Positron Physics
in our Galaxy and the Laboratory

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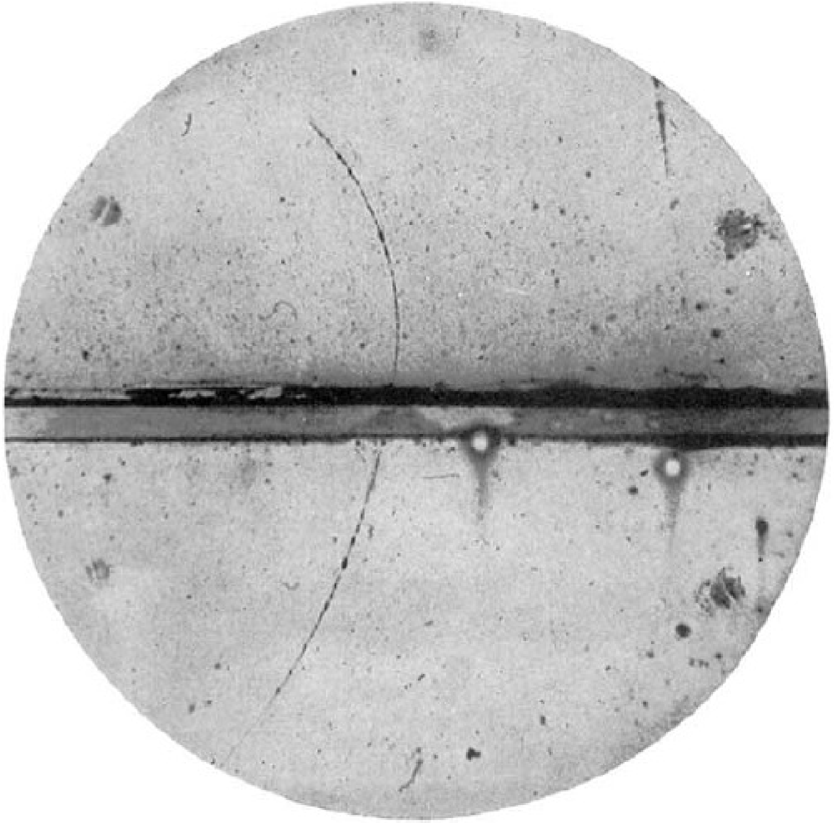
Kepler Kolloquium 15. 1. 2010

- **Antimatter Positron**
- **Positrons in gas and solid state**
- **radiation by annihilation of positron und electron**
- **positronen signals from our galaxy:**
  - **measurements with SPI in the satellite INTEGRAL**
  - **Positron sources and annihilation in the interstellar medium**
- **monoenergetic positron beam NEPOMUC at FRM II**
- **examples for instruments at NEPOMUC: CDBS, PAES**
- **bound e^+e^- systems**
- **positron traps and their application**

history:

P. Dirac 1928: Theoretical prediction of the positron as antiparticle of the electron

Pb



Positron physics started with radiation from the universe …

Detection of the positron in the cosmic radiation
by C.D. Anderson 1932

(cloud chamber, curvature of the track after transmission through lead, length of the track)

Complete transformation of matter/antimatter <-> radiation:

1) Annihilation

positron + electron → electromagnetic radiation

e+ + e- → γ + γ or γ + γ +γ or **(**γ + γ +γ + γ**)** ..

$2\ m_e c^2 = 2 \times 511$ keV =1022 keV „annihilation energy"

(1 Watt corresponds to the annihilation of 6,1 x 10^{12} e^+/s)

2) Production of positron-electron pairs from radiation

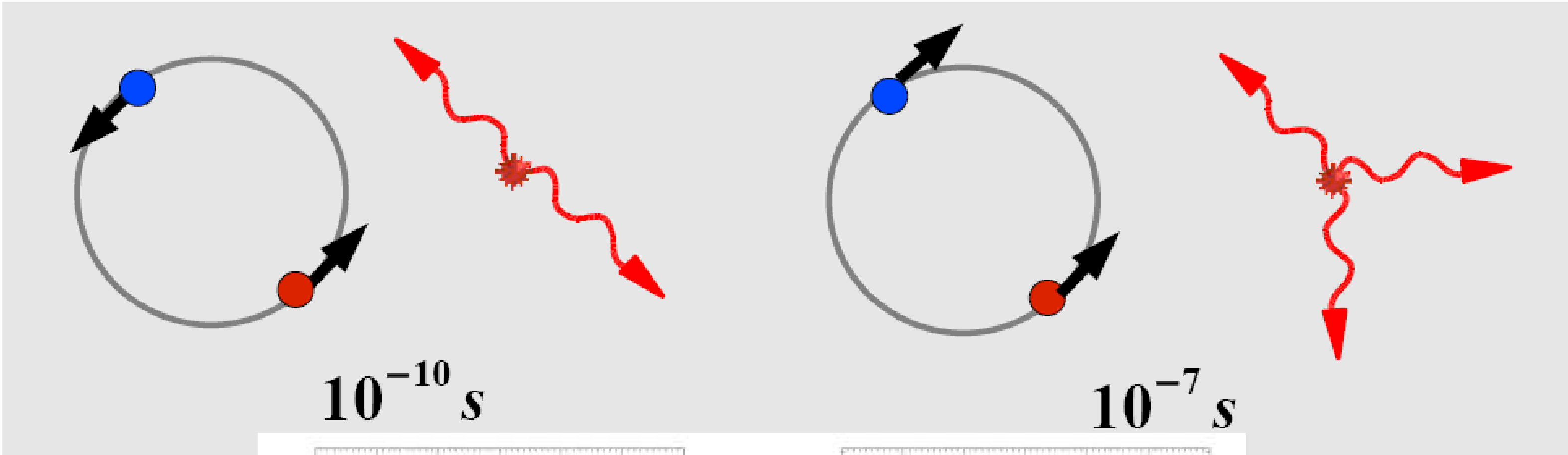
γ + electromagnetic field → $e^+ + e^-$

γ + γ → $e^+ + e^-$

Bound state **positronium (Ps),** analog to hydrogen atom

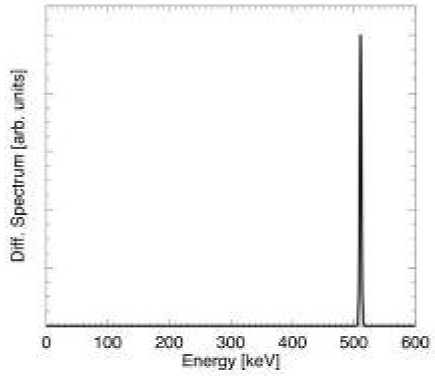
Binding energy in the ground state: 6,8 eV =1/2 binding energy of H

Para Positronium, I=0 Ortho Positronium I=1

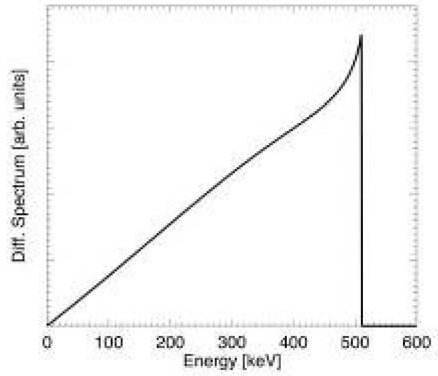


2 Gammas, monoenergetic

(here spectrum in one detector)



511 keV Line



Positronium Continuum

3 Gammas, continous

(here spectrum in one detector)

production of the Ps: proportional to (2I+1)

ratio of radiation of ortho/para= (3x3)/(2x1)= 4,5

But: lifetime of ortho Ps much longer than para Ps: In solids conversion ortho to para possible

Fate of a high energetic positron in medium till annihilation:

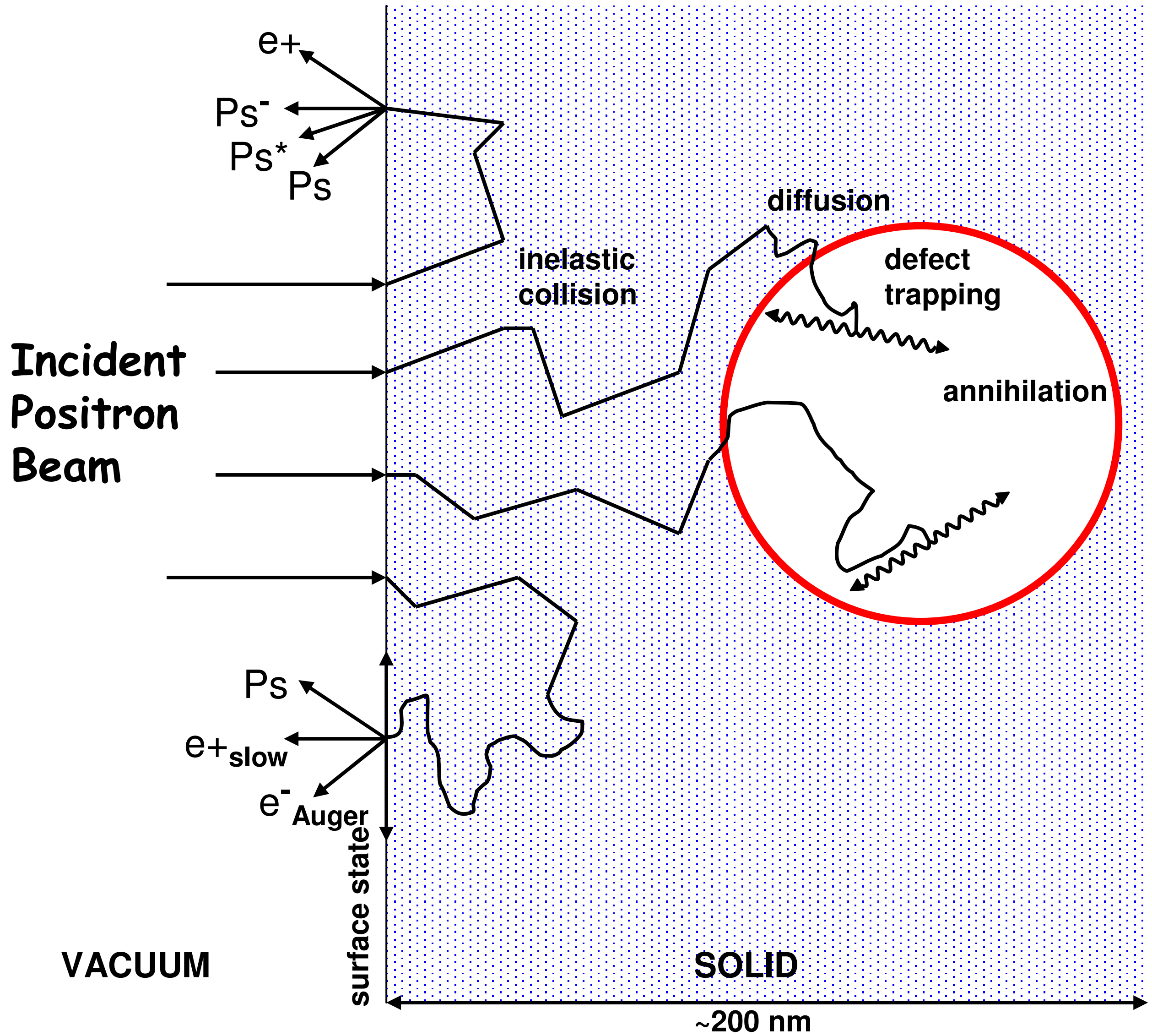
Slowing down (by ioinisation, scattering):

Annihilation probability in the fast slowing down process is low: Only a few % of the positrons are lost by annihilation down to positron energies of about 100 eV

At lower energies: annihilation directly with electrons or via Ps formation

- in solid state
- in gases

Positron as nano probe in solid state



Positrons fate:

- thermalization:~few ps
- diffusion ~100ps
  → **~100 nm**
- defect trapping
- **annihilation into 2 collinear γ–quanta**

- positron lifetime τ

→ **ρ (e-)**

→ **defects**

- Doppler-broadening ΔE

  Angular correlation ΔΘ

→ **p(e-)**

→ **defects & elements**

Gases: cross section for positrons at atomic hydrogen and free electrons

Threshold energy for Ps formation = 6,8 eV: 13,6 eV needed to ionise the H atoms, 6,8 eV gain by Ps formation

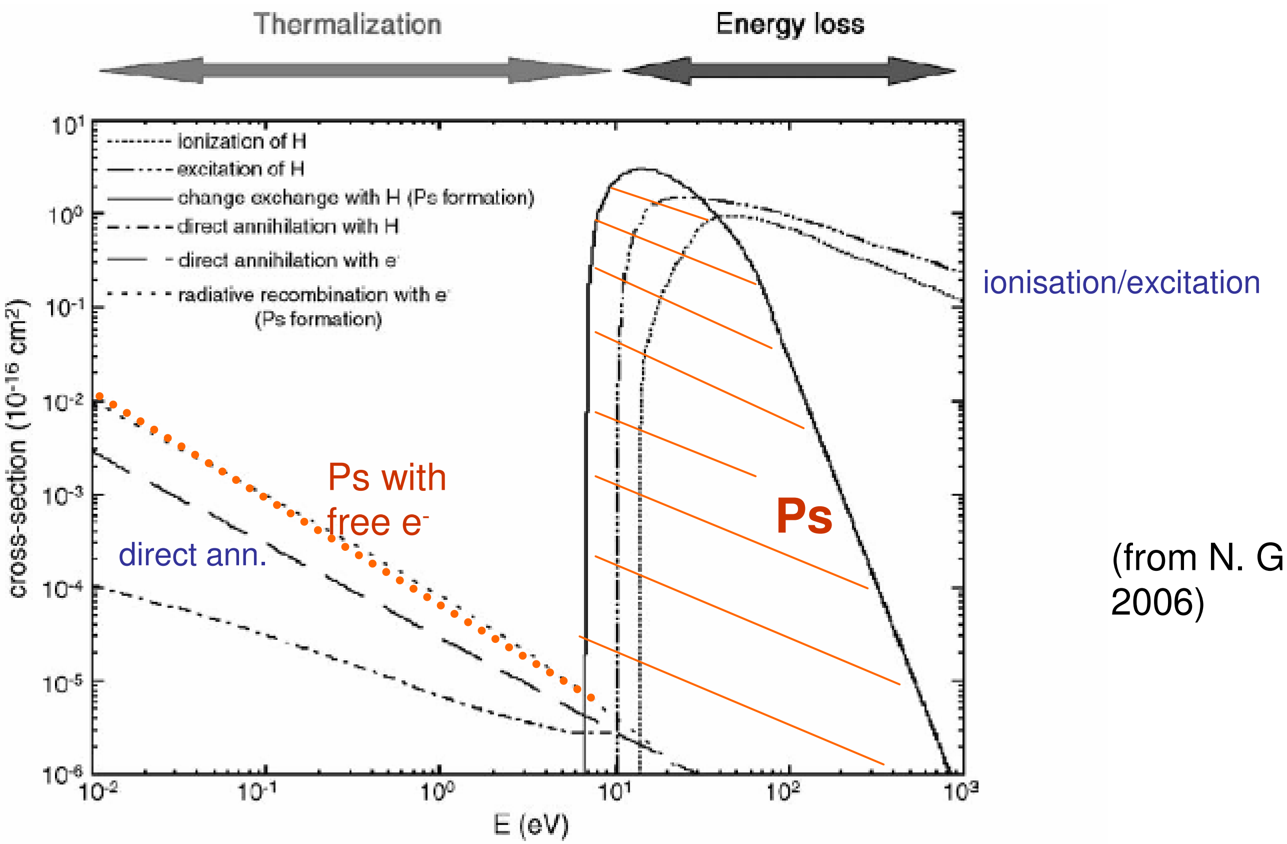


Fig. 3. Cross sections of positron processes with free electrons and hydrogen atoms at energies below 1 keV.

