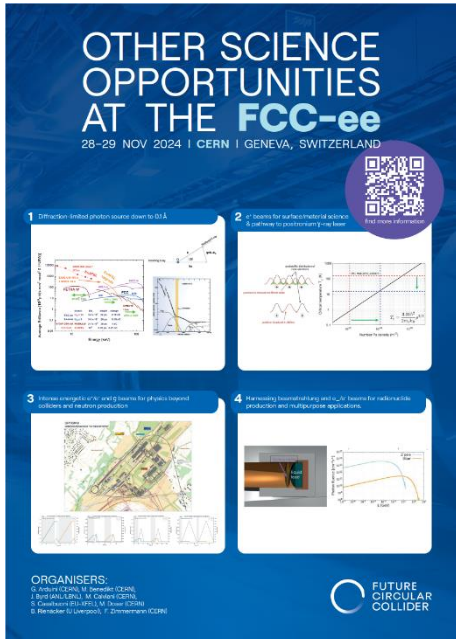


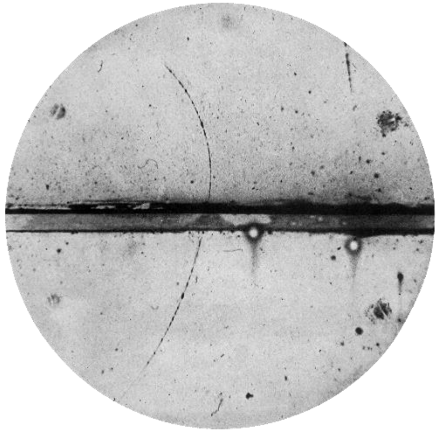
Low-energy dense positron beams

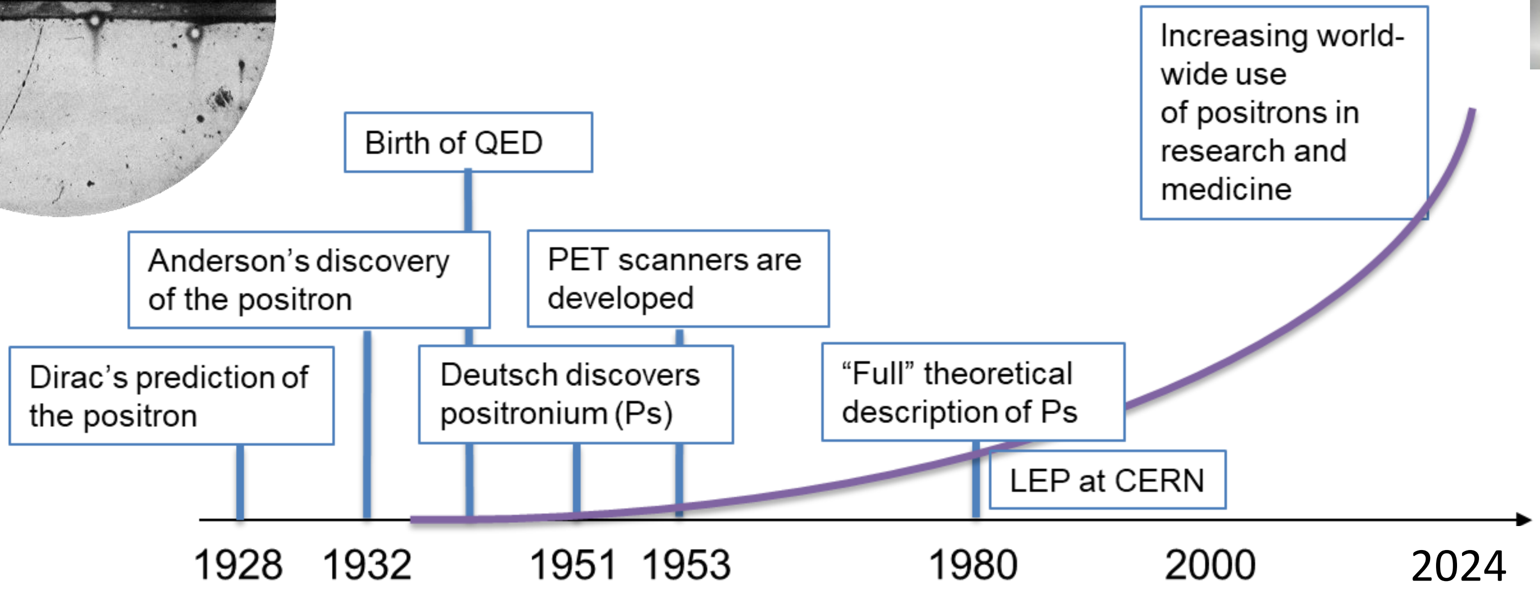
FUTURE CIRCULAR COLLIDER

Other Science Opportunities at the FCC-ee

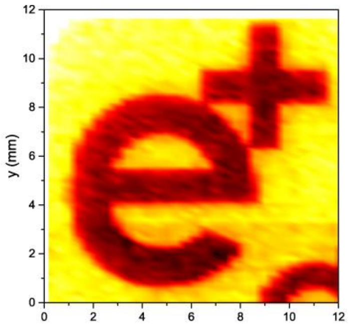
Benjamin Rienäcker | Research Associate | University of Liverpool / QUASAR Group

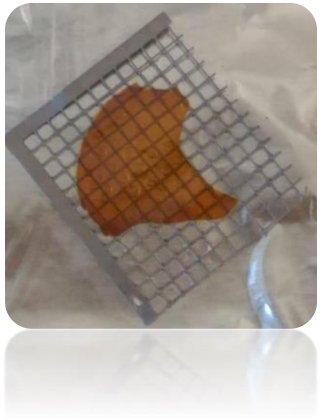
A century worth of positrons ...





$$(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi = 0$$





1/3 – Radionuclide sources

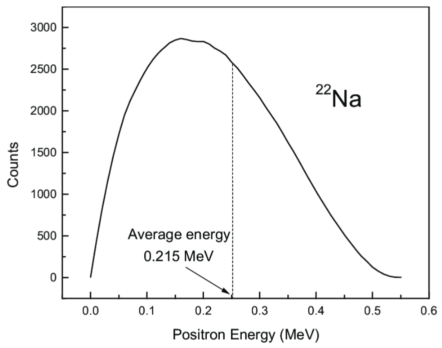
Radionuclides	Half-life	Positron decay (%) b)	Maximum positron energy (keV)	Average positron energy (keV)	Main γ-rays (keV) [%]
