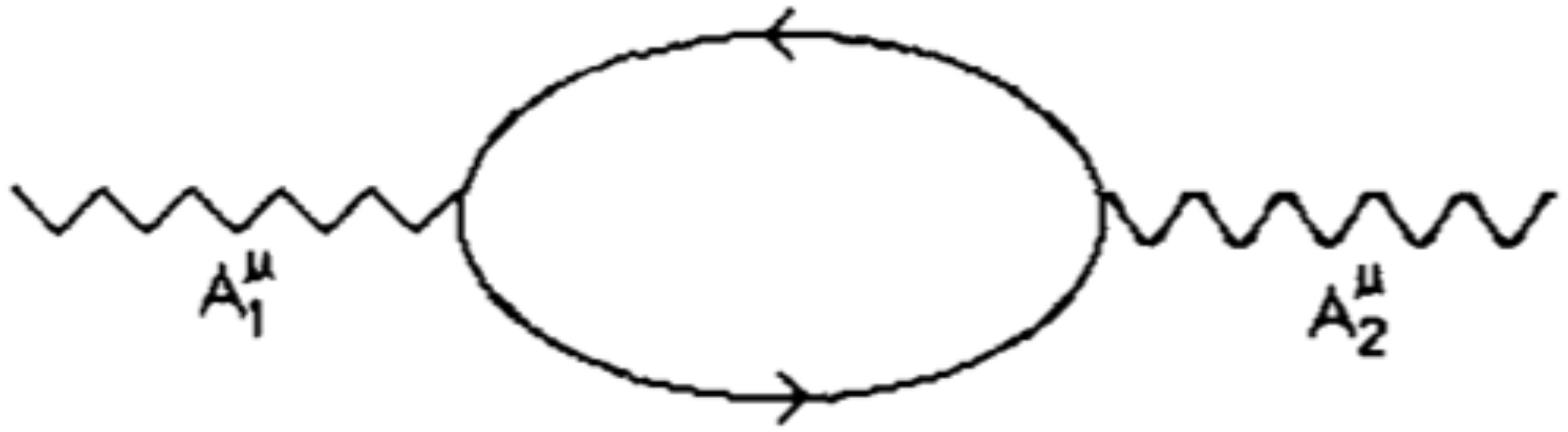
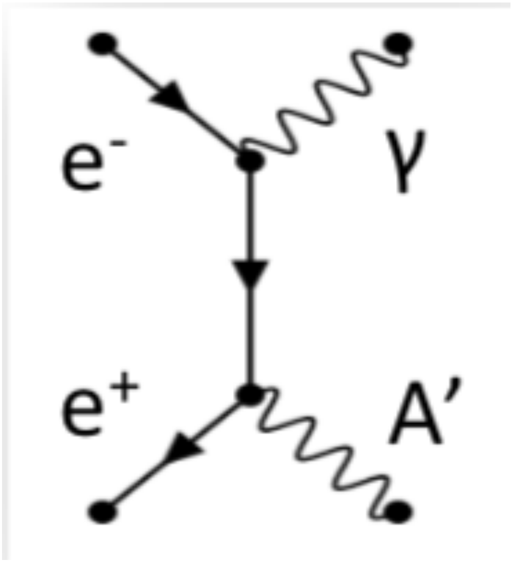


Fig. 1.

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.

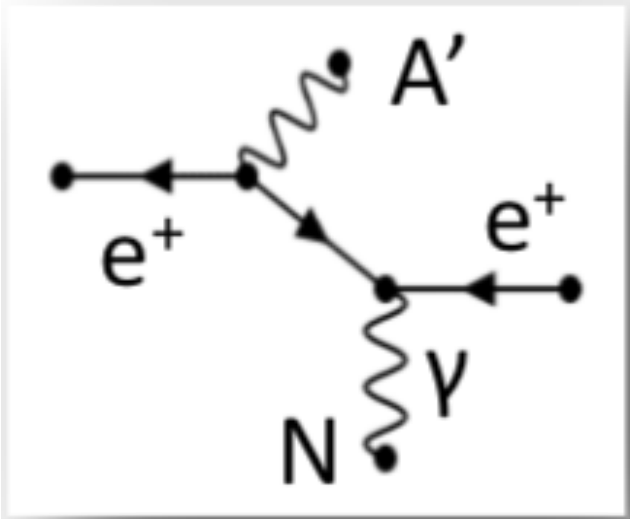
DARK PHOTON PRODUCTION IN e^+ AND e^- PROCESSES:

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



✓

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



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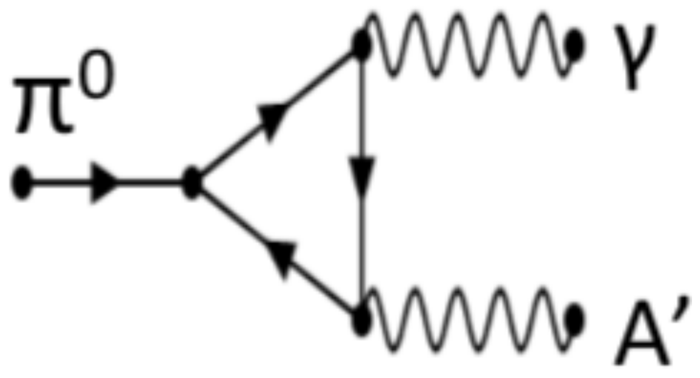
- MESON DECAY: $\pi^0/\eta/\eta' \rightarrow \gamma A'$

