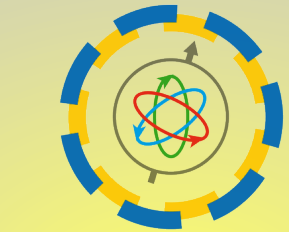
Proposal for Mirror Matter investigation

in J-PET experiment



Krzysztof Kacprzak on behalf of J-PET Collaboration

3rd Symposium on Positron Emission Tomography
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Outline

- Beyond the Standard
- Looking into the mirror
- Recent experiments and results
- J-PET contribution
- Nonsignal and backgrounds
- Plans for analysis
- Summary

Beyond the Standard (1)

Motivations given by (as usual) astrophysical observations
- e^+/e^- excess in cosmic ray flux, positron spectrum in primary cosmic rays, 511 keV gamma ray signal from the galactic center, annual modulation of the dark matter halo

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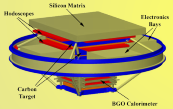
ATIC 
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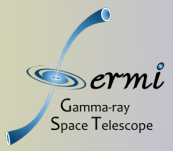
Fermi 

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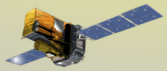
INTEGRAL 
DAMA/LIBRA 

Beyond the Standard (2)

Ortho-Positronium atoms can be a window/mirror for searches beyond Standard Model. First experiments for outside SM physics were conducted to explain o-Ps lifetime calculation/measurement discrepancy. Several examples:

- **Visible Exotic** decays:
o-Ps $\rightarrow \gamma + X$ (long-lived boson, i.e. axion);
o-Ps $\rightarrow \gamma + X \rightarrow \gamma + 2\gamma$ (short-lived boson);

- **Forbidden**: o-Ps $\rightarrow 2\gamma$ (angular momentum), 4γ (C symmetry)

- **Invisible**: o-Ps $\rightarrow$ *invisible*. Possible scenarios: extra dimensions, fractional electric charge, light boson, **Dark Matter** in form of **Mirror Matter**.

Looking into the mirror (1)

Existence of **Mirror Matter** was proposed in 1956 by Lee and Yang
[T.D., Yang C. N. Phys. Rev. 1956. V. 104. P. 254.]

- x $\rightarrow$ -x through **PR** transformation where **R** is the transformation of the particle into a reflected state from mirror space
- Each particle has a mirror partner with the same properties and opposite chirality
- Mirror particles interact with light matter mainly through gravity $\rightarrow$ Dark Matter candidates
- $\gamma -$ mirror γ' interaction via kinetic mixing

$$\mathcal{L}_{kin-mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

Looking into the mirror (2)

