Photon-induced reactions: an overview

Kerstin Sonnabend

496. Wilhelm und Else Heraeus-Seminar on
„Astrophysics with modern small-scale accelerators“
Physikzentrum Bad Honnef

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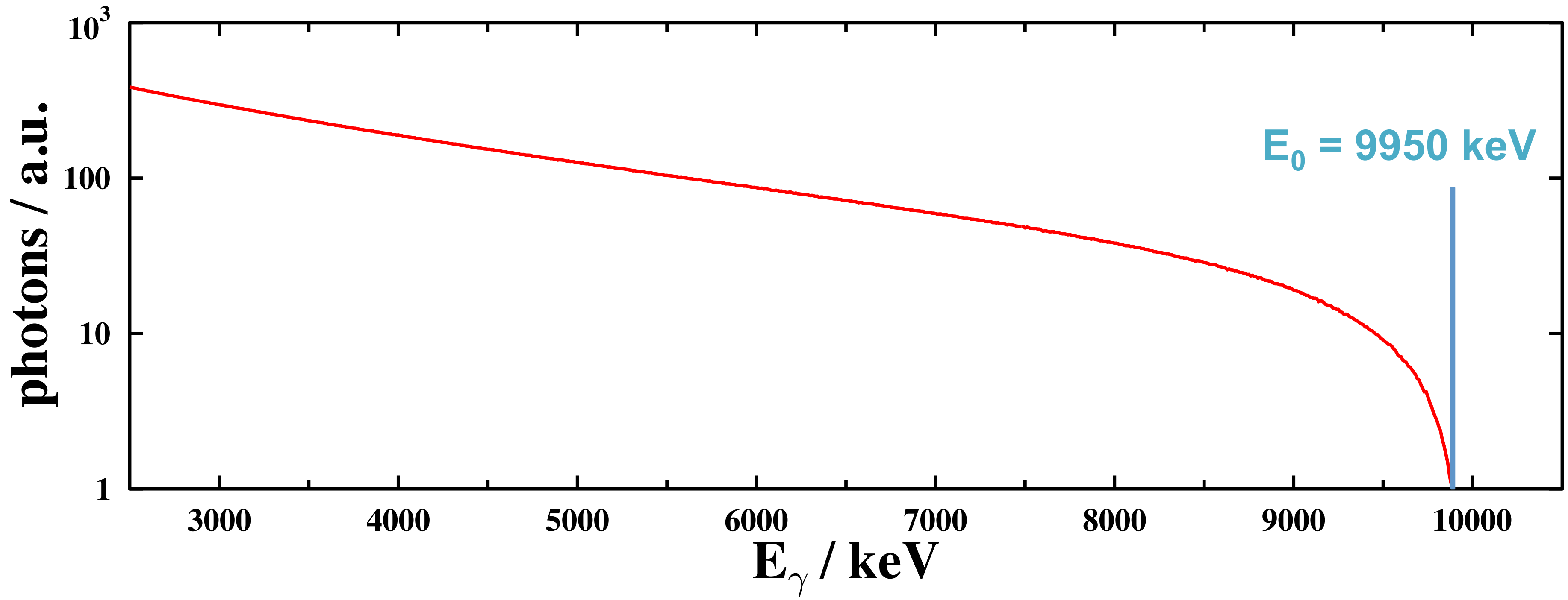
  - Virtual photons

Photon sources

Bremsstrahlung facilities - principles

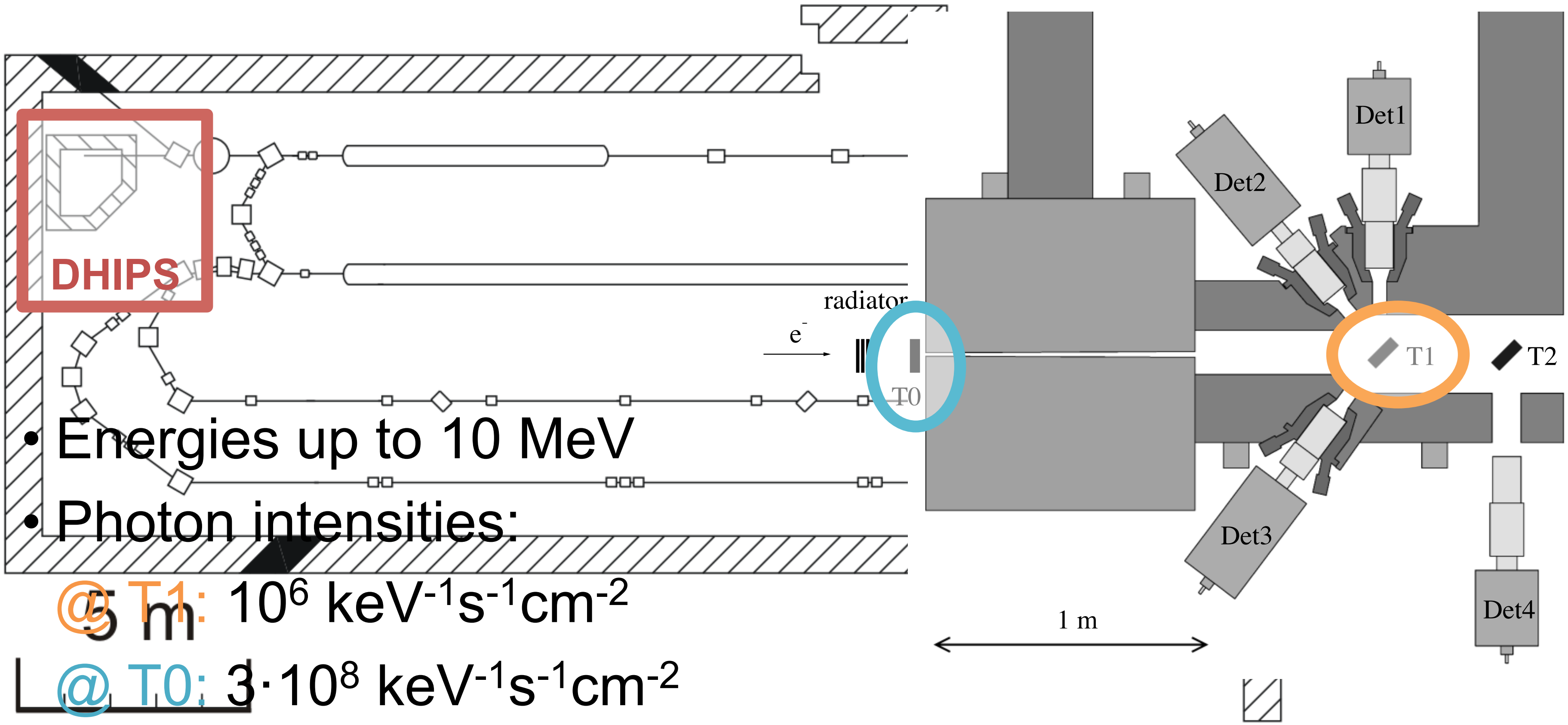
- Production by stopping of electron beam with energy E_0
- Continuous-energy photon spectrum with max. energy E_0



Photon sources

Bremsstrahlung facilities - examples

- **DHIPS @ S-DALINAC, Darmstadt, Germany**

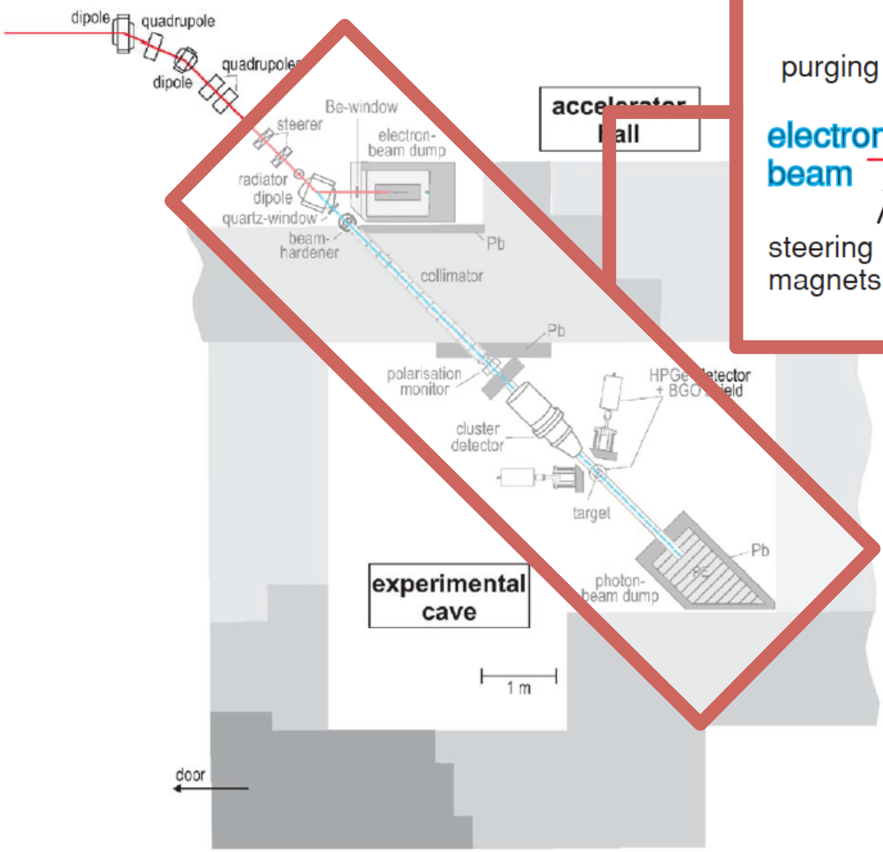


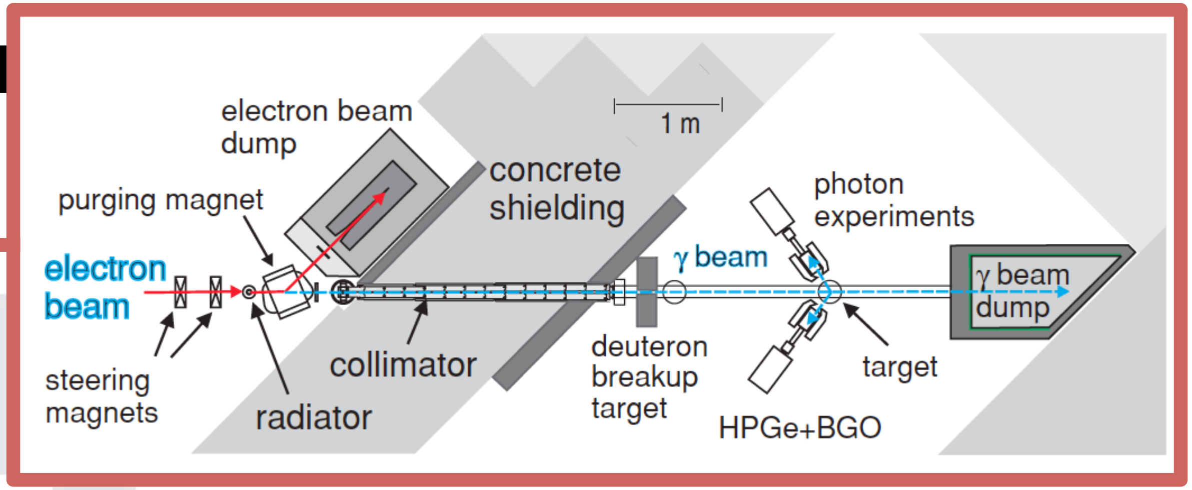
- Energies up to 10 MeV
- Photon intensities:
  - @ T1: 10^6 keV^{-1}s^{-1}cm^{-2}
  - @ T0: $3 \cdot 10^8$ keV^{-1}s^{-1}cm^{-2}

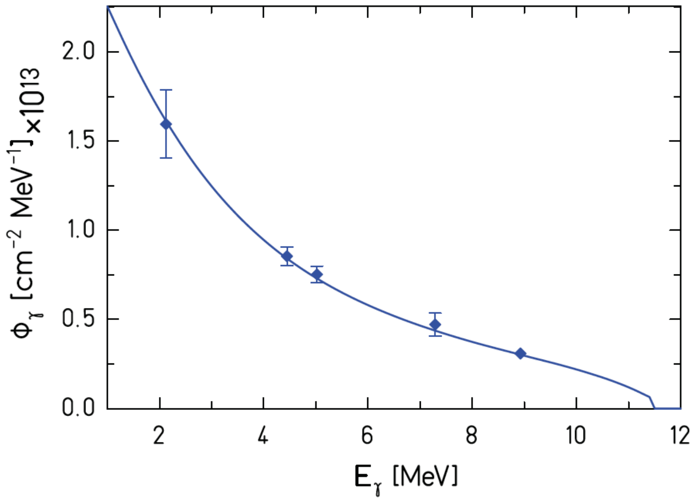
K. Sonnabend *et al.*, Nucl. Instr. Meth. Phys. Res. A **640** (2011) 6

