Dark Sector Studies with the PADME Experiment

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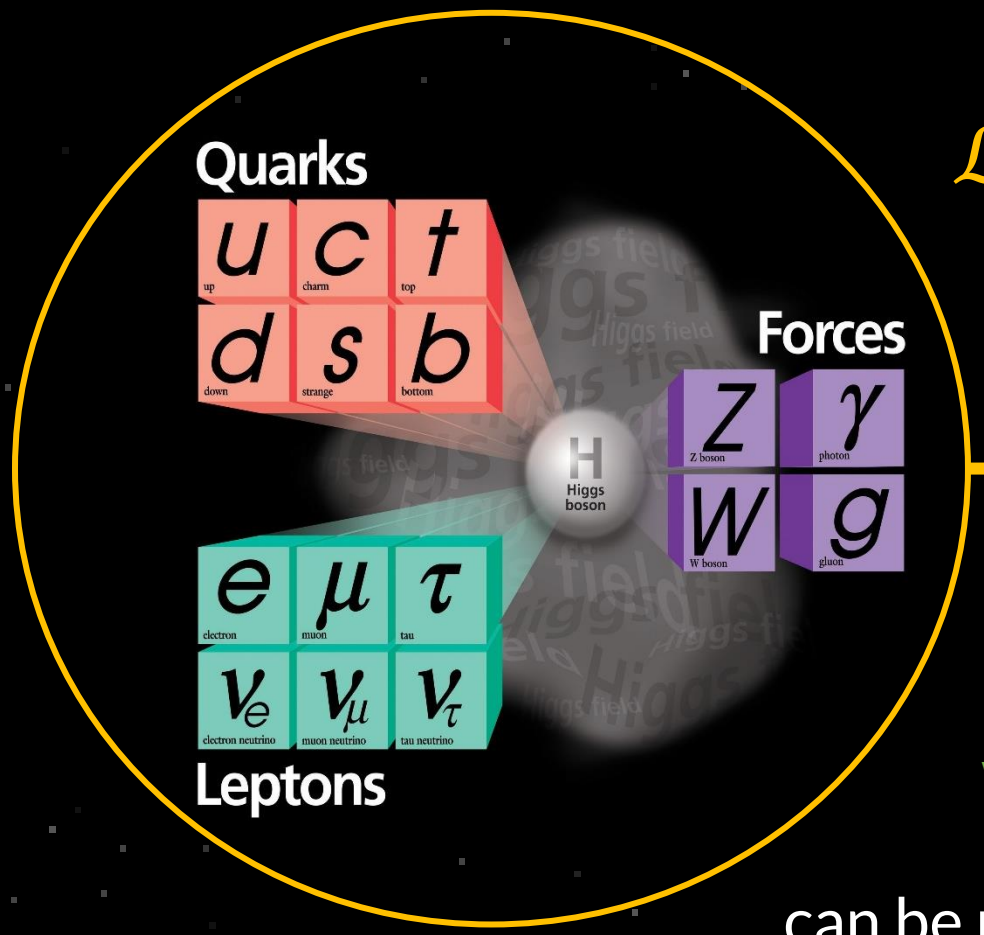
The Dark Sector Paradigm

Standard Model



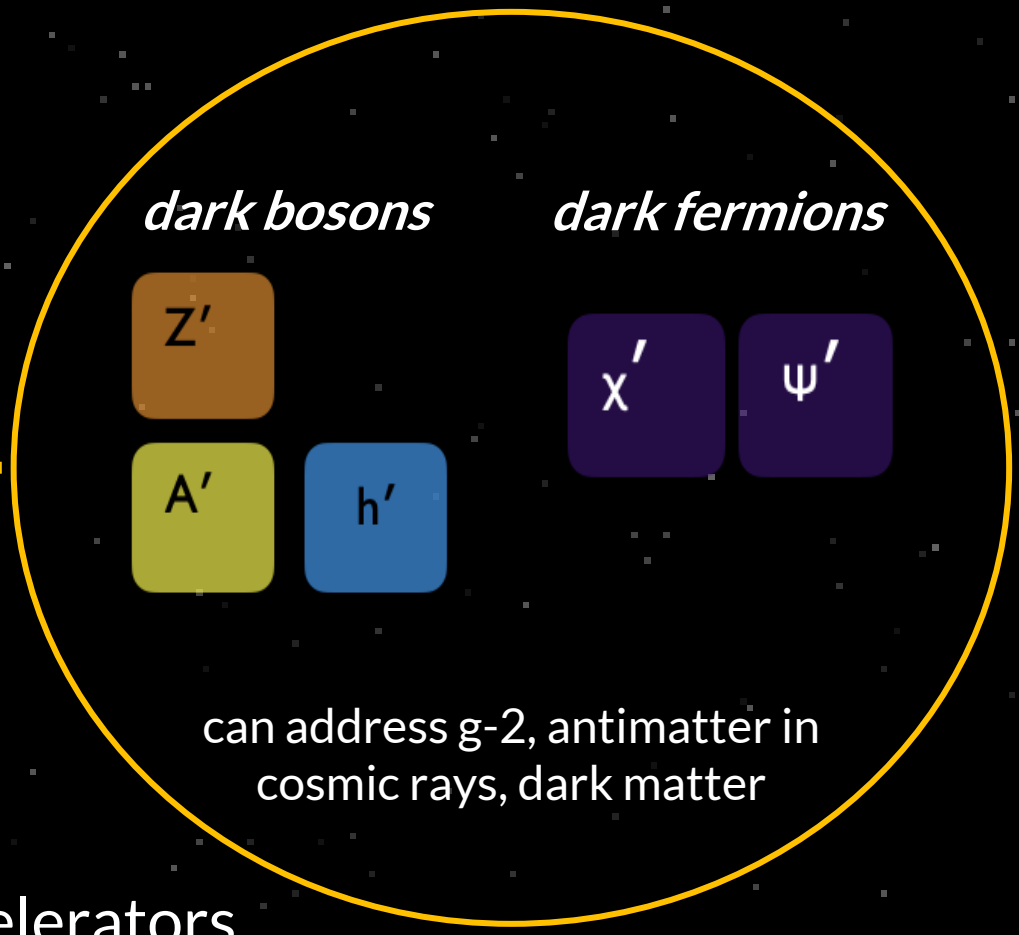
$$\mathcal{L} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

Portal

Mediator

Feeble interaction with ordinary matter

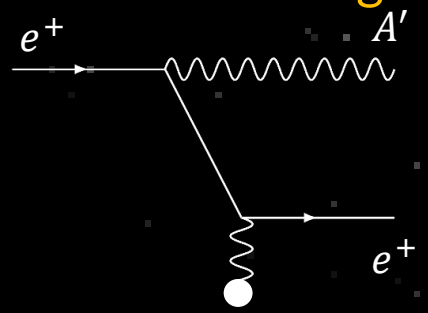
Dark Sector



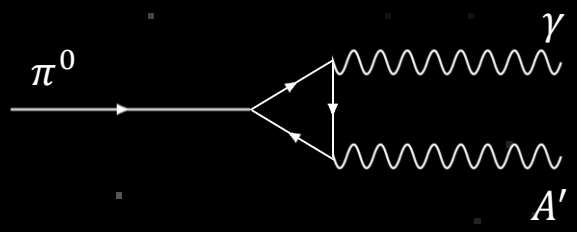
can be produced at accelerators
can decay back to ordinary matter

Dark Photon Production

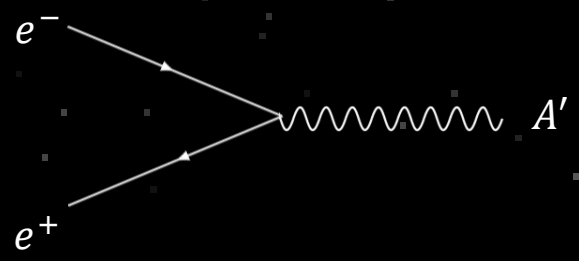
A'-strahlung



meson decay

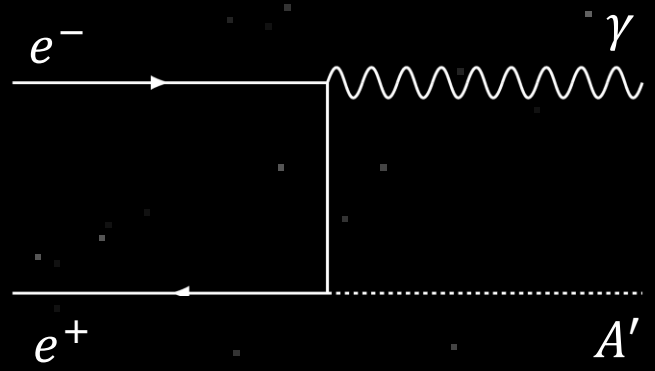


resonant annihilation



Positron Annihilation into Dark Matter Experiment

annihilation with SM photon



A' produced in e^+e^- annihilation
positron (beam) ↔ electron (target)

