Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

iNPC2022
Cape Town, South Africa

THE STUDY OF THE *X17* ANOMALY WITH THE PADME EXPERIMENT

P.Gianotti on behalf of the PADME collaboration

Outline

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

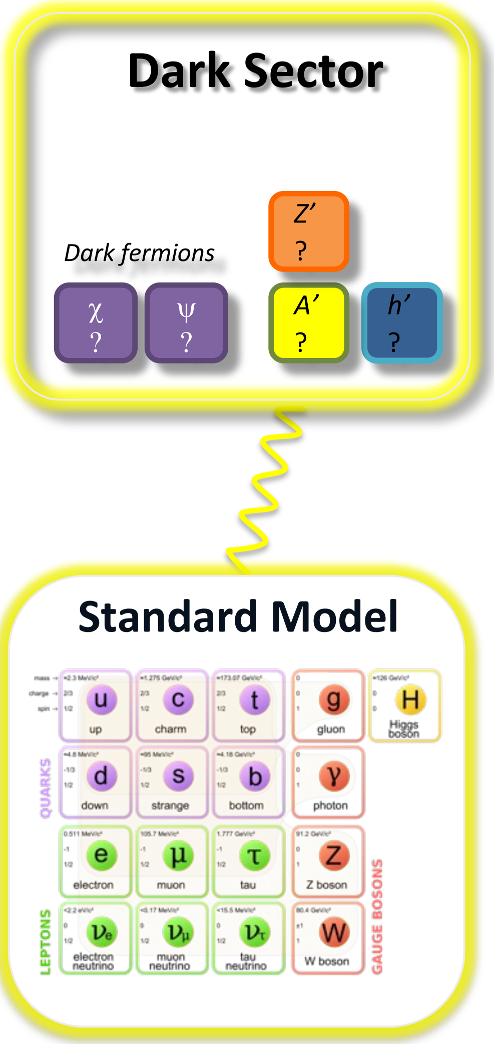
New Forces

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.

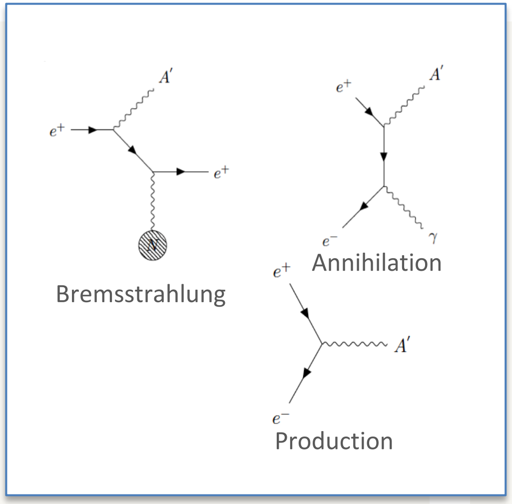


The search for this new mediator *A'* is the goal of the PADME experiment at LNF.

A′ production and decay

A′ can be produced using e^+ via:

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



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

- No dark matter particles lighter than the *A′*:
  - $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, 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
  - $A' \rightarrow \chi\chi \sim 1$. These are the so called **"invisible"** decays

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

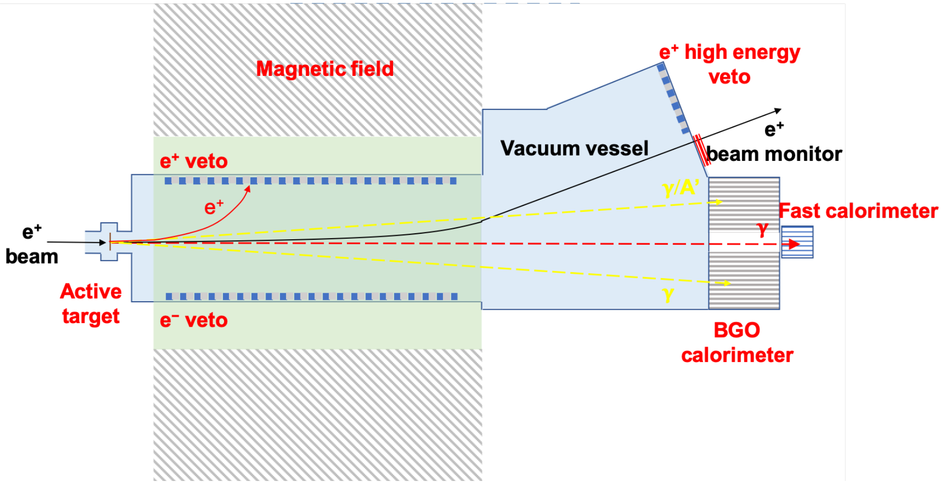
$$e^+e^- \rightarrow A'\gamma$$

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

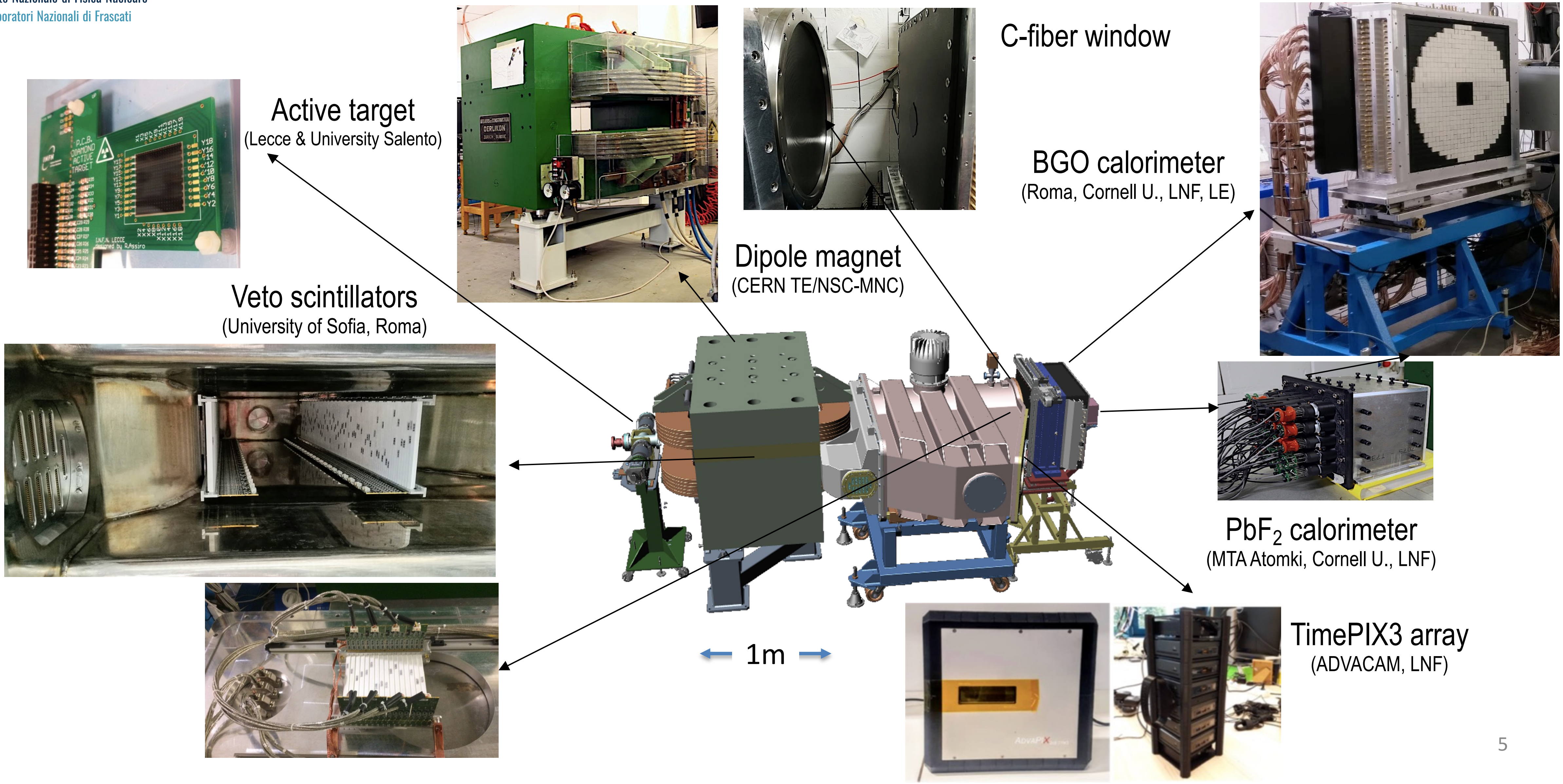
Know e^+ beam **momentum and position**, measuring the recoil photon **position** and **energy**

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

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

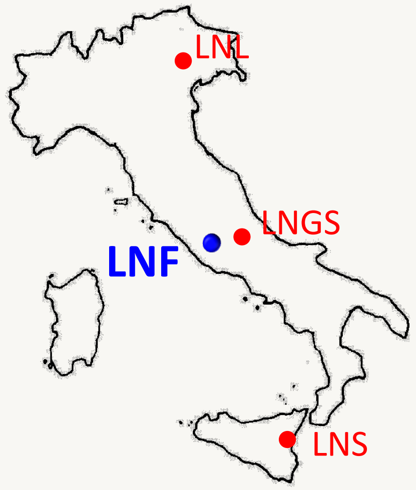


The PADME detector in a nutshell

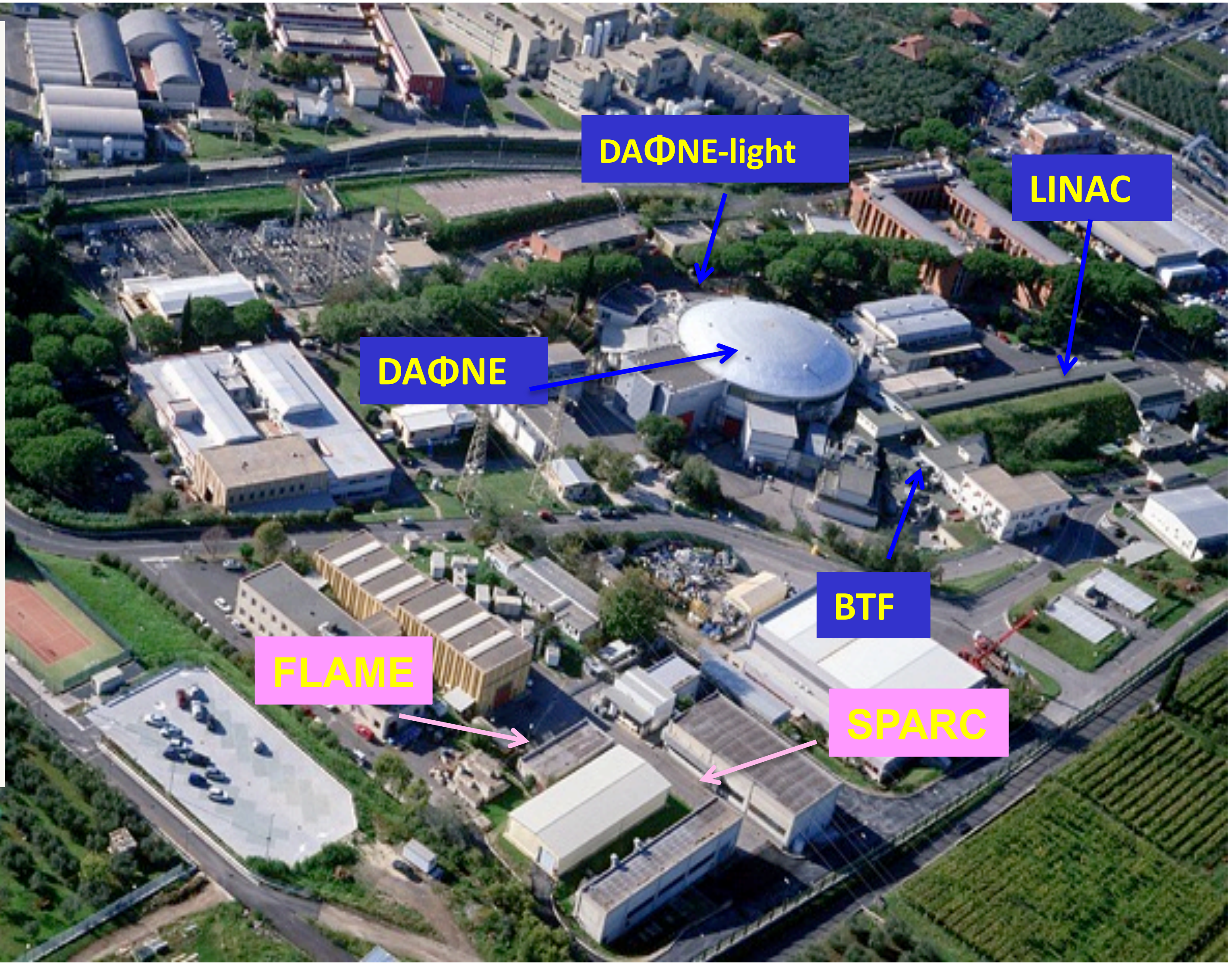


Frascati Laboratory of INFN

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.