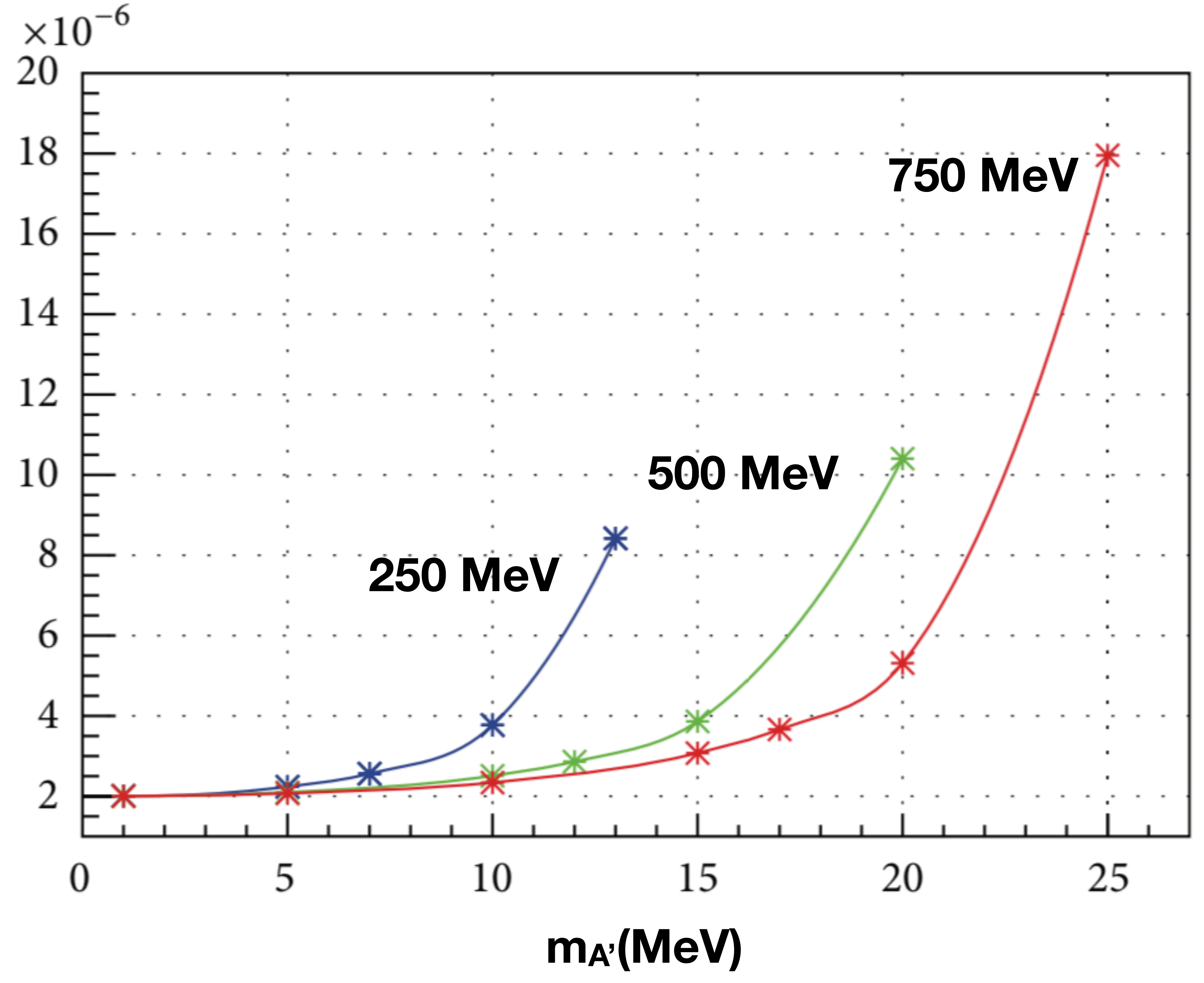


✗

Dark Photon in PADME

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

