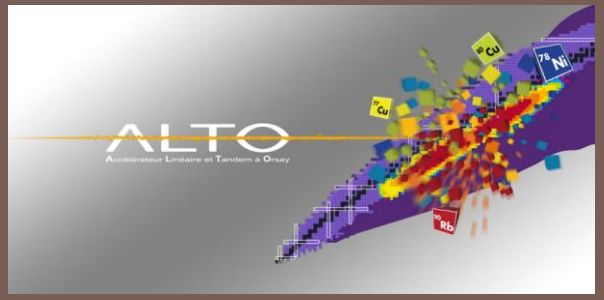


# The ν-BALL PROJECT at IPN ORSAY

N. Jovancevic (IPNO)
M. Lebois (IPNO)
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D. Etasse (LPC Caen)

# Outline

- **ν-ball hybrid spectrometer**
- **Experimental Campaign**

- **$^{252}$Cf ionisation chamber + ν-ball**

- **Neutron induced reaction γ spectroscopy:**

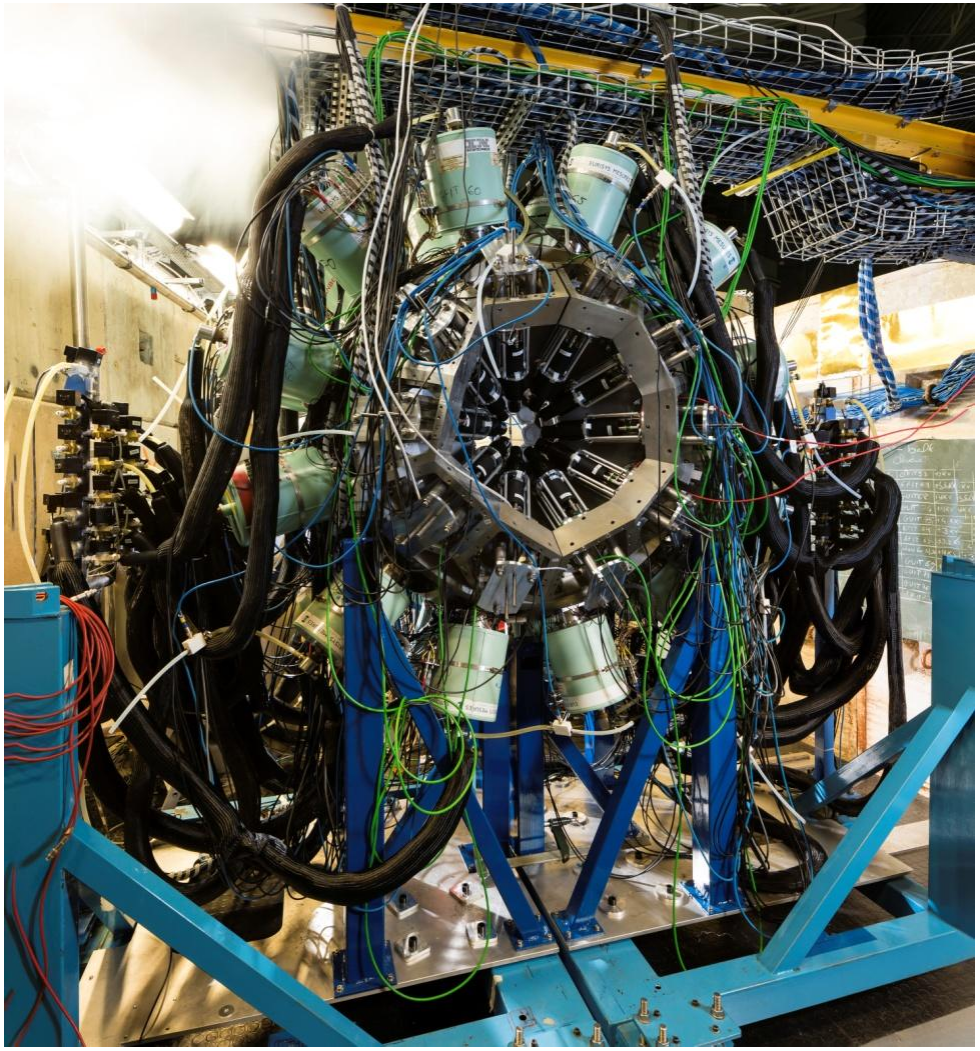
1. Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions
2. Spectroscopy above the shape isomer in $^{238}$U

# ν-ball hybrid spectrometer

Motivation:

1. Neutron source with ALTO
- Spectroscopy of the neutron-rich nuclei
- Fission isomers

2. High sensitivity fast timing studies to extract information about nuclear moment or deformations



# ν-ball hybrid spectrometer

**24 Clovers around 90°**
$d_{center}$ = 20.88 cm
$\Delta\theta$ = 10.35°

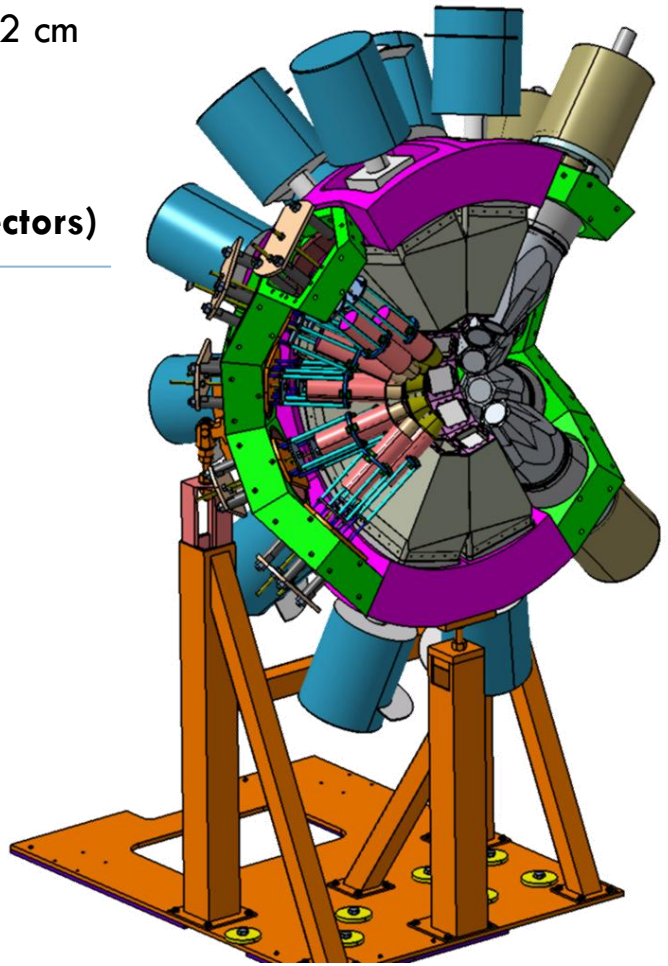
**10 Phasel HPGe**
$d_{center}$ = 18 cm
$\Delta\theta$ = 20.1°
Loan
Pool

**20 $LaBr_3$ 1.5"x2"**
$d_{center}$ = 15.2 cm
$\Delta\theta$ = 14.3°
FATIMA Coll.
NPL Loan
**(PARIS detectors)**

- Hybrid spectrometer Ge/LaBr
- "FASTER" Digital DAQ
  - 184-200 *Independent* Channels (106 Ge, 20 LaBr, 58 BGO)
  - 500 Ms/s, 12 effective bits QDC for LaBr3
  - 125 Ms/s, 14 effective bits ADC for HPGe and BGO
- Coupling with neutron source
- Calorimetry
- Efficiency

~ 6.3% for Ge

~ 0.8% for LaBr

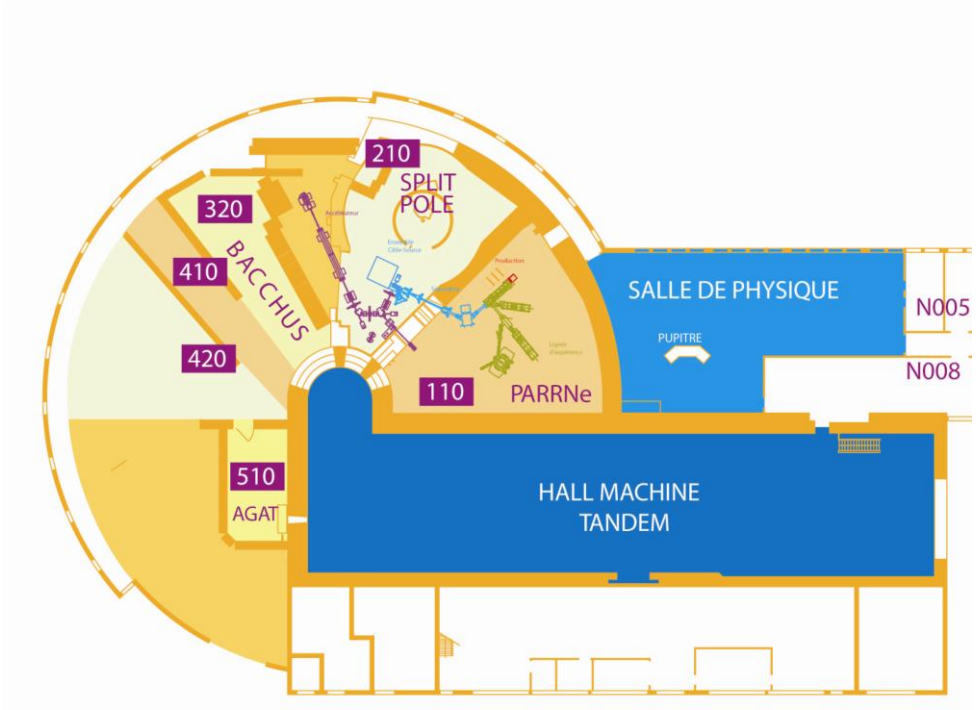


# ν-ball hybrid spectrometer
# ALTO facility

**Standard Tandem beams**

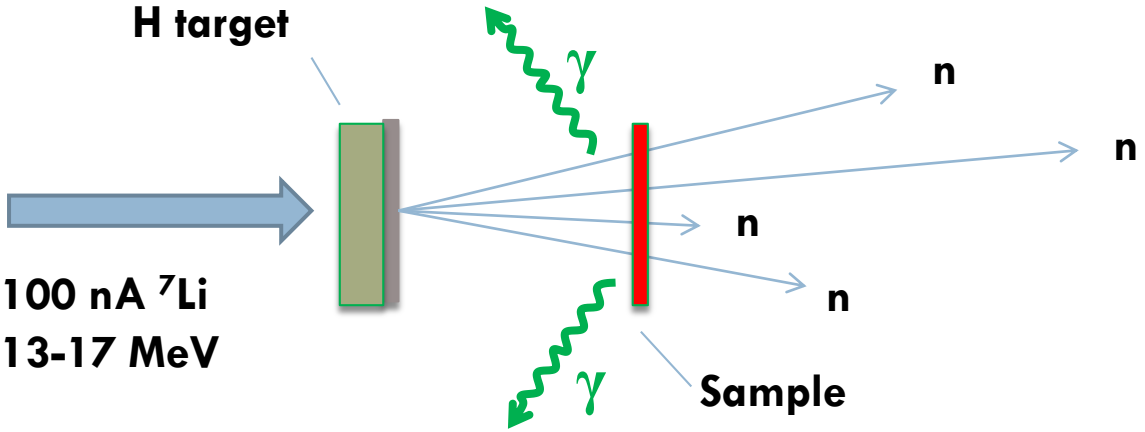
- from **H, $^{3}$He, $^{4}$He, ..., $^{14}$C, ...** up to **$^{127}$I**
- terminal voltage: from **< 1 MV** up to **14.5 MV**
- **beam pulsing**: pulse width **1 – 2 ns**; repetition rate – **200 ns** or more
- **new ions source** installed (800 enA of $^{7}$Li)

ALTO
Accélérateur Linéaire et Tandem à Orsay



# LICORNE

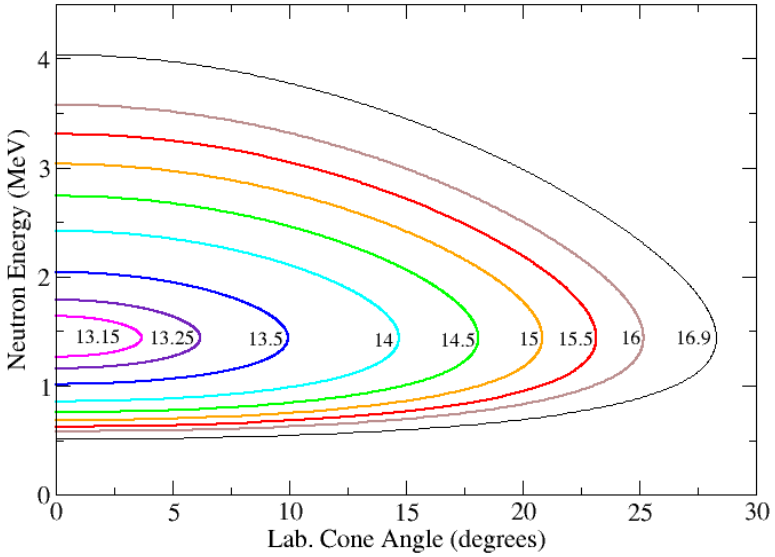
## Lithium Inverse Cinematiques ORsay Neutron source

