DARK SECTOR SEARCHES AT THE PADME EXPERIMENT

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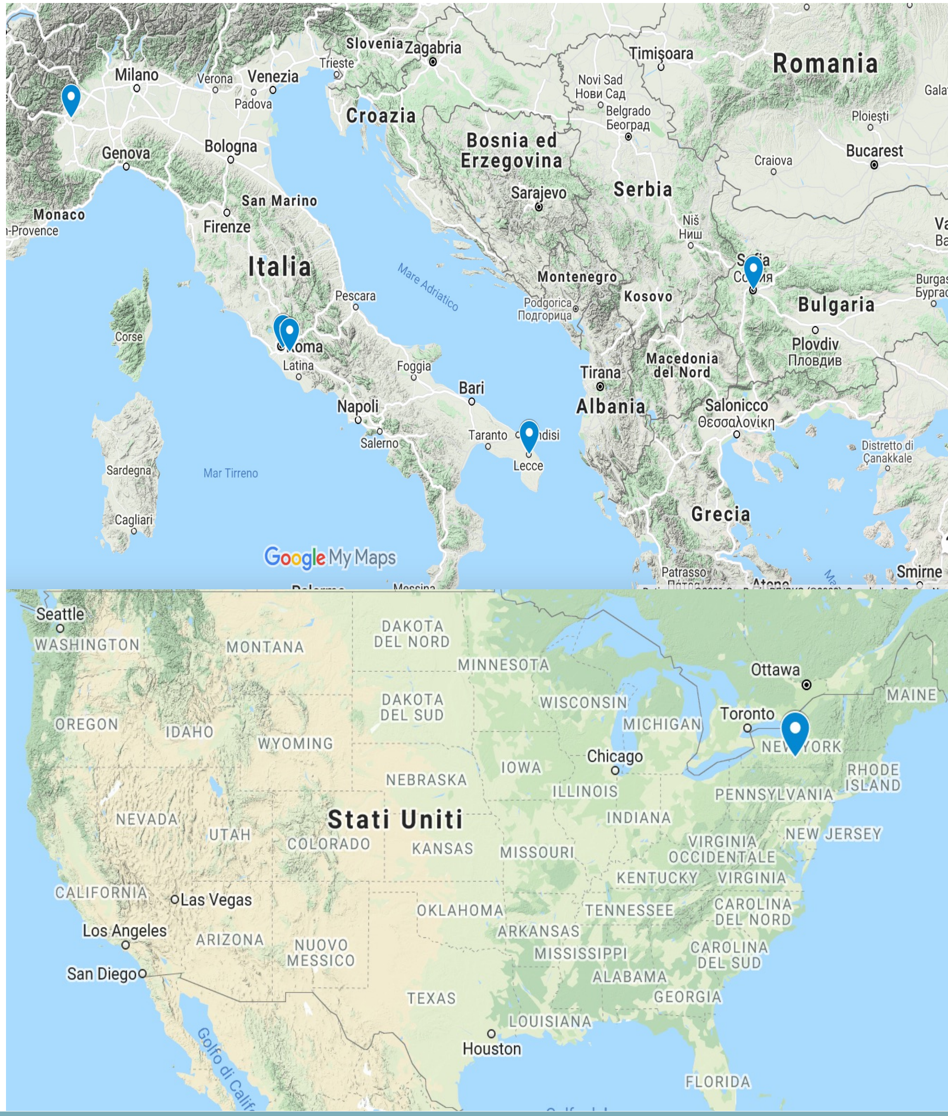
Outline

- What's the cosmological evidence for dark matter?
- What is the "dark sector"?
- What are dark photons and axions?
- What is the PADME experiment?
- How do we conduct (in)visible searches?
- What's next at PADME?

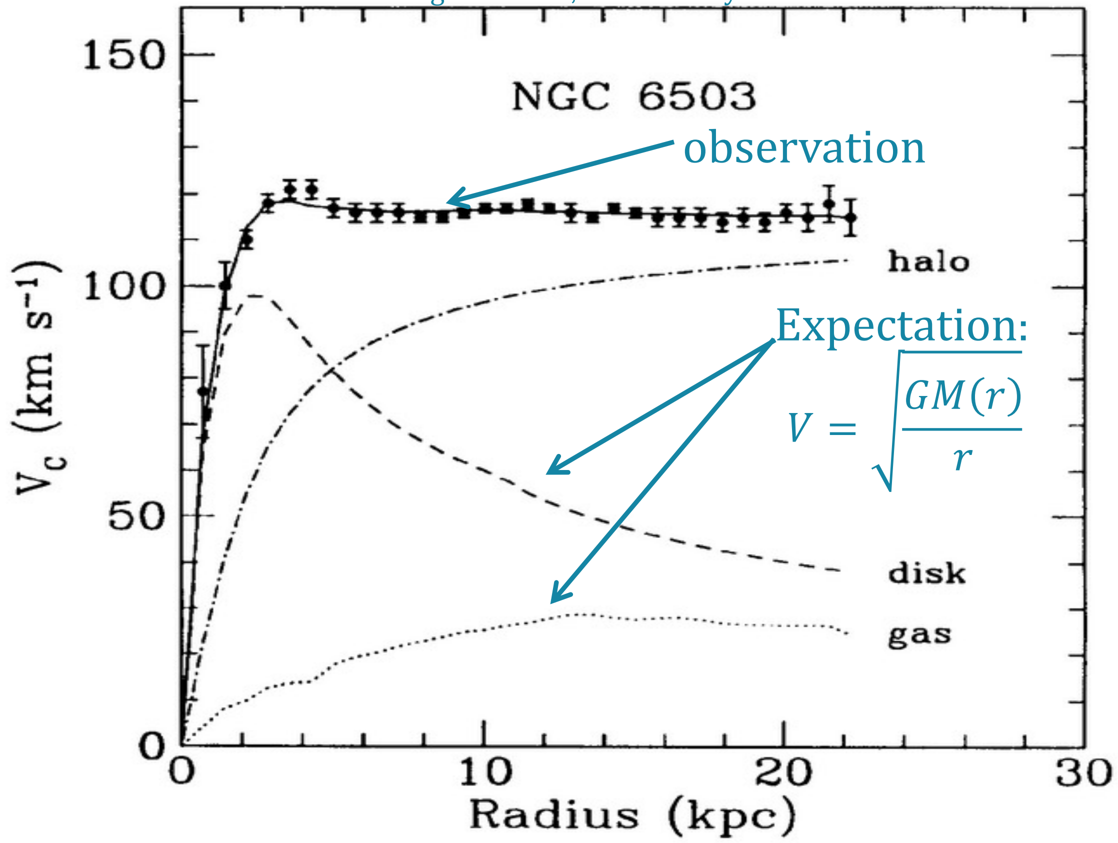
PADME Geography:
PADME groups around the world



