Building Bridges 2018

AE-Barcelona Knowledge Hub

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Instytut Fizyki Jądrowej
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Polskiej Akademii Nauk

Exotic shapes and collective phenomena in excited atomic nuclei

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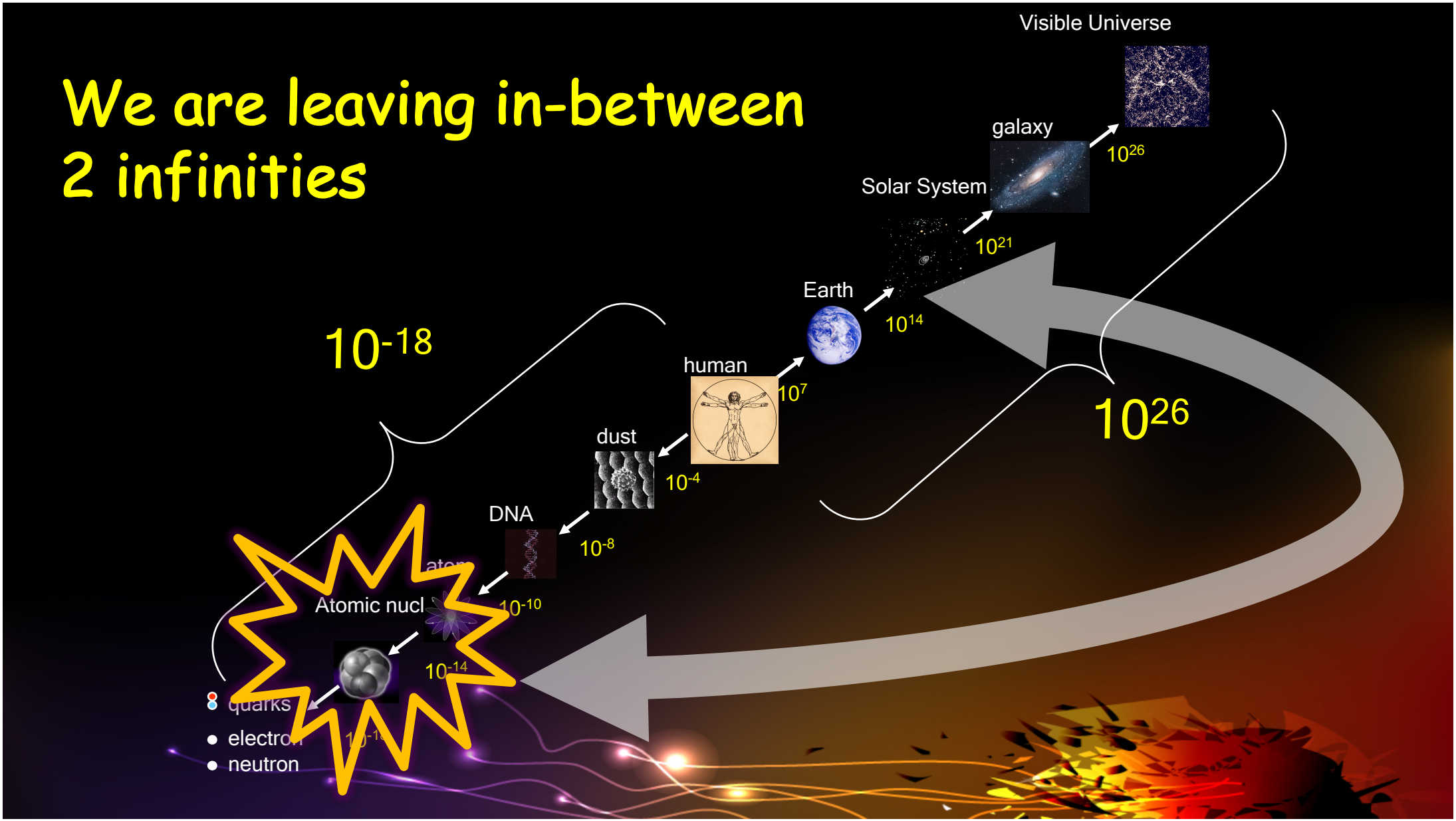
Plan

1. Short introduction: 2 infinities
2. Shape evolution of the rotating celestial bodies
3. Nuclear Jacobi shape transition and Giant Dipole Resonance
4. First results from the CCB facility in Krakow
5. Summary

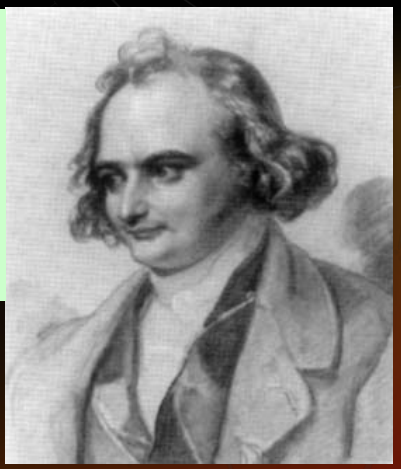
We are leaving in-between 2 infinities

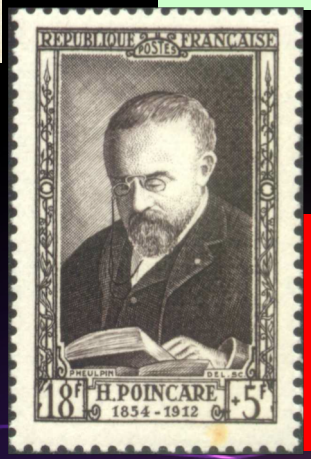


Rotating Earth with increasing speed: MacLaurin, Jacobi and Poincare shapes

Colin MacLaurin (1742, Scotland): With increasing rotational speed, gravitational bodies begin to flatten and take on the shape of the „disc" shapes (*oblate*).

Carl Gustav Jacob Jacobi (1834, Prussia): At a certain rotational speed, the rotating bodies can rapidly change their shape from a flattened to a very elongated "cigar" (*prolate*) or elongated 3-axis ellipsoid. This is called Jacobi's bifurcation.



