# Introduction to nuclear physics with accelerated beams

*O. Sorlin (GANIL)*

What are limits of stability ?

Which new phenomena emerge at the drip lines (halo, clustering, breaking mirror symetry… ) ?

How do nuclear structure and shape evolve along the chart of nuclides ?

How does nuclear structure change with Temperature and Spin value ?

How to unify nuclear structure and reaction approaches ?

How to probe the density and isospin dependence of the nuclear equation of state ?

What are nuclear processes that drive the evolution of stars and galaxies in the universe ?

How / where are nuclei synthesized in the universe ?

Find a universal interaction, based on fundamental principles, that can model nuclear structure and reactions in nuclei and in stars (i.e. from the *fm to $10^4$ km*, over $10^{22}$ orders of magnitude)

# Accelerators, reactions and instrumentation

**Facilities:**
GANIL, GSI, Dubna,
RIKEN, Licorne

Stable / radioactive beams
5 - 500 MeV/A

**Detectors:**
Charged particles: GRIT, ACTAR-TPC
$\gamma$-rays: AGATA, nu-ball, PARIS

**Reactions:**
Fusion, transfer, Fission, knockout...

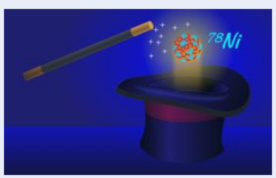
**spectrometer**

Neutron wall
EXPAND

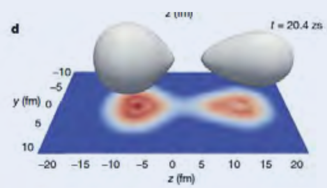
**Implantation**
Residual nuclei
$\beta$, $\alpha$-decay,
isomeric decay

## A wide variety of phenemona to understand

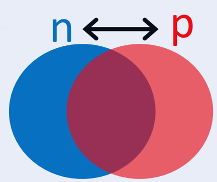
Magic nuclei



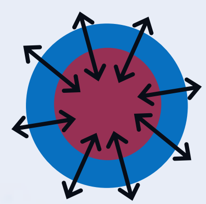

Fission, pear shapes

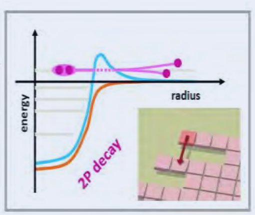


GDR

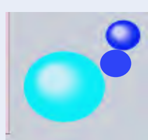



Soft GMR

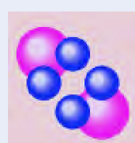




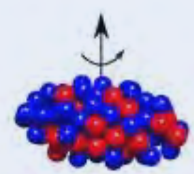

Exotic decays



2n halo

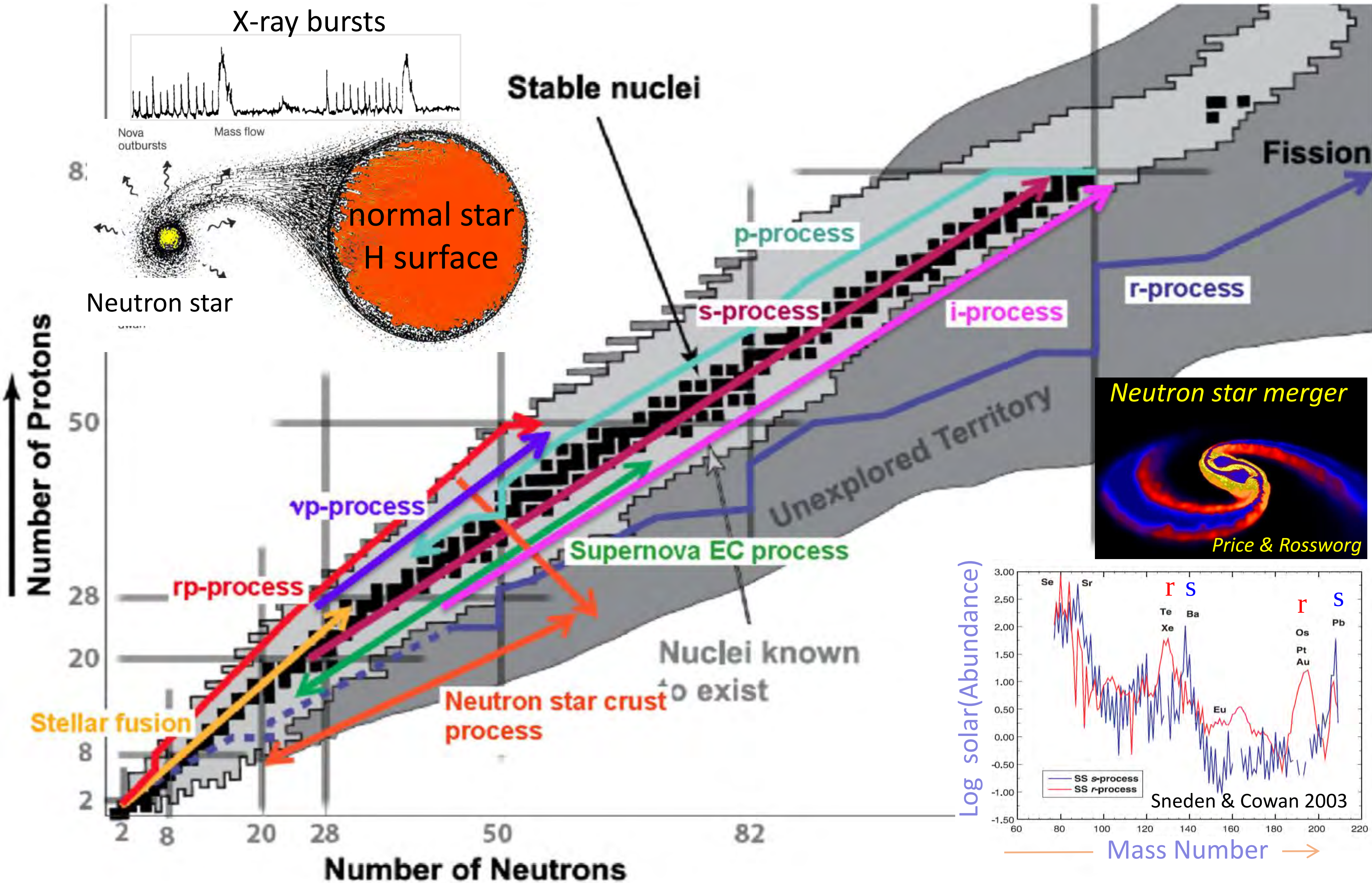


molecular cluster



rotation- deformation

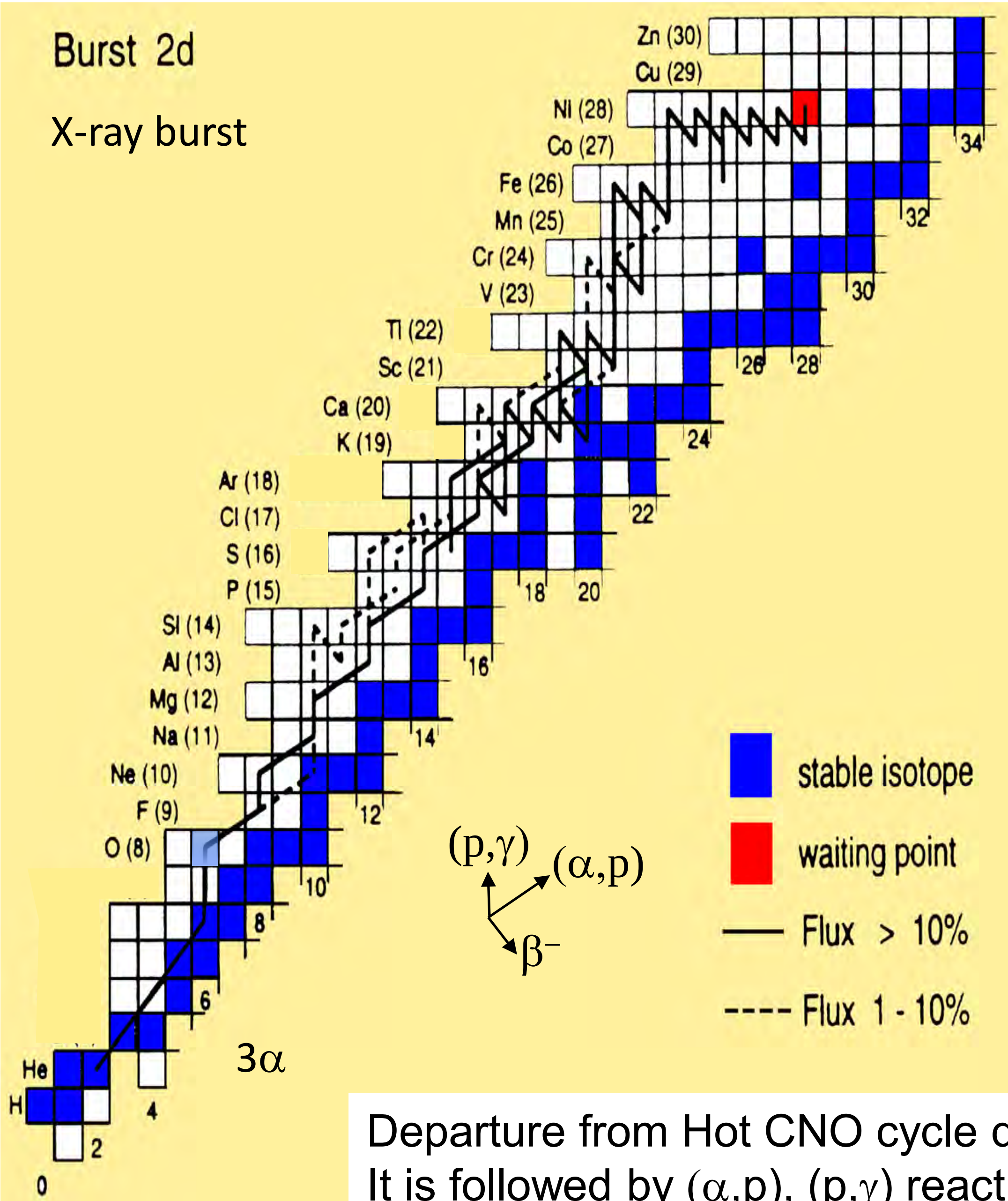
# Nuclear physics impact many astrophysical processes

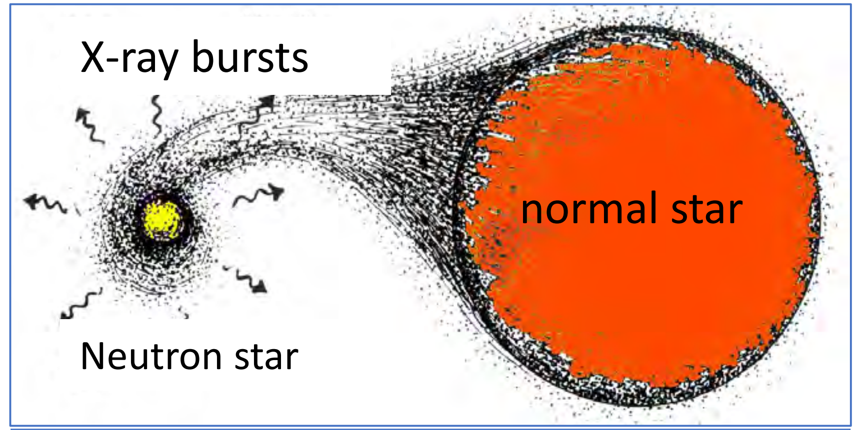


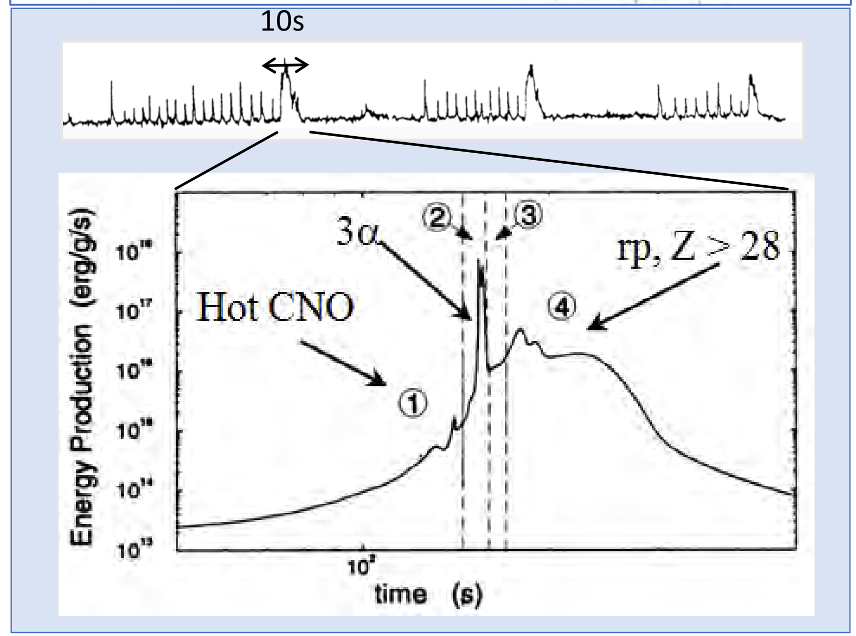

H. Schatz (2016)

# Nuclear astrophysics

# Energy profile of X-ray burst and nuclear physics



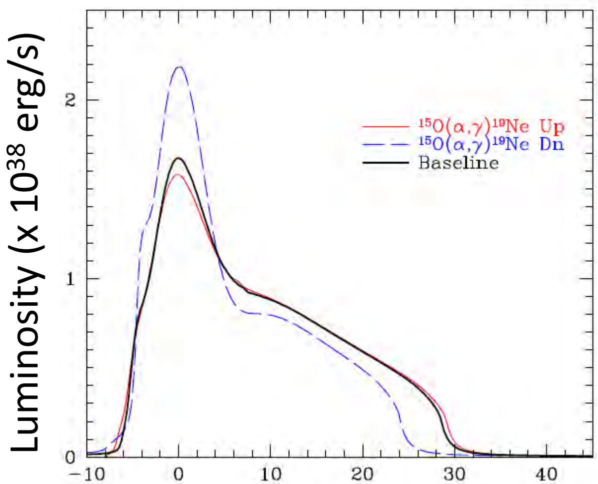



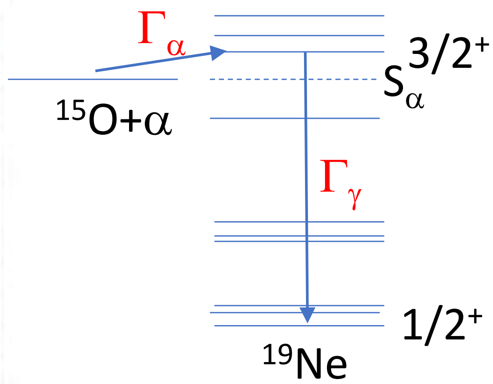




Departure from Hot CNO cycle depends crucially on $^{15}O(\alpha,\gamma)^{19}Ne$ reaction
It is followed by $(\alpha,p)$, $(p,\gamma)$ reactions and $\beta$-decays

# Determination of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate

*Cyburt et al. ApJ 830 (2016)*




$^{15}O + \alpha \rightarrow {}^{19}Ne + \gamma$ mainly through $3/2^+$

$N_A\langle\sigma v\rangle \propto \omega\gamma$ [MeV] exp (-11.6 $E_\alpha$[MeV]/$T_9$)

$\omega\gamma = (2J_r+1)/2(2J_T+1) \times \Gamma_\alpha \Gamma_\gamma/(\Gamma_\alpha+\Gamma_\gamma)$

Branching $\Gamma_\alpha$ and $\Gamma_\gamma$ are needed

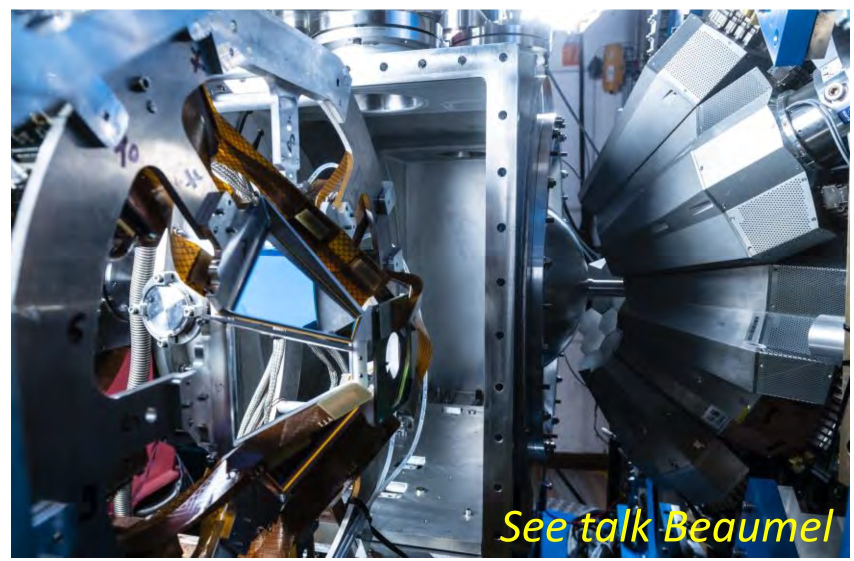
Use $^{15}O$ ($^7Li$,t) $^{19}Ne$ transfer reaction to simulate $\alpha$ capture

$^{15}O$ (4.7 MeV/A) beam at $10^7$pps from SPIRAL1
Tritons in segmented charged particle detector (MUGAST)
$\gamma$-rays in high efficiency/resolution (AGATA)
Recoil $^{19}Ne$ at focal plane of VAMOS spectrometer

World-leading experience in charged-particle arrays -> GRIT

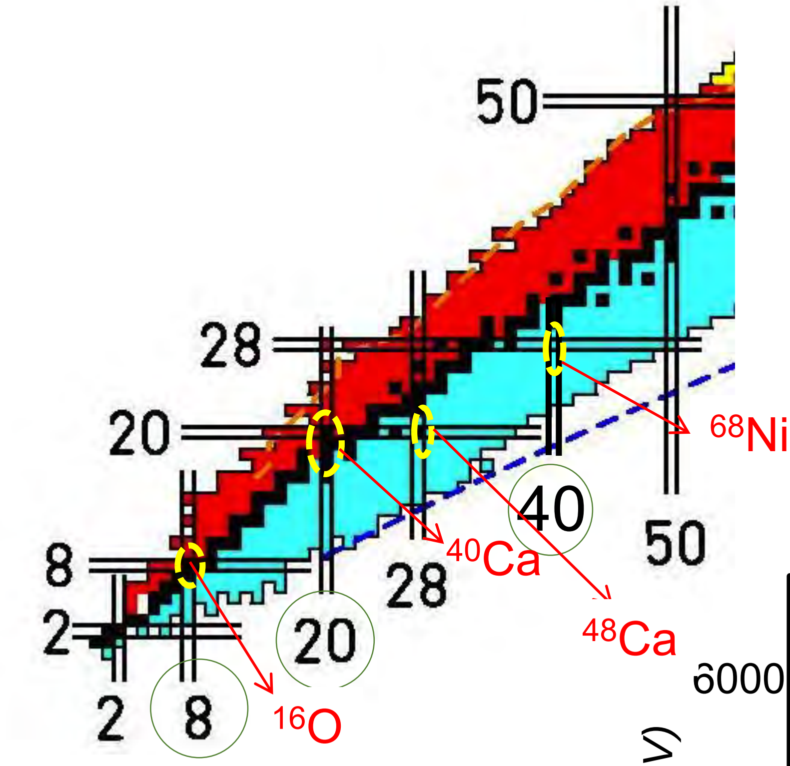
*Diget et al., To be performed at GANIL/VAMOS July 2019*

MUGAST / AGATA array



# Magic nuclei and shell evolution far from stabilty

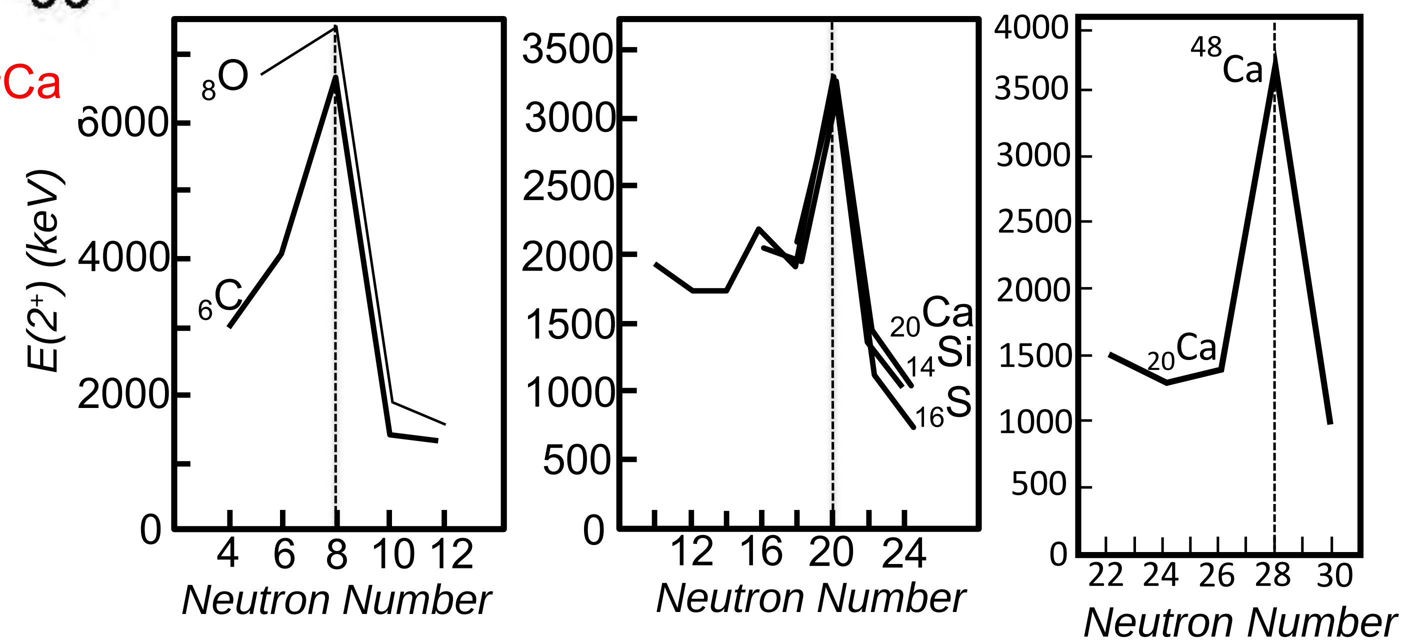
# Magic numbers in the valley of stability



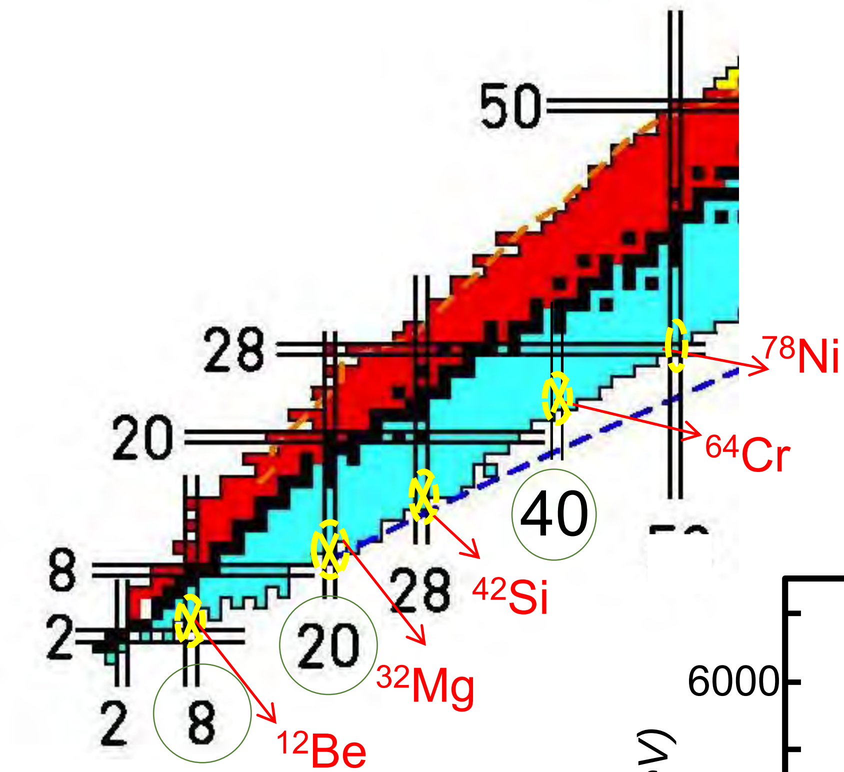

The neutron numbers 8, 20 and 28 were considered as magic over several decades

-> large gap between occupied and valence states

Increase of $2^+$ energy at N= 8, 20,28



# Assuming our world was more neutron-rich



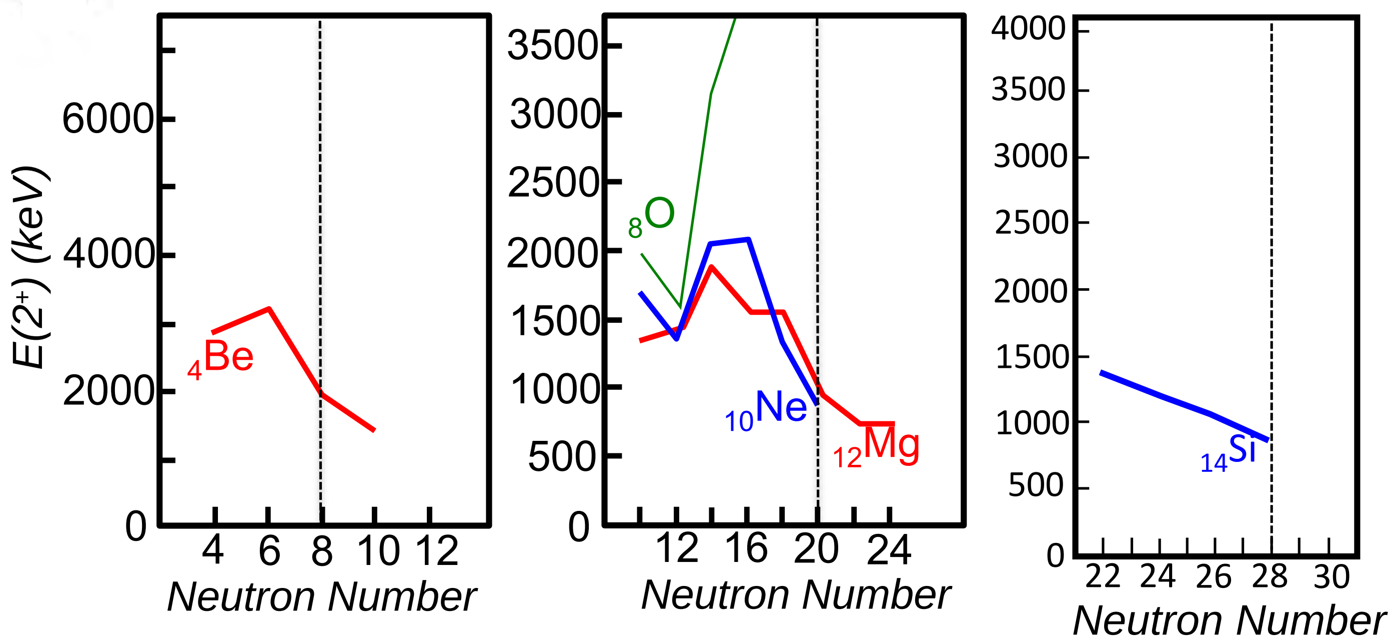

While removing protons, the same loss of magicity occurs for all magic numbers

→ role of proton-neutron interactions, poorly known far from stability

While deformation appears at relatively low energy, the measured $2^+$ of $^{78}$Ni reveals that magicity is kept at N=50