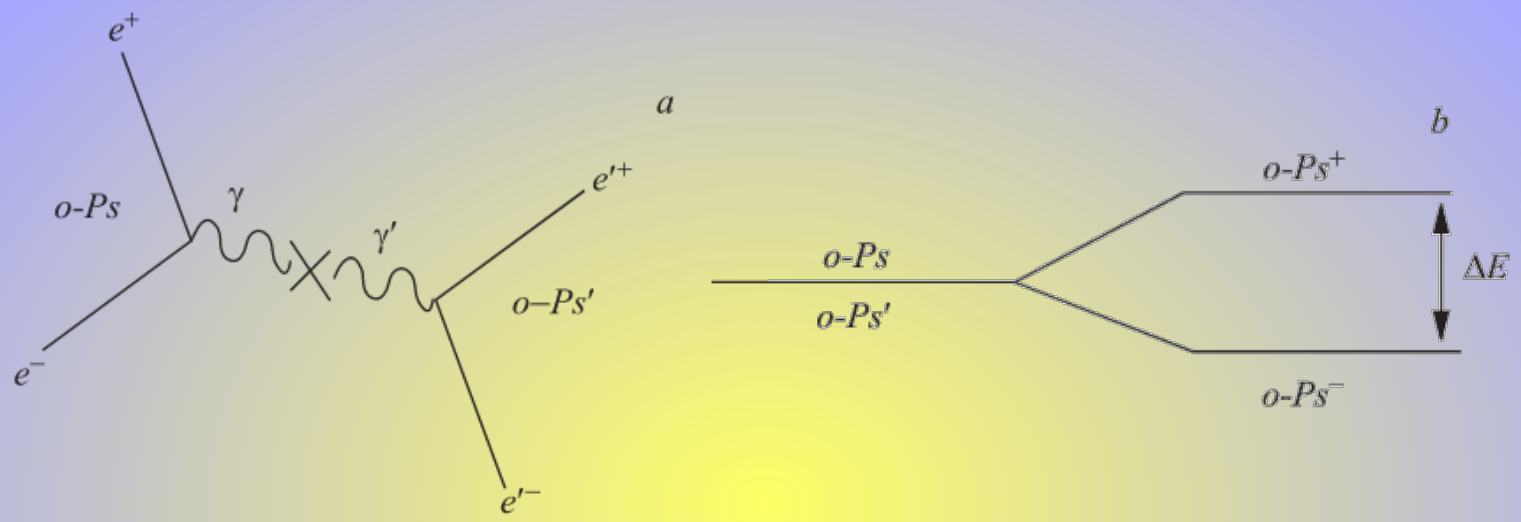


Figure from: [P. Crivelli et al 2010 JINST 5 P08001]

o-Ps can be connected via one-photon annihilation to its mirror version **o-Ps′** and can be confirmed in experiments

- Precision measurements of the o-Ps decay rate and compare it to QED calculations.
- **Direct search for invisible decays**

Looking into the mirror (3)

Invisible decays of ortho-positronium:

- In vacuum: [Glashow S. L. Phys. Lett. B. 1986. V. 167. P. 35.]

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

  where $\Delta E = 2h\epsilon f$ with $f = 8.7 \cdot 10^4$ contribution of the ortho-para splitting fom one-photon annihilation diagram

- In a cavity we need to consider the rate of elastic collisions with the target - Γ_{coll}. The collisions disrupt the ordinary-mirror oscillations (quantum decoherence)
- In the case $\Gamma_{coll} \gg \Gamma_{3\gamma}$