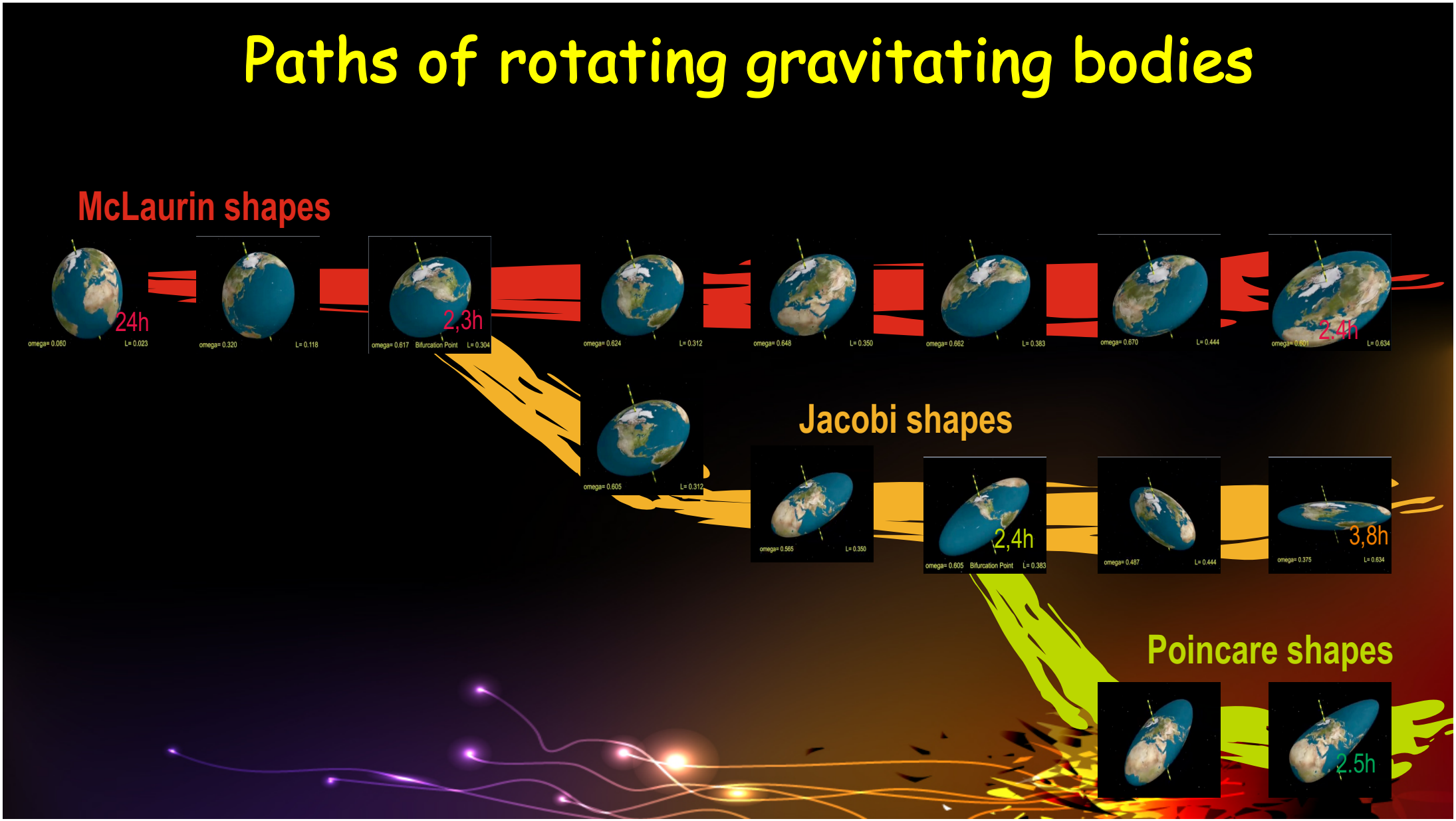


Henri Poincare (1885, France): Predicted that the path of elongated Jacobi's ellipsoid at very high rotational velocities encounters further bifurcation points, where elongated shapes can change into pear-shaped (*octupole*) shapes.

Rotating Earth with increasing speed: MacLaurin, Jacobi and 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

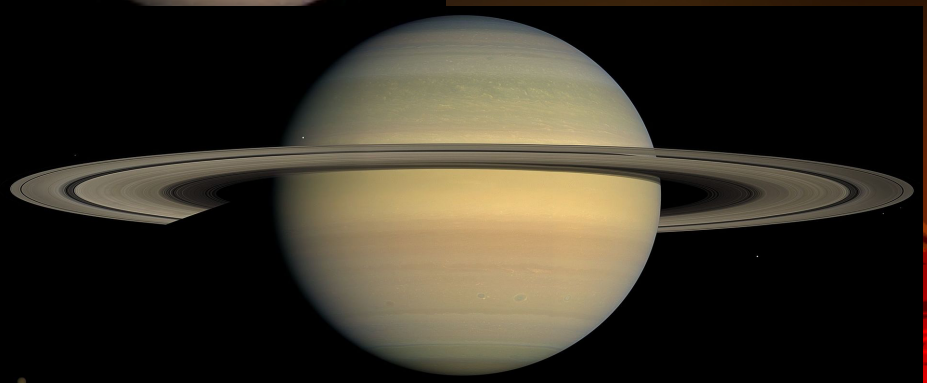
Paths of rotating gravitating bodies



Earth
Rotation period= 24h
Equator velocity= 0.5 km/s
Flateness ≈ 0.3%

Jupiter
Rottion period = 9h 50m
Equator velocity = 12.6 km/s
Flateness ≈ 6.5%

Saturn
Rotation period= 10h 39m
Equator velocity = 9.9 km/s
Flateness ≈ 10%



MacLaurin shapes

Haumea: A dwarf planet that resides in the Kuiper belt and is one of the fastest rotating large objects in our solar system.

Rotation period = 3h 54m
Equator velocity= 0.5 km/s
Dimensions: 1960 x 1518 x 996 (km)
Triaxial shape, with axis ratio 2: 1.5: 1

Extremely elongated asteroid 1I/2017 U1

Jacobi shapes?

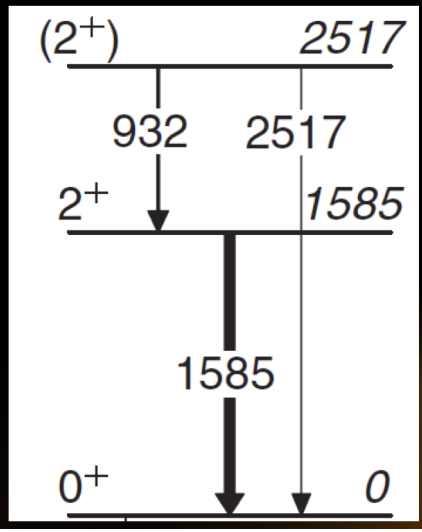
Nuclear Jacobi shape transitions

- R. Beringer, W.K. Knox, *Phys. Rev.* 121 (1961) 1195:

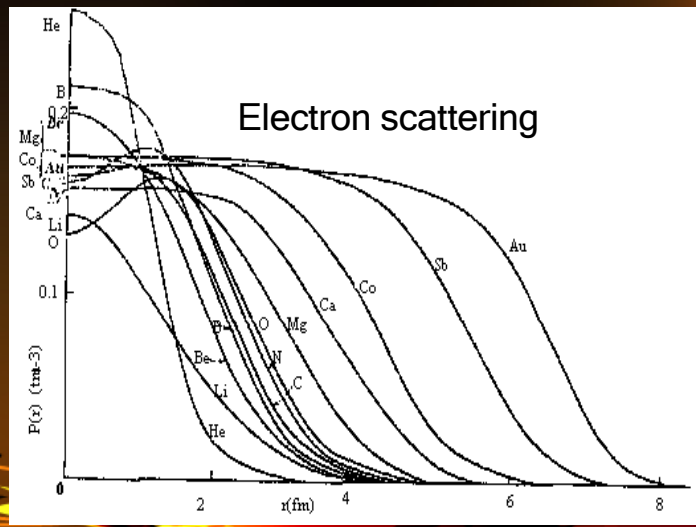
Hypothesis: in hot rotating atomic nuclei Jacobi shapes might emerge

The **atomic nucleus** is the central part of the atom with the size of $10^{-14} \div 10^{-15}$ m (or several fentometers), built of Z protons and N neutrons (ie with A nucleons).

All physical systems we know, if they are $\langle d \rangle \leq 10^{-10}$ m, are quantal. This means that the energies of such systems (and therefore the nuclei) are quantized - discrete instead of continuous.



