Positronium a Portal to the Mirror Sector

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Talk prepared for the Patras WS 2011 28th of June, 2011

Outline

1. Mirror Matter (MM)
2. MM & Positronium (Ps)
3. Ps experiment

The hidden/Mirror sector -1

For an excellent review see Okun, Phys.Usp. 50 (2007) 380-389 [hep-ph/0606202]

In their famous paper on „Question of Parity Conservation in Weak Interactions“ to save left-right symmetry of the Lagrangian Lee and Yang postulated the existence of hypothetical right-handed protons.

T. D. Lee and C. N. Yang, 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 overall right–left symmetry. If this is the case, it should be pointed out, there must exist two kinds of protons pR and pL, the right-ended one and the left-ended one.*”

10 years later Kobzarev, Okun and Pomeranchuk discussed various phenomenological aspects of the idea suggested by Lee and Yang, a parallel hidden (mirror) sector of particles which is an exact duplicate of the observable particle sector.

I. Kobzarev, L. Okun and I. Pomeranchuk, Sov. J. Nucl. Phys. 3 (1966) 837.

The hidden/Mirror sector-2

In 1991, Foot, Lew and Volkas presented the old original idea of mirror matter in the modern context of gauge theories.

R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B 272 (1991) 67

$$\mathcal{L} = \mathcal{L}_{SM}(e, u, d, \gamma, \ldots) + \mathcal{L}_{SM}(e', u', d', \gamma', \ldots)$$

For each type of particle, such as electron, proton and photon,
there is a corresponding mirror particle with the same mass as the ordinary one.
R-parity interchanges the roles of left and right chiral fermion fields so that in the sector mirror particles experience *V* +*A* (i.e. right-handed) mirror weak interactions.

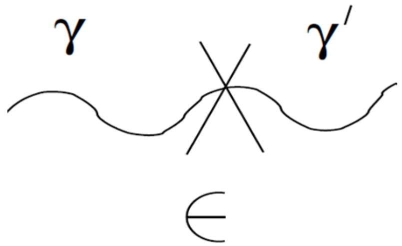
If such particles exist in nature, then mirror symmetry would be exactly conserved.

The two sectors would interact through gravitation.
Non-gravitational interaction via colourless and neutral particles with their mirror conterparts would also be possible.

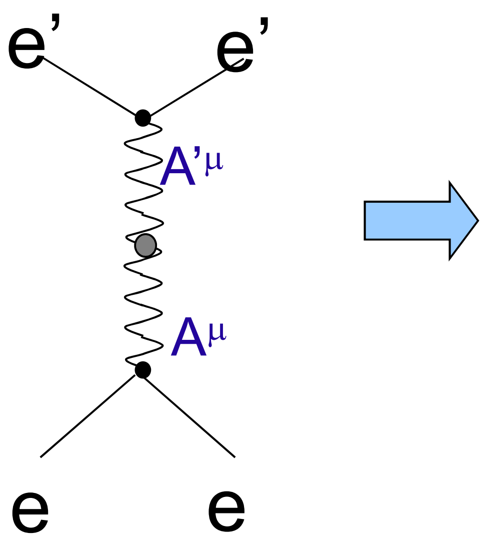
Kinetic mixing

The kinetic mixing is a renormalizible gauge invariant terms that can be added to the Lagrangian

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



E.g Mirror electrons are coupled to ordinary electrons with an effective charge $2\varepsilon e$



Implications for cosmological observations.

Cosmology of Mirror Matter

For a recent review see Ciarcelluti,Int.J.Mod.Phys.D19:2151-2230,2010.

- O and M particles have the same microphysics in symmetric models, however their cosmological abundance and hence the cosmological evolution should be different not to be in conflict with BBN prediction.

- Therefore in the early universe the M-system should have a lower temperature than the ordinary particles T'<T.

BBN limit upper bound x<0.5 where $x = \frac{T'}{T}$

Z. Berezhiani, Phys.Lett.B503:362-375,2001

Bound on mixing from LSS and CMB: $\epsilon \sim 10^{-9}$

P. Ciarcelluti, R. Foot, Phys. Lett. B 679 (2009) 268

It seems that this concept could explain the coincidence between visible and DM densities in a natural way.

$$\beta = \frac{n'_b}{n_b} \cong 5$$

L. Bento and Z. Berezhiani, Phys. Rev. Lett. 87, 231304 (2001)

MM elastic scattering

Rutherford scattering of mirror nuclei H', He', O', Fe' with matter.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{elastic}} = \frac{\epsilon^2\alpha^2 Z^2 Z'^2 M_{red}^2}{4M_{A'}^4 v_{cm}^4 \sin^4\frac{\theta_s}{2}} F_A^2(qr_A)F_{A'}^2(qr_{A'})$$

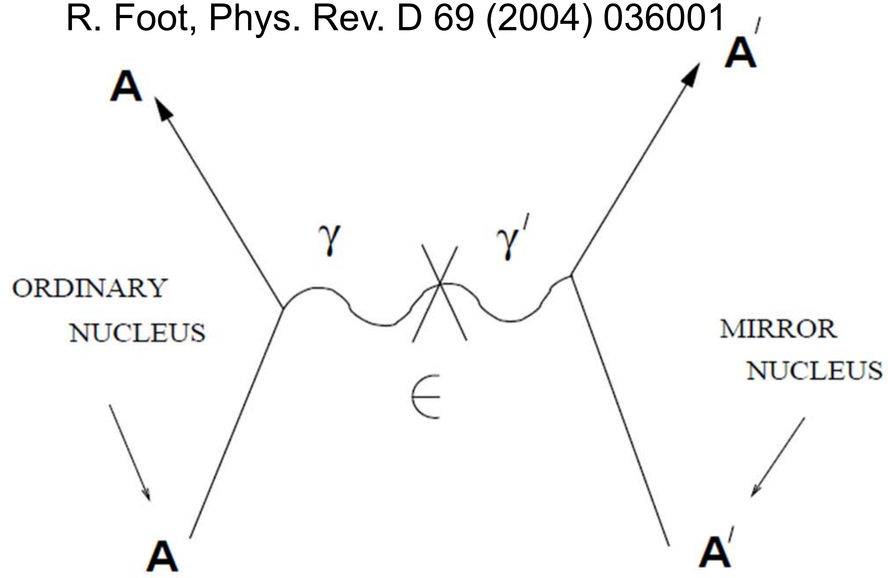
R. Foot, Phys. Rev. D 69 (2004) 036001

In term of the recoil energy:

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}$$

where

$$\lambda \equiv \frac{2\pi\epsilon^2 Z^2\alpha^2}{m_A} F_A^2(qr_A)$$



$$\frac{dR}{dE_R} \propto \frac{1}{E_R^2}$$ Is the main difference of scattering via massless or light mediator rather than the commonly used contact (four fermions) interaction.

Velocity distribution of MM

Assuming a Maxwellian distribution of the mirror particles halo

$$f_i(v) = e^{-\frac{1}{2}m_i v^2/T} = e^{-v^2/v_0^2[i]}$$

$$[i = e', H', He', O', Fe' \ldots]$$

$$v_0^2[i] = \frac{2T}{m_i} = v_{rot}^2 \frac{\overline{m}}{m_i} = v_{rot}^2 \frac{m_p}{m_i} \frac{1}{2 - \frac{5}{4} Y_{He'}}$$

$$T \simeq \frac{1}{2} \bar{m} v_{rot}^2$$

$$\bar{m} = \sum n_i m_i / \sum n_i$$

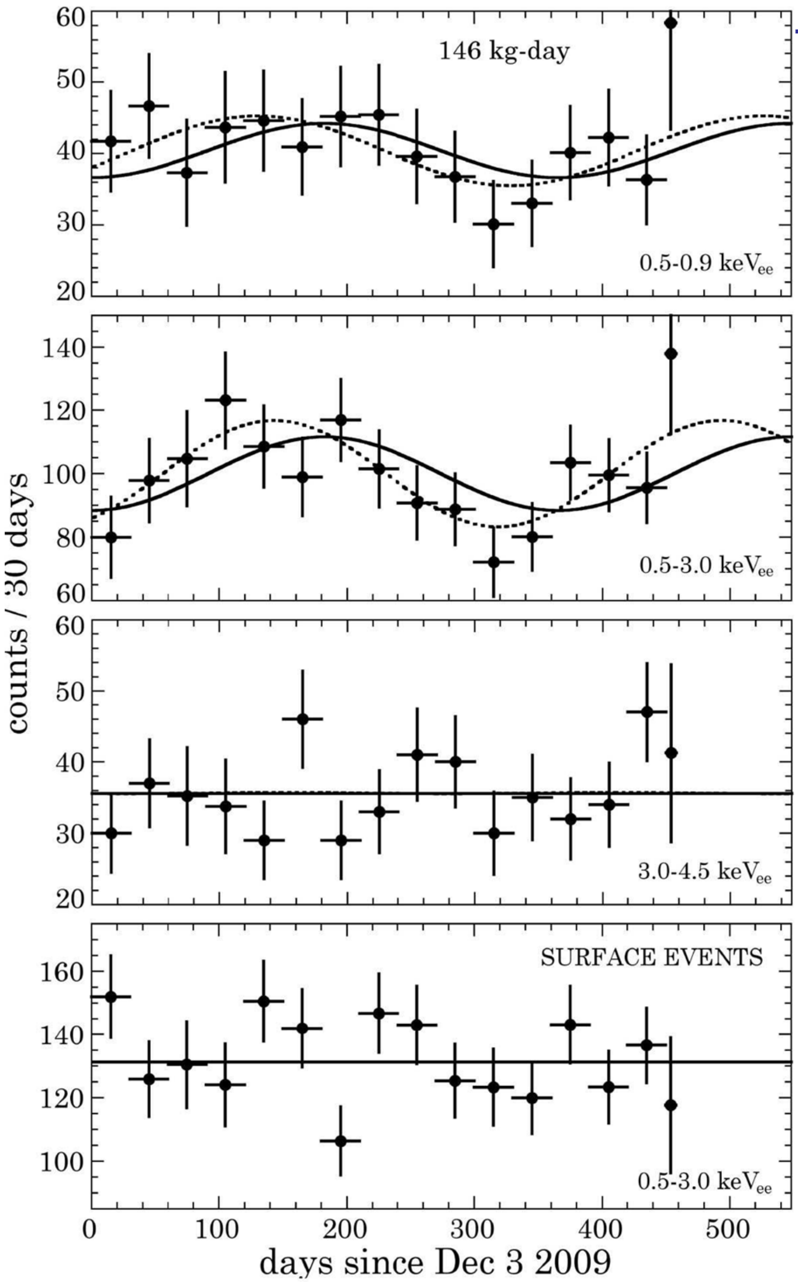
P. Ciarcelluti, R. Foot, Phys. Lett. B 679 (2009) 268

From BBN $Y_{He'} \approx 0.9$

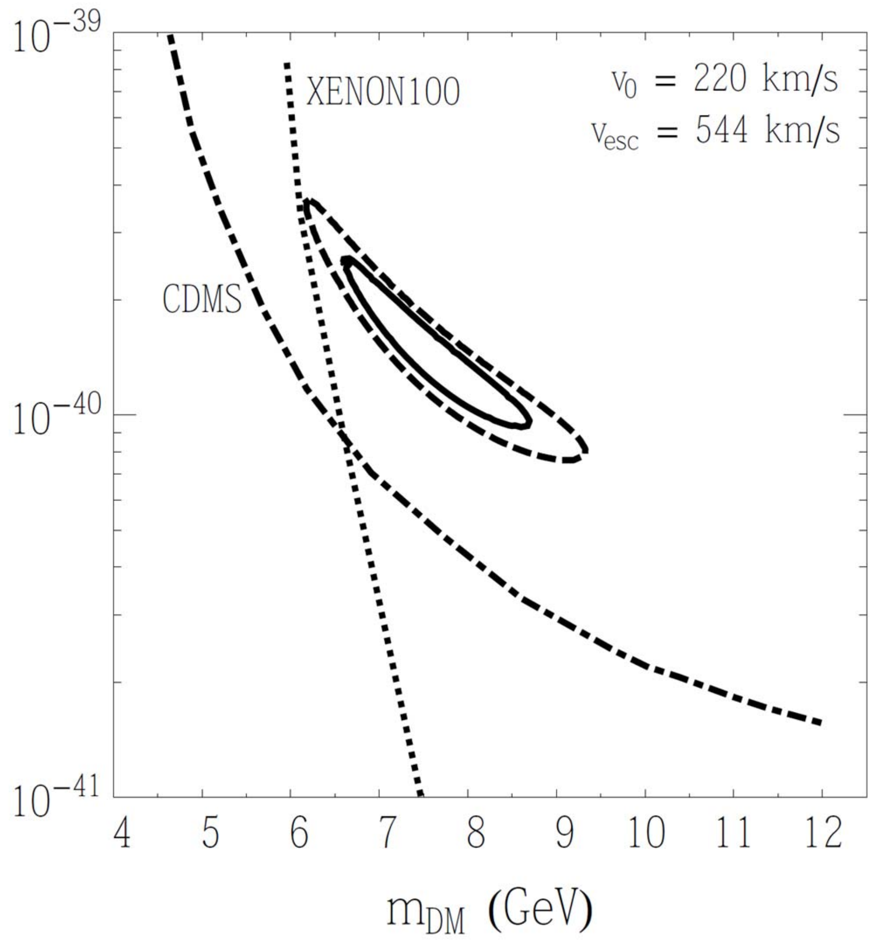
This velocity dispersion affects the rate of dark matter interactions.