^{18}F	109.77 min	96.73	634	250	no γ
^{68}Ga (Ge)	67.71 min f)	87.72	1899	836	1077.3 [3.2]
		1.19	822	353	
^{124}I	4.18 d	$\Sigma\beta^+$	2138	975	602.7 [62.9]
^{22}Na	2.602 a	90.33	546	216	1274.5 [99.9]
^{48}V	15.974 d	49.9	695	290	983.5 [99.98]; 1312.1 [98.2]

Positron Emission Tomography (PET) (^{18}F, ^{68}Ga, ^{124}I)

Tool in research (^{22}Na, ^{48}V)

^{22}Na (halflife 2.6 years):

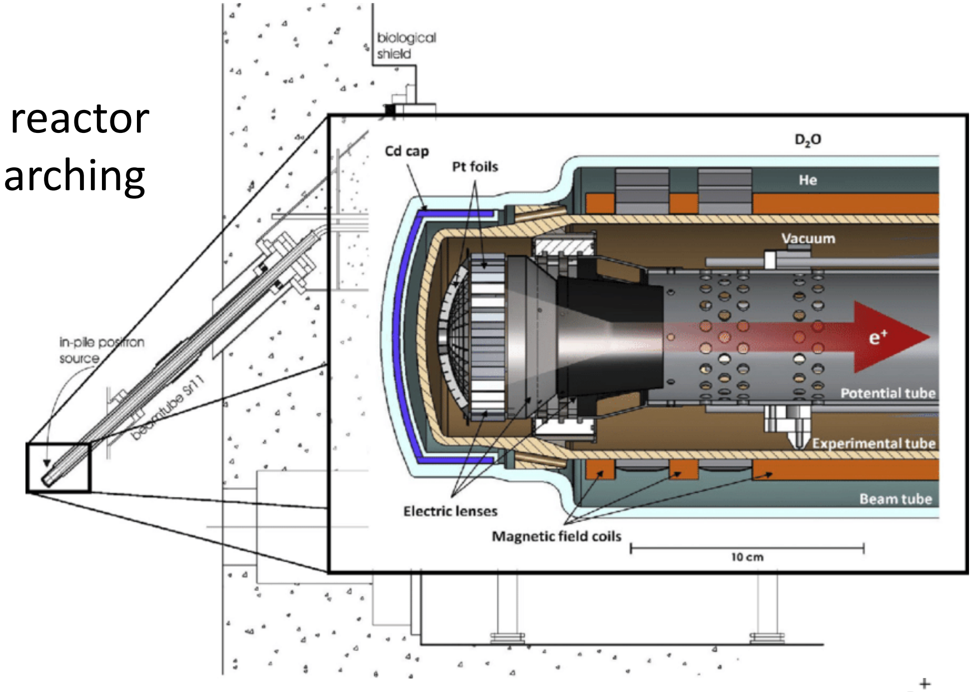
- Most common laboratory positron source.
- Single supplier world-wide for intense sources (50mCi)
- 4-pi source with $2 \cdot 10^9$ e⁺/s at @ 0-546keV
- Moderated beam: $3 \cdot 10^6$ e⁺/s at @ 6eV



