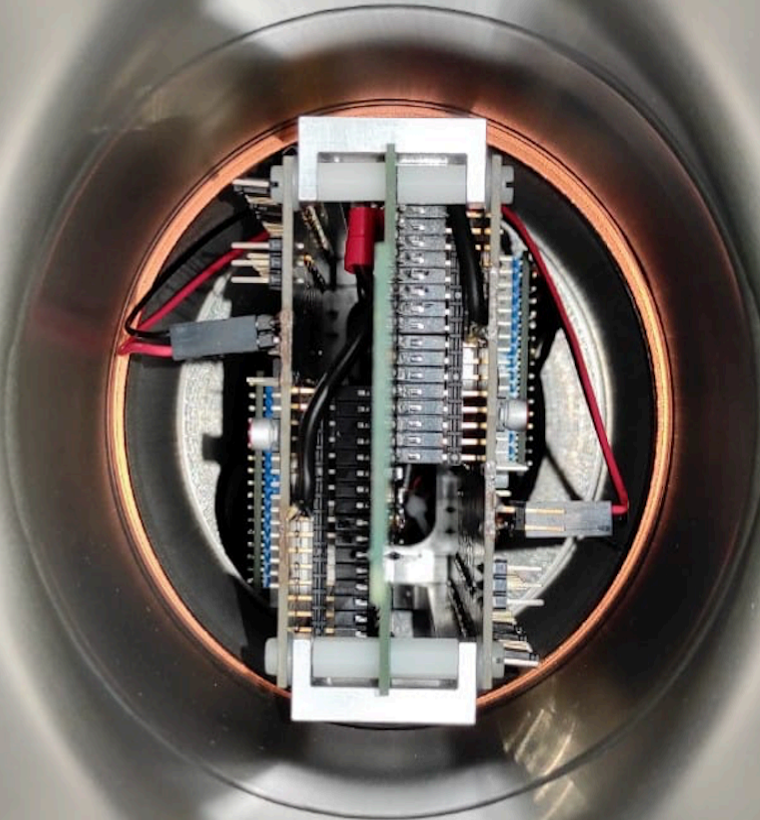
SIF, 106° congresso - 14 settembre 2020



L'esperimento PADME

Barbara Sciascia

for the PADME Collaboration

The collaboration

Positron Annihilation into Dark Matter Experiment

M. Raggi and V. Kozhuharov, Adv. High Energy Phys.2014, 959802 (2014), 1403.3041.
M. Raggi, V. Kozhuharov, and P. Valente, EPJ Web Conf.96, 01025 (2015), 1501.01867.




INFN Istituto Nazionale di Fisica Nucleare

Sofia University St. Kliment Ohridski Bulgaria

MTA atomki Debrecen

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

SAPIENZA Università di Roma

Università degli Studi di Roma Tor Vergata

Università del Salento

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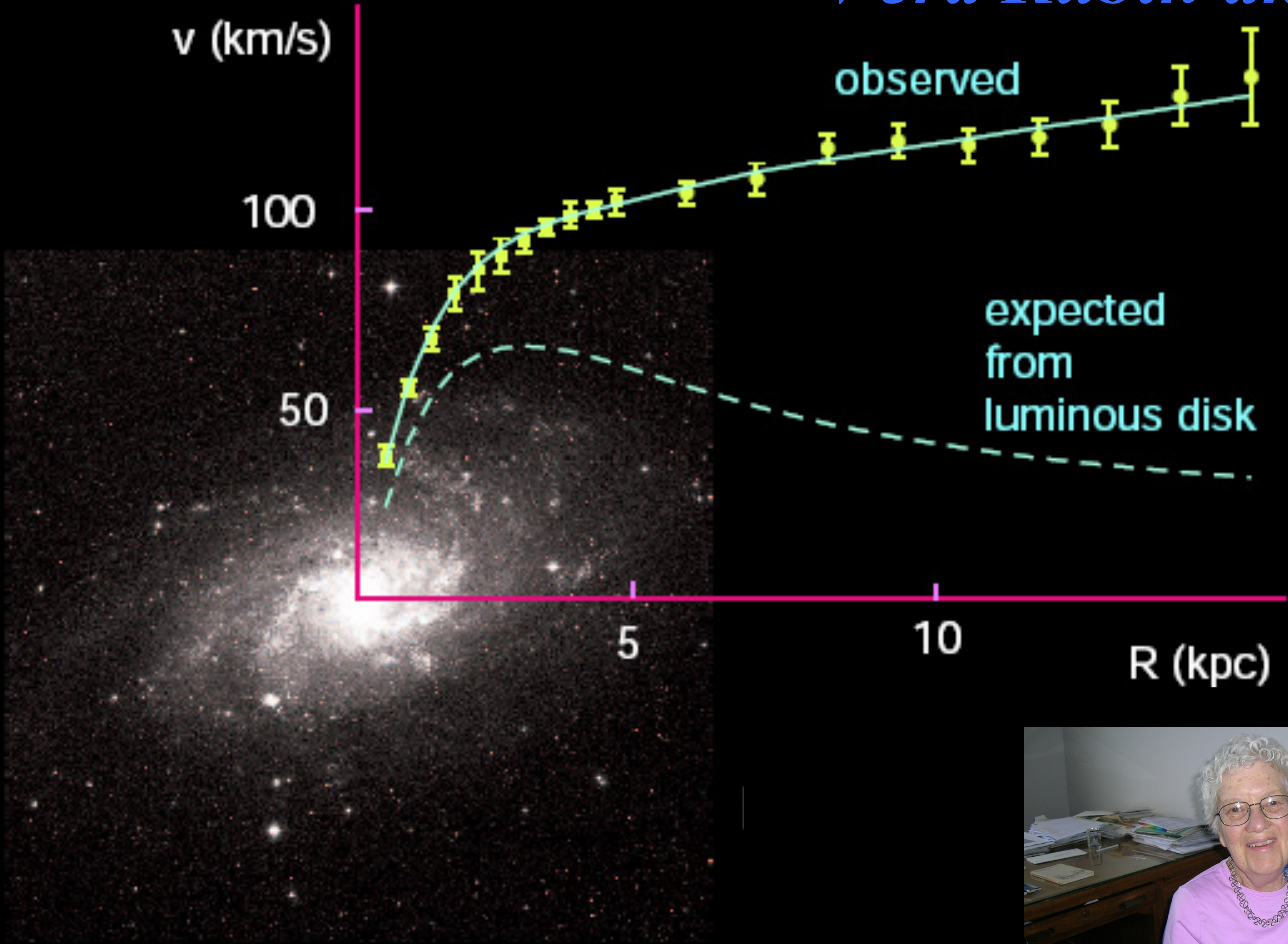
William & Mary CHARTERED 1693

The University of Iowa

Fritz Zwicky and the Coma cluster

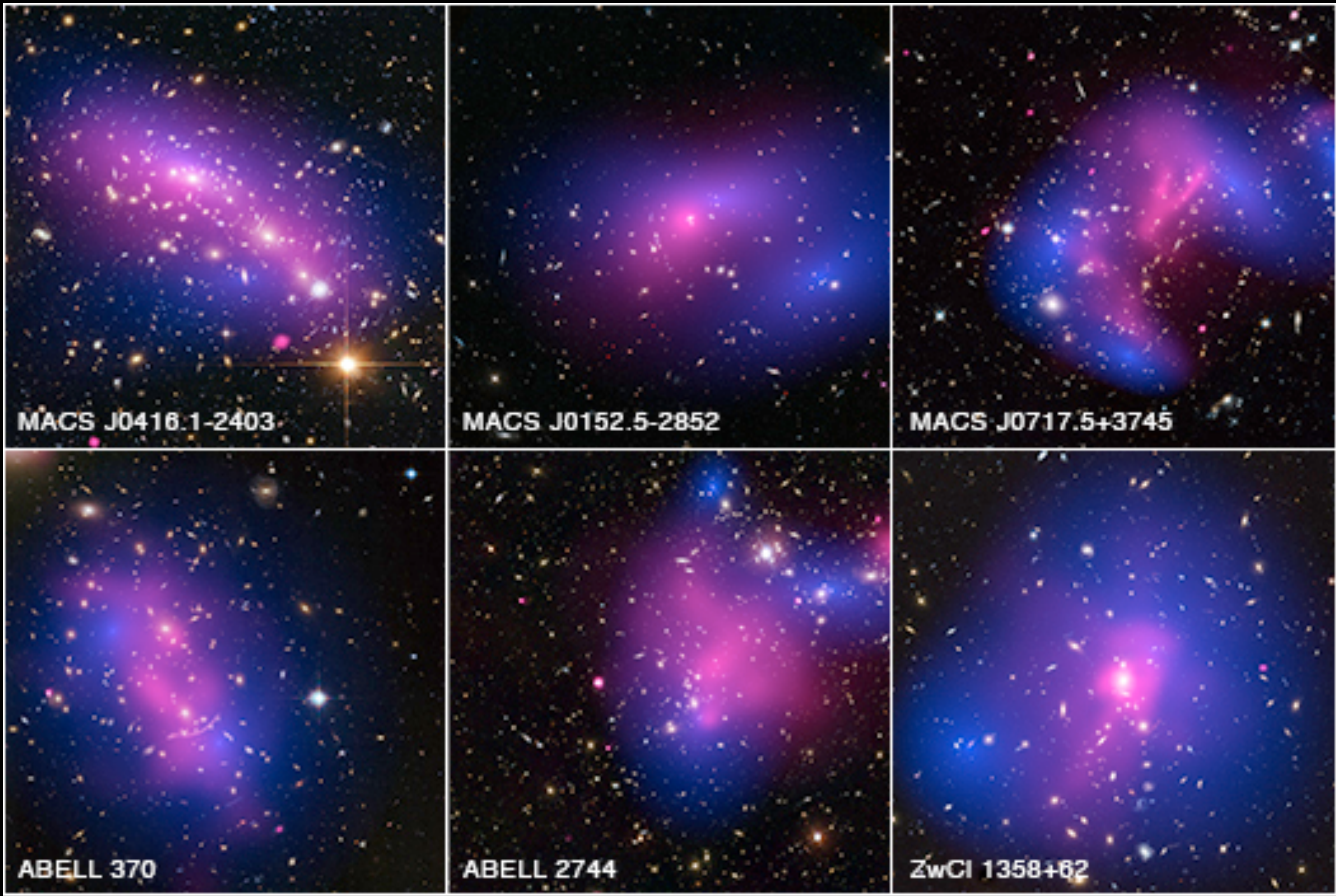
[By NASA / JPL-Caltech / L. Jenkins (GSFC) - http://www.spitzer.caltech.edu/images/1803-ssc2007-10a1-Dwarf-Galaxies-in-the-Coma-Cluster,]

Vera Rubin and M33

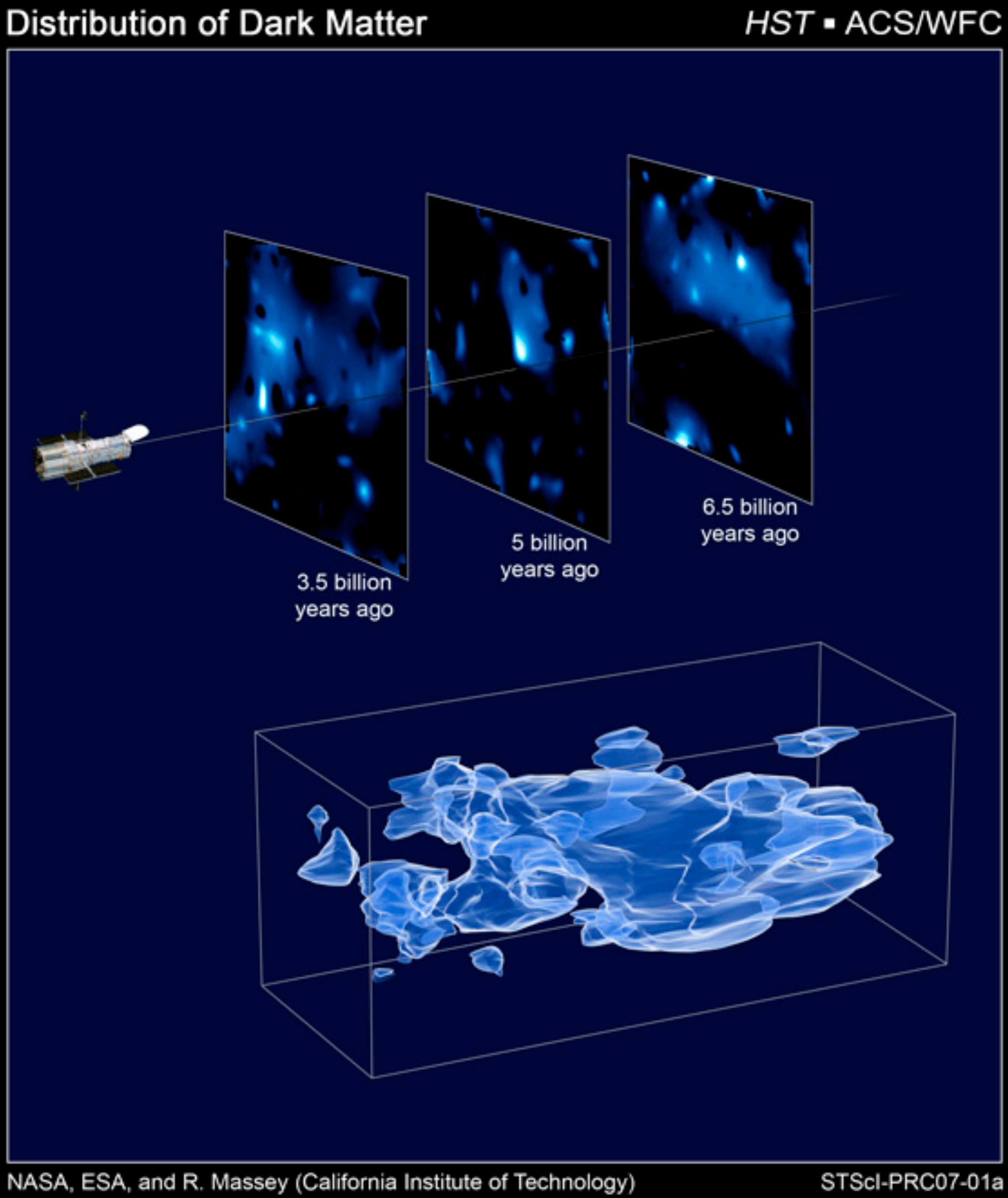


[Credit: X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)]

Galaxy clusters

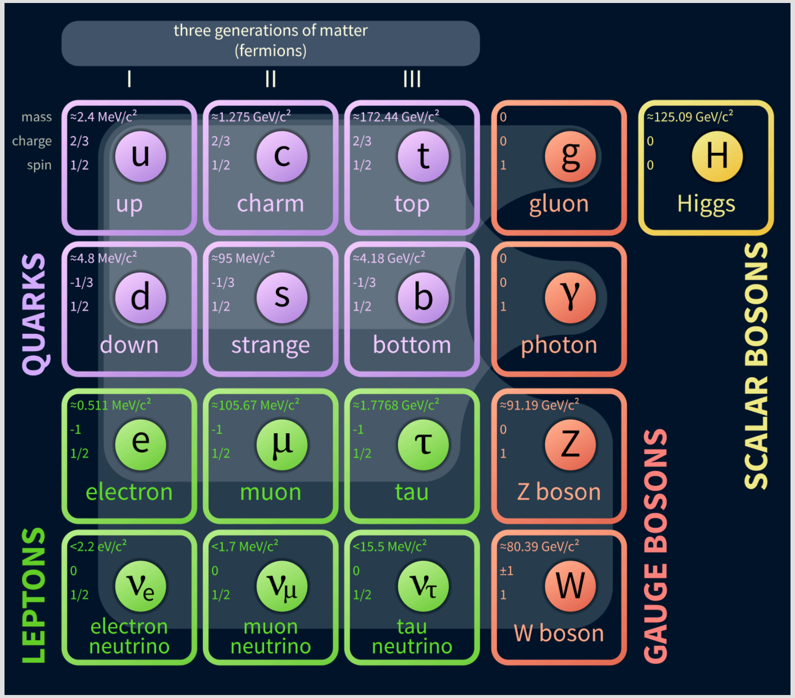


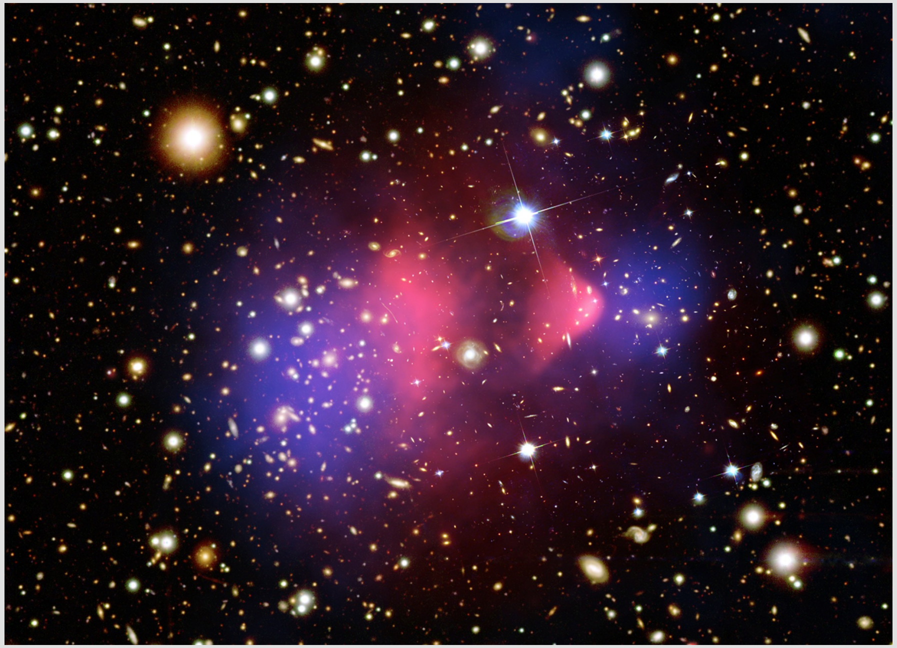
Distribution of Dark Matter



DM, not the only open point

- No explanation for the quark hierarchy
- Why are there 3 families/generations?
- No real explanation for CP violation
- Why it is only found in the weak interaction?
- Mass value of the Higgs boson
- EW and strong unification
- Neutrino masses
- …

