Dark sector searches in positron annihilations

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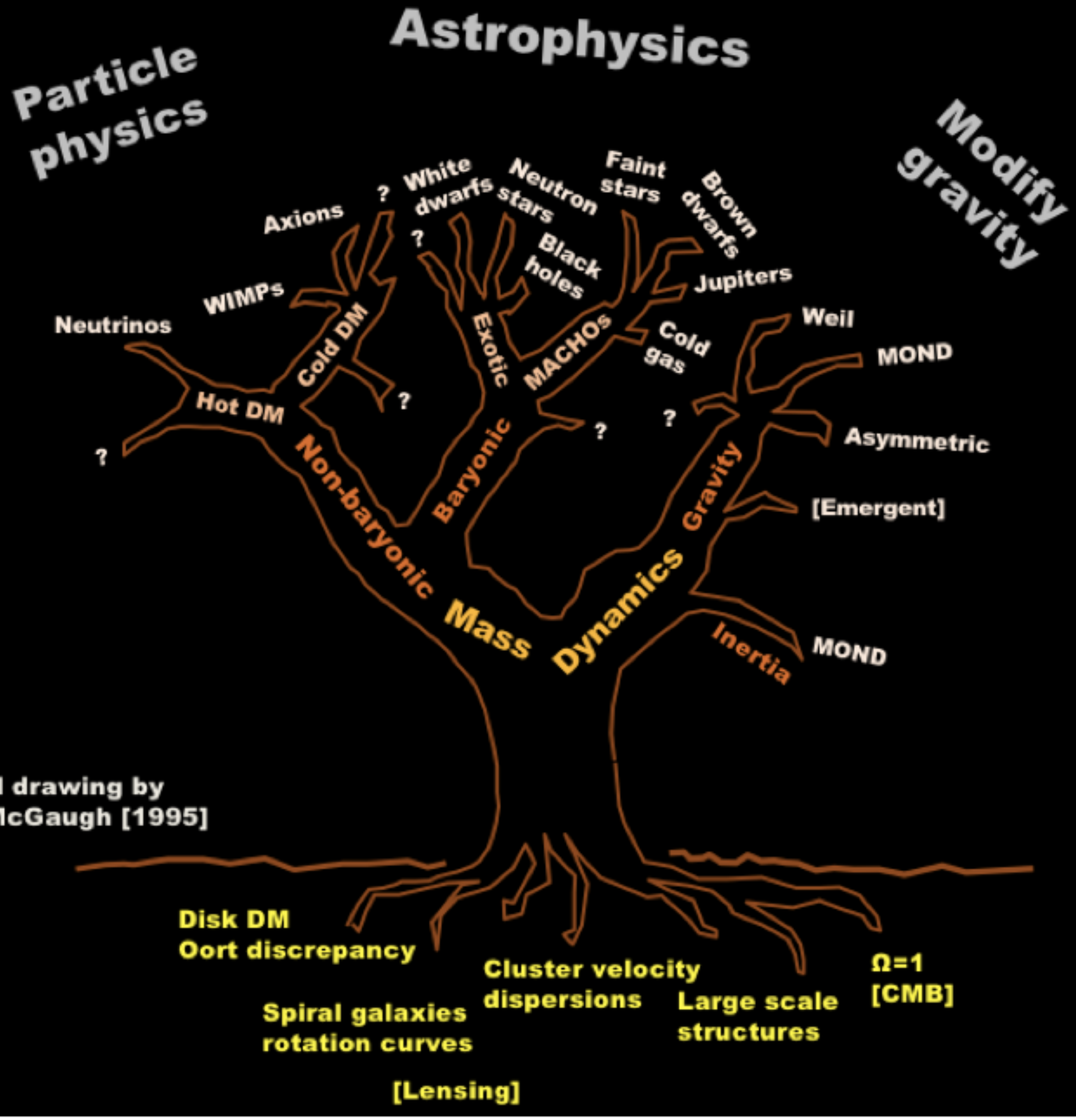
We (particle physicists) are **eagerly** looking for the **dark matter**, but

... Can it be **light**?
... Can we find it at **accelerators**?

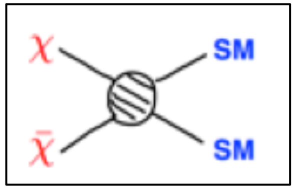


Original drawing by
Stacy McGaugh [1995]

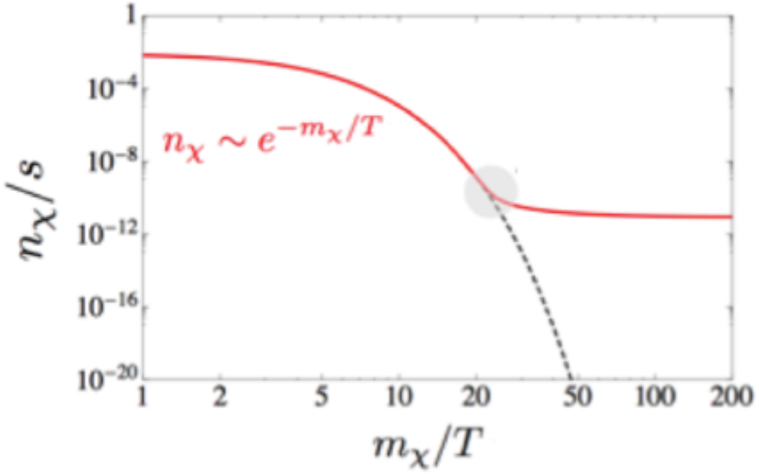
Relic DM and freeze-out

Thermal history of the Universe

- DM particles χ were created thermally in the early universe
- They stay in chemical equilibrium with SM particles through $2 \rightarrow 2$ annihilations



- At thermal equilibrium same number density as photons
- As the Universe cooled, the number of DM particles and photons would decrease **together**, as long as $T \gtrsim m_\chi$
- When the temperature dropped **below** $\boldsymbol{m_\chi}$ the number density $\boldsymbol{n_\chi}$ started to exponentially decrease
- No relics today, unless **transition out of equilibrium** or "**freeze-out**", when the probability of annihilation becomes too **small** fixing n_χ (before neutrino decoupling and BBN)
- The WIMP "miracle" is just that: $\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$



- **Non-thermal** production is also possible:
  - From the decay of heavier particles
  - During a phase transition
  - Production at the end of inflation
  - Asymmetric annihilation
- Or we can have a **new, very weak interaction**

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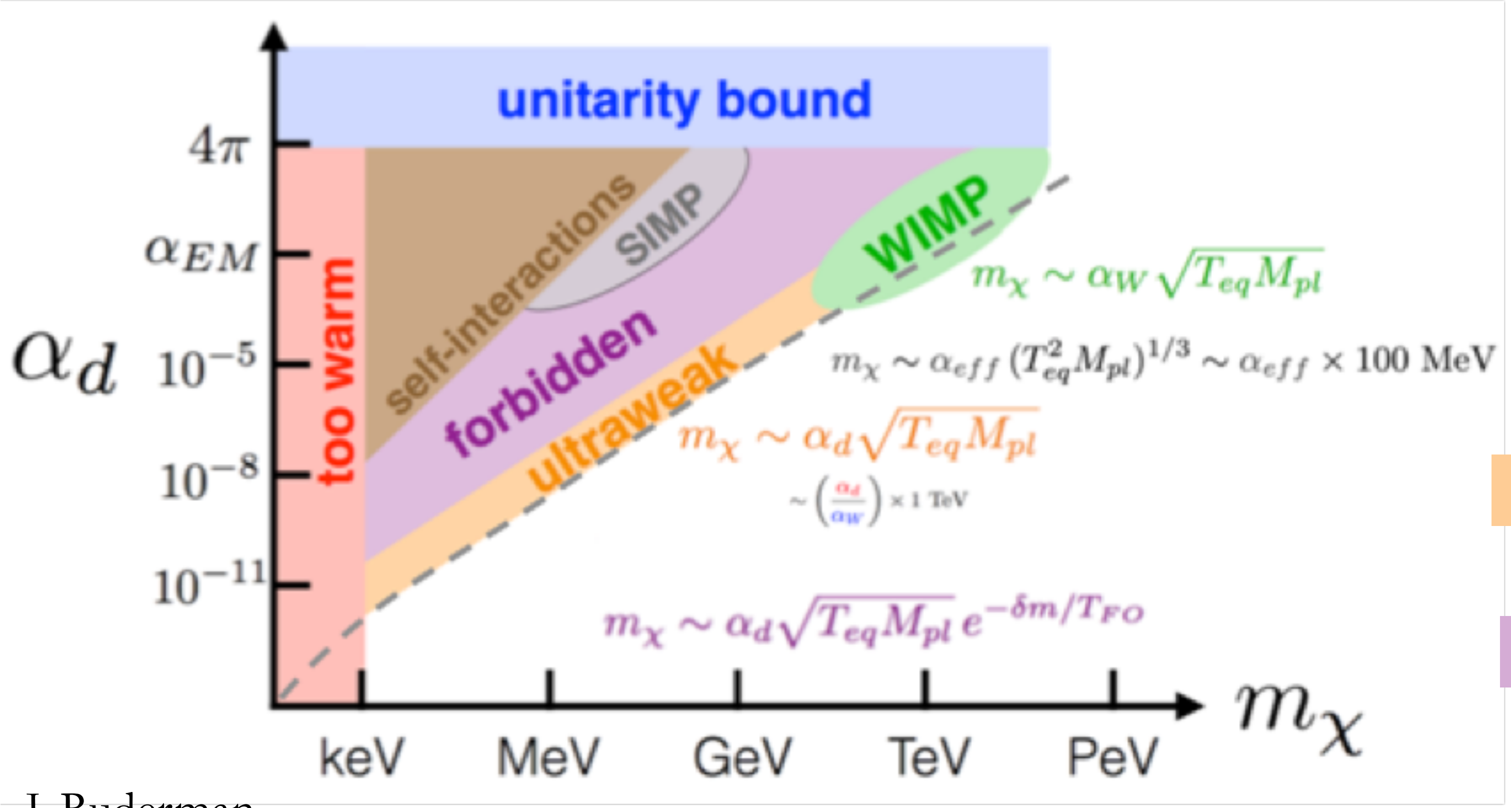
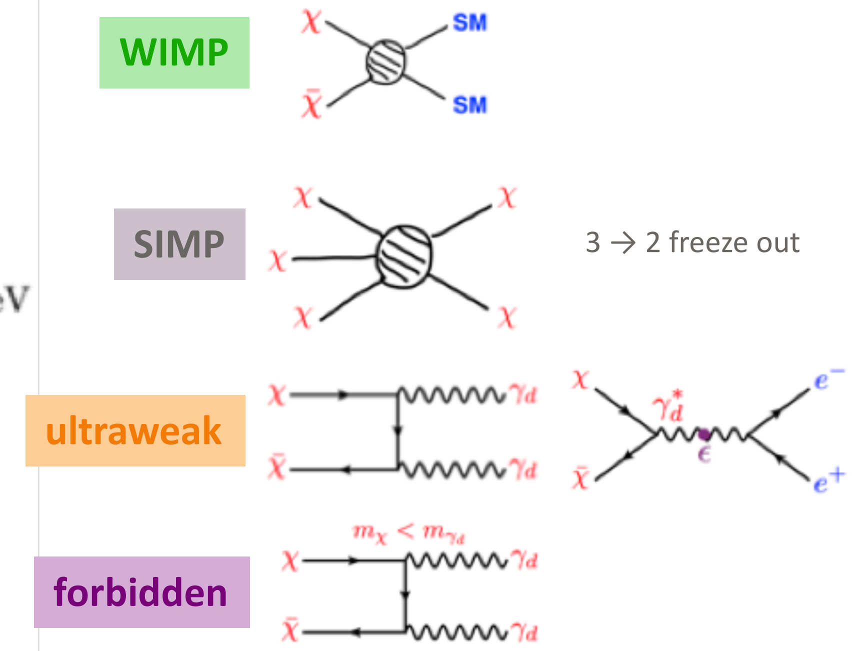
Dark freeze-out



J. Ruderman



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Dark force & dark sector

Dark (or hidden) sector:

DM particles **completely neutral** under SM forces, with **new interactions**

Portal:

A mediator particle of the **new interaction**, interacting **very weekly** with SM particles

DM, dark sector and portals

Dark (or hidden) sector:

DM particles **completely neutral** under SM forces, with **new interactions**

Portal:

A mediator particle of the **new interaction**, interacting **very weekly** with SM particles

- The portal can be scalar, fermion, vector, axion…
- The relic dark matter (DM) can be either a portal particle or just coupled to a portal via a hidden interaction
- Different portals can co-exist: e.g. dark photon and Higgs, or dark photon and axion
- Dark sectors invoked not only for the DM problem, but also for solving other puzzles:
  - Muon $g-2$ anomaly, proton radius, inflation, ^{8}Be anomaly, …
- The vector portal is the **simplest** both from the theory [additional U(1) gauge symmetry] and experiment point of view [just replace an ordinary photon with a dark one in any QED process]
- Different mechanism with respect to the WIMP **freeze-out** are possible for getting the right amount of relic DM
- Wide **mass** and **coupling** ranges

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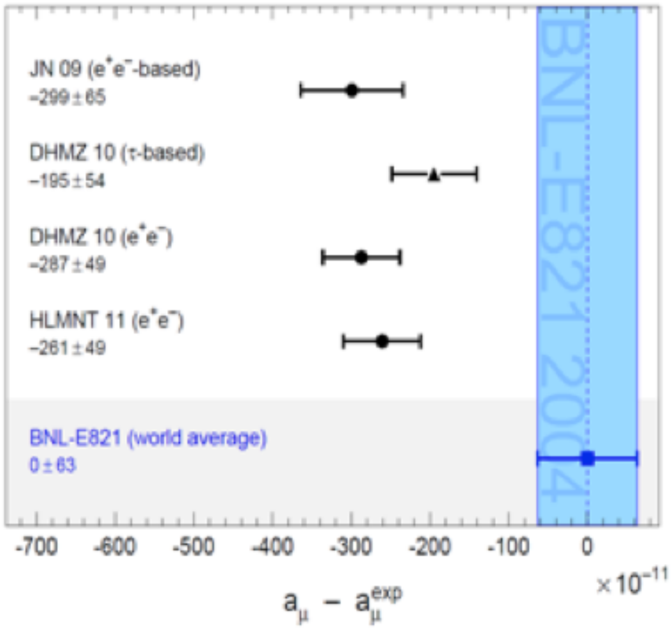
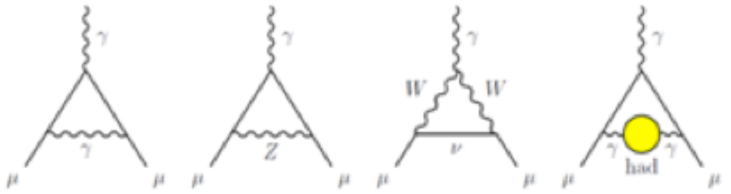
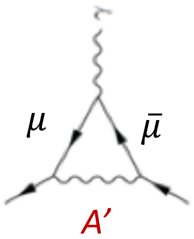
Muon g–2 SM discrepancy



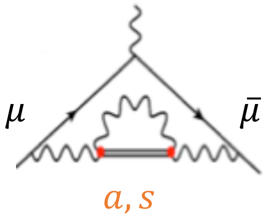
g–2 in the Standard Model



g–2 and A'

