



# Future research program on prompt $\gamma$ -ray emission in nuclear fission

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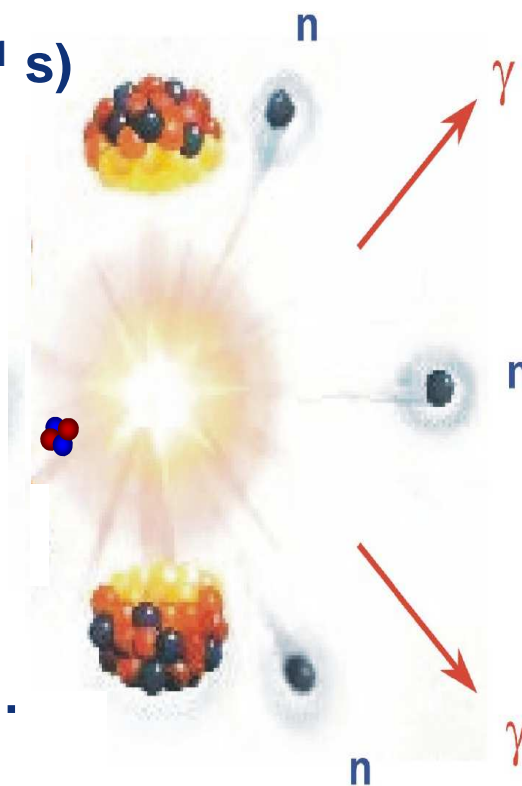
- **Introduction – the problem**
- **Renaissance of PFG measurements**
- **Recent achievements**
- **Problem solved?**
- **Further data needs → future instruments**

# The fission process

prompt neutrons ( $10^{-18}$  s)

fission fragments ( $10^{-21}$  s)

prompt  $\gamma$ -rays ( $10^{-16}$  s)



ternary  $\alpha$ , t, d,  $^{10}\text{Be}$ ...

kinetic energy  
prompt  $\gamma$ -rays

heat

prompt neutrons  
(delayed neutrons)

chain reaction

ternary  $\alpha$ , t, d

gas production  
in the fuel (waste)

fission fragments

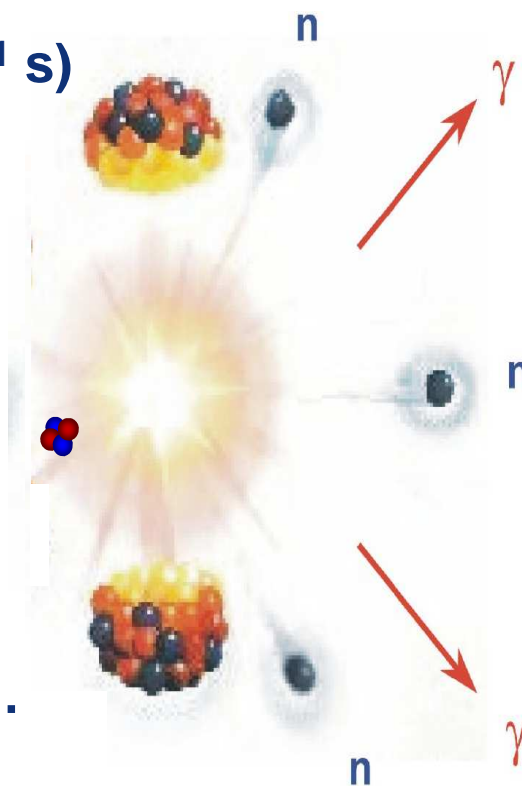
decay heat,  
toxicity (waste)

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kinetic energy	}	heat
prompt $\gamma$ -rays		
prompt neutrons (delayed neutrons)	}	chain reaction
ternary $\alpha$ , t, d		
fission fragments	}	gas production in the fuel (waste) decay heat, toxicity (waste)

- **Prediction of  $\gamma$ -heating for design of Gen-IV reactors**
  - About 10 % of total energy released in the core of a standard nuclear reactor by fission  $\gamma$ -rays
  - Around 40 % of those due to prompt  $\gamma$ -decay of fission products
  
- **Modelling requires uncertainty not larger than 7.5 % ( $1\sigma$ )**
  - By then: available  $\gamma$ -ray emission data determined in **early 1970' s**,
  - **Under-prediction of  $\gamma$ -heating by 10 - 28 % for  $^{235}\text{U}$  and  $^{239}\text{Pu}$**
  
- ⇒ **OECD/NEA Nuclear Data HPRL (H:3,H:4):**
  - ⇒ measurement of prompt  $\gamma$ -ray emission from  $^{235}\text{U}(n,f)$  and  $^{239}\text{Pu}(n,f)$

- Spectral mean  $\gamma$ -ray energy/fission

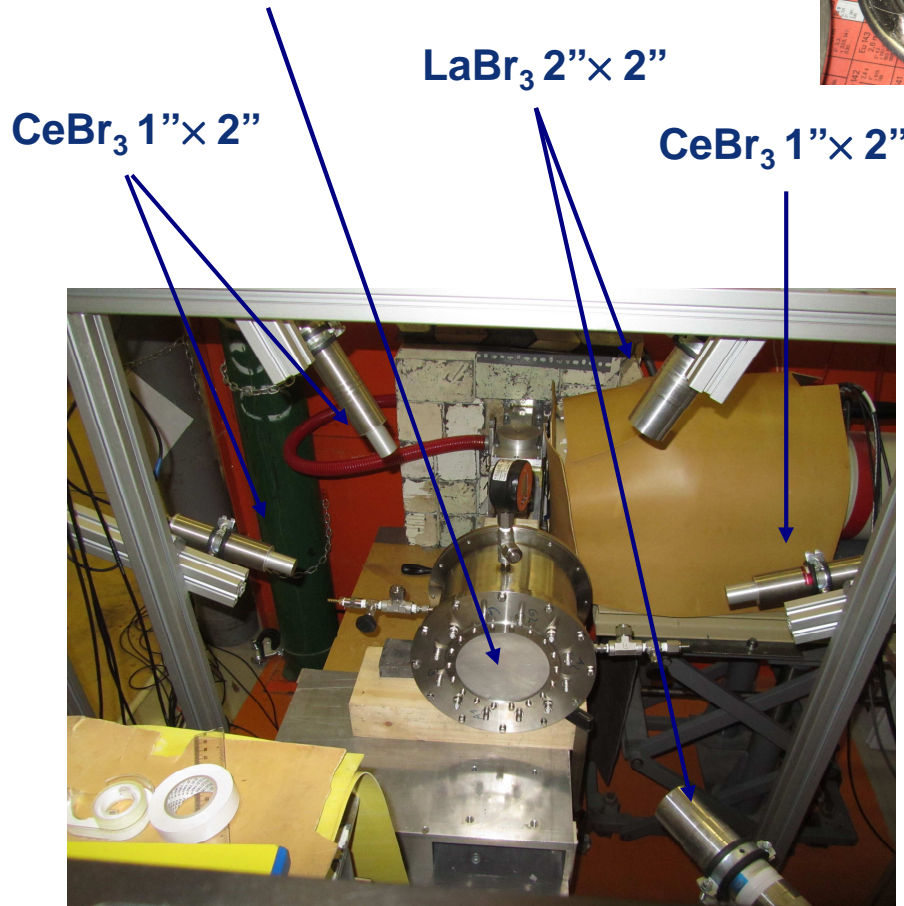
$\gamma$ -ray multiplicity

- Total  $\gamma$ -ray energy per fission
- Correlation with fission fragment properties ( $A$ , TKE,  $\nu_n$ )
- Dependence on excitation energy ( $E_n = 25 \text{ meV} - 10 \text{ MeV}$ )

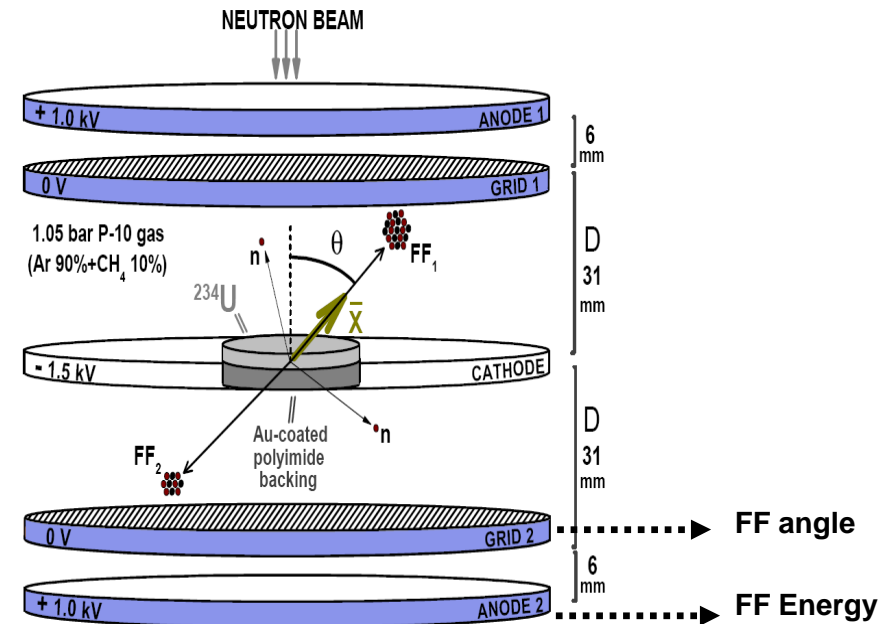
- **Cerium-doped lanthanum chloride ( $\text{LaCl}_3:\text{Ce}$ )**
- **Cerium-doped lanthanum bromide ( $\text{LaBr}_3:\text{Ce}$ )**
- **Cerium bromide ( $\text{CeBr}_3$ )**
  
- **High intrinsic peak efficiency, (high) energy resolution, excellent timing-resolution for efficient neutron/ $\gamma$ -ray discrimination (TOF)**

