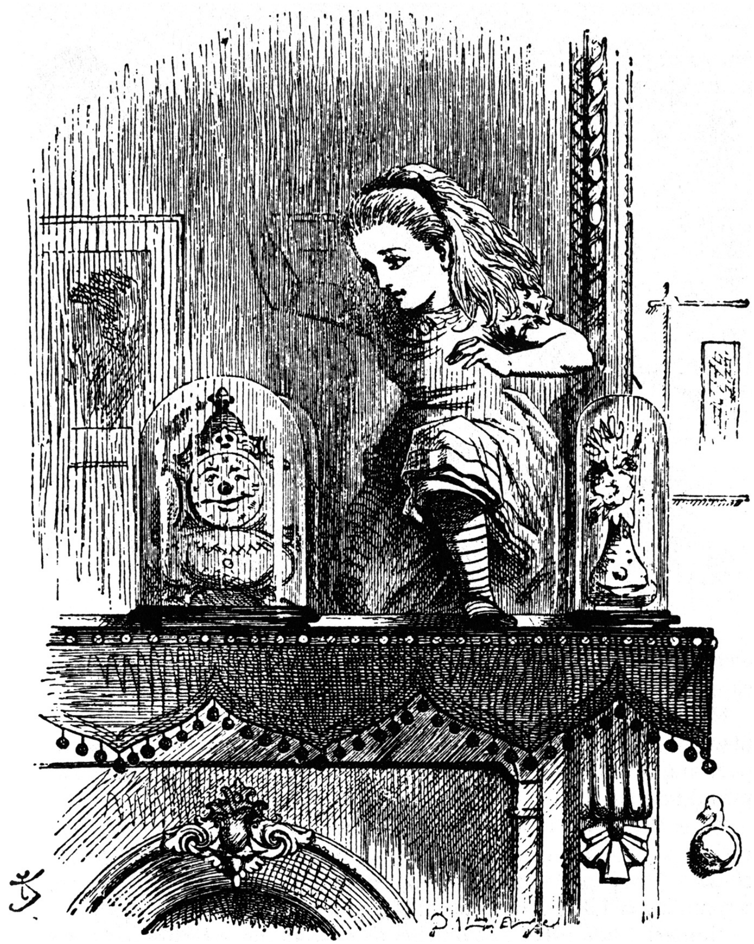


What Alice can find through the Looking-Glass
About mirror matter searches with J-PET

Wojciech Krzemień

“Is Quantum Theory exact?
From quantum foundations to quantum applications”
Frascati, 25.09. 2019

Disclaimer

- Rather ideas than results ...

- In collaboration with:

  Steven Bass, Krzysztof Kacprzak, Paweł Moskal and Elena Perez del Rio

- … but for any errors in the presentation you should blame me,

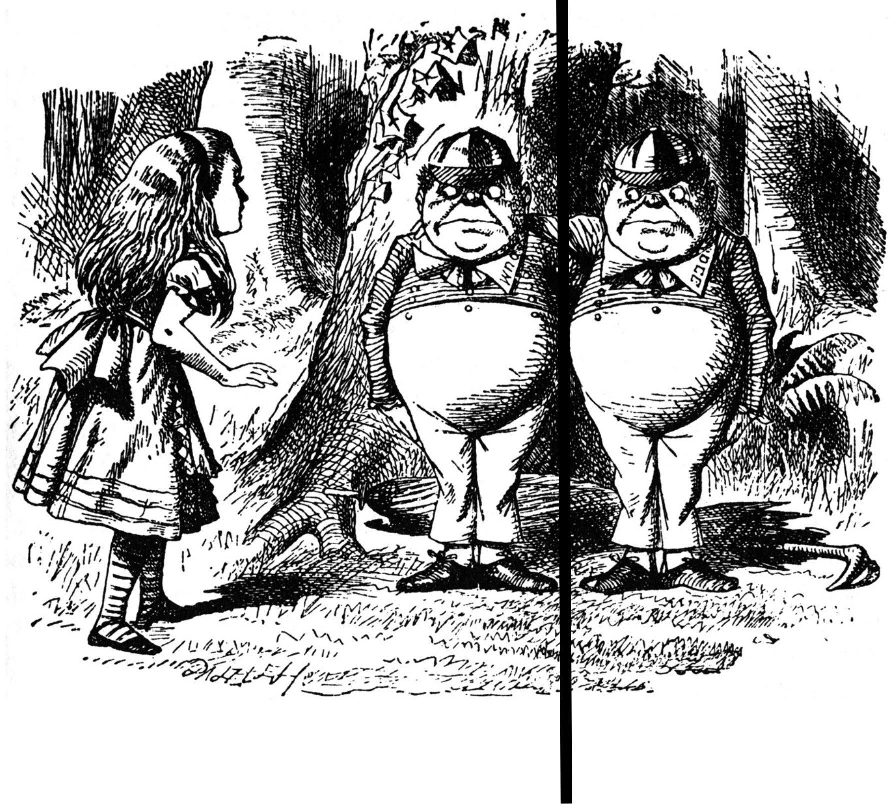
- All Alice drawing by John Tenniel

Parity (mirror) symmetry

Parity transformation: $x \rightarrow -x$

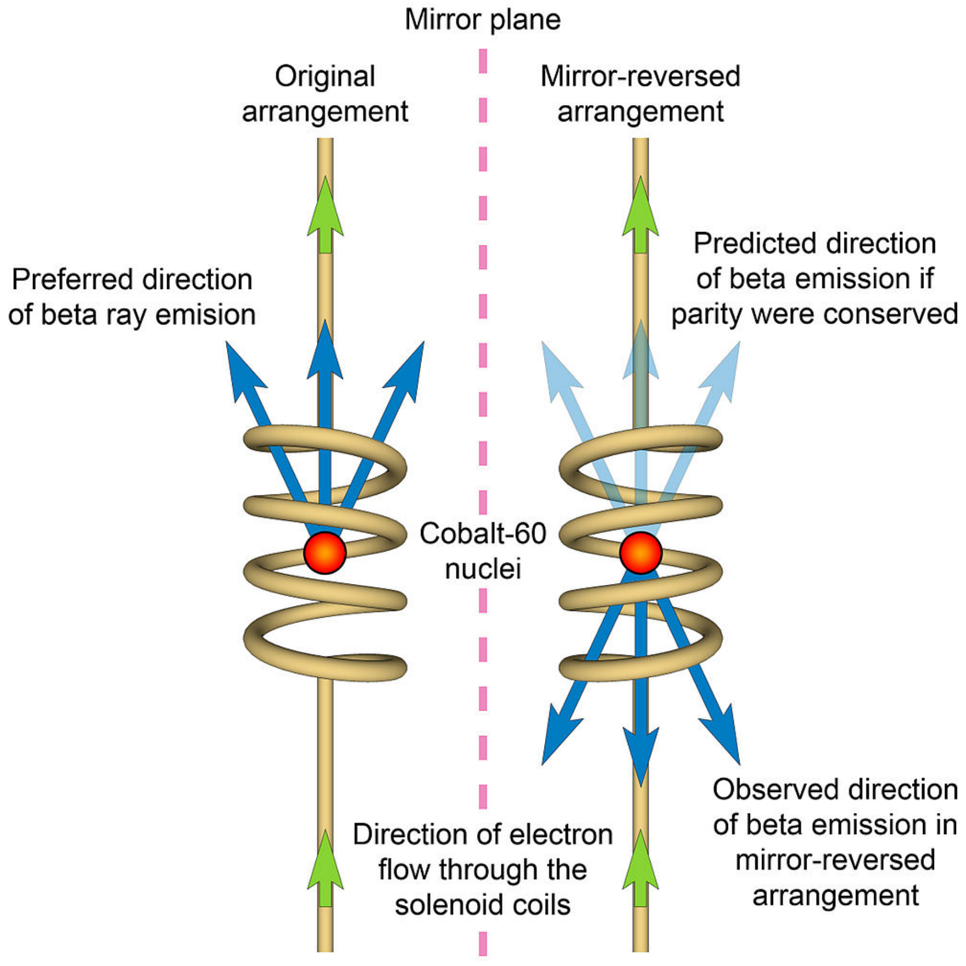
$y \rightarrow -y$

$z \rightarrow -z$



Our world is not (parity-) symmetric

Weak interactions violates parity



Our world is not (parity-) symmetric

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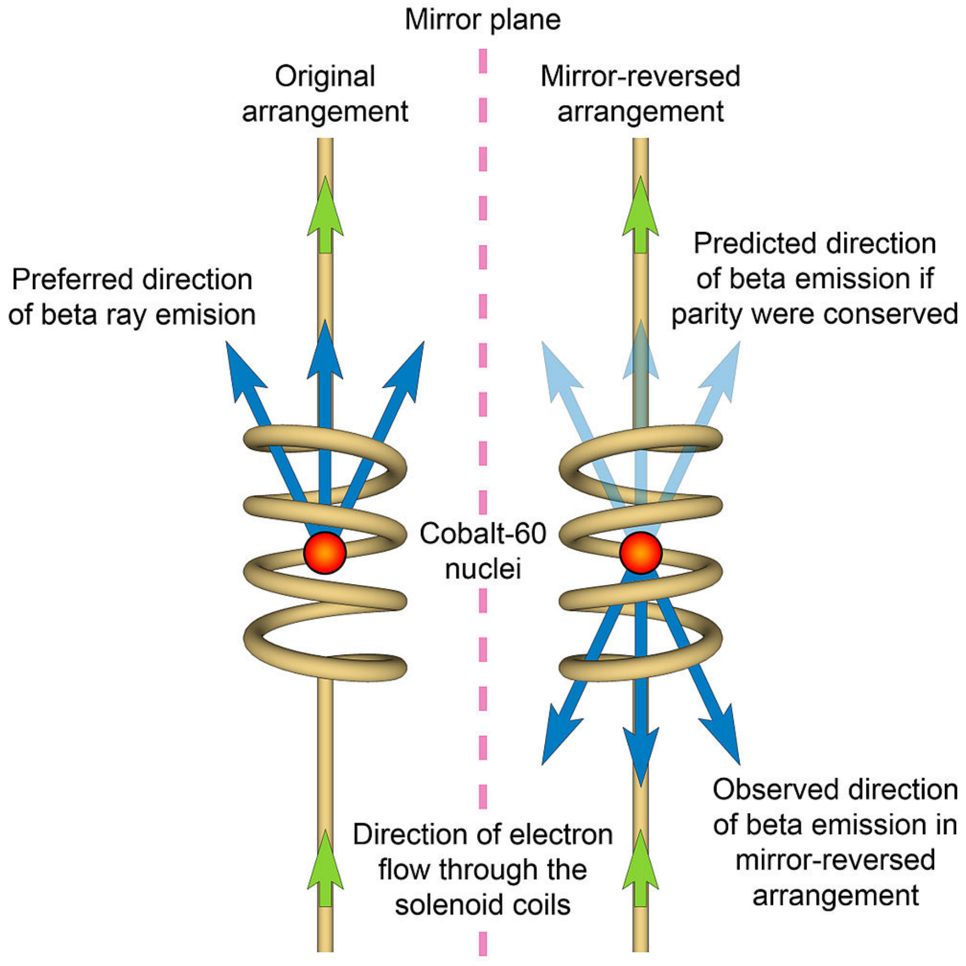


Experimental confirmations:

C. S. Wu et al.

Phys. Rev. 105 (1956) 1413

R. L. Garwin, L. Lederman and R. Weinrich

Phys. Rev. 104 (1956) 254

How to „restore” parity (mirror) symmetry?

Lee and Yang „Question of parity conservation in weak interactions”

Phys. Rev. 104 (1956) 254

How to „restore” parity (mirror) symmetry?

Lee and Yang „Question of parity conservation in weak interactions”

Phys. Rev. 104 (1956) 254

If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry.

In such a picture the supposedly observed right-and-left asymmetry is therefore ascribed not to a basic non-invariance under inversion, but to a cosmologically local preponderance

Short history of mirror matter (models)

Kobzarev, Okun & Pomeranchuk – hidden mirror sector

Glashow – orthopositronium as a probe to mirror matter world

S. L. Glashow Phys. Lett. B 167 (1986) 35

A lot of different ideas and models based on the mirror matter

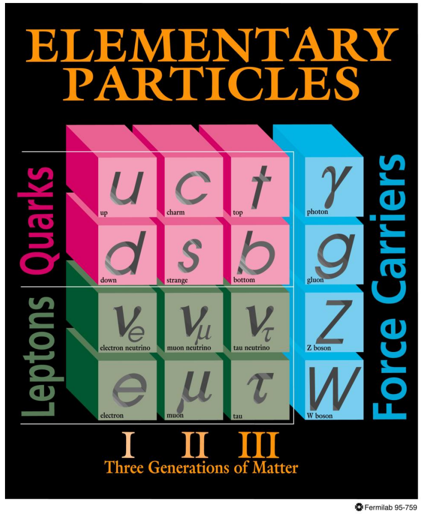
L. B. Okun Phys. Usp. 50 (2007) 380-389
[hep-ph/0606202]

(Foot, Gninenko, Kobzarev Pomeranchuk, Berezhiani, Mohapatra and others):

- mirror astrophysics
- mirror cosmology
- mirror symmetry breaking
- mirror searches at LHC (mixing of normal and mirror higgs)

Matter

Mirror matter



Left-handed particle

Right-handed antiparticle

Right-handed particle

Left-handed antiparticle

G = SU(3) x SU(2) x U(1)

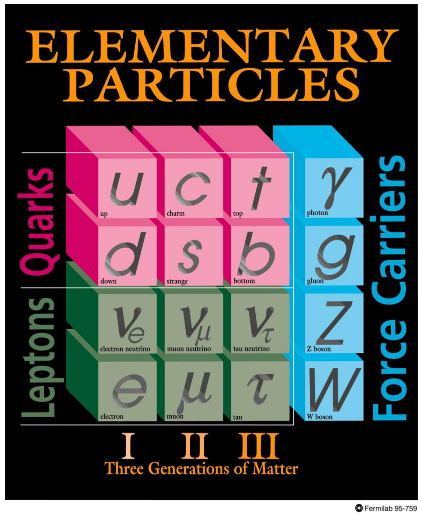
G' = SU(3)' x SU(2)' x U(1)'

V-A for weak interactions

V+A for weak interactions

Gravity as common force

How mirror matter can interact with matter?