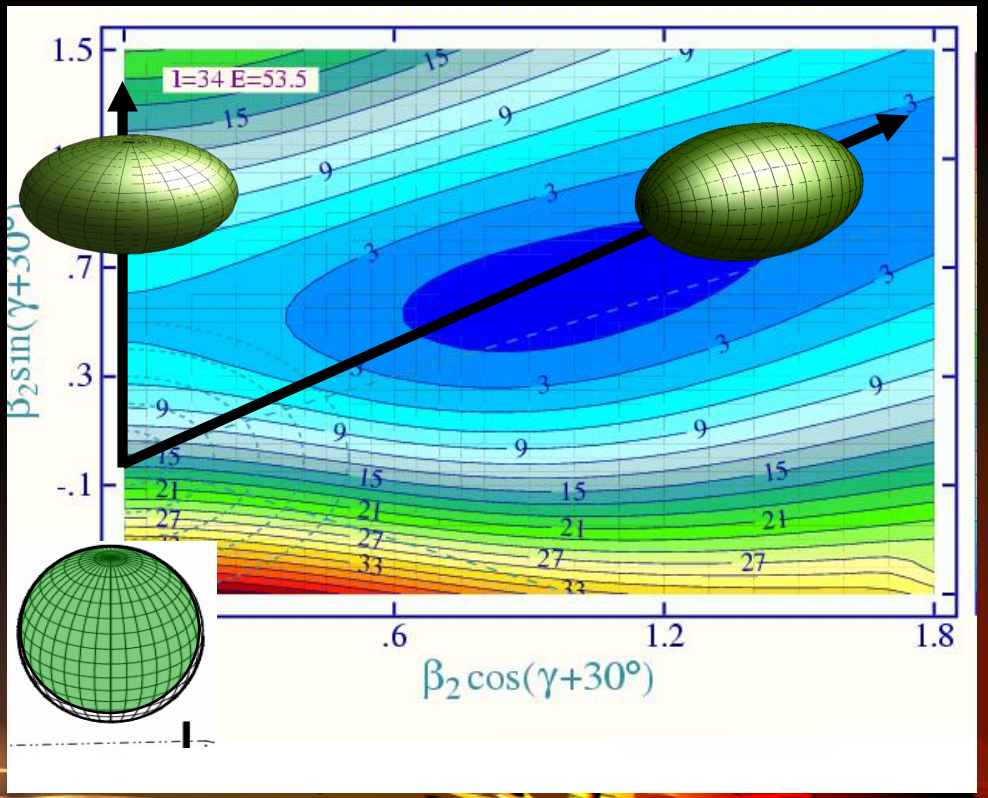
It turns out, however, that many nuclear properties are successfully described by classical models that use such concepts from the macroworld as shape, deformation, rotation, vibration, etc.This is the consequence of short range of nuclear interactions, which in turn produces rather well defined surface of atomic nucleus - thus the **concept of a shape** can be used.



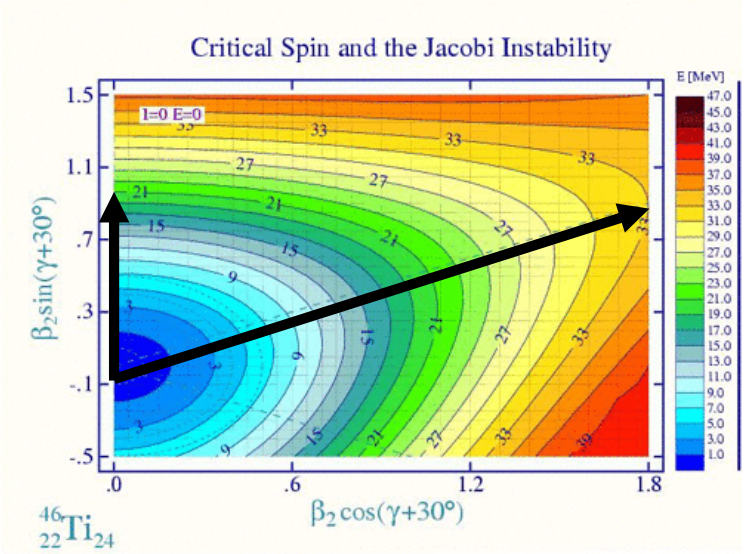
- S. Cohen, F. Plasil, W.J. Swiatecki, *Ann. Phys. (N.Y.)* 82 (1974) 557: **Rotating liquid drop model**

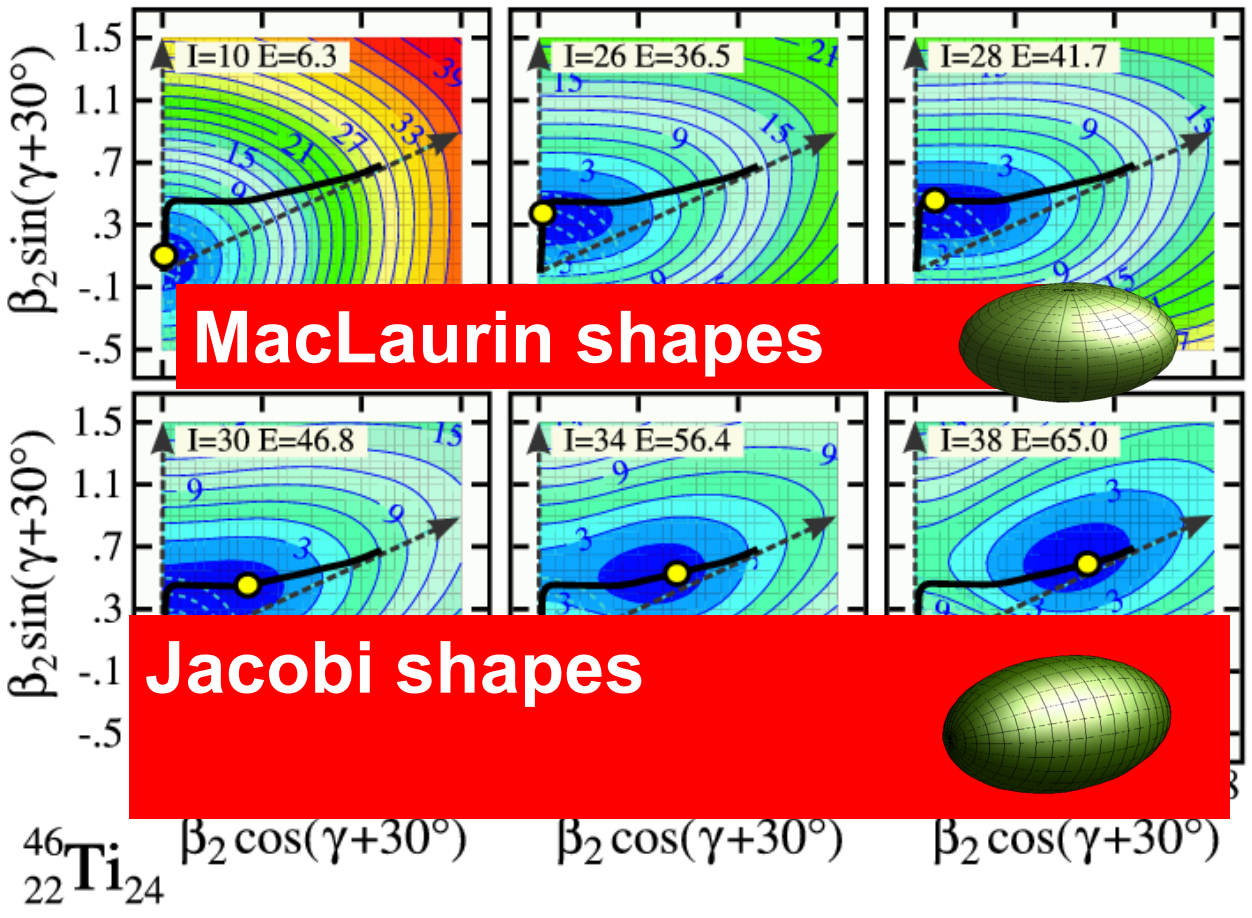
- K. Pomorski, J. Dudek, *Phys. Rev.* C67 (2003) 044316: **LSD (Lublin-Strasbourg Drop) Model**