*Taniuchi et al. Nature 569 (2019)*

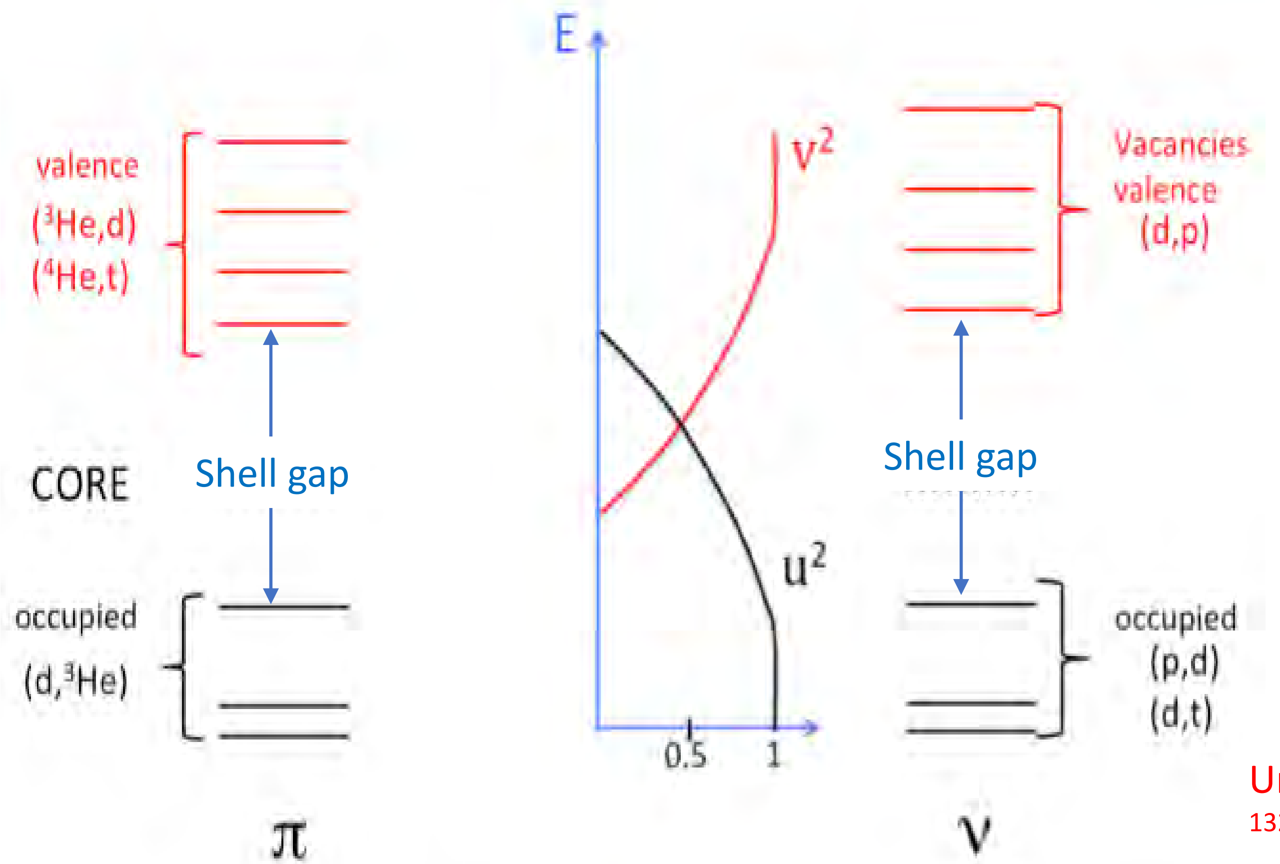
No sign of shell closure and magic nuclei

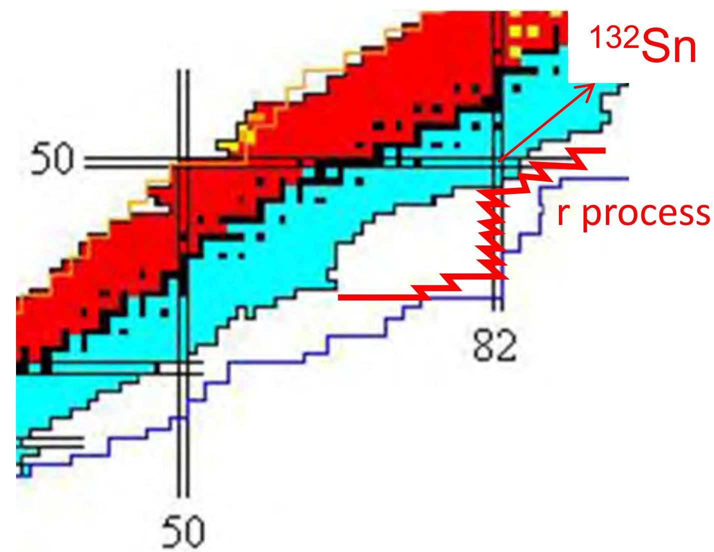


# Shell evolution and transfer reactions

The change of magicity comes from the reduction of shell gaps and increase of correlations

Probe the evolution of proton and neutron orbits far from stability using various transfer reactions




Understand shell evolution at N=82 below $^{132}$Sn for the building of the r process peak

Need of charged particle detectors, gamma-arrays, as well as cryogenic targets in same cases

*See talk Beaumel*

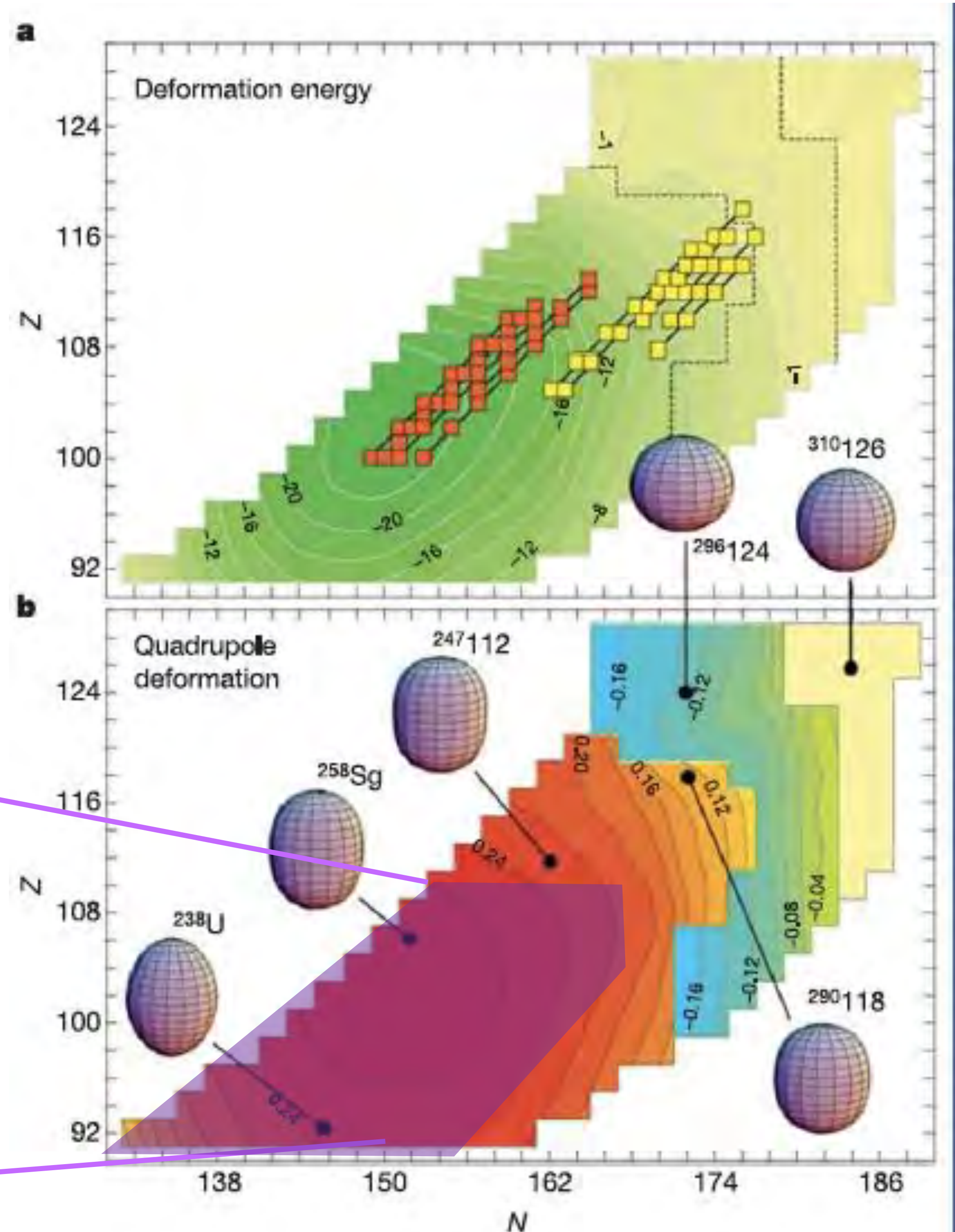
# Super Heavy Elements

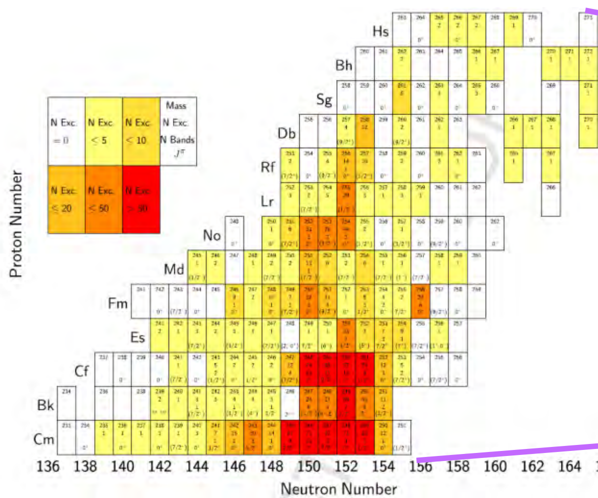
# Motivation for studying super-heavy elements

Discover the heaviest elements whose location is likely connected to spherical shell gaps
whose location is unknown (Z=114, 120, 126 ?)

Study their decay properties:
$\alpha$ & fission competition

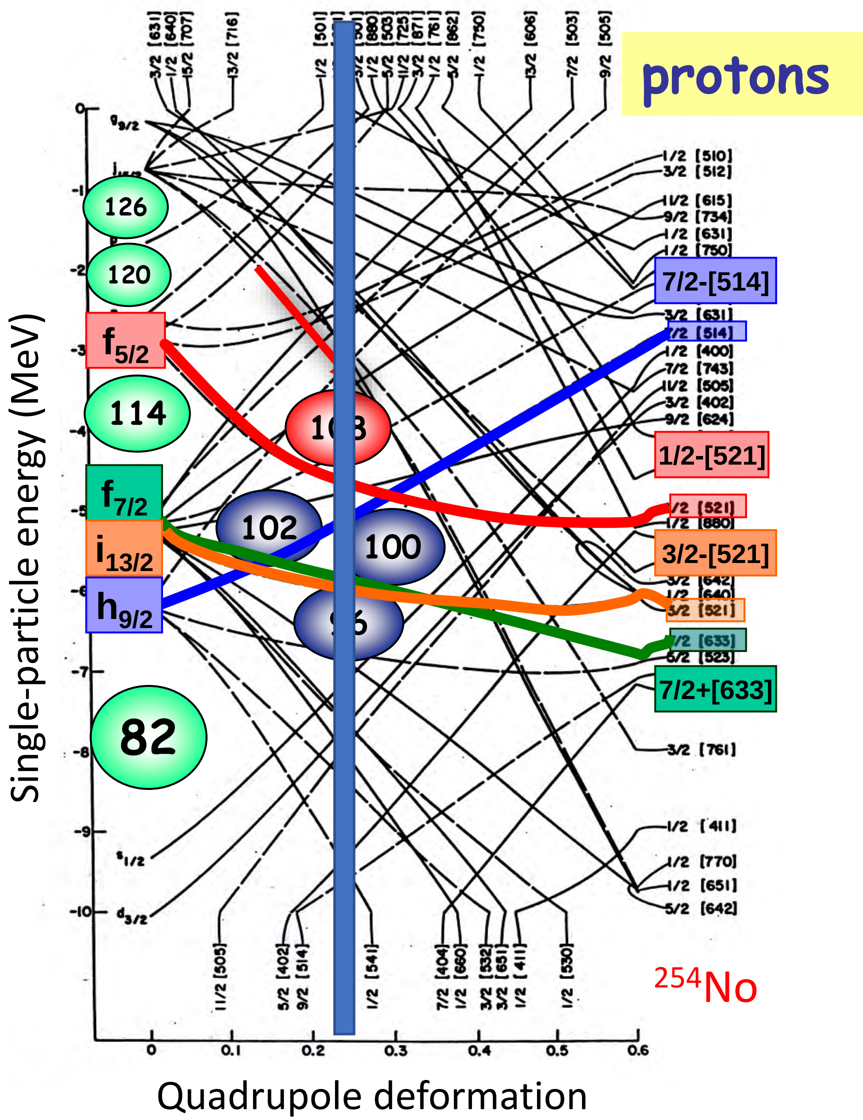
Study the structure of the heavy nuclei:
- Ascertain the discovery of SHE
- Confront experiment to models for better predictivility of shell structure in the region

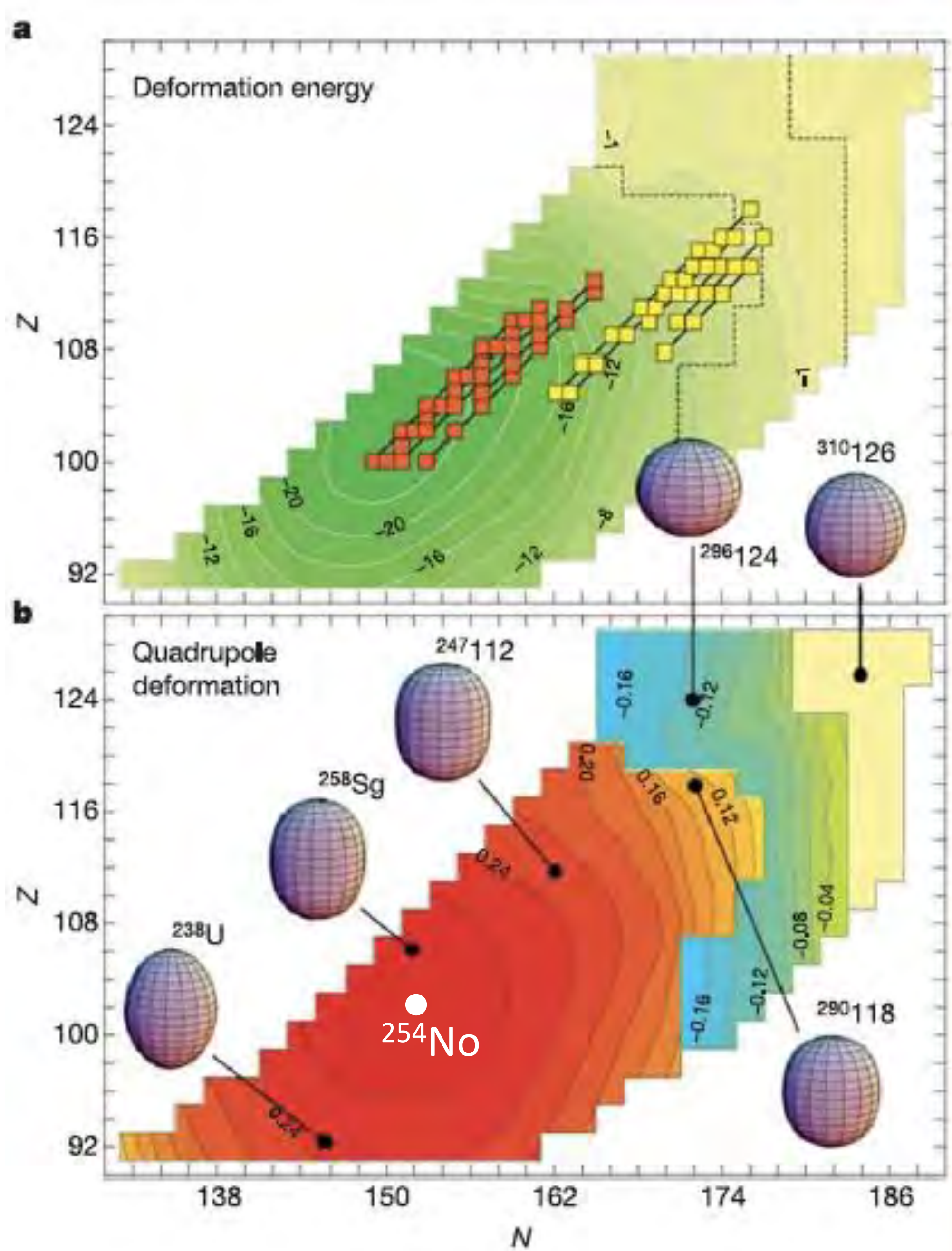


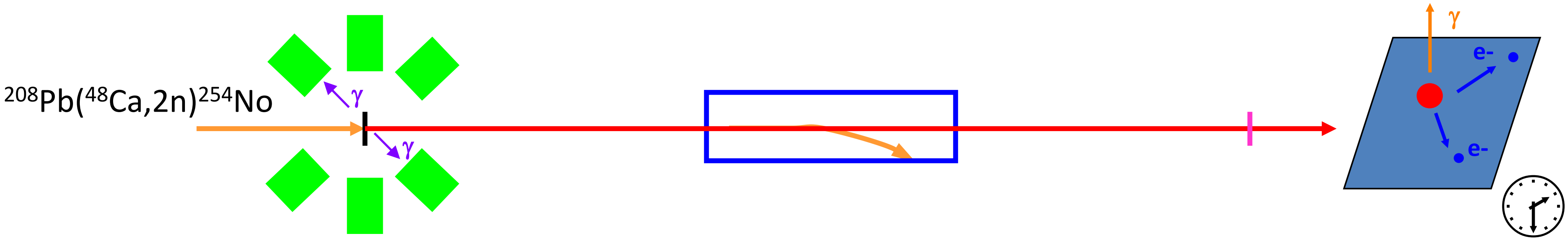
# Motivation for studying super-heavy elements

Identify orbits in deformed nuclei to trace back to the amplitudes of the spherical shell gaps



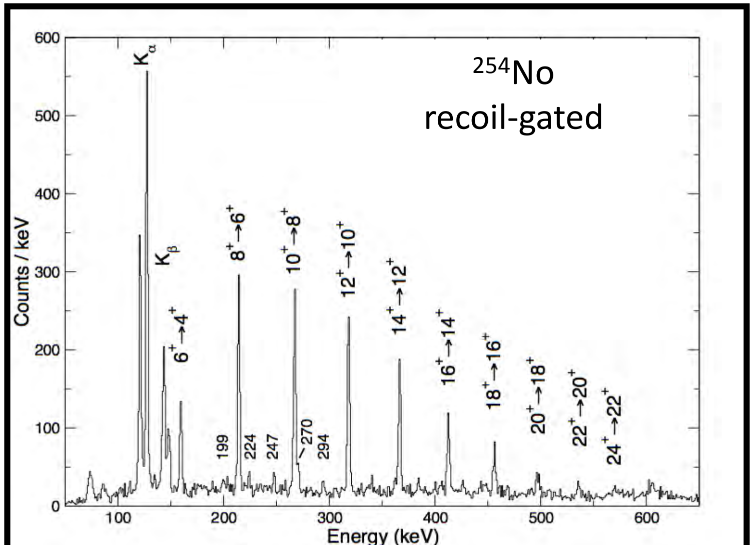



# Spectroscopy of the very heavy nucleus $^{254}$No

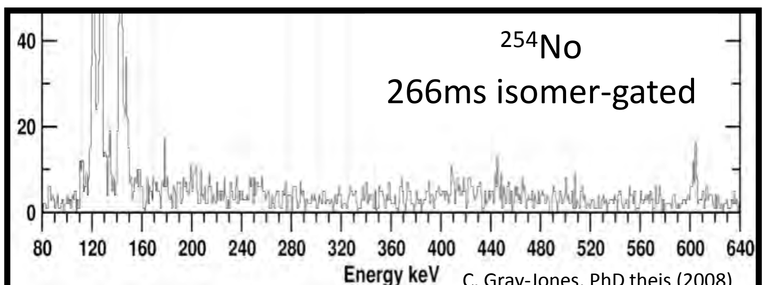



at the target

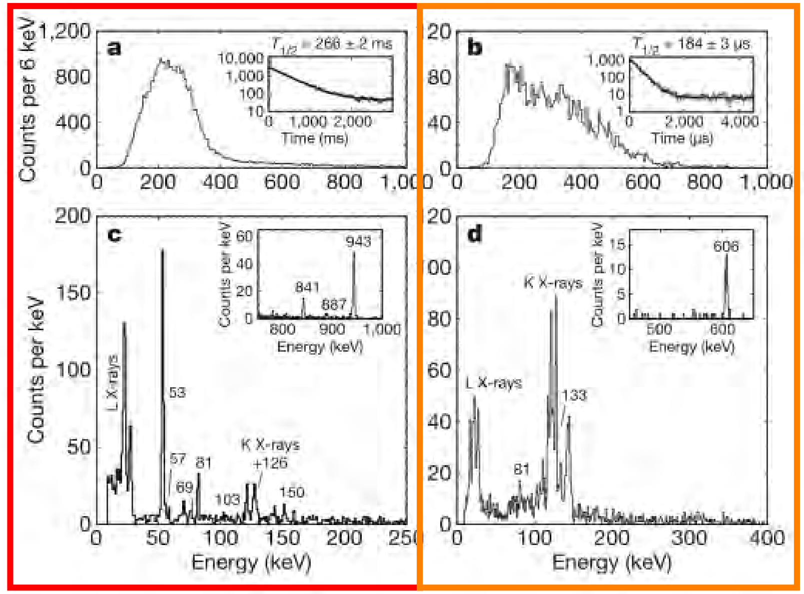
Two isomers discovered (study at the focal plane)




unpublished, see also: S.Eeckhaudt,P.T.Greenlees et al.,EPJA 26 (2005) 227




C. Gray-Jones, PhD theis (2008)




266 ms decay

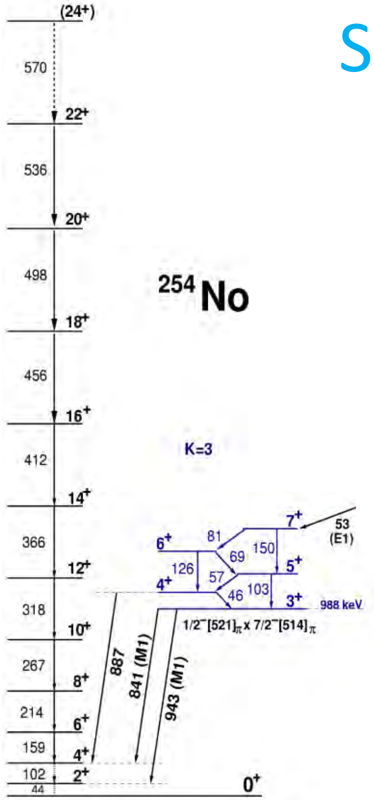
184 μs decay

*Herzberg et al., Nature 442 (2006)*

*Tandel et al., PRL. 97 (2006)*

Combine in-beam and delayed spectroscopy

# Spectroscopy of very heavy nuclei at Dubna



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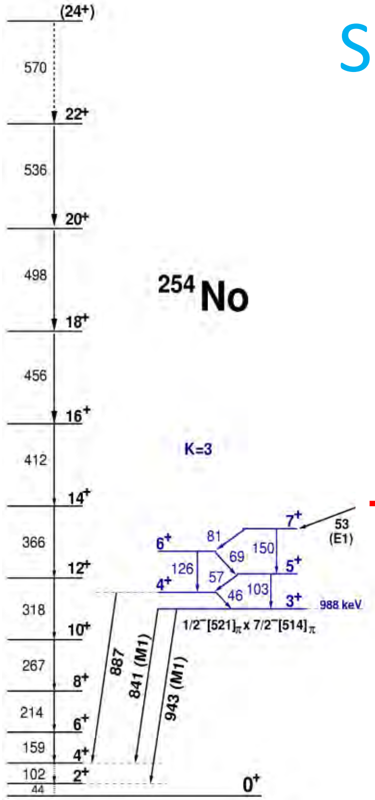
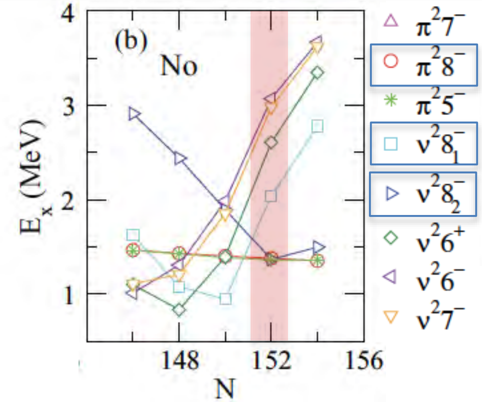