C.E. Aalseth et al. arXiv:1106.0650 [astro-ph.CO]

CoGeNT



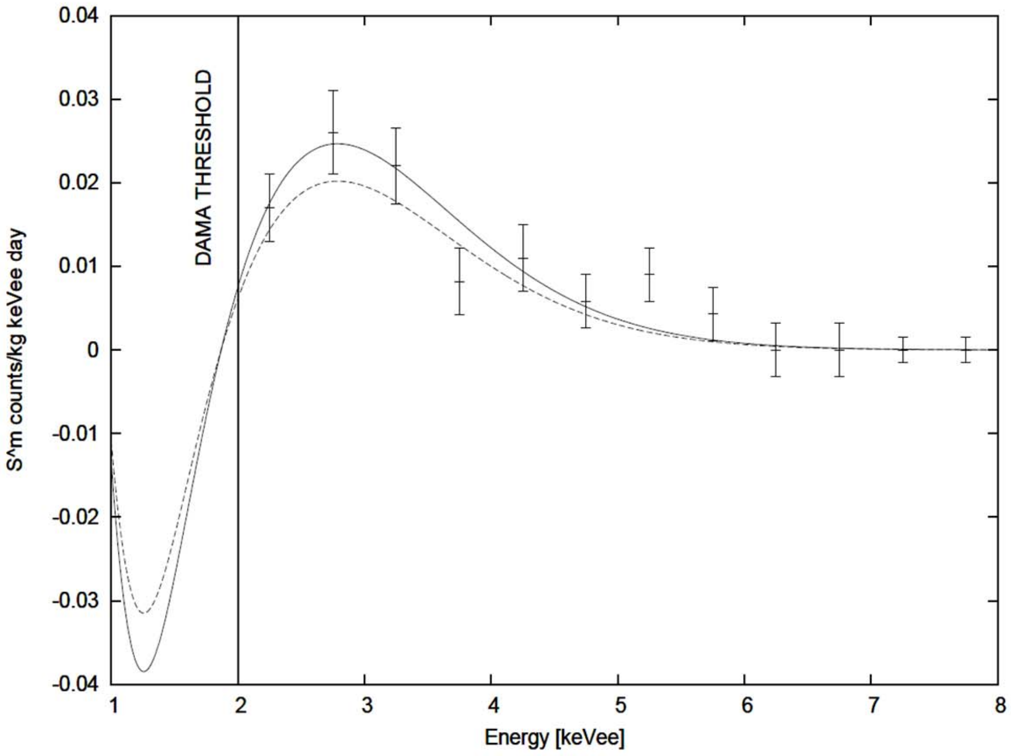
D. Hooper and C. Kelso. arXiv:1106.1066 [astro-ph.CO]



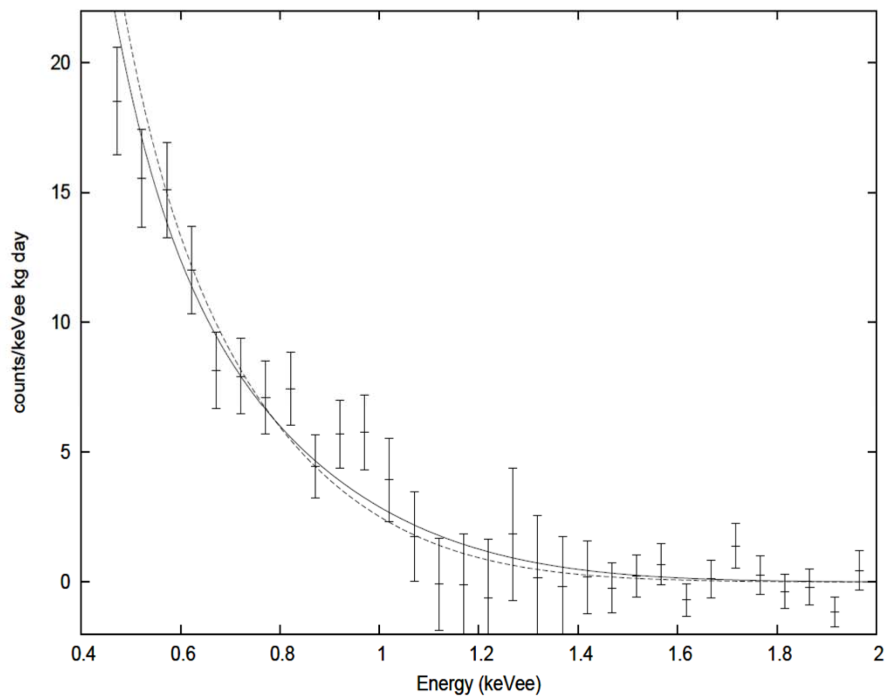
Even for light WIMPs it seems difficult to reconcile DAMA and CoGeNT with the other experiments like XENON and CDMS

DAMA and CoGeNT for MM

R. Foot, Phys. Rev. D 82 (2010) 095001
R. Foot, arXiv:1106.2688 [hep-ph]



Fit of the DAMA and CoGeNT signals in the MM scenario



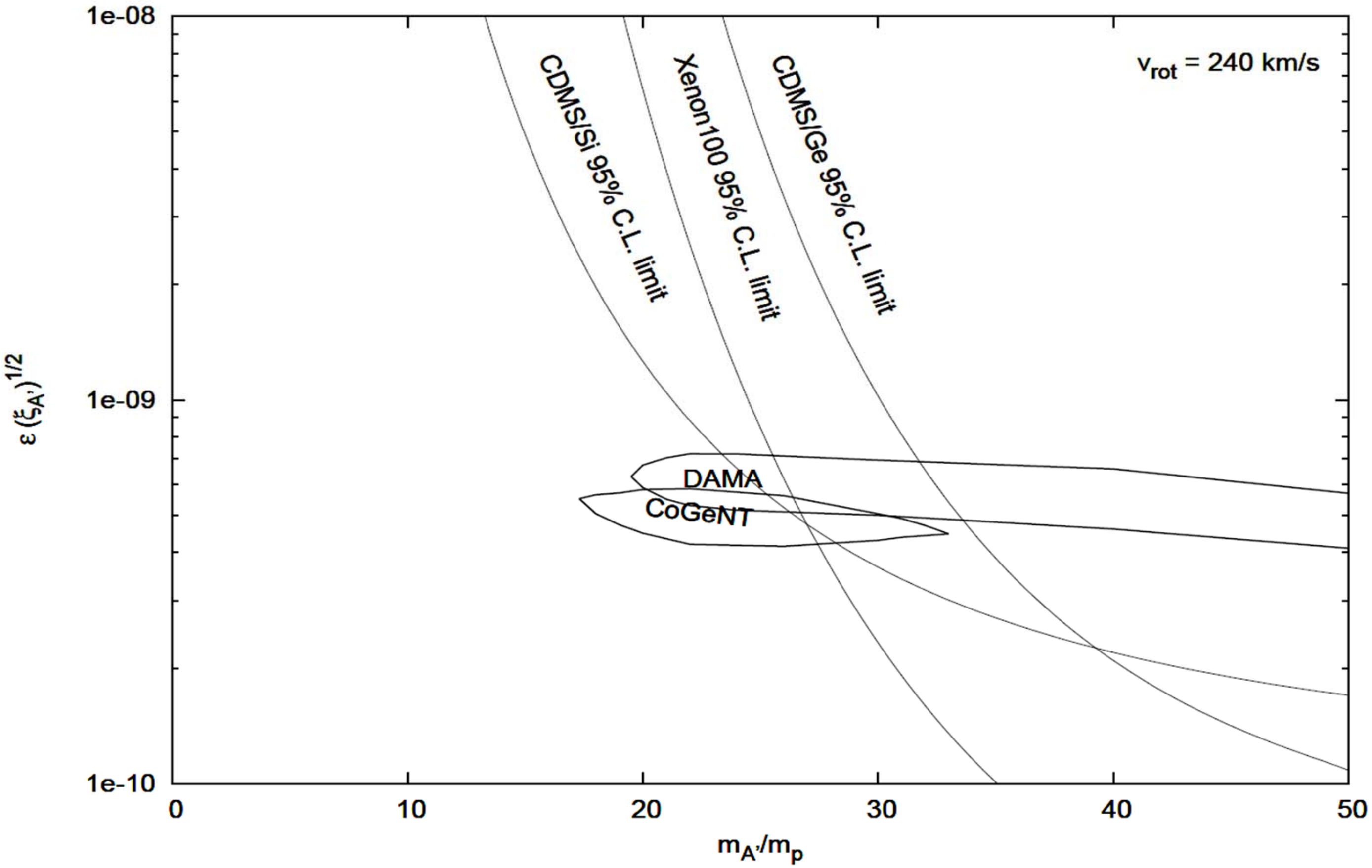
$$\epsilon\sqrt{\xi_{A'}} \approx (7 \pm 3) \times 10^{-10}$$

$$\frac{m_{A'}}{m_p} \approx 22 \pm 8$$

$\xi_{A'} \equiv n_{A'} m_{A'}/(0.3\, GeV/cm^3)$ is the halo mass fraction of the species A'

Exclusion plot for MM

R. Foot, arXiv:1106.2688 [hep-ph]



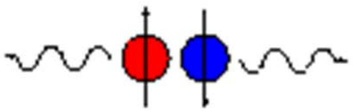
Future experiments should be able to distinguish between mirror/hidden sectors and other theoretical explanations.
A possibility is to use positronium as a probe for such a mirror sector.

