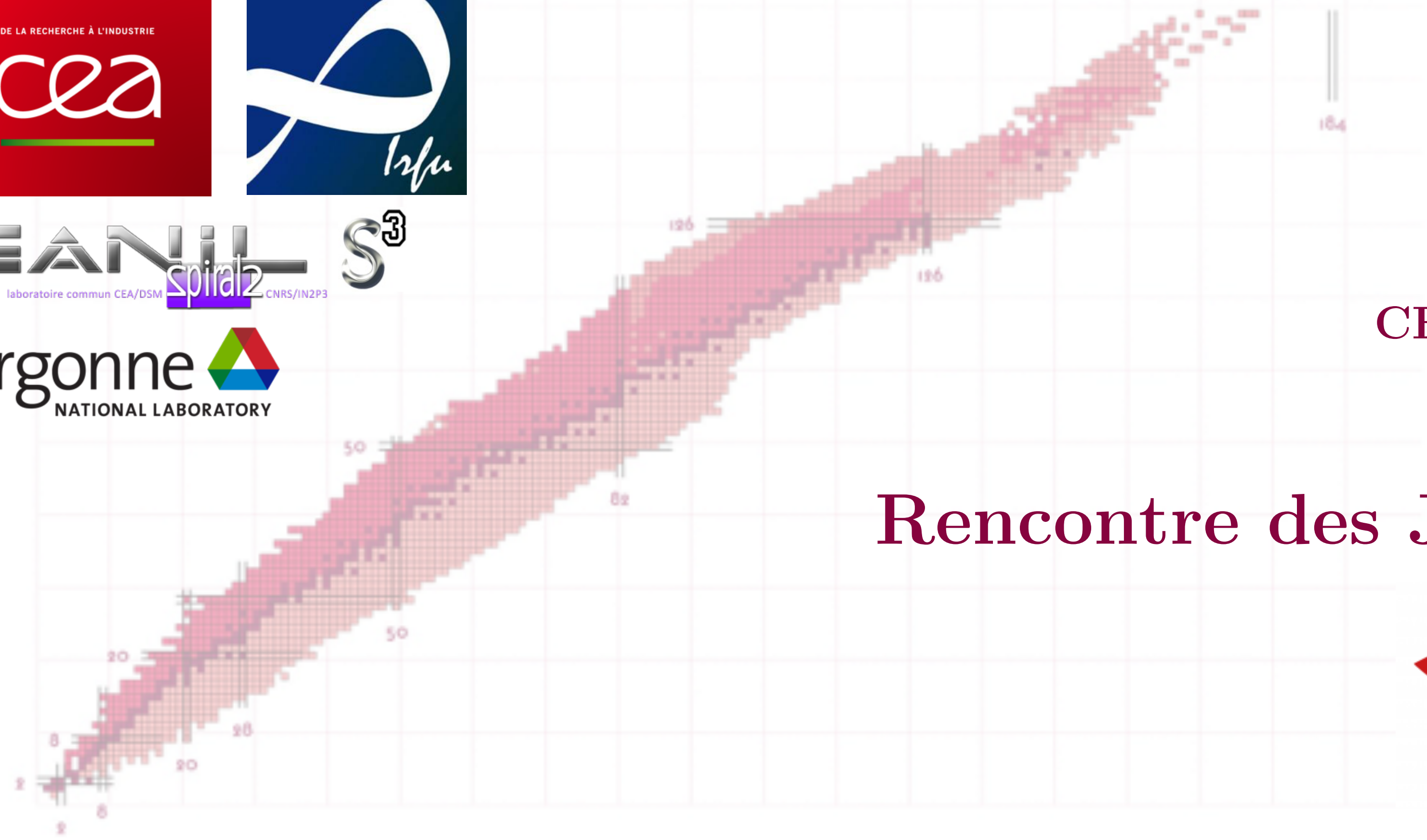


Zoé Favier

CEA Saclay, IRFU/DPhN, France

Rencontre des Jeunes Physicien.ne.s

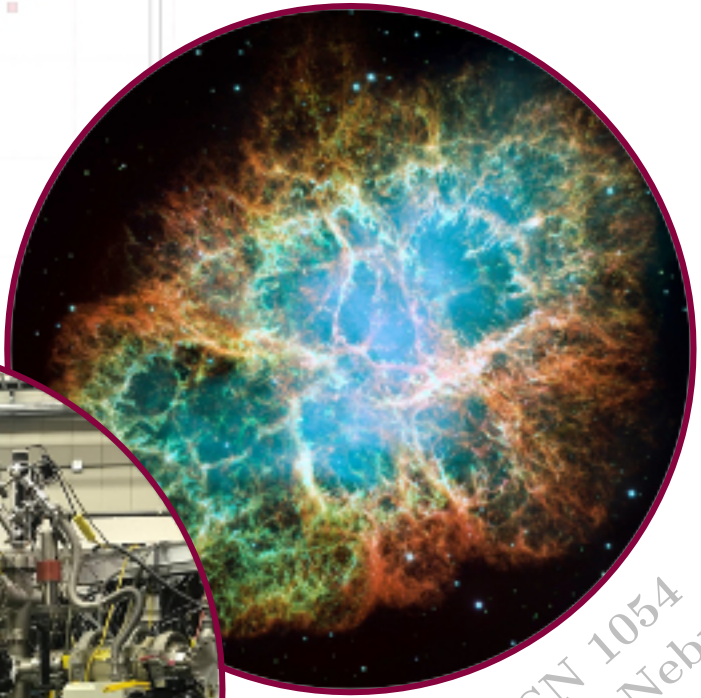
Société Française de Physique

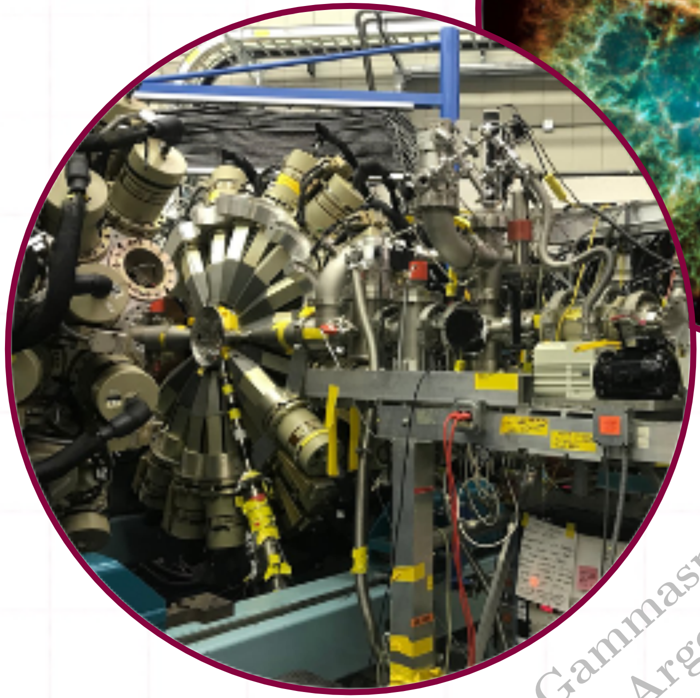
RJP

Stellar nucleosynthesis and superheavy elements in our Universe and in the lab!

Superheavy elements in our Universe and in the lab!

- Introduction – SHE definitions
- Physics motivations – the Universe?
  - Stellar nucleosynthesis
  - r-process and SHE
- Reaction mechanisms
  - Fusion-evaporation
  - MNT reactions
- My PhD work – the lab!
  - MNT experiment at Argonne
  - Development of SIRIUS


SN 1054 Crab Nebula


Gammasphere Argonne

Superheavy elements in our Universe and in the lab!

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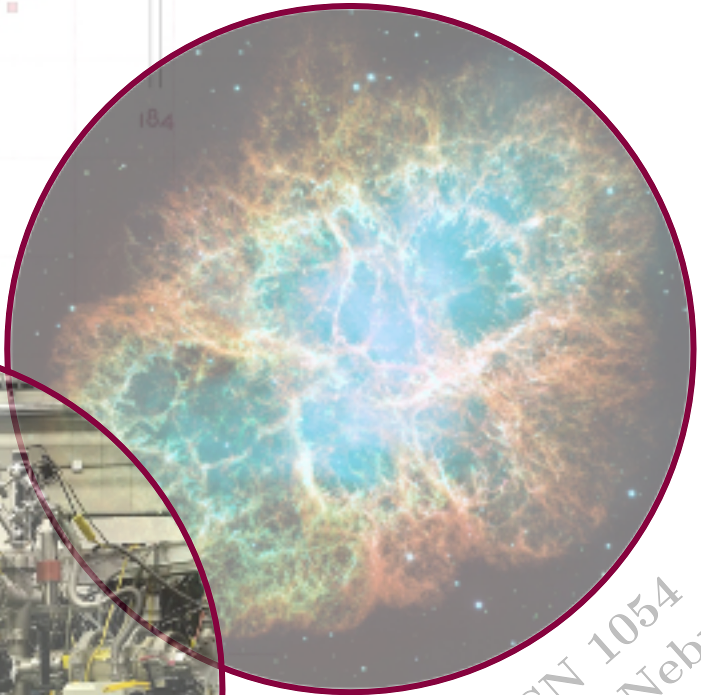
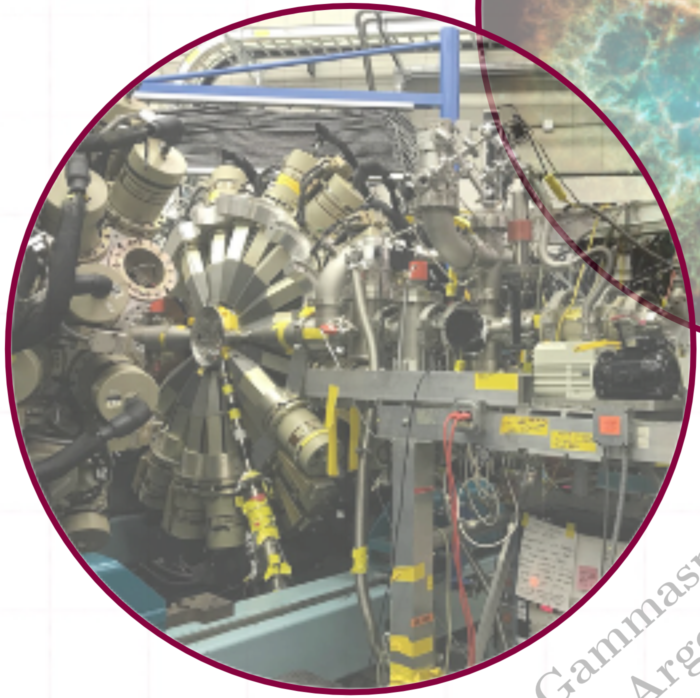




SN 1054
Crab Nebula

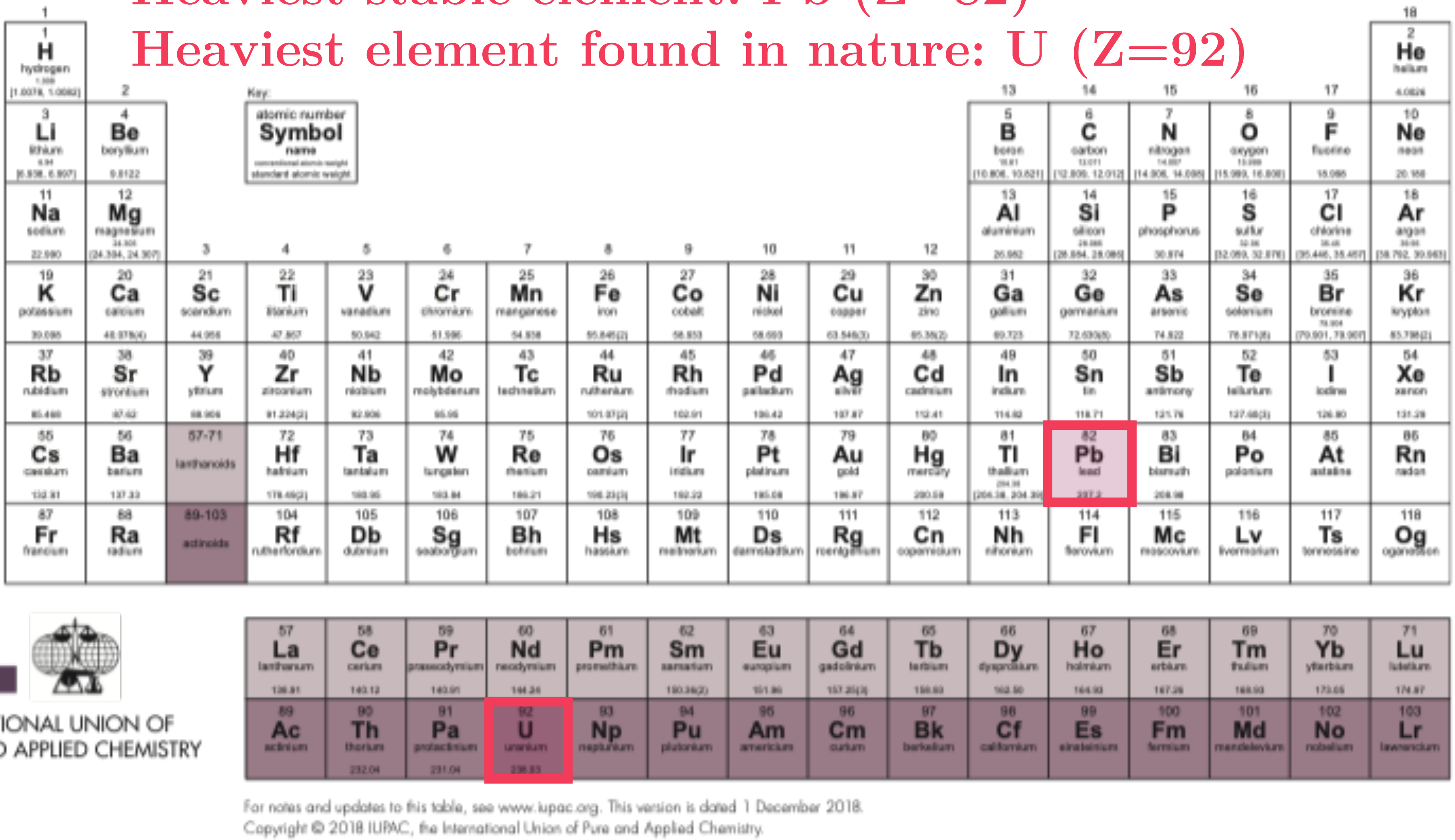
Gammasphere
Argonne

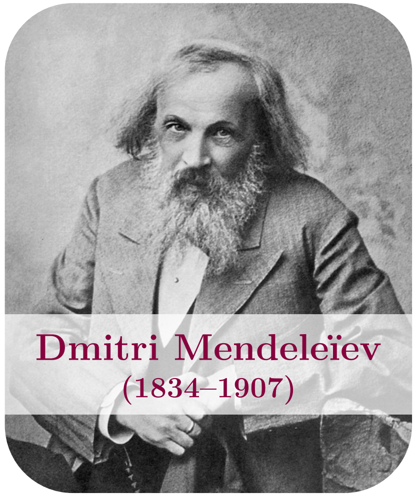
Periodic table of the elements

1 square = 1 element = Z protons

Heaviest stable element: Pb (Z=82)

Heaviest element found in nature: U (Z=92)





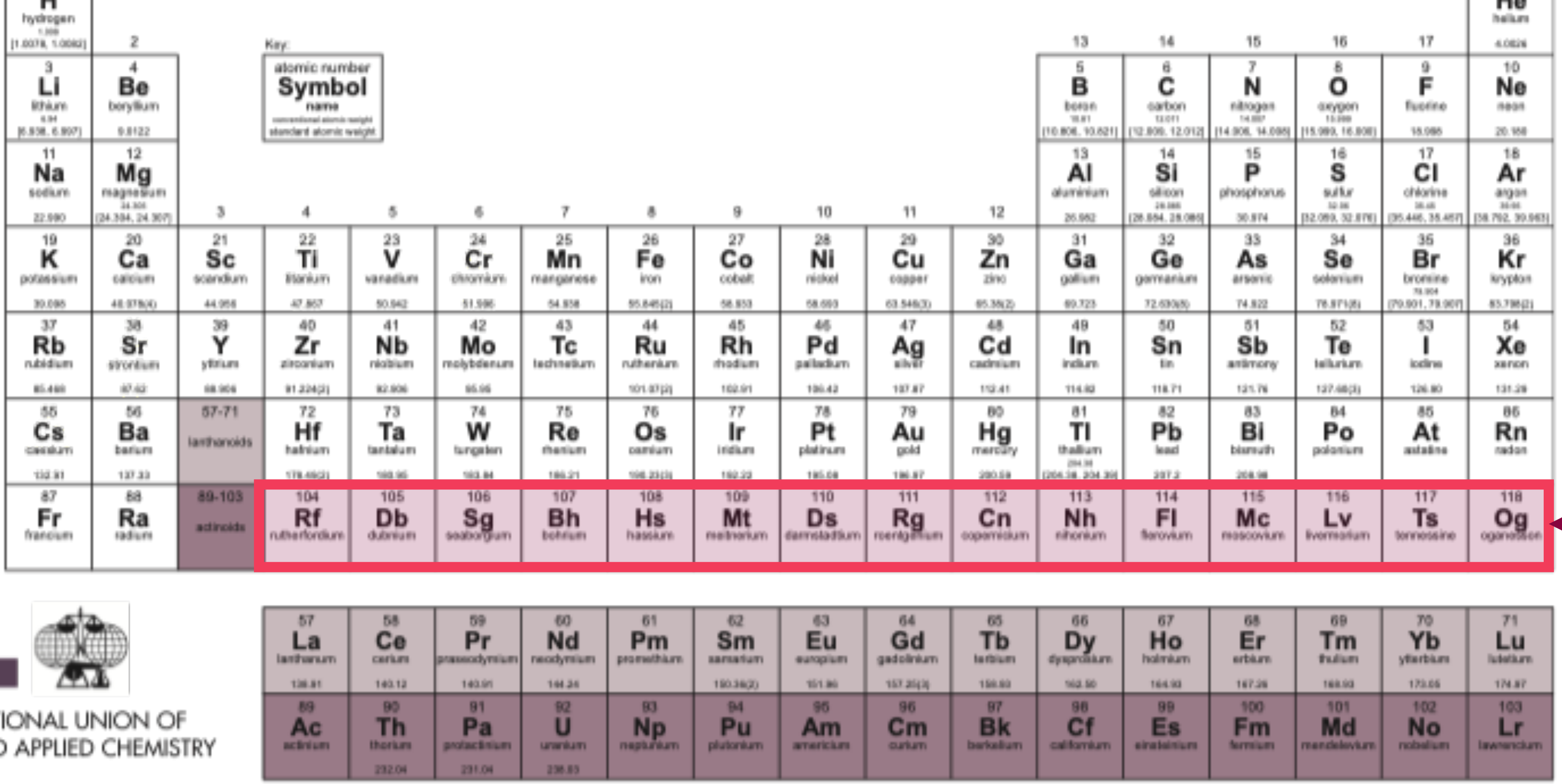
Dmitri Mendeleïev (1834–1907)

