

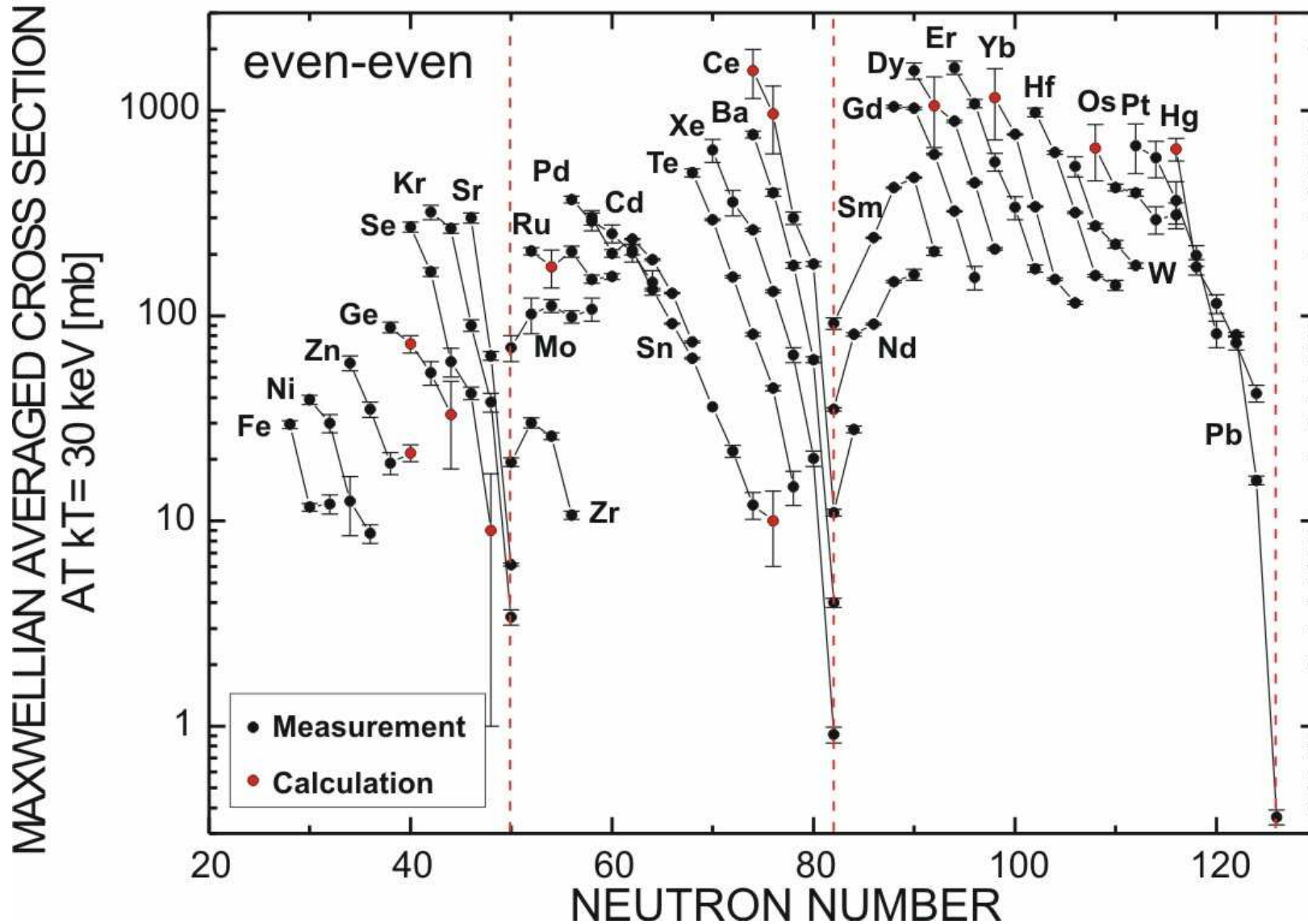
neutron capture data in the keV region

- milestones along the road
- state of the art: detectors, methods, and facilities
- outlook to future work

milestones in neutron capture measurements

1960s	pulsed VdG, eLINACs	MR & C ₆ D ₆ detectors	MCA, computers
1980s	spallation neutrons LAMPF	4 π BaF ₂ , activation	CAMAC, PC, MC simulations
2000...	n_TOF, J-PARC nELBE, FRANZ	AMS	fast digitizers