Bremsstrahlung facilities - examples

• ELBE @ HZ Dresden-R







R. Schwengner *et al.*,
NIM A **555** (2005) 211
C. Nair *et al.*,
PRC **78** (2008) 055802

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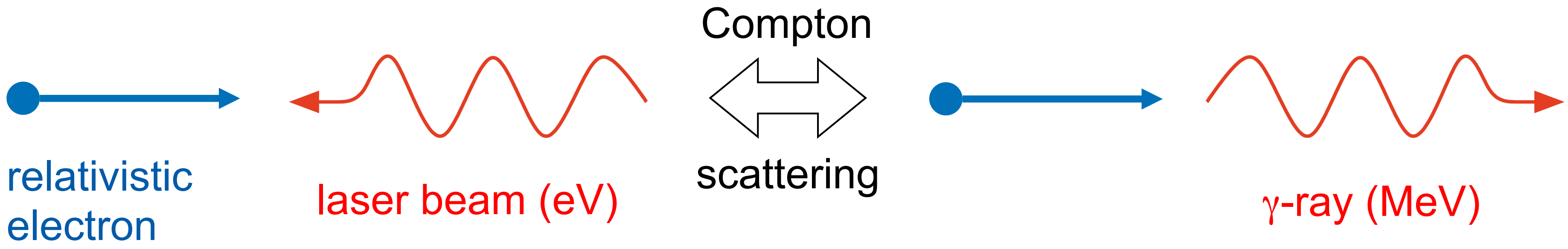
Laser Compton Backscattered (LCB) photons - principles



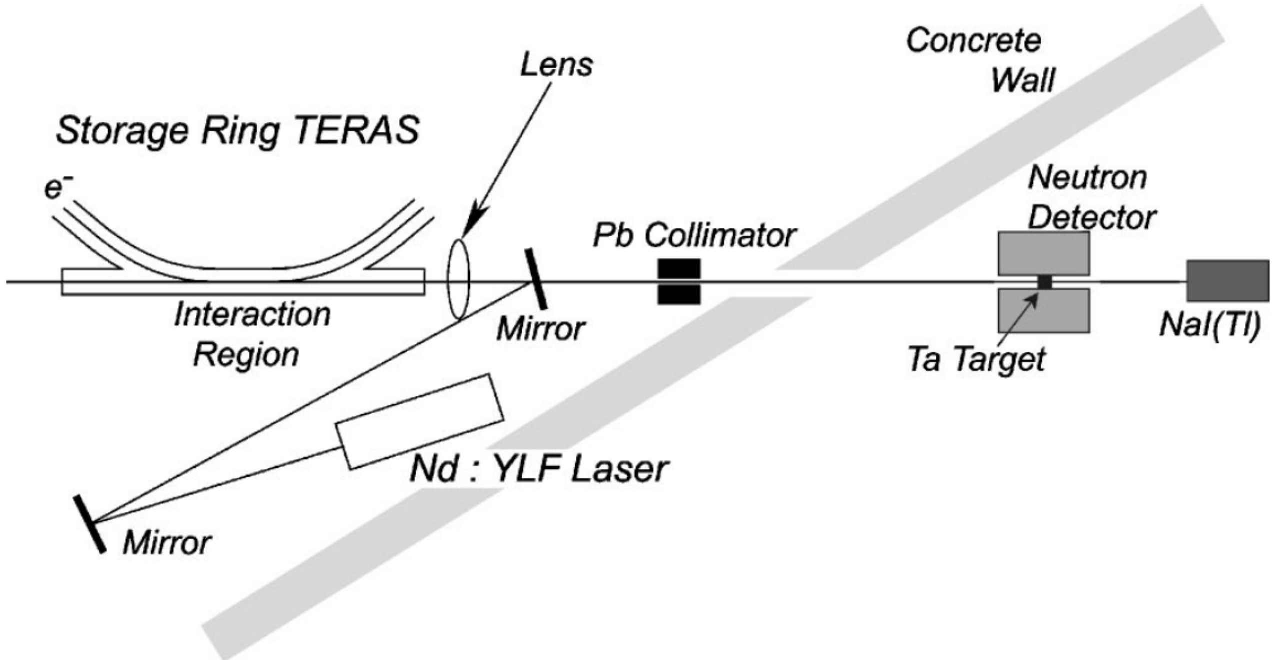
$$E_\gamma = \frac{\hbar\omega \cdot \left(1 - \beta \cdot \cos\theta_i\right)}{1 - \beta \cdot \cos\theta_f + \frac{\hbar\omega}{E_{electron}}\left(1 - \cos\theta_{photon}\right)}$$

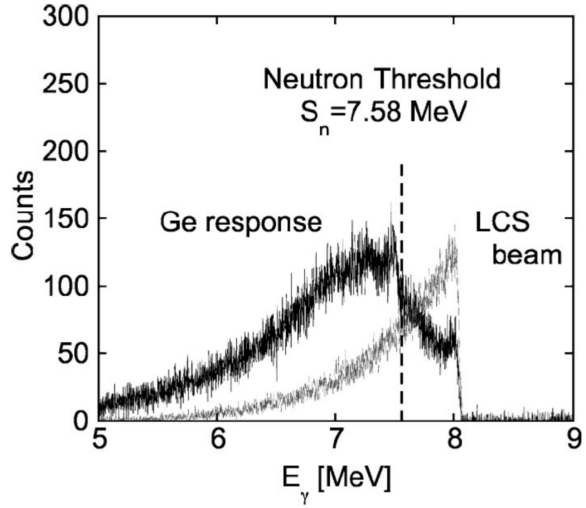
- Example: E_{laser} = 3.3 eV, $E_{electron}$ = 450 MeV (γ = 882)
  $\rightarrow E_\gamma$ = 10 MeV
- Compton scattering preserves polarization
  $\rightarrow$ (quasi-) monoenergetic 100% linearly polarized high-energy photon beam

Photon sources

LCB photons - examples

- **TERAS @ AIST, Tsukuba, Japan**



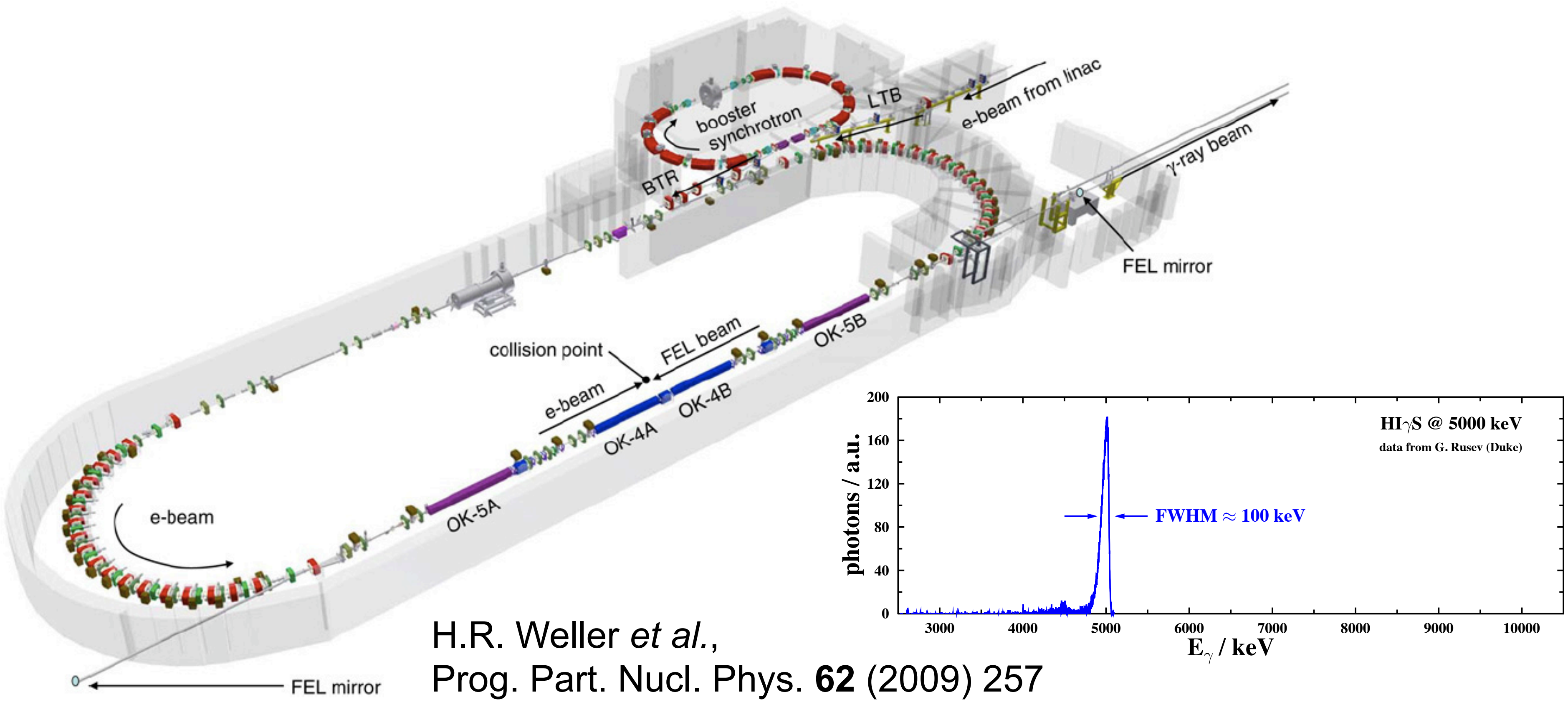


H. Utsunomiya *et al.*, Phys. Rev. C **67** (2003) 015807

Photon sources

LCB photons - examples

- **HIγS @ DFELL, Durham, NC, USA**



H.R. Weller *et al.*,
Prog. Part. Nucl. Phys. **62** (2009) 257

Activation method

1. Produce unstable nuclei in particle- or photon-induced nuclear reaction, *e.g.* (α,γ), (p,n), (n,γ), or (γ,n)
2. Determine reaction yield Y offline using γ spectroscopy or alternative methods, *e.g.* accelerator mass spectrometry

- Advantages:
  - Measurement of weak γ branchings (*e.g.* ^{185}W: $T_{1/2}$ = 75 d, I_γ(125 keV) ≈ 10^{-4})
  - Usage of naturally composed targets (*e.g.* ^{196}Hg, ^{198}Hg, ^{199m}Hg, ^{200}Hg)
  - Activate targets simultaneously (*e.g.* Zr, Re, Ir, and Au)
- Restrictions:
  - Appropriate lifetime of product nucleus
  - Appropriate γ transitions in decay of product nucleus
  - Limited to stable (or very long-lived) nuclei

Experimental approaches

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In-beam technique

- Measure reaction product(s) with efficient detector array

- Advantages:
  - Generally applicable
  - Energy- and time-resolved measurements
- Restrictions:
  - Highly-enriched target material
  - Contaminations of target material
  - Natural and beam-induced background
  - Lower sensitivity

