Shapes and shape coexistence
And
Connection between experiments at the Oslo Cyclotron and CERN-ISOLDE

Sunniva Siem

Nuclear and particle spring school 1-4 April 2019, CERN

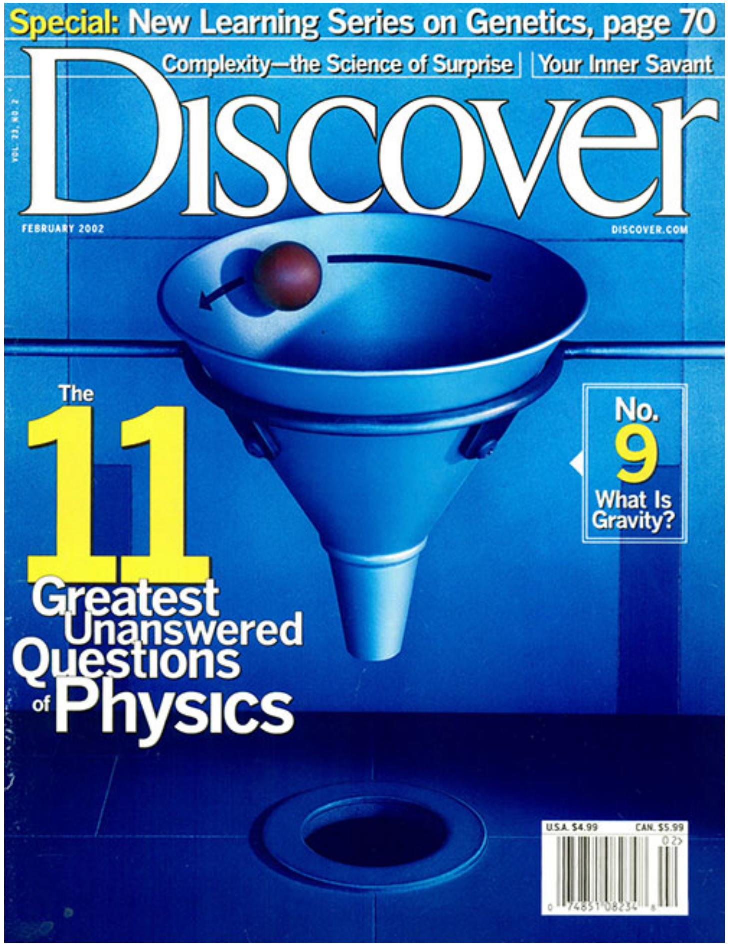
Outline of the talk

- Motivation
- Experiments in Oslo
- Moving toward neutron rich nuclei: experiments at ISOLDE
- Shapes and shape coexistence

- INTPART – student exchange and international collaborations

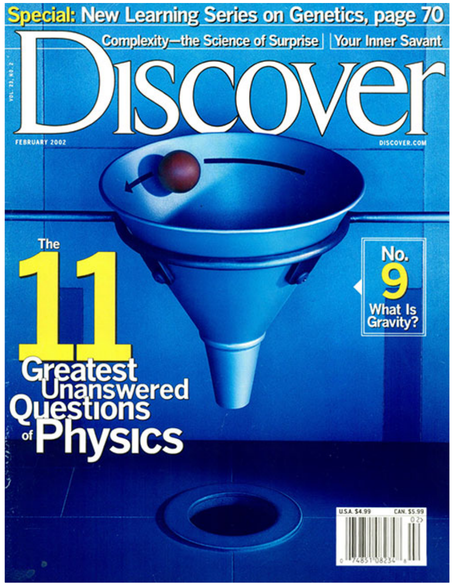

What motivates us? The big questions like:
➢ Where do the elements we are made of come from?
➢ How and where were they created?

USA: National Research Councils board on Physics and Astronomy made a list over the 11 Greatest Unanswered Questions of Physics



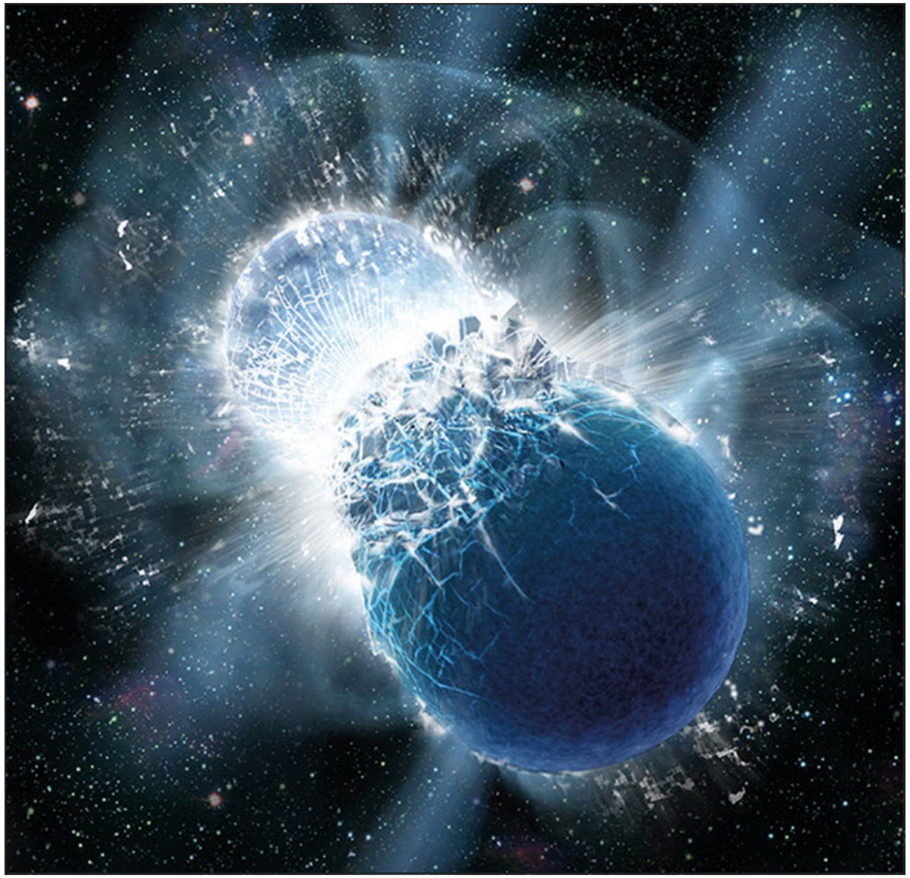
How were the heavy elements from iron to uranium made?

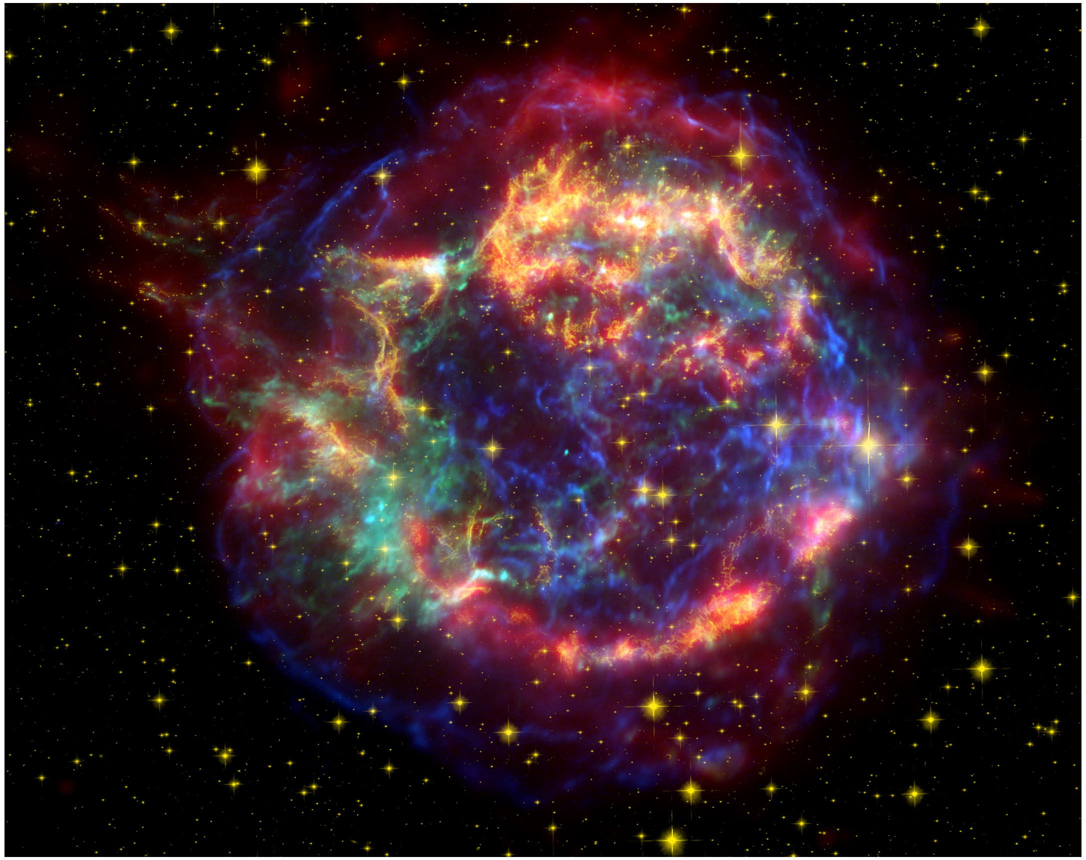
Half of the elements are produced in the r-process nucleosynthesis.
The r-process must happen in an environment with a very high neutron density



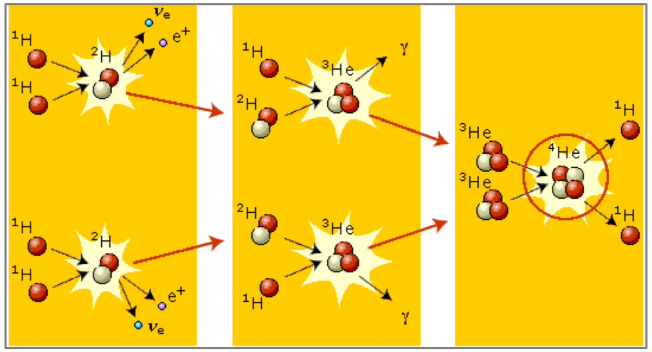
Neutron star mergers?

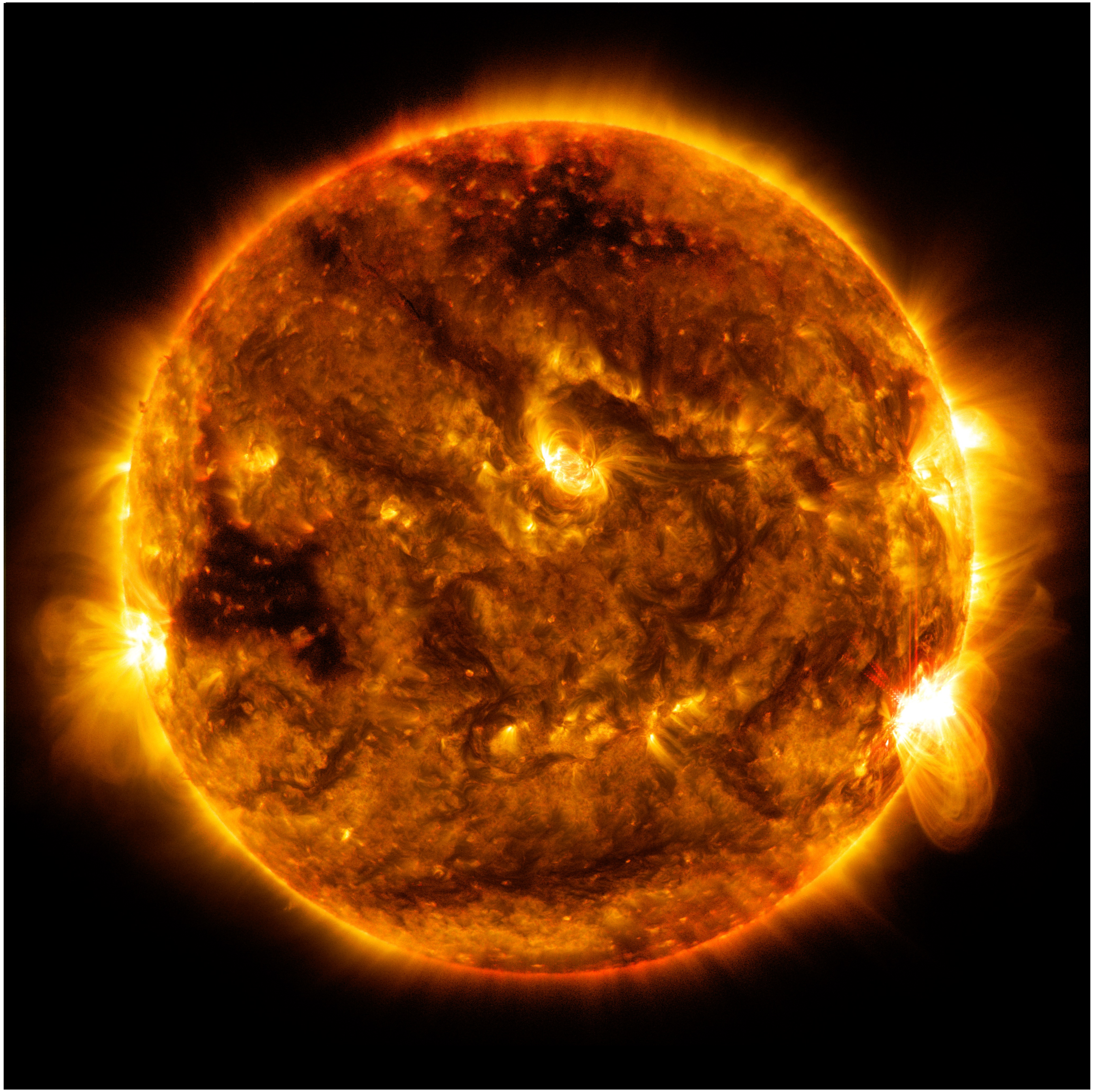
Supernova explosions?





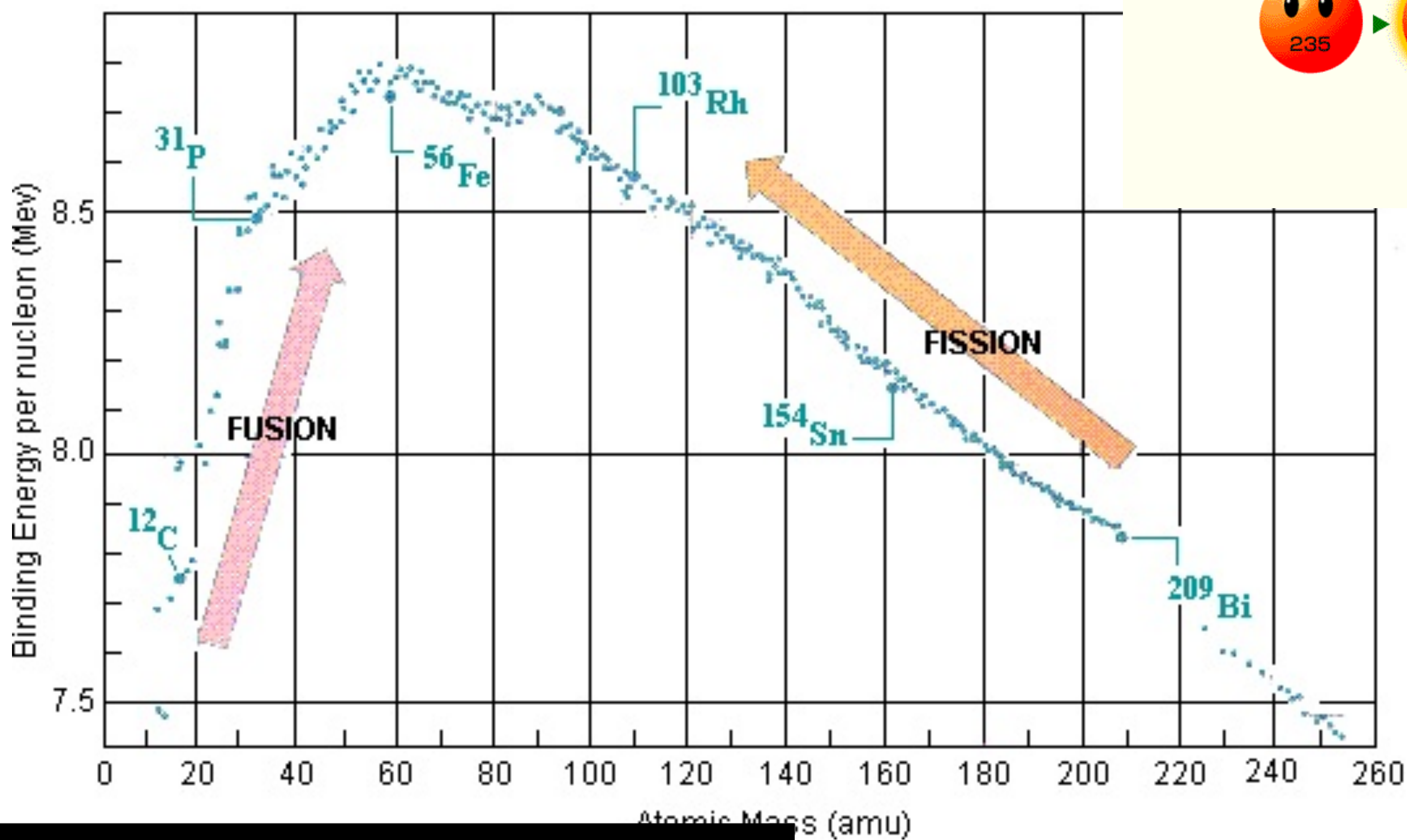
The *light* elements are made in stars by fusion processes

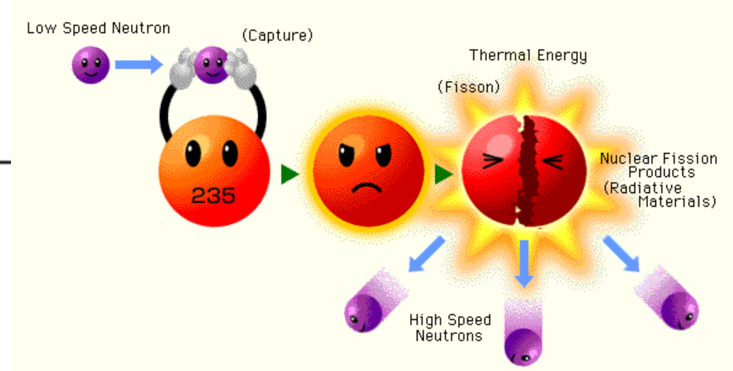


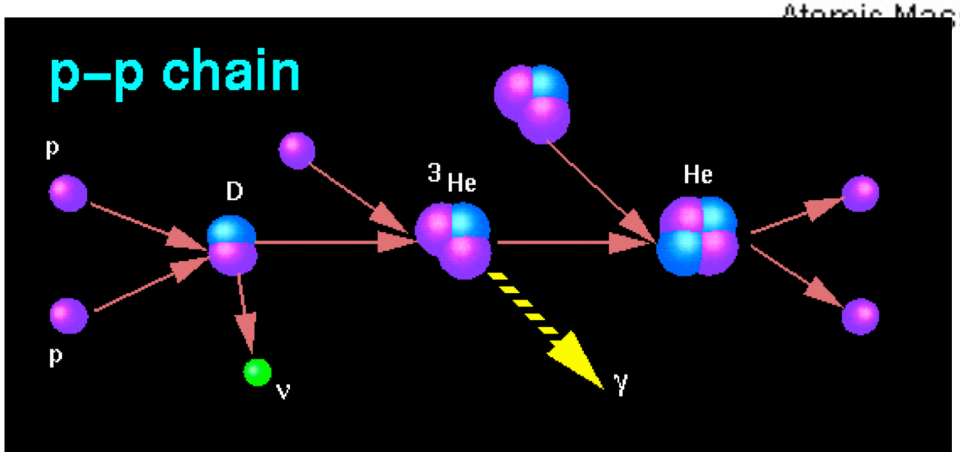


the sun "burns" by fusing light nuclei, starting with hydrogen

fusion in stars will take us all the way up to iron

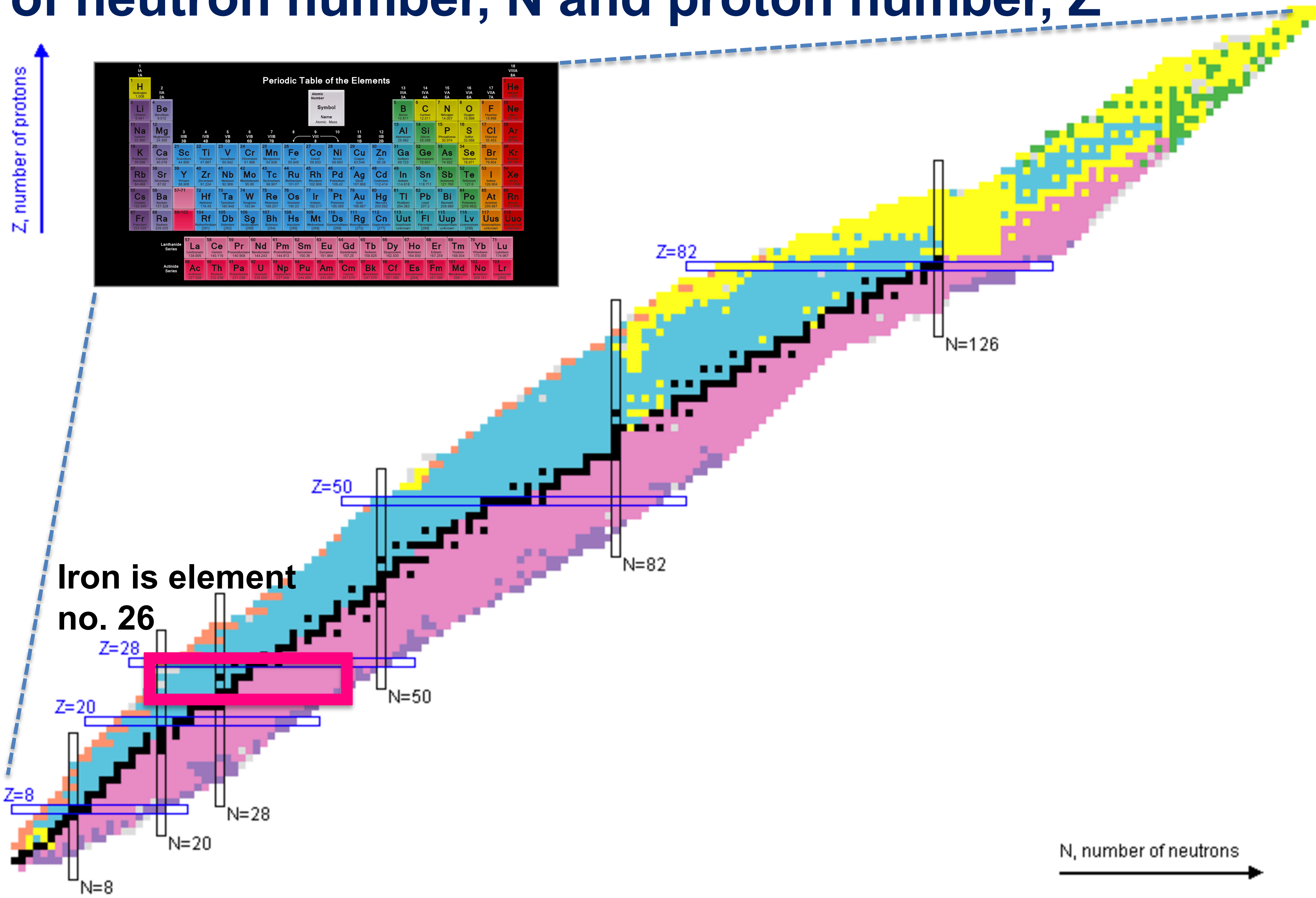




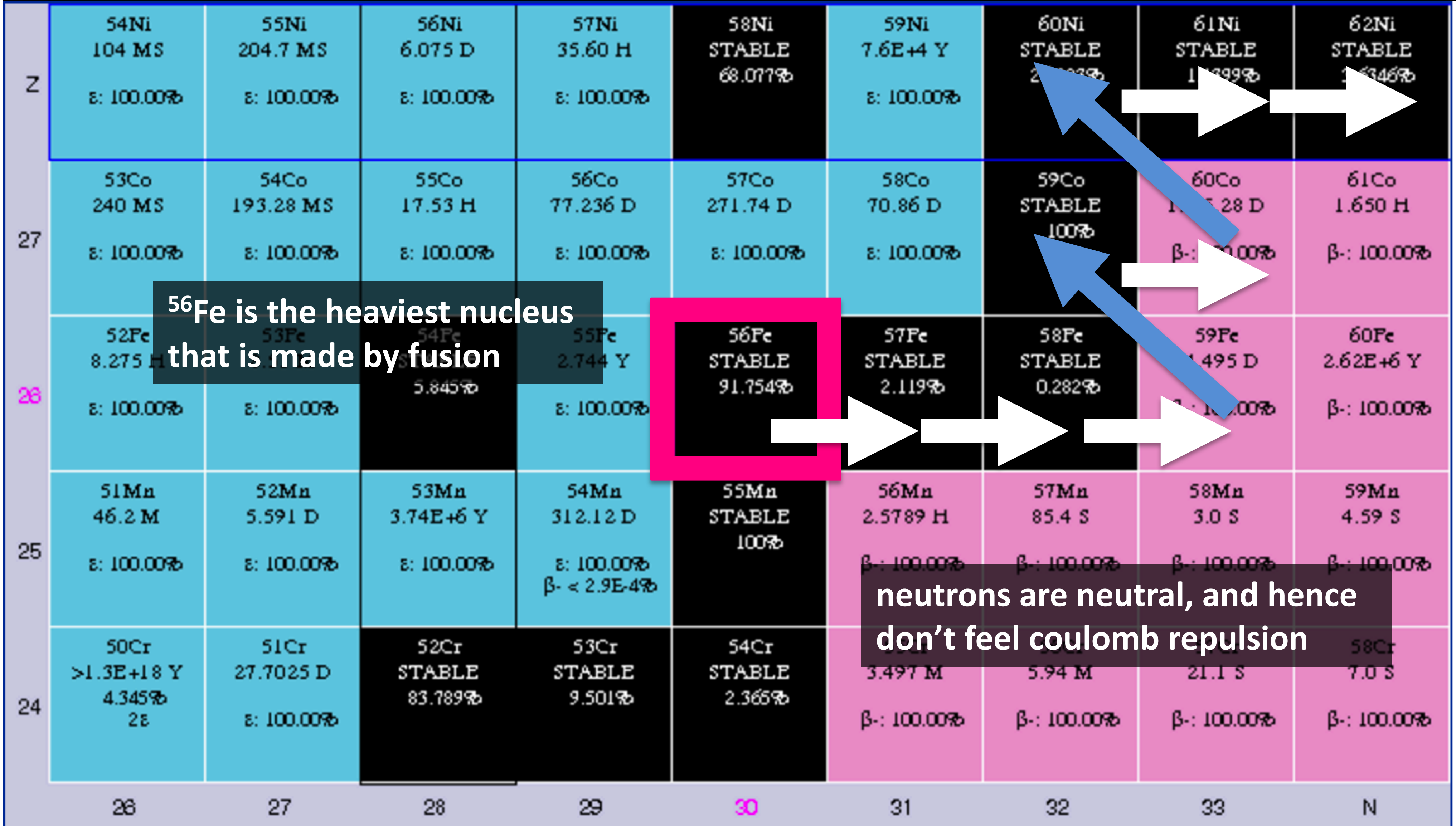


mass can be transformed to energy, E = mc^2, by fission or fusion

The chart of nuclides: all known nuclei as a function of neutron number, N and proton number, Z