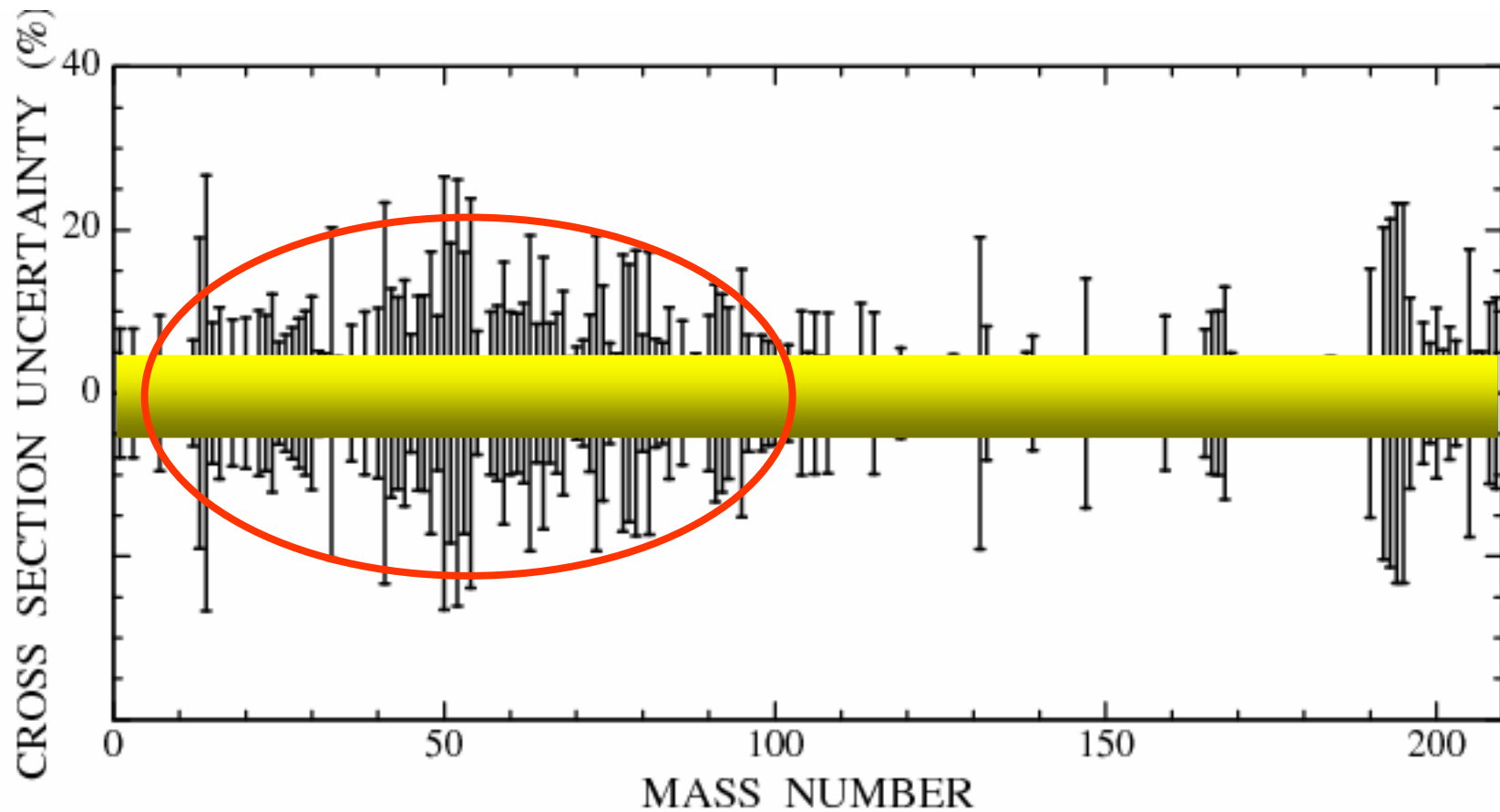
MACS data @ $kT=30$ keV



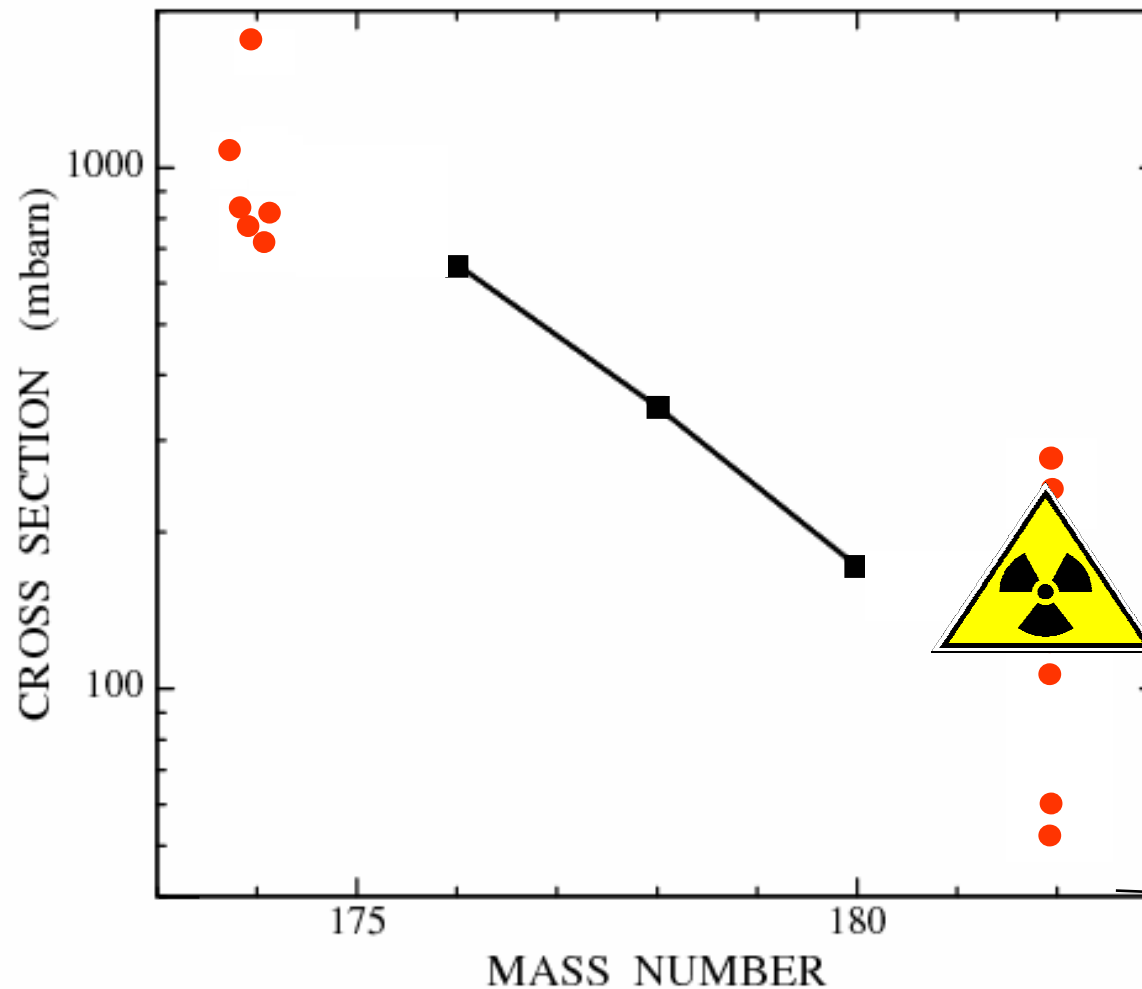
Brookhaven
CERN
Dubna
Geel
Gent
Harwell
Karlsruhe
Livermore
Los Alamos
Notre Dame
Oak Ridge
Obninsk
Rensselaer
Tokyo

status and requests

needed: cross sections with uncertainties between **1** and **5%**



what about theory?



^{176}Hf , ^{178}Hf , ^{180}Hf :
MACS uncertainties
1 - 2%

exercise joined
by 6 leading groups:
calculate MACS of
 ^{174}Hf and ^{182}Hf
prior to measurement