Recent results – an overview

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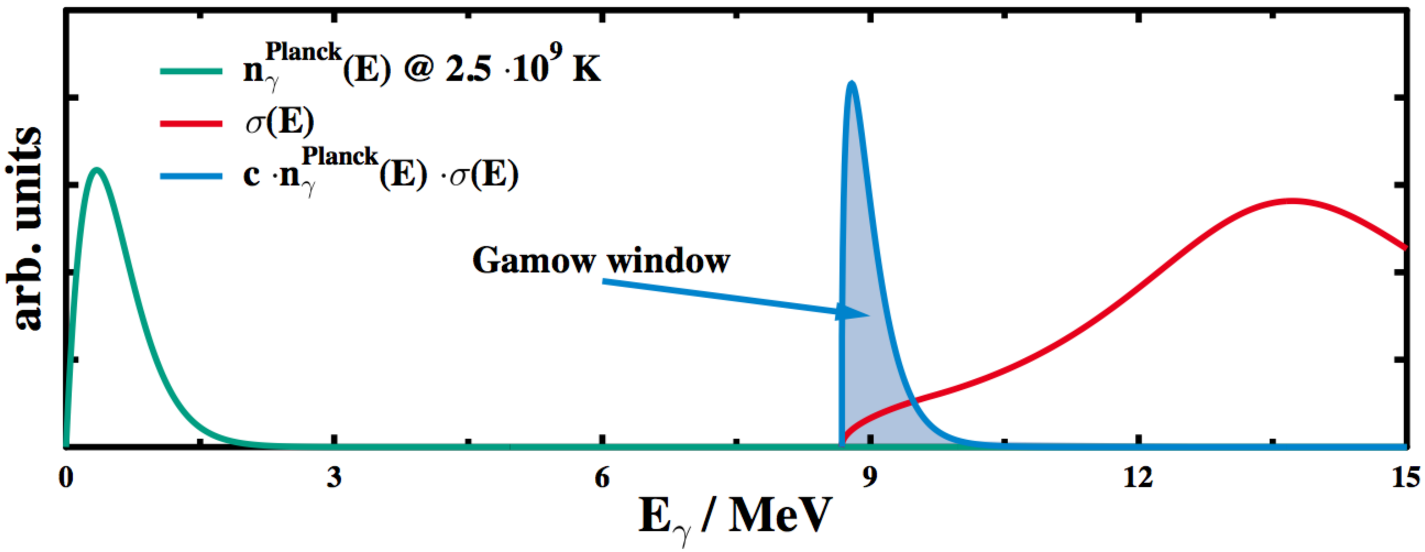
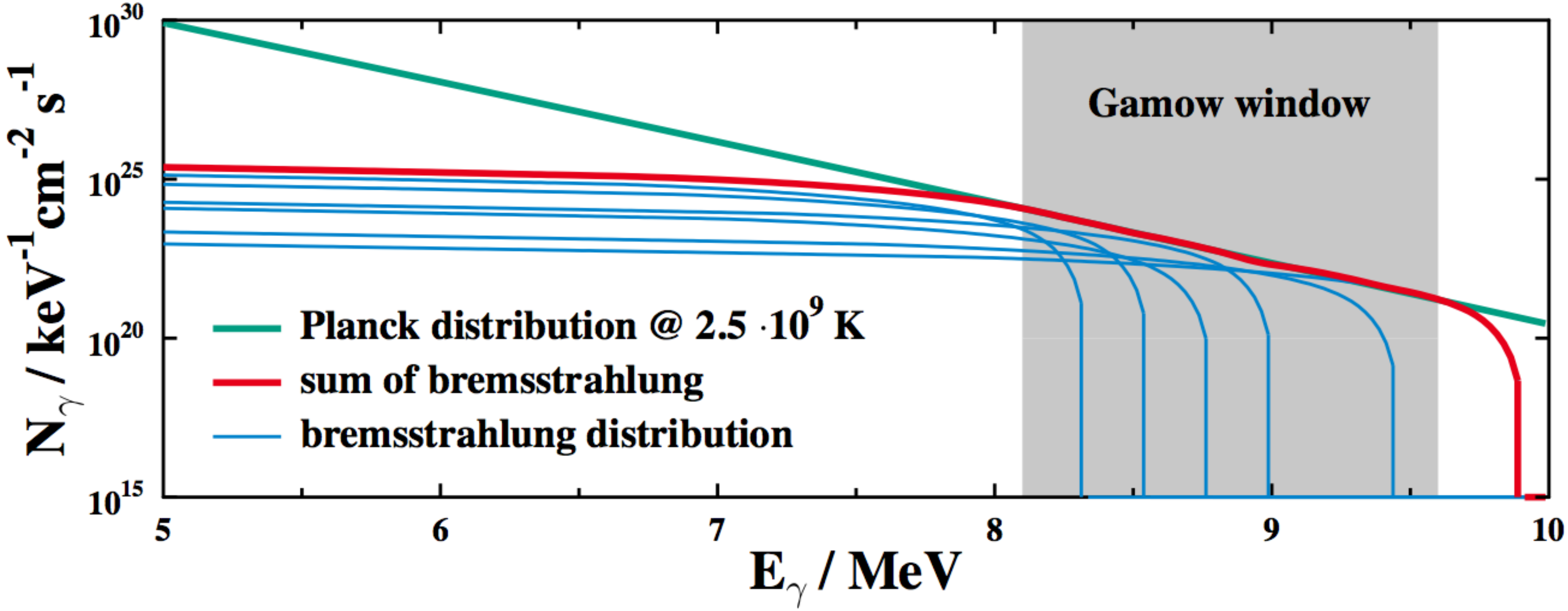
„Gamow window“ of (γ,n) reactions

- **Planck distribution**: $n_\gamma^{\text{Planck}} dE = \frac{1}{\pi^2(\hbar c)^3} \cdot \frac{E^2}{\exp(E/kT)-1} \cdot dE$
- **σ(E)** with typical threshold behaviour
- **Reaction rate**: $\lambda(T) = \int c \cdot n_\gamma^{\text{Planck}} \cdot \sigma(E) \cdot dE$



Recent results – an overview

Approximate Planck spectrum by bremsstrahlung spectra



→ Determine ground-state reaction rates at typical *p*-process temperatures ($T_9 \approx 2 - 3$)

Recent results – an overview

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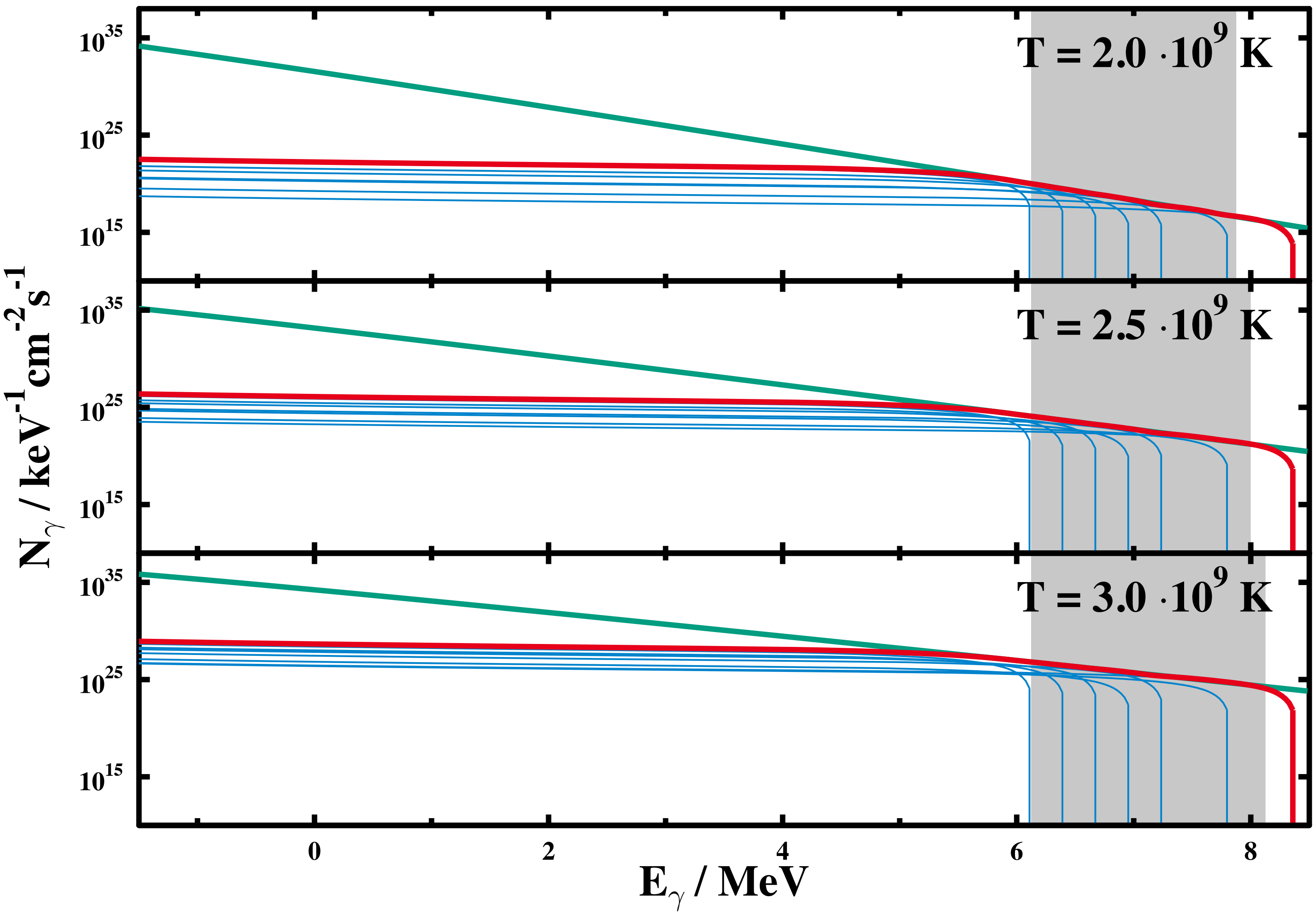
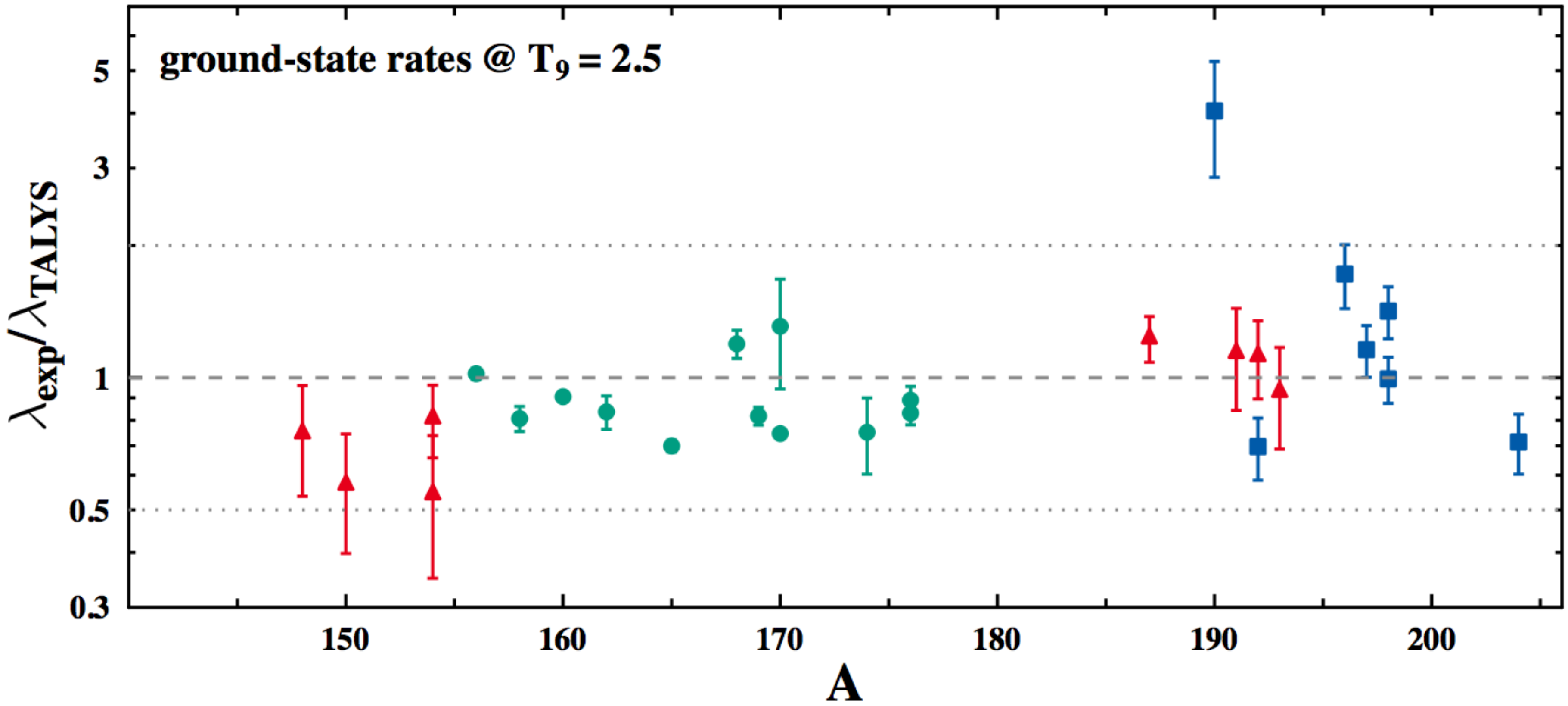