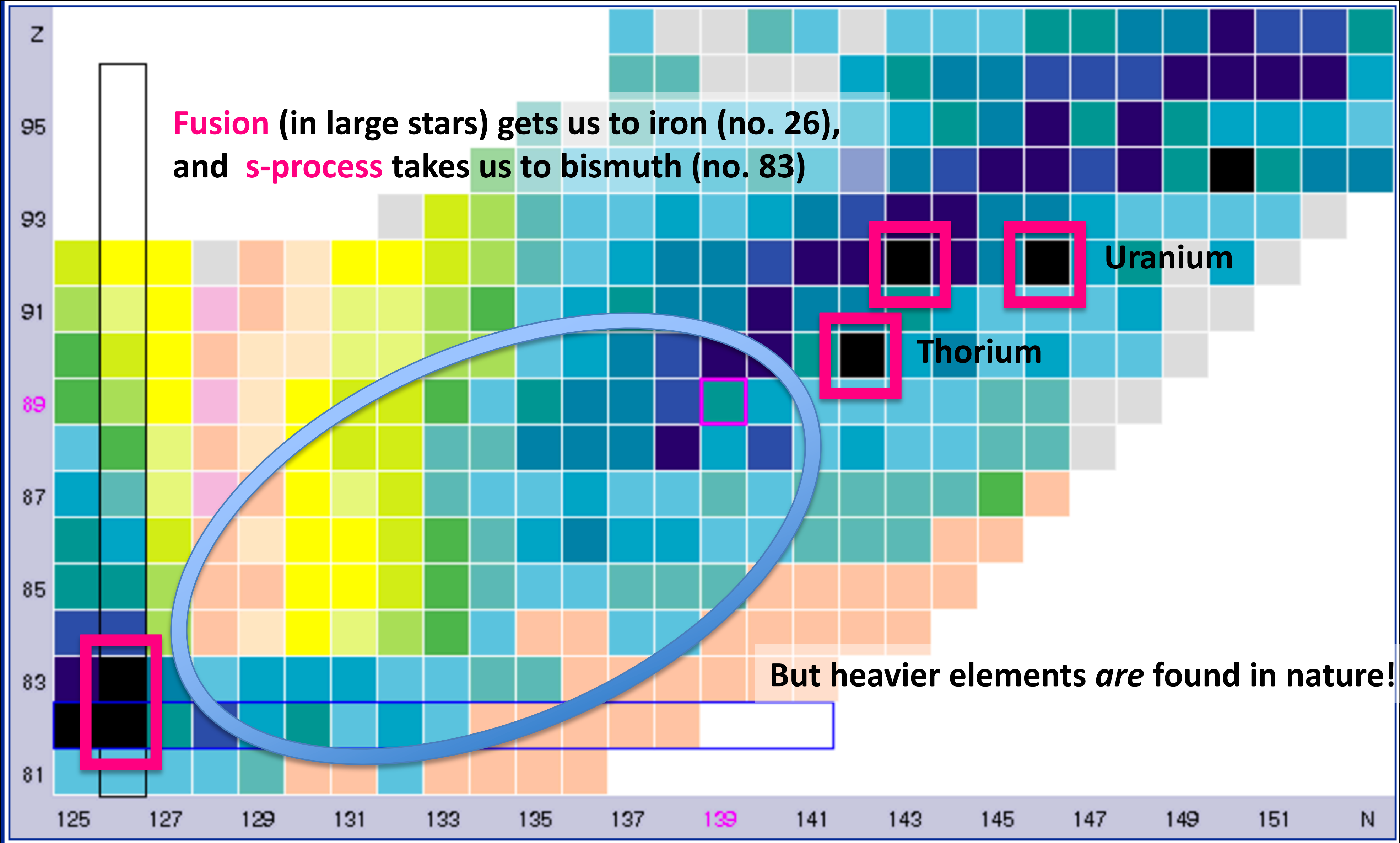


The *s-process* is the process where stable nuclei capture neutrons at a slow pace to produce heavier elements

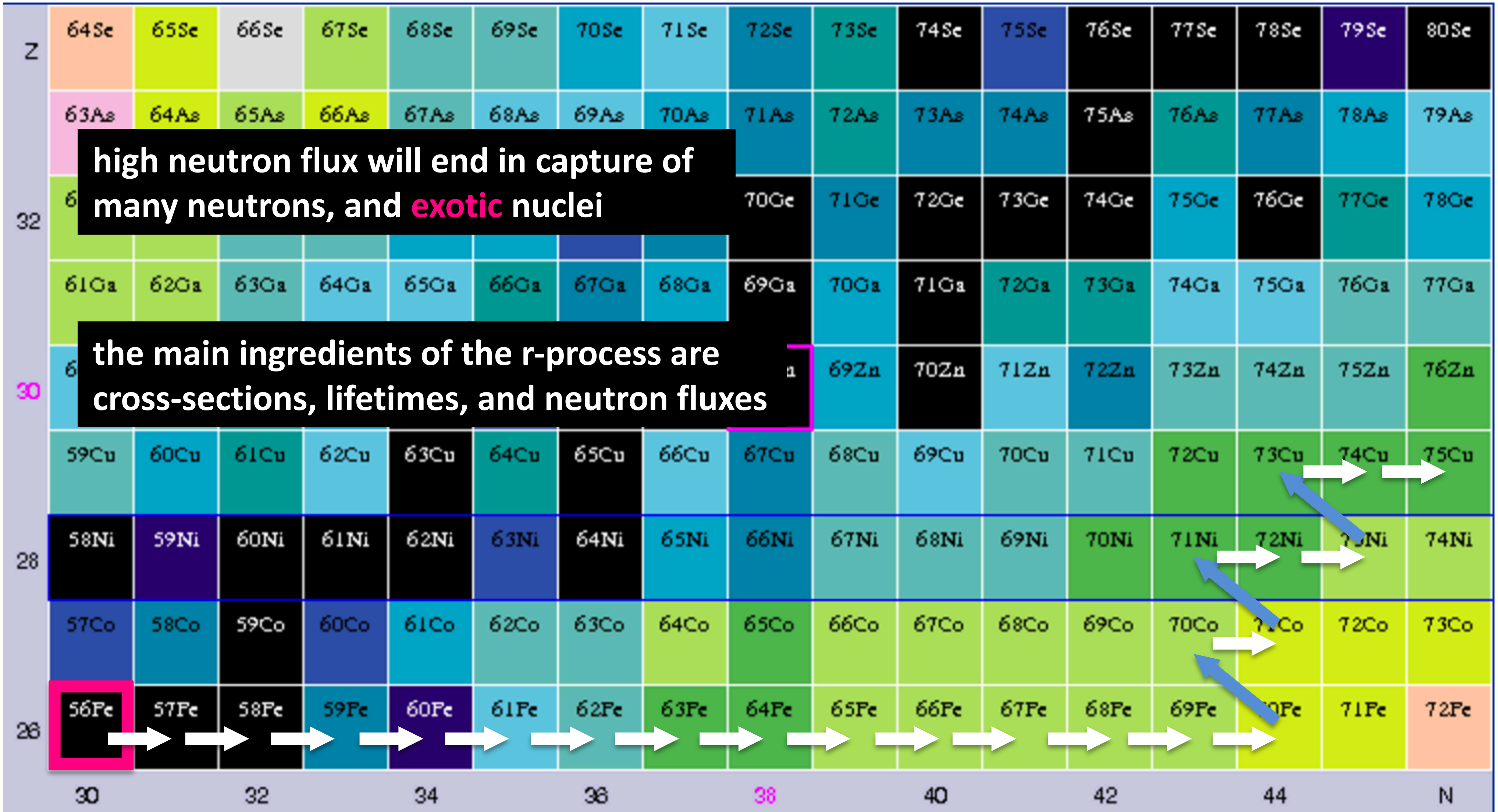


s-process is "easy": seeds are stable, need capture cross-sections we can easily measure, and a neutron density we can imagine

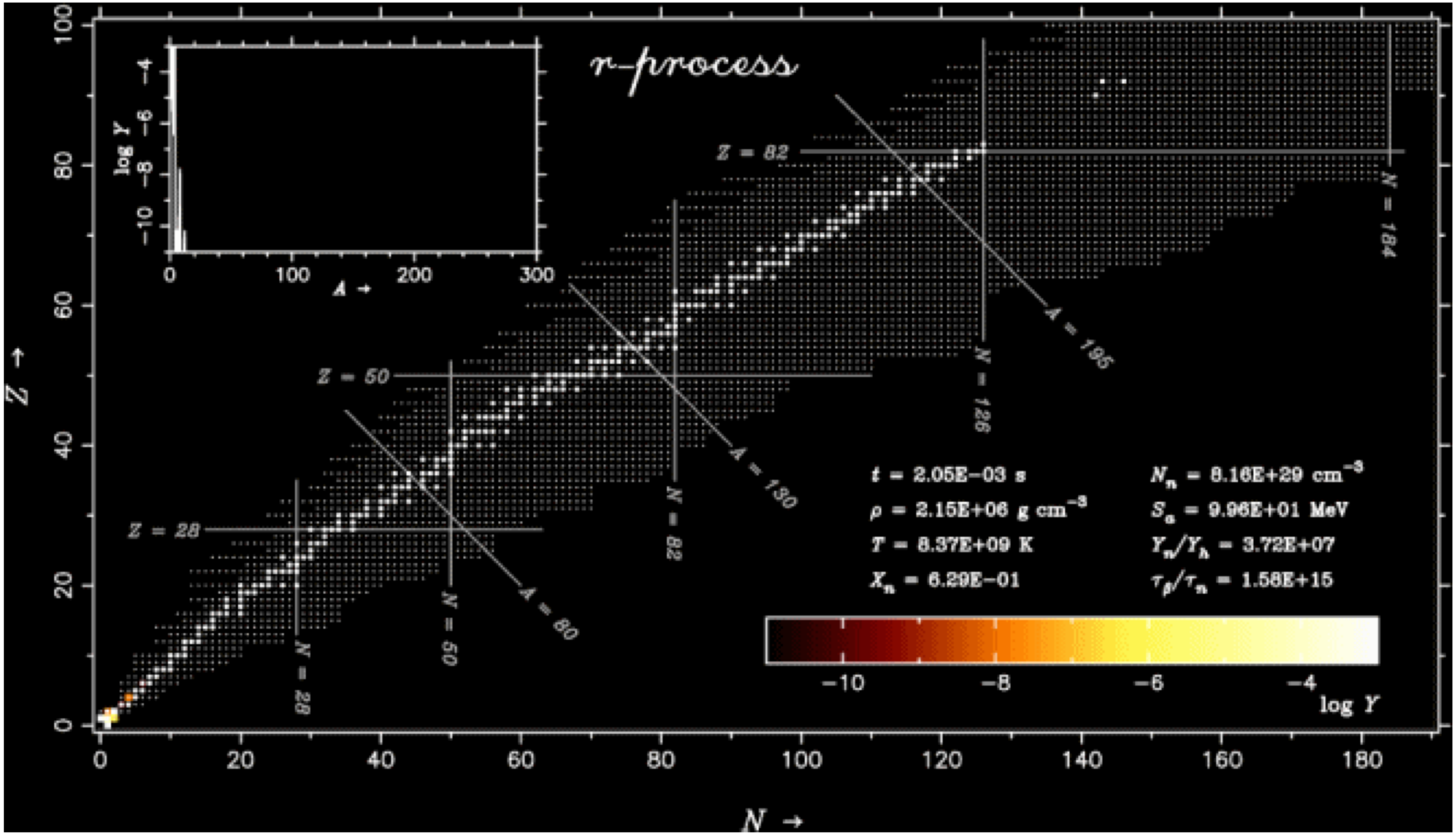
The s-process terminates at ^{209}Bi, when there are no more stable nuclei to capture neutrons



The *r-process* is the based on the idea that neutron density is high, and neutron captures are faster than beta decay



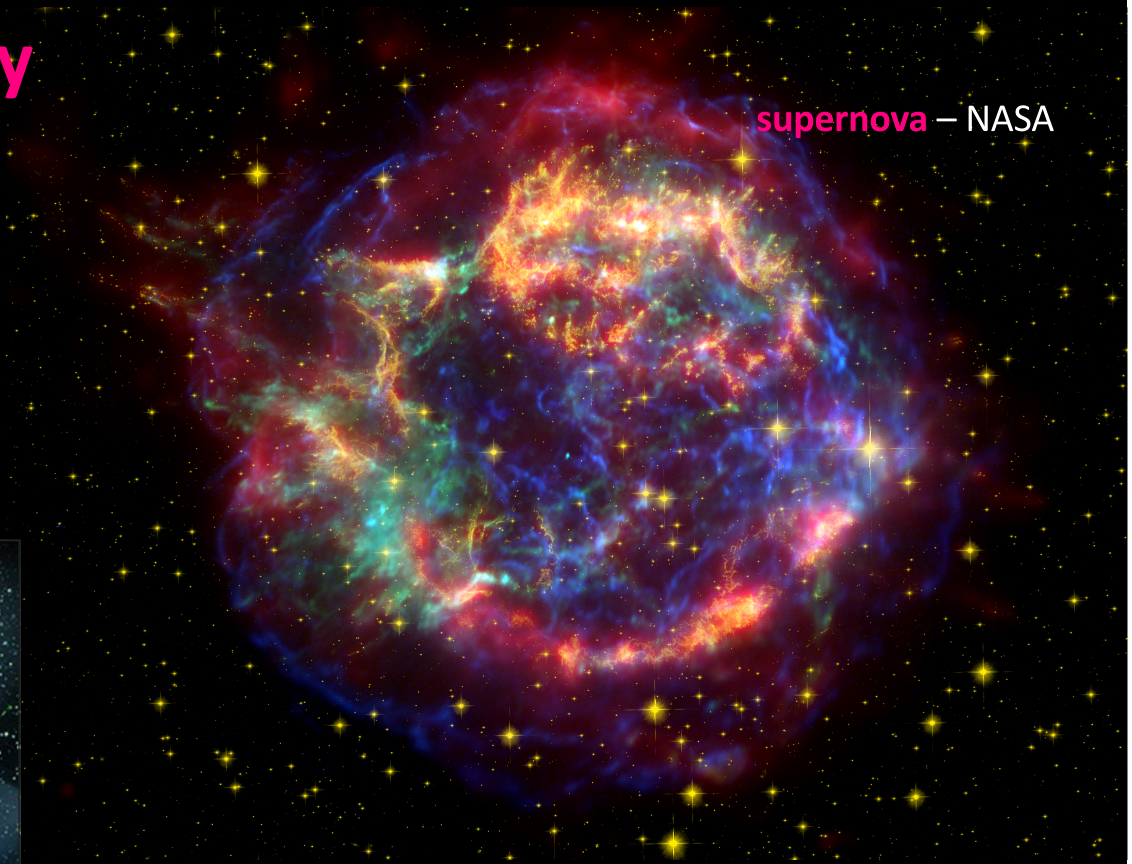
what goes into the animation are cross-sections, lifetimes, and fluxes



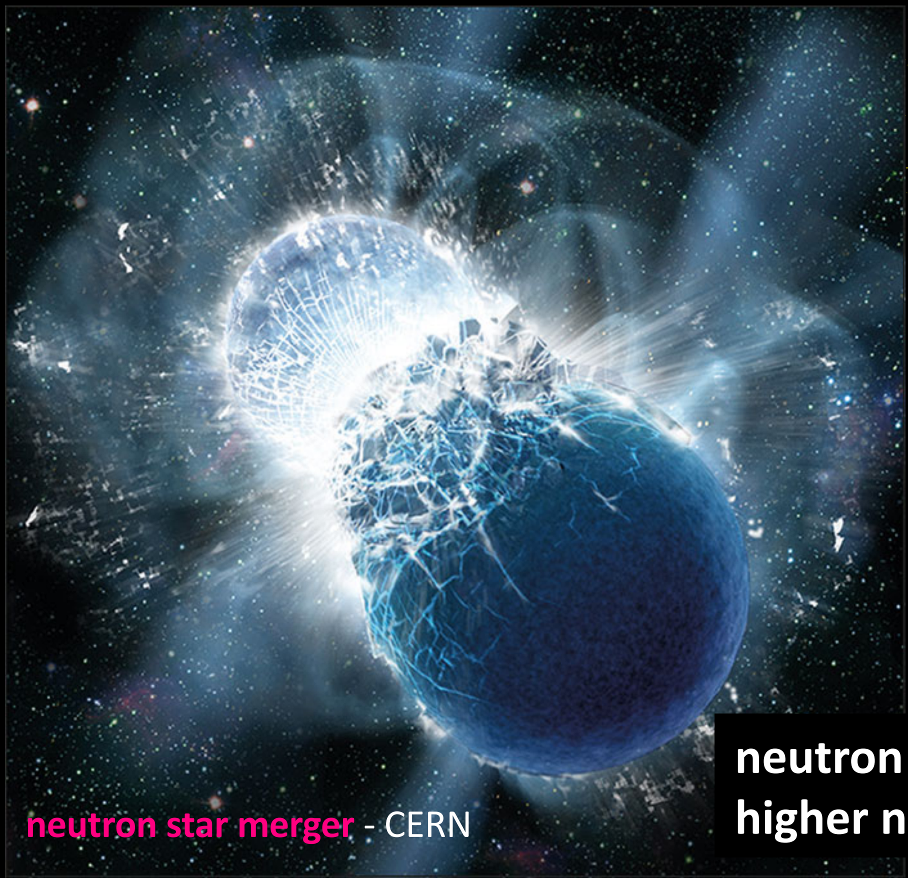
the elemental abundance a simulation gives can be compared to the experimental one

The r-process must happen in an environment with a very high neutron density

free neutrons beta decay with an average lifetime of 15 minutes

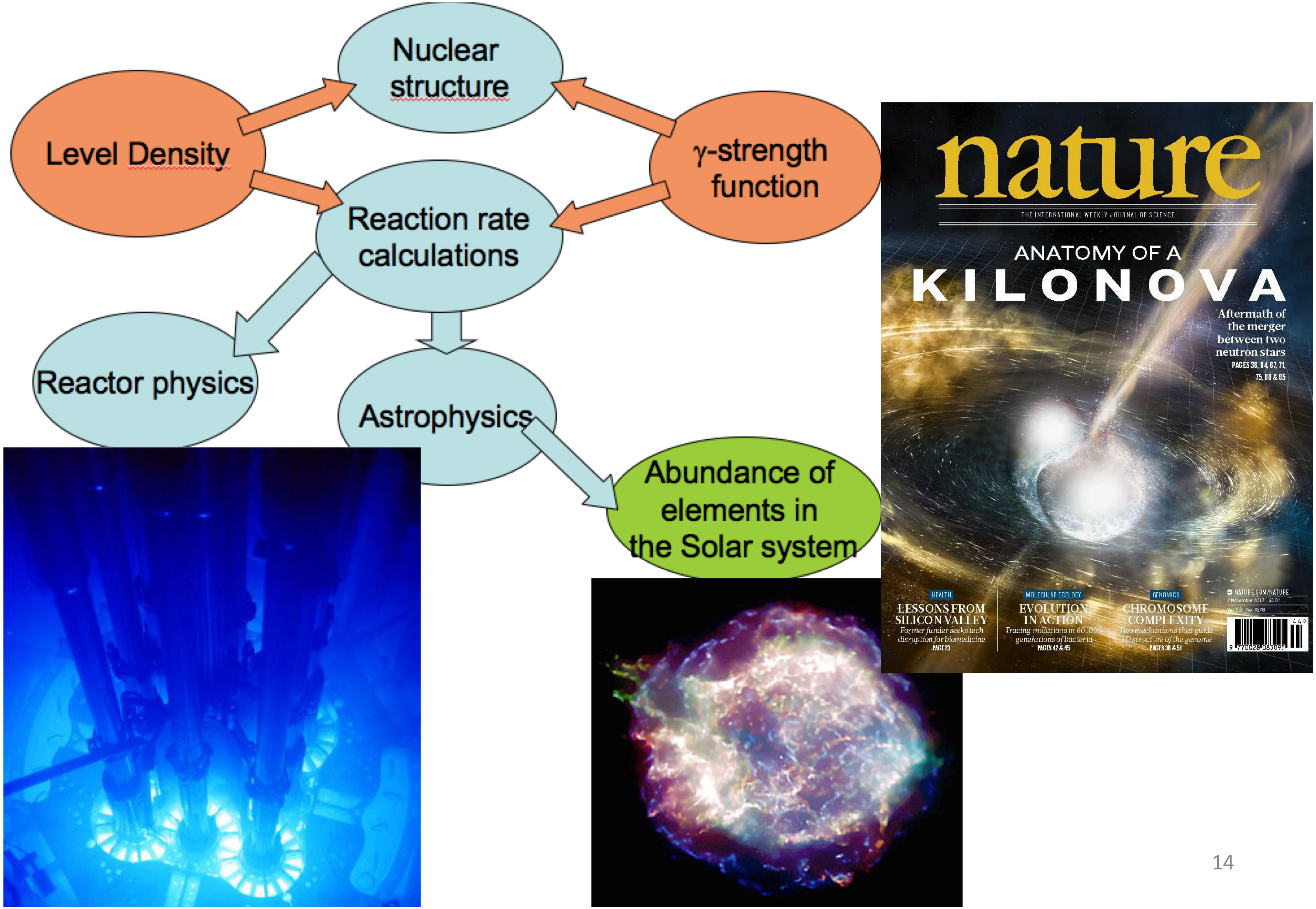


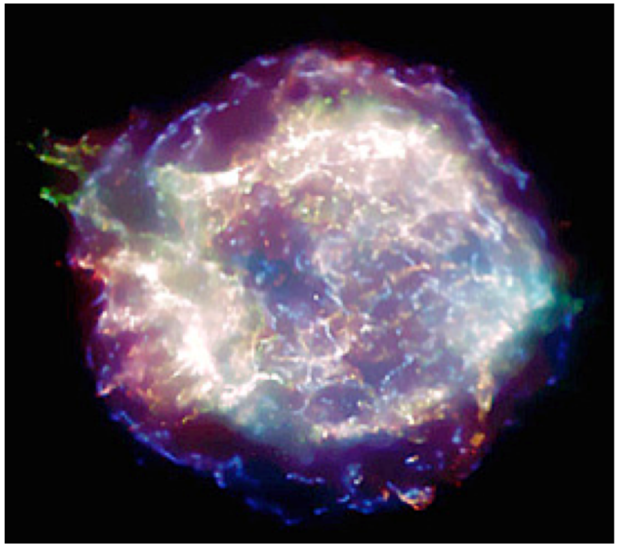
supernovae were thought to be the prime production site of the r-process

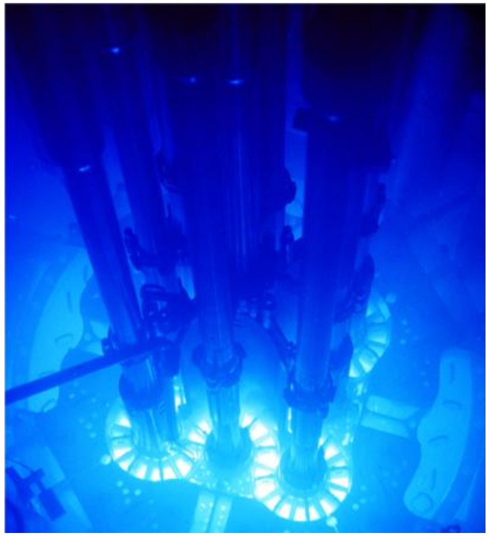


neutron star mergers have a higher neutron density

How can we contribute?







