Physics Highlights and Challenges: Nuclear Physics

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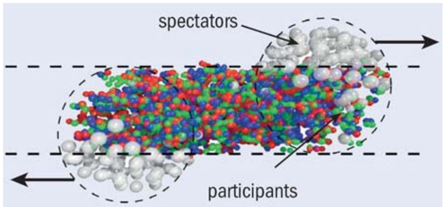
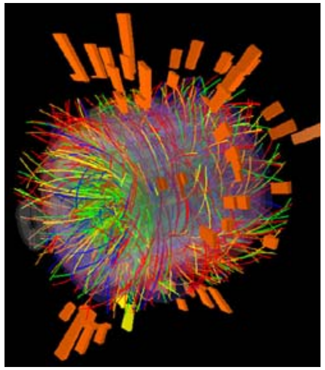
- Nuclear-physics research: aim
- Status of nuclear theory: ab-initio approaches
- Selection of some recent highlights (disclaimer)
- Conclusion and outlook

Nuclear-Physics Research - Aim

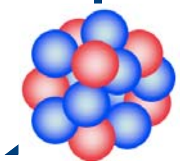
- Unravel the fundamental properties of nuclei from their basic constituents
- Investigating the strong and weak interaction at work the nuclear medium



- Links to
  - Atomic Physics / Chemistry (e.g. heavy element region)
  - Nuclear Astrophysics / Nucleosynthesis
  - Fundamental Interaction Studies
  - Societal Aspect (e.g. medical radioisotopes)

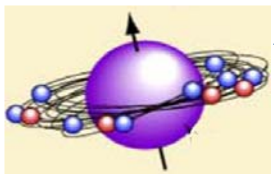


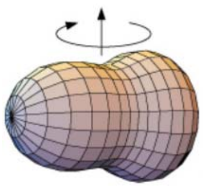
Energy

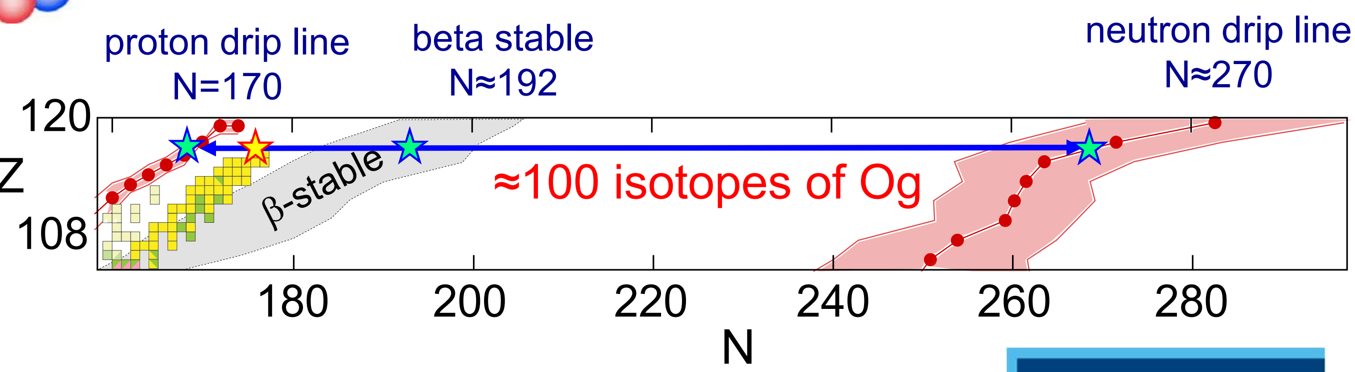


N/Z - isospin

Spin - Deformation







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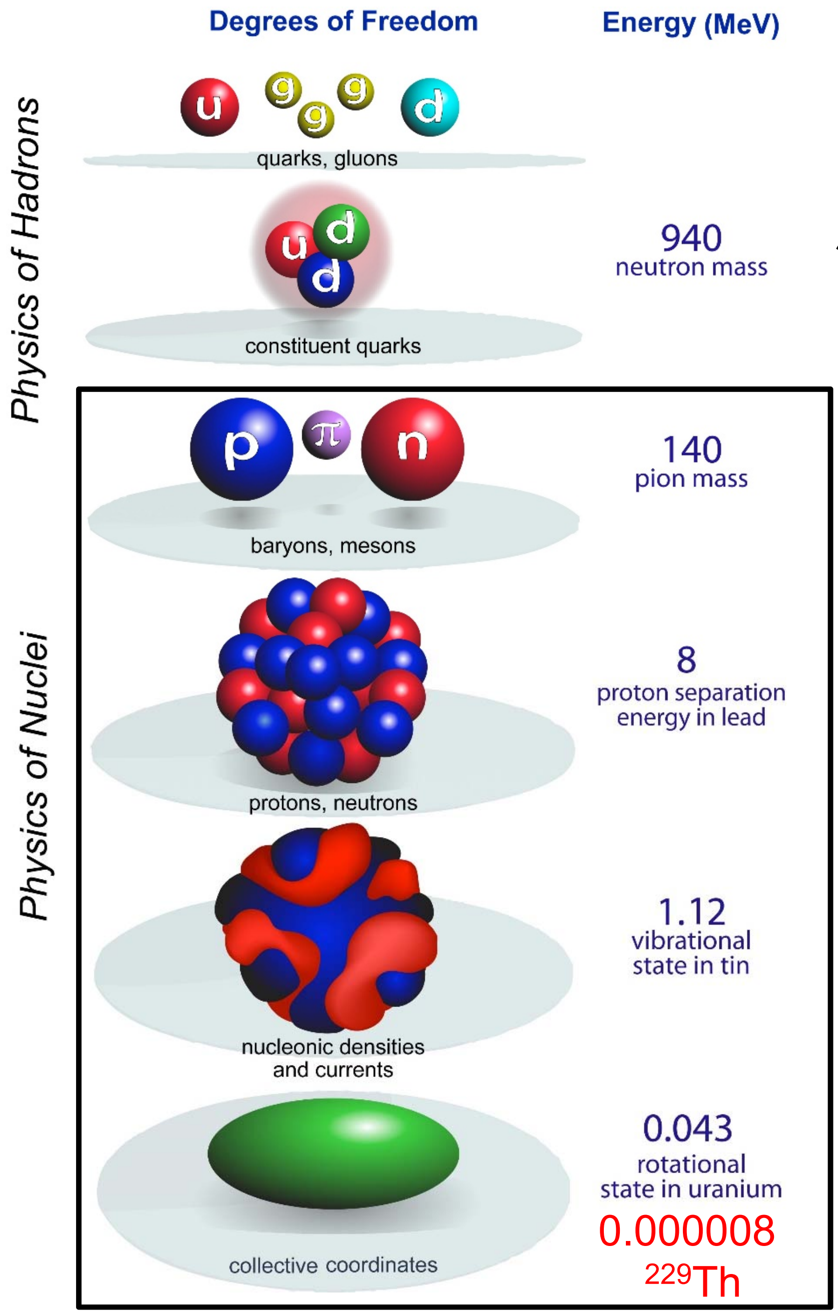
Erler,- Nature 486 (2012)

How are nuclei made and organized?



QCD
Effective Field Theory

“Ab-initio Calculations”

Configuration Interactions
Density Functional Theory
Collective Models

See: U. Meiβner

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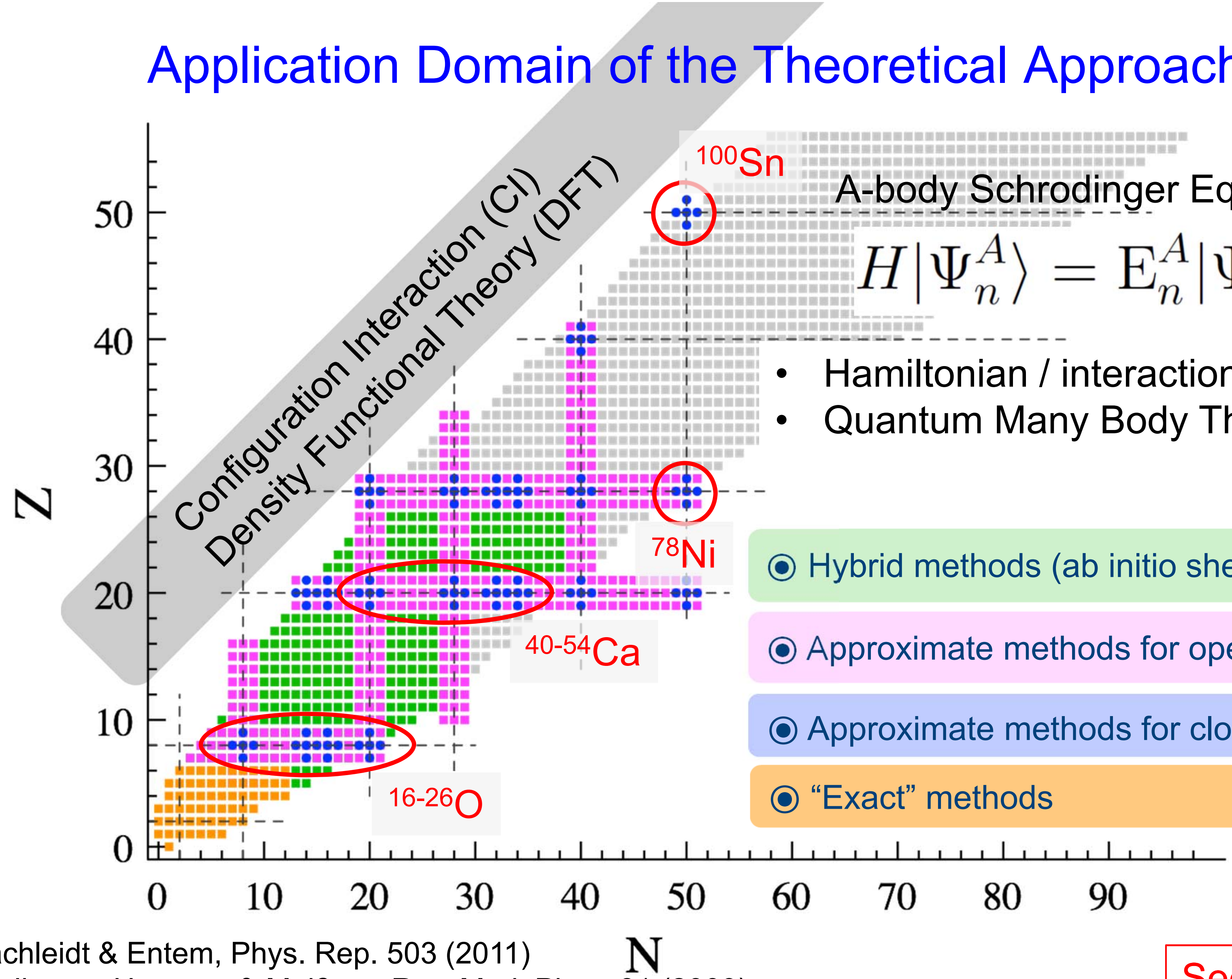
Courtesy: W. Nazarewicz - MSU, T. Duguet - CEA

Application Domain of the Theoretical Approaches



A-body Schrodinger Equation

$$H|\Psi_n^A\rangle = E_n^A|\Psi_n^A\rangle$$

- Hamiltonian / interaction (Chiral EFT)
- Quantum Many Body Theory

◉ Hybrid methods (ab initio shell model)

◉ Approximate methods for open-shells

◉ Approximate methods for closed-shells

◉ "Exact" methods

Machleidt & Entem, Phys. Rep. 503 (2011)
Epelbaum, Hammer & Meißner, Rev. Mod. Phys. 81 (2009)
Hagen,- Rept. Prog. Phys. 77 (2014)
Hergert,- Phys. Rep. 621 (2016)

