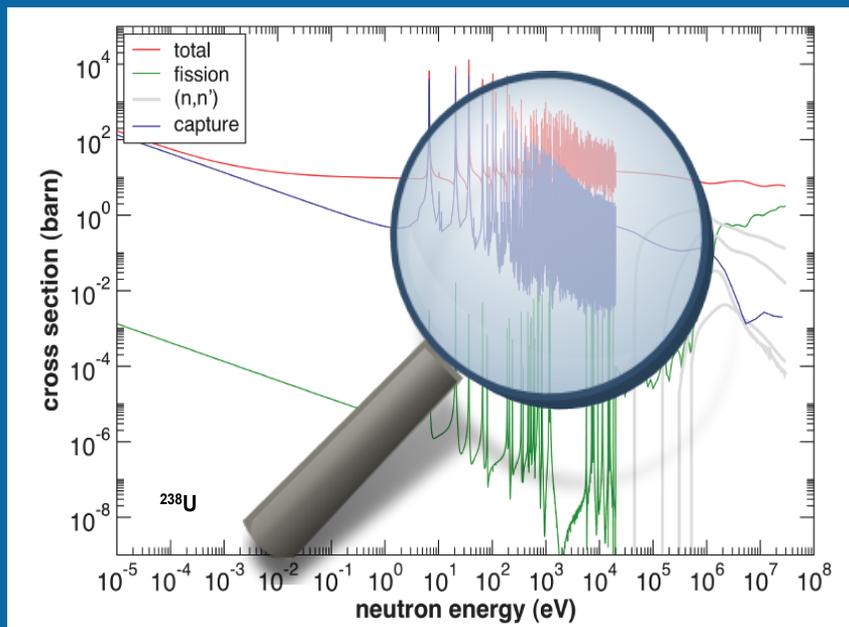


# Fission-fragment dependent prompt and isomeric gamma-ray emission in nuclear fission



**Stephan Oberstedt**

**Joint Research Centre**

the European Commission's  
in-house science service



JRC Science Hub: [ec.europa.eu/jrc](https://ec.europa.eu/jrc)

# Outline

- **Motivation**
- **History and recent achievements**
- **Recent instrument developments**
- **VESPA++**
- **Timeline/outlook**

# Motivation

- We would like to understand nuclear fission 😊

# Motivation

- **We would like to understand nuclear fission ☺**
- **Energy production (fragment yield/decay heat)**
- **Nuclear waste forecast and handling**
- **Radio-isotope production for medical applications**

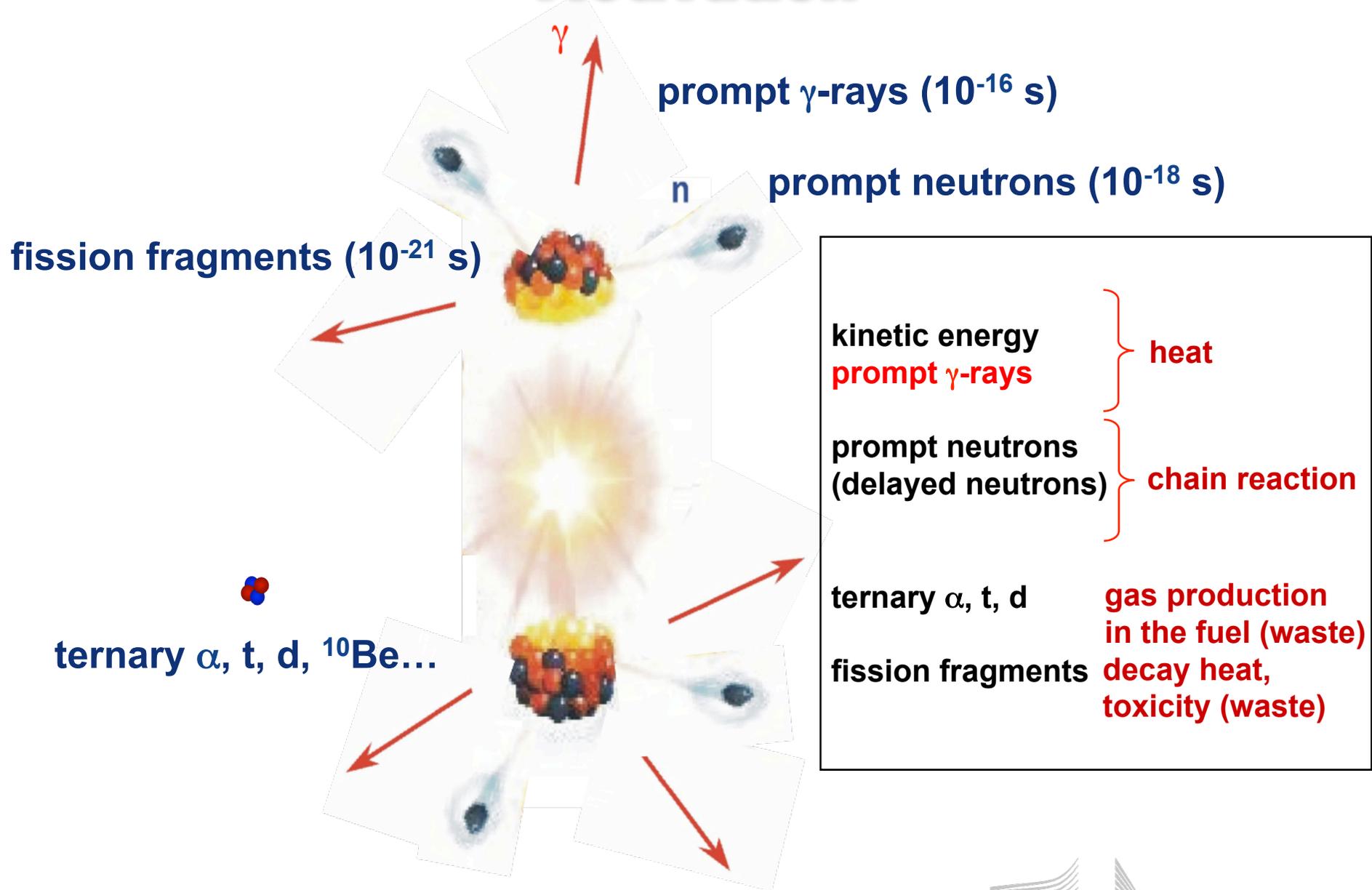
# Motivation

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- **Nuclear magic shells (large deformation/neutron excess)**
- **Astrophysics relevance (r-process, fission cycling)**
- **Nucleosynthesis in the Universe**

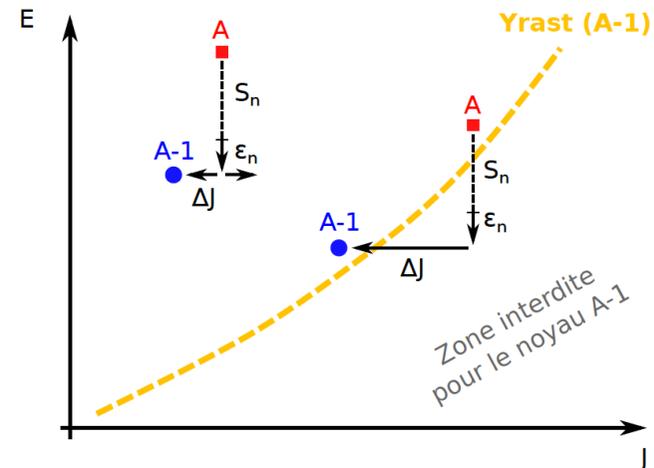
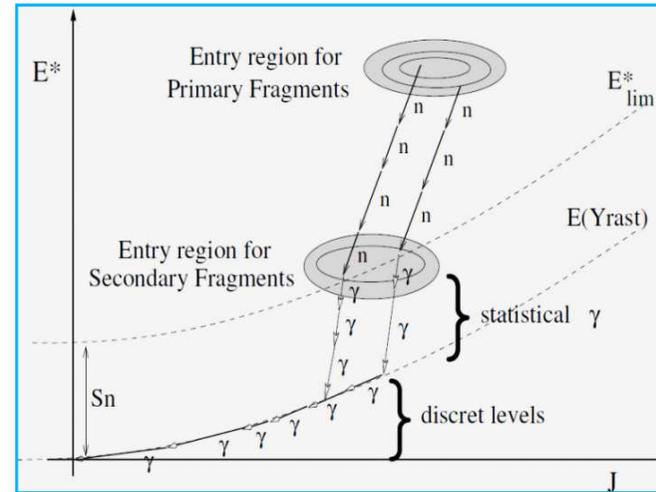
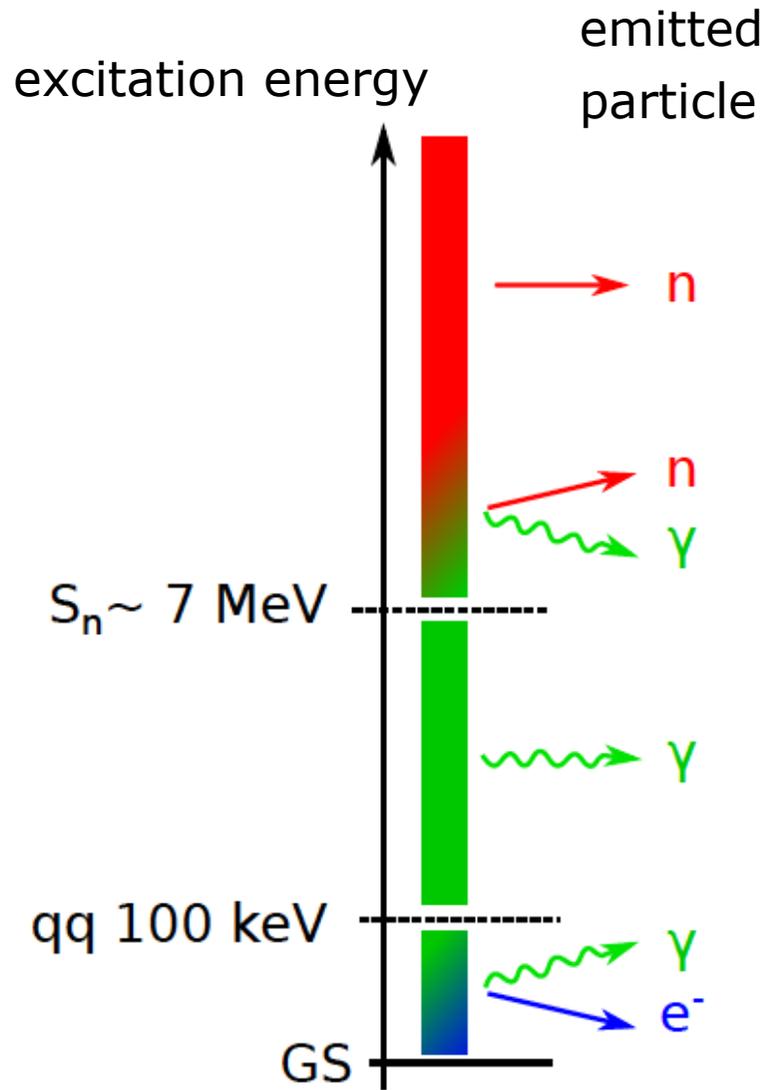
# Motivation

- We would like to understand nuclear fission ☺
- Energy production (fragment yield/decay heat)
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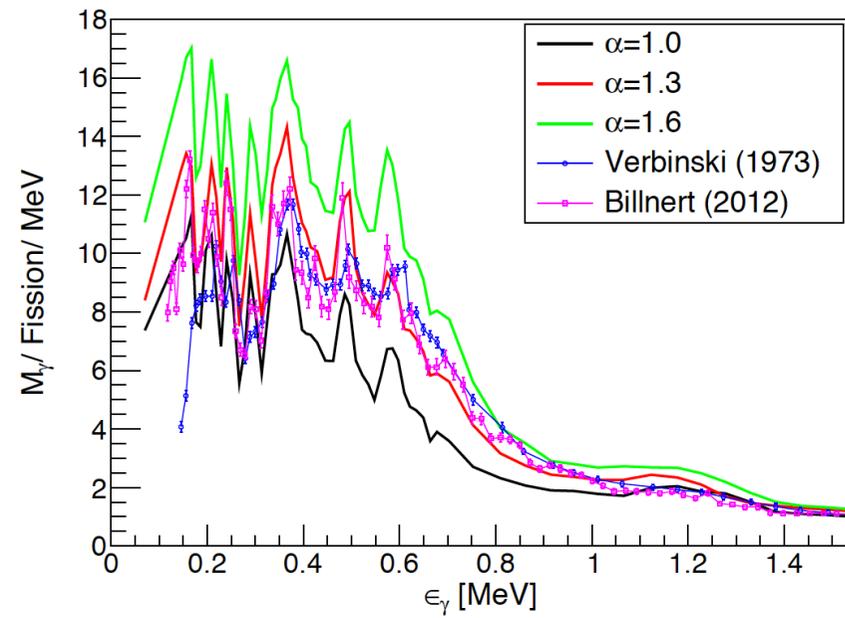
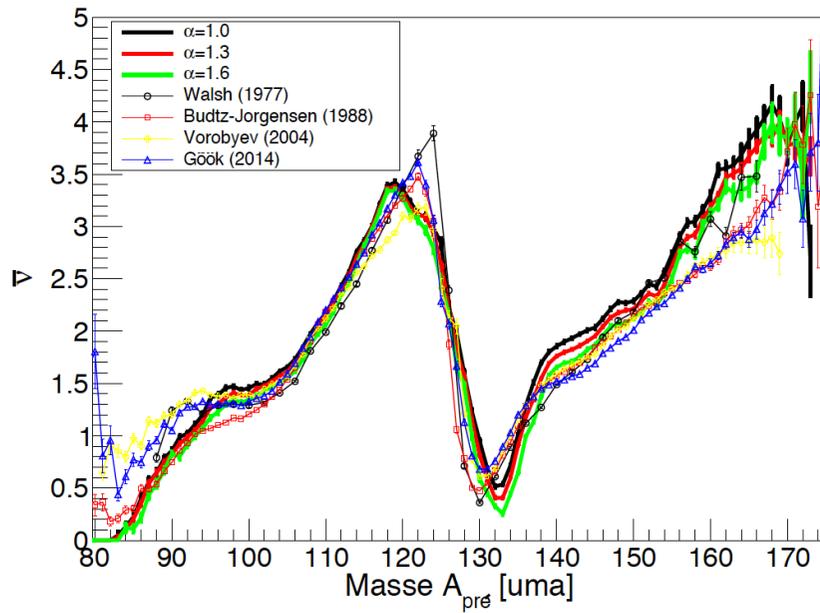
# Motivation



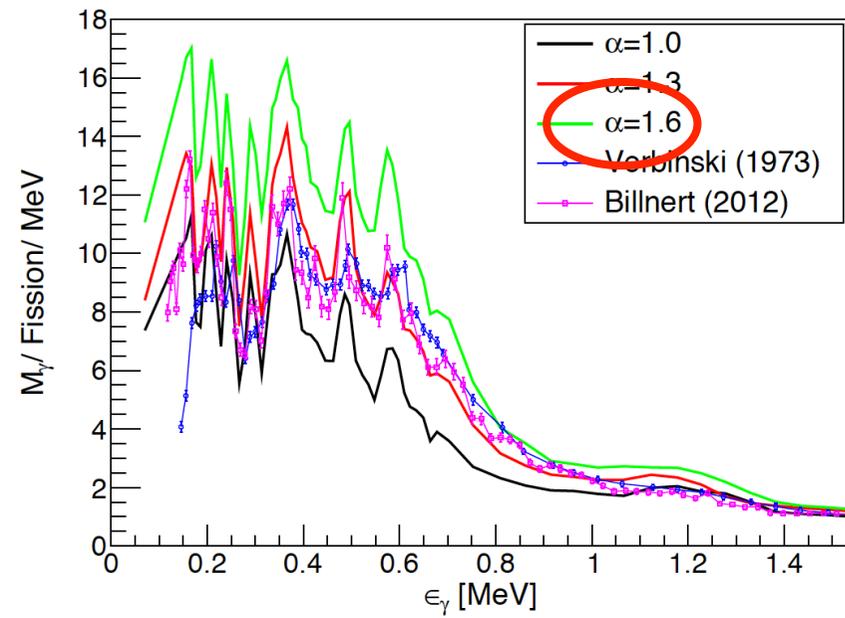
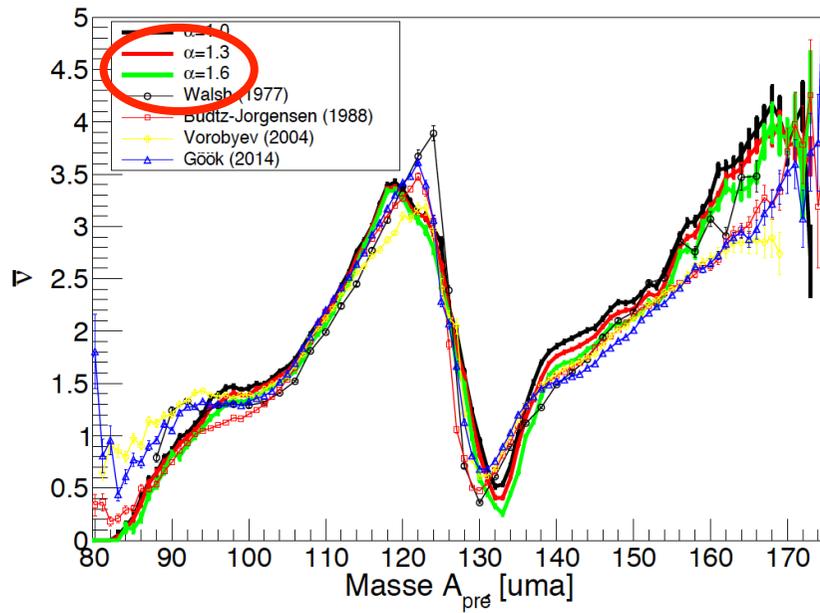
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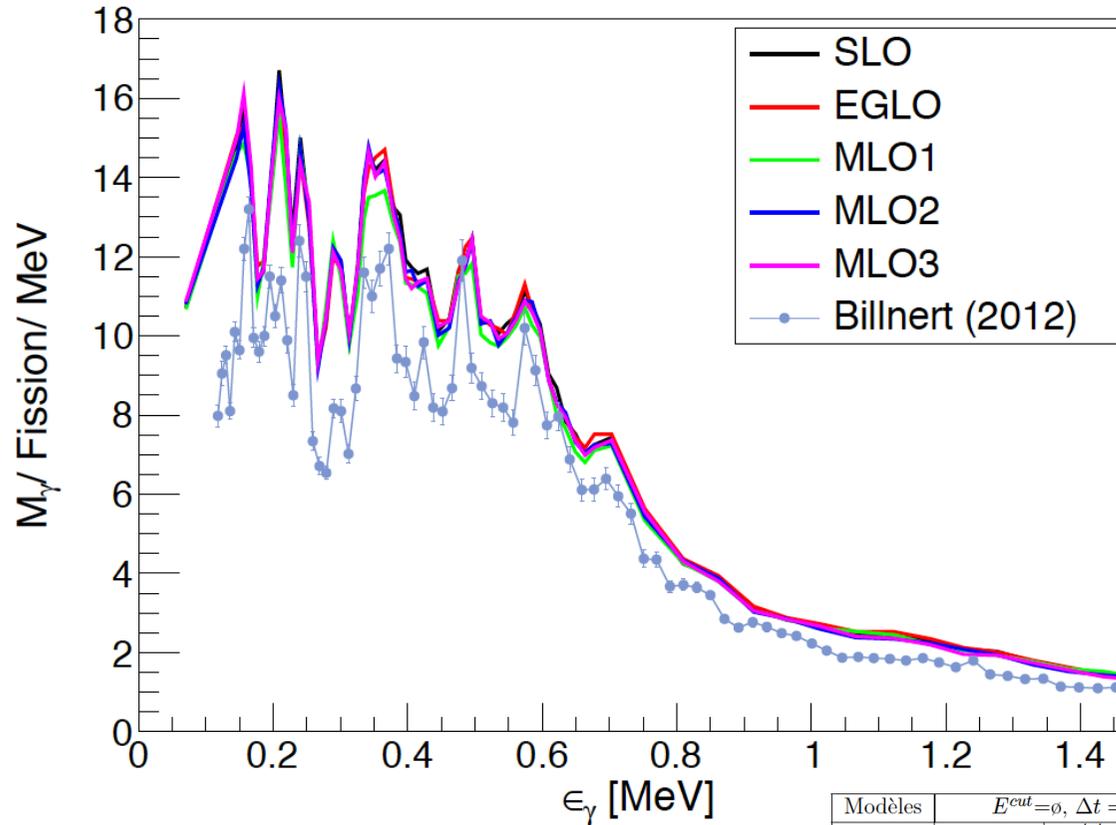
# Motivation