What we can measure in Oslo:

- Nuclear Level densities
- gamma strength functions

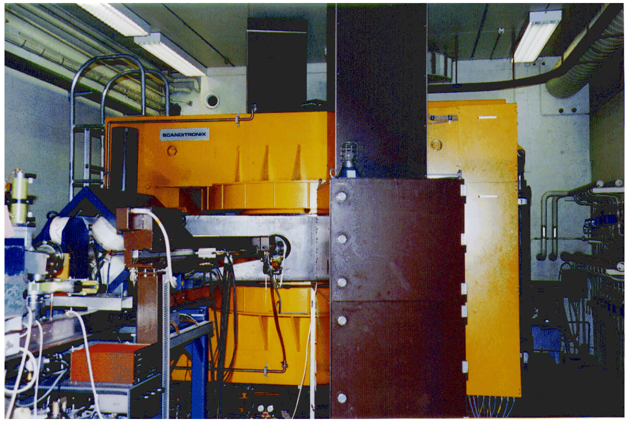
Which are:

- Fundamental nuclear properties -> information on pairing, shell structure, temperature, collective effects…
- inputs in cross section calculations, needed for reactor simulations and nucleosynthesis of elements in stars.
- Can help improve models of Nuclear level densities and gamma strength functions -> needed for exotic nuclei which can´t be measured

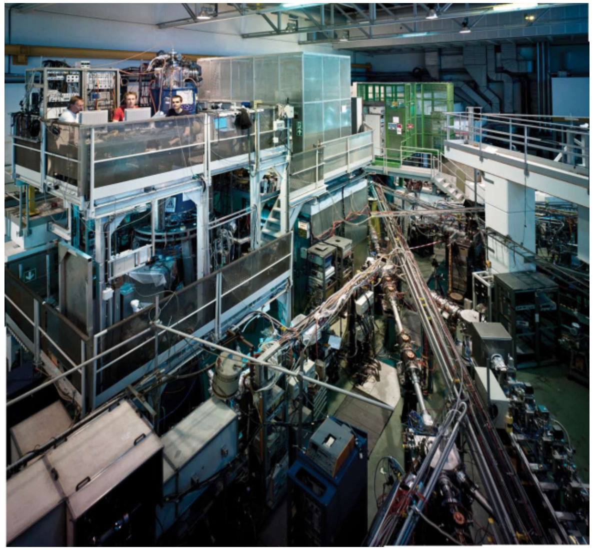
➢ Not all cross sections can be measured directly
➢ Simulations not better than the input data

Complementary techniques

stable ion beams: OCL,
Berkeley (US), Orsay (France),
iThemba (South Africa)



radioactive ion beams:
ISOLDE (CERN), MSU (USA),
GANIL (France), RIKEN (Japan)



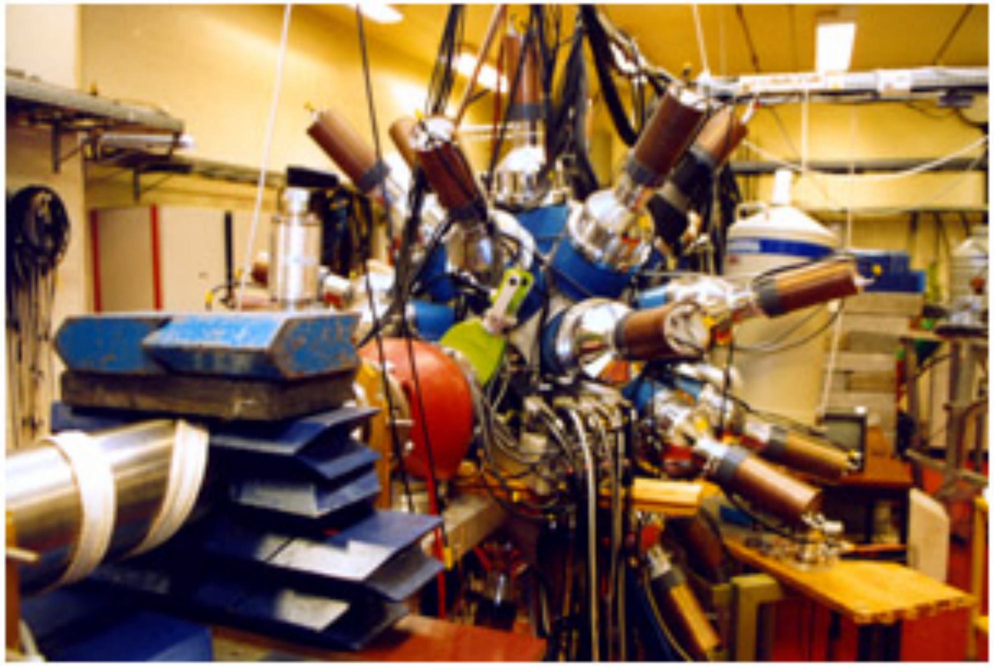
Photon beams: SPRING-8 (Japan)
Future: ELI-NP (Bucharest)

Experimental setup @ OCL

- Beam: p, d, 3He, α with energies up to 30-45 MeV

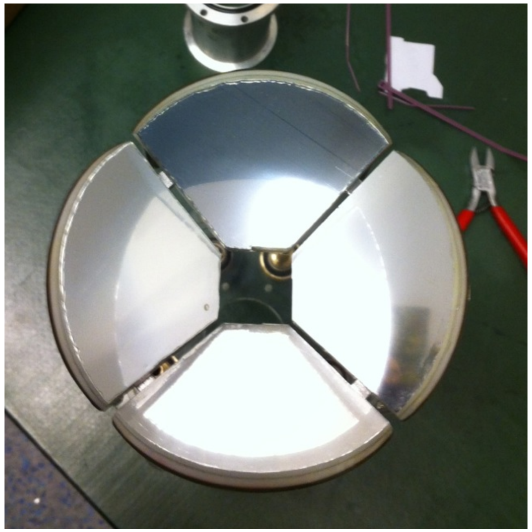
- Reactions: (^{3}He,$\alpha\gamma$), (^{3}He,^{3}He'γ), (p,p´γ), (d,pγ), (p,tγ) ++

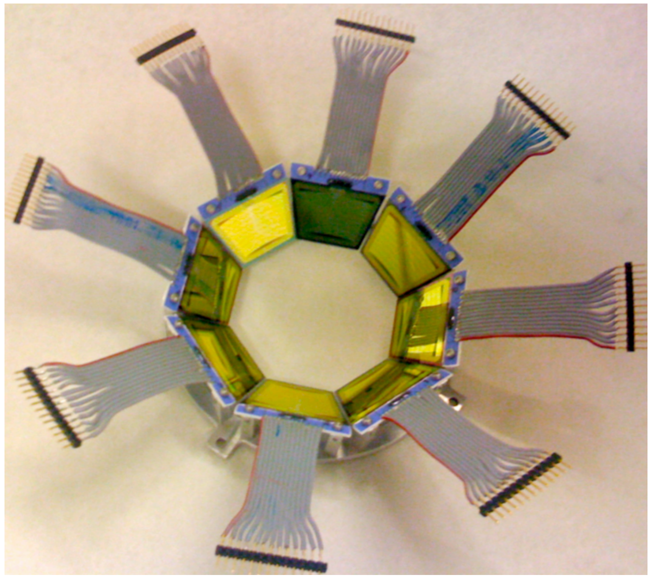
- CACTUS: 28 5" x 5" NaI(Tl), $\varepsilon \approx 15\%$ @ E_γ=1.33 MeV



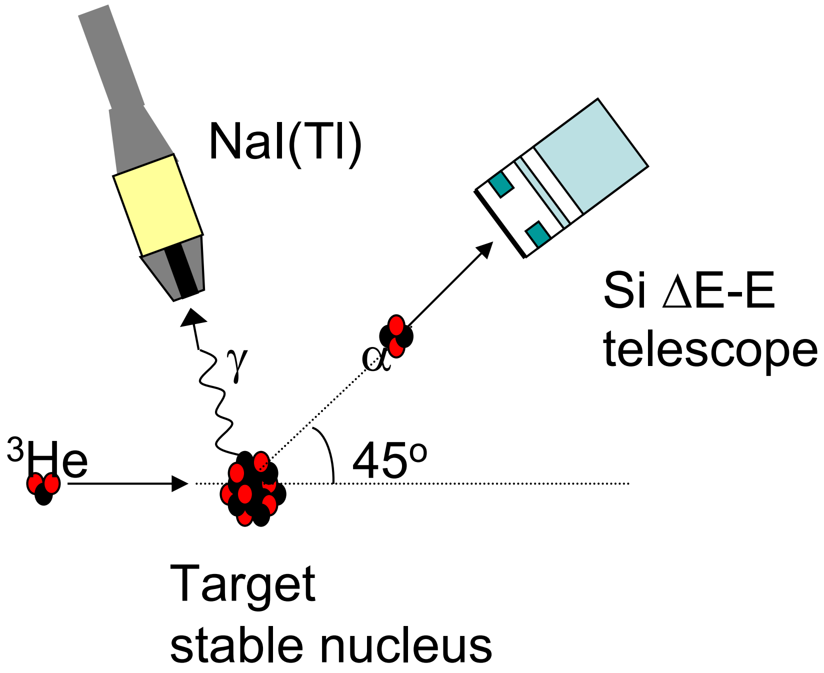
- SiRi: 64 Si ΔE-E particle telescopes, $\Delta\theta \approx 2^o$

- PPAC fission detector called NIFF

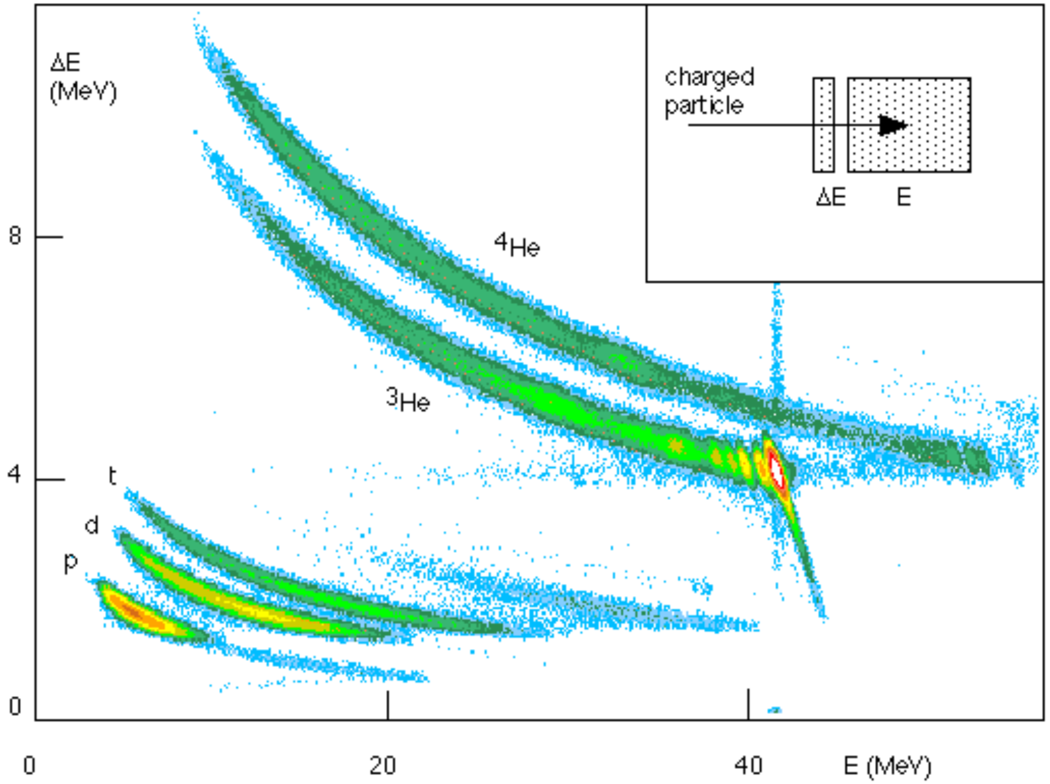




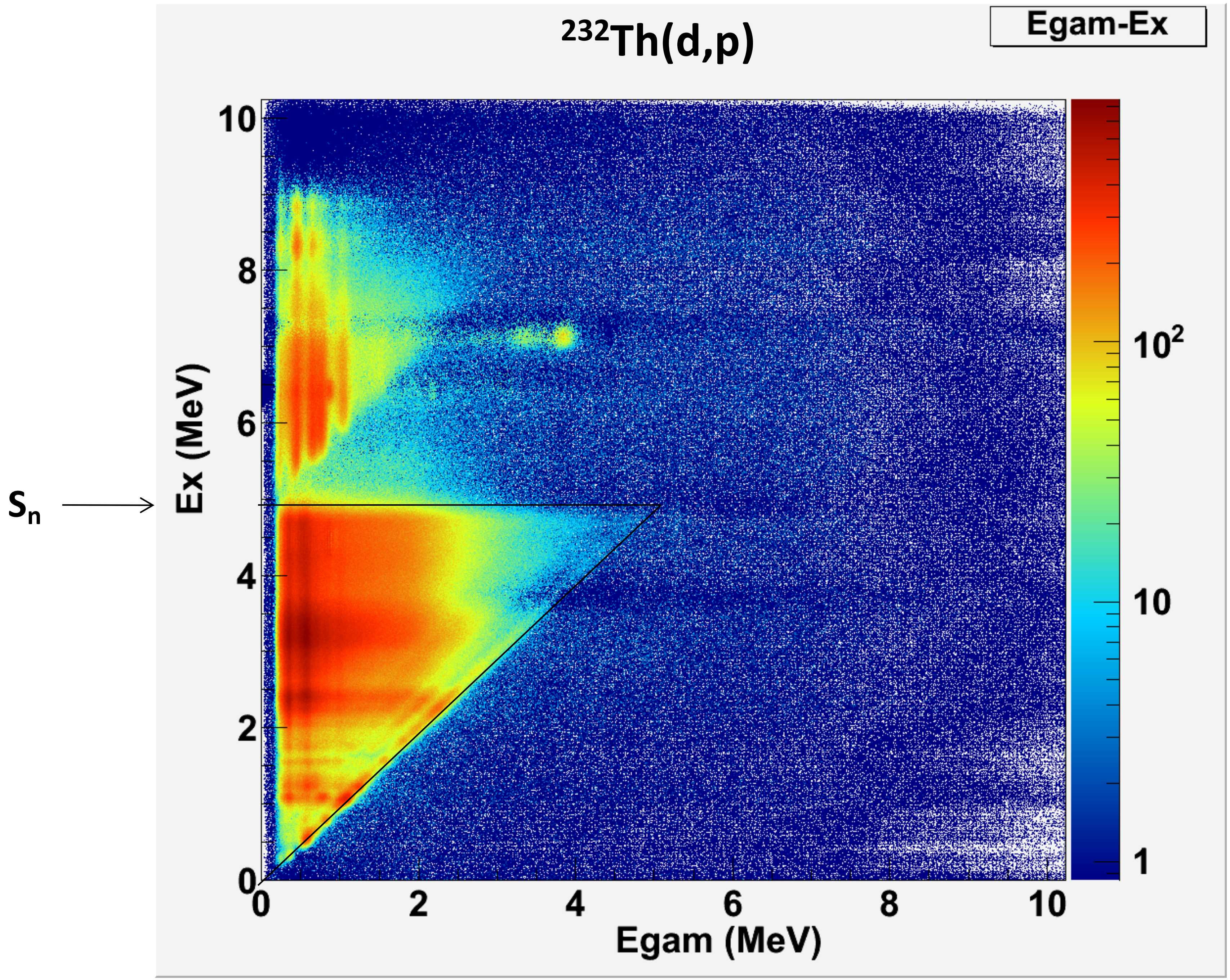
OCL
Oslo Cyclotron Laboratory



Particle identification,
Typical ΔE-E bananas:

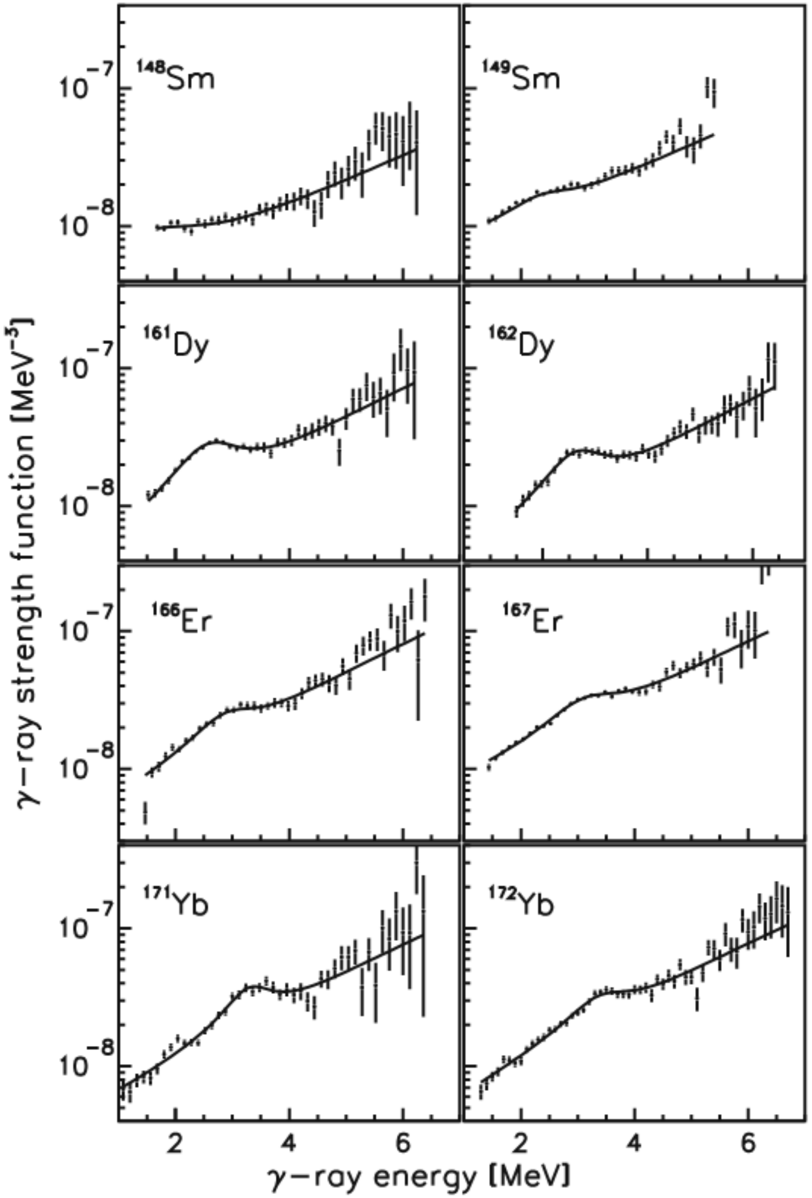


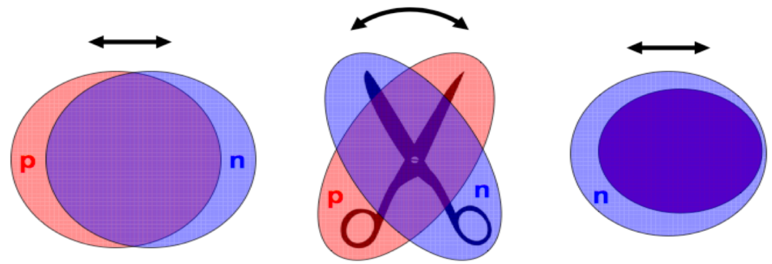
Particle gamma coincidences

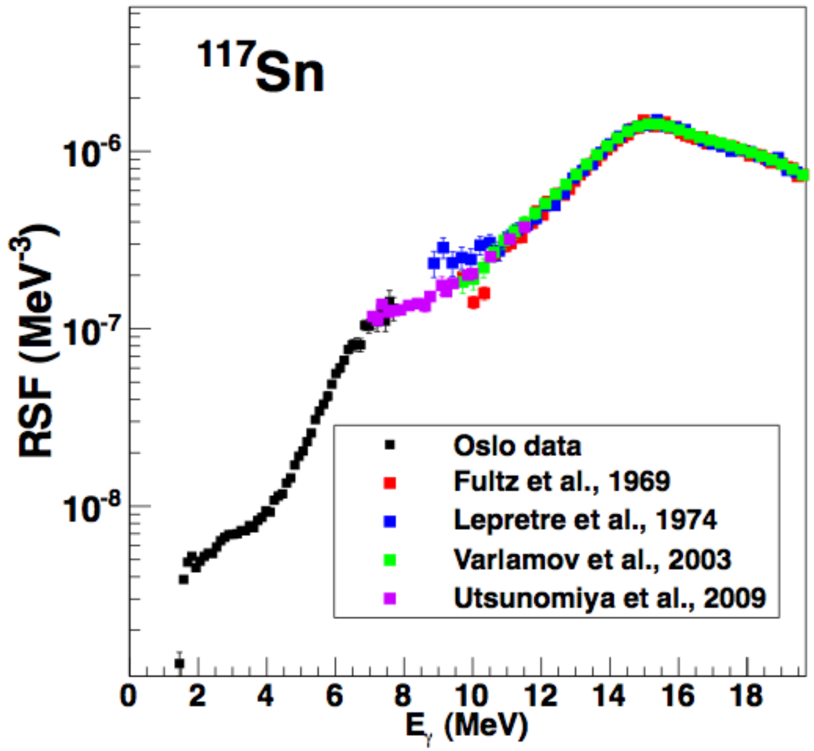


^{232}Th(d,p)
Egam-Ex
Ex (MeV)
Egam (MeV)
S_n
0
2
4
6
8
10
1
10
10^2

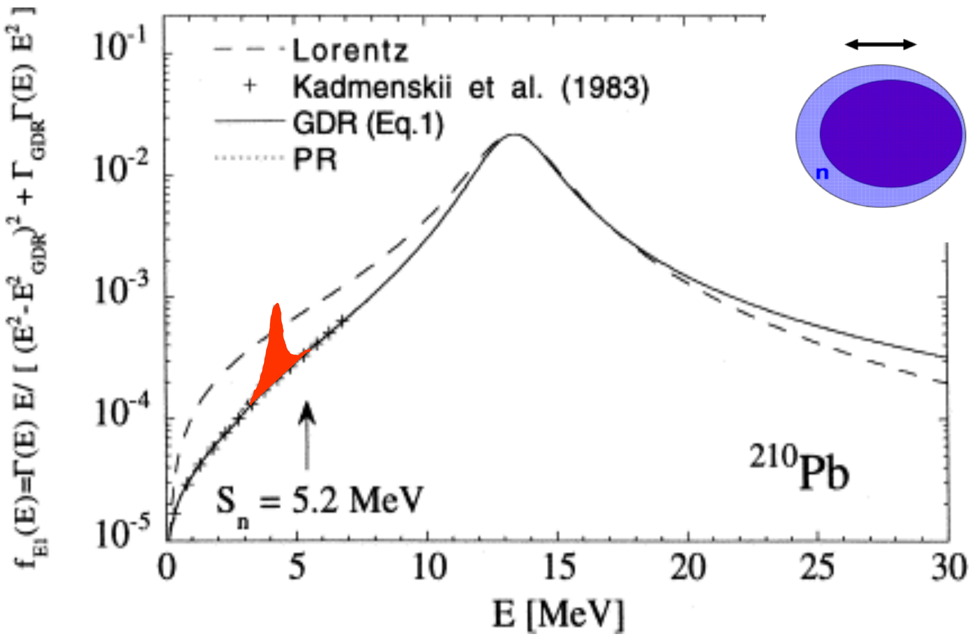
Small resonances on the tail of the Giant Dipole Resonance



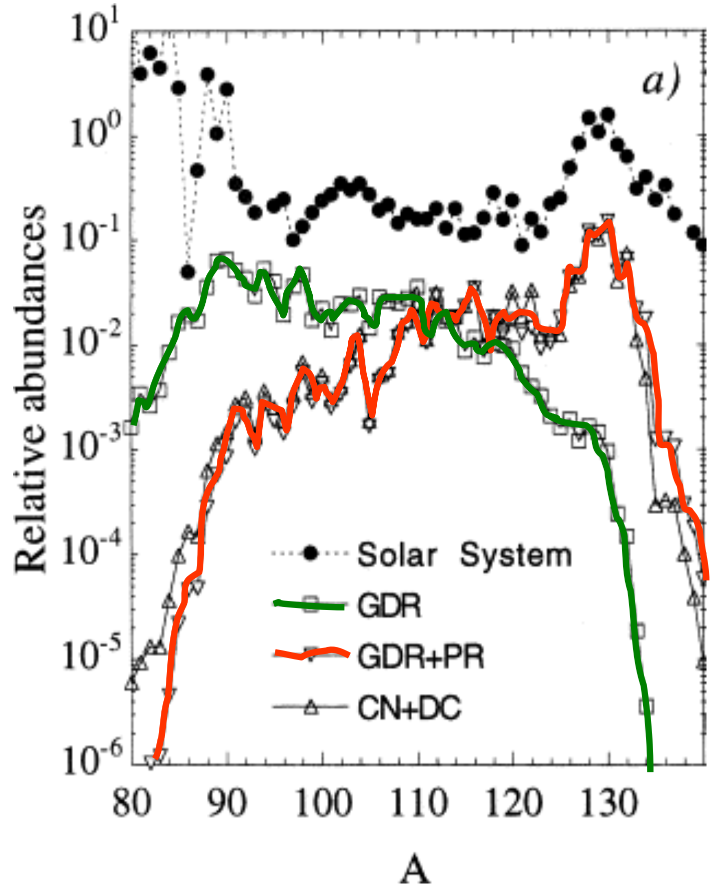


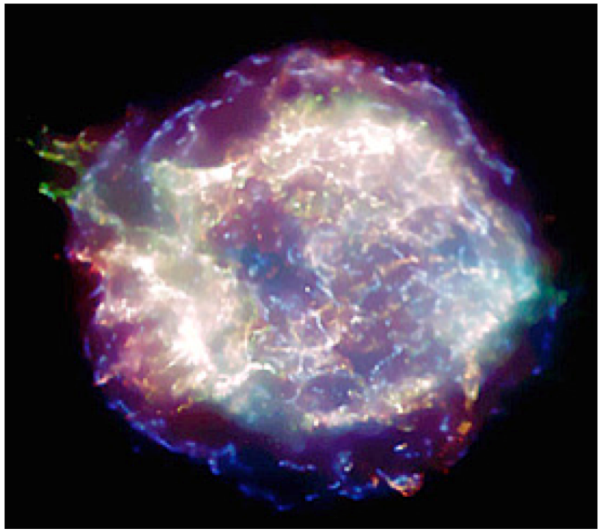


[Utsunomiya et al., PRC 80, 055806 (2009); Agvaanluvsan et al, PRL 102, 162504 (2009)]