Signal

$e^+e^- \to A'\gamma$

Background

$e^+e^- \to \gamma\gamma(\gamma)$

$e^+N \to e^+N\gamma$

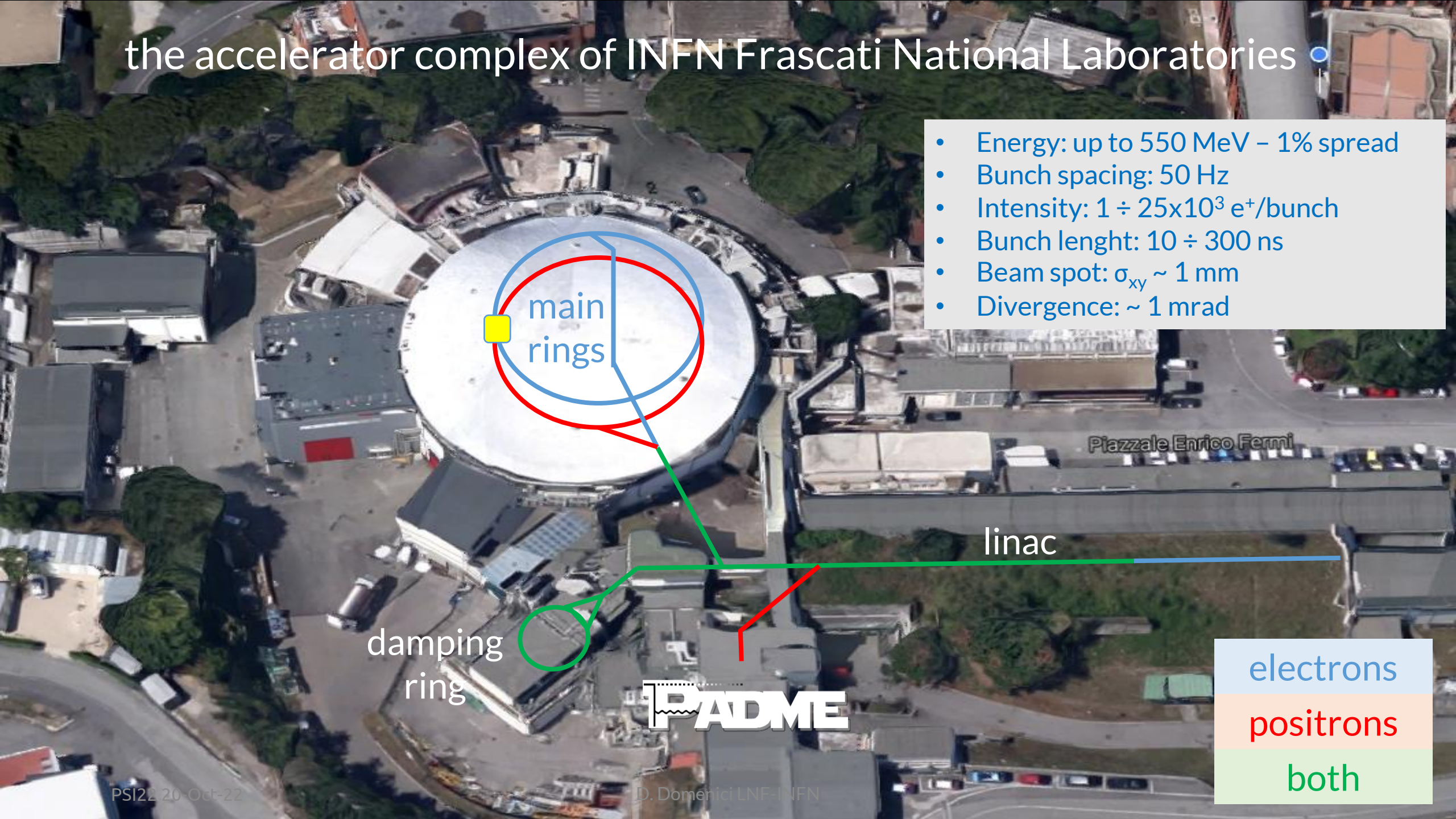
beam induced

coupling constant can be extracted

$$\frac{\sigma(e^+e^- \to A'\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} \sim \varepsilon^2$$

the accelerator complex of INFN Frascati National Laboratories

- Energy: up to 550 MeV – 1% spread
- Bunch spacing: 50 Hz
- Intensity: 1 ÷ 25x10^3 e$^+$/bunch
- Bunch lenght: 10 ÷ 300 ns
- Beam spot: σ_{xy} ~ 1 mm
- Divergence: ~ 1 mrad



Dark Photon Decay

Phenomenology can hugely vary depending on the detailed structure of the hidden sector and simultaneous presence of many mediators

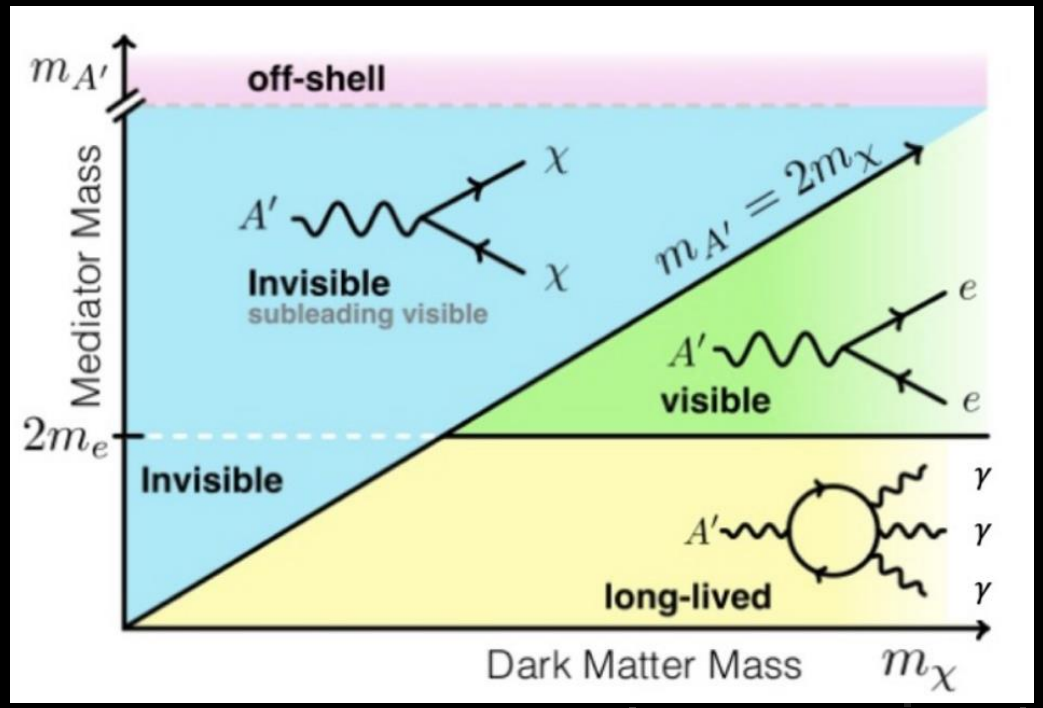
Mass spectrum

$m_{A'} > 2m_e$ or $m_{A'} < 2m_e$

$m_{A'} > 2m_\chi$ or $m_{A'} < 2m_\chi$

Visible decays to SM particles

Invisible decays (+ visible but long-lived mediators)



PADME design driven by the detection of A' into invisible decay with missing mass technique

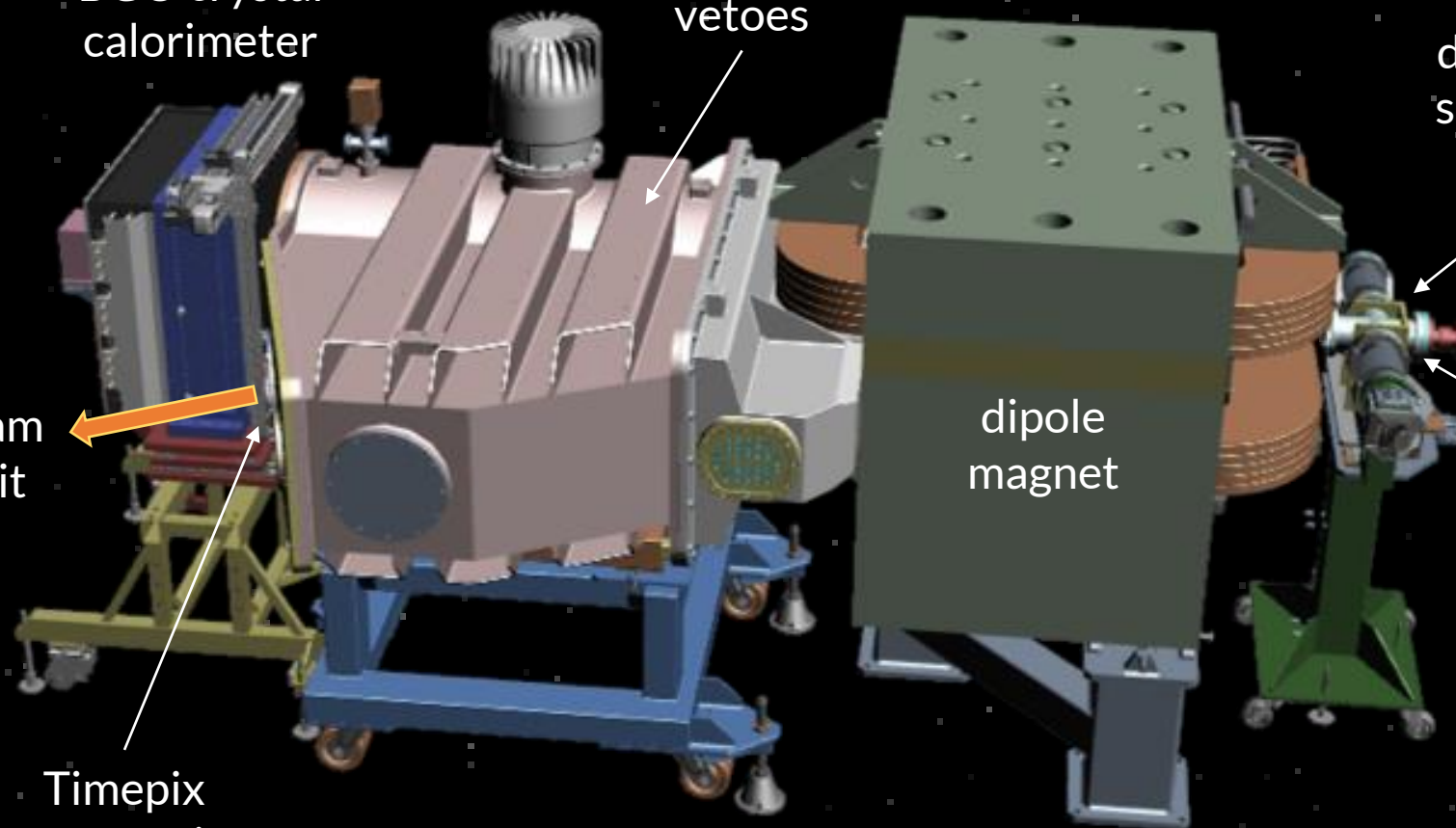
$$M^2_{A'} = (\bar{P}_{e^+} + \bar{P}_{e^-} - \bar{P}_\gamma)^2$$