See: U. Meiβner

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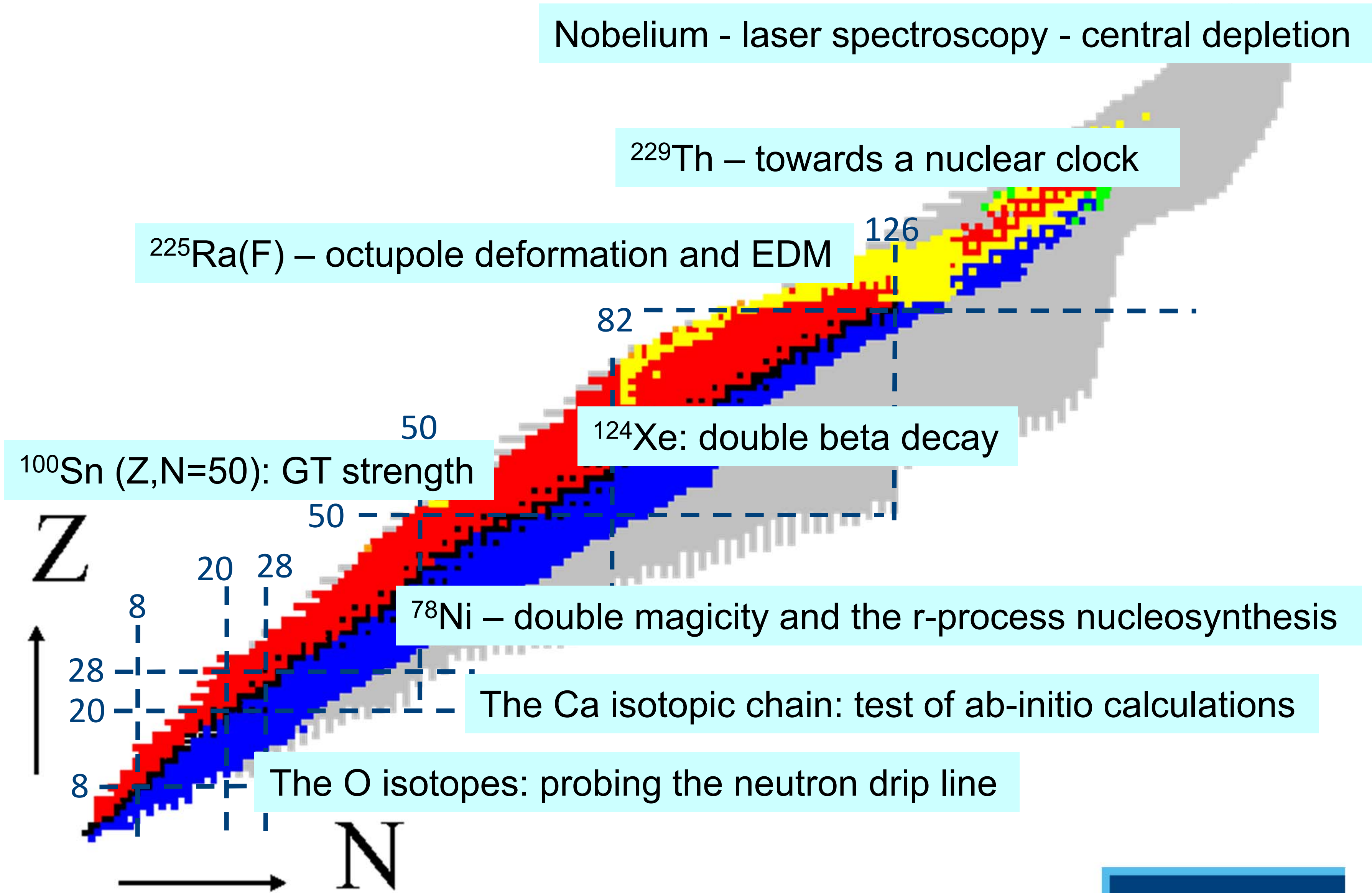
Courtesy: T. Duguet – CEA

A tour around the chart of nuclei



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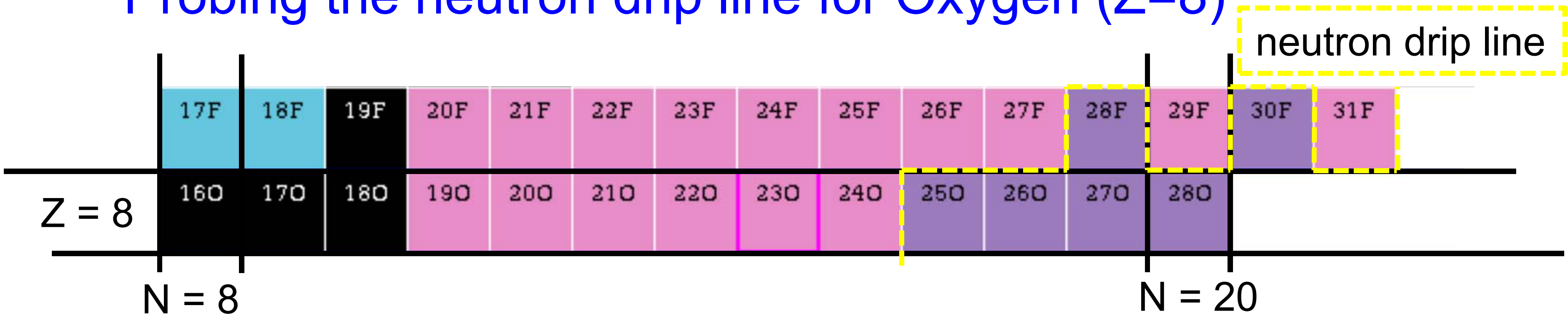
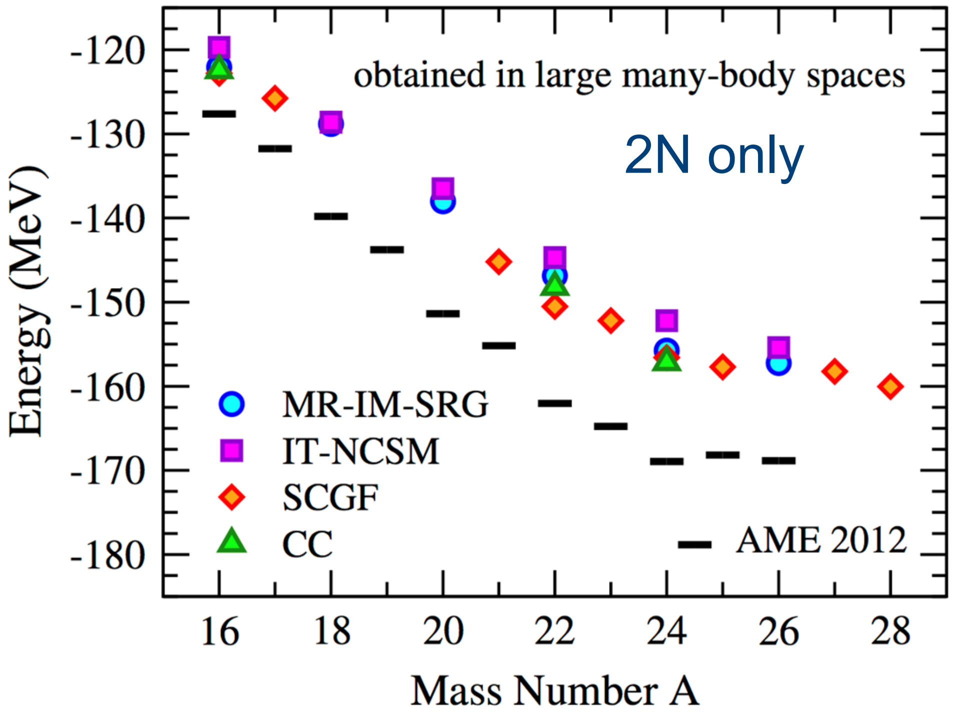
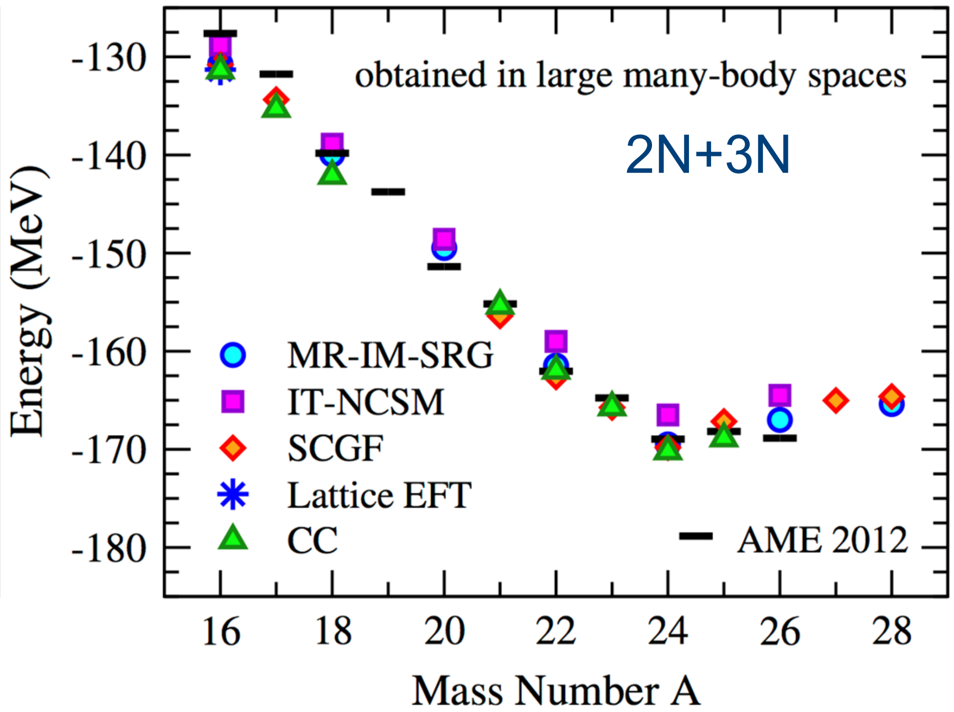
Probing the neutron drip line for Oxygen (Z=8)



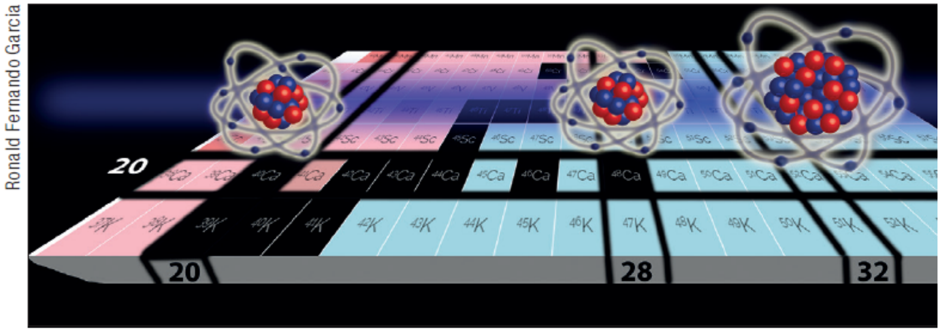


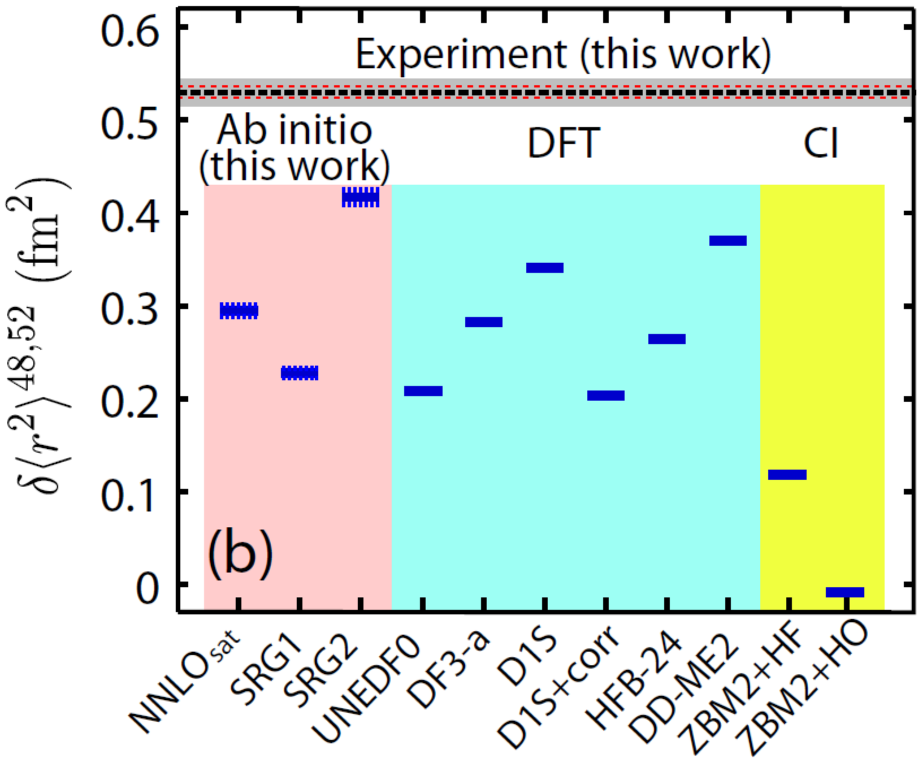


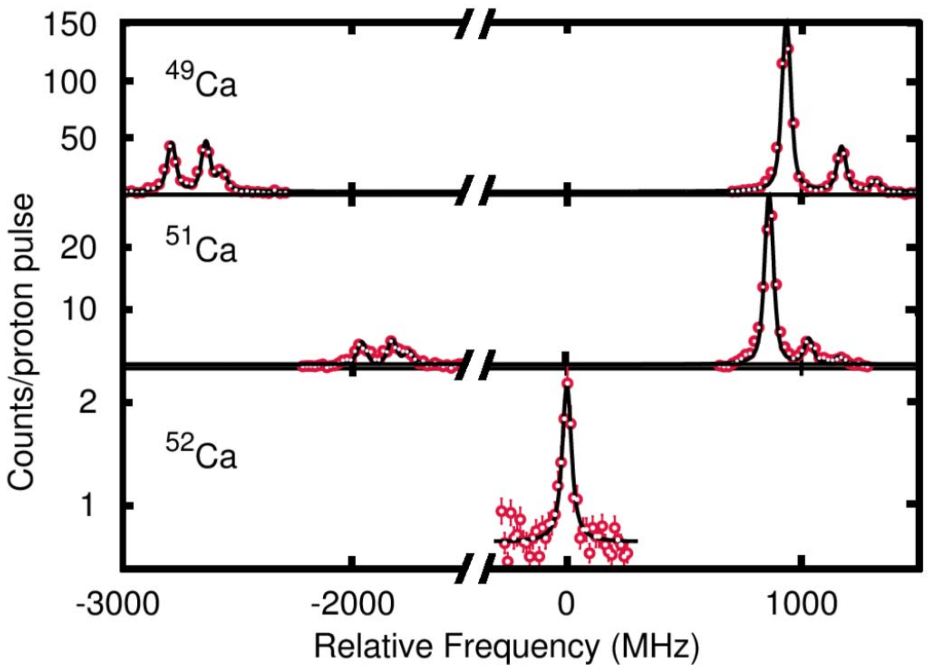
See e.g.: Hebeler,- Annu. Rev. Nucl. Part. Sci. (2015)

