ETH zürich

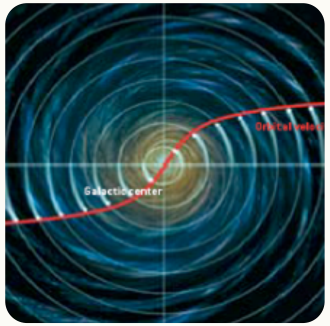
IPA

A search for massless dark photons in positronium decays

3rd Jagiellonian symposium on Fundamental and Applied Subatomic Physics, Krakow (2019)

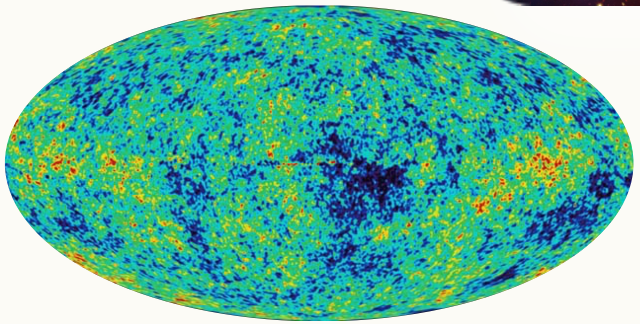
Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics

Dark Matter: Astro + Cosmology through Gravitational effects



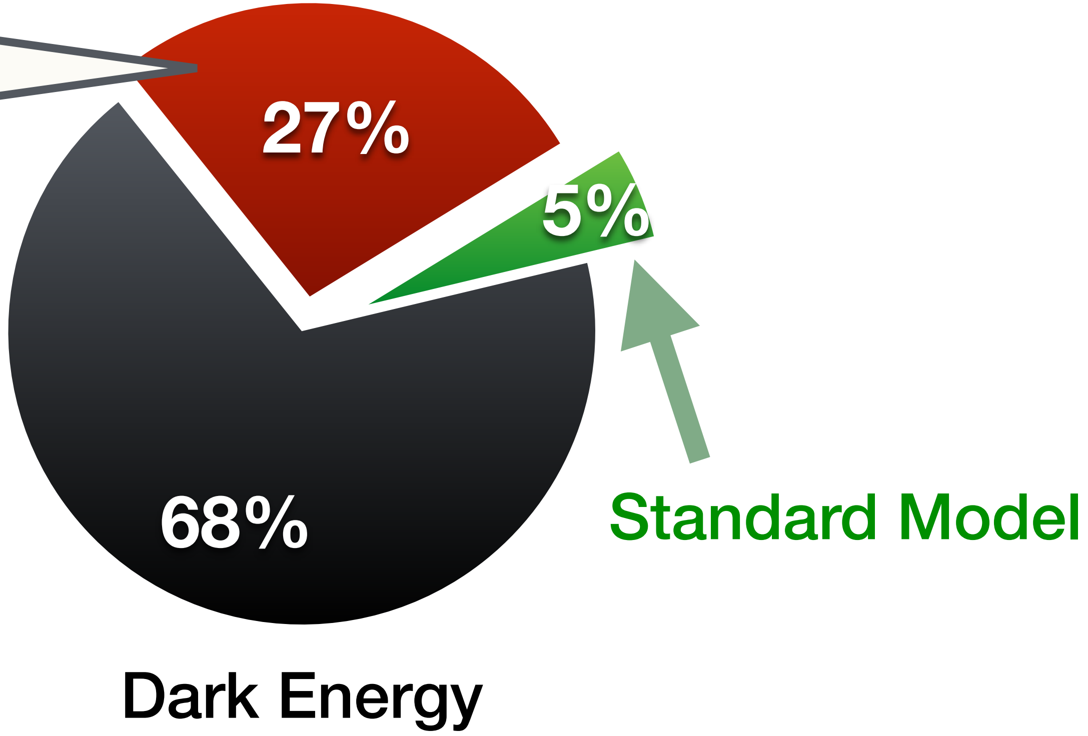
GALACTIC
ROTATION CURVES

GRAVITATIONAL
LENSING



COSMIC MICROWAVE BACKGROUND

ΛCDM (Lambda Cold Dark Matter)



Interaction DM-SM other than gravity? If so very weak…

Only gravitationally? Nightmare scenario from a particle physicist point of view.

$$\Omega_{DM} \sim 5\Omega_{SM}$$

Relic densities of Standard Matter (SM) and Dark Matter (DM) are "similar"

SUGGESTS COMMON ORIGIN BETWEEN SM and DM.

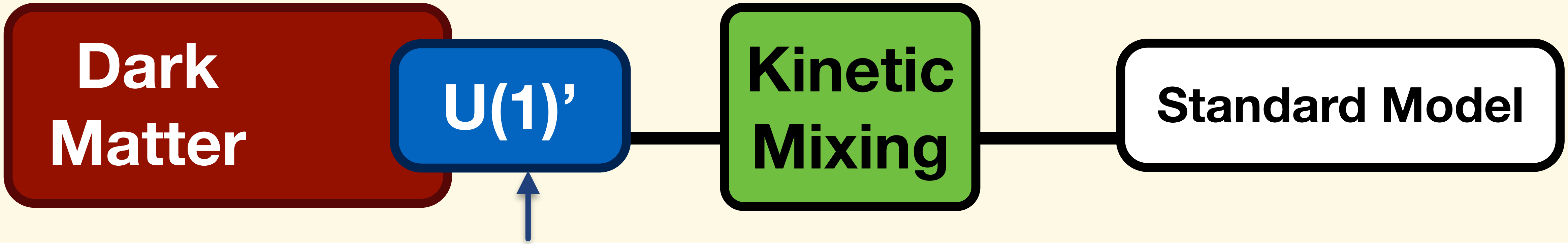
Can those be related with **A SINGLE THEORY?**

The vector portal - Dark photons

B. Batell, M. Pospelov and A. Ritz, Phys. Rev. D80 (2009) 095024.

- "Axion" $\frac{1}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a$ axions & axion-like particles (ALPs)
- "Higgs" $\lambda H^2 S^2 + \mu H^2 S$ exotic Higgs decays?
- "Vector" $\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$ dark photon A′
- "Neutrino" $\kappa (HL) N$ sterile neutrinos?

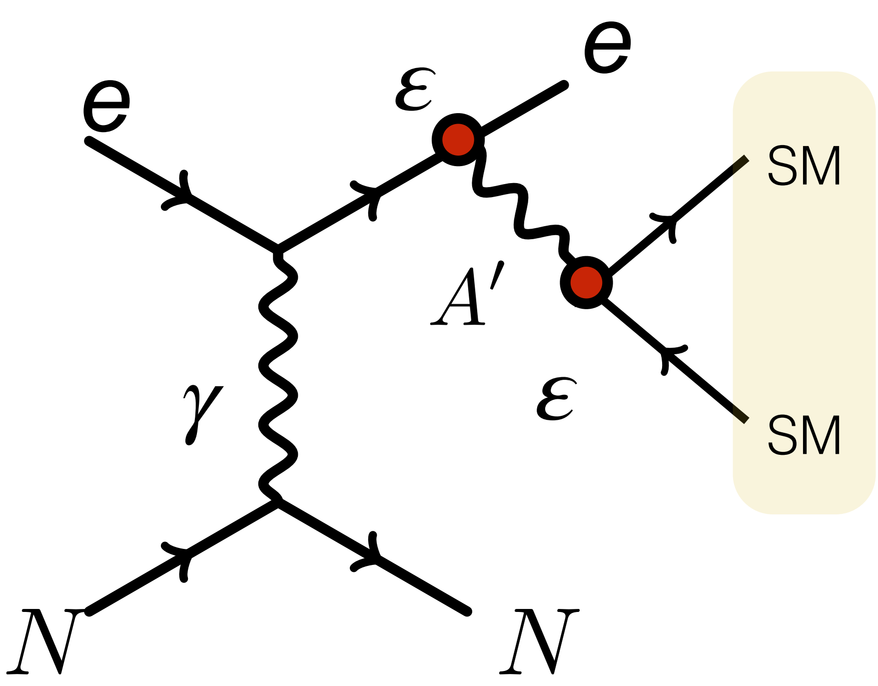
FOCUS OF THIS TALK



NEW FORCE CARRIED BY A NEW **VECTOR** BOSON: **DARK PHOTON**

Signatures for Dark Photons at Fixed target exp. (NA64@CERN)