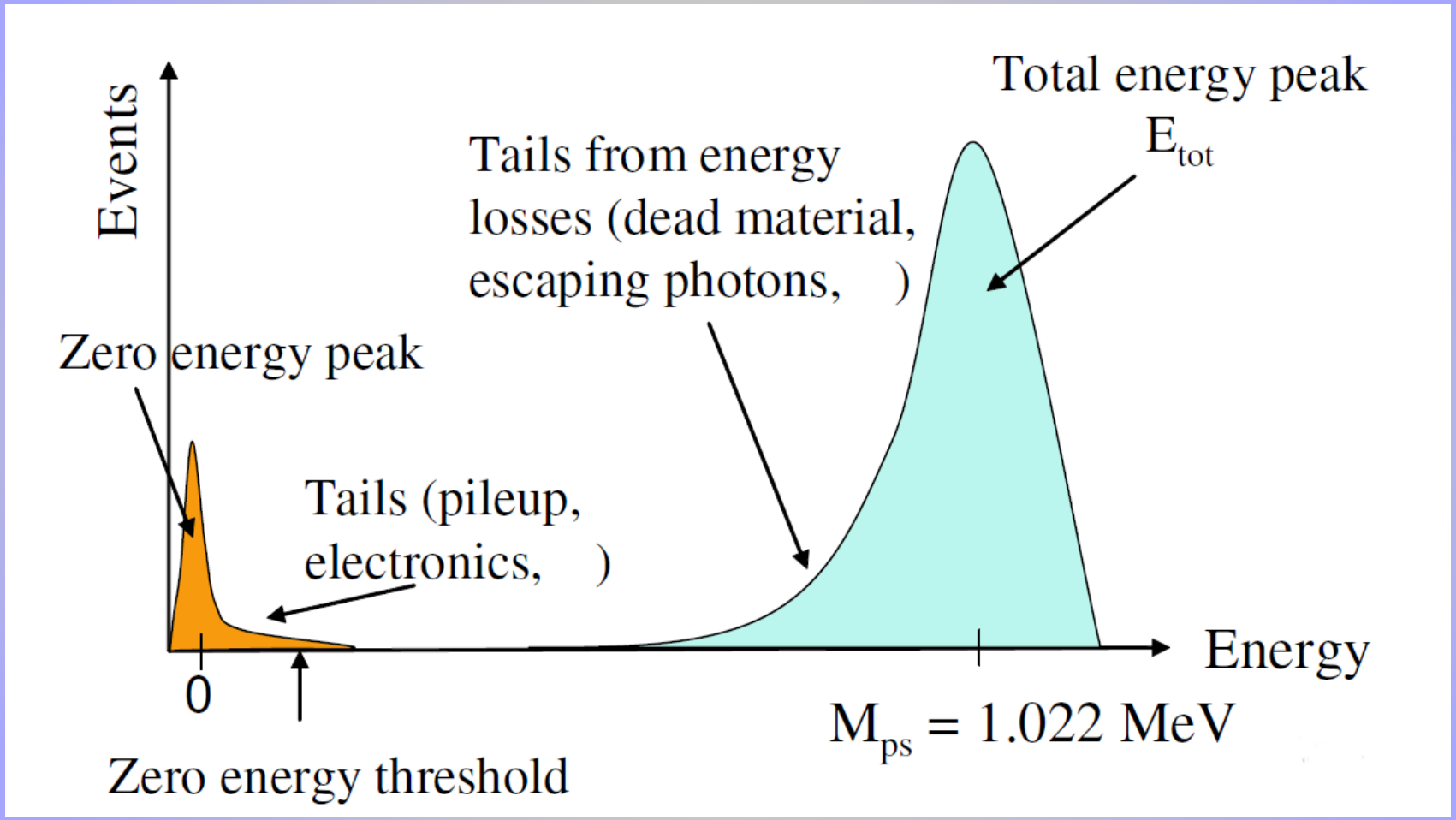
$$\Gamma_{obs} \approx \Gamma_{3\gamma}\left(1 + \frac{2(2\pi\epsilon f)^2}{\Gamma_{coll}\Gamma_{3\gamma}}\right)$$

Recent experiments and results (1)

Two experiments were performed at **ETH** in **Zurich** with common characteristics:

- Time measurement: time start by triggering on positron, time stop when detecting any of the annihilation photons
- Use of a calorimeter (BGO crystals) to measure the energy of ortho-positronium decay products and calculate $E_{tot} = \sum E_i^{\gamma}$
- Search for excess events (peak) in the spectrum below the noise level threshold
- The shape of the background below noise threshold based on Monte Carlo simulations.

Recent experiments and results (2)



[Phys. Rev. D 75, 032004]

Recent experiments and results (3)

- **Experiment 1** [Phys. Rev. D 75, 032004]
  - Positron source Na^{22} in aerogel
  - Positron tagging using a squeezed scintillating fiber
  - High systematics due to elastic collisions/background
- **Experiment 2** [Accepted to PRD 04.05 2018]
  - Positron beam
  - positron tagging using Micro-Channel Plate detector tagging secondary electrons released by a positron hitting the target
  - Lower o-Ps rate
  - Decay in vacuum
  - Suppression of extra sources of background due to interactions in target

Recent experiments and results (4)

Results from those investigations: upper limits for o-Ps $\rightarrow$ invisible:

- Searches in cavity [Phys. Rev. D 75, 032004]
  Br $< 4.2 \times 10^{-7}$ (90% C.L.)
  Photon mixing strength $\epsilon < 1.55 \times 10^{-7}$ (90% C.L.)
- Searches in vacuum [Accepted to PRD 04.05 2018]
  Br $< 5.9 \times 10^{-4}$ (90% C.L.)
  Photon mixing strength $\epsilon < 3.1 \times 10^{-7}$ (90% C.L.)