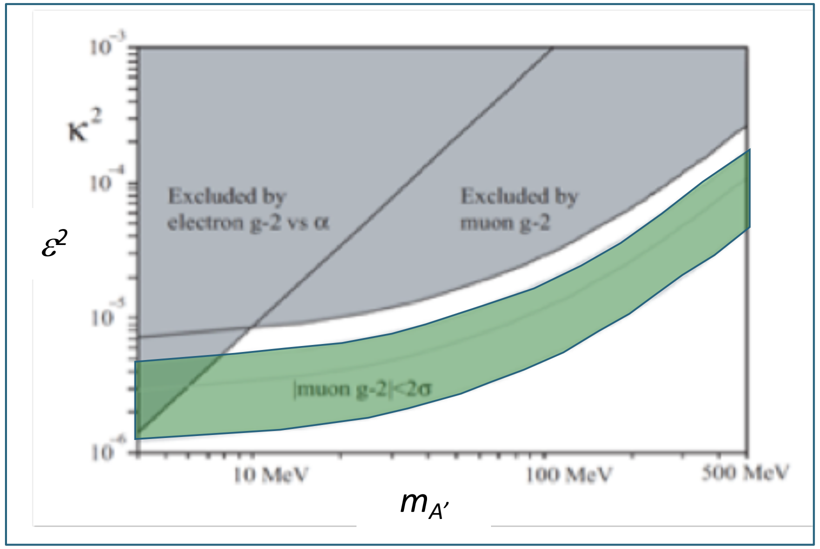


g–2 and ALP



- 3σ discrepancy between theory & experiment
- Additional diagram with dark photon exchange can fix the discrepancy (with sub-GeV A' masses)

$$\Delta a_\mu = \frac{\varepsilon^2 \alpha}{2\pi} \times \begin{cases} 1 & \text{for} \quad m_\mu \ll m_{A'} \\ \frac{2m_\mu^2}{3m_{A'}^2} & \text{for} \quad m_\mu \ll m_{A'} \end{cases}$$



- Theoretically very attractive…
  - Spoiler alert: parameter space for dark photon already excluded, **at least with present g–2 value…**
  - Prejudice: let's try to introduce something solving **also another** problem

- … eagerly waiting for the new g–2 measurement

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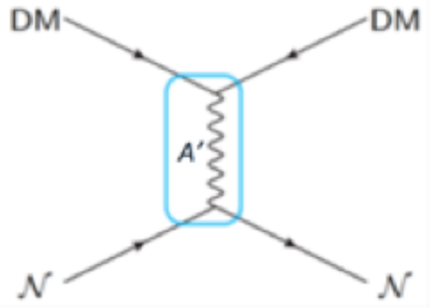
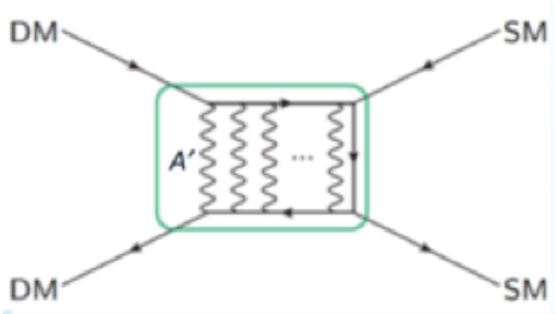
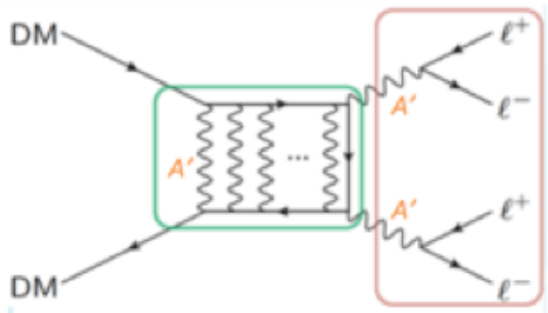
More motivations



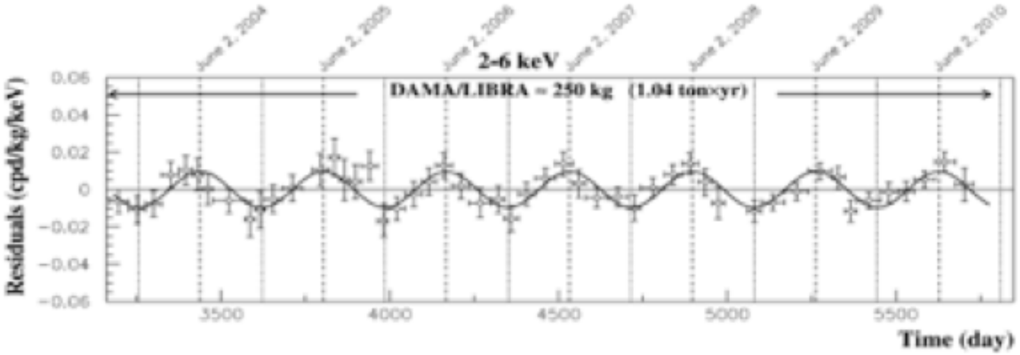
A dark photon would affect both
DM **scattering** on nuclei



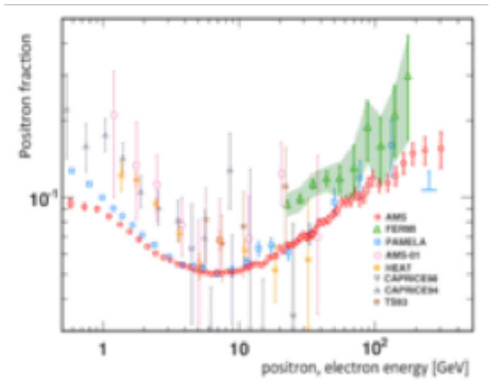
and DM **annihilations**

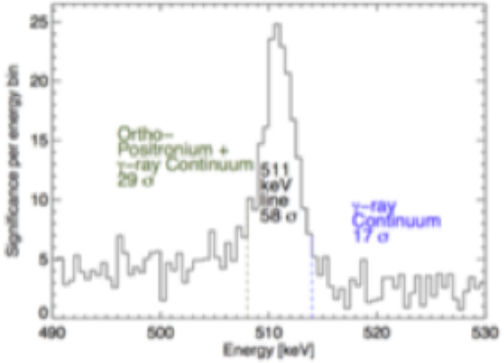


e.g. making them naturally
lepto-philic



- DAMA/LIBRA modulation





- Positron eccess from PAMELA, FERMI, AMS-01
- 511 keV line form INTEGRAL/SPI
- …

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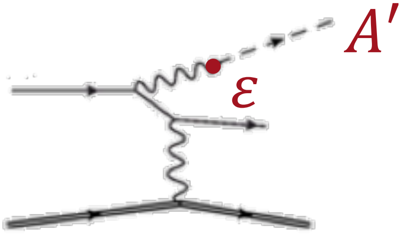
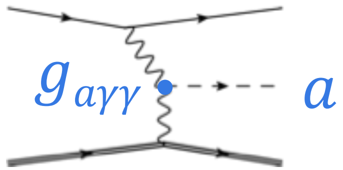
Dark photon production and decay

Production:

- In any process with an ordinary photon, we can substitute it with a **dark photon** (*A'*): *A'*-strahlung, π^0,η decays, e^+e^- annihilations

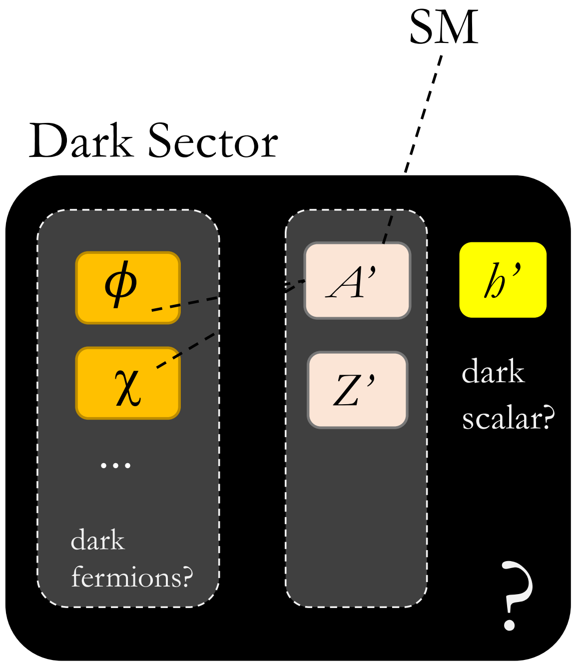
- In the case of **axion-like particles**, we also have the Primakov production mechanism





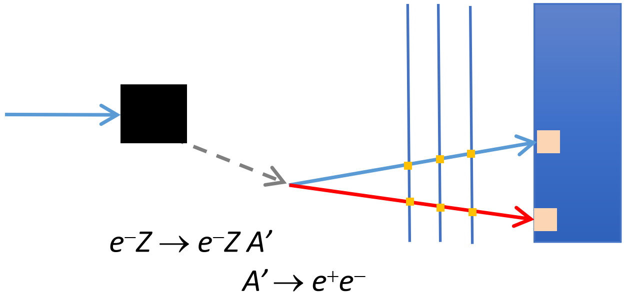
Decay: two possibilities

- Looking for decays to SM particles (**lepton pairs** or hadrons if above threshold) or the so-called "**visible**" decays; limits generally rely on the assumption that ***A'*→ leptons** is dominant, i.e. the dark photon is the **lightest particle in the dark sector**
- Not looking at the final state, removing the latter assumption, relying on missing energy/momentum or missing mass for identifying "**invisible**" decays ***A'*→ $\chi\chi$**



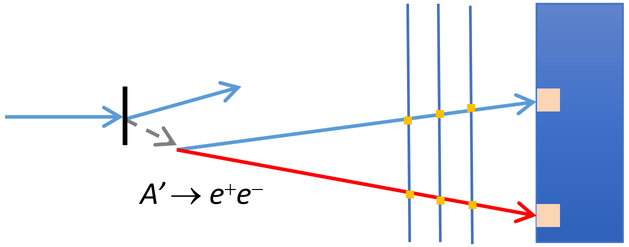
Dark photon experiments at (electron) accelerators

visible decays



Dump

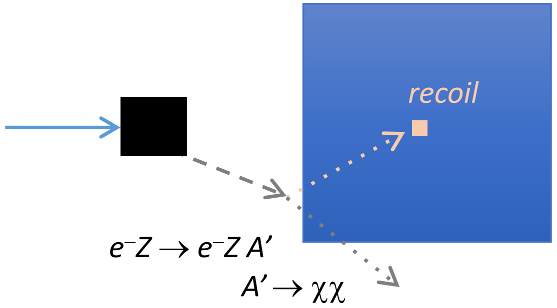
(E-137, E-141, E-774, Orsay, ...)



Thin target

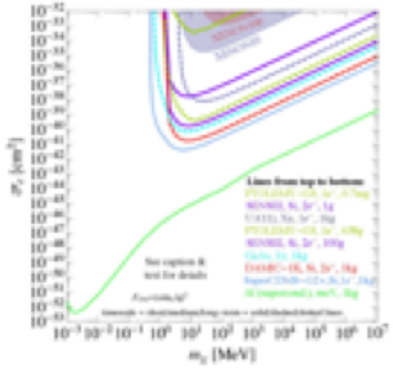
(APEX, HPS, A1)

invisible decays



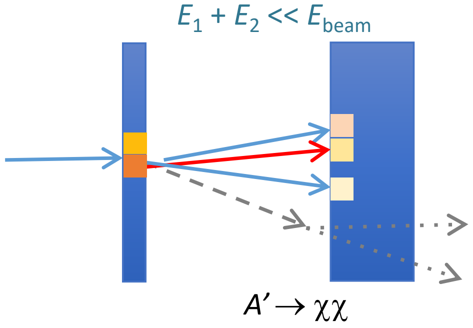
Dump+recoil

(BDX)



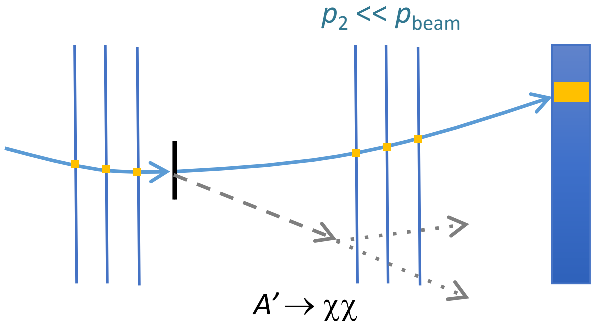
Reminder:
DM-electron cross section

Additional parameters: $\boldsymbol{\alpha_D}$ and $\boldsymbol{m_\chi}$



Missing energy

(NA64)

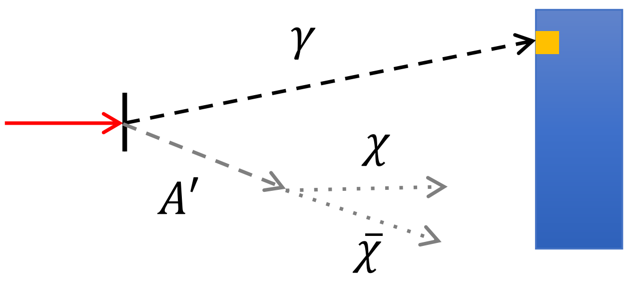


Missing momentum

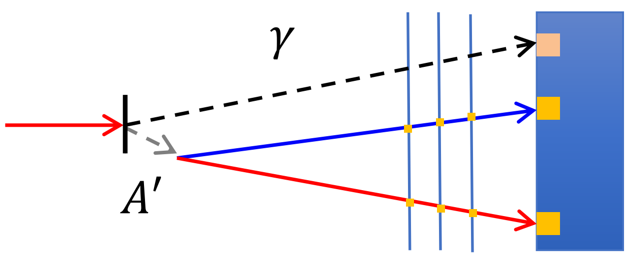
(LDMX)

Positron annihilations

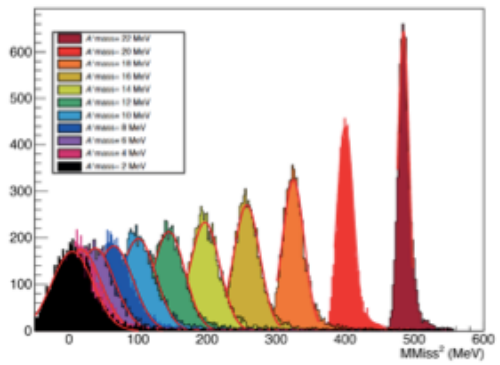
invisible decays



visible decays



- No assumption on the *A'* decays and coupling to quarks (just assume coupling to leptons for production)
- Limits the coupling of **any new light particle** produced in annihilations: scalars (*h'*), vectors (*A'*) and ALPs
- Of course one can also look for e^+e^- pairs in the final state



- To compute $m^2_{miss} = (\underline{P}_{\gamma} - \underline{P}_{e+})^2$ we need a **positron beam** with **known 4-momentum**, and:
  1. Small energy and angular spread
  2. Small transverse spot
- We also need to precisely measure the **photon momentum**

