

# Zoé Favier

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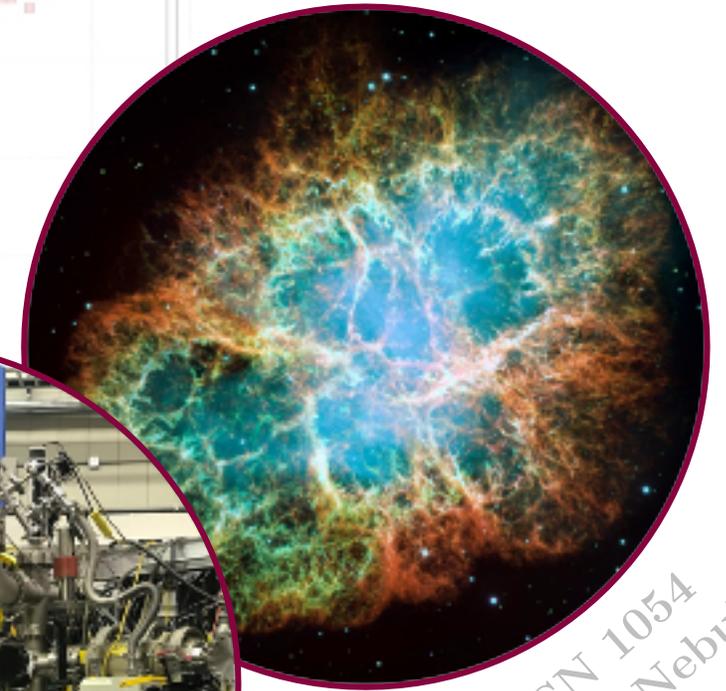
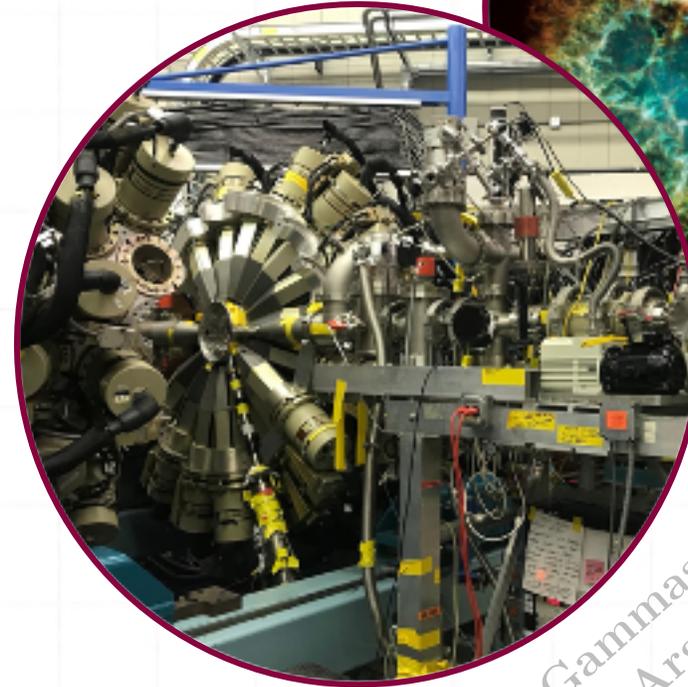
## Rencontre des Jeunes Physicien.ne.s



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<sup>26</sup>
  - r-process and SHE
- Reaction mechanisms
  - Fusion-evaporation<sup>50</sup>
  - MNT reactions<sup>82</sup>
- My PhD work<sup>50</sup> – the lab!
  - MNT experiment at Argonne<sup>20</sup>
  - Development of SIRIUS<sup>20</sup>

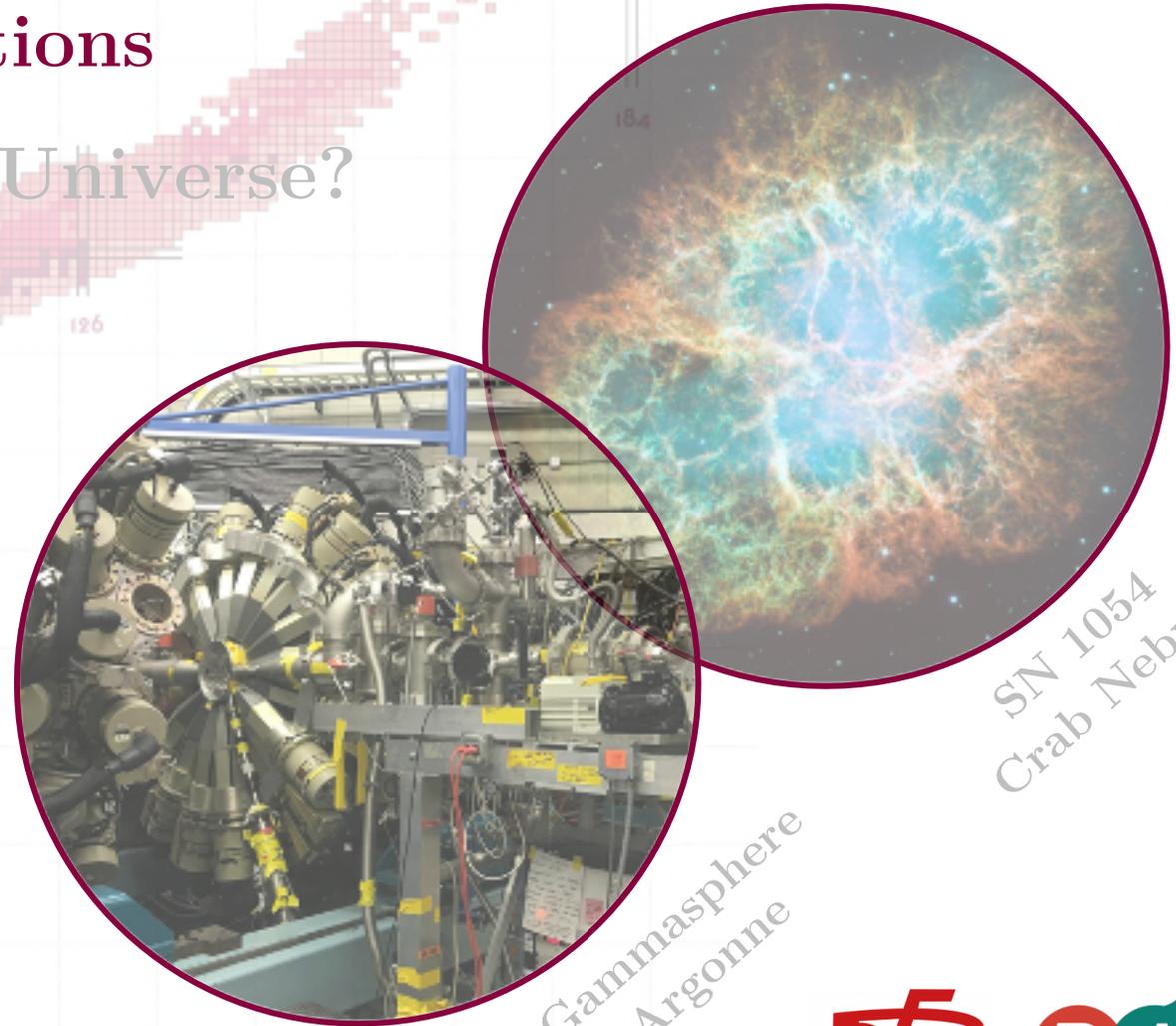


SN 1054  
Crab Nebula

Gammasphere  
Argonne

# Superheavy elements in our Universe and in the lab!

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# Periodic table of the elements

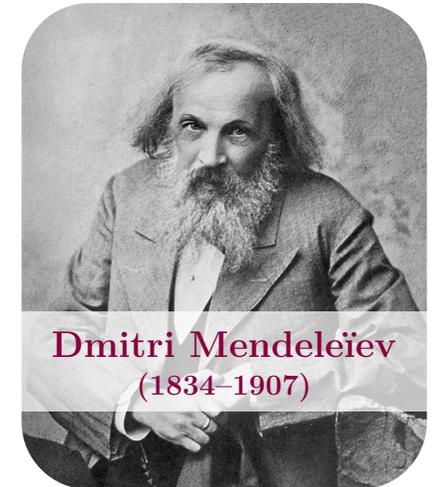
1 square = 1 element = Z protons

Heaviest stable element: Pb (Z=82)

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

1 <b>H</b> hydrogen 1.008 [1.0078, 1.0082]																	18 <b>He</b> helium 4.0026						
3 <b>Li</b> lithium 6.94 [6.938, 6.957]	4 <b>Be</b> beryllium 9.0122																	13 <b>B</b> boron 10.81 [10.806, 10.821]	14 <b>C</b> carbon 12.011 [12.009, 12.012]	15 <b>N</b> nitrogen 14.007 [14.006, 14.009]	16 <b>O</b> oxygen 15.999 [15.989, 16.006]	17 <b>F</b> fluorine 18.998	10 <b>Ne</b> neon 20.180
11 <b>Na</b> sodium 22.990	12 <b>Mg</b> magnesium 24.305 [24.304, 24.307]																	13 <b>Al</b> aluminum 26.982	14 <b>Si</b> silicon 28.086 [28.084, 28.089]	15 <b>P</b> phosphorus 30.974	16 <b>S</b> sulfur 32.06 [32.059, 32.076]	17 <b>Cl</b> chlorine 35.45 [35.446, 35.457]	18 <b>Ar</b> argon 39.948 [39.942, 39.963]
19 <b>K</b> potassium 39.098	20 <b>Ca</b> calcium 40.078 [40.078, 40.078]	21 <b>Sc</b> scandium 44.956	22 <b>Ti</b> titanium 47.867	23 <b>V</b> vanadium 50.942	24 <b>Cr</b> chromium 51.996	25 <b>Mn</b> manganese 54.938	26 <b>Fe</b> iron 55.845 [55.845(2)]	27 <b>Co</b> cobalt 58.933	28 <b>Ni</b> nickel 58.693	29 <b>Cu</b> copper 63.546 [63.546(3)]	30 <b>Zn</b> zinc 65.38 [65.38(2)]	31 <b>Ga</b> gallium 69.723	32 <b>Ge</b> germanium 72.630 [72.630(5)]	33 <b>As</b> arsenic 74.922	34 <b>Se</b> selenium 78.971 [78.971(8)]	35 <b>Br</b> bromine 79.904 [79.901, 79.907]	36 <b>Kr</b> krypton 83.798 [83.798(2)]						
37 <b>Rb</b> rubidium 85.468	38 <b>Sr</b> strontium 87.62	39 <b>Y</b> yttrium 88.906	40 <b>Zr</b> zirconium 91.224 [91.224(2)]	41 <b>Nb</b> niobium 92.906	42 <b>Mo</b> molybdenum 95.94	43 <b>Tc</b> technetium	44 <b>Ru</b> ruthenium 101.07 [101.07(2)]	45 <b>Rh</b> rhodium 102.91	46 <b>Pd</b> palladium 106.42	47 <b>Ag</b> silver 107.87	48 <b>Cd</b> cadmium 112.41	49 <b>In</b> indium 114.82	50 <b>Sn</b> tin 118.71	51 <b>Sb</b> antimony 121.76	52 <b>Te</b> tellurium 127.46 [127.46(2)]	53 <b>I</b> iodine 126.90	54 <b>Xe</b> xenon 131.29						
55 <b>Cs</b> cesium 132.91	56 <b>Ba</b> barium 137.33	57-71 lanthanoids	72 <b>Hf</b> hafnium 178.49 [178.49(2)]	73 <b>Ta</b> tantalum 180.95	74 <b>W</b> tungsten 183.84	75 <b>Re</b> rhenium 186.21	76 <b>Os</b> osmium 190.23 [190.23(2)]	77 <b>Ir</b> iridium 192.22	78 <b>Pt</b> platinum 195.08	79 <b>Au</b> gold 196.97	80 <b>Hg</b> mercury 200.59	81 <b>Tl</b> thallium 204.38 [204.38, 204.39]	82 <b>Pb</b> lead 207.2	83 <b>Bi</b> bismuth 208.98	84 <b>Po</b> polonium	85 <b>At</b> astatine	86 <b>Rn</b> radon						
87 <b>Fr</b> francium	88 <b>Ra</b> radium	89-103 actinoids	104 <b>Rf</b> rutherfordium	105 <b>Db</b> dubnium	106 <b>Sg</b> seaborgium	107 <b>Bh</b> bohrium	108 <b>Hs</b> hassium	109 <b>Mt</b> meitnerium	110 <b>Ds</b> darmstadtium	111 <b>Rg</b> roentgenium	112 <b>Cn</b> copernicium	113 <b>Nh</b> nihonium	114 <b>Fl</b> flerovium	115 <b>Mc</b> moscovium	116 <b>Lv</b> livermorium	117 <b>Ts</b> tennessine	118 <b>Og</b> oganesson						

Key:  
atomic number  
**Symbol**  
name  
conventional atomic weight  
standard atomic weight



57 <b>La</b> lanthanum 138.91	58 <b>Ce</b> cerium 140.12	59 <b>Pr</b> praseodymium 140.91	60 <b>Nd</b> neodymium 144.24	61 <b>Pm</b> promethium	62 <b>Sm</b> samarium 150.36 [150.36(2)]	63 <b>Eu</b> europium 151.96	64 <b>Gd</b> gadolinium 157.25 [157.25(2)]	65 <b>Tb</b> terbium 158.93	66 <b>Dy</b> dysprosium 162.50	67 <b>Ho</b> holmium 164.93	68 <b>Er</b> erbium 167.26	69 <b>Tm</b> thulium 168.93	70 <b>Yb</b> ytterbium 173.05	71 <b>Lu</b> lutetium 174.97
89 <b>Ac</b> actinium	90 <b>Th</b> thorium 232.04	91 <b>Pa</b> protactinium 231.04	92 <b>U</b> uranium 238.03	93 <b>Np</b> neptunium	94 <b>Pu</b> plutonium	95 <b>Am</b> americium	96 <b>Cm</b> curium	97 <b>Bk</b> berkelium	98 <b>Cf</b> californium	99 <b>Es</b> einsteinium	100 <b>Fm</b> fermium	101 <b>Md</b> mendelevium	102 <b>No</b> nobelium	103 <b>Lr</b> lawrencium

For notes and updates to this table, see [www.iupac.org](http://www.iupac.org). This version is dated 1 December 2018.  
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# Super Heavy Elements (SHE)

Transactinides:  $Z \geq 104$  (protons)

1 <b>H</b> hydrogen 1.008 [1.0078, 1.0082]																	18 <b>He</b> helium 4.0026						
3 <b>Li</b> lithium 6.94 [6.938, 6.957]	4 <b>Be</b> beryllium 9.0122																	13 <b>B</b> boron 10.81 [10.806, 10.821]	14 <b>C</b> carbon 12.011 [12.009, 12.012]	15 <b>N</b> nitrogen 14.007 [14.006, 14.009]	16 <b>O</b> oxygen 15.999 [15.989, 16.008]	17 <b>F</b> fluorine 18.998	10 <b>Ne</b> neon 20.180
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Key:  
atomic number  
**Symbol**  
name  
conventional atomic weight  
standard atomic weight



Iouri Oganessian (1933-)

118

Og

Oganesson

[294]

2  
8  
18  
32  
32  
18  
8

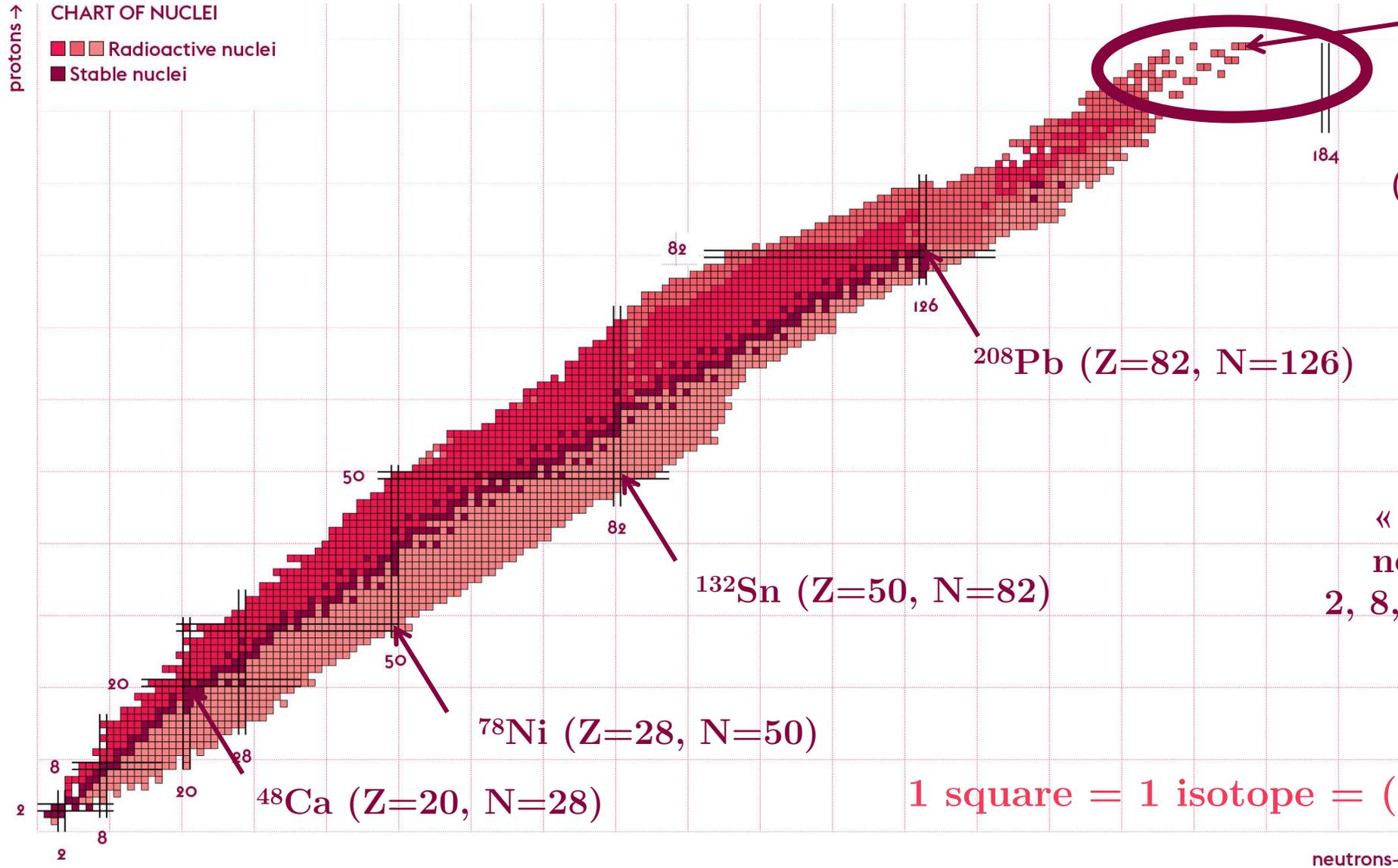


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Discovered in 2012  
Named in 2016

# The chart of nuclides – the Sagrè chart



(Z=118, N=176)

Superheavy nuclei  
(Island of stability?)