2/3 – Reactor sources

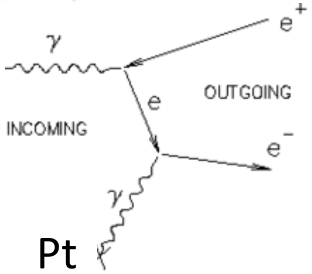
Example: Neutron induced positron source Munich (**NEPOMUC**), Germany

Research reactor
FRM-II, Garching



$$^{113}\mathrm{Cd} + \mathrm{n} \rightarrow {}^{114}\mathrm{Cd} + \gamma(9\ \mathrm{MeV})$$

$3 \cdot 10^9$ e^+/s at @ E_L = 1keV
$5 \cdot 10^7$ e^+/s at @ E_L = 20eV



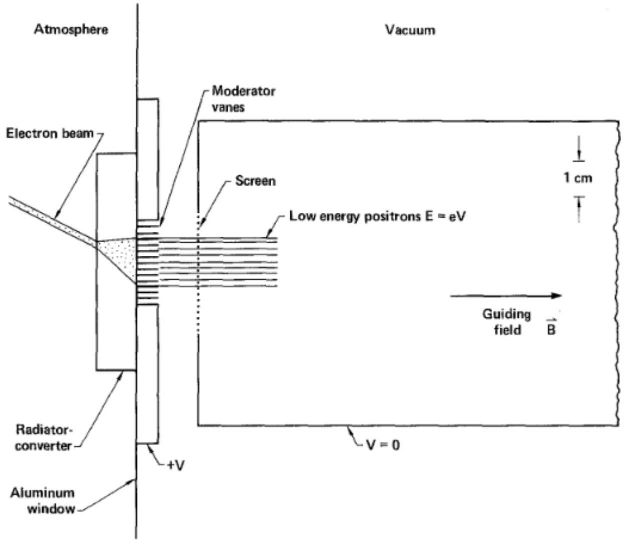
Other reactor-based positron sources:

- **ILL** (Institut Laue-Langevin) in France
- **KUR** (Kyoto University Research Reactor) in Japan
- **POSH** (Delft University of Technology) in the Netherlands
- **PULSTAR** (NC State University) in the USA

3/3 – Accelerator sources

Linac	e^- energy MeV	e^- beam power W	slow e^+ flux 10^7 e^+/s	efficiency 10^{-7} e^+/e^-
Oak Ridge [38]	180	55000	10	0.53
Livermore [37]	100	11000	1000	16
ETL, Japan [39]	75	300	1.0	6
KEK [41]	55	600	5	7.3
Ghent [40]	45	3800	2	0.4
Giessen [36]	35	3500	1.5	0.2
Mitsubishi, Japan [42]	18	16	0.077	1.35
GBAR, CERN	9	2500	5	0.28
Saclay, CEA [33]	4.3	300	0.2	0.05

