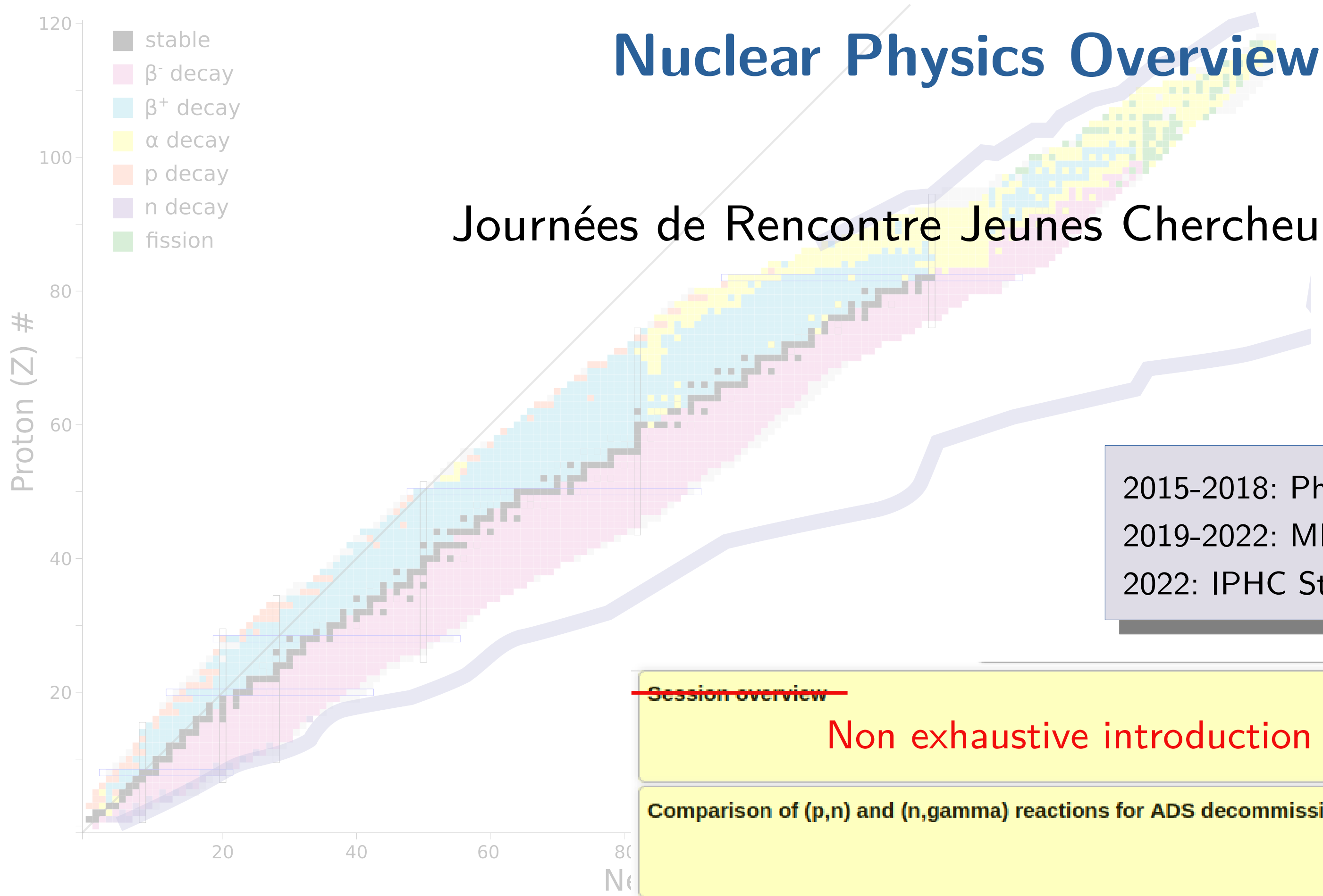
Nuclear Physics Overview

Journées de Rencontre Jeunes Chercheurs 2023



2015-2018: PhD: DPhN, CEA Saclay – Reactor ν

2019-2022: MPIK Heidelberg – Reactor ν

2022: IPHC Strasbourg – Nuclear astrophysics

~~Session overview~~ *Aurélie Bonhomme*

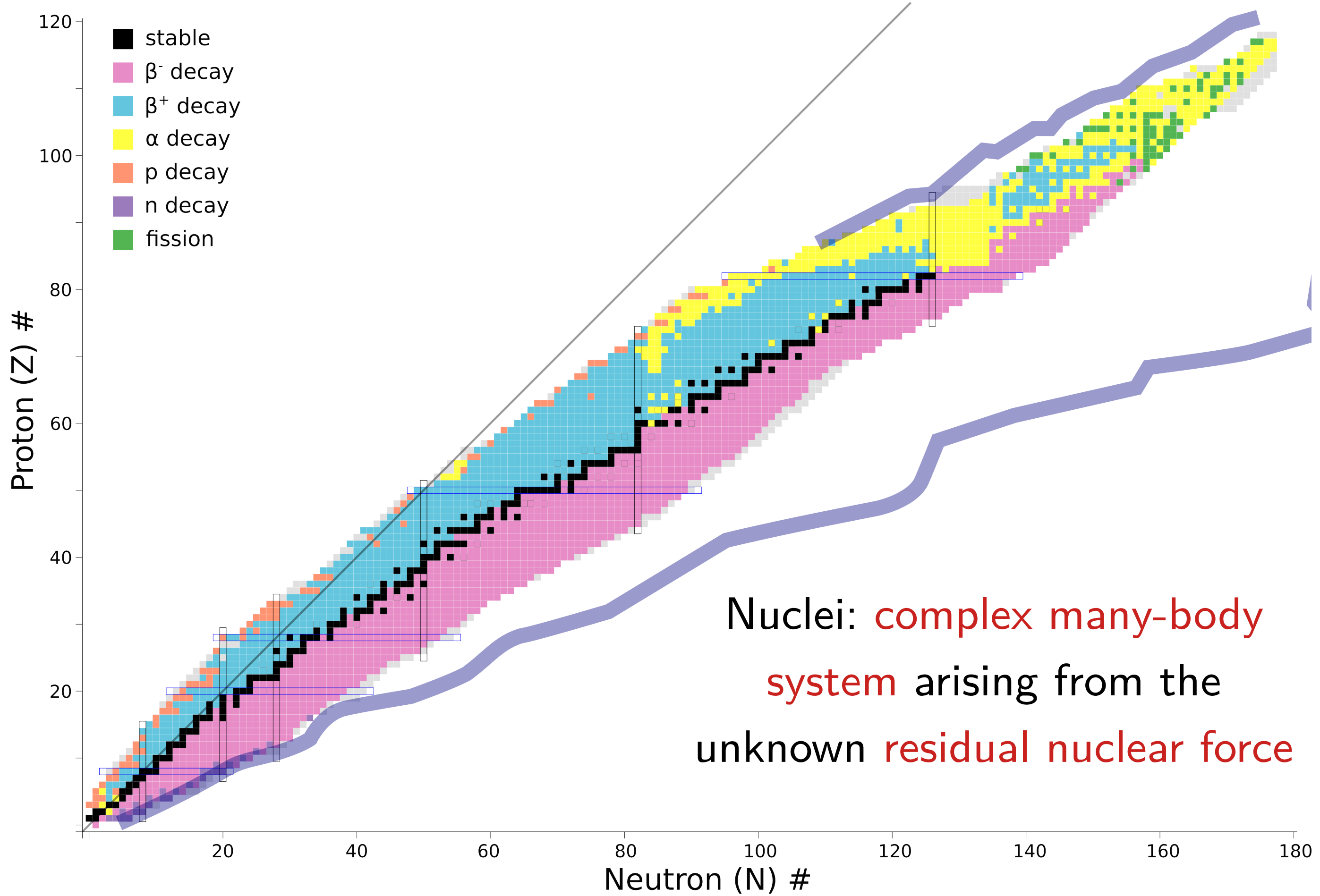
Non exhaustive introduction to nuclear physics!

17:00 - 17:30

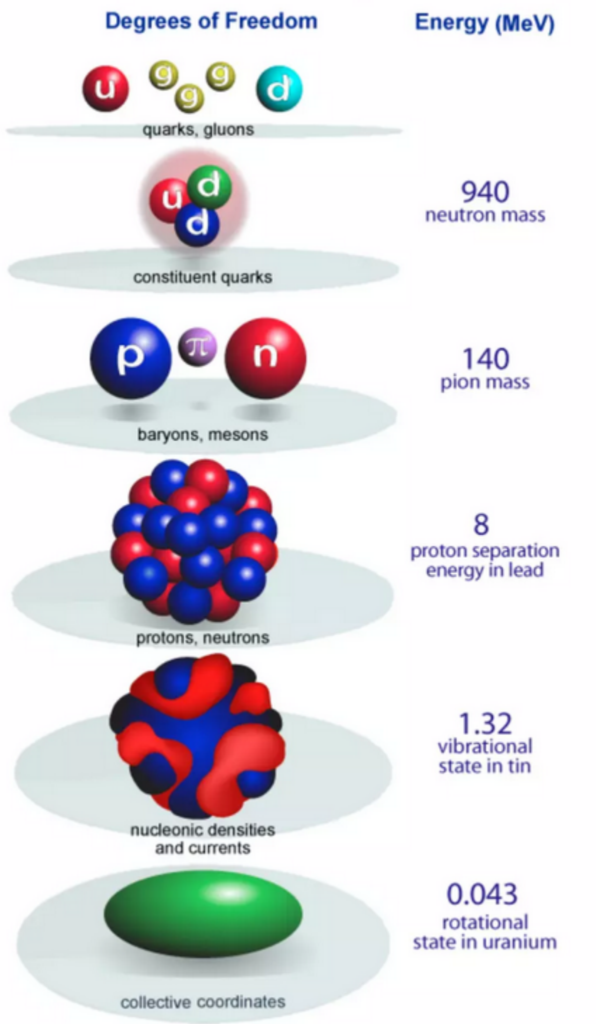
Comparison of (p,n) and (n,gamma) reactions for ADS decommissioning *M. Jonathan COLLIN*

17:30 - 18:00

The nuclear physics landscape



Nuclei: complex many-body system arising from the unknown residual nuclear force

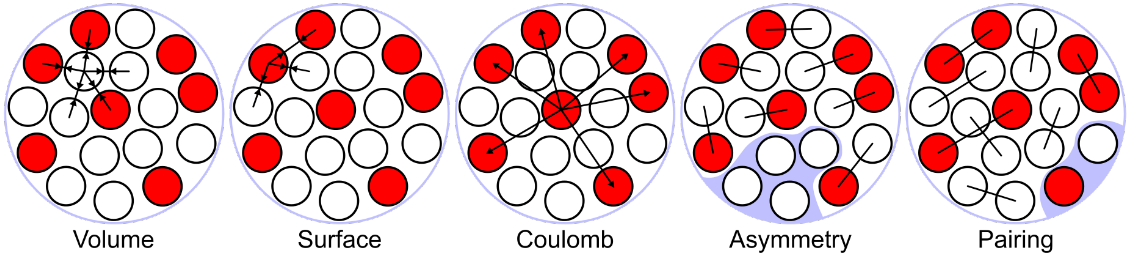


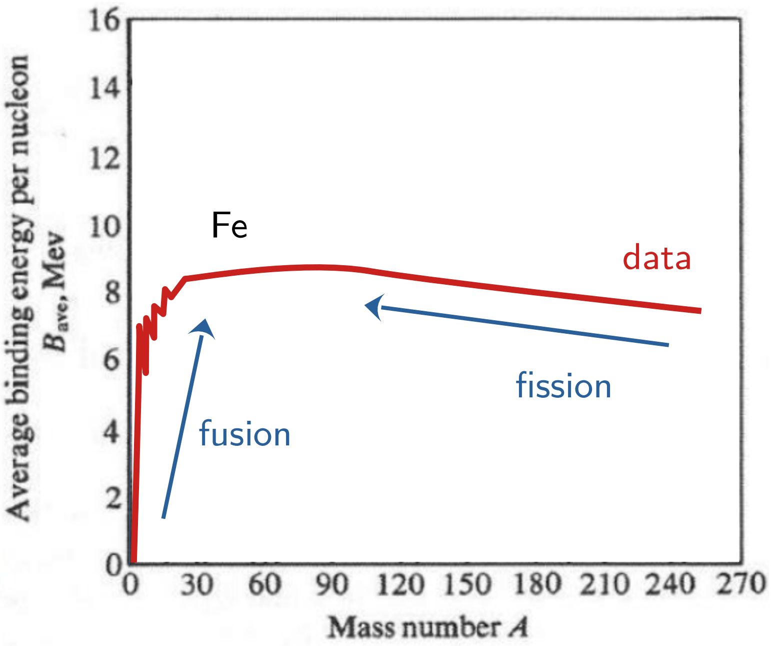
The liquid drop model (1939)

Semi-empirical approach to describe binding energy

$\rightarrow$ understand fission

$$B(Z,A) = a_V A - a_S A^{2/3} - \frac{a_C Z^2}{A^{1/3}} - \frac{a_A (N-Z)^2}{A} + \delta$$