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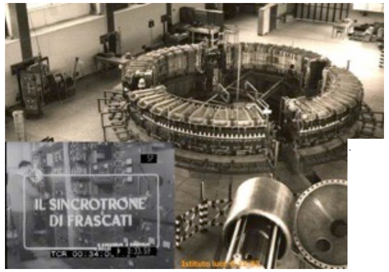
The LNF accelerators history

Electron Synchrotron
(1959-1975) E=1 GeV



LNF-54/48 (1954)

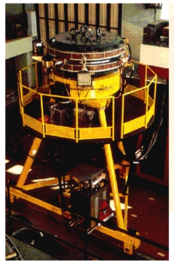
Il progetto italiano di un elettrosincrotone.

G. Salvini

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

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

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)

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)

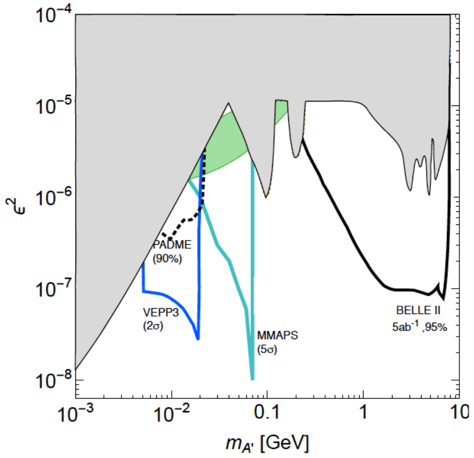
colliders in the world

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

Dark sector studies at PADME

Other DM approaches can be addressed by PADME

Dark Photon A’
arXiv:1608.08632v1

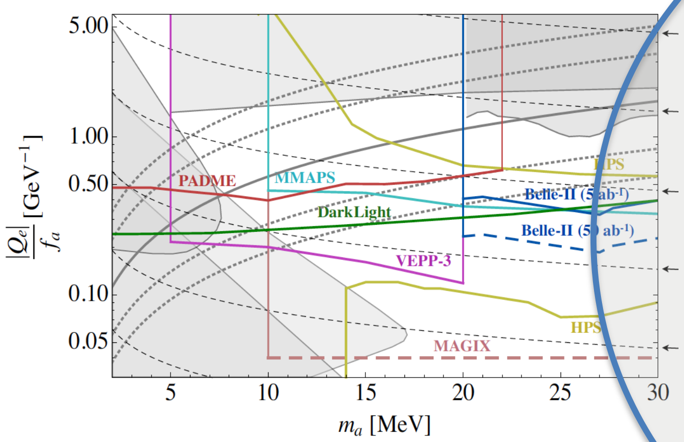


$e^+e^- \to \gamma A'$

Visible, invisible decays:

$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092

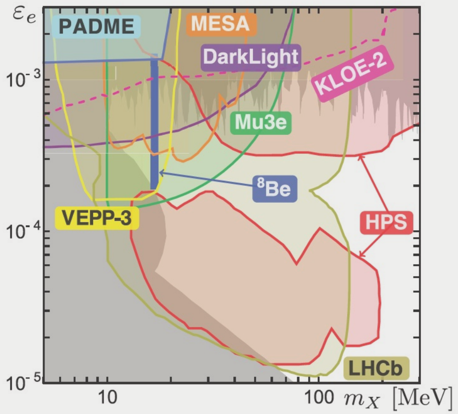


$e^+e^- \to \gamma a$

ALPs final states:

$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

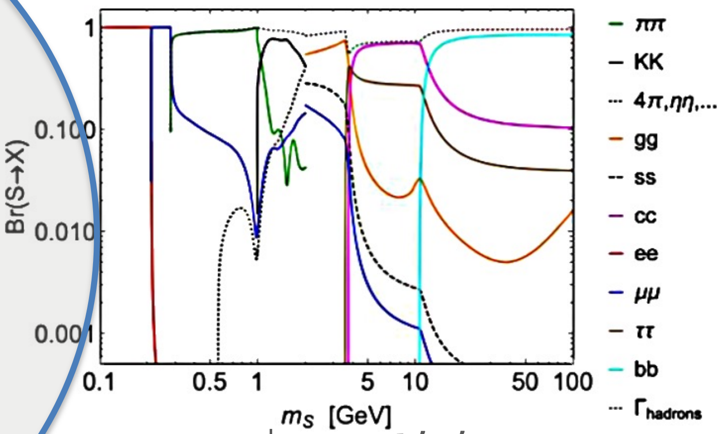
Be anomaly - X boson
PRD 95 (2017) 035017



$e^+e^- \to \gamma X_{17}$

Final state $X_{17} \to e^+e^-$

Dark Higgs
arXiv:2102.12143v1



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

dark higgs decay: h'

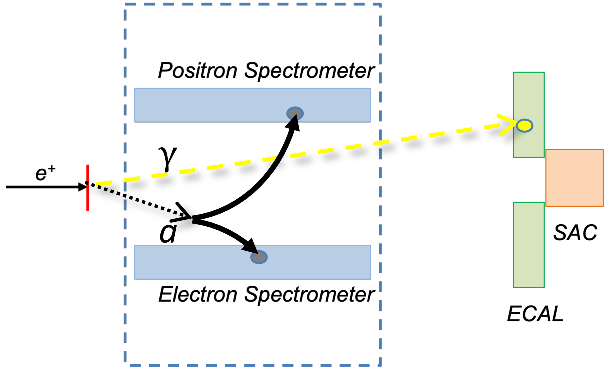
$\to A'A', A' \to e^+e^-, \chi\bar{\chi}$

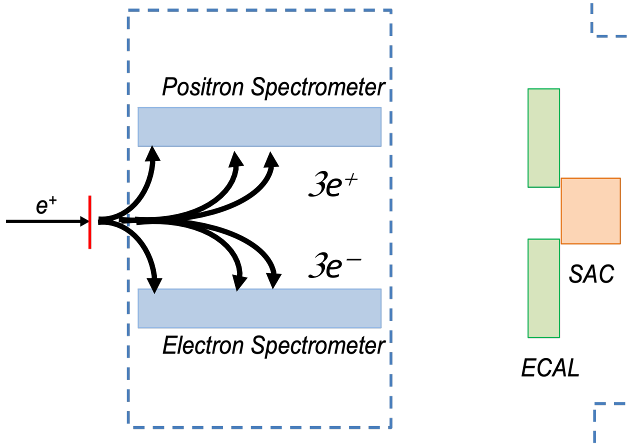
Final state: $A'A'A' \to e^+e^-\, e^+e^-\, e^+e^-$

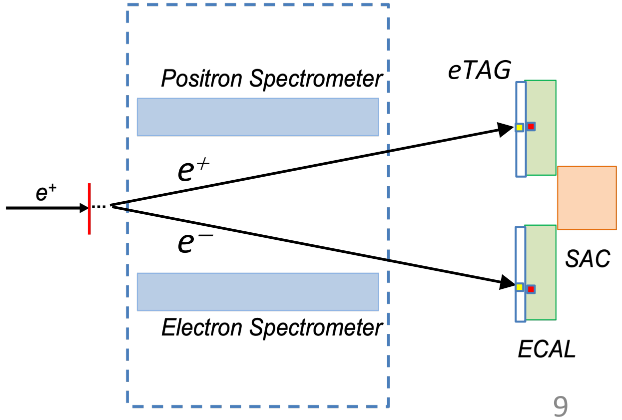
Dark sector studies at PADME

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

- Axion Like Partiles $e^+e^- \rightarrow \gamma a$
  - visible decays: $a \rightarrow \gamma\gamma, ee$
  - invisible decay: $a \rightarrow \chi\bar{\chi}$
- Dark Higgs $e^+e^- \rightarrow h'A'; h' \rightarrow A'A'$
  - final state: $A'A'A' \rightarrow e^+e^-e^+e^-e^+e^-$
- *X17* Boson $e^+e^- \rightarrow X_{17};\ X_{17} \rightarrow e^+e^-$
  - tuning beam energy and slightly modifying the detector



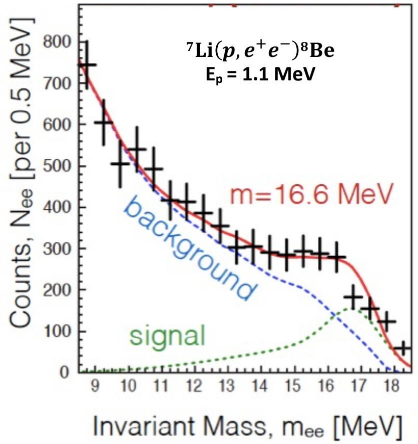




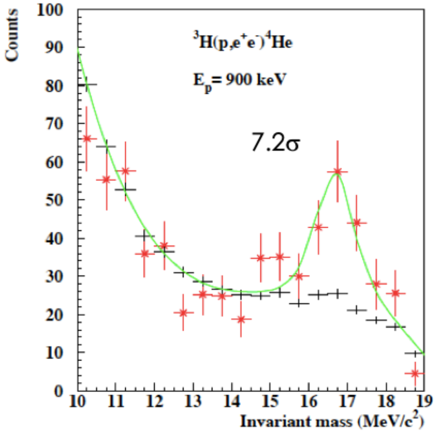
The ^{8}Be anomaly

The study of de-excitation of light nuclei via IPC pointed out an anomaly in the decay of ^{8}Be and ^{4}He.

$m_X = 16.7 \pm 0.35(stat) \pm 0.5(sys) MeV$ $\quad m_X = 16.90 \pm 0.12(stat) \pm 0.21(sys) MeV$

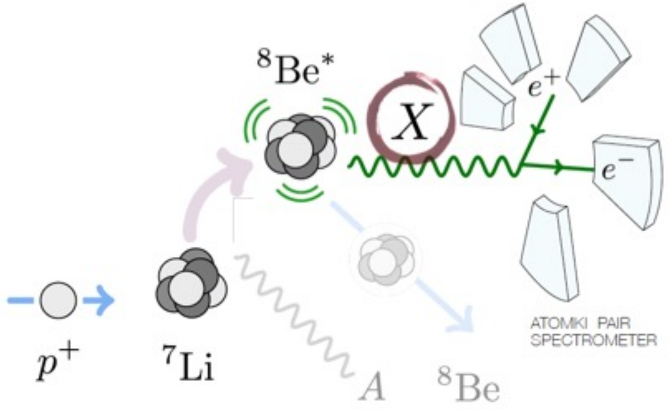


Phys. Rev. Lett. **116**, 042501 (2016)



Phys. Rev. C **104**, 044003 (2021)

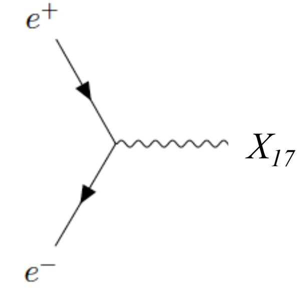
Is the *X* a signal of a dark matter particle?



