Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

HADRON 2023

INVESTIGATING THE DARK SECTOR WITH THE PADME EXPERIMENT

P. Gianotti
for the PADME collaboration

Outline

- Dark Matter issue
- Dark Matter production with positron beams
- Frascati Lab
- The *X17* Anomaly
- PADME status, plans and prospects

The Nature of Dark Matter

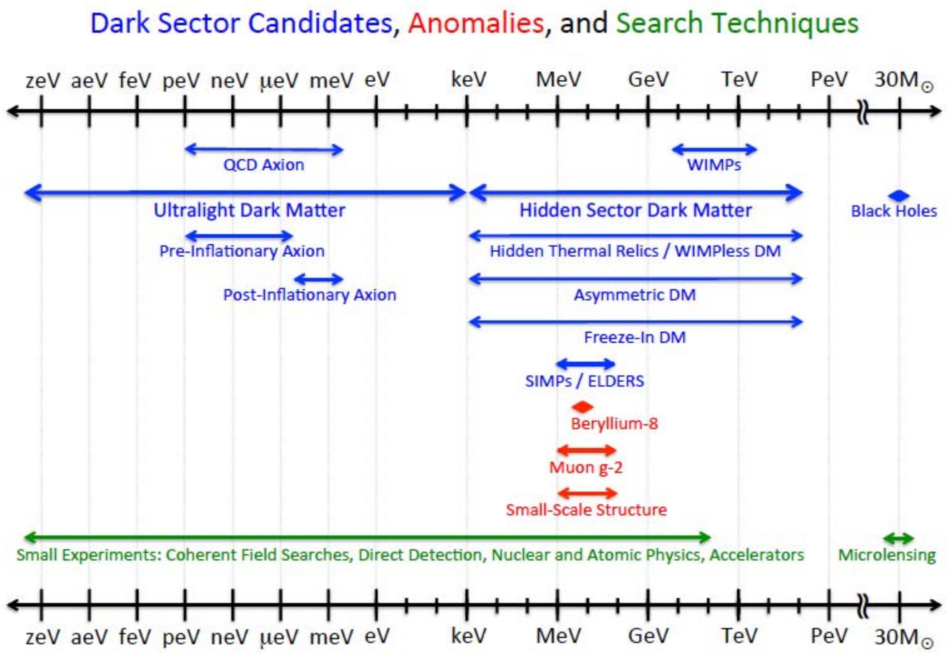
Despite its abundance, we don’t yet know what is made of.

Theorized WIMPs haven’t yet shown up.

Physicists are looking for signals in region previously unexplored.

The “new” approach rather than relying on a single experiment is trying to form a net of small dedicated experiments.

Theories are postulating DM could be lighter than previously thought. It could be made of other not yet discovered particles: **Axions, ALP, Dark Higgs, X17.**



arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

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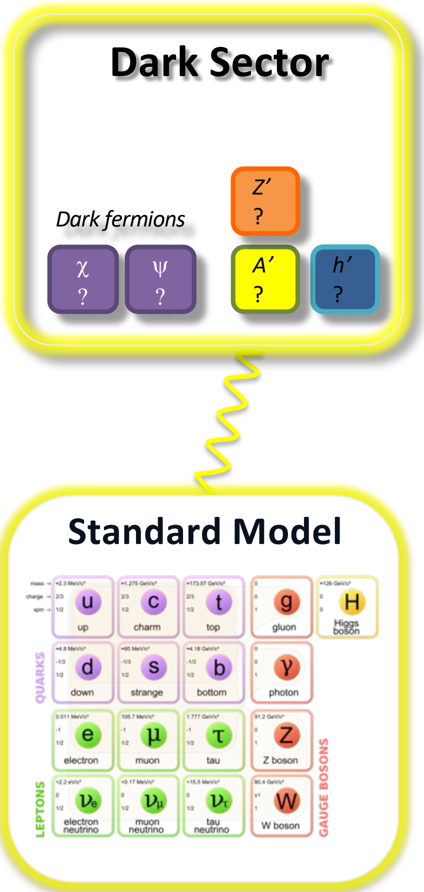
New Forces

There are many attempts to look for new physics phenomena to explain Universe **dark matter** and dark energy.

One class of simple models just adds an additional $U_D(1)$ symmetry to SM, with its corresponding vector boson (*A'*)

$$U(1)_Y + SU(2)_{Weak} + SU(3)_{Strong} [+U_D(1)]$$

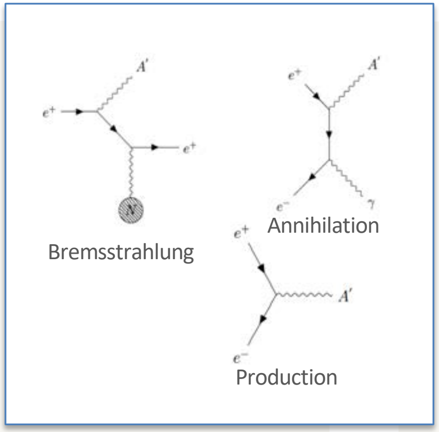
The ***A'*** could itself be the **mediator** between the **visible** and the **dark sector** mixing with the ordinary photon. The effective interaction between the fermions and the dark photon is parametrized in term of a factor **ε** representing the mixing strength.



Holstom, PLB 166 (1986) 196

The search for this new mediator *A'* is the main goal of the PADME experiment at LNF.

A’ production and decay



A’ can be produced using e+ via:

- Bremsstrahlung: $e^+N \to e^+NA'$
- Annihilation associate production: $e^+e^- \to \gamma A'$
- Annihilation direct production: $e^+e^- \to A'$

For the *A’* decay two options are possible:

- No dark matter particles lighter than the *A’*:
  - $A' \to e^+e^-, \mu^+\mu^-$, hadrons, **“visible”** decays
  - For $M_{A'} < 210$ MeV *A’* only decays to e^+e^- with $BR(e^+e^-) = 1$
- Dark matter particles χ with $2M_\chi < M_{A'}$
  - *A’* will dominantly decay into pure DM
  - $BR(l^+l^-)$ suppressed by factor ε^2
  - $A' \to \gamma\gamma \sim 1$. These are the so called **“invisible”** decays

PADME aims to produce *A’* via the reaction:

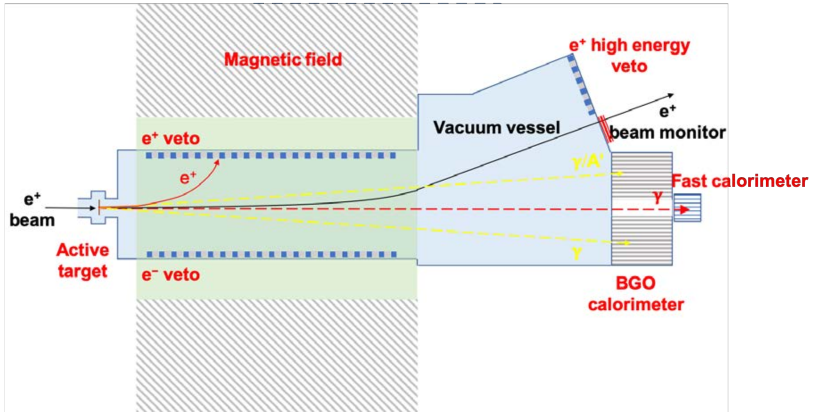
$$e^+e^- \to A'\gamma$$

This technique allows to identify the *A’* even if it is stable or decays into dark sector particles $\chi\bar{\chi}$.

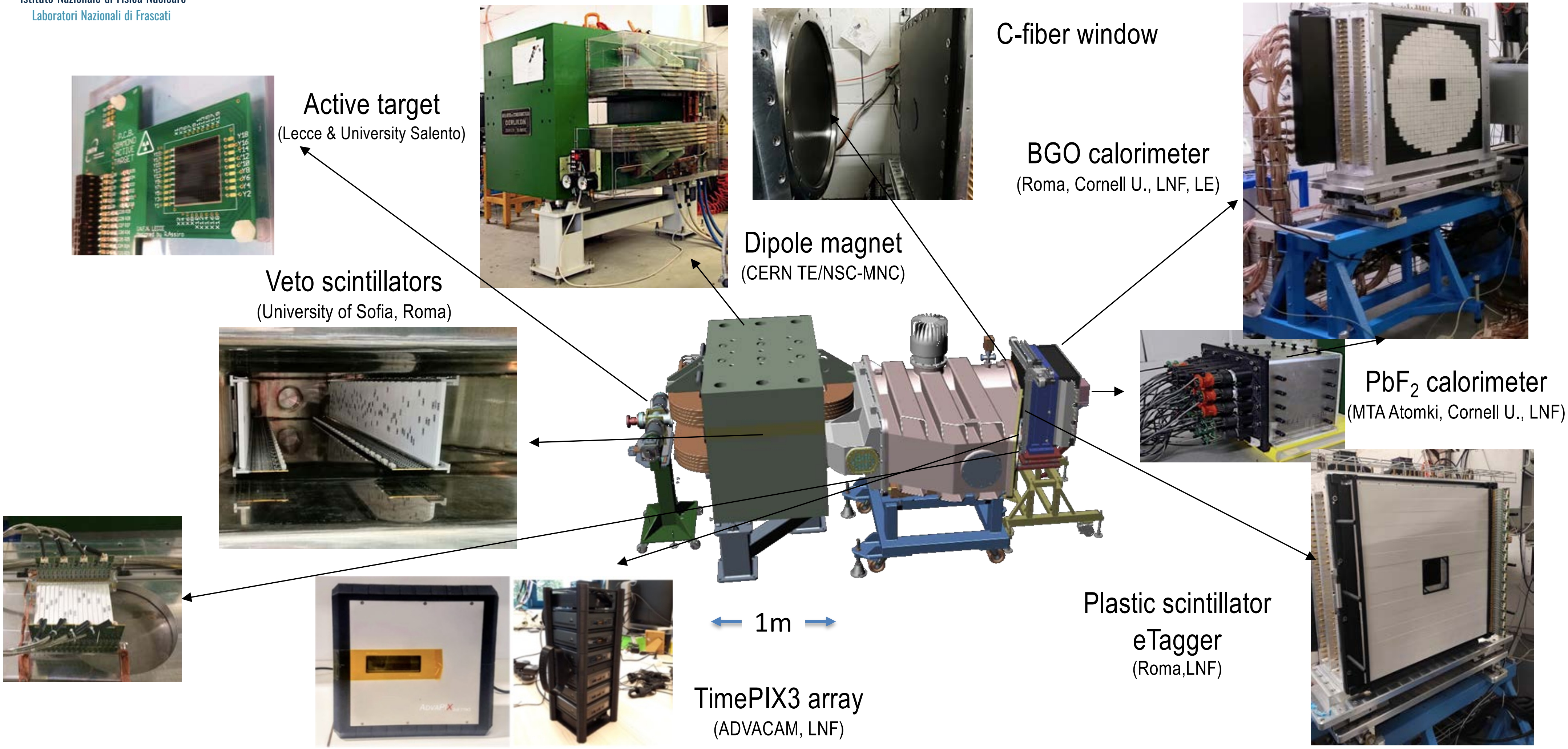
Know e+ beam **momentum and position**, measuring the recoil photon **position** and **energy**

