

PHOTON 2019

INTERNATIONAL CONFERENCE ON THE STRUCTURE AND THE INTERACTIONS OF THE PHOTON

06/06/2019

FEDERICA GIACCHINO LNF-INFN



A LIGHT DARK MATTER PORTAL: THE AXION-LIKE PARTICLE

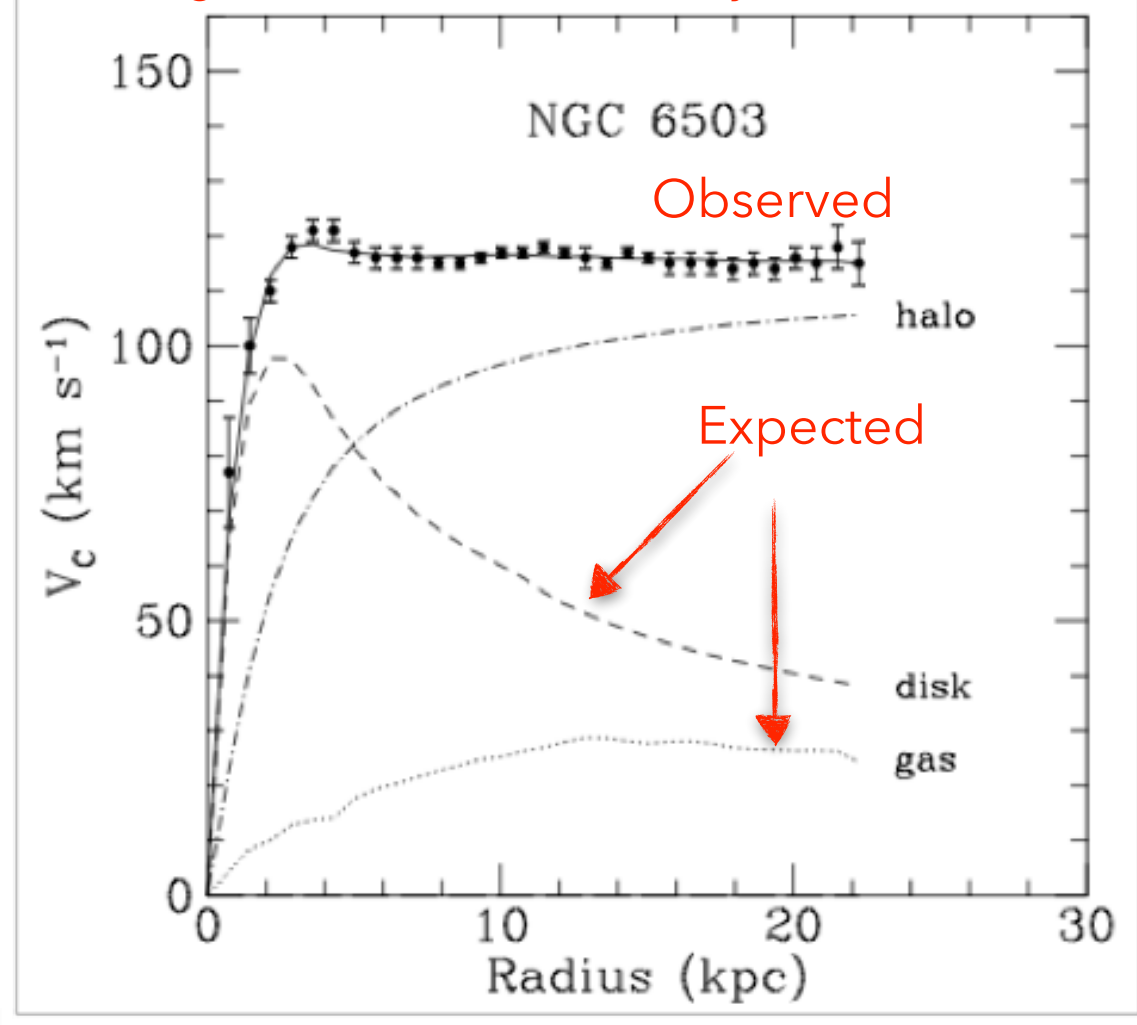
TABLE OF CONTENTS

- ▶ *INTRO TO DARK MATTER*
- ▶ *LIGHT DARK MATTER PORTALS*
- ▶ *AXION-LIKE PARTICLES*
- ▶ *SEARCH FOR ALP: PADME EXPERIMENT AND ITS PHENOMENOLOGY*

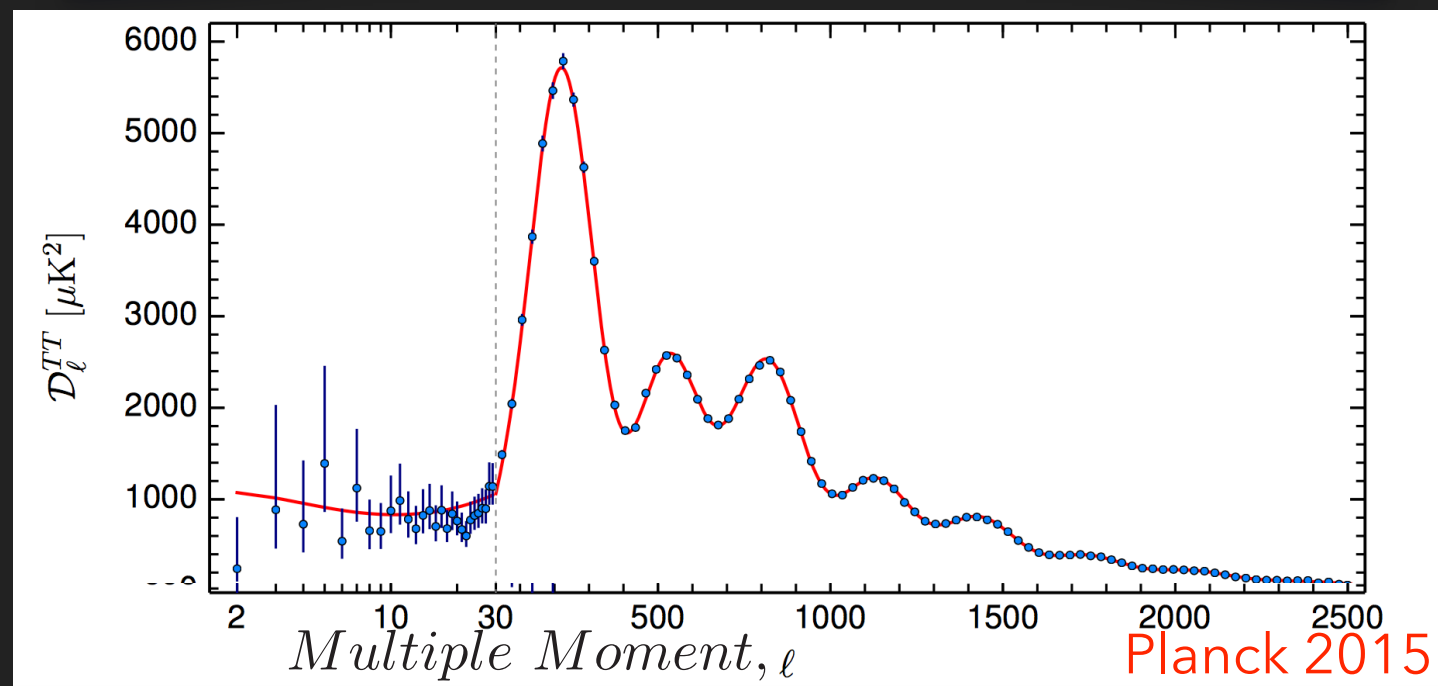
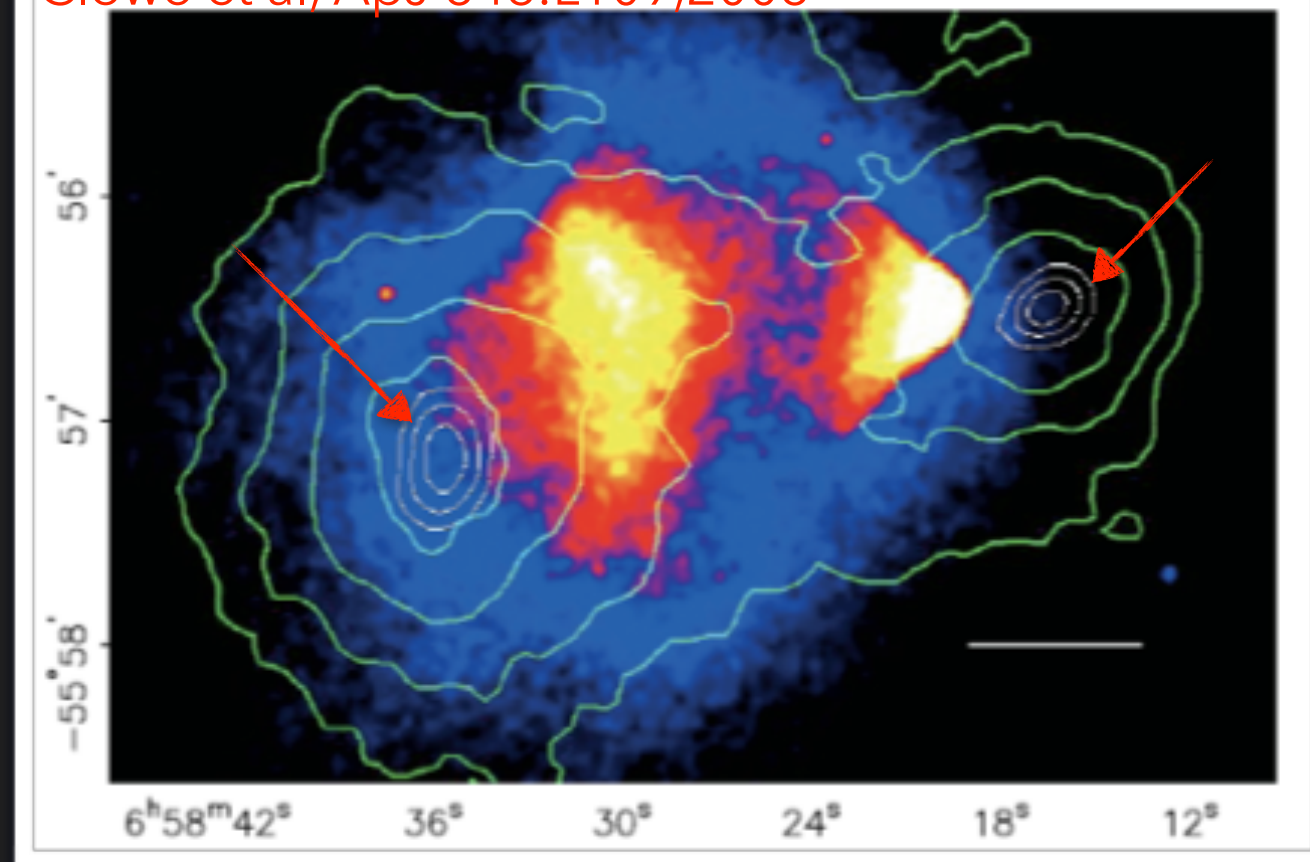
WHY DARK MATTER:

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

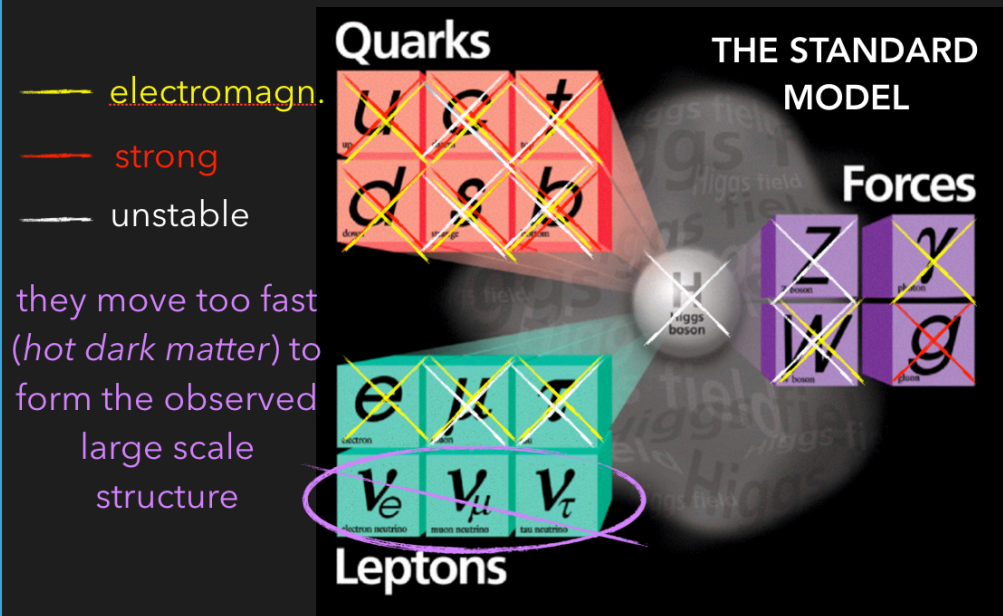
K. G. Begeman et al, Mon.Not.Roy.Astron.Soc. 249



Clowe et al, ApJ 648:L109,2006



WHAT IS THE DARK MATTER:



PROPERTIES

ITS RELIC ABUNDANCE Planck 2015

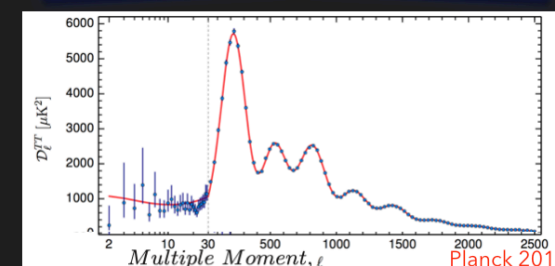
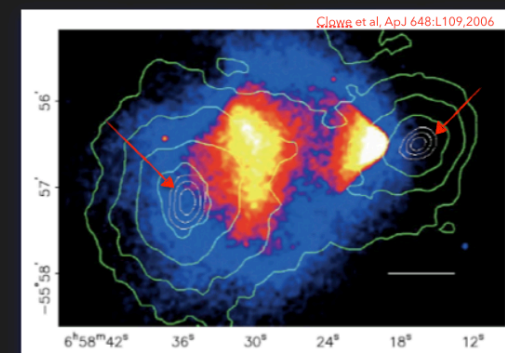
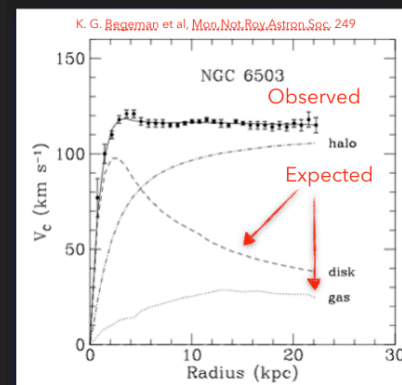
$$\Omega_{DM} h^2 = 0.1198 \pm 0.0015$$

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 MATTER:

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





SIMPLIFIED MODEL:

- ▶ extension to SM w/ only the relevant parameters
- ▶ not considering what happens at UV-scale
- ▶ opening the possibility to directly produce the mediator

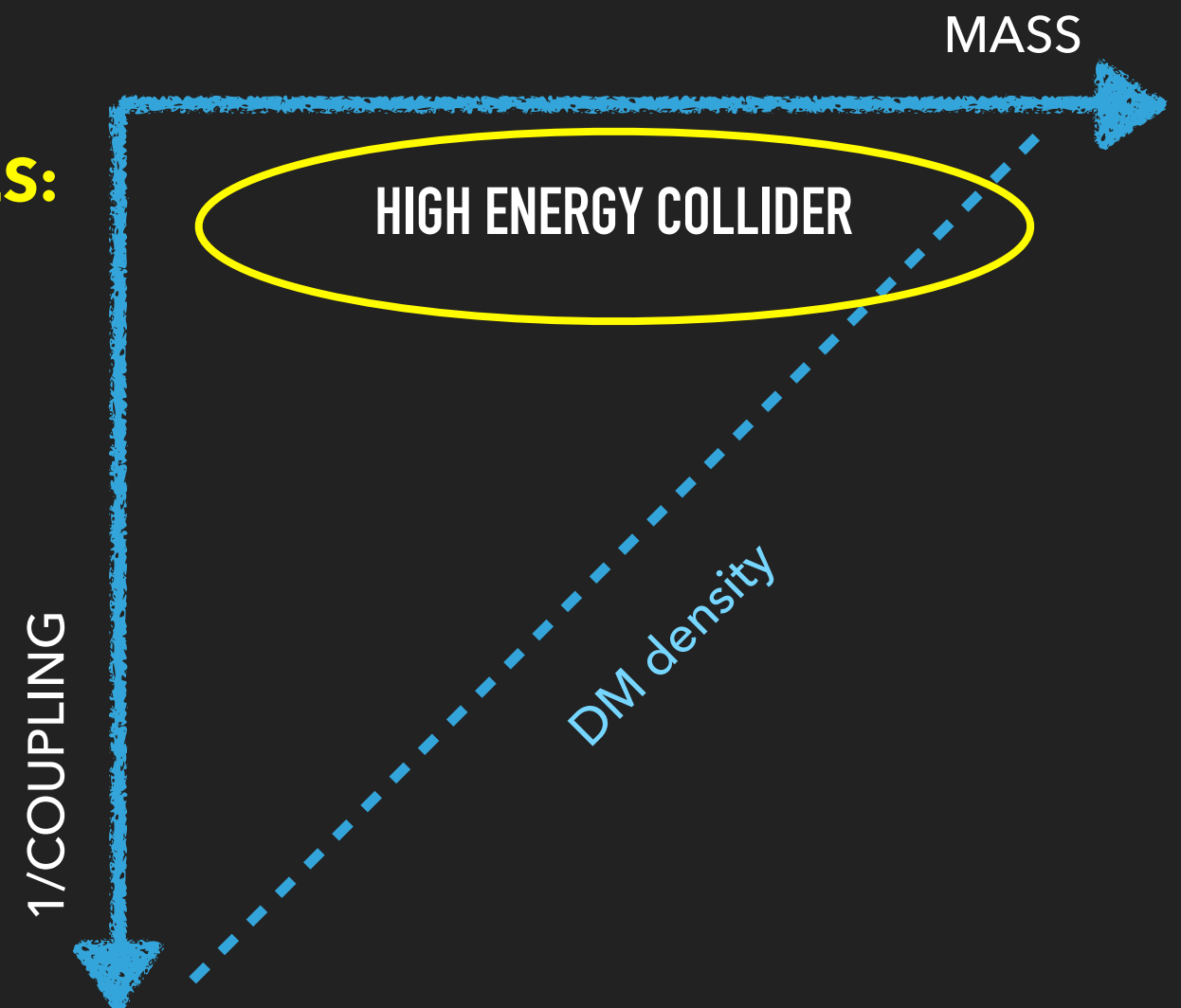


WEAKLY INTERACTIVE MASSIVE PARTICLES:

thermally produced in Early Universe with masses at GeV-TeV and annihilation cross-section of electroweak scale.