# Motivation



# Motivation



## Different Radiative Strength Functions:

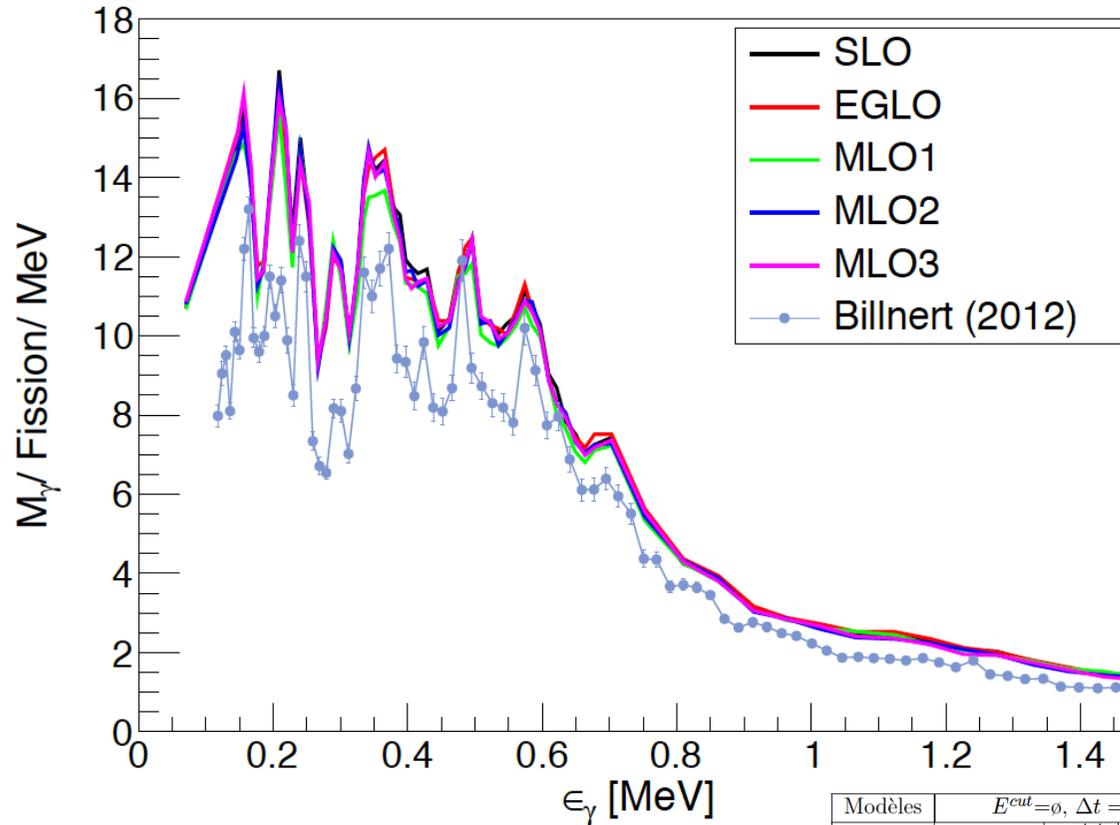
SLO : Standard Lorentzian

EGLO: Enhanced Generalized Lorentzian

MLO : Modified Lorentzian

Modèles	$E^{cut}=\emptyset, \Delta t =3 \text{ ns}$			$E^{cut}=100 \text{ keV}, \Delta t =3 \text{ ns}$		
	$\langle E_{\gamma}^{tot} \rangle$	$\overline{M}_{\gamma}^{tot}$	$\langle \epsilon_{\gamma}^{lab} \rangle$	$\langle E_{\gamma}^{tot} \rangle$	$\overline{M}_{\gamma}^{tot}$	$\langle \epsilon_{\gamma}^{lab} \rangle$
SLO	8.11	11.48	0.707	8.00	9.97	0.802
EGLO	8.01	11.44	0.701	7.90	9.92	0.796
MLO1	8.05	11.25	0.717	7.95	9.74	0.816
MLO2	8.08	11.39	0.710	7.97	9.87	0.807
MLO3	8.04	11.39	0.707	7.93	9.86	0.804
Billnert				6.64 $\pm 0.08$	8.3 $\pm 0.08$	0.80 $\pm 0.01$

# Motivation



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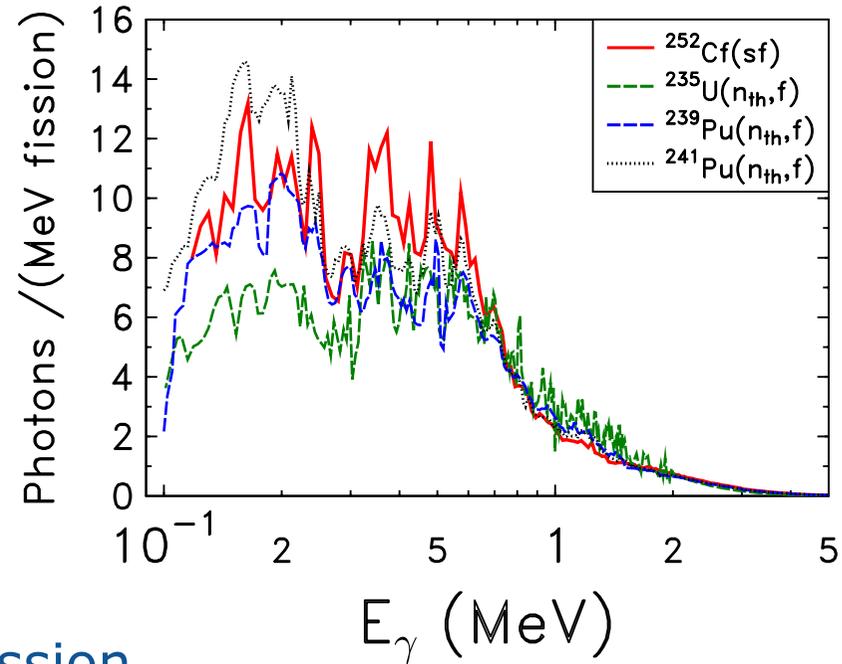
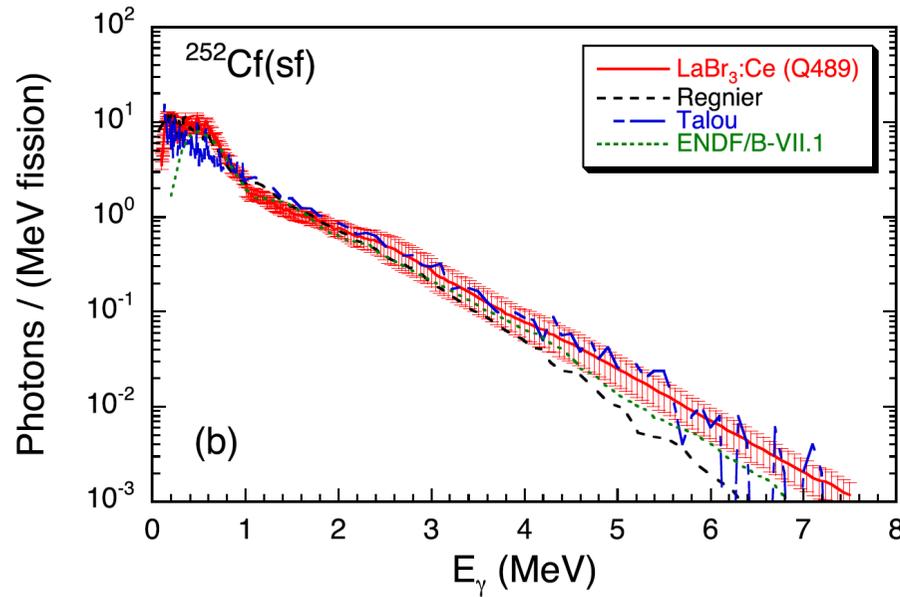
Modèles	$E^{cut}=0, \Delta t=3 \text{ ns}$			$E^{cut}=100 \text{ keV}, \Delta t=3 \text{ ns}$		
	$\langle E_{\gamma}^{tot} \rangle$	$\bar{M}_{\gamma}^{tot}$	$\langle \epsilon_{\gamma}^{lab} \rangle$	$\langle E_{\gamma}^{tot} \rangle$	$\bar{M}_{\gamma}^{tot}$	$\langle \epsilon_{\gamma}^{lab} \rangle$
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# Motivation

- We need to get information about the initial spin distribution of the formed fragments,
  - About the multipolarity of PFGs, and
  - Need to complete information about nuclear isomeric states
- 
- ⇒ Angular distribution of PFGS ( $A^*$ , TKE;  $\cos\theta_F$ )
  - ⇒ Population yields of isomers in the de-exciting fragments
  - ⇒ Determination of isomer lifetimes

- Motivation
- **History and recent achievements**
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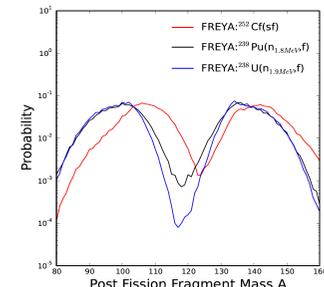
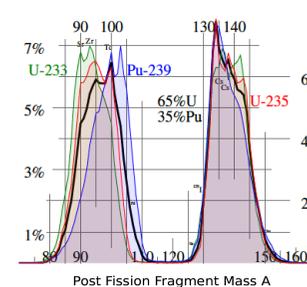
# History



- ✓ thermal-neutron induced fission
- ✓ average PFGS characteristics

$$M_{\gamma}, \langle E_{\gamma, \text{tot}} \rangle \text{ and } \varepsilon_{\gamma} = \langle E_{\gamma, \text{tot}} \rangle / M_{\gamma}$$

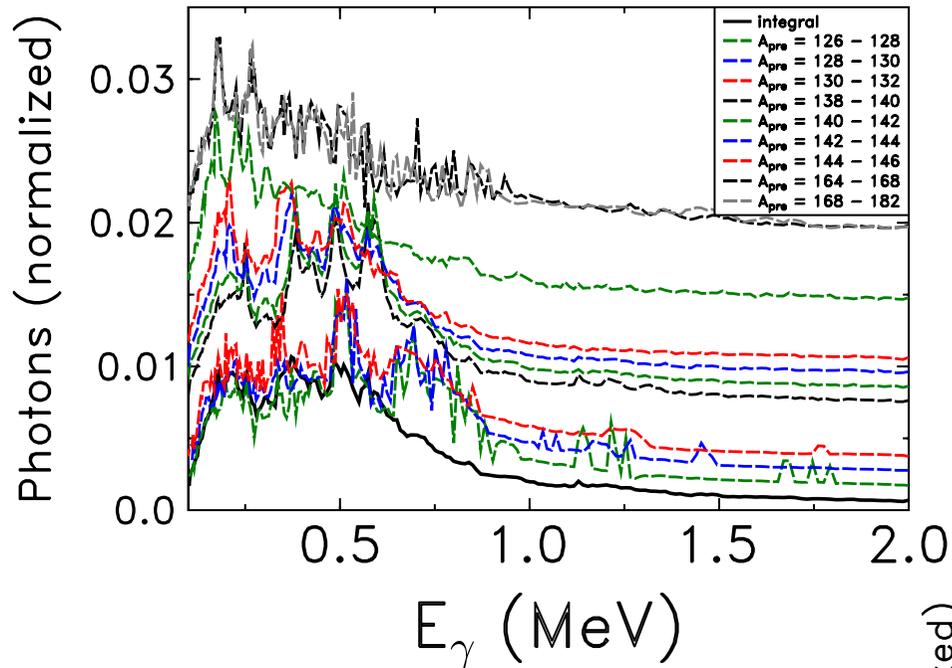
- ✓ measured @ JRC-Geel and KFKI



A. Oberstedt et al., Phys. Rev. C92, 014618 (2015)

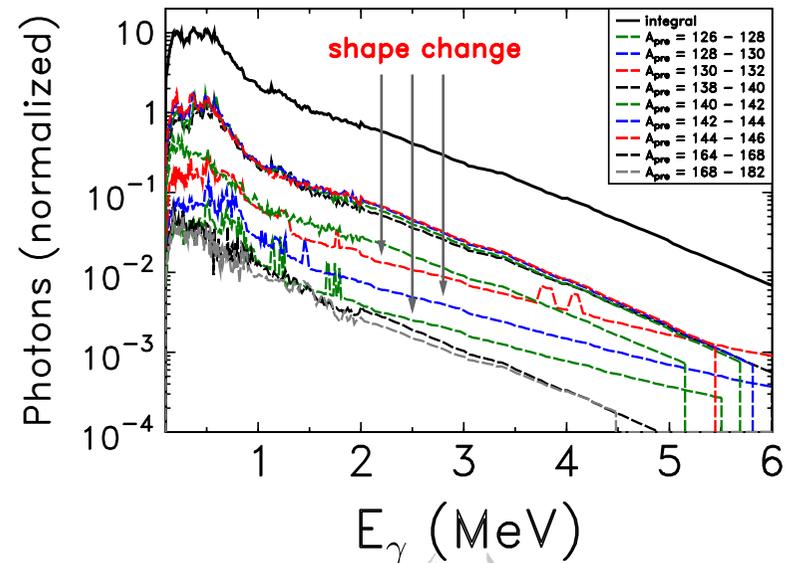
S. Oberstedt et al., Eur. Phys. J 51A (2015) 178

# History



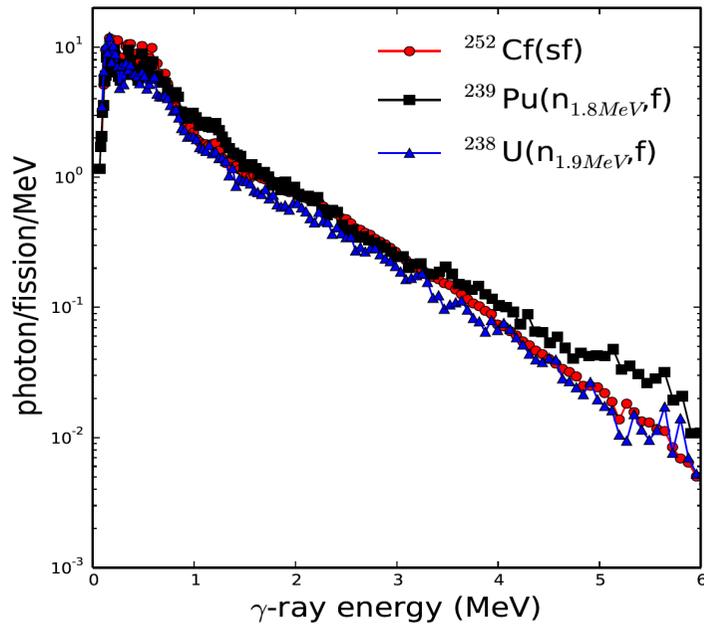
$^{252}\text{Cf}(\text{sf})$

- ✓ Mass(-pair) PFGS characteristics
- ✓ Possible to get also for  $^{246,248}\text{Cm}(\text{sf})$
- ✓  $^{233,235}\text{U}$ ,  $^{239}\text{Pu}$  @ thermal n-beams

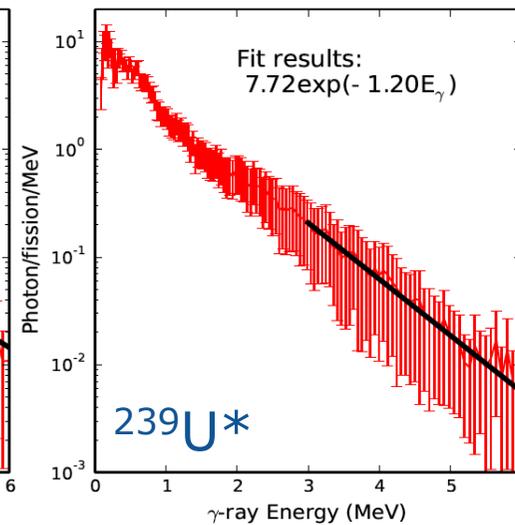
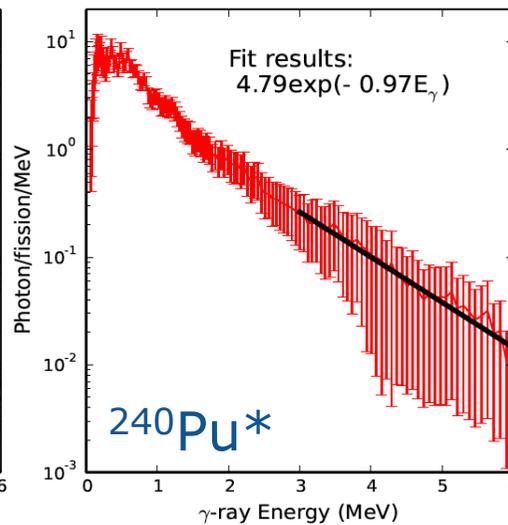
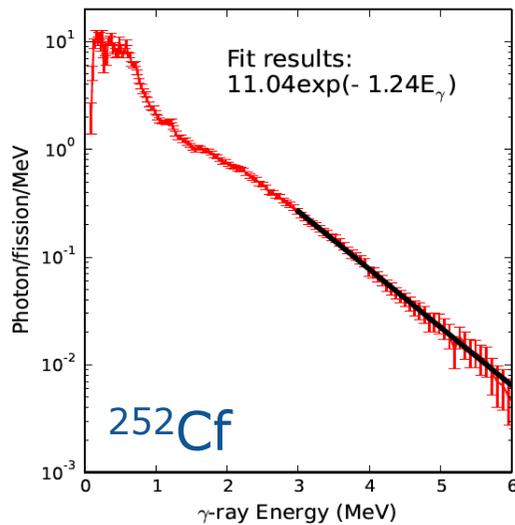