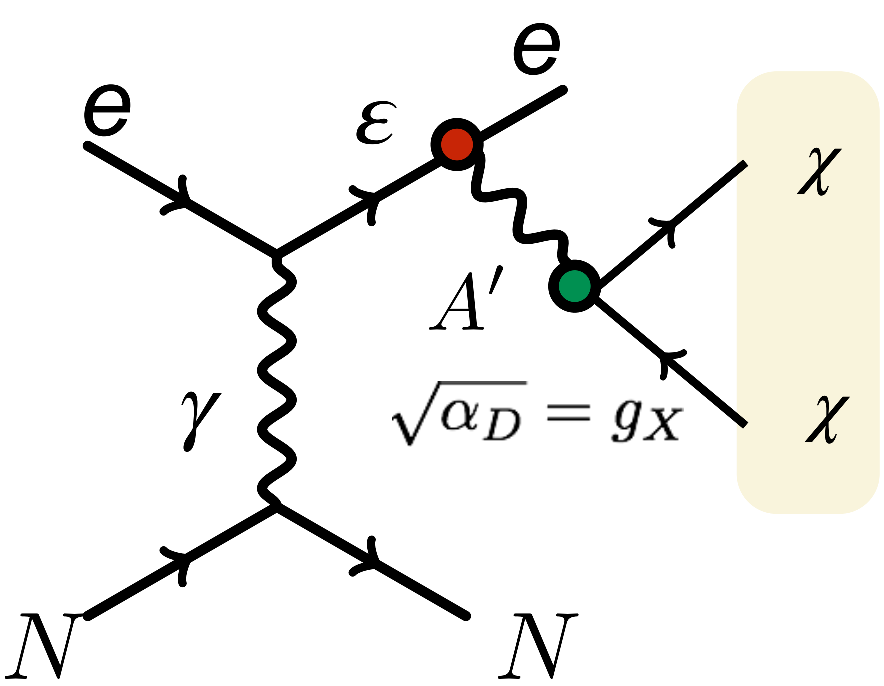
VISIBLE DECAY MODE $m'_A < 2m_X$



Pair production of SM particles

NA64, Phys. Rev. Lett. 120, 231802 (2018)

INVISIBLE DECAY MODE $m'_A > 2m_X$



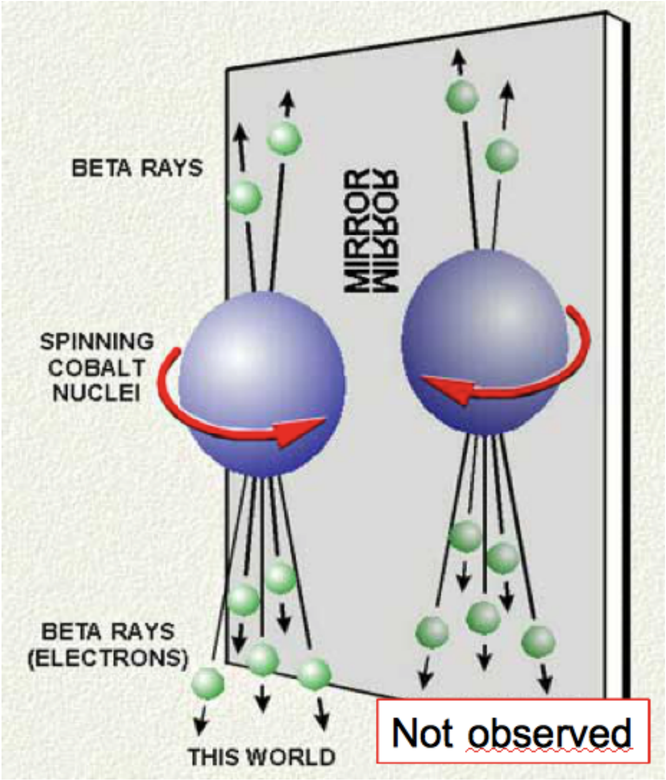
Missing Energy/momentum

NA64, Phys. Rev. Lett. 118, 011802 (2017),

NEW: **arXiv:1906.00176**

The Massless Dark photon case - the Mirror Sector

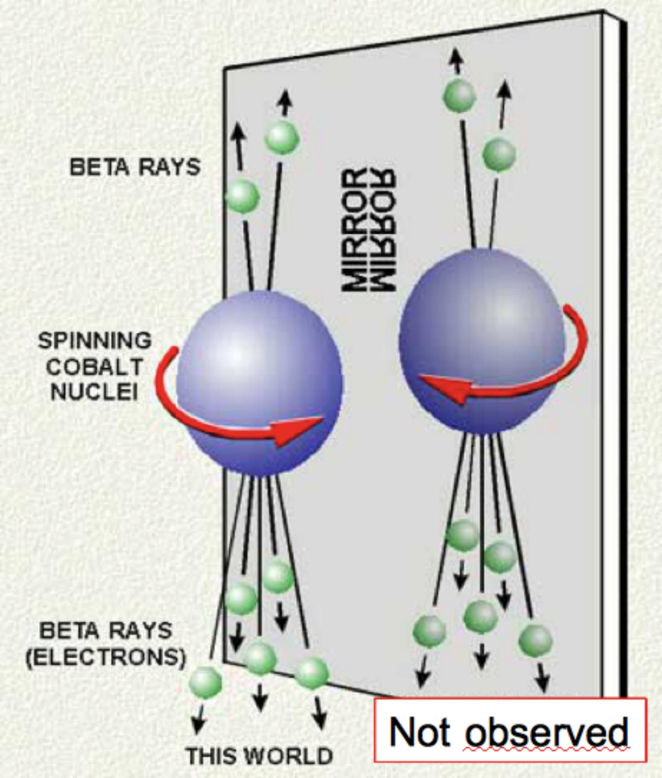
Parity violation in weak interaction



T.D. Lee and C.N. Yang, Phys. Rev. 104, 4 (1956)
C.S. Wu et al., Phys. Rev. 105, 1413 (1957)
R.L.Garwin, L.M.Lederman, M.Weinrich, Phys. Rev. 105, 1415 (1957)

The Massless Dark photon case - the Mirror Sector

Parity violation in weak interaction



T.D. Lee and C.N. Yang, Phys. Rev. 104, 4 (1956)
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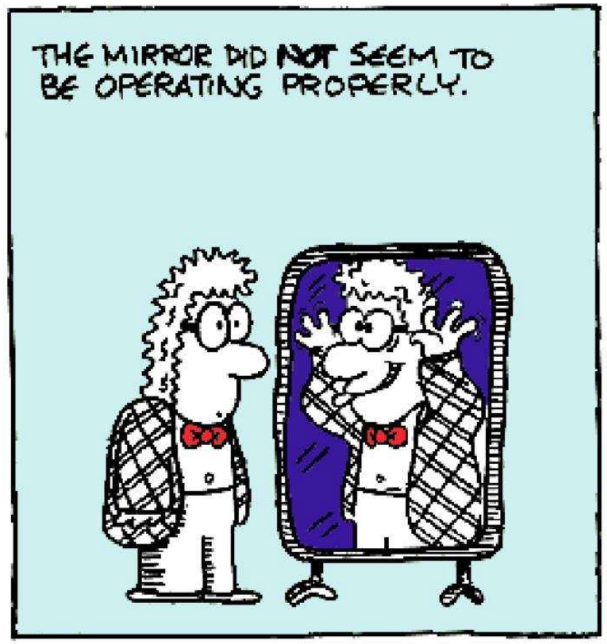
R.L.Garwin, L.M.Lederman, M.Weinrich, Phys. Rev. 105, 1415 (1957)



W. Pauli in a letter to V. Weisskopf,
"Now after the first shock is over, I begin to collect myself. Yes, it was very dramatic."

Is Nature left-right asymmetric?

- In the standard model parity violation introduced from beginning in the Lagrangian.

$$\begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, \quad l_R^-, \quad \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad u_R, \; d_R$$

- Is nature really left-right asymmetric or do we happen to live in a universe dominated by particles with such properties?