⋮



10-100kHz repetition rate

Tungsten wired: $\varepsilon = < 10^{-3}$

moderated

10^5 e^+/pulse

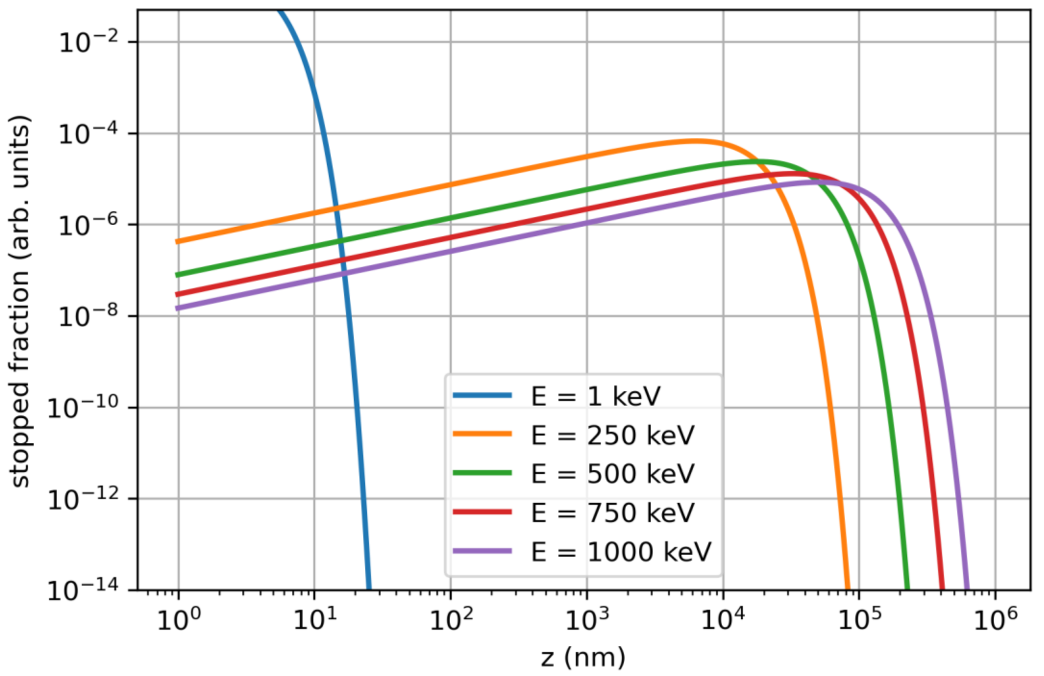
$10^9..10^{10}$ e^+/sec

at @ E_L = 0.05-20keV

Appl. Phys. A 43, 247-255 (1987)

Positron moderators

Positron implantation profile on W
(Makhov profile)



1mm

Positron Affinity A_+ (eV)

Li -7.36	Be -3.11												
Na -7.12	Mg -6.18											Al -4.41	Si -6.95
K -7.05	Ca -6.40	Sc -5.10	Ti -4.06	V -3.44	Cr -2.62	Mn -3.72	Fe -3.84	Co -4.18	Ni -4.46	Cu -4.81	Zn -5.24		Ge -6.69
Rb -6.98	Sr -6.41	Y -5.31	Zr -3.98	Nb -2.93	Mo -1.92	Tc -1.67	Ru -1.92	Rh -3.10	Pd -5.04	Ag -5.36	Cd -5.78		Sn -7.60
Cs -6.94	Ba -6.13	Lu -4.90	Hf -3.70	Ta -2.63	W -1.31	Re -0.97	Os -0.89	Ir -1.53	Pt -3.36	Au -4.59			Pb -5.56

Moderator	Source	Fig. 15	ϵ	e^+/sec	Footnotes/notes
Laboratory beams					
Cu(111)+*S*	(A1)	(a)	$\sim 1\times 10^{-3}$	2.8×10^{6}	a
W(110)	(A1)	(a)	$\sim 2\times 10^{-3}$	5.6×10^{6}	b,c
W(110)	(A2)	(a)	$\sim 3\times 10^{-3}$	8.4×10^{6}	d/untested
W vanes	(A3)	(b)	$\sim 7\times 10^{-4}$	2.2×10^{6}	e
Ne ($\sim$1 μm)	(A3)	(d)	$\sim 7\times 10^{-3}$	2.2×10^{7}	f
Foils	(A3)	(c)			
W(100)			$\sim 6\times 10^{-4}$	1.9×10^{6}	g,h/$\sim$1 μm
Ni(100)			$\sim 7\times 10^{-4}$	2.2×10^{6}	h/$\sim$0.3 μm
W polycrystalline			$\sim 2.6\times 10^{-4}$	8.3×10^{5}	h/$\sim$6 μm
W polycrystalline			$\sim 1\times 10^{-4}$	3.2×10^{5}	i/$\sim$15 μm
Ni polycrystalline			$\sim 1\times 10^{-4}$	3.2×10^{5}	h–j/$\sim$5 μm
Ni polycrystalline			$\sim 2.5\times 10^{-4}$	8.0×10^{5}	h/$\sim$2 μm
Intense beams					
Cu(111)+*S*	(A4)	(e)	2.4×10^{-4}	8×10^{7}	k/dc beam
W vanes	(A5)	(b)	1.5×10^{-6}	8.6×10^{8}	l/1440 pps
W vanes	(A6)	(b)	$\sim 9\times 10^{-6}$	5×10^{7}	m/100 pps
W vanes	(A7)	(b)	2.4×10^{-8}	2×10^{6}	n/estimated only