# Renaissance of PFG measurements

## Twin Frisch-grid ionization chamber

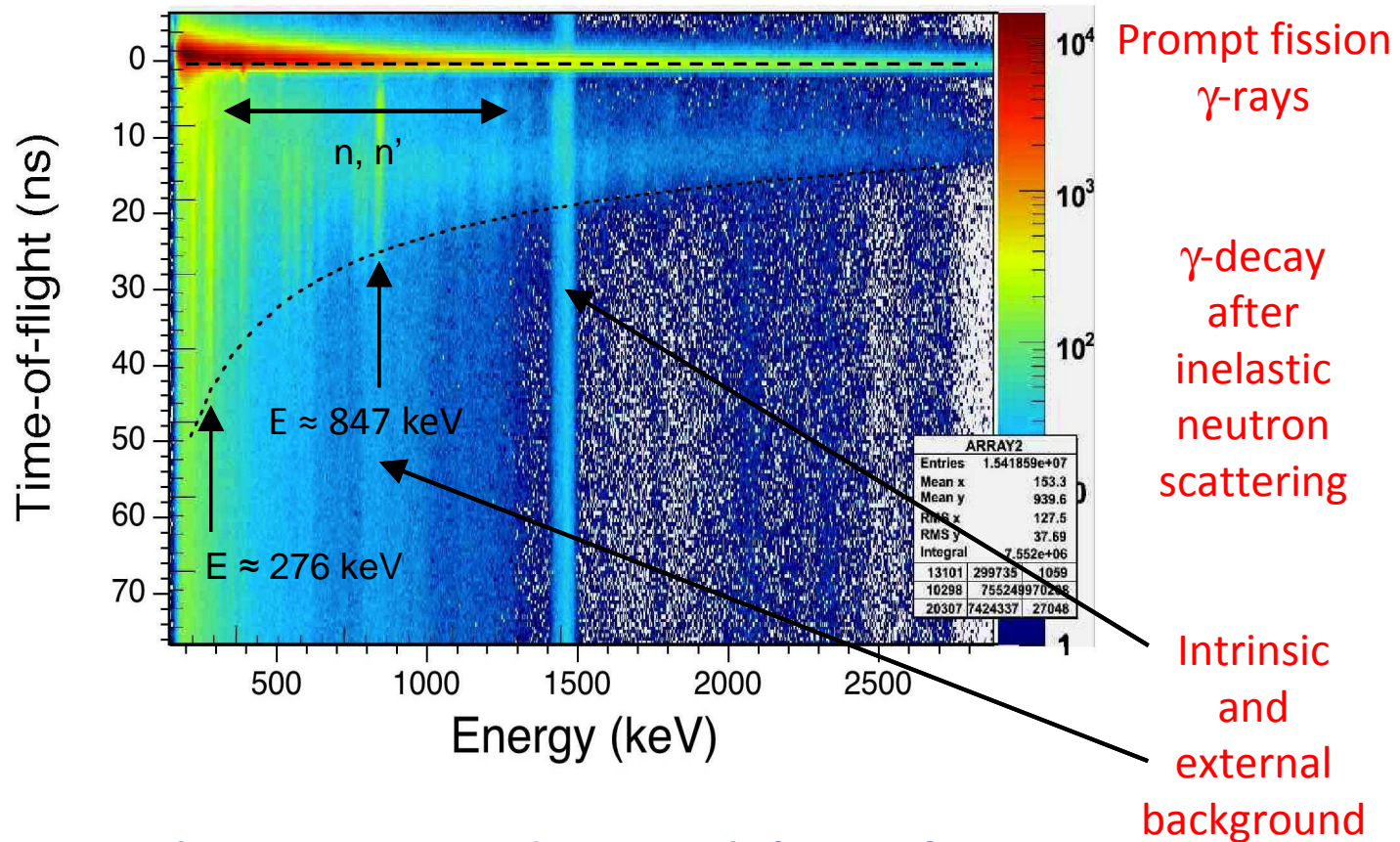


- active sample on polyimide backing
- backing only 30 μg/cm<sup>2</sup> thick
- Vacuum deposition, molecular plating
- <sup>232</sup>Th, <sup>233-238</sup>U, <sup>239,241</sup>Pu (IRMM SP group)

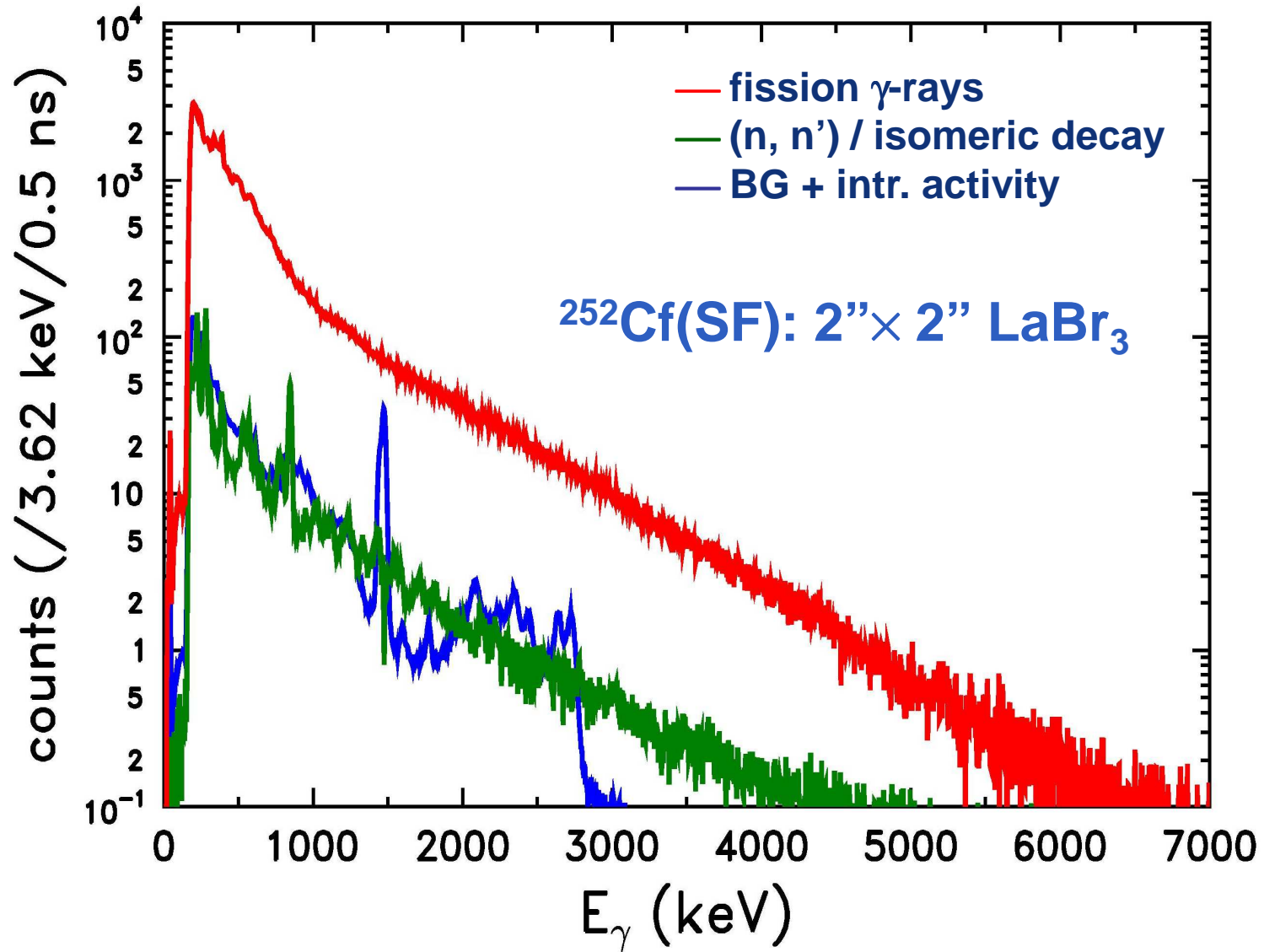




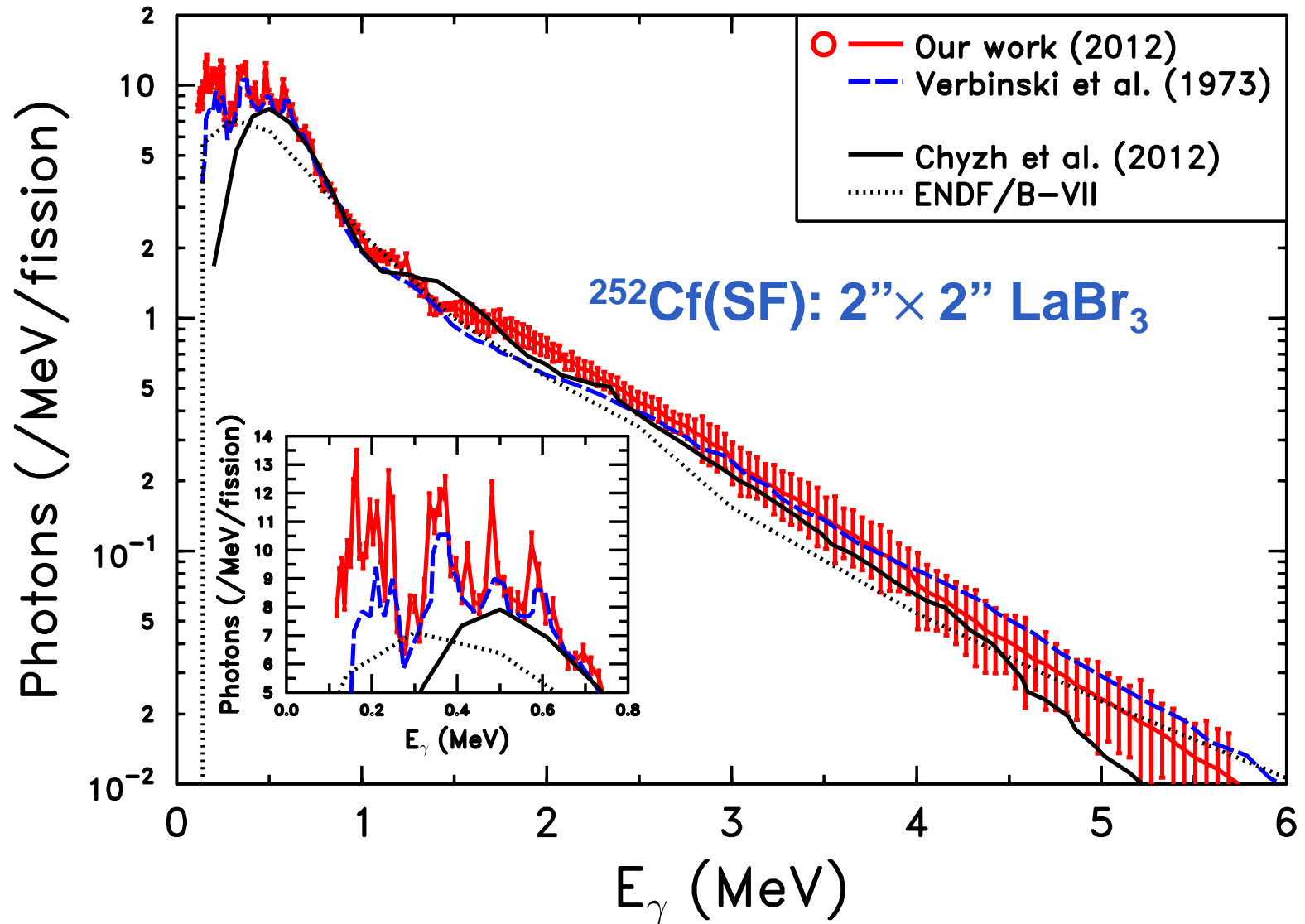
# Renaissance of PFG measurements



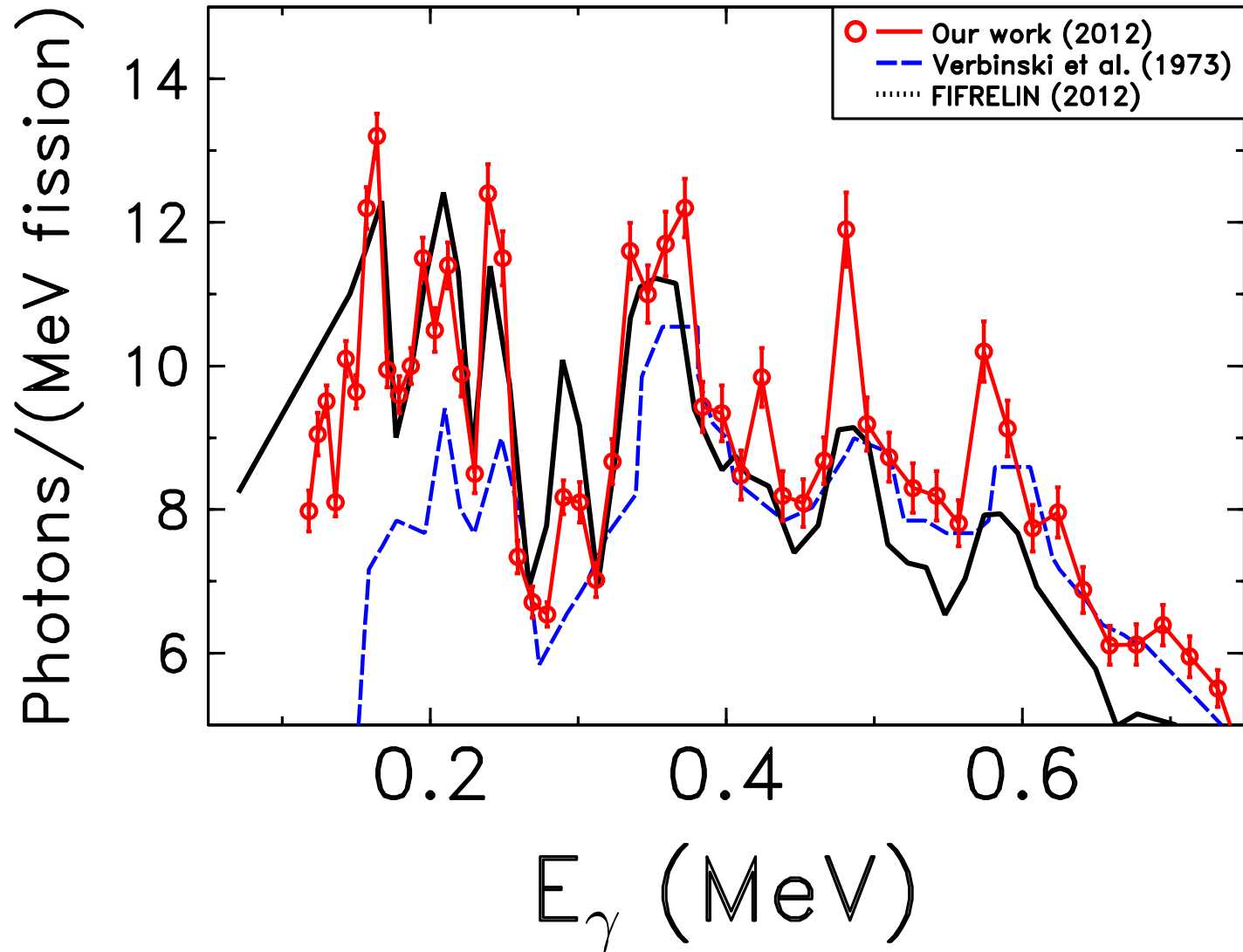
Photons in coincidence with fission fragments