see also C. Weniger' talk

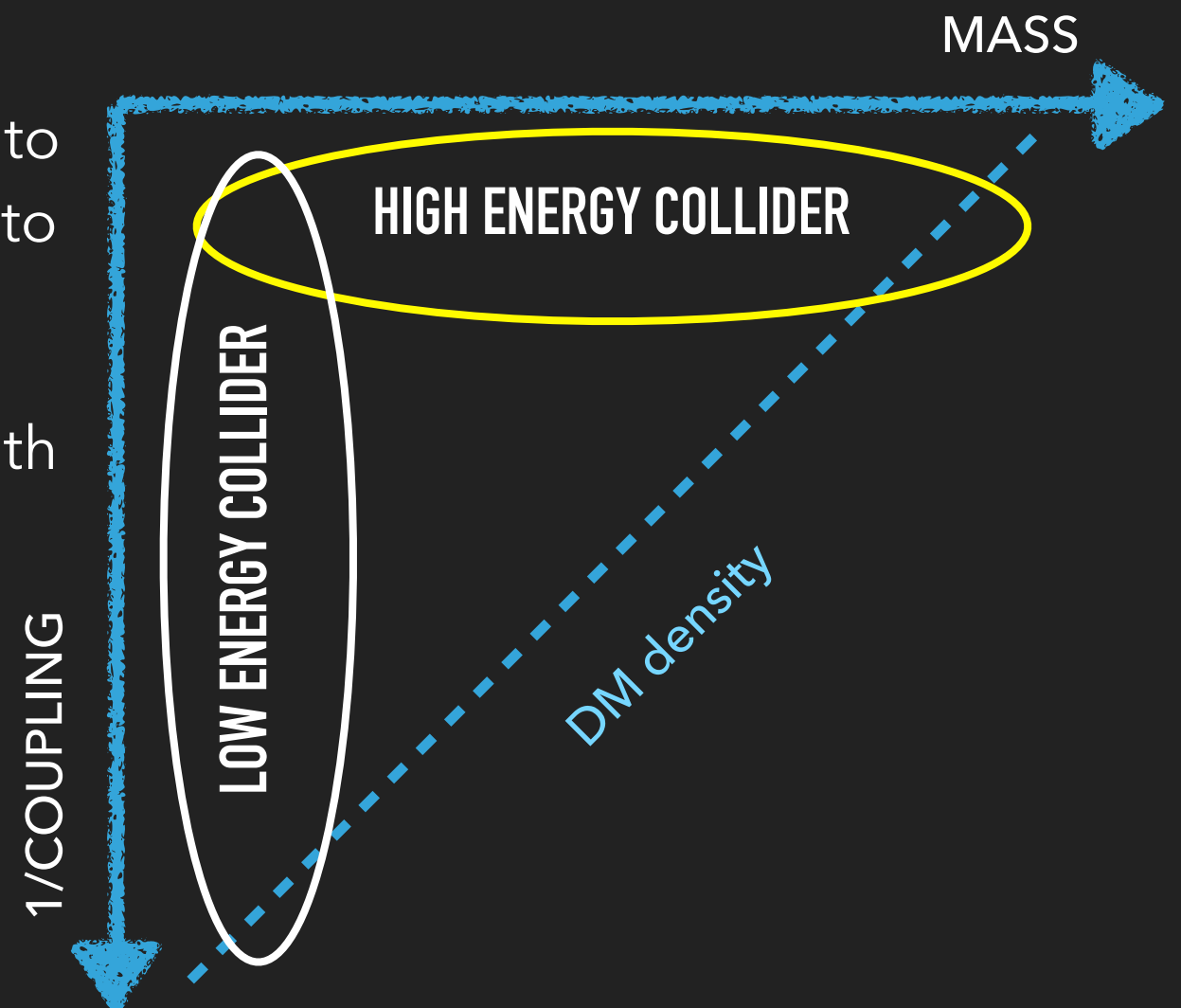
BUT NO CONVINCING SIGNAL



**STANDARD
MODEL SECTOR****PORTAL****DARK SECTOR**

Low-energy frontier experiments are starting to probe light masses and very feebly coupling to SM with high-intensity.

see Chu' talk "Light Dark States associated with photons"



AXION-LIKE PARTICLE (ALP)

**GENERALISATION OF
AXION PARTICLE:**

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry

Motivated by string theories [*Arvanitaki 2010, Cicoli 2012*], proposed in many extensions to the SM to address open problem as Strong-CP Problem [*Peccei&Quinn 1977, Hook 2014, Fukuda et al. 2015*] or Hierarchy Problem [*Graham et al. 2015*], possible solution for the muon magnetic moment anomaly [*Chang et al. 2001, Marciano et al. 2016*]

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry



NOT NECESSARILY THE QCD AXION:

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry



NOT NECESSARILY THE QCD AXION:
so mass and couplings are independent
parameters

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry



NOT NECESSARILY THE QCD AXION:
so mass and couplings are independent
parameters

⇒ Wide Mass Range: at masses $< \text{MeV}$ implications for cosmology and astrophysics (see Galanti's talk), at $\gtrsim \text{MeV}$ they have implications in particle physics

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM

} pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry



NOT NECESSARILY THE QCD AXION:
so mass and couplings are independent
parameters

⇒ Wide Mass Range: at masses $< \text{MeV}$ implications for cosmology and astrophysics (see Galanti's talk), at $\gtrsim \text{MeV}$ they have implications in particle physics

⇒ Role in the dark sector: dark matter (WISPy) or portal

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry



NOT NECESSARILY THE QCD AXION:
so mass and couplings are independent
parameters

⇒ Wide Mass Range: at masses $< \text{MeV}$ implications for cosmology and astrophysics (see Galanti's talk), at $\gtrsim \text{MeV}$ they have implications in particle physics

⇒ Role in the dark sector: dark matter (WISPy) or **portal**

AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:

- ▶ Light
- ▶ Pseudo-scalar Particle
- ▶ Derivative Coupling to SM



pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry



NOT NECESSARILY THE QCD AXION:
so mass and couplings are independent
parameters

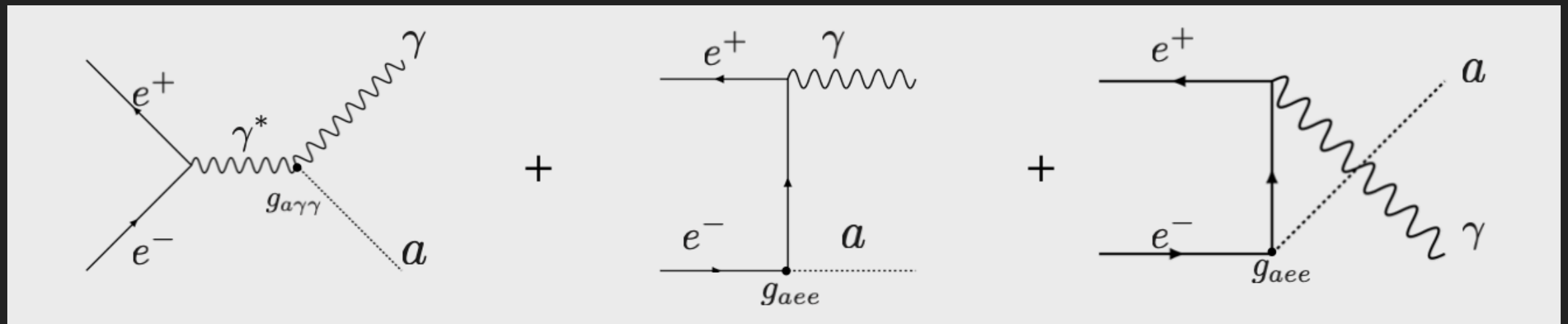
Increasing interest for experimental searches at accelerators: assuming a leptophilic ALP $\Rightarrow$ Lepton beam/fixed target, e.g. PADME,...

Lepton Beam/Collider, e.g. Belle II,...

HOW TO DETECT IT? ACCELERATOR PHYSICS (JUST ASSUME LEPTOPHILIC ALP)

The effective ALP Lagrangian [assumed valid for scales $< O(\text{TeV})$]:

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



HOW TO DETECT IT? ACCELERATOR PHYSICS (JUST ASSUME LEPTOPHILIC ALP)

The effective ALP Lagrangian [assumed valid for scales $< O(\text{TeV})$]:

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

► visible decay $a \rightarrow l^+ l^-, \gamma\gamma$ at $M_{dm} > M_a/2$:

signal: $\gamma\gamma\gamma, e^+/e^- + \gamma$

HOW TO DETECT IT? ACCELERATOR PHYSICS (JUST ASSUME LEPTOPHILIC ALP)

The effective ALP Lagrangian [assumed valid for scales $< O(\text{TeV})$]:

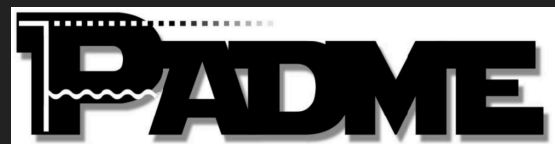
$$\mathcal{L}_{alp} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} M_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - i g_{aee} m_e a \bar{\psi} \gamma^5 \psi + \mathcal{L}_{DM}$$

- ▶ visible decay $a \rightarrow l^+ l^-, \gamma\gamma$ at $M_{dm} > M_a/2$:

signal: $\gamma\gamma\gamma, e^+/e^- + \gamma$

- ▶ invisible: long-lived or portal $a \rightarrow DM DM$ at $M_{dm} < M_a/2$:

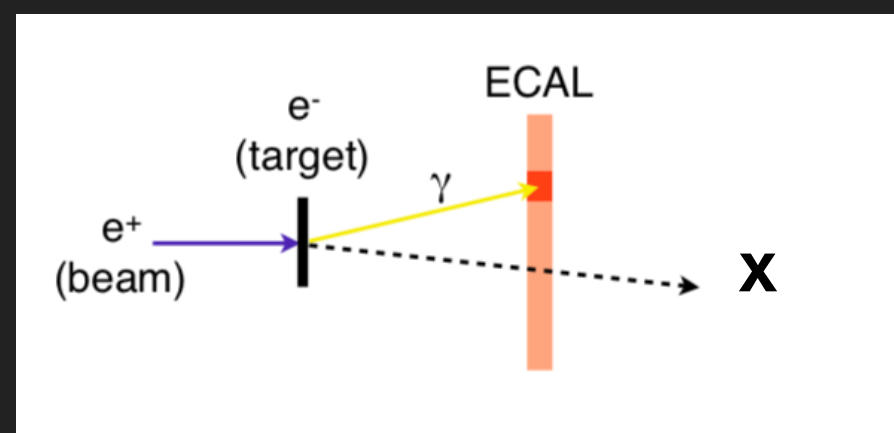
signal: $1\gamma + \text{missing energy/momentum/mass}$



EXPERIMENT (SEE CLARA TARUGGI' TALK)

It is a Positron Annihilation into Dark Matter Experiment which searches the **light dark particle** using a positron beam on a thin diamond target, detecting the SM photon produced in the annihilation reaction:

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



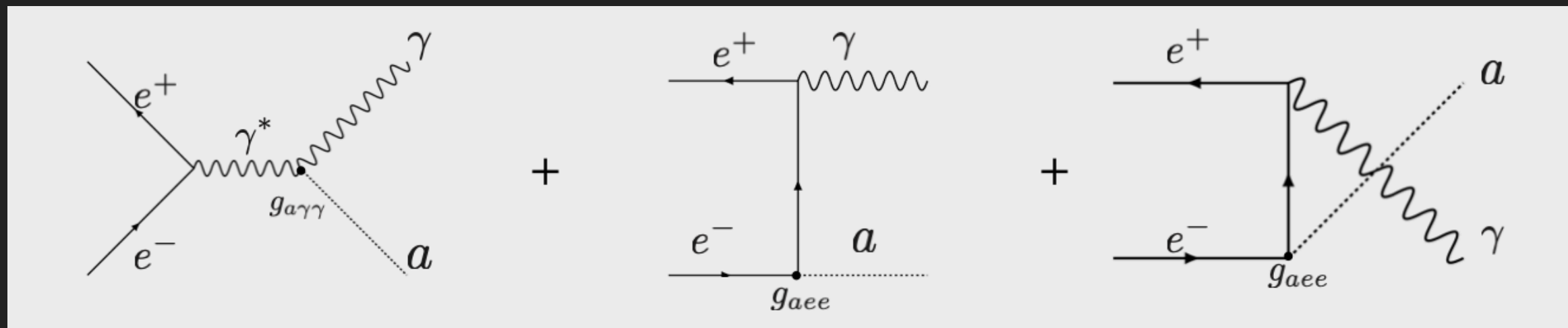
where **X** is the light dark particle and therefore measuring the event as a peak in missing mass:

KNOWING BEAM ENERGY AND POSITION
MEASURING PHOTON ENERGY AND POSITION

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

The PADME technique is completely model independent (it only requires a lepton coupling)

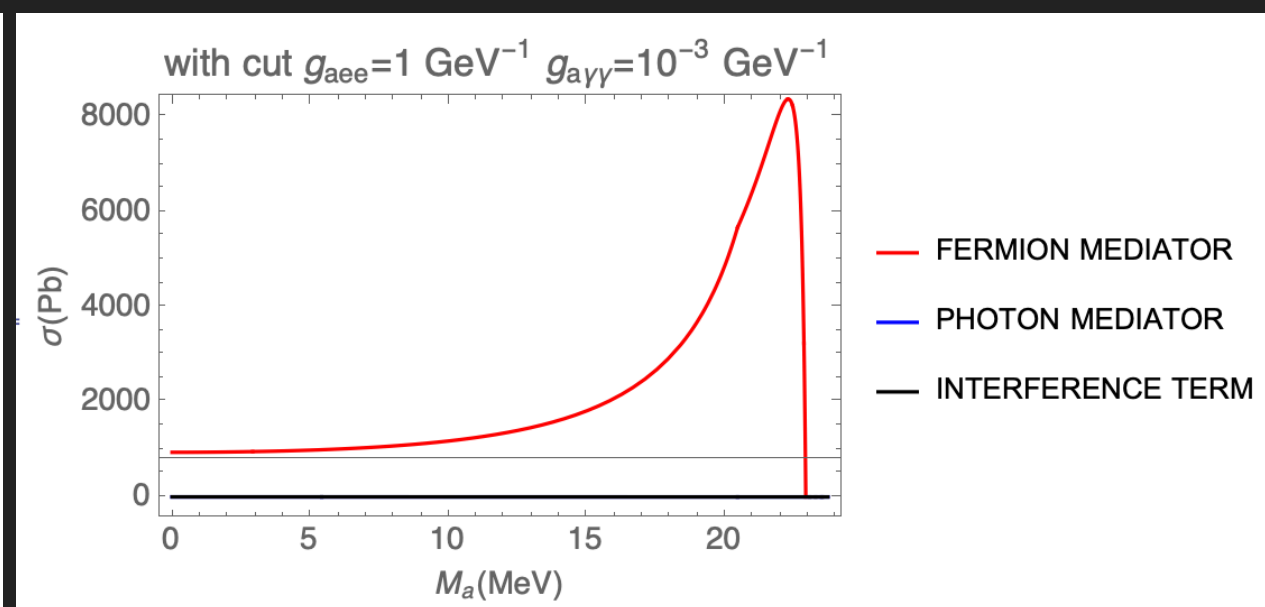
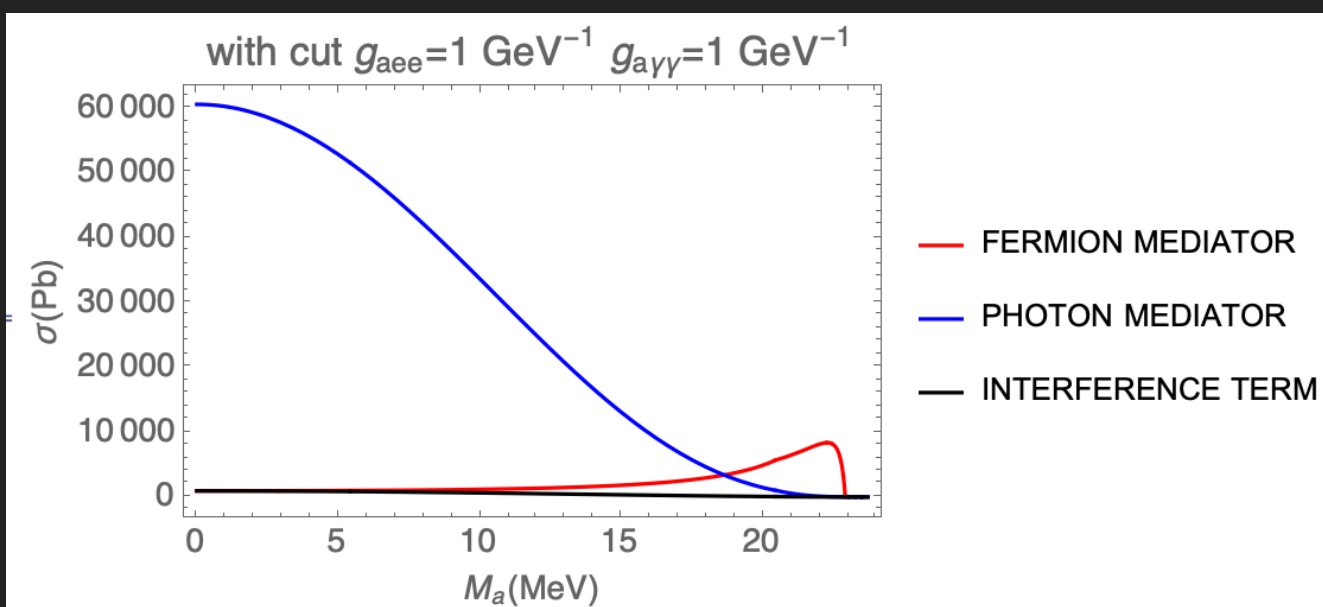
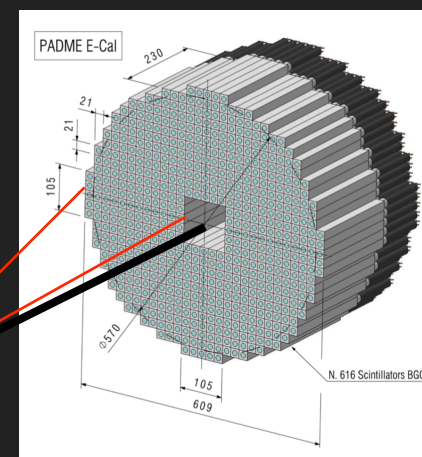
ALP-PHOTON PRODUCTION AT PADME



