Search for Mirror Matter with Positronium

and a new measurement of its lifetime

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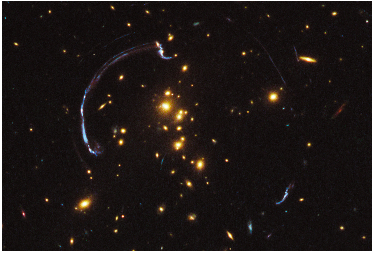
Dark Matter

Cosmological observations

- Cosmic Microwave Background spectrum
- Galaxy rotation curves
- Gravitational lensing

No candidate from Standard Model

New physics



Gravitational lensing, from Hubble mission

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DM Candidates

- Axions
- Supersymmetric particles
- Sterile neutrinos
- Hidden sectors: dark boson

Illustration by Sandbox Studio, Chicago

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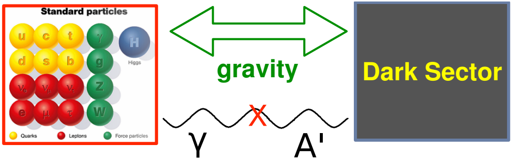
Hidden Sectors

Main interaction: gravity
Kinetic mixing $\gamma \Longleftrightarrow$A'



Recent review [*arXiv:1707.04591*]

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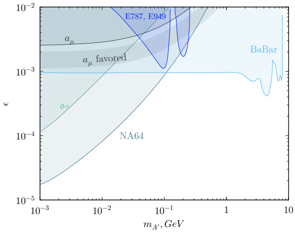
- Massive A': NA64



NA64 Experiment, [*Phys. Rev. D 97, 072002 (2018)*]

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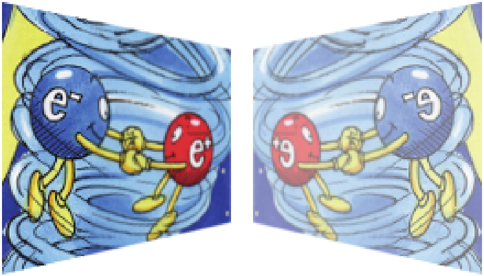
- Massive A': NA64
- Mass-less case: Mirror Sector

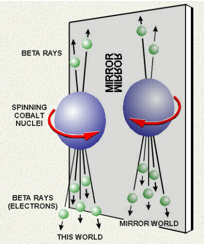


What is the Mirror Sector?

Hidden sector with a new set of mirror particles: same properties (e.g. mass and charge), but opposite chirality, and same micro-physics

It was proposed by Lee and Yang in 1956 to restore parity as a fundamental symmetry of nature

Recent review: [*L. B. Okun, Phys. Usp. 50, 380 (2007)*]



e	e'
ν	ν'
p	p'
n	n'
$\bar{e}$	$\bar{e}'$
$\bar{\nu}$	$\bar{\nu}'$
$\bar{p}$	$\bar{p}'$
$\bar{n}$	$\bar{n}'$
W, Z	W', Z'
γ	γ'

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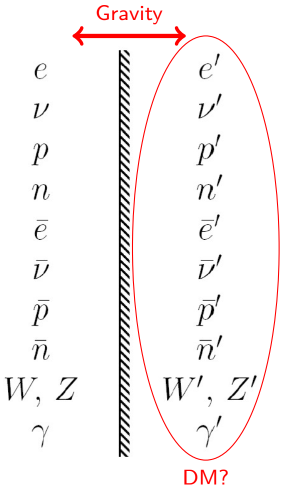
Interactions between the two Sectors

- Gravity
- Suitable DM candidate: massive and stable



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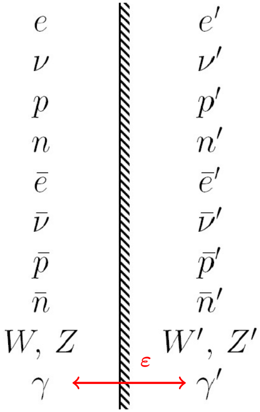
Interactions between the two Sectors

- Gravity
- Suitable DM candidate: massive and stable

Other Interactions?