(from N. Guessoum et al. 2006)

Cross section for direct annihilation without Ps formation is by many orders of magnitude smaller!

What can we learn from the spectroscopy of the annihilation radiation?

- 511 keV line width and form show the Doppler shift of the radiation by the kinetic energy of e^-,e^+ at annihilation:

10 eV kinetic energy gives **1,6 keV Doppler shift** for the 511 keV annihilation line

($\Delta E_{Doppler}$=1/2 $p_L c$; high momentum of a massive particle compared to radiation!)

-> temperature of the e^-,e^+ (line broadening) -> velocity (broadening; line shift)

- The ratio of continuum to line in the radiation spectrum yields the part of Ps production and subsequent annihilation from the Ps state.

Note on Ps in material: Depending on the material the long living ortho Ps converts and decays via two 511 keV radiation!

-> medium of anniliation

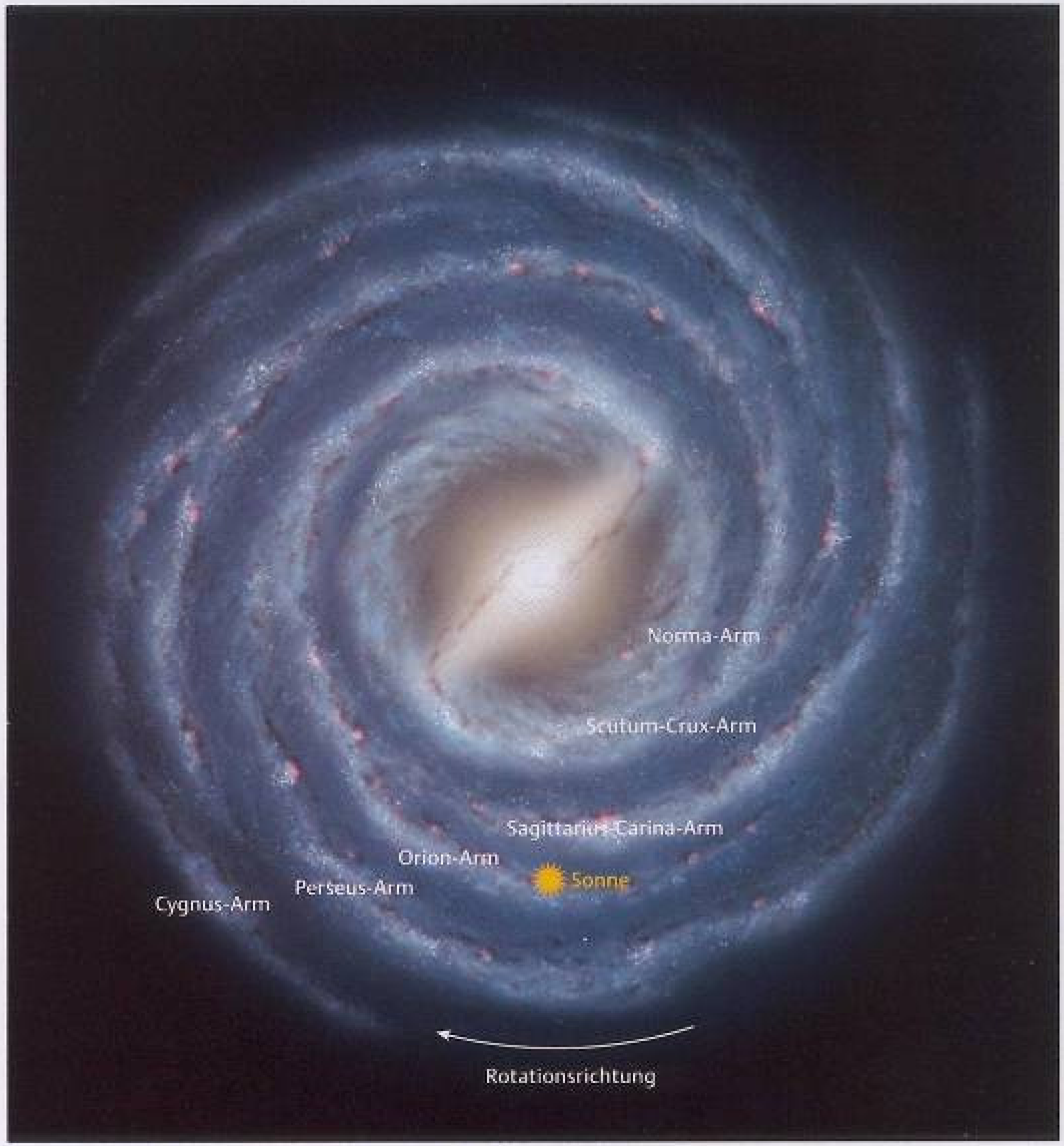
- **Probability for annihilation** ("positron life time") depends on the material structure/gas type and the **electron density**.

Positrons in our Galaxy:

Measurement of the Annihilation radiation

data and interpretation from INTEGRAL collaboration, specifically from Roland Diehl (MPE Garching and Excellence Cluster ‚Origin of the Universe‘)

Abb. 9: Modell der Spiralarmstruktur unserer Milchstraße mit vier Armen und dem zentralen Balken. Spiralarme und Balken sind nicht aneinander gekoppelt und können deshalb mit unterschiedlicher Geschwindigkeit rotieren (Graphik: R. Hurt (SSC), JPL-Caltech, NASA).



distance sun to cetre of our galaxy 8,5 kpc = 27,6 MLj

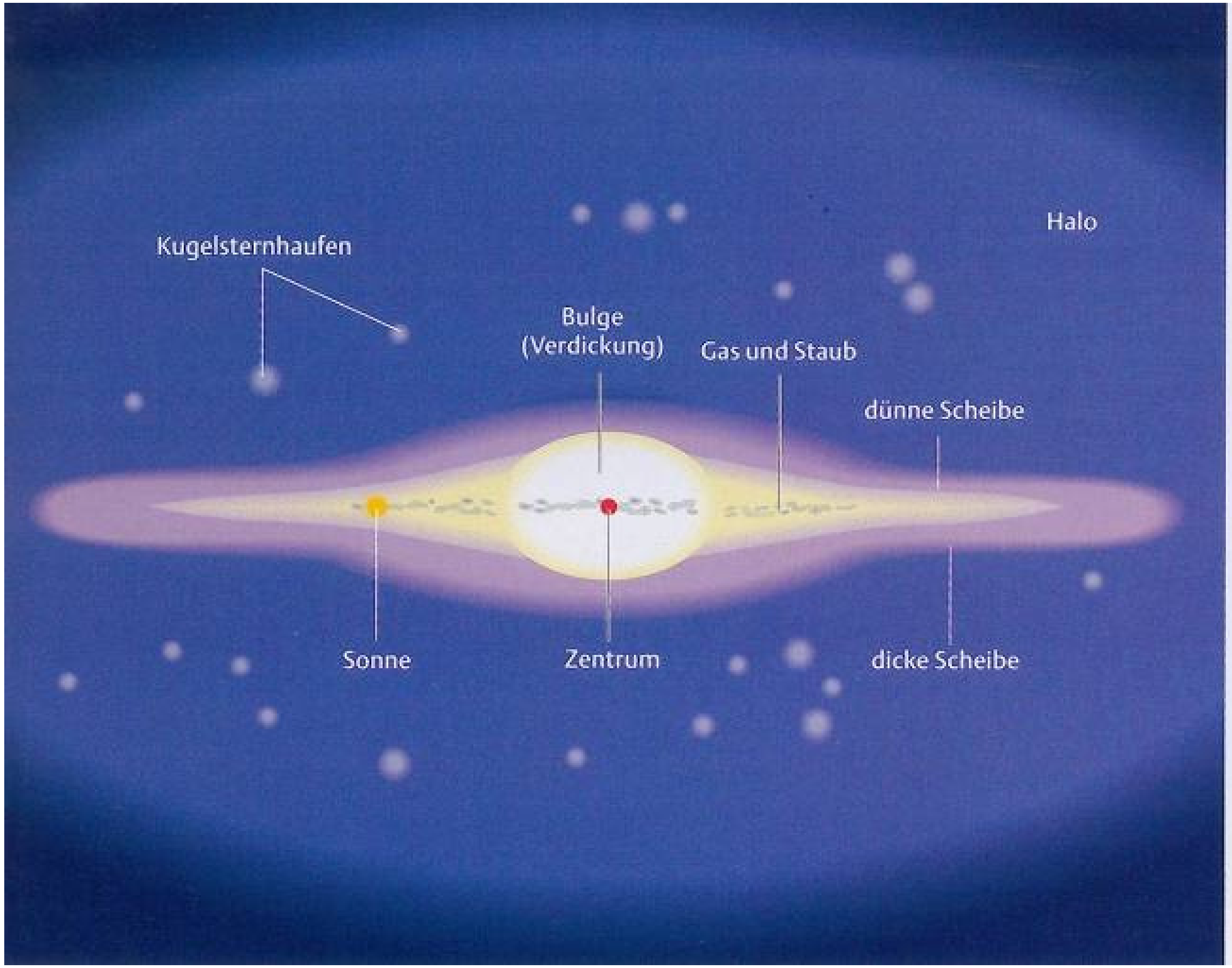
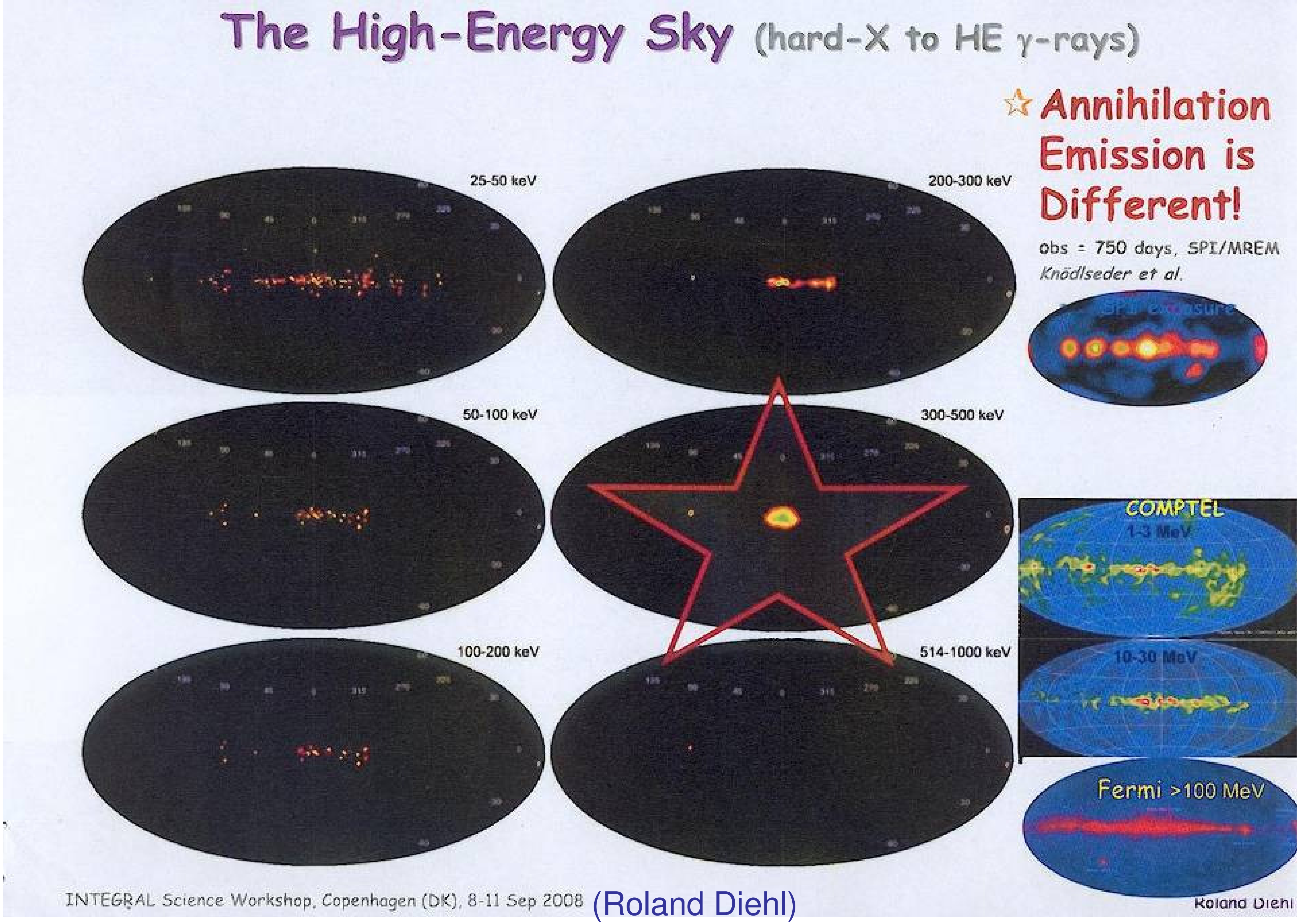


Abb. 8: Unsere Galaxis besteht aus der dünnen Scheibe mit Sternen (gelb), Gas und Staub (grau), der dicken Scheibe aus älteren Sternen (pink), dem abgeplatteten Bulge (weiß) mit dem zentralen Schwarzen Loch sowie dem Halo mit den auffälligen Kugelsternhaufen. Die dunkle Materie geht weit über den Halo hinaus. (Bild: Reinhold Henkel/SuW)

bulge: 1,2 kpc width



(Roland Diehl)

SPI Spektrometer in the satellit INTEGRAL (since 2002 in orbit)

SPectrometer **I**NTEGRAL

INTErnational **G**amma **R**ay astrophysics **L**aboratory

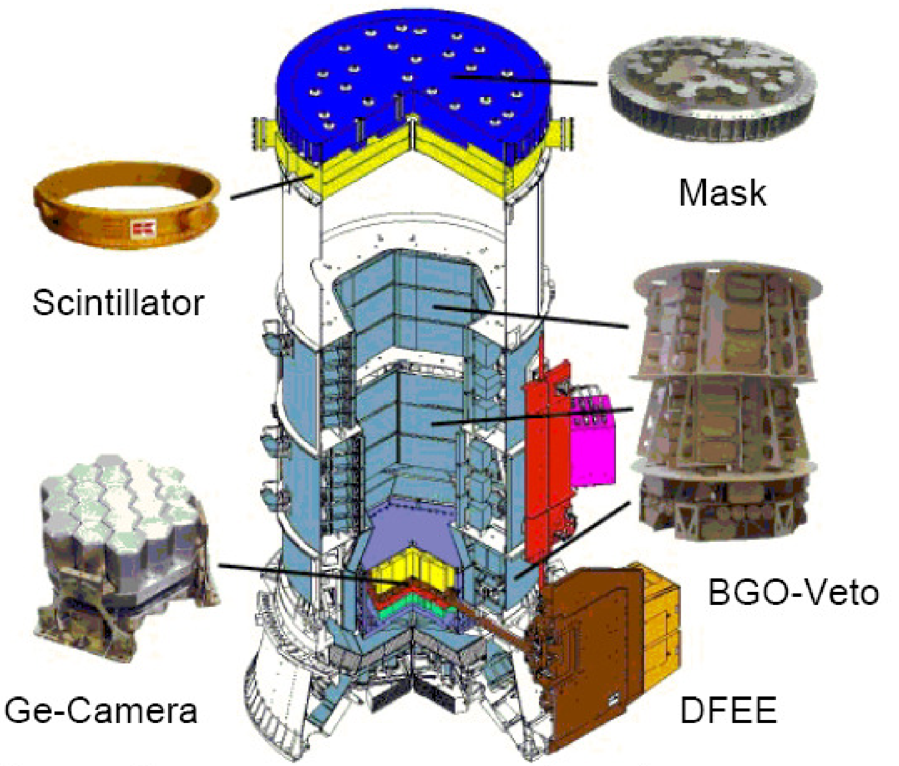


Fig. 6: The Spectrometer SPI aboard INTEGRAL, composed of the mask together with a scintillator, the anti-coincidence veto shield made of BGO crystals, the Ge detection plane and the DFEE.