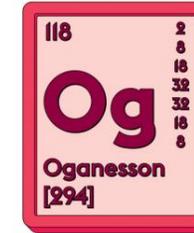
« Magic » numbers of  
neutrons and protons:  
2, 8, 20, 28, 50, 82, 126, (?)

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

# Half-lives of the isotopes

Half-life: rate at which a radioactive isotope decays ( $t_{1/2}$ )

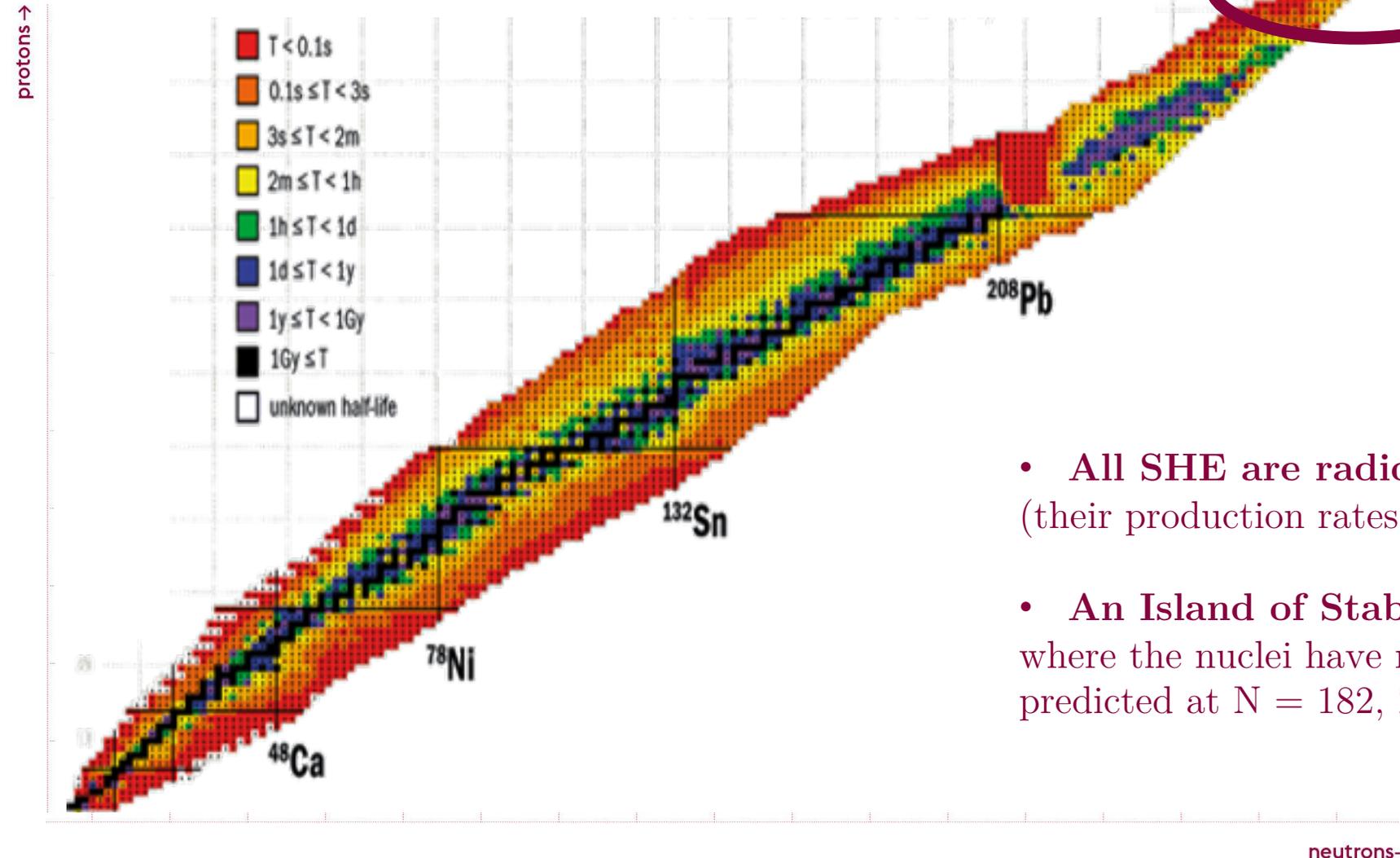
Interval of time required for one-half of the atomic nuclei of a radioactive sample to decay.



( $Z=118$ ,  $N=176$ )

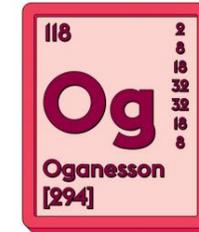
Superheavy nuclei

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



- All SHE are radioactive (their production rates  $\searrow$  with number of protons  $Z \nearrow$ )
- An Island of Stability where the nuclei have relatively long half-lives ( $> 1$  year) predicted at  $N = 182$ ,  $Z = 114$  or  $120$  or  $126$ .

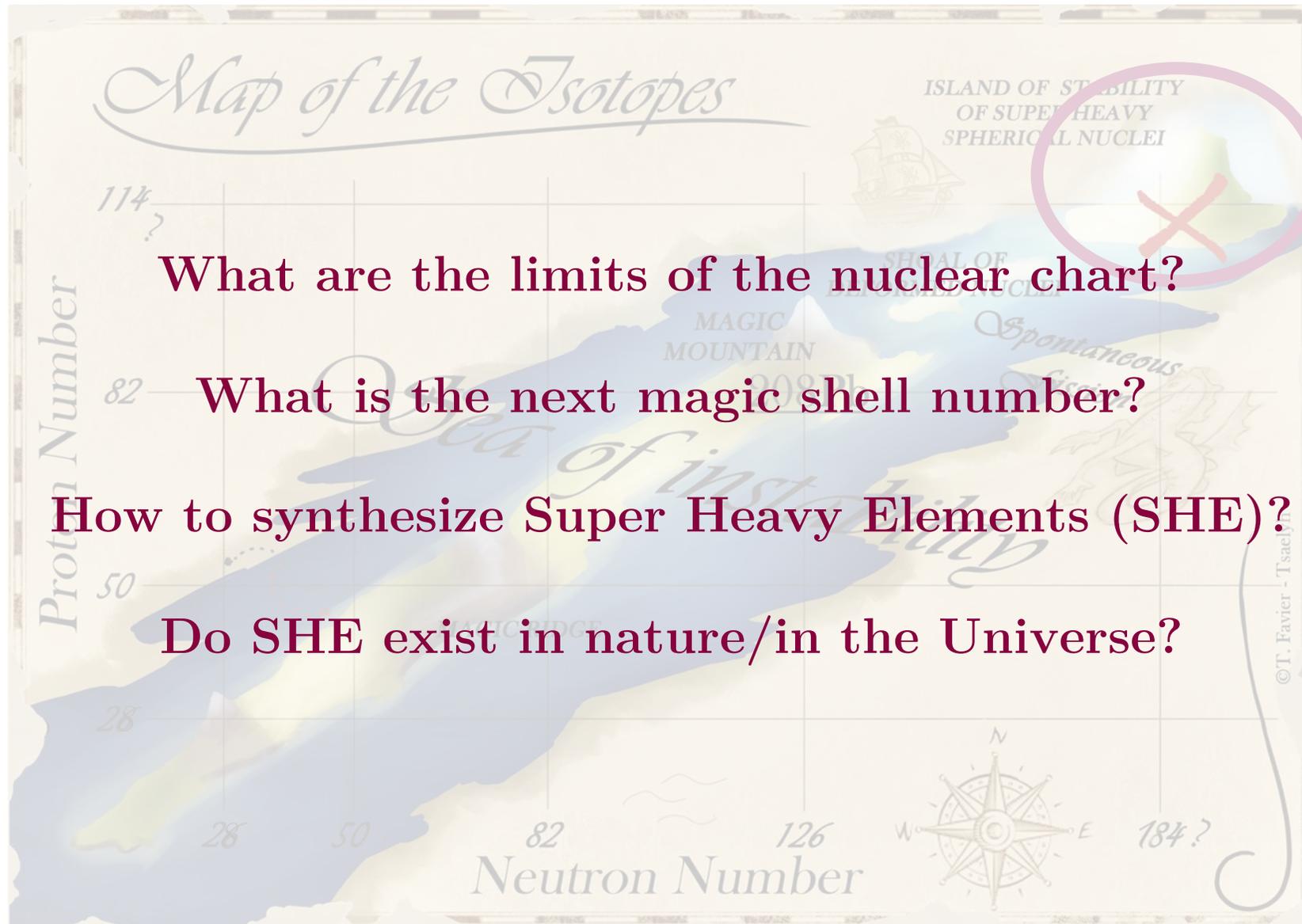
# Island of stability (spherical SHE nuclei)?



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

Height ↗  
Stability ↗

# Island of stability (spherical SHE nuclei)?

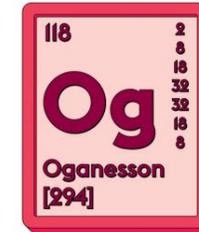


What are the limits of the nuclear chart?

What is the next magic shell number?

How to synthesize Super Heavy Elements (SHE)?

Do SHE exist in nature/in the Universe?

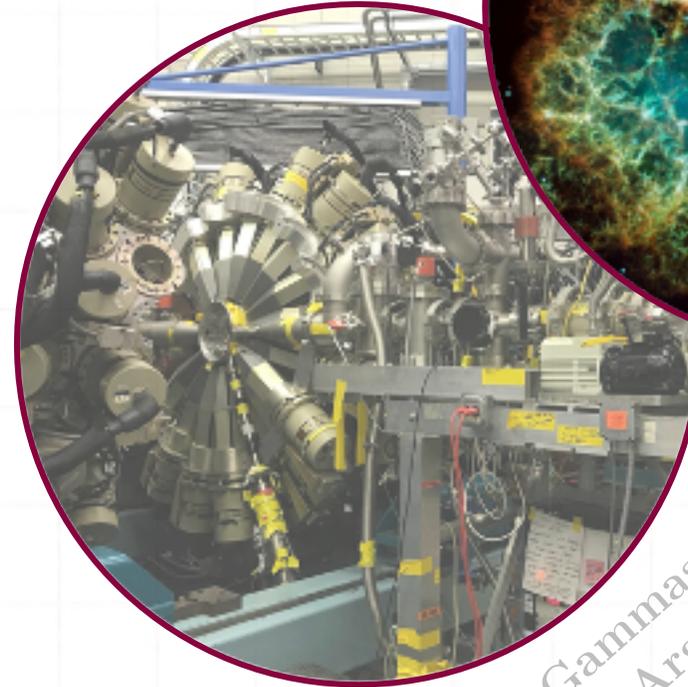


Superheavy nuclei  
( $t_{1/2} > 1$  year?)