Charge radii: sensitive to shell gaps and deformation

Ca (Z=20) closed proton shell







- Large charge radius of ^{52}Ca

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Charge radii: sensitive to shell gaps and deformation

- Gamma-ray spectroscopy

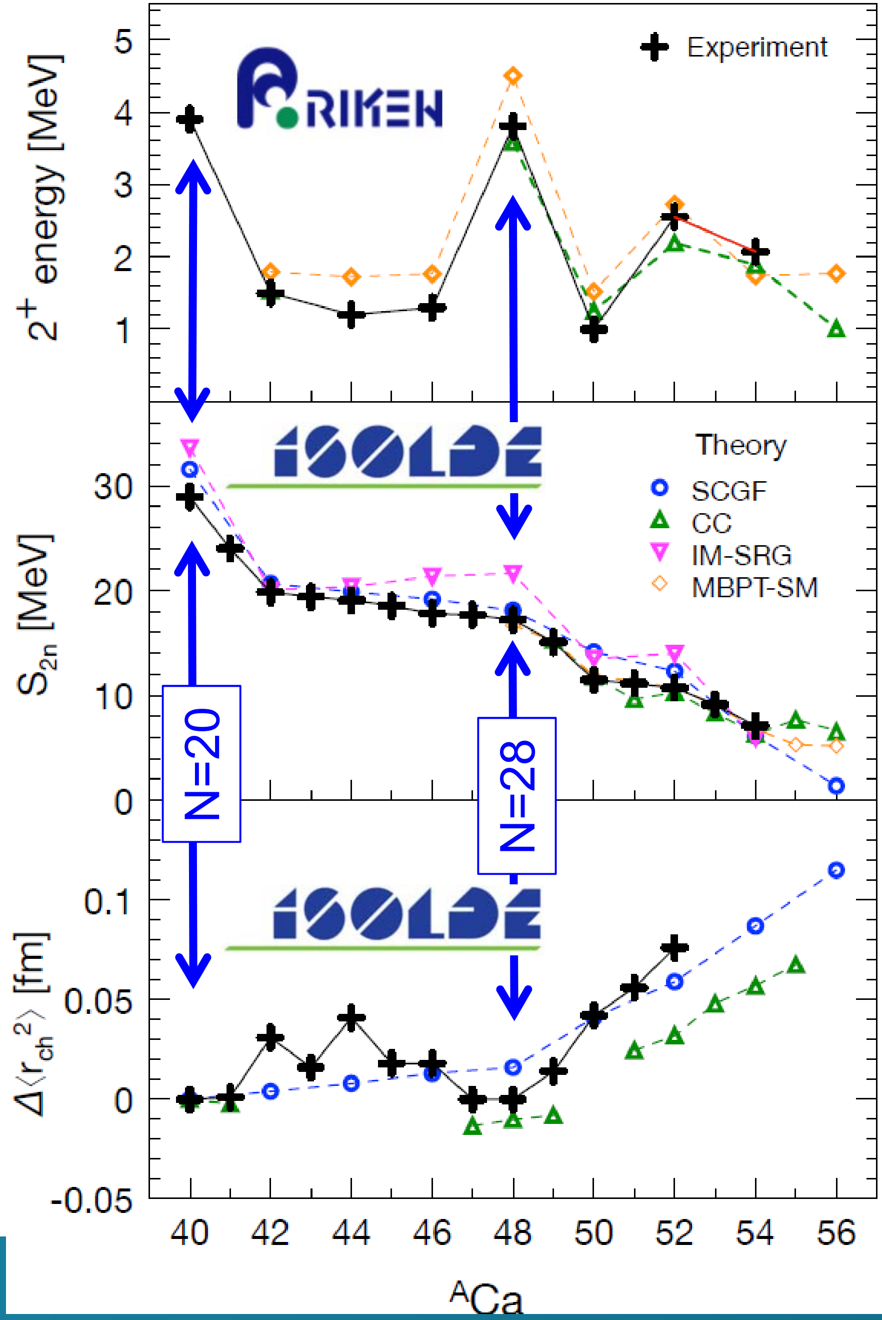
Steppenbeck,- Nature 502 (2013)

- Mass measurements

Wienholtz ,- Nature 498 (2013)

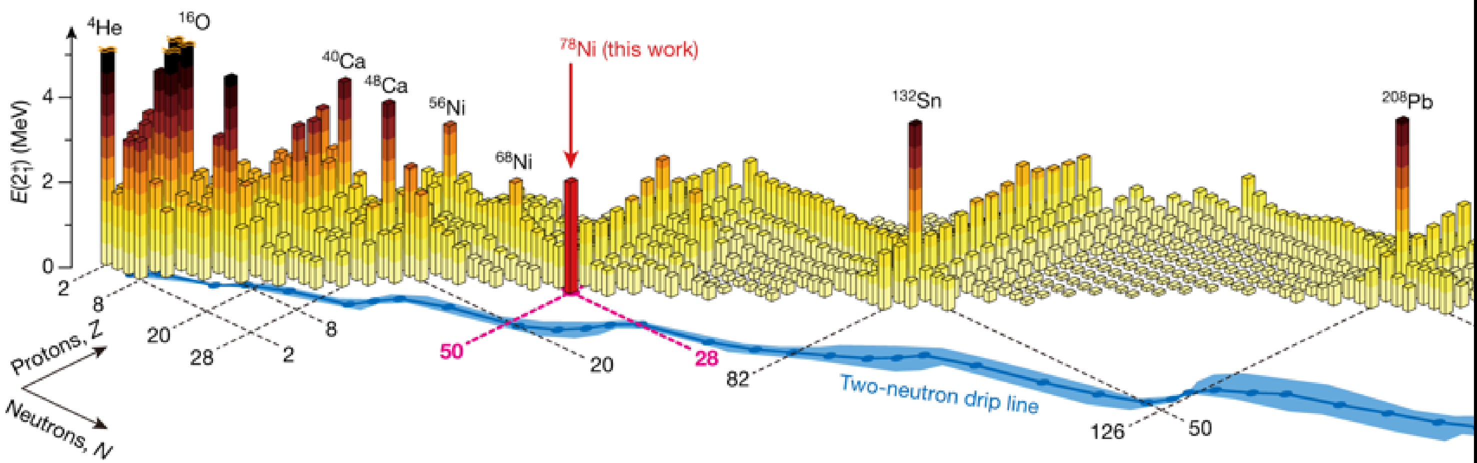
- Laser spectroscopy

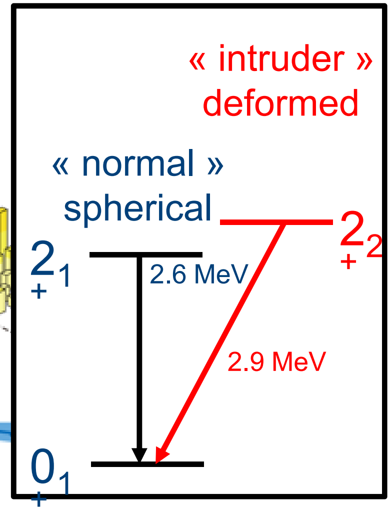
Garcia Ruiz,- Nature Physics 12 (2016)

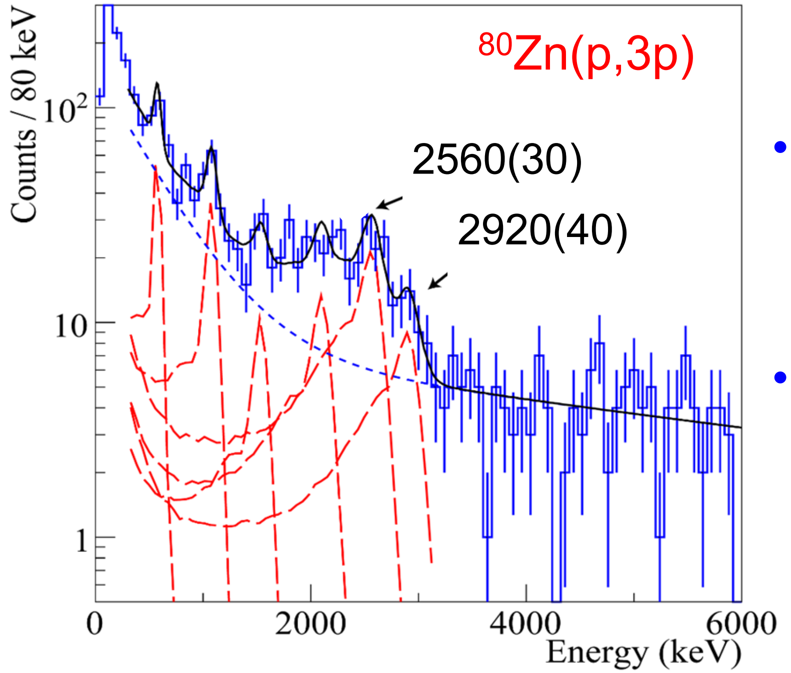


See also: A.J. Miller,- Nature Physics 15 (2019)

First spectroscopy of the doubly-magic nuclei ^{78}Ni



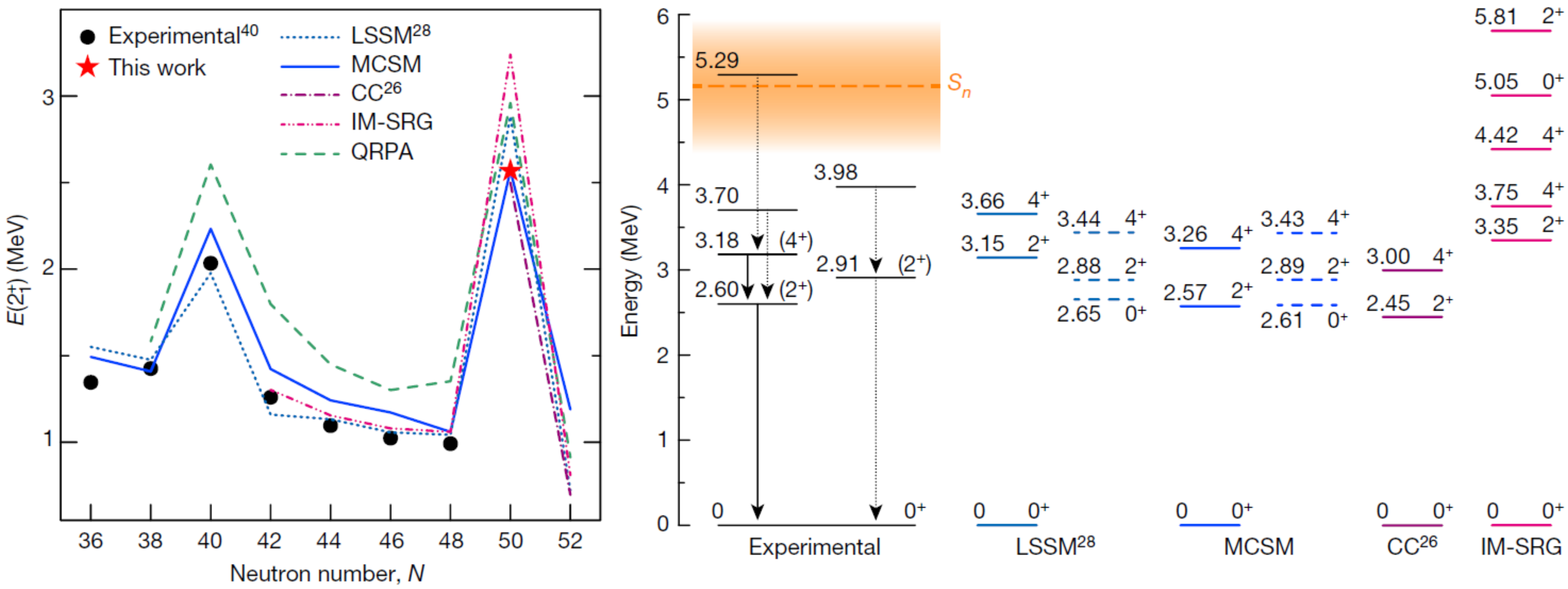




- Development of a liquid hydrogen target combined with in-beam gamma-ray spectroscopy
- First 2^+ state of ^{78}Ni at 2.6 MeV

Courtesy: A. Obertelli – TU Darmstadt

Taniuchi,- Nature 569 (2019)



- ^{78}Ni is doubly magic
- Comparison with ab-initio and phenomenological shell model
- Possible disappearance of the N=50 shell closure beyond ^{78}Ni

