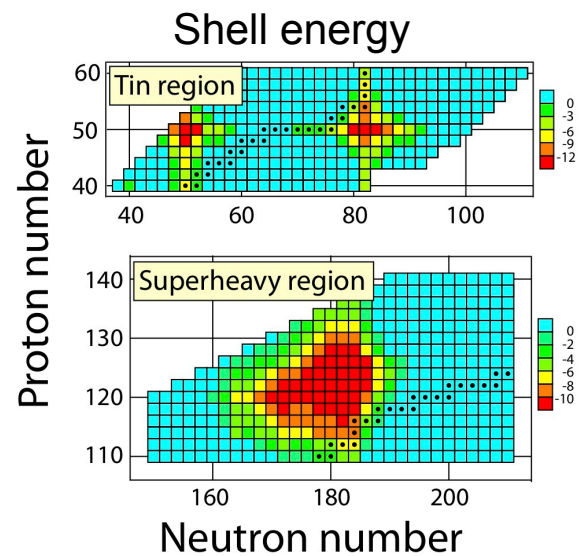
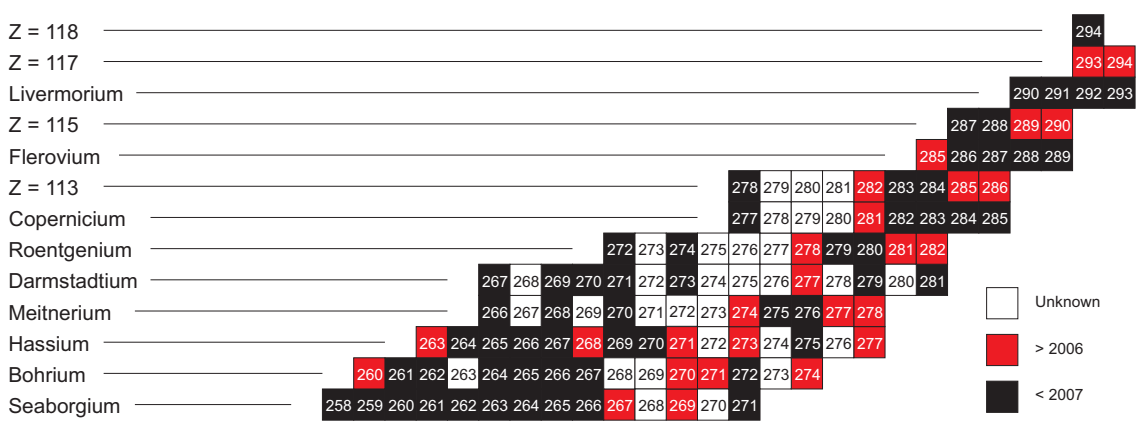
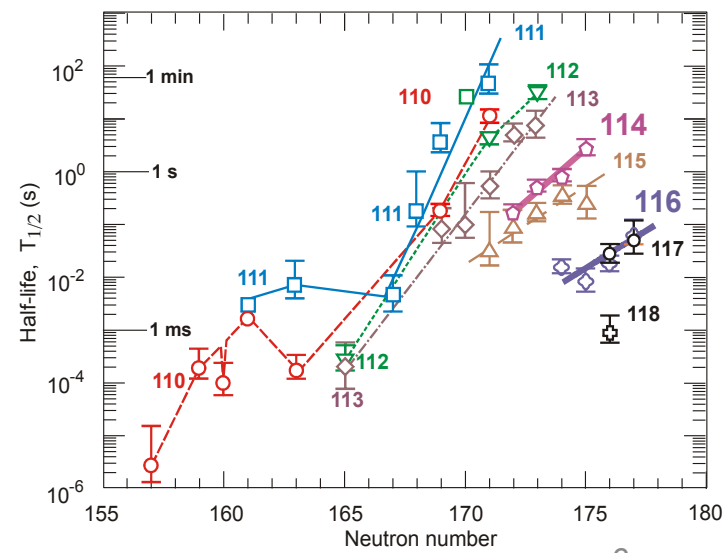
What are the limits of atoms and nuclei? Do very long-lived superheavy nuclei exist in nature?

Structure of nuclei at the limit of mass and charge (Coulomb frustration)
Cosmic origin of superheavy nuclei?
Very relativistic atoms with $Z\alpha \rightarrow 1$