- Kinetic mixing: $\gamma \longleftrightarrow \gamma'$
- Portal to our sector: **positronium**



BBN Limit: $\varepsilon < 3 \times 10^{-8}$

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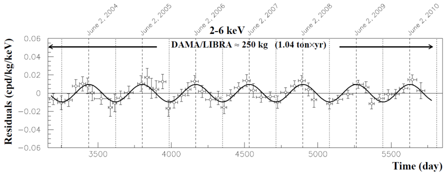
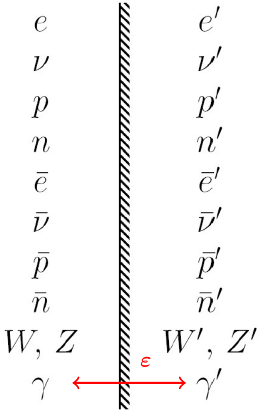


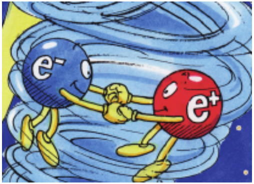
Anomaly reported by the DAMA/LIBRA colaboration could be explained with $\varepsilon \sim 4 \times 10^{-9}$ [*Cerulli et al., EPJ C 2017*]

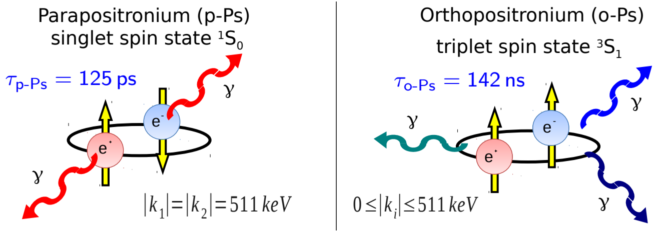


BBN Limit: $\varepsilon < 3 \times 10^{-8}$

What is Positronium

- Bound state of electron and positron
- Two different spin configurations:
  - Singlet state: para-positronium (p-Ps)
  - Triplet state: ortho-positronium (o-Ps)
- It *always* decays (SM) into photons: $E = \sum k_i = 1.022\,\text{MeV}$





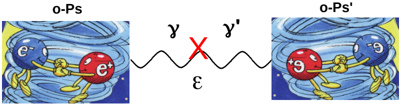
$$\sum_i k_i = 1.022\,\text{MeV}$$

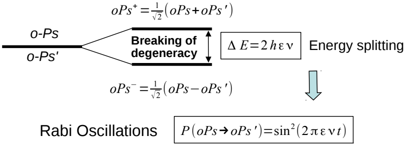
Positronium – Mirror Positronium Oscillations

- Kinetic mixing photon – mirror-photon
- One-photon virtual annihilation channel

} o-Ps ⟷ o-Ps' Rabi oscillations

[S. L. Glashow, Phys. Lett. B167, 35 (1986)]





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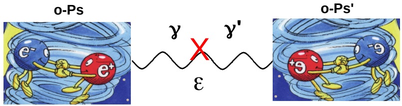
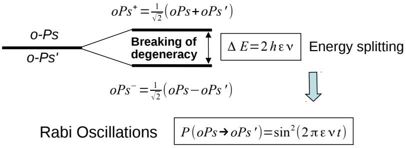
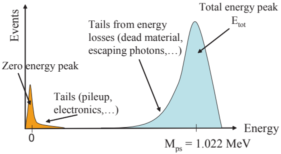




Experimental signature: o-Ps' decays into mirror-photons $\Longrightarrow$ missing energy

Br (o-Ps → o-Ps') $\Longrightarrow$ Br (o-Ps → invisible)

Background: zero-energy compatible events



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Decays, interactions with matter and electromagnetic fields $\Longrightarrow$ density matrix approach:

$$\dot{\rho} = \frac{1}{\mathrm{i}\hbar}\left[H, \rho\right] + \dot{\rho}_{rel}$$

- Density matrix of the states $\rho(t) = \begin{pmatrix} \rho_{11}(t) & \rho_{12}(t) \\ \rho_{21}(t) & \rho_{22}(t) \end{pmatrix}$
- Hamiltonian of the system $H = \hbar \begin{pmatrix} \frac{1}{2}\left(\frac{\Delta}{\hbar} + \omega_{12}\right) & -\Omega \\ -\Omega & -\frac{1}{2}\omega_{12} \end{pmatrix}$
- Relaxation term $\dot{\rho}_{\mathrm{rel}} = \begin{pmatrix} -\gamma_1 \rho_{11}(t) & -\left(\frac{\gamma_1+\gamma_2}{2} + \gamma_{\mathrm{coll}}\right)\rho_{12}(t) \\ -\left(\frac{\gamma_1+\gamma_2}{2} + \gamma_{\mathrm{coll}}\right)\rho_{21}(t) & -\gamma_2 \rho_{22}(t) \end{pmatrix}$