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

Only a minimal assumption: *A’* couples to leptons

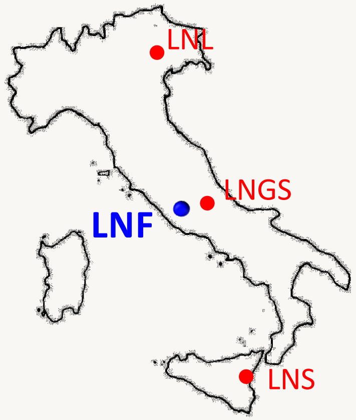


The PADME detector components

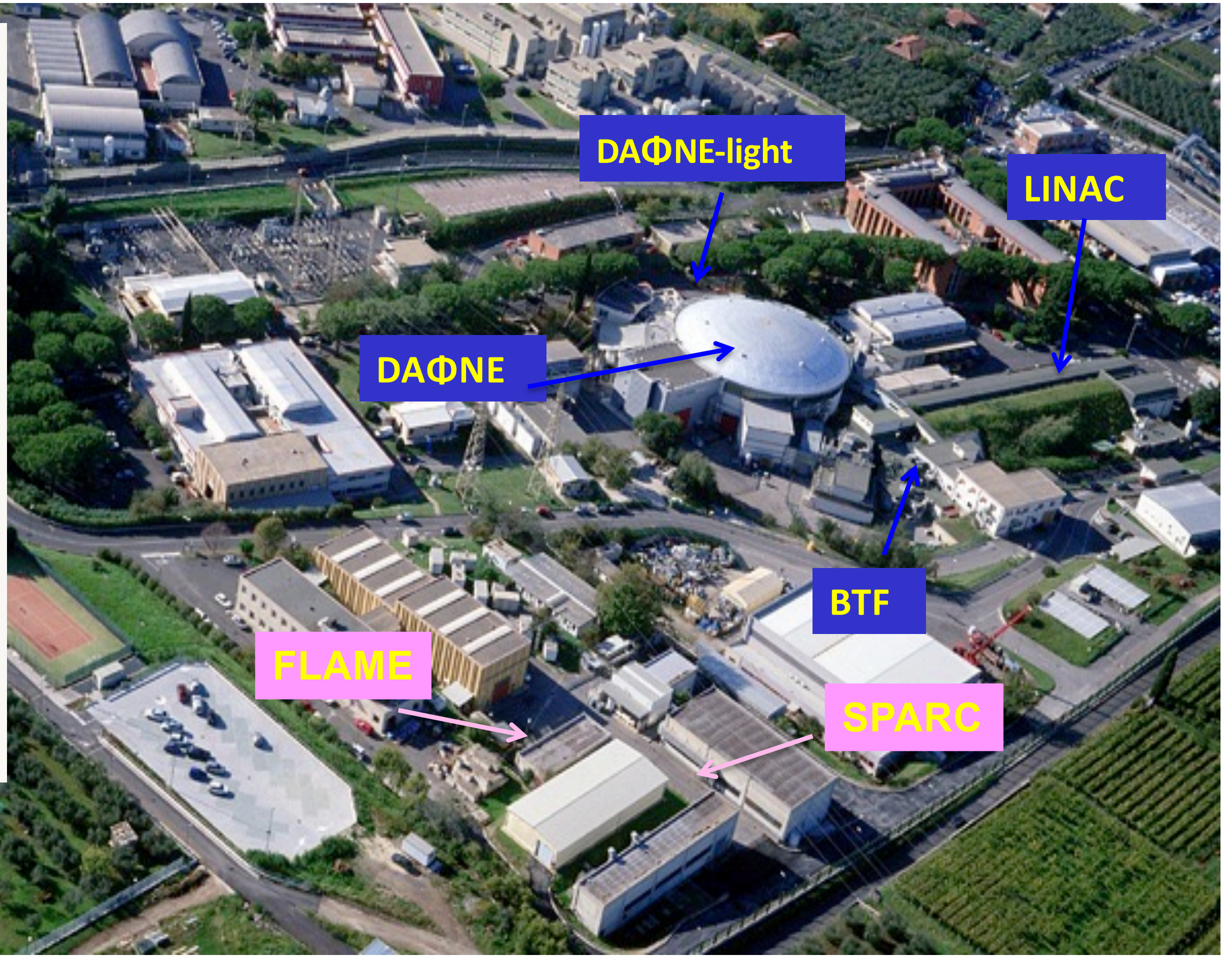


Frascati Laboratory of INFN

LNF is the largest and the oldest of the 4 laboratories that INFN owns in Italy.



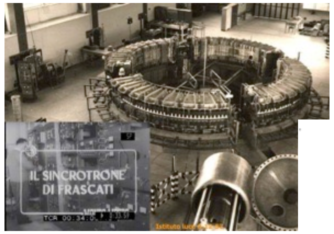
Since its foundation is devoted to particle physics with accelerators and novel particle detector development.



The LNF accelerators history

INFN
LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Electron Synchrotron
(1959-1975) E=1 GeV



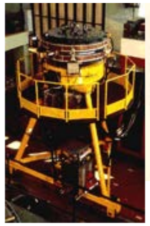
LNF-54/48 (1954)

Il progetto italiano di un elettrosincrotone.

G. Salvini

Istituto di Fisica dell'Università - Pisa
Istituto Nazionale di Fisica Nucleare - Sezione Acceleratore

AdA 1960-1965
E.c.m. 500 MeV



B. Touschek

The Frascati Storage Ring.

C. Bernardini, G. F. Corazza, G. Ghigo
Laboratori Nazionali del CNEN - Frascati

B. Touschek
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 7 Novembre 1960)

AdA was the first matter antimatter storage ring with a single magnet (weak focusing) in which e+/e- were stored at *250 MeV*

ADONE (1968- 1993)
E.c.m. 3 GeV 100 m

DAΦNE (1999)
E.c.m. 1020 MeV 100 m

SPARC_LAB (2004)
E=150 MeV LINAC

N. Cabibbo

the "Bible"

VOLUME 124, NUMBER 5

Electron-Positron Colliding Beam Experiments

N. Cabibbo and R. Gatto
Istituti di Fisica delle Università di Roma e di Cagliari, Italy and Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy
(Received June 8, 1961)

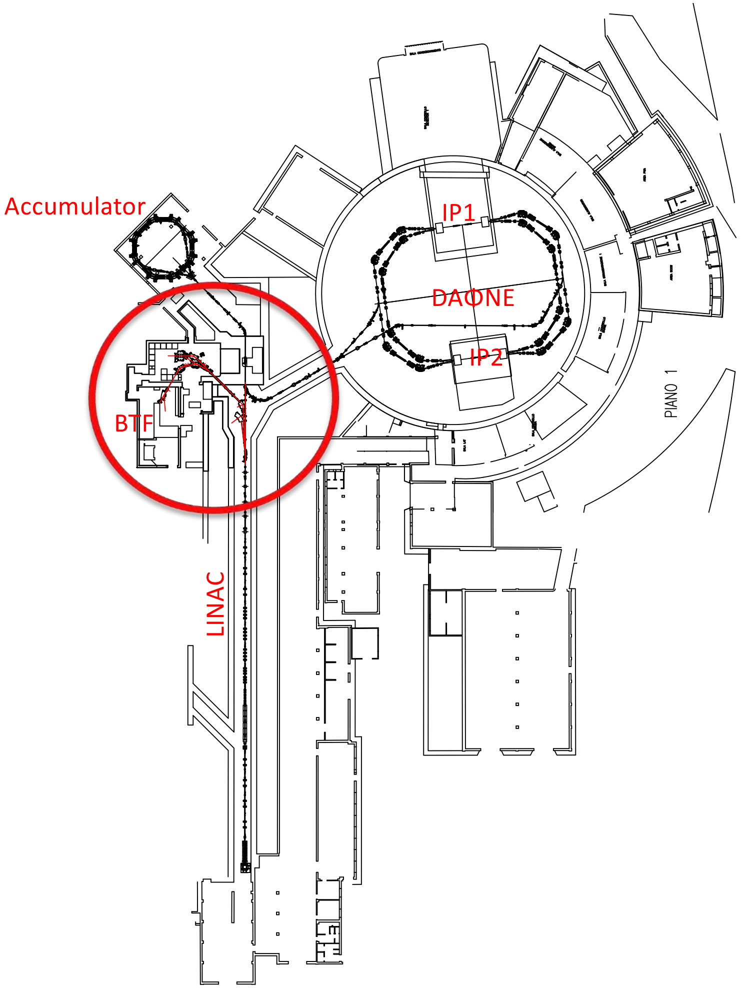
colliders in the world

1961	AdA	Frascati	Italy
1964	VEPP2	Novosibirsk	URSS
1965	ACO	Orsay	France
1969	ADONE	Frascati	Italy
1971	CEA	Cambridge	USA
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	Germany
1975	VEPP-2M	Novosibirsk	URSS
1977	VEPP-3	Novosibirsk	URSS
1978	VEPP-4	Novosibirsk	URSS
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	SpS	CERN	Switzerland
1982	P-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanforrd	USA
1989	BEPC	Beijing	China
1989	LEP	CERN	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAΦNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan
2000	RHIC	Brookhaven	USA
2003	VEPP-2000	Novosibirsk	Russia
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland

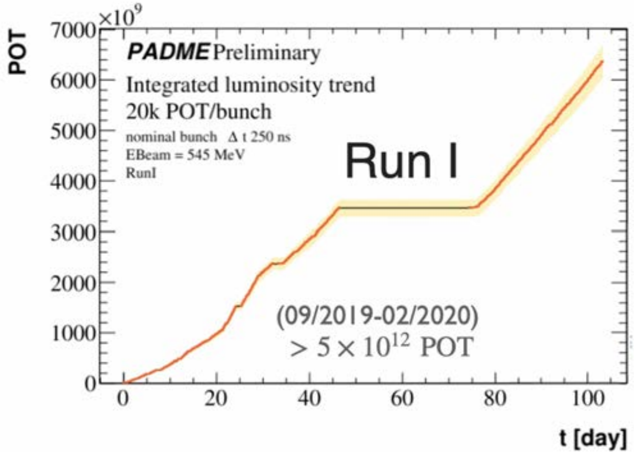
LNF LINAC beam line

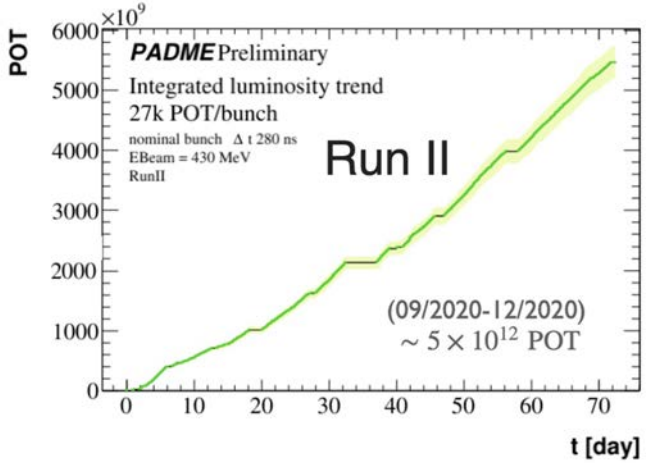
	electrons	positrons
Maximum beam energy (E_{beam})[MeV]	800 MeV	550 MeV
Linac energy spread [Δp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 - 40	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot σ [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