The dark matter problem

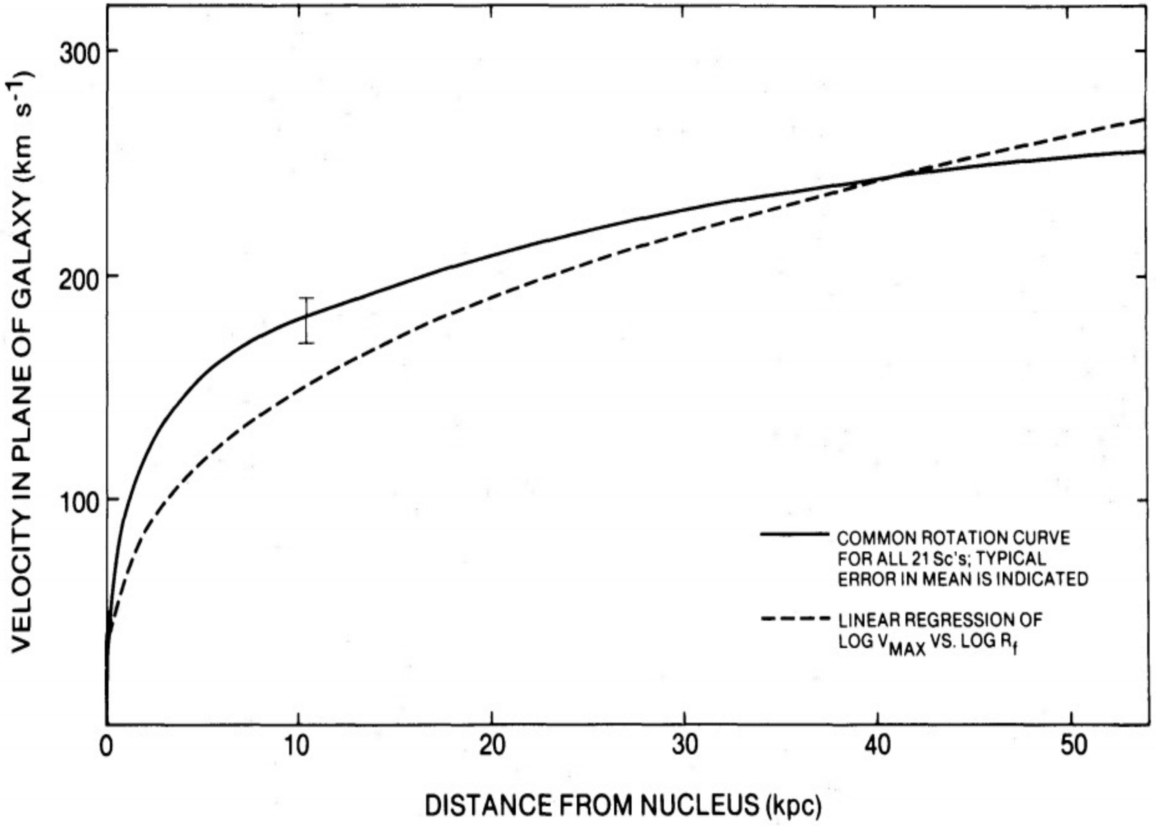
- Galactic rotation curves

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



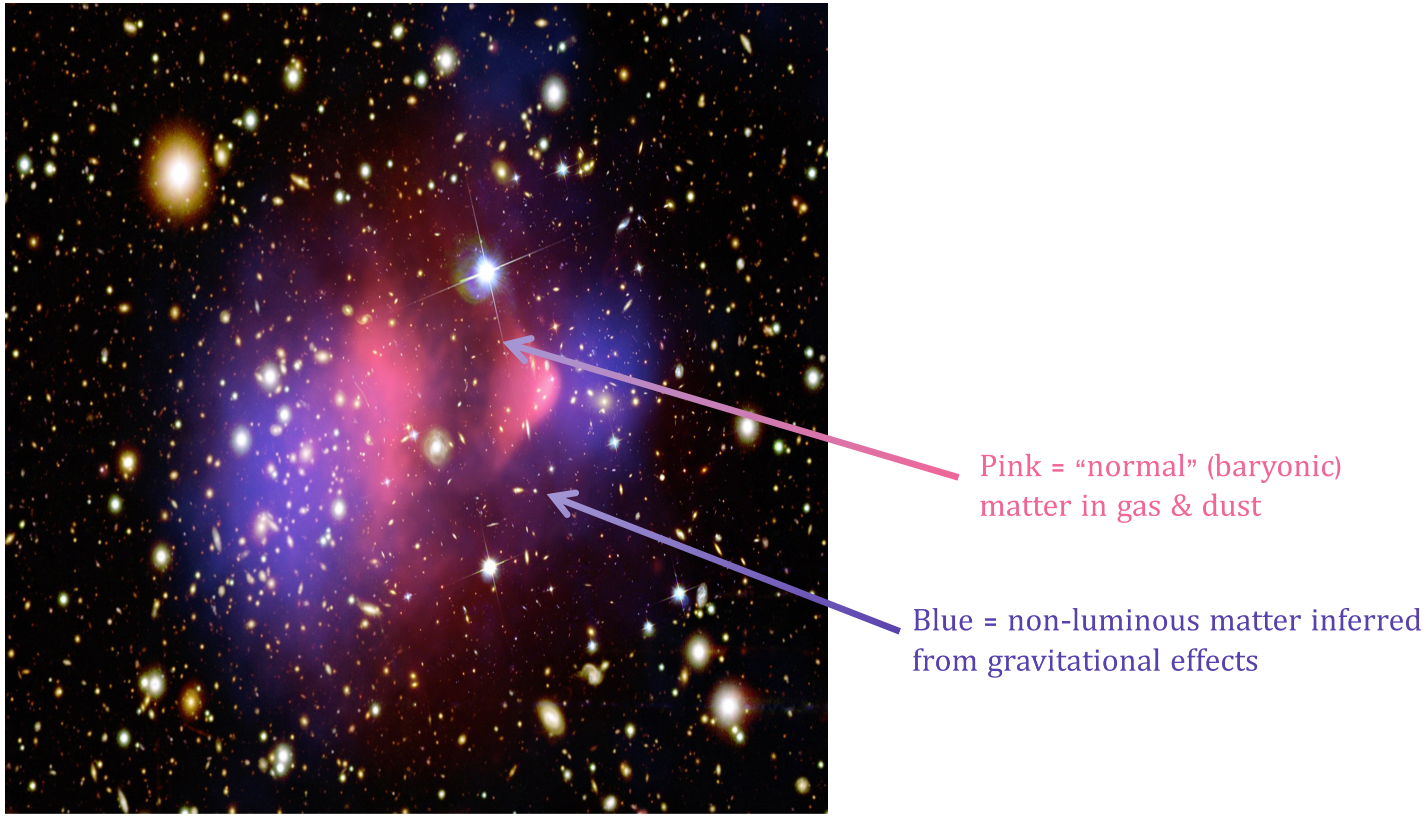
- Stars within galaxies

The Astrophysical Journal, 238:471-487, 1980 June 1



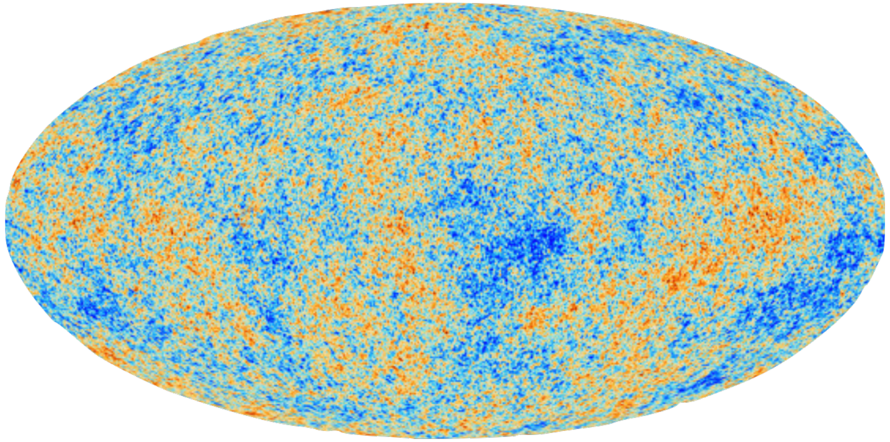
The dark matter problem

- Gravitational lensing, eg via the bullet cluster

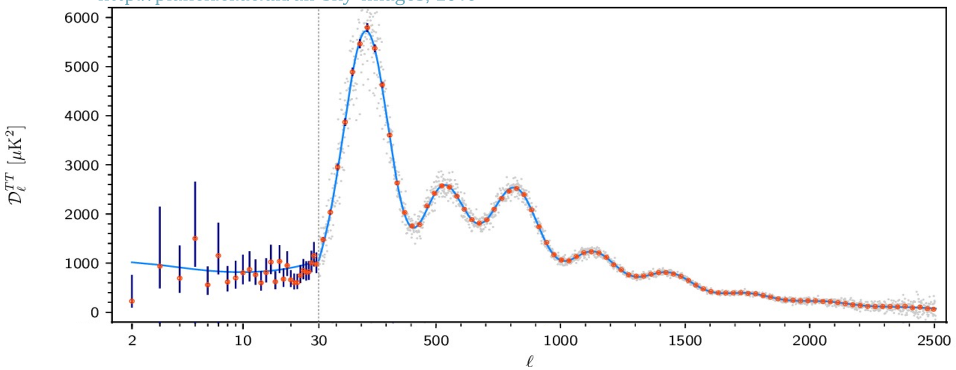


X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

- Anisotropies in the cosmic microwave background



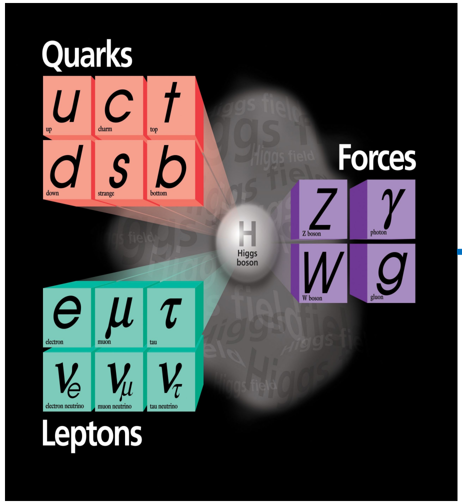
Planck Collaboration. Cosmic microwave background (mollweide). Available online at http://planck.cf.ac.uk/all-sky-images, 2019



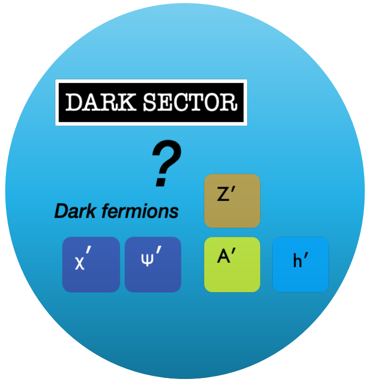
Aghanim, Planck Collaboration N. et al. "Planck 2018 results: V. CMB power spectra and likelihoods." *Astronomy and Astrophysics* 641 (2019): 1-92.

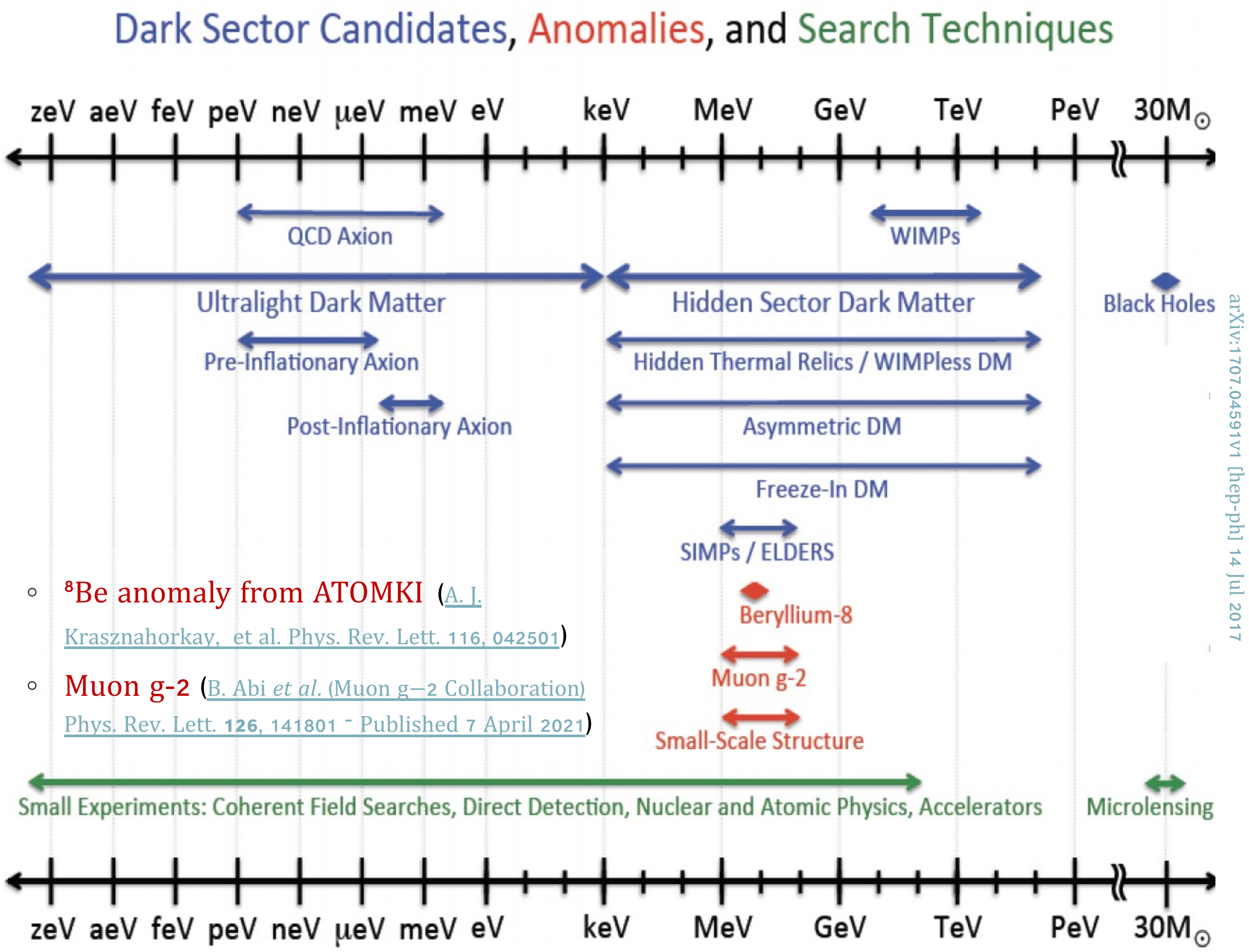
The dark sector & portal models

- The "dark sector" = hypothetical particles which make up dark matter
- It could connect feebly to the Standard Model (SM) via a "portal" particle
- Two portals at PADME:
  - Massive vector boson "dark photon" (A')
  - Pseudoscalar "axion-like-particle" (ALP)



Portal – A'?

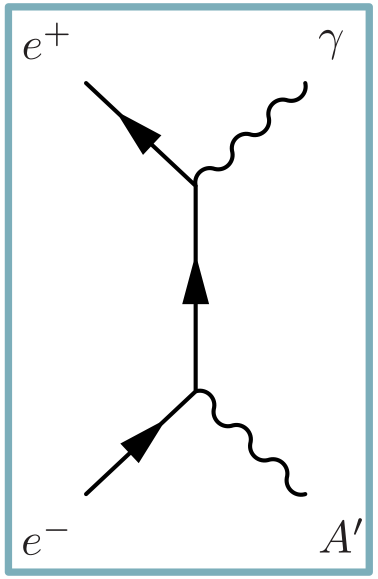


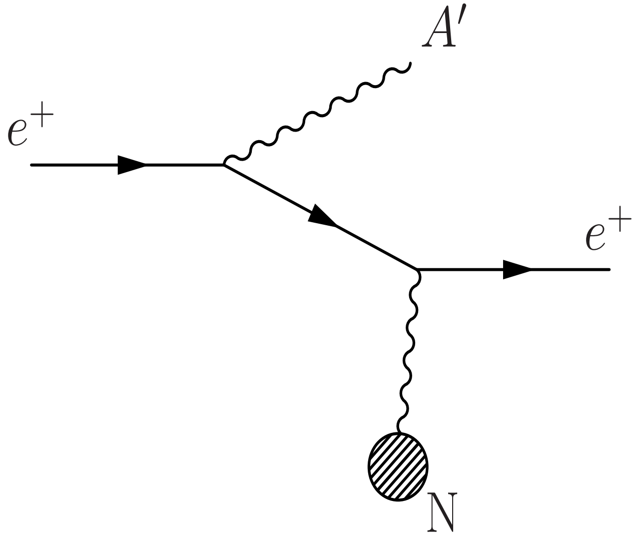


- ^{8}Be anomaly from ATOMKI (A. J. Krasznahorkay, et al. Phys. Rev. Lett. 116, 042501)
- Muon g-2 (B. Abi *et al.* (Muon g−2 Collaboration) Phys. Rev. Lett. 126, 141801 – Published 7 April 2021)