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

United Nations Educational, Scientific and Cultural Organization · International Year of the Periodic Table of Chemical Elements

Super Heavy Elements (SHE)

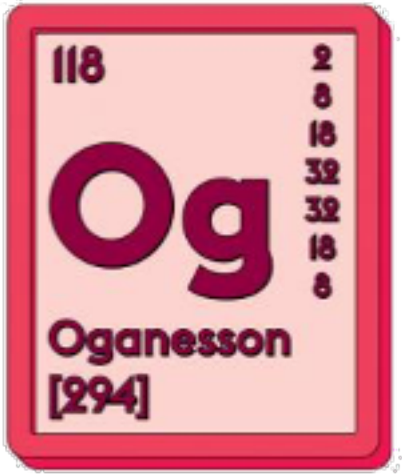
Transactinides: Z ≥ 104 (protons)



INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

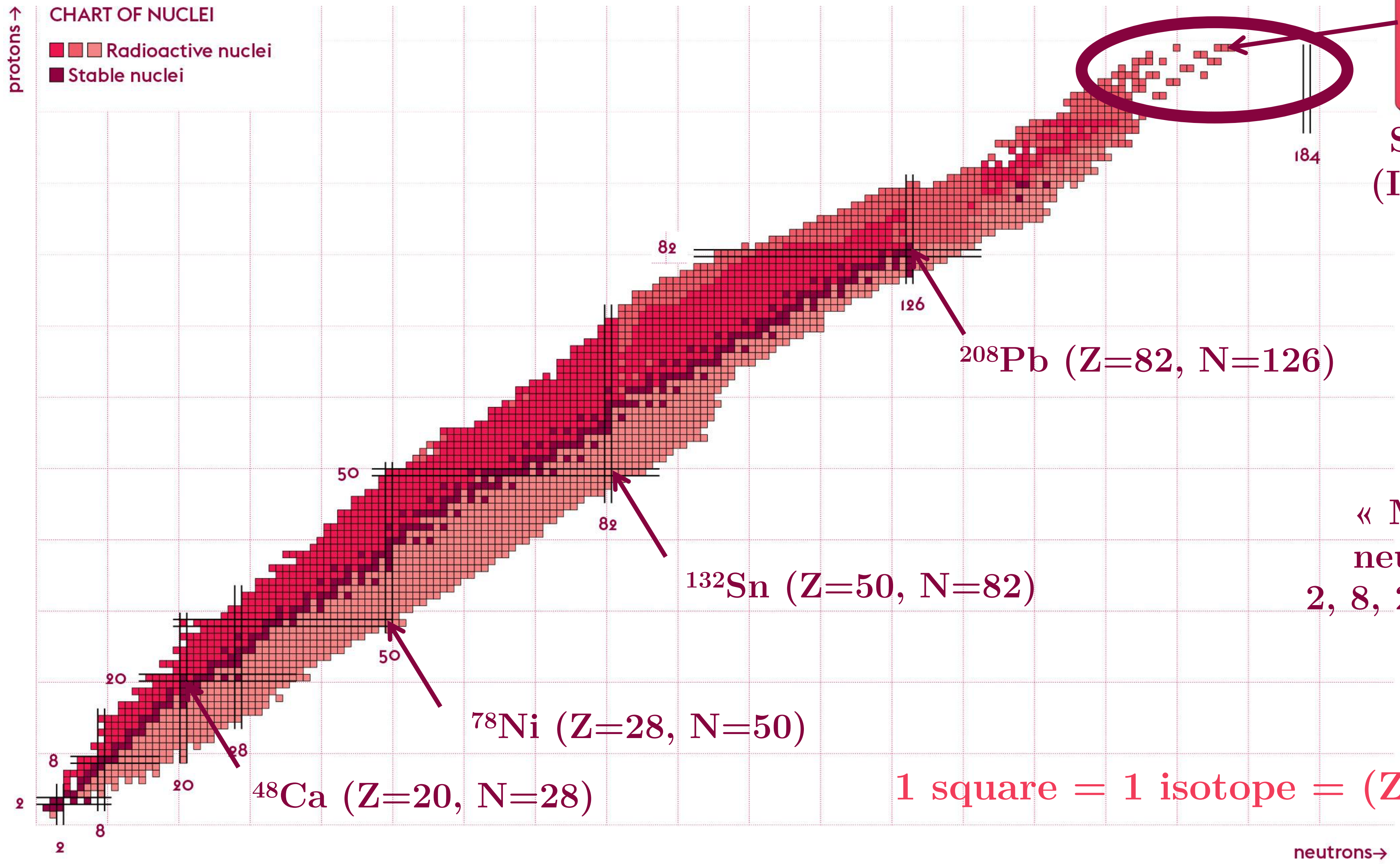
For notes and updates to this table, see www.iupac.org. This version is dated 1 December 2018.

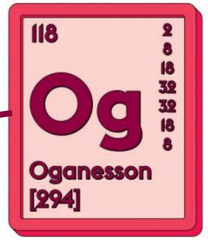
Iouri Oganessian
(1933–)



Discovered in 2012
Named in 2016

The chart of nuclides – the Sagrè chart





(Z=118, N=176)

Superheavy nuclei
(Island of stability?)

^{208}Pb (Z=82, N=126)

^{132}Sn (Z=50, N=82)

^{78}Ni (Z=28, N=50)

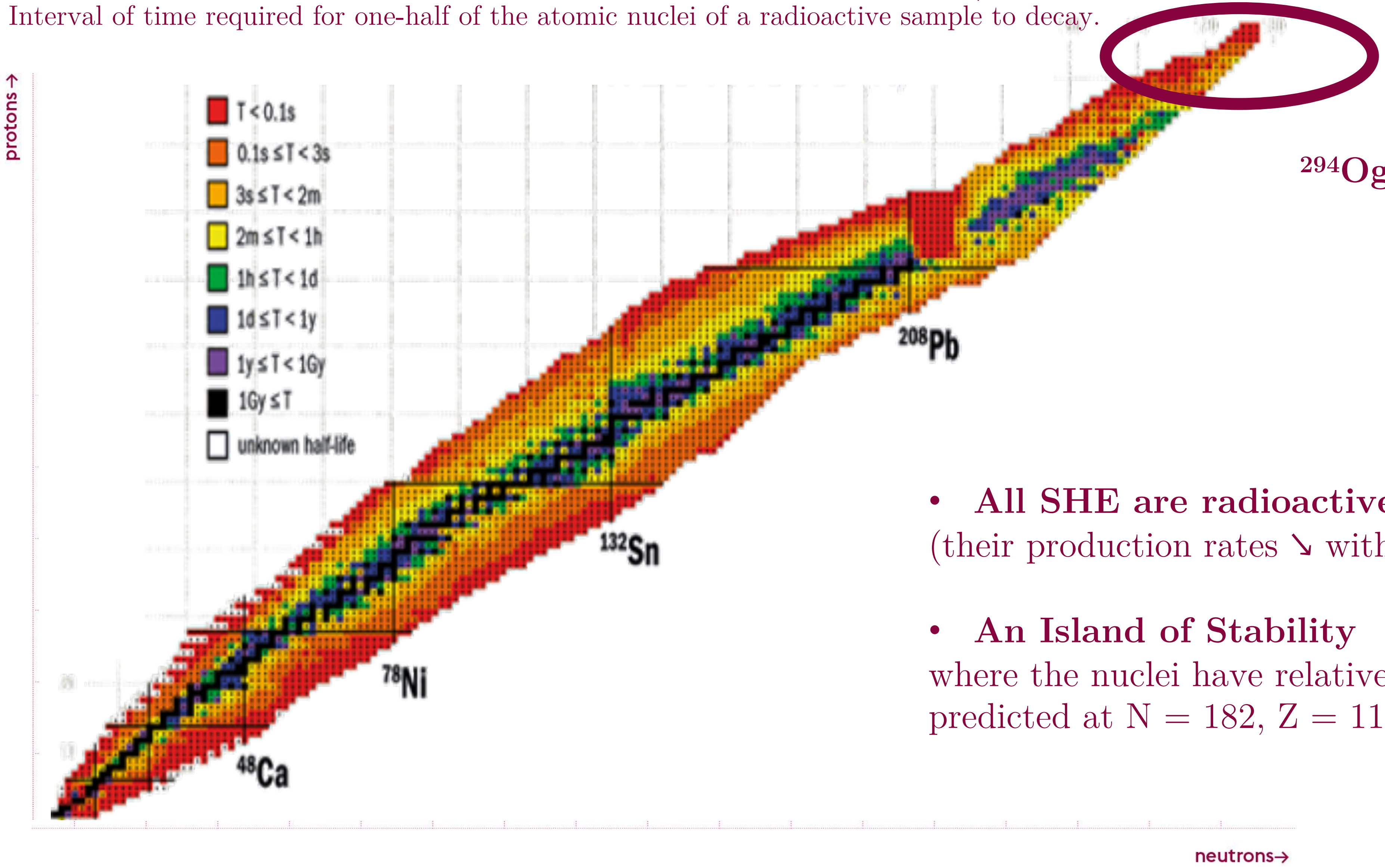
^{48}Ca (Z=20, N=28)

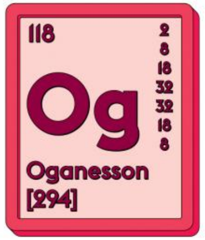
« Magic » numbers of neutrons and protons:
2, 8, 20, 28, 50, 82, 126, (?)

1 square = 1 isotope = (Z protons, N neutrons)

Half-lives of the isotopes

Half-life: rate at which a radioactive isotope decays ($t_{1/2}$)
Interval of time required for one-half of the atomic nuclei of a radioactive sample to decay.





(Z=118, N=176)

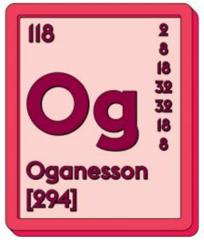
Superheavy nuclei

^{294}**Og: $t_{1/2} = 0{,}89\ ^{+1{,}07}{}_{-0{,}31}$ ms**

- **All SHE are radioactive**
(their production rates ↘ with number of protons Z ↗)

- **An Island of Stability**
where the nuclei have relatively long half-lives (> 1 year) predicted at N = 182, Z = 114 or 120 or 126.

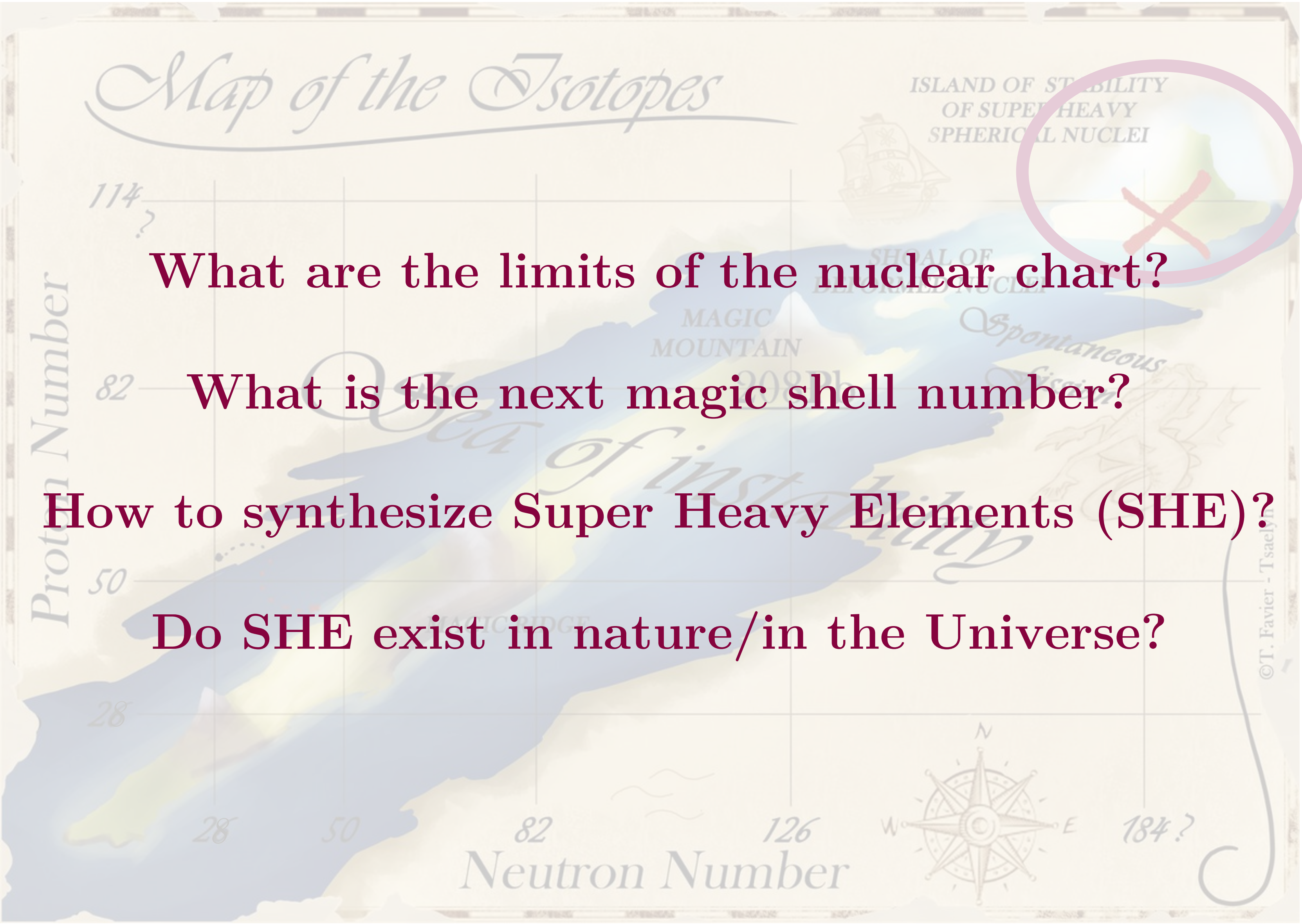
Island of stability (spherical SHE nuclei)?



Superheavy nuclei
($t_{1/2} > 1$ year?)

Height ↗
Stability ↗

Island of stability (spherical SHE nuclei)?

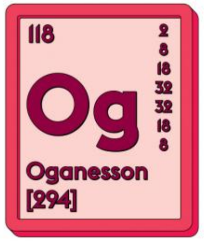


What are the limits of the nuclear chart?

What is the next magic shell number?

How to synthesize Super Heavy Elements (SHE)?

Do SHE exist in nature/in the Universe?



Superheavy nuclei
($t_{1/2} > 1$ year?)

Height ↗
Stability ↗

Superheavy elements in our Universe and in the lab!

