Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati


# THE PADME SCIENTIFIC PROGRAM

P.Gianotti on behalf of the PADME collaboration

# Outline

- Dark Matter hunting
- Frascati Lab
- Dark Matter production with positron beam
- The PADME experiment
- Status, plans and prospects

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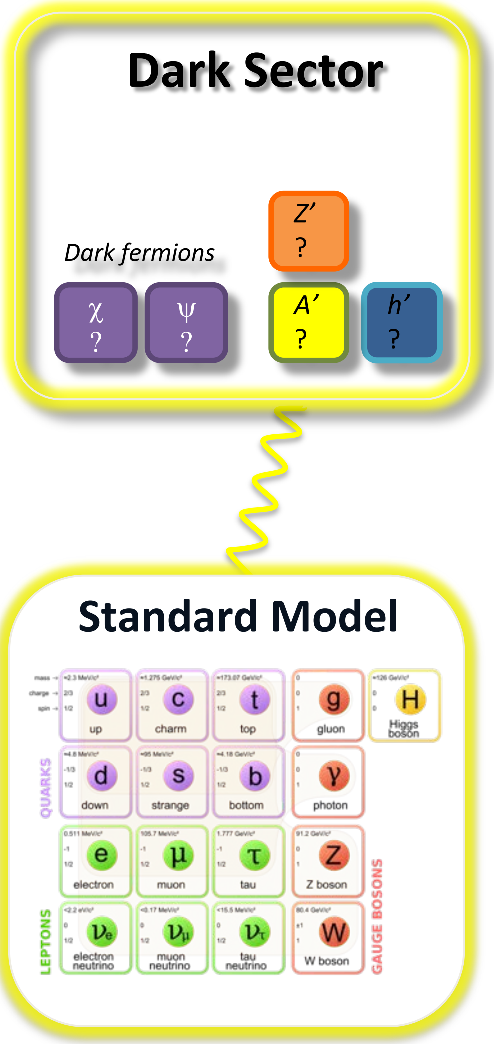
# *New Forces*

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

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

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

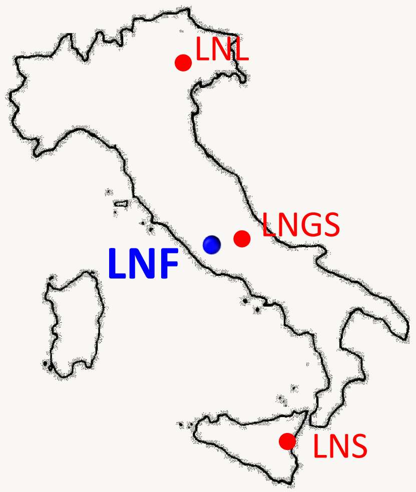
The ***A'*** could itself be the **mediator** between the **visible** and the **dark sector** mixing with the ordinary photon. The effective interaction between the fermions and the dark photon is parametrized in term of a factor ε representing the mixing strength.



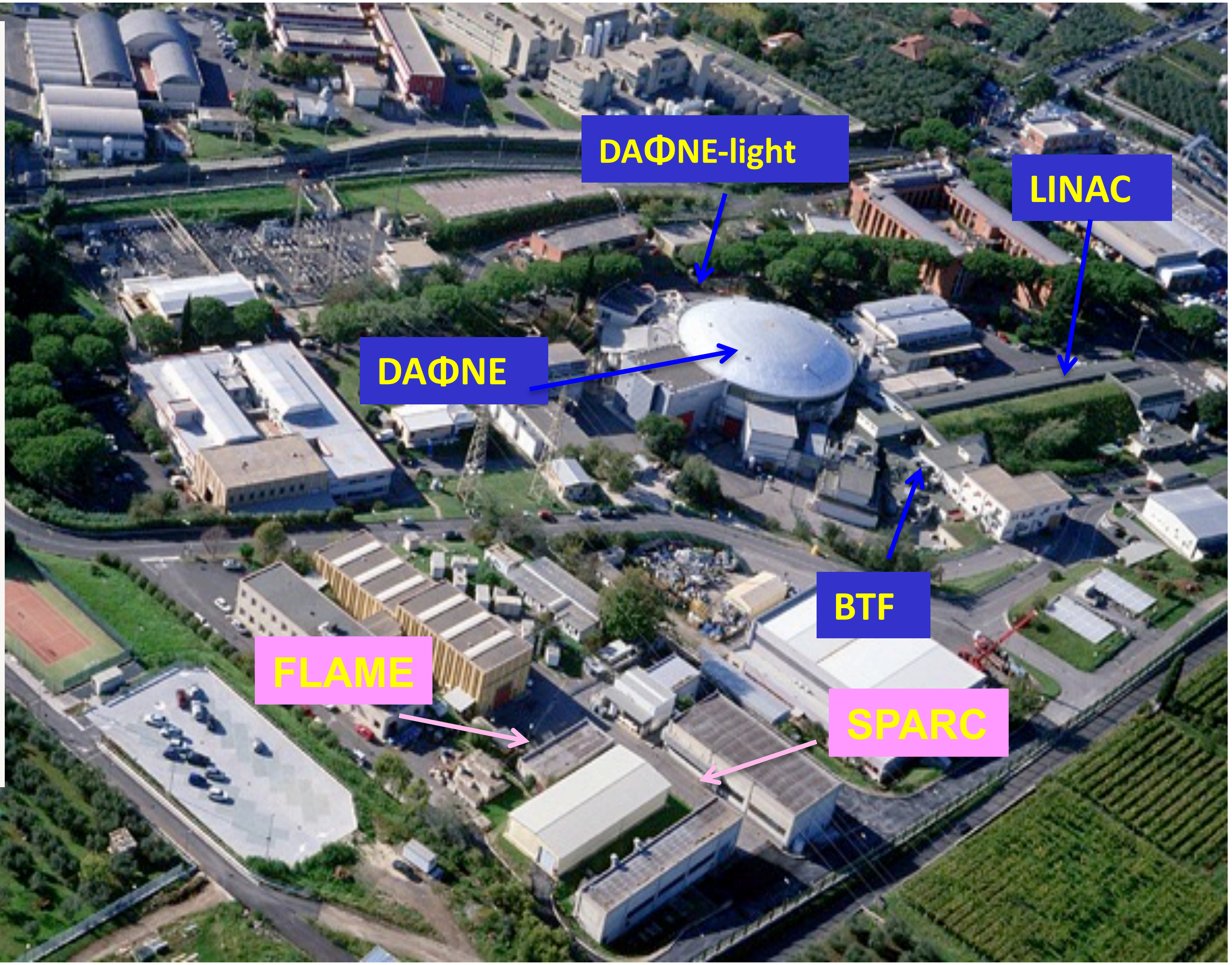

**The search for this new mediator *A'* is the goal of the PADME experiment at LNF.**

# 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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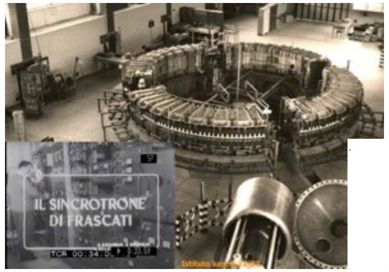
# The LNF accelerators history

Electron Synchrotron
(1959-1975) E=1 GeV




LNF-54/48 (1954)

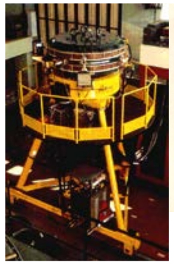
**Il progetto italiano di un elettrosincrotone.**

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 |

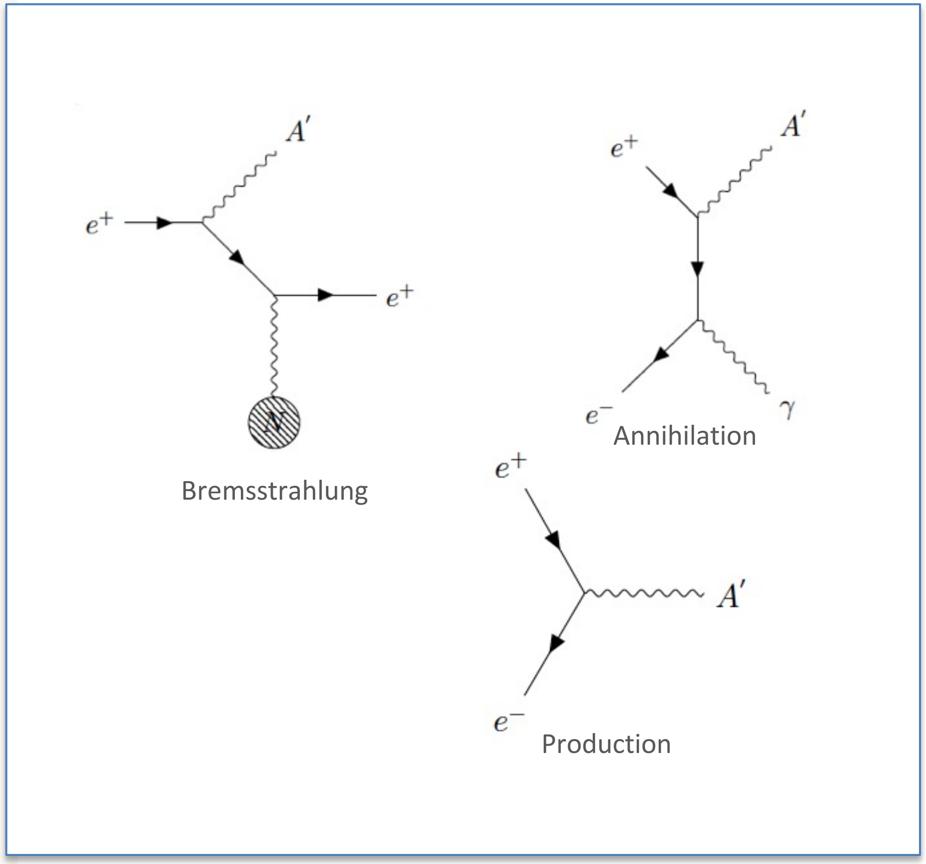
# *A′ production and decay*

*A′* can be produced using $e^+$:

- In $e^+$ collision on target via:
  - Bremsstrahlung: $e^+N \rightarrow e^+NA'$
  - Annihilation: $e^+e^- \rightarrow \gamma A'$
  - Direct production

For the *A′* decay modes 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 $\chi$ with $2M_\chi < M_{A'}$
  - *A′* will dominantly decay into pure DM
  - $BR(l^+l^-)$ suppressed by factor $\varepsilon^2$
  - $A' \rightarrow \chi\chi \sim 1$. These are the so called **"invisible"** decays



# The PADME experiment

PADME main goal is to produce A’ via

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

For the *A’* decay modes

The first phase of the experiment foresees to investigate **“invisible”** decays

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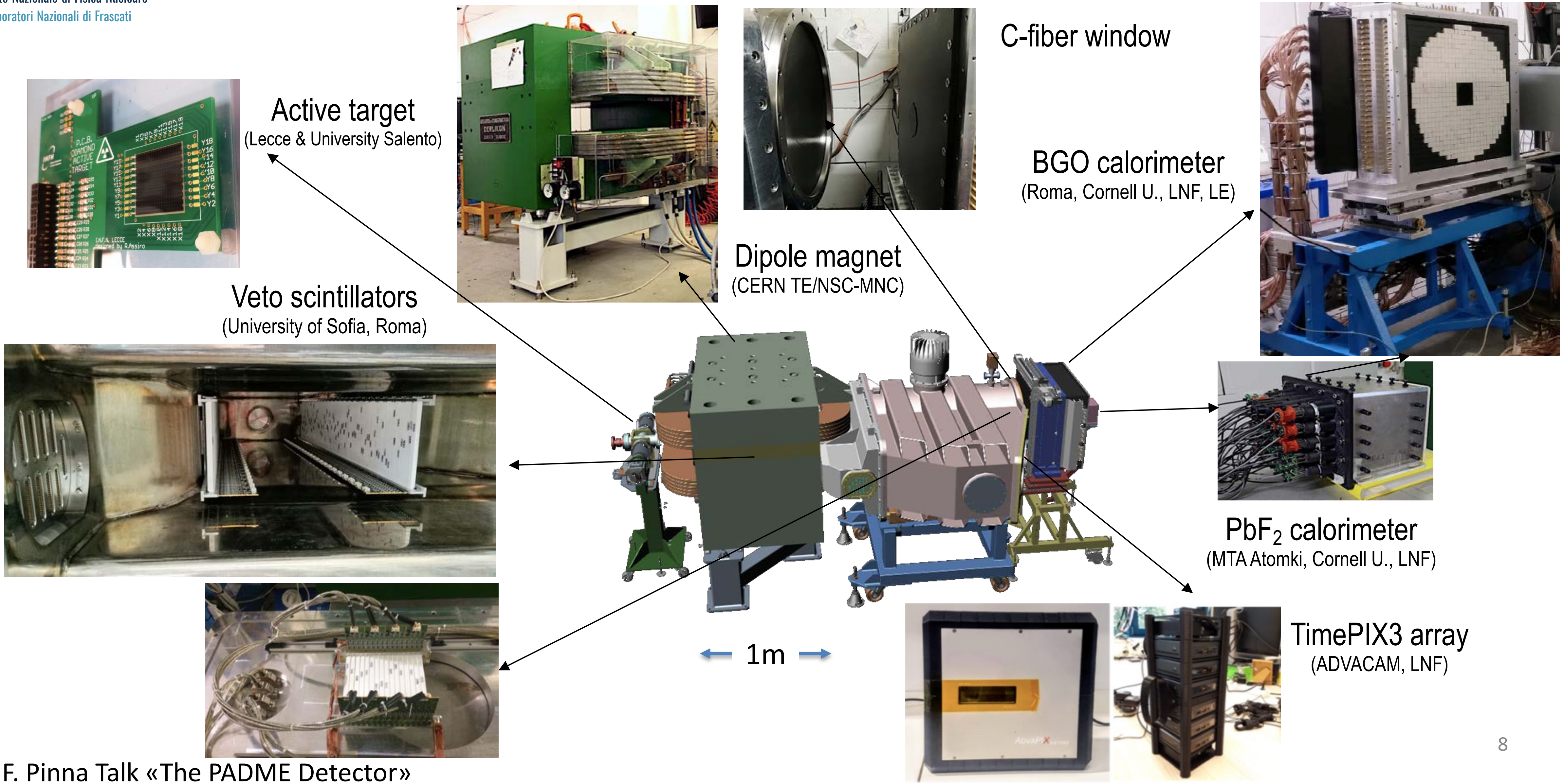
# *The PADME detector in a nutshell*