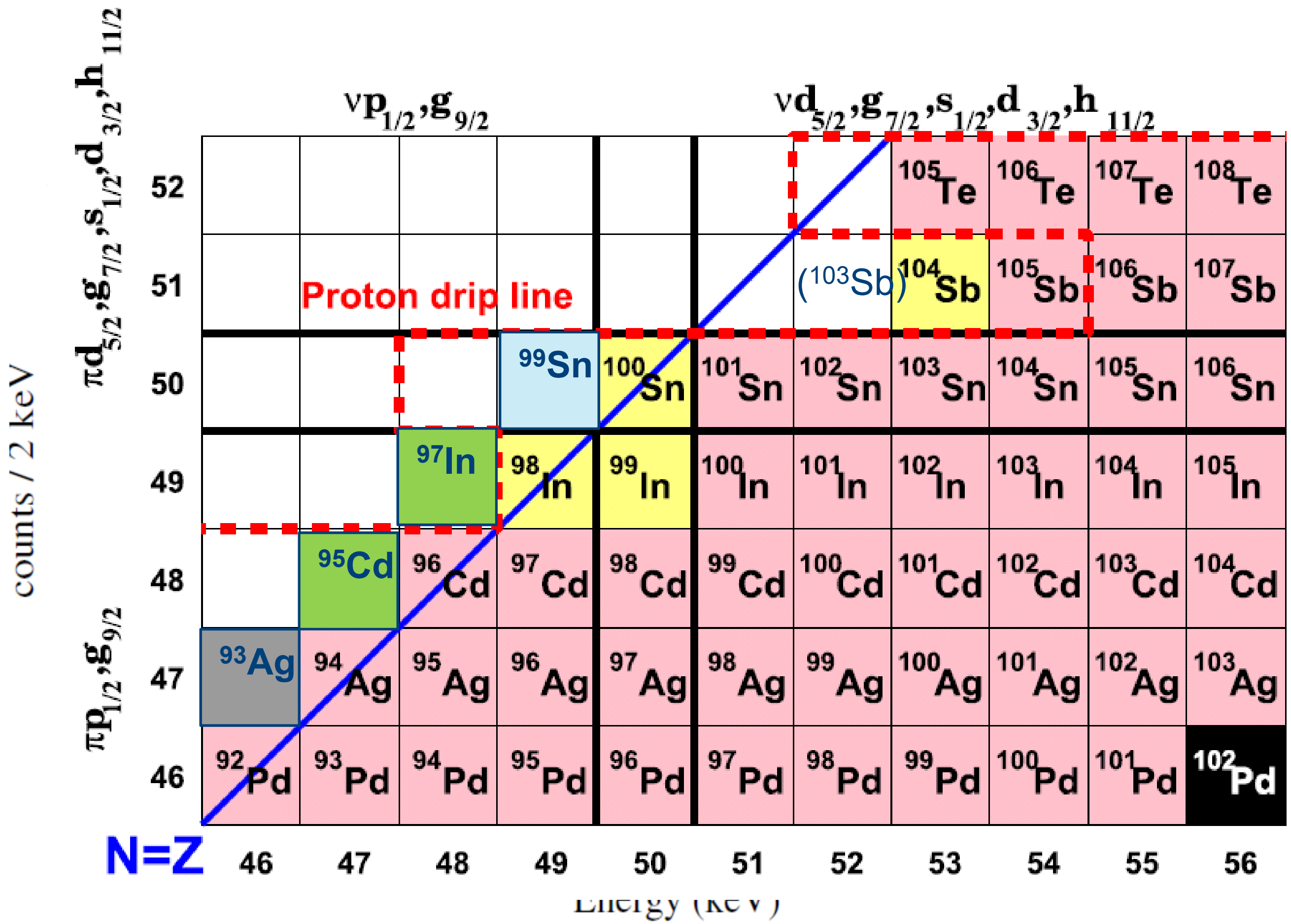
(Dobaczewski,- Phys. Rev. Lett. 72 (1994))

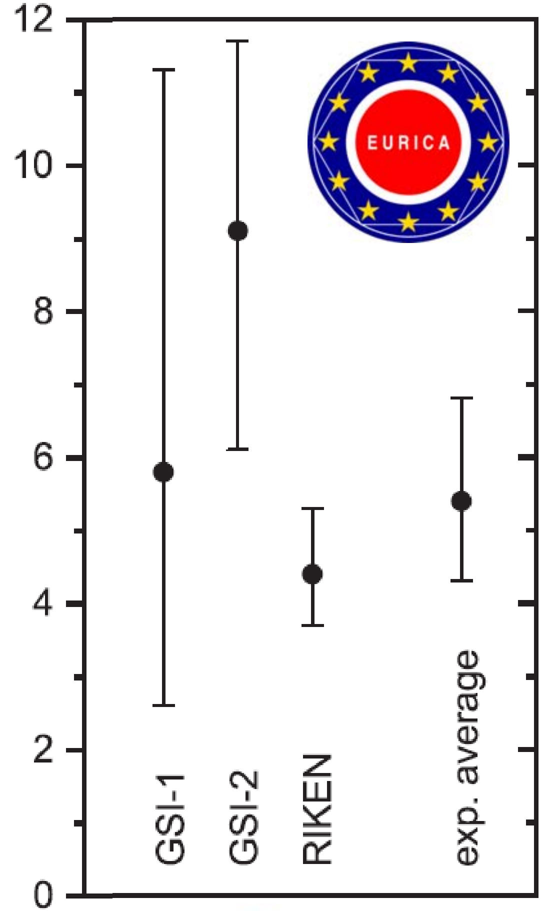
- Impact nuclear astrophysics (r-process nucleosynthesis)

- Challenges – increased production rate at FAIR Phase 0 Research Program

See: G. Martinez Pinedo

Gamow-Teller β decay of ^{100}Sn (Z,N=50)



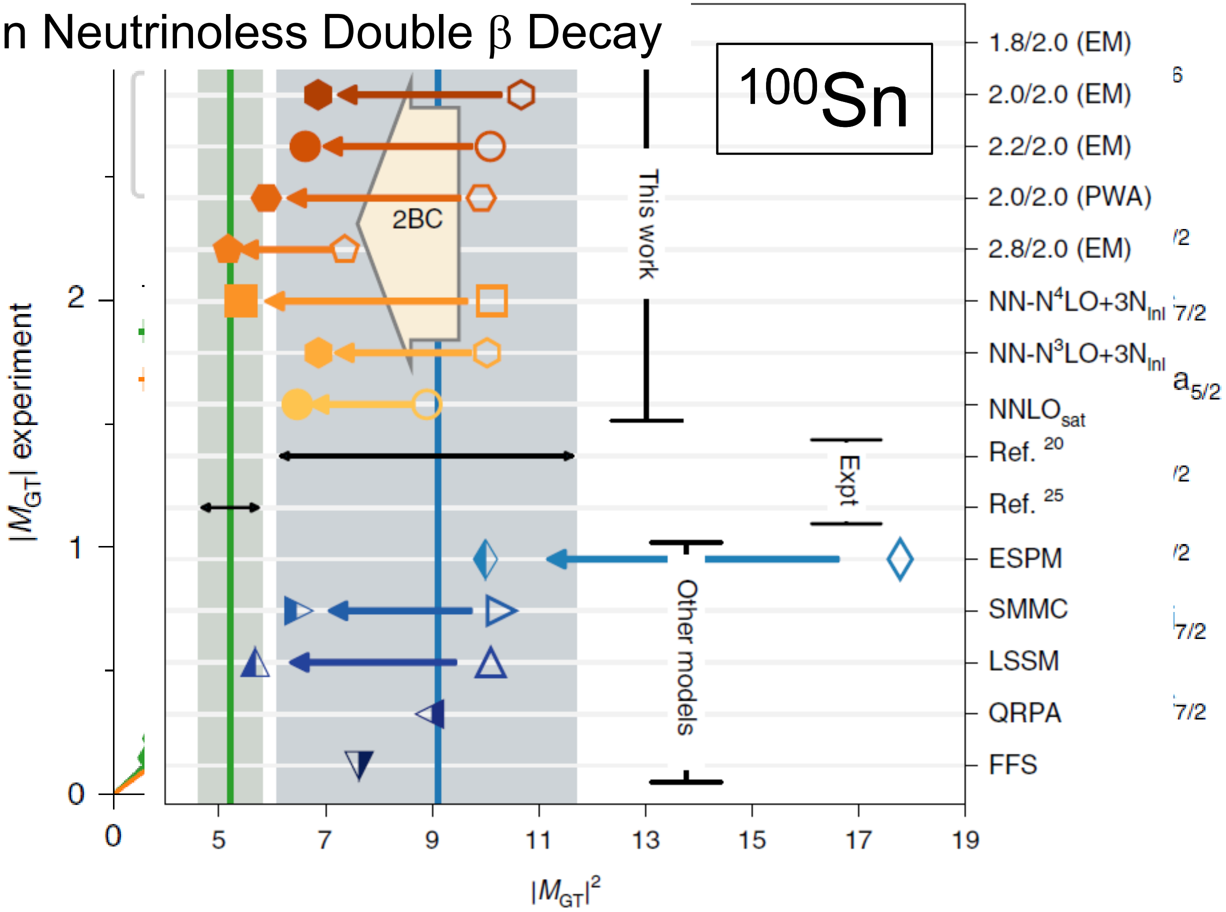


- Increased radioactive beam rates expected at:

Lubos,- PRL 122 (2019) – Gysbers,- Nature Physics (2019)

Gamow-Teller β decay of ^{100}Sn (Z,N=50)

- Discrepancy between experimental and theoretical β decay rates resolved from first principles (see e.g. Towner "Quenching of spin matrix elements in nuclei" Phys. Rep. 155 (1987)) → g_A (1,27) quenched ~ 0.75
- EFT based ab-initio calculations including maximum correlations and coupling of weak interactions via two-body currents (2BC)
- Impact on Neutrinoless Double β Decay

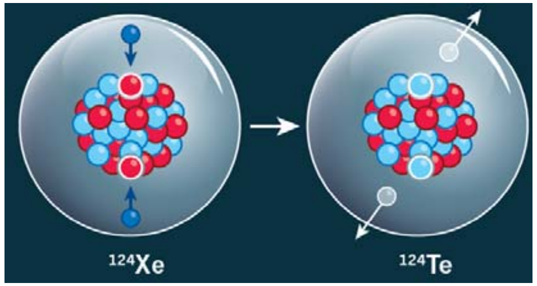


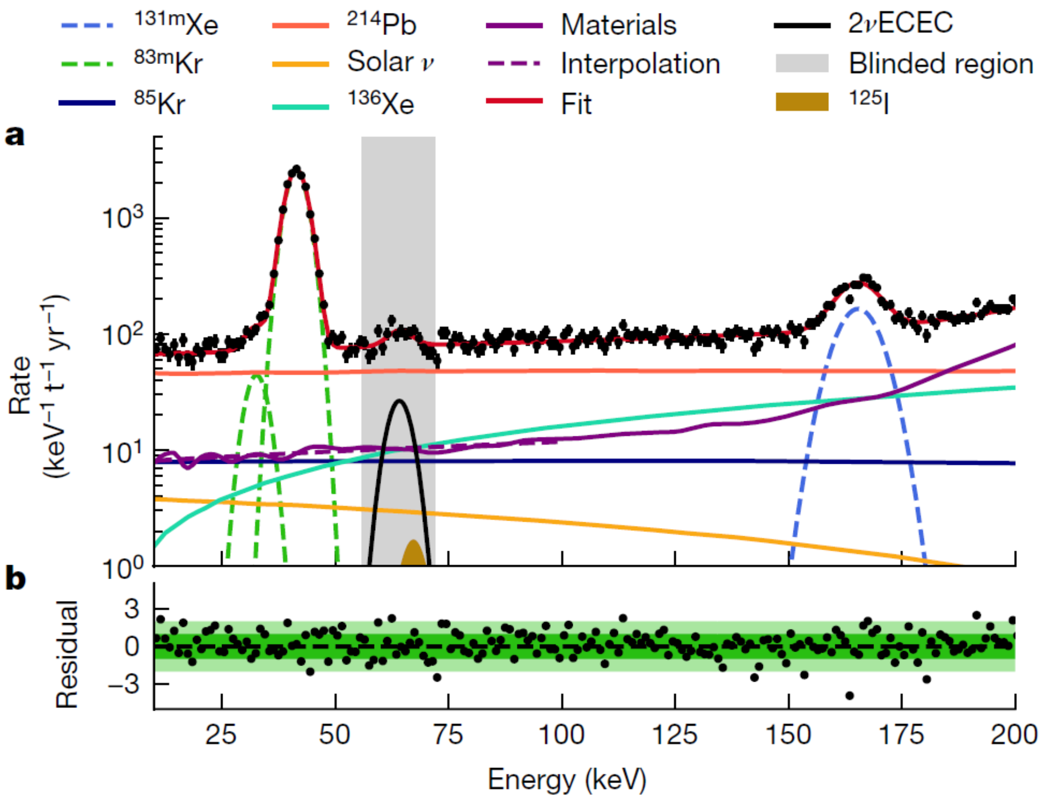
nature
International journal of science

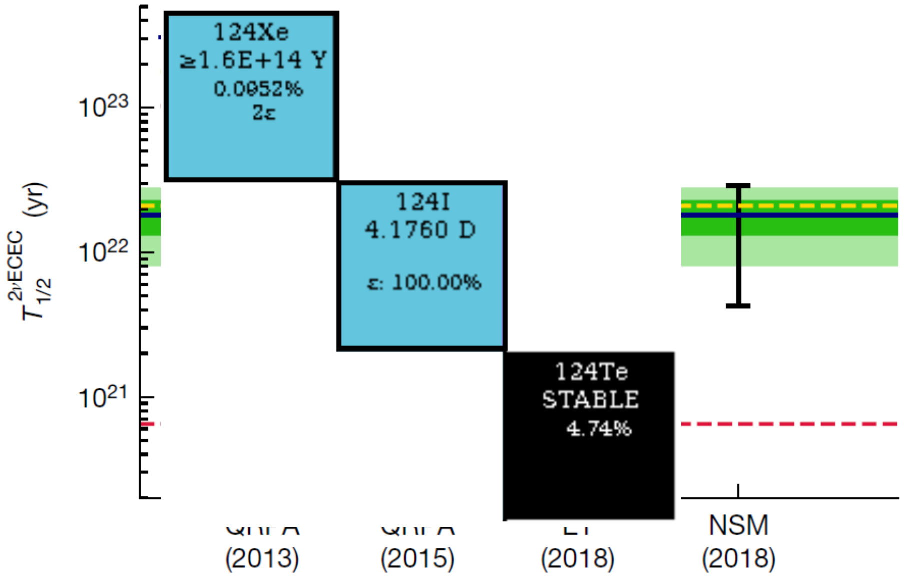
Letter | Published: 24 April 2019

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

XENON Collaboration*







- Proportional to the fourth power of the weak coupling constant
- Important step towards detecting neutrino-less double beta decay