Portal production at PADME

- e^+ beam onto a thin diamond target
- $E_{beam} < 550\ MeV$ gives us access to:
  - Associated production (nominal mechanism at PADME)
  - A'-strahlung
  - Resonant annihilation
- Identical processes for the A' and ALPs
- $\frac{N(e^+e^- \to A'\gamma)}{N(e^+e^- \to \gamma\gamma)}$ gives information about strength of SM-A' interaction

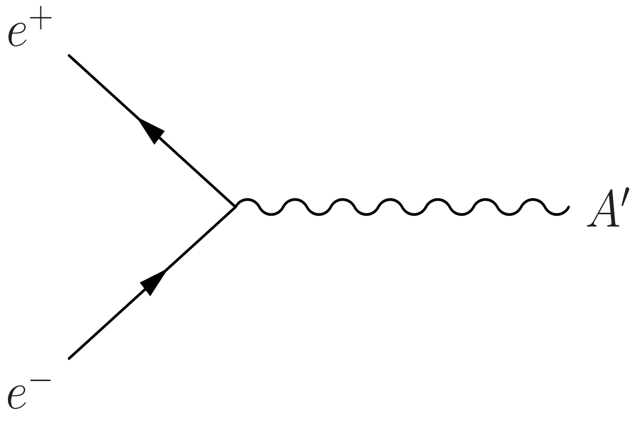




ϵ = SM-A' coupling

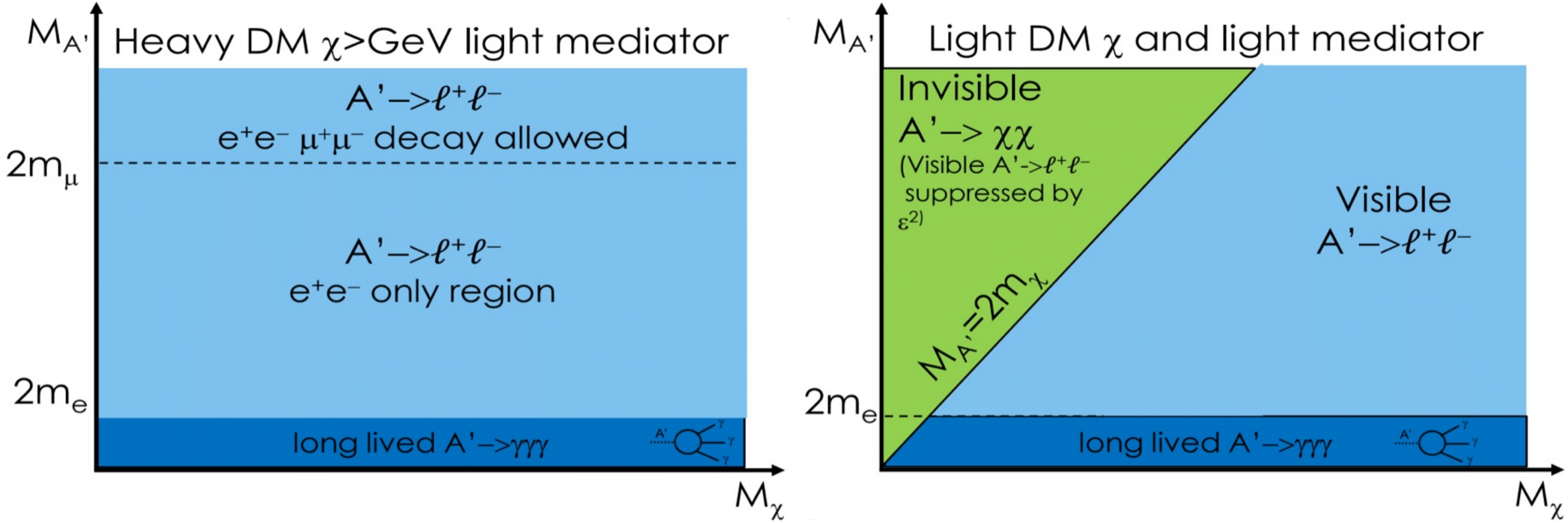
$$\frac{\sigma(e^+e^- \to A'\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)} \times \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \epsilon^2 \times \delta$$

δ = phase space correction, analytically calculable



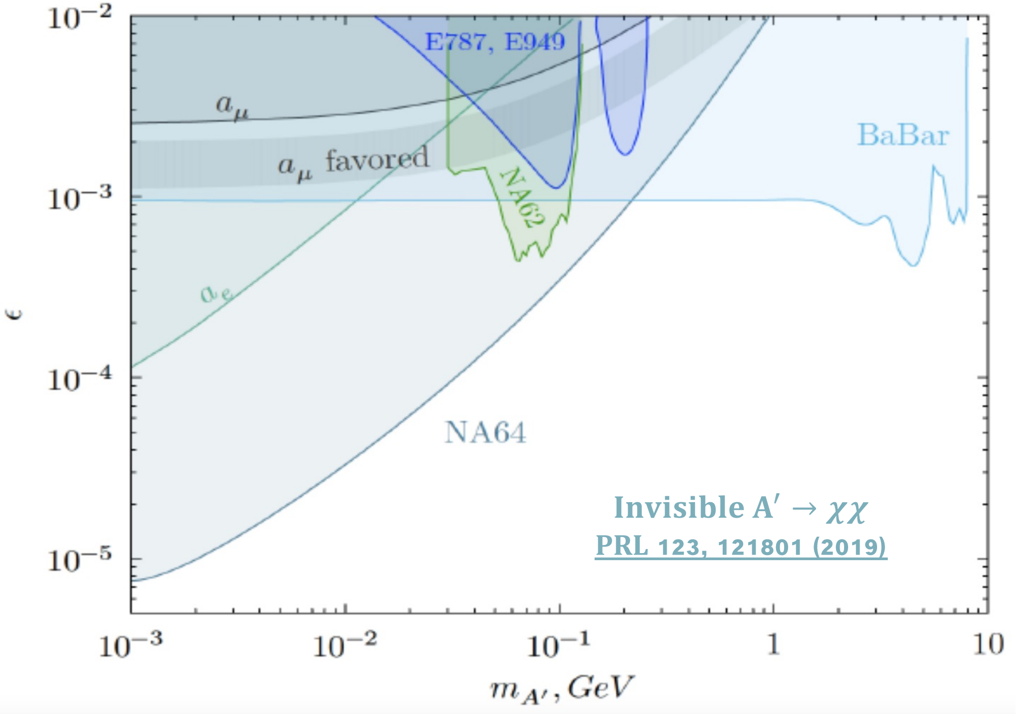
Portal decay models

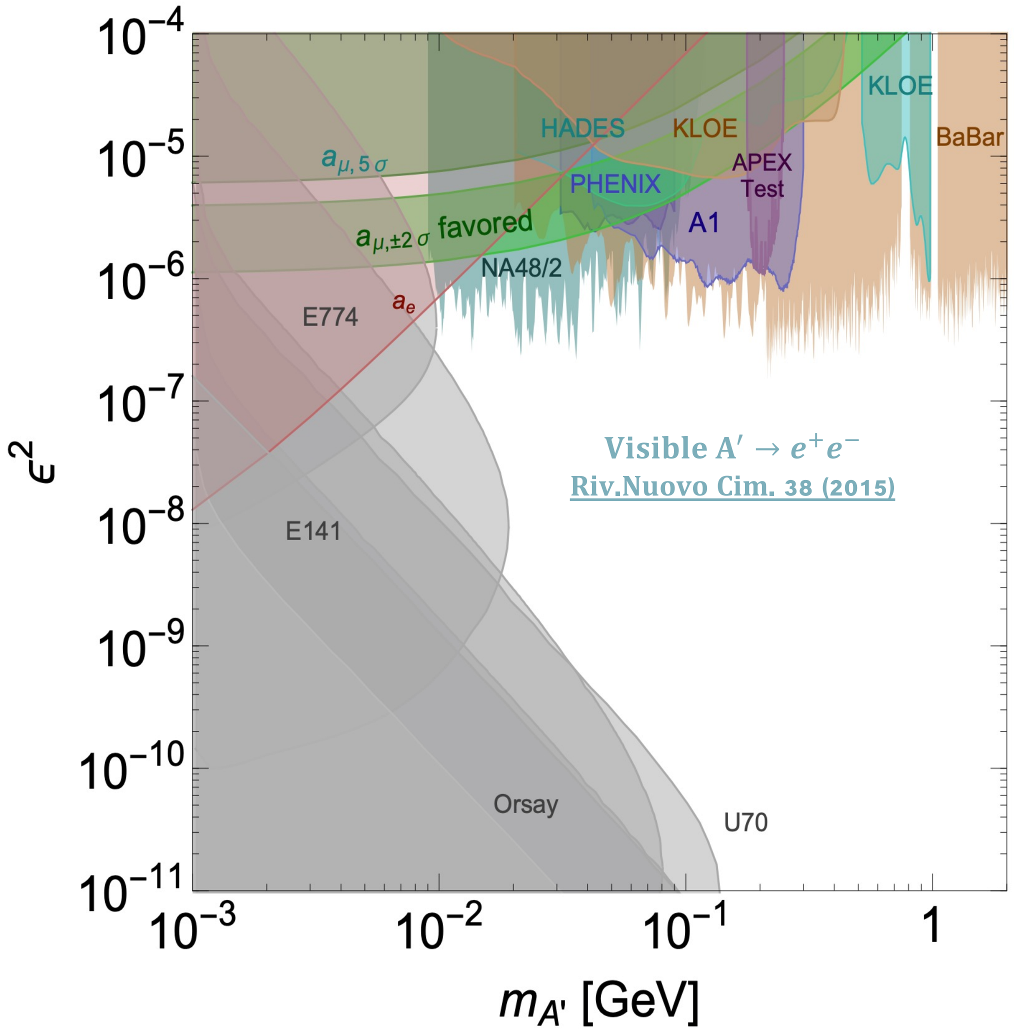
- Portal decay depends on its mass ($M_{A'}$) wrt dark sector particles (M_χ) and the electron (M_e):
  - Light portal & heavy DM: $M_{A'} < 2\,M_\chi$ and $M_{A'} < 2\,M_e \Rightarrow$ long-lived, decays only into 3 SM photons
  - Light portal & light DM: $M_{A'} < 2\,M_e$ but $M_{A'} > 2\,M_\chi \Rightarrow$ decays only to dark sector particles ("invisible" decay)
  - Heavy(ish) portal: $M_{A'} > 2\,M_e$ and $M_{A'} > 2\,M_\chi \Rightarrow$ decays predominantly through "invisible", but also decays through "visible"



Current constraints: Dark photons

- Models are based on two characteristics:
  - Portal mass
  - Coupling constant to SM
- At low A' masses there's still plenty of open space to explore!