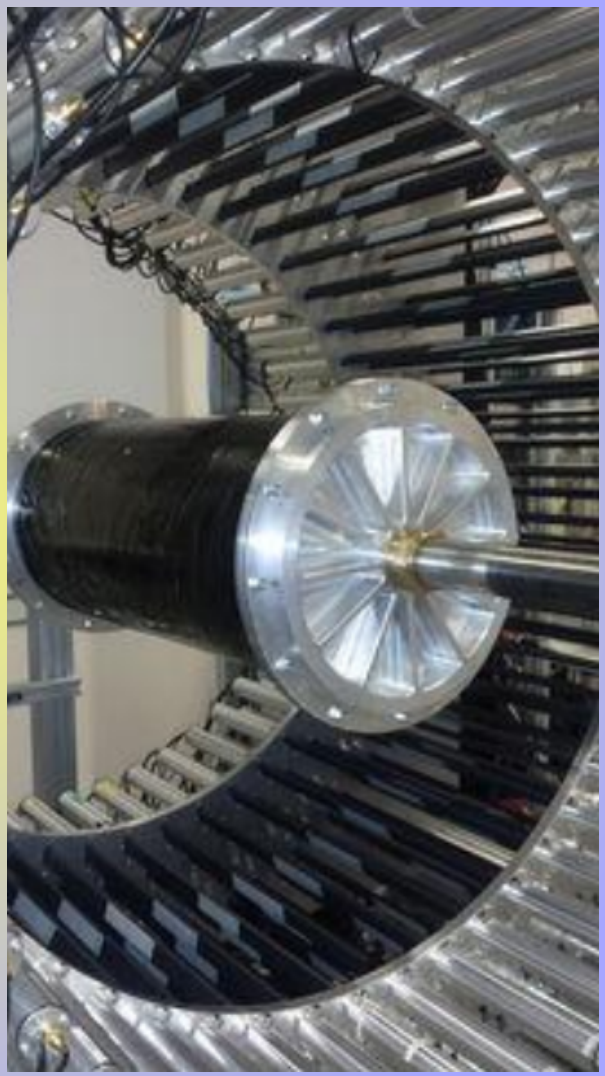
J-PET contribution (1)

Measurements with J-PET detector can contribute to Mirror Matter searches, offering different approach in direct search of invisible o-Ps decays.

Two methods can be used:

- Count rates of o-Ps created in cavities of porous material (similar to first Zurich experiment)
- Study of events below noise threshold (similar to both Zurich experiments)

Use the measurement with big annihilation chamber with porous material on the inner walls for enhanced production of o-Ps and static positron source (i.e. Na^{22})



J-PET contribution (2)

- **First approach**: Standard in J-PET reconstruction of o-Ps $\rightarrow 3\gamma$

$N(\text{o-Ps} \rightarrow \text{invisible}) =$

$$N^{SM-MC}(\text{o-Ps} \rightarrow 3\gamma) + N_{BKG}^{SM-MC} - N^{OBS}(\text{o-Ps} \rightarrow 3\gamma) - N_{BKG}$$

- **Second approach**: counting N_{VETO} events: one hit being de-excitaiton, and all others (if any) below the energy threshold