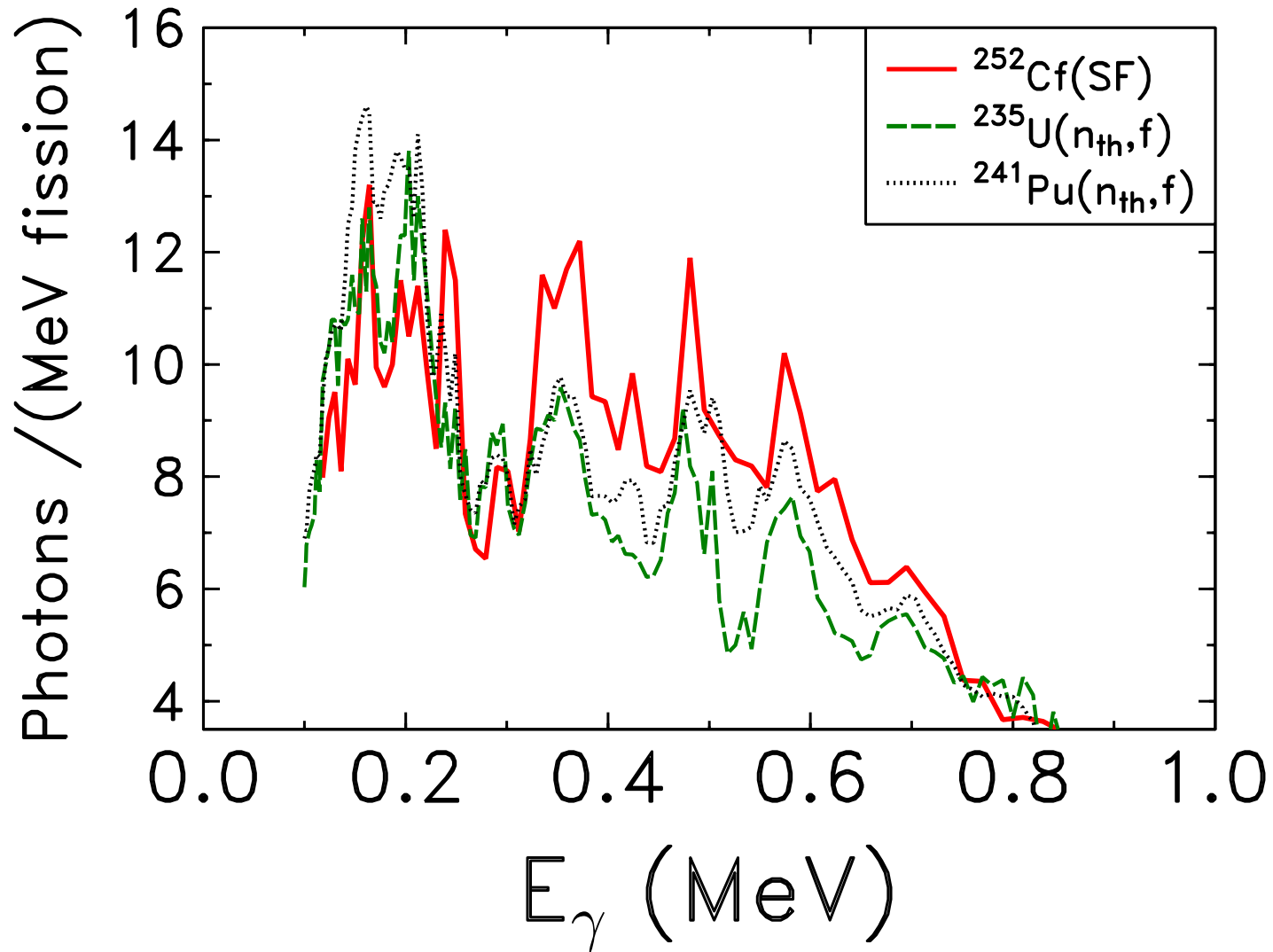
# Recent achievements



# Recent achievements



# Recent achievements



PhD thesis work of R. Billnert

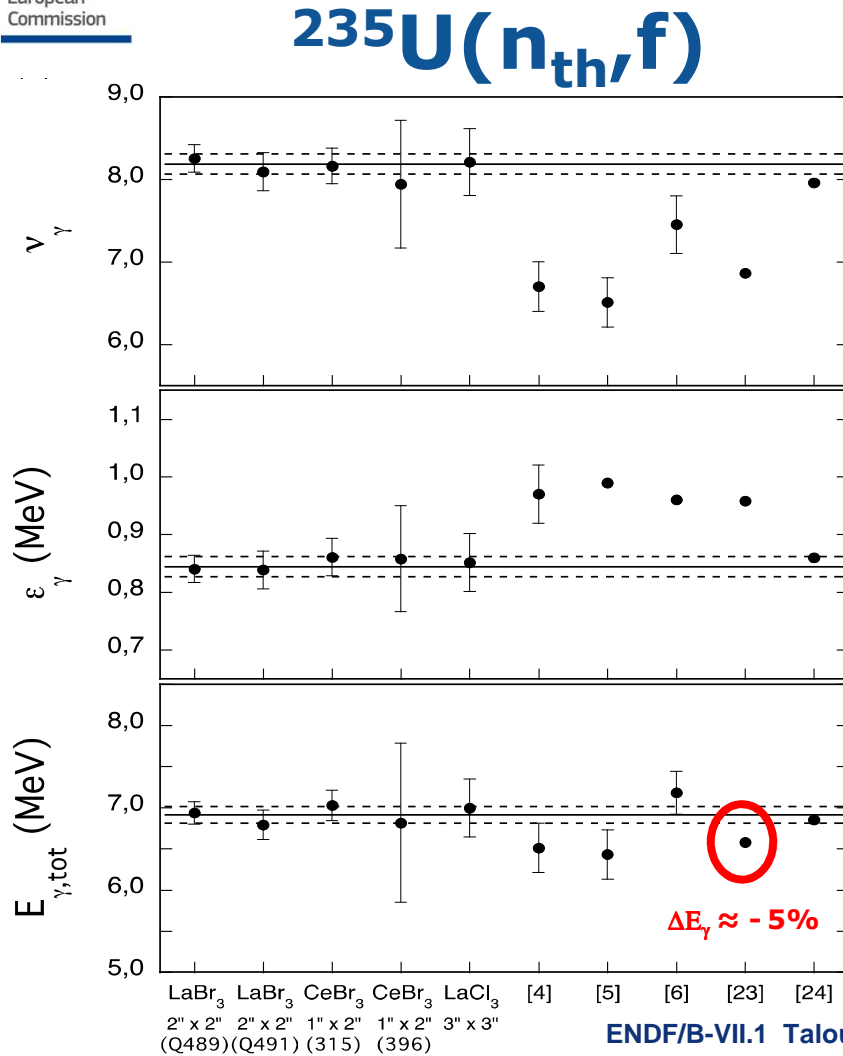
R. Billnert et al., Phys. Rev. C 87, 024601 (2013)

A. Oberstedt et al., Phys. Rev. C 87, 051602 (2013)

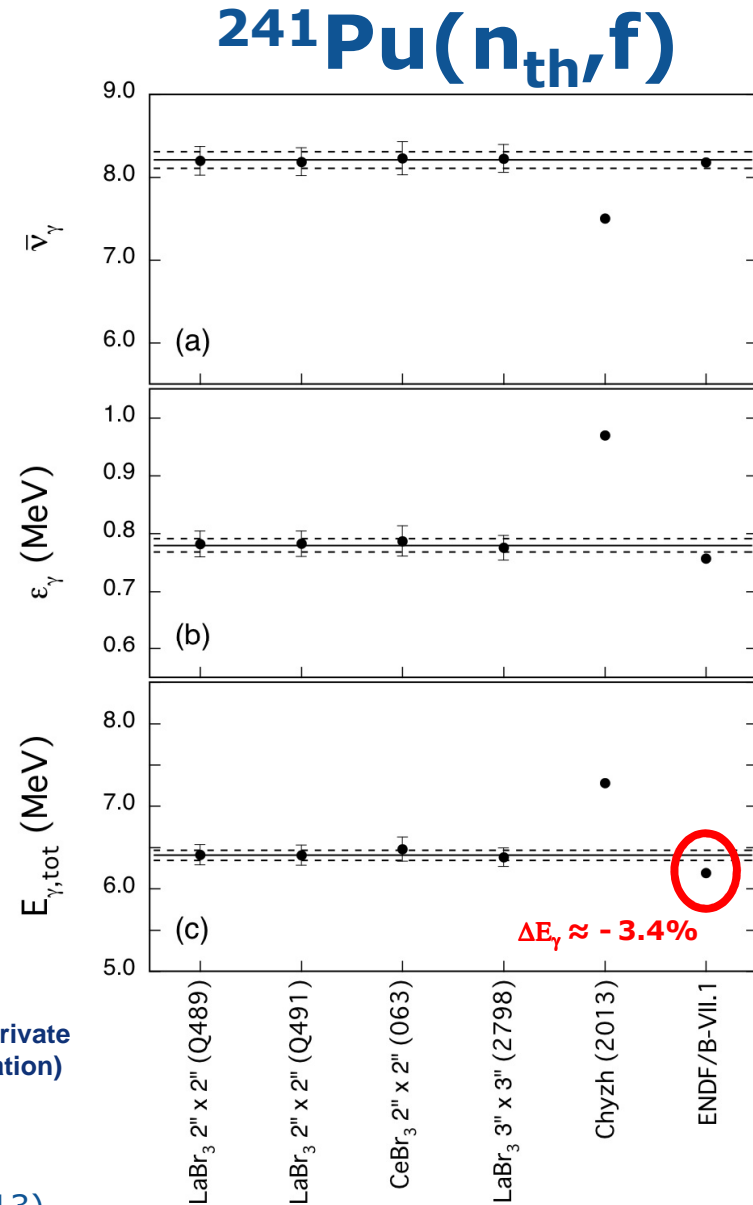
S. Oberstedt et al., Phys. Rev. C 90, 024618 (2014)



# Recent achievements



ENDF/B-VII.1 Talou et al. (private communication)