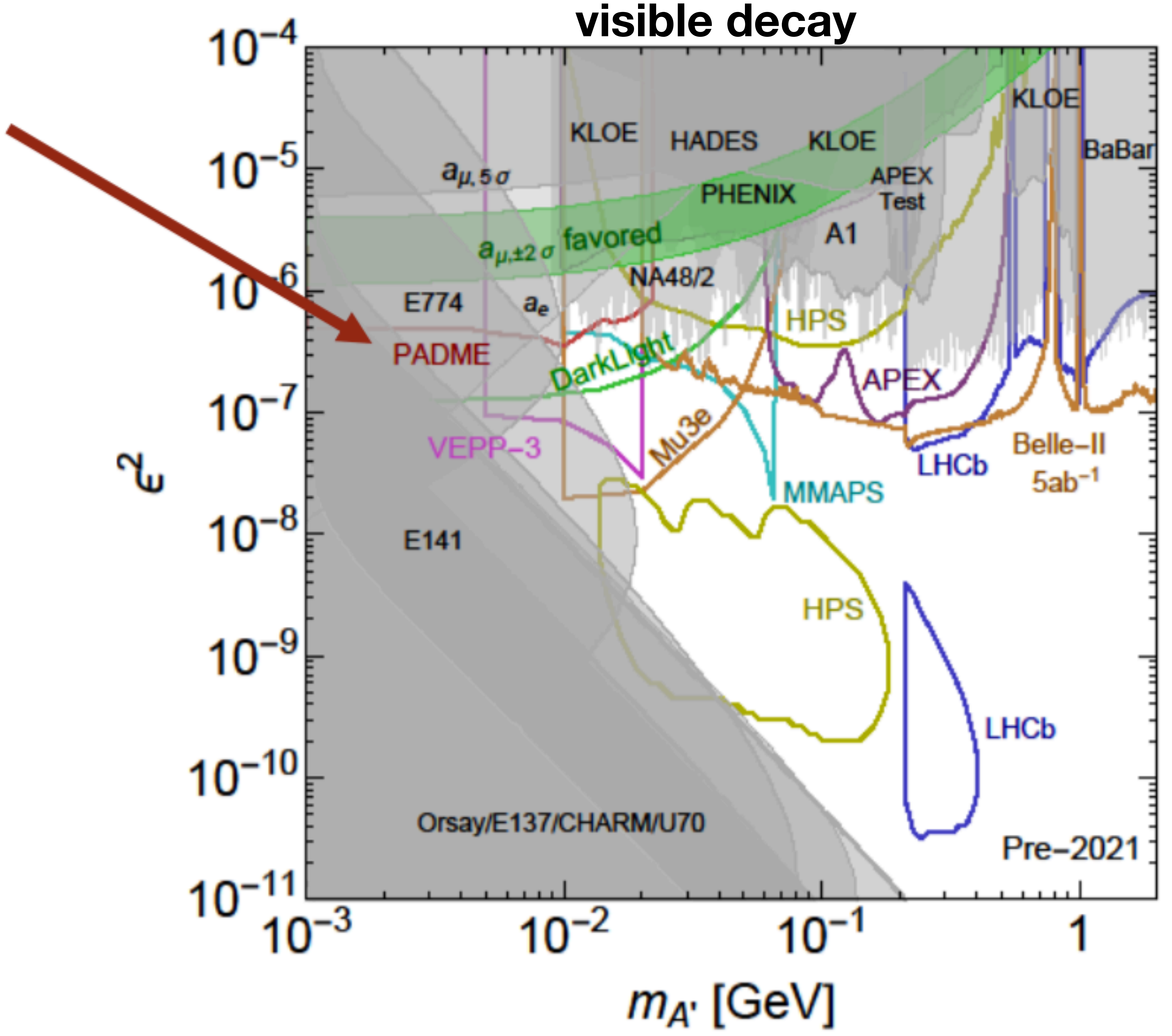
Cross-section enhancement with the approach of the production threshold