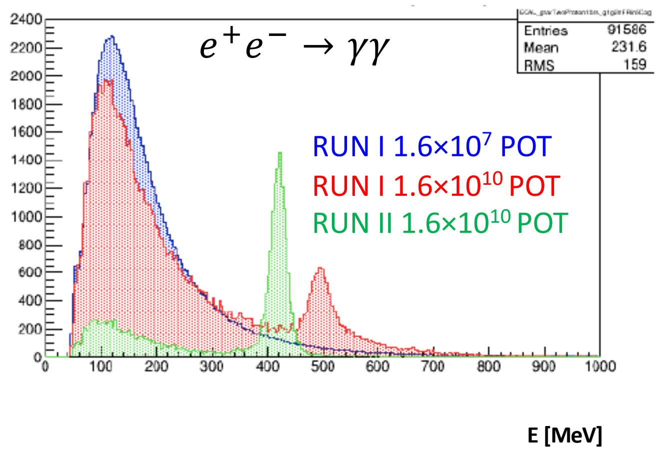
- Able to provide electrons and positrons
  - PADME Duty cycle aprox 50*200 ns= 10^{-6} s
  - The accessible $M_{A'}$ region is limited by E_{beam}
    - 0-23.7 MeV can be explored with 550 MeV e^{+} beam



PADME Data Taking

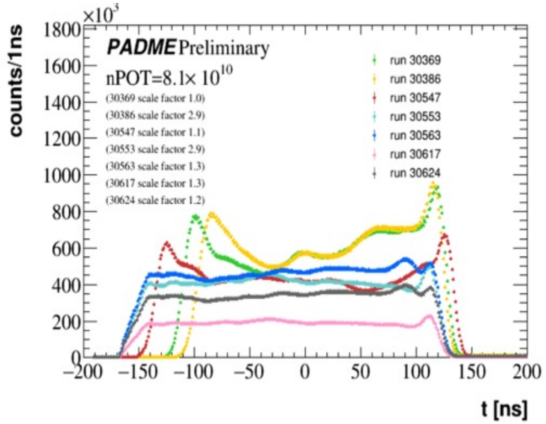






- Two physics runs in winter **2019** and winter **2020.** Similar statistics, approximately 1/2 of minimal goal (10^{13} particles-on-target). Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
- Run Ia secondary beam; Run 1b primary beam->Reduced beam-induced background
- Run II wrt Run I:
  - Detailed MC simulation of beamline [JHEP 09 (2022), 233]
  - **Improved vacuum separation** between experiment and beamline
  - Less beam-induced background with primary wrt secondary beam
  - Longer beam bunch to reduce pile-up

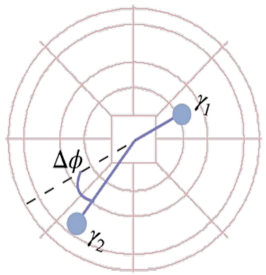
Bunch Length and Structure

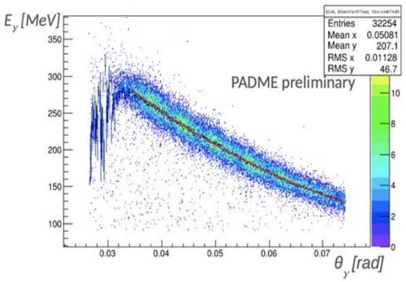


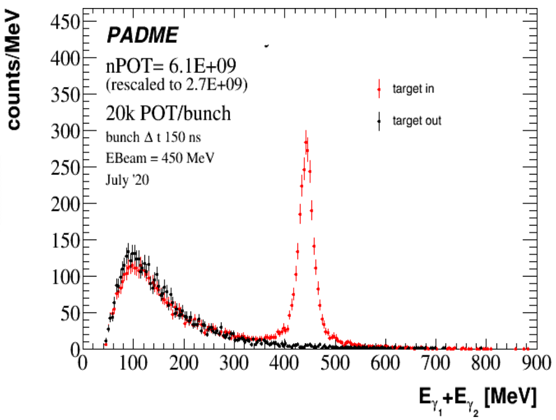
$e^+e^- \rightarrow \gamma\gamma$ cross section

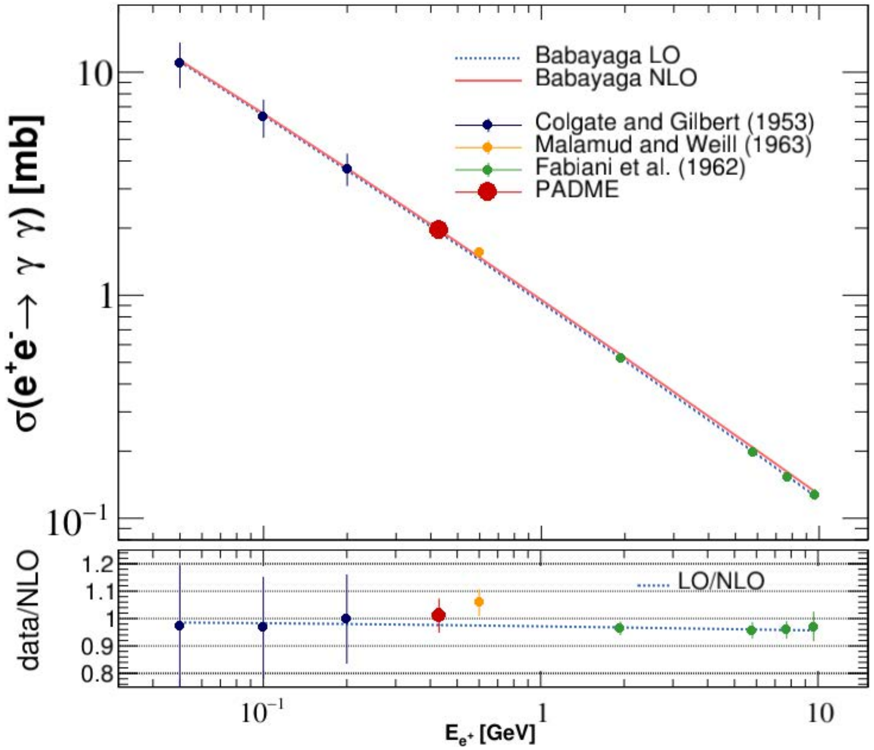
[Phys.Rev.D 107 (2023) 012008](#)

- Below 0.6 GeV known only with 20% accuracy.
- Can be sensitive to sub-GeV new physics since available measurement $e^+e^- \rightarrow non-charged\ particles$.
- Used 10% of Run II sample.
- Tag-and-probe method on two back-to- back clusters exploiting energy-angle correlation.









$$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})\ \text{mb}$$

QED @NLO $\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005\ (\text{stat}) \pm 0.0020\ (\text{syst})$ mb

[Phys.Lett.B 663 (2008) 209-213](#)

Dark Sector Studies at PADME

The PADME approach can explore the existence of any new particle produced in e^+e^- annihilations:

- Axion Like Partiles $e^+e^- \to \gamma a$

  visible decays: $a \to \gamma\gamma, ee$

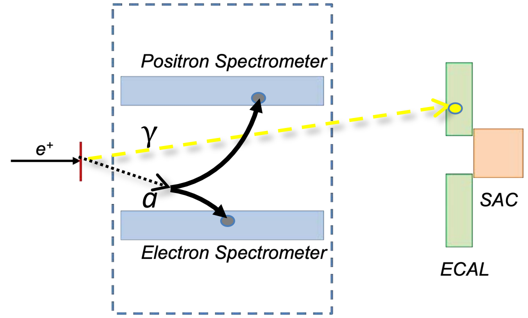
  invisible decay: $a \to \chi\bar{\chi}$

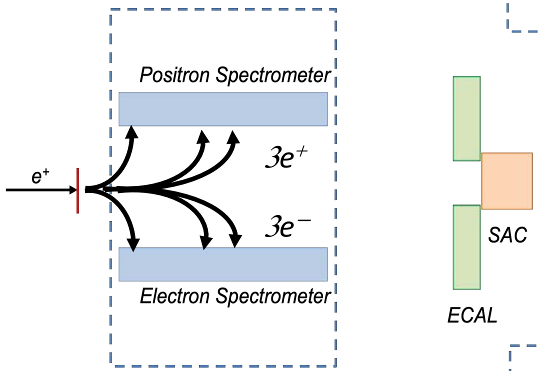
- Dark Higgs $e^+e^- \to h'A'; h' \to A'A'$

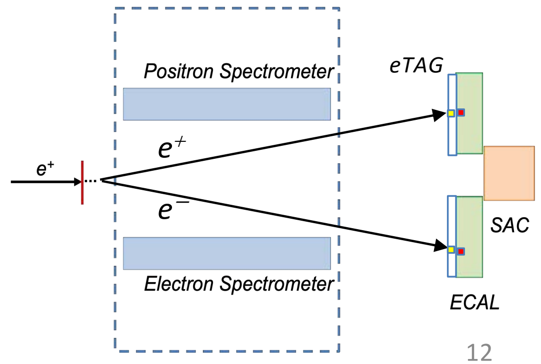
  final state: $A'A'A' \to e^+e^-e^+e^-e^+e^-$

- X_{17} Boson $e^+e^- \to X_{17};\ X_{17} \to e^+e^-$

  tuning beam energy and slightly modifying the detector



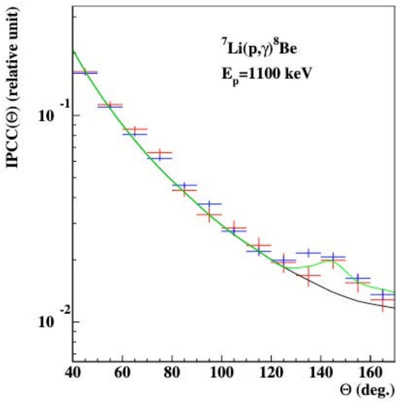




The ^{8}Be anomaly

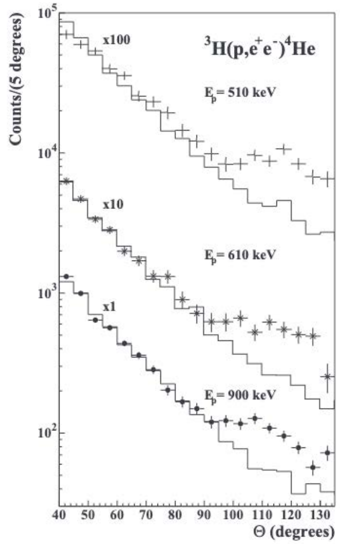
Studying de-excitation of light nuclei via IPC,
an anomaly appeared in the decay of ^{8}Be, ^{4}He and ^{12}C.