Positronium

- Positronium is the bound state of an electron with its anti-particle the positron
- Bounds and self-annihilates through the same interaction

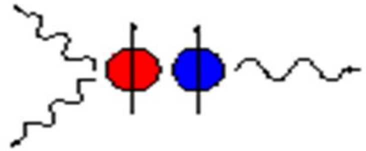
•Two ground states:

Parapositronium (p-Ps) singlet spin state $^1S_0$



τ≈125 ps (in vacuum)

Orthopositronium (o-Ps) triplet spin state $^3S_1$



τ≈142 ns (in vacuum)

Photon-less decays

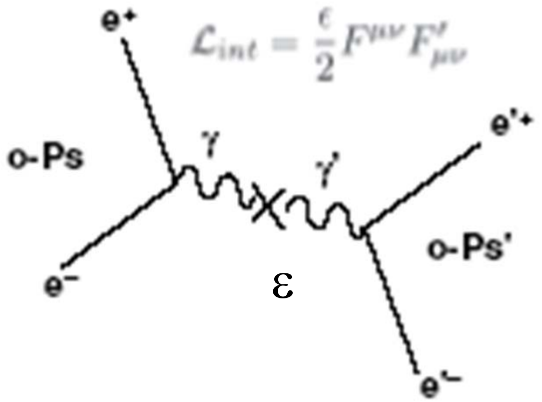
$$\Gamma(o-Ps \rightarrow \nu_e\bar{\nu}_e) \lesssim \frac{G_F^2\alpha^3 m_e^5}{24\pi^2}(1+4s^2)^2 = 6.2\times10^{-18}s^{-1}$$

$$\Gamma(o-Ps \rightarrow \nu_l\bar{\nu}_l) \lesssim \frac{G_F^2\alpha^3 m_e^5}{24\pi^2}(1-4s^2)^2 = 9.5\times10^{-21}s^{-1} \qquad l\neq e$$

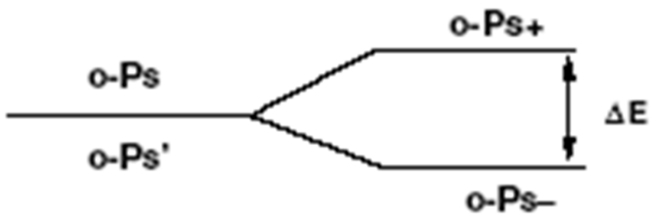
Mirror matter & Ps

The mirror matter could have a portal to our world through photon-mirror photon mixing (ε).

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



•<u>Breaking of degeneracy</u>: o-Ps is connected via a one-photon annihilation diagram to its mirror version, giving rise to ordinary-mirror oscillations with characteristic frequency εf where f=8.7×10^4 Mhz (contribution of (o-Ps)-(p-Ps) splitting from one-photon annihilation)



$$\begin{cases} (o-Ps+o-Ps')/\sqrt{2} \\ (o-Ps-o-Ps')/\sqrt{2} \end{cases}$$

•Energy splitting:

$$\boxed{\Delta E = 2h\varepsilon f}$$

•Oscillation probability:

$$\boxed{P(o-Ps \rightarrow o-Ps') = \sin^2(2\pi\varepsilon f t)}$$

Experimental signature

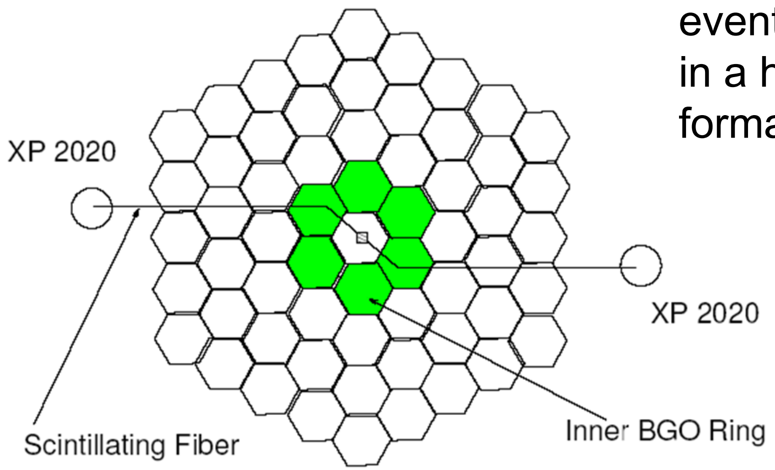
The oscillation results in modification of decay rate of o-Ps, the observation of this effect is very difficult!

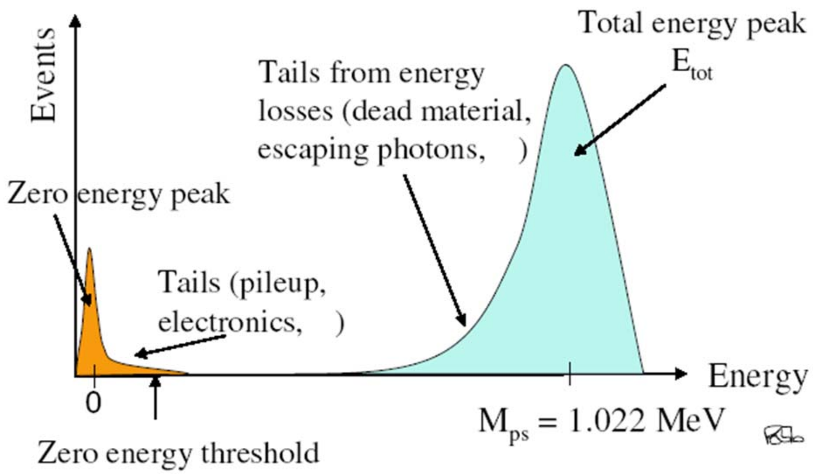
Another experimental signature is o-Ps invisible decay.

For the long time observation of o-Ps in vacuum:

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

The *o-Ps* → *invisible* decay would appear as an event compatible with zero-energy deposition in a hermetic γ-detector surrounding the o-Ps formation region.

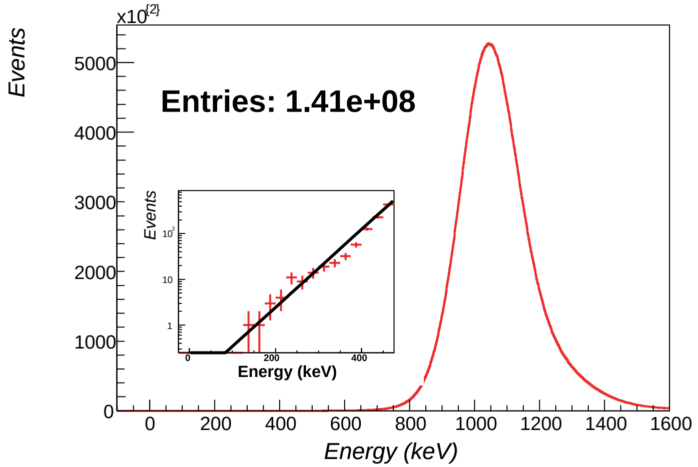




Our Previous Experiment

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

Positron from ^{22}Na source formed Ps in an aerogel target with closed pores.
(no positron beam was used and experiment not in vacuum)



Since no event was observed in the signal region, this result provides an upper limit on the o-Ps -> invisible

$$Br(o-Ps \rightarrow invisible) = 2.3/(N_{o-Ps} \cdot \epsilon) \leq 4.2 \times 10^{-7}$$

Matter destroy the coherence of oscillation

⇨ Suppression of the *o−Ps* - *o−Ps'* conversion

Effect of electromagnetic fields is negligible for the experimental conditions used in the experiment.

Considering suppression due to collision of Ps in the pores ($\Gamma_{coll} \sim 10^4$)

⇨ limit on $\varepsilon \leq 1.5 \times 10^{-7}$

Vacuum vs Aerogel Exp.

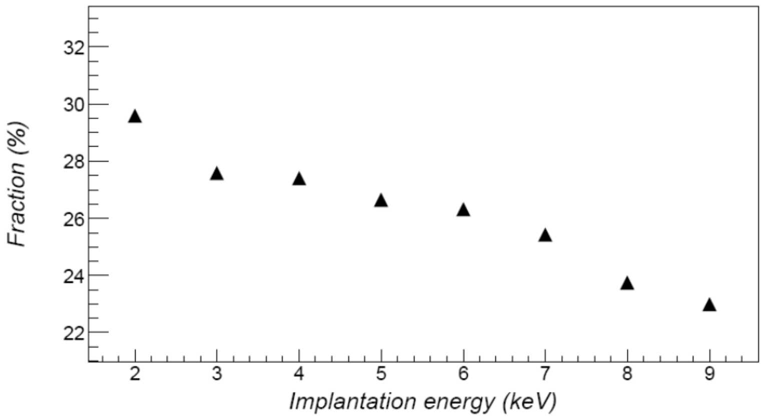
- 10^3 more statistics can be collected with the same number of positrons

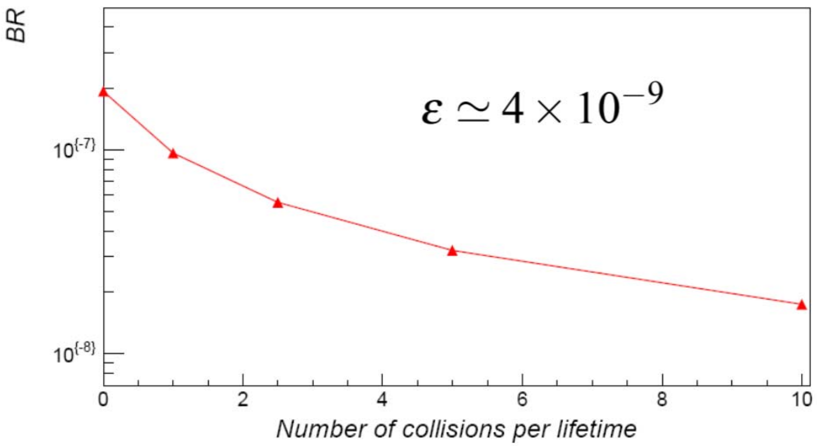
- Ps mean free path in a vacuum cavity: 30 mm while in the aerogel pores 100 nm

⇒ Γ_{coll} is a factor 10^4 smaller

⇒ 100 times more sensitivity on the mixing strength ε

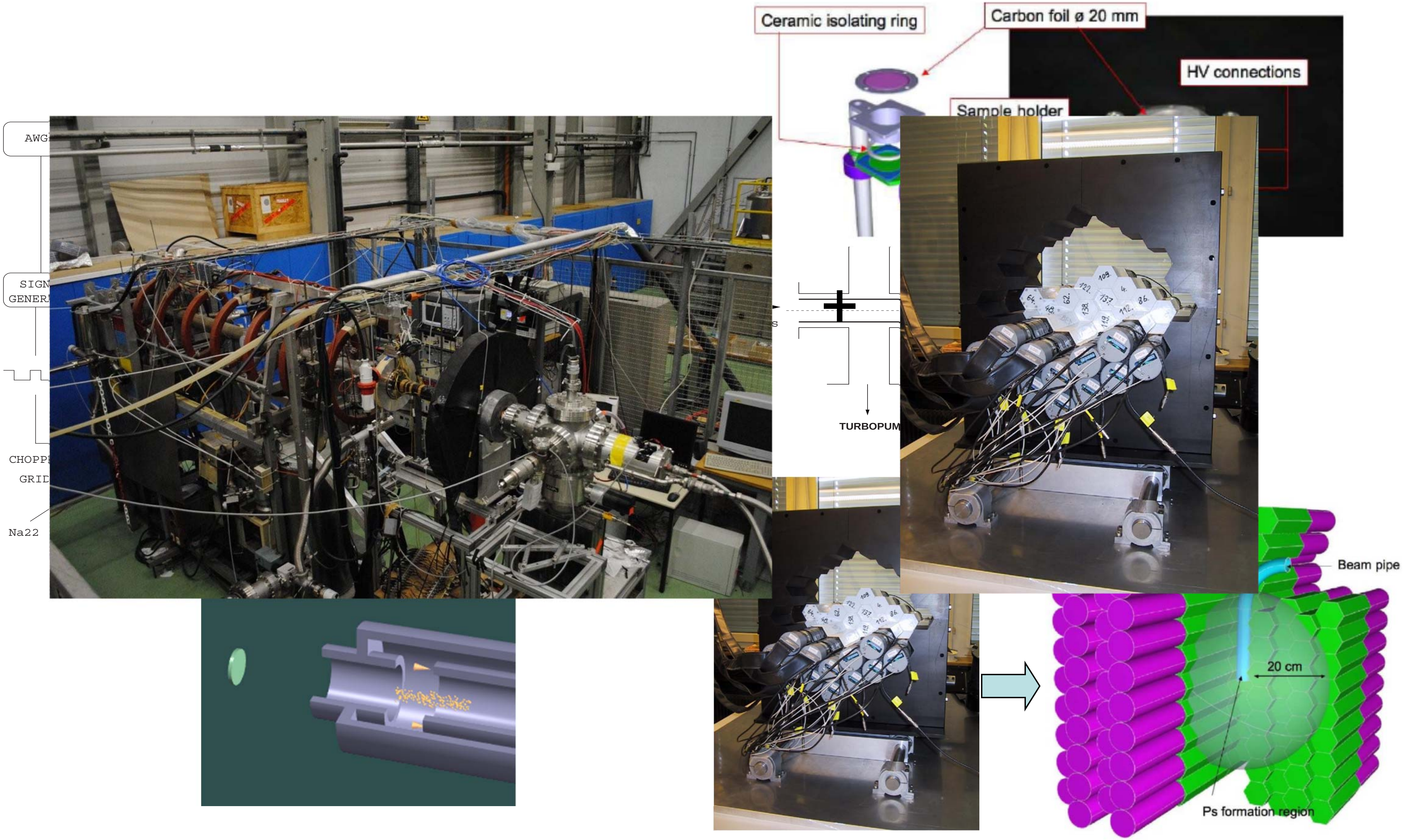
- Changing e^+ energy ⇒ energy of Ps emitted in vacuum ⇒ change $\Gamma_{coll} \sim v$