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$$\dot{\rho}_{11}(t) = -\Gamma\rho_{11}(t) - i\Omega\left[\rho_{12}(t) - \rho_{21}(t)\right] \qquad \rho_{11}(0) = 1$$

$$\dot{\rho}_{22}(t) = -\Gamma\rho_{22}(t) + i\Omega\left[\rho_{12}(t) - \rho_{21}(t)\right] \qquad \rho_{22}(0) = 0$$

$$\dot{\rho}_{12}(t) = -\left(\Gamma + \gamma_{coll}\right)\rho_{12}(t) - i\left[\Omega\rho_{11}(t) + \frac{1}{2}\Delta\rho_{12}(t) - \Omega\rho_{22}(t)\right] \qquad \rho_{12}(0) = 0$$

$$\dot{\rho}_{21}(t) = -\left(\Gamma + \gamma_{coll}\right)\rho_{21}(t) + i\left[\Omega\rho_{11}(t) + \frac{1}{2}\Delta\rho_{12}(t) - \Omega\rho_{22}(t)\right] \qquad \rho_{21}(0) = 0$$

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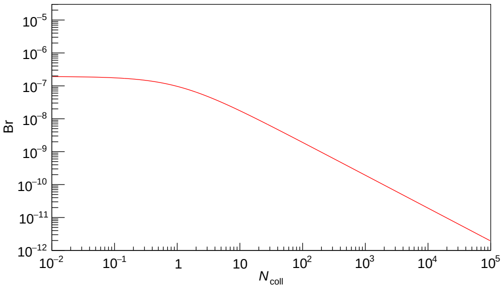
$$Br = \frac{\int_0^{t_G} \rho_{22}(t)}{\int_0^{t_G} \rho_{11}(t) + \int_0^{t_G} \rho_{22}(t)}$$

[*Crivelli et al., JINST 5, P08001 (2010)*]



Oscillation probability suppression introduced by collisions with matter

Experimental Design

- Create o-Ps and confine it in vacuum with a low collision rate
- Detect the annihilation photon
- If o-Ps $\rightarrow$ o-Ps' happens, no photon will be detected
- Signal cross-check via collision rate modulation

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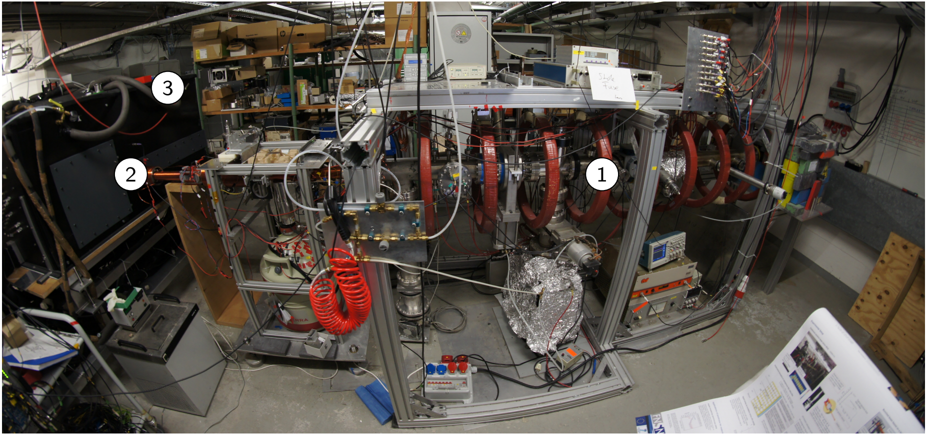
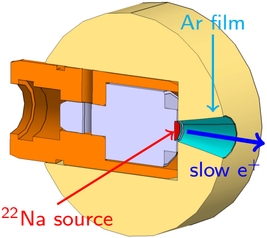
Dangerous Background