Only theoretical assumption: A' couples to leptons

Here is PADME

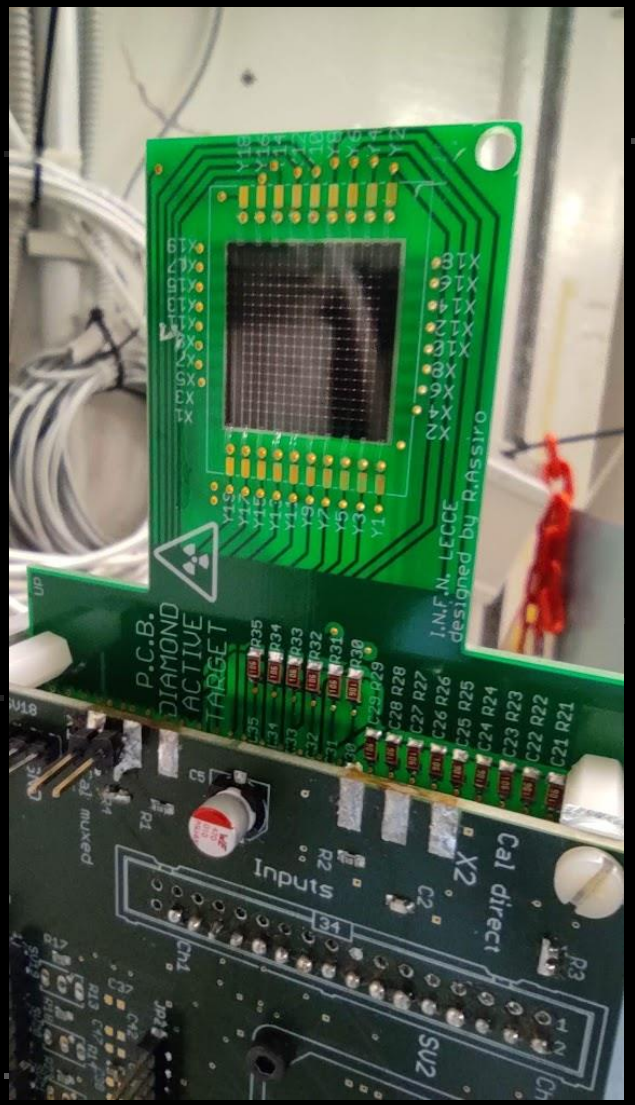
Commissioning paper [2022 JINST 17 P08032]

The PADME Detector



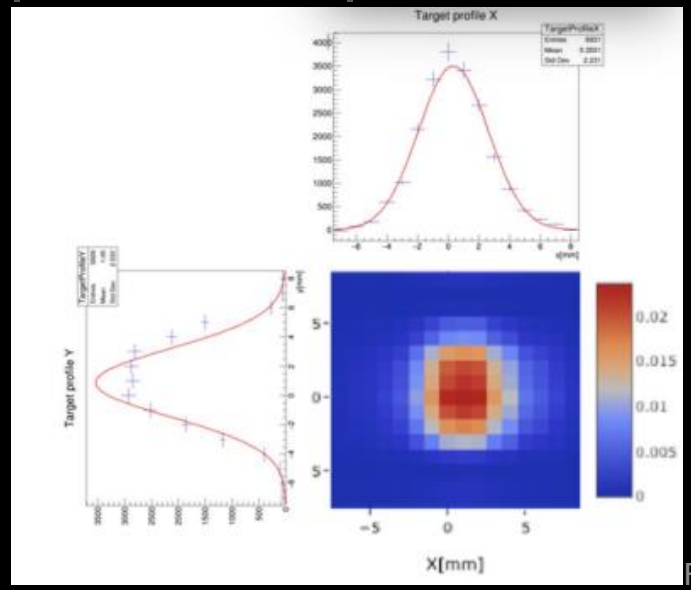
Detector: Beam Monitors

Diamond active annihilation target

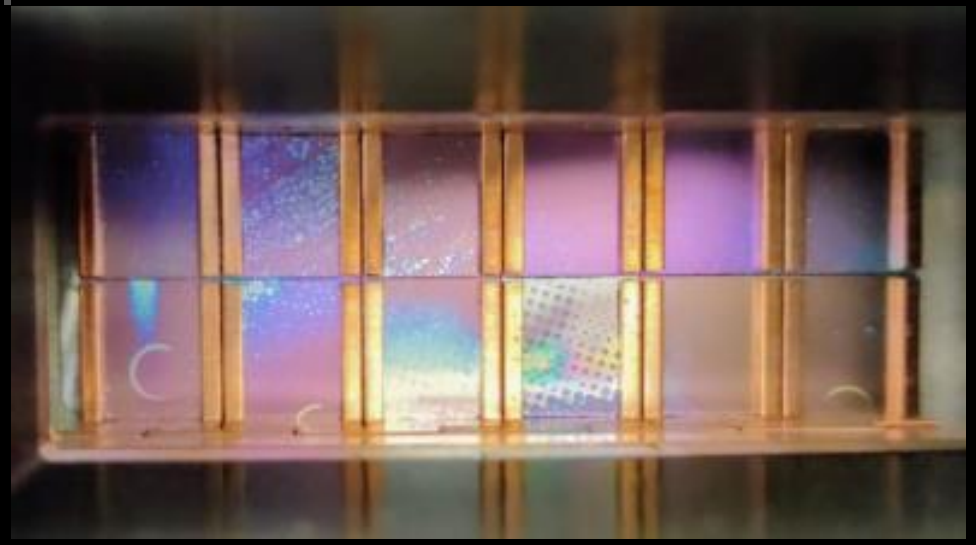


single bunch XY profile
and beam multiplicity

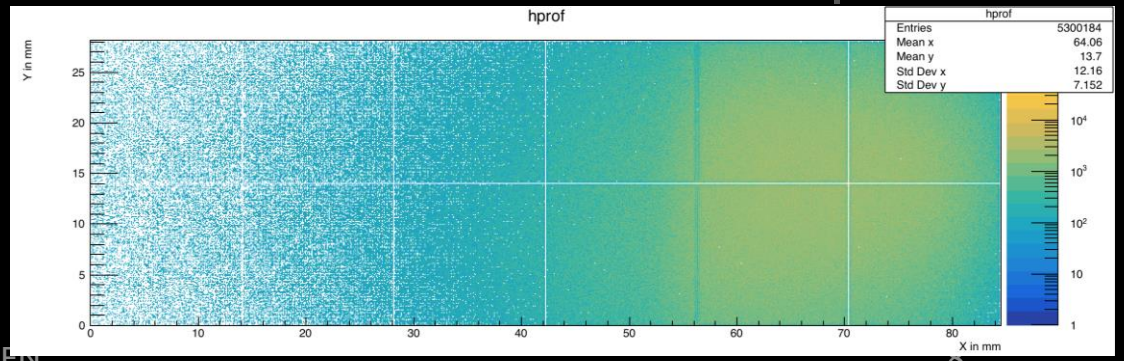
20x20x0.1 mm^3 pCVD sensor
16+16 XY graphite strips
1 mm pitch
60 μm resolution
10% intensity measurement
[NIM A 162354 (2019)]



Downstream Timepix

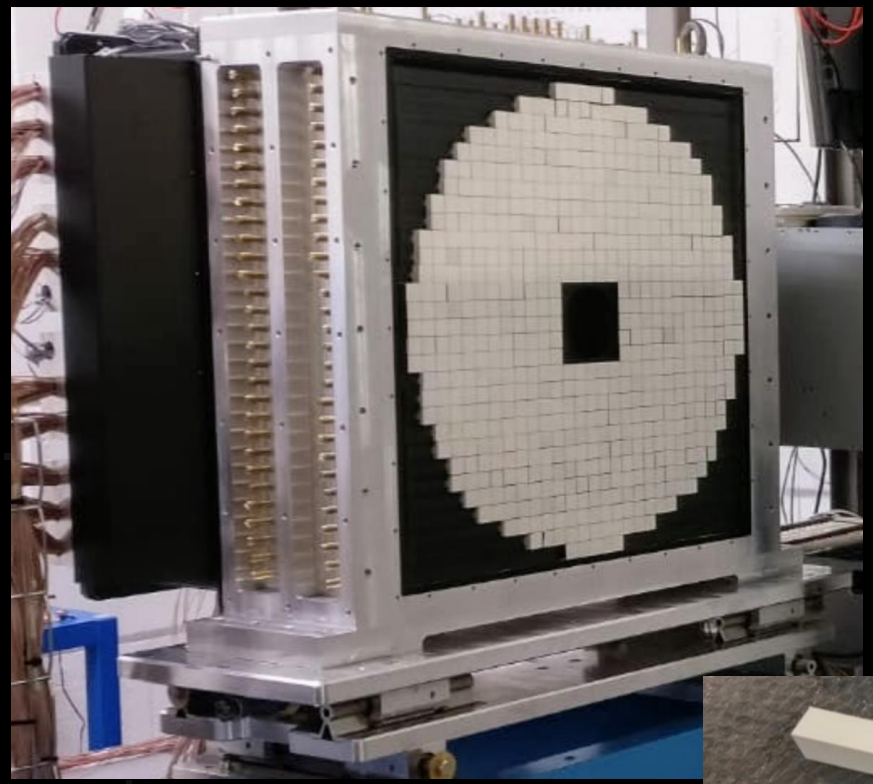


2x6 matrix of 14x14 mm2 Timepix3
0.13 μm CMOS technology
256x256 pixel matrix, 55x55 $μm^2$