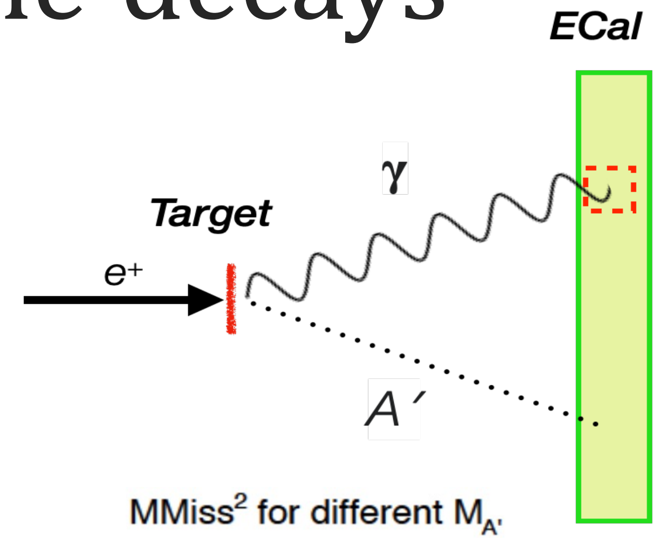


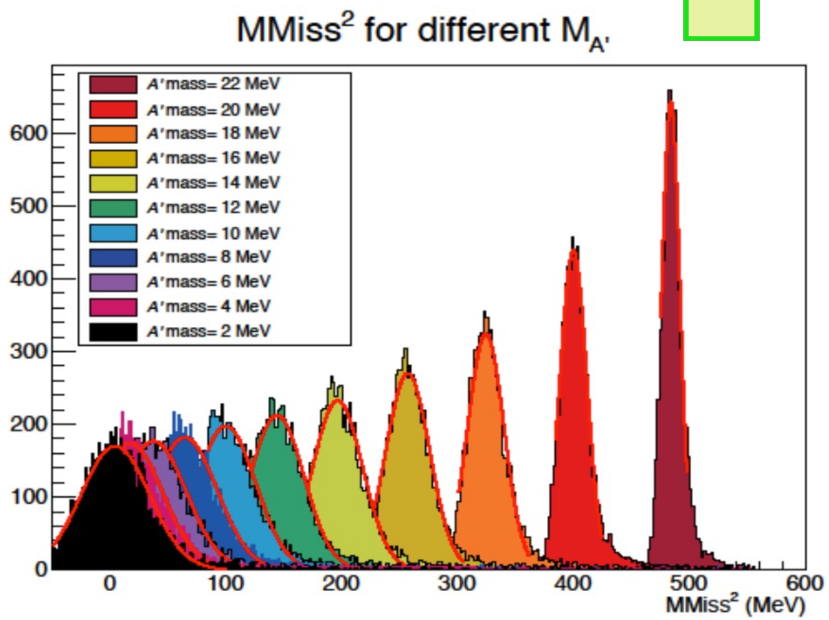
The experimental signature: Invisible decays

- Production: $e^+e^- \rightarrow A'\gamma$
- Experimental signature = 1 SM photon
- Electromagnetic calorimeter (ECal) measures energy & position of photon
- Knowing:
  - The beam energy
  - The position of interaction in the target
  - The position & energy of the SM photon

We reconstruct the kinematics of the interaction & therefore $M_{A'}$:

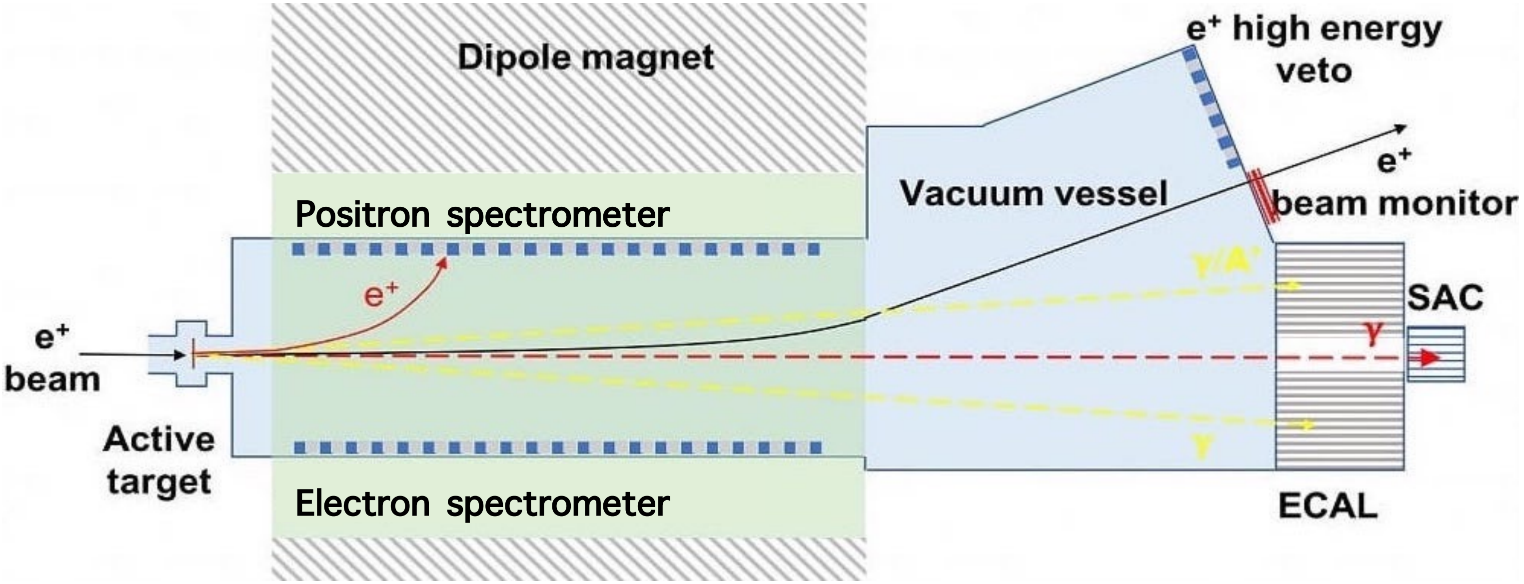
$$M_{A'}^2 = \left(E_{beam} + M_{e^-} - E_\gamma\right)^2$$

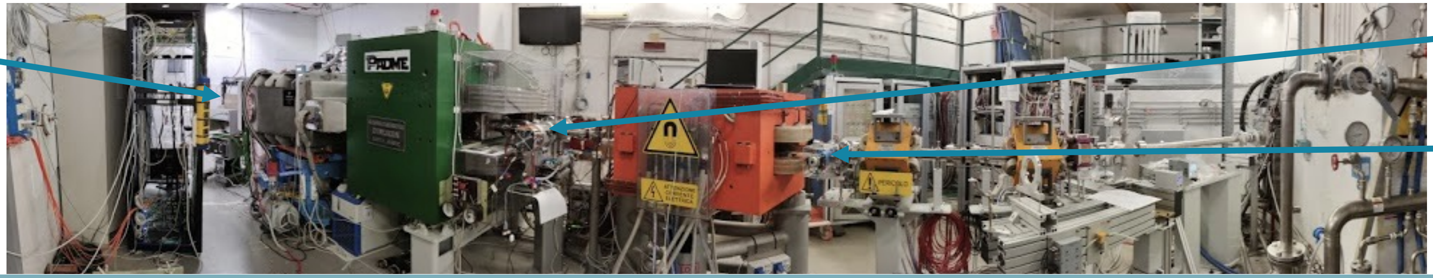




Experimental setup

- PADME was designed to detect associated production of A' with γ
- However, adding a second spectrometer allows us to search for visible decays

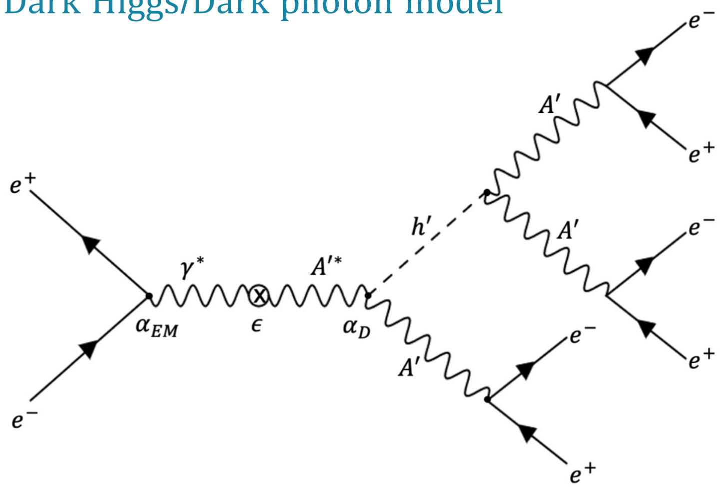


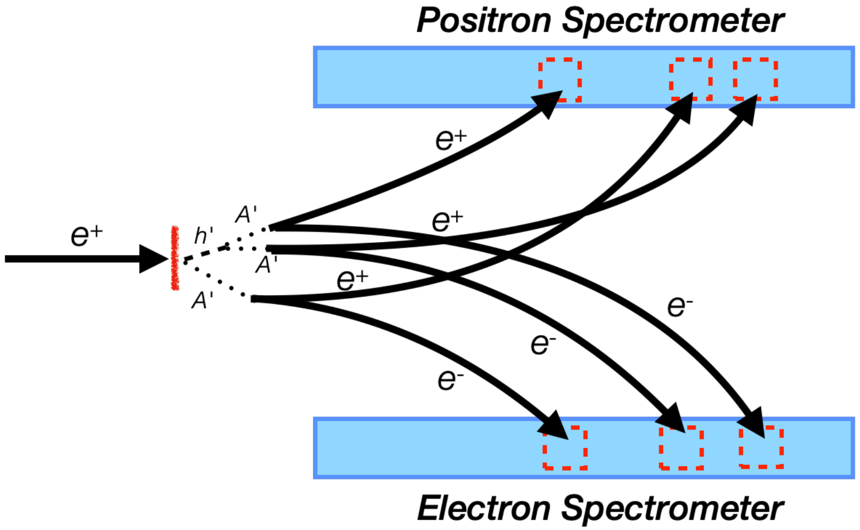


The experimental signature: Visible decays

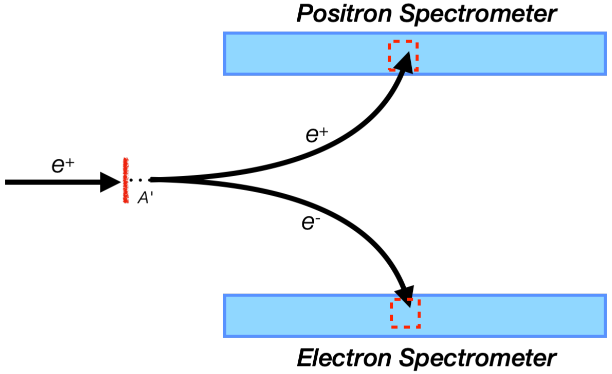
- Visible signatures ⇒ multi-lepton final states
- Of particular interest are:
  - Resonant A' production with $A' \to e^+e^-$
  - $e^+e^- \to 3(e^+e^-)$ via dark Higgs: SM background is supressed by α^6 ($O(10^{-13})$, giving a high BSM signal/SM background ratio