K=8
$8^-$ 1293 KeV
266 ms

Band on top of 8- isomer
not observed in $\gamma$-ray spectrum

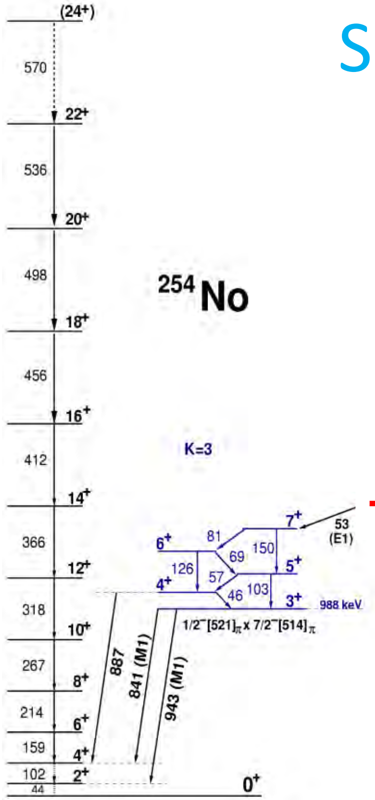



| Configuration | $g_K$ |
|---|---|
| $\{7/2^-[514]_\pi \otimes 9/2^+[624]_\pi\}^{(8-)}$ | 1.006 |
| $\{7/2^+[624]_\upsilon \otimes 9/2^-[734]_\upsilon\}^{(8-)}$ | -0.021 |
| $\{7/2^+[613]_\upsilon \otimes 9/2^-[734]_\upsilon\}^{(8-)}$ | -0.279 |

$\pi^2$ or $\nu^2$ state ?

*H.L. Liu et al., PRC 89 (2014)*

# Spectroscopy of very heavy nuclei at Dubna

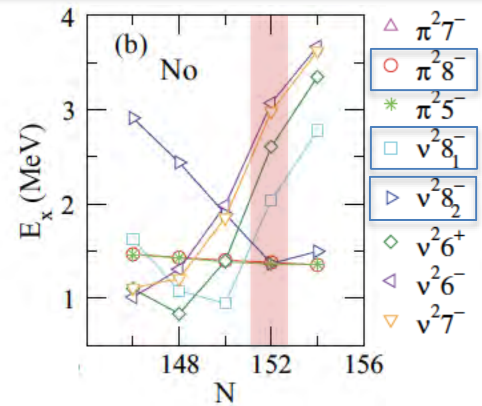



K=8

8⁻ 1293 KeV

266 ms

Band on top of 8- isomer
not observed in γ-ray spectrum

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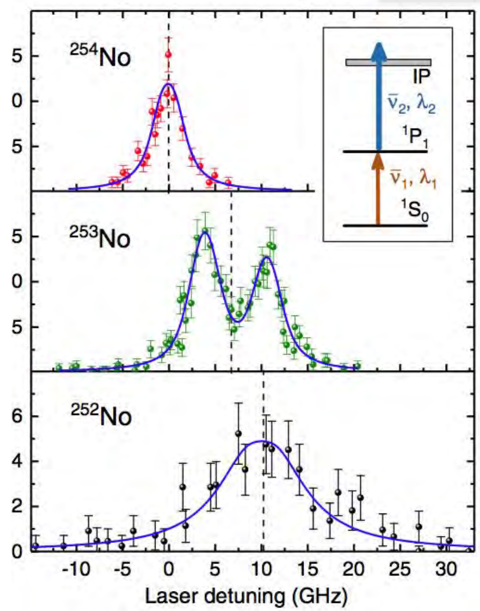
*See talk Hauschild*

*S. Raeder et la., PRL 120 (2018)*




Hyperfine splitting in $^{253}$No: I($^{253}$No)=9/2

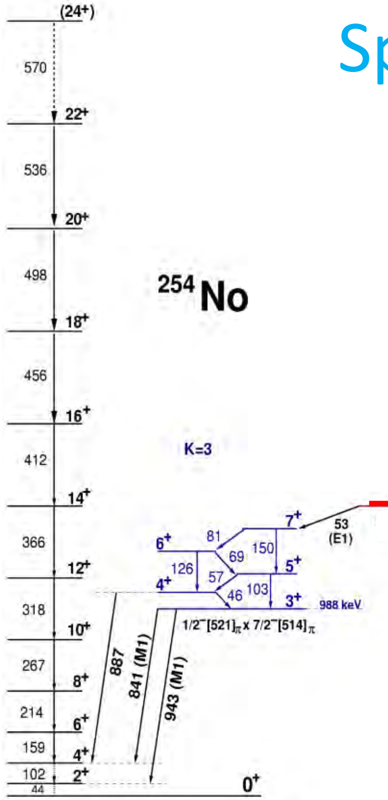
$g_K$=-0.22(5)

(confirming results from prompt & decay spectroscopy of $^{253}$No)

Laser spectroscopy of the long-lived 8⁻ isomer
foreseen in 2020 @ GSI/SHIP

*See talk Jurado / Lescene*

# Spectroscopy of very heavy nuclei at Dubna

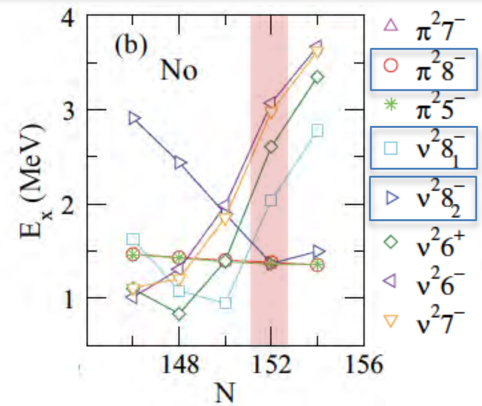



K=(16)
(16⁺) 2.5 MeV
184 μs

Experiment planned end of 2019 @ Dubna
-> shed light on nature of the short-lived isomer

K=8
$8^-$ 1293 KeV
266 ms

Band on top of 8- isomer
not observed in $\gamma$-ray spectrum

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*See talk Hauschild*

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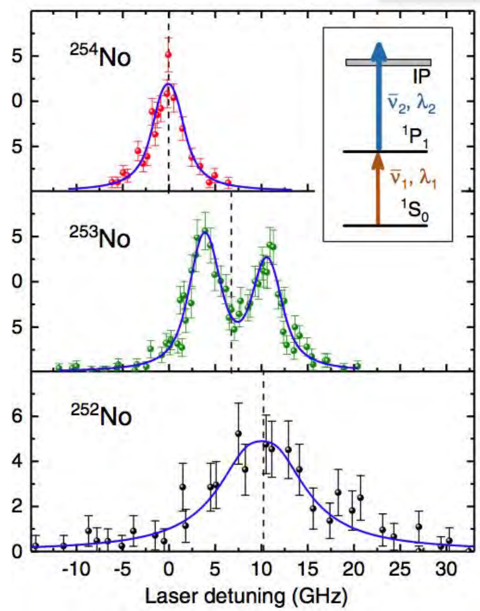


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*See talk Jurado / Lescene*

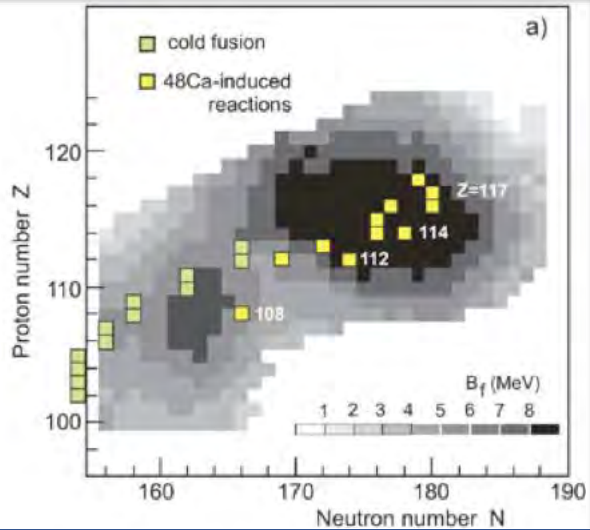
# Nuclear fission

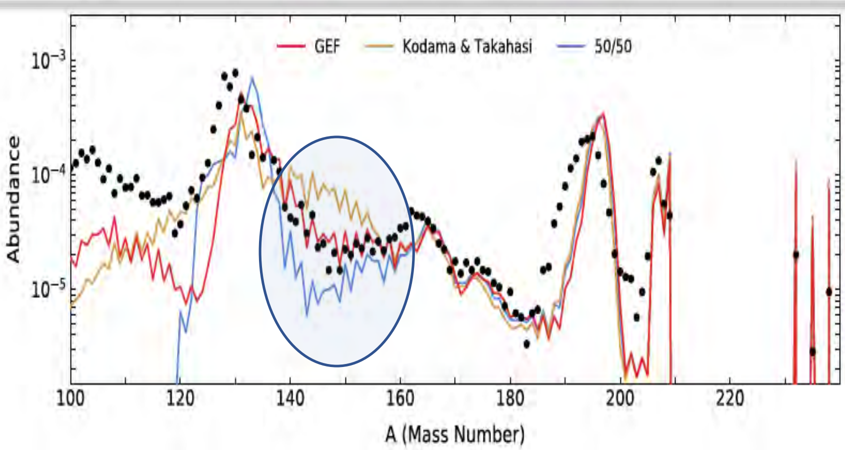
Licorne (nu-ball), SOFIA & Cryring@GSI, GANIL/VAMOS

# Selected features related to fission

Fission yields needed for societal applications
Fission allows to produce neutron-rich nuclei at high J

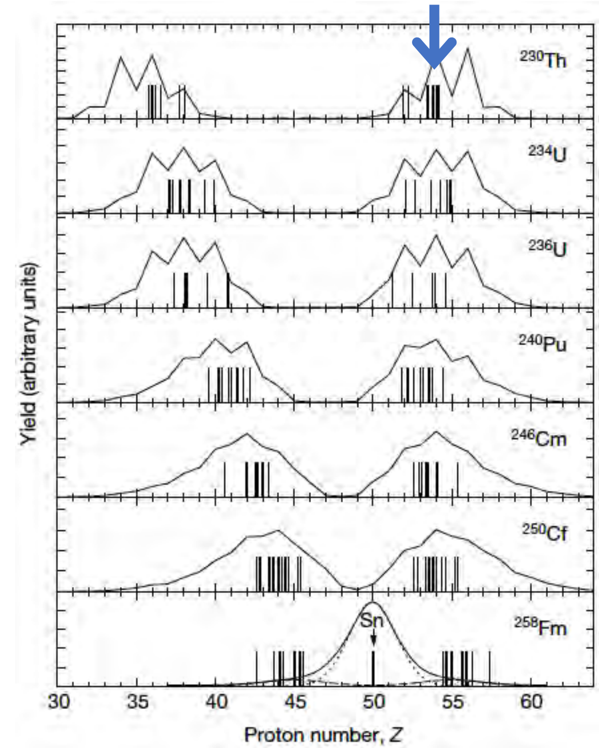
Fission competes with the synthesis of the heaviest and hyperdeformed nuclei *(see talk Hauschild)*




*Vassh et al. in prep*

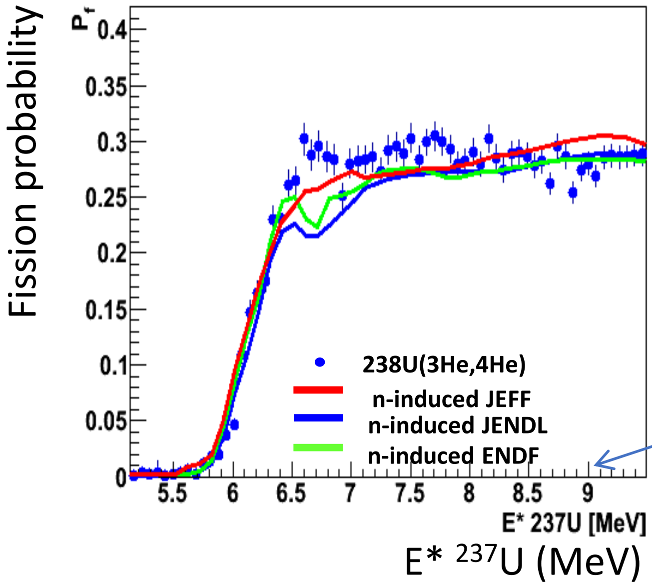
Amount of Lanthanide produced in Binary Neutron Stars depends on the fission yields of very heavy nuclei

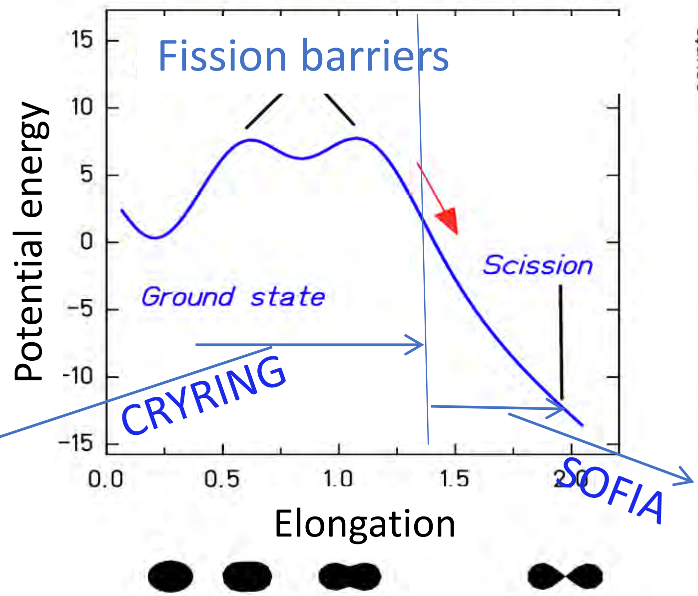


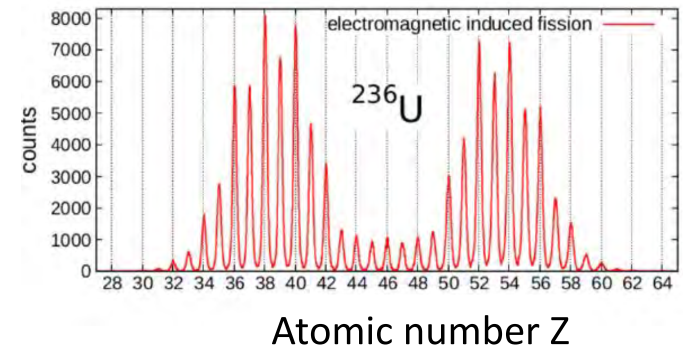

Evolution of fission yields show that:
- Fission is mostly asymmetric
- No yield enhancement at (magic) Z=50
- One fragment keeps the same Z !

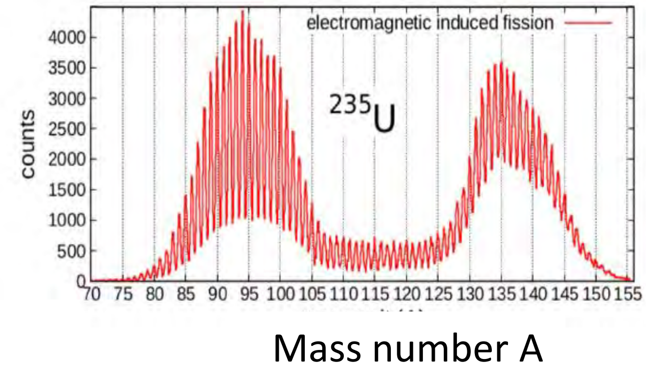
No fully microscopic description so far

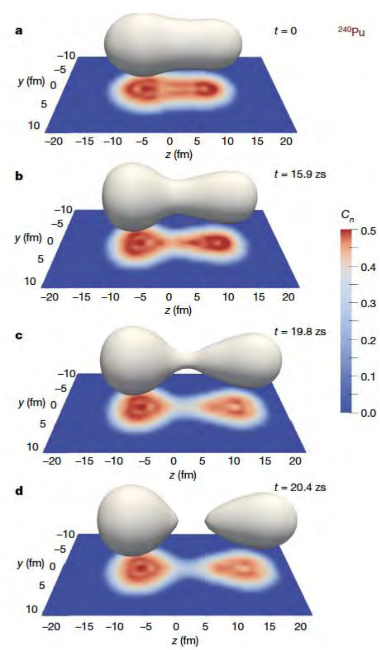
# The dynamics of nuclear fission




*Scamps, Cimenel, Nature 564 (2018)*

Fission probabilities

-Sensitive to structural evolution to fission barrier

-Most direct way to determine fission barriers

-Neutron-induced fission cross sections are highly important for societal applications

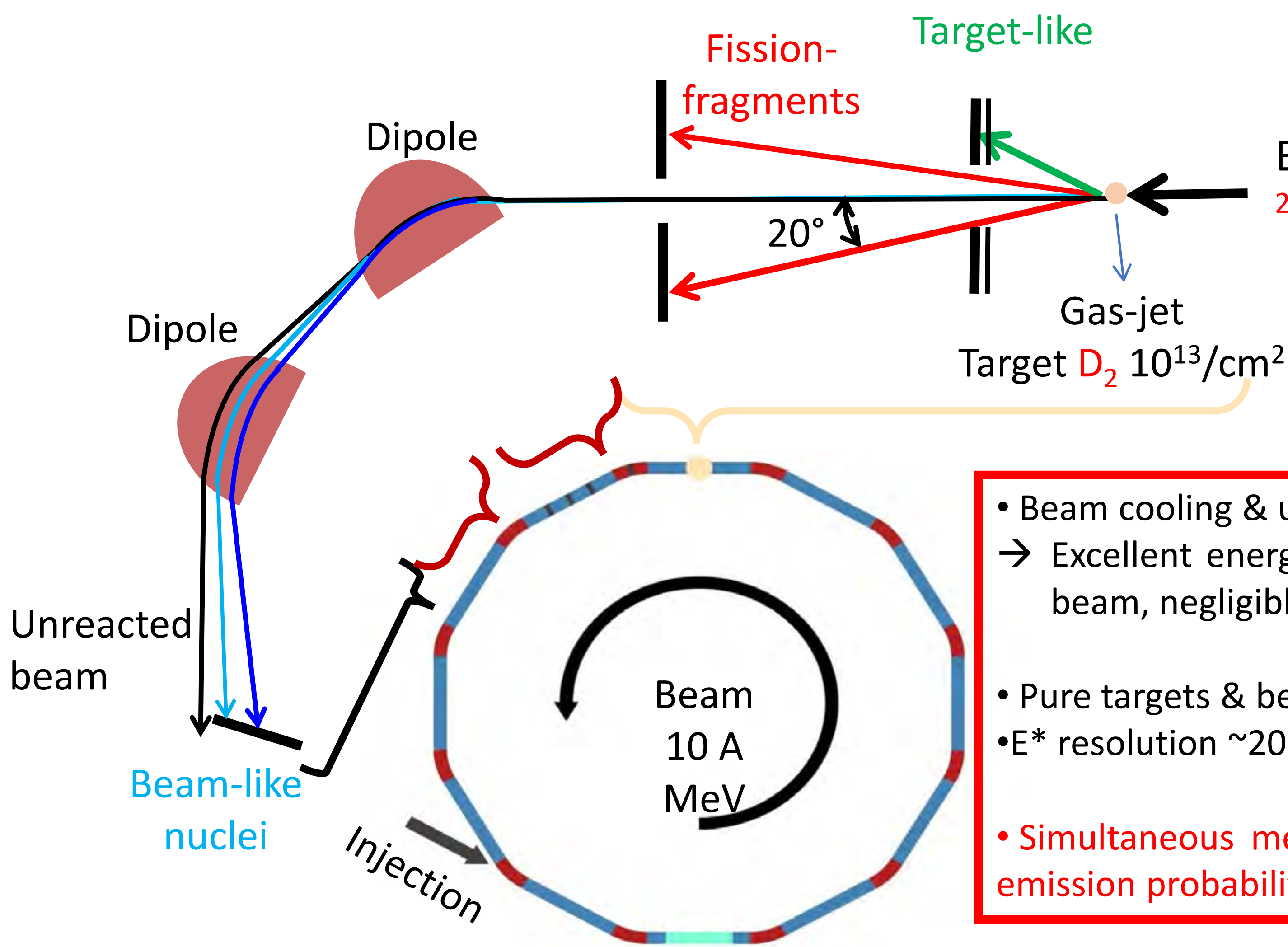
Fission-fragment yields

-Sensitive to evolution from the barrier to scission

-Role of shell effects and pairing at extreme deformation

-The decay of the fission fragments determine the residual power of a nuclear reactor in an accidental configuration.