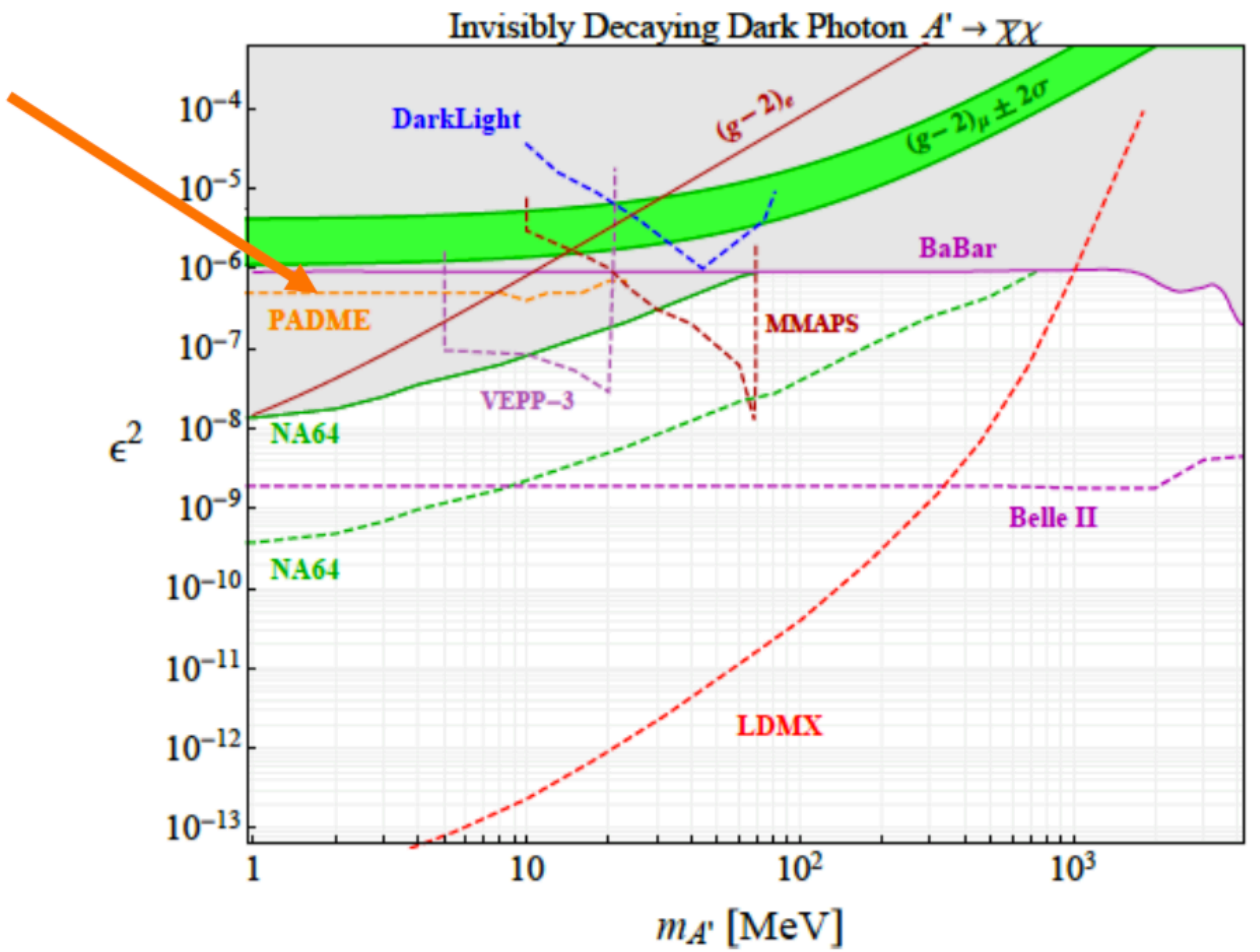


Dark Photon in PADME

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

visible decay





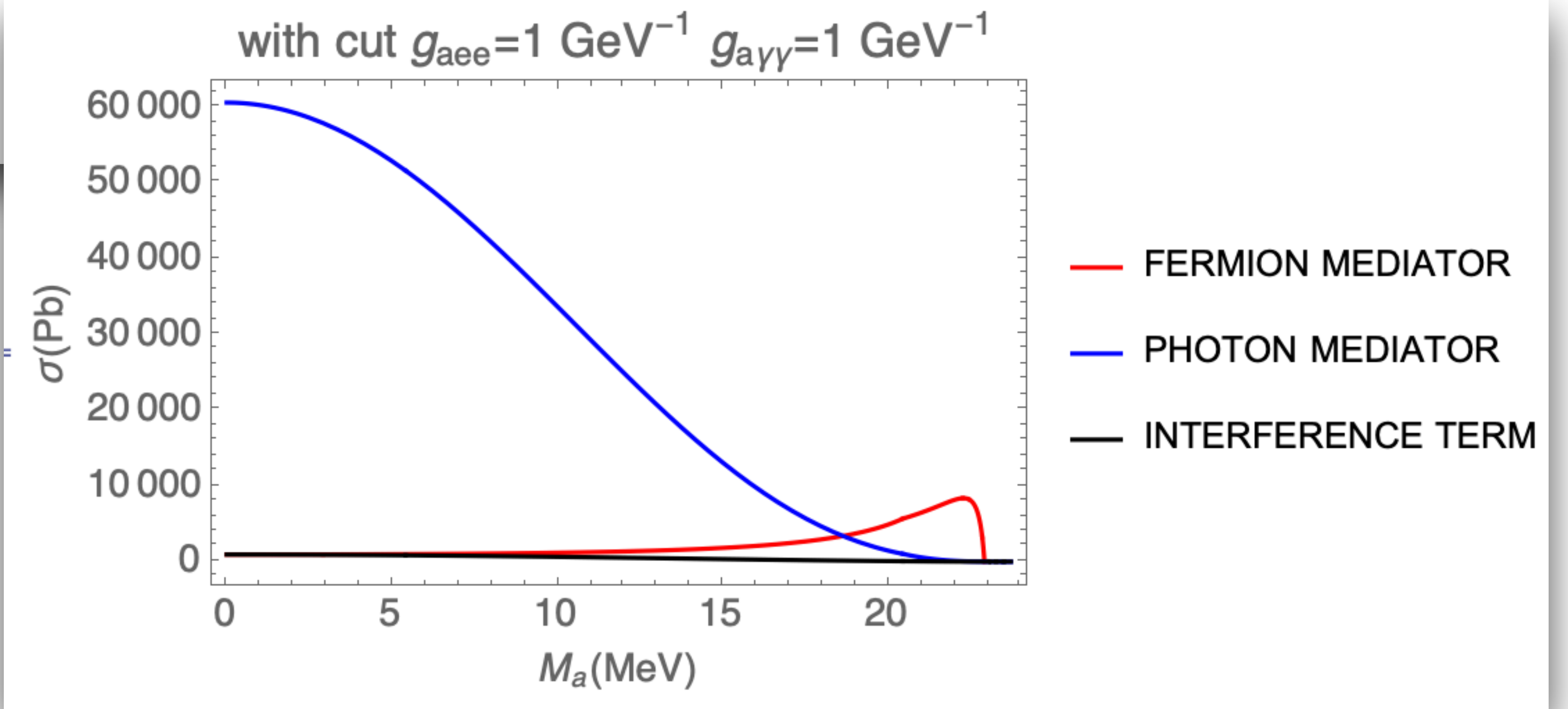
$e^+e^- \to a + \gamma$ in PADME