"Status and future of nuclear matrix elements for neutrinoless double-beta decay: a review"
Engel,- Rep. Prog. Phys. 80 (2017)

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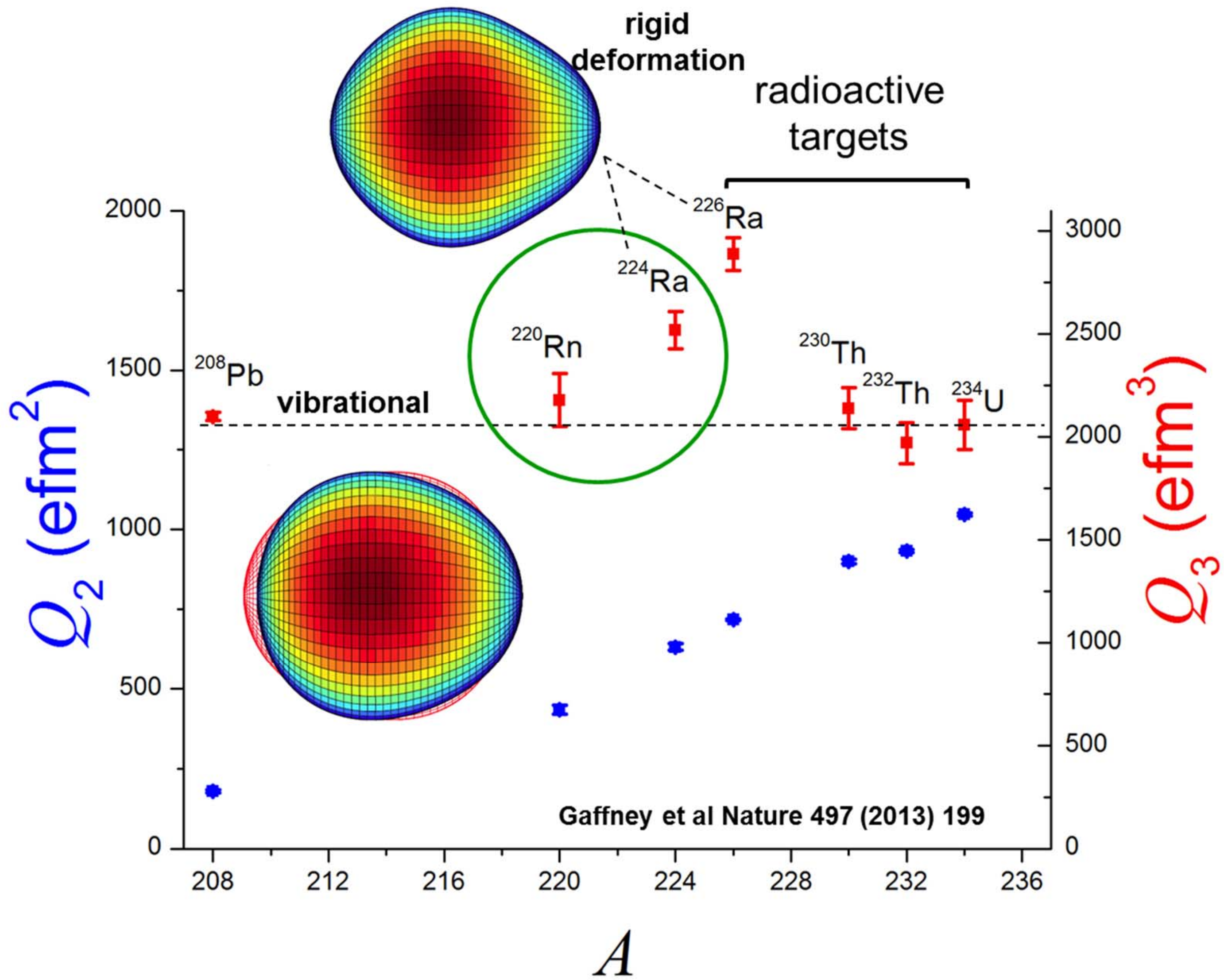
Pear-shaped nuclei at ISOLDE



Octupole enhanced atomic EDM

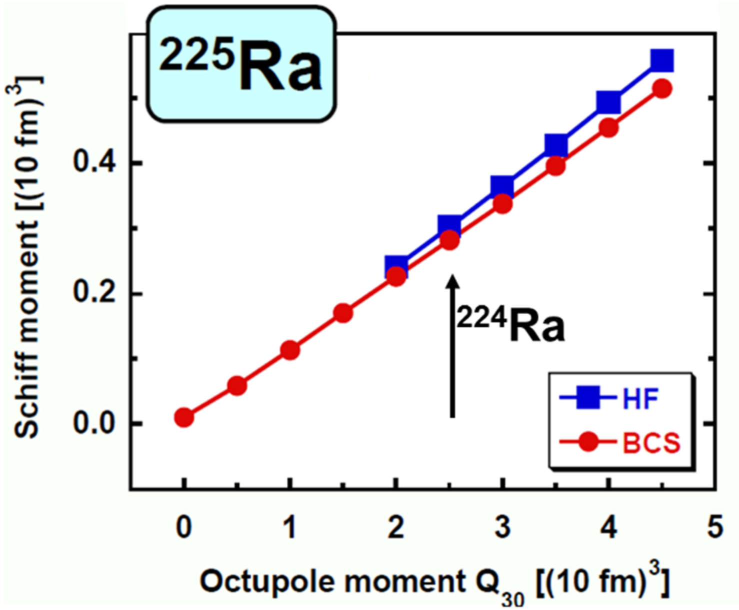
related to Q_3

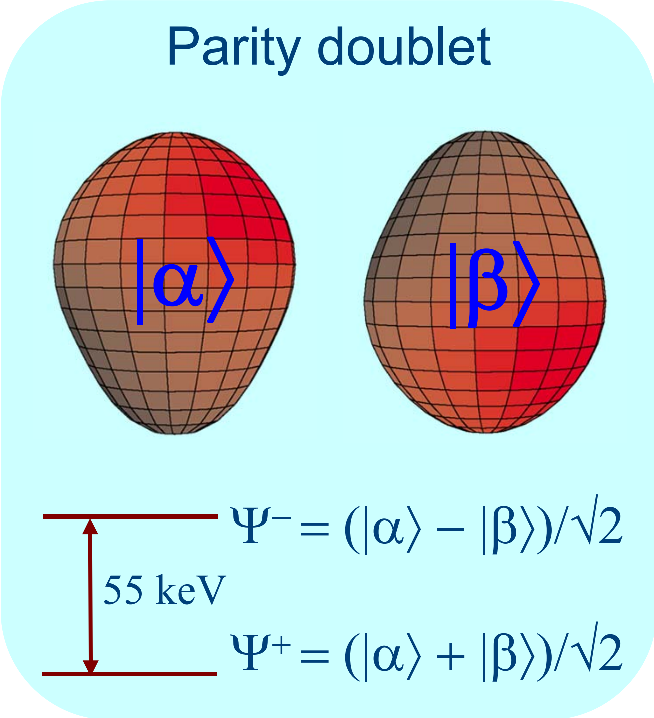
P,T-violating n-n interaction

Schiff moment: $$S = -2\frac{J}{J+1}\frac{<\hat{S}_z><\hat{V}_{PT}>}{\Delta E}$$

$I = ½$

$t_{1/2}$ = 15 d





See: N. Severijns

Shiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nucleir

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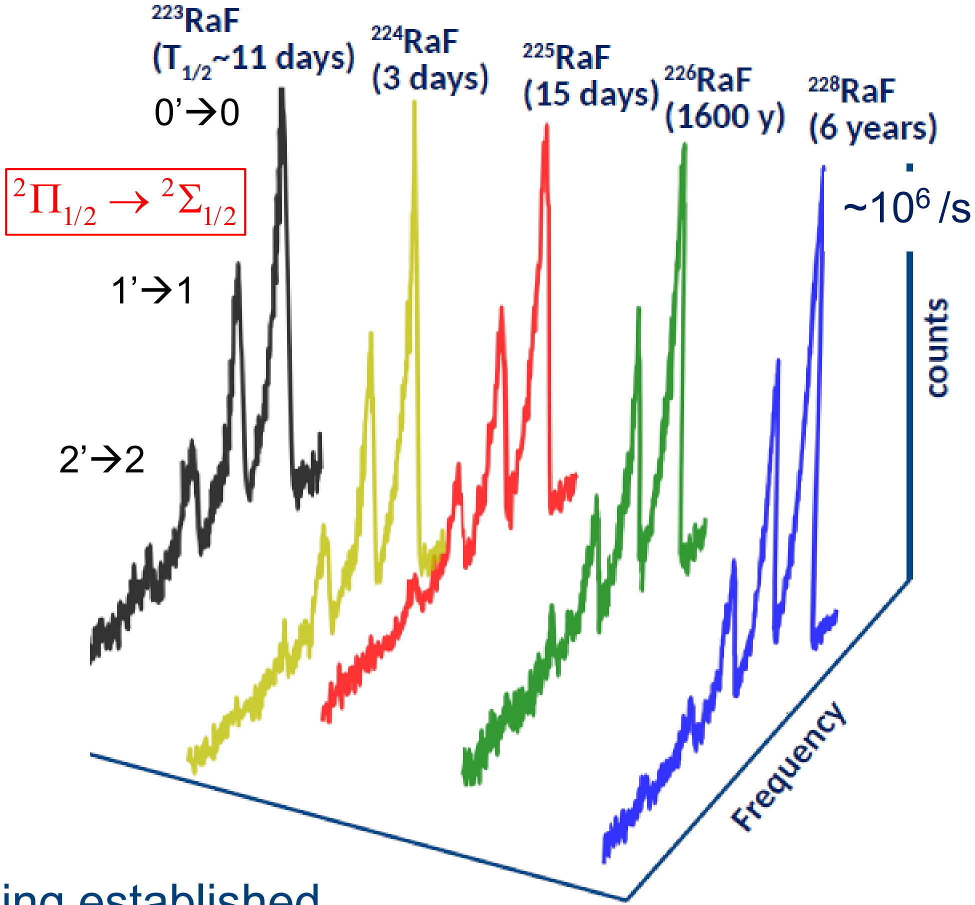
Dobaczewski,- Phys. Rev. Lett. (2018)

^{225}Ra Atom Traps (ANL - Parker,- PRL (2015))
Radium fluoride (RaF) spectroscopy

