EUROPEAN UNION

Structural Instruments 2014-2020

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# Systematic study of the de-excitation of neutron-rich nuclei produced in various fission reactions

Andreas Oberstedt

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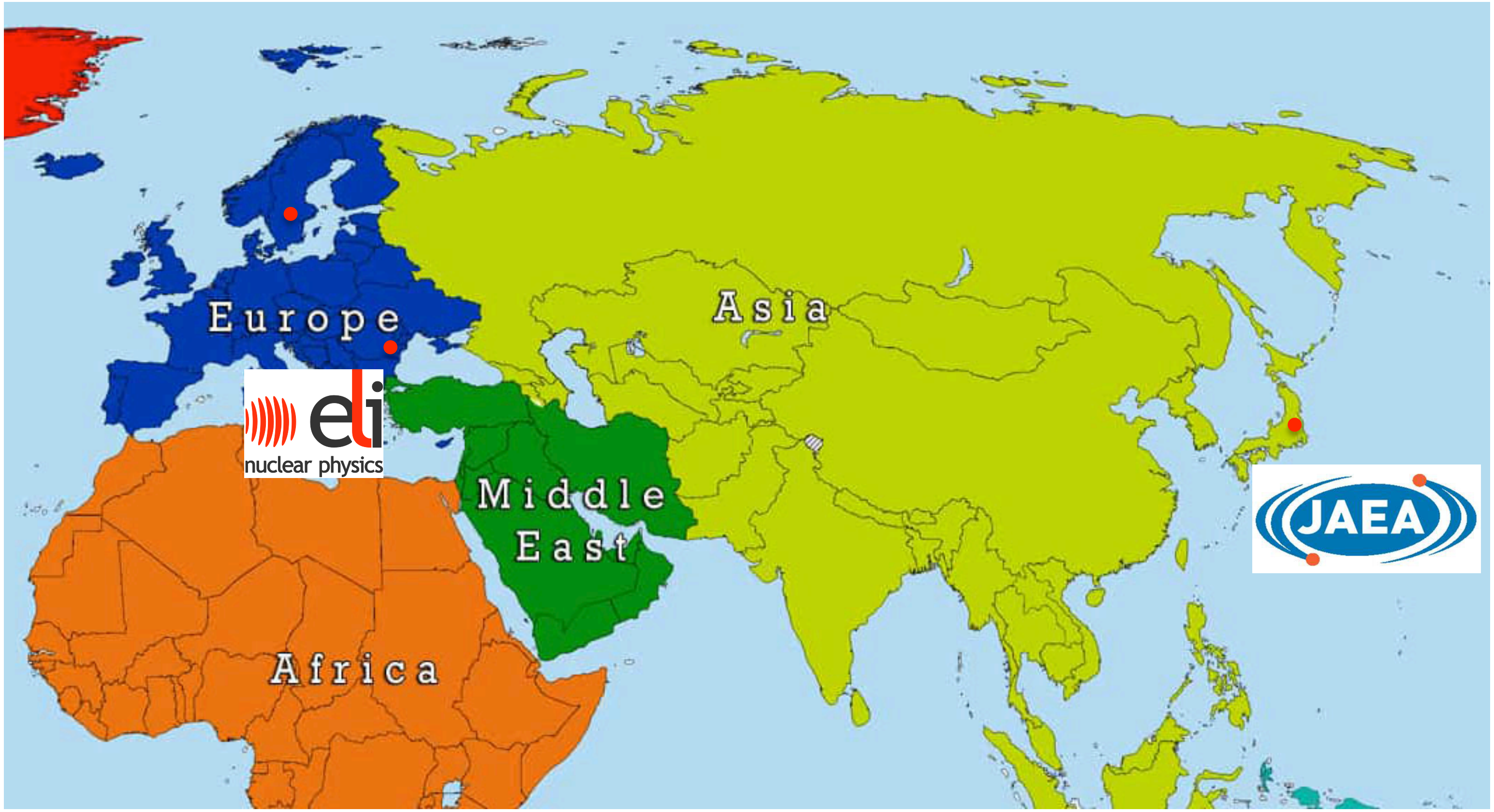
# Outline

- About ELI-NP
- Overview: the fission process
- On-going work
    - PFGS characteristics
    - dependence of compound system
    - impact of excitation energy
    - angular distribution & multipolarities
    - dependence of fragment mass
- Summary
- Outlook

# About ELI-NP

## Extreme Light Infrastructure – Nuclear Physics



# About ELI-NP

## Extreme Light Infrastructure – Nuclear Physics

# About ELI-NP

## Extreme Light Infrastructure – Nuclear Physics

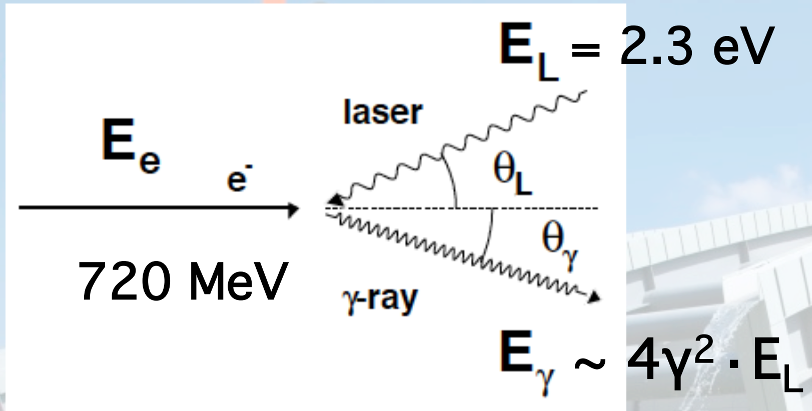
- Nuclear physics experiments to characterize laser – target interactions
- Photo-nuclear Physics
- Exotic Nuclear Physics and Astrophysics
  - complementary to other ESFRI Large Scale Physics Facilities (FAIR – Germany, SPIRAL-2 – France)
- Applications based on high-intensity laser and very brilliant $\gamma$ beams
- ELI-NP in “Nuclear Physics Long Range Plan in Europe” as a major facility

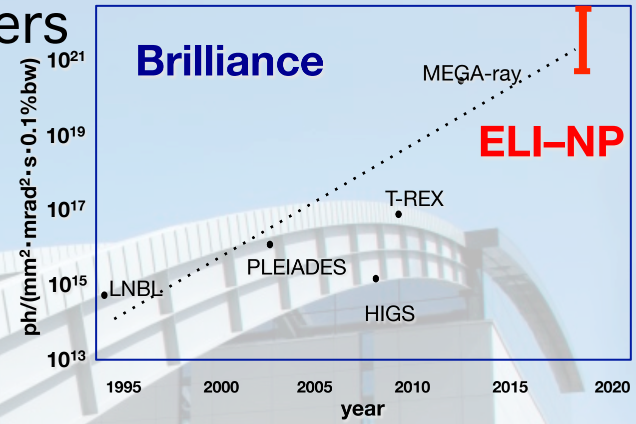
ESFRI = European Strategy Forum on Research Infrastructures

# About ELI-NP

## Extreme Light Infrastructure – Nuclear Physics

- Electron linac + two 10 PW lasers

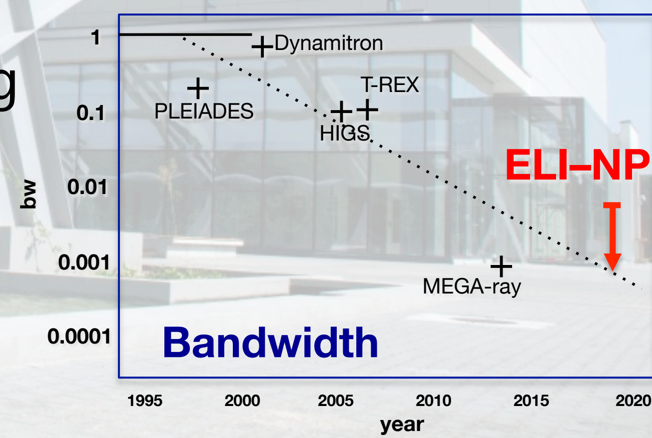



- Laser Compton backscattering

$$E_\gamma = 2\gamma_e^2 \cdot \frac{1+\cos\theta_L}{1+(\gamma_e\theta_\gamma)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L$$

Strongly forward-focused

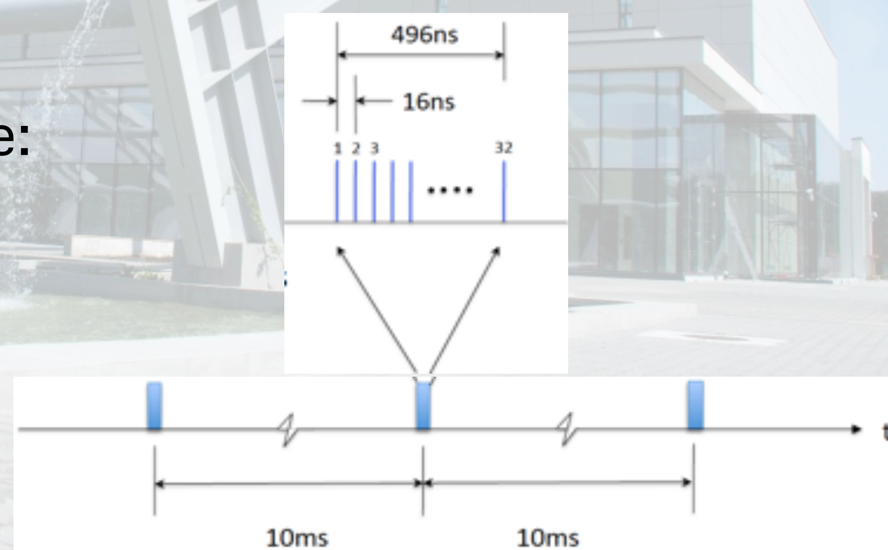



- Narrow bandwidth (≤ 0.3%) γ beams up to 19.5 MeV

# About ELI-NP
## Gamma Beam System (GBS)

Characteristics:

- beam size: 1 mm at 10 m distance from collimator
- energy spread: 50 keV at $E_\gamma$=10 MeV
- linear polarization: > 95%
- time structure: micro-pulses at 16 ns distance
- photons/pulse: $10^5$
- photons/macro-pulse:
- $32 \times 10^5 \approx 3 \times 10^6$
- photons/s: $3 \times 10^8$



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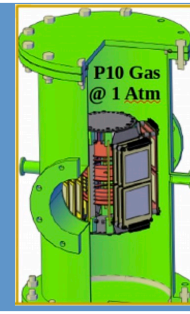
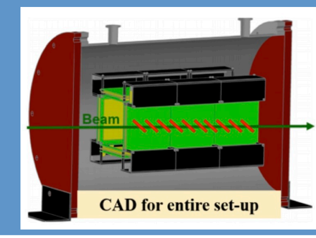
## Photo-fission at ELI-NP – Physics cases




| Observables | ELI-BIC | ELITHGEM |
|---|---|---|
| (binary) fission fragments | • (γ, f) cross sections<br>• distributions (A, Z, $E_{kin}$, θ)<br>• dependence on $E_γ$ | • (γ, f) cross sections<br>• angular distributions (θ, ϕ)<br>• dependence on $E_γ$ |
| (ternary) light charged particles | • energy and angular distributions<br>• probabilities, yields<br>• coincidences | |

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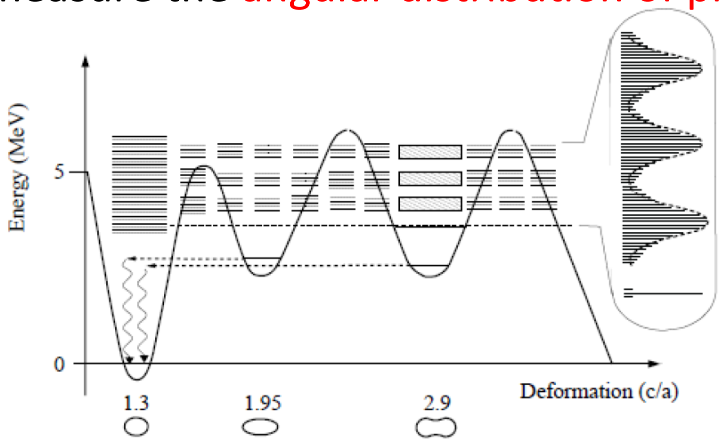


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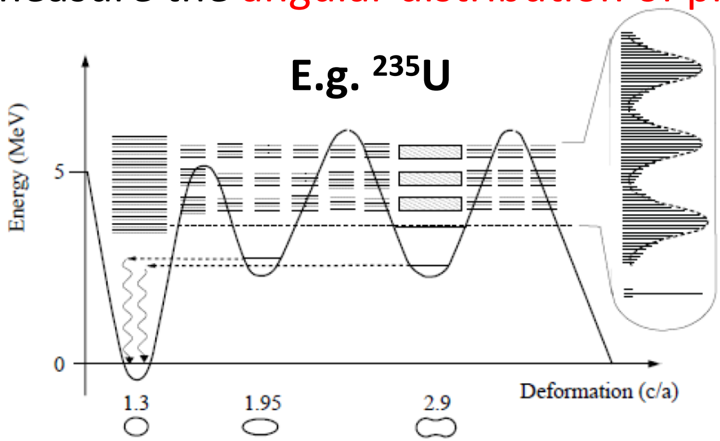


**$^{235}$U(γ, f)**

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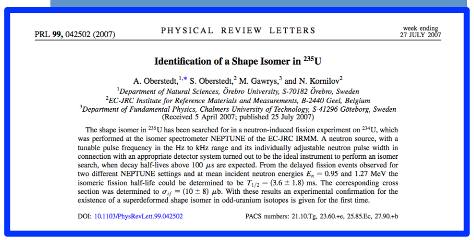

PRL 99, 042502 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

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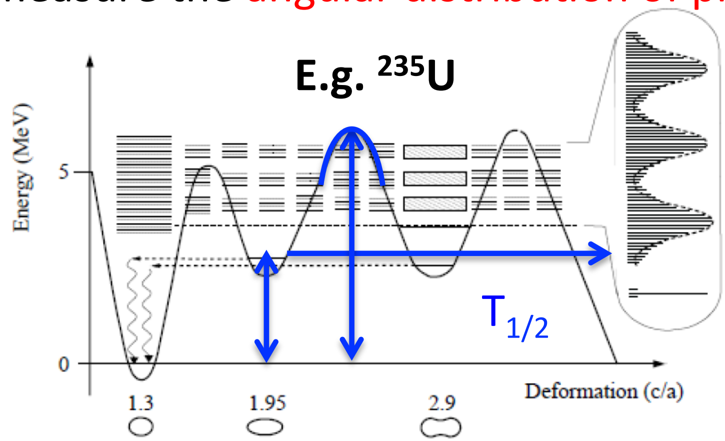


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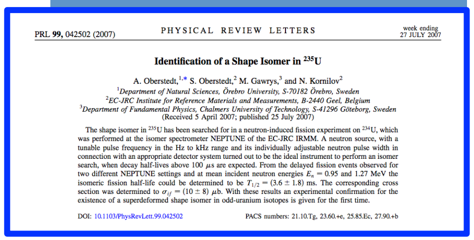
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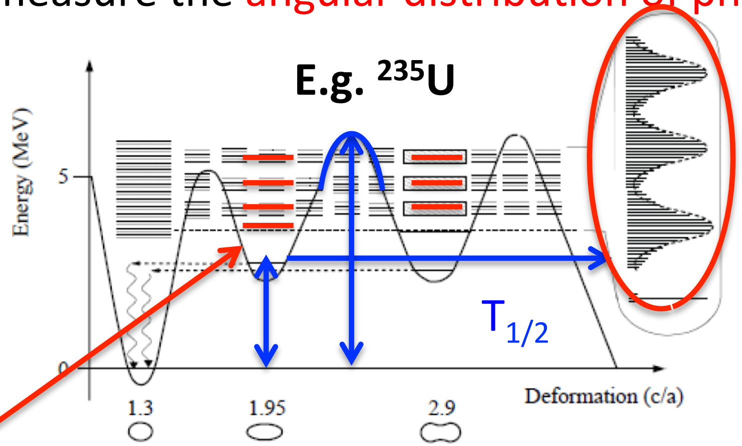


**ELITHGEM**

transmission
resonance
spectroscopy

**$^{235}U(\gamma, f)$**

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**$^{232}Th(\gamma, f)$ or $^{234,238}U(\gamma, f)$**

- cross section and angular distributions (higher resolution than with Bremsstrahlung)

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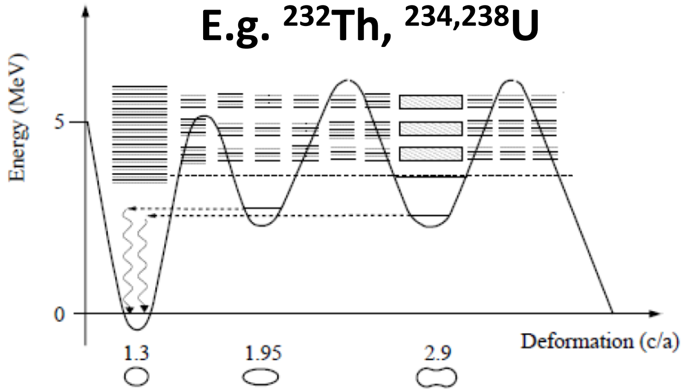
E.g. $^{232}$Th, $^{234,238}$U

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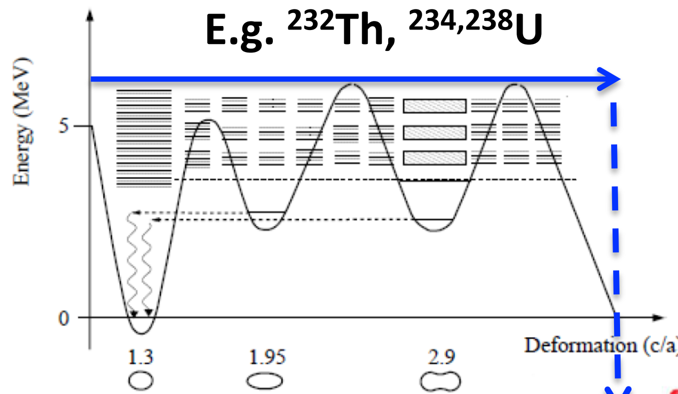