1. Left-right symmetric models, symmetry restored at higher energies (V+A suppressed by heavy W_R mass)
   Pati and Salam, Phys. Rev. D10, 275 (1974) Mohapatra and Pati, Phys. Rev. D11, 566 (1975), Senjanovic and Mohapatra, D12, 1502 (1975)

2. Postulation of the existence of a sector of **mirror particles**
   Lee and Yang, Phys. Rev. 104, 4 (1956)

The mirror sector

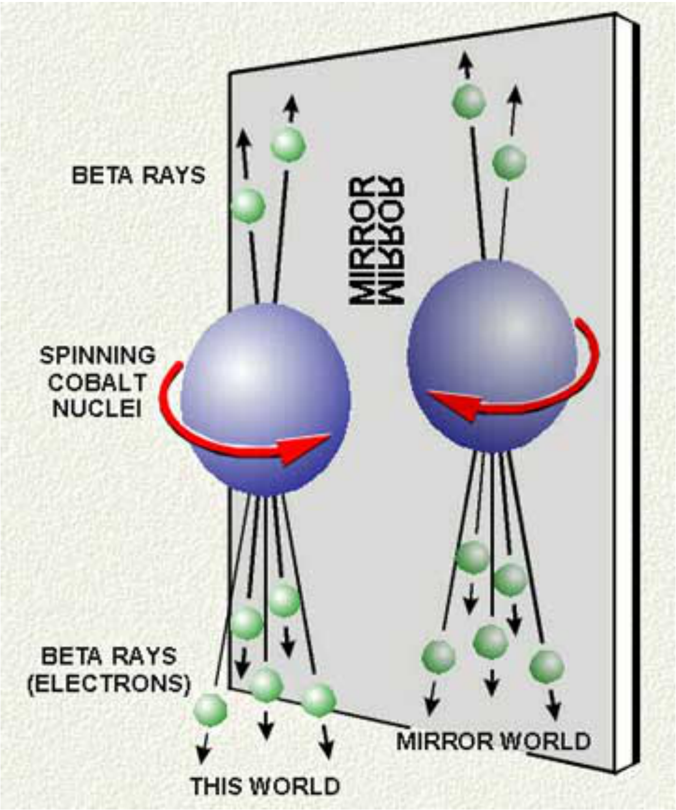
Ordinary particle sector

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'

Mirror particle sector

→ Mirror particles: same properties of ordinary particles but chirality of fields inverted.
→ Same micro-physics governs interactions among mirror particles but they experience V+A weak interaction.

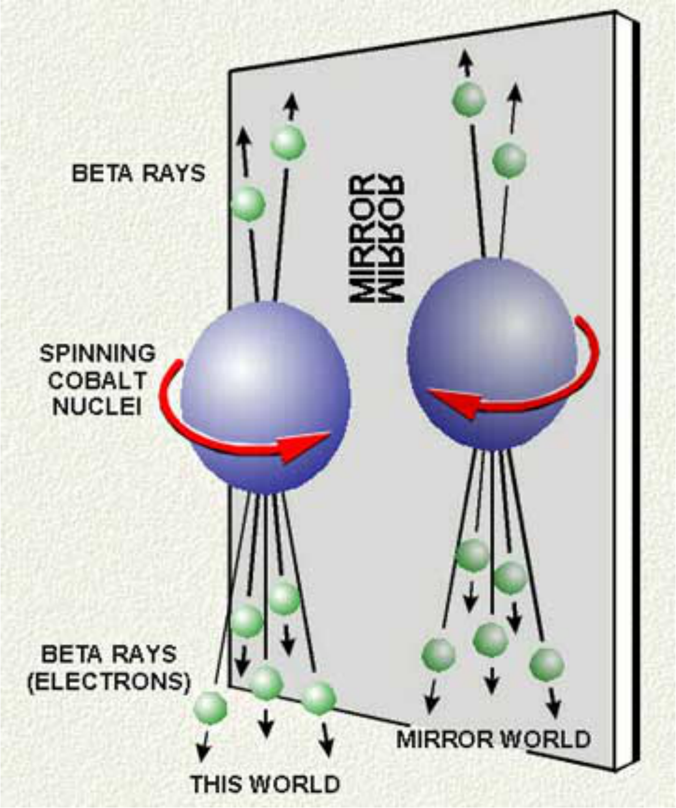
The mirror sector



If such a sector of particle exists
→ mirror symmetry conserved
→ left-right symmetry of nature restored

For a review see,Okun, Phys.Usp. 50 (2007) 380-389 [hep-ph/0606202] and Ciarcelluti,Int.J.Mod.Phys.D19:2151-2230 (2010).

The mirror sector



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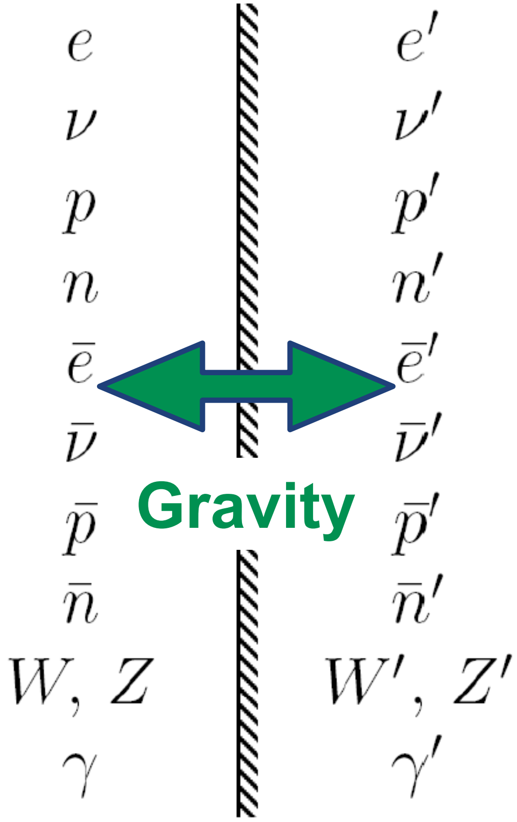
- Doubling the number of elementary particles to solve problems seems to be unnatural … but … it has been done before!
- Relativity + QM ⇒ **anti-matter**

The mirror sector

Ordinary particle sector

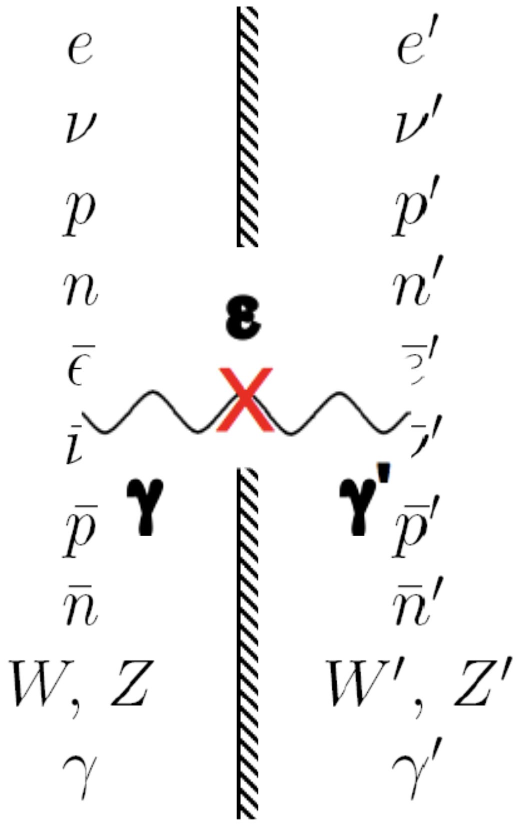


Mirror particle sector

The mirror sector would interact through gravitation with us.
→ Mirror particles (stable and massive) are very good dark matter candidates.

The mirror sector

Ordinary particle sector

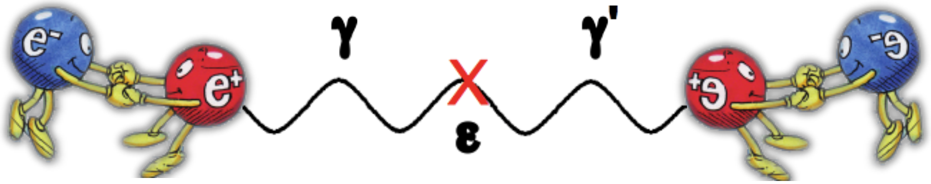


Mirror particle sector

The mirror sector could interact through photon mirror-photon kinetic mixing:
→ Implications for cosmology.
→ Bounds (LSS, CMB, BBN): mixing strength $\epsilon < 3 \times 10^{-8}$

B. Holdom, Phys. Lett. B166, 196 (1986)

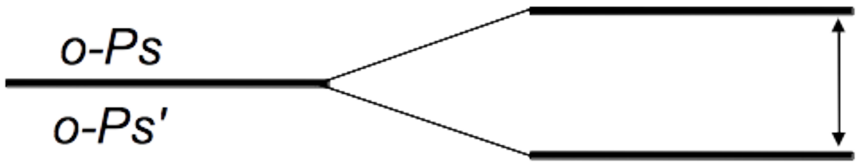
Positronium as a portal to the Mirror sector