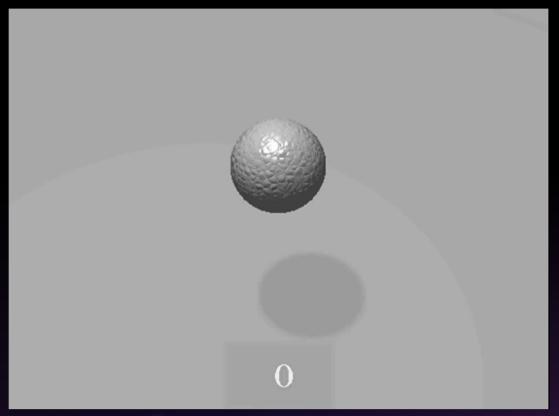
Model of a rotating drop with an added surface curvature term and new parameters from the available experimental data. The model calculates potential energy maps for given value of angular momentum



Predicted evolution of the shape of the 46Ti nuclei in calculations with the LSD model



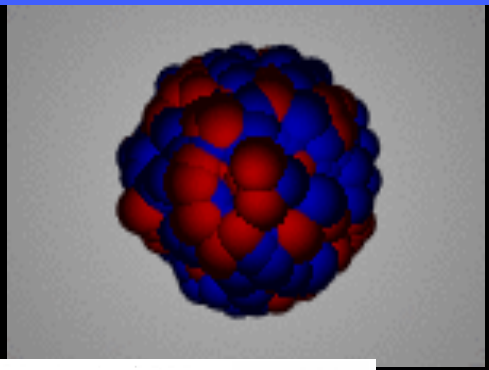




Shape evolution: Sphere➔"Disc"➔Triaxiality➔"Cigar" (➔fission)

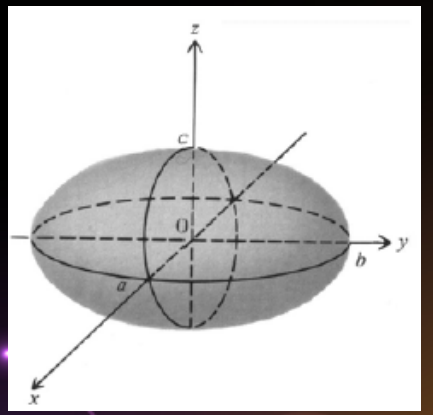
Giant Dipole Resonace(GDR) – a tool to study shapes of hot nuclei

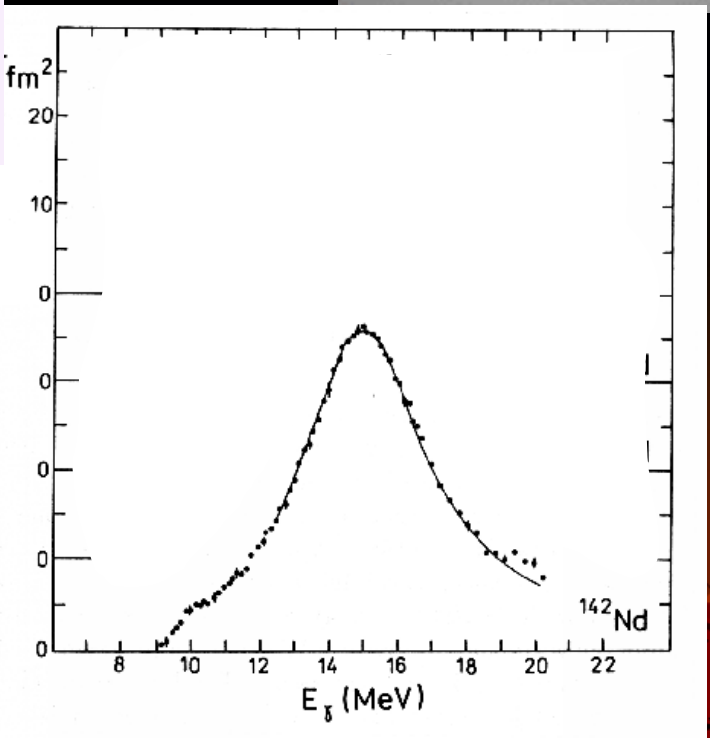
GDR - Collective oscillation of all neutrons against all protons



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

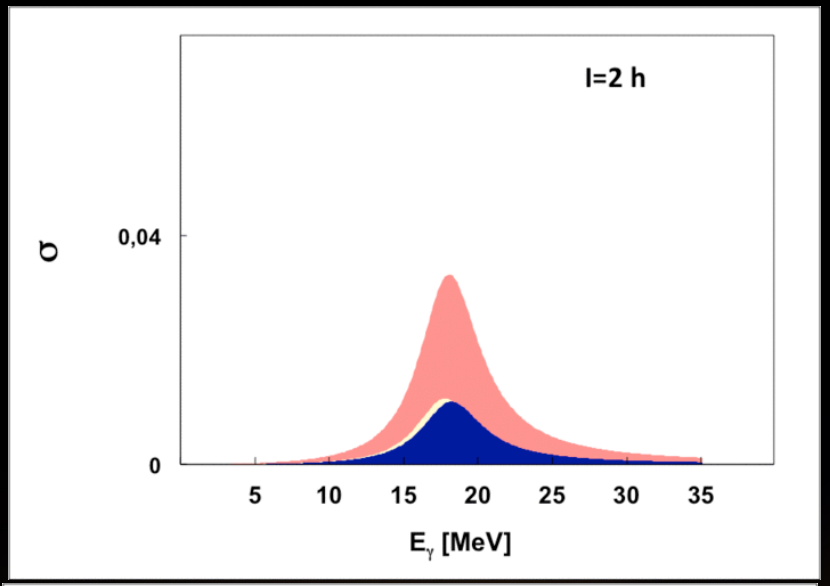
$$E_k = \hbar\omega_k = \hbar\omega_{GDR} \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos(\gamma - \frac{2\pi}{3}k)\right]$$



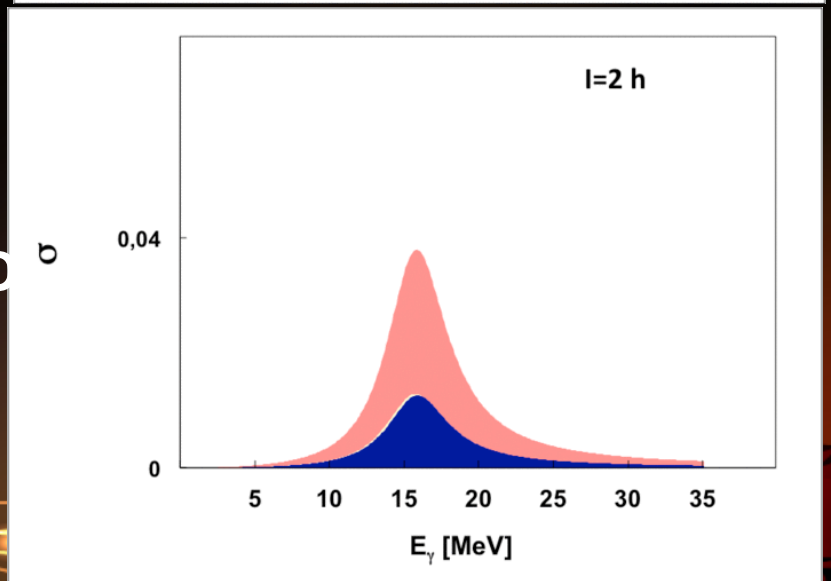


The appearance of a low energy component in the GDR strength - a signal of existence of the Jacobi shape