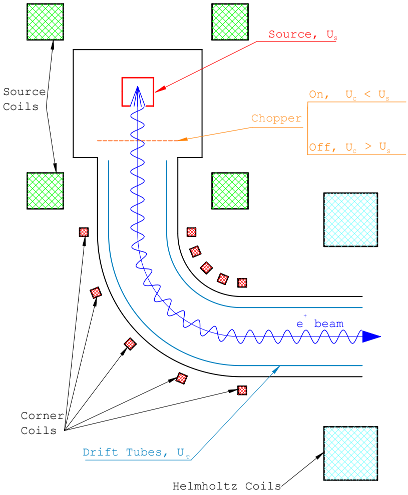
- No positron in the cavity
- Photon escapes the detector

1. Slow Positron Beam
2. Positronium Converter and Vacuum Cavity
3. Hermetic Calorimeter

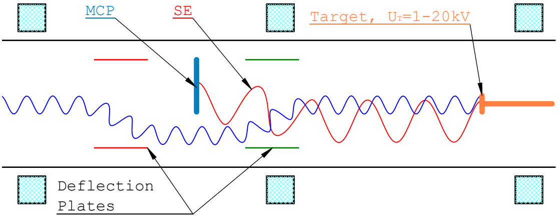


- Monoenergetic positron beam with magnetic confinement

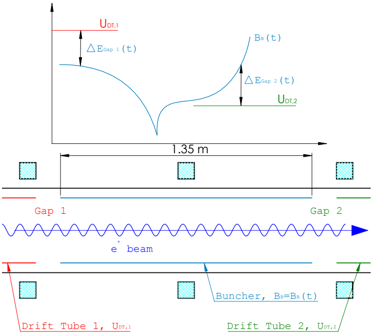


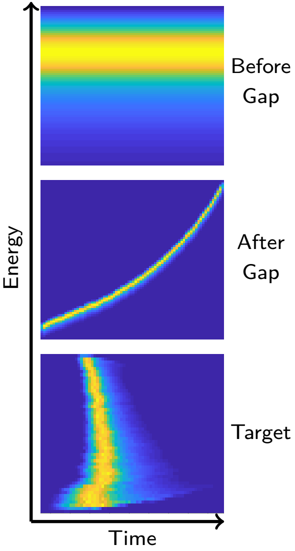


- Monoenergetic positron beam with magnetic confinement
- Positron arrival tagging via SE detection with an MCP



- Monoenergetic positron beam with magnetic confinement
- Positron arrival tagging via SE detection with an MCP
- Positron bunching system





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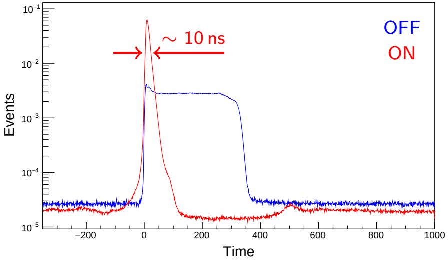

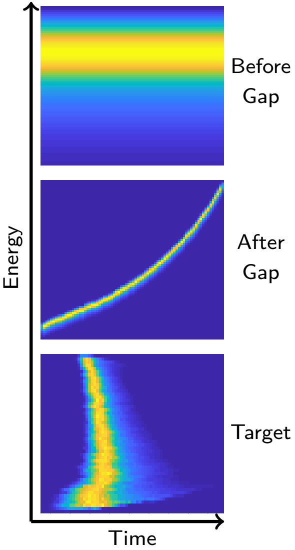

- Monoenergetic positron beam with magnetic confinement
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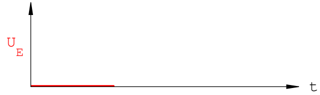
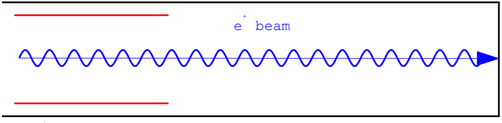
- Positron bunching system
- Positron re-implantation electrode





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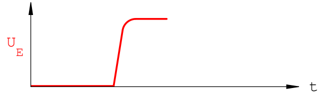