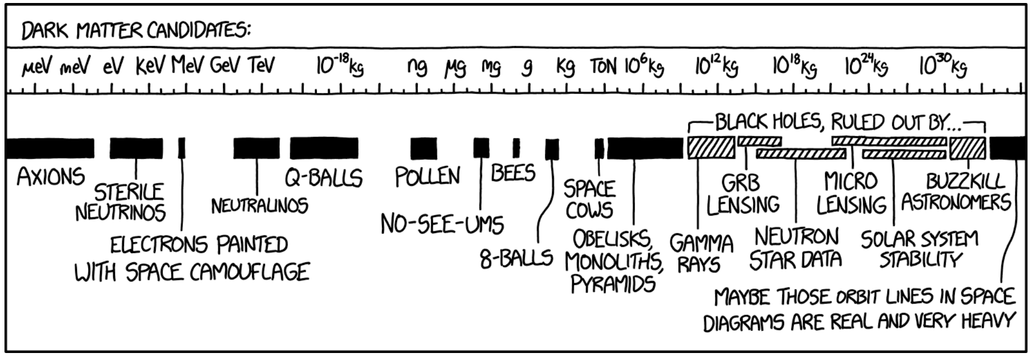




- Dark matter and dark energy
- No explanation for baryogenesis
- Gravity
- …

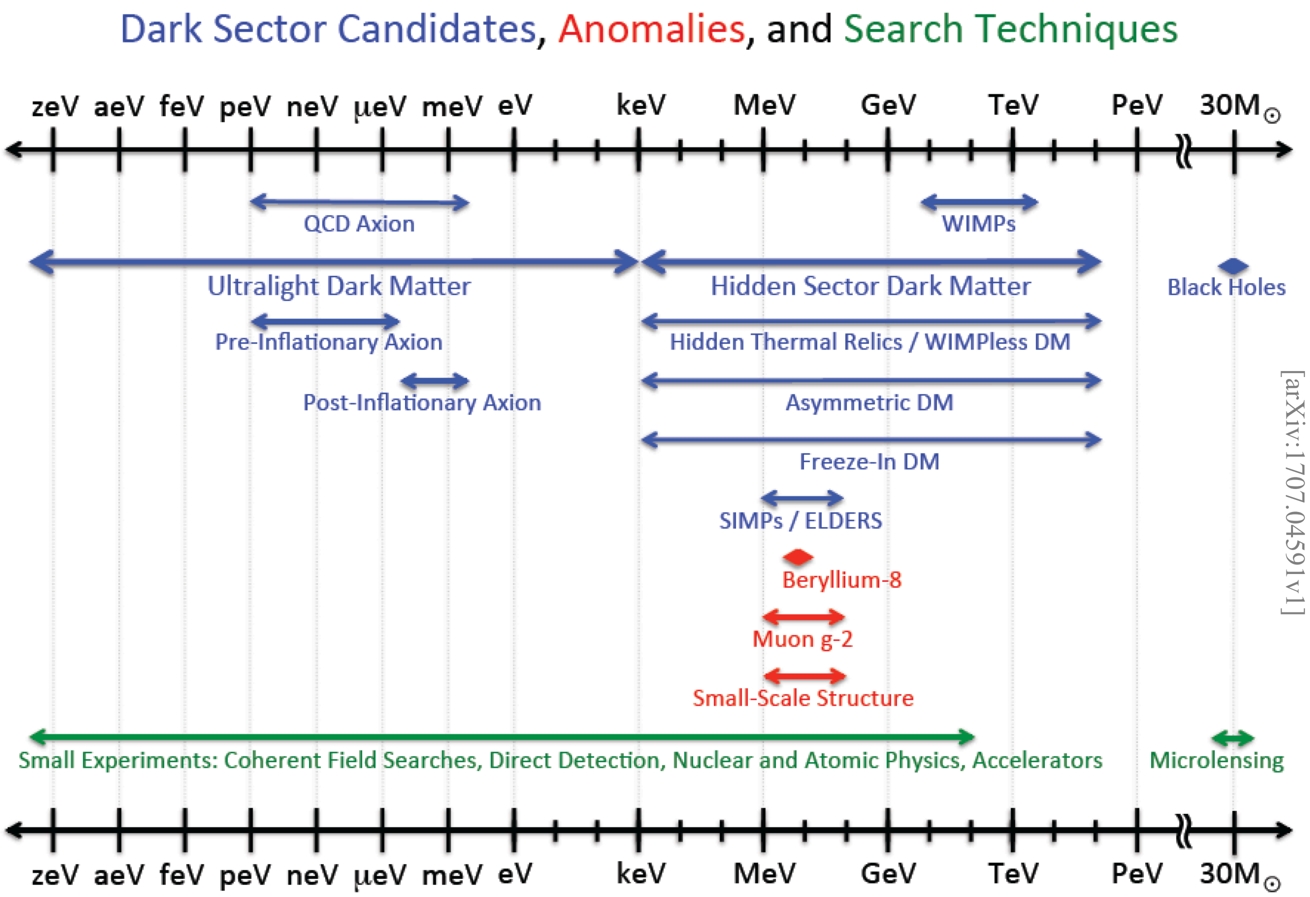
The nature of Dark Matter

Credits: https://xkcd.com/2035/



The most appealing solutions to the DM problem are models which at the same time can fix other anomalies:

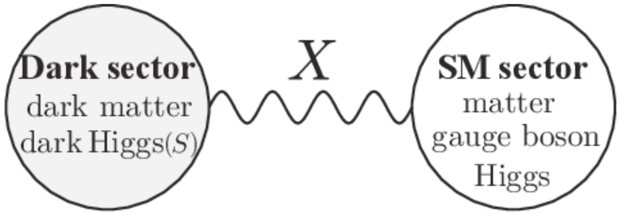
- a Peccei-Quinn (light) axion would save the strong CP problem
- an additional particle coupling to leptons, like a DP, could match the muon g-2 anomaly

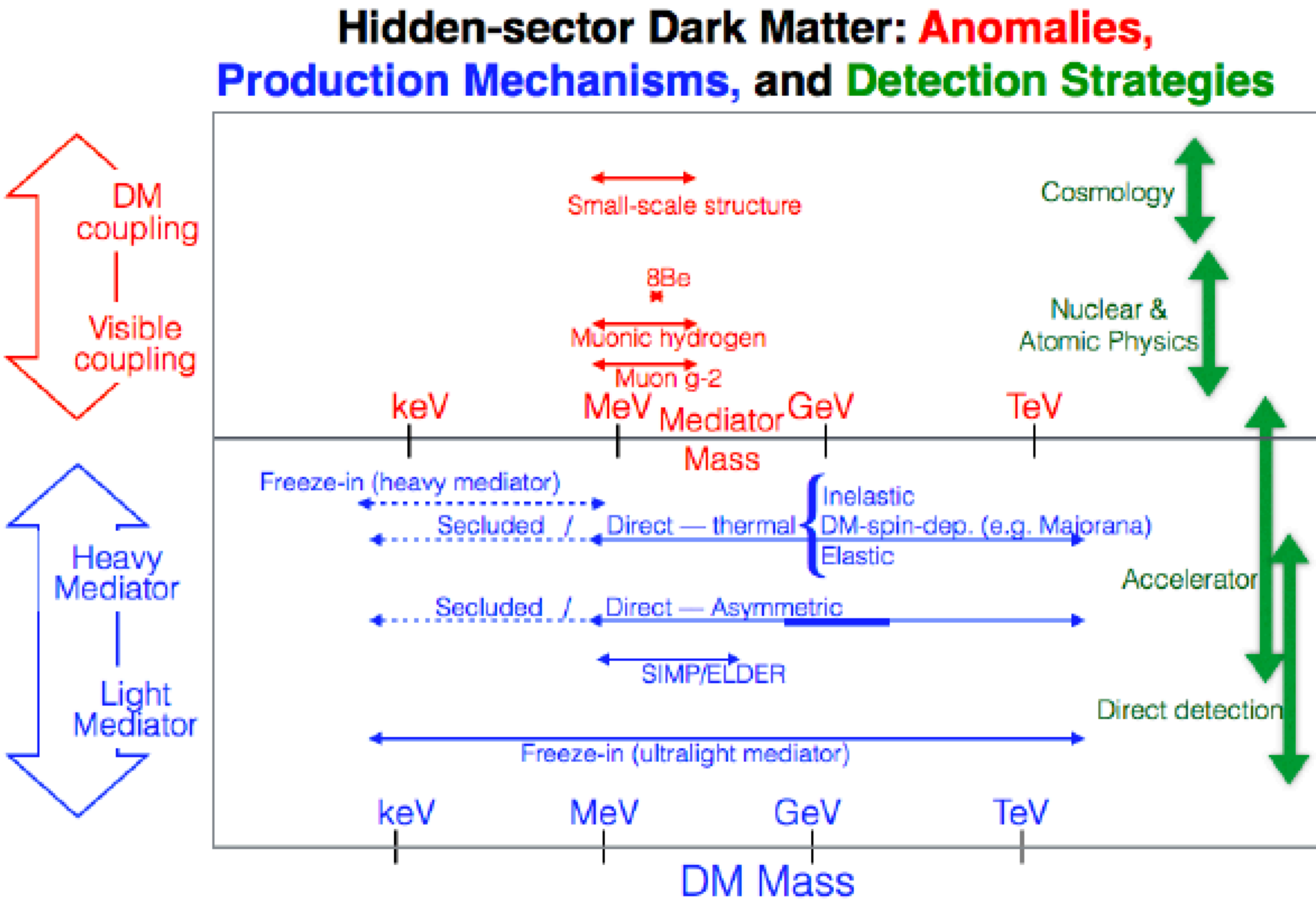


[arXiv:1707.04591v1]

Hidden-sector Dark Matter

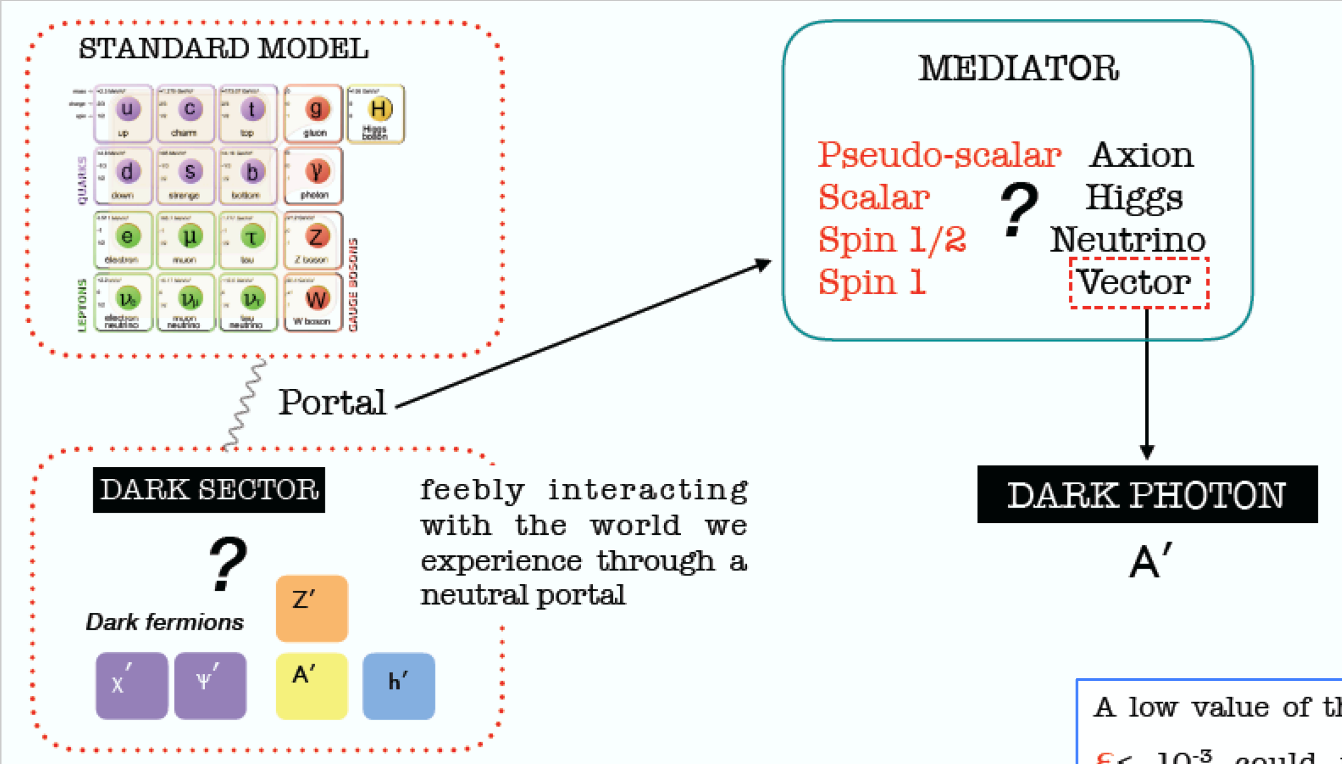
Credits: arXiv:1609.01605v2





[arXiv:1707.04591v1]

A dark portal

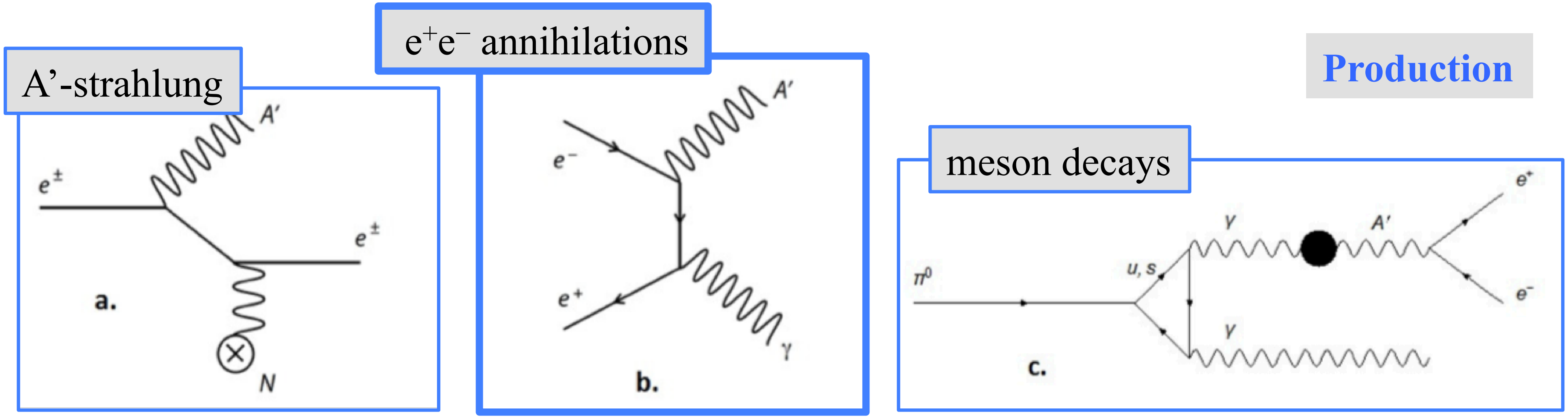


A low value of the mixing parameter $\varepsilon < 10^{-3}$ could justify the lack of experimental evidence for such scenario so far.

$$L_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{dark}^{\mu\nu}$$

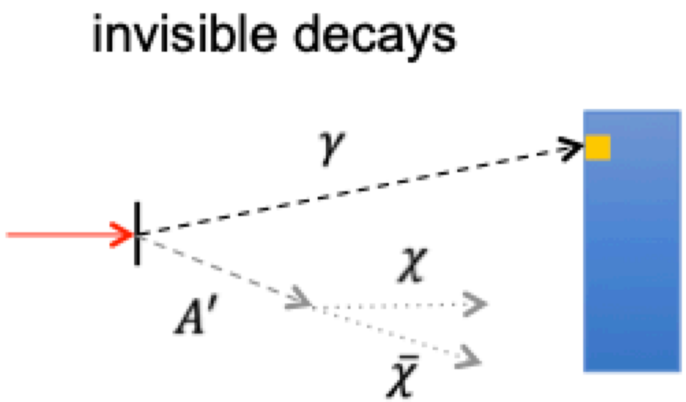
The simplest mechanism that could determine weak couplings between SM particles and the A′ field is the mixing with the Standard Model photon described by the kinetic mixing term in the Lagrangian