Beam Energy: 550 MeV

Angular Acceptance of ECAL: $0.026 < \theta(\text{rad}) < 0.083$

CUT: $E_\gamma > 30 \text{ MeV}$



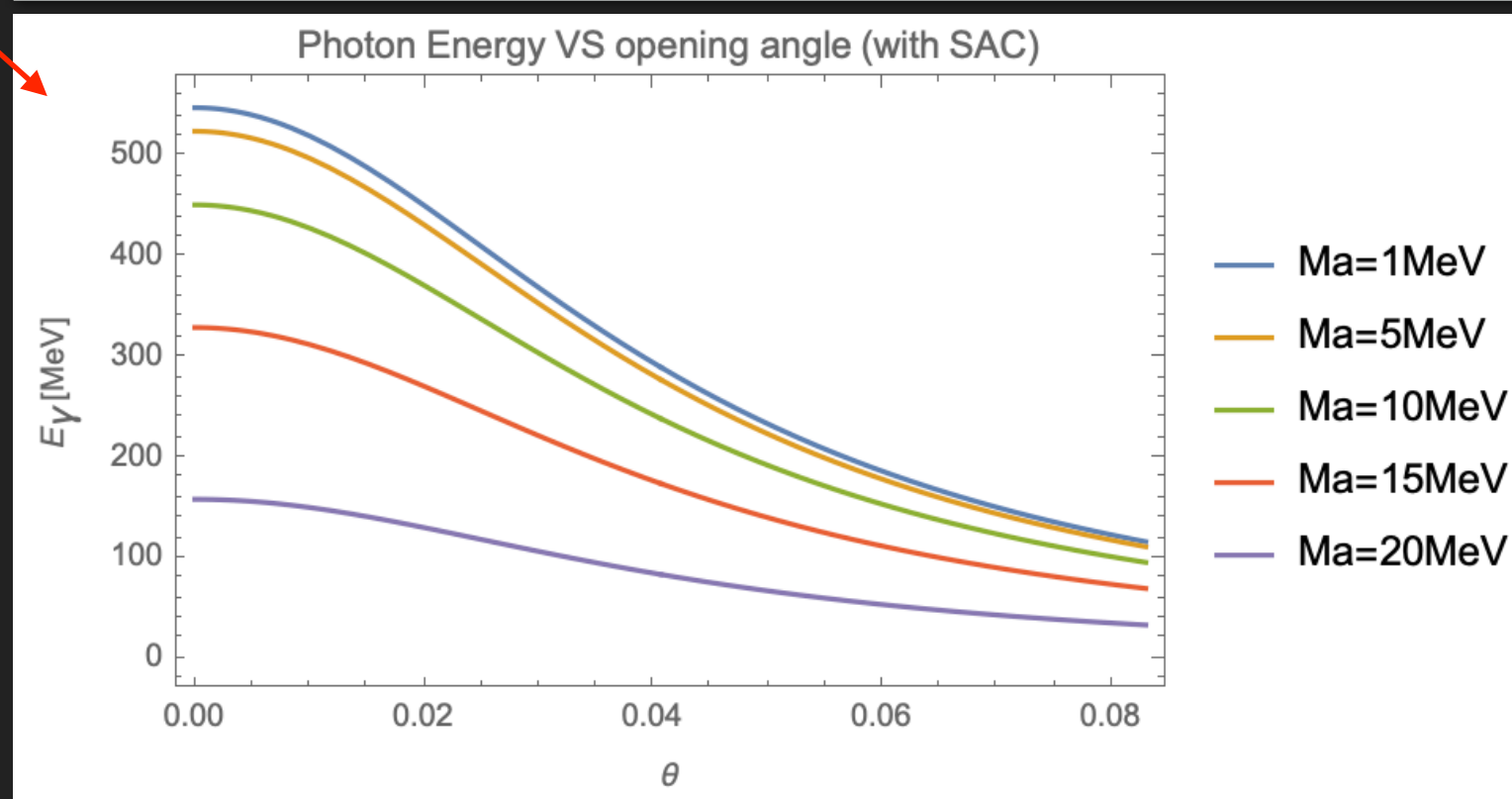
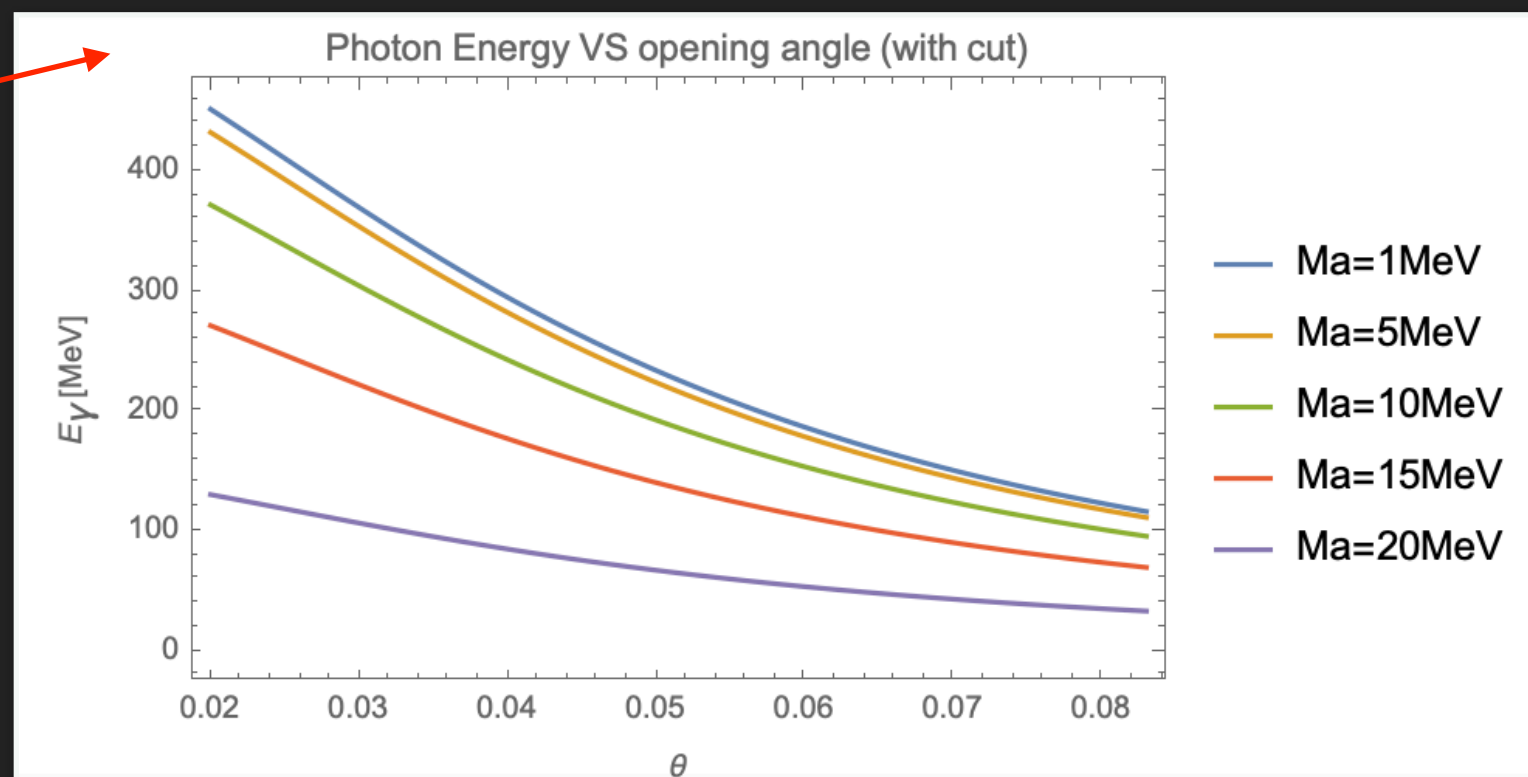
ALP-PHOTON PRODUCTION AT PADME

PADME Cut:

- ▶ $0.026 < \theta(\text{rad}) < 0.083$ and $E_\gamma > 30$ MeV
- ▶ including SAC $0 < \theta(\text{rad}) < 0.083$

COMMENT:

- AT SMALL ANGLES EASIER TO DISTINGUISH THE ALP MASSES
- AT SMALL ALP MASSES THE CALORIMETER RESOLUTION ENERGY IS CRUCIAL IN ORDER TO DISTINGUISH THE DARK PARTICLE