E. Nardi *et al.*, **"Resonant production of dark photons in positron beam dump experiments"** Phys.Rev. D**97** (2018) no.9, 095004

By setting the e$^+$ beam at ~283 MeV PADME has the unique opportunity to have a resonant production of the X.
Several uncertainties:

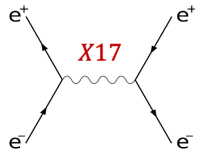
- resonance width (0.5 eV);
- electron velocities in the target;
- optimal target.



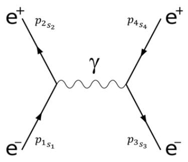
X17 study @ PADME

- Same ATOMKI observables: 2 leptons in the final state, but **different production**
- 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 of course also produced in $\gamma\gamma$ events

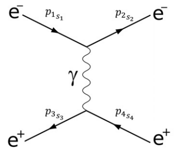
Signal



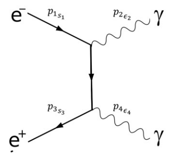
Background



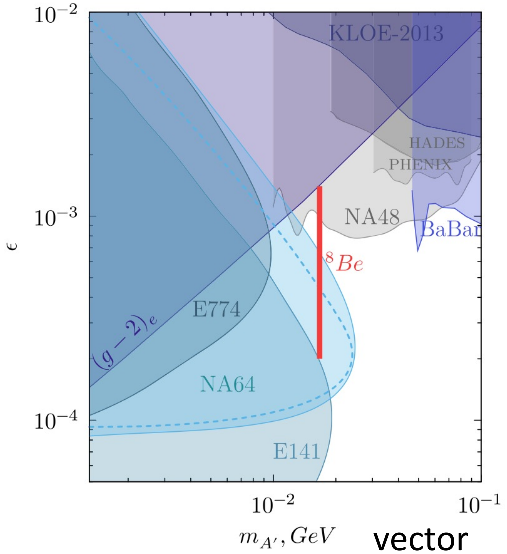
s channel



t channel

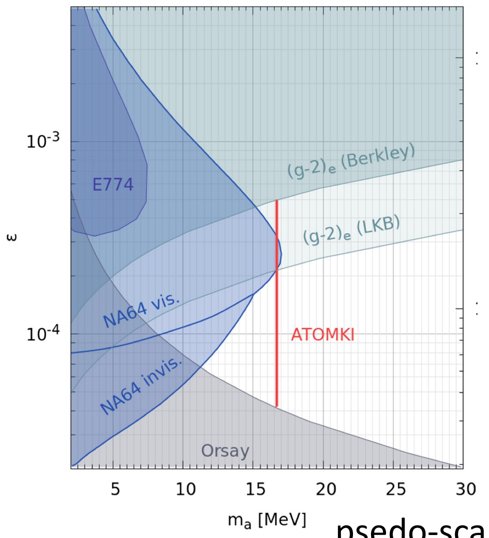


Phys. Rev. D **101**, 071101 (R) (2020)



vector

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



psedo-scalar

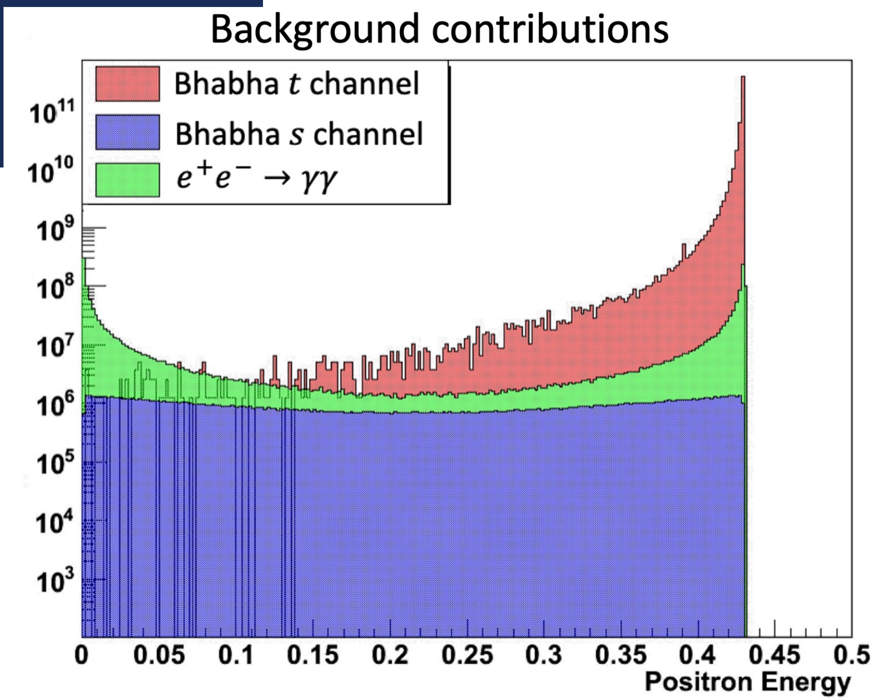
The nature of the X17 anomaly is not uniquely defined. Different interpretations consider a **vector** or **pseudo-scalar** particle of 17 MeV/c^2

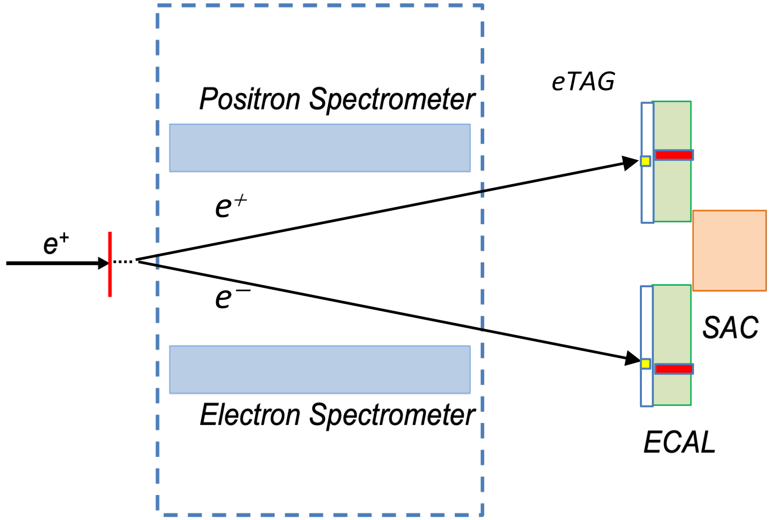
PADME X17 setup

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

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

- Whit **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 from photons or electrons in ECal
  - New detector: Electron tagger (**ETag**) plastic scintillator slabs with same ECal vertical size.





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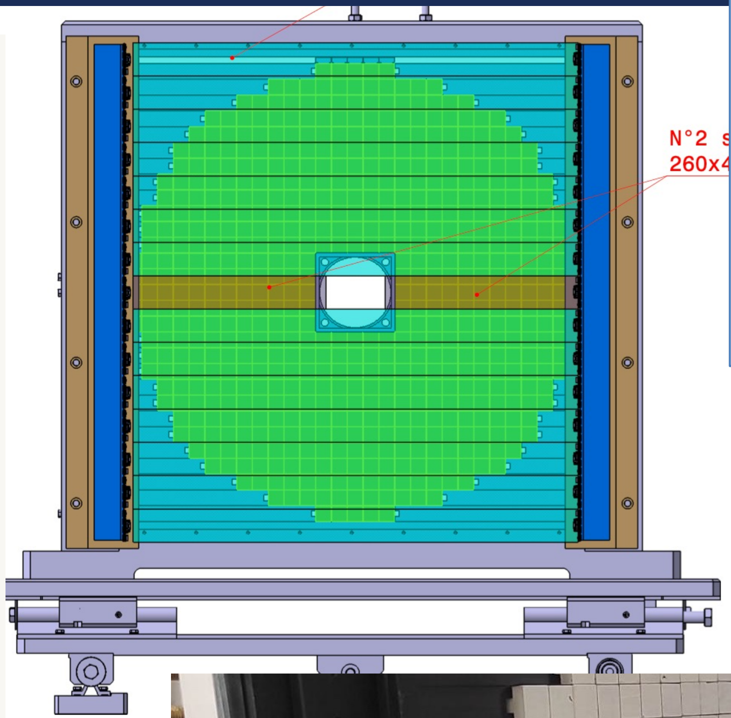
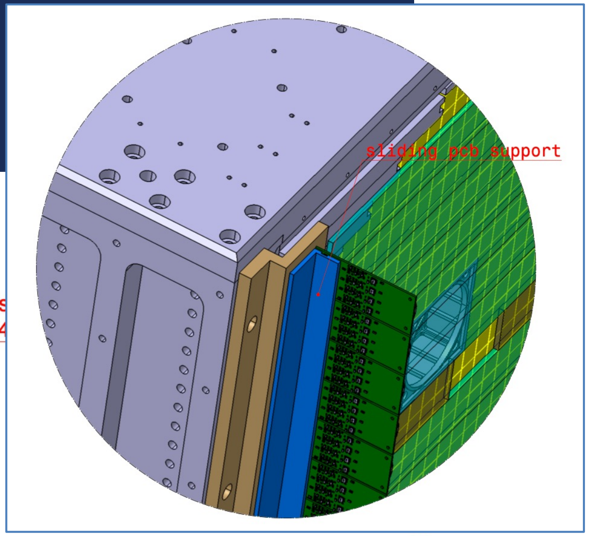
PADME eTag

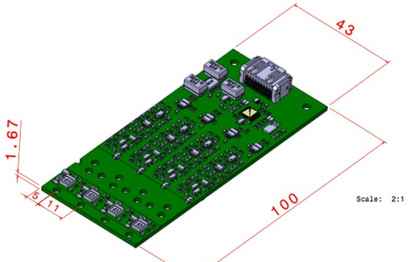
The new **eTag** has been designed and assembled (2021-2022):

- 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.