Dark Photon signals

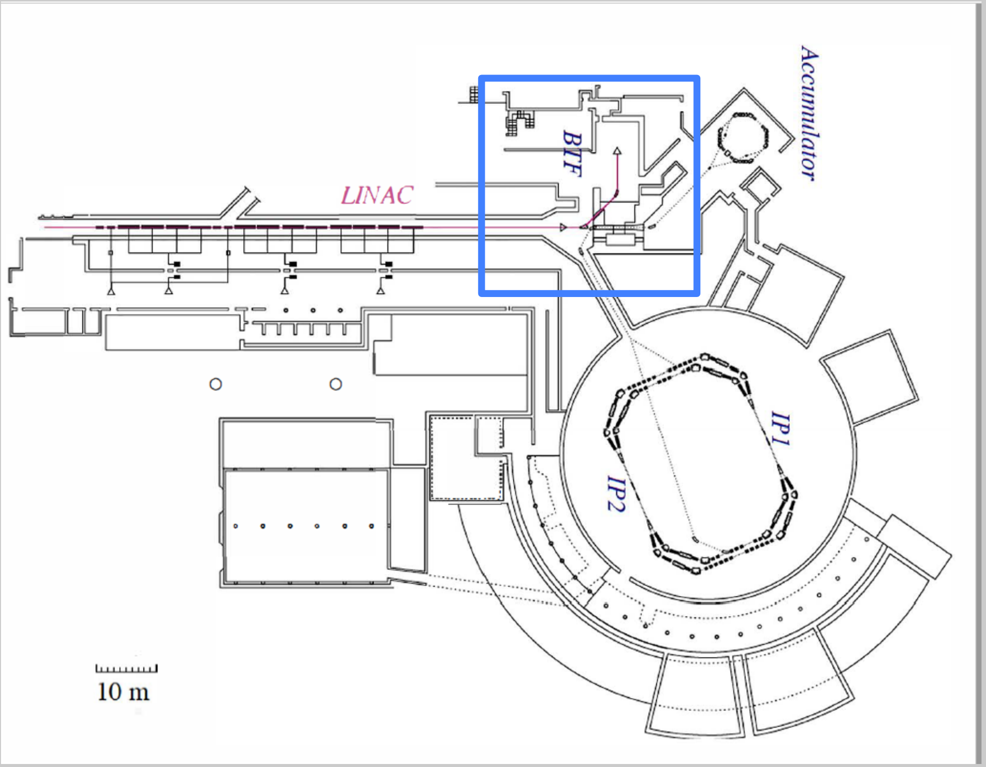


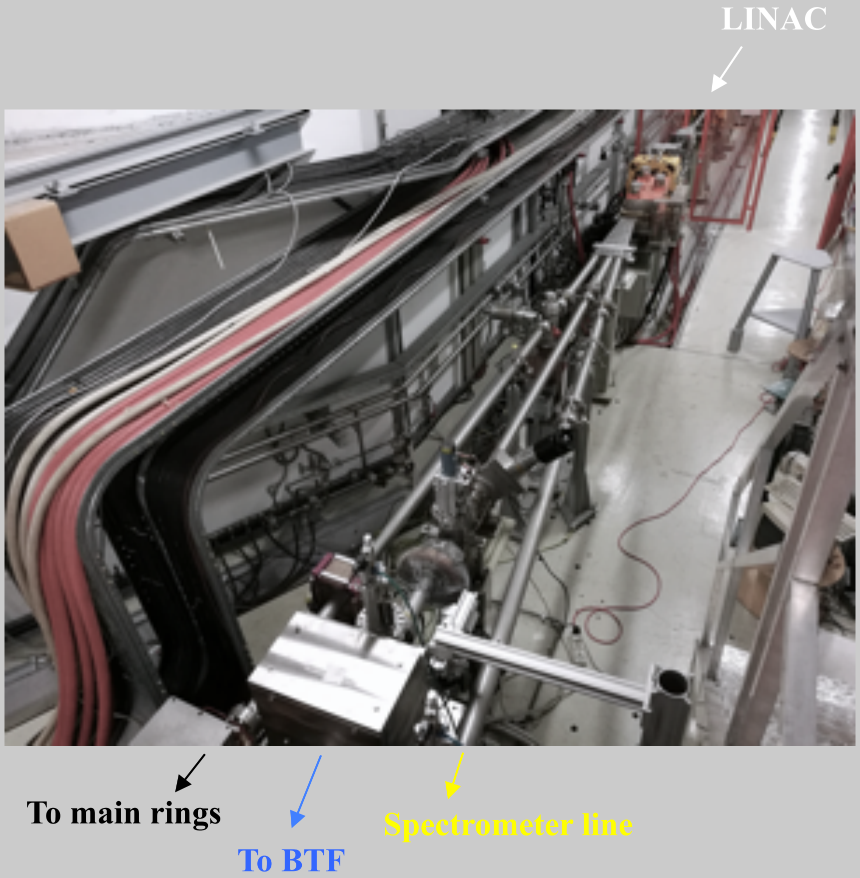
PADME approach:

- **Study Dark Photon produced in $e^+e^- \to \gamma A'$ events**
- No assumption on the A' decay and coupling to quarks (just assume coupling to lepton for production)
- **Invisible decay study limits the coupling of any new light particle produced in the annihilation (scalar, h', vectors, A', and ALPS)**.
- Luminosity: from high intensity pulsed positron beam impinging on the atomic electrons of a fixed target



Daphne accelerator complex





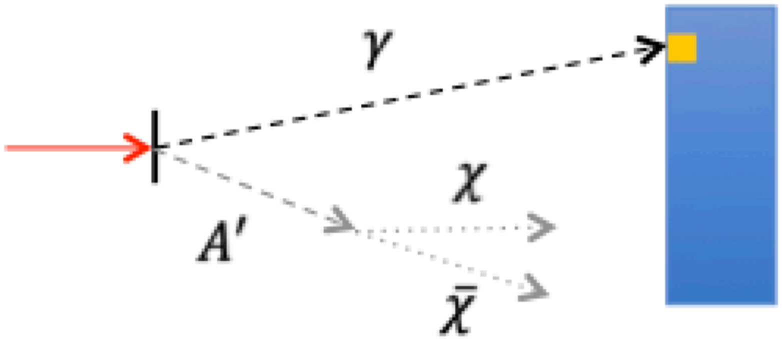
PADME is installed in the Beam Test Facility (BTF) of the Laboratori Nazionali di Frascati

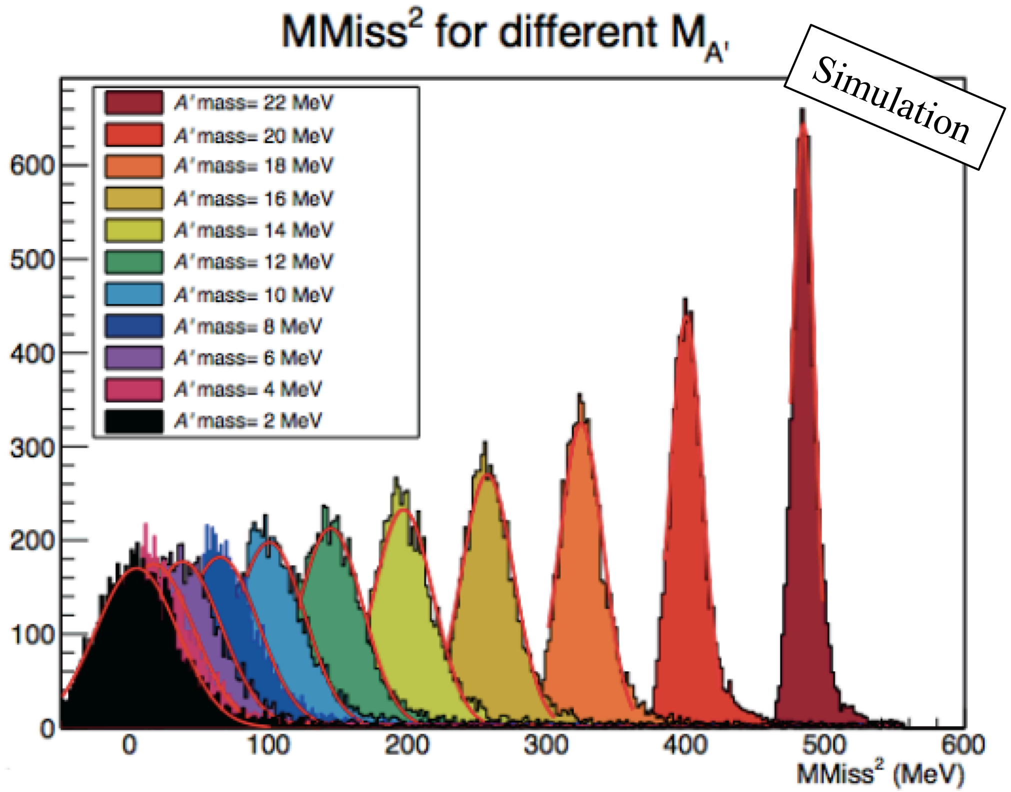
- BTF: part of the DAΦNE accelerator complex
- Φ-factory: in the main rings: e^+e^- collisions with $E_{CM} \sim m_\Phi = 1.02$ GeV
- **positrons/electrons** beams from LINAC; **PADME nominal beam**: e^+, E_{MAX}=550 MeV (with the current setup), multiplicity ~ 20k e^+/bunch, bunch duration 200 ns, frequency 49 Hz

Dark Photon signals

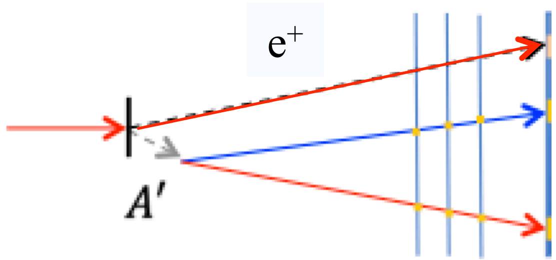
Main channel: invisible dark photon decays
- clear signature from missing mass technique
- **mass up to $M_{A'}$= 23.7 MeV can be explored**

$$M^2_{Miss} = (P_{beam} + P_e - P_\gamma)^2$$



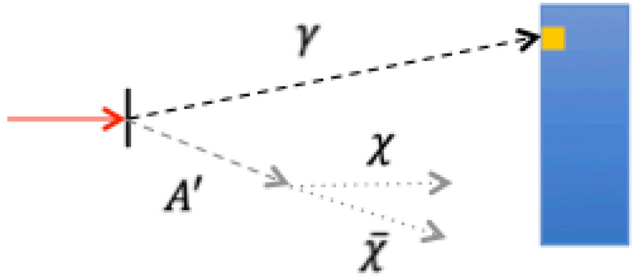


Under investigation: sensitivity to visible dark photon decays generated by A'-strahlung
- reconstruct invariant mass of the detected e^+e^- pair from A'
- **mass up to $M_{A'}$ ~100 MeV can be explored**

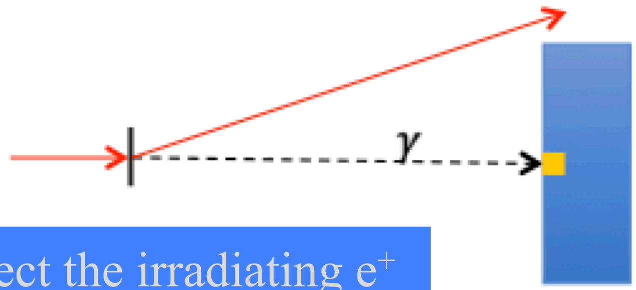


Signal (invisible) and background

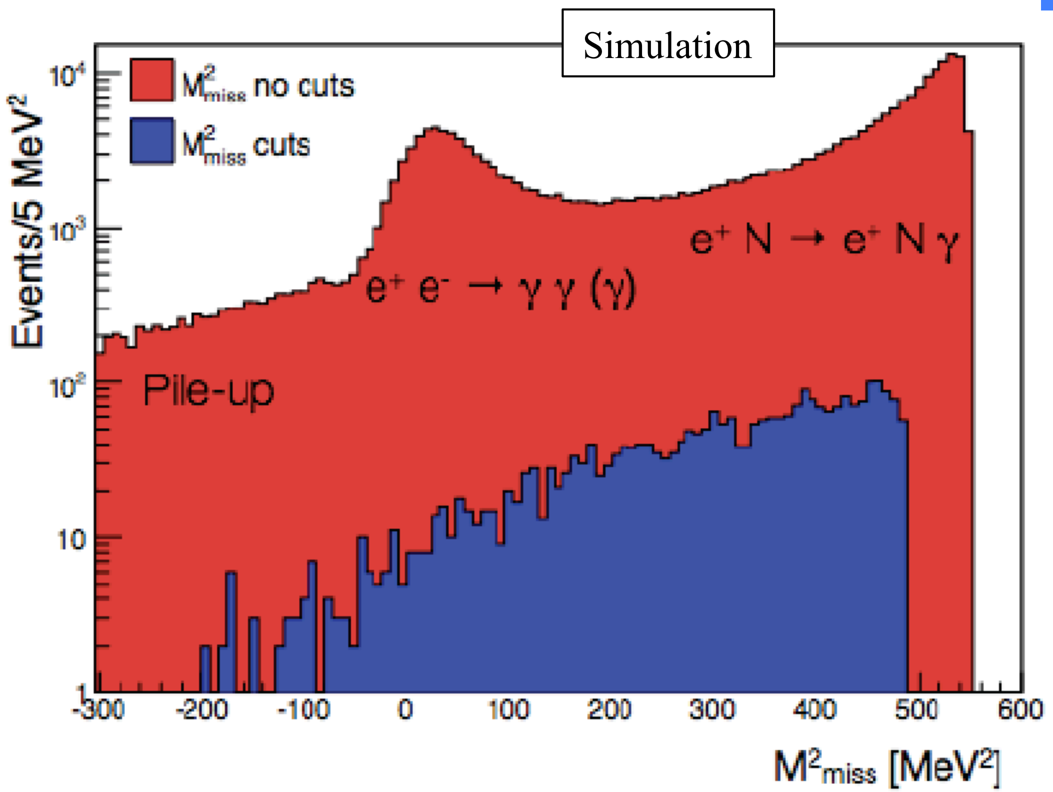
Signal: invisible decay of A'



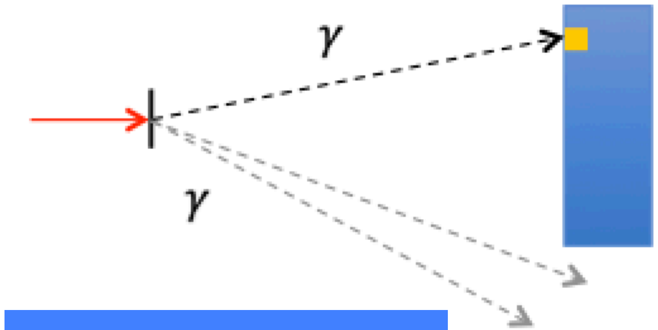
Background: Bremsstrahlung + lost e^+



- detect the irradiating e^+
- cut on photon energy

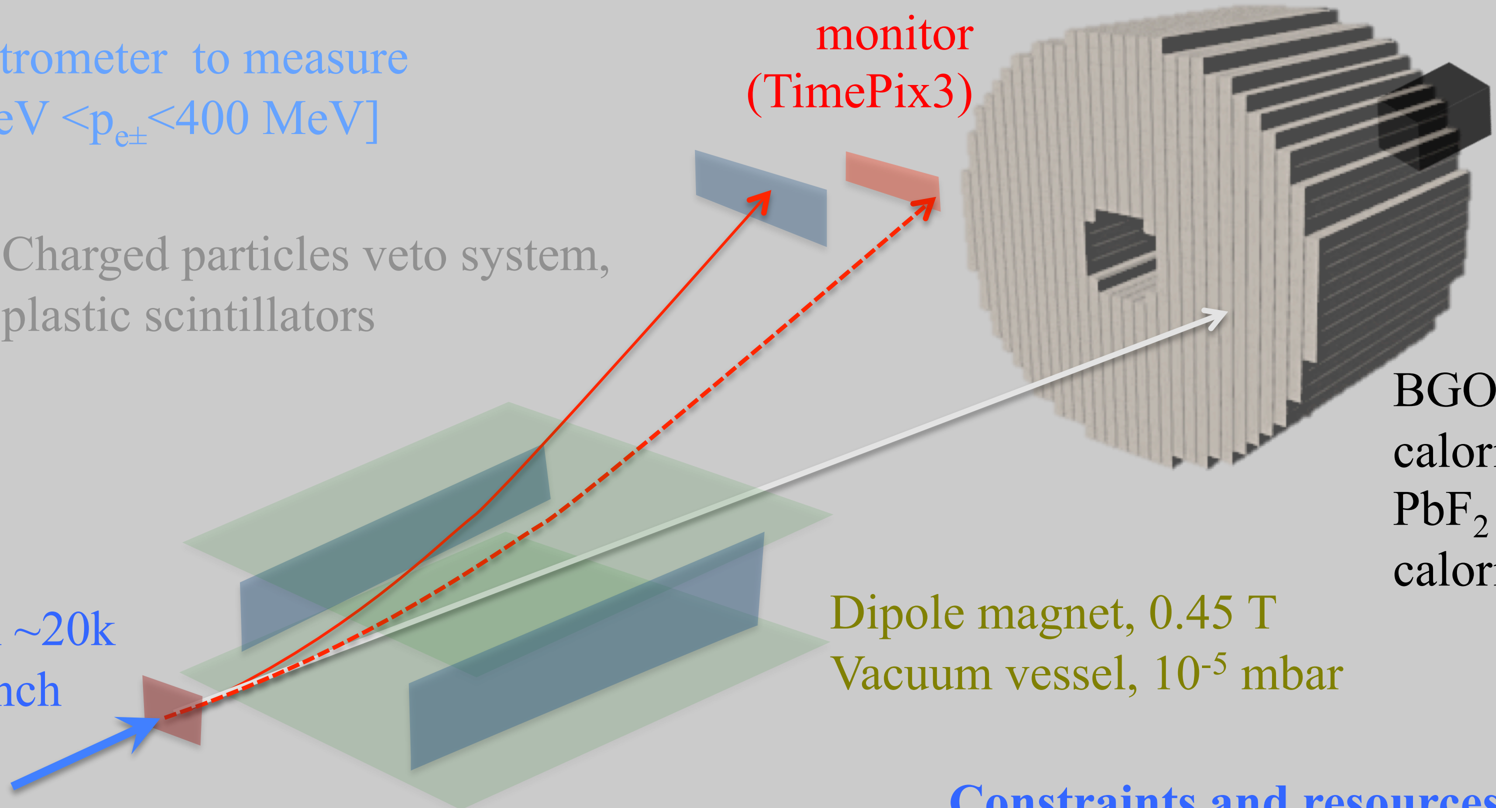


Background: 2 or 3 photons, 1 detected



- Hermetic detector
- granularity
- energy resolution

Experimental setup



Constraints and resources

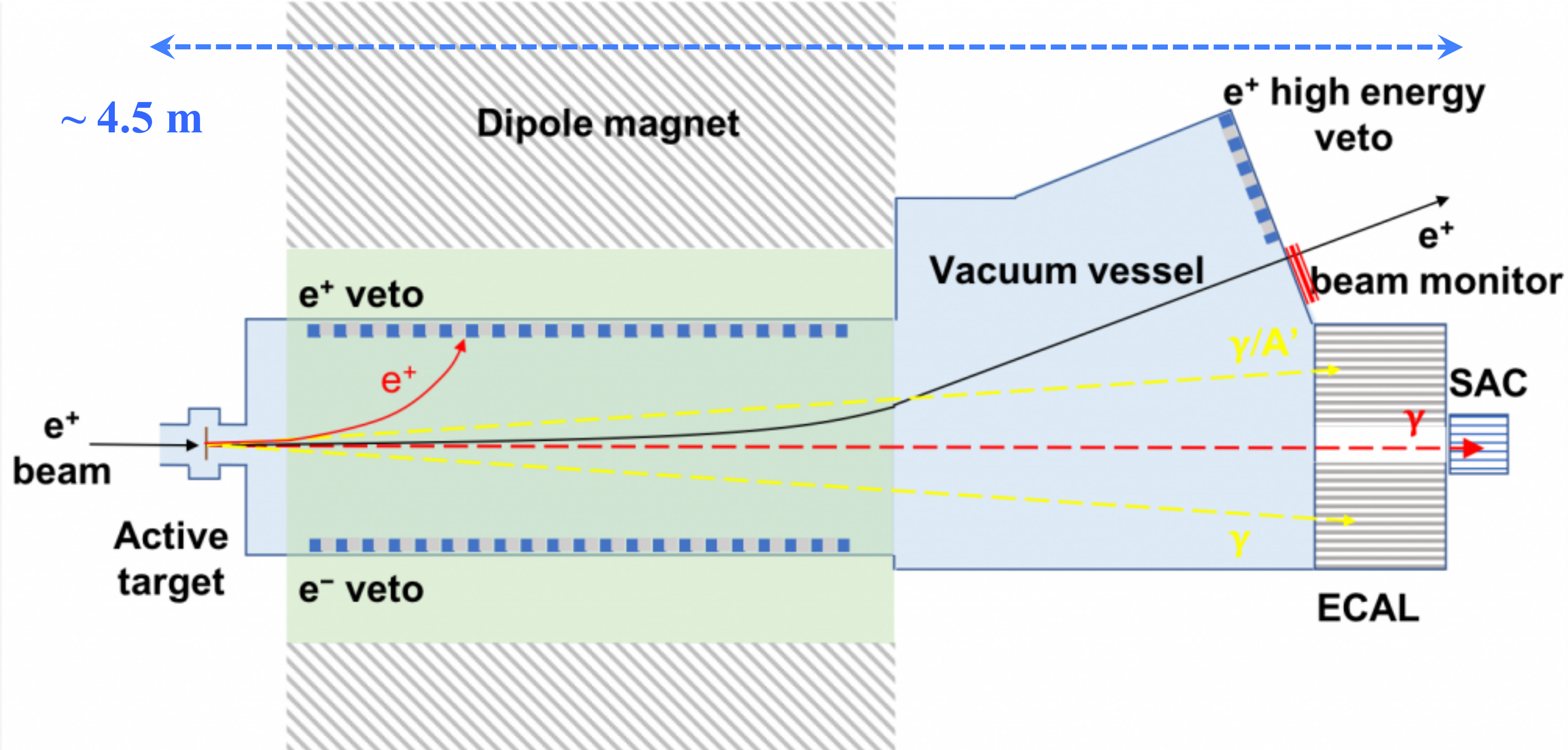
a) Maximum length and transverse size: available space in the BTF hall