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

Coupling between oPs and oPs' ⇒ breaking of degeneracy

$$o-Ps^{+}=\frac{1}{\sqrt{2}}\left(o-Ps+o-Ps'\right)$$



$$\Delta E=2h\varepsilon\nu$$

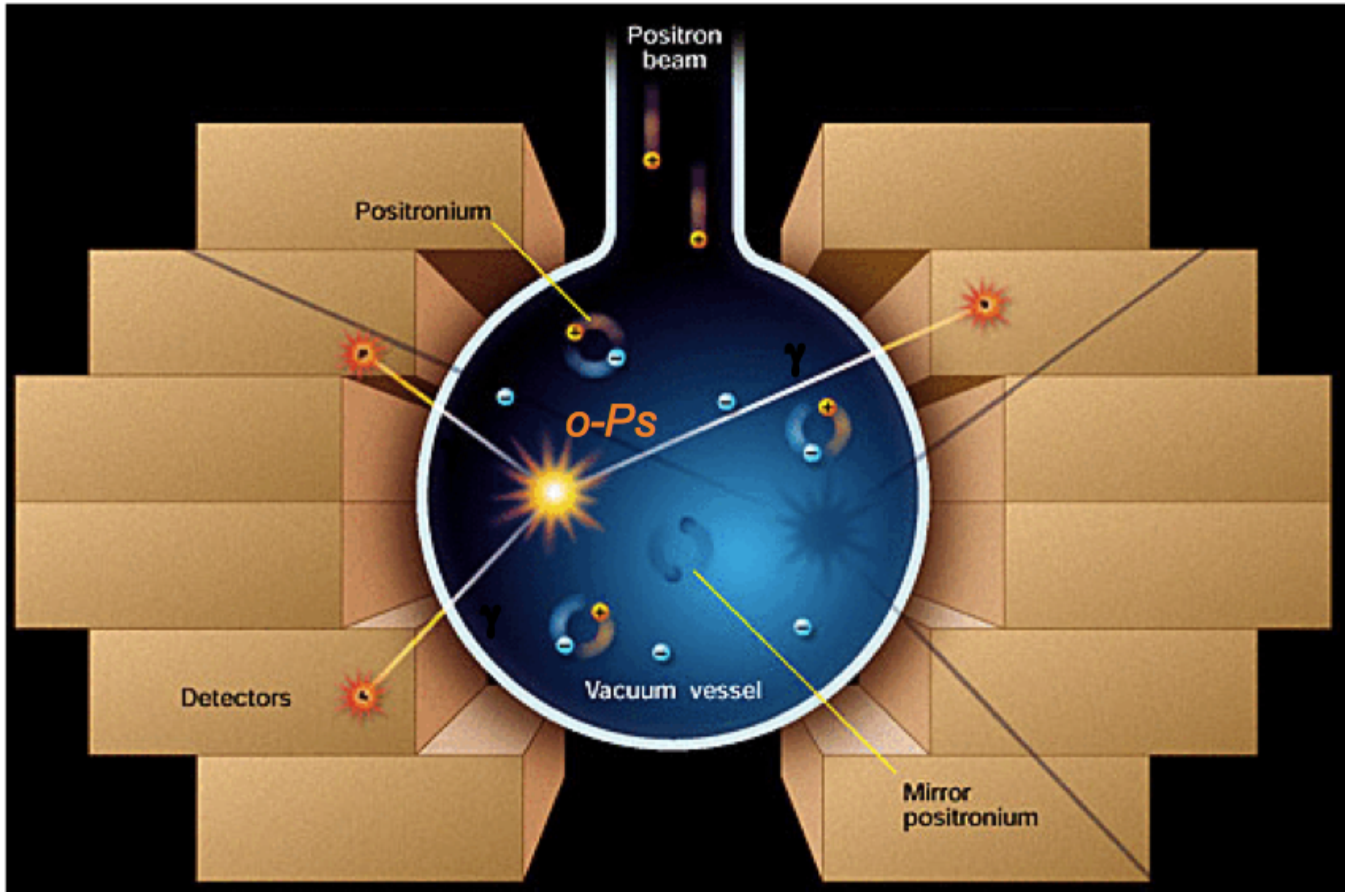
Energy splitting

$$o-Ps^{-}=\frac{1}{\sqrt{2}}\left(o-Ps-o-Ps'\right)$$

Rabi oscillation:

$$P\left(o-Ps\rightarrow o-Ps'\right)=\sin^{2}\left(2\pi\varepsilon\nu t\right)$$

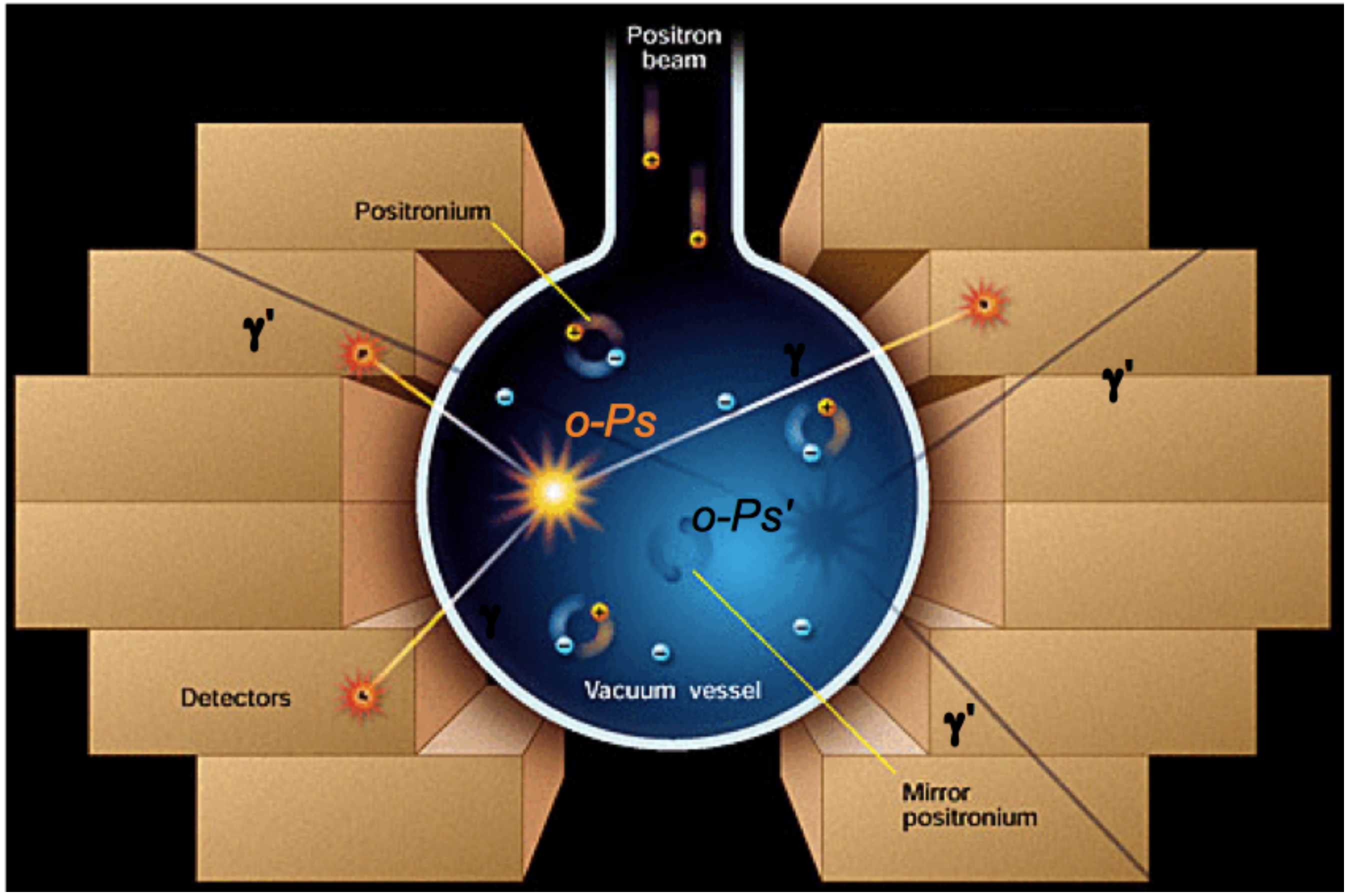
Experimental signature: oPs → invisible decay (missing energy)



Standard model decay: o-Ps → 3γ

→ energy deposition of 1022 keV (Ps mass, $E = mc^2$)

Experimental signature: oPs → invisible decay (missing energy)