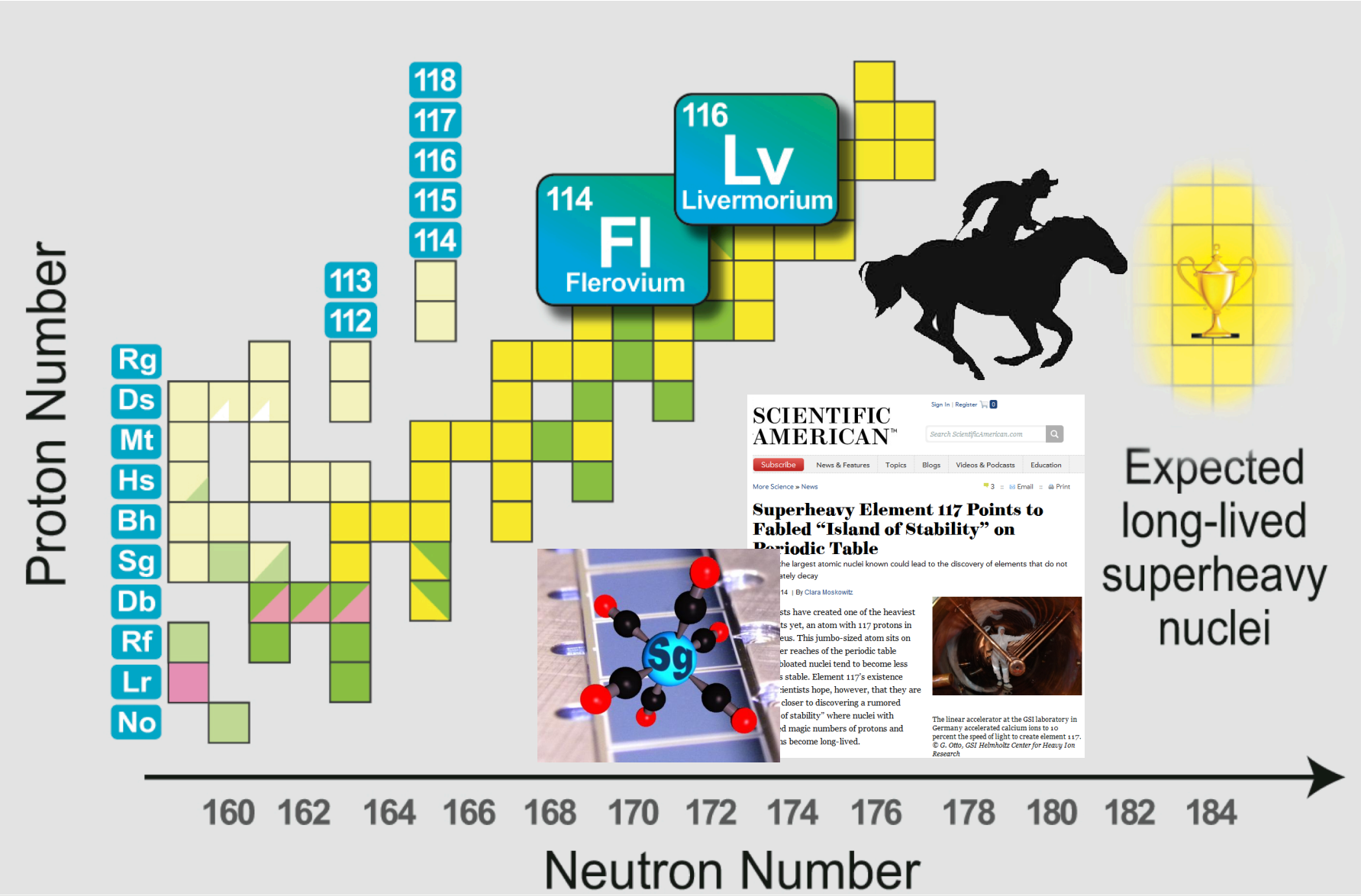
- Around 30 new superheavy isotopes found since 2007
- Z=114 (Fl) and 116 (Lv) named
- Z=117, 115 confirmed
- Unique spectroscopic data above Z>102
- Chemistry of Z=106, 114







The Quest: Towards long-lived superheavy nuclei

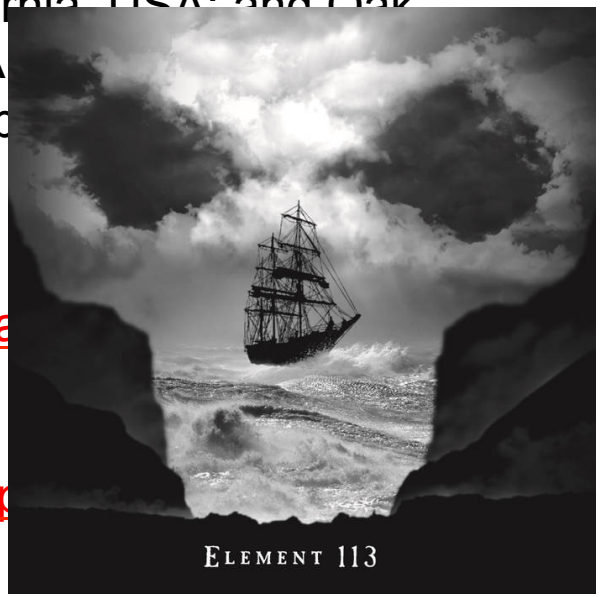


Four elements earn permanent seats on the periodic table

IUPAC announcement (Dec. 30, 2015):
http://www.iupac.org/news/news-detail/article/discovery-and-assignment-of-elements-with-atomic-numbers-113-115-117-and-118.html

Element 113 (temporary working name and symbol: ununtrium, Uut)
The RIKEN collaboration team in Japan have fulfilled the criteria for element *Z*=113 and will be invited to propose a permanent name and symbol.

Elements 115, 117, and 118 (temporary working names and symbols: ununpentium, Uup; ununseptium, Uus; and ununoctium, Uuo)
The collaboration between the Joint Institute for Nuclear Research in Dubna, Russia; Lawrence Livermore National Laboratory, Californ
Ridge National Laboratory, Oak Ridge, Tennessee, USA
criteria for element *Z*=115, 117 and will be invited to prop
and symbols.