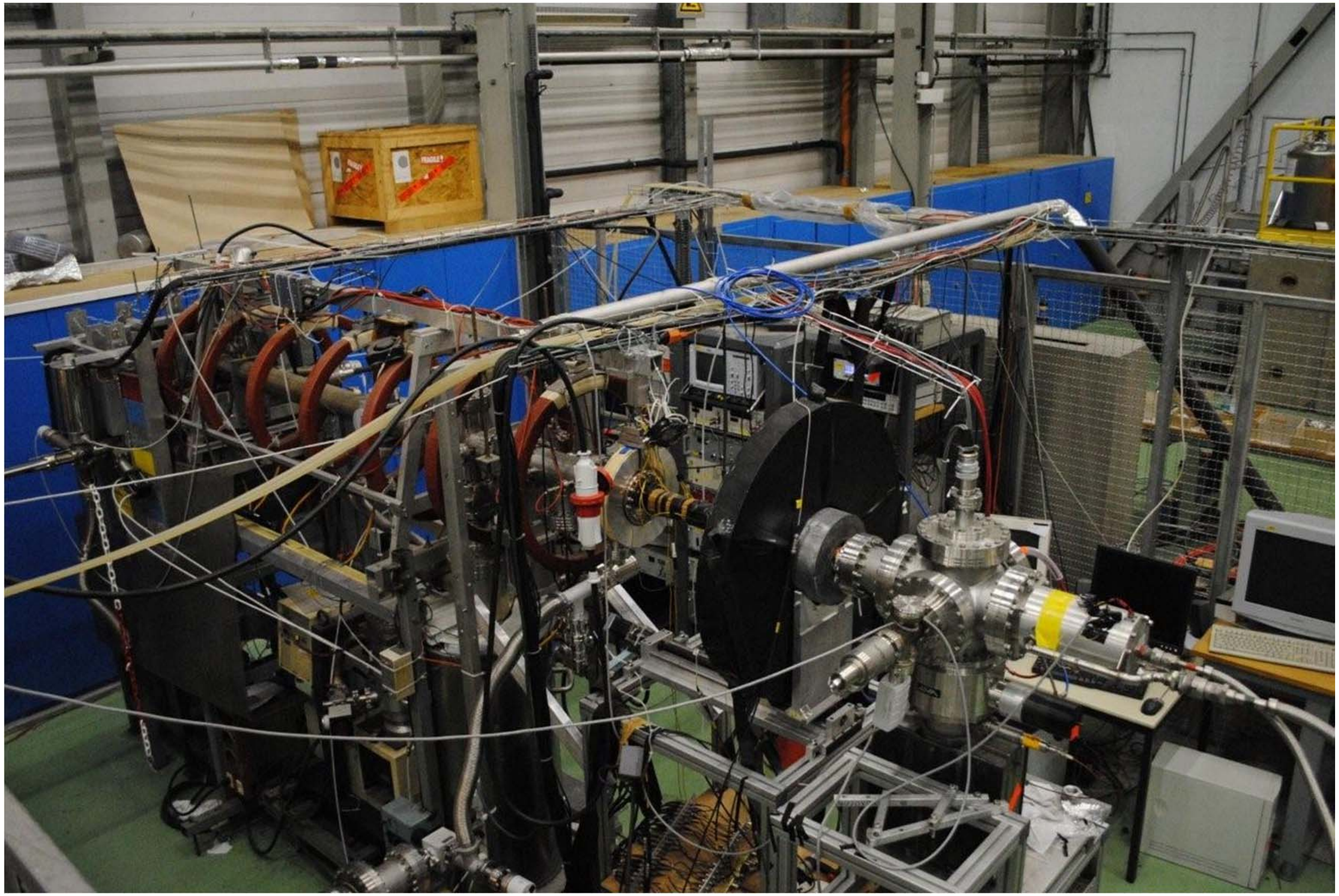


⇒ Modify the oscillation probability without affecting the background

New experiment in vacuum



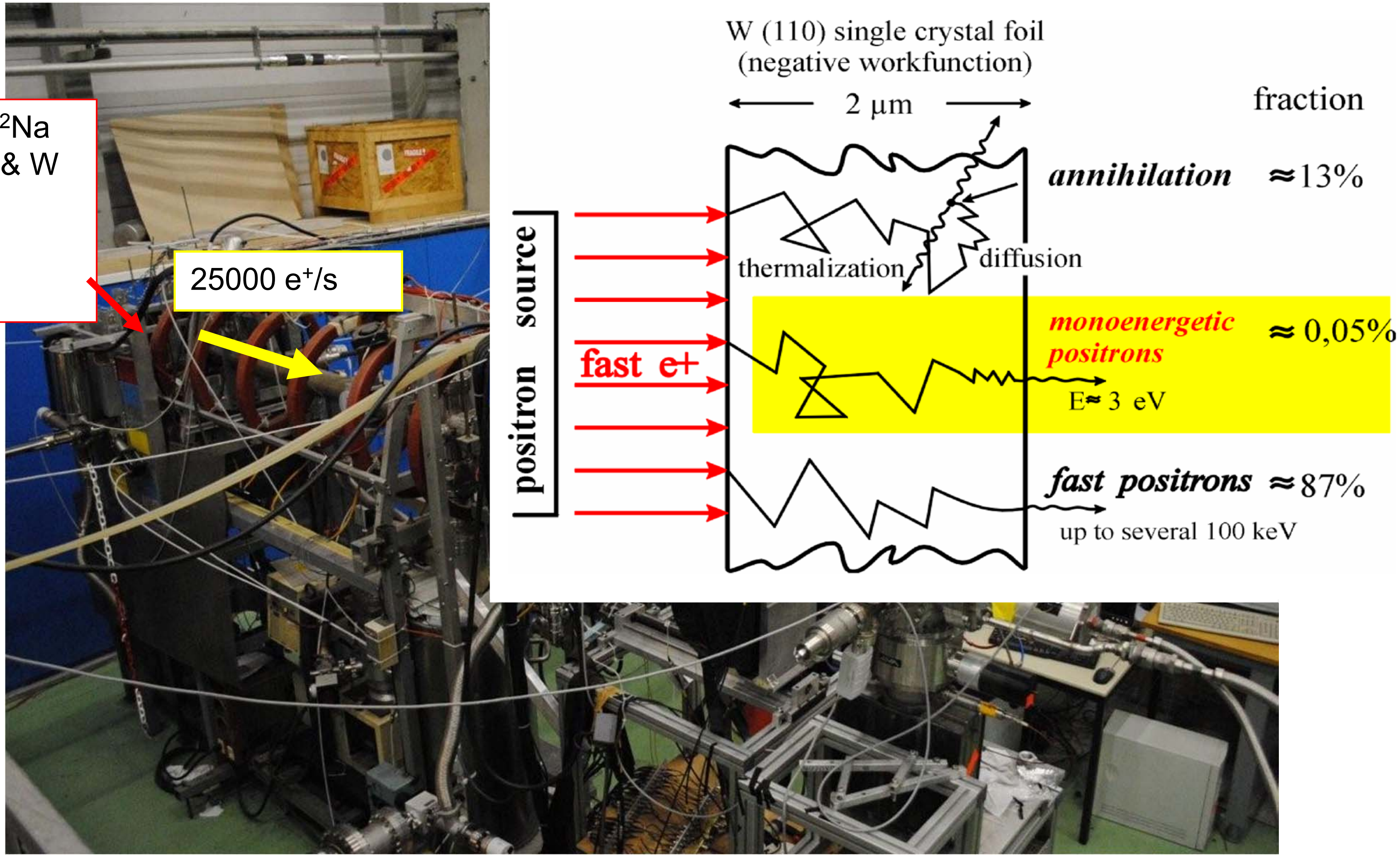
ETHZ slow positron beam



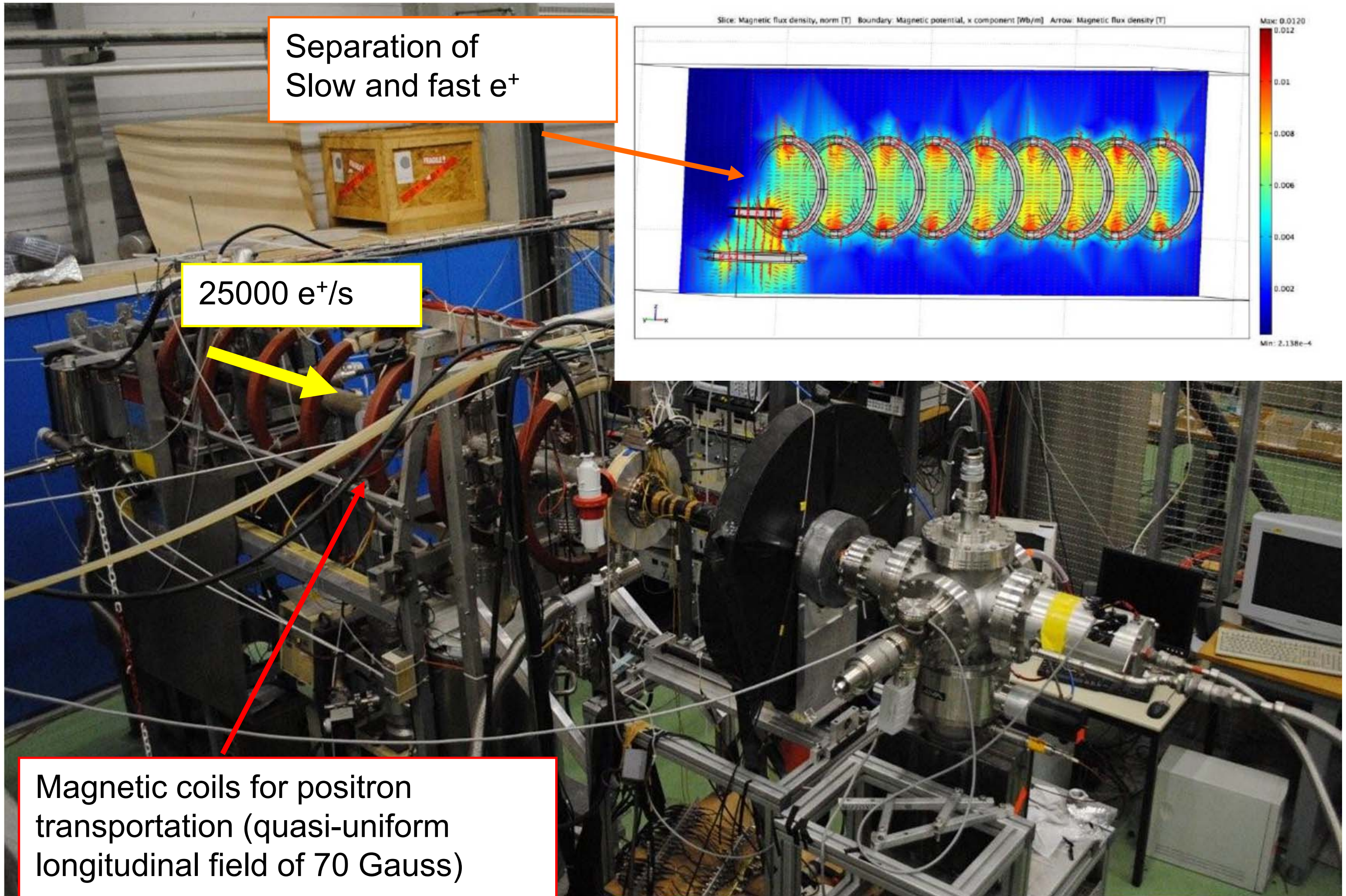
ETHZ slow positron beam

250 MBq ^{22}Na e+ source & W moderator chamber

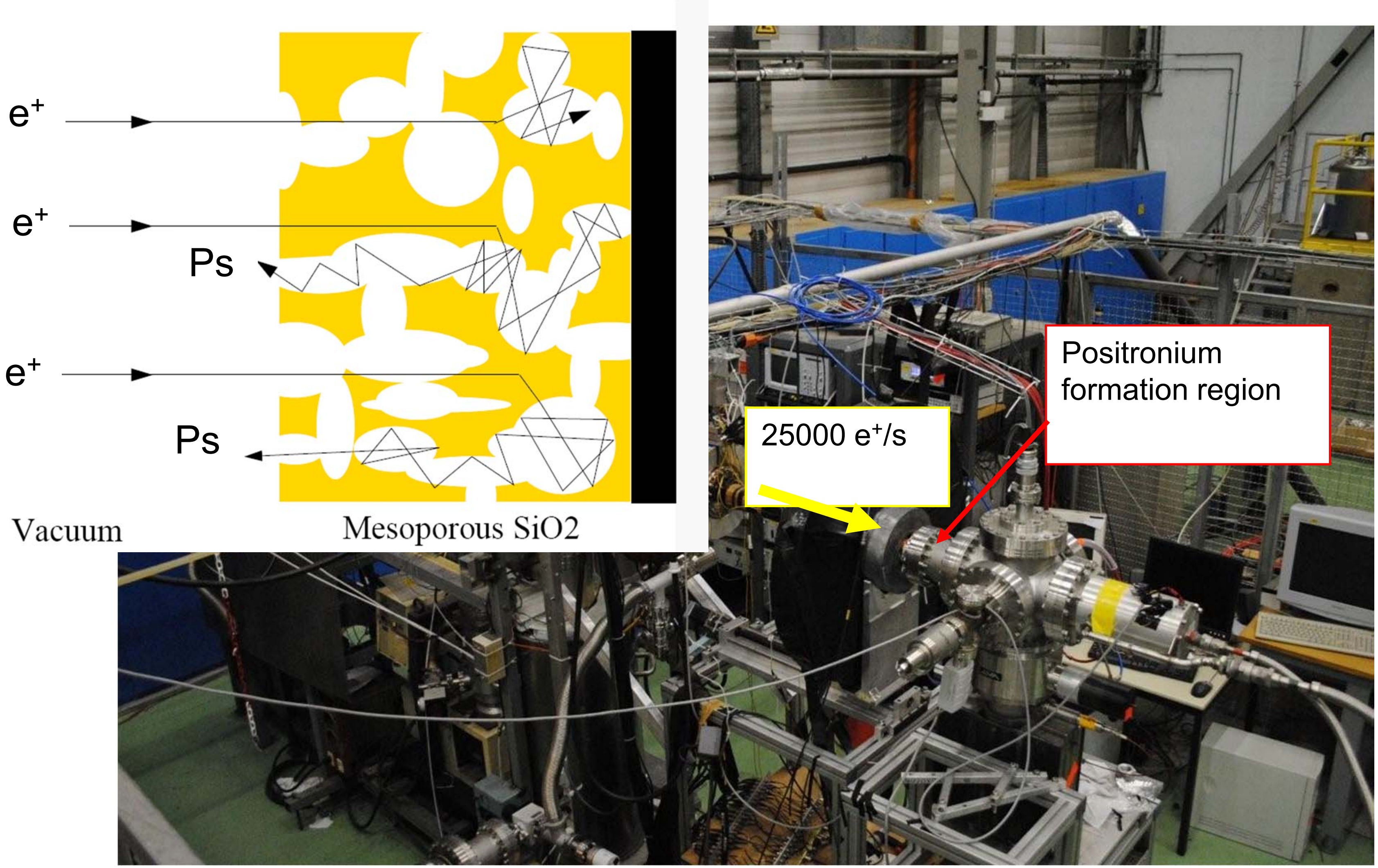