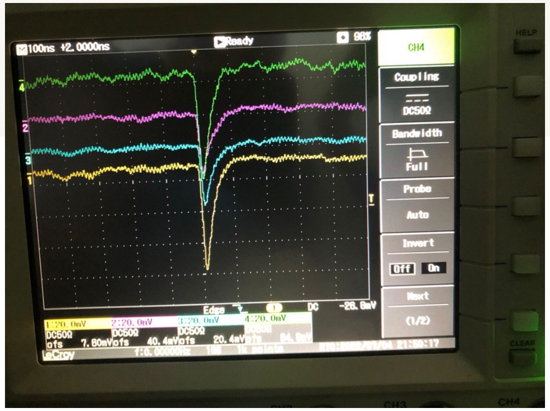
Commissioning took place Jul. 2022

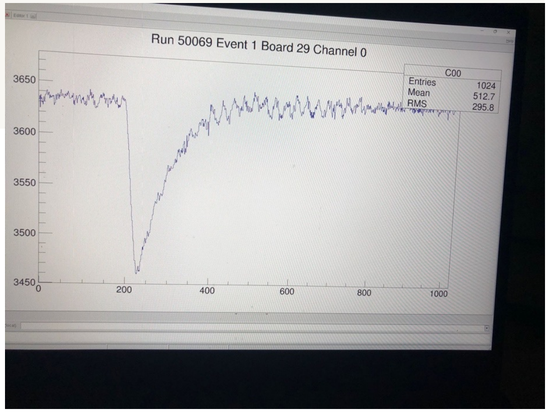






LNF-SEA design





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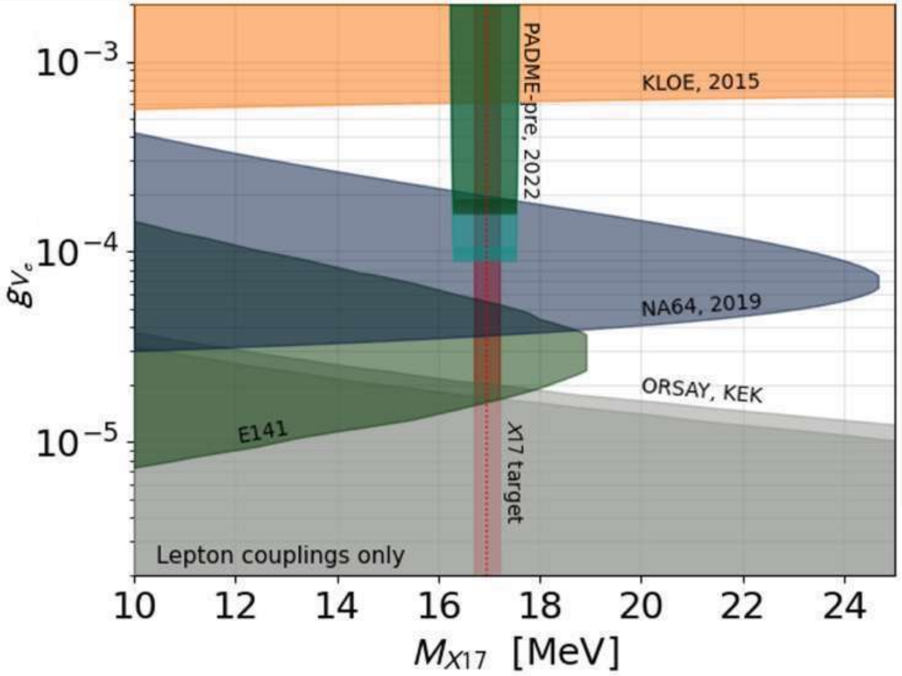
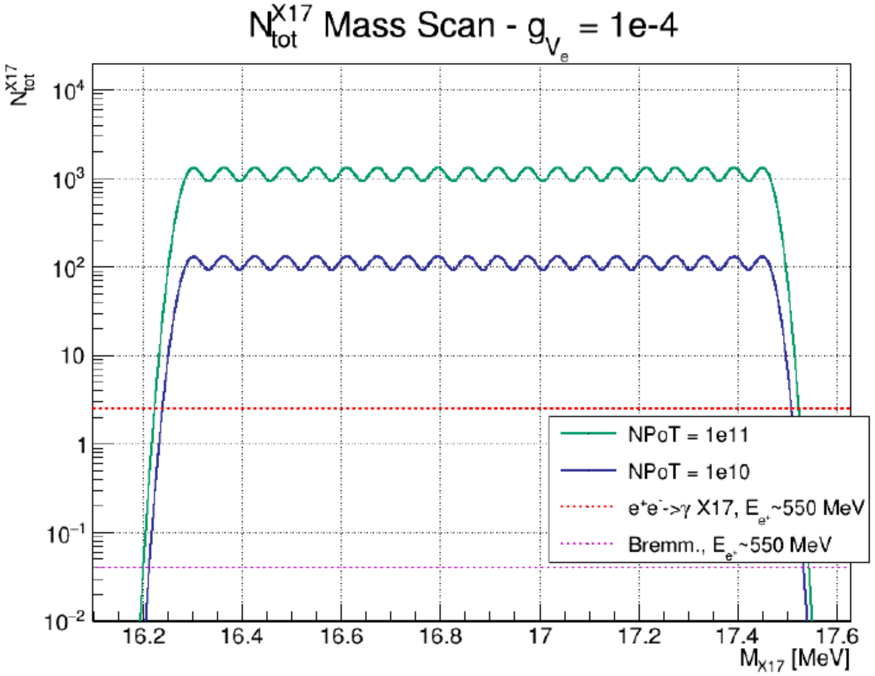
Expected results

X17 mass is known with limited precision (*~0.2* MeV/c^2) the PADME strategy to search a signal is:

- explore a mass interval centred around 17 MeV/c^2 varing E_{e^+} almost continuously (~ 2 MeV) in the range 260-300 MeV.





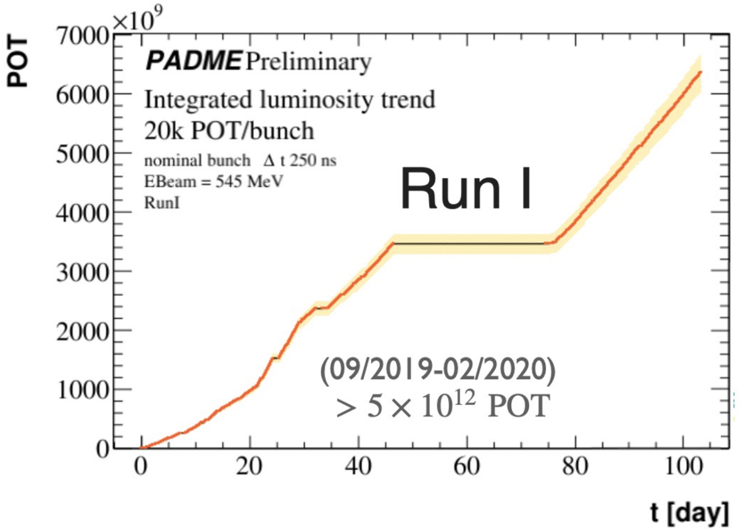
Number of X17 expected at PADME for each of the 21 points of the energy scan.

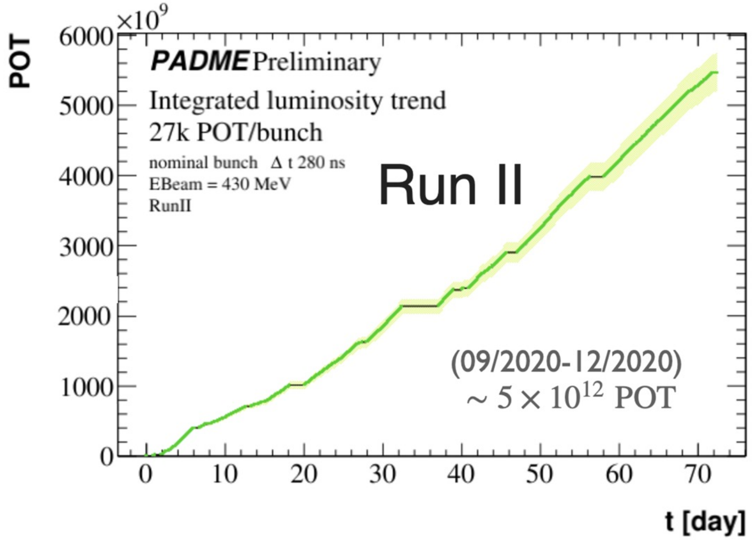
Experimentally

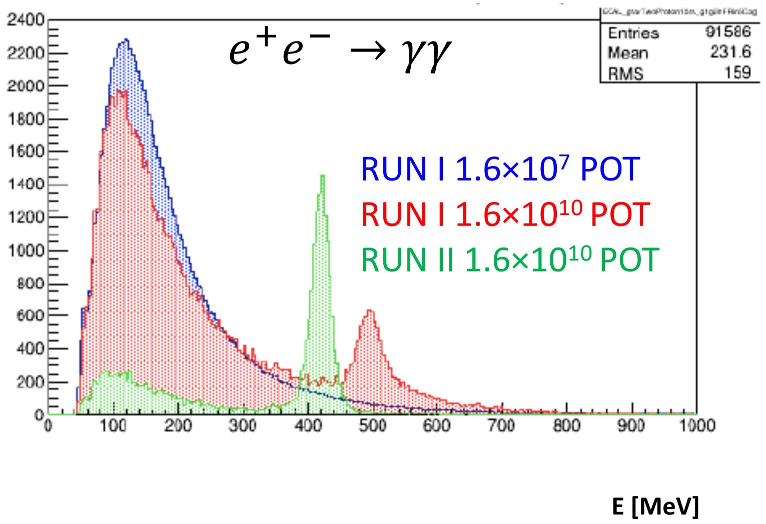
$$N^X \propto \frac{N_{meas}(e^+e^-) - N_{calc}(e^+e^-)}{N_{PoT}}$$

for each energy point

PADME data





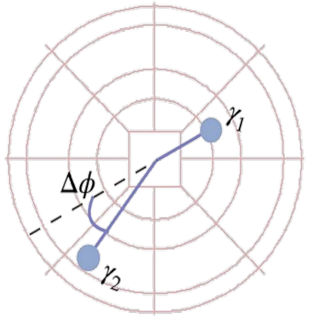


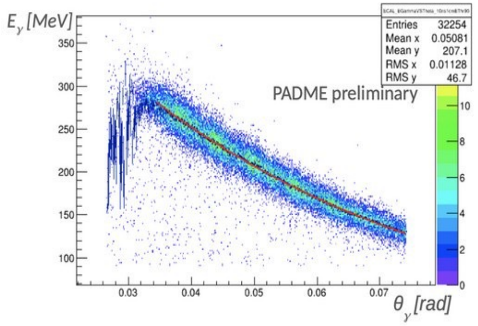
- Two physics runs in winter **2019** and winter **2020**
- Run II wrt Run I
  - Similar statistics, approximately 1/2 of minimal goal (10^{13} particles-on-target)
  - Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
  - **Improved vacuum separation** between experiment and beamline
  - Less beam-induced background with primary wrt secondary beam
- Run III expected in winter 2022