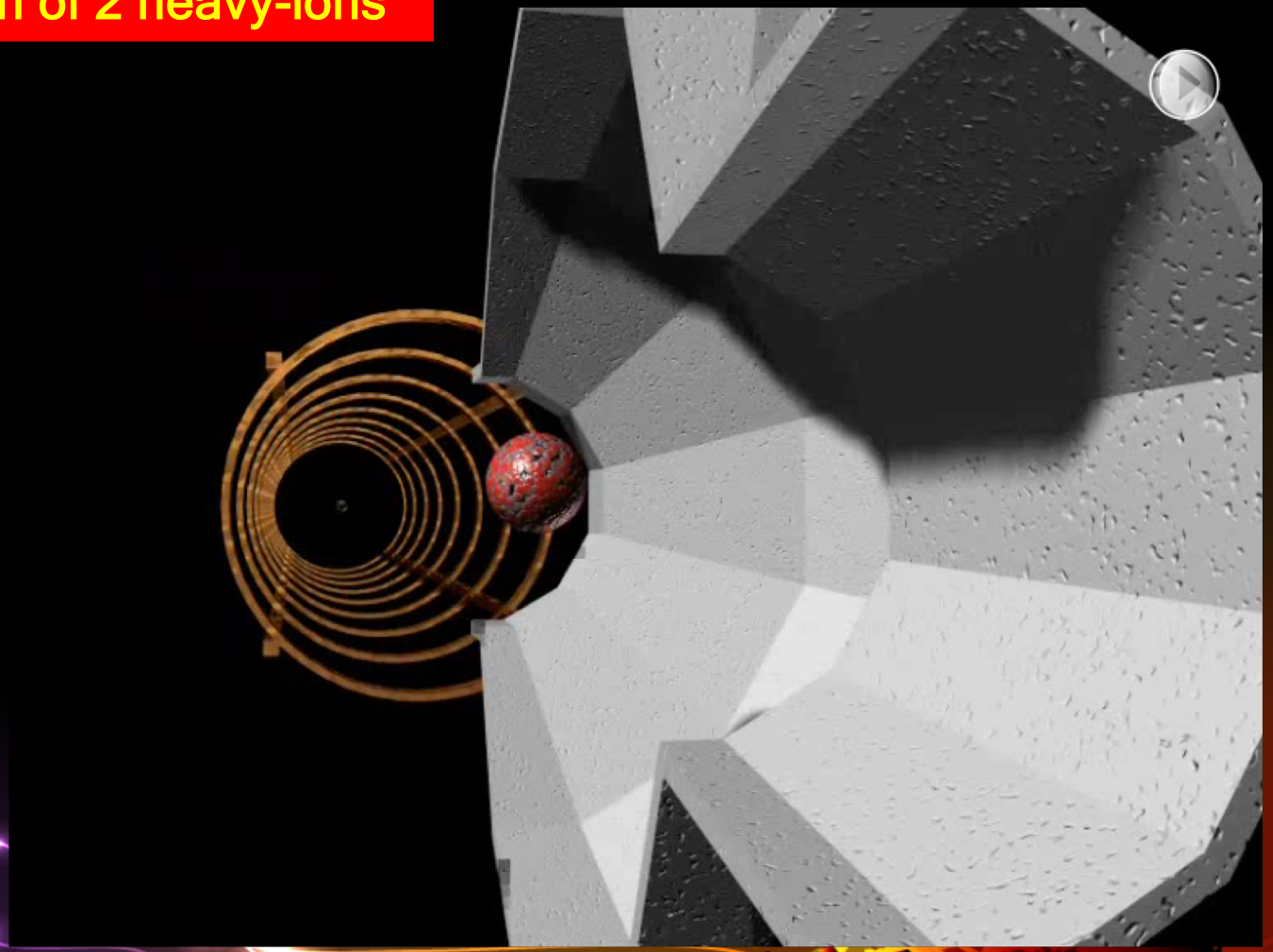
^{46}Ti



^{88}Mo

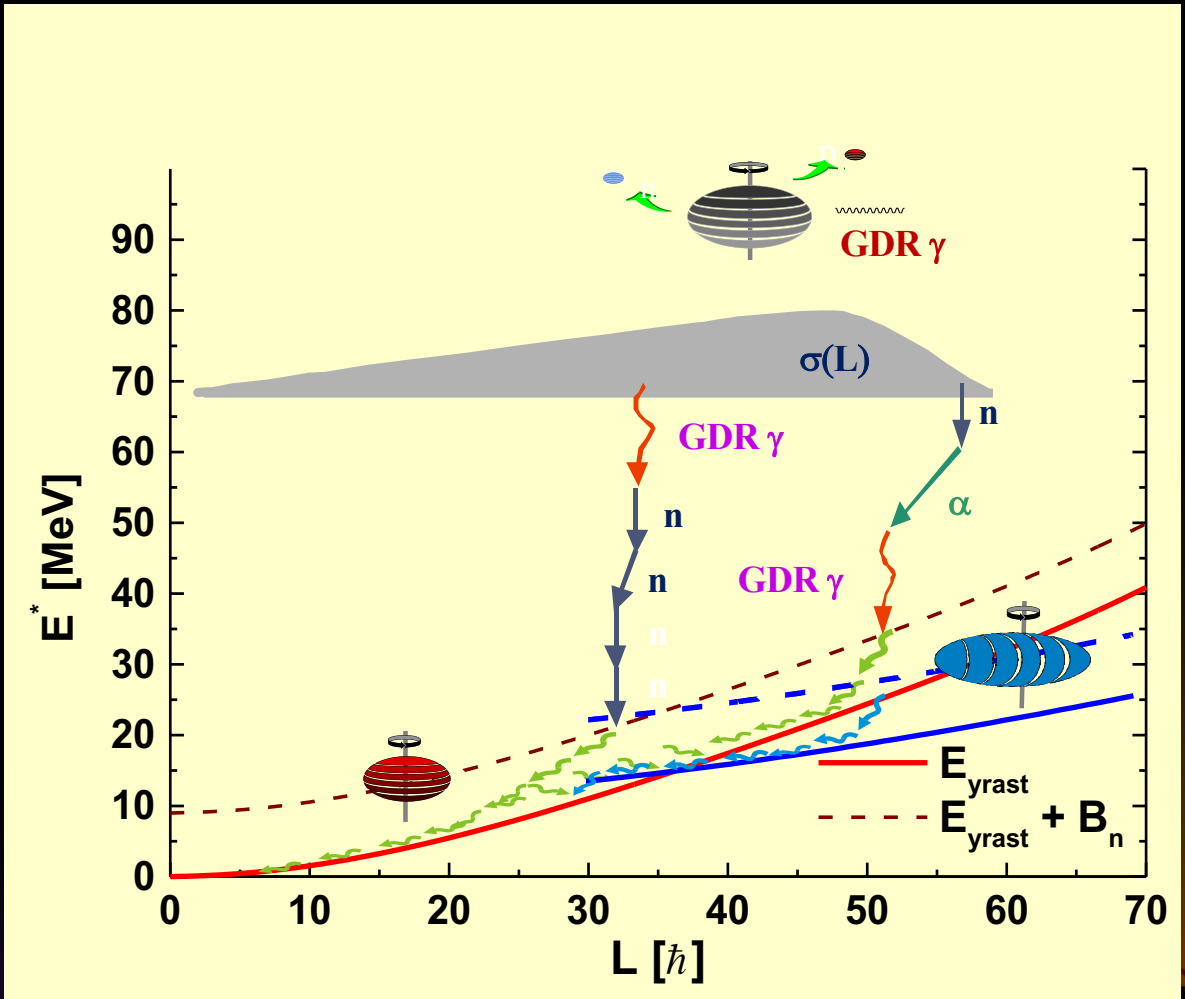


How to heat a nucleus and force it to rotate?
Fusion-eveporation reaction of 2 heavy-ions



