Laboratoire Kastler Brossel
Physique quantique et applications

DE LA RECHERCHE À L'INDUSTRIE
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Exotic Nuclei and Astrophysics:

First spectroscopy of ^{110}Zr

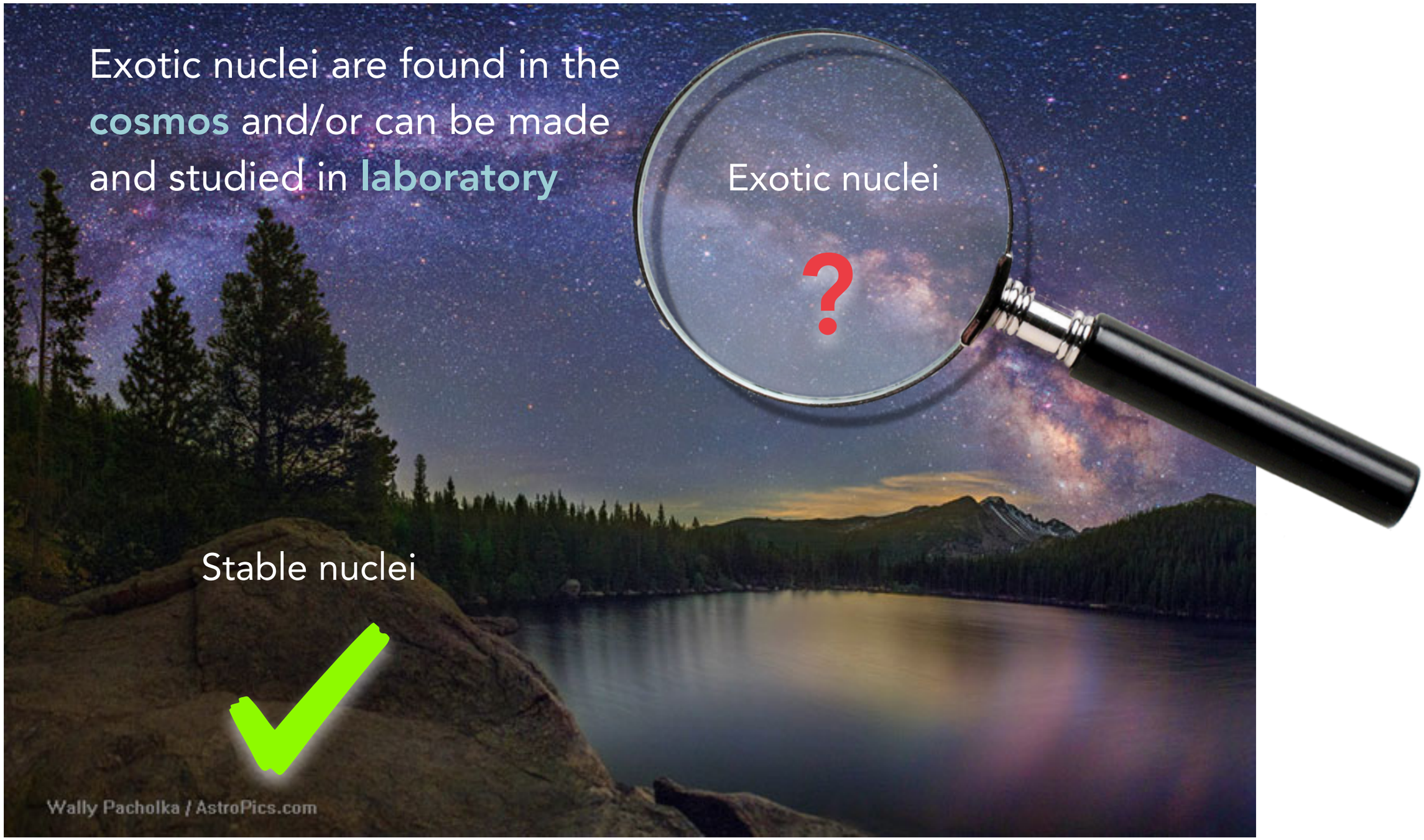
Nancy Paul

PhD. Advisors: Alexandre Obertelli and Anna Corsi

November 29, 2019

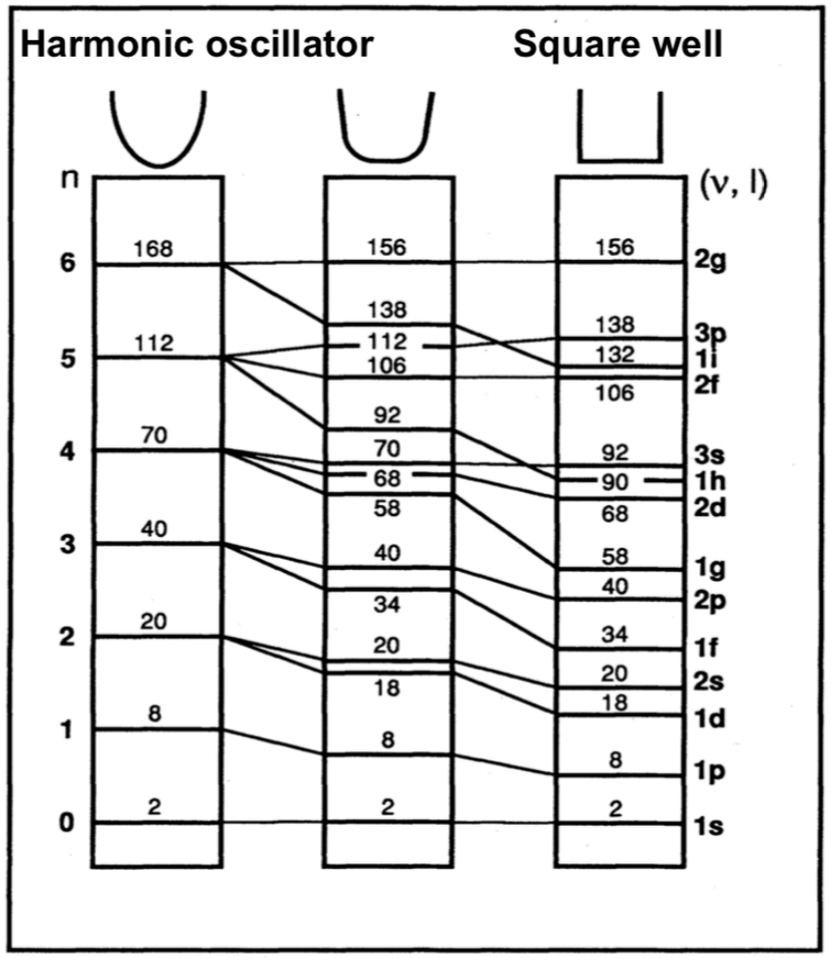

Wally Pacholka / AstroPics.com

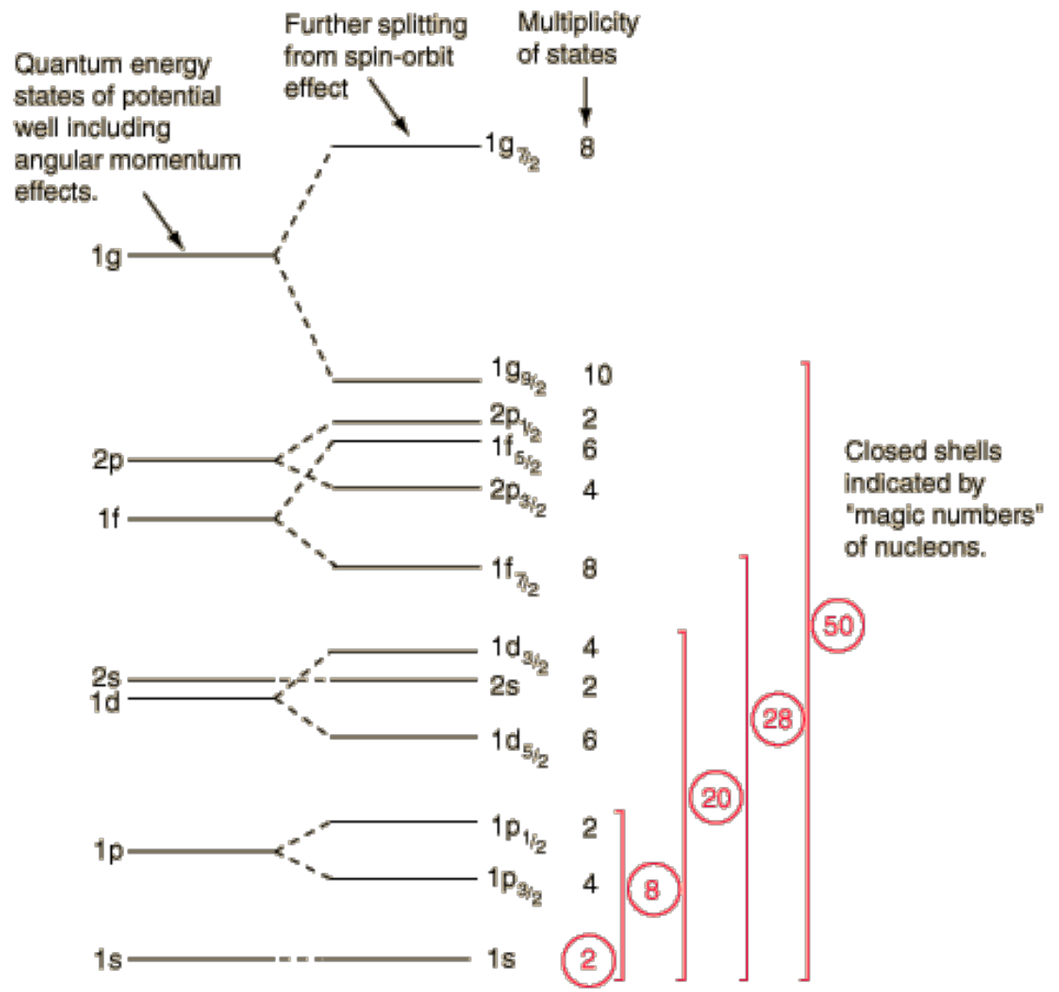

Stable nuclei
Wally Pacholka / AstroPics.com


Exotic nuclei are found in the cosmos and/or can be made and studied in laboratory
Exotic nuclei
?
Stable nuclei
Wally Pacholka / AstroPics.com