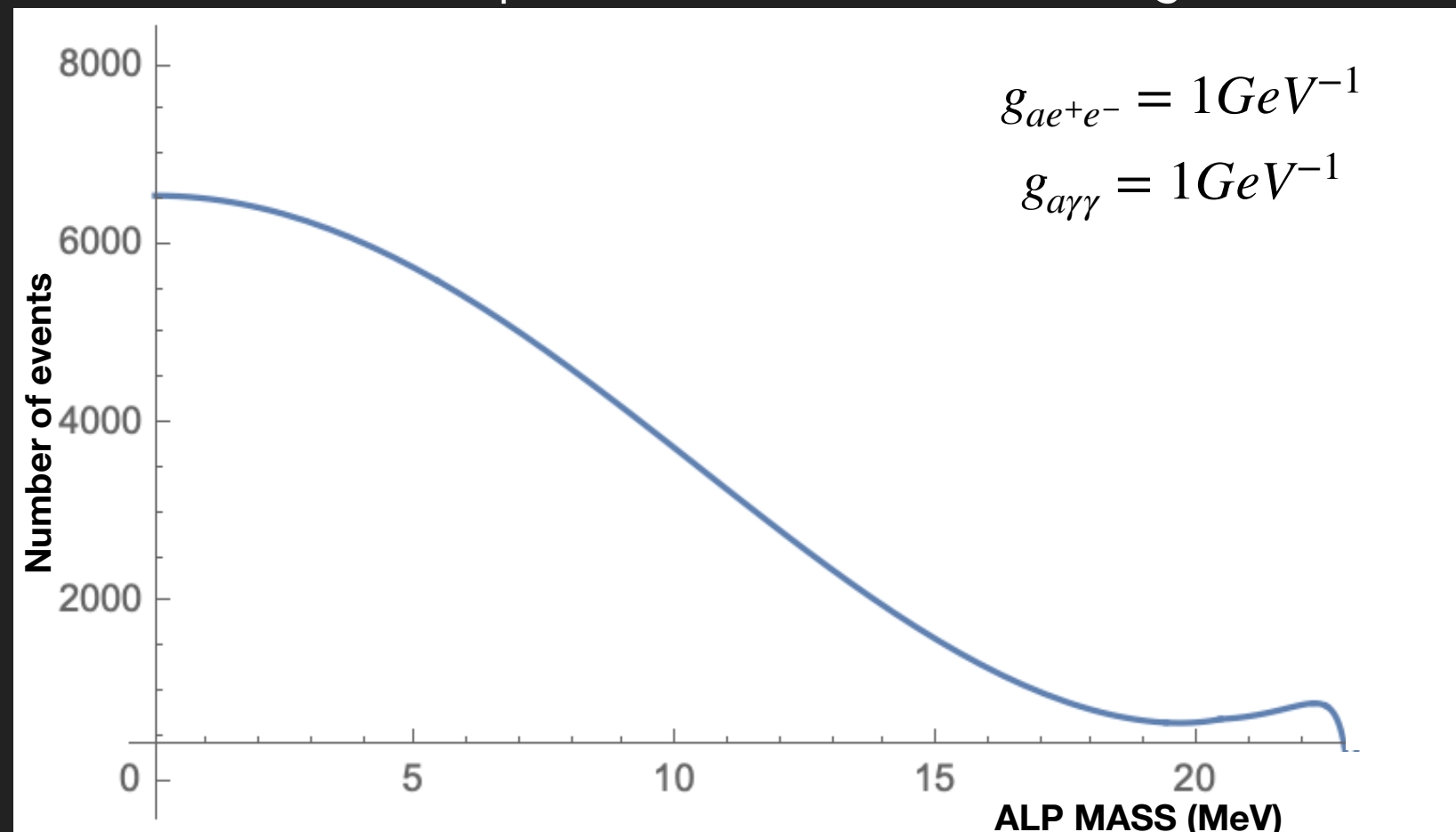


ALP-PHOTON PRODUCTION AT PADME

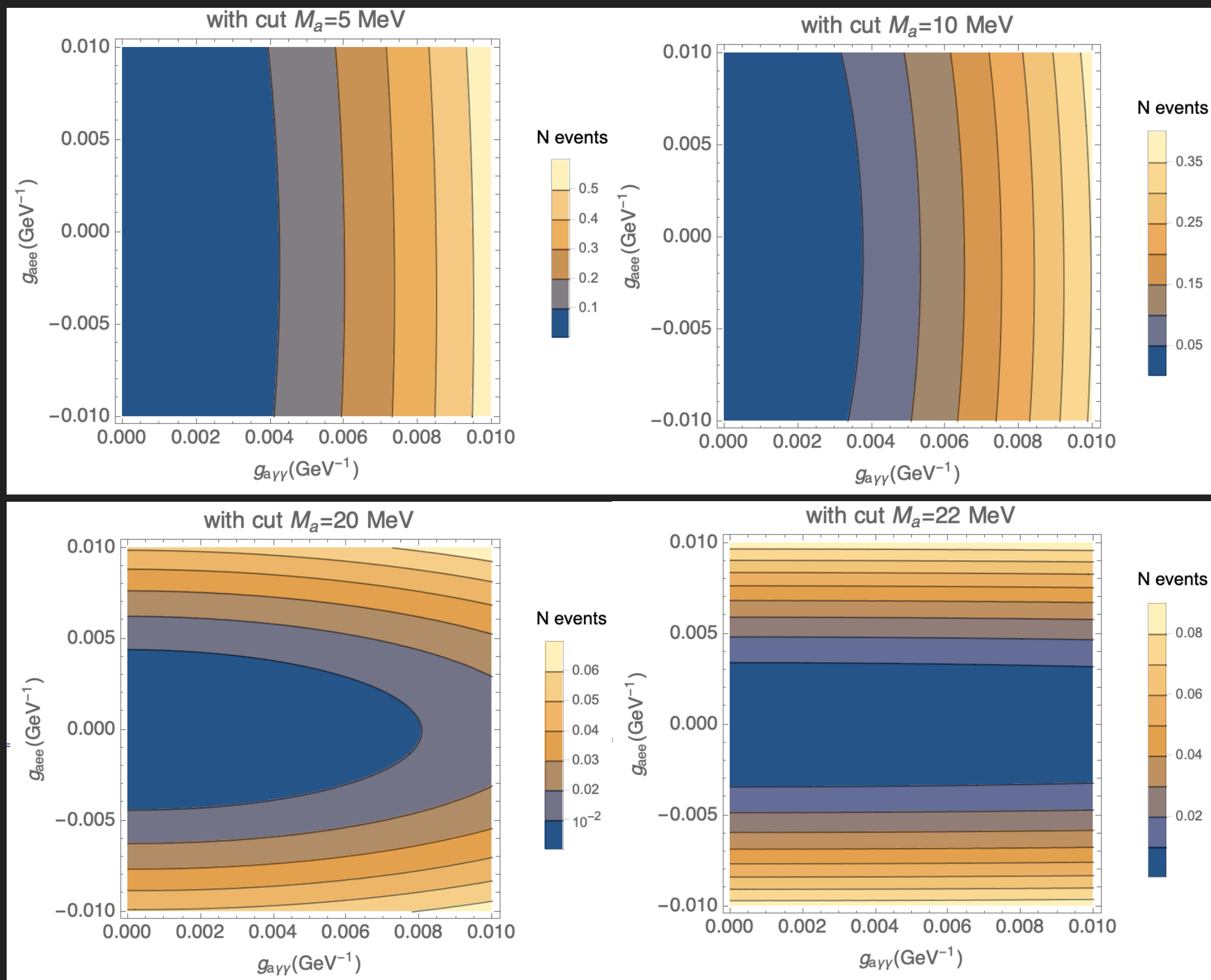
In PADME $P = N_e \sigma_{e^+e^- \rightarrow a\gamma} = 6d_{\text{target}} N_A \frac{\rho}{A} \sigma_{e^+e^- \rightarrow a\gamma}$

N_e : #_{tot} of e^- on target per unit surface area
 d_{target} : target thickness = 100 μm
 ρ : diamond density 3.5 g/cm^3
 A : atomic mass = 12 g/mol

Number of e^+e^- in γ ALP events in PADME assuming 10^{13} PoT



ALP-PHOTON PRODUCTION AT PADME



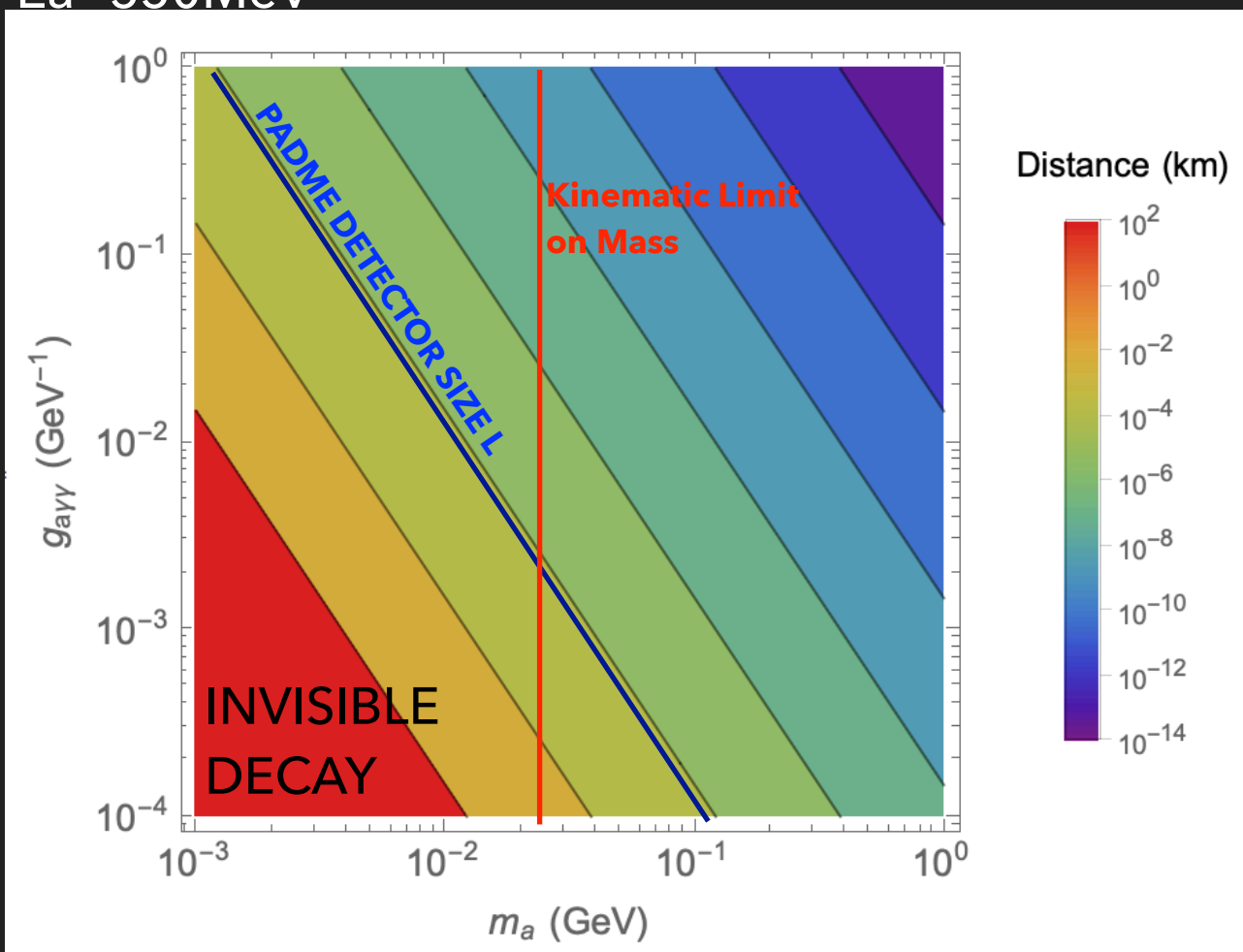
WHAT ABOUT VISIBLE DECAYS OF ALPS IN PADME?

