The latest Brussels models

W. Ryssens, G. Scamps, M. Bender, & S. Goriely

16th of December 2021

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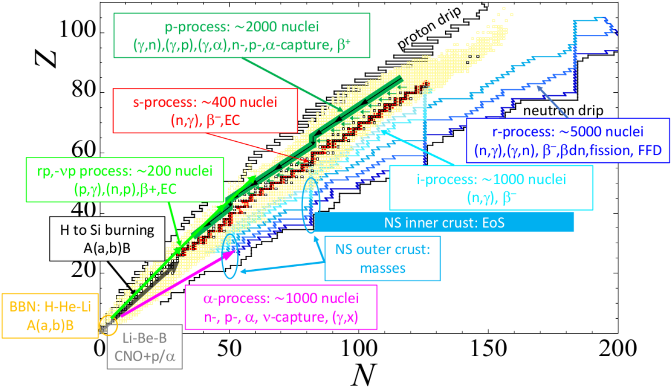
Nuclear data for astrophysics



M. Arnould & S. Goriely, Prog. Part. Nuc. Phys. **112**, 103766 (2020).

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^{\rho}\, \rho(\vec{r})\rho(\vec{r}) + C^{\tau}\, \rho(\vec{r})\, \tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple $|\Psi\rangle = |0\rangle_{\rm HFB}$

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- Study observables **locally**
- Fitted on $\lesssim 10$ nuclei
- Typically ~ 15 parameters
- **Advanced** calculations

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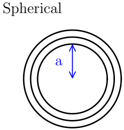
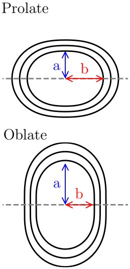
We are bringing the "structure" to the "astro" scale!

Symmetry breaking; nuclear shapes

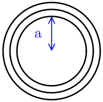




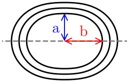
One DOF: β_{20}

Symmetry breaking; nuclear shapes

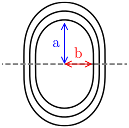
Spherical



Prolate

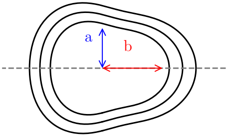


Oblate



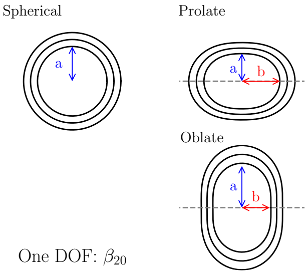
One DOF: β_{20}

Reflection-asymmetric (RA)



Two DOF: β_{20}, β_{30}

Symmetry breaking; nuclear shapes



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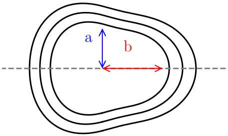
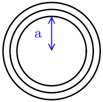


Two DOF: β_{20}, β_{30}

2D

Symmetry breaking; nuclear shapes

Spherical



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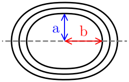

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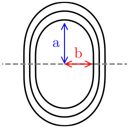

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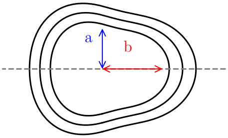
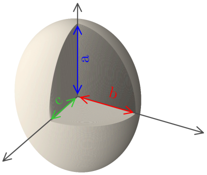


Two DOF: β_{20}, β_{30}

2D

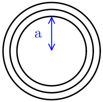
3D

Triaxial



Two DOF: (β_{20}, β_{22}) or (β, γ)

Spherical



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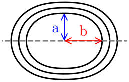

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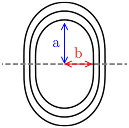

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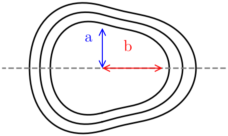

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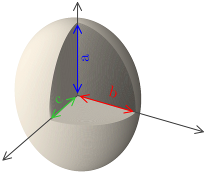

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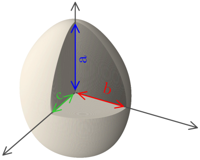

Three DOF: $(\beta, \gamma, \beta_{30})$

Symmetry breaking; time-reversal

Assumption of $> 95\%$ EDF calculations

$$\check{T}|\mathrm{HFB}\rangle = e^{i\phi}|\mathrm{HFB}\rangle$$

$\rightarrow$ **massively** simplifies calculations
$\rightarrow$ implies $\langle \boldsymbol{J} \rangle = 0$

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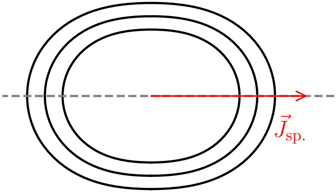