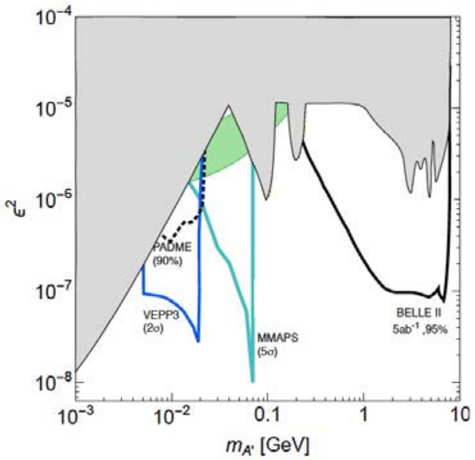



See F. Pinna Talk «The PADME Detector»

# Dark sector studies at PADME

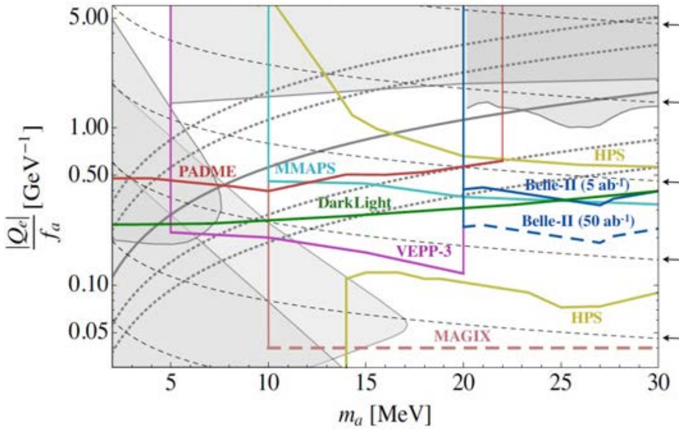
There other items related to the DM issue that can be addressed by PADME

Dark Photon A’
arXiv:1608.08632v1



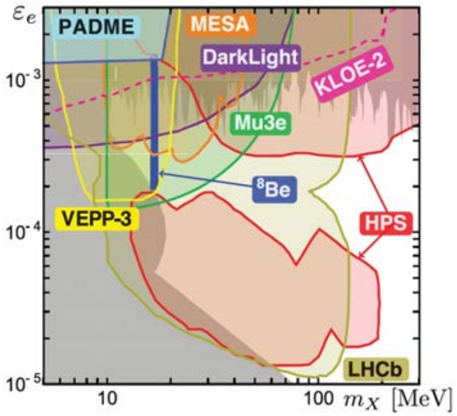

$e^+e^- \rightarrow \gamma A'$
Visible, invisible decays:
$A' \rightarrow \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092



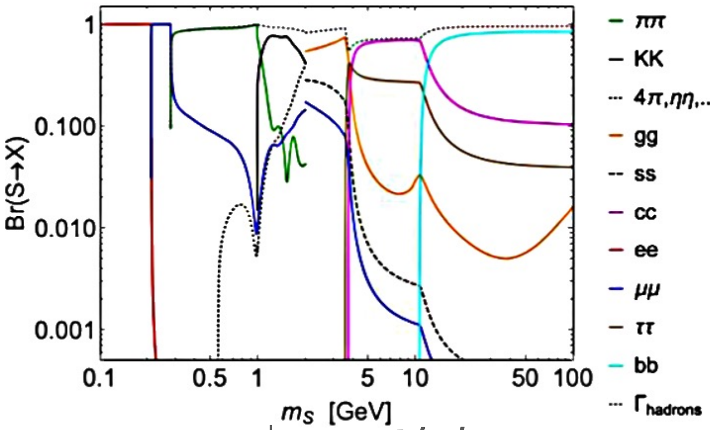

$e^+e^- \rightarrow \gamma a$
ALPs final states:
$a \rightarrow \chi\bar{\chi}, e^+e^-, \gamma\gamma$

BE anomaly - X boson
PRD 95 (2017) 035017




$e^+e^- \rightarrow \gamma X_{17}$
Final state X17→ee

Dark higgs
arXiv:2102.12143v1




$e^+e^- \rightarrow h'A'$
dark higgs decay: $h' \rightarrow A'A', A' \rightarrow e^+e^-, \chi\bar{\chi}$
Final state: $A'A'A' \rightarrow e^+e^-\ e^+e^-\ e^+e^-$

# SM Physics at PADME

QED cross sections in the region 100 MeV-1GeV are poorly known. PADME has the opportunity to make some measurements:

- $e^+e^- \to \gamma\gamma$: ~$10^7$ candidates/year.
  By product of luminosity and $A$' invisible search
  Needed also to compute absolute calorimeter energy scale

- $e^+e^- \to \gamma\gamma\gamma$: ~$10^4$-$10^5$ candidates/year.
  BG to invisible $A$' decays

- $e^+e^- \to e^+e^-$:
  Can be used as luminosity reference to crosscheck target and timepix
  Huge statistics but may have problems with pile-up at 25K$e^+$

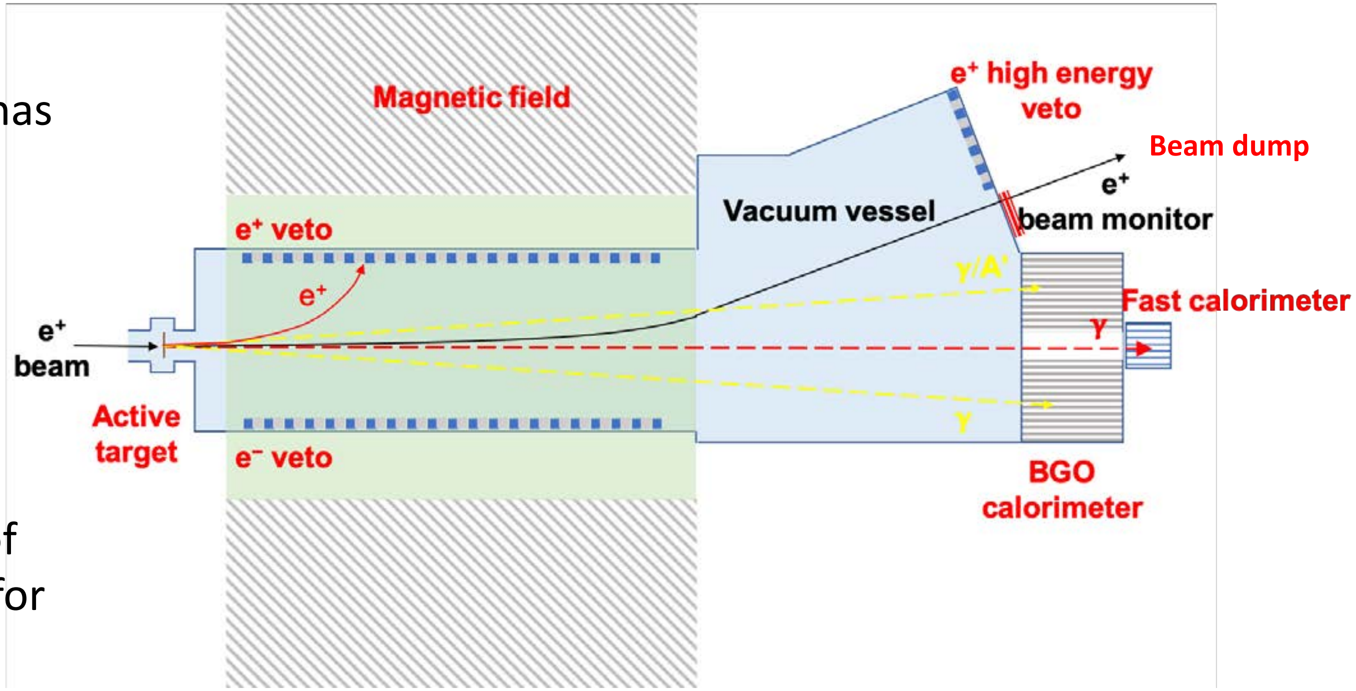
- $e^+e^- \to e^+e^-e^+e^- e^+e^-$:
  Unknown SM cross section not trivial to compute (too many diagrams)
  Difficult to be measured due to acceptance issues (P track too low)
  Background for Dark Higgs searches need to be evaluated

# 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.

# A’ production at PADME

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 if predominantly decays into dark sector particles $\chi\bar{\chi}$ .

**Know $e^+$ beam momentum and position**

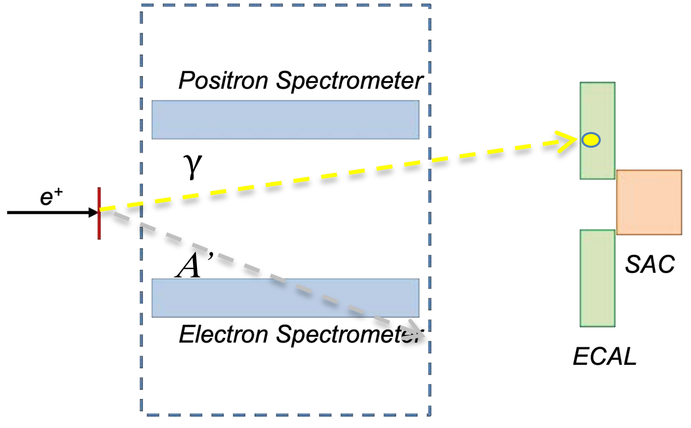
- Tunable intensity (in order to optimize annihilation vs. pile-up)

**Measure the recoil photon position and energy**

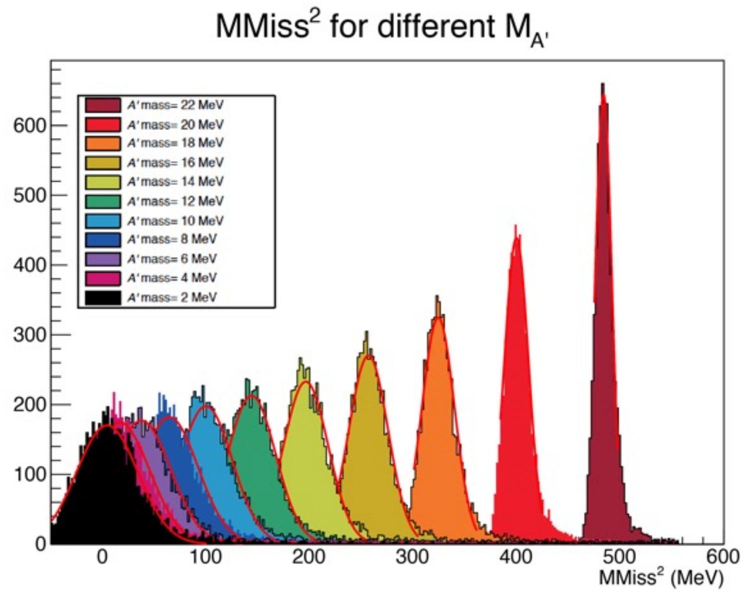
Calculate $M^2{}_{miss} = (\bar{P}_{e^+} + \bar{P}_{e^-} - \bar{P}_\gamma)^2$