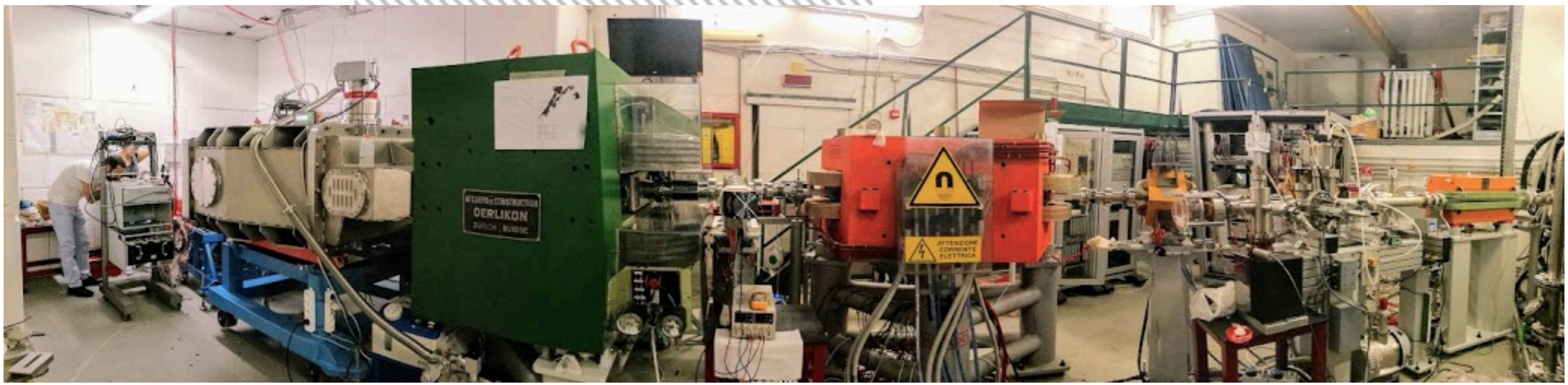
b) Magnet (moderate, <0.5 T, field needed)

- Large gap **dipole from CERN** (23 cm)

c) Available **BGO crystals from L3 ECal**

Experimental setup



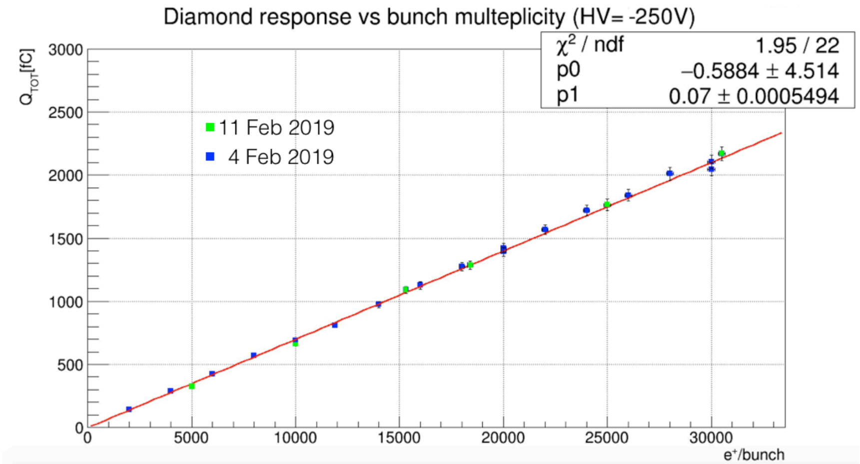


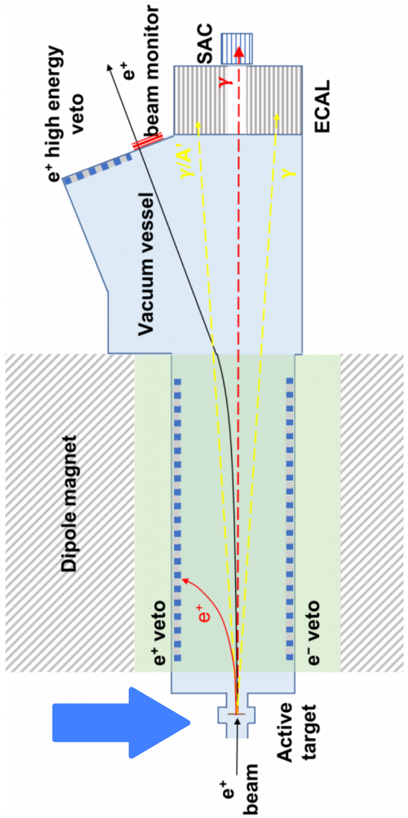
Diamond Active Target

Beyond being the target, gives information about incoming beam (position, size and intensity)

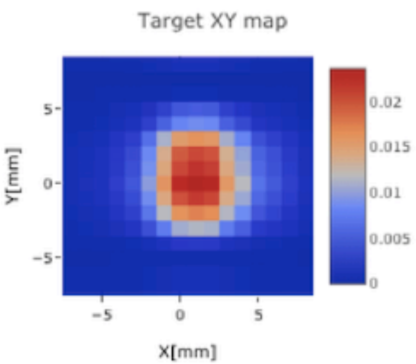
[Nucl.Instrum.Meth.A 898 (2018) 105-110 arXiv:1709.07081 [phyiscs,ins-det]]

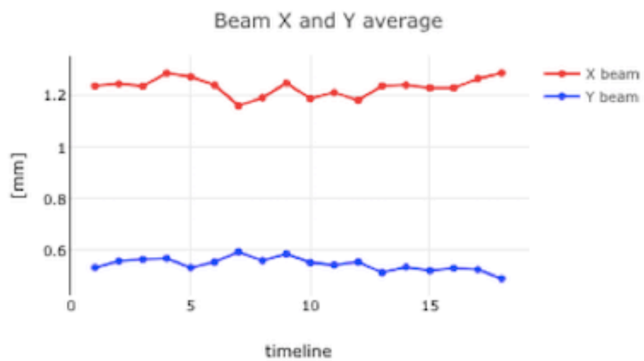
- Very good linearity of collected charge with respect to number of e^+/bunch
- With present FEE, good performance from 5k particles/ bunch

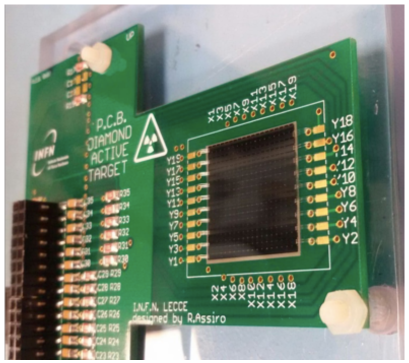




CVD (Chemical Vapor Deposition) $20 \times 20 \times 0.1$ mm^3 polycrystal diamond; 16×16 connected graphitic strips (x and y)







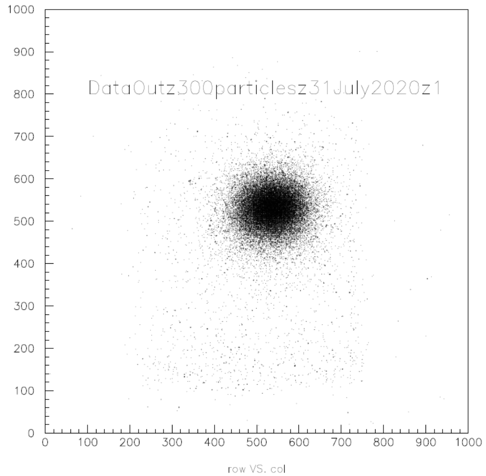
Mimosa (Beam monitor)

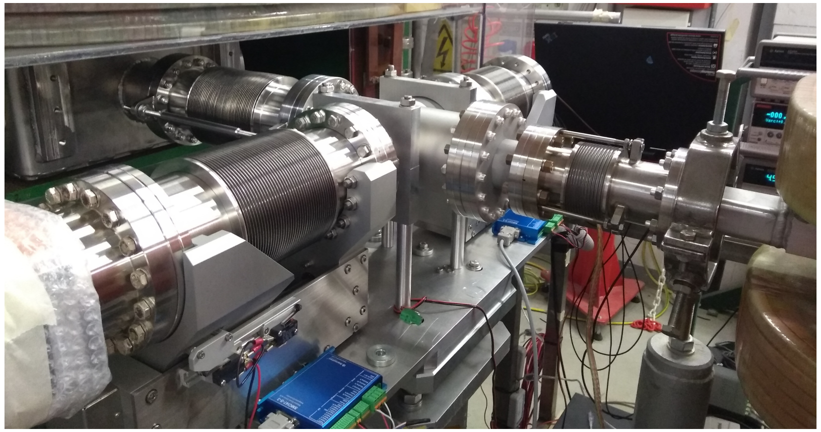
Gives information about beam position **and divergence**.

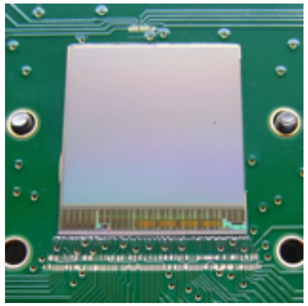
Best performance obtained with a multiplicity of ~ 300-1000 particles/bunch (preliminary studies show that can give reliable information up to 3k particles/bunch)

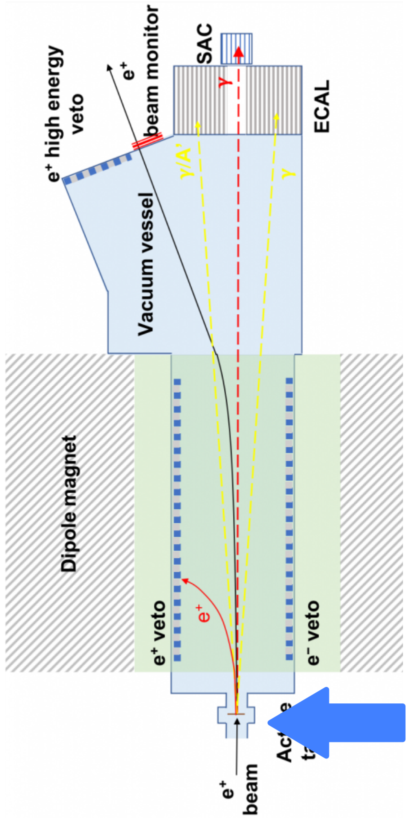
Cannot be used during data taking (beam deterioration); used for beam-setup (a step motor moves target and MIMOSA on position)

MIMOSA-28: monolithic pixel tracker in vacuum (first time)
20.8 μm pitch, 20.2 × 22.7 mm^2 area





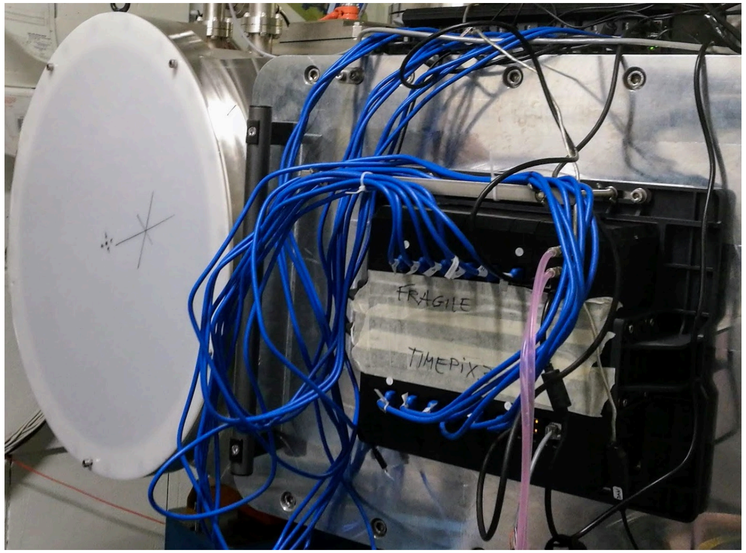


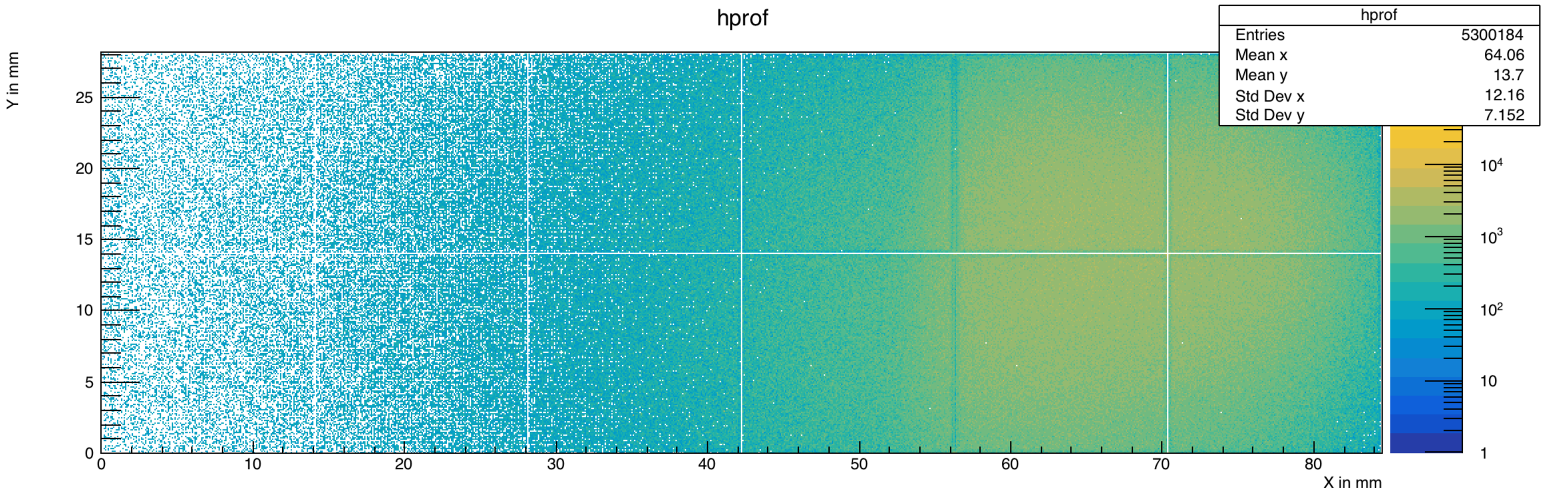


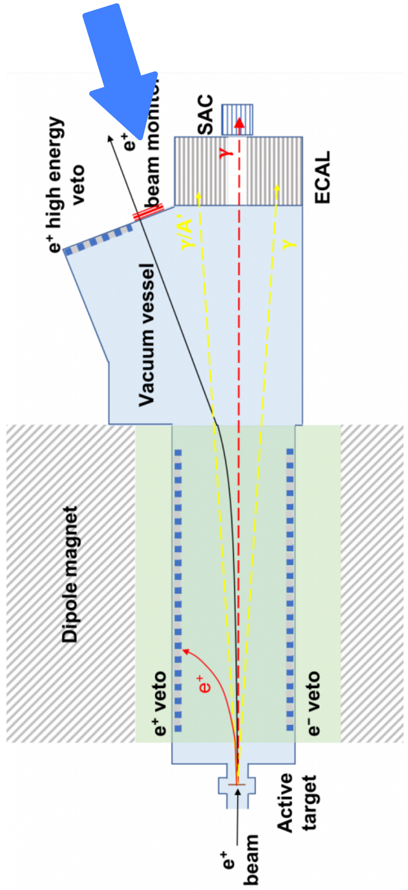
TimePix3 (Beam monitor)

Monitor for the not interacting e^+ beam; measure position, time and energy of each particle.

