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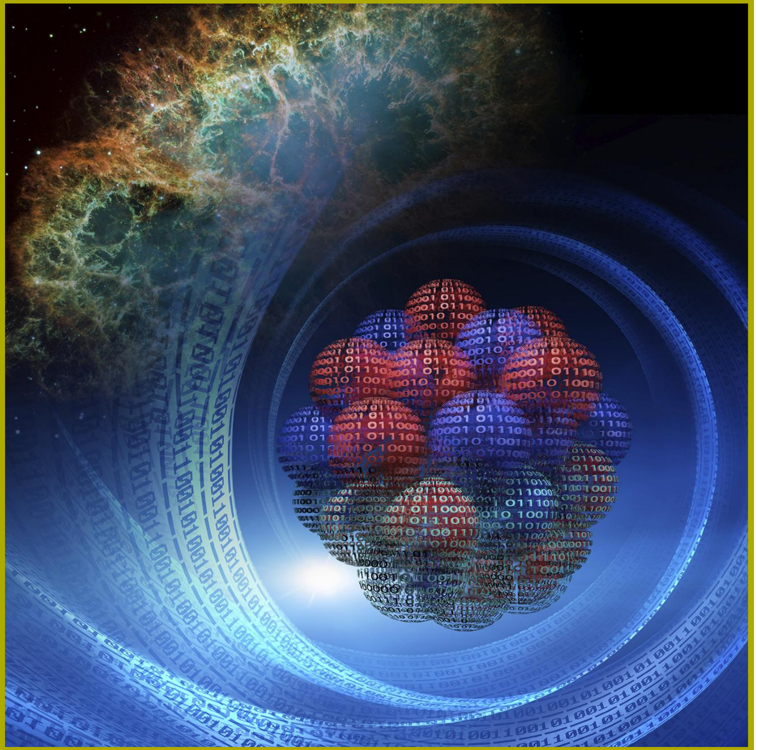

Image credit: Andy Sproles, ORNL

# Nuclear mass models for astrophysics applications

**W. Ryssens**, G. Scamps, G. Grams, I. Kullman, M. Bender and S. Goriely

September 2022

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ULB

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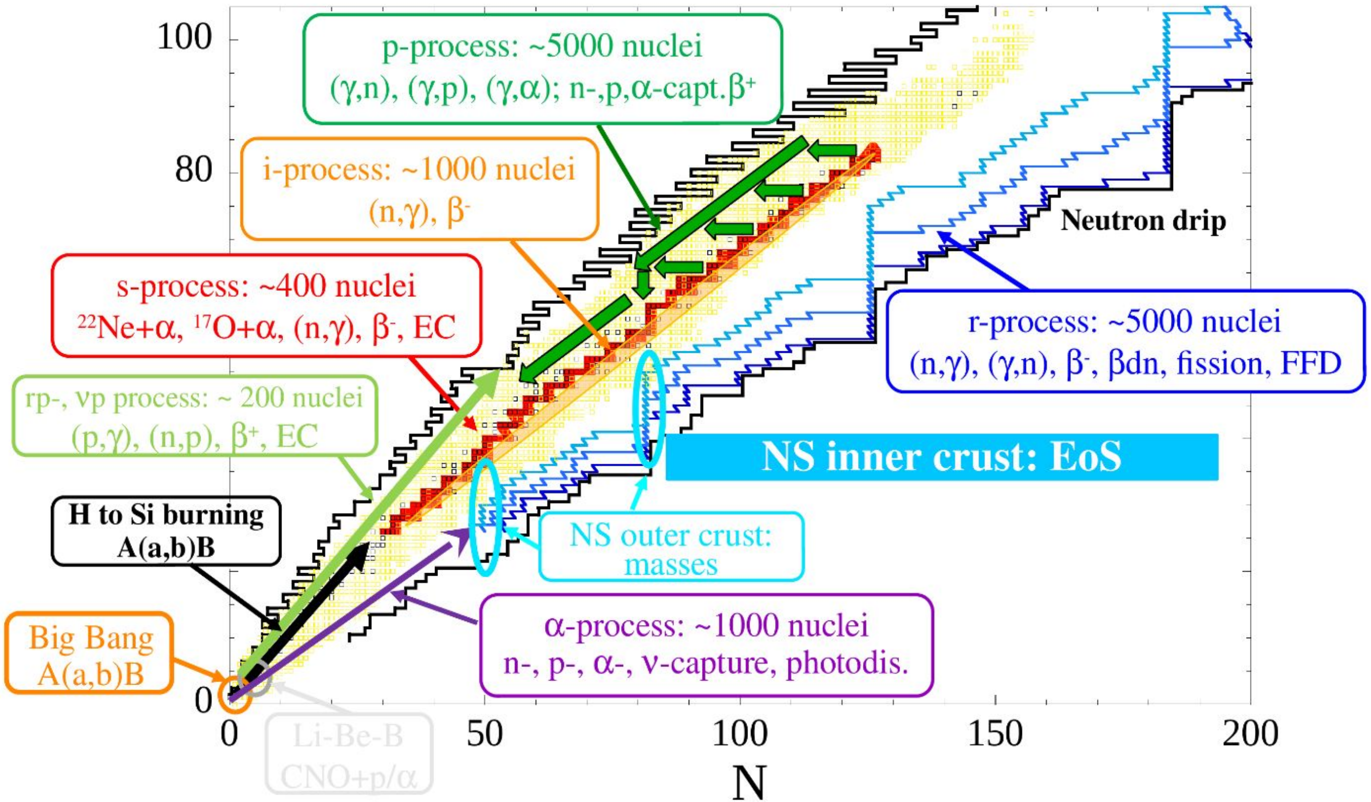
# The challenge for nuclear theory

Image credit: S. Goriely, ULB



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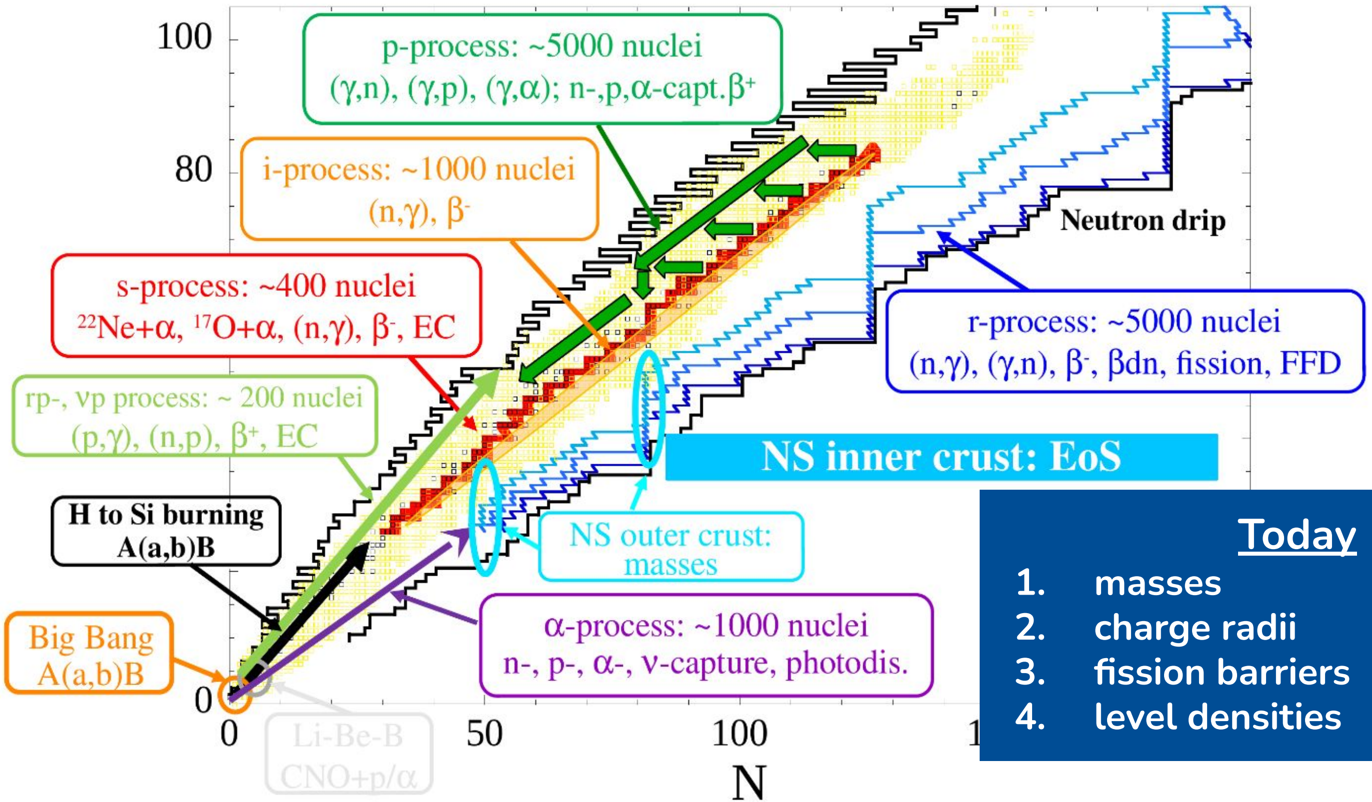


## Today

1. masses
2. charge radii
3. fission barriers
4. level densities

# Skyrme **E**nergy **D**ensity **F**unctionals (**EDF**s)



$$E \sim \int d^3r \Big[ C^{\rho} \rho(\mathbf{r}) \rho(\mathbf{r}) + C^{\tau} \tau(\mathbf{r}) \rho(\mathbf{r}) + \dots \Big]$$