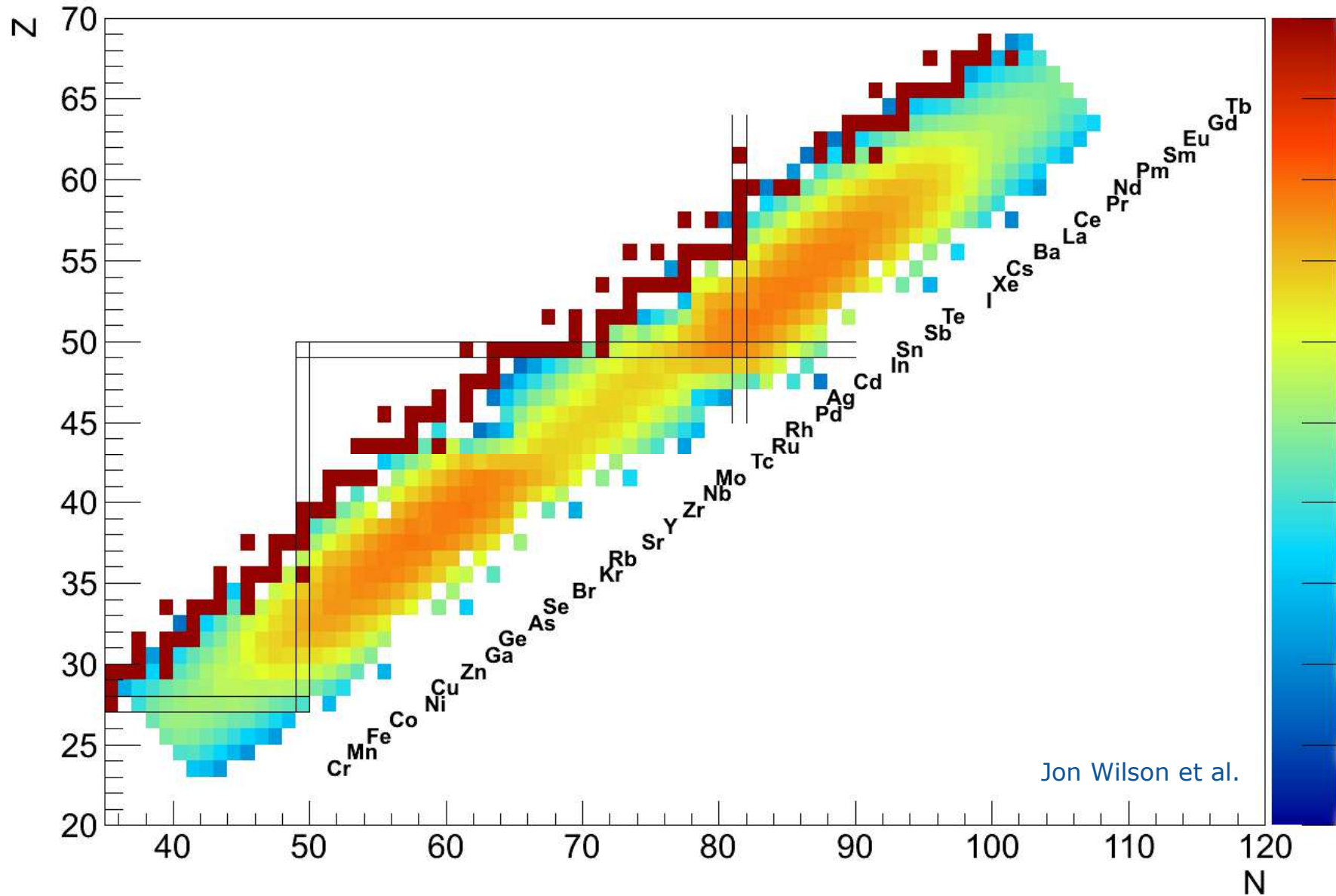


PhD thesis work of R. Billnert  
 A. Oberstedt et al., Phys. Rev. C 87, 051602 (2013)  
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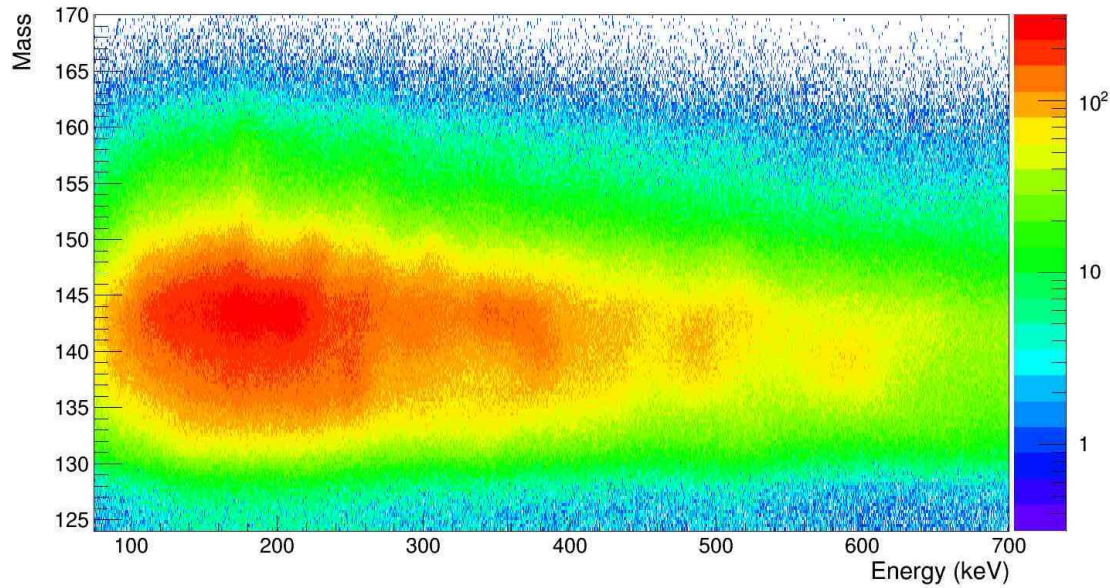
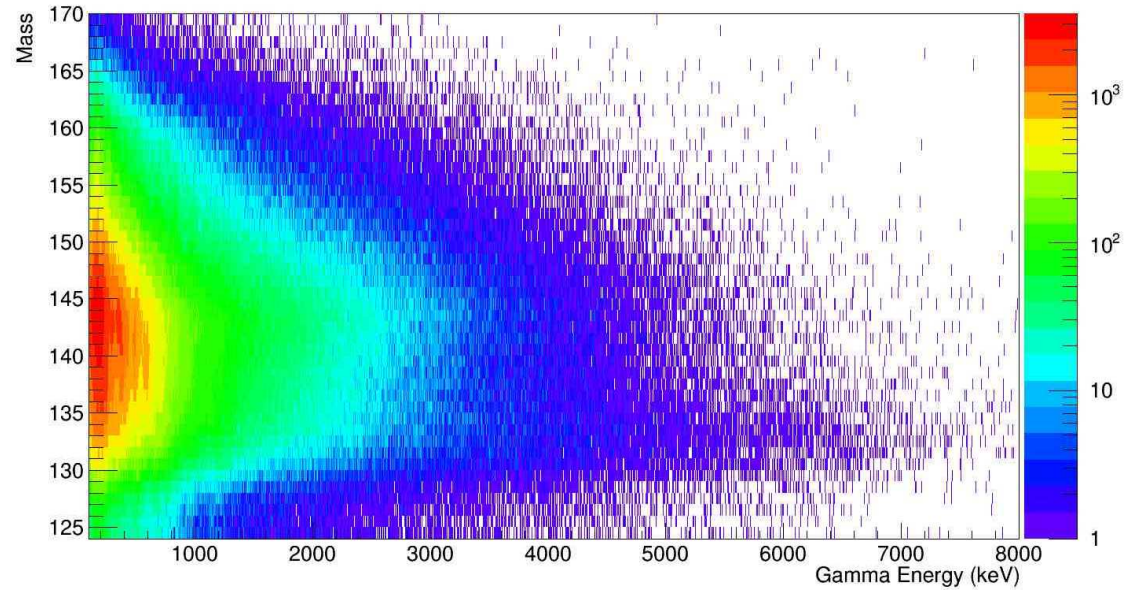