S. Oberstedt et al., Eur. Phys. J 51A (2015) 178

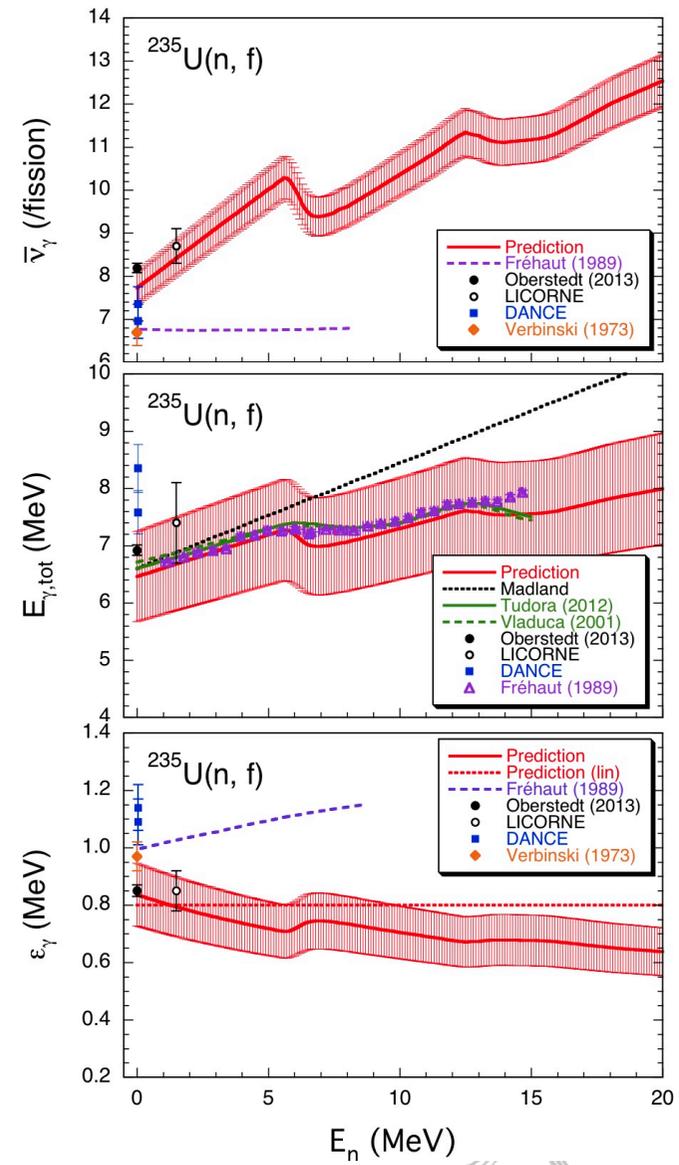
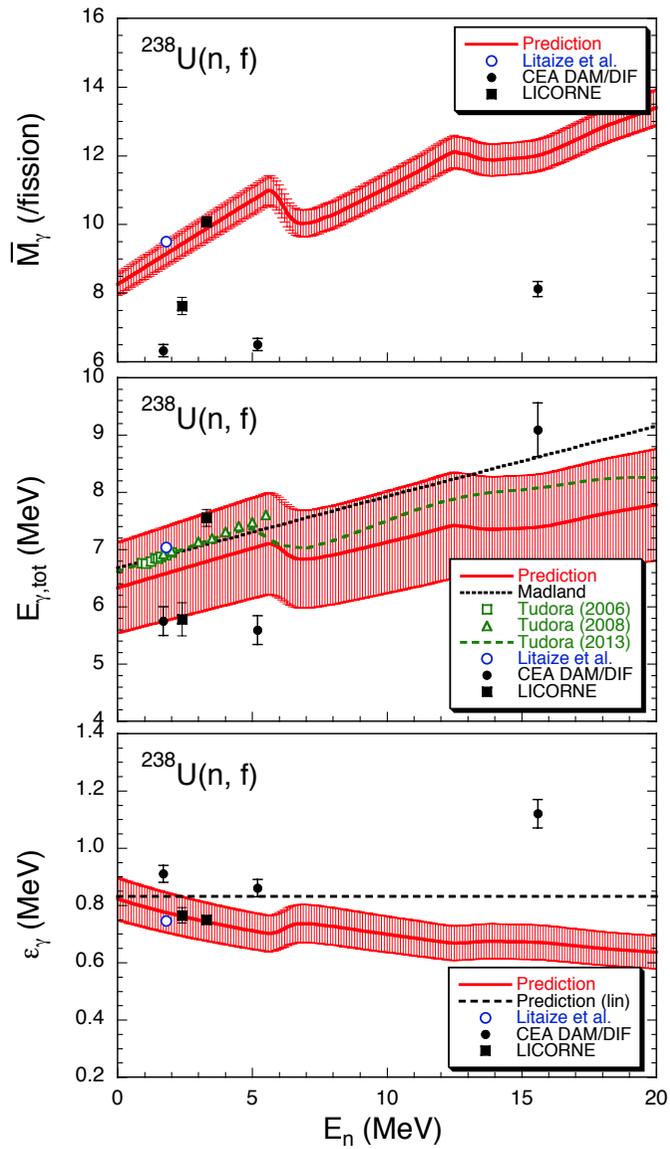
# History



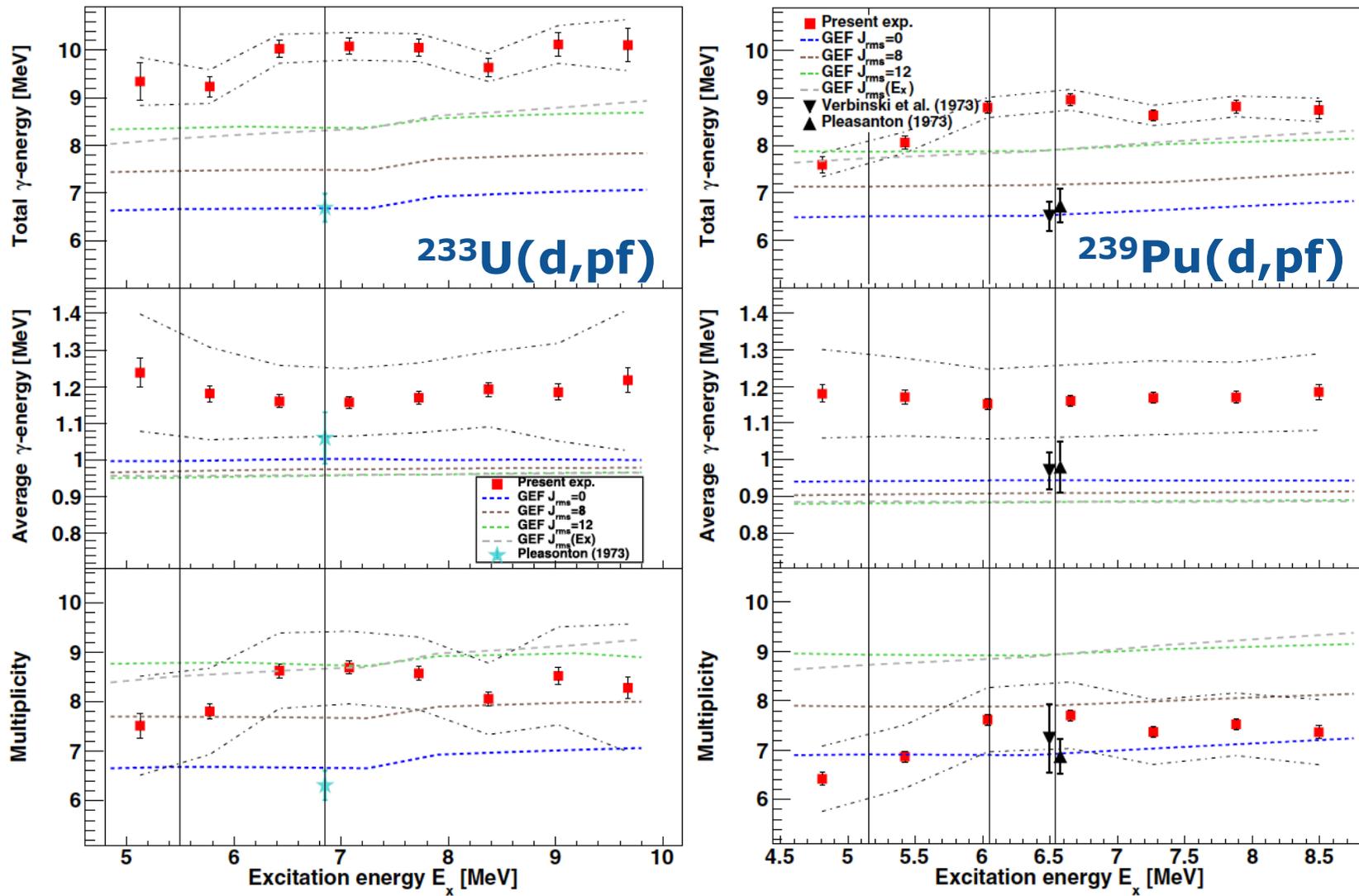
- ✓ fast-neutron induced fission
- ✓ Energy-dependent average PFGS characteristics
- ✓ measured @ ALTO/LICORNE



# History

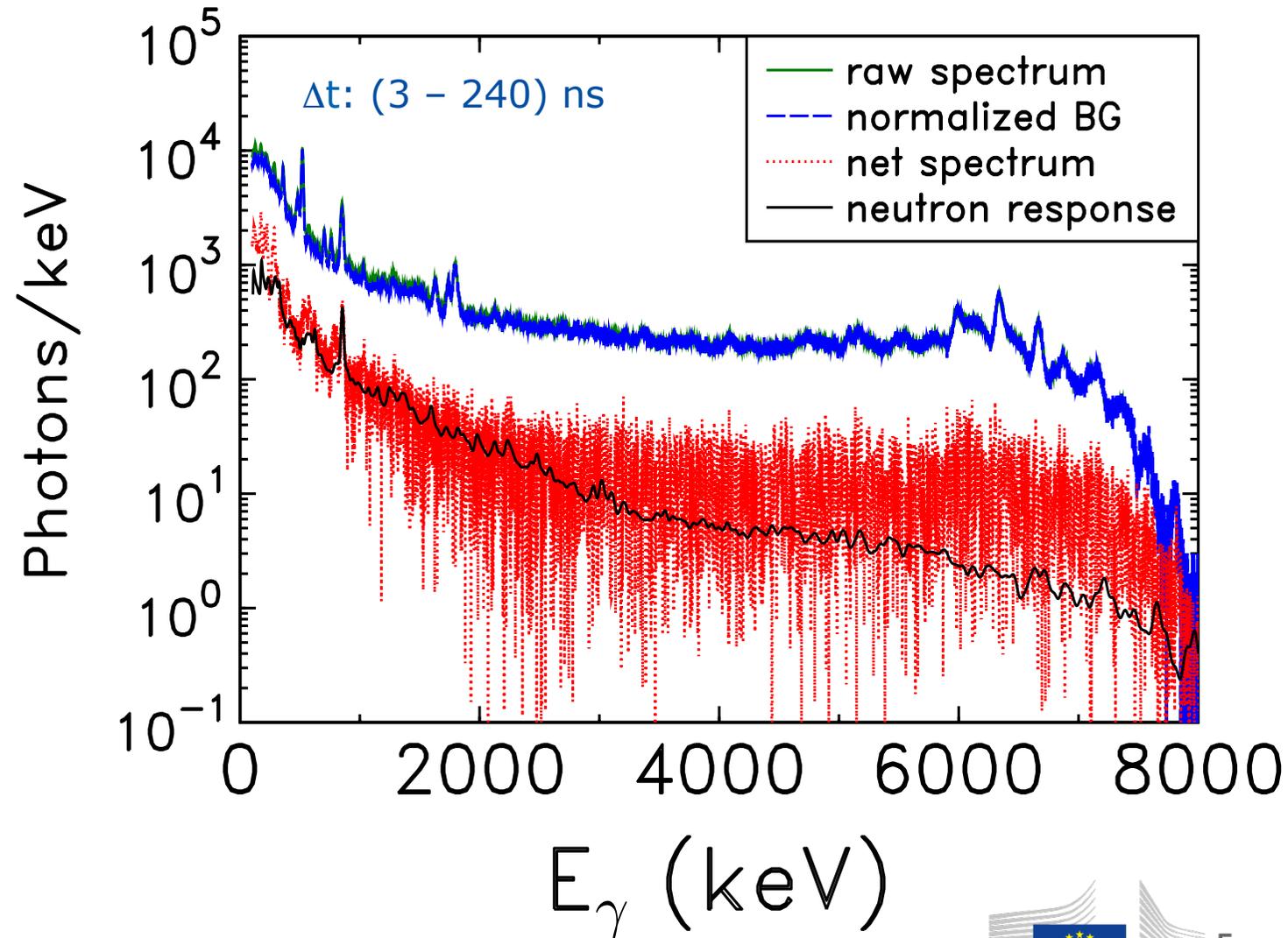


# History



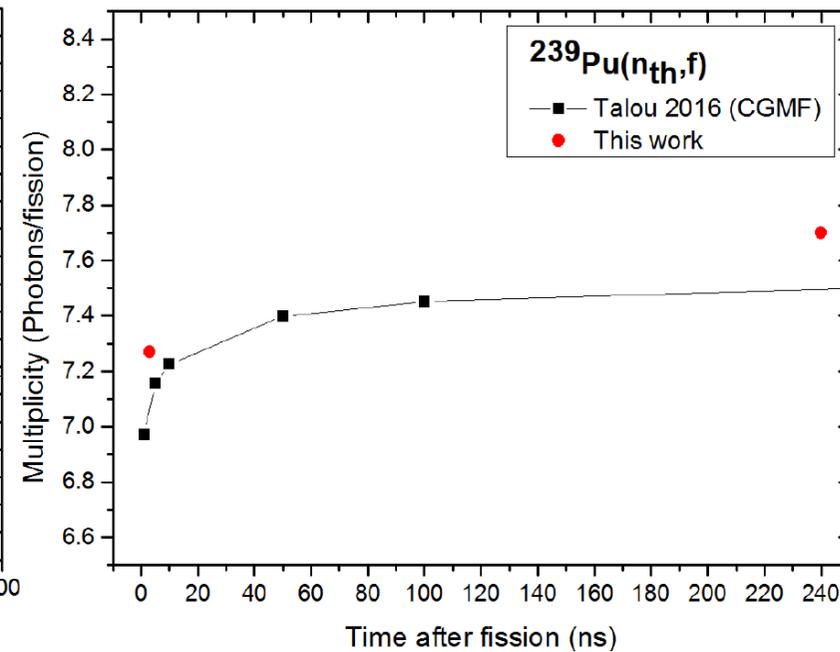
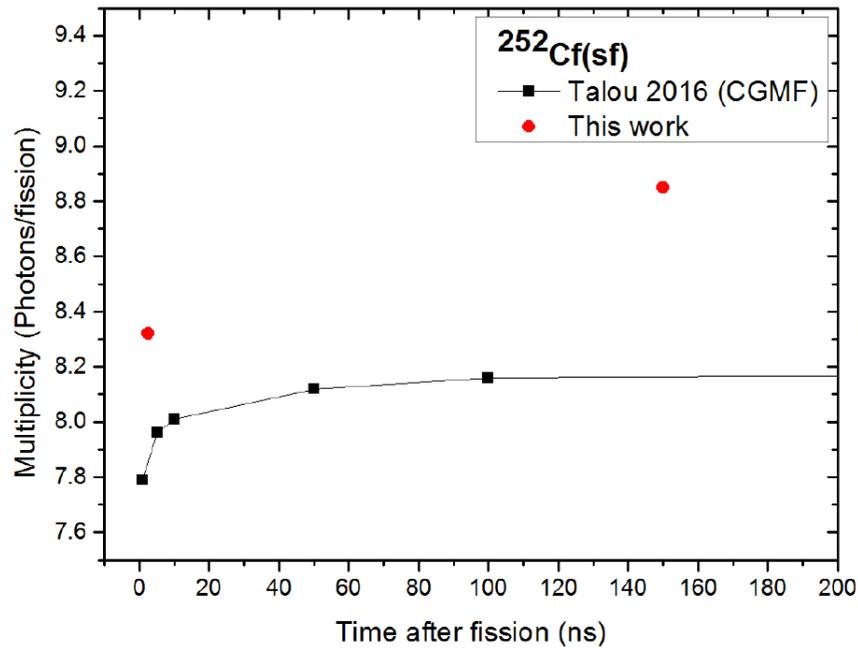
# Recent achievements