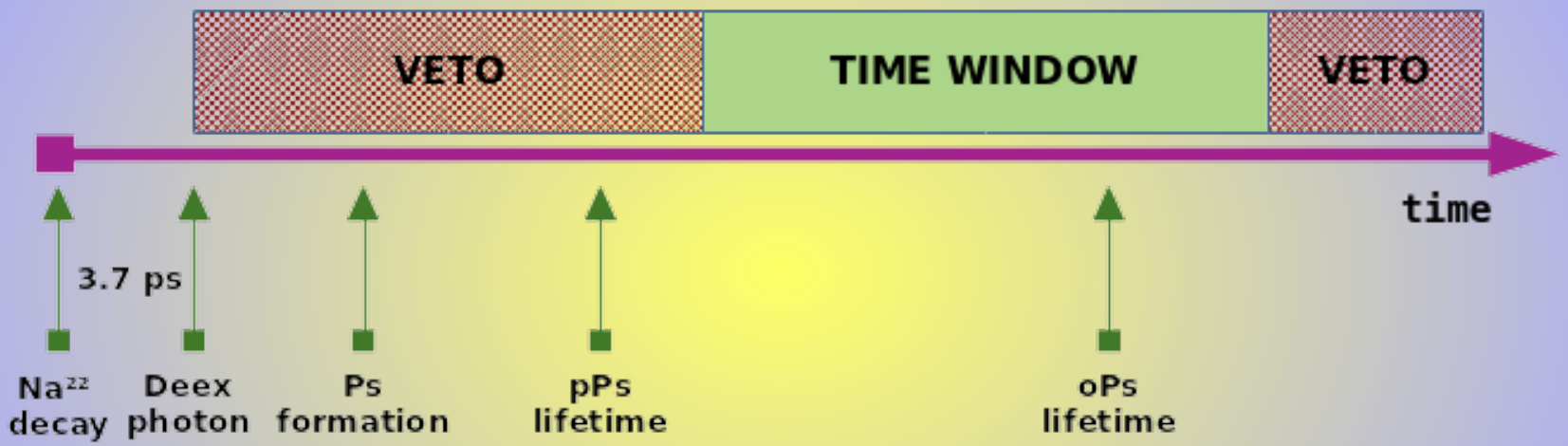
$N(\text{o-Ps} \rightarrow \text{invisible}) =$

$$= N_{VETO} - N_{noise+BKG} - N_{prod}(\text{o-Ps} \rightarrow 3\gamma)(1-\epsilon_1)(1-\epsilon_2)(1-\epsilon_3)$$

where $\epsilon_{ortho} = \epsilon_1 \times \epsilon_2 \times \epsilon_3$ - three gamma accepted as originating in o-Ps decay

Nonsignal and backgrounds (1)

First approach: waiting for nothing...



Data analysis would involve counting rates in the selected time window of o-Ps, p-Ps and to compare it to detailed Monte Carlo study of efficiencies for J-PET detector.