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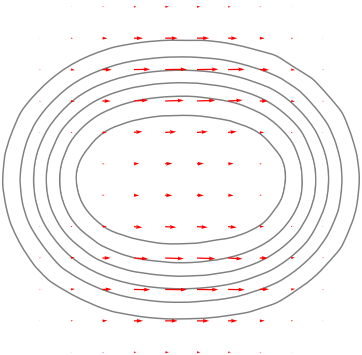

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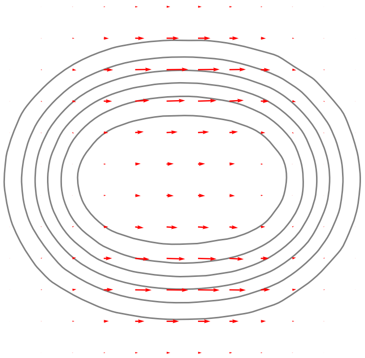
What is impacted by time-odd terms?

- ✗ Even-even g.s.
- ✓ Odd-N and/or Z g.s.
- ✓ Even-even excited states
- ✓ Dynamics (QRPA, TDHF(B), ...)
- ✓ ...



The models

BSkG = Brussels Skyrme on a Grid
= GSk from last year

BSk31 (Old)

BSkG1 (New-ish)

BSkG2 (New!)

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- Axial shapes
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- 22 parameters
- 3D $\vec{r}$-space
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BSkG2 (New!)

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BSkG2 (New!)

- 25 parameters
- 3D $\vec{r}$-space
- Triaxial shapes
- $\langle \hat{J} \rangle \neq 0$
- Preliminary
- Vibrational corr.

Tools

How do we fit $> \mathbf{20}$ parameters on $\mathbf{2408}$ masses efficiently?

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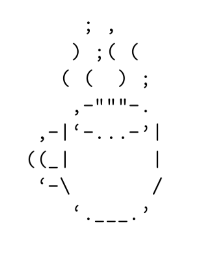
How do we fit > 20 parameters on **2408** masses efficiently?

MOCCa



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- Robust and quick
- Symmetry options

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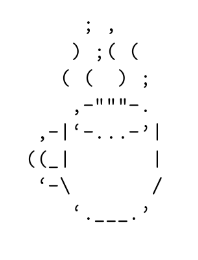

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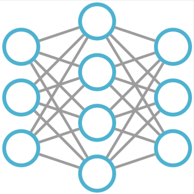
Machine learning



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- Simulate MOCCa calculations
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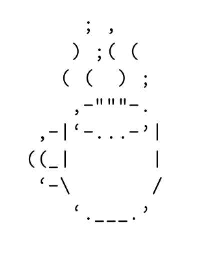

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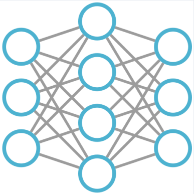

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MOCCa since 2020: new algorithms (almost) **guarantee** convergence for odd nuclei

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All results shown were obtained with a **full** MOCCa calculation.

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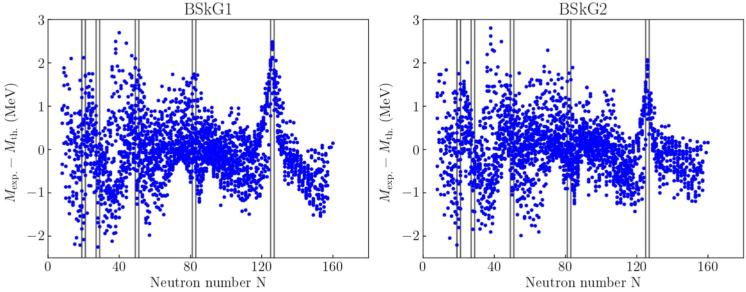
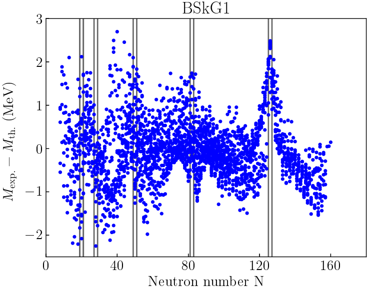
Machine learning is **only** used to perform the interaction fitting.