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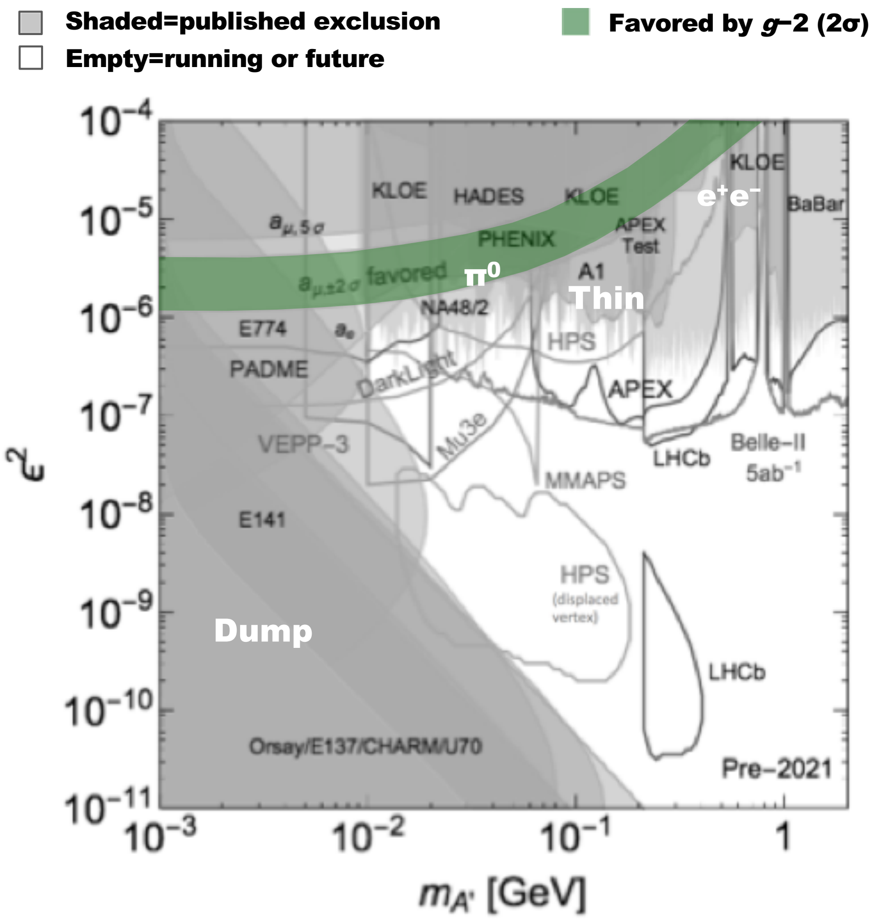
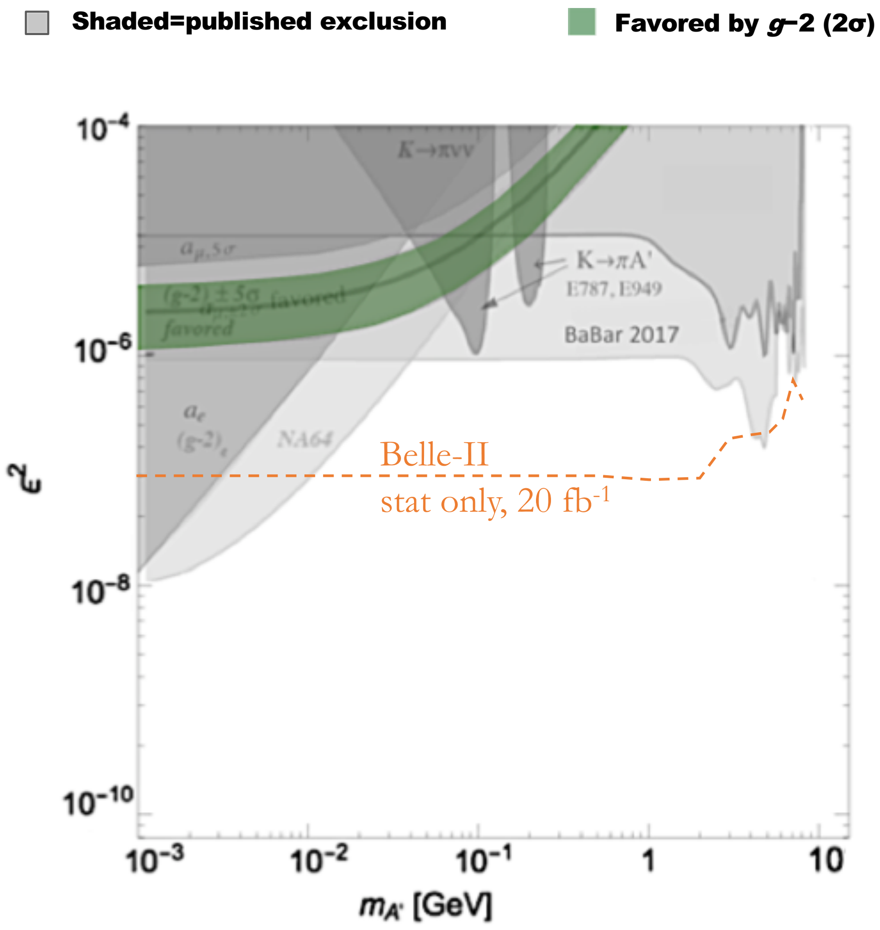
Dark photon searches status: visible



- Many experimental techniques with different production mechanisms
- Basic assumptions:
  - Dark photon **kinetically mixed** with ordinary photon (universal coupling)
  - Visible decays: $BR(A' \rightarrow e^+e^-) \sim 1$
- g-2 favoured band **excluded**

Dark photon searches status: invisible



- NA64: e^- dump **missing energy**
- BaBar : $e^+e^- \rightarrow \gamma +$ **missing mass**

Competition is though:

- NA64 increasing the statistics
- Belle-II starts taking data **this year** (see De Sangro's talk)

Is a dark force already with us?

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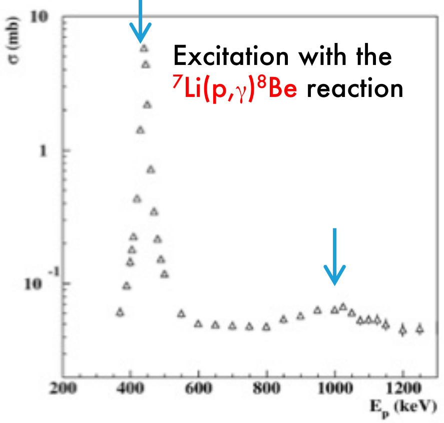
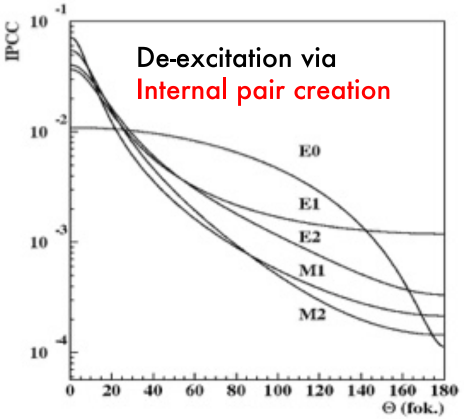
^{8}Be anomaly

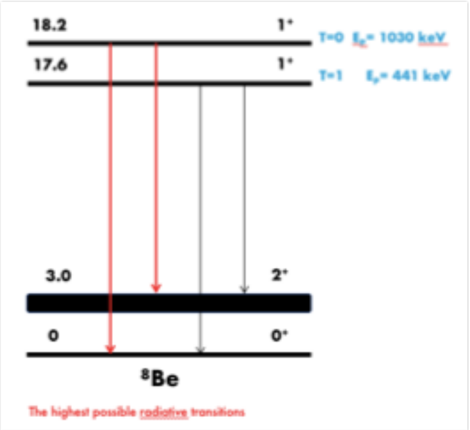
- **^{7}Li(p, γ)^{8}Be** reactions, using ≈1 MeV p beam, with **excellent energy spread**
- Measure **rate vs. angle** of **e+ e− internal pair conversions**
- An **anomalous bump** in the angular distribution, for one transition energy

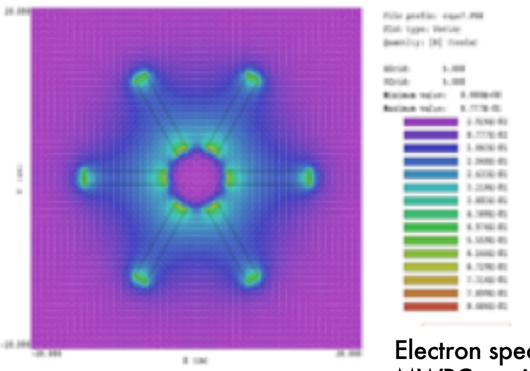
Experiment performed at MTA Atomki, Decrebecen (Hungary)

Improved experiments proposed in Purdue (PRIME Lab), Notre Dame U. (NSL) and other labs.





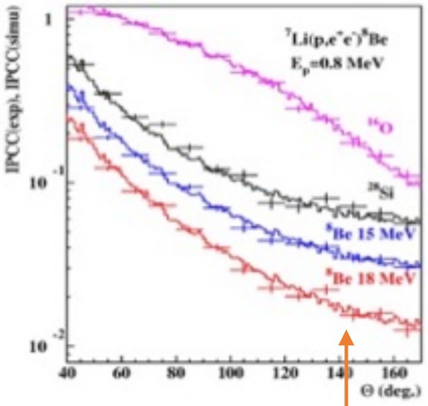




Electron spectrometer
MWPC + scintillators

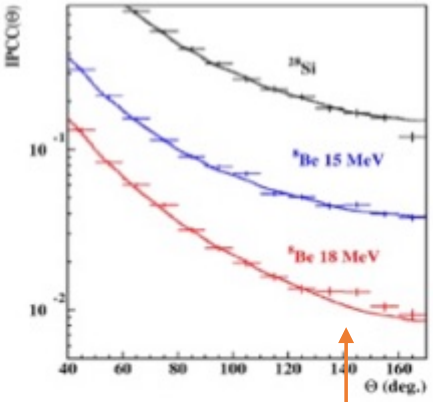
Off resonance

E$_p$=0.8 MeV

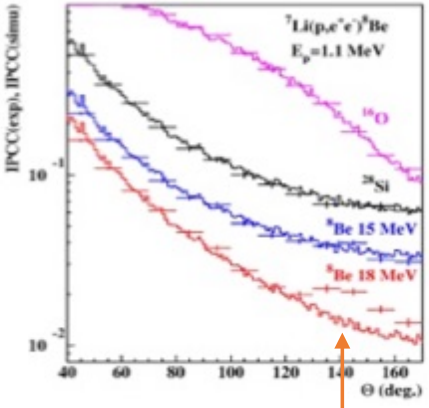


On resonance

E$_p$=1.04 MeV



E$_p$=1.10 MeV



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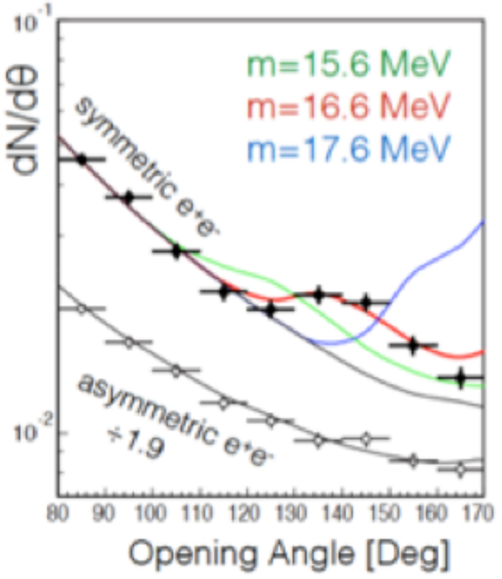
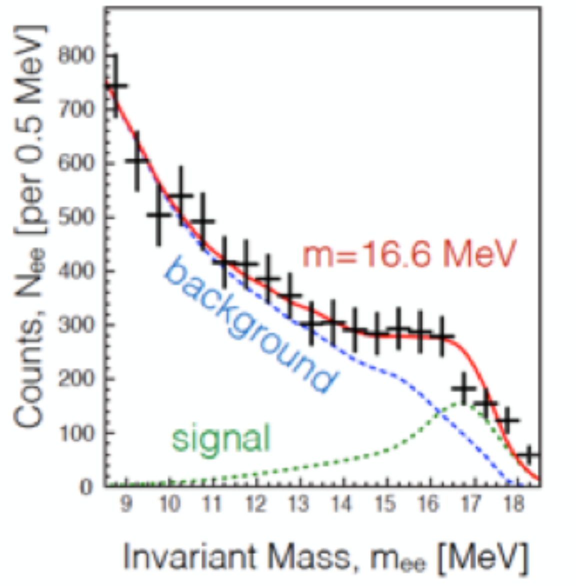
A proto-phobic boson?

6.8σ excess, can be interpred as a **new boson** (vector is favored) m=16.6 MeV

A. Krasznahorkay et al., "Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson",

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

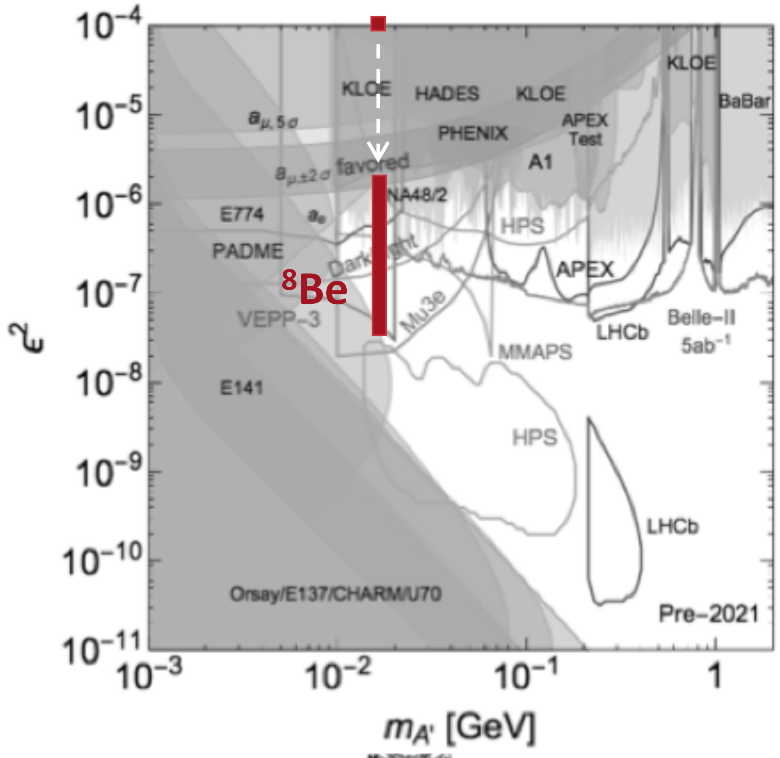




Not compatible with present limits: too high coupling unless we give up universal coupling of the dark photon to quark and leptons

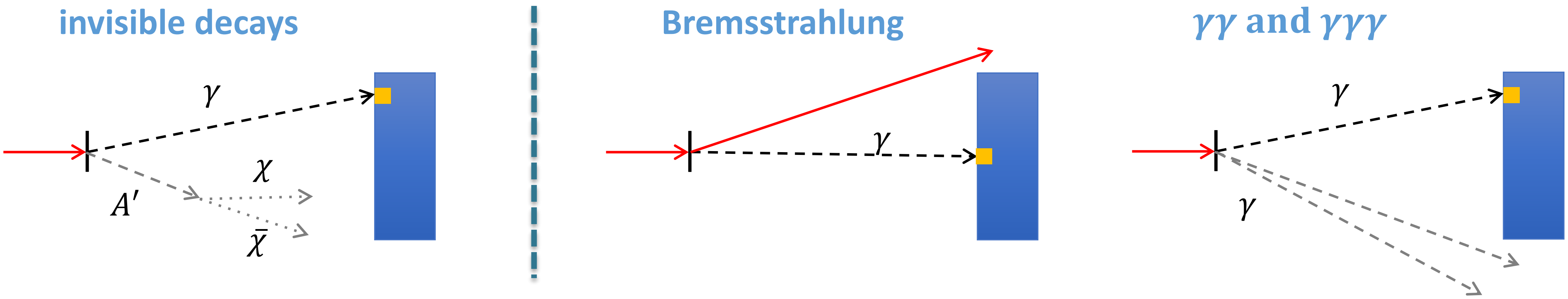
J. Feng et al., "Protophobic Fifth Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions",

Phys. Rev. Lett. 117, 071803 (2016)

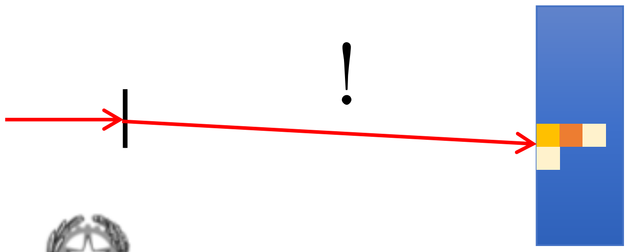


Can PADME give an answer?