+ some newer materials like 4H/6H-SiC ...

Schultz and Lynn, 1988

Combination positron sources

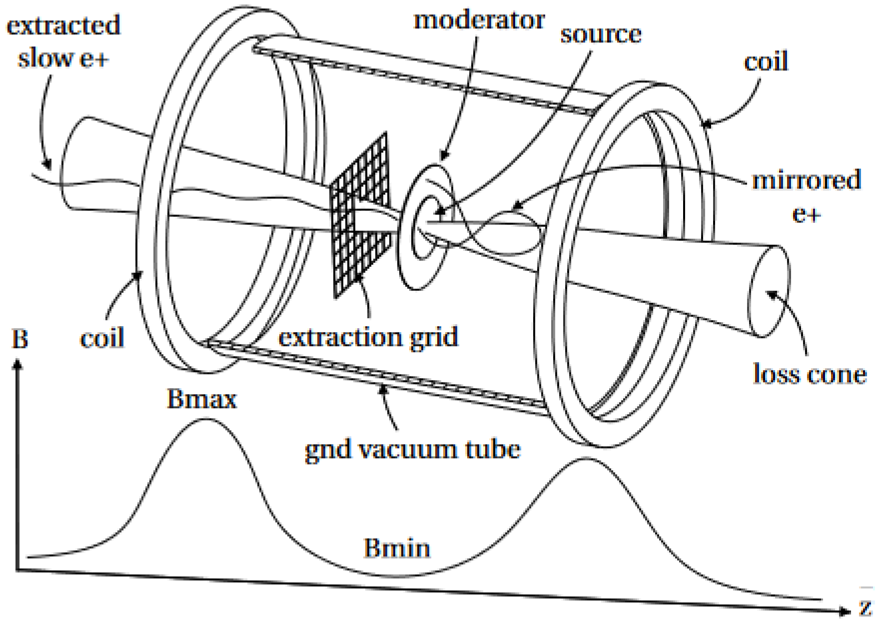
Proton Synchrotron (8-12 MeV)

$$^{48}\mathrm{Ti} + \mathrm{p} \rightarrow {}^{48}\mathrm{V} + n$$

Radionuclides	Half-life
^{48}V	15.974 d

W moderator + magnetic bottle

$4 \cdot 10^3$ e$^+$/s at @ E_L = 100eV



L. Gerchow et al., *Instruments* **2018**, *2*, 10
DOI: 10.3390/instruments2030010

Low energy positrons in experiments

Isotope sources (β^+- decay)

Pair production with:
- Nuclear reactor-based sources
- Accelerator-based sources

e^+ with MeV energy

Moderator
$\varepsilon \approx 10^{-3}..10^{-2}$

Decelerator?

e^+ with eV energy

Continuous slow e^+ beam

e^+ beam

Trapping, cooling, remoderation, bunching
$\varepsilon \approx 10^{-1}$

Applications of slow positrons
- Bulk defect studies
- Surface and dislocation probing
- Electronic structures

Conversion into positronium (Ps)
$\varepsilon \approx 10^{-1}$

$\varepsilon \approx 10^{-1} \ldots 10^{-?}$

Experiments with slow Ps
- Precision tests of QED
- Fundamental symm. (CPT, WEP)
- BEC with Ps
- Porosimetry