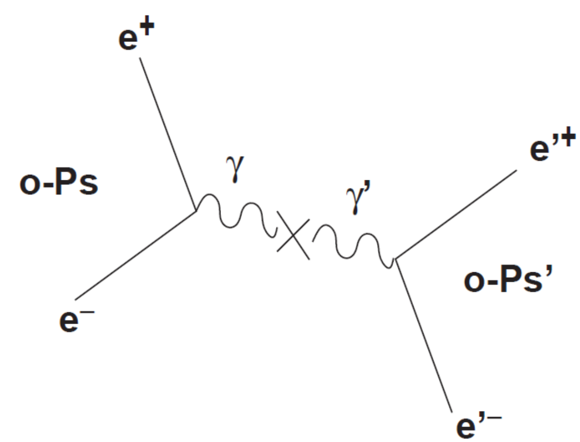


- Gravity is the common force:

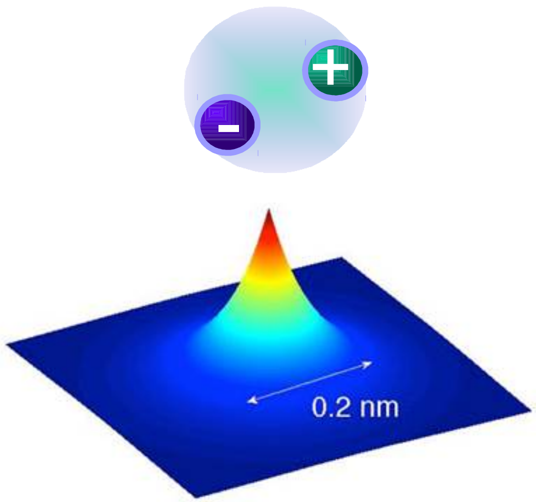
  Mirror matter particles as candidates for **dark matter**

- New kind of interactions:

  $L = L + L' + L_{mix}$ - kinetic mixing term



Orthopositronium



$S = 0$ $\quad \downarrow\uparrow - \uparrow\downarrow \quad$ $^1S_0$ **Para-positronium**

$\uparrow\uparrow$

$S = 1$ $\quad \uparrow\uparrow + \downarrow\downarrow \quad$ $^3S_1$ **Ortho-positronium**

$\downarrow\downarrow$

	$^1S_0$	$^3S_1$
L	**0**	**0**
S	**0**	**1**
J	**0**	**1**

$C\,|Ps\rangle = (-1)^{L+S}\,|Ps\rangle$

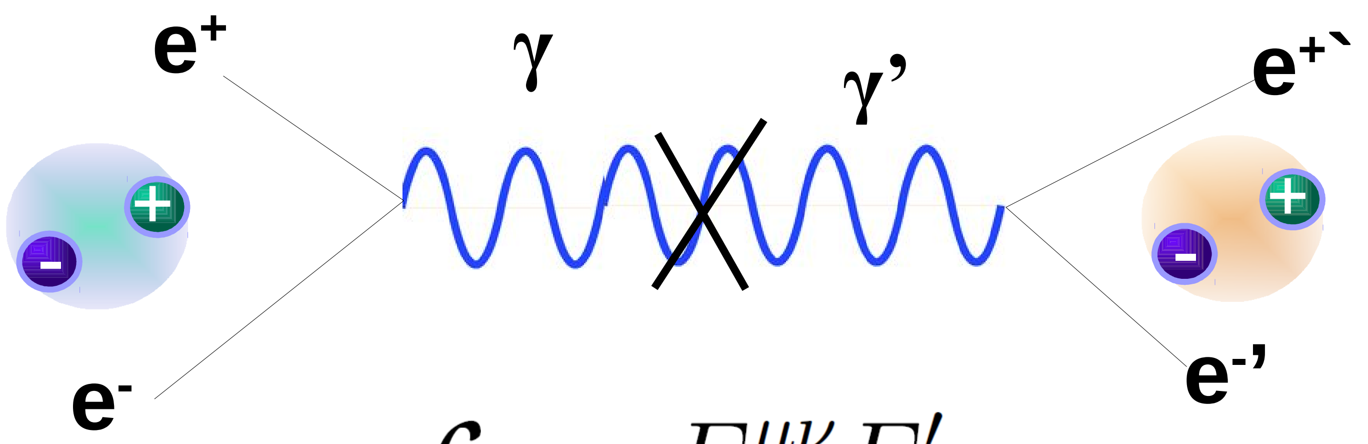
$C\,|n\gamma\rangle = (-1)^{n}\,|n\gamma\rangle$

	$^1S_0$	$^3S_1$
C	+	-
P	-	-
CP	-	+

$^1S_0$ **Para-positronium**	**p-Ps** $\rightarrow$ **2n γ**	**tau(p-Ps) ≈ 125 ps**
$^3S_1$ **Ortho-positronium**	**o-Ps** $\rightarrow$ **(2n+1) γ**	**tau(o-Ps) ≈ 142 ns**

o-Ps and mirror o-Ps’

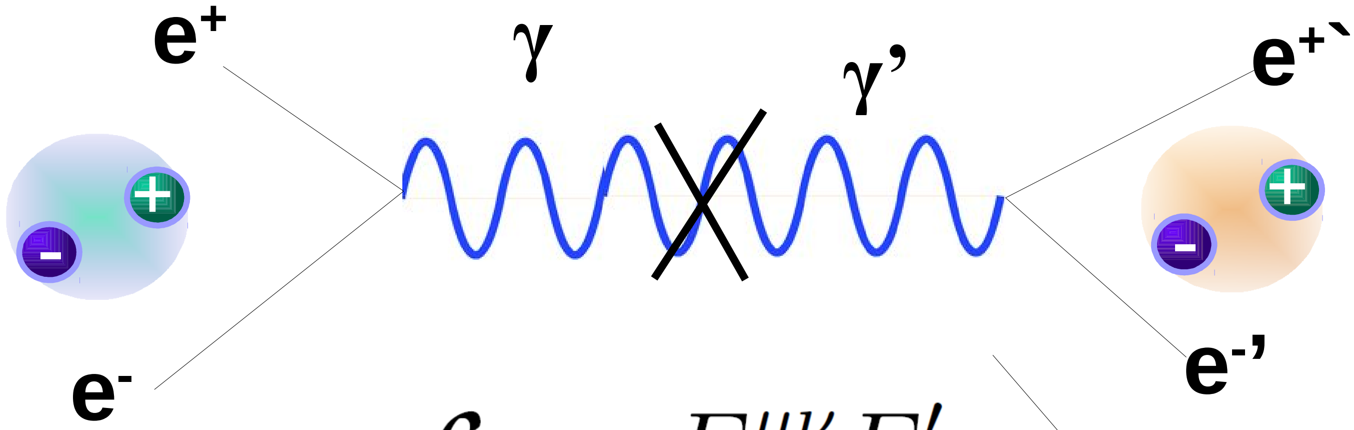
S. L. Glashow Phys. Lett. B 167 (1986) 35



$$\mathcal{L} = \epsilon F^{\mu\nu} F'_{\mu\nu}$$

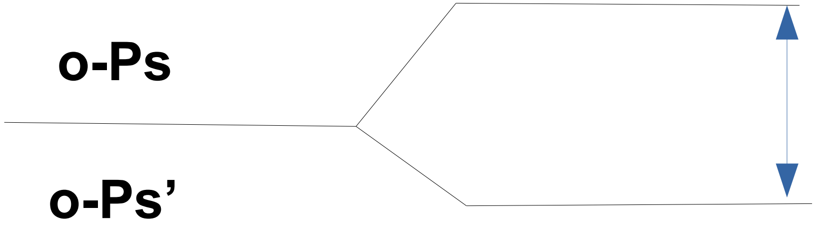
o-Ps and mirror o-Ps’