Backgrounds

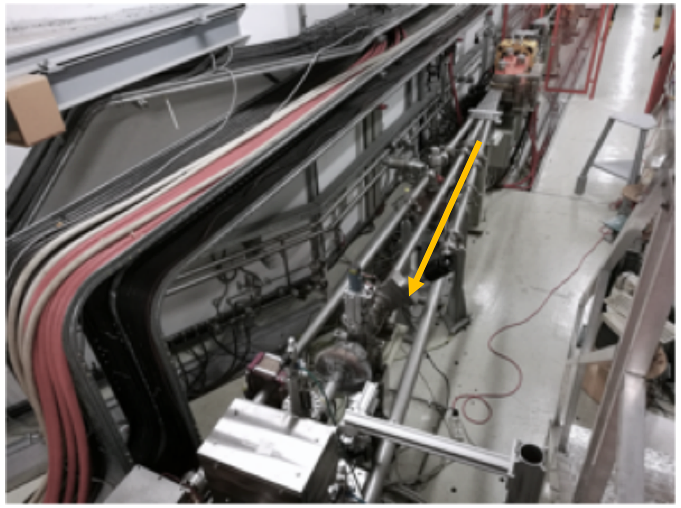


- Measure precisely the photon position **and** energy
- Ermeticity
- Low Z target optimizes annihilation/Bremsstrahlung
  - H and He (gas), Li, Be, B, C, …
- Bremsstrahlung poses a strong rate constraint on the photon detector
  - Especially at small angles
- We have to get rid of the **positron beam**
  - Sweeping magnetic field
  - Through hole
  - Internal (gaseous) target (**Darklight**, **VEPP-3**)

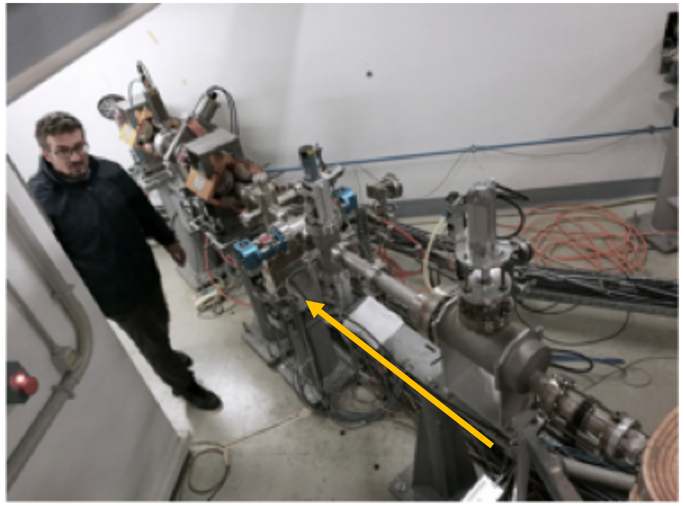


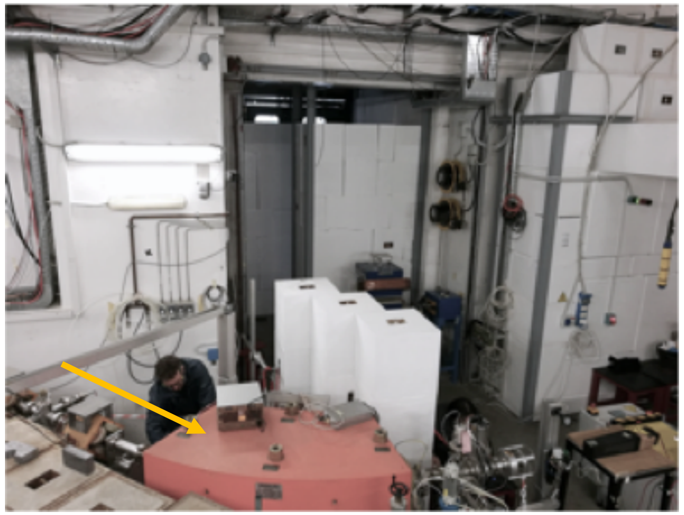
Positrons from Frascati LINAC


LINAC



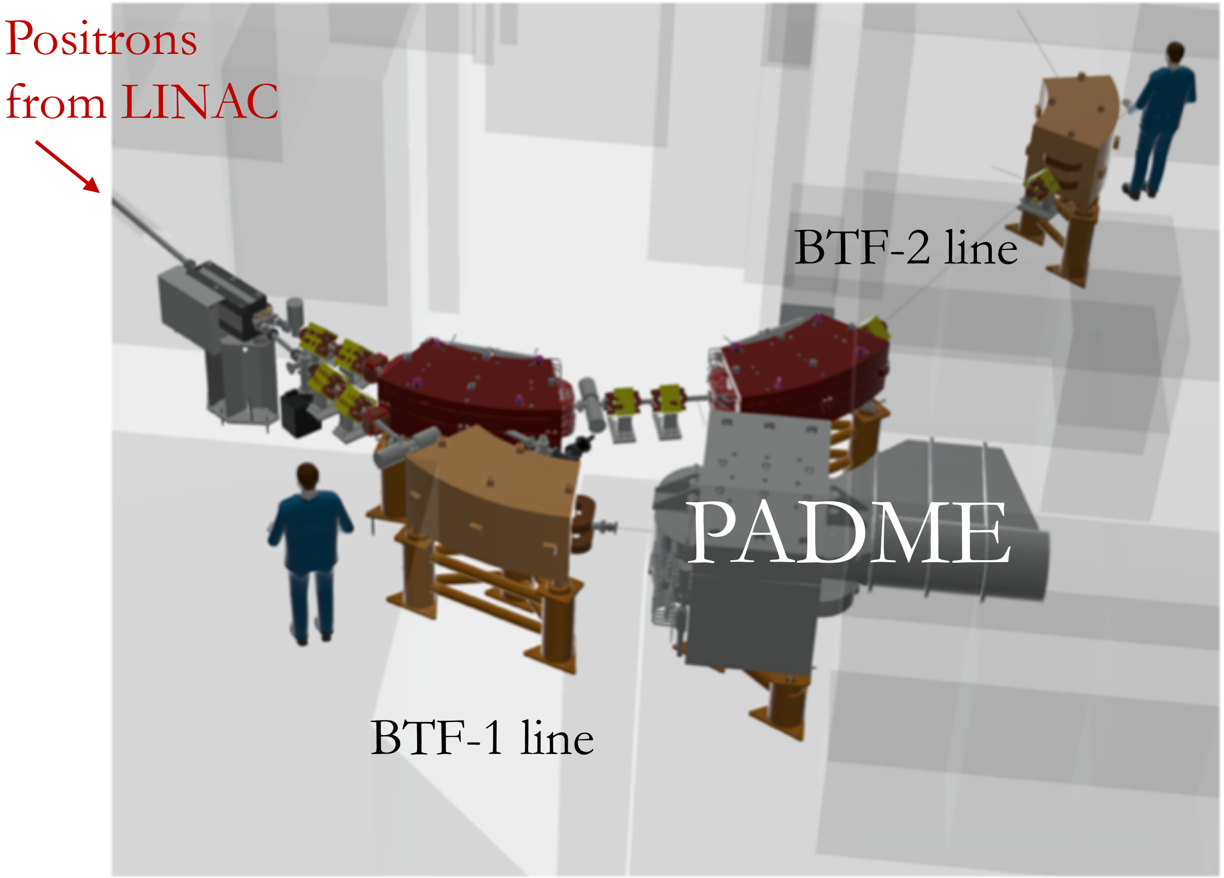
BTF branch


BTF branch



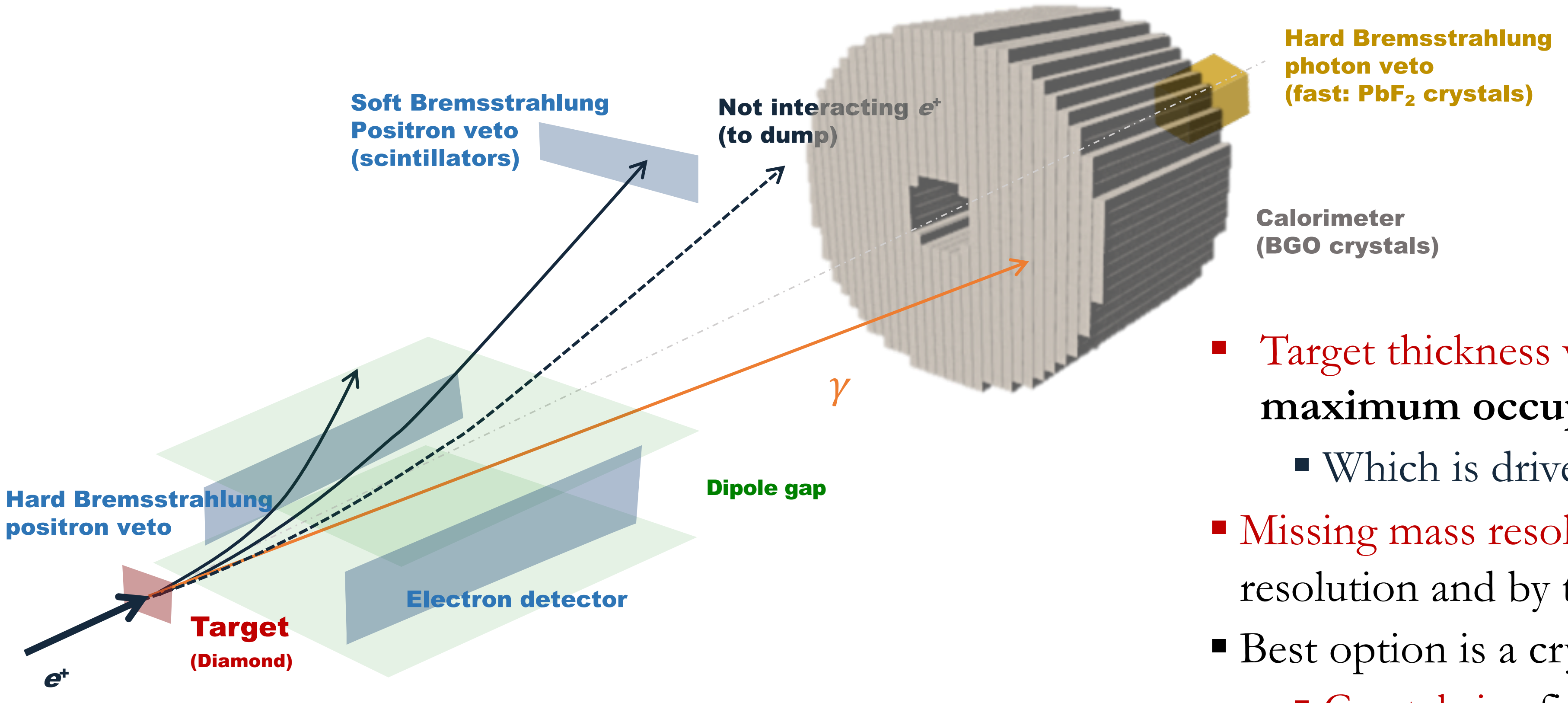
BTF hall

Positron beam-line



- Positrons from DAΦNE LINAC:
  - Maximum **energy 550 MeV**
  - Up to 0.5 nC/pulse
- **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: **1 mm** $\sigma_{x,y}$, **1 mrad** divergence
- **Reduced length**: maximum **5-6 m** downstream of the beam exit

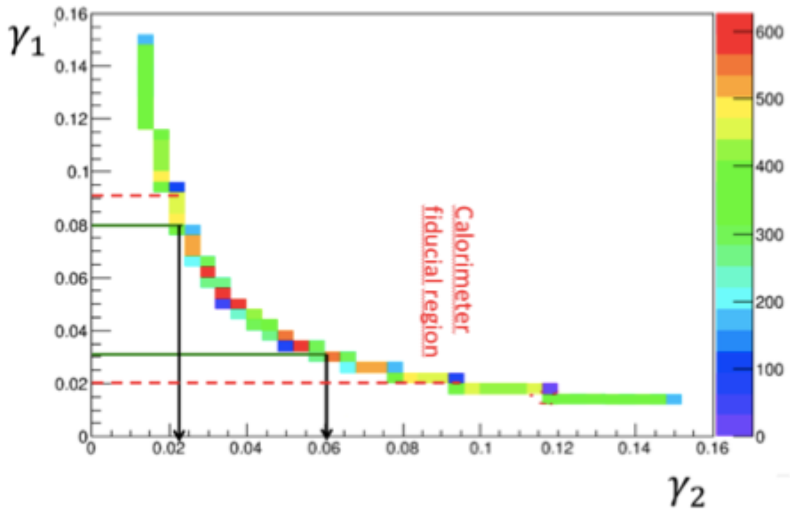
PADME experiment design



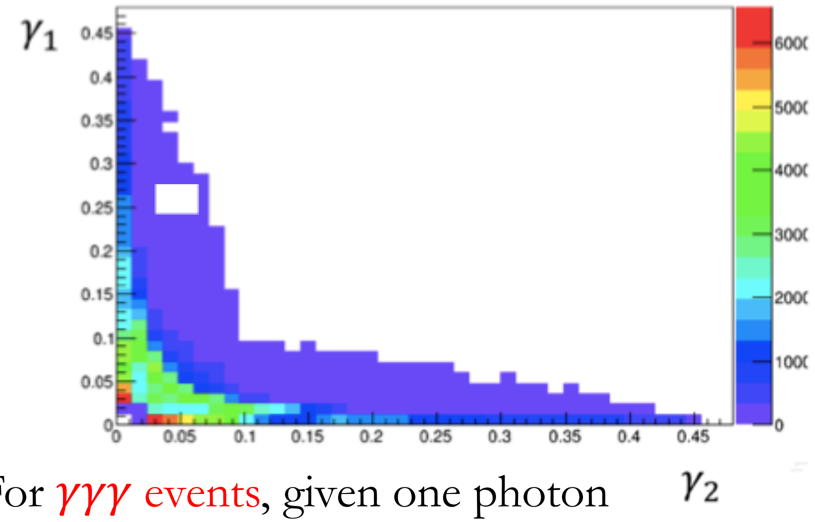
- Keep it **compact**
- Use large-gap dipole magnet

- Target thickness vs. beam intensity fixed by **maximum occupancy**
  - Which is driven by **time response** of detectors
- Missing mass resolution given by spatial+energy resolution and by the **distance**: aim at **4-5 MeV/c^2**
- Best option is a crystal calorimeter
  - Crystal size fixed by Moliére radius
  - Calorimeter size fixes the number of crystals
  - Distance + dipole gap fixes the **acceptance**
  - Hole in main calorimeter + a small angle fast detector to cope with rate
- Everything in **vacuum**

Backgrounds

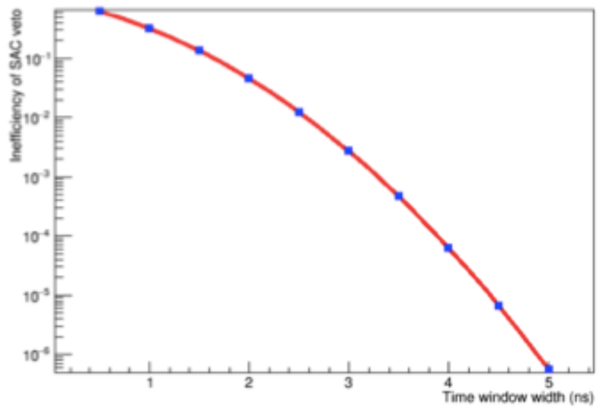


For $\gamma\gamma$ events, given one photon in fiducial region, also the second is in the **calorimeter**



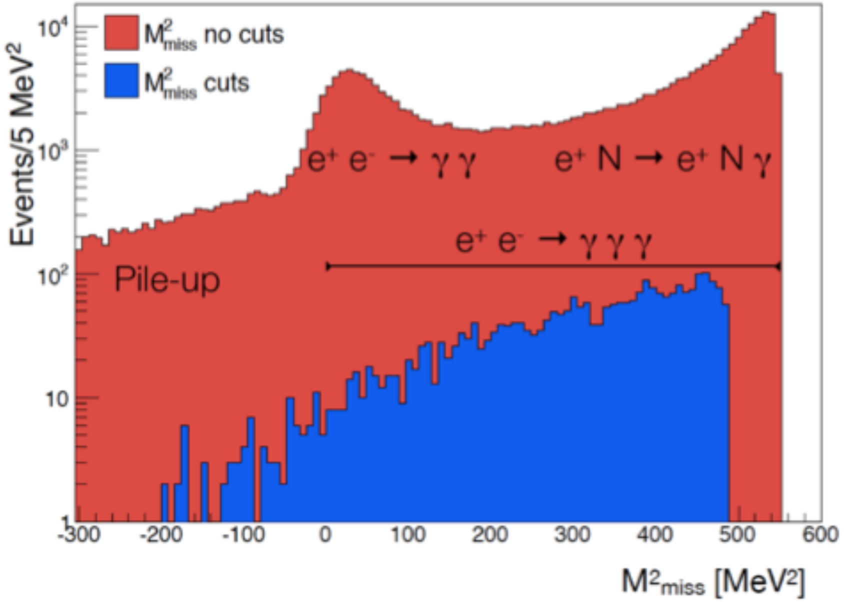
For $\gamma\gamma\gamma$ events, given one photon in fiducial region, the **small angle calorimeter** is crucial to recover full efficiency on second photon