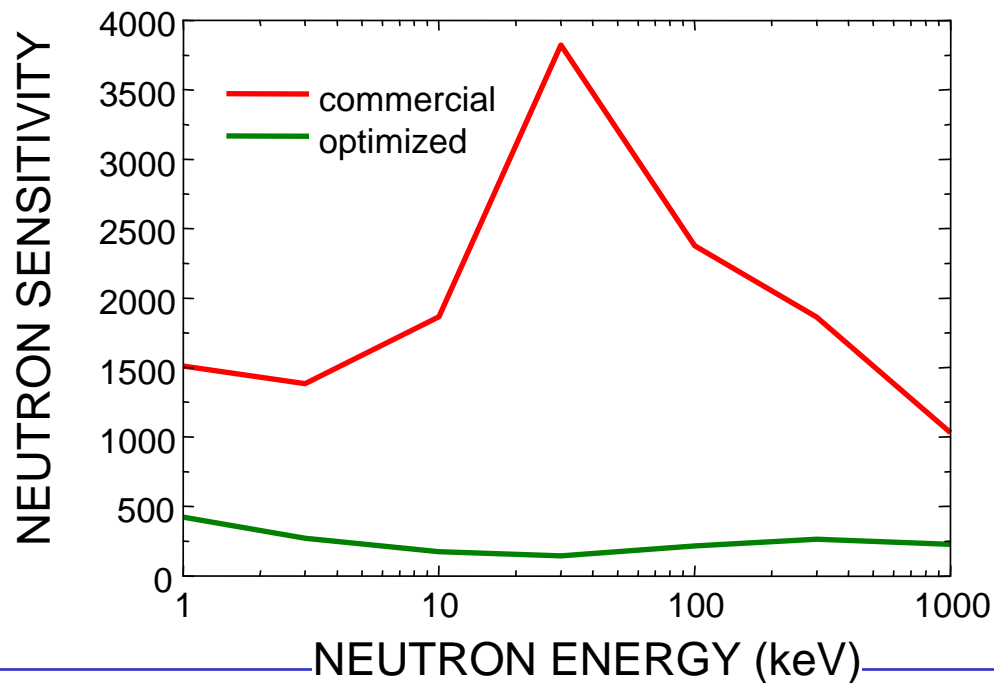
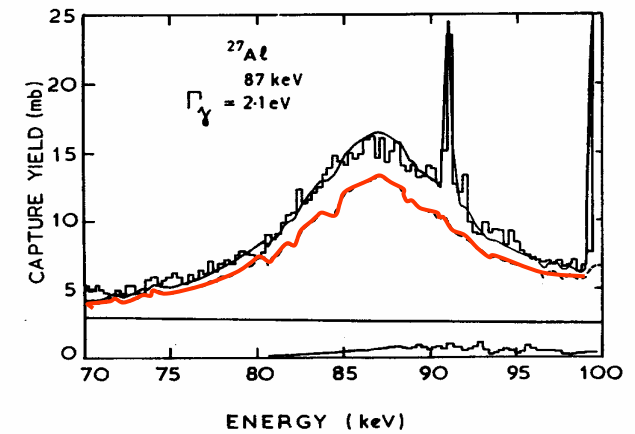
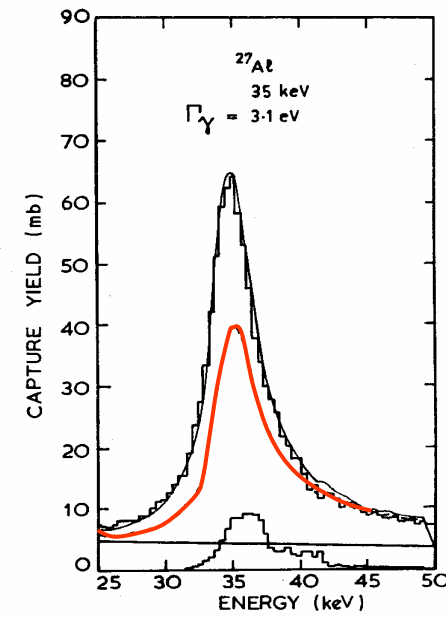
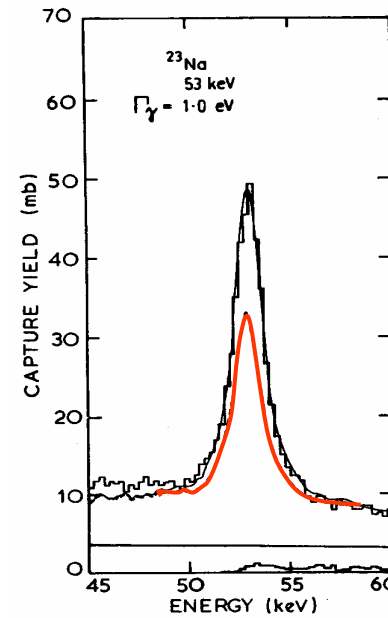
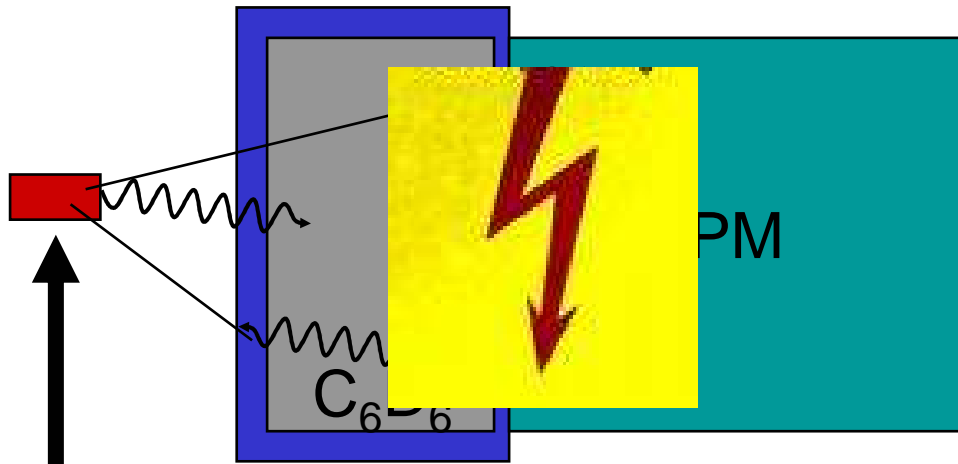
what determines **q**uality of (n, γ) data?

- **neutron source** (energy range, flux, resolution, backgrd)
- **samples** (available mass, purity, activity)
- **detectors** (resolution, efficiency, sensitivity)
- **data acquisition** (fast digitizers, off-line analyses)
- **data analysis** (simulations, R-matrix codes)
- **methodology** (TOF or activation)

state of the art γ -ray detectors

- efficiency: important for measurements of small cross sections and to compensate for sample mass or weak neutron neutron flux
- segmentation: multi-detector arrays for higher efficiency, angular distribution and background suppression, γ calorimeters (FZK, LANL, n_TOF)
- sensitivity: improved background suppression (C_6D_6 detectors)
- resolution: compromised by efficiency, high resolution **HPGe** detectors crucial for activation measurements