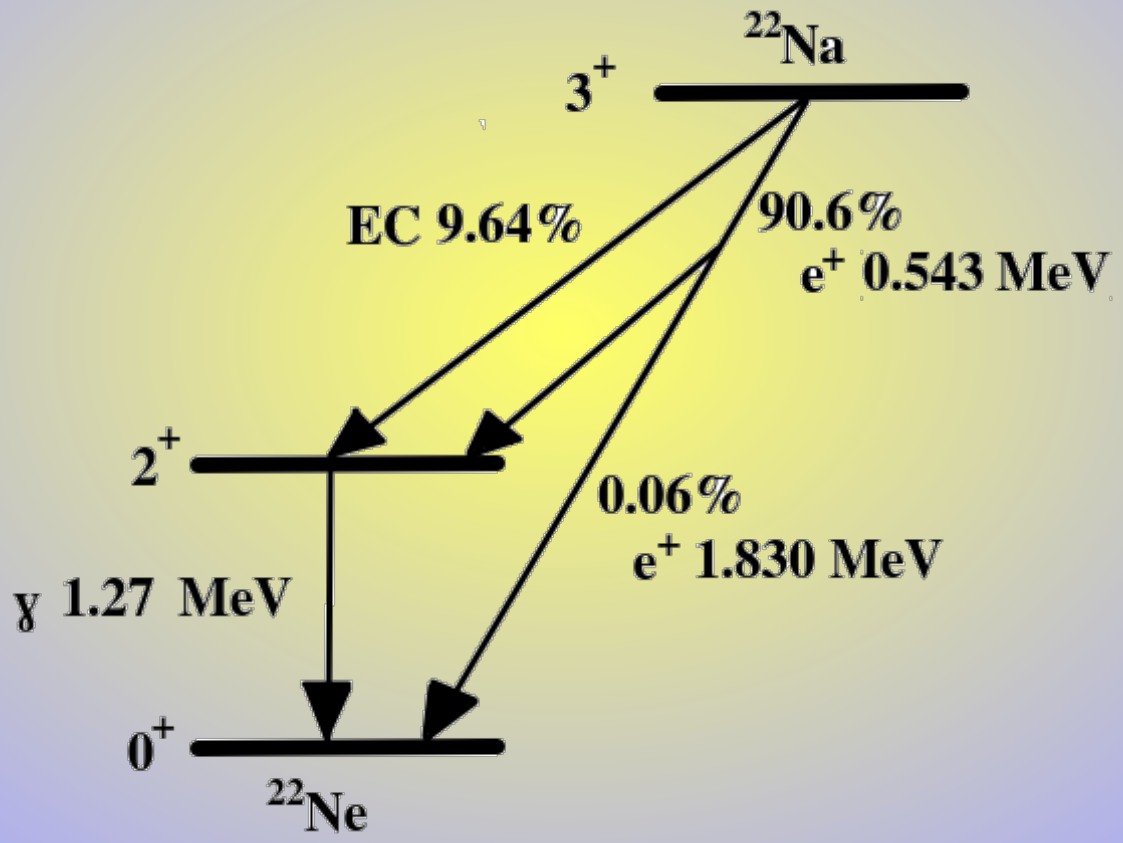
Nonsignal and backgrounds (2)

Background processes:

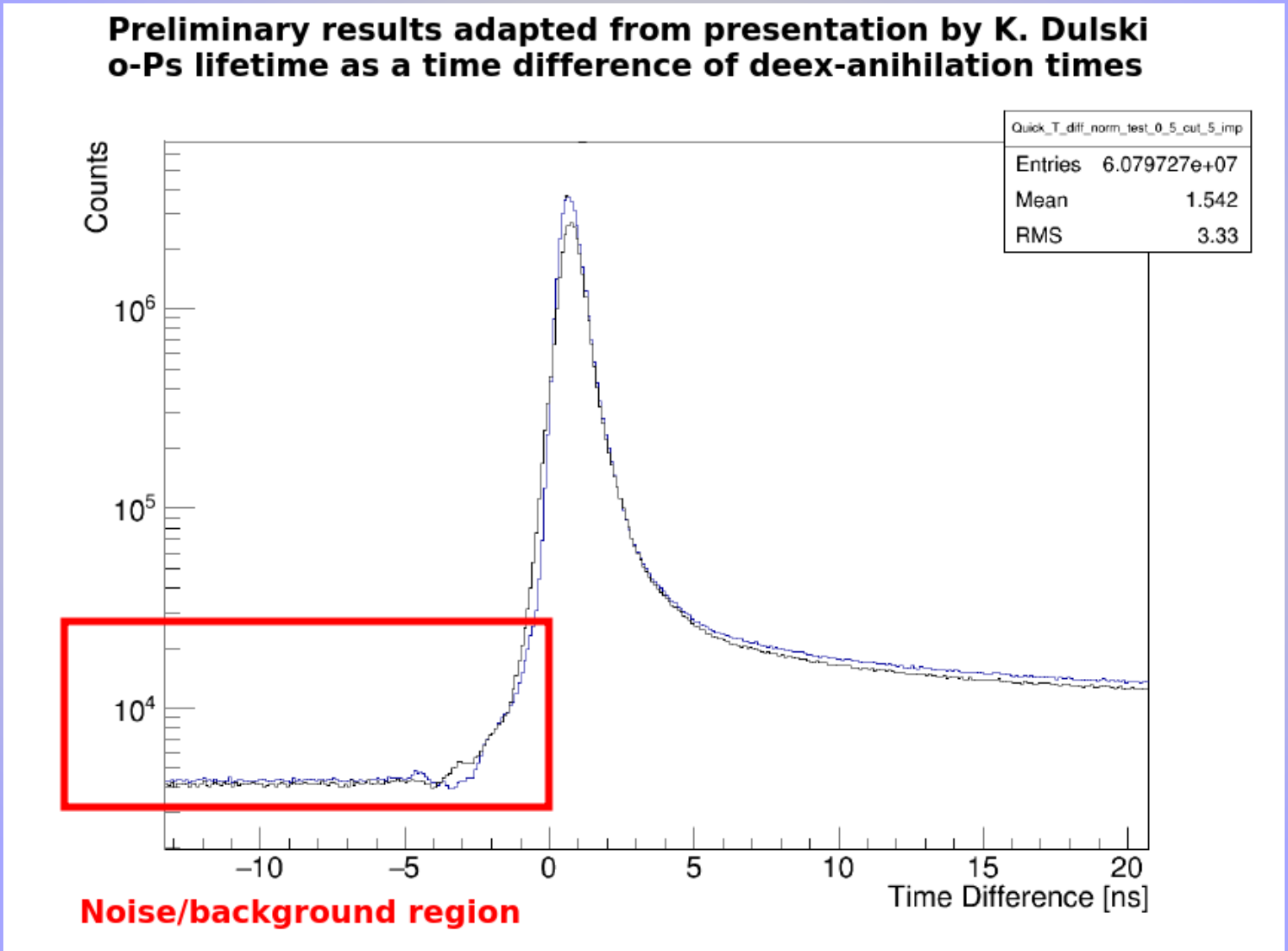
- **Pick-off process**: o-Ps $\rightarrow e^+e^- \rightarrow$ p-Ps $\rightarrow \gamma\gamma$
- **Electron Conversion EC** (next slide)
- **Random coincidences**
- direct annihilation $e^+e^- \rightarrow 2\gamma$: it is only 1% and occurs only in case the de-excitation gamma is miss-identified
- de-excitation gamma (multi-)scattering
- Electronics / dark noise
- invisible SM decay o-Ps $\rightarrow \nu\overline{\nu}$ negligible: BR $< 10^{-18}$
- p-Ps $\rightarrow 2\gamma$ not detected: lifetime so short it should have minimum impact. The time window cut should take care of it.
- o-Ps $\rightarrow 3\gamma$ not detected.

Nonsignal and backgrounds (3)

Electron Conversion: emission of a deexcitation photon with no possible o-Ps formation in 9.64(9)% of the Na^{22} decays [Na^{22} tables]



Nonsignal and backgrounds - below threshold (4)



Plans for analysis

- Efficiency studies with Monte Carlo simulations - software development in progress
- Reconstruction of data from measurement with big annihilation chamber - 55 days of data taking recorded on tapes
- Detailed studies of pick-off process for the material used in annihilation chamber
- Random coincidences/cosmic radiation identification and rejection
- Calculating upper limits for branching ratio of o-Ps $\rightarrow$ invisible and parameter ϵ of mirror world kinetic-mixing

Side note: preliminary estimations of feasible Br values show, that J-PET experiment seems to be able to reach competitive limits of Br(o-Ps $\rightarrow$ invisible) $< 10^{-8}$, mainly due to large rates of o-Ps production.

Summary

- Conducted investigations show that J-PET detector is able to contribute to Mirror Matter searches - sector of particle physics beyond Standard Model
- Searches can be done with two approaches (and combination of them): direct invisible decays and noise/background below threshold studies
- Large o-Ps production rates, proper efficiency estimations and mastering background reduction techniques are possible within the framework of J-PET experiment, which gives hopes for competitive results of upper limit estimations to be achieved in reasonable time.

End

Thank you for your attention