Late-time emission



# Recent achievements

## Late-time emission

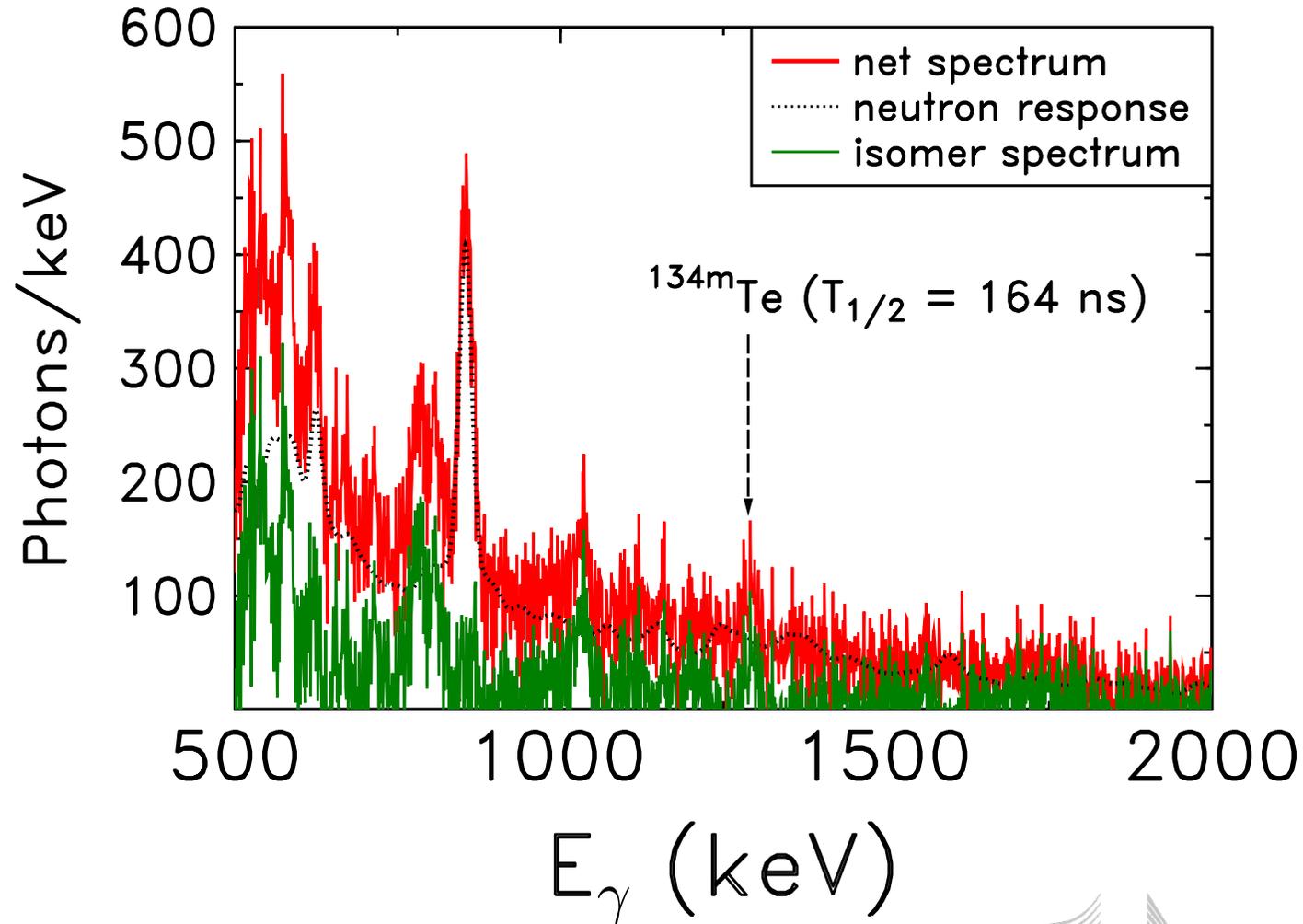


Time window: (3 – 150) ns

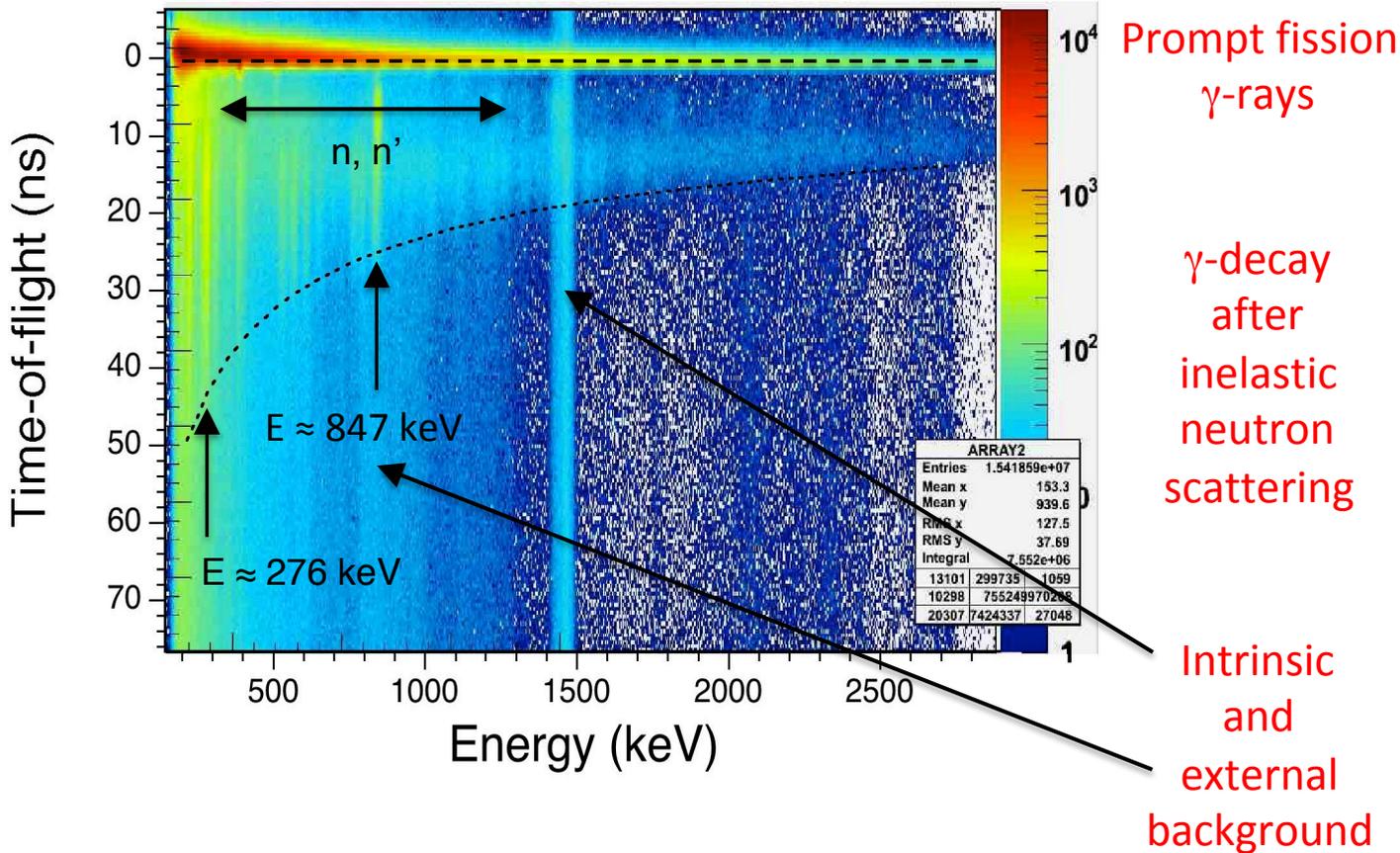
Time window: (3 – 240) ns

# Recent achievements

Late-time emission (integrated over all A\* and TKE!)