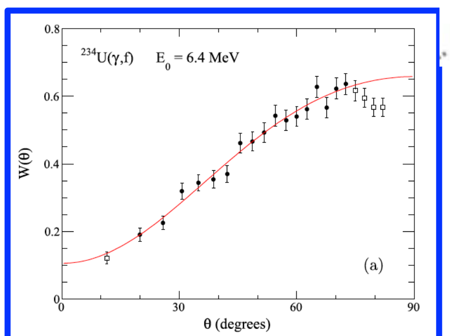


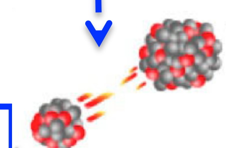

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PHYSICAL REVIEW C **96**, 044301 (2017)

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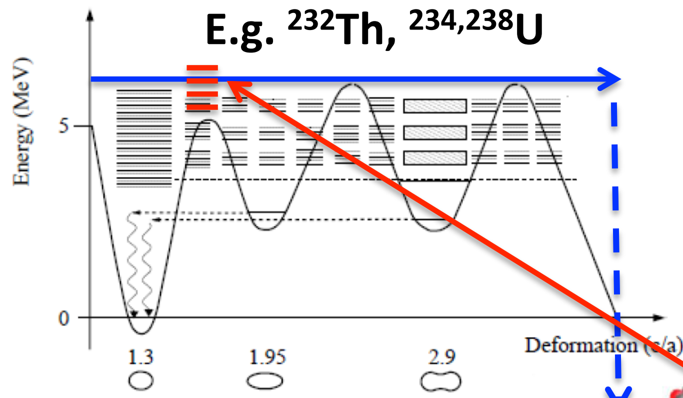


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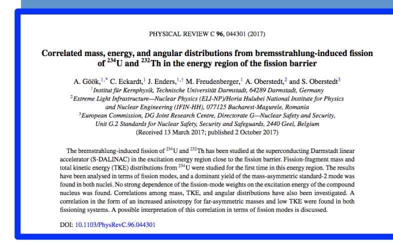
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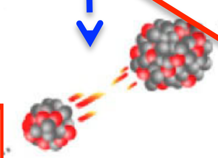

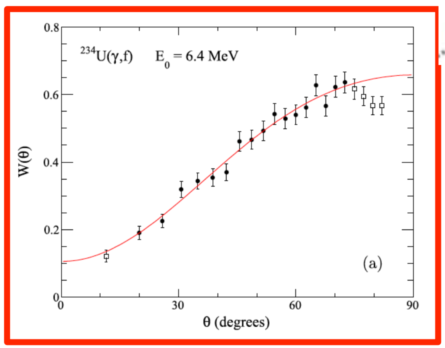


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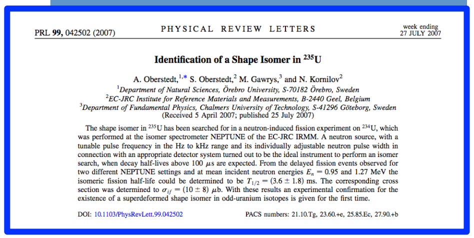

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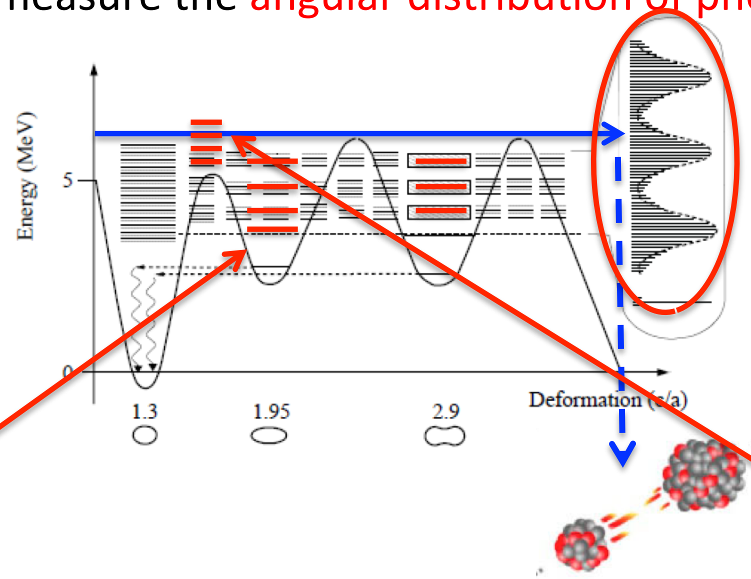


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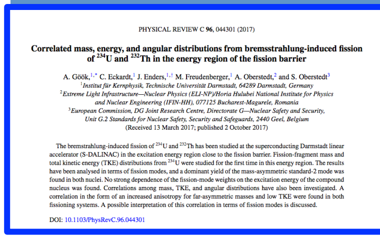

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**$^{232}Th(\gamma, f)$ or $^{234,238}U(\gamma, f)$**

- cross section and angular distributions (higher resolution than with Bremsstrahlung)

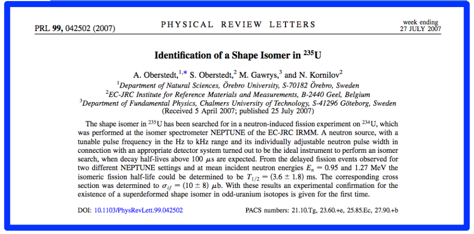
# About ELI-NP

## Day-1 experiments on Photo-fission

From Technical Design Report (TDR):

First, we will measure the absolute photofission cross-sections of actinide targets …
We further propose to measure the angular distribution of photofission fragments.

**ELI-BIC**

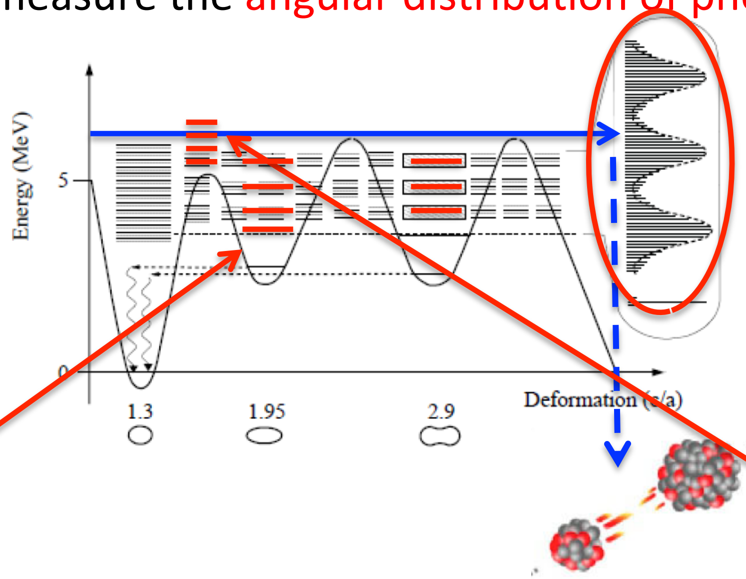

PRL **99**, 042502 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

**Identification of a Shape Isomer in $^{235}U$**

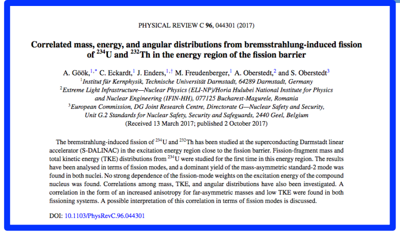
A. Oberstedt,[1,*] S. Oberstedt,[2] M. Gawrys,[3] and N. Kornilov[2]
[1]Department of Natural Sciences, Örebro University, S-70182 Örebro, Sweden
[2]EC-JRC Institute for Reference Materials and Measurements, B-2440 Geel, Belgium
[3]Department of Fundamental Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden
(Received 5 April 2007; published 25 July 2007)

The shape isomer in $^{235}U$ has been searched for in a neutron-induced fission experiment on $^{234}U$, which was performed at the isomer spectrometer NEPTUNE of the EC-JRC IRMM. A neutron source, with a tunable pulse frequency in the Hz to kHz range and its individually adjustable neutron pulse width in connection with an appropriate detector system turned out to be the ideal instrument to perform an isomer search, when decay half-lives above 100 $\mu$s are expected. From the delayed fission events observed for two different NEPTUNE settings and at mean incident neutron energies $E_n = 0.95$ and 1.27 MeV the isomeric fission half-life could be determined to be $T_{1/2} = (3.6 \pm 1.8)$ ms. The corresponding cross section was determined to $\sigma_{if} = (10 \pm 8)$ $\mu$b. With these results an experimental confirmation for the existence of a superdeformed shape isomer in odd-uranium isotopes is given for the first time.

DOI: 10.1103/PhysRevLett.99.042502 PACS numbers: 21.10.Tg, 23.60.+e, 25.85.Ec, 27.90.+b




**ELITHGEM**


PHYSICAL REVIEW C **96**, 044301 (2017)

**Correlated mass, energy, and angular distributions from bremsstrahlung-induced fission of $^{234}U$ and $^{232}Th$ in the energy region of the fission barrier**

A. Göök,[1,*] C. Eckardt,[1] J. Enders,[1,†] M. Freudenberger,[1] A. Oberstedt,[2] and S. Oberstedt[3]
[1]Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
[2]Extreme Light Infrastructure—Nuclear Physics (ELI-NP)/Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH), 077125 Bucharest-Magurele, Romania
[3]European Commission, DG Joint Research Centre, Directorate G—Nuclear Safety and Security, Unit G.2 Standards for Nuclear Safety, Security and Safeguards, 2440 Geel, Belgium
(Received 13 March 2017; published 2 October 2017)

The bremstrahlung-induced fission of $^{234}U$ and $^{232}Th$ has been studied at the superconducting Darmstadt linear accelerator (S-DALINAC) in the excitation energy region close to the fission barrier. Fission-fragment mass and total kinetic energy (TKE) distributions from $^{234}U$ were studied for the first time in this energy region. The results have been analysed in terms of fission modes, and a dominant yield of the mass-asymmetric standard-2 mode was found in both nuclei. No strong dependence of the fission-mode weights on the excitation energy of the compound nucleus was found. Correlations among mass, TKE, and angular distributions have also been investigated. A correlation in the form of an increased anisotropy for far-asymmetric masses and low TKE were found in both fissioning systems. A possible interpretation of this correlation in terms of fission modes is discussed.

DOI: 10.1103/PhysRevC.96.044301

**$^{235}U(\gamma, f)$**

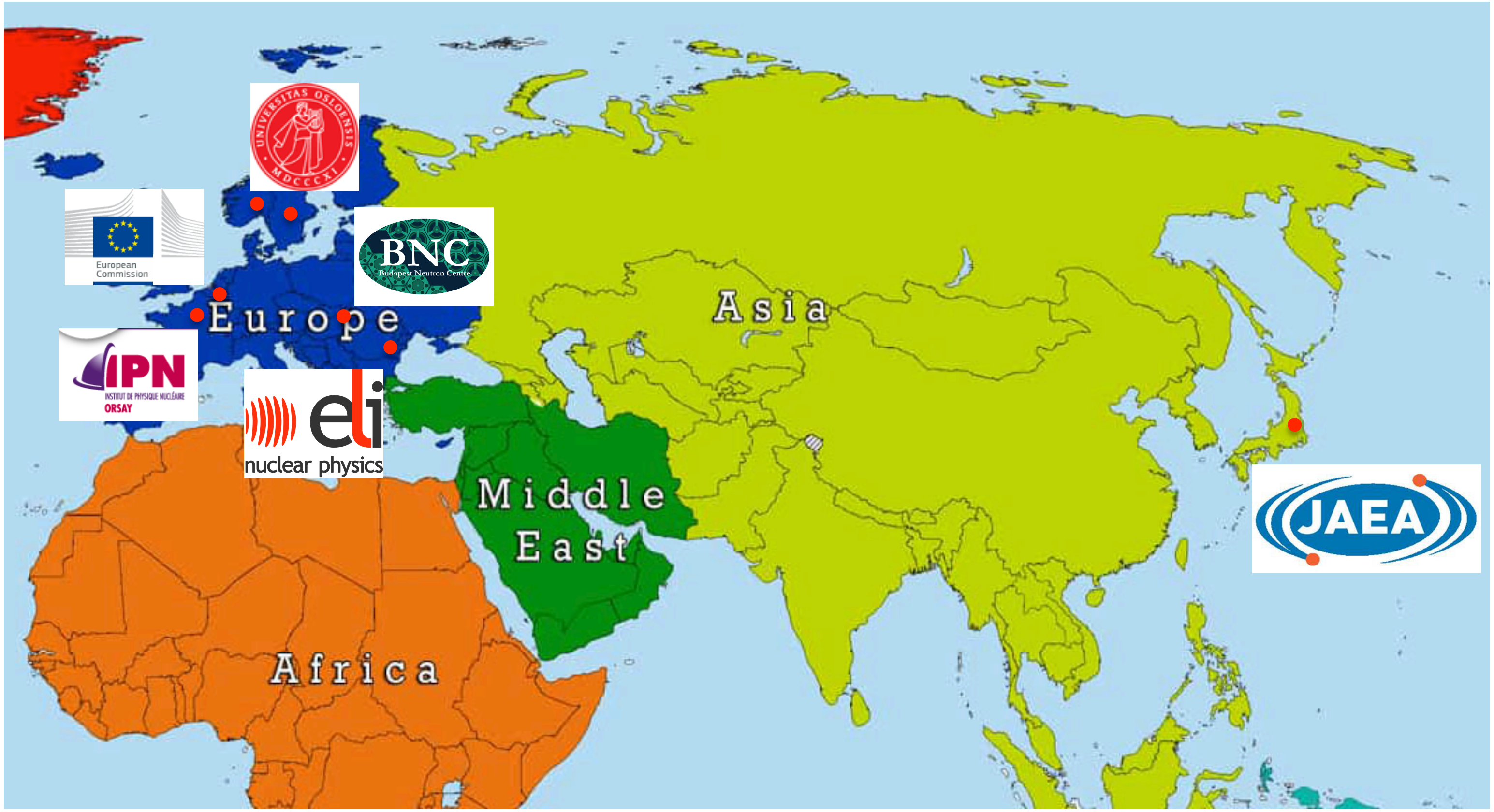
- isomeric fission (complementary to $^{234}U(n, f)$)
- ternary fission yields

However, not before 2023! Until then …

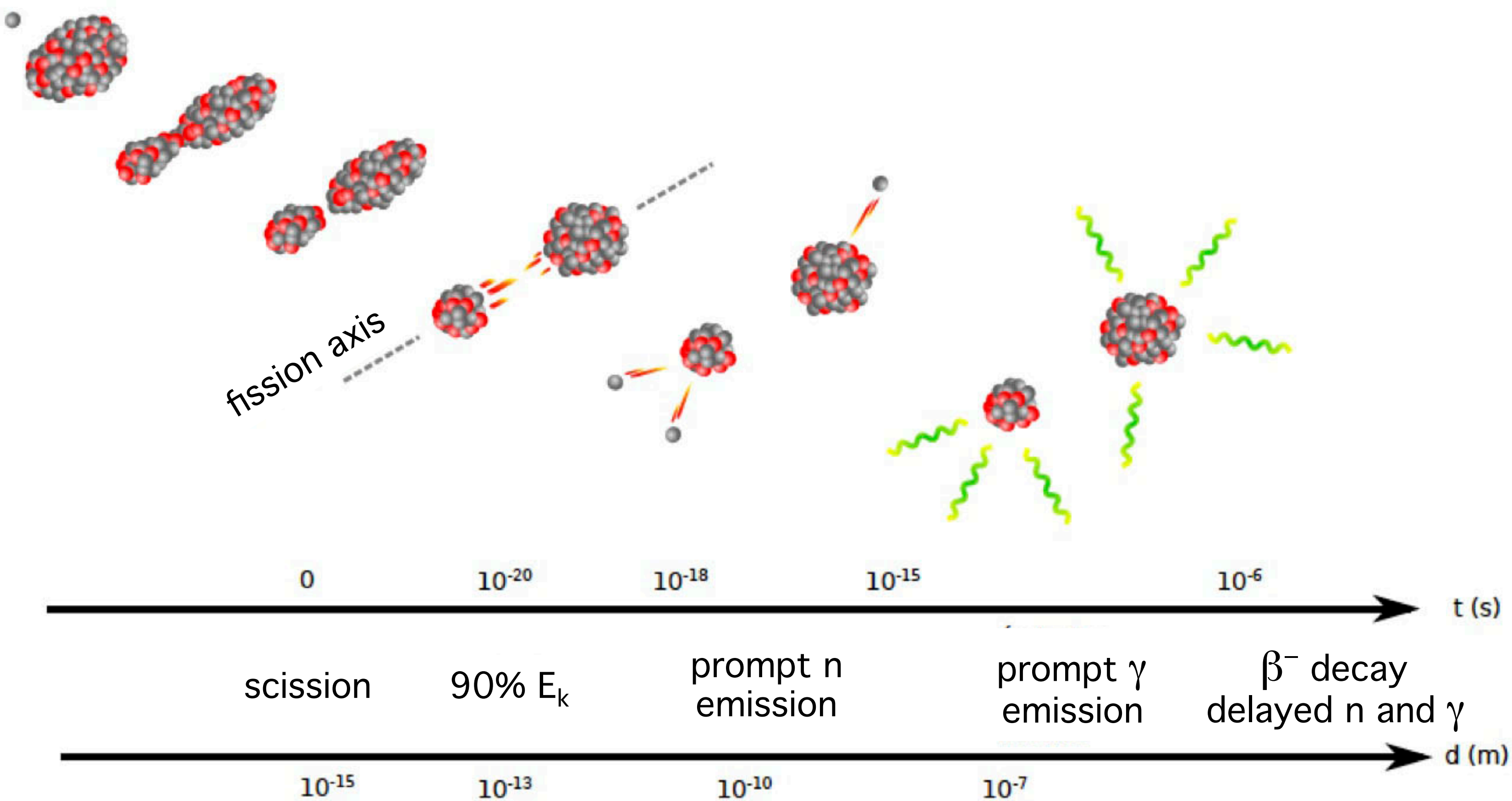
**$^{232}Th(\gamma, f)$ or $^{234,238}U(\gamma, f)$**

- cross section and angular distributions (higher resolution than with Bremsstrahlung)