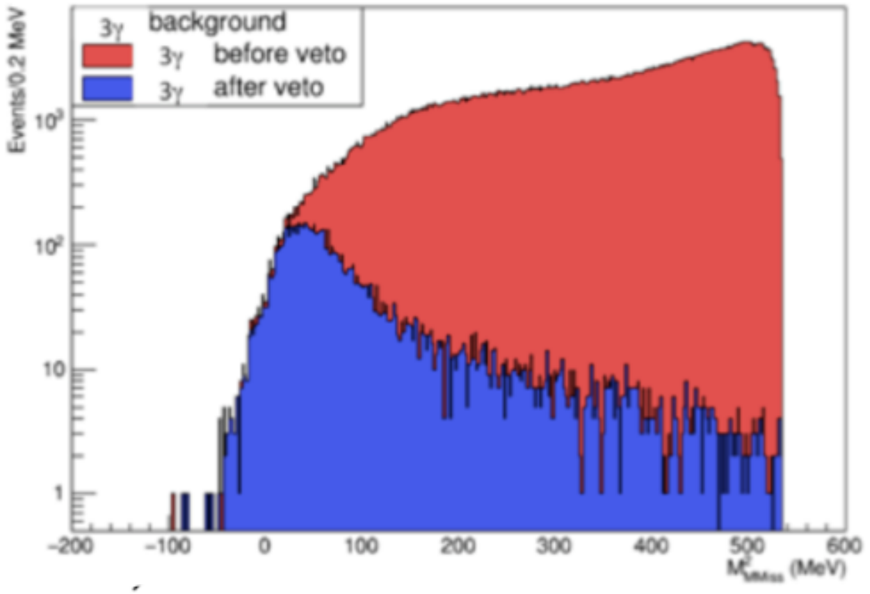
Residual background dominated by Bremsstrahlung with positron missed by the scintillating bars veto

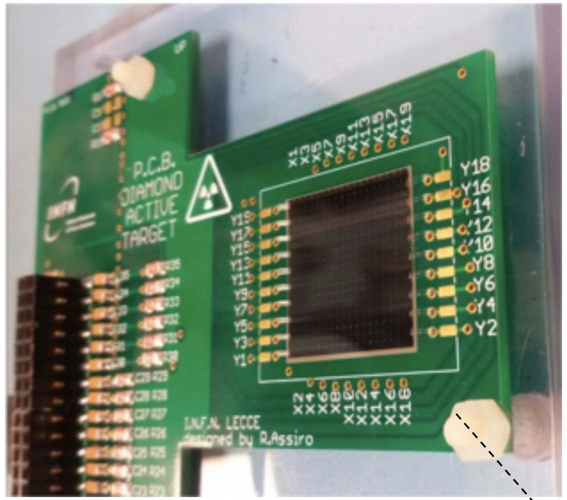


The veto inefficiency strongly depends on **timing performance** of the **small angle calorimeter** …

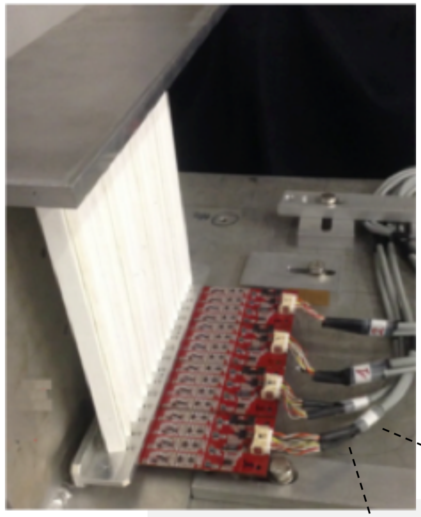
… but a longer veto window decreases the signal acceptance (over-veto)







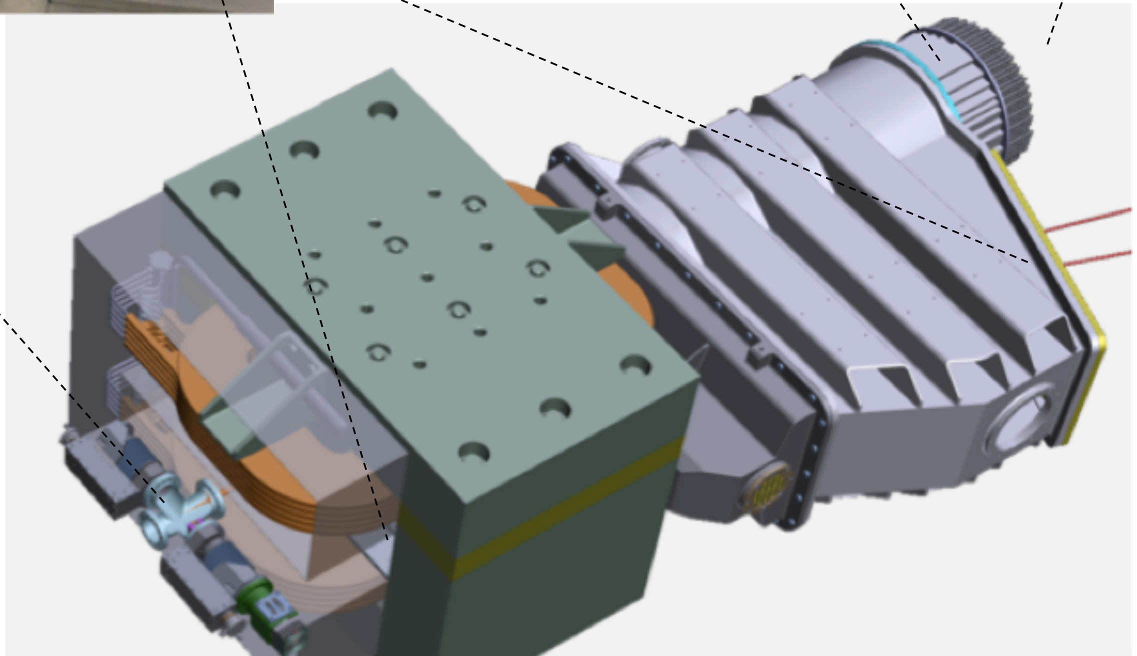
Diamond with grafite strips:
All-Carbon active **target**, beam position & size and luminosity monitor
Custom electronics readout



Scintilling bars with SiPM readout for rejecting Bremsstrahlung background events (tagging positrons)
Inside vacuum vessel

Very fast PbF_2 Cherenkov calorimeter for rejecting 2 and 3 photon background events and withstand Bremsstrahlung rate
Fast PMT readout

BGO calorimeter

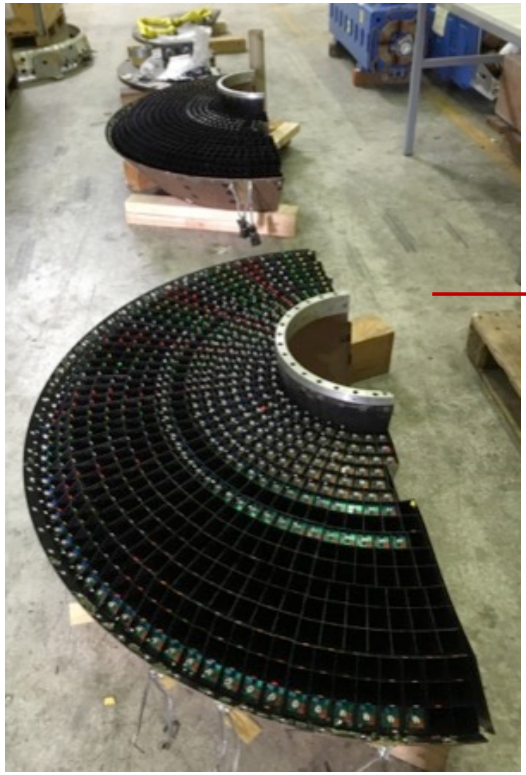


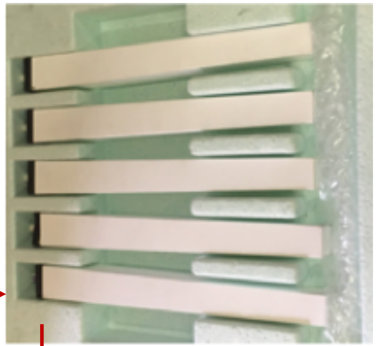
Spare dipole from CERN SPS
(23 cm gap, 1 m long)

Calorimeter

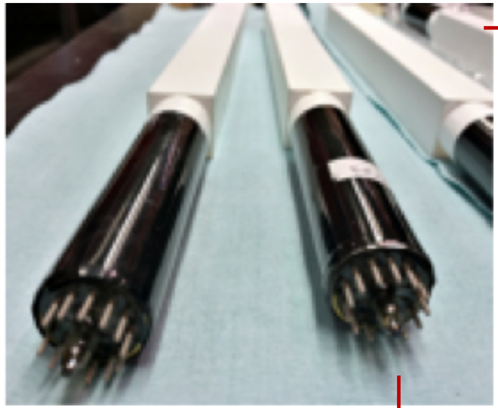
~1 year ago

700 BGO crystals extracted from L3 e.m. calorimeter endcap

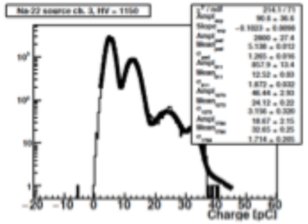


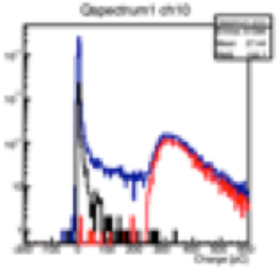


Remove photosensor; Anneale; Machine; Polish



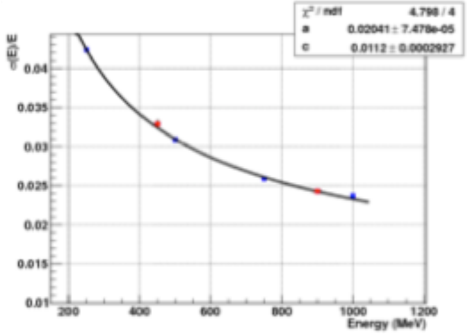
Glue PMT; Optical paint

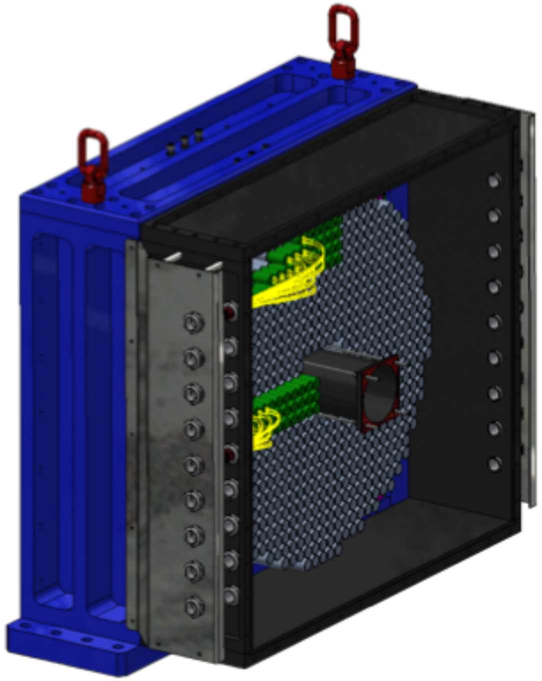




Calibration: 511 keV (^{22}Na);
Calibration: 18 MeV (cosmics)