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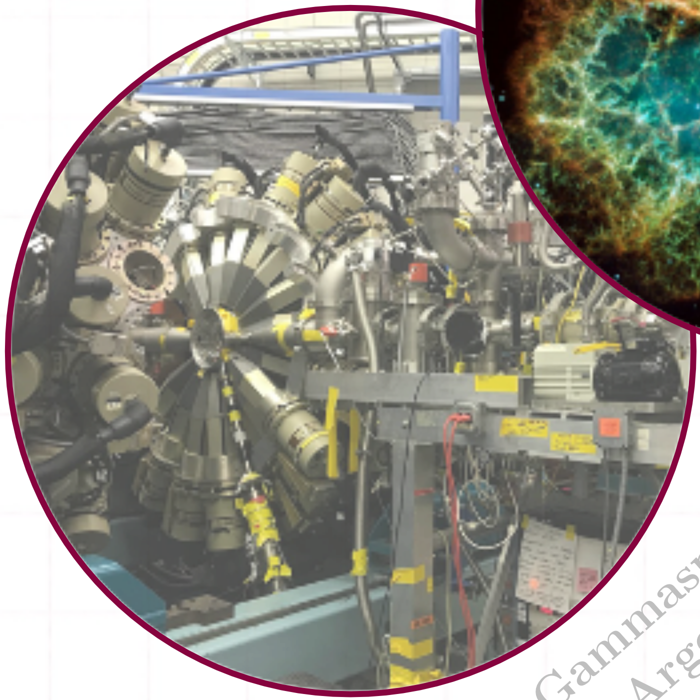
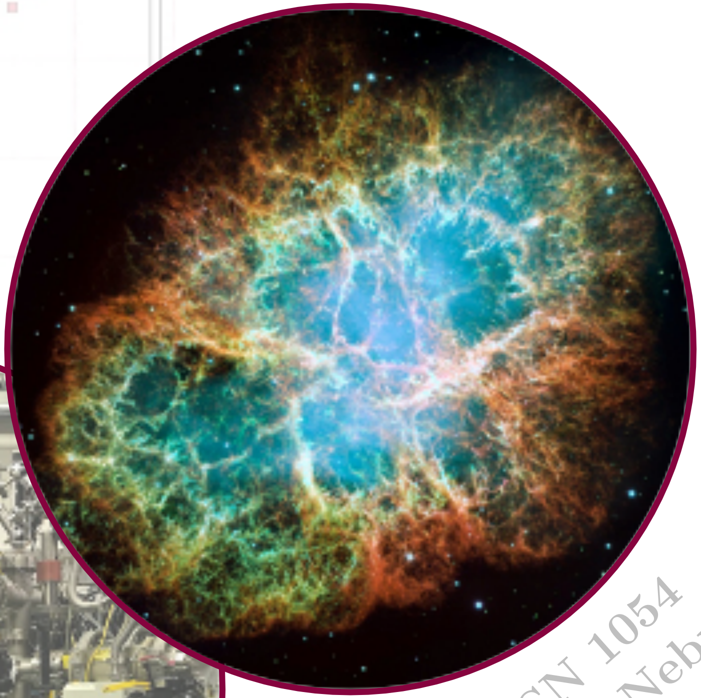
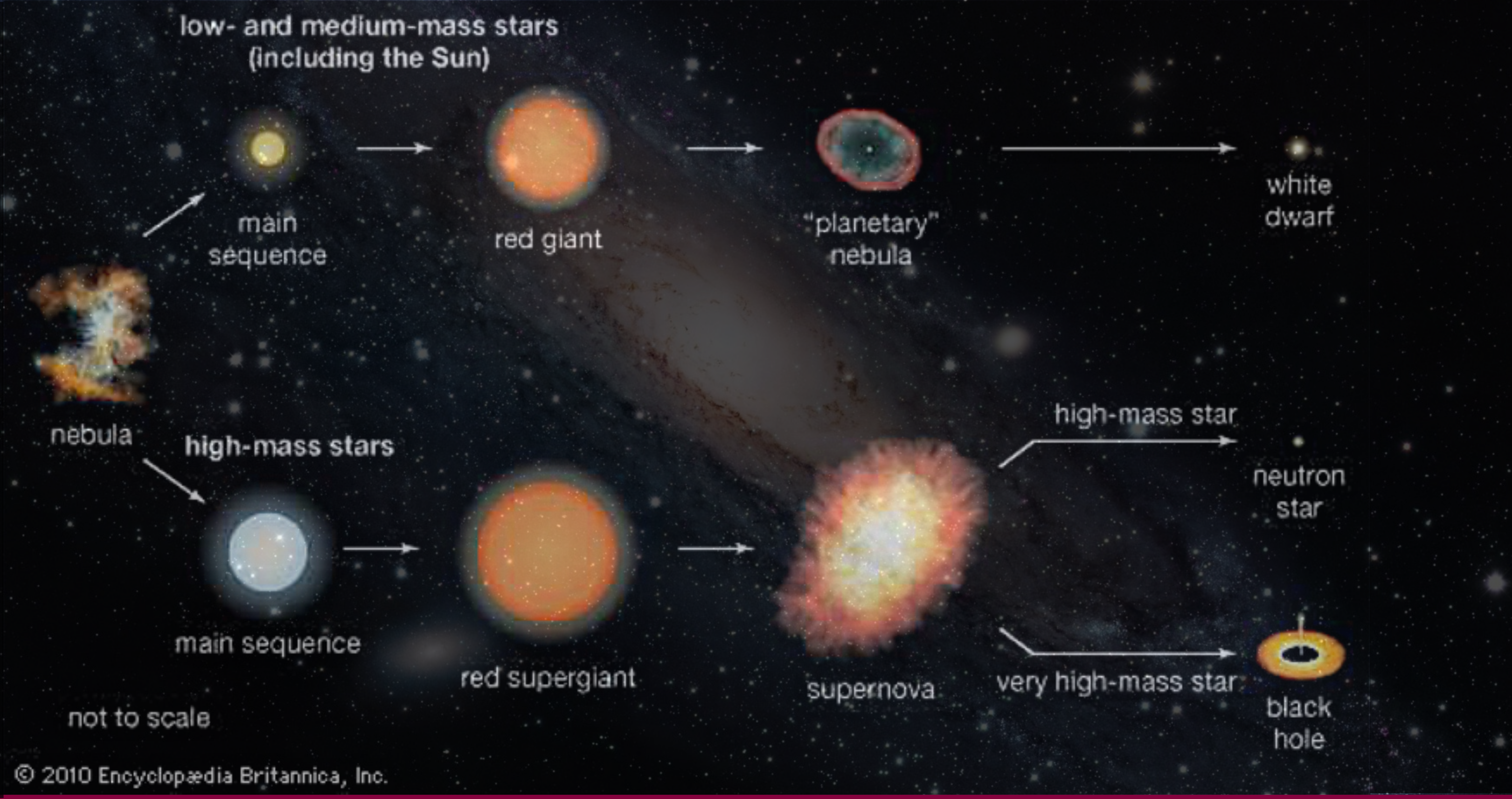


Gammasphere
Argonne



SN 1054
Crab Nebula

Stellar life cycle (stellar evolution)



Where are the SHE? – Astrophysical sites

Earth

(12 000 km)

Sun

(1 392 684 km)

Supernovae

(size a few solar masses)

Somewhere else?

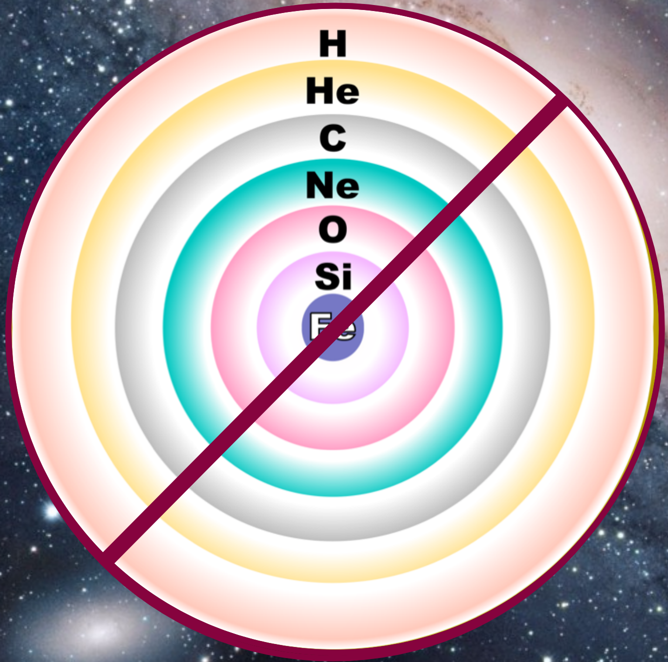
Not to scale

Where are the SHE? – Astrophysical sites

Heaviest element found:
U (Z=92)

Earth

Stellar Iron core and
onion like structure



Stars

Core-colapse
Exploding stars
r-process?

Supernovae
(size a few solar masses)

Somewhere else?

Not to scale

Where are the SHE? – Astrophysical sites

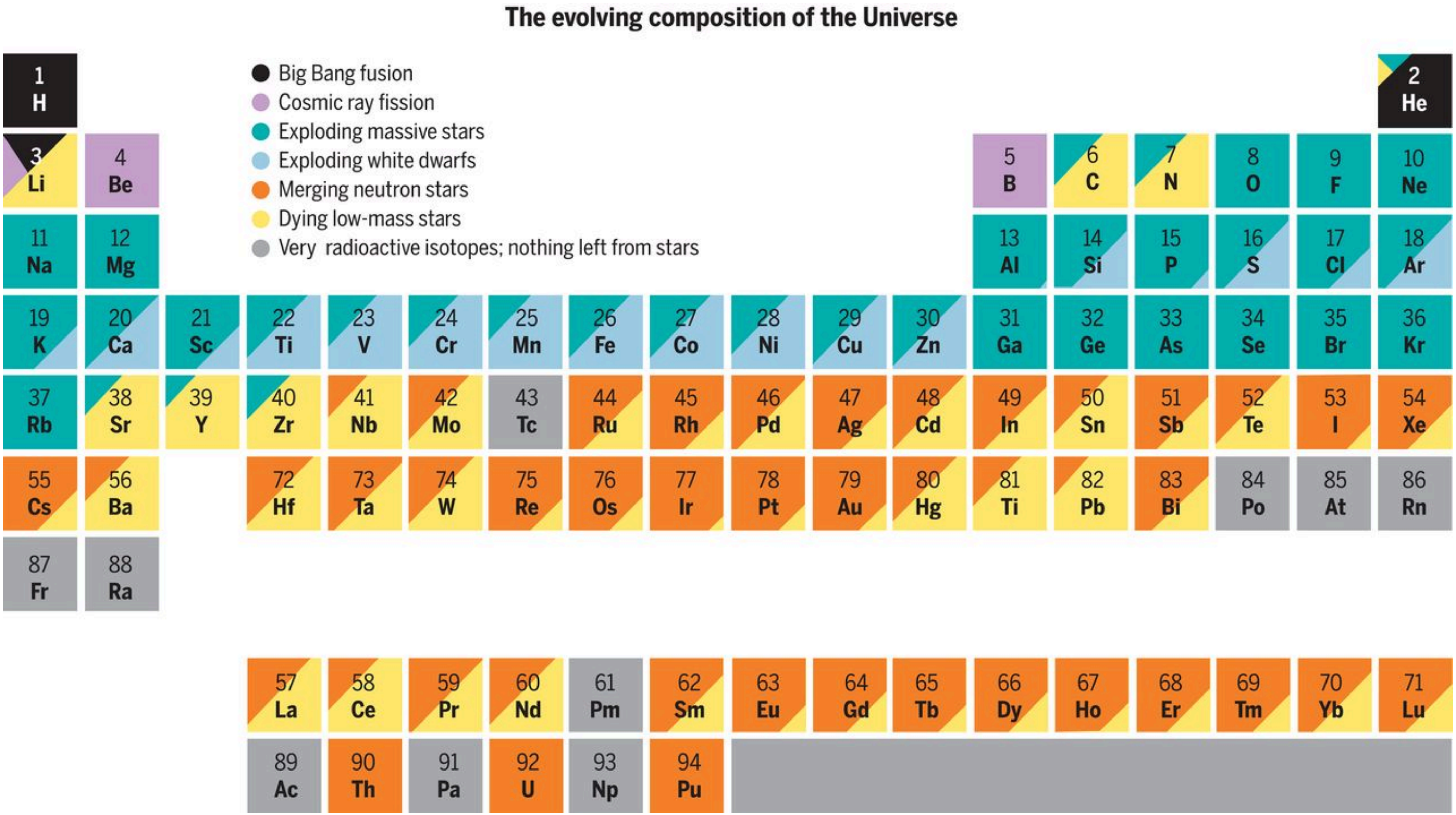
Mergers of 2 neutron stars (NS-NS)
or Merger of a neutron star (NS) and a black hole (BH)

The observation of GRB170807A/GW170817 originating from a neutron star merger has been published on October 16, 2017 and is a first proof of the nucleosynthesis of heavy elements in the r-process.

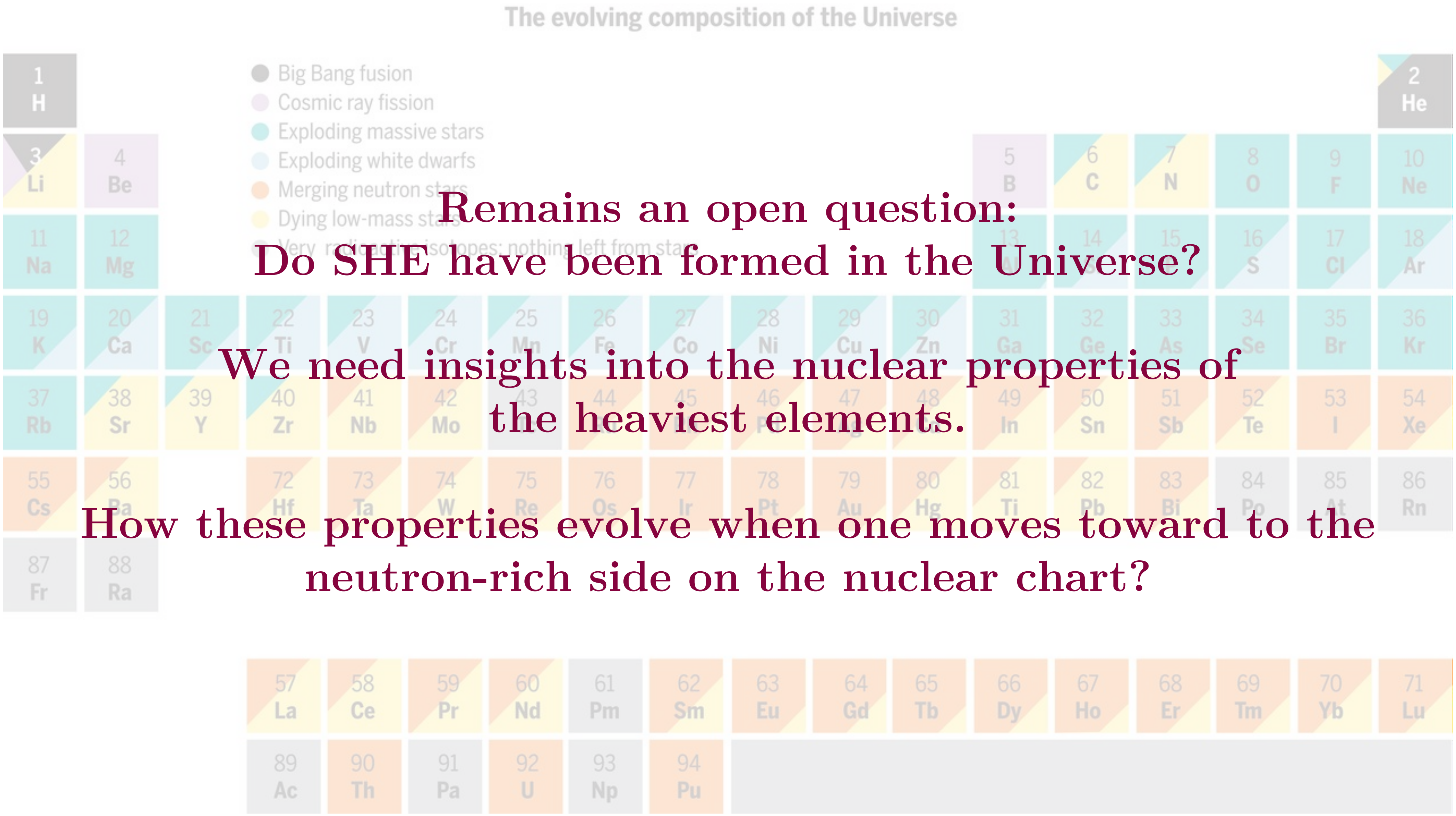
Somewhere else?

Not to scale

Cosmological origin of each element – missing SHE!



Cosmological origin of each element – missing SHE!



Remains an open question:
Do SHE have been formed in the Universe?

We need insights into the nuclear properties of the heaviest elements.

How these properties evolve when one moves toward to the neutron-rich side on the nuclear chart?

Superheavy elements in our Universe and in the lab!