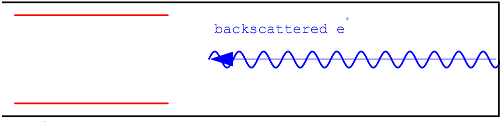

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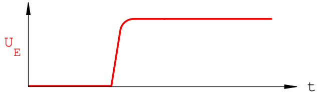
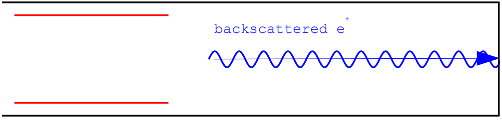
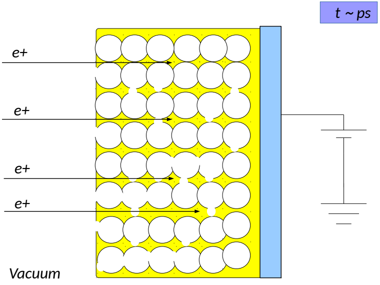




Positronium Formation in Porous Silica Thin Films

1. Implantation with few keV energy (20 to 200 nm) and rapid (ps) thermalization in the bulk



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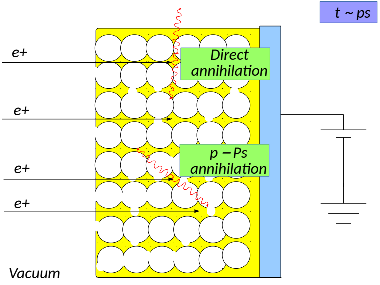
2. Positron diffusion $\Longrightarrow$ direct annihilation or Ps formation (25 % p-Ps, 75 % o-Ps)



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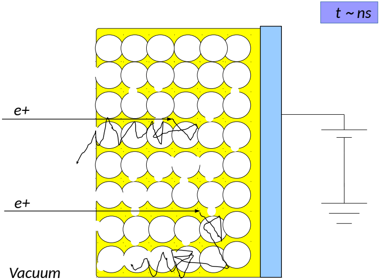
3. o-Ps diffusion to pore surface $\Longrightarrow$ thermalization and diffusion in pore network



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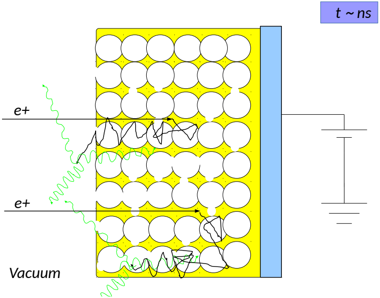

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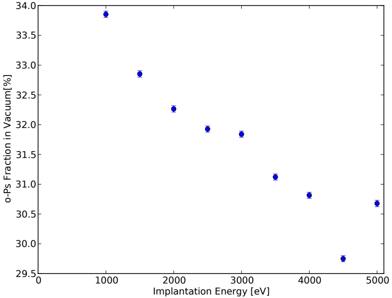
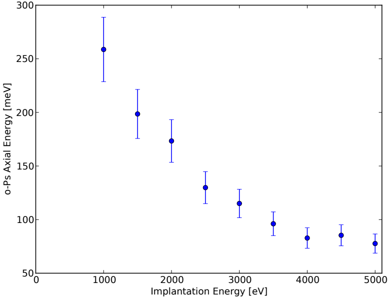
5. Characterization via annihilation spectroscopy: o-Ps yield and kinetic energy





Signal: absence of energy deposition in a calorimeter surrounding the o-Ps cavity:

- Low probability of photon escape $\Longrightarrow$ hermeticity
- Low probability of energy losses $\Longrightarrow$ reduction of dead material

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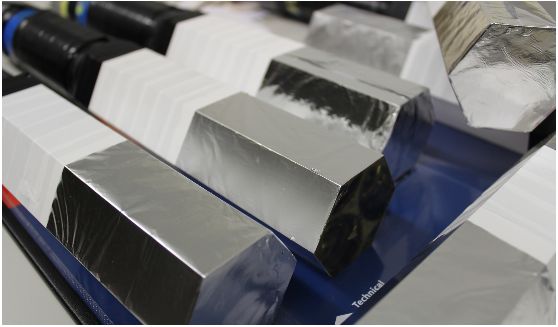
Design guided with Geant4 simulation:

- Detectors: available BGO scintillators, refurbished to reduce dead material



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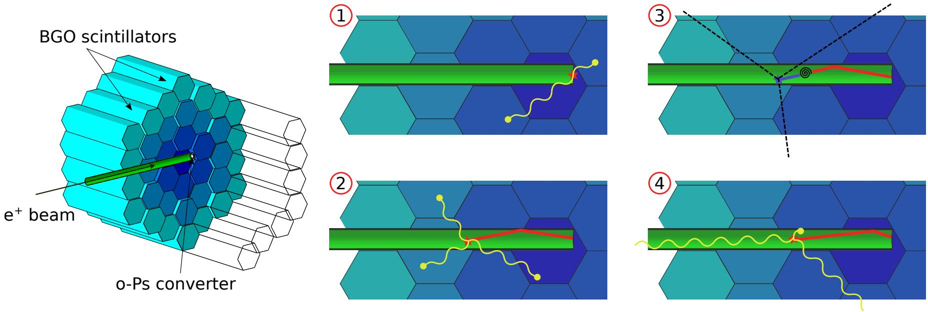
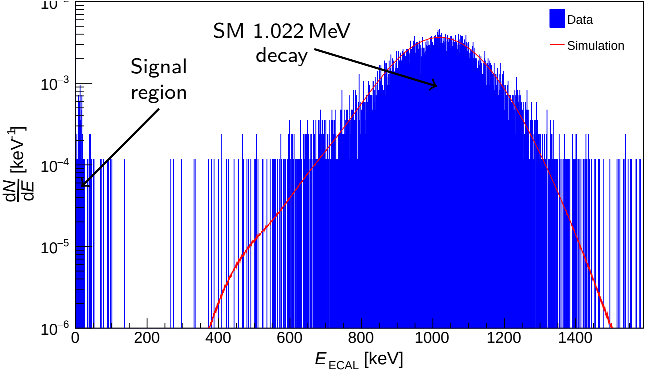
- Geometry: honeycomb structure around the o-Ps cavity



E_{ECAL} spectrum with SM peak at 1.022 MeV in good agreement with simulation



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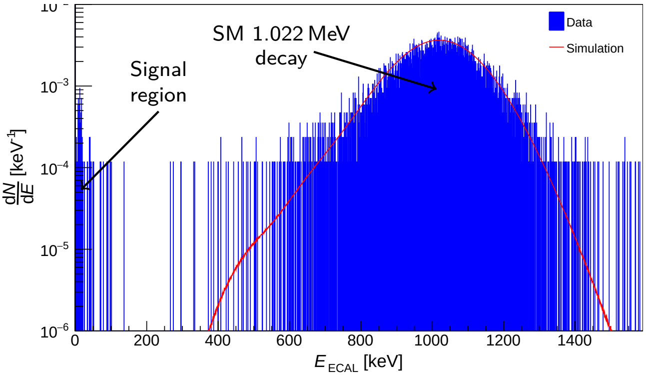

Events in the signal region identified as:

- Backscattered positrons $\Longrightarrow$ re-implantation electrode

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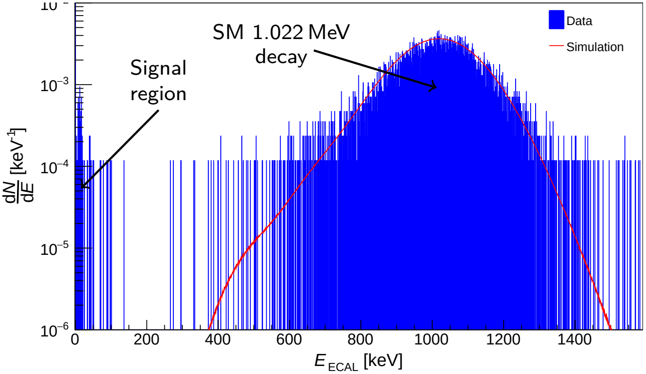

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- Trigger accidentals $\Longrightarrow$ beam-off measurement estimation

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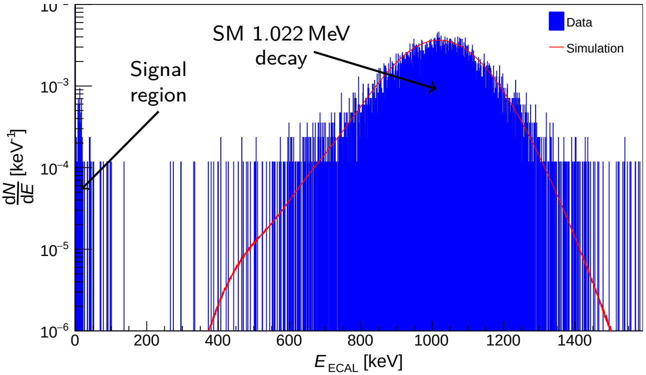