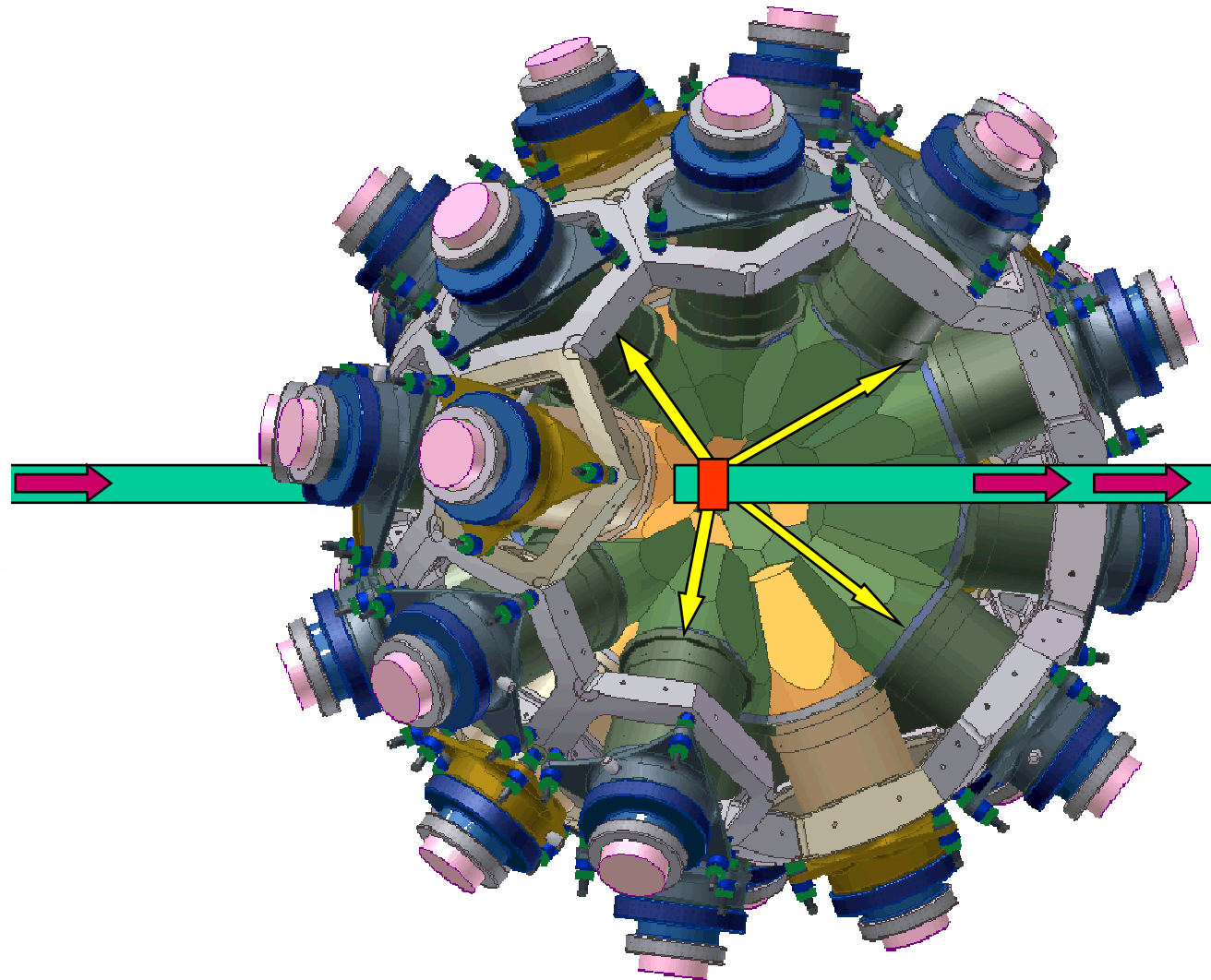
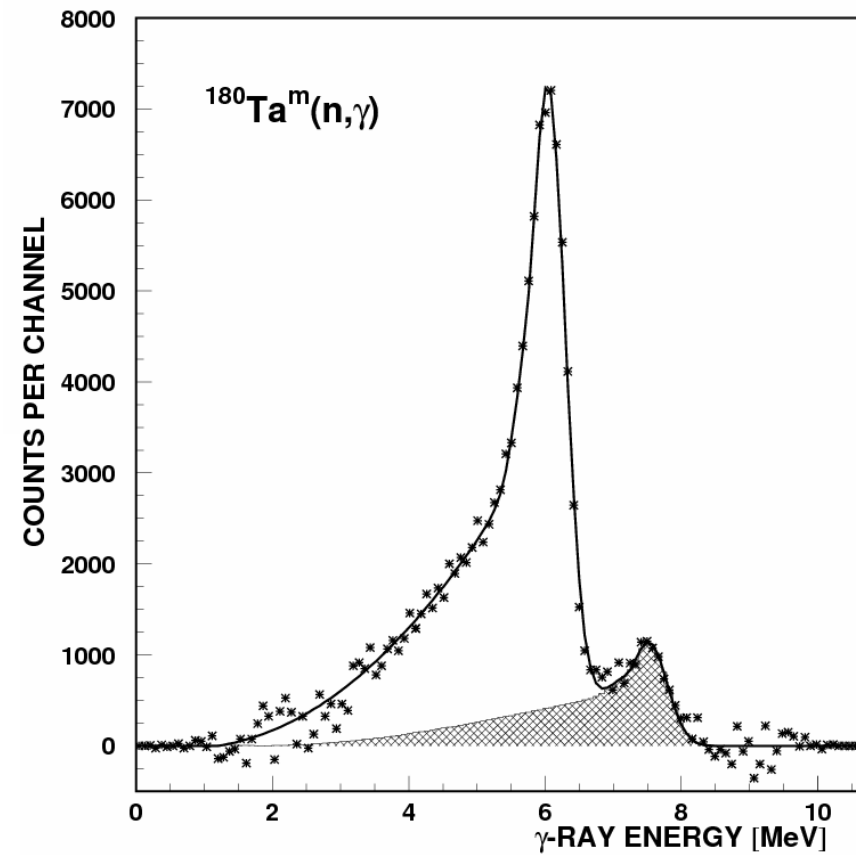
optimized detectors: C_6D_6