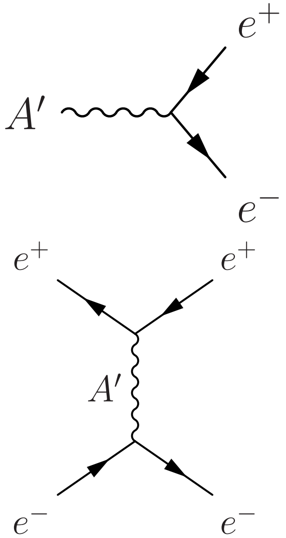
Dark Higgs/Dark photon model





e^+e^- final state



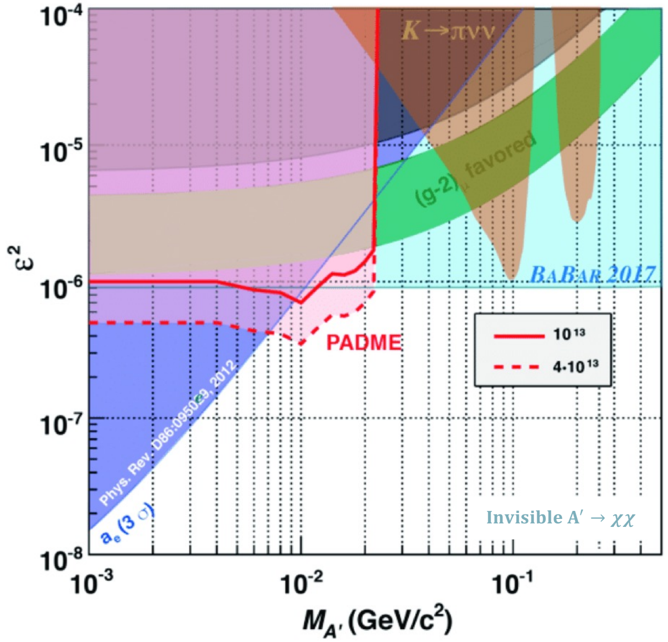


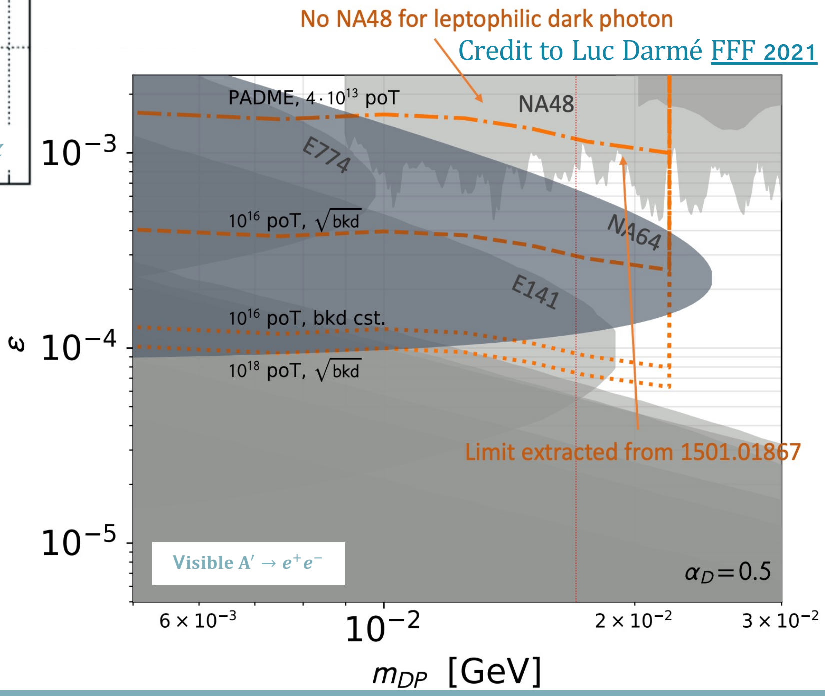
Projected physics reach

- The mass reach of PADME is governed by the beam energy

$$\sqrt{s} = \sqrt{2m_e * E_{beam}}$$

- At maximum $E_{beam} = 550$ MeV, maximum $m_{A'} < 23.7$ MeV
- The reach in coupling strength depends on pile-up and beam background
- With 10^{13} total positrons on target, $\epsilon > 10^{-3}$

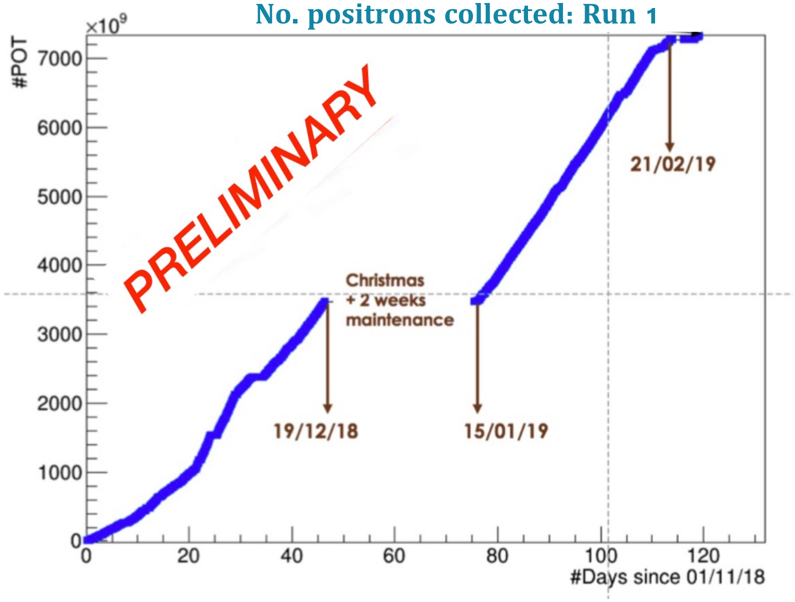




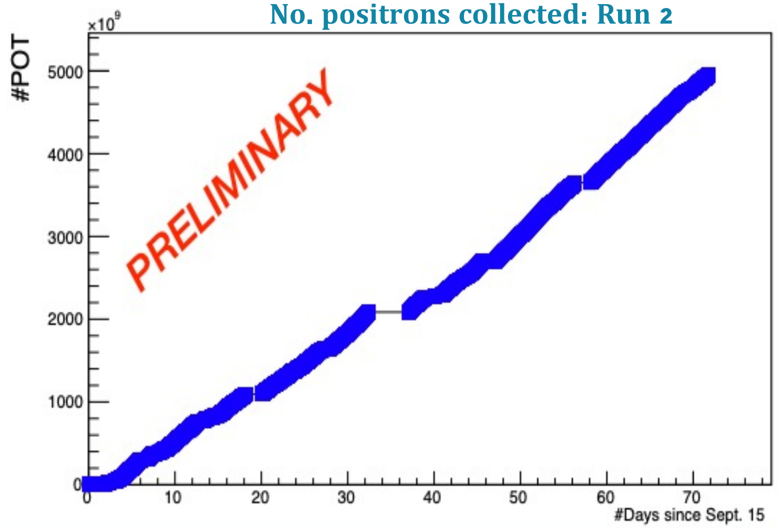
Experimental status

- After two physics runs we've measured the following number of positrons on target (POT):
  - Run 1 = 7×10^{12} POT
  - Run 2 = 5.5×10^{12} POT
  - Precision = 5%
- The collaboration is now in data-analysis mode and planning our next steps

No. positrons collected: Run 1

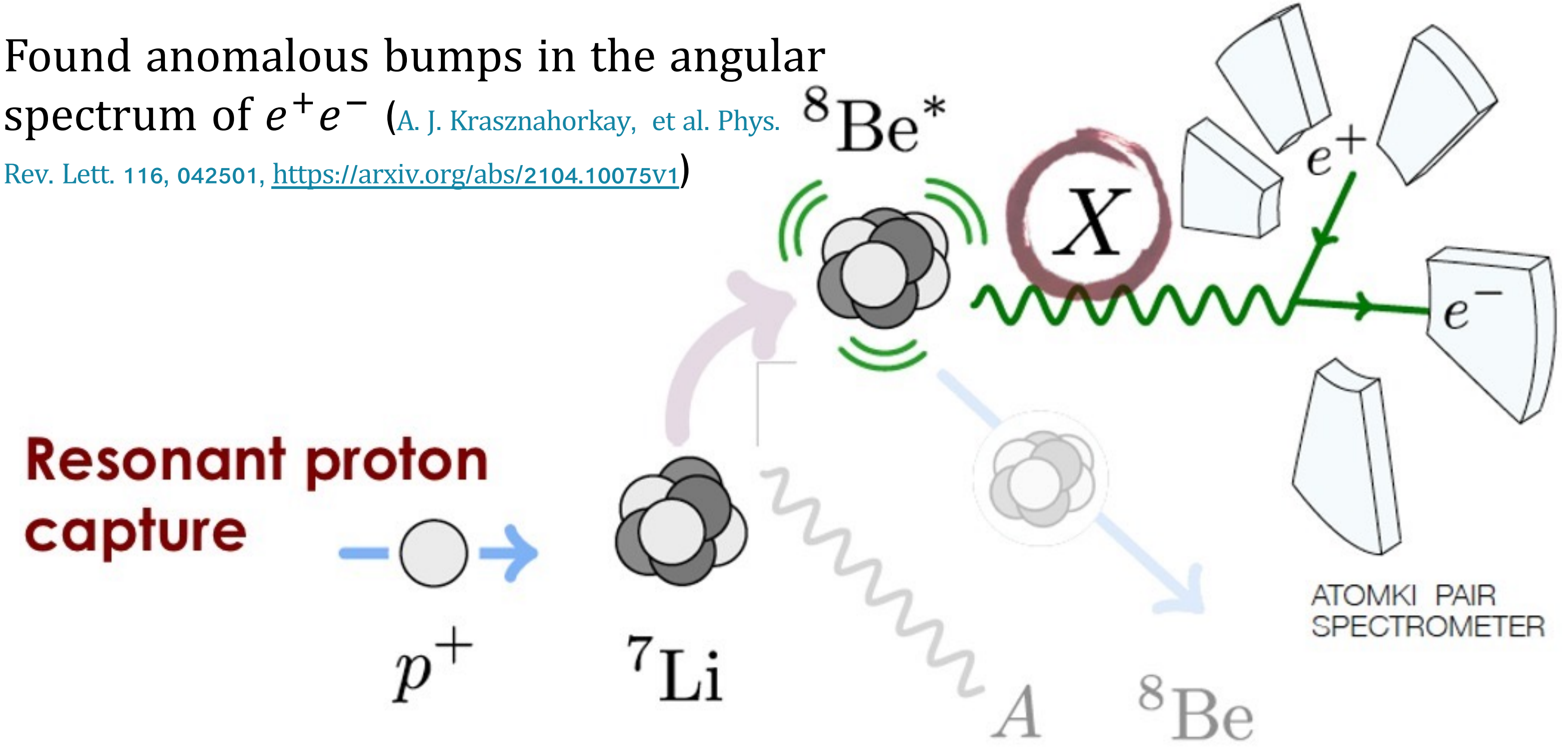


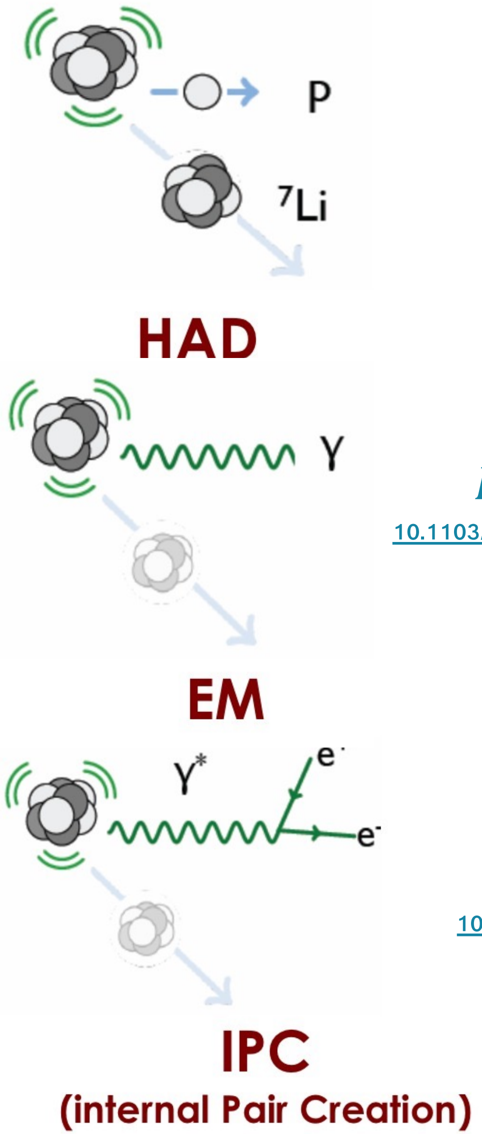
No. positrons collected: Run 2



Next steps: ^{8}Be/^{4}He anomaly

- Collaboration at ATOMKI institute in Hungary
- Studying IPC decays of excited ^{8}Be/^{4}He nuclei
- Found anomalous bumps in the angular spectrum of e^+e^- (A. J. Krasznahorkay, et al. Phys. Rev. Lett. 116, 042501, https://arxiv.org/abs/2104.10075v1)