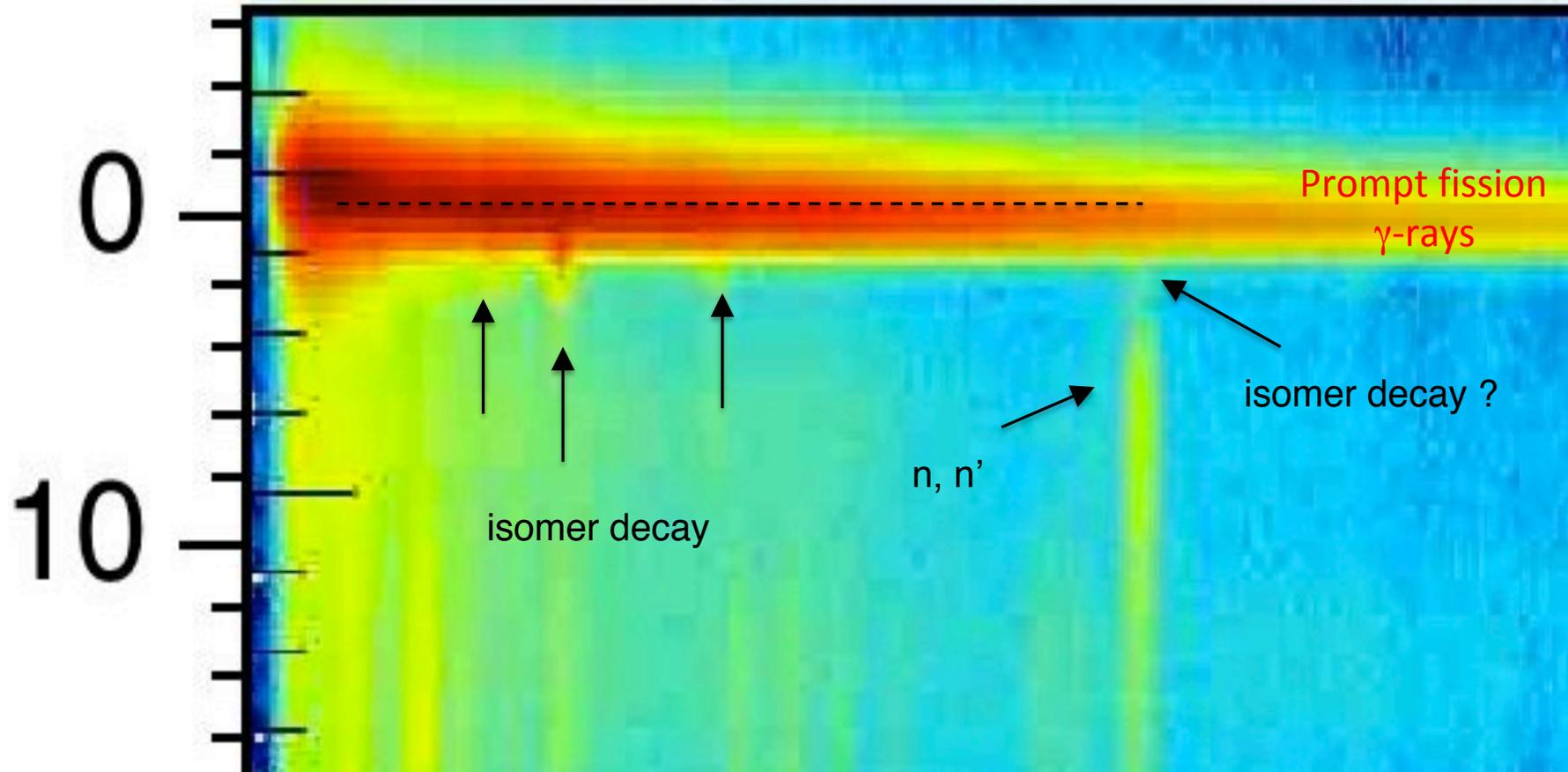


# Recent achievements



Photons in coincidence with fission fragments

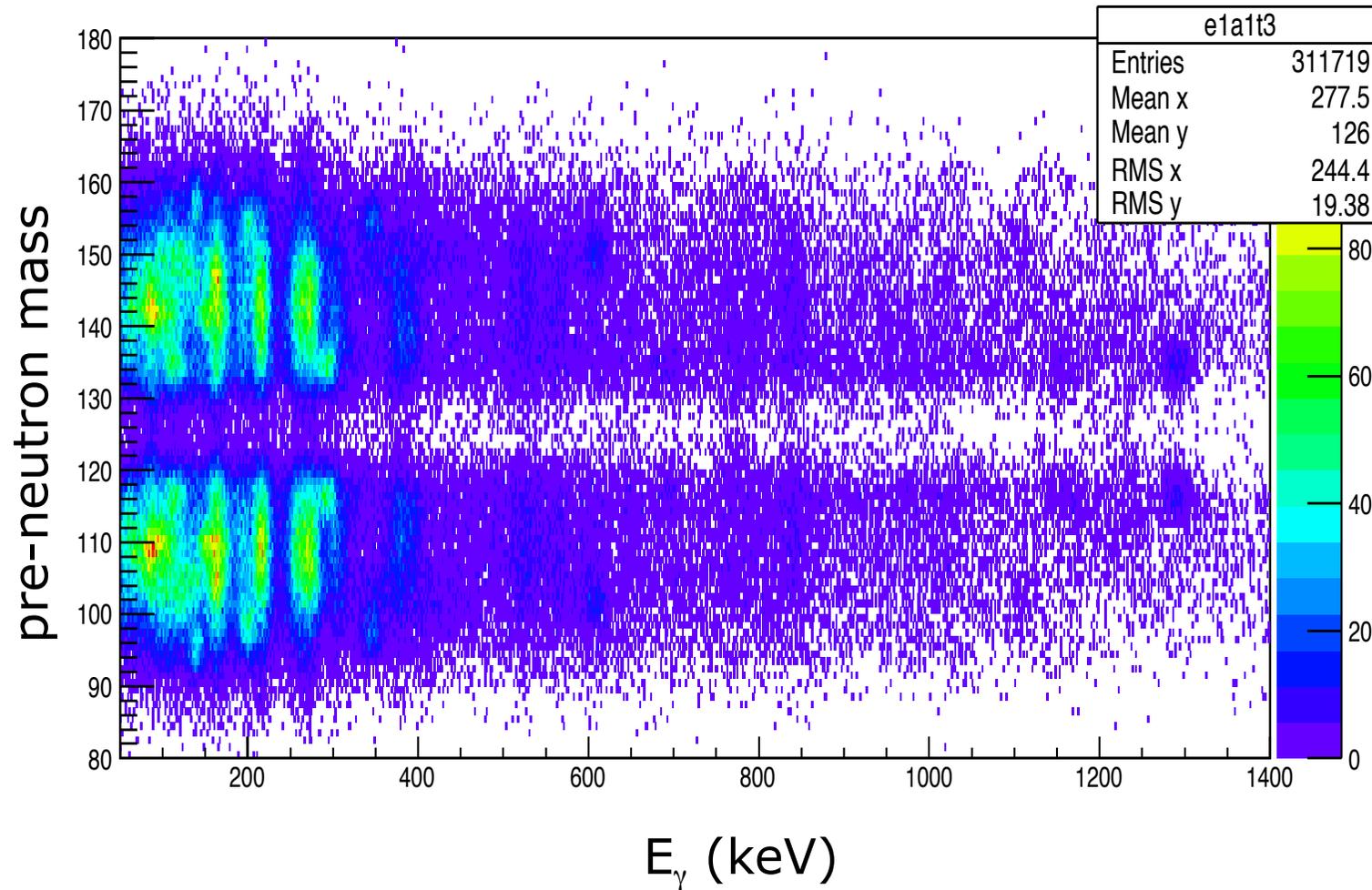
# Recent achievements



Photons in coincidence with fission fragments

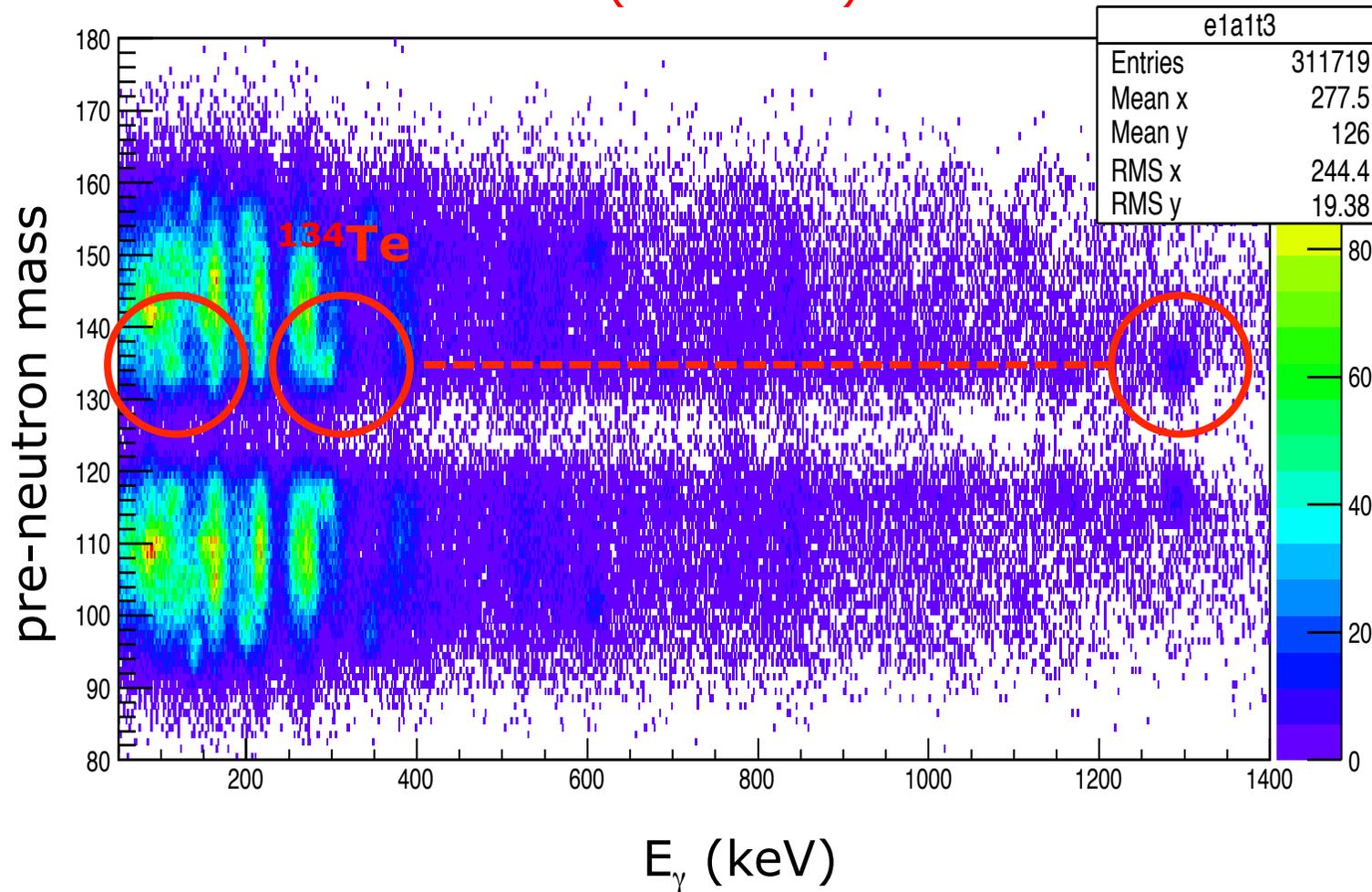
# Recent achievements

$\Delta t = 30 - 110$  ns

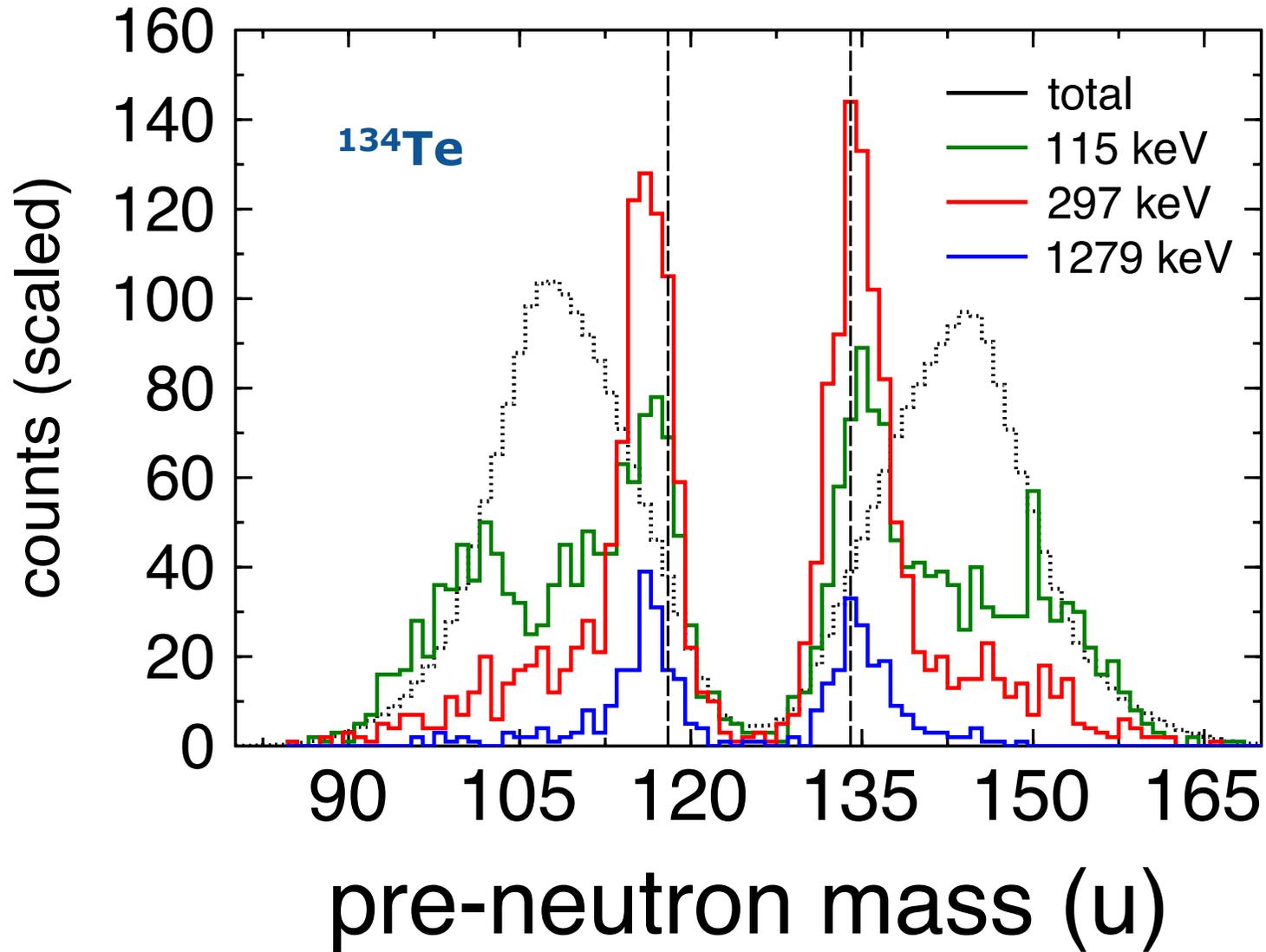


# Recent achievements

$\Delta t = (30 - 110) \text{ ns}$

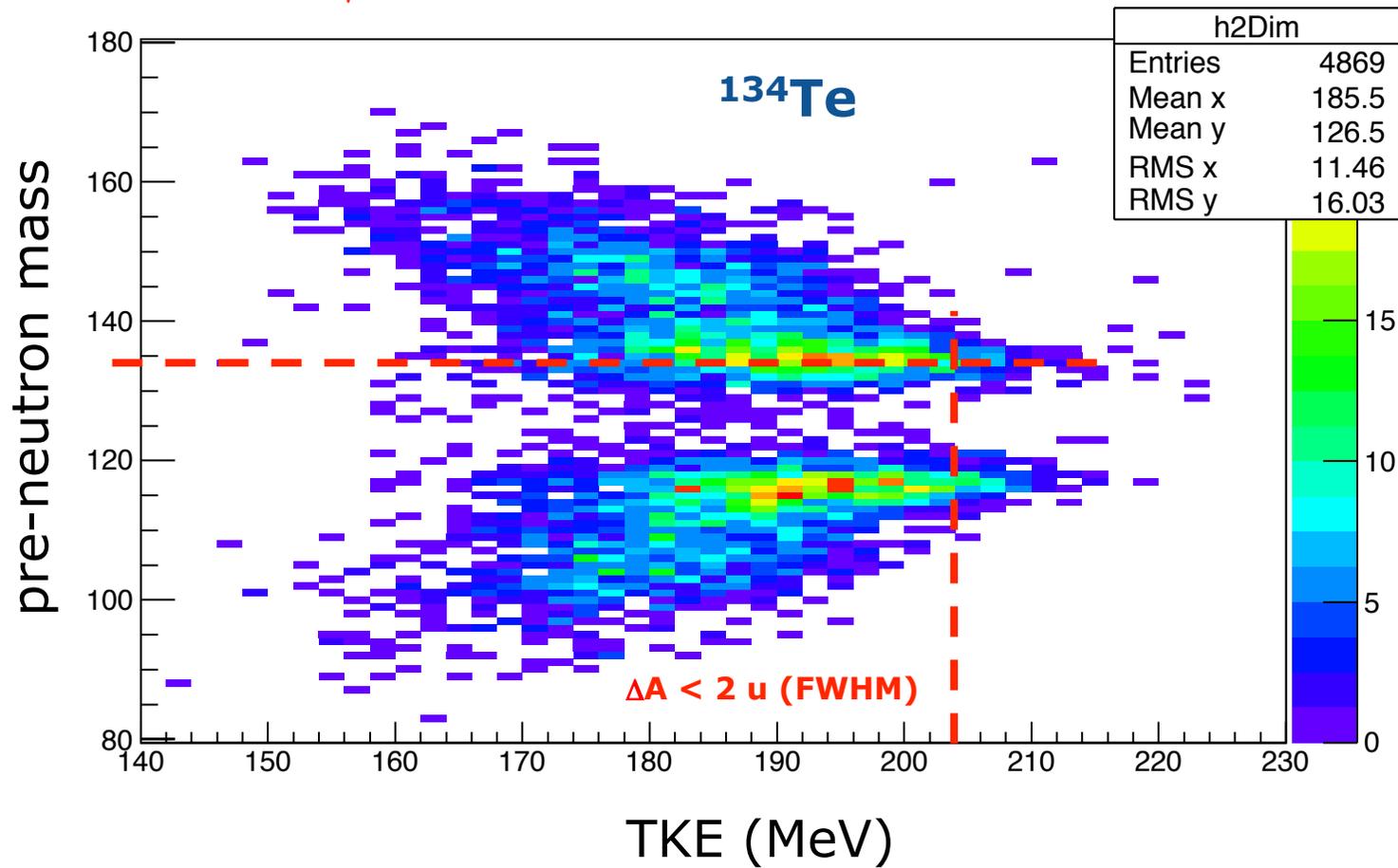


# Recent achievements



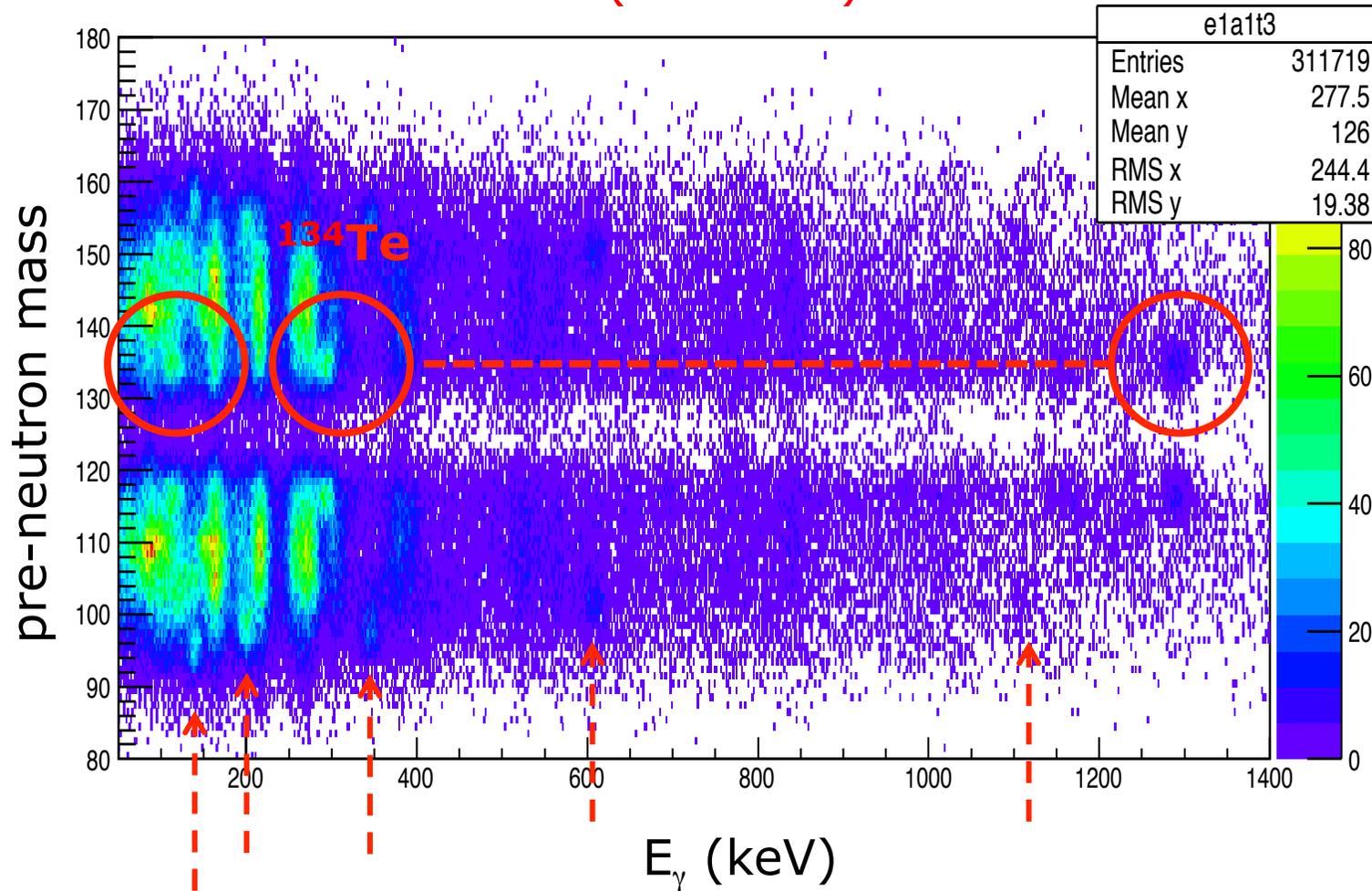
# Recent achievements

$E_\gamma = 297 \text{ keV}; \Delta t = (30 - 110) \text{ ns}$



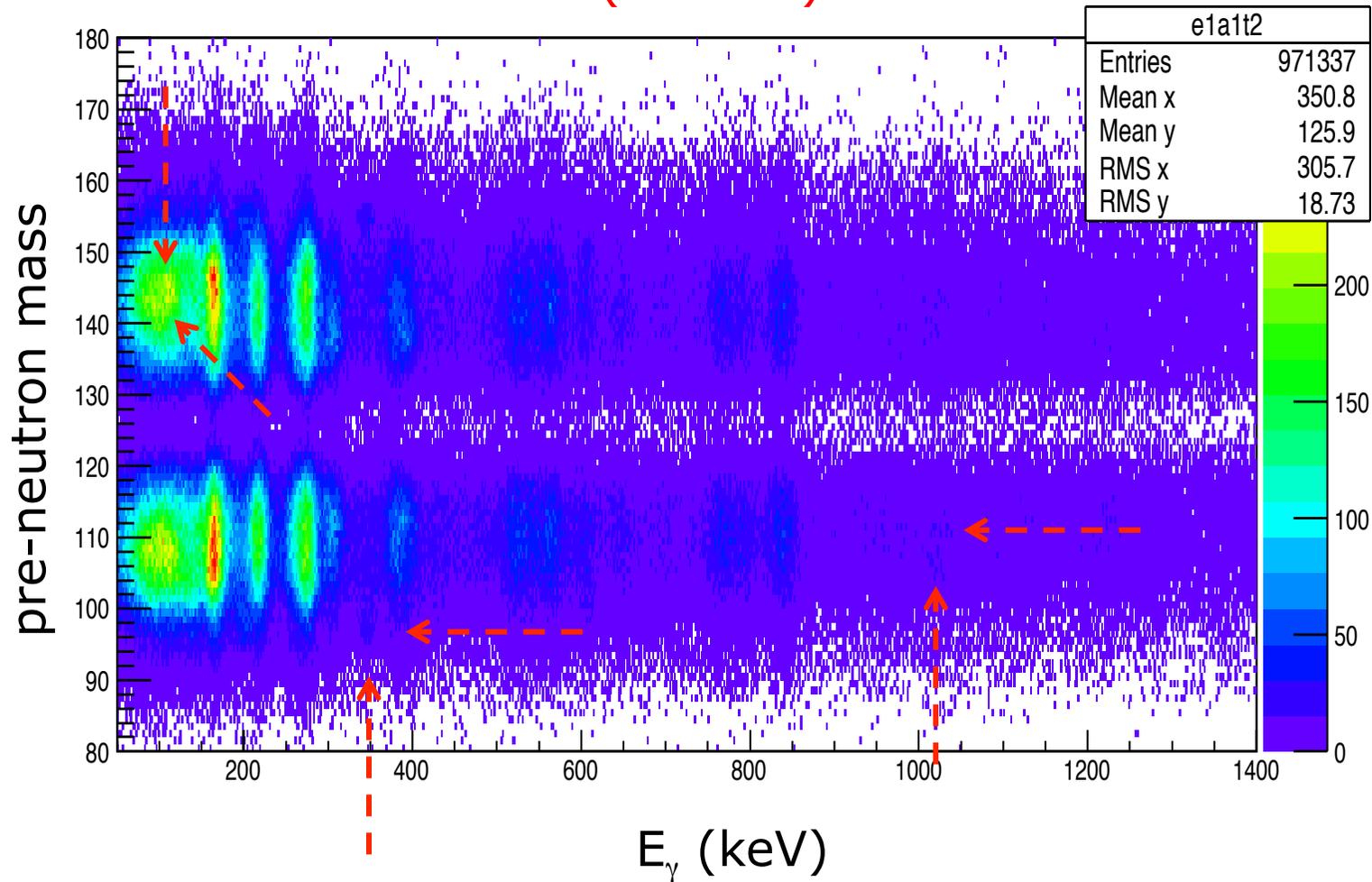
# Recent achievements

$\Delta t = (30 - 110) \text{ ns}$



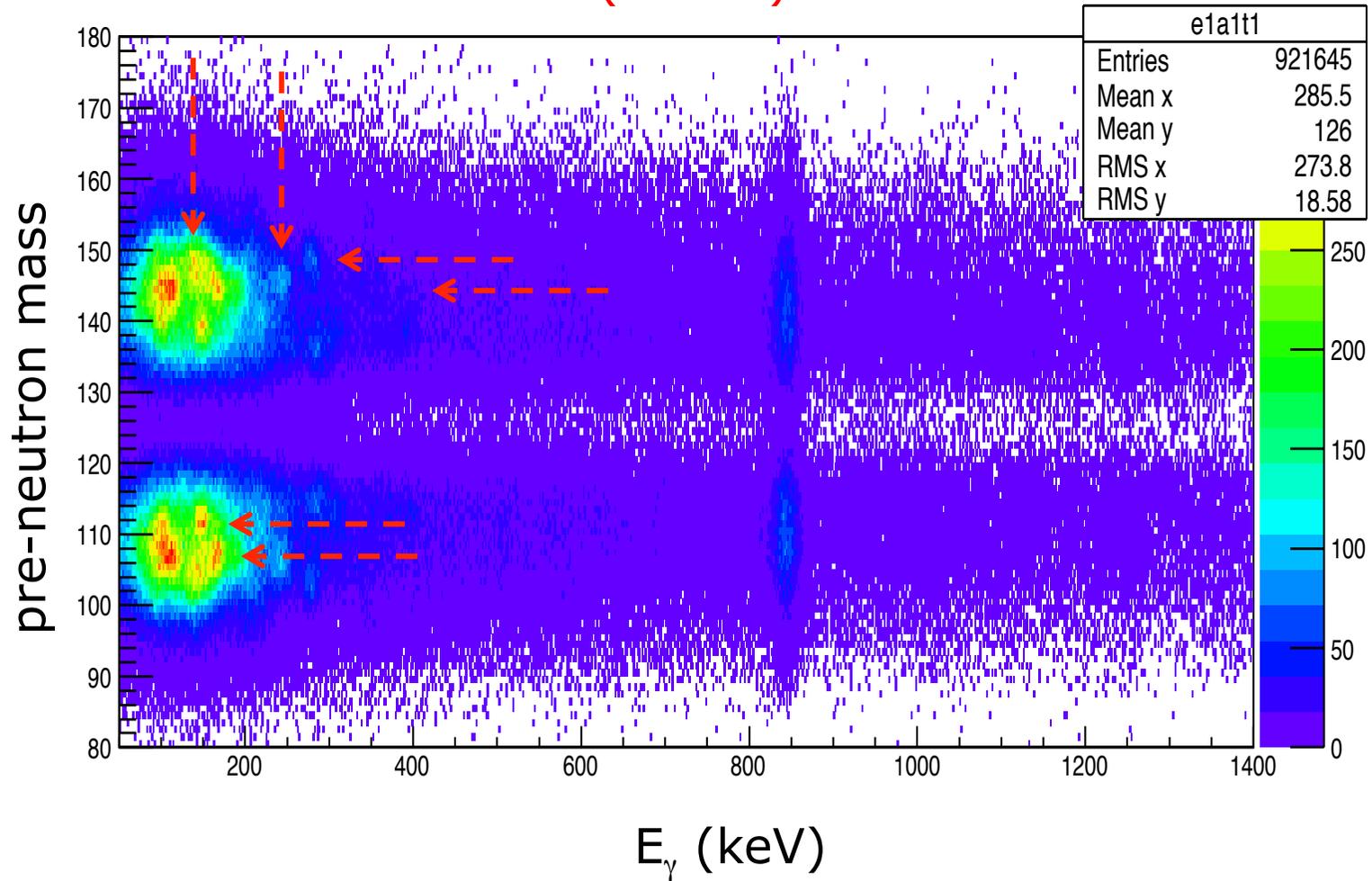
# Recent achievements

$\Delta t = (10 - 30) \text{ ns}$



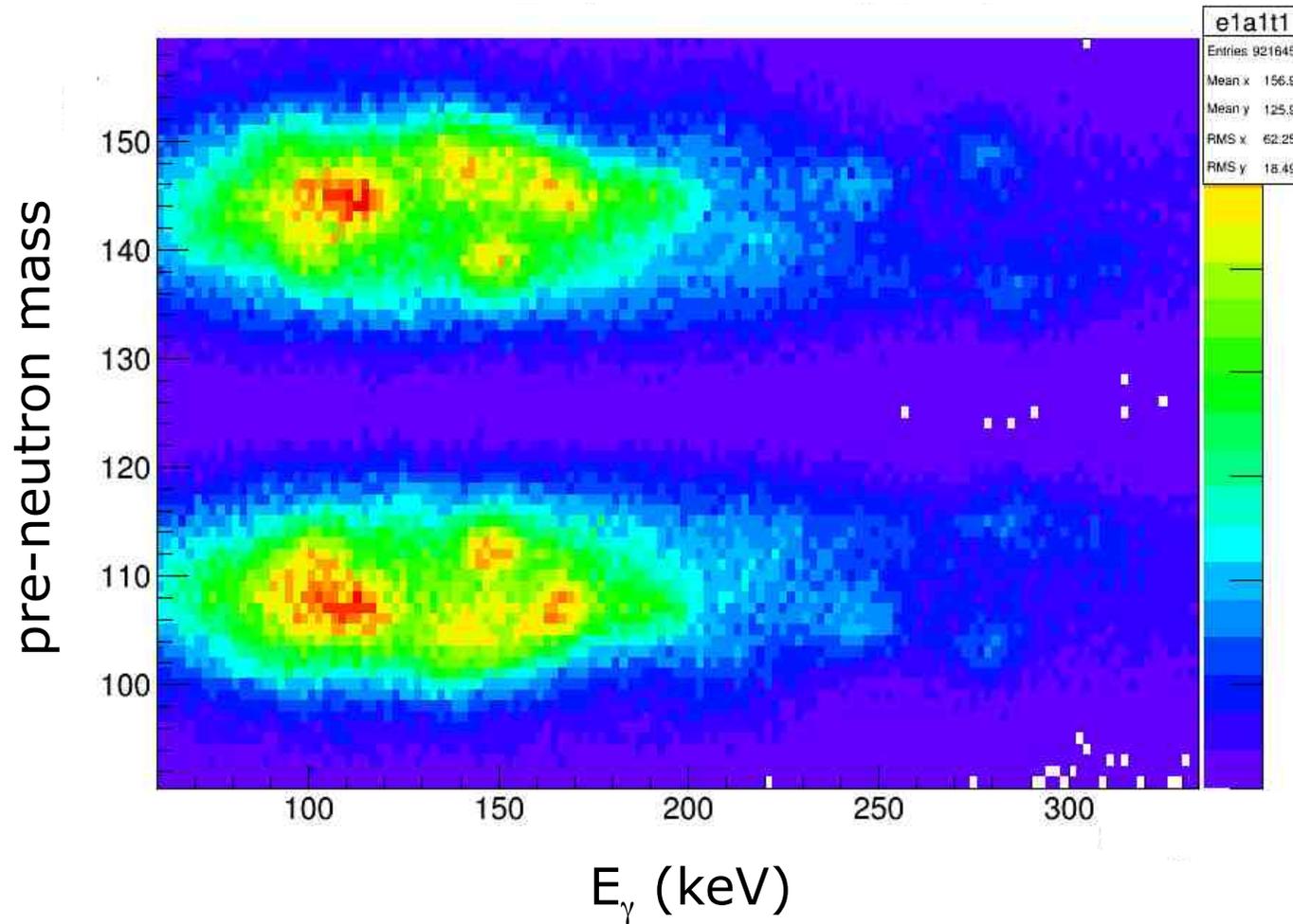
# Recent achievements

$\Delta t = (3 - 10) \text{ ns}$



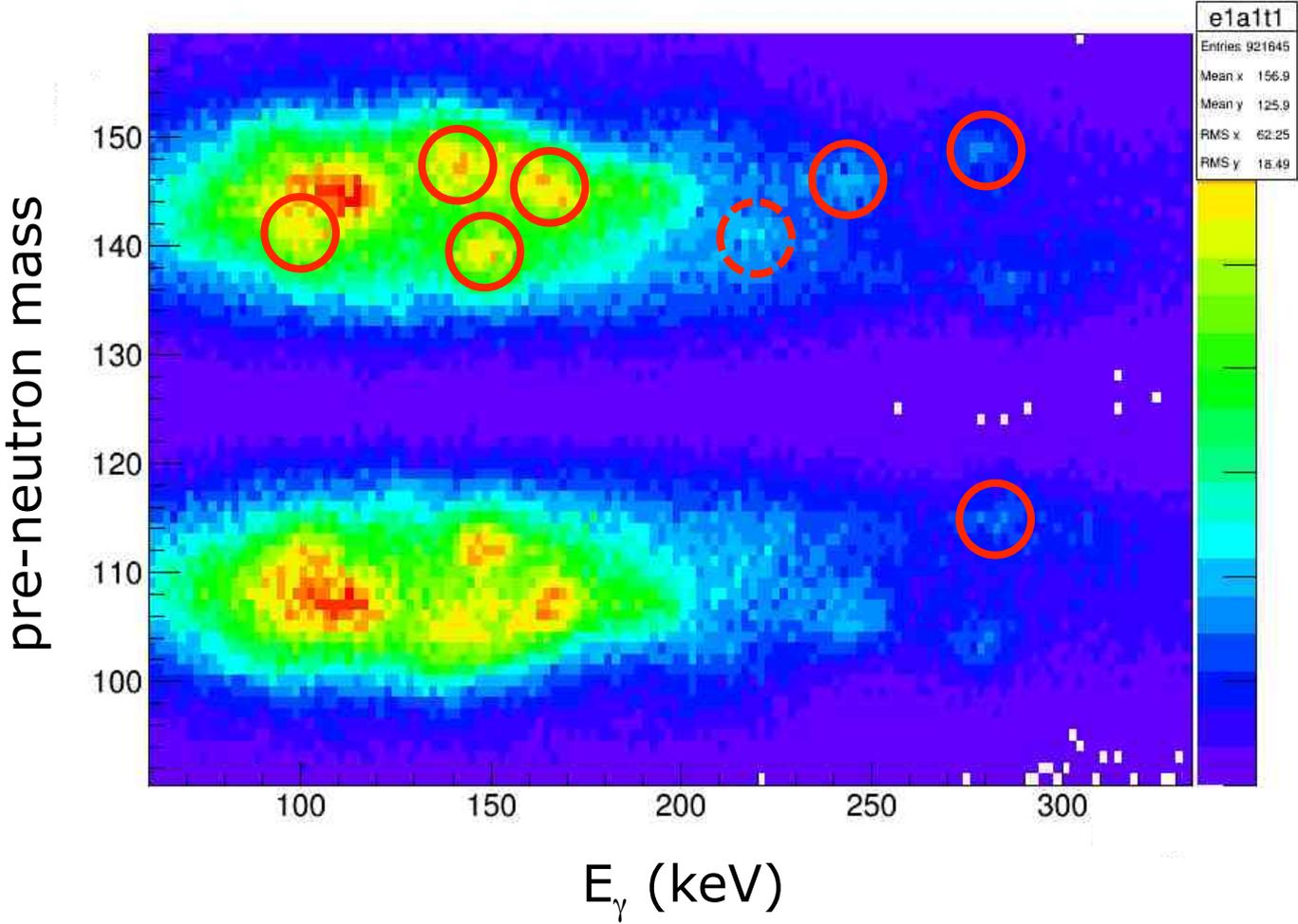
# Recent achievements

$\Delta t = (3 - 10) \text{ ns}$