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Local densities of a **HFB** state

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(~ **25** parameters)

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Fitted to:

- **2457** masses
- **884** charge radii
- Infinite matter properties

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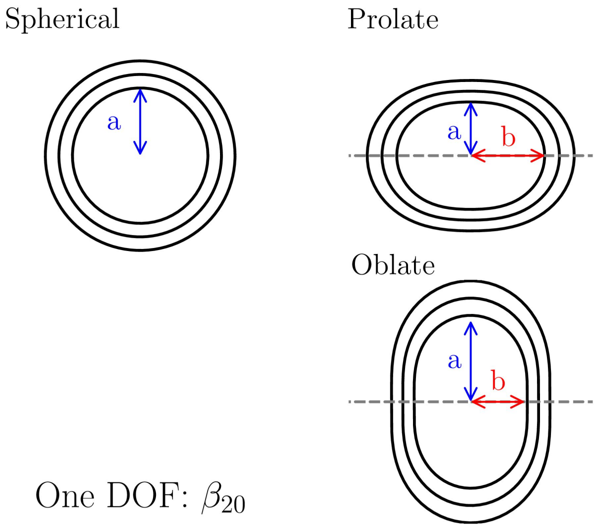
**Where does the physics enter?**

- Complexity of the **wave-function**
- Selection (and weighting) of **fitting data**
- **Functional form** of the EDF

# Brussels models in 1-2-**3 dimensions**!




**Before: BSk1-32**

- Axially symmetric
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- Cheap to simulate!

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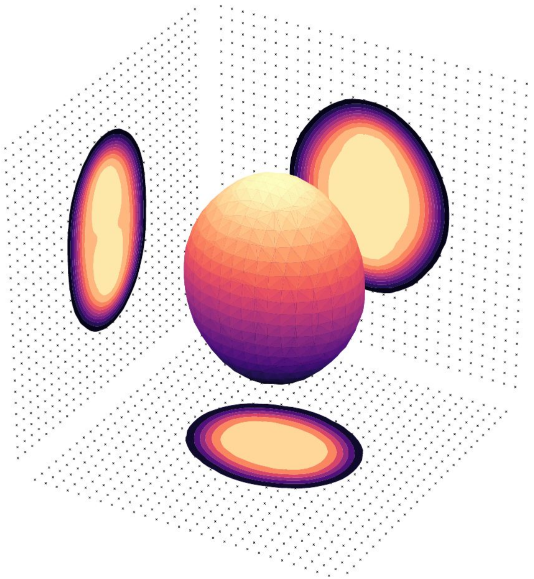

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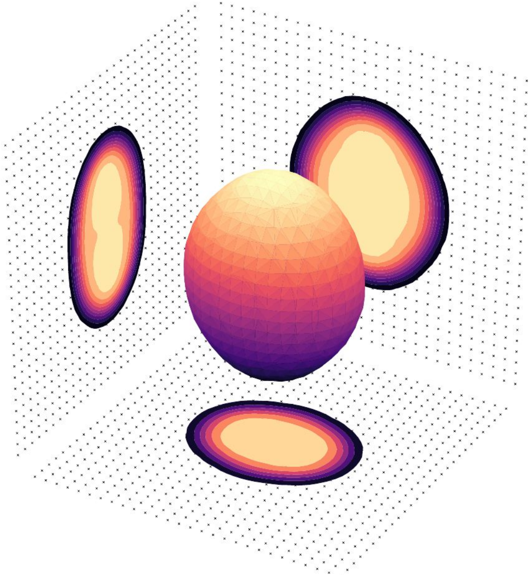

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W. R. PhD Thesis, ULB (2016).
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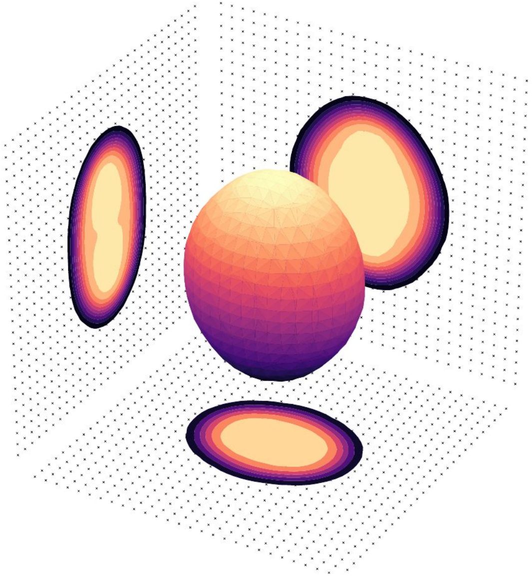

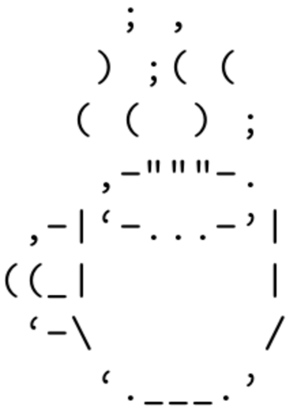

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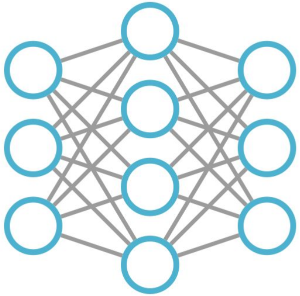

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- **machine learning** to accelerate fit

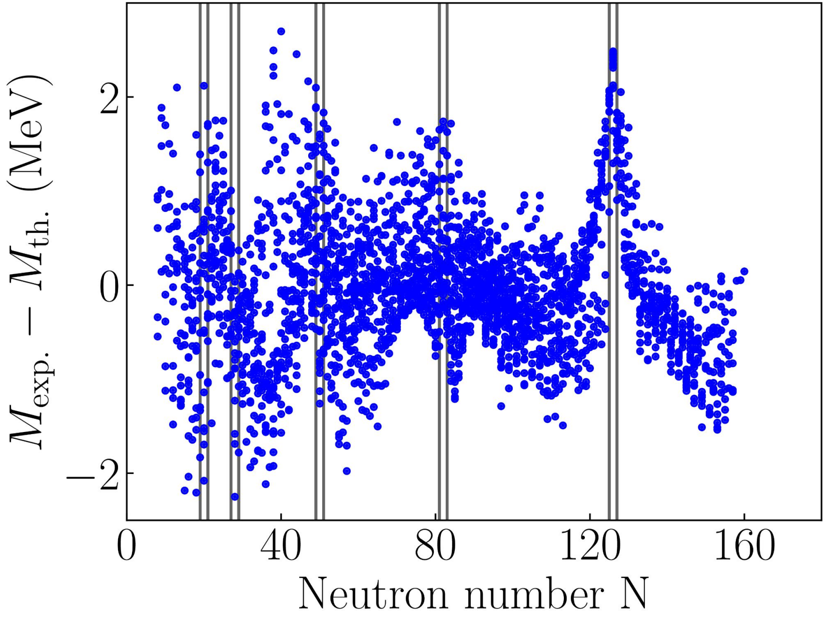
# BSkG1 & 2: **the raw numbers**



BSkG1:

- triaxial deformation

| σ (MeV) | BSkG1 | BSkG2 | BSk14 | FRLDM |
|---|---|---|---|---|
| 2457 masses | 0.741 | | 0.729 | 0.808 |
| 884 charge radii (fm) | 0.027 | | 0.039 | - |
| 45 primary barriers | | | | |
| 45 secondary barriers | | | | |
| 28 Isomer energies | | | | |




**BSkG2: W. Ryssens et al., arXiv:2208.06455 [nucl-th]**
BSkG1: G. Scamps et al., EPJA 57, 333 (2021).
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BSkG2:
- triaxial deformation
- time-reversal breaking
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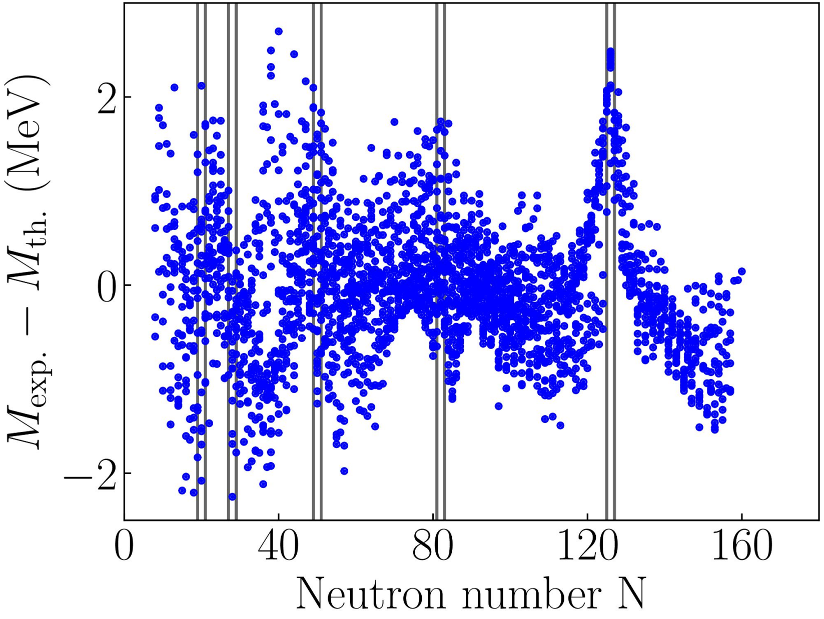