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

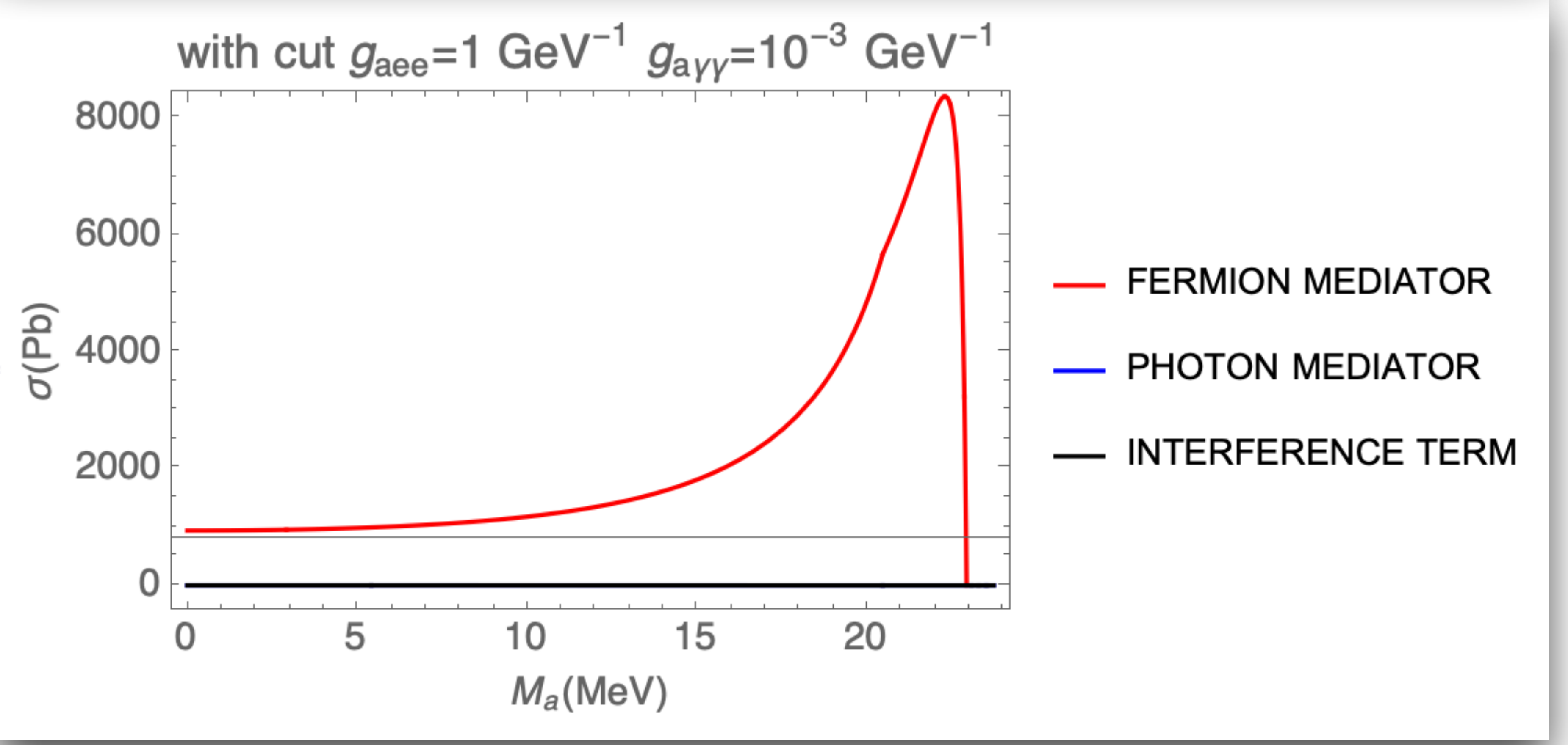
$$+ \alpha\, g_{a\gamma\gamma}\, g_{aee}\, m_e^2 \frac{(s-m_a^2)^2}{2\,\beta^2\, s^3}\log\frac{1+\beta}{1-\beta}$$