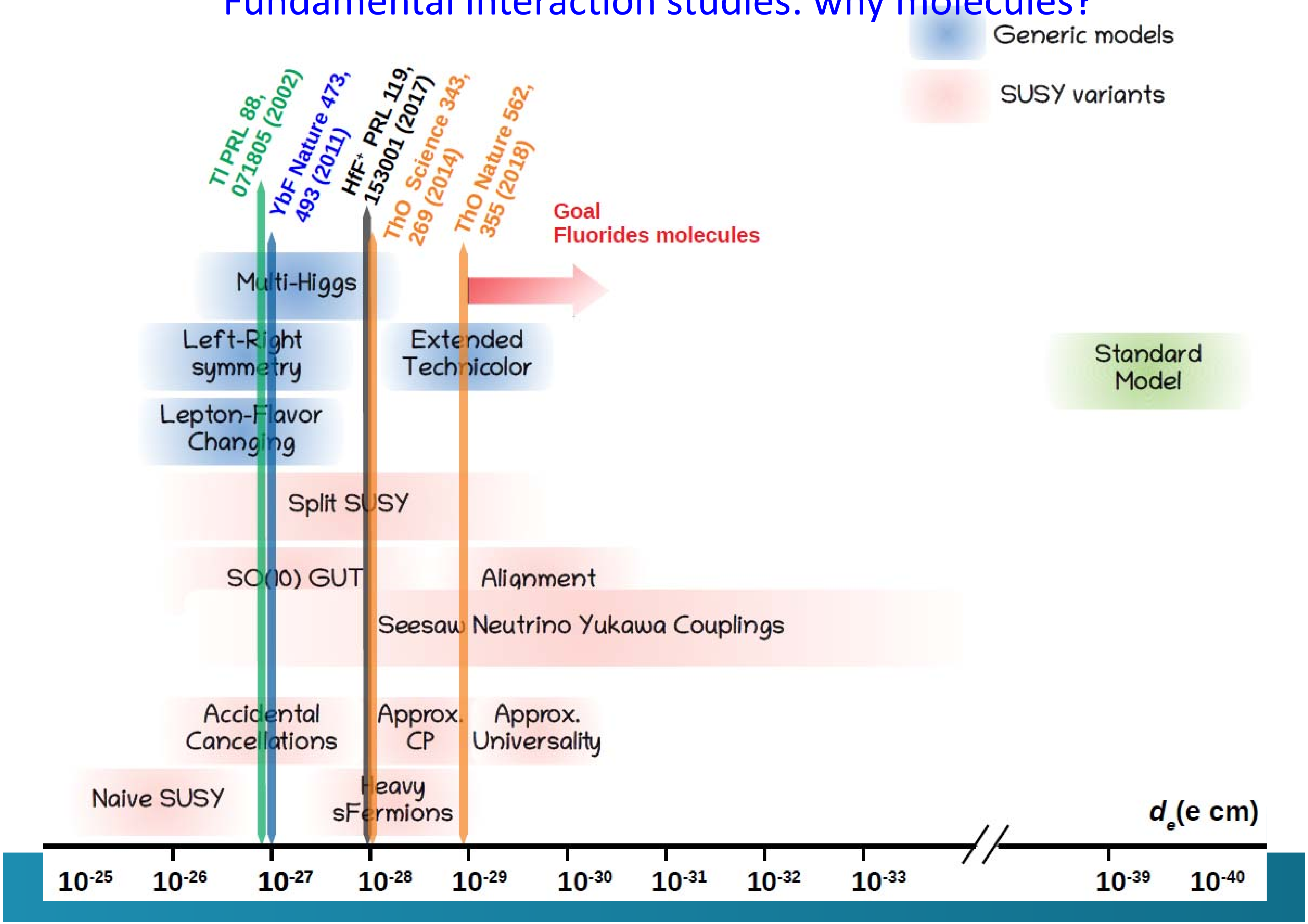


First Experimental Spectroscopy

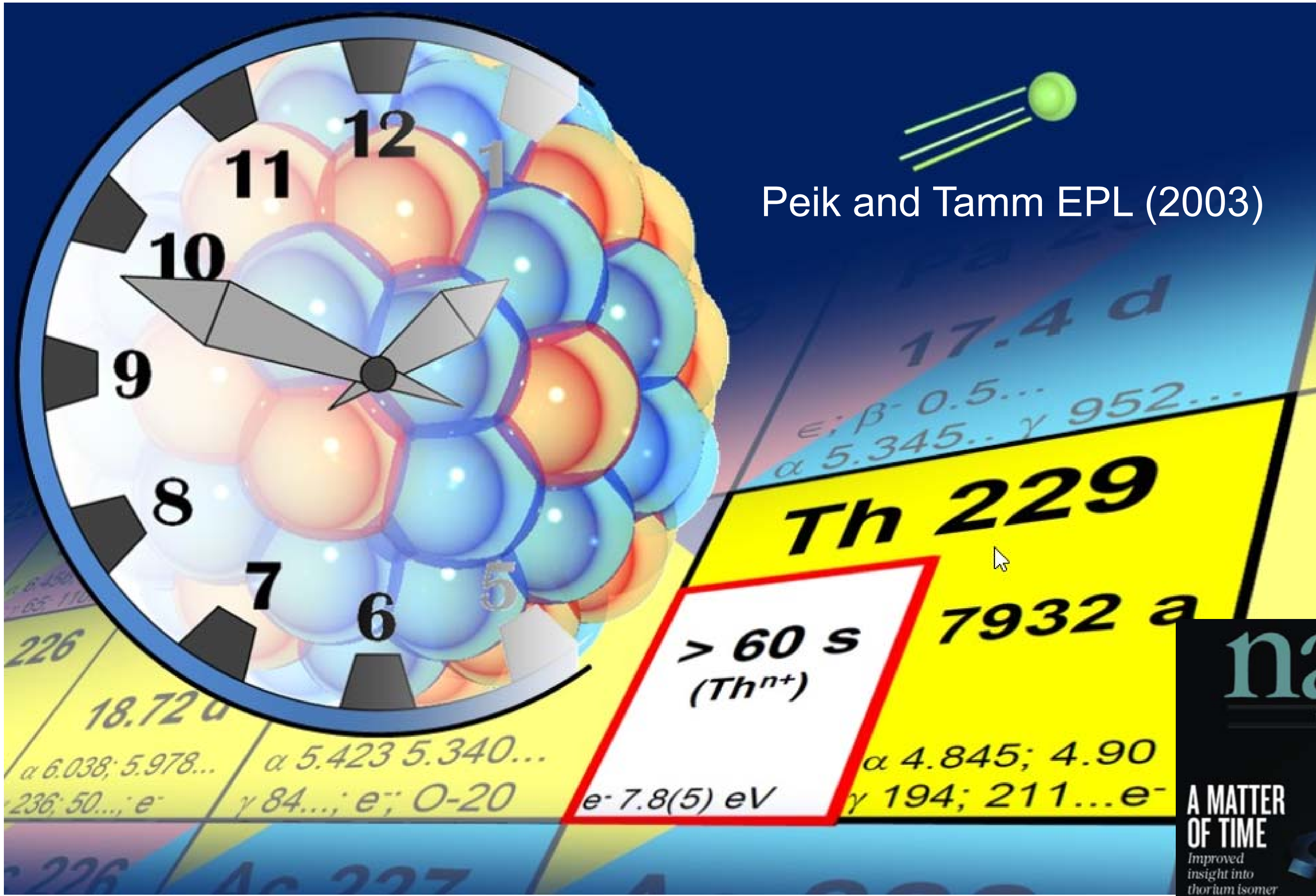
➔ Transitions observed

➔ Suitable scheme for laser cooling established

Fundamental Interaction studies: why molecules?

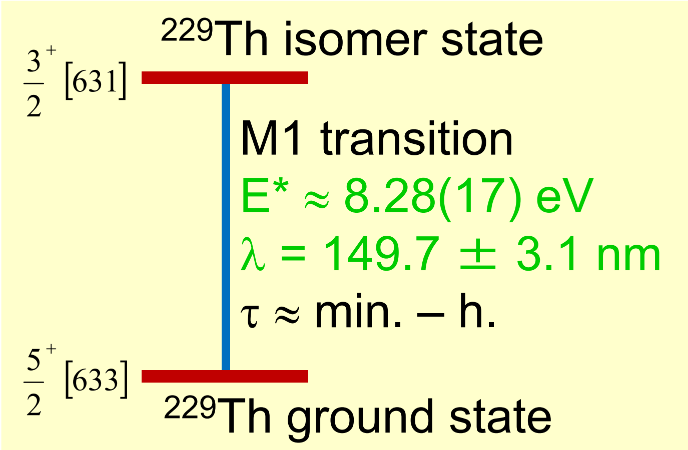


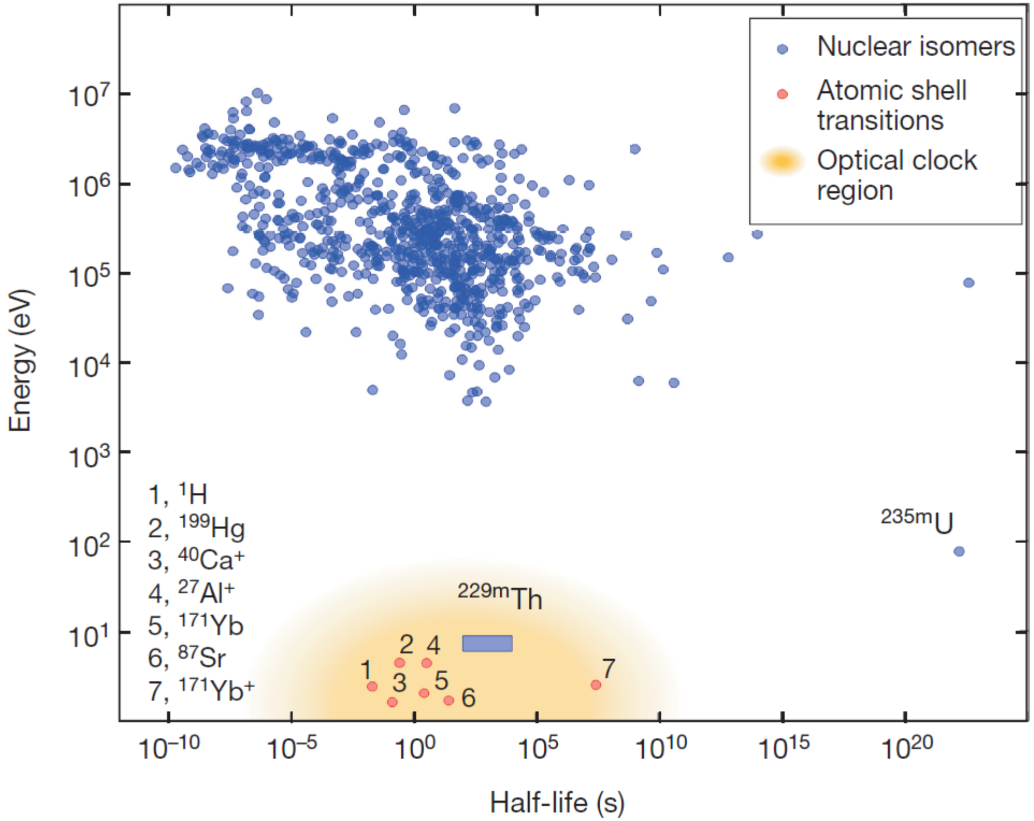
The ^{229m}Th Isomer – towards a Nuclear Clock



Unique properties of the ^{229m}Th Isomer

- Bridge between nuclear physics / atomic physics / laser physics/ metrology / solid state physics





→ $\Delta E/E \sim 10^{-20}$: extremely stable nuclear frequency standard: 'nuclear clock'

- Applications of an ultra-precise clock (Peik and Tamm EPL (2003)):
  - Improved precision of satellite-based navigation
  - Search for time variation of fundamental constants (Flambaum,- PRL (2006))
  - 3D gravity sensor ('relativistic geodesy') (Mehlstäubler,- Rep. Prog. Phys. (2018))

Recent Progress on the ^{229}Th isomer

- Existence of ^{229m}Th: first direct detection via IC decay — von der Wense,- Nature 533 (2016)
- Half-life of neutral ^{229m}Th: $t_{1/2}$ = 7 µs → $\alpha_{IC} \sim 10^9$ — Seiferle,- Phys. Rev. Lett. 118 (2017)
- Hyperfine structure of ^{229m}Th — Thielking,- Nature 556 (2018)
- Isomeric excitation energy: — Seiferle,- Nature 573 (2019)

$\boxed{E^* = 8.28 \pm 0.17 \text{ eV} \rightarrow \lambda = 149.7 \pm 3.1 \text{ nm}}$

- Improved isomer population schemes:

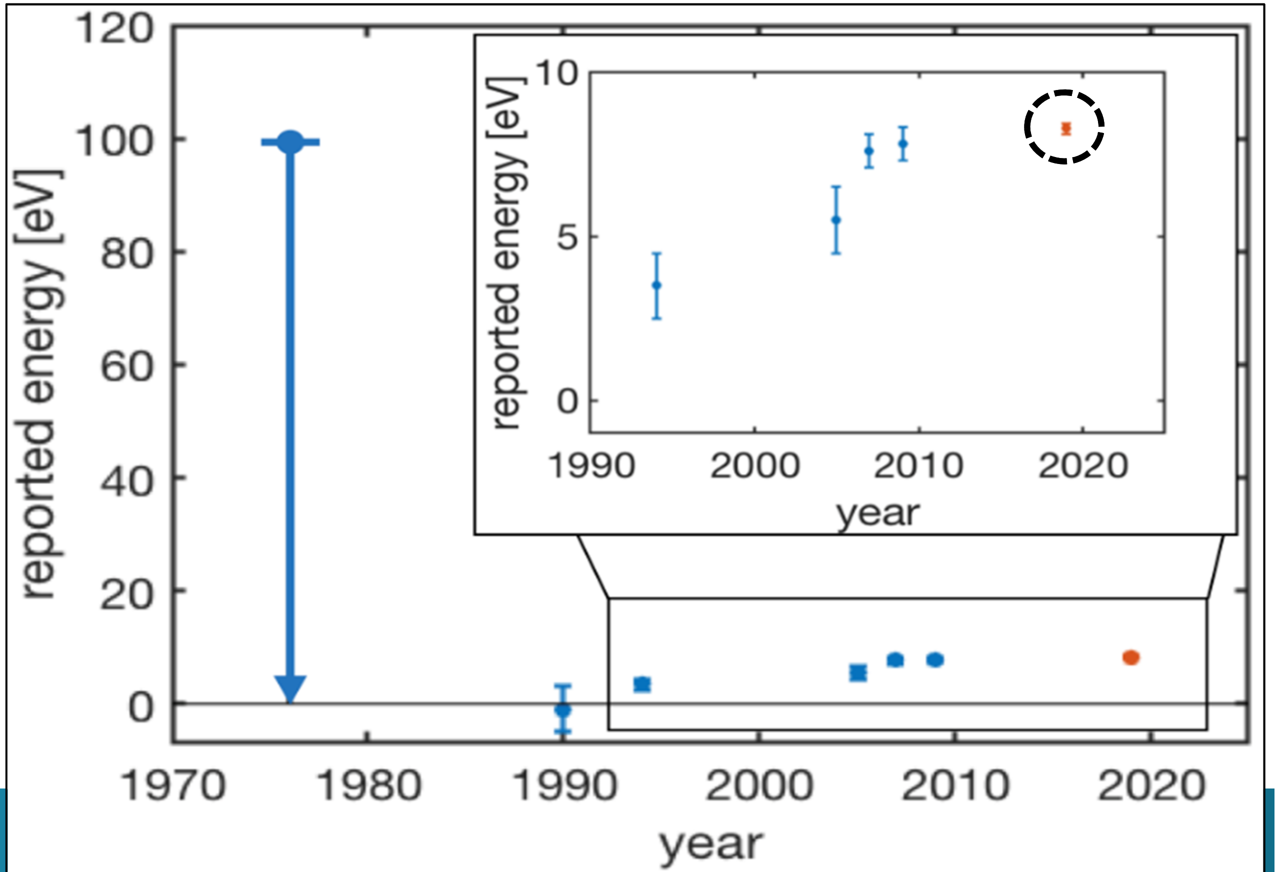
→ X-ray pumping of 2nd excited state

Masuda,- Nature 573 (2019)

→ via β decay from ^{229}Ac

Verlinde,- PRC (2019)

- Challenges: observation of the radiative decay
- The door is open for the realization of a first nuclear clock



Courtesy: P. Thirolf - Munich

What is known about the heaviest elements?