Only minimal assumption: $A'$ couples to leptons

$$\sigma(e^+e^- \to \gamma A') = 2\epsilon^2\sigma(e^+e^- \to \gamma\gamma).$$




$$e^+e^- \to \gamma\ (E_{miss})$$



# Expected results

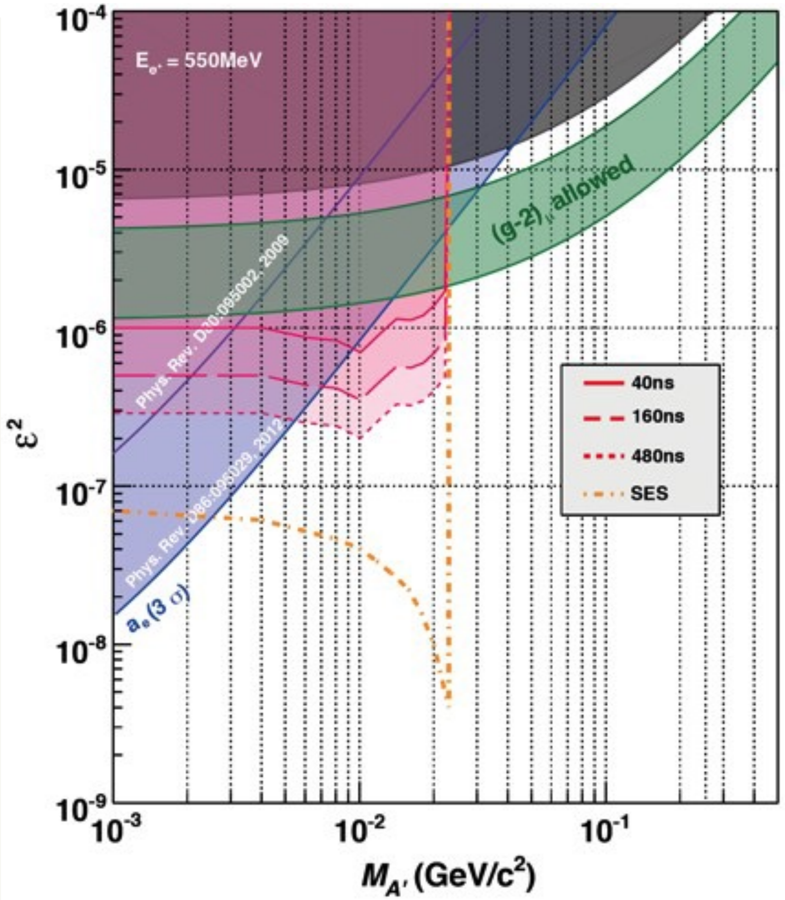
The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.

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.

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

With a 60% efficiency and a bunch length of 200 ns
$4 \times 10^{13}$ POT = 20000 $e^+$/bunch x2 x$3.1 \times 10^7$s x 0.6x49 Hz

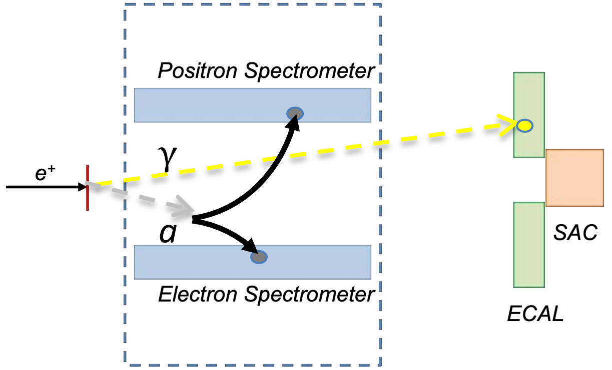
$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \cdot \delta$$

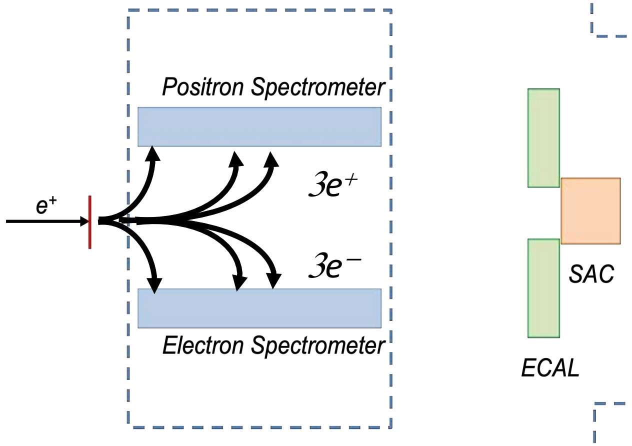


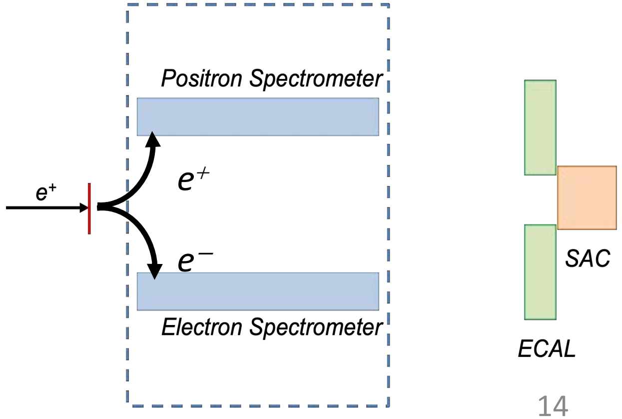
# Other dark sector studies

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



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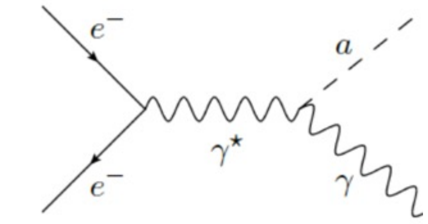
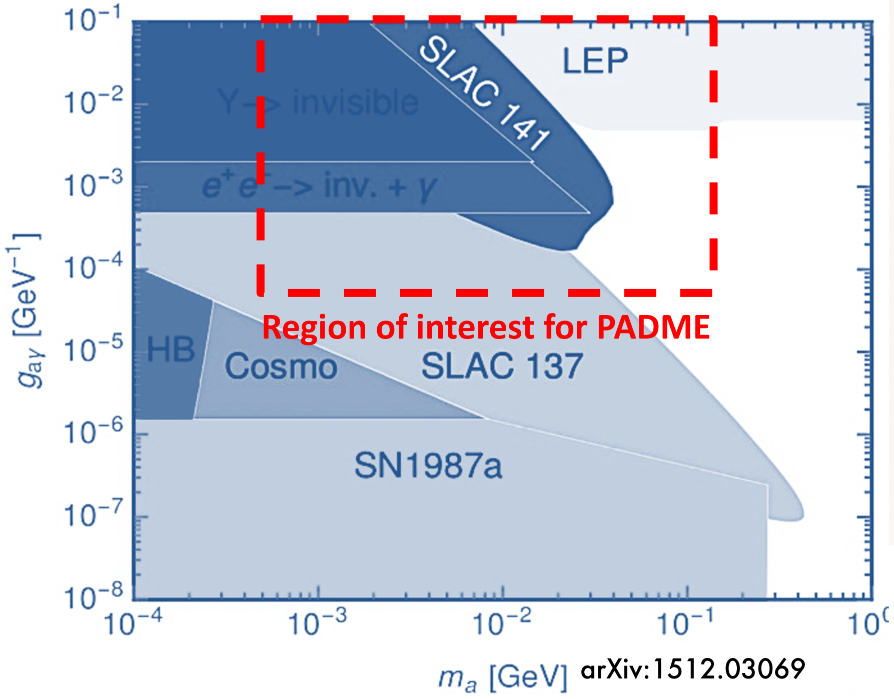
# *Axion Like Particles*

PADME can search for long living ALPs produced in electron positron annihilation through a virtual off-shell photon.




In the mass region < 100 MeV, $a$ is long lived and would manifest via missing mass

**Limits on ALPs coupling to photons**

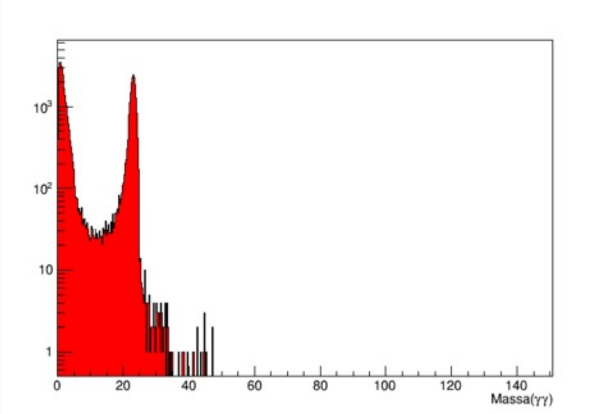



arXiv:1512.03069

In the visible decay mode $a \to \gamma\gamma$, even without any selection cut, PADME will be background free for masses > 50MeV.

Other accessible final states:

- $a \to e^+e^-$
- $a \to \chi\bar{\chi}$ same signature of dark photon



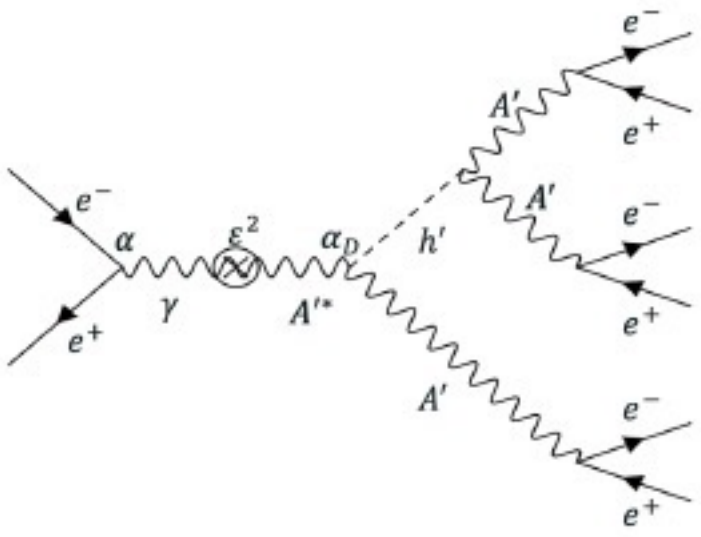
# Dark Higgs

$e^+e^- \to h'A' \to 3(e^+e^-)$ under the hypotheses :

- $m_{h'} < 2m_{A'}; m_{A'} > 2m_e$
- $\sigma_{h'A'} \sim 1000$ pb $[\sigma_{e^+e^-} \to 3(e^+e^-) \sim 1500$ pb$]$

PADME could produce ~ 150 *h'* in one year data taking.

[arXiv:2012.04754]




Even a modest BG rejection obtained with the present PADME veto system, will allow the dark sector to become the dominant process

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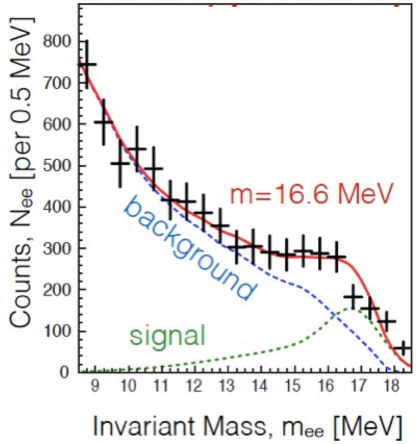
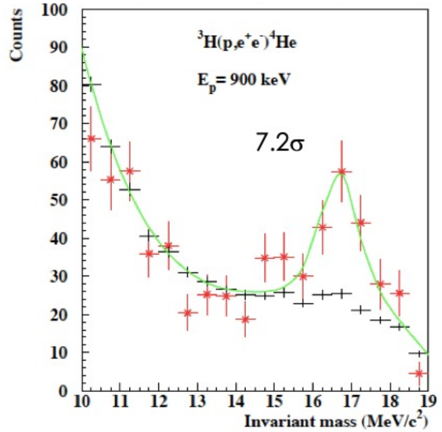
# *The $^{8}$Be anomaly*

The study of atomic transitions of light nuclei has evidenced an anomaly in the decay of $^{8}$Be and $^{4}$He.

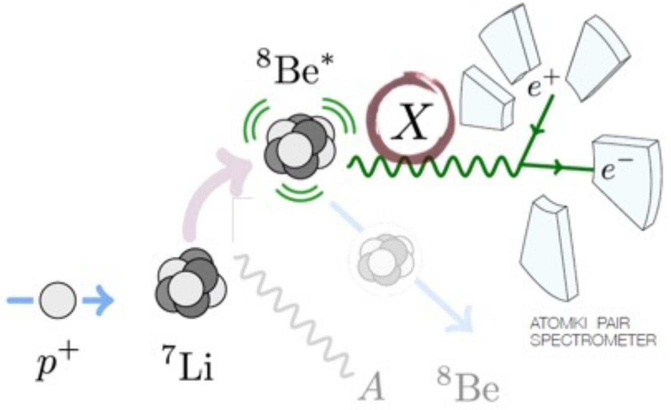
$m_X = 16.7 \pm 0.35(stat) \pm 0.5(sys) MeV$ $m_X = 16.90 \pm 0.12(stat) \pm 0.21(sys) MeV$




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




Is the X a signal of a dark particle?