Detector: Calorimeters

Electromagnetic Calorimeter ECAL



annihilation events
bremmstrahlung suppression

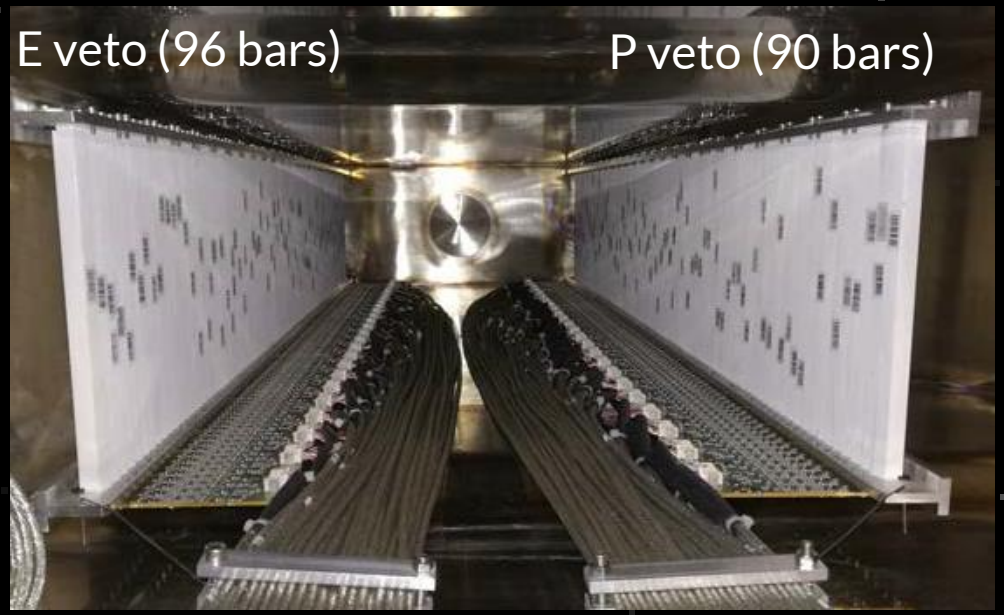
616 scintillating BGO crystals
21×21×230 mm^3
PMT readout
σE/E = 2.8% at 490 MeV
BGO decay time = 300 ns
Radiation length = 20.5 X_0
[JINST 15 (2020) T10003]

Small Angle Calorimeter SAC

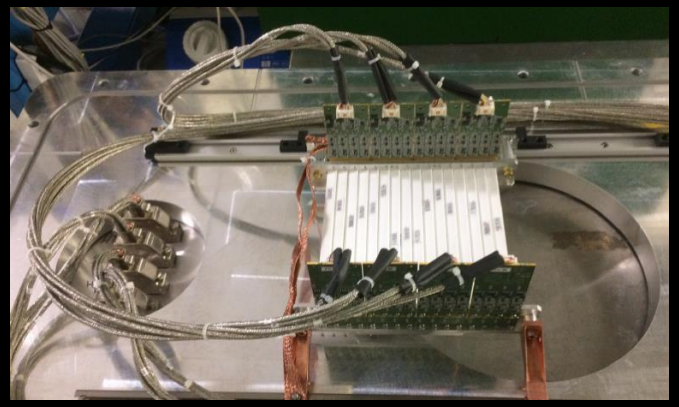
25 Cherenkov PbF_2 crystals
30×30×140 mm^3
PMT readout
PbF_2 signal time = 3 ns
Time resolution = 80 ps
Rate capability = 40 cluster/bunch
[NIM A 919 (2019) 89]

Detector: Charged Particles Vetoes

Electron-Positron Vetos
EVETO-PVETO



HEP veto
(16 bars)



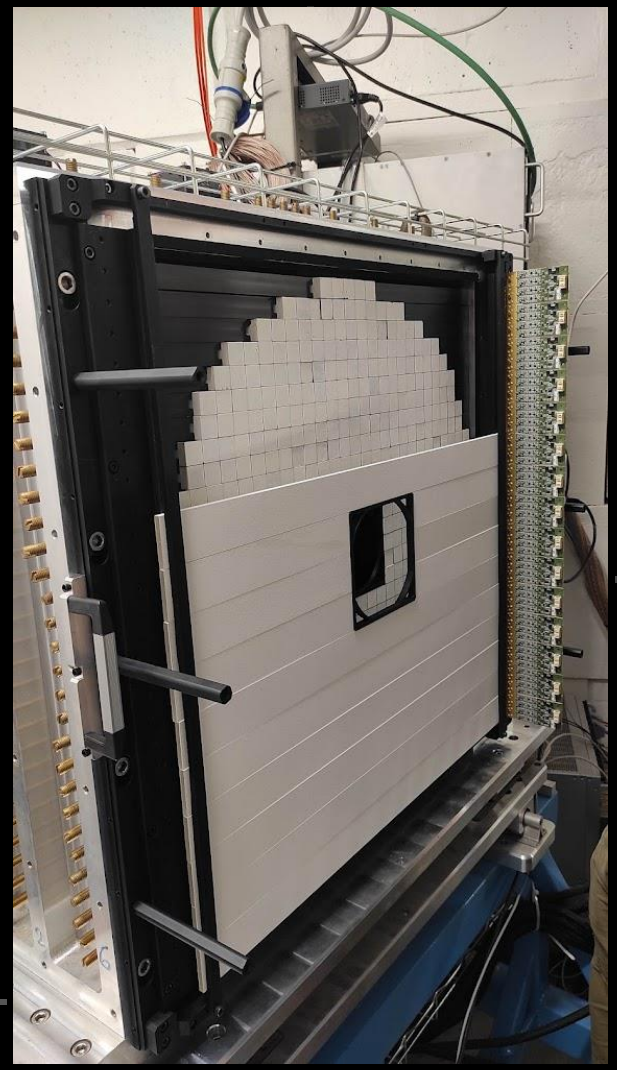
bremmstrahlung suppression
detection of visible decays

plastic scintillators bars
10x10x178 mm^3
WLS fiber + 3x3 mm^2 SiPM
500 ps time resolution
2% momentum resolution
[NIM A 936 (2019) 259]
[JINST 15 (2020) 06, C06017]

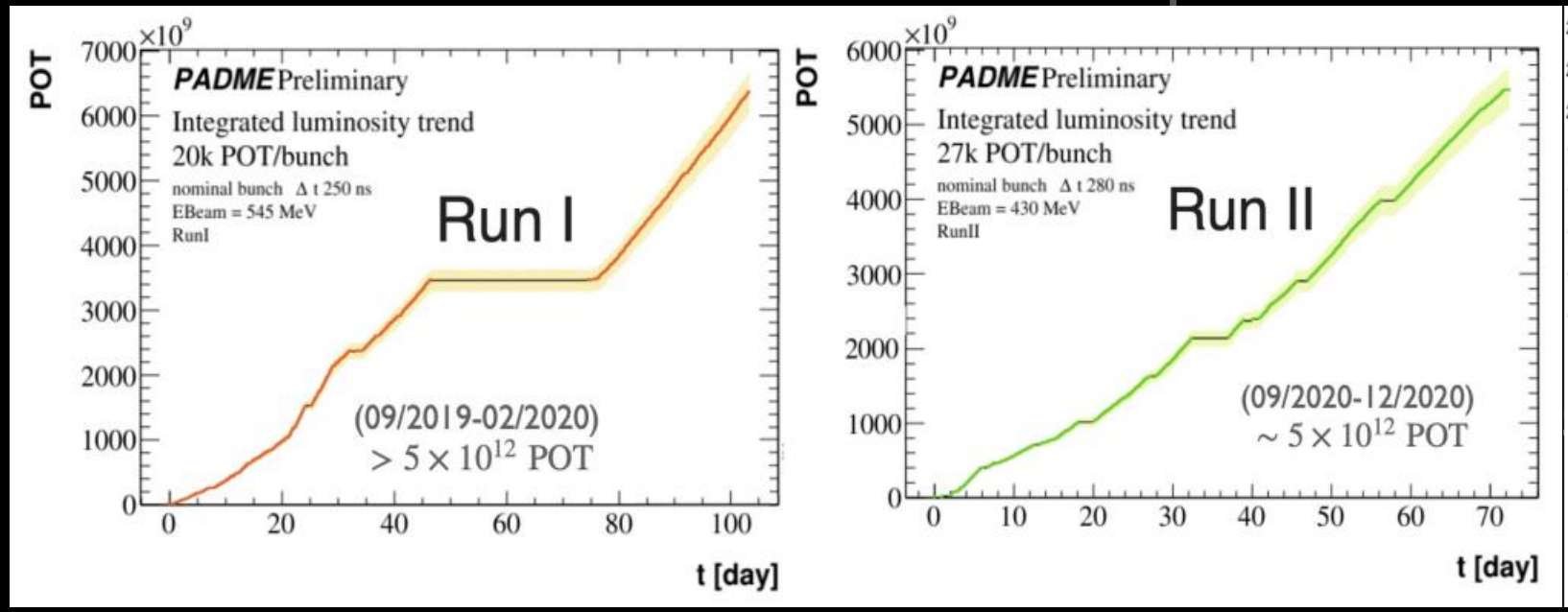
photon veto for X17 run

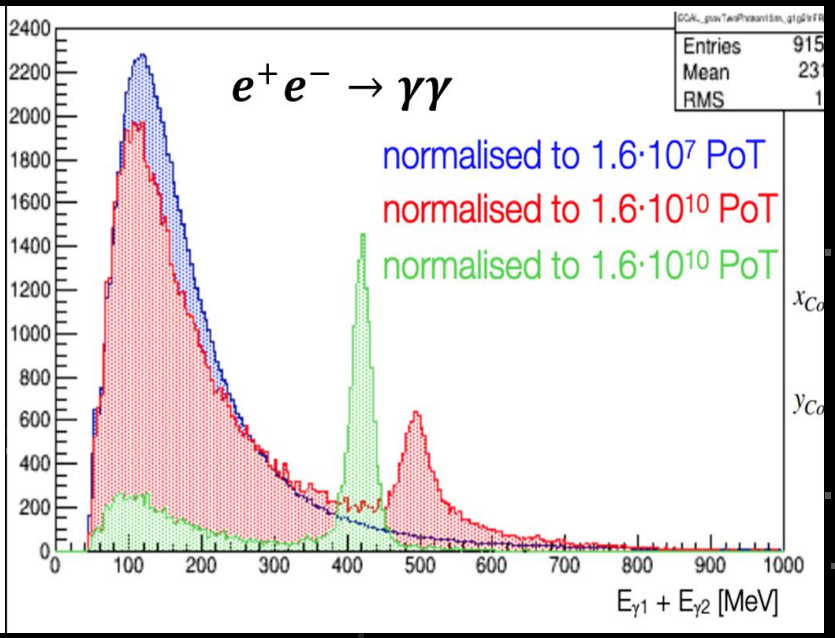
16 scintillators 600x45x5 mm^3
4 SiPM direct readout on
both sides
installed in 2022