# About ELI-NP
## … experiments elsewhere



# The fission process



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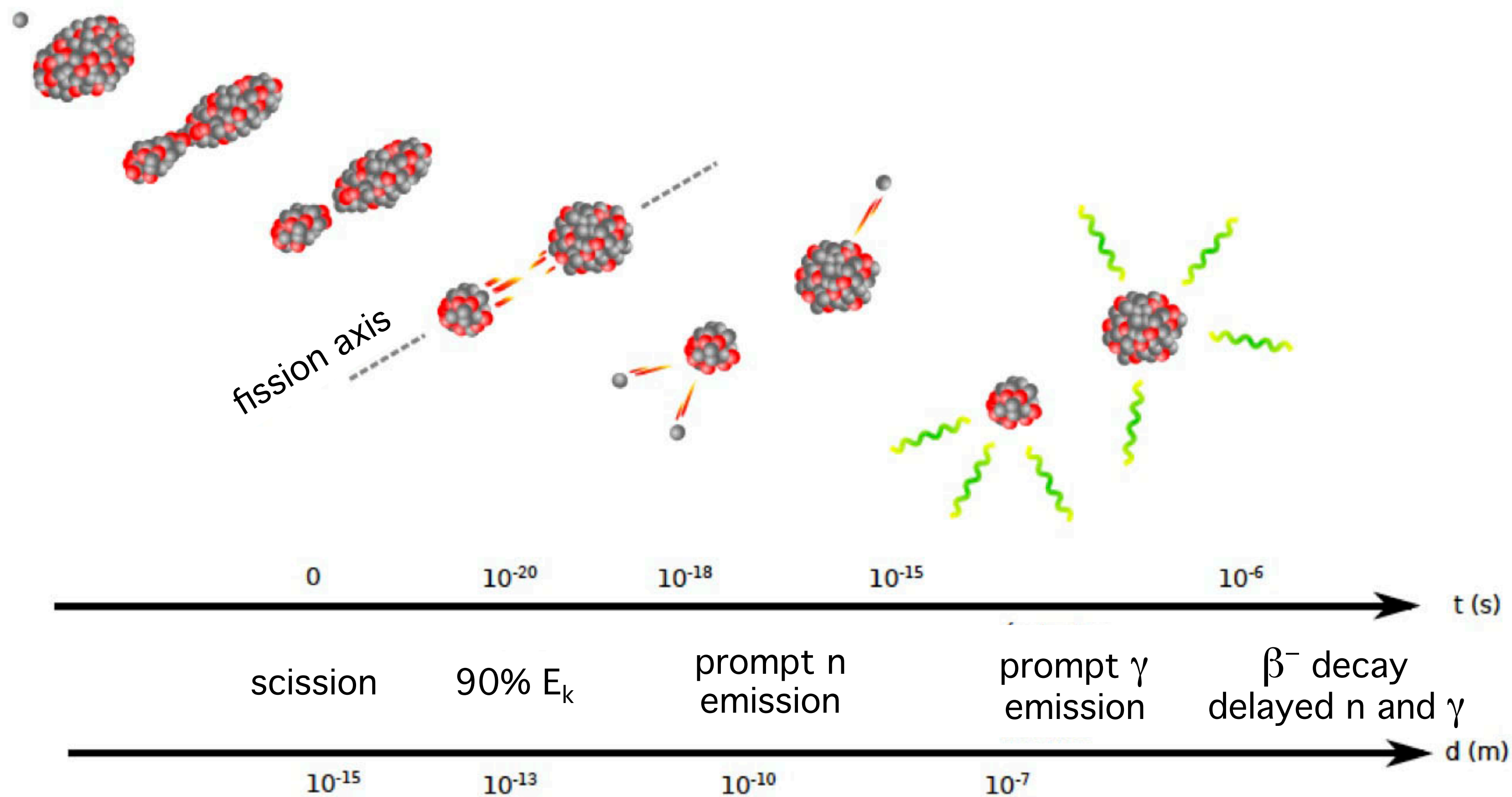
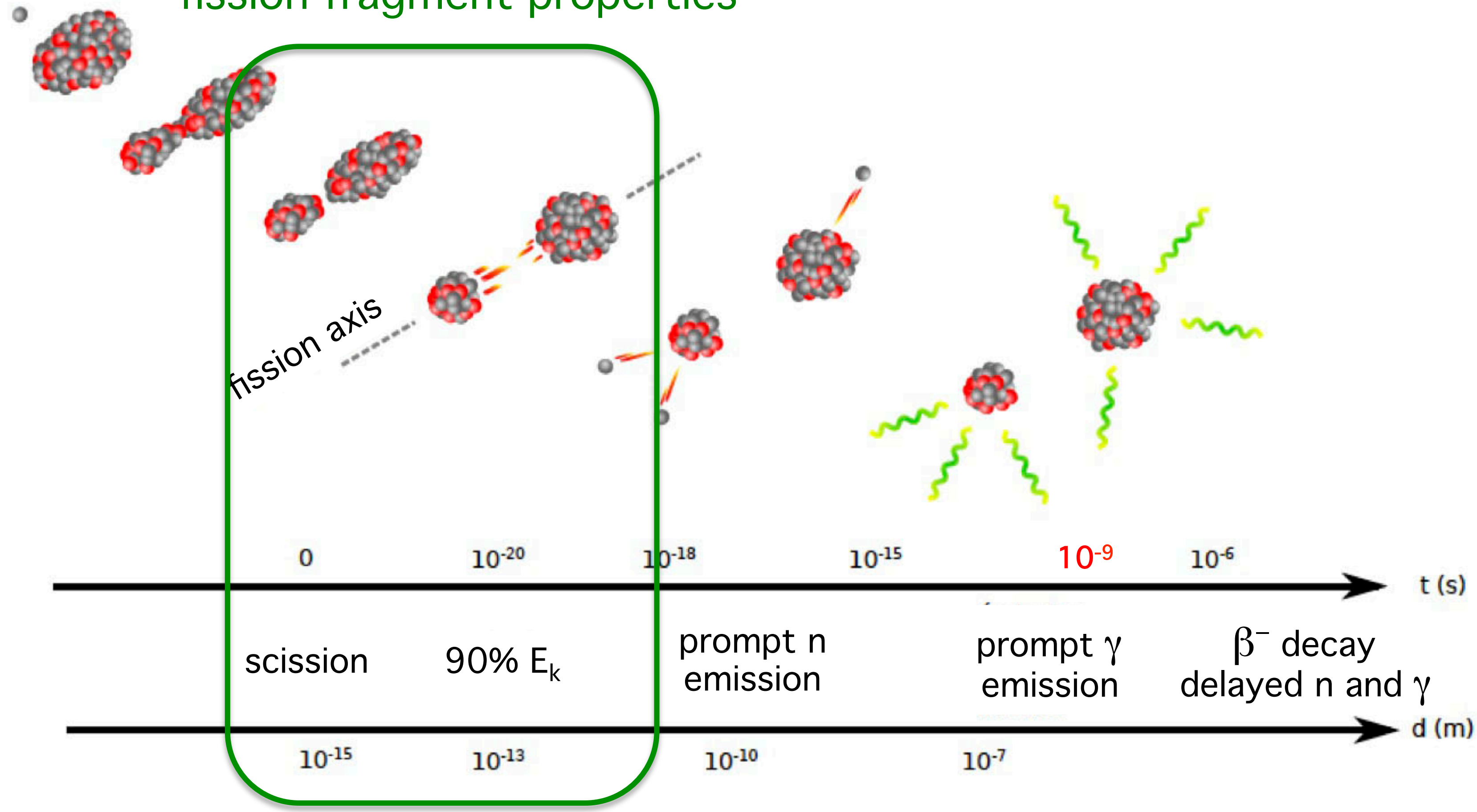



| For reactor applications: | nuclear energy | chain reaction | heat | reactor control |
|---|---|---|---|---|

# The fission process

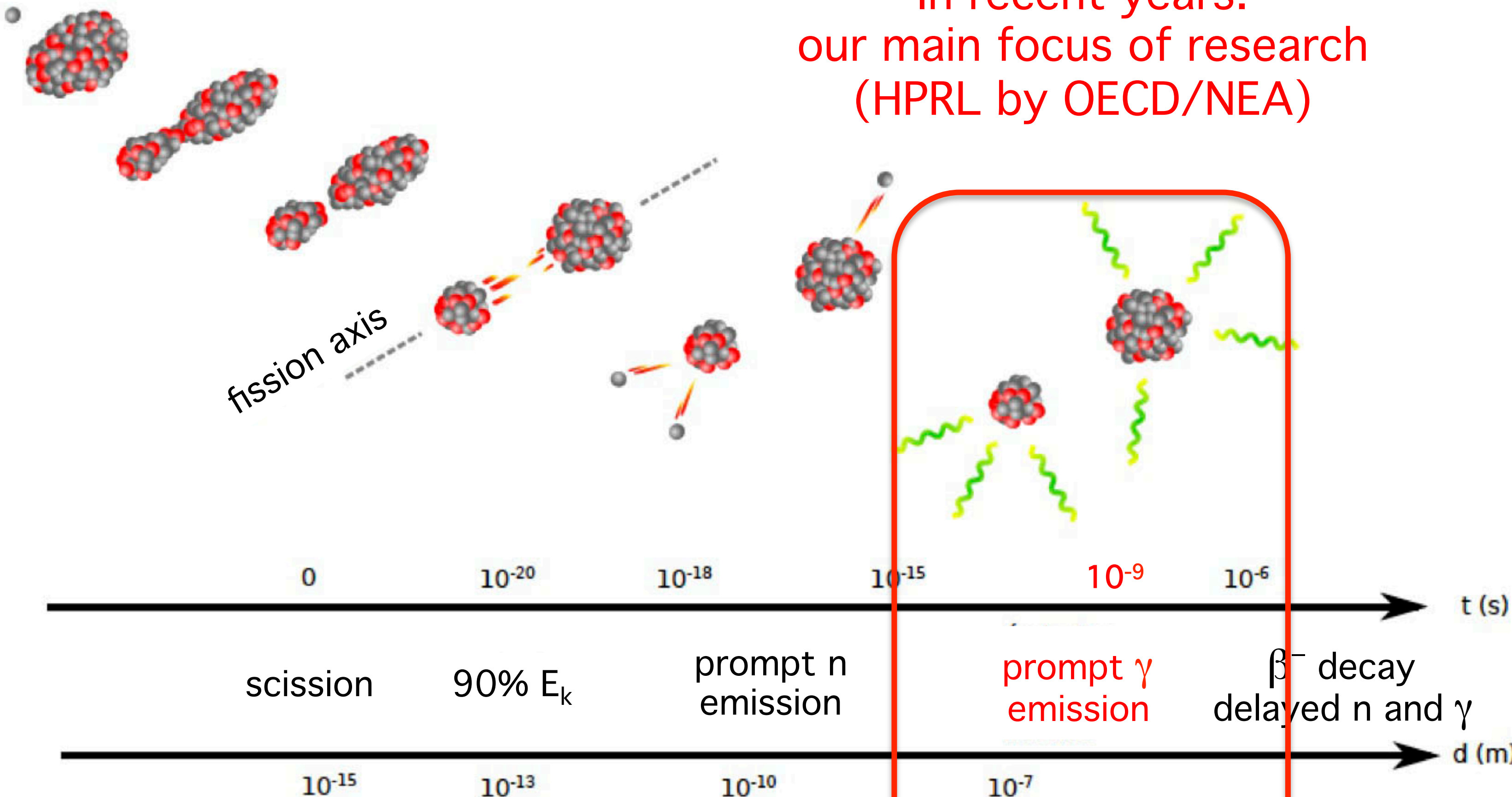
To start with at ELI-NP:
fission fragment properties




For reactor applications: nuclear energy | chain reaction | heat | reactor control

# The fission process

In recent years:
our main focus of research
(HPRL by OECD/NEA)




For reactor applications: nuclear energy | chain reaction | heat | reactor control

# On-going work

- For the past years: precise measurement of prompt fission $\gamma$-ray spectra (PFGS)

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- Determination of characteristics:
  - $<M_\gamma>$, $<\varepsilon_\gamma>$, and $<E_{\gamma,tot}>$

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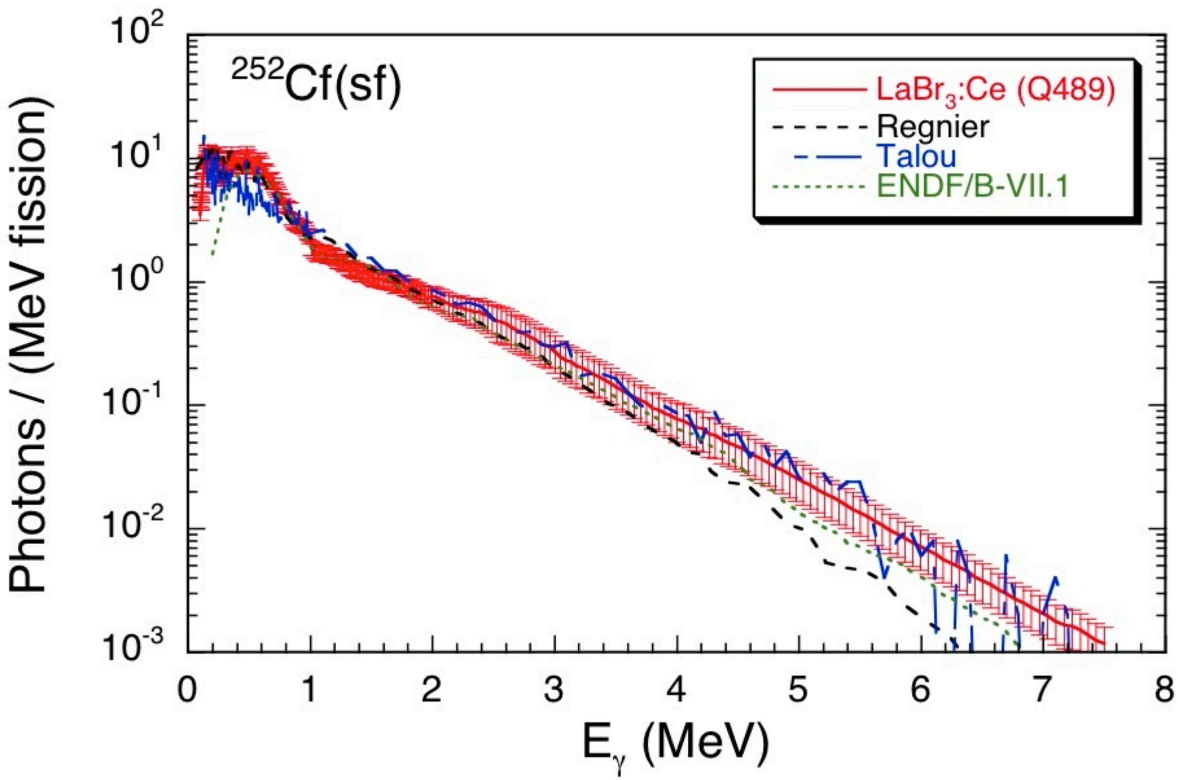
- For the past years: precise measurement of prompt fission $\gamma$-ray spectra (PFGS)
- Determination of characteristics:
  - $<M_{\gamma}>$, $<\varepsilon_{\gamma}>$, and $<E_{\gamma,tot}>$
- Study of the dependence of A and Z
- Study of energy dependence
- Details about the de-excitation process of fission fragments

# On-going work

## PFGS: High precision γ-ray measurements



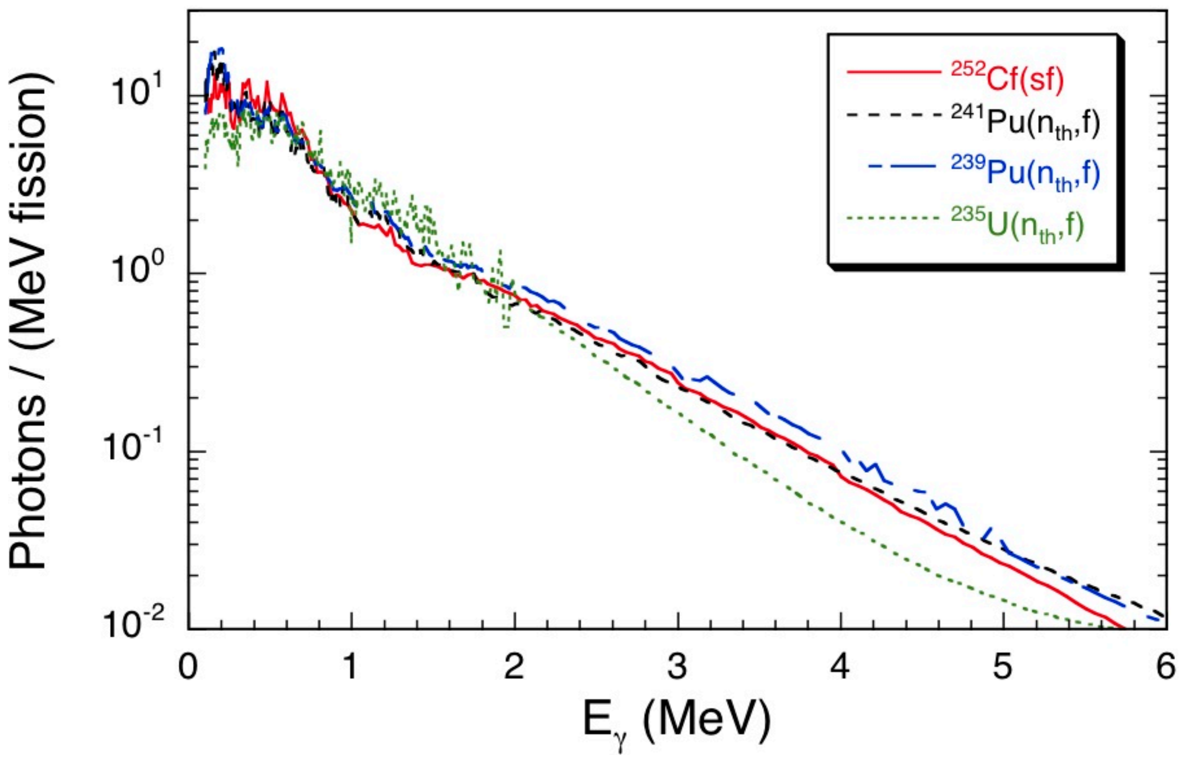

Excellent agreement between our experimental results and those from advanced model calculations *)