25000 e^+/s



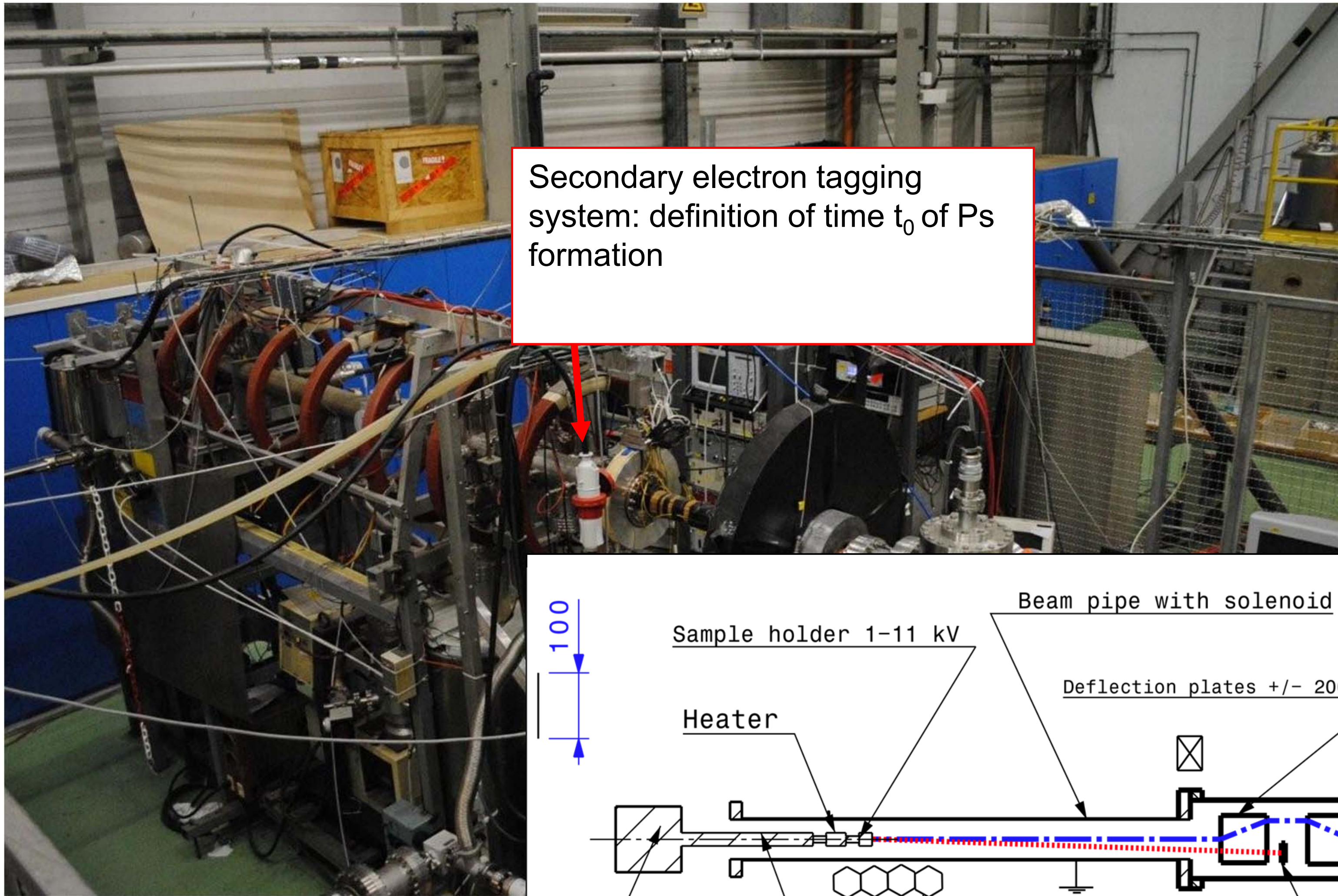
Positron transportation



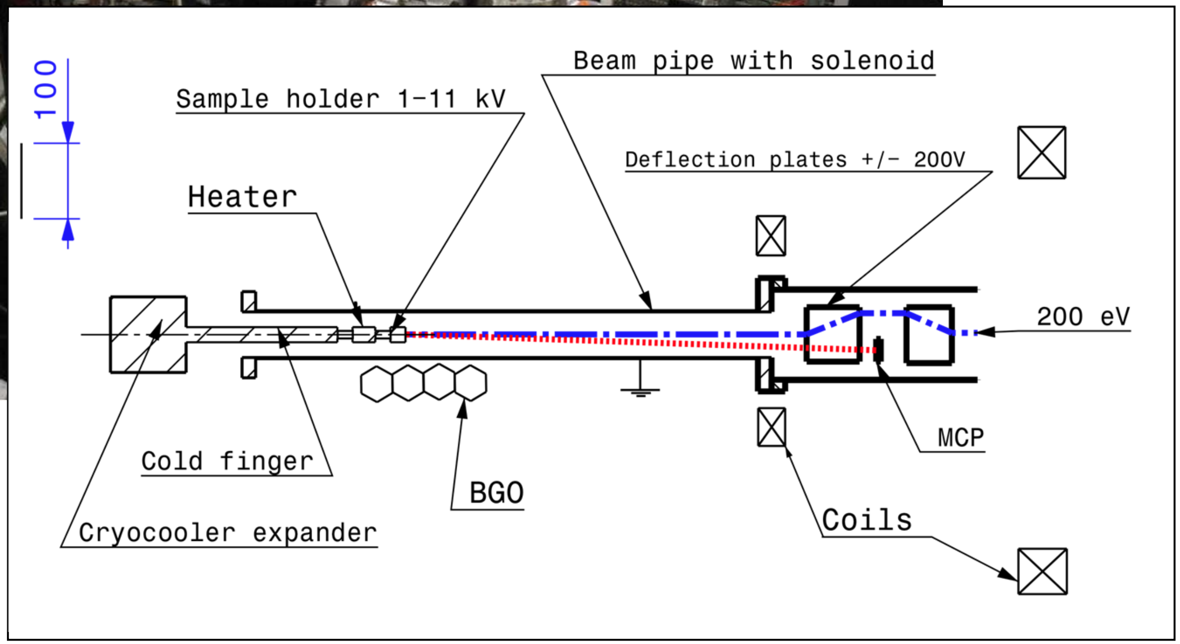
Positronium formation



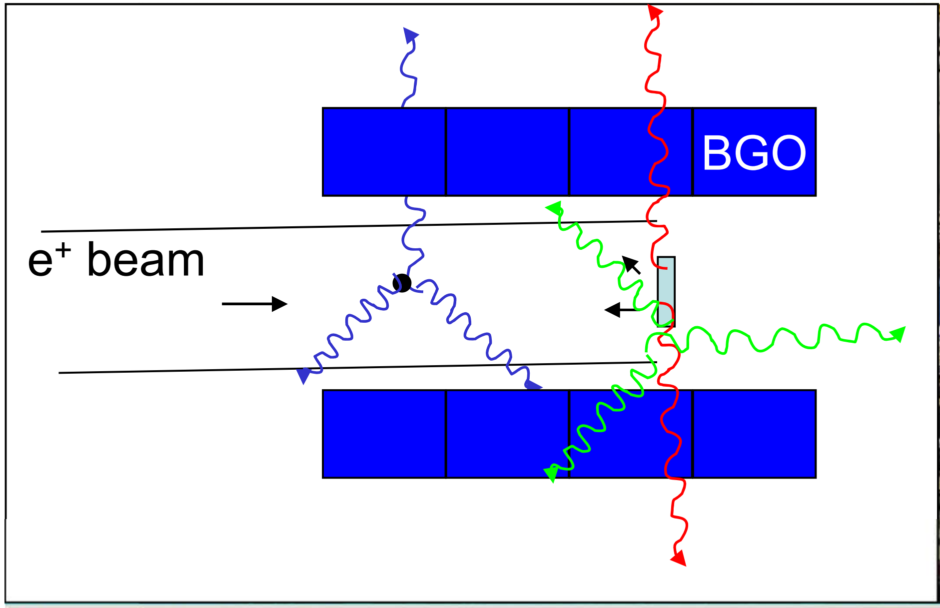
Tagging system

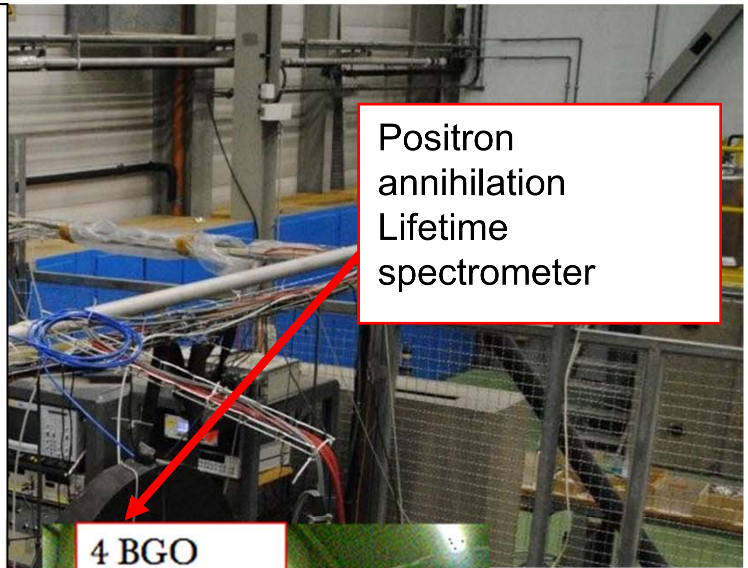


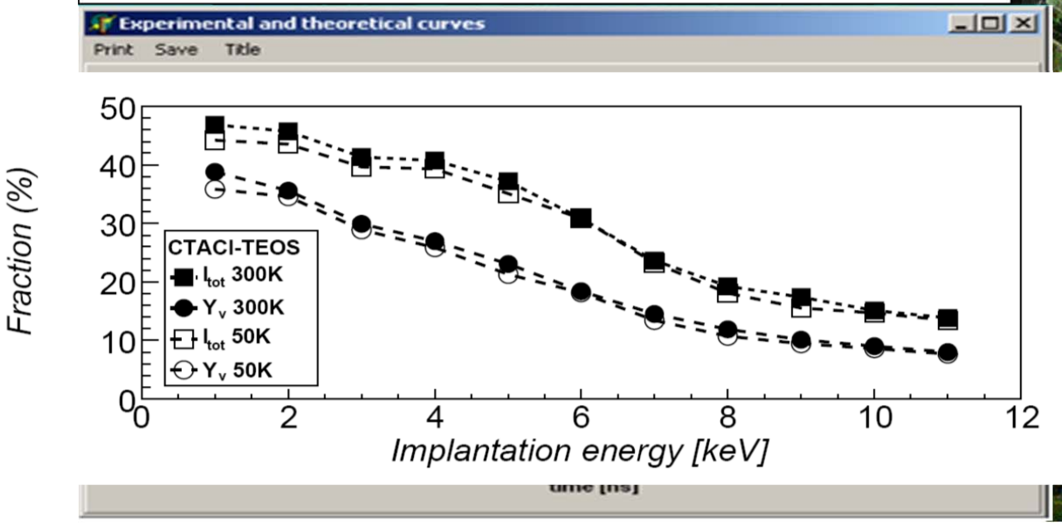
Secondary electron tagging system: definition of time t_0 of Ps formation