Energy shells in quantum systems

Rev. Mod. Phys. 65, 611 (1993) After Mayer and Jensen, 1955

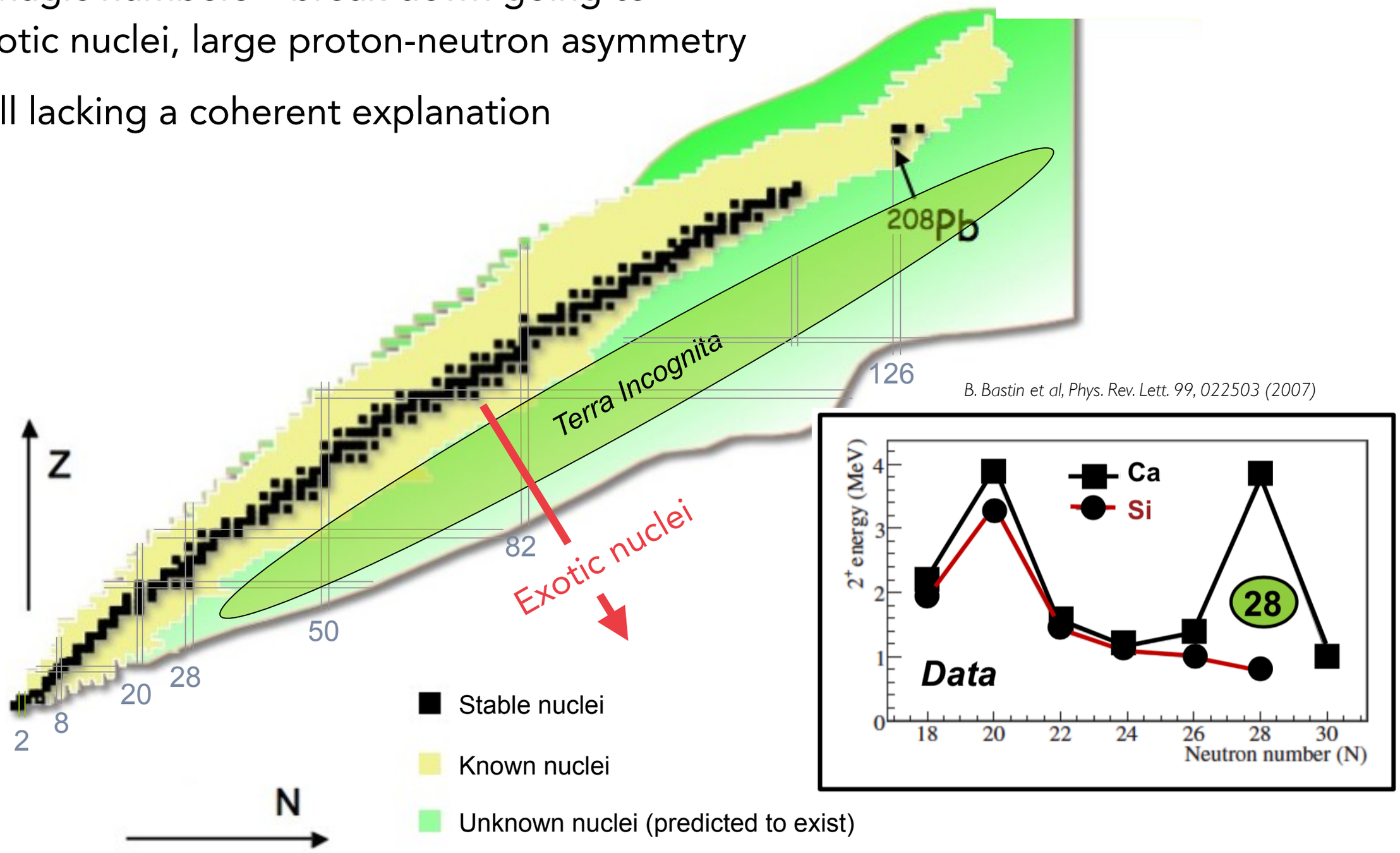




- Basic property of finite quantum systems
- Electrons in atoms, atoms in clusters, nucleons in nuclei
- Nuclear shells evidenced in binding energies [Elasser, 1933], solar abundances [Burbidge,1957], half-lives..
- Nuclear « magic numbers » : 2, 8, 20, 28, 50, 82, 126

Exotic nuclei and structure evolution

- « Magic numbers » break down going to exotic nuclei, large proton-neutron asymmetry
- Still lacking a coherent explanation



B. Bastin et al, Phys. Rev. Lett. 99, 022503 (2007)

The rapid neutron capture process

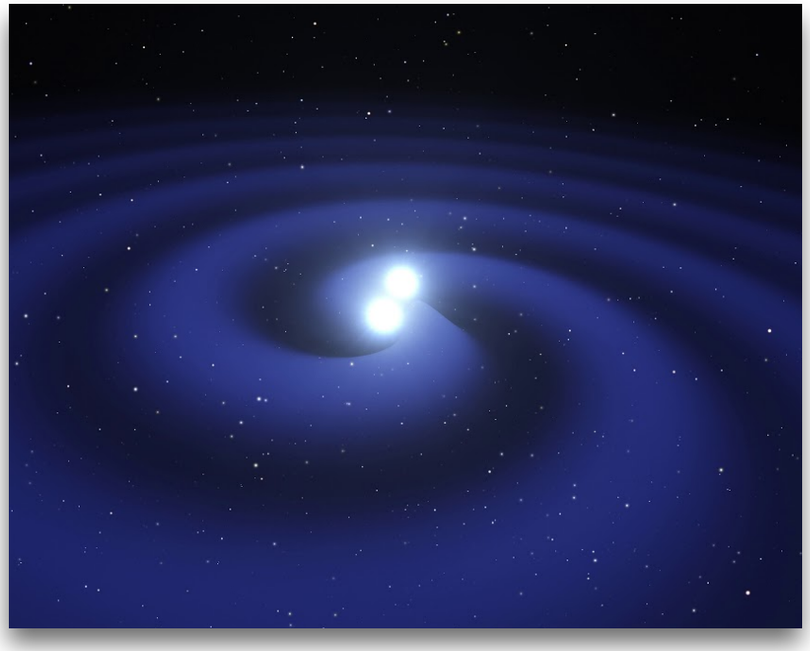
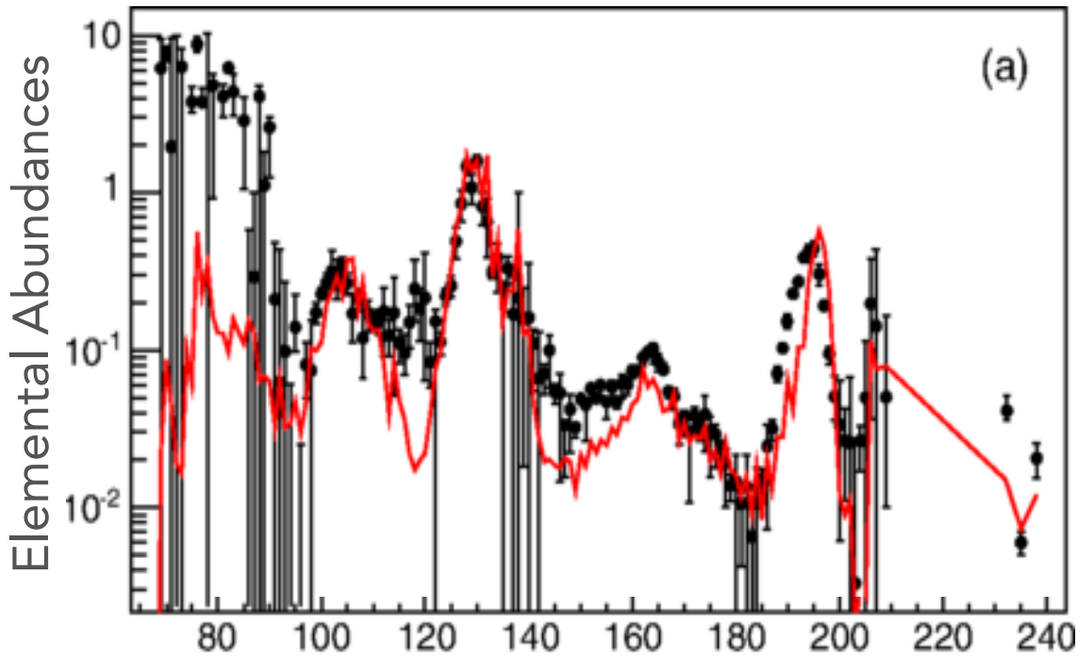