S. L. Glashow Phys. Lett. B 167 (1986) 35



$$\mathcal{L} = \epsilon F^{\mu\nu} F'_{\mu\nu}$$

o-Ps+ = 1/sqrt(2) * (o-Ps +o-Ps’)



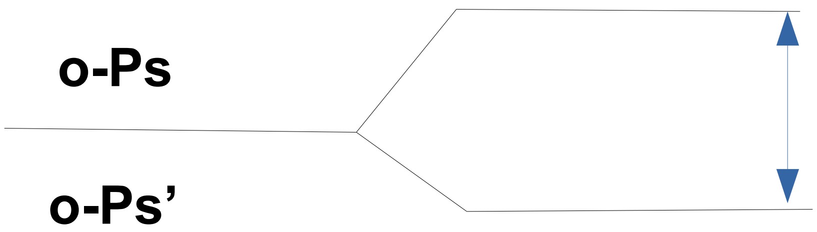
$$\Delta E = 2h\epsilon f$$

$$f = 8.7 \times 10^4 \text{ MHz}$$

o-Ps- = 1/sqrt(2) * (o-Ps -o-Ps’)

o-Ps and mirror o-Ps' oscillations

o-Ps$^+$ = 1/sqrt(2) * (o-Ps +o-Ps')



$$\Delta E = 2h\epsilon f$$

o-Ps$^-$ = 1/sqrt(2) * (o-Ps -o-Ps')

$$f = 8.7 \times 10^4 \ \mathrm{MHz}$$

$$\omega = 2\pi\epsilon f$$

$$P(\mathrm{o-Ps} \to \mathrm{o-Ps'}) = \sin^2 \omega t$$

$$Br(o-Ps \to invisible) = \frac{2(2\pi\epsilon f)^2}{\Gamma_{3\gamma}^2 + 4(2\pi\epsilon f)^2}$$

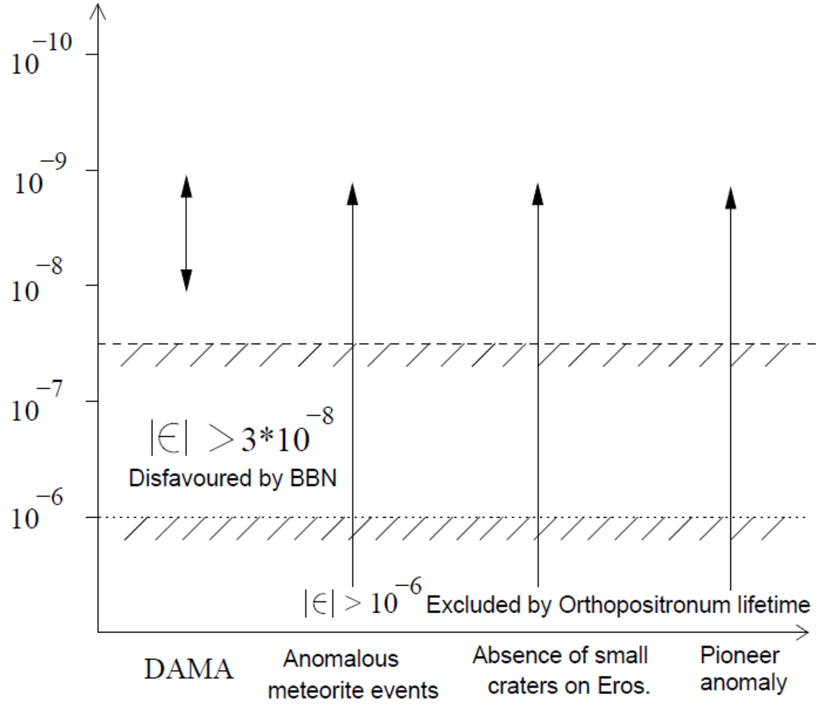
In vacuum !!!

Astro-physical observation constraints

R. Foot . Phys.Rev.D 69 (2004) 036001

- From primordial abundance of ^{4}He: $\epsilon \leq 3 \times 10^{-8}$ $Br(o-Ps \to invisible) < 10^{-5}$

- Mirror matter as dark matter e.g. mirror matter halo of galaxies
- DAMA astrophysical observations reinterpreted within the mirror matter model: ~4 * 10^{-9} ϵ $Br(o-Ps \to invisible) \simeq 2 \times 10^{-7}$



A. Rubbia Int.J.Mod.Phys. A19 (2004) 3961-3985[hep-ph/0402151v1]

How would it manifest experimentally?

o-Ps’ escapes detection → Br(oPs → invisible) = ?

from SM predictions Br(oPs → $\nu\bar{\nu}$) < O(10^{-18})

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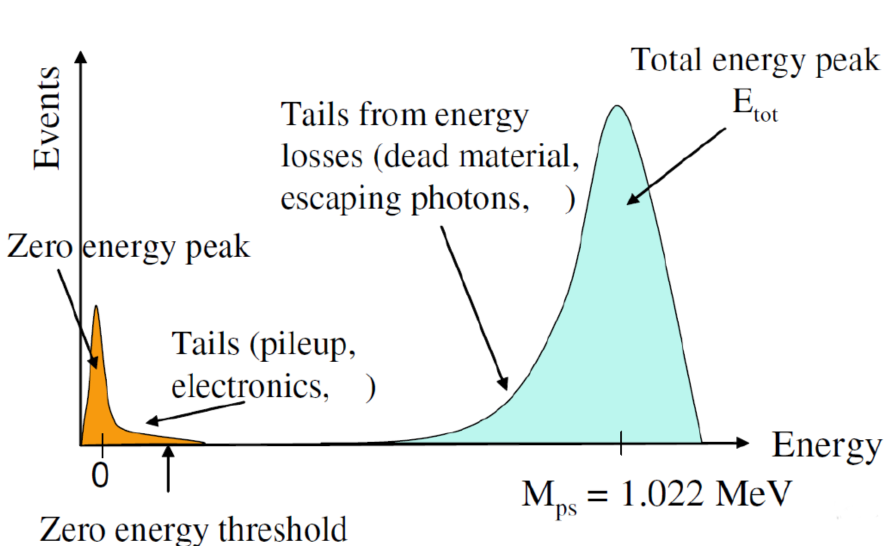
Searching for „zero-signal" events