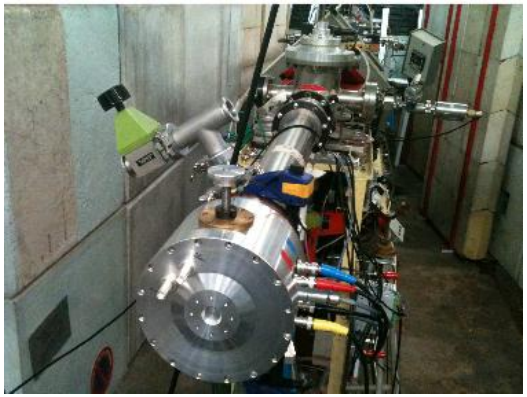


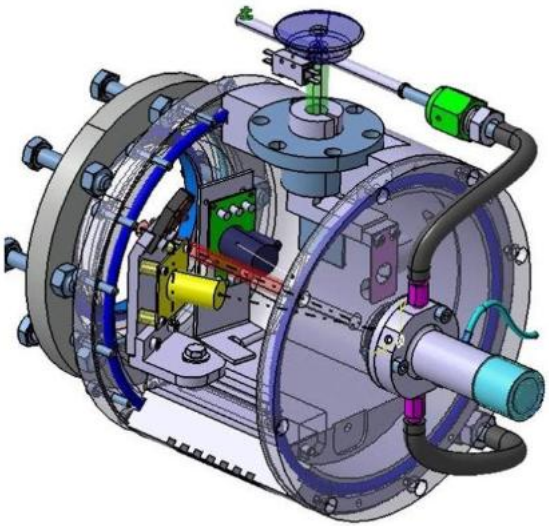

**Intensely focused monoenergetic neutron source:**

**$10^{7}$ n/s/steradian**

**$E_n$=0.5 – 4 MeV**

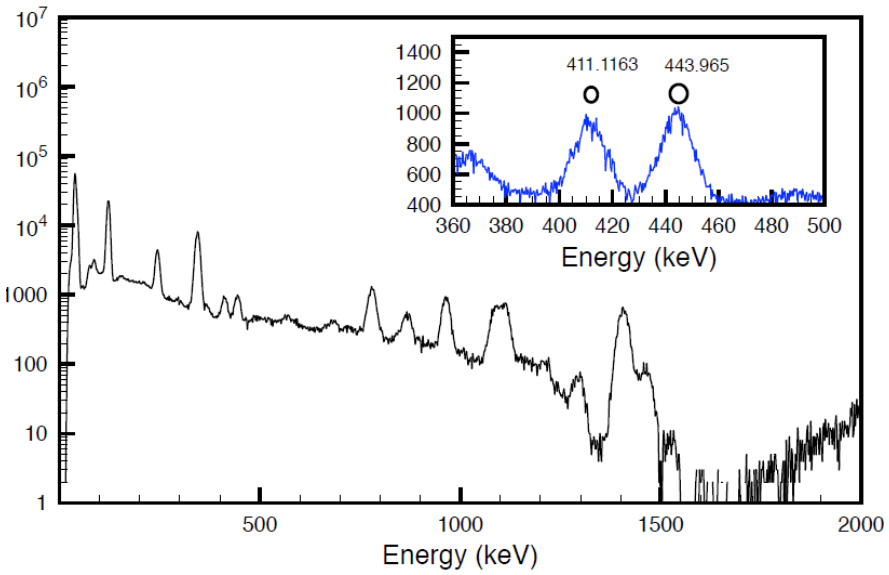


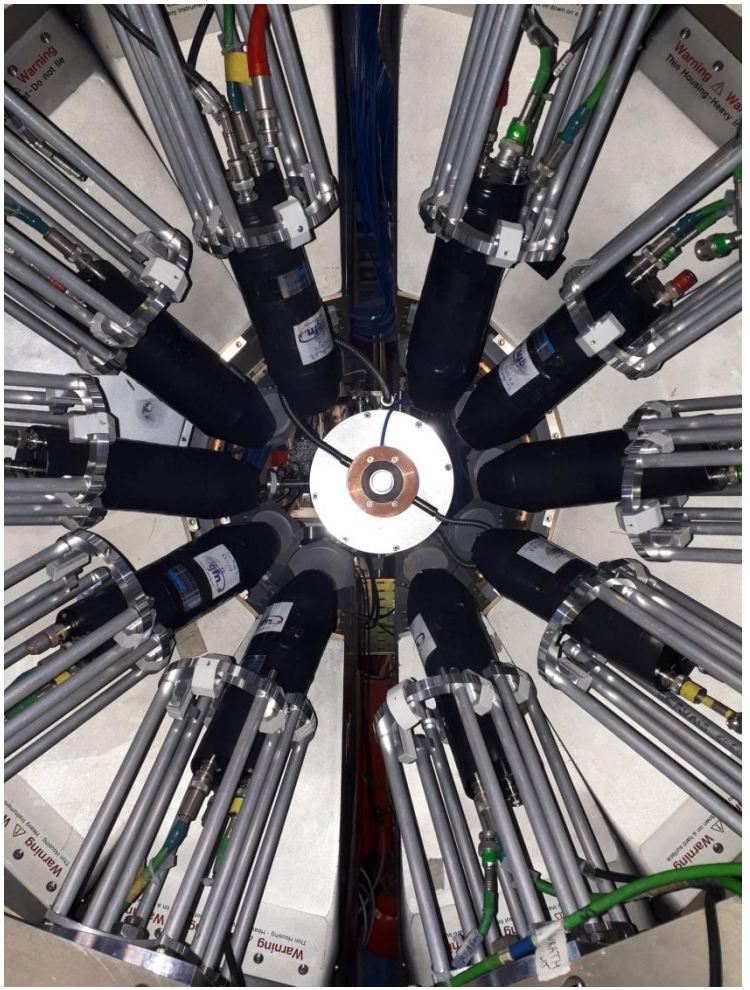





# ν-ball hybrid spectrometer

**20 $LaBr_3$ 1.5"x2"**



Time Resolution: ~250ps

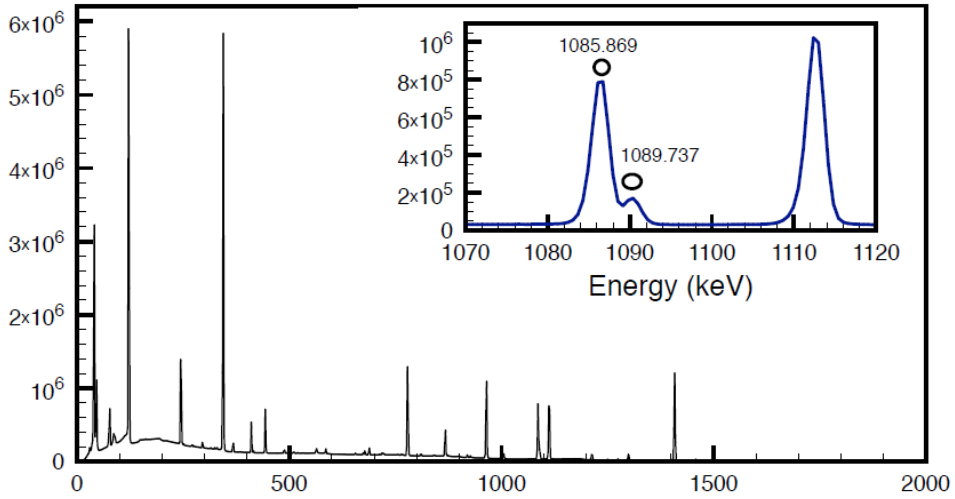
Energy Resolution (@662 keV): 2,6%

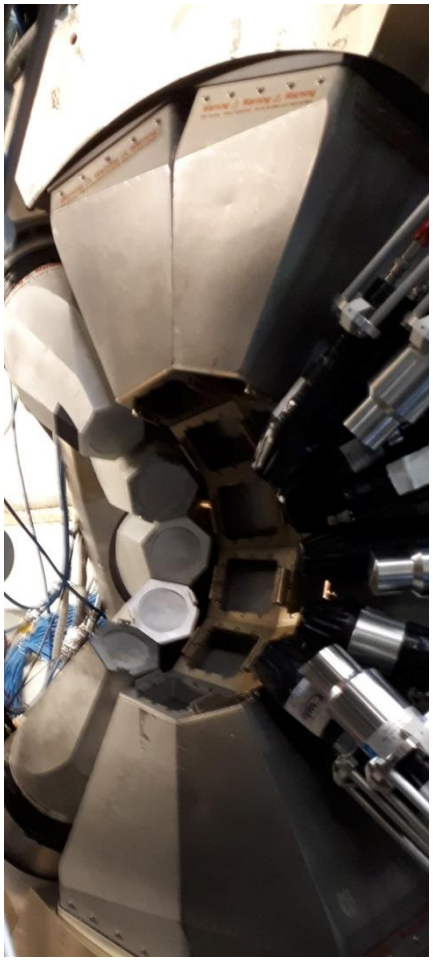
Photopeak efficiency (@1.33 MeV): 0.5%

# ν-ball hybrid spectrometer

**24 Clovers**

**10 Phasel HPGe**



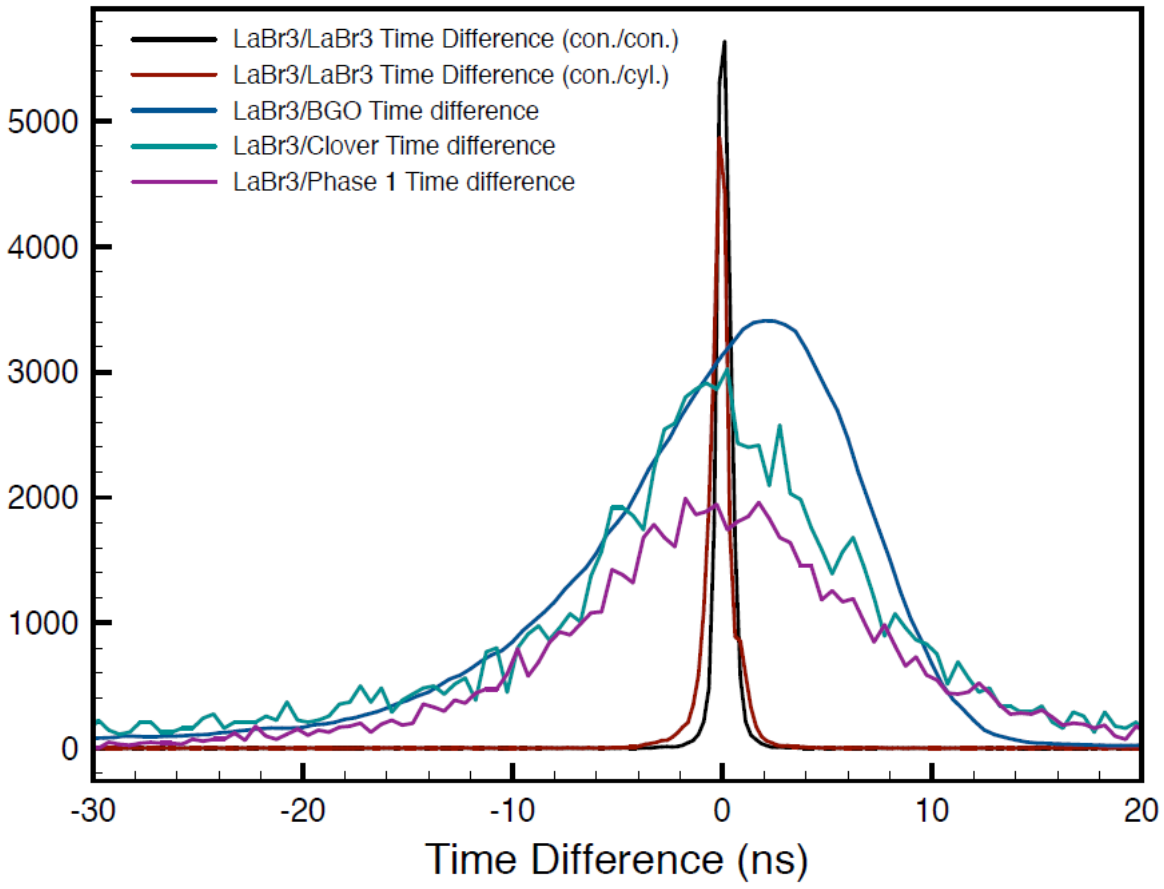
Time Resolution: ~13 ns

Energy Resolution (@1.33MeV): 2.8 keV

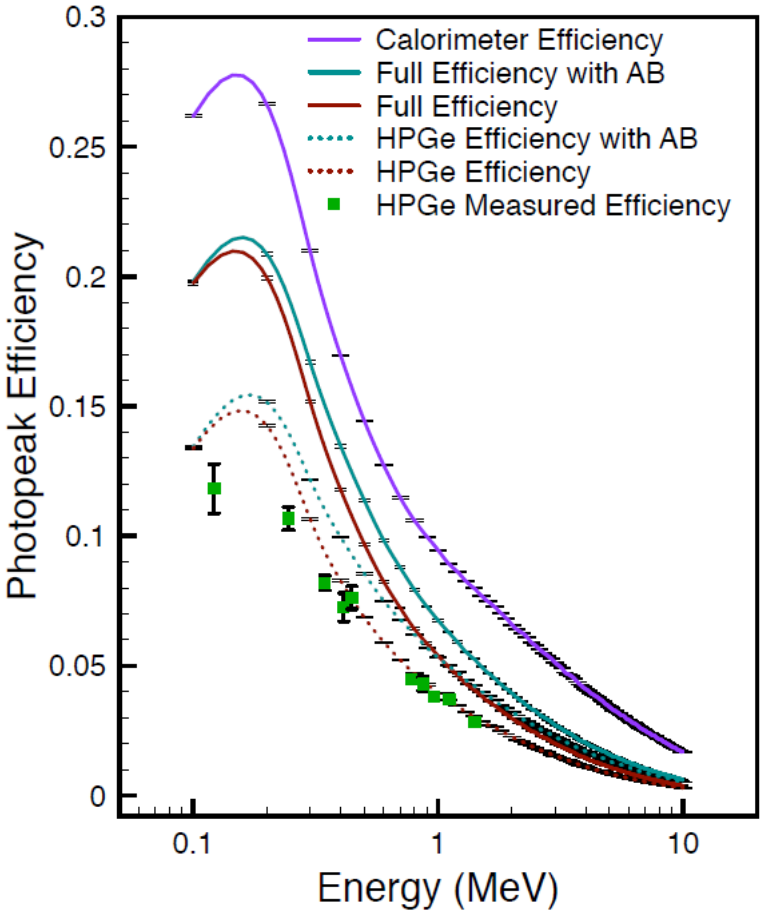
Photopeak efficiency (@1.33MeV): 6.3%

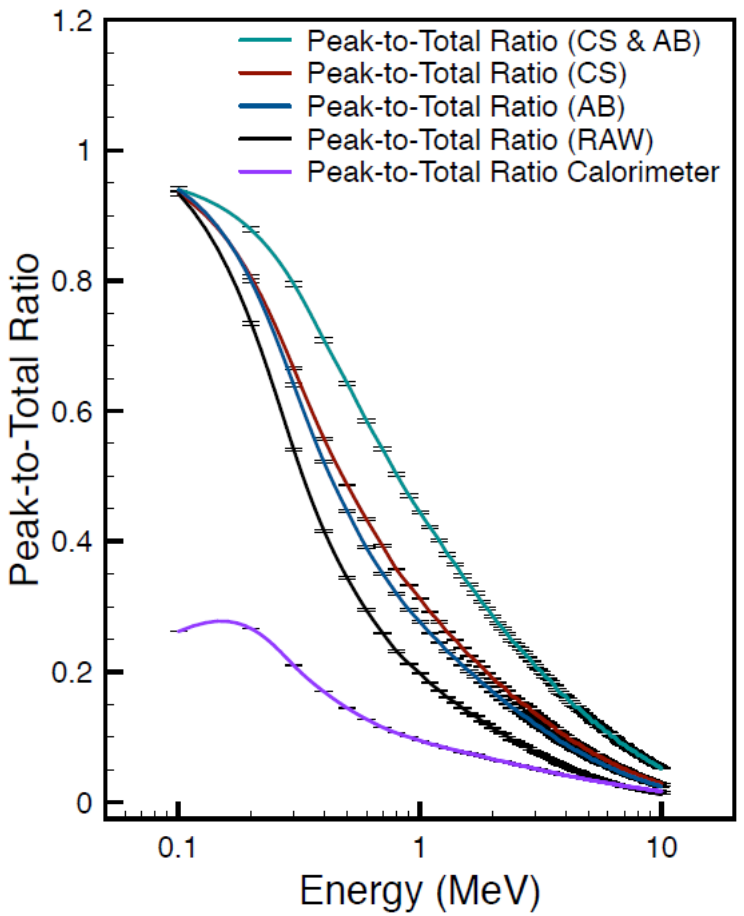
# ν-ball hybrid spectrometer

*The measured timing performances*



# ν-ball hybrid spectrometer



# Experimental Campaign (November 2017 – July 2018)

**Heavy Ion Reaction γ spectroscopy:**

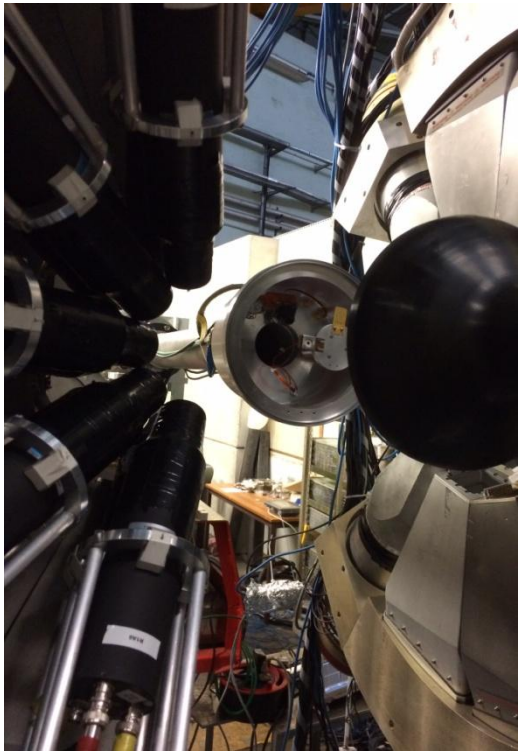
- Half-life measurement and isomer spectroscopy in the neutron rich deformed nucleus $^{166}$Dy
- Electromagnetic transition rates in the nucleus $^{136}$Ce
- Pinning down the structure of $^{66}$Ni by 2n- and 2p-Heavy-Ion transfer reactions and g-factor measurement
- A study on the transition between seniority-type and collectivity excitations in the YRAST $4^+$ state of $^{206}$Po
- Measurement of the super-allowed branching ratio of $^{10}$C
- Feeding of low-energy structures of different deformations by the GDR decay: the nuBall array coupled to PARIS

**Neutron induced reaction γ spectroscopy:**

- Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions
- Spectroscopy above the shape isomer in $^{238}$U

# Experimental Campaign

HI Setup




# Experimental Campaign: tight schedule

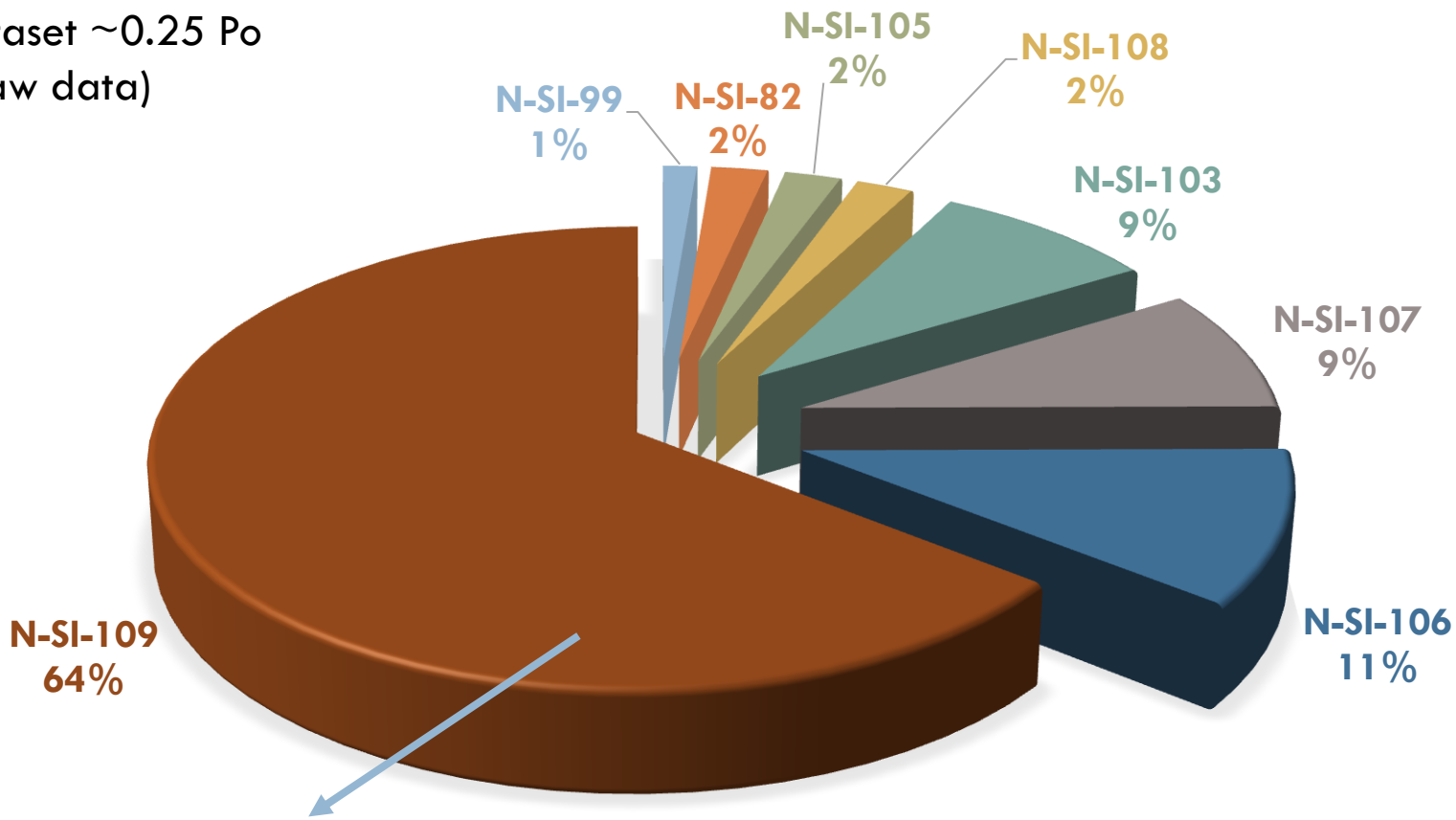
3192 hrs
of beam time

Including 2856 hrs
For 1st semester 2018

| | | |
|---|---|---|
| 18/29 | 01/05-24/07 | Beam Line preparation / Cabling |
| 36-46 | 04/09-13/11 | nu-ball mounting / BGO gain matching / HPGe preparation |
| 46 | 13/11/17 | R&D ALTO |
| | | Commissioning nu-ball |
| 47 | 20/11/17 | Commissioning nu-ball |
| 48 | 27/11/17 | N-SI-99 |
| 49 | 04/12/17 | N-SI-106 |
| 4 | 22/01/18 | N-SI-105 |
| 5 | 29/01/18 | N-SI-108 |
| 6 | 05/02/18 | |
| 7 | 12/02/18 | N-SI-109 |
| 8 | 19/02/18 | N-SI-109 |
| 9 | 26/02/18 | Machine Maintenance |
| 10 | 05/03/18 | Machine Maintenance |
| 11 | 12/03/18 | N-SI-100 |
| 12 | 19/03/18 | N-SI-82 |
| 13 | 26/03/18 | N-SI-82 |
| 14 | 02/04/18 | public holiday |
| 15 | 09/04/18 | N-SI-109 |
| 16 | 16/04/18 | N-SI-109 |
| 17 | 23/04/18 | N-SI-109 |
| 18 | 30/04/18 | ARTE / Machine Maintenance |
| 19 | 07/05/18 | Machine Maintenance |
| 20 | 14/05/18 | N-SI-103 |
| 21 | 21/05/18 | public holiday / N-SI-103 |
| 22 | 28/05/18 | |
| 23 | 04/06/18 | N-SI-106 |
| 24 | 11/06/18 | N-SI-107 |
| 25 | 18/06/18 | Final Calibration |
| 26-30 | 25/06->26/07 | Detector Maintenance / Packing / Shipment to Jyvaskyla |

# Experimental Campaign: the full dataset

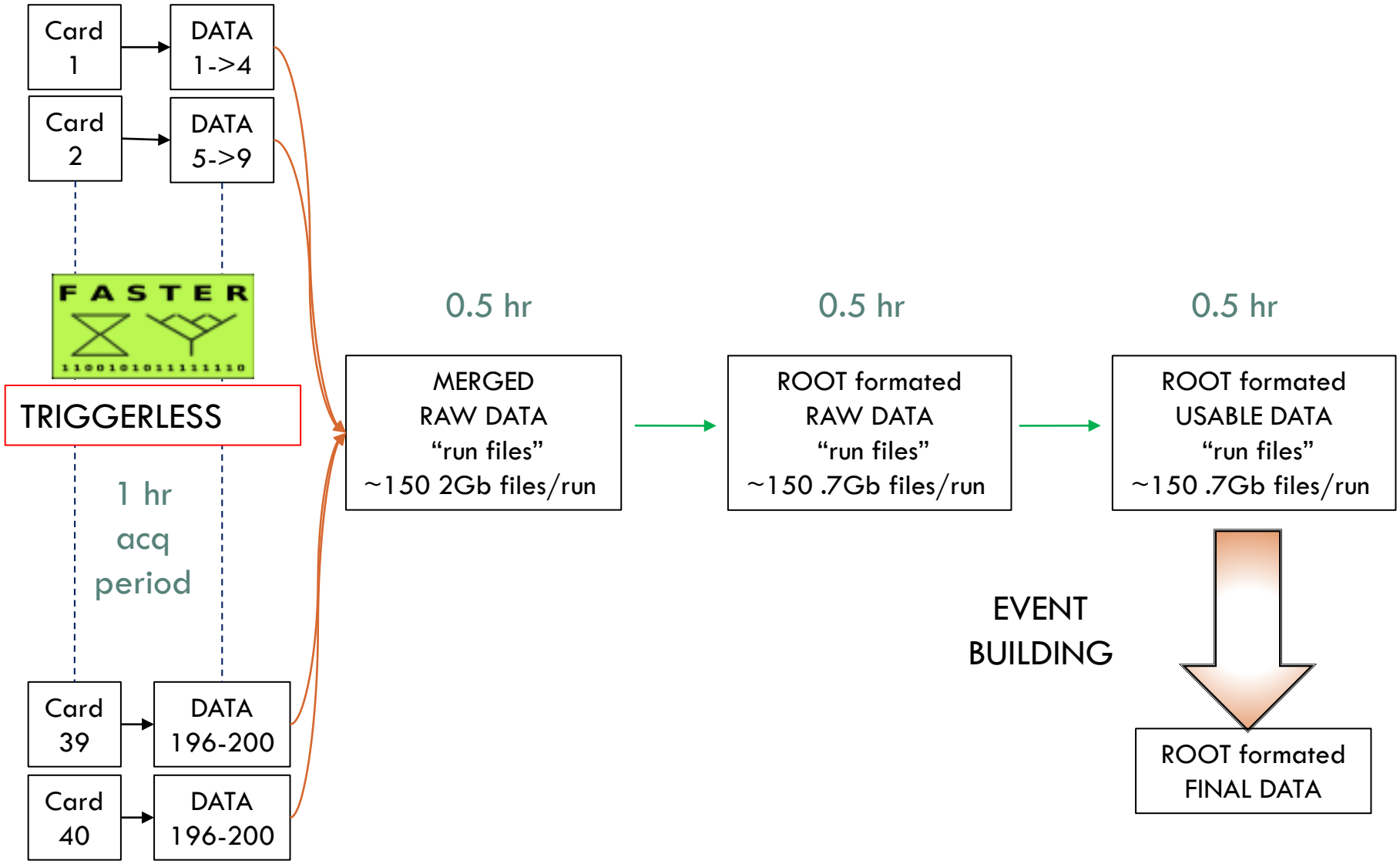
ν-ball dataset ~0.25 Po
(raw data)