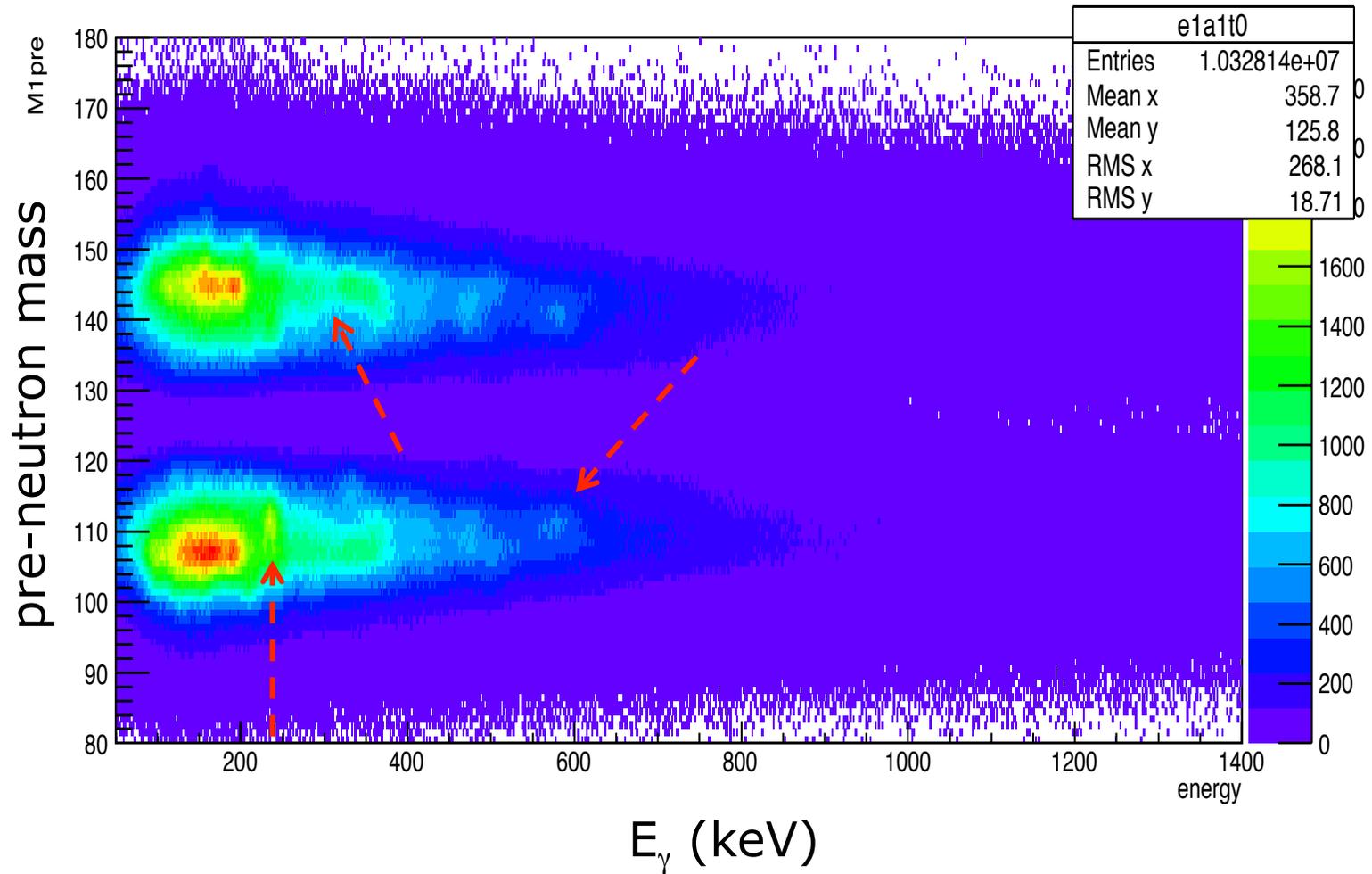
# Recent achievements

Fission\_A1pre vs LaBr3 (Q489)



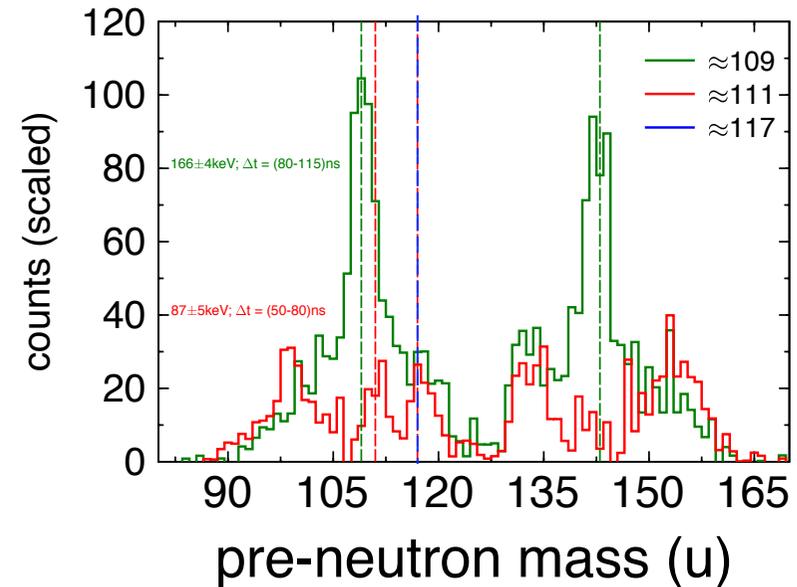
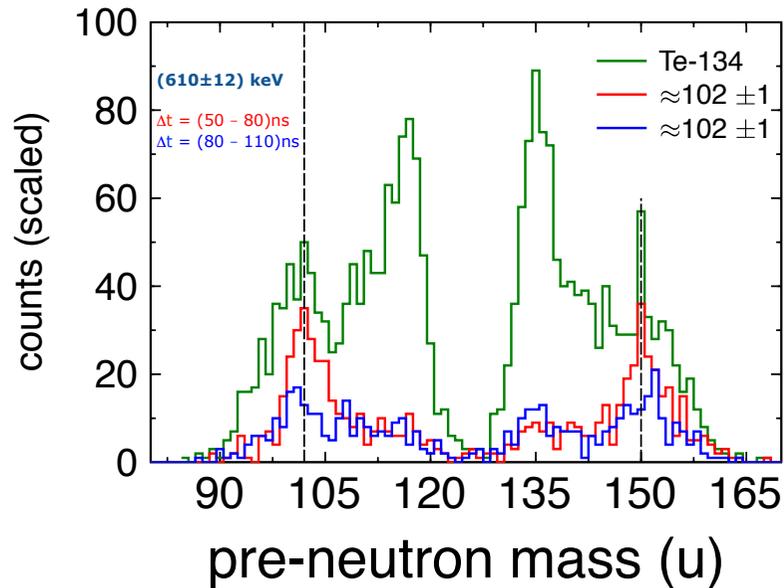
# Recent achievements

$\Delta t = \pm 3 \text{ ns}$



# Recent achievements

## Mass-correlated isomeric $\gamma$ -rays (cont'd)



- **Easier identification looking at FF +  $\gamma_1$  +  $\gamma_2$**
- **But number of events presently too small!**
- **Time interval too short for proper  $T_{1/2}$  determination**

# How to advance?

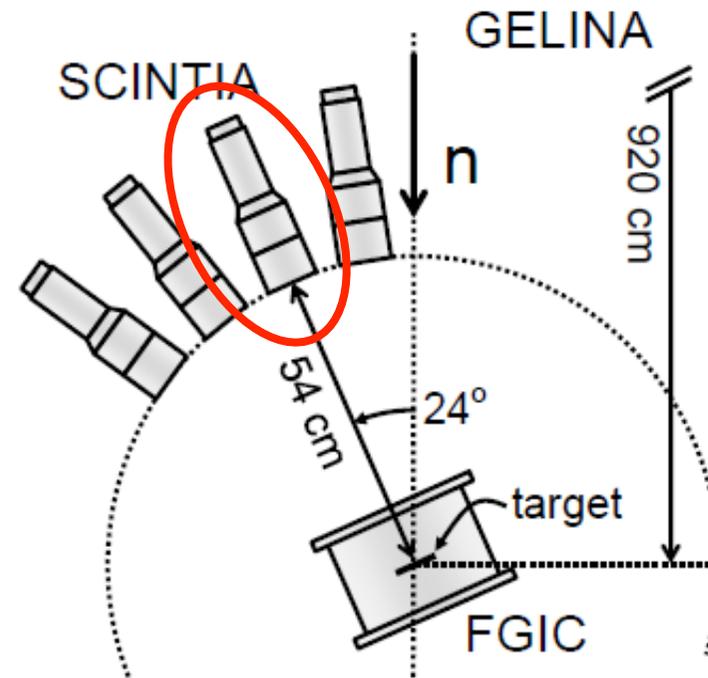
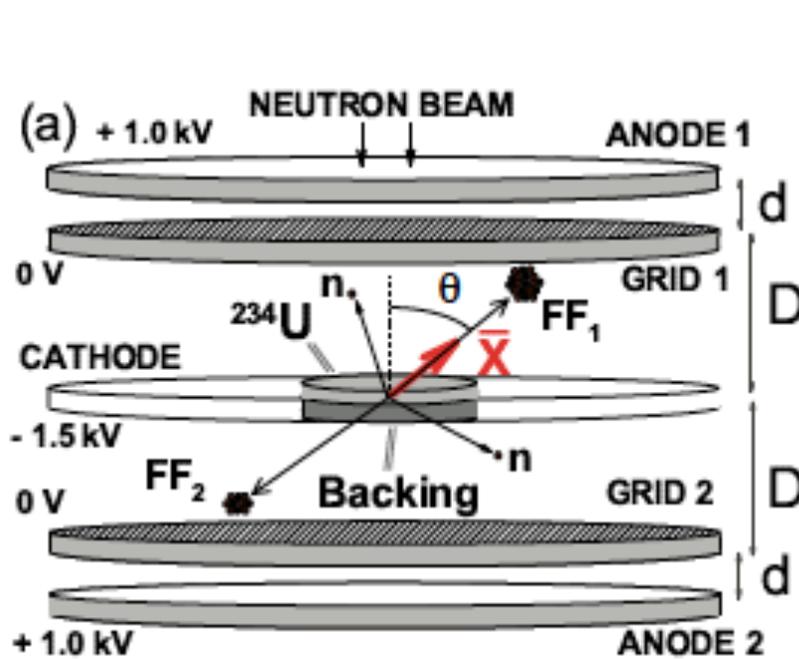
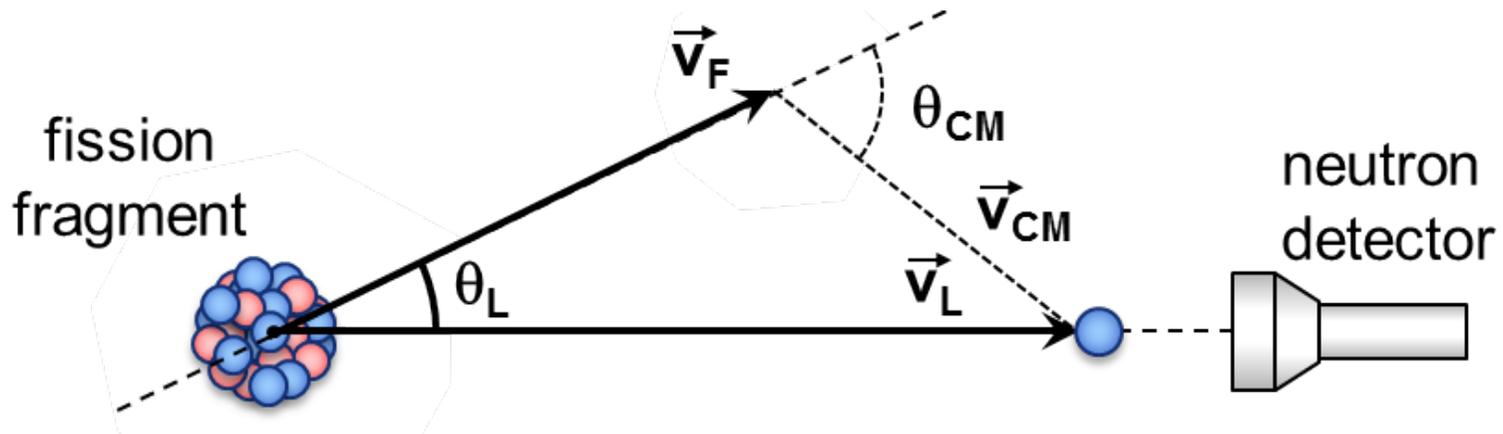
- Best possible mass (energy) resolution
- “Perfect” prompt neutron suppression in the PFGS spectra
- Largest possible time window to access isomer decay beyond 10  $\mu\text{s}$  after fission
- High detection efficiency to get best possible count-rate
- We need FF- $\gamma$ - $\gamma$  triples for identification of isotope (A,Z)
- PFGS angular distribution (multipolarity of the  $\gamma$ -ray)

