First PARIS experiments in the ENSAR2 TNA facilities

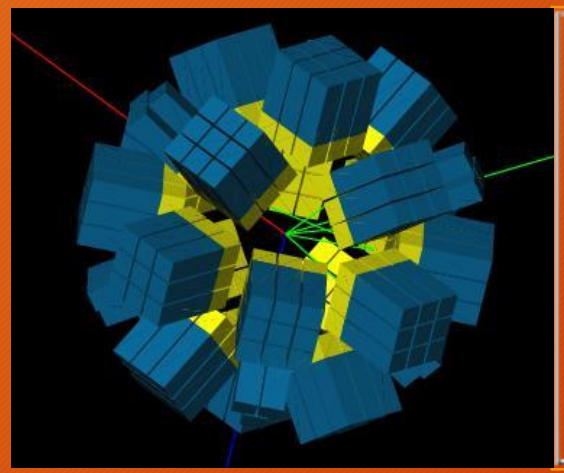
Adam Maj

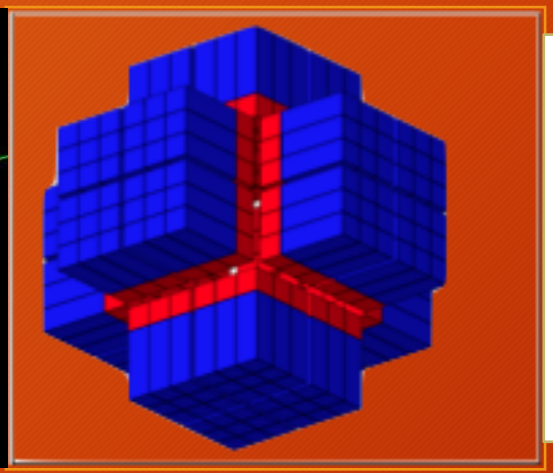
IFJ PAN Kraków

PHOTON ARRAY FOR STUDIES WITH RADIOACTIVE ION AND STABLE BEAMS

PARIS desing concepts:

High efficiency gamma detector, based on new scintilation materials, consisting of 2 shells *(or 1 phoswich shell)* for medium resolution spectroscopy and calorimetry of γ-rays in large energy range





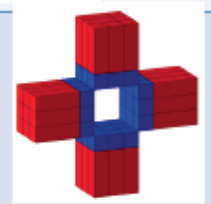
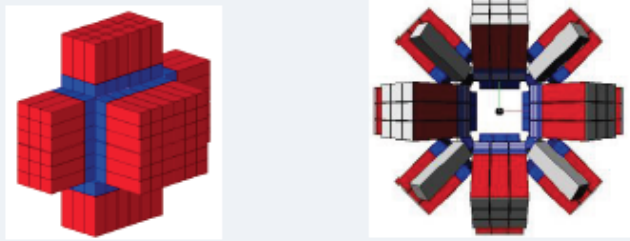
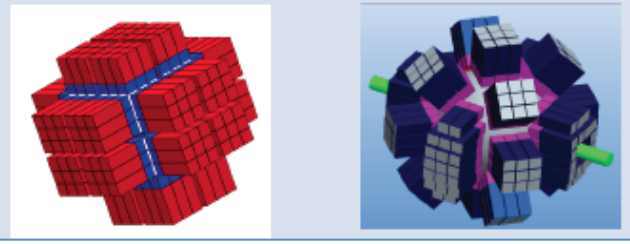
PARIS to be made of clusters:
Cluster = *9 phoswiches*
This allows, in its final phase,
cubic or *semi-spherical* geometry
with 24 clusters (216 phoswiches)

First idea: 2006, Construction started in 2010

PARIS Demonstrator MoU and PARIS phases

MoU on PARIS Demonstrator (Phase 2) was prepared and agreed to be signed by IN2P3 (France), COPIN (Poland), GANIL/SPIRAL2 (France), TIFR/BARC/VECC (India), IFIN HH (Romania), INFN (Italy), UK, Turkey

PARIS phases and cost estimates

Phase 1 **2011/2012** PARIS cluster	1 cluster: 9 phoswiches		250 k€	**Decided** Funds: SP2PP, ANR, Orsay, Strasbourg, Kraków, Mumbai Tests in-beam and with sources
Phase 2 2018 PARIS Demonstrator	5 clusters: 45 phoswiches		1100 k€	**Only if Phase1 validated** Funds: MoU Ph1Day1 exp@S3
Phase 3 2020 PARIS 2π	12 clusters: 108 phoswiches		≈ 2 M€	**Only if Phase2 validated** Funds: MoU, PARIS consortium Ph2Day1 exp. wit AGATA and GASPARD Other exp.
Phase 4 2022? PARIS 4π	≥24 clusters: ≥216 phoswiches		≈ 4 M€	**Only if Phase3 validated** Funds: PARIS consortiun Regular experimer in various labs

Presently (June 2017) PARIS collaboration has:

- 1 LaBr3_NaI cluster (Saint Gobain)
- 1 CeBr3_NaI cluster (Scionix)
- A number of LaBr3_NaI phoswiches (Saint Gobain)

IPN Orsay

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AGATA@GANIL

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S3@GANIL

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CCB Krakow

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LNL/SPES

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SPIRAL2 phase2

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PARIS Organization

PARIS Steering Committee
(by nominations of the MoU partners):

- **IN2P3 France: F. Azaiez**
- **GANIL France: M. Lewitowicz**
- **COPIN Poland: B. Fornal (dep.chair)**
- **India: V. Nanal (chair)**
- **Italy: A. Bracco**
- **Romania: M. Stanoiu**
- **UK: W. Catford**
- **Turkey: S. Erturk**
- ~~**Bulgaria: D. Balabanski**~~

PARIS Project Manager
(nominated by PSC)
A. Maj (Poland)

Working Groups and their Coordinators
(proposed by PPM and aproved by PSC):

Geant4 simulation: **O. Stezowski** (Lyon)
Detectors: **O. Dorvaux** (Strasbourg)
Electronics and DAQ: **P. Bednarczyk** (Krakow)
Mechanical integrations: **I. Matea** (Orsay)
Data analysis: **S. Leoni** (Milano)
New materials: **F. Camera** (Milano)
New Physics case: **I. Mazumdar** (Mumbai)

PARIS Management Board:
PARIS Project Manager + WG coordinators

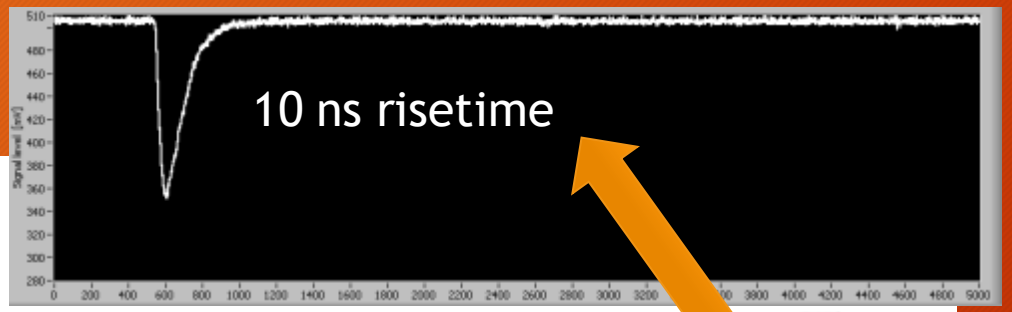
PARIS Collaboration Council:

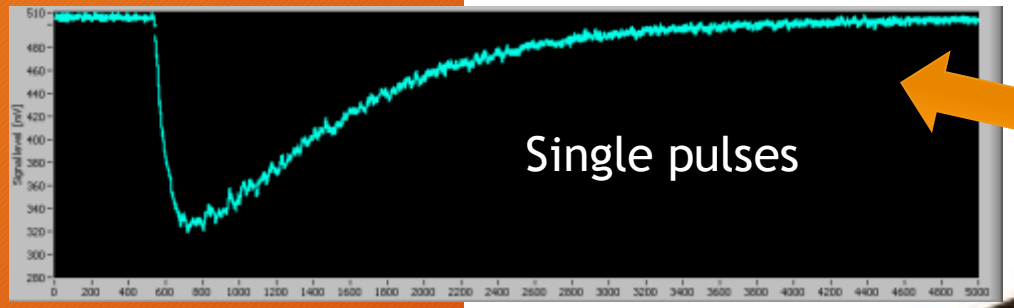
David Jenkins (University of York, UK) - chair and PARIS spokesman
Sudhee R. Banerjee (VECC Kolkata, India)
Franco Camera (INFN and University of Milano, Italy)
Wilton N. Catford (University of Surrey, UK)
Marco Cinausero (LNL Legnaro, Italy)
Sandrine Courtin (IPHC Strasbourg, France)
Zsolt Dombradi (ATOMKI Debrecen, Hungary)
Camille Ducoin (IPN Lyon, France)
Sefa Ertuerk (Nigde, Turkey)
Juergen Gerl (GSI, Germany)
Anil K. Gourishetty (IIT Roorkee, India)
Maria Kmiecik (IFJ PAN Krakow, Poland)
Suresh Kumar (BARC Mumbai, India)
Marc Labiche (STFC Daresbury, UK)
Vandana Nanal (TIFR Mumbai, India)
Pawel Napiorkowski (HIL Warsaw, Poland)
Marek Ploszajczak (GANIL, France)
Mihai Stanoiu (IFIN-HH Bucharest, Romania)
Jonathan Wilson (IPN Orsay, France)

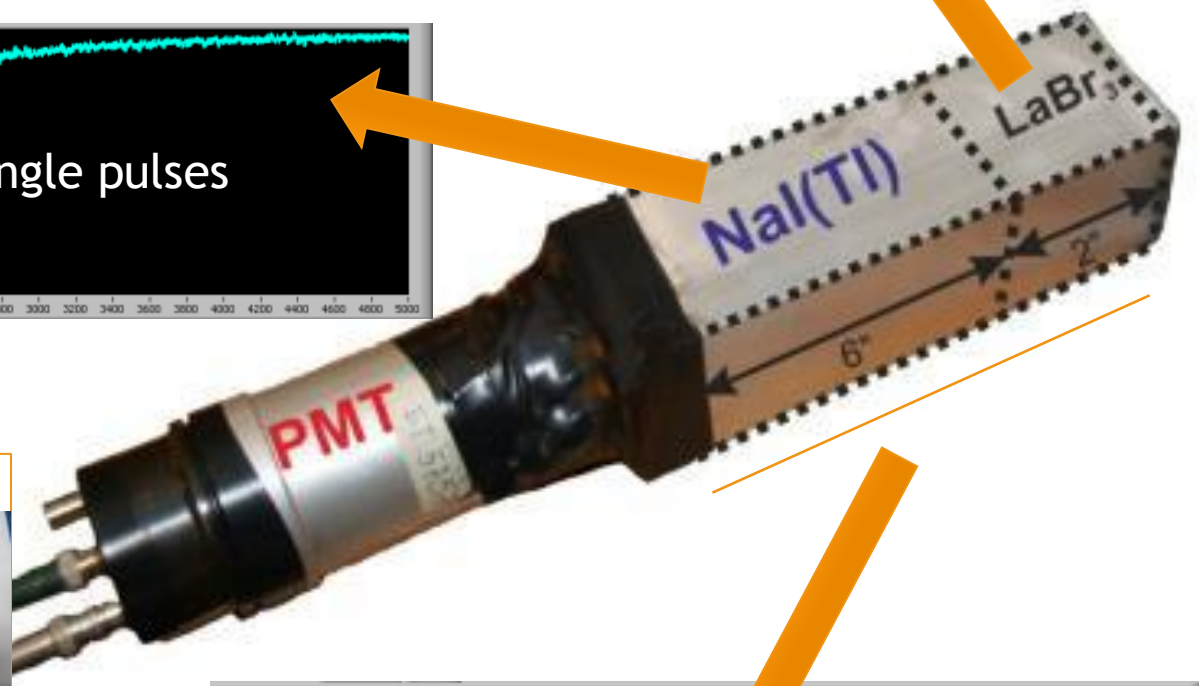
Campaign Spokespersons

GANIL: C. Schmitt / M. Ciemala
IPN Orsay: I. Matea
IFJ PAN Kraków: M. Ciemała

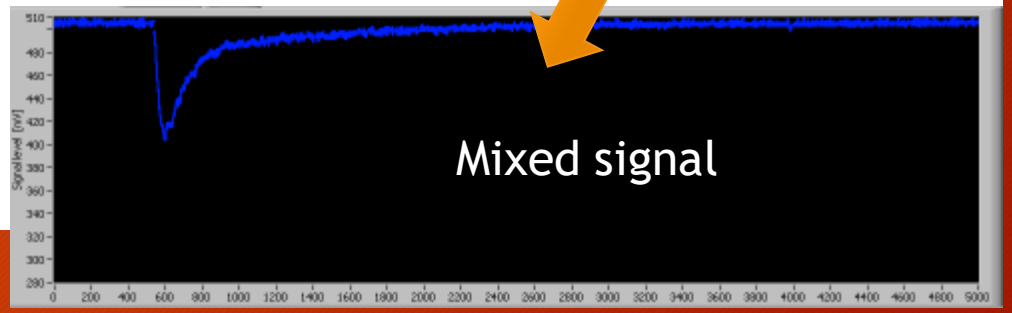
The PARIS PHOSWICH at work

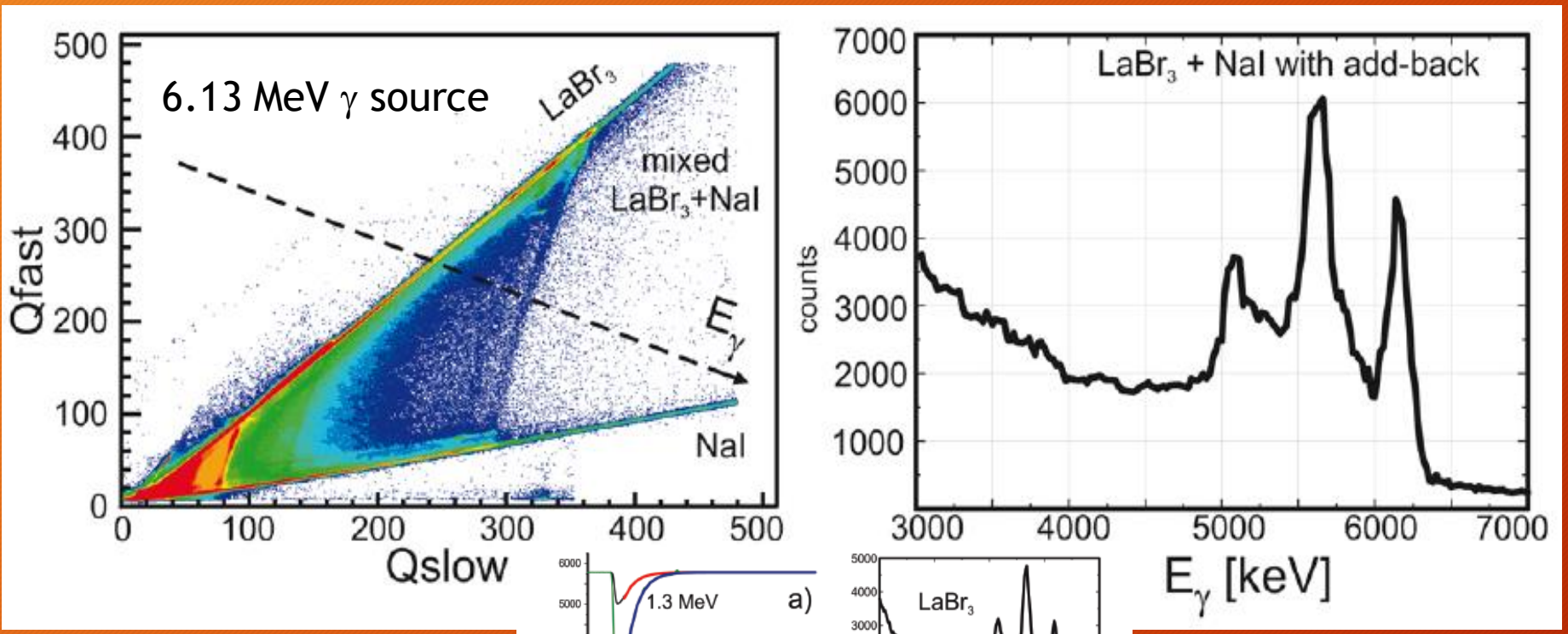


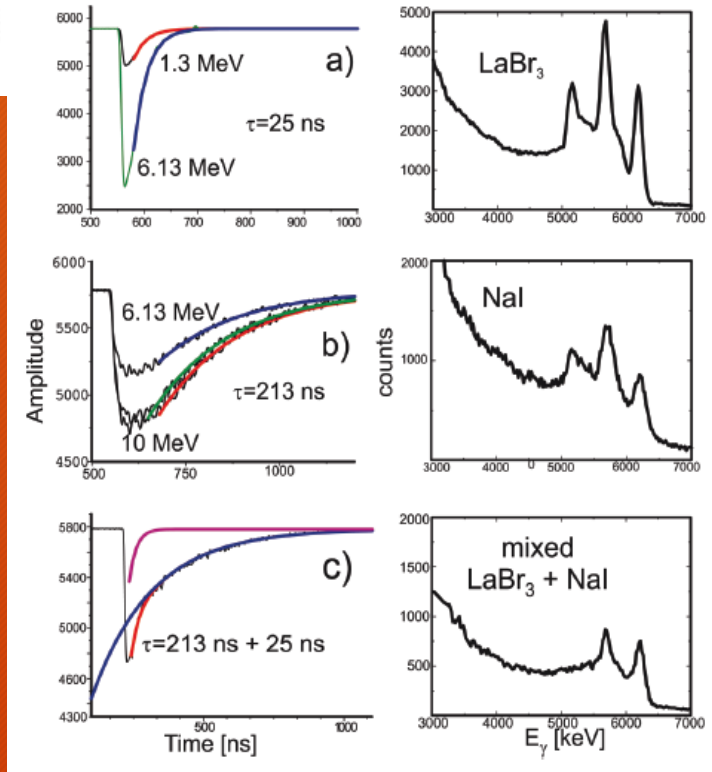




HAMAMATSU







A test measurement at IFJ PAN, Kraków (2011) with BafPro module from Milano

- Sources
- proton beam

LaBr3 resolution (seen through 6” long NaI): ca. 4%

The phoswich concept works !