Recent results – an overview

DHIPS @ S-DALINAC, Darmstadt, Germany



S. Müller, PhD thesis, TU Darmstadt (2009)

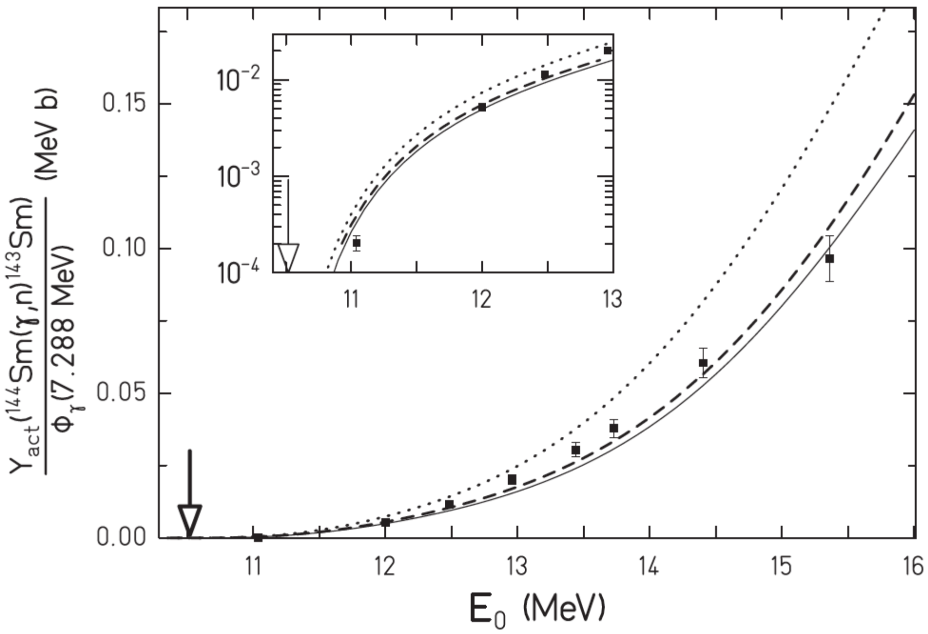
J. Hasper, K. Sonnabend *et al.*, Phys. Rev. C 77 (2008) 015803

K. Sonnabend *et al.*, Phys. Rev. C 70 (2004) 035802

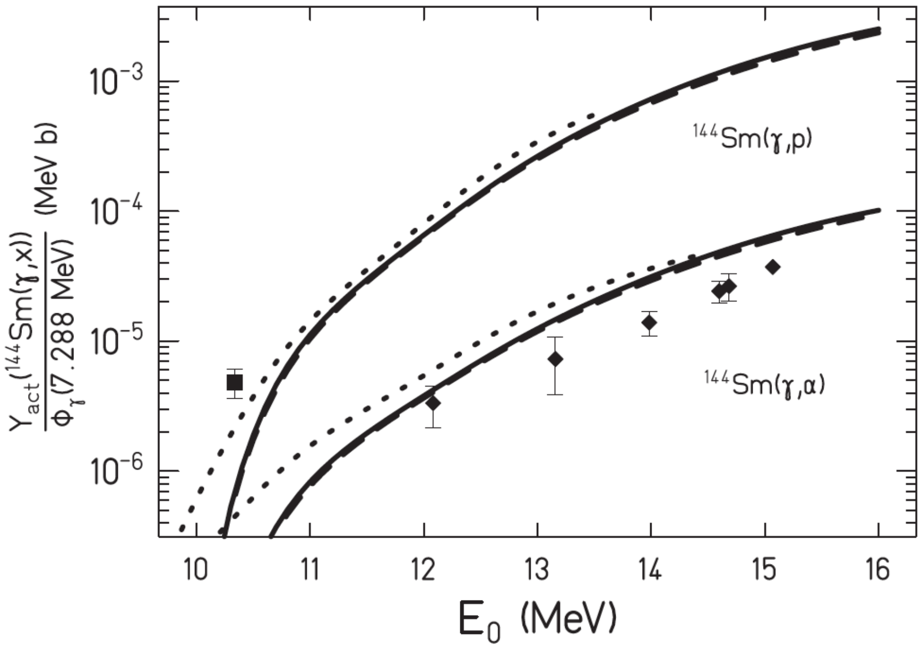
Recent results – an overview

ELBE @ HZ Dresden-Rossendorf, Germany

$^{144}Sm(\gamma,n)$: experiment vs. theory



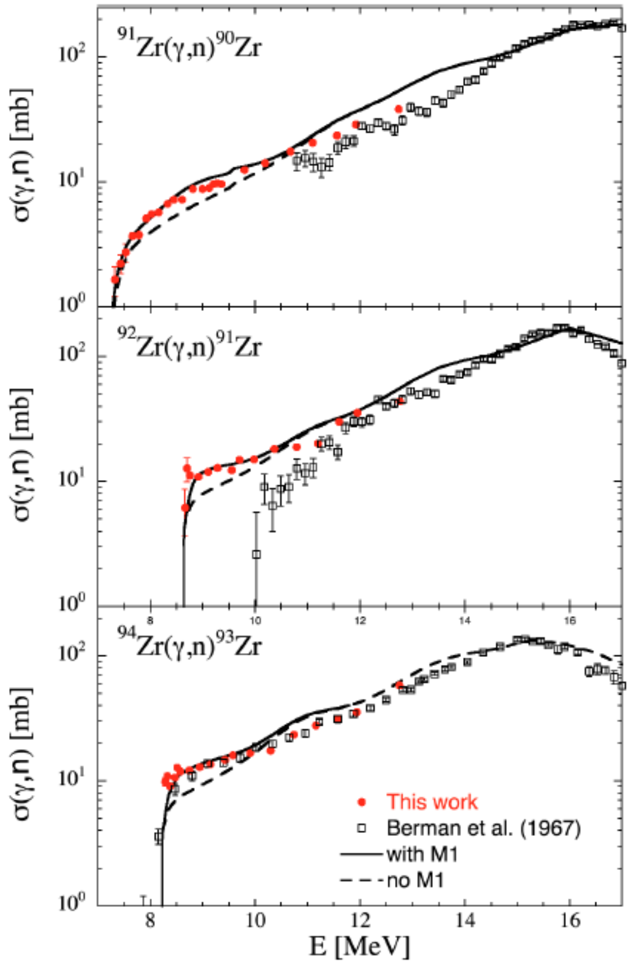
$^{144}Sm(\gamma,x)$: experiment vs. theory



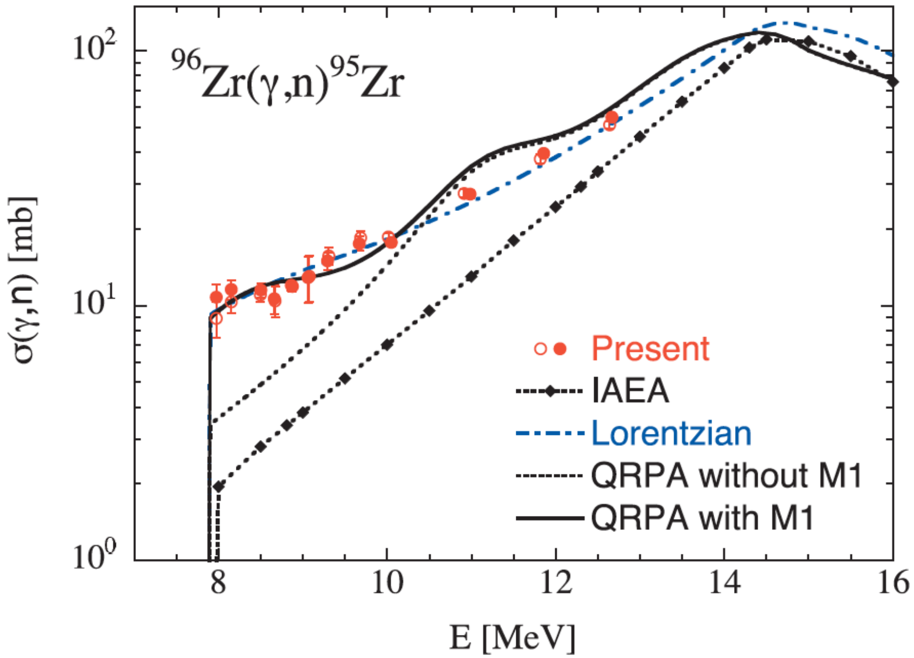
C. Nair *et al.*, Phys. Rev. C **81** (2010) 055806

Recent results – an overview

TERAS @ AIST, Tsukuba, Japan



$^{91, 92, 94, 96}Zr(\gamma,n)$: experiment vs. theory



H. Utsunomiya *et al.*, Phys. Rev. Lett. **100** (2008) 162502
H. Utsunomiya *et al.*, Phys. Rev. C **81** (2010) 035801

Recent results – an overview

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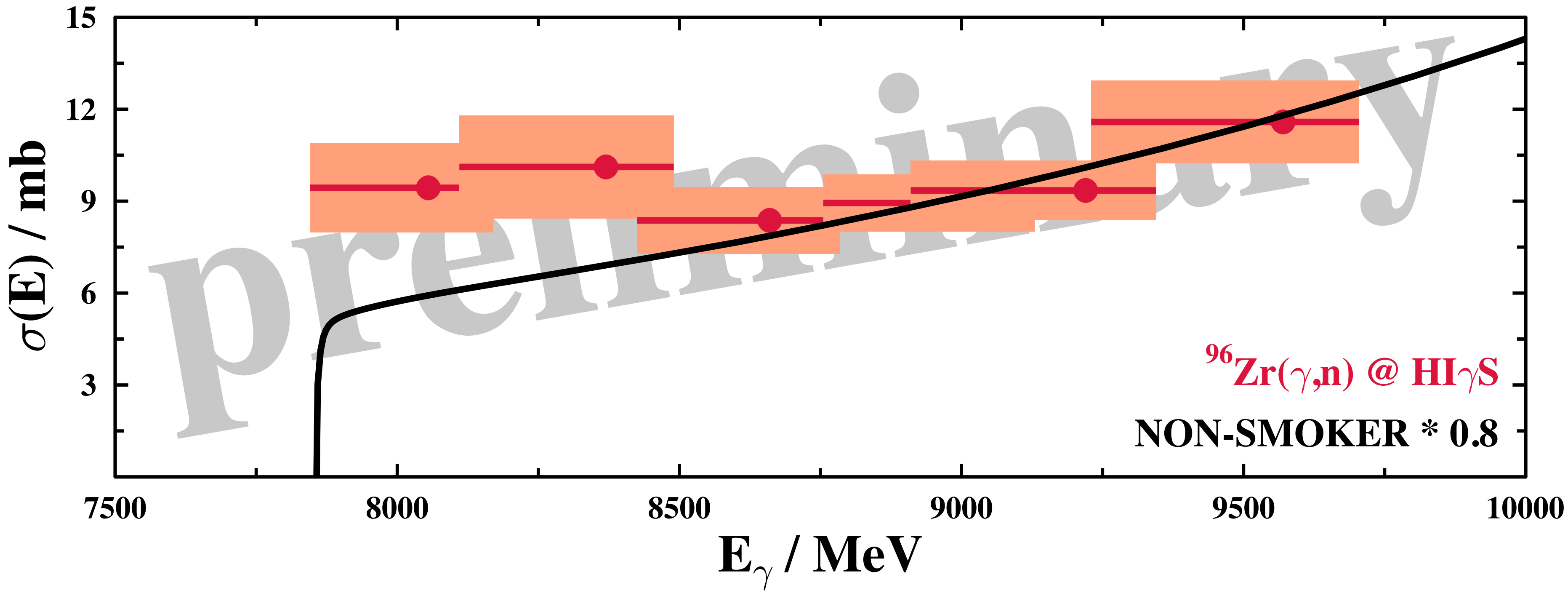
HIγS @ DFELL, Durham, NC, USA