# How to advance?

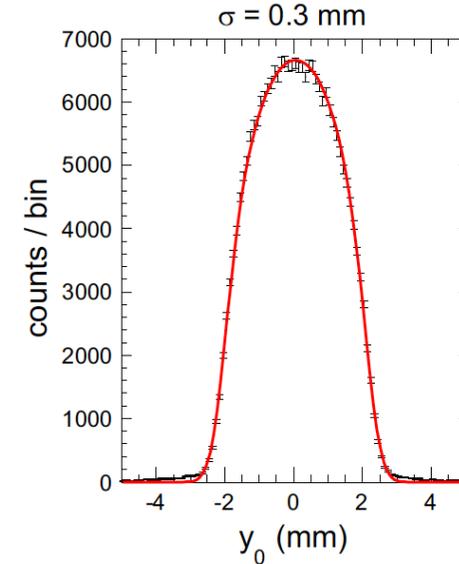
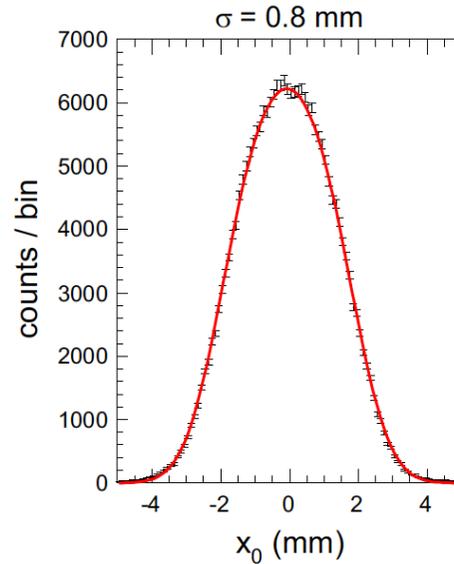
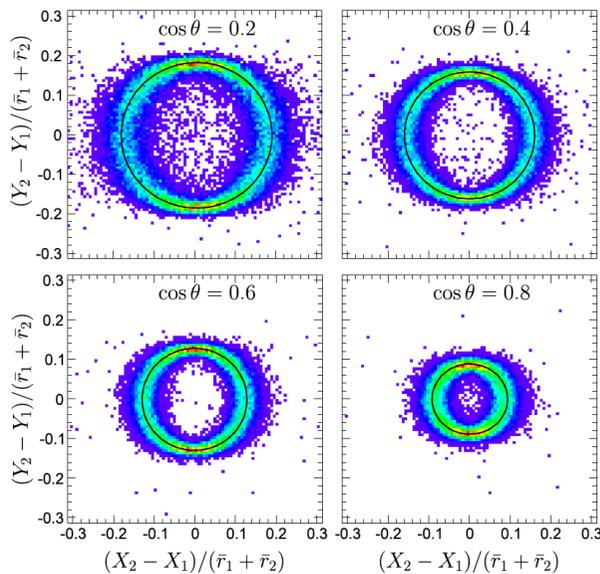
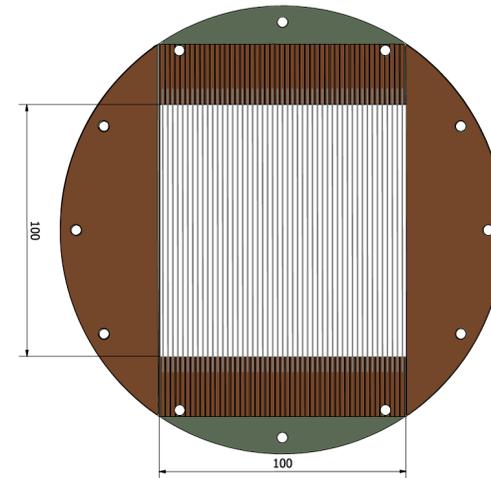
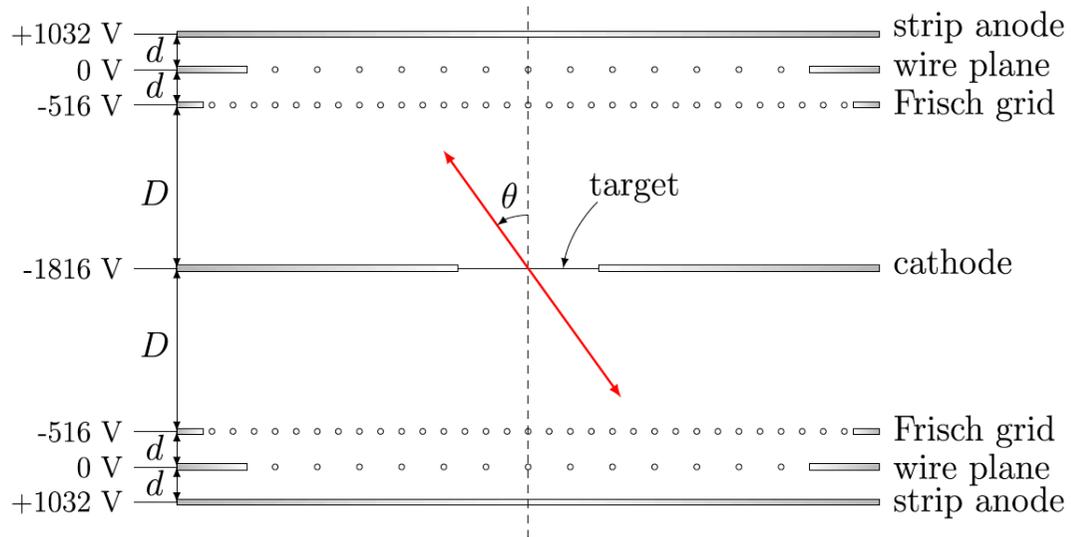
- Best possible mass (energy) resolution
- “Perfect” prompt neutron suppression in the PFGS spectra
- ✓ Close distance to the sample that “all” neutrons have passed “before” the isomer decay, i.e. w/i  $\Delta t = (3 - 30) \text{ ns @ } 15 \text{ cm}$
- Largest possible time window to access isomer decay beyond  $10 \mu\text{s}$  after fission
- ✓ Triggerless digital DAQ with “online” trace analysis
- High detection efficiency to get best possible count-rate
- We need FF- $\gamma$ - $\gamma$  triples for identification of isotope (A,Z)
- PFGS angular distribution (multipolarity of the  $\gamma$ -ray)

- Motivation
- History and recent achievements
- **Recent instrument developments**
- VESPA++
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# Recent instrument developments

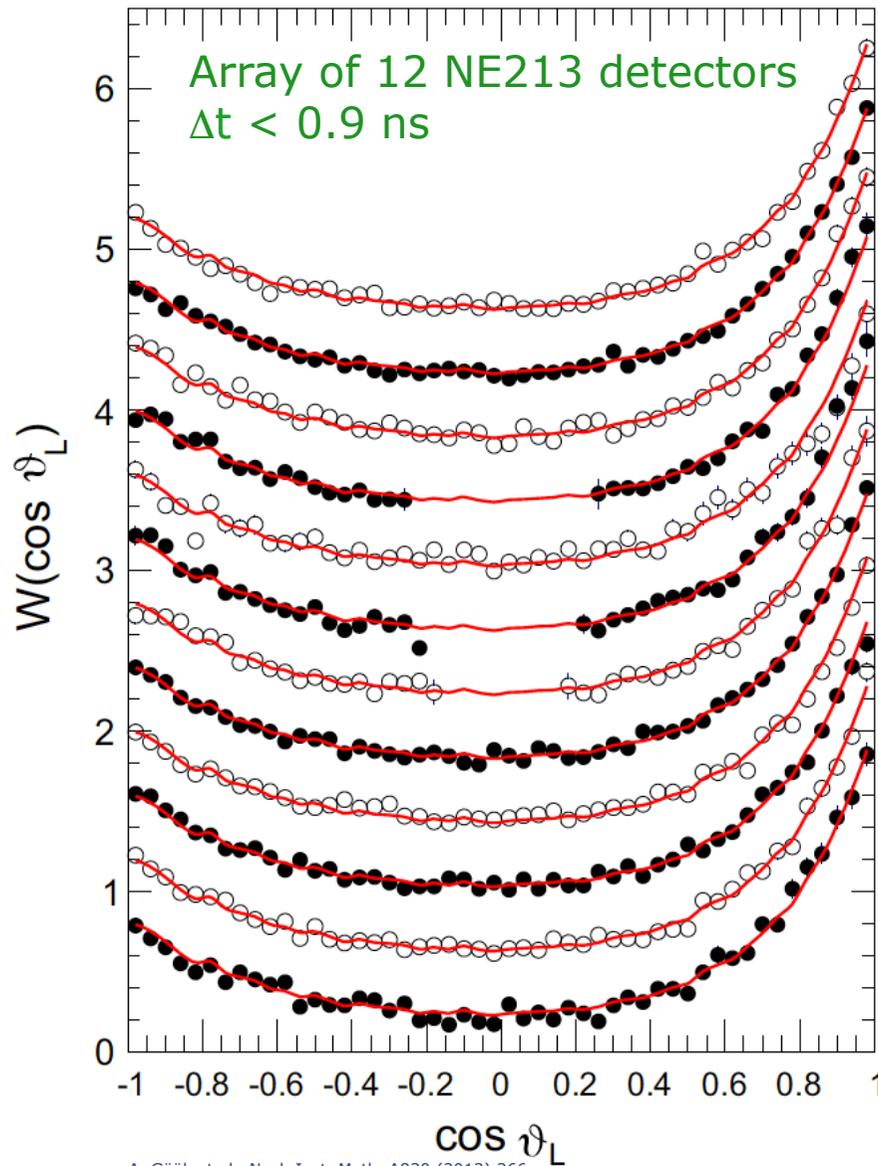


# Recent instrument developments

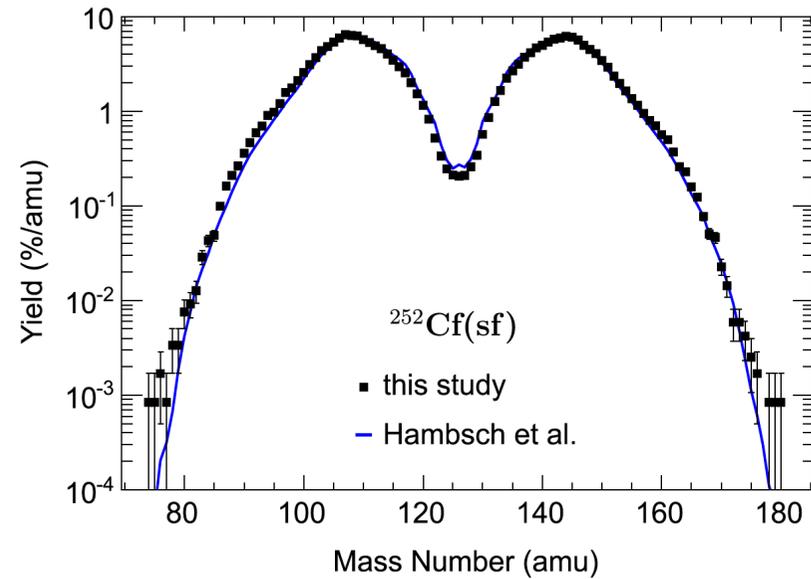


A. Göök et al., Nucl. Inst. Meth. A830 (2013) 366

# Recent instrument developments

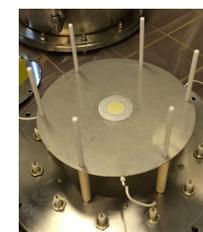


A. Göök et al., Nucl. Inst. Meth. A830 (2013) 366



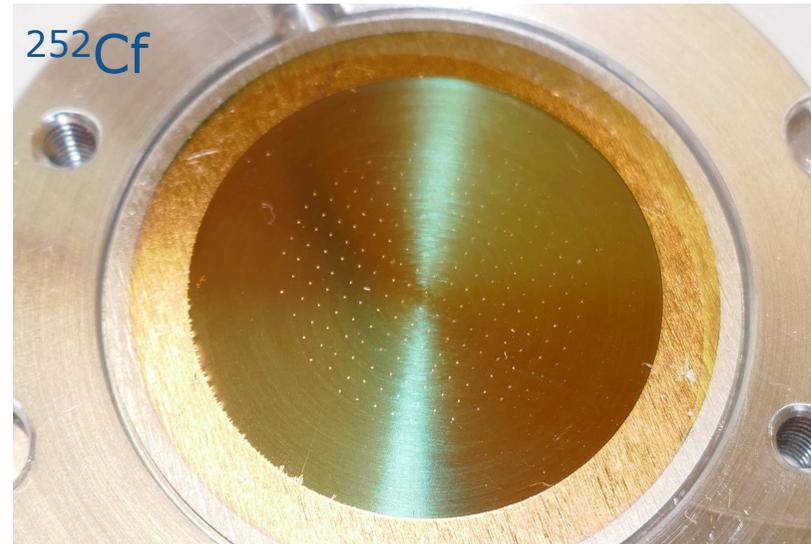
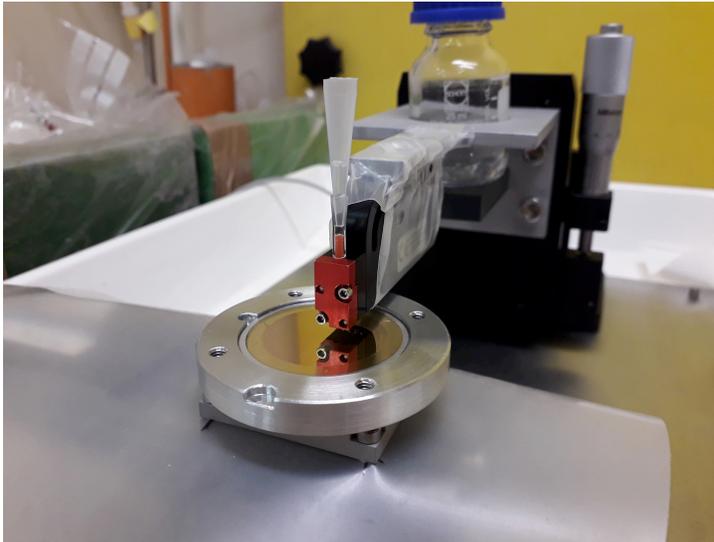
# Recent instrument developments

- Homogenous (thin) target layer
- Thin homogenous backing, standardly 35  $\mu\text{g}/\text{cm}^2$  PI (for  $^{252}\text{Cf}$  targets 225  $\mu\text{g}/\text{cm}^2$  Ni)
- In general limit of available glove-boxes for vacuum evaporation, in JRC Geel only available for  $^{235,238}\text{U}$  (and  $^{239}\text{Pu}$ )
- For all other isotopes “only” molecular plating available  
=> not suitable for the production of spectroscopic targets



- ✓ New technique developed at JGU Mainz: **Drop-on-demand!**

# Recent instrument developments



Suitable for any isotope one can get into solution!