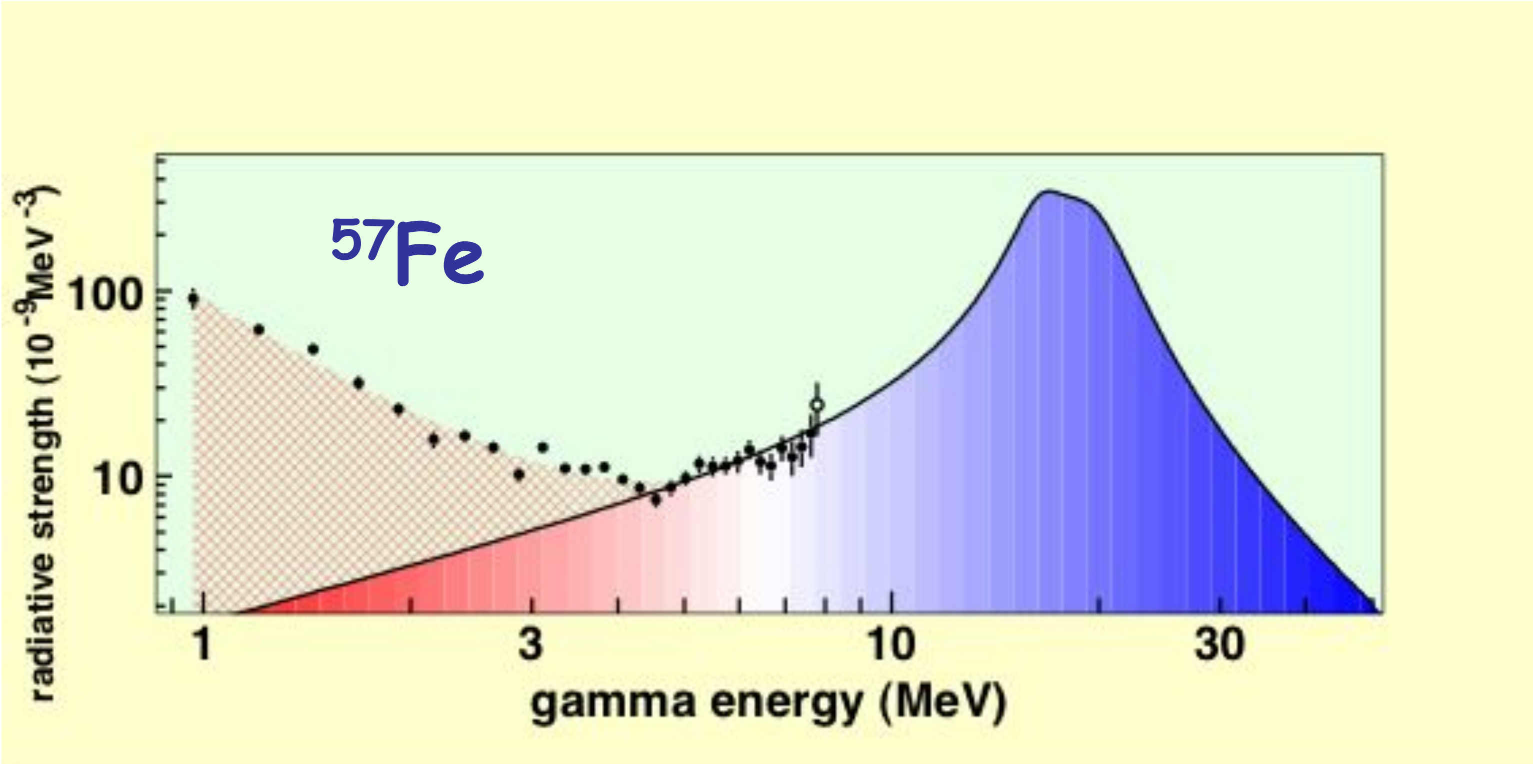
S. Goriely Phys. Lett. B 436 (1998)





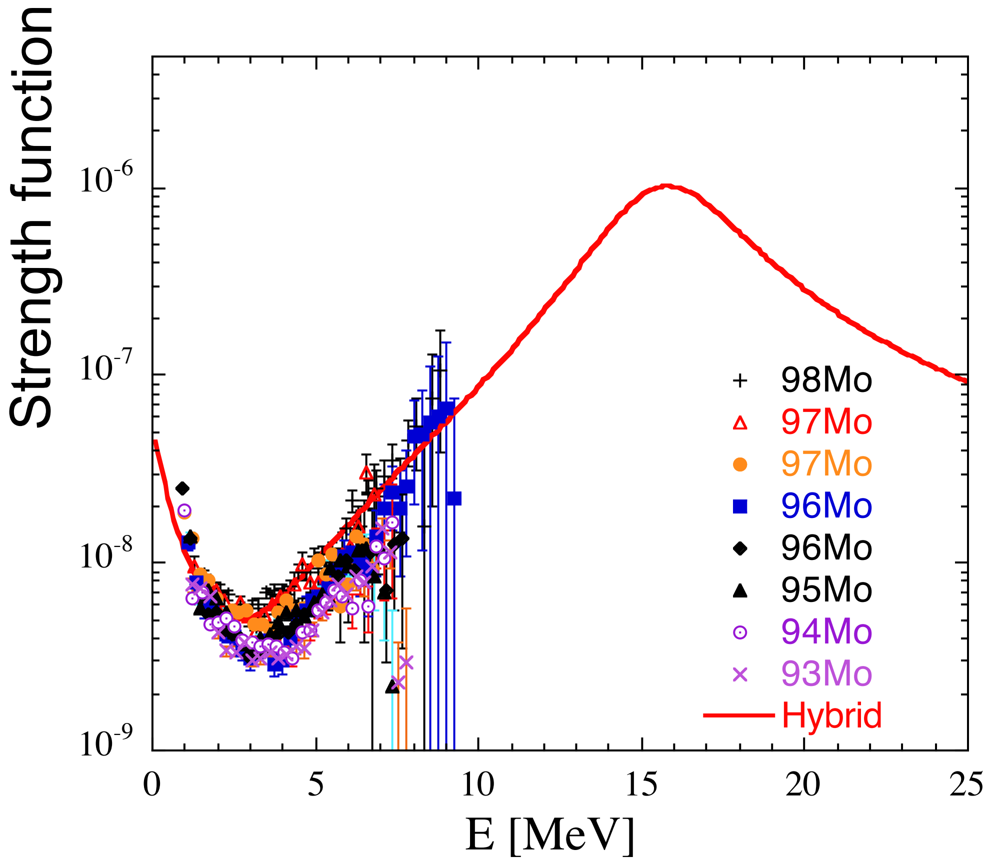
small resonances can have a big effect on abundances…

Low energy enhancement of the gamma strength function

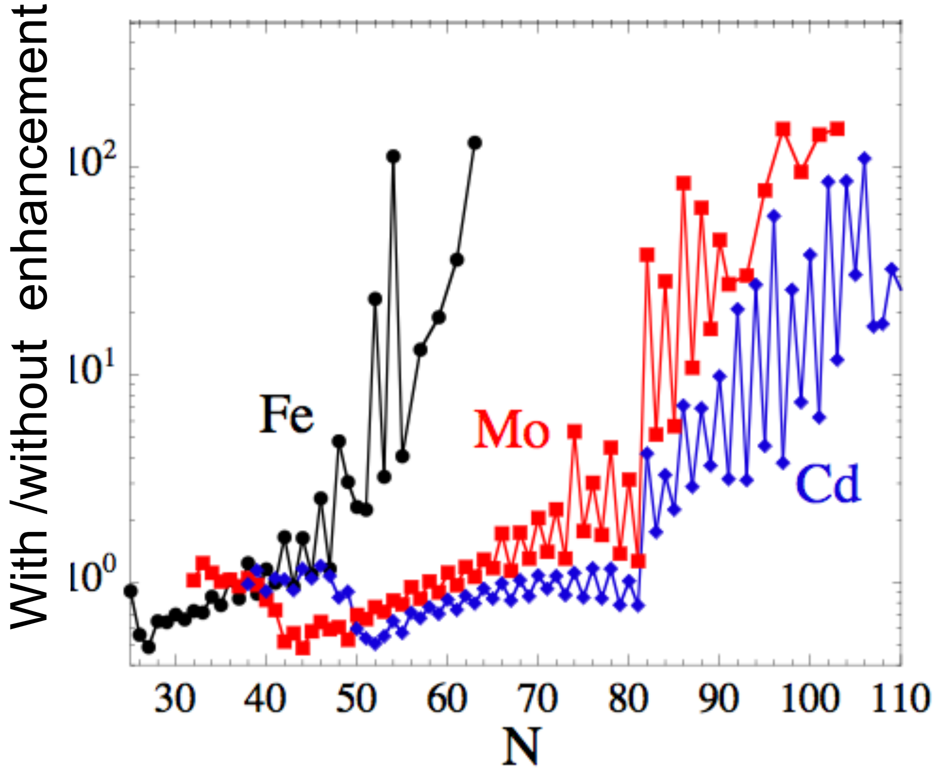


A.Voinov et al. Phys.Rev.Lett. 93, 142504 (2004)

How does this enhancement affect neutron capture cross sections?
-> Motivation to study n-rich nuclei



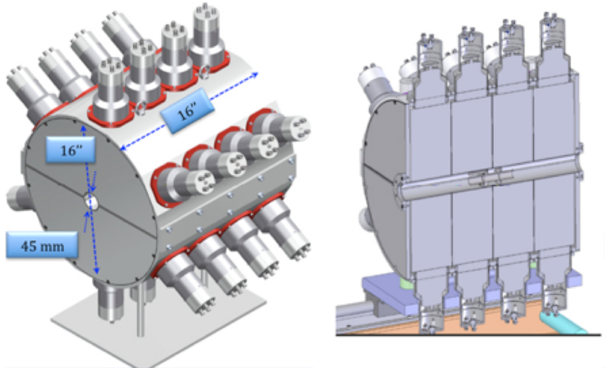
Assuming the strength functions of Mo isotopes all have the same energy trend



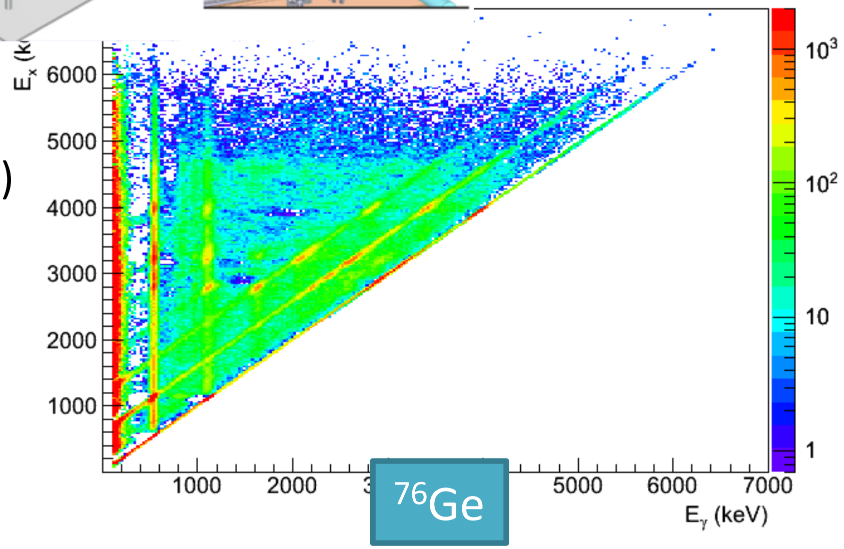
A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

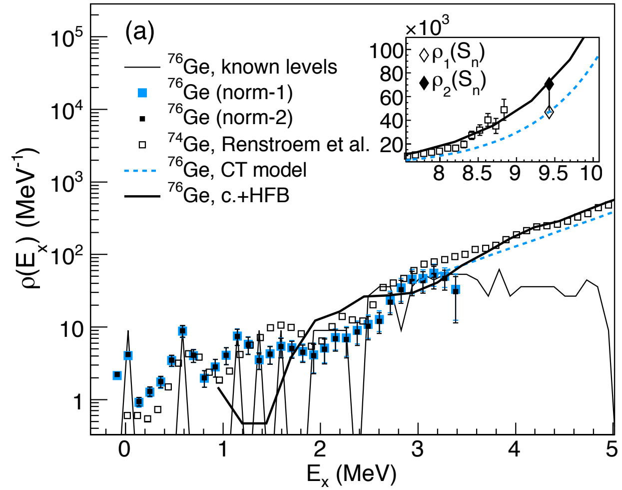
β-Oslo: new technique for neutron-rich nuclei

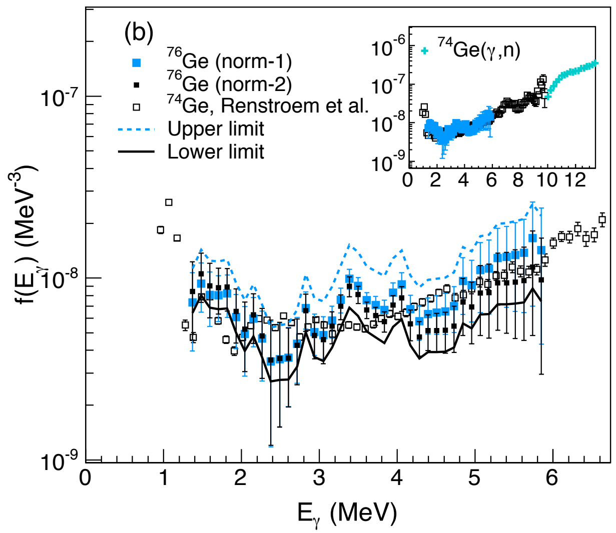
Total absorption spectrometer SuN (segmented NaI) @ NSCL/MSU
[A. Simon, S. Quinn, A. Spyrou *et al.*, NIM A **703,** 16 (2013)]



β-decay of ^{76}Ga
(≈500 pps, $T_{1/2}$=32.6s)
– measuring γ-decay of ^{76}Ge

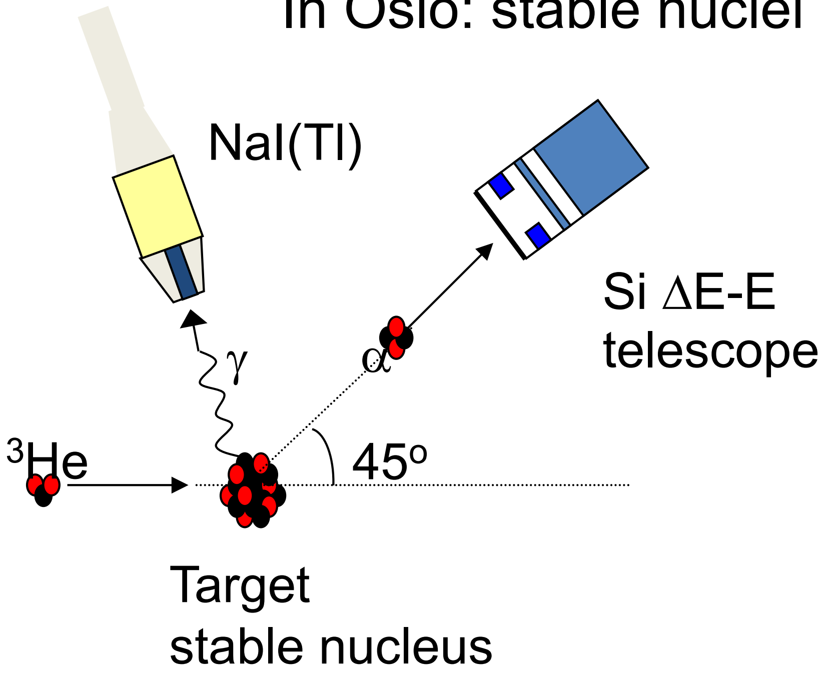




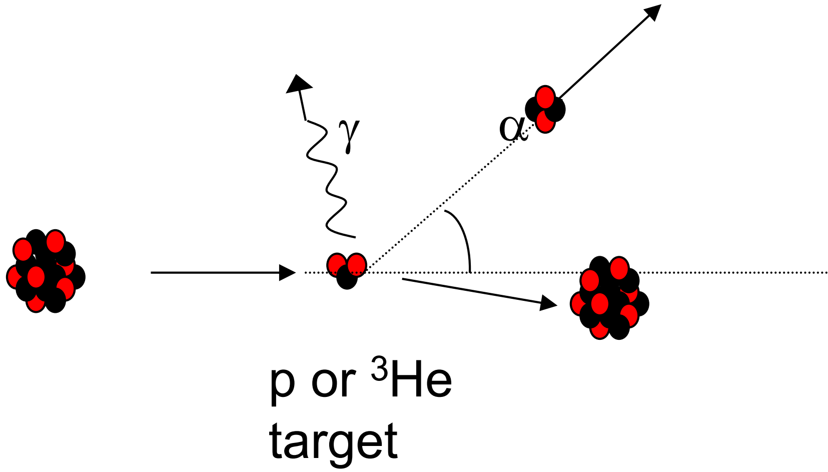


[A. Spyrou, S.N. Liddick, A.C. Larsen *et al., Phys. Rev. Lett 113, 232502* (2014)]

In Oslo: stable nuclei



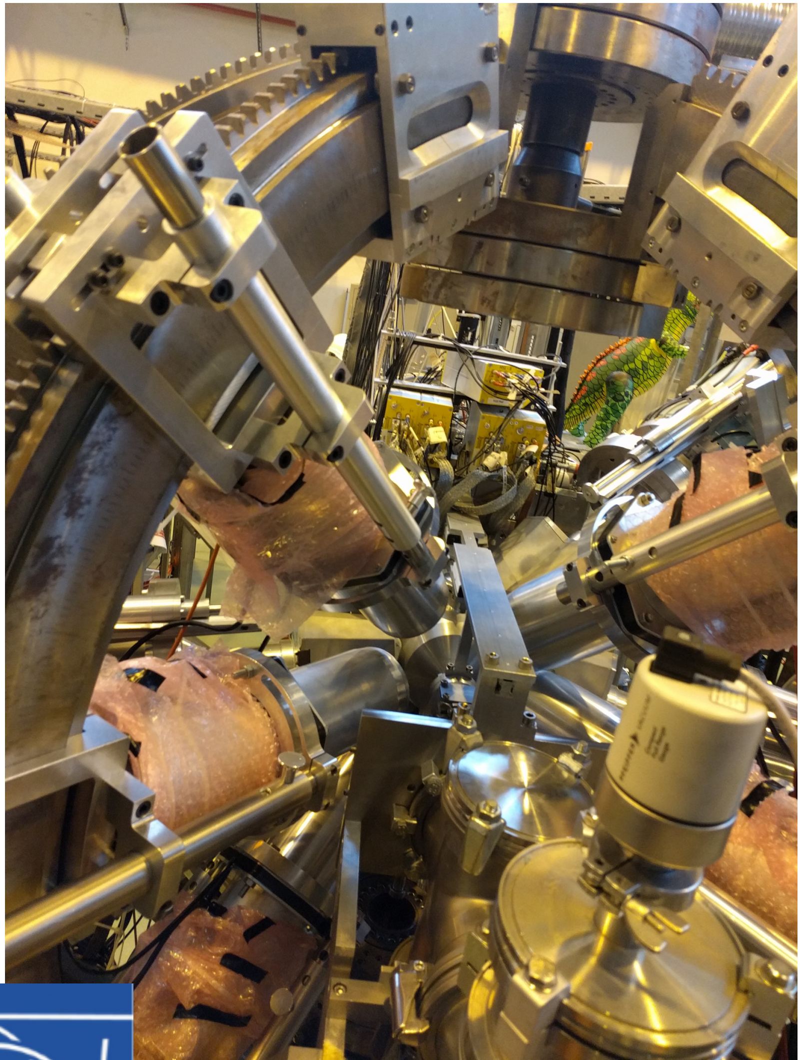
Exotic beams, using inverse kinematics



Oslo Method well established for normal kinematics,
Performed a proof of principle experiment in inverse kinematics
With stable beam at iThemba -> it works!

Next step using radioactive beams from ISOLDE

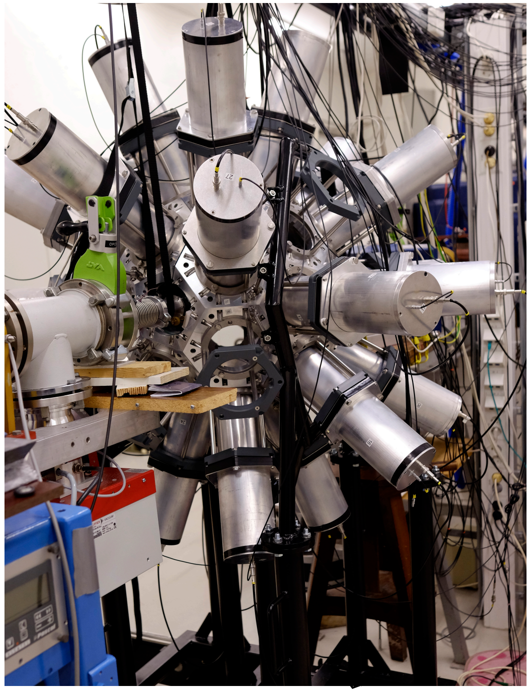
A very successful experiment at ISOLDE November 2016
Collaboration UiO and iThemba LABS South Africa



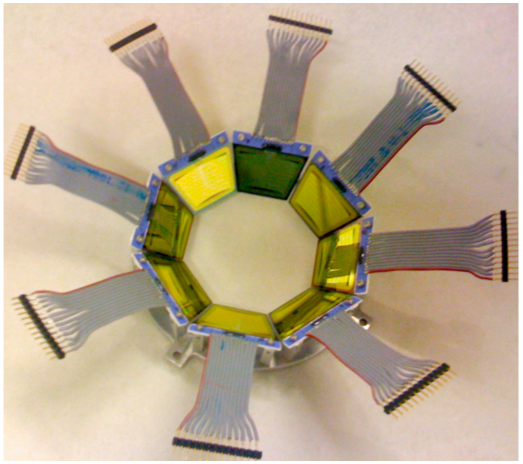
CERN

ISOLDE

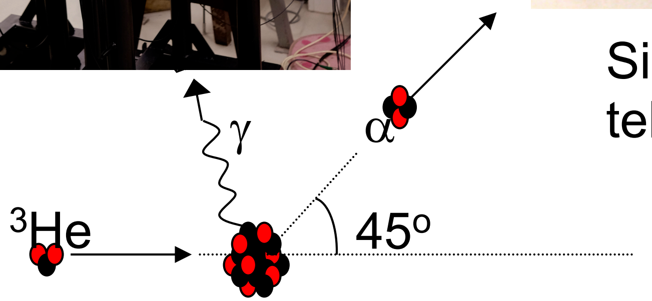
Neutron capture rates of La isotopes



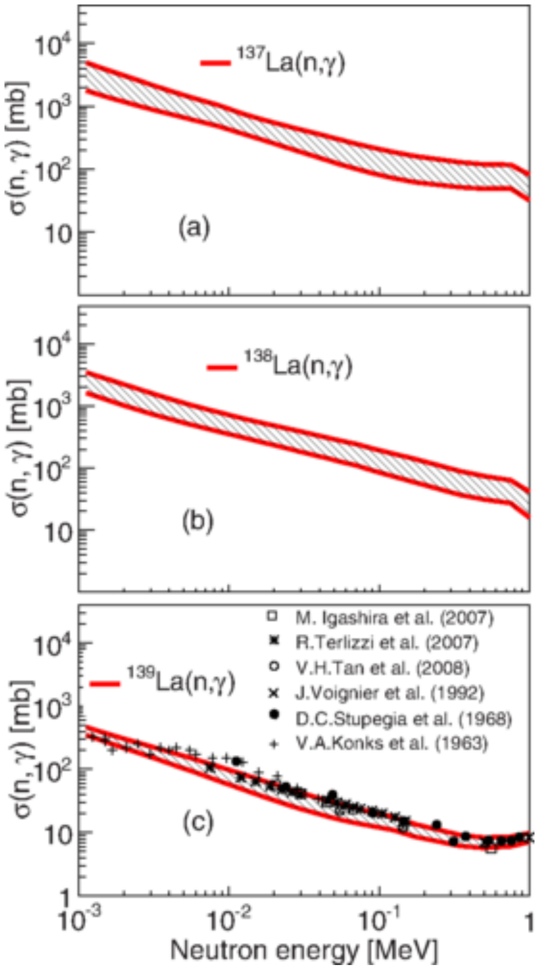
OSCAR



Si ΔE-E telescope



Target nucleus

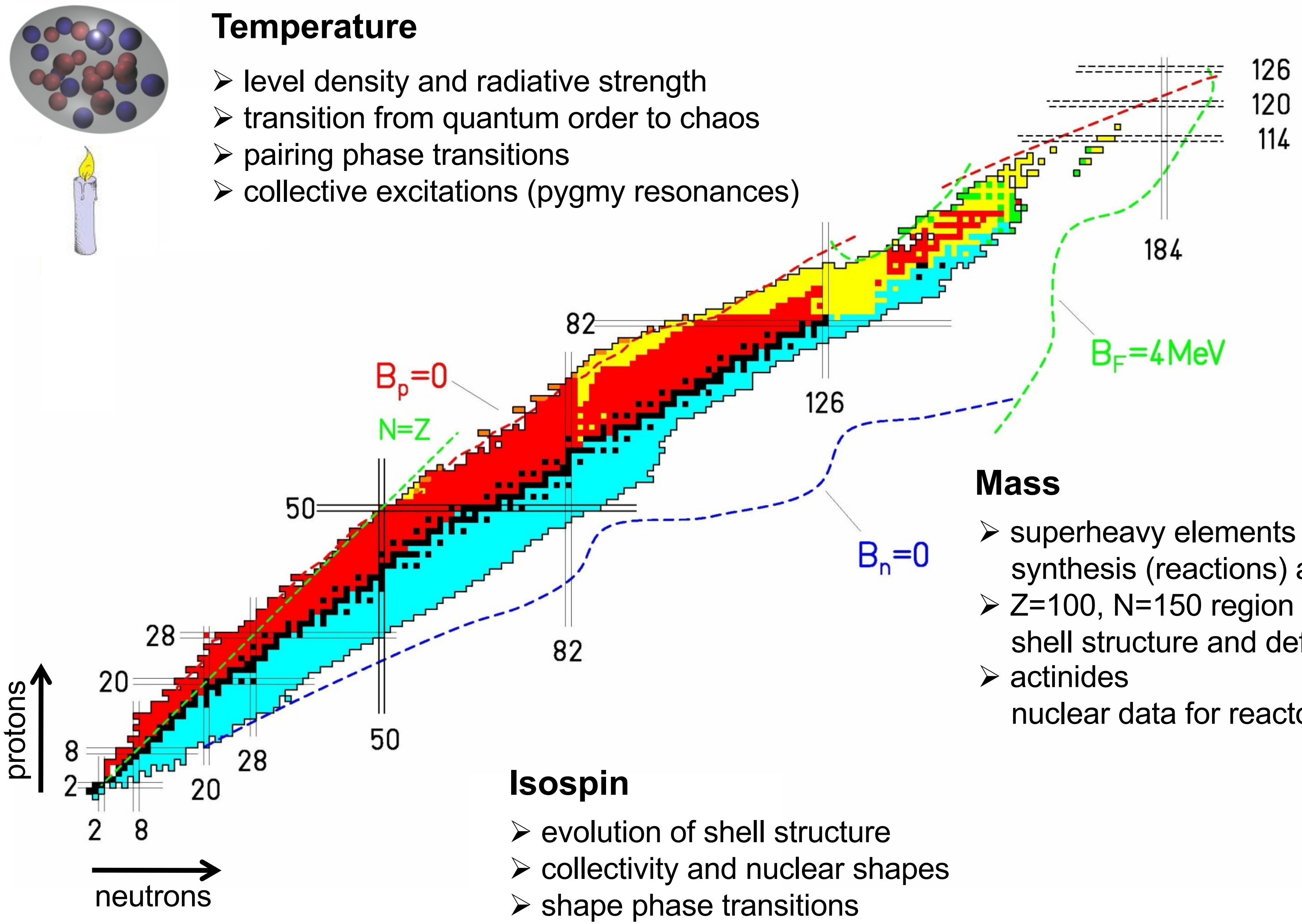


B.V. Kheswa et al., Phys. Lett. B 744, 268 (2015)
B.V. Kheswa et al., Phys. Rev. C 95, 045805 (2017)