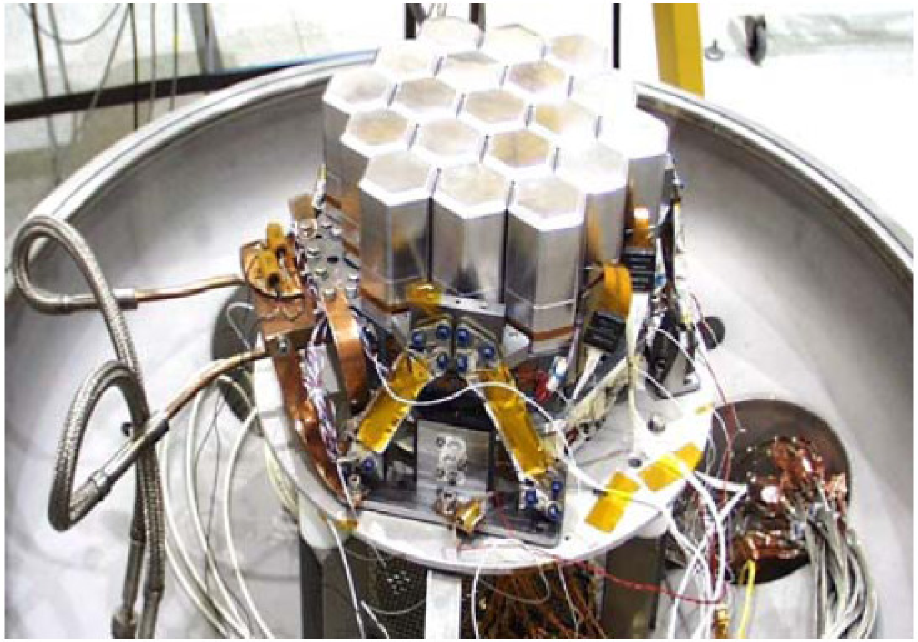
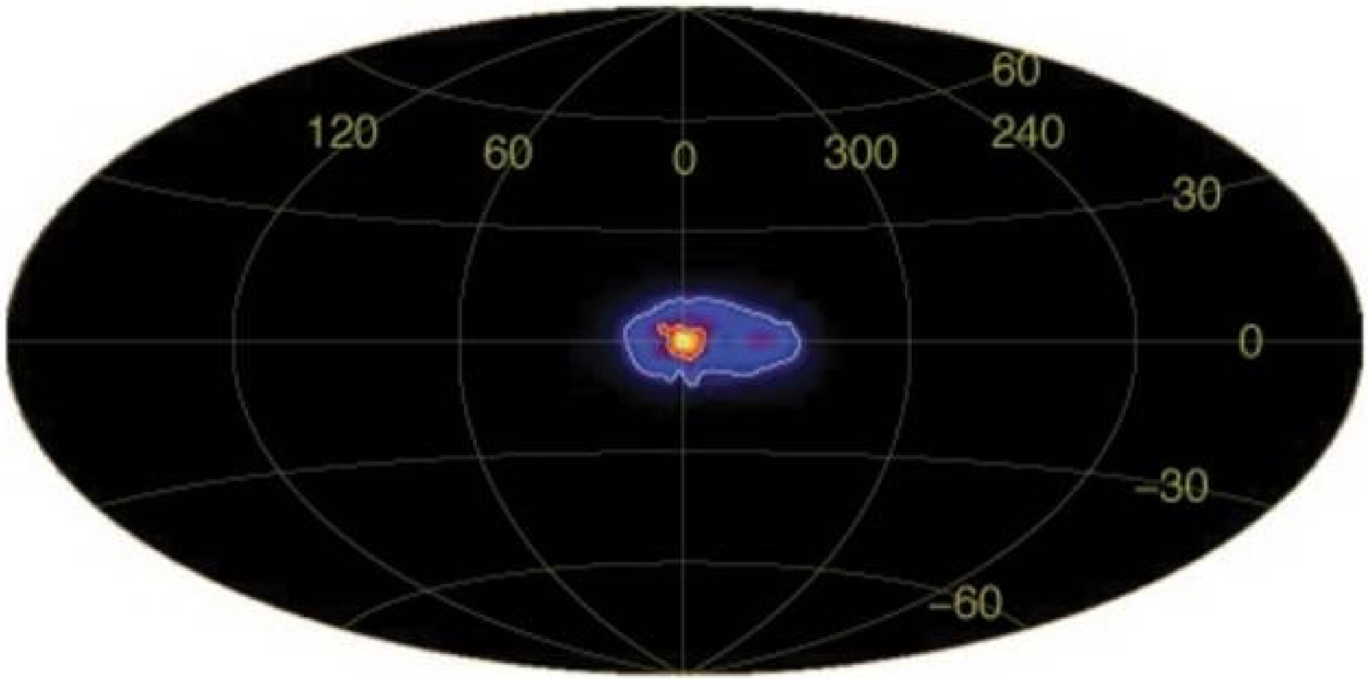


Fig. 7: The Germanium camera of the Spectrometer SPI aboard INTEGRAL. 19 Ge crystals of ~1kg each are assembled together to form a detector of ~500 cm^2 area.

Characteristics: solid angle 16°, angular resolution 3° (coded mask), 19 Ge detektors with 2 keV resolution at 511 keV



Spatial distribution of the 511 keV line-intensity in our galaxy:
concentrated at the bulge with 8° (1.2 kpc at distance 8.5 kpc)

(G. Weidenspointer et al. 2008)

(compare: angular resolution of the SPI spectrometer at INTEGRAL is 3°)

Positron slowing-down and annihilation in the interstellar medium

N. Guessoum et al. / Applied Surface Science 252 (2006) 3352–3361

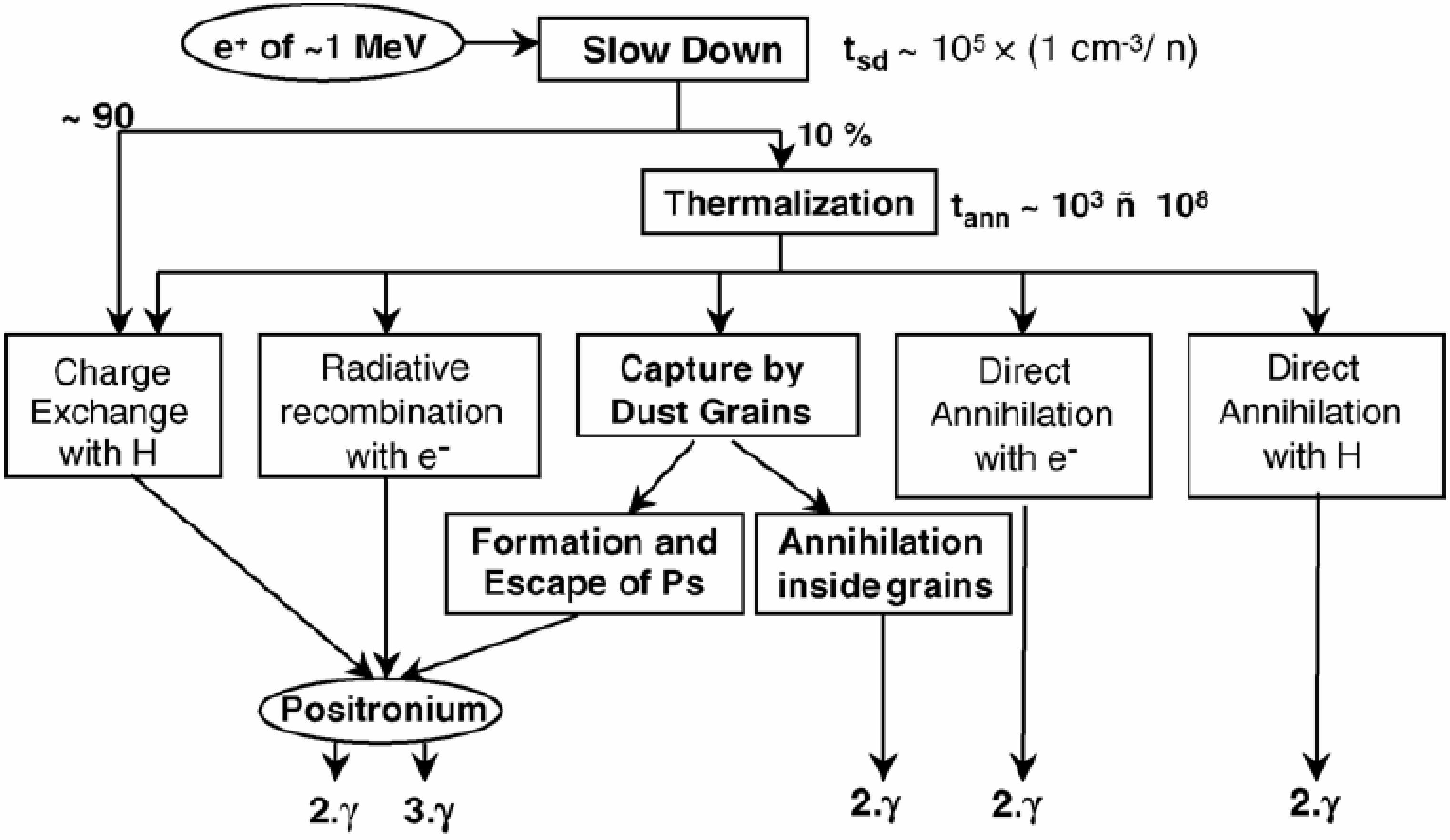


Fig. 2. Schematic description of the "lives and deaths" of positrons in the ISM.

Diffusions length of the positrons about 50-250 pc (?)

(compare: 511 keV radiation from bulge about 1200 pc) positrons and interstellar dust (typical 10nm -300 nm)

=> positrons in solid state

N. Guessoum et al.: The lives and deaths of positrons in the ISM 179

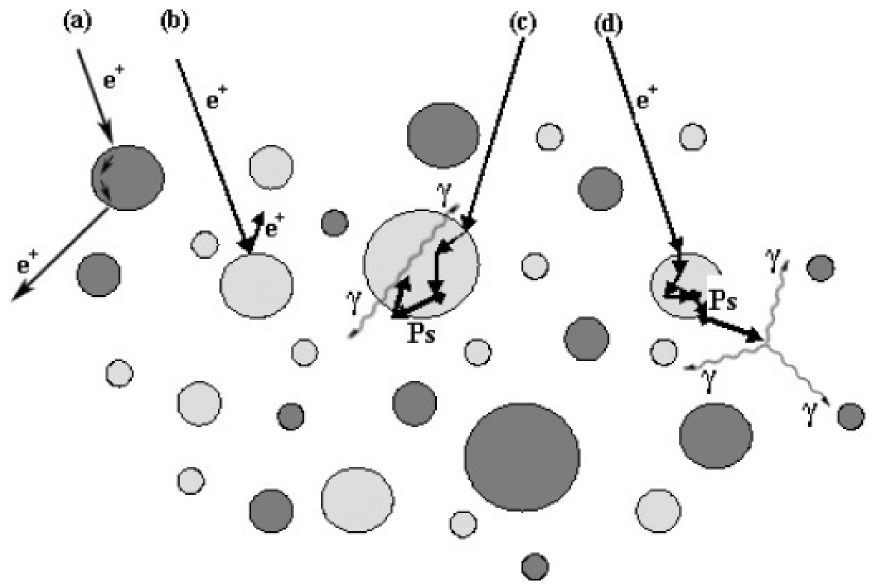


Fig. 4. Collisions and subsequent annihilation of positrons with grains (of various sizes and types) – **a)** positron re-emission; **b)** positron backscattering; **c)** positronium in grain, **d)** positronium ejection.