Single sensor: 256 × 256 matrix, pixel pitch 55 μm
Whole detector: 12 sensors (786·432 pixels), 8.4 × 2.8 cm^2
(So far, the biggest TimePix3 array used for particle physics)







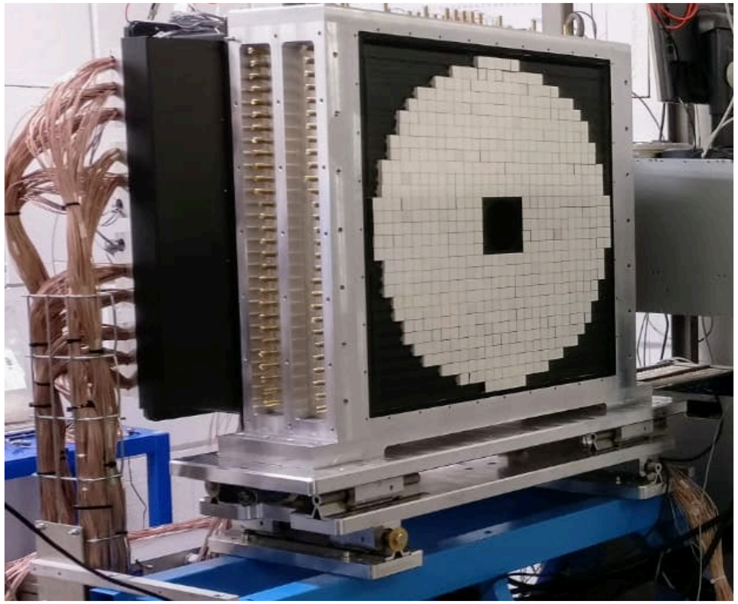
ECal (main calorimeter)

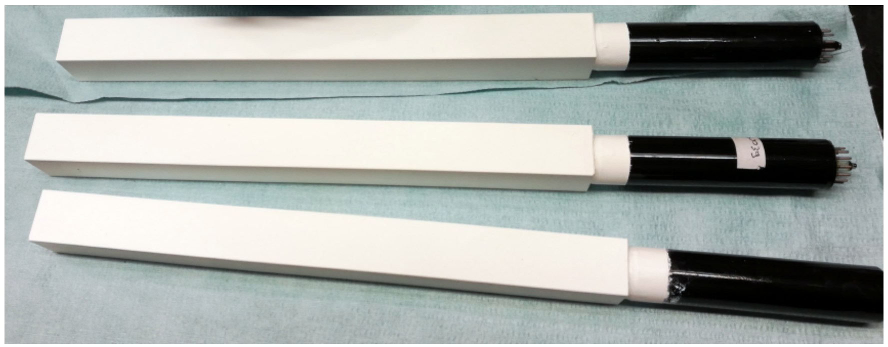
[arXiV: 2007.14240 [physics.ins-det]
Submitted to JINST]

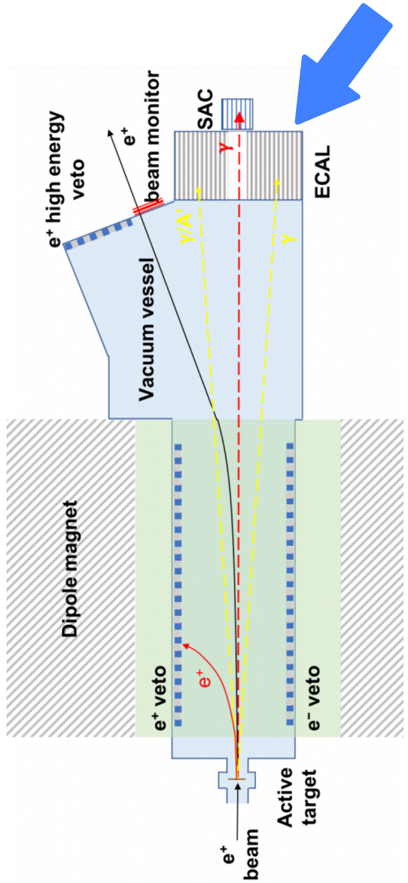
Detect the γ in the final state (**to close E_{MISS} kinematics**).
Cylindrical shape (~30 cm radius); central hole of 10.5×10.5 cm^2 (Bremsstrahlung rate too high for BGO)

Angular coverage: [15.7, 82.1] mrad
Readout sampling: 1 GHz, 1024 samples

616 2.1 × 2.1 × 23 cm3 BGO crystals, scintillation light, ~300 ns decay time, coupled to HZC Photonics XP1911 PMT







SAC (Small Angle Calorimeter)

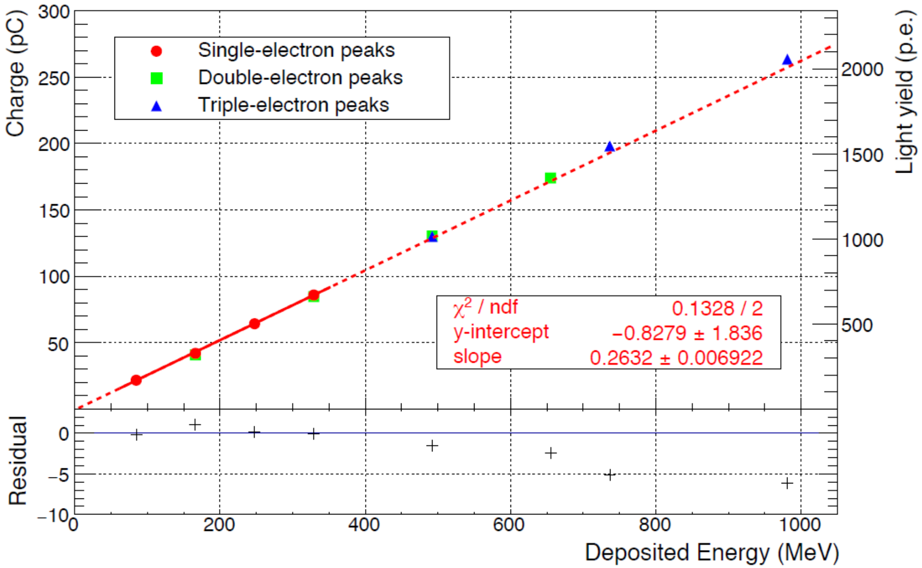
[Nucl.Instrum.Meth.A 919 (2019) 89-97
arXiv:1809.10840 [physics.ins-det]]

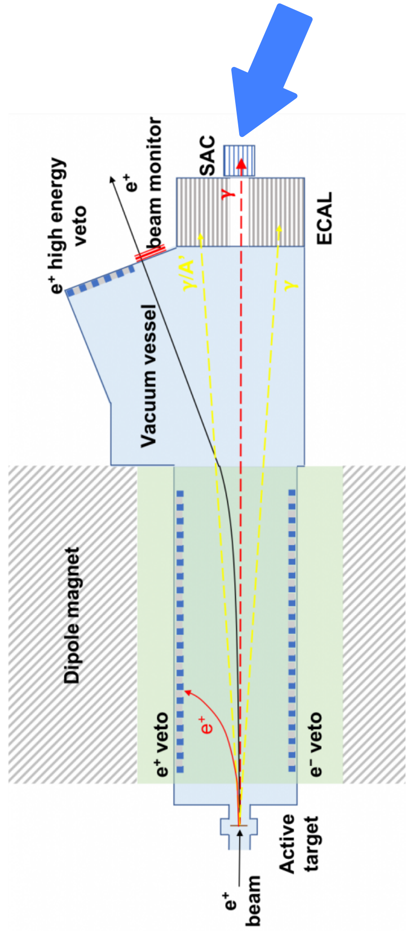
Must sustain the high Bremsstrahlung radiation rate (~100 MHz)

Fast signals (~2 ns)
Angular coverage:
[0, 18.9] mrad

25 3 × 3 × 14 cm^3 PbF2 crystals (Cherenkov)
Coupled to fast Hamamatsu R13478UV PMT; readout sampling: 2.5 GHz, 1024 samples.

Two independent calibrations (beam and cosmic rays)

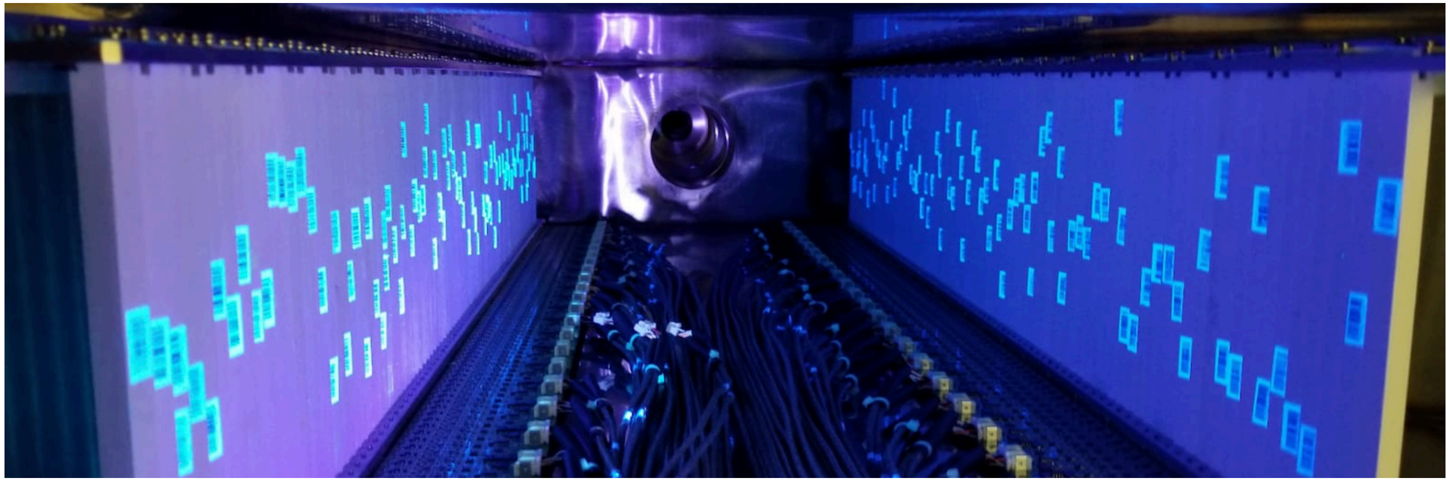


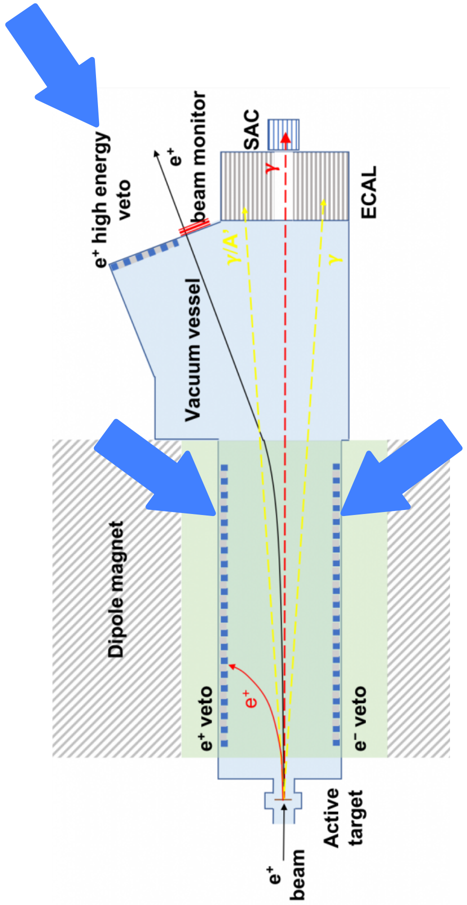


Positron/electron vetoes

See contribution by Beth Long:
"Simulazione e elaborazione di segnali nei Veto di PADME"
https://agenda.infn.it/event/23656/contributions/120239/

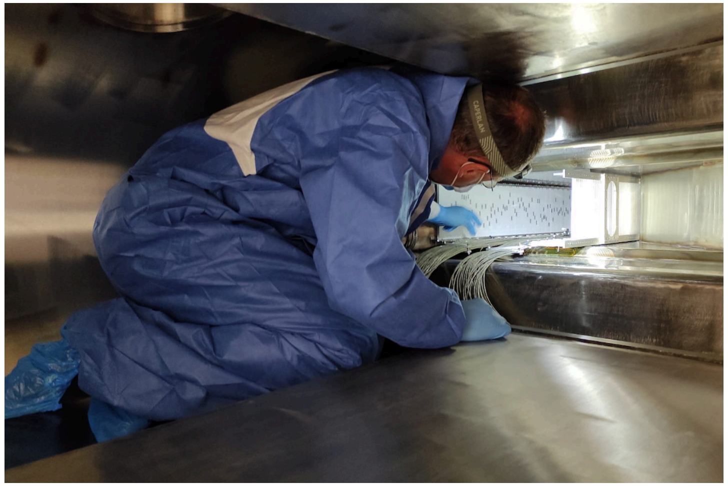
[AIP Conf.Proc. 2075 (2019) 1, 080005]





Veto/identify e^-/e^+:
- Soft Bremsshrahlung background
- Hard Bremsshrahlung background
- Beam-induced background
- Visible A' decays

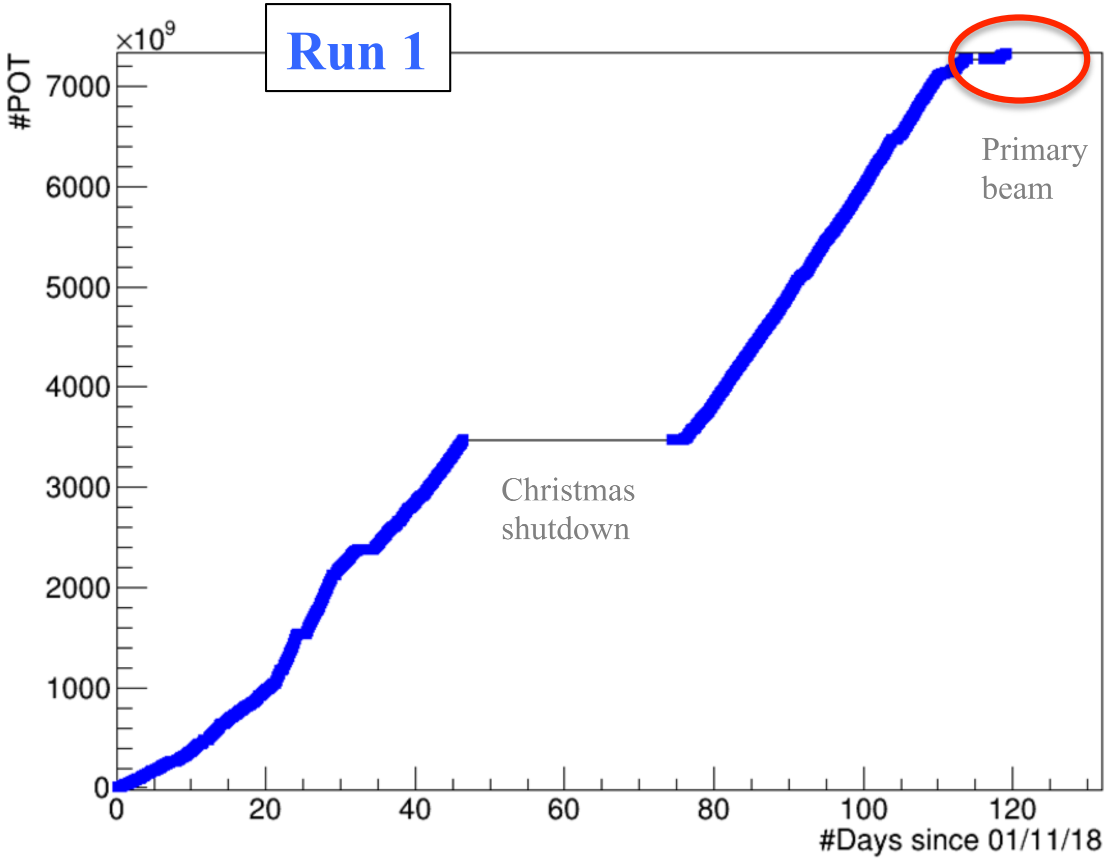
Operate in vacuum (10^{-5} mbar) and magnetic field (~ 0.45 T)



Data taking

Run 1 (Oct 2018 - Feb 2019): beam and background studies aiming at the cleanest possible data sample [~0.7 $\times 10^{11}$ POT on disk]

Run 2 (July 2020 - Dec 2020):
- Jul-Aug: detector back in operation post-lockdown; calibration runs
- **16 Sept: data taking for physics**



Secondary beam: e^+ from e^- accelerated on a target, followed by energy selection (E_{MAX} = 550 MeV)

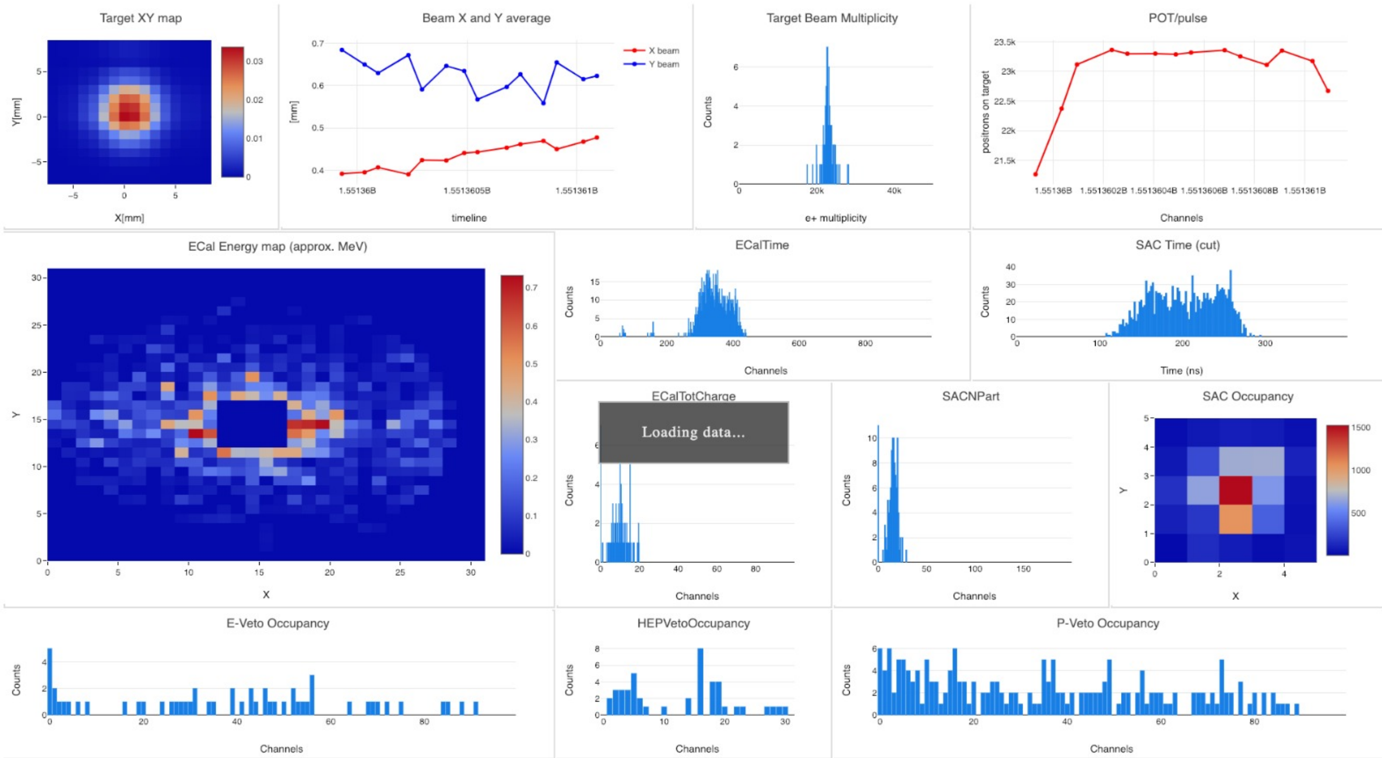
Primary beam: after the production, e^+ accelerated to the desired energy (E_{MAX} = 490 MeV)

