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**?
Relic DM and freeze-out

Thermal history of the Universe

- DM particles $\chi$ 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 $m_\chi$ the number density $n_\chi$ started to exponentially decrease.
- No relics today, unless transition out of equilibrium or “freeze-out”, when the probability of annihilation becomes too small fixing $n_\chi$ (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.
Dark freeze-out

\[ m_X \sim \alpha_d \sqrt{T_{eq} M_{pl}} e^{-\delta m / T_{FO}} \]

\[ m_X \sim \alpha_{eff} (T_{eq}^2 M_{pl})^{1/3} \sim \alpha_{eff} \times 100 \text{ MeV} \]

J. Ruderman
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

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Portal:
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- 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, $^8\text{Be}$ 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

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

- 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
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 excess from PAMELA, FERMI, AMS-01
- 511 keV line form INTEGRAL/SPI
- …
Dark photon production and decay

Production:
- In any process with an ordinary photon, we can substitute it with a dark photon ($A'$):
  - $A'$-strahlung, $\pi^0, \eta$ decays, $e^+e^-$ annihilations
- In the case of axion-like particles, we also have the Primakov production mechanism

\[ A' \rightarrow \epsilon \]

\[ g_{\gamma\gamma} \rightarrow a \]

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 $A' \rightarrow$ 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 $A' \rightarrow \chi\chi$
Dark photon experiments at (electron) accelerators

**visible decays**

\[ e^- Z \rightarrow e^- Z A' \]
\[ A' \rightarrow e^+ e^- \]

**Dump**

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

**Thin target**

(APEX, HPS, A1)

**invisible decays**

\[ e^- Z \rightarrow e^- Z A' \]
\[ A' \rightarrow \chi \chi' \]

**Dump+recoil**

(BDX)

**Missing energy**

(NA64)

**Missing momentum**

(LDMX)

Reminder:

DM-electron cross section

Additional parameters:

\[ \alpha_D \] and \[ m_\chi \]
Positron annihilations

- 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 ($b'$), vectors ($A'$) and ALPs
- Of course one can also look for $e^+e^-$ pairs in the final state

- To compute $m^2_{\text{miss}} = (P_\gamma - P_{e^+})^2$ 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
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: $\text{BR}(A' \rightarrow e^+ e^-) \sim 1$
  - $g-2$ favoured band excluded
Dark photon searches status: invisible

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

**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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\[^8\text{Be anomaly}\]

- \(^7\text{Li}(p, \gamma)^8\text{Be}\) reactions, using \(\approx 1\text{ MeV}\) \(p\) 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, Decebecen (Hungary)

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

- **Excitation** with the \(^7\text{Li}(p, \gamma)^8\text{Be}\) reaction
- **De-excitation** via internal pair creation

**Off resonance**

- \(E_p = 0.8\text{ MeV}\)

**On resonance**

- \(E_p = 1.04\text{ MeV}\)
- \(E_p = 1.10\text{ MeV}\)
A proto-phobic boson?

6.8$\sigma$ excess, can be interpreted as a **new boson** (vector is favored) $m=16.6$ MeV


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

Can PADME give an answer?
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

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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**

- 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 $4-5 \text{ MeV}/c^2$
- Best option is a crystal calorimeter
  - Crystal size fixed by Molière 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

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

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**In vacuum**

- Hard Bremsstrahlung photon veto (fast: PbF$_2$ crystals)
- Soft Bremsstrahlung positron veto (scintillators)
- Not interacting $e^+$ (to dump)
- Electron detector
- Dipole gap
- Target (Diamond)
For $\gamma\gamma$ events, given one photon in fiducial region, also the second is in the calorimeter.

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

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

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

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

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

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

BGO calorimeter

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

Very fast PbF$_2$ Cherenkov calorimeter for rejecting 2 and 3 photon background events and withstand Bremsstrahlung rate
Fast PMT readout
~1 year ago
700 BGO crystals extracted from L3 e.m. calorimeter endcap

- Remove photosensor;
- Anneal;
- Machine;
- Polish

Glue PMT;
Optical paint

Beam-testing:
2% resolution at 1 GeV

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

Next step:
assembly and installation

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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

- 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

Large improvement in sensitivity up to $24 \text{ MeV}/c^2$ (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)

CHESS-upgrade

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PADME@Cornell (North)

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- **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/c²**
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/c²

L. Marsicano (JPOS ‘17)
Pushing the limits

Superimposed on summary plots in arXiv:1707.04591
PADME can search for long living ALPs by looking for \( 1\gamma + M^2_{\text{miss}} \) final states (same search as invisible dark photon).

In the \textit{visible} final state \( a \rightarrow \gamma\gamma \) all production mechanisms can be exploited, extending the mass range in the region of \( \approx 100\text{MeV} \).

Visible final states: \( e^+\gamma\gamma, \gamma\gamma\gamma \)
Background to ALPs searches

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

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

Even without any selection cut PADME will be background free for masses $>\sim 50\text{MeV}$
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**, \(X(17\text{ MeV})\) 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 (24 MeV/c\(^2\) mass)
  - Pulse length \(\sim 200\) 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 (78 MeV/c\(^2\) mass)
  - Even more at a possible JLAB 11 GeV positron beam (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)*