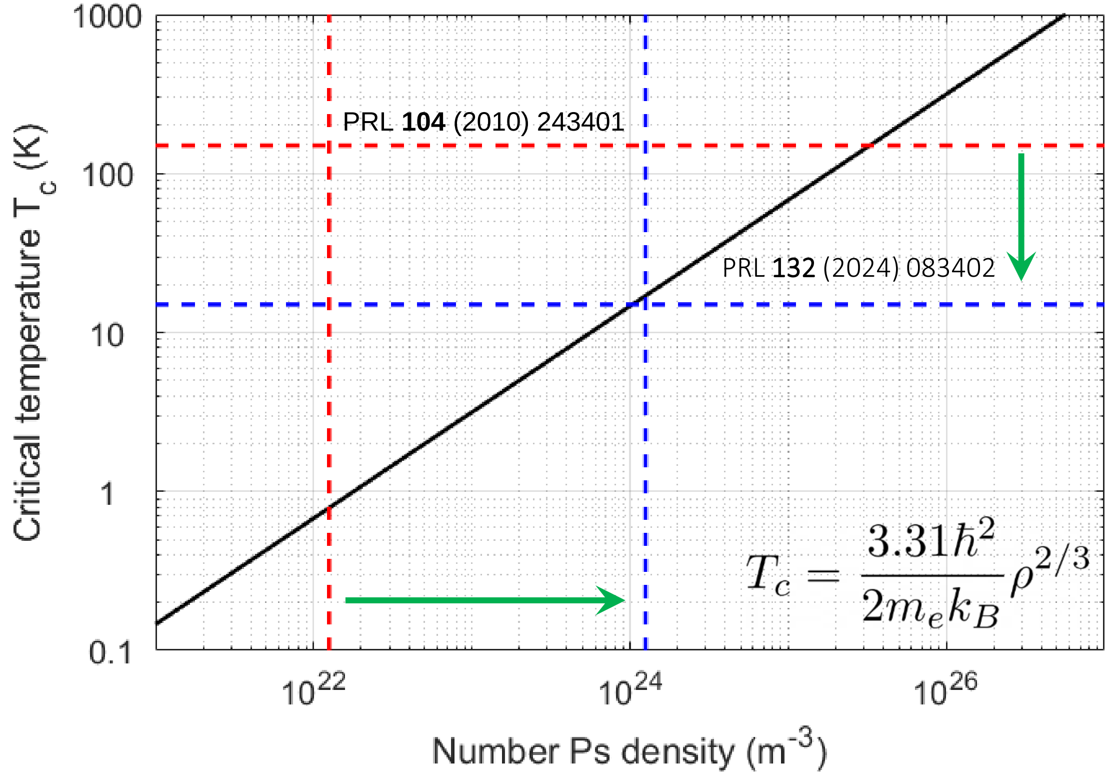
Physics with slow positrons

Low energy positron/positronium physics at one glance:

1. Bose-Einstein condensates (**BEC**) with positronium
2. Fundamental **symmetry** tests (annihilation channels)
3. Precision **QED** studies (Ps spectroscopy)
4. **Material** studies (defect studies)

1/3 Towards Bose-Einstein condensates

Efforts towards the first Bose-Einstein condensation of Ps



Nanoporous silicon targets are able to produce Ps at temperatures of **150K** and below.

Laser cooling precooled positronium atoms could reduce the temperature by **200K, i.e. down to <10K**

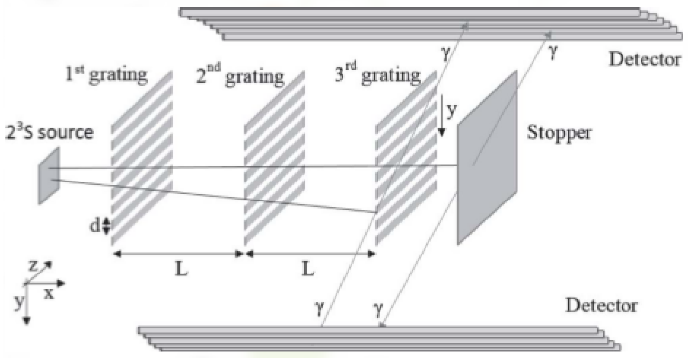
A positronium density of $10^{15}\mathrm{mm}^{-3}$ is necessary for forming a BEC. The currently available positron sources cannot reach that.

When a Ps-BEC annihilates, a coherent burst of gamma rays is emitted.
A proposed way to build a 511 keV gamma ray laser!