# High-precision decay-probability measurements at CRYRING



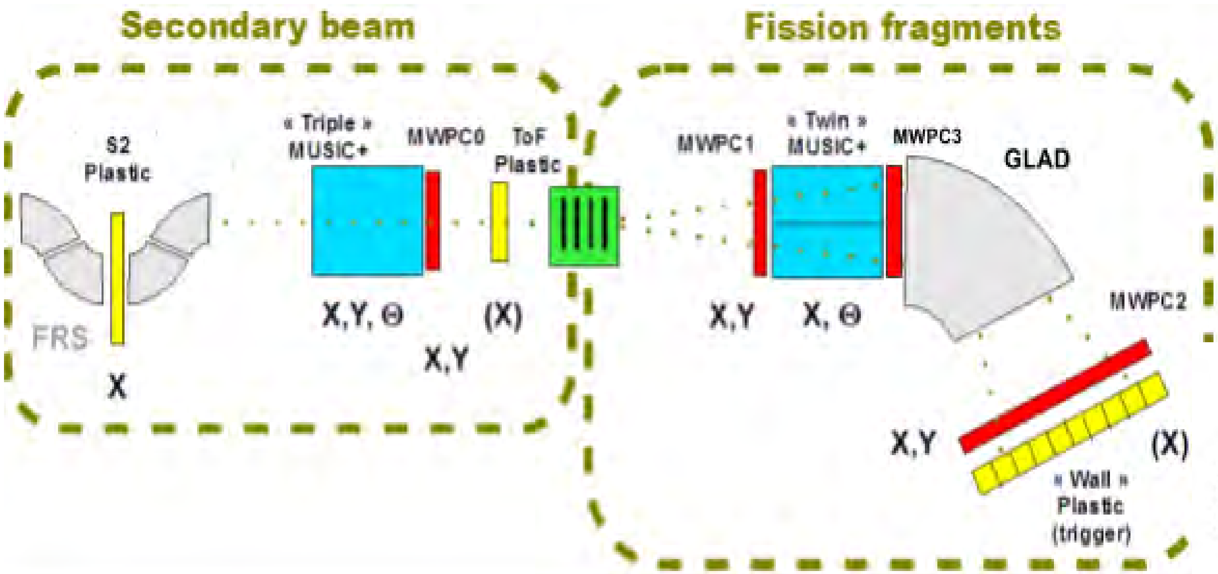

- Beam cooling & ultra-thin gas-jet target
  → Excellent energy and position resolution of the beam, negligible straggling effects

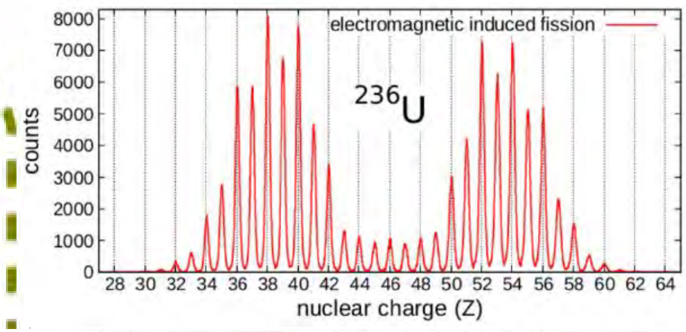
- Pure targets & beams
- E* resolution ~200 keV, ≈100% efficiency

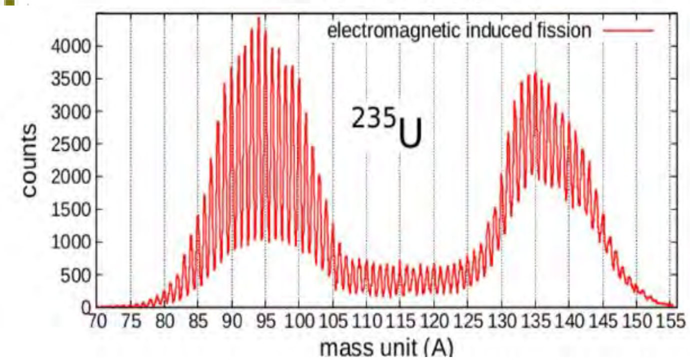
- Simultaneous measurement of fission, γ- and n-emission probabilities of many short-lived nuclei

*see talk Jurado*

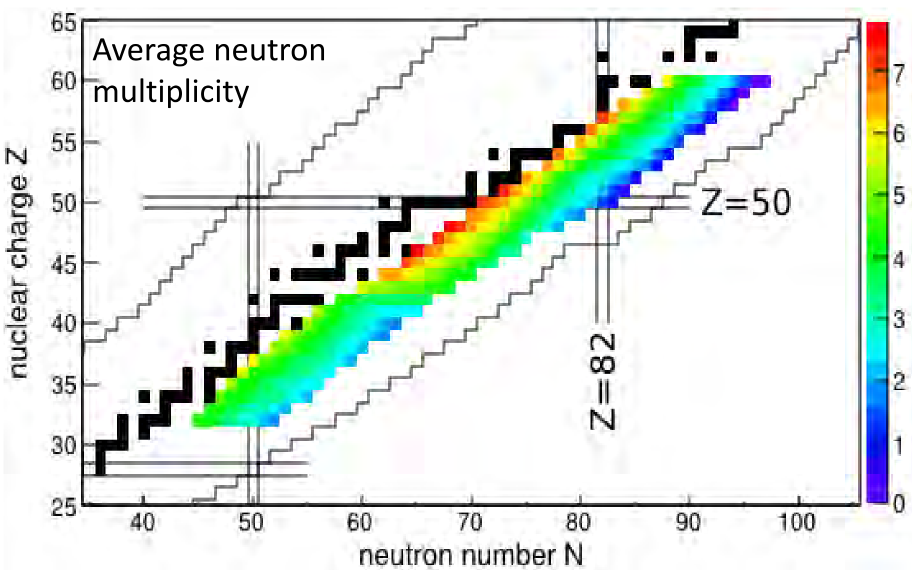
# High-precision fission-fragment yields with SOFIA




*A. Chatillon et al. Phys. Rev. C 99 (2019) 054628*
*E. Pellereau et al. Phys. Rev.C 95 (2017) 054603*




- Outstanding Z and A resolution
- Full identification of both fragments event-by-even
- Measurement of prompt neutron mult. with Z & N
- Access to a wide range of exotic fissioning systems

UNIQUE

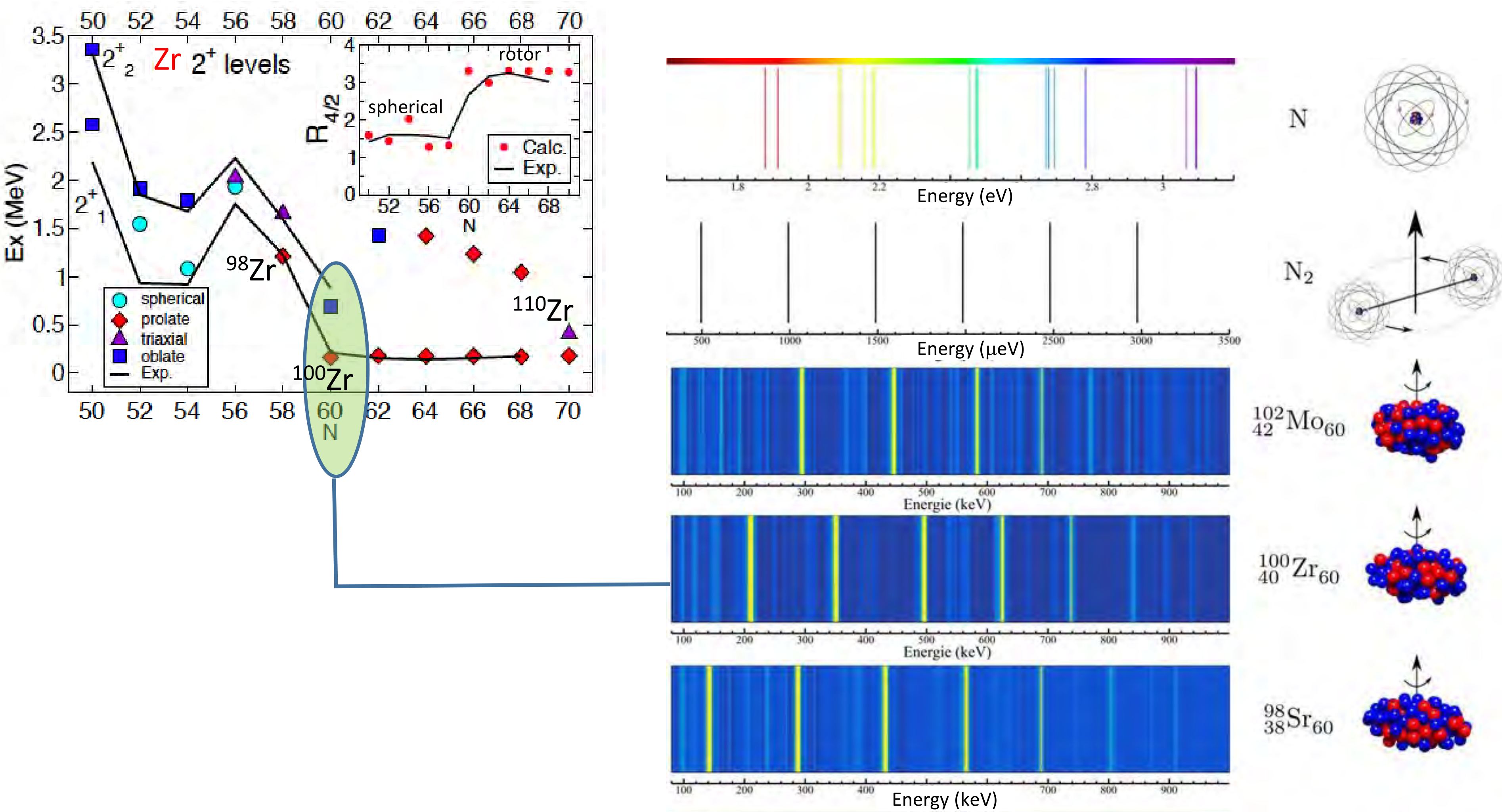
*See talk Jurado*

Nuclear deformation

> Shell evolution
> Hyperdeformation

# Nuclear shapes and deformation at N=60

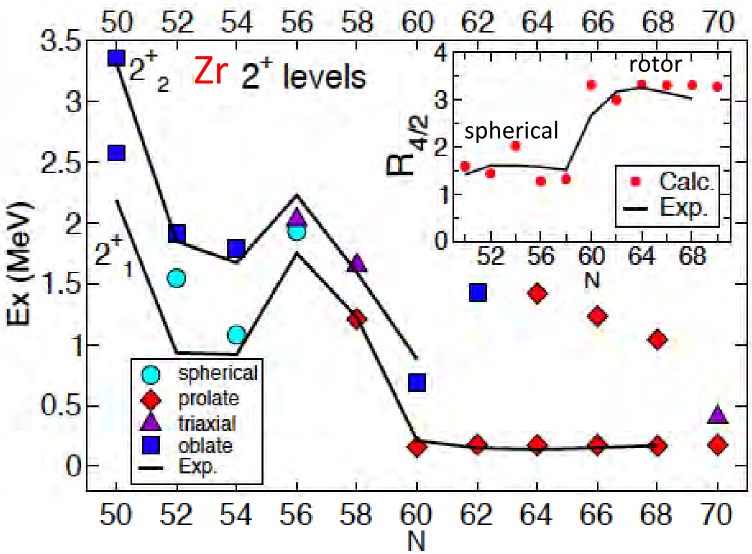
*Togashi et al., PRL 117 (2016)*




*GANIL/ VAMOS*

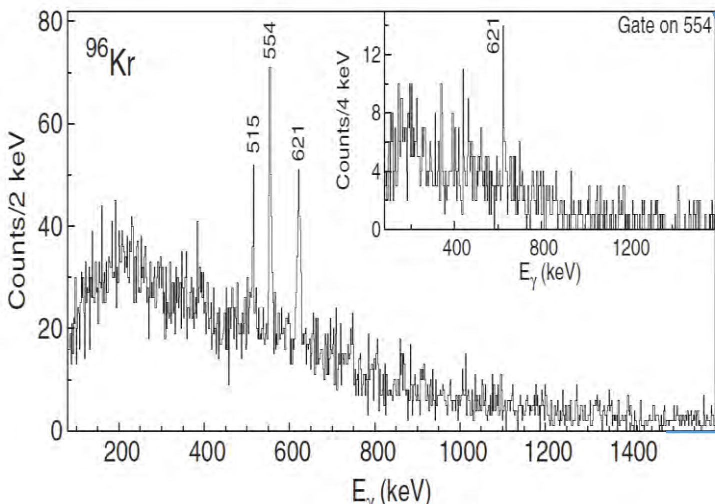
# Does deformation persist at N=60 at Z=36 ?

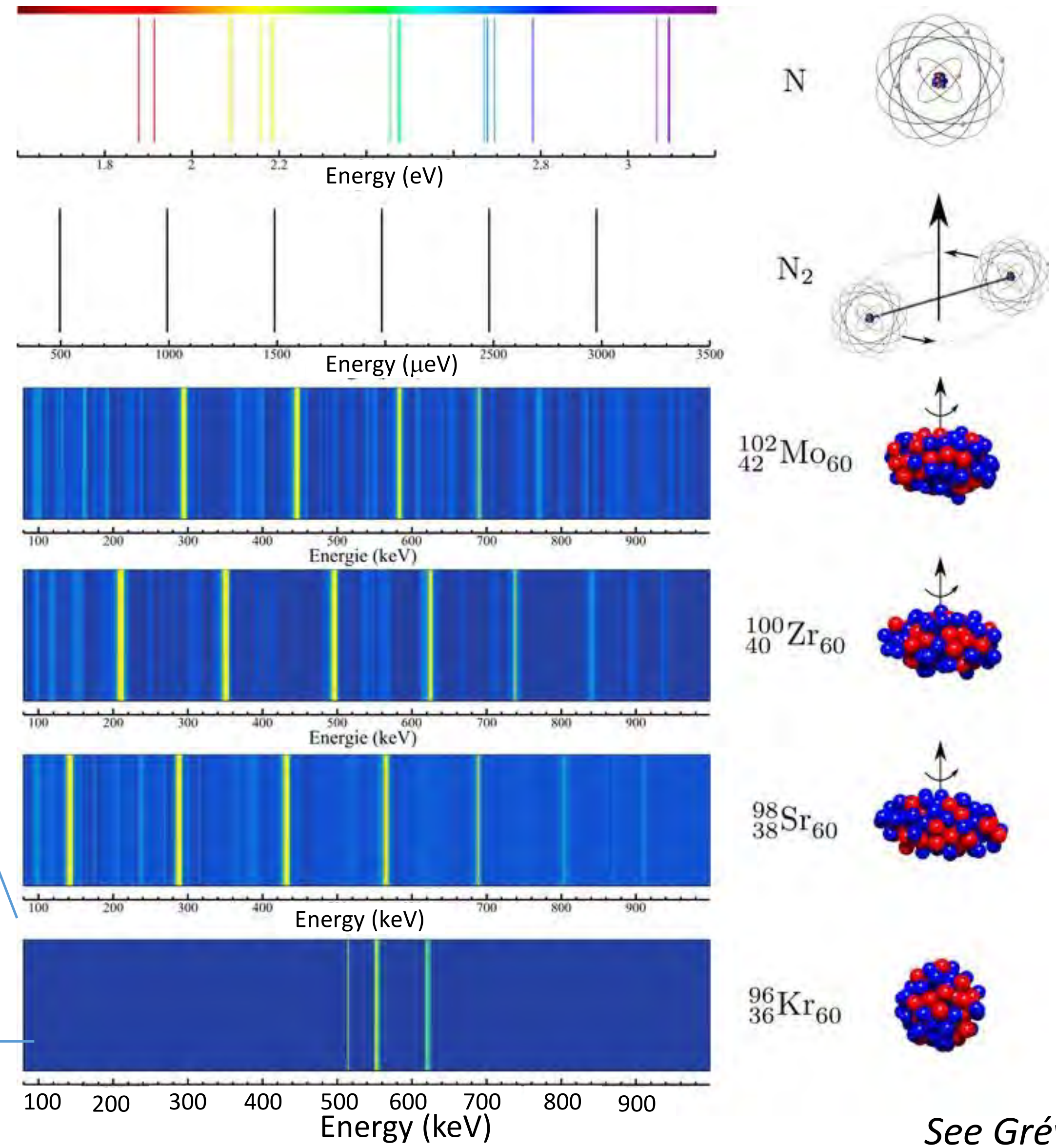
Togashi et al., PRL 117 (2016)




Specific role of the tensor $g_{9/2}$ - $g_{7/2}$ pn interactions to induce deformation

Dudouet et al, PRL 117 (2017)



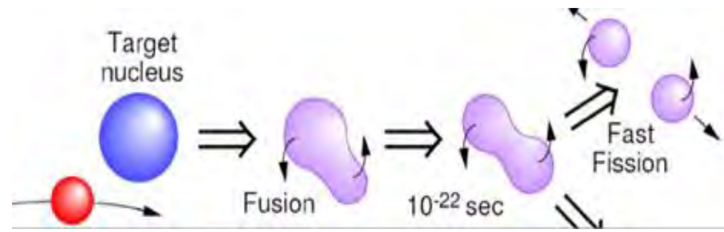

*See Grévy*

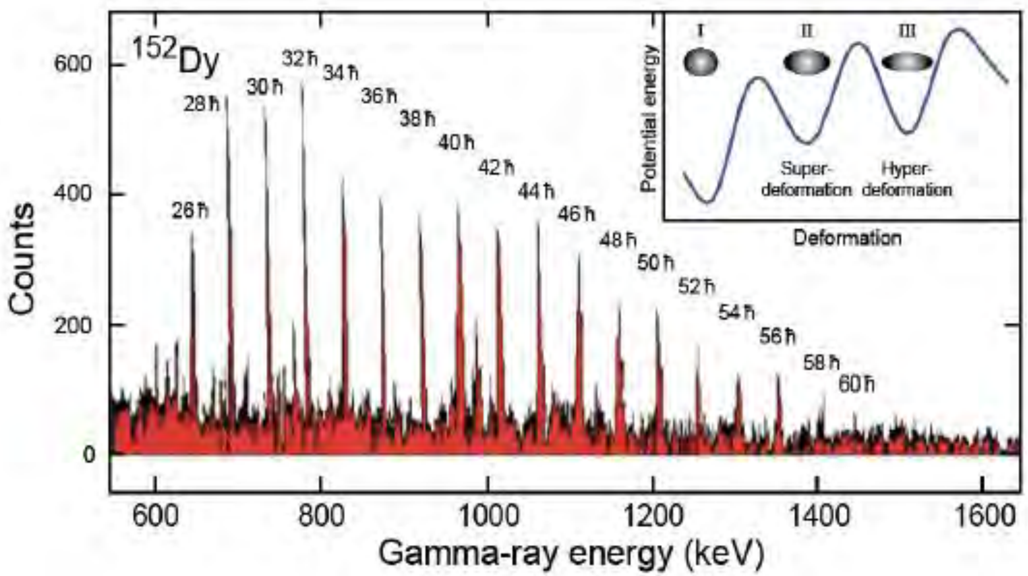
# Search for hyperdeformation in atomic nuclei

Find the best way to produce a maximally elongated nucleus
-> high angular momentum

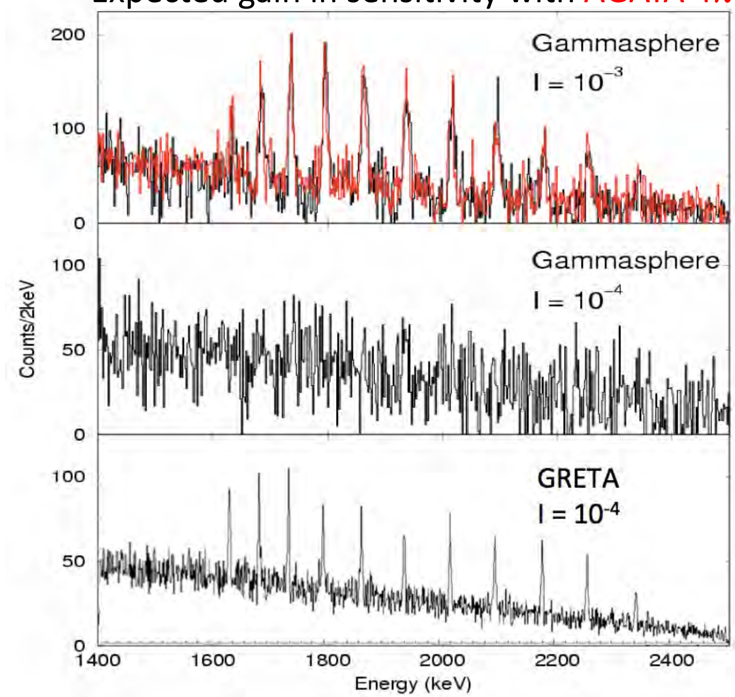
Competition between hyperdeformation / Jacobi shapes / fission

Find a needle in a haystack -> requires extremely high sensitivity




Expected gain in sensitivity with AGATA 4π

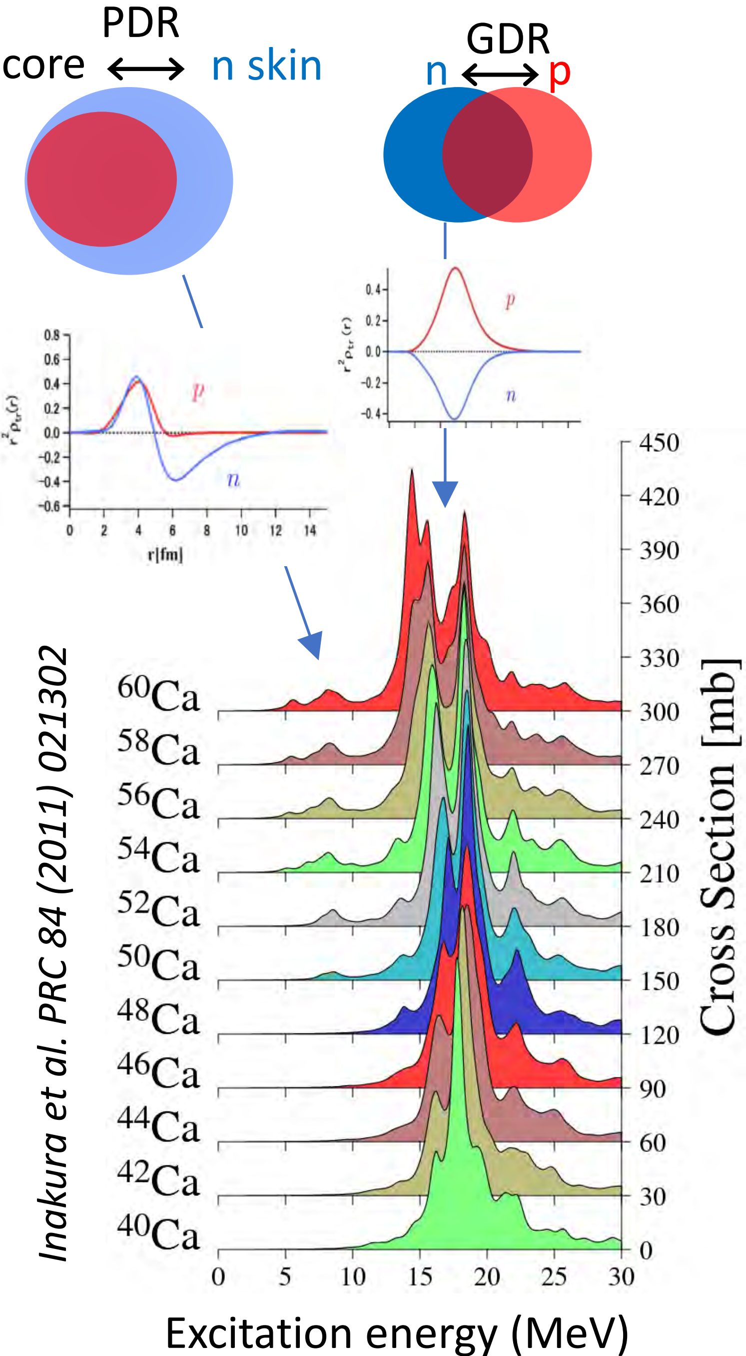



*See talk Lopez-Martens*

# Soft and giant excitations in nuclei

> Symmetry energy
> Nuclear matter incompressibility

# Pigmy and giant dipole excitations in neutron-rich nuclei



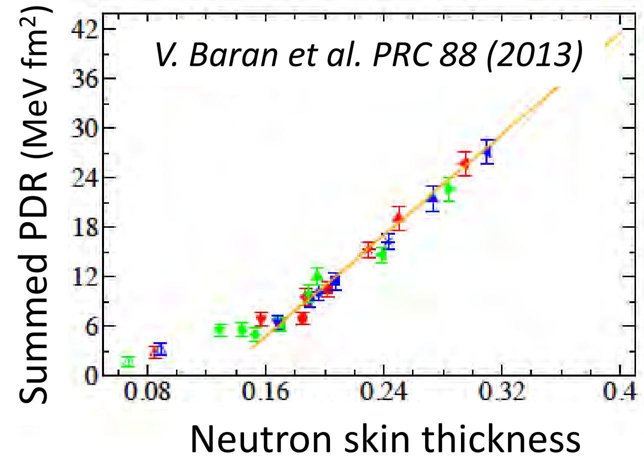

Challenges:

Prove the appearance of PDR at large N/Z (few cases so far)

Prove its E1 character.

Study its configuration using Nuclear and Coulomb Probes

Determine %EWSR of the total E1 strength in the PDR



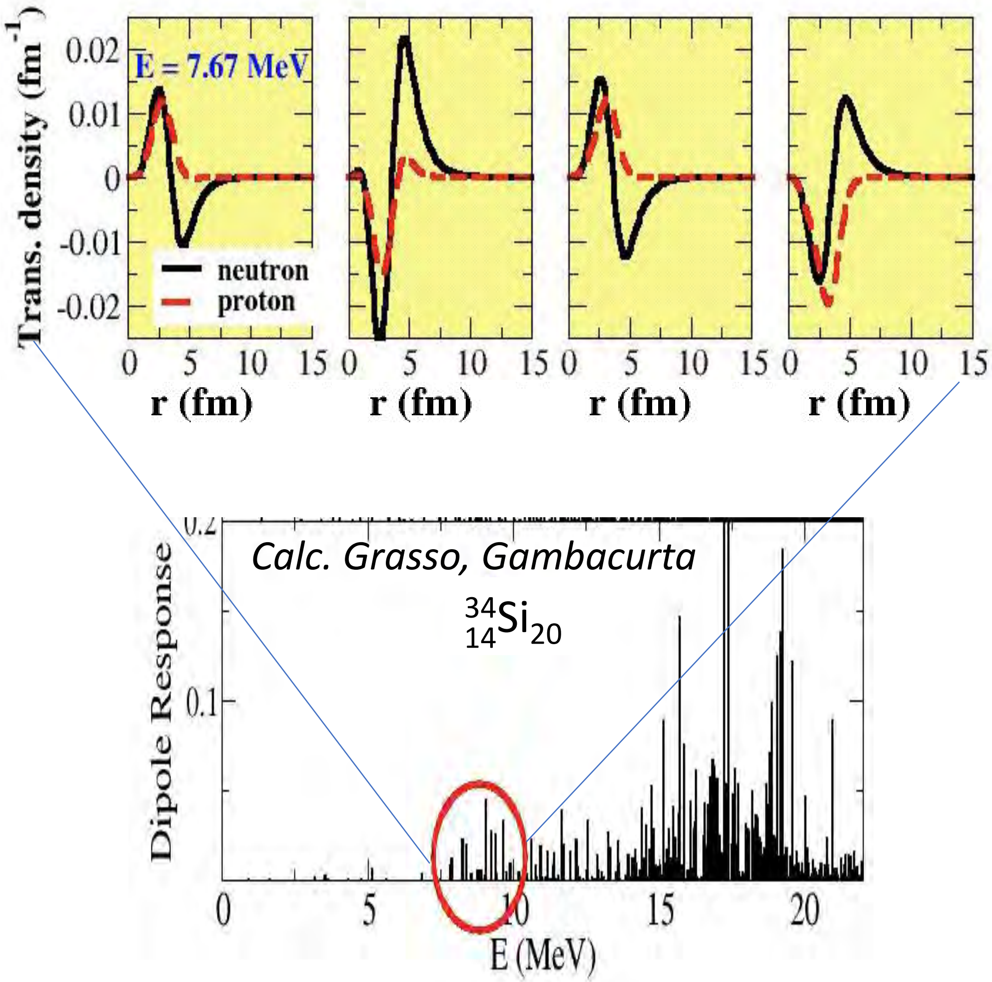

General interest:

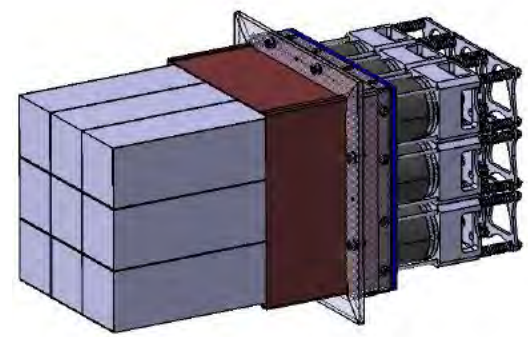
Information on the size of neutron skin in nuclei, on neutron star's radii and the EOS of asymmetric nuclear matter

PDR may considerably speed-up neutron captures in rapid capture nucleosythesis (if present at suitable energies and with large E1 strengths).