European  
Commission

# Recent achievements



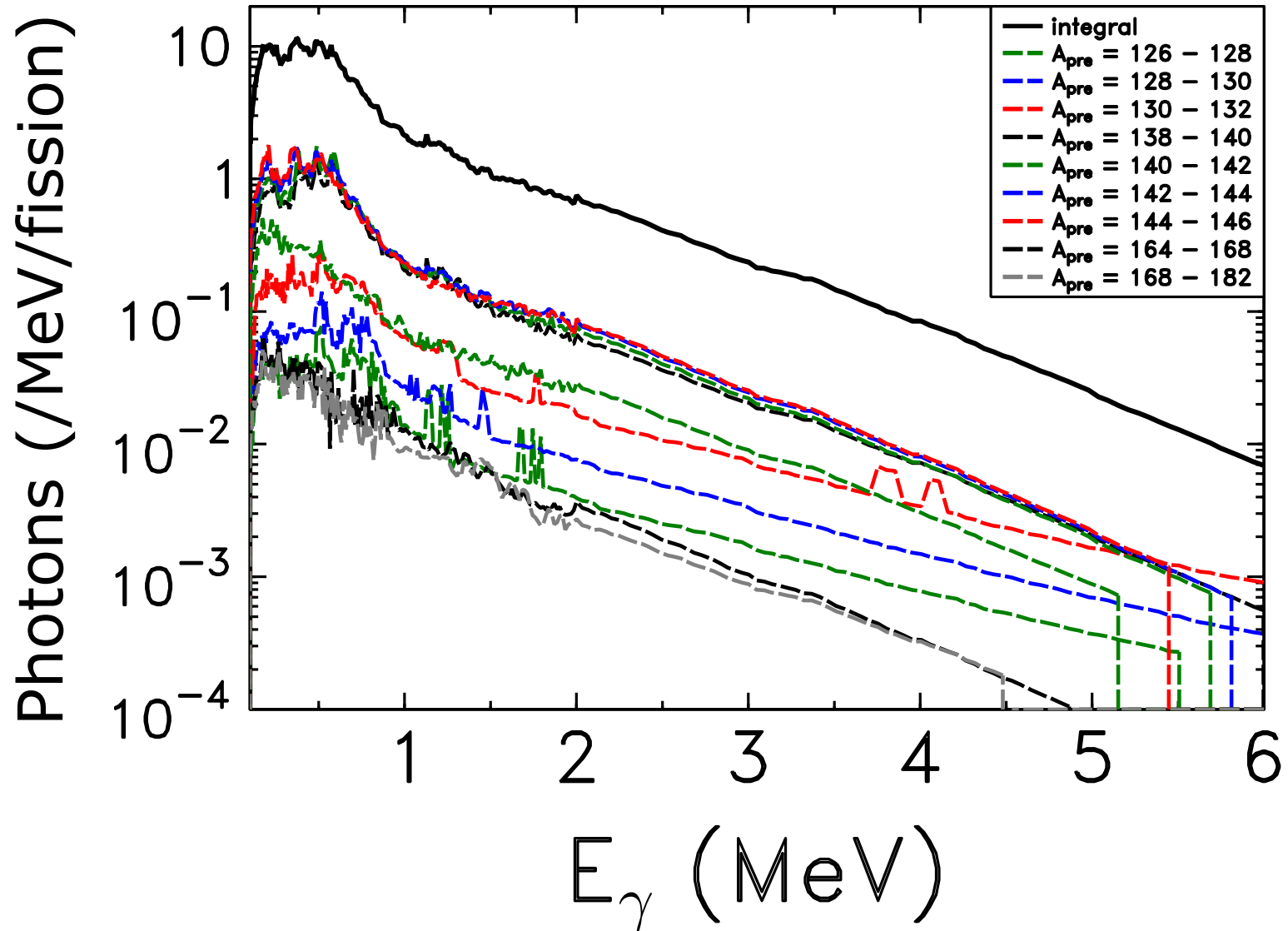
## $^{252}\text{Cf}(\text{SF})$



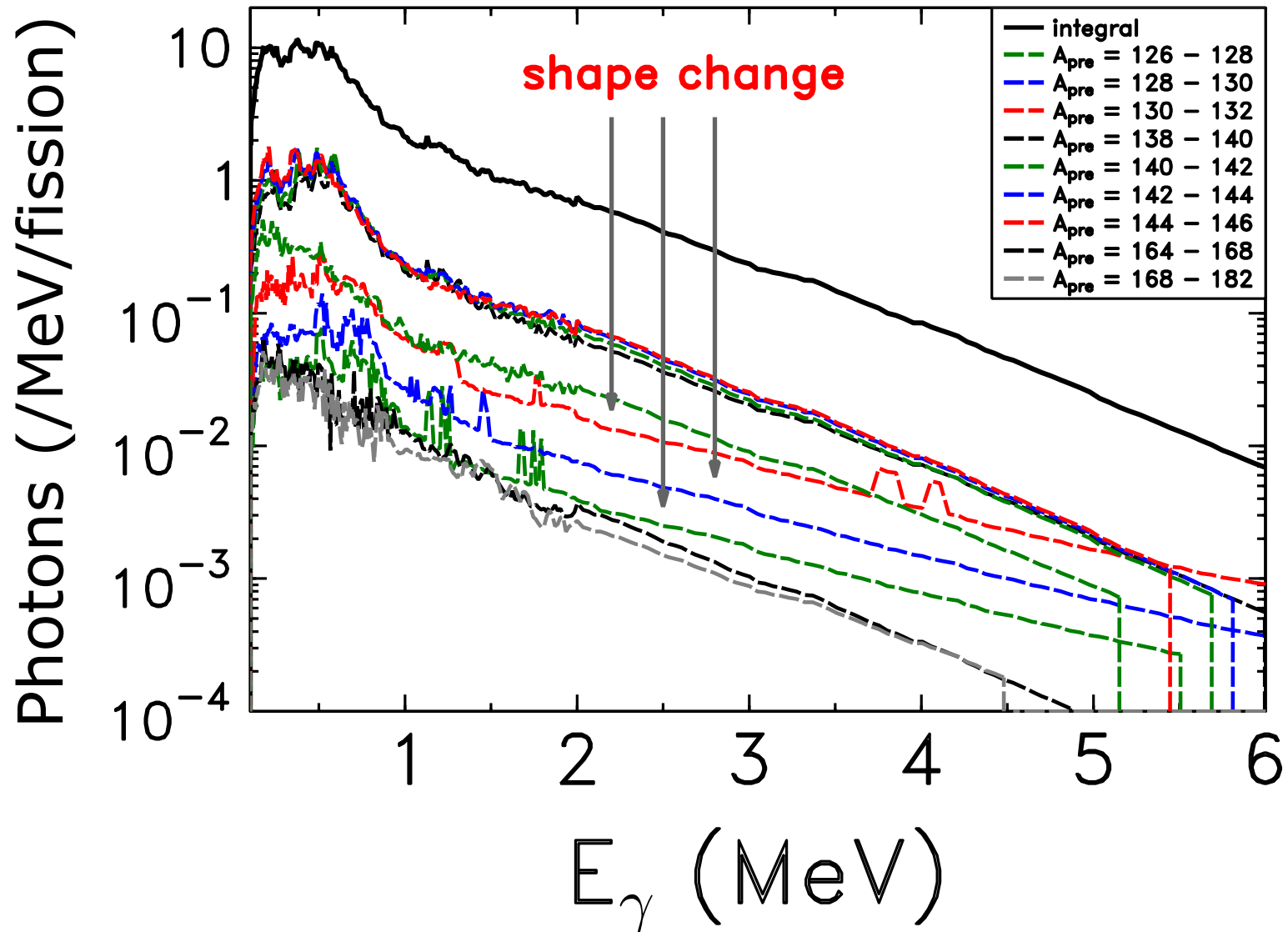
## PFG spectral data ( $A^*$ )