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

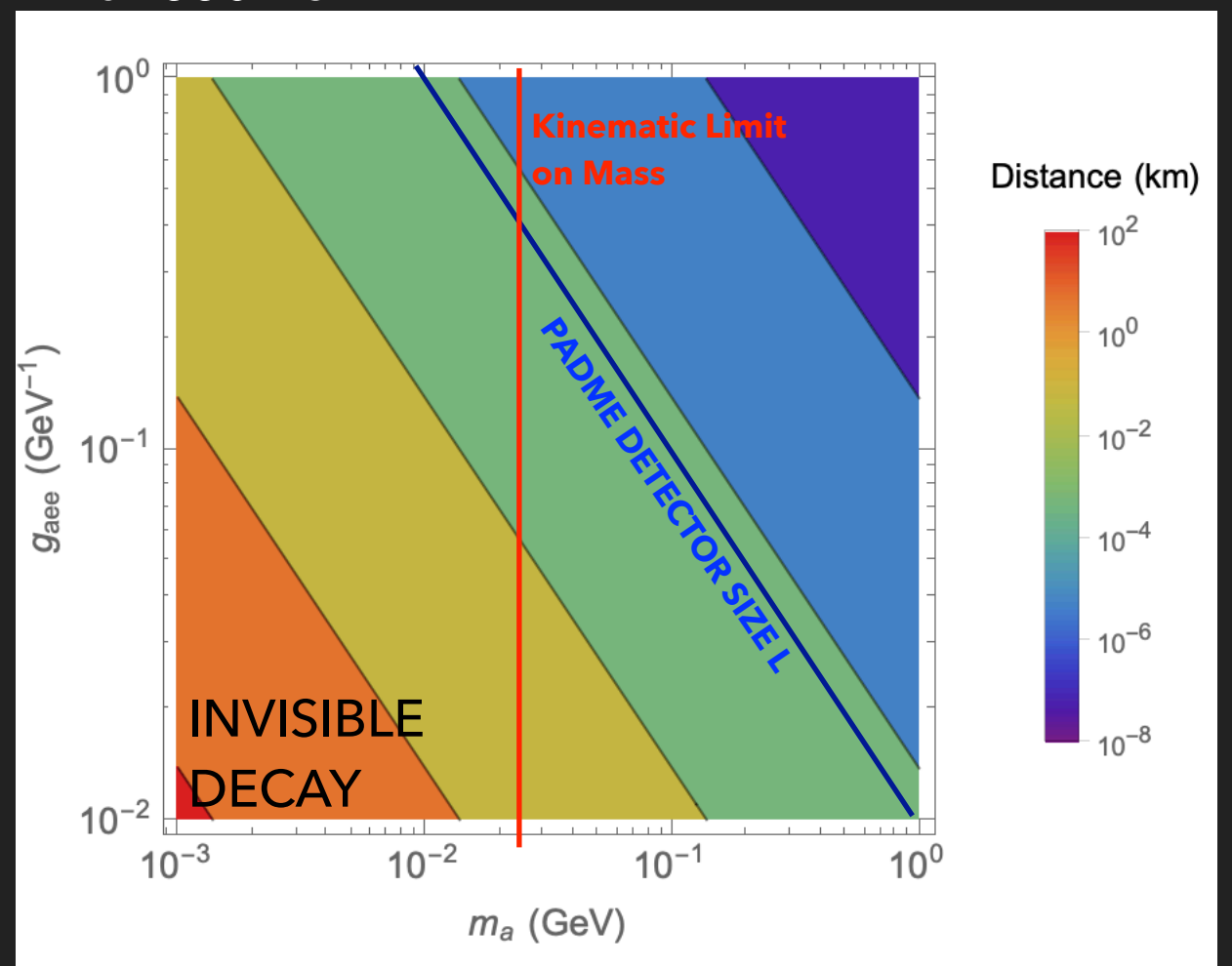
$$\Gamma_{a \rightarrow \gamma\gamma} = \frac{64\pi c E_a h}{g_{a\gamma\gamma}^2 M_a^4}$$