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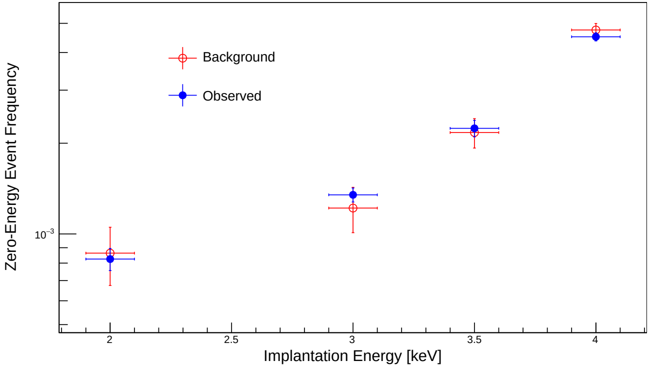
- Trigger accidentals $\Longrightarrow$ beam-off measurement estimation
- ? Signal

- Number of observed events compatible with expected background



[*Vigo et al., arXiv:1803.05744, accepted in PRD*]

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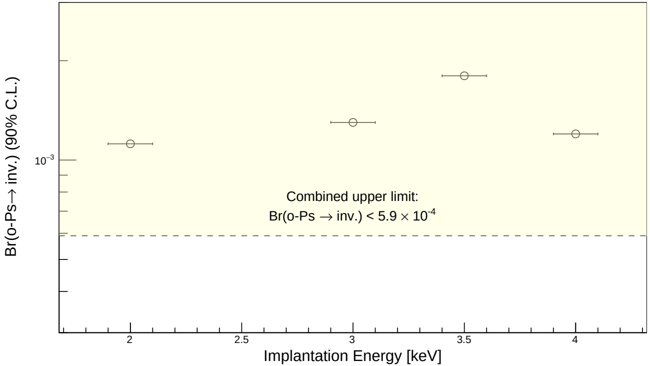

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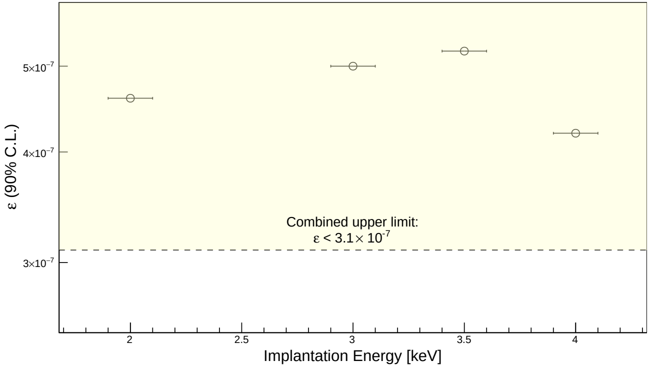

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- Purely leptonic system $\Longrightarrow$ ideal system for QED tests
- Theoretical value two orders of magnitude more precise than experiment

$$\lambda_{\text{th.}} = (7.039\,970 \pm 0.000\,010)\,\mu\text{s}^{-1} \quad (1.5\,\text{ppm}) \quad [\textit{Adkins et. al., PRL 2000}]$$

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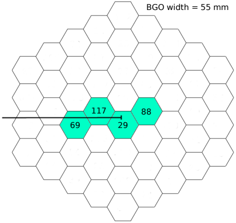
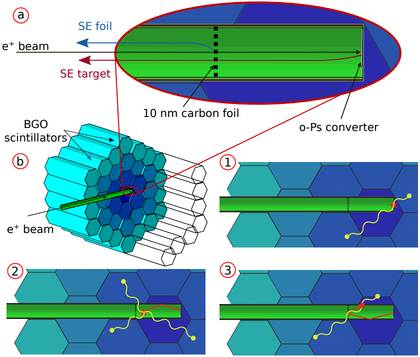
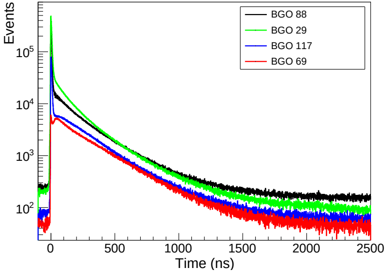
Main Limitations

