# Rotation induced shapes and collective phenomena in excited atomic nuclei

*An overview of studies coordinated by groups from IFJ PAN Krakow and HIL Warsaw*

**Adam Maj** (IFJ PAN Krakow)

*Thanks to:*
M. Kmiecik, P. Bednarczyk, M. Ciemała, B. Wasilewska (Krakow)
P. Napiorkowski, K. Hadyńska-Klęk, E. Grodner, J. Srebrny (Warsaw)
M. Zielińska (Saclay)
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F. Gramegna (Legnaro)
*and*
*EUROBALL, AGATA, HECTOR, PARIS and GARFIELD collaborations*

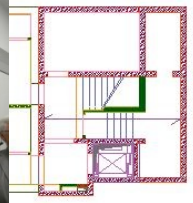
*and Rafał Maj for the animations*

SSNET'17
International Conference on Shapes and Symmetries in Nuclei: from Experiment to Theory
Gif sur Yvette, November 6th - 10th 2017

# INTRODUCTION


WARSZAWA
Warsaw University
(with Heavy Ion Laboratory)
KRAKÓW
Institute of Nuclear Physics
(with Cyclotron Centre
Bronowice)
POLSKA
DENMARK
RUSSIA
BELARUS
UKRAJINA
SLOVAKIA
GERMANY
Morze Bałtyckie
Pomorze
Warszawa
Kraków
Gdańsk
Gdynia
Bydgoszcz
Toruń
Poznań
Łódź
Wrocław
Katowice
Lublin
Białystok
Rzeszów
Kielce
Częstochowa
Szczecin
Koszalin
Olsztyn
Elbląg
Włocławek
Radom
Płock
Kalisz
Konin
Piła
Leszno
Zielona Góra
Gorzów Wielkopolski
Legnica
Wałbrzych
Opole
Bielsko-Biała
Tarnobrzeg
Mielec
Jarosław
Przemyśl
Sanok
Krosno
Jasło
Dębica
Stalowa Wola
Zamość
Chełm
Puławy
Skierniewice
Piaseczno
Ostrołęka
Łomża
Ciechanów
Biała Podlaska
Brest
Kobryn
Vawkavysk
Slonim
Kovel'
Novovolyns'k
L'viv
Drogobyč
Stryj
Sambir
Humenné
Prešov
Žilina
Považská Bystrica
Beskidy
Wisła
Bug
Warta
Odra
Notec
Zatoka Gdańska
Zalew Wiślany
Zatoka Pomorska
Kaliningrad
Marijampolė
Wejherowo
Lębork
Słupsk
Tczew
Malbork
Starogard Gdański
Kwidzyn
Chojnice
Grudziądz
Kołobrzeg
Świnoujście
Szczecinek
Stargard Szczeciński
Wagrowiec
Gniezno
Ostrów Wielkopolski
Kutno
Pabianice
Tomaszów Mazowiecki
Piotrków Trybunalski
Bełchatów
Sieradz
Skarżysko-Kamienna
Kraśnik
Ostrowiec Świętokrzyski
Radomsko
Lubin
Bolesławiec
Nysa Zamłynie
Zabrze
Gliwice
Tychy
Racibórz
Sosnowiec
Dębica
Frankfurt/ Oder
Cottbus
Hoyerswerda
Dresden
Görlitz
Pirna
Děčín
Liberec
Ústí nad Labem
Teplice
Hradec Králové

**GE PETTrace**
Cyclotron
for
Radioisotope and
Radiopharmaceutical
Production

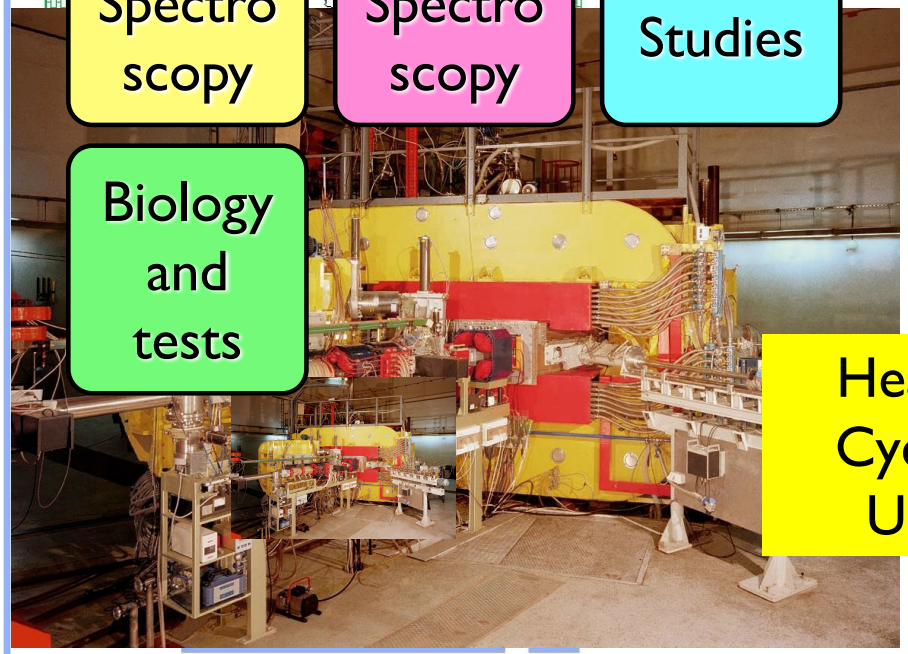


Offline Spectro scopy

Gamma Spectro scopy

Reaction Studies

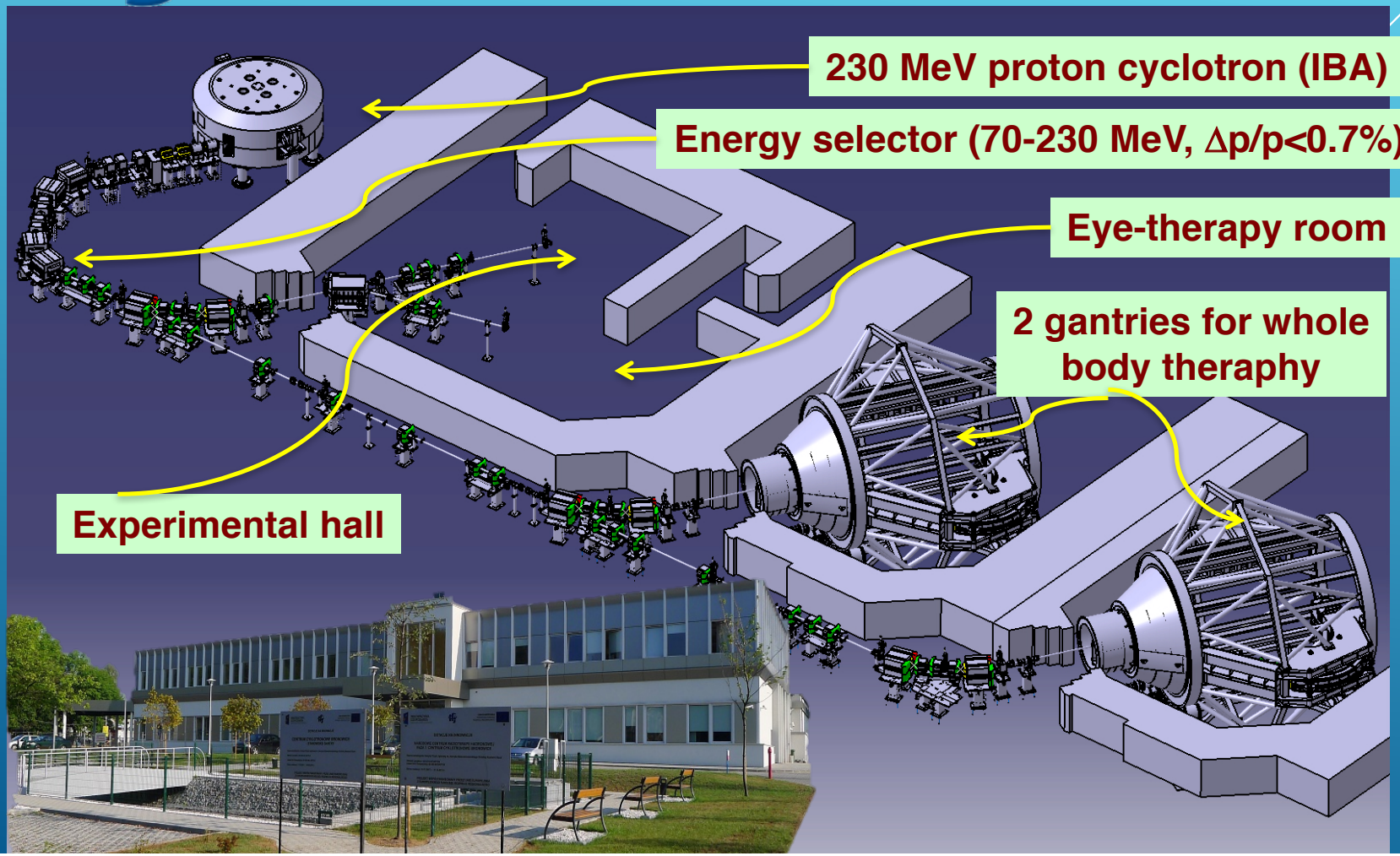
Biology and tests



Heavy Ion Cyclotron U-200P

HIL ŚLCJ

# Cyclotron Center Bronowice
# Institute of Nuclear Physics Polish Academy of Sciences
# Krakow, Poland



# National Laboratory of Cyclotrons
## Warsaw / Kraków

A consortium between HIL UW and IFJ PAN

The nuclear physics research programme of NLC aims at obtaining high quality data on nuclear properties at and around the valley of stability. Therefore, it is complementary to the programmes of large-scale European RIs, which are concentrated on the physics of nuclei very far from the stability line, often at the limits of detection.

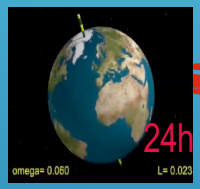
The investigations carried out in Warsaw and Kraków are also in many aspects complementary - at CCB high-energy proton beam is available while at SLCJ beams of heavier nuclei from boron to argon can be accelerated.