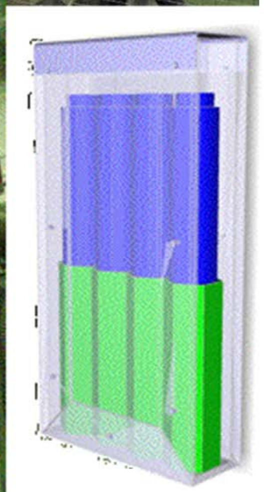


Positronium yield in vacuum

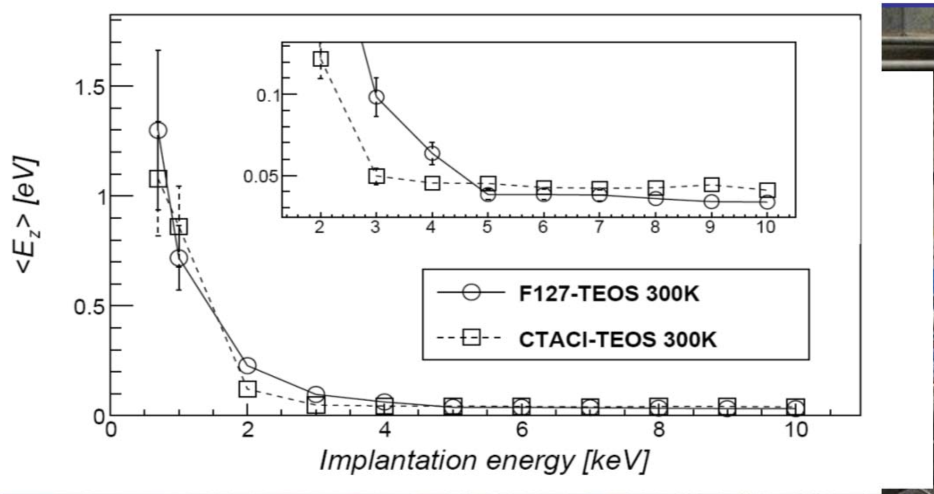


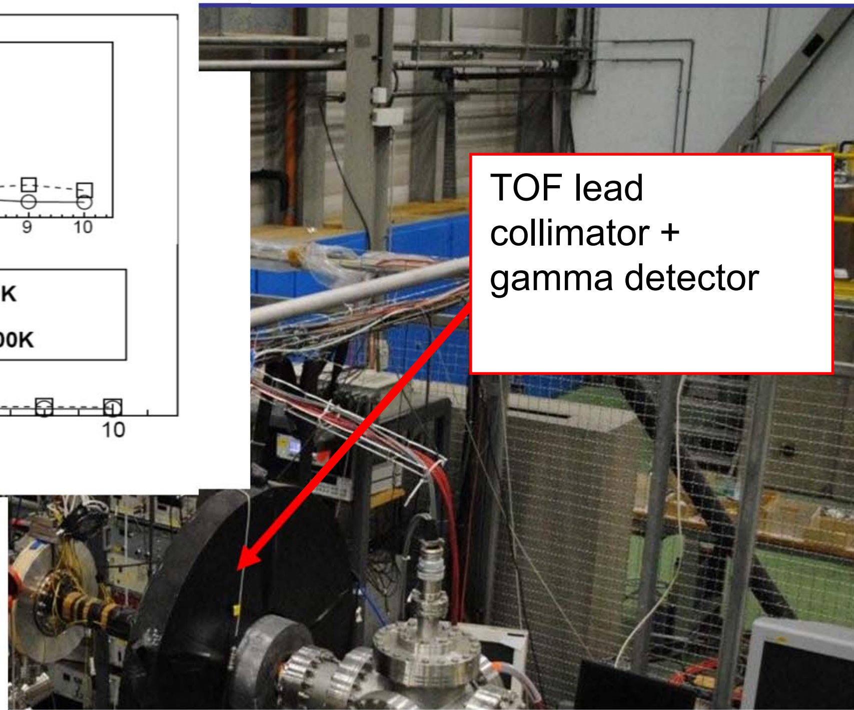


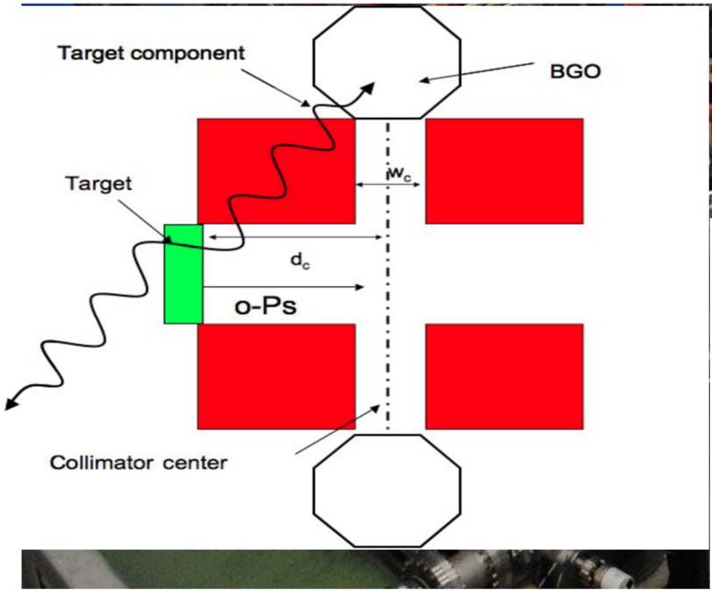


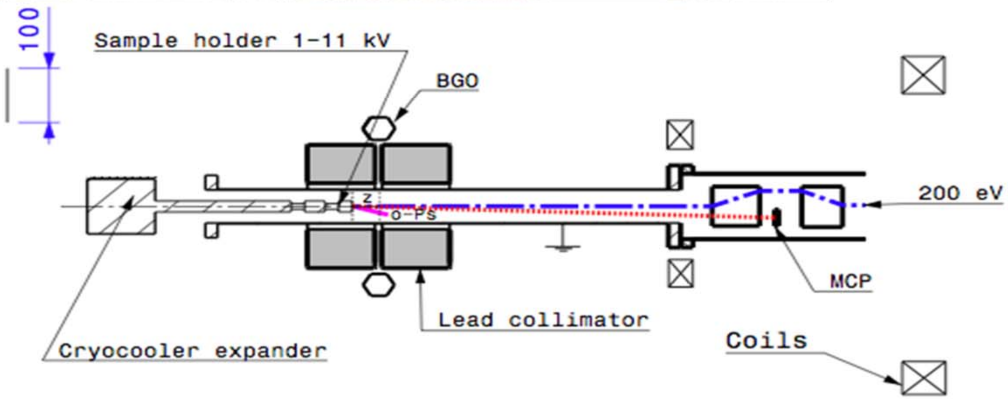


Positronium emission velocity





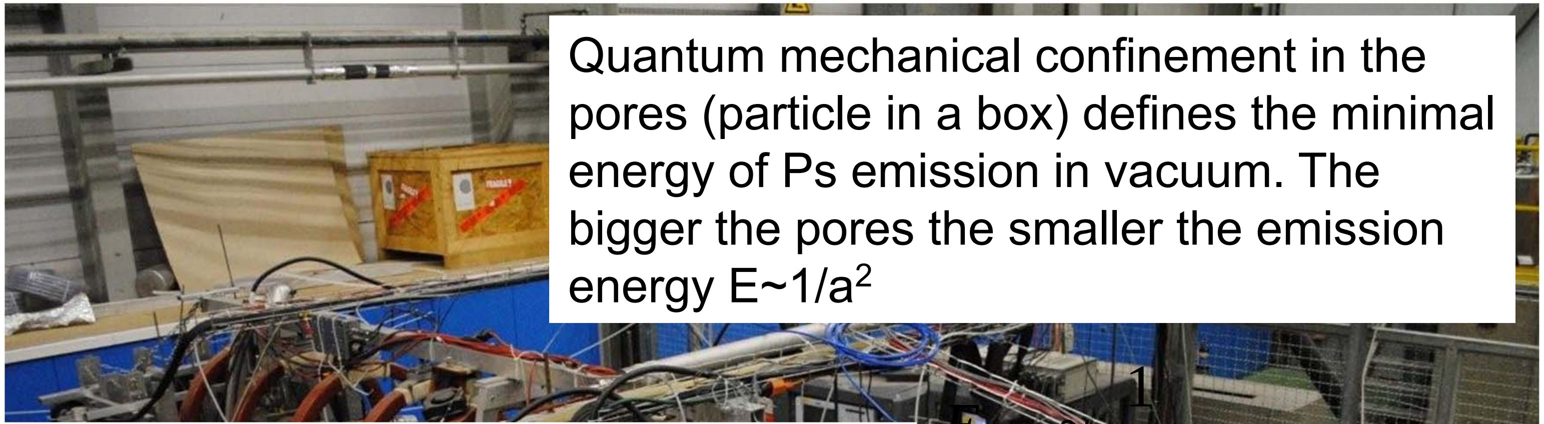


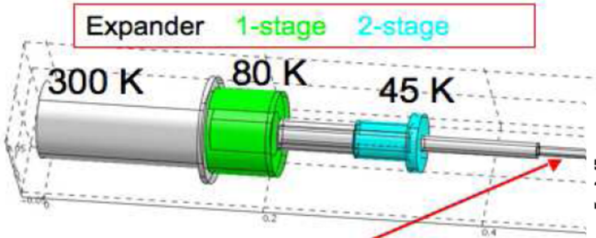


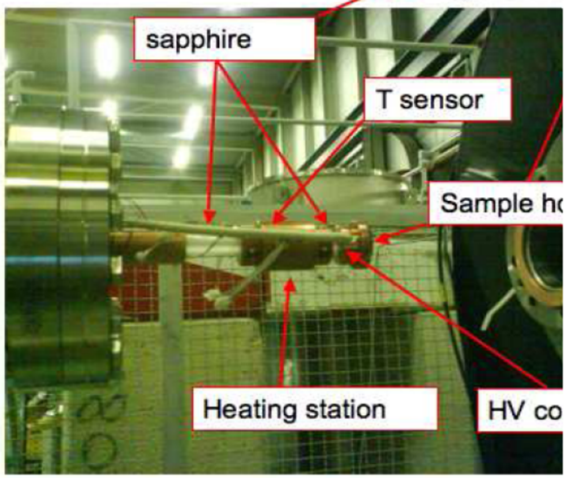
Ground state energy in the pores

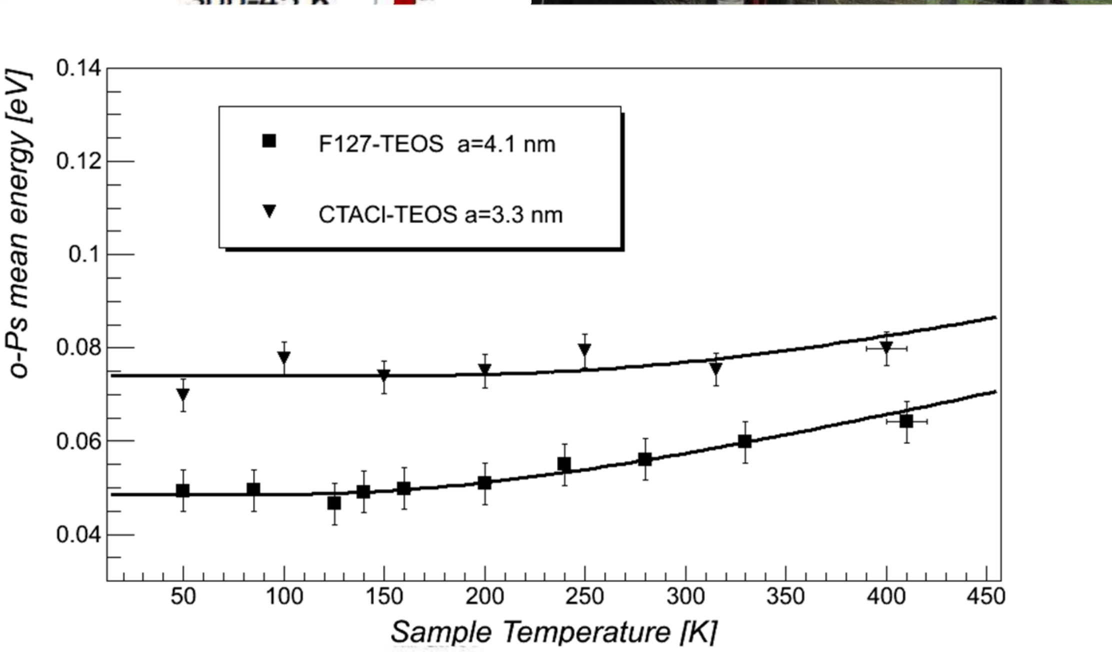