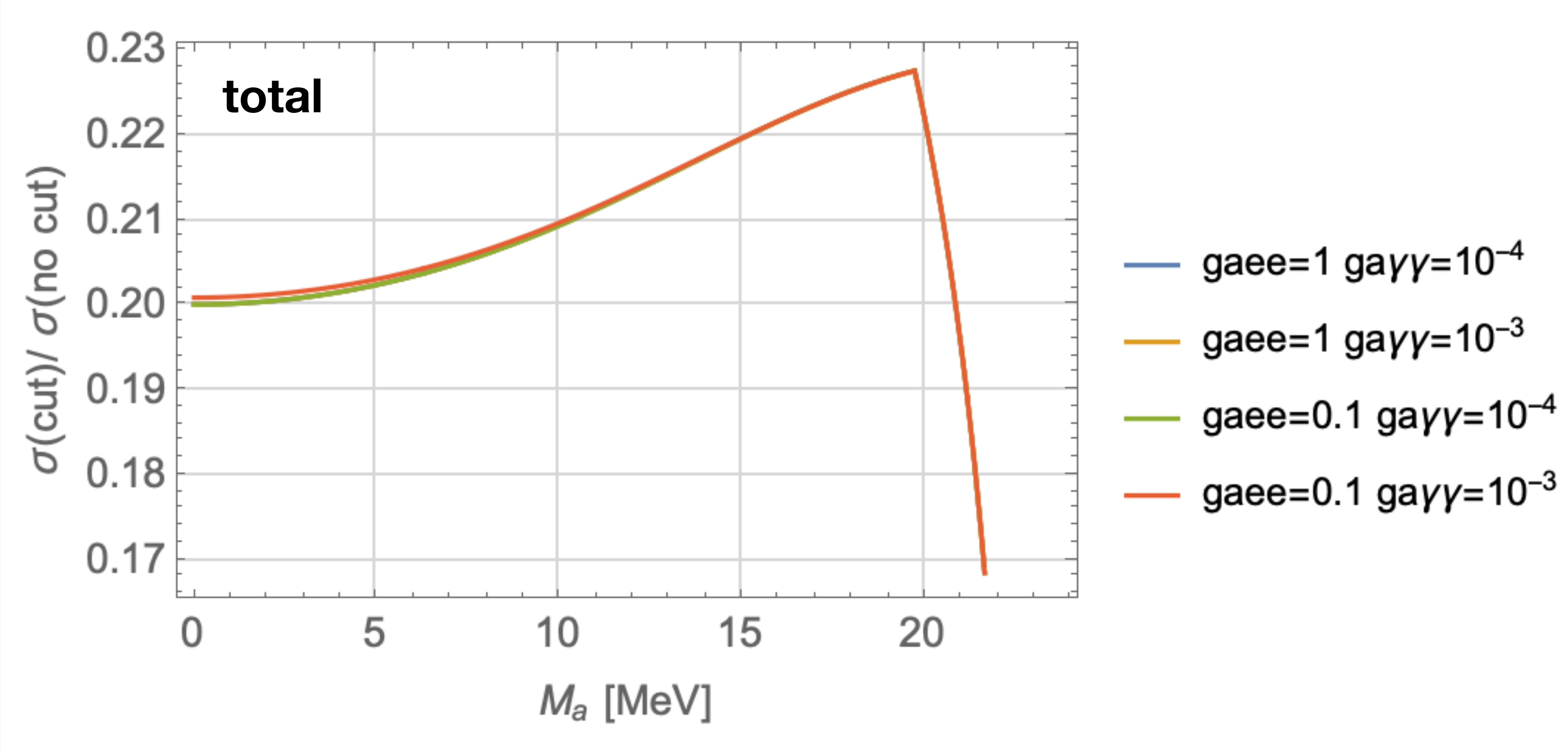
with $\beta = \sqrt{1-\frac{4m_e^2}{s}}$.

- Considering the angular acceptance of ECAL (20<θ<83 mrad), Energy beam of 550 MeV and photon energy larger than 30 MeV