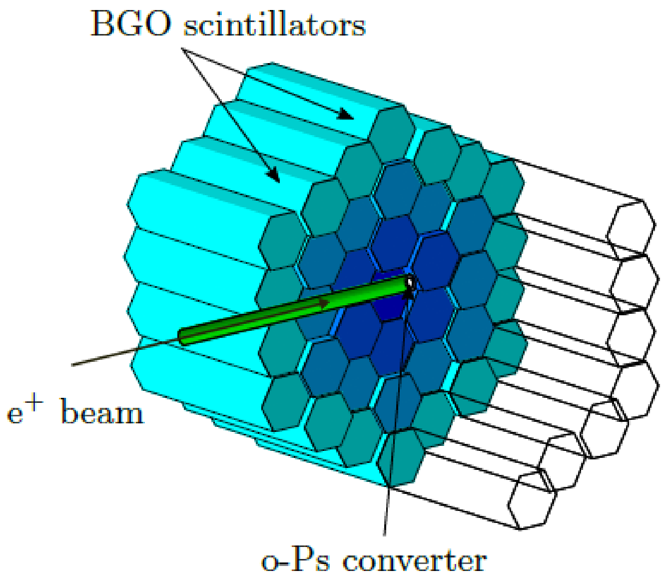


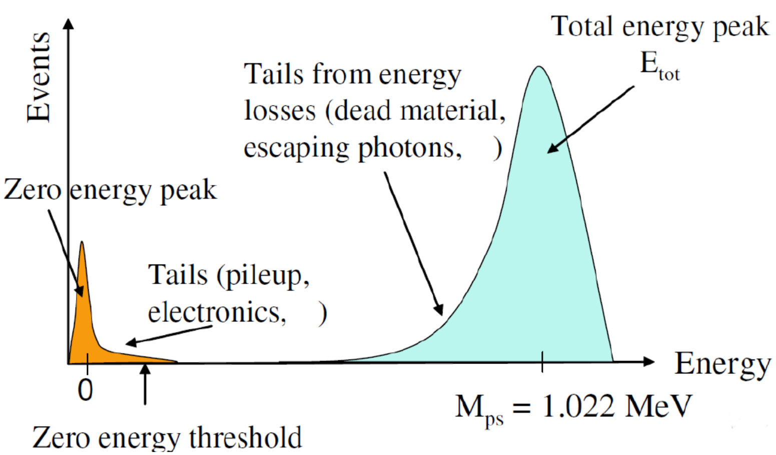
P. Crivelli Phd Thesis, ETHZ(2006)

Precise o-Ps lifetime measurements

… and compare with QED predictions

Searching for „zero-signal” events





P. Crivelli Phd Thesis, ETHZ(2006)

C. Vigo et al . Phys.Rev.D 97 (2018) 092008

- Several measurements by ETHZ group
- Use of slow positron beam (~15000 e^+/s) on thin silica films (~ 30% prob. of o-Ps)
- Micro-Channel Plate detector to tag positron (Start signal)
- Highly hermetic BGO calorimeter (total signal efficiency ~92%)
- Decay of o-Ps in a vacuum cavity

$$\mathrm{BR}(\text{o-Ps} \to \text{invisible}) < 5.9 \times 10^{-4}\,, \qquad 90\%\ \mathrm{C.L.}$$

$$\varepsilon \; < \; 3.1 \times 10^{-7} \;\; (90\,\%\;\; \mathrm{C.}\;\; \mathrm{L.})$$

Precise measurments of o-Ps lifetime

$$P(\mathrm{o-Ps} \to \mathrm{o-Ps}') = \sin^2 \omega t$$

$$\omega = 2\pi\epsilon f$$

$$f = 8.7 \times 10^4 \ \mathrm{MHz}$$

Number of observed o-Ps

$$\mathbf{N = (1 - \sin^2(\omega t))\, e^{-\Gamma t} \approx \exp[-(\omega t)^2 - \Gamma t]}$$

Compare lifetime with QED calculations

$$\Gamma(\mathrm{o-Ps} \to 3\gamma, 5\gamma) = \frac{2(\pi^2 - 9)\alpha^6 m_e}{9\pi}\left[1 + A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}\ln\alpha + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^3}{2\pi}\ln^2\alpha + C\frac{\alpha^3}{\pi}\ln\alpha + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots\right]$$

S. Bass Acta Phys. Pol. B 50 no7 (2019) 1319

o-Ps lifetime

Non-relativistic QED predictions up to NNLO:

$$\Gamma = 7.039979(11) \times 10^6\,\mathrm{s}^{-1}$$

Experimental results:

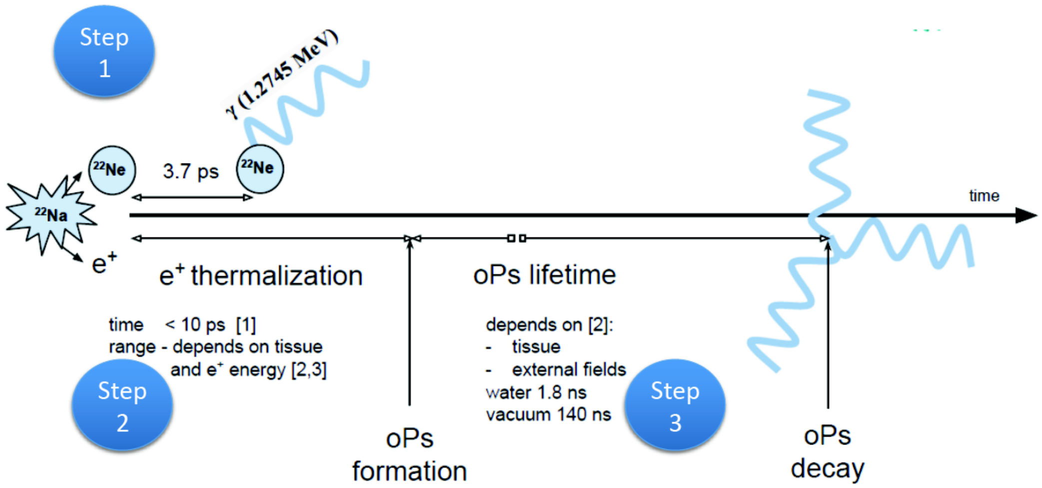
$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$ **Tokyo group**

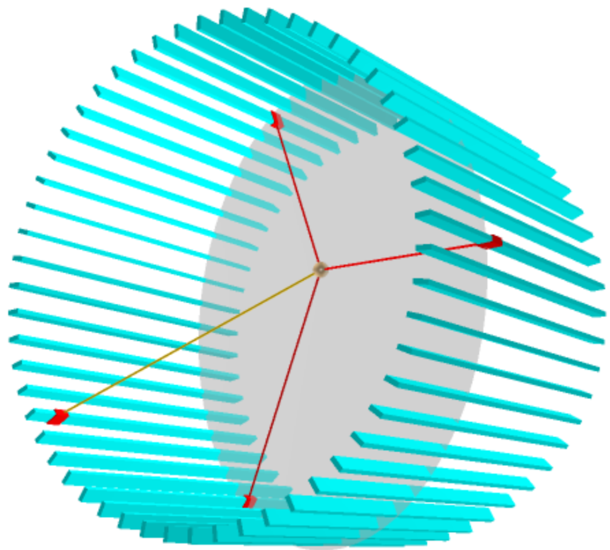
$$\Gamma = 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6\,\mathrm{s}^{-1}$$ **Ann Arbor group**

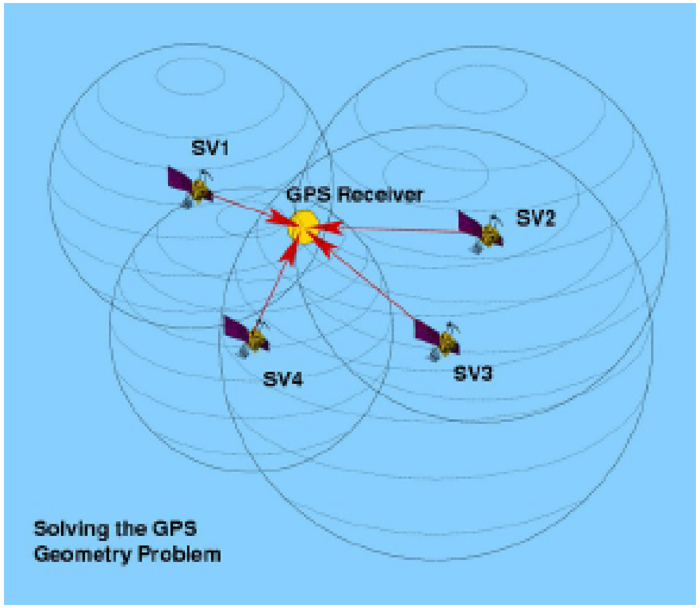
Theory predictions 100 times more precise:
10^{-6} vs 10^{-4}