Phys. Rev. Lett. 116, 042501 (2016)
JPC 1056 no. 1, 012028 (2018)



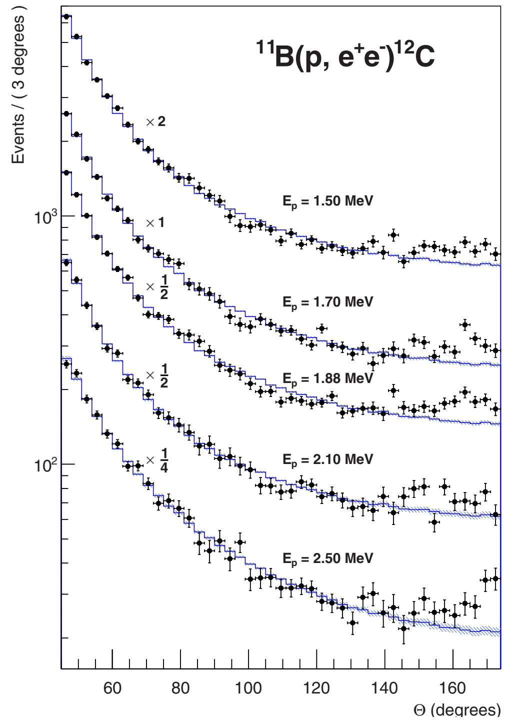
$m_X = 17.01 \pm 0.16(stat) \pm 0.21(sys) MeV$

Phys. Rev. C 104, 044003 (20

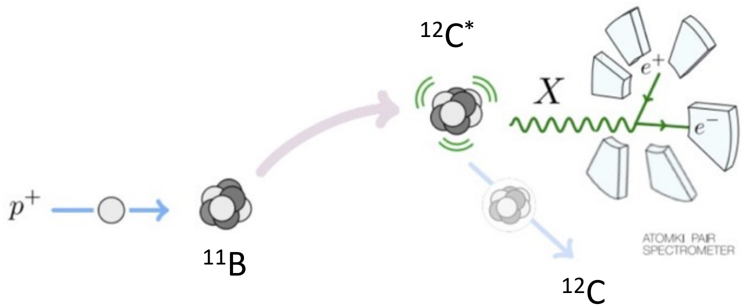


$m_X = 16.94 \pm 0.12(stat) \pm 0.21(sys) MeV$

Phys. Rev. C 106, L061601 (2022)



$m_X = 17.3 \pm 0.11(stat) \pm 0.20(sys) MeV$



Is the *X* a signal of a dark matter particle?

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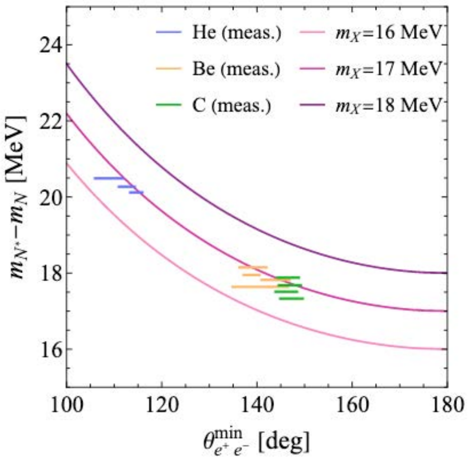
Theoretical interpretation

- All the three anomalies $\gtrsim 7\sigma$, hard to claim statistical fluctuations
- The introduction of a new particle improves the fits to the data
- SM explanations strongly disfavoured ^{8}Be [*PLB 773 (2017) 159-175*] ^{4}He [*PRD (2021) 2104.04808*]
- ^{8}Be - ^{4}He - ^{12}C anomalies are kinematically & dynamically consistent for V (and AV) [*PRD 102 (2020) 036016*]
- For ^{12}C the effect was predicted, and then confirmed by experimental data [*PRD 2006.01151 [hep-ph]*]
- X17 couples differently to up and down quarks. Coupling to electron neutrino is also allowed in the framework of NSI



arXiv:2304.09877v1 [hep-ph]

TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}_{4P}^{(0)}$ is a dimension-four operator that mediates a P-wave decay to a spin-0 X boson.

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	…	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	…	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)	…

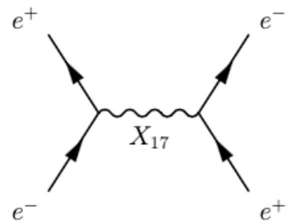
Phys.Rev.D 102 (2020) 036016

X17 study @ PADME

X17 can be resonantly produced with positron beams [Phys.Rev. D97 (2018) no.9, 095004]

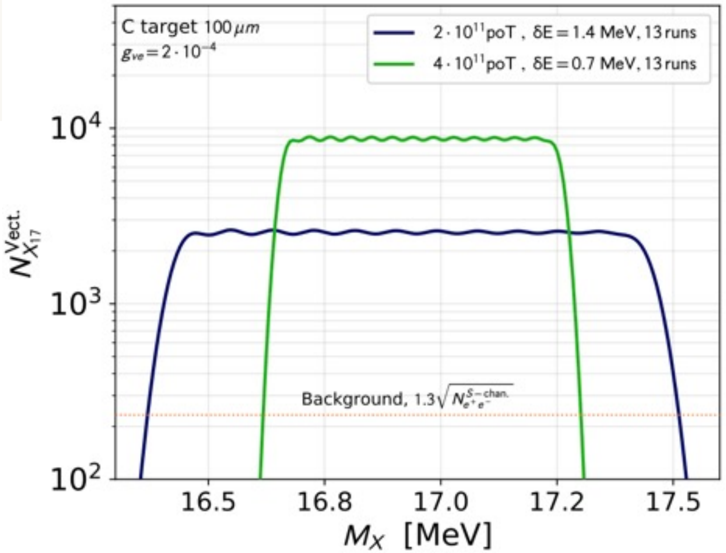
Using constraints from Atomki measurements two spin-parity assumptions have been considered [Darmé et al. Phys. Rev. D 106 (2022) 115036]

- vector boson 1^{--} $$\mathcal{N}_{X_{17}}^{\text{Vect.}} \simeq 1.8 \cdot 10^{-7} \times \left(\frac{g_{ve}}{2 \cdot 10^{-4}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$
- pseudoscalar particle 0^{-+} $$\mathcal{N}_{X_{17}}^{\text{ALP}} \simeq 5.8 \cdot 10^{-7} \times \left(\frac{g_{ae}}{\text{GeV}^{-1}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$



The data taking strategy consists in counting $e^+ e^-$ events varying beam energy in small steps in the range E ∈ [265; 297] MeV.

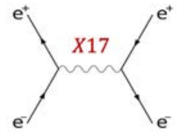
The sensitivity of the scan depends on the energy step ΔE used in the scan.



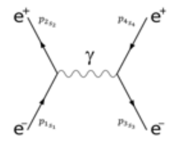
X17 study @ PADME

- Same ATOMKI observables: 2 leptons in the final state, but **different production reaction**
- Expected cross section enhancement from **resonant production** in e^+e^- annihilations at $\boldsymbol{E_{e^+} \sim 283}$ **MeV**
- Main backgrounds:
  - **Bhabha scattering**, both from the s channel and t channel
  - Two clusters in the calorimeter produced in $\gamma\gamma$ events

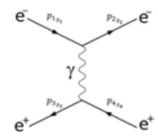
Signal



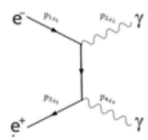
Background



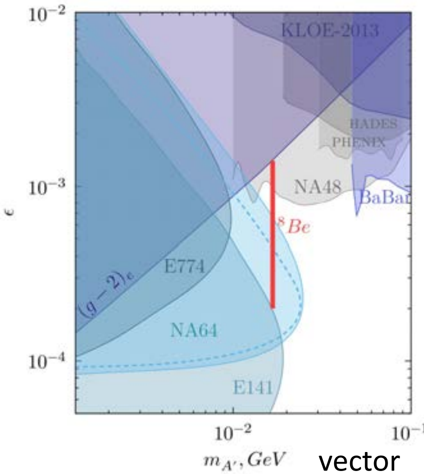
s channel



t channel

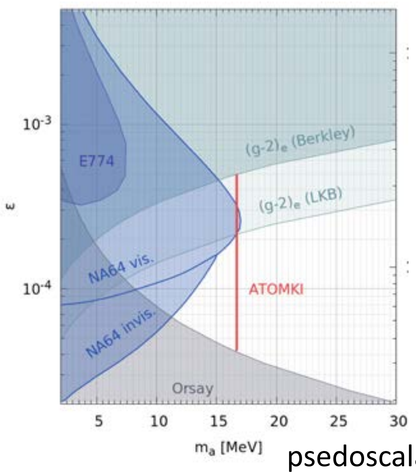


Phys. Rev. D **101**, 071101 (R) (2020)



vector

Phys. Rev. D **104**, L111102 (2021)



psedoscalar

[Phys. Rev. D 106 (2022) 115036](#)

TABLE I. Expected number of background and signal events per 1×10^{10} positrons on target. The t-channel values before selection cuts correspond to $e^{\pm}$ with energies larger than 1 MeV. The acceptance cuts do not include the $\gamma\gamma$ tagging from the ETag. BG, background; Ev., events; Acc., acceptance; ch., channel.

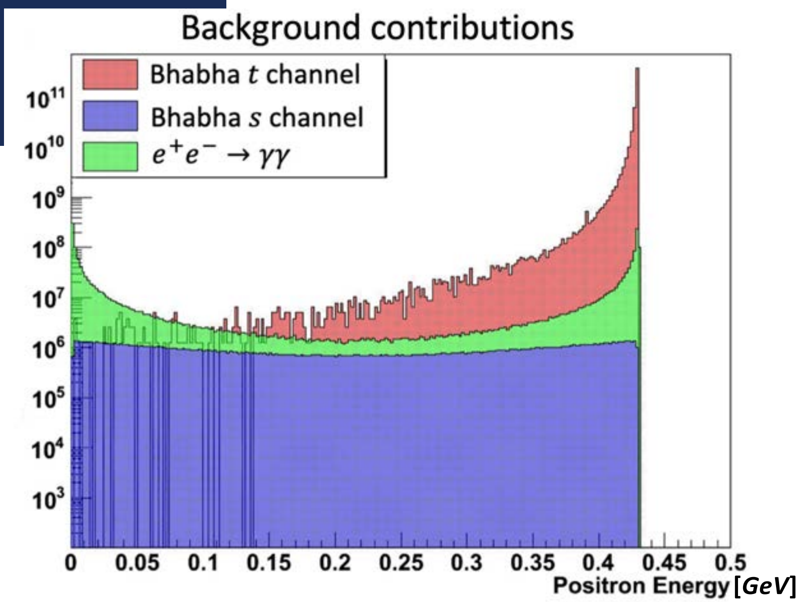
BG process	No. of Ev.	No. of Ev. in Acc.	Acc.
$e^+e^- \to e^+e^-$ (t- ch.)	5.4×10^7	6.9×10^4	0.13%
$e^+e^- \to e^+e^-$ (s- ch.)	3.2×10^4	6.4×10^3	20%
$e^+e^- \to \gamma\gamma$	2.9×10^5	1.3×10^4	4.5%
$e^+e^- \to X_{17} \to e^+e^-$	1250	250	20%

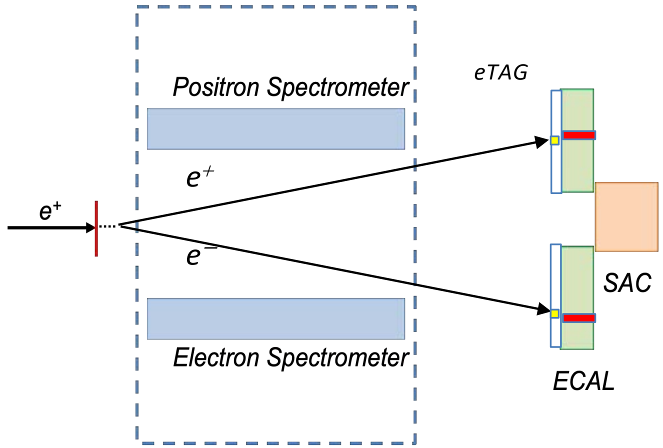
PADME X17 setup

PADME veto spectrometers cannot be used to constrain e^+e^- vertices **not coming from the production target.**

Idea: identify $e^+e^- \to e^+e^-$ using the BGO calorimeter, as for $\gamma\gamma$ events.