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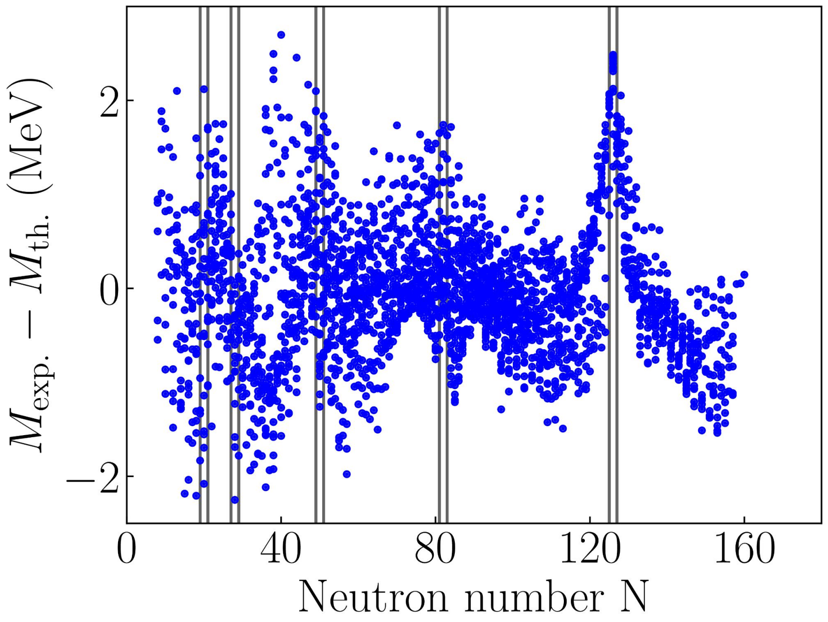
| 884 charge radii (fm) | 0.027 | **0.027** | 0.039 | - |
| 45 primary barriers | 0.87 | **0.44** | 0.61 | 0.79 |
| 45 secondary barriers | 0.86 | **0.47** | 0.70 | 1.35 |
| 28 Isomer energies | 0.45 | **0.49** | 0.93 | 1.04 |

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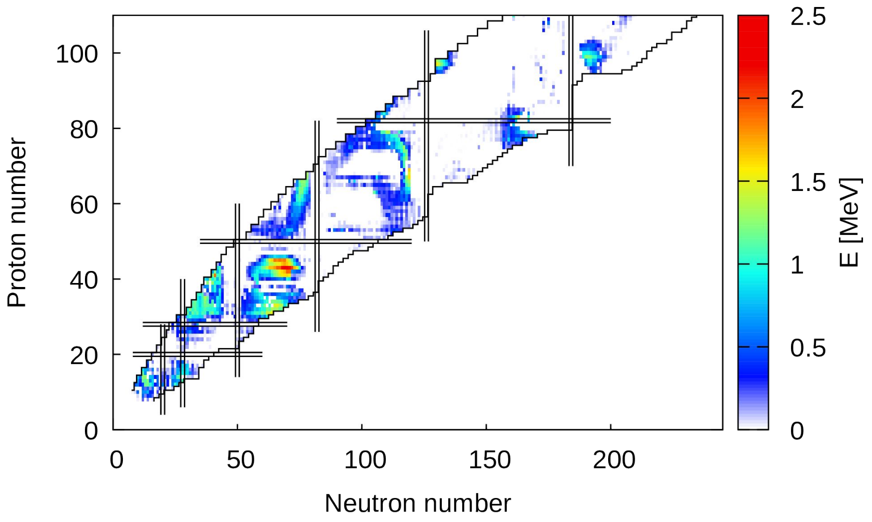
# What is the effect on **masses**?






**Triaxial deformation**

G. Scamps et al., EPJA 57, 333 (2021).

- most nuclei remain axial
- several regions of triaxiality
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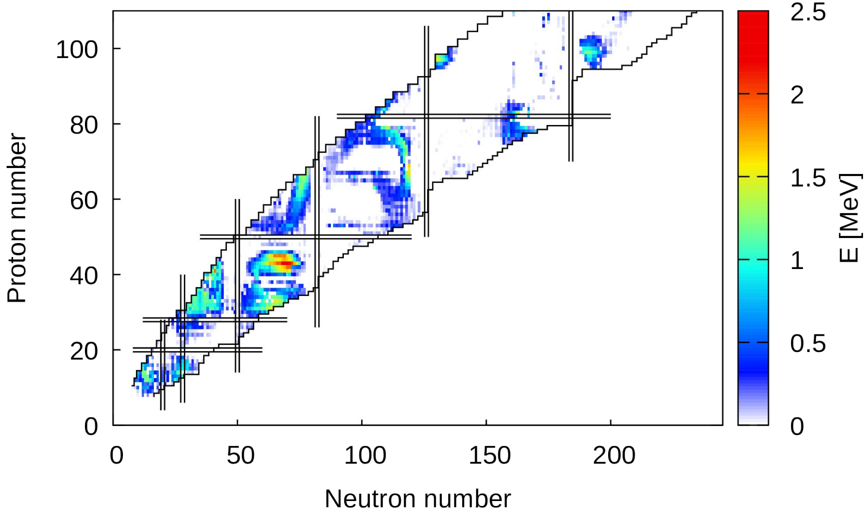


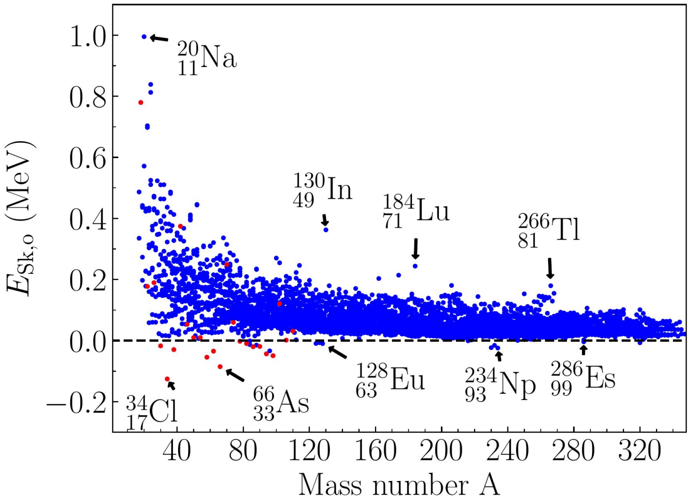


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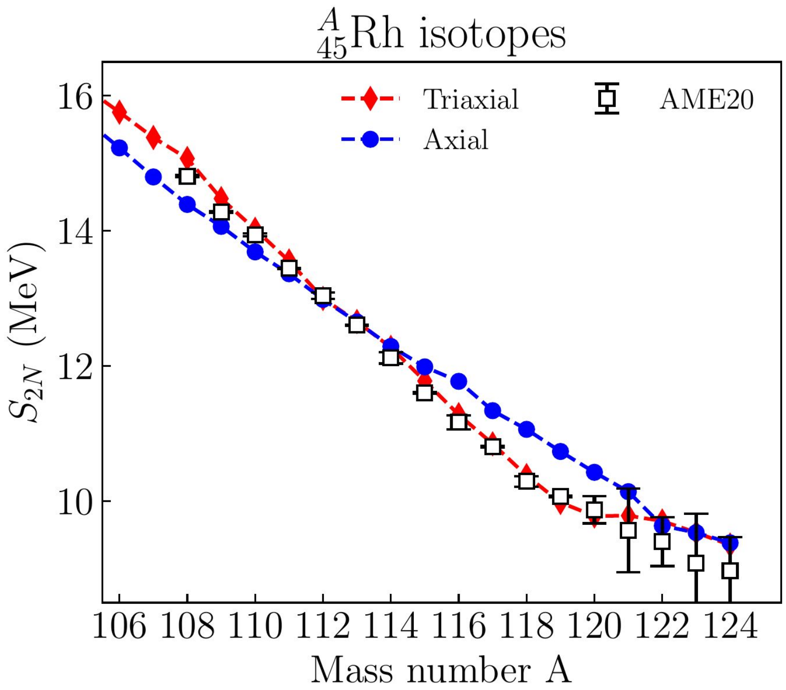
**Time-reversal breaking**

W. Ryssens et al., arXiv:2208.06455.

- included during fit, **no** simplifications
- reduces binding energies
- overall small effect

# Detailed studies possible: **Z ≅ 45**.

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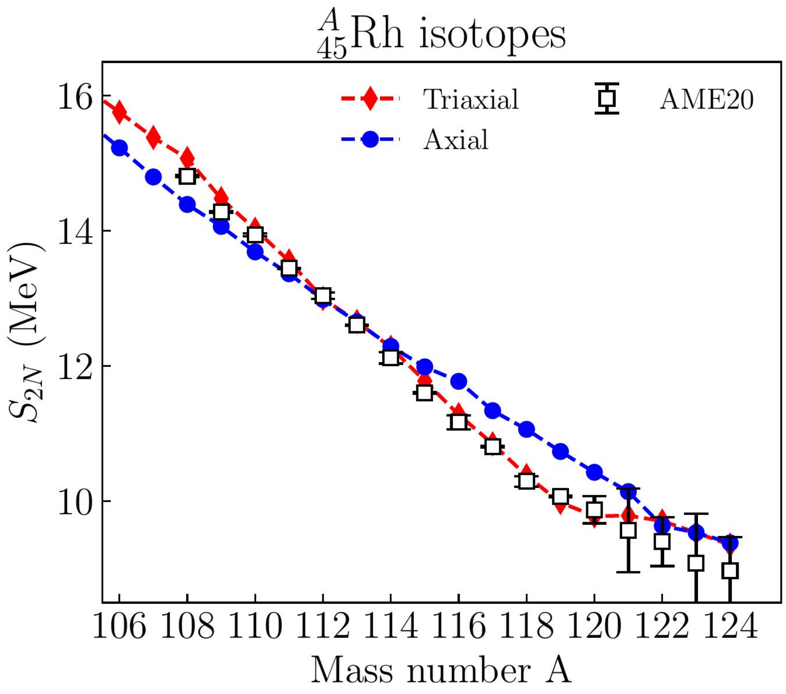