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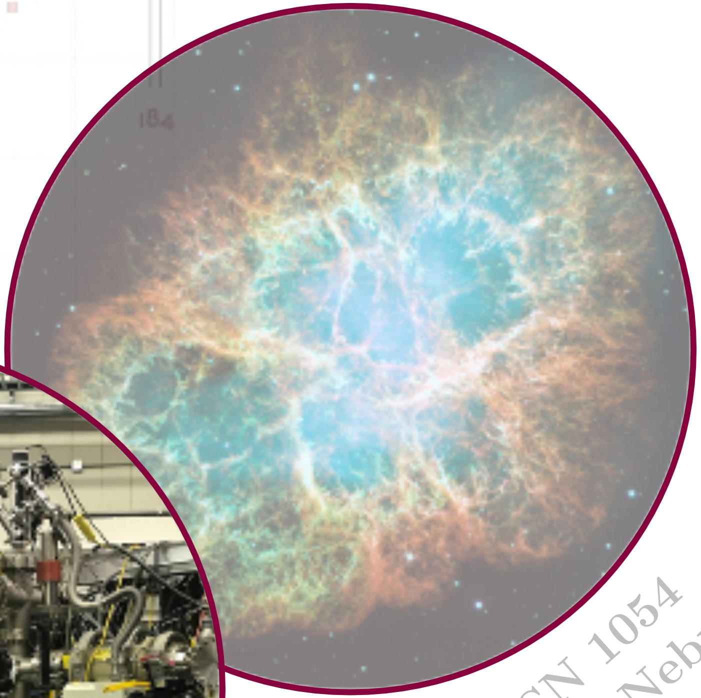

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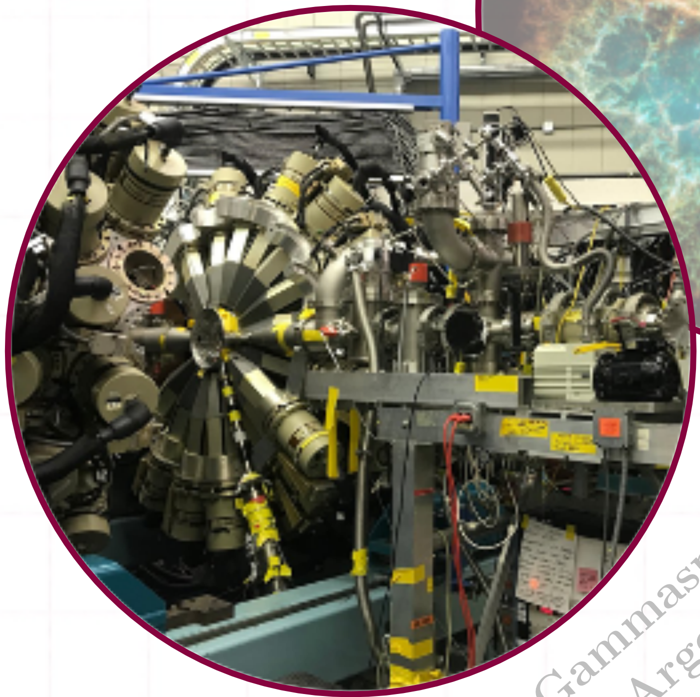

Gammasphere
Argonne

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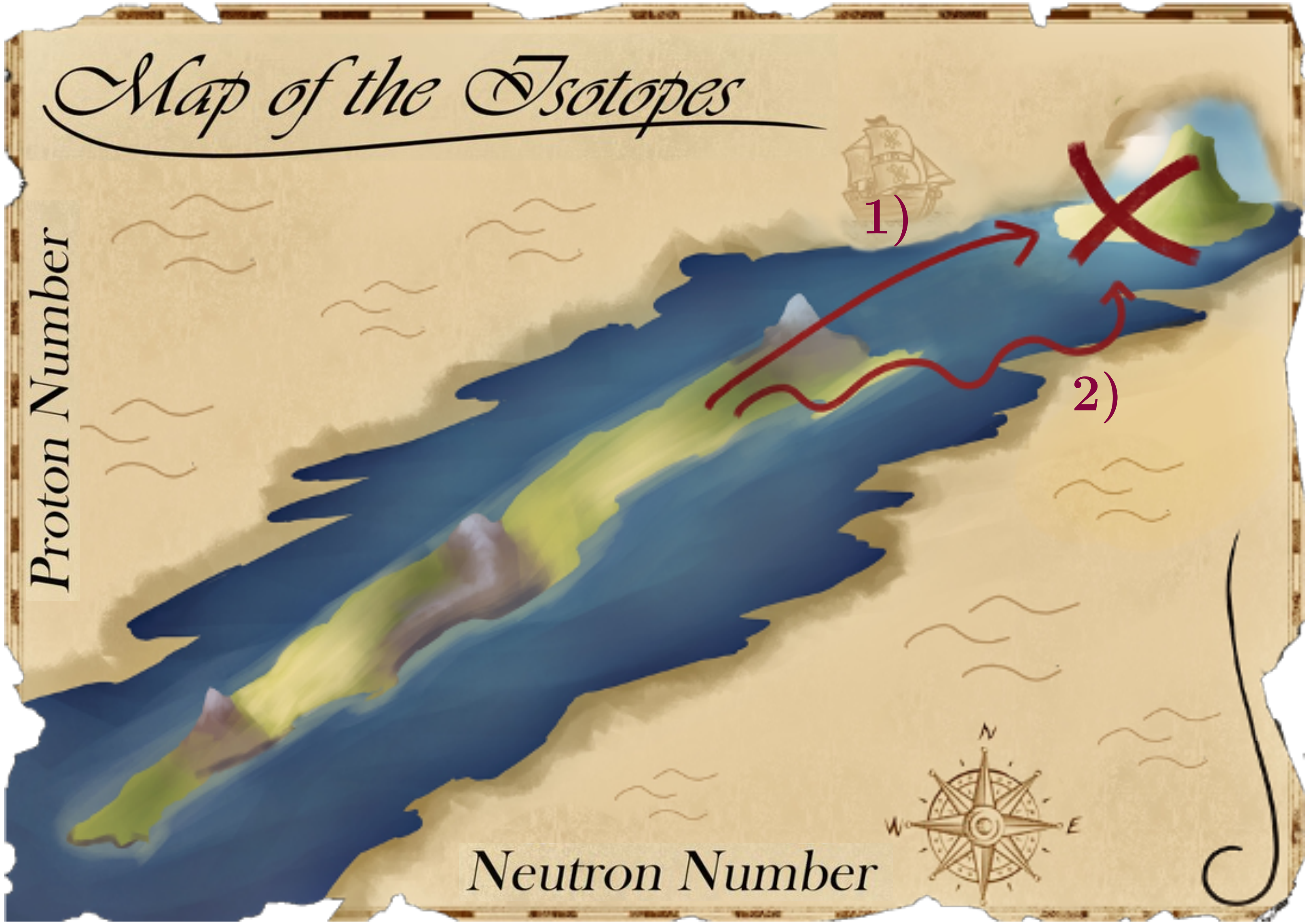
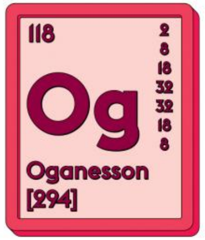
RJP

Reaction mechanisms to produce SHE



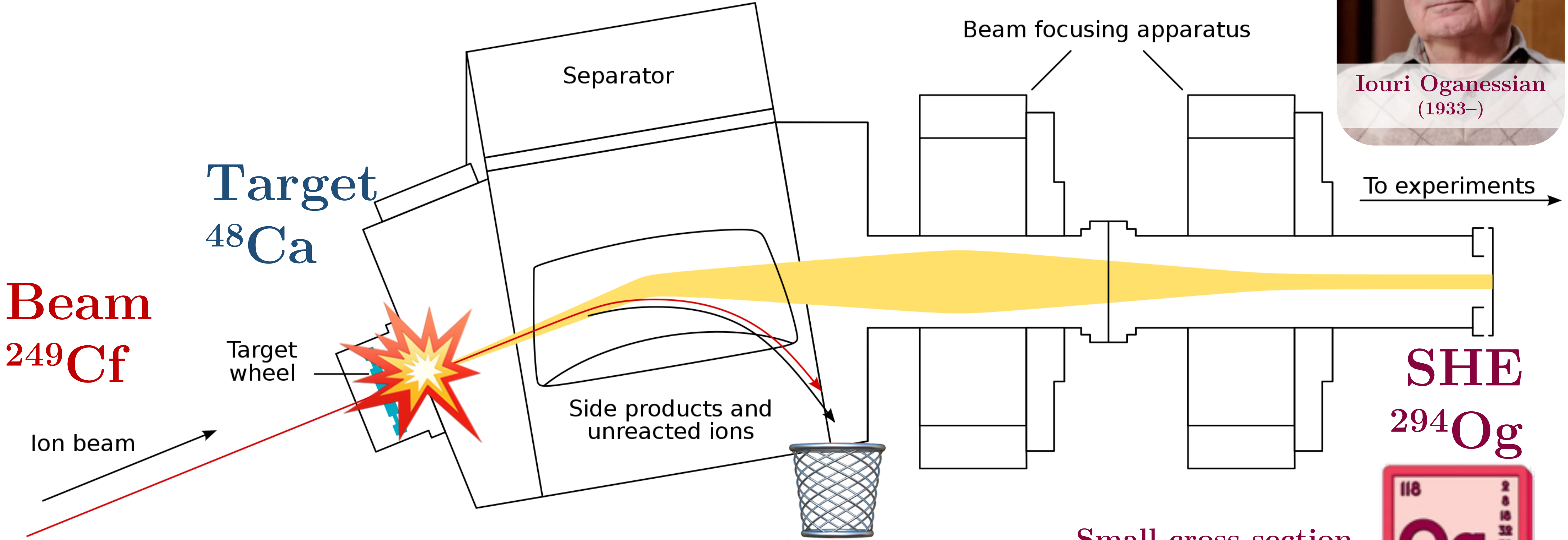


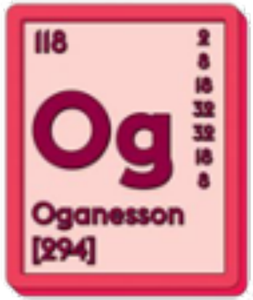
1) Fusion-evaporation

2) MultiNucleon Transfer (MNT)

Discovery of Oganesson at JINR (Dubna🇷🇺)

1) Fusion-evaporation

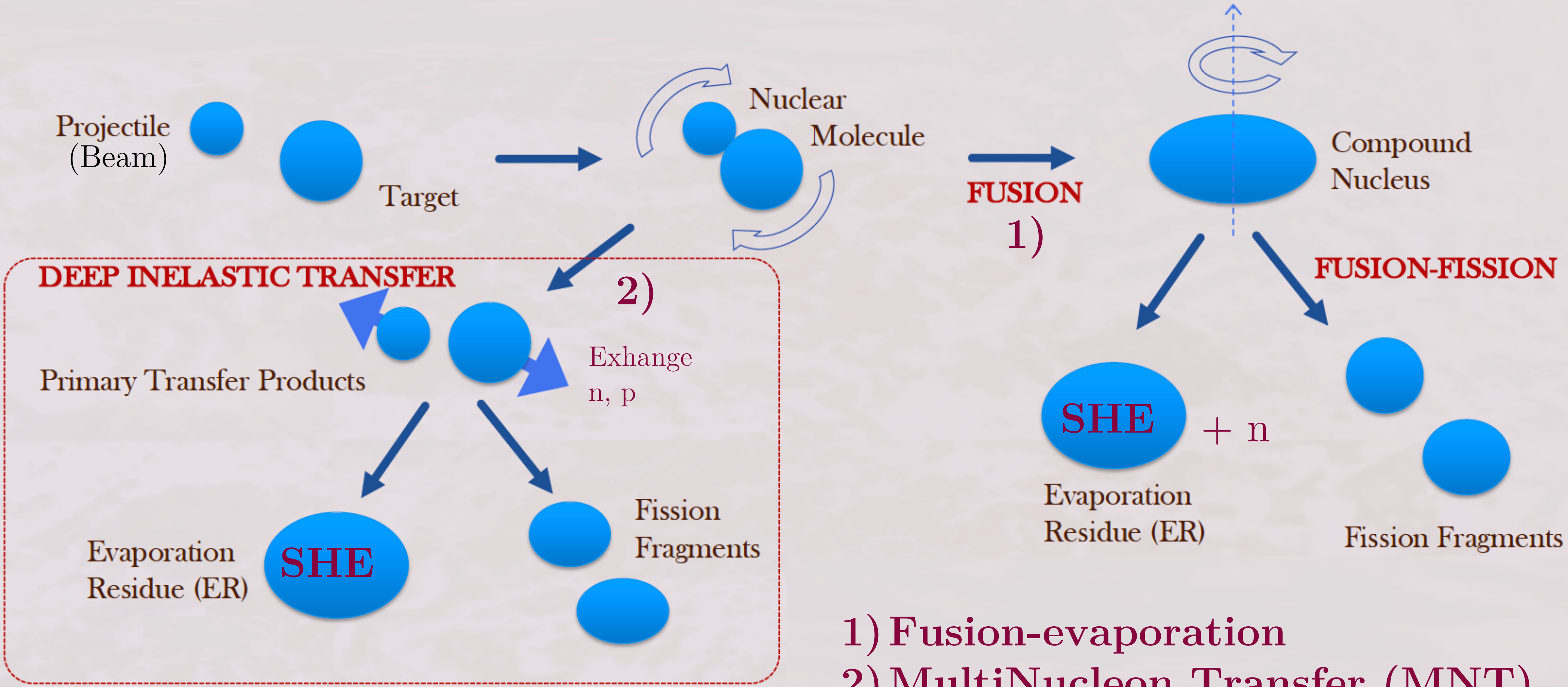




Small cross-section
(probability of production)

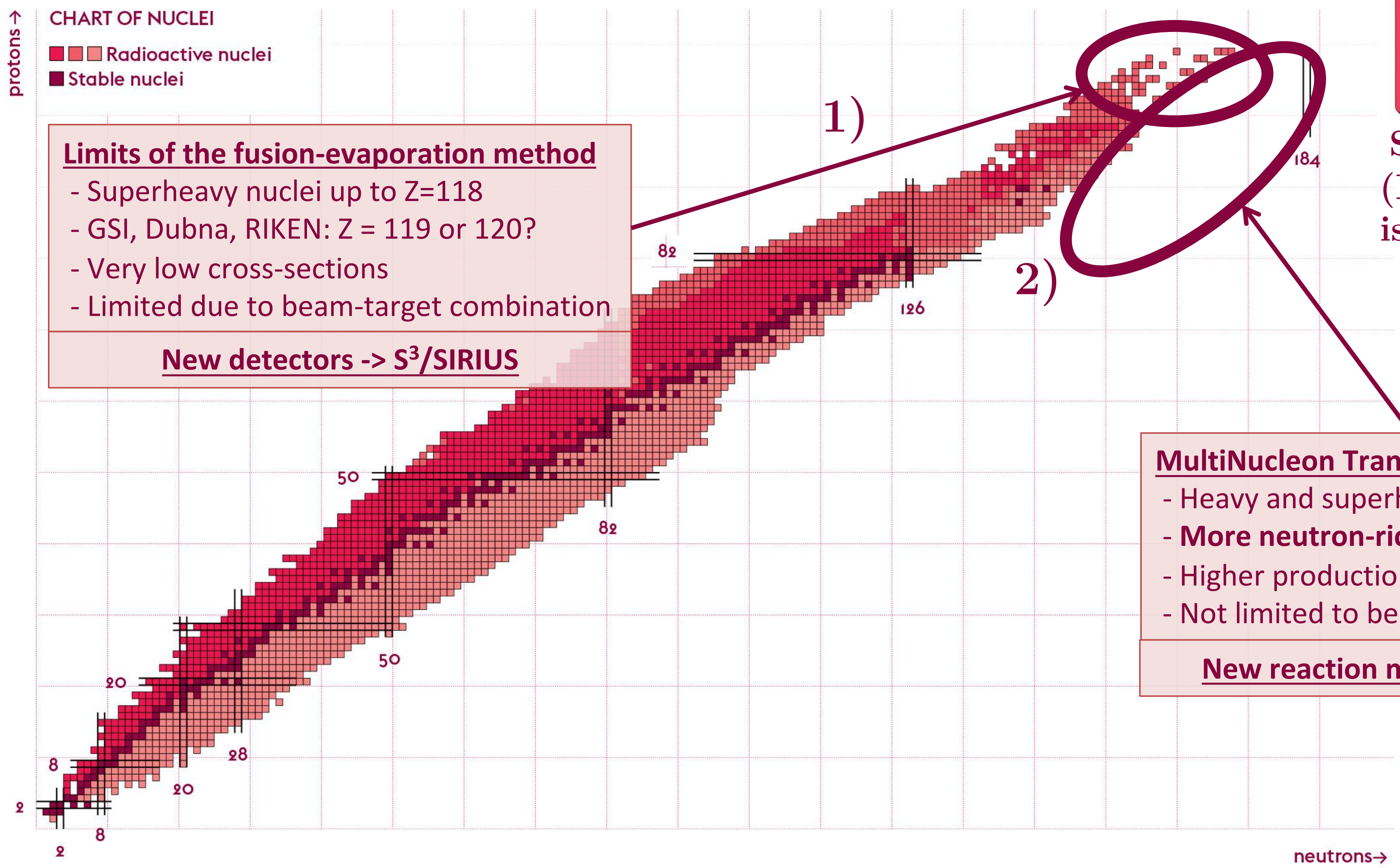
Only 3 nuclei produced during several months of experiment.

Reaction mechanisms to produce SHE



1) Fusion-evaporation
2) MultiNucleon Transfer (MNT)

Reaction mechanisms towards the SHE!



Limits of the fusion-evaporation method
- Superheavy nuclei up to Z=118
- GSI, Dubna, RIKEN: Z = 119 or 120?
- Very low cross-sections
- Limited due to beam-target combination

New detectors -> S^3/SIRIUS

118 Og Oganesson [294] 2 8 18 32 32 18 8 (Z=118, N=176)

Superheavy nuclei (More neutron-rich island of stability?)