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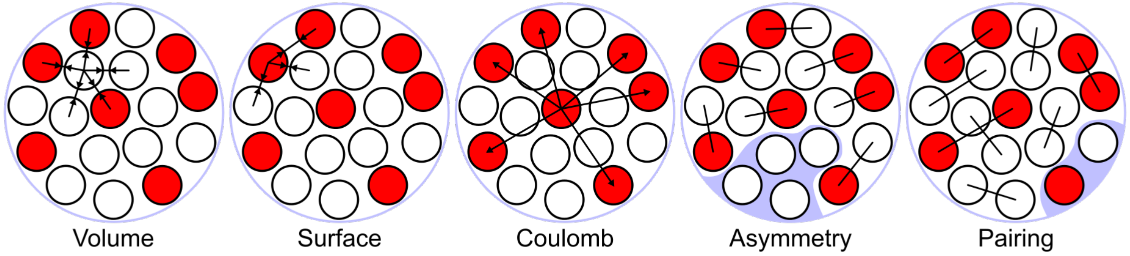

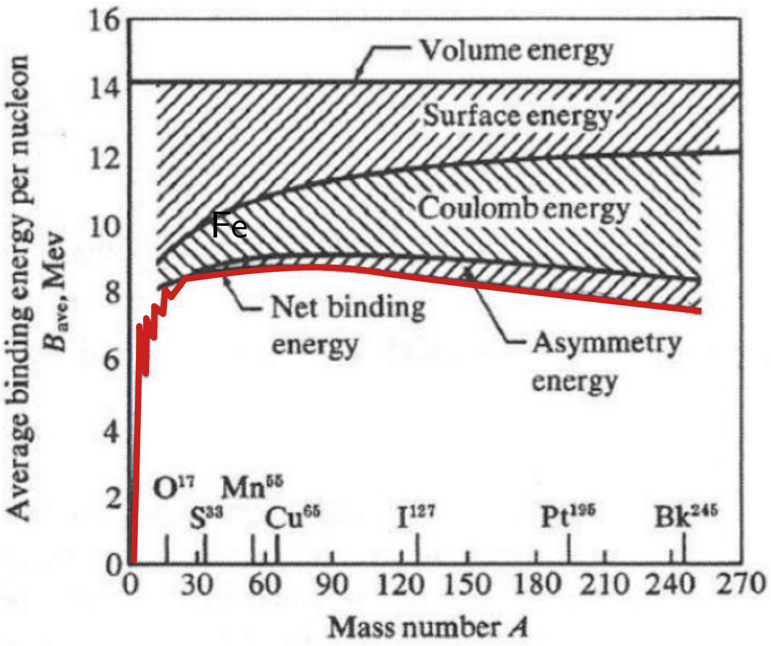

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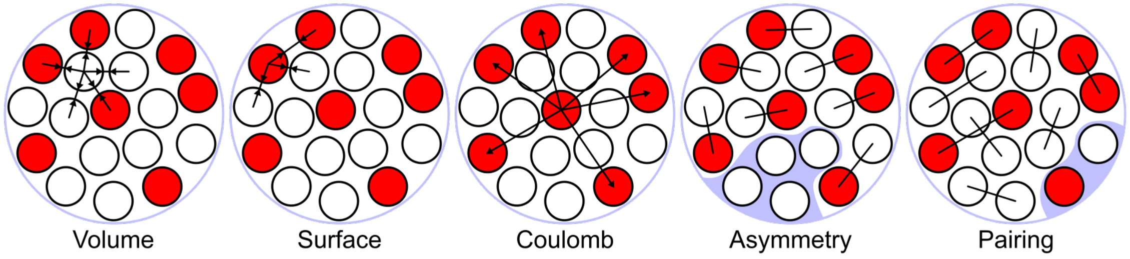
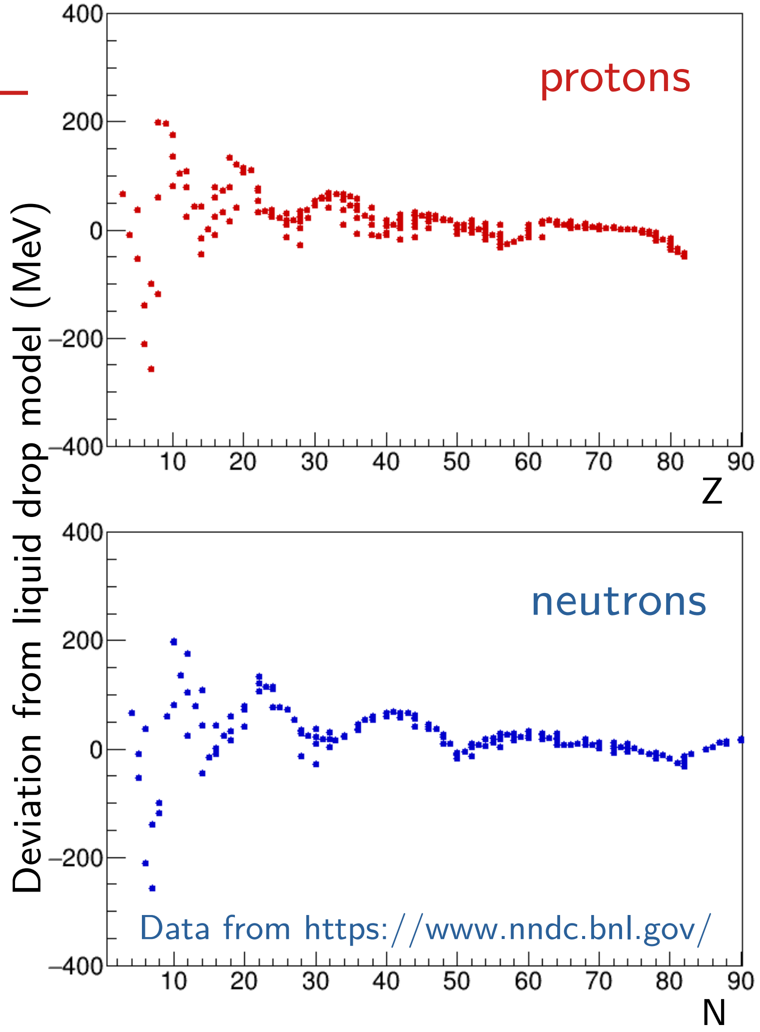


Deviation for magic numbers in protons/neutrons
$\rightarrow$ Evidence of a shell structure



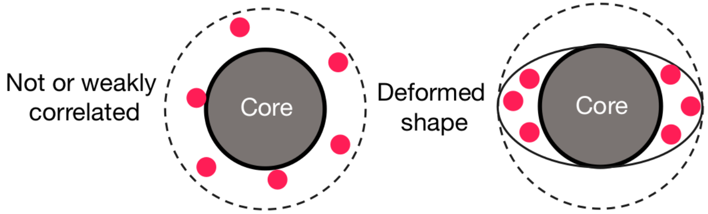
The shell model (from 1949)

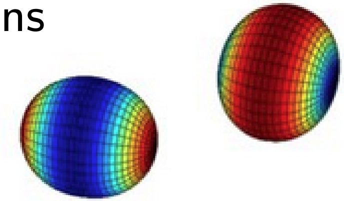
Magic numbers **(2, 8, 20, 28, 50, 82, 126)** → Evidence of a shell structure

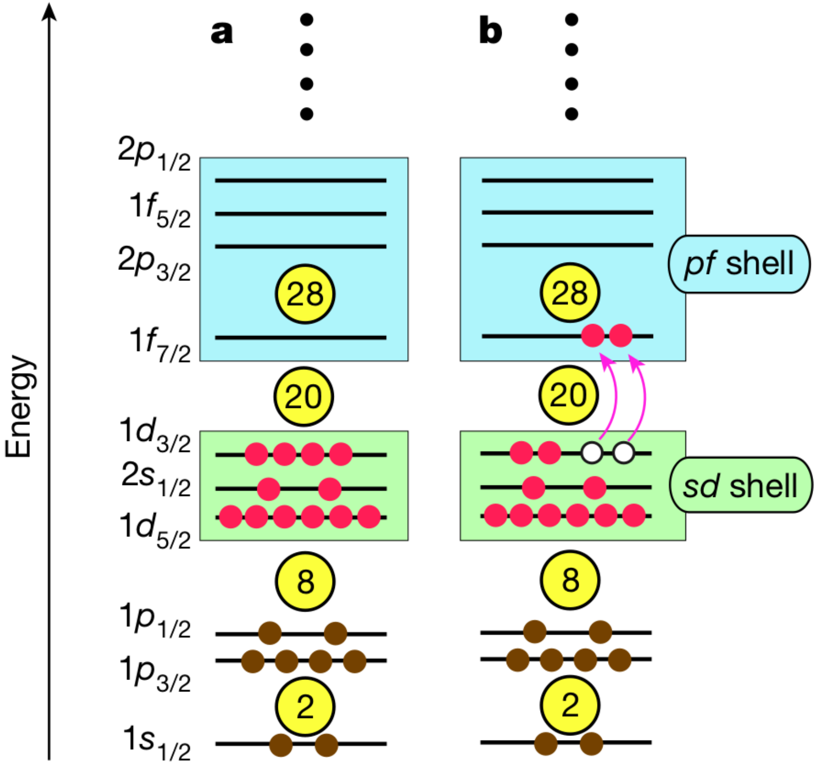
- HO (or Wood-Saxons) + spin-orbit (SO) coupling
  → reproduces magic numbers !
  Mayer and Jensen: Nobel Prize 1963

2nd Nobel woman

- Successful for closed shells ~ spherical nuclei
- Outside closed shells (90% of the nuclei!)
  deformations, collective excitations







Tsunoda *et al.* Nature **587** (2020)

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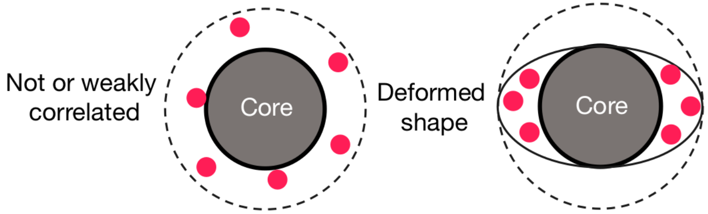
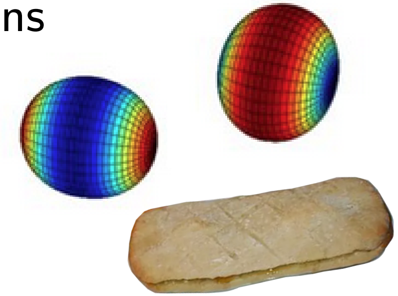
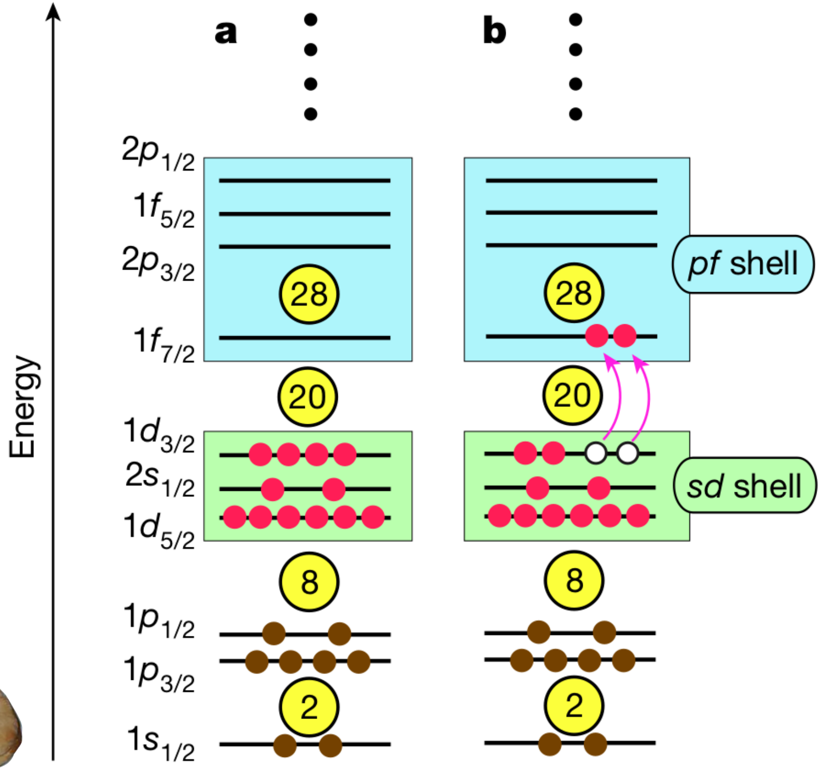
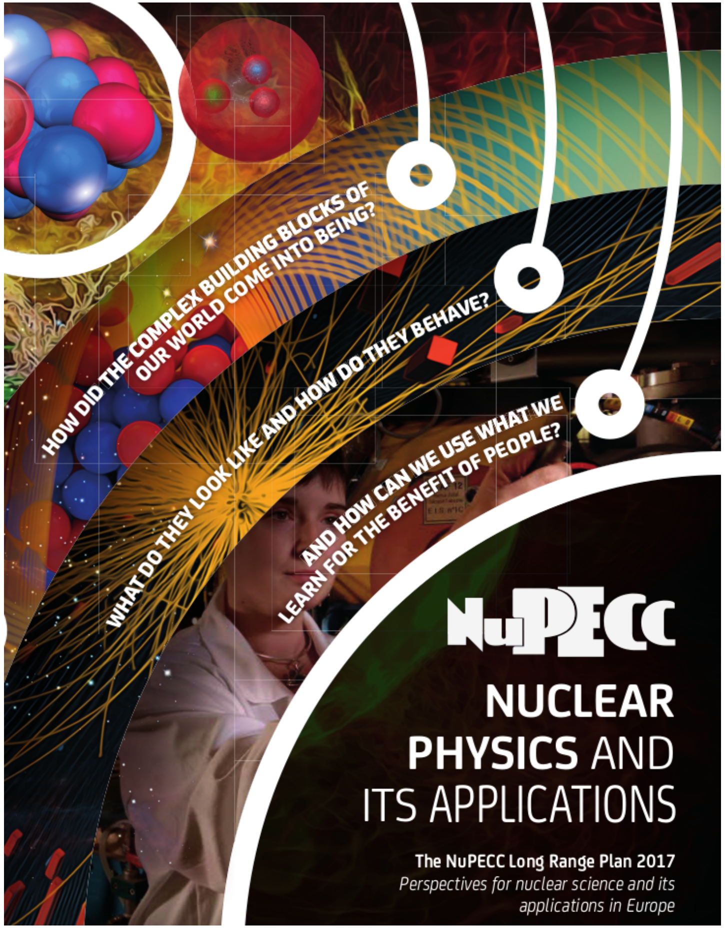






Tsunoda *et al.* Nature **587** (2020)

Open questions



- How does the complexity of nuclear structure emerge from the interactions between the nucleons?