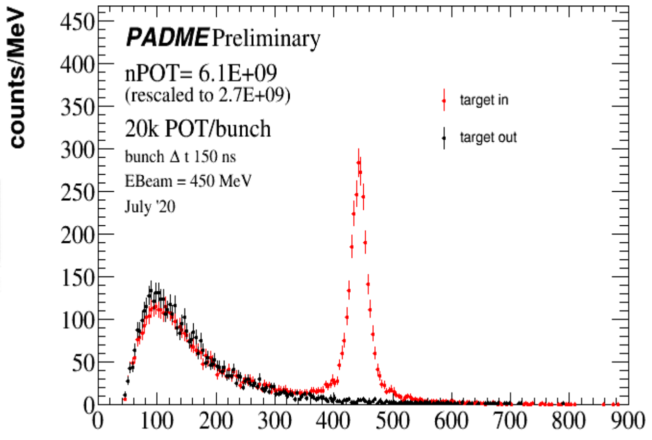
$e^+e^- \to \gamma\gamma$ cross section

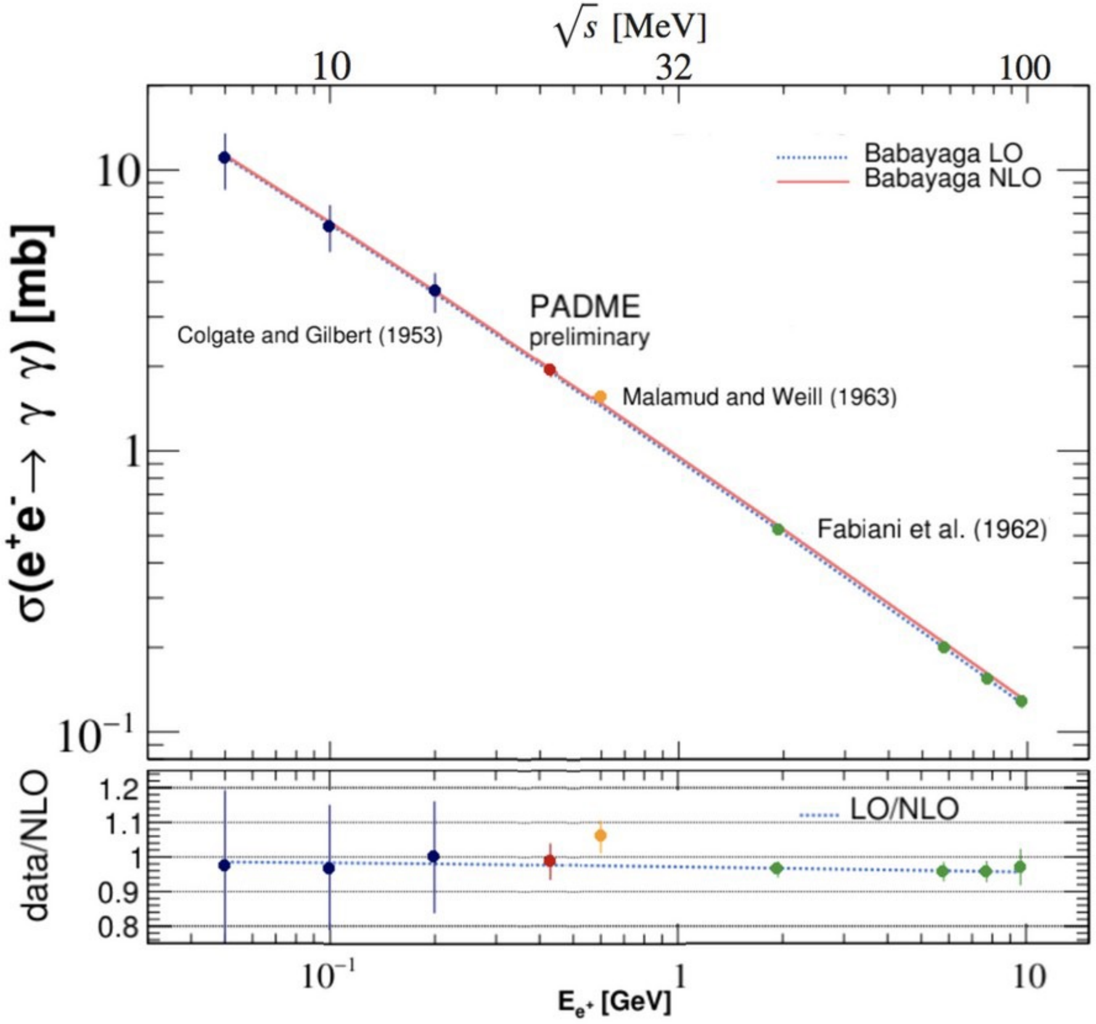
$e^+e^- \to \gamma\gamma$ cross section

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









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

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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;
- Two data takings: Run-I, Run-II analysis is ongoing;
- Many physics items can be explored:
  - visible dark photon decays, ALPs searches, Fifth force, dark Higgs, ***X17* boson**
- Data taking to confirm/disprove *X17* existence ongoing.

PADME is exploring the DARK SECTOR…

Backup

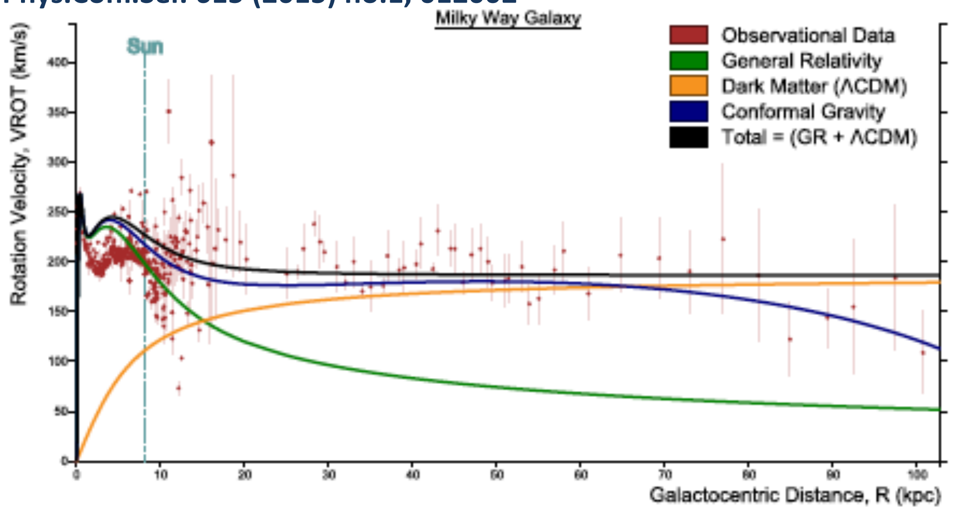
The Dark Matter issue

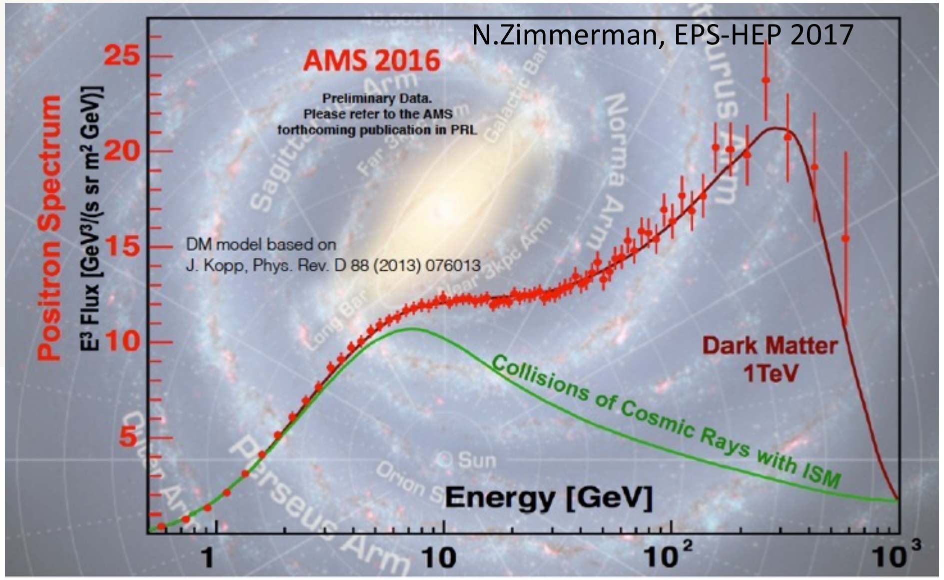
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

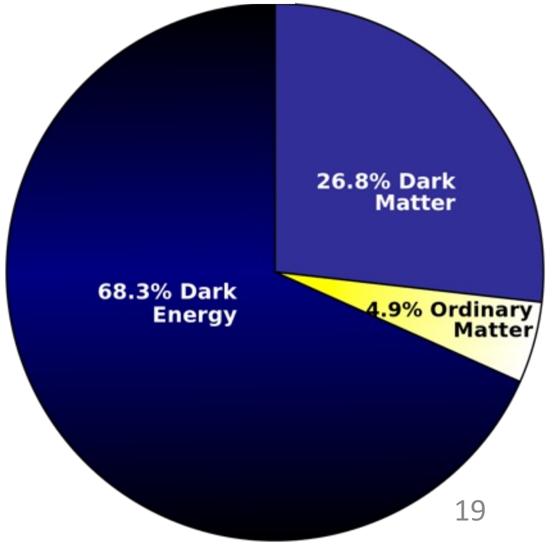
The abundance of this new entity is 5 times larger than SM particles.

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

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







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The Nature of Dark Matter

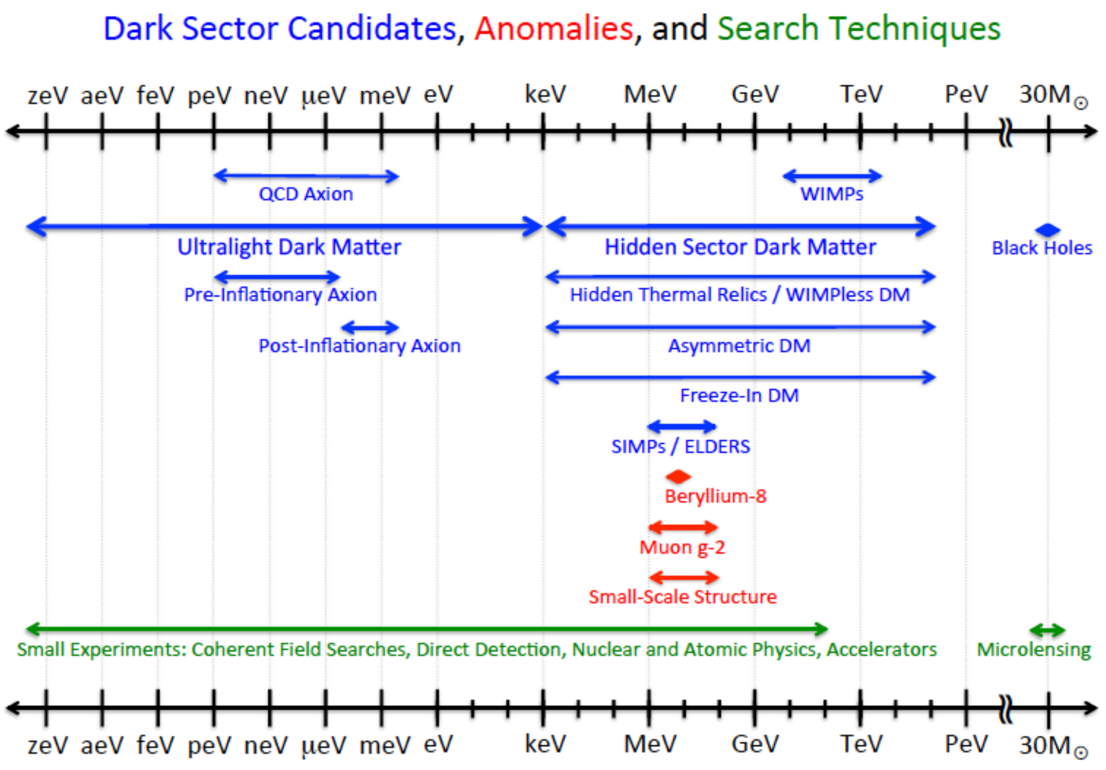
Despite its abundance, we don’t yet know what is made of.