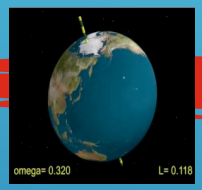
From 2016 NLC (CCB at IFJ PAN and HIL at Warsaw University) is a part of the HORIZON2020 ENSAR2 project as Transnational Access Facility

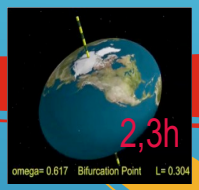
# MOTIVATION

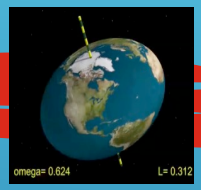
# Evolution paths of the rotating gravitating bodies

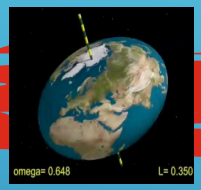
## McLaurin shapes

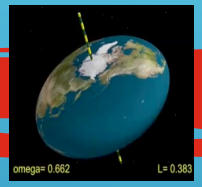


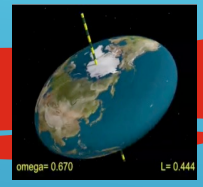



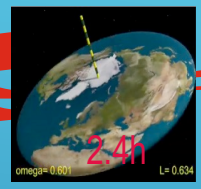



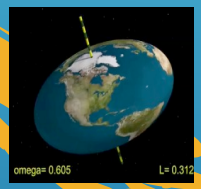



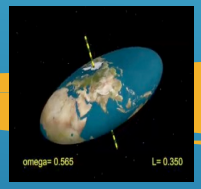



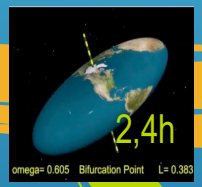



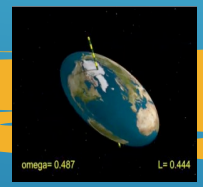



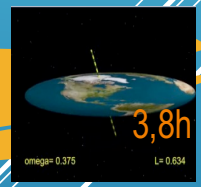



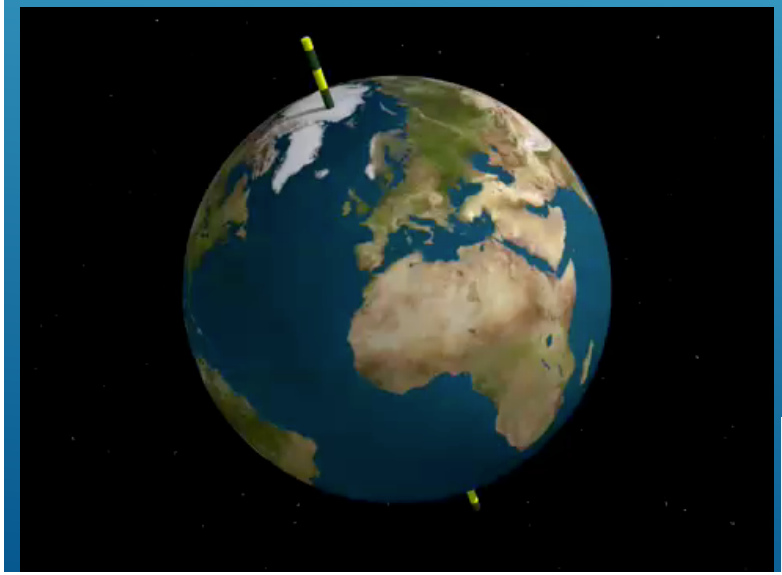

## Jacobi shapes



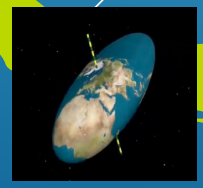



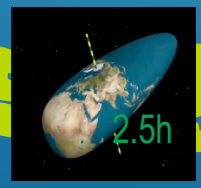



## Poincare shapes



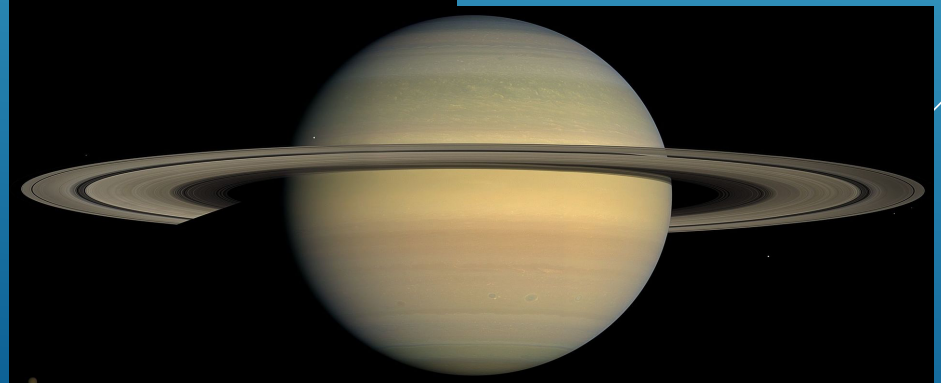



*Based on talk by Prof.. Etienne Ghys*
*of the Unité de Mathématiques*
*Pures et Appliquées de l'E.N.S. de Lyon*
*www.josleys.com/show_gallery.php?galid=313*

**Earth**
Period of rotation = 24h
Equator speed = 0.5 km/s
Flateness ≈ 0.3%

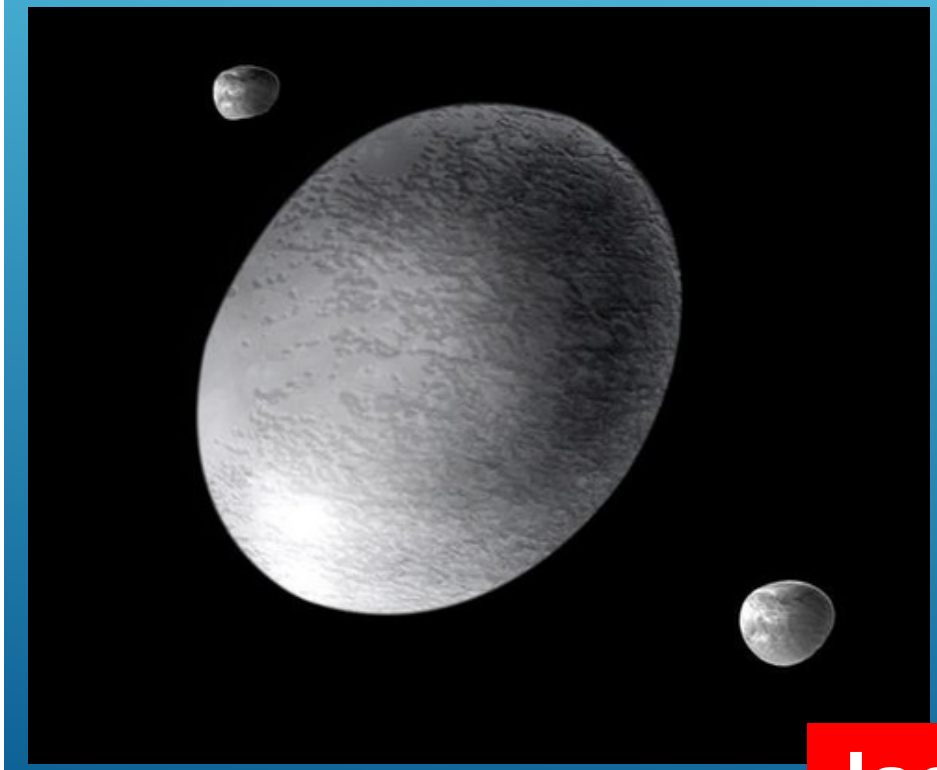
**Jupiter**
Period of rotation = 9h 50m
Equator speed = 12.6 km/s
Flateness ≈ 6.5%

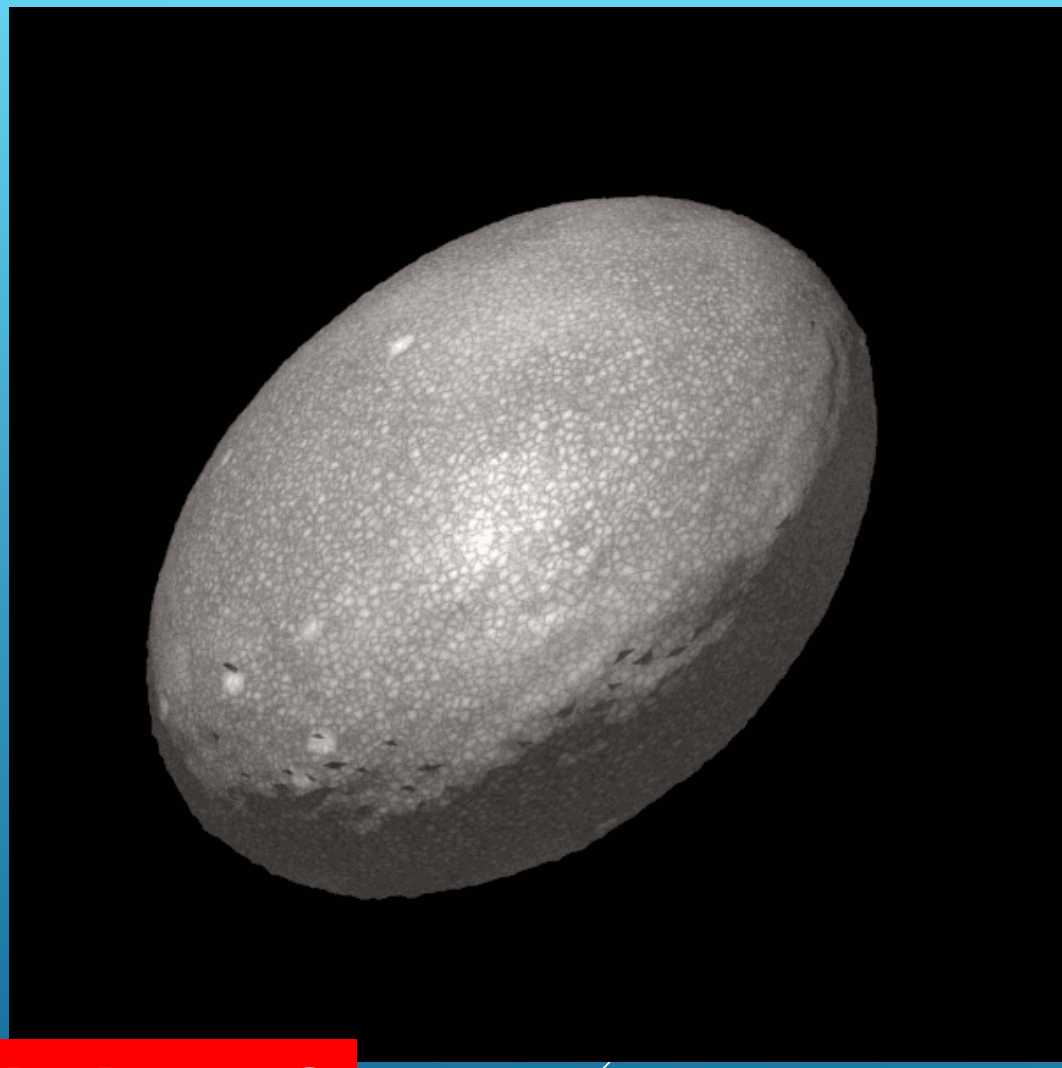
**Saturn**
Period of rotation = 10h 39m
Equator speed = 9.9 km/s
Spłaszczenie ≈ 10%