M. Zieblinski et al.,
Acta Phys.Pol. B44, 651 (2013)

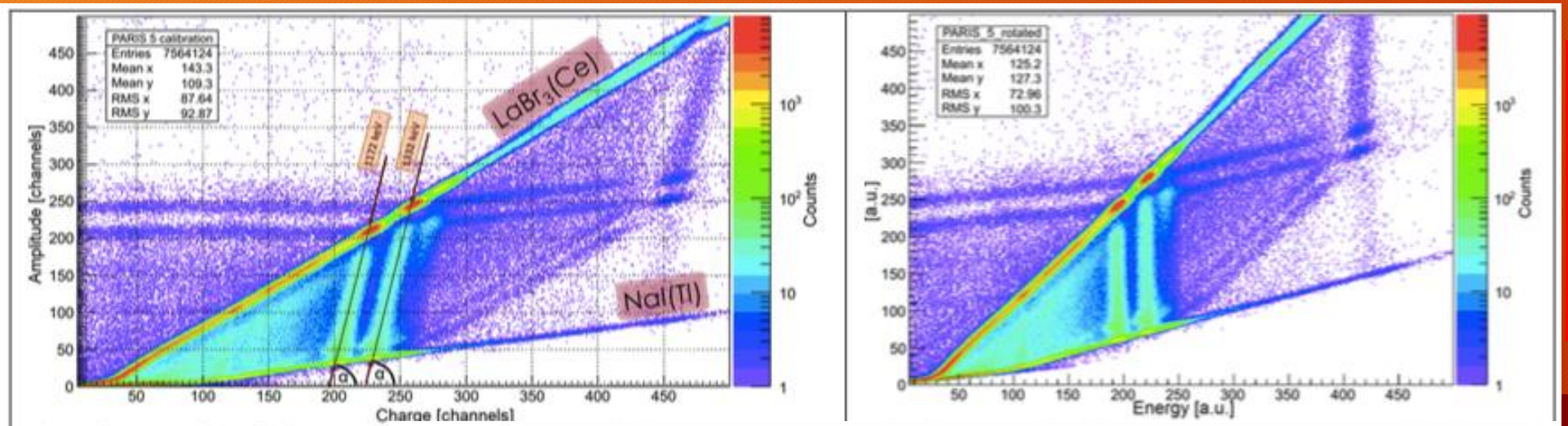


Fig. 4) Example of charge vs
calibration run. Lines of ev
energy was deposited in on
same energy deposited and

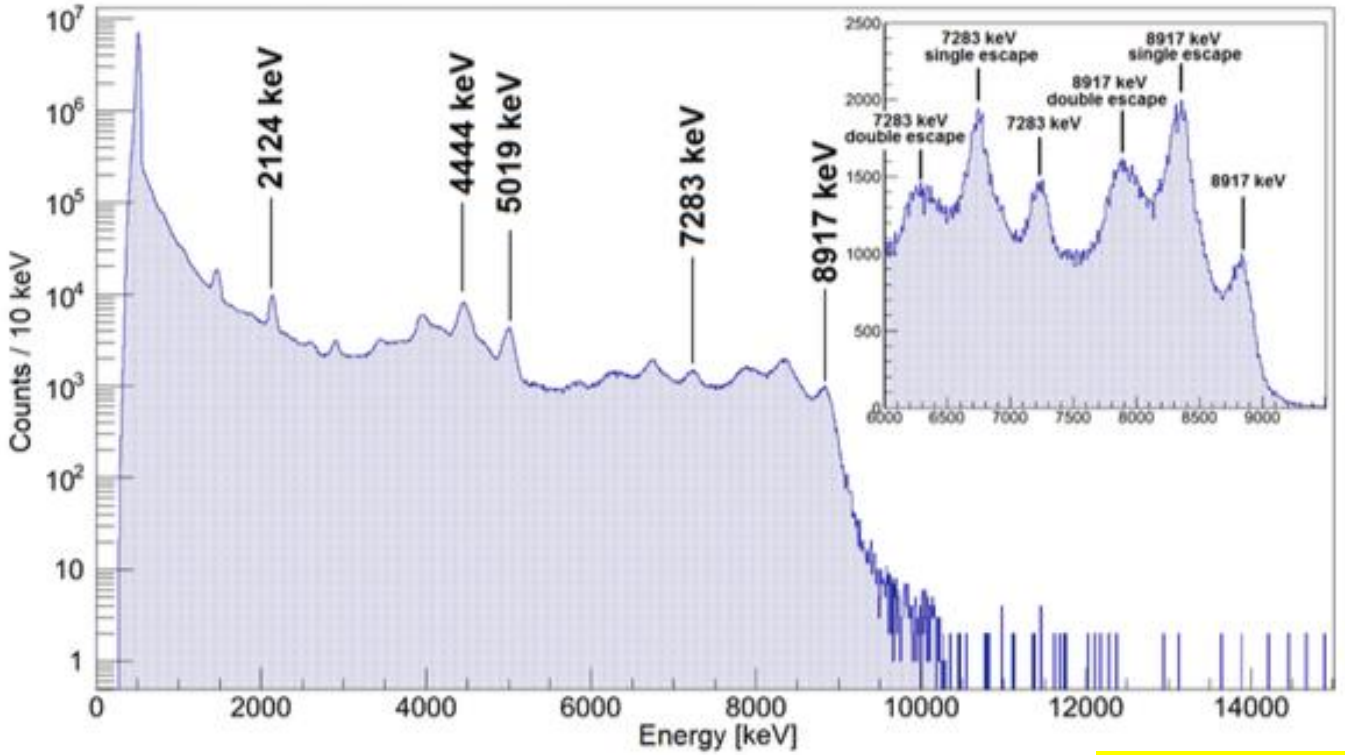


Fig. 6) Energy add-back spectrum of the PARIS cluster.

B. Wasilewska et al., paper in preparation

ELBE facility, Dresden, 2013
NRF (Nuclear Resonance Fluorescence) experiment (Mazumdar, Maj, Schwengner et al.)

Beam 15 MeV electrons: brehmstallung gamma beam on ^{11}B target

Resolution after add-back ca. 4.5%

The cluster concept works!

Options of electronics for PARIS

1) NUMEXO2 - a general-purpose digital card for GANIL based experiments (collaboration with EXOGAM2 and NEDA projects)

Implementation of the GTS interface into the NUMEXO2 VIRTEX 5 FPGA is currently being finalized.

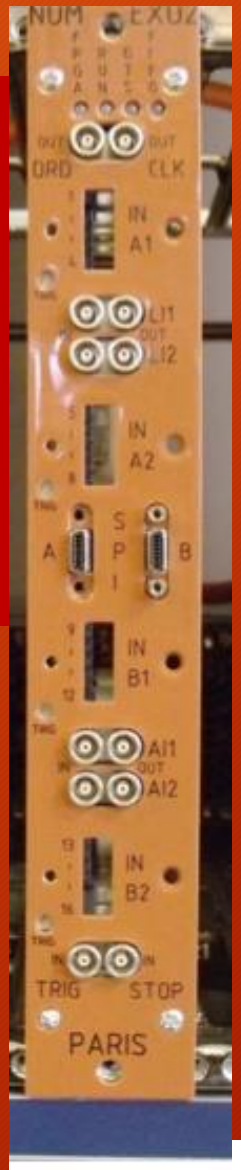
A dedicated PARIS FADS front end electronics (mezzanine) is being designed. The digitizer will be integrated with the NUMEXO2 carrier board. Implementation of algorithms for on line PSA on the FPGA Virtex6LX platform is in progress.

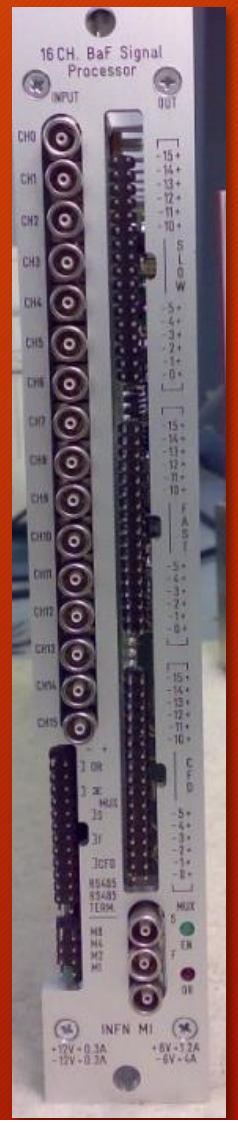
2) **Analogue electronics** based on **Milano "PARIS_Pro"** cards (S. Brambilla et al.) + **AGAVA** interface (A. Czermak et al..):
Already tested in AGATA LNL and GSU camapigns!
Will be used for first experiments with AGATA. (integrated to the VAMOS branch)

3) Comercial digitizers (V1730, 16 channel, 500 MS/s, 12/14 bit CAEN digitizer)

Tested in Krakow, July 2015 - works very well (good time reolutin, time resolition - 0.7ns, low deadtime)

4) Occasionally other local digitizers (e.g. FASTER in IPN Orsay)





First PARIS experiments in IPN Orsay

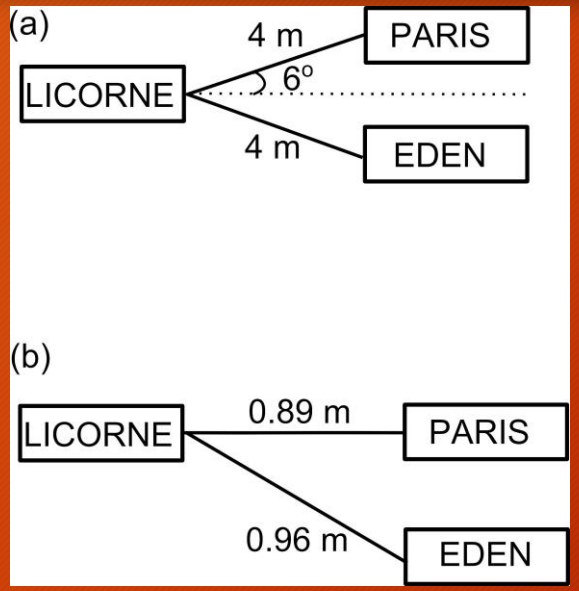
Testing PARIS with fast neutron from LICORN
I. Matea, J. Wilson et al. (done in 2016)

Courtesy of Michal Ciemiala

Test performer at IPN Orsay with Li/BiCORNE neutron source.

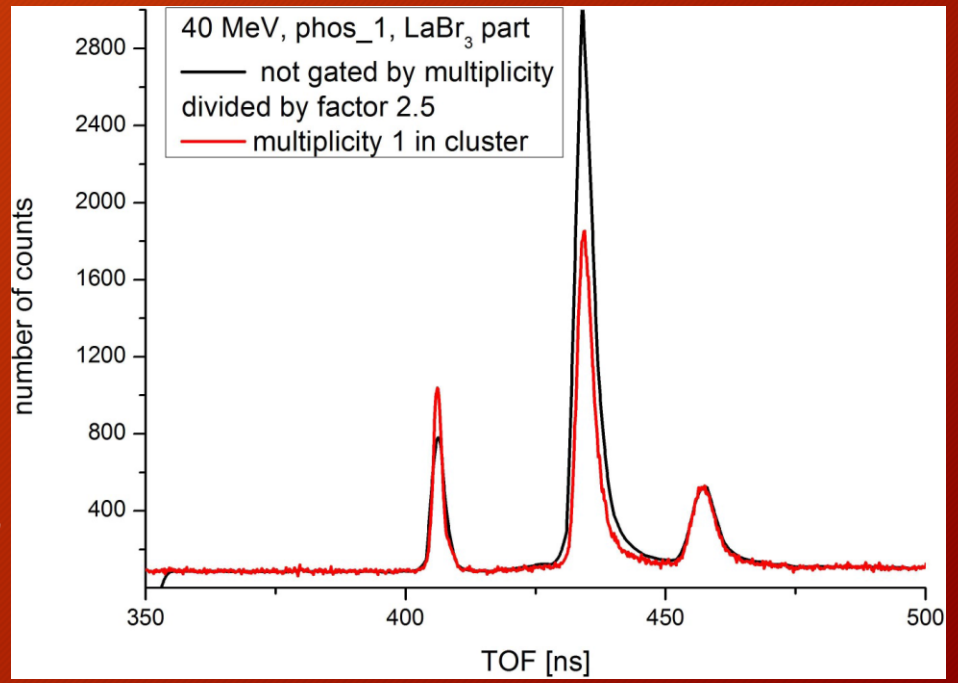
Neutrons produced in inverse kinematic reaction $^{1}H(^{11}B,^{11}C)n$

9 PARIS phoswiches used (1 cluster) and EDEN neutron detector for monitoring

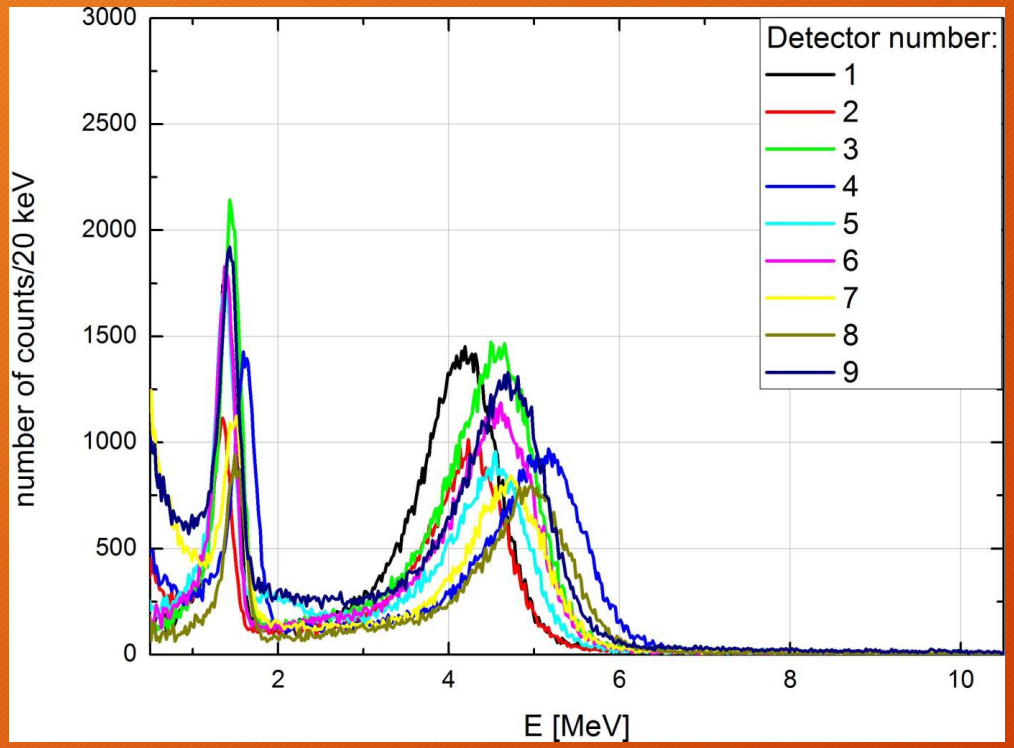


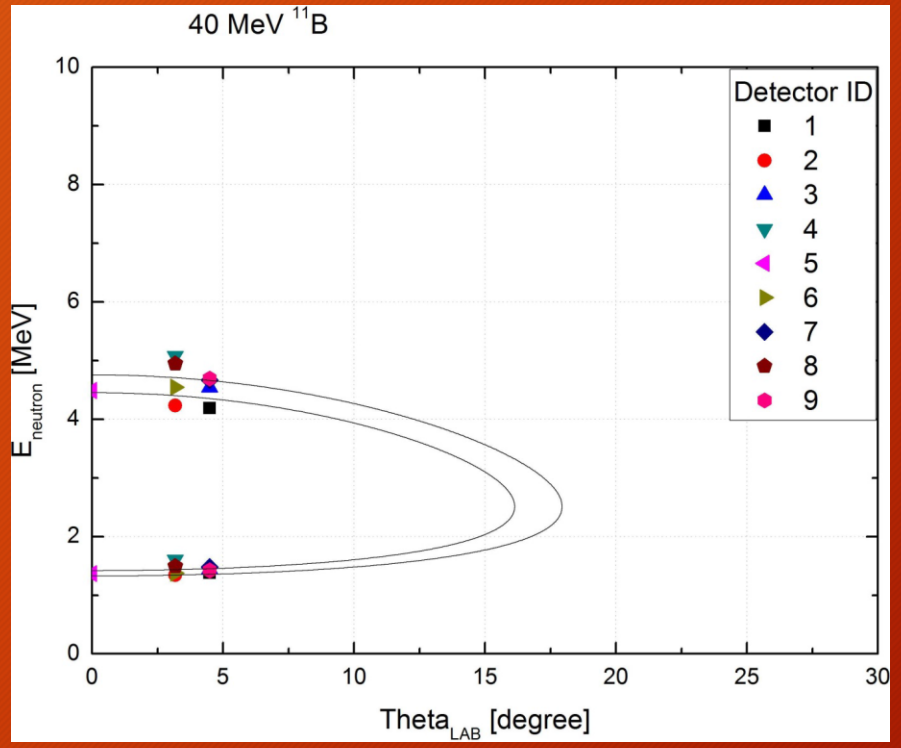
Schematic view

ToF for PARIS phoswich: prompt gamma (from ^{11}B), fast and slow neutrons.