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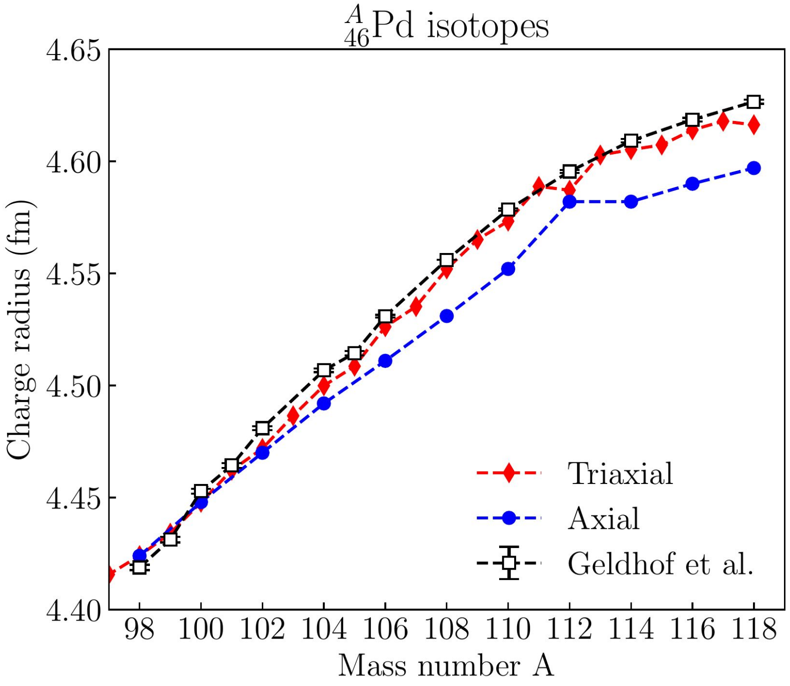


Data from S. Geldhof et al., PRL 128, 152501 (2022).

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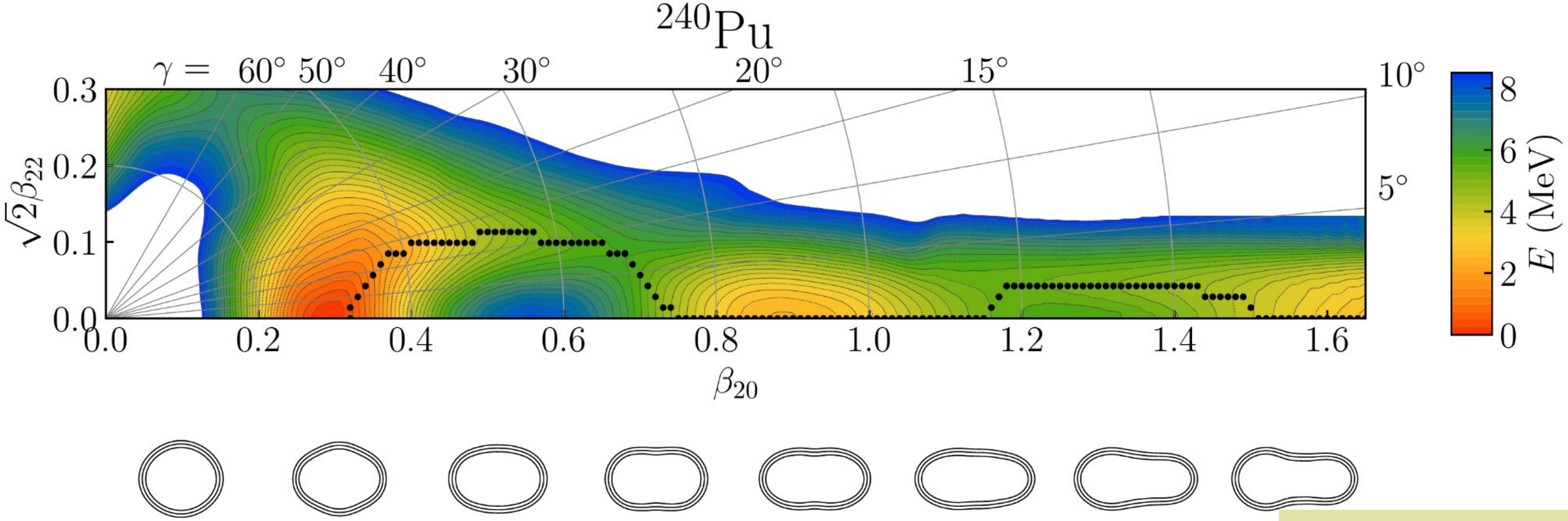


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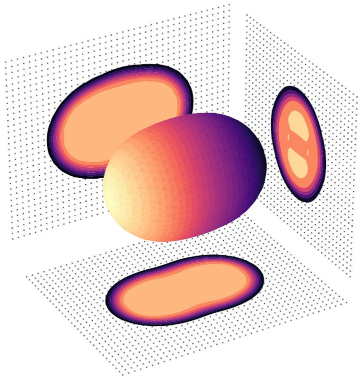