neutrons

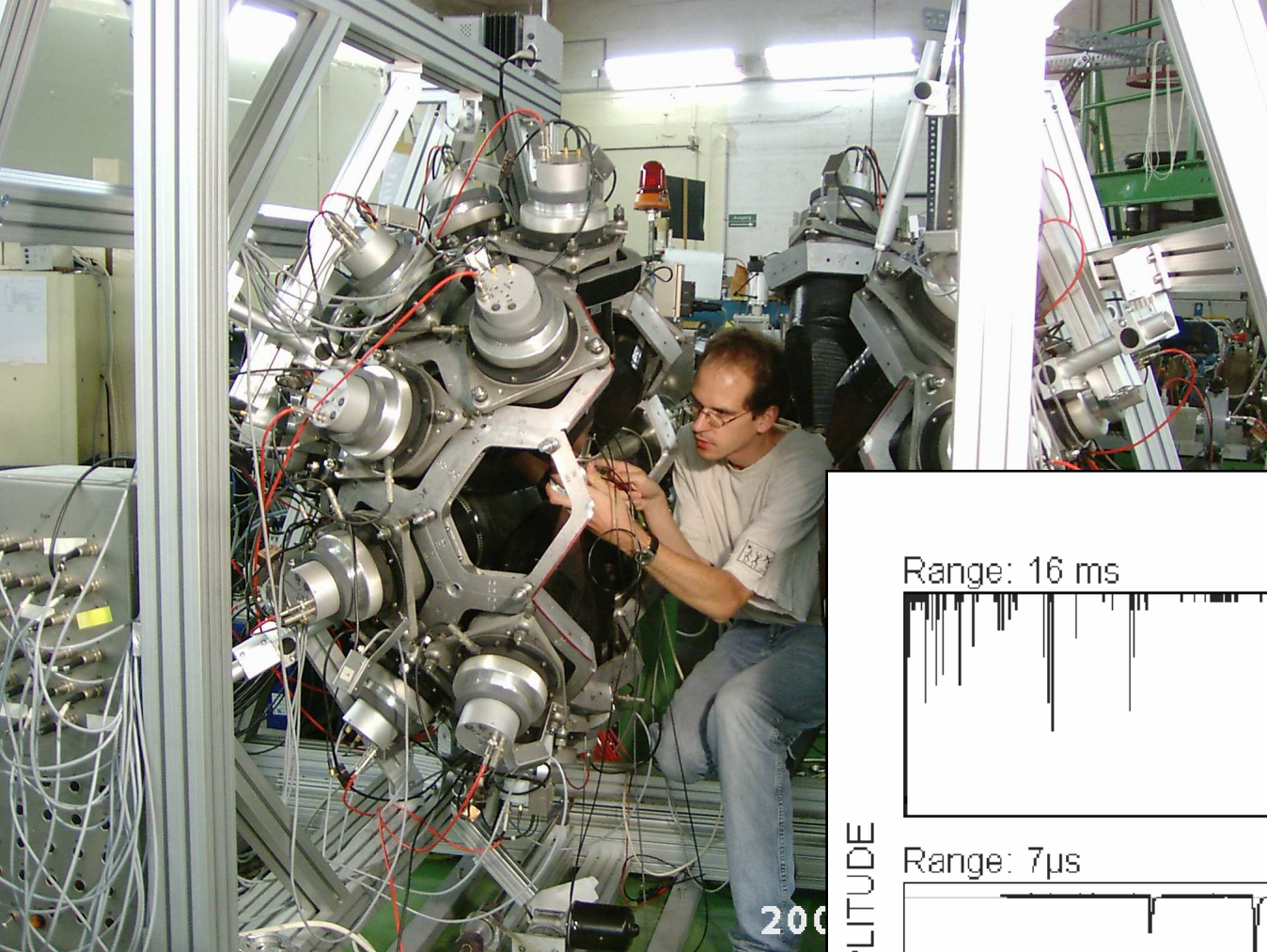
γ -ray calorimeters & simulations

42 independent modules
in total 60 l of BaF₂

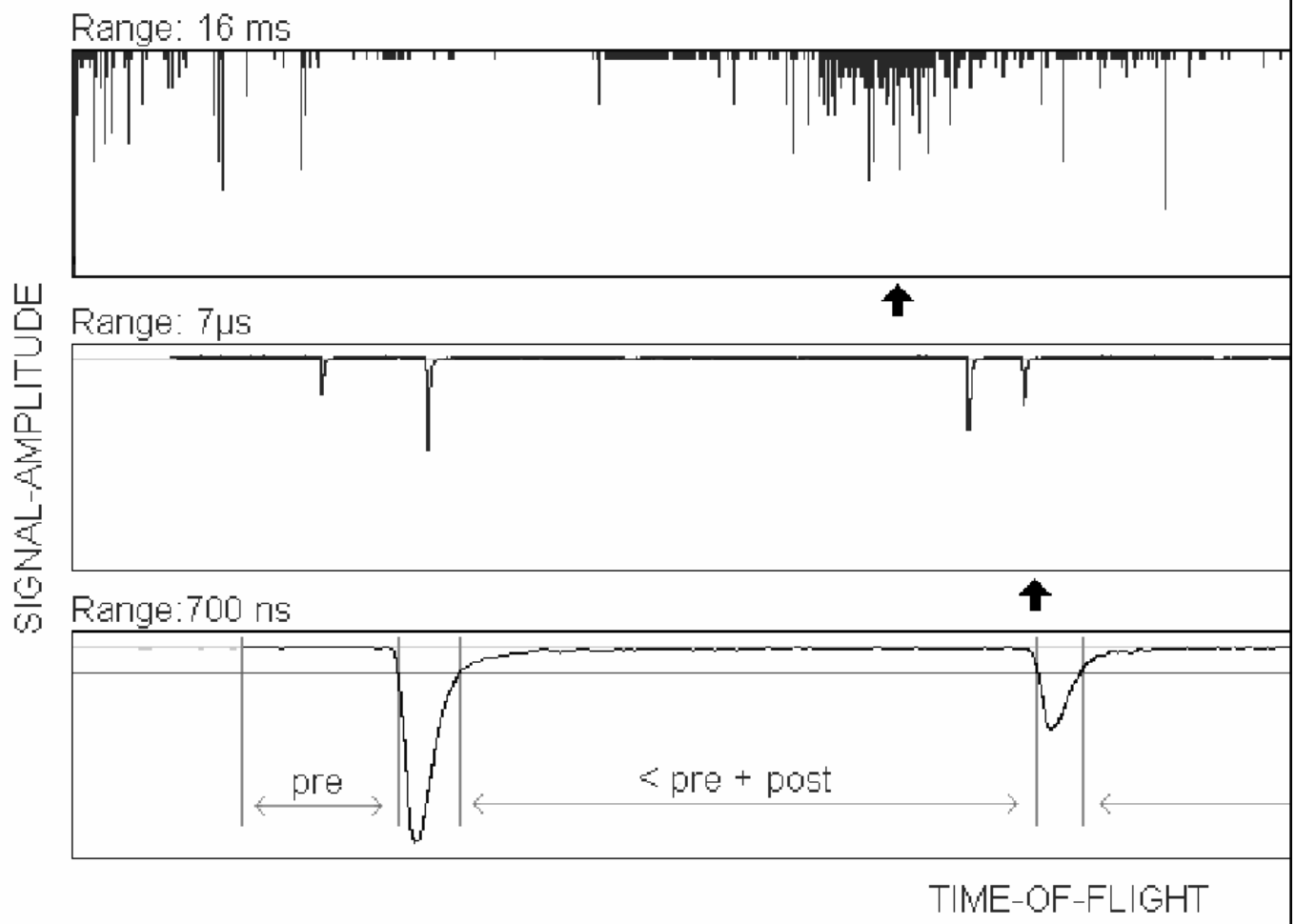


data acquisition and analysis

- completeness: data taking with flash-ADC for flexible and comprehensive off-line analysis (fast digitizers for recording full detector response, e.g. over 16 ms with 500 MS/s)
- simulations: MCNP and GEANT are becoming standard tools for planning of experiments and – necessarily - for the analysis of cross section measurements with complex detector arrays