  Nuclear structure and reactions

- What are the limits of nuclear stability in terms of the numbers and proportions of protons and neutrons in a nucleus?

  Exotic / super-heavy nuclei

- How and where in the Universe are the chemical elements produced?

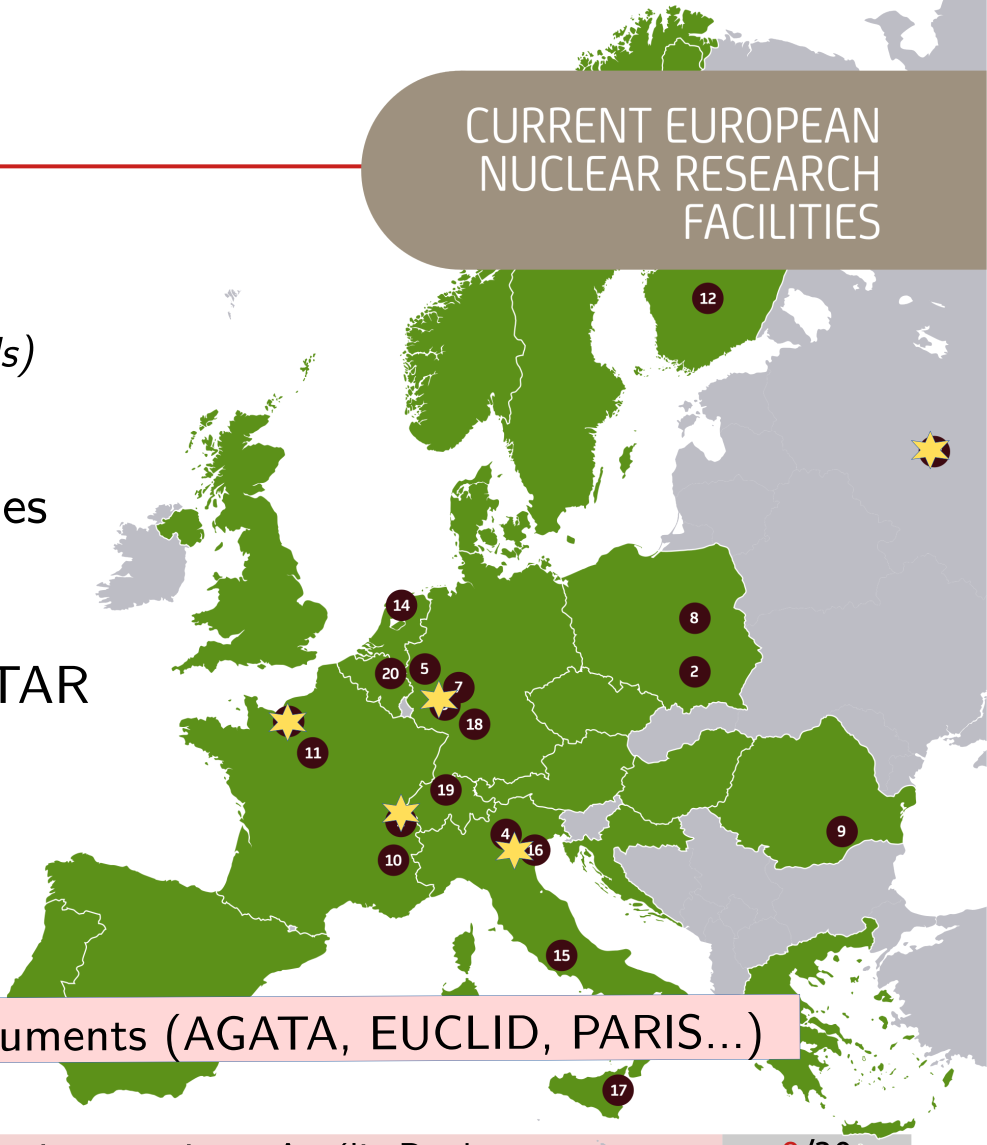
  Nuclear astrophysics

- What are the benefits for society?

Facilities and instruments

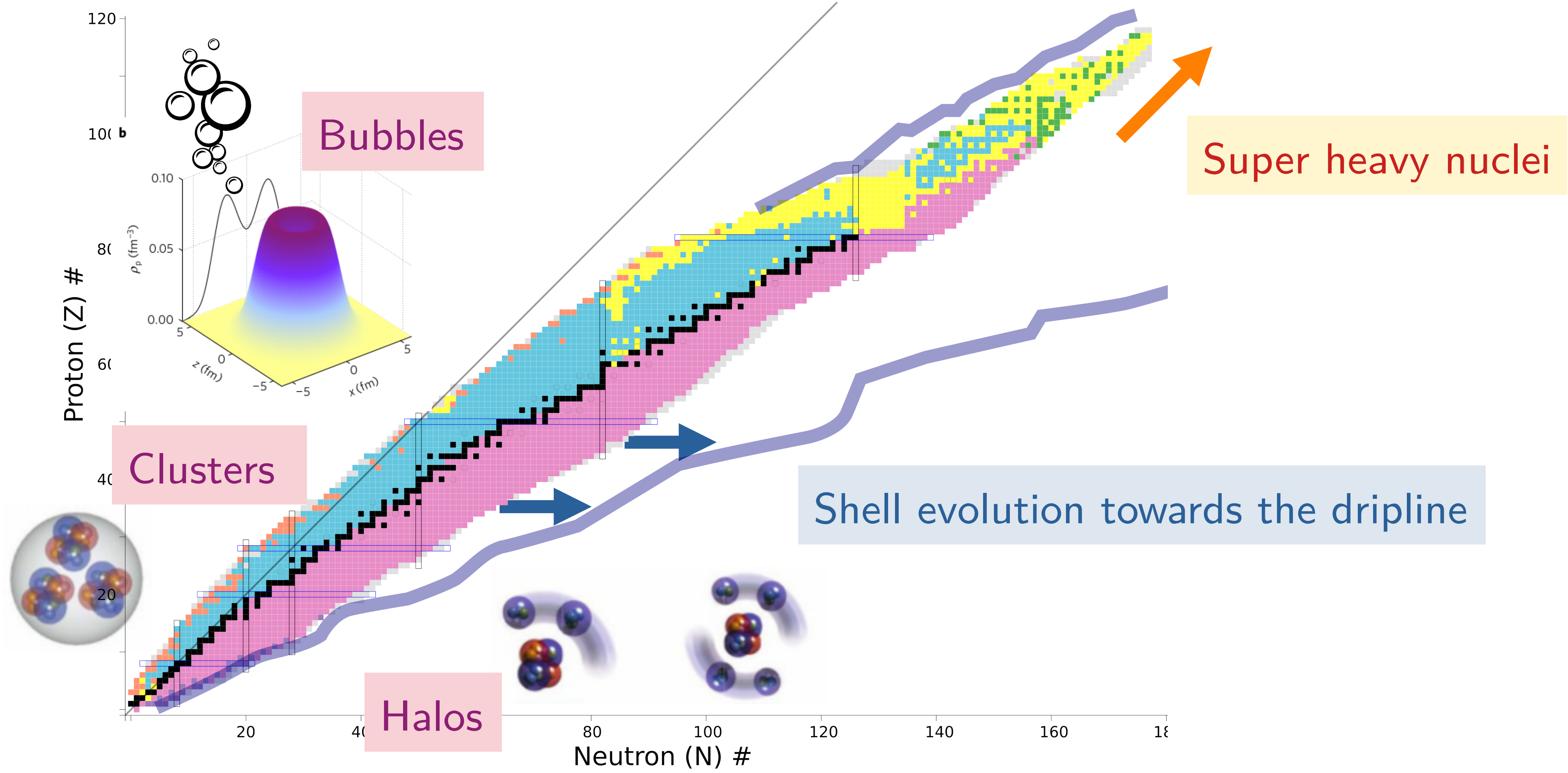
- **ISOLDE** @CERN→ HIE-ISOLDE
- **GANIL** *(Grand Accélerateur National d'Ions Lourds)*
  Heavy-ion accelerator complex
  → SPIRAL2: intense beams of rare isotopes
- **GSI**: light and heavy ions for exotic nuclei
  → FAIR *(Facility of Antiproton Research)*, NUSTAR
- **INFN** Legnaro: neutron-rich nuclei
- **JNR** (Dubna): dedicated for heavy-ion
  collisions for super heavy elements

+ **FRIB** (US) **RIKEN** (Japan)...



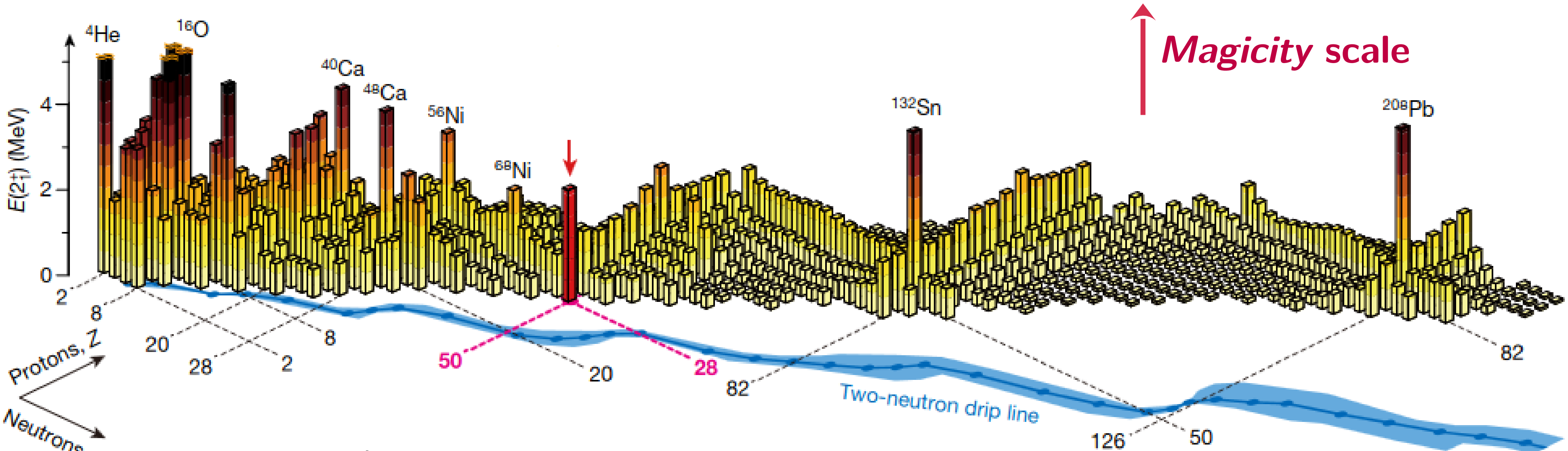
+ instruments (AGATA, EUCLID, PARIS...)