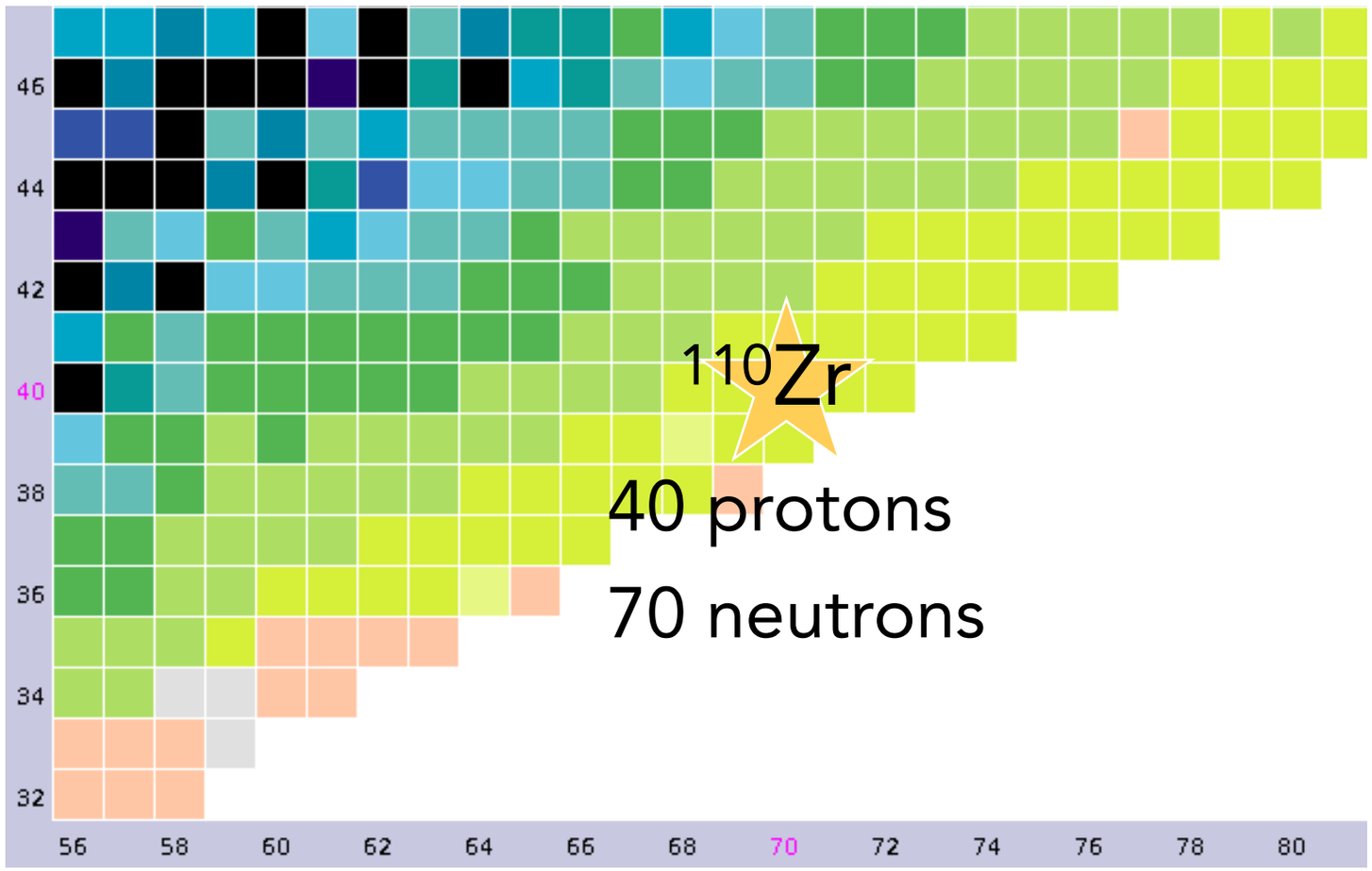
Figure from the European Space Agency

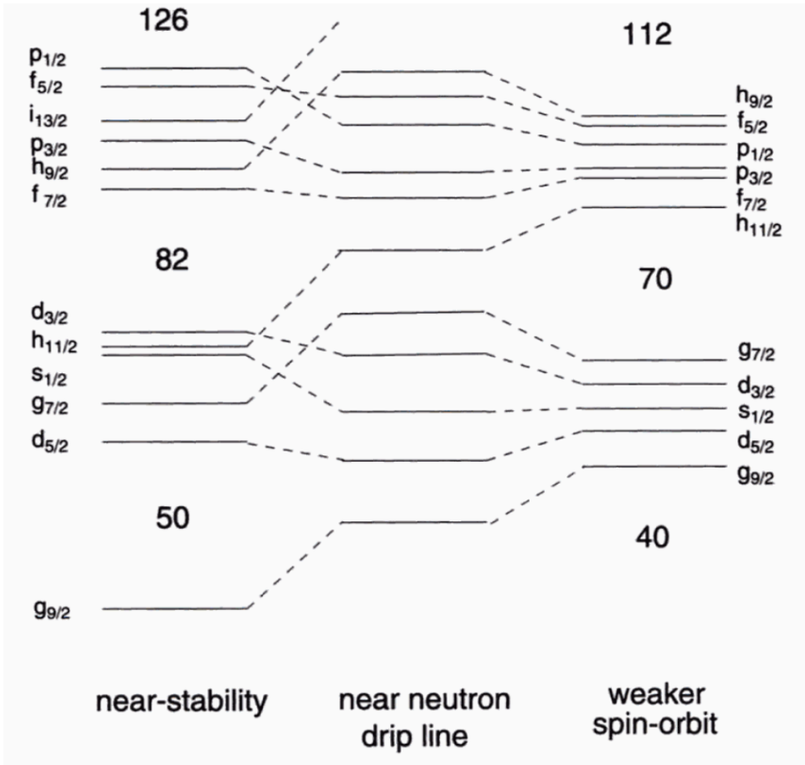
Figure adapted from Lorusso et al PRL 114, 192501 (2015)



- **~50% of abundances of heavy elements** (Fe-U) thought to originate in rapid neutron capture process (r-process)
- **Astrophysical site debated** : Neutron star merger (yes, gravitational wave confirmation), Core-collapse supernova? Some other extreme environment?
- **Nuclear physics debated : Need to understand heavy neutron-rich nuclei !**

The case of ^{110}Zr



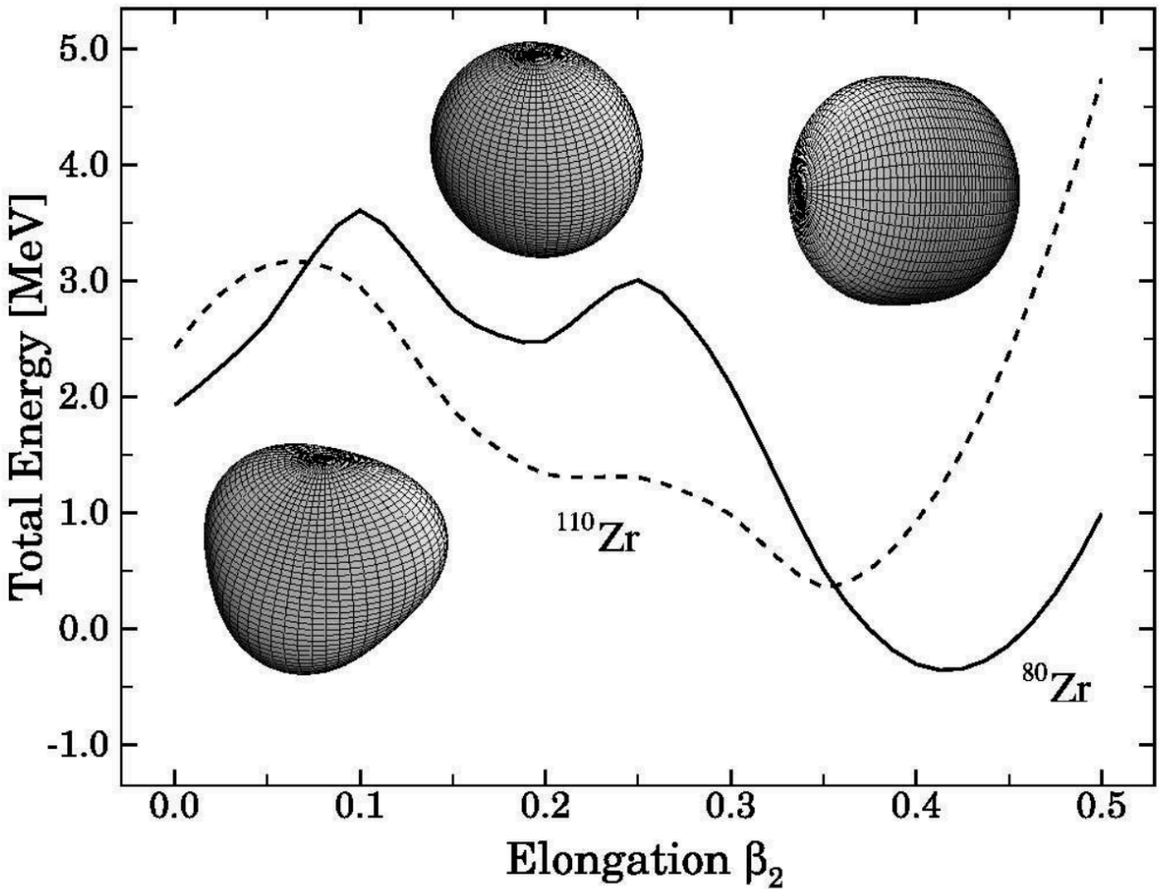


R. Casten, *Nuclear Structure from a Simple Perspective*, Oxford University Press (2001).

- Potential **weakening of spin-orbit coupling** in ^{110}Zr
- Could give rise to stabilisation in spherical or tetrahedral shape
  - Accumulate material near A=110 in the r-process, **resolve model problems**?
- Astrophysical motivation —> many theoretical predictions

The case of ^{110}Zr

Figure from Schunk and Dudek, IJMP E (2003).



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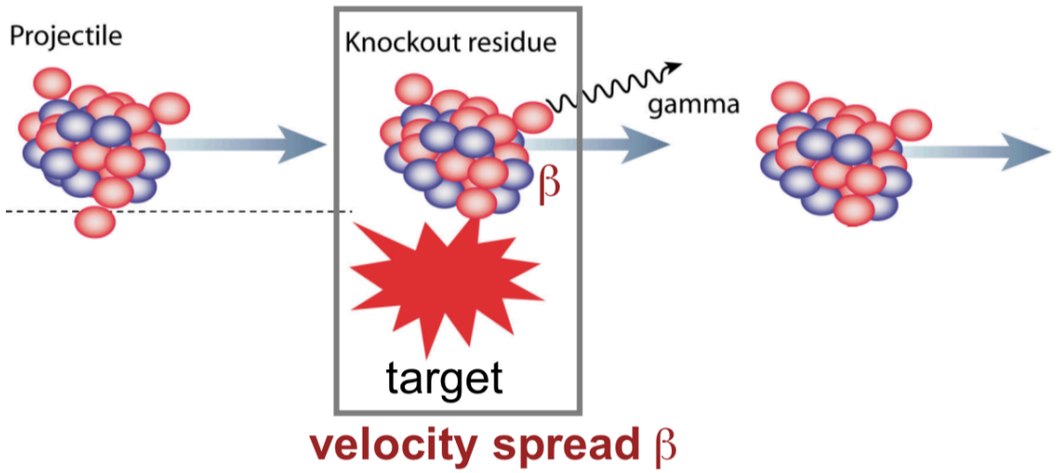
Key benchmark of exotic nuclear structure evolution

Experimental Setup at RIKEN

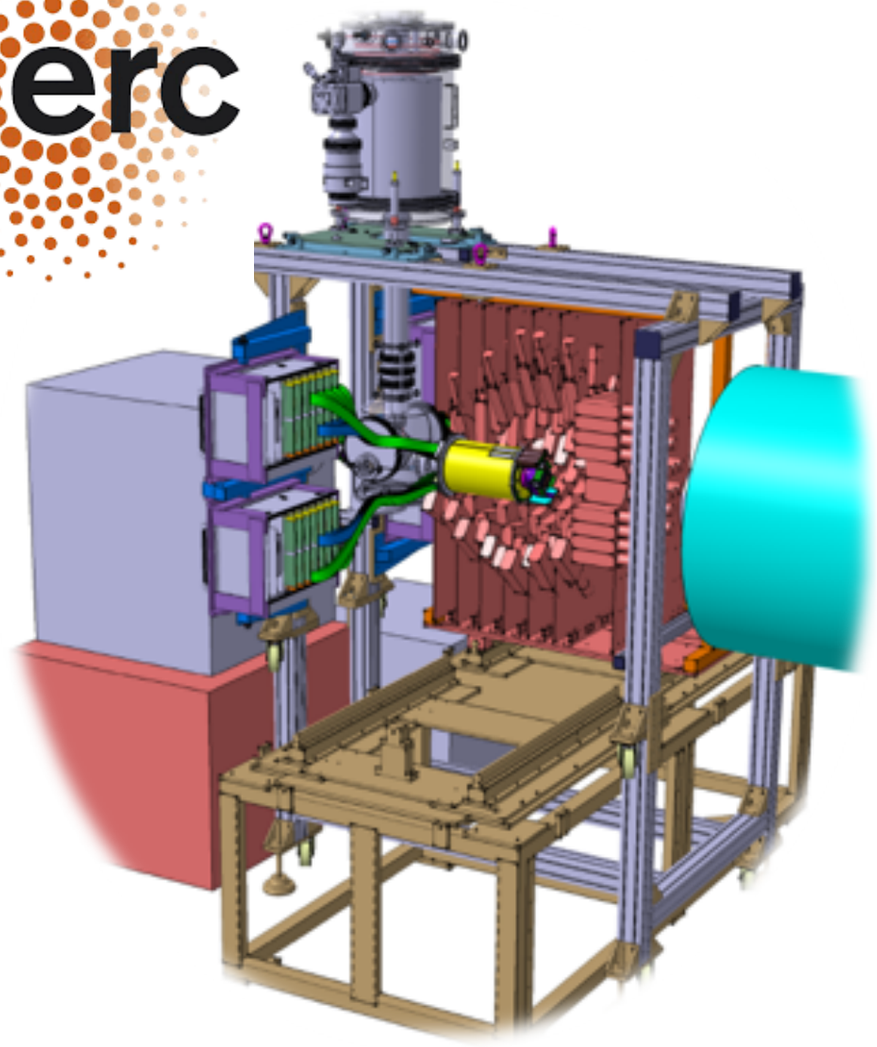
^{110}Zr produced by proton removal on a 10 cm long liquid hydrogen target
In-beam gamma ray spectroscopy of excited nuclear states