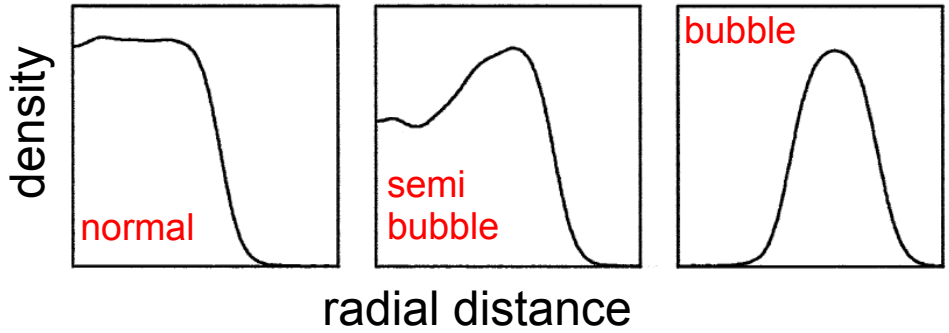


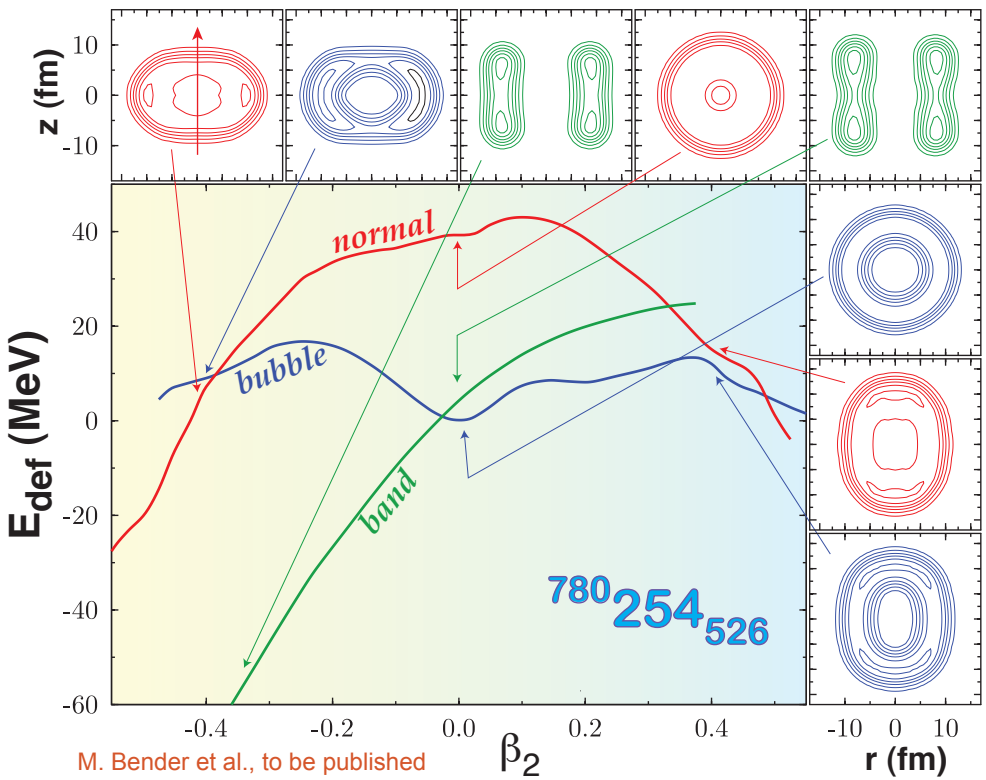
https://www.inverse.com/article/9768-four-elements-are-a
the-periodic-table

https://www.sciencenews.org/article/four-elements-earn-p
periodic-table

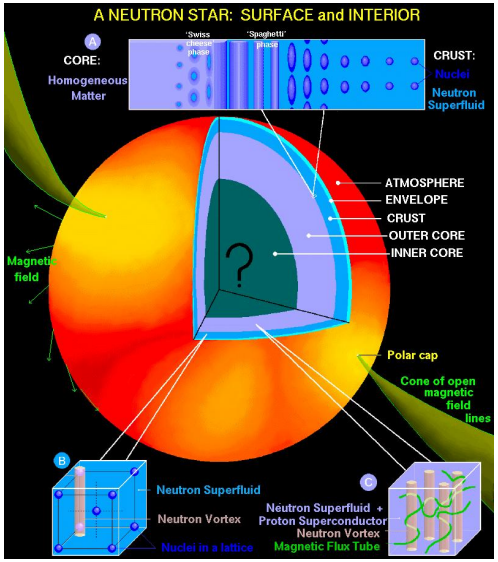
Exotic topologies of superheavy nuclei: Coulomb frustration

Battle between long-range (Coulomb) and short-range (nuclear) interactions





M. Bender et al., to be published



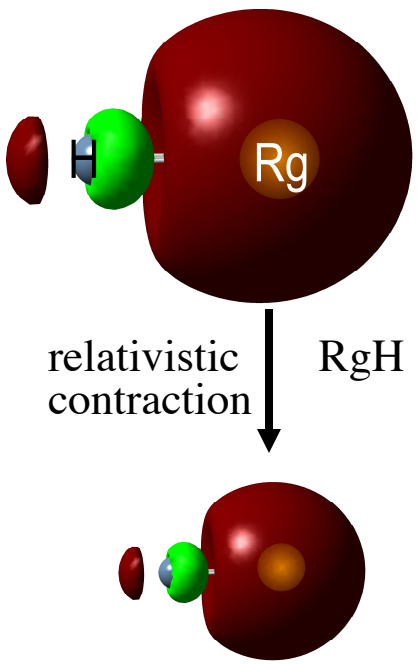
Self-consistent calculations confirm the fact that the "pasta phase" might have a rather complex structure, various shapes can coexist, at the same time significant lattice distortions are likely and the neutron star crust could be on the verge of a disordered phase.