Atomic nuclei under extreme conditions

Temperature

- level density and radiative strength
- transition from quantum order to chaos
- pairing phase transitions
- collective excitations (pygmy resonances)

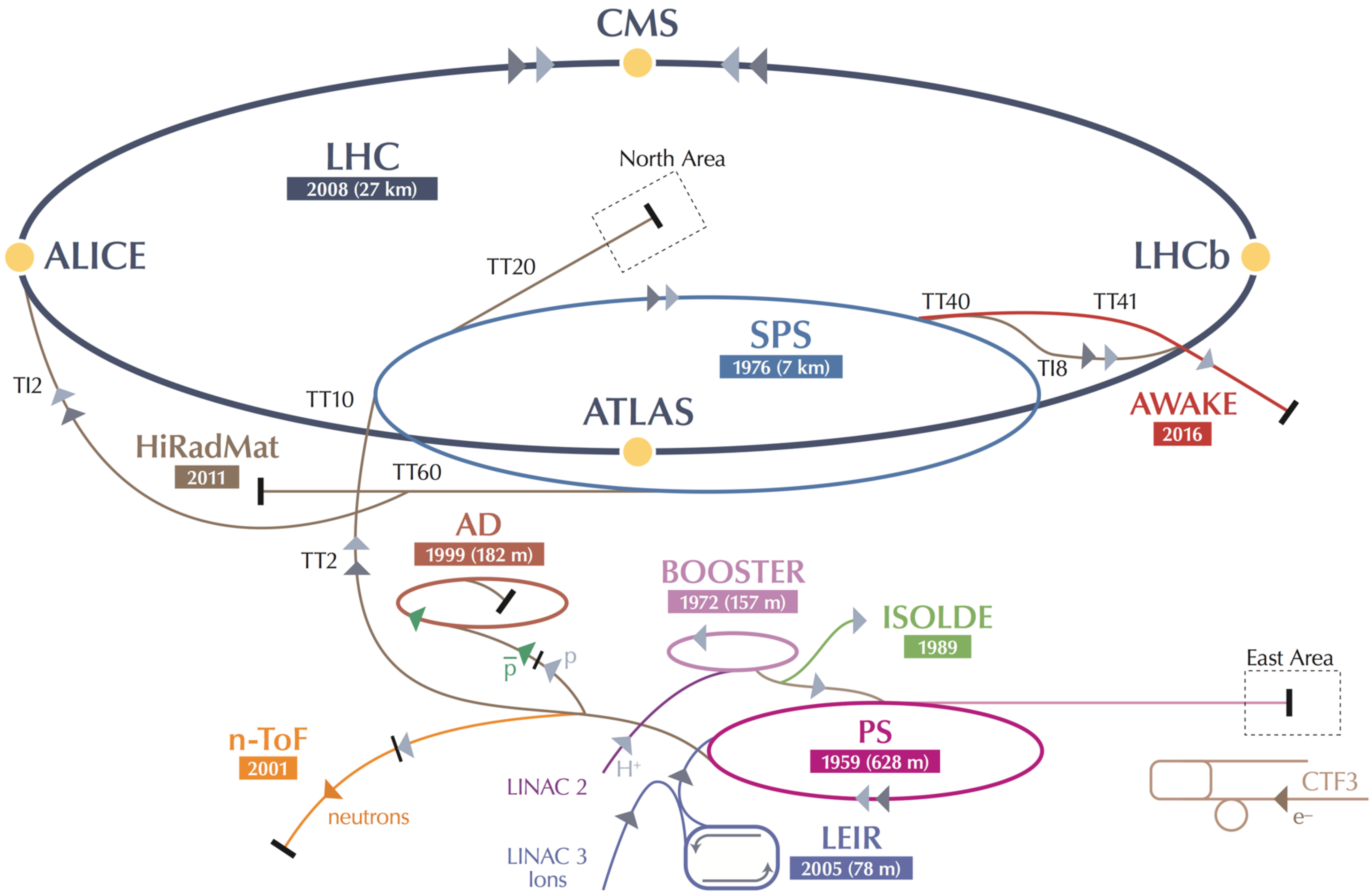


Mass

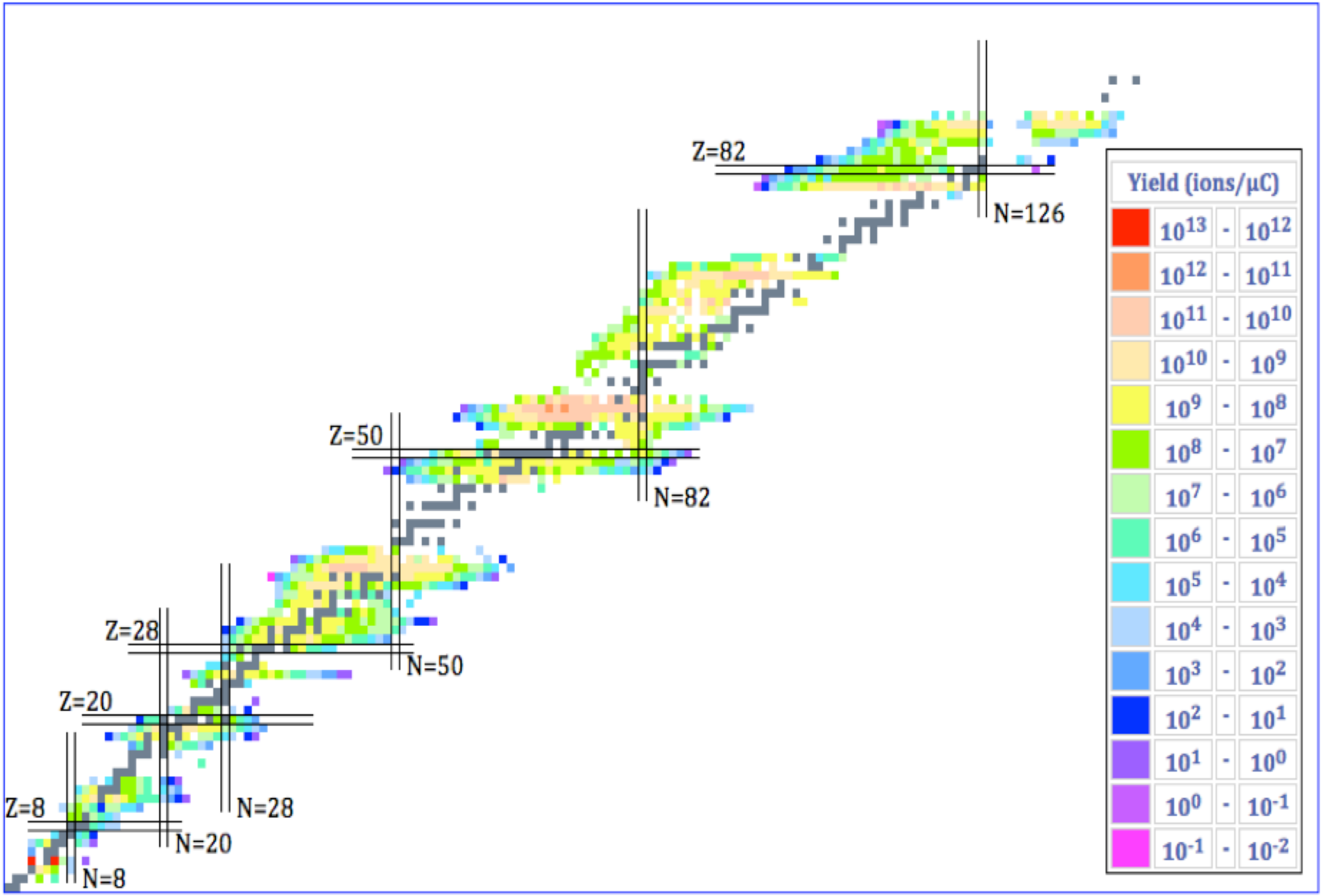
- superheavy elements
  synthesis (reactions) and chemistry
- Z=100, N=150 region
  shell structure and deformation
- actinides
  nuclear data for reactor physics

Isospin

- evolution of shell structure
- collectivity and nuclear shapes
- shape phase transitions
- nucleosynthesis / astrophysics


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
p̄
p
n-ToF
2001
H+
PS
1959 (628 m)
CTF3
e–
neutrons
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)

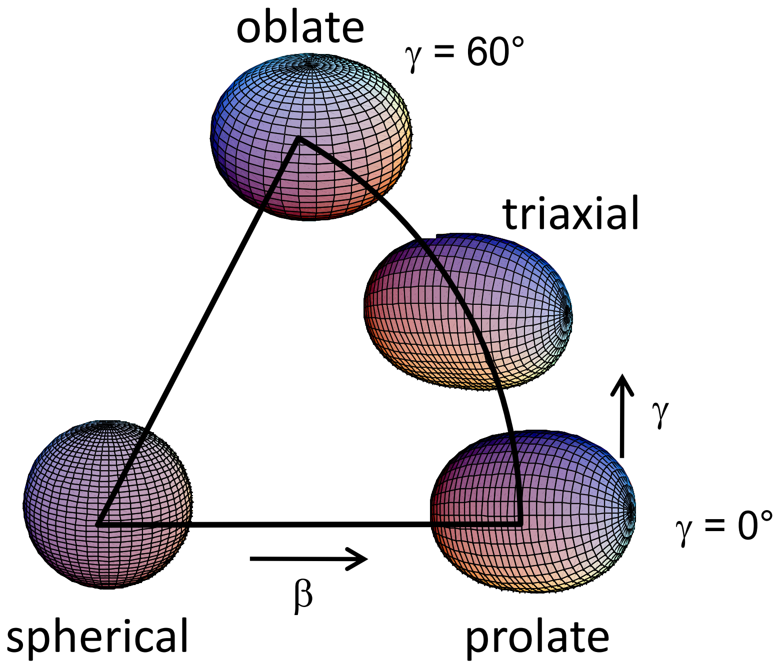
ISOLDE – The world's premier factory for designer nuclei



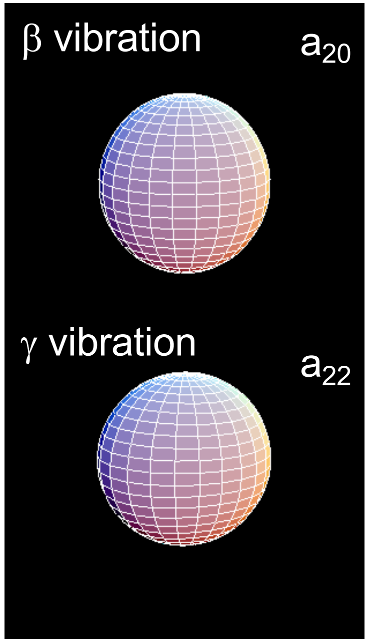
Nuclear deformation

liquid drop properties ⇔ shell effects

quadrupole shapes



quadrupole vibrations



higher-order deformation:
octupole shapes

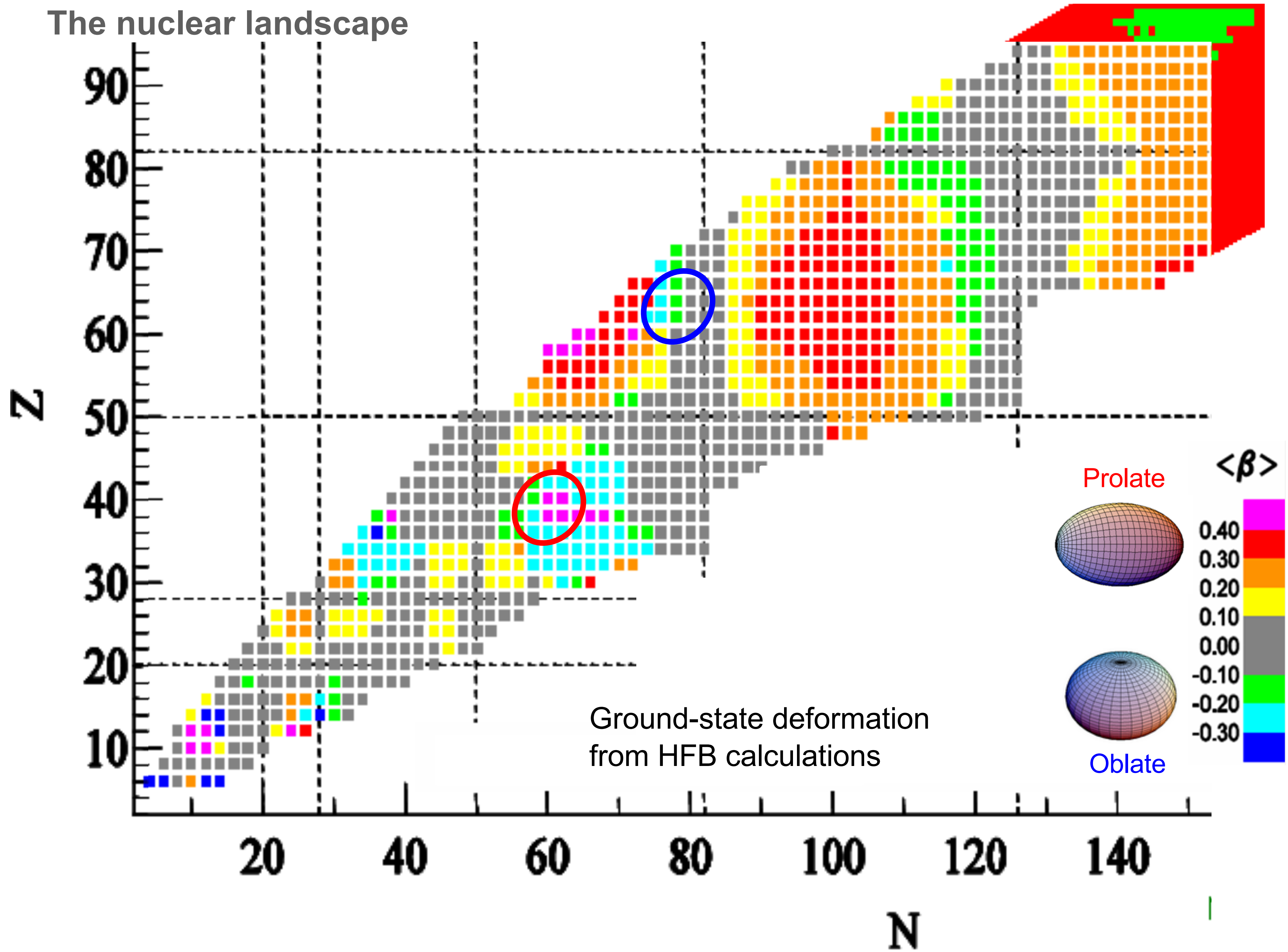
L.P. Gaffney et al.
Nature 497, 199 (2013)

^{220}Rn and ^{224}Ra
Coulomb excitation
at ISOLDE

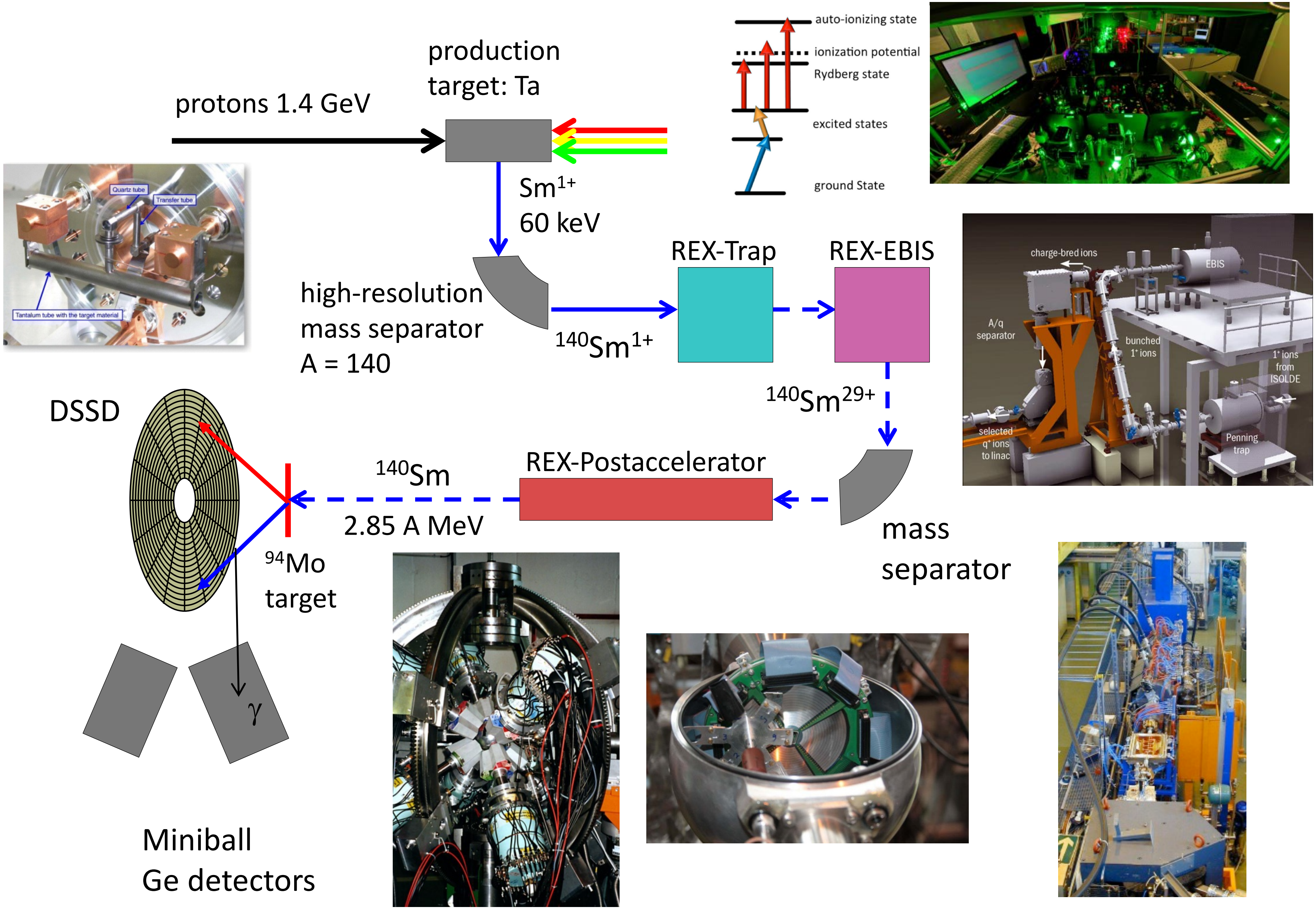
observables:

- charge distribution ⇒ electric quadrupole moment
- electromagnetic transition rates between quantum states

The nuclear landscape



Isotope separation on-line and postacceleration at ISOLDE

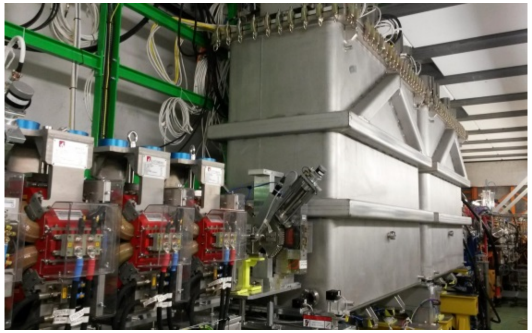


IS558: Multi-step Coulomb excitation of ^{140}Sm

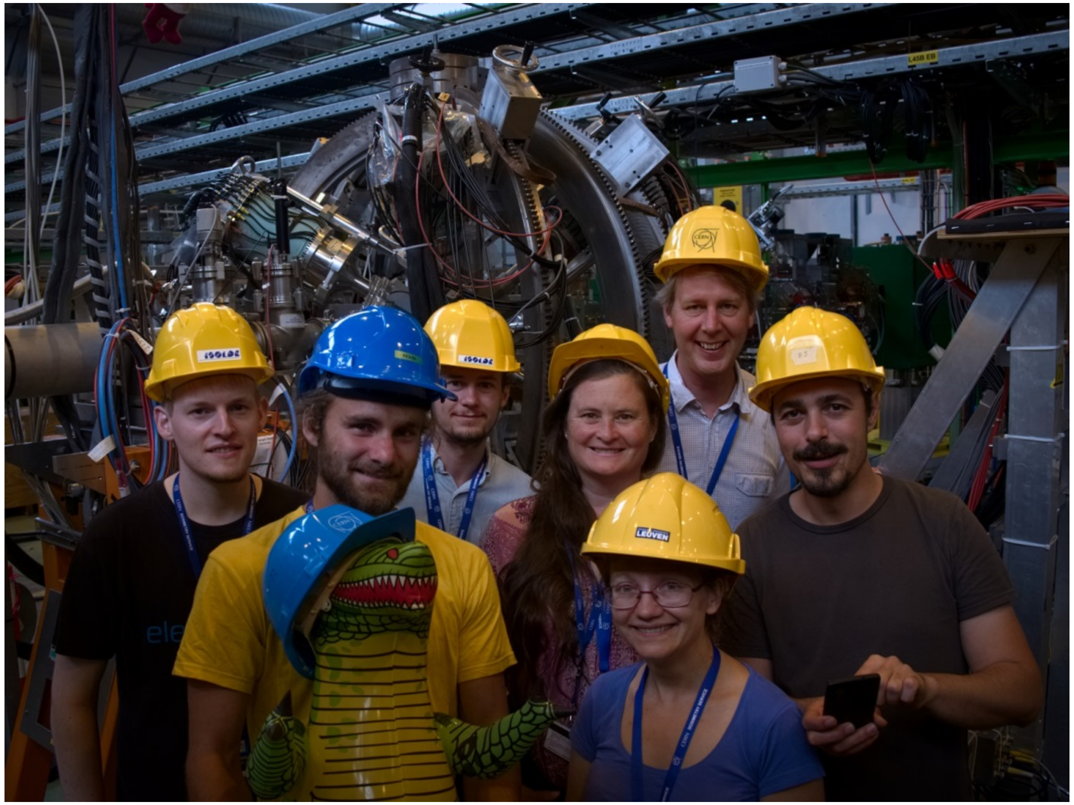
- study of nuclear shapes and shape coexistence
- benefitting from HIE-ISOLDE upgrade
- data for UiO student