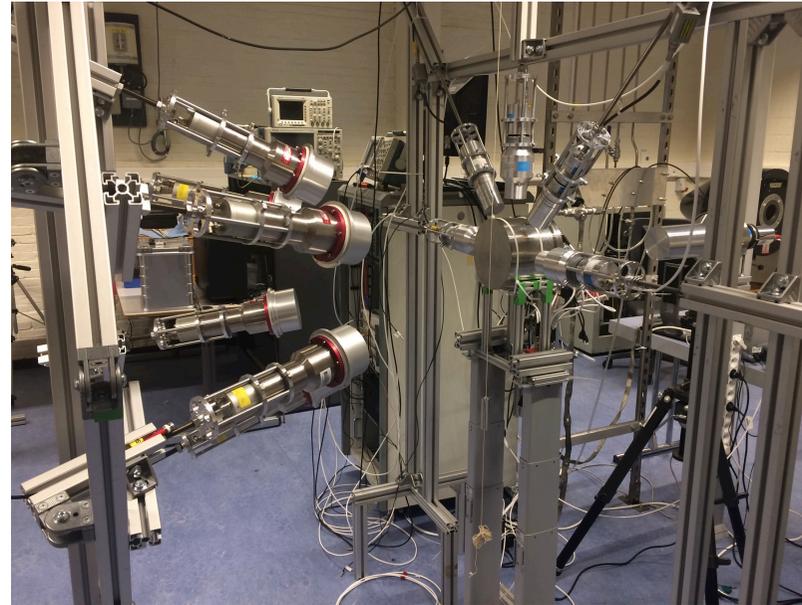
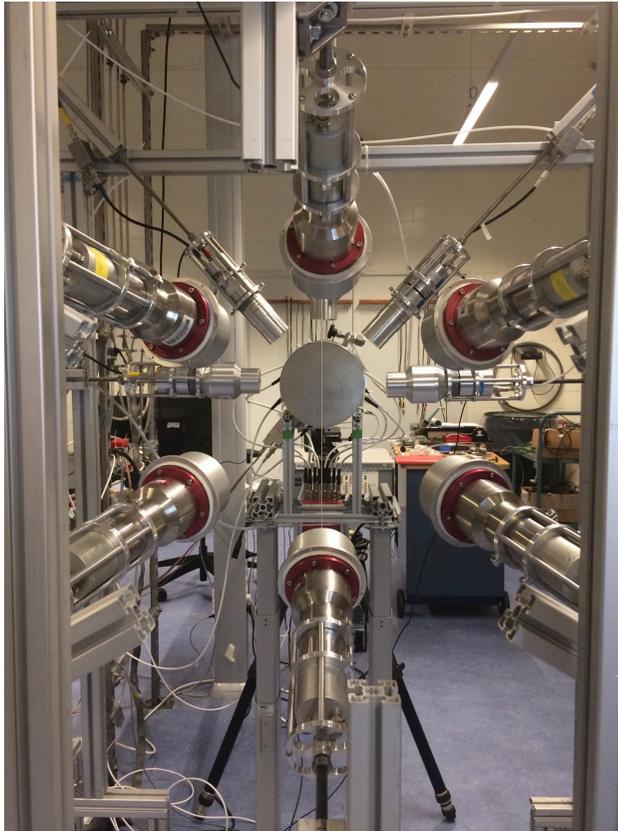
*K. Eberhardt et al., Johannes Gutenberg University, Mainz*

- Motivation
- History and recent achievements
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- **VESPA++**
- Timeline/outlook

# VESPA++

- $^{252}\text{Cf}$  target (5000 fissions/s) on PI backing
  
- VESPA:
  - ✓ 5  $\text{LaBr}_3$  of 51mm × 51mm (diameter × length) @ 15cm
  - ✓ 1  $\text{LaBr}_3$  of 89mm × 205mm (diameter × length) @ 30 - 40cm
  
  - ✓ *Additional at a later stage:*
    - 5  $\text{LaBr}_3$  of 76mm × 76mm (diameter × length) @ 30cm (TU Darmstadt)
  
- VESPA+ :
  - ✓ 6 liquid/crystal scintillator detectors 102mm × 51mm (diameter x length)
  
- VESPA++ :
  - ✓ Position sensitive TFGIC

# VESPA++



## **V**ersatile **S**Pectroscopy **A**rray

- + neutron array
- + position sensitive TFGIC

- Motivation
- History and recent achievements
- Recent instrument developments
- VESPA++
- **Timeline/outlook**

# Timeline / outlook

- Start of the VESPA++ commissioning run:  
November 2018 (with  $\approx 2000$  fissions/s)
- Development and testing of data analysis procedure
- Upon arrival of a fresh  $^{252}\text{Cf}$ -on-PI target (5000 fissions/s)  
start of an **11 months** data taking (=> Spring 2019)

# Timeline / outlook

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start of an **11 months** data taking ( $\Rightarrow$  Spring 2019)

➤  $N_{f,\text{tot}} = 10^{11}$  !!!

With  $M_\gamma \approx 8$

➤  $N_{f\gamma} = 7.8 \times 10^9$

➤  $N_{f\gamma\gamma} = 7.6 \times 10^8$

➤  $N_{f\gamma\gamma\gamma} = 7.4 \times 10^6$

$\Rightarrow 10^6$  events for  $Y(A) = 0.2\%$

# Timeline / outlook

- Start of the VESPA++ commissioning run:  
November 2018 (with  $\approx 2000$  fissions/s)
- Development and testing of data analysis procedure
- Upon arrival of a fresh  $^{252}\text{Cf}$ -on-PI target (5000 fissions/s)  
start of an **11 months** data taking ( $\Rightarrow$  Spring 2019)

➤  $N_{f,\text{tot}} = 10^{11}$

With  $M_\gamma \approx 8$

➤  $N_{f\gamma} = 7.8 \times 10^9$

➤  $N_{f\gamma\gamma} = 7.6 \times 10^8 \quad \Rightarrow \quad 10^6 \text{ events for } Y(A) = 1\%$

➤  $N_{f\gamma\gamma\gamma} = 7.4 \times 10^6$

- Data good for PhD (master) students

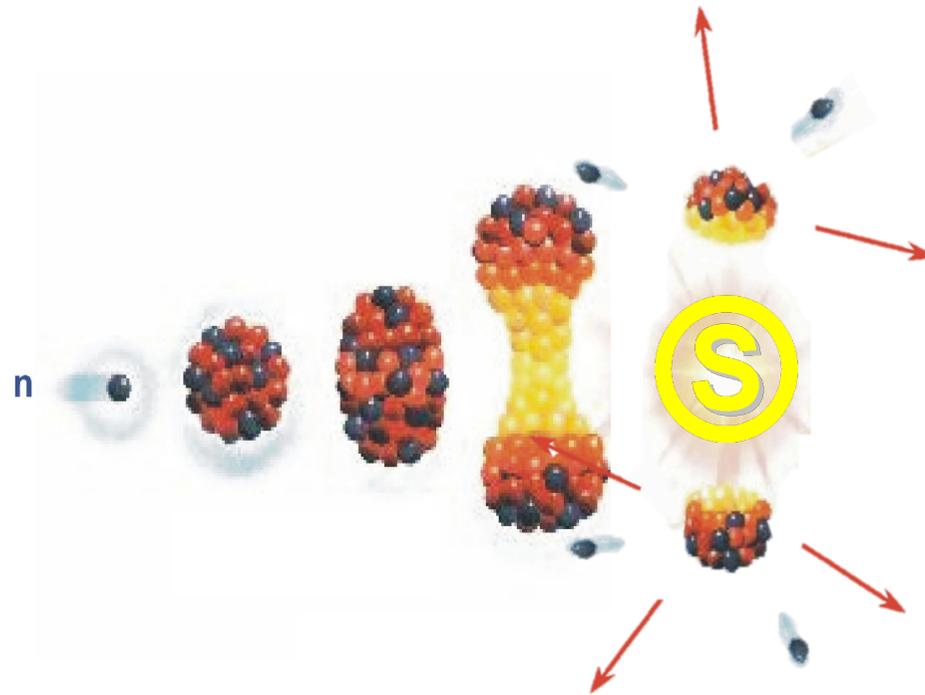


European  
Commission

# Before closing...

- If you agree on the potential of the coming data for nuclear fission (de-excitation) model benchmarking
- Formulation of data requests to be taken up in the OECD/NEA High Priority data Request List
- Possible support can come through common experiments within the EUFRAT Access Programme to EU research facilities

# Thank you very much for Your attention

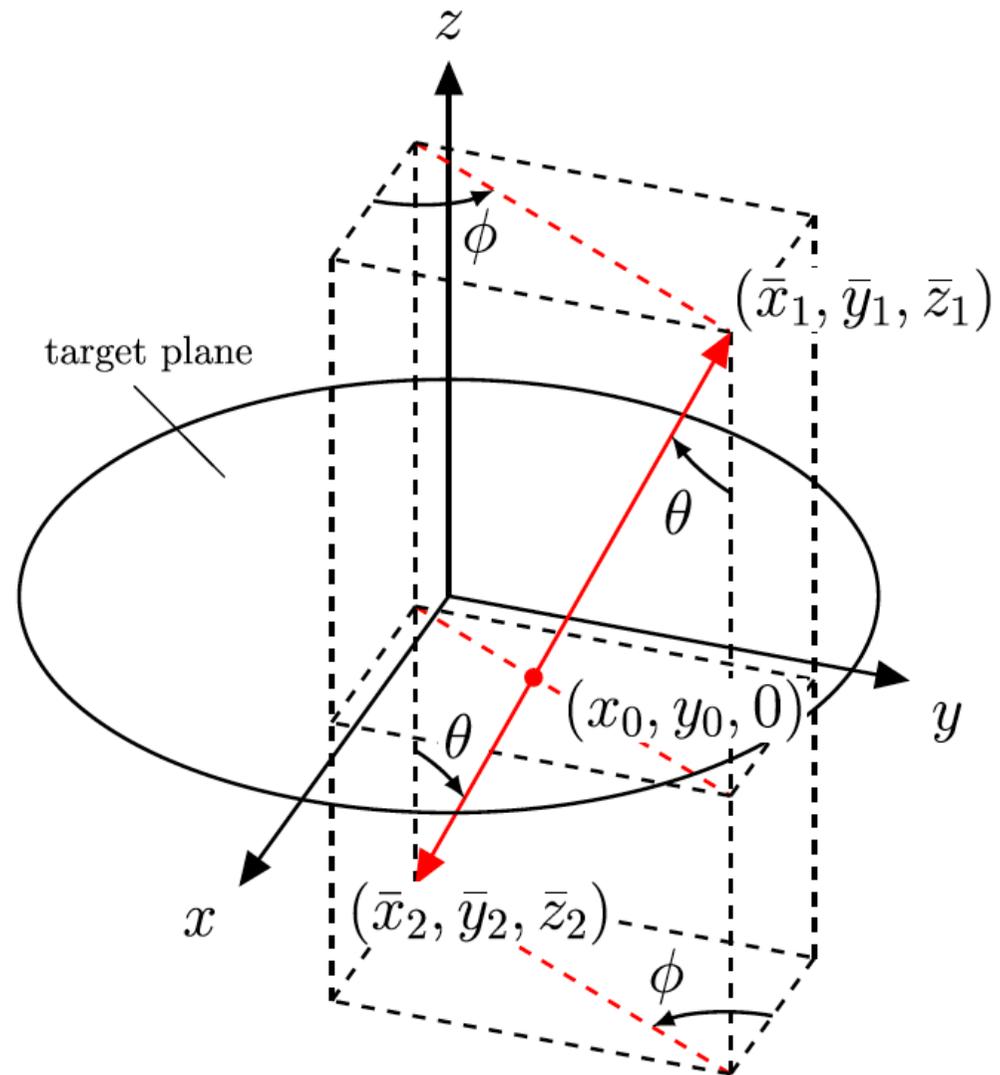


R. Billnert, C. Bonaldi, D. Choudhury, K. Eberhardt, A. Gatera, W. Geerts, A. Göök, M. Lebois, A. Moens, A. Oberstedt, M. Peck, Ch. Schmitt, G. Sibbens, M. Vidali, J.N. Wilson, Qi L.,...

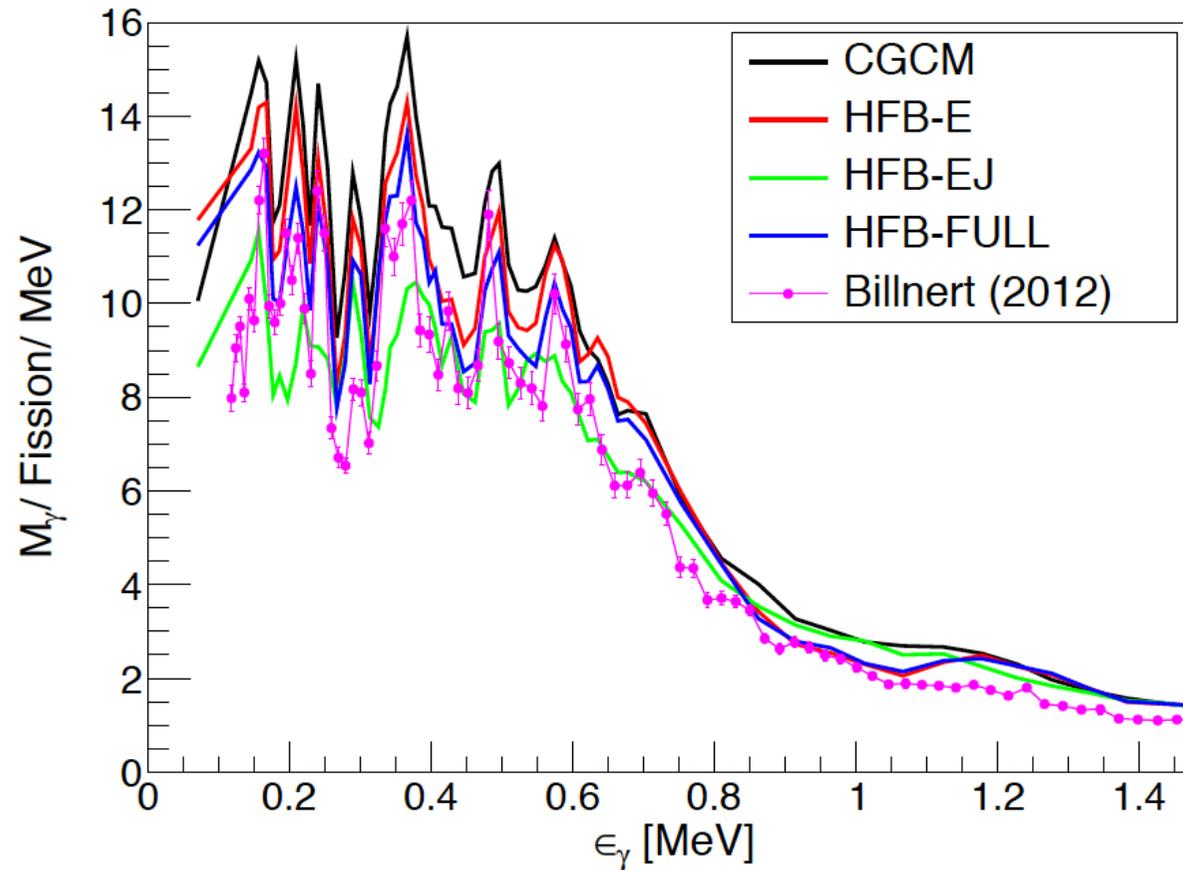




# Recent instrument developments



# Motivation

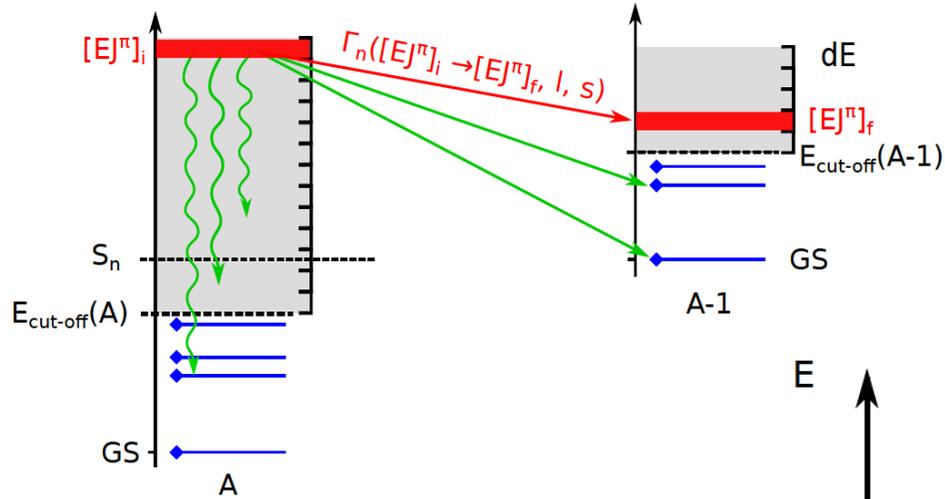


Different Level Density Functions:

CGCM: Composite Gilbert Cameron Model

HFB-X: Hartree-Fock Bogoljubov

# Motivation

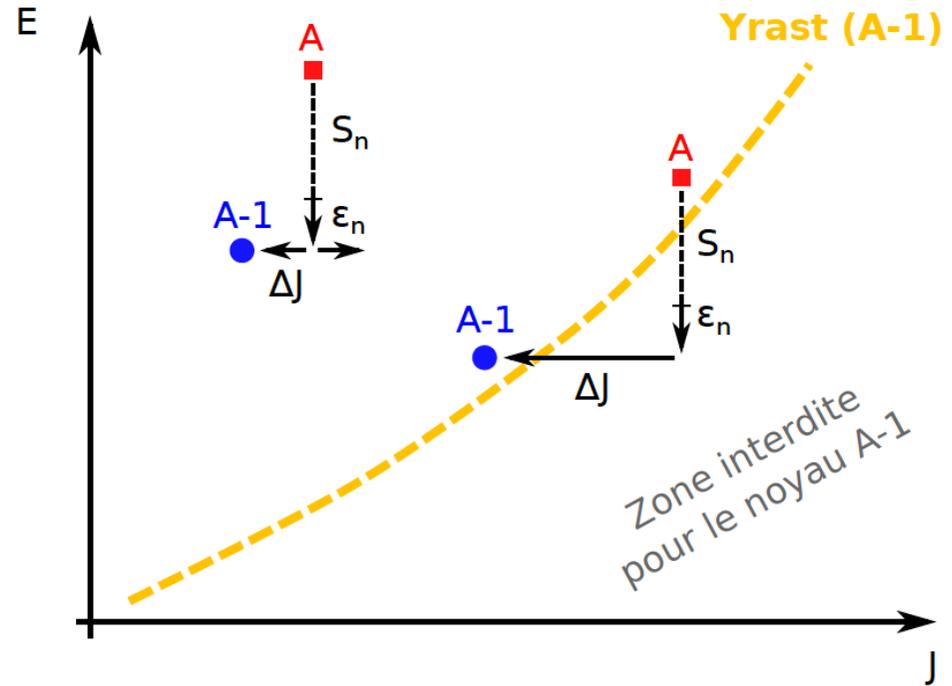


$$H\phi = E\phi \quad \pi\phi = \pm\phi$$

$$J^2\phi = J(J+1)\hbar^2\phi \quad J_z\phi = M\hbar\phi$$

$$\phi = |E, J, M, \pm \rangle$$

- Nuclear levels are quantized
- No level in A-1 after neutron emission
- $\gamma$ -emission instead



# Prompt fission $\gamma$ -ray emission

Measured:

- prompt fission  $\gamma$ -ray spectrum (PFGS)

Determined:

- average multiplicity  $\bar{M}_\gamma$
- mean energy per photon  $\varepsilon_\gamma$
- total photon energy  $E_{\gamma,\text{tot}}$

Deduced:

- multiplicity distribution

- $^{252}\text{Cf}(\text{sf})$  R. Billnert et al., PRC 87 (2013)  
A. Oberstedt et al., PRC 92 (2015)
- $^{235}\text{U}(\text{n}_{\text{th}}, \text{f})$  A. Oberstedt et al., PRC 87 (2013)
- $^{241}\text{Pu}(\text{n}_{\text{th}}, \text{f})$  S. Oberstedt et al., PRC 90 (2014)
- $^{240,242}\text{Pu}(\text{sf})$  S. Oberstedt et al., PRC 93 (2016)
- $^{239}\text{Pu}(\text{n}_{\text{th}}, \text{f})$  A. Gatera et al., PRC 95 (2017)
- $^{233}\text{U}(\text{n}_{\text{th}}, \text{f})$  D. Choudhury et al., data analysis on-going