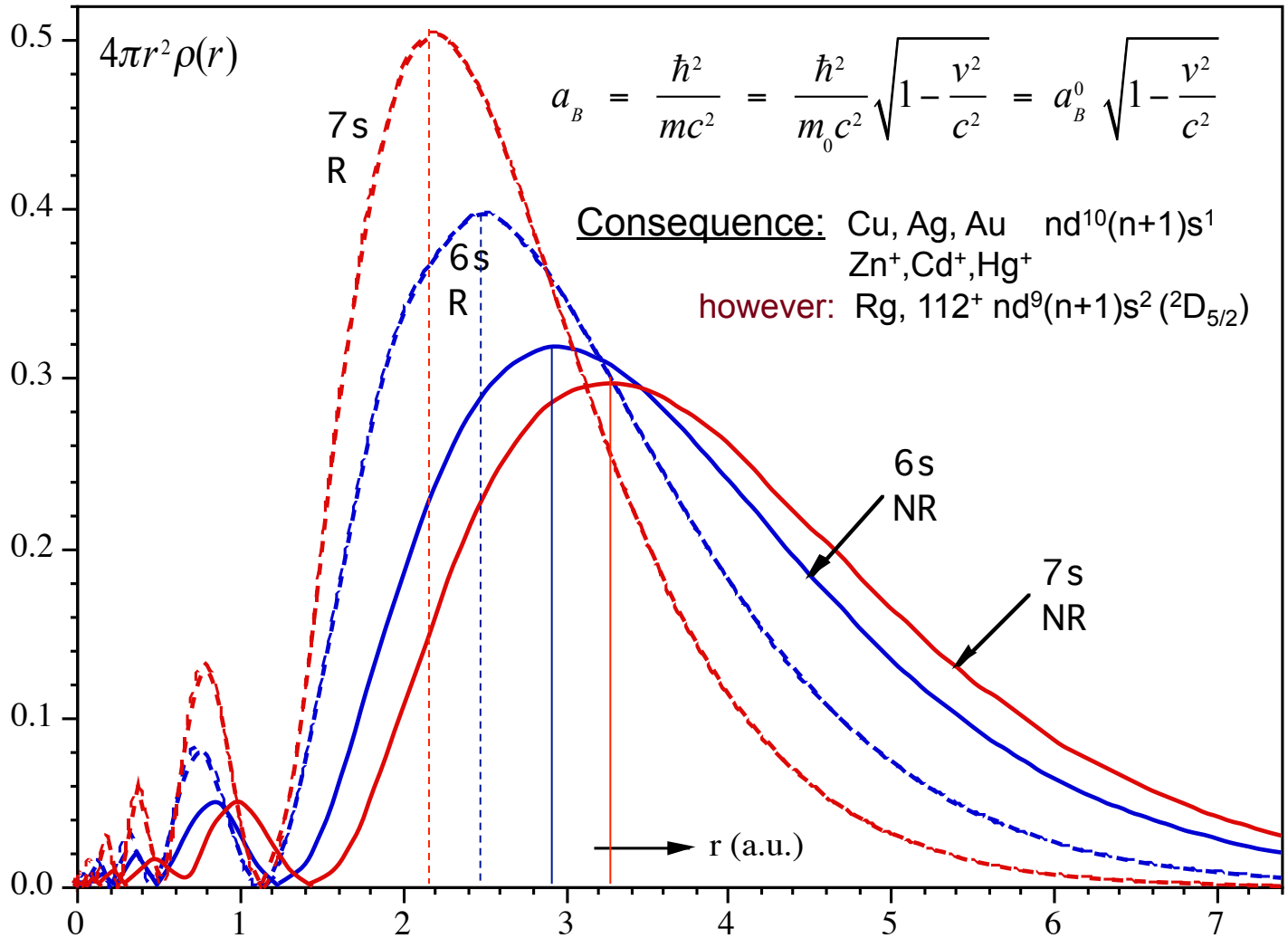
A challenge is to assess stability of such forms

What are chemical properies of superheavy elements?