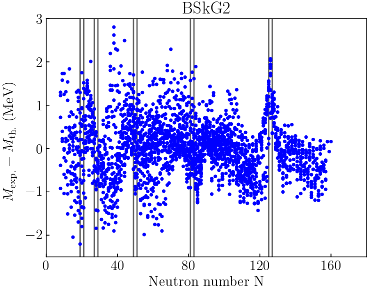
Masses



BSkG1
BSkG2
3
2
1
0
−1
−2
0
40
80
120
160
$M_{\rm exp.} - M_{\rm th.}$ (MeV)
Neutron number N

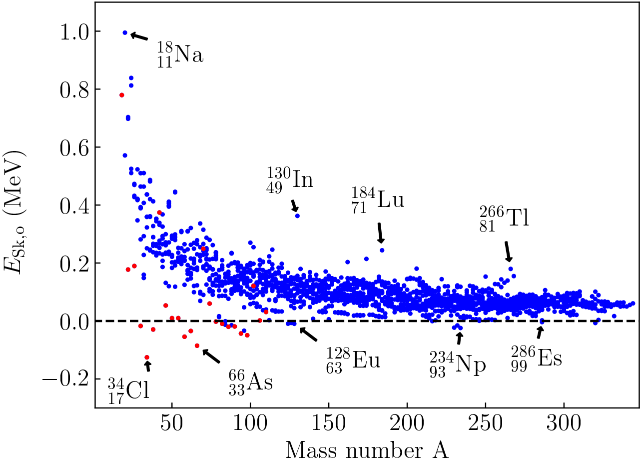
Masses



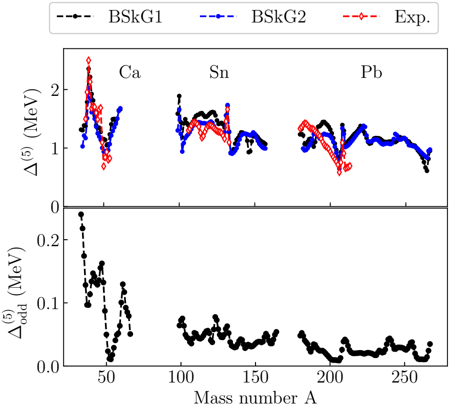


	Old		**New**	
	BSk27	BSk32	BSkG1	BSkG2
Parameters	24	33	22	25
$\sigma(M)$ [MeV]	0.512	0.586	0.741	0.678
$\sigma(S_n)$ [MeV]	0.425	0.489	0.466	0.500
$\sigma(Q_\beta)$ [MeV]	0.516	0.601	0.645	0.619

Time-odd contributions



Mass differences



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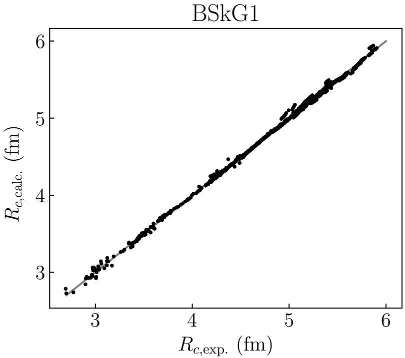
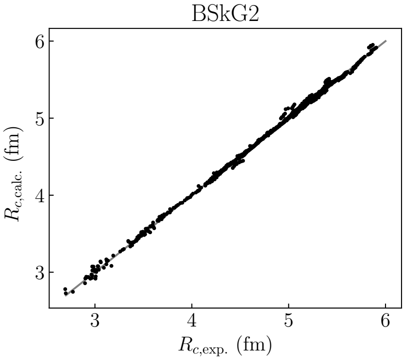
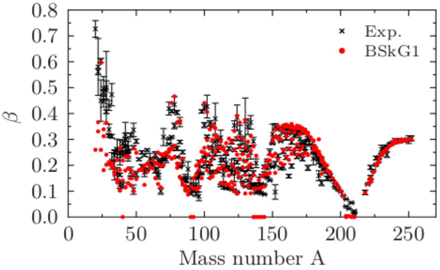
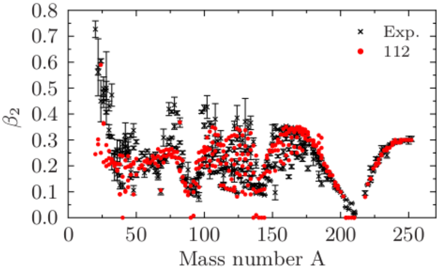