Results





Left: Energy spectra for PARIS phoswiches (from ToF); Right mean energies of neutrons (points) compared to calculated values for reaction kinematics (solid lines).
^{11}B beam Energy equal to 40 MeV

Table:
Energy resolution with effect of summing over different neutron energies
(see right upper figure – solid lines).

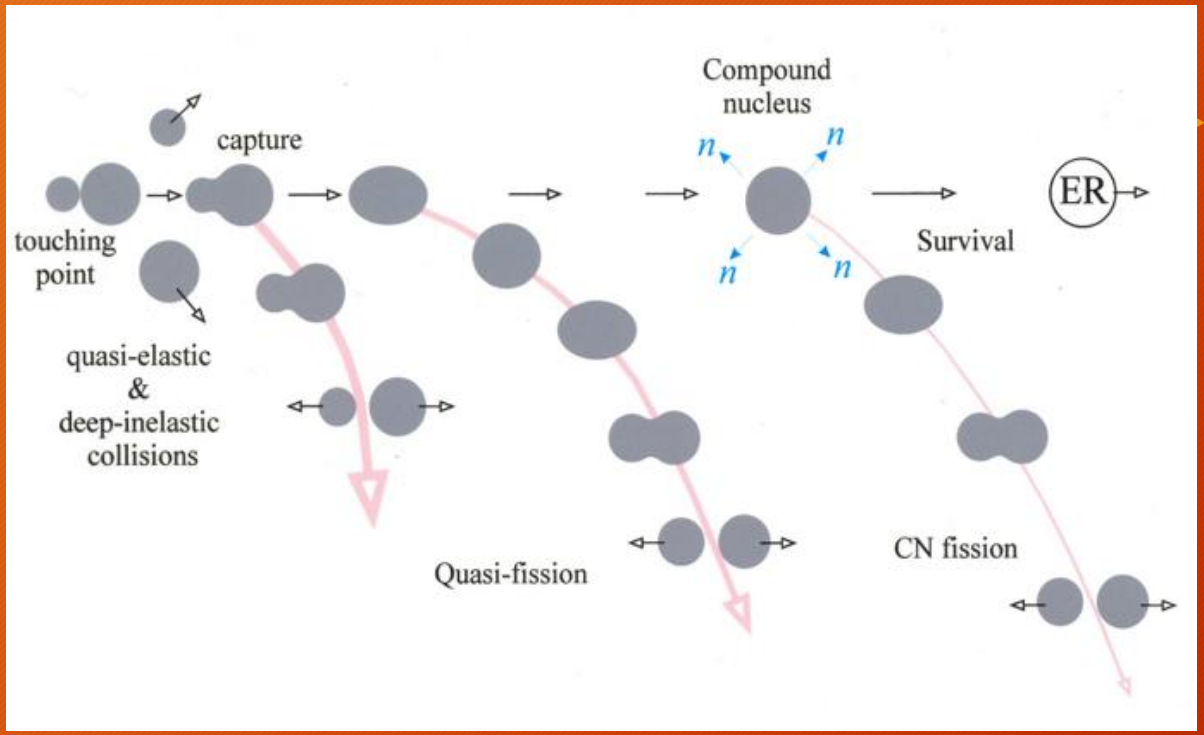
E_{mean} [MeV]	FWHM [MeV]
5.89	1.46
4.61	0.98
1.44	0.26
1.13	0.18

Conclusion:
PARIS can be used as n-ToF detector

A. Kozulin et al. “Prompt γ-rays as a probe of nucleardynamics” (June 2016)
Motivation and Goal: Challenging fission around the interaction barrier

Courtesy of Julia Harca

$$^{32}S + ^{197}Au \rightarrow ^{229}Am^{*},\ E^{*} \approx 43\ MeV$$



- Coupling of 3 detection systems: CORSET + ORGAM + PARIS;
- Extracting details on the shell effects characterizing two competing processes **fusion-fission (CNF)** and **quasi-fission (QF)** : (A, TKE) correlation;
- Measurement of prompt γ-rays in coincidence with binary reaction fragments obtained in the reactions : *low and high energy* γ-rays for further insight.

  - Are population and feedings of specific isotopes preferred in different mechanisms or CNF modes
  - How does the γ-ray multiplicity or the sum energy evolve with fragment mass A, TKE or their variances?

Experimental Setup: CORSET

$^{32}S + ^{197}Au \rightarrow ^{229}Am^*,\ E^* \approx 43$ MeV

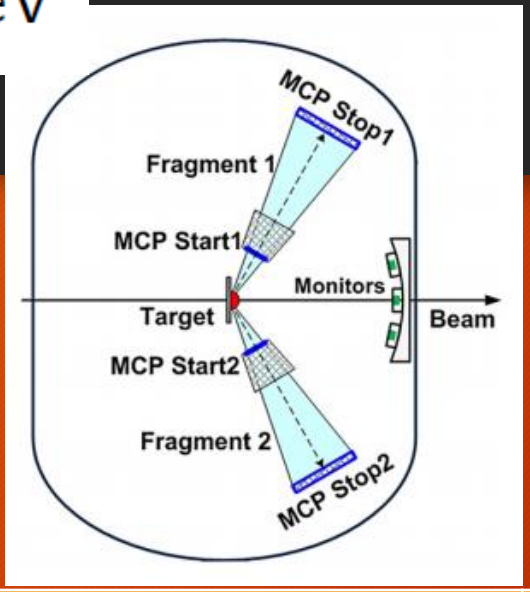
- CORSET:

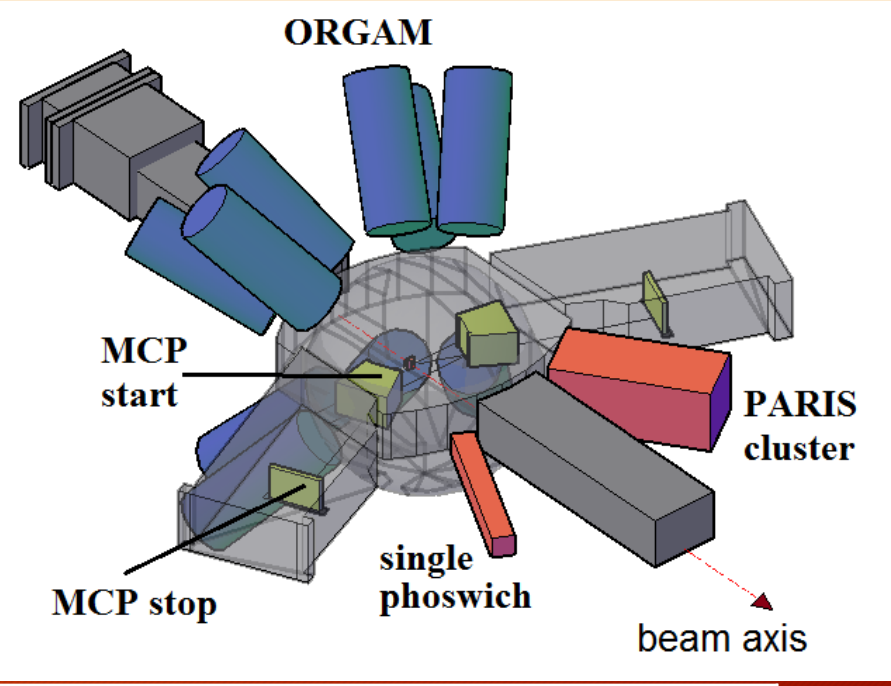
Measured parameters:

- ToF, X, Y

Extracted parameters :

- Velocity, energy, angles
- mass of fission fragments



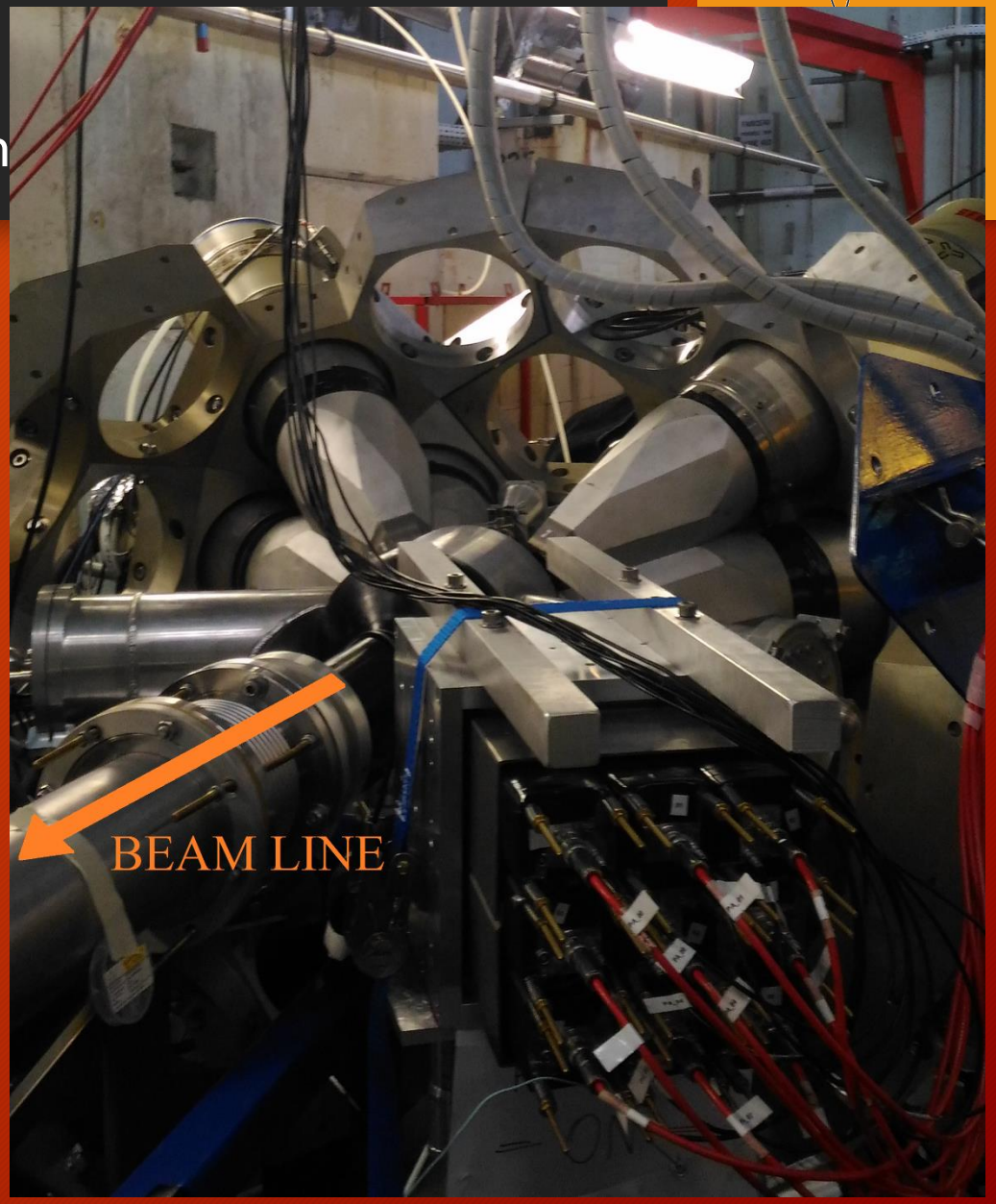


Parameter	Value
The Coulomb barrier (in lab. sys)	167 MeV
Irradiation time	~4 days
Beam current	~90 nA
Collected statistics for fission fragments	207168
Excitation energy of the CN	43 MeV

Experimental Setup: Coincident γ-rays

- ORGAM: Prompt γ-rays coincident with fission fragments (FF).
- PARIS: Prompt -rays (including high-energy) coincident with FF.

Parameter	ORGAM	PARIS
Number and type of Detectors	10 x Ge + BGO shielding	10 x LaBr3(Ce)-NaI(Tl) *(phoswich)*
Photo-peak Efficiency	~1%	~1%
Energy resolution	2.6(3.4)keV @121(1408)keV	62keV @1332keV
Dynamical range	$E_\gamma < 2.5MeV$	$E_\gamma < 20MeV$

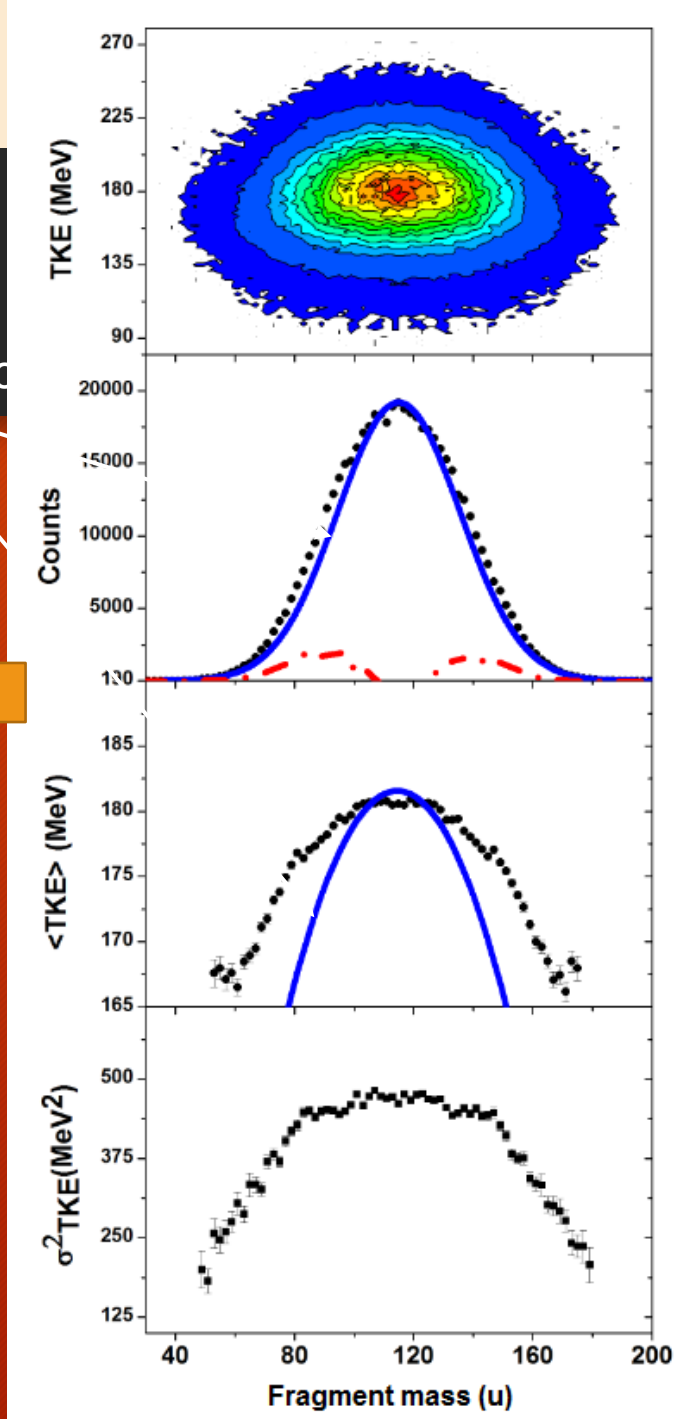


CORSET Data

$^{32}S + ^{197}Au \rightarrow ^{229}Am^*$, $E^* \approx 43$ MeV

E_{lab} (MeV)	$\theta_{lab}^{grazing}$ (deg)	η_0	Z_pZ_t	B_{lab}^{Bass} (MeV)
166	141.5	0.72	1264	164.8

LDM predictio



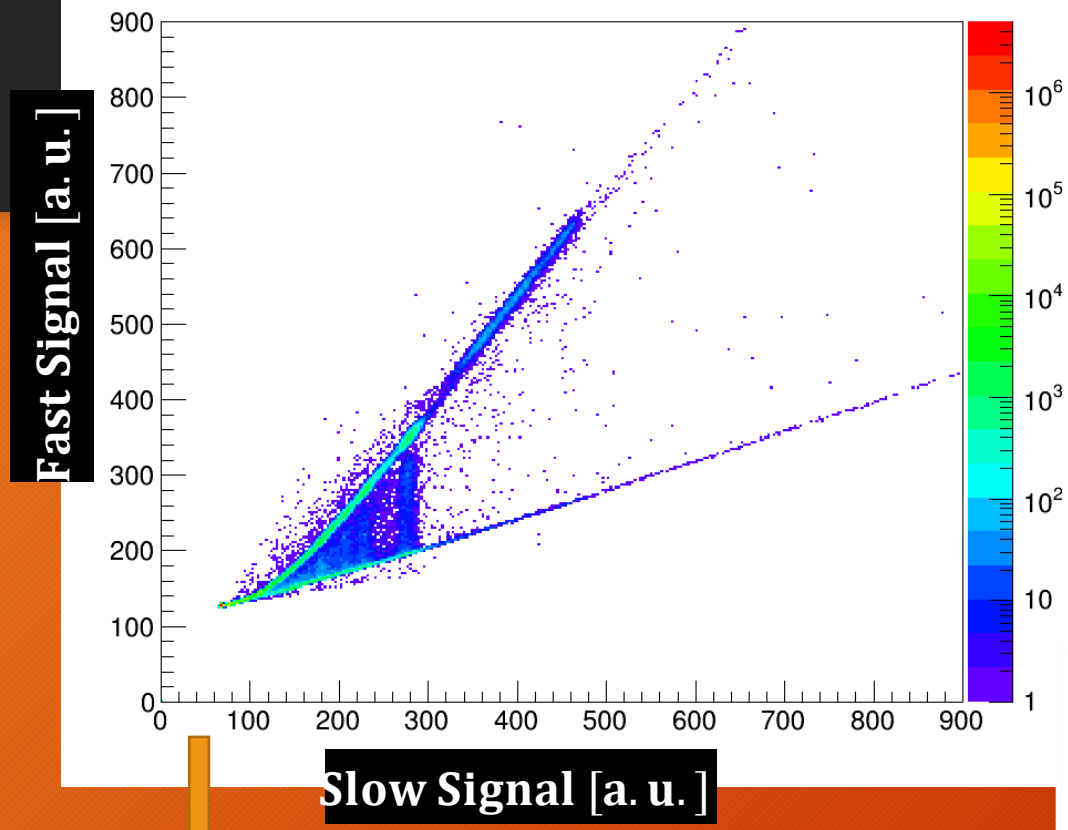
- Asymmetric splitting accounts for 10% of the fission events.