- With **magnet off** the e^+e^- will reach ECal
  - Precise measurement (3%) of electron-positron pair momentum and angles;
  - Reconstruction of invariant mass of the pairs (small pile-up).
- To identify clusters of photons or electrons in ECal
  - New detector: Electron tagger (**eTAG**) plastic scintillator slabs with same ECal vertical size.

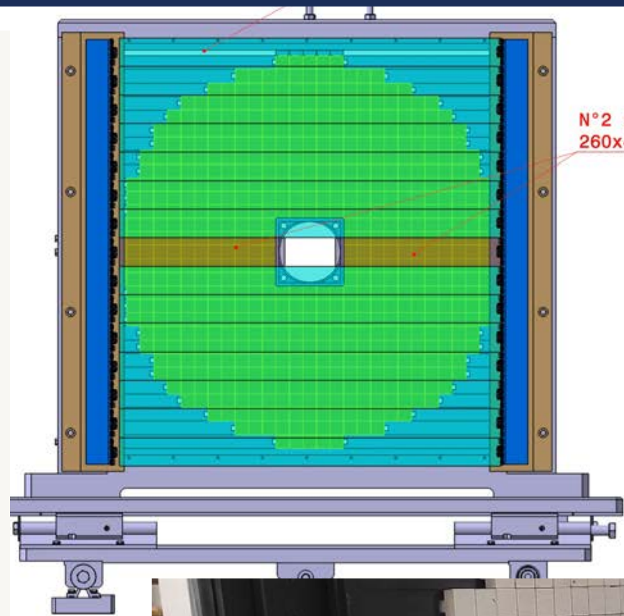


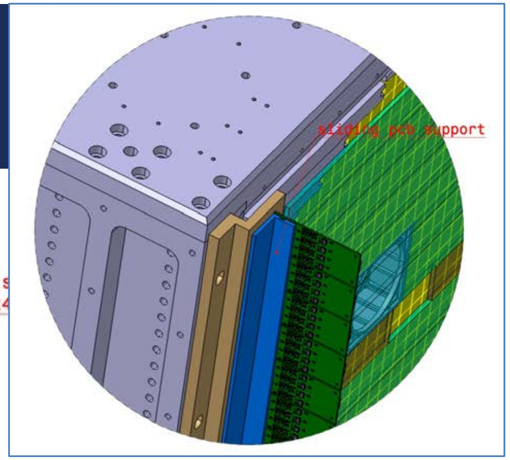


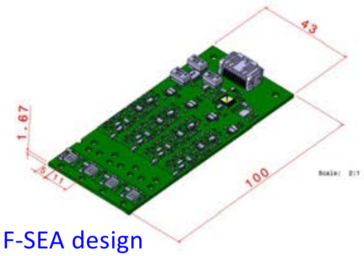
PADME eTAG

The new **eTAG** has been designed and assembled (2021-2022):

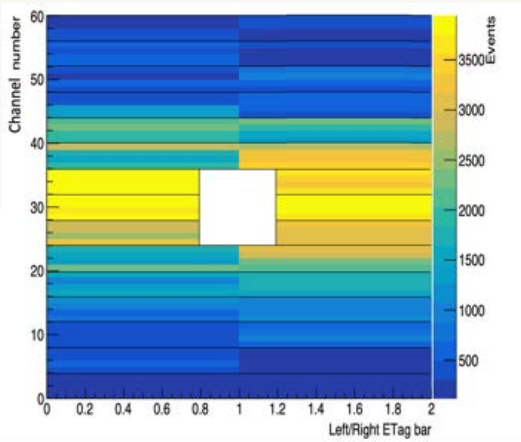
- 16 scintillators BC408 (600x45x5 mm^3);
- readout with 4 SiPMs (Hamamatsu S13360) on both sides. Same electronic cards developed for the veto detectors;
- Mechanical structure attached to the Ecal frame.





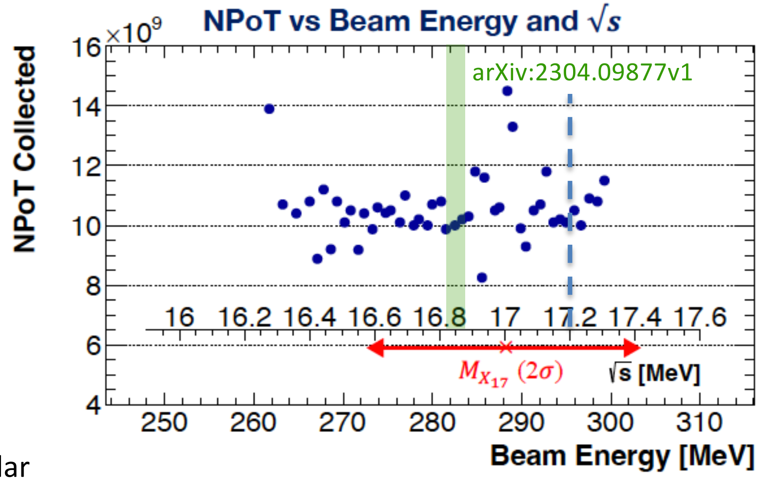


LNF-SEA design



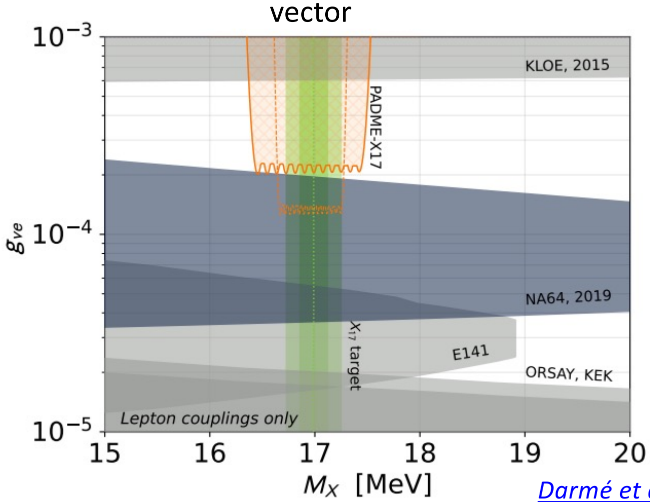
Run III Expected results

- Background from Bhabha scattering under control down to ε = few 10^{-4}
- Challenge: achieve a precise luminosity and systematic errors control (<1%)
- Collected 10^{10} POT per each point of the scan
- PADME maximum sensitivity in the vector case
- The PADME precision on M_{X17} measurement: ΔM_{X17} =(17.47-16.36)/47 ~ 20 KeV

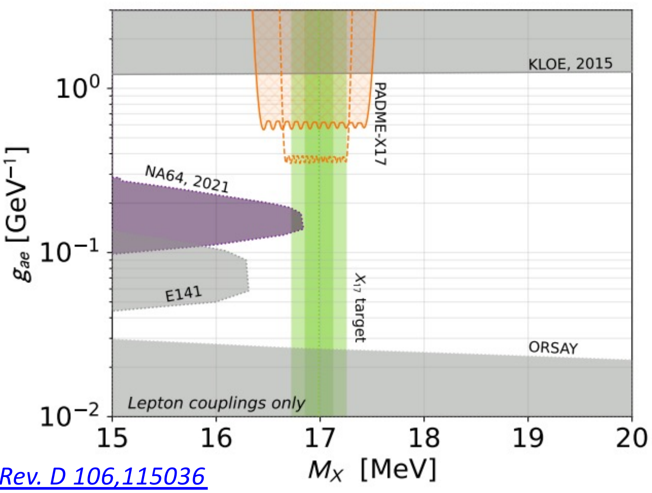


Dots points explored by PADME
RED Combined Be,He,C Atomki mass ranges
GREEN mass range fit results in arXiv:2304.09877v1
mass limit from C

vector

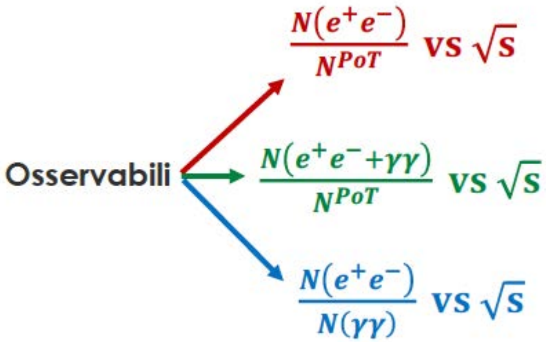


psedoscalar

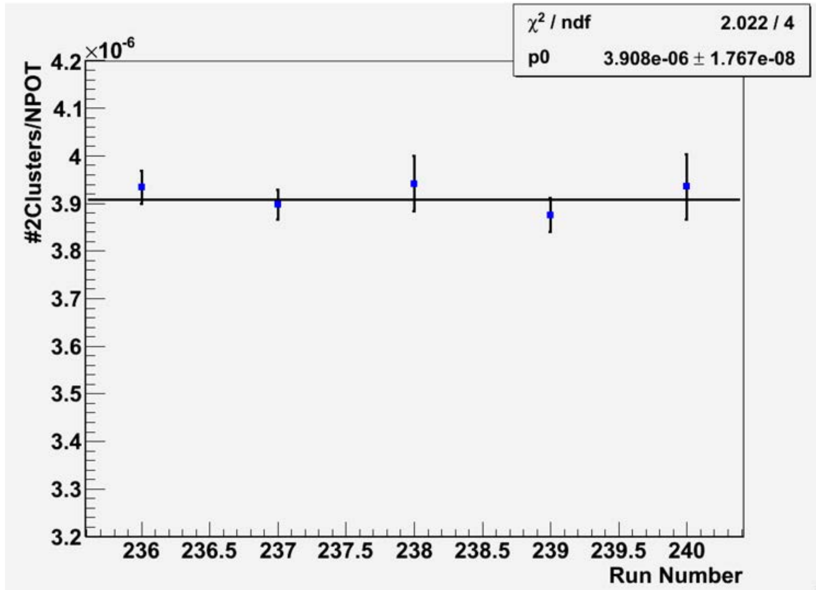


Darmé et al. Phys. Rev. D 106,115036

Analysis Strategy



- Several observables can be used with different outcomes:
  - **N(2cl)/N$_{PoT}$** = existence of X_{17}
    - High statistical significance
    - No Etag related systematic errors
  - **N(2e)/N(2γ)** = existence of X_{17}
    - lower statistical significance due to 2γ cross section
    - Independent from N_{PoT}
  - **N_{e+e-}/N_{PoT}** = vector nature of X_{17}
    - Systematic errors due to ETag tagging efficiency stability
  - **$N_{\gamma\gamma}/N_{PoT}$** = pseudoscalar nature of X_{17}
    - Systematic errors due to ETag tagging efficiency stability