*) full Hauser-Feshbach Monte Carlo simulations by

- D. Regnier et al. (code: FIFRELIN, CEA Cadarache)
- P. Talou et al. (code: CGMF, LANL)

# On-going work

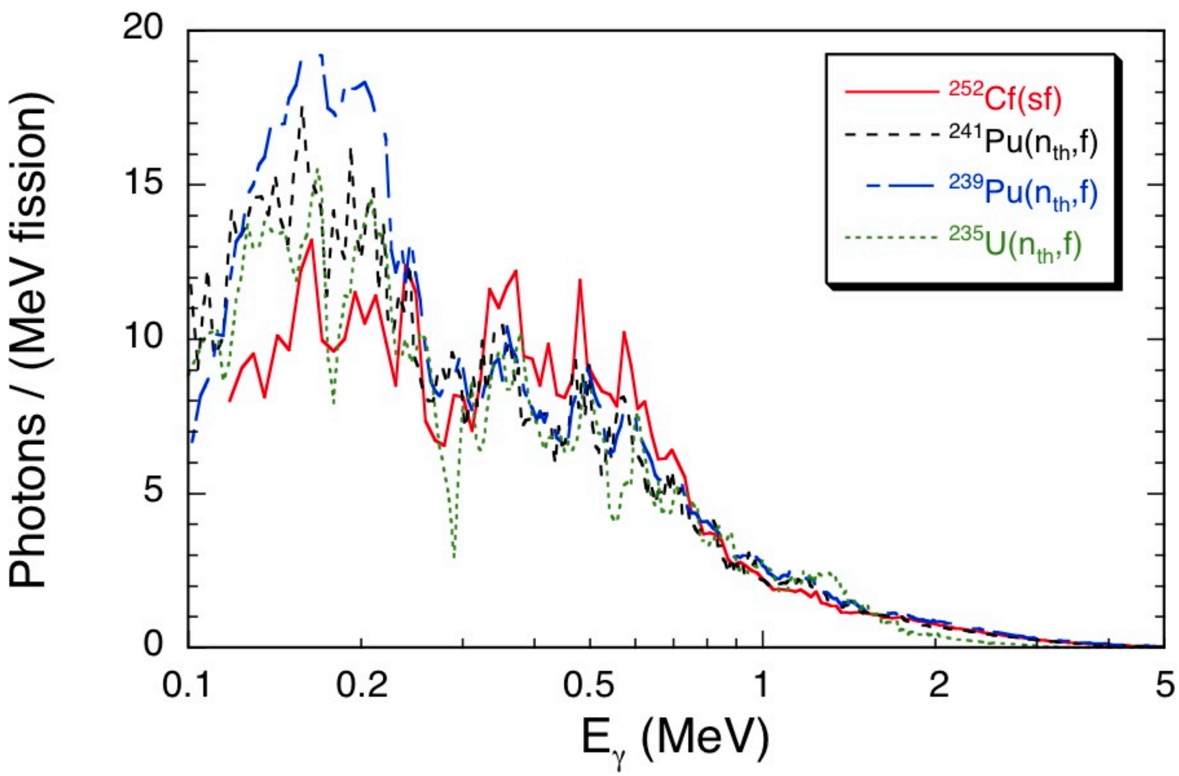
## PFGS: High precision γ-ray measurements




Examples for different compound systems

# On-going work

## PFGS: High precision γ-ray measurements

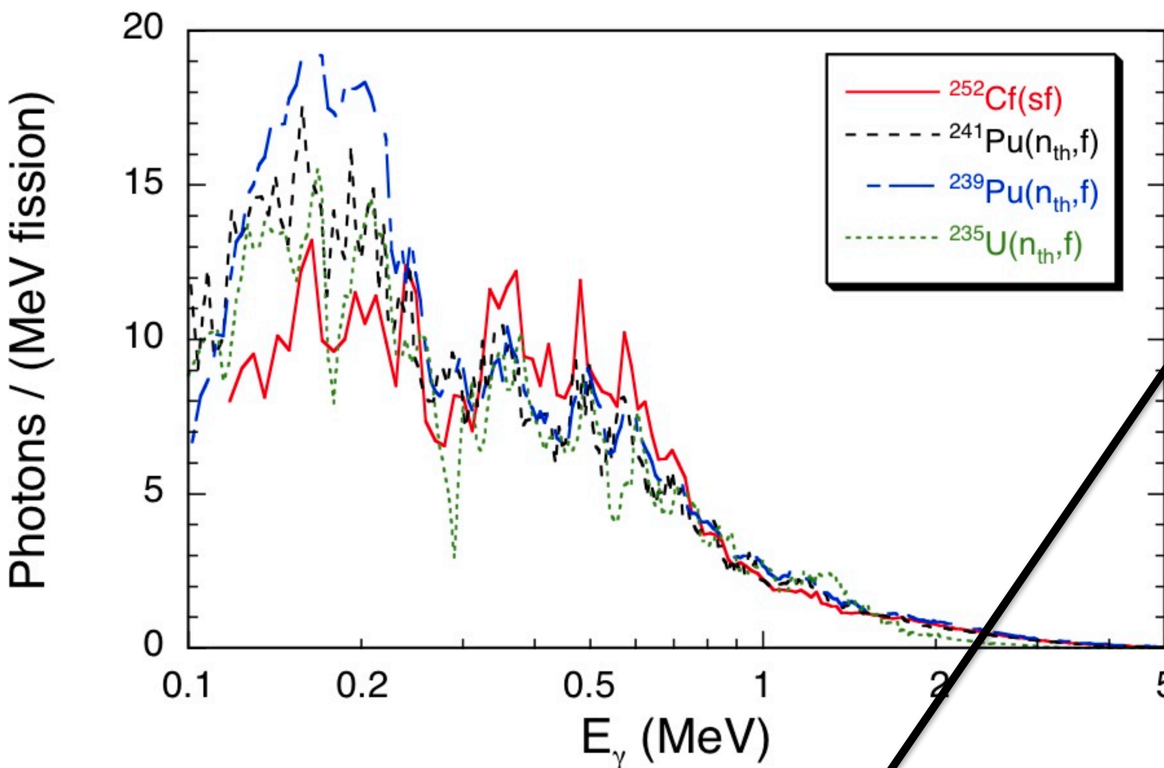


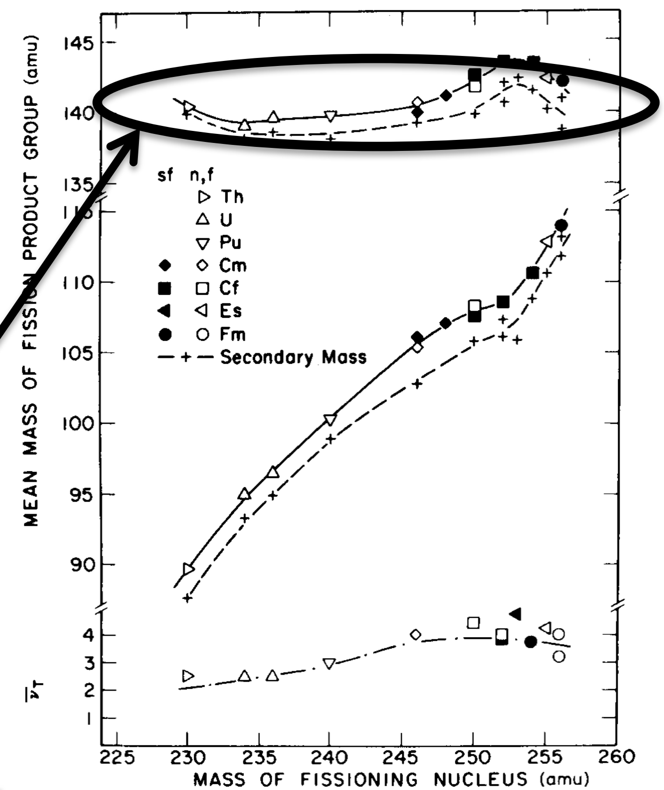

Examples for different compound systems

Similar low energy peak structures !

# On-going work

## PFGS: High precision γ-ray measurements



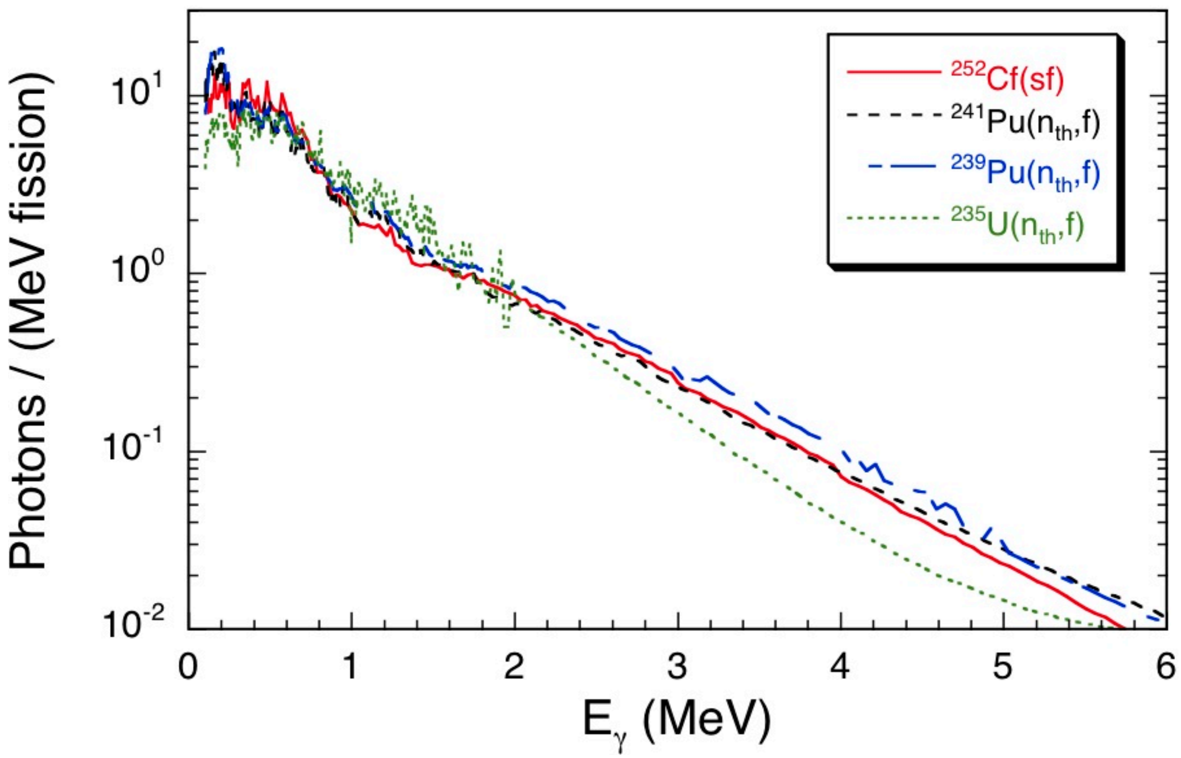

Similar low energy peak structures !

(J. Wagemans)

Due to de-excitation of the (same) heavy fragments ?

# On-going work

## PFGS: High precision γ-ray measurements




Examples for different compound systems

# On-going work

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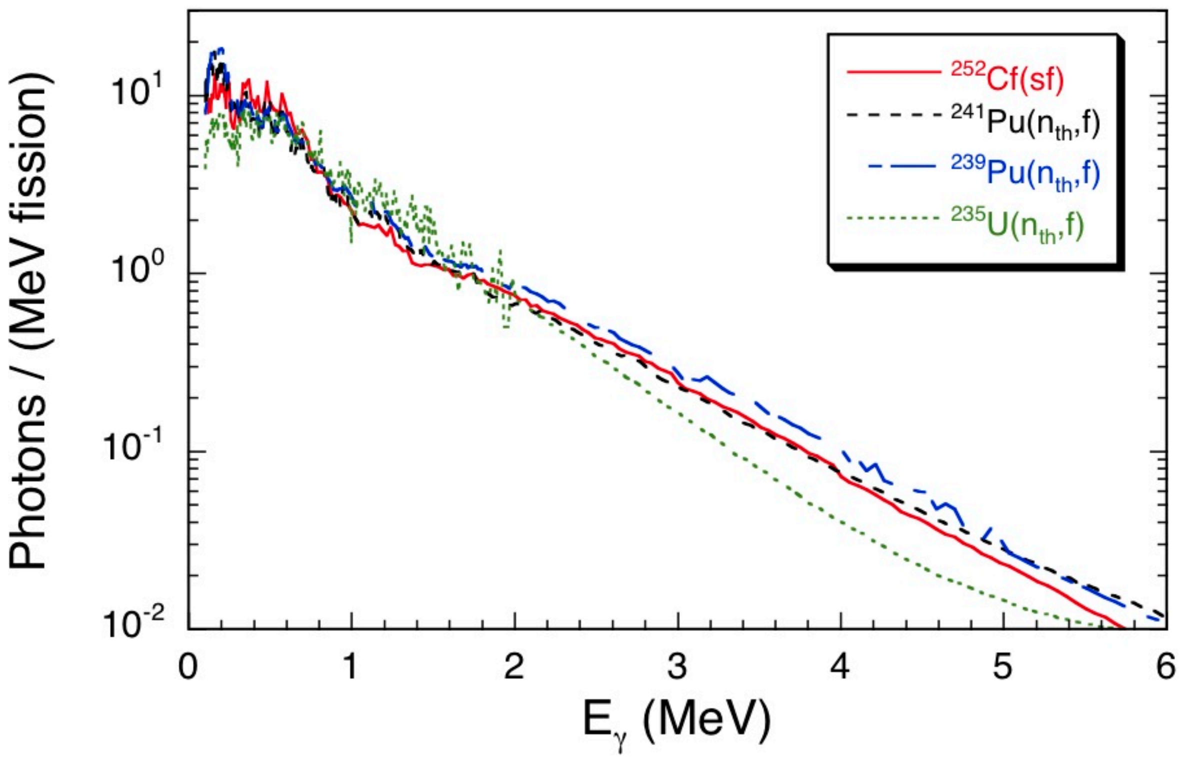


Examples for different compound systems

PFGS characteristics:

$$\overline{M}_\gamma = \int N_\gamma(E_\gamma)dE_\gamma$$

$$\mathrm{E}_{\gamma,\mathrm{tot}} = \int E_\gamma \times N_\gamma(E_\gamma)dE_\gamma$$

$$\epsilon_\gamma = \mathrm{E}_{\gamma,\mathrm{tot}}/\overline{M}_\gamma$$

# On-going work

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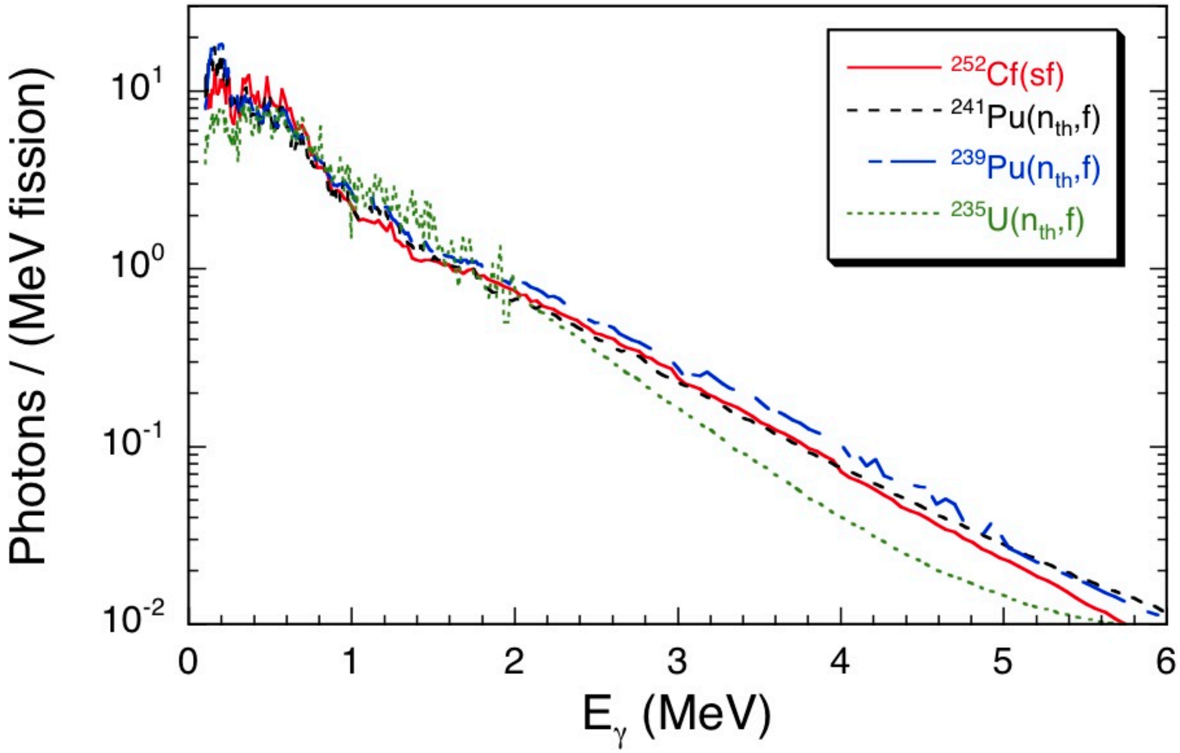