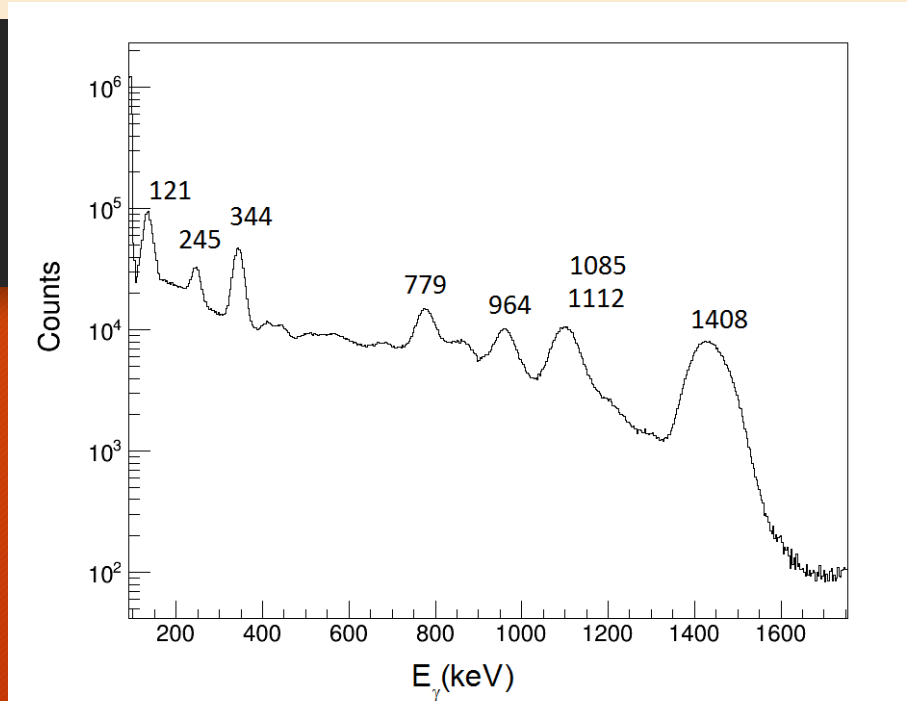
CNF modality or QF?

- Structured shape of the <TKE>(A) and its variance dependency.

Access to velocity vectors of FF and angles between FF and γ-ray detectors granted to be used for precise Doppler corrections on γ-ray energies

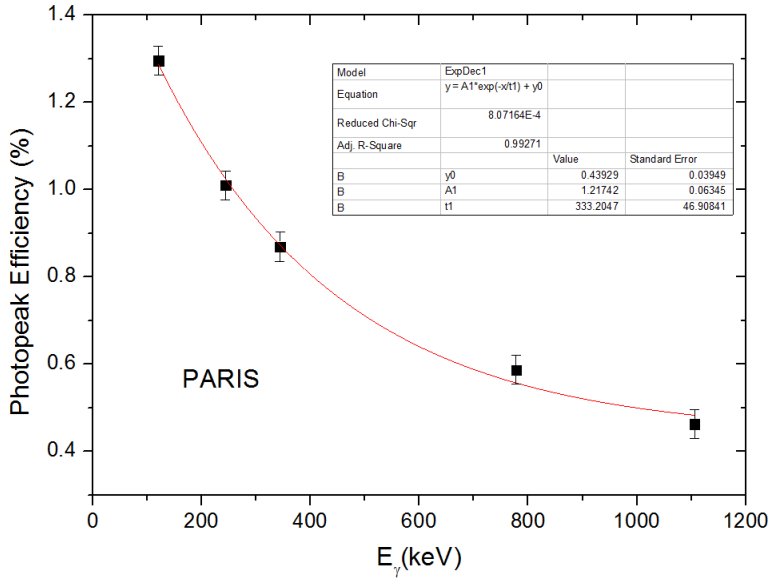
PARIS *calibration source ^{152}Eu*



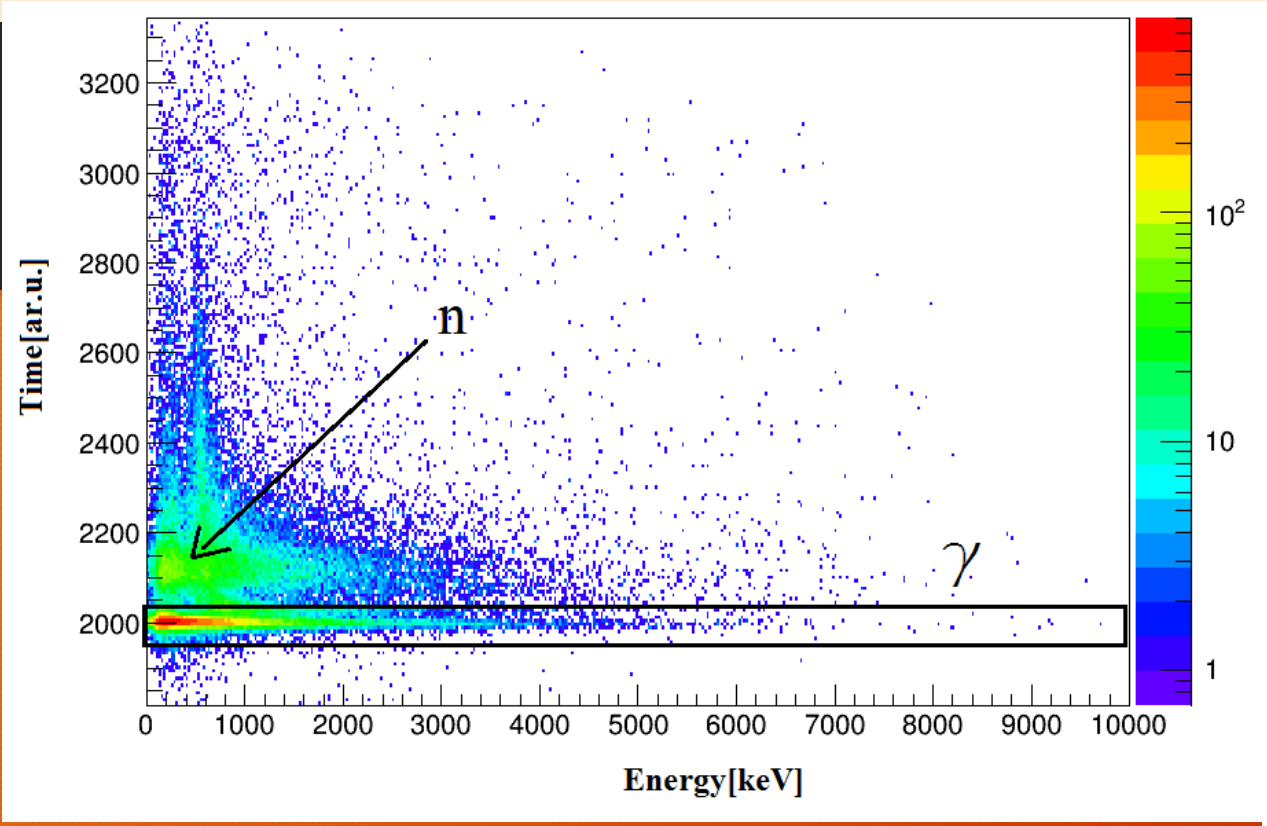


1. "Internal" add-back: by rotating the matrix to form parallel lines with the Y axis
   → Reconstruction of the total en

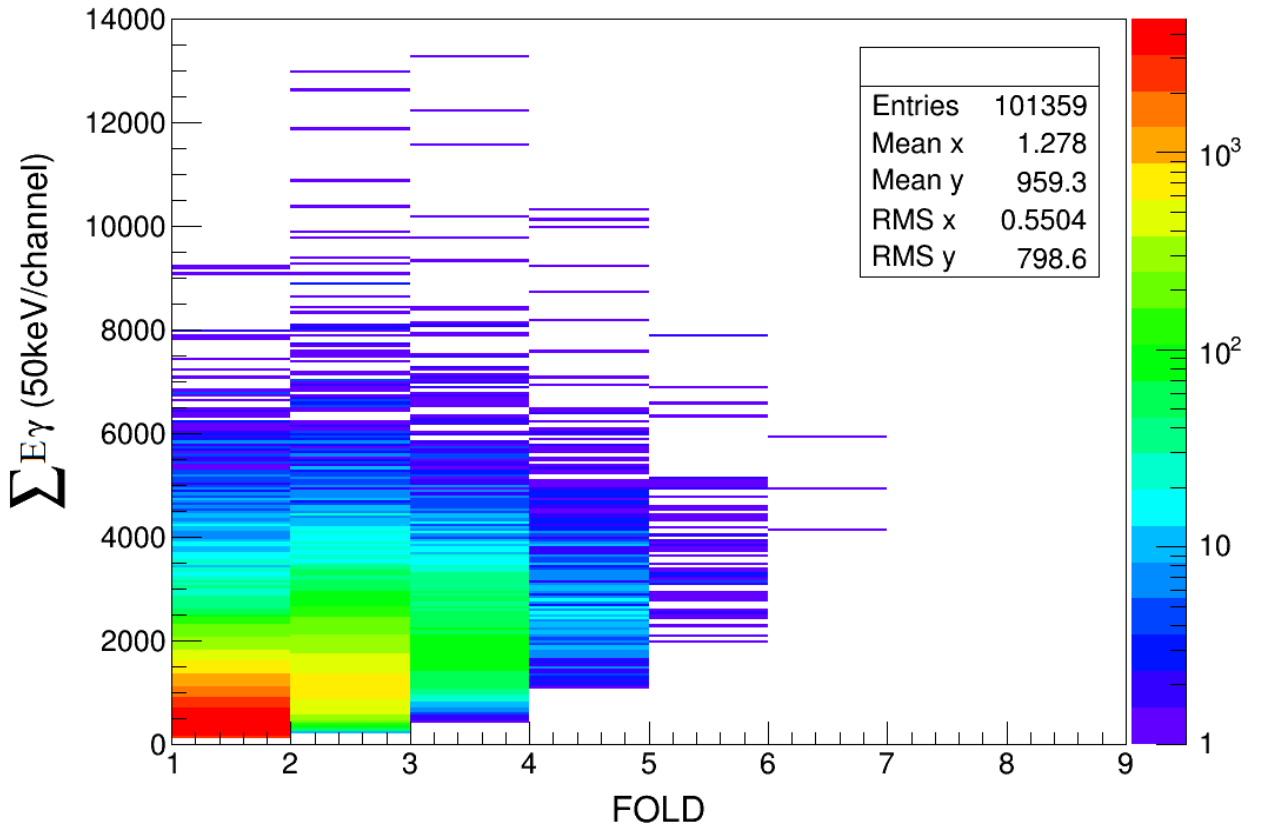
2. External add-back: the cluster configuration allows to add the escaped scattered γ-rays together and fill the original spectrum with the whole detected energy of the photon.



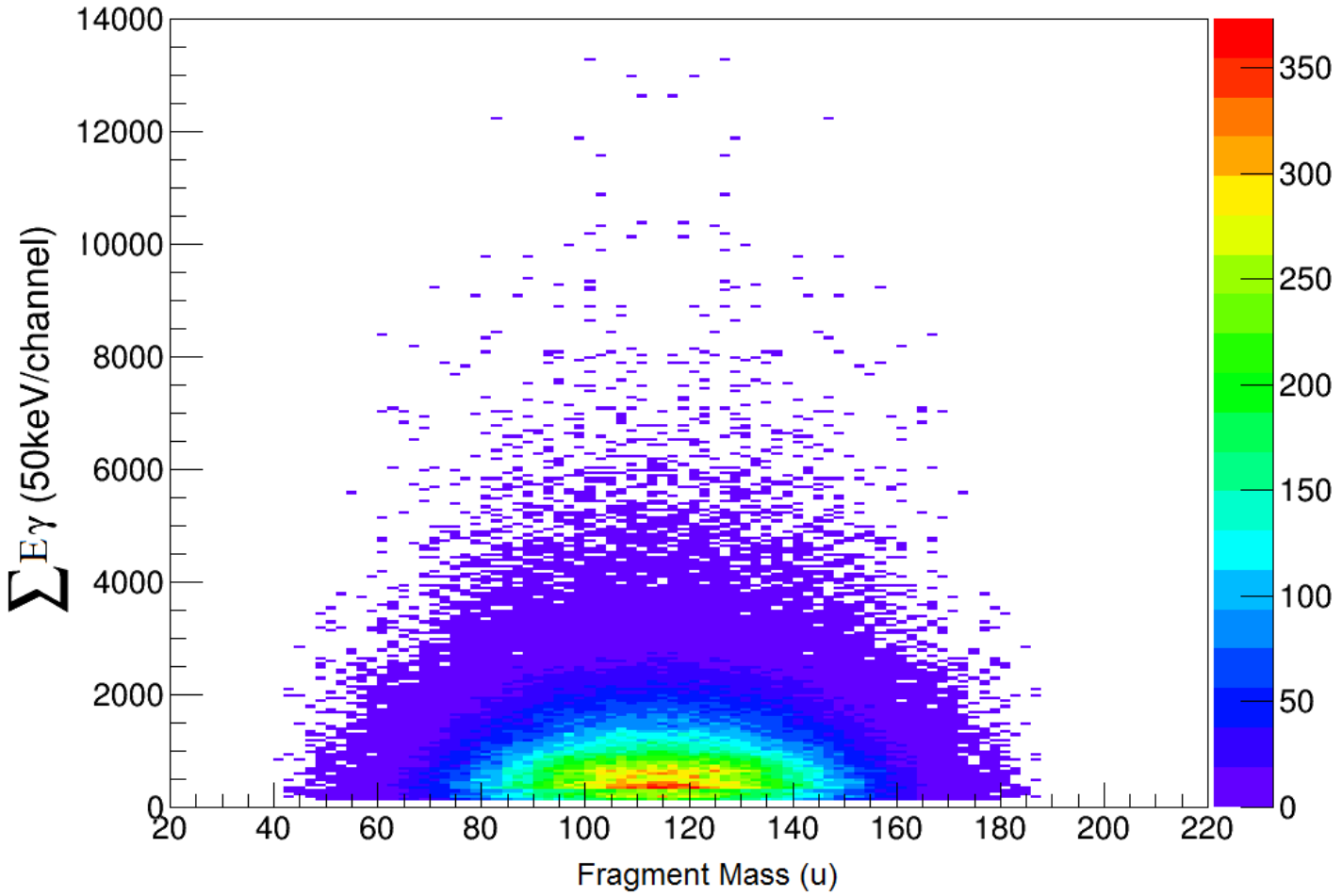
γ- Coincident with FF

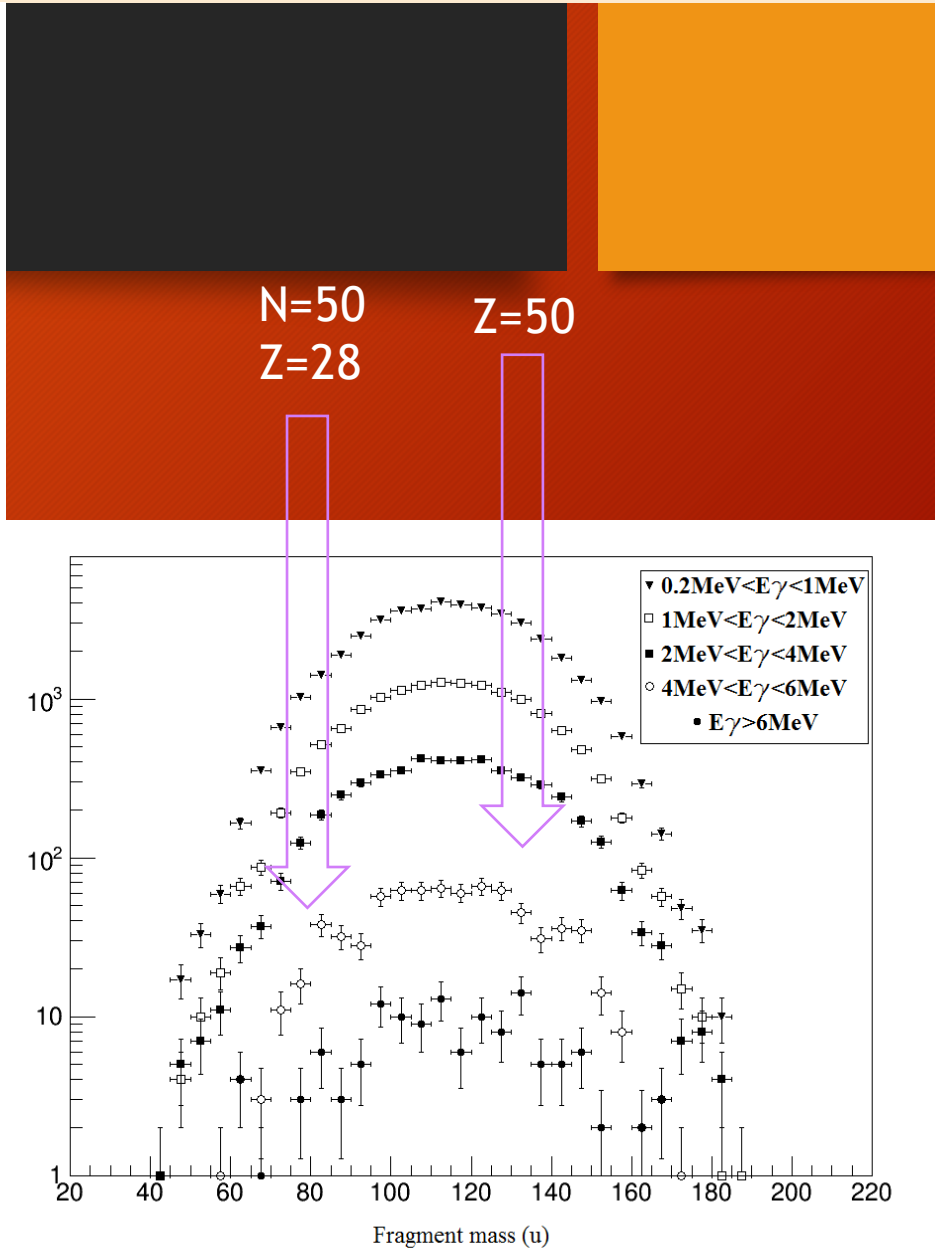


- Good time resolution allowing discrimination of γ-rays against neutrons.
- Wide energy range.
- Able to accept a high counting rate.