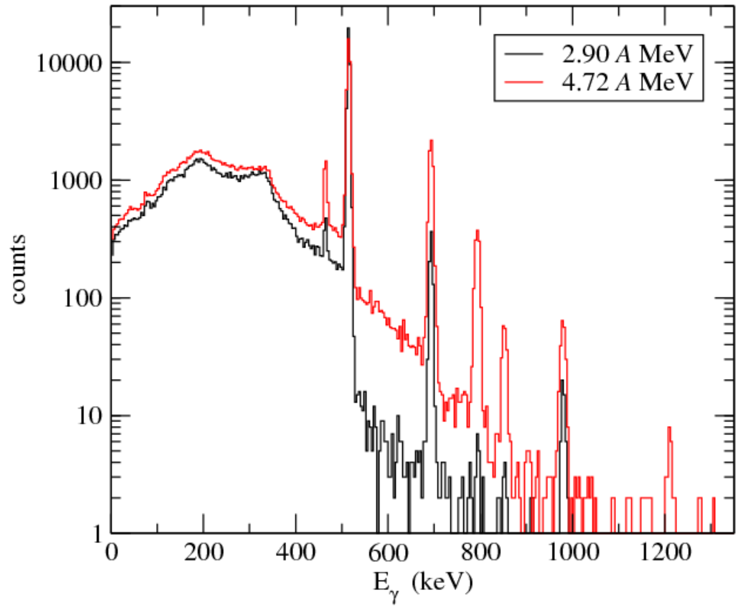
2012: ^{140}Sm+94Mo @2.85 MeV/u
2017: ^{140}Sm+208Pb @ 4.7 MeV/u

2016

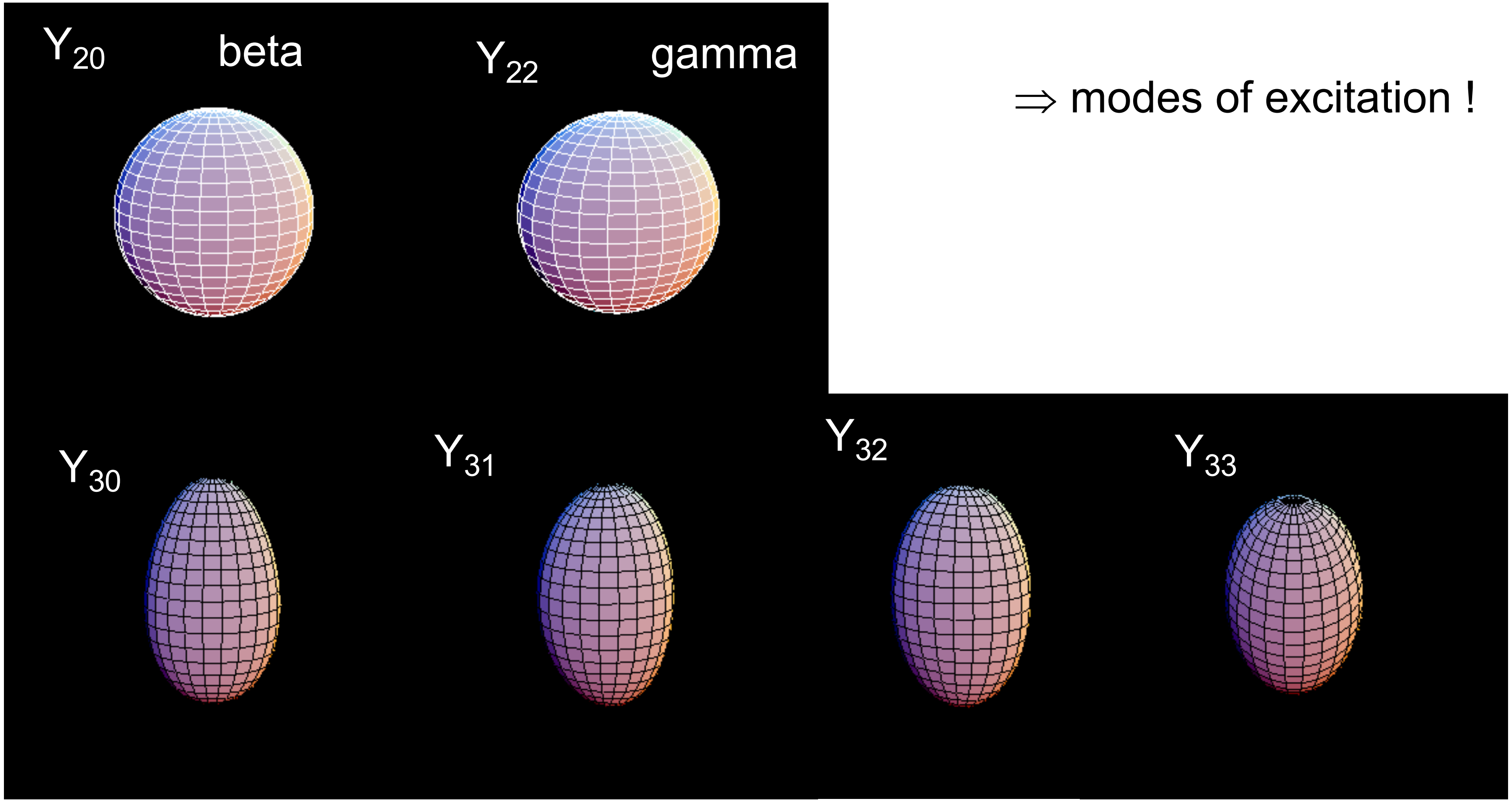


2017



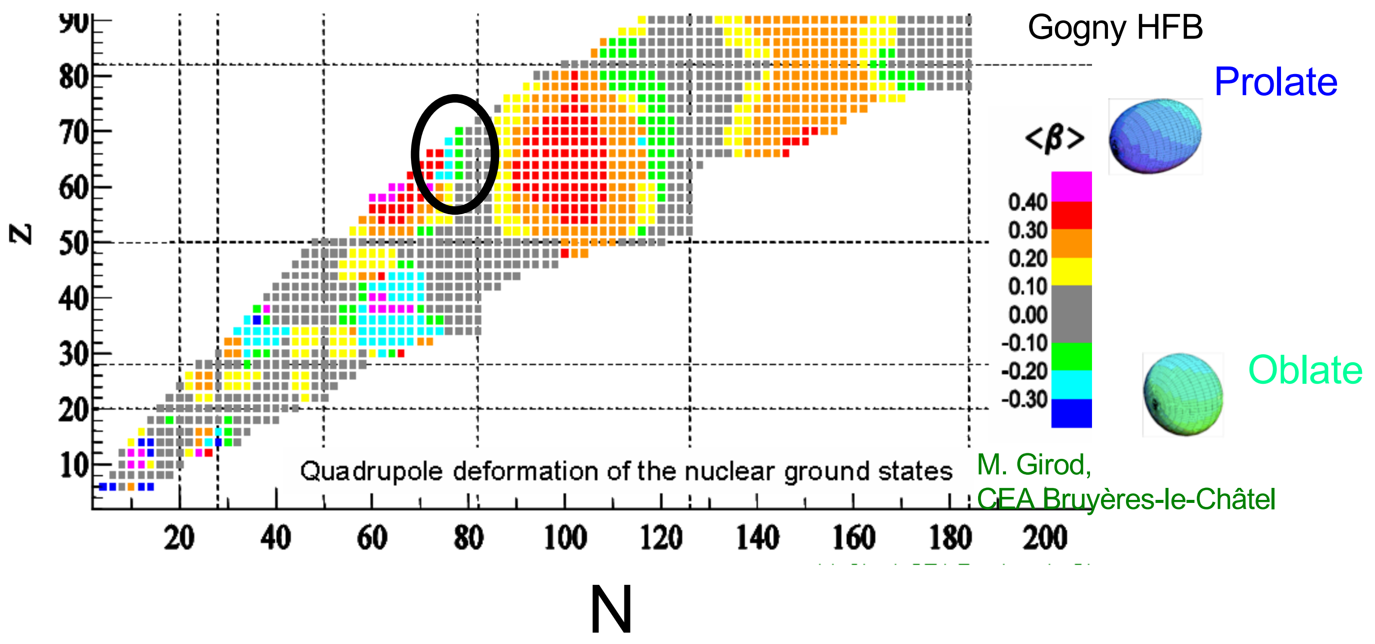


deformation can be dynamic: $a_{\lambda\mu}(t)$

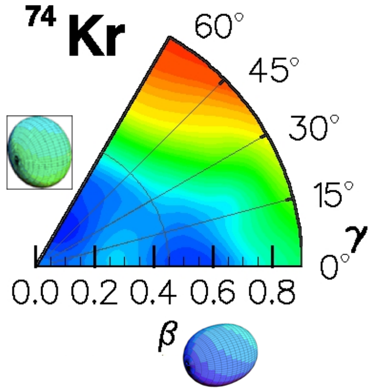


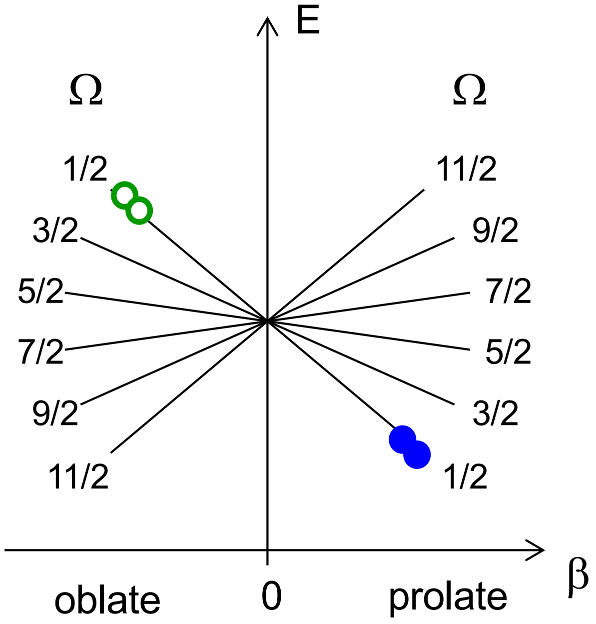
⇒ modes of excitation !

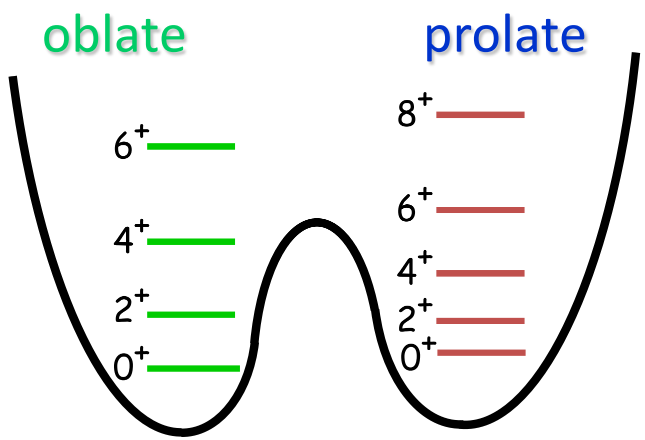
Studies of exotic short lived nuclides

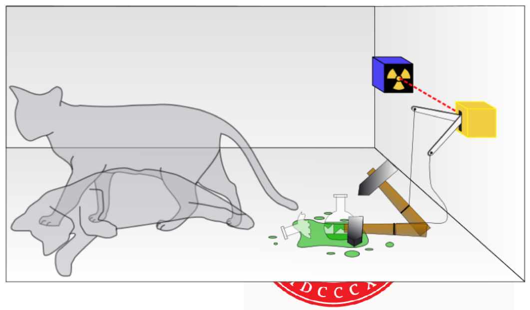


potential energy surface

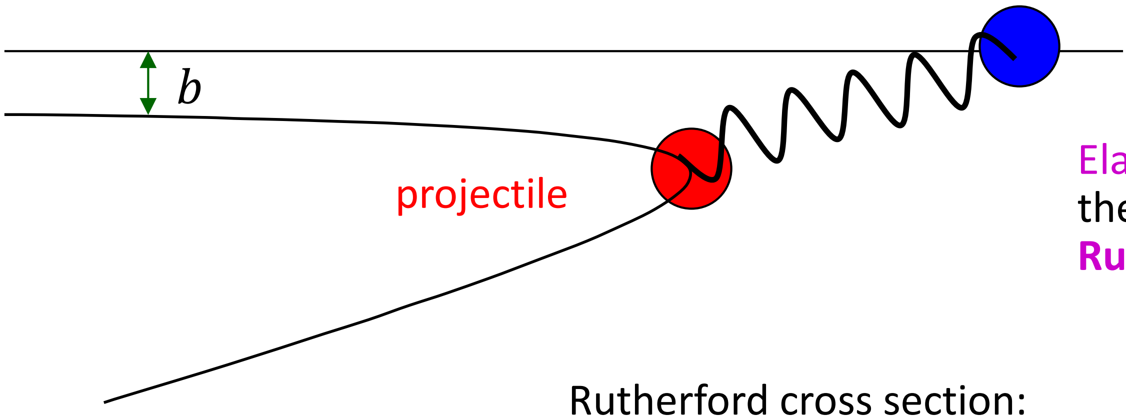








Coulomb excitation



Elastic scattering of charged particles under the influence of the Coulomb field:
Rutherford scattering

Rutherford cross section: $$\left(\frac{d\sigma}{d\Omega}\right)_{el} = \left(\frac{a_0}{2}\right)^2 \sin^{-4}\left(\frac{\theta_{cm}}{2}\right)$$

with $2a_0$ the distance of closest approach for head-on collisions

Nuclear excitation by the electromagnetic interaction acting between two colliding nuclei:
Coulomb excitation

excitation of both target and projectile possible
often magic nucleus (e.g. ^{208}Pb) as
- projectile ⇒ target Coulomb excitation
- target ⇒ projectile Coulomb excitation
  important technique for radioactive beams

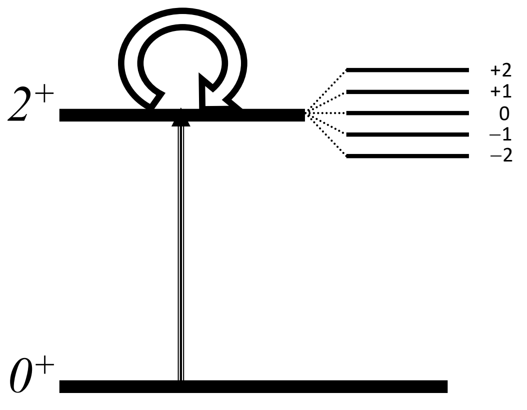
“safe” Coulomb excitation at low energy: purely electromagnetic process

safe condition: distance of closest approach $2a_0 > 1.25\left(A_p^{1/3} + A_t^{1/3}\right) + 5\ \mathrm{fm}$

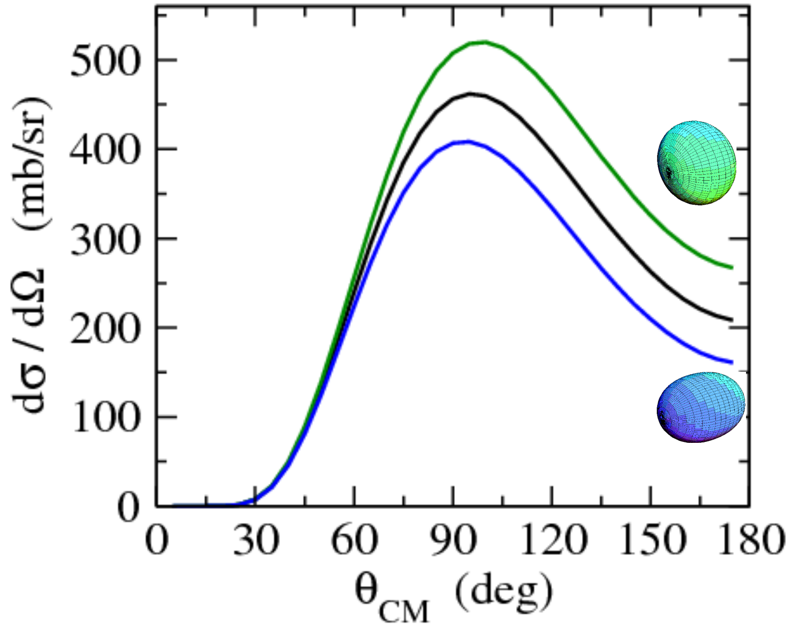
⇒ choose beam energy and scattering angle (i.e. impact parameter) accordingly

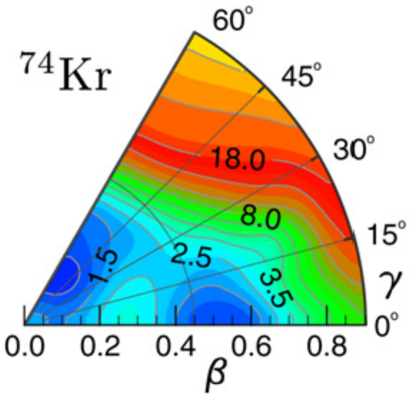
⇒ purely electromagnetic process, can be calculated with high precision

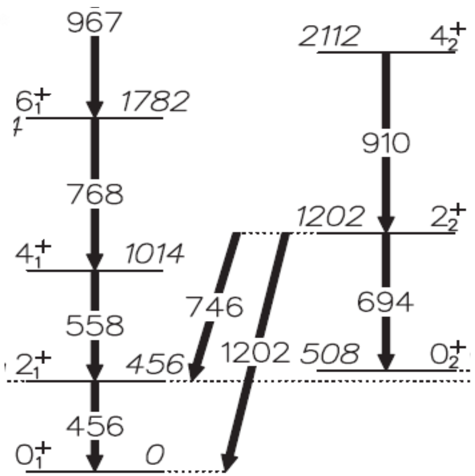
Reorientation effect



$b^{(2)}_{0^+\to 2^+} \propto \langle 2^+|M(E2)|2^+\rangle\langle 2^+|M(E2)|0^+\rangle$







to extract *B(E2)* and Q_s

- ➢ differential measurement of cross section (as a function of scattering angle)
- ➢ large θ_{cm} most sensitive

Idea: measure $Q_s(2_1^+)$ and $Q_s(2_2^+)$

(remember: $Q_s(0^+) = 0$)

Problem: ^{74}Kr is radioactive ($T_{1/2}$=11.5 min)

➢ radioactive beam

Strategies

lifetime measurement ⇒ transition probabilities ⇒ model-dependent information on shape

↕

comparison with theoretical models
e.g. beyond-mean field theories

⇒ quantitative test of the model

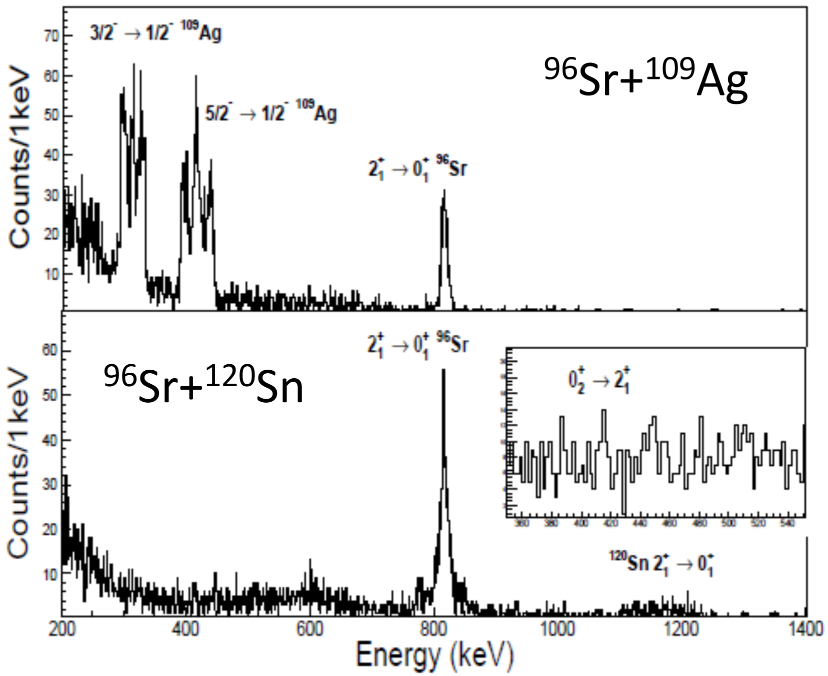
↕

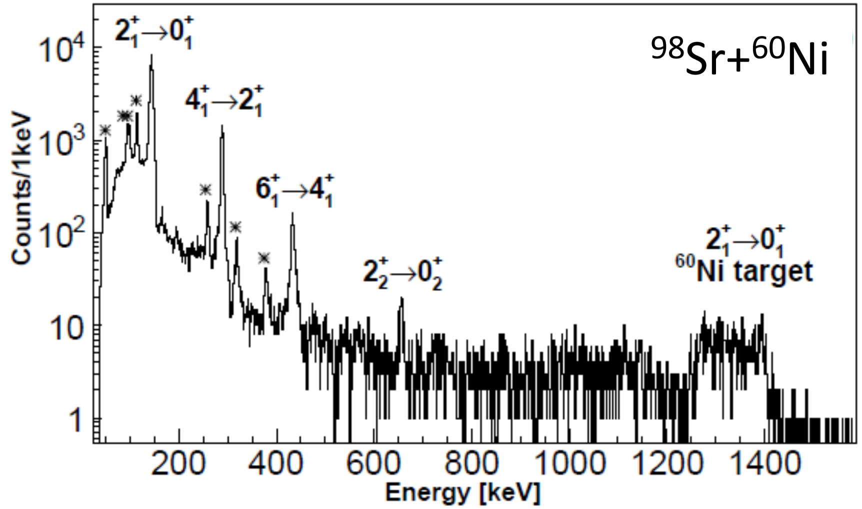
Coulomb excitation ⇒ transition probabilities
⇒ spectroscopic quadrupole moments

→ model-independent information on shape

also sensitive to the sign of Q_s

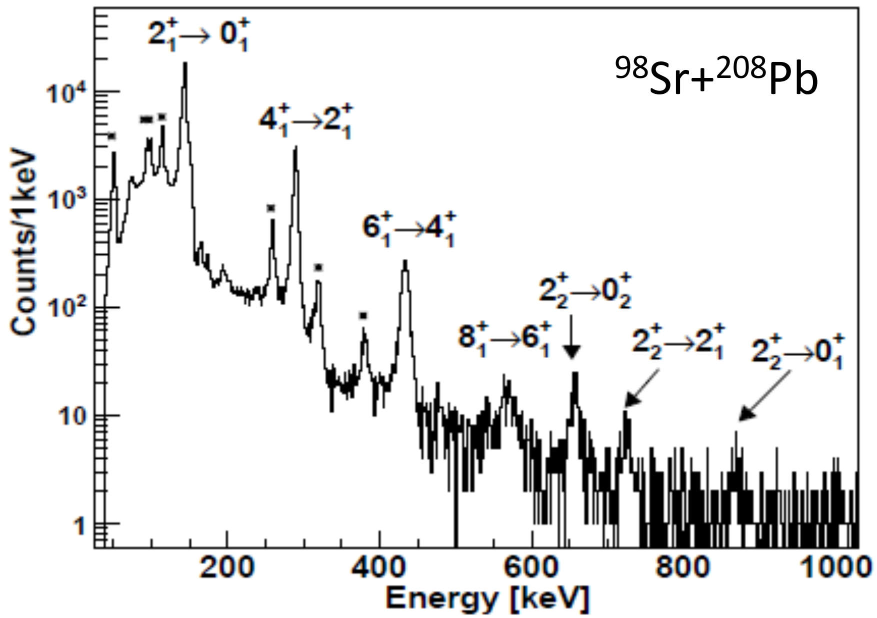
Coulomb excitation of ^{96,98}Sr at CERN – ISOLDE





Doppler correction for projectiles

normaliztion to known $B(E2)$ values in target



Coulomb excitation probabilities:
(as function of θ and Z)
$\Rightarrow$ B(E2) values
$\Rightarrow$ spectroscopic quadrupole moments Q_s
(reorientation effect)

E. Clément et al.
Phys.Rev.Lett. 116, 022701 (2016)
Phys.Rev. C 94, 054326 (2016)

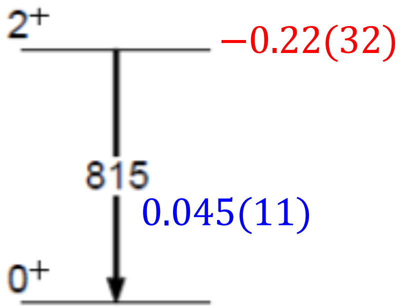
Coulomb excitation of ^{98}Sr at CERN – ISOLDE