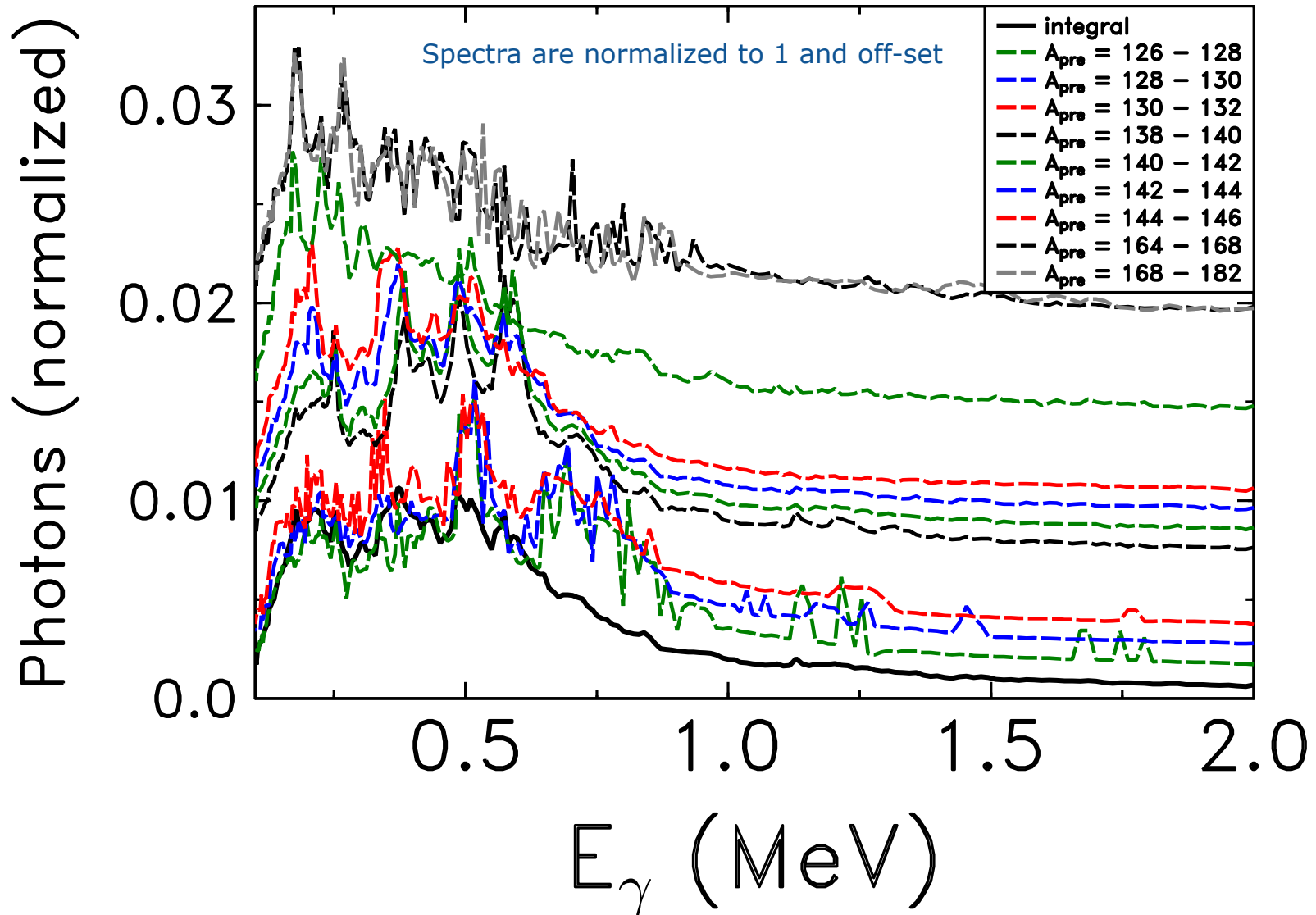
# Recent achievements



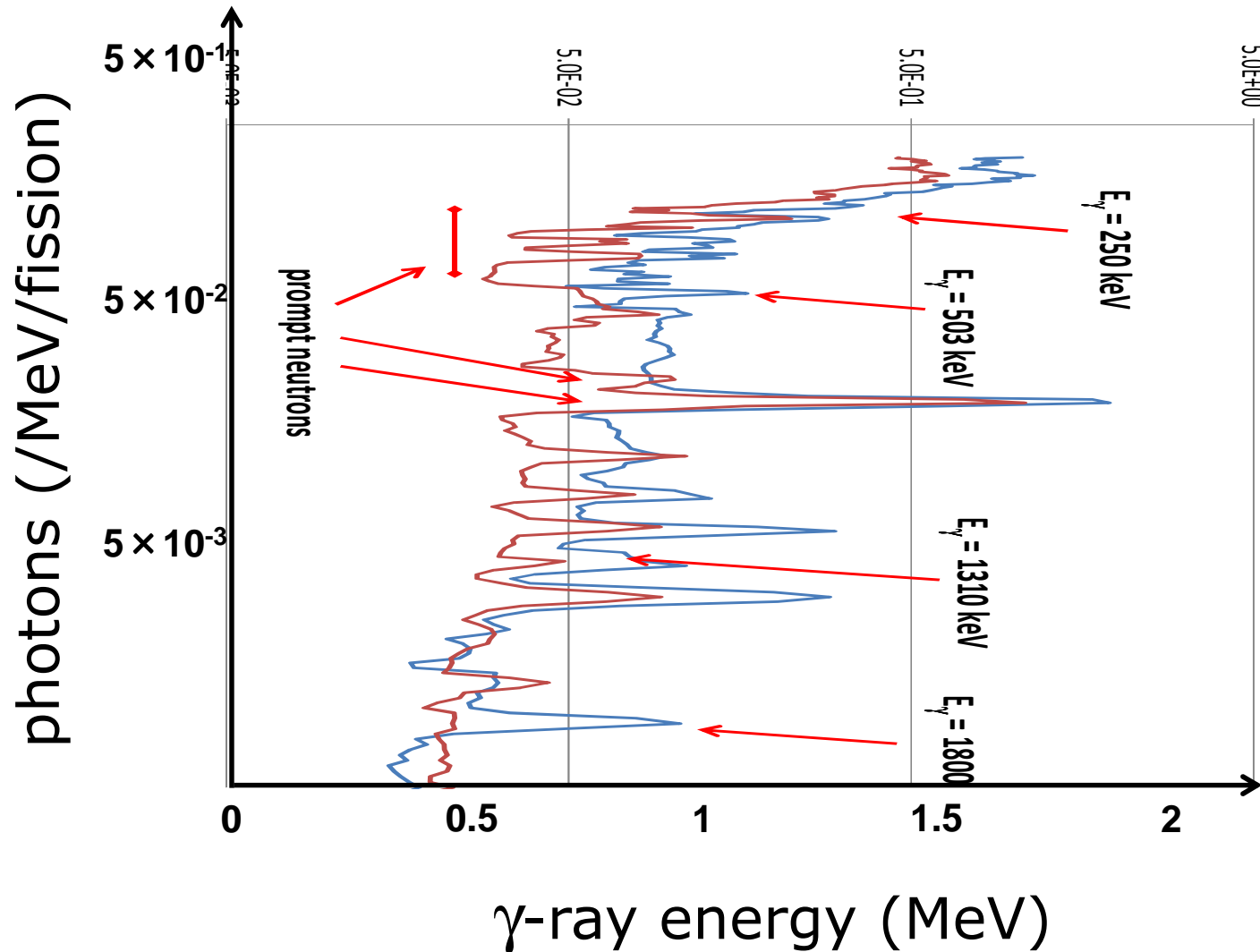
# Recent achievements



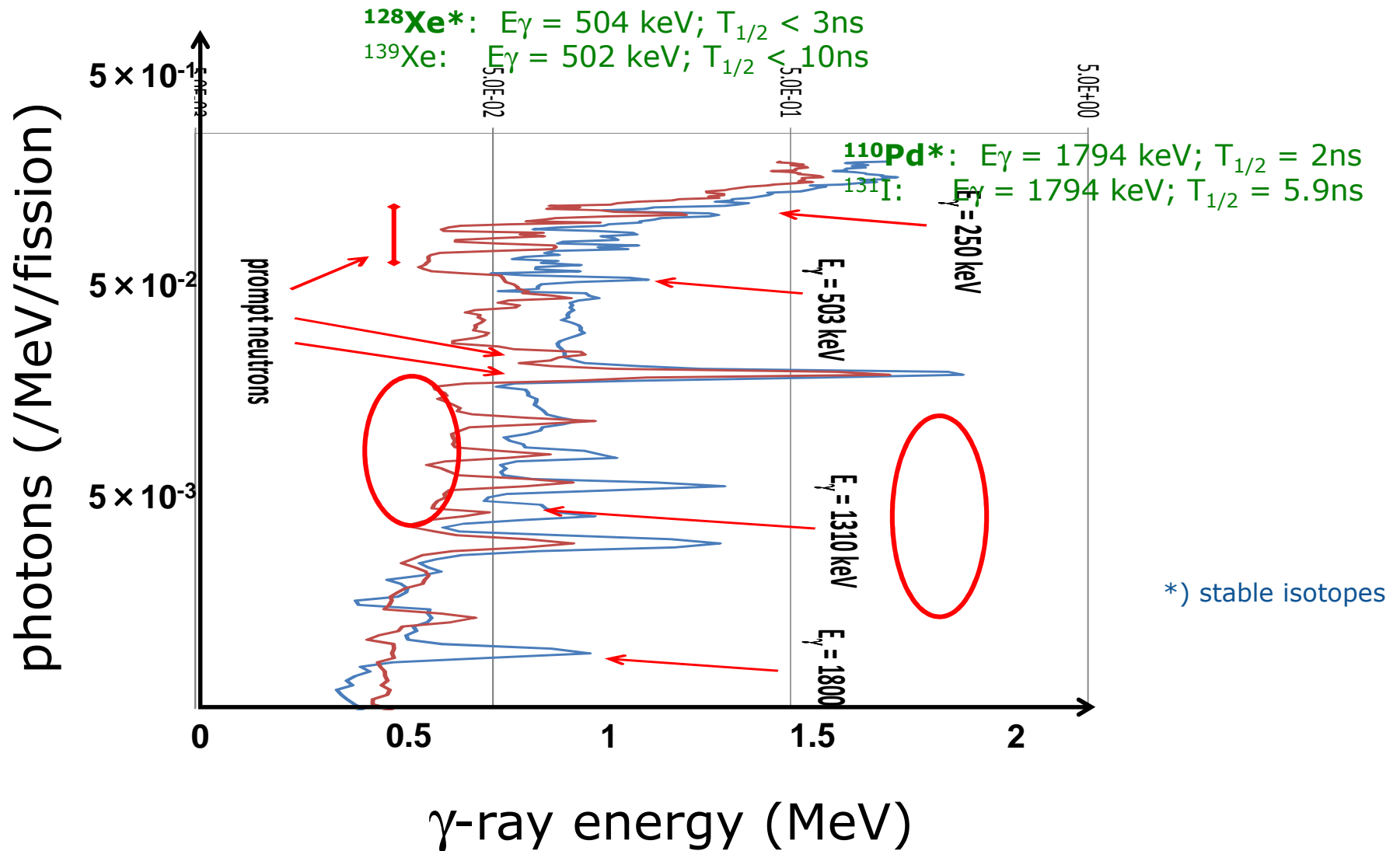
# Recent achievements



## Off-prompt (isomeric) spectral data



# Recent achievements



## Lithium Inverse Cinematiques ORsay NEutron source



J.N. Wilson  
M. Lebois  
P. Halipré  
D. Verney  
I. Matea  
B. Leniau

...

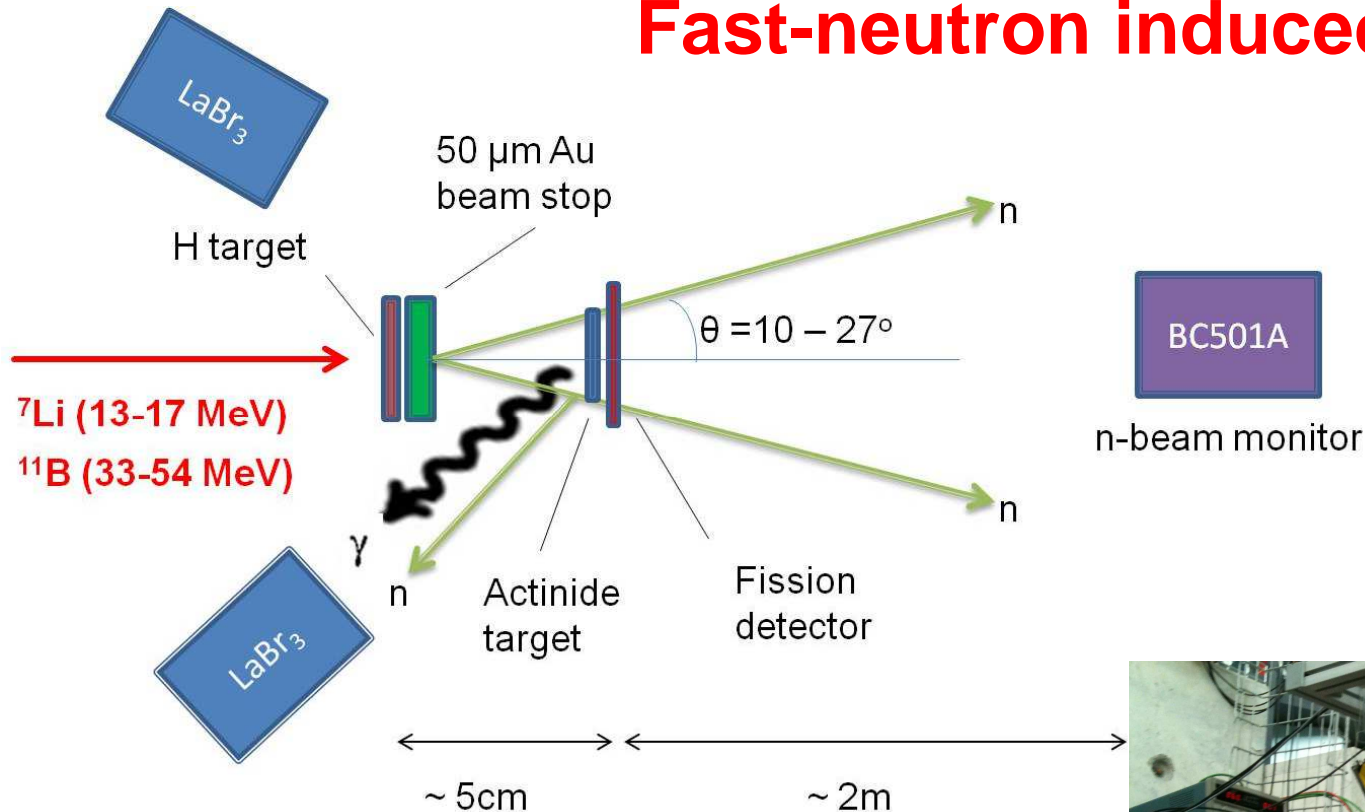
S. Oberstedt

**Unité mixte de recherche  
CNRS-IN2P3  
Université Paris-Sud 11**

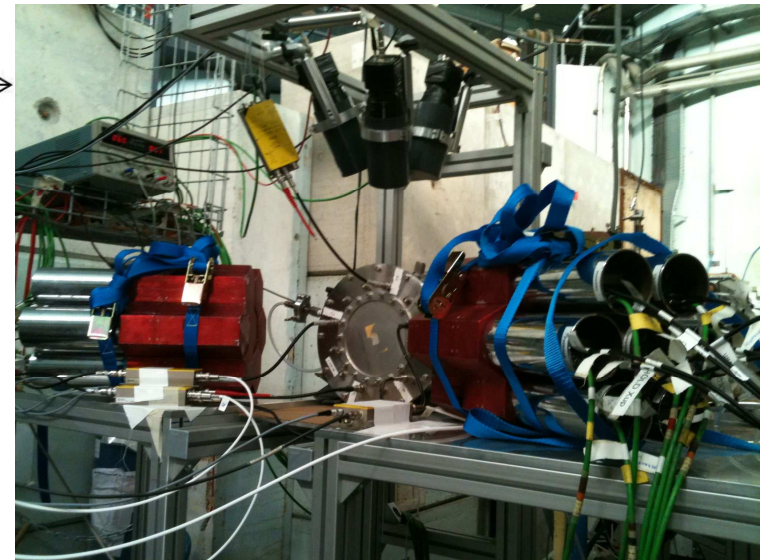
91406 Orsay Cedex  
Tél. : +33 1 69 15 73 40  
Fax : +33 1 69 15 64 70  
<http://ipnweb.in2p3.fr>



## Fast-neutron induced PFGS



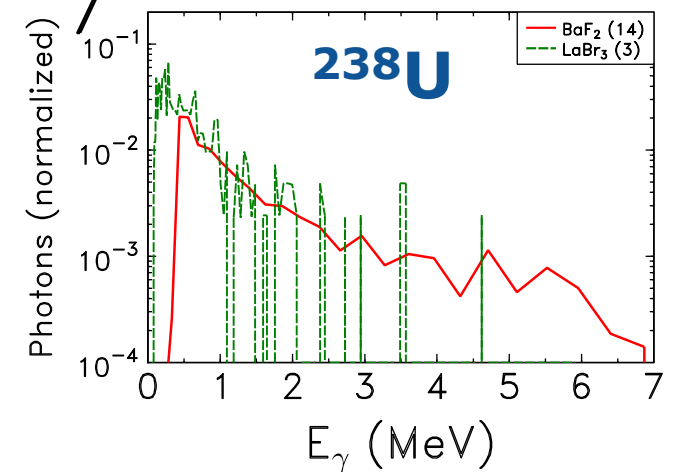
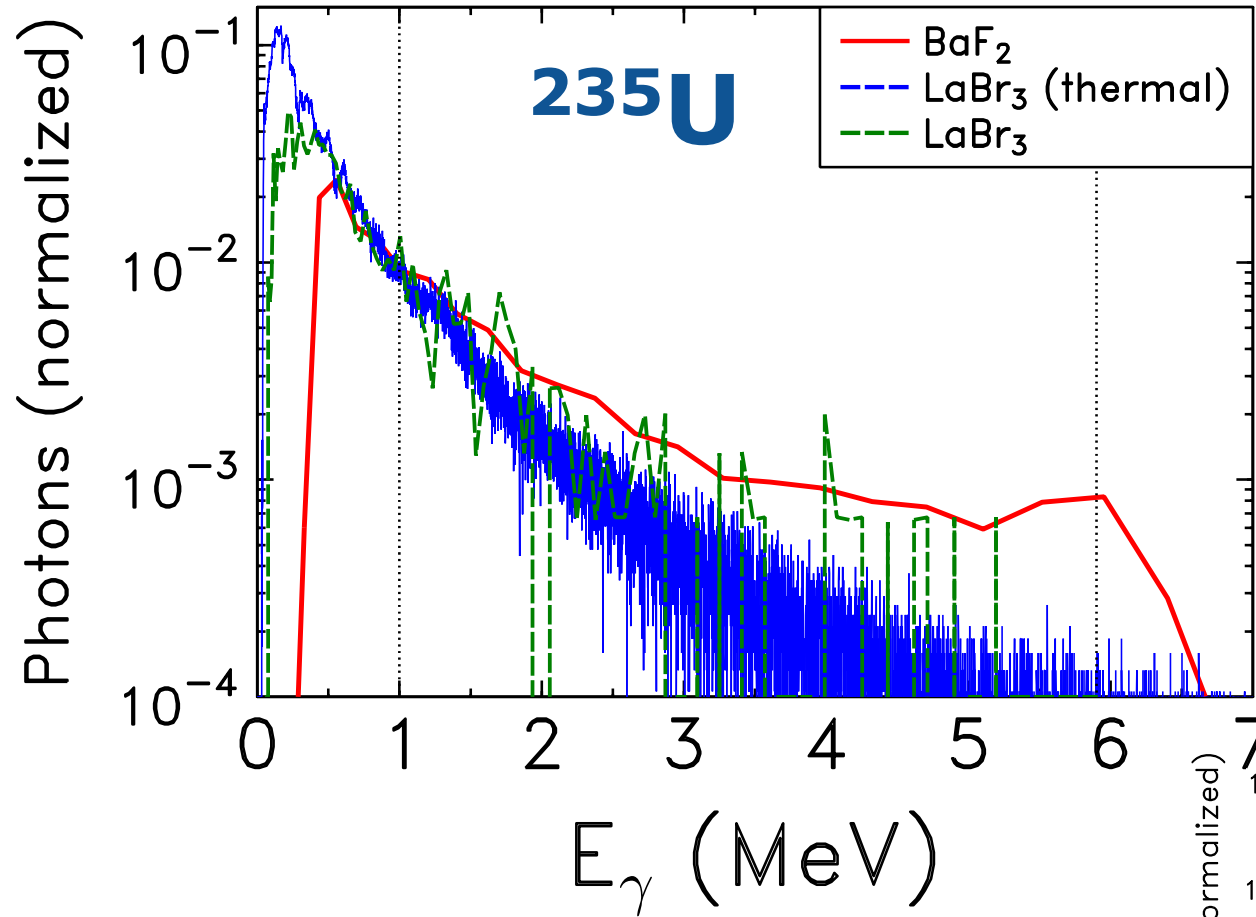
**Fast reactor spectrum**  
 **$\langle E_n \rangle = 1.5 \text{ MeV}$**