Courtesy of Jerzy Grębosz

Formation and decay of compund nuclei



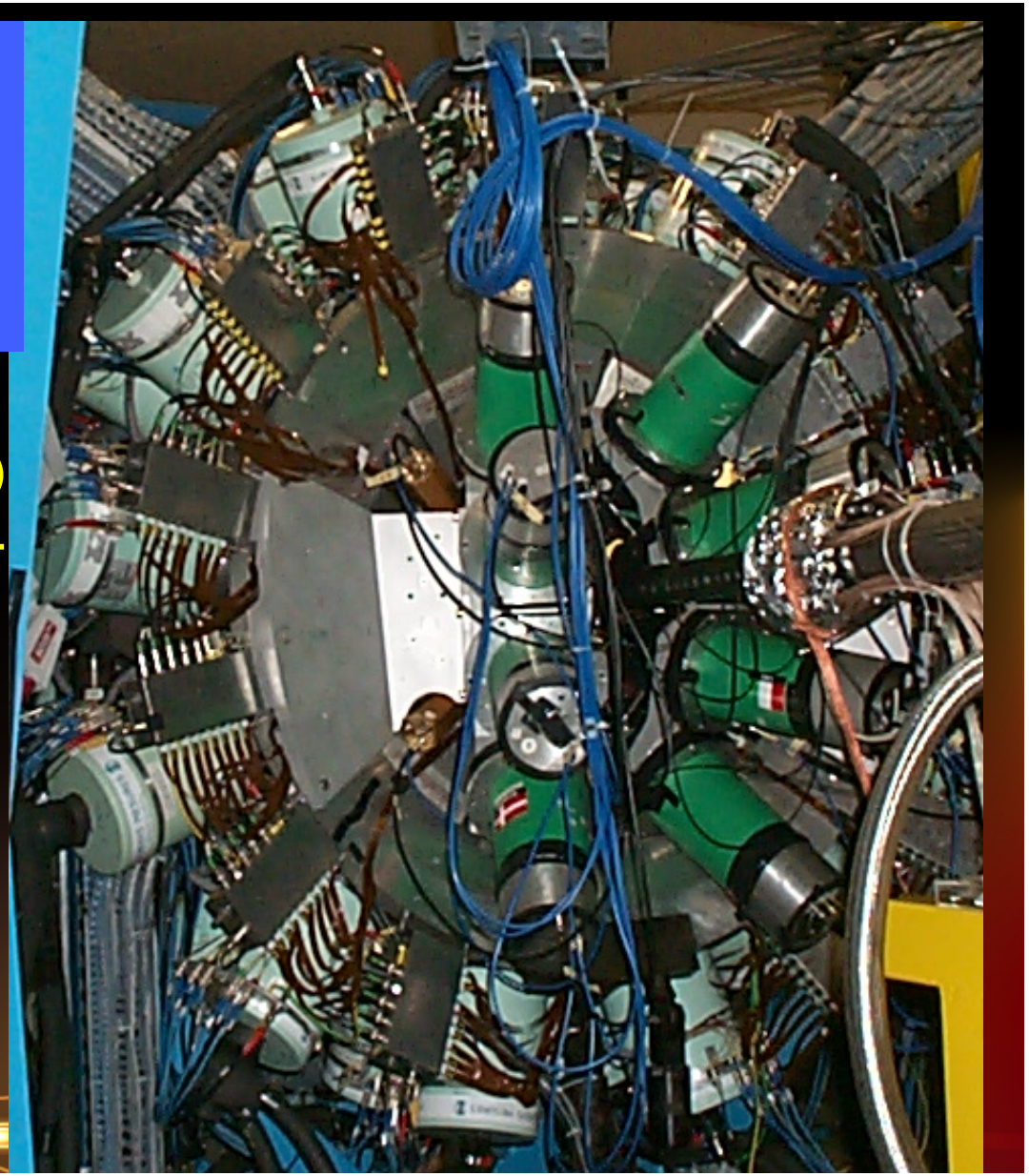
$P_\gamma / P_n \approx 10^{-3}$

A.Maj, M. Kmiecik, M. Ciemała, K. Mazurek,
B. Wasilewska et al. (IFJ PAN Kraków)
M. Kicińska-Habior i innie (ŚLCJ UW)
J. Dudek (Uni Strasbourg)
K. Pomorski (UMCS Lublin)

Experiments in Strasbourg (France)
HECTOR + EUROBALL

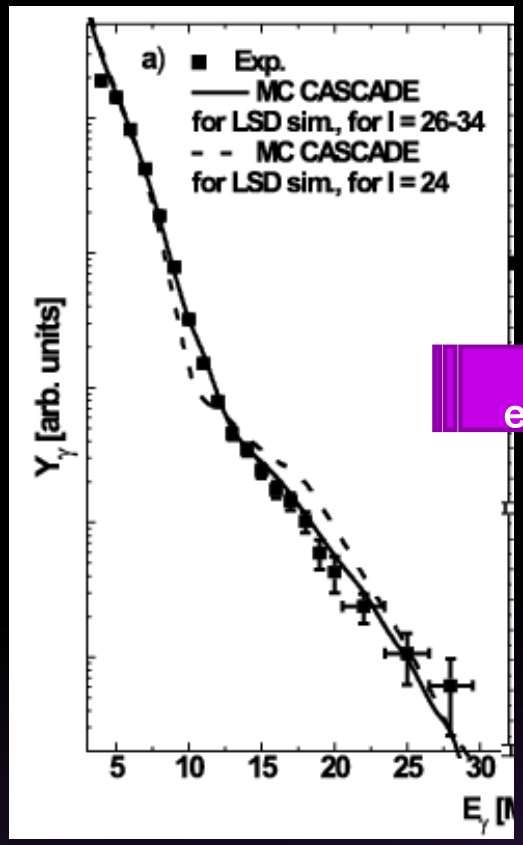
105 MeV $^{18}O + ^{28}Si \Rightarrow ^{46}Ti^*$
$I_{max} \approx 35\ \hbar$, $E^* = 88$ MeV

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

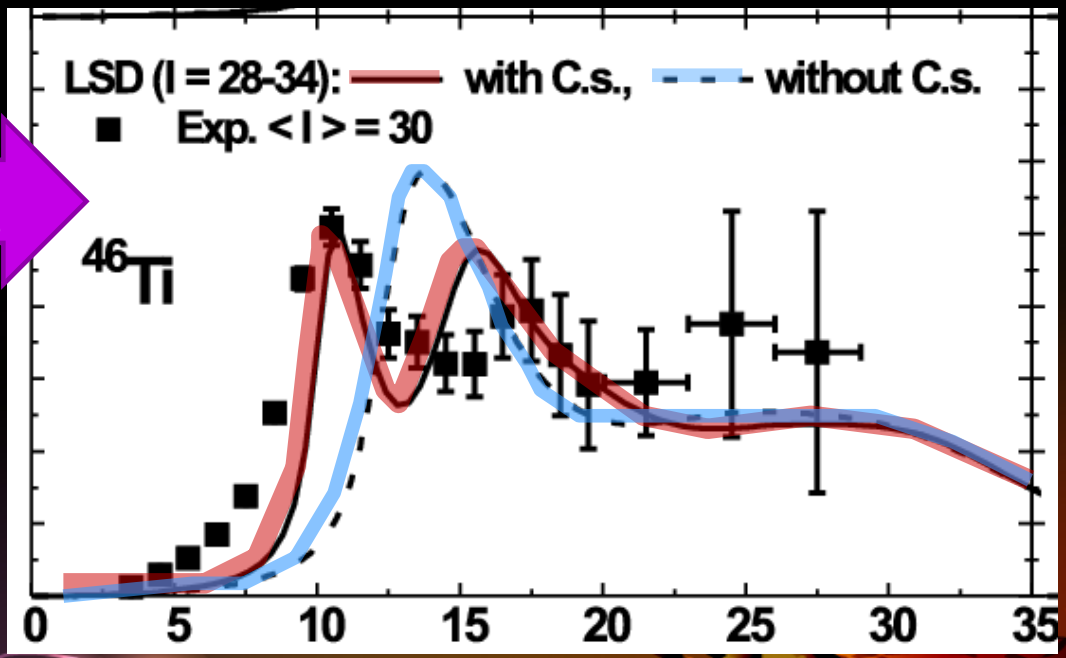


Experiment versus theory

The existence of Jacobi nuclear shapes at 46Ti at high spins was confirmed for the first time