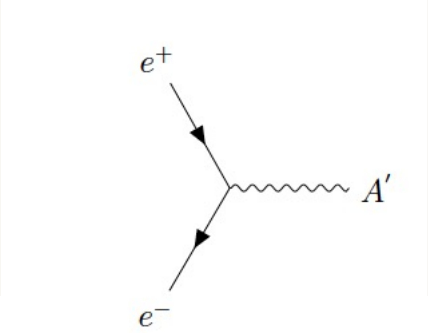



E. Nardi *et al.*, **"Resonant production of dark photons in positron beam dump experiments"** Phys.Rev. D97 (2018) no.9, 095004

Setting the e$^{+}$ beam at 282.7 MeV might lead to the observation of the resonant production of the X.
Several uncertainties:

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

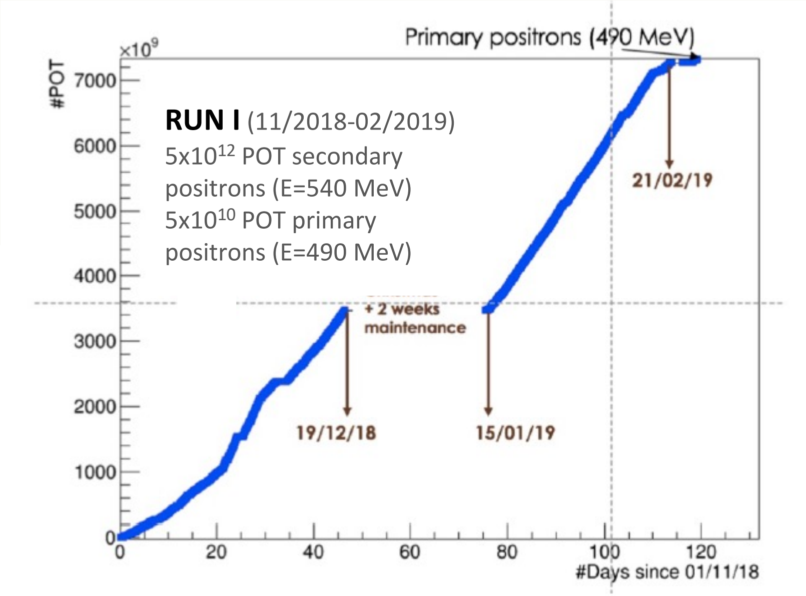
The idea is an interesting opportunity that will be explored by PADME next year.

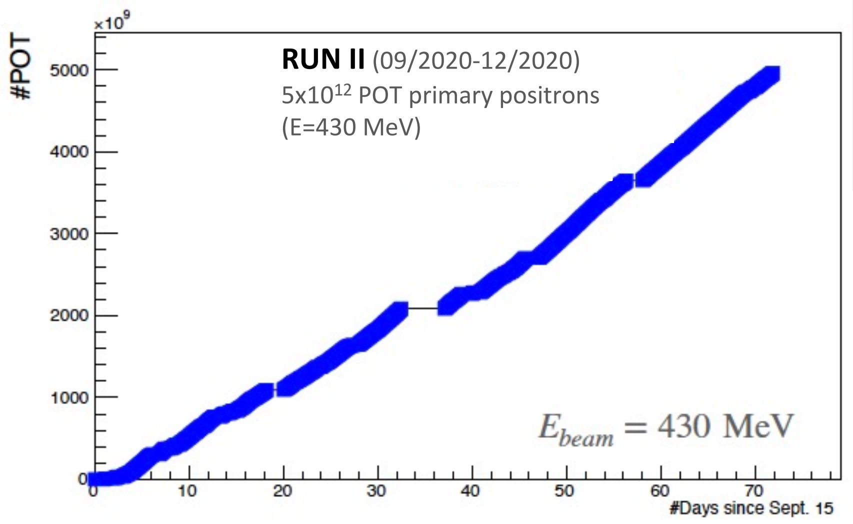


# PADME initial physics program

The PADME physics program started October 2018 with detector commissioning/calibration and beam tuning. Two run periods: RUN I (Oct.18-Feb.19); RUN II (Sep.20-Dec.20).

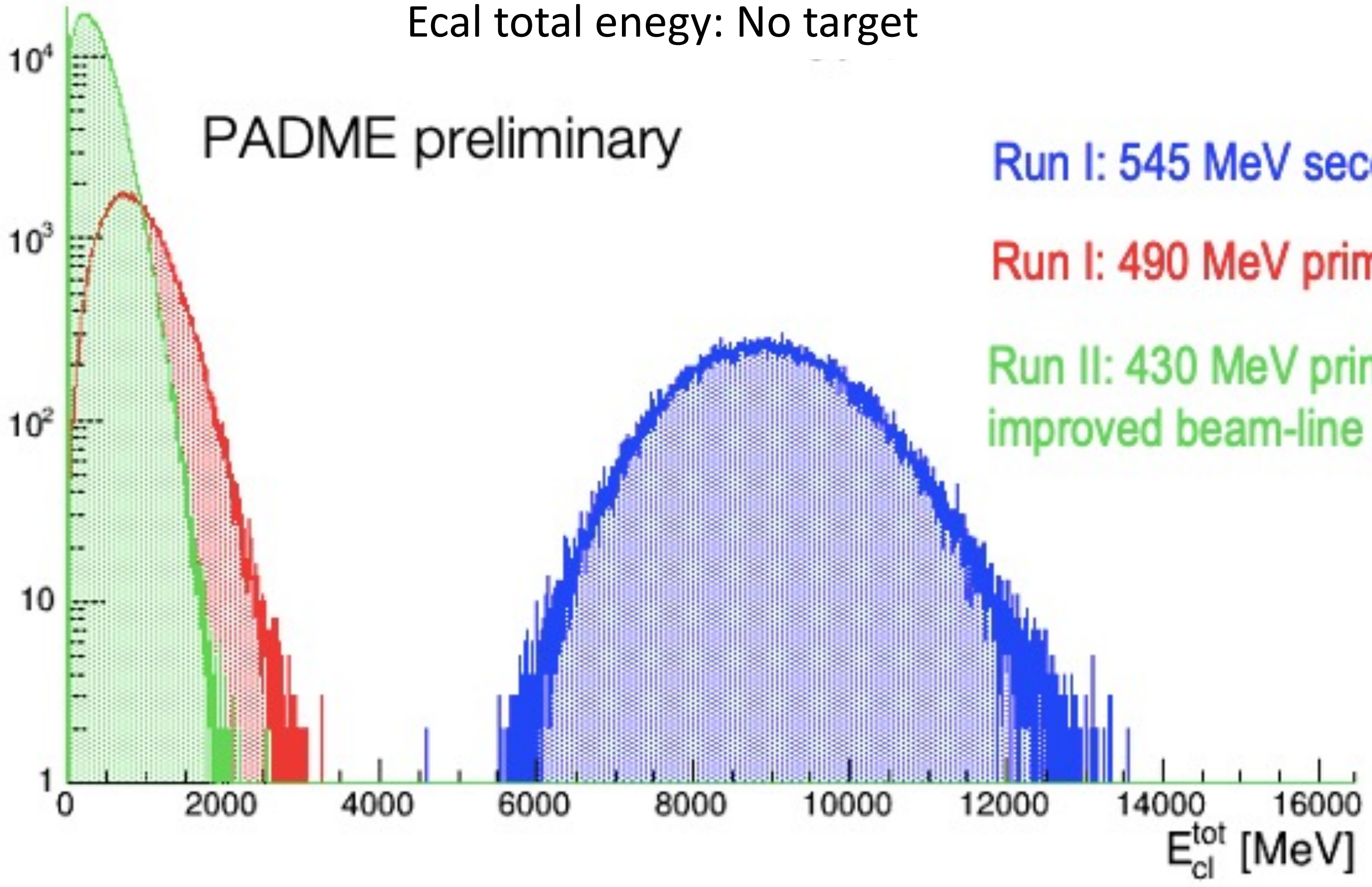
- Background understanding:
  - – Multiphoton annihilation e+e- → γ γ, e+e- → γ γ γ, e+e- → γ γ γ γ, ….
  - – Bremsstrahlung in the field of the nuclei – lack of experimental data in the range of O(100 MeV), precision of GEANT4 - ~ (3-4) %
  - – Photon emission in the field of orbital electrons



# Background studies

Ecal total enegy: No target

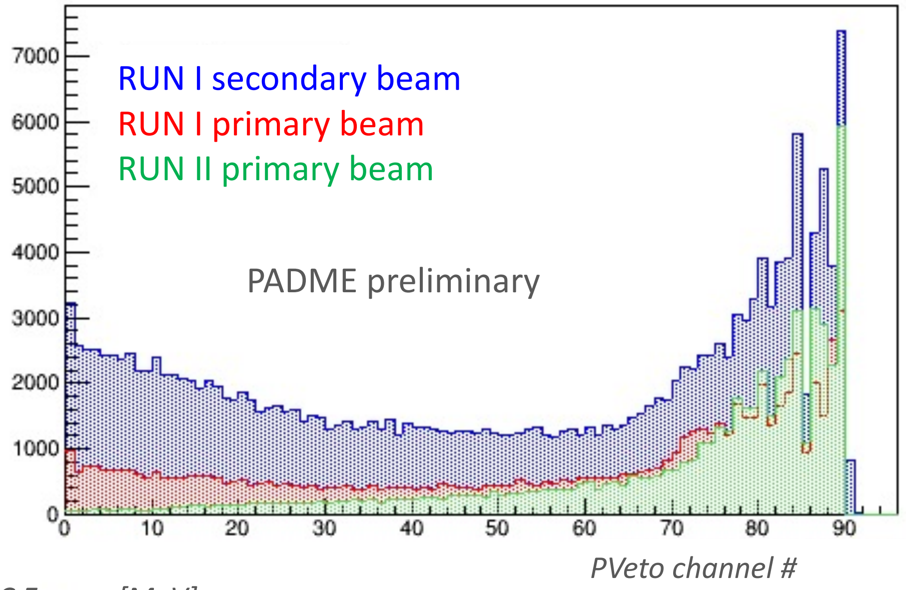


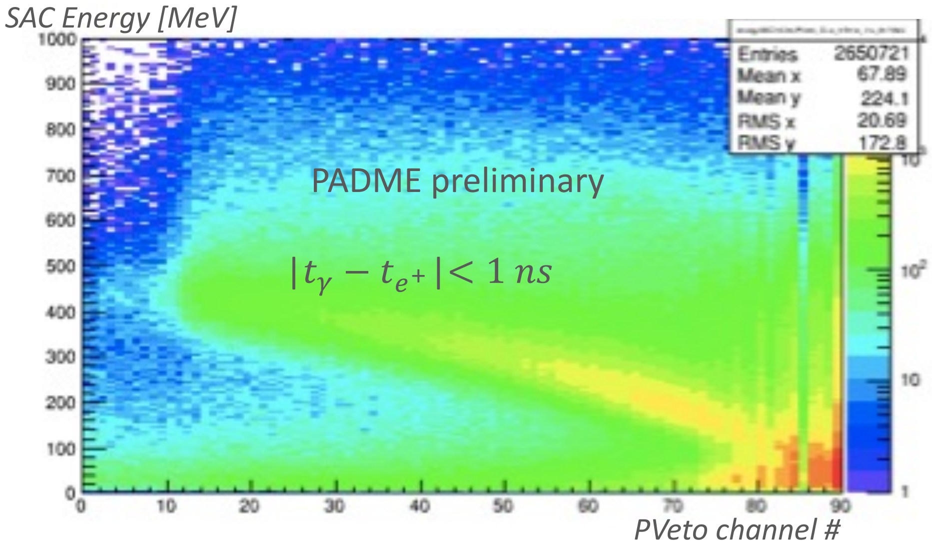

Background index:

| | |
|---|---|
| Run I: 545 MeV secondary, 25k e+, 250 ns | 0.36 MeV/$e^+$ |
| Run I: 490 MeV primary, 25k e+, 250 ns | 0.03 MeV/$e^+$ |
| Run II: 430 MeV primary, 28k e+, 280 ns improved beam-line | 0.013 MeV/$e^+$ |