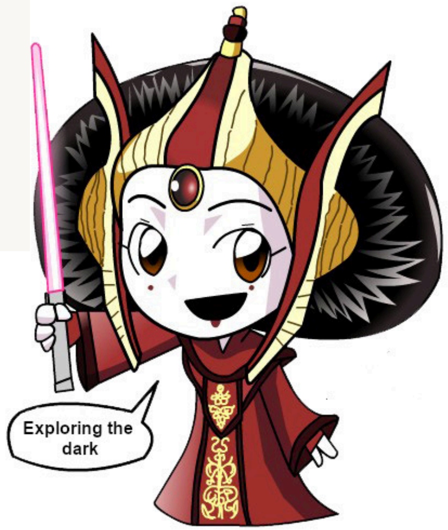
- Stability ~0.8% over the 5 runs @402 MeV
  - evidence of relative σ_{NPOT}<0.5%
- Good χ^2 means no significant systematic over statistical errors

Conclusions

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

- PADME is the first experiment to study the reaction $e^+e^- \rightarrow \gamma A'$ with a model independent approach;
- Three data takings: analysis is ongoing;
- Many physics items can be explored:
  - visible/invisible dark photons, ALPs search, Fifth force, dark Higgs, ***X17* boson**

PADME is exploring the DARK SECTOR…



Backup

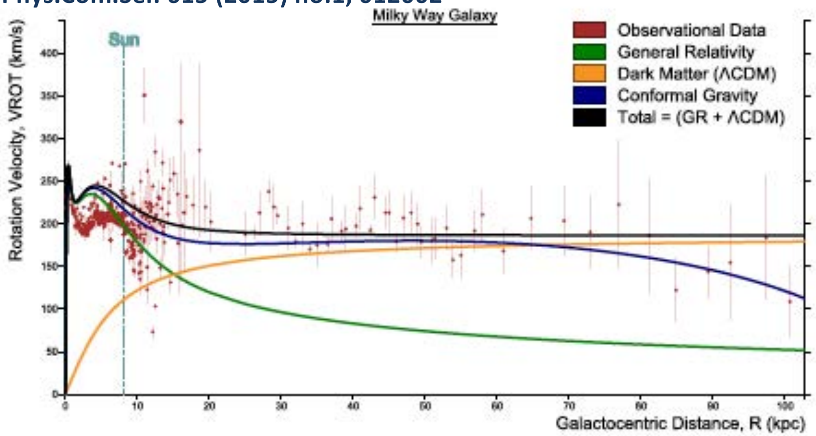
The Dark Matter issue

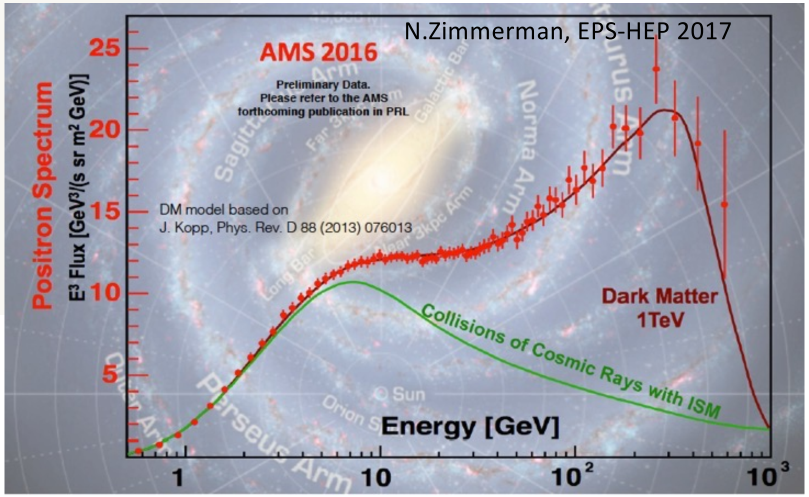
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

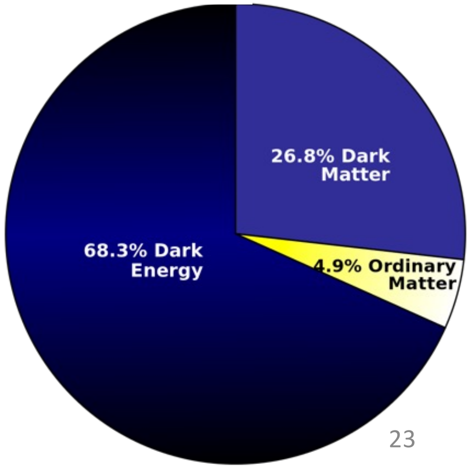
The abundance of this new entity is 5 times larger than SM particles.

Dark Matter is the best indication of physics beyond SM (BSM)

J.Phys.Conf.Ser. 615 (2015) no.1, 012002







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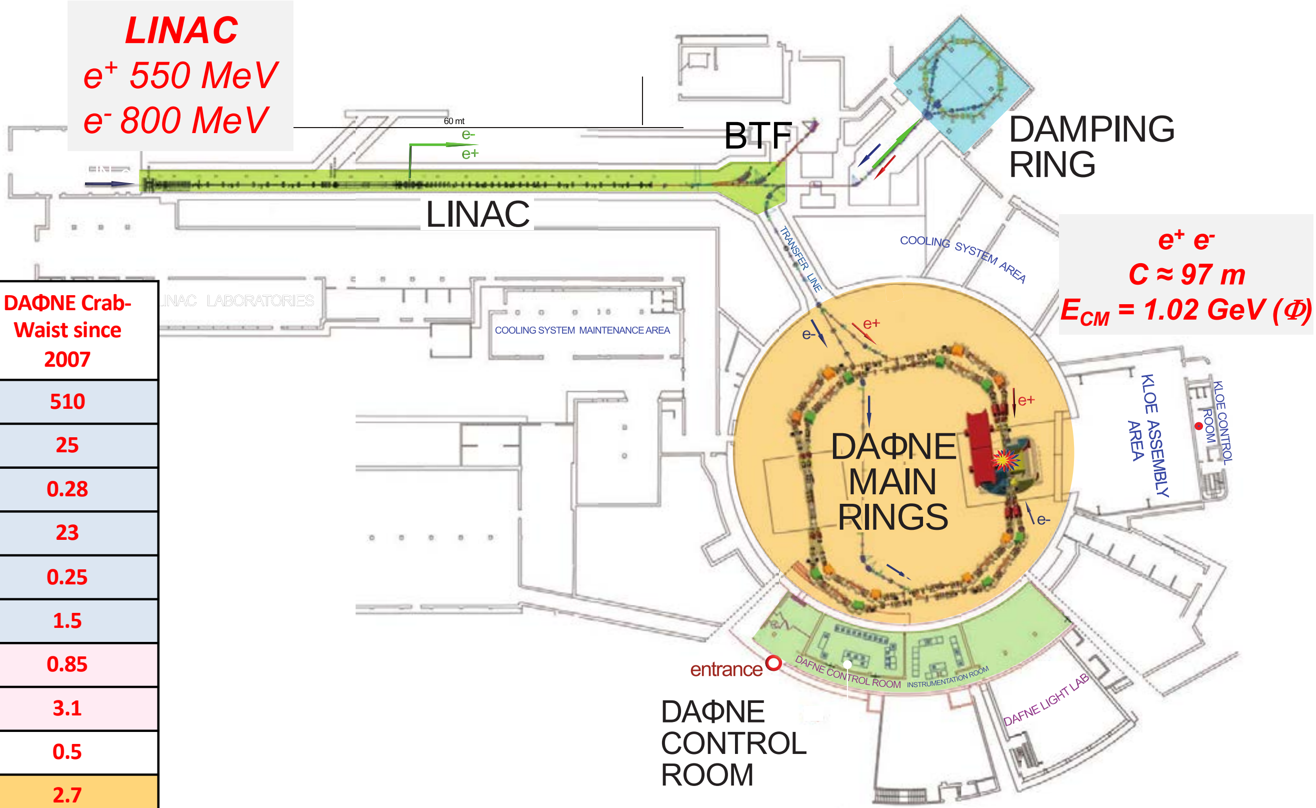
DAΦNE Complex



	DAΦNE native 2000÷2006	DAΦNE Crab-Waist since 2007
Energy [MeV]	510	510
$\Theta_{cross}/2$ [mrad]	12.5	25
ε_x [mm·mrad]	0.34	0.28
β_x^* [cm]	160	23
σ_x^* [mm]	0.7	0.25
$\Phi_{piwinski}$	0.6	1.5
β_y^* [cm]	1.80	0.85
σ_y^* [μm] low current	5.4	3.1
Coupling [%]	0.5	0.5
Bunch spacing [ns]	2.7	2.7
I_{bunch} [mA]	13	13
σ_z [mm]	25	15
N_{bunch}	120	120

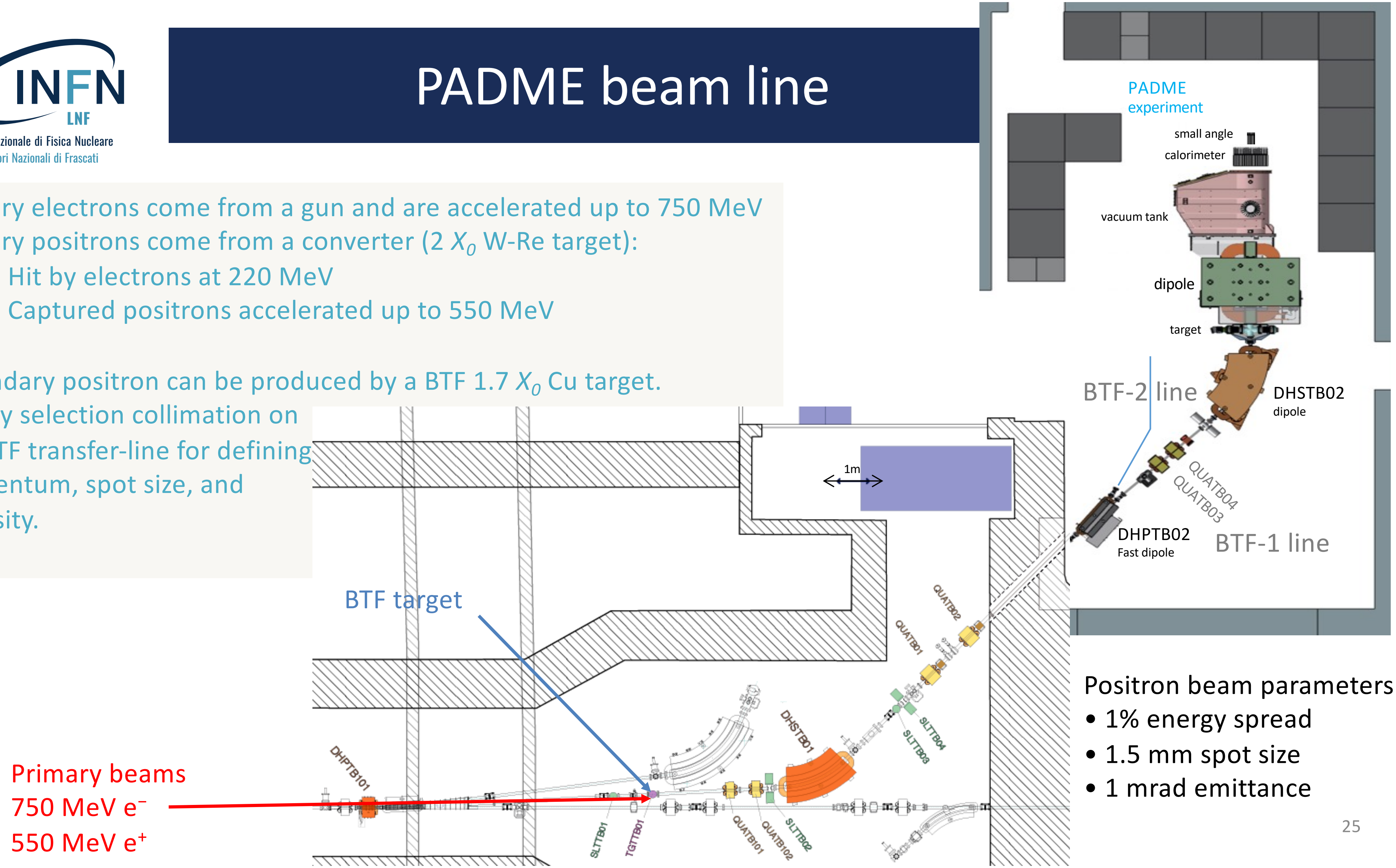
DAΦNE implemented succesfully a new kind of beam-beam interaction: the Crab-Waist collision scheme