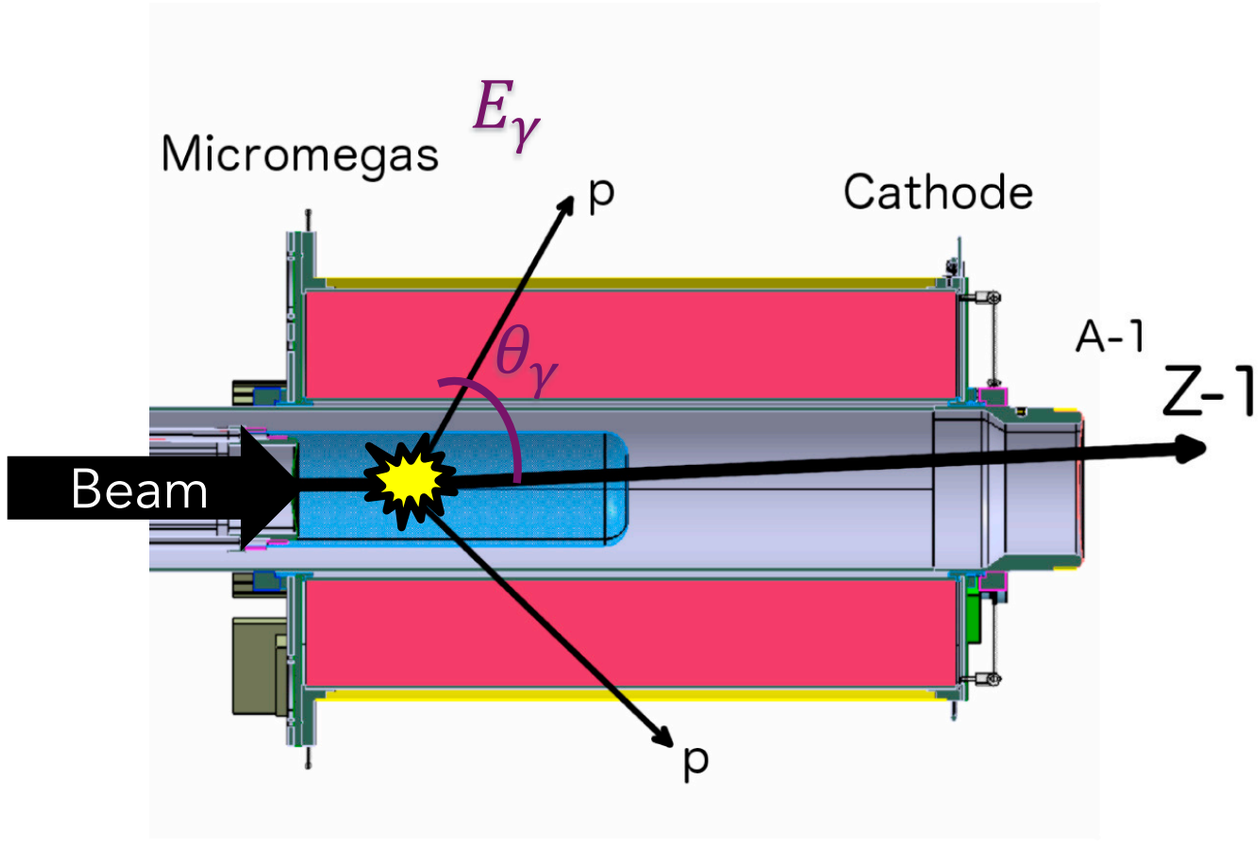
Primary beam: ^{238}U
Energy: 345 MeV/U
Intensity: 30 pnA
β @ LH2 target: 0.6c

Target thickness = tradeoff between luminosity and resolution



Doppler Correction with MINOS



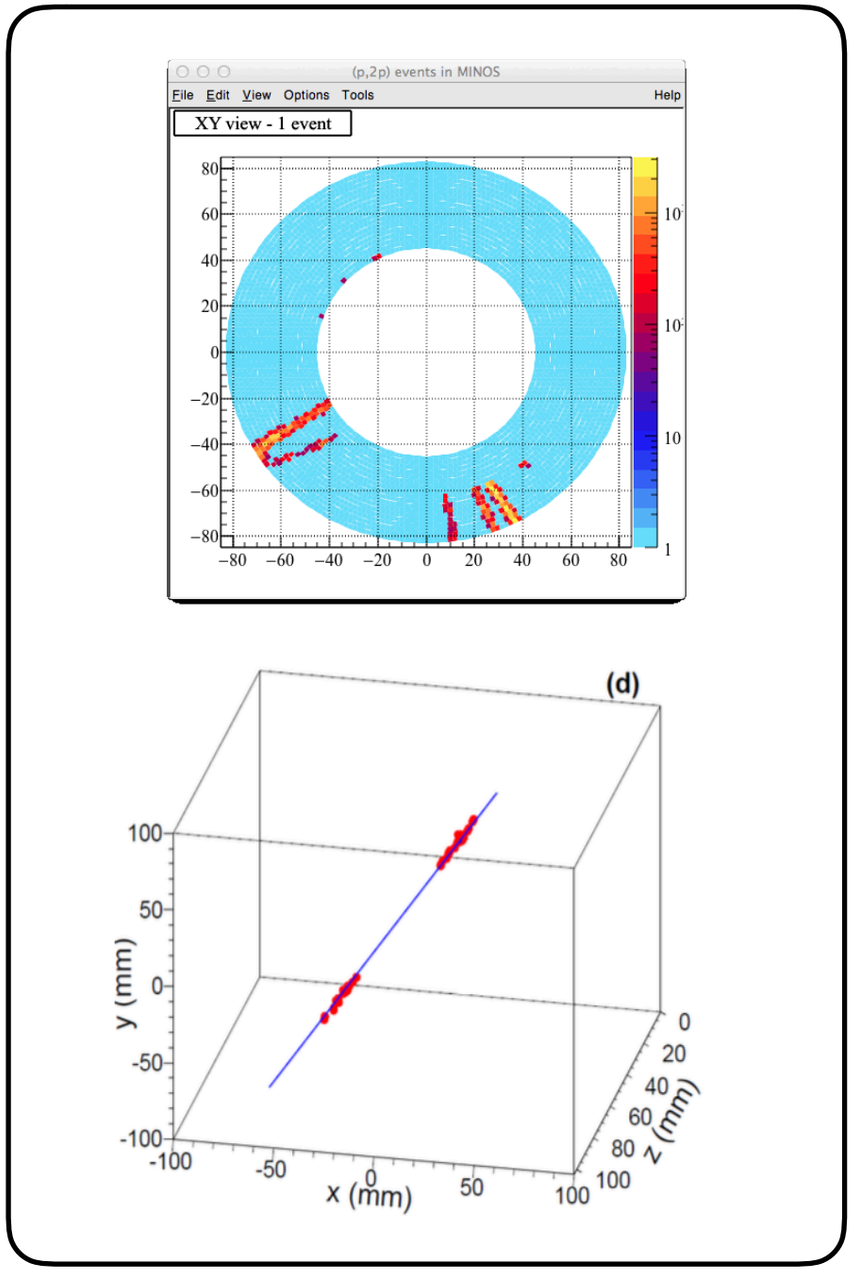


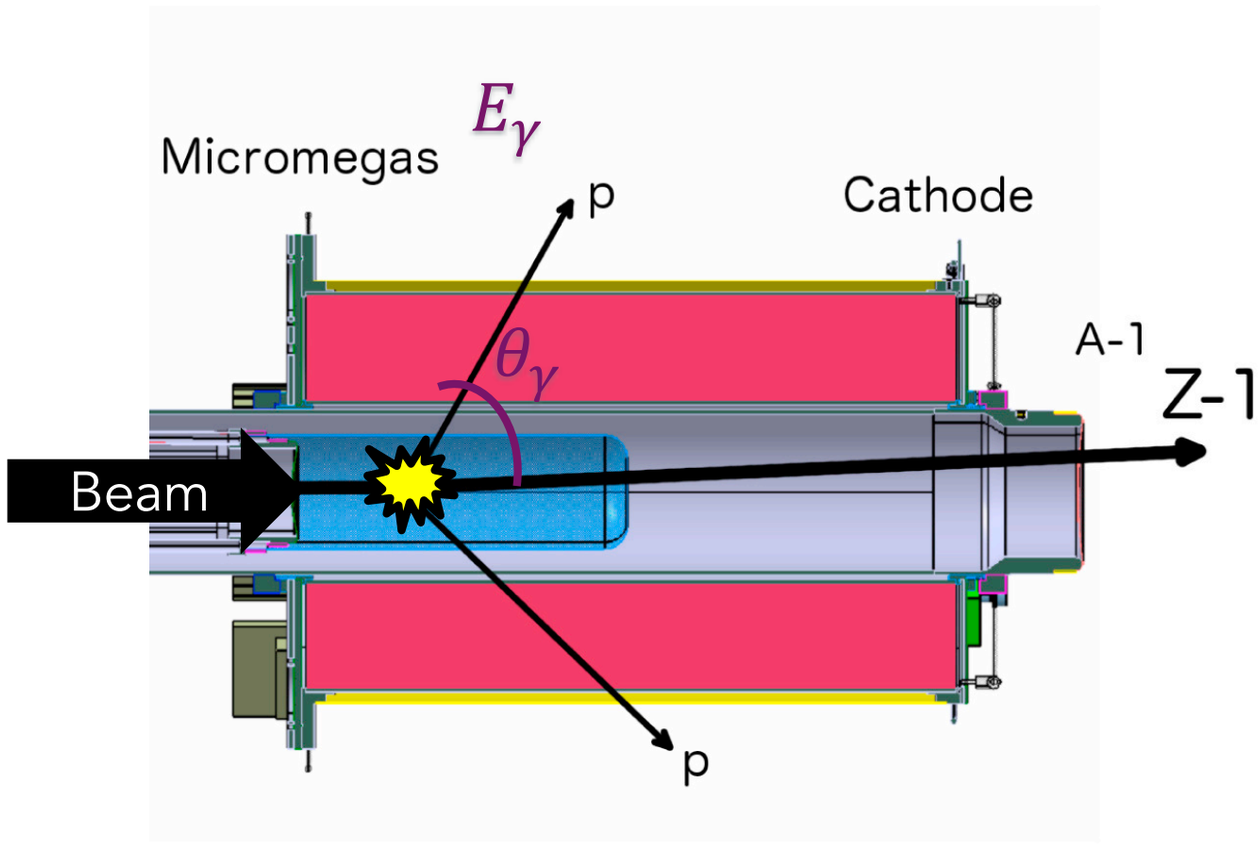
$$E_{dop} = \frac{E_\gamma(1 - \beta cos\theta_\gamma)}{\sqrt{1-\beta^2}}$$

- Track reconstruction in 3D based on combined charge and time measurements
- Vertex position → Determine β and θγ of gamma ray detected in DALI2

MINOS figures from Obertelli et al, EPJA 50 (2014), Santamaria et al, NIM A 905 (2018), A. Corsi, D. Calvet