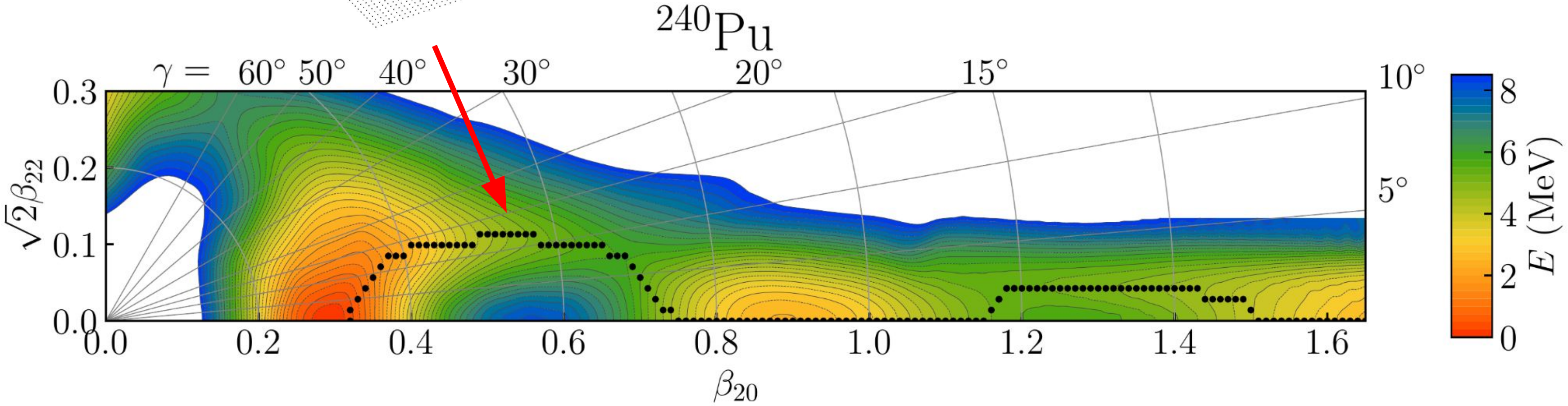


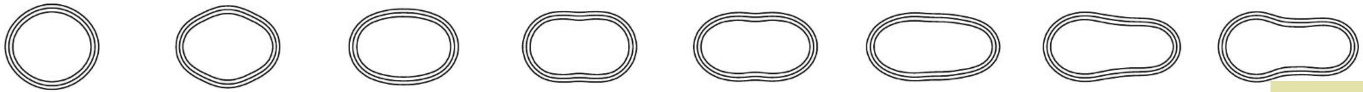

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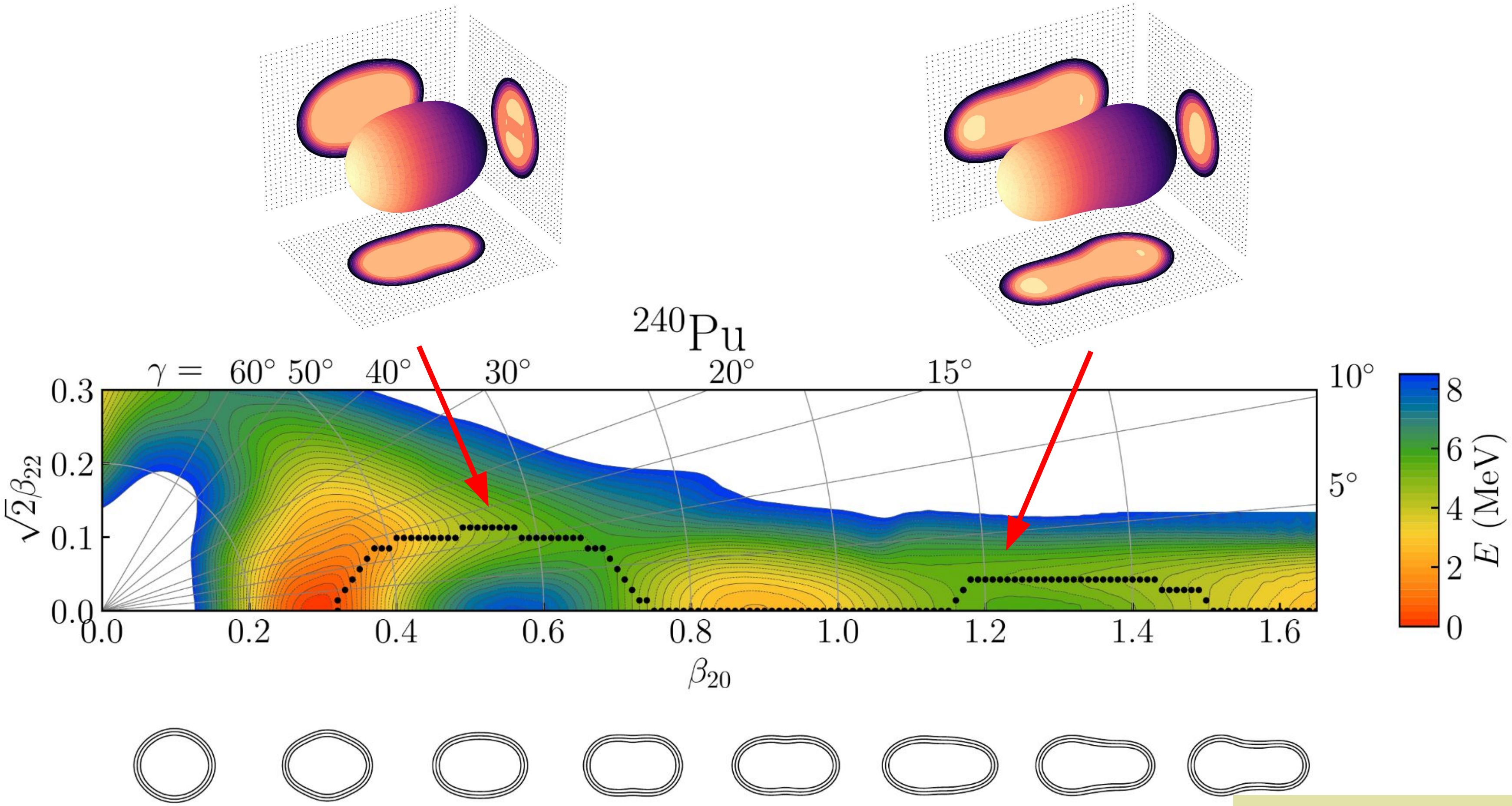


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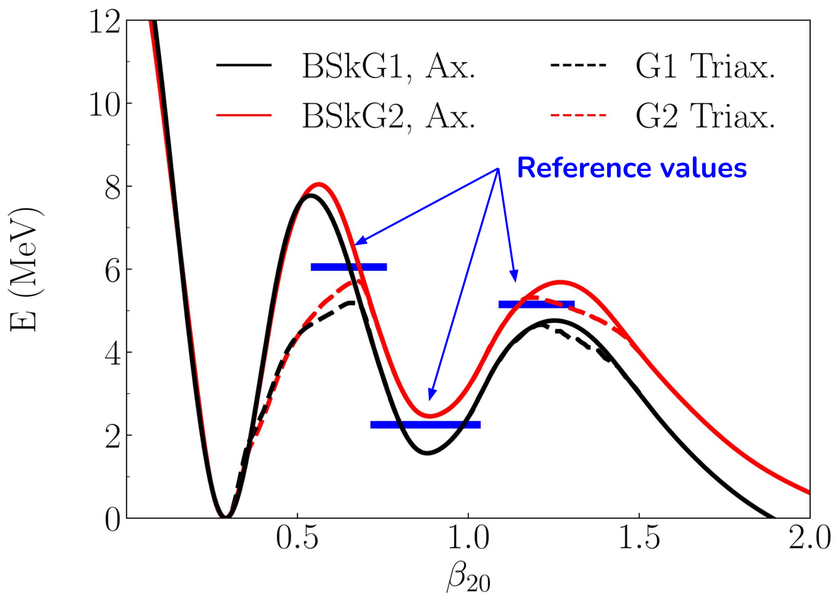
# Triaxiality has a **large** effect on barriers



Reference values from R. Capote et al.,Nuclear Data Sheets **110**, 3107 (2009).




**Triaxial deformation for 240Pu**

- Large effect on inner barrier
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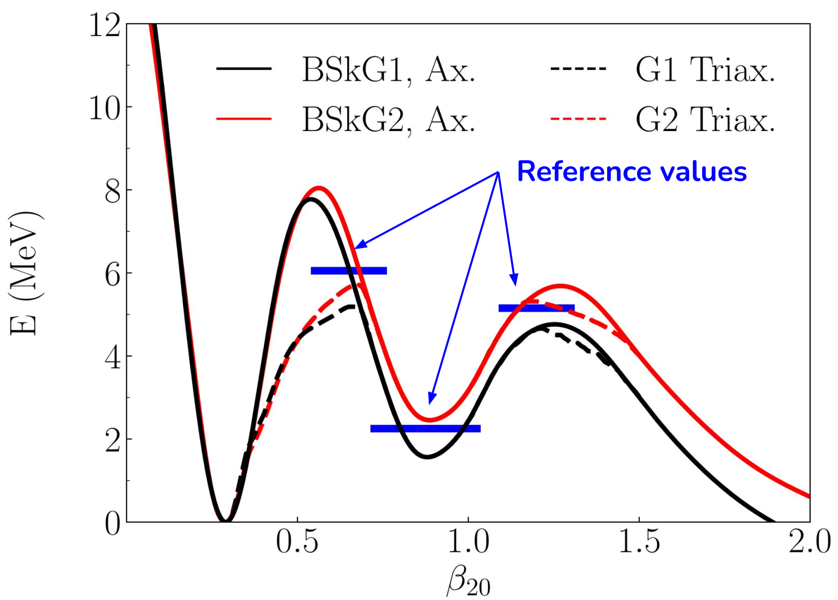


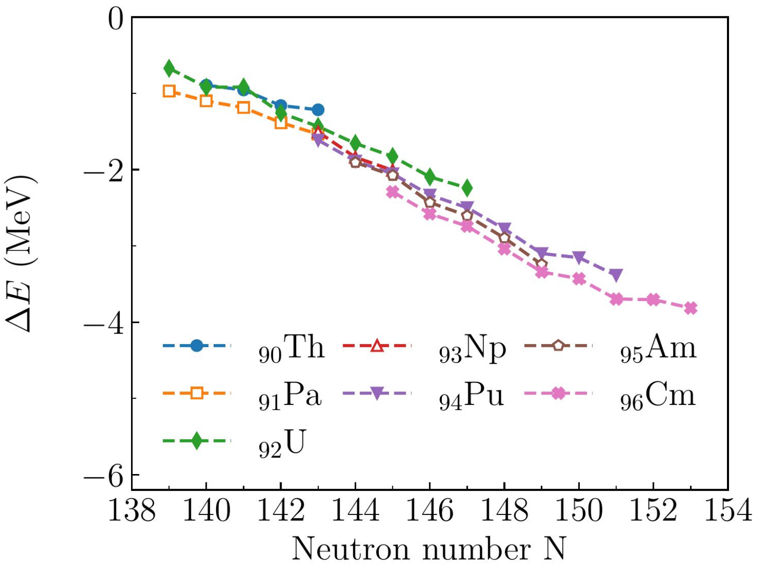


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**Triaxial deformation for actinides**

- Larger effects with growing N
- reminder: **σ(fission) < 0.5 MeV**
- what other regions does it affect?

# What is the effect on **nuclear level densities?**

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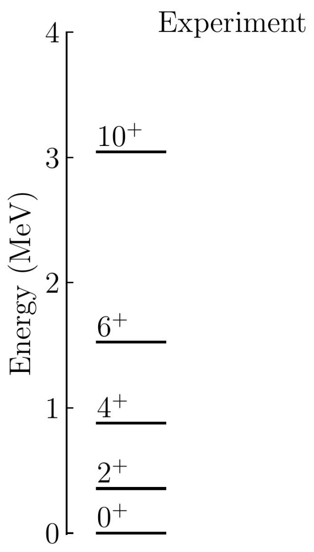


**Broken symmetries impact NLDs**

- **axial** rotors give rise to **sparse** spectra

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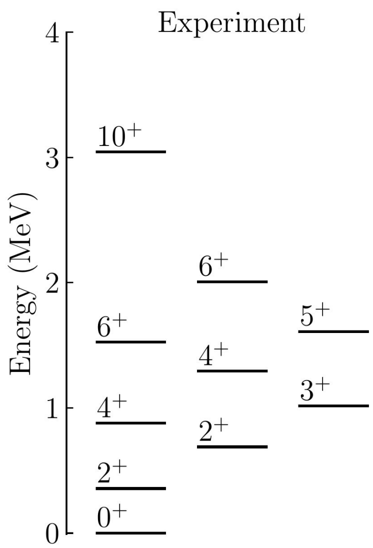