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.**

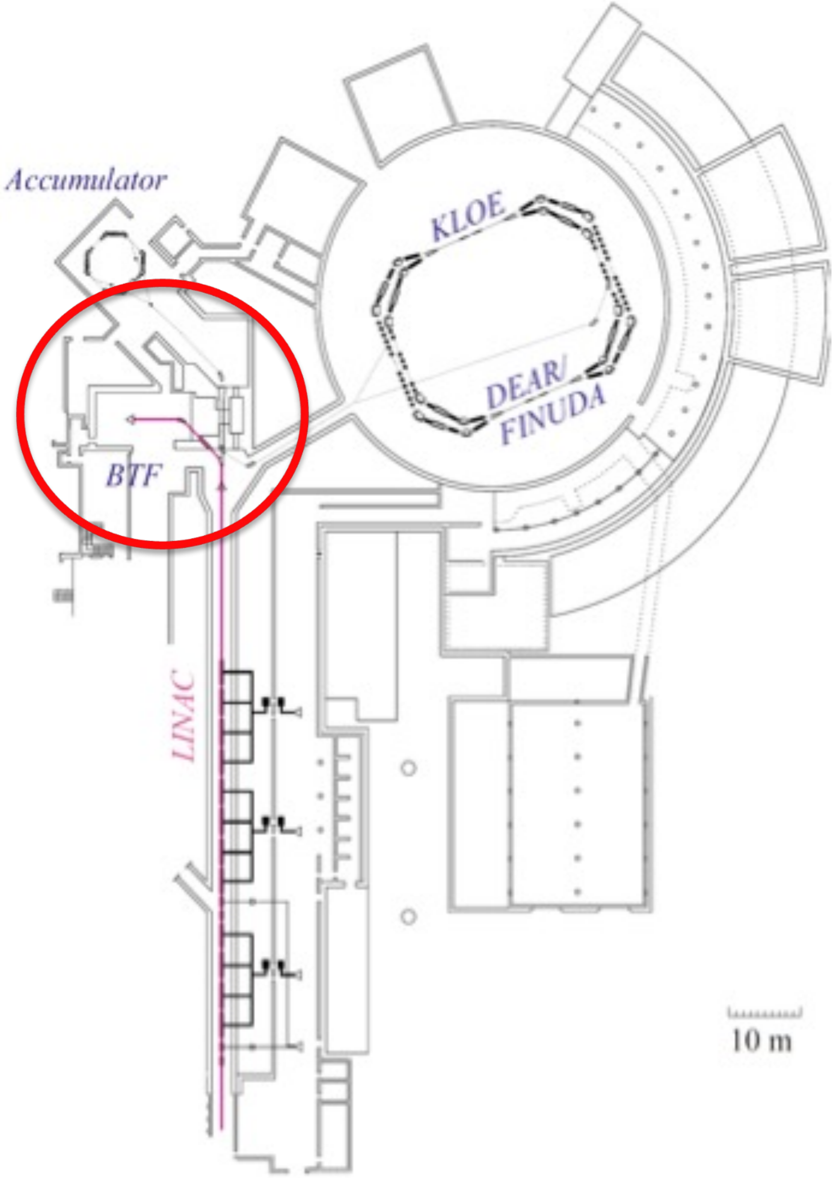


arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

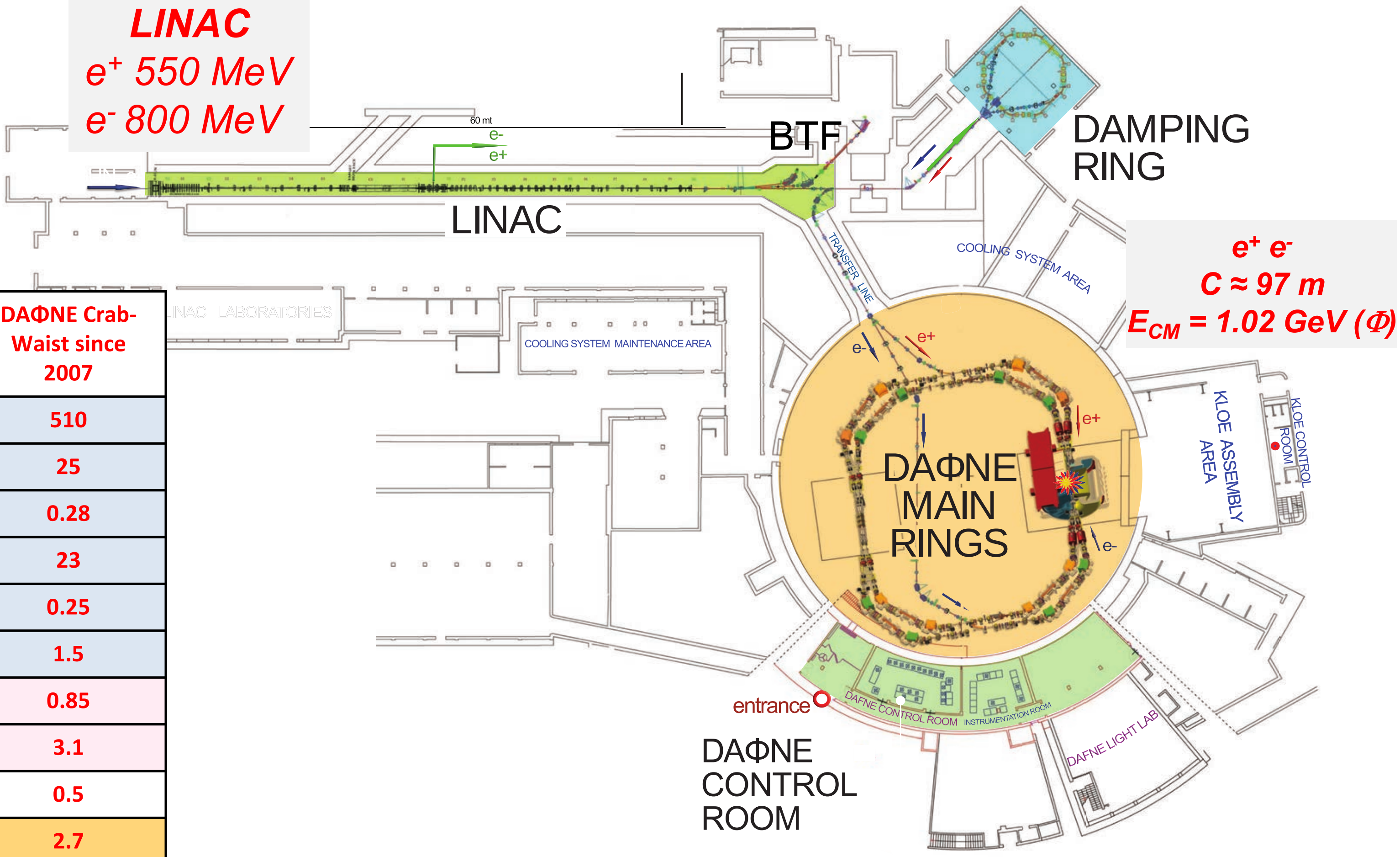
LNF LINAC beam line

	electrons	positrons
Maximum beam energy (E_{beam})[MeV]	800 MeV	550 MeV
Linac energy spread [$\Delta p/p$]	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
  - Duty cycle 50*40 ns= 2×10^{-7} s
    work done to reach 250 ns bunch length
- The accessible $M_{A'}$ region is limited by E_{beam}
  - 0-23.7 MeV can be explored with 550 MeV e^+ beam



DAΦNE Complex



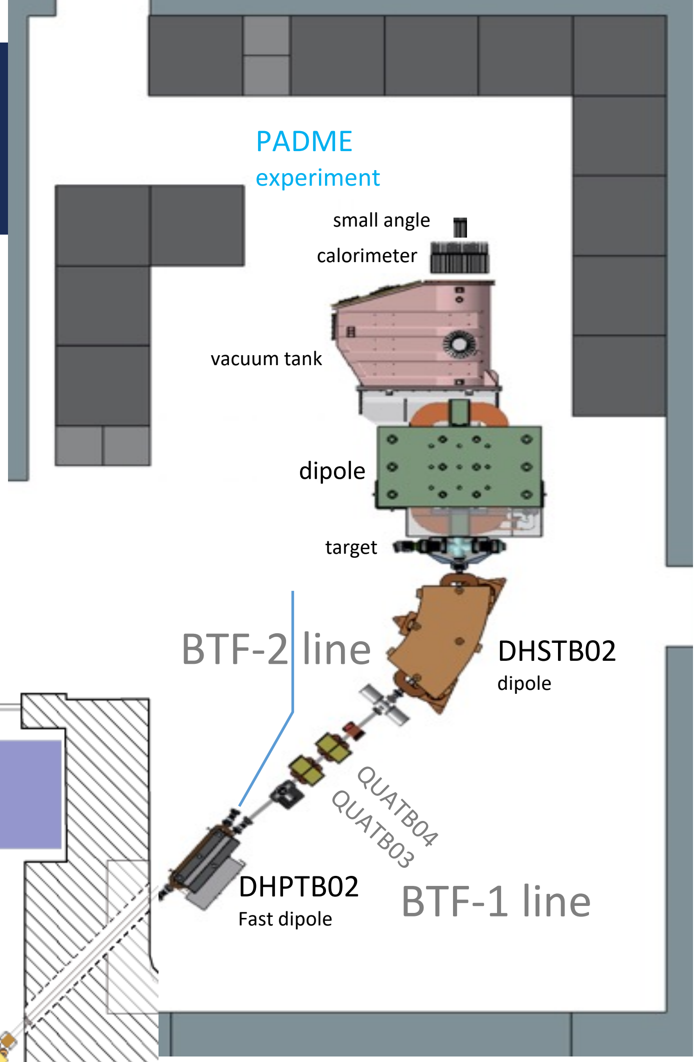
	DAΦNE native 2000÷2006	DAΦNE Crab-Waist since 2007
Energy [MeV]	510	510
$\Theta_{cross}/2$ [mrad]	12.5	25
ε_x [mm·mrad]	0.34	0.28
β_x^* [cm]	160	23
σ_x^* [mm]	0.7	0.25
$\Phi_{piwinski}$	0.6	1.5
β_y^* [cm]	1.80	0.85
σ_y^* [μm] low current	5.4	3.1
Coupling [%]	0.5	0.5
Bunch spacing [ns]	2.7	2.7
I_{bunch}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

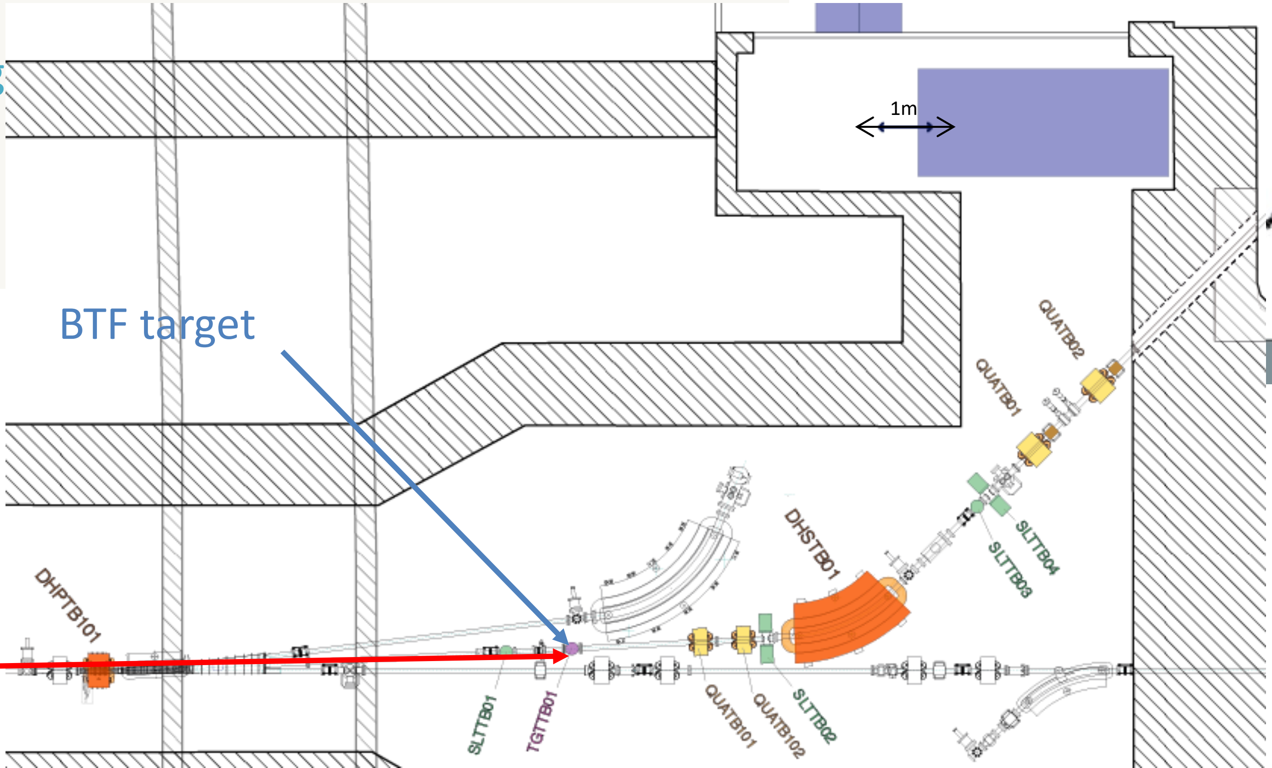
DAΦNE implemented succesfully a new kind of beam-beam interaction: the Crab-Waist collision scheme

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.