Doppler Correction with MINOS





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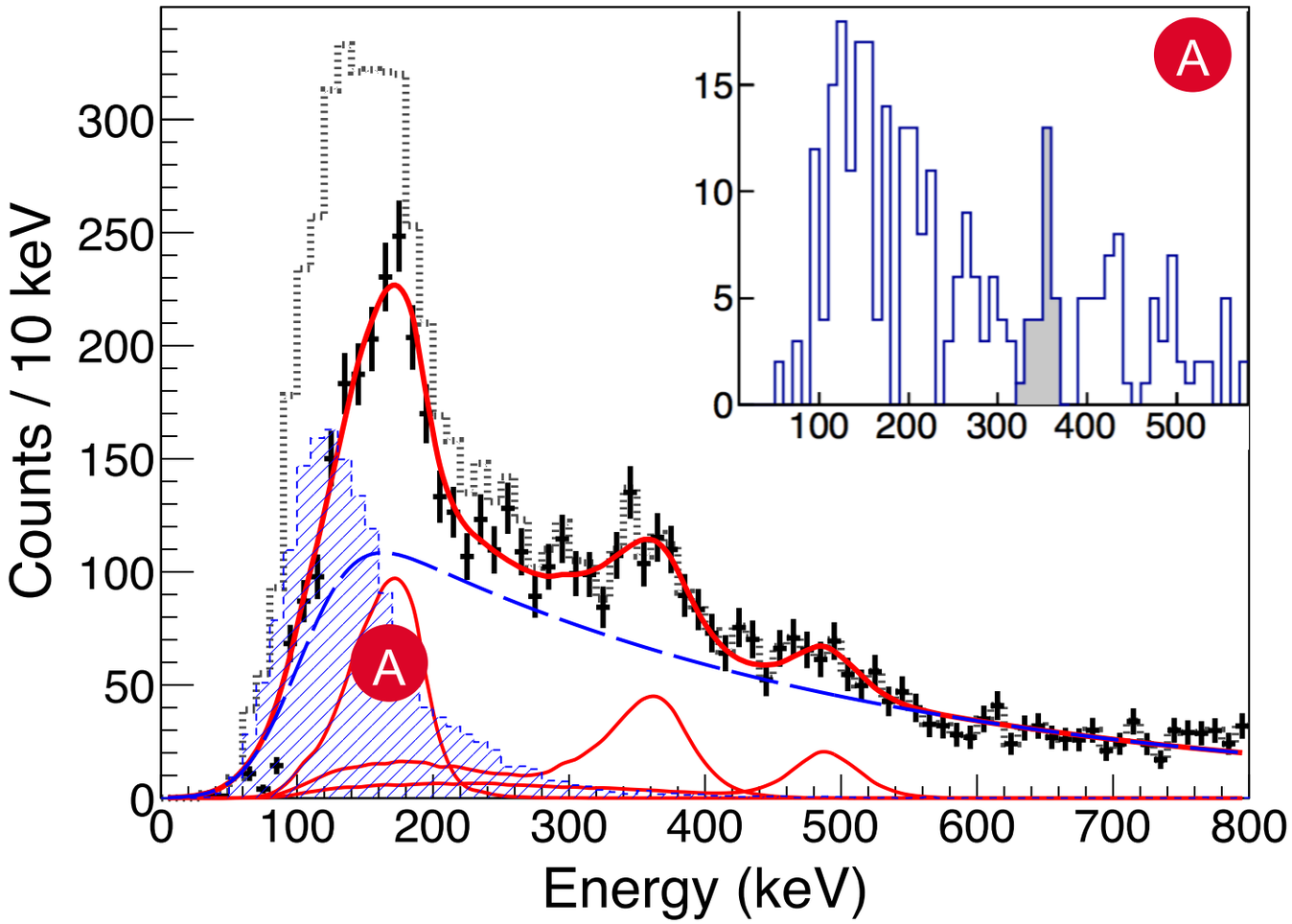
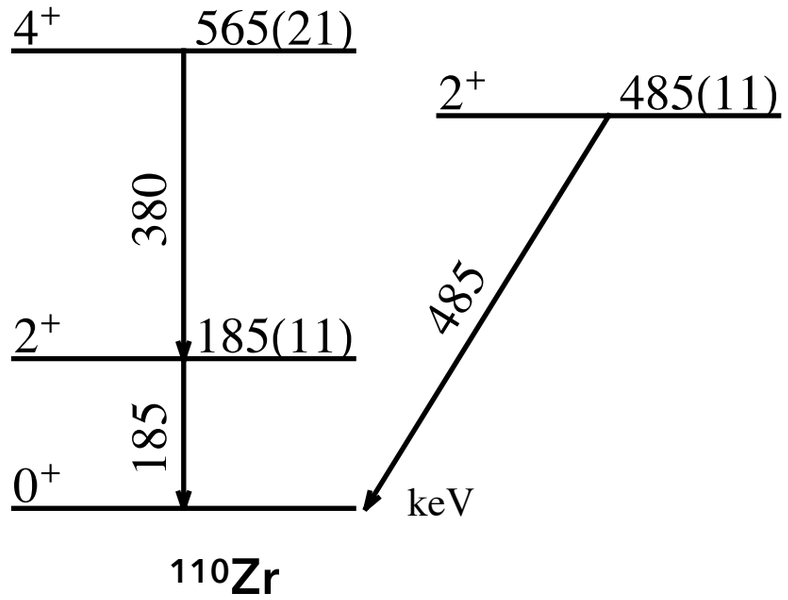
Gamma spectrum ^{110}Zr

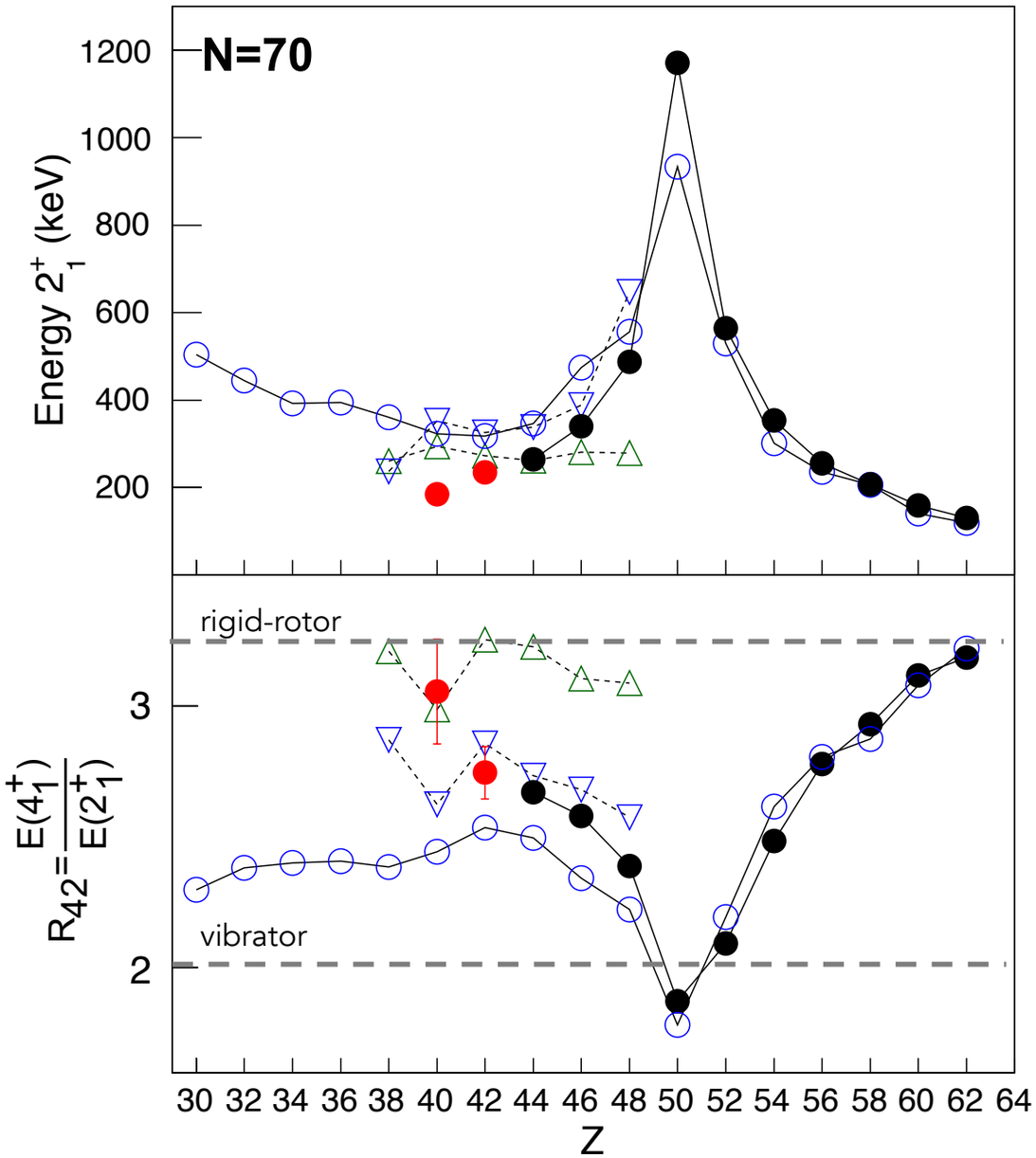
Gate 150-210 keV





- Few stats, background subtraction essential
- Gamma-gamma coincidence allows to build level scheme

Comparison with theory



NNDC-evaluated data

This work

D1S-5DCH
Delaroche, Girod, Libert (CEA)

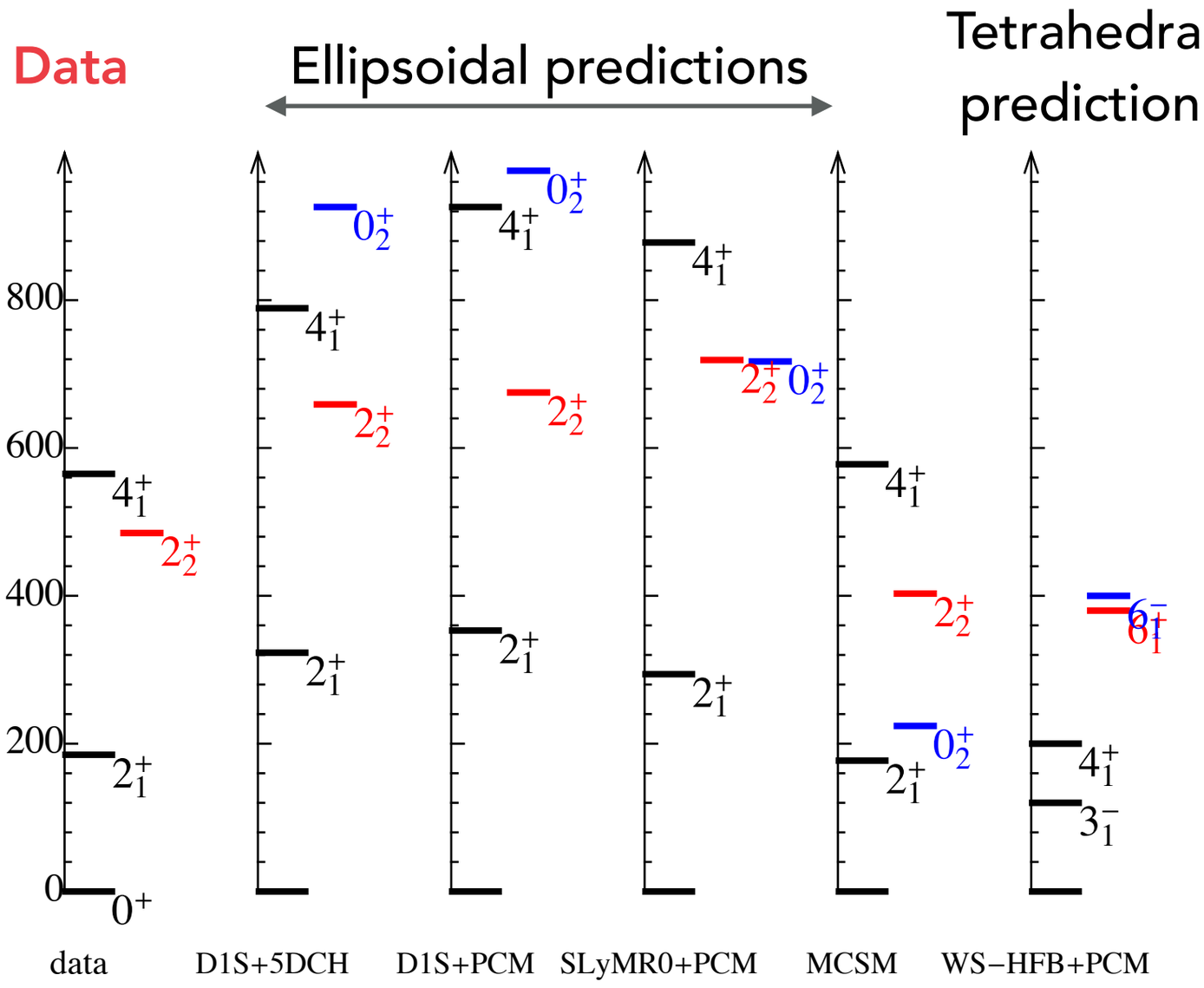
D1S-PCM
T. R. Rodriguez (UA Madrid)