γ-rays- Coincident with FF

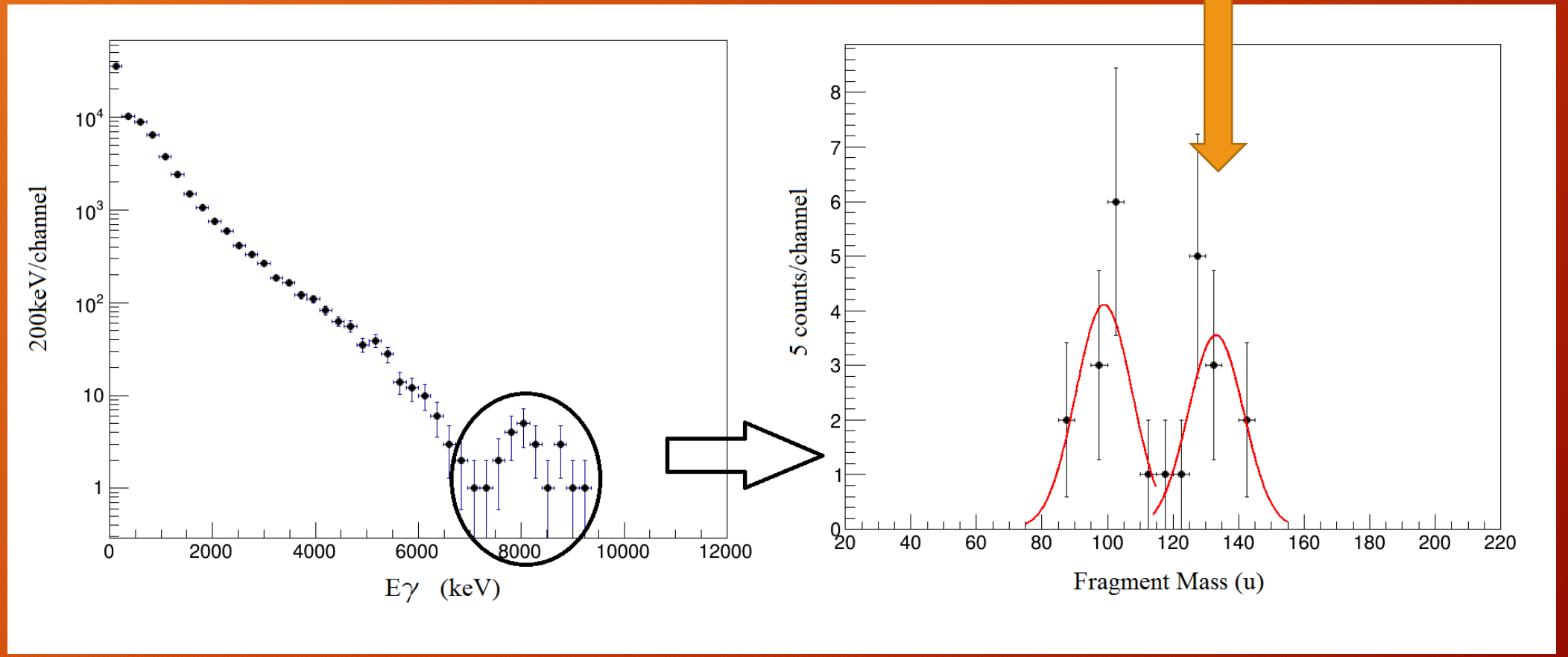




sensitivity for nuclear structure effects at spherical and deformed shel
closure proximity

γ-rays- Coincident with FF

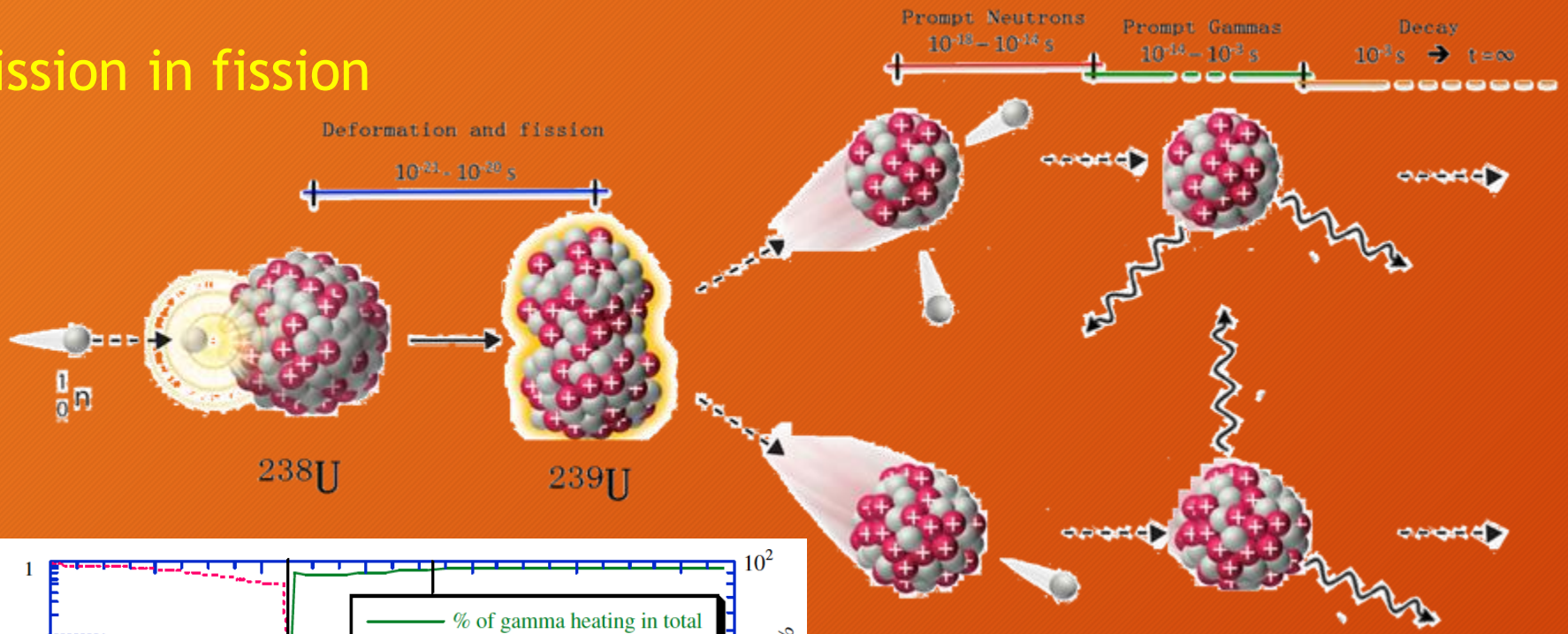
The high energy component of the γ -ray spectrum shows a dependency on the fragment mass split, particularly in the region of masses 120-132

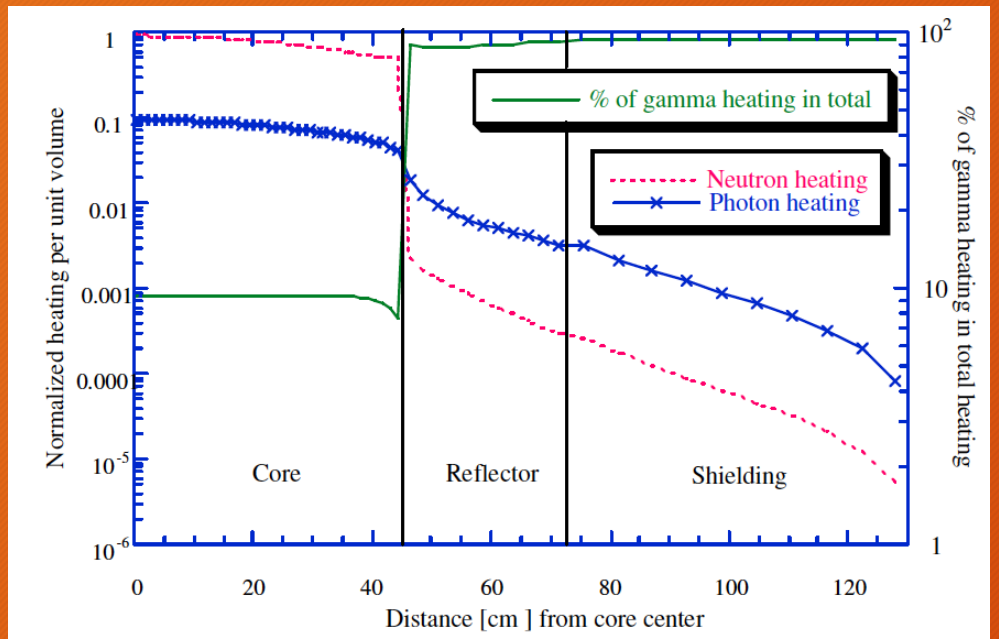


M. Lebois et al. "Prompt gamma and neutron emission for ^{238}U fast neutron induced fission as a function of incident neutron energy" (April 2016)

Courtesy of
M. Lebois
Q. Liqiang

Gamma emission in fission

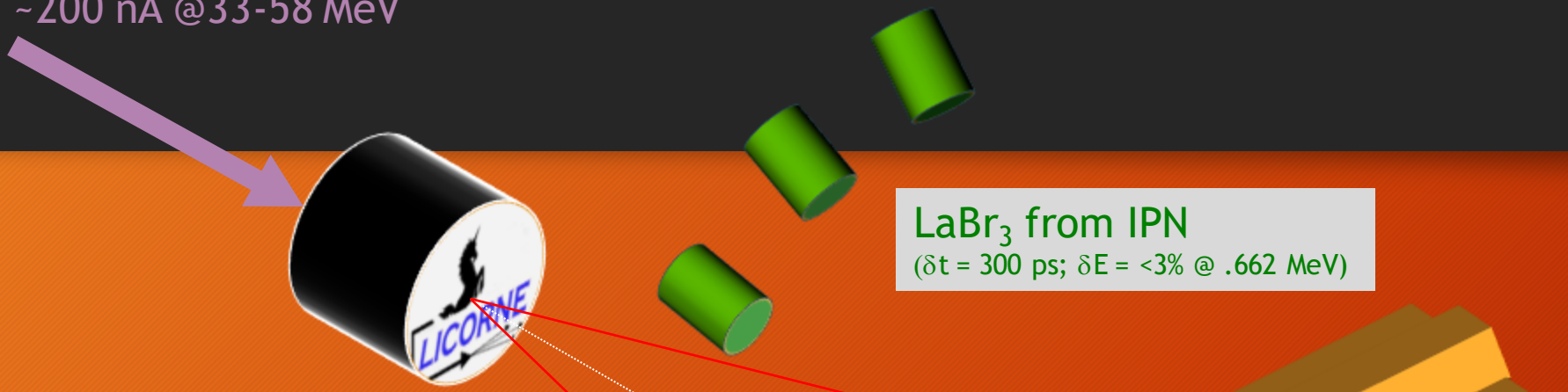




- 10% of energy released is in the form of gamma rays
- Gamma heating dominates in non-fissile components
- 30% underestimate of in-core gamma heating effects!
- OCDE/NEA high priority list for GEN IV (fast neutrons) and ADS (3 -> 10 MeV)

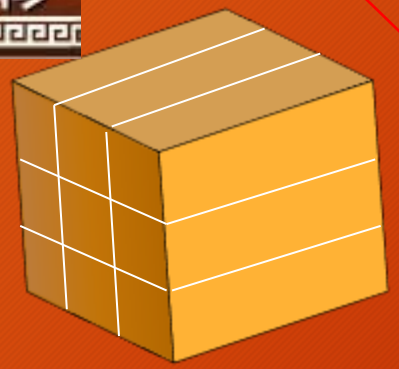
Experimental Setup:
Measurement of prompt γ from ^{238}U fast neutron induced fission

^{11}B beam
~200 nA @33-58 MeV

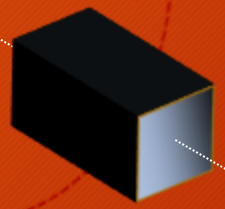


$LaBr_3$ from IPN
(δt = 300 ps; δE = <3% @ .662 MeV)

BaF2 Cluster
from Château de Cristal
(δt = 600 ps; δE = 10% @ .662 MeV)



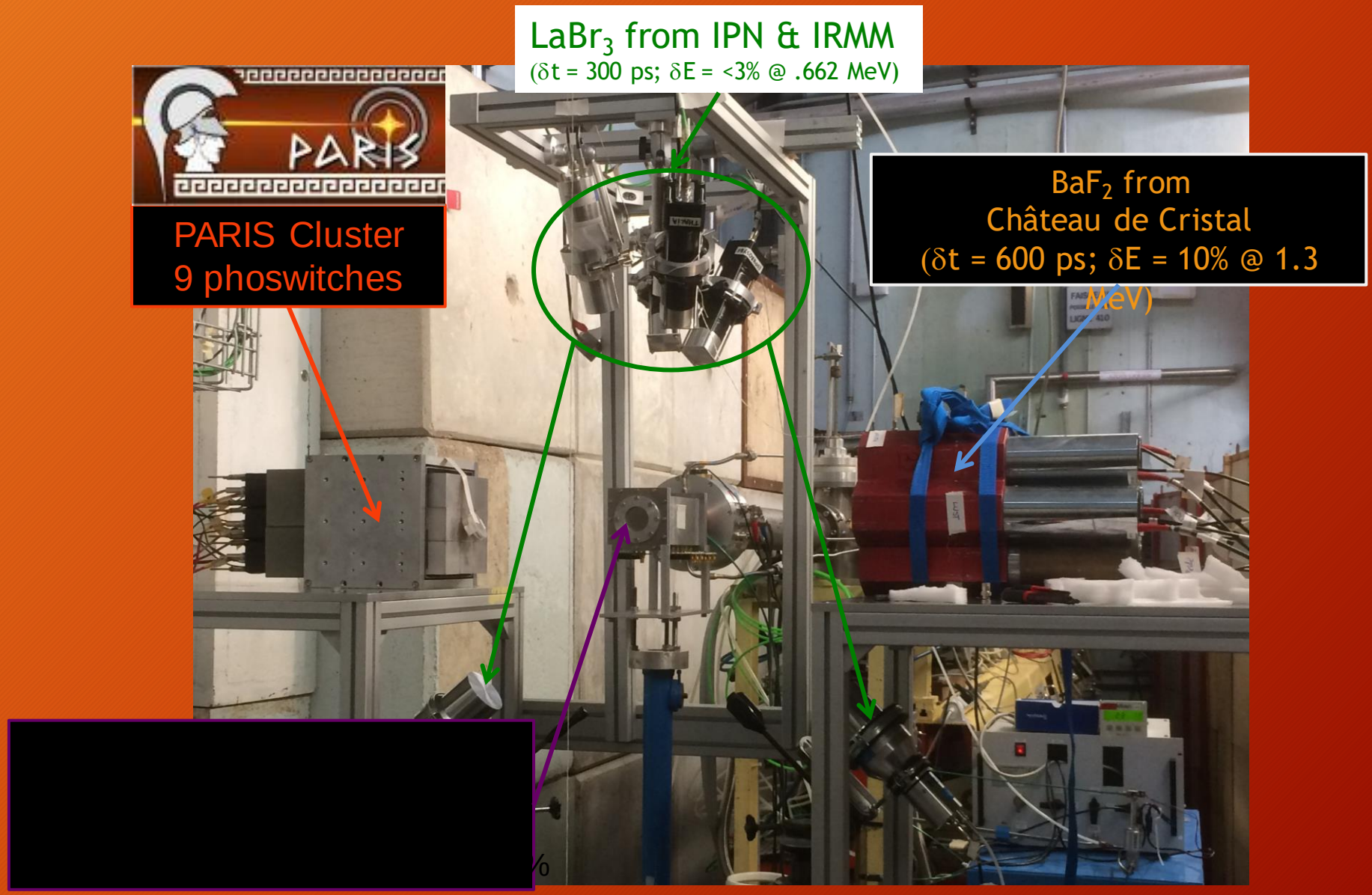
PARIS Cluster
(δt = 600 ps;
δE = 4-8% @ .662 MeV)