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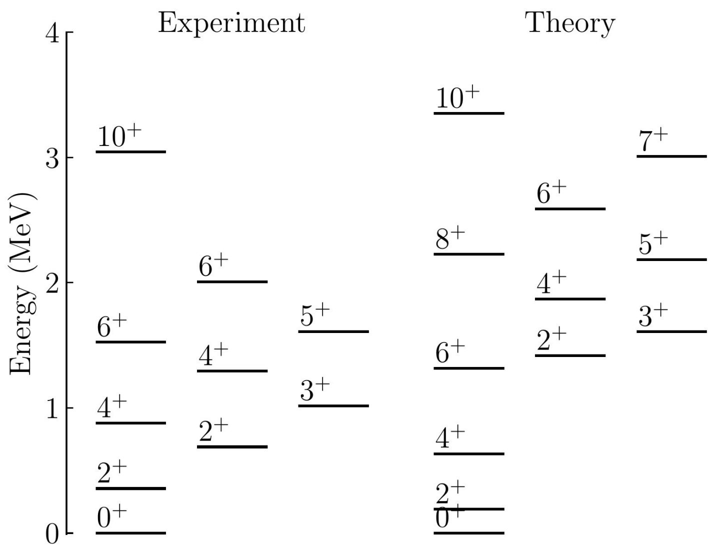


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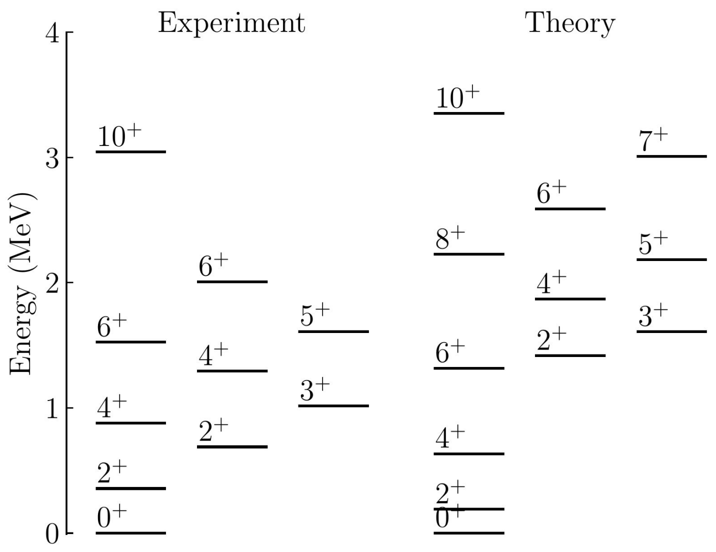


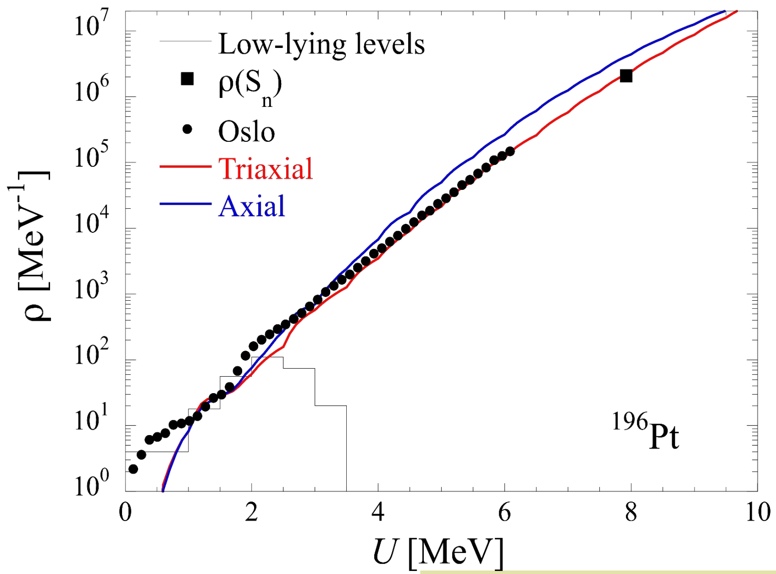


F. Giacoppo et al., PRC 90, 054330 (2014).

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**Level densities with BSkG2**

- not always higher level density
- but a **different energy dependence**!

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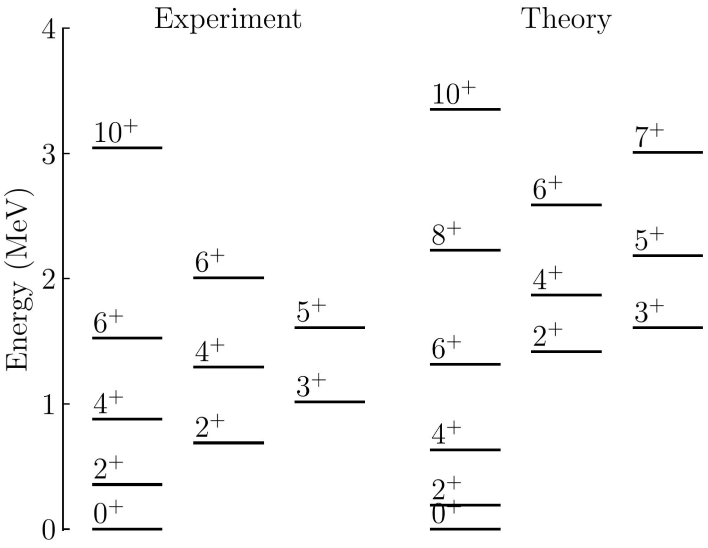


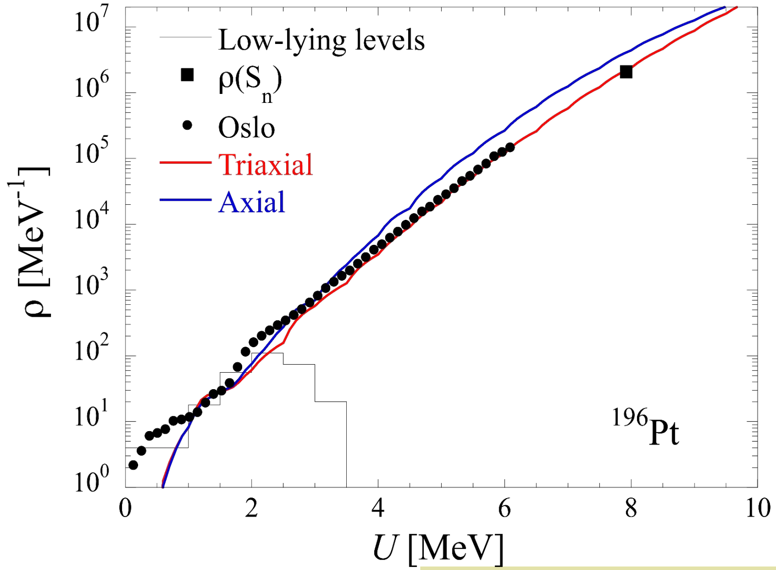


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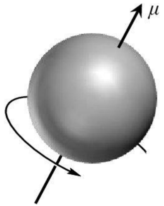
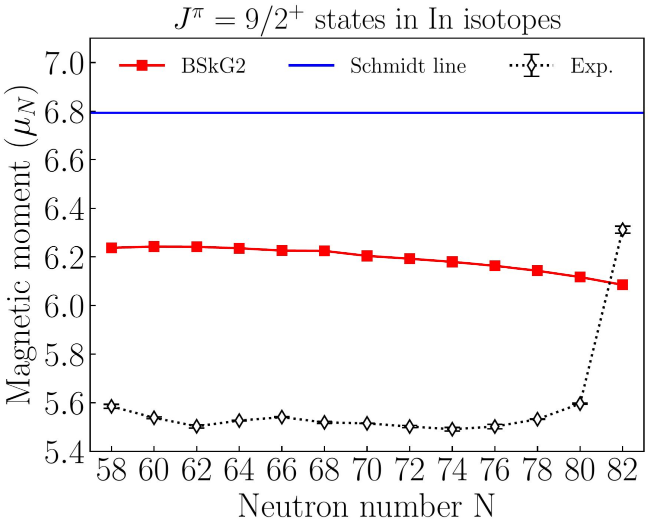
### Level densities with BSkG2

- not always higher level density
- but a **different energy dependence**!
- systematic calculations underway

# The future: **new observables**





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**Magnetic moments**

- time-reversal breaking needed!
- BSkG2 produces part of polarisation

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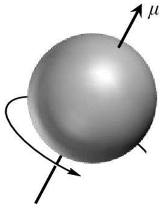