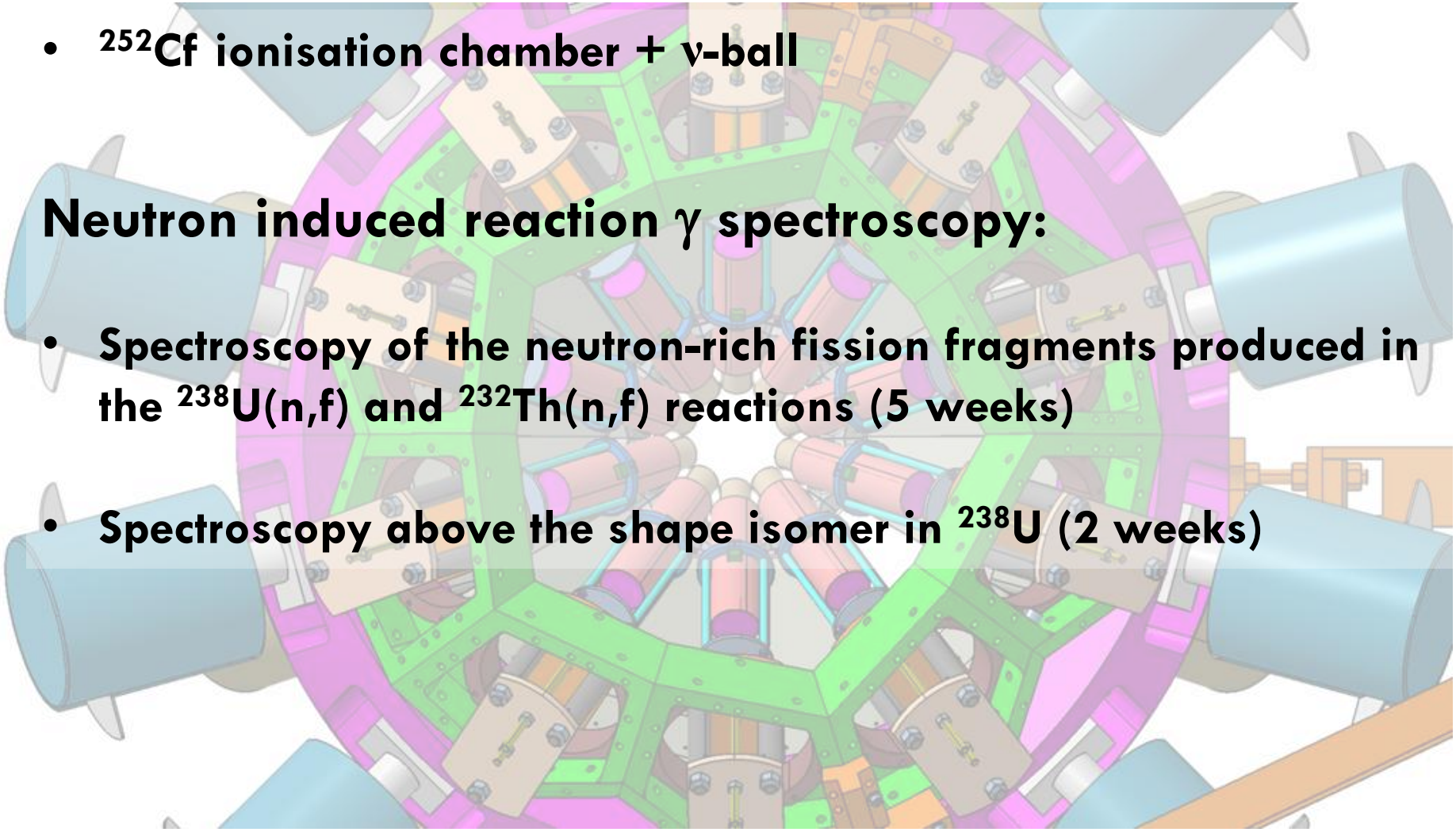

N-SI-109 dataset ~50 To
(ROOT format data)

N-SI-109 dataset ~10 To
(Event built data)

# Experimental Campaign: data processing



# Experimental Campaign



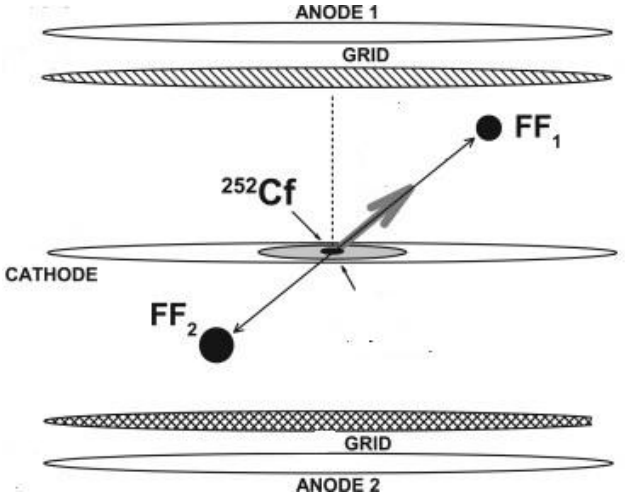
- $^{252}$Cf ionisation chamber + ν-ball

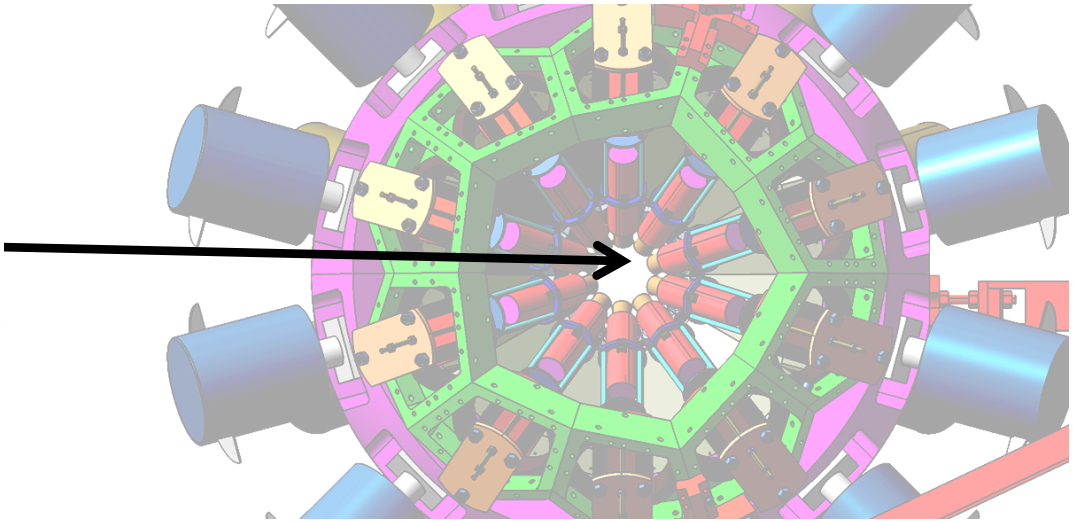
**Neutron induced reaction γ spectroscopy:**

- Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions (5 weeks)
- Spectroscopy above the shape isomer in $^{238}$U (2 weeks)

# $^{252}$Cf ionisation chamber + ν-ball

- $^{252}$Cf – spontaneous fission

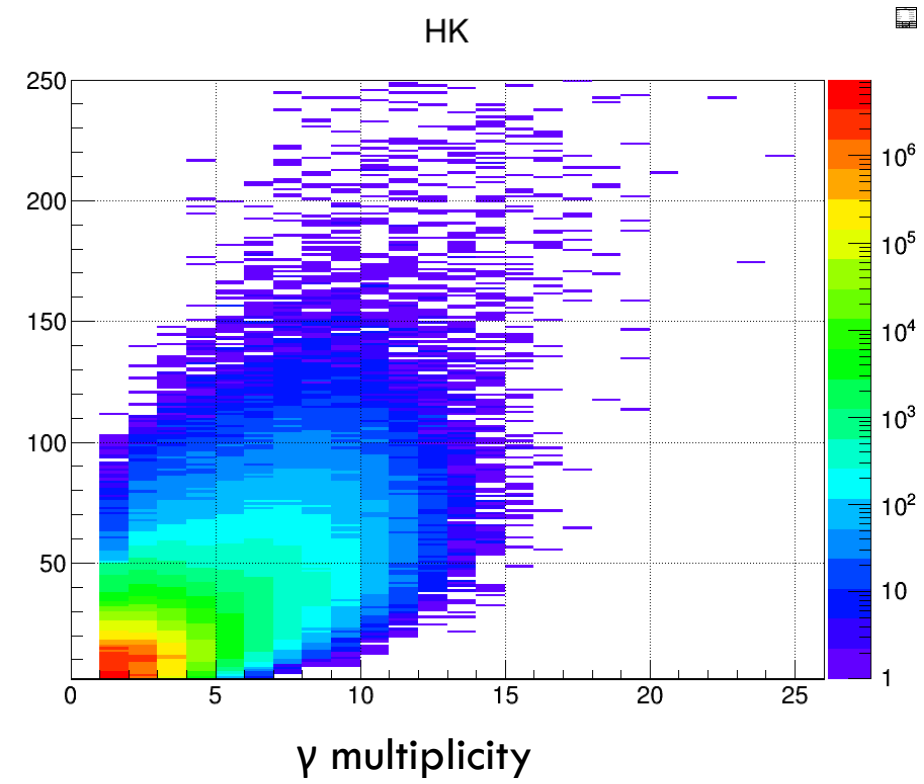


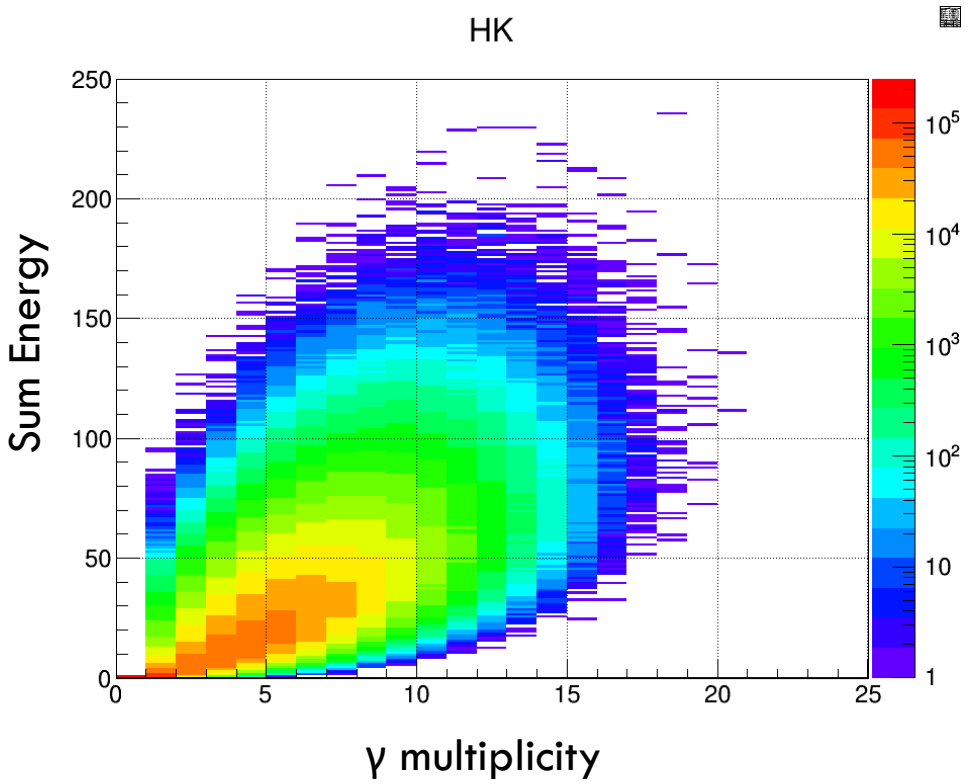
# $^{252}$Cf ionisation chamber + ν-ball

## ν-ball calorimetry

$^{152}$Eu beta decay events

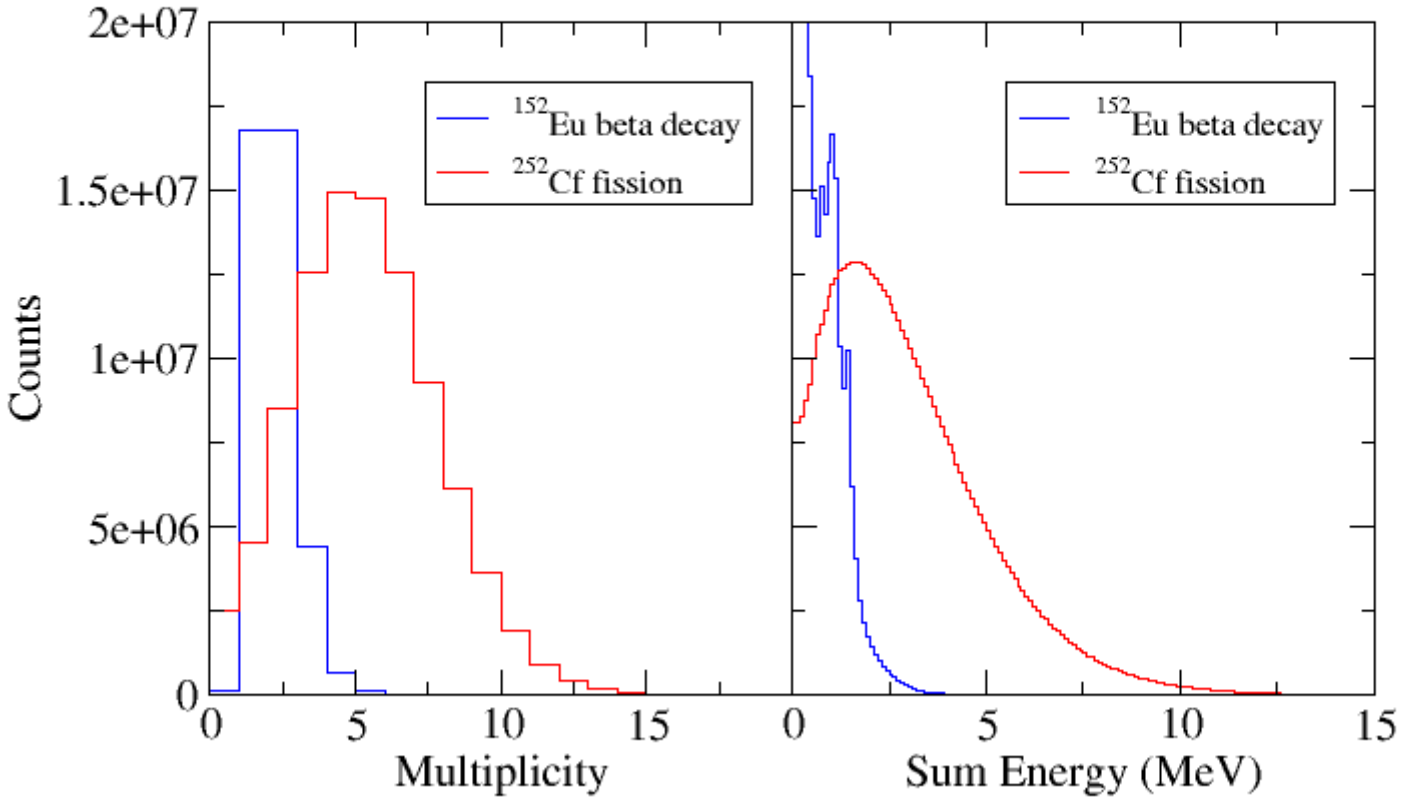



$^{252}$Cf fission events



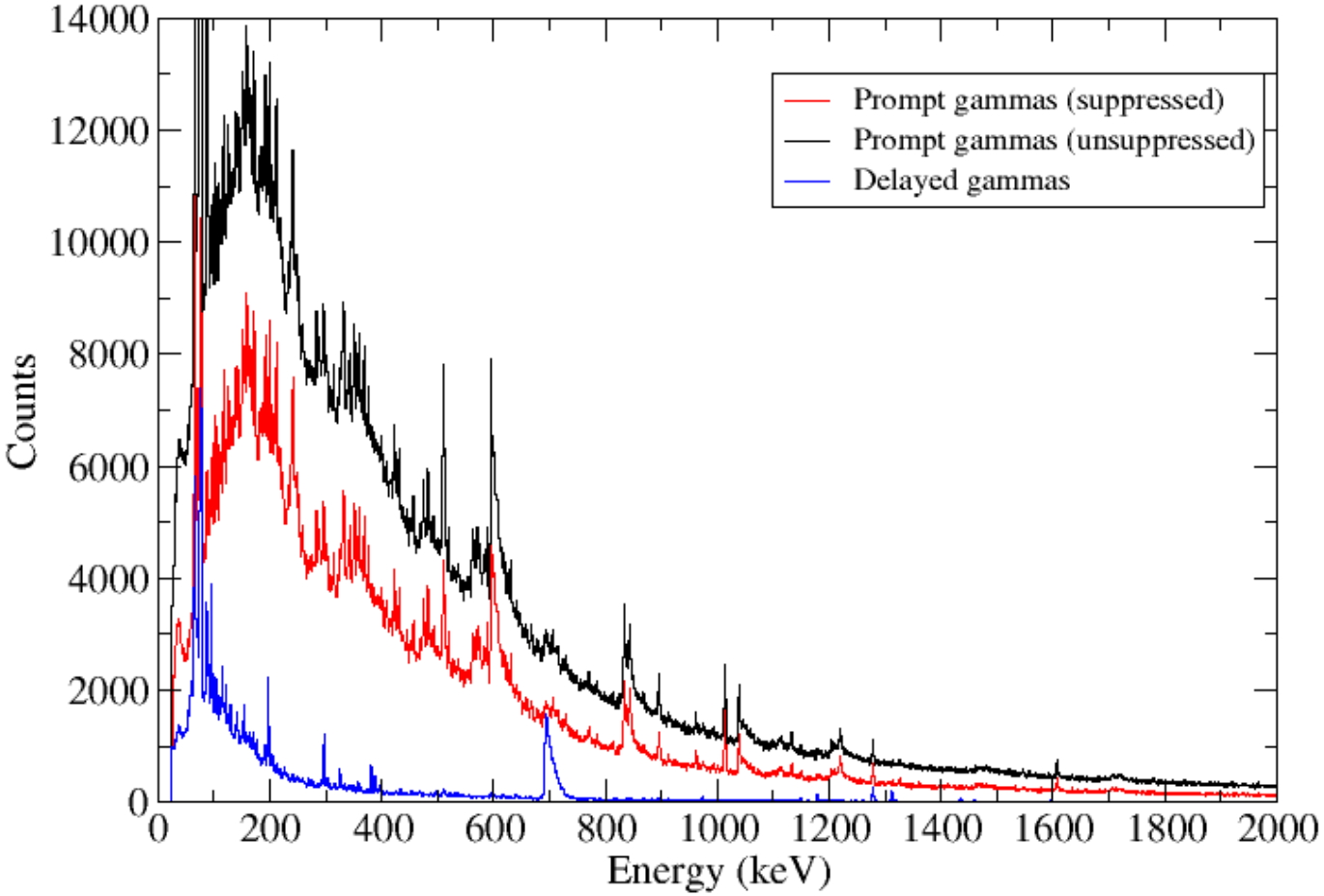
# $^{252}$Cf ionisation chamber + ν-ball

## ν-ball calorimetry



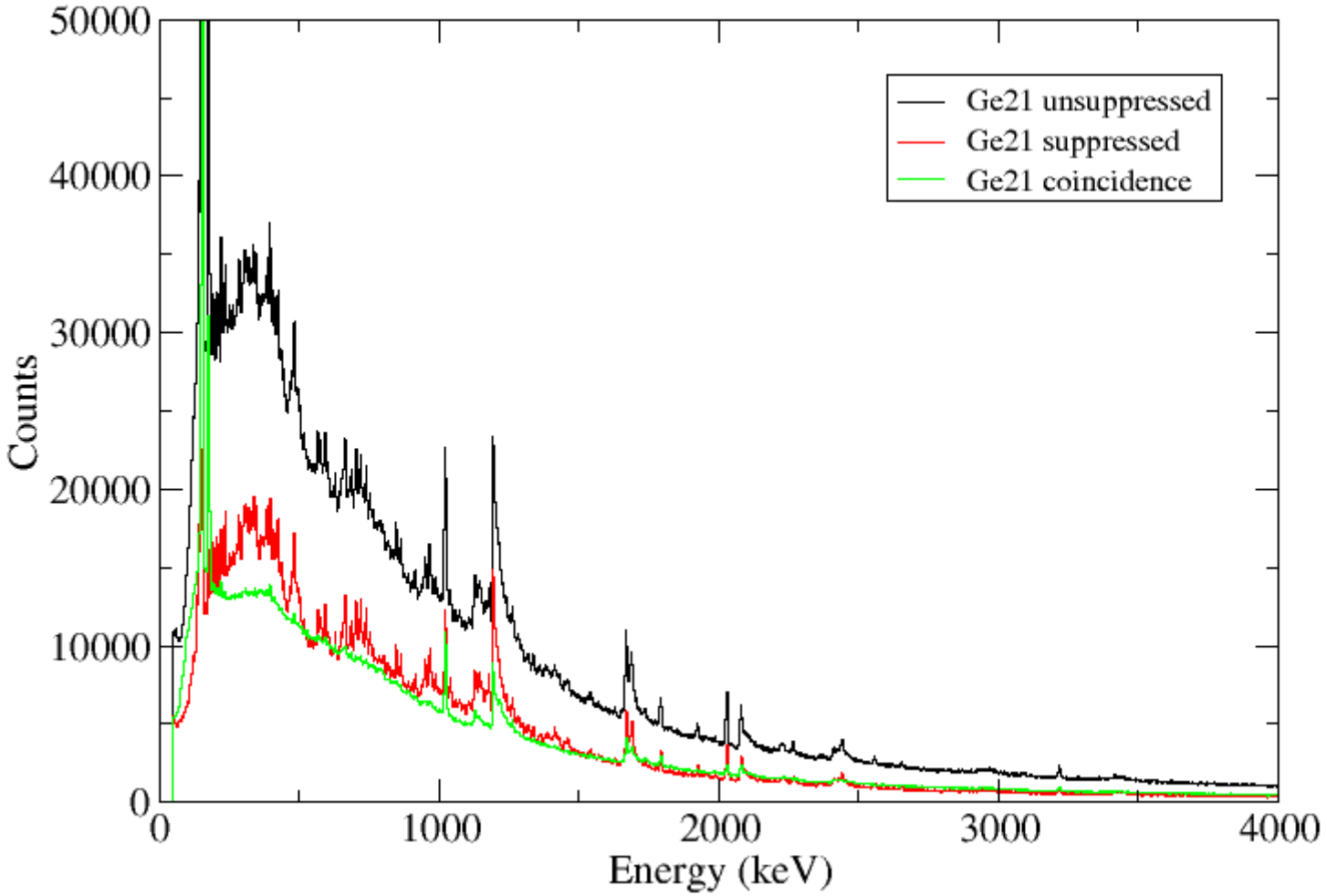
# $^{252}$Cf ionisation chamber + ν-ball