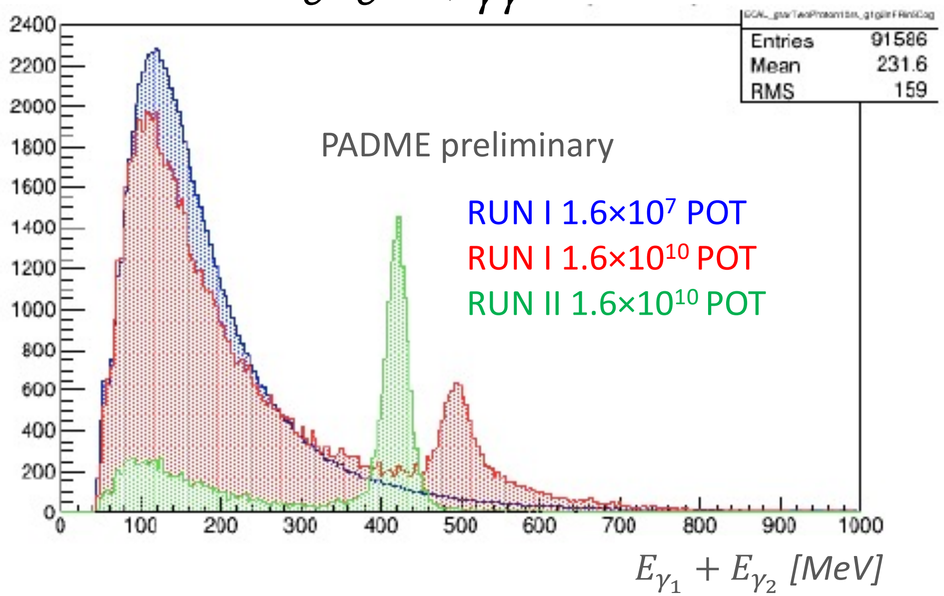
# PADME SM studies

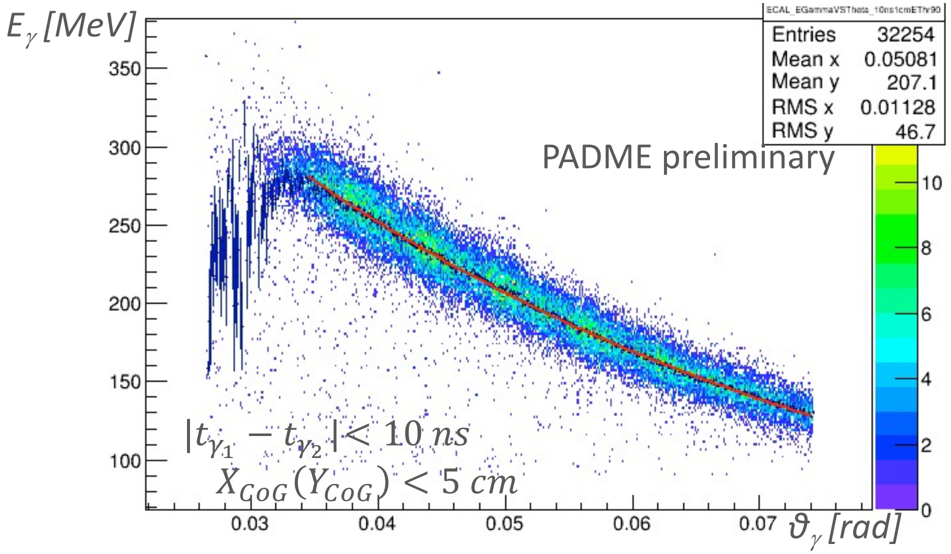
$e^+N \rightarrow e^+\gamma$




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



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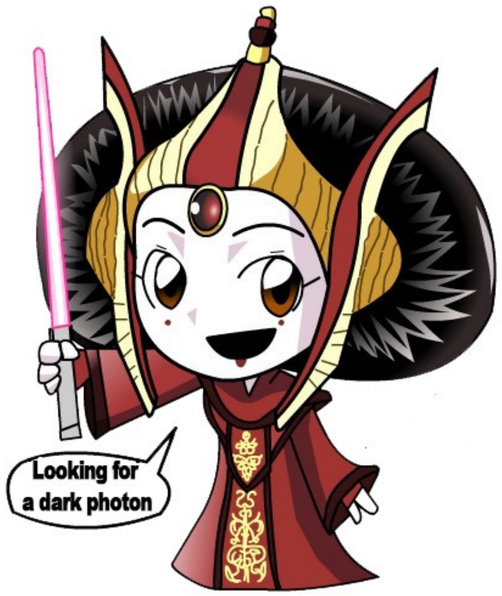
# Conclusions

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

- PADME is the first experiment to study the reaction $e^+e^- \to \gamma A'$, $A \to \chi\chi$ with a model independent approach;
- Data analysis is ongoing;
- Many physics items can be explored:
  - visible dark photon decays, ALPs searches, Fifth force, dark Higgs, X17 boson

PADME is starting to explore the DARK SECTOR…



# Backup

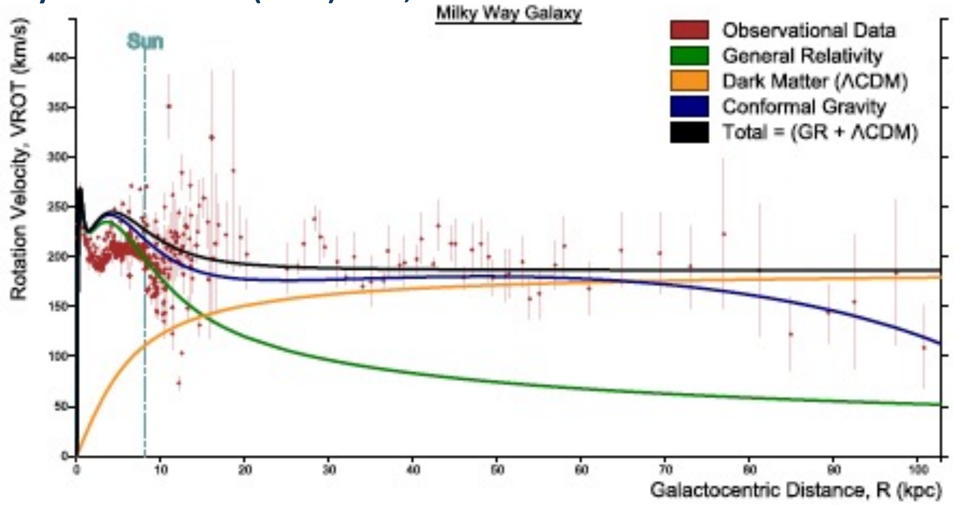
# The Dark Matter issue

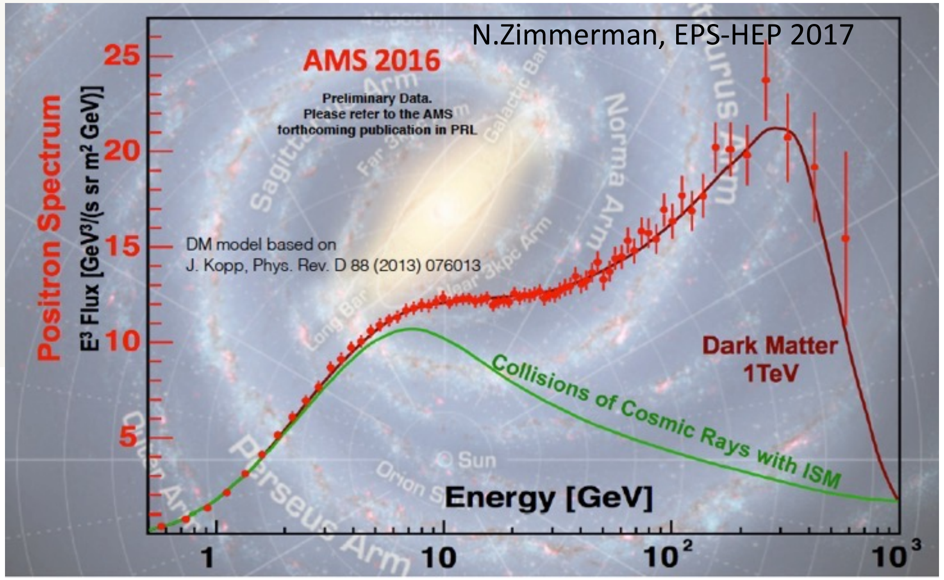
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

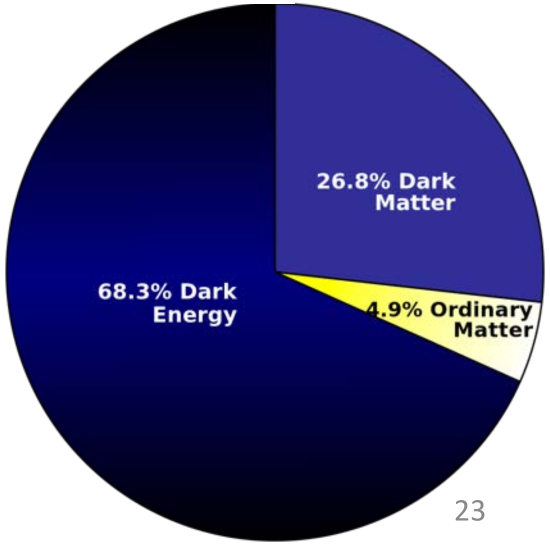
The abundance of this new entity is 5 times larger than SM particles.

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

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



# The Nature of Dark Matter

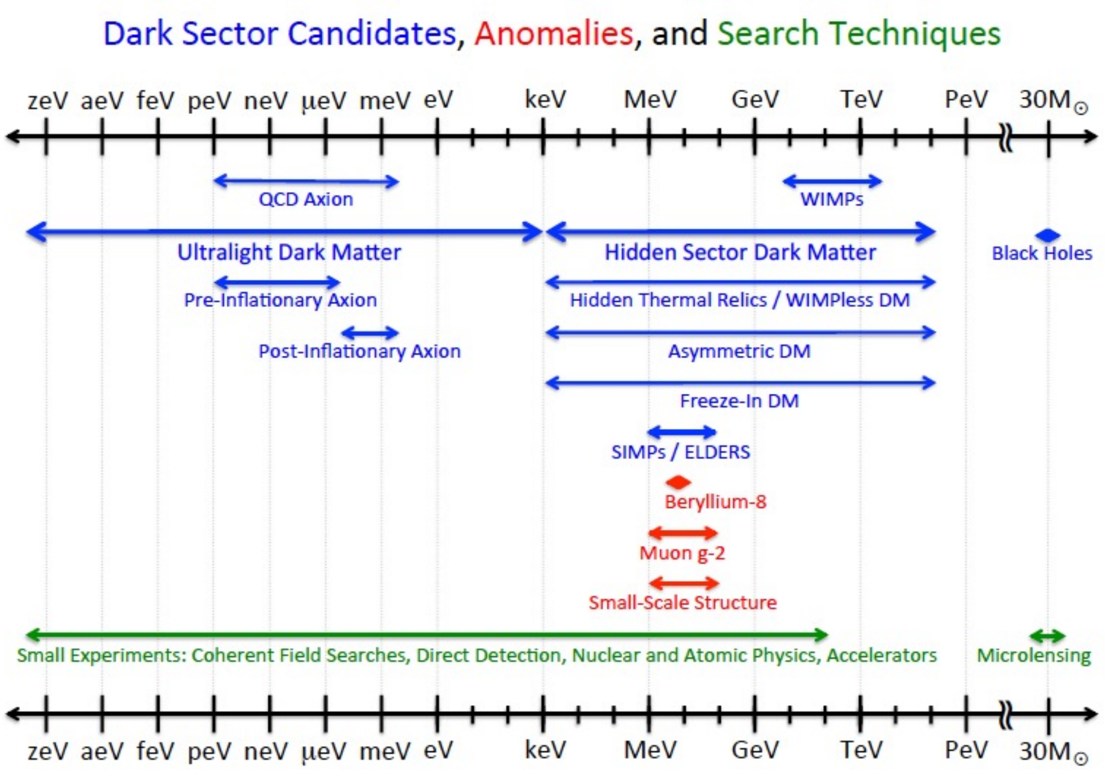
Despite its abundance, we don't yet know what is made of.