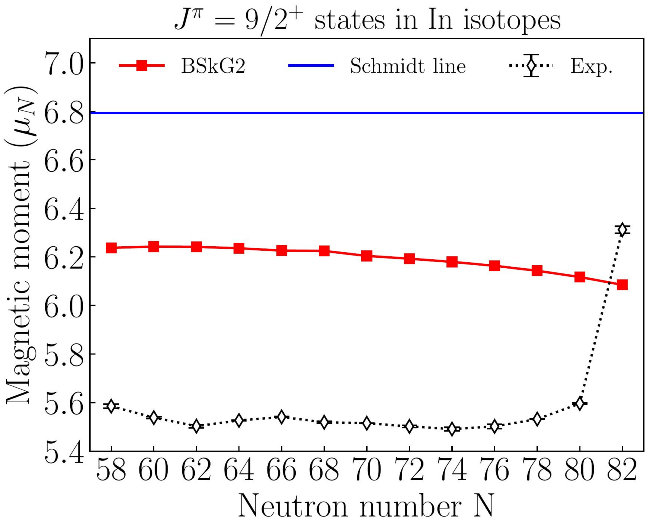


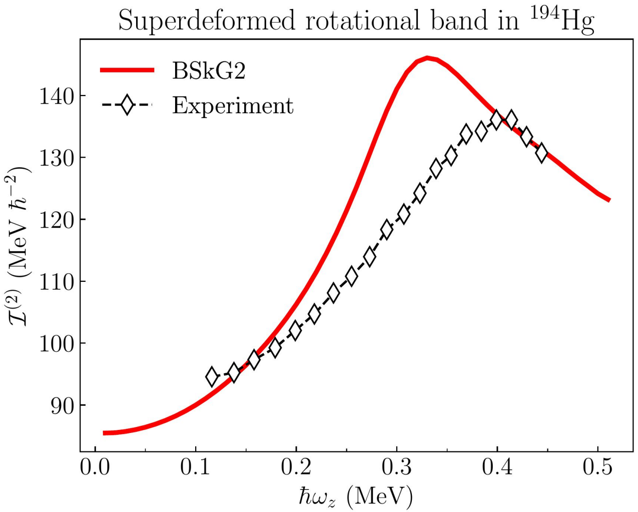


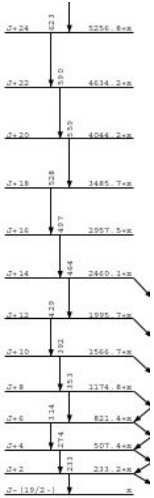

SD-1 band
(1998Bu03,1994Jo10)

## Magnetic moments

A. R. Vernon et al., Nature 607, 260 (2022),
J. Eberz et al., NPA 464, 9 (1987).

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## Rotational bands

B. Singh et al., Nuclear Data Sheets **97**, 241 (2002).

- time-reversal breaking needed!
- BSkG2 reproduces MOI decently well

# The future: **neutron stars**

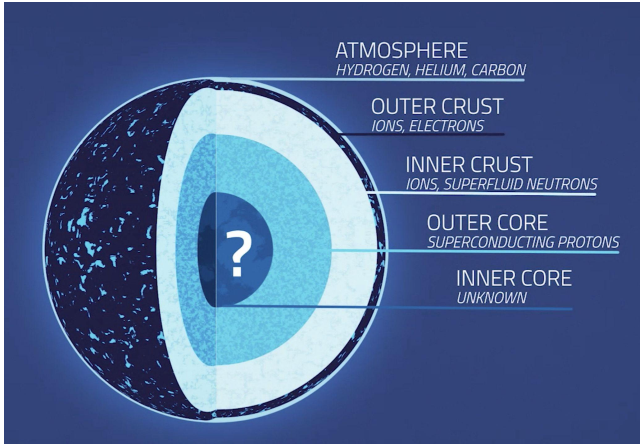


Image credit: NASA conceptual image lab

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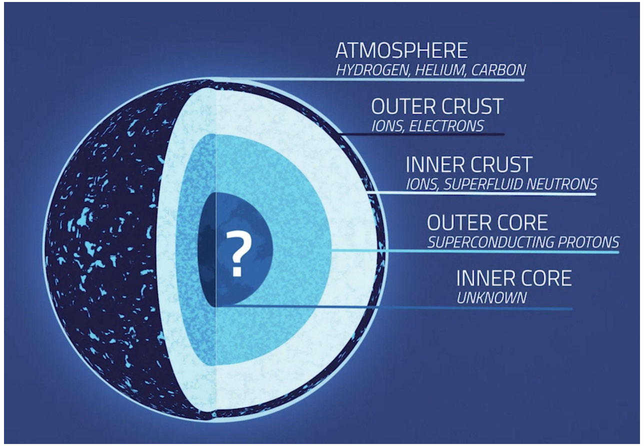


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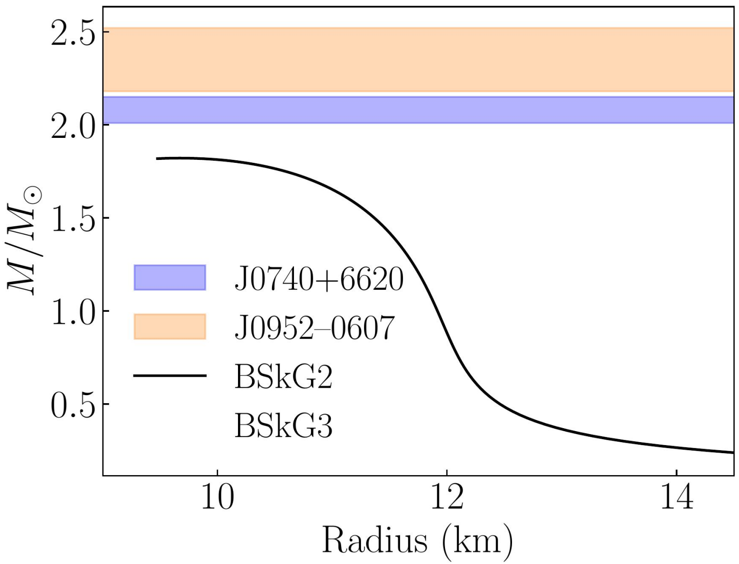



E. Fonseca *et al.*, ApJL **915**, L12 (2021) ; R. W. Roman *et al.*, ApJL **934**, L17 (2022).

# The future: **neutron stars**

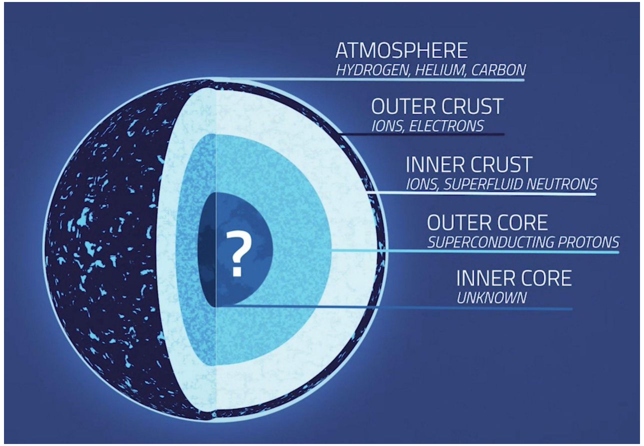
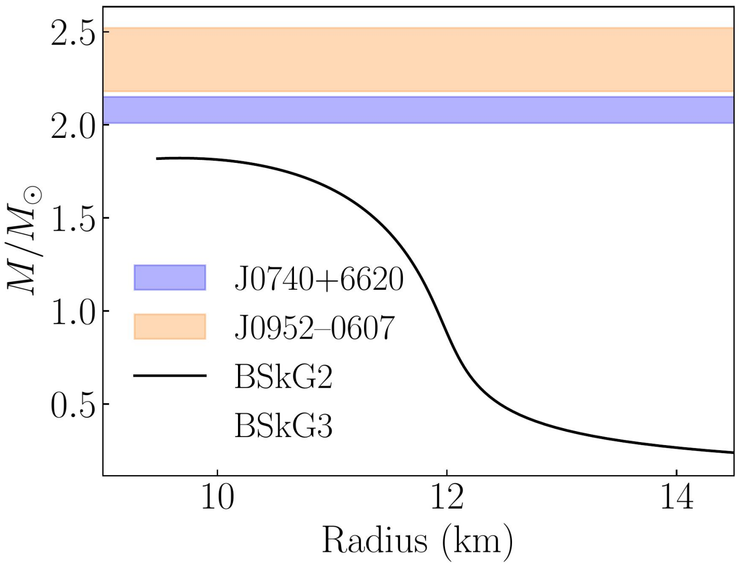



Image credit: NASA conceptual image lab



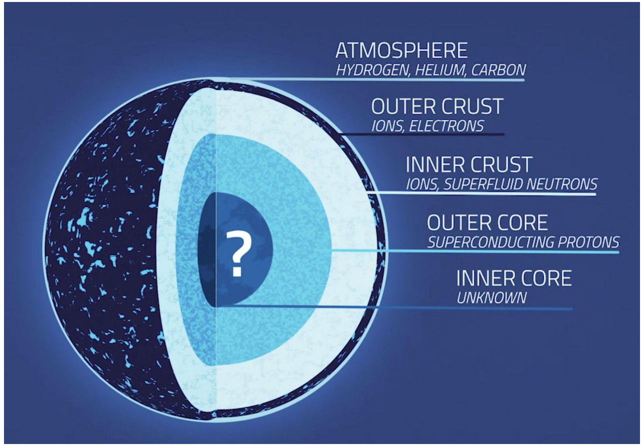

E. Fonseca *et al.*, ApJL **915**, L12 (2021) ; R. W. Roman *et al.*, ApJL **934**, L17 (2022).

## Extending the functional form

- microscopically motivated pairing
- extra density dependencies in the EDF

# The future: **neutron stars** and **BSkG3**



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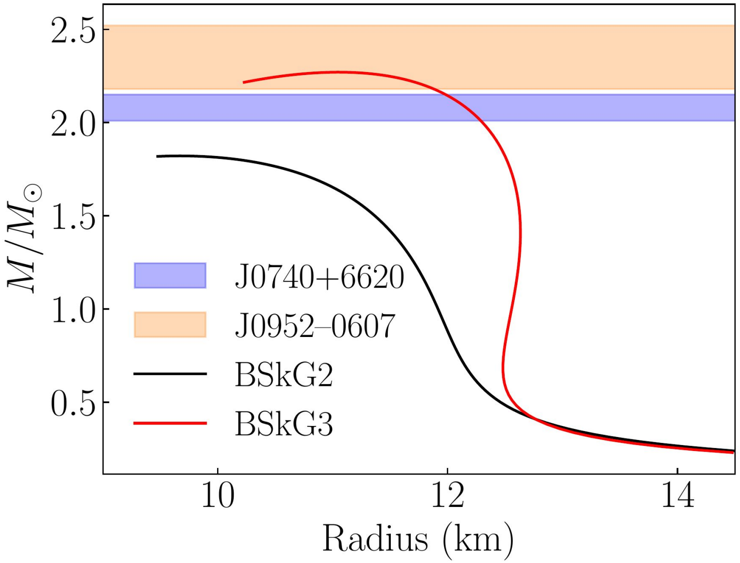


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## Extending the functional form

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## BSkG3

- as good for finite nuclei as BSkG2…
- …but able to support massive pulsars
- See our poster by G. Grams et al.!