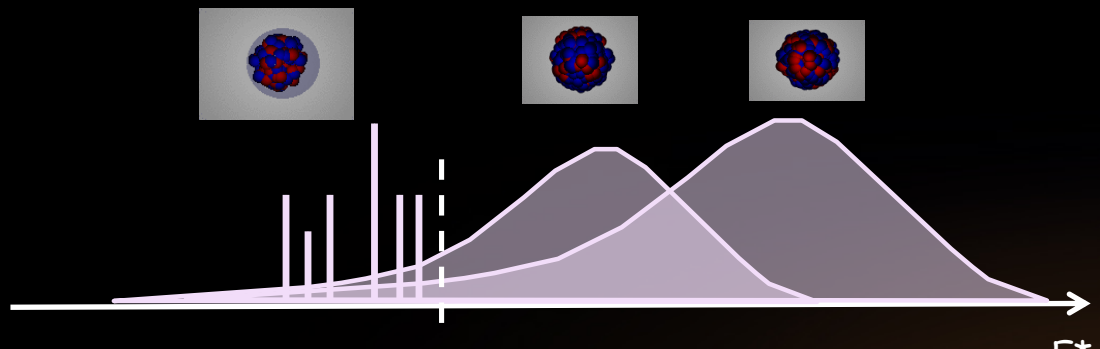
Statistical evaporation code



Other collective excitations

large fraction of nucleons in nucleus take part in excitation

excited in fusion – evaporation or inelastic scattering reactions
(γ, γ'), (p,p'), (α, α'), heavy ions



„pygmy" states - PDR
Pygmy Dipole Resonance
- Soft Dipole Mode
- low-lying dipole strength
(low collectivity)

ISGQR
Isoscalar
Giant
Quadrupole
Resonance

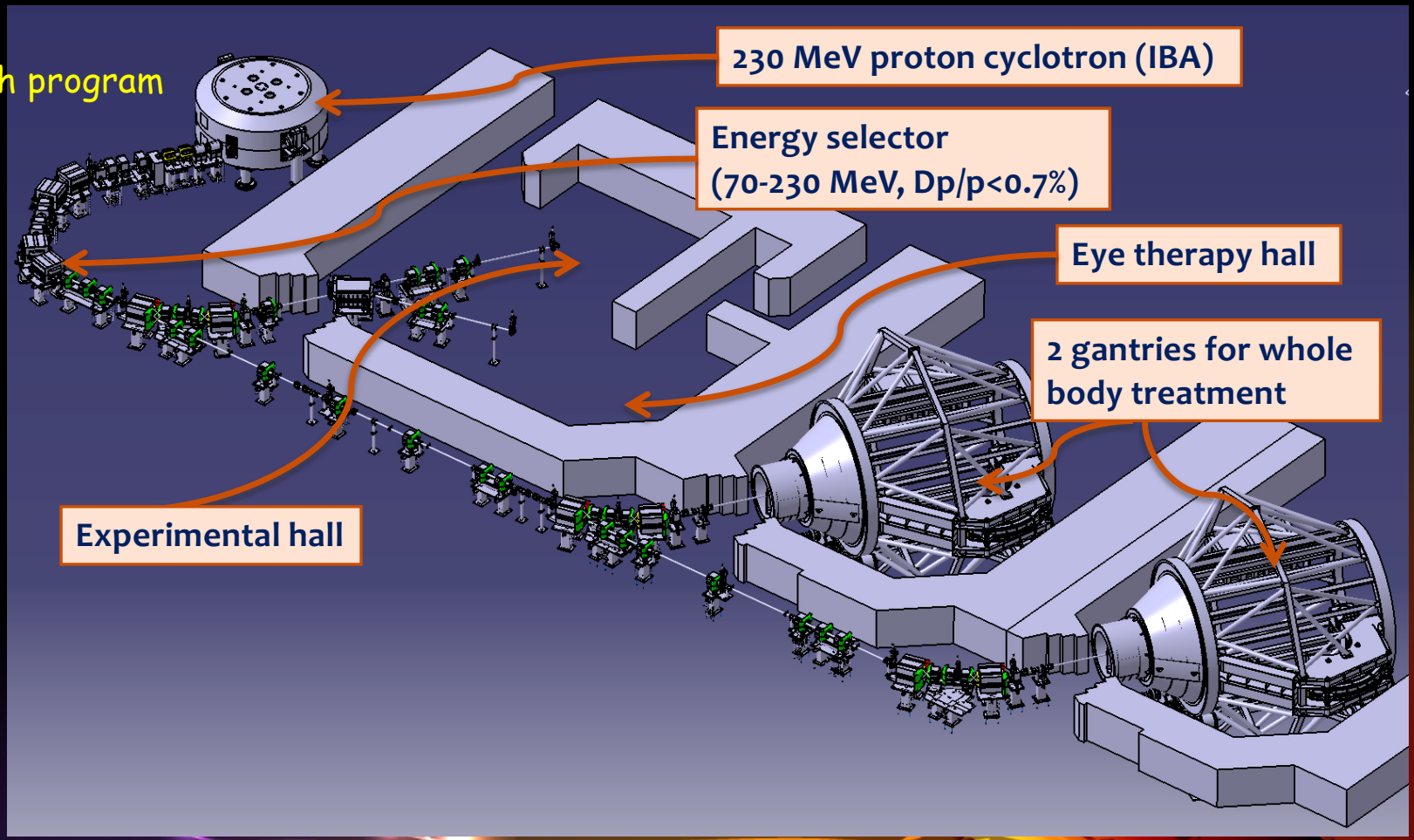
IVGDR
Isovector
Giant Dipole
Resonance

GDRγ decay: ~ 10^{-3} – 10^{-4}
GQR γ decay: ~ 10^{-5} – 10^{-6}

Cyclotron Center Bronowice (CCB) at IFJ PAN Krakow

proton cancer therapy,
and additionally **research program**
concerning:

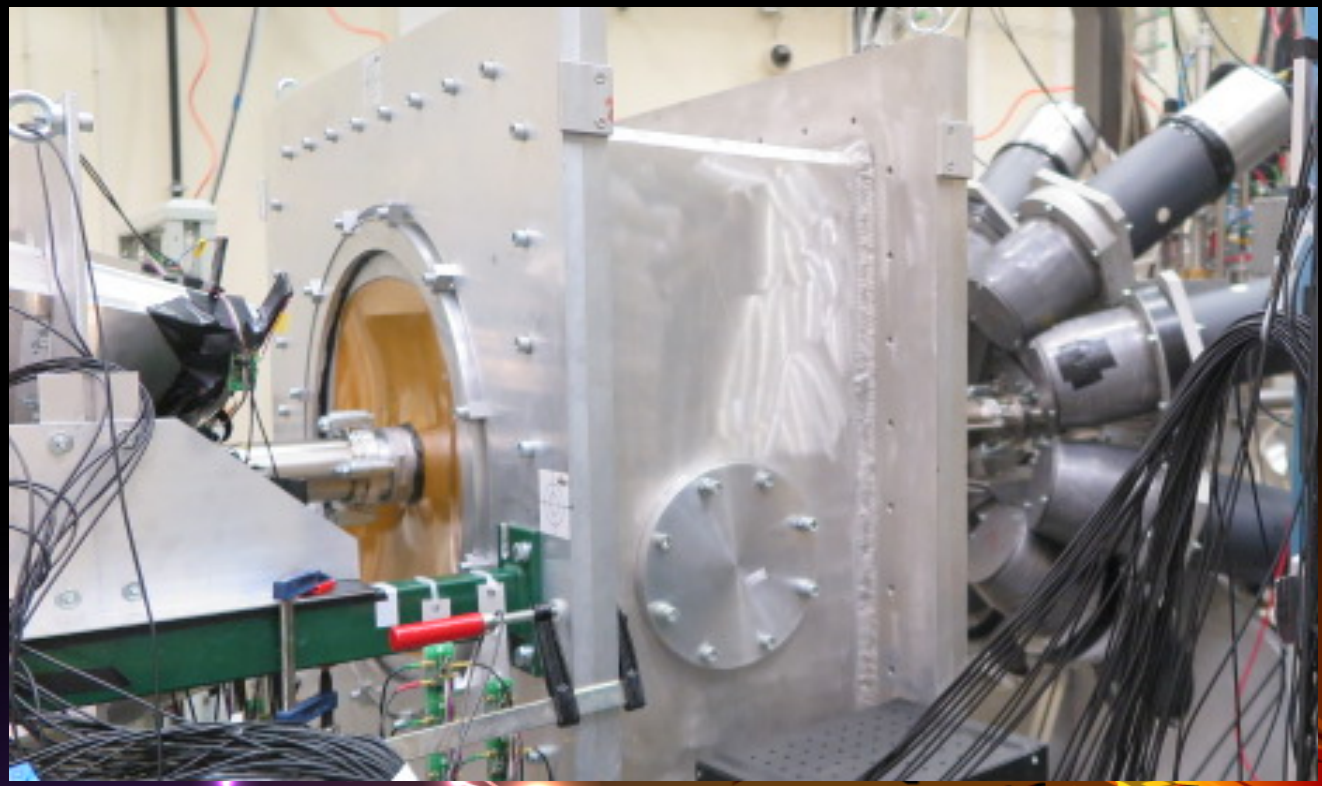
- nuclear physics,
- radiobiology
- dosimetry
- and medical physics



Experimental setup

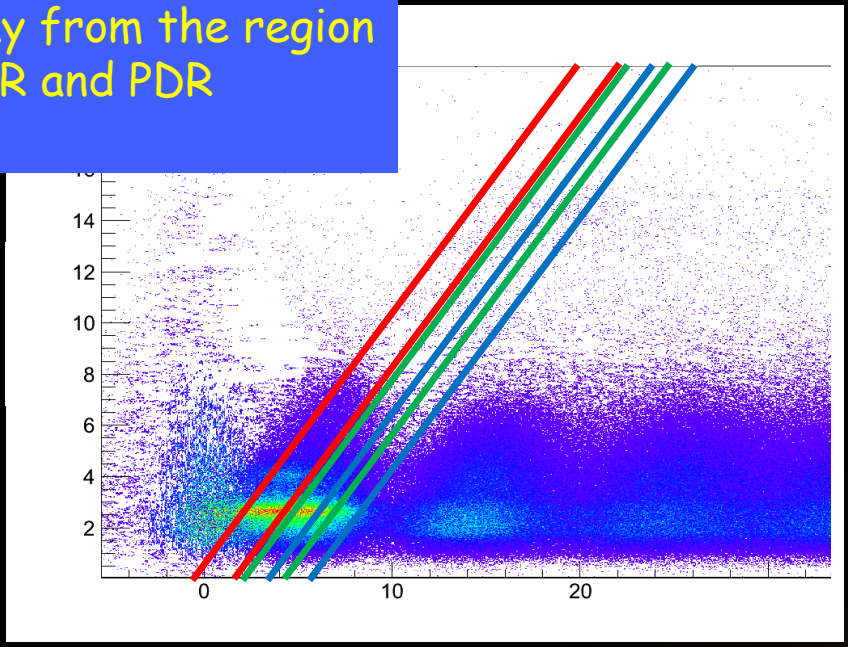
KRATTA (16 CsI telescopes)

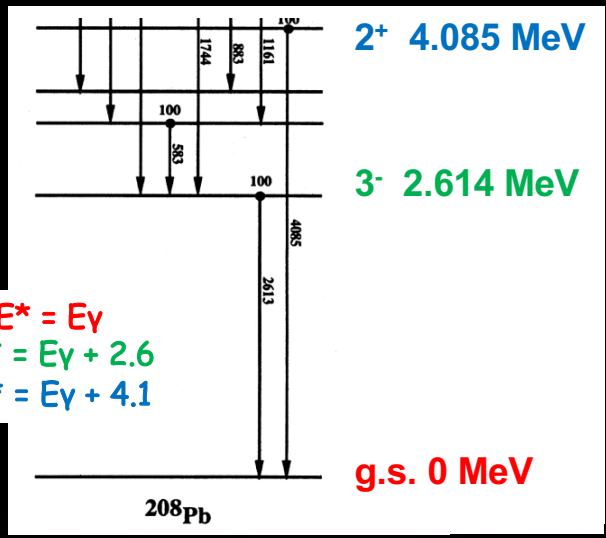
HECTOR (8 BaF_2)
$LaBr_3$ (large volume 8"x3.5")
PARIS (cluster of 9 „phoswiches"
$LaBr_3/CeBr_3$ + NaI)

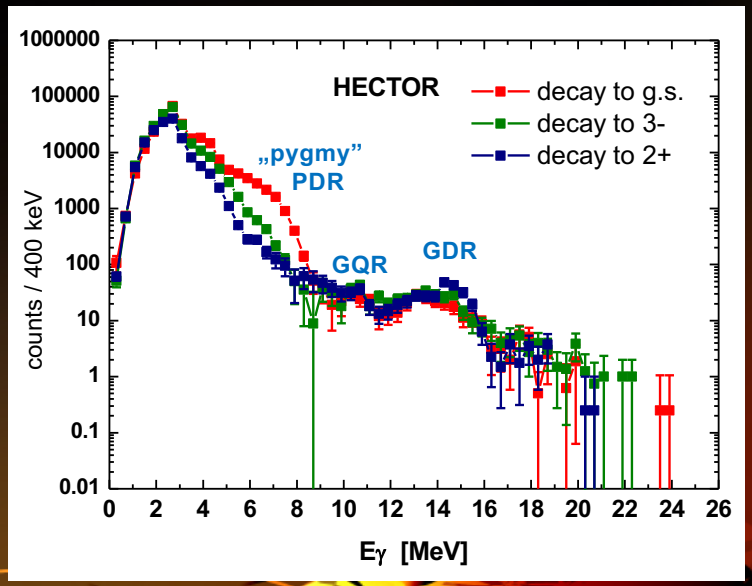


First results from the CCB facility

gamma decay from the region of GDR, GQR and PDR observed







Observation 1:
Axel-Brink hypothesis holds for GDR, but not for PDR

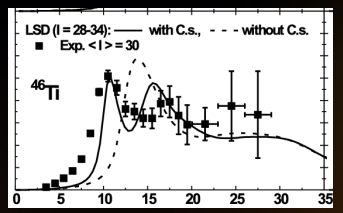
Observation 2:
Strong enhancement of gamma strength below neutron binding energy (PDR) - possible importance for understanding the r-proces in creation of heavy elements during supenova explosions or neutron star mergers

B. Wasilewska, M. Kmiecik, A. Maj et al. to be published

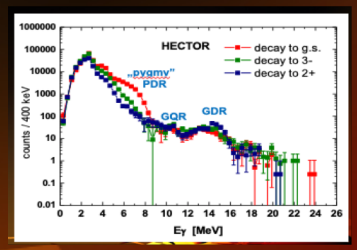
Summary

- The evolution of the shape of rotating atomic nuclei is quite similar to the evolution of the shape of rotating celestial bodies and can be well described by classic models

- Experimental evidence for the existence of Jacobi nuclear shapes have been found



- New medical proton facility in Krakow (CCB) starts producing interesting results in basic science: on collective modes in stable nuclei



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