Nuclear structure: selected topics



Exploring the extremes: the neutron drip line

Energy of the first 2+ excited state



magic numbers: 2, 8, 20, 28, 50, 82, 126

Taniuchi *et al.* Nature **569**, 53–58 (2019)

Exploring the extremes: the neutron drip line

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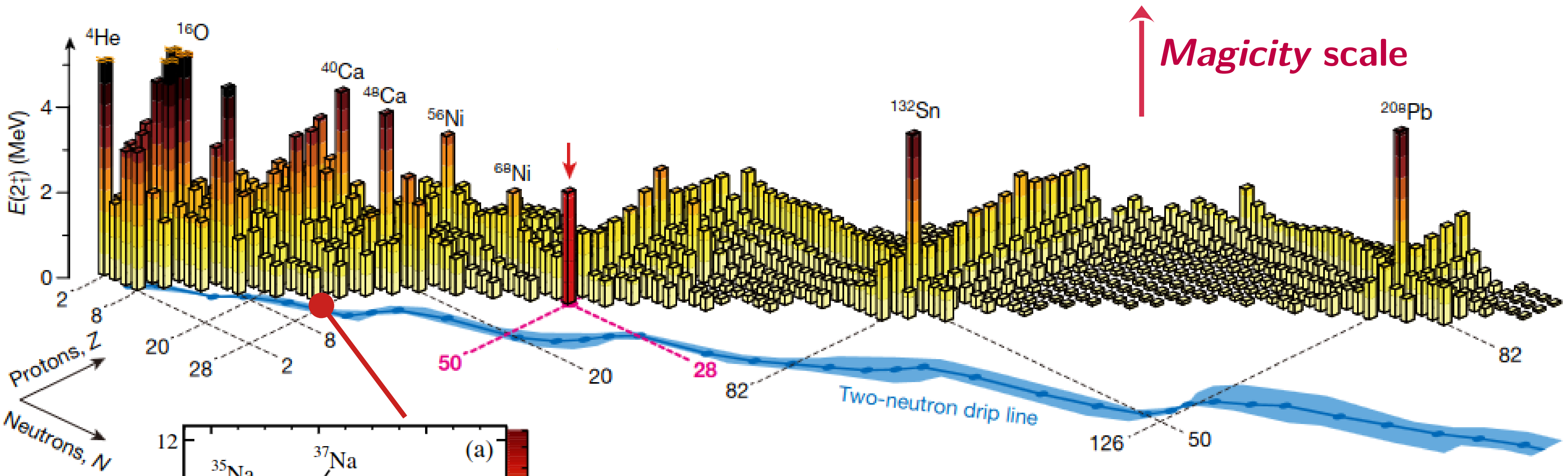

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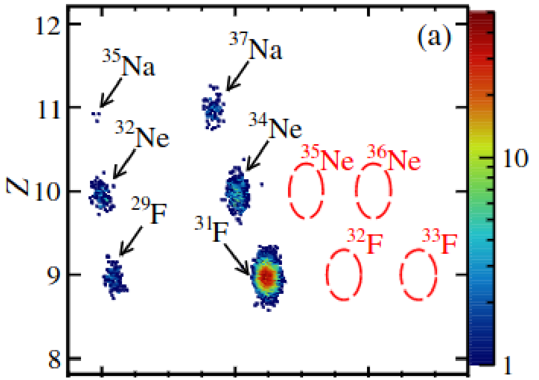
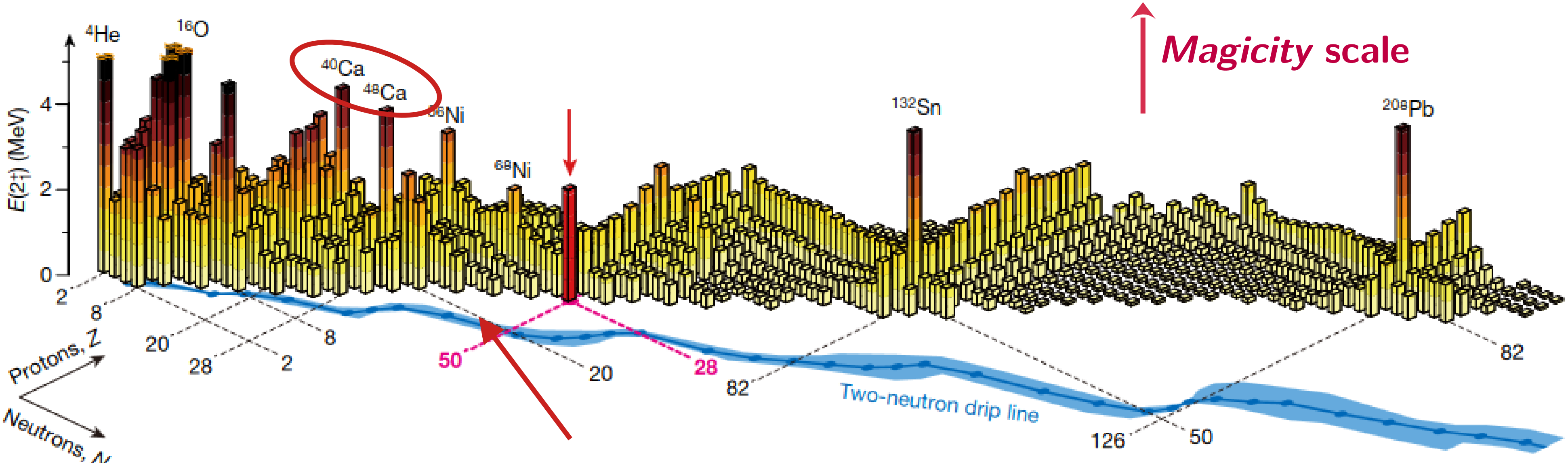


- Experimentally measured only until Ne (Z=10)

Ahn *et al.* Phys. Rev. Lett. **123** (2019)

Exploring the extremes: the neutron drip line

Energy of the first 2+ excited state



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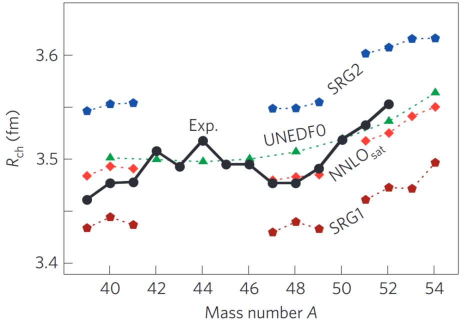

- Ca: exemplary case of shell evolution

  Caurier et al. PRC **75** (2007)

- New neutron magic numbers? N=32, 34

  Garcia-Ruiz *et al.* Nature Phys **12** (2016)

Exploring the extremes: the neutron drip line

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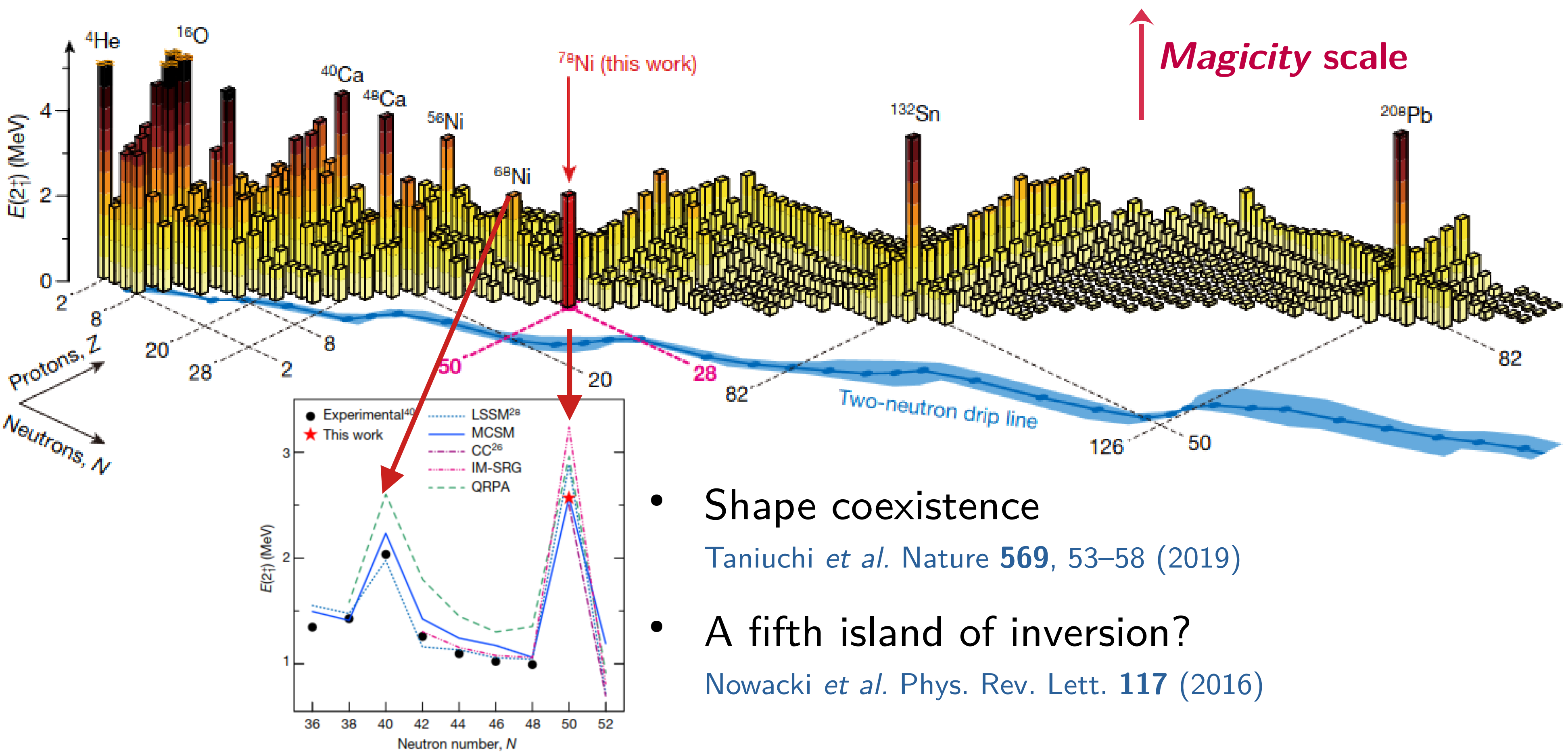


Taniuchi *et al.* Nature **569**, 53–58 (2019)

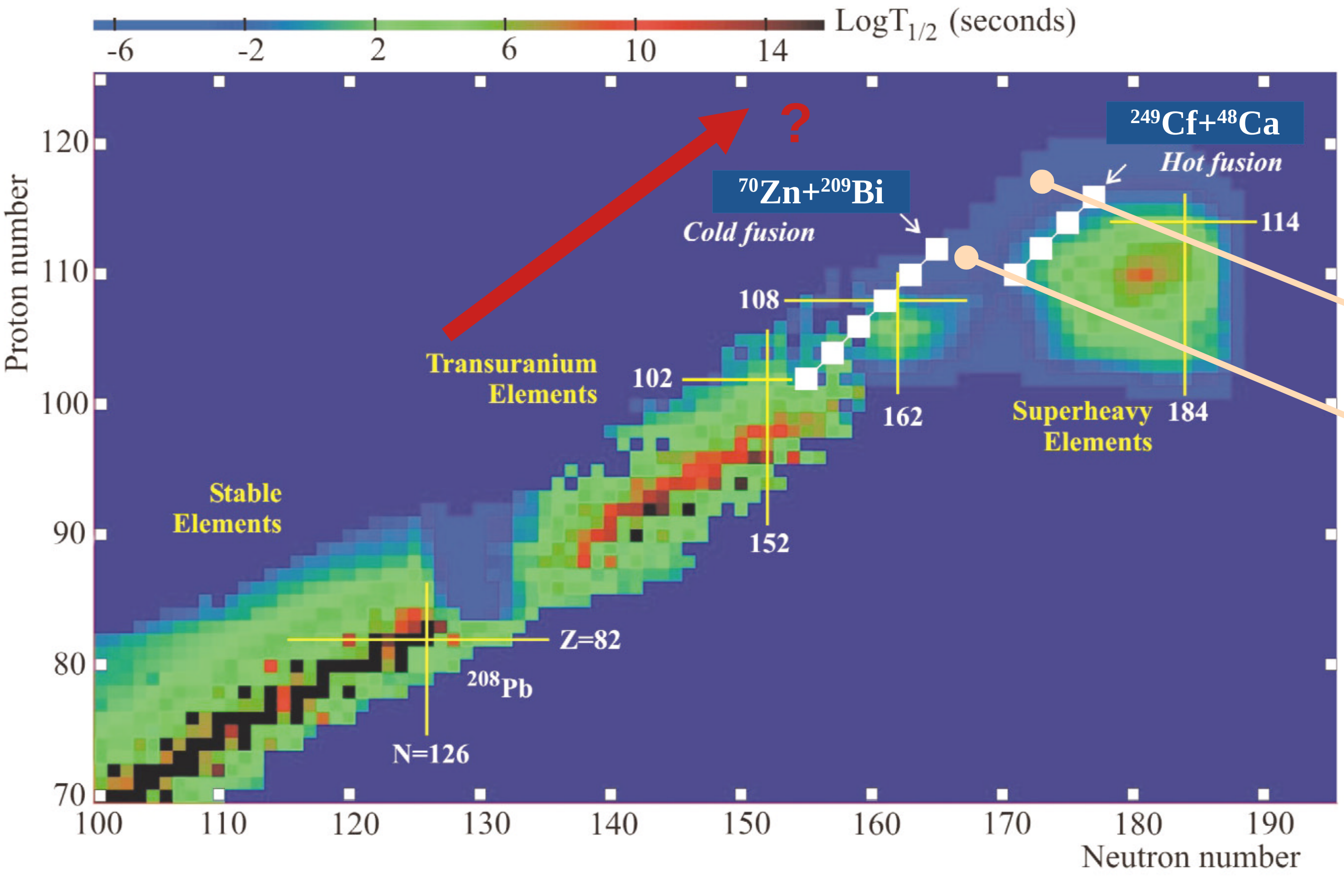
- Shape coexistence

  Taniuchi *et al.* Nature **569**, 53–58 (2019)

- A fifth island of inversion?