# Conclusion

We provide **data for applications** that
- depends on a **limited number of parameters**
- incorporates the **maximum** of nuclear structure **physics**
- with a **focus on absolute masses**…
- but not at the cost of **other observables** (radii, barriers, …)

**BSkG1:** G. Scamps et al., EPJA 57, 333 (2021).
**BSkG2:** W. Ryssens et al., arXiv:2208.06455 [nucl-th]

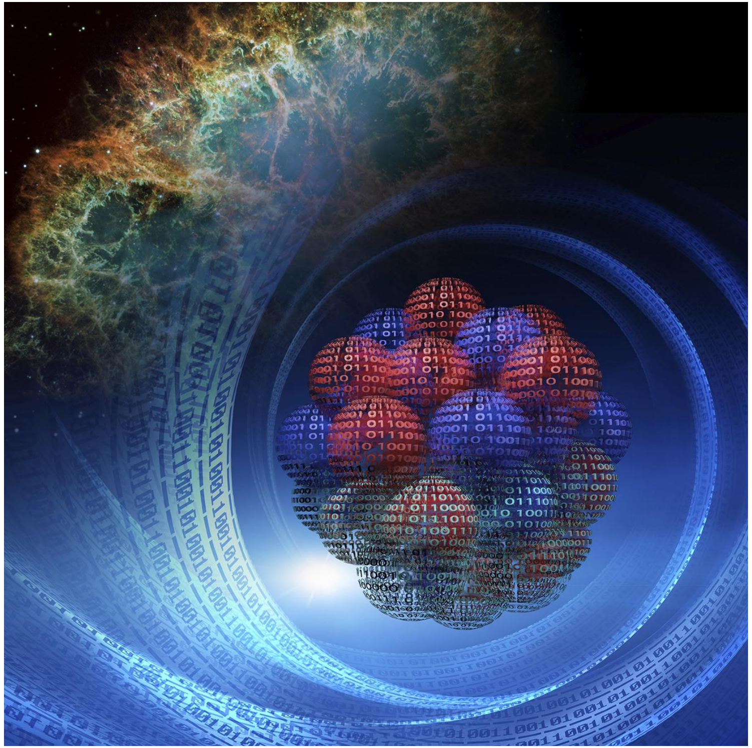

Image credit: Andy Sproles, ORNL

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- **Triaxial deformation**: ground states, barriers, NLD's,…
- **Time-reversal breaking**

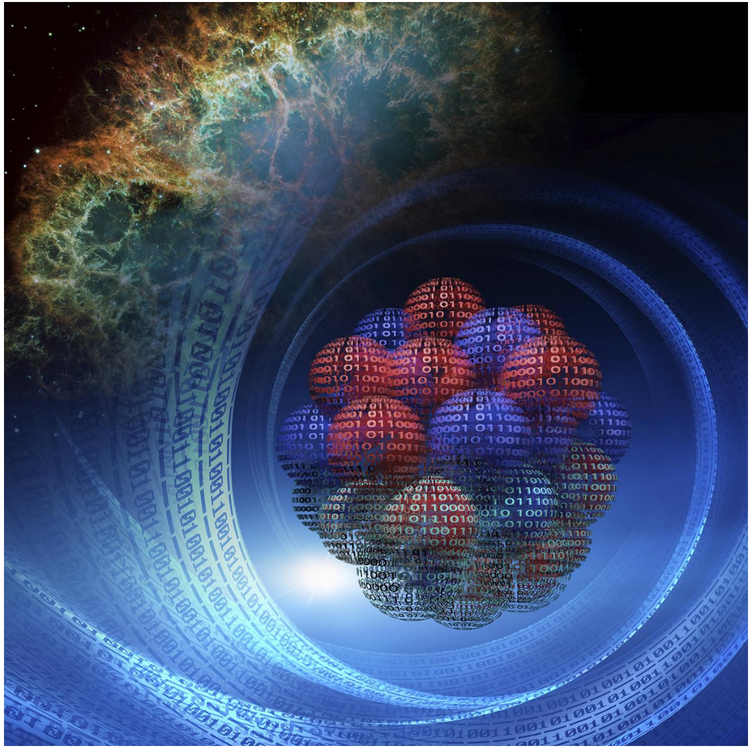

Image credit: Andy Sproles, ORNL

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- σ(masses) < 0.8 MeV
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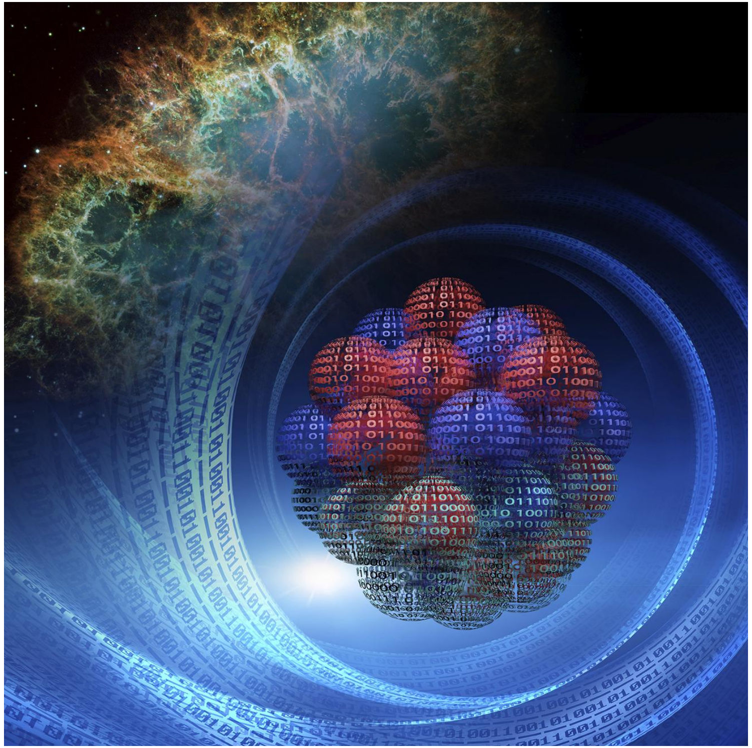

Image credit: Andy Sproles, ORNL

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Coming up:
- **Level density** tables for thousands of nuclei
- **Fission** tables for thousands of nuclei
- **BSkG3:** improved neutron matter EOS.

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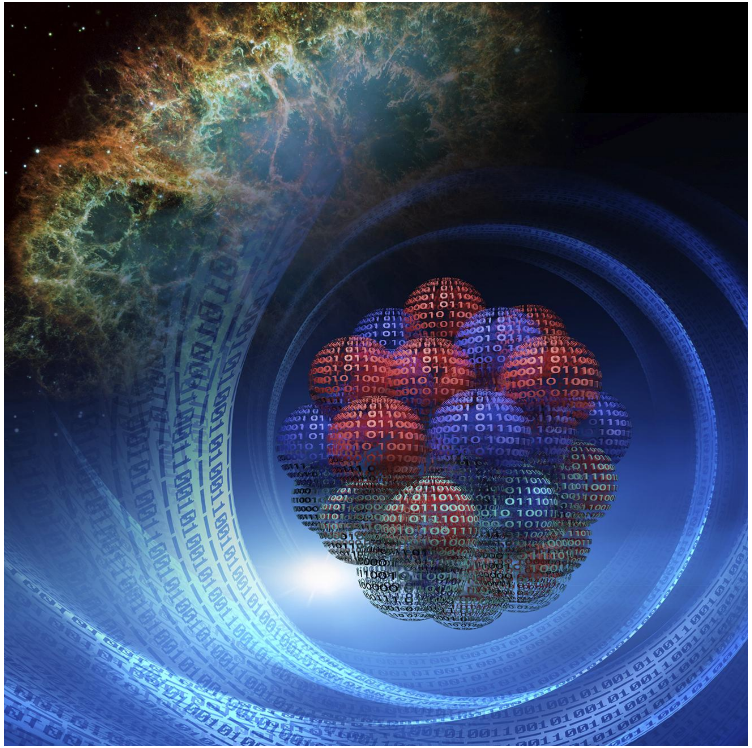

Image credit: Andy Sproles, ORNL

# Thank you for…

## …… the collaboration!

ULB

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iP2i LES 2 INFINIS LYON

M. Bender

## …… the computing time!

CÉCI

Cenaero

## …… the funding!

fnrs LA LIBERTÉ DE CHERCHER

## …… your attention!