Quantum mechanical confinement in the pores (particle in a box) defines the minimal energy of Ps emission in vacuum. The bigger the pores the smaller the emission energy E~1/a[2]

$$E_{min} \sim \frac{1}{a^2}$$





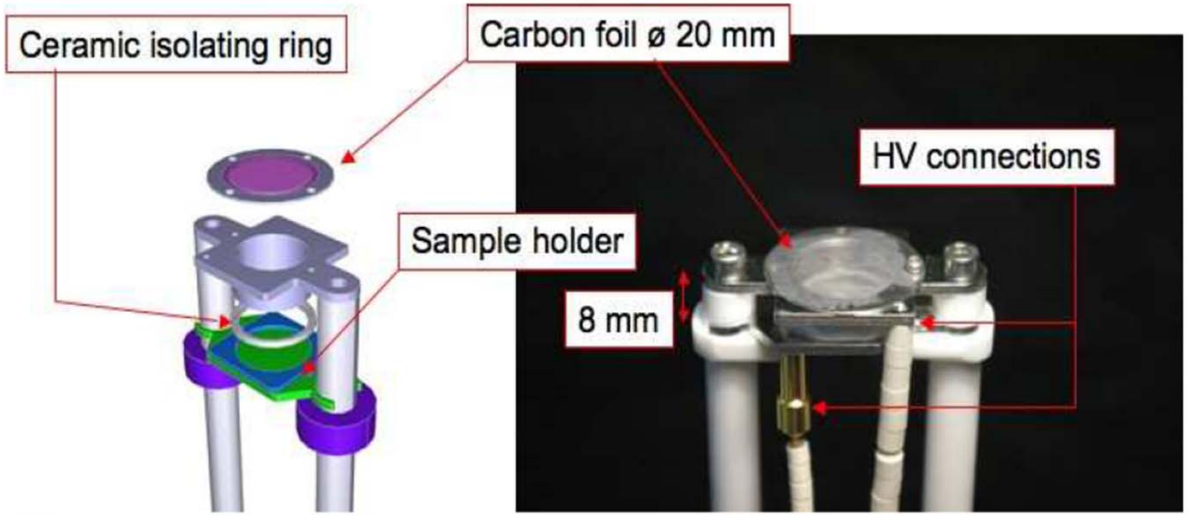


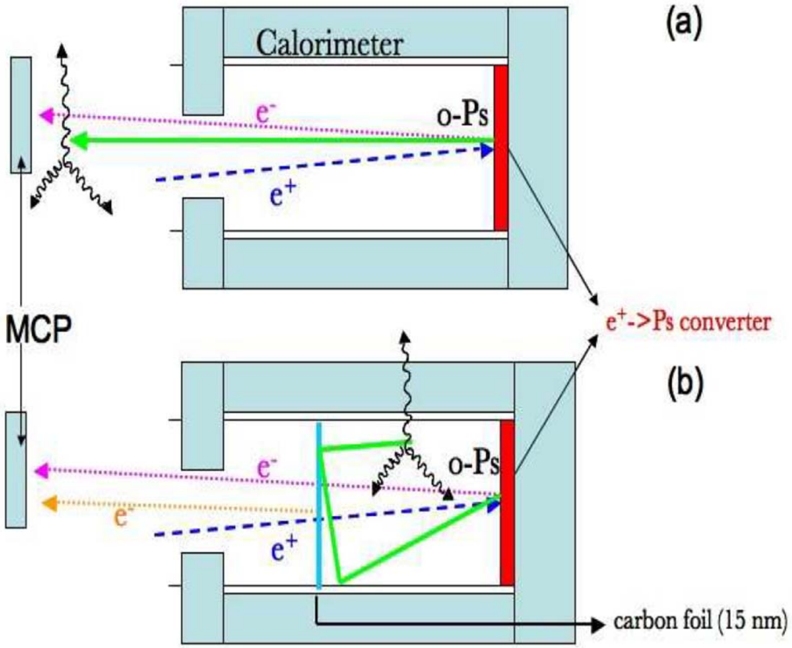


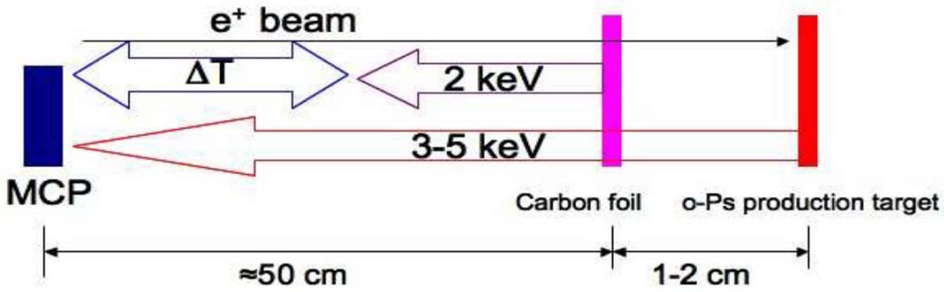
P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010)

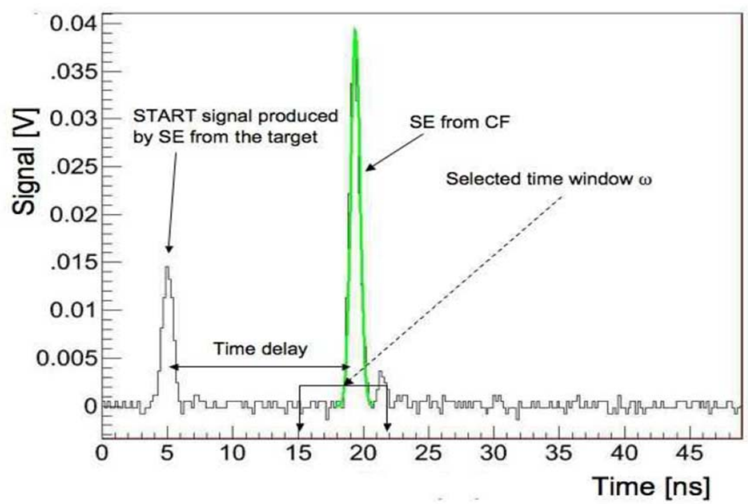
Positronium confinement

Use of thin Carbon foils (15-20 nm) to confine
Ps in the vacuum cavity and enhance the confidence level of the trigger.