  Nowacki *et al.* Phys. Rev. Lett. **117** (2016)

Exploring the extremes: super heavy nuclei



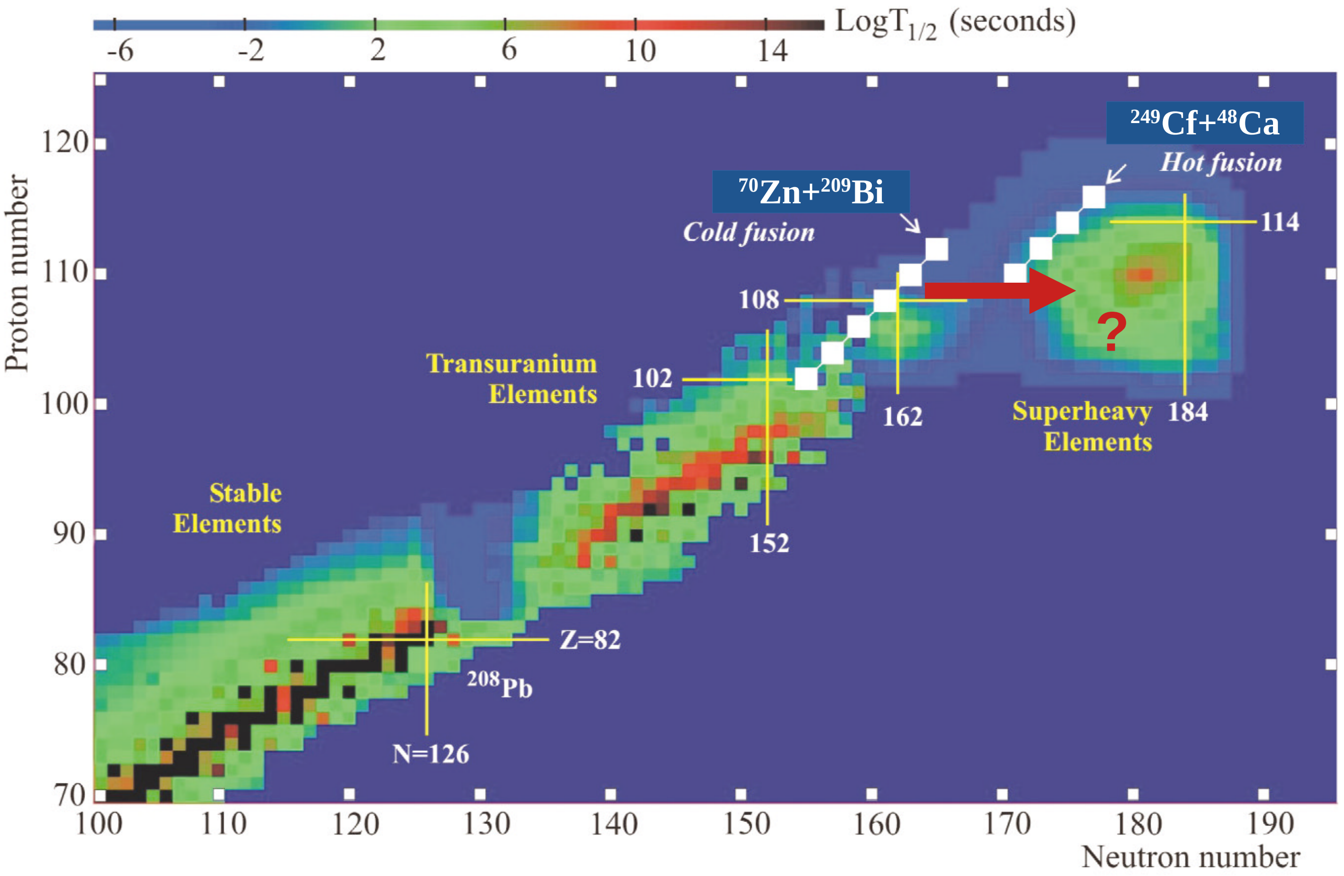
Oganessian Pure Appl. Chem., **78**, 5 (2006)

- What is the heaviest element?

2002, Dubna
Z=118 (Oganesson)

2003, RIKEN
Z=113 (Nihonium)
3 atoms in 553 days...

Exploring the extremes: super heavy nuclei



Oganessian Pure Appl. Chem., **78**, 5 (2006)

- What is the heaviest element?
- Is there an island of stability and where?

	Z	N
HFB	126	184
RMF	120	172
WS	114	184
FRLD	114	178

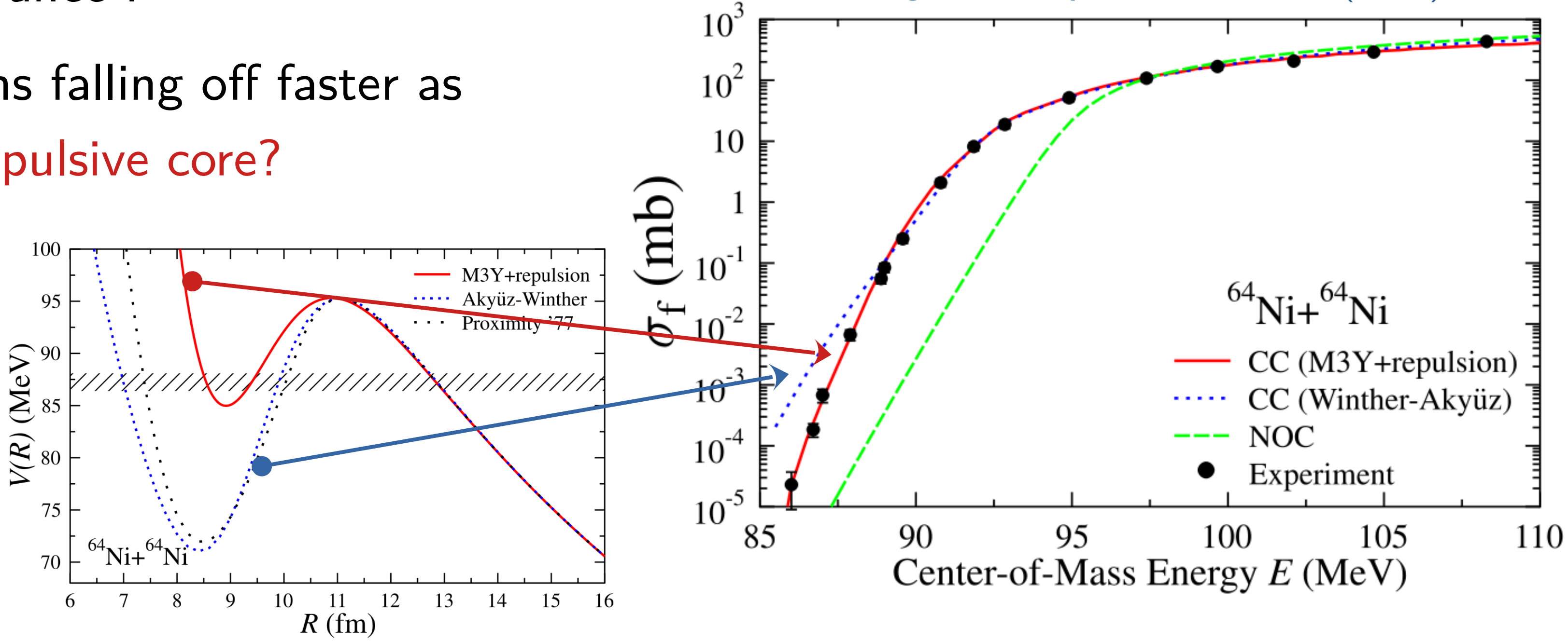
Reaction dynamics : modern fusion studies

- Fusion hindrance :

  cross-sections falling off faster as expected: repulsive core?

Mișicu and Esbensen, PRL **96** (2006)

Jiang *et al.* Phys. Rev. Lett. **93** (2004)

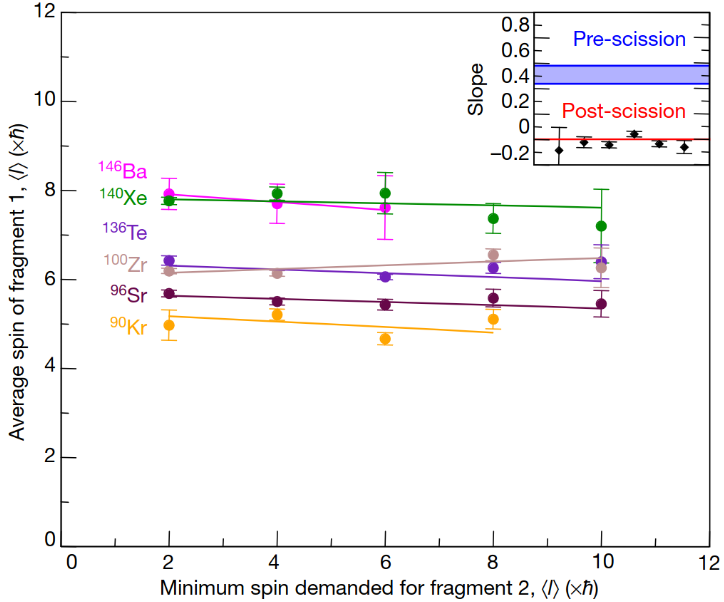


Pauli repulsion! Simenel *et al.*, PRC **95** (2017)

Reaction dynamics : modern fission studies

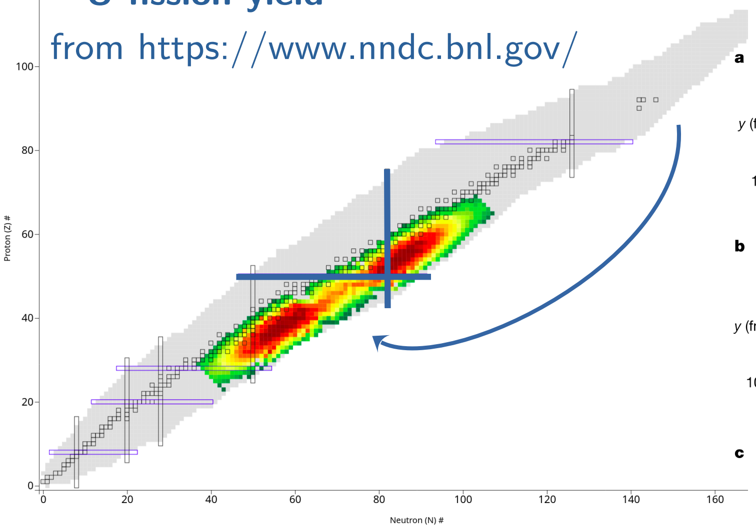
- Mechanism of spin generation of fission fragments?

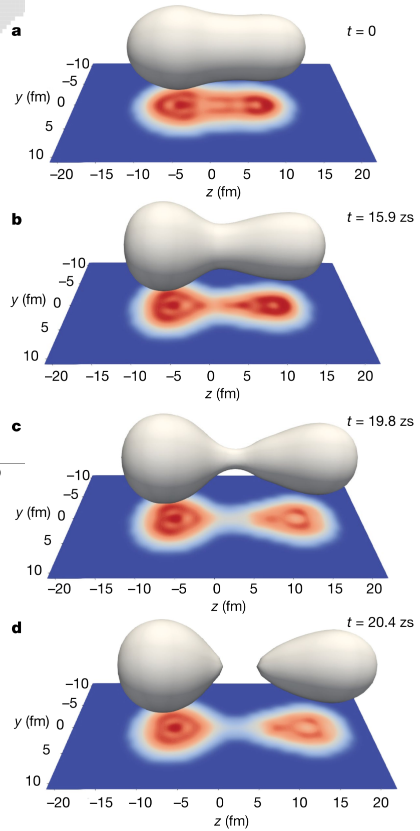
  Wilson *et al.* Nature **590** (2021)



^{235}U fission yield

from https://www.nndc.bnl.gov/



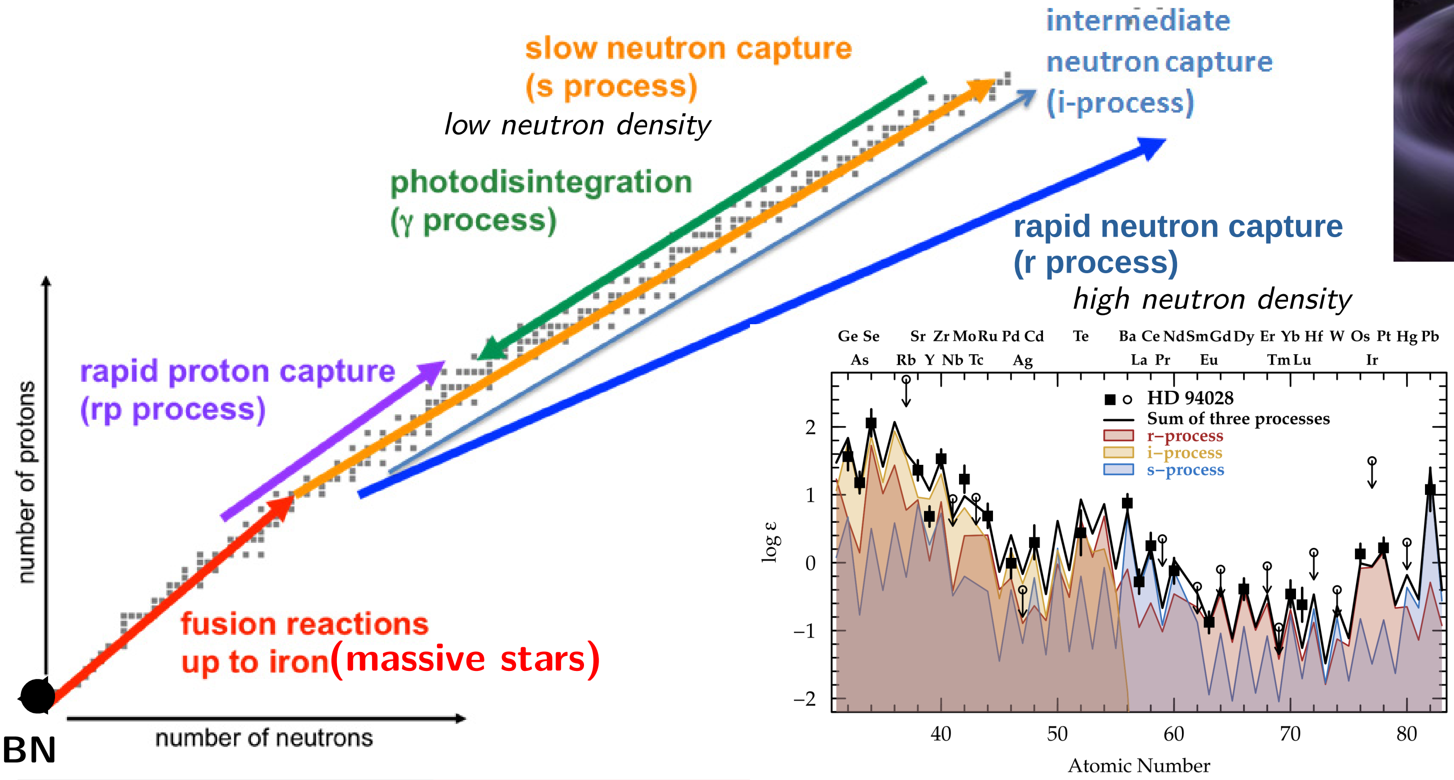


- Towards a microscopic description?