- Statistics (pile-up in non-beam experiments)
- Collisional quenching of fast positronium

- Confinement of o-Ps in a cavity:
    - Tagging enhancement (DM search)
    - Homogeneous efficiency







[*Vigo et al., arXiv:1805.06384*]

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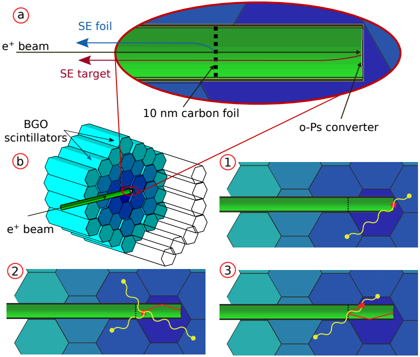

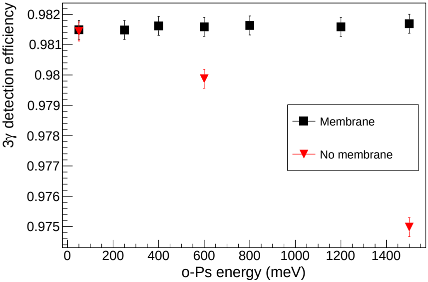

[*Vigo et al., arXiv:1805.06384*]

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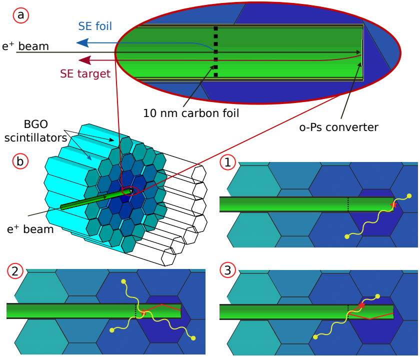
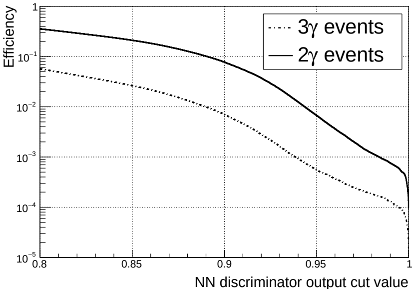
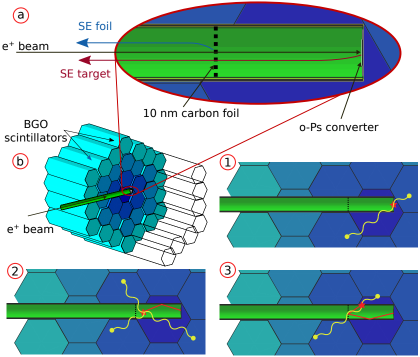




[*Vigo et al., arXiv:1805.06384*]

- Confinement of o-Ps in a cavity:
  - Tagging enhancement (DM search)
  - Homogeneous efficiency
- Detector granularity $\Longrightarrow$ measure and subtract 2γ spectrum
- Detector hermeticity $\Longrightarrow$ veto pile-up



Expected precision:

- 25 ppm syst.
- 100 ppm stat. (first stage)

[*Vigo et al., arXiv:1805.06384*]

- ✓ First experimental search for photon-less decays of o-Ps in vacuum
- ✓ No evidence of new physics, limit on MM coupling constant

$$\varepsilon < 3.1 \times 10^{-7} \quad \left(90\,\%\ \text{C. L.}\right)$$

- ✓ Proof of principle: positron implantation energy $\Longrightarrow$ collision rate $\Longrightarrow$ signal modulation
- × Limiting factor: background from trigger accidentals

Sensitivity Goal: $\varepsilon \sim 4 \times 10^{-9}$

- ✓ Increase positron rate $\Longrightarrow$ larger S/N ratio } new data next month
- ✓ Improve tagging system } new data next month
- o-Ps cavity upgrade

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} new data next month

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Lifetime Measurement

- Current experimental precision 2 orders of magnitudes worse than QED calculations
- Parasitic measurement using the same setup
- Reduce main systematic effects in previous measurements:
  - Fast o-Ps escaping
  - Wall collision quenching
- Expected precision: 100 ppm, limited only by statistics

Thank you!

PI: P. Crivelli

Additional credits: M. Raajimakers
L. Gerchow
B. Radics
A. Rubbia