signals from a single n_TOF
neutron burst recorded with
fast digitizer



200

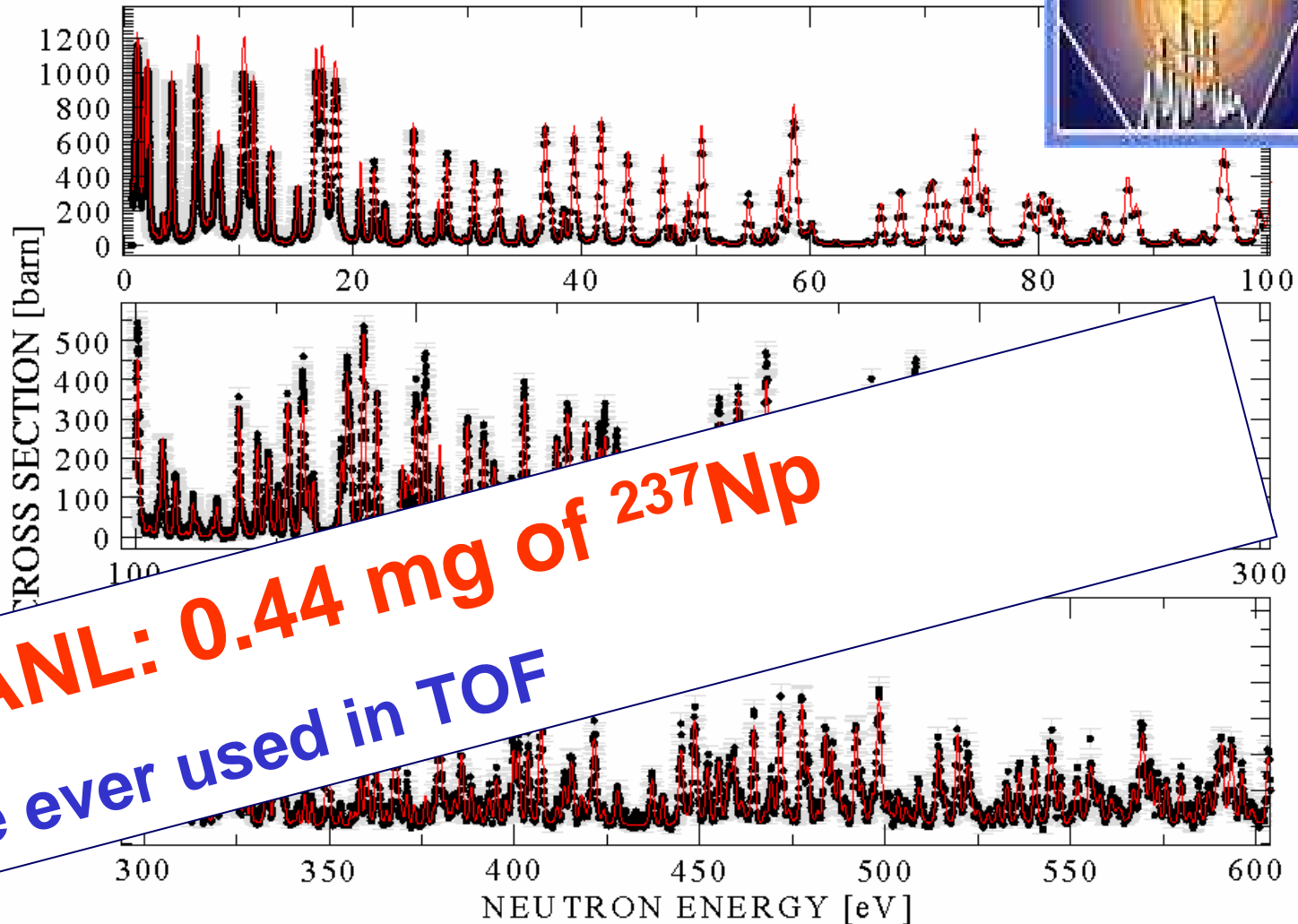
resolution & sensitivity

$^{151}\text{Sm}(n,\gamma)$



➔ more than
200 „new“ resonances

important for obtaining
level densities & strength
functions for improved
Hauser-Feshbach
calculations



recently at LANL: 0.44 mg of ^{237}Np
smallest sample ever used in TOF

comparison of pulsed neutron sources

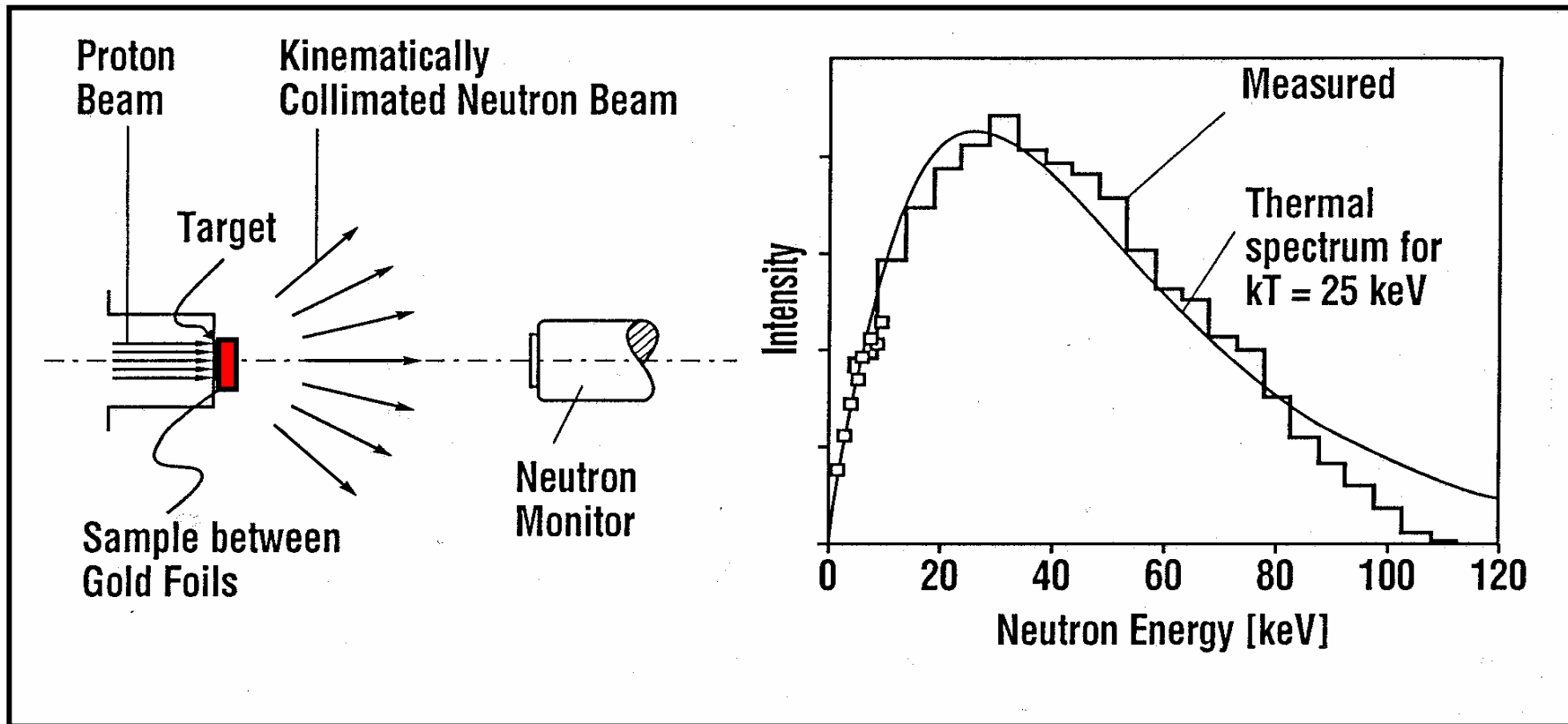
Facility	Neutron flux at sample [cm ⁻² s ⁻¹ dec ⁻¹]	Repetition rate [Hz]	Flight path [m]	Pulse width [ns]	Neutron energy range [eV]
Karlsruhe	$1 \cdot 10^4$	250K	0.8	0.7	$10^3 - 2 \cdot 10^5$
LANSCCE at Los Alamos	$5 \cdot 10^5$	20	20	250	th 10^5
n_TOF at CERN	$5 \cdot 10^4$	0.4	185	6	th 10^6
GELINA at Geel	$5 \cdot 10^4$	800	30	1	th 10^6
ORELA at Oak Ridge	$2 \cdot 10^4$	525	40	8	th 10^6