Tests of fundamental symmetries and BSM searches

Tests of the Weak Equivalence Principle with leptonic systems

Image from EPJ D **74** (2020) 79



Requires cold long-lived Ps sources in very high amounts

Searches for rare Ps annihilation channels

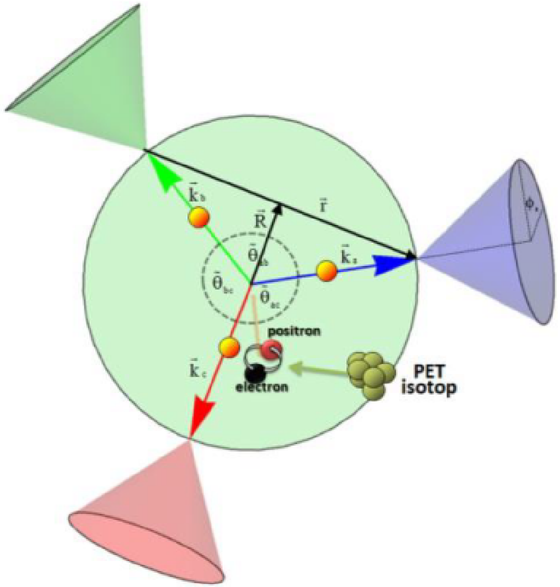
Table from Phys. Part. Nucl. **37** (2006) 321-346

Decay mode	90% upper limit, ppm
$\gamma + X$	5–1 1.1 340
$\gamma + X \longrightarrow \gamma + 2\gamma$	28 300
$\gamma\gamma$	233 350
$\gamma\gamma\gamma$	2.6 3.7
$\gamma + X_1 + X_2$	44
Invisible	2.8 540

Rare-event searches limited by statistics

Detection of multipartite entanglement in Ps annihilation γ rays

Image from Sci. Rep. **9** (2019) 8166



Requires simultaneous detection of three Compton scattering events

3/3 Precision QED tests

New precision QED measurements with colder Ps sources

	Hydrogen-like electronic atom	Positronium
Nuclear effects		
• Magnetic moment (HFS)	$(Z\alpha)^2 m/M$ or $\alpha(Z\alpha)m/m_p$	α^2
• Charge distribution	$(Z\alpha mcR_N/\hbar)^2$	—

Ps is an ideal system to test bound state QED due to the absence of nuclear effects

Decay times

$$\Gamma_o^{th} = 7.039979(11)\ \mu s^{-1},$$
$$\Gamma_p^{th} = 7989.6178(2)\ \mu s^{-1},$$

$$\Gamma_o^{exp} = 7.0404(10)^{stat.}(8)^{syst.}\ \mu s^{-1}$$
$$\Gamma_p^{exp} = 7990.9(1.7)\ \mu s^{-1}$$

Phys. Part. Nucl. **37** (2006) 321-346

Searches for BSM physics in:

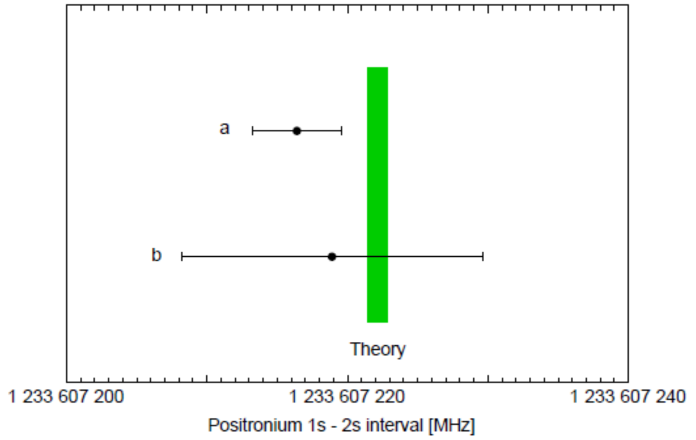
- **energy intervals**
- **decay rates**
- **decay modes**

?

- **Fifth fundamental force**
- **Axion-like particles**
- **Symmetry violations**

1^3S-2^3S transition frequency

Phys. Rep. **422** (2020) 1-63



Limited by second order Doppler effect, requires colder Ps sources

Take home message

Material Science: non-destructive nanoprobes
=> possibly beam time for global partners in industry and academia?

Positrons

Next generation Ps sources with high intensity, low energy and higher density

Better measurement efficiency (results/time)

Higher data quality (less systematics)

Unlocking exciting new possibilities
(e.g. Ps-BEC, precision QED, BSM)

A new intense low-energy e+ beam at CERN

THANK YOU