We learn from the observation of the annihilation radiation:

- Size and location of the source
- Intensity of the positron source
- Temperature of annihilating medium (line broadening)
- Longitudinal velocity of the annihilation medium (line shift)
- Medium: gas, solid,…? From para/ortho ratio; wings of the line

…

Spectrum of the annihilation radiation from the bulge of our galaxy

Fit for 8000 K hot gas of atomic hydrogen, 10% ionised

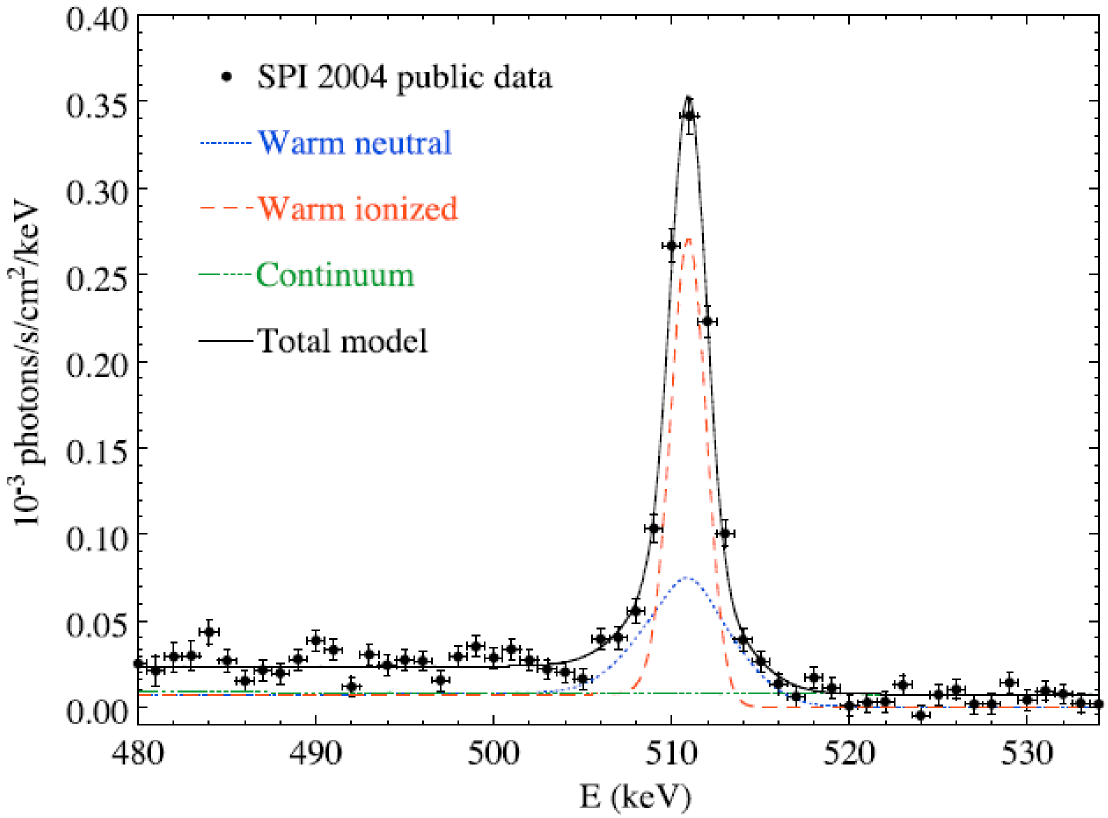


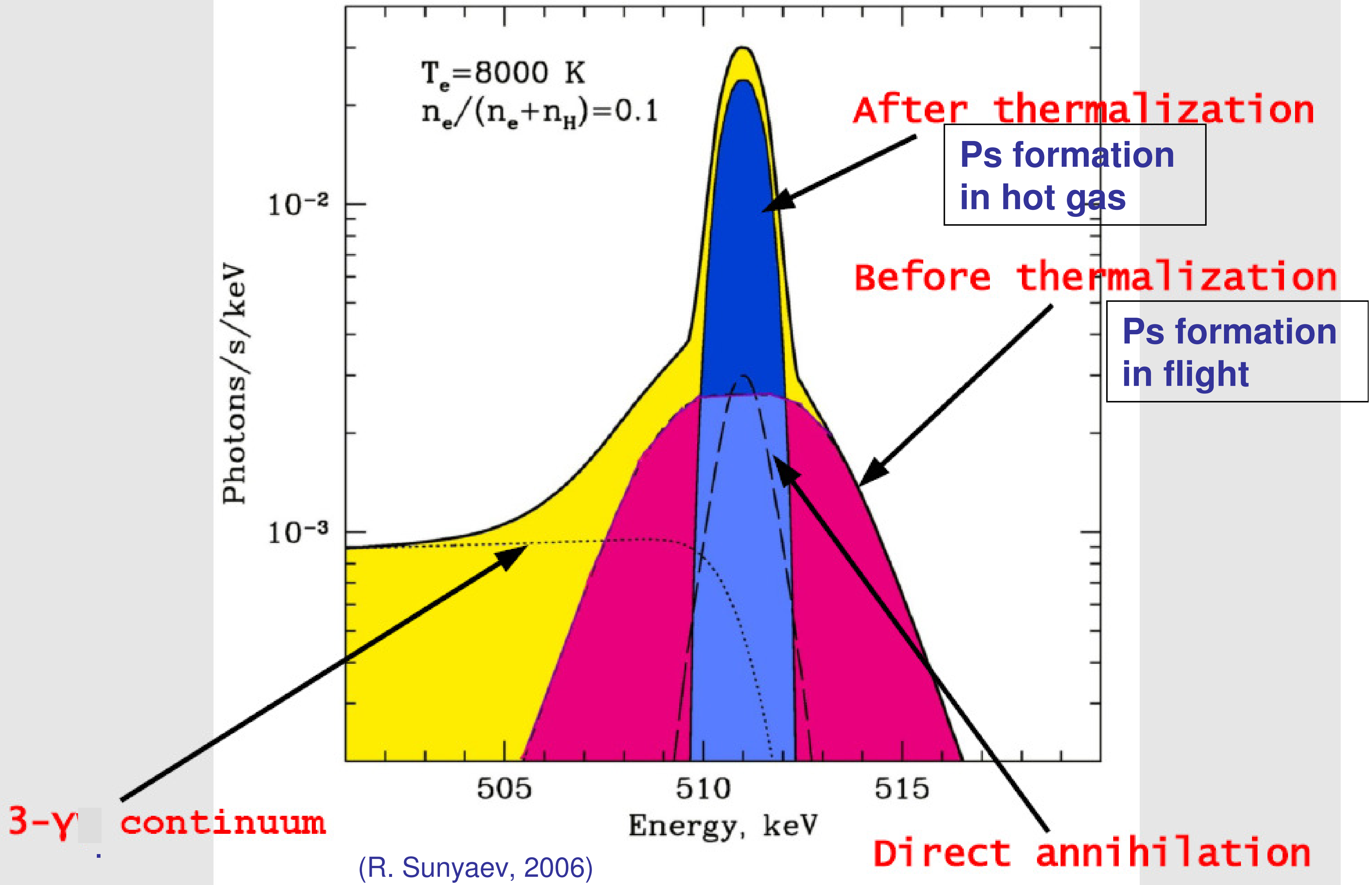
Fig. 5. Best fit of the spectrum measured by SPI with the warm components of the ISM and the Galactic continuum. Contributions from the molecular, cold and hot components are not needed to explain the data.

(P. Jean et al. A&A 445(2006) 579)

Ratio of the continuum to 511 keV line close to 4,5 (Ps) (96.7+-2.2%)

511 keV linie shape for an atomic H gas at 8000 K and 10% ionised

-> reproduces spectrum observed by SPI



(R. Sunyaev, 2006)

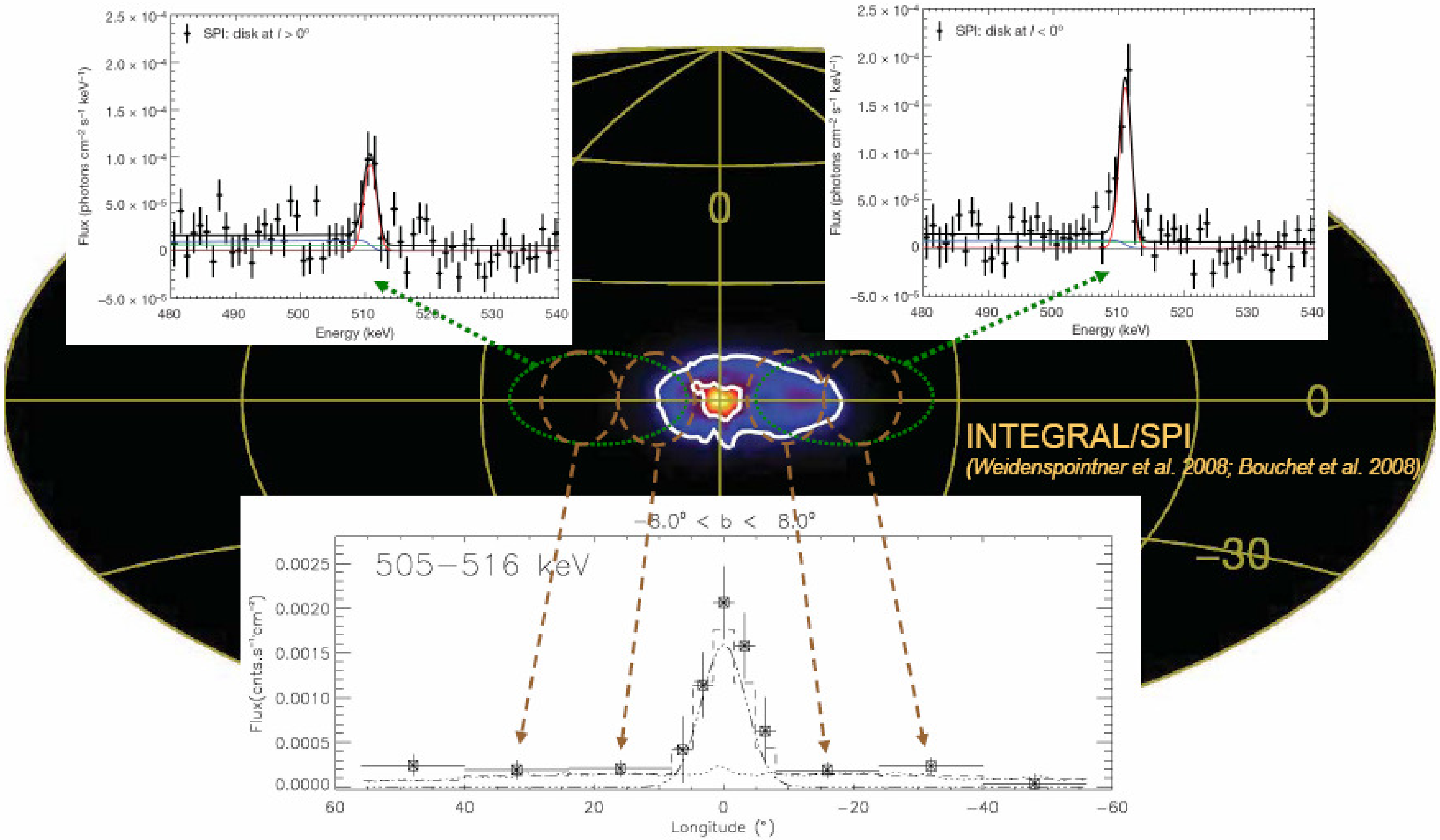


Figure 4: The annihilation line from the disk of the Galaxy is now seen clearly, in addition to the bright bulge region. An asymmetry favoring the inner-disk part in the fourth Galactic quadrant is consistently found, depending on the approach of instrumental-background modeling very clearly in one analysis [73] (*top*), and as a hint only in an alternative analysis [77] (*bottom*)

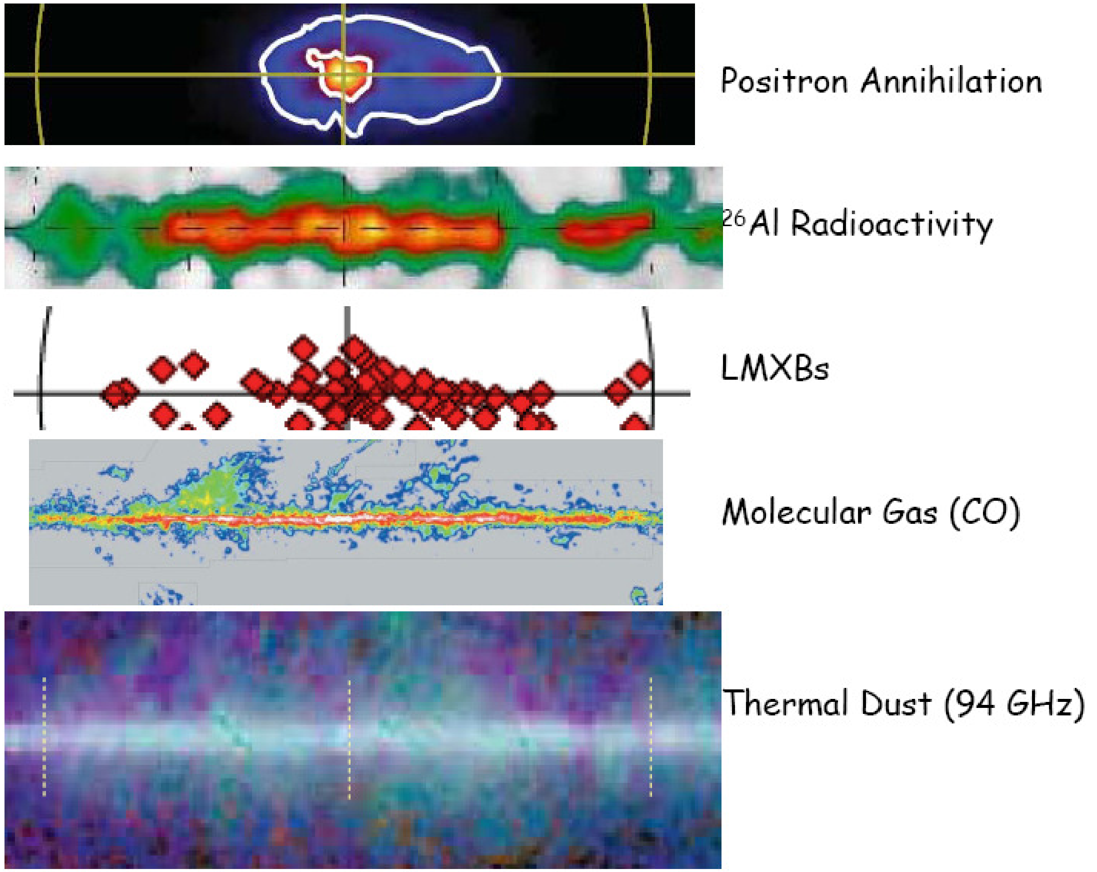


Figure 5: Comparisons of the morphology of positron annihilation emission along the plane of the Galaxy with tracers of candidate positron sources may help to illuminate their different contributions within the disk of the Galaxy, and by inference, any residual annihilation in the bulge which might need more exotic explanations such as large-scale positron transport through the Galaxy's halo, or annihilation of dark-matter particles.

Sources of the positrons:

➢measured **bulge** flux with SPI for the 511 keV line: **10^{-3} Photons/cm^2 s**

Back calculation to the source at a distance of 8,5 kpc (=27,6 M Lj): **$2 \cdot 10^{43}$ e^+/s**

➢Measured flux from **disc** of our galaxy similar, **about 10^{-3} Photons/cm^2 s**

➢ **origin of the positron annihilation lines?**

Must explain concentration in the bulge, intensities, annihilation in medium, …

•ß$^+$ emitter (^{56}Ni chain, ^{44}Ti, ^{26}Al) in the nucleo synthesis of supernovae (see R.E. Lingenfelter et al. PRL 203 (2009)3

•Accreting binaries

•Decay of the unknown dark matter particles

•…..