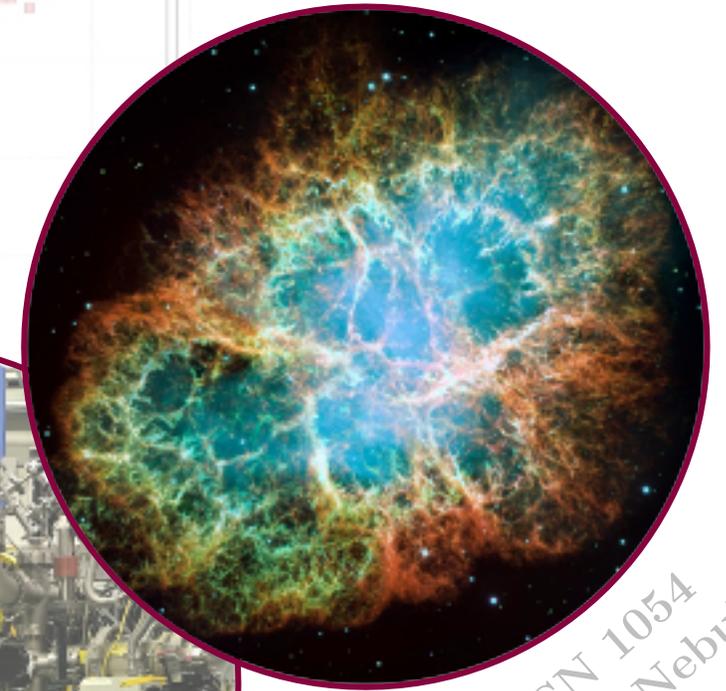
Height ↗  
Stability ↗

# Superheavy elements in our Universe and in the lab!

- 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

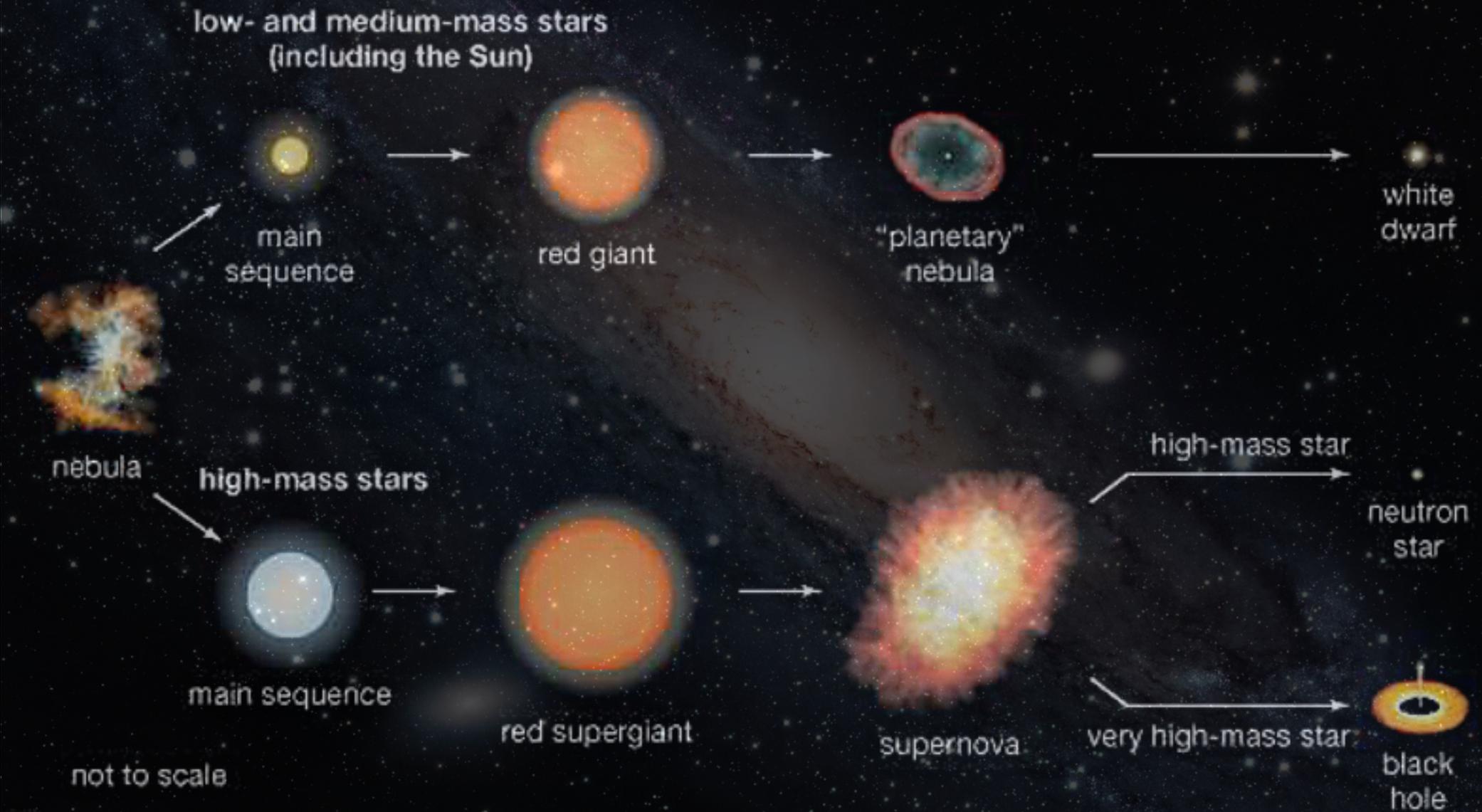


Gammasphere  
Argonne



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Crab Nebula

# Stellar life cycle (stellar evolution)

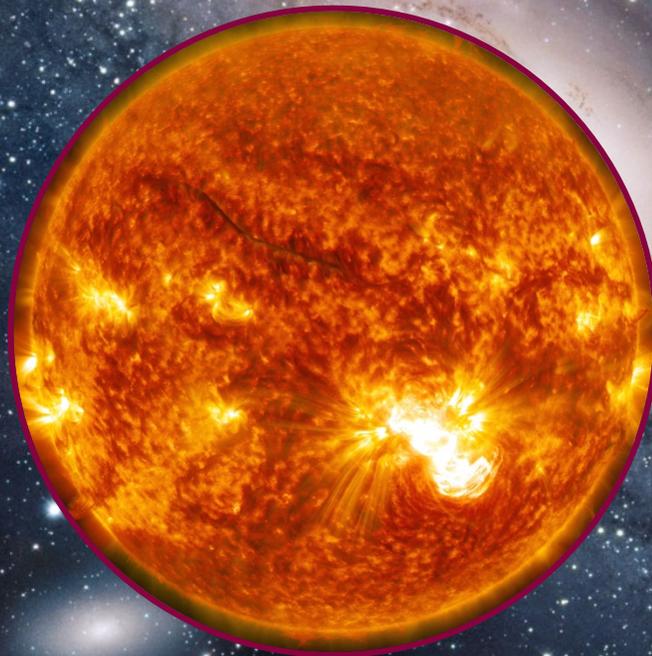


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# Where are the SHE? – Astrophysical sites



**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

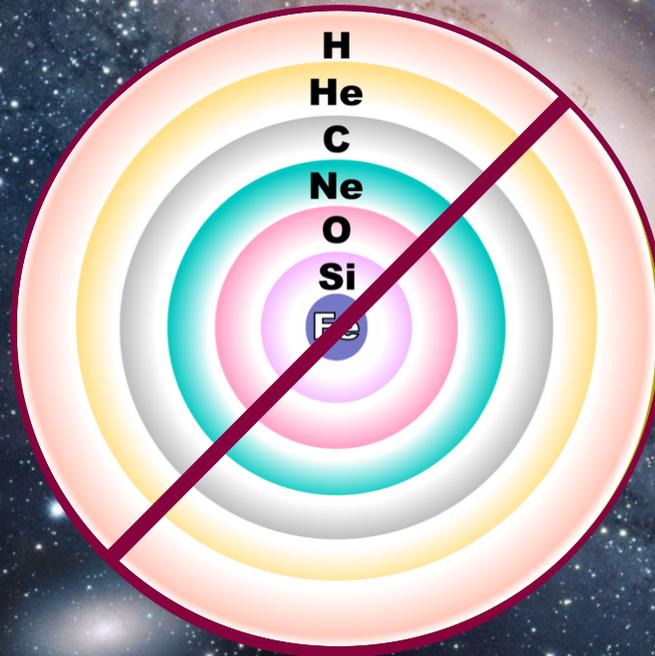
Heaviest element found:

U (Z=92)

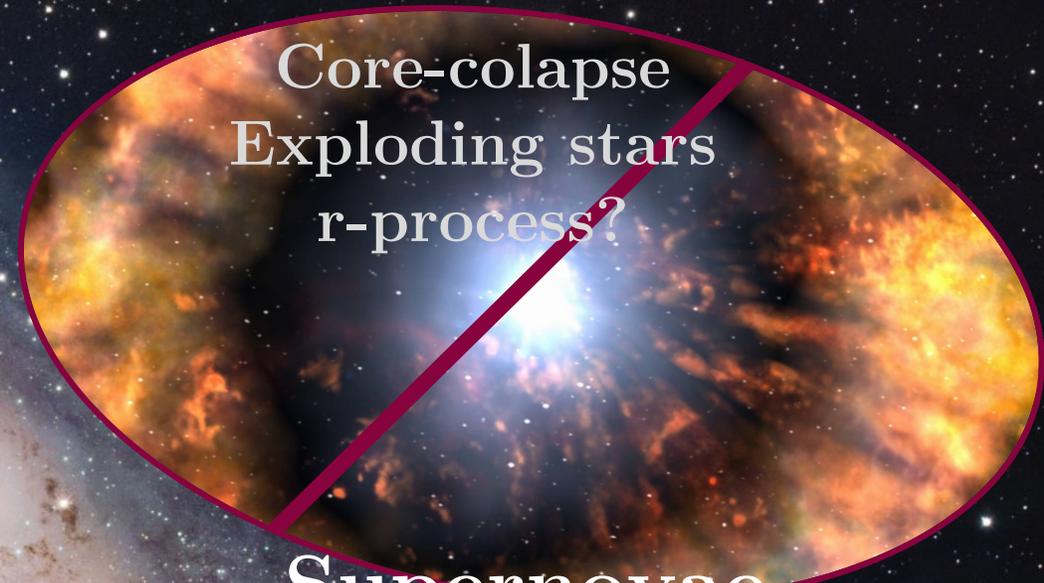


Earth

Stellar Iron core and  
onion like structure



Stars



Core-collapse  
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)



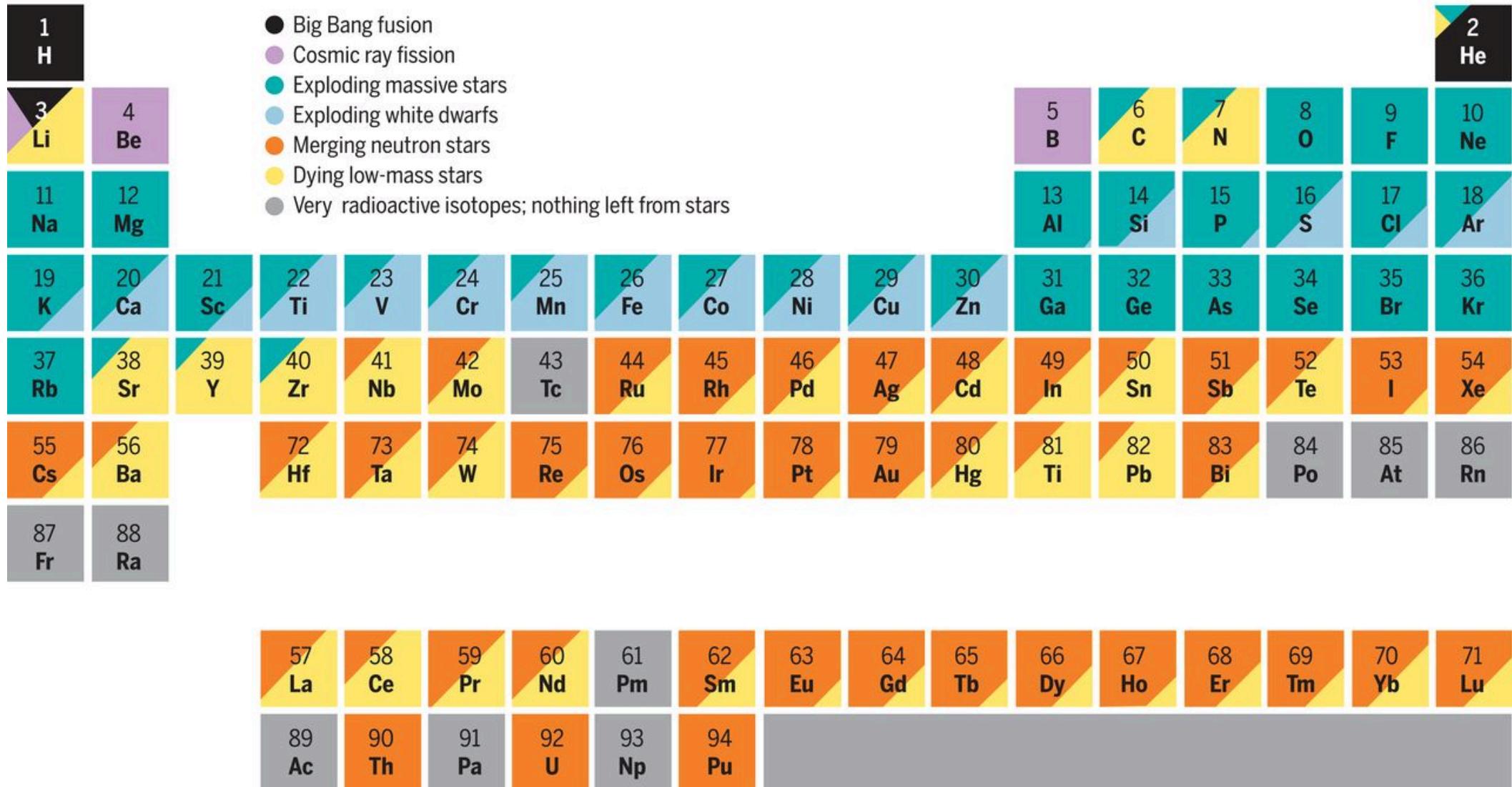
The observation of GRB170807A/GW170817 originating from a neutron star merger has been published on October 16, 2017 and is a first proof of the nucleosynthesis of heavy elements in the r-process.

Somewhere else?

Not to scale

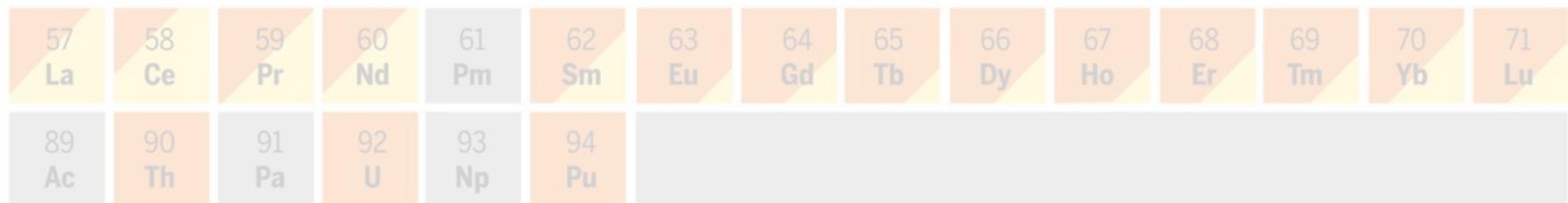
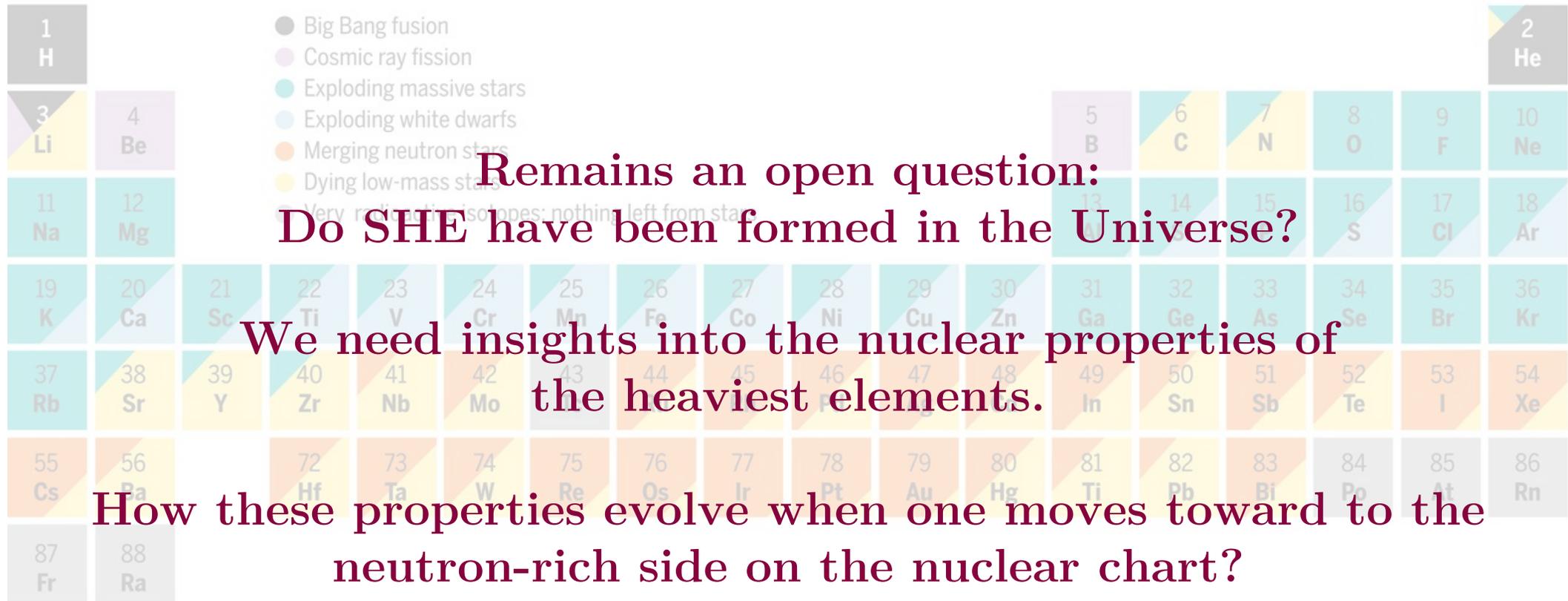
# Cosmological origin of each element – missing SHE!

The evolving composition of the Universe



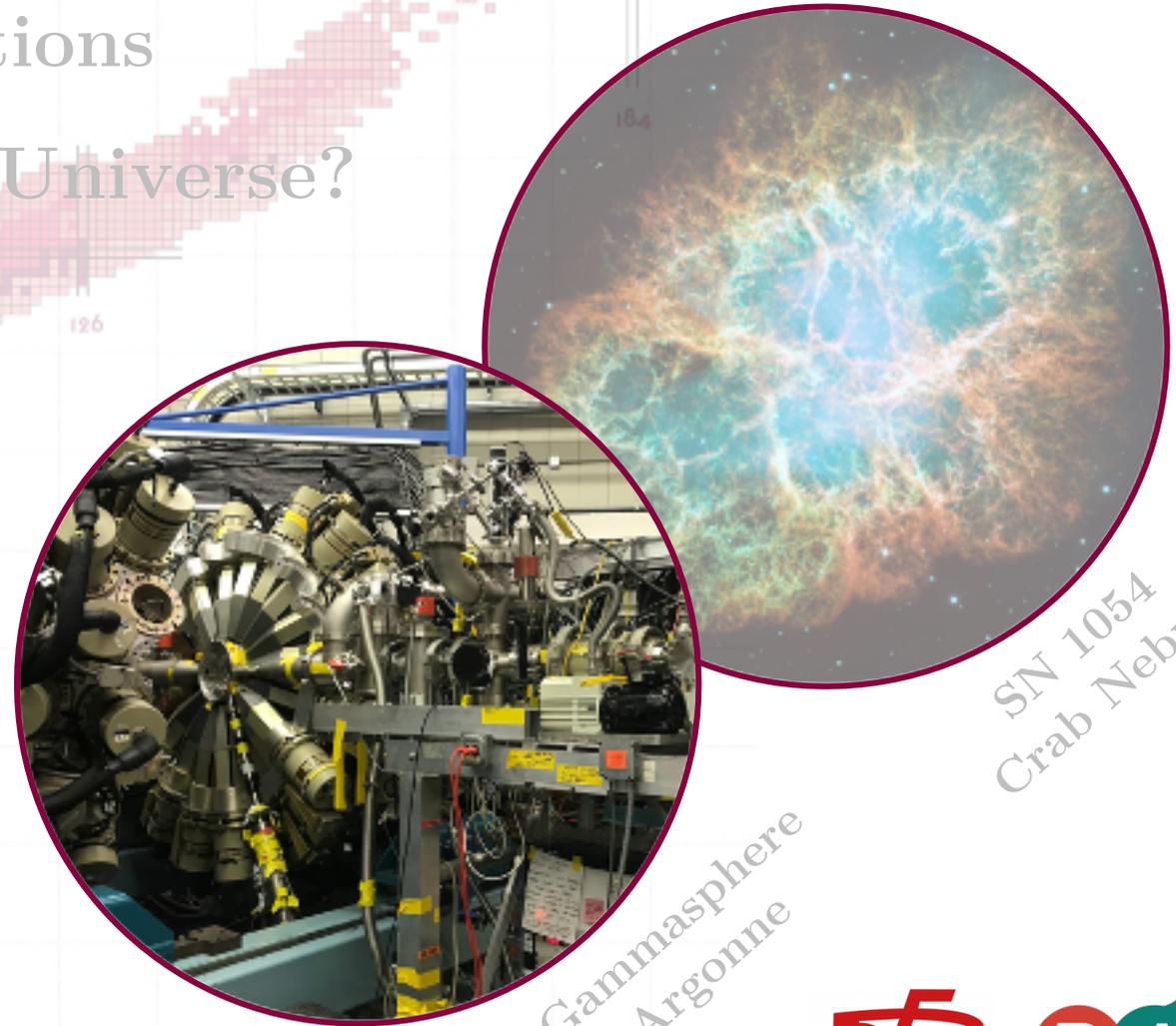
# Cosmological origin of each element – missing SHE!