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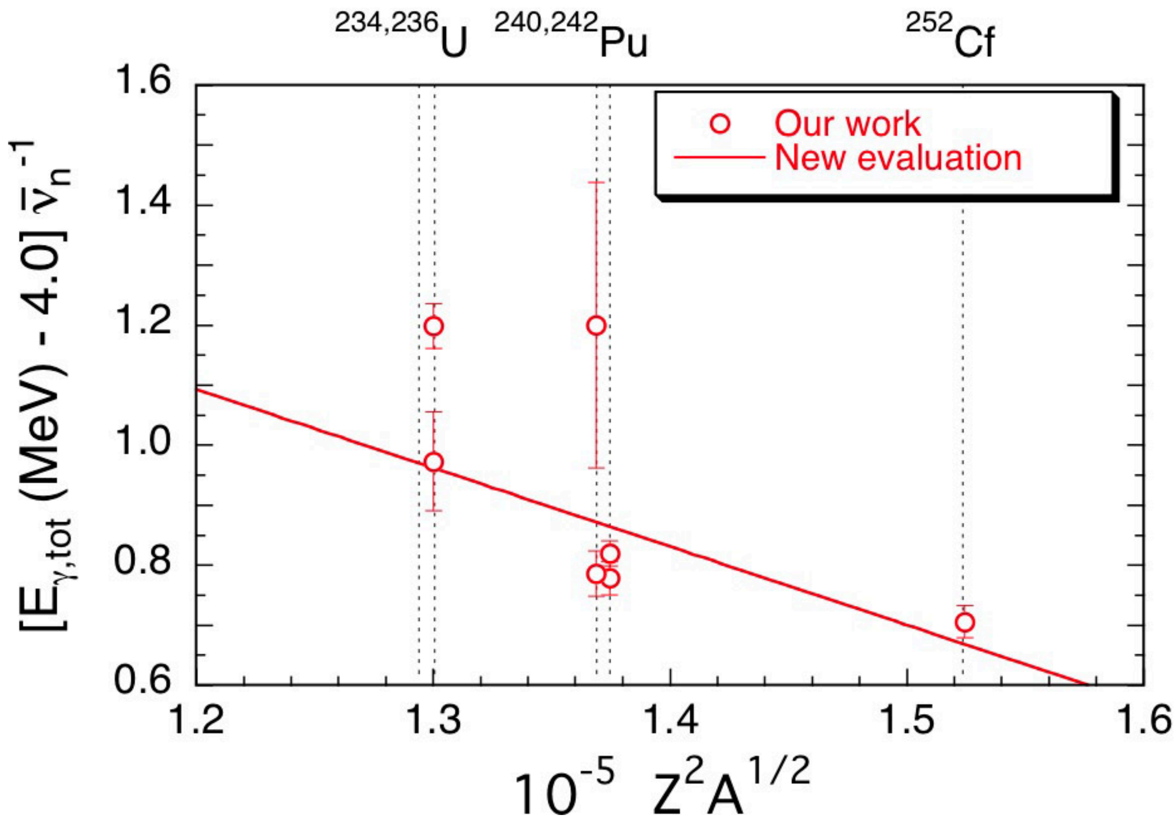
↳ Systematics !

$$\epsilon_\gamma = \mathrm{E}_{\gamma,\mathrm{tot}} / \overline{M}_\gamma$$

# On-going work

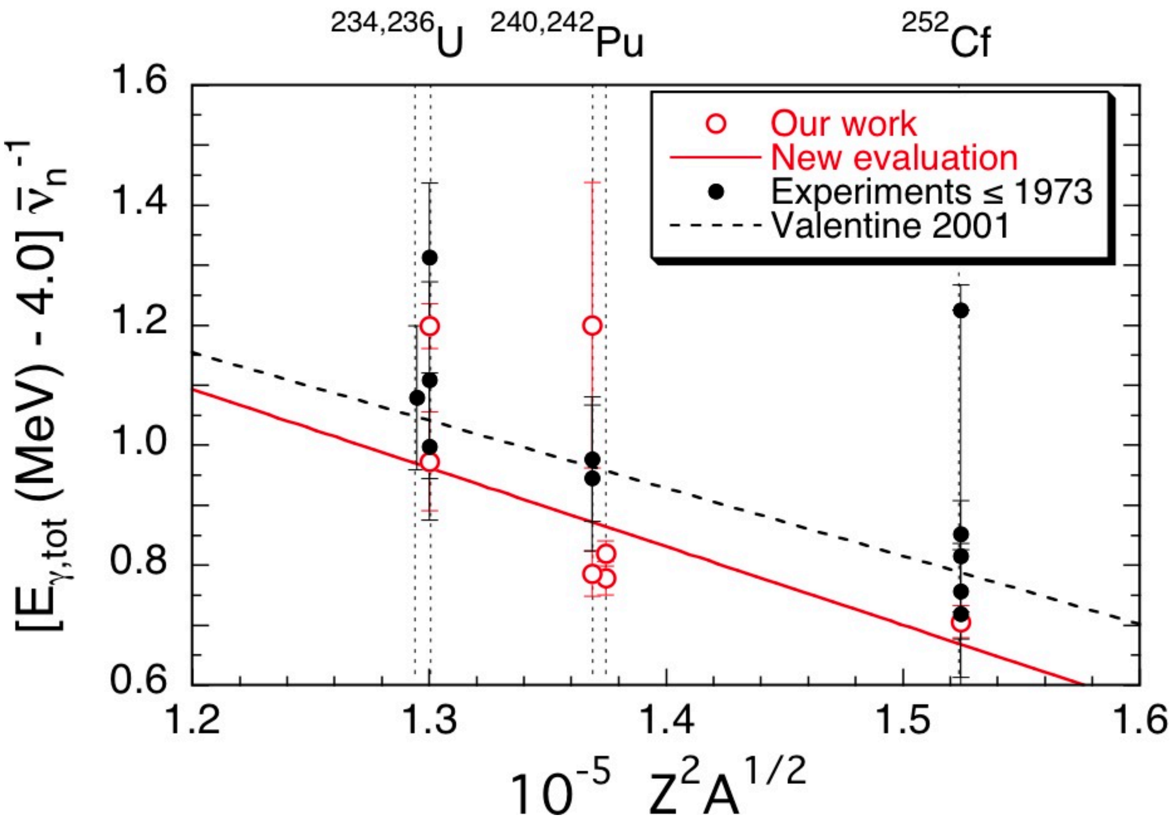
## A and Z dependence: Systematics of PFGS




($n_{th}$,f) and (sf) only!

According to Nifenecker (1972) and Valentine (2001), revised 2017: A. Oberstedt et al., PRC 96, 034612

# On-going work
## A and Z dependence: Systematics of PFGS

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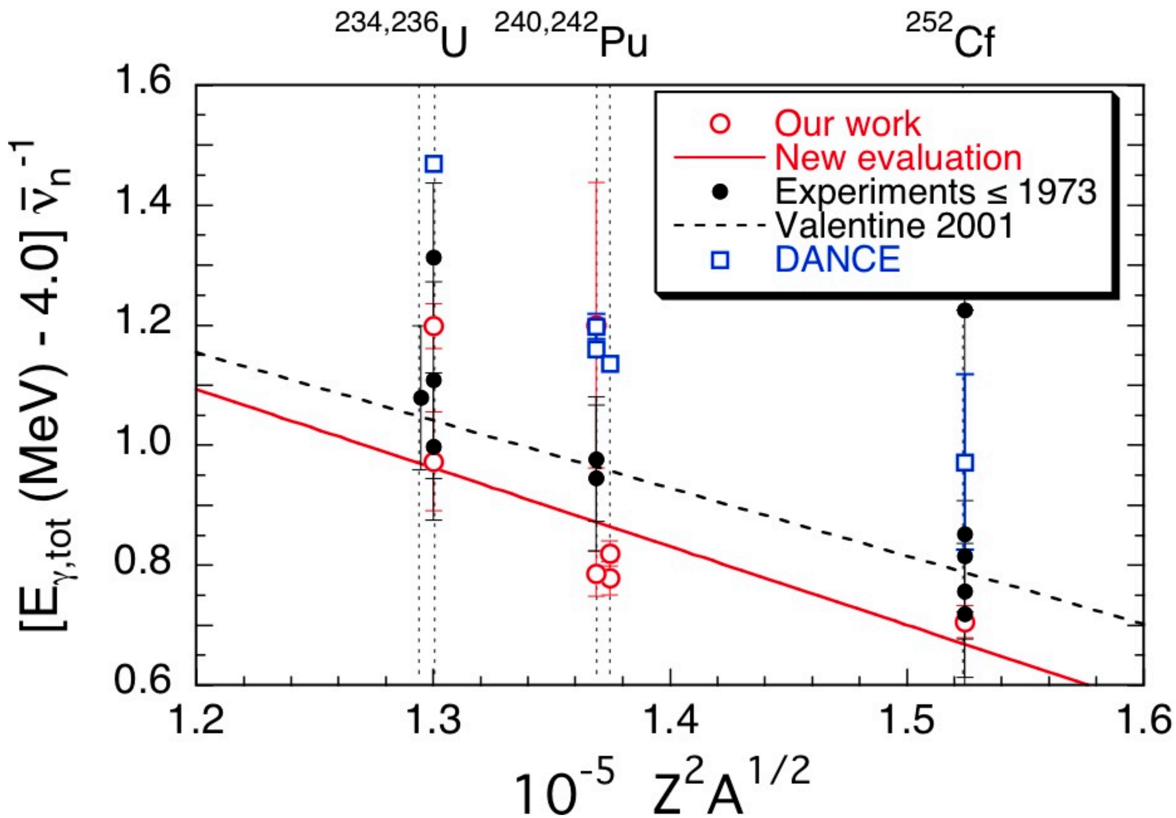


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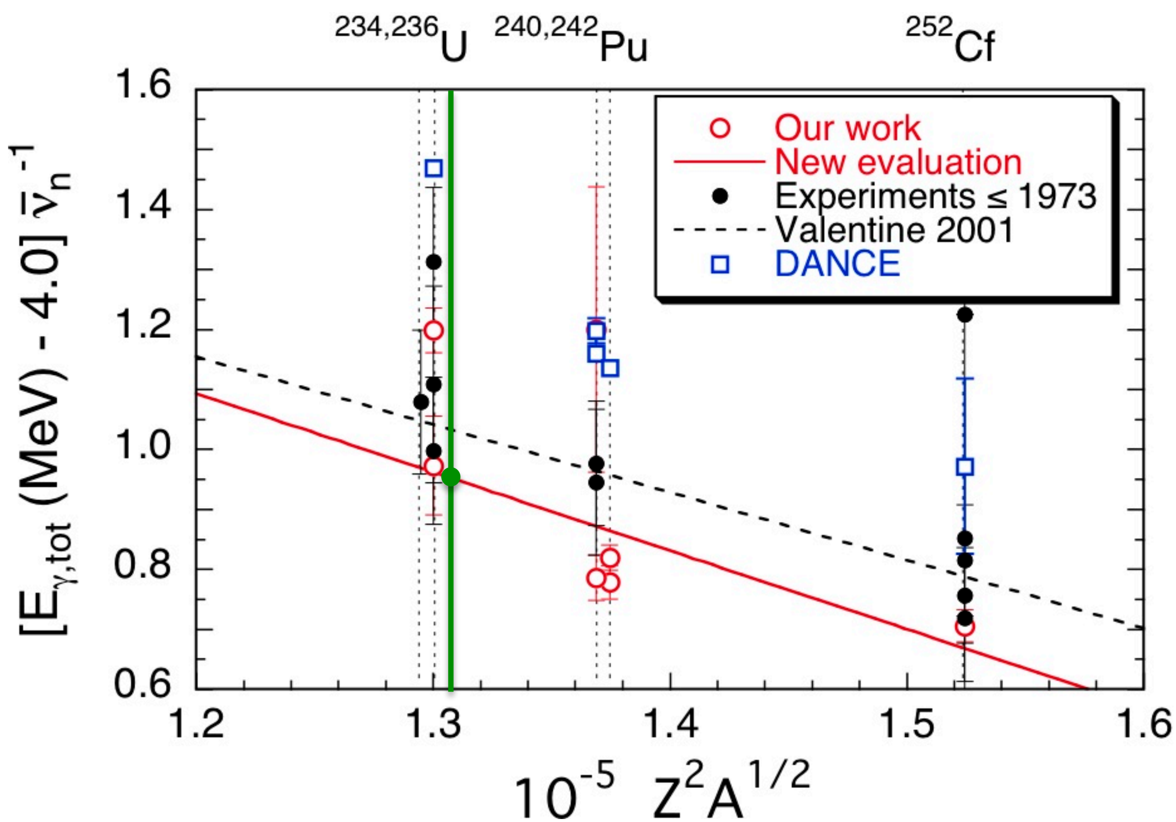



($n_{th}$,f)

and

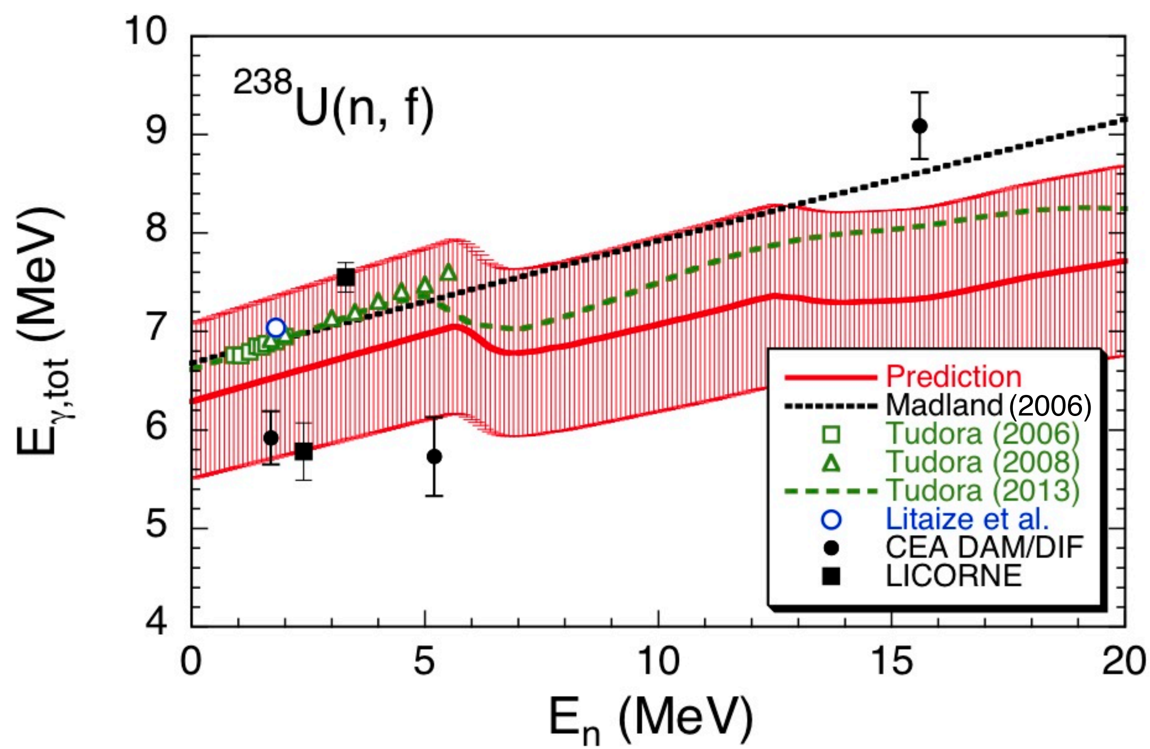
(sf)

only!

Allows interpolation to unmeasured fissioning systems, here $^{238}U(n_{th},f)$: A. Oberstedt et al., PRC 96, 034612

# On-going work
## Energy dependence

From thermal to fast neutron-induced fission

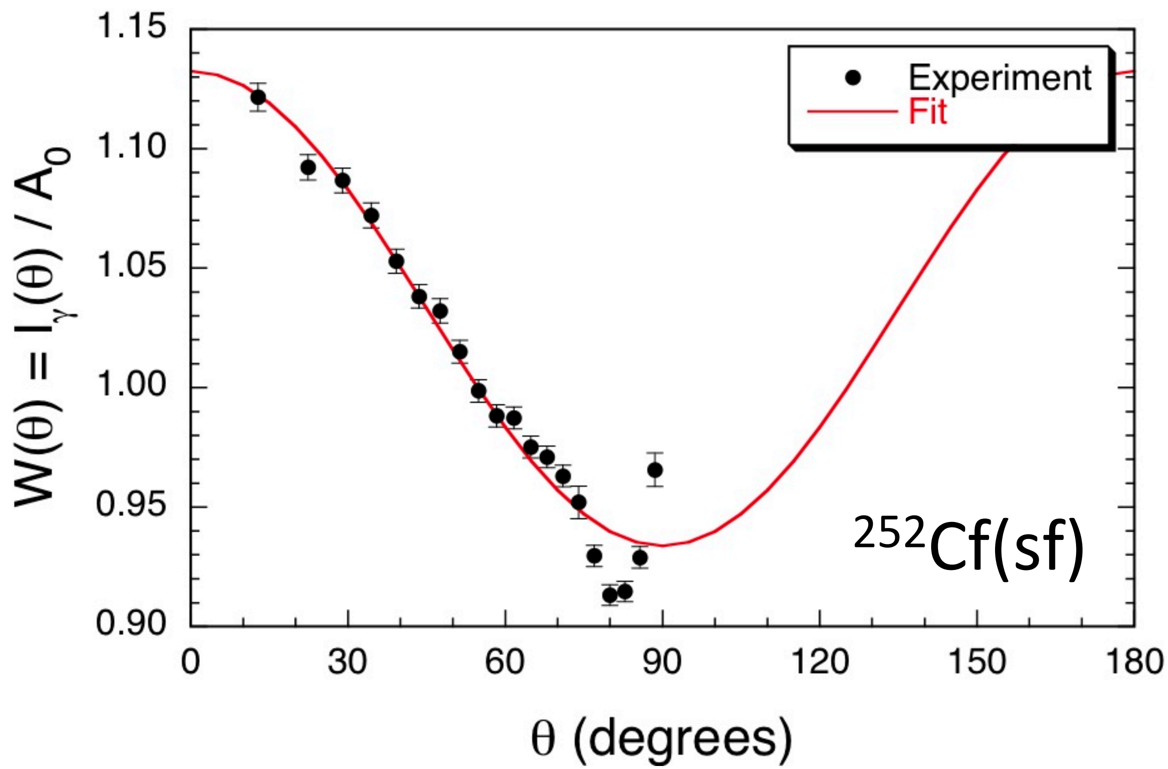



A. Oberstedt et al., PRC 96, 034612 (2017)

- Tudora: Point-by-Point model
- Litaize et al.: FIFRELIN code, Nucl. Data Sheets 118, 216 (2014)
- CEA DAM/DIF & LICORNE: preliminary experimental results

# On-going work

## Prompt fission γ-ray angular distributions




Statistical uncertainties only!

$$\text{Fit: } I_\gamma(\theta) = A_0\,[1 + \{A_2/A_0\}P_2(\cos\theta) + \{A_4/A_0\}P_4(\cos\theta)]$$

$$\text{Fit result: } \{A_2/A_0\} = 0.13 \pm 0.03$$

# On-going work

## Angular distributions and multipolarities

| $^{252}$Cf(sf) | Experiment (this work) | | Calculations (FIFRELIN*)) | |
|---|---|---|---|---|
| $\bar{M}_\gamma$ | 8.28 ± 0.51 | | 8.28 | (adjusted) |
| $\bar{M}_\gamma$ (L = 1) | 2.31 | (28 %) | 3.20 | (39 %) |
| $\bar{M}_\gamma$ (L = 2) | 5.97 | (72 %) | 1.45 | (17 %) |
| $\bar{M}_\gamma$ (experim. ) | --- | | 3.63 | (44 %) |
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*) A. Chebboubi, priv. comm.