Future : Focussing Laue lens spectrometer GRI (Gamma Ray Imager)

->Resolution of point like positron sources

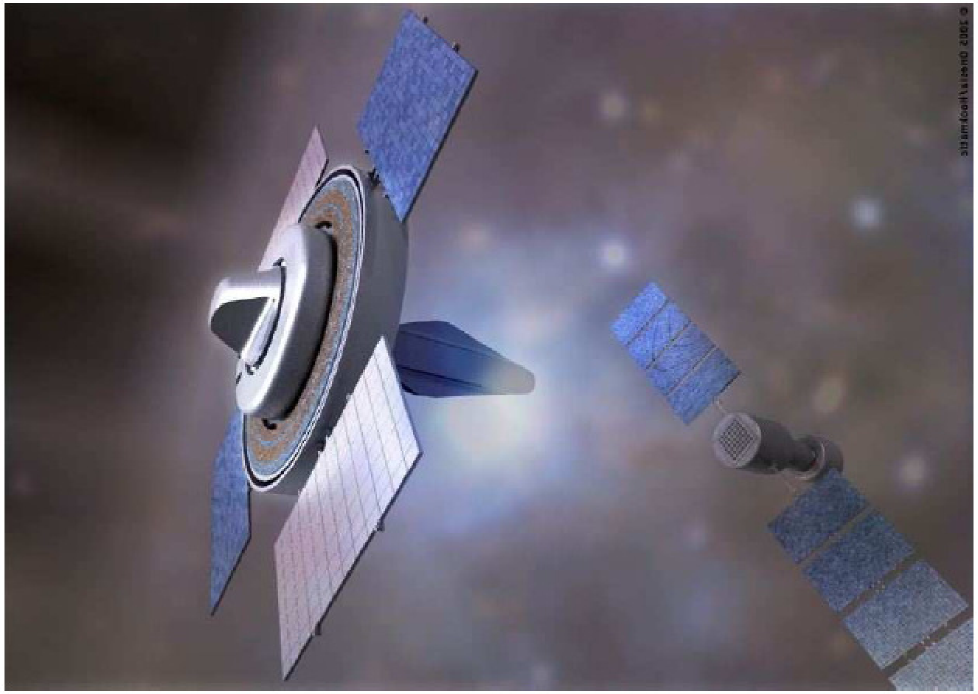


Figure 7. Artists view of the future European gamma-ray telescope. A Laue lens, situated on the left spacecraft, is focusing gamma-rays onto a small detector, situated on the right spacecraft. Both spacecrafts are in formation flight with a typical focal length between a few tens and a few hundreds metres.

(from J. Knödlseder 2005)

Positron beam in the laboratory:

NEPOMUC

Neutron Induced **Po**sitron Source **Mu**ni**c**h

FRM II

Production of positrons:

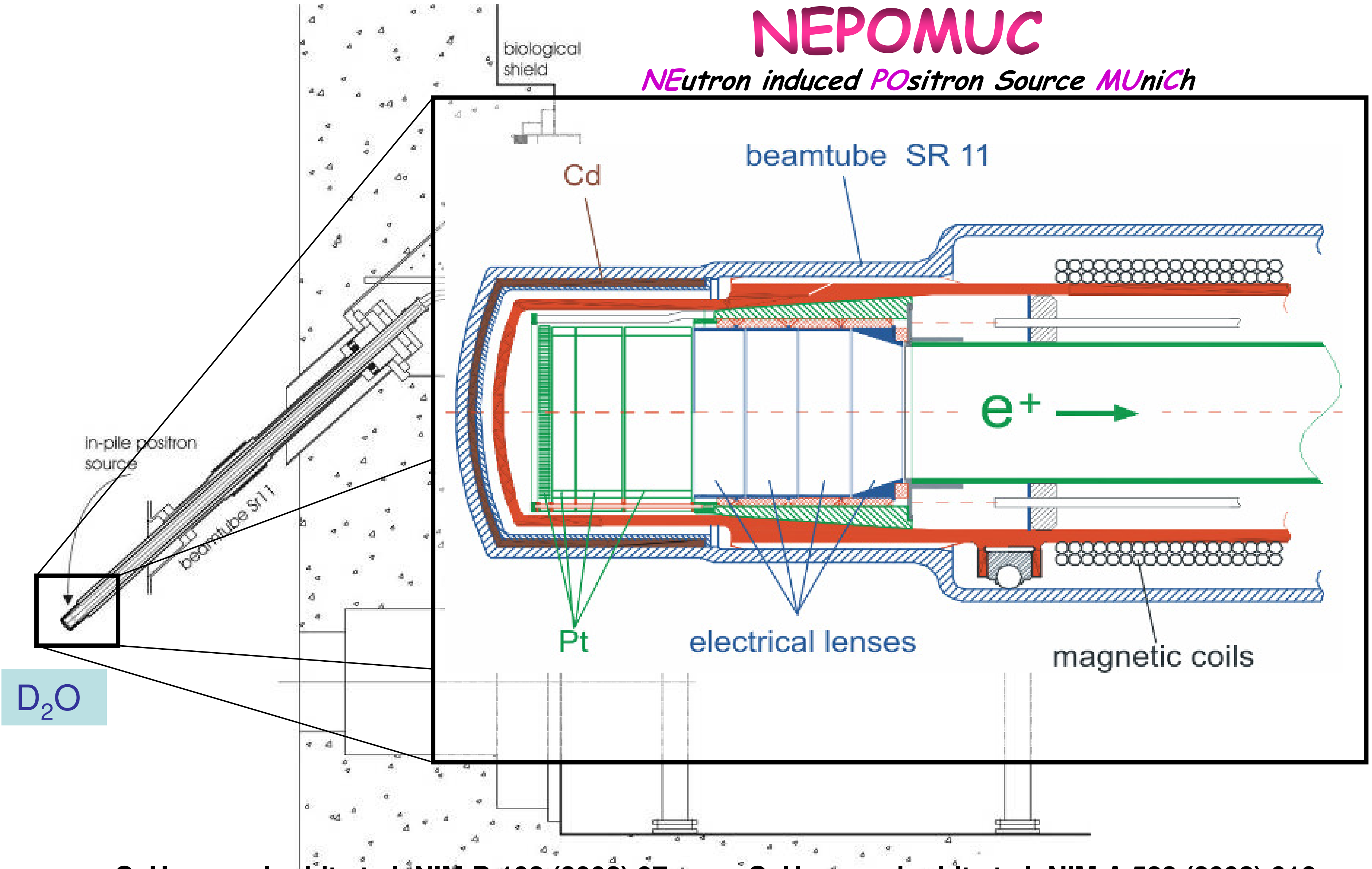
prompt gamma radiation from $^{113}Cd(n,gamma)^{114}Cd$

=> Pt absorber => electron-positron pairs

=> positron slowing –down and moderation in Pt

=> monoenergetic positron beam

Beamtube SR 11at FRM II



C. Hugenschmidt et al. NIM B 192 (2002) 97, ….. , C. Hugenschmidt et al. NIM A 583 (2008) 616

Characteristics of the FRM-II positron source NEPOMUC

In-pile part (MCNP calculation):

- thermal neutron flux at the beam tube tip without Cd: **2×10^{14} n/cm²s**
- Neutron capture rate in the 3 mm thick cadmium cap: **2×10^{13}/cm²s**
  (neutron flux depression because of large Cd cap!)
- Gamma flux E>1.5 MeV in tip. **4×10^{13} /cm²s**
- Fast to thermal neutron ratio at beam tube site: about **1:1000**
- fast positron yield in the platinum: **4×10^{13} /s**

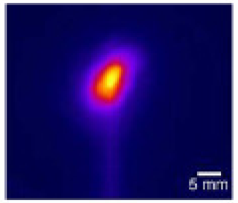
Since March 2008 new in-pile positron source (routine value):

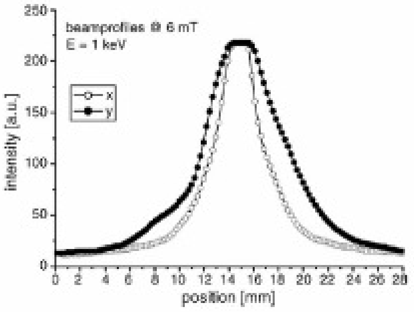
$9 \cdot 10^{8}$ e+/s at 1 keV

Unprecedented intensity of a low-energy positron beam, C. Hugenschmidt et al. NIM A 583(2008)616

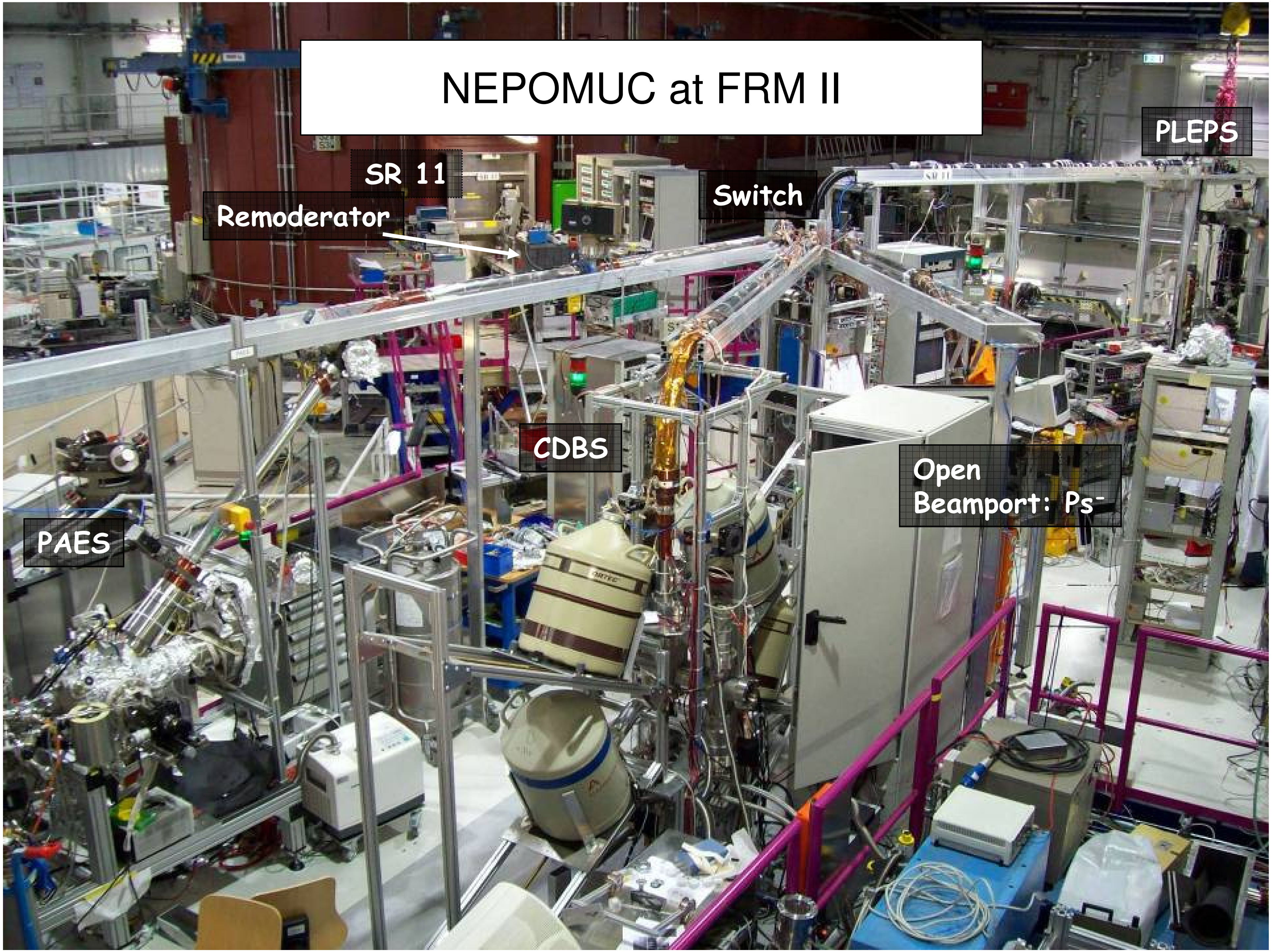
Moderated/remoderated beam at experimental site:

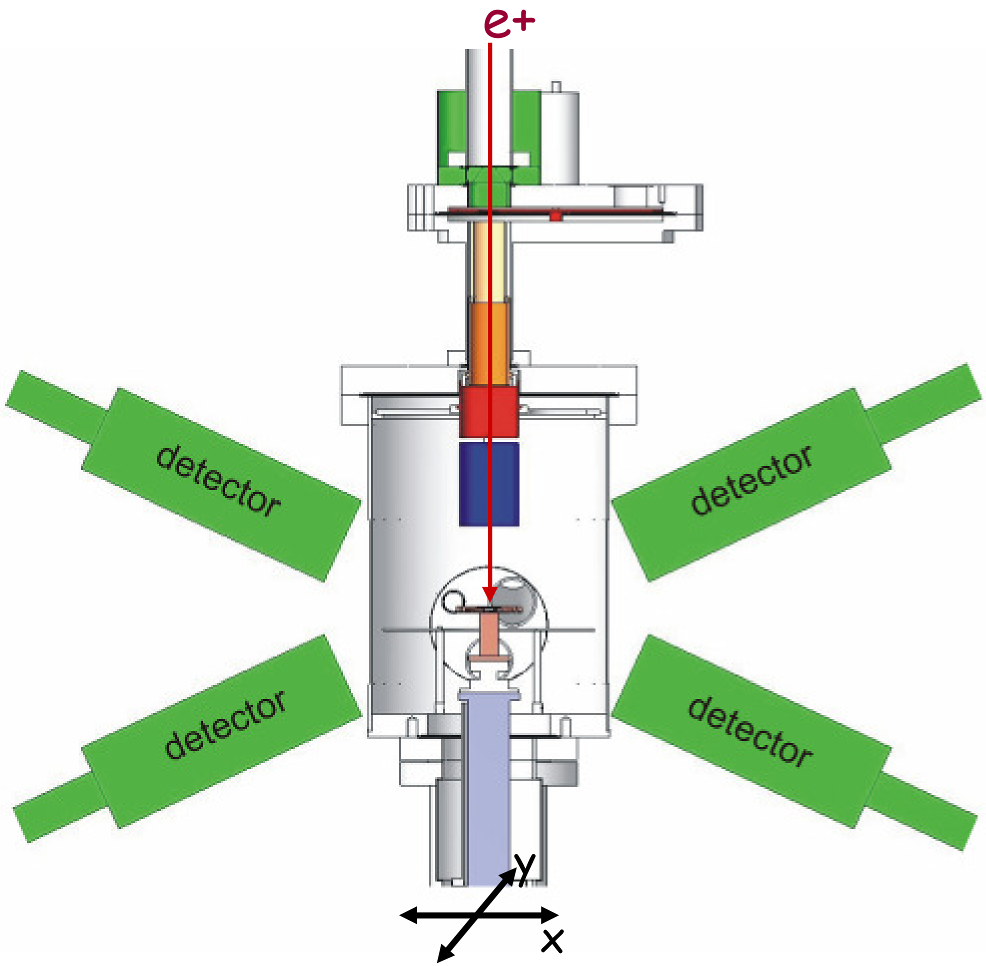
- e^{+} energy 10 ….3000 eV
- measured intensity **$9 \cdot 10^{8}$ e^{+}/s at 1 keV (FWHM 7 mm)**
- Remoderated beam **$2 \cdot 10^{7}$ e^{+}/s , 20 eV (FWHM 2 mm)**