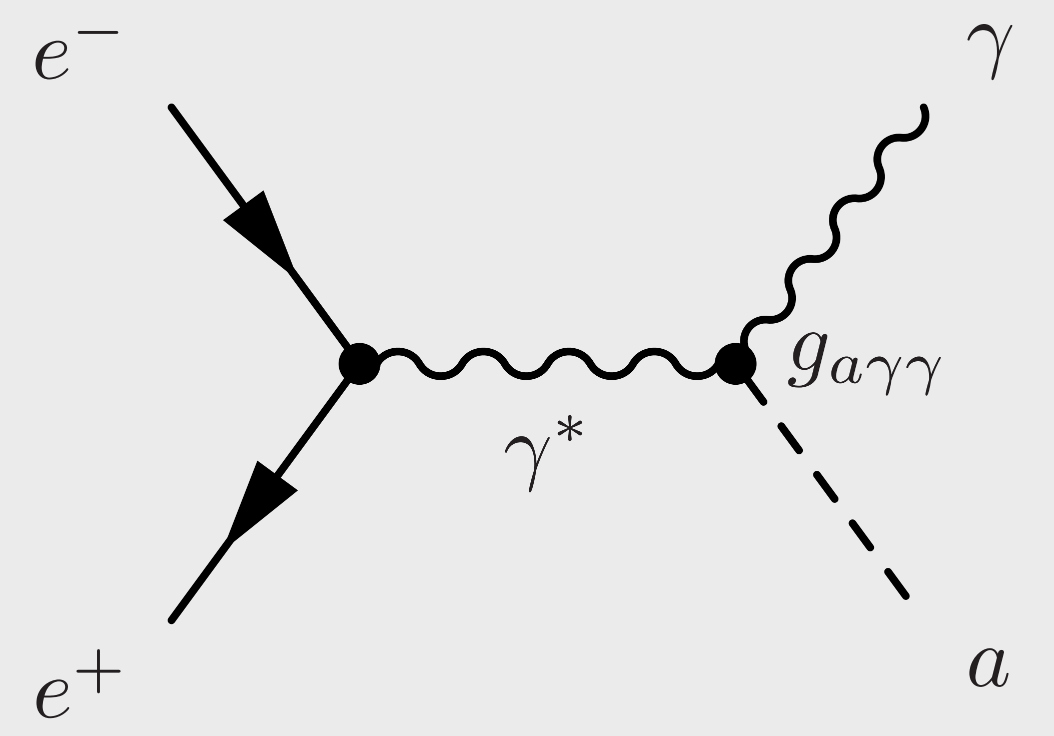


but considering current constraints on couplings →

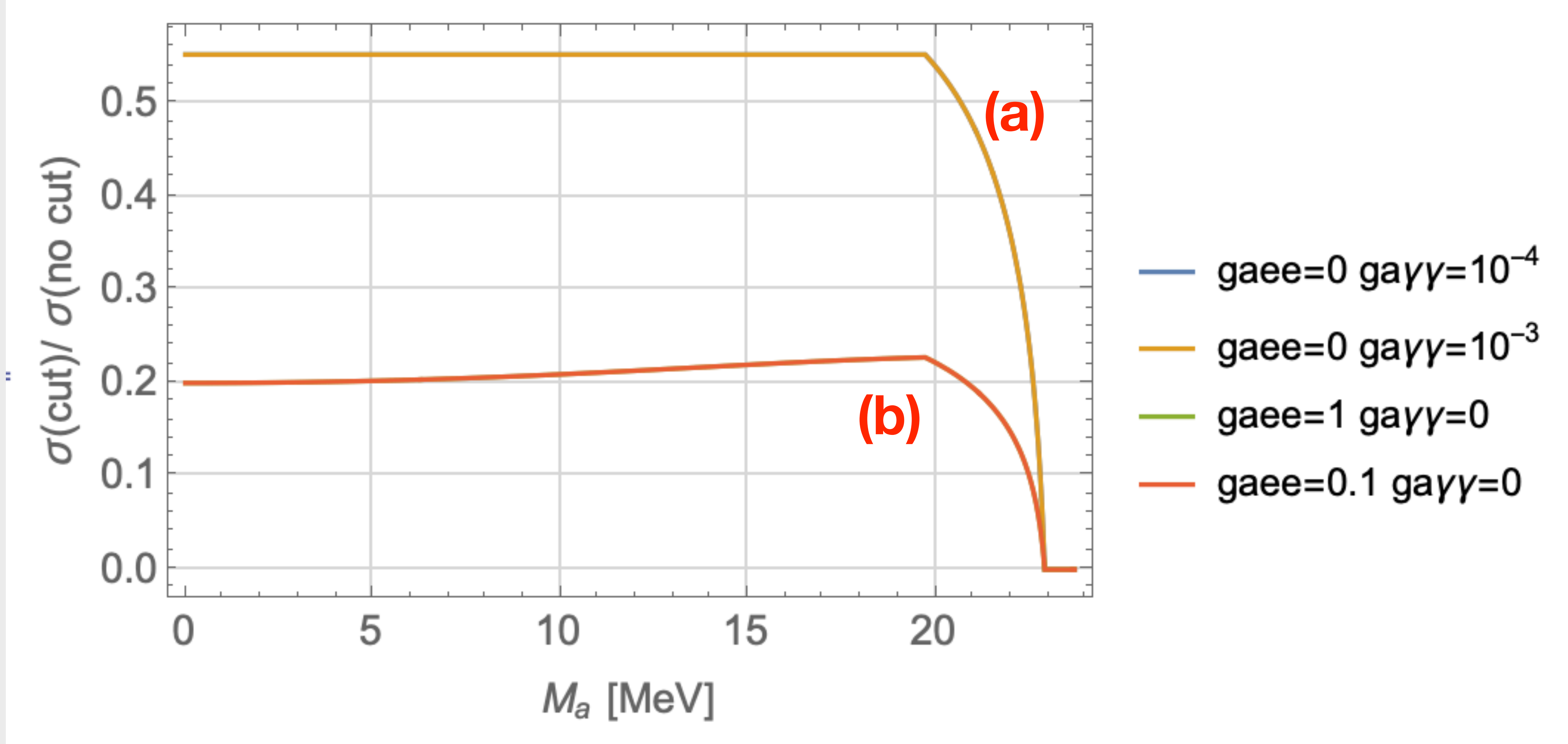


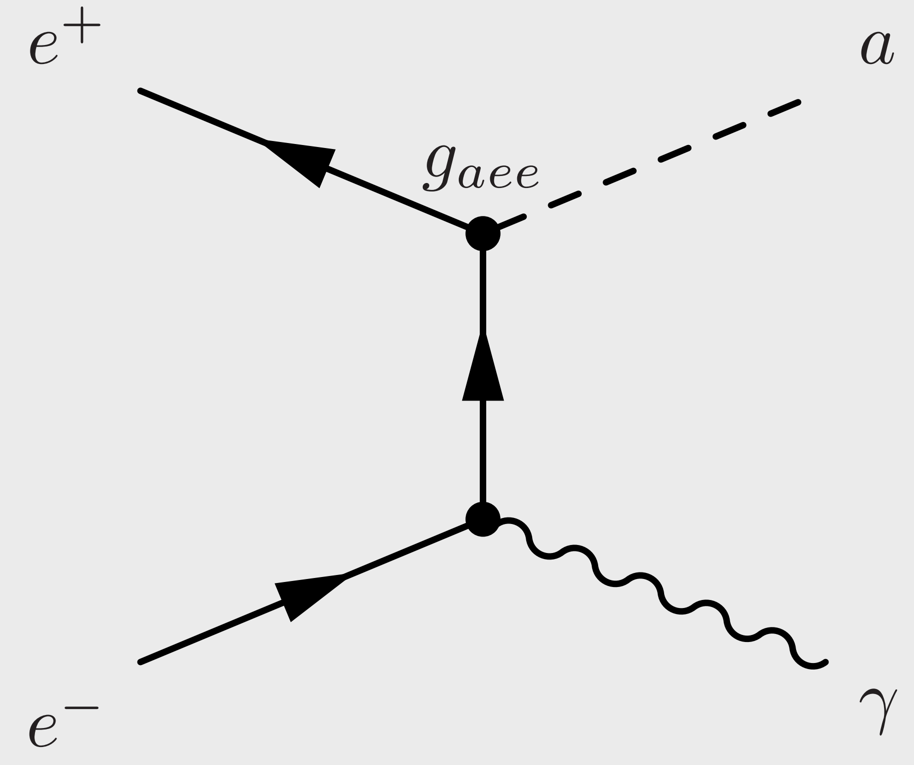


Ratio between the cross-section with cut $0.02 \leq \theta \leq 0.093$ and $E_\gamma > 