$BR \sim 10^{-5}$

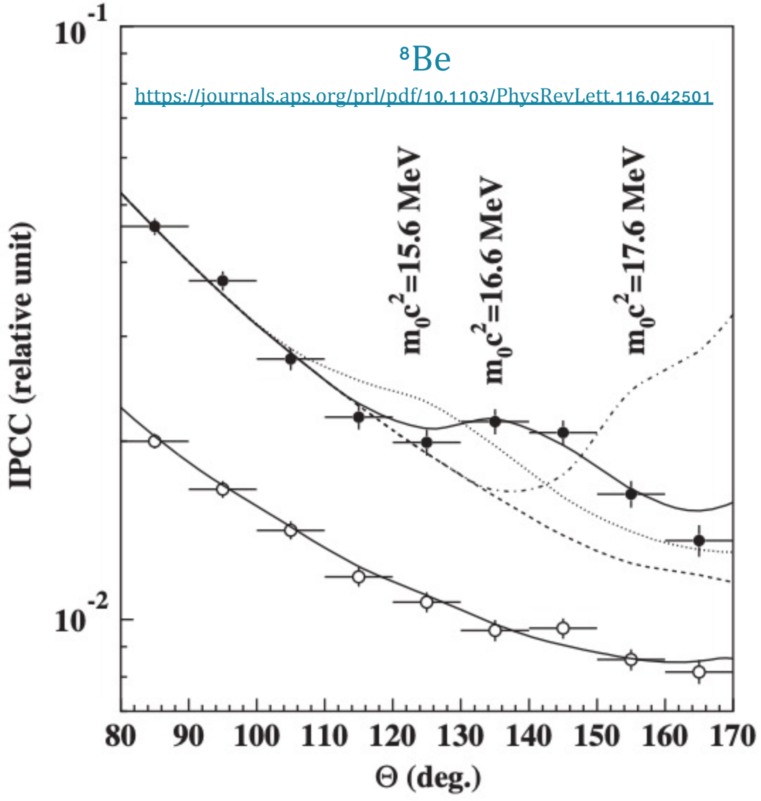
10.1103/PhysRevLett.117.071803

$BR \sim 10^{-8}$

10.1103/PhysRevD.95.035017

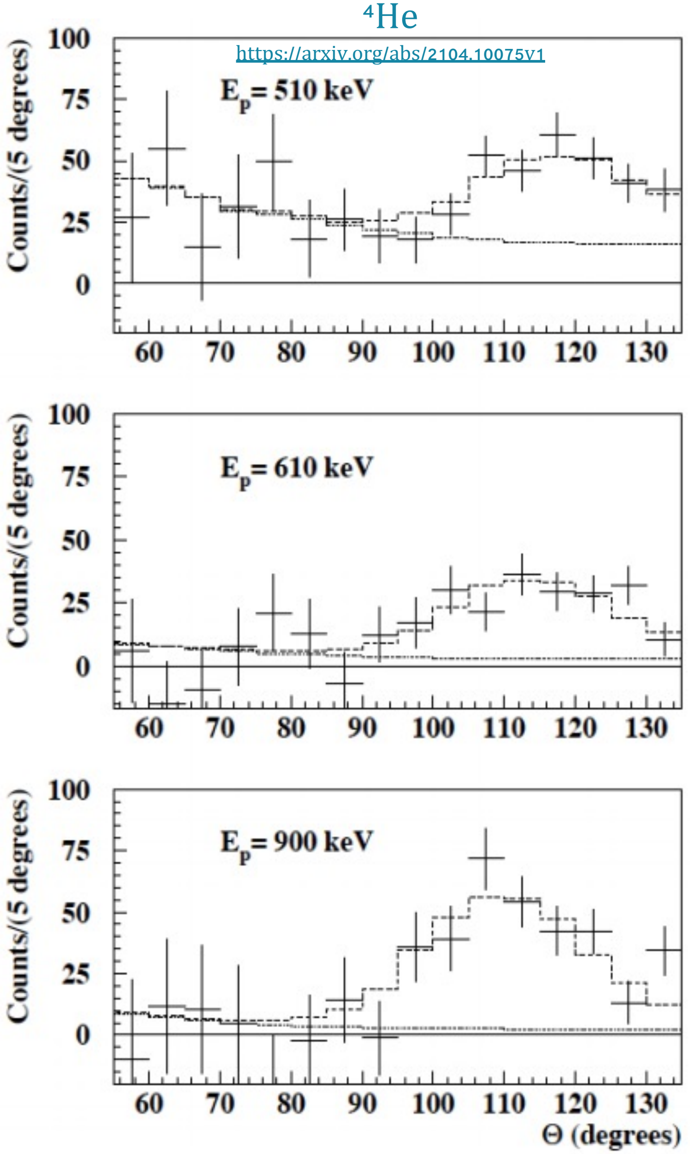
Next steps: ^{8}Be/^{4}He anomaly

- The bumps are consistent with the creation of a new particle with mass 17 MeV



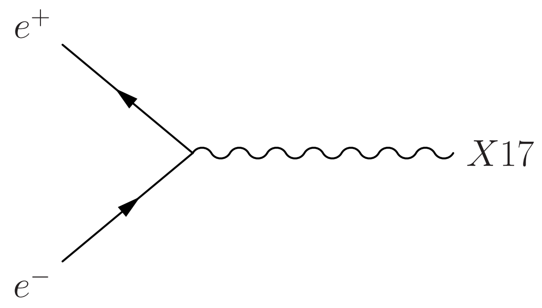
^{4}He

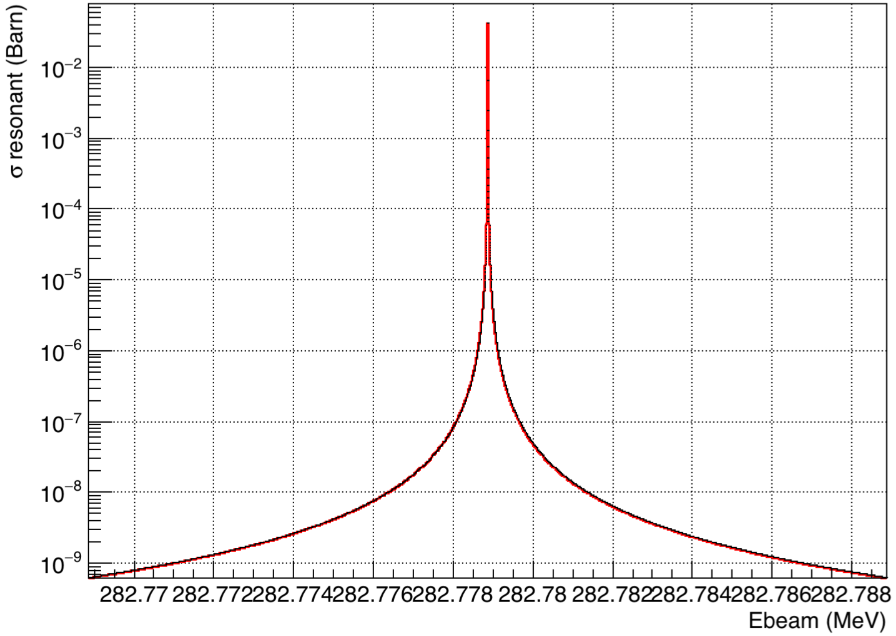
E_p (keV)	IPCC $\times 10^{-4}$	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	



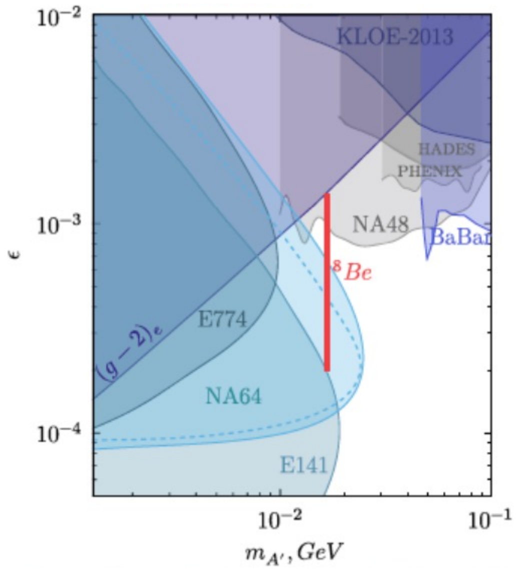
Next steps: ^{8}Be/^{4}He anomaly

- If the anomaly is due to a new particle, reversing the process must be possible
- Annihilating an e^+ with an e^- at exactly the right energy to create this new particle ("on resonance") increases the cross section of production significantly
- The e^+ energy needed to produce a 17 MeV particle on resonance is 282 MeV
- LNF is the only facility in the world able to do this!

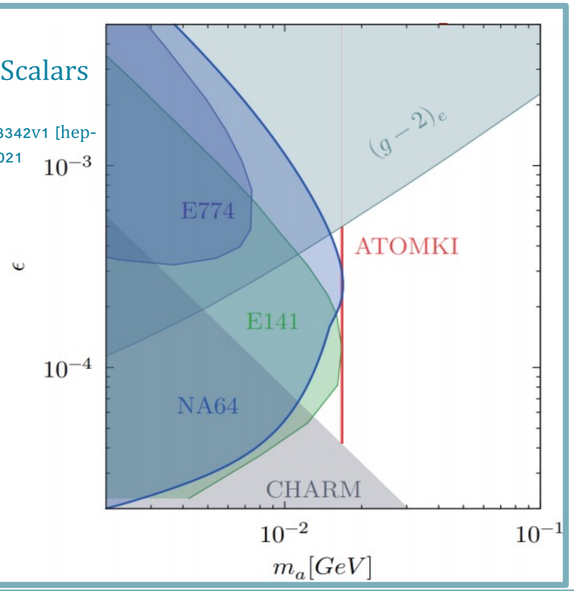




Vectors (A')
Phys. Rev. D 101, 071101(R) (2020)



Pseudo Scalars (ALPS)
arXiv:2104.13342v1 [hep-ex] 27 Apr 2021



Conclusions

- PADME was designed and constructed to search for a dark photon in e^+e^- annihilation
- There are a number of accessible models and final states available to PADME
- The PADME collaboration is now performing physics analysis on data from Run 2
- We also have big plans for the future!
- Further reading is available here:

  - M. Raggi and V. Kozhuharov, Proposal to Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac, Adv. High Energy Phys. 2014 (2014) 959802 [arXiv:1403.3041].
  - R. Assiro et al., Performance of the diamond active target prototype for the PADME experiment at the DAΦNE BTF, Nucl. Instrum. Meth. A 898 (2018) 105 [arXiv:1709.07081].
  - P. Albicocco et al. Characterisation and performance of the PADME electromagnetic calorimeter, JINST 15 T10003 (2020) [arXiv:2007.14240] .
  - S. Ivanov and V. Kozhuharov, The charged particle veto system of the PADME experiment, AIP Conf. Proc. 2075 (2019) 080005.
  - A. Frankenthal et al., Characterization and performance of PADME's Cherenkov-based small-angle calorimeter, Nucl. Instrum. Meth. A 919 (2019) 89 [arXiv:1809.10840].

- For more info, don't hesitate to get in touch!

Thank you for your attention and

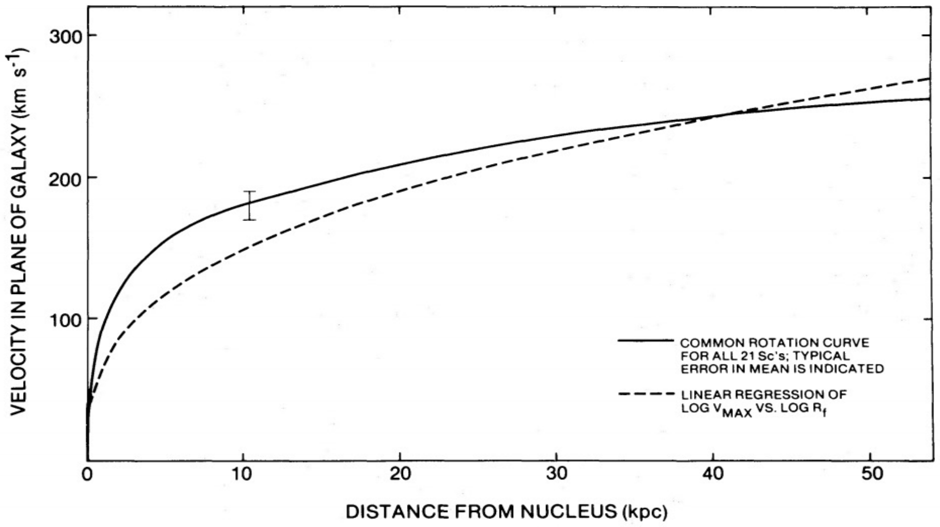
let's turn the dark on!