Electron Tagger
ETAG



Data Taking Runs





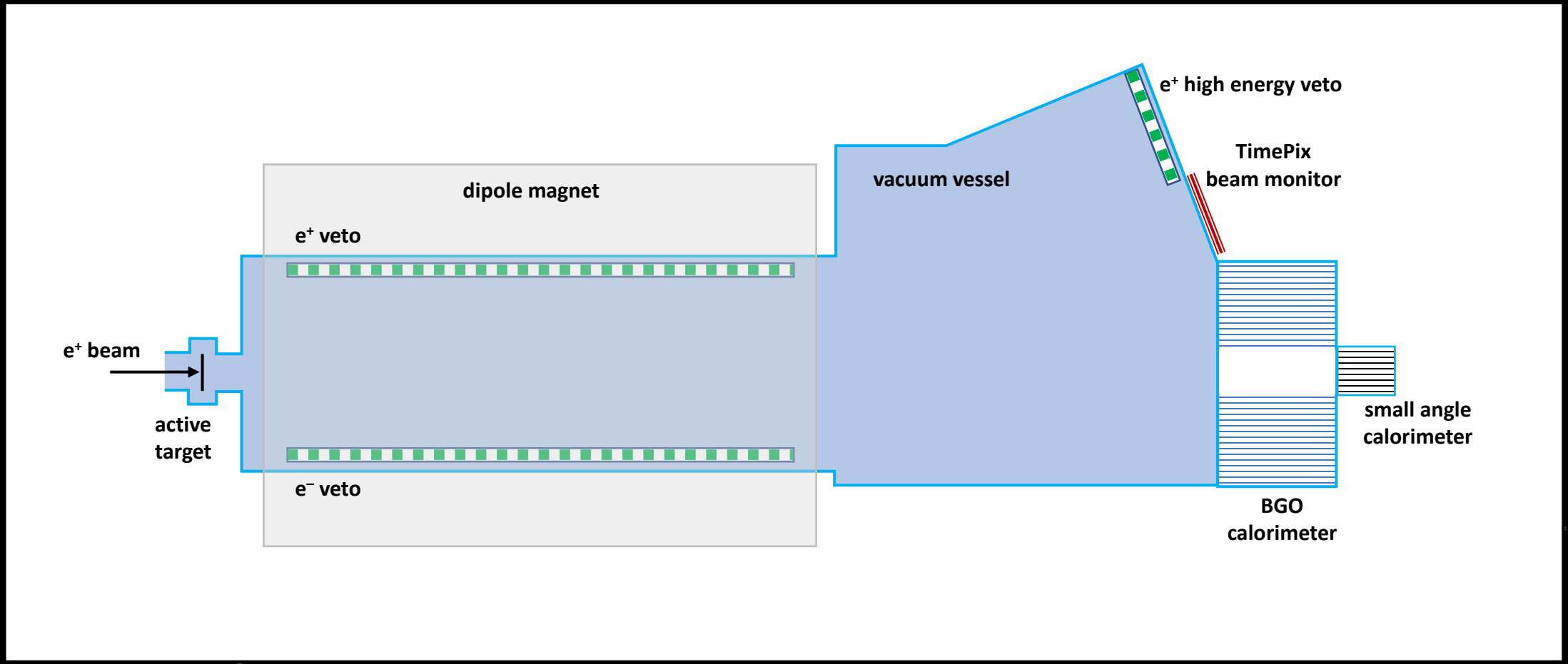
RUN1 – 2019
Secondary Beam
7x10^{12} POT
250 μm Be window
545 MeV
25kPOT / 250 ns bunch

RUN1 – 2019
Primary Beam
250 μm Be window
490 MeV
25kPOT / 250 ns bunch

RUN2 – 2020
Primary Beam
6x10^{12} POT
125 μm Mylar window
430 MeV
28kPOT / 280 ns bunch

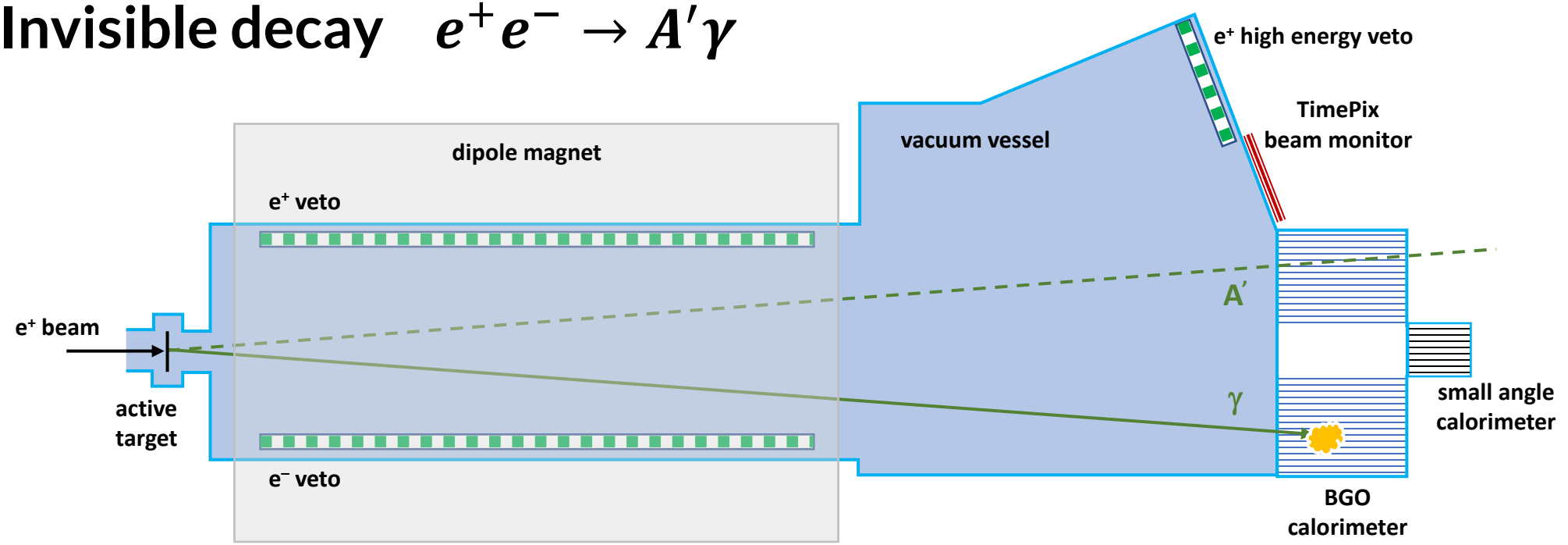
RUN3 – 2022 – X17 search
Primary Beam
ongoing
125 μm Mylar window
283 MeV
2kPOT / 260 ns bunch