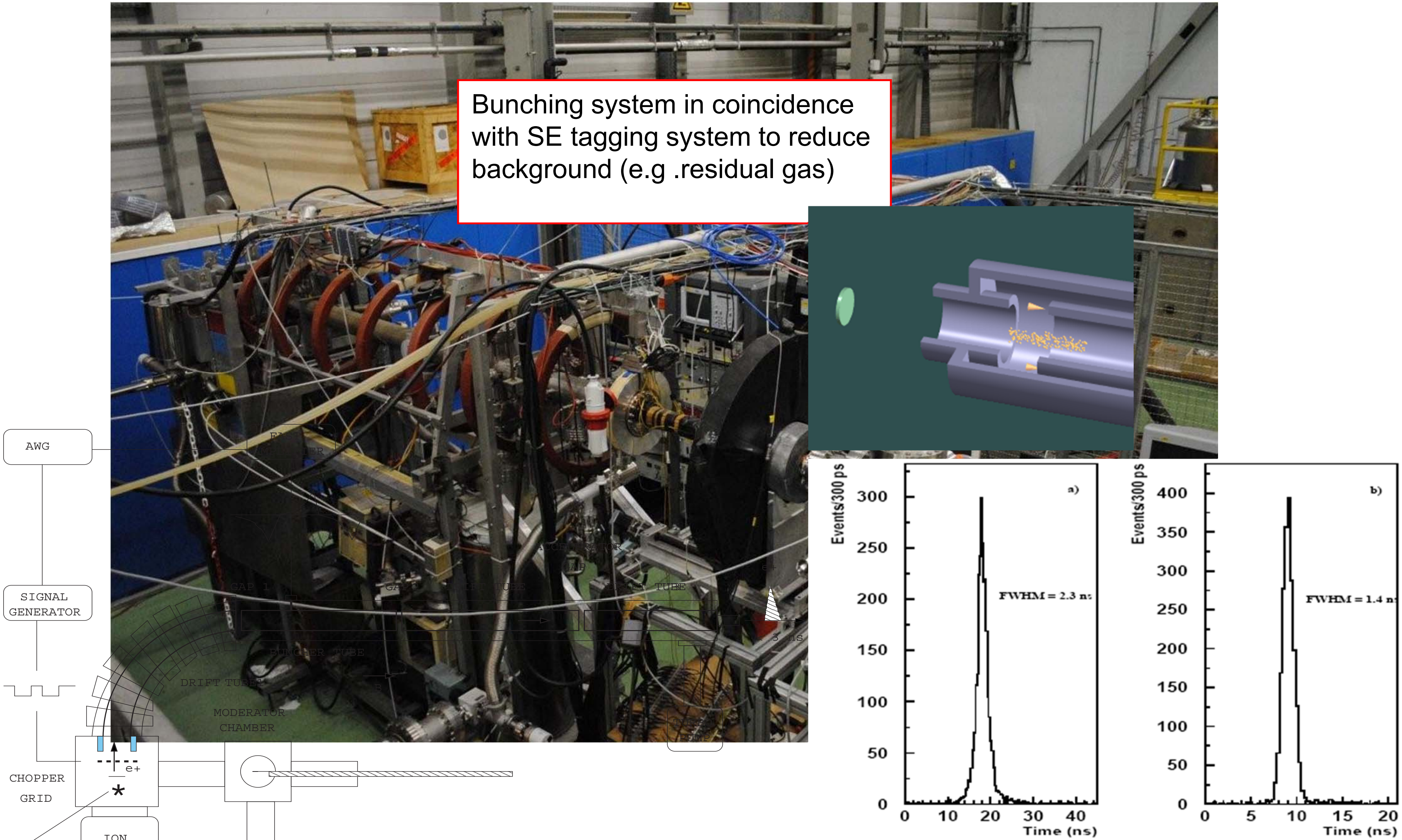








Positron bunching mode



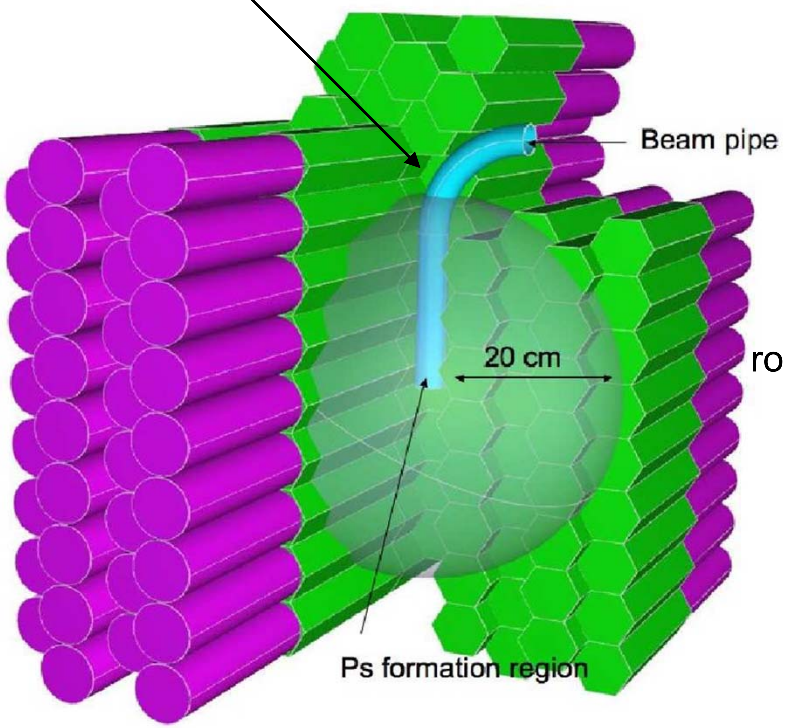
Bunching system in coincidence with SE tagging system to reduce background (e.g .residual gas)

Initial pulse of 300ns

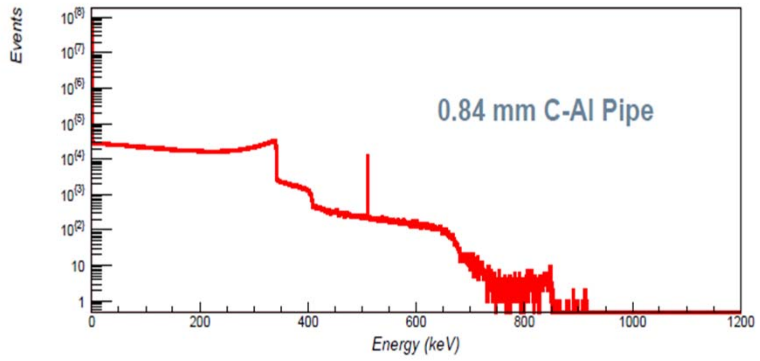
initial pulse of 120ns

BGO calorimeter

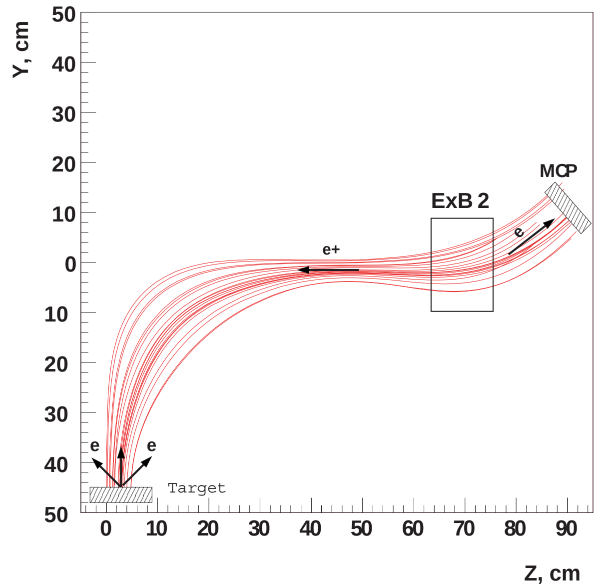
Curved pipe to avoid direct escape of annihilating photons.
Low Z (Al-C as produced for H1)-> low loss of energy.



Energy loss in the beam pipe



SE transportation



Expected sensitivity

- If DAMA/LIBRA and COGeNT annual signal modulation are generated by elastic scattering of mirror matter → $\varepsilon \approx 1\times10^{-9}$

⇨ 31 signal events (0-energy) in the ECAL during 1 month of data taking.

	BACKGROUND SOURCE	expected
1)	Photon detection loss: Hermiticity Dead Material Resolution	$< 10^{-7}$
2)	Positron backscattered from carbon foil	$< 10^{-7}$
3)	Positron Backscattered from SiO2	$< 10^{-7}$
4)	Fast o-Ps from carbon foil	$5 \times < 10^{-8}$
5)	Fast o-Ps from target	$<< 10^{-8}$

30 background events expected.

Important cross-check:
e^+ energy from 5 keV ->2-3 keV
⇨ number of signal events will be 2 times smaller without affecting the background!

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

- This result will confront directly the interpretation of the observed signals in terms of the mirror dark matter.

Outlook

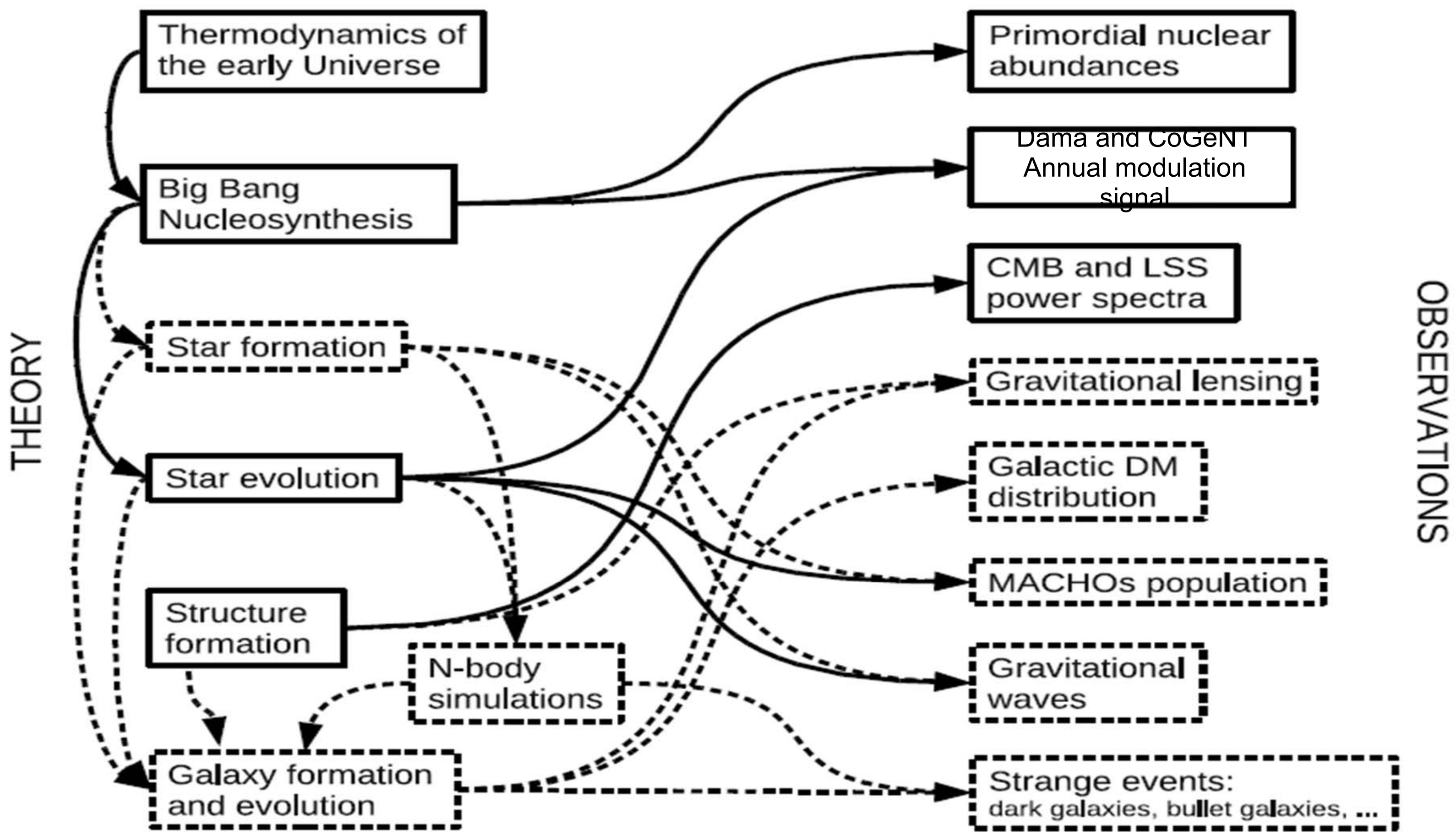
All the key elements are available.

To do: thin beam pipe with low Z, test tagging system in curved geometry and mechanics for the BGO calorimeter.

A PhD position and some funding were asked.

Outlook of Cosmology of MM

P. Ciarcelluti,Int.J.Mod.Phys.D19:2151-2230,2010.



Still some work has to be done. Especially N-body simulations to understand if a self-interacting inhomogeneous dark matter candidate as MM can be distributed in a halo without collapsing and in a way that is consistent with the observations.