The evolving composition of the Universe



# 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

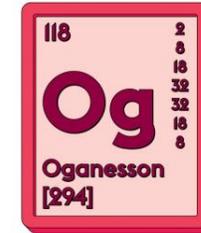
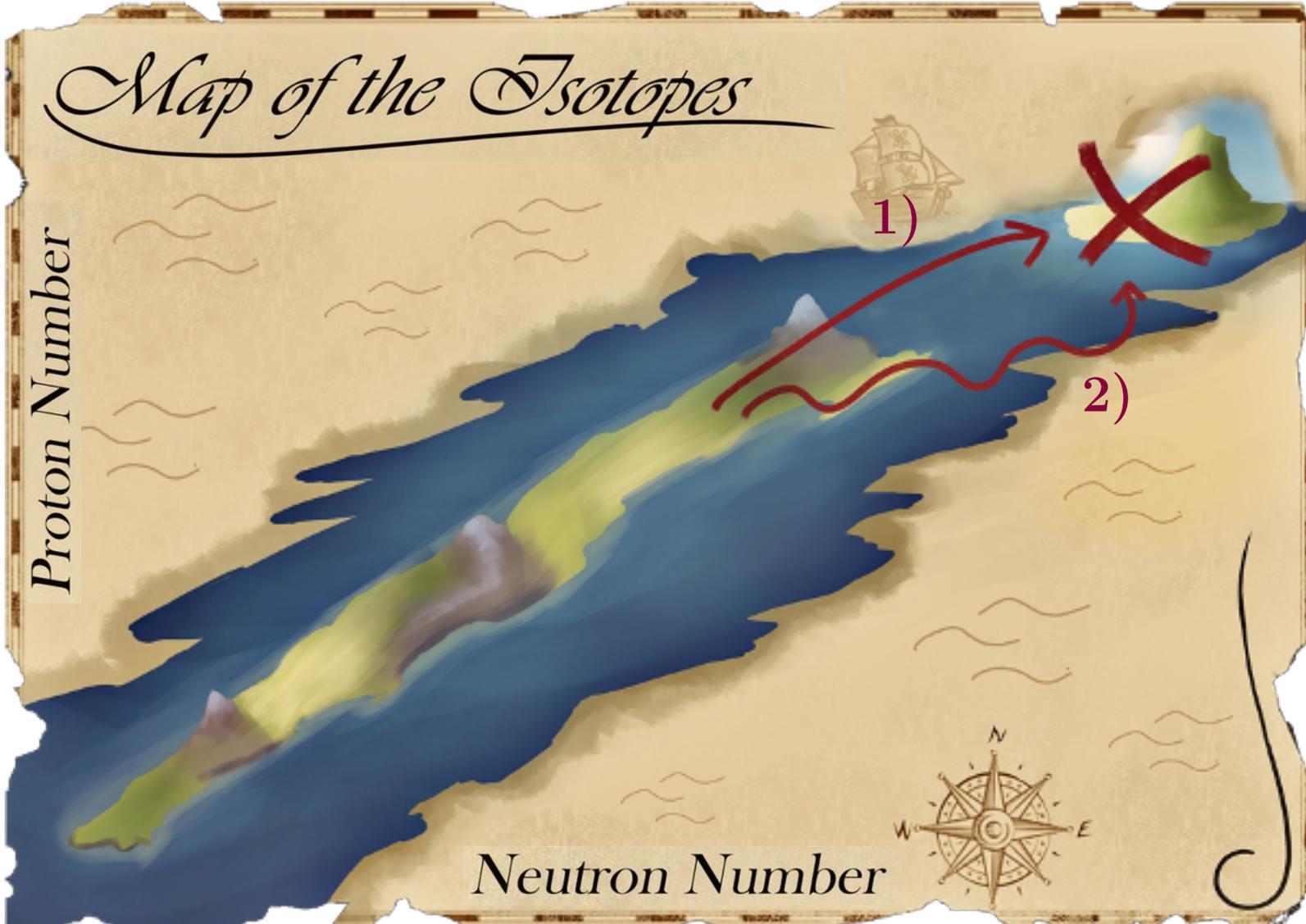


SN 1054  
Crab Nebula

GammaSphere  
Argonne



# Reaction mechanisms to produce SHE



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

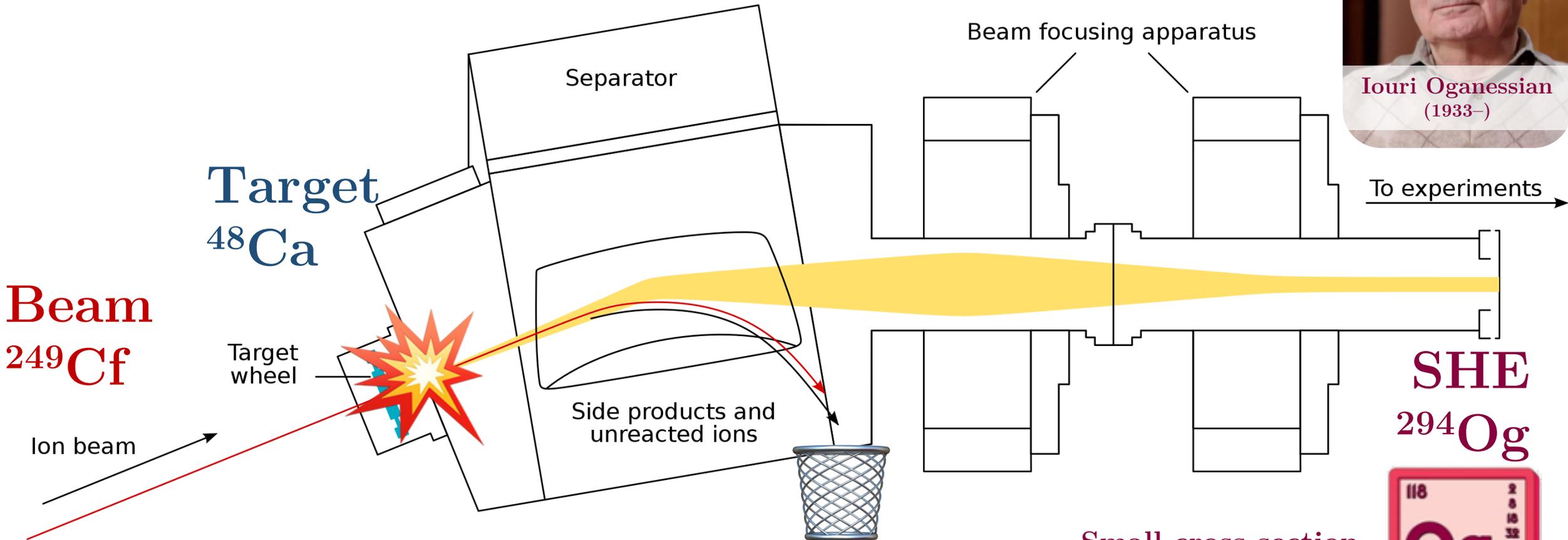
# Discovery of Oganesson at JINR (Dubna )



Iouri Oganessian  
(1933-)

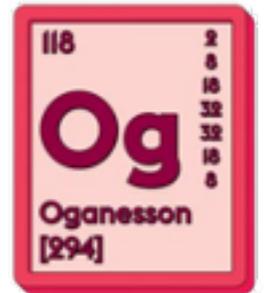
To experiments →

## 1) Fusion-evaporation

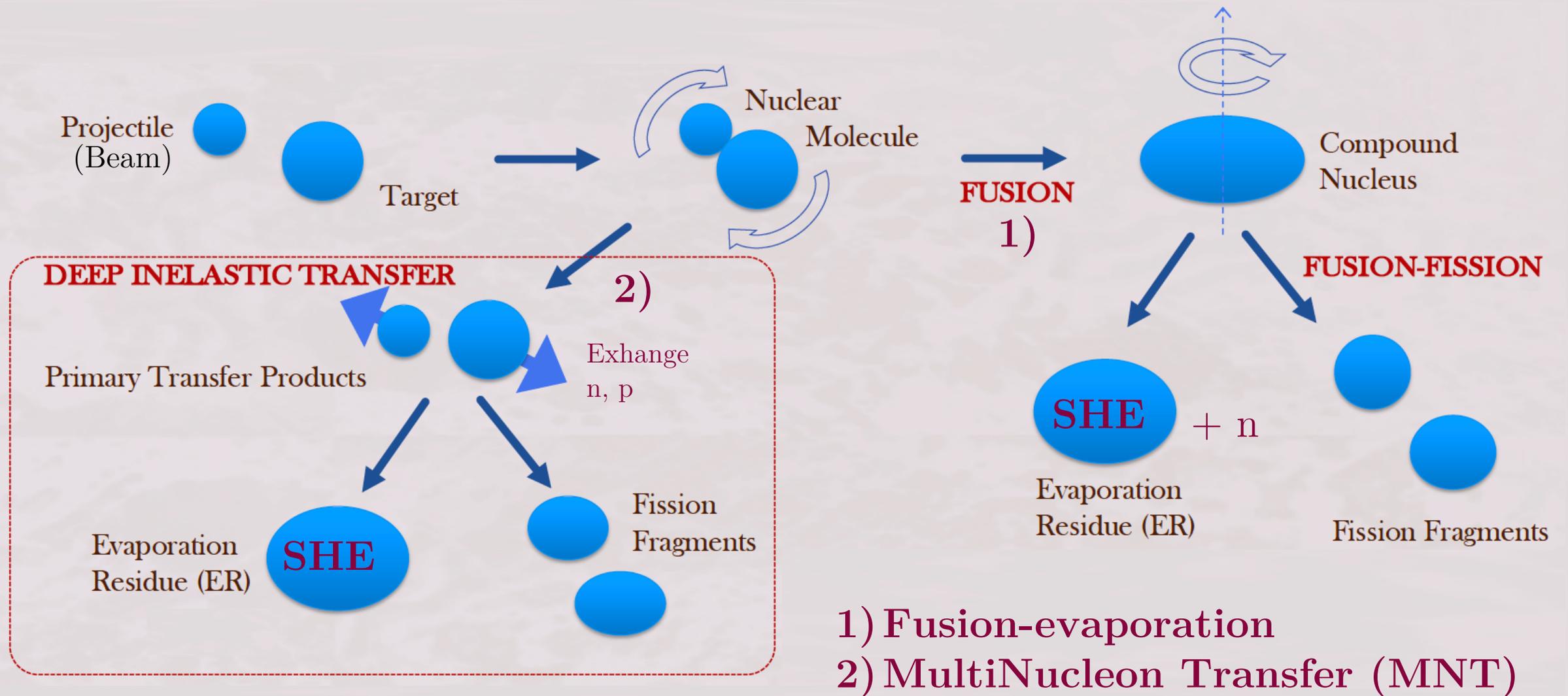


Small cross-section  
(probability of production)

Only 3 nuclei produced during several months of experiment.

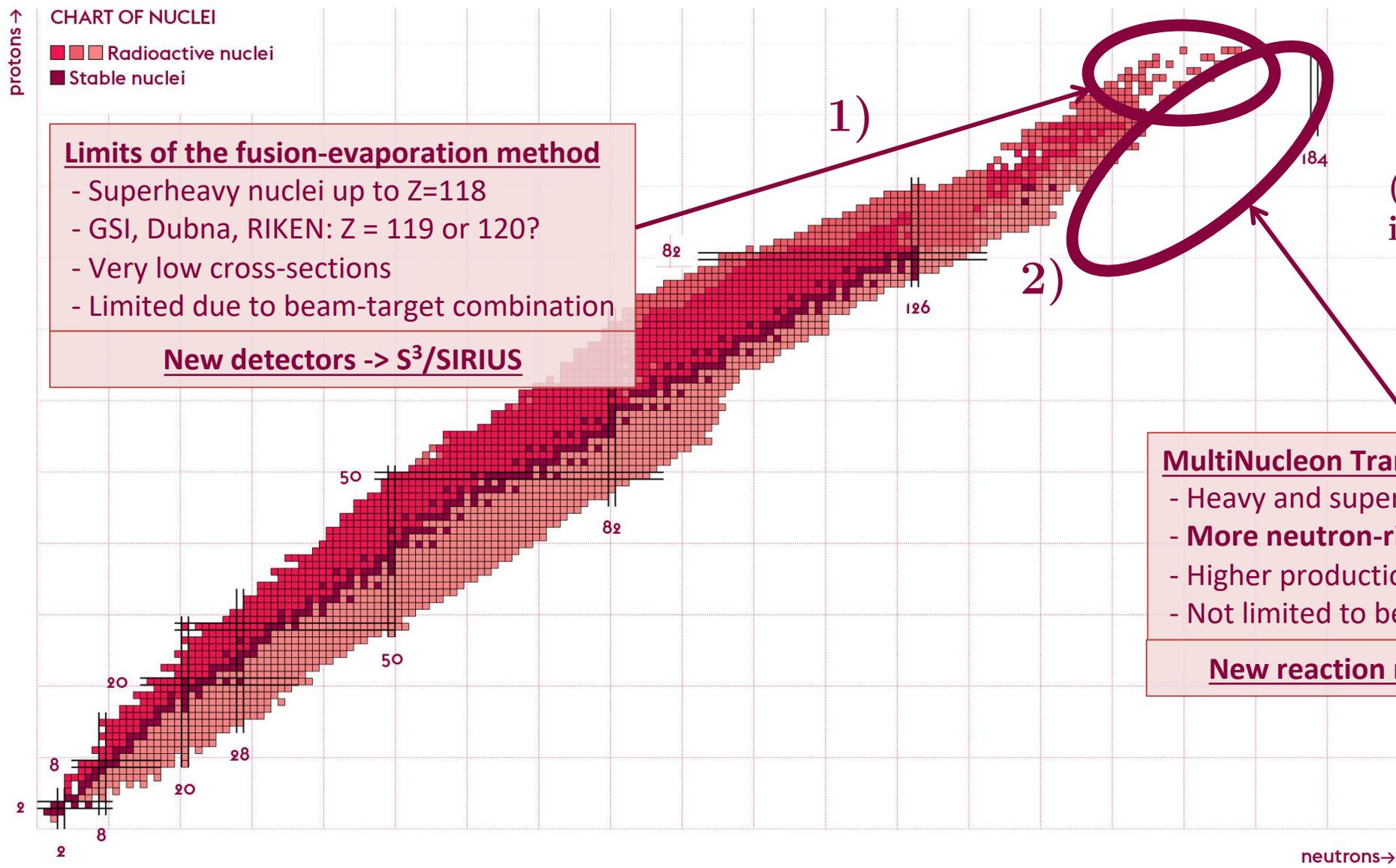


# Reaction mechanisms to produce SHE



- 1) Fusion-evaporation
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# 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<sup>3</sup>/SIRIUS**

118	2
<b>Og</b>	8
	16
	32
	16
	8
Oganesson	
[294]	