Primary beams
750 MeV e^-
550 MeV e^+

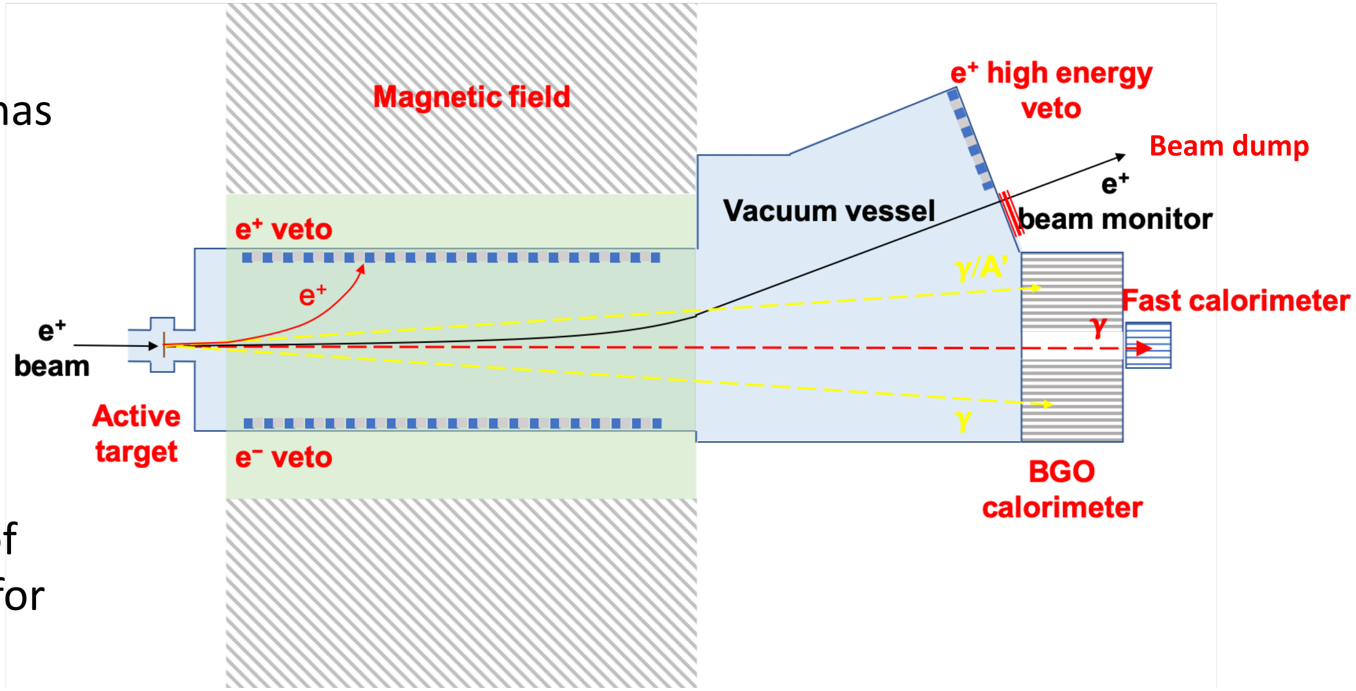
Positron beam parameters:
- 1% energy spread
- 1.5 mm spot size
- 1 mrad emittance

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:

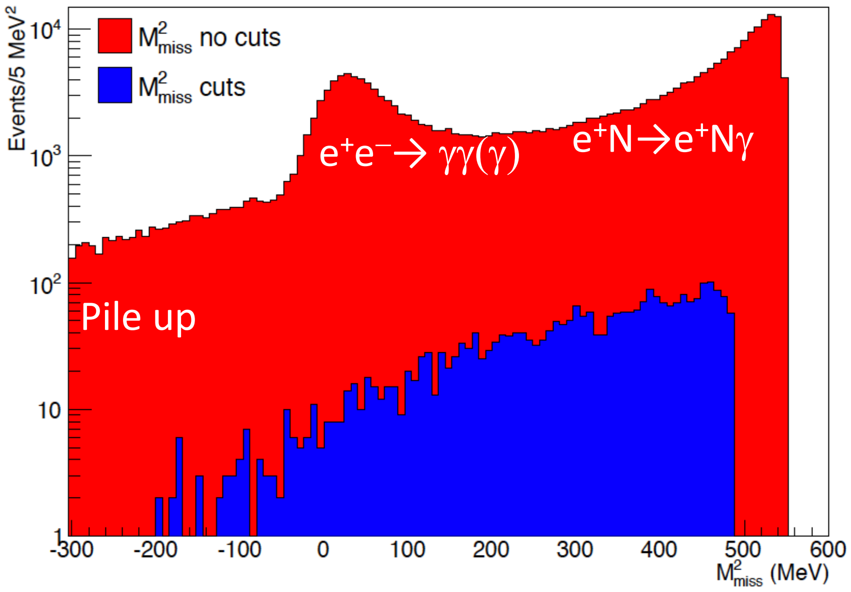
$$e^+N \to e^+N\gamma; e^+e^- \to \gamma\gamma; e^+e^- \to \gamma\gamma\gamma$$

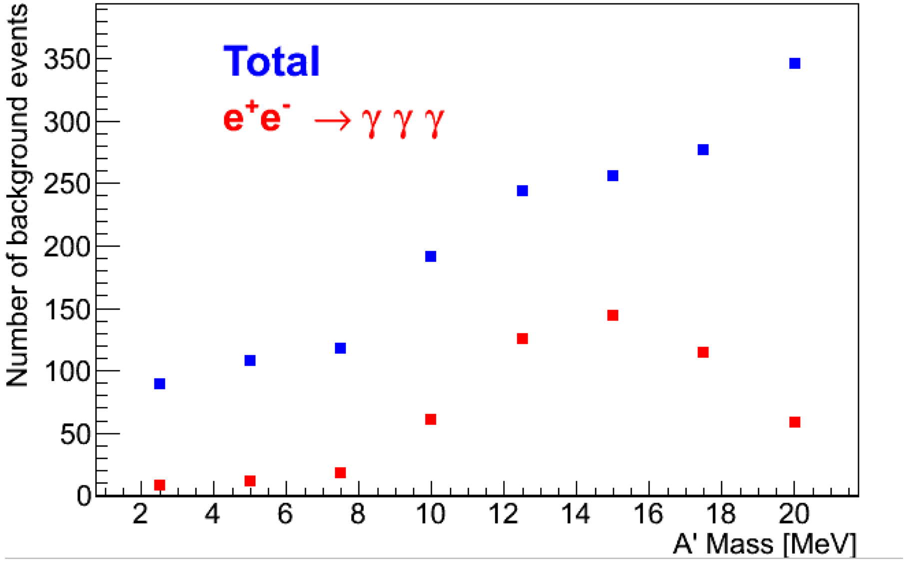
In order to furtherly reduce background, the inner sides of the **magnetic field** are instrumented with **veto** detectors for positrons/electrons.

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

Background studies

Data M_{miss}^2





- BG sources are: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$, $e^+N \rightarrow e^+N\gamma$, 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

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Expected results

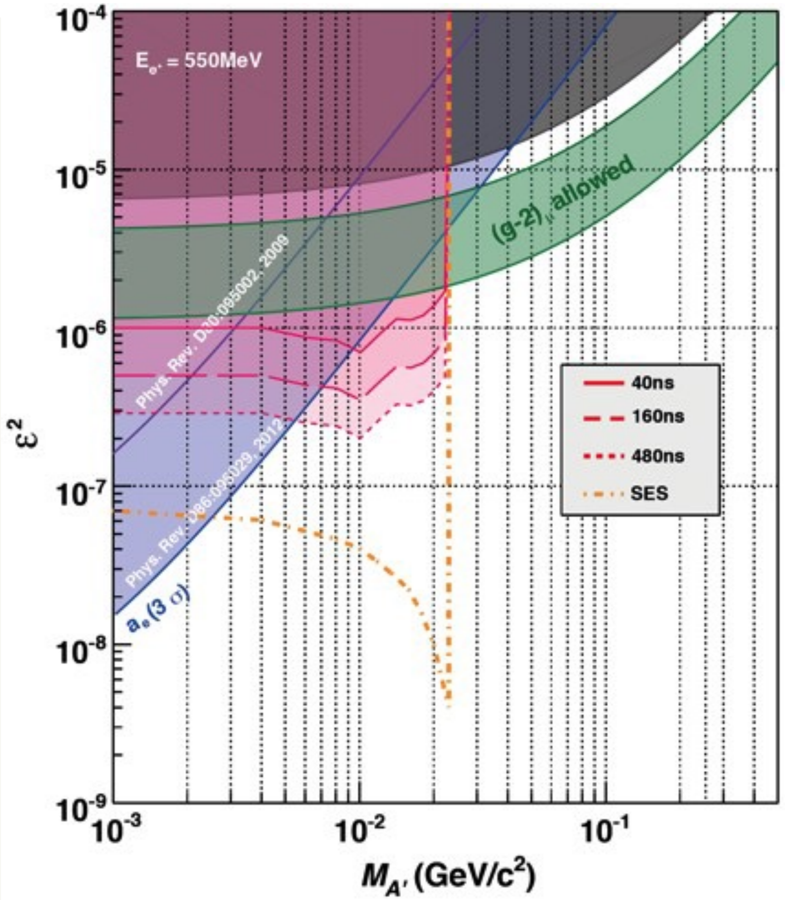
The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.