# MacLaurin shapes

**Haumea** (a dwarf planet in the Kuiper belt with 2 moons: Hi'iak and Namaka)
**Period of rotation = 3h 54m**
**Pole speed = 0.5 km/s**
**Dimensions: 1960 x 1518 x 996 (km)**
**3-axial shape: 2 : 1.5 : 1**





**Jacobi shape?**

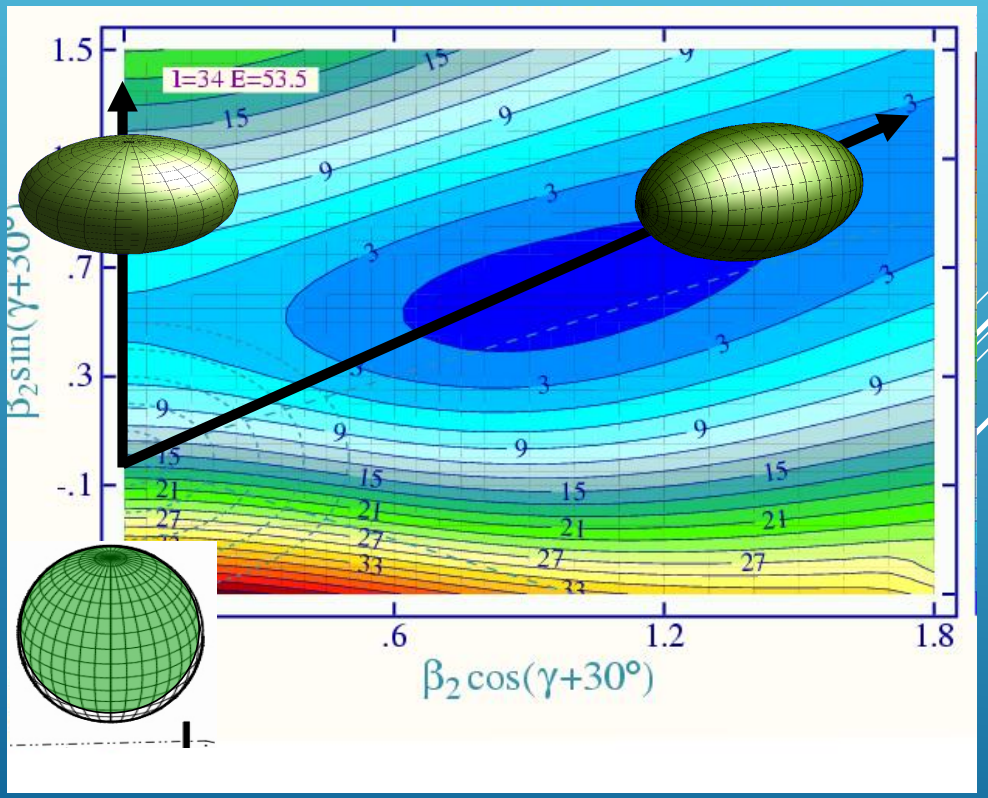
*(source: Wikipedia)*

## And what might happen in rotating nuclei?

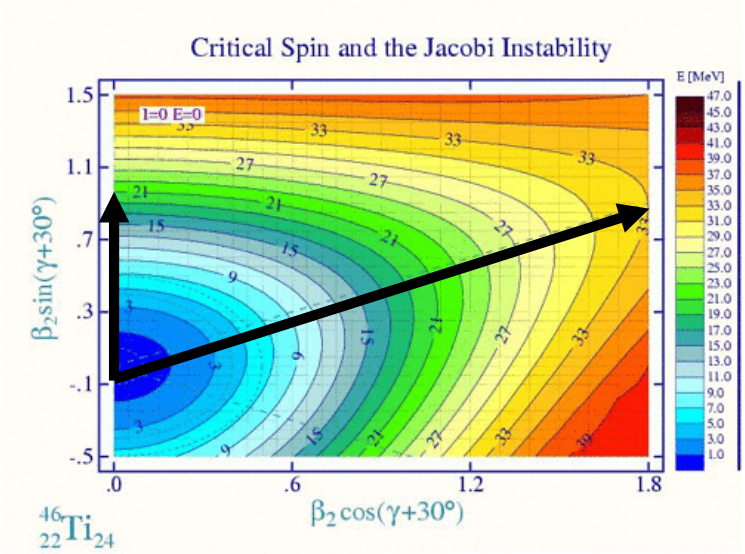
- R. Beringer, W.K. Knox, *Phys. Rev.* 121 (1961) 1195: **In hot roating nuclei Jacobi shape might occur**

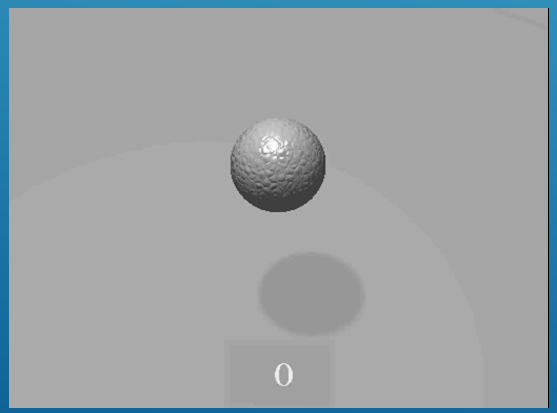
- S. Cohen, F. Plasil, W.J. Swiatecki, *Ann. Phys. (N.Y.)* 82 (1974 ) 557: **Rotating liquid drop model**

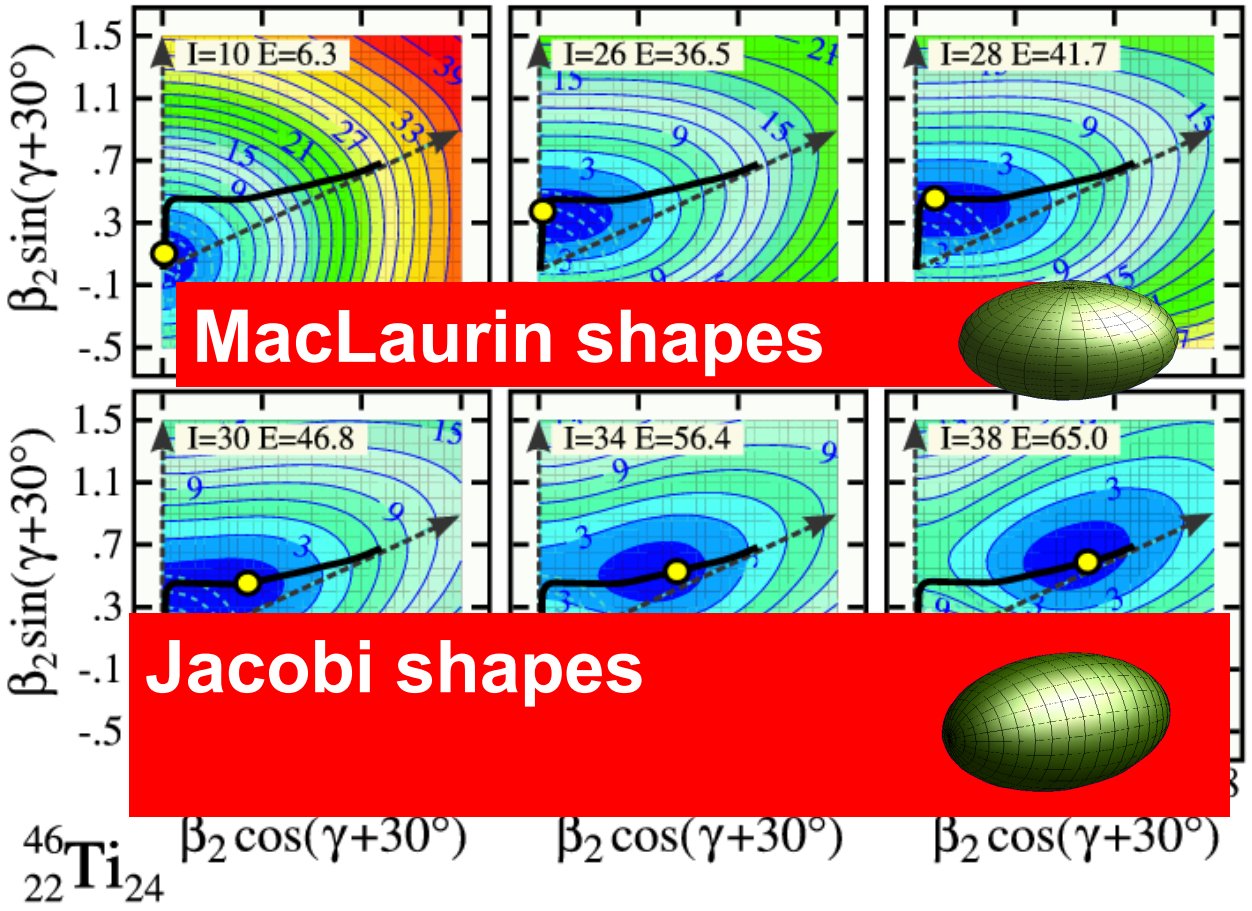
- K. Pomorski, J. Dudek, *Phys. Rev.* C67 (2003) 044316: **LSD (Lublin-Strasbourg Drop) Model**



# Expected shape evolution for $^{46}$Ti in LSD model



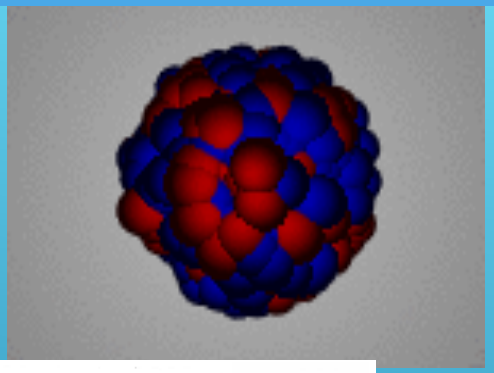






**Shape evoluton**: Sphere➔disc➔tri-axial elipsoid➔"cigar" (➔fission)

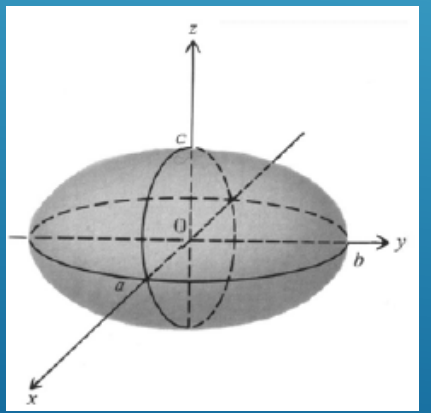
# Giant Dipole Resonance (GDR) – a tool to study shapes of hot nuclei