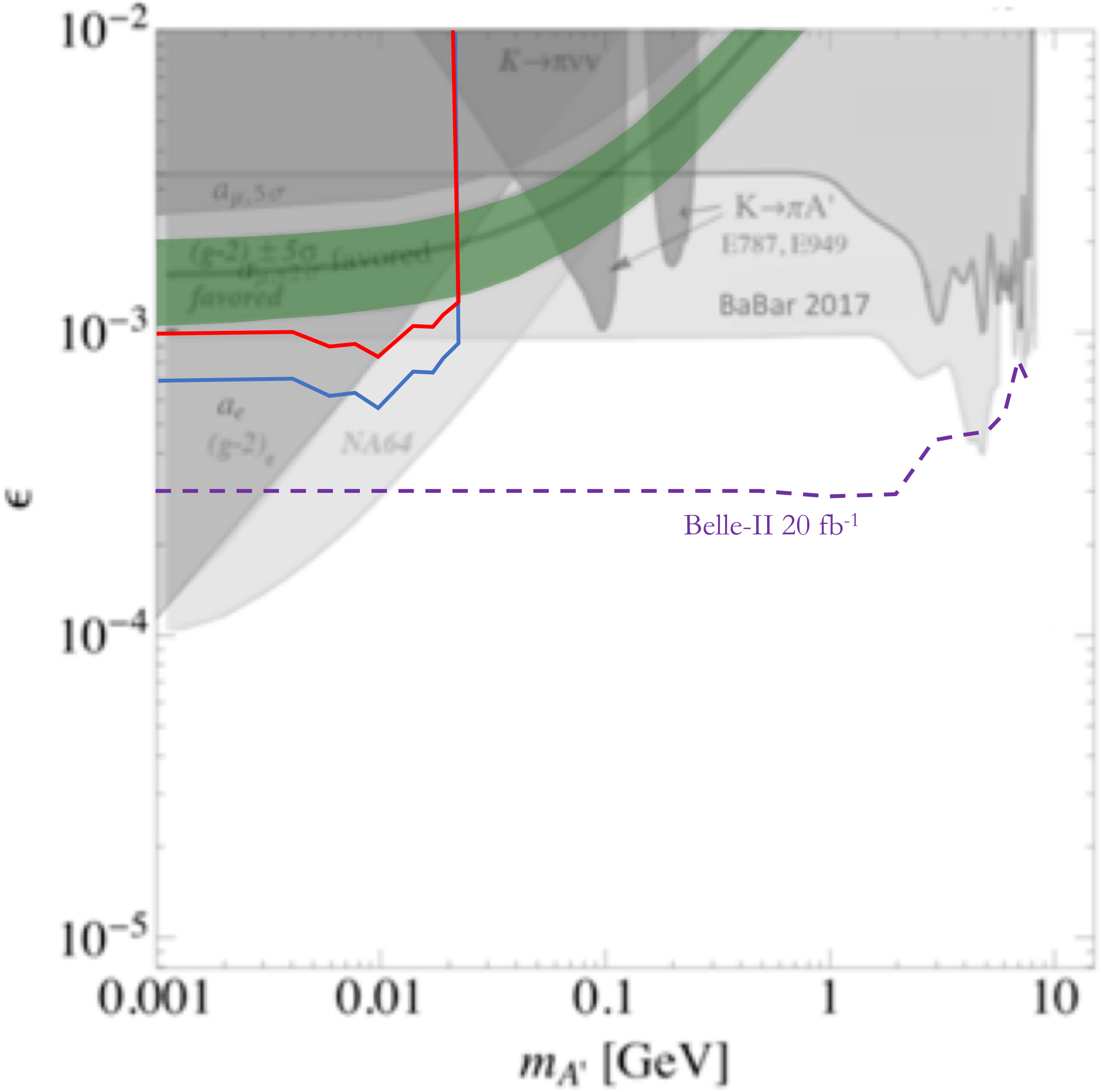
Beam-testing:
2% resolution at 1 GeV





Next step:
assembly and installation

PADME (invisible) sensitivity



— 1×10^{13} e^+ on target

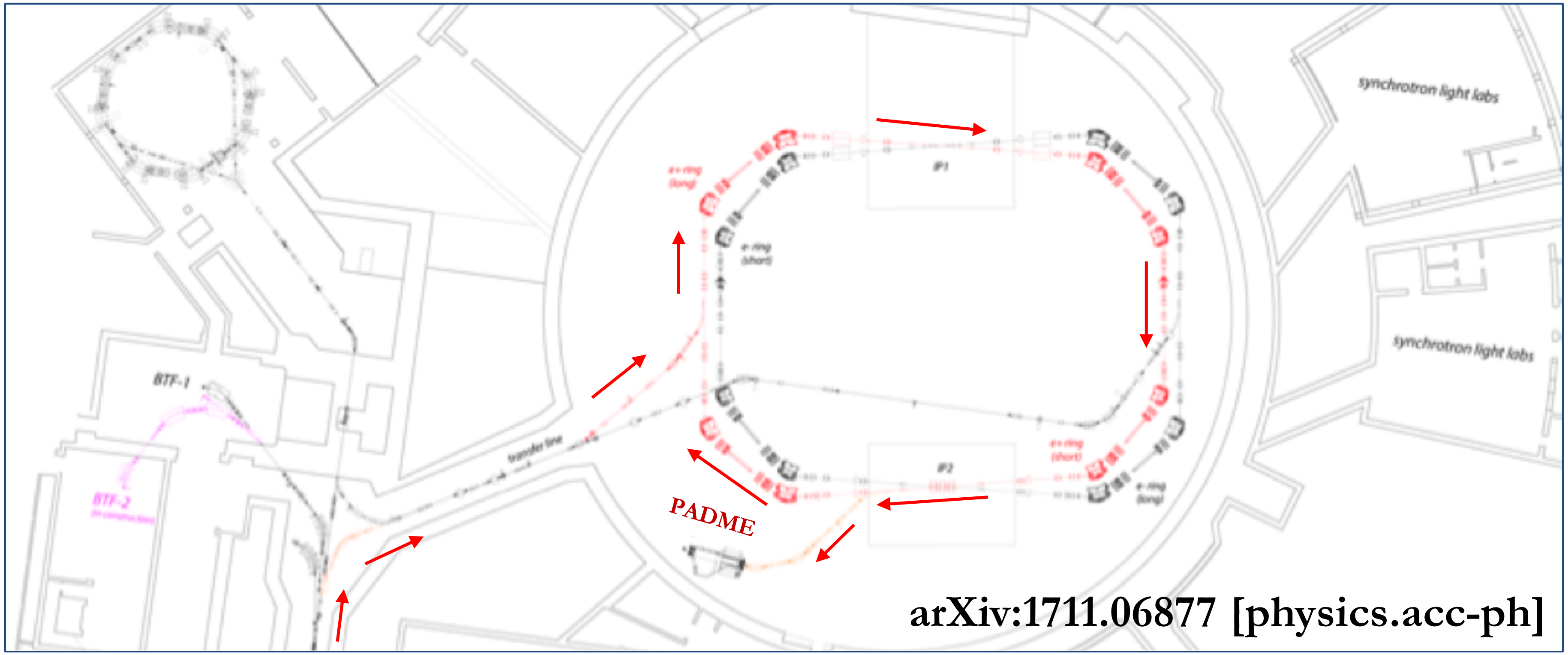
— 4×10^{13} e^+ on target

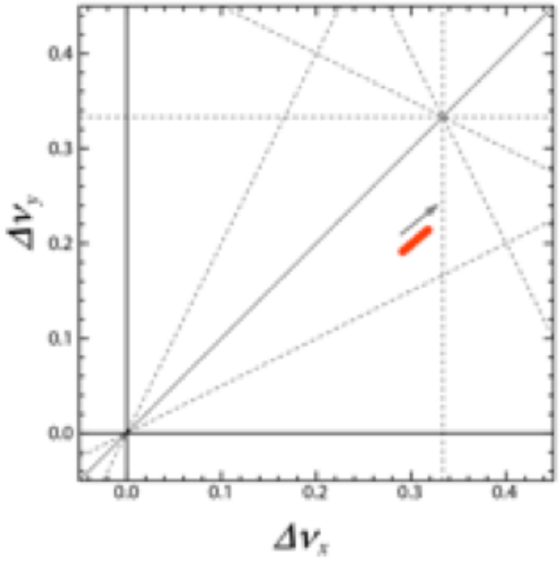
PADME Run 1

6 months of data taking in 2018, starting in April

Possible **Run 2** after Siddharta data-taking at DAΦNE collider in late 2019?

DAΦNE as positron pulse stretcher ring





POSEYDON

- Direct injection of long LINAC pulses (up to **325 ns**, entire length of ring)
- Use 1/3 of integer resonant extraction
- Use synchrotron energy loss + ring chromaticity to drive the beam towards resonance (ring RF off)
- (With) without damping with the four wigglers, increase the spill up to **(0.2) 0.4 ms**
- **2000×** duty-cycle with respect to the LINAC/BTF beam

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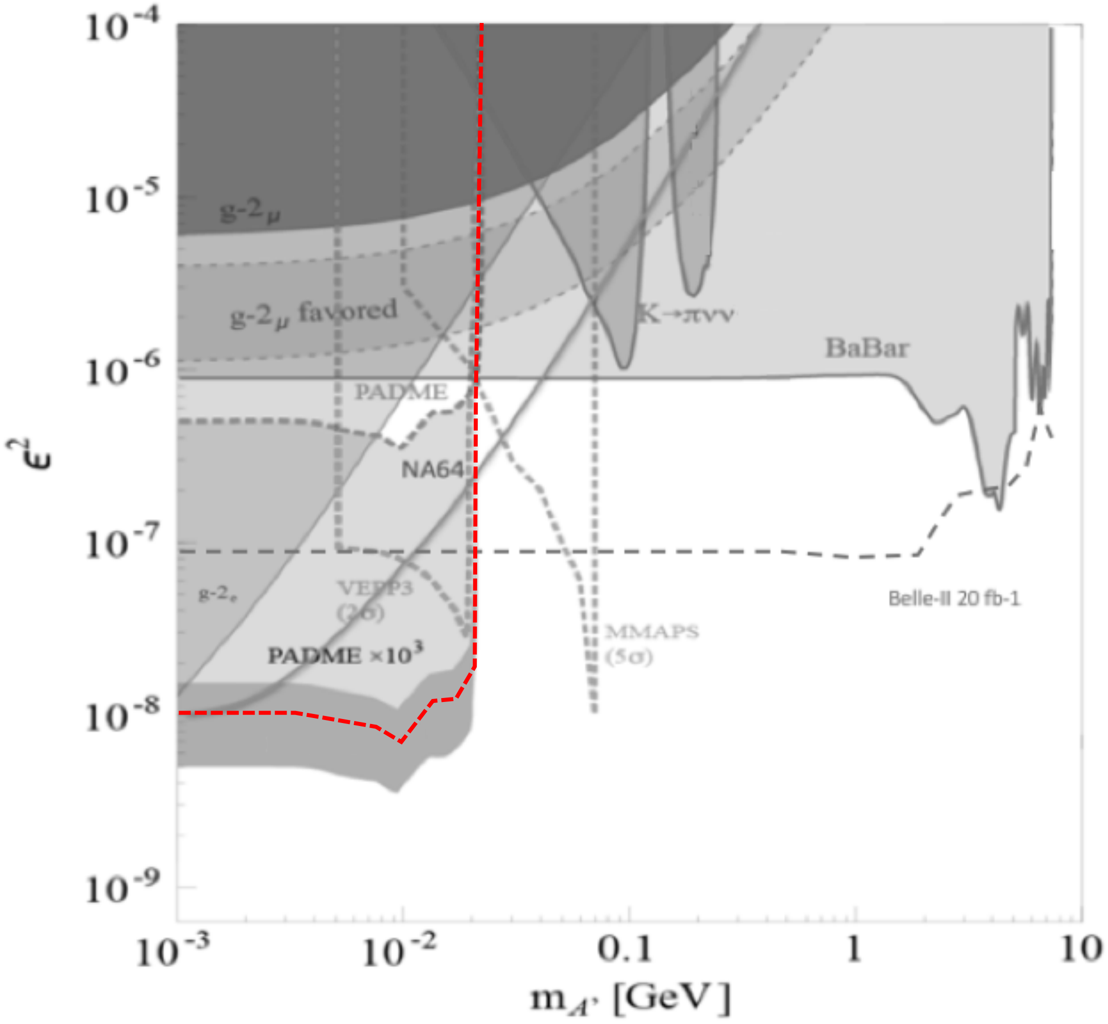
PADME@DAFNE sensitivity



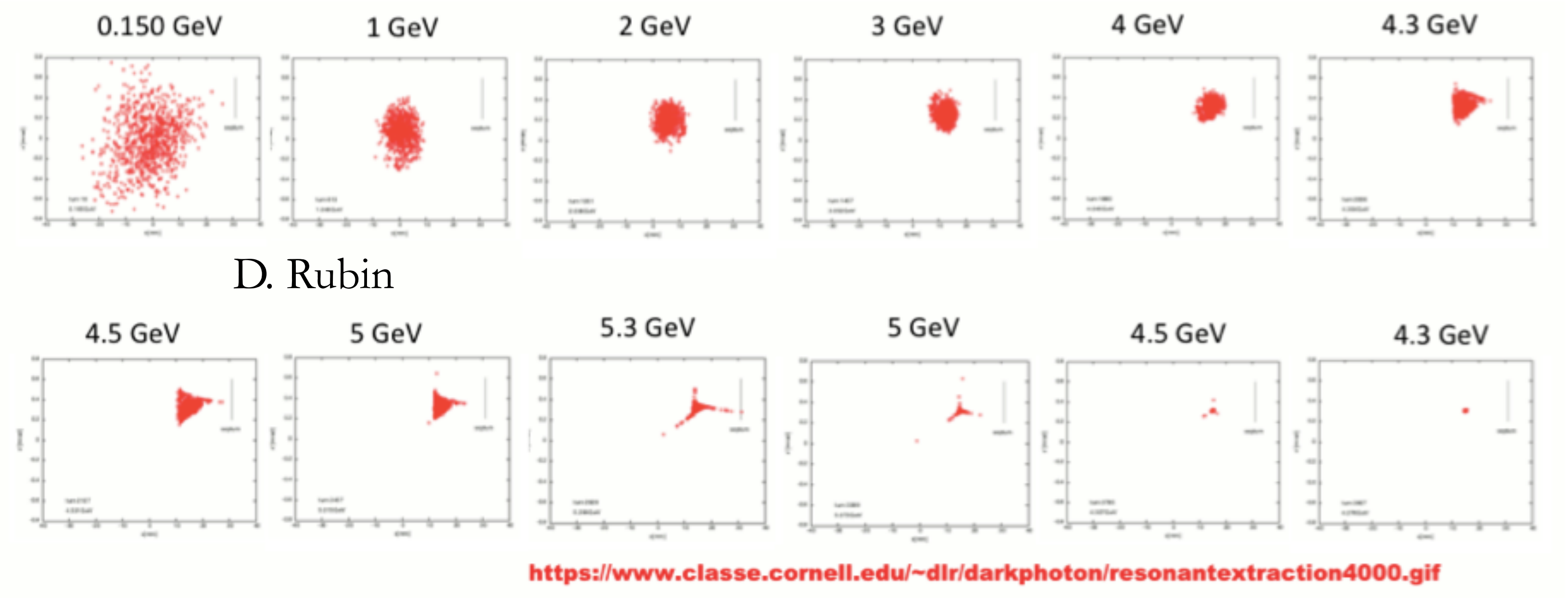
Large improvement in sensitivity up to **24 MeV/c^2** (shown 1 year of running)

It would be possible to extend to higher masses **but**:

- (Some of the) DAΦNE dipoles already close to the maximum field limit
- Being 550 MeV the maximum positron energy from the LINAC, the ring should **ramp** to increase the energy
- Significant **cost** and **time**
- Only improves with **square root** of beam energy

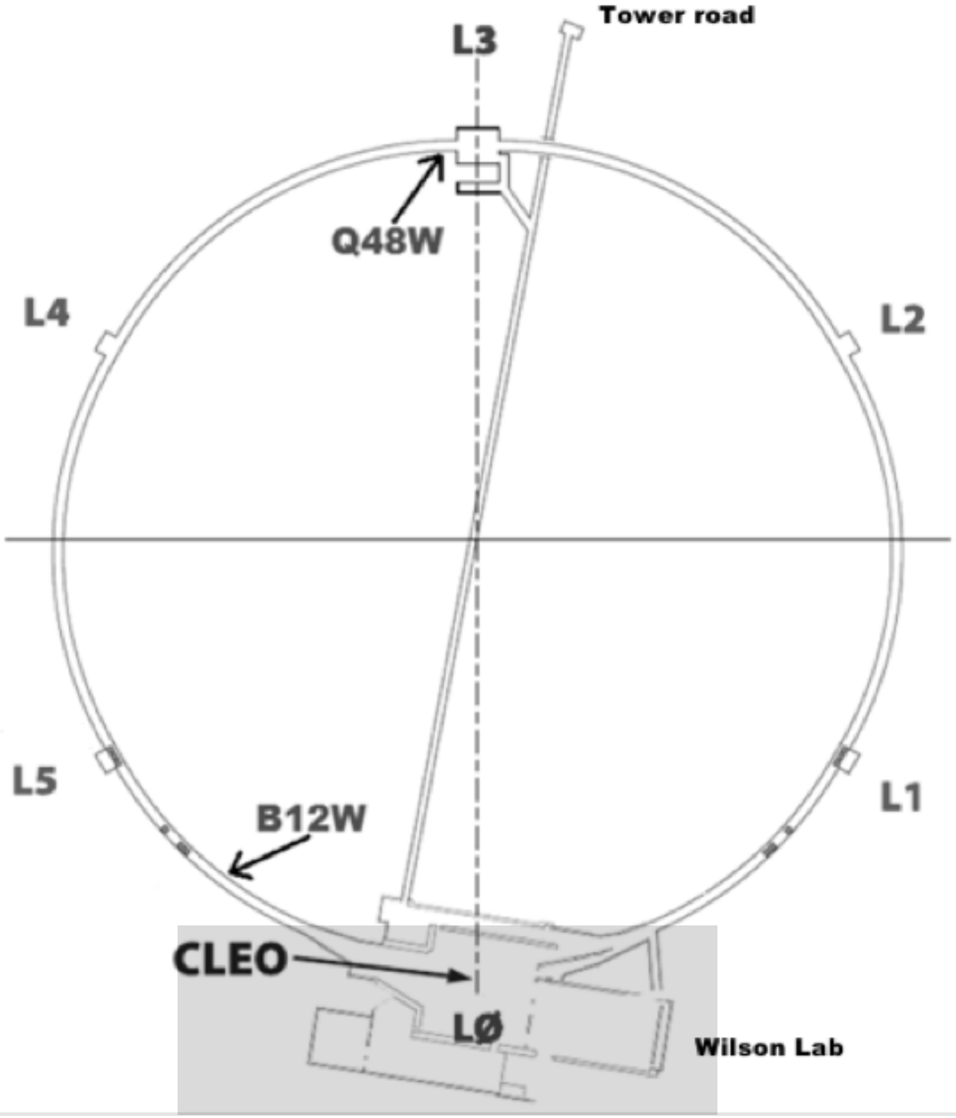
PADME@Cornell: positron extraction

- LINAC: 150 MeV **positrons**
- Synchrotron: **5.4 → 6.0 GeV**
- Storage ring gets "top off" every 3 min for **X-ray facility, CHESS**
- Other 2.8 minutes → feed into positron extraction
- No approved plan of reversing synchrotron for electron operation
- **Resonant extraction**