Timing separation



# $^{252}$Cf ionisation chamber + ν-ball

Compton suppression

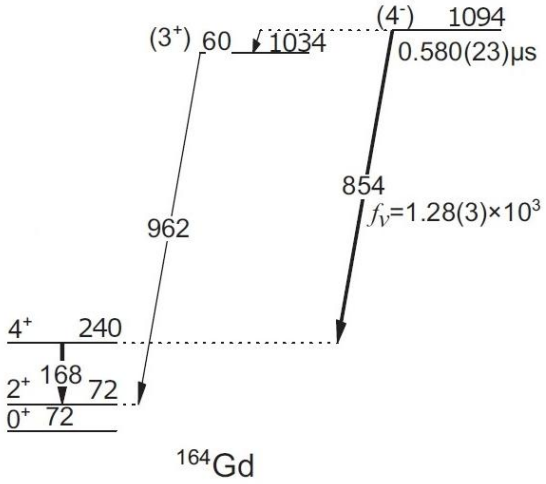


# $^{252}$Cf ionisation chamber + ν-ball

## First preliminary results:

### RIKEN

Isomer in $^{164}$Gd discovered at BIGRIPS focal plane in 2017



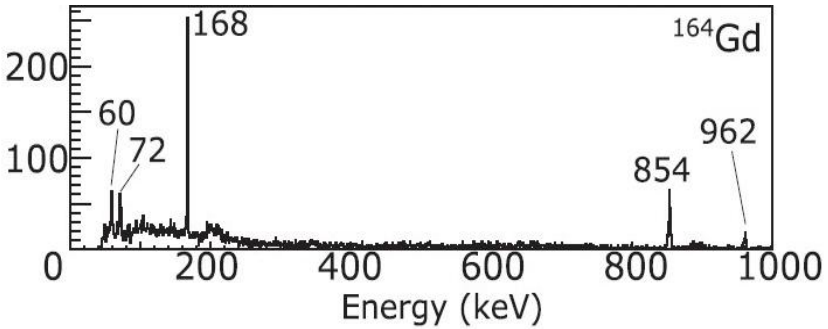

### ν-ball

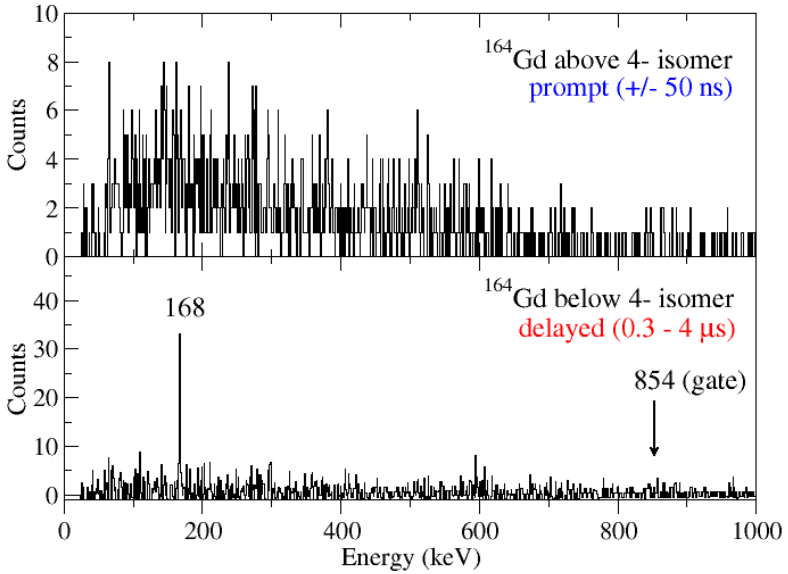
$^{164}$Gd isomer identified after only 48 hours of data

< 0.01% of the total yield

Decays from states *above* the isomer observed for the first time

Prompt decays impossible to observe



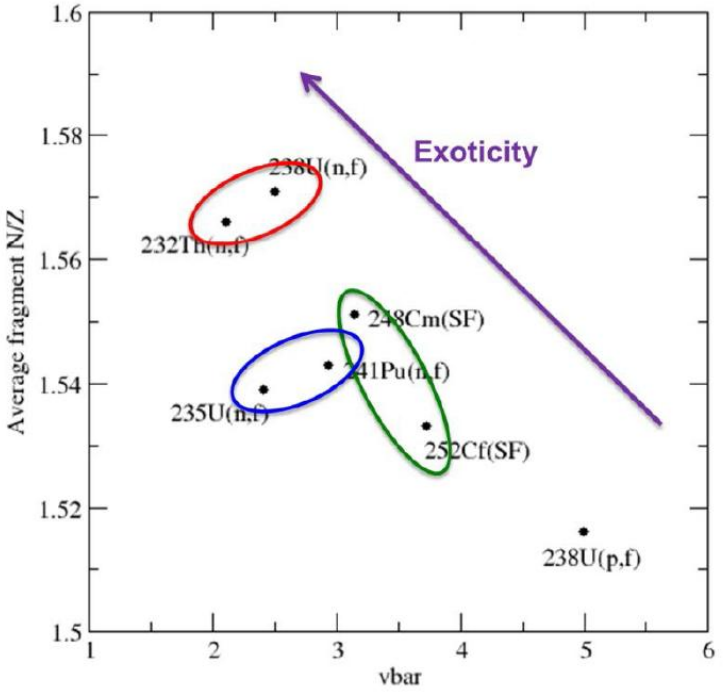
# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

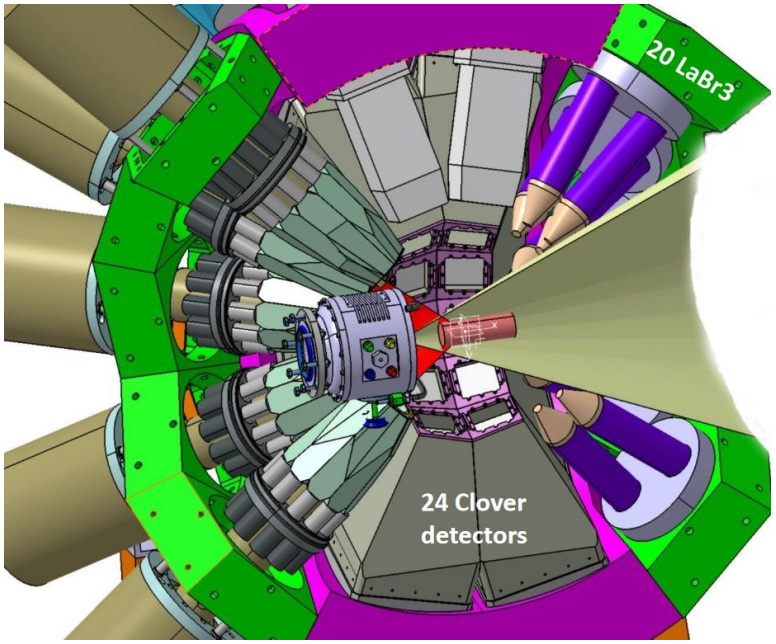
- $^{238}$U(n,f) and $^{232}$Th(n,f) reactions with fast neutrons
- Production and study hundreds of neutron-rich nuclei
- Synergy between $^{238}$U(n,f) and $^{232}$Th(n,f) data sets

Spontaneous Fission
$^{252}$Cf(SF), $^{248}$Cm(SF)
(Gammasphere, Euroball)

Fission induced by thermal neutrons
$^{235}$U($n_{th}$,f) $^{241}$Pu($n_{th}$,f)
(EXILL Exogam@ILL)

Fission induced by fast ~2 MeV neutrons
$^{238}$U(n,f), $^{232}$Th(n,f)
(LICORNE @ IPN Orsay)

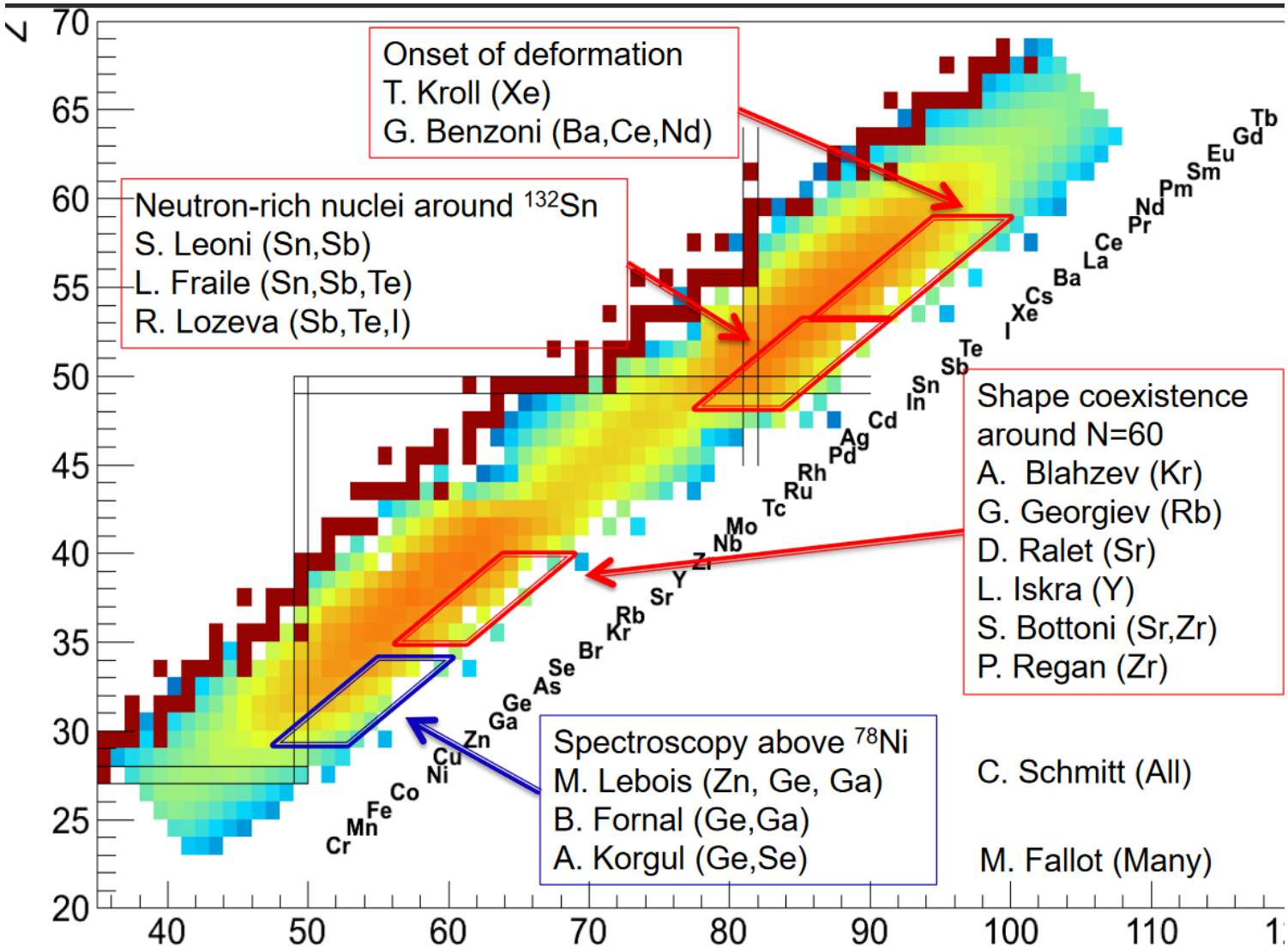


# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

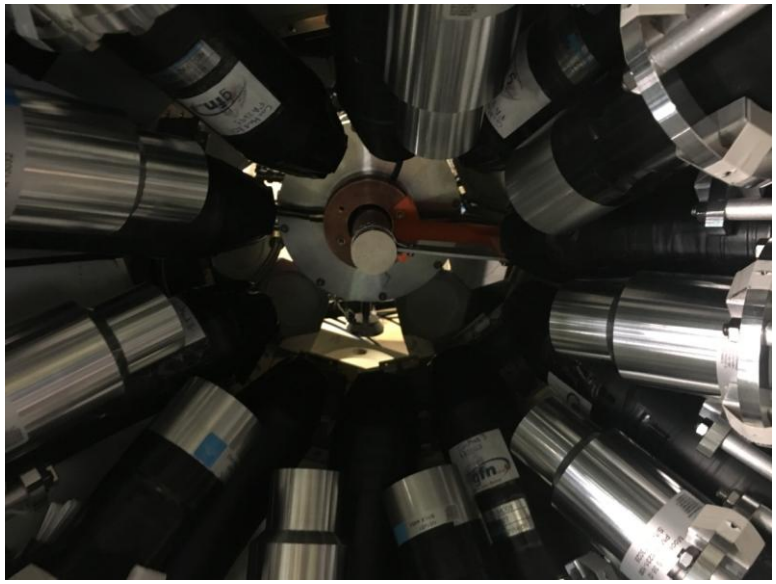
1) Lifetime measurements in the 132Sn region
2) Shape coexistence investigation beyond N=60 in the strontium isotopes
3) Study of fission fragment isotopic yields
4) Lifetime measurements around N=90
5) YRAST state sudies in the 78Ni region
6) Spectroscopy of high-spin multiplets in few-valence-particle nuclei around 132Sn
7) Gamma spectroscopy in the north-east region of double magic 78Ni – search for neutron radioactivity
8) Evolution of the deformation across the yttrium chain in the neutron-rich nuclei around A=100
9) Tracking shape evolution beyond N=60 in Sr and Zr isotopes
10) High-precision measurement of the quadrupole transition moments in 102Zr
11) Development of deformation in the Ce-Ba-Nd isotopic chains
12) Nuclear structure studies in preparation for TAS spectroscopy at ALTO
13) Shape coexistence around neutron-rich N=60: Spherical vs. well-deformed structures in the Rb isotopes
14) Study of shape-coexstence and single-particle states in neutron-rich Kr isotopes
15) Fast-timing investigation of single particle and collective states in Te isotopes and other neutron-rich nuclei around 132Sn
16) Gamma and fast-timing spectroscopy of odd Ge and Se isotopes

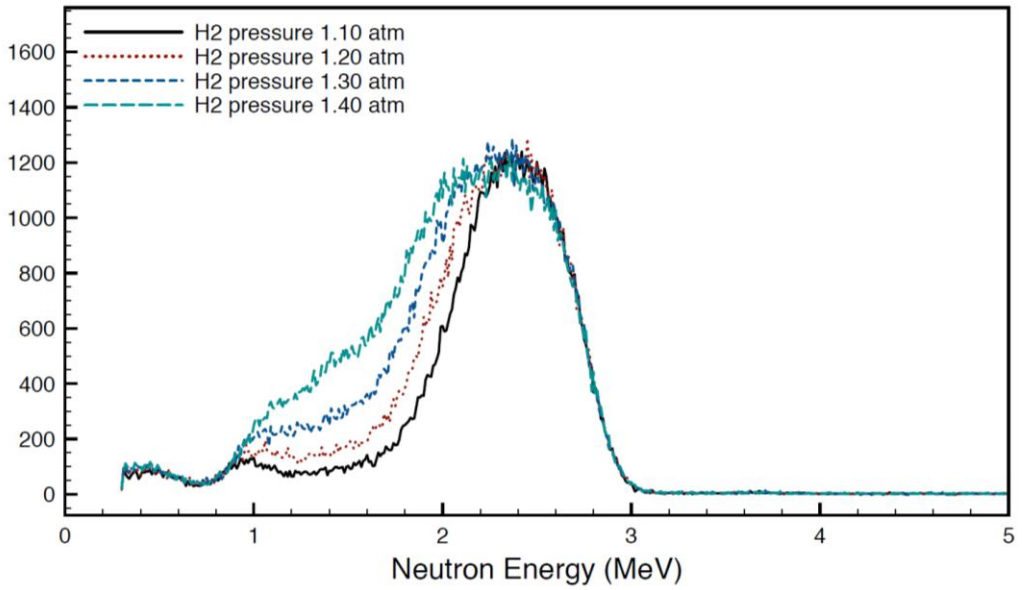
# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions



# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

$^{238}$U(n,f)