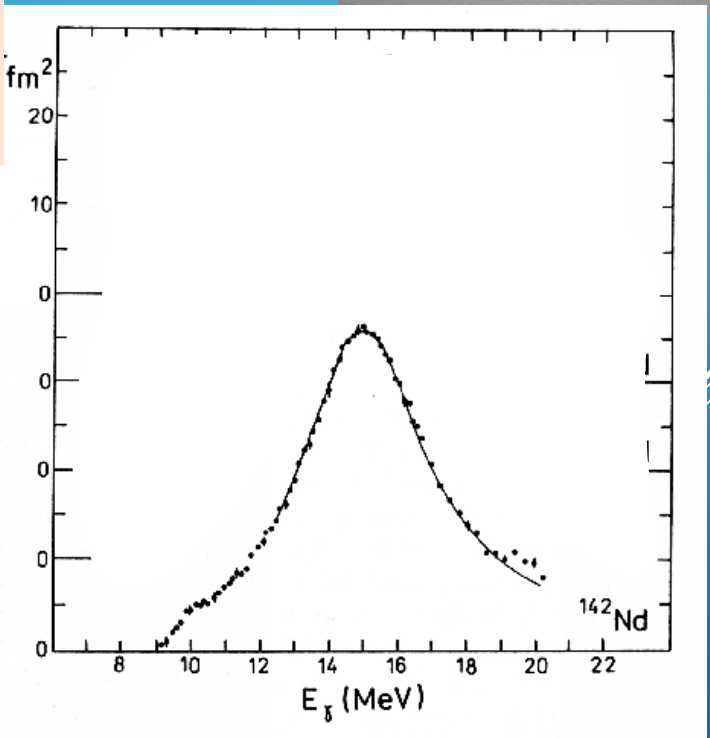
GDR – collective oscillation of all protons against all neutrons



$$E_{GDR} = \hbar\varpi \approx \frac{79}{A^{1/3}} MeV \propto \frac{1}{R}$$

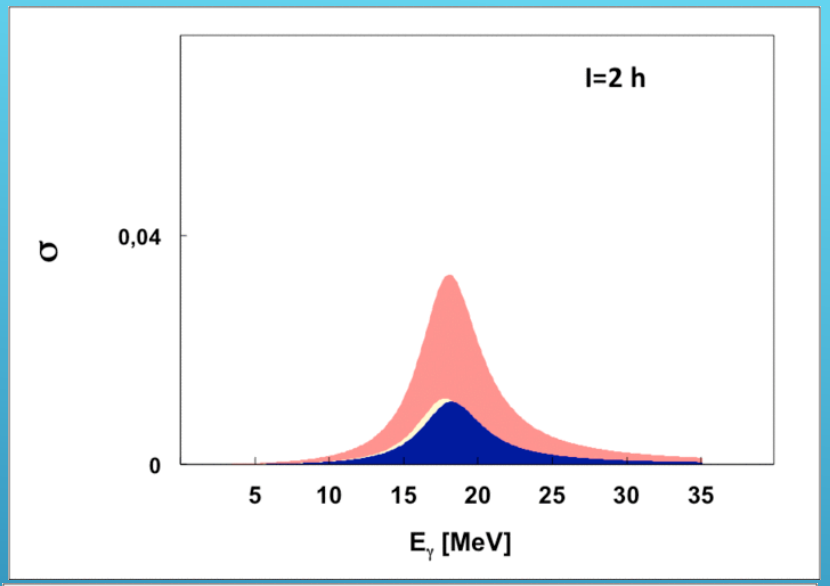
$$E_k = \hbar\omega_k = \hbar\omega_{GDR} \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos(\gamma - \frac{2\pi}{3}k)\right]$$



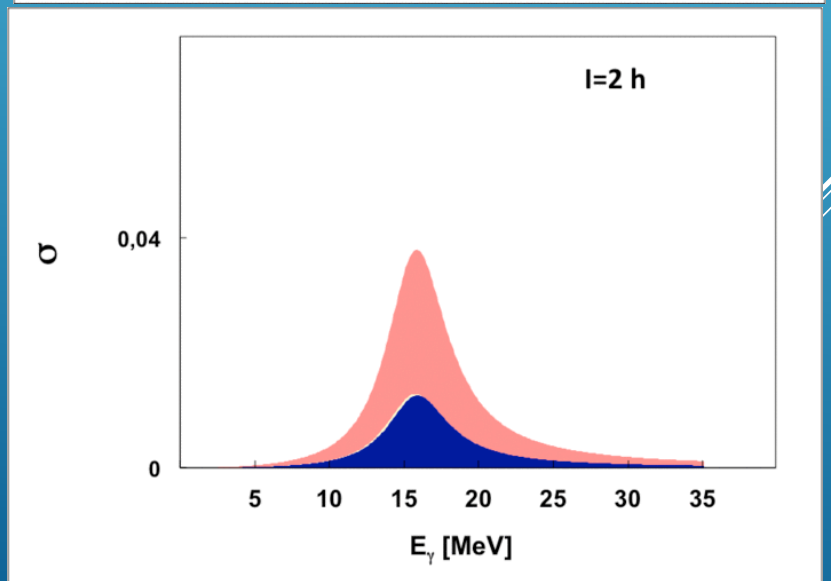



**Appearance of low energy component in GDR strenght function – an indicator for Jacobi shapes**

$^{46}$Ti




$^{88}$Mo



# EXPERIMENTAL HIGHLIGHTS

## High-spin spectroscopy group in IFJ PAN Krakow

P. Bednarczyk, J. Styczen, W. Męczynski, M. Lach, K. Zuber, M. Matejska-Minda, A. Maj et al.

Collaboration with groups of D. Curien, G. Duchen, J. Dudek (Strasbourg), G. De Angelis (LNL Legnaro)

**High spin structure, band termination, search for superdeformation etc. in the mass region 40 < A < 90**
**Constracting RFD (Recoil Filter Detector) and using it with Ge-arrays**

*Cf. Talk by Piotr Bednarczyk on Friday*

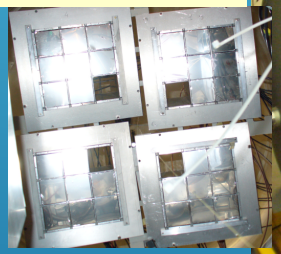
# Giant Dipole Resonance group at IFJ PAN Krakow

A. Maj, M. Kmiecik, B. Fornal, M. Ciemala, B. Wasilewska, K. Mazurek et al.

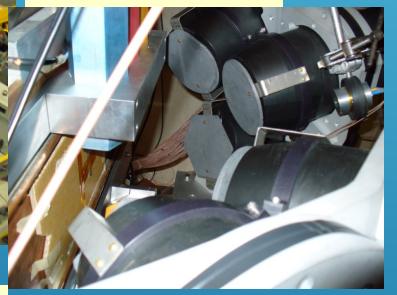
Collaboration with groups of A. Bracco (Milano), J. Dudek (Strasbourg), M. Kicińska-Habiow (Warsaw)

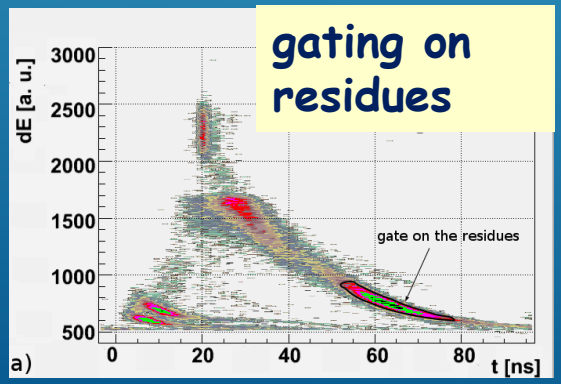
**Example of a highlight: GDR strength function in $^{88}$Mo at very high temperatures**

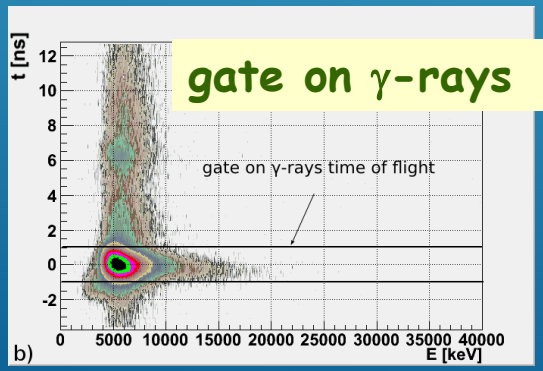
phoswich detectors




HECTOR detectors






**Experiment performed in LNL Legnaro**

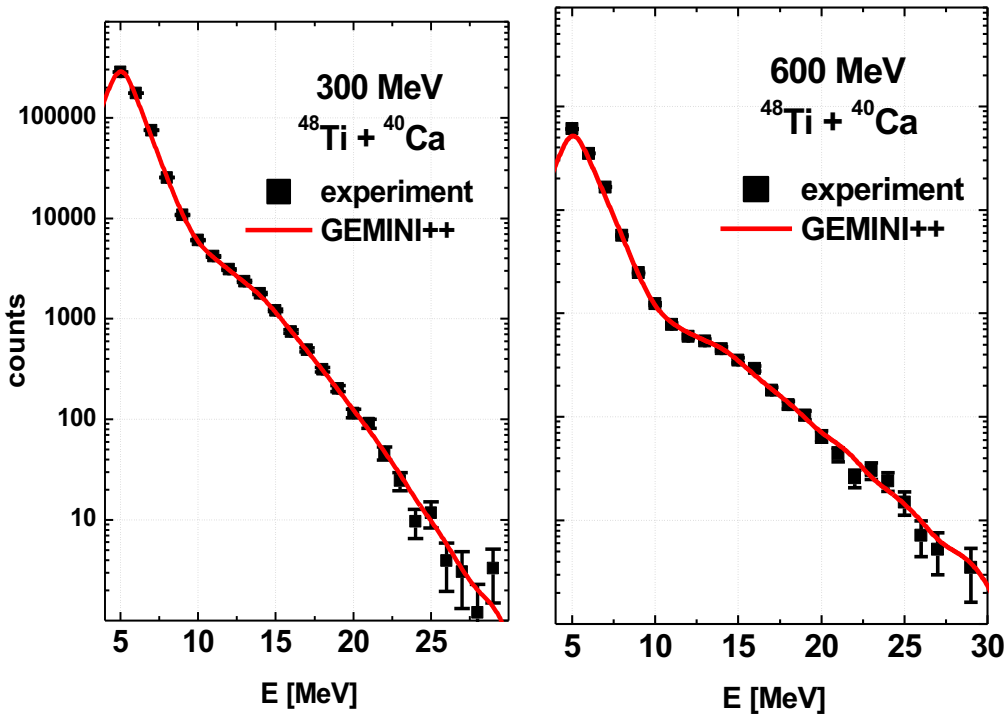
**300, 600 MeV $^{48}$Ti on $^{40}$Ca target**