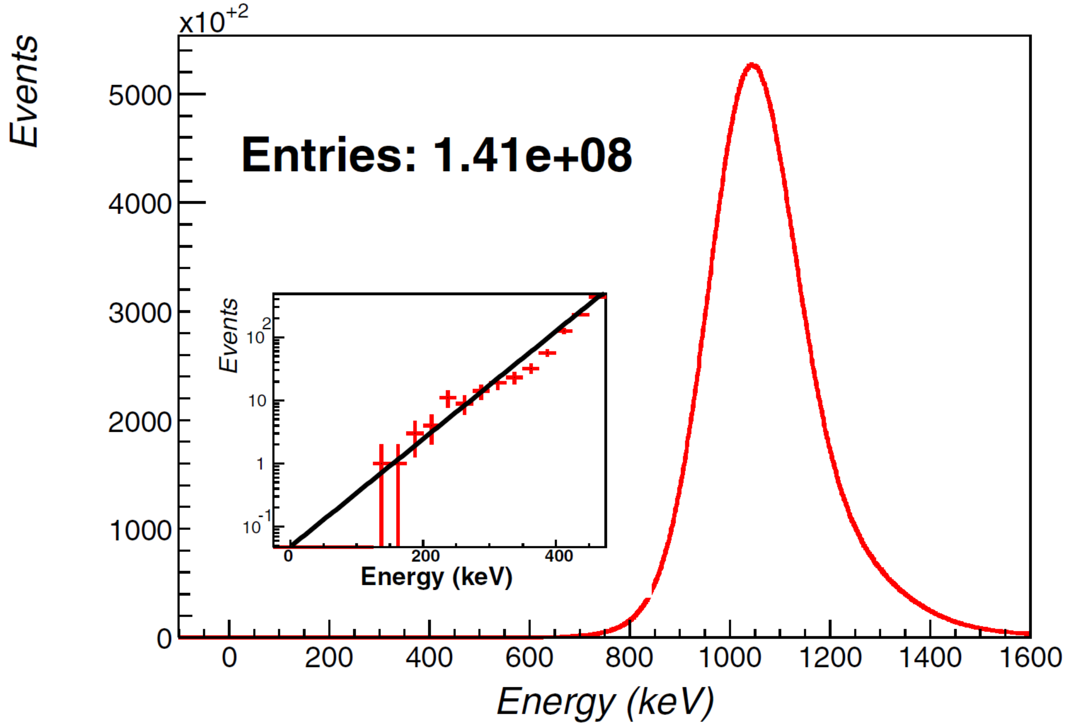


Invisible decay: o-Ps → oPs' → 3γ'

→ no energy deposition (event compatible with 0 energy)

Search for oPs → invisible decay (aerogel experiment)

A. Badertscher, P. Crivelli et al., Phys. Rev. D. 75, 032004 (2007)



o-Ps → 3γ

→ E_{SUM} = 1022 keV

No events in the signal region

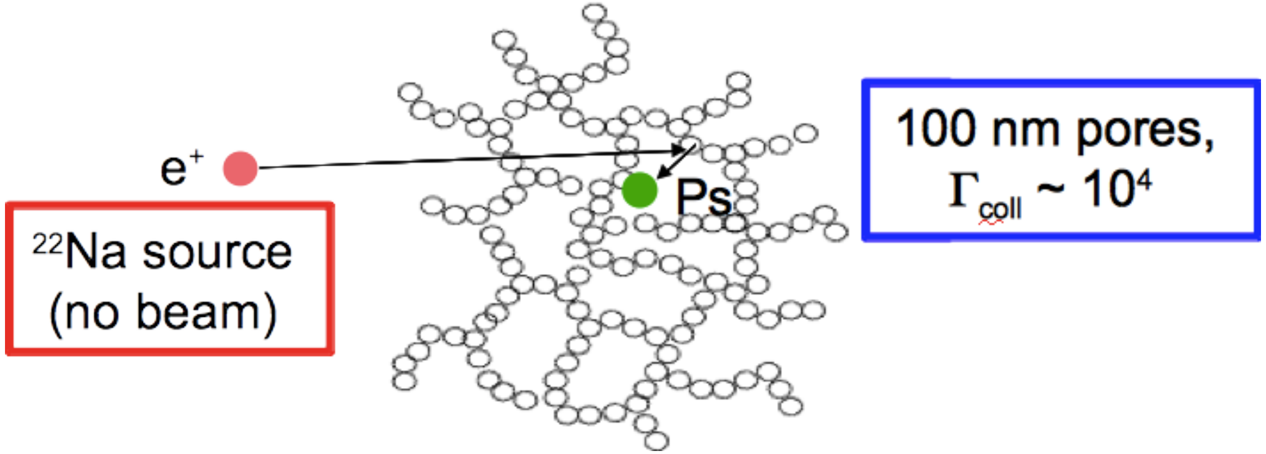
→ Upper bound : Br(oPs → invisible) ≤ 4.2 x 10^{-7}

→ Stringent limit on physics beyond the standard model

Search for oPs → invisible decay (aerogel experiment)

A. Badertscher, P. Crivelli et al., Phys. Rev. D. 75, 032004 (2007)

Aerogel target, SiO2 grains 100 nm



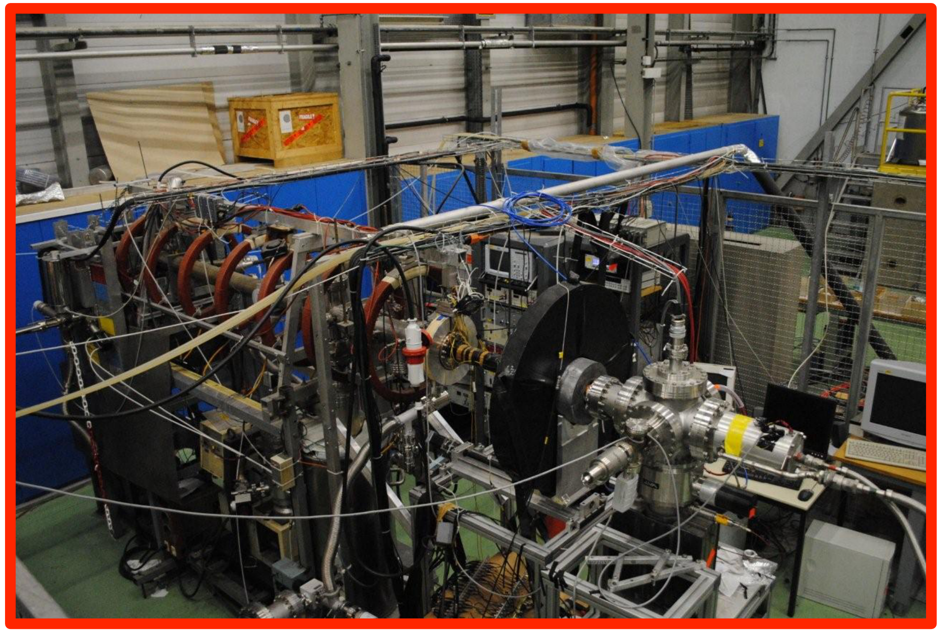
Collisions with matter destroy coherence of oscillation suppressing *o–Ps* - *o–Ps‘* conversion ~$\sqrt{N_{collisions}}$. Has to be taken into account (large systematic uncertainty)
→ limit on $\epsilon \leq 1.5 \times 10^{-7}$

Search for oPs → invisible decay in a vacuum cavity

- Ps mean free path in a vacuum cavity: 30 mm → 1-2 collision instead of 10^4
- Cross check: change Ps velocity ~ N_{coll} Number of signal 2 times smaller without affecting the background!