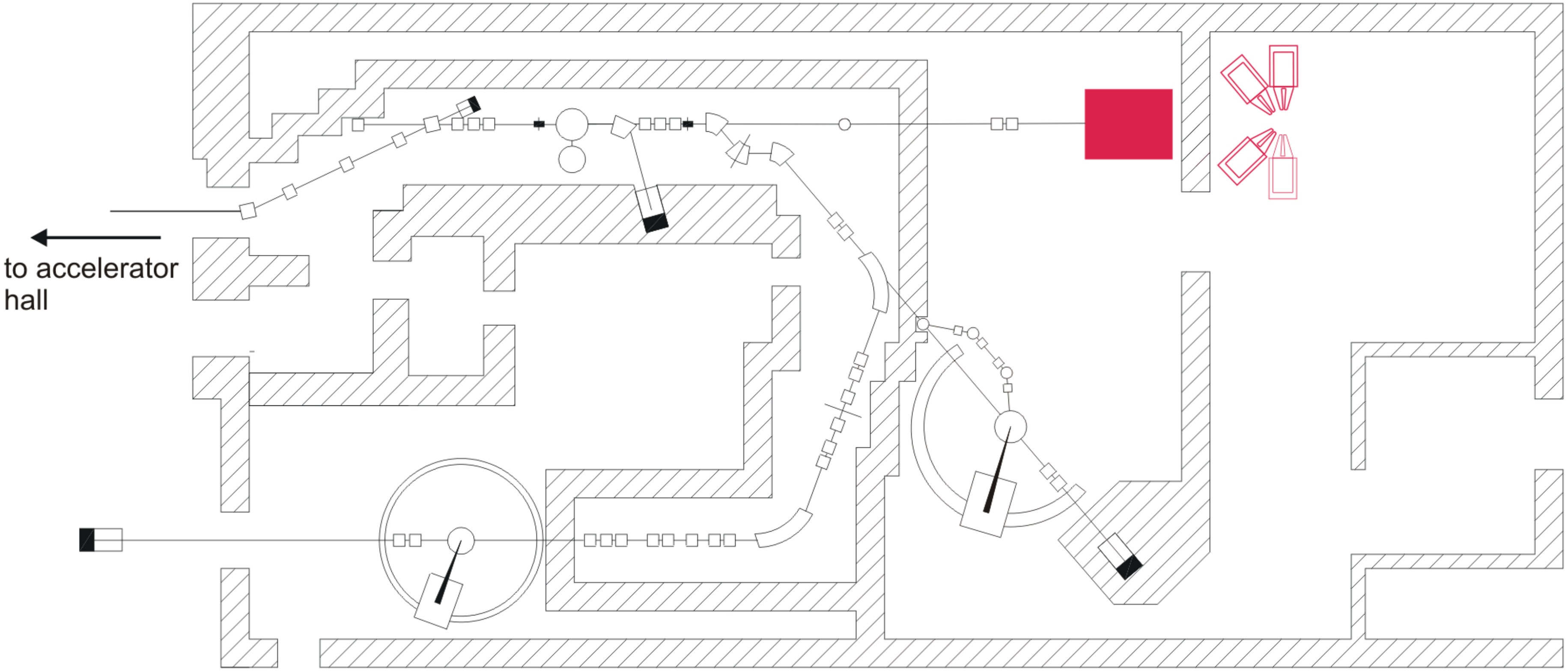
- ^{96}Zr(γ,n): activation of naturally composed targets



→ Enhancement of cross section also observed

Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany



D. Savran *et al.*,
Nucl. Instr. Meth. Phys. Res. A **613** (2010) 232

Other techniques: Tagged photons

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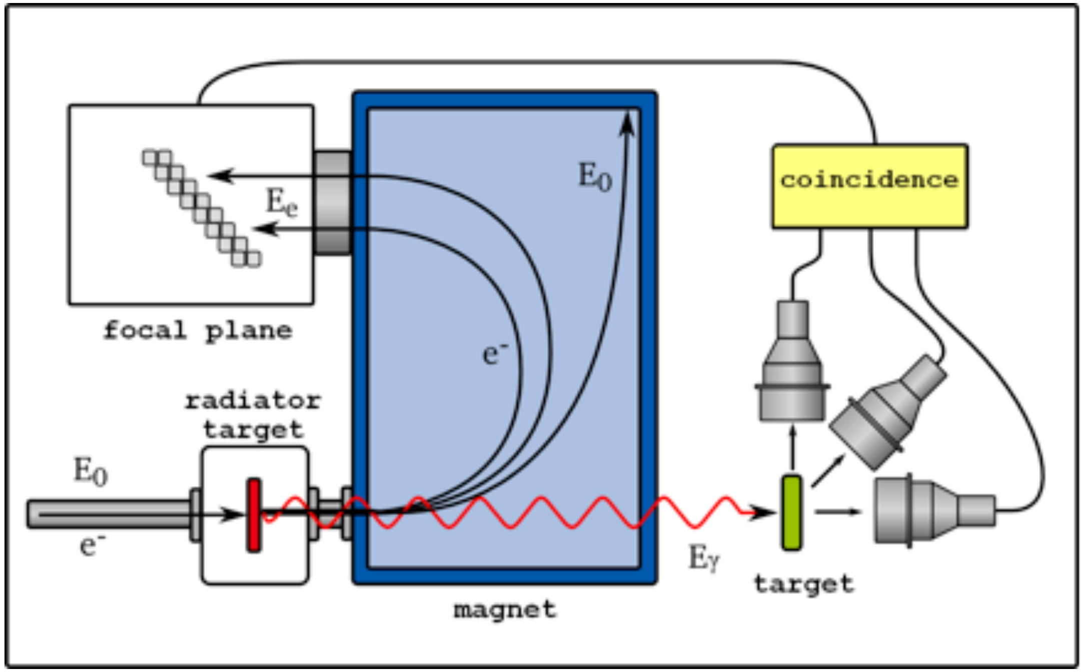
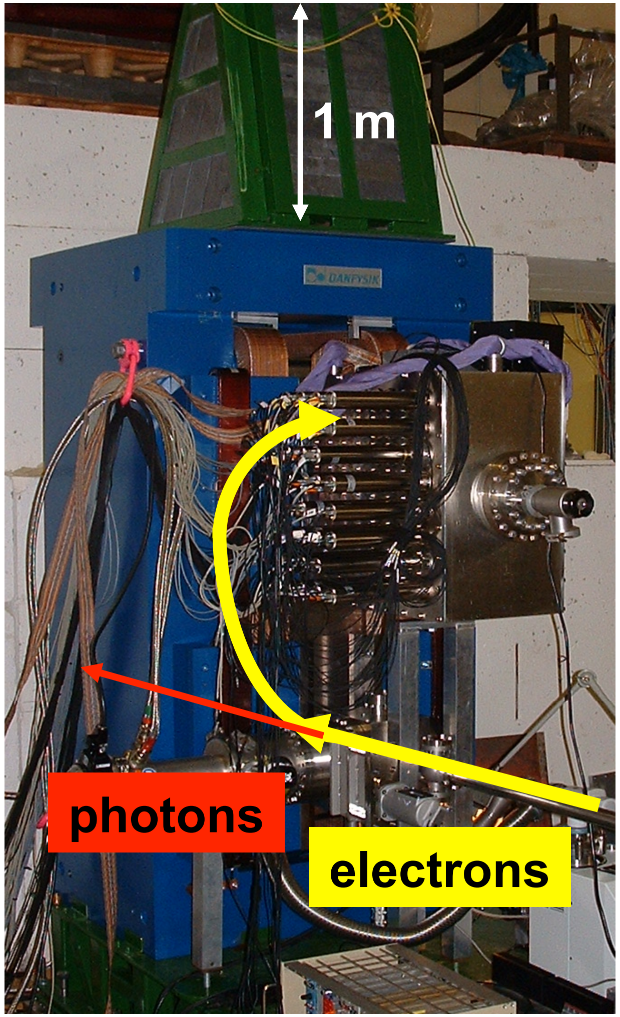
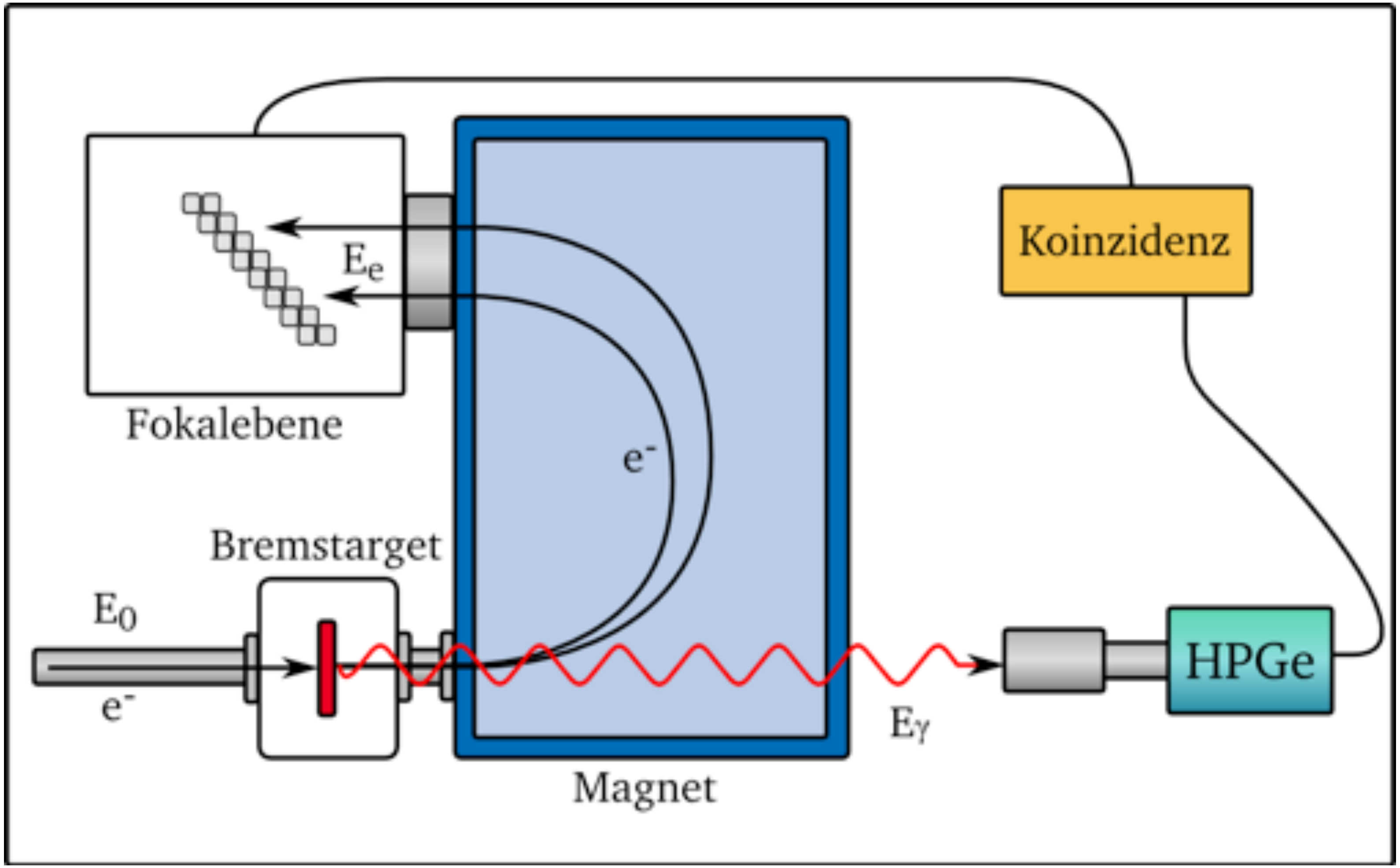




Photon energy:	$E_\gamma = E_0 - E_e$
Energy range:	6 MeV ≤ E_γ ≤ 20 MeV
Energy resolution:	ΔE = 25 keV @ 10 MeV
Energy window:	≈ 2 to 3 MeV
Photon intensity:	≈ 10^3 keV^{-1}s^{-1}cm^{-2}