new facilities and upgrades

Frankfurt	$1 \cdot 10^7$	250K	0.8	<1	$10^3 - 2 \cdot 10^5$
J-PARC	$5 \cdot 10^6$	25	15	100	th 10^5
LANSCCE upgrade	$5 \cdot 10^6$	20	20	250	th 10^5
n_TOF at CERN	$3 \cdot 10^6$	0.4	185	6	th 10^6
Spiral-2	$3 \cdot 10^5$	88M	5	0.1	$10^5 - 10^6$

activation technique at $kT=25$ keV

- neutron production via ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction at Van de Graaff
- induced activity measured with HPGe detectors



- **possible when product nucleus is radioactive**
- **very high sensitivity → small samples & small cross sections**
- **use of natural samples possible, no enriched sample necessary**
- **Direct Capture component included**

activation: unique sensitivity

4-5 orders of magnitude higher flux than best TOF facilities!

→ measurement of **μbarn** cross sections

→ measurements with **ng** samples,
important for cross sections of unstable isotopes

28 ng ^{147}Pm

activation versus TOF

Facility	Neutron flux at sample [cm ⁻² s ⁻¹ dec ⁻¹]	Repetition rate [Hz]	Flight path [m]	Pulse width [ns]	Neutron energy range [eV]
Karlsruhe, TOF	$1 \cdot 10^4$	250K	0.8	0.7	10^3 - $2 \cdot 10^5$
LANSCCE at Los Alamos	$5 \cdot 10^5$	20	20	250	th 10^5
Karlsruhe, activation	$3 \cdot 10^9$				10^3 - $2 \cdot 10^5$

Frankfurt	$1 \cdot 10^7$	250K	0.8	<1	10^3 - $2 \cdot 10^5$
J-PARC	$5 \cdot 10^6$	25	15	100	th 10^5
LANSCCE upgrade	$5 \cdot 10^6$	20	20	250	th 10^5
Frankfurt, activation	$1 \cdot 10^{12}$				10^3 - $2 \cdot 10^5$

future strategies

key cross sections need to be checked

- **discrepancies:** different methods show inconsistent results
- **uncertainties:** in „historic“ data often underestimated or not recognized

state of the art techniques mandatory

- **facilities:** spallation sources LANSCE, n_TOF, J-PARC, intense low energy accelerators or eLINACS
- **detectors:** optimized and highly segmented 4π arrays
- **DAQ:** fast digitizers for recording full information
- **analysis:** GEANT and MCNP simulations

complementary measurements

- **redundancy:** measurement and data analysis repeated with different perspectives
- **consistency:** combination of independent experiments (e.g. TOF and activation/AMS)
- **sensitivity:** better accuracy, small and unstable samples

thank you

how good are current data?