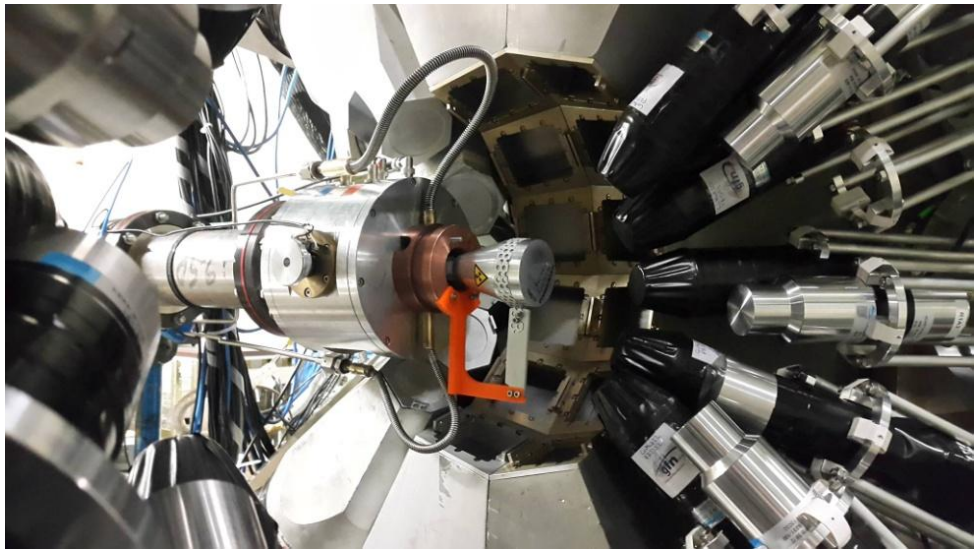


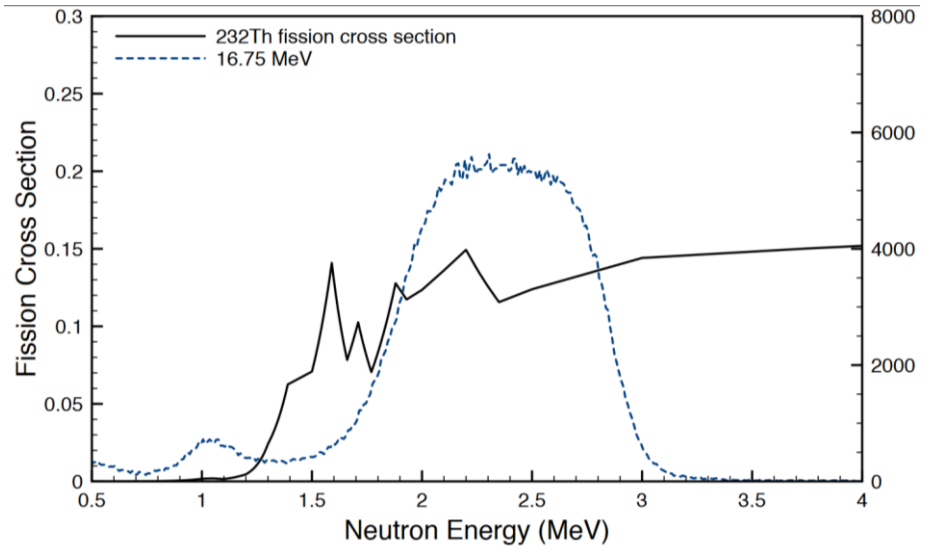

2 weeks

$E_{Li}$=16.4 MeV
m= 81 g

# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

## $^{232}$Th(n,f)





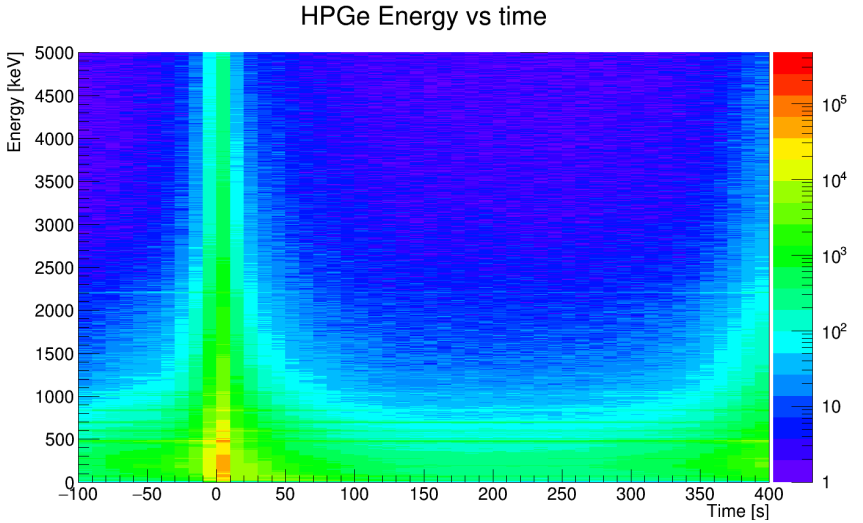

3 weeks

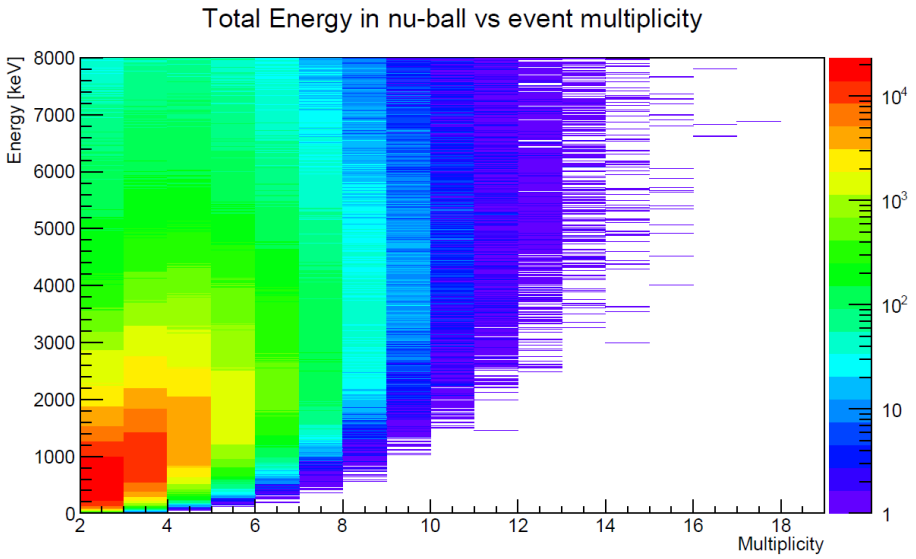
$E_{Li}$=16.75MeV

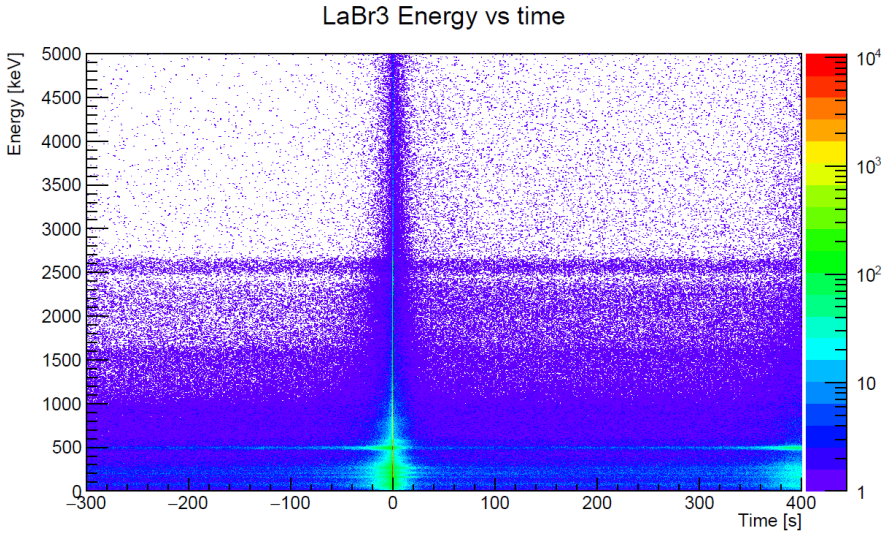
m= 129 g

# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

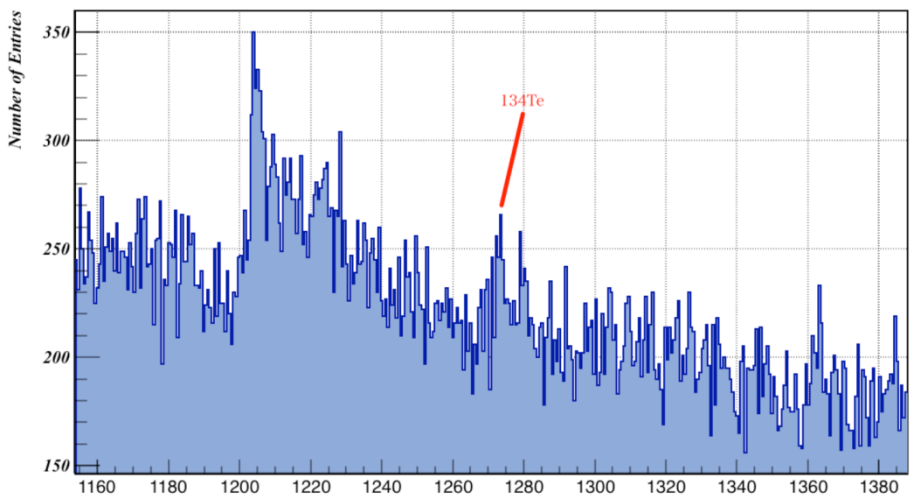
- Selectivity:
  - pulsed beam
  - calorimetry (fission tag)
  - fast timing
  - $\gamma\gamma$ and $\gamma\gamma\gamma$ coincidence



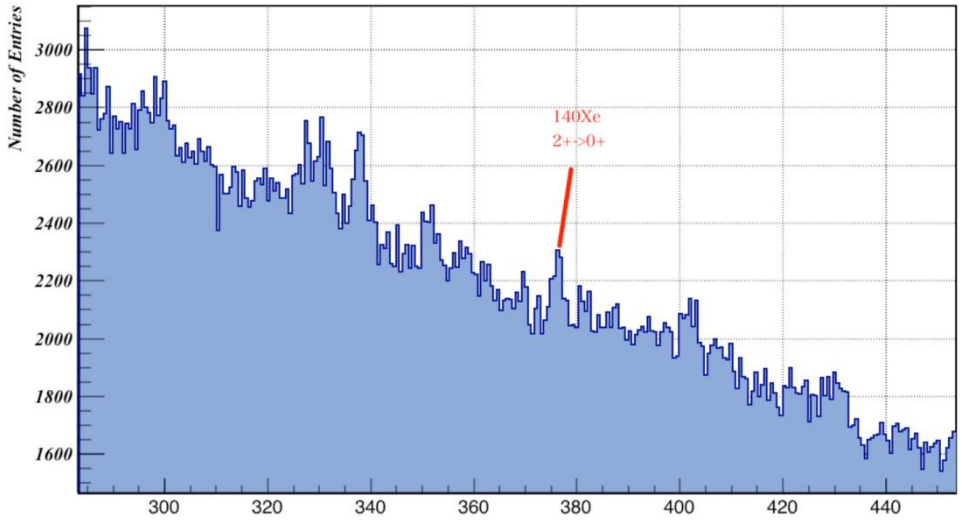



# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

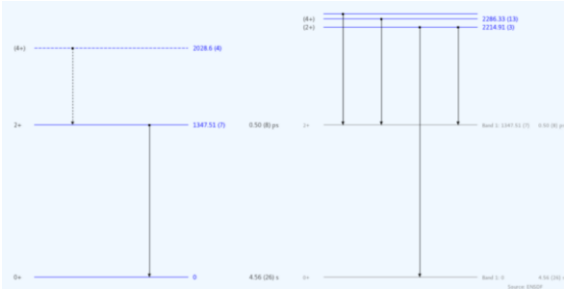


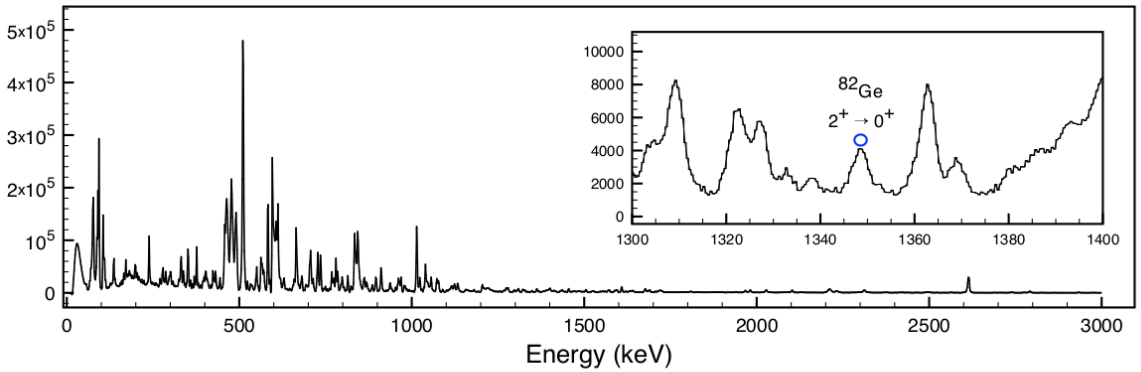

$^{232}$Th(n,f)

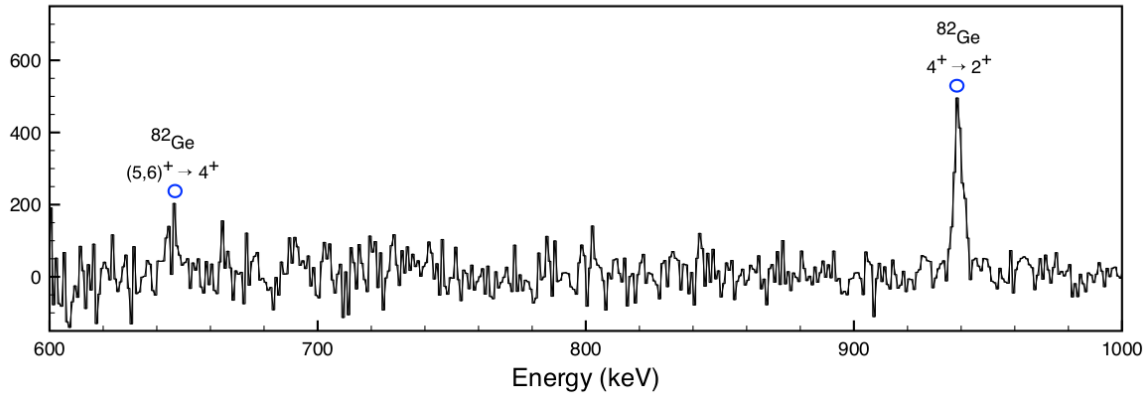


# Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions

Preliminary results (only half of Thorium data
- The lower part of **the level scheme of $^{82}$Ge** (Z=32, N=50) has been reconstructed by gating on the $2^+ \rightarrow 0^+$ transition





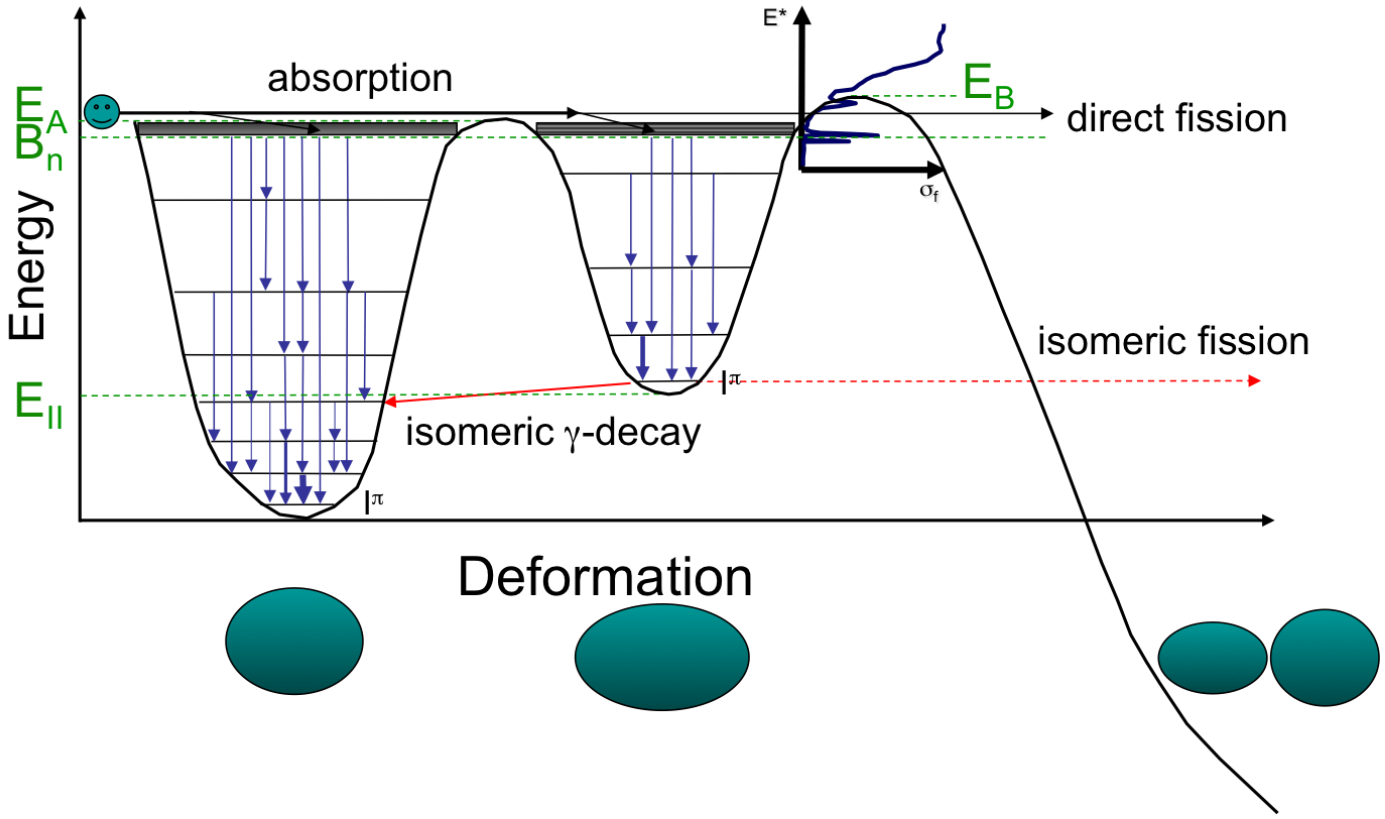
# Spectroscopy above the shape isomer in $^{238}U$

- Fission isomer characteristic
  - half-life
  - partial half-lives: isomeric fission, back-decay to 1$^{st}$ minimum
  - branching ration
- Fission barrier parameters
  - Barrier height
  - Transmission
  - Nuclear structure above super-deformed ground-state

Isomeric fission fragment characteristics

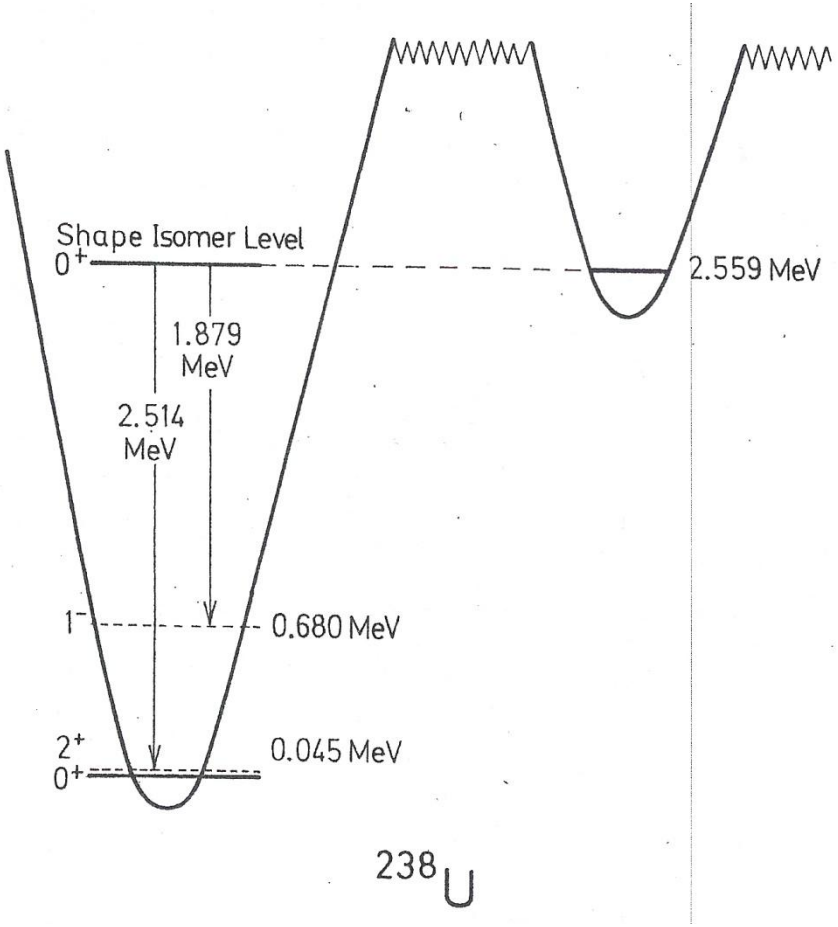
# Spectroscopy above the shape isomer in $^{238}U$

- **Spectroscopy above the shape isomer**



# Spectroscopy above the shape isomer in $^{238}U$

**Study of the $^{238}U$ shape isomer**



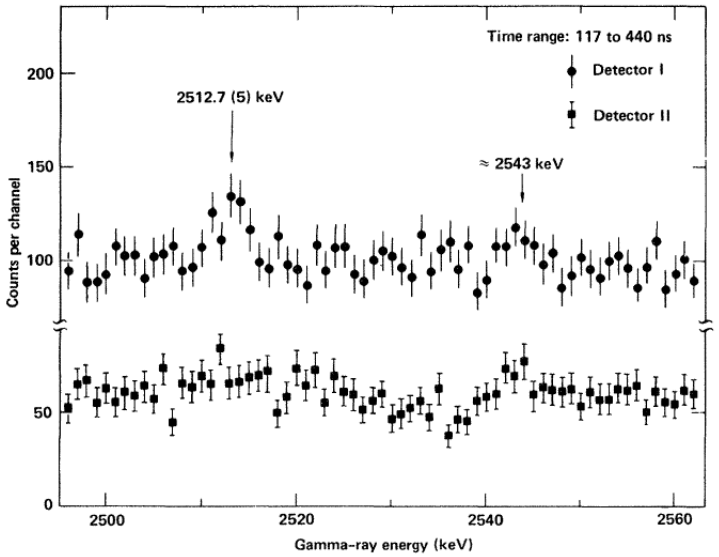
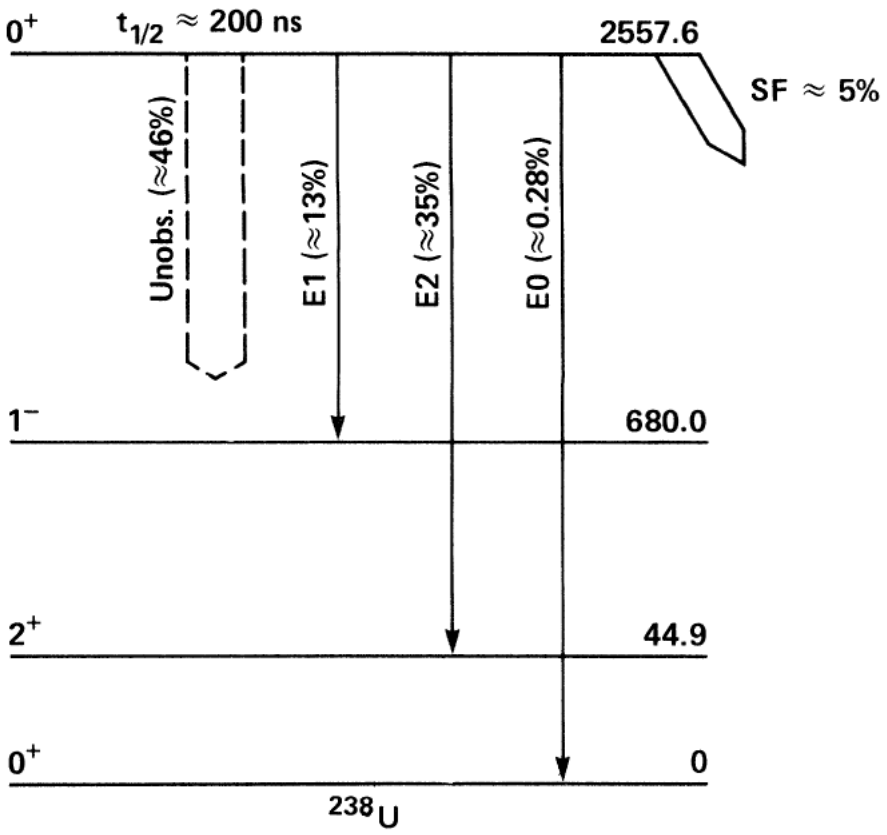




FIG. 2. Parts of $\gamma$-ray spectra recorded by the two detectors shown in Fig. 1 in the time range from 117 to 440 ns after a short burst of 18-MeV deuterons hitting a natural uranium target. The line at 2512.7 keV is present only in the upper spectrum and is, therefore, attributed to genuine target events (i.e., to the decay of the $^{238}U$ shape isomer). The 2543-keV line exhibited by both spectra is a typical (unidentified) room-background line.