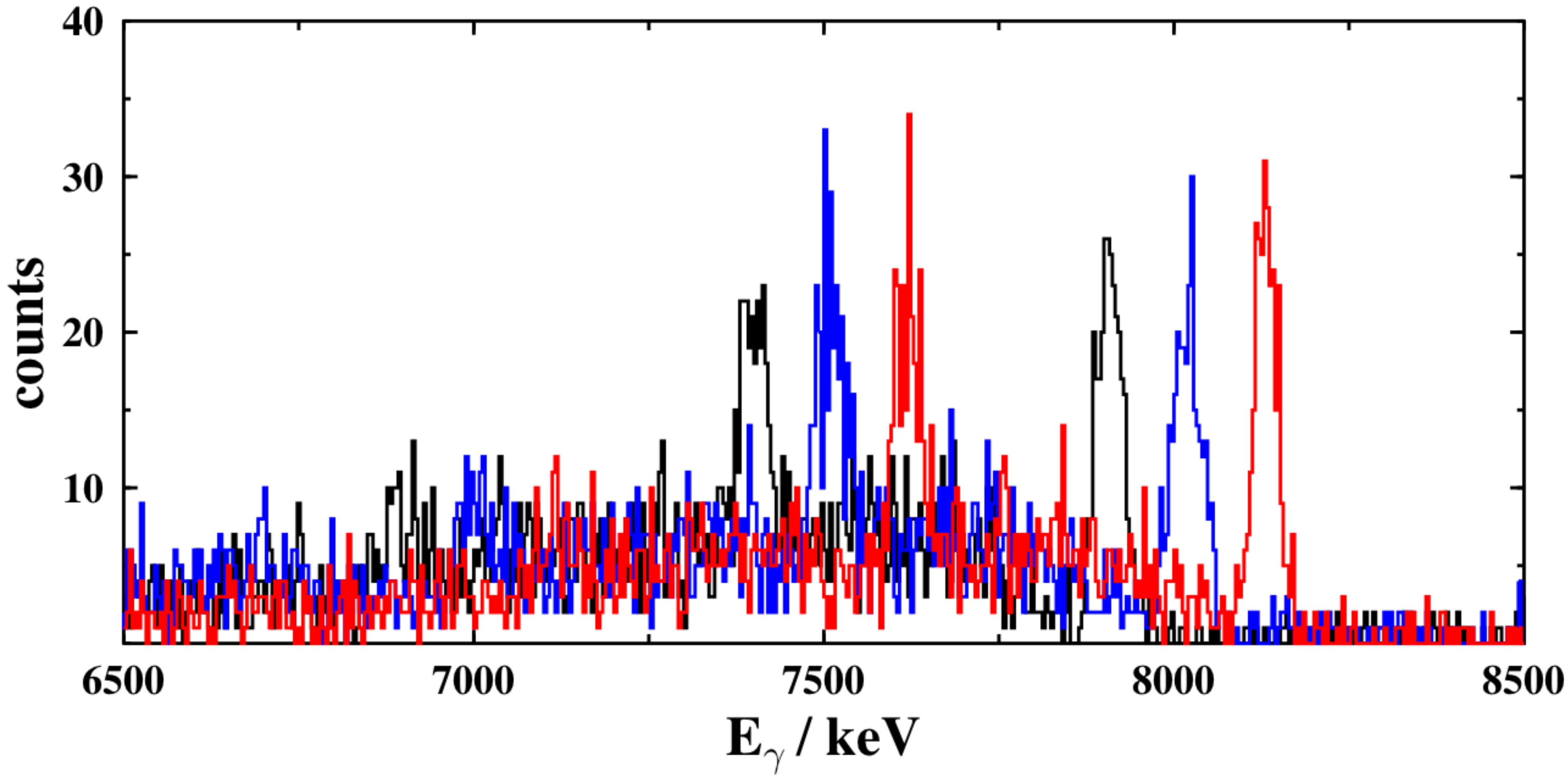
Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany



Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany



Other techniques: Tagged photons

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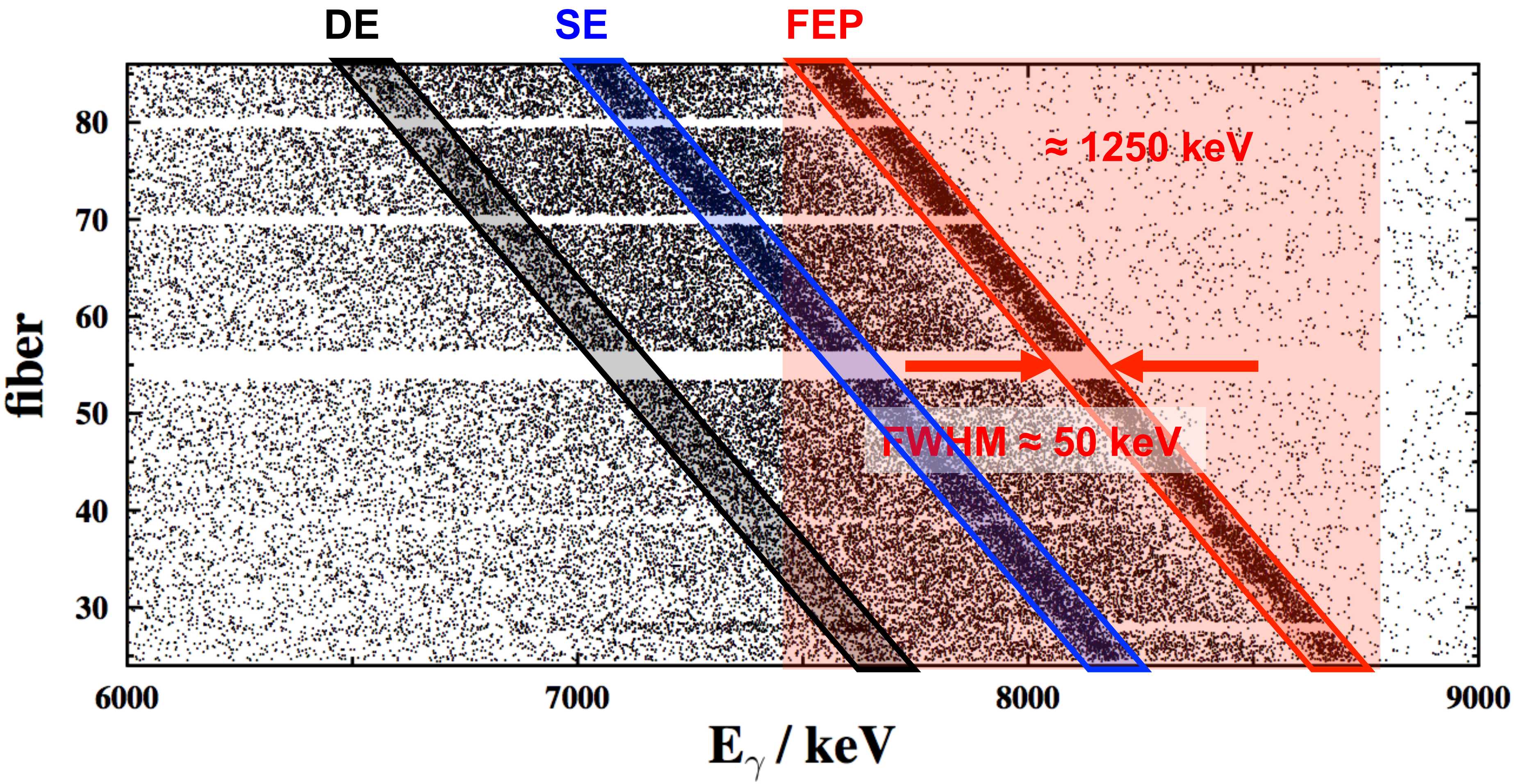

Other techniques: Tagged photons

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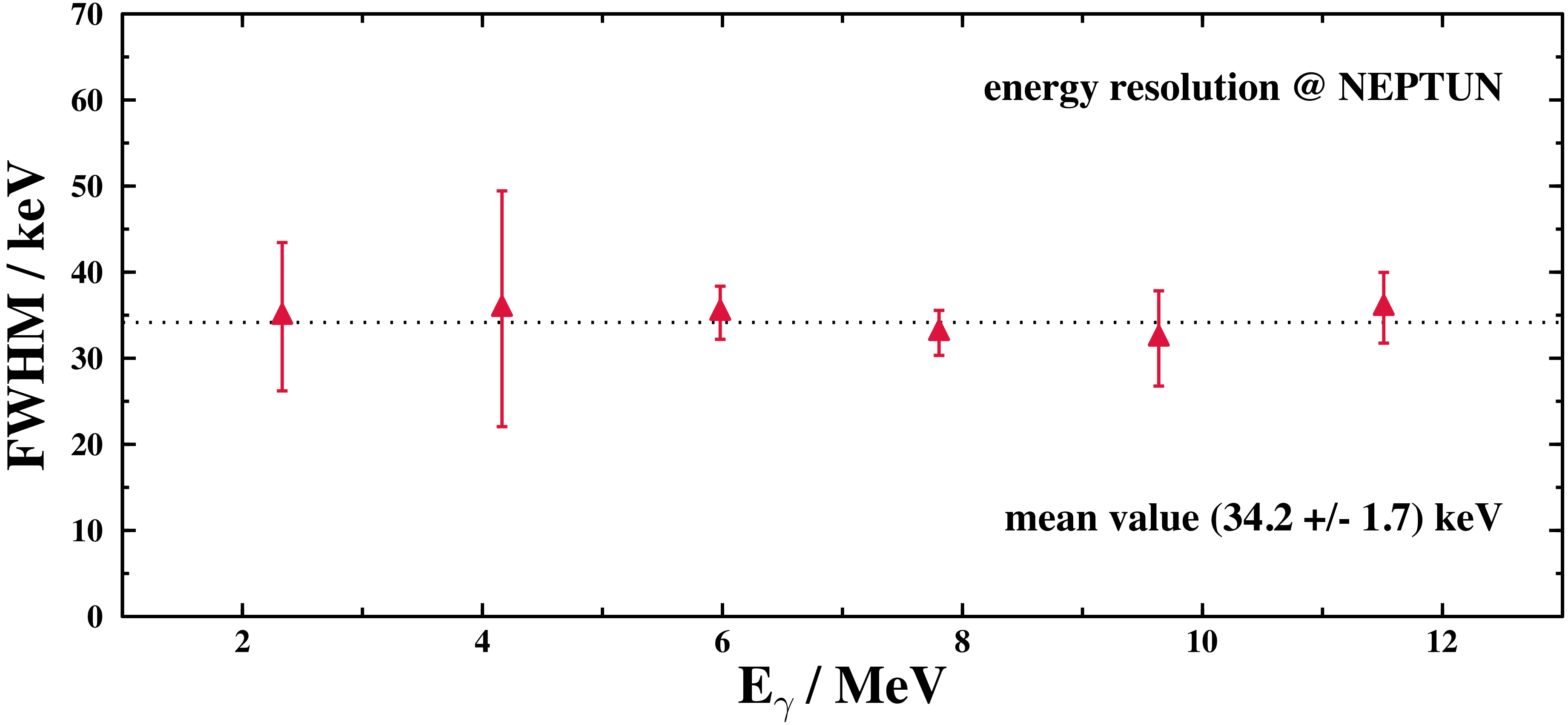
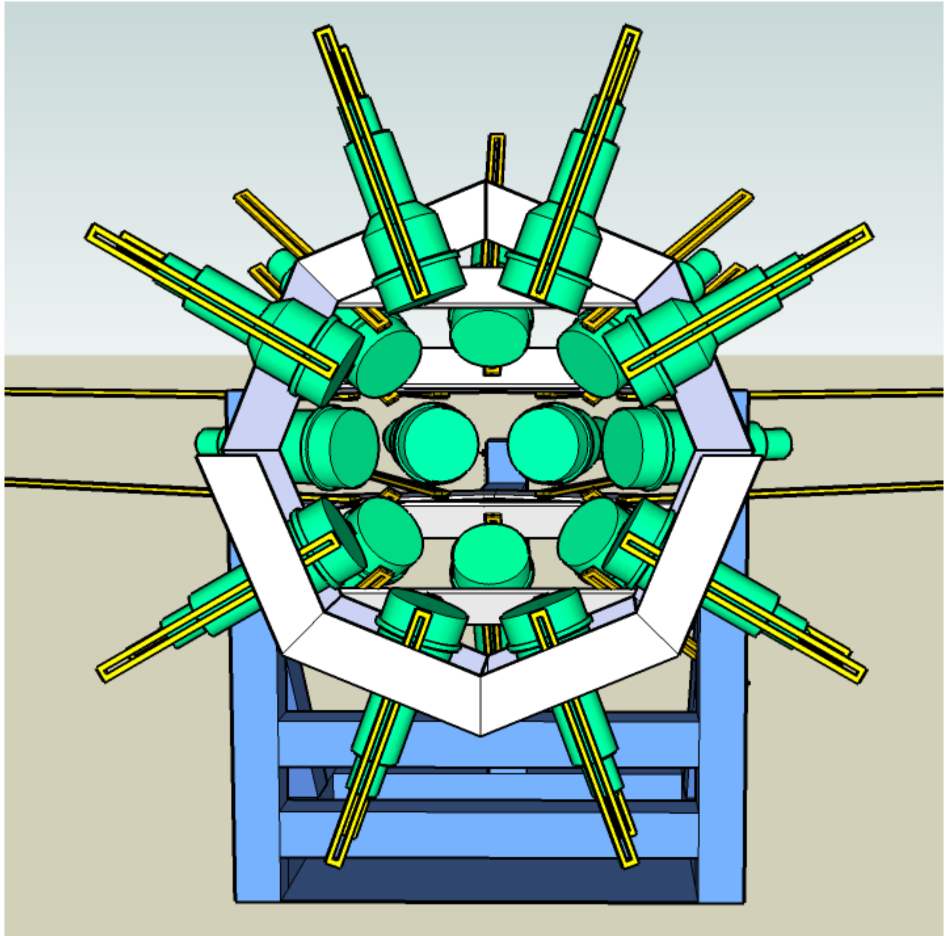