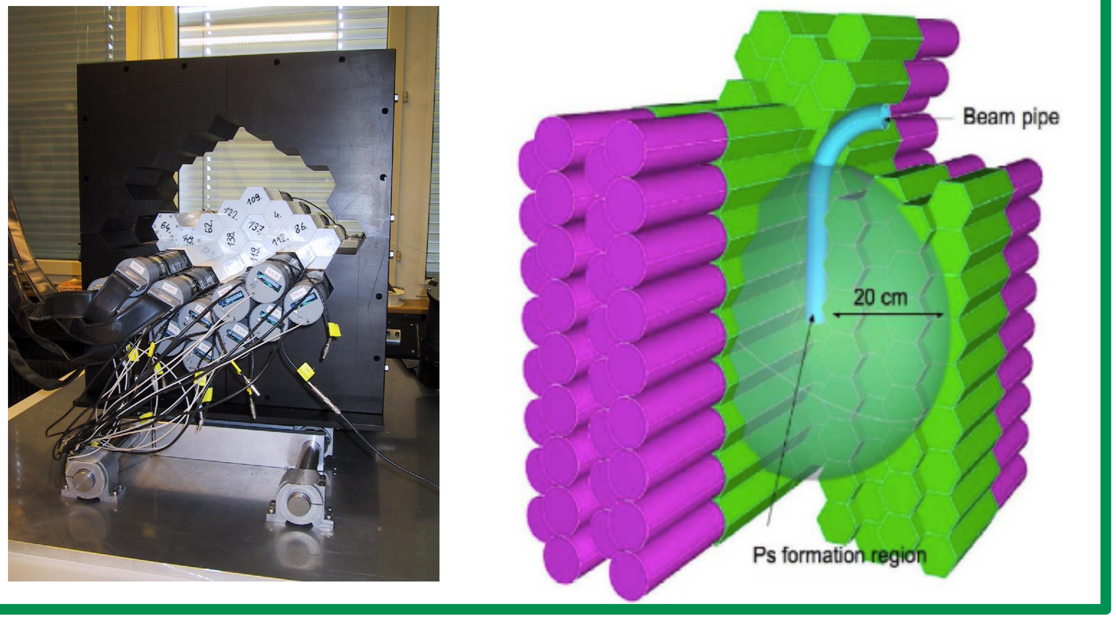
P.Crivelli et al., JINST 5, P08001 (2010)

Positron beam



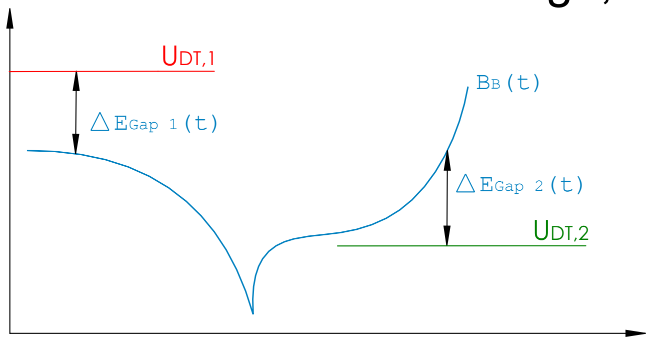
\+

Hermetic gamma detector

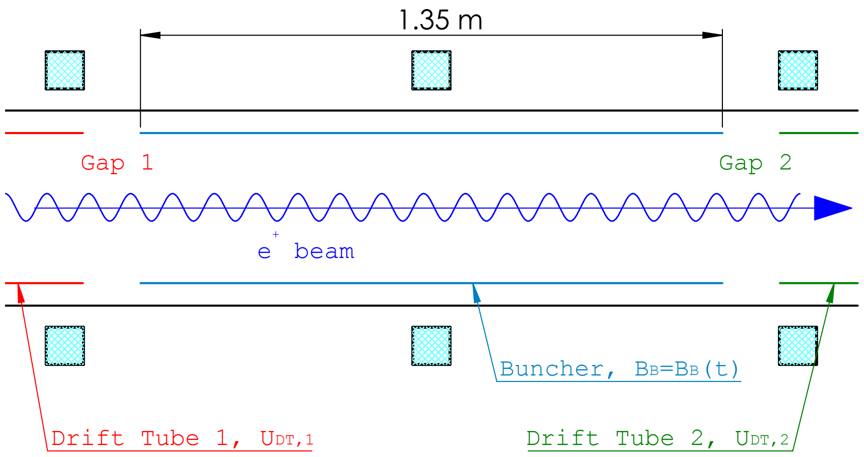


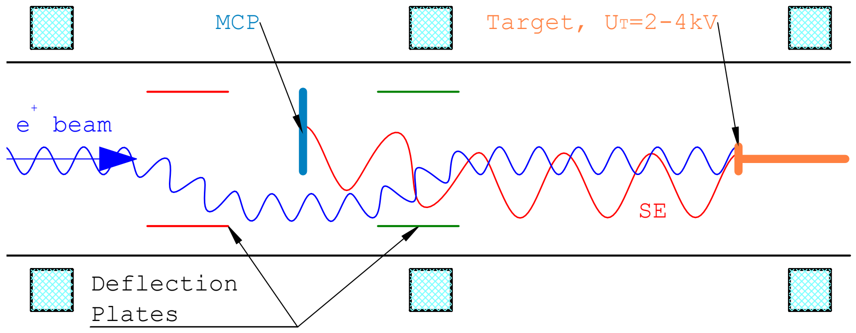
Low energy positron beam - tagging

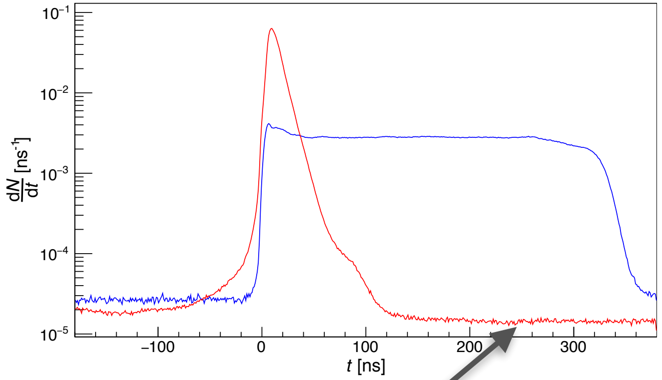
C. Vigo, L. Gerchow, L. Liszkay, A. Rubbia, and P. Crivelli Phys. Rev. D 97, 092008 (2018)