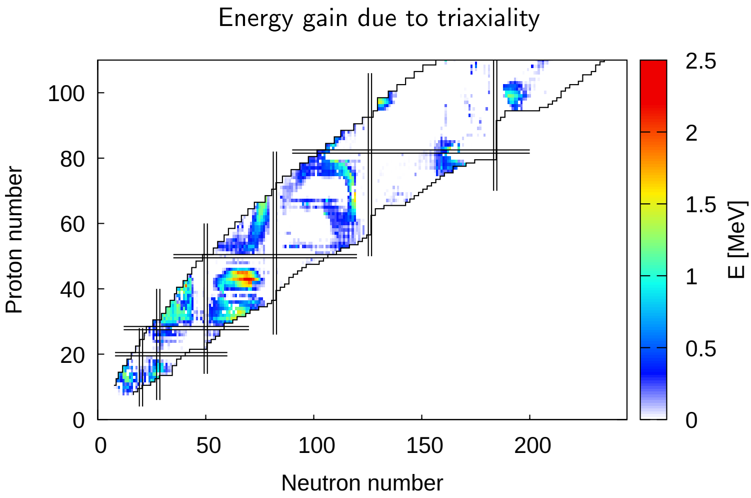
	BSk27	BSk32	BSkG1	BSkG2
$\sigma(M)$ [MeV]	0.512	0.586	0.741	0.678
$\sigma(R_c)$ [fm]	0.028	0.027	0.027	0.027

Deformations

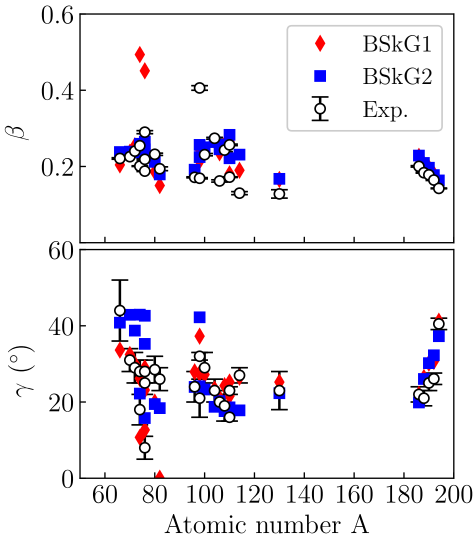




Triaxiality: where?



Triaxiality: comparison to experiment



Data extracted by M. Zielińska

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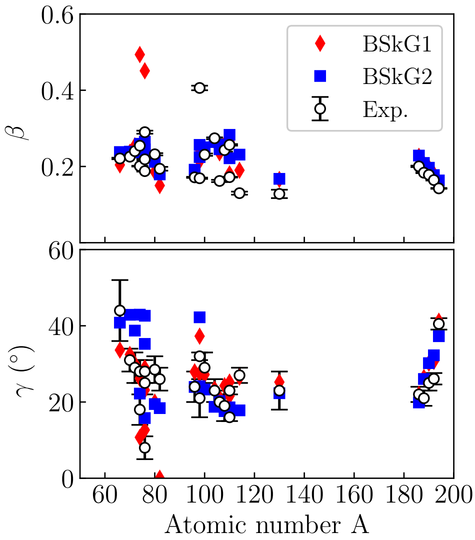
L. E. Svensson et al., NPA **584**, 547 (1995).
L. Morrison et al., PRC **102**, 054304 (2020).
C. Y. Wu et al., NPA **607**, 178 (1996).

Triaxiality: comparison to experiment



Data extracted by M. Zielińska

M. Rocchini et al., PRC **103**, 014311 (2021).
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K. Wrzosek-Lipska et al., APB **51**, 789 (2020).
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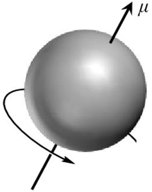
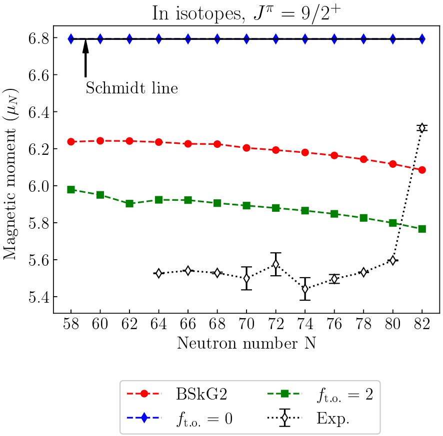
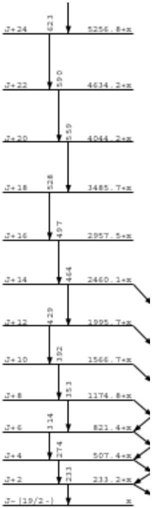
Heavy-ion collissions at LHC probe triaxiality of ^{129}Xe!
B. Bally et al., arXiv 2108.09578[nucl-th] .