SLyMR0-PCM
Bally (CEA), Bender (IPNL),
Heenen (Université Libre de Bruxelles)

- No sign of stabilisation in first excited state systematics
- R_{42} ratio suggests well-deformed nucleus

N. Paul et al., Physical Review Letters 118, 032501 (2017)

Comparison with theory (cont'd)



Comparison with theory (cont'd)

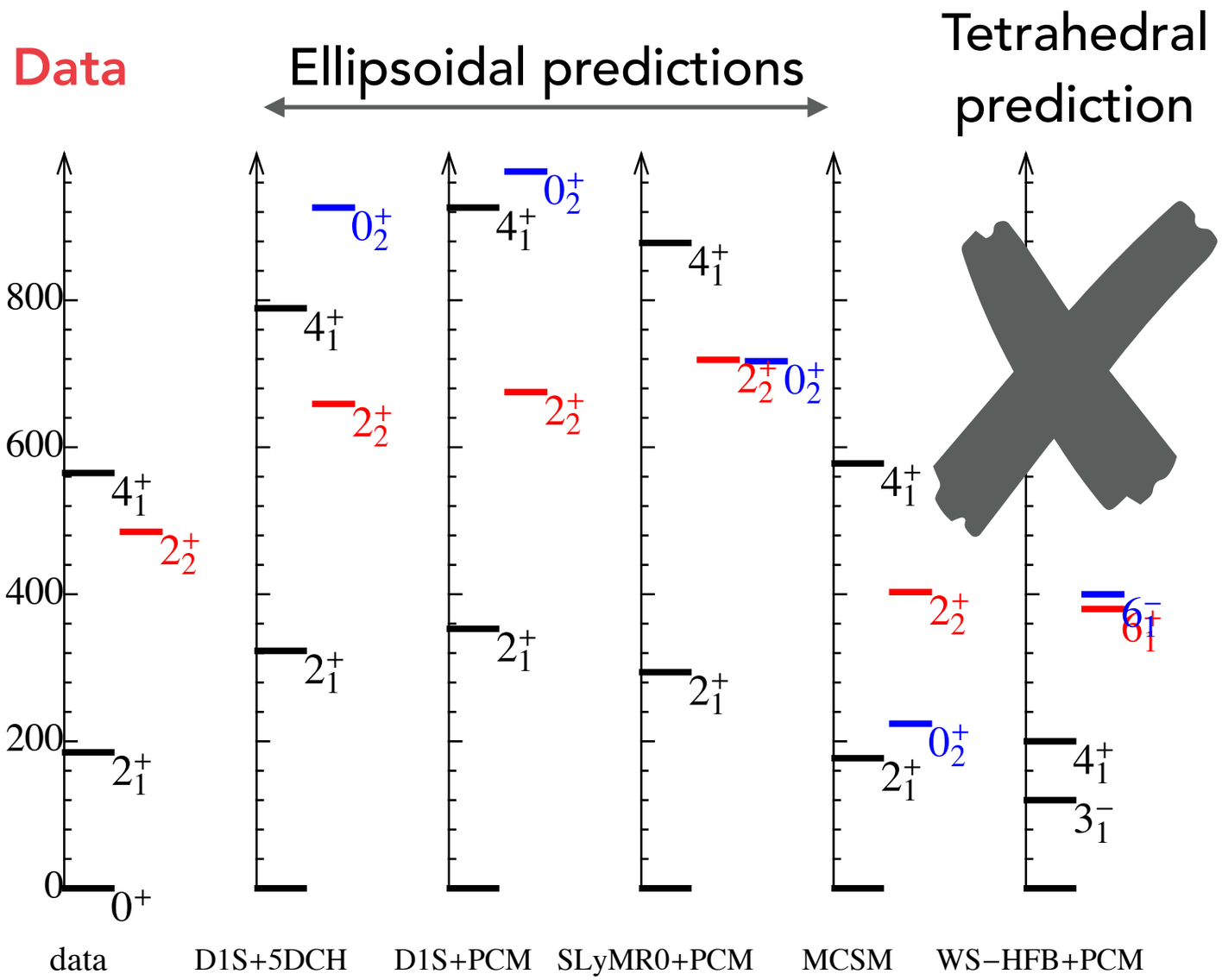
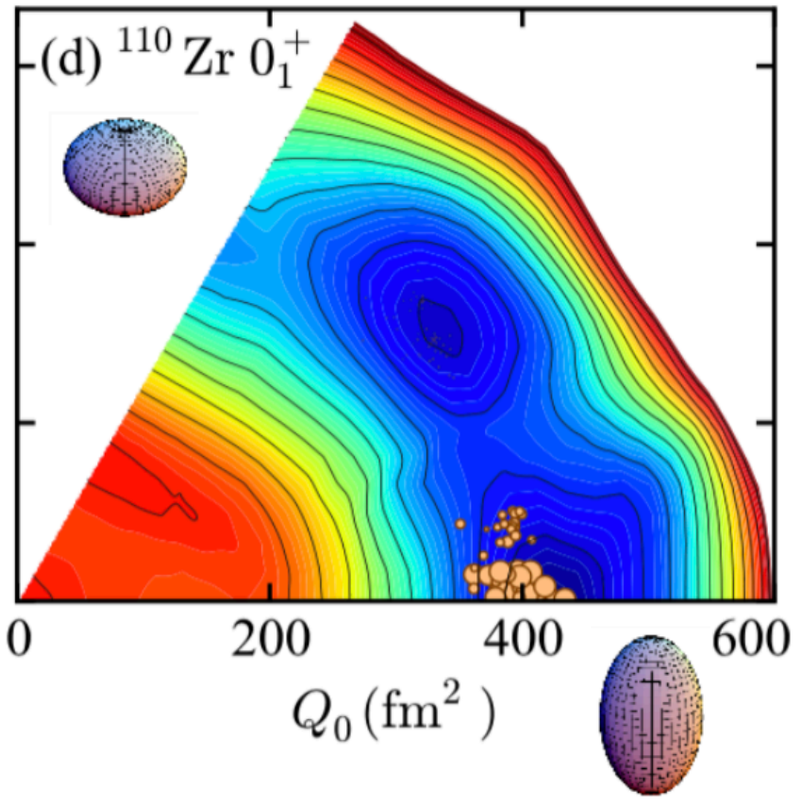
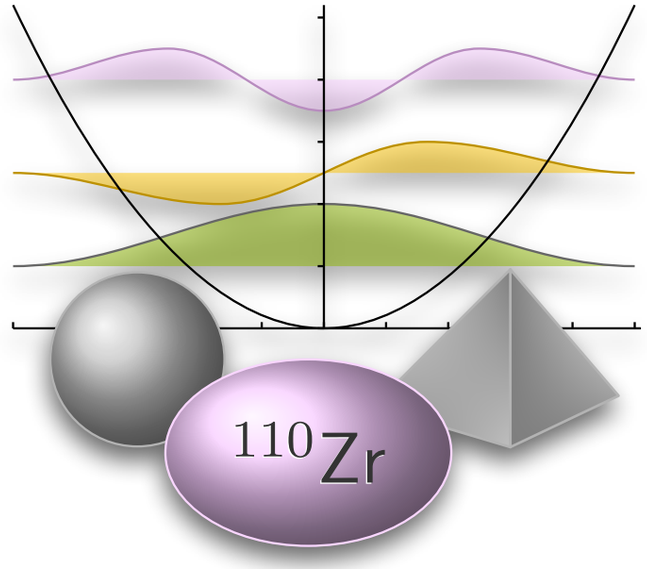


Figure from Togashi et al, PRL 117 (2016)



Comparison of the experimental spectrum with beyond-mean-field models suggests that ^{110}Zr is *not spherical, nor tetrahedral, but even more deformed than anticipated*

Where do we go from here ?



- Spectroscopy of ^{110}Zr did not reveal a surprising quantum configuration that could solve r-process problems.
- Results show even more deformation than could have been expected in a « non-stabilized » case

- Demonstrates the outstanding problem of understanding exotic quantum structure evolution
- But there's hope ! New facilities in Europe, FAIR (GSI), SPIRALII (GANIL) and new methods (antiprotons at CERN) to probe the most exotic systems

We need you !

A. Obertelli, A.Corsi, G. Authelet, D. Calvet, F. Château, A. Delbart, J.-M. Gheller, A. Giganon, A. Gillibert, V. Lapoux, C. Péron, A. Peyaud, E.C. Pollacco, J.-Y. Roussé, C. Santamaria, C. Louchart, B. Bally, M. Girod, J.P. Delaroche, J. Libert

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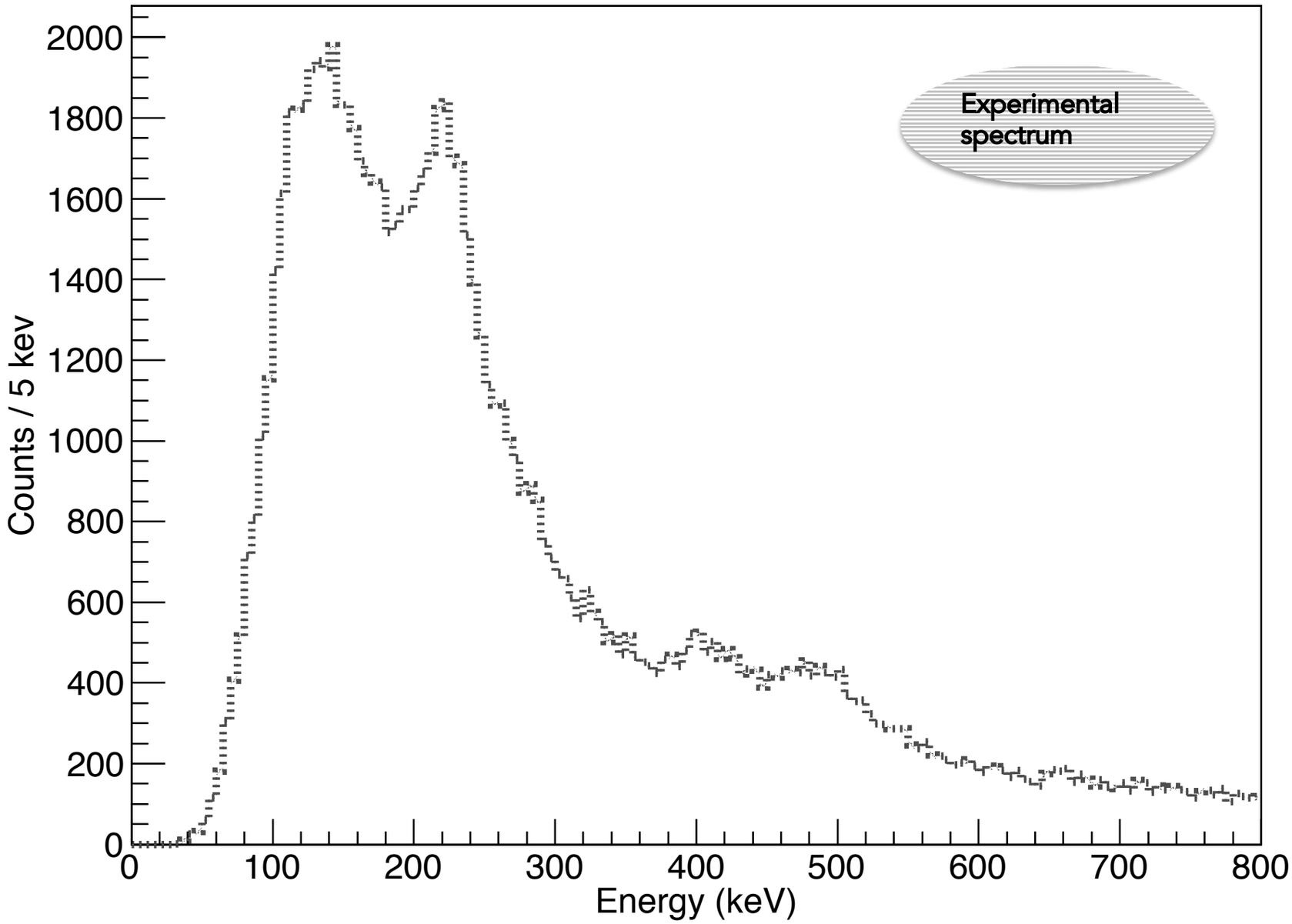
B. Ding, Z. Liu