30$ MeV and cross-section without cut in function of the ALP mass (M_a) for different values of coupling



(a)



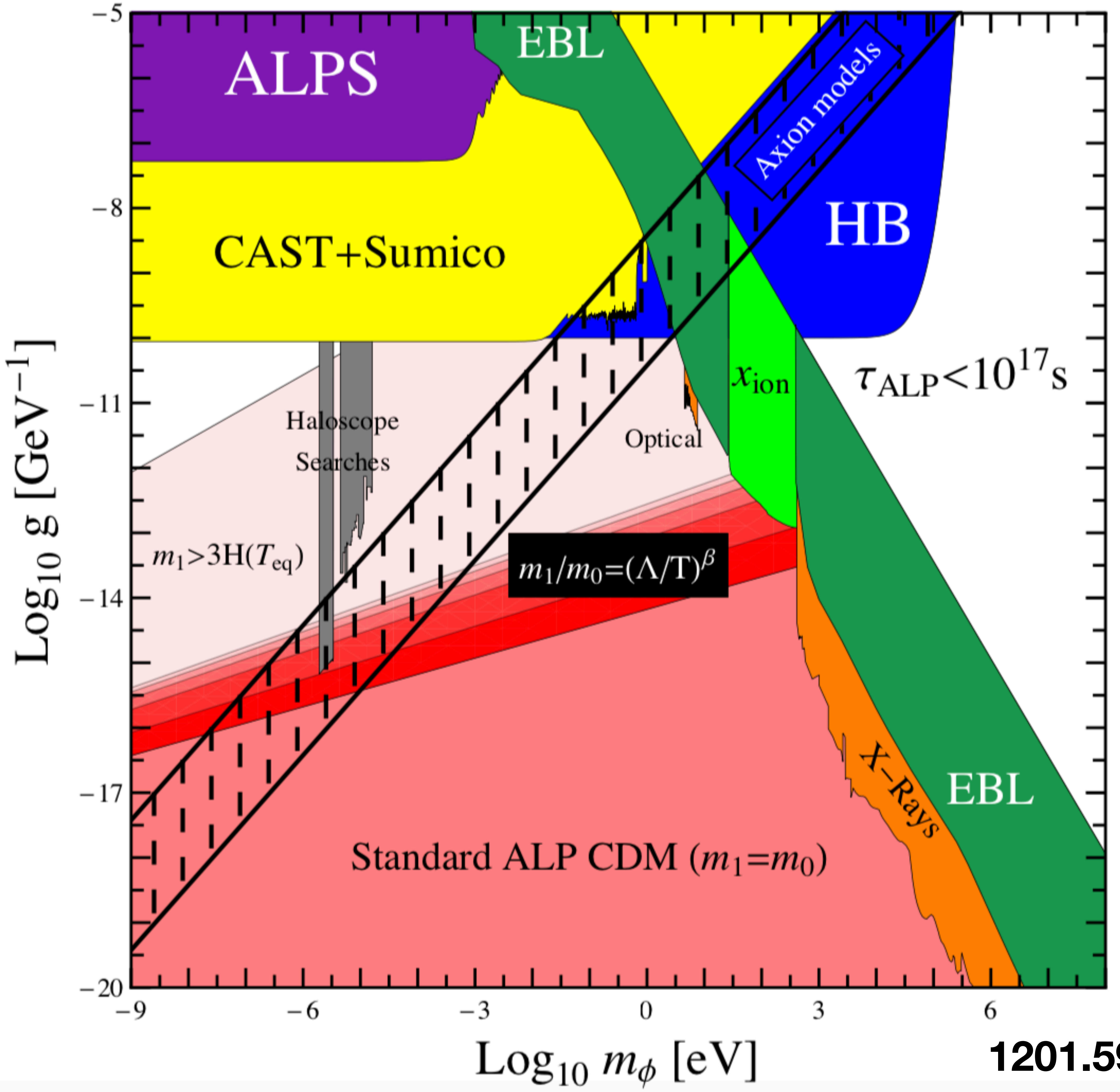


(b)

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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