D. Savran *et al.*, Nucl. Instr. Meth. Phys. Res. A **613** (2010) 232

Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany

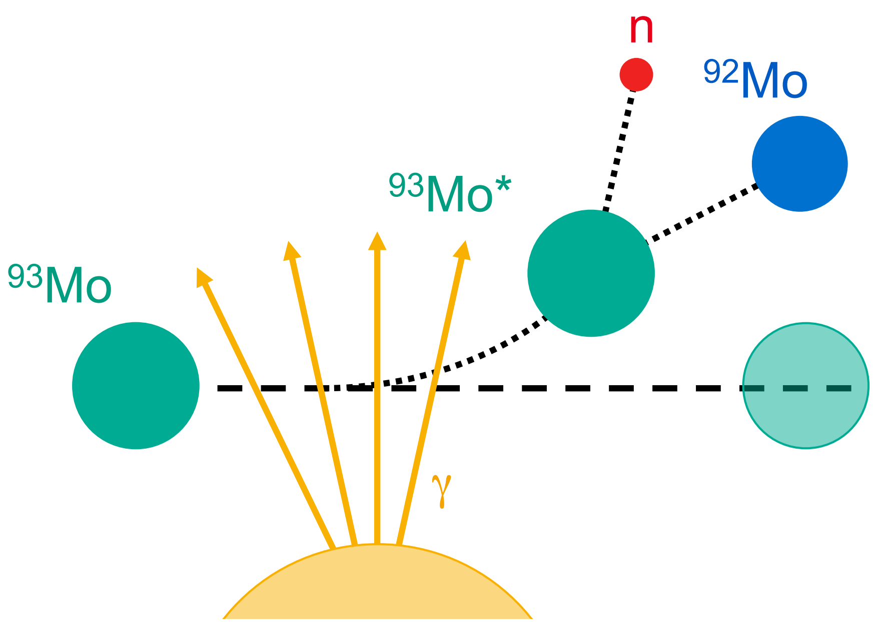
- 13 liquid scintillator neutron detectors
  (pulse shape discrimination)
- 4 additional ^{10}B loaded liquid scintillator detectors
  (discrimination by $^{10}B(n,\alpha)^{7}Li$)
- angular momentum (granularity) and energy of neutrons (TOF)
  → distinguish between decay to ground and excited states



V. Simon, M.Sc. Thesis & M. Duchêne, B.Sc. Thesis, TU Darmstadt

Other techniques: Virtual photons

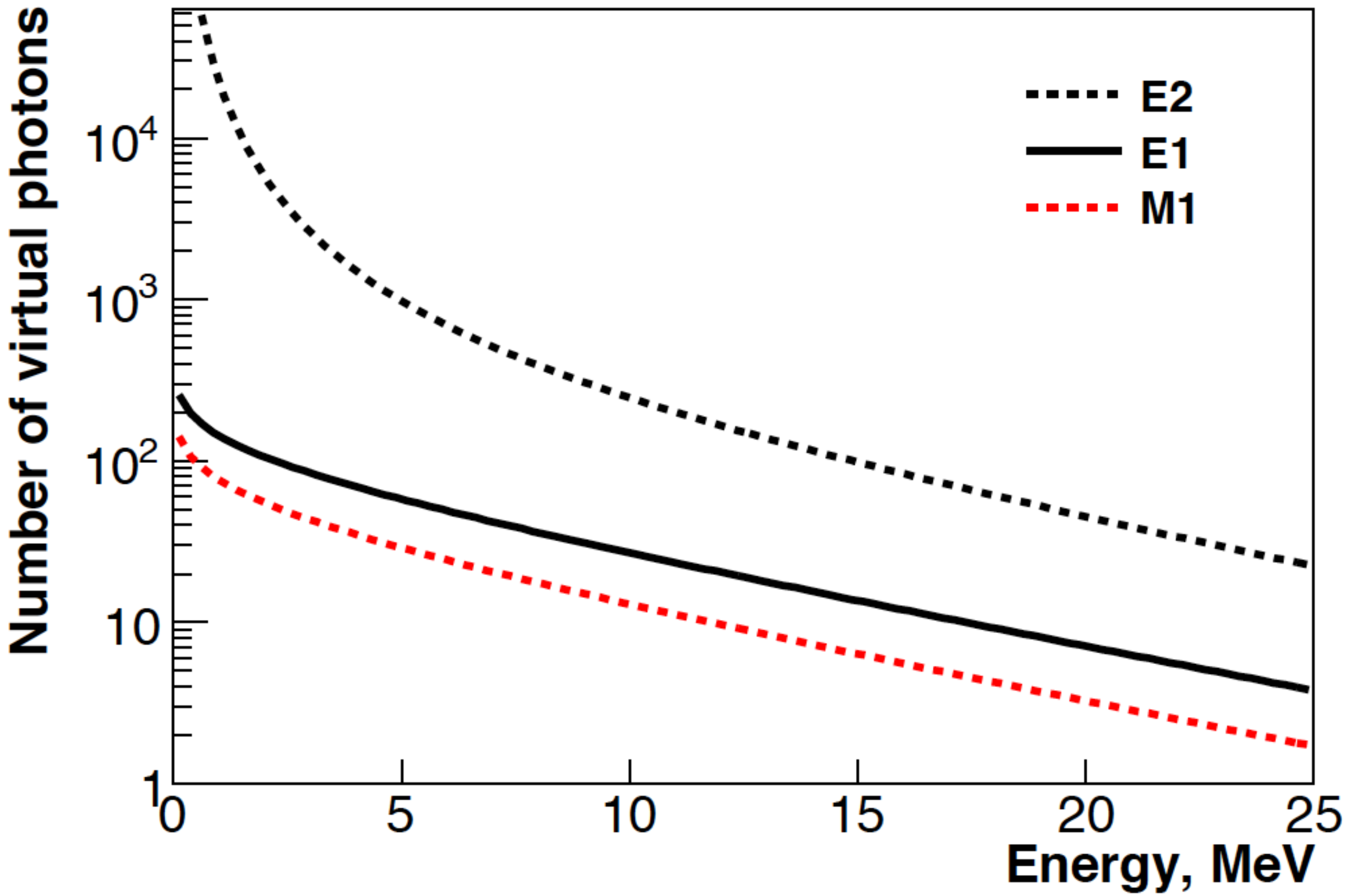
Coulomb dissociation in inverse kinematics @ LAND/R^3B



- CD cross section of Pb(^{93}Mo,^{92}Mo+n)Pb yields cross section of ^{93}Mo(γ,n)^{92}Mo
- Kinematically complete measurement needed
- Detection of all reaction products with energy information

Other techniques: Virtual photons

Coulomb dissociation in inverse kinematics @ LAND/R³B



O. Ershova, PhD thesis, Goethe-University Frankfurt

Other techniques: Virtual photons

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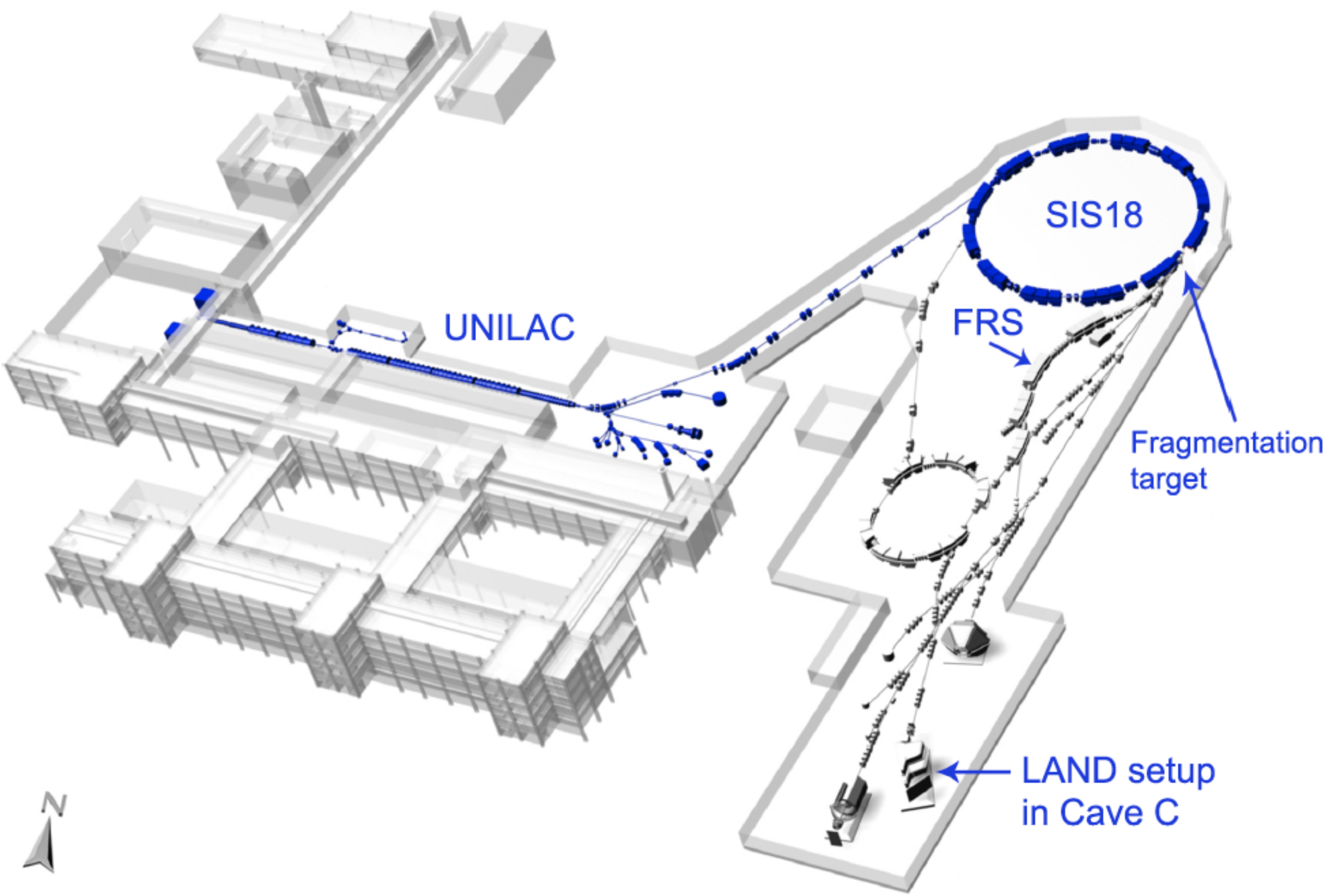