T. R. Rodriguez

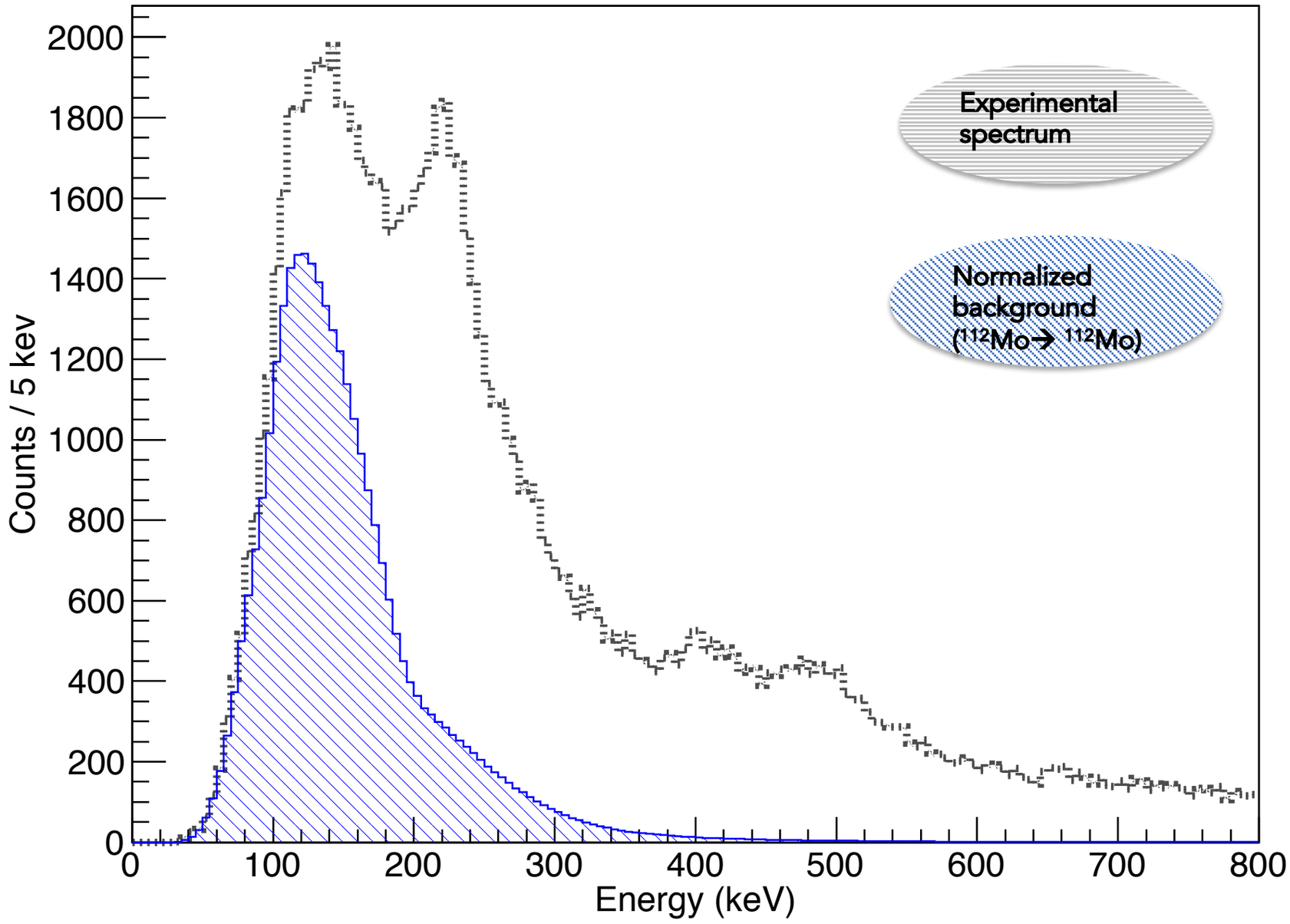
P.H. Heenen

Backup

High statistics test case: ^{112}Mo



High statistics test case: ^{112}Mo



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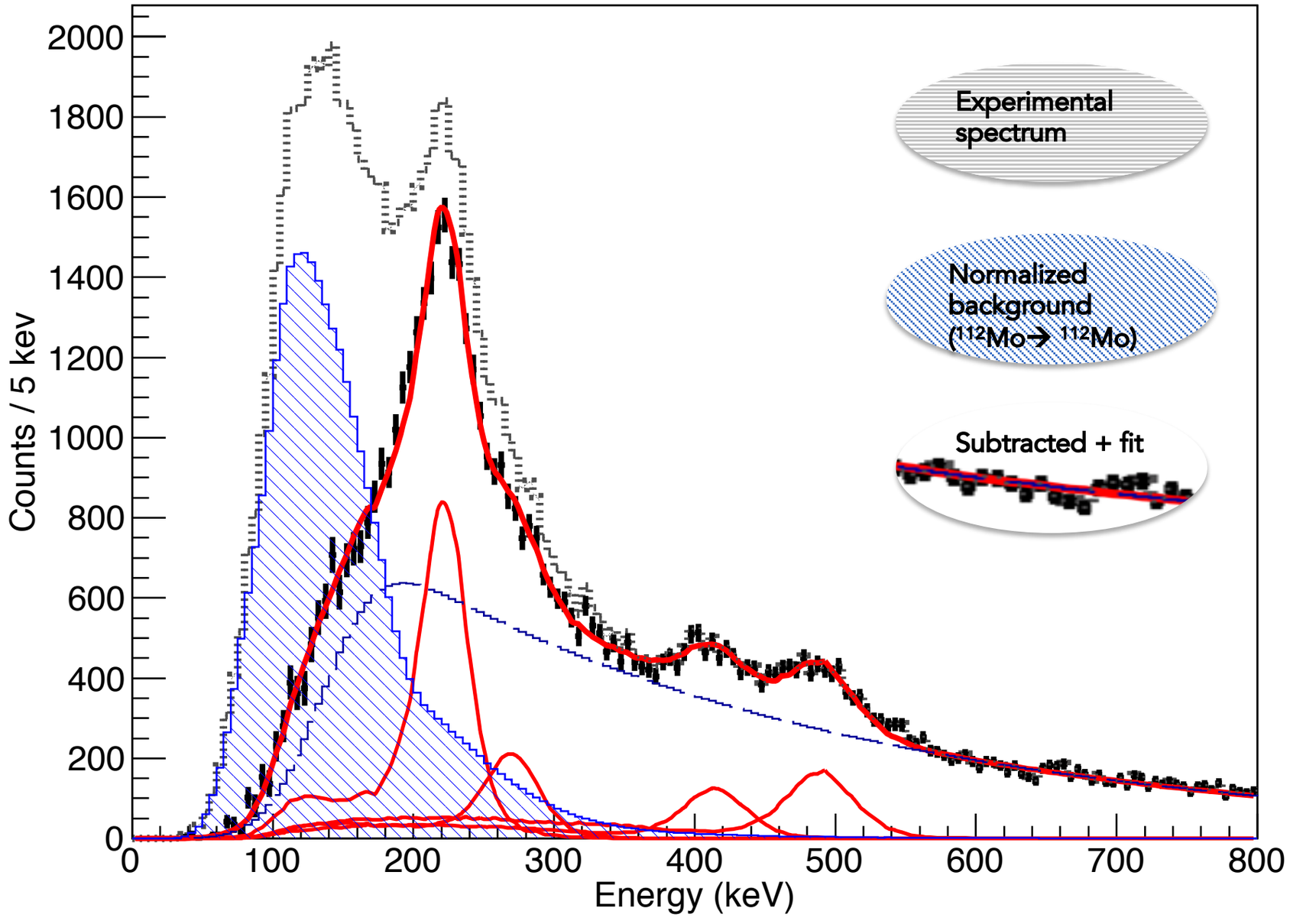
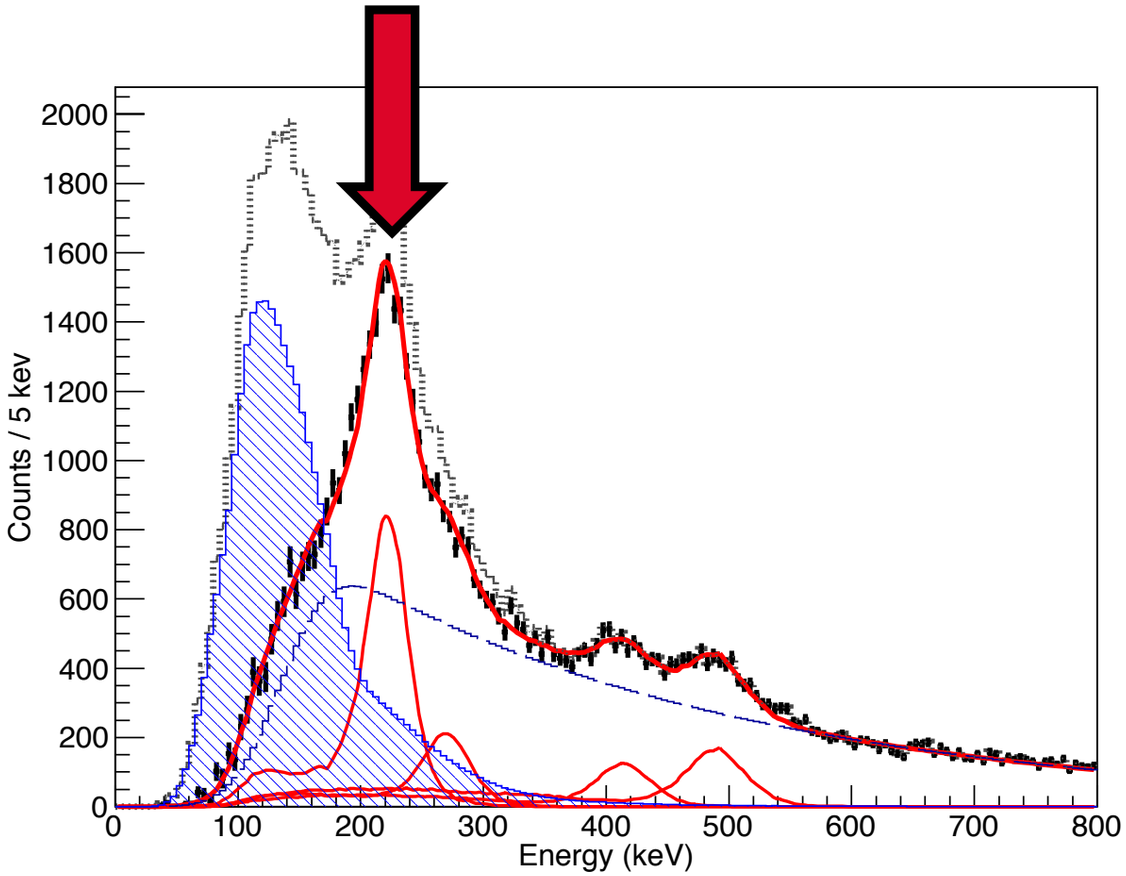
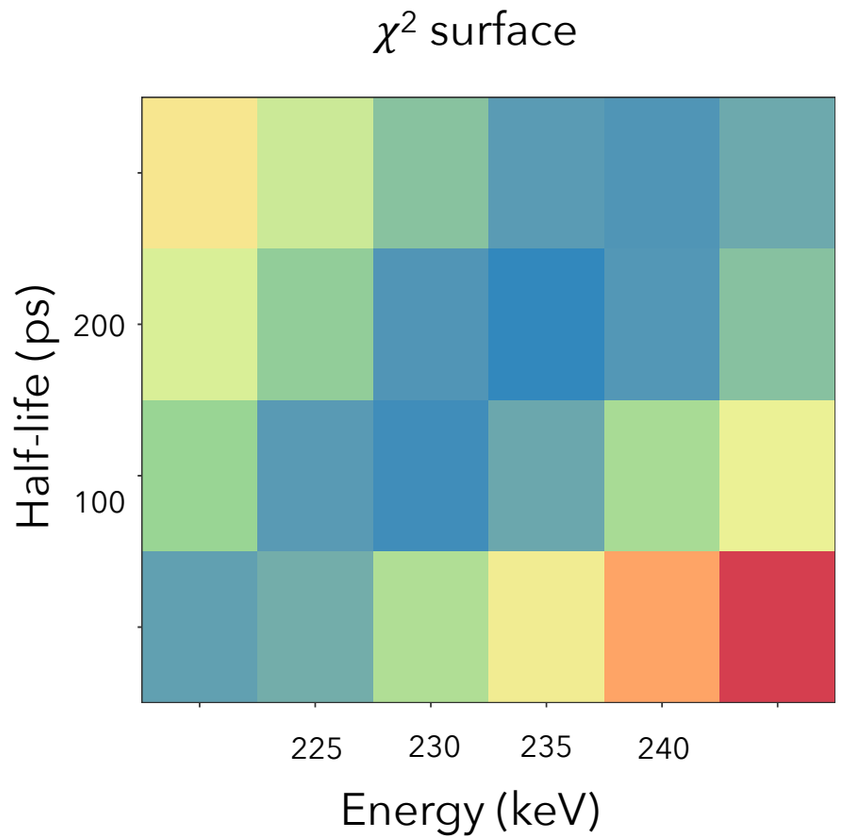