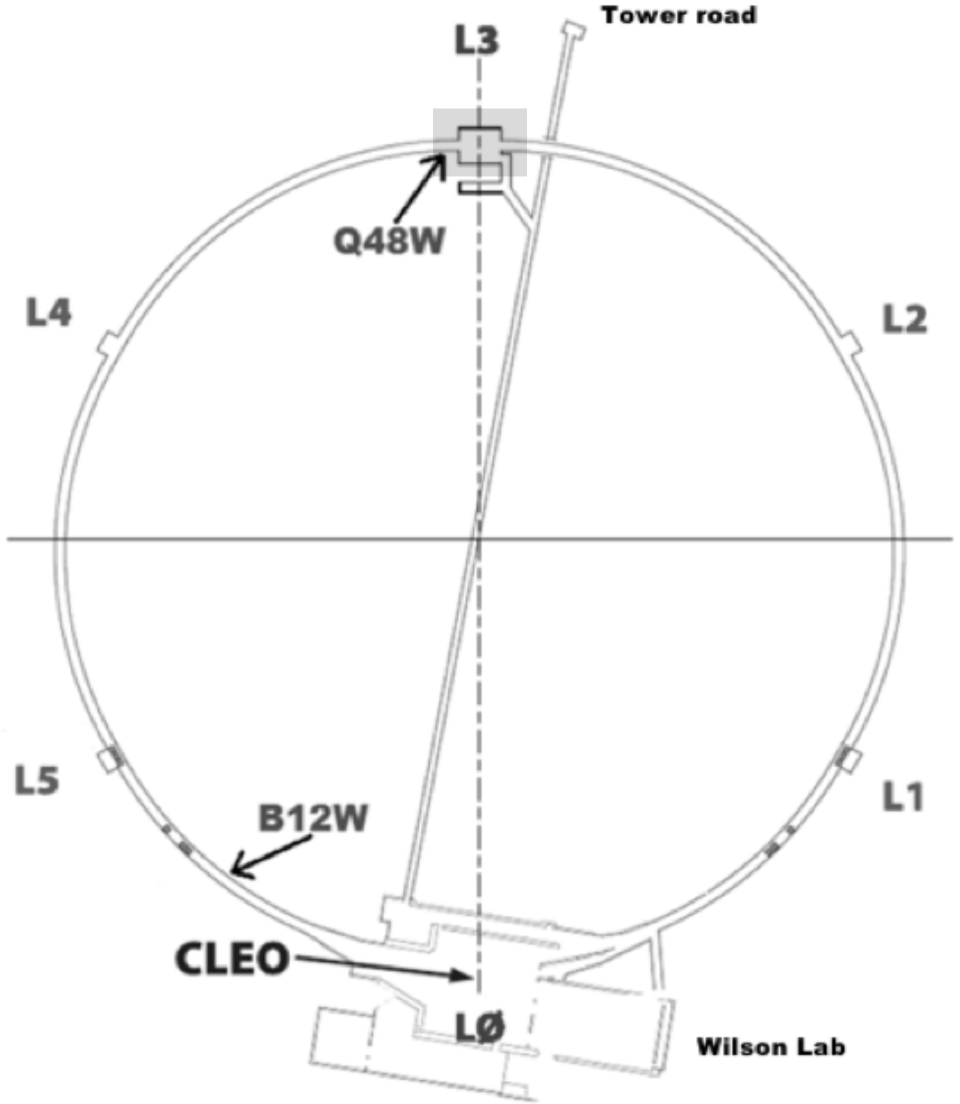


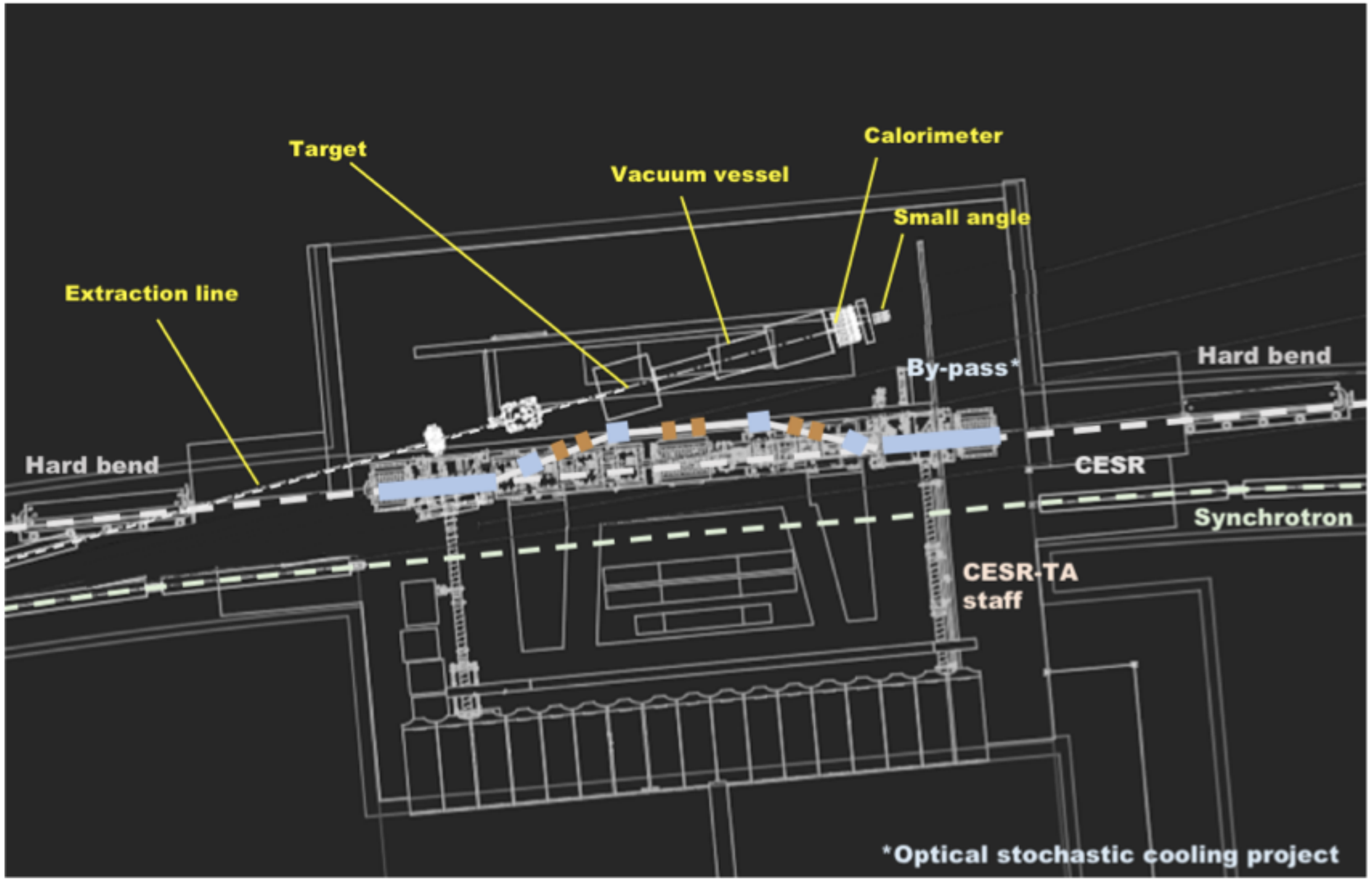
  - Previously implemented in 1970s
  - Minimize pileup—slow extraction: ~**1000 turns** (**2.5 ms**)
  - Quadrupoles shift tune to 1/3 of integer
  - Sextapoles shrink stable phase space: # of stable particles decrease over turns
  - Septa give final **kick**/steers into positron extraction beamline

PADME@Cornell (South)

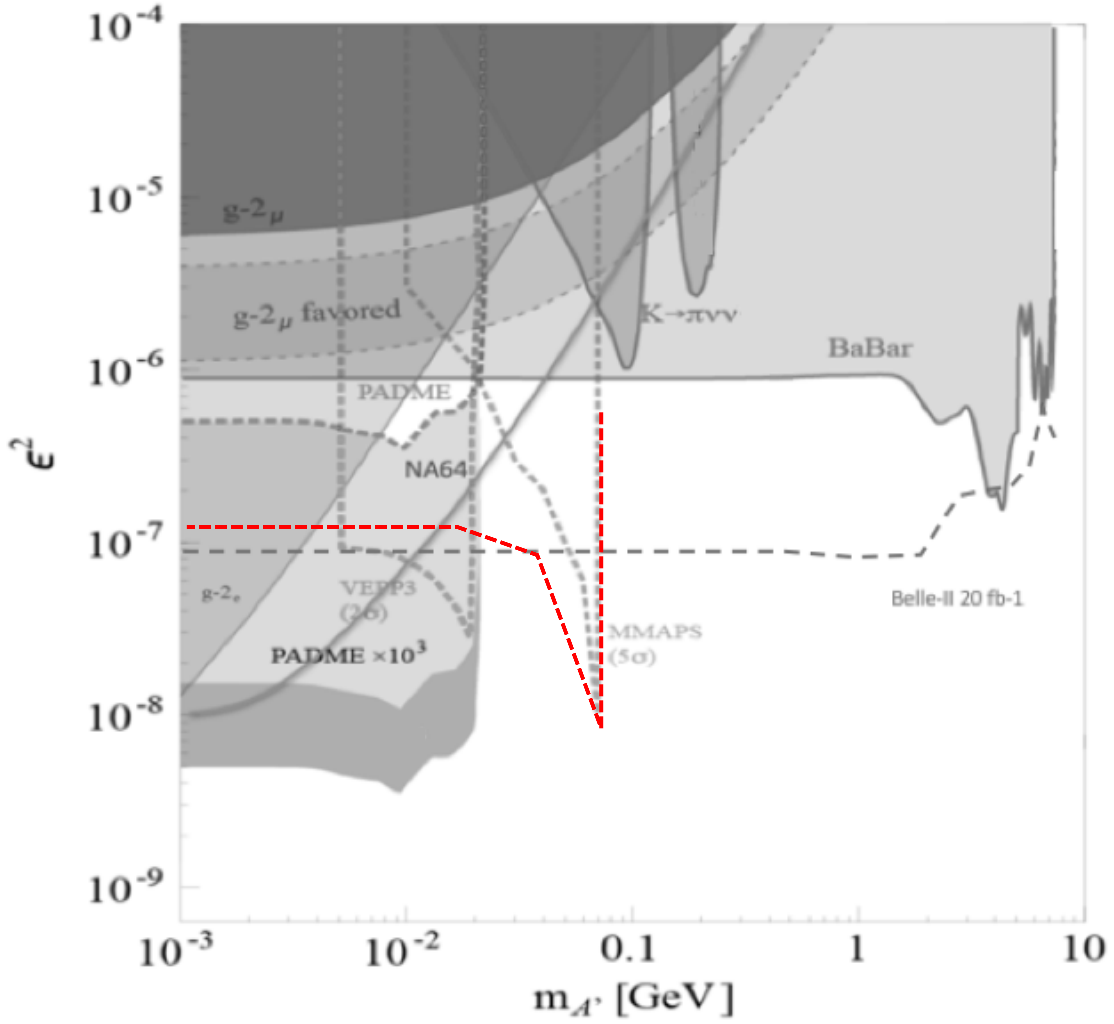


PADME@Cornell (North)