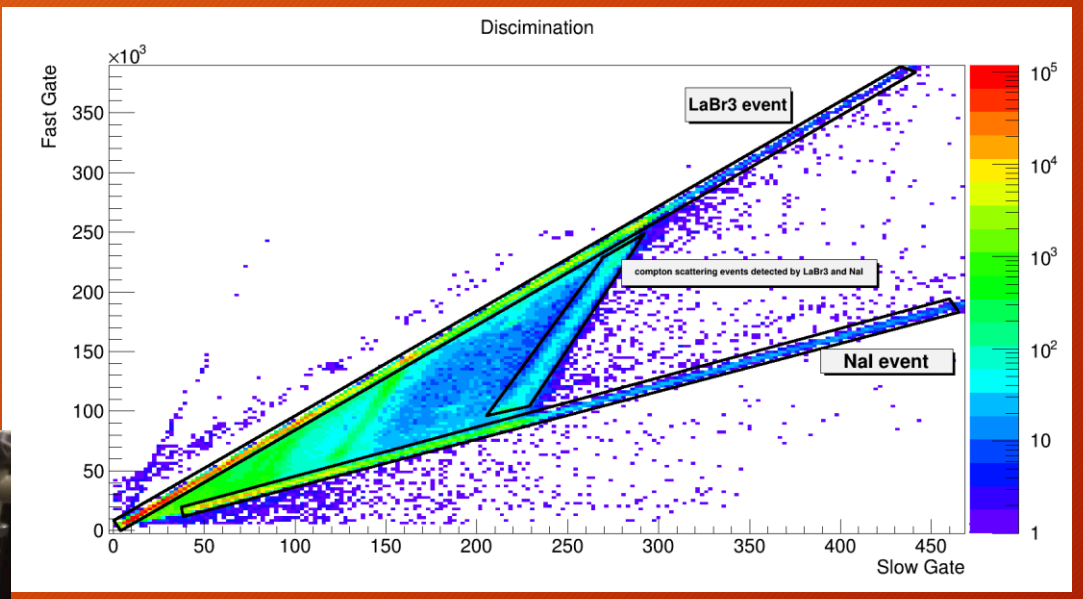
n cone
emission
(< 35°)

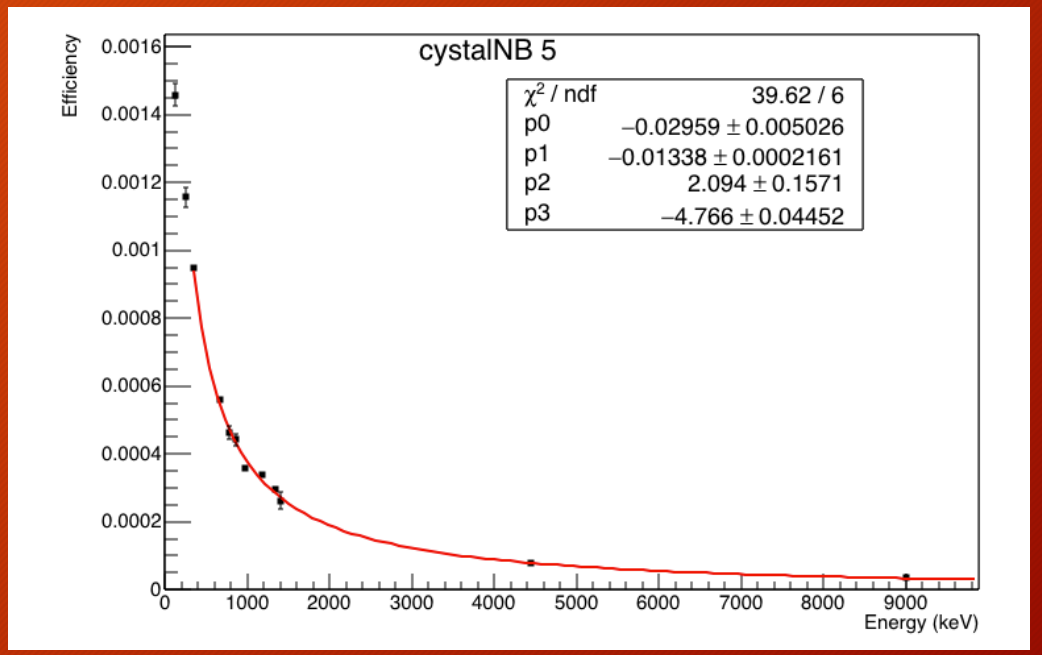
Ionisation Chamber
^{238}U target
300 mg ; ø = 33 mm;
(δt = 730 ps; δE = 500 keV; ε = 100%)

MEASUREMENT OF STATISTICAL PROPERTIES OF GAMMA EMISSION IN FISSION (MARCH 2016)

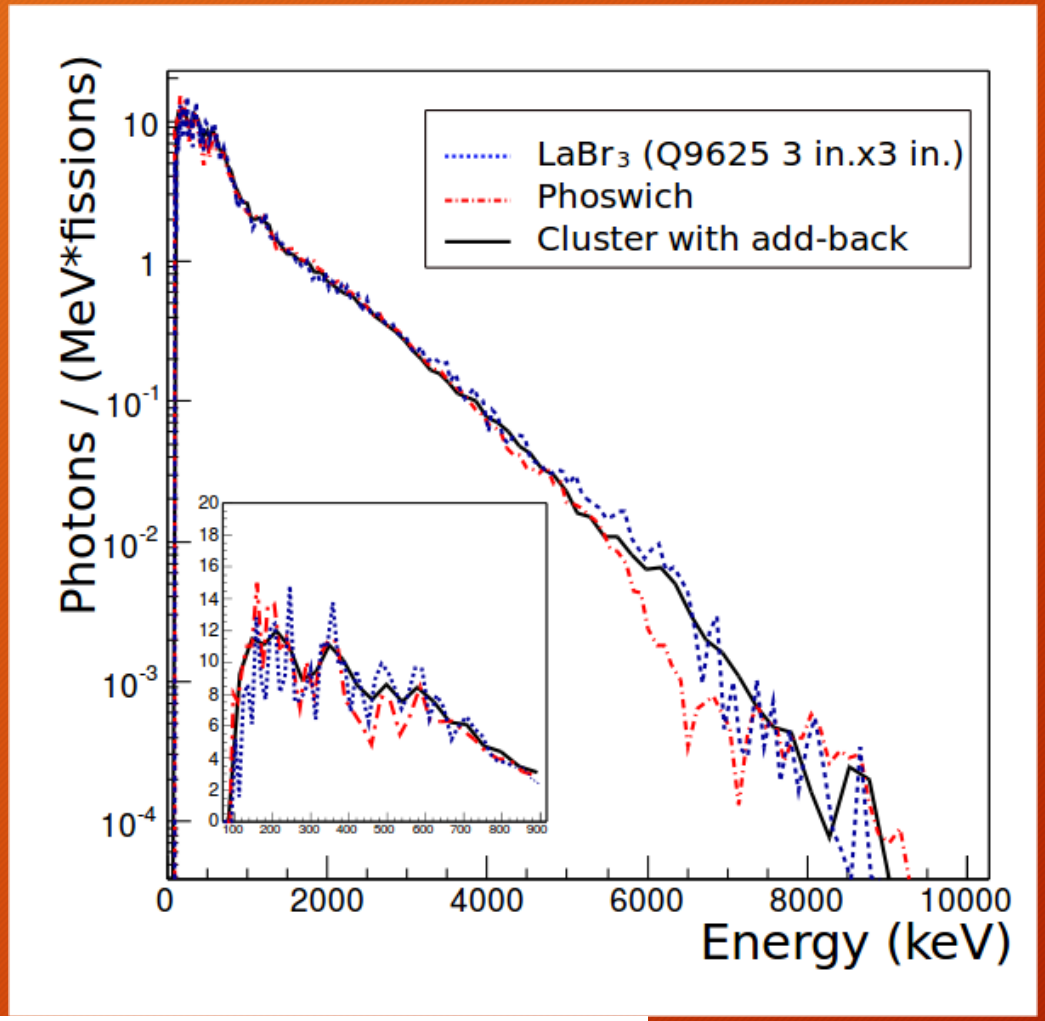


MARCH 2016 EXPERIMENT: DATA ANALYSIS (CALIBRATIONS)





Q. Liqiang, PhD thesis



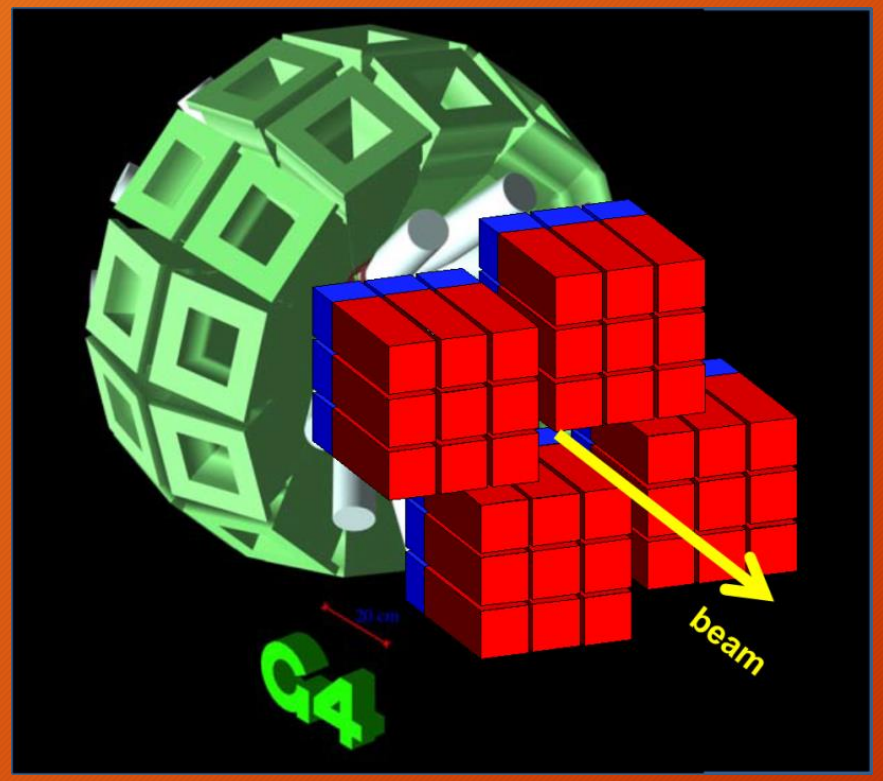
Results	M_γ	$E_{\gamma,tot}$(MeV)	ϵ_γ
This work ($LaBr_3$)	8.30±0.15	6.60±0.05	0.80±0.02
This work (Paris)	8.40±0.19	6.70±0.08	0.80±0.02
R. Billnert et al. [1]	8.30±0.09	6.64±0.10	0.80±0.01
Chyzh et al. [2]	8.14±0.40	7.65±0.55	0.94±0.05
ENDF/B-VII.1	7.85	6.13	0.78

[1] Billnert, R., et al. Physical Review C, 87(2), 024601.

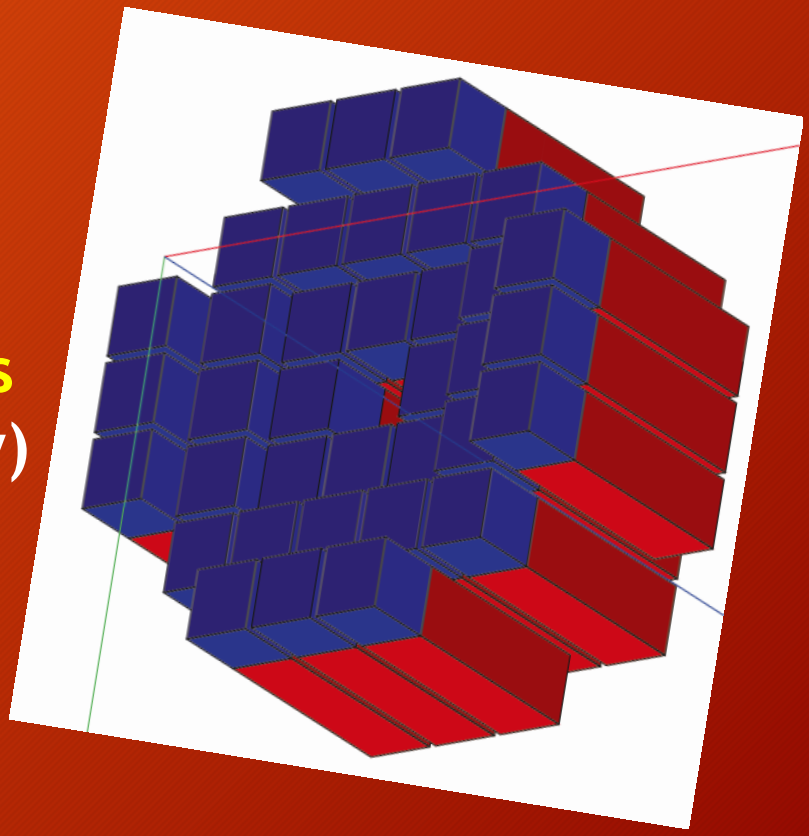
[2] Chyzh, A., et al. Physical Review C, 85(2), 021601.

Experiments accepted for IPN Orsay and planned for 2018

1. B. Blank et al., „Measurement of the super-allowed branching ratio of ^{10}C”
2. P.J. Napiorkowski et al., „Coulomb excitation of super-deformed band in ^{40}Ca”
3. M. Kmiecik, F. Crespi, J. Wilson et al., „Feeding of low-energy structures in ^{188}Pt of different deformations by the GDR decay: the nuBall array coupled to PARIS”

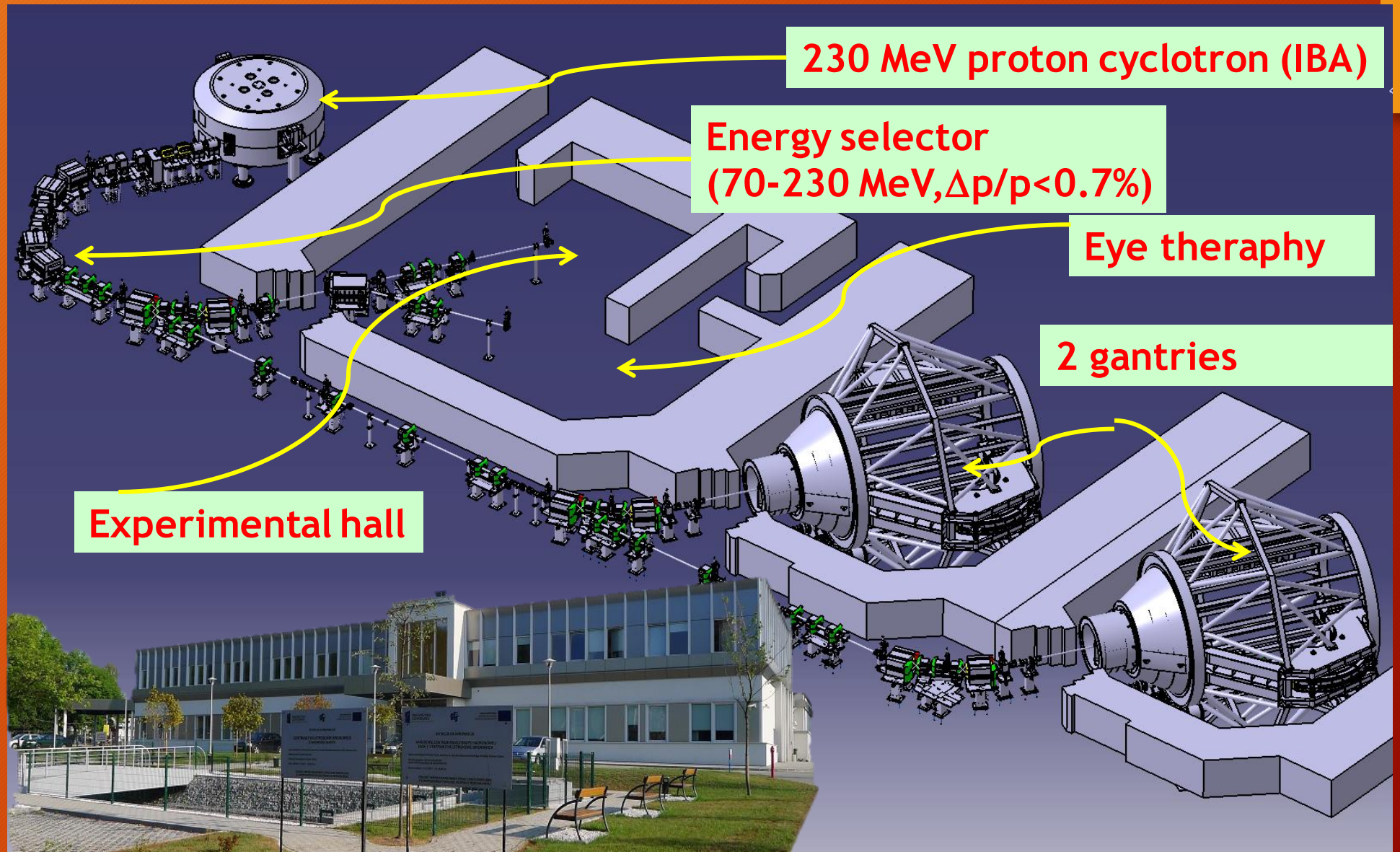


4 clusters
or
36 phoswiches
(wall geometry)