MultiNucleon Transfer (MNT) reactions
- Heavy and superheavy nuclei?
- **More neutron-rich nuclei**
- Higher production cross-section?
- Not limited to beam-target combination

New reaction mechanisms -> MNT

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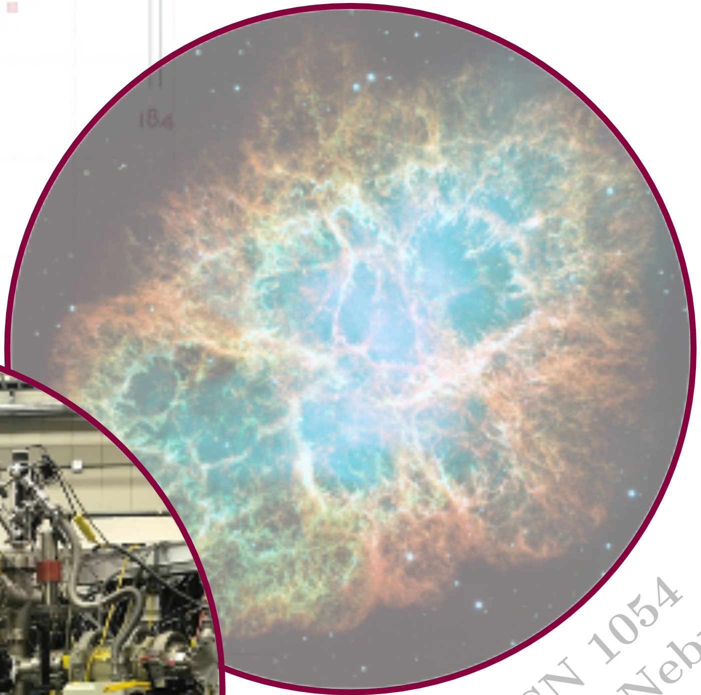

SN 1054
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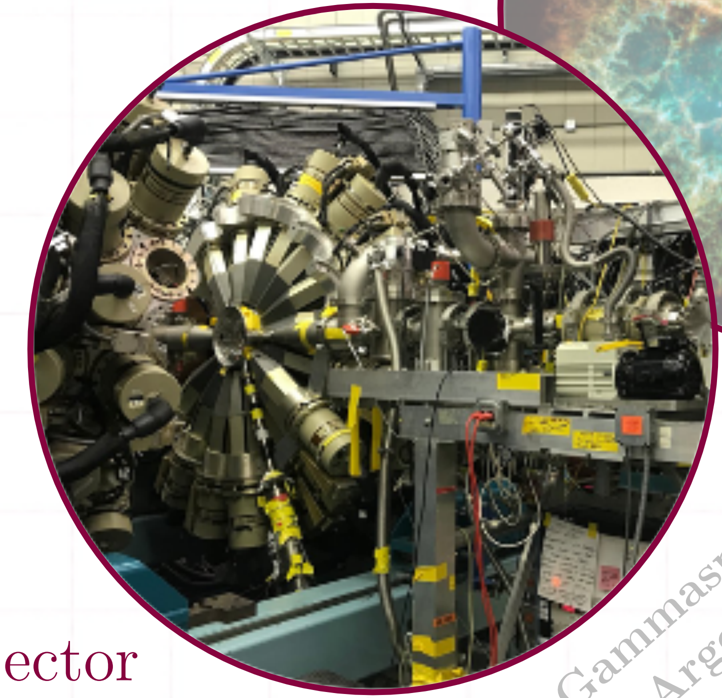

Gammasphere
Argonne

Société Française de Physique

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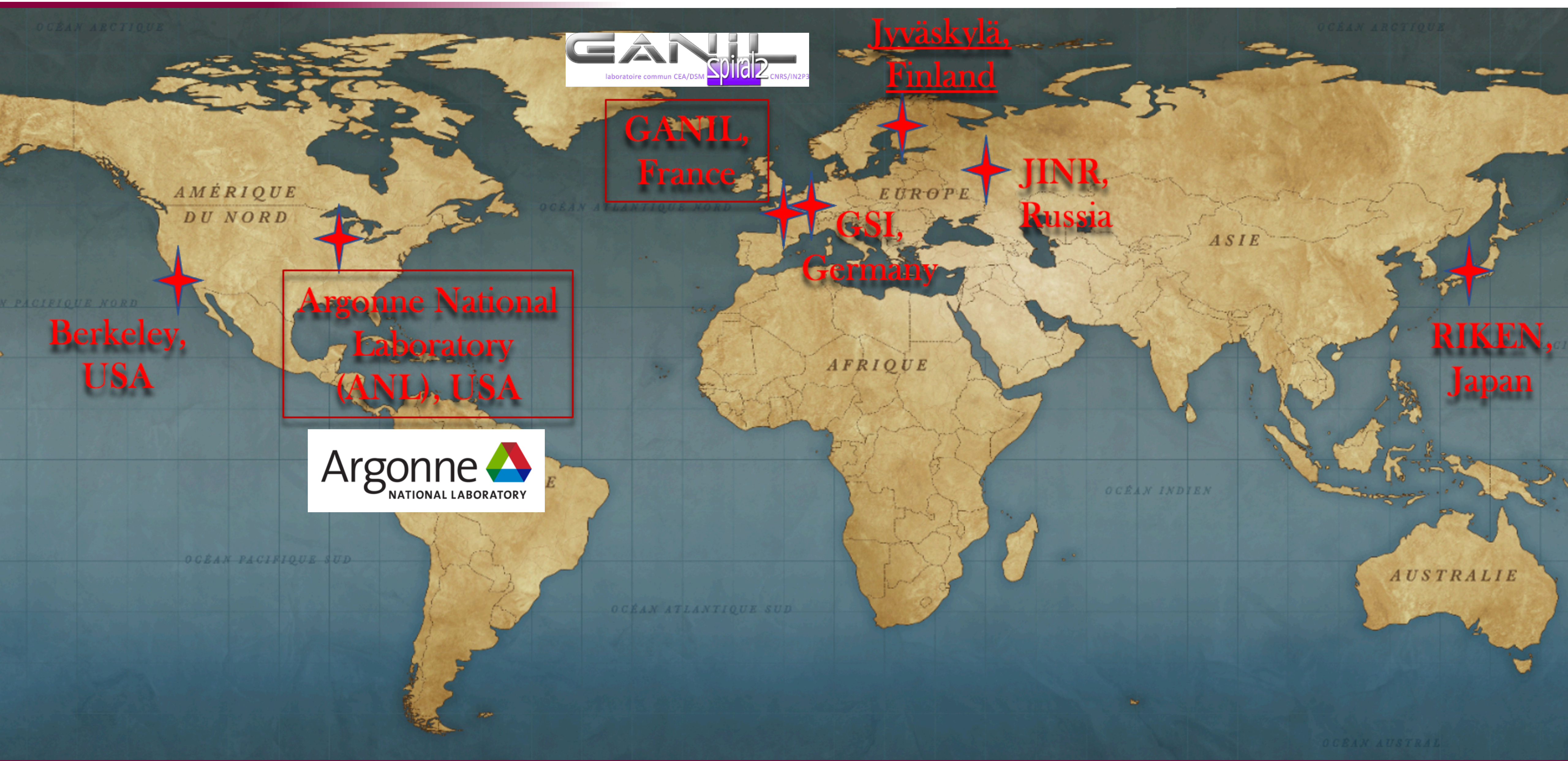
Worldwide facilities – international collaborations



Multinucleon transfer reactions (MNT) at Argonne

Proposed the experiment

Carried out the experiment in Nov 2019

Analyse the data

Synthesis of heavy and superheavy neutron-rich nuclei in multinucleon transfer reactions close to 0°

Z. Favier, B. Sulignano, Ch. Theisen, A. Drouart, Th. Goigoux, W. Korten, M. Siciliano, M. Vandebrouck, M. Zielińska
CEA Saclay, IRFU/DPhN, Gif-sur-Yvette, France

D. Seweryniak, M.P. Carpenter, B.B. Back, P. Copp, T. Huang, F.G. Kondev, T. Lauritsen, D. Potterveld, G. Savard
Argonne National Laboratory, Argonne, USA

W. Loveland
Oregon State University, Corvallis, USA

P. Reider, L. Kaya
University of Cologne, Cologne, Germany

A. Korichi
CSNSM, Orsay, France

S. Antalic
Comenius University, Bratislava, Slovakia

D. Ackermann, H. Savajols
GANIL, Caen, France

J. Khuyagbaatar, A. Di Nitto, S. Heinz
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

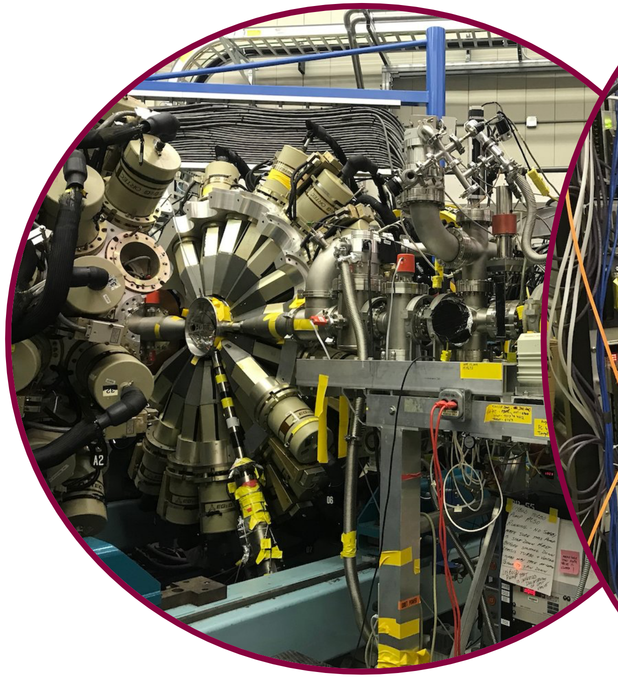
March 2019

Abstract

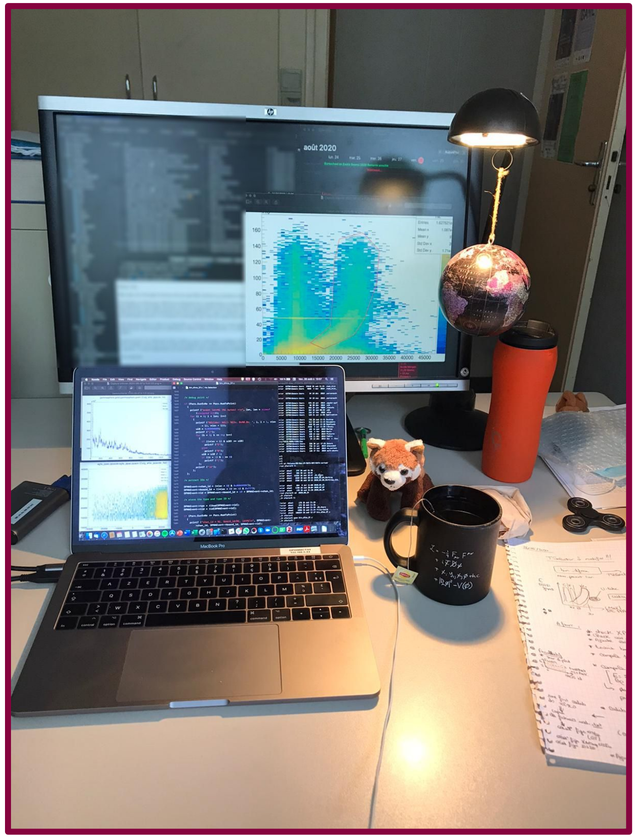
Information on the heaviest elements have been obtained up to now via fusion evaporation reactions. It is however well known that the only nuclei one can reach using fusion-evaporation reactions are neutron deficient and moreover in a very limited number (because of the limited number of beam-target combinations). An alternative to fusion-evaporation can be deep-inelastic collisions. Indeed, theoretical calculations [1] predict large cross-sections for neutron-rich heavy elements production close to zero degrees and recent experiments have been performed showing exciting results [2, 3, 4]. The goal of this proposal is to investigate deep inelastic reactions mechanisms in the heavy elements region using the Gammasphere germanium array coupled to AGFA separator with the implantation-decay station (DSSD) and germanium detector at the focal plane. The multinucleon transfer reaction with a ^{136}Xe beam on a ^{238}U target at zero degrees and near barrier collision energies has to be considered as a "first step towards" experiment for future synthesis of new superheavy neutron-rich isotopes. This proposal is part of a PhD thesis project.

1

Accepted at PAC2019

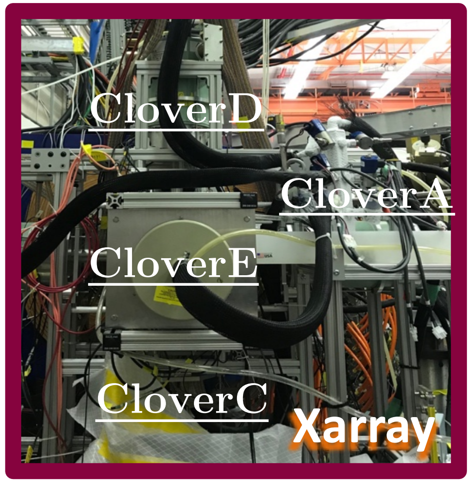


Argonne NATIONAL LABORATORY



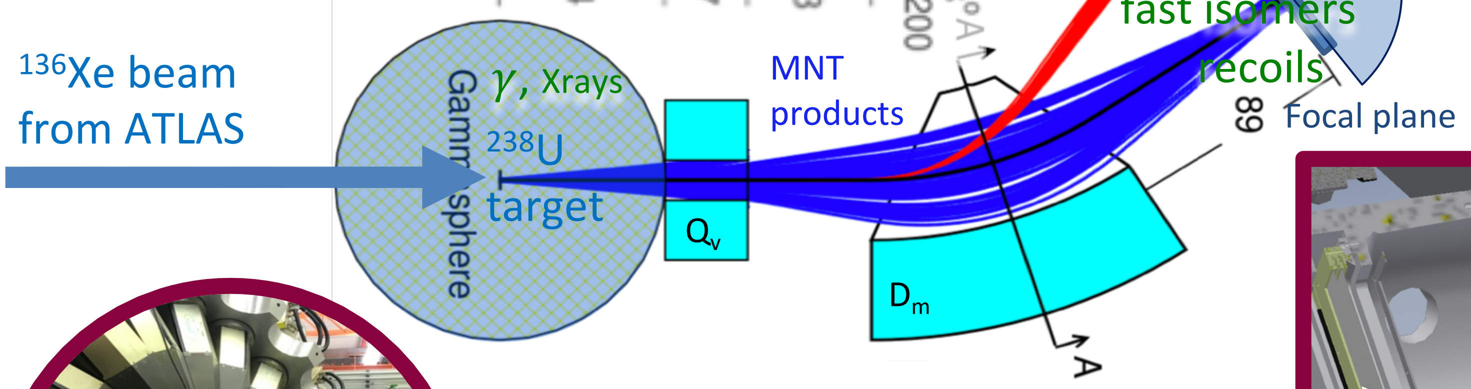
Multinucleon transfer reactions (MNT) at Argonne

- **Proof-of-principle experiment to study neutron-rich heavy nuclei using MNT reactions**
- 1st MNT reaction using AGFA @ANL to produce heavy nuclei
- **Beam**: **^{136}Xe** @605, 705 and 809MeV
- **Target**: **^{238}U** (UF4 300µg/cm^2 + C 40µg/cm^2)
- Innovative solutions to increase AGFA helium pressure up to 3Torr (Ti window after the target chamber)

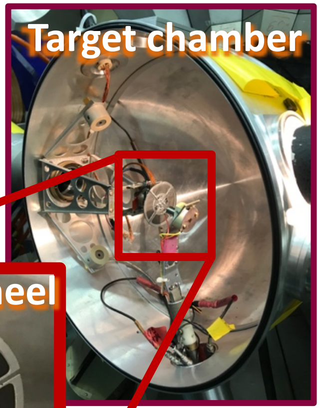


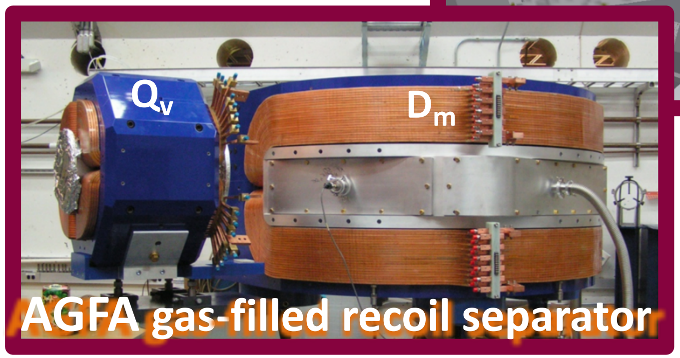
Target-like products identification

(coincidences)