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.**

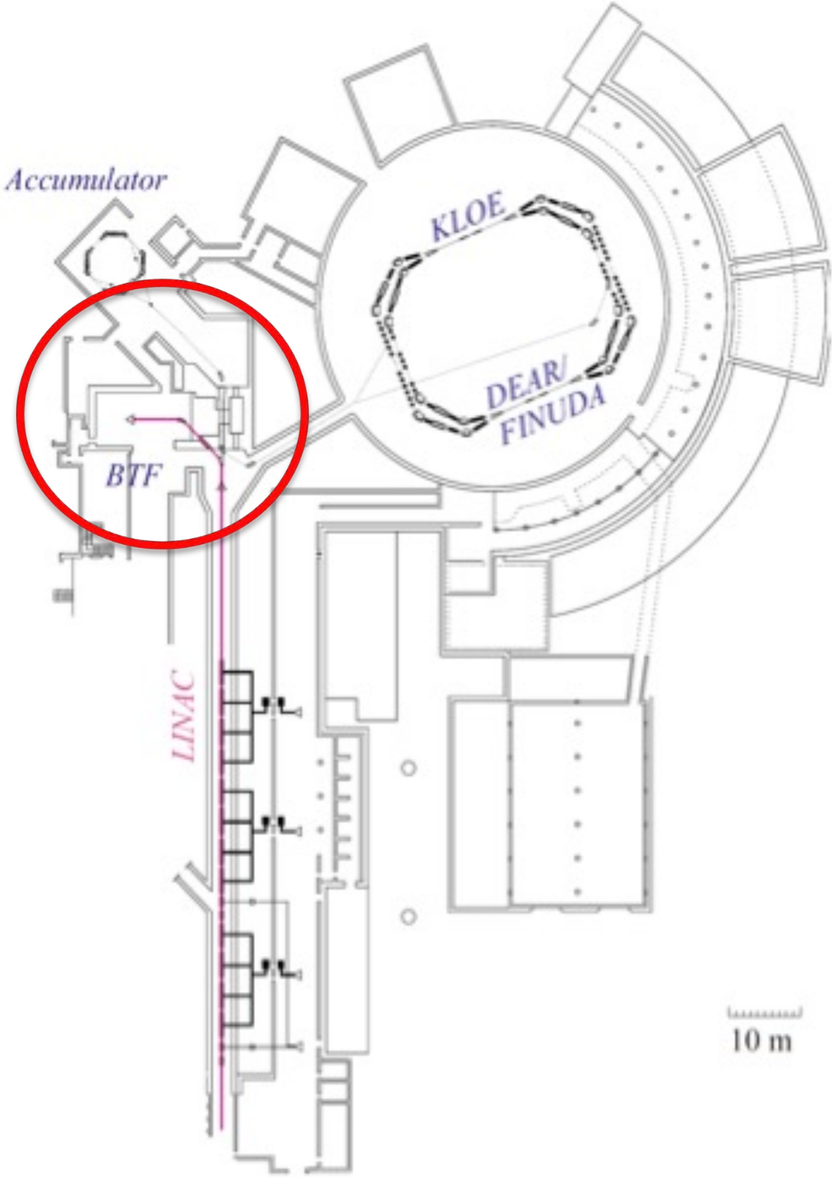



arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

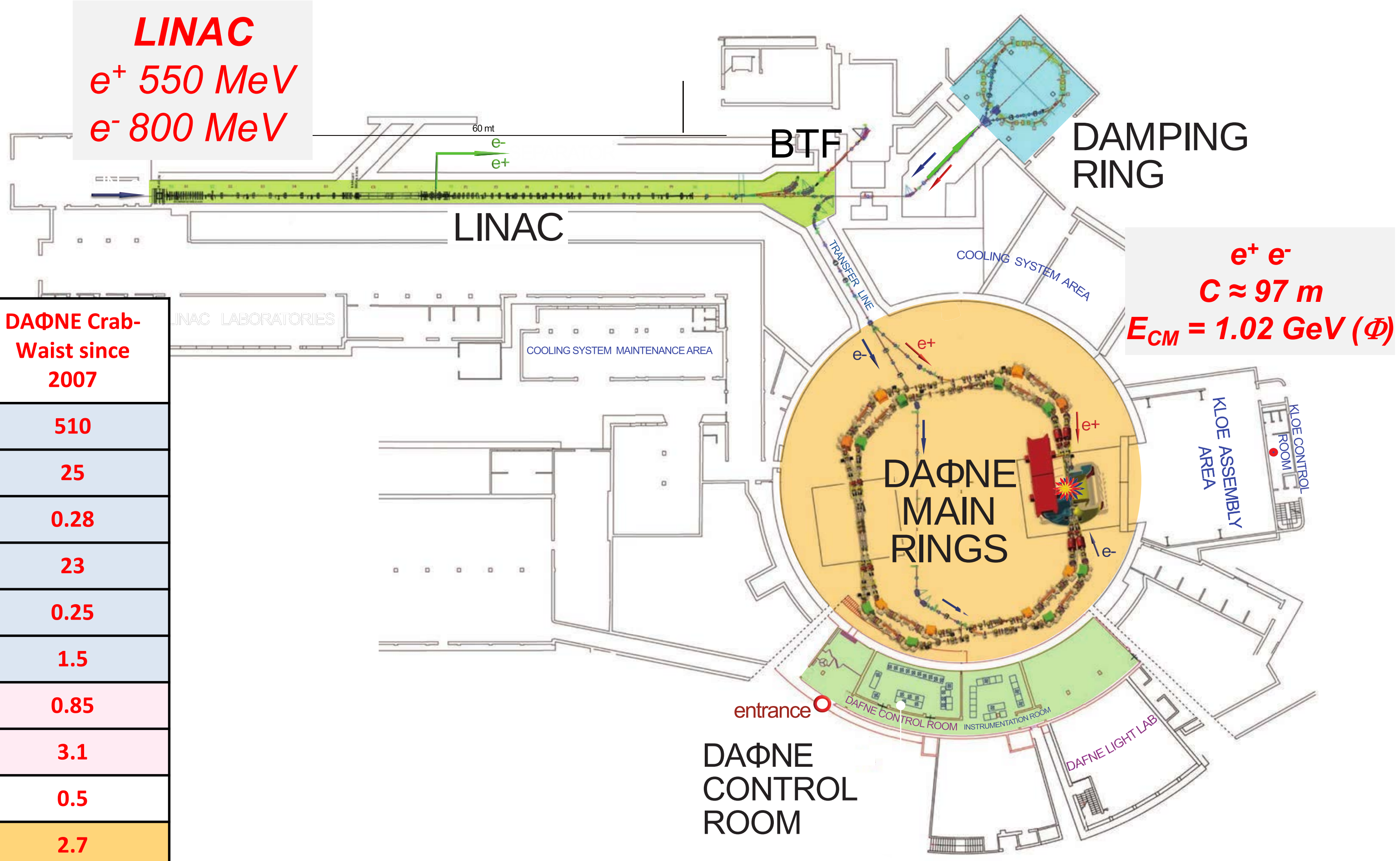
# LNF LINAC beam line

| | 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 $\sigma$ [mm] | <1 mm | |
| Beam divergence | 1-1.5 mrad | |

- Able to provide electrons and positrons
  - Duty cycle 50*40 ns= $2\times10^{-7}$ 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 |
| $\varepsilon_x$ [mm·mrad] | 0.34 | 0.28 |
| $\beta_x^*$ [cm] | 160 | 23 |
| $\sigma_x^*$ [mm] | 0.7 | 0.25 |
| $\Phi_{piwinski}$ | 0.6 | 1.5 |
| $\beta_y^*$ [cm] | 1.80 | 0.85 |
| $\sigma_y^*$ [μm] low current | 5.4 | 3.1 |
| Coupling [%] | 0.5 | 0.5 |
| Bunch spacing [ns] | 2.7 | 2.7 |
| $I_{bunch}$ [mA] | 13 | 13 |
| $\sigma_z$ [mm] | 25 | 15 |
| $N_{bunch}$ | 120 | 120 |

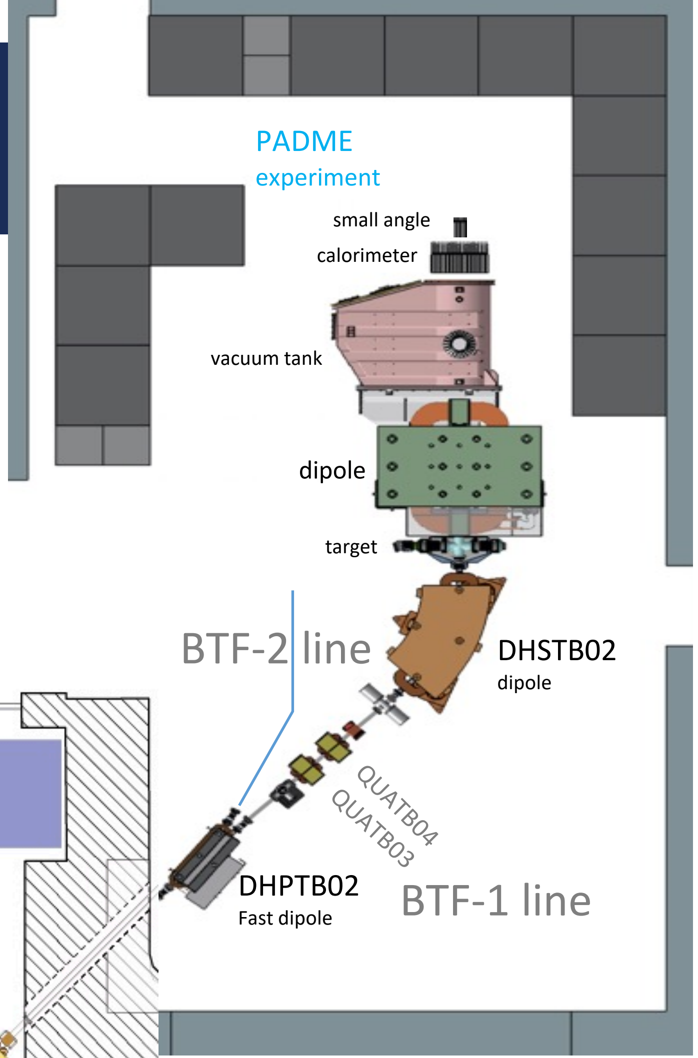
DAΦNE implemented succesfully a new kind of beam-beam interaction: the Crab-Waist collision scheme

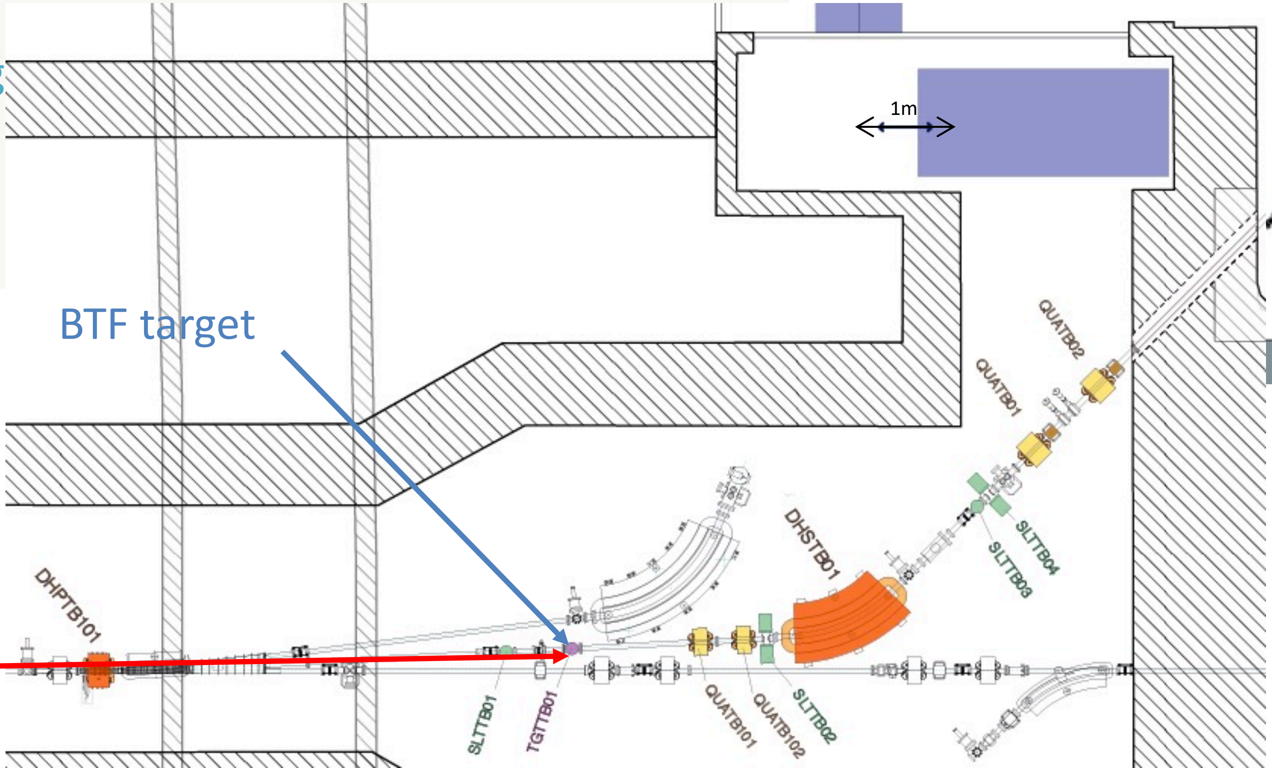
# PADME beam line

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.