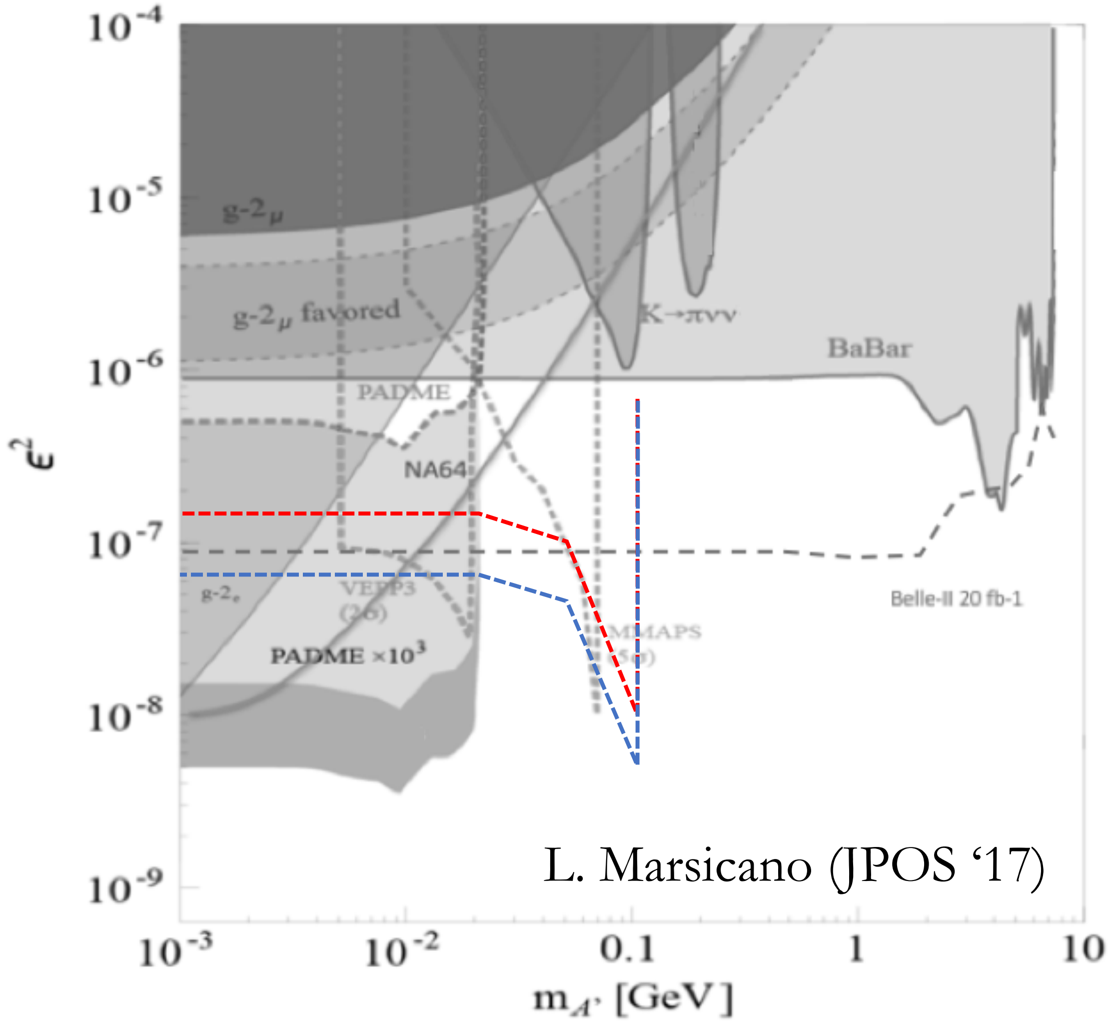


PADME@Cornell sensitivity



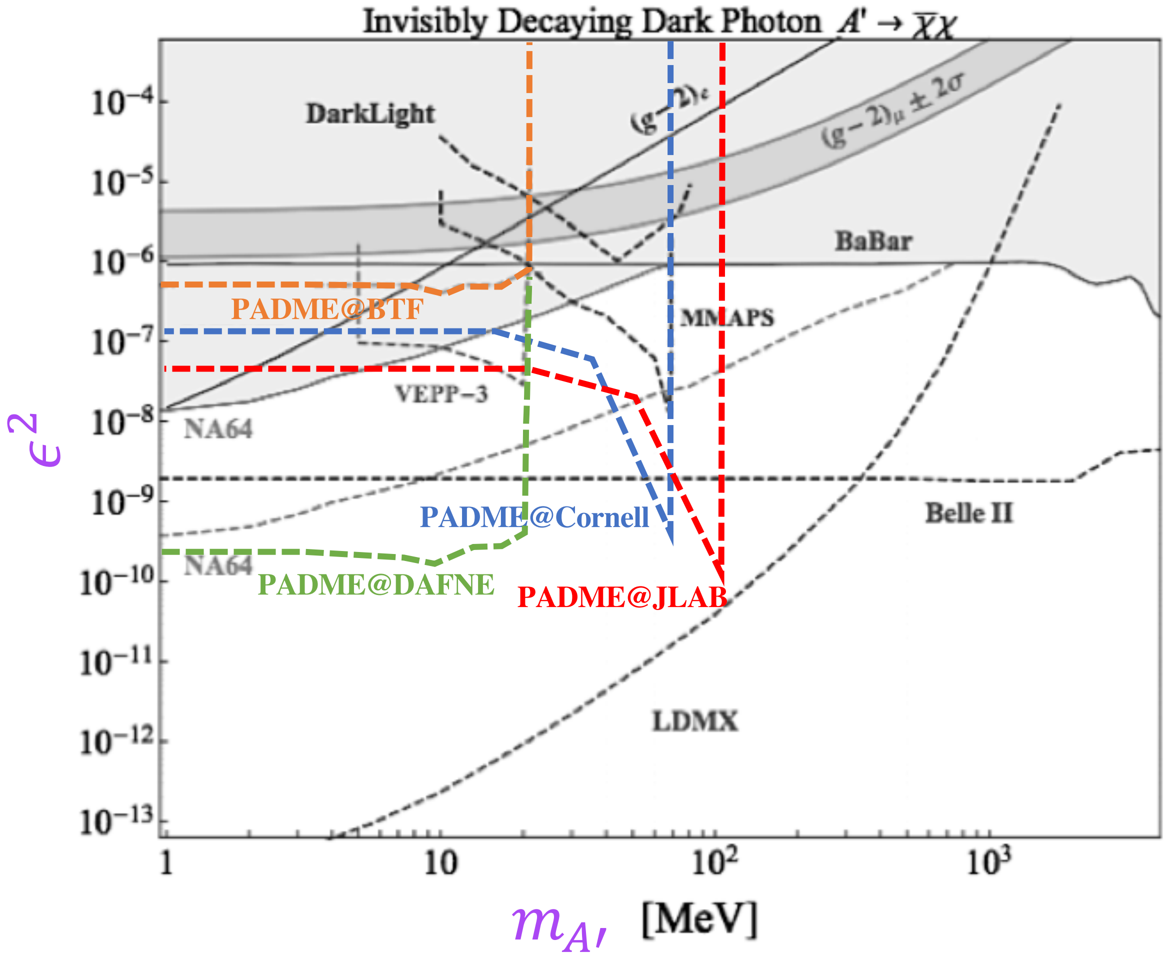
- **Very preliminary** rescaling **PADME** MC at 6 GeV (fixed) energy
- 1 year PADME@Cornell
- Different detector configuration with respect to Cornell MMAPS proposal:
  - Crystal calorimeter: BGO vs. CsI
  - Central hole + fast small angle calorimeter
  - Sweeping magnet, positron veto detectors
  - Extend mass reach to **78 MeV/c^2**

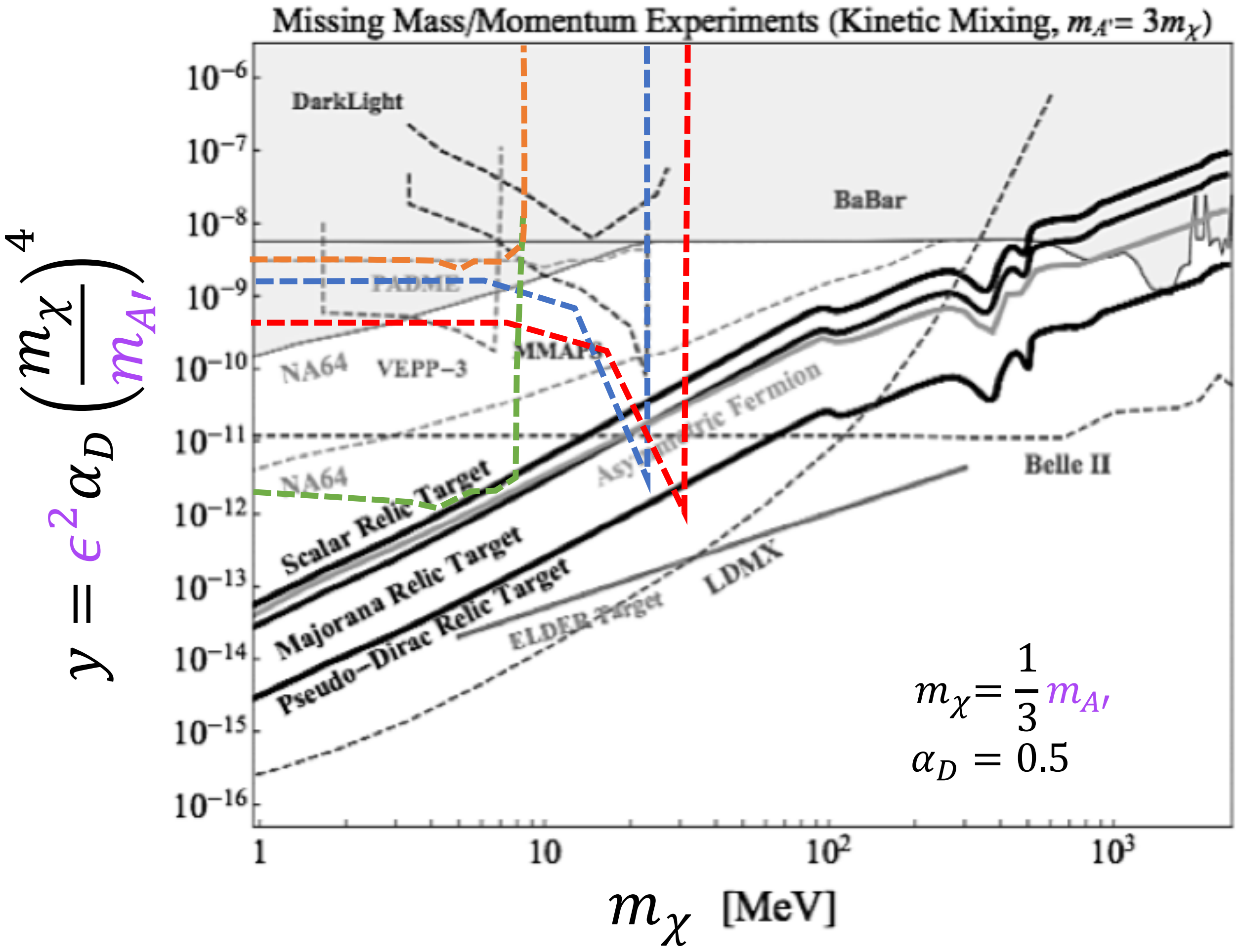
PADME@JLAB sensitivity



- Workshop on the proposal of accelerating positrons with CEBAF (JPOS ’17 at JLAB)
- **Very preliminary** using PADME MC, 11 GeV
- 1 year, **50%** duty cycle,
  - 10 nA of positrons
  - 100 nA of positrons
- Mass reach extended to **106 MeV/c^2**

Pushing the limits

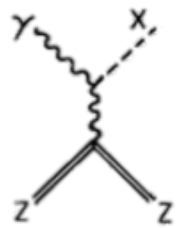




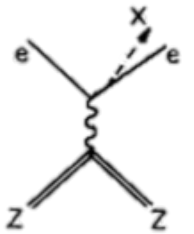
Superimposed on summary plots in **arXiv:1707.04591**

Axion-like particles

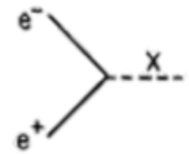
Primakoff



Bremsstrahlung

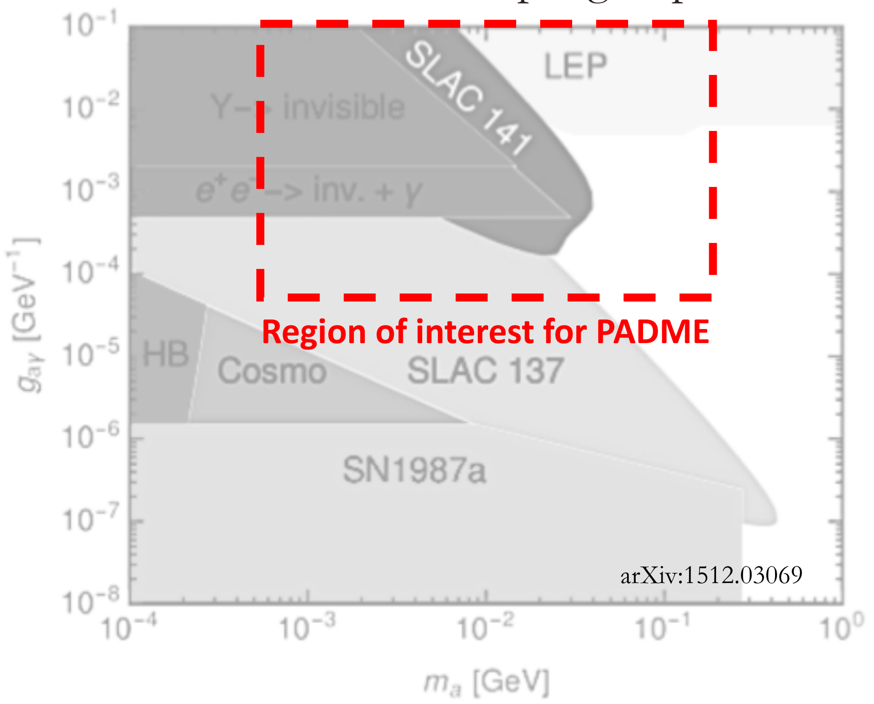


Annihilation

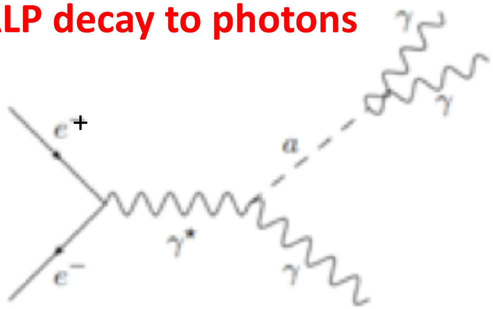


- PADME can search for long living ALPs by looking for $1\,\gamma + M^2{}_{miss}$ final states (same search as **invisible** dark photon)
- In the **visible** final state $a \to \gamma\gamma$ all production mechanisms can be exploited, extending the mass range in the region of $\approx$100MeV
- Visible final states: $e^+\gamma\gamma, \gamma\gamma\gamma$

Limits on ALPs coupling to photons



ALP decay to photons



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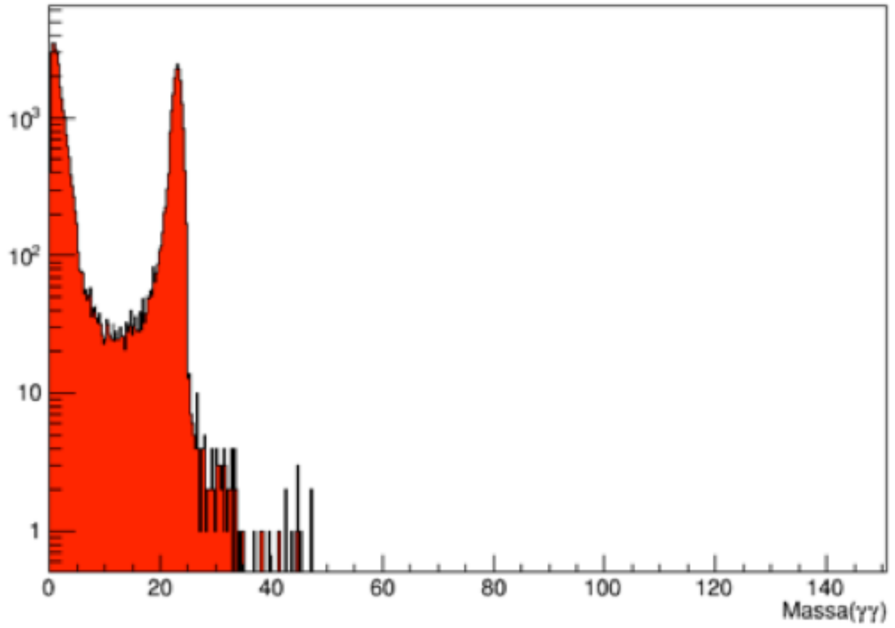
Background to ALPs searches



Invariant $\gamma\gamma$ mass for all events collected by calorimeter (2×10^{10} e^+ events) with two in-time clusters

Even **without any selection cut** PADME will be background free for masses >~ 50MeV

- Main background $e^+e^- \to \gamma\gamma, e^+e^- \to \gamma\gamma(\gamma)$ has a kinematic limit at $M_{\gamma\gamma}$ =24 MeV/c^2
- Background at higher masses is due to **overlapping photons** from different Bremsstrahlung interactions
  - Can be suppressed by using the **veto detectors**

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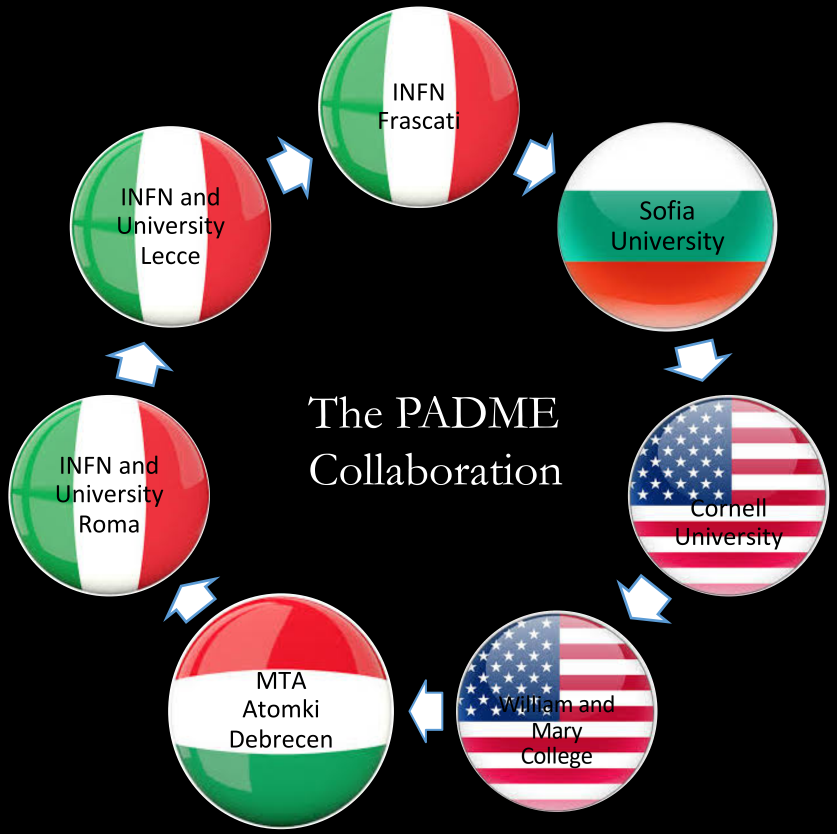
Outlook

- The PADME experiment was approved in **Sep. 2015** (funded for **2016-2018**)
- All main components are **ready**…
  - Diamond active target, magnet, DAQ and online system, clock and timing distribution
- …or under **construction**
  - Calorimeter structure, scintillating bars veto, small angle assembly
- Data taking starting end of **April 2018**, 6 months planned (at least **10^{13} positrons on target**)
  - This is the limit for improving over BaBar result
  - Competition with Belle-II coming run
- We will search for **dark photon**, **X(17 MeV) boson**, and **ALPs** both in the **invisible** and **visible** channels (using the same data-set)
- The main limitations at the Frascati beam-test facility are:
  - **Energy limited** to 550 MeV ($\mathbf{24\ MeV/c^2}$ mass)
  - Pulse length **~200 ns**, limiting the maximum beam intensity due to **pile-up**
- With modest investments, slow extraction of **long** beam spills from **DAΦNE positron ring** or the **Cornell synchrotron** can very significantly extend the reach of PADME
  - At Cornell also the mass reach is greatly extended thanks to the 6 GeV maximum energy ($\mathbf{78\ MeV/c^2}$ mass)
  - Even more at a possible JLAB 11 GeV positron beam ($\mathbf{106\ MeV/c^2}$ mass)



The hardest thing of all is to find a **black cat** inside a **dark room.**

Especially if there is **no cat.**

(Confucius)