  Scamps and Simenel Nature **564** (2018)

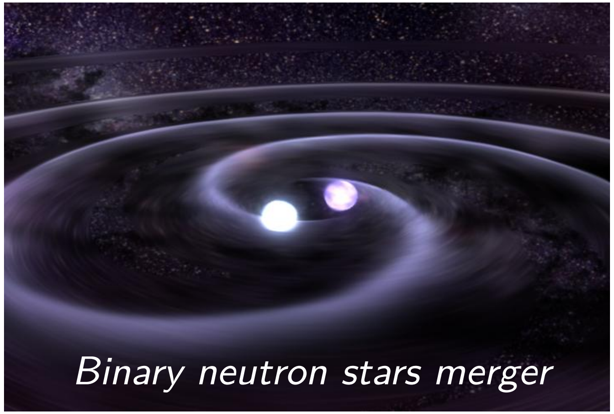
Nuclear astrophysics

Understand chemical abundance evolution and astrophysical production sites



Reifarth ejc2014.sciencesconf.org

arXiv:2205.07996


Binary neutron stars merger


Core-collapse supernovae

Nuclear astrophysics

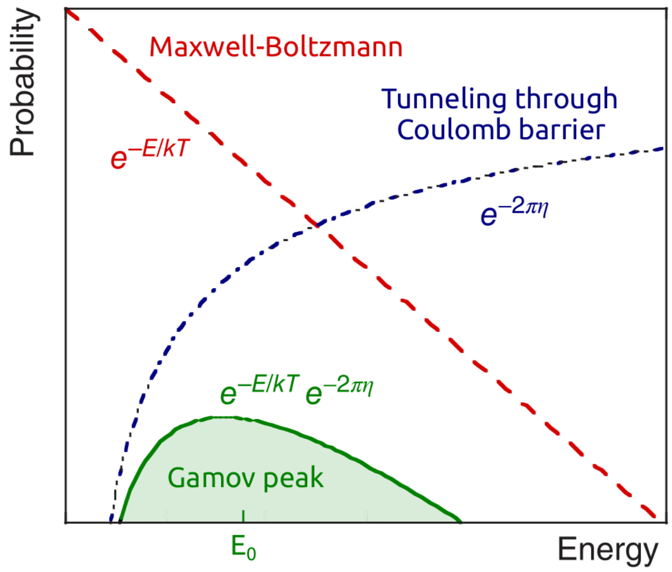
Nuclear reaction rates governs energy production, creation of elements $r = N_x N_y <\sigma v> (1+\delta_{xy})$

nuclear physics!

Available energy = thermal energy (kT)
→ depends on astrophysical scenario!

- **Neutron captures:** E ~ thermal energy (kT)
- Nuclear reactions between **charged particles:**
  thermal energy (kT) vs. Coulomb barrier: TUNNELLING
  → Relevant energy = Gamow windows
  Ex: $T_{sun} \sim 15.10^6$K, kT~1keV E_C=500keV → E_G=5.9keV

1. Quiescent burning (fusion in stars) → σ ~ (pbarn-nbarn)
2. Explosive burning → unstable species!



adapted from Iliadis 2015

Quiescent stellar burning

- The special case of $^{12}C+^{12}C$

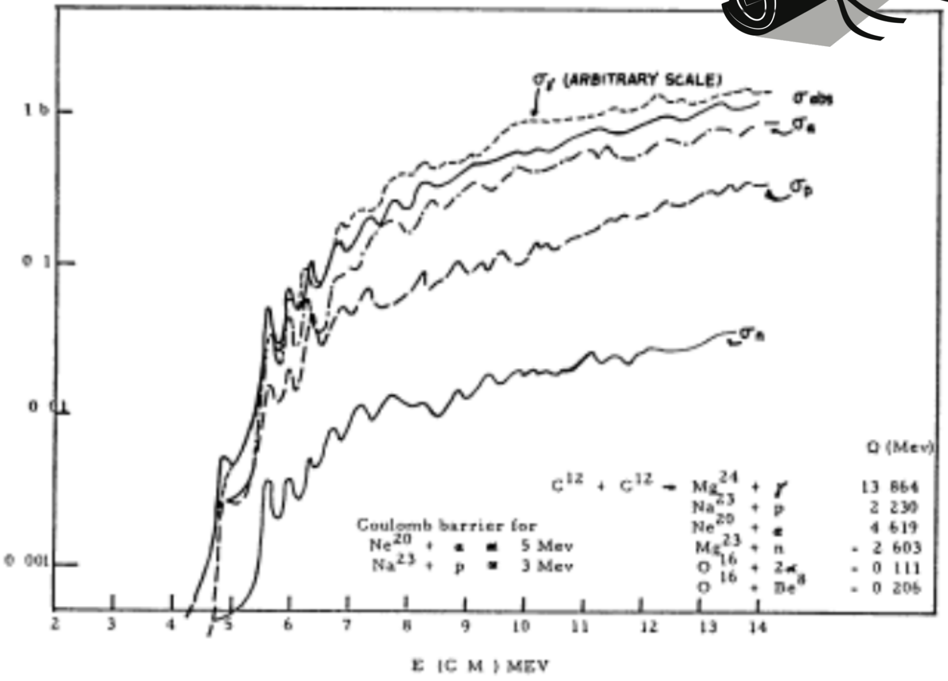


FIG. 1.—Experimental cross-sections for the $C^{12}+C^{12}$ reactions

Hubert Reeves PhD (1960)

CARBON, OXYGEN, AND NEON THERMONUCLEAR REACTION RATES

HUBERT REEVES*

Département de Physique, Université de Montréal, Montréal, P.Q.

Received October 7, 1961; revised November 20, 1961

ABSTRACT

Recent experimental results obtained with the Chalk River Tandem accelerator are used to calculate the rate of thermonuclear reactions involving carbon, oxygen, and neon nuclei. The astrophysical relevance of these reactions and of the subsequent processes is discussed briefly.

I. INTRODUCTION

Extensive measurements of the nuclear reactions between C^{12}, N^{14}, and O^{16} and heavier nuclei have recently been carried out with the Chalk River Tandem accelerator (Almqvist, Bromley, and Kuehner 1960; Bromley, Kuehner, and Almqvist 1960). Although an analysis of the properties of these reactions appears to be complicated, it might still be possible to extract from the data at least some crude estimates of certain thermonuclear reaction rates which are of importance for the understanding of stellar evolution. Such reactions are expected to provide the energy sources for the stars in the red giant branches. It is expected, for instance, that, following the helium-burning stage, the stellar core, composed mainly of carbon and oxygen, will contract until it reaches temperatures that are high enough to guarantee the nuclear reaction rate corresponding to the radiation output of the star. In this paper we want to compute the thermonuclear rate of energy generation from isotopes of carbon, oxygen, and neon.

Several papers have been written on the carbon and oxygen thermonuclear reactions, prior to the advent of the Chalk River results (Hayashi *et al.* 1958; Cameron 1959*a*). Rather indirect methods had then been used to evaluate the rates. In one of these papers (Reeves and Salpeter 1959) an upper and a lower limit to the rates of $C^{12}+C^{12}$ had been evaluated, and the subsequent discussion had been extensive enough to encompass both the upper and lower limit. Since the present estimate falls in between these limits, a part of this discussion can be carried out, and will be summarized later in this paper.

II. DATA

a) $C^{12}+C^{12}$

In Figure 1 are shown the cross-sections for the various outcomes of the $C^{12}+C^{12}$ reaction. Although the relative accuracy between various neighboring points of these curves is excellent (the uncertainty is less th
the absolute values and the relative accuracy
The data of Almqvist (1960) represent the y
(due to the thresholds of the counters) at 42°
at 27°, and of neutrons of all energies at 30°
the α and *p* missed because of the bias on the
of the total number of α and *p* emitted is a
first states in Ne^{20} could always be detected, a
these levels and the next higher levels, the b
more probable. Alphas could also come from
portance of this reaction at low C^{12} energy ca
grounds, as will be discussed in a later parag

* During a stay at Theoretical Physics, A.E.C.L.,

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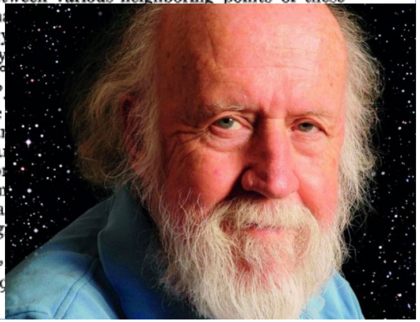


Quiescent stellar burning

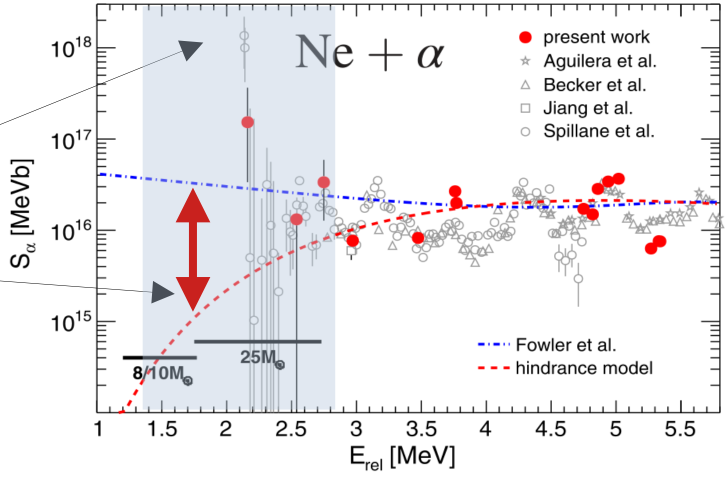
- The special case of $^{12}C+^{12}C$

  Fruet *et al.* PRL **124** (2020)

Hint of a low energy resonance?

Fusion hindrance?

Relevant range for massive stars



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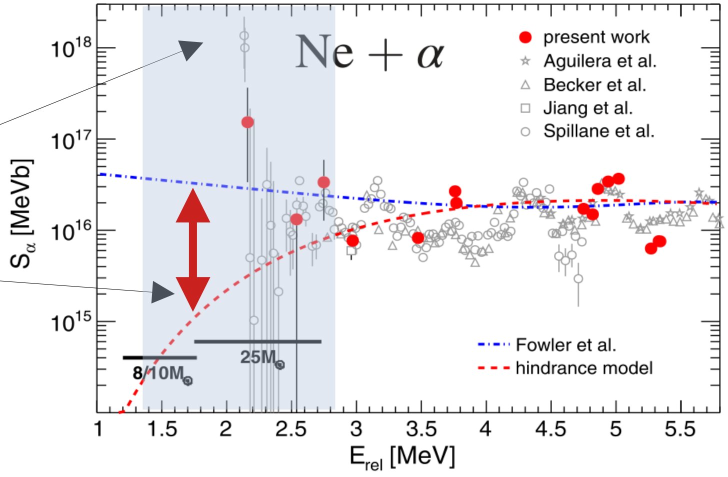
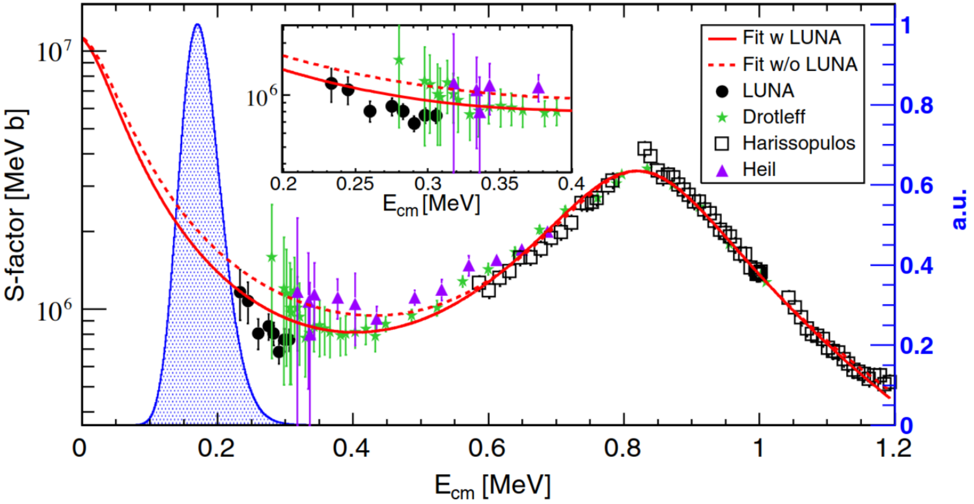