Courtesy of Peter Schwerdtfeger

The relativistic 7s contraction in Au and Rg



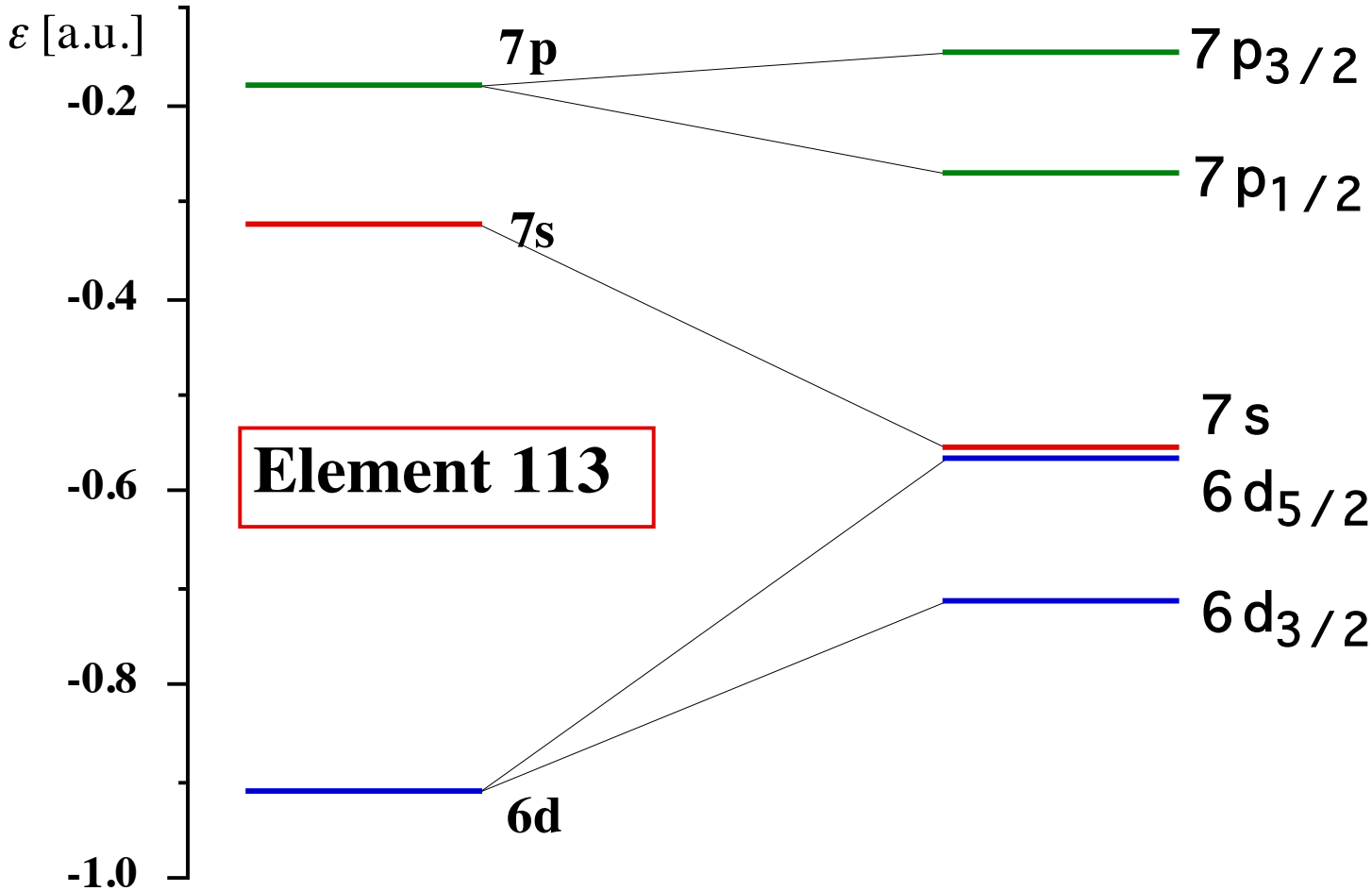


E. Eliav, U. Kaldor, P. Schwerdtfeger, B. Hess, Y. Ishikawa, *Phys. Rev. Lett.* 73, 3203 (1994).

M. Seth, P. Schwerdtfeger, M. Dolg, K.Faegri, B.A. Hess, U. Kaldor, *Chem. Phys. Lett.* 250, 461 (1996).

Relativistic shell-expansions and spin-orbit

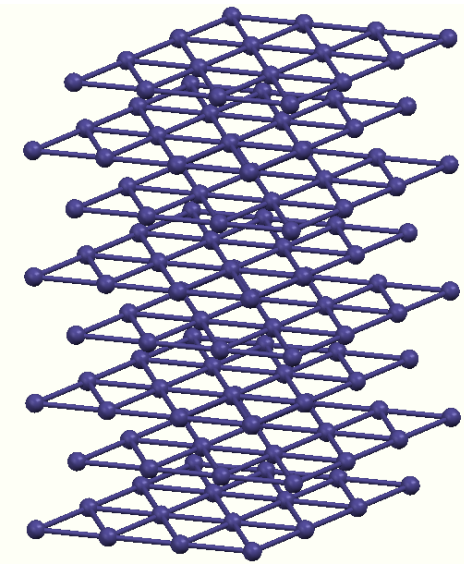
Due to the increased relativistic shielding by the *s*-orbitals, the diffuse $p_{3/2}$ and higher angular momentum orbitals will expand relativistically



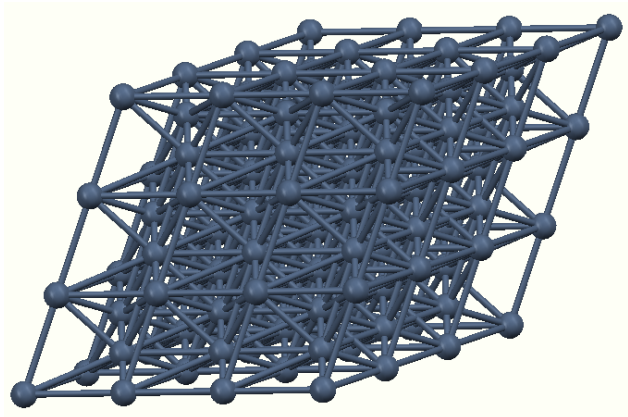
C. Thierfelder, P. Schwerdtfeger, A. Koers, A. Borschevsky, B. Fricke, *Phys. Rev. A* 80, 022501-1-10 (2009).

Is Copernicium a Group 12 Metal?

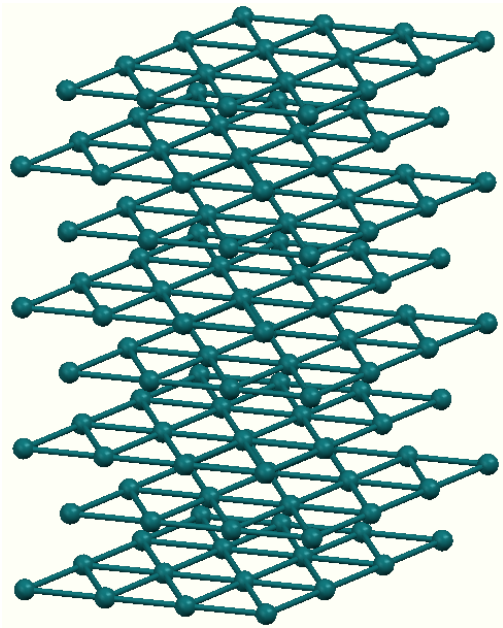
30	2 8 18 2
Zn	
Zinc	
65.409	
48	2 8 18 18 2
Cd	
Cadmium	
112.411	
80	2 8 18 32 18 2
Hg	
Mercury	
200.59	
112	2 8 18 32 32 18 2
Cn	
(285)	



Zn, Cd (*hcp*, *P63/mmc*)



Hg (*rhomb.*, *R-3mr*)