examples for messurements at NEPOMUC


NEPOMUC at FRM II
SR 11
Remoderator
Switch
PLEPS
CDBS
Open
Beamport: Ps⁻
PAES



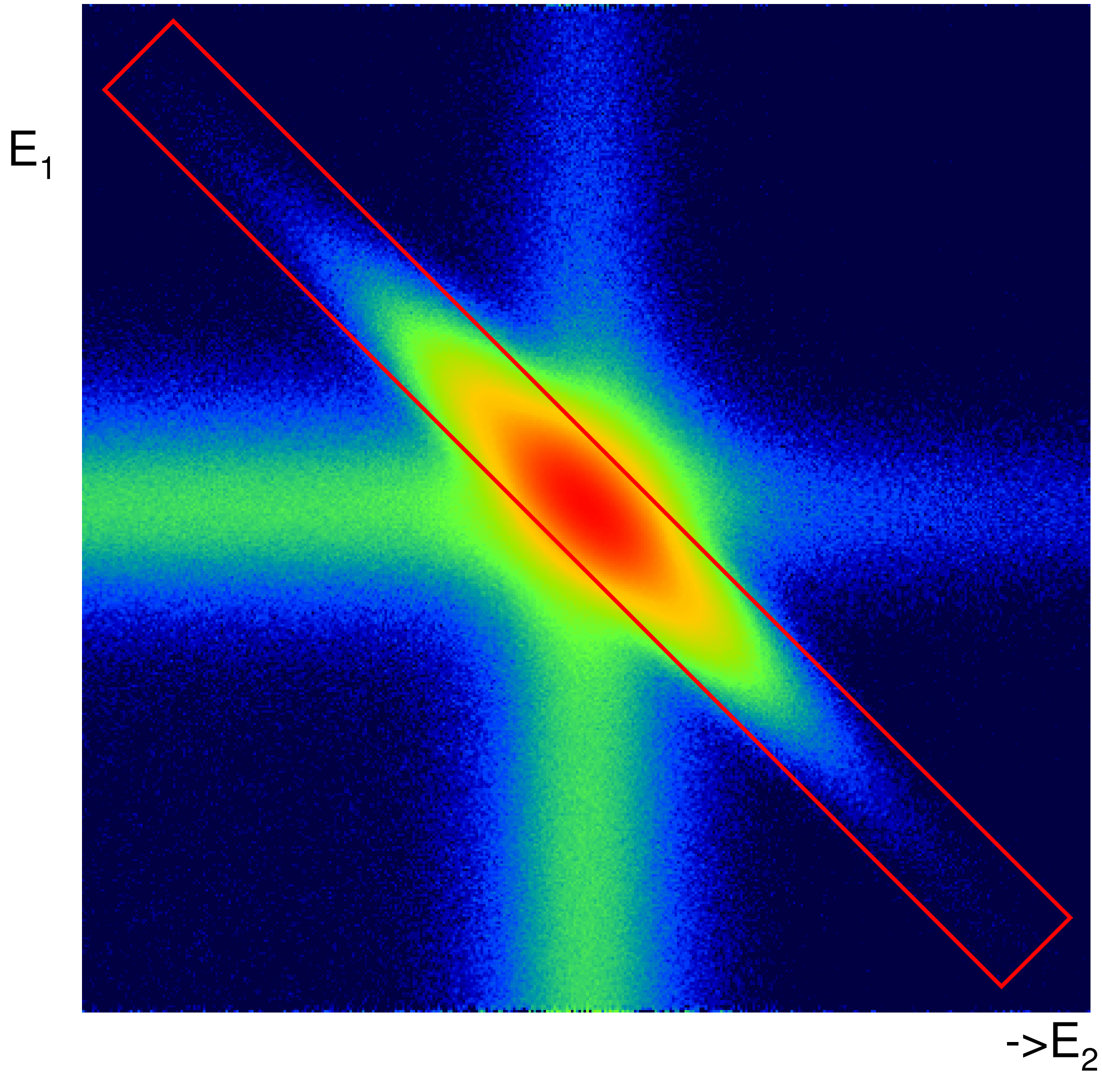
Coincidence
Doppler
Broadening
Spectroscopy

(**CDBS**)

at NEPOMUC

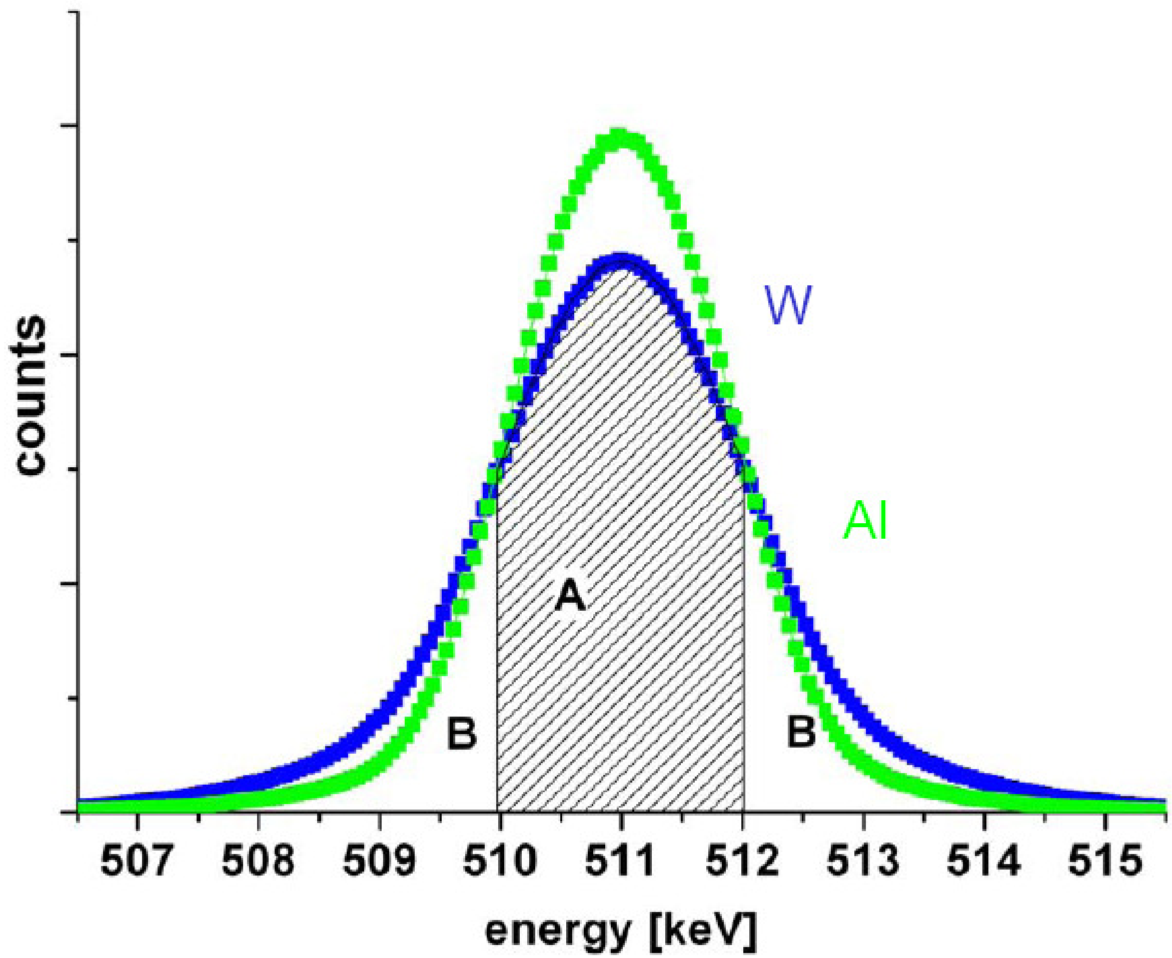
4 HP Ge Detectors

CDB: Coincidence Doppler-Broadening



$$E = E_1 + E_2 = (511 \text{ keV} - \Delta E)_1 + (511 \text{ keV} + \Delta E)_2 = 1022 \text{ keV}$$

Element dependent line width

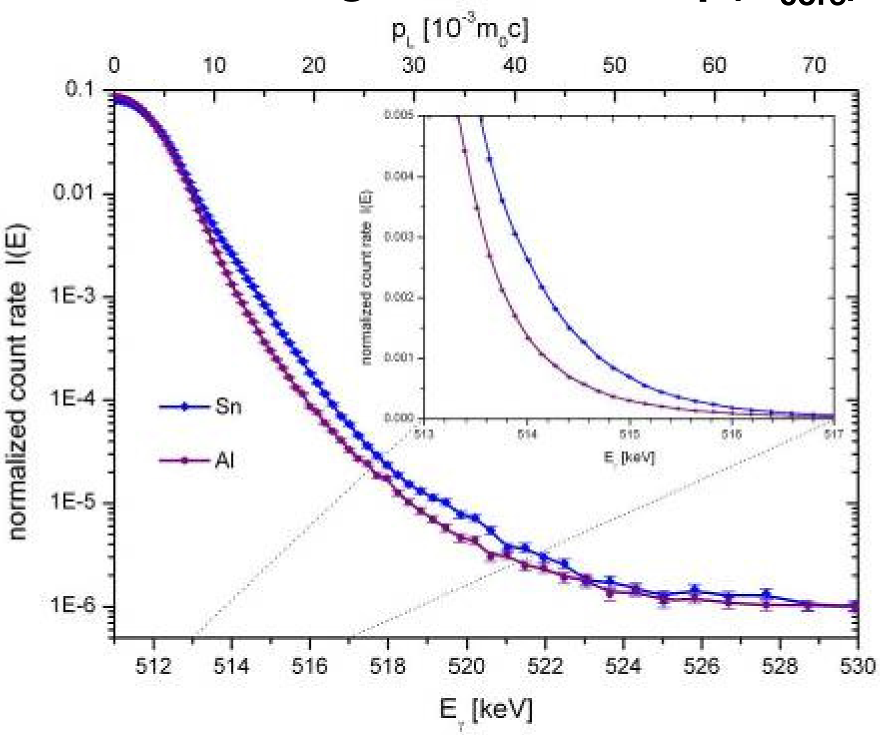


Coincident Doppler-Broadening – CDB

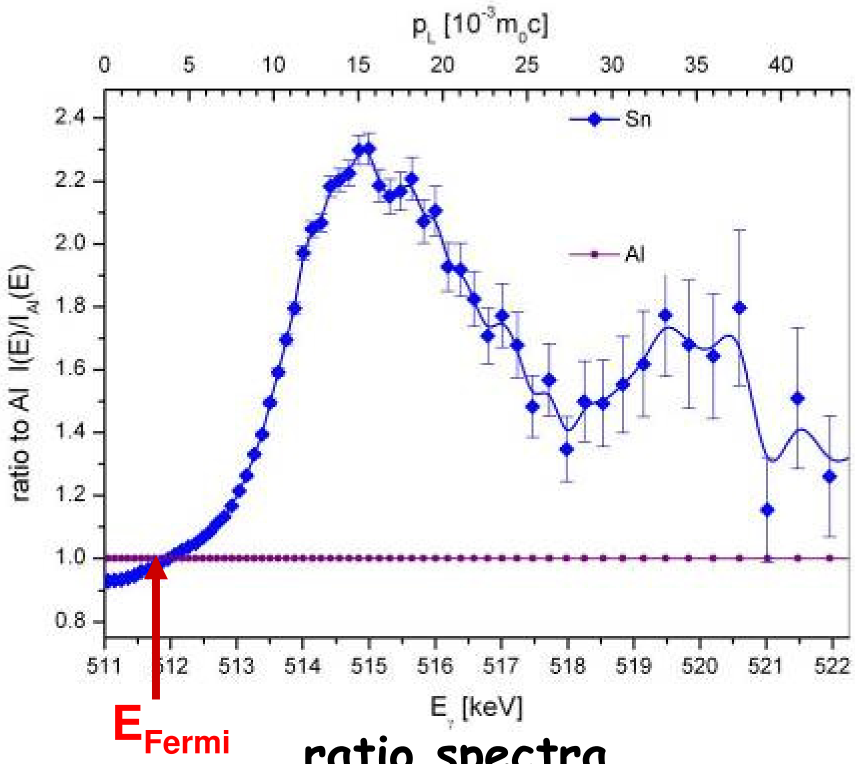
→ NEPOMUC's intensity → coincident detection of annihiliation γ's:

- **Background suppression and higher p(e⁻)-resolution**
- **Revealing events at high Doppler-shift**