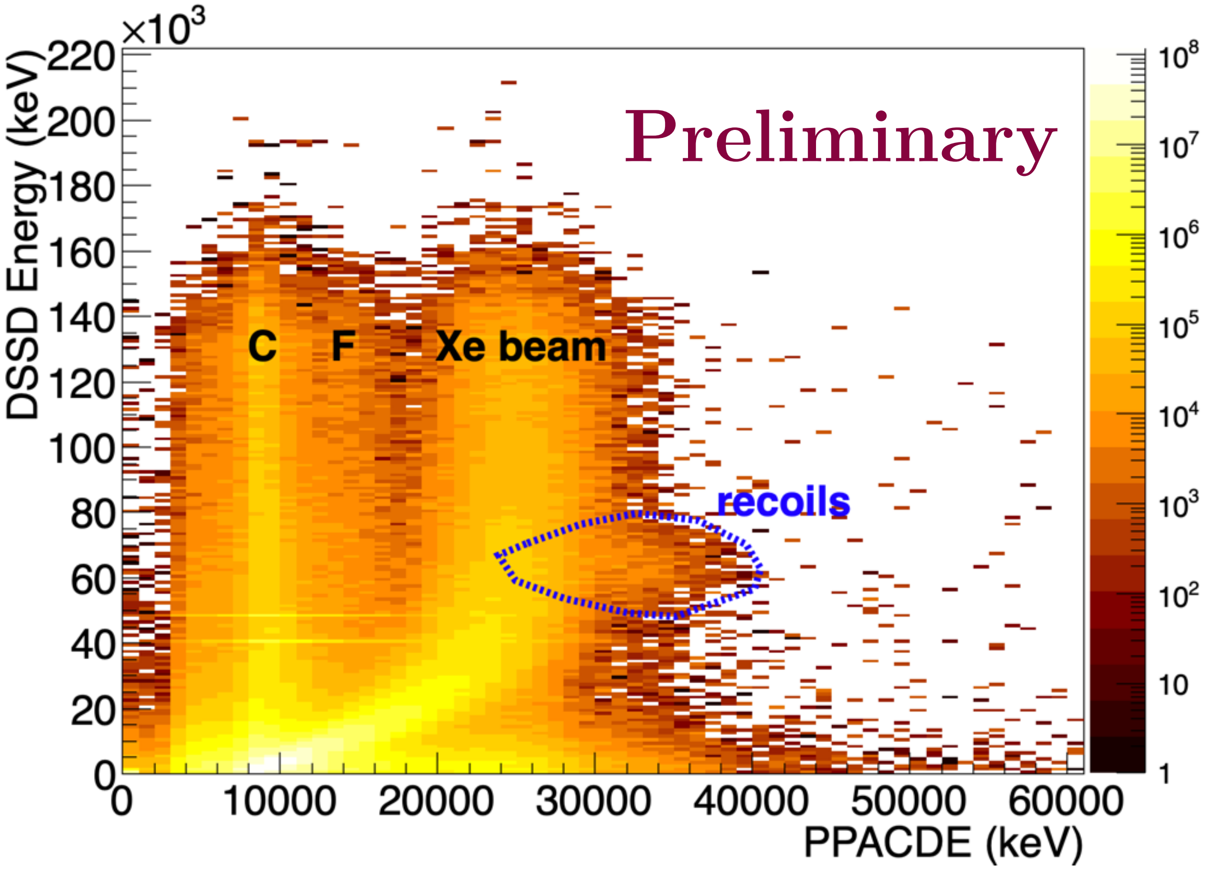
Data Analysis is on going

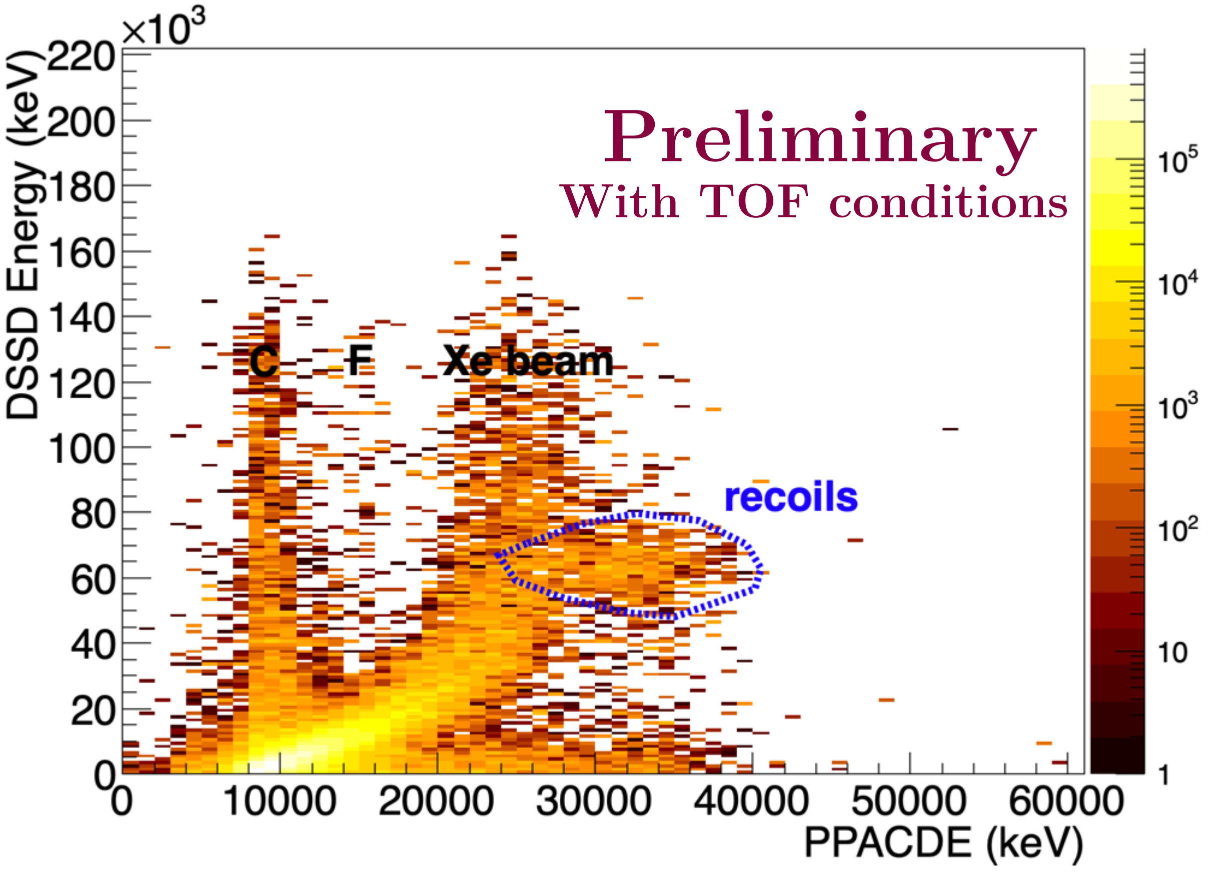




Argonne NATIONAL LABORATORY

Identification of neutron-rich nuclei (recoils)





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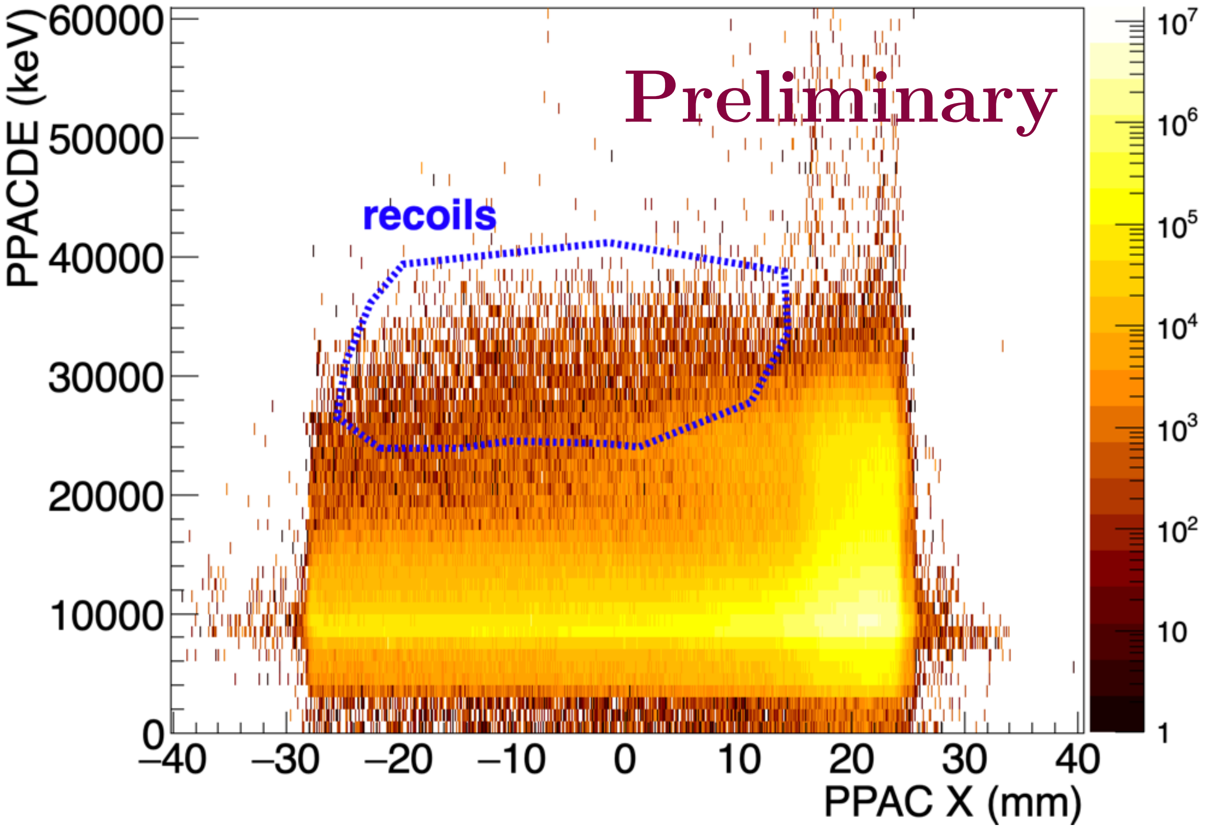
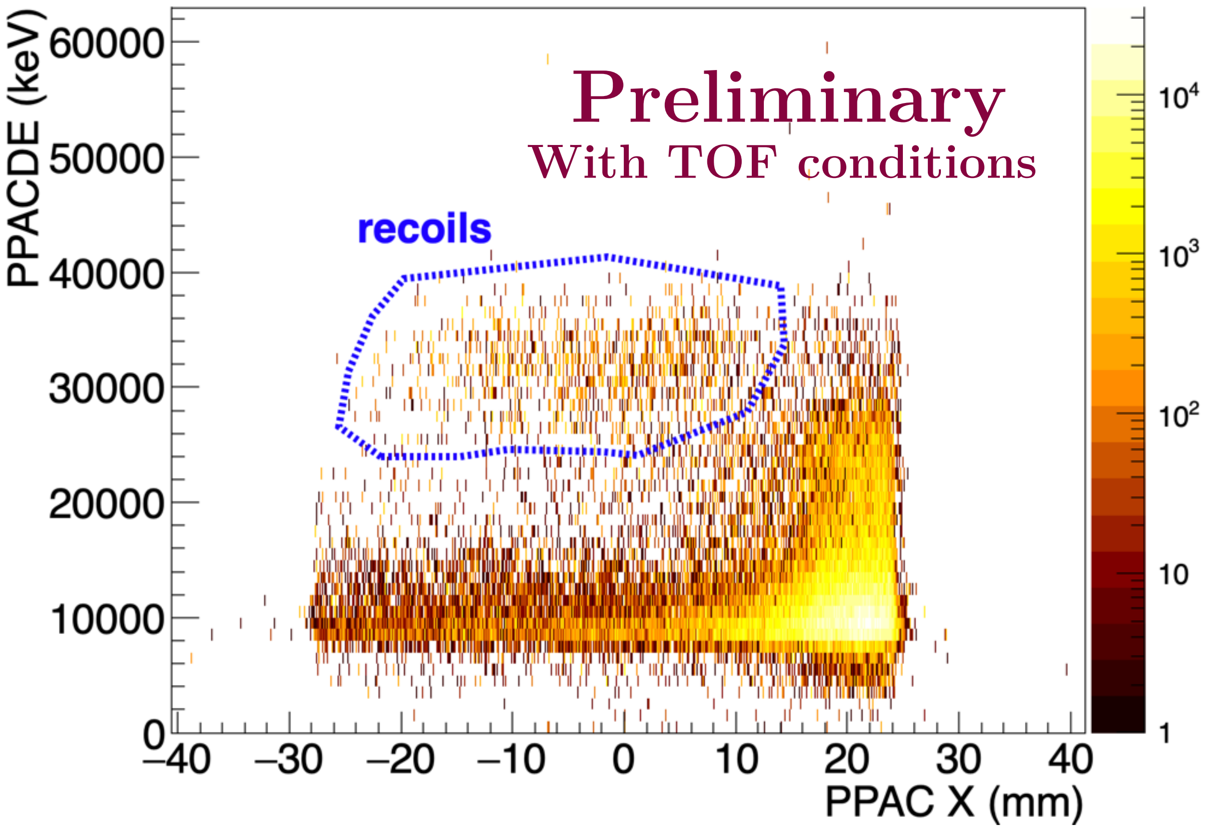
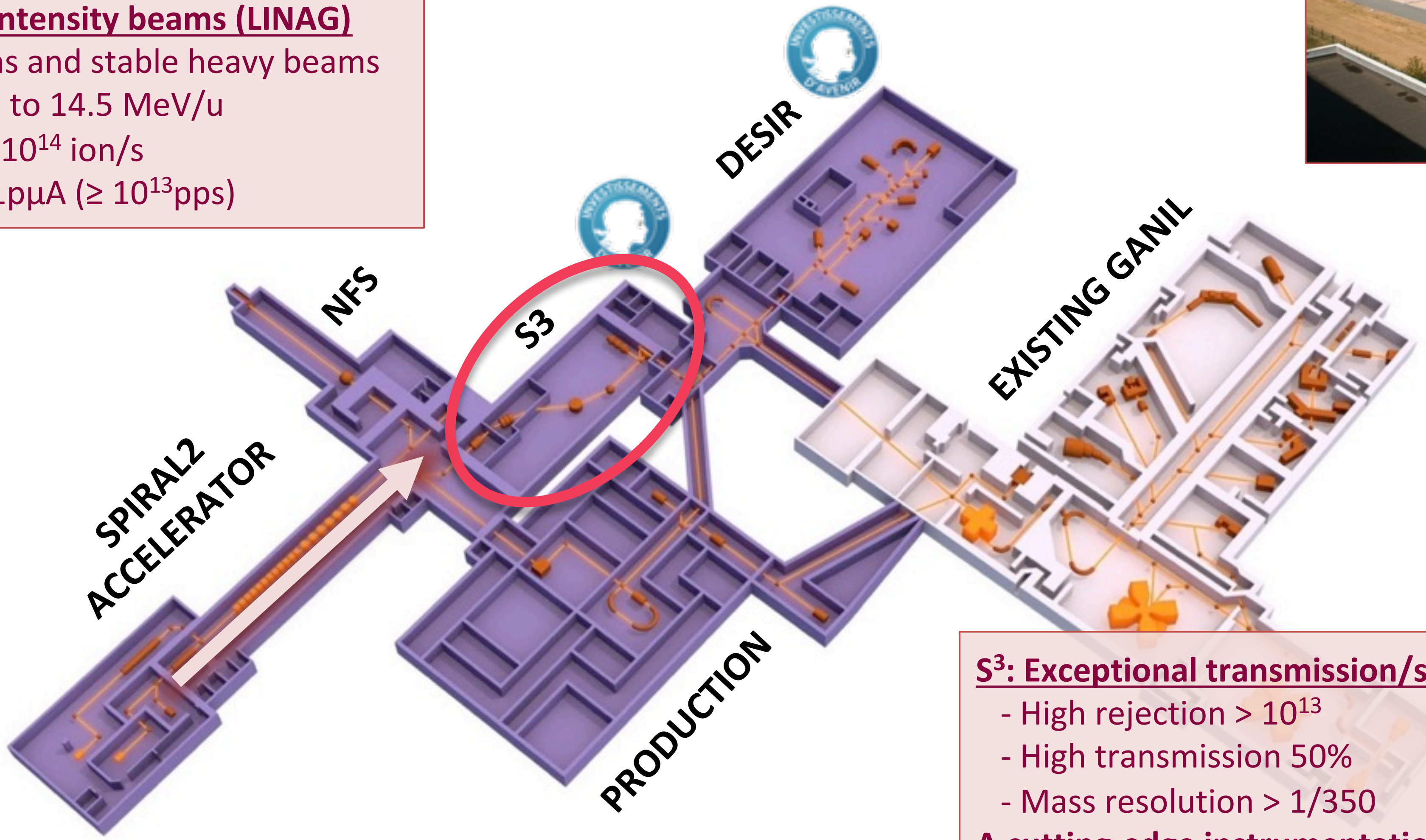




S^3 in the SPIRAL2 project at GANIL

Very high intensity beams (LINAG)
- Deuterons and stable heavy beams
- E_{beam}= up to 14.5 MeV/u
- Intensity 10^{14} ion/s
  beyond 1pμA (≥ 10^{13}pps)