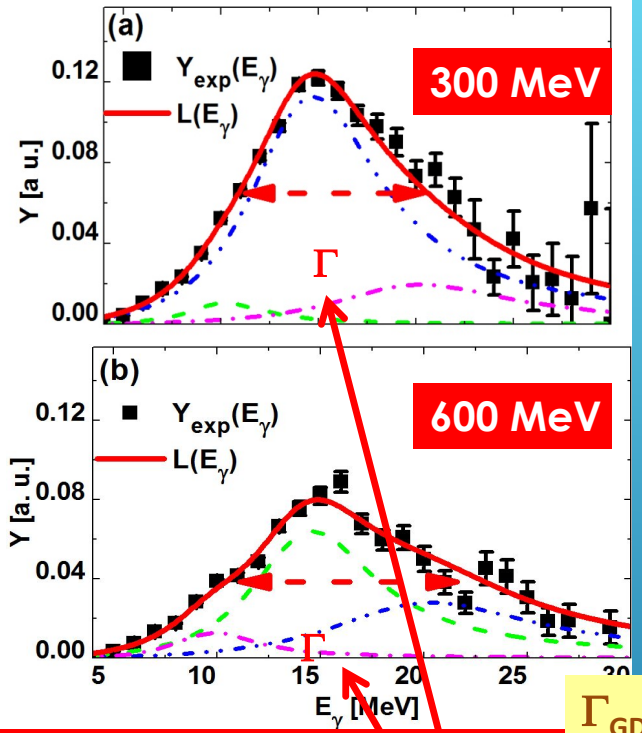
$^{88}$Mo E* = 125, 262 MeV

T = 3, 4.5 MeV

$L_{max}$ > L for fission barrier

## Results



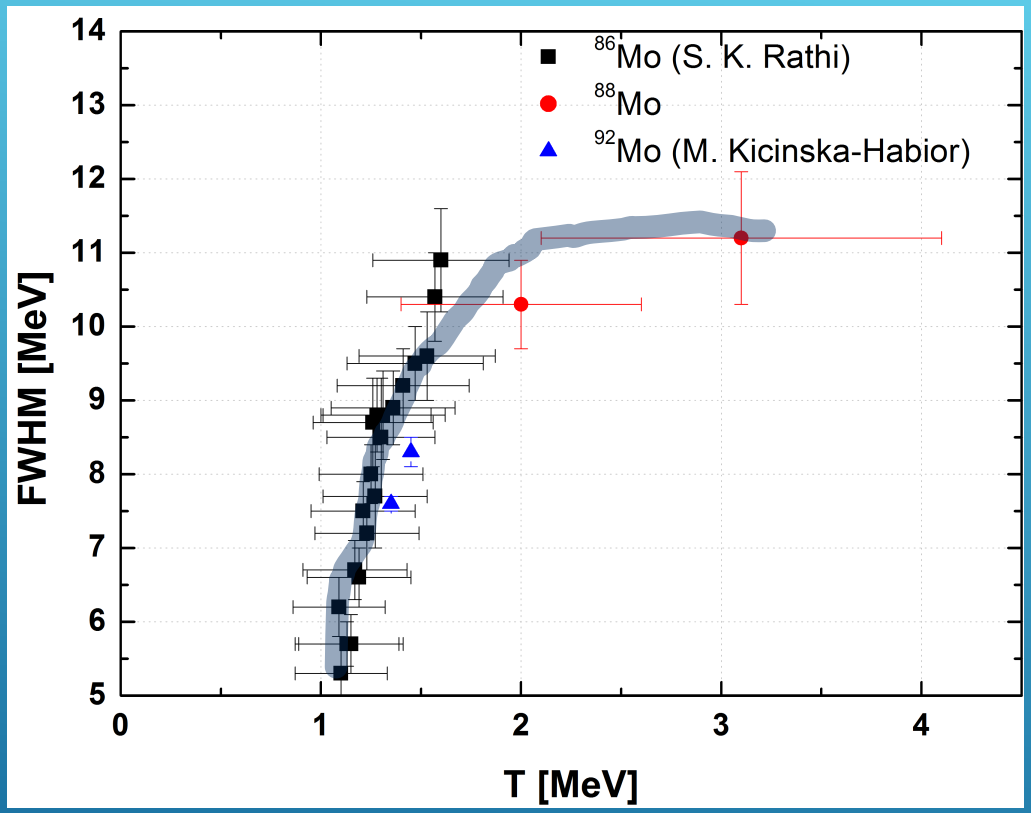




Effective width Γ - FWHM of strength function

$\Gamma_{GDR300} = 9.9 \pm 0.7$ MeV

$\Gamma_{GDR600} = 10.3 \pm 0.9$ MeV

M. Ciemala et al.,
Phys.Rev. C 91, 054313 (2015)




M. Ciemala et al.,
Phys.Rev. C 91, 054313 (2015)

**Obtained GDR width were compared with previously measured in nuclei from $^{88}$Mo region**

*S.K. Rathi et al., Phys. Rev. C 67 (2003) 024603*

*M. Kicińska-Habior et al., Phys. Rev. C 45 (1992) 569*

**Results indicate onset of the GDR width saturation for T > 2 MeV.**

# High-spin and GDR group at IFJ PAN Krakow

A. Maj, M. Kmiecik, P. Bednarczyk, J. Styczen, M. Ciemala, K. Mazurek et al.

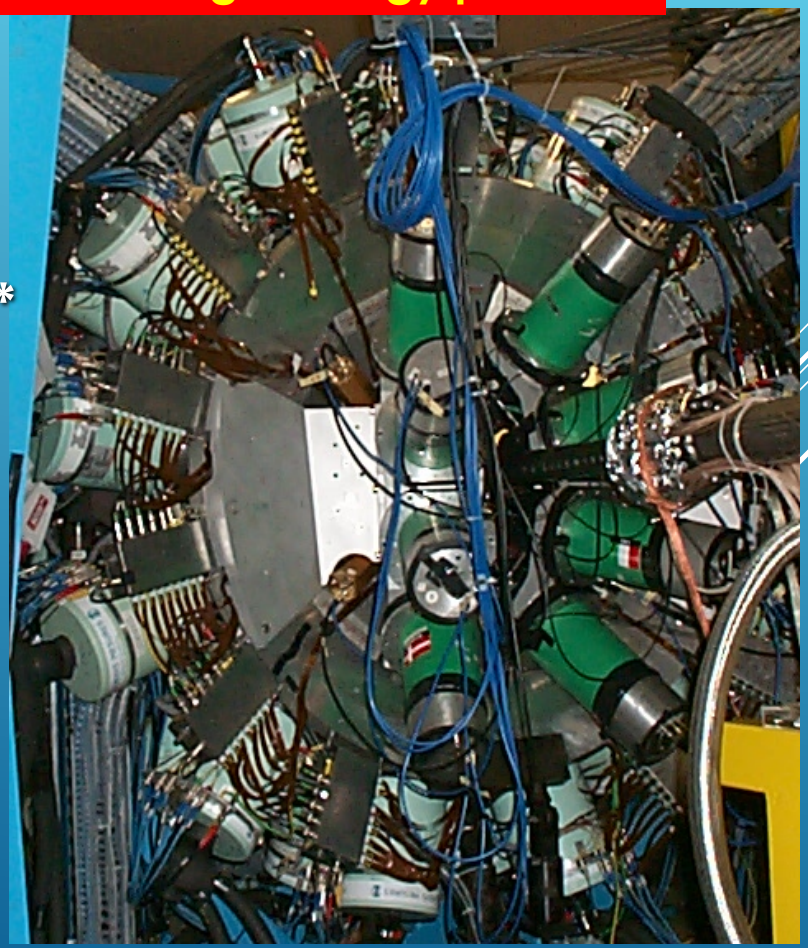
Collaboration with groups of A. Bracco (Milano), J. Dudek (Strasbourg)

**Measurements of coincidences between discrete transitions anf high-energy photons**

## Experiments in Strasbourg (France)
## HECTOR + EUROBALL

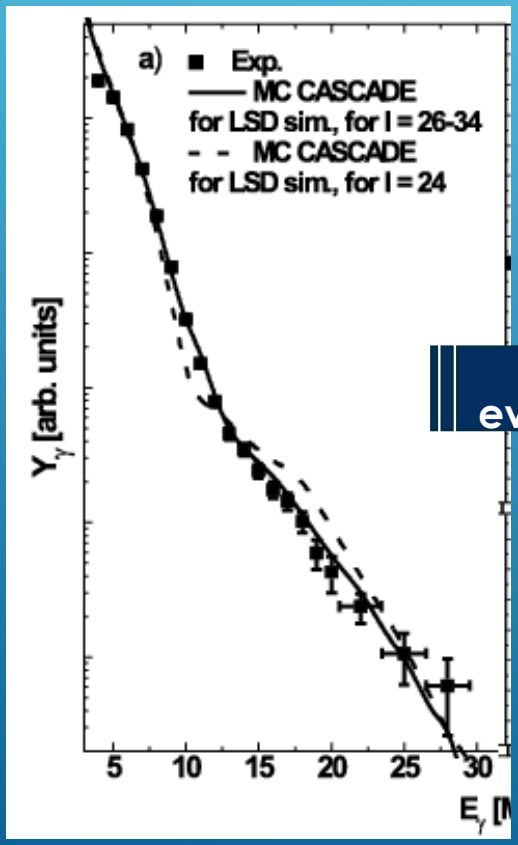
105 MeV $^{18}O + ^{28}Si \Rightarrow ^{46}Ti^*$

$I_{max} \approx 35\ \hbar$, E* = 88 MeV



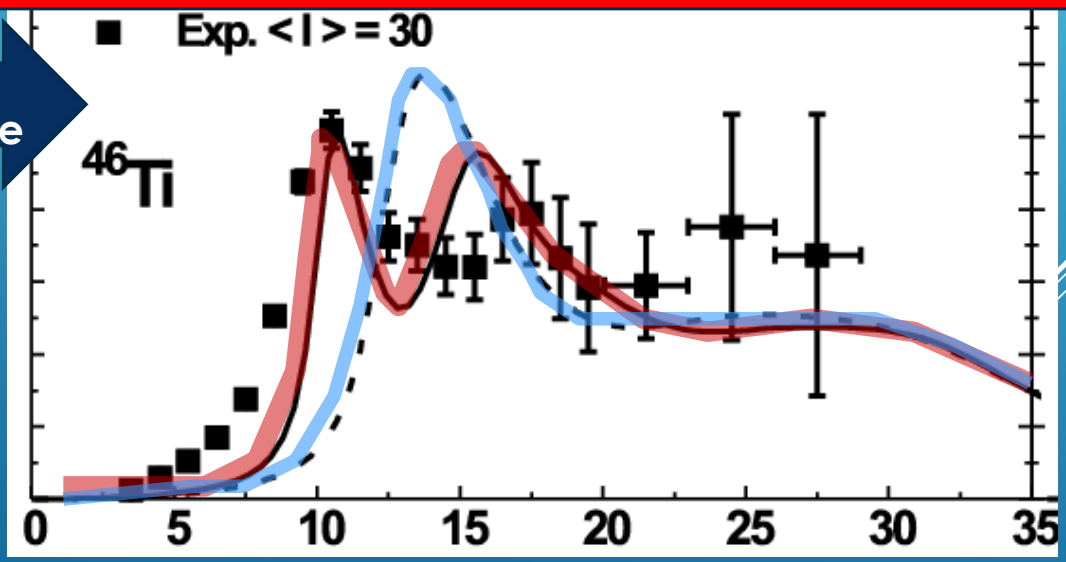
A.Maj et al., Nucl. Phys. A731, 319 (2004)
A.Maj et al., Eur. Phys. J. A20, 165 (2004)
M. Kmiecik et al., Acta Phys. Pol. B36, 1169 (2005)