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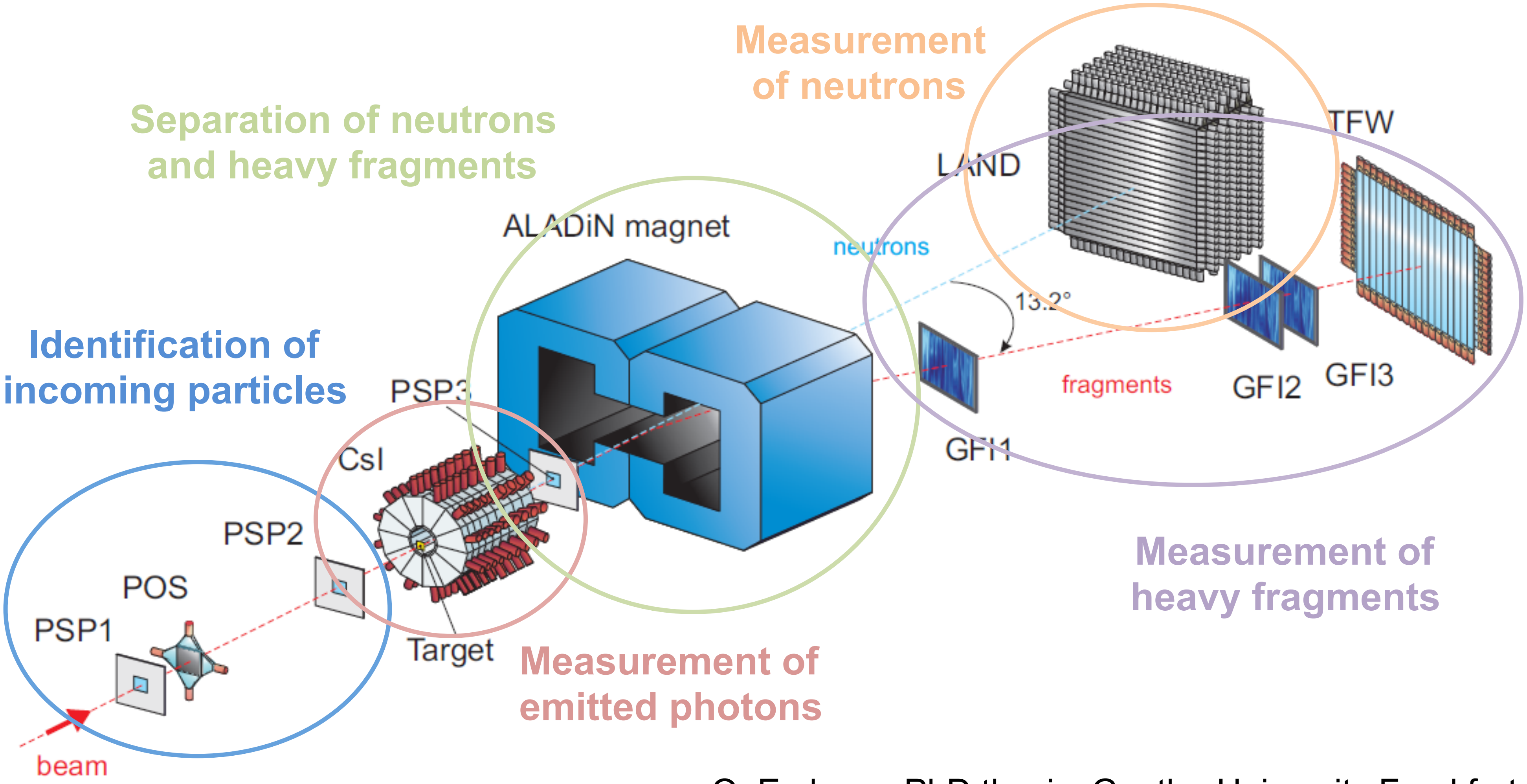

O. Ershova, PhD thesis, Goethe-University Frankfurt

Other techniques: Virtual photons

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Comparison to results with real photons

- ^{100}Mo(γ,n) measured & analysed at TU Darmstadt: results approve theoretical predictions

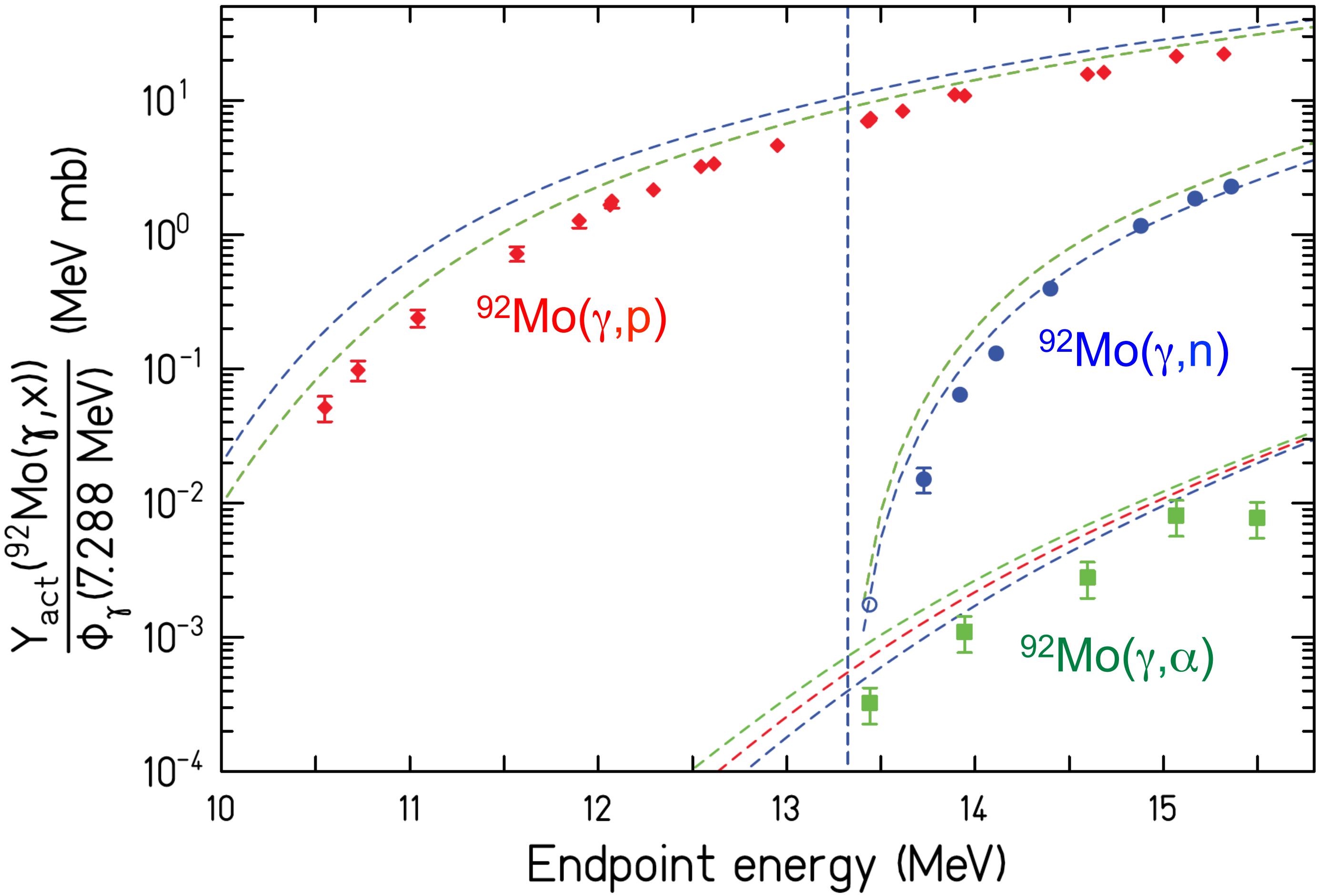
  I. Tews, B.Sc. Thesis, TU Darmstadt

- ^{92}Mo(γ,n) and ^{100}Mo(γ,n) measured & analysed at Helmholtzzentrum Dresden-Rossendorf:
  - ^{100}Mo(γ,n): results approve theoretical predictions
  - ^{92}Mo(γ,n): disentangle contribution of ^{92}Mo(γ,p), energy dependence of cross sections correctly predicted

  M. Erhard *et al.*, Phys. Rev. C **81** (2010) 034319

Other techniques: Virtual photons

Comparison to results with real photons



M. Erhard *et al.*, Phys. Rev. C **81** (2010) 034319

Other techniques: Virtual photons

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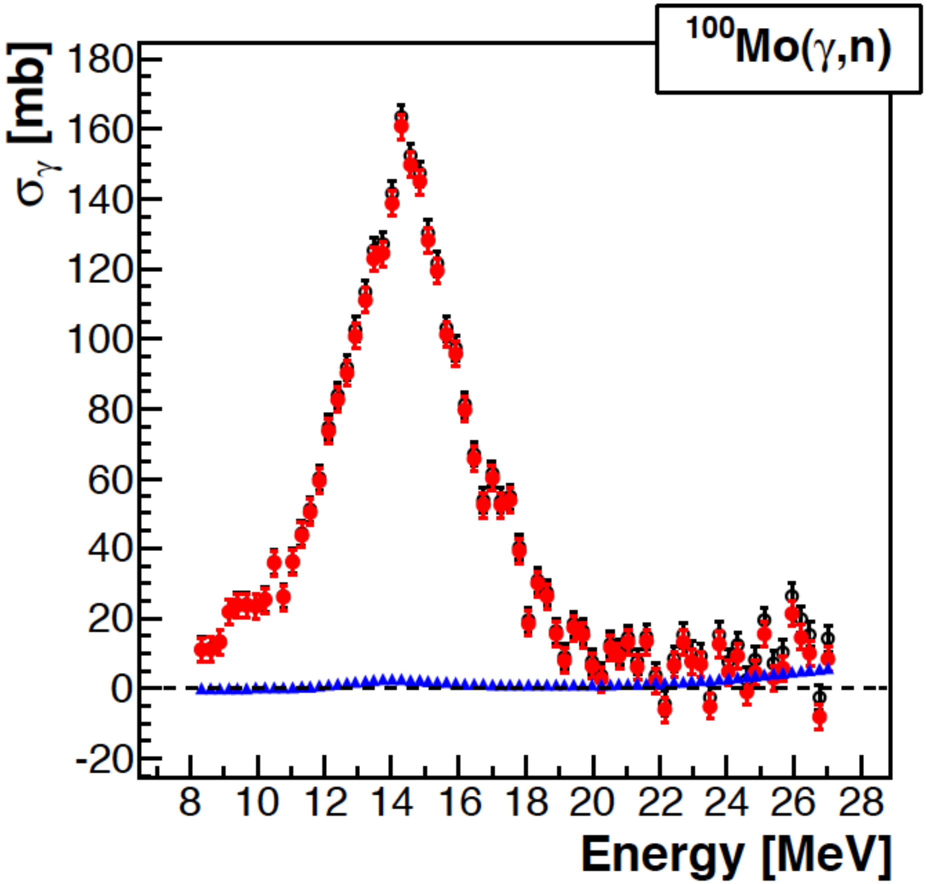
Comparison to results with real photons



H. Beil *et al.*, Nucl. Phys. A **227** (1974) 427

	^{100}Mo 1n		
	σ_{CE}, mb	Δ_{stat}, %	Δ_{syst}, %
This work	799	2	10
Beil et al.	997	1	6
$\sigma^{\text{This work}}/\sigma^{\text{Beil}}$	0.8 ± 0.1		
$\sigma^{\text{Erhard}}/\sigma^{\text{Beil}}$	0.89 ± 0.09		

- scaling factor compared to H. Beil *et al.* agrees within uncertainties for real and virtual photons

O. Ershova, PhD thesis, Goethe-University Frankfurt

Summary & Outlook

- Different photon sources offer a variety of experimental approaches
  - Activation with bremsstrahlung
  - In-beam with LCB photons
  - High-resolution studies with tagged photons
  - Study of unstable isotopes with CD in inverse kinematics

- New high-intense and high-resolution photon sources under development → ELI-NP @ Bucharest, Romania
- Extension of LAND/R^3B setup to measure ratios of $(\gamma,\alpha)/(\gamma,n)$ and $(\gamma,p)/(\gamma,n)$ reaction rates
- Determine (n,γ) cross section from data on (γ,n) reaction

Many thanks to...

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  S. Altstadt, C. Beinrucker, O. Ershova, M. Fonseca, M. Gilbert, J. Glorius, K. Göbel, T. Heftrich, A. Koloczek, S. Kräckmann, K. Landwehr, C. Langer, O. Meusel, M. Mikorski, R. Plag, M. Pohl, A. Rastrepina, R. Reifarth, C. Ritter, S. Schmidt, Z. Slavkovská, T. Thomas, M. Volknandt, and M. Weigand

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- Institut für Kernphysik, Universität zu Köln:

  M. Elvers, J. Endres, J. Hasper, A. Sauerwein, and A. Zilges

- GSI Helmholtzzentrum für Schwerionenforschung & FIAS:

  B. Löher, D. Savran, and C. Wälzlein

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