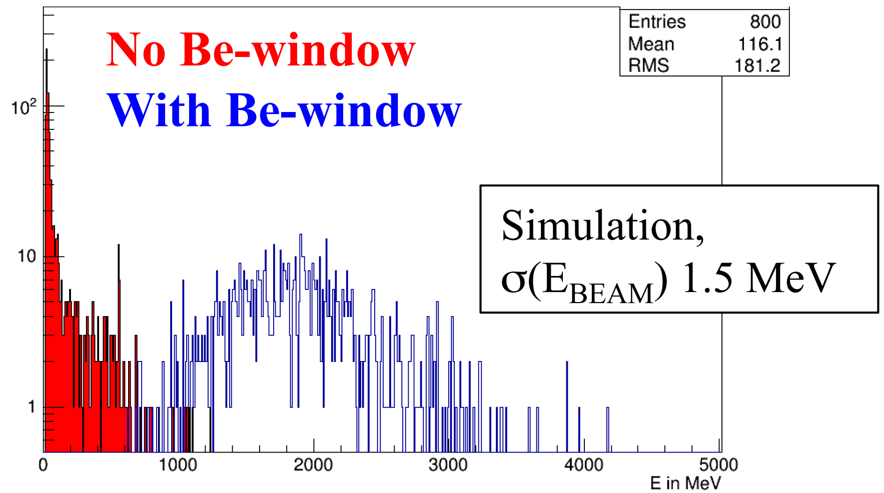
Commissioning and beam-bkg study

Commissioning data-taking: Run 1 + July 2019

Online monitor, DCS
Sub-detectors calibration
Beam optimization

Background studies

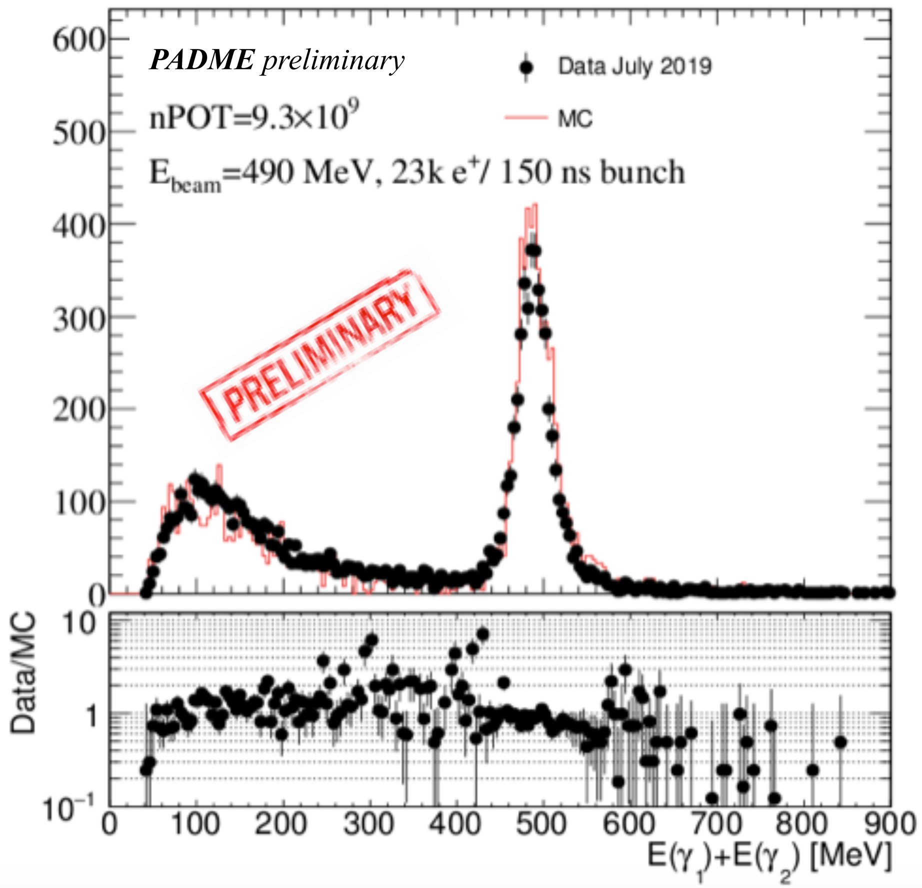


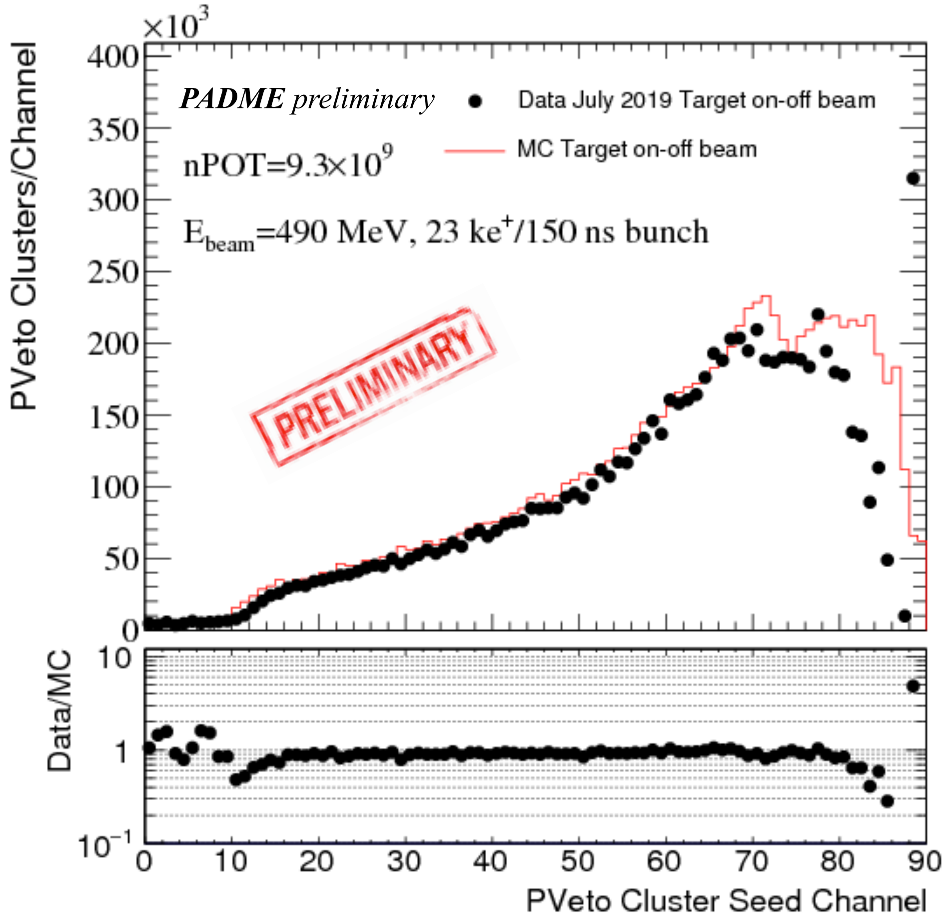


Observation of an unknown source of beam-induced background (July 2019)

Main cause likely due to the beam hitting Be-window separating BTF and PADME vacuums.
A **new mylar window** has been installed.

Ongoing physics-background study





Annihilation $e^+e^- \rightarrow \gamma\gamma$ signal clearly visible with primary beam
(selection cuts: $\Delta t<10$ ns, $\Delta\phi<20^o$, centre-of-gravity<1cm)

Bremsstrahlung yield on positron veto
(after subtraction of beam induced yield in a calibration run without target)

Expected dark photon results

[M. Raggi, "The PADME experiment", Frascati Physics Series Vol. 66 (2018)]

PADME hypothetical excluded region in the parameter space (kinetic mixing, $M_{A'}$) for Dark Photon invisible decay (for two different integrated luminosities 10^{13} and 4×10^{13} PoT)

Higher luminosity mainly limited by the positron beam intensity:

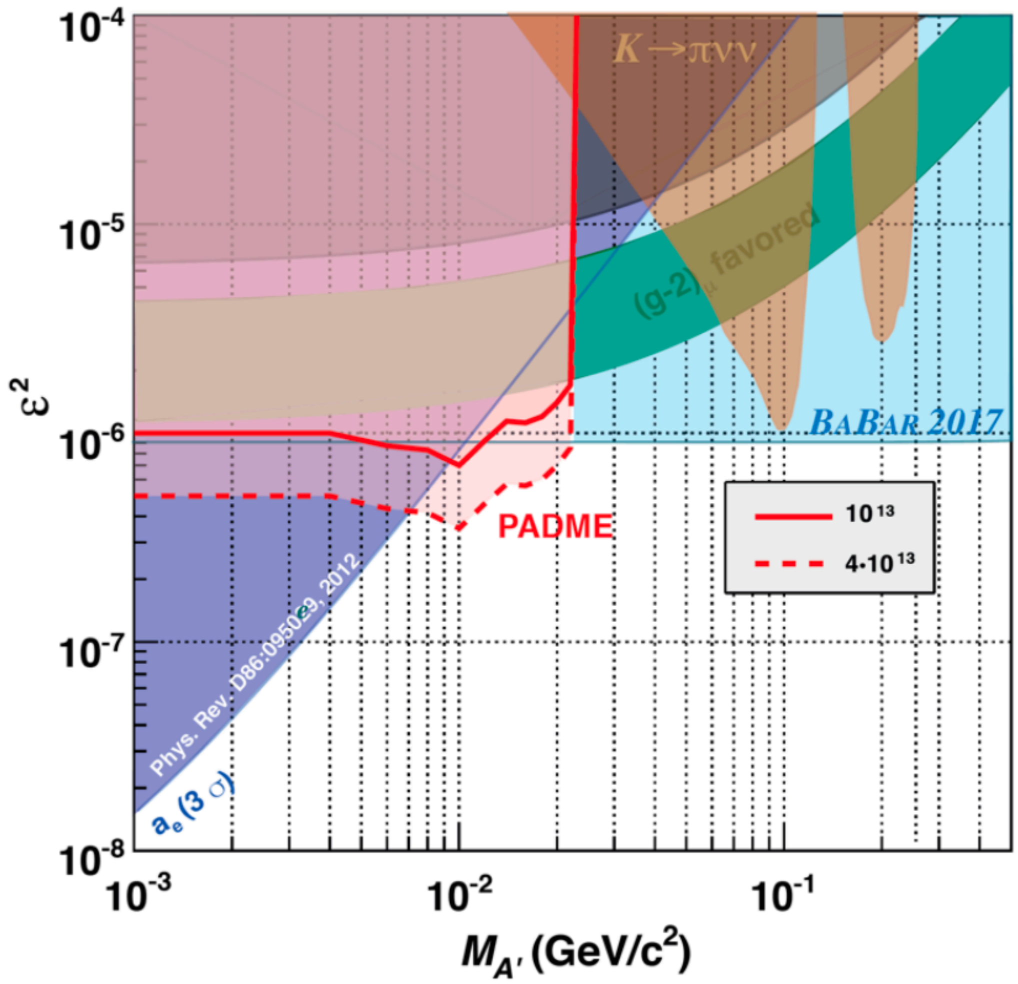
limiting pile-up and over-veto

- dictated by detectors time resolution

time structure of the positron beam

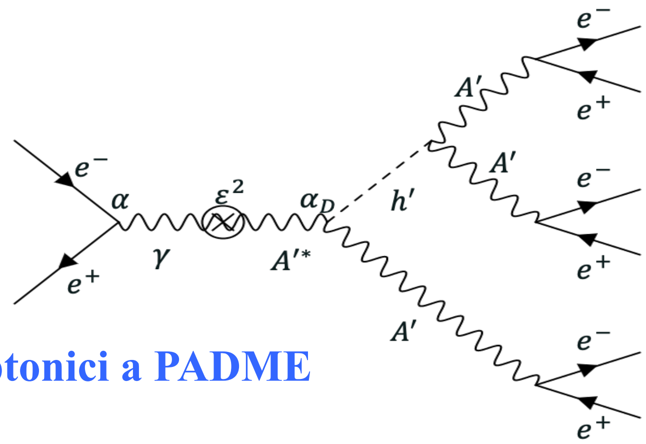
- LINAC maximum repetition rate: 50 Hz
- LINAC maximum pulse length is ~300 ns (due to RF compression)

Final sensitivity strongly depends also on control and rejection of beam-induced background



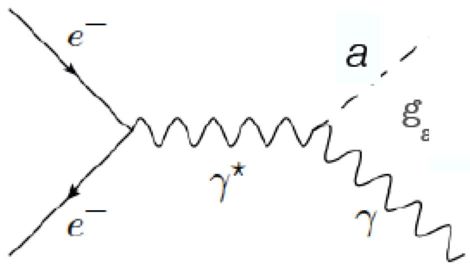
Additional searches

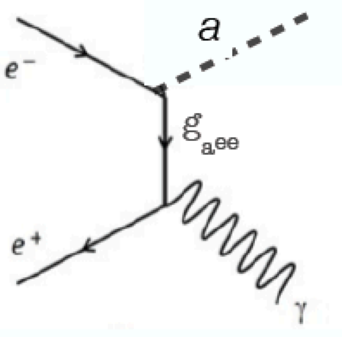
Dark Higgs: Assuming a minimal model with the dark photon mass generated by a dark Higgs, the dark photon can be produced in the Higgs-strahlung process $e^+e^- \rightarrow A'h'$



See contribution by Gabriele Martelli:
Ricerca di nuova Fisica attraverso lo studio di eventi multileptonici a PADME
https://agenda.infn.it/event/23656/contributions/120241/

Axion Like Particles (ALP):
Selection applied for the DP valid also for ALP search
(Theoretical feasibility study on going in PADME).
- ALP invisible decay or visible but long lived ALP,
  (final state: γ + missing mass)
- ALP visible decays: $a \rightarrow \gamma\gamma$ or $a \rightarrow e^+e^-$,
  (accessible final state: $\gamma\gamma\gamma$ or γe^+e^-)





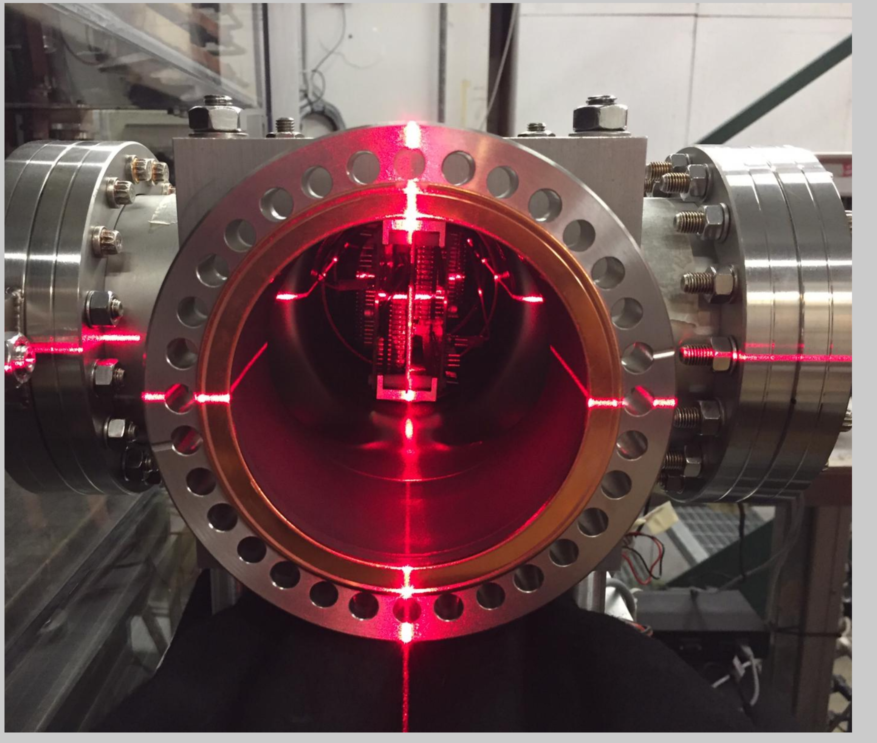
Protophobic X boson:
Signal anomaly in excited ^{8}Be and ^{4}He atomic transitions (arXiv:1504.01527 and 1910.10459)
PADME could search for a hadrophobic dark boson m_X = 17 MeV/c^2, needs:
- beam energy at 282.7 MeV; thicker target; increased multiplicity; optimized resonances finder

Conclusions and future plans

- PADME: designed and built to **search for Dark Photons** using the missing mass technique (search independent from Dark Photon decay modes) can **access other new particles** (ALP, Dark Higgs,...)