Coincidence with positron bunching and detection of secondary electrons



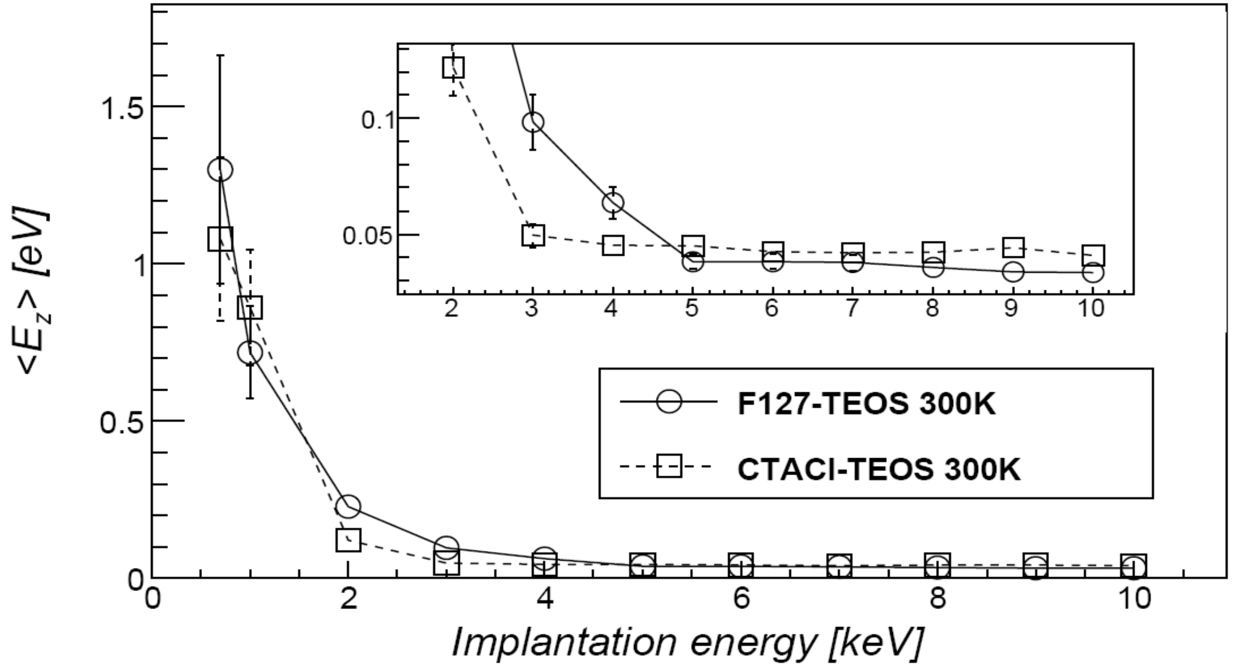


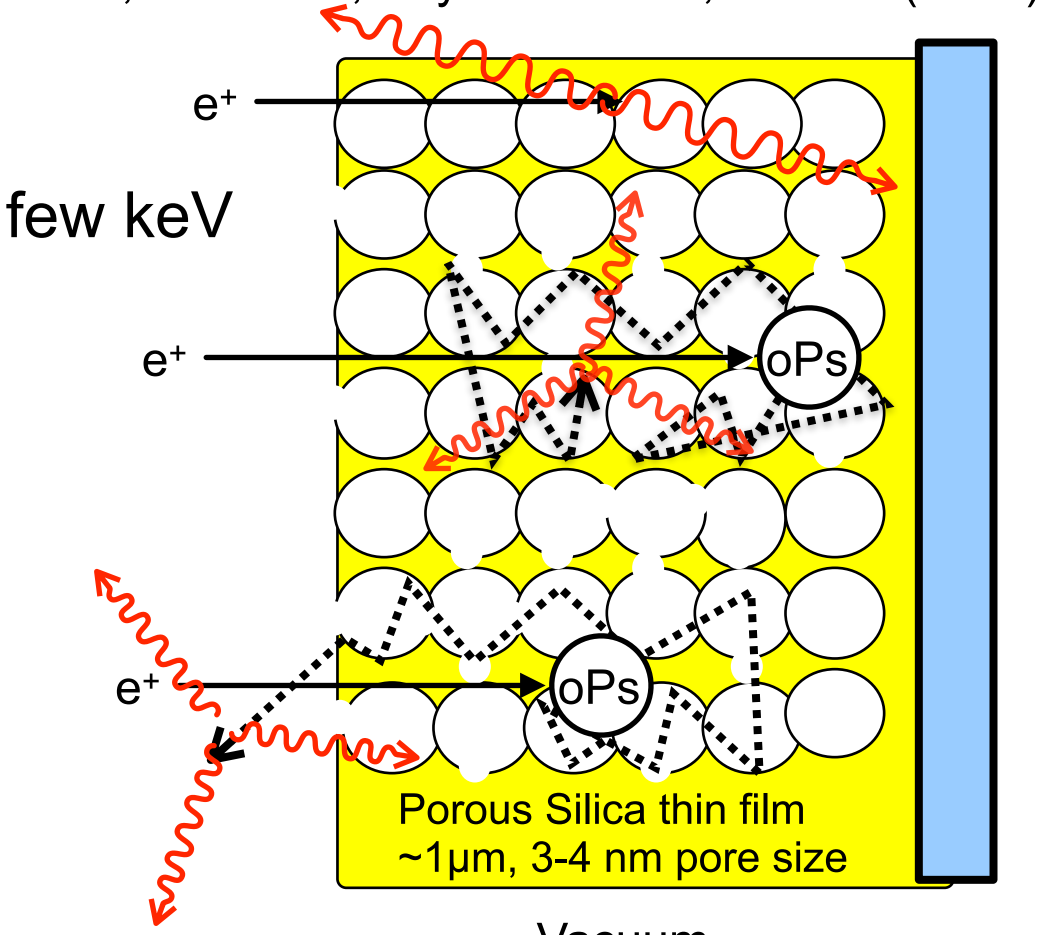


Flat background from accidental triggers ~10^{-4}
mainly e- from target at HV not correlated with e+

Positron-positronium converter - porous SiO_2

P. Crivelli, U. Gendotti, A. Rubbia, L. Liszkay, P. Perez, C. Corbel, Phys. Rev. A81, 052703 (2010)





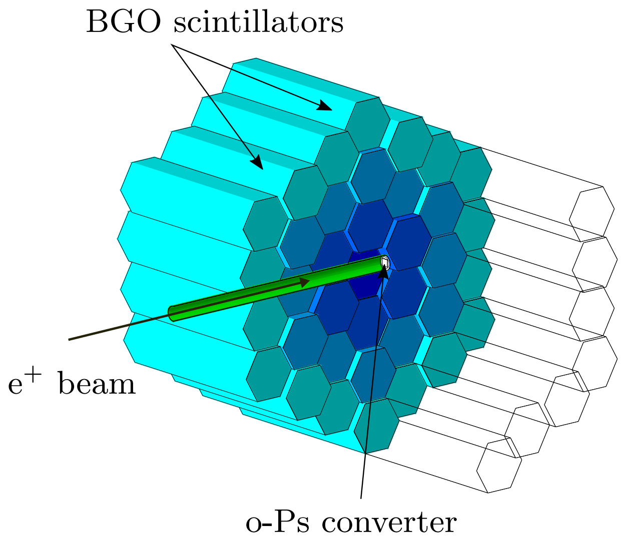
$\tau_{\mathrm{oPs,\,vac}} = 142\ \mathrm{ns}$

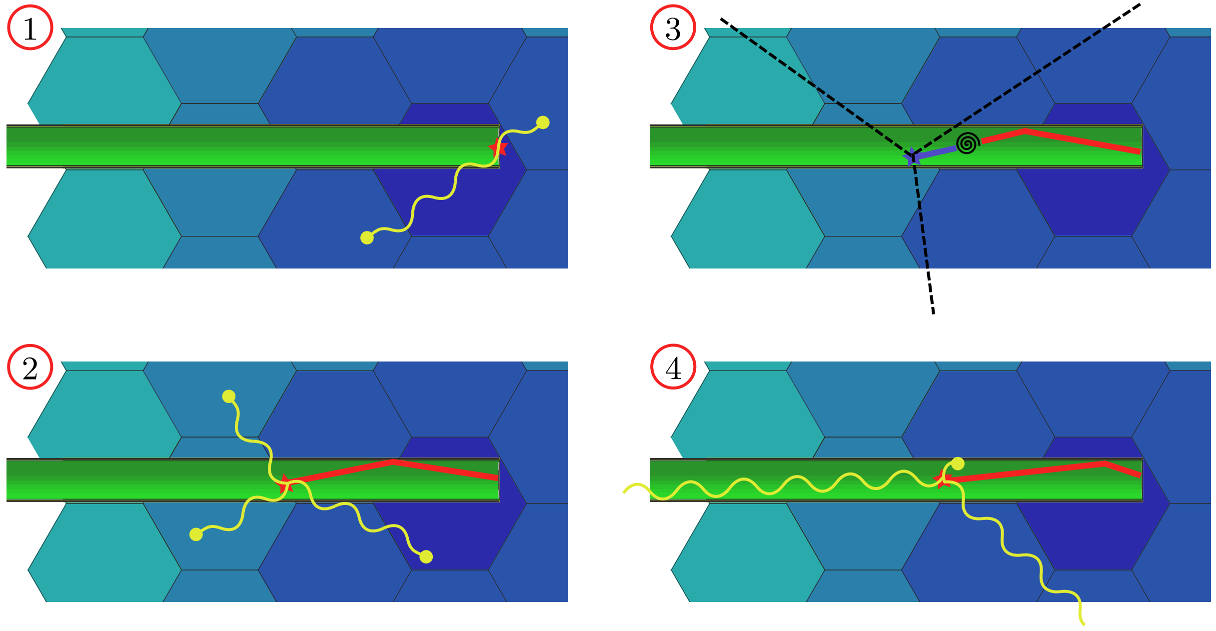
Ps mean energy ~ 1/(e^+ implantation energy)

→ $N_{collisions}$ ~ 1/(e^+ implantation energy)

Detection of annihilation photons

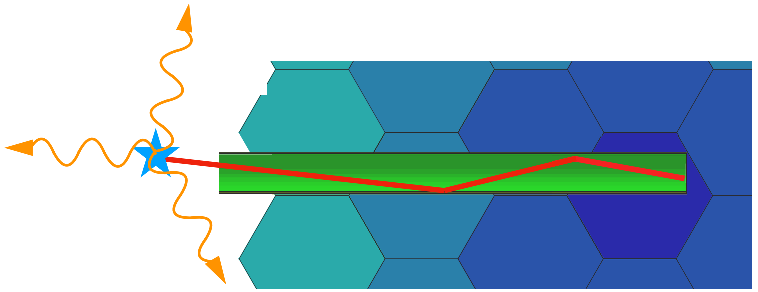
C. Vigo, L. Gerchow, L. Liszkay, A. Rubbia, and P. Crivelli Phys. Rev. D 97, 092008 (2018)





ECAL: $20X_0$ @ 511 keV

- Energy losses and hermeticity $<10^{-7}$
- Main limitation: positronium/positron escaping the detection region $\sim 10^{-5}$



oPs → invisible decay in a vacuum cavity - first results (2018)

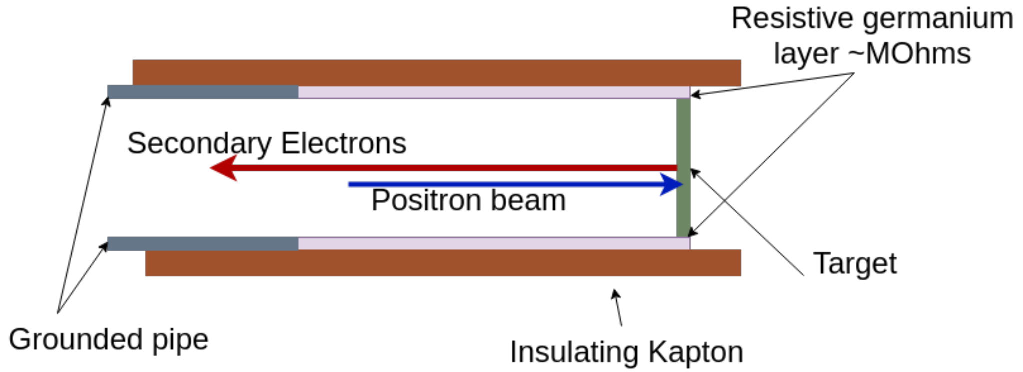
- First results: no excess above expected background observed
  → limit similar to aerogel experiment but without systematic related to collisions.