First PARIS experiments in CCB at IFJ PAN Krakow

Cyclotron Center Bronowice (CCB, part of TNA NLC Warsaw-Krakow)
Institute of Nuclear Physics Polish Academy of Sciences
Krakow, Poland

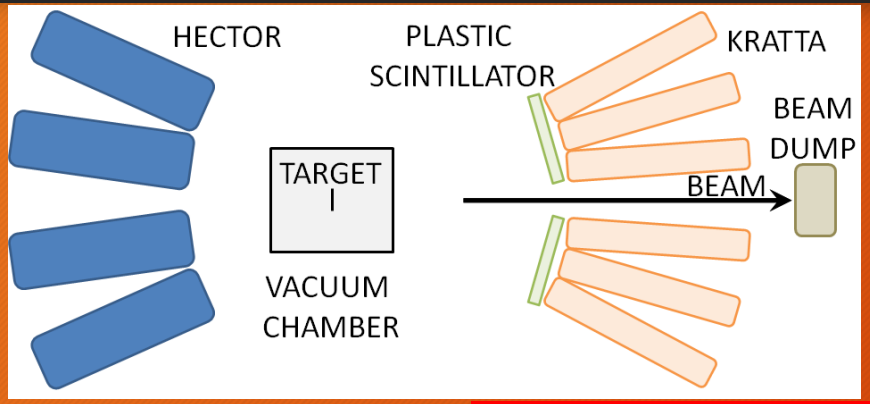


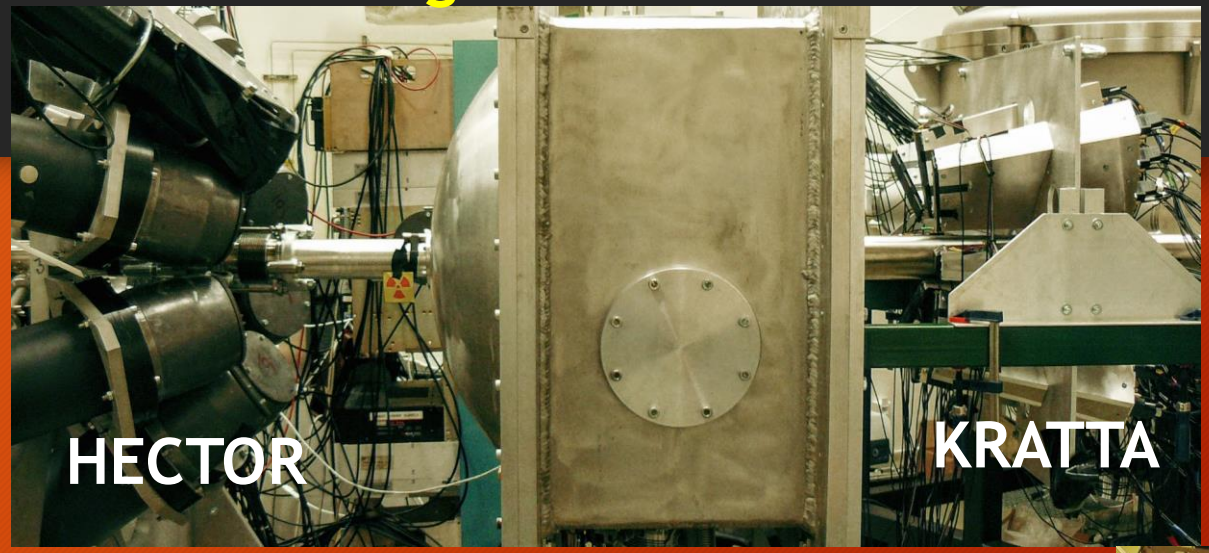
LoI: Studies of resonance states in nuclei using high-energy proton beam in p,p' reactions at forward angles

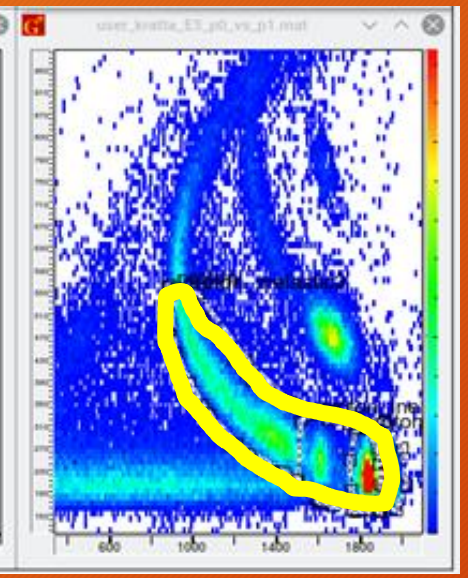
F. Crespi, M. Kmiecik et al.

HECTOR, PARIS, KRATTA

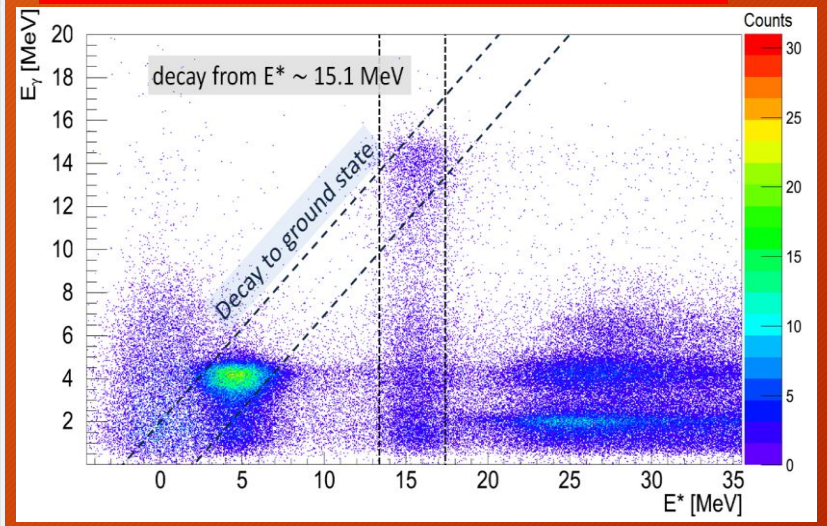
Courtesy of Basia Wasilewska

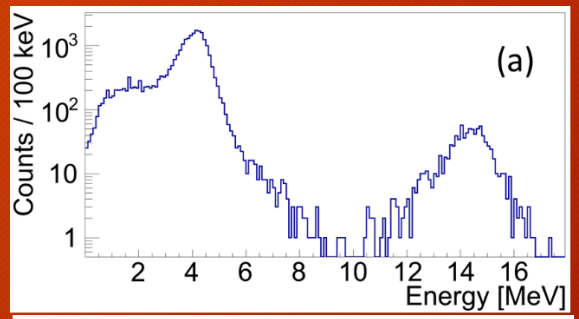


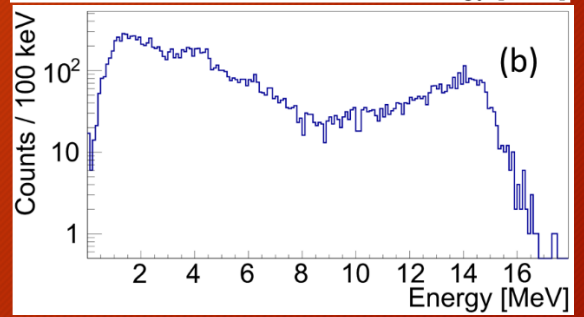




85 MeV p on ^{12}C - calibration

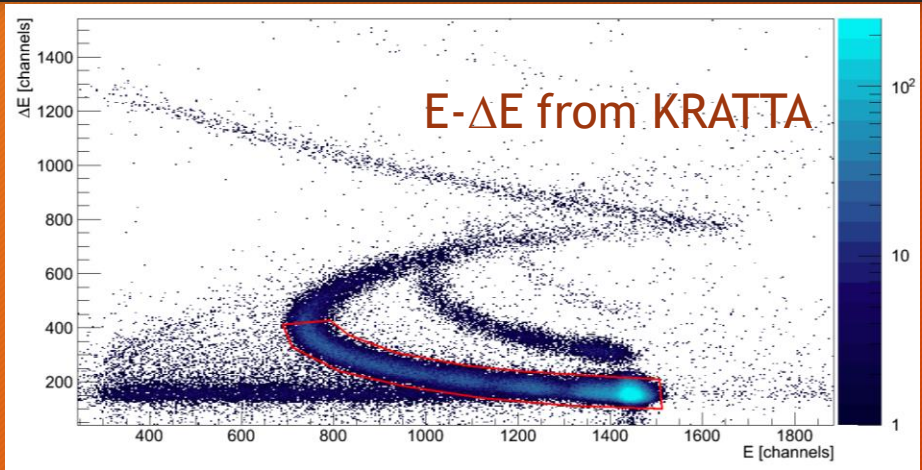


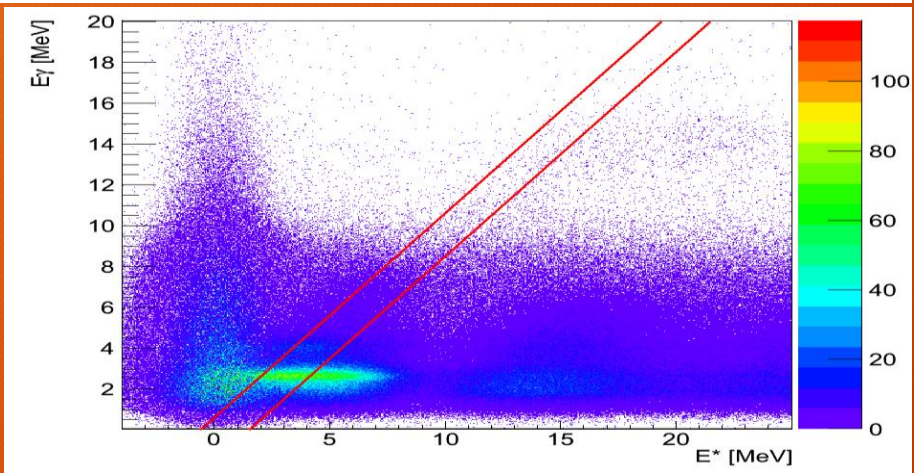


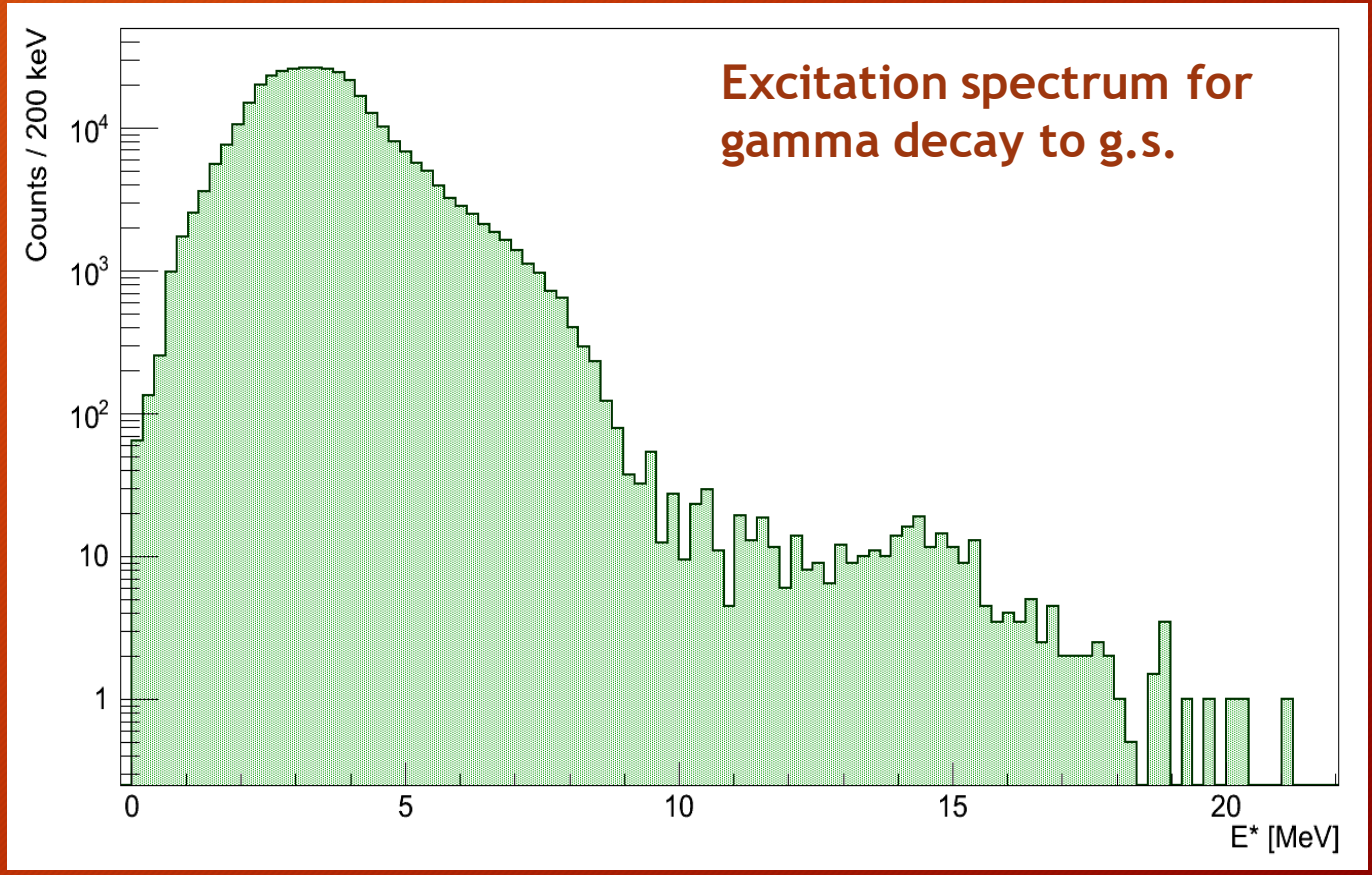


First experiment (March 2017): Studies of gamma decay of GQR (E_{GQR}=10.6 MeV) and GDR (E_{GDR}=13.9 MeV) in ^{208}Pb