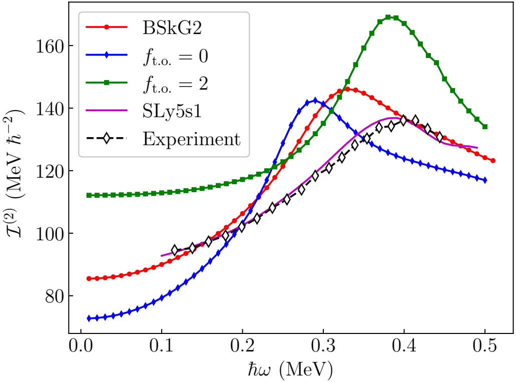


Exp. data from A. Vernon et al., under review at Nature. DOI:10.21203/rs.3.rs-611360/v1

Superdeformed rotational band in ^{194}Hg

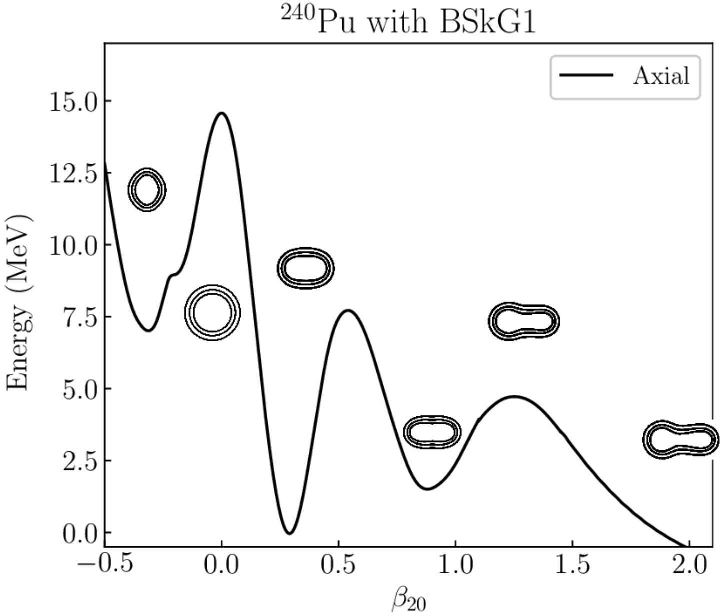


SD-1 band
(1998Bu03,1994Jo10)



Exp. data from B. Singh, Nuclear Data Sheets 97, 241 (2002).

Triaxiality: fission



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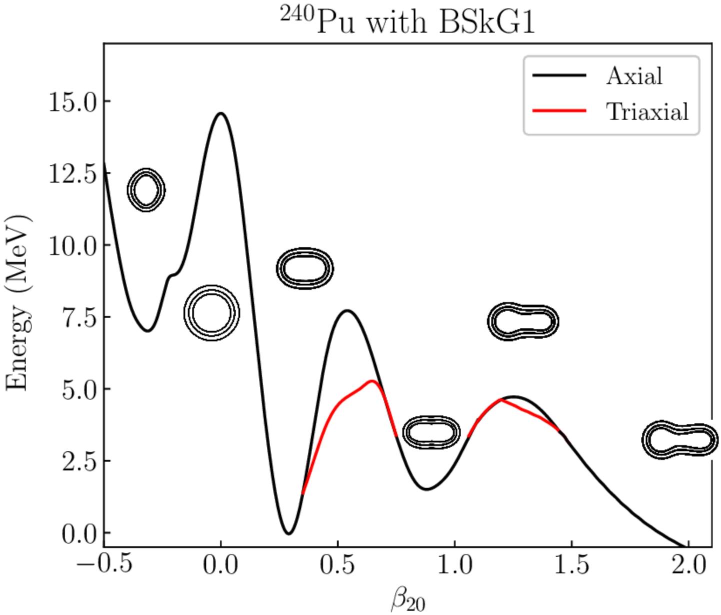