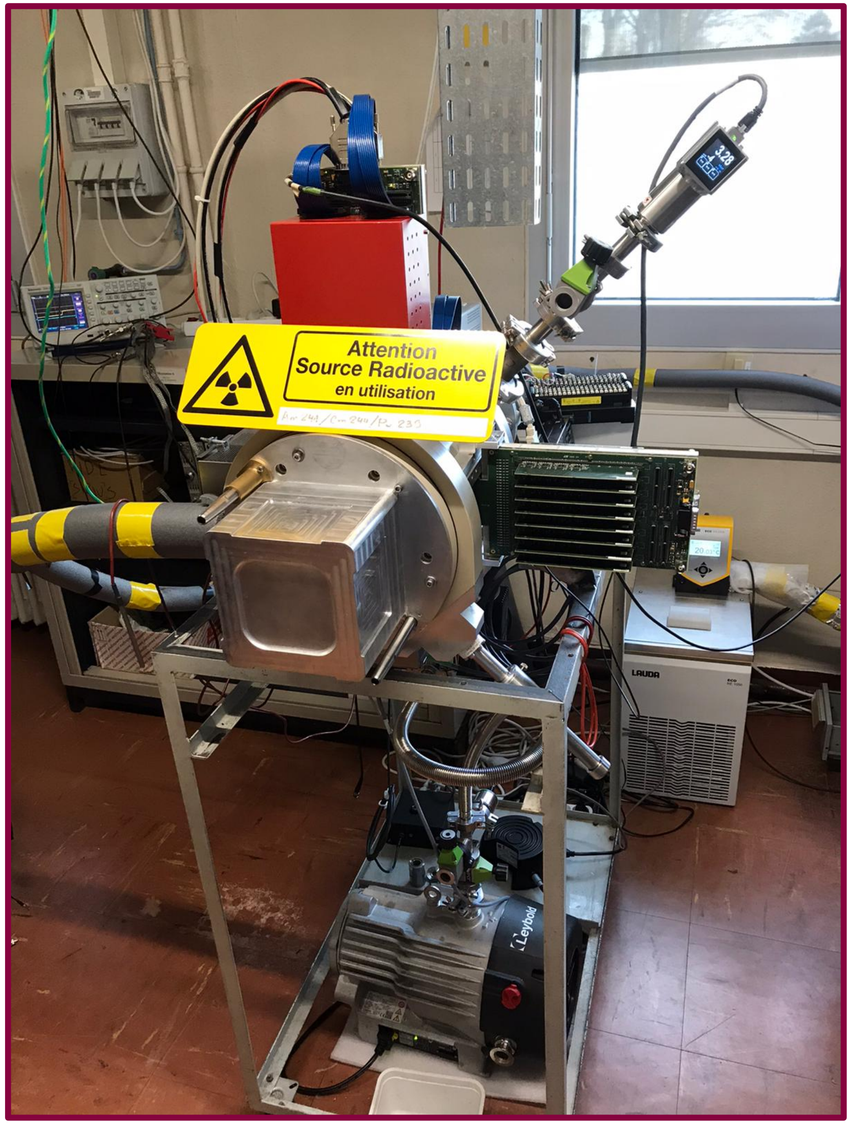


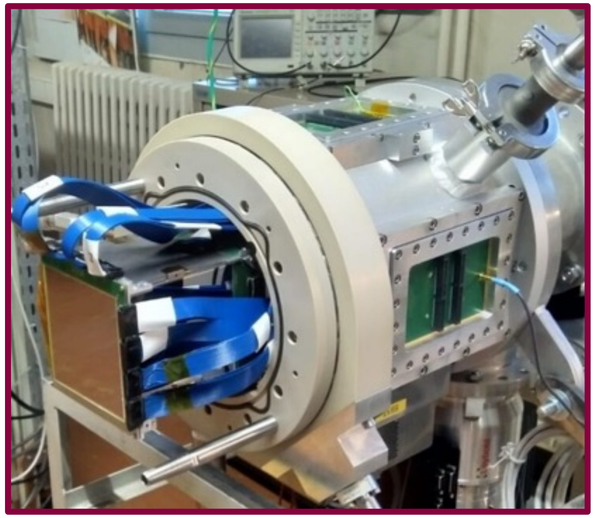
Caen, France

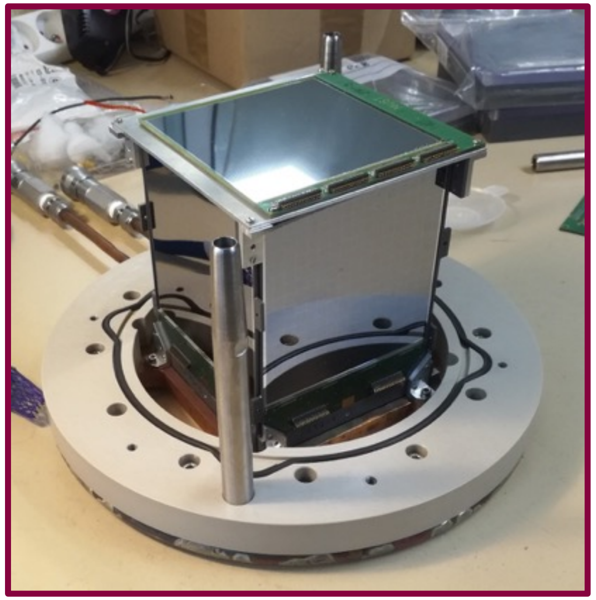
S^3: Exceptional transmission/selection combination
- High rejection > 10^{13}
- High transmission 50%
- Mass resolution > 1/350

A cutting-edge instrumentation for S^3 (SIRIUS, LEB, FISIC…)

SIRIUS detectors





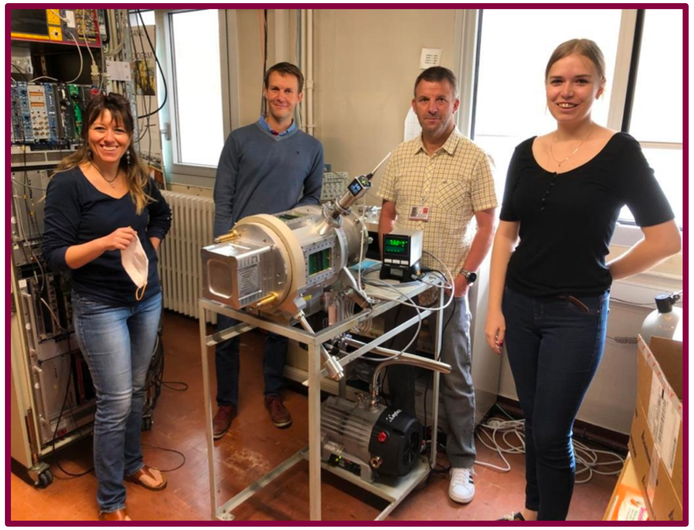


Decay station

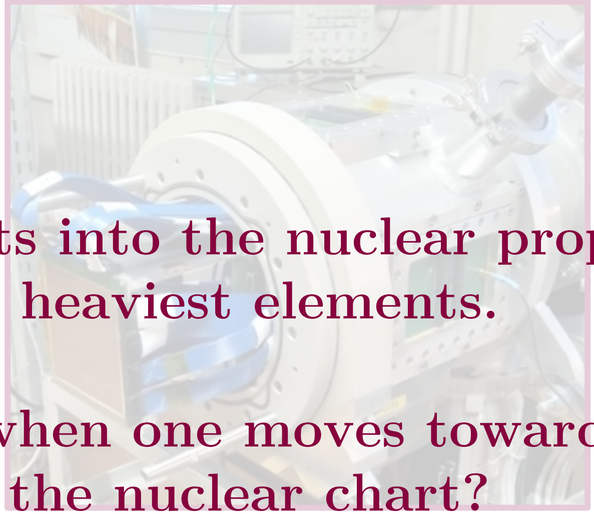
SIRIUS

Delayed spectroscopy

Isomeric/decay spectroscopy at the mass dispersive focal plane (α, e-, fission, γ)



MNT reactions and new detectors



Decay station

SIRIUS

Isomeric/decay

spectroscopy at the mass

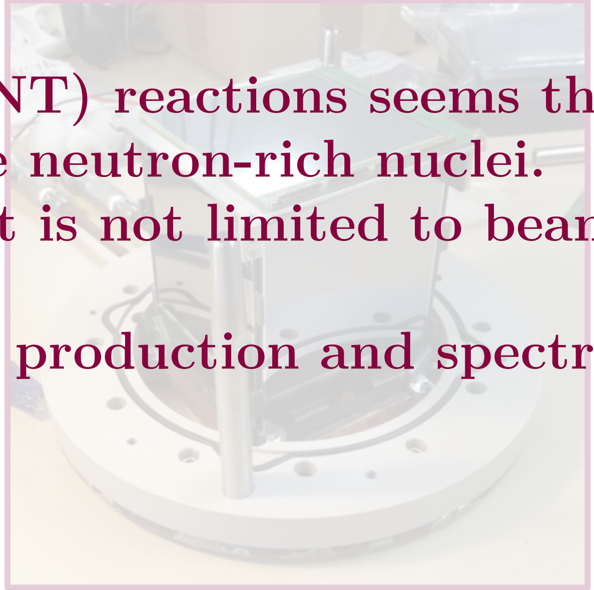
(α, e-, fission, γ)

We need insights into the nuclear properties of the heaviest elements.

How these properties evolve when one moves towards the neutron-rich side on the nuclear chart?

MultiNucleon Transfer (MNT) reactions seems the new path for SHE!
More neutron-rich nuclei.
It offers new possibilities as it is not limited to beam-target combinations.

New detectors for the production and spectroscopy of SHE.



Superheavy elements in our Universe and in the lab!

Conclusion – SHE Z $\geq$ 104 (protons): new elements!

- Spherical and “stable” ($t_{1/2} > 1$ year)?
- Island of stability seems to be more neutron-rich.
- International race for the SHE! Limits of existence of the matter.

In the Universe

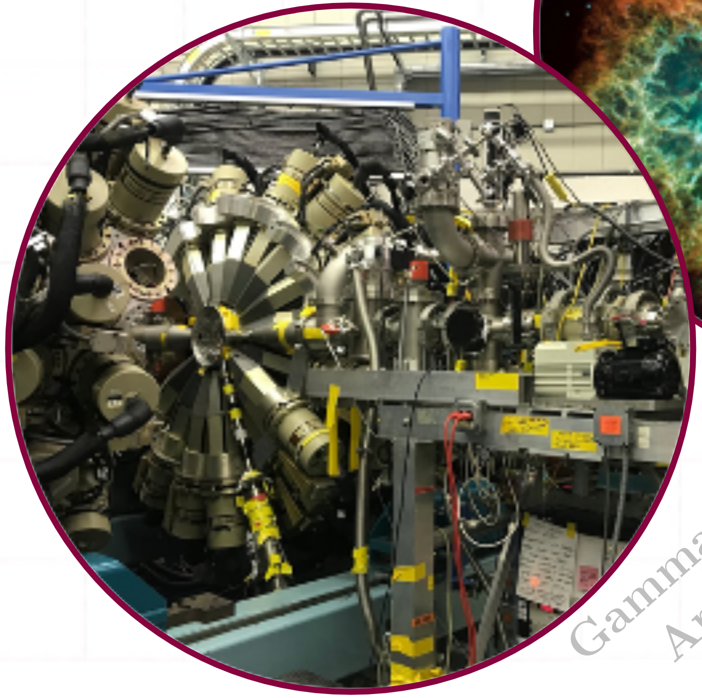
- Stellar nucleosynthesis
- r-process up to U/Th?
- NS-NS and NS-BH mergers

Reaction mechanisms

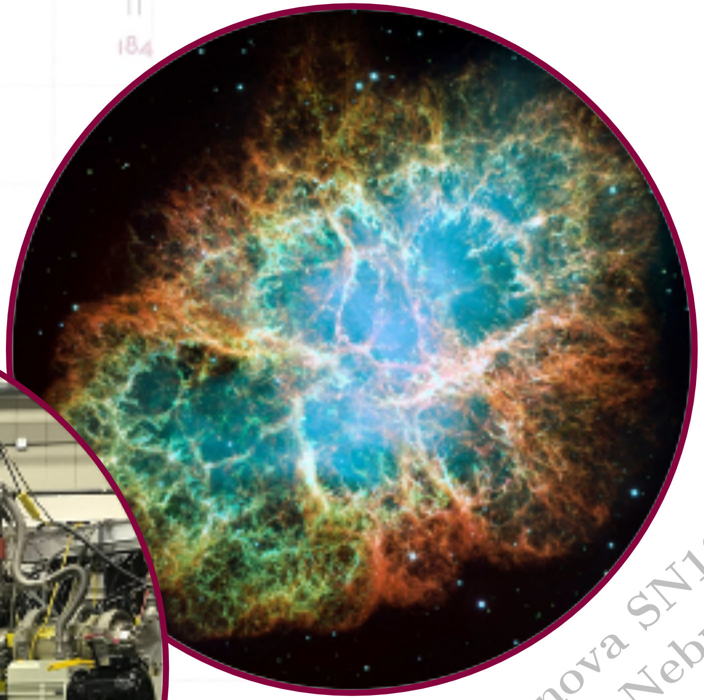
- Fusion-evaporation is limited
- MNT reactions are very promising!
- Small cross-sections/ few SH nuclei

My PhD work – the lab!

- MNT experiment at Argonne
- Development of SIRIUS soon at GANIL



Gammasphere
Argonne



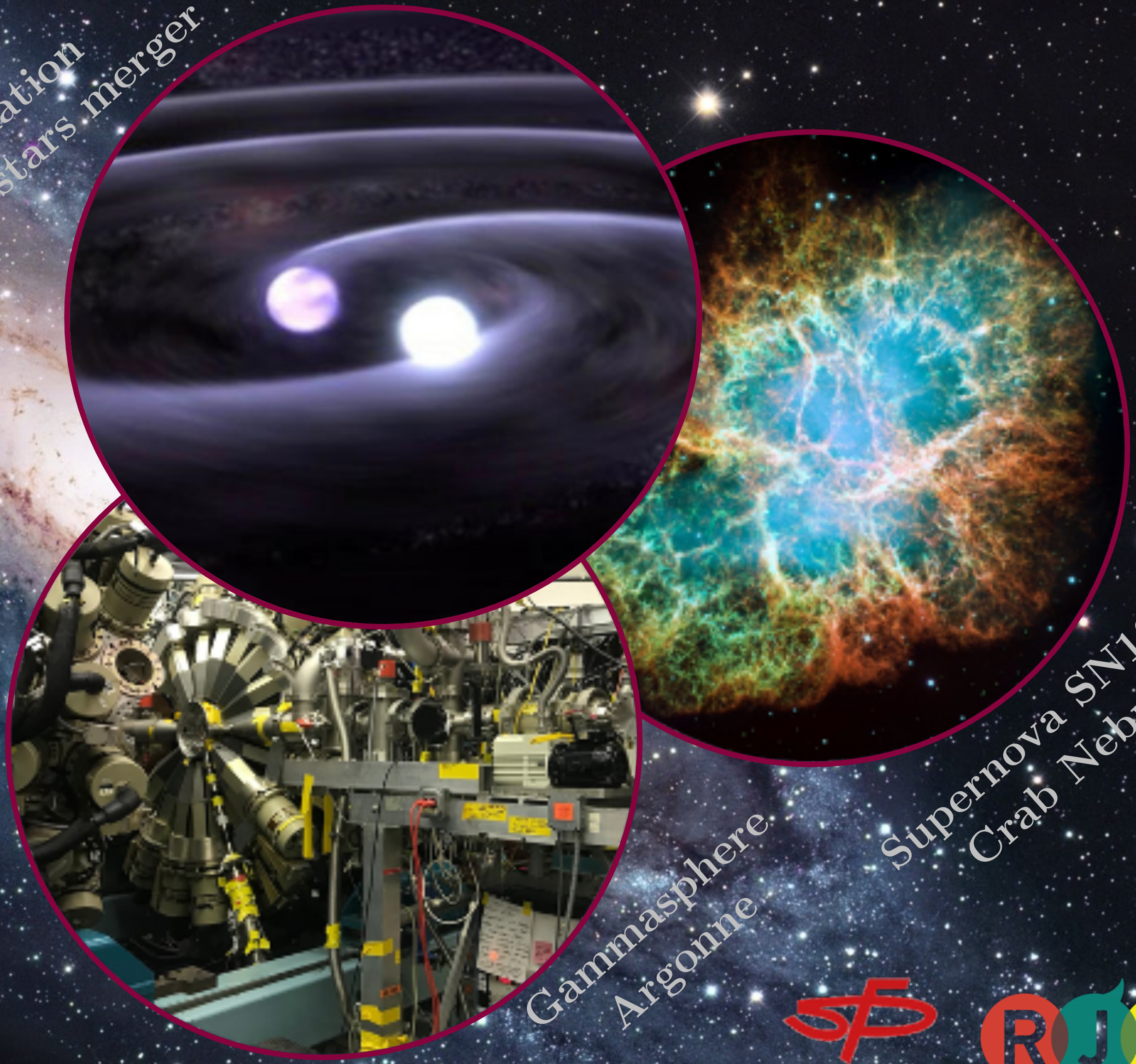
Supernova SN1054
Crab Nebula

Société Française de Physique

Superheavy elements in our Universe and in the lab!