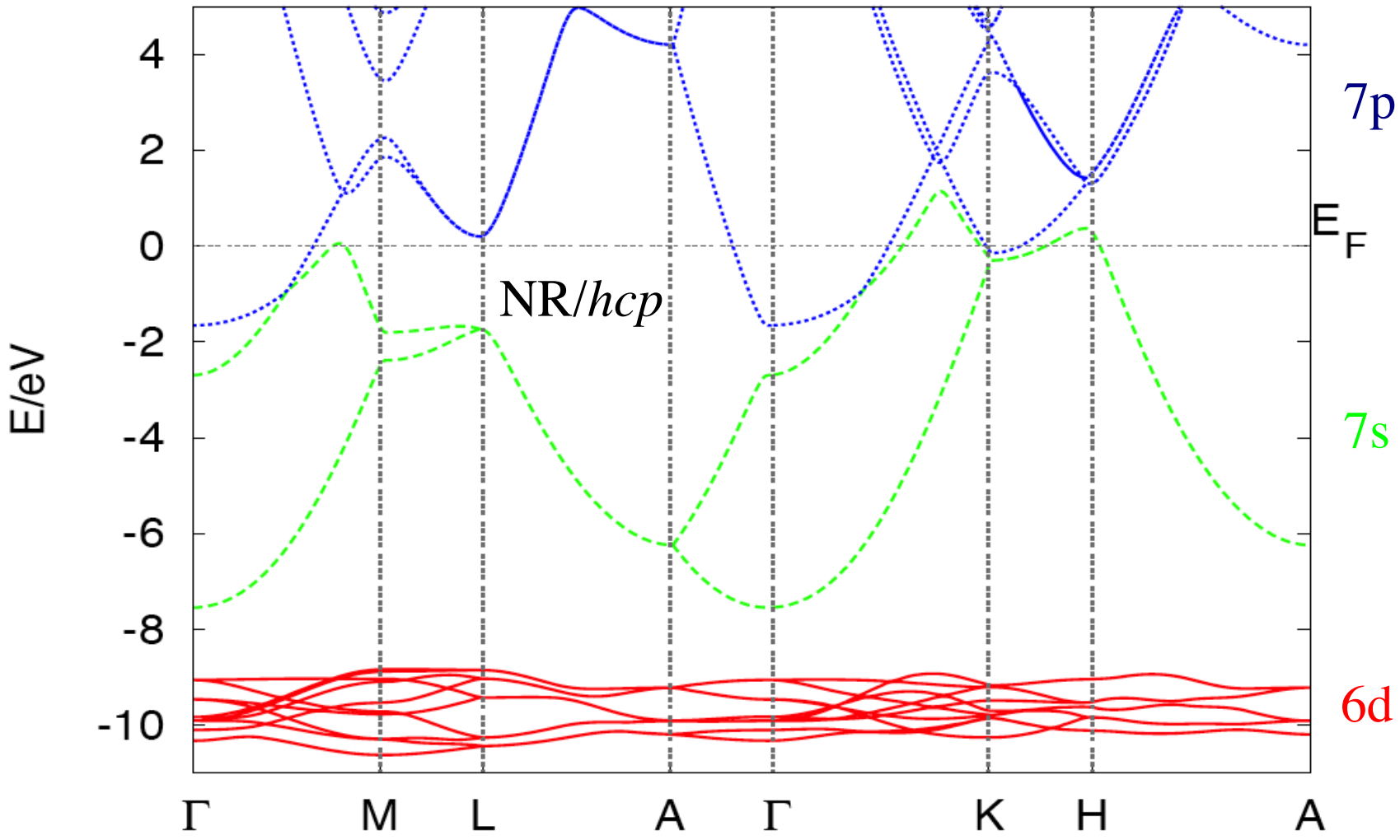


112 (*hcp*, *P63/mmc*)

?

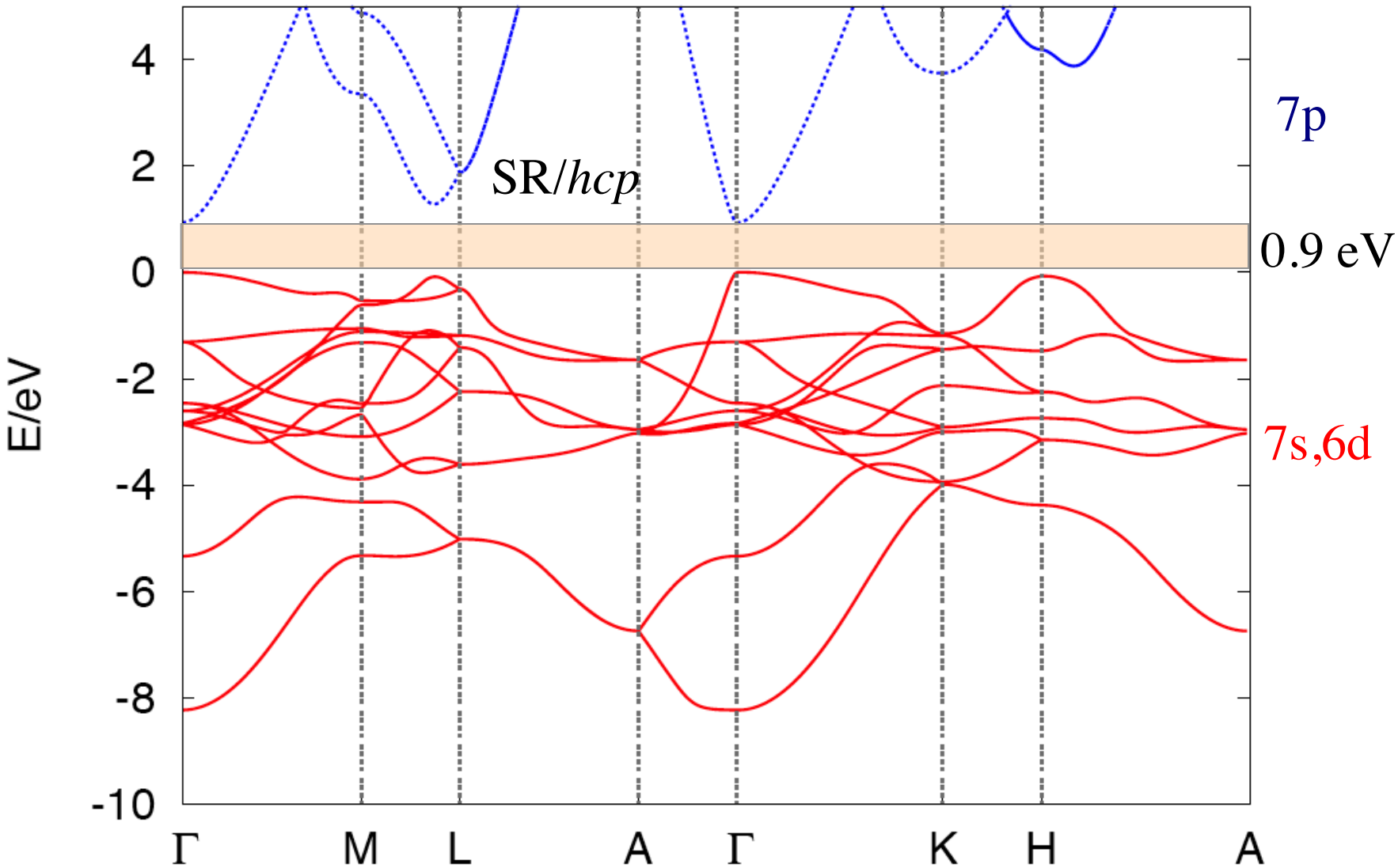
N. Gaston, I. Opahle, H. W. Gäggeler, P. Schwerdtfeger, *Angew. Chem. Int. Ed.* 46, 1663 (2007).