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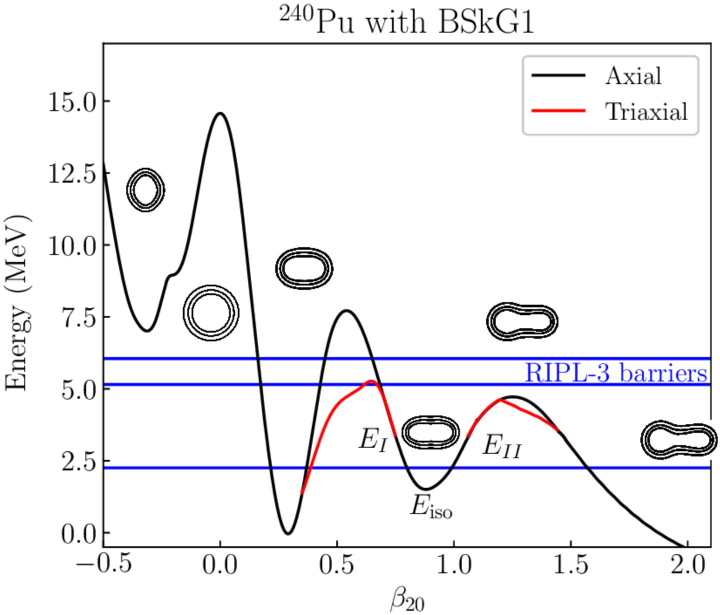
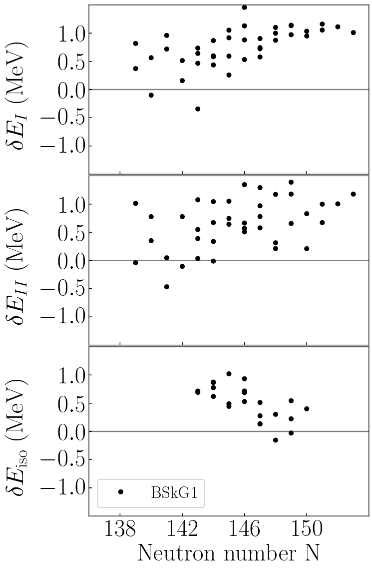


BSkG2: improved fission barriers above $Z > 90$



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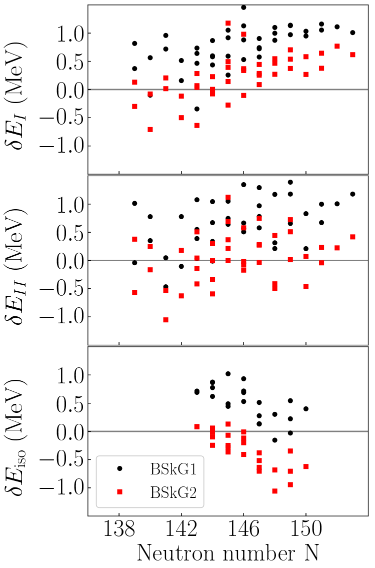

Vibrational corr. offers **3 parameters**

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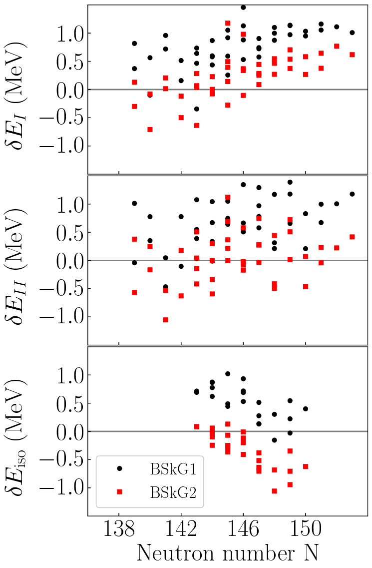

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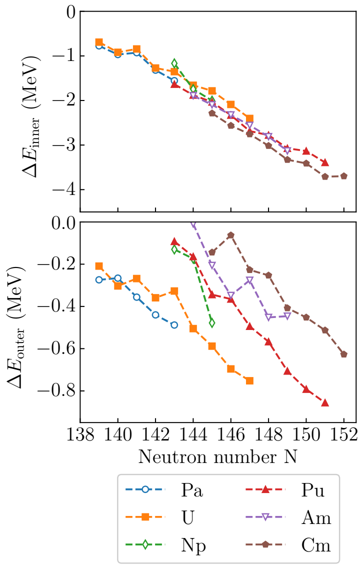

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Conclusions & Outlook

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- Groundstate octupole collectivity
- Complete the fission model (G. Scamps, J.-F. Lemaître)
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- Move into extended Skyrme forms (L. Batail, G. Grams and IP2I Lyon)
  - → t_4/t_5 terms for stiffer EOS (with)
  - → N2LO for deformed shell gaps

Thanks!

Thanks for. . .