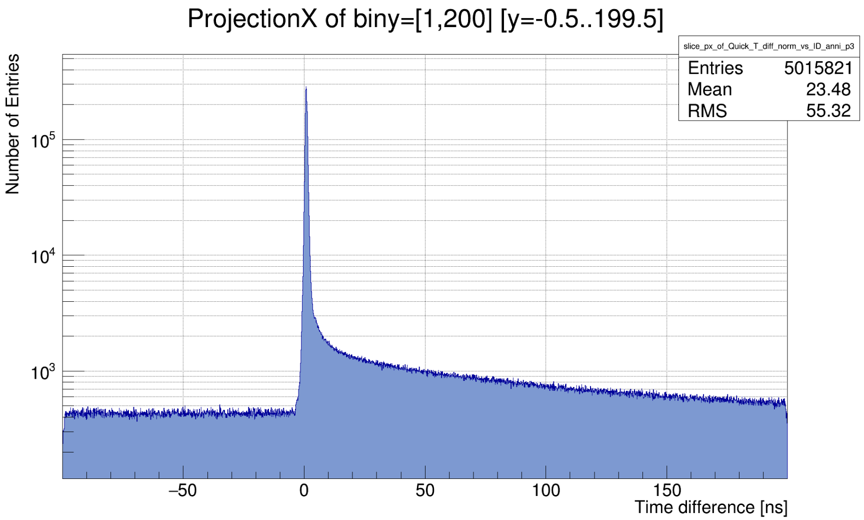
S. Bass Acta Phys. Pol. B 50 no7 (2019) 1319

Determination of Ps lifetime in J-PET





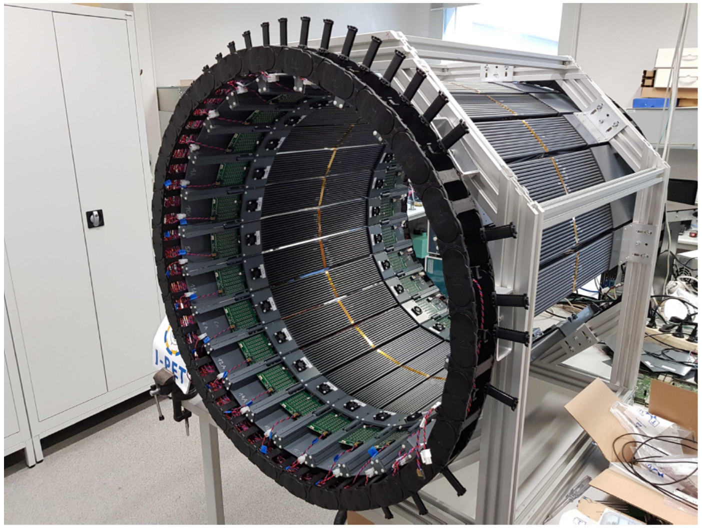


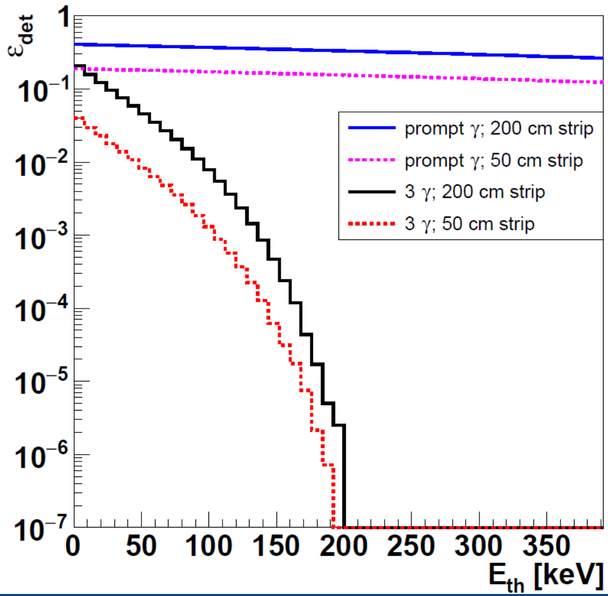


K. Dulski → p-Ps lifetime

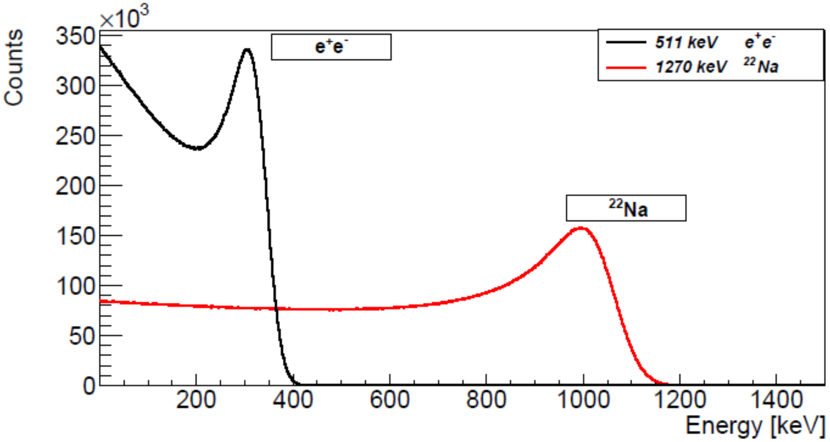
A. Gajos et al. Nucl. Instrum. Methods. A819 (2016) 54

Invisible decays and J-PET ?





P. Moskal, D. Kisielewska et al. Phys. Med. Biol. 64 (2019) 055017



Simple estimate (no background):