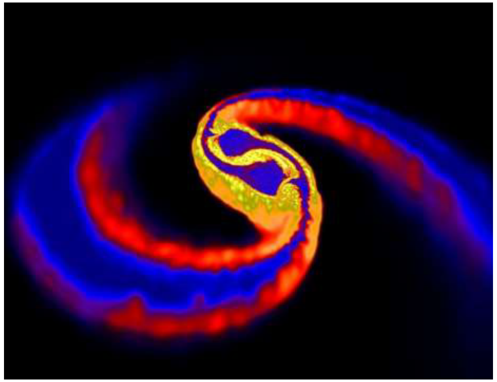


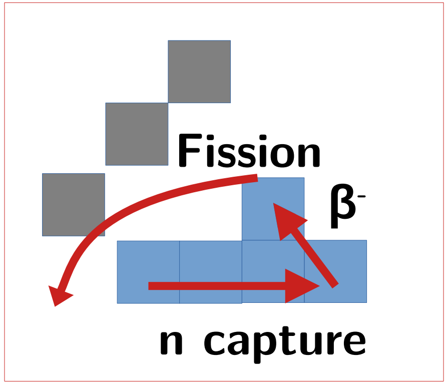
- A main neutron source for the s-process: $^{13}C(\alpha,n)^{16}O$ Ciani *et al.* Phys. Rev. Lett. **127** (2021)

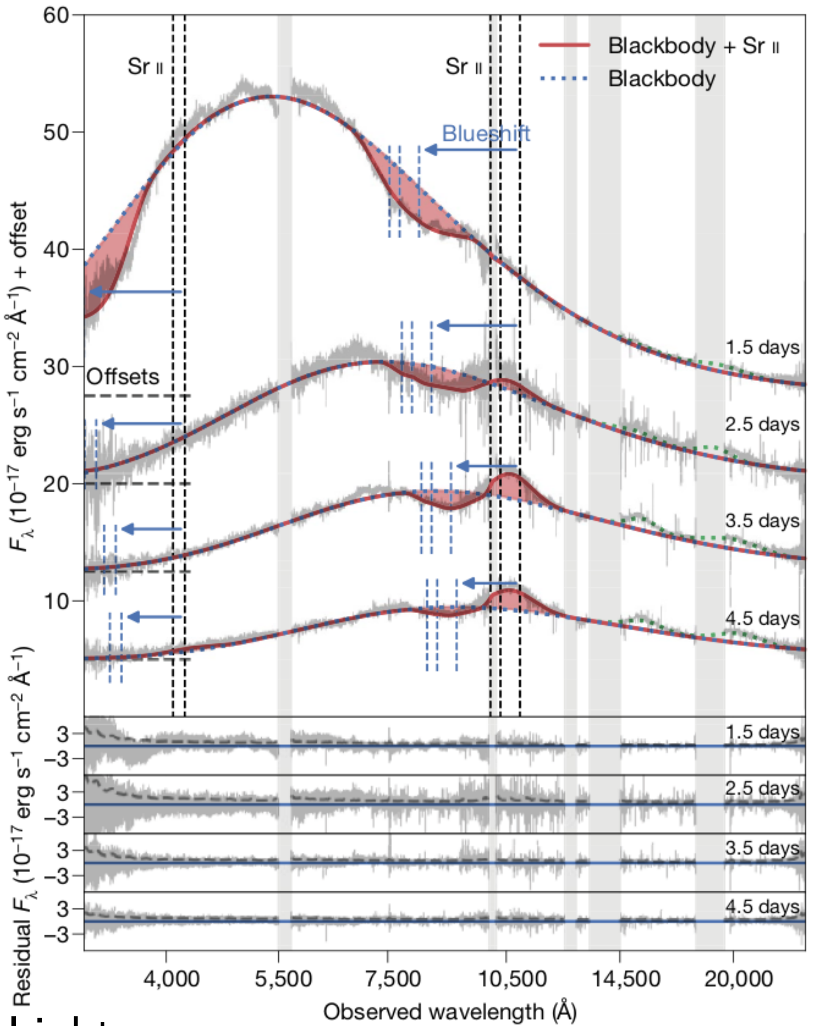
Going underground! LUNA

Explosive burning

- Kilonova associated with GW170817:
  EM transient (~1-10 days)
- Identification of strontium: support of r-process
  Watson *et al.* Nature **574** (2019)
- Complex modelling







Astrophysical simulations ↔ Nucleosynthesis ↔ Light curves

On the relevance of nuclear databases…

- Low energy neutron physics

GEANT4 A SIMULATION TOOLKIT

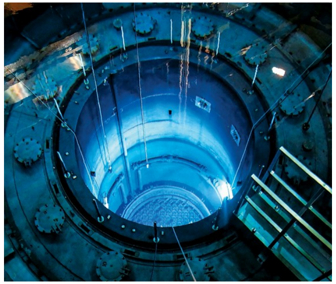
JEFF-33
ENDF/B-VIII
JENDL
...

- Improved data for medicine, nuclear technology…

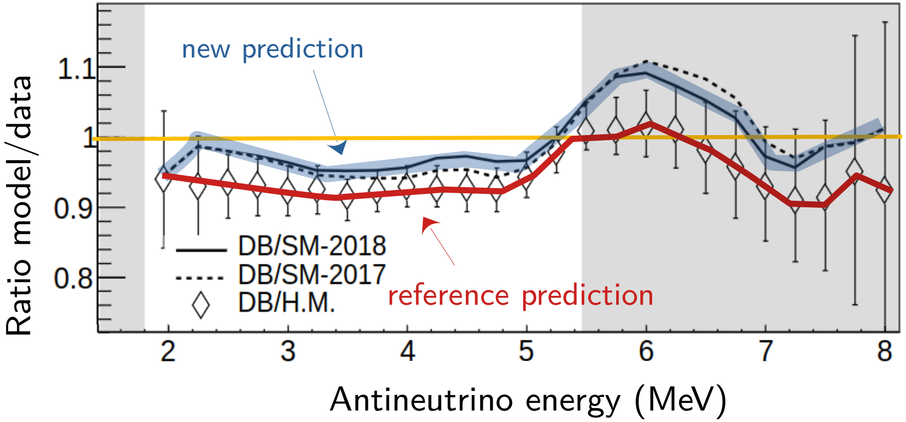
JANIS Web https://www.oecd-nea.org/janisweb/

Comparison of (p,n) and (n,gamma) reactions for ADS decommissioning
Jonathan COLLIN

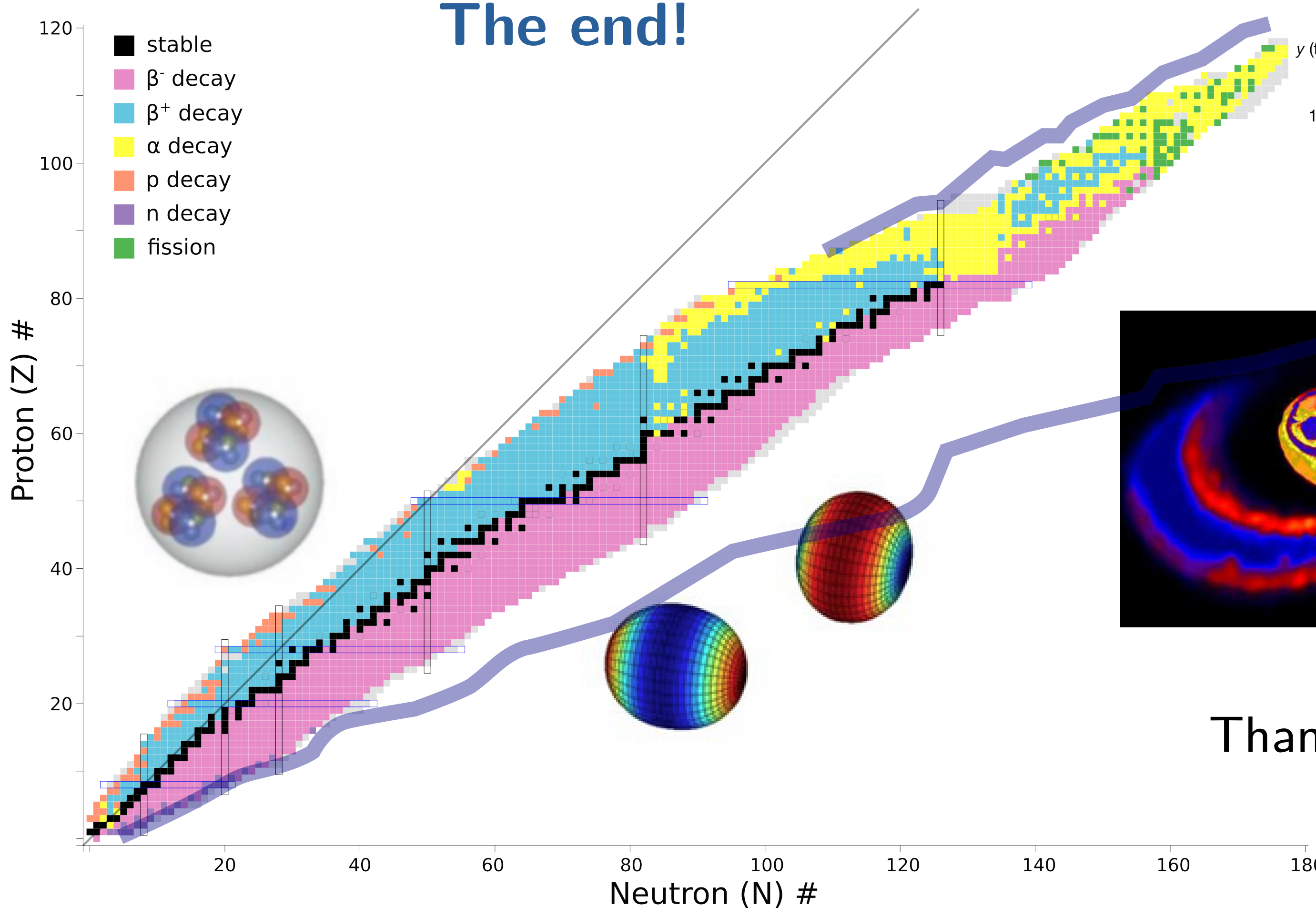
- Reactor antineutrino flux prediction

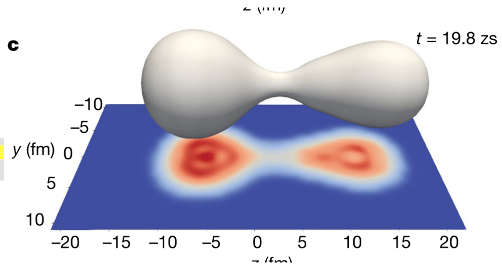


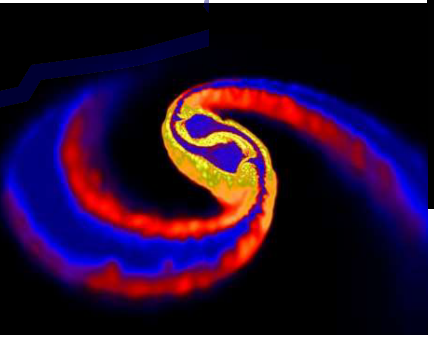
arXiv:2304.14992 (2022)
Estienne *et al.* Phys. Rev. Lett. **123** (2019)

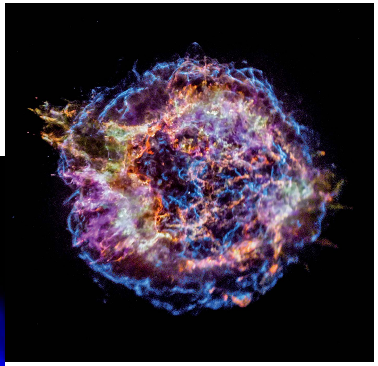


The end!





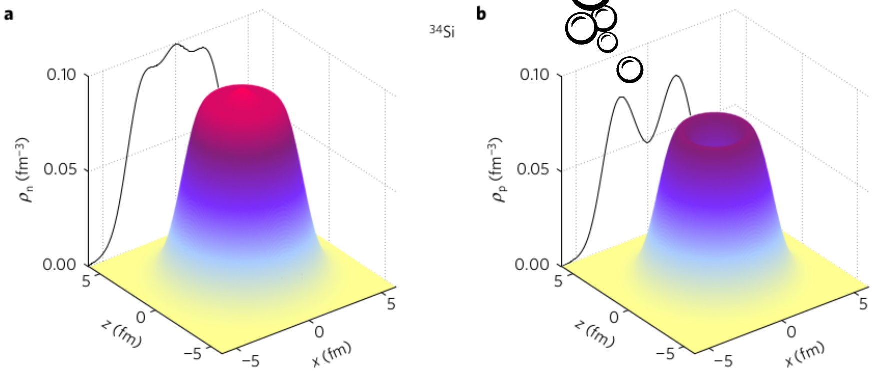




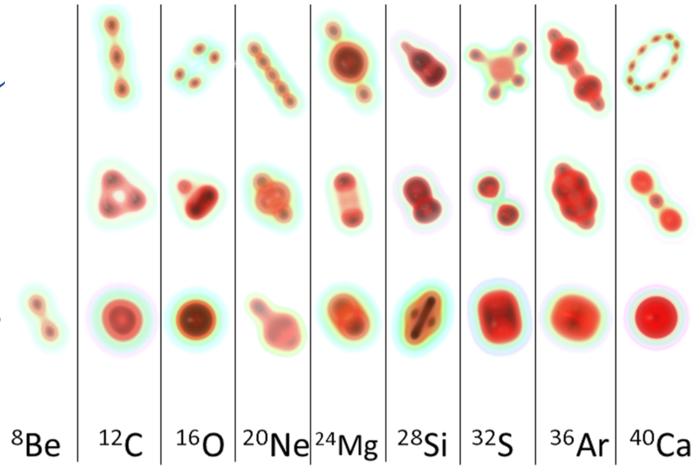
Thanks for your attention!