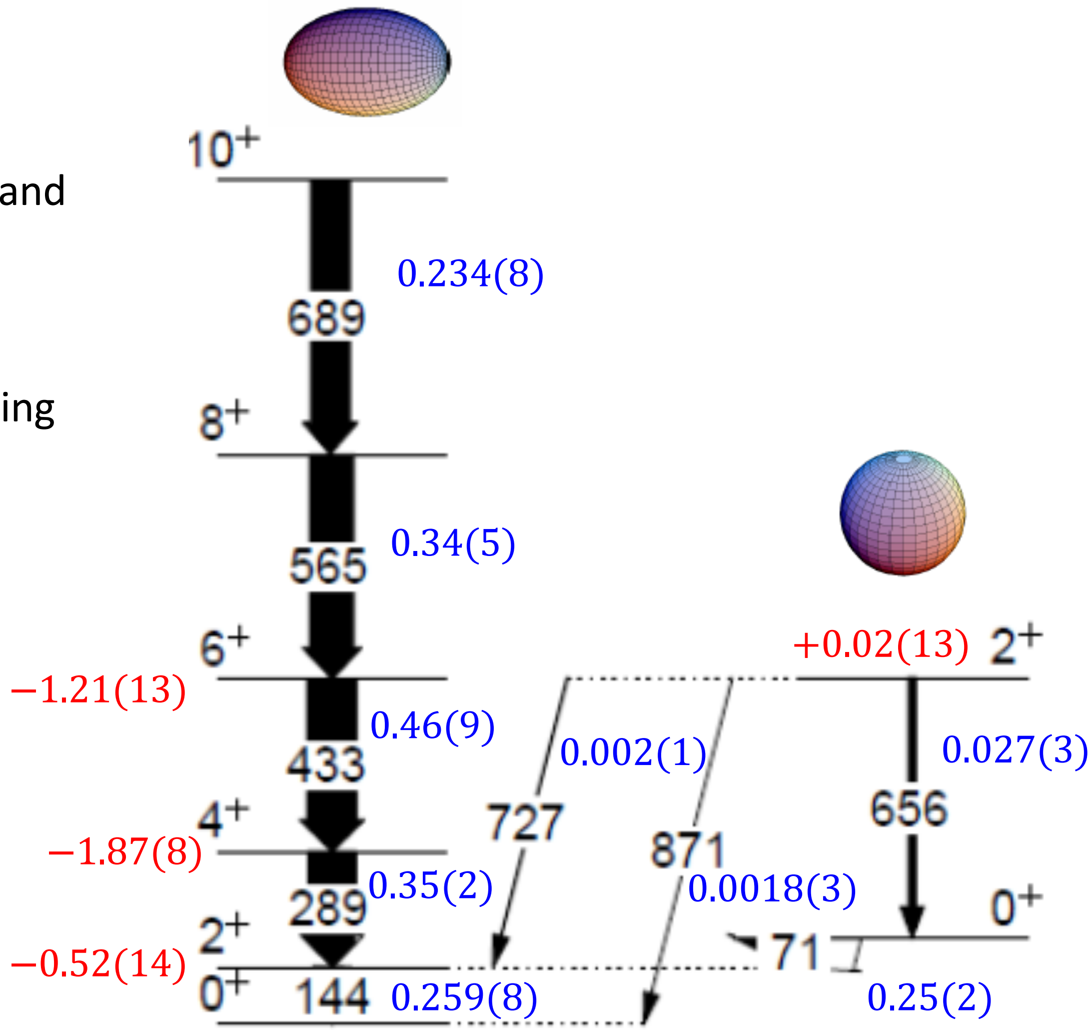
^{98}Sr

- rotational behavior of ground-state band
- excited configuration similar to ^{96}Sr
- quadrupole moments confirm shape coexistence
- $B(E2; 2_2^+ \rightarrow 0_1^+)$ indicates strong mixing

$B(E2;\downarrow)$ $[e^2\mathrm{b}^2]$

Q_s $[e\mathrm{b}]$





^{96}Sr

- $Q_s(2_1^+) \approx 0$
  $\Rightarrow$ no static quadrupole deformation
- sizeable $B(E2)$
  $\Rightarrow$ vibrational character of 2_1^+

E. Clément et al.
Phys.Rev.Lett. 116, 022701 (2016)
Phys.Rev. C 94, 054326 (2016)

INTPART project:
Nuclear Shapes and Resonances in Education

4.5 MNOK over 3 years

University of California Berkeley,	Prof. Lee Bernstein
University of Stellenbosch,	Assoc. Prof. Paul Papka
iThemba LABS,	Senior Scientist Mathis Wiedeking
University of Oslo	Prof. Sunniva Siem

Funded by:

UiO : Universitetet i Oslo

Berkeley UNIVERSITY OF CALIFORNIA

NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

UNIVERSITEIT STELLENBOSCH UNIVERSITY

The Research Council of Norway

SIU NORWEGIAN CENTRE FOR INTERNATIONAL COOPERATION IN EDUCATION

The INTPART project has 3 work packages

1. Research

2. Education

3. Student exchange

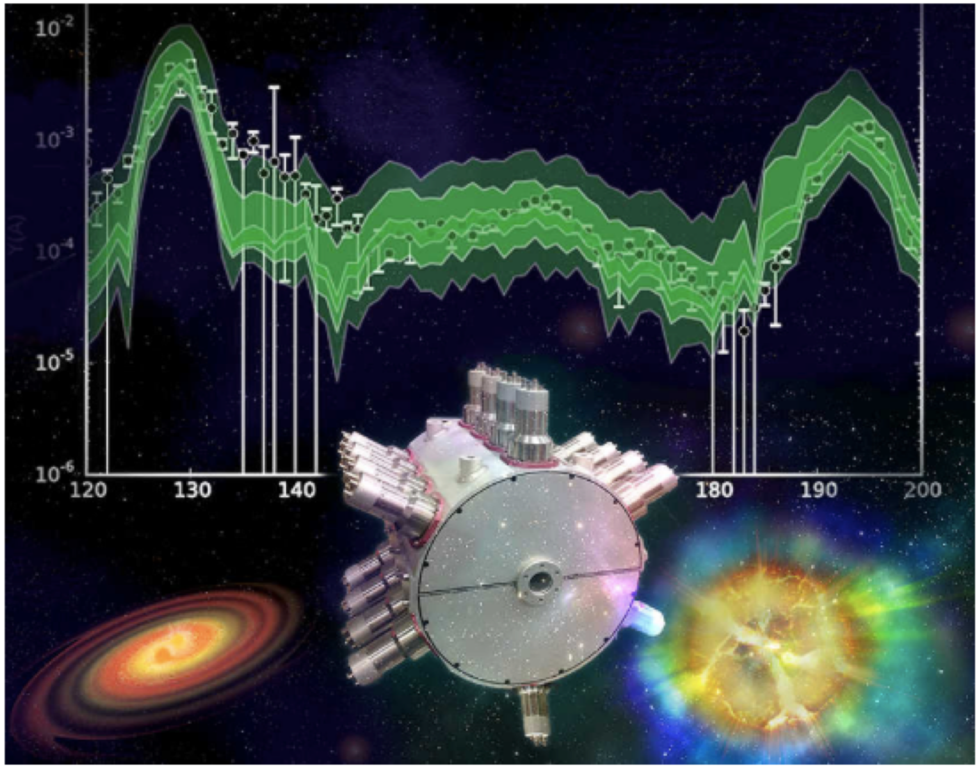
UNIVERSITEIT STELLENBOSCH UNIVERSITY

HOME ABOUT PEOPLE INSTRUMENTS EVENTS CONTACT

Advanced Nuclear Reactions and Applications in Astrophysics

8-22 November 2017, Stellenbosch University, Merensky building, Room Delta, NARGA

This course will provide the students with an understanding of the main astrophysical processes to produce elements in the cosmos. In particular, the connection of nuclear physics data to astrophysical relevant cross sections will be covered, which includes hands-on experience with the state-of-the-art TALYS reaction code to deepen the understanding of the interplay of nuclear physics and astrophysics.



Courtesy of Erin O'Donnell, Michigan State University

Lecturers

S. Siem (Oslo)
C. Tellefsen (Oslo)
A. Goergen (Oslo)
B.V. Kheswa (UJ)
A. Spyrou (MSU)
S. Goriely (ULB)

http://www.physics.sun.ac.za/nuclear/berkeley-oslo-stellenbosch-itl.html

Hand-on training in TALYS

Learning by discussing

Innovation in education:
Testing new ways to teach physics

New friendships

Thank you for your attention

Main infrastructure:
Oslo Cyclotron Laboratory

Users:

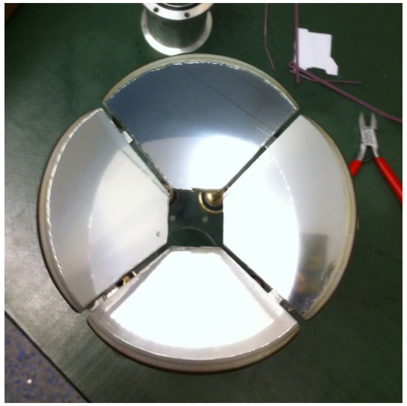
Nuclear Physics: Basic research

Biophysics: proton irradiation of cells

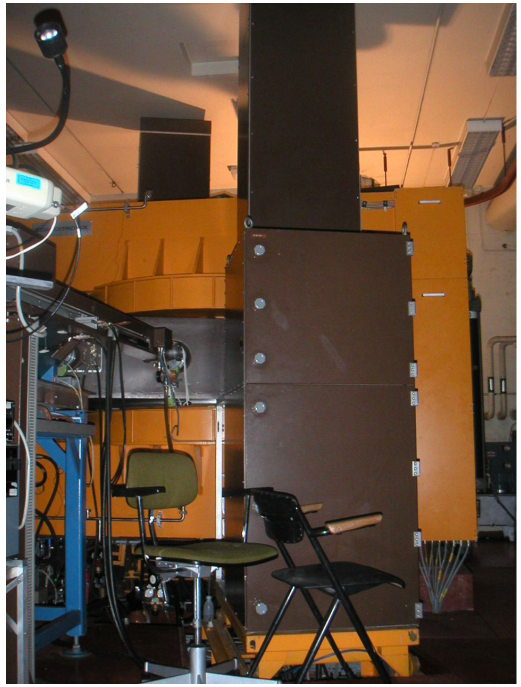
ESS: tests of scintillating materials

ALICE: Radiation hardness tests

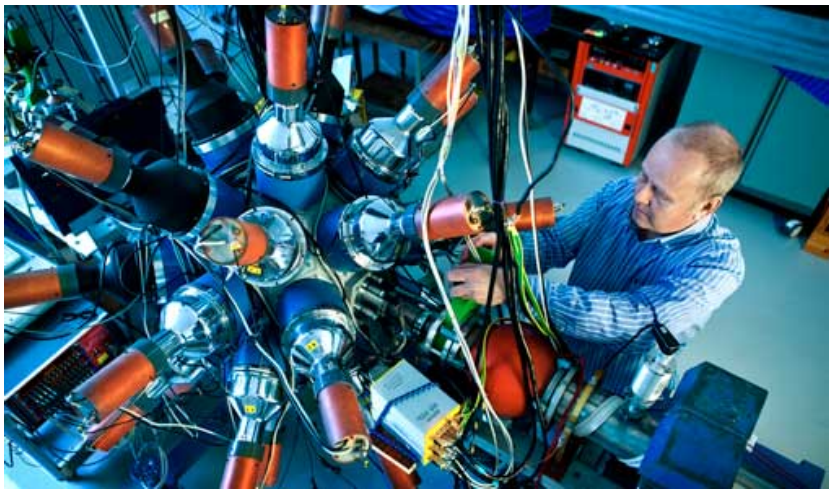
R&D on Medical Isotop Production



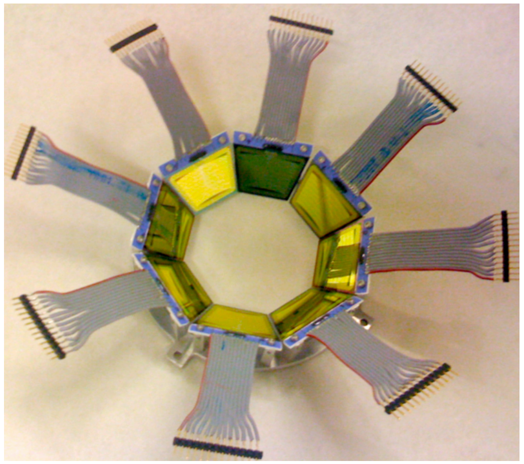
PPAC (fission det.)



Cyclotron



CACTUS (gamma detectors)

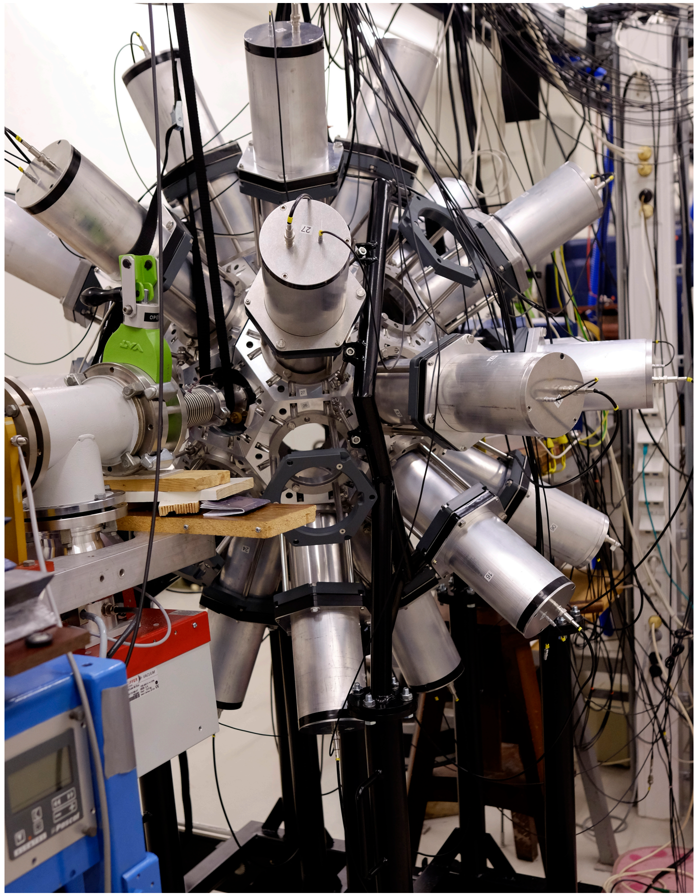


SiRi (particle det.)

OCL
Oslo Cyclotron Laboratory

CACTUS detectors replaced With OSCAR

OSCAR
Oslo Scintillator Array



- New infrastructure: 23 MNOK (ca 2.56 M Euro)
- 30 Large volume (3,5 x 8) LaBr3 detectors
- Better energy resolution
- Better timing
- Possibilities for new types of experiments
- We welcome new collaborations
- 1st experiment full array in April

OCL
Oslo Cyclotron Laboratory

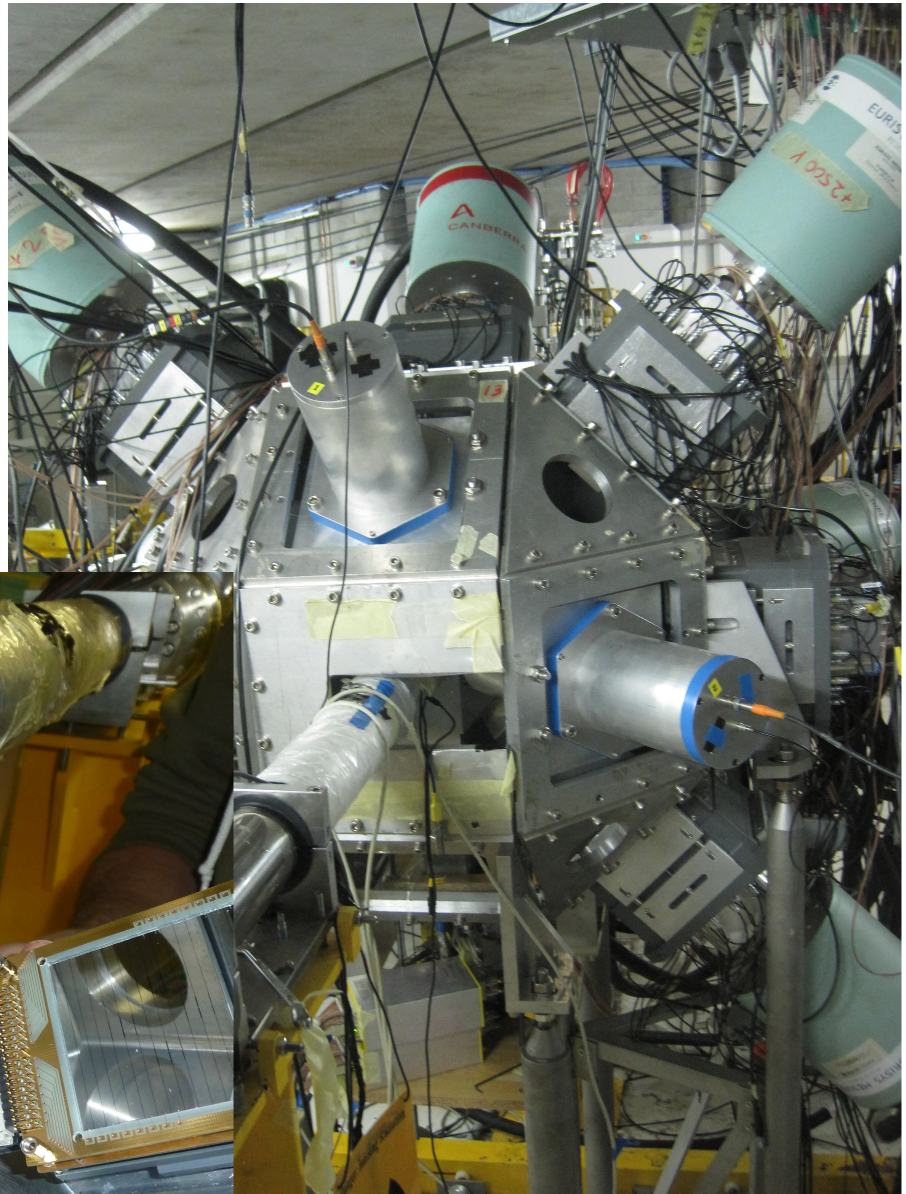
The Research Council of Norway

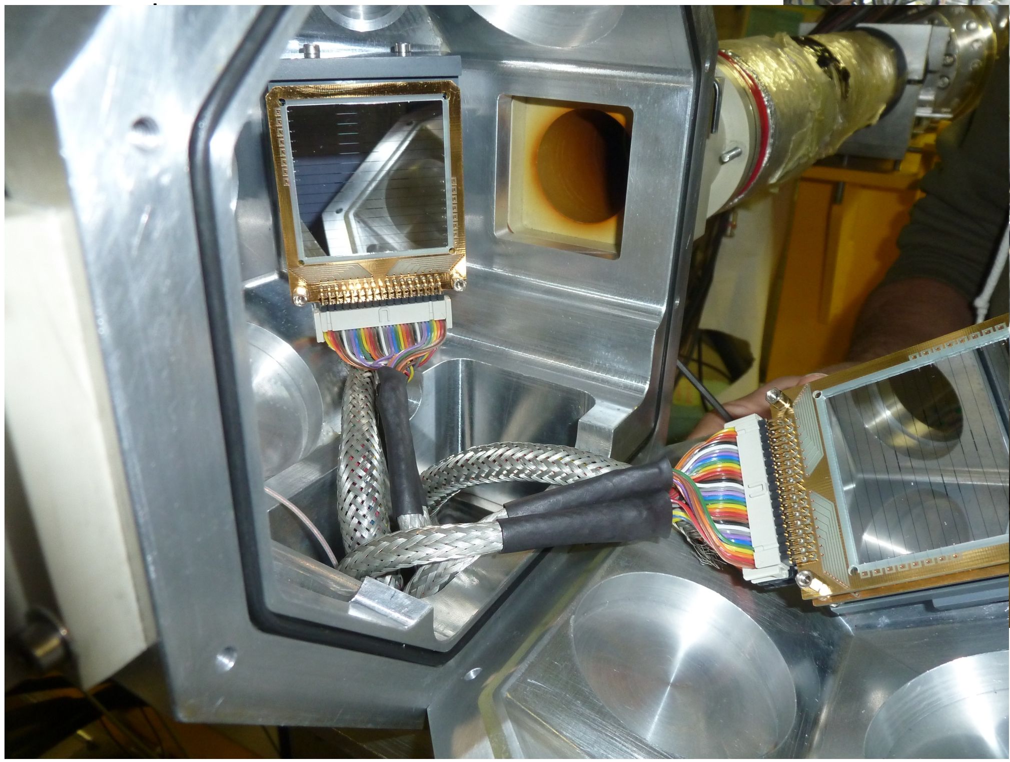
INVESTIGATING THE LOW ENERGY ENHANCEMENT IN THE GAMMA STRENGTH FUNCTION OF 85Kr and 133Xe IN INVERSE KINEMATICS

New Experiments at iThemba November 2017:

Vetle Ingeberg PhD (Krypton) &. Hannah Berg MSc (Xenon)

- Experiment at iThemba LABS in April/May 2015
- ^{86}Kr beam at 300 MeV
- ≈ 160 hours on target
- 8 Compton suppressed CLOVER detectors
- 2 Large volume (3.5x8”) $LaBr_3$(Ce) from Oslo
- Two particle ΔE – E telescopes consisting of square DSSD

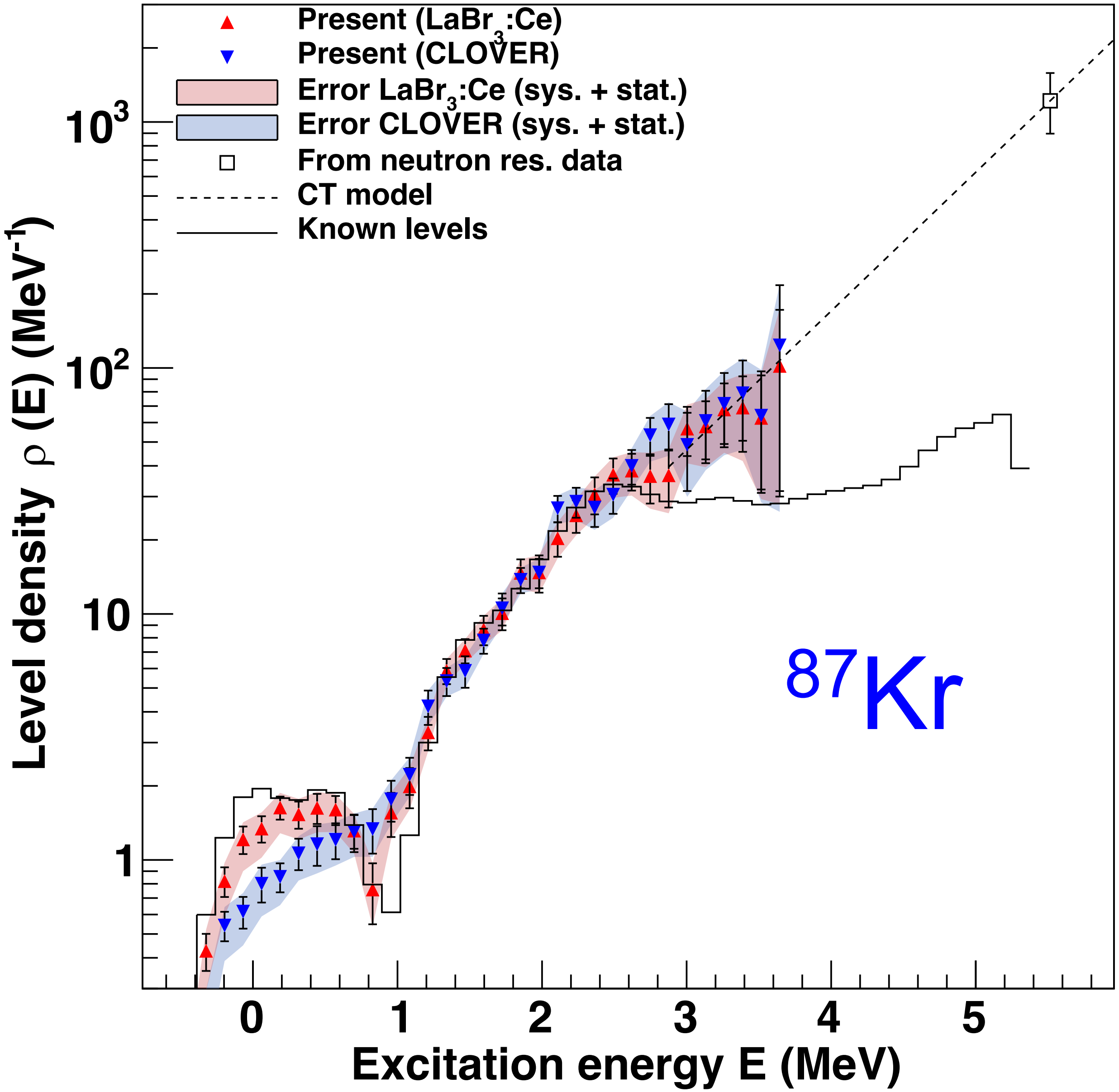


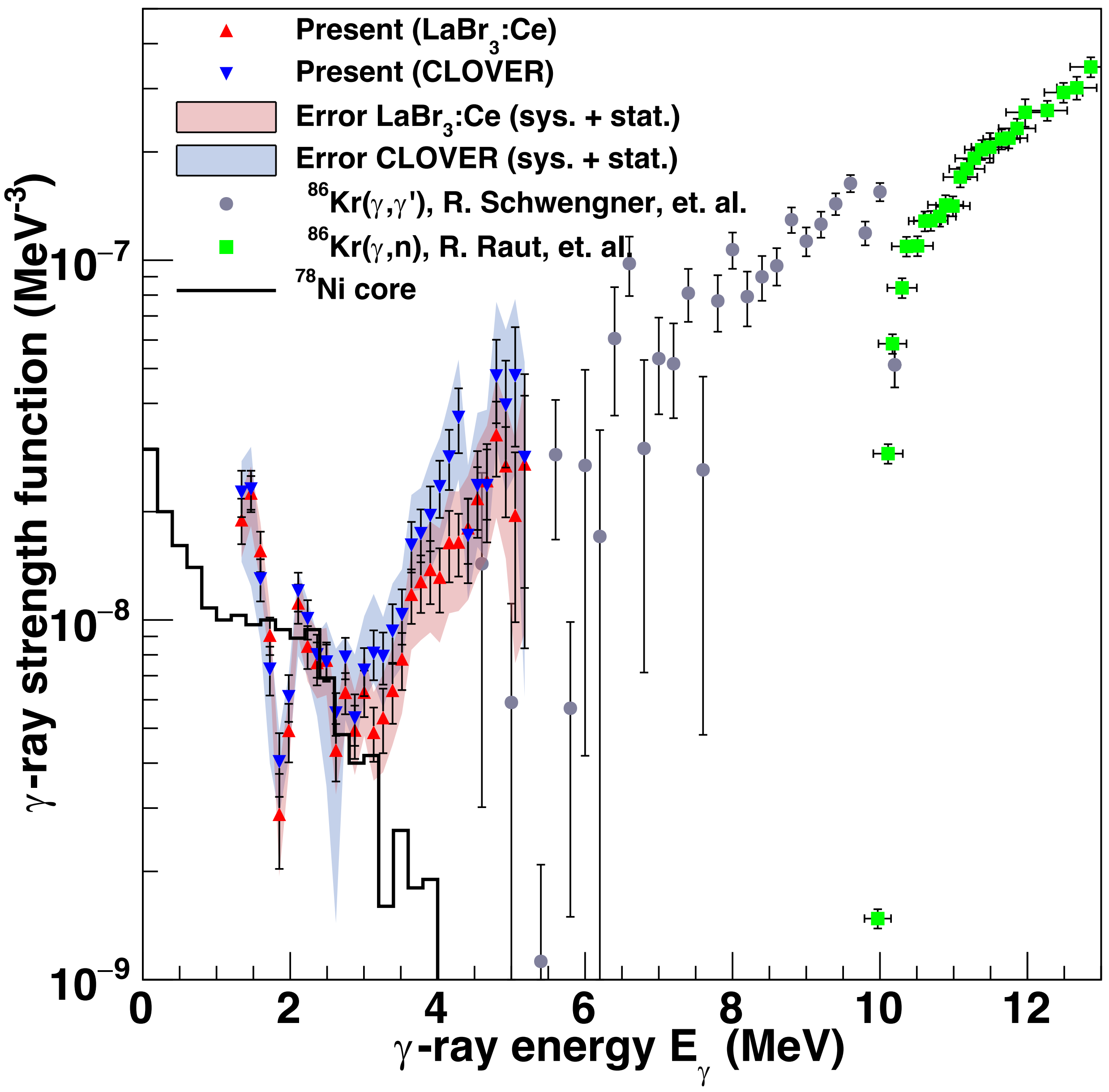


Slide from V. Ingeberg

Proof of principle experiment

V. W. Ingeberg master thesis
and
PRL in preparation





87Kr

V.W.Ingeberg PRL in preperation

LNPS calculations by Kamila Sieja

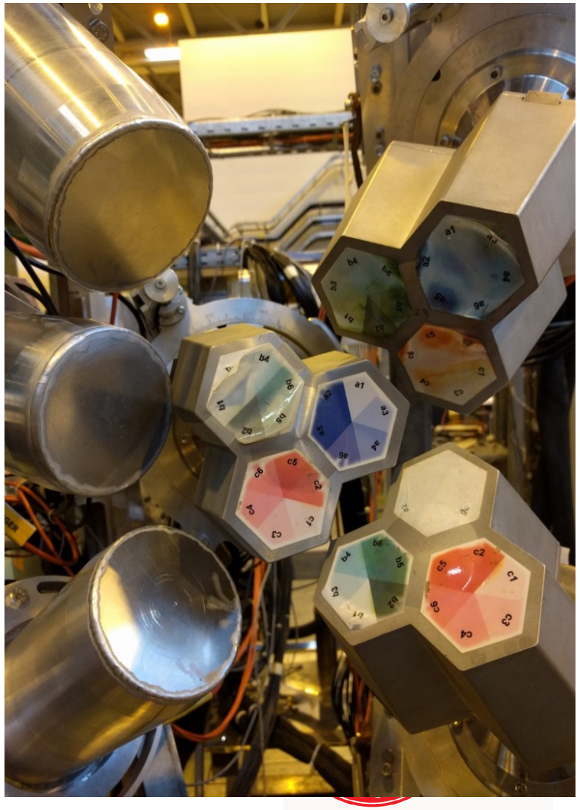
ISOLDE experiments led by University of Oslo:

IS559: Statistical properties of warm nuclei: Investigating the low-energy enhancement in the gamma strength function of neutron-rich nuclei
Spokesperson: S.Siem (Oslo) and M.Wiedeking (iThembe LABS)
Datataking completed November 2016, analysis ongoing

IS451: Shape coexistence in neutron-rich Sr isotopes
Spokesperson: E. Clément (GANIL) and A. Görgen
completed / published

IS495: Study of nuclear shapes in neutron-deficient rare earth isotopes
Spokesperson: A. Görgen and S. Siem
completed / published

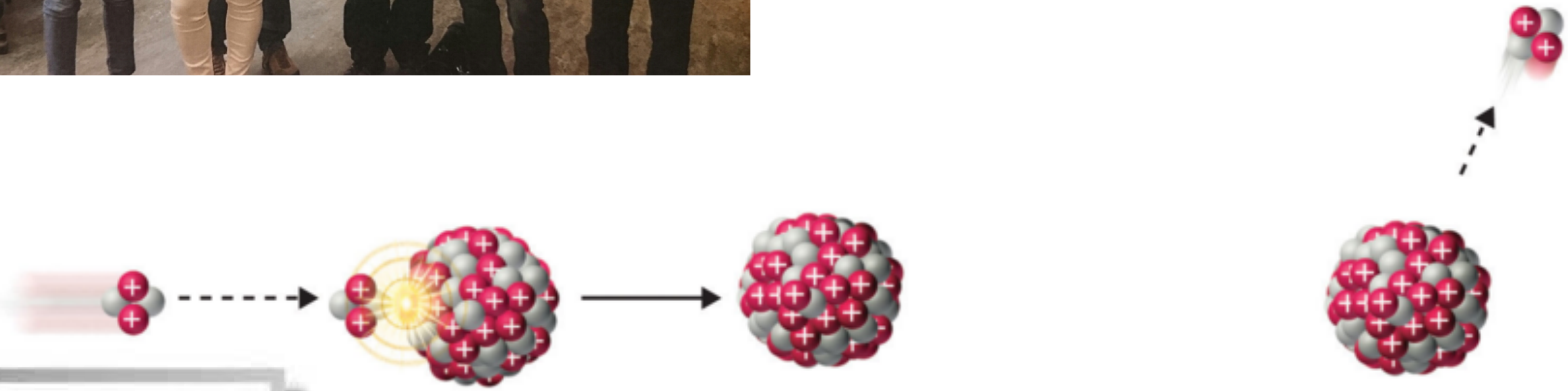
IS558: Shape transition and coexistence in neutron-deficient rare earth isotopes
Spokesperson: A. Görgen
Data taking completed august 2017



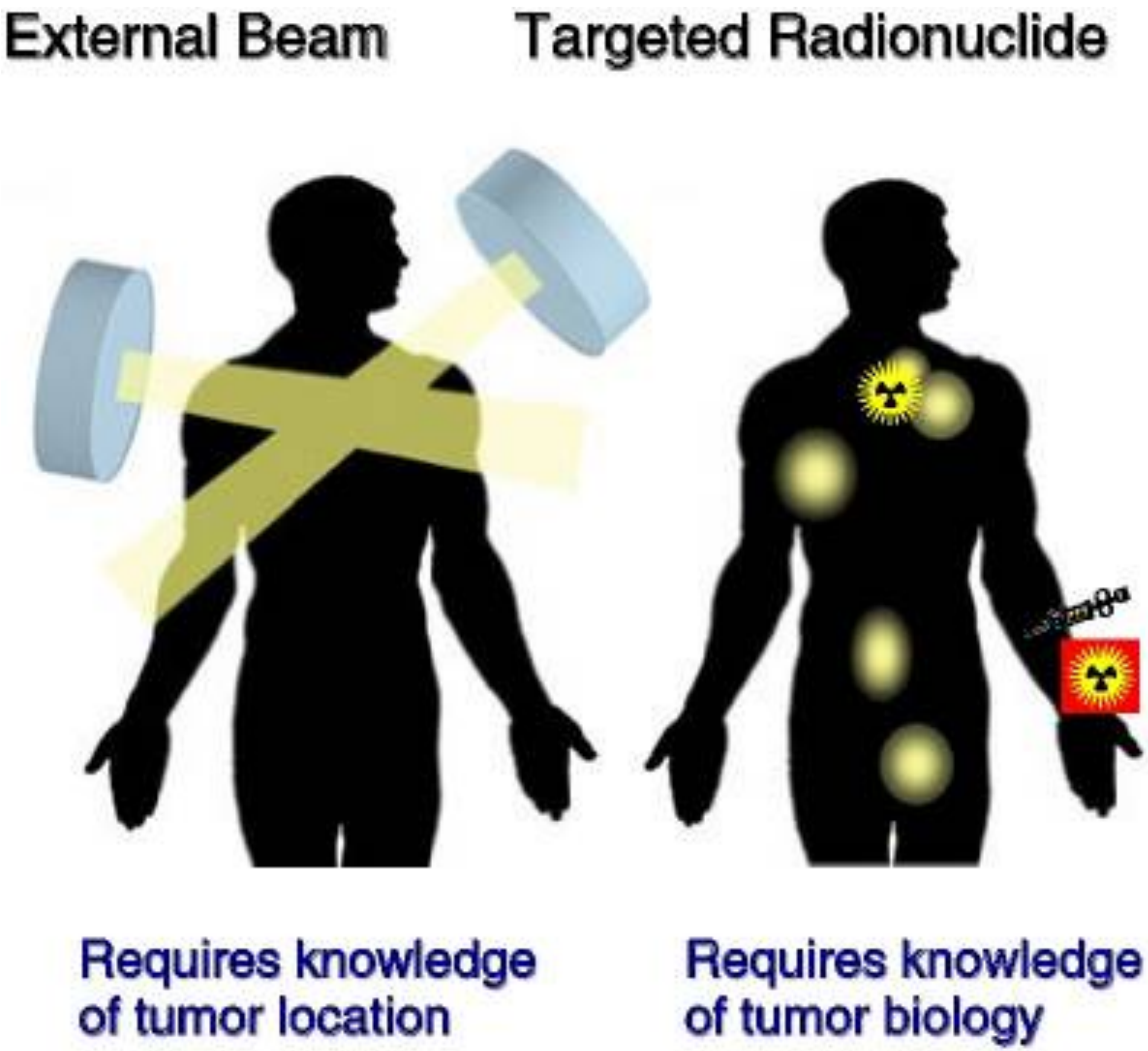
New target design for ^{211}At production at OCL

Advantages:

- Can take higher beam intensity, giving higher yields of ^{211}At.
- Closed target, easier/safer to transport
- Less contaminants and less waste
- quicker to do chemical separation



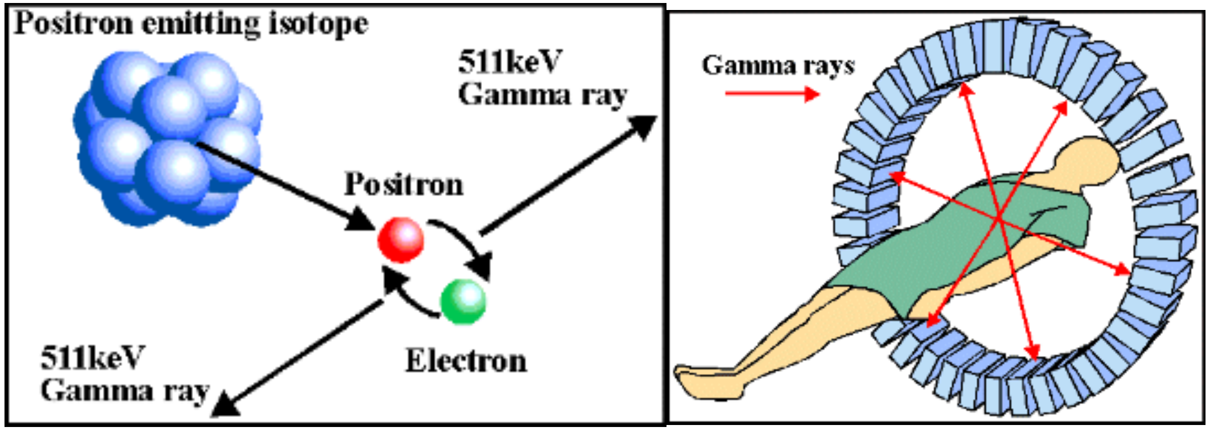
$$\text{alpha} + {}^{209}\text{Bi} \rightarrow {}^{211}\text{At}$$



Less dose to healthy tissue

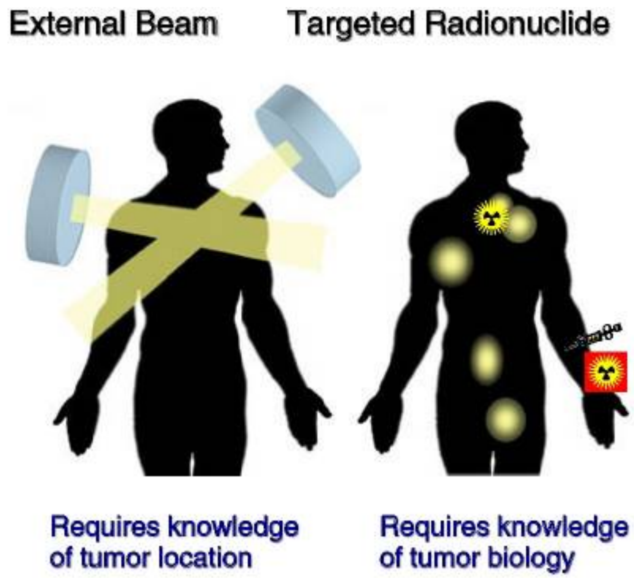
R&D work at the Cyclotron on medical isotopes for diagnostics and for treatment

Oslo Cyclotron was the production cite for 18F used in PET scans

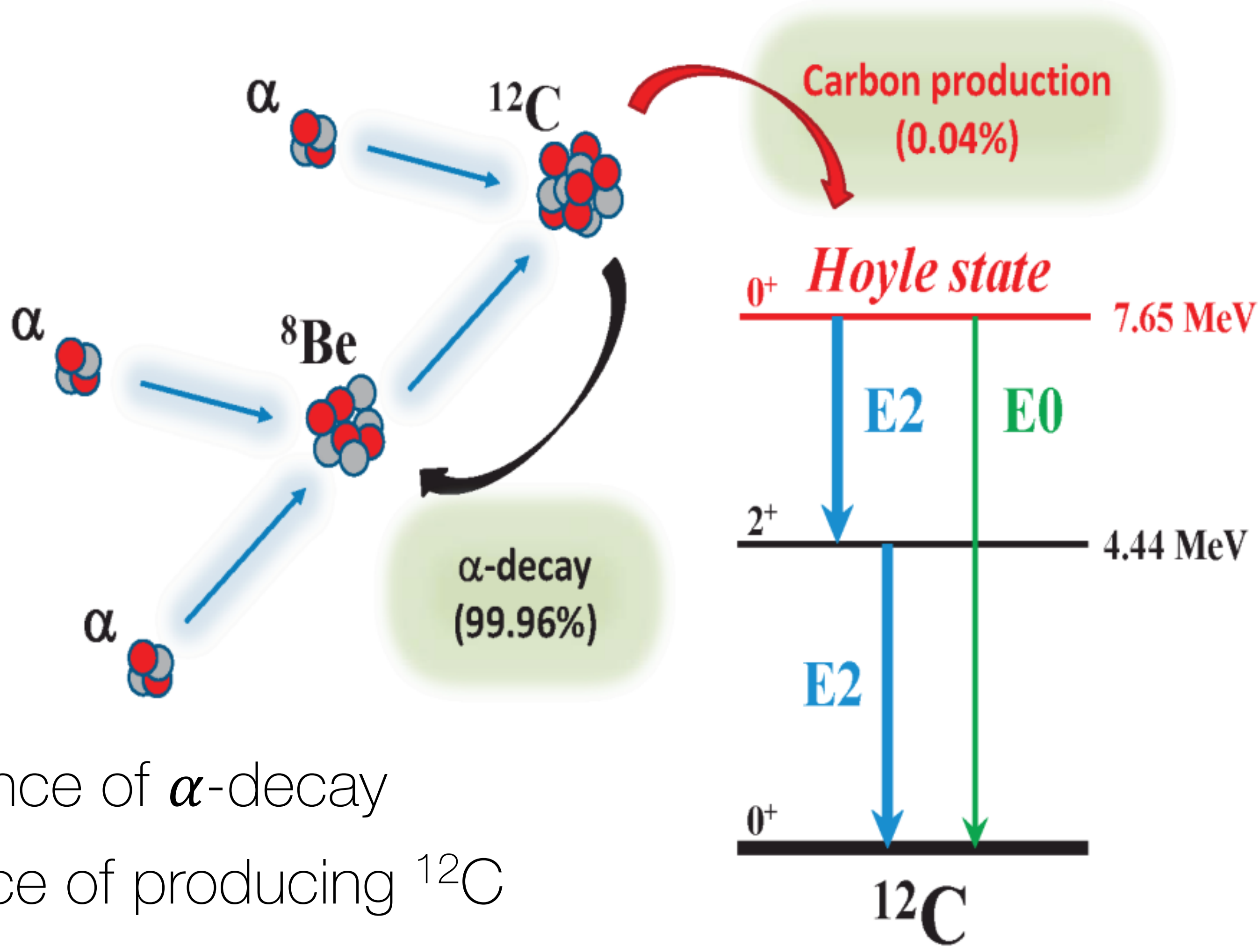


- Optimizing production
- Target development
- New production method (cyclotron in stead of reactor) for 99mTc and other isotope.

SFI application in progress
On medical isotopes for society.



The Hoyle state

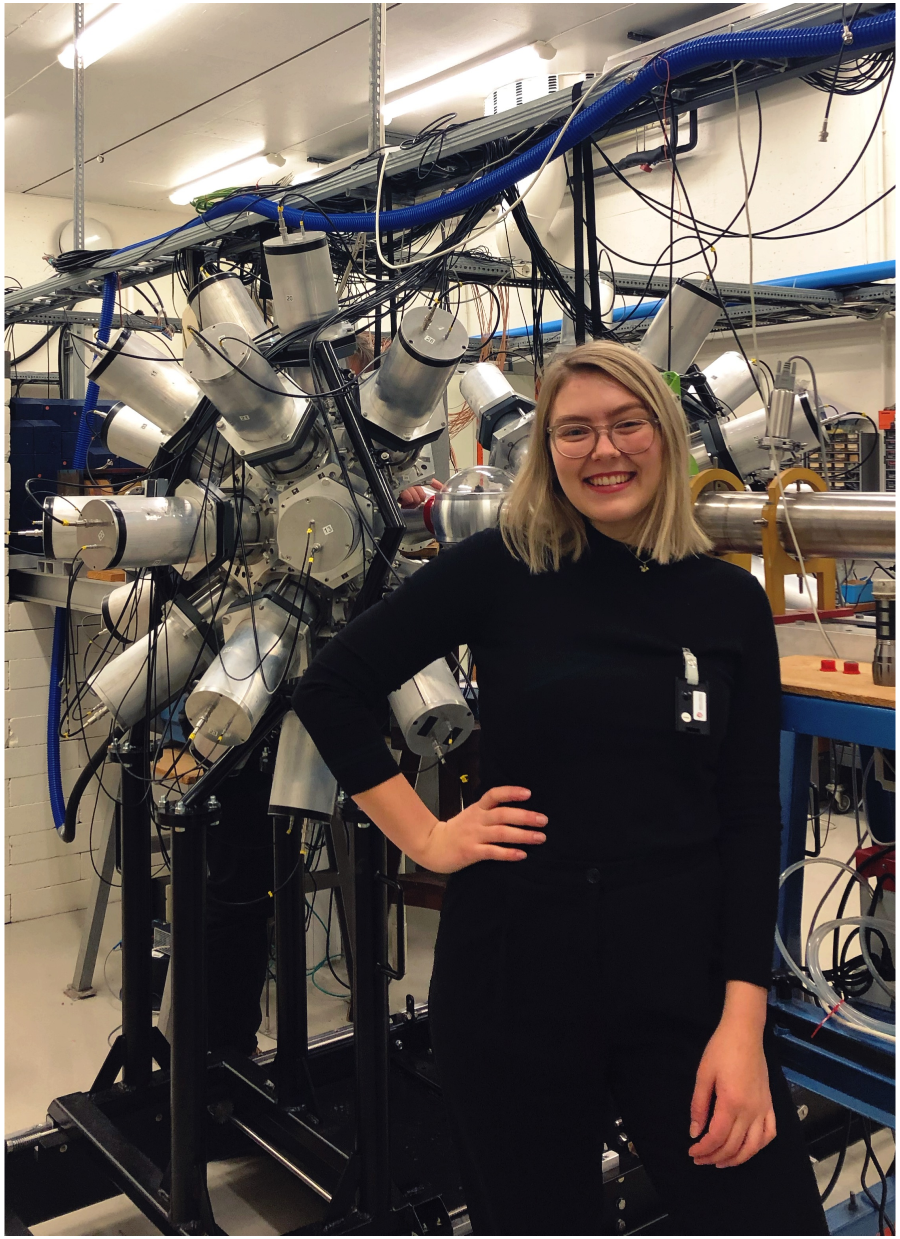


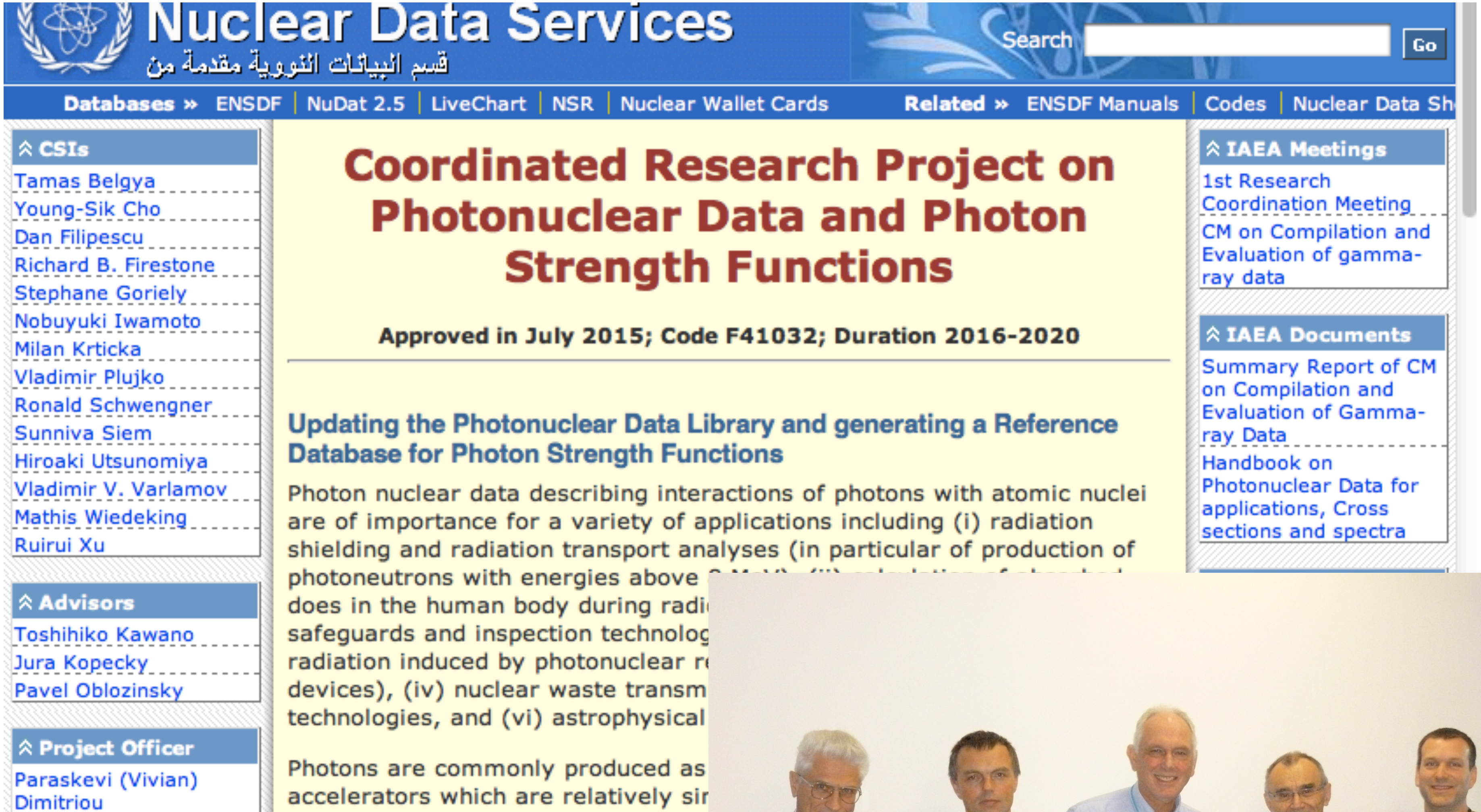
- 99.96% chance of α-decay
- 0.04% chance of producing ^{12}C
- Measure the highly energetic photons
- Want to improve earlier measurements

Image: Alshahrani M. B.

This experiment would not have been possible without OSCAR

Thank you!





Nuclear Data Services

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- Hiroaki Utsunomiya
- Vladimir V. Varlamov
- Mathis Wiedeking
- Ruirui Xu

Advisors
- Toshihiko Kawano
- Jura Kopecky
- Pavel Oblozinsky

Project Officer
- Paraskevi (Vivian) Dimitriou

Coordinated Research Project on Photonuclear Data and Photon Strength Functions

Approved in July 2015; Code F41032; Duration 2016-2020

Updating the Photonuclear Data Library and generating a Reference Database for Photon Strength Functions

Photon nuclear data describing interactions of photons with atomic nuclei are of importance for a variety of applications including (i) radiation shielding and radiation transport analyses (in particular of production of photoneutrons with energies above
does in the human body during radi
safeguards and inspection technolog
radiation induced by photonuclear r
devices), (iv) nuclear waste transm
technologies, and (vi) astrophysical

Photons are commonly produced as
accelerators which are relatively si

IAEA Meetings
- 1st Research Coordination Meeting
- CM on Compilation and Evaluation of gamma-ray data

IAEA Documents
- Summary Report of CM on Compilation and Evaluation of Gamma-ray Data
- Handbook on Photonuclear Data for applications, Cross sections and spectra

Consultants meeting at:
IAEA International Atomic Energy Agency