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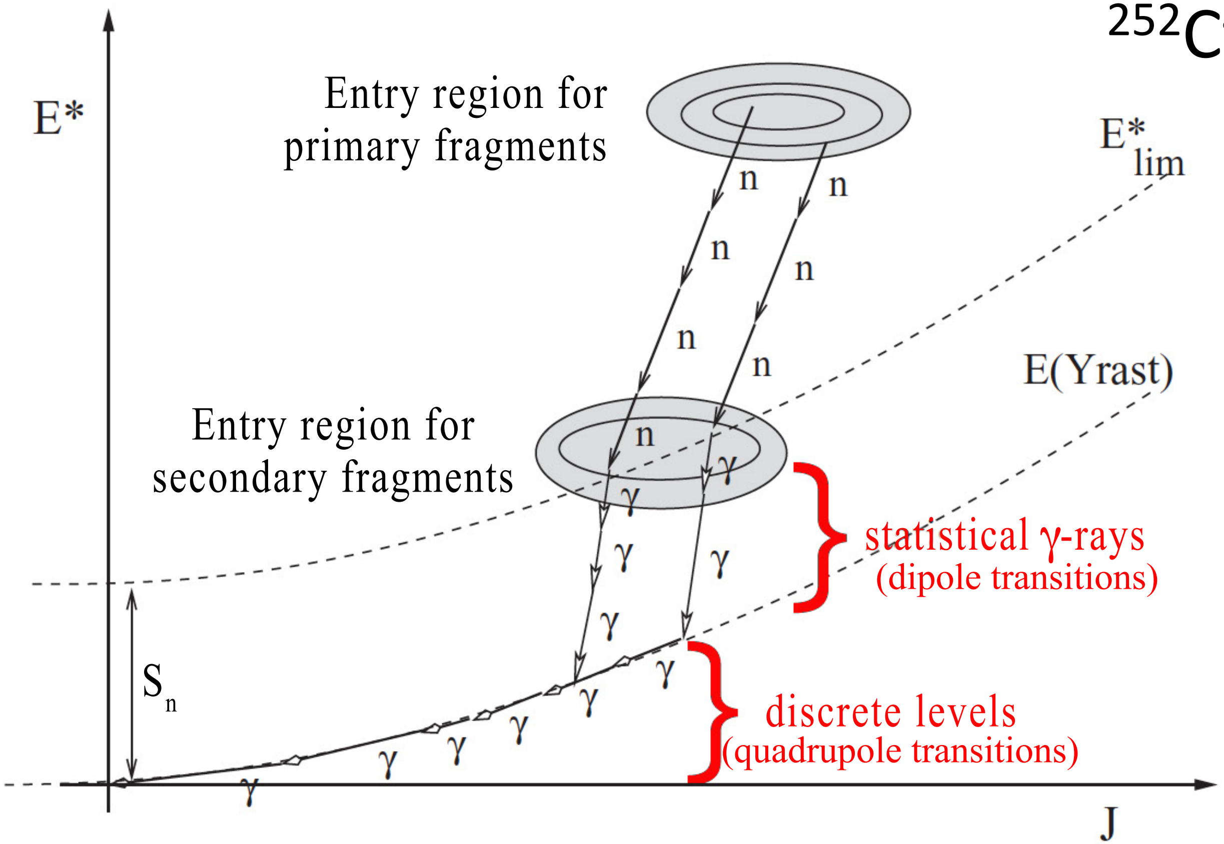
PRELIMINARY

*) A. Chebbouibi, priv. comm.

# On-going work

## Sequential emission of neutrons and γ-rays

$^{252}$Cf(sf)




O. Litaize et al., PRC 82, 054616 (2010)

# On-going work
## Sequential emission of neutrons and γ-rays

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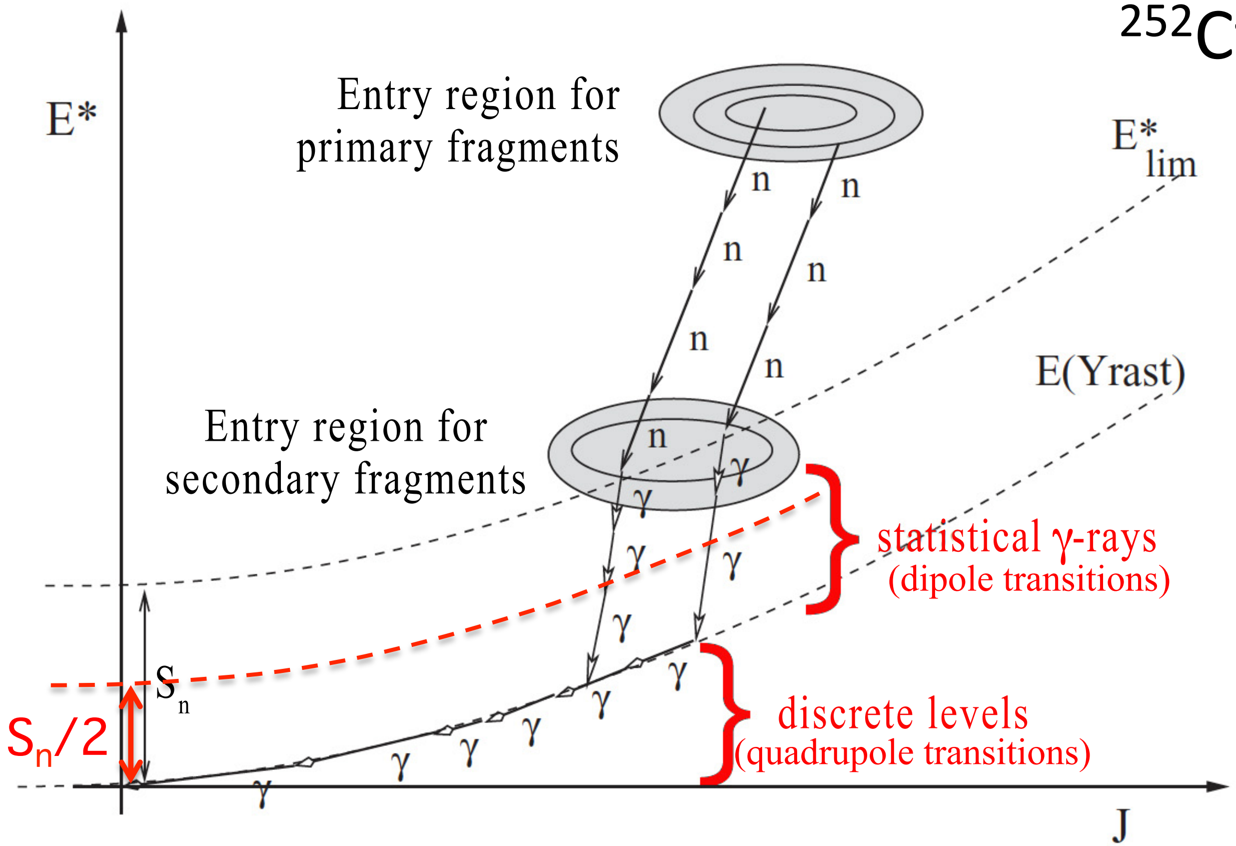

# On-going work

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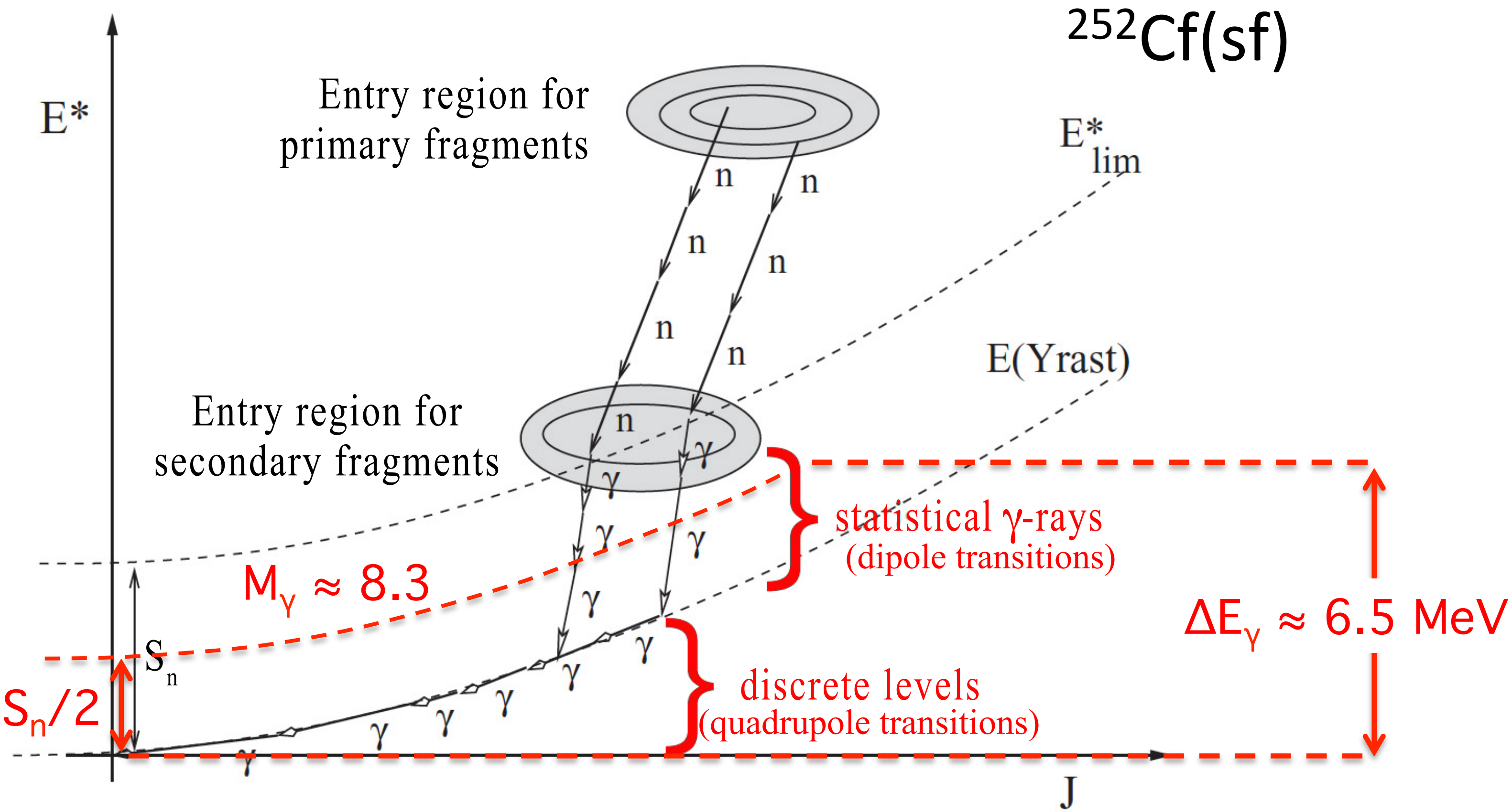

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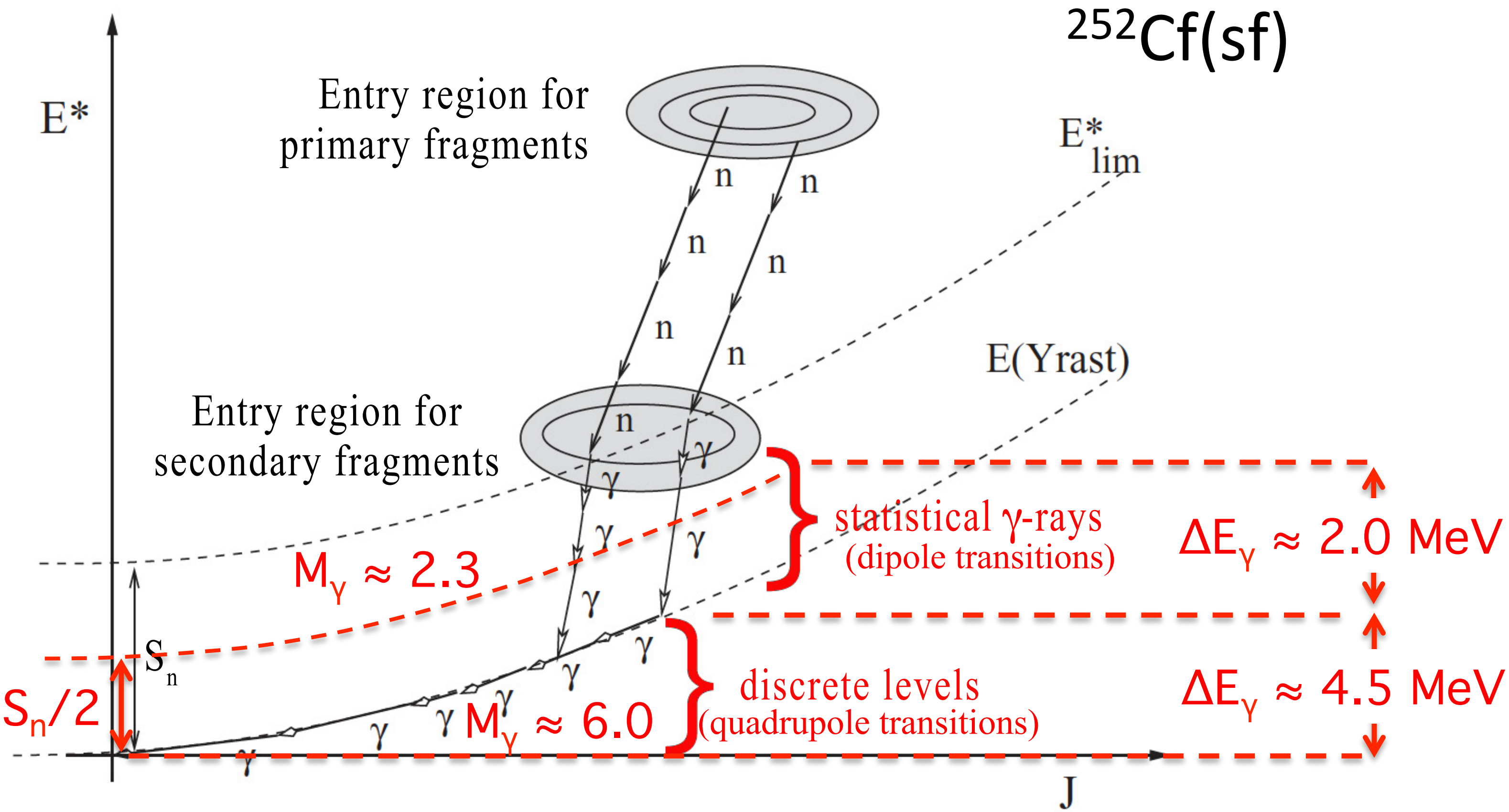

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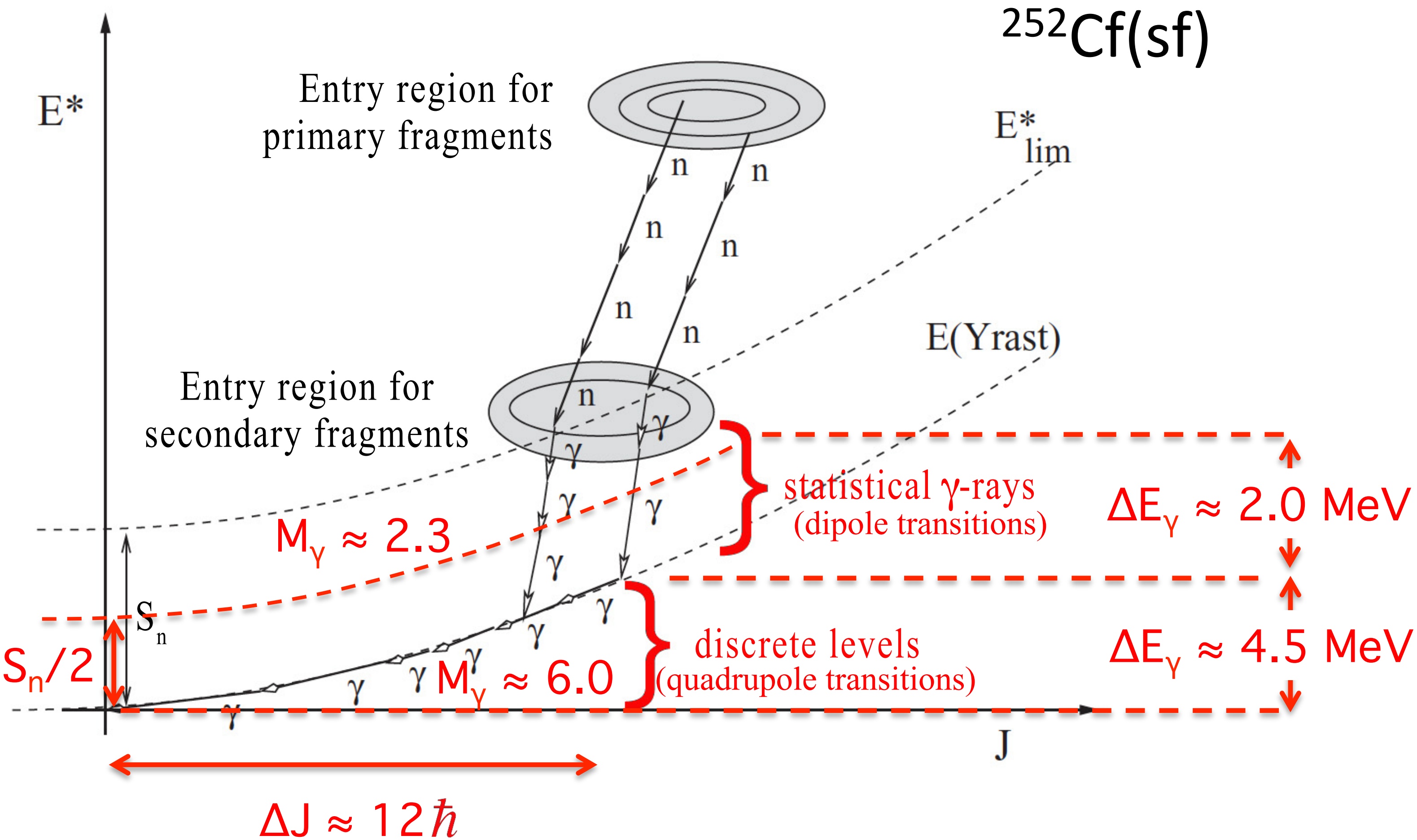