Backup

The dark matter problem

- The first evidence for non-luminous matter came from galactic rotation curves
- The same effect was then seen by Vera Rubin et al. for stars within galaxies
- “The conclusion is inescapable that nonluminous matter exists beyond the optical galaxy” (Rubin et al. The Astrophysical Journal, 238:471-487, 1980 June 1)

The Astrophysical Journal, 238:471-487, 1980 June 1



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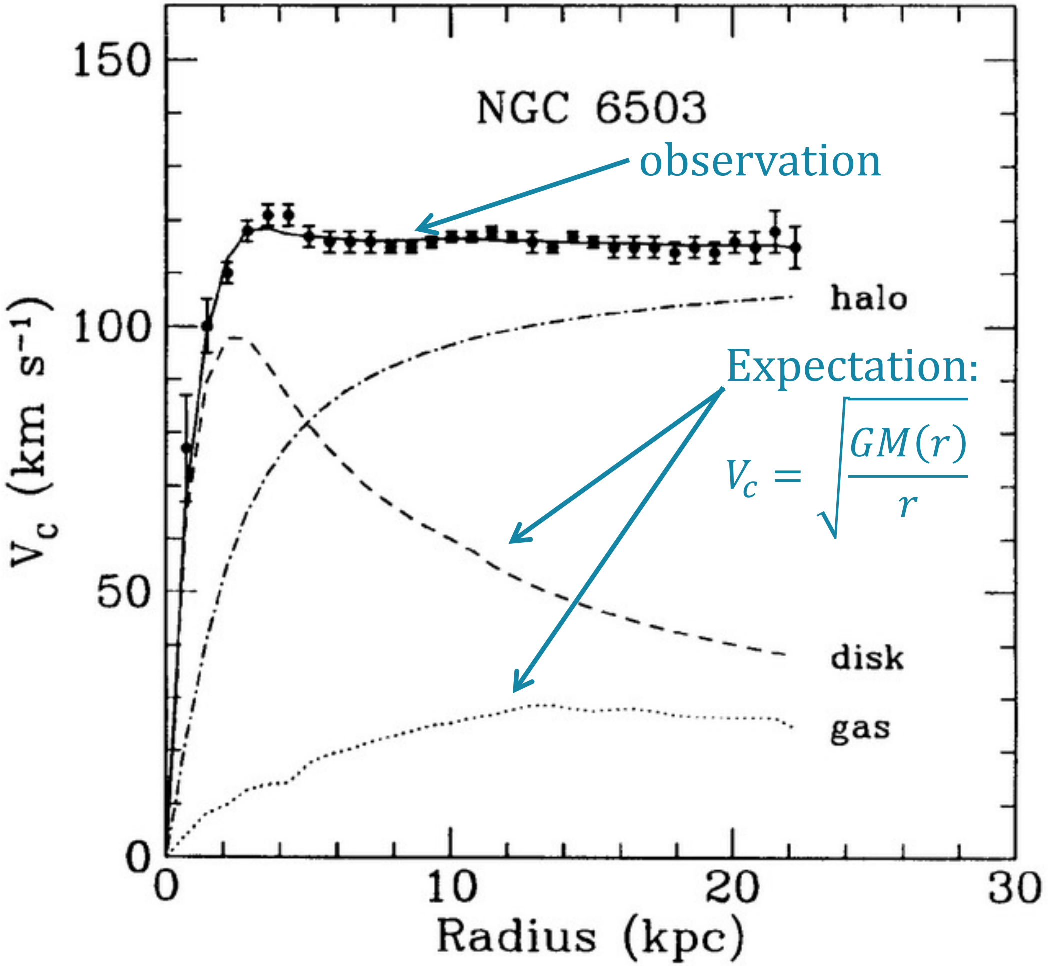
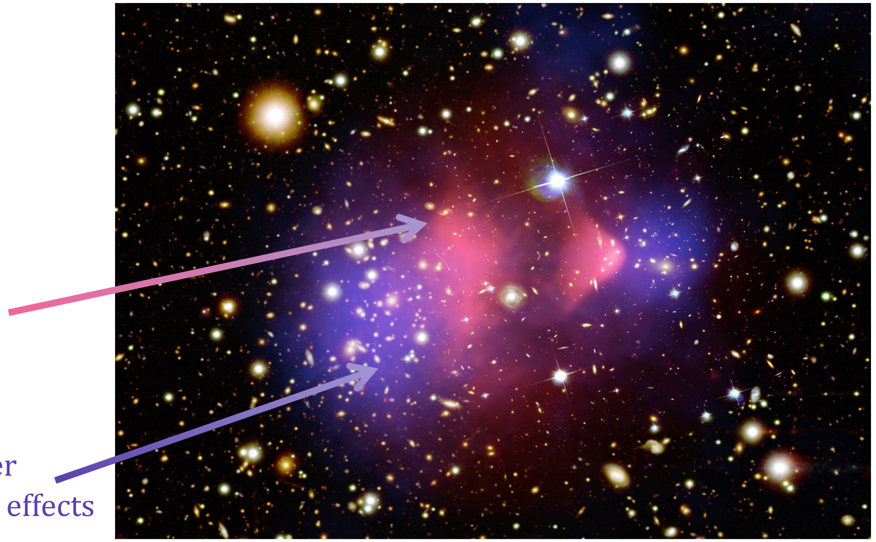
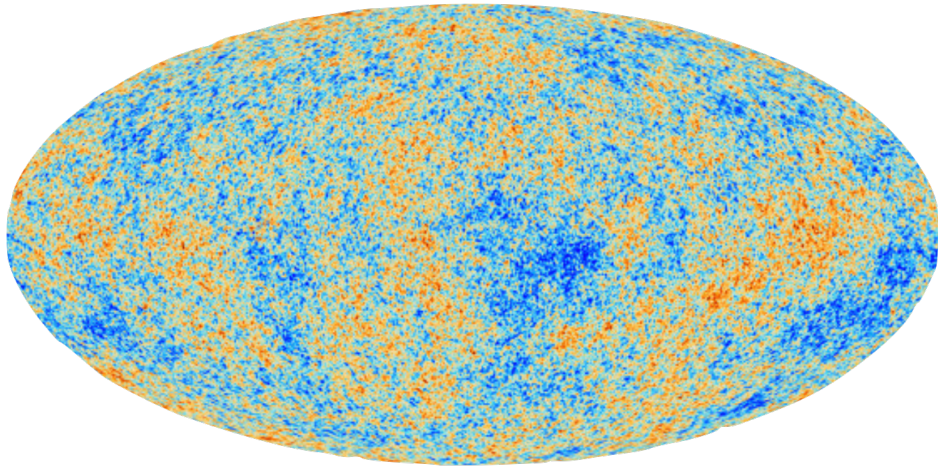


The dark matter problem

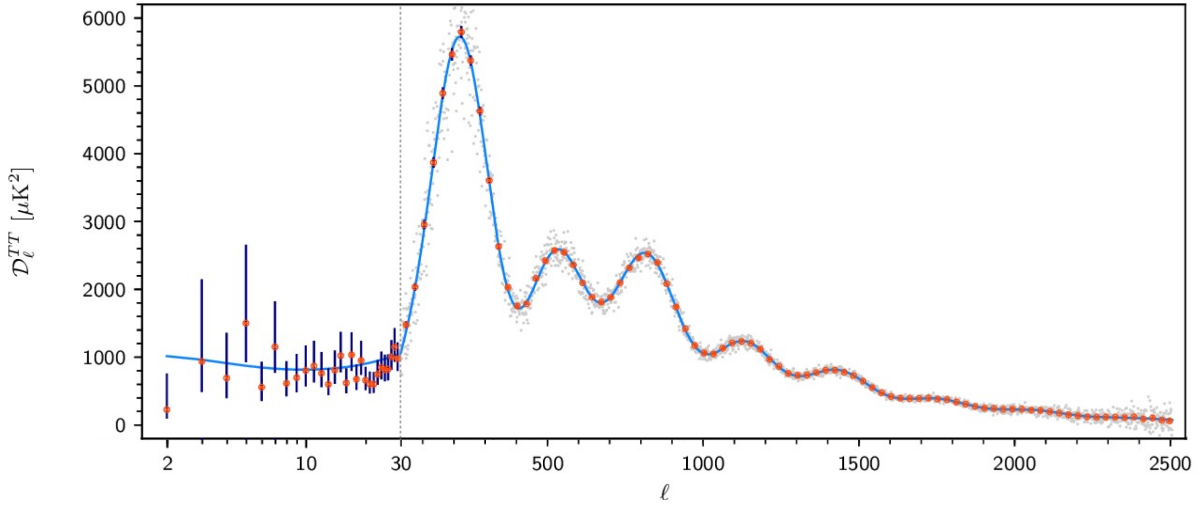
- Gravitational lensing, eg via the bullet cluster, also gives information about the existence and distribution of non-luminous matter
- The bullet cluster collision also tells us that the dark matter (DM) self-interaction cross-section is low
- Anisotropies in the cosmic microwave background also give evidence for DM



X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



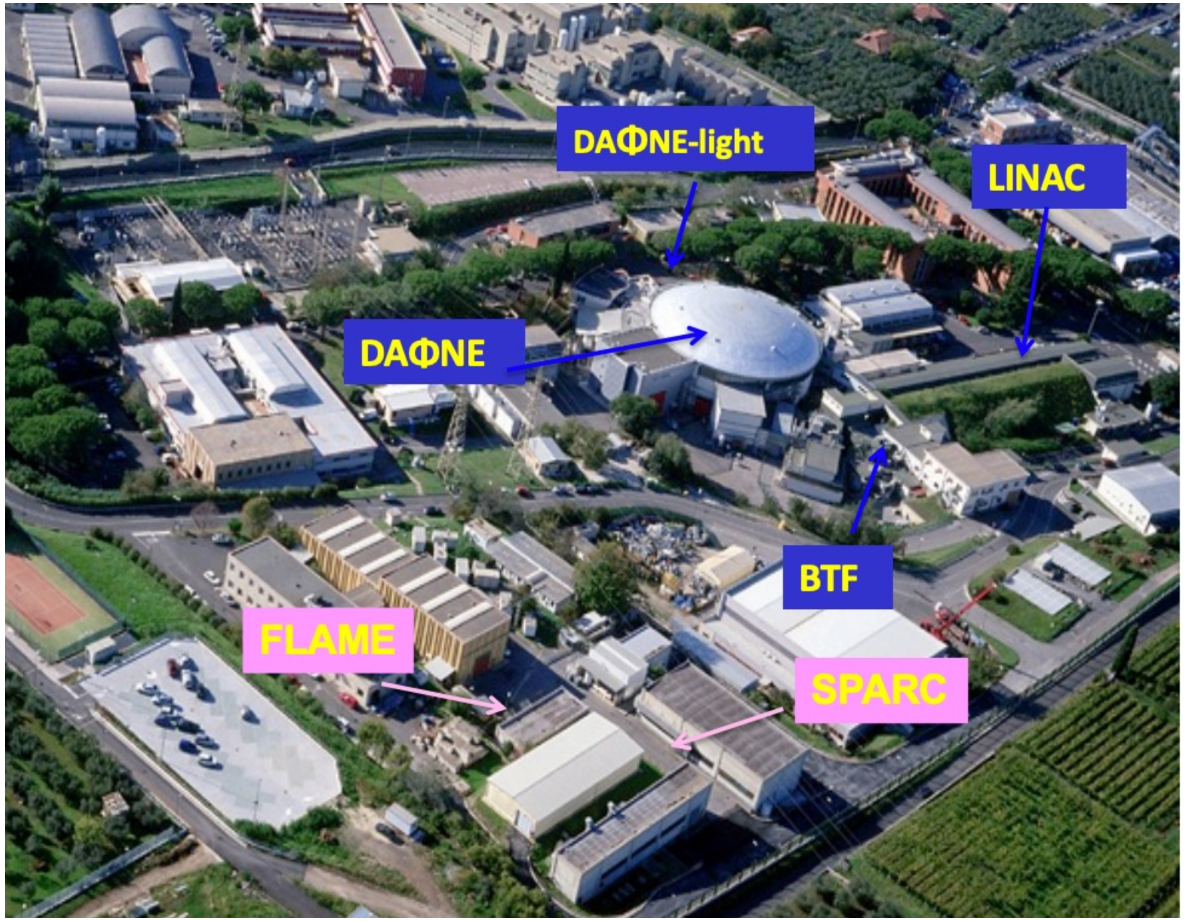
Planck Collaboration. Cosmic microwave background (mollweide). Available online at http://planck.cf.ac.uk/all-sky-images, 2019



Aghanim, Planck Collaboration N. et al. "Planck 2018 results: V. CMB power spectra and likelihoods." *Astronomy and Astrophysics* 641 (2019): 1-92.