J. Kantele, Physical Review C, 29 (5), 1984.

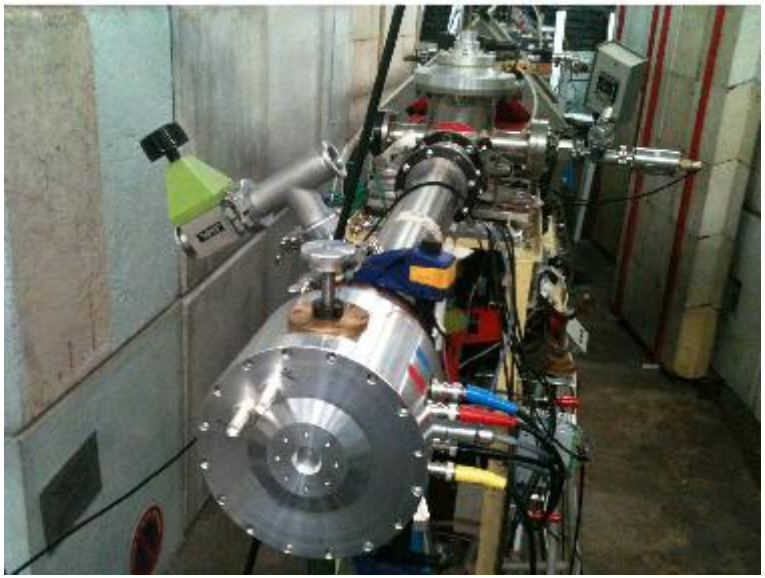
# Spectroscopy above the shape isomer in $^{238}U$

**Study of the $^{238}U$ shape isomer**



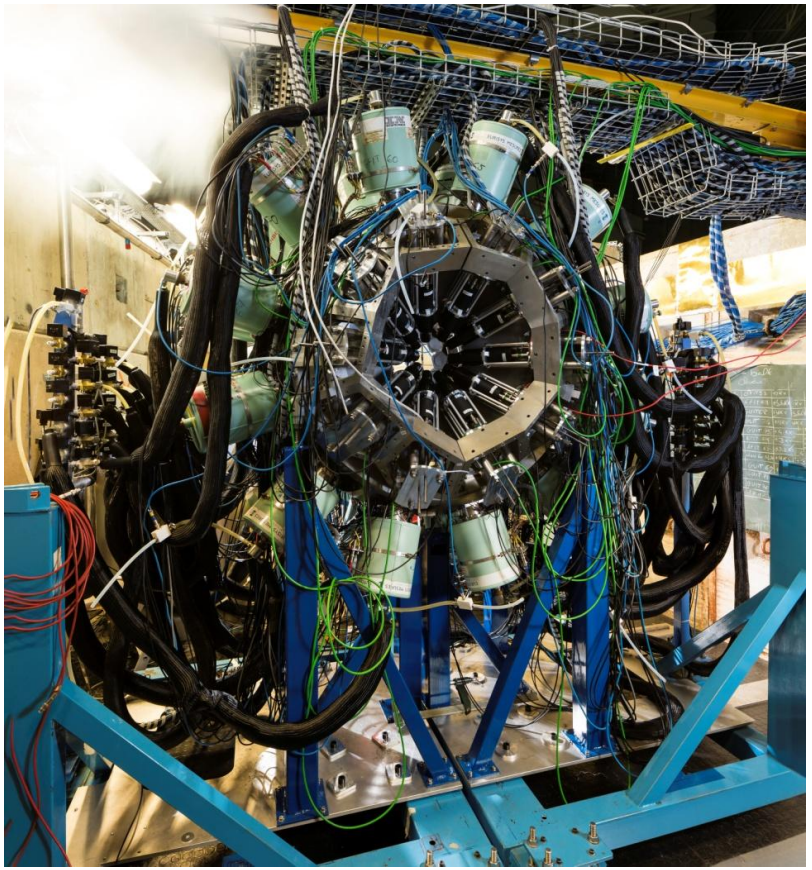
# Spectroscopy above the shape isomer in $^{238}U$

$^{238}U(n,n')$, LICORNE neutron source and nu-ball



**LICORNE**

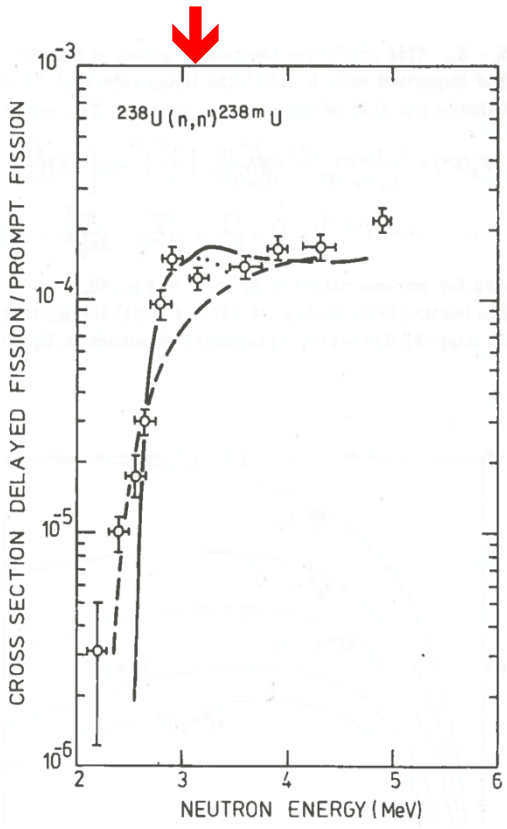
+



**ν-ball**

# Spectroscopy above the shape isomer in $^{238}$U

$^{238}$U(n,n'), LICORNE neutron source




- $E_n$ = (3.7 ± 0.3) MeV
- $\sigma_{IF} \approx 80$ μb
- IT/IF ≈ 95/5
- $\sigma_{IT} \approx 1.5$ mb

- Directional fast-neutron source
  - High and pulsed neutron flux on target
  - Allows using a detector array
  - High peak efficiency with ν-Ball
  - High energy resolution and fast timing

# Spectroscopy above the shape isomer in $^{238}U$

## Experimental setup and measurements

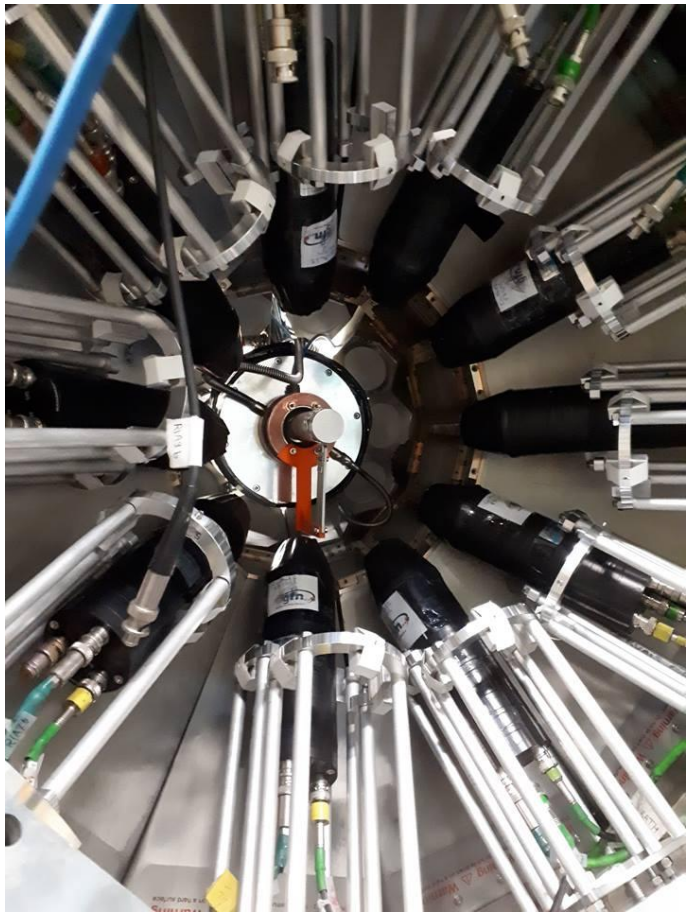
-May 2018

Experimental measurement
(6 days)

- Target mass 81g

140 hr of data

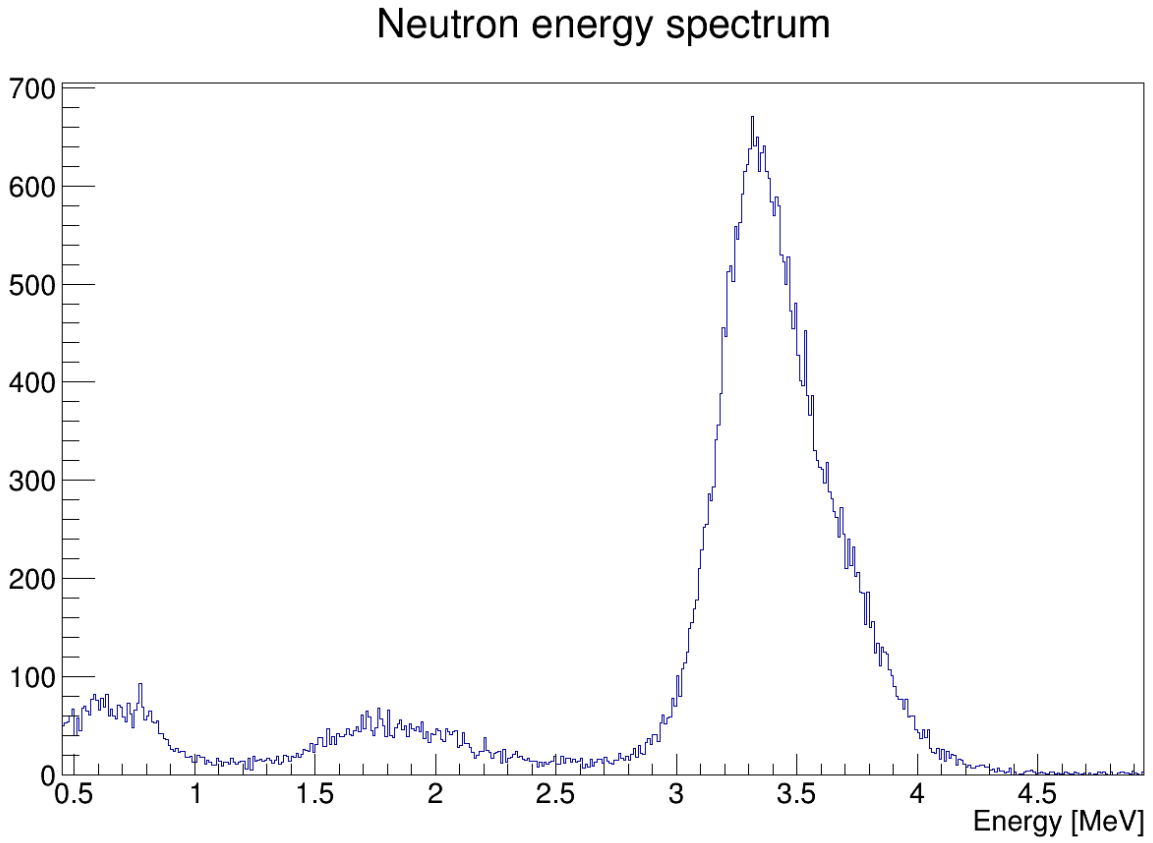
~25 Tb row FASTER data
~6 Tb ROOT format data



# Spectroscopy above the shape isomer in $^{238}U$

## Experimental setup and measurements

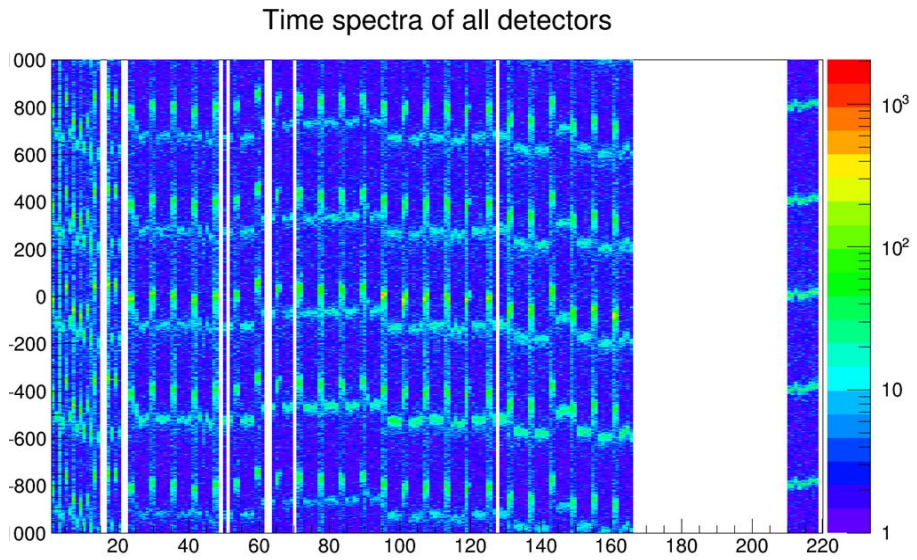
- **$^{7}Li$ beam with energy of 18.5 MeV**

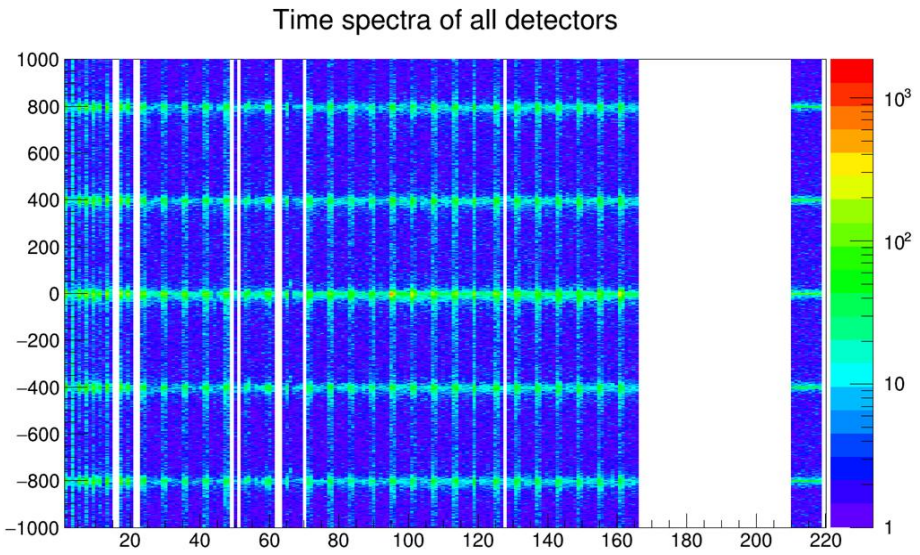


# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

Time alignment



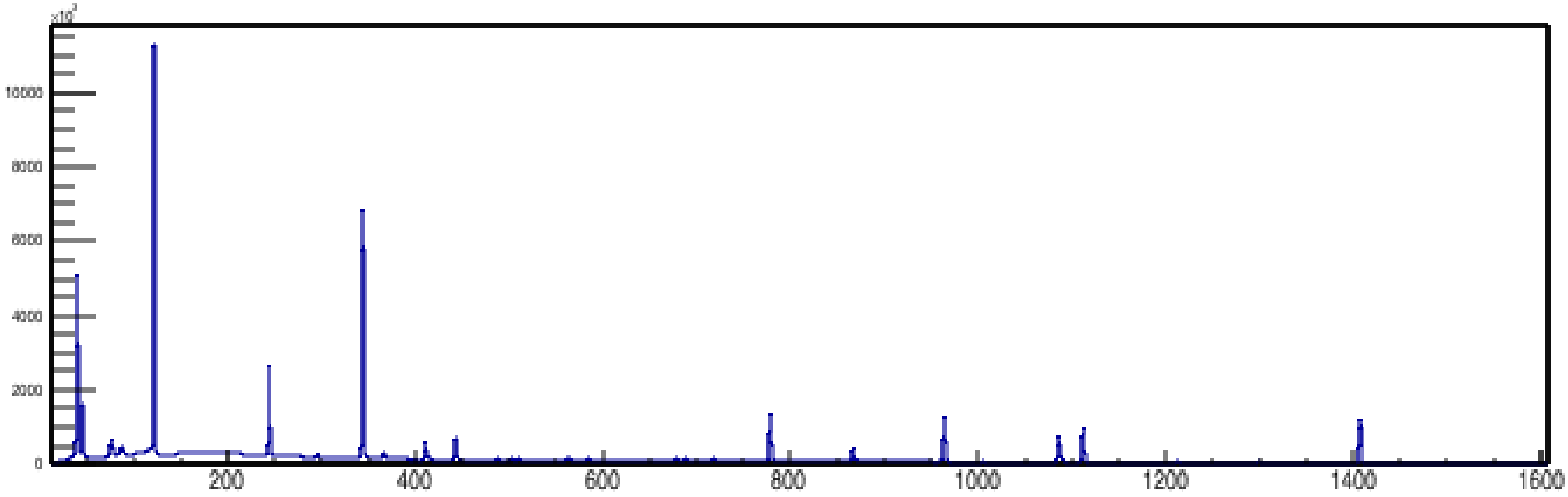
# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

Data analysis
- calibration

| | |
|---|---|
| HPGe | $^{152}Eu$ |
| $LaBr_3$ | $^{60}Co$ |
| | $^{232}Th$ |

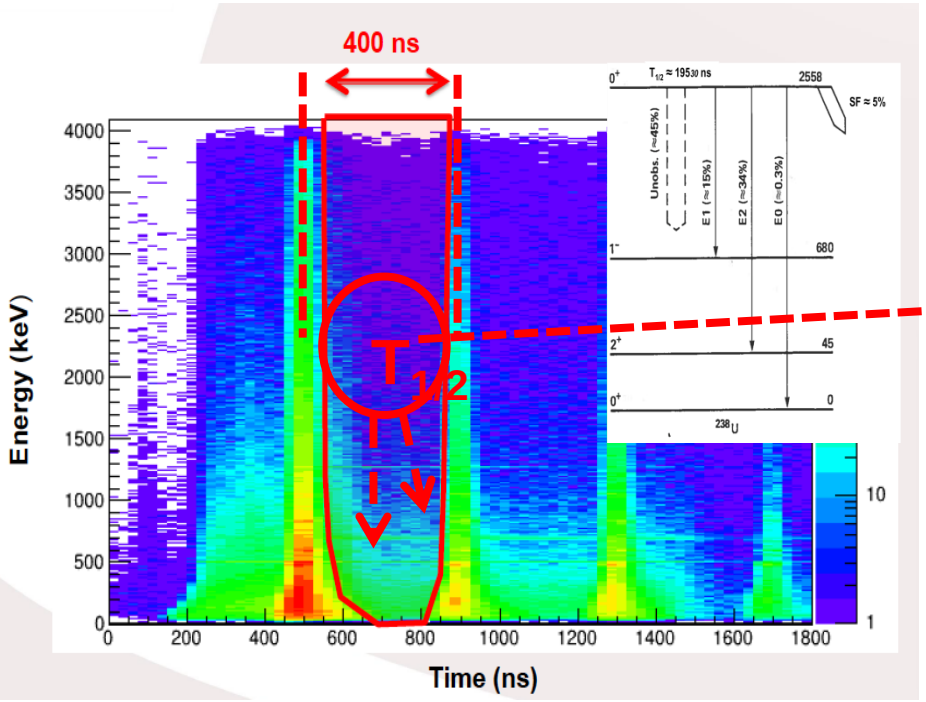
| | |
|---|---|
| BGO | $^{137}Cs$ |
| | $^{22}Na$ |
| | $^{232}Th$ |