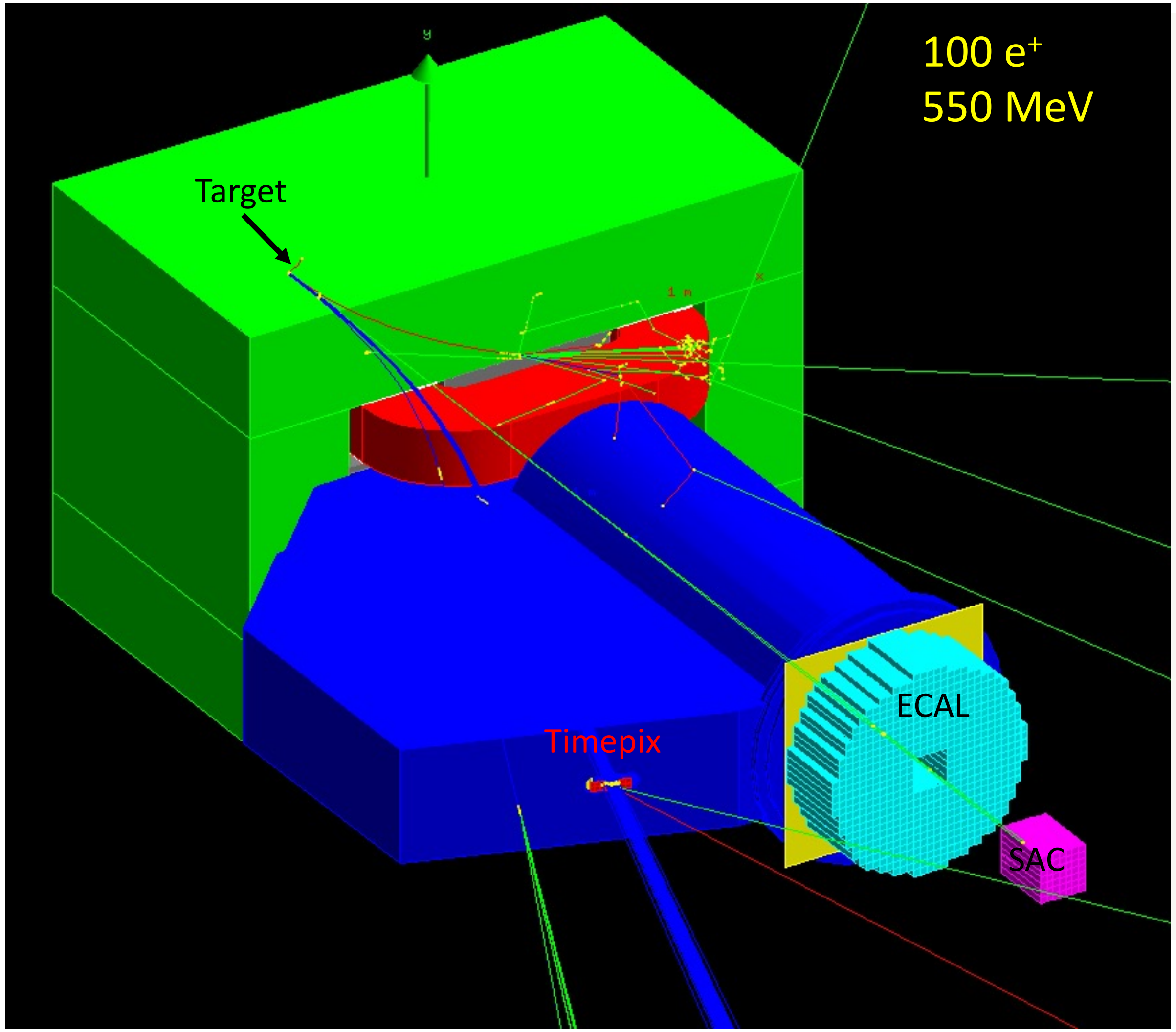




Primary beams
750 MeV $e^-$
550 MeV $e^+$

Positron beam parameters:

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

# Monte Carlo simulations



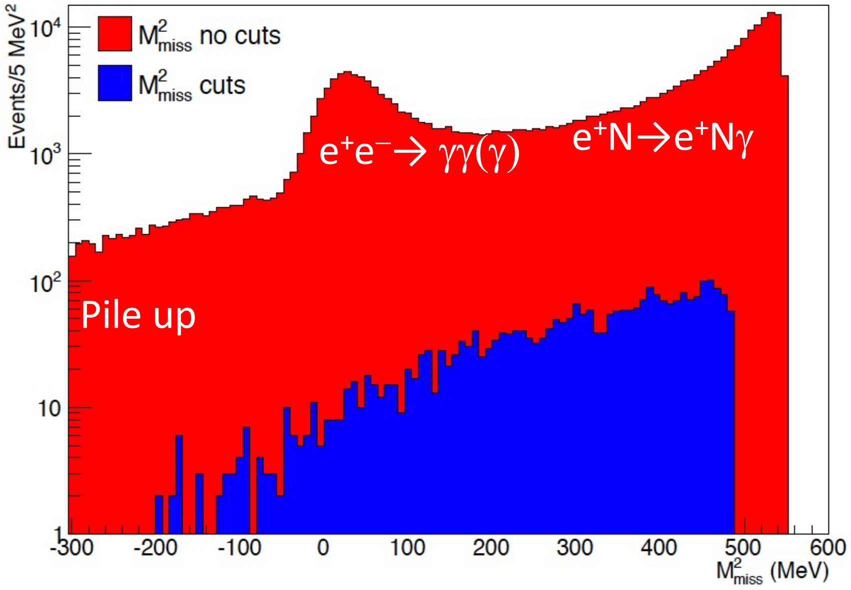

**MC simulations main components**

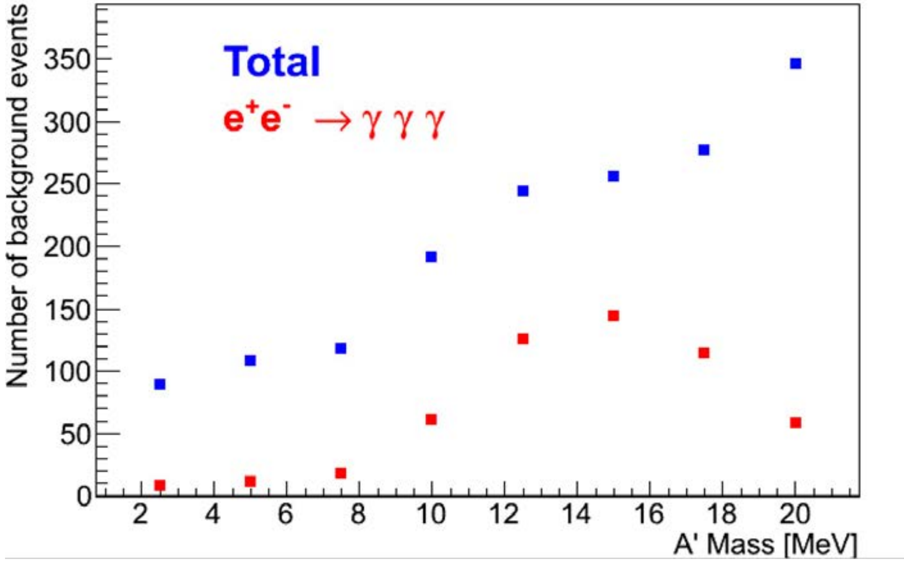
- $e^+$ on target simulated in GEANT4
  - Dedicated MC $e^+e^- \to \gamma\gamma(\gamma)$ CalcHEP
- Dedicated *A'* annihilation generator
- Need fast simulation to get $10^{11}$ evt
  - Showers in the SAC not simulated
  - Beam dumping not simulated

- Realistic treatment of the beam
  - Energy spread, emittance, micro-bunching, and beam spot
- Final geometry for all detectors implemented
  - Measured magnetic field map
- Major passive materials implemented
- Complete detector digitization

# 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

# Background cross-sections

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

| Background process | $\sigma$ ($E_{beam}$ = 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 |

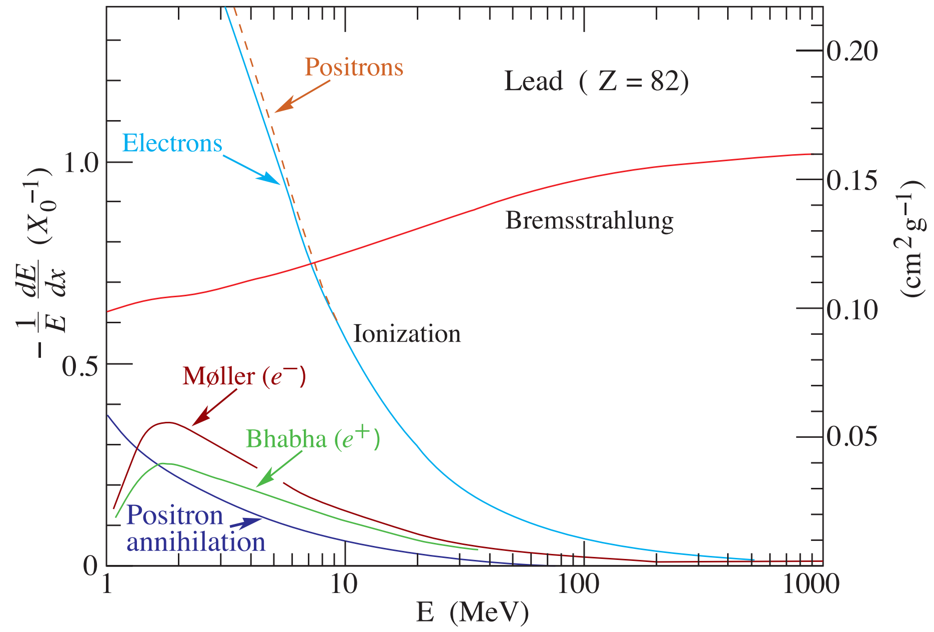
# Different experiments exploiting missing mass technique

| | PADME | MMAPS | VEPP3 |
|---|---|---|---|
| Place | LNF | Cornell | Novosibirsk |
| Beam energy | 550 MeV | Up to 5.3 GeV | 500 MeV |
| $M_{A'}$ limit | 23 MeV | 74 MeV | 22 MeV |
| Target thickness [$e^-/cm^2$] | $2 \times 10^{22}$ | $O(2 \times 10^{23})$ | $5 \times 10^{15}$ |
| Beam intensity | $8 \times 10^{-11}$ mA | $2.3 \times 10^{-6}$ mA | 30 mA |
| $e^+e^- \to \gamma\gamma$ rate [$s^{-1}$] | 15 | $2.2 \times 10^6$ | $1.5 \times 10^6$ |
| $\epsilon^2$ limit (plateau) | $10^{-6}$ | $10^{-6}$ - $10^{-7}$ | $10^{-7}$ |
| Time scale | 2017-2018 | ? | 2020 (ByPass) |
| Status | Approved | Not funded | Proposal |

Both MMAPS and VEPP3 will use CsI crystals from CLEO.