PADME Detector Outline



PADME Detector Outline

Invisible decay $e^+e^- \rightarrow A'\gamma$

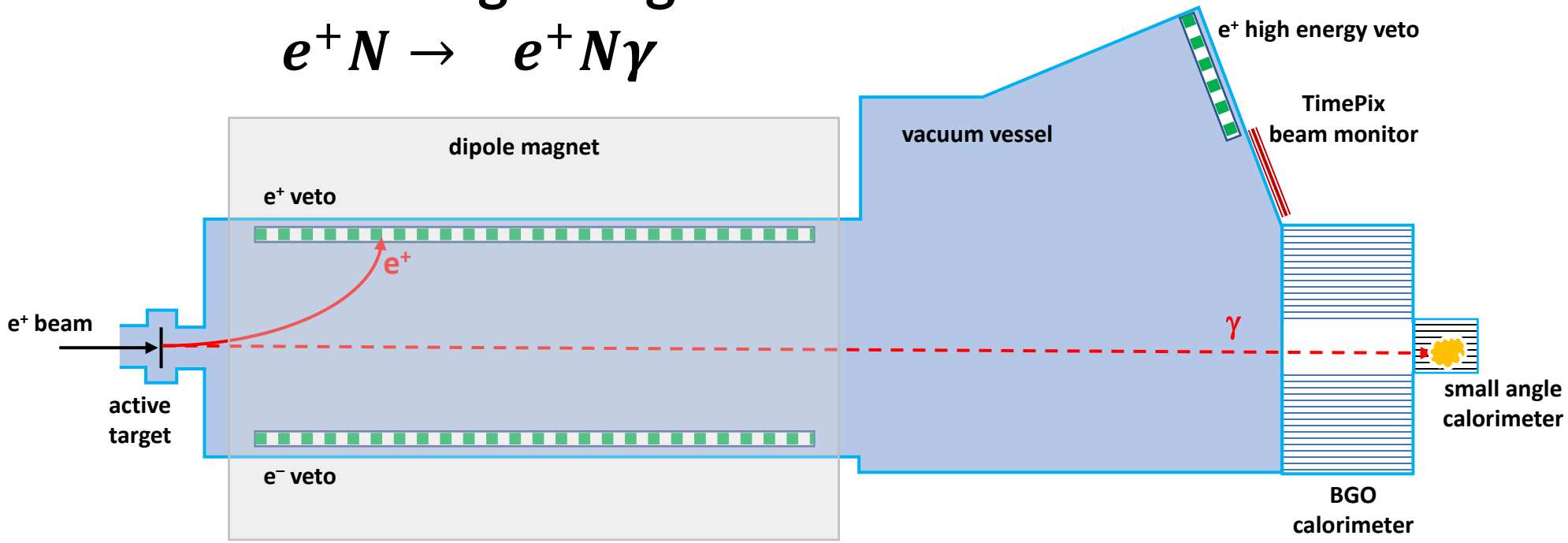


one γ and no in time activity in the detectors

PADME Detector Outline

Bremmstrahlung background

$$e^+N \rightarrow \quad e^+N\gamma$$



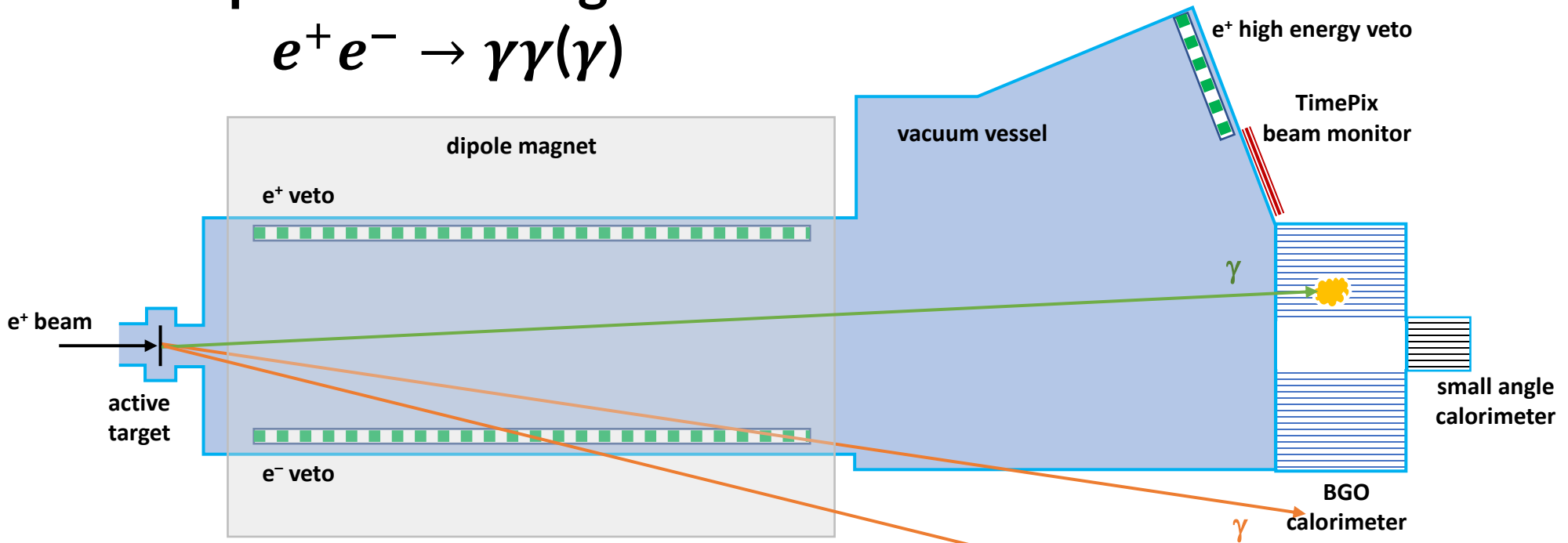
one γ but low energy e^+ in time in the veto/spectrometer

σ = 4b / C atom @ E_γ = 1 MeV

PADME Detector Outline

SM photons background

$$e^+e^- \rightarrow \gamma\gamma(\gamma)$$



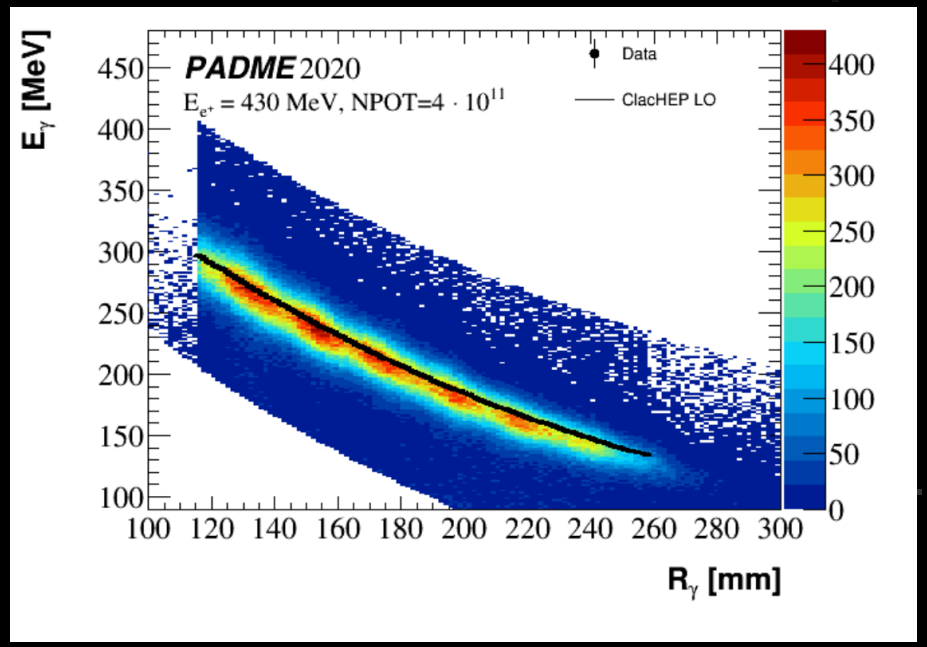
one (or two) γ not in detector acceptance

$\sigma = 0.15\text{mb} @ E_\gamma > 1\ \text{MeV}$

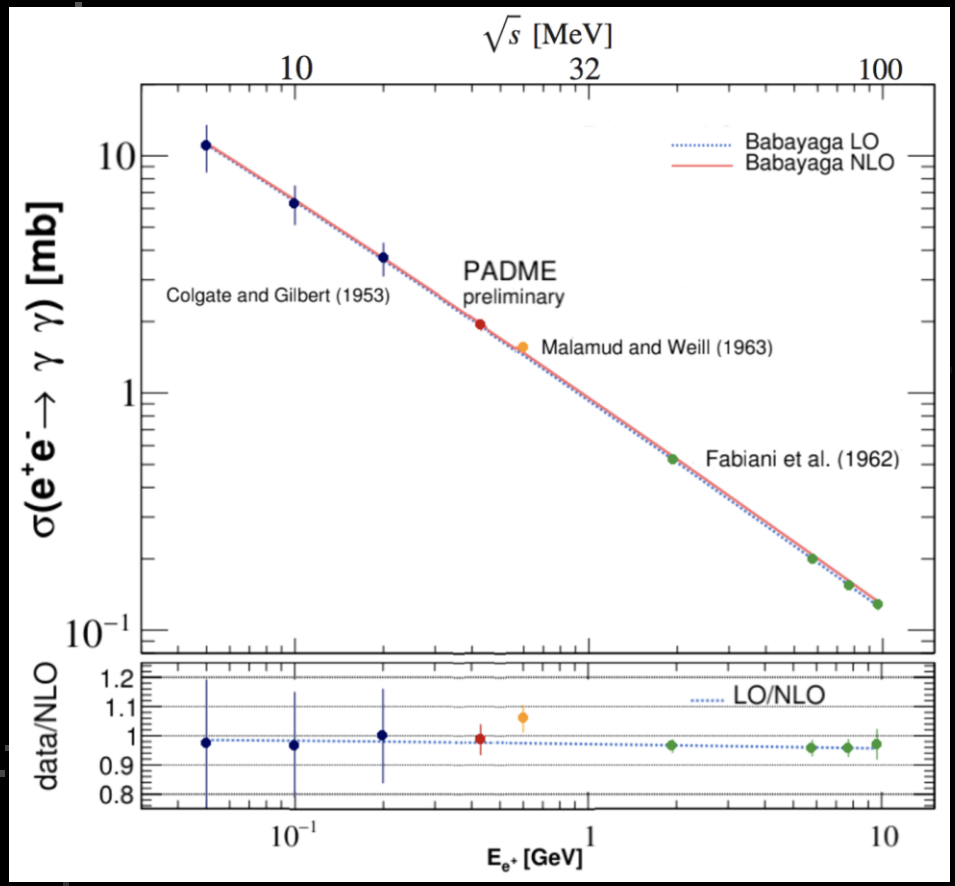
$e^+e^- \to \gamma\gamma$ Cross-Section

Physics case:

- known only with 20% accuracy below 0.6 GeV
- Most recent measurement is 60 y old
- Used 10% of Run2 sample