New elements / names (2016)

89-103 actiniden	rutherfordium 104 Rf	dubnium 105 Db	seaborgium 106 Sg	bohrium 107 Bh	hassium 108 Hs	meitnerium 109 Mt	darmstadtium 110 Ds	roentgenium 111 Rg	copernicium 112 Cn	nihonium 113 Nh	flerovium 114 Fl	moscovium 115 Mc	livermorium 116 Lv	tennessine 117 Ts	oganesson 118 Og

Chemistry: Cn (Z=112)
A. Turler,- NPA 944 (2015)

lanthaan 57 La 138,9	cerium 58 Ce 140,1	praseod 59 P 140,9	144,2		150,4	152,0	olinium 64 Gd 157,3	terbium 65 Tb 158,9	dysprosium 66 Dy 162,5	holmium 67 Ho 164,9	erbium 68 Er 167,3	thulium 69 Tm 168,9	ytterbium 70 Yb 173,1	lutetium 71 Lu 175,0
actinium 89 Ac	thorium 90 Th 232,0	protactinium 91 Pa 231,0	uranium 92 U 238,0	neptunium 93 Np	plutonium 94 Pu	americium 95 Am	curium 96 Cm	berkelium 97 Bk	californium 98 Cf	einsteinium 99 Es	fermium 100 Fm	mendelevium 101 Md	nobelium 102 No	lawrencium 103 Lr

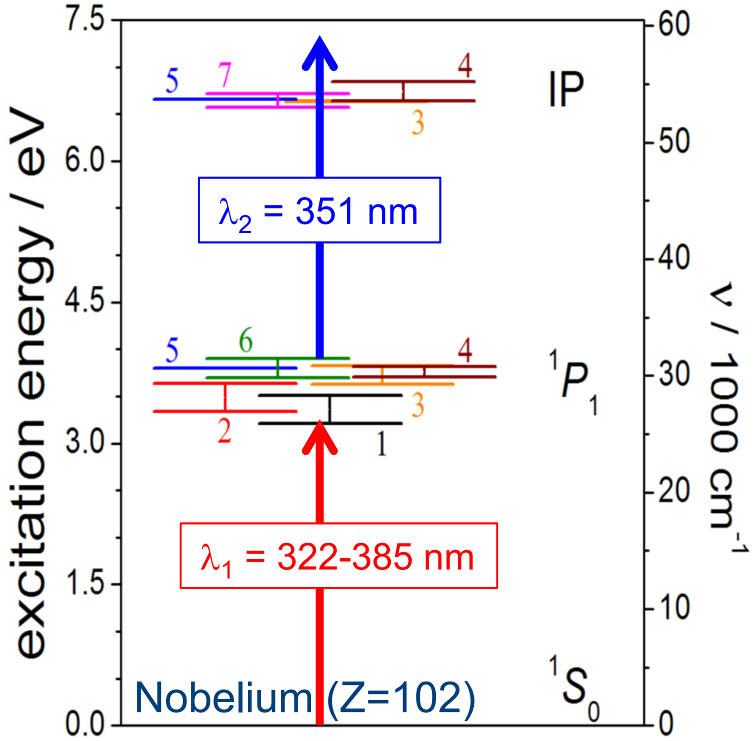
Atomic physics: No (Z=102)
M. Laatiaoui,- Nature (2016)

Atomic physics: IP Lr
Sato,- Nature (2015)

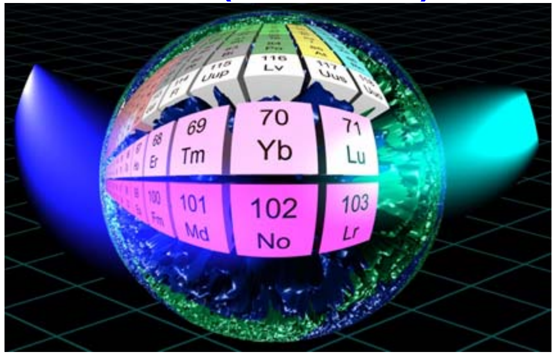
→ Laser spectroscopy in the heavy element region

Atomic observables: levels, transition strengths, IP
Nuclear observables: I, μ, Q, Isotope Shift → $\delta\langle r^2\rangle$

Atomic levels and Ionization potential: nobelium (Z=102)
"one atom at a time"



Atomic ground state: $[Rn]5f^{14}7s^2\ ^1S_0$



- Zα → 1: large QED contribution & relativistic effects in the electronic structure
- Strong electron correlations
- Benchmark predictive power of atomic theory
- Ionization potential (IP) → chemical properties
- Determination of nuclear properties

Model calculations

1, 2 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15
3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514
4 (RCC): V.A.Dzuba et al., Phys. Rev. A 90 (2014) 012504
5 (MCDF): Y.Liu et al., Phys. Rev. A 76 (2007) 062503
6 (MCDF): P.Indelicato et al., Eur. Phys. J. D 45 (2007) 155
7 (extrapolation): J.Sugar, J. Chem. Phys. 60 (1974) 4103

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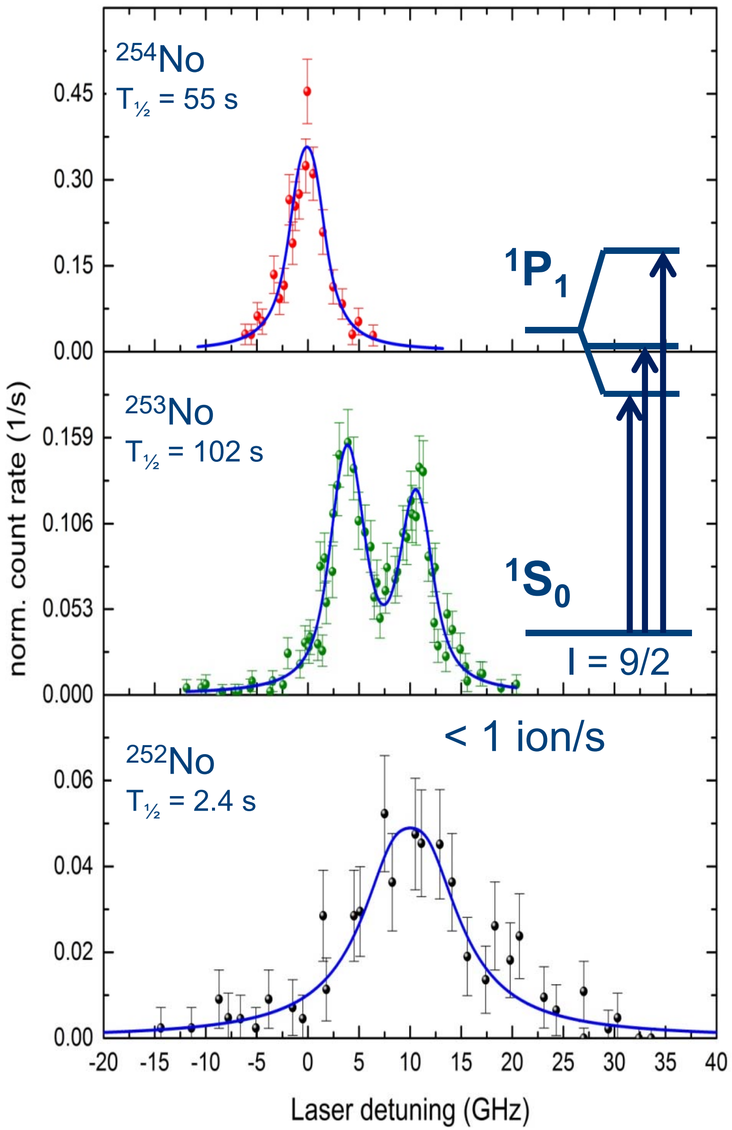
Courtesy: S. Raeder, M. Laatiaoui

Laser ionization spectroscopy of ^{252,253,254}No



- Theory-guided search for the atomic transition

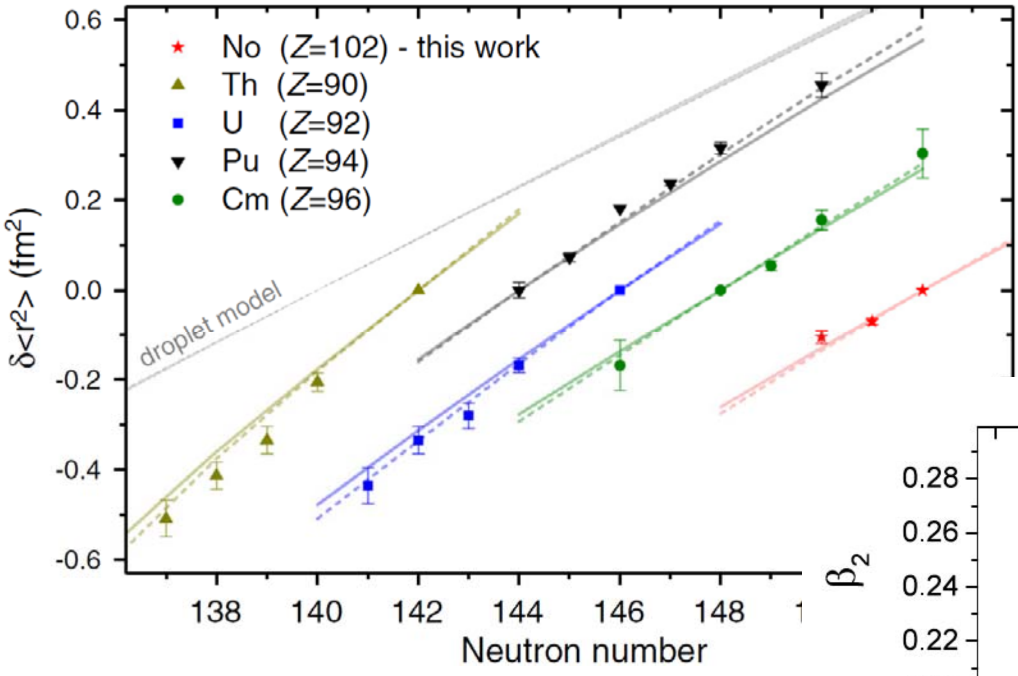
	ν_1 (cm^{-1})	A_{ki} (s^{-1}) x 10^8
Experiment	29,961.457(7)$_{stat}$	4.2 (2.6)$_{stat}$
IHFSCC [3]	30,100(800)	5.0
MCDF [6]	30,650(800)	2.7

	IP (cm^{-1})	$^3D_3$
Experiment	53444,0 (4)	29652 (+8/-1)
IHFSCC [1]	53489 (800)	29897 (800)

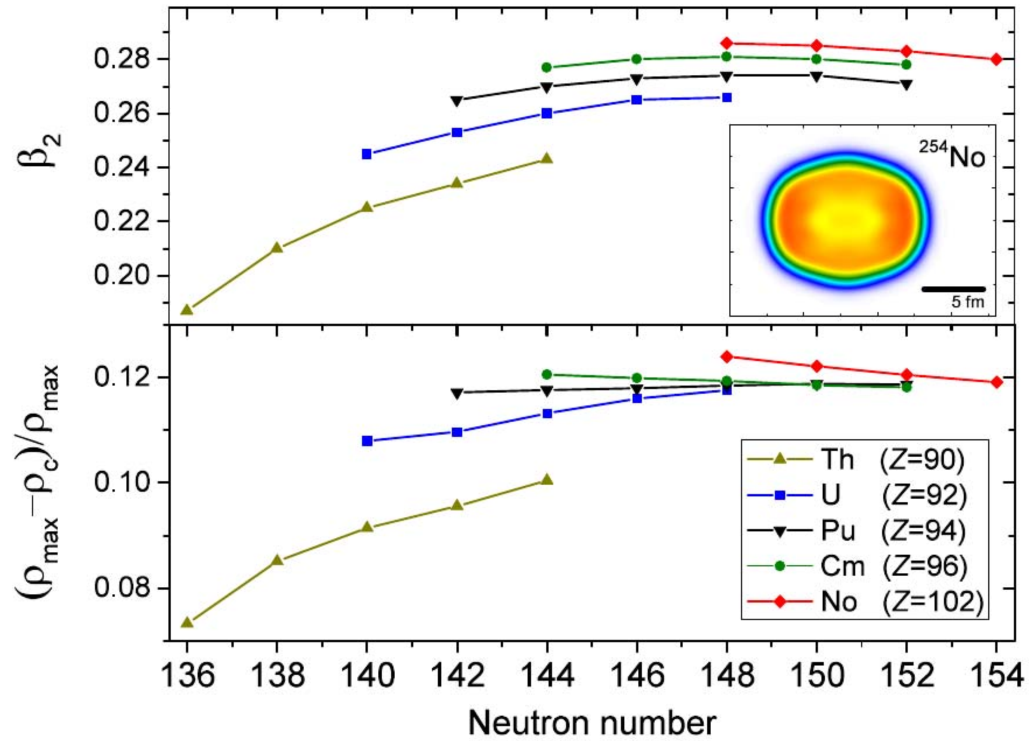
Laatiaoui,- Nature 538 (2016), Raeder,- PRL120 (2018), Chhetri,- PRL120 (2018)