C. Vigo, L. Gerchow, L. Liszkay, A. Rubbia, and P. Crivelli Phys. Rev. D 97, 092008 (2018)

- Main limitations: accidental triggers, positronium escaping the detection region

Setup Improvement

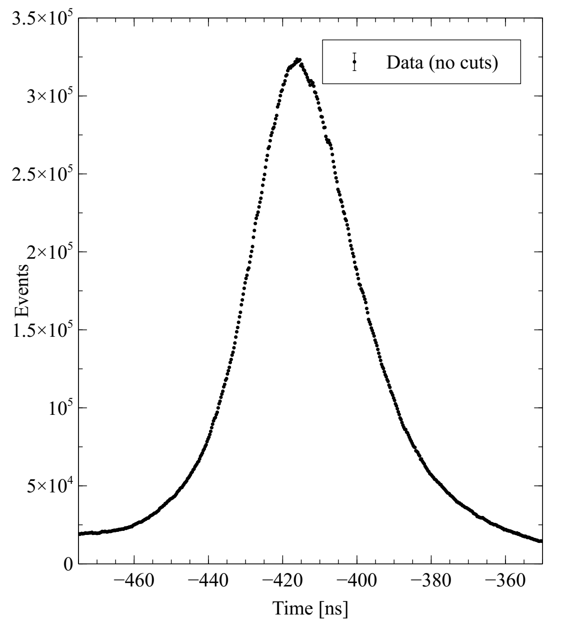
- e+ flux improved by 1 order of magnitude (W meshes cryogenic moderator)
- Redesign of vacuum cavity to reduce e- emission due to HV

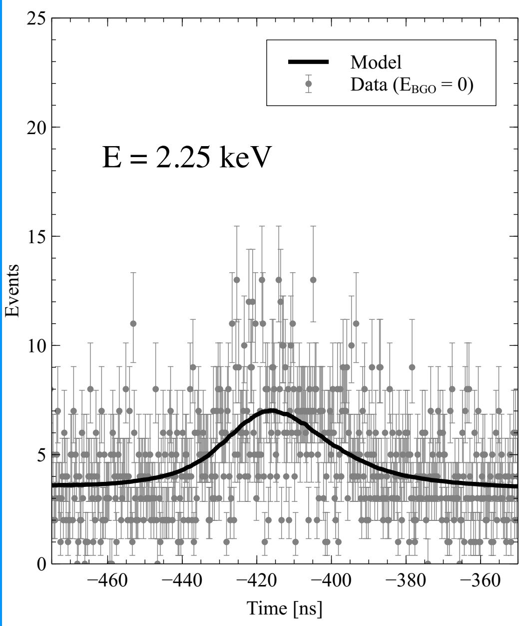


oPs → invisible decay in a vacuum cavity - latest results (2019)

M. Raaijmakers, L. Gerchow, B. Radics, A. Rubbia, C. Vigo and P. Crivelli, arXiv 1905.0912

Time distribution of positrons on target





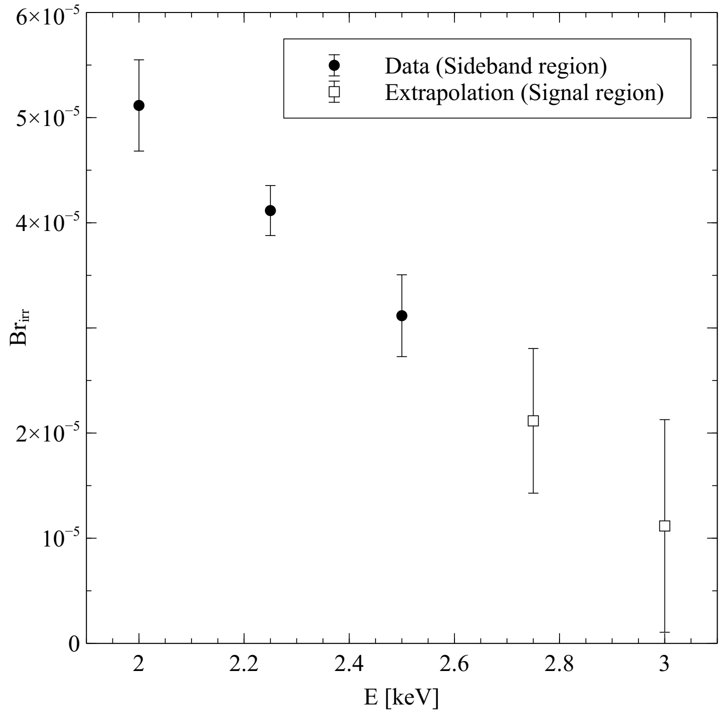
Time distribution of events compatible with 0-energy
Shape of signal or signal-like background driven by e+ arrival on target

oPs → invisible decay in a vacuum cavity - latest results (2019)

M. Raaijmakers, L. Gerchow, B. Radics, A. Rubbia, C. Vigo and P. Crivelli, arXiv 1905.0912

Ps escaping detection region ~ $1/E_{e+}$
→ lowest energy points (sidebands)
→ estimation irreducible background

Bayes theorem for signal branching ratio



No excess of events for 4.6 x 10^7 Ps decays

$$\mathcal{BR}(\text{o-Ps} \rightarrow \text{o-Ps'} \rightarrow \text{invisible}) < 4.0 \times 10^{-5}$$

Mixing strength **γ-γ'** $\varepsilon < 5.8 \times 10^{-8}$

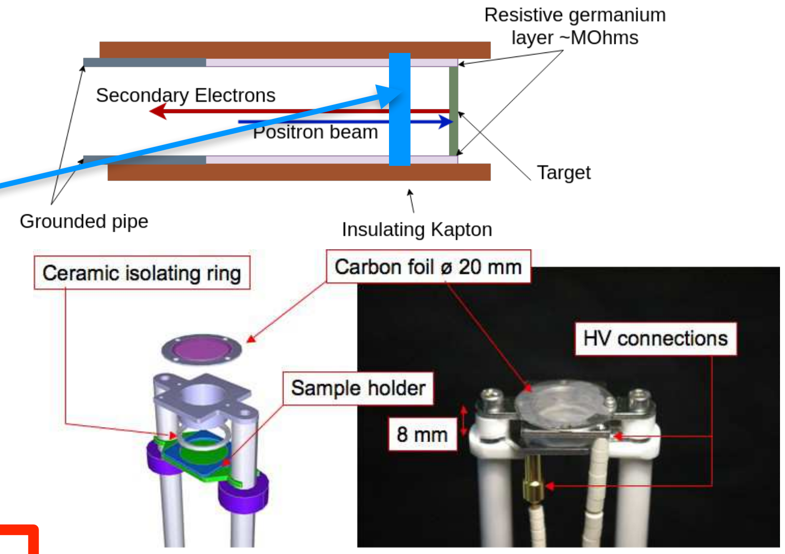
Summary and Outlook

- Latest results: no excess above expected background observed
  → for the first time limit comparable to contraints from cosmology.

- **Main limitations:** accidental triggers, positronium escaping the detection region

Possible improvements

- Higher e+ flux (Neon moderator) and better energy spread (Ni/W remoderator)
- Implementation of 10-20 nm carbon foil to block Ps escaping the detection region



- GOAL: reach a sensitivity on mixing strength of $\epsilon \sim 10^{-9}$

(not excluded by cosmology, motivated by BSM theories, cross check DAMA claim….)

Acknowledgments

THANK YOU SO MUCH FOR YOUR ATTENTION!

ETH Zurich group:
Prof. André Rubbia, Balint Radics and Lars Gerchow
Undergraduate Students: Mark Raaijmakers, Alessandro Battaglioni and Hevjin Yarar

Former members: David Cooke and Carlos Vigo

A special thank to Sergei Gninenko, Alexander Belov, Laszlo Liszkay, Rich Vallery and Flip Tanedo (for letting me adapt some of his slides)

Grant No. ETH-35-14-2