Exploit energy vs polar angle correlation to select photons

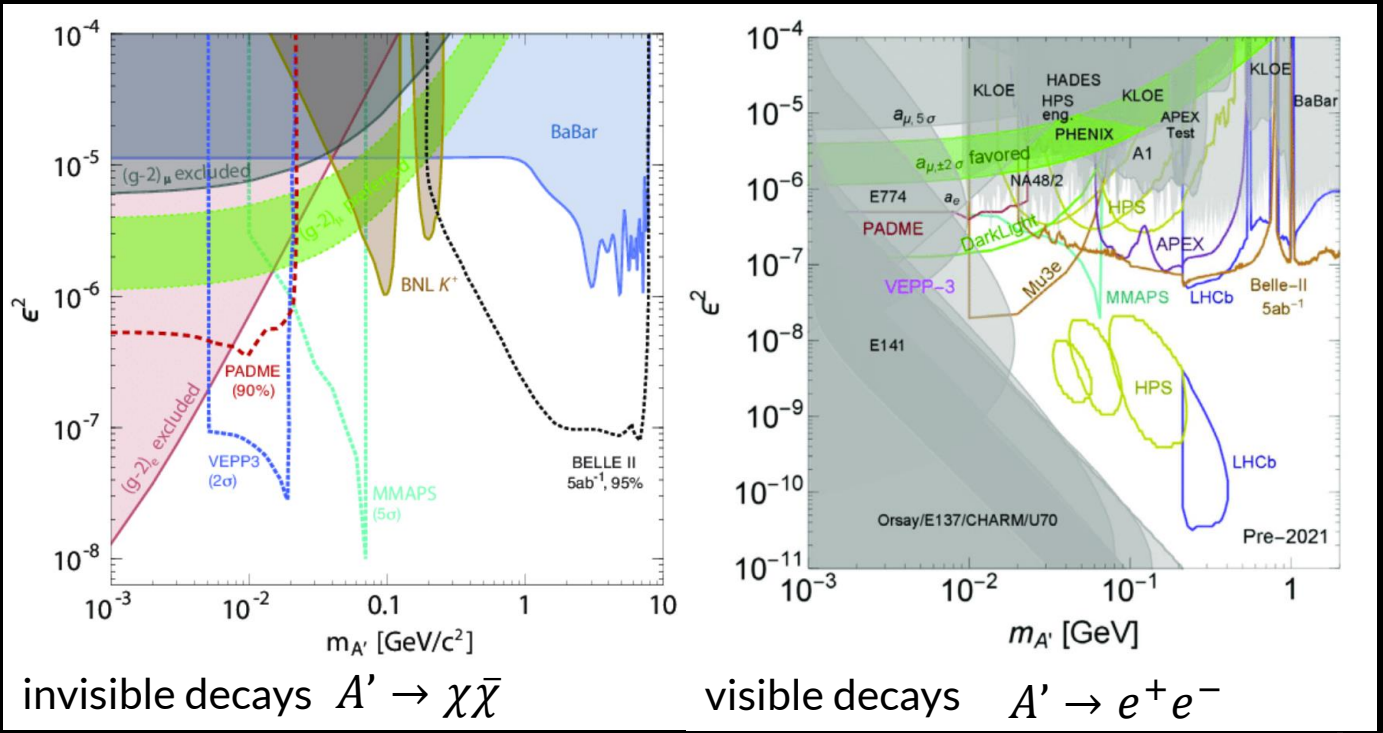


$\sigma(e^+e^- \to \gamma\gamma) = (1.977 \pm 0.018_{stat} \pm 0.118_{syst})$ mb

5.5% uncertainty: most precise measurement in this energy regime

PADME Studies: Dark Photon

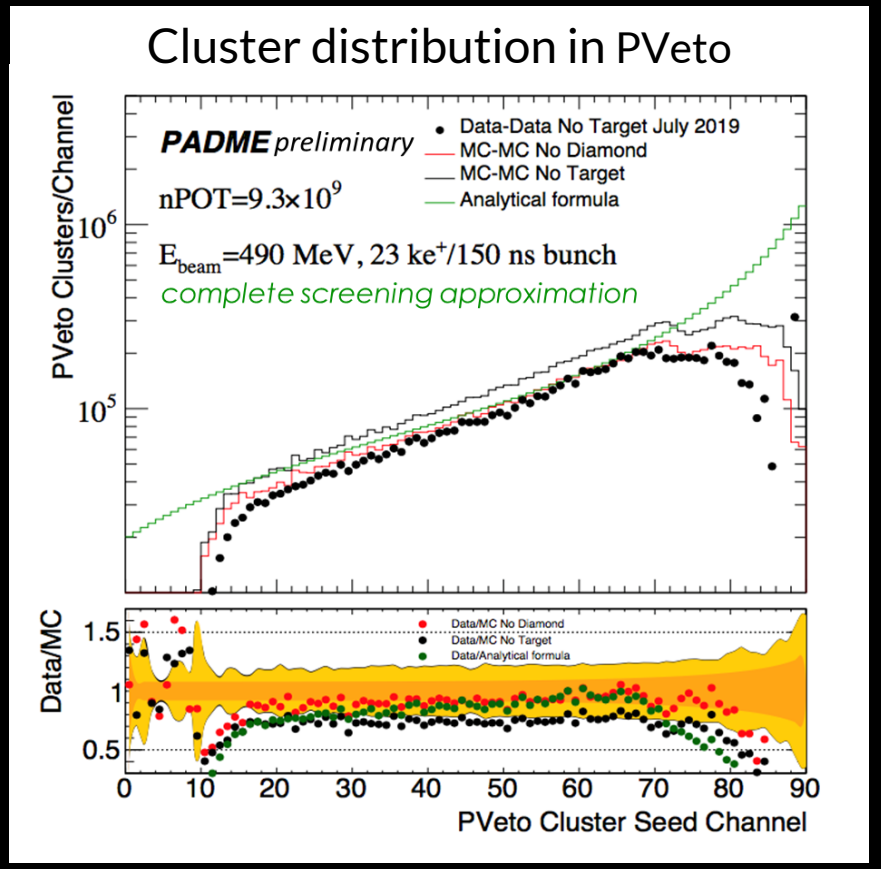
Dark Photon PADME sensitivity [arXiv:1608.08632v1]



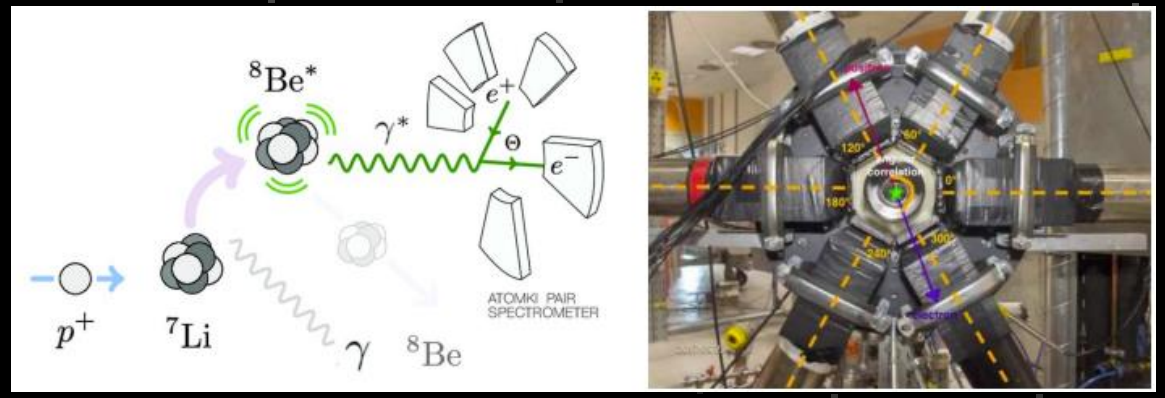
invisible decays $A' \rightarrow \chi\bar{\chi}$ visible decays $A' \rightarrow e^+e^-$

Background reduction on Run2 data ongoing
(AI-assisted ECAL reconstruction, improved veto conditions using machine learning)

Bremsstrahlung photon distribution in agreement with Monte Carlo simulation and analytical calculation



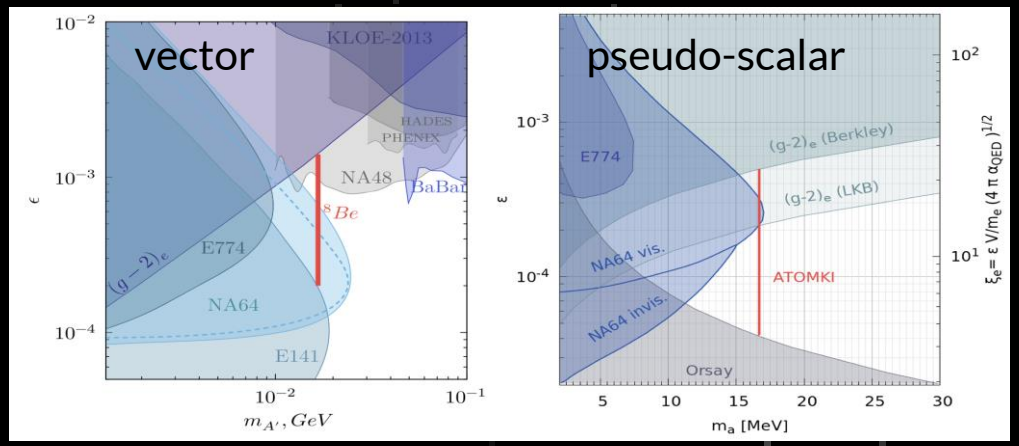
What is the X17 Boson



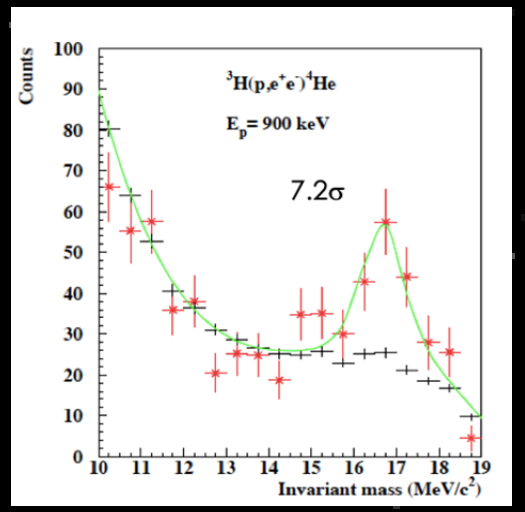
De-excitation of light nuclei via Internal Pair Creation shows anomalies in decays of ^{8}Be, ^{4}He and ^{12}C

All are explainable with a resonance of

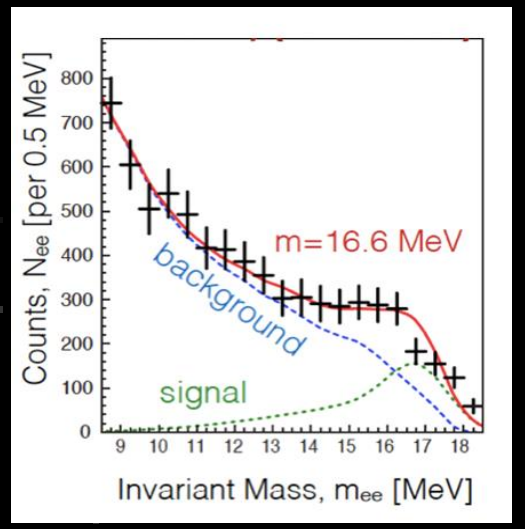
m_X = 16.86 ± 0.17(stat) ± 0.20(syst) MeV



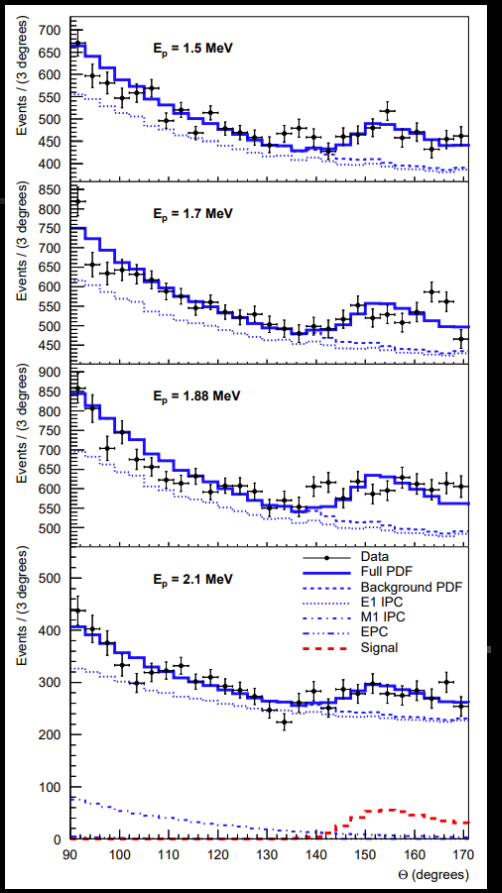
Nature of X17 not uniquely defined



Phys. Rev. Lett. 116, 042501 (2016)



Phys. Rev. C 104, 044003 (2021)