High statistics test case: ^{112}Mo

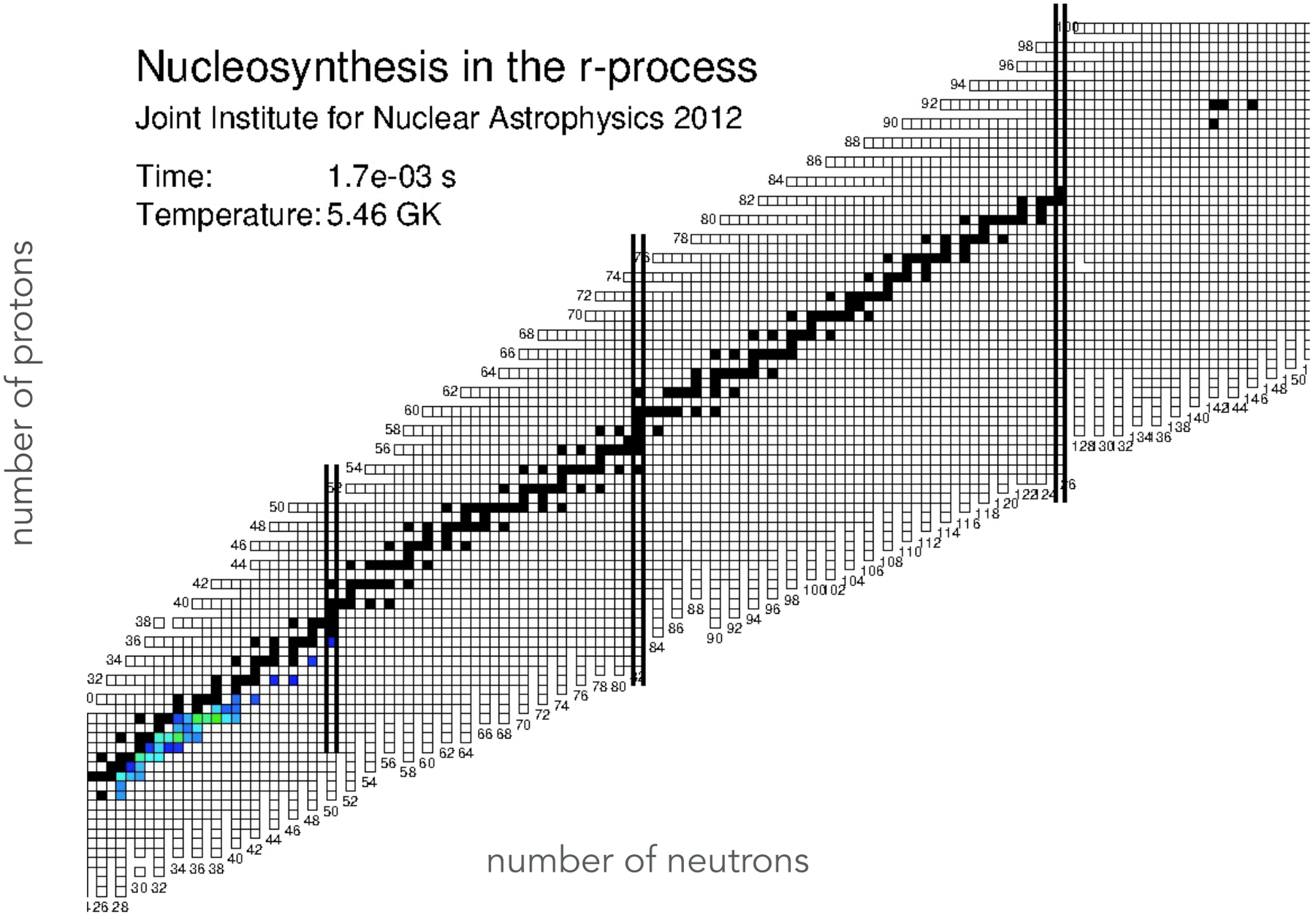




$$p(x,N) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\sigma_i} exp\left(-\frac{1}{2}\frac{(x_i - M_i)^2}{\sigma_i^2}\right)$$
$$= \frac{1}{\sqrt{(2\pi)^n}\prod_{i=1}^{N}\sigma_i} exp\left(-\frac{1}{2}\sum_{i=1}^{N}\frac{(x_i - M_i)^2}{\sigma_i^2}\right)$$
$$= \frac{1}{\sqrt{(2\pi)^n}\prod_{i=1}^{N}\sigma_i} exp\left(-\frac{1}{2}\chi^2\right)$$
$$= C\ exp\left(-\frac{1}{2}\chi^2\right)$$

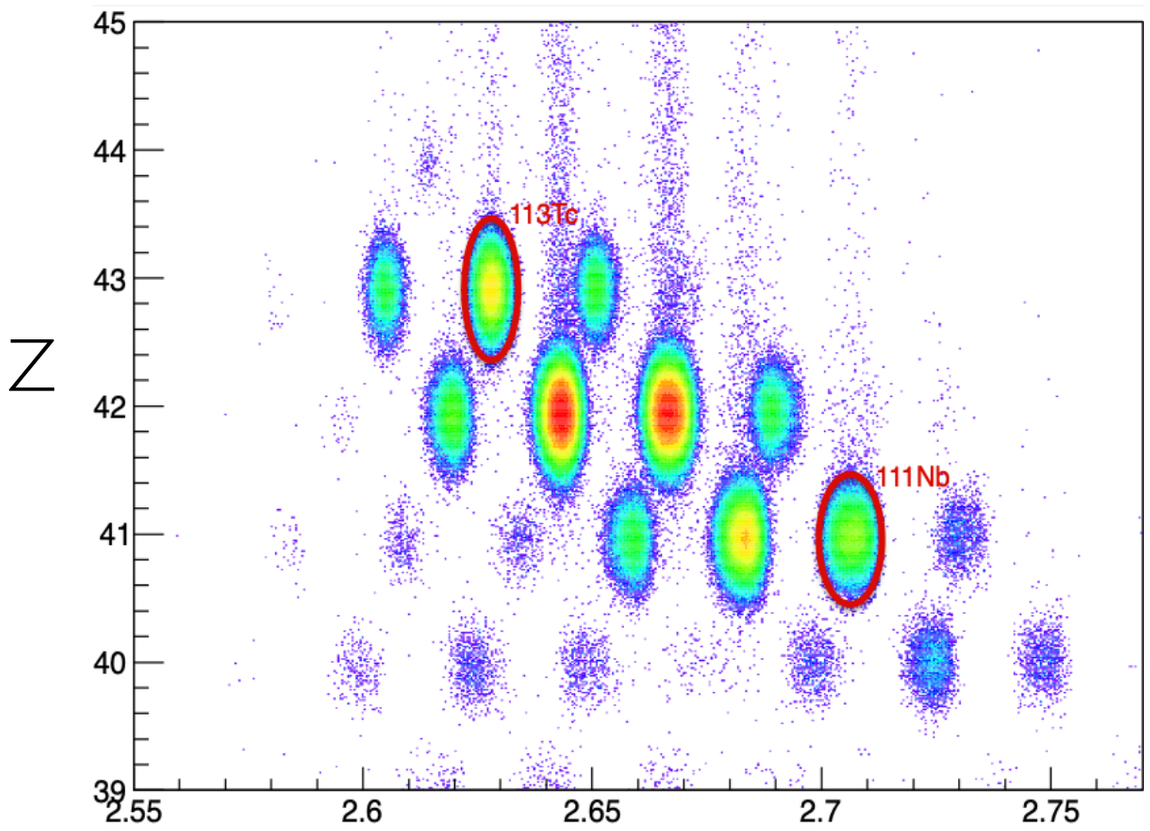
- χ^2 surfaces in the energy/half-life plane analysed to obtain best fit to spectrum
- Angular divided fits also considered, as well as feeding effects

The rapid neutron capture process



Identification des ions à RIKEN

Entrée du cible



Sortie du cible