PADME beam line

Primary electrons come from a gun and are accelerated up to 750 MeV
Primary positrons come from a converter (2 X_0 W-Re target):

- Hit by electrons at 220 MeV
- Captured positrons accelerated up to 550 MeV

Secondary positron can be produced by a BTF 1.7 X_0 Cu target.
Energy selection collimation on the BTF transfer-line for defining momentum, spot size, and intensity.



Positron beam parameters:

- 1% energy spread
- 1.5 mm spot size
- 1 mrad emittance

Signal and Background

PADME signal events consist of single photons measured with high precision and efficiency by a forward **BGO calorimeter**.

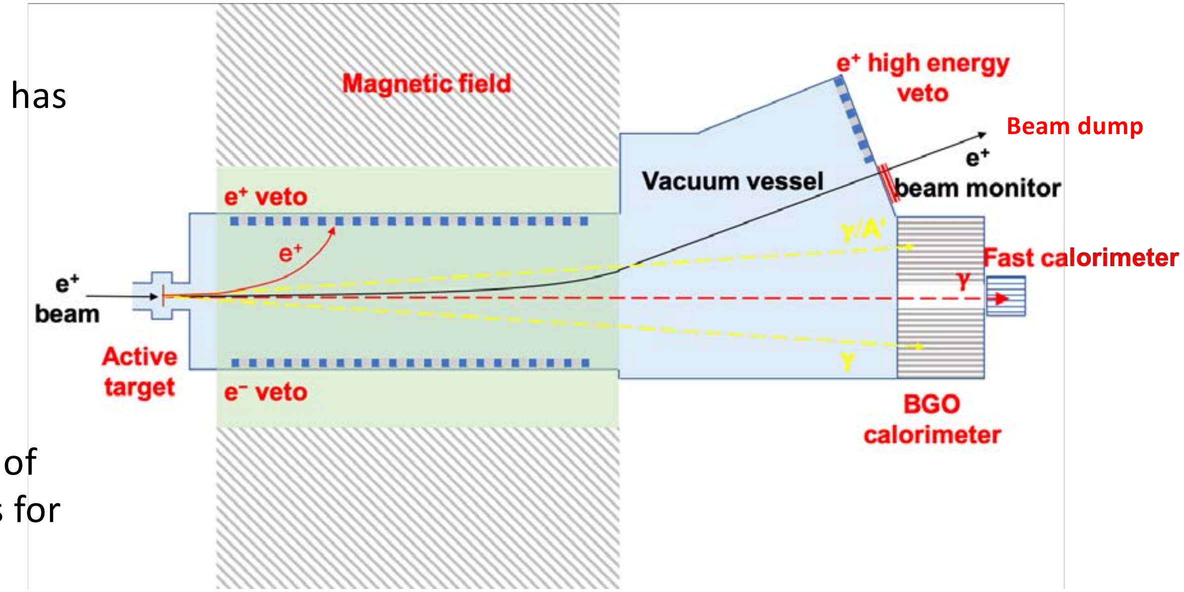
Since the **active target** is extremely thin (~100 μm), the majority of the positrons do not interact.
A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

The main source of background for the *A'* search are Bremsstrahlung events. This is why the **BGO calorimeter** has been designed with a central hole.

A **fast calorimeter** vetos photons at small angle (θ<1°) to cut backgrounds:

$$e^+N \rightarrow e^+N\gamma; e^+e^- \rightarrow \gamma\gamma; e^+e^- \rightarrow \gamma\gamma\gamma$$

In order to furtherly reduce background, the inner sides of the **magnetic field** are instrumented with **veto** detectors for positrons/electrons.



For higher energy positron another **veto** is placed at the end of the vacuum chamber.

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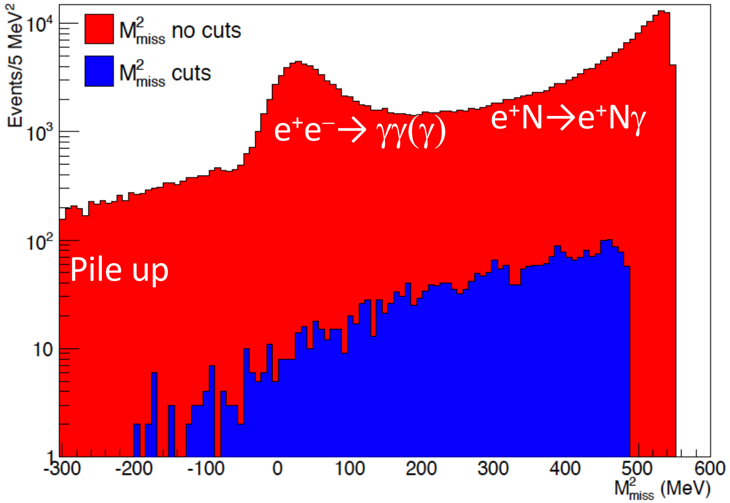
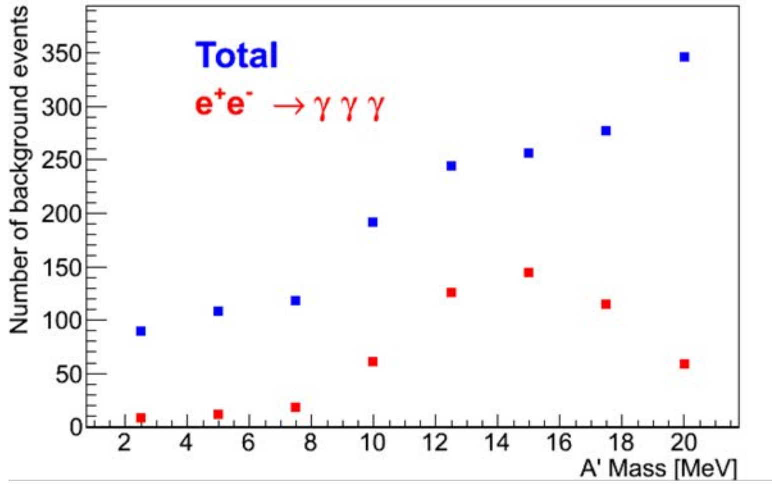
Background studies

Data M_{miss}^2





- BG sources are: $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$, $e^+N \to e^+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss2}.
- **Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)$beam)**
  - New Veto detector introduced to reject residual BG
  - New sensitivity estimate ongoing

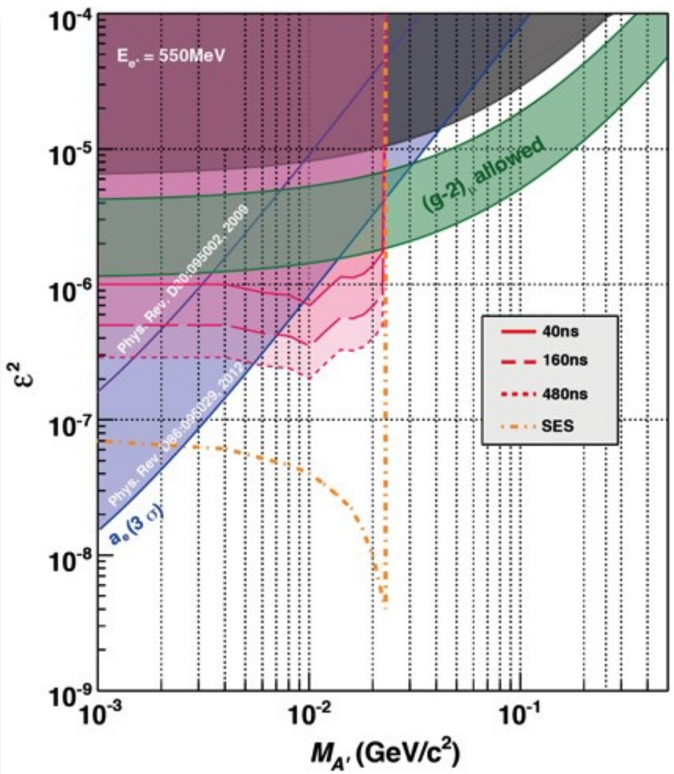
Expected results

The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.
The picture is showing the PADME expected sensitivity as a function of the beam characteristics. PADME started taking data in Oct. 2018 with a bunch length of ~ 250 ns. In 2020 bunch length reached 350 ns.

2.5×10^{10} fully GEANT4 simulated 550 MeV e^+ on target events.
Number of BG events is extrapolated to 1×10^{13} positrons on target.