(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

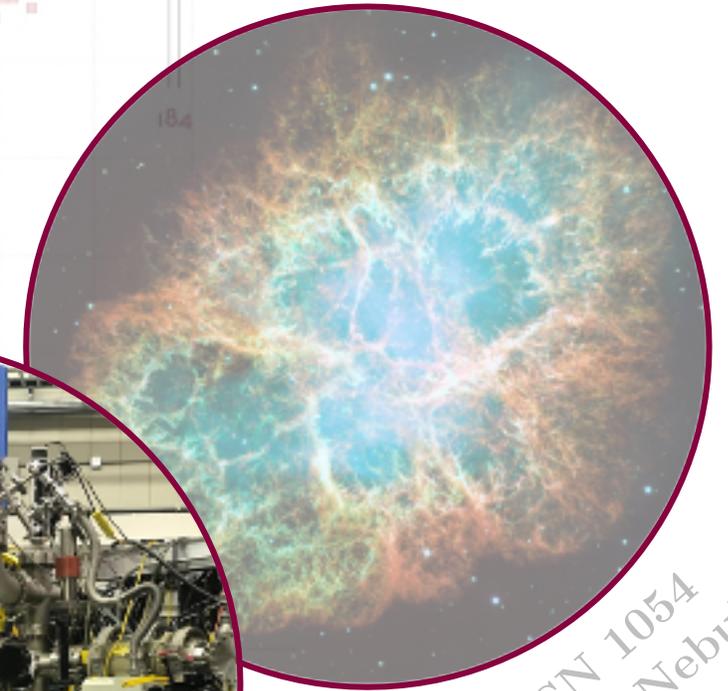
**New reaction mechanisms -> MNT**

# 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 the SIRIUS detector

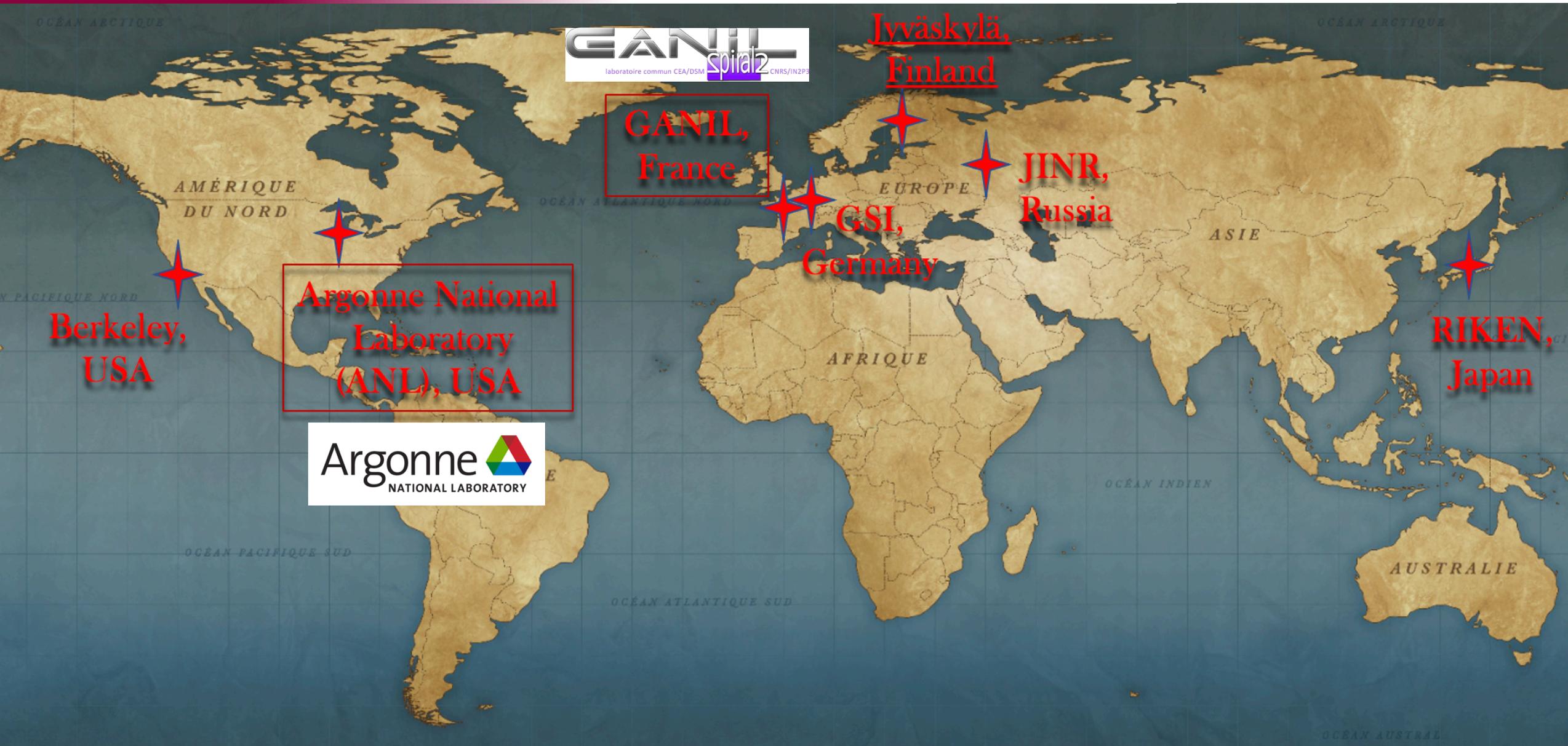


Gammasphere  
Argonne



SN 1054  
Crab Nebula

# 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. Zielinska  
CEA Saclay, IRFU/DPhN, Gif-sur-Yvette, France

D. Seweryniak, M.P. Carpenter, B.R. 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

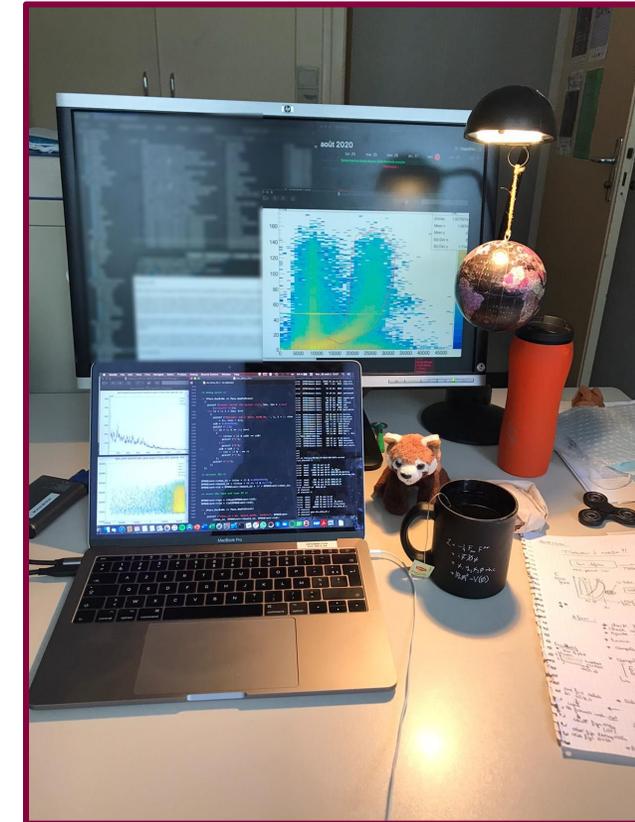
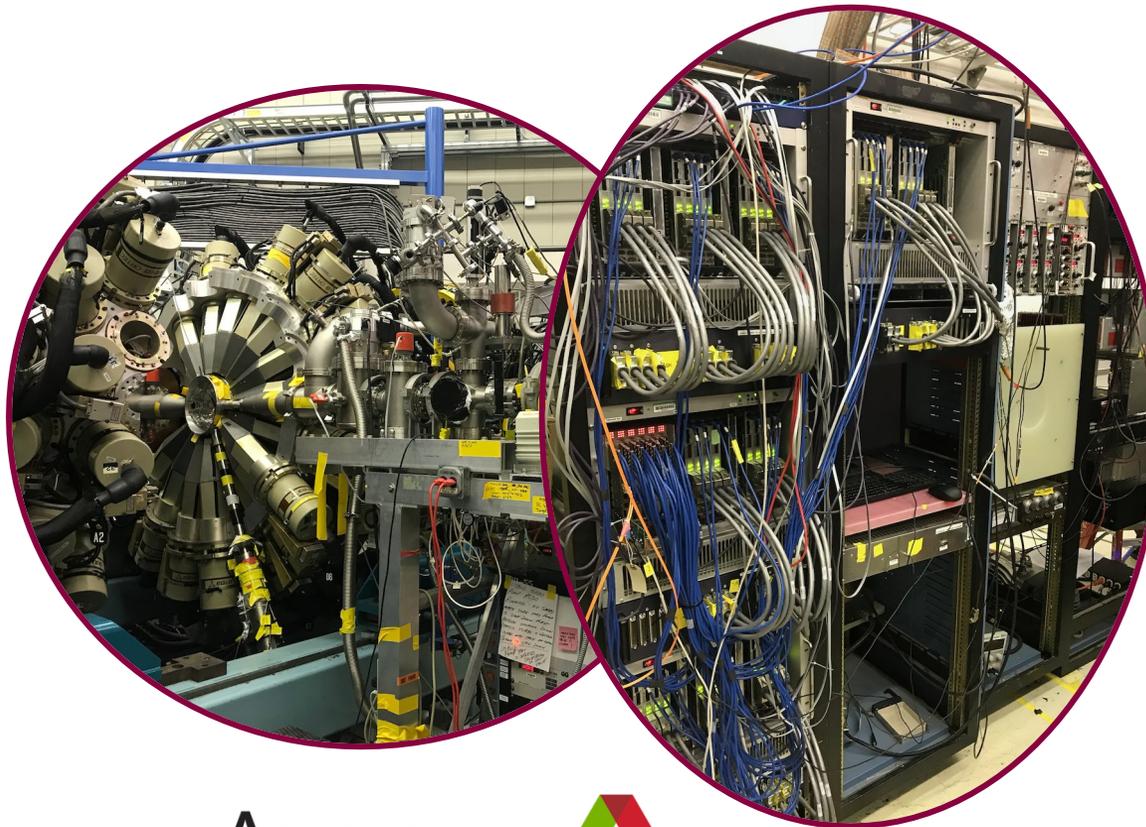
J. Khuyagbaatar, A. Di Nitto, S. Heinz  
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

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 model 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 Gammaphone 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  $^{136}\text{Xe}$  beam on a  $^{229}\text{U}$  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



# Multinucleon transfer reactions (MNT) at Argonne

- Proof-of-principle experiment to study neutron-rich heavy nuclei using MNT reactions

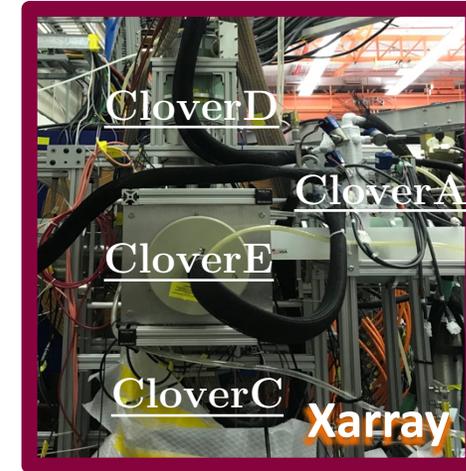
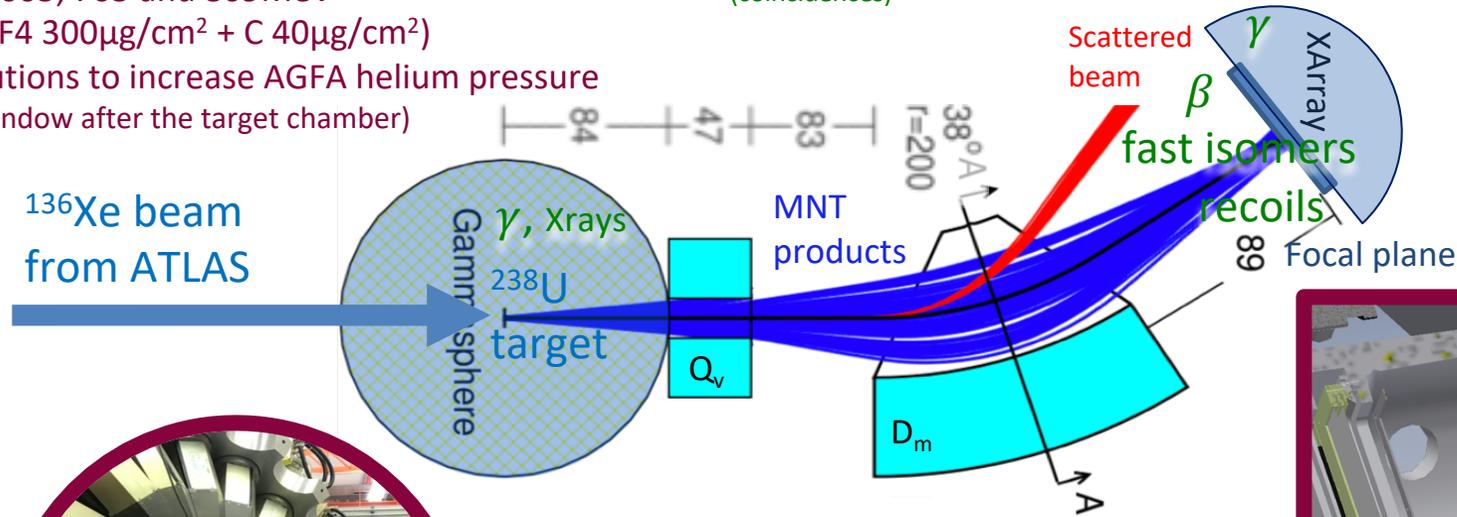
- 1<sup>st</sup> MNT reaction using AGFA @ANL to produce heavy nuclei

- **Beam:**  $^{136}\text{Xe}$  @ 605, 705 and 809 MeV

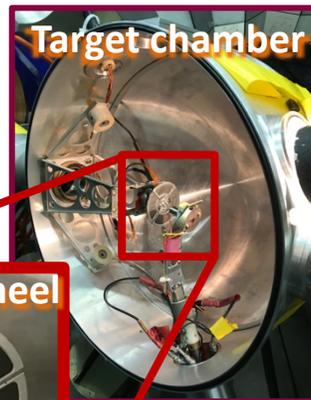
- **Target:**  $^{238}\text{U}$  (UF<sub>4</sub> 300 μg/cm<sup>2</sup> + C 40 μg/cm<sup>2</sup>)

- Innovative solutions to increase AGFA helium pressure up to 3 Torr (Ti window after the target chamber)