## High-energy gamma spectra from the GDR decay in $^{46}$Ti in coincidenes with discrete transitions in $^{42}$Ca



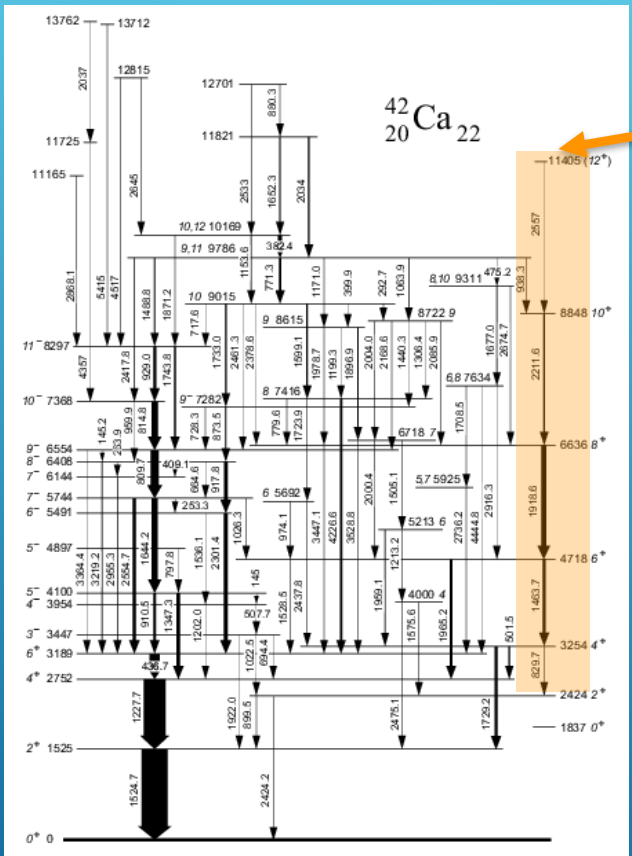

- Demonstration *(for the first time)* of the existence of nuclear Jacobi shapes in $^{46}$Ti at high spins
- Illustration of the Coriolis splitting of the GDR strength function

Statistical evaporation code

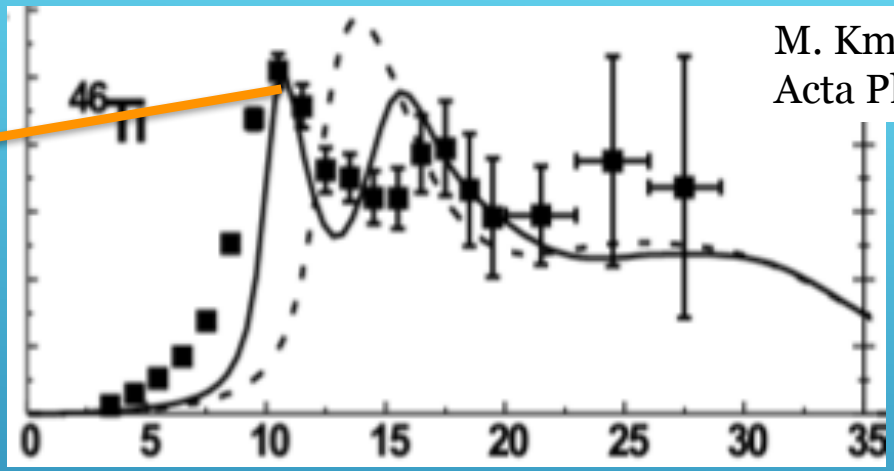



A.Maj et al., Nucl. Phys. A731, 319 (2004)

# Additional observation




*Level scheme:*
*M. Lach et al., Eur Phys J. A12, 381 (2001)*
*EB+RFD exp.*




M. Kmiecik et al.,
Acta Phys. Pol. B36, 1169 (2005)

It was observed, for the first time, that the **low-energy component** of the **GDR** (connected to Jacobi shape) is **preferentially feeding** one of the rotational bands (presumable **SD**) in $^{42}$Ca,

**Question**: Is this band indeed SD?

**Answer** (A. Maj, F. Azaiez, P. Napiorkowski):
Let's examine this band by
Coulomb Excitation using AGATA in LNL Legnaro

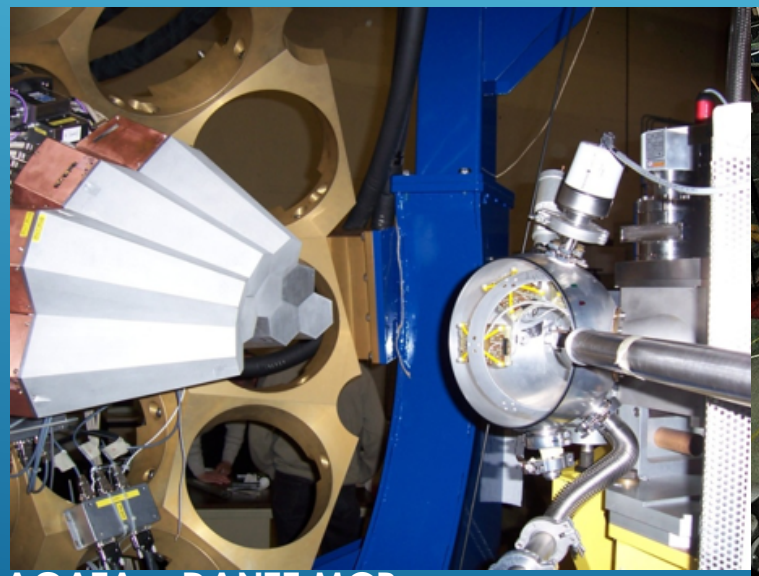
# Coulomb Excitation group in HIL Warsaw

**P. Napiorkowski, J. Srebrny**, K. Hadyńska-Klek, K, Wrzosek et al.

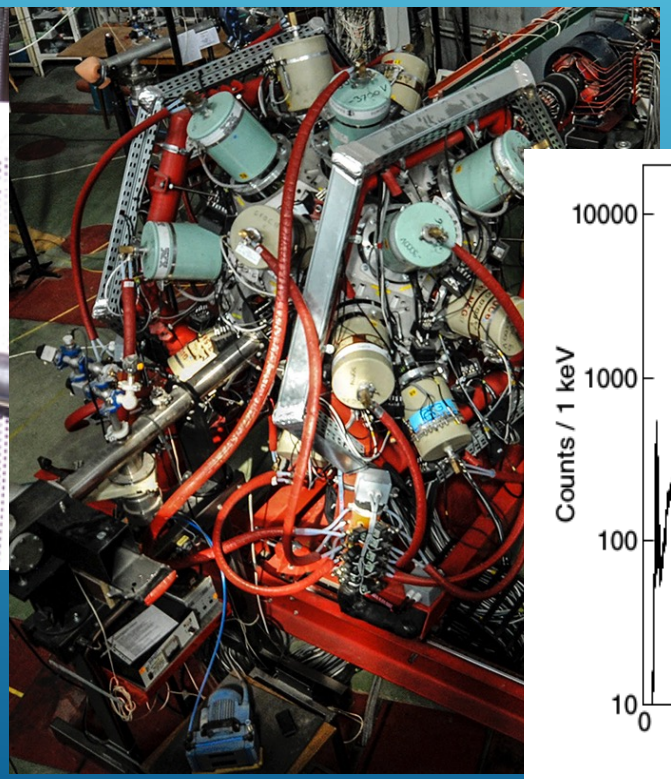
Collaboration with IFJ PAN (A. Maj, P. Bednarczyk, M. Kmiecik, B. Fornal,…), IPN Orsay (F. Azaiez,…), LNL Legnaro (J.J. Valiente-Dobon,…), CEA Saclay (M. Zielińska, W. Korten), …

**Coulomb excitation of $^{42}$Ca**

**2 experiments performed**

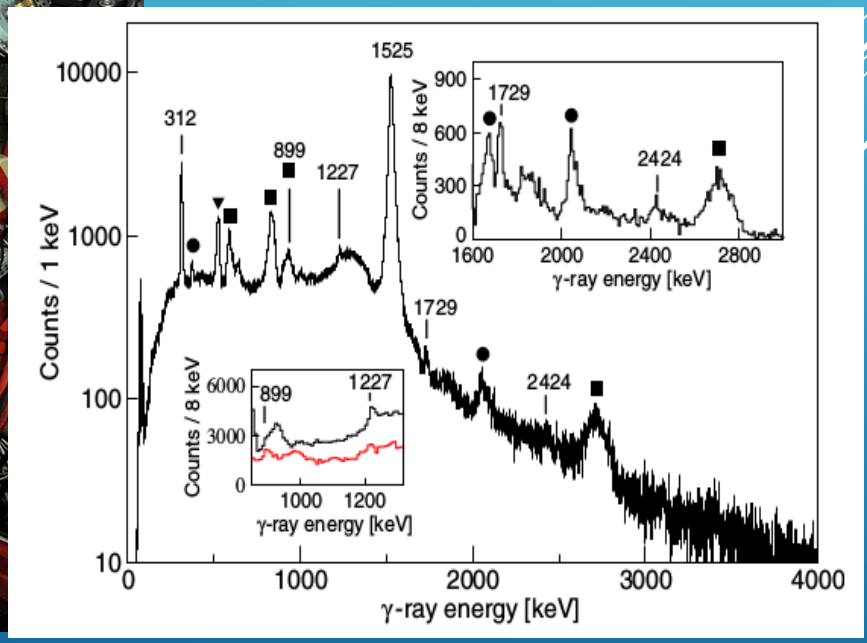


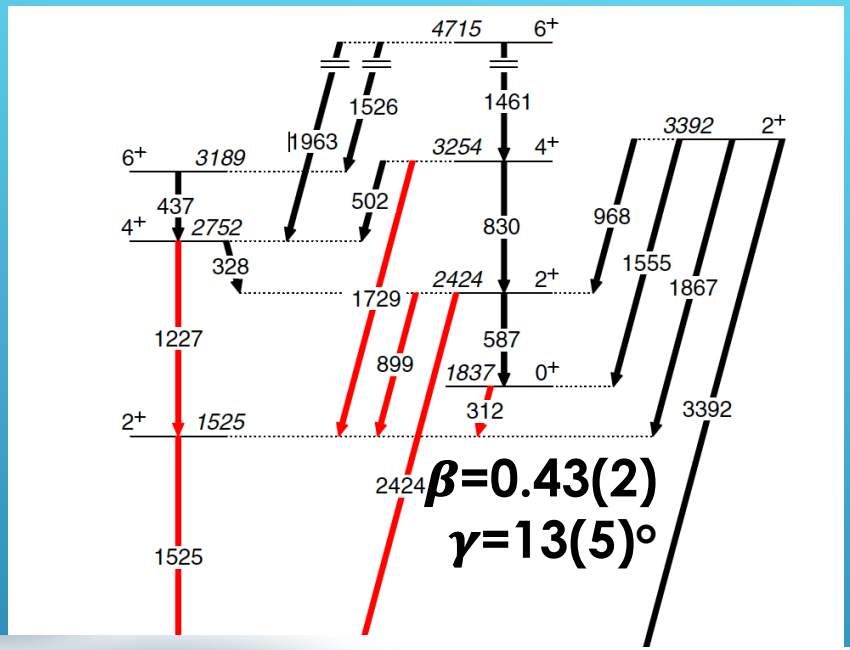
AGATA + DANTE MCP
(LNL Legnaro)