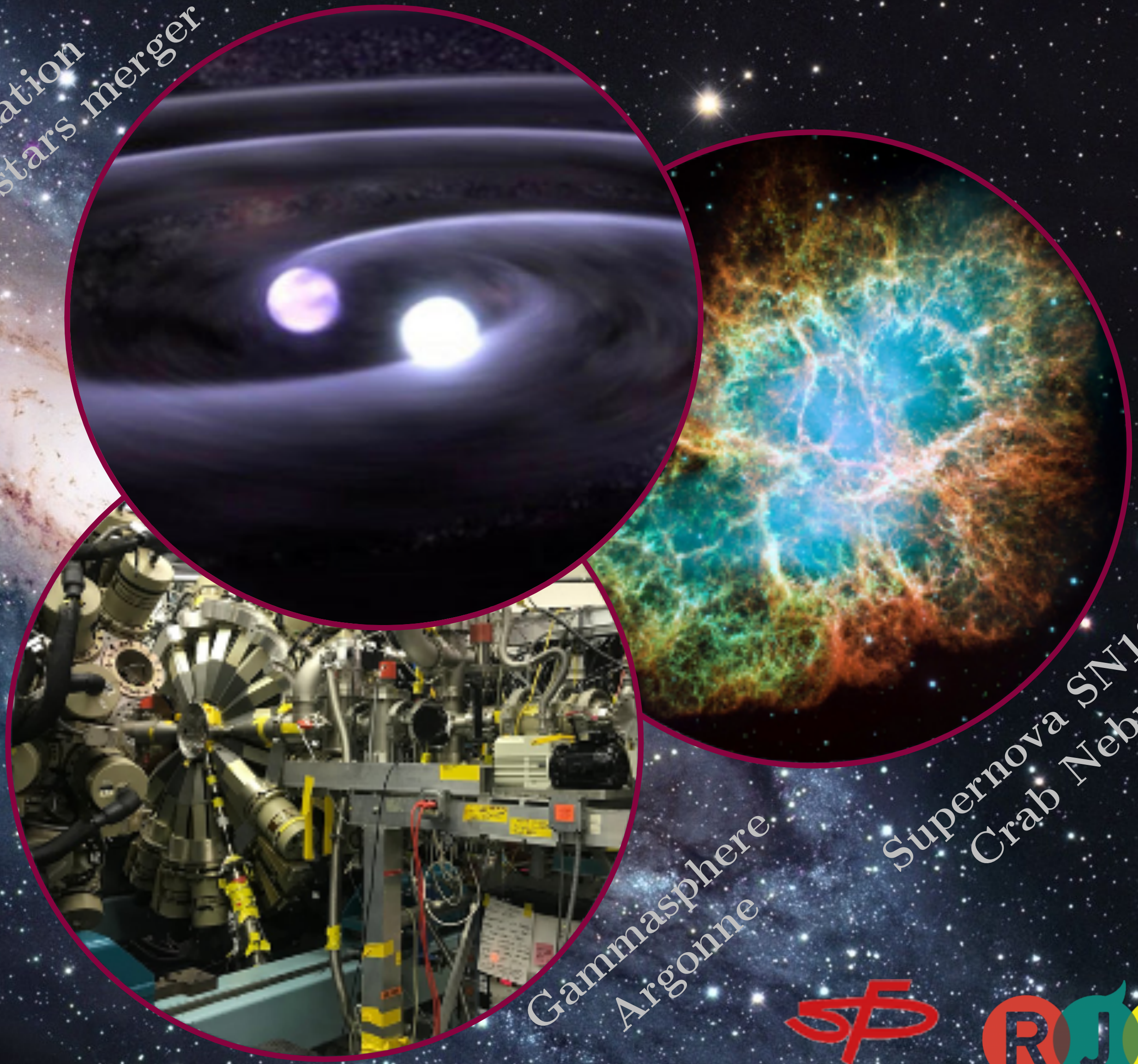
Thanks

for your attention



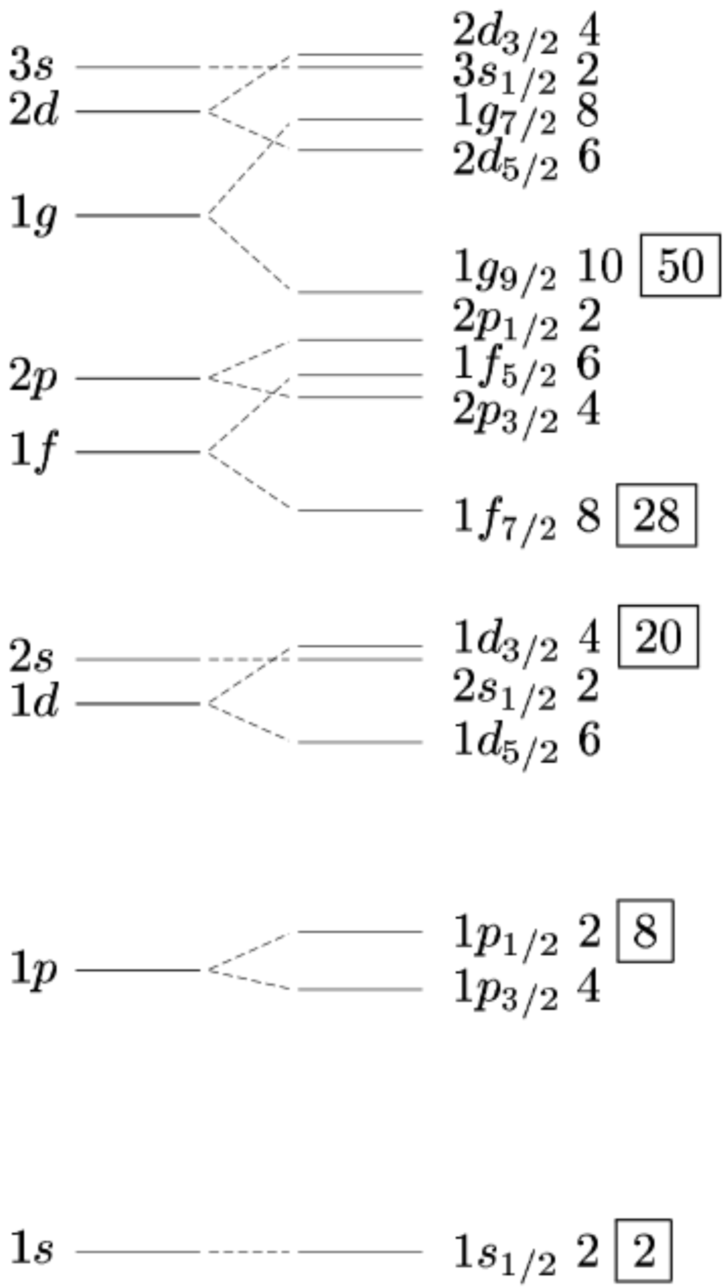
Superheavy elements in our Universe and in the lab!

Backup slides



The Shell Model

Maria Goeppert Mayer
(1906-1972)

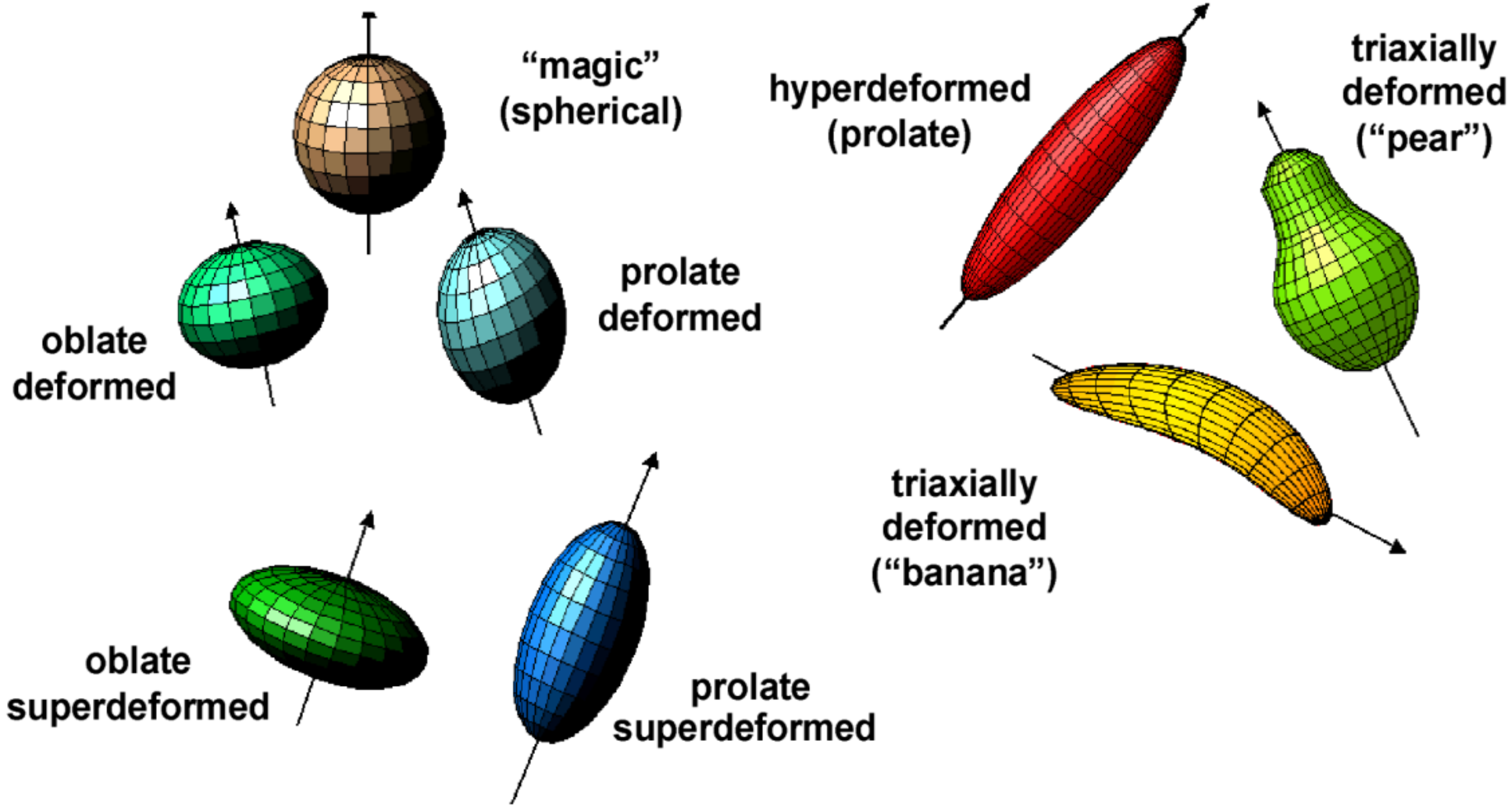


Shell model developed
by Maria Goeppert Mayer
at Argonne National Laboratory

with P. Wigner
and J. Hans D. Jensen

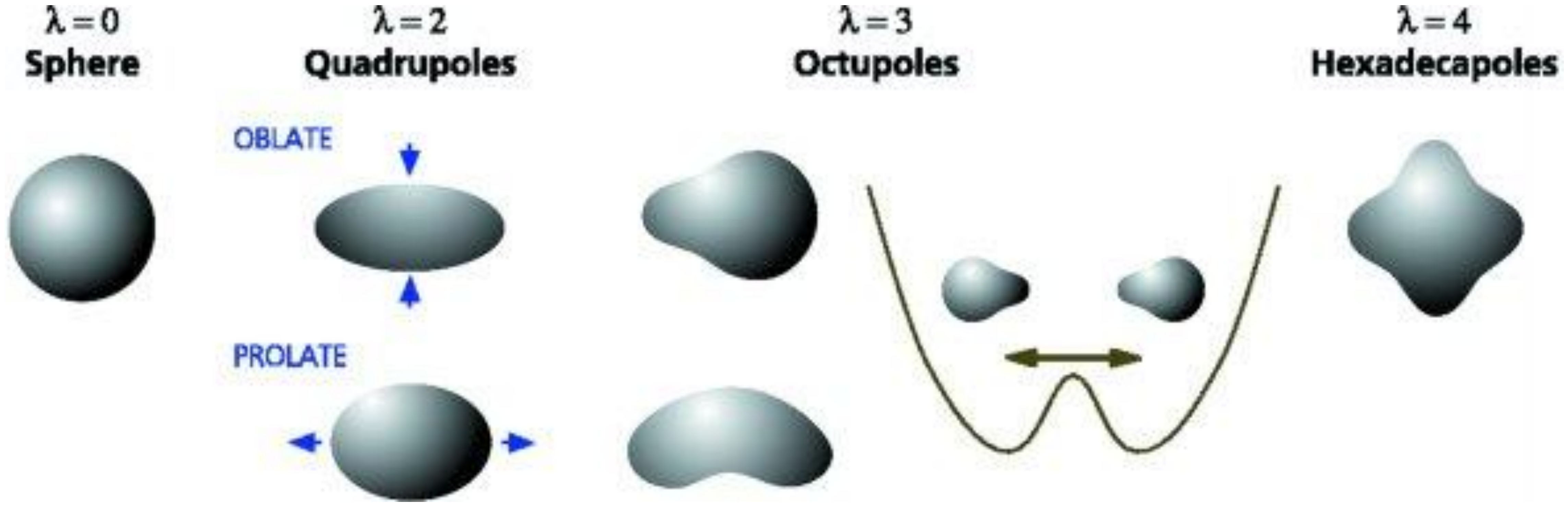
Nobel Physics Prize in 1963.

Shapes of the nuclei



The nuclei are rarely spherical (magic numbers). On the contrary, they are deformed.

Shapes of the nuclei – main multipoles



- $\boldsymbol{\lambda = 1}$ describes the displacement of the centre of mass and therefore cannot give rise to intrinsic excitation of the nucleus – ignore !
- **$\boldsymbol{\lambda = 2}$ is the most important term and describes quadrupole deformation**
- $\boldsymbol{\lambda = 3}$ describes octupole shapes which can look like pears (m = 0), bananas (m = 1) and peanuts (m =2,3)
- $\boldsymbol{\lambda = 4}$ describes hexadecapole shapes

Quadrupole deformation

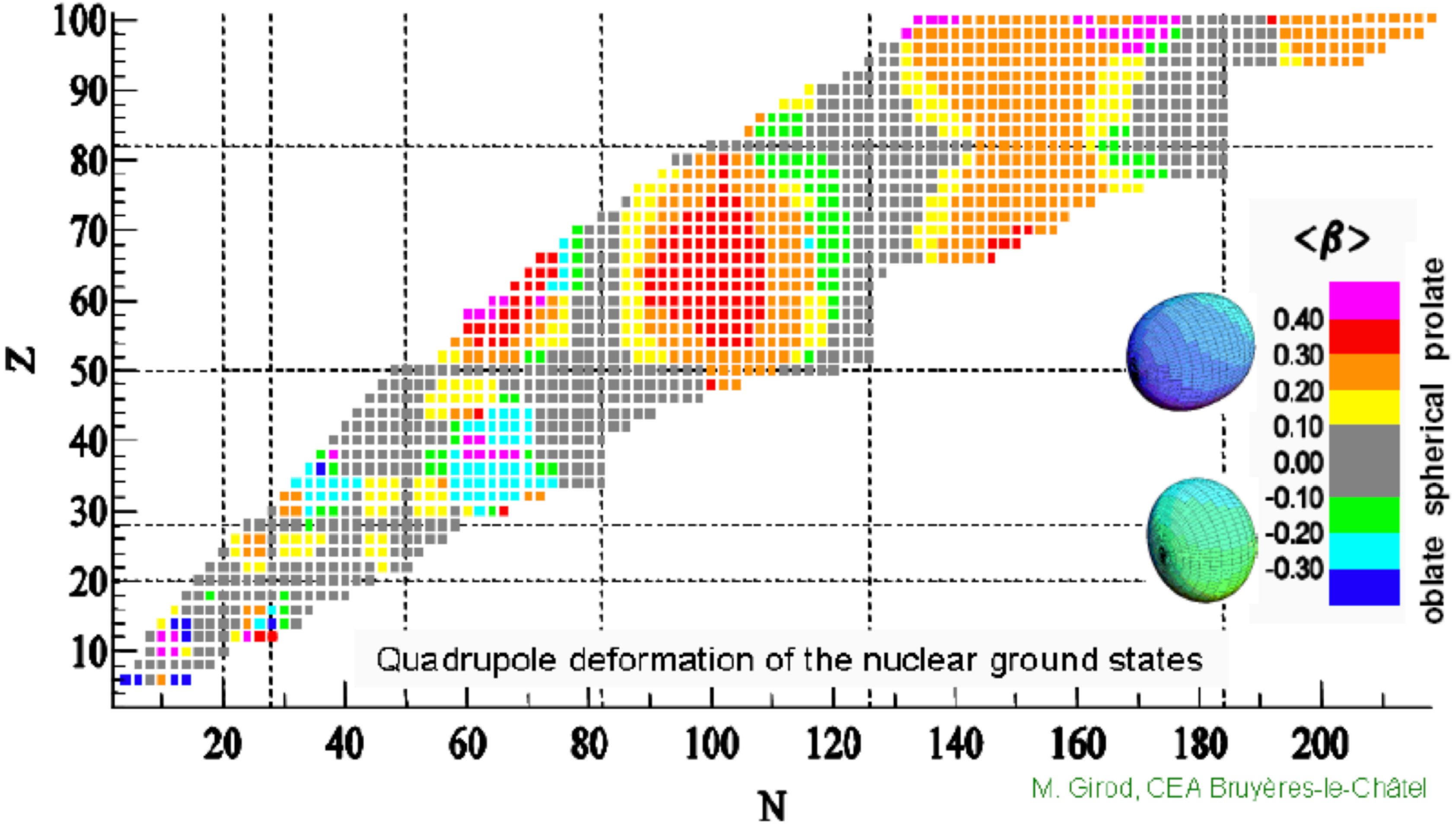


Fig.1. Nuclear chart showing the ground-state shapes predicted by a Hartree-Fock-Bogolyubov (HFB) calculation with the Gogny D1S effective interaction. The classical shell closures, or magic numbers, are marked by dotted lines. Large prolate deformations (β>0) are found above the Z=50 and below the N=82 shell closures, with a small area of oblate shapes (β<0) for Z≥62 and N≈78.

Stellar life cycle (detailed)