# Pigmy and giant dipole excitations in $^{34}Si$ @ GANIL/LISE

Use a radioactive beam of $^{34}Si$ at $5.10^4$ pps in $CH_2$, C and Pb targets
-> Use of Nuclear and Coulomb probes to study the E1 response to both excitations



PARIS : 8 modules of Phoswich NaI & $LaBr_3$

High-efficiency up to 30 MeV

Good granularity (≈ 4.5 cm x 4.5 cm)

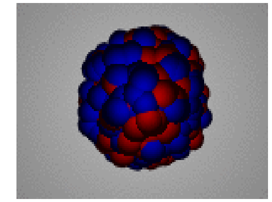
Good energy resolution (4%)

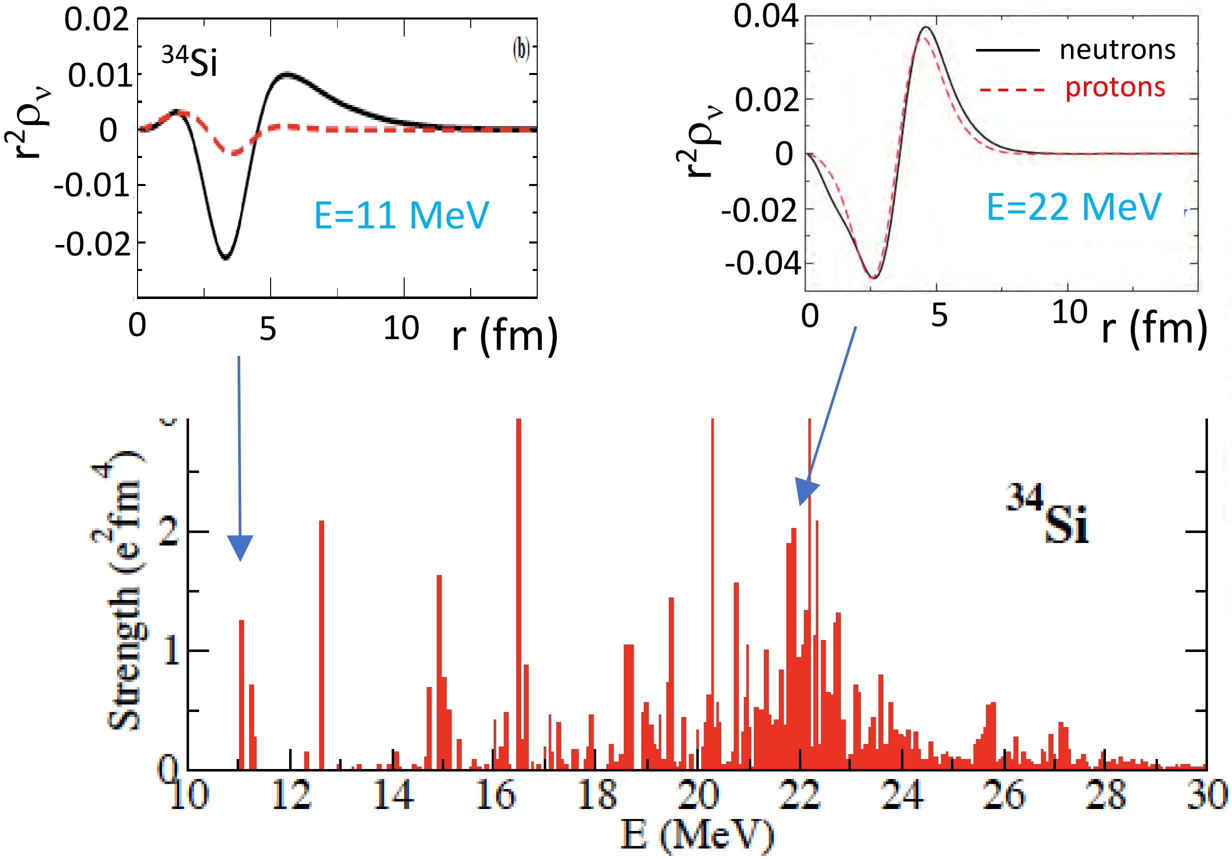
Excellent timing resolution (≈ 150ps)

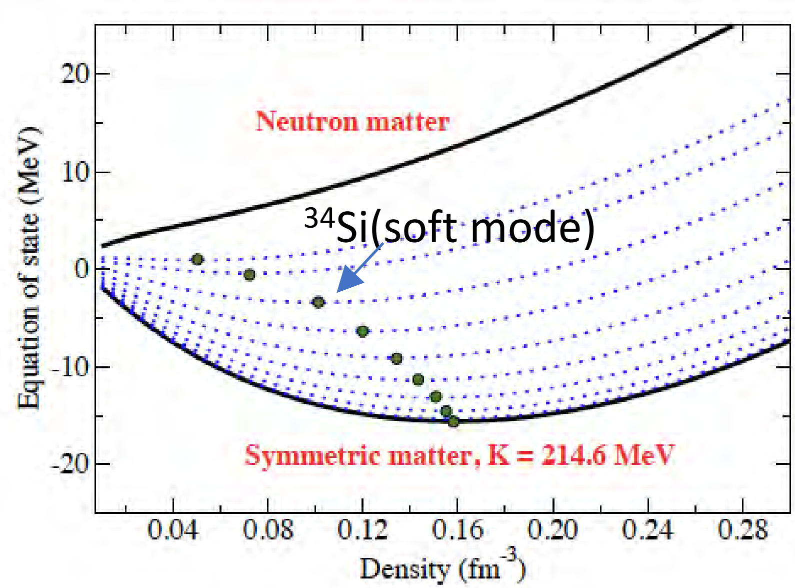
# Soft and giant monopole modes in exotic nuclei

$$K = 9\rho_0^2\left(\frac{\partial^2 E^{sym}/A}{\partial\rho^2}\right)_{\rho=\rho_0}$$

Incompressibility modulus of nuclear matter






*M. Grasso et al. submitted to PRC*

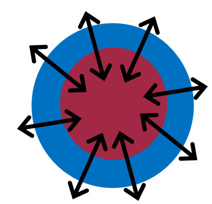
$$E \sim 5.22A^{-1/3}\sqrt{K}$$

Low-energy modes involve only neutrons over the entire volume of the nucleus

-> Incompressibility modulus of almost pure neutron matter -> CC Supernovae

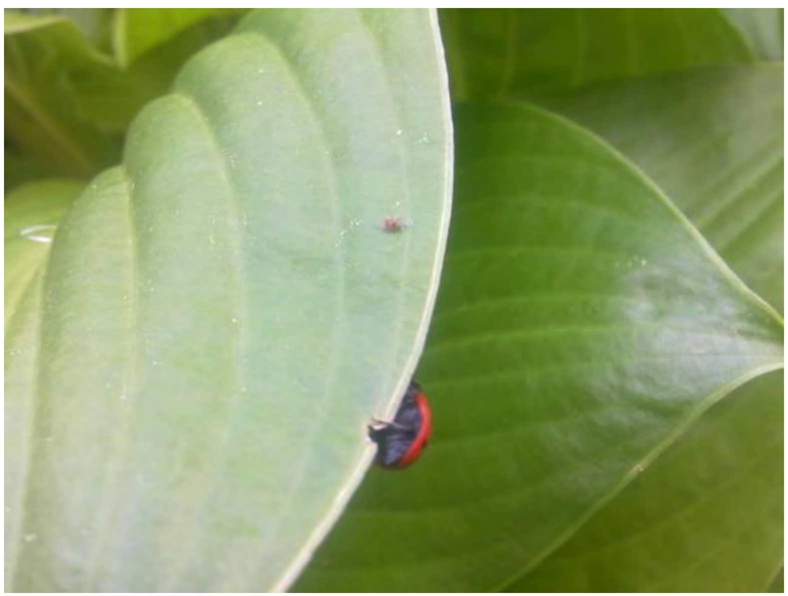
-> Experimental evidence and characterization of this mode (*M. Vandebrouck PRL (2014)*)

Soft GMR



# Physics at the drip line

Mild changes / almost same models applied

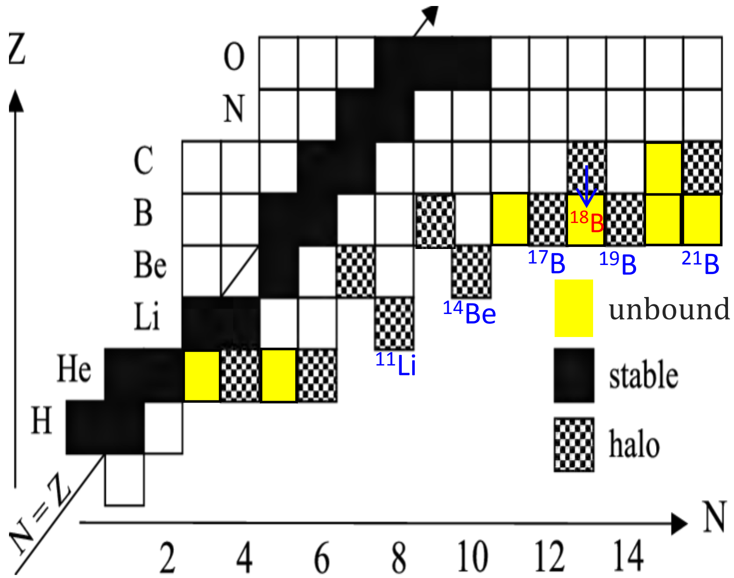


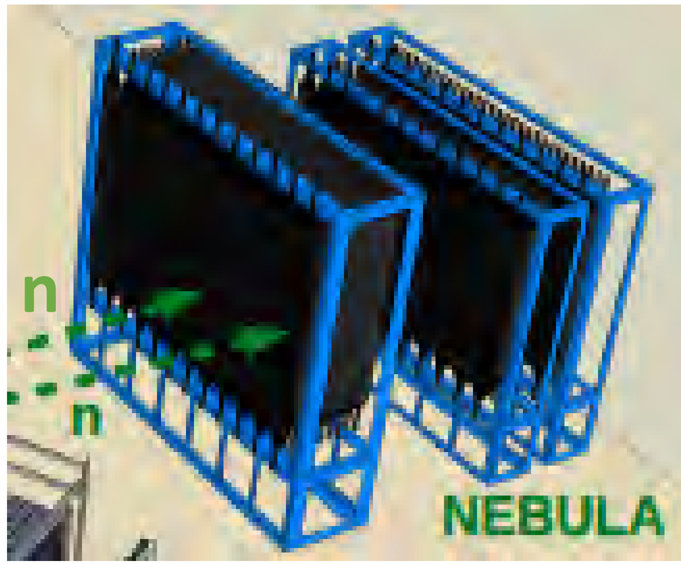
OR

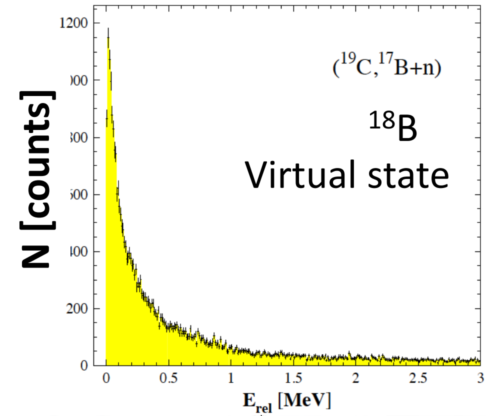
Drastics change / new models and concepts needed

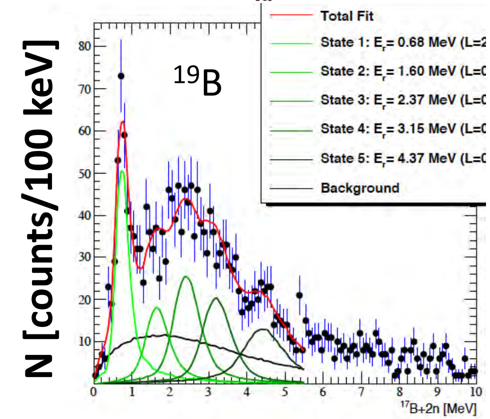
# Evolution of nuclear pairing close and beyond the drip line at RIKEN

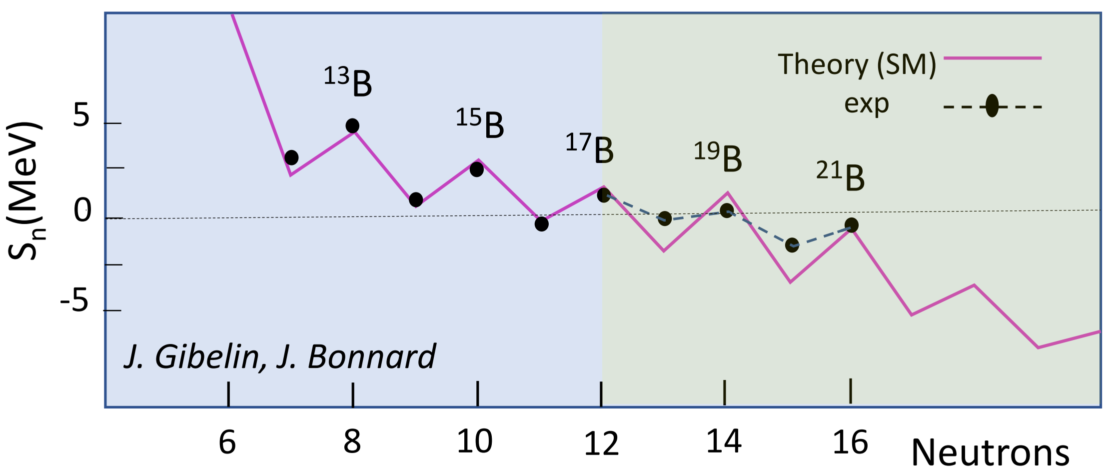
Study of 1n and 2n decays of unbound B nuclei at RIKEN allows rather accurate determinations of $S_n$ values beyond the drip line



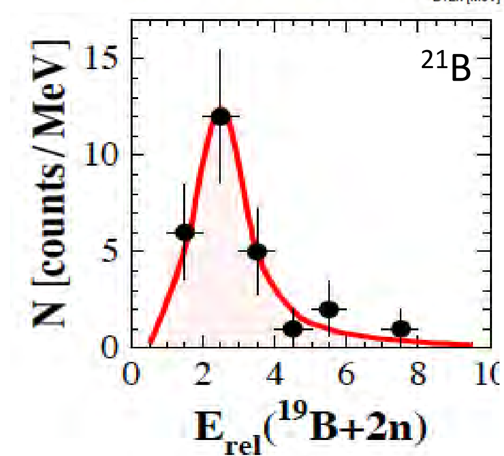




Gapless superconductivity?

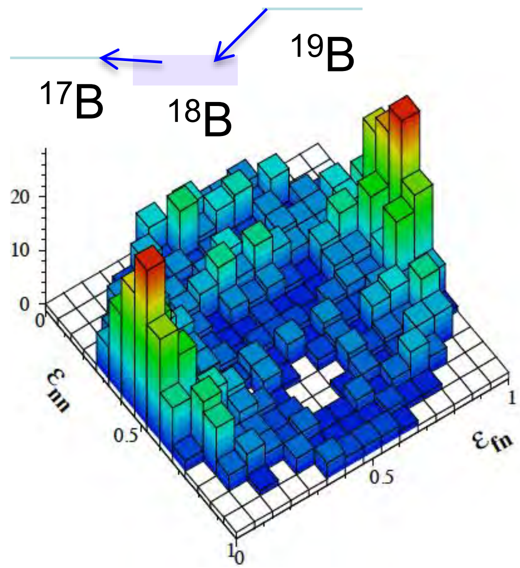


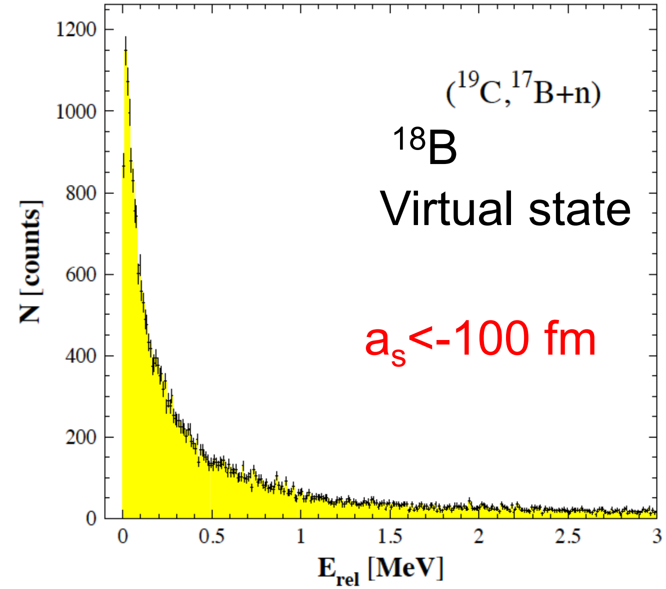

*S. Leblond et al. PRL (2019)*

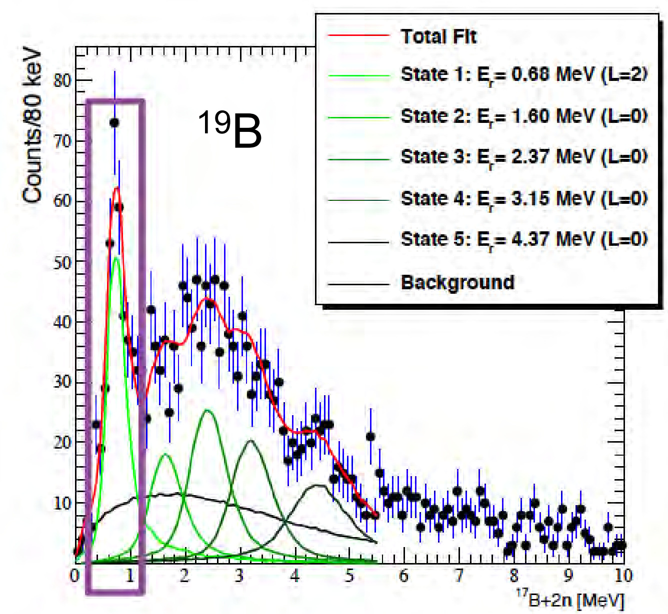
# Exotic decay of borromean systems: the $^{19}B$ case

Sequential decay of $^{19}B$ through the virtual state in $^{18}B$

*J. Gibelin, M. Marques et al.*



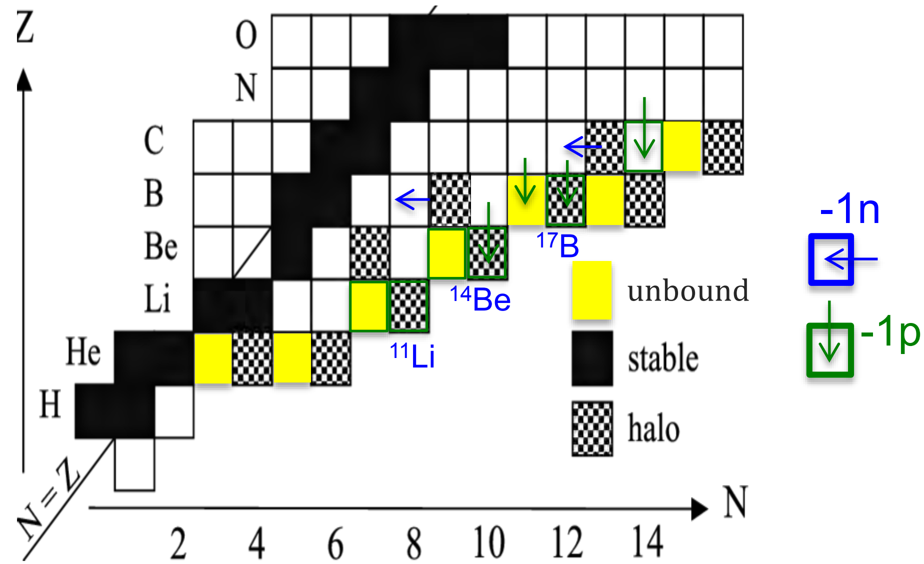

Other systems under study, e.g. $^{16}Be$ decay

*B. Monteagudo, M. Marques*

*See talk N. Orr*

# Study of 2n and 4n correlations in atomic nuclei at FAIR/GSI

Planned studies 2020 (core+4n, haloes, drip-line)

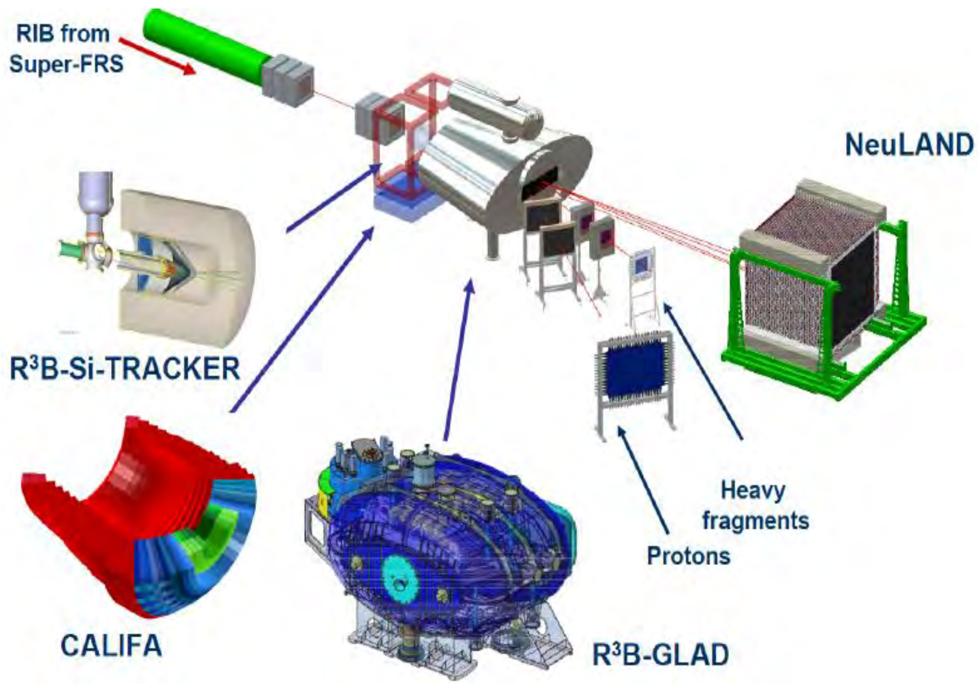



## Program:

Use of quasi-free proton knockout mechanism to promote 1n, 2n or 4n in the continuum

Spectroscopy of drip-line nuclei with excellent energy resolution -> shell evolution

Study of 2n or 4n correlations as a function of nuclear structure and the proximity of the drip line -> Evolution of nuclear superfluidity




## Means:

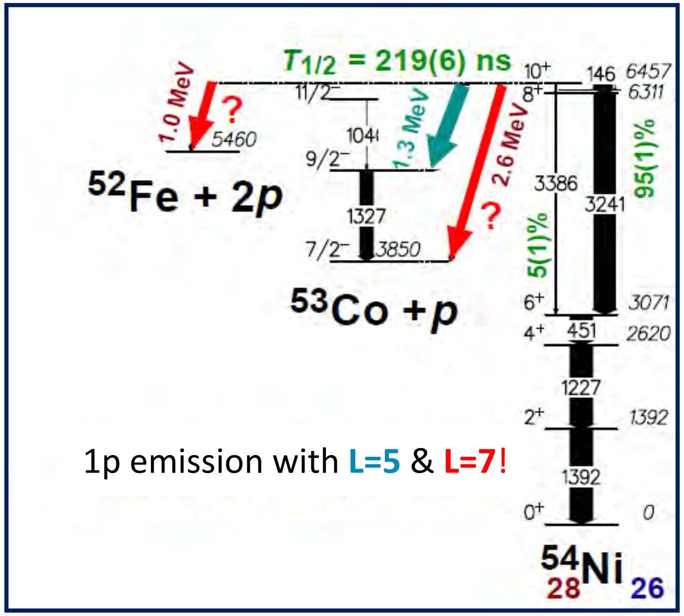
Study of all step of the reaction with full kinematics for ions and neutrons