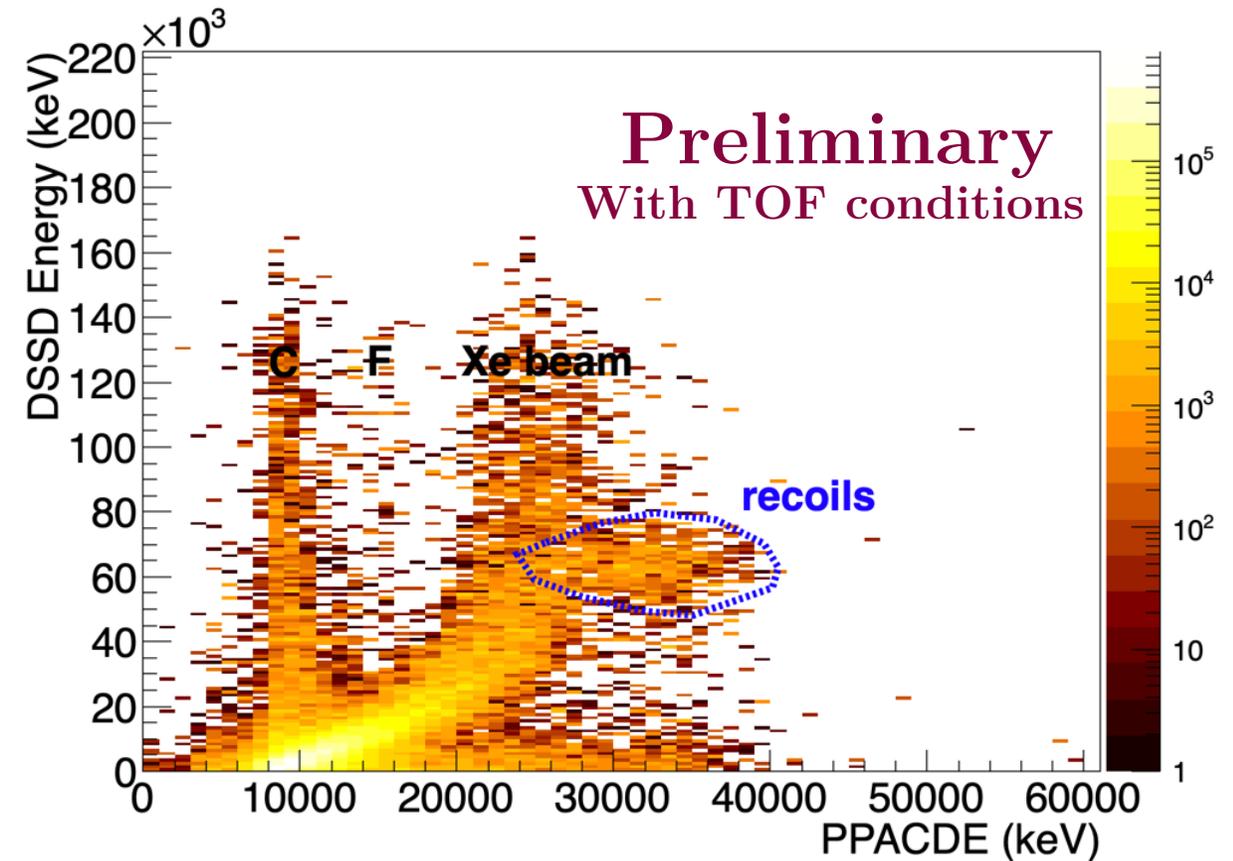
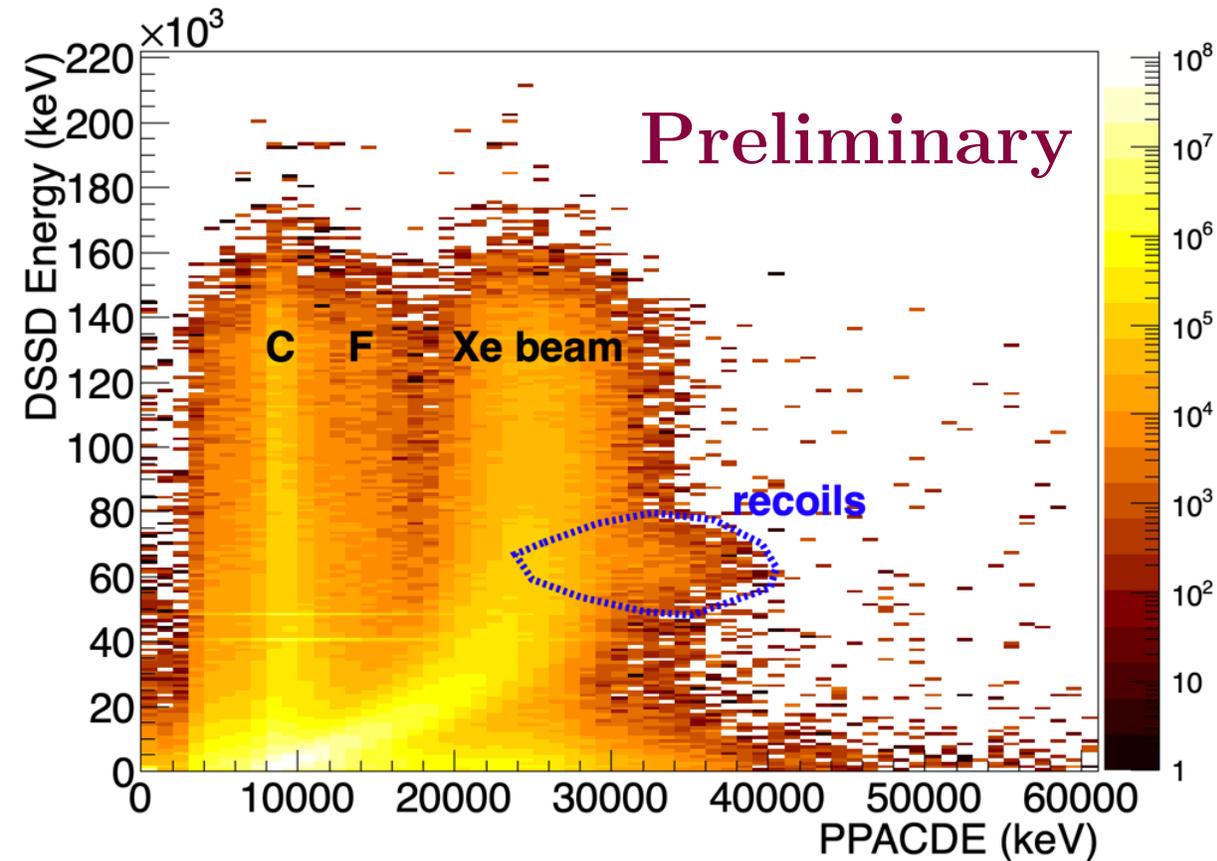
Target-like products identification  
(coincidences)



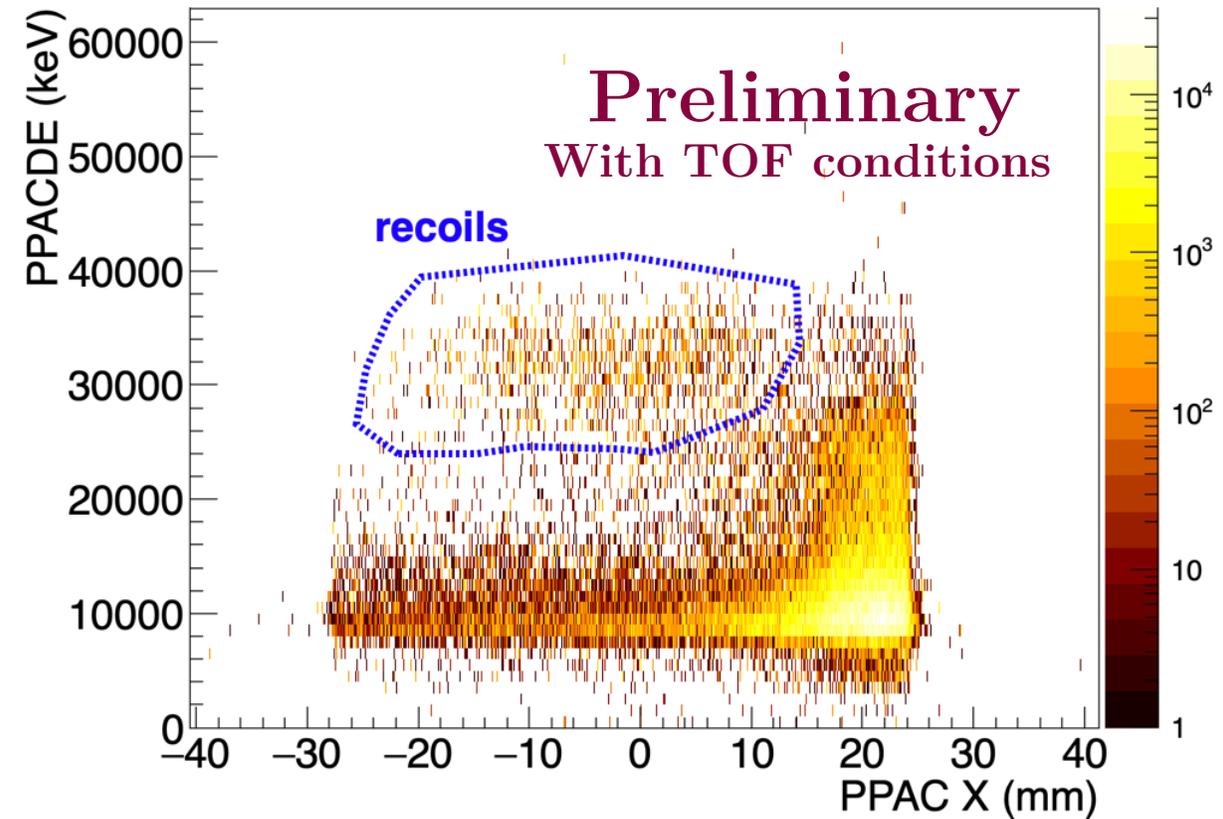
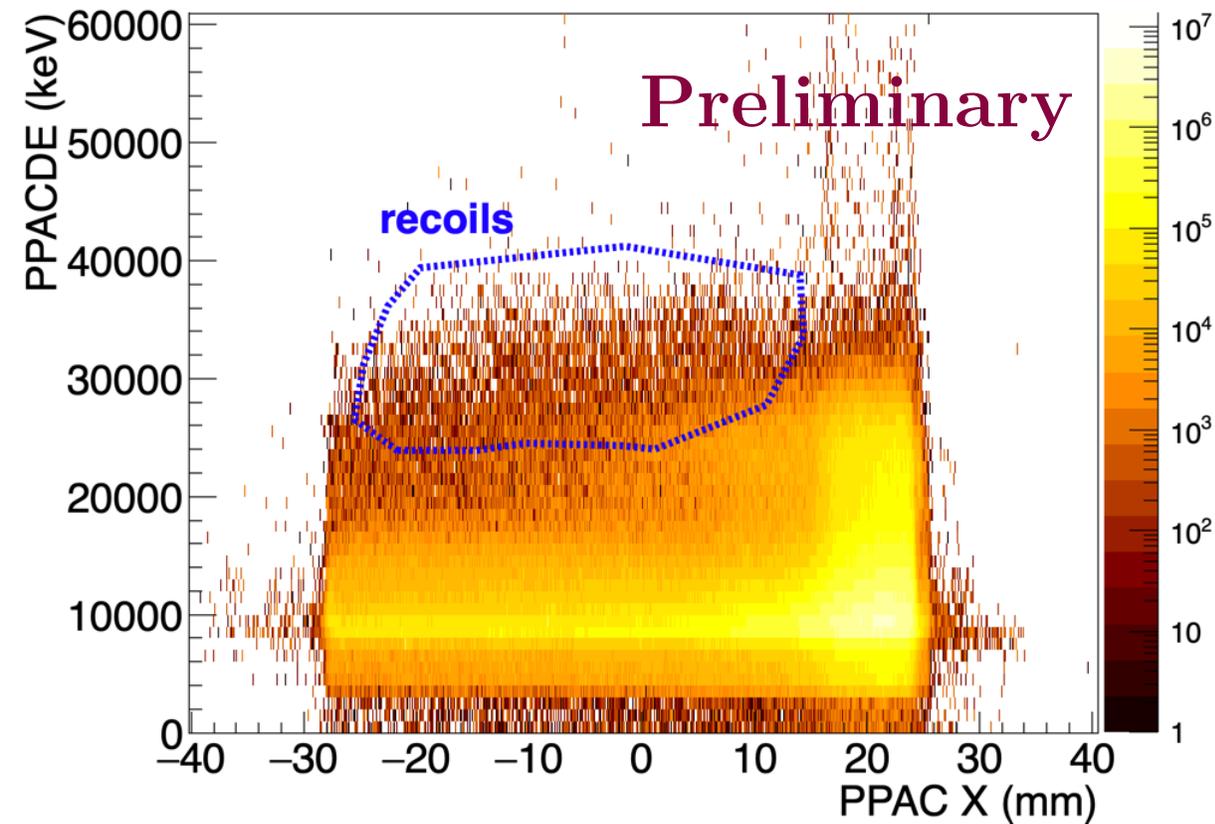
Data Analysis is on going



# Identification of neutron-rich nuclei (recoils)



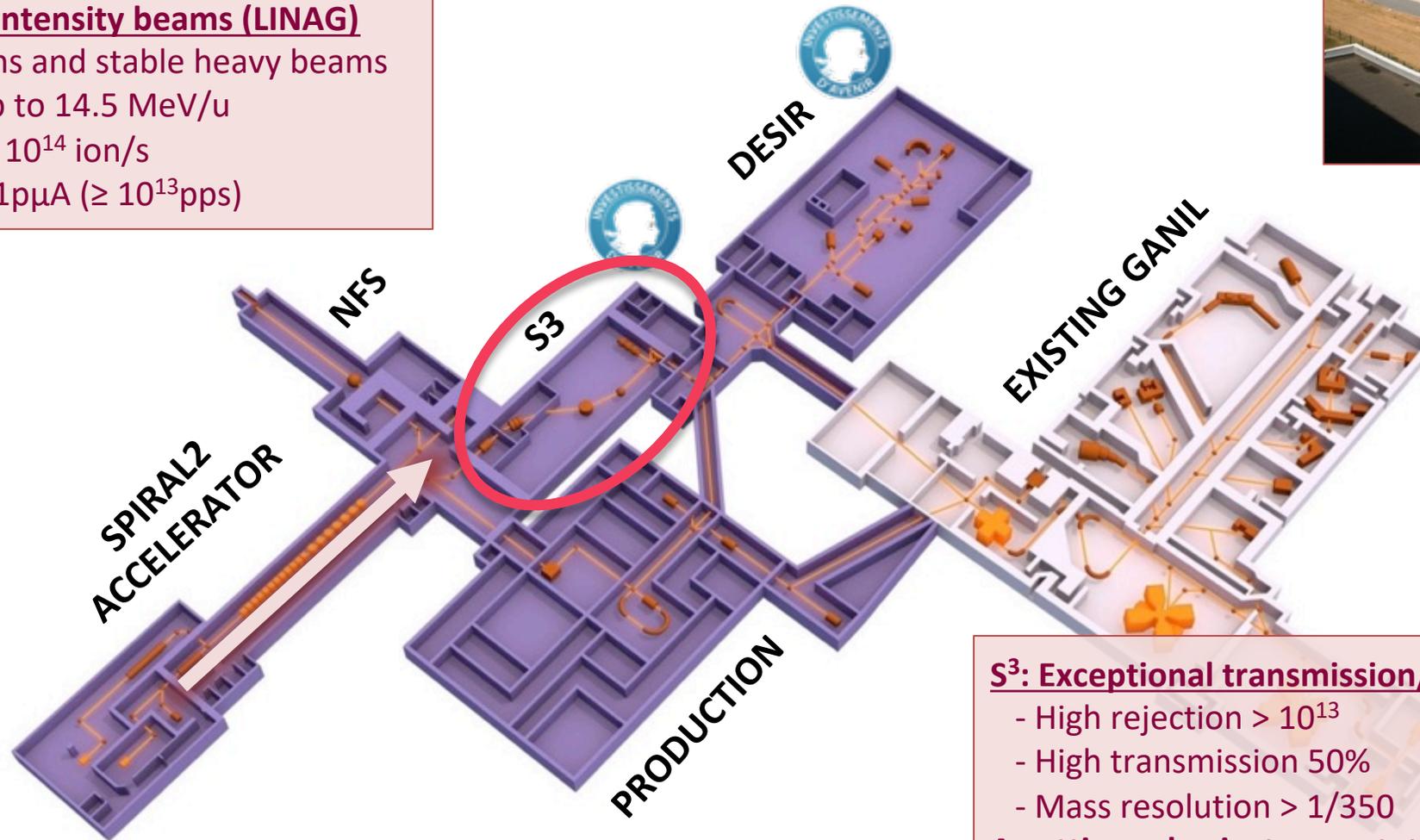
# Identification of neutron-rich nuclei (recoils)



# S<sup>3</sup> in the SPIRAL2 project at GANIL

## Very high intensity beams (LINAG)

- Deuterons and stable heavy beams
- $E_{\text{beam}}$  = up to 14.5 MeV/u
- Intensity  $10^{14}$  ion/s  
beyond  $1\mu\text{A}$  ( $\geq 10^{13}$ pps)