Band Structure of Copernicium



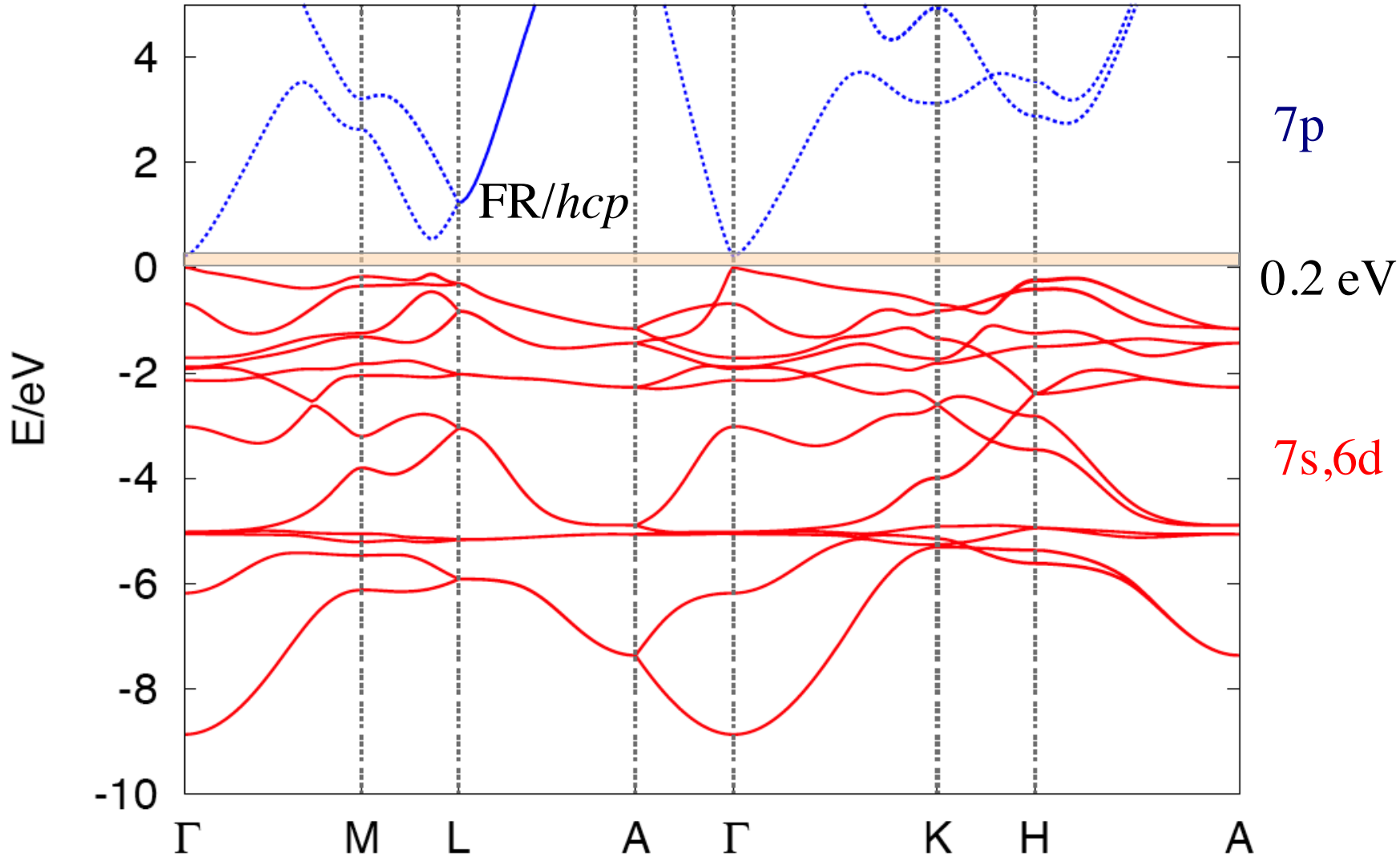
Metal at the nonrelativistic level (as is Zn, Cd and Hg)