With a 60% efficiency and a bunch length of 200 ns
4×10^{13} POT = 20000 e^+/bunch x2 x3.1x10^7s x 0.6x49 Hz

$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)}\frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon\cdot\delta$$



Background cross-sections

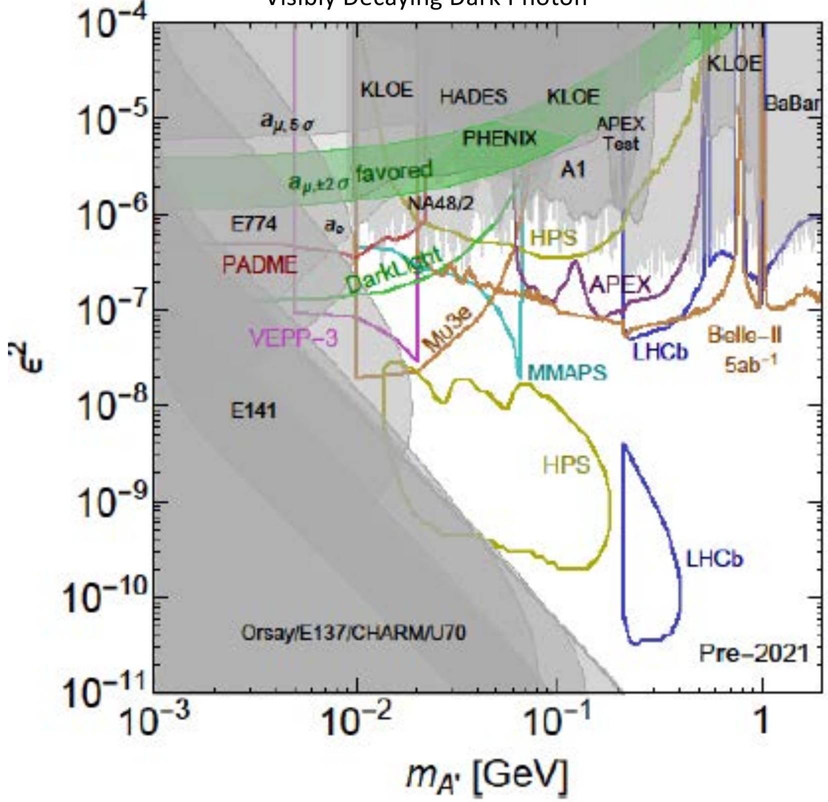
Table 1: *Dominant background contributions to the missing mass technique*

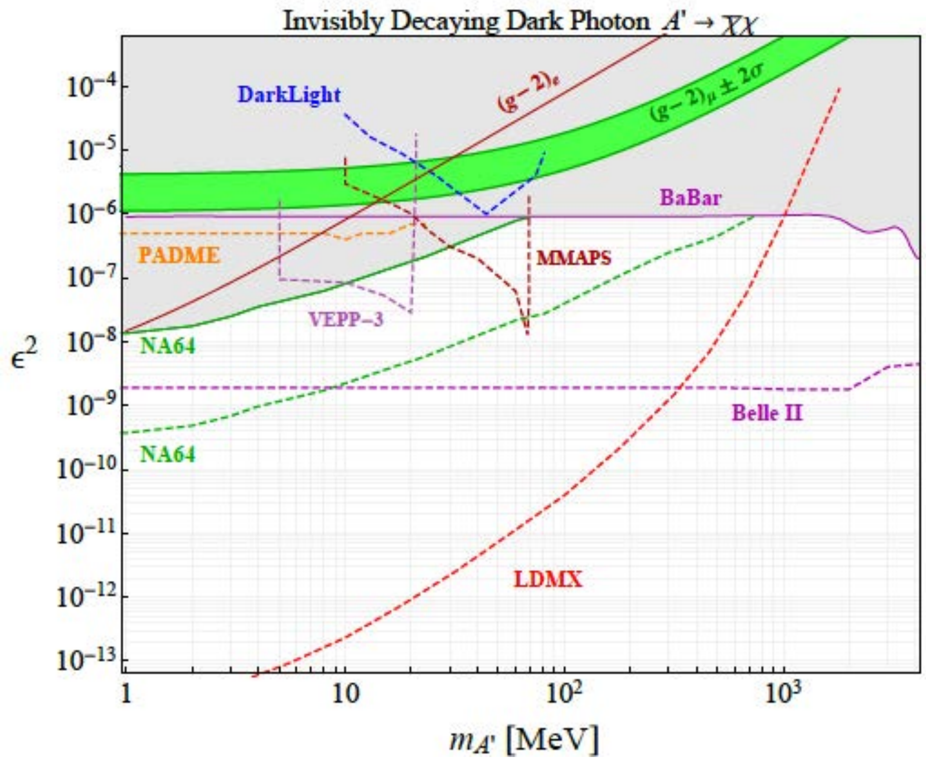
Background process	σ (E_{beam} = 550 MeV)	Comment
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+N \to e^+N\gamma$	4000 mb	$E_\gamma > 1MeV$, on carbon
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	$E_\gamma > 1MeV$, CalcHEP 16)
$e^+e^- \to e^+e^-\gamma$	188 mb	$E_\gamma > 1MeV$, CalcHEP

Cross sections values derived by CalcHEP at the sqrt(s) = 17 MeV

$e^+e^- \to e^+e^-$	515.8 mb
$e^+e^- \to \gamma\gamma$	2.73 mb

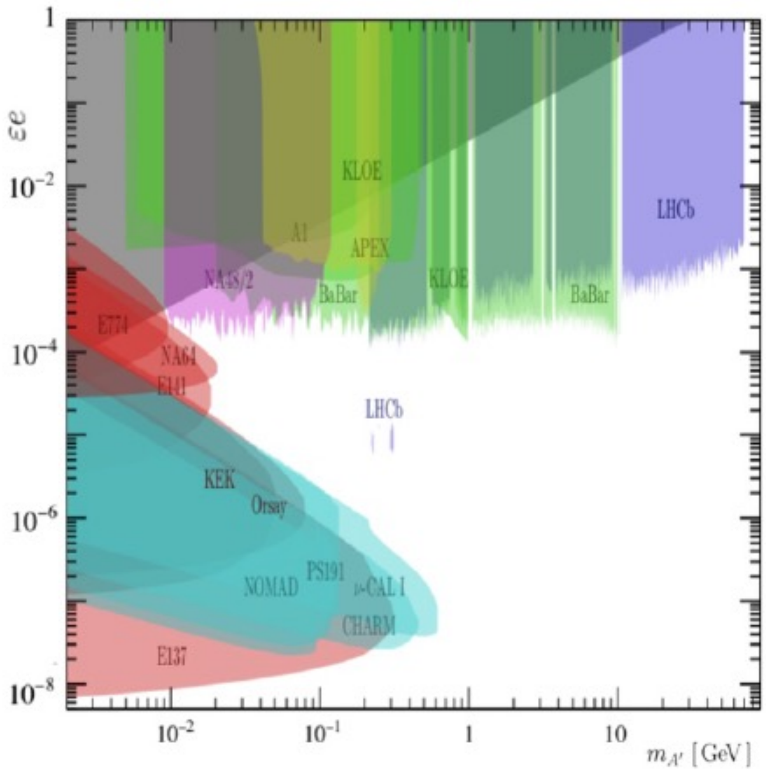
Visibly Decaying Dark Photon



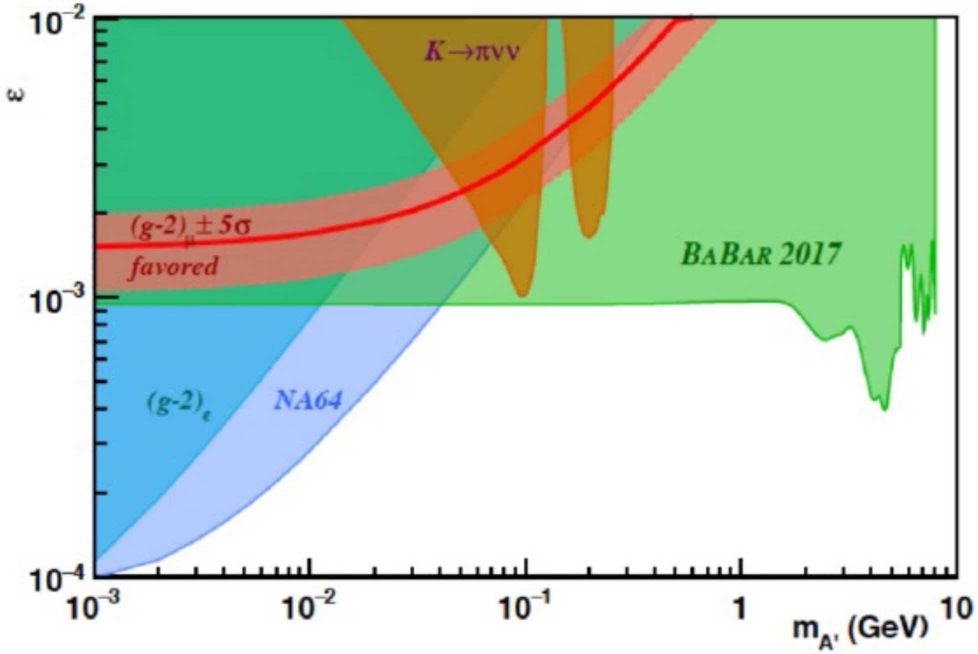


Status of exclusion

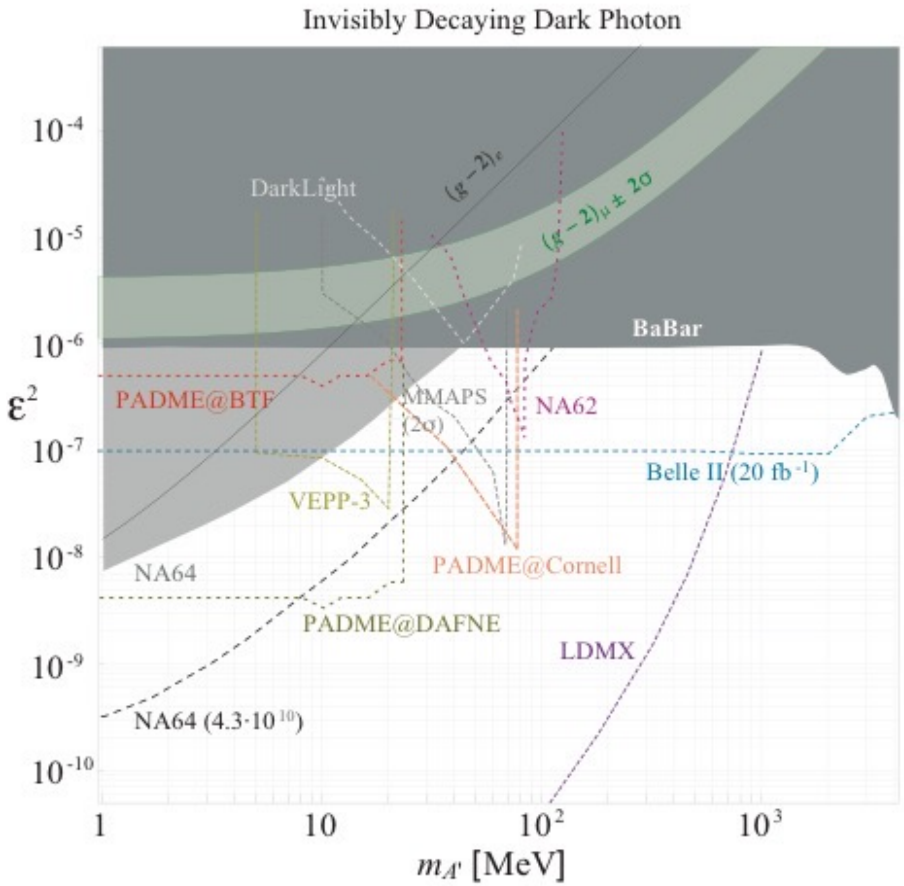
Visible decays



Invisible decays



PADME prospects



PADME sensitivity is limited by:

- the Linac duty-cycle 50Hz x (40-250) ns/bunches
- Beam energy 550 MeV limits $M_{A'} < 23.7$MeV

There are plans to move PADME to other positron beam line:

- Cornell
- Jlab
- DAFNE extracted beam