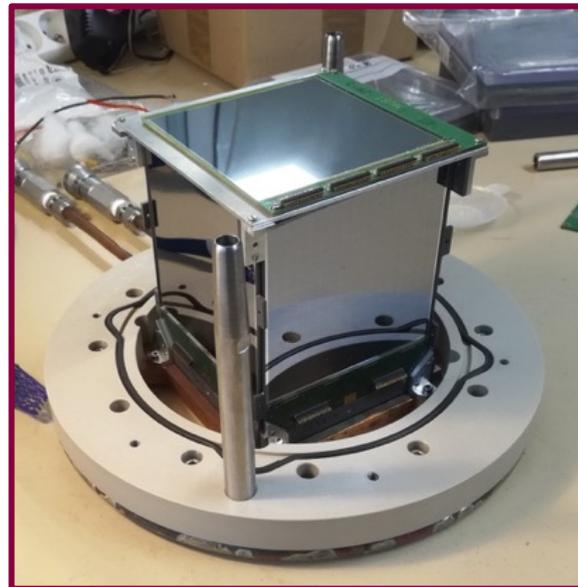
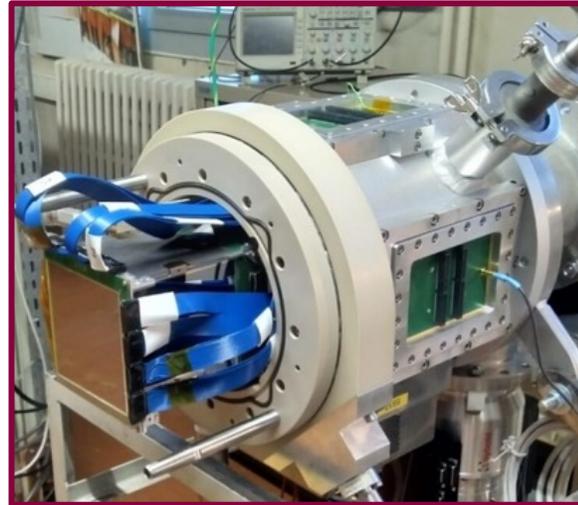
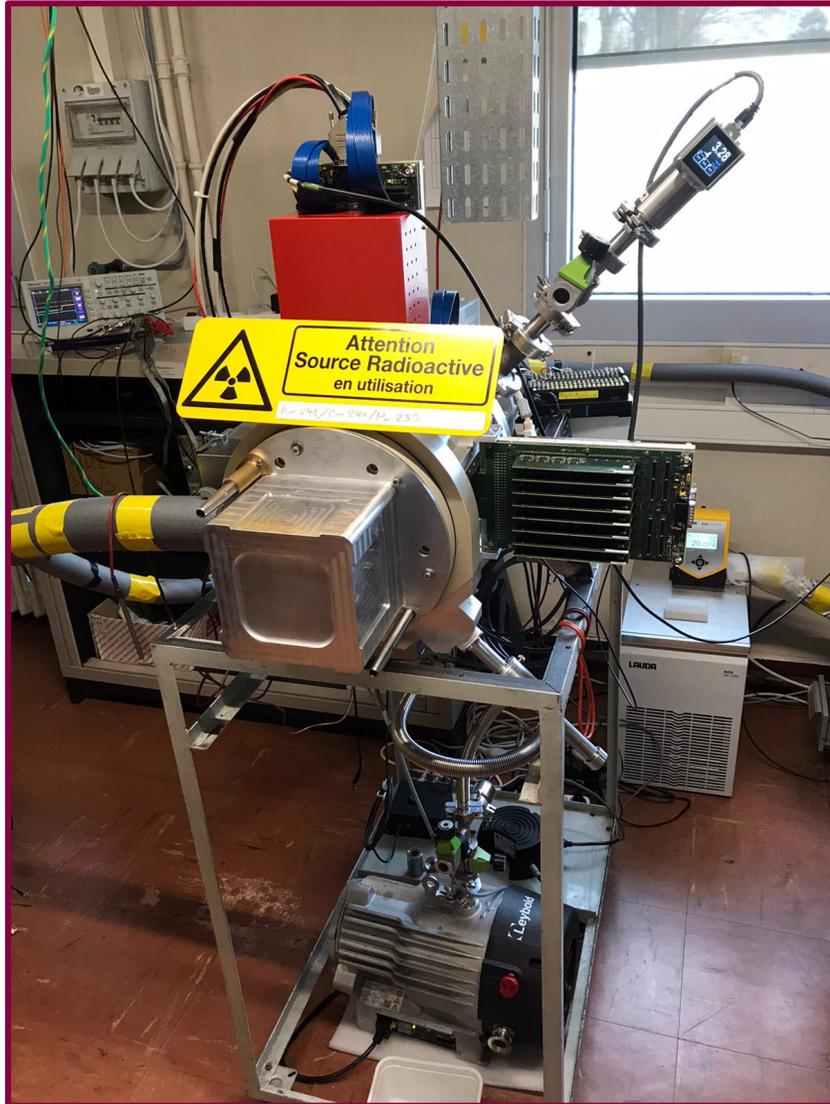
Caen, France

## S<sup>3</sup>: Exceptional transmission/selection combination

- High rejection  $> 10^{13}$
- High transmission 50%
- Mass resolution  $> 1/350$

A cutting-edge instrumentation for S<sup>3</sup>  
(SIRIUS, LEB, FISIC...)

# SIRIUS detectors



Decay station

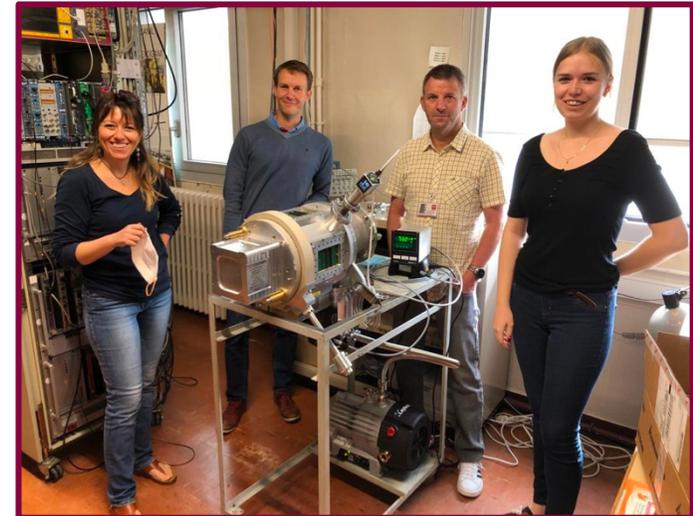
**SIRIUS**

Delayed spectroscopy

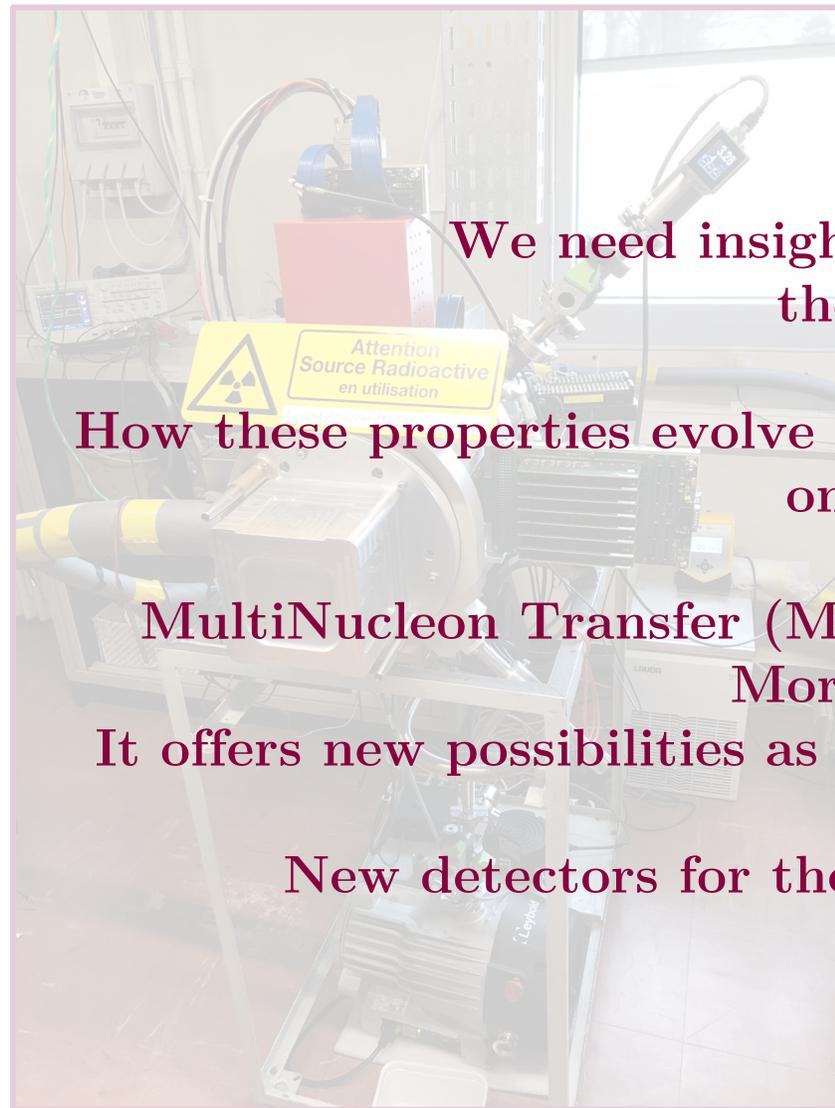
Isomeric/decay

spectroscopy at the mass  
dispersive focal plane

( $\alpha$ , e $^-$ , fission,  $\gamma$ )



# MNT reactions and new detectors



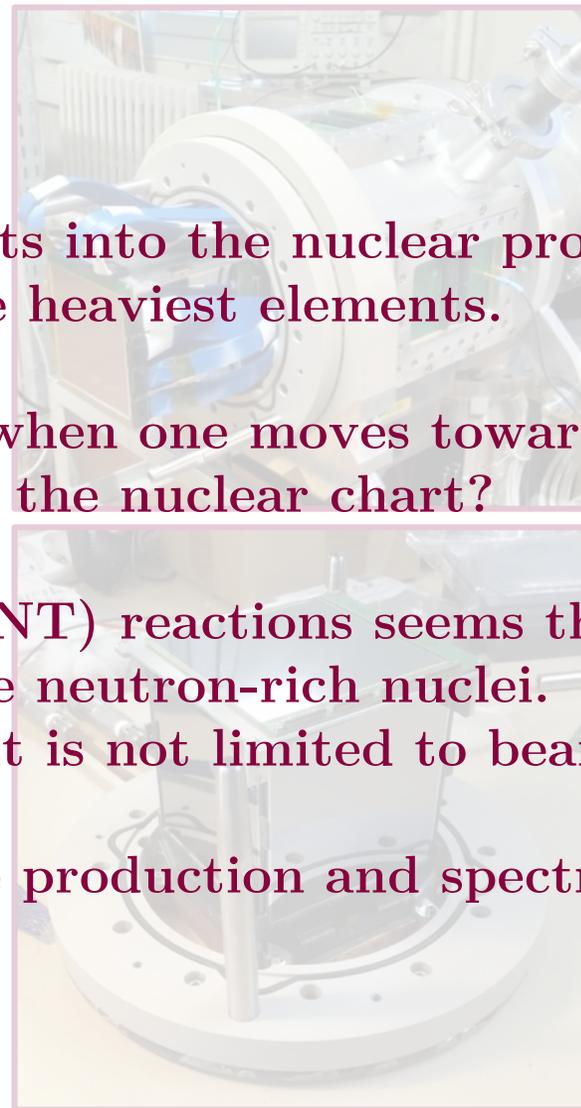
We need insights into the nuclear properties of the heaviest elements.

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.



Decay station

**SIRIUS**

Delayed spectroscopy

Isomeric/decay spectroscopy at the mass  
spectroscopy at the mass  
( $\alpha$ , e<sup>-</sup>, fission,  $\gamma$ )



# 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

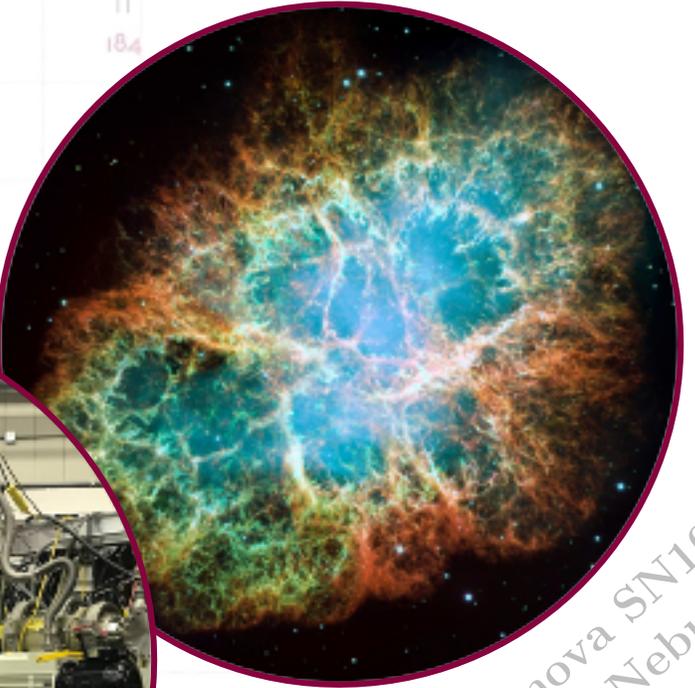
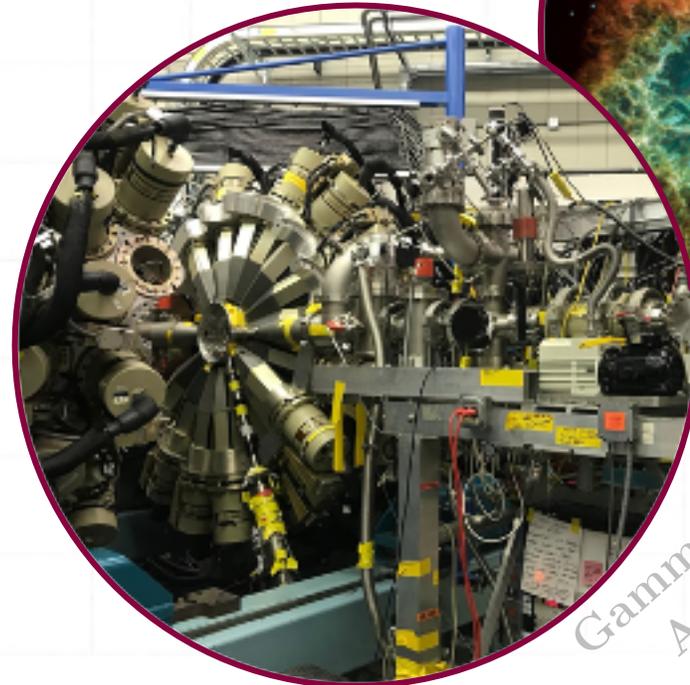
- Stellar nucleosynthesis
- r-process up to U/Th?
- NS-NS and NS-BH mergers

## 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



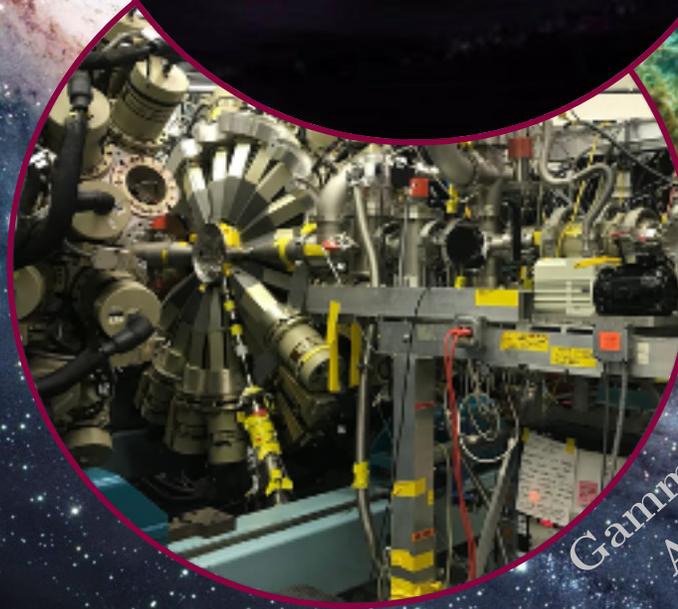
# Superheavy elements in our Universe and in the lab!

*Thanks  
for your attention*

Simulation  
neutron stars merger



Supernova SN1054  
Crab Nebula



GammaSphere  
Argonne



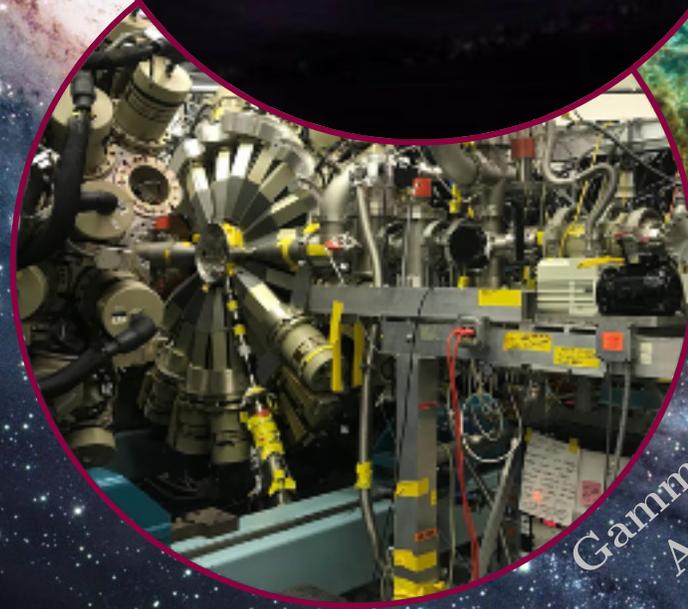
# Superheavy elements in our Universe and in the lab!