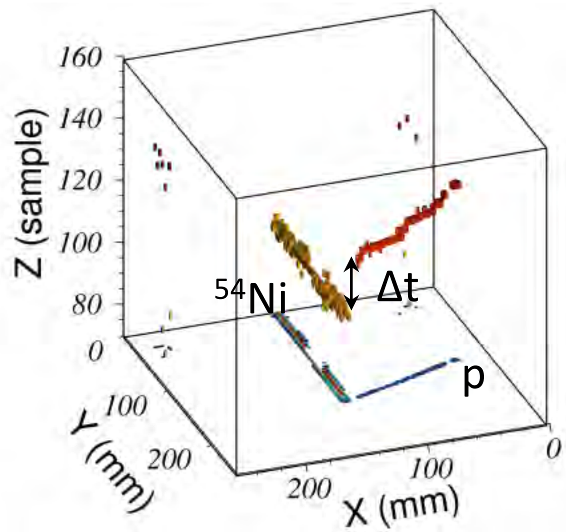
Very good neutron energy resolution (NEULAND)
Highest efficiency worldwide

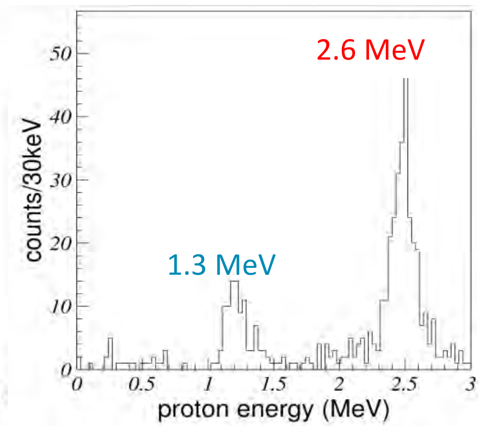
Good $\gamma$ energy resolution and efficiency (CALIFA)

*See talk Jurado / Sorlin*

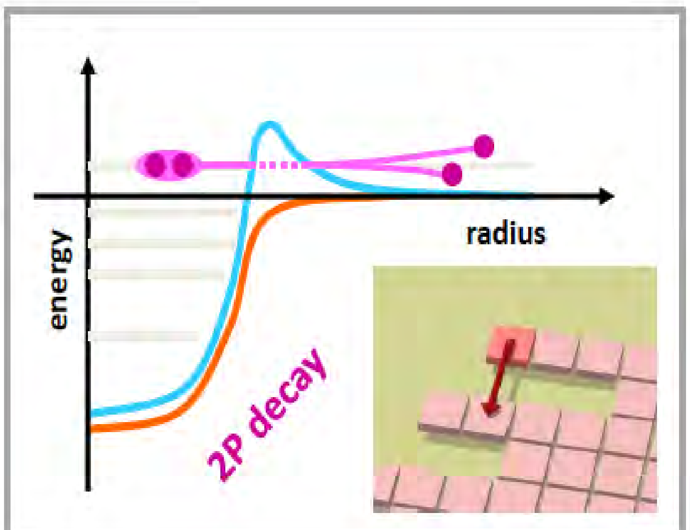
# Direct 1p or 2p radioactivity at the proton drip line with ACTAR-TPC



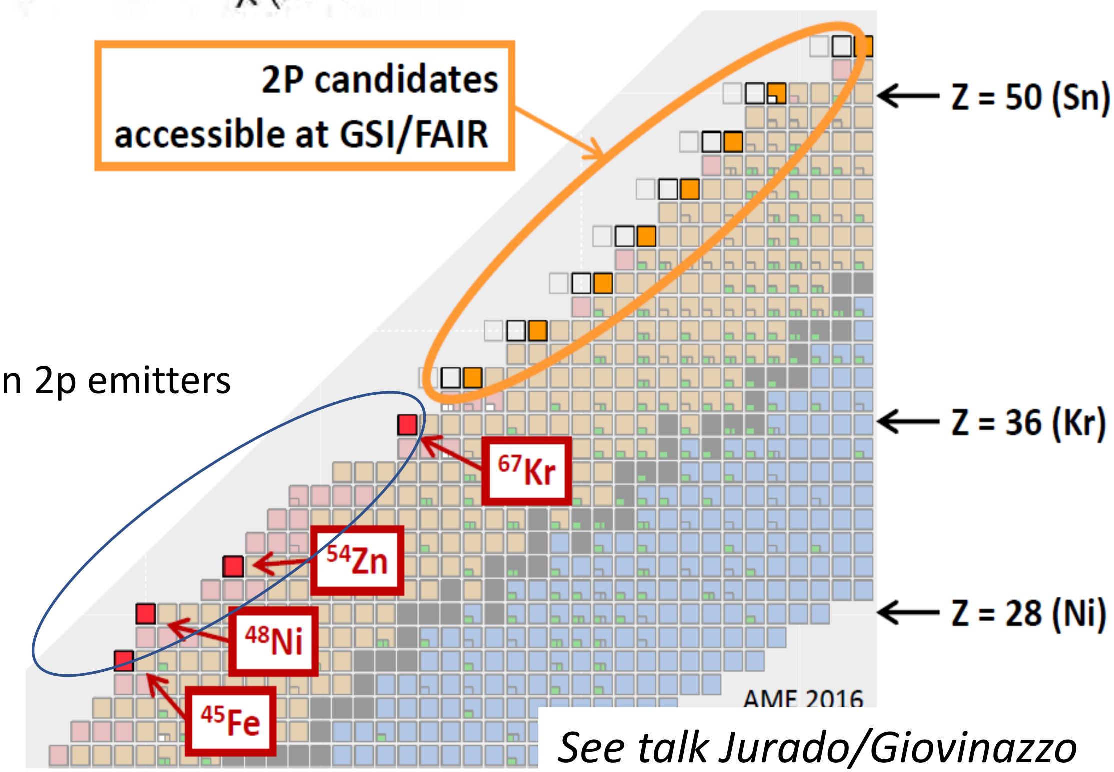




LISE/GANIL (2019)
With ACTAR-TPC




Understanding the 1p & 2p radioactivity processes require proper modeling of the nuclear structure and the dynamics

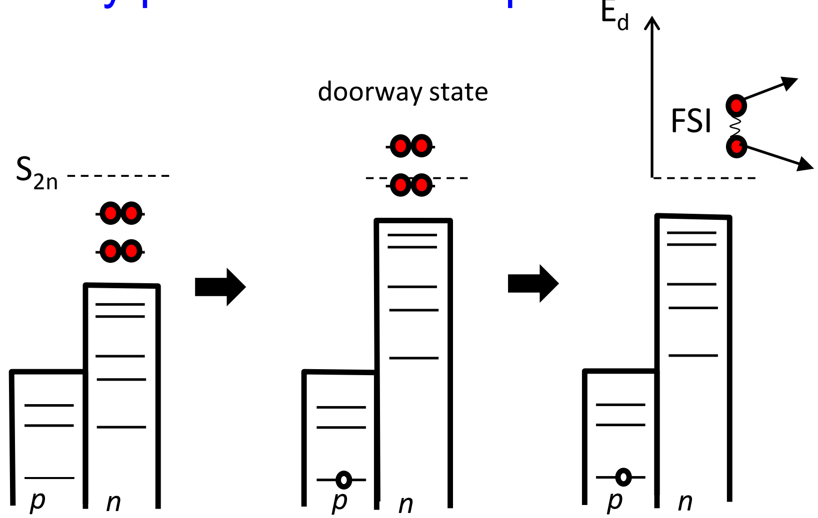



*See talk Jurado/Giovinazzo*

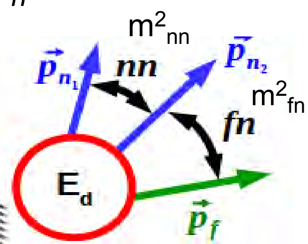
The end – backup slides after

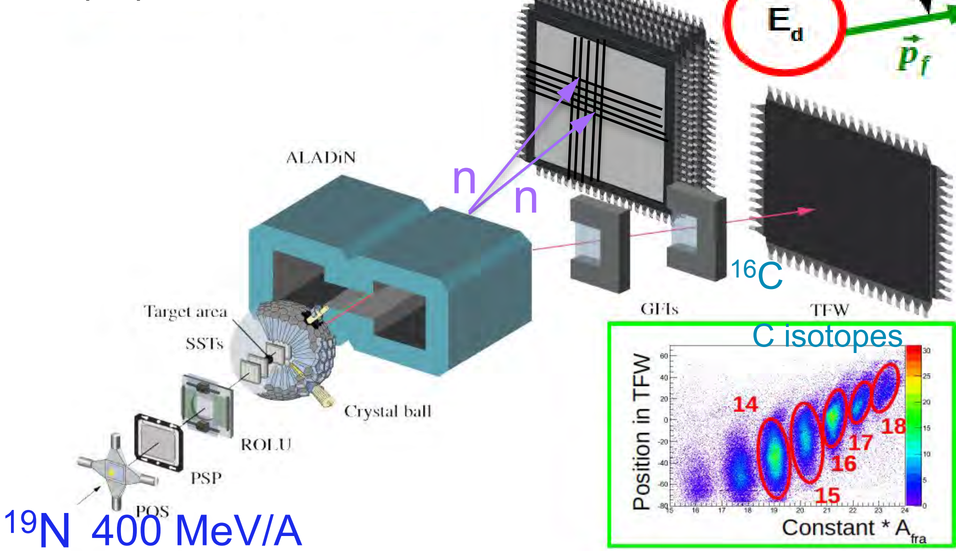
# Study of 2n correlations in atomic nuclei at GSI/R3B

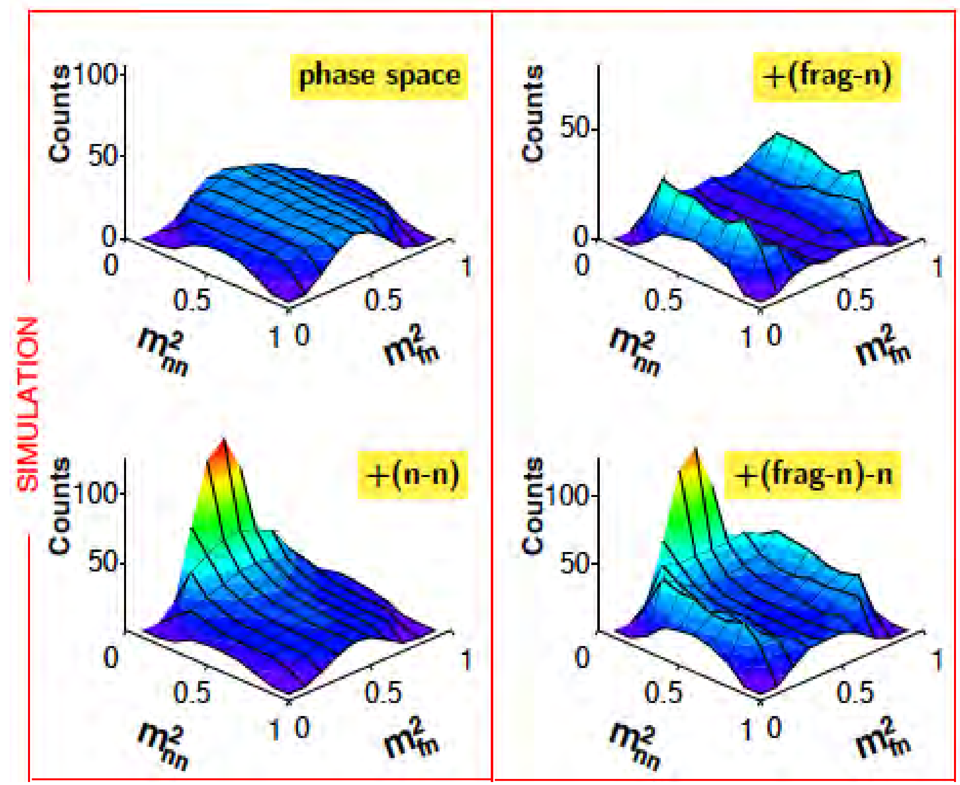
Use quasi-free proton knockout reaction from to suddenly promote neutron pairs in the continuum




$^{19}N(-p) \rightarrow {}^{18}C^* \rightarrow {}^{16}C + 2n$

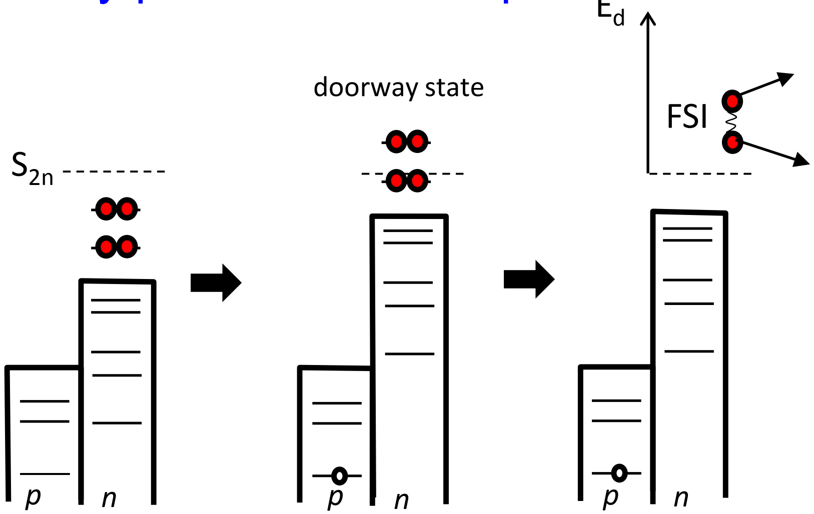


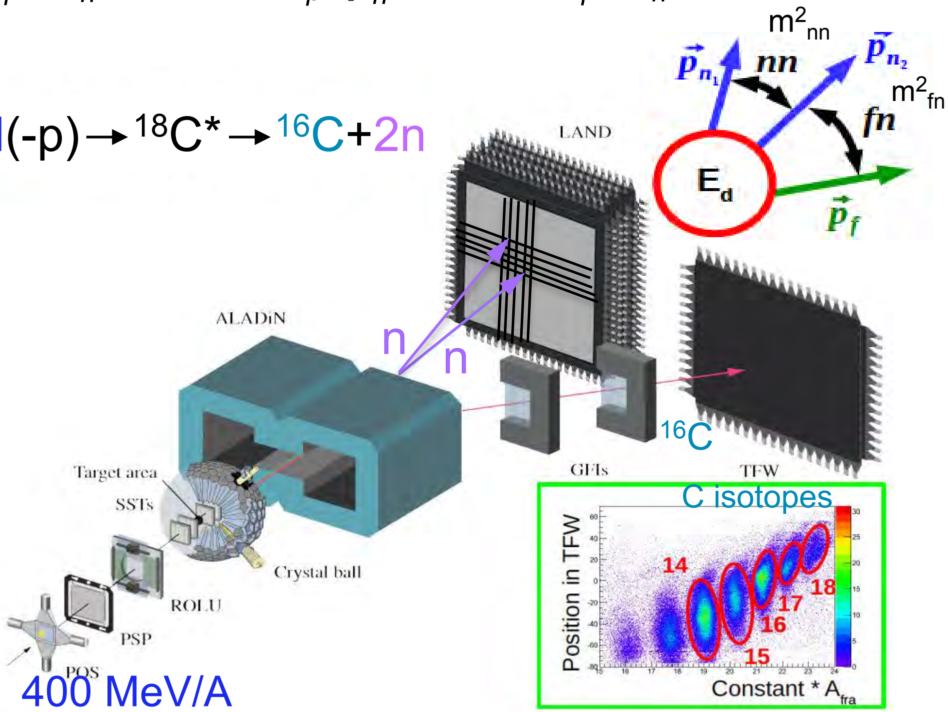



# Study of 2n correlations in atomic nuclei at GSI/R3B

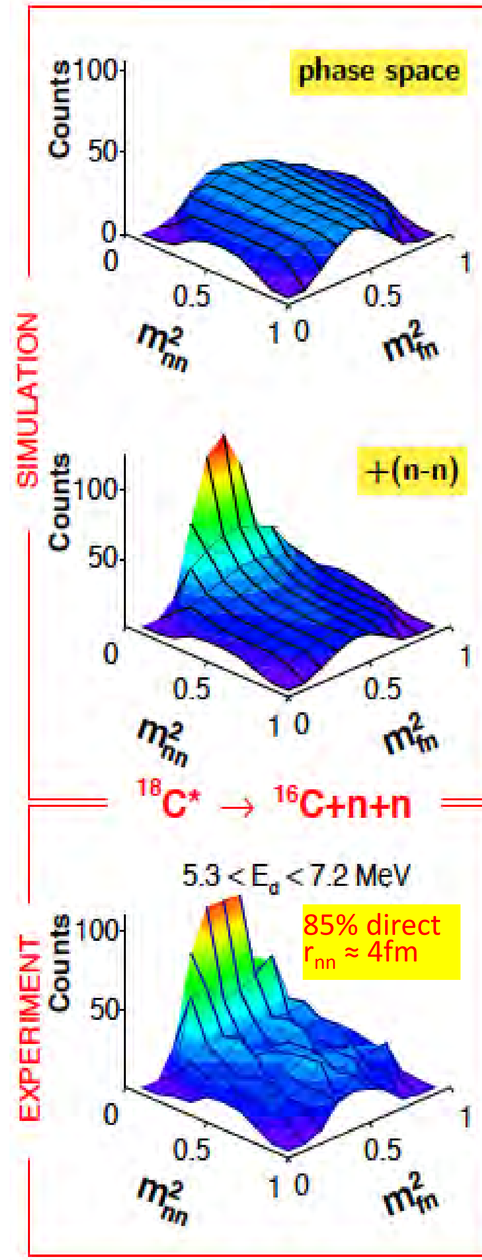
Use quasi-free proton knockout reaction from to suddenly promote neutron pairs in the continuum




$^{19}N(-p) \rightarrow {}^{18}C^* \rightarrow {}^{16}C+2n$




$^{19}N$ 400 MeV/A

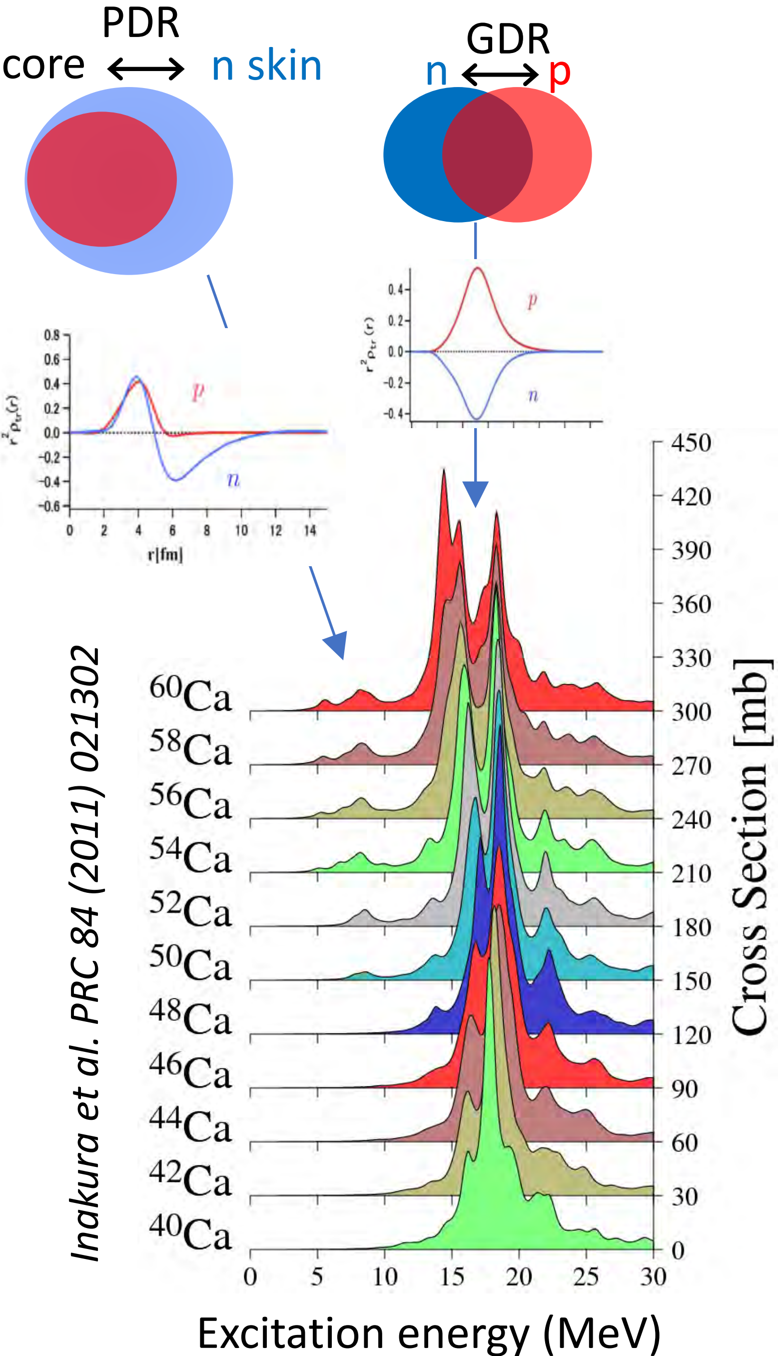



Small relative n-n momentum -> $r_{nn} \approx 4$ fm

Neutrons decay by pair in 85% cases, even up to $E_d$=12 MeV

*Revel et al. PRL120 (2019)*

# Pigmy and giant dipole excitations in neutron-rich nuclei




*Inakura et al. PRC 84 (2011) 021302*

$\alpha_D = \sum B(E1)/E$ dipole polarizability

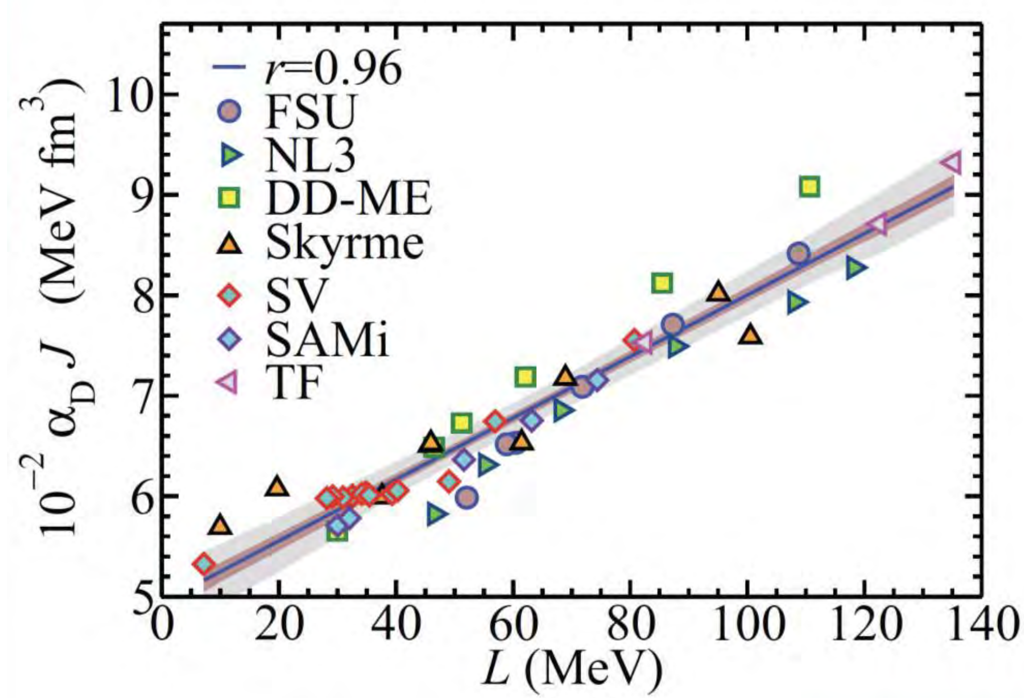
Nuclear EOS. : $E/A(\rho,\delta) = E/A(\rho,0) + S(\rho)\,\delta^2$

Symetry energy: $S(\rho) = J + L/(3\rho_0) \times (\rho-\rho_0) + \ldots$

J: Symmetry energy at saturation density

L: Slope at the saturation energy

$\rho=\rho_n+\rho_p$, $\delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$