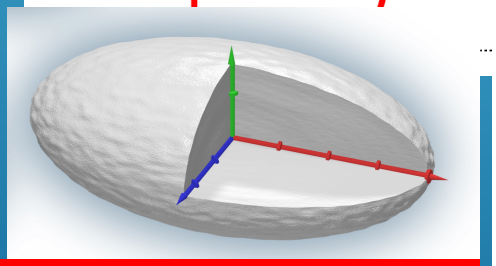


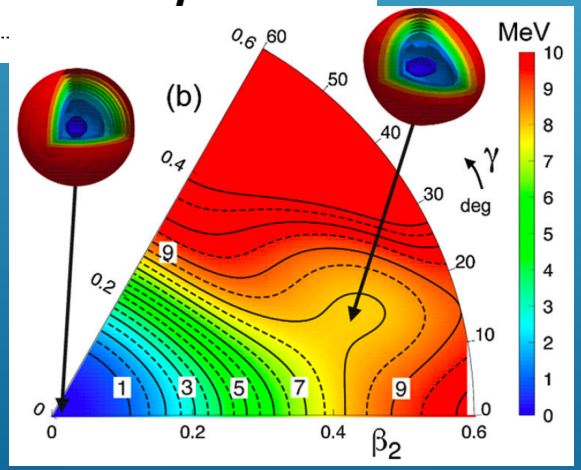
EAGLE + DSSD
(HIL Warsaw)

K. Hadynska-Klek et al.,
Phys. Rev. Lett. 117, 062501 (2016)








*HF calculations – F. Nowacki*

**A hint for existence of triaxial superdeformation, seen for the first time in so light nuclei**

The set of reduced matrix elements in $^{42}$Ca and corresponding B.E2. values were extracted.
Two key pieces of information regarding the deformation of the sideband have been obtained for the first time:

a) The B(E2)($2_2^+$->$0_2^+$)
b) Spectroscopic quadrupole moment of the $2_2^+$.

Their values are consistent with large quadrupole deformation of this band and small triaxality.

**Another possible conclusion/speculation:**

**Elongated 3-axial deformation of the *Jacobi shapes of hot nuclei* tends to be preserved in the decay process down to *cold rotating structures***

**Tri-axial nuclei ➔ nuclear chirality**

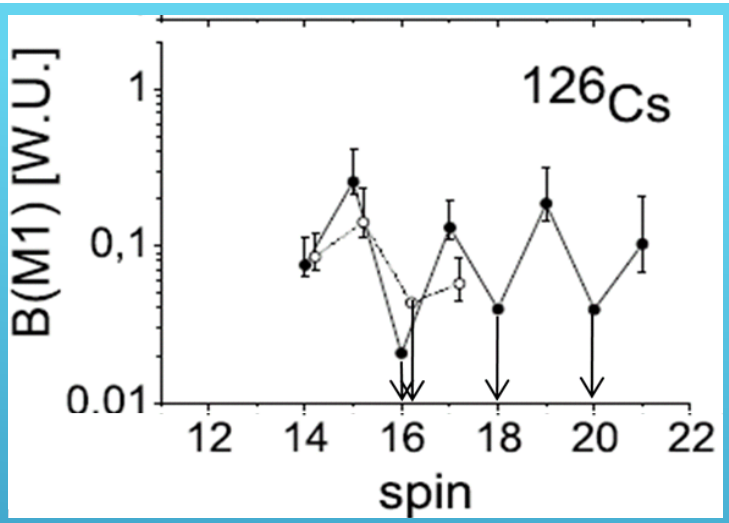
*(cf. Talks by Ernest Grodner and Krzysztof Starosta)*

## Chirality group in HIL Warsaw

E. Grodner, Ch. Droste, T. Morek, K. Starosta, J. Srebrny,
J. Kownacki, L. Prochniakk et al.

Collaboration with J. Dobaczewski, S.G. Rohoziński, P. Olbratowski (Warsaw University), C. Petrache (Orsay) and others

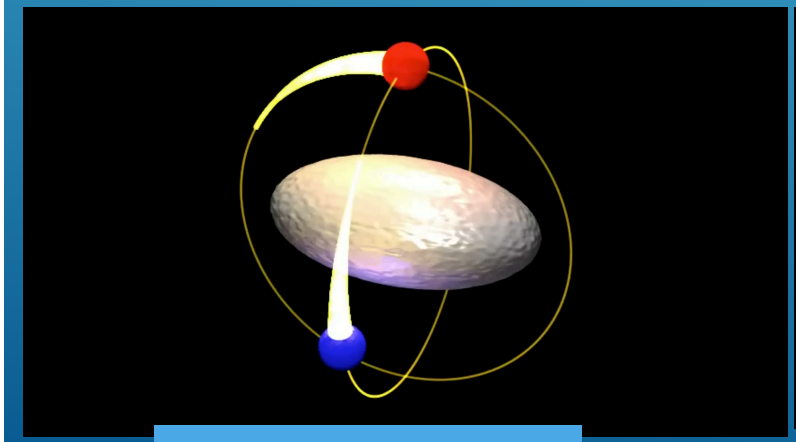
**In HIL were measured for the first time B(EM)'s in chiral bands ($^{130}$La, $^{126}$Cs, $^{124}$Cs, $^{122}$Cs)**



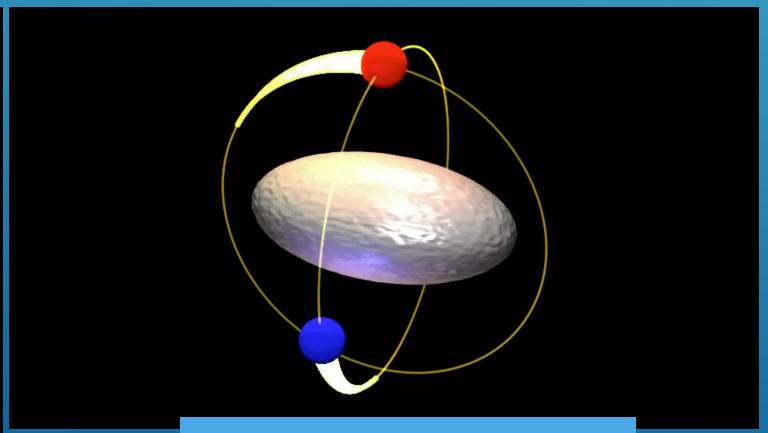

E. Grodner et al., Phys. Rev. Lett. 97 (2006) 172501

E. Grodner et al., Phys. Lett. B703 (2011) 46

T. Marchlewski et al., Acta Phys. Pol. B46 (2015) 689



Left-handed system



Right-handed system

# PLANS FOR NEAR FUTURE WITH PARIS ARRAY

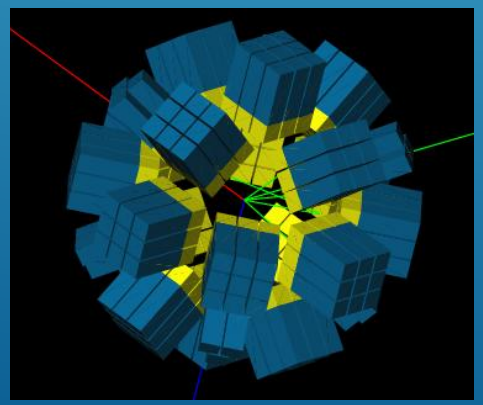
# PHOTON ARRAY FOR STUDIES WITH RADIOACTIVE ION AND STABLE BEAMS

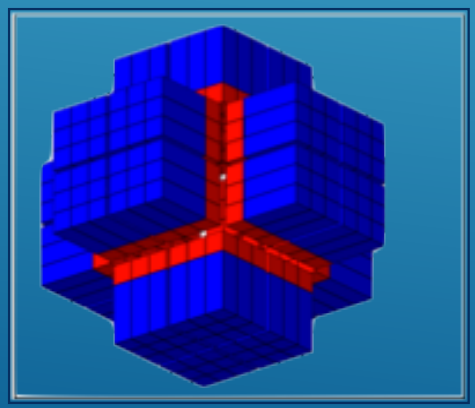
First idea: 2006 (SPIRAL2 LoI by A. Maj, D. Jenkins, J.P. Wieleczko, J.A. Scapracci)
Construction started in 2010 (PARIS Project Manager: A. Maj)

## 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 $\gamma$-rays in large energy range**

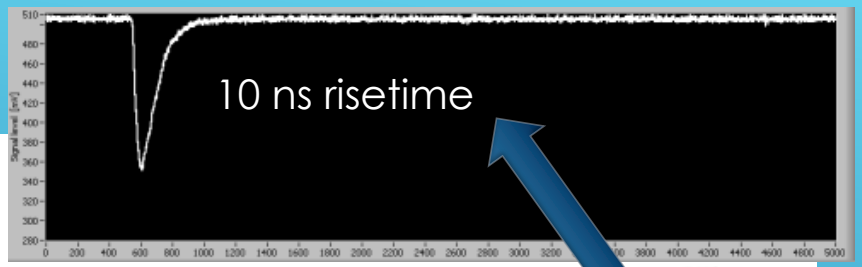
A. Maj et al., Acta Phys.Pol. B40, 565 (2009)