- **Successful commissioning**. Data taken helped also to understand the beam-induced background, strongly reduced after beam-line upgrade in July 2020

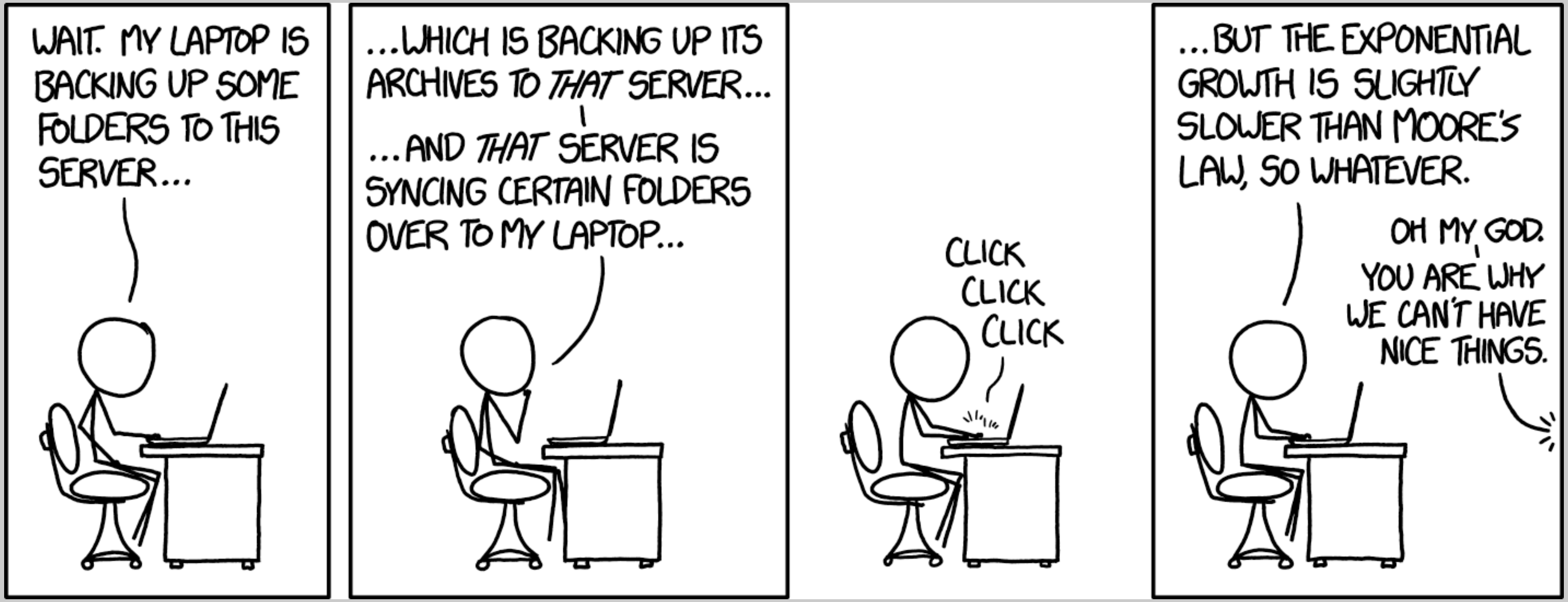
- **Data taking for physics (Run 2) is starting this week** with all anti-CoViD19 measures in place



Future ahead

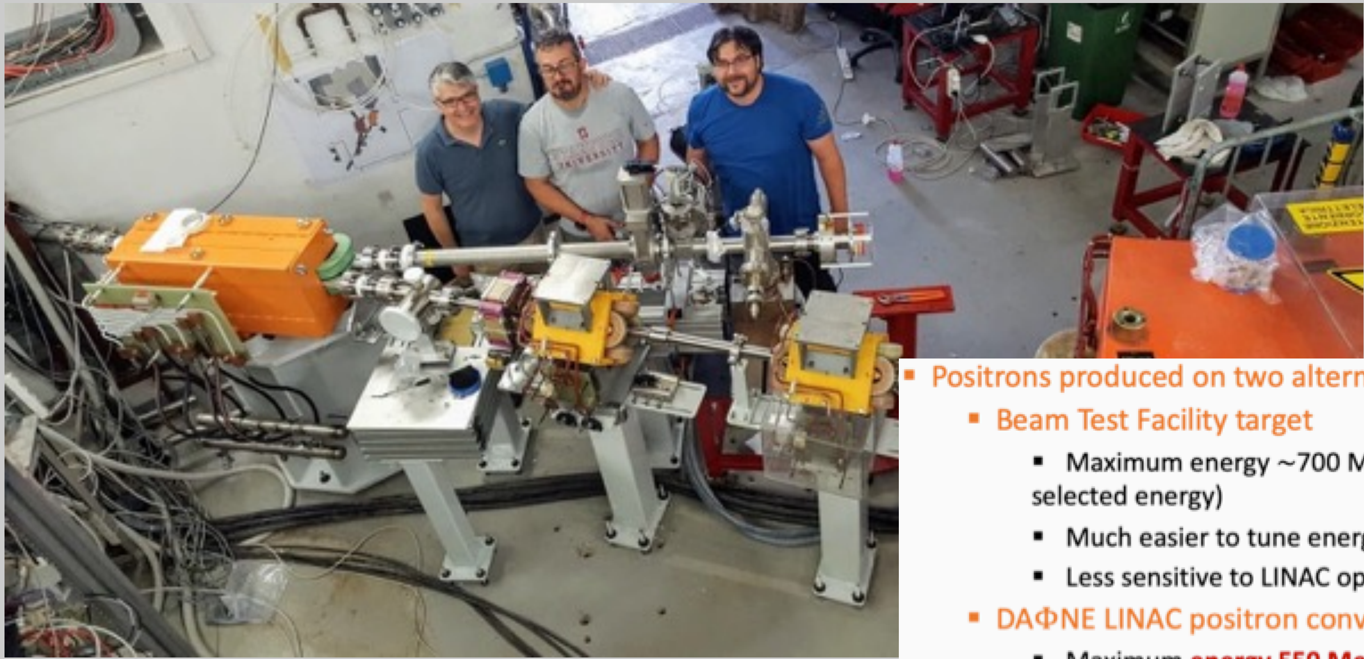
Implement non/resonant extraction of positrons from **DaΦne positron ring**,
Move PADME in the US:
- **to the Wilson Laboratory at Cornell**
(6 GeV e^+ beam, **extends by a factor of ~3 dark photon mass reach**; in case of e^+ slow resonant extraction, enhanced sensitivity to the kinetic mixing coupling.)
- **to Jefferson Lab**
(12 GeV e^+ beam, **extends by a factor of ~6 dark photon mass reach**)

Back up…



[Credits: https://xkcd.com/1718/]

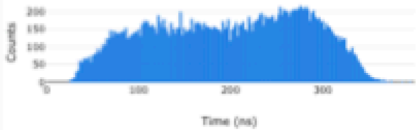
Beam line details



- Positrons produced on two alternative targets:
  - Beam Test Facility target
    - Maximum energy ~700 MeV (intensity strongly reduced increasing the selected energy)
    - Much easier to tune energy
    - Less sensitive to LINAC optics variations
  - DAΦNE LINAC positron converter:
    - Maximum **energy 550 MeV**
    - Up to 0.5 nC/pulse
    - Less beam-induced background, better momentum spread

	e^-	e^+
Maximum beam energy (E_{beam})	750 MeV	550 MeV
LINAC energy spread	0.5%	0.5%
Typical charge	2 nC	0.85 nC
Bunch lenght	1.5-200 ns	1.5-200 ns
LINAC repetition rate	1-50 Hz	1-50 Hz
Typical emittance	1 mm mrad	~1 mm mrad
Beam spot size	< 1 mm	< 1 mm
Beam divergence	1-1.5 mrad	1-1.5 mrad

- **Low repetition rate**: **50 Hz** LINAC (–1 shot/s, used for monitoring)
- Short pulses due to RF compression for getting high energy in a relatively short S-band LINAC:

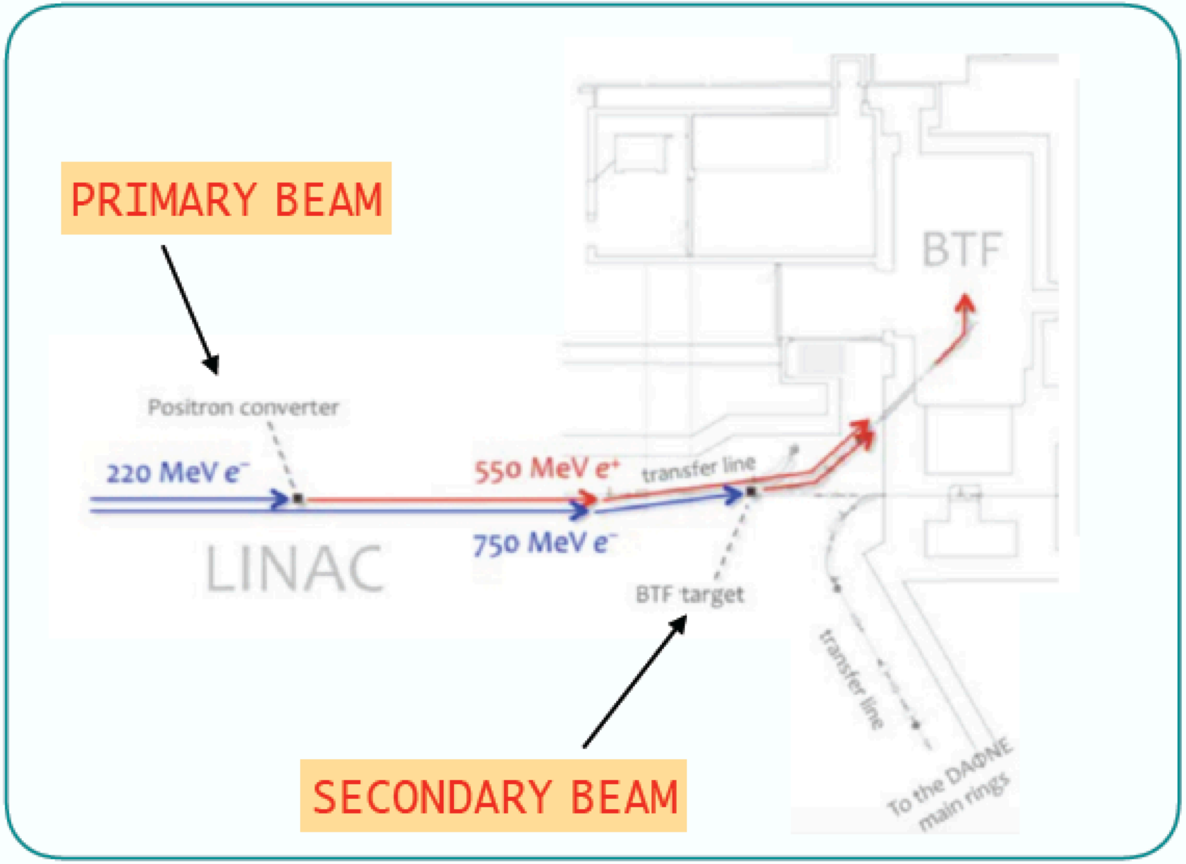


  - Generally 10 ns for injections into the collider rings
  - Optimization for PADME: **pulse length up to ~200 ns**
- Good beam quality: **2-3 mm** $\sigma_{x,y}$, **1 mrad** divergence

Primary and secondary beam

The positrons can be produced in two ways:

- directly from the LINAC thanks to a W-Re positron converter (Primary beam)
- through a Cu target placed just before the BTF experimental hall (Secondary beam)



Important features

Window which divide the vacuum of the LINAC from the one of PADME in Beryllium up to September 2019.

Improvements to the beamline of 2020

- Wider beam pipe in some parts
- Window in Mylar placed further from the detector

LESS BEAM BACKGROUND

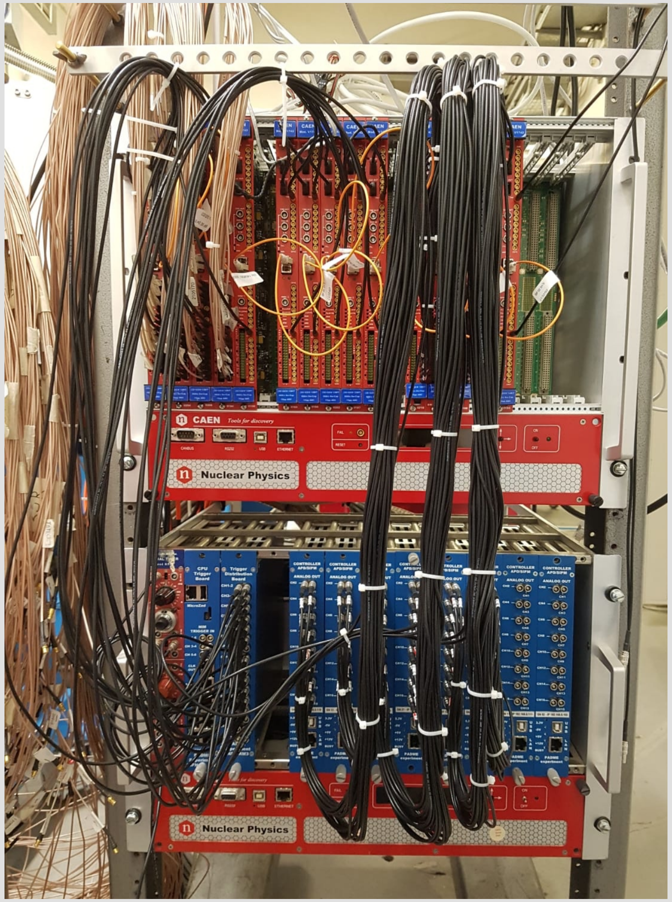
Trigger and DAQ

[J.Phys.Conf.Ser. 898 (2017) 3, 032024]

Two kinds of board provide trigger in PADME:
- CPU trigger board (6 inputs)
- Trigger distribution boards (2 × 32 channels)

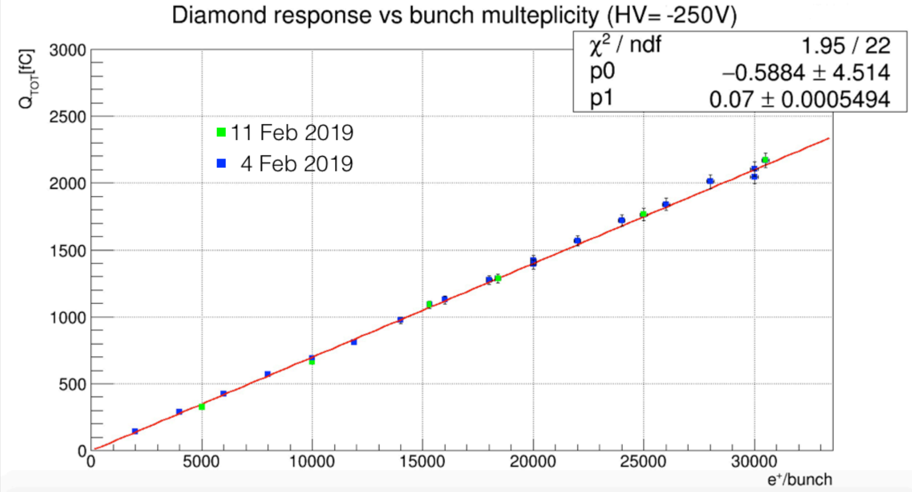
CPU trigger boards generate signal in 3 configurations:
- BTF bunch, for physics runs
- Cosmic, for calibration runs
- Random, for pedestal studies

Data are collected by **a two-level readout system**:
- L0 PCs collect data from every board and perform zero suppression (if desired)
- L1 PCs perform event merging and process raw-data into .root files

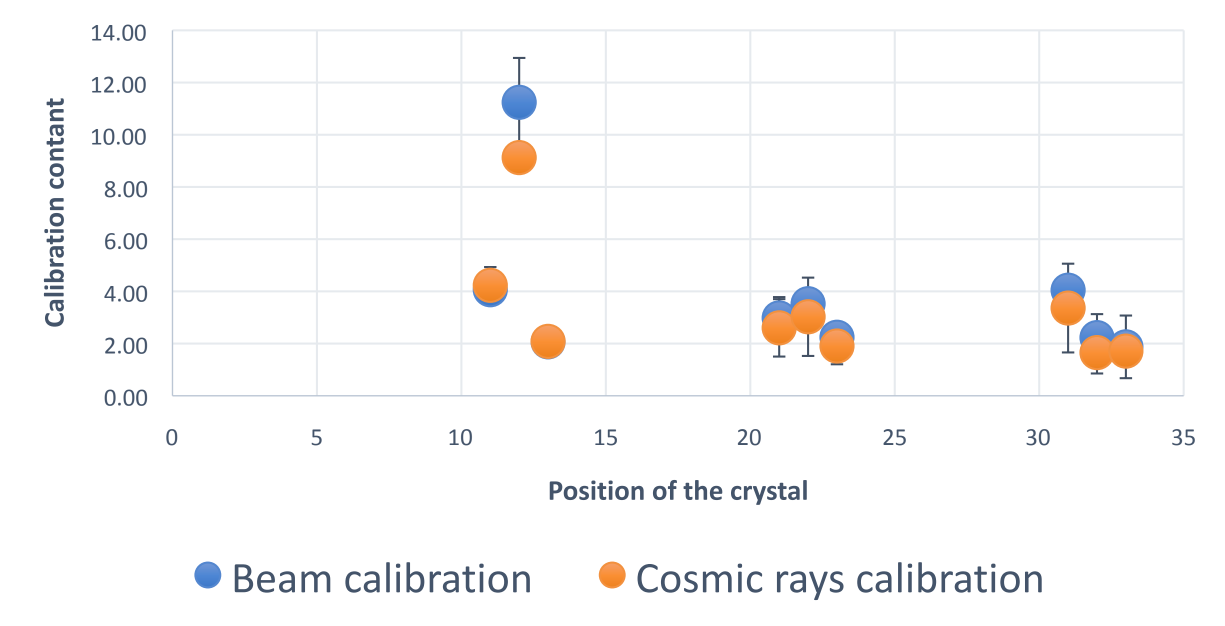


Calibration studies

Target: calibrated at the end of commissioning, very good reproducibility and linearity
ECAL: first order calibration on scintillating units before calorimeter assembly. Cosmic ray calibration used to check units calibration
SAC: beam calibration performed on 9/25 crystals. The results from the beam calibration were cross-checked with cosmic rays calibration