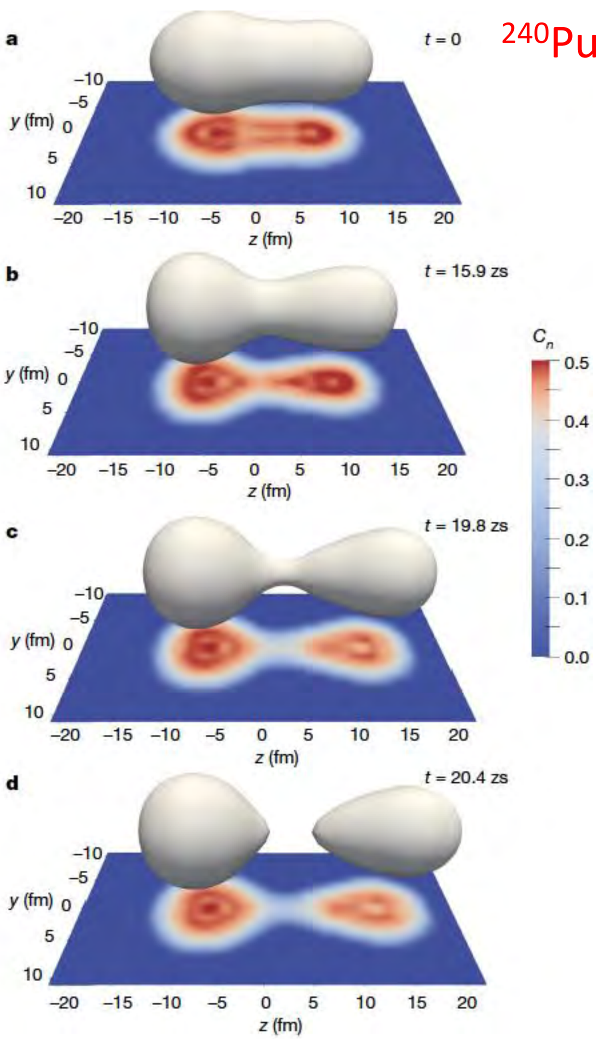


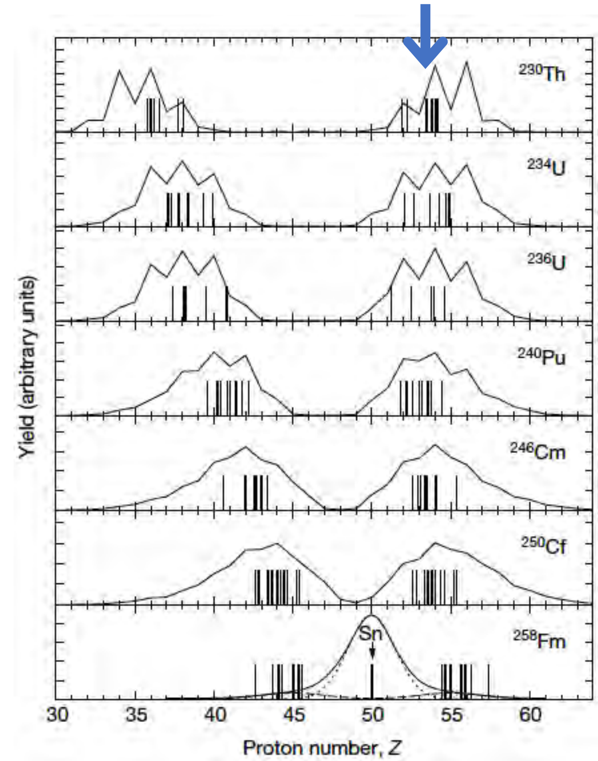

*Roca-Maza PRC 88 (2013) 024316*

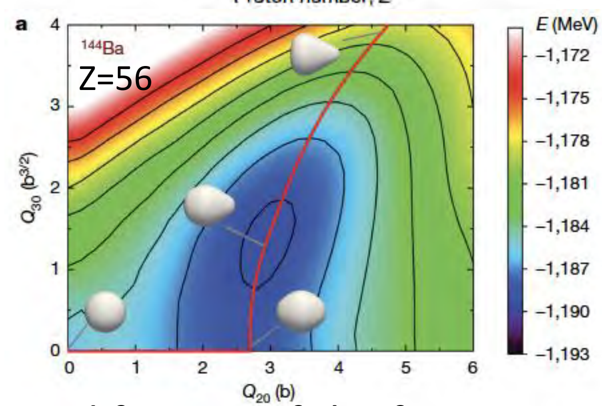
# Microsocopic modelling of fission

G. Scamps and C. Cimenel, Nature 564 (2018)

Evolution to fission

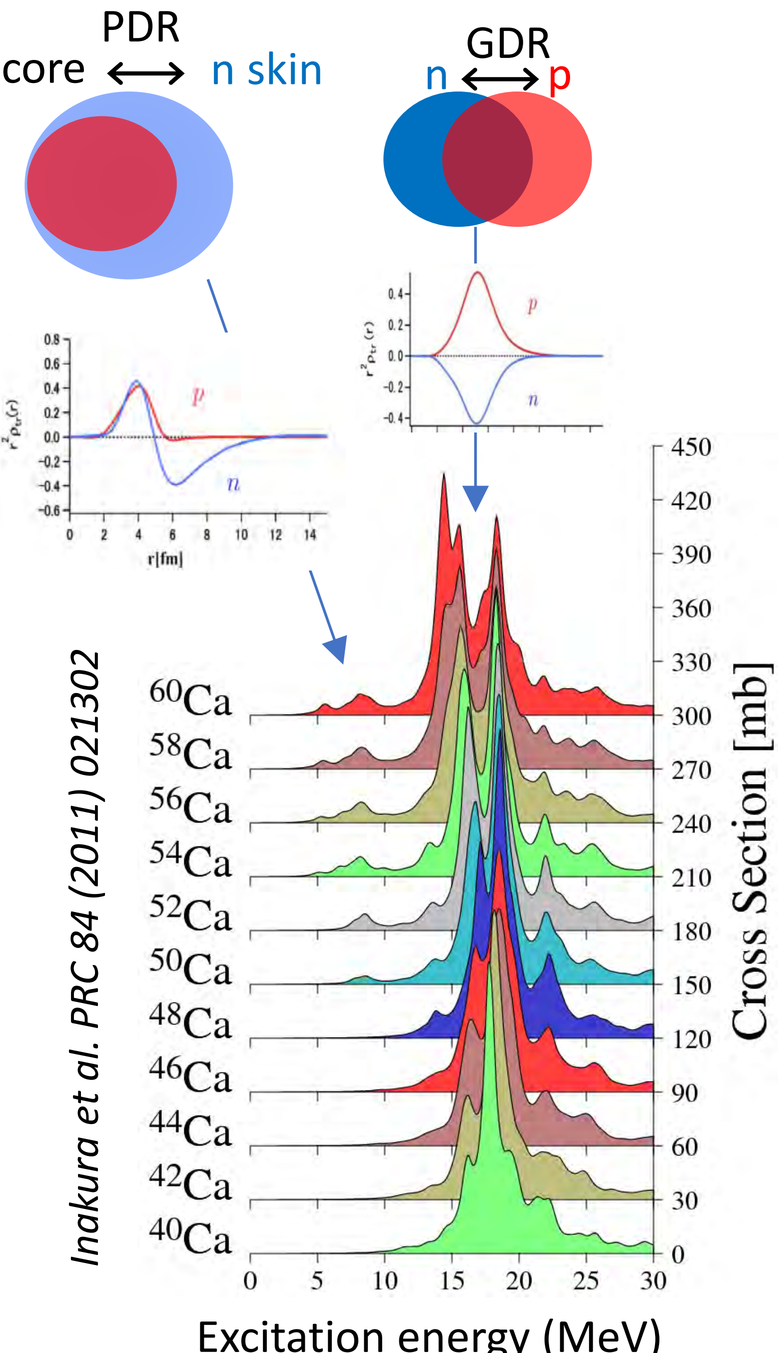



At the scission point, octupole shapes are preferred for one of the fragment
Maximum fission yield around Z=52-56 where octupole-deformed nuclei are found.

# Pigmy and giant dipole excitations in neutron-rich nuclei



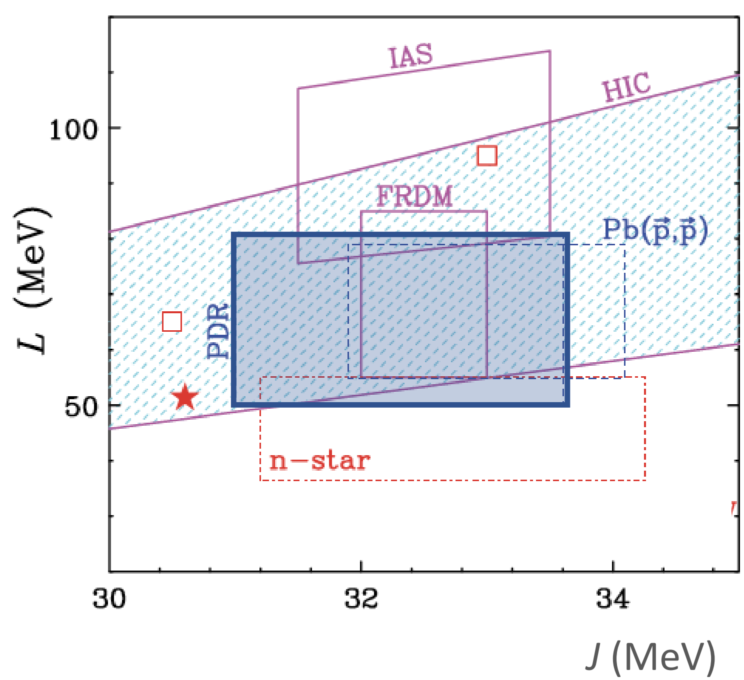

Nuclear EOS : $E/A(\rho,\delta) = E/A(\rho,0) + S(\rho)\,\delta^2$

Symetry energy: $S(\rho) = J + L/(3\rho_0) \times (\rho-\rho_0) + \ldots$

J: Symmetry energy at saturation density

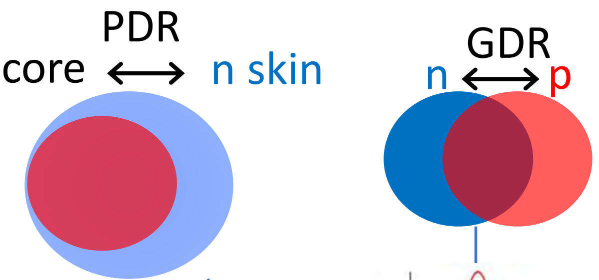
L: Slope parameter

$$\rho=\rho_n+\rho_p,\ \delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$$




Tsang et al.PRC 86 (2012)

# Pigmy and giant dipole excitations in neutron-rich nuclei



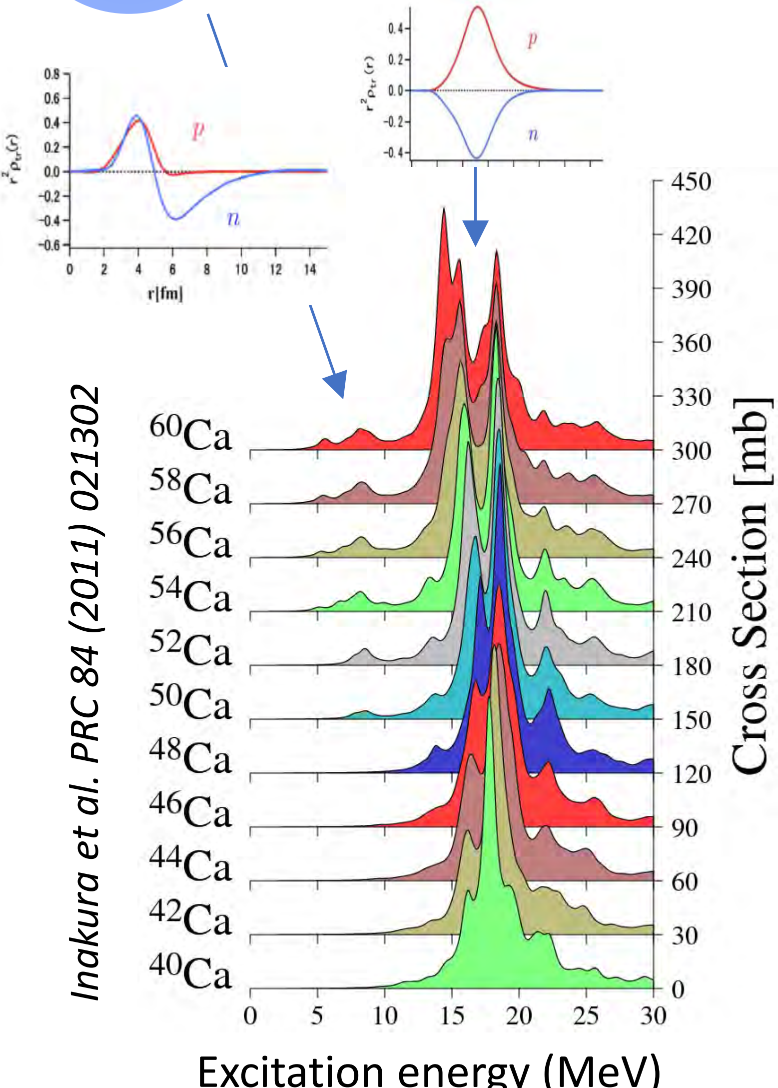

Nuclear EOS : $E/A(\rho,\delta) = E/A(\rho,0) + S(\rho)\,\delta^2$

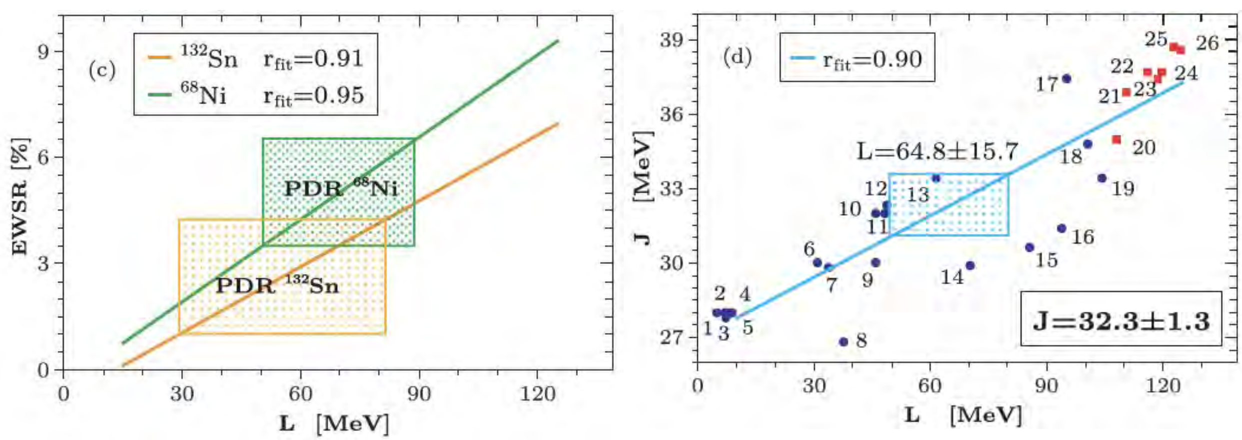
Symetry energy: $S(\rho) = \mathbf{J} + \mathbf{L}/(3\rho_0) \times (\rho-\rho_0) + \ldots$

J: Symmetry energy at saturation density

L: Slope parameter

$\rho=\rho_n+\rho_p,\ \delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$

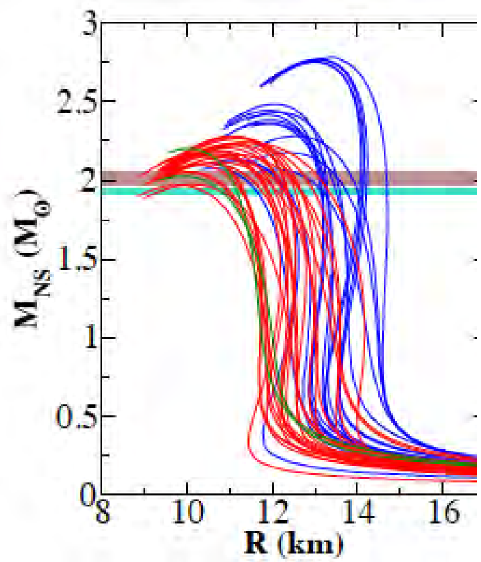


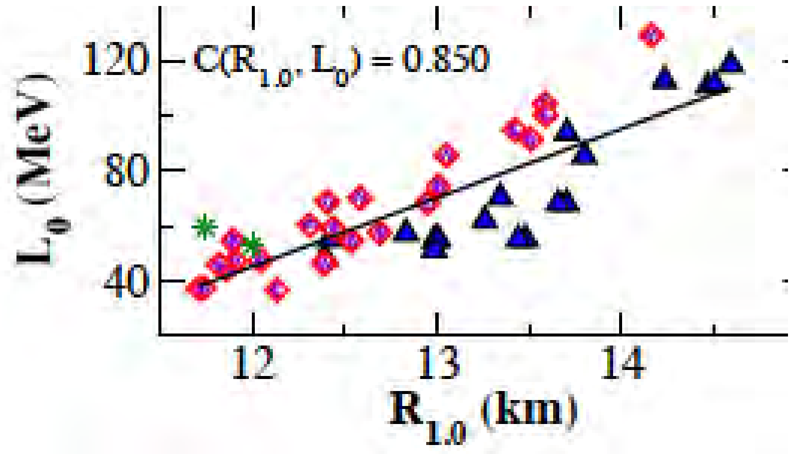

*Carbone et al., PRC 81 (2010)*

# Pigmy and giant dipole excitations in neutron-rich nuclei

Link between slope parameter and Neutron Star radius

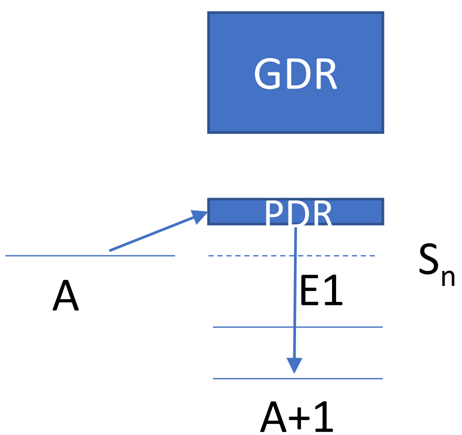



Radius of 1 solar mass




Alam et al. 94 (2016)

Ling between the energy and strength of the PDR and neutron capture rates



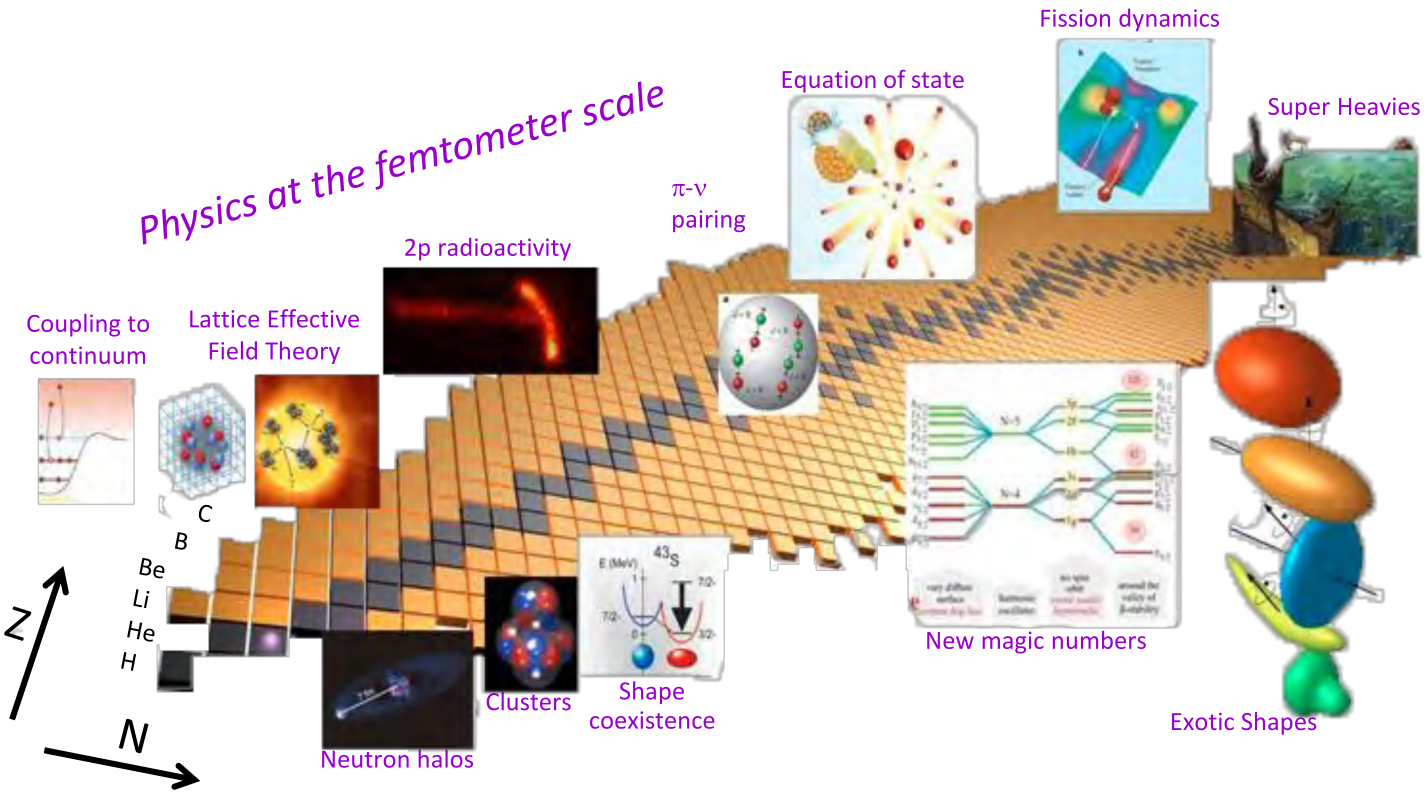

PDR can enhance the neutron capture rate for the r process by orders of magnitude

*(A.C. Larsen et al., PPNP in press)*

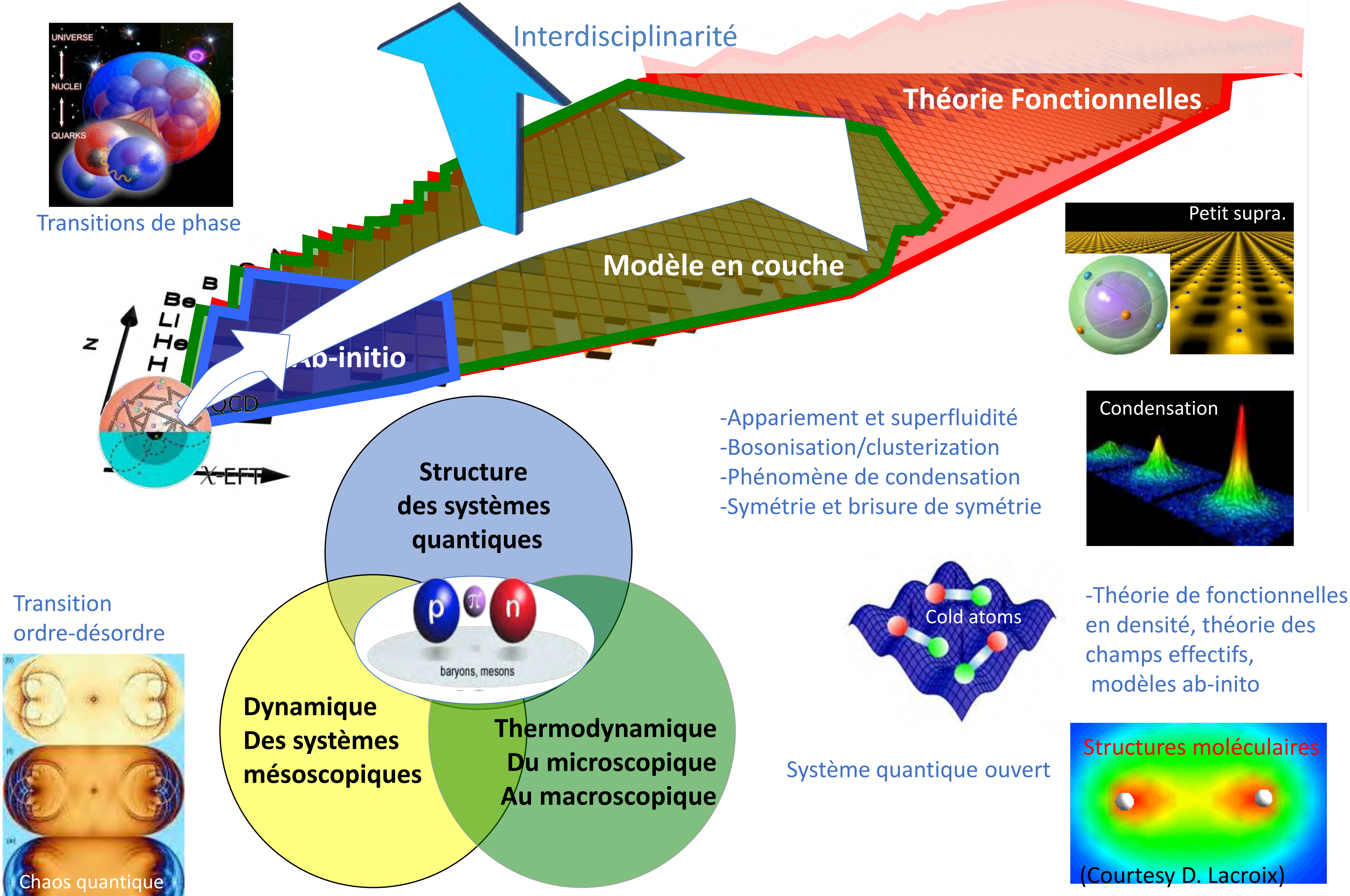
# Introduction to nuclear physics with accelerated beams