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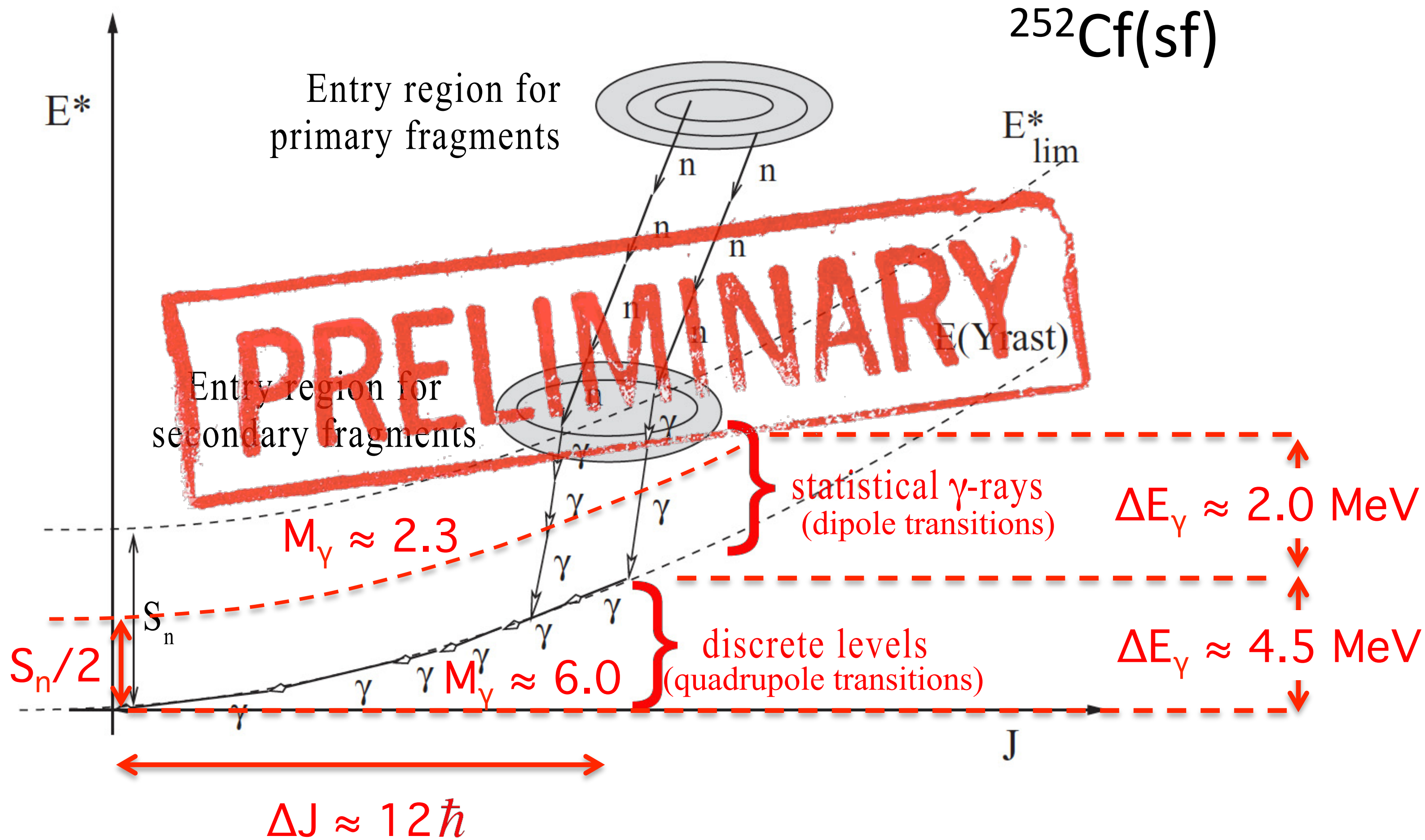
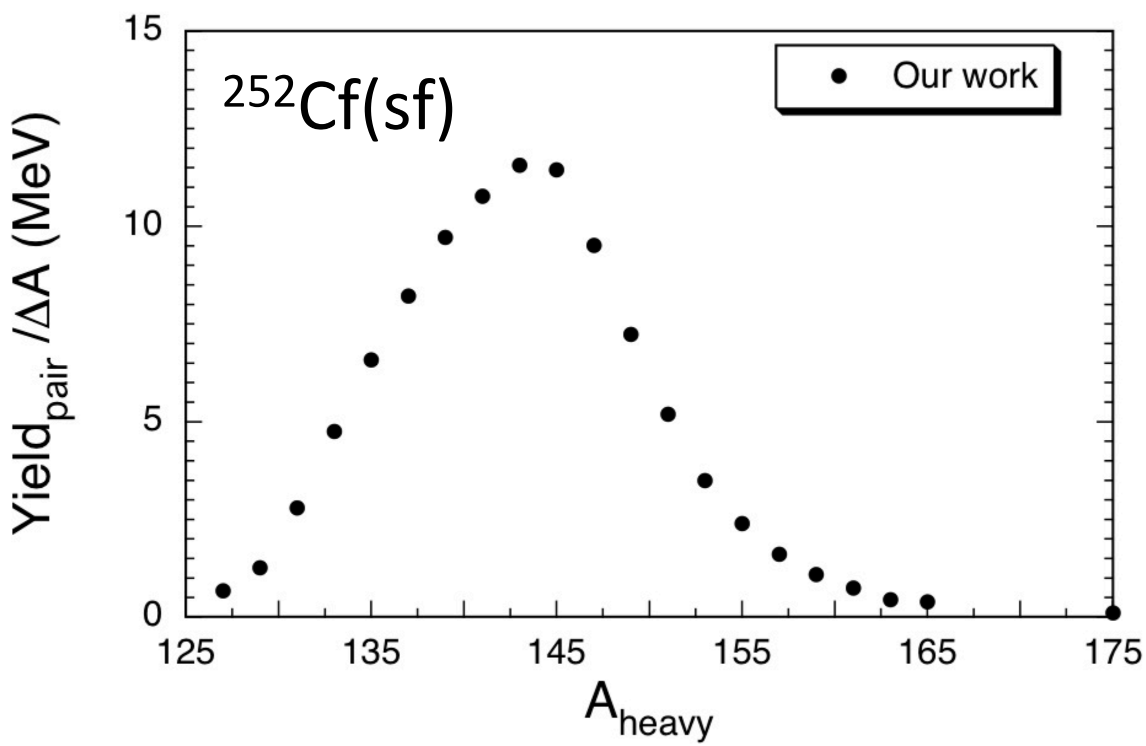


# On-going work

## Dependence of fragment mass

Measurement of fission fragment (pair) yields




- Due to limited mass resolution of FGIC: ΔA = 2 … 7

# On-going work
## Dependence of fragment mass

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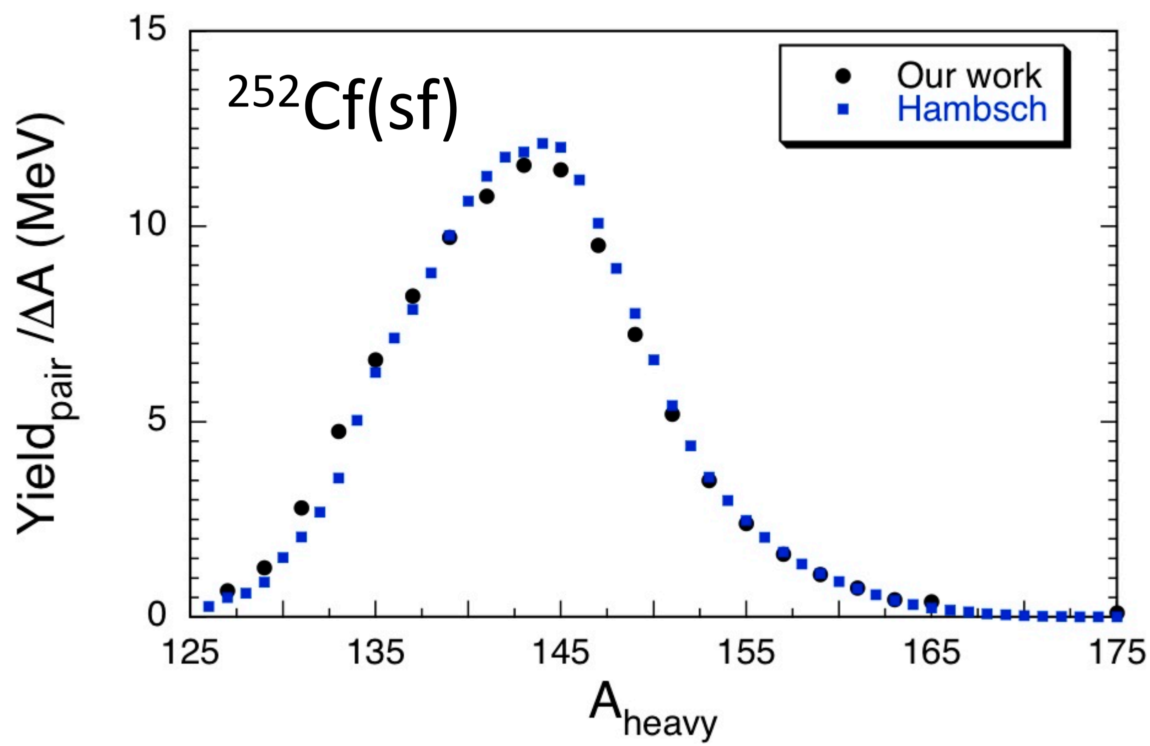
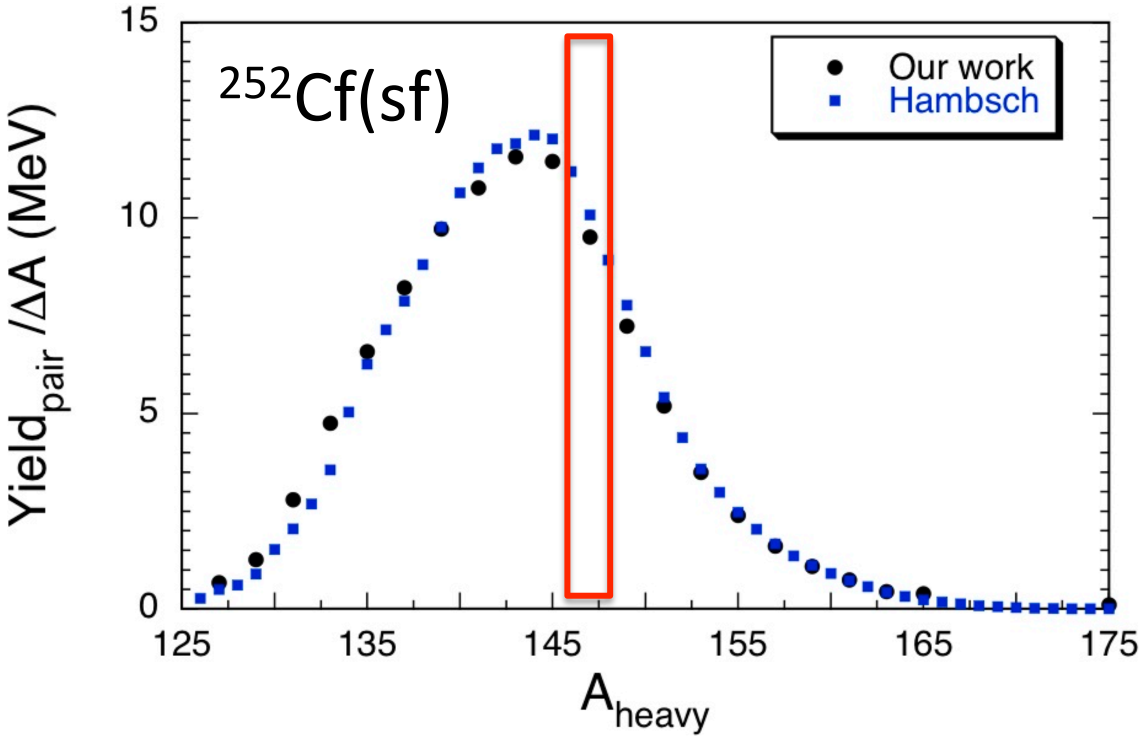



- Good agreement with previous results from Hambsch (priv. communication)

# On-going work

## Dependence of fragment mass

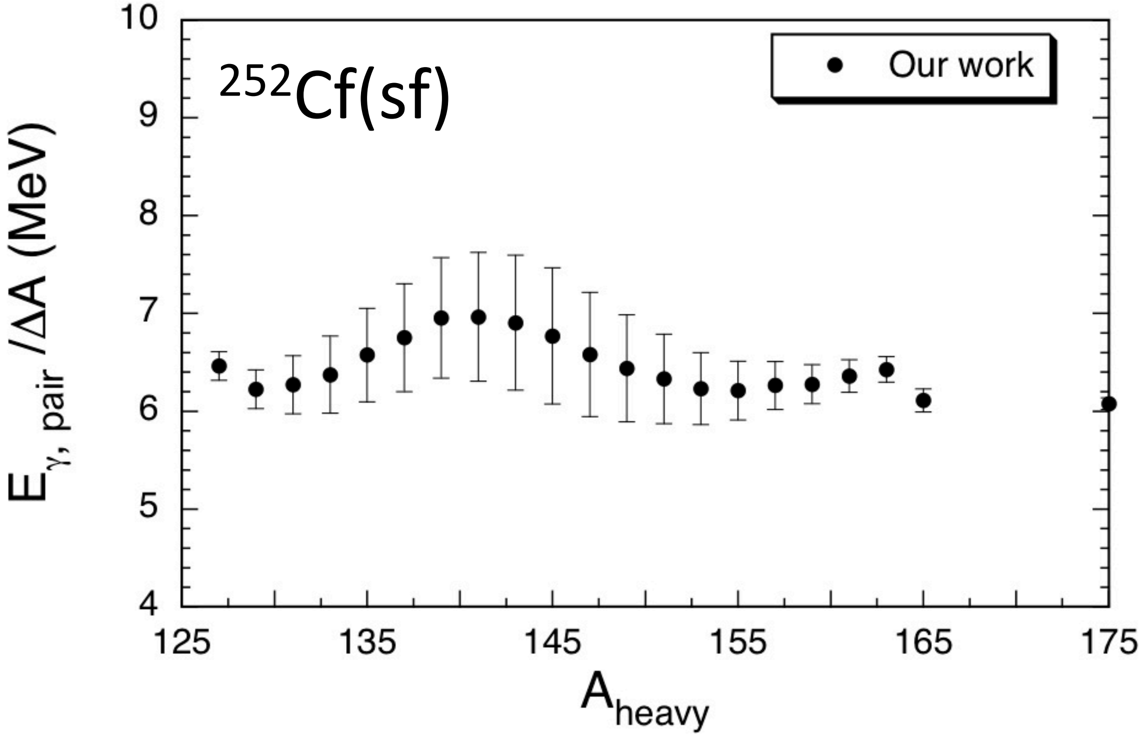
Measurement of fission fragment (pair) yields




- Creating PFGS gated on fission fragment mass (region)
- Determining their characteristics

# On-going work
## Dependence of fragment mass

Average total γ-ray energy per fission fragment pair




- Observe: so far data from only one $LaBr_3$ detector!