. . . the **help**:

BSkG1/2		MOCCa	
S. Goriely	ULB, BE	P.-H. Heenen	ULB, BE
G. Scamps	INT, US	M. Bender	IP2I, FR
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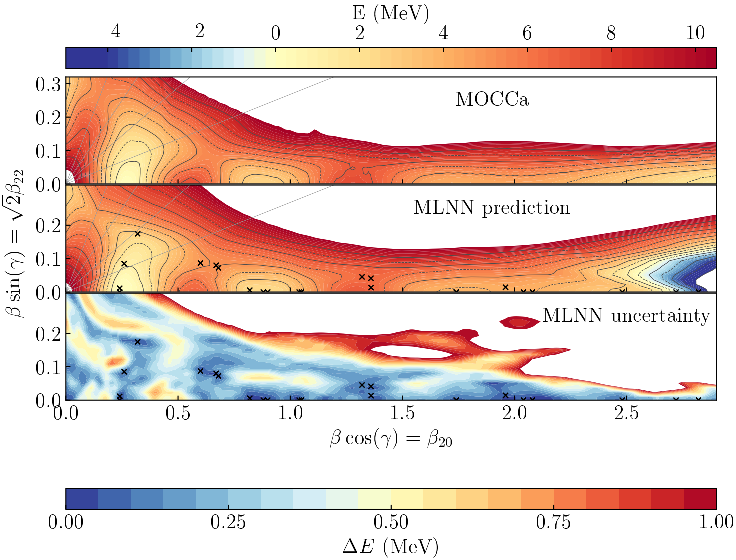
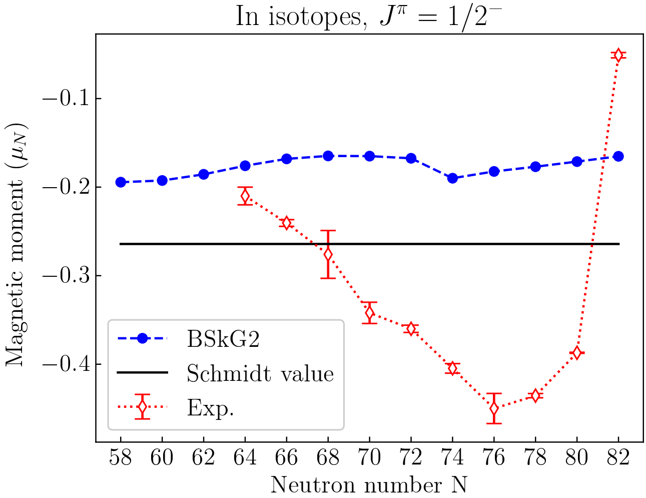
. . . your **attention**!

A taste of things to come

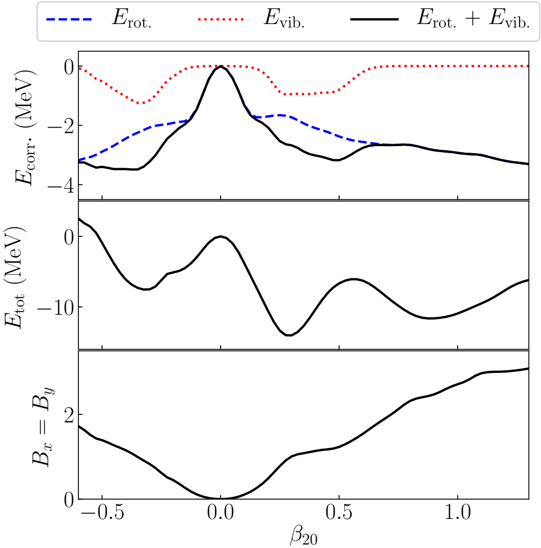


Bonus!