$$\Gamma_{a \rightarrow e^+e^-} = \frac{8\pi c E_a h}{g_{aee}^2 M_a^2 M_e^2}$$

E_a=550MeV

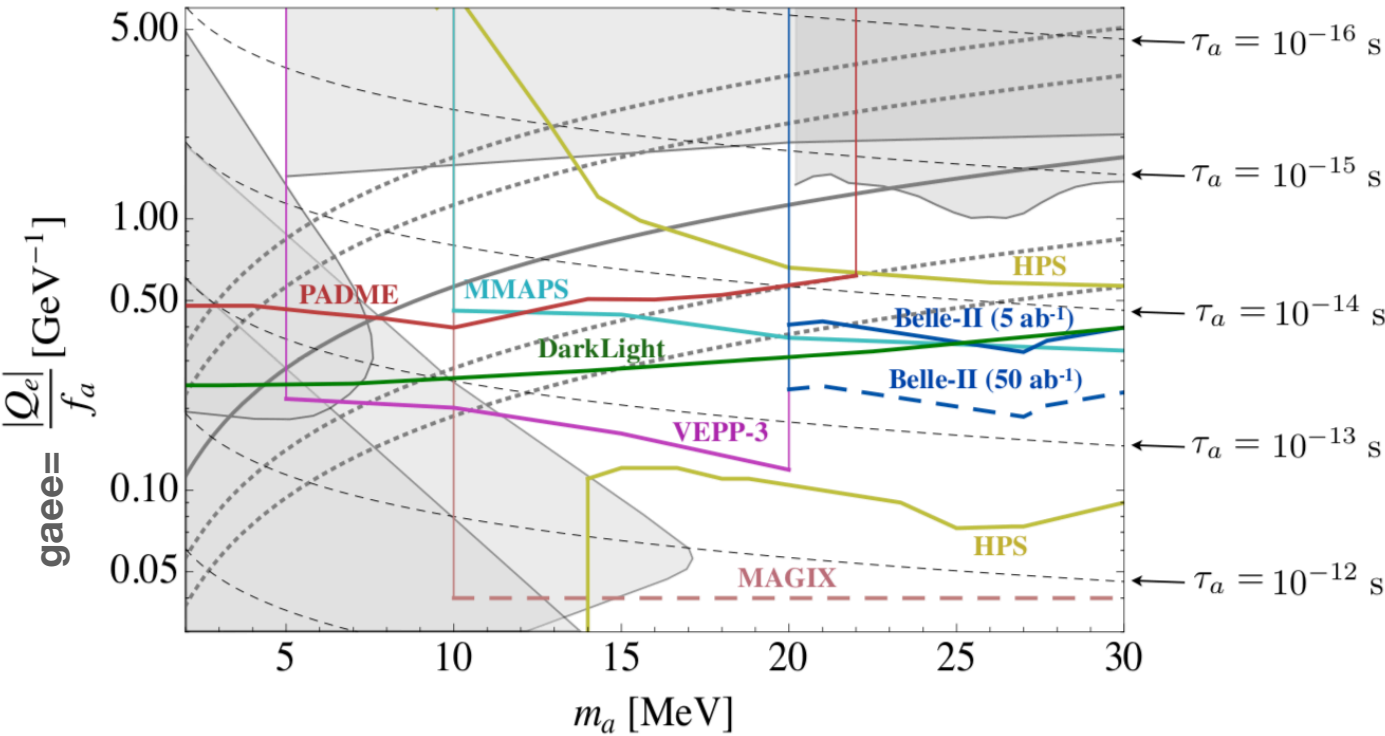


E_a=550MeV

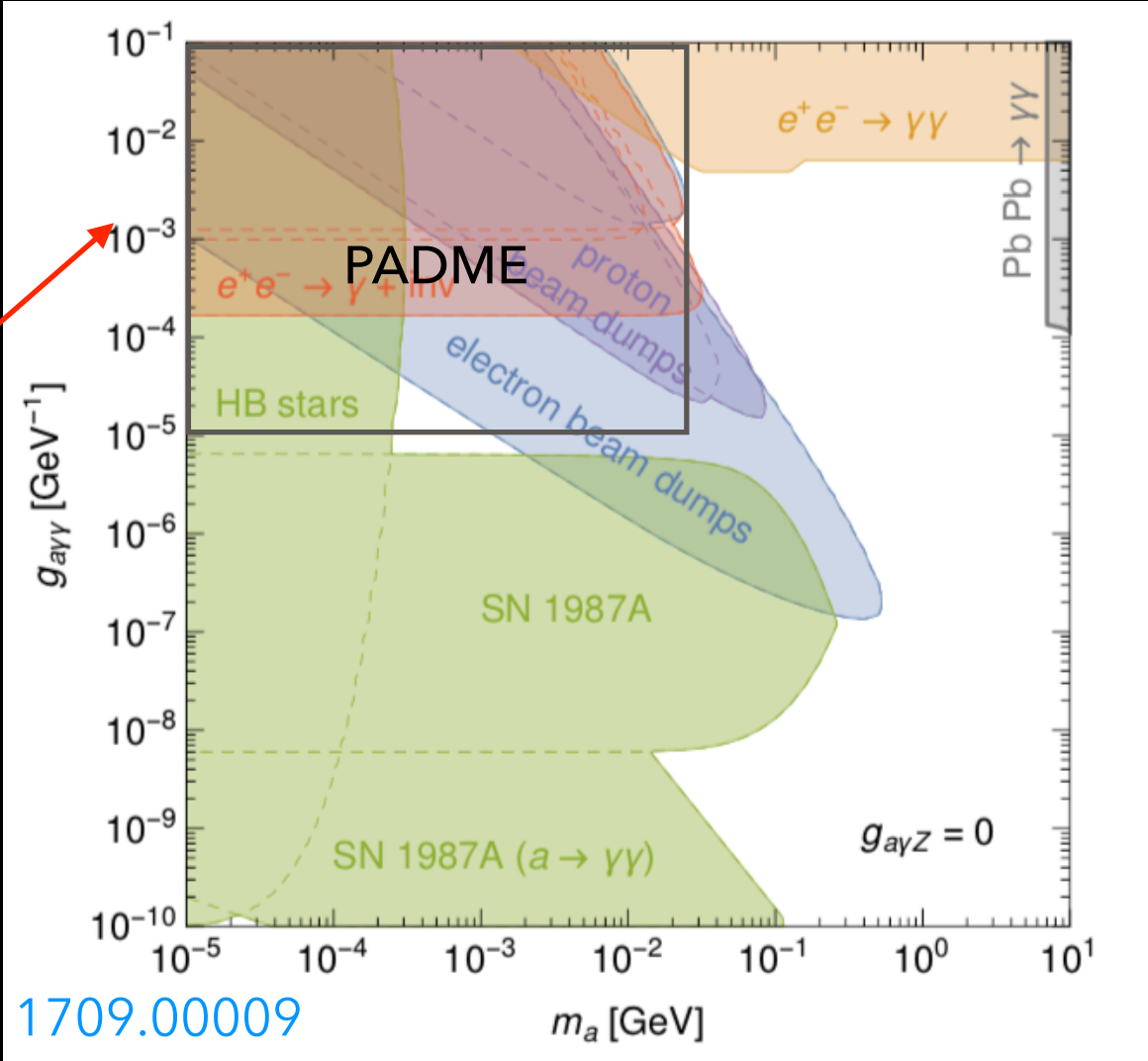


CONSTRAINTS

Alves and Weiner JHEP07(2018)092



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



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

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 $m_{A'} > 5.5 \text{ GeV}$ and $-0.4 < \cos\theta < 0.6$ for $m_{A'} < 5.5 \text{ GeV}$. 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

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

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 $L_D = 275 \text{ cm}$ [59], we can then reinterpret the full BaBar bound in the context of ALPs.

1709.00009

CONCLUSION

- ▶ INVESTIGATE LIGHT DARK MATTER PORTALS
- ▶ AXION-LIKE PARTICLE IS A PROMISING DM PORTAL
- ▶ PADME EXPERIMENT CAN DETECT AN ALP SIGNAL
- ▶ LET'S WAIT FOR RESULTS FROM PADME
- ▶ WHAT IS THE INTERACTION WITH THE DARK MATTER?

CONCLUSION

- ▶ INVESTIGATE LIGHT DARK MATTER PORTALS
- ▶ AXION-LIKE PARTICLE IS A PROMISING DM PORTAL
- ▶ PADME EXPERIMENT CAN DETECT AN ALP SIGNAL
- ▶ LET'S WAIT FOR RESULTS FROM PADME
- ▶ WHAT IS THE INTERACTION WITH THE DARK MATTER?

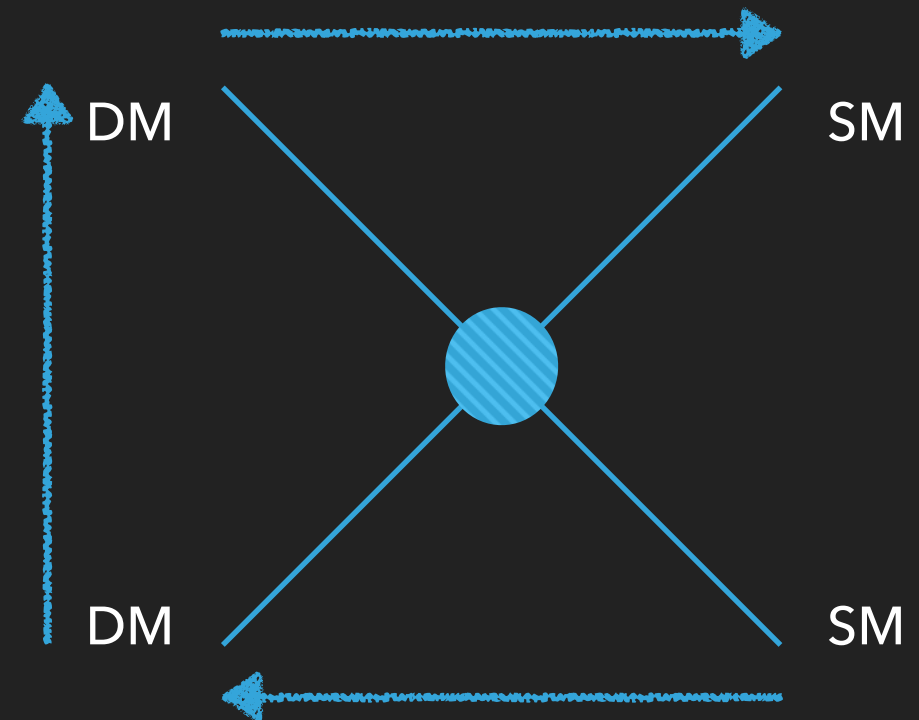
THANKS FOR ATTENTION!!

BACKUP SLIDES

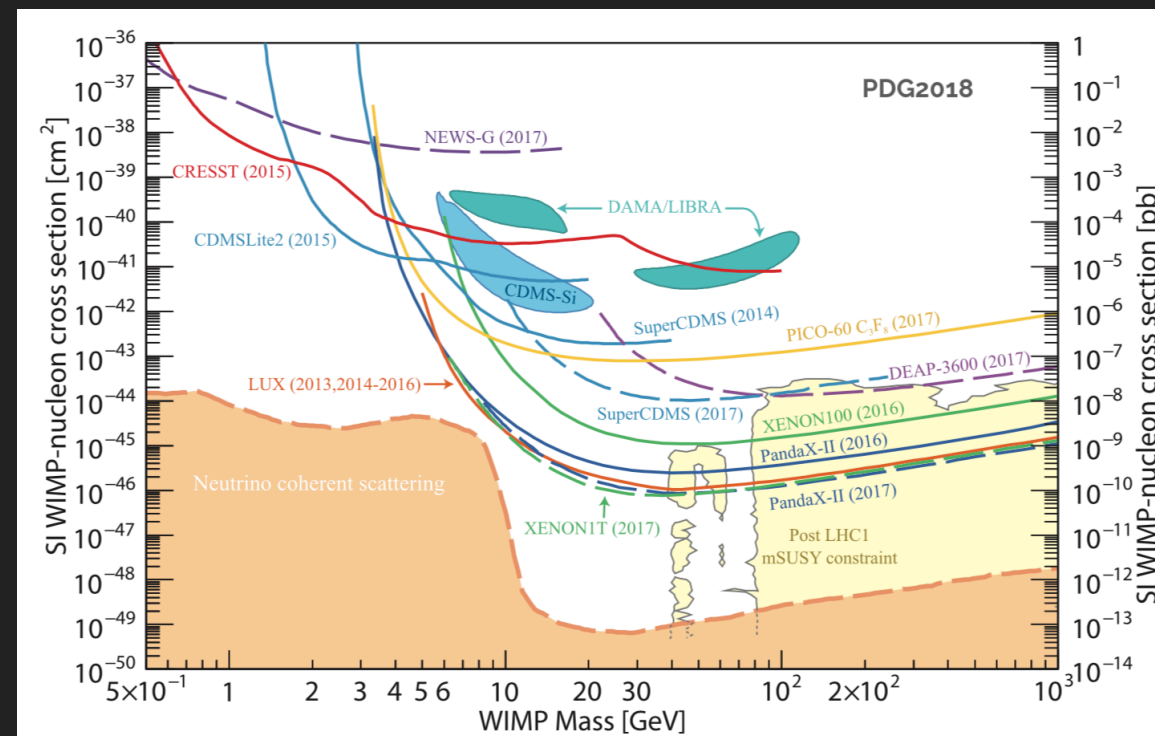
WIMP: Weakly Interacting Massive Particles

$$\Omega_{DM} h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{M_{DM}^2}{g^4}$$

- ▶ GeV-TeV mass scale
- ▶ weak scale cross-section



NO CONVINCING SIGNAL IN SPITE OF SPECTACULAR IMPROVEMENTS IN DIRECT DETECTION SENSITIVITY



PHOTON-PHOTON PRODUCTION AT PADME