Complexity of nuclear structures

- Central density depletion : “bubble” observed in ^{34}Si by proton removal
  Mutschler *et al.* Nature Phys **13**, 152–156 (2017)
- Z/N dependency test of the SO potential

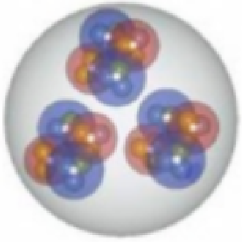


Ebran Phys. Rev. C **90** (2014)



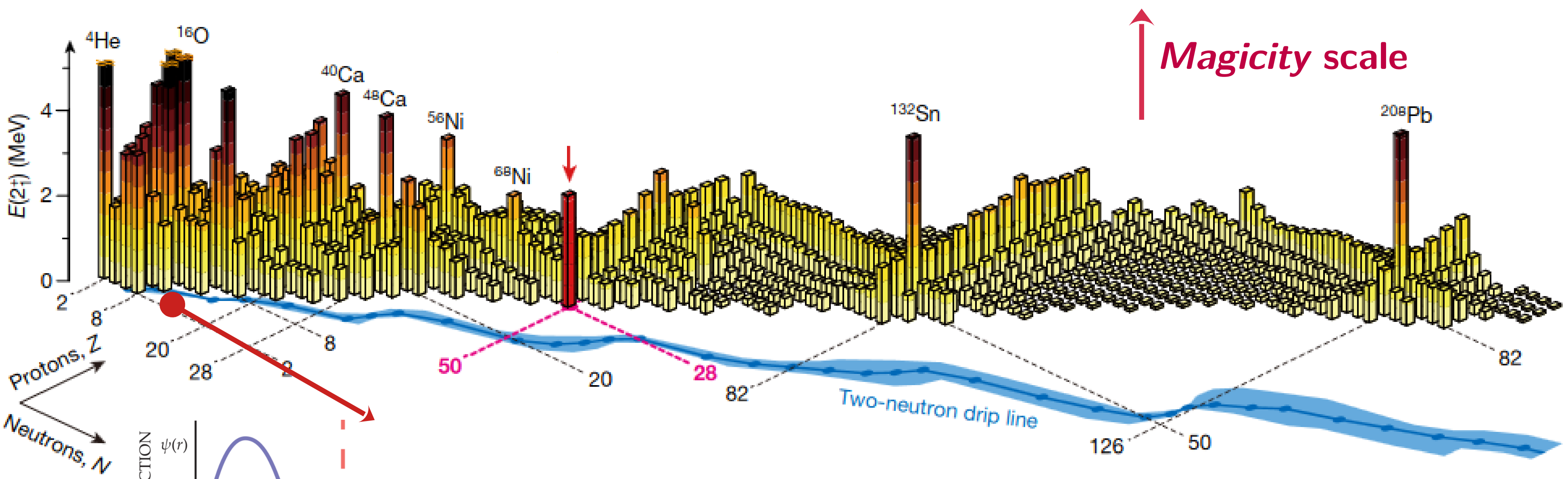
- Nuclear clustering : Ikeda
  Ikeda *et al.* Prog. Theo. Phys. Suppl. **E68** (1968)
- Theoretical predictions now from first principles
  Ebran *et al.* Nature **487**, 341–344 (2012)

The triple alpha
^{12}C Hoyle state

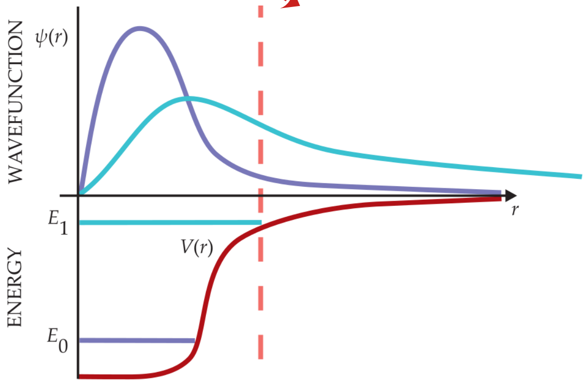


Exploring the extremes: the neutron drip line

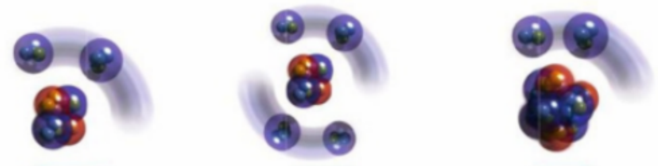
Energy of the first 2+ excited state



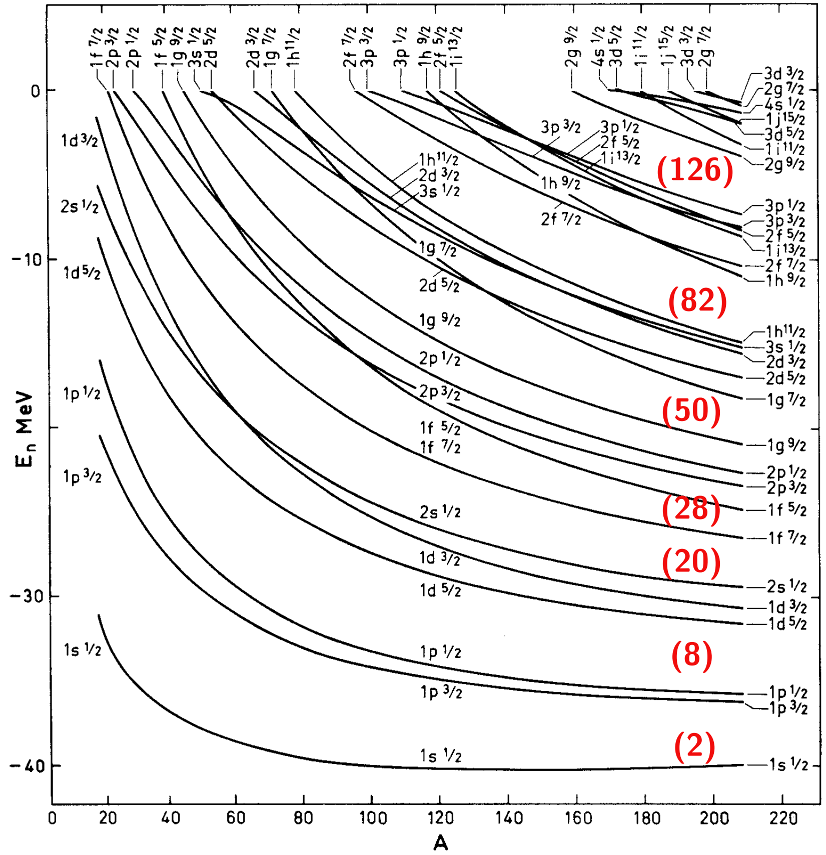
Taniuchi *et al.* Nature **569**, 53–58 (2019)



- Exotic structures : halos, neutron skins



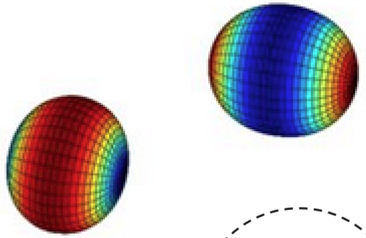
The shell model



Bohr and Mottelson (1998)

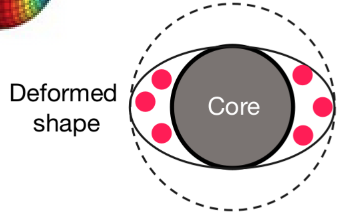
$$H = H_0 + H_1$$ → **residual interaction**

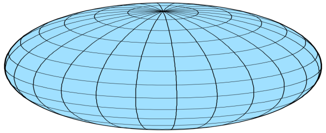
H_0 → **easy to solve**

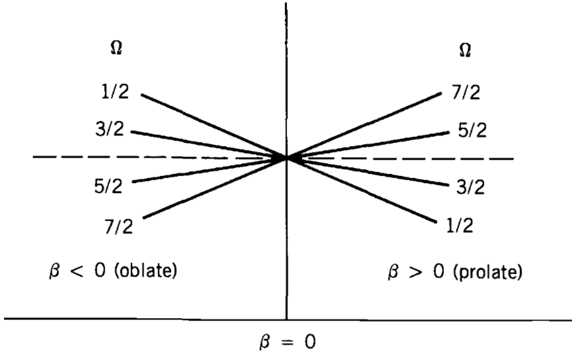


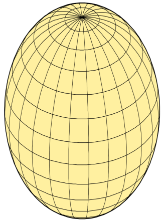
Evolution of the shell structure

- Single particle excitations
- Collective excitations









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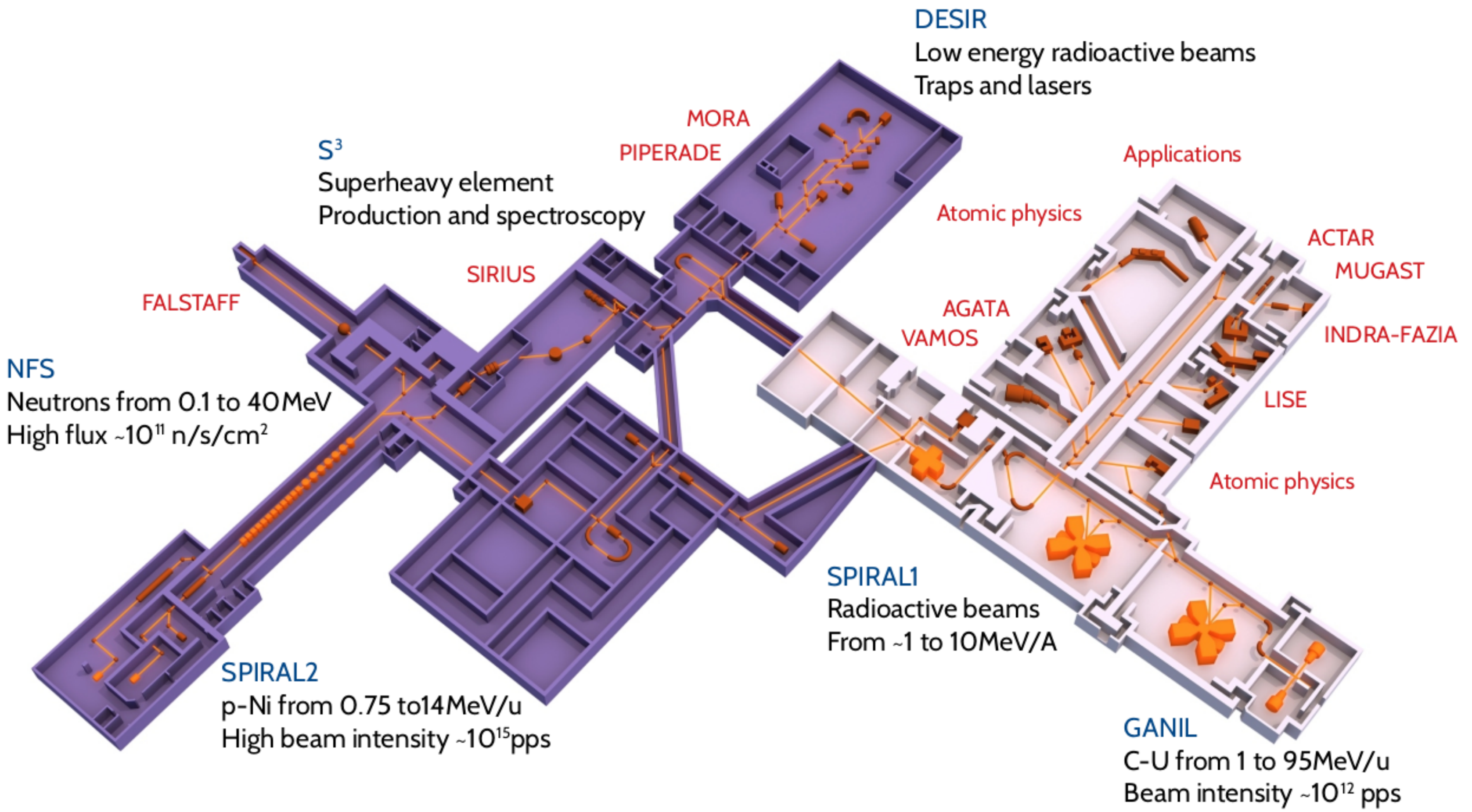

From Diego Gruyer, JRJC2021