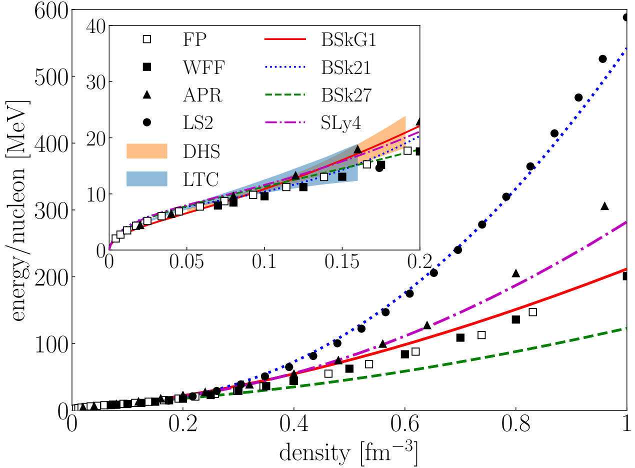
More In isotopes



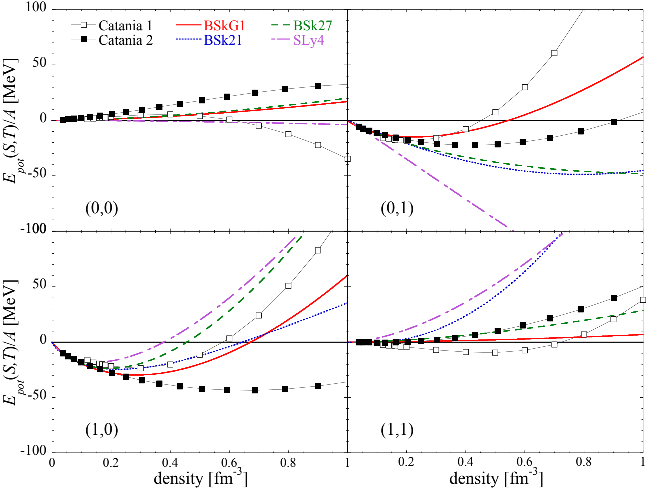
Example of the collective correction: ^{240}Pu



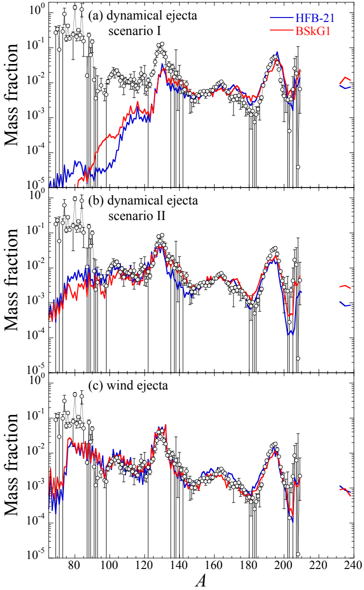
Neutron matter



Symmetric matter

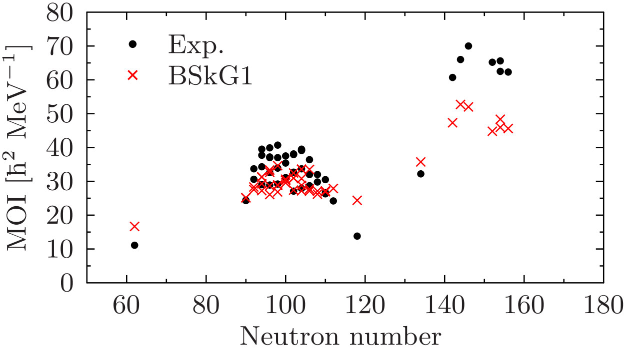


R-process

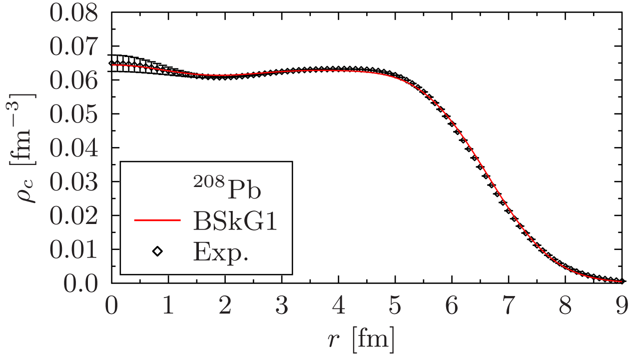


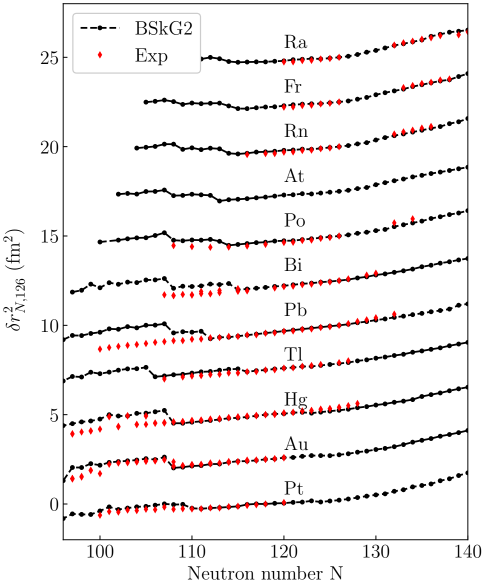
(a) dynamical ejecta
scenario I
HFB-21
BSkG1
(b) dynamical ejecta
scenario II
(c) wind ejecta
Mass fraction
A
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
80
100
120
140
160
180
200
220
240

Moment of inertias



Charge density




BSkG2
Exp
Ra
Fr
Rn
At
Po
Bi
Pb
Tl
Hg
Au
Pt
$\delta r^2_{N,126}$ (fm^2)
Neutron number N
25
20
15
10
5
0
100
110
120
130
140