Source activity $=10^6$

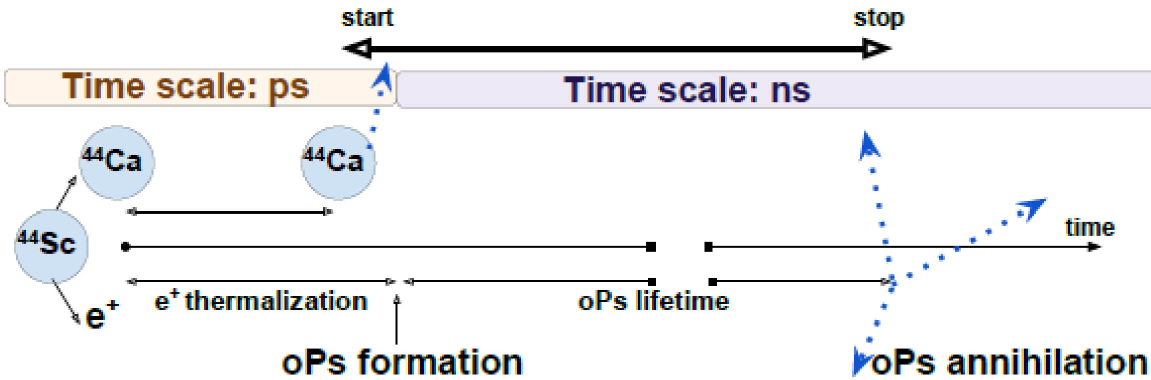
XAD-4 o-Ps creation prob. = 29%

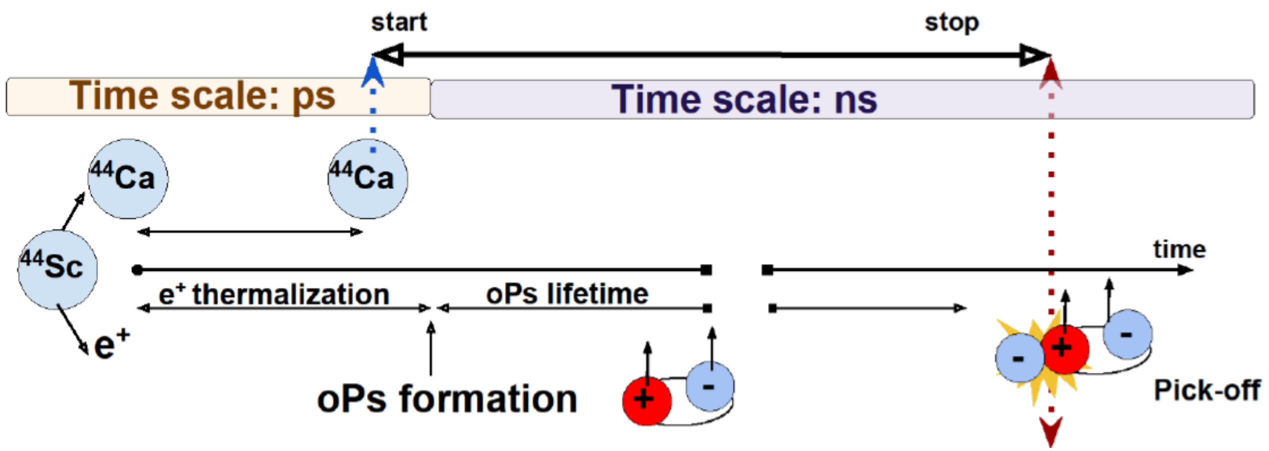
o-Ps/year generated $\sim 10^{14}$

Registration efficiency for the new detector

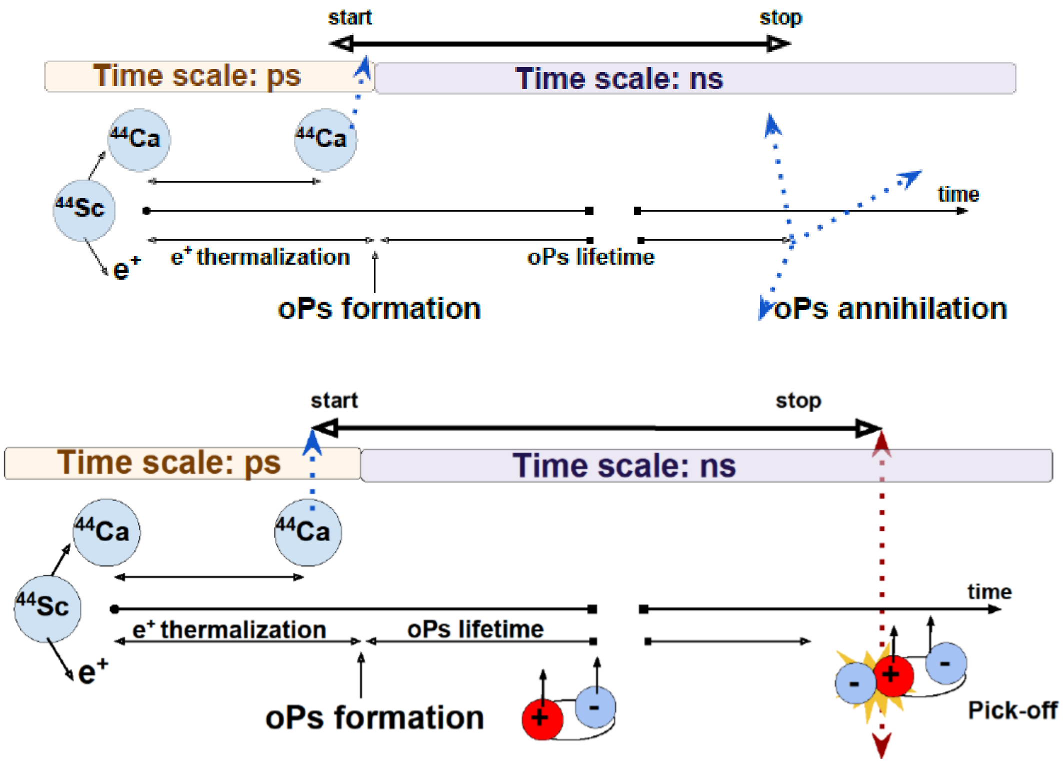
After two years of data taking $<10^{-5}$

The main experimental challenge: pick-off effect





The main experimental challenge: pick-off effect



$$\lambda_{obs}(t) = \lambda_{o-Ps} + \lambda_{pick}(t)$$

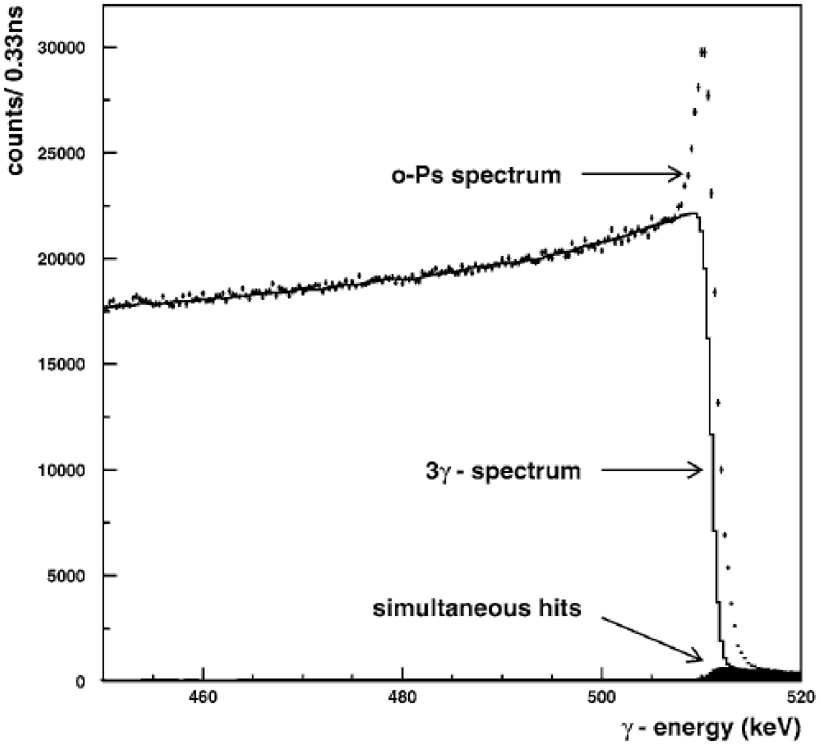
$$\lambda_{\text{pick}}(t) = n\sigma_{\text{a}}v(t)$$