→ high momenta → $p(e^-_{core})$ → elemental signature



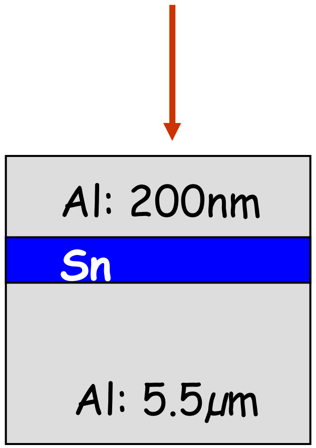
normalized photon intensity

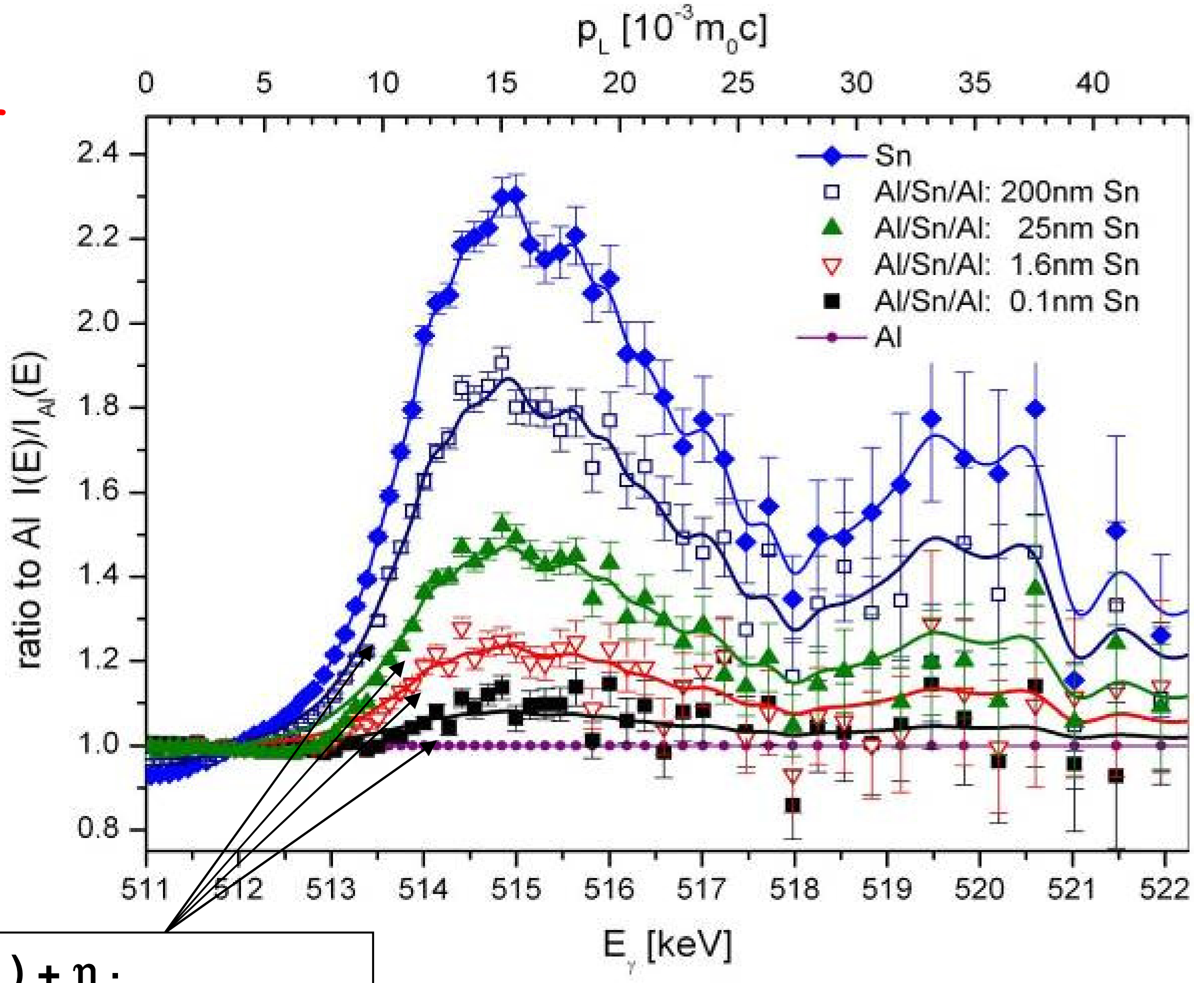


ratio spectra

Al/Sn/Al: CDB-Ratio Spectra

6 ... 15 keV e^+





$$I_{ratio}(E) = (1 - \eta) + \eta \cdot I_{Sn}(E)/I_{Al}(E)$$

C. Hugenschmidt et al. PRB 77 (2008) 092105

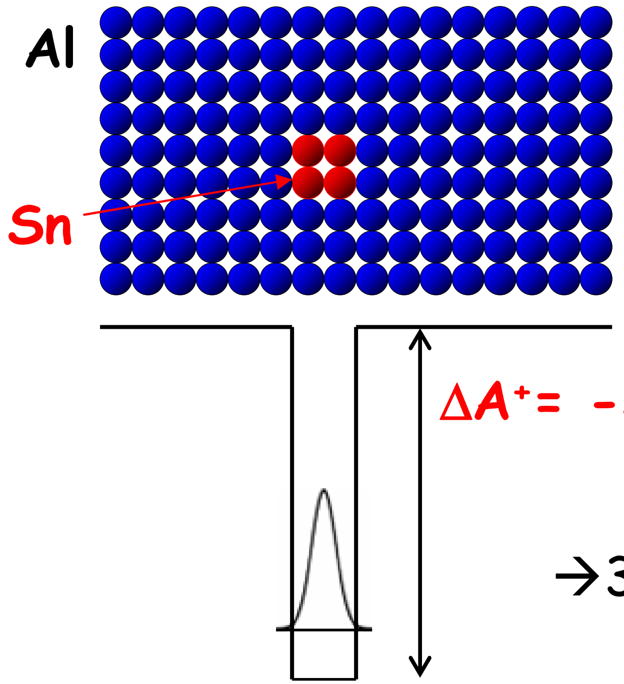
CDB-Results: Al/Sn/Al

Even 0.1 nm Sn embedded in Al visible !

→ not only defects

→ positron **diffusion** and very effective **trapping** at Sn !)

(high positron affinity of Sn)



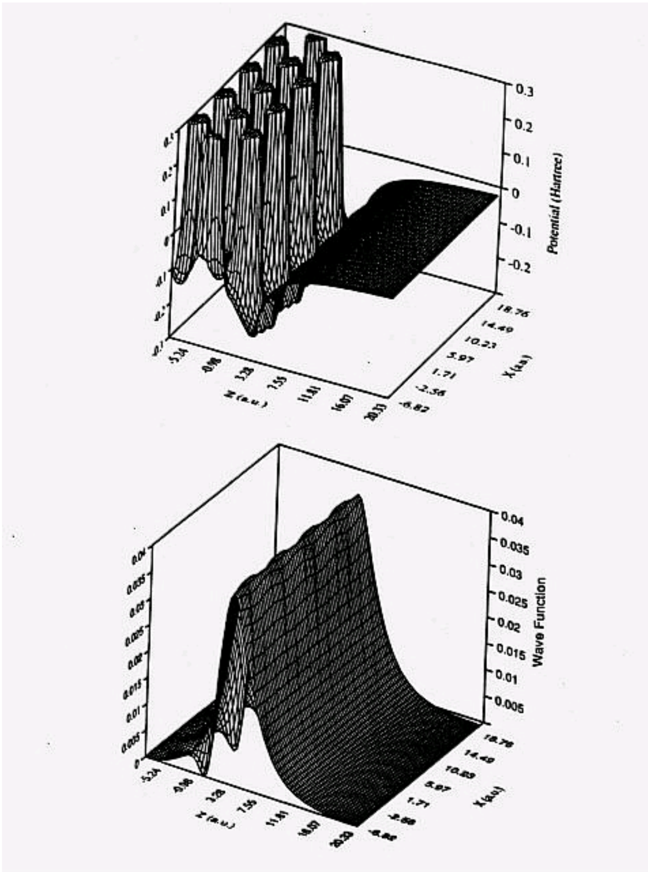
ΔA^{+}= -3.2 eV → r_c = 0.17 nm < d_{Sn}

→3D e+ confinement in Sn-(sub)nano clusters

→ Sn cluster rich Al layer

e+ Surface State
as positron trap

atomic potential at Cu(100) surface

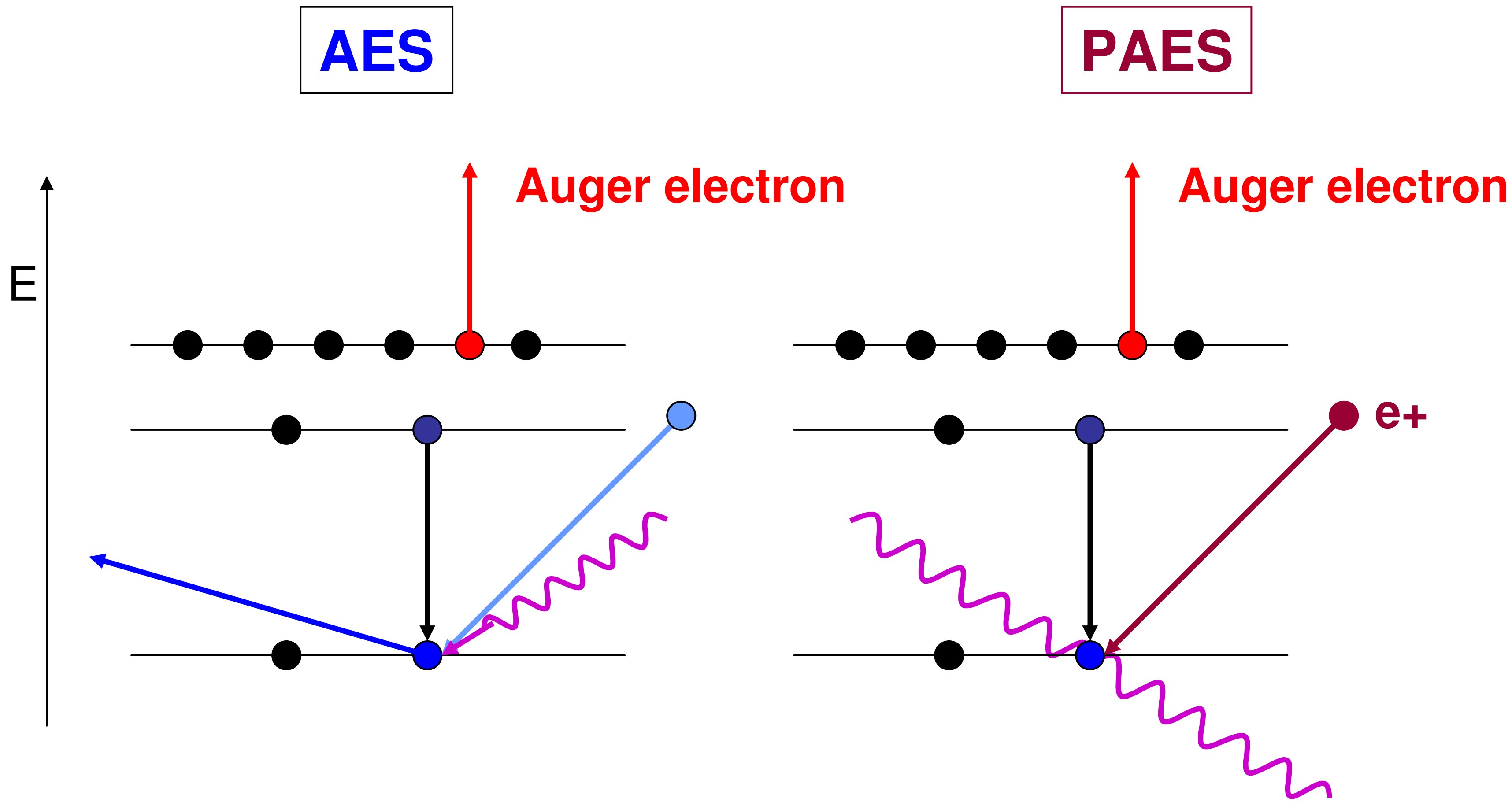


Surface potential
→ positron trapping

e+ ground state wave function

A. Weiss et al., 1992

AES - Auger Electron Spectroscopy - PAES

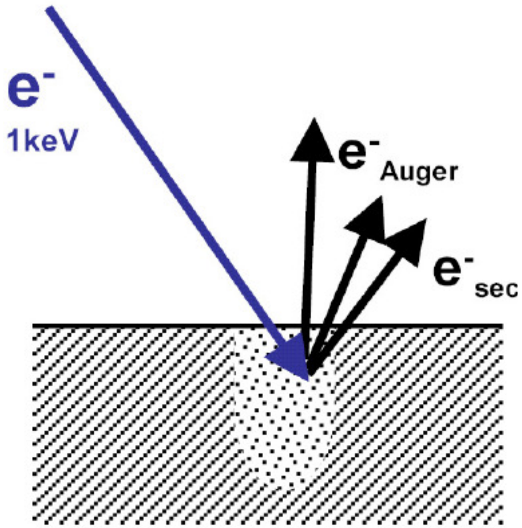


Auger **E**lectron **S**pectroscopy

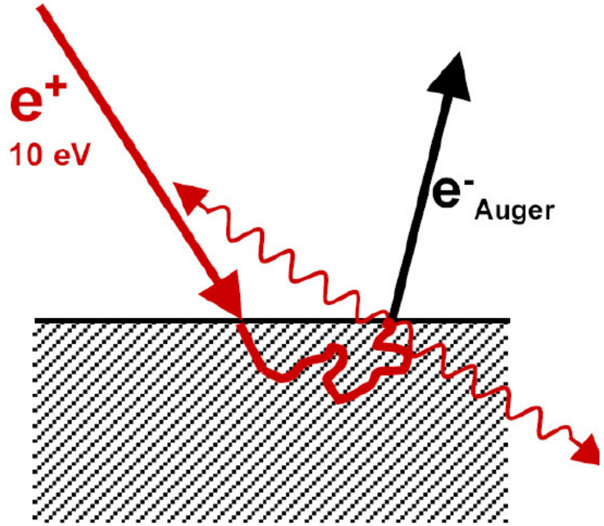
Positron **A**nnihilation induced
Auger **E**lectron **S**pectroscopy

Emission of Auger-Electrons

EAES



PAES



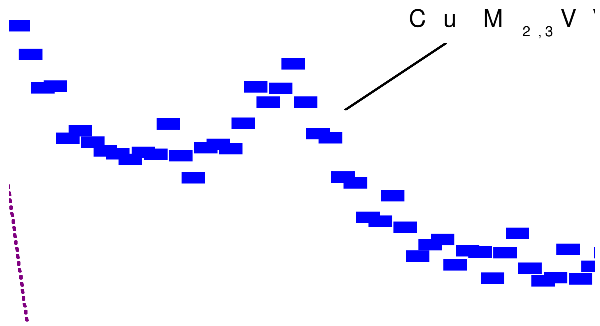
PAES features:

- non- destructive
- extremely surface sensitive (topmost atomic layer)
- no background in the energy range of the Auger peaks

→many applications in surface science:
catalysis at surfaces, surface alloys…

- e^+ Diffusion
- e^+ Trapping in Oberfläche
- Annihilation mit Core e^-
- Emission von Auger e^-

PAES Augerline of copper surface



480 hours measuring time at 22Na based positron beam PHD ,B. Strasser et al, TUM 2002

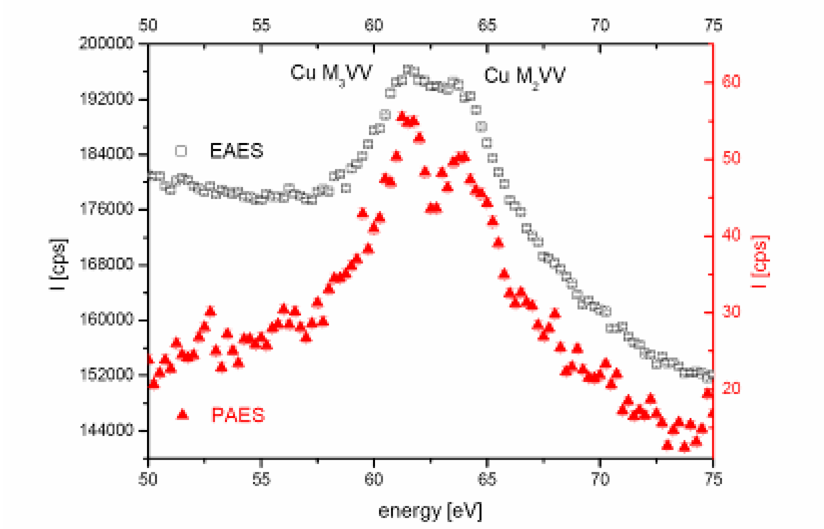


FIG. 2. High resolution spectroscopy of the Cu $M_{2,3}VV$-transition with EAES (open squares) and PAES (full triangles). The energy resolution was set to $\frac{\Delta E}{E} = 1\%$. The double peak structure was clearly resolved with PAES.