Dark sector searches at PADME

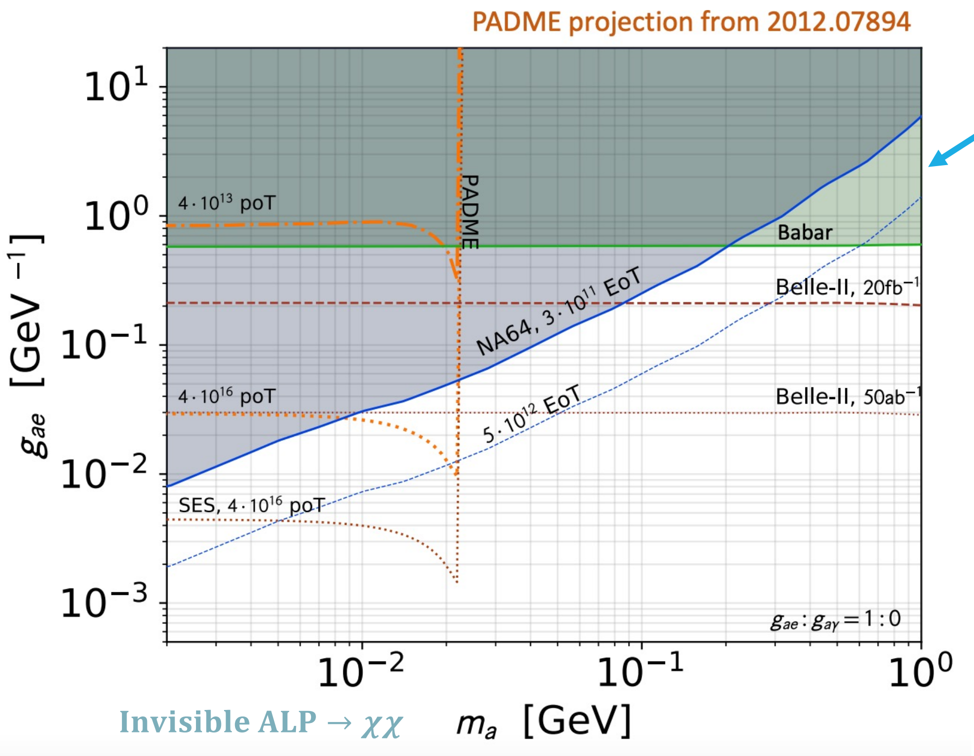
- PADME = Positron Annihilation to Dark Matter Experiment
- PADME is installed in the Beam Test Facility at the INFN National Laboratories of Frascati (LNF)
- LNF has been devoted to particle physics research and accelerator development ever since its foundation

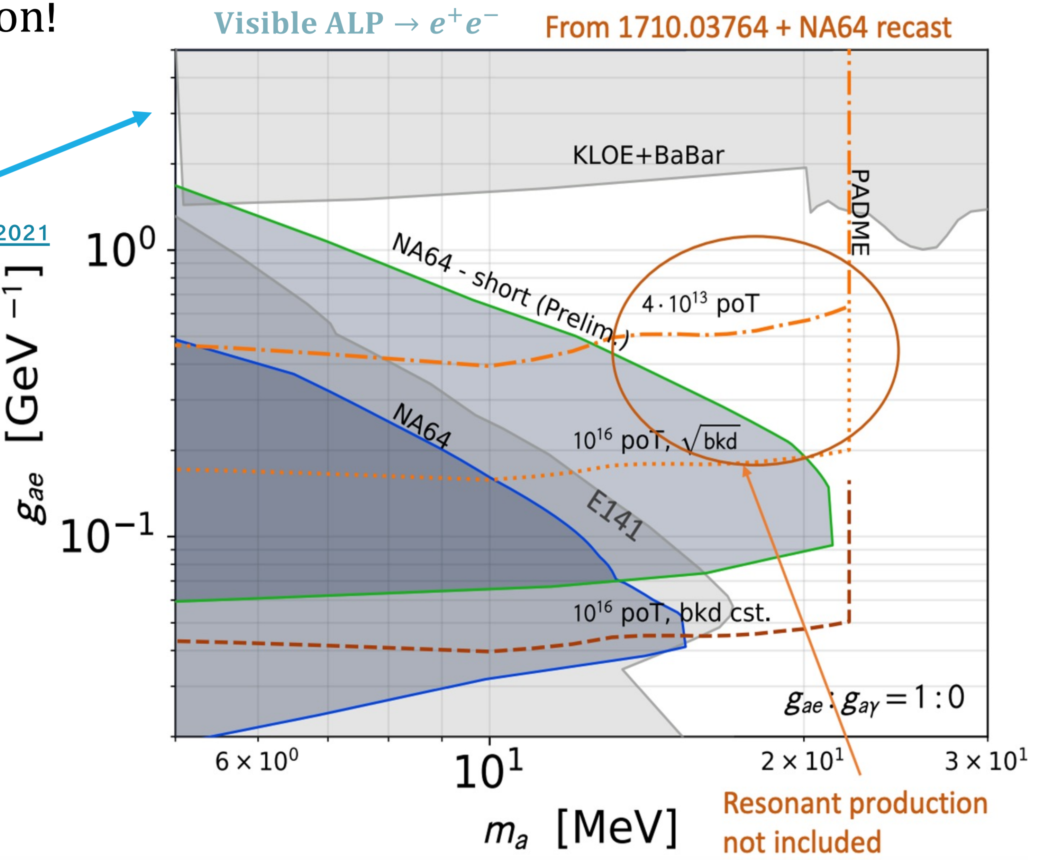


Current constraints: ALPs

- Plenty of space to be explored here to, and in the same mass region!

Credit to Luc Darmé FFF 2021

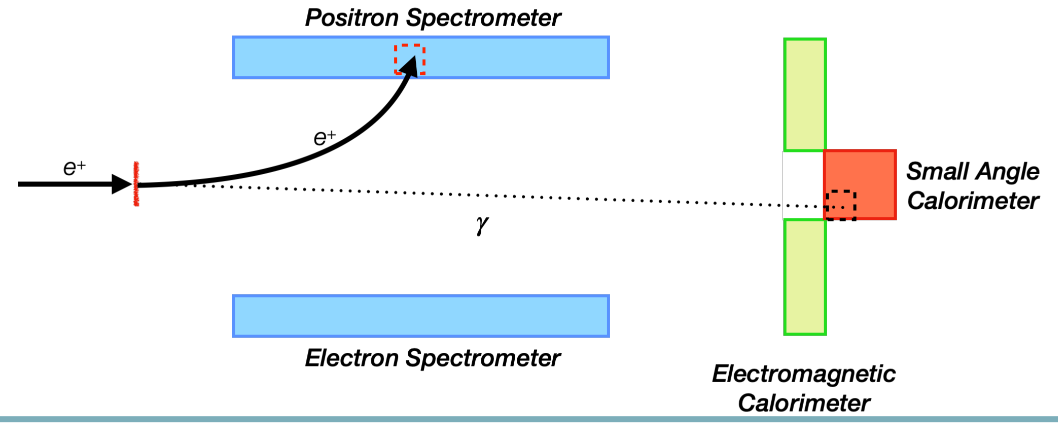




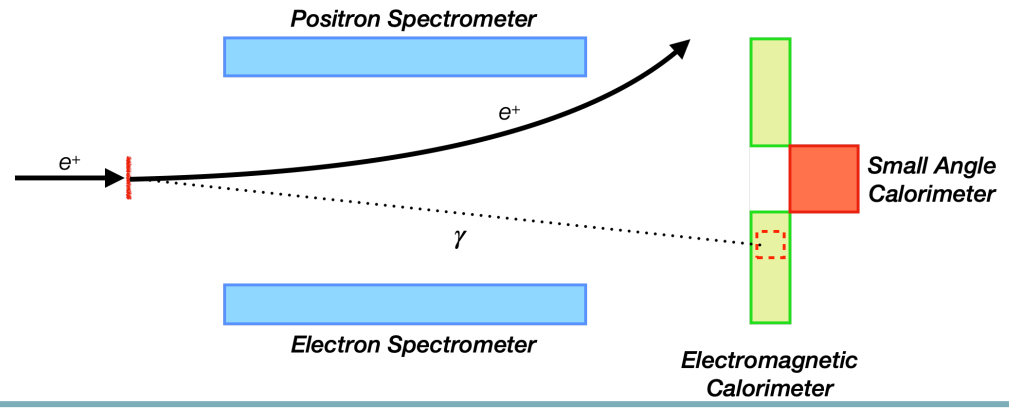
Experimental backgrounds: Invisible decays

- We have two principle sources of background:
  - Bremsstrahlung in the target: missing e^+
  - 2 (3) photon annihilation where 1 (2) of the photons goes undetected
- Bremsstrahlung suppression:
  - A magnetic field deflects the positron into the "Positron Veto (PVeto)" detector
  - Since the Bremsstrahlung photon is usually emitted with a small angle to the beam, a central hole in the ECal allows the photon to pass into the Small Angle Calorimeter (SAC), which is designed to cope with the high rate

Bremsstrahlung detected ✓



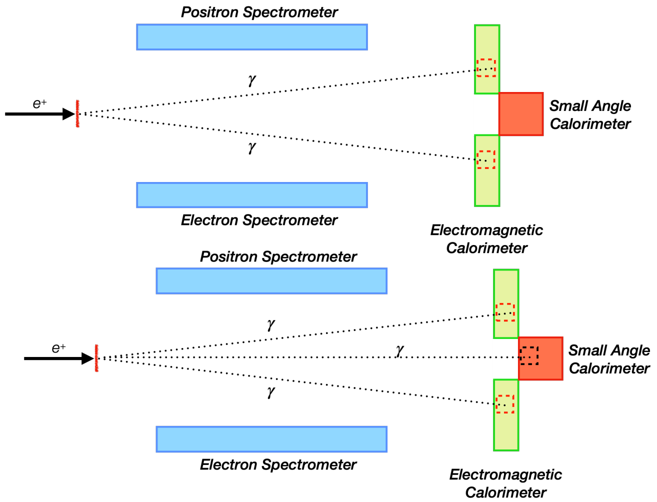
Bremsstrahlung undetected: background ✗



Experimental backgrounds: Invisible decays

- We have two principle sources of background:
  - Bremsstrahlung in the target: missing e^+
  - 2 (3) photon annihilation where 1 (2) of the photons goes undetected
- Annihilation background suppression:
  - We veto events with 2 in-time photons in ECal
  - Maximising granularity, angular coverage and energy resolution of ECal reduces the probability of photons escaping detection

All photons detected ✓



Undetected photon(s): background ✗