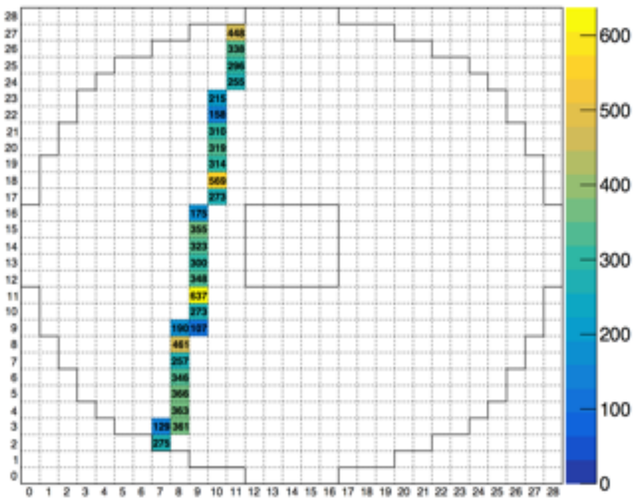


Target: collected charge vs beam multiplicity (evaluated by lead glass Cherenkov calorimeter)

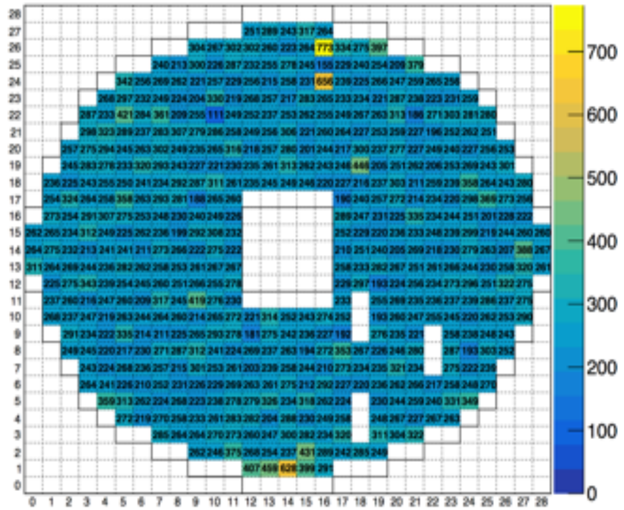


SAC: calibration constants obtained through beam calibration (blue) and through cosmic rays calibration (orange)

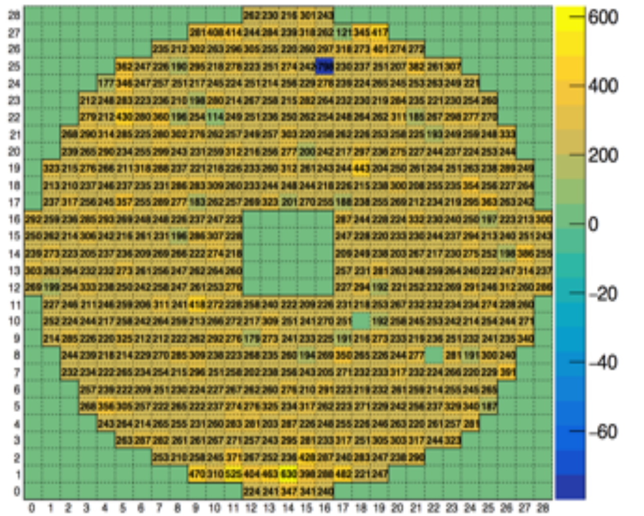
Calorimeter performance



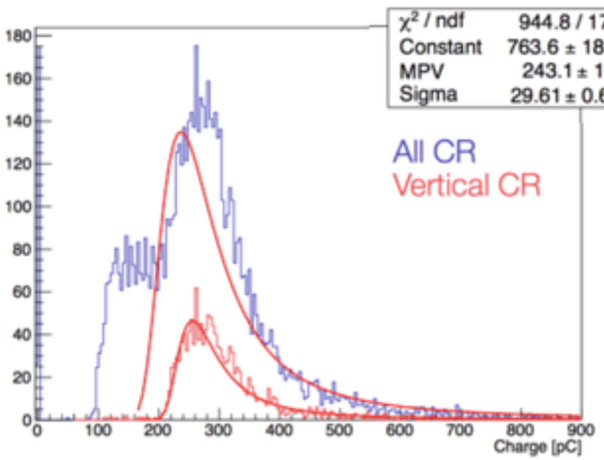
Cosmics calibration of calorimeter

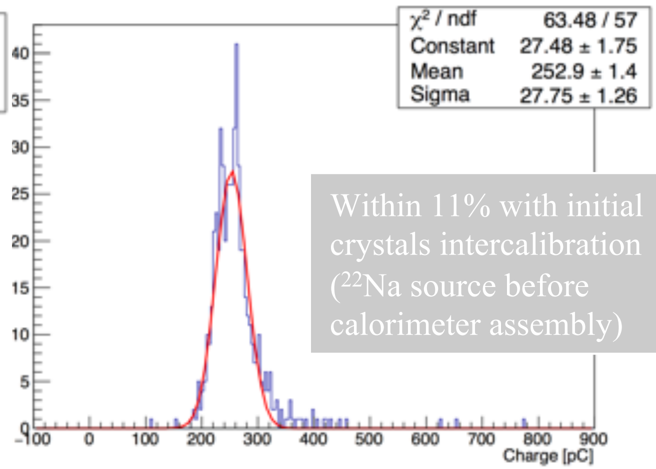


Full calibration map

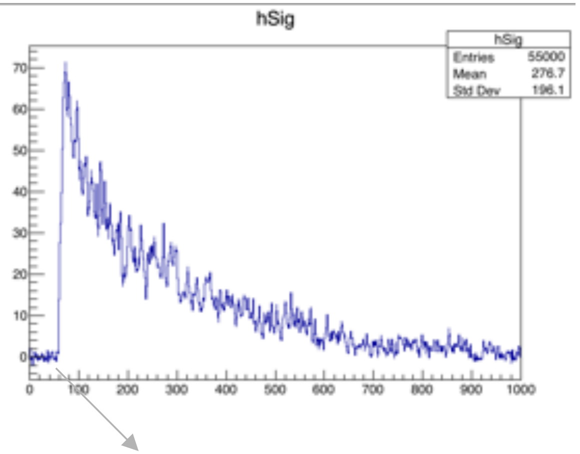


<1% dead/very inefficient cells



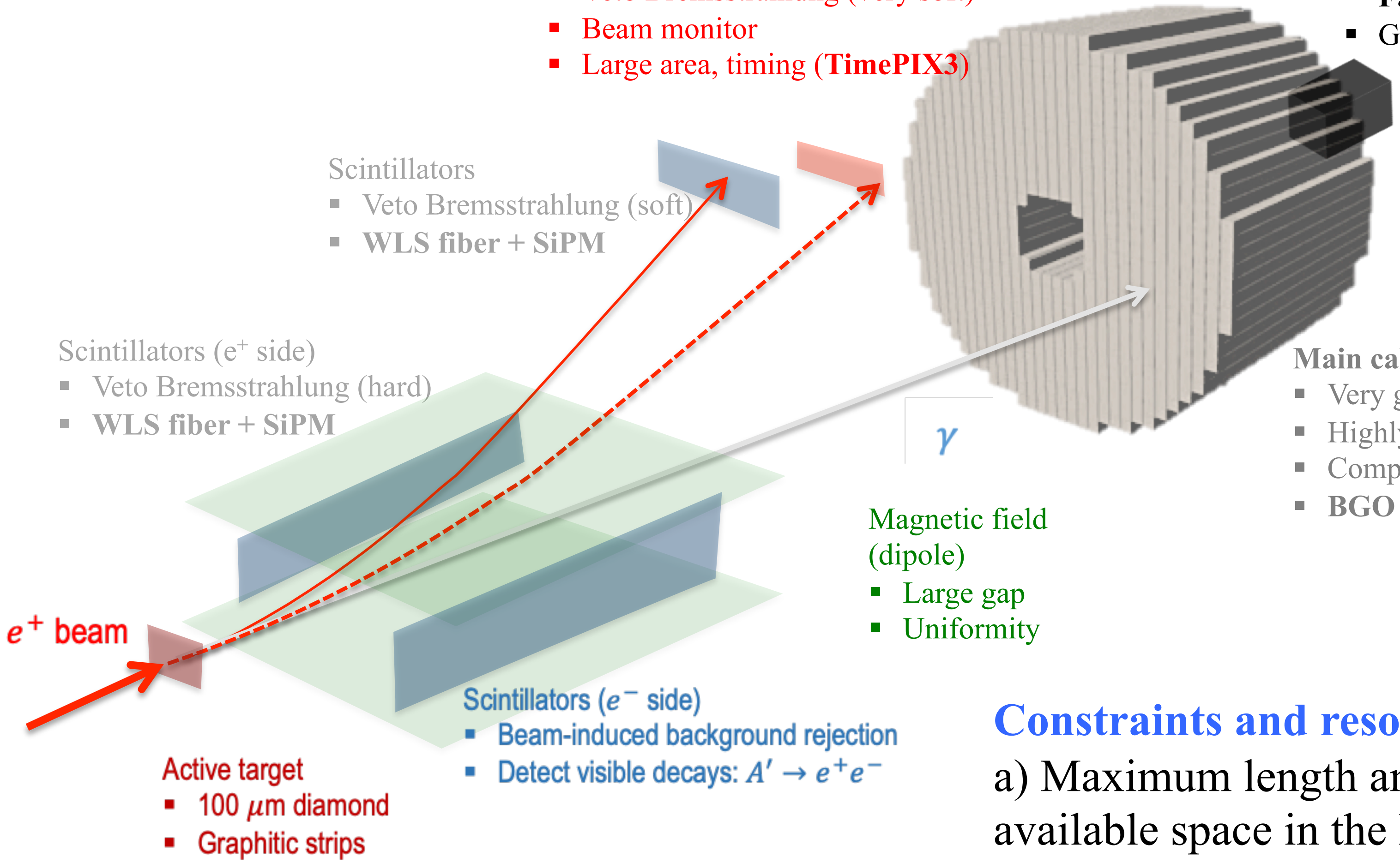


Within 11% with initial crystals intercalibration (^{22}Na source before calorimeter assembly)



Pedestal from the first sample width ~550 keV

Experimental setup



Small-angle calorimeter
- Veto Bremsstrahlung (hard)
- Recover 3 photons events acceptance
- **Fast** (Cherenkov)
- Good light yield: **PbF_2**

Main calorimeter
- Very good **energy resolution**
- Highly **segmented**
- Compact
- **BGO** crystals, readout by PMT's

Constraints and resources

a) Maximum length and transverse size: available space in the BTF hall

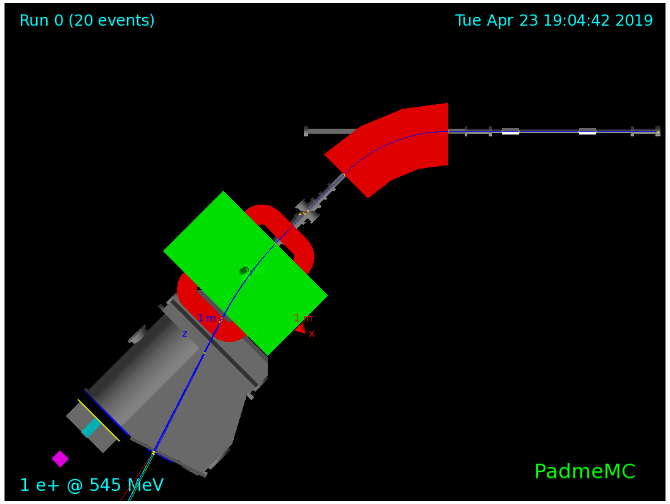
b) Magnet (moderate, <0.5 T, field needed)

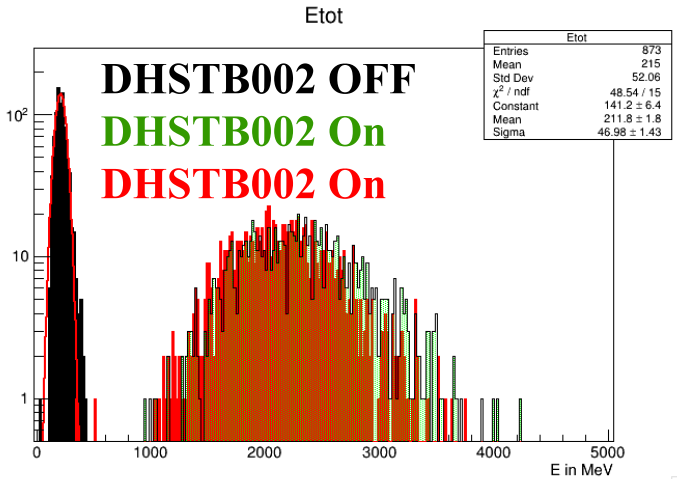
- Large gap **dipole from CERN** (23 cm)

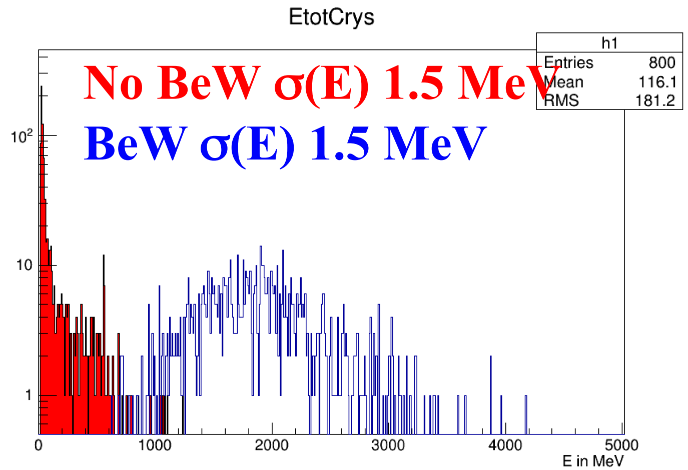
c) Available **BGO crystals from L3 ECAL**

Understand beam background

Observation of an unknown source of beam-induced background during July 2019
The main cause for beam background seemed to be due to the beam hitting beryllium window separating BTF vacuum from PADME vacuum.
Beam energy resolutions incompatible with the measured beam spot
Background energy distribution in data is very similar to Monte Carlo (MC) one when using a beam with an energy resolution of 1.5 MeV
A new MC simulation also introduced the magnet geometry of the beam line and the target support



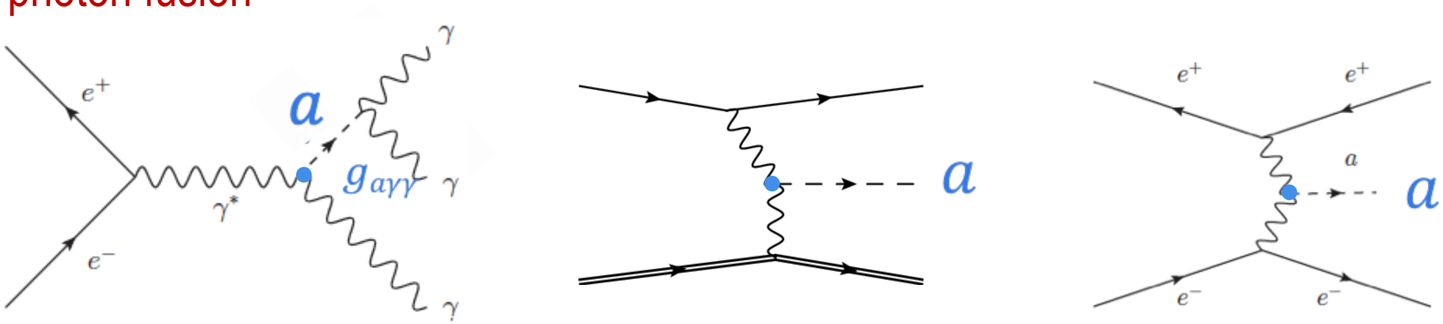




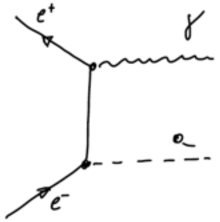
MC

ALPS at PADME

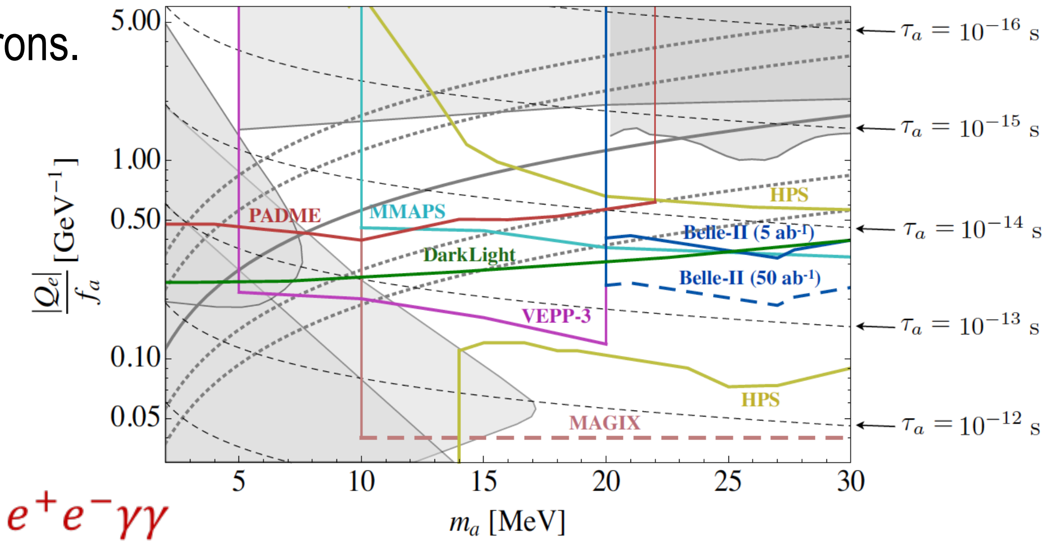
- For axion-like particles coupled to photons different production mechanisms: annihilation and photon fusion



- More promising for PADME ALPs coupled to electrons.



$$\mathcal{L}_a^{\text{eff}} \supset \frac{Q_e}{f_a} m_e \, a \, \bar{e} i \gamma_5 e \,,$$



- Final states observable at PADME:
  - Visible ALP decays ($a \to \gamma\gamma$): $\gamma\gamma\gamma$, $e^+\gamma\gamma$, $e^+e^-\gamma\gamma$
  - Invisible ALP decays: γ + missing mass

D.S.M. Alves and N. Weiner JHEP07(2018)092

- Main background is $\gamma\gamma$, but limited by invariant mass (24 MeV)
- Studies ongoing at LNF theory division, promising (good granularity and resolution of calorimeters)