# On-going work
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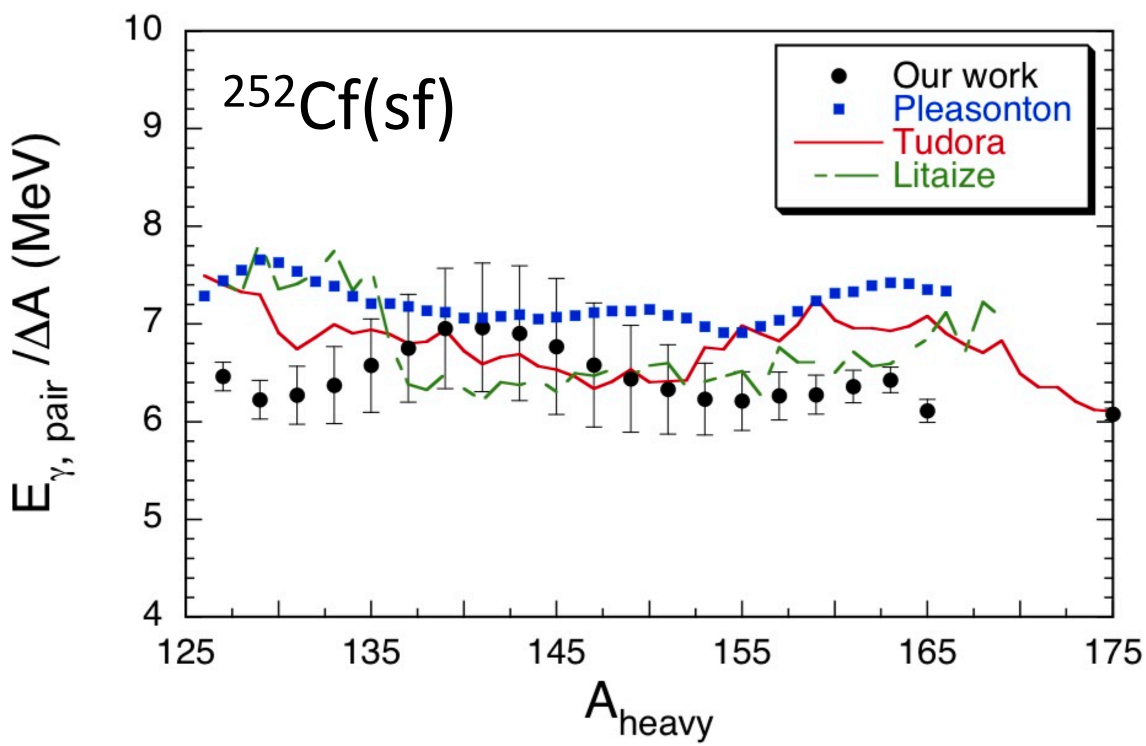


- Comparison with experimental (symbols) and calculated values (lines)

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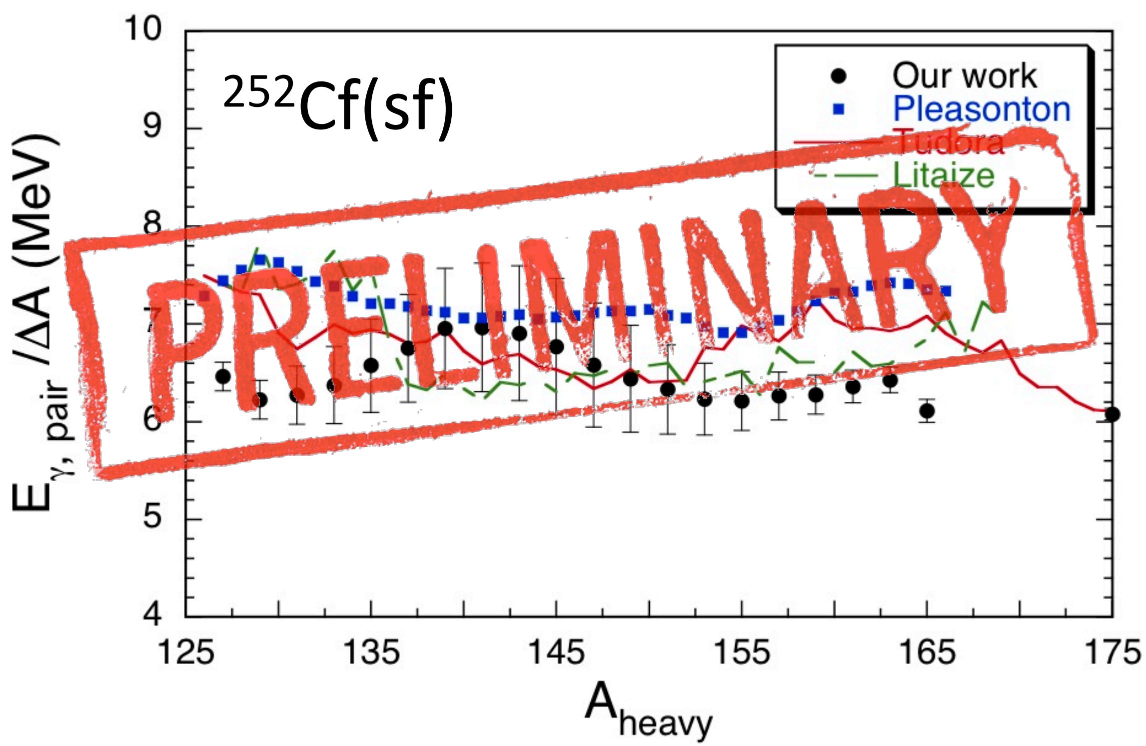


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# Summary

- ✓ High precision PFGS measurements → reference for model calculations

# Summary

## Overview: studied systems so far

eli nuclear physics

IFIN-HH

# Summary

## Overview: studied systems so far


compound systems

Previous work: ☐ (sf)

# Summary

## Overview: studied systems so far


compound systems

Previous work: ☐ (sf), $(n_{th}, f)$

# Summary

## Overview: studied systems so far


Previous work: ☐ (sf), $(n_{th}, f)$, (n, f)

# Summary

## Overview: studied systems so far


Previous work: ☐ (sf), ($n_{th}$, f), (n, f), **(d, pf)**

# Summary

## Overview: studied systems so far


compound systems

Previous work: ☐ (sf), ($n_{th}$, f), (n, f), (d, pf)

# Summary

## Overview: studied systems so far


Previous work: ☐ (sf), $(n_{th}, f)$, (n, f), (d, pf)

Recent experiment: ⬚ (sf)

# Summary

## Overview: studied systems so far


compound systems

Previous work: ☐ (sf), ($n_{th}$, f), (n, f), (d, pf)

Recent experiment: ☐ (sf), ($n_{th}$, f)

# Summary

## Overview: studied systems so far


Previous work: ☐ (sf), ($n_{th}$, f), (n, f), (d, pf)

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# Summary

## Overview: studied systems so far


Previous work: (sf), ($n_{th}$, f), (n, f), (d, pf)

Recent experiment: (sf), ($n_{th}$, f)

Approved proposals: (n, f)

# Summary

- ✓ High precision PFGS measurements → reference for model calculations
- ✓ Revised systematics for spontaneous and thermal neutron-induced fission
- ✓ Predictions of PFGS characteristics for fast neutron-induced fission -> rather good agreement
- ✓ Measured γ-ray angular distribution from $^{252}Cf(sf)$ → dominant E2 character, in good agreement with previous observations + FIFRELIN calculations (in progress)
- ✓ Preliminary results : PFGS dependence of fragment mass
- ✓ Data analysis of recent experiments in progress, e.g. $^{233}U(n_{th}, f)$ PFGS

# Outlook

- New results from recent measurements
- Study of PFGS characteristics depending on fission fragment mass (continued)
- New experiments are approved and scheduled
- Study of entrance channel effects
  - (n,f) vs. (d,pf)
  - (p,p'f) vs. (γ,f)
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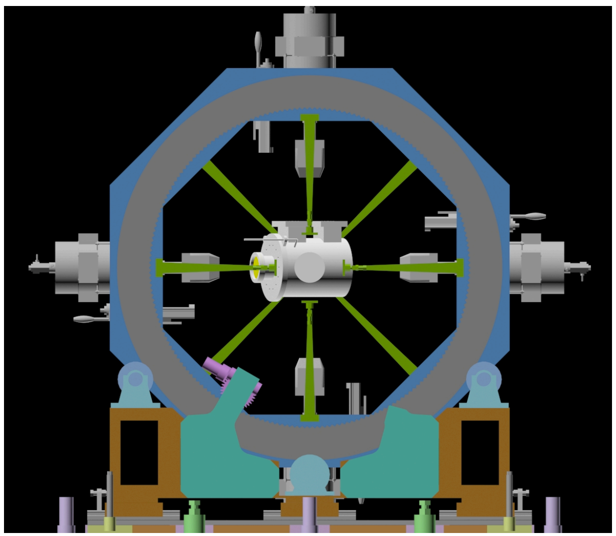
  - (p,p'f) vs. (γ,f)
  - etc.

→ Photo-fission at ELI-NP !

# Outlook

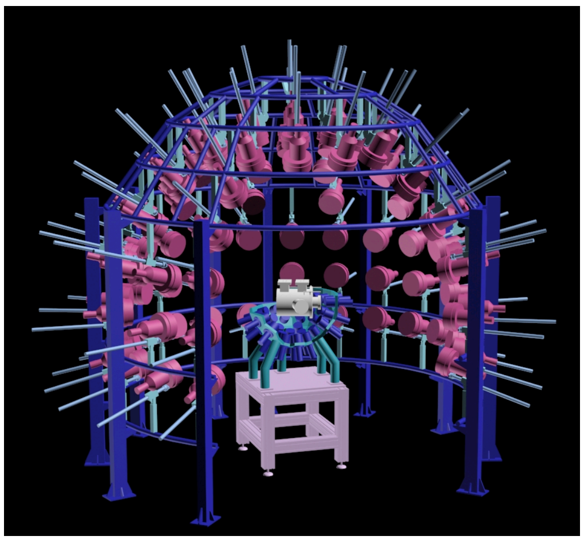
## ELI-NP and further photo-fission physics goals

ELIADE



8 Ge clover detectors

ELIGANT



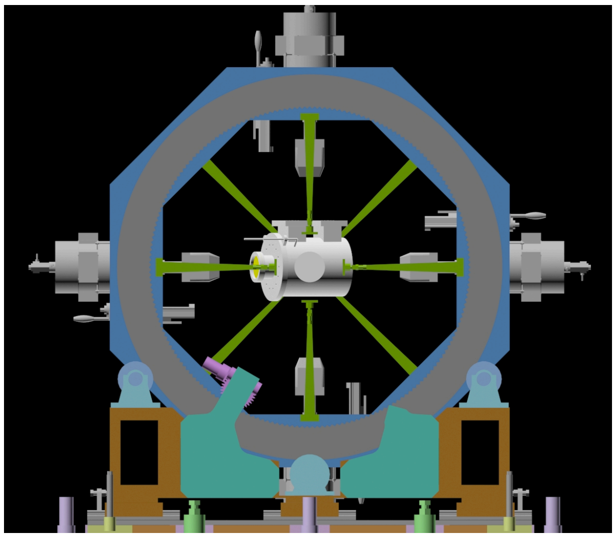
30 $LaBr_3$ or $CeBr_3$
20 $^{7}Li$ glass det.
30 liquid scintillators

# Outlook

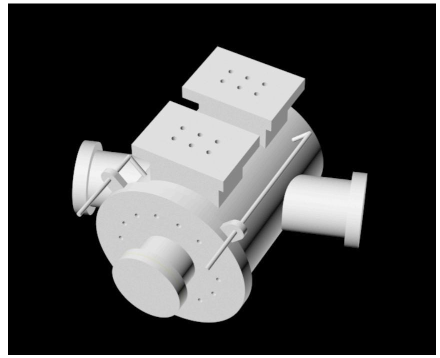
## ELI-NP and further photo-fission physics goals

New position-sensitive twin FGIC (TU Darmstadt)

\+ ELIADE

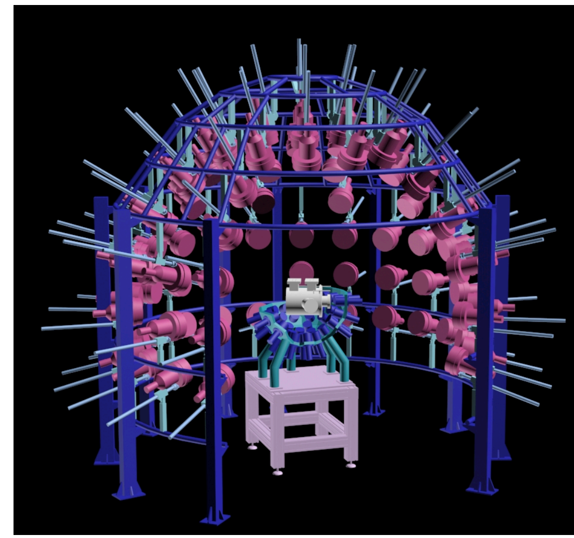


8 Ge clover detectors



(courtesy M. Peck)

\+ ELIGANT



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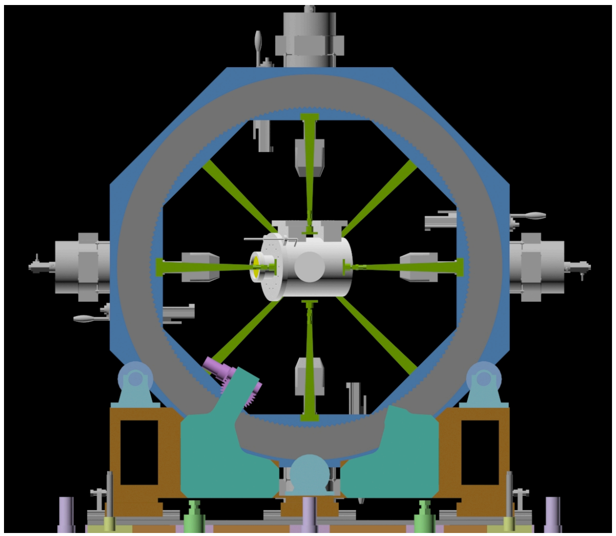
# Outlook

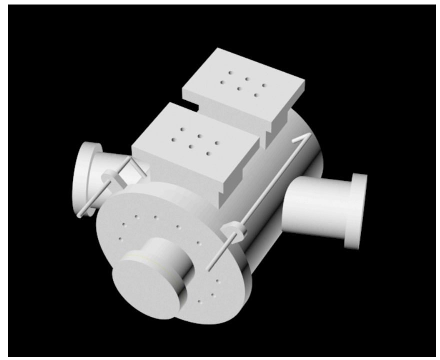
## ELI-NP and further photo-fission physics goals

New position-sensitive twin FGIC (TU Darmstadt)

\+

ELIADE





(courtesy M. Peck)

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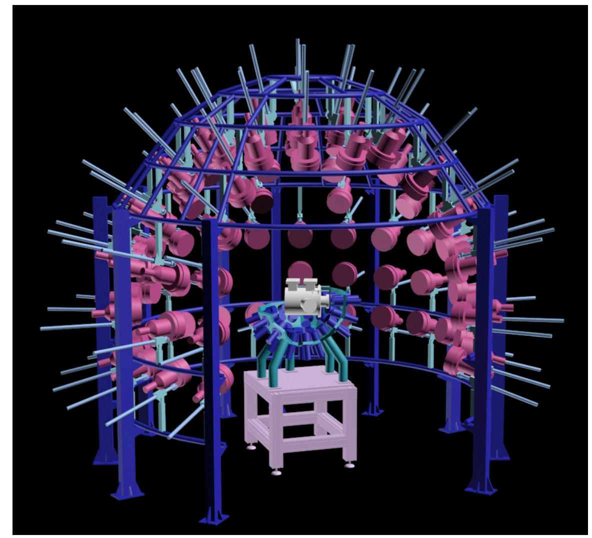
ELIGANT



- Study of the fission fragment de-excitation process
  - measurement of fission fragments, γ rays and neutrons
  - correlations !

# Outlook

- New results from recent measurements
- Study of PFGS characteristics depending on fission fragment mass (continued)
- New experiments are approved and scheduled
- Study of entrance channel effects
  - (n,f) vs. (d,pf)
  - (p,p'f) vs. ($\gamma$,f)
  - etc.

→ Photo-fission at ELI-NP !

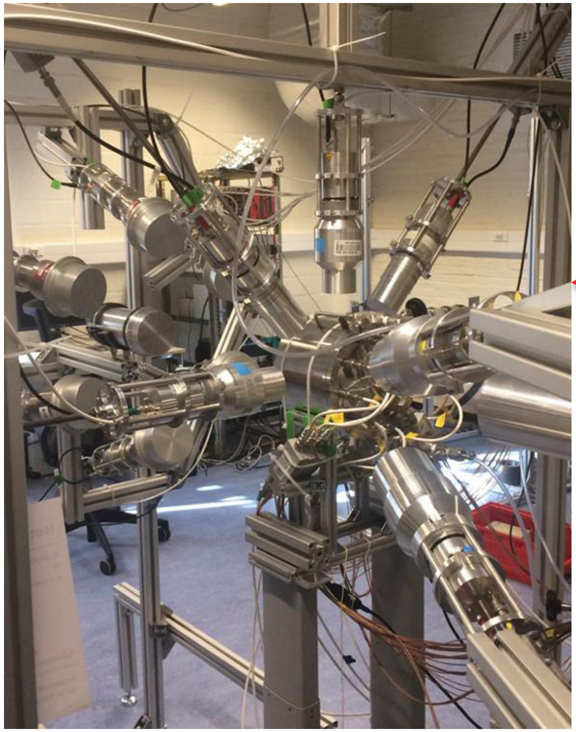
→ Particle-induced fission elsewhere !

# Outlook

## Particle-induced fission studies

VESPA++ @ JRC Geel

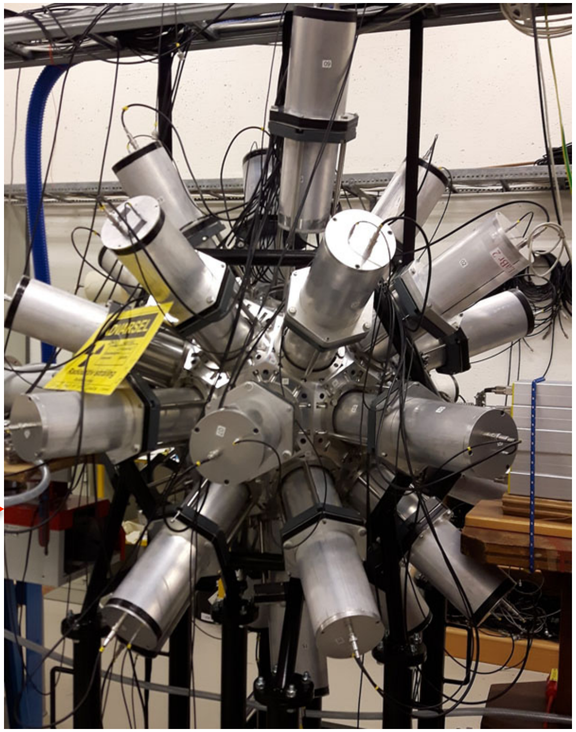
OSCAR @ OCL



(n,f) and (sf)

vs.

(p,p'f) and (d,pf)



8 $LaBr_3$ detectors
7 liquid scintillators
+ pos. sensit. FGIC

30 $LaBr_3$ detectors
+ TPC

# The collaborators

T. Belgya, R. Billnert, R. Borcea, T. Brys, A. Chatillon, D. Choudhury, A. Cita, S. Courtin, J. Enders, M. Fallot, G. Fruet, A. Gatera, W. Geerts, G. Georgiev, A. Göök, C. Guerrero, P. Halipré, F.-J. Hambsch, D.G. Jenkins, Z. Kis, B. Laurent, M. Lebois, L. Le Meur, A. Maj, P. Marini, B. Maróti, T. Martinez, I. Matea, A. Moens, L. Morris, V. Nanal, P. Napiorkowski, M. Peck, A. Porta, F. Postelt, A. Oberstedt, S. Oberstedt, L. Qi, L. Szentmiklosi, K. Takàcs, S.J. Rose, G. Sibbens, S. Siem, C. Schmitt, O. Serot, M. Stanoiu, D. Vanleeuw, M. Vidali, B. Wasilewska, J.N. Wilson, A.-A. Zakari, F. Zeiser …

PhD students

# ありがとうございました!