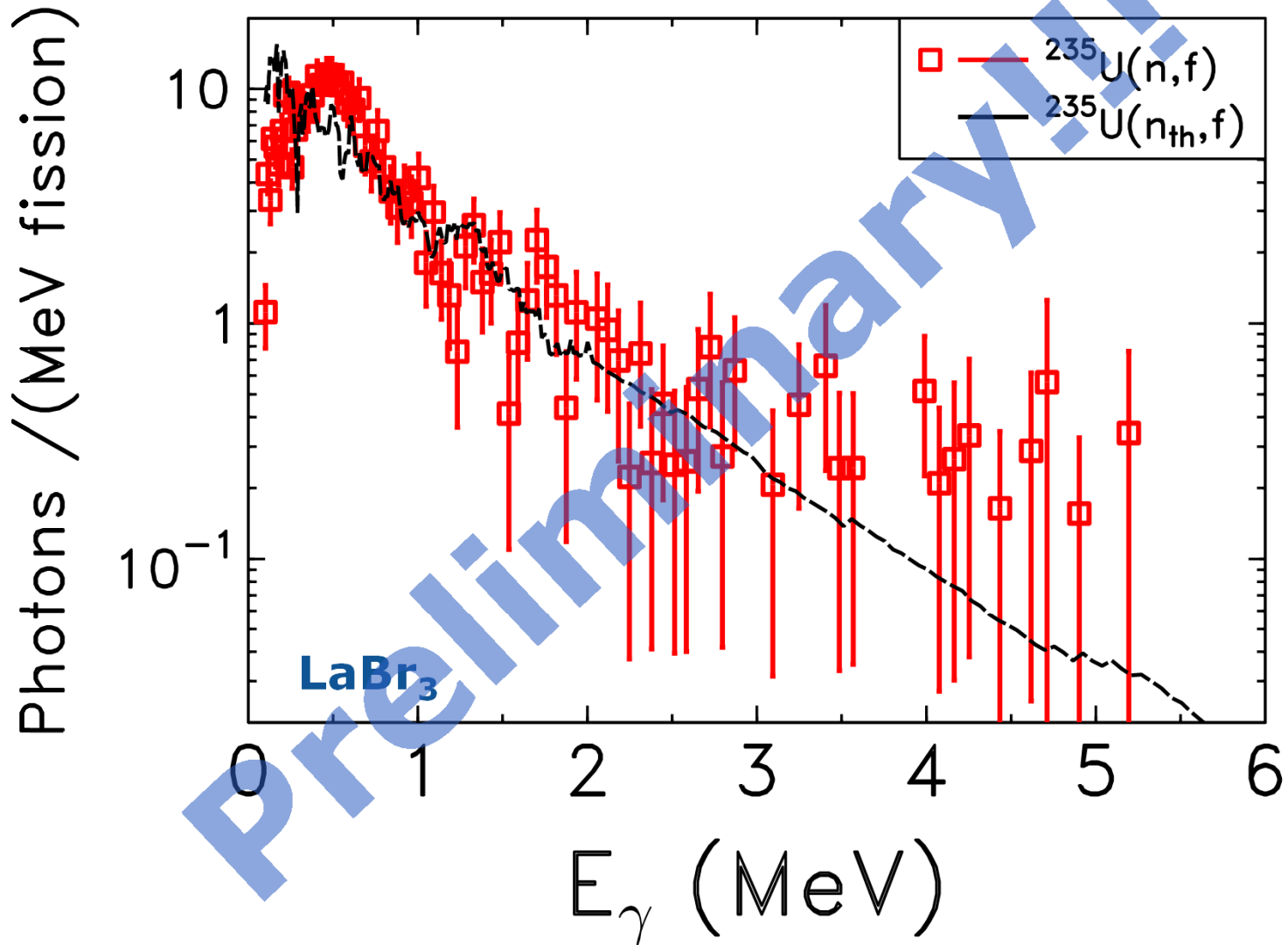
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# Recent achievements



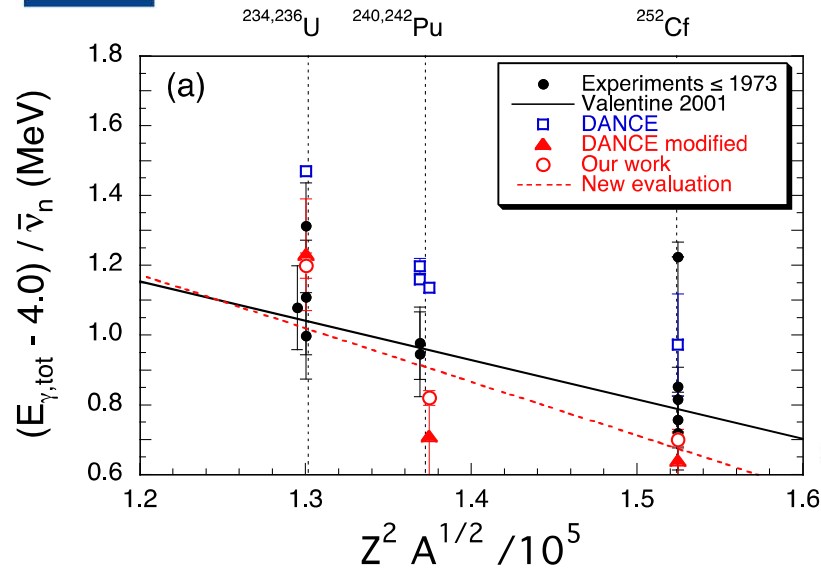


# Recent achievements





# Recent achievements

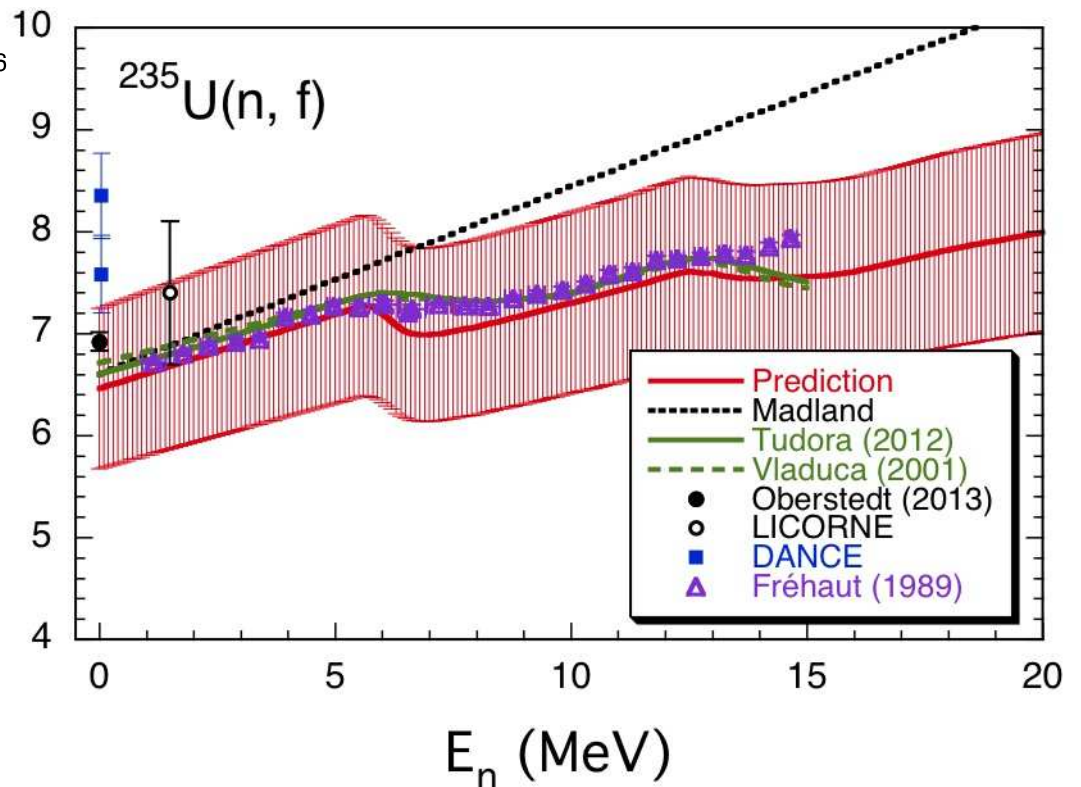


Systematic trend as a function of incident neutron energy

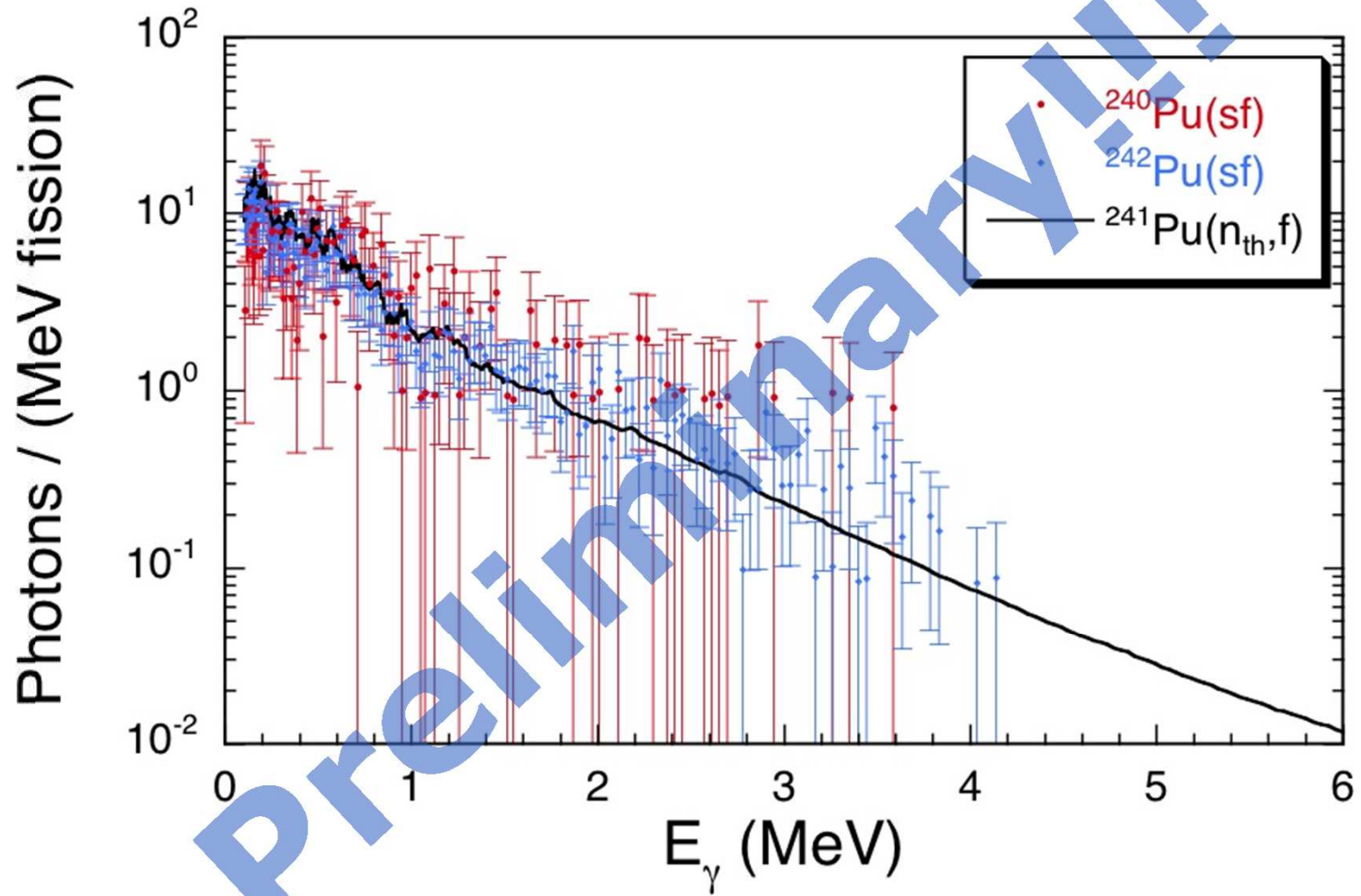
Parameterization according to Valentine (2001)