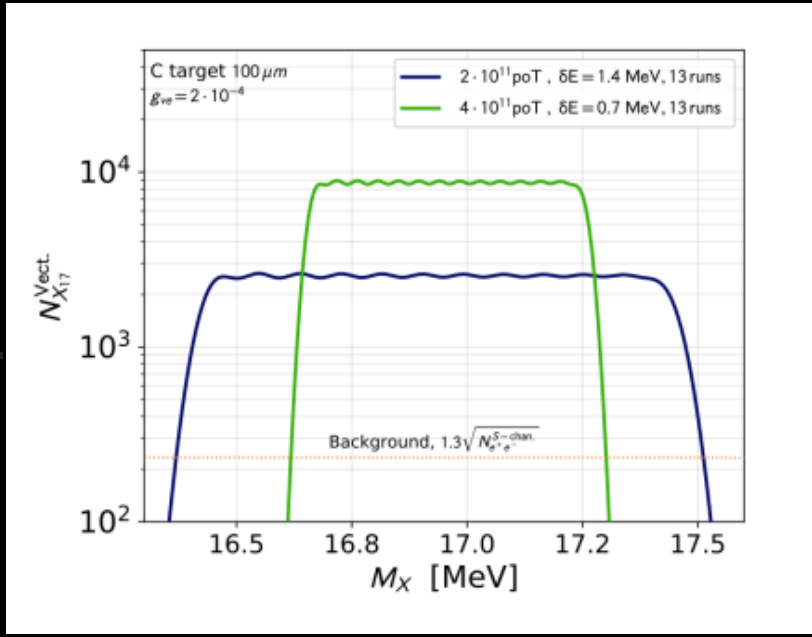
[arXiv:2209.10795]

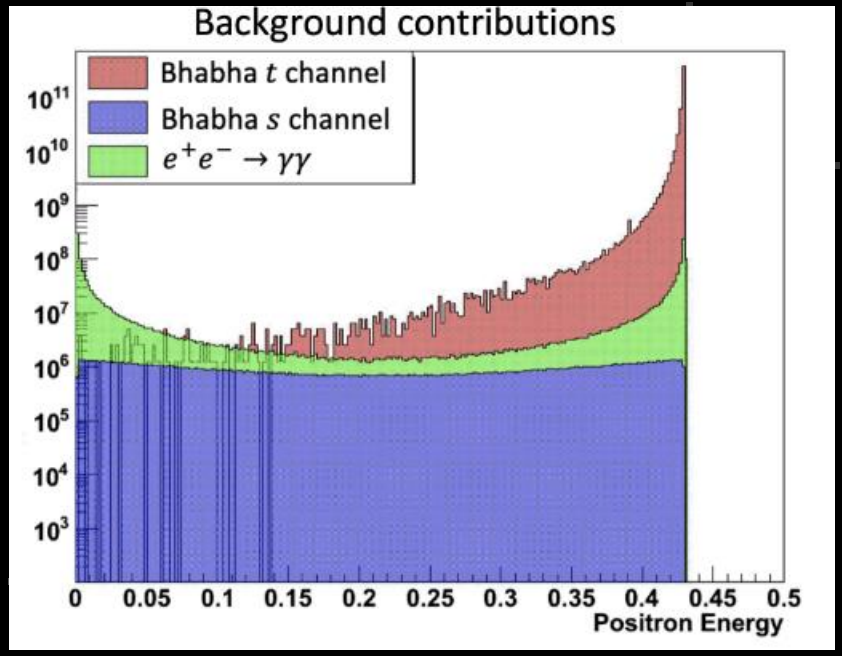
22 Sep 22

PADME X17 Setup

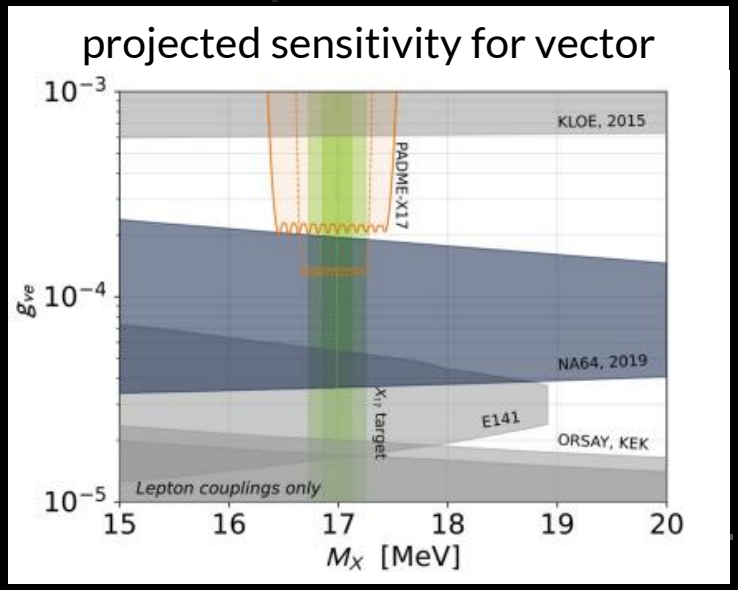
Independent production mode to test existence of X17:
resonant production at E(e^+) ~ 283 MeV ($\sqrt{s}$ ~ 17 MeV)
large enhancement of cross-section

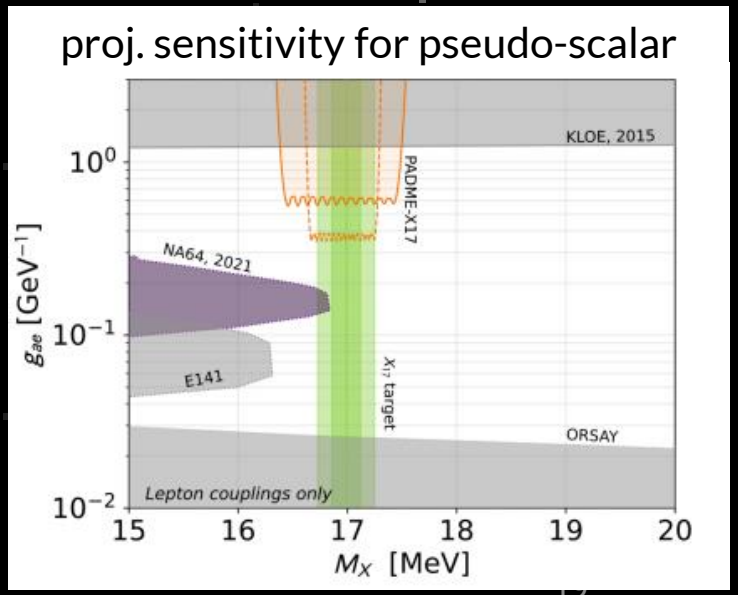
Scan the range 260 – 300 MeV
in 2 MeV steps





Signal should emerge on top of
Bhabha s- and t-channel
backgrounds

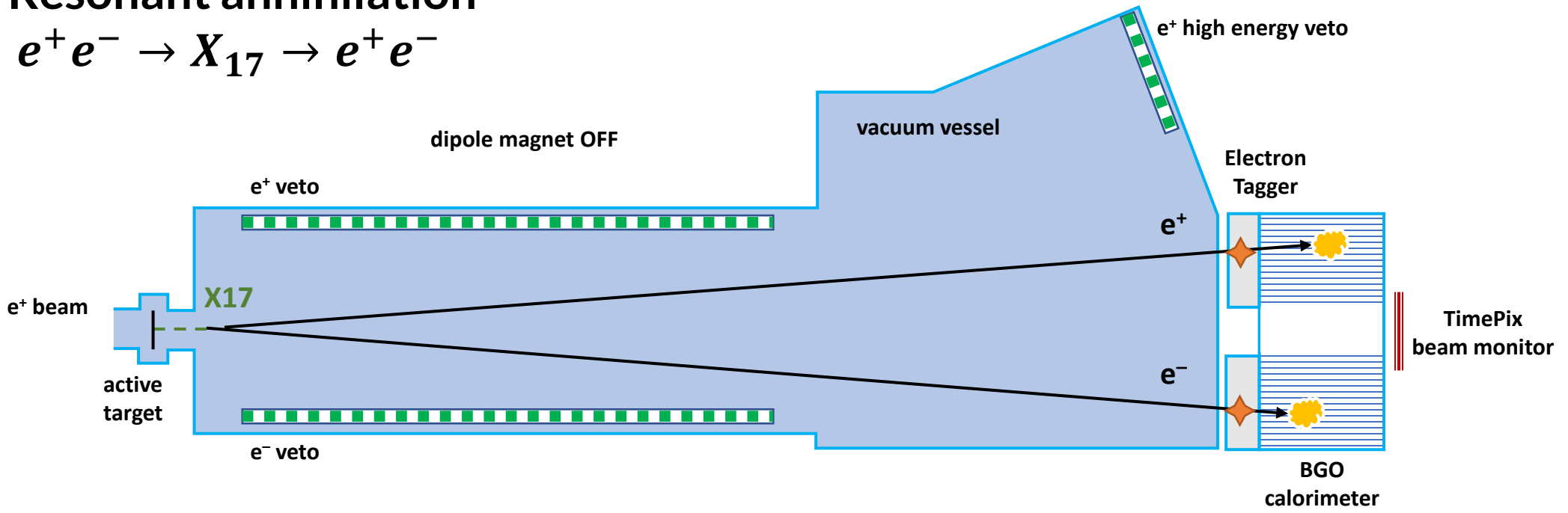




PADME Studies: X17 Boson

Resonant annihilation

$$e^+e^- \rightarrow X_{17} \rightarrow e^+e^-$$



Different detector setup: magnet off, no SAC, TimePix on beamline,Electron Tagger in front of BGO
Signature: lepton pair in the ECAL tagged by ETAG

Conclusions

The PADME experiment searches for signals of dark matter in positron annihilations since 2019

Run1 used to largely improve the beam background
Run2 (5×10^{12} POT) allows precision analysis

The measurement of $\sigma(e^+e^- \rightarrow \gamma\gamma)$ at 430 MeV has been published

The reaction $e^+e^- \rightarrow \gamma A'$ is under study with a model independent approach

Complete set of Dark Sector studies can be explored:
visible dark photon decays, ALPs searches, Fifth force, dark Higgs

Run3 data taking ongoing to confirm/disprove *X17* existence