Laser ionization spectroscopy of ^{252,253,254}No

- Isotope shift for $^{252\text{-}254}$No measured → change in charge radii: input from atomic theory

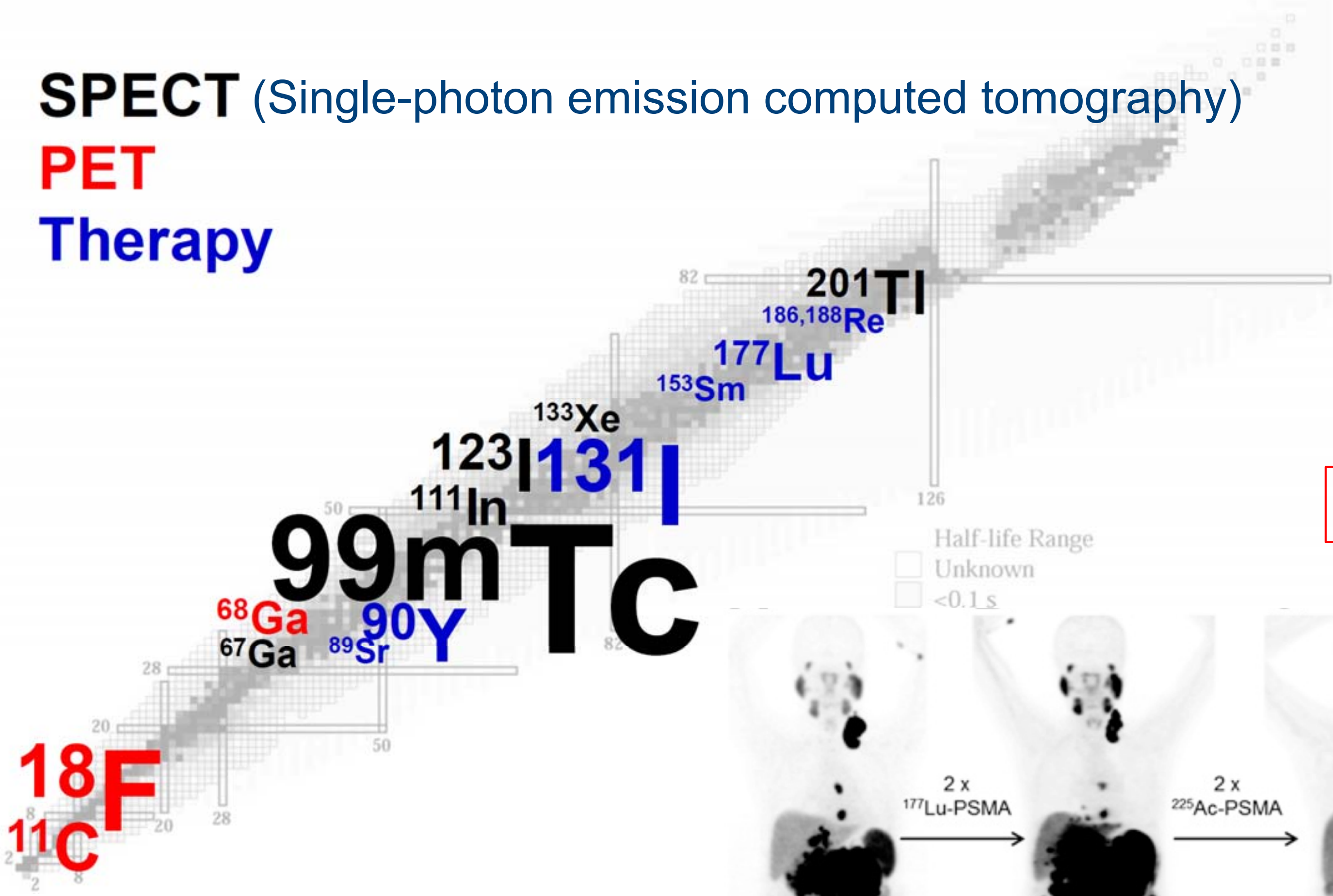


- Deformation from DFT calculations: Coulomb frustration

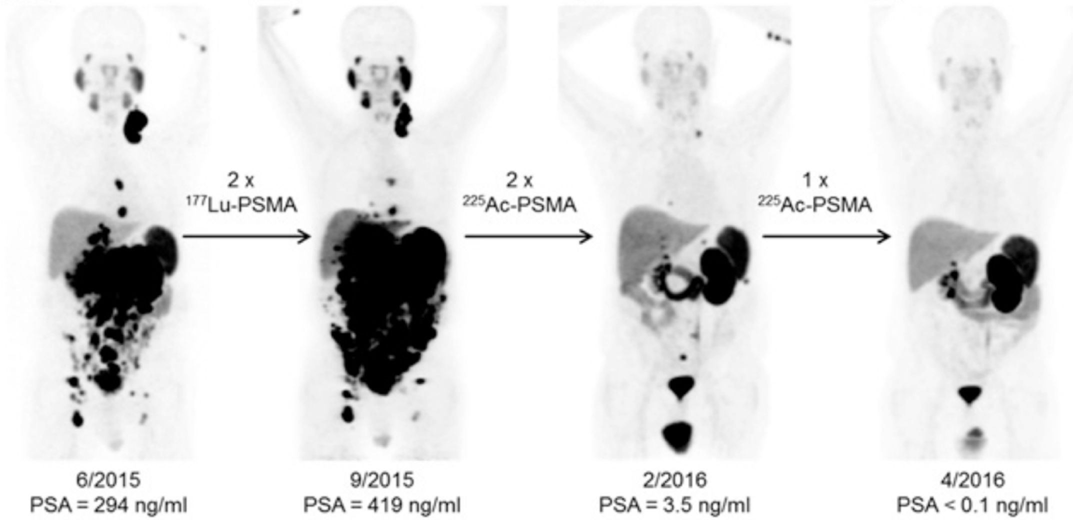


Laatiaoui,- Nature 538 (2016), Raeder,- PRL120 (2018), Chhetri,- PRL120 (2018)

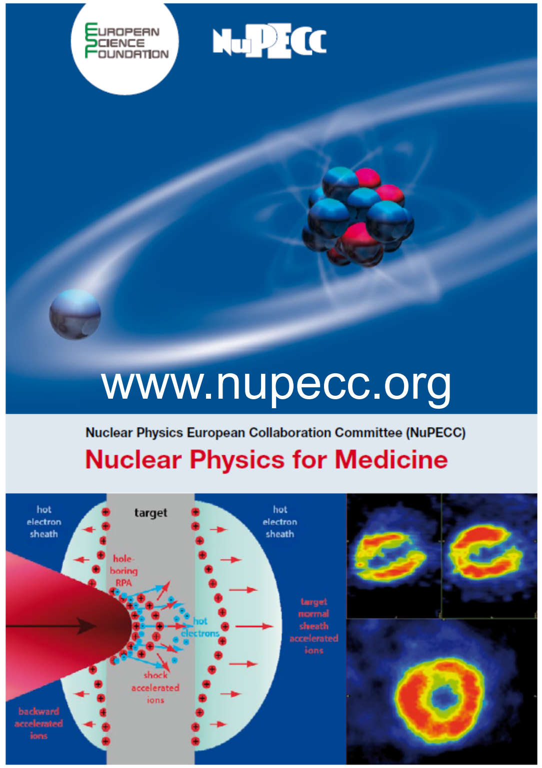
The Chart of Nuclides – Nuclear Medicine Perspective



See: M. Durante

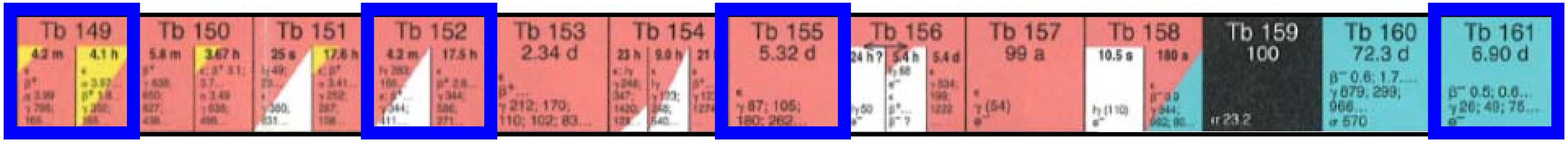


- Innovative radioisotopes for Medicine
  - Terbium: a unique element for nuclear medicine



α ($T_{1/2}$=4.1 h)

γ ($T_{1/2}$=5.32 d)



β^+/EC($T_{1/2}$=17.5 h)

β^- ($T_{1/2}$=6.9 d)

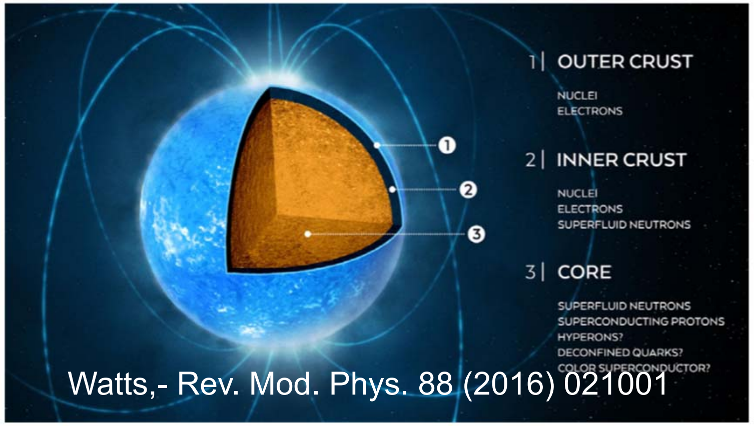
courtesy U. Köster

Conclusion and Outlook

- A limited number of highlights tailored to this symposium were shortly presented, covering different aspects of nuclear-physics research

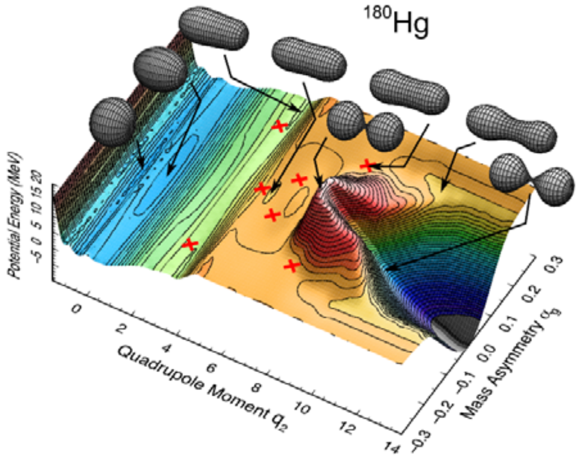
Not included:

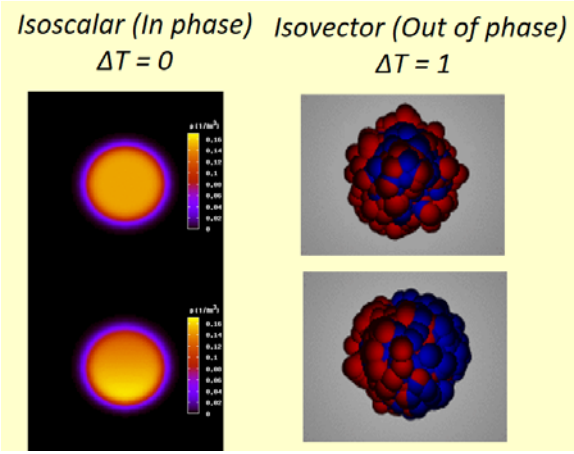
➢ EOS of neutron-rich nuclei and neutron stars



Watts,- Rev. Mod. Phys. 88 (2016) 021001

➢ Developments in fission modeling





➢ Low-momentum transfer hadronic probes

(nuclear matter distributions, Giant Monopole Resonances,…)

➢ ……

Conclusion and Outlook

- Ab-initio models are progressing fast and will have a strong impact on the predictability of nuclear properties

- Upcoming facilities (and upgrades) like e.g. FAIR, SPIRAL2, HIE-ISOLDE, SPES, MYRRHA, … and developments/improvements of instrumentation is boosting the field (see M. Lewitowicz)

- Nuclear-physics research is a multi-facetted research area reaching out to many different field of science and applications

- Thanks to G. Neyens, R. Garcia Ruiz, M. Laatiaoui, S. Raeder, W. Nörtershäuser, K. Blaum, I. Moore, N. Kalantar, T. Aumann, A. Obertelli, P. Thirolf, Th. Duguet, V. Soma, S. Goriely, W. Nazarewicz,…