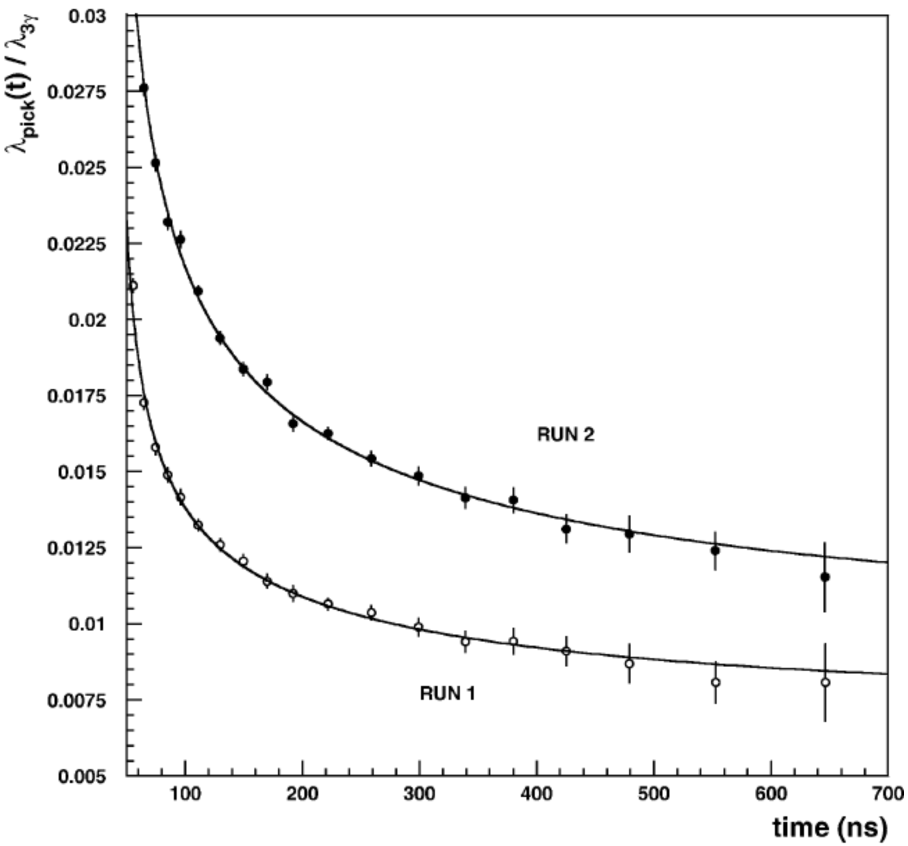
velocity of o-Ps

target density

annihilation cross-section

Tokyo group method



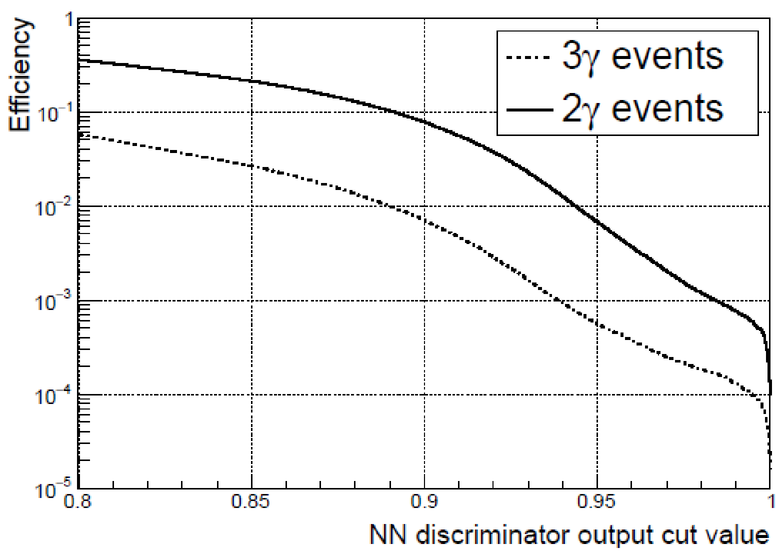


$$N(t) = N_0' \exp\left(-\lambda_{3\gamma} \int_0^t \left(1 + \frac{\lambda_{\text{pick}}(t')}{\lambda_{3\gamma}}\right) dt'\right)$$

O. Jinnouchi et al. Phys. Lett. B 572 (2003) 117

Neural network classifier for pick-off $\lambda_{pick}(t)$ determination

ETHZ method proposal



C. Vigo et al. (2019) [805.06384v]

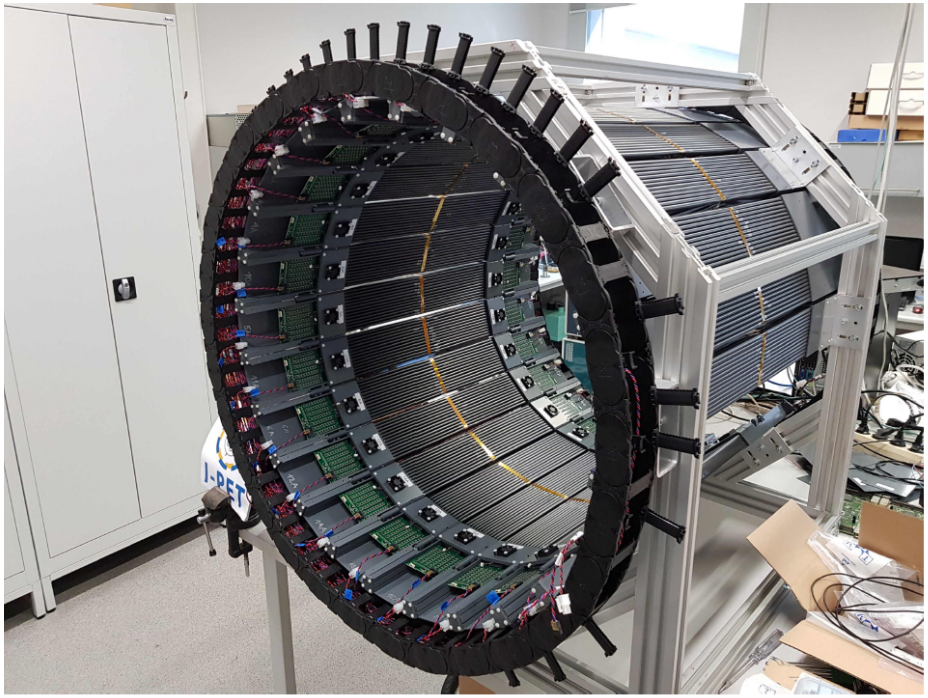
J-PET

- very good timing resolution
- very good angular resolution (~1 deg)
- vertex determination with trilateration methods

- very good topological cut

+

- reasonable energy resolution



In the future:
Modular J-PET with positron beam?

Mirror matter and cosmological evolution

www.discovery.org

Conclusions

- Mirror matter particles as proposed Dark Matter candidates
- Constraints from astrophysical observations (DAMA & DAMA/LIBRE)
- Orthopositronium system as a probe of the mirror world
- J-PET as a suitable detection system for o-Ps lifetime measurements
- Main challenge is the pick-off background
- In the future : J-PET with positron beams?

Thank you for your attention

Properties

- 192 detection modules arranged in 3 layers
  - 19x5x500 mm^3 EJ-230 scintillator strips + Hamamatsu R9800 photomultipliers.

- Novel digital front-end electronics probing signals at multiple thresholds.
  [M. Pałka et al. JINST 12 (2017) no.08, P08001]

- Trigger-less and reconfigurable DAQ system.
  [G. Korcyl et al. Acta Phys.Polon. B47 (2016) 491]

- Annihilation gamma quanta hit time measurement:
  $\sigma_t(0.511\ \mathrm{MeV}) \sim 125$ ps. [P. Moskal et al., Nucl.Instrum.Meth. A775 (2015) 54-62]

- Gamma quanta energy resolution:
  $\sigma_E/E = 0.044/\sqrt{E(\mathrm{MeV})}$ [P. Moskal et al. Nucl.Instrum.Meth. A764 (2014) 317]

- Resolution of photons relative angles measurement ~ 1^o.

- o-ps spin and photon polarization measurement.