*O. Sorlin (GANIL)*

| | |
|---|---|
| **- Structure nucléaire** | ➢ Comment évoluent les effets de couches (nombres magiques, formes) ? Quelles sont les limites d'existence des noyaux en isospin et masse |
| **- Astrophysique nucléaire** | ➢ Comment sont synthétisés les éléments chimique dans l'Univers Quelle est l'équation d'état de la matière nucléaire ? (lien avec explosions stellaires, étoiles à neutrons, NSM …) |
| **- Mécanismes de réaction** | ➢ Comment parvenir à une description microscopique des processus de fusion, fission et collisions nucléaires rapprochées ? |
| **- Interactions fondamentales** | ➢ Peut-on trouver des indices de la physique BSM ? |

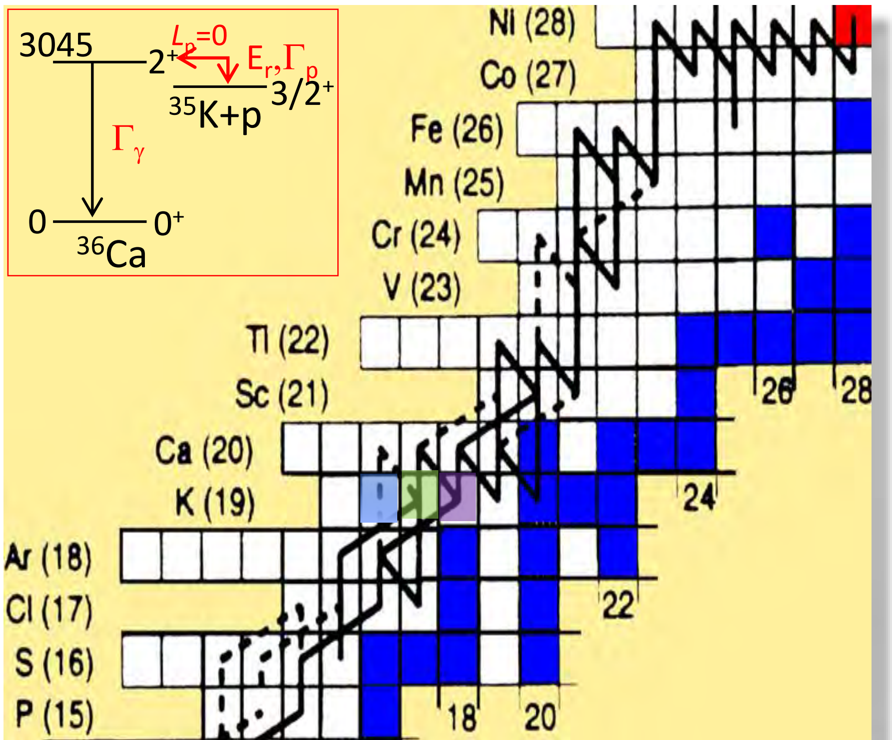


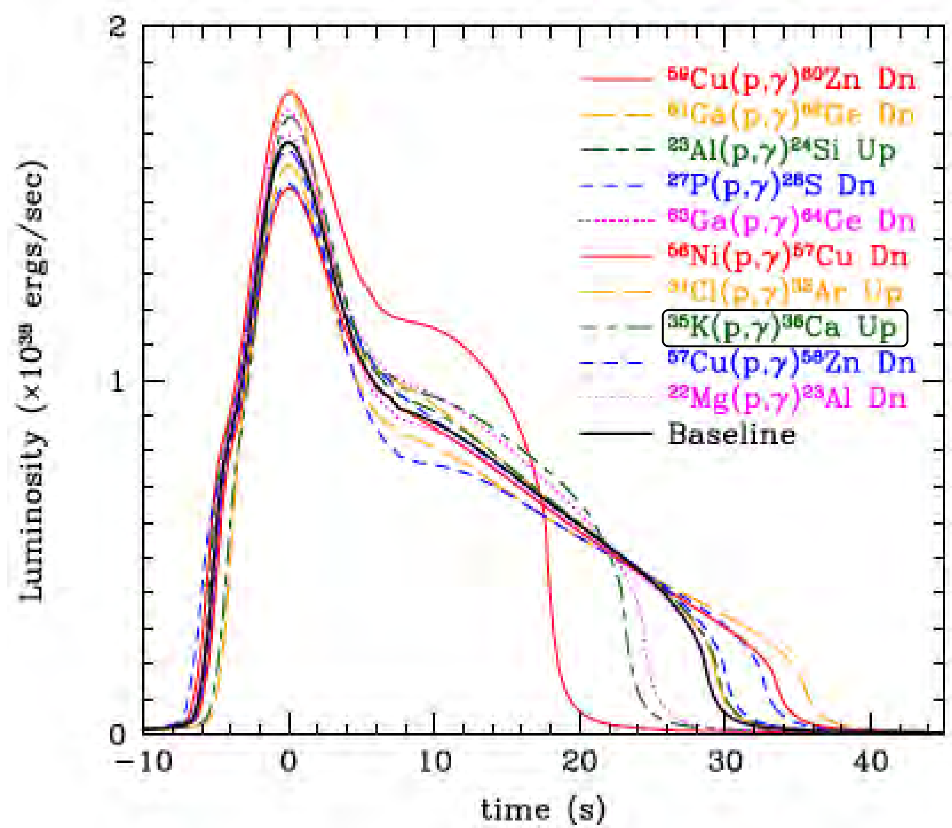
# Tendances actuelles en physique théorique



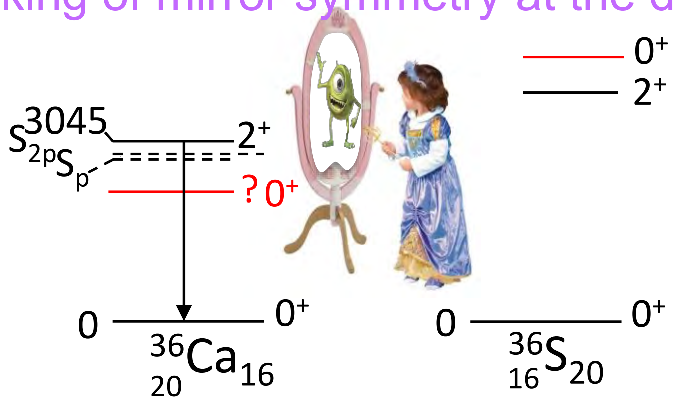
# Motivations for studying $^{36}$Ca

## Influence of the rapid proton capture rates




## Breaking of mirror symmetry at the drip line

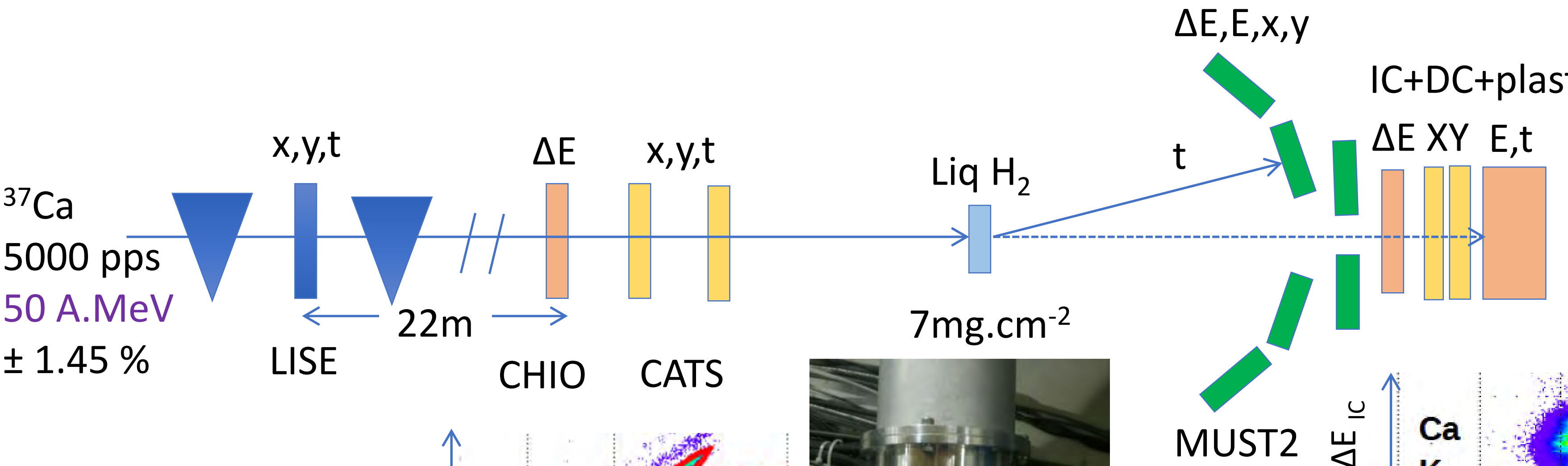


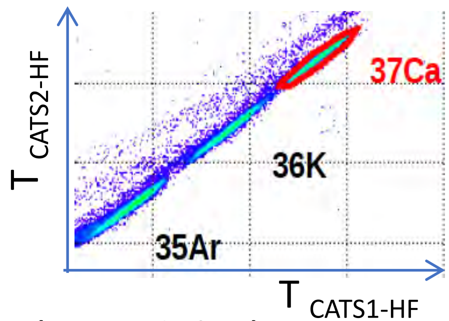

Study of $^{36}$Ca using $^{37}$Ca(p,d) and $^{38}$Ca(p,t) reactions

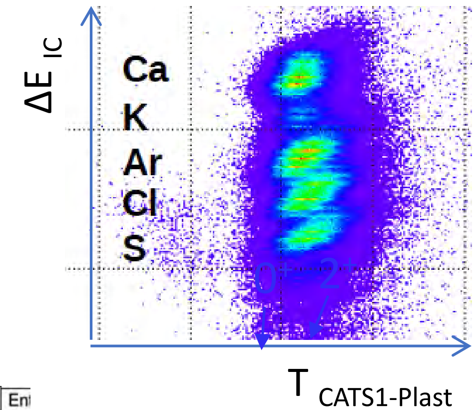
$^{37,38}$Ca beams produced with LISE spectrometer at 50MeV/A

Detection of the charged particles with MUST2

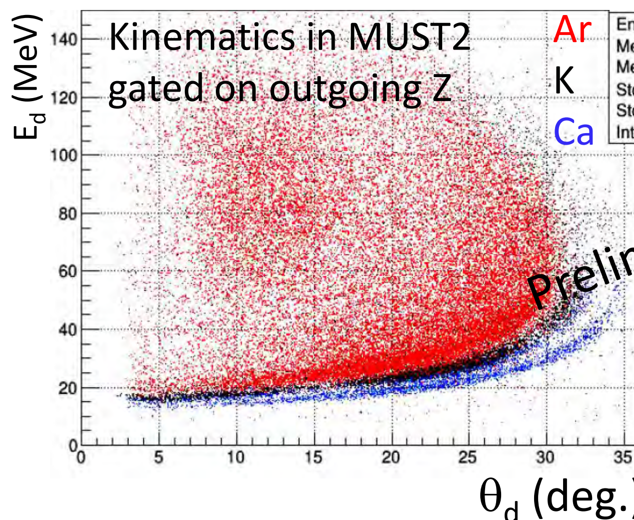
# Experimental set up to study $^{36}$Ca – Preliminary results

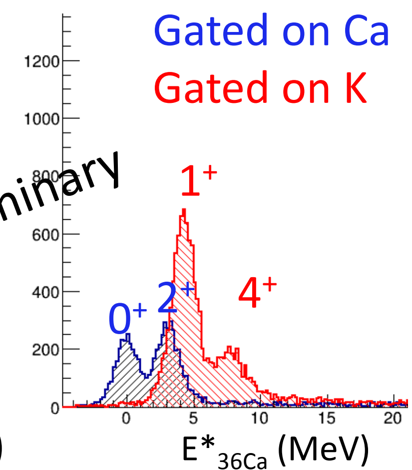


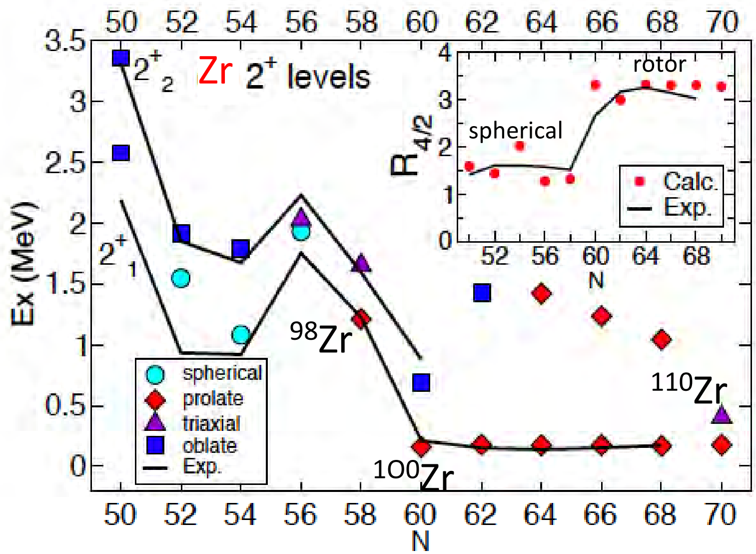

MUST2 array (8 modules)

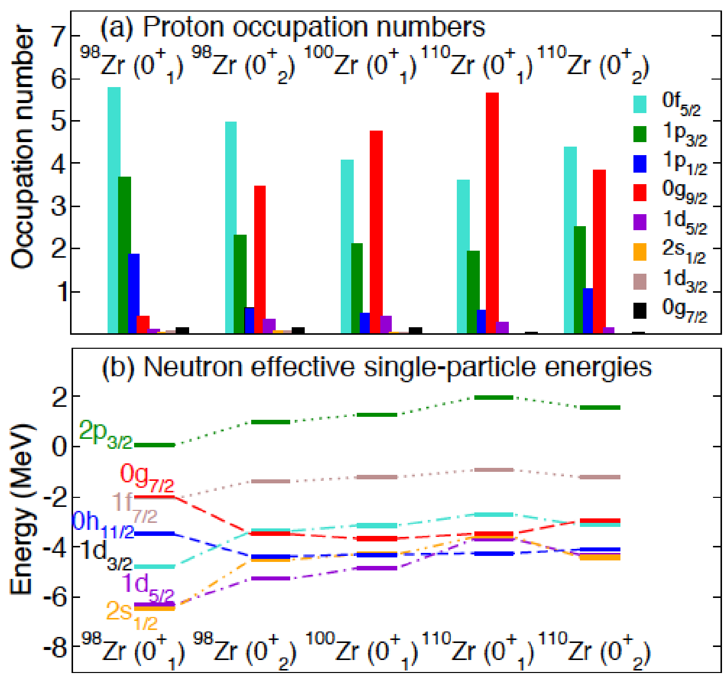


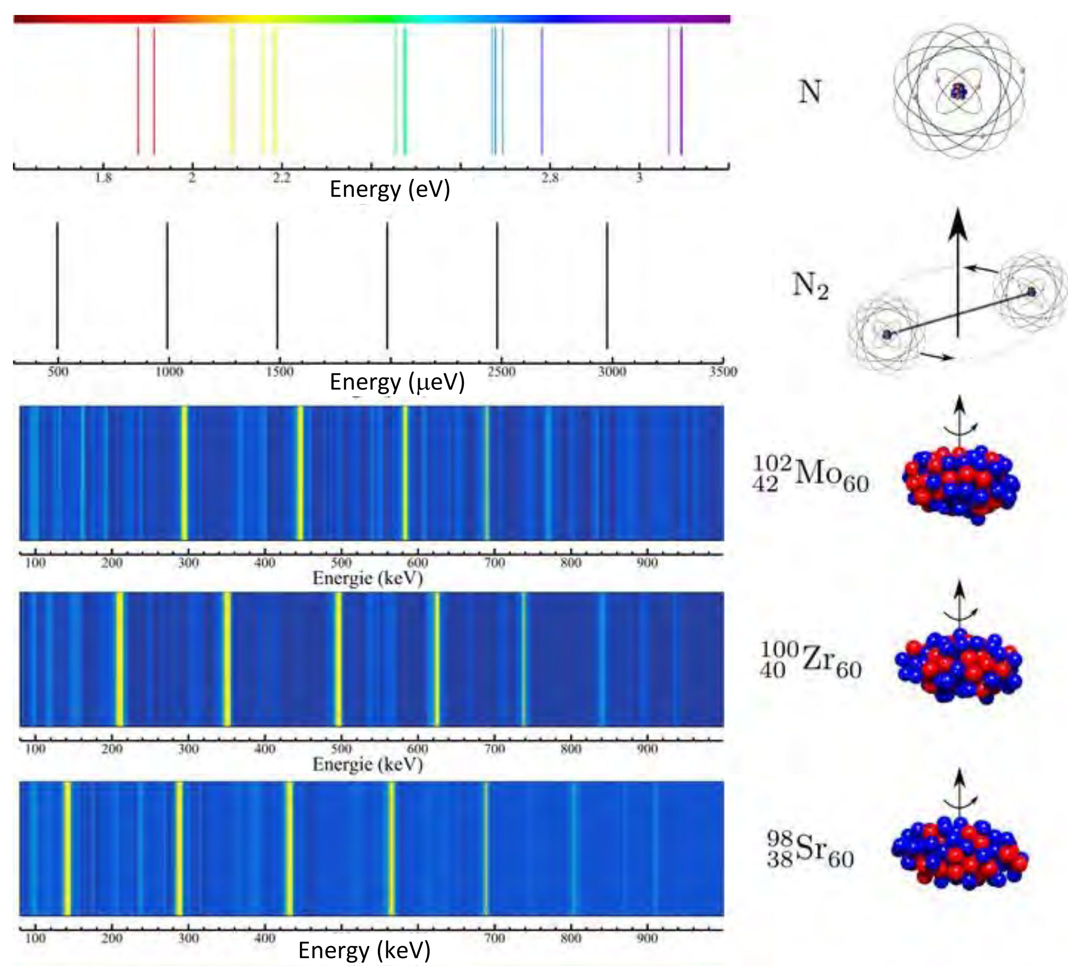



# Nuclear shapes and deformation at N=60

*Togashi et al., PRL 117 (2016)*

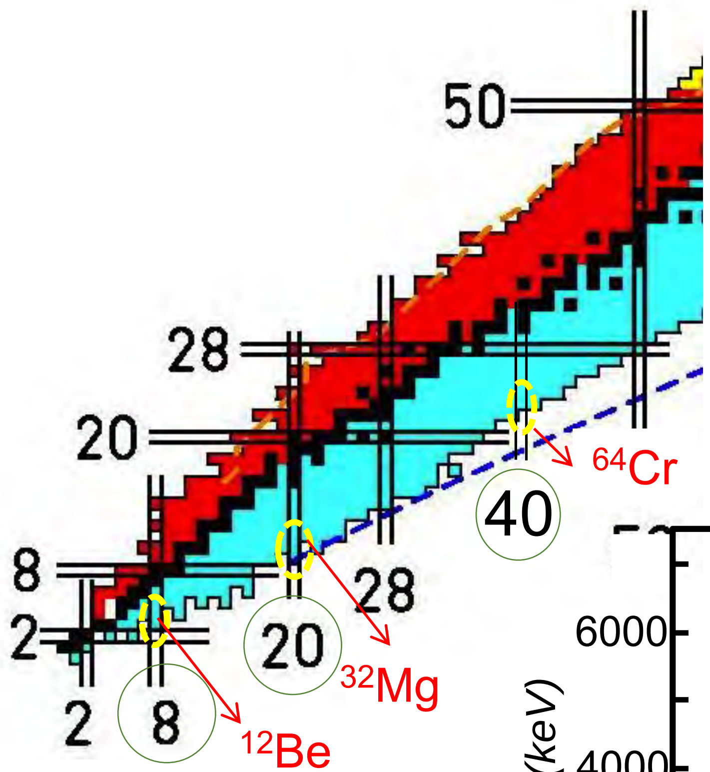



Specific role of the tensor attractive $g_{9/2}$ - $g_{7/2}$ and repulsive $g_{9/2}$ - $d_{5/2}$ proton-neutron interactions to cluster the neutron orbits and induce deformation

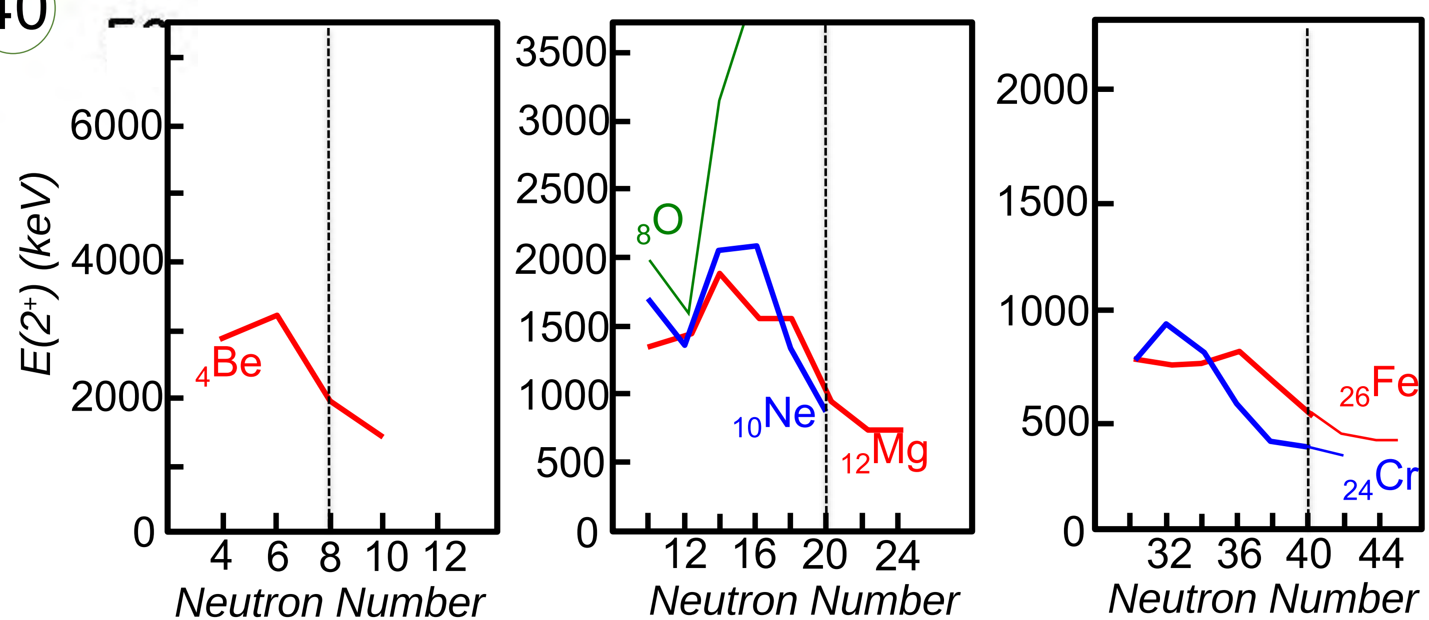
# Assuming our world was more neutron-rich




While removing protons, the same loss of magicity occurs for all magic numbers

→ role of proton-neutron interactions, poorly known far from stability

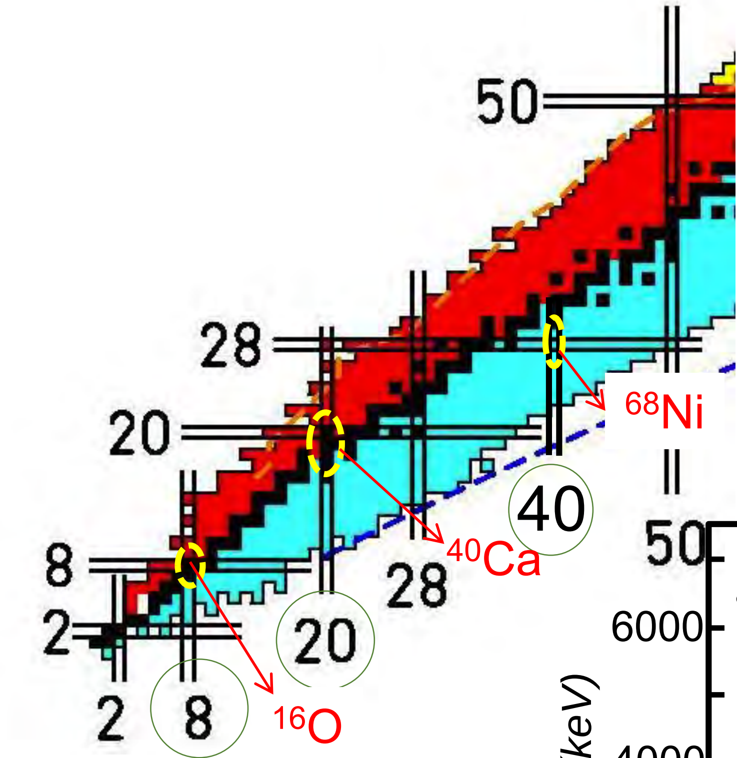
No sign of shell closure and magic nuclei (no increase of 2$^+$ energy at N=8, 20, 40)




N=40

↳ Hannawald PRL 82 (1999), Sorlin, EPJA16 (2003), Aoi, PRL 102 (2009), Gade PRC 81 (2010)
W. Rother PRL106 (2011), Lenzi PRC82 (2010), Santamaria PRL 115 (2015), …

# Magic numbers in the valley of stability




The neutron numbers 8, 20 and 28 were

Increase of $2^+$ energy at N=8, 20, 40