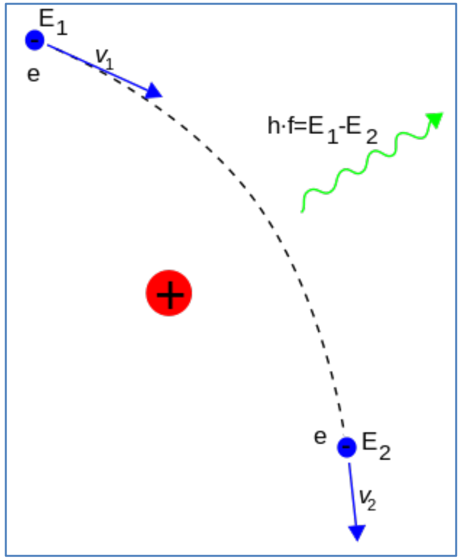
$\sigma(E)/E = 3\%/\sqrt{E}$ @ 180 MeV

# Bremsstrahlung

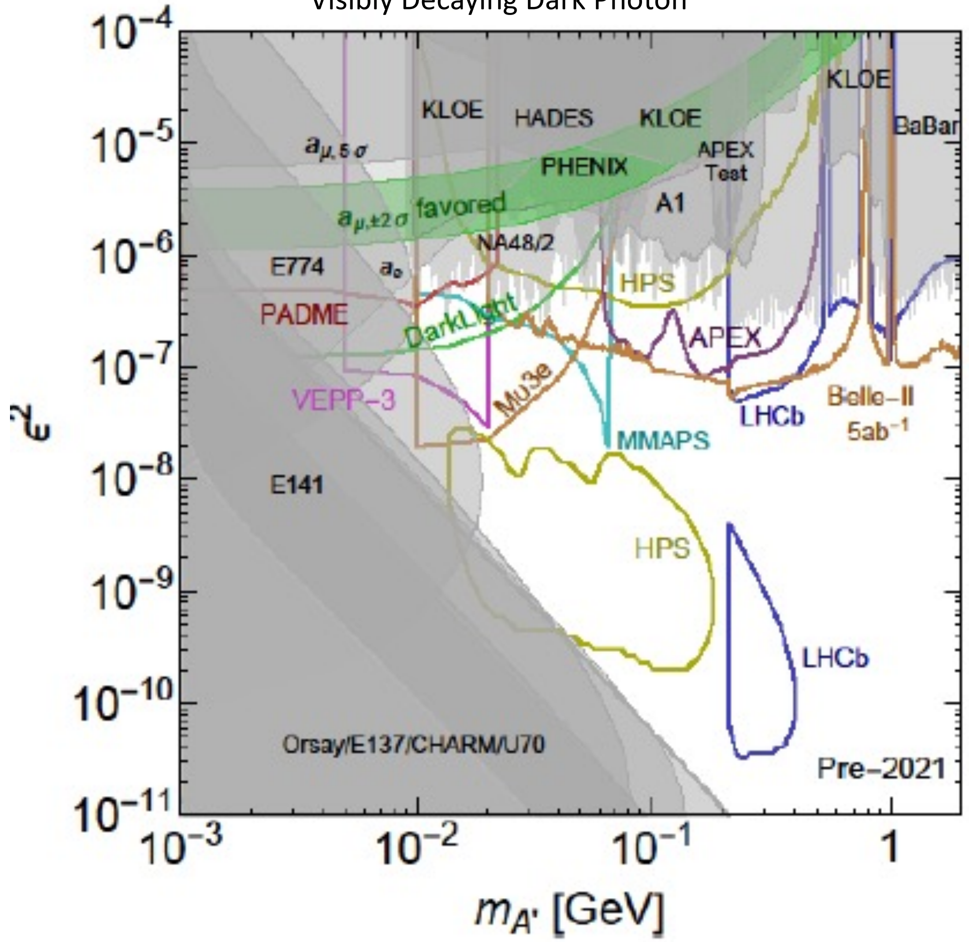


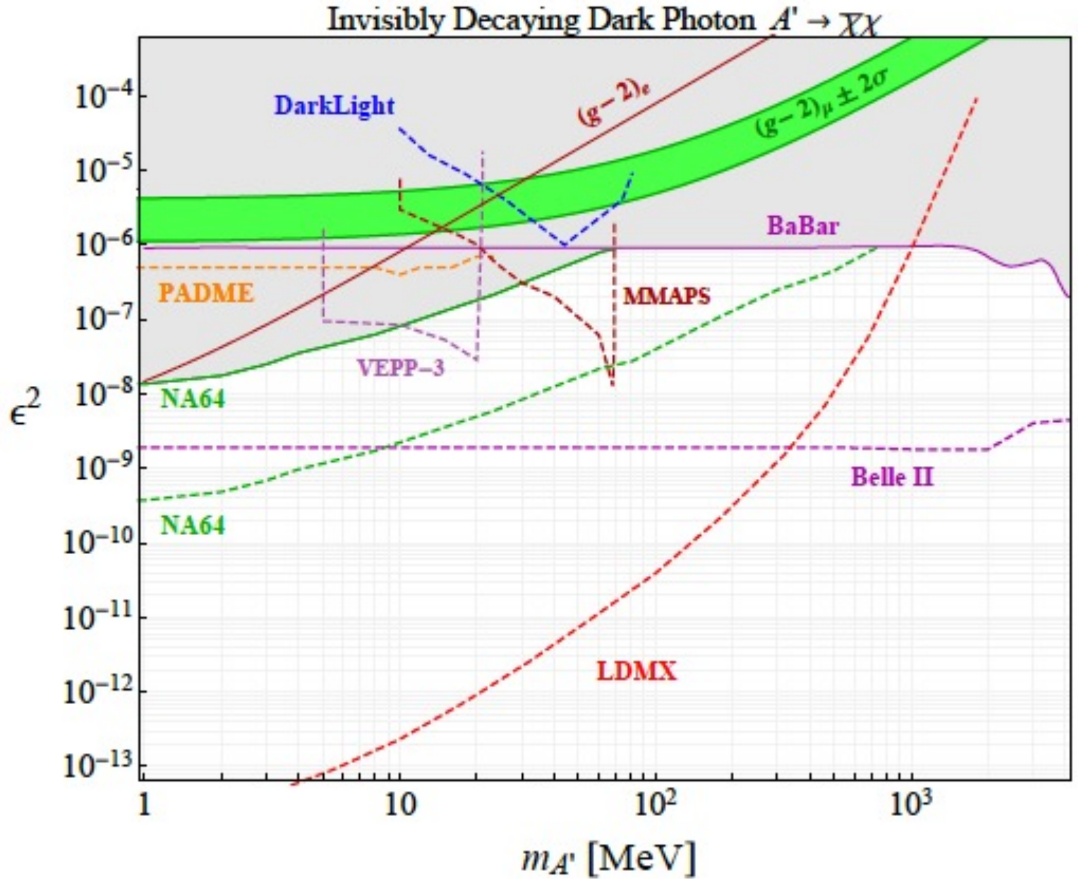

$$-\langle\frac{dE}{dx}\rangle \approx \frac{4N_a Z^2 \alpha^3 (\hbar c)^2}{m_e^2 c^4} E \ \ln\frac{183}{Z^{1/3}}$$

$N_a$ number of atoms per unit of volume,
Z atomic number



Visibly Decaying Dark Photon

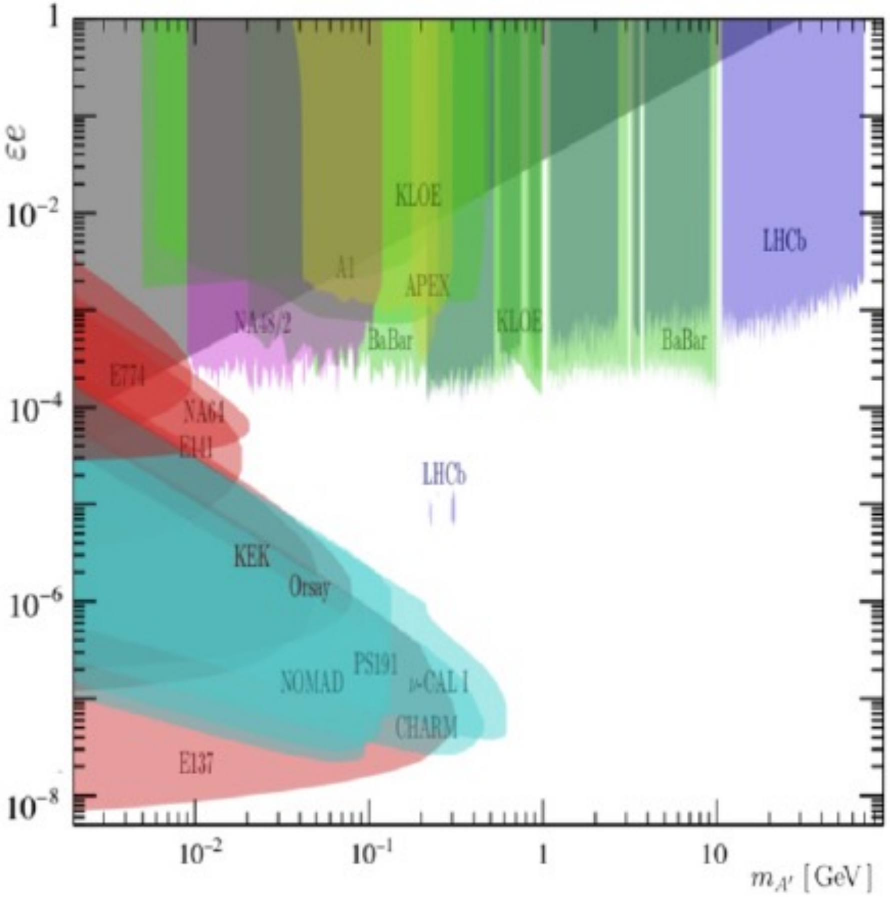


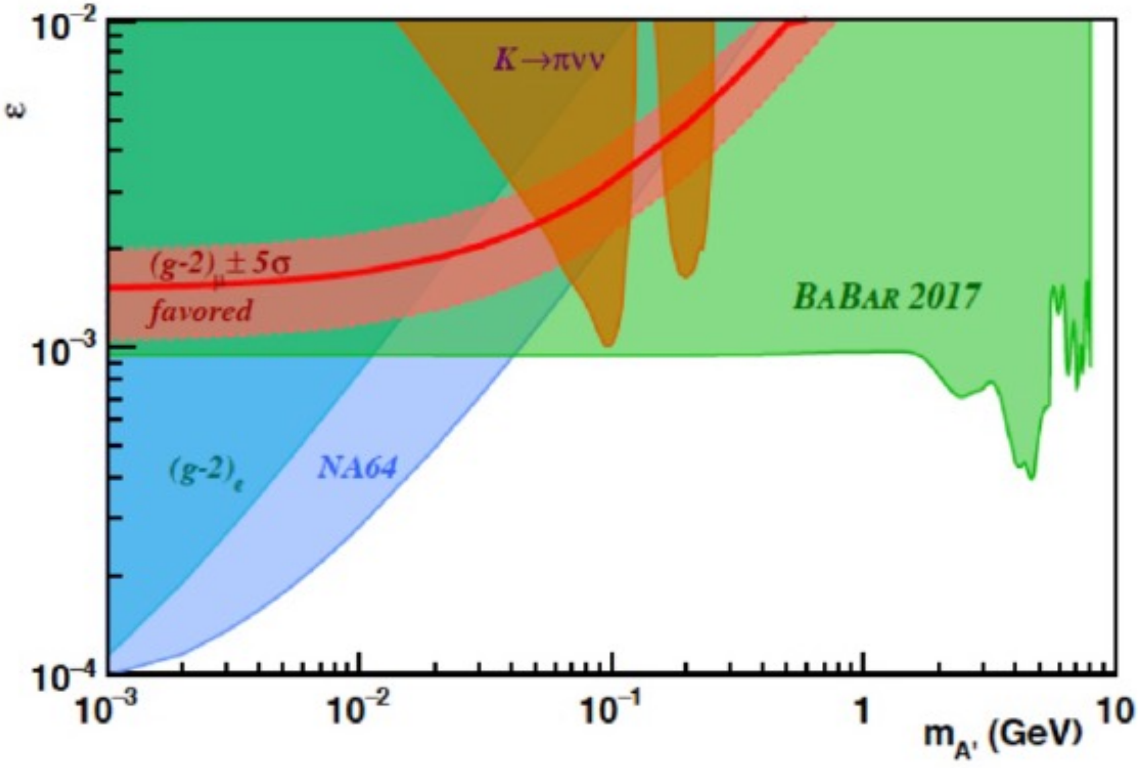
INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

# Status of exclusion

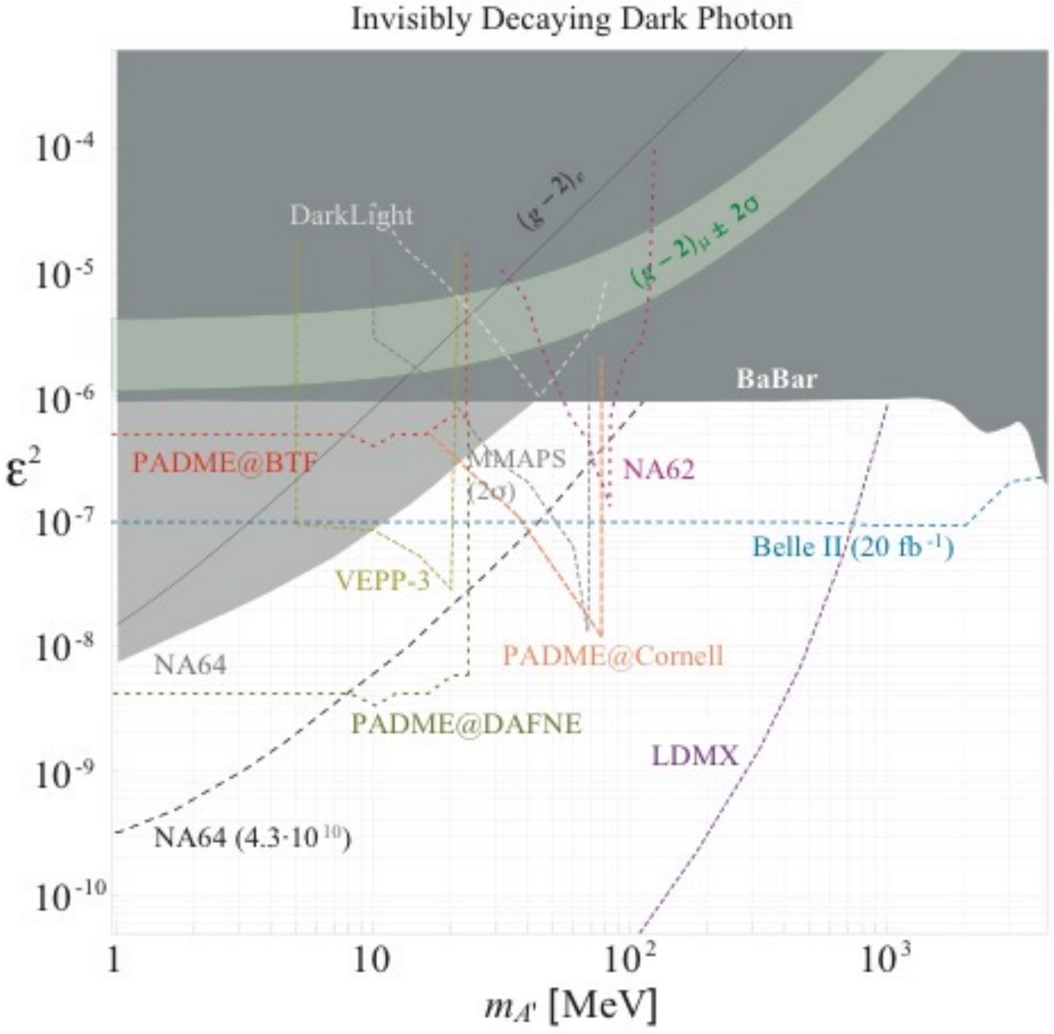
## Visible decays




## 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