*Backup slides*

Simulation  
neutron stars merger



Supernova SN1054  
Crab Nebula



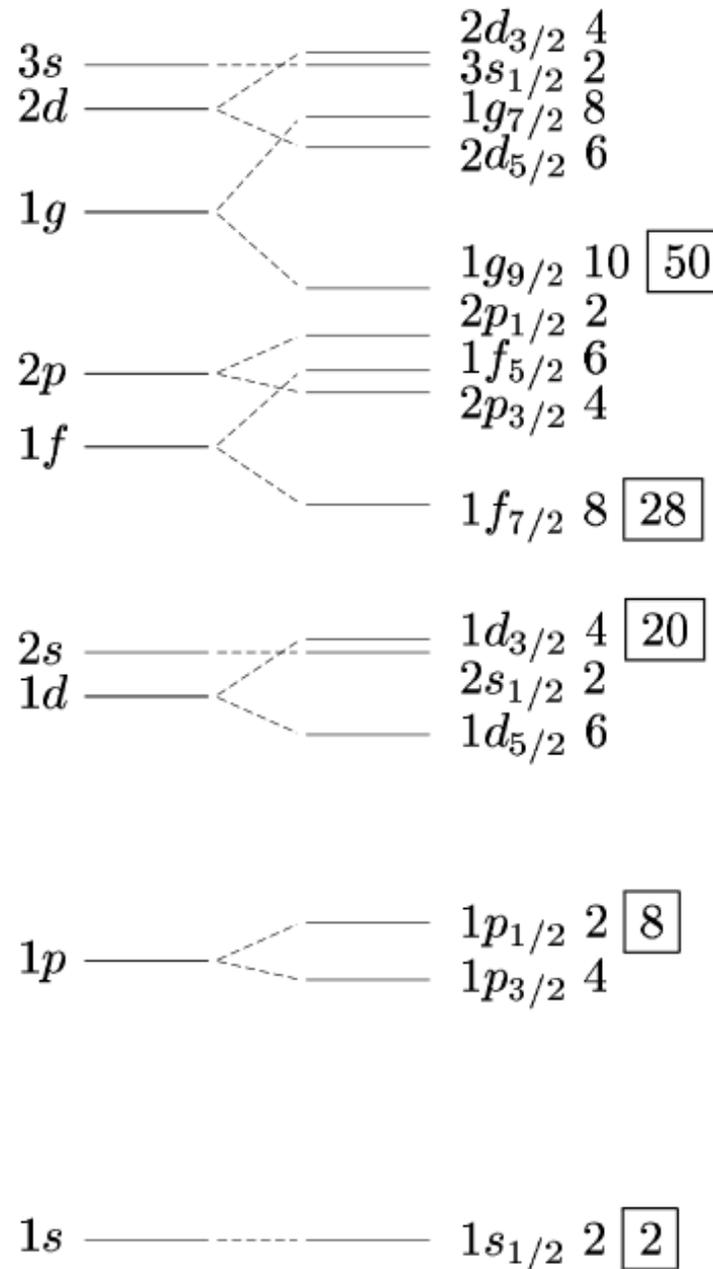
GammaSphere  
Argonne



# The Shell Model



Maria Goeppert Mayer  
(1906-1972)

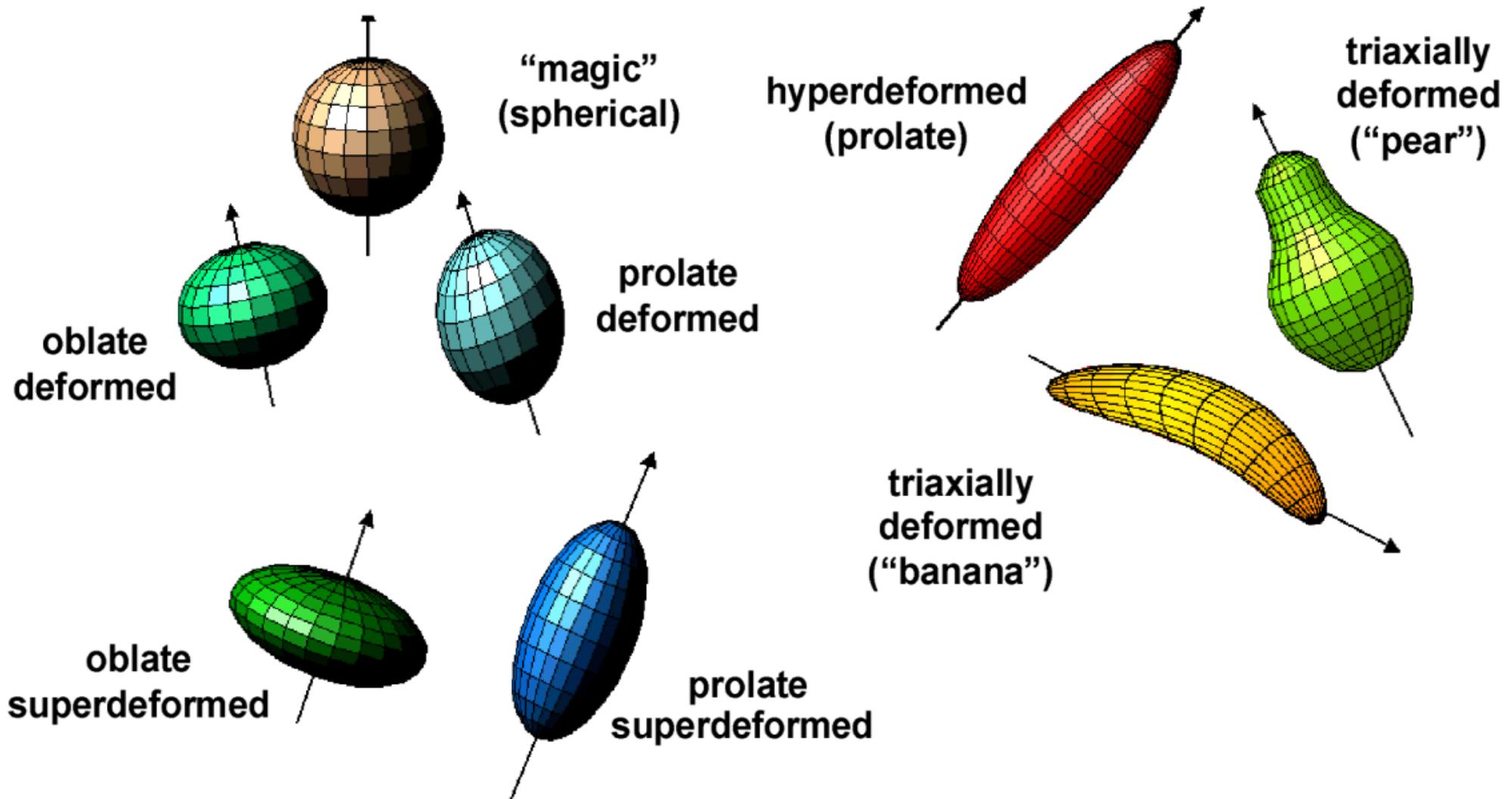


Shell model developed  
by Maria Goeppert Mayer  
at Argonne National Laboratory

with P. Wigner  
and J. Hans D. Jensen

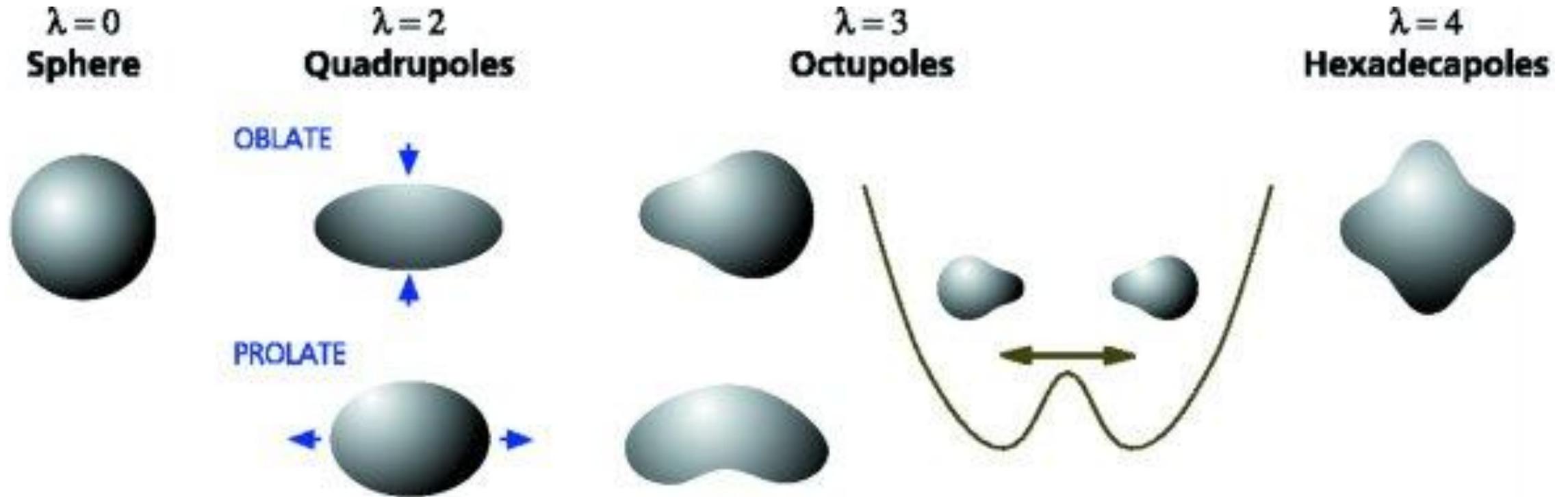
Nobel Physics Prize in 1963.

# Shapes of the nuclei



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

# Shapes of the nuclei – main multipoles



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

# Quadrupole deformation

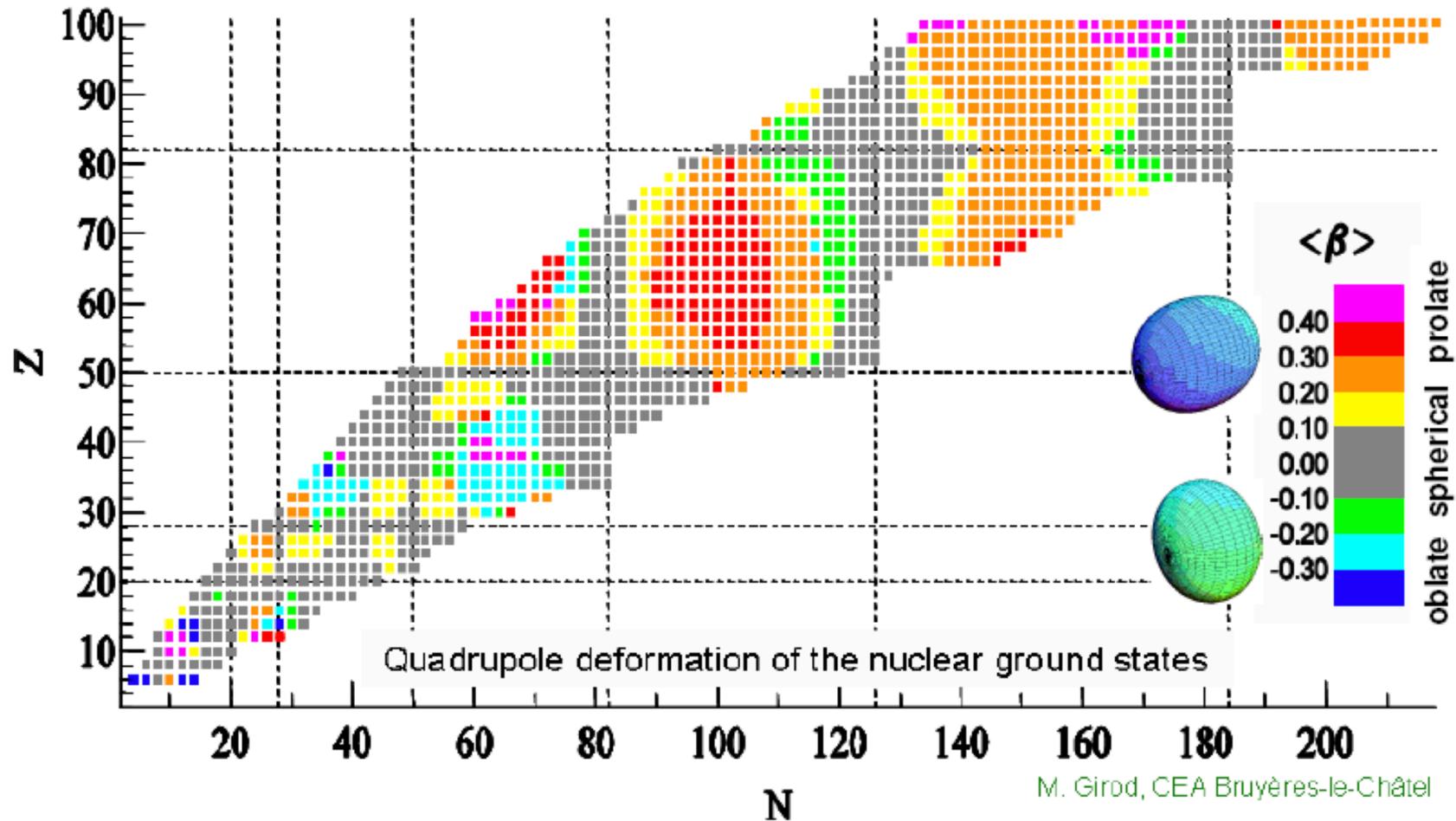
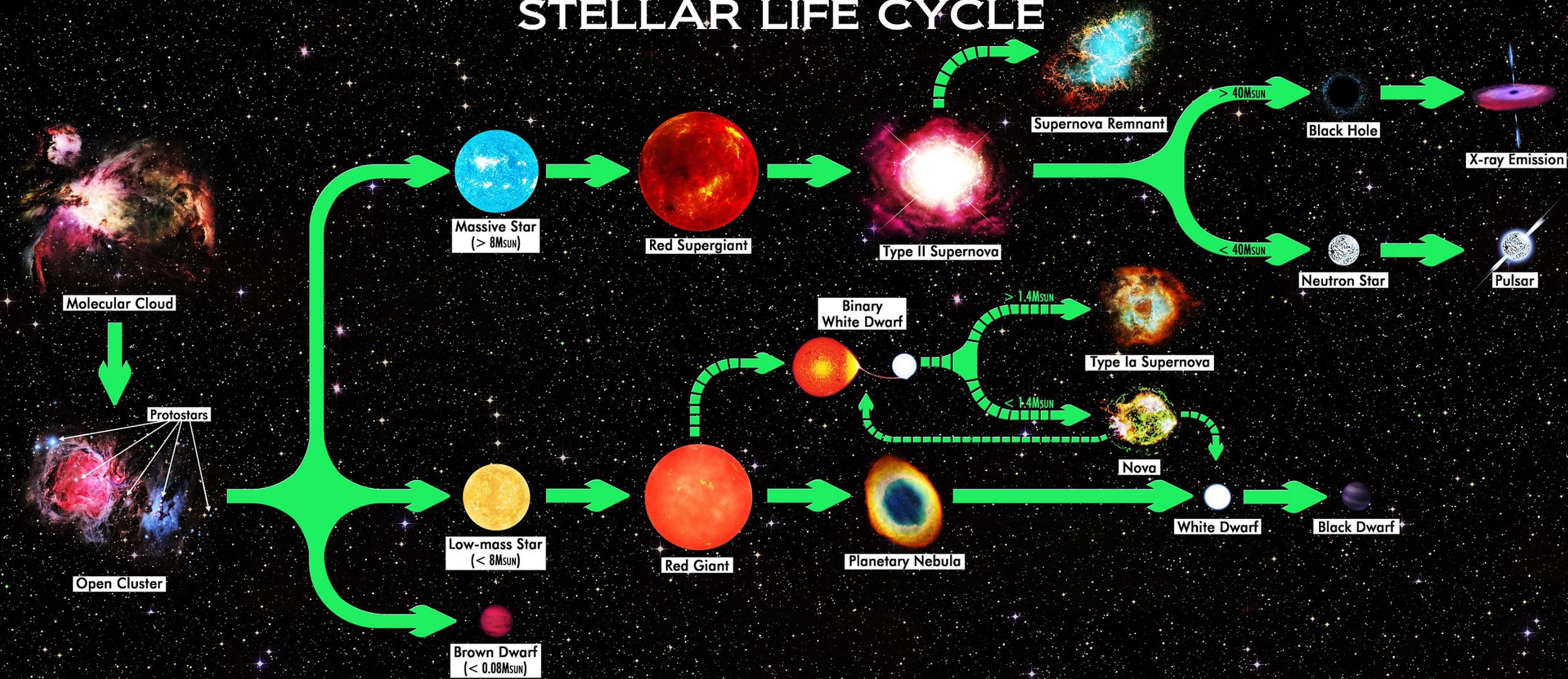


Fig.1. Nuclear chart showing the ground-state shapes predicted by a Hartree-Fock-Bogolyubov (HFB) calculation with the Gogny D1S effective interaction. The classical shell closures, or magic numbers, are marked by dotted lines. Large prolate deformations ( $\beta > 0$ ) are found above the  $Z=50$  and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

# Stellar life cycle (detailed)

## STELLAR LIFE CYCLE



Birth

Main Sequence

Old Age

Death

Remnant