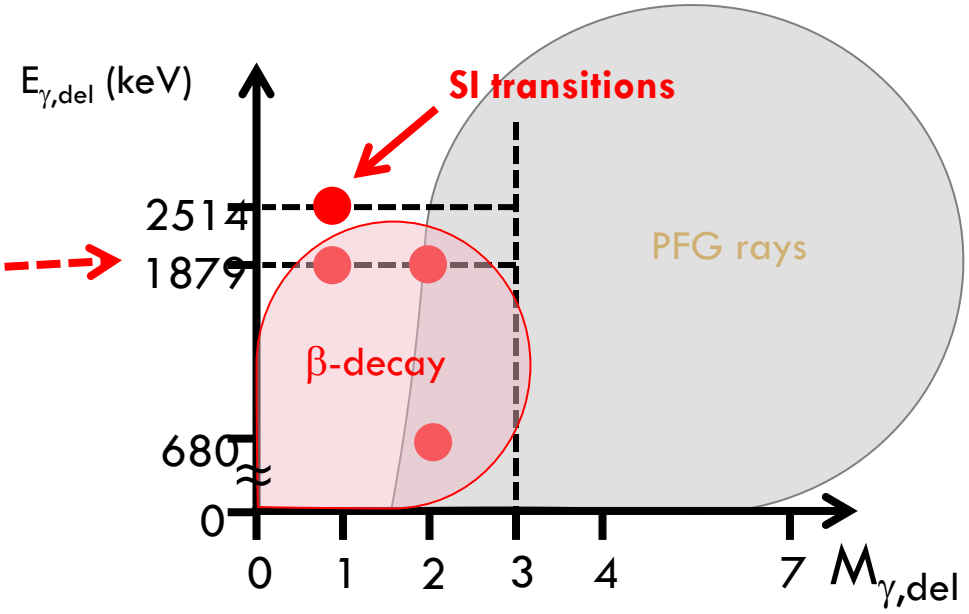


# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

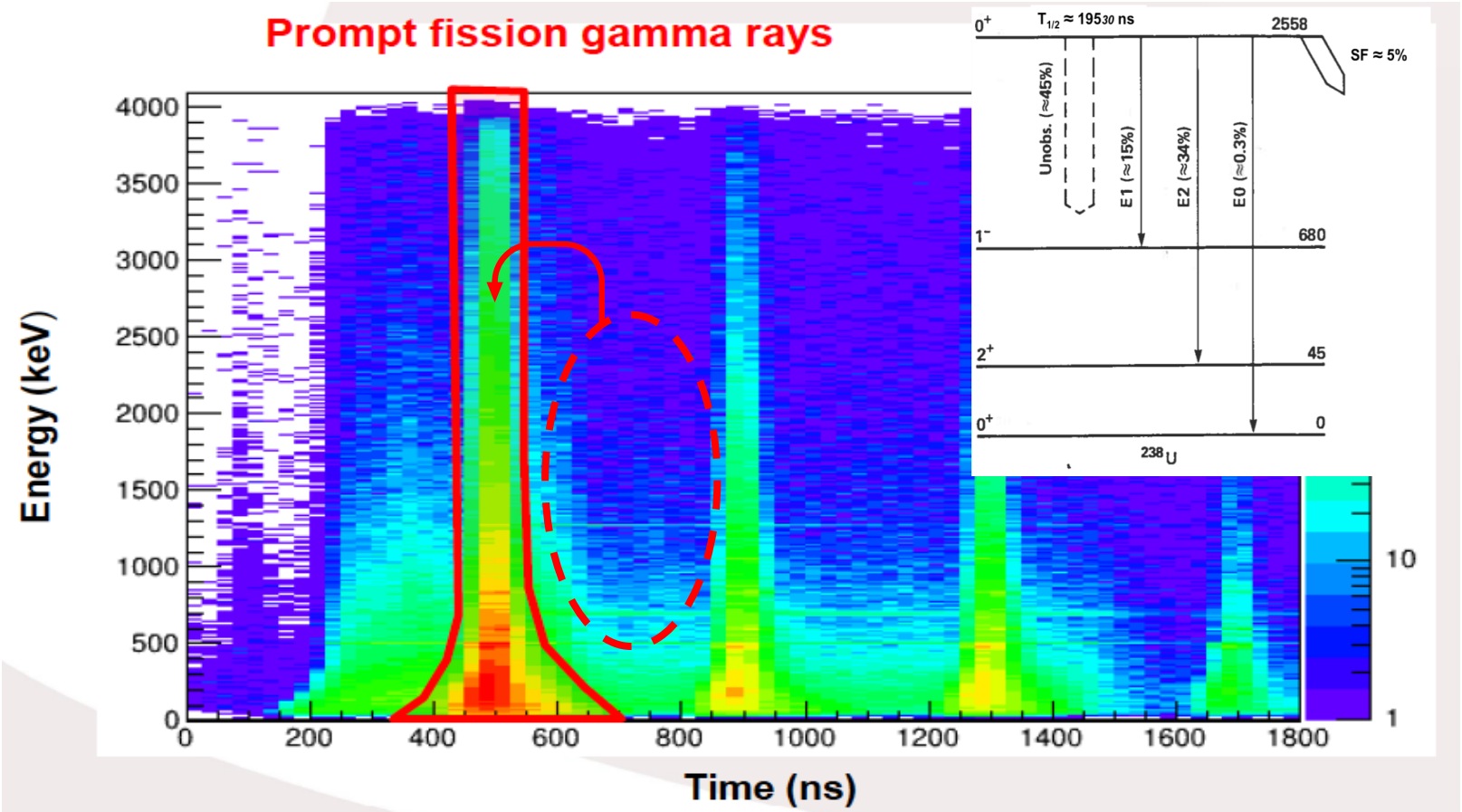
### Data analysis scheme



# Spectroscopy above the shape isomer in $^{238}U$

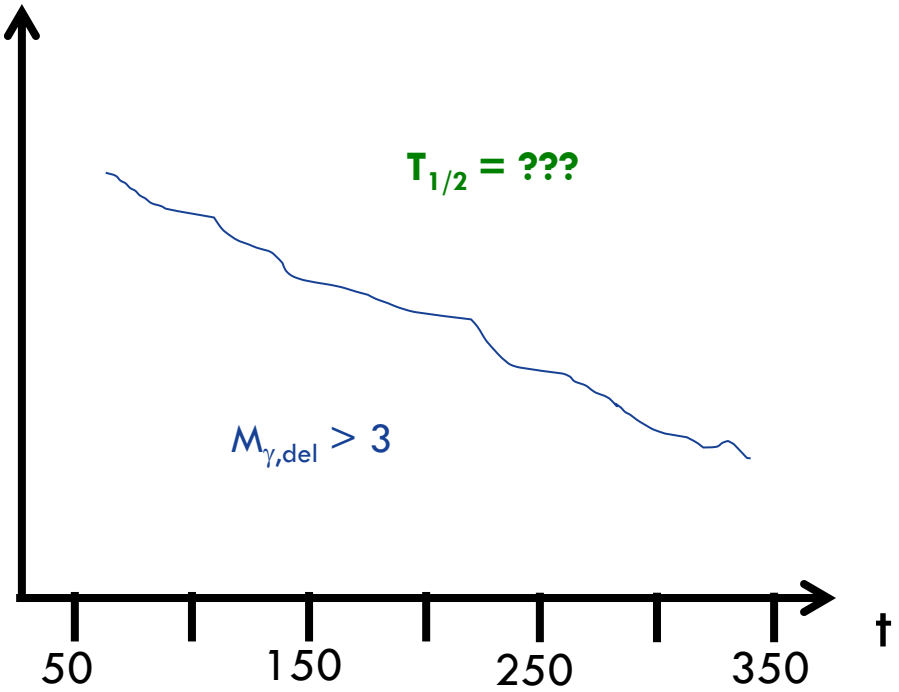
## Preliminary Analysis



# Spectroscopy above the shape isomer in $^{238}U$

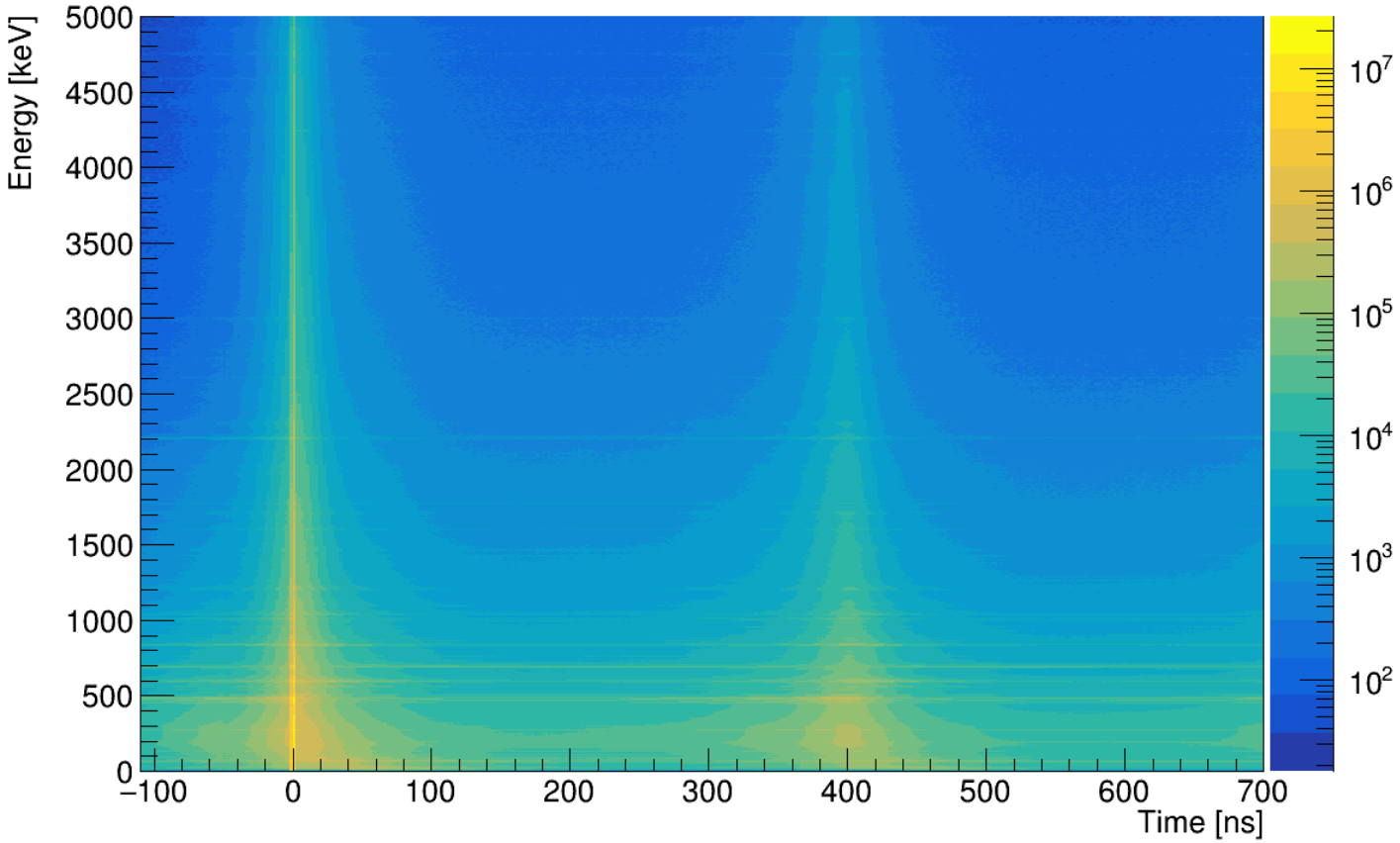
## Preliminary Analysis

- From the $E_{g,del}(M_{g,del})$ we project $E_{g,del}$ for $M_{g,del} > 5$
- Check time distribution -> is it compatible with $T_{1/2}$



# Spectroscopy above the shape isomer in $^{238}U$

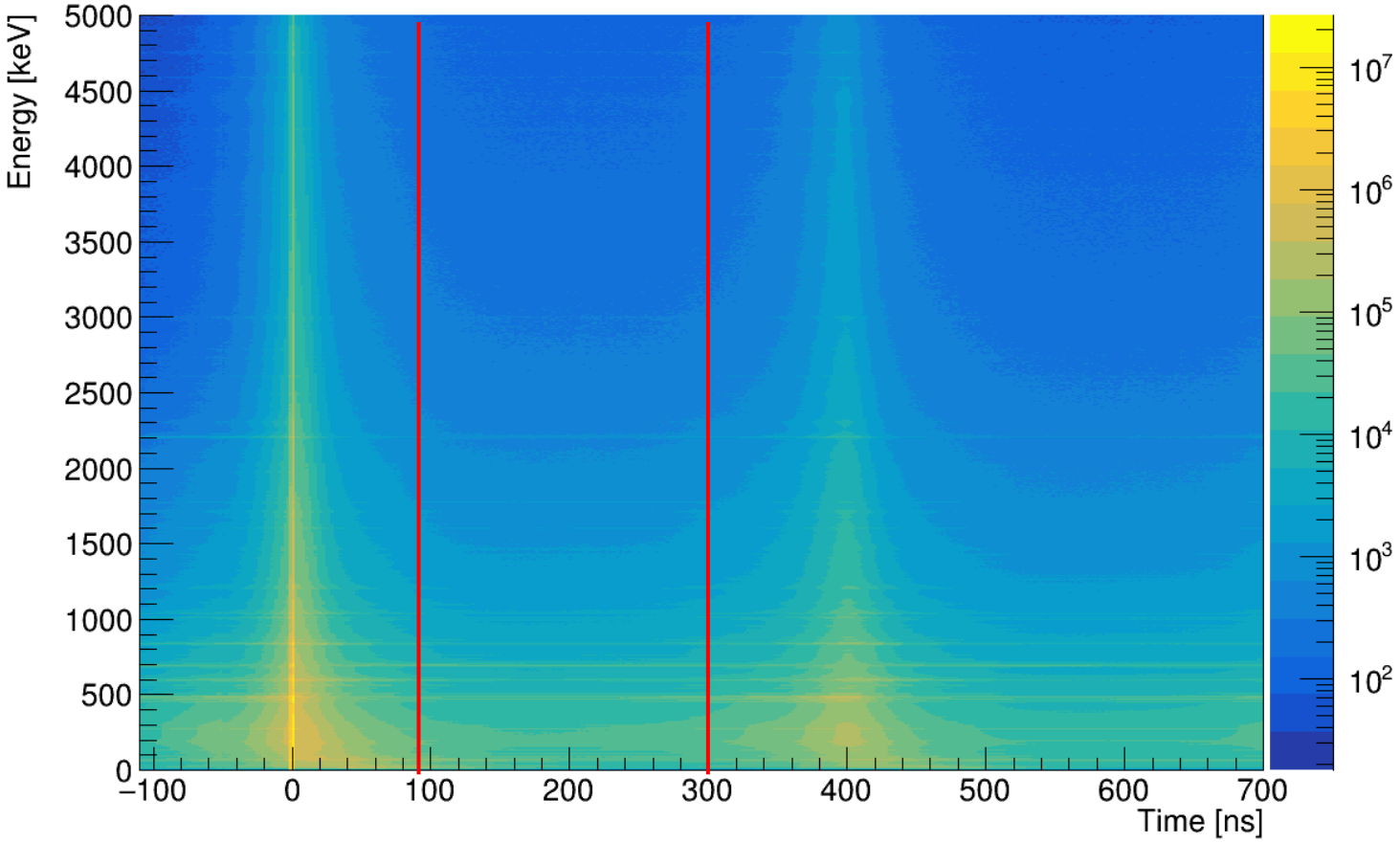
## Preliminary Analysis




Ge detectors – time vs Energy spectrum

# Spectroscopy above the shape isomer in $^{238}U$

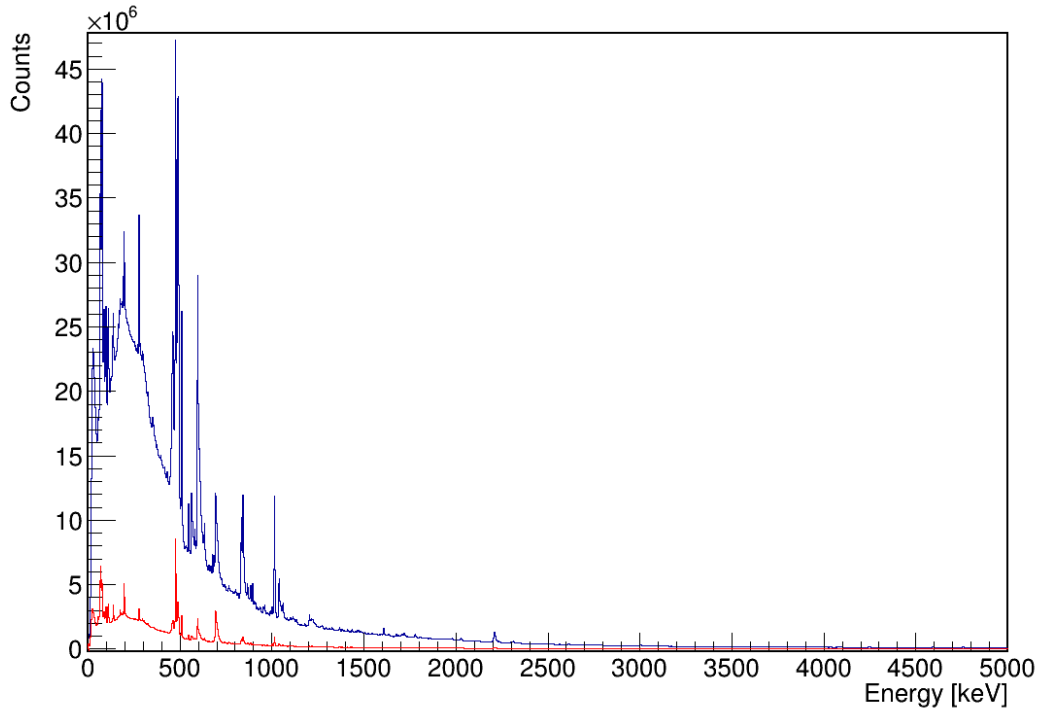
## Preliminary Analysis




Ge detectors – time vs Energy spectrum

# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

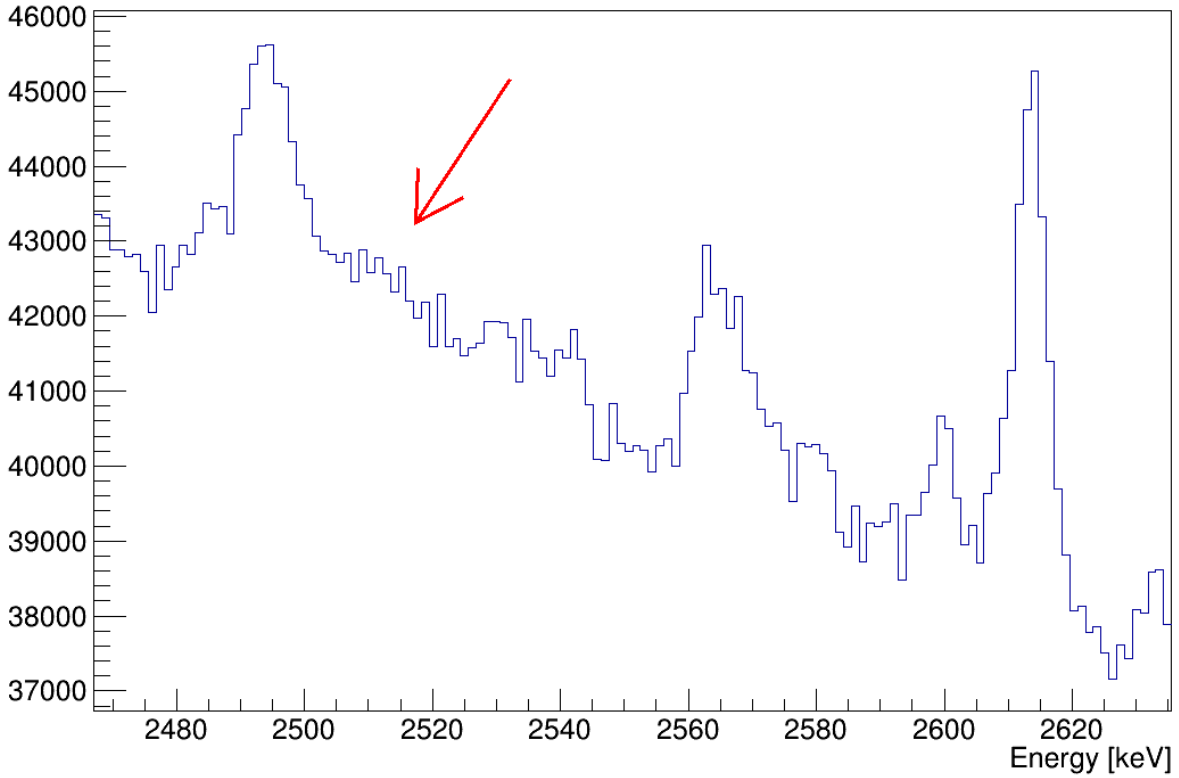



Prompt spectrum

Delay spectrum

# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

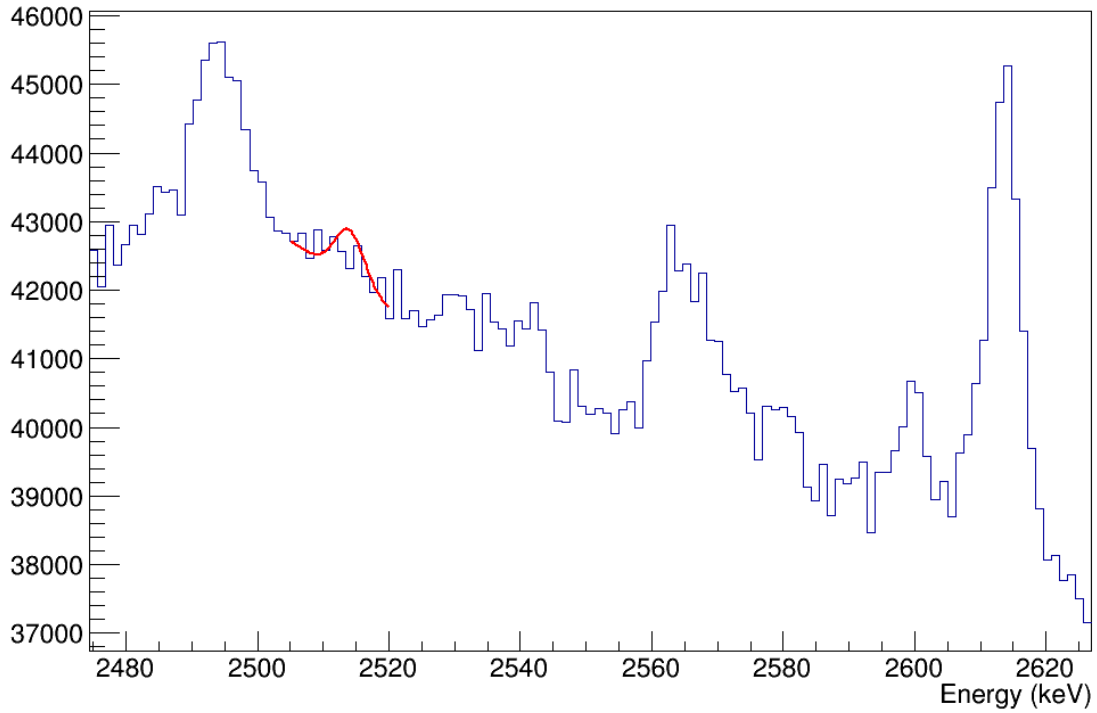



9.5 hr

Ge Delay spectra (100 ns – 300 ns)

# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

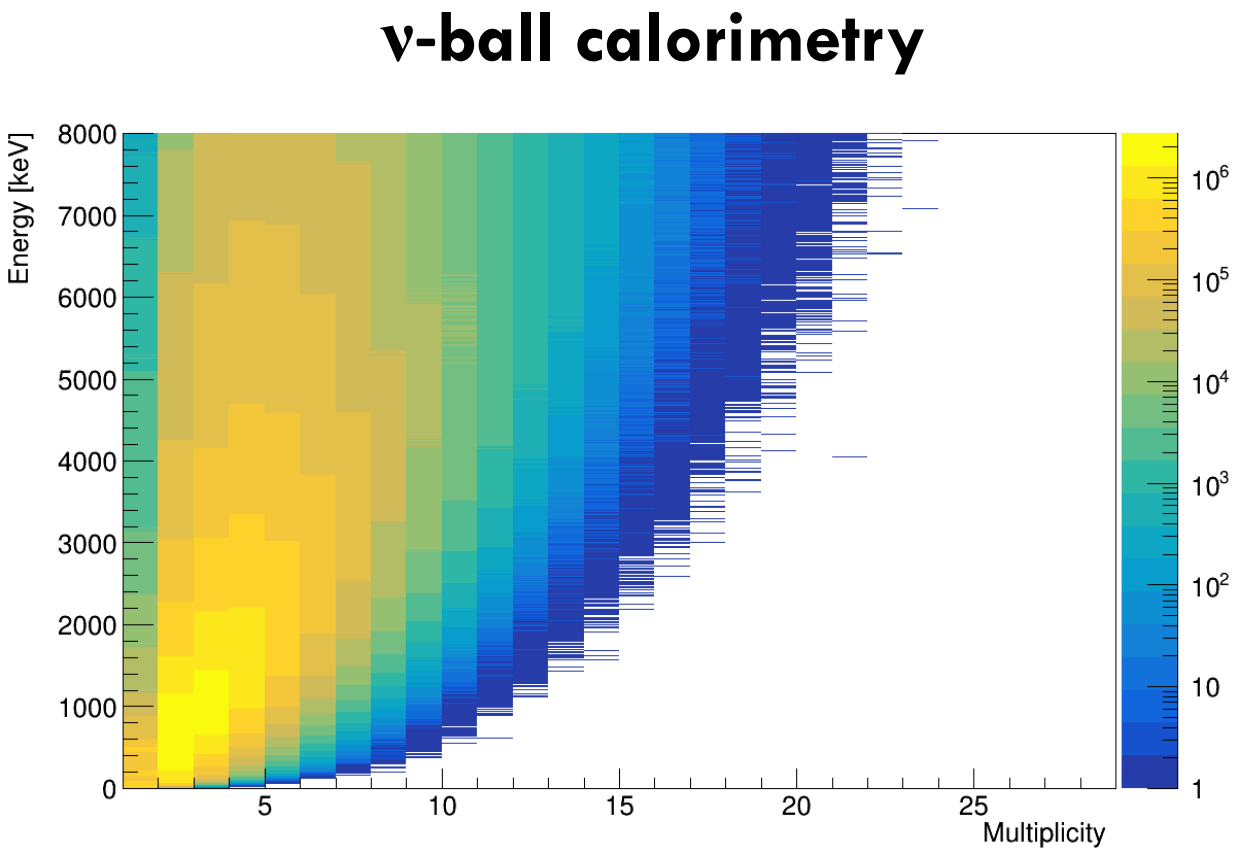



9.5 hr

2514 keV , Expected number of detected event N=6500

# Spectroscopy above the shape isomer in $^{238}U$

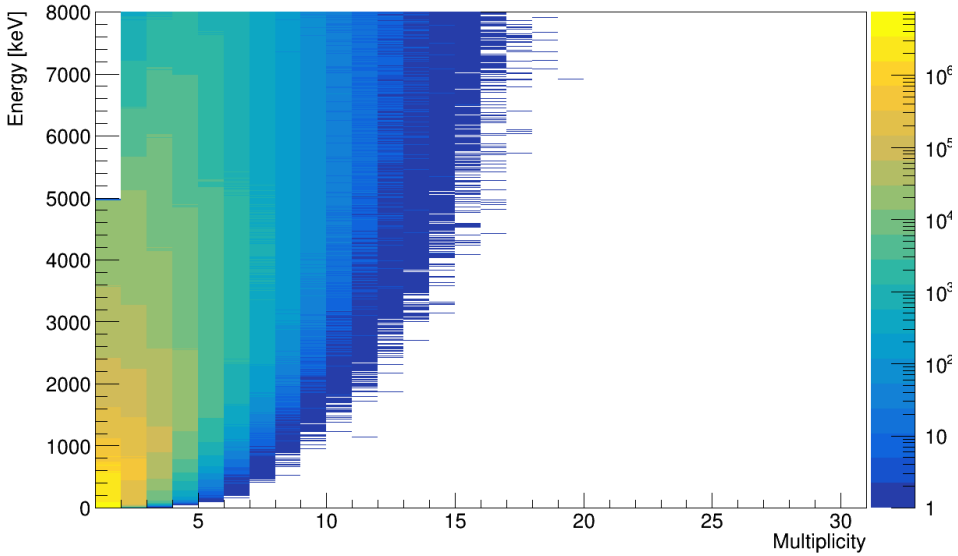
## Preliminary Analysis



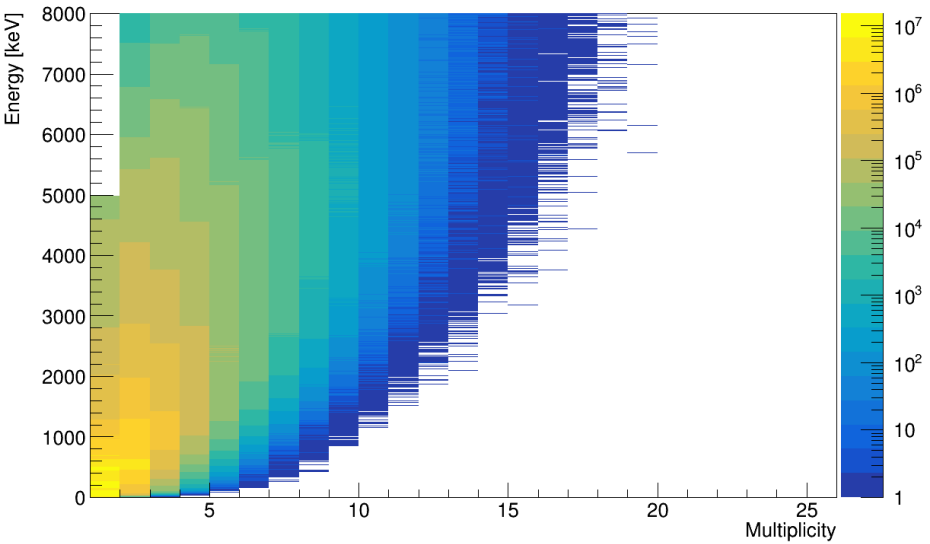
# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

### ν-ball calorimetry




Delay Events

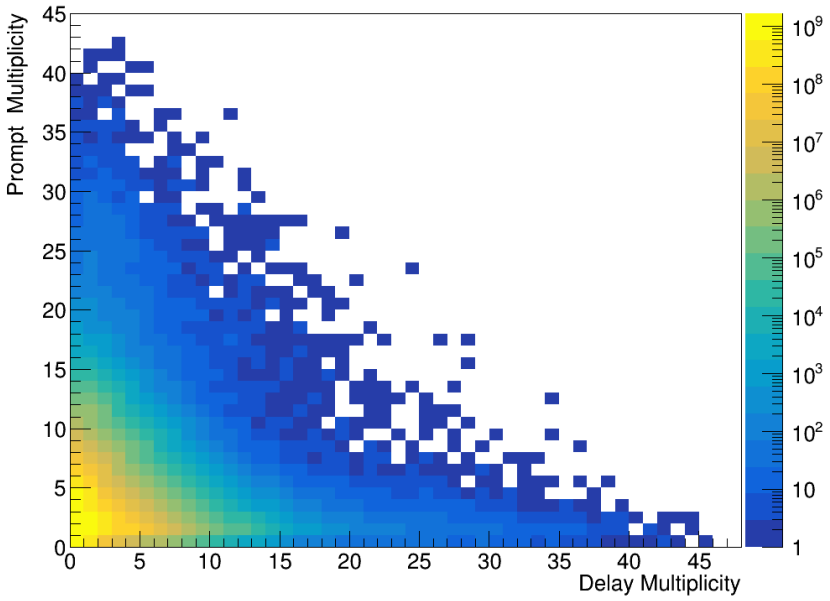


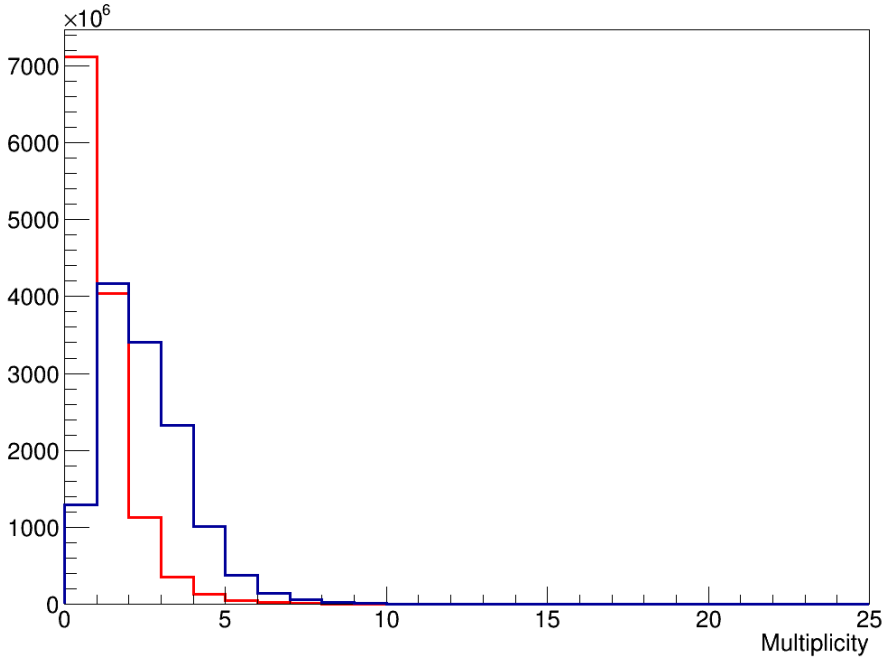

Prompt Prompt

# Spectroscopy above the shape isomer in $^{238}$U

## Preliminary Analysis

### ν-ball calorimetry




Prompt multiplicity

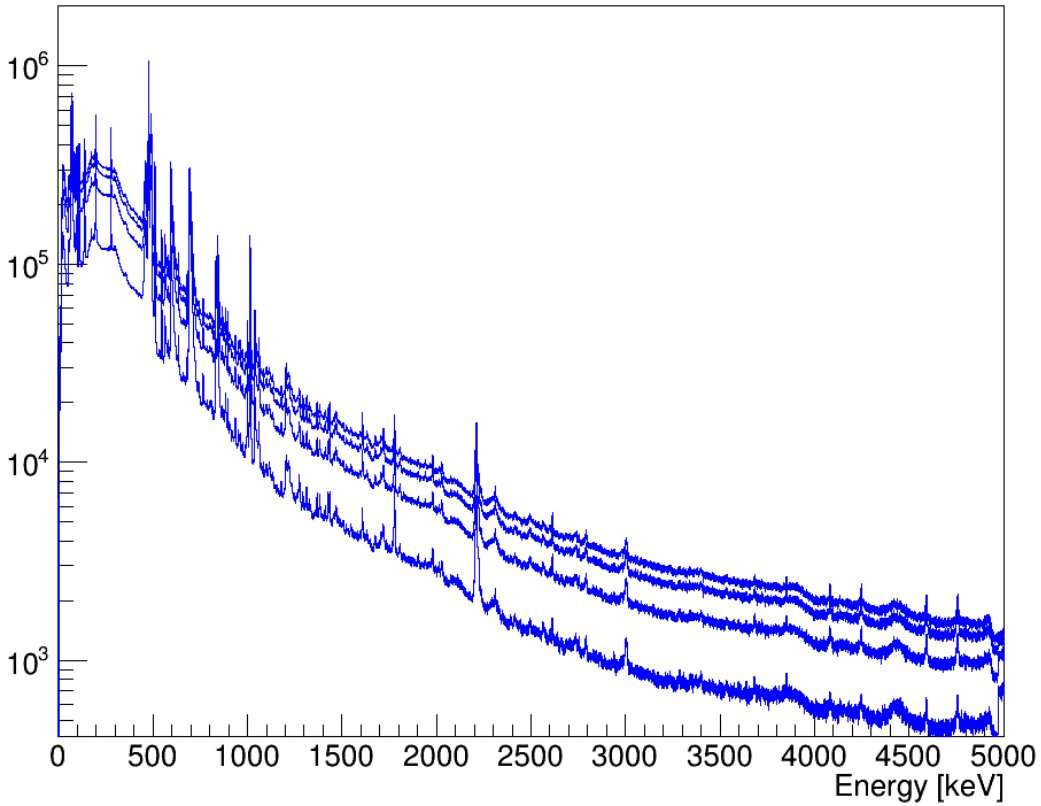
Delay multiplicity

# Spectroscopy above the shape isomer in $^{238}U$

## Preliminary Analysis

Prompt multiplicity 1

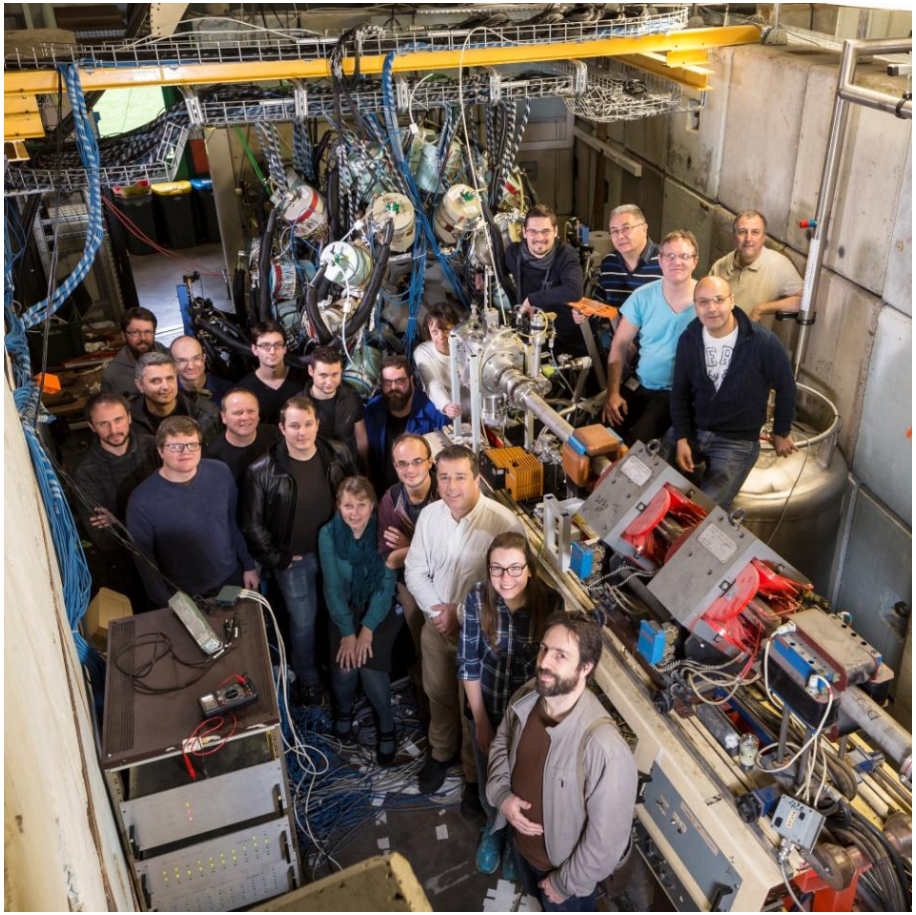
Delay multiplicity
- 1
- 2
- 3
- 4



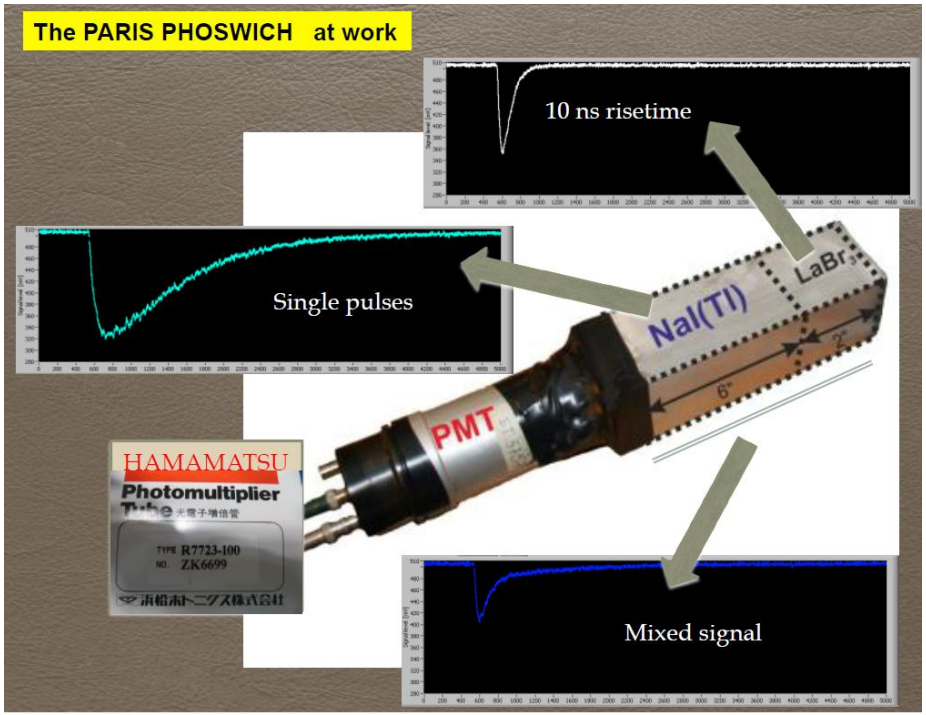
# Summary

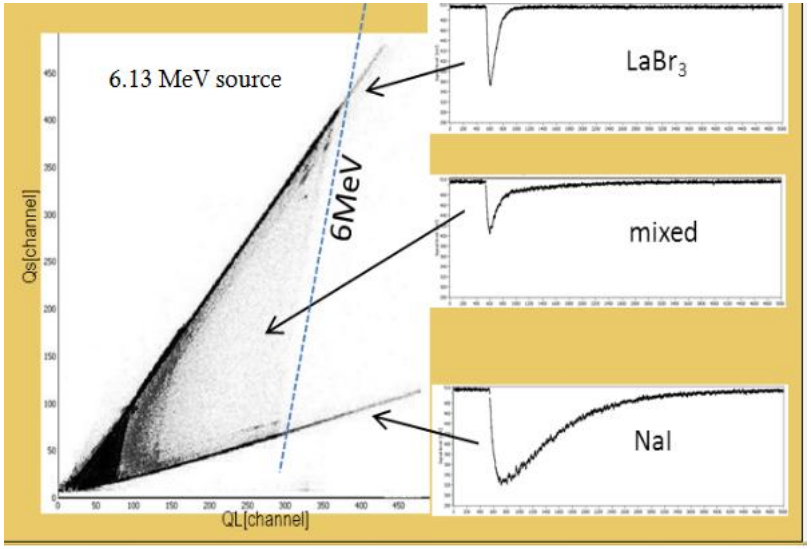
- Coupling $\nu$-ball hybrid spectrometer with LICORNE neutron source
- 3 experiments about neutron induced reaction $\gamma$ spectroscopy was done.
- Analysis of data set is in the progress.

M.Lebois[1,2], J.N. Wilson[1,2], D. Thisse[1,2], L. Qi[1,2], I. Matea[1,2], F. Ibrahim[1,2], D. Verney[1,2], M. Babo[1,2], C.Delafosse[1,2],F. Adsley[1,2], G. Tocabens[1,2], Y. Popovitch[2], J.Nemer[2], A. Lopez-Martens[6], K. Hauschild[6], J. Ljungall[6], D. Etasse[15], D. Ralet[15], R. Canavan[3,4], C. Henrich[9], N. Cieplicka-Otynczak[16], L. Cortes[17] , N. Warr[10], K. Miernik[12], M. Rudigier[3,4], I. Kröll[9], P-A. Söderström[5], K. Belvedere[3], K. Rezynkina[8], P. Koseoglou[9], J. Wiederhold[9], L. Fraile[18], S. Bottoni[7], E. Adamska[12], A. Algora[19], J. Benito Gracia[18], G. Benzoni[7], A. Blazhev[11], A. Boso[3,4], R. Chakma[6], P. Davies[20], R-B. Gerst[11], A. Gottardo[1], V. Guadilla-Gomez[21], G. Hafner[11], I. Homm[9], L. Iska[16], T. Kurtukia[22], R. Lozeva[6], M. Piersa[12], P. Regan[3,4], D. Reygadas Tello[23], V. Sanchez[18], C. Surder[9], M. Yavachova[24], M. Fallot[21], B. Fornal[16], S. Leoni 7, C. Schmitt[22], M. Heine[22], F. Zeiser[26], W. Paulson[26], D. Gestvang[26], S. Oberstedt[13], D. Knežević[14], A. Dragić[14], Zs. Podolyak[3,4], R. Shearman[3,4], M. Diakaki[25], A. Oberstedt[5], M. Bunce[4], P. Inavov[3,4]



**Thank you**


The PARIS PHOSWICH at work
10 ns risetime
Single pulses
NaI(Tl)
LaBr3
PMT
HAMAMATSU
Photomultiplier
TYPE R7723-100
NO. ZK6699
Mixed signal


6.13 MeV source
6MeV
Qs[channel]
QL[channel]
LaBr3
mixed
NaI