New coefficients based on new experimental data

$E_{\gamma,tot}$  (MeV)



# Recent achievements



- **More experimental groups active:**
  - ✓ LANL DANCE
  - ✓ Bruyères-le-Châtel (J.-M. Laborie,...)
  
- **Theoretical groups:**
  - ✓ CEA Cadarache (O. Serot, O. Litaize, D. Regnier)
  - ✓ LANL (P. Talou et al.)
  - ✓ K.-H. Schmitt and others

# Problem solved?

$$\langle E_{\gamma, \text{tot}} \rangle$$

target isotope	$E_{\text{th}}$ (MeV)	our work (MeV)	ENDF/B-VII (MeV)	excess (%)
$^{252}\text{Cf}$	0	$6.63 \pm 0.08$	6.13	8.2
$^{235}\text{U}$	thermal	$6.92 \pm 0.09$	6.58	5.2
	1.5	$7.4 \pm 0.7$ *)	6.58	$12 \pm 2$
$^{241}\text{Pu}$	thermal	$6.41 \pm 0.06$	6.19	3.6

\*) preliminary

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- **The observed increase in average total PFG energy can only partially explain the observed heat excess**
- **Of course,  $^{239}\text{Pu}(n_{\text{th}}, f)$  still to be measured (Spring'15)**



## Problem solved? But...

- **No major deviation from historical PFGS data found !!!**
- **The observed increase in average total PFG energy can only partially explain the observed heat excess**
- **Of course,  $^{239}\text{Pu}(n_{\text{th}}, f)$  still to be measured (Spring'15)**
- **New prompt spectral data serve to establish systematic trends as a function of incident neutron energy**
- **Mass-dependent emission spectra may help theoreticians benchmarking their emission models**

- **Under-prediction of the prompt  $\gamma$ -heating due to other sources**
  - ✧ **Fast-neutron induced fission**
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- Fast-neutron induced fission on  $^{238}\text{U}$  (in progress)
- Photo-fission on  $^{235,238}\text{U}$  and  $^{239}\text{Pu}$  at  $E_0 = 6 - 10 \text{ MeV}$

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- **Definition: PFGS – what about  $\Delta t >$  tens of ns?**
- **Mass-dependent PFG emission**
- **Prompt neutron –  $\gamma$ -ray competition**

- **Fast-neutron induced fission: NFS, LICORNE, ...**
- **Photo-fission: S-DALINAC, ELSA, ..., ELI-NP**
- **Large-area  $\gamma$ -ray detector arrays**
- **Of particular interest may be hybrid-arrays, combining high efficiency and fast timing with high energy resolution**
- **Combined neutron- and  $\gamma$ -ray detector arrays**

## Geel LANthanide halide Detector array for Isomer Studies



CeBr<sub>3</sub>: 5.08 cm x 5.08 cm (diameter x length)

HPGe 45% rel.

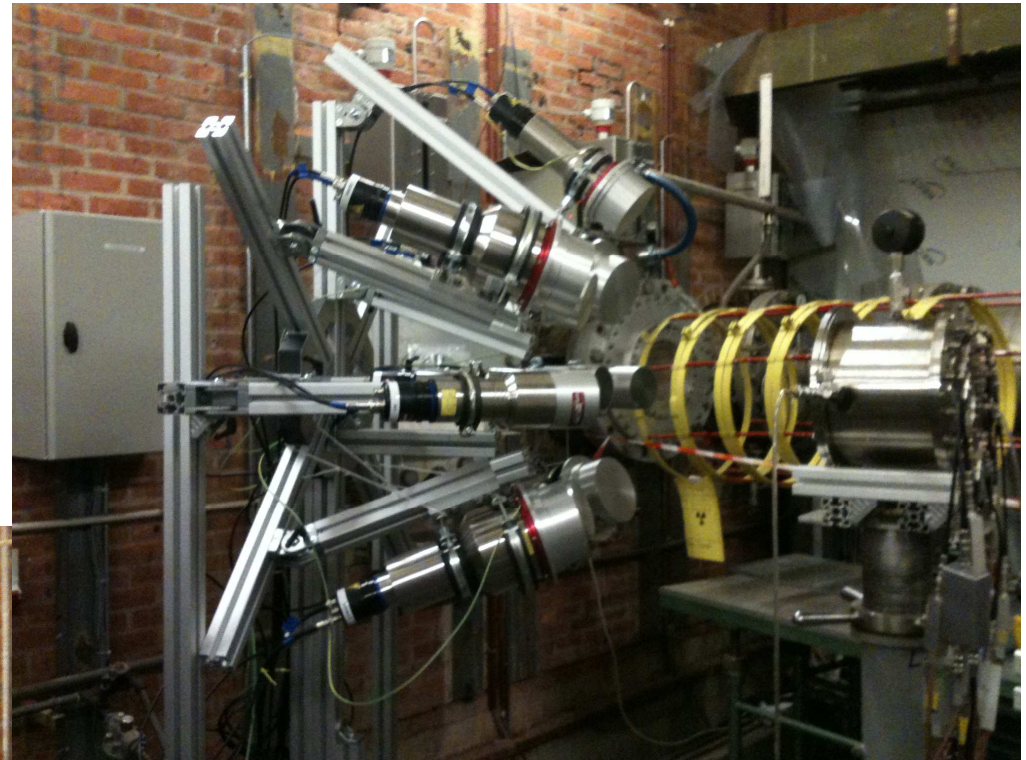
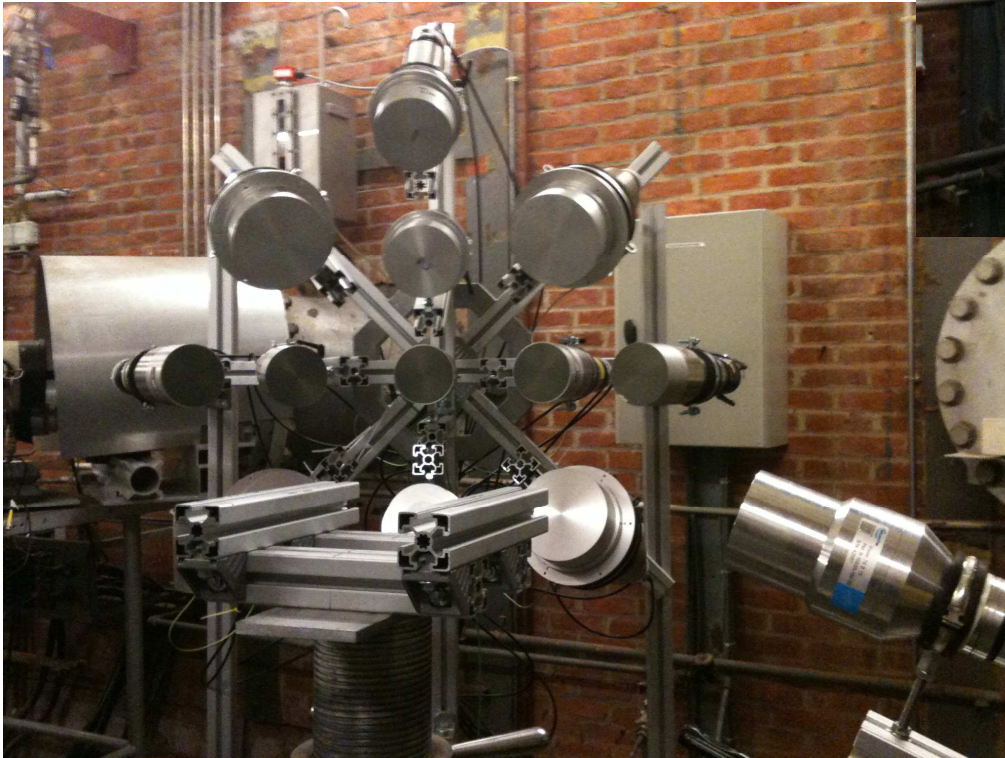
1<sup>st</sup> phase: 8 x CeBr<sub>3</sub>  
4 HPGe detectors (45% rel.)

2<sup>nd</sup> phase: 15 x CeBr<sub>3</sub>  
8 HPGe detectors (45% rel.)

Spectroscopy of super-deformed states and fission  
shape isomer decay in actinides

Studies of PFGS from resonance- and fast-neutron  
induced fission (<sup>234,235,238</sup>U, <sup>237</sup>Np and <sup>239,241</sup>Pu)

**13 neutron detectors**  
**TFGIC with  $\cos\theta$  and  $\phi$  resolution**



## SCINTIA

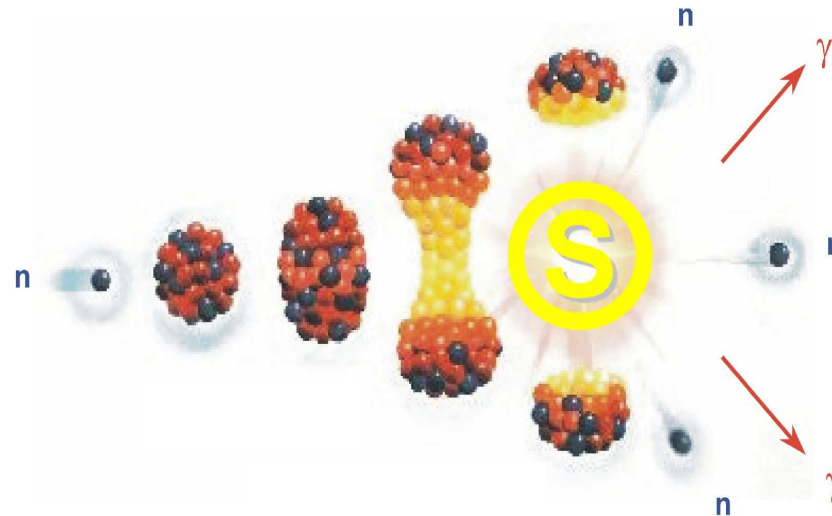
Combined with

**3" × 3" LaBr<sub>3</sub> detector(s)**



European  
Commission

# Nothing without a good team!



T. Belgya, R. Billnert, T. Brys, A. Gatera, W. Geerts, A. Göök, C. Guerrero, P. Halipré, F.-J. Hamsch, Z. Kis, M. Lebois, B. Leniau, T. Martinez, I. Matea, A. Oberstedt, L. Szentmiklosi, K. Takács, D. Verney, M. Vidali, J. Wilson and ...