85 MeV protons on ^{208}Pb - preliminary results

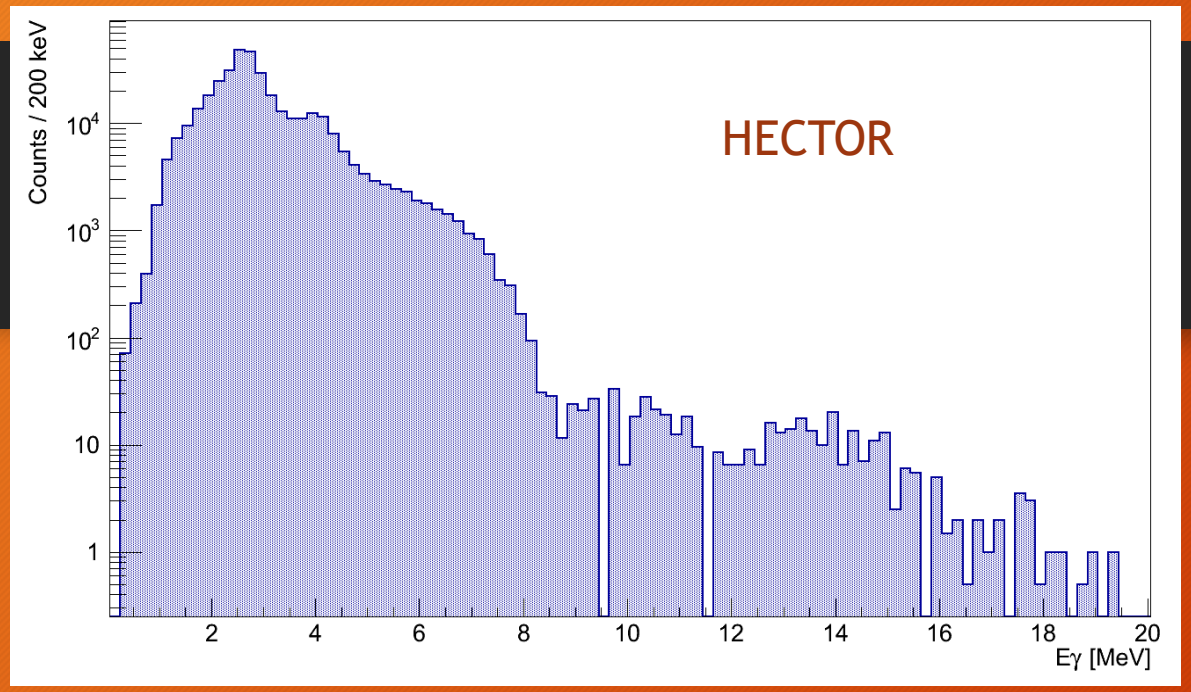




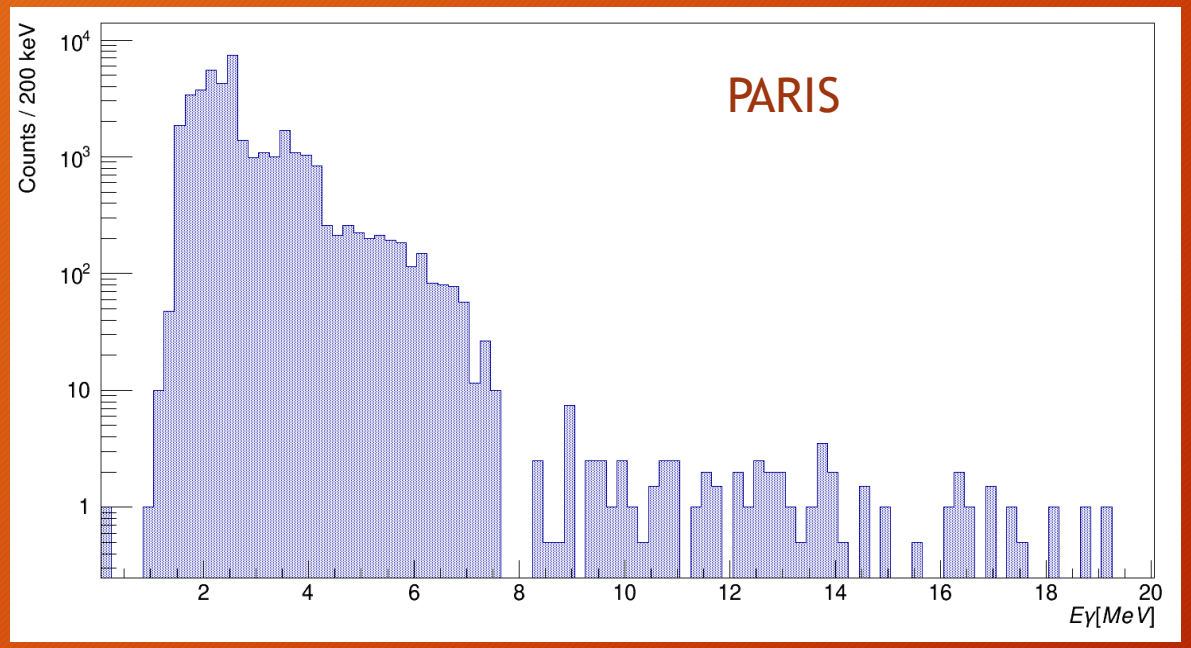


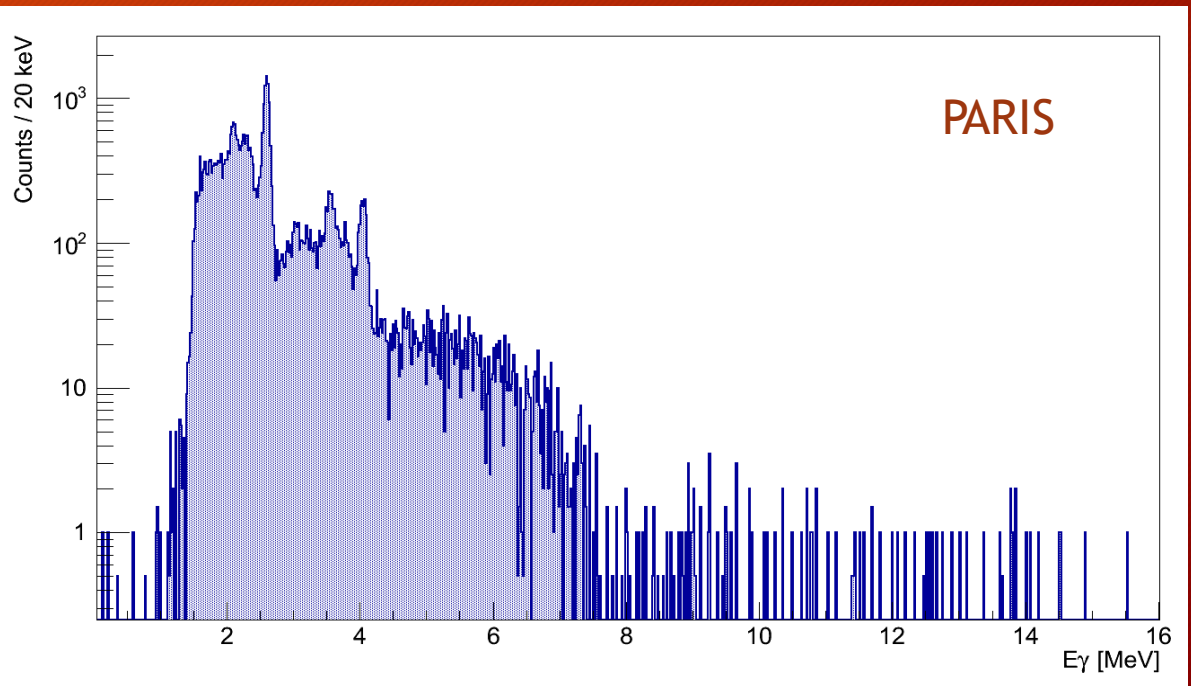
Excitation energy from measured scattered proton energy and angle

Gamma-spectra
Decay to g.s.



Experiment will be continued to gain more statistics





Other accepted experiments at CCB in IFJ PAN Krakow using PARIS (to be done 2017/2018)

- Investigations of (p,2p) reactions in order to identify deep single-particle proton-hole states (Bracco, Fornal): HECTOR, PARIS, KRATTA
- Investigation of proton induced spallation (Ch. Schmitt, D. Mancuzi): HECTOR, PARIS, KRATTA

First PARIS experiments in GANIL (tbd. July 2017 and 2018)

PARIS coupled to AGATA@GANIL (from July 2017)

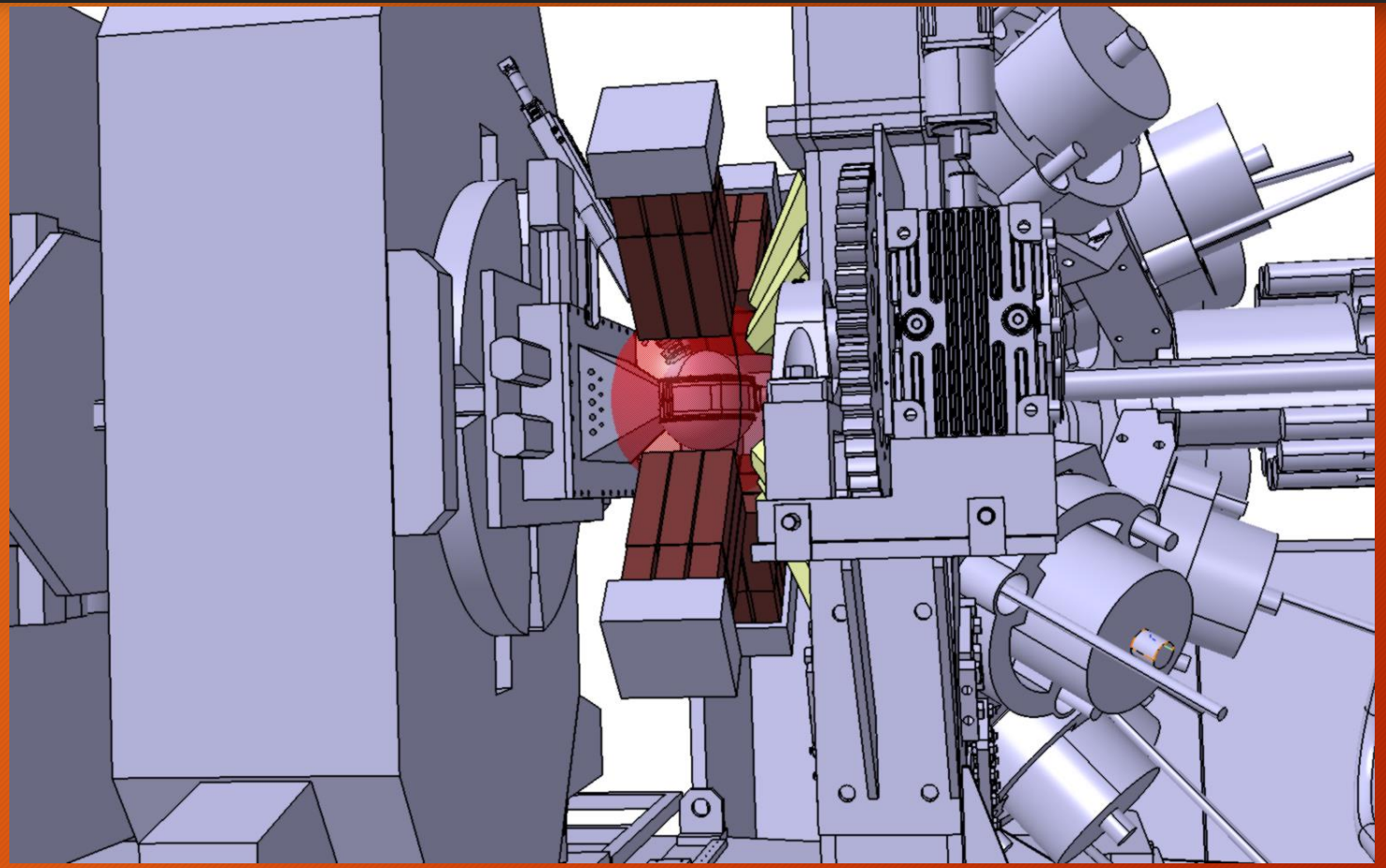
3 proposals accepted by the GANIL PAC

- S. Leoni, B. Fornal, M. Ciemala et al., **Lifetimes in A=18 region measured with PARIS (**2 clusters + 2 large LaBr3), ***AGATA***, ***VAMOS***, ***Plunger*** ***(11-23 July 2017)***

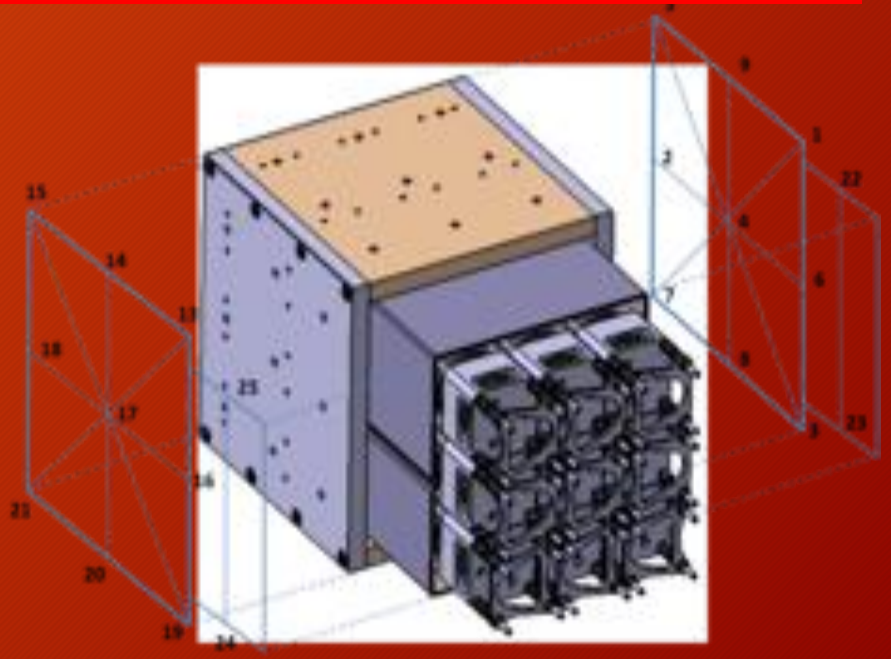
- P. Bednarczyk, A. Maj et al., **Investigation of a high spin structure in ^{44}Ti via discrete and continuumγ-spectroscopy** with ***AGATA***, ***PARIS*** (4 clusters) and ***DIAMANT***

- B. Fornal, S. Leoni, M. Ciemala et al., **„Gamma decay from near-threshold states in 14C: a probe of clusterization phenomena in open quantum systems", AGATA** (4 clusters) **, PARIS, NEDA, DIAMAND, DSSD**

Experimental setup: AGATA, VAMOS, PARIS



A shield for VAMOS magnetic field needed!



LoI for PARIS with LISE@GANIL positively received, proposal will be submitted soon
M. Vanderbrouck, Y. Blumenfeld et al.,
„Study of giant and pygmy resonances in exotic nuclei at LISE",
ACTAR TPC, Chateau de Cristall, CATS, PARIS, large LaBr3

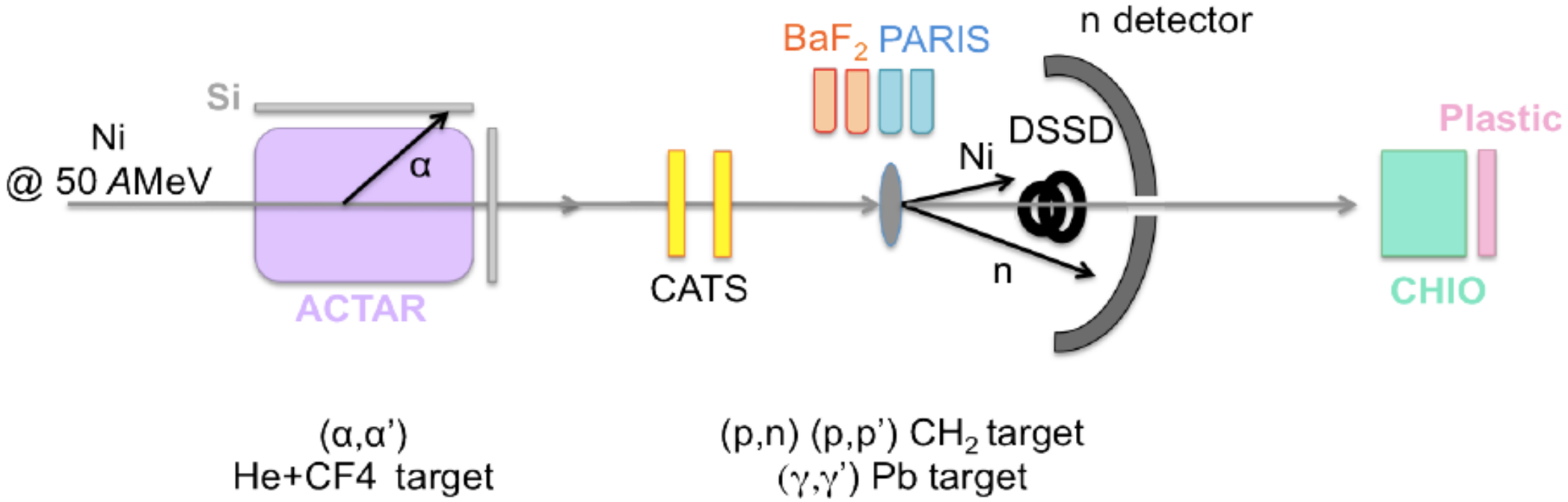


Figure 4: Proposed experimental setup.

7 preliminary LoIs for PARIS4SPES campaign in LNL Legnaro (2019/2020?)

- **GDR decay of hot rotating nuclei in A=130 mass region** (Maj, Leoni): GALLILEO, RFD
- **Measurement of Isospin Mixing in N=Z medium mass nuclei** (F. Camera): HECTOR+, GALLILEO
- **Measurement of the Dynamical Dipole emission** and the symmetry term of the EOS (F. Camera, G. Casini): HECTOR+, fusion_evaporation det.
- **Entry distributions for fragments produced in deep- inelastic collisions** with stable and radioactive beams (Królas)
- **Heavy-ion binary reactions** as a tool for detailed gamma spectroscopy in exotic regions (Leoni, Maj): PRISMA, GALILEO
- **High-spin gamma ray spectroscopy of heavy, octupole deformed Ac and Fr** nuclei produced in fusion evaporation reactions with the intense A~90 Rb radioactive beams at SPES (Bednarczyk): GALILEO
- **GDR feeding od the SD bands in A=30-60 region** (P. Bednarczyk, M. Kmiecik, F. Camera)

Possible use of PARIS at DESPEC?

Discussion during HISPEC/DESPEC meeting
York, September 27-28, 2016

GSI/FAIR

Generally - in all cases where the efficiency is the most important factor and not neccesseary the energy resolution

- Experiments in which PARIS could be a complementary detector to TAS
- Astrophysical experiments
- Beta decay to PDR states
- Beta delayed neutron emission
- Spectroscopy of very exotic (=rare) nuclei
- g-factor measurements (PARIS clusters have magnetic shieldins)
- ….

Conclusions

- **LaBr3+NaI phoswich is a viable solution for the elements of the PARIS calorimeter, also in terms of its meeting the requirements for energy and timing resolution**
- **Presently we explore the performance of 1 cluster of 9 phoswich detectors. Source and in-beam testing were done recently**
- **First experiments with 1 cluster were done in 2 TNA facilities: IPN Orsay and CCB at IFJ PAN Krakow.**
- **Soon experimental campaings in which PARIS will be coupled to AGATA will start in GANIL**
- **Other possible PARIS experiments, also in another TNA facilities (e.g. LNL Legnaro, GSI/FAIR), are discussed**

Acknowledgements

- M. Ciemała, M. Kmiecik, B. Wasilewska, B. Fornal, P. Bednarczyk (IFJ PAN Kraków)
- A. Bracco, S. Leoni, S. Brambilla. F. Crespi, F. Camera (University of Milano)
- O. Dorvaux, C. Schmitt (IHPC Strasbourg)
- M. Lebois, Q. Liqiang, J. Wilson, I. Matea (IPN Orsay)
- P. Napiorkowski (HIL Warsaw)
- J. Harca (JINR Dubna)
- M. Harakeh (KVI Groningen)
- M. Lewitowicz (GANIL)

- Technical staff of IPN Orsay, IFJ PAN Krakow, GANIL Caen

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