1,3 hours measuring time at NEPOMUC

J. Mayer et al, subm. to PRC 2010

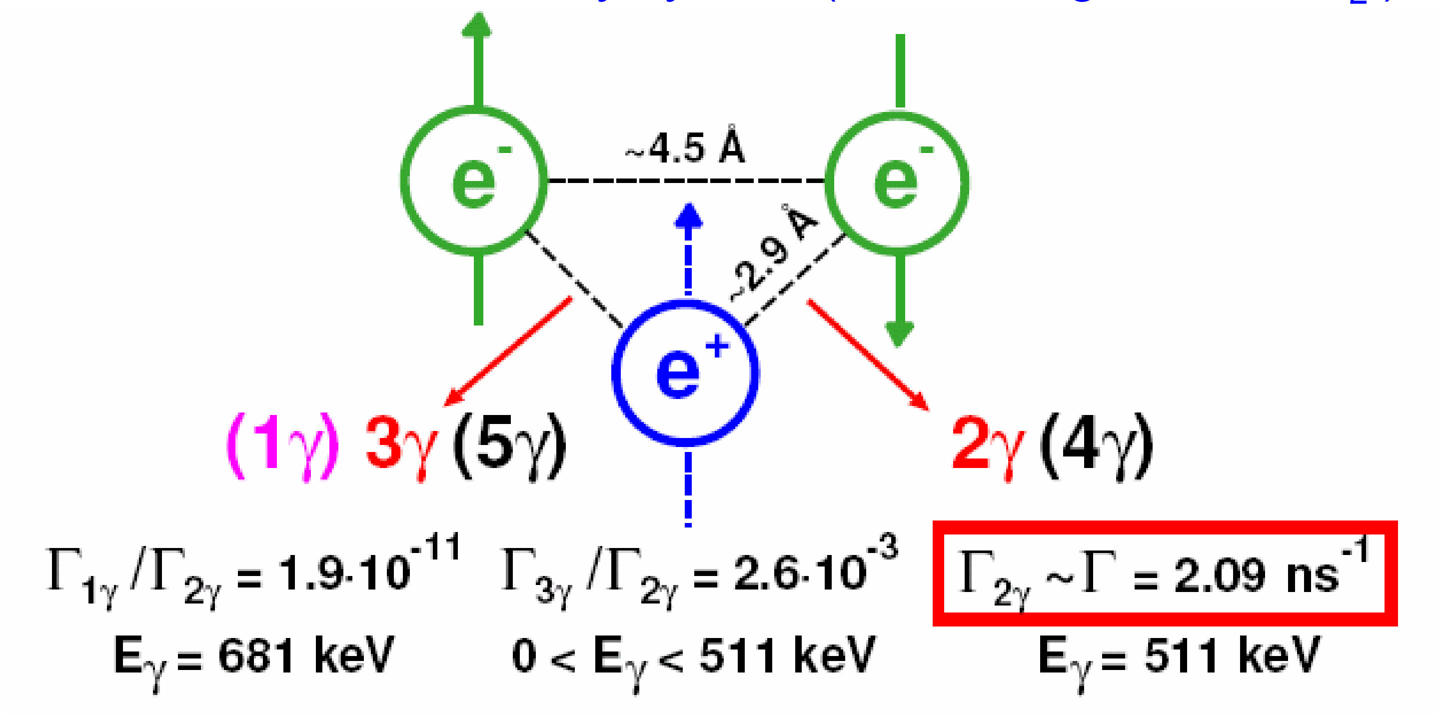
properties of bound e^+ e^- states

Object	composed of	analog zu hydrogen	bindung energy	Life time (free)
positron	e^+	p		∞
Ps	e^+e^-	H	6,8 eV	para Ps 0,125ns ortho Ps 142 ns
Ps^-	$e^+e^-e^-$	H^-	0,33 eV (in Ps + e^-)	0,4 ns
Ps^+	$e^+ e^+e^-$	Anti- H^-		theor. 0,4 ns
Ps_2	$e^+e^-e^+e^-$	H_2	0,44 eV (in Ps + Ps)	theor. 0,5 ns

No further bound systems, but possible studies of Bose-Einstein Condensates, plasma, …

Negative Positronium Ion: Ps^-

A fundamental 3-body system (contrasting H^-, He, H^+_2)



binding energy: only 0,326 eV

exp.: A.P. Mills et al **Γ=2.09±0.09 ns^{-1}** PRL 46 (1981) 717; PRL 50 (1983) 671

F. Fleischer et al **Γ=2.089±0.015 ns^{-1}** PRL 96 (2006) 063401 (MPI Heidelberg)

MPI Heidelberg Experiment zur Lebensdauer des Ps^-

MPI Heidelberg 2005; seit 2007 NEPOPMUC FRM II

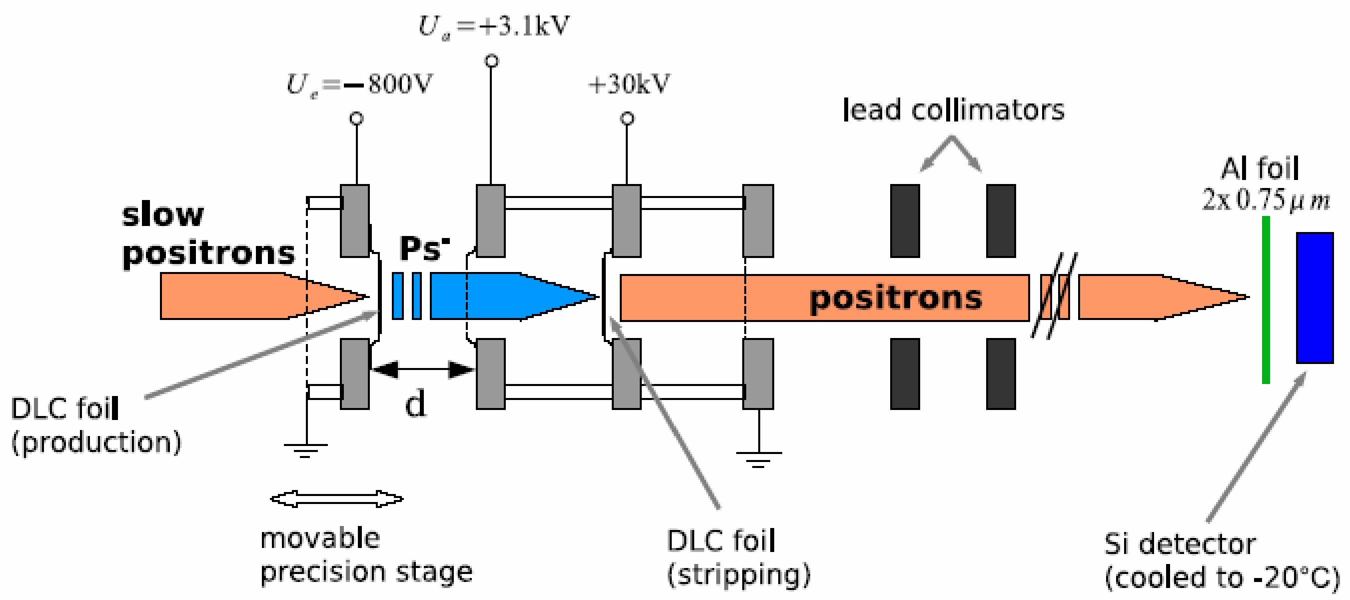
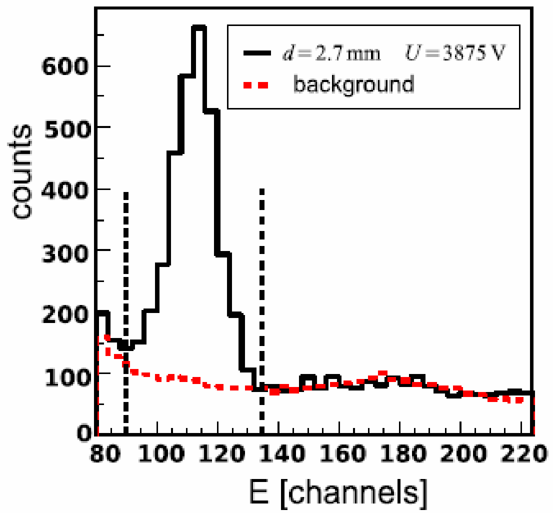


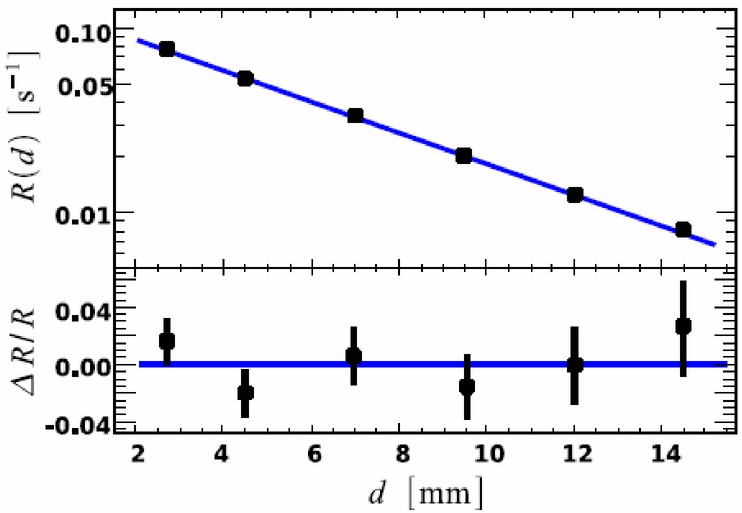
Fig. 1. Schematic view of the experimental arrangement to produce and detect Ps^- ions. The setup is surrounded by a solenoidal magnetic field of 100 – 130 G.

F. Fleischer et al PRL 96 (2006) 063401

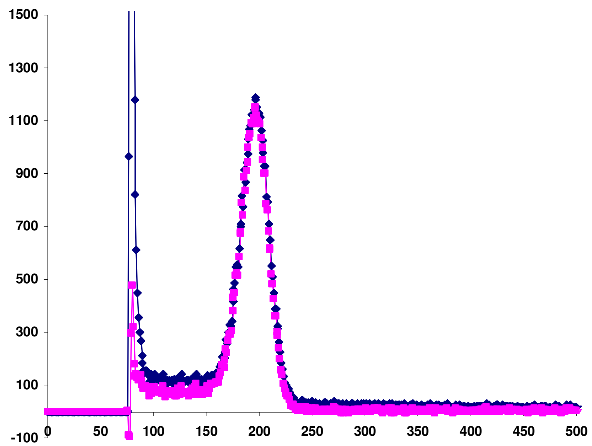
Result MPI Heidelberg 2005/6 (Na-22 positron source)



Signal in the Si detector of the ~40 keV positrons from the stripping of the Ps^-



decay of the Ps^- over the distance d



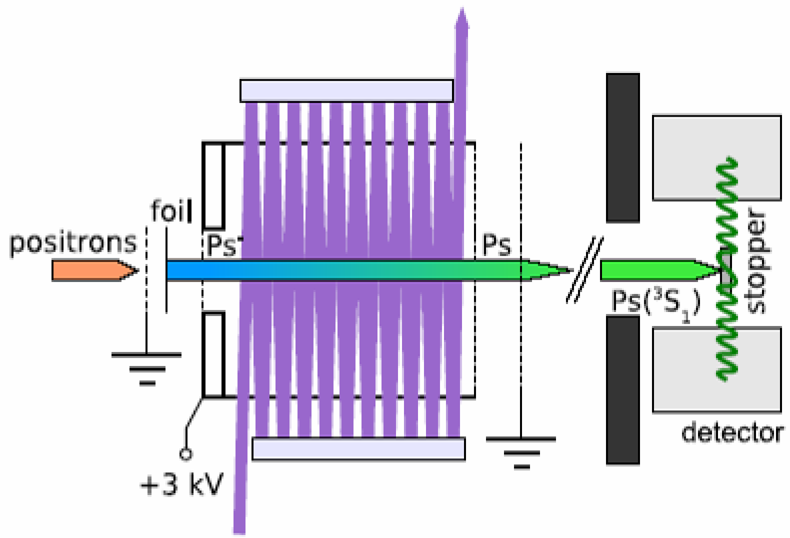
New measurement at **NEPOMUC (March 2007).**

(blue with background)

Rate at 2.7mm: 2.5 cts/s compared to the 0.08 cts/s in the former experiment at Heidelberg

Expected result: three times improved precision for the Ps^- lifetime

Production of a monoenergetic positronium beam



Production of a monoenergetic positronium beam by photodetachment of Ps^- . A multipass geometry is used for a large overlap of the Ps^- with the laser beam.

Test of mirror world and for invisible decays in Ps decay: Deviation from QED prediction for the free life time

➢ **oscillation into mirror world:**

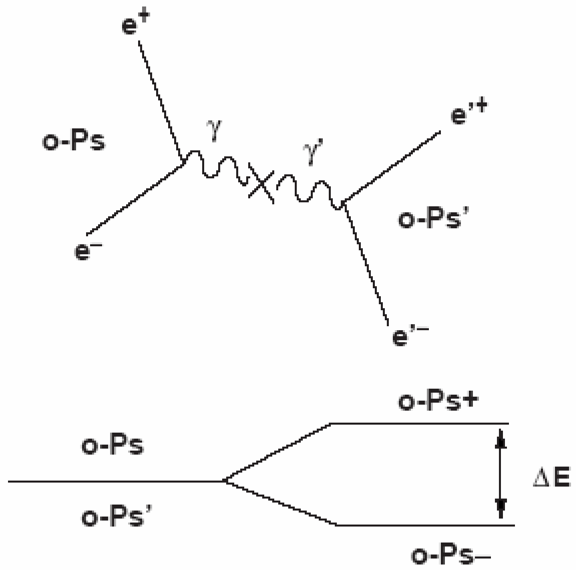


Figure 1: *The double degeneracy between orthopositronium mass eigenstates of ordinary o-Ps and mirror o-Ps' is broken when a small mixing (upper picture) term is included.*

➢ **Extra decay width by invisible decay branches**

➢ **also: search for gamma-free decay (trigger by ‚fast' e+)**

➢**positron physics is an interdisciplinary field of science both in fundamental research and applications: solid state physics, surface physics, particle physics, atomic physics, astrophysics, medical diagnostic (PET) ...**

➢**At present the exchange of ideas between the NEPOMUC group and the INTEGRAL collaboration has started and may lead to lab measurements simulating the interstellar medium such as:**

•**on dust grains: interaction, bulk/surface annihilation, Positrons backscattering, Ps formation and Ps escape**

•**Positron annihilation in specific gases and solids**

(see also N. Gurssoum et al Apl. Surface Science 252 (2006) 3352)

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NEPOMUC Gruppe