$^{151}\text{Sm}(n,\gamma)$

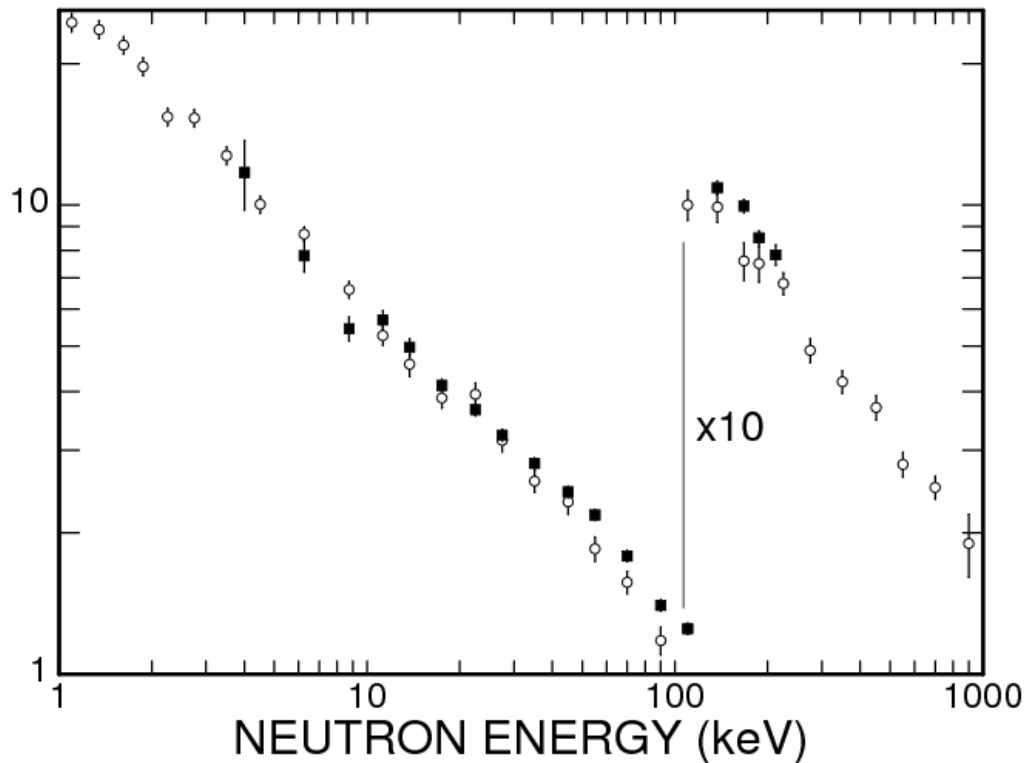


- 150 mg
- $t_{1/2} = 93$ yr, **156 GBq**

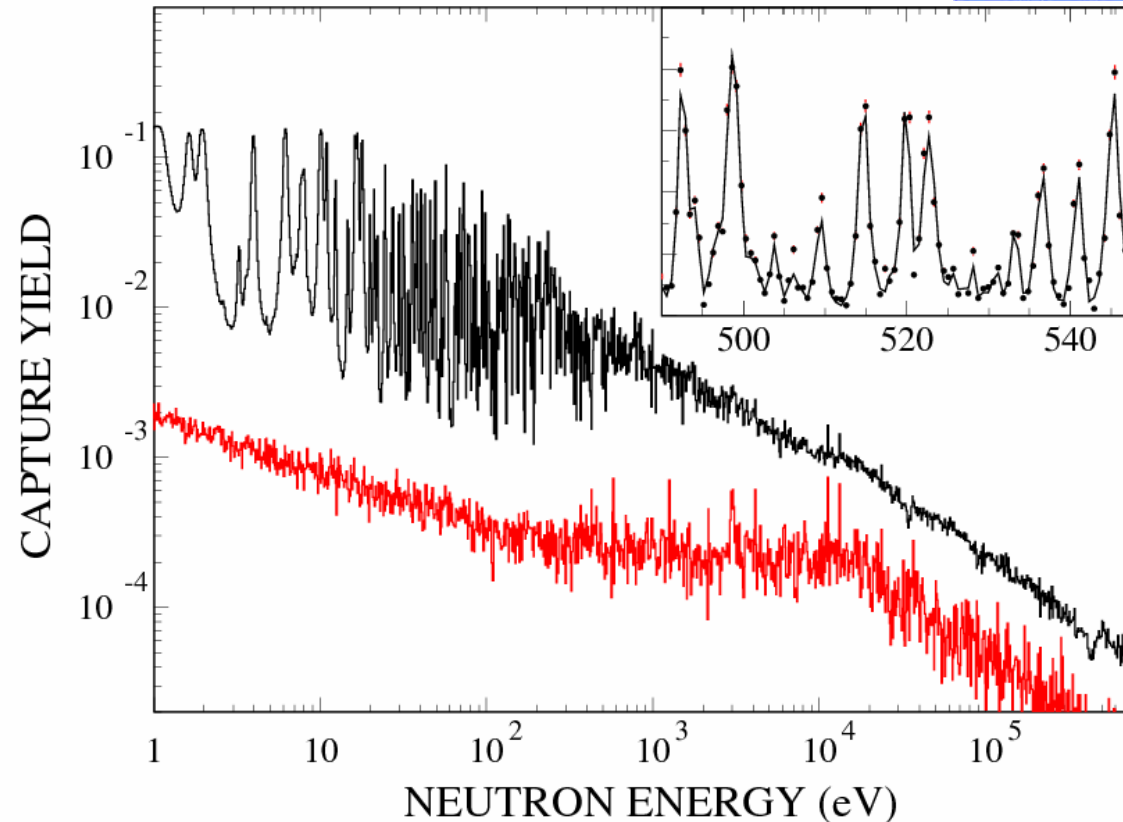


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

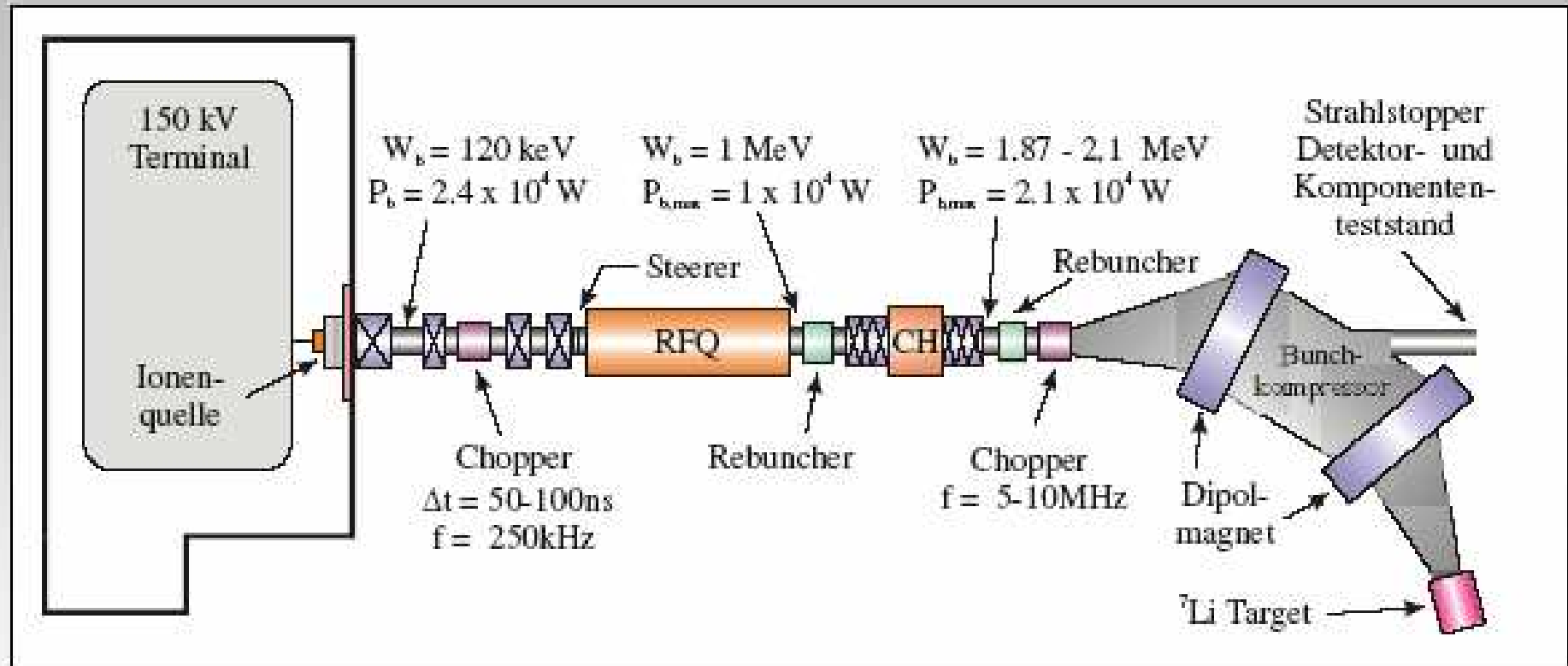
$\pm 2.4\%$



$\pm 4.5\%$



the Frankfurt Neutron source at the SGZ



$$E_p = 1.9 - 2.4 \text{ MeV}, \Delta t = 1 \text{ ns}$$

TOF mode: 250 kHz, 2 mA **or** CW mode: 175 MHz, 200 mA

n_TOF measurements on Zr isotopes



C Moreau for the n_TOF collaboration, ND2004, Santa Fe