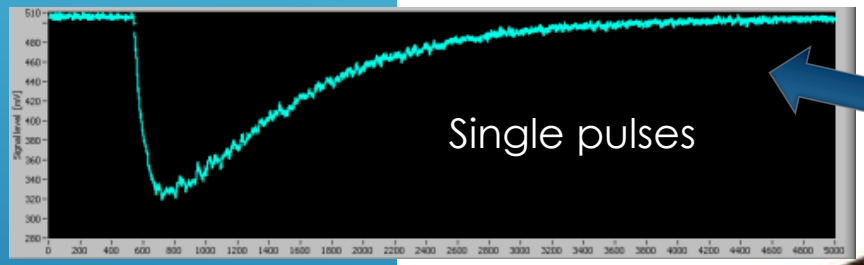


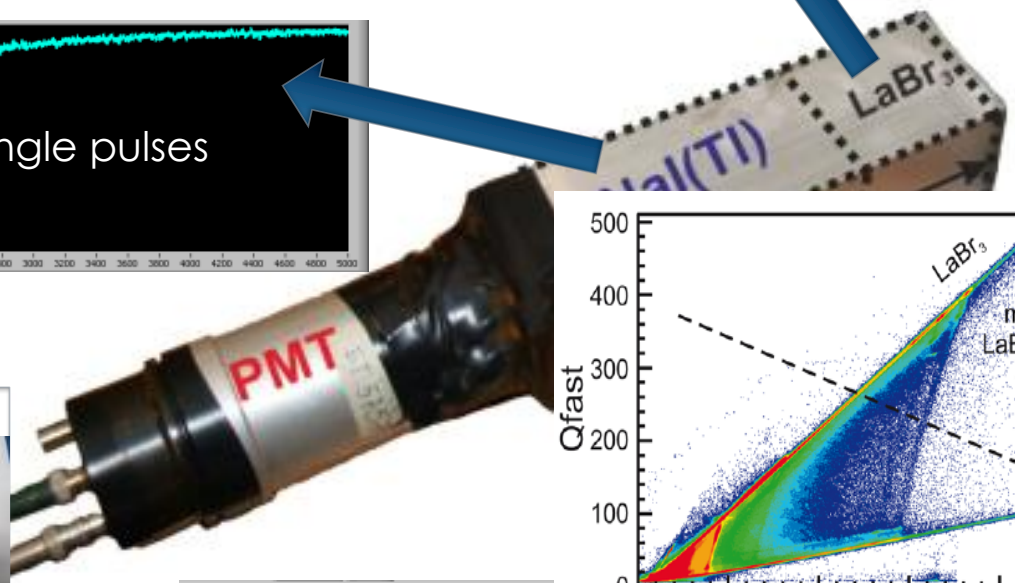


***PARIS to be made of clusters:***
**Cluster = 9 *phoswiches***
**This allows, in its final phase, *cubic* or *semi-spherical* geometry with 24 clusters (216 phoswiches)**

# The PARIS PHOSWICH at work

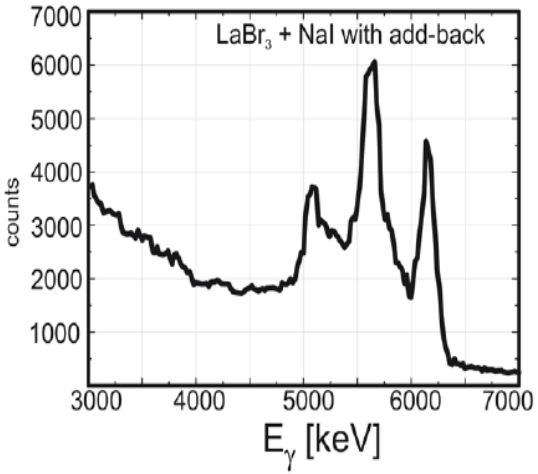


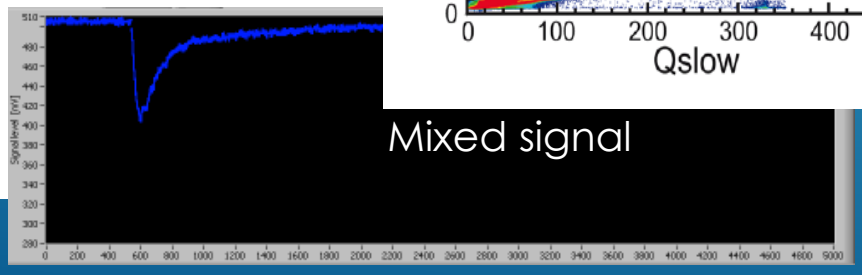







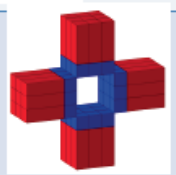
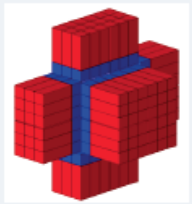
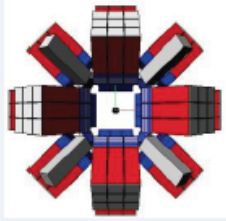
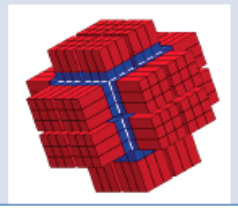
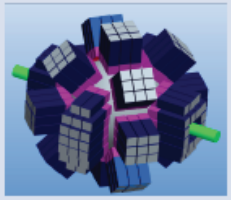
Mixed signal

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

# 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*<br>**2011/2012**<br>PARIS cluster | 1 cluster:<br>9 phoswiches |  | 250 k€ | **Decided**<br>Funds: SP2PP, ANR, Orsay, Strasbourg, Kraków, Mumbai<br><br>Tests in-beam and with sources |
| *Phase 2*<br>**2018**<br>**PARIS Demonstrator** | 5 clusters:<br>45 phoswiches |  | 1100 k€ | **Only if Phase1 validated**<br>Funds: MoU<br><br>Ph1Day1 exp@S3 |
| *Phase 3*<br>**2022**<br>**PARIS 2π** | 12 clusters:<br>108<br>phoswiches |   | ≈ 2 M€ | **Only if Phase2 validated**<br>Funds:<br>MoU, PARIS consortium<br><br>Ph2Day1 exp. wit<br>AGATA and GASPARD<br>Other exp. |
| *Phase 4*<br>**2024?**<br>**PARIS 4π** | ≥24 clusters:<br>:216<br>phoswiches |   | ≈ 4 M€ | **Only if Phase3 validated**<br>Funds:<br>PARIS consortiun<br><br>Regular experimer<br>in various labs |

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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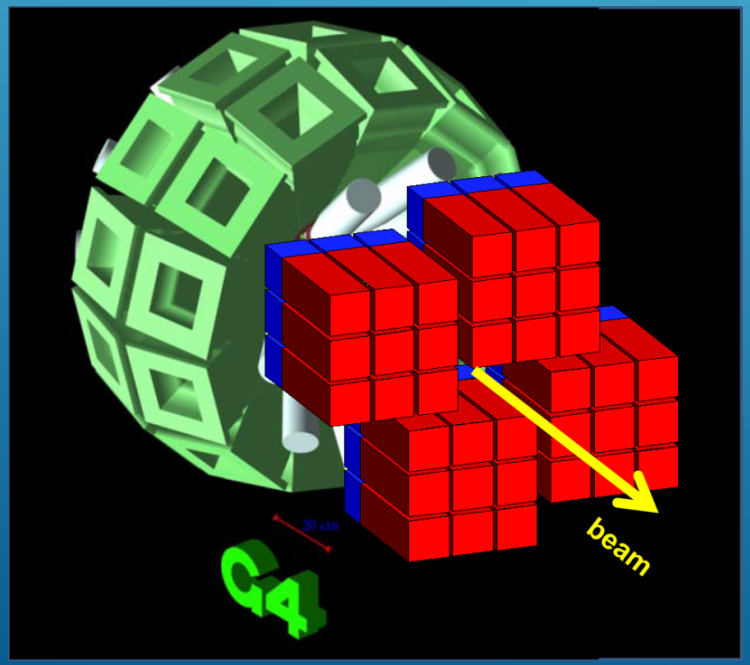
**Presently PARIS collaboration posesses 3 clusters**

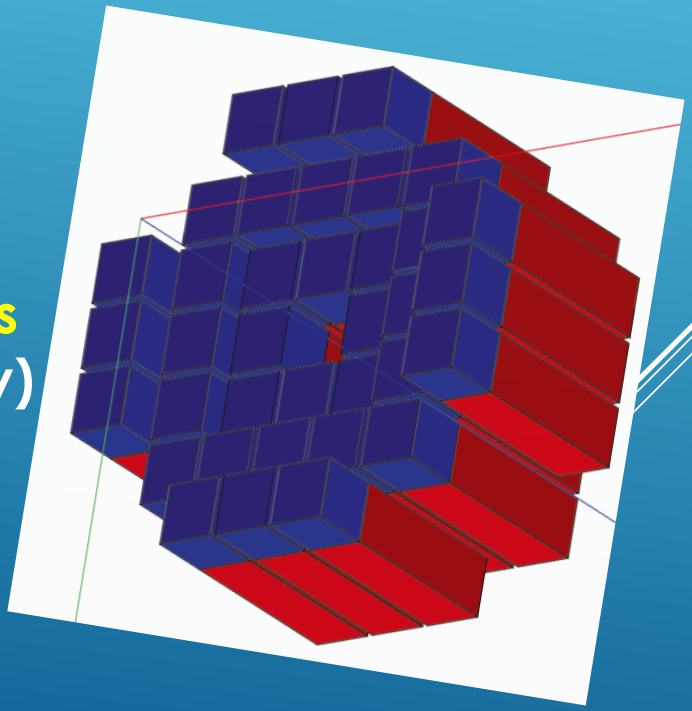
**4 clusters are expected at the beginning of 2018**

# EXPERIMENTS ACCEPTED FOR IPN ORSAY AND PLANNED FOR 2018

1. P.J. NAPIORKOWSKI ET AL., „COULOMB EXCITATION OF SUPER-DEFORMED BAND IN $^{40}$CA"
2. 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 GANIL

## PARIS coupled to AGATA@GANIL

**3 proposals accepted by the GANIL PAC**

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

- 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, PARIS, NEDA, DIAMAND, DSSD**

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

***Cf. Talk by Piotr Bednarczyk on Friday***

# FIRST PARIS EXPERIMENTS IN KRAKOW

M. Kmiecik, F. Crespi et al. „Collective modes excited via inelastic scattering of fast protons”

*Cf. Talk by Maria Kmiecik later today*

# SUMMARY

- The groups from 2 polish nuclear physics facilities: IFJ PAN Krakow and HIL Warsaw, are very active in the field of studying properties of rotating nuclei: nuclear shapes and collective phenomena
- Main results: superdeformation and tri-axial superdeformation in light nuclei, Jacobi shape transitions, nuclear chirality etc.
- NLC – the consortium of HIL and IFJ PAN, offers beam time, instrumentation, and in addition, the Transnational Access via the ENSAR2 project
- PARIS, the novel gamma-ray detector for medium resolution spectroscopy and for high-energy gamma-rays, is becoming operational
- The perspectives for studies the Shape and Symmetries in rotating Nuclei are good – new results might be presented at the SSNET18, 19, .....

**Thank You: Jurek and Costel**