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 x3.1×10^7s x 0.6x49 Hz

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

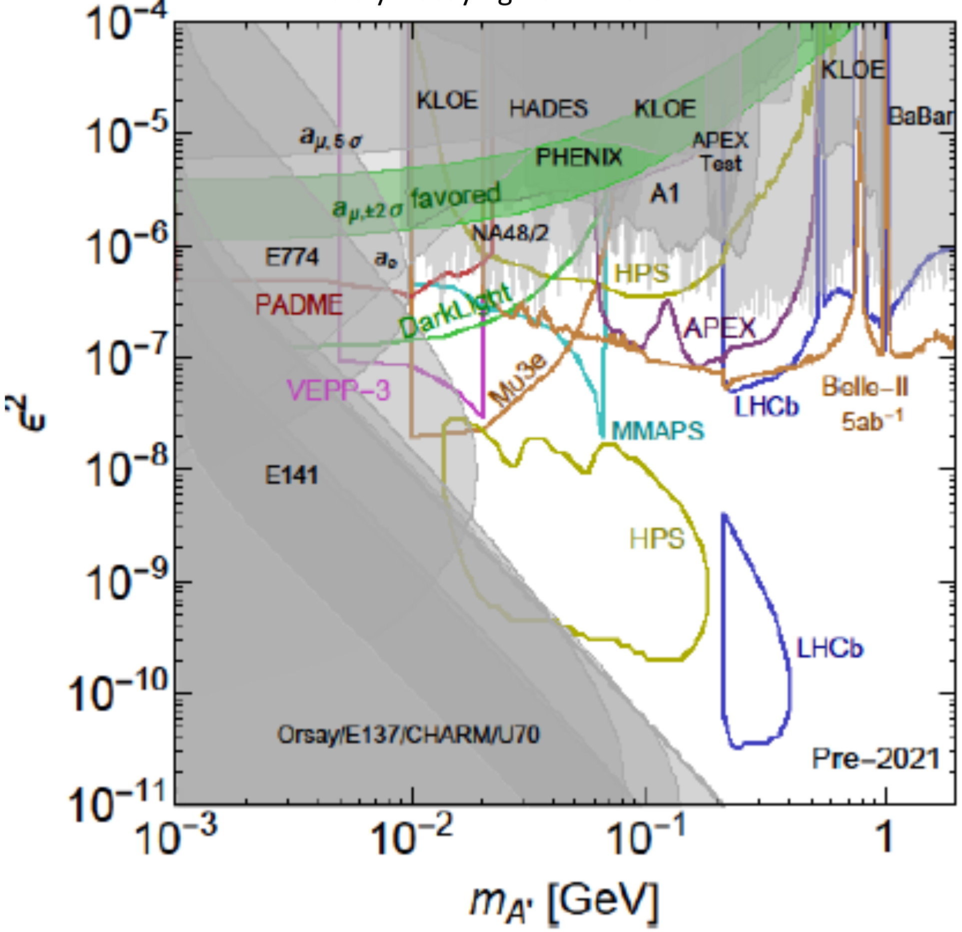


Background cross-sections

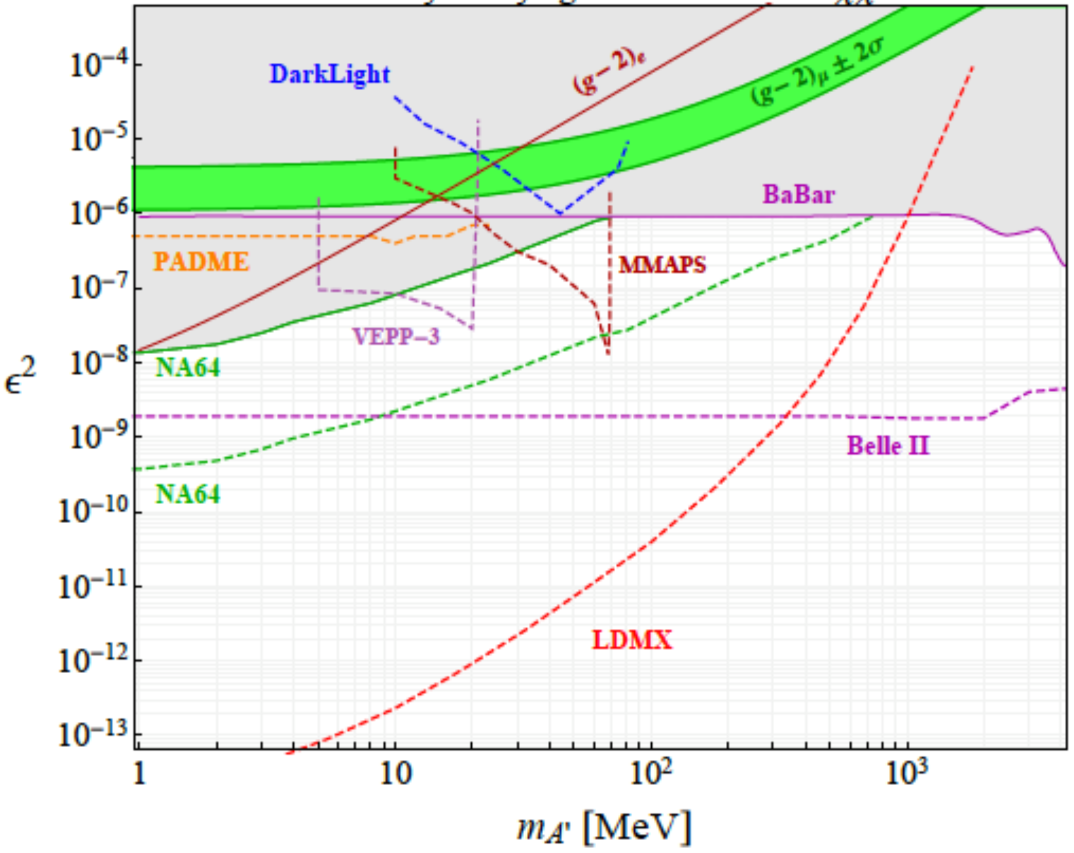
Table 1: *Dominant background contributions to the missing mass technique*

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

Visibly Decaying Dark Photon

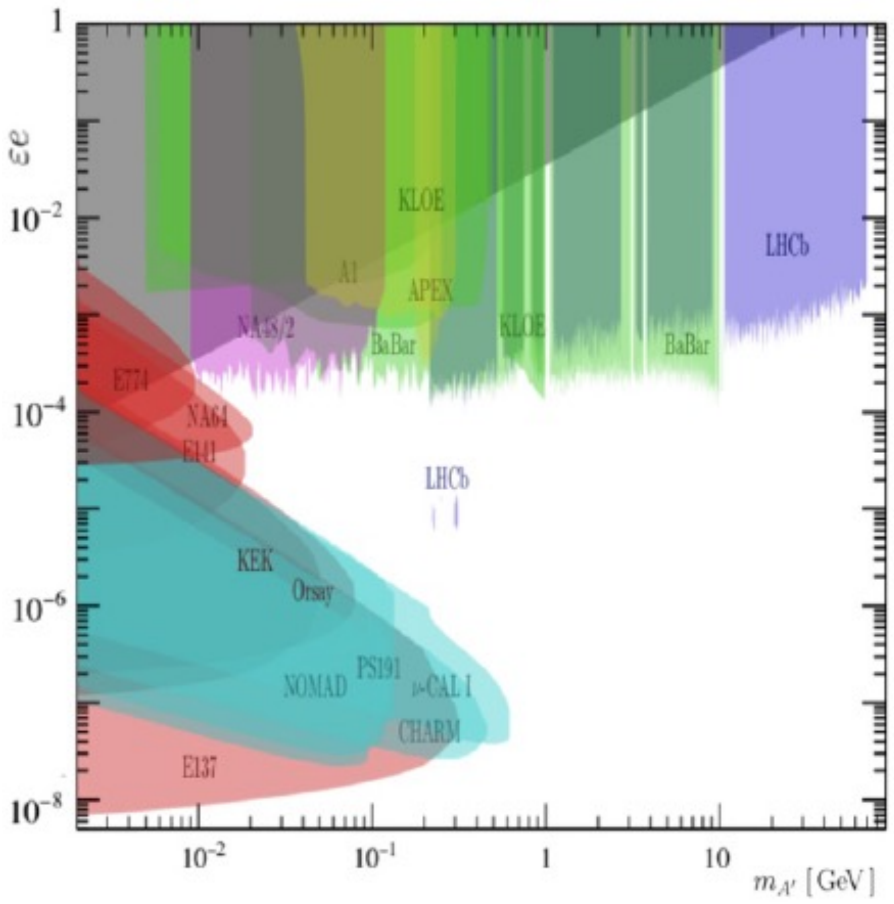


Invisibly Decaying Dark Photon $A' \to \bar{\chi}\chi$

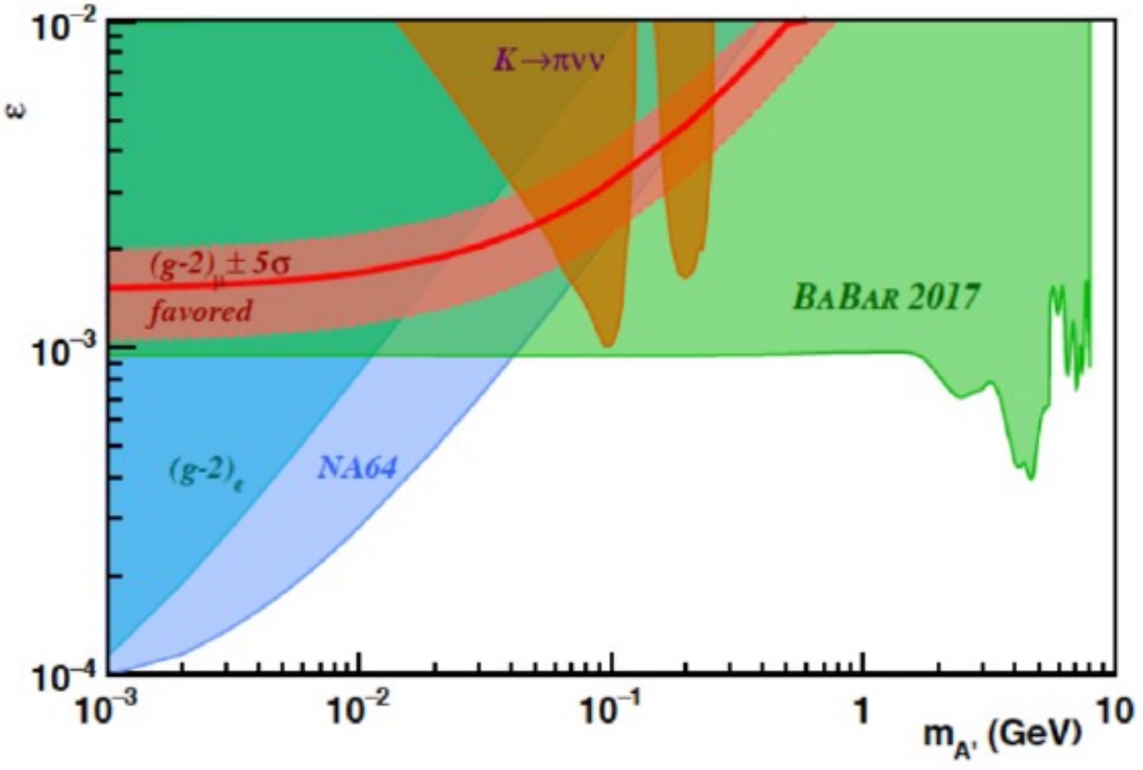


Status of exclusion

Visible decays



Invisible decays



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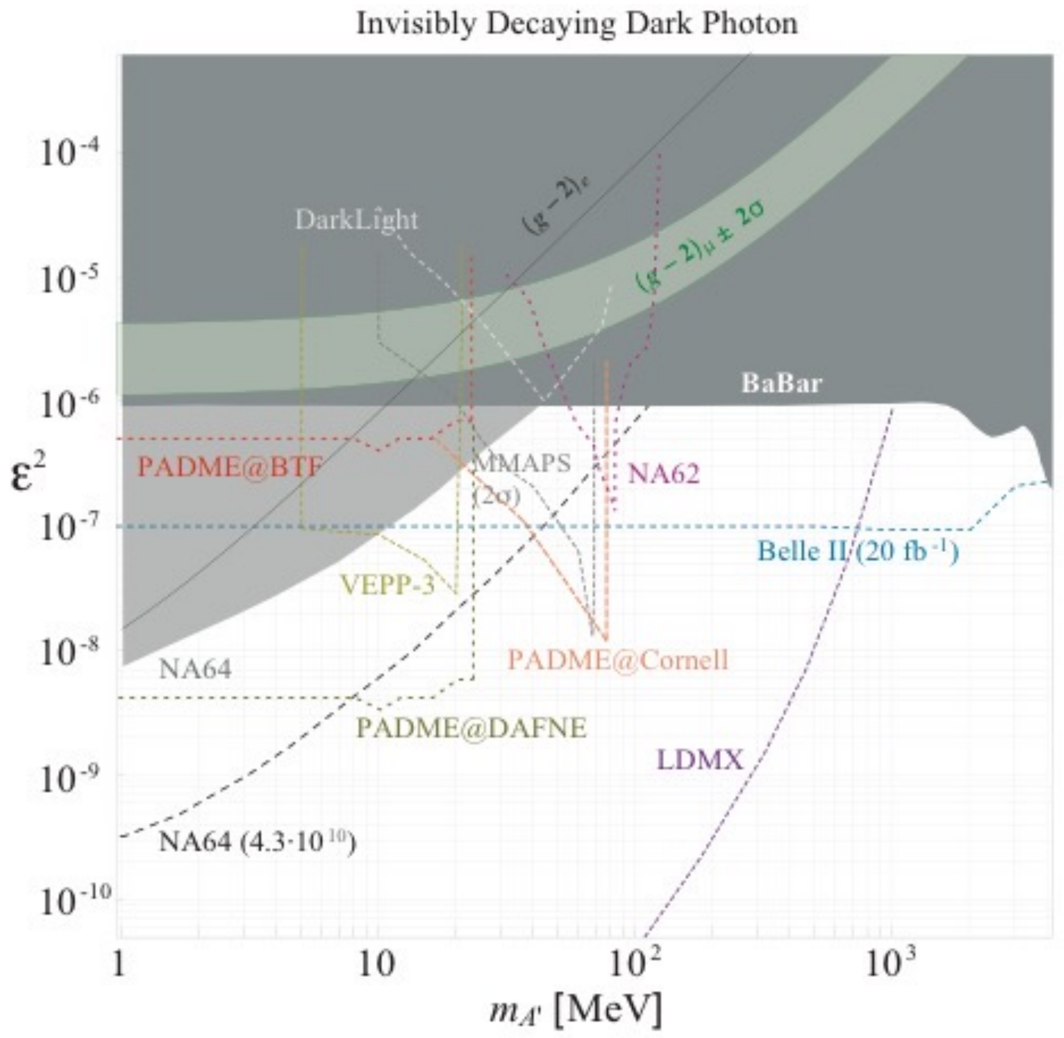
PADME prospects



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