Band Structure of Copernicium



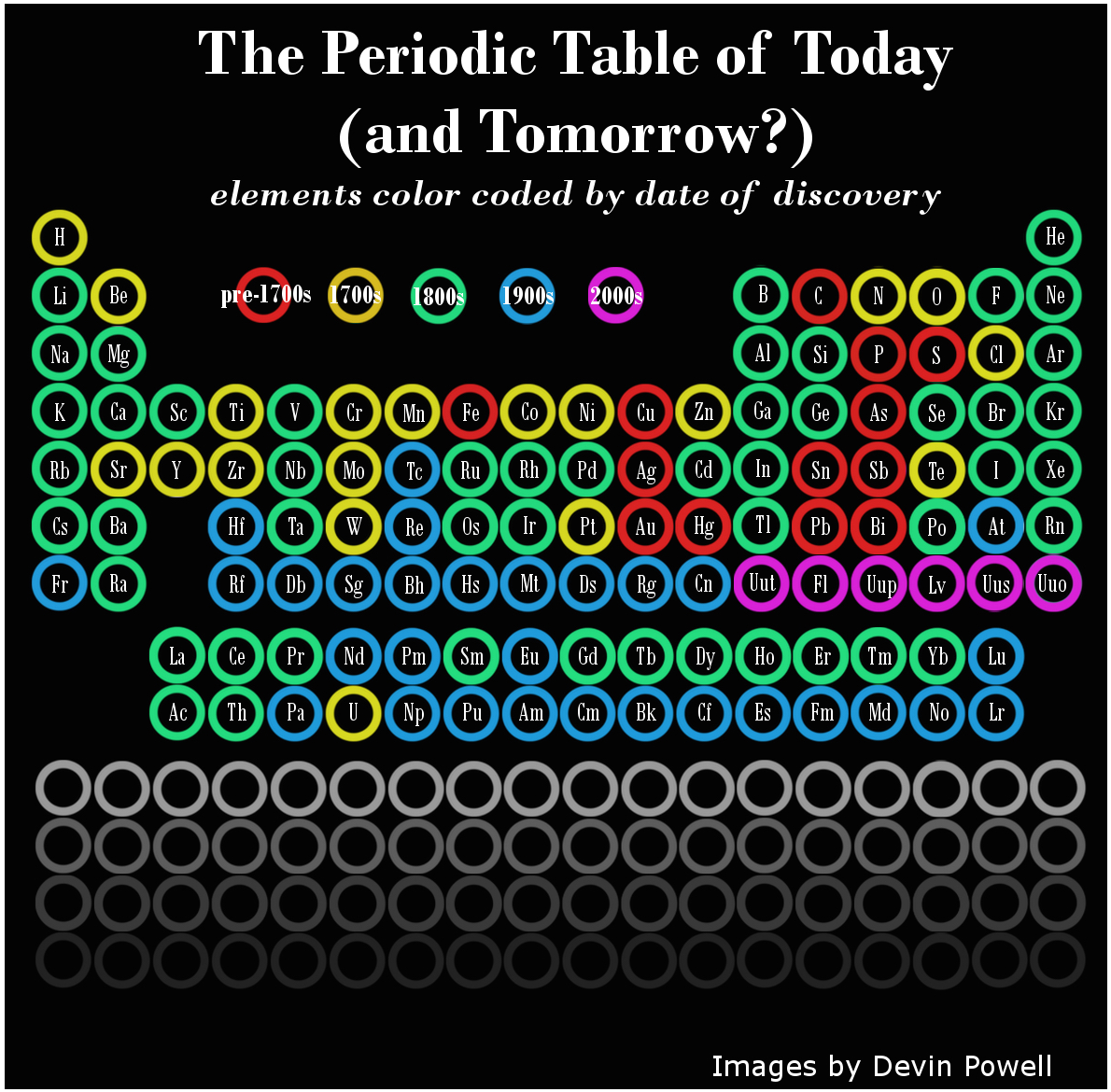
Insulator at the scalar relativistic level

Band Structure of Copernicium



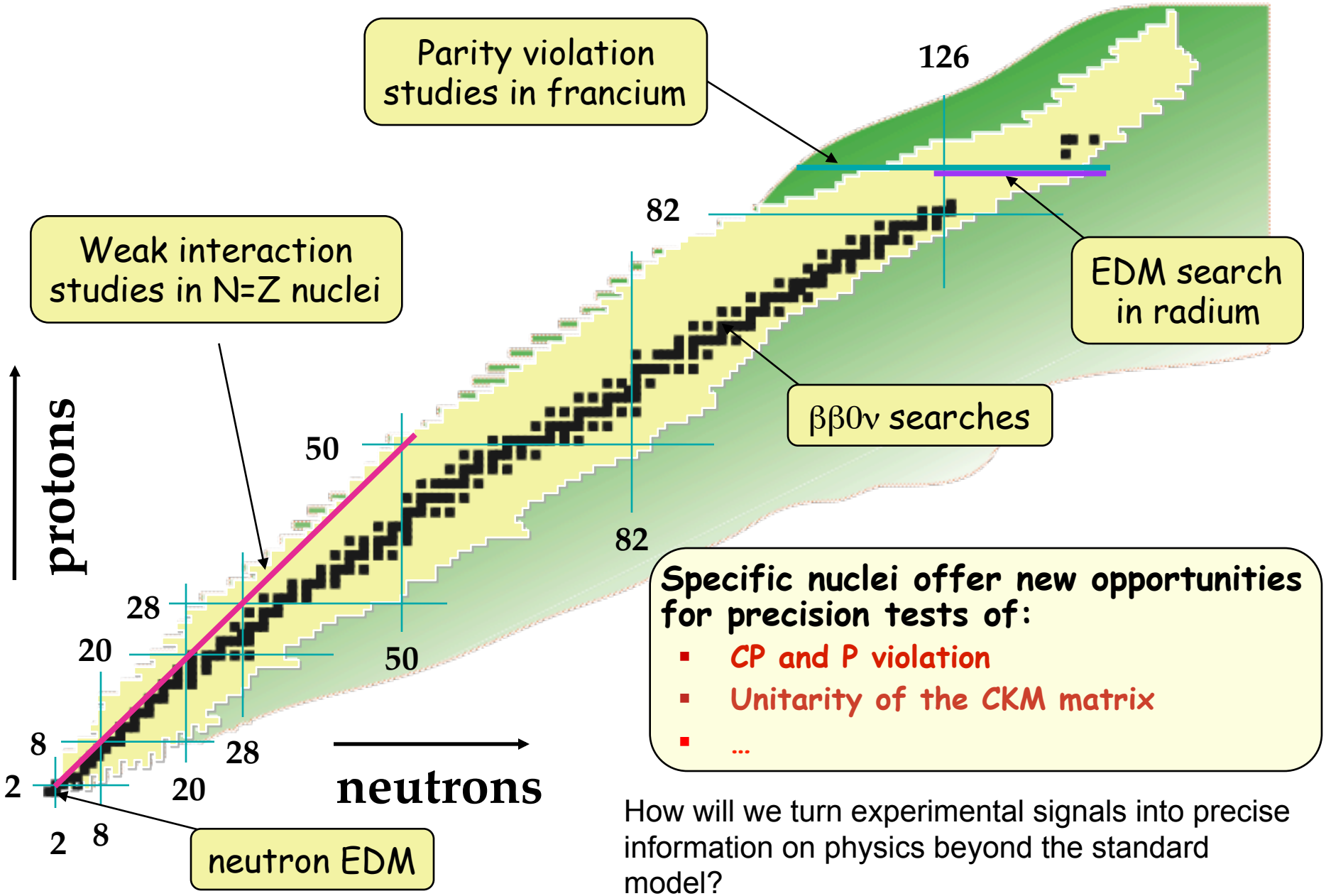
Semiconductor at the fully relativistic level (cohesive energy similar to Hg)

When Will We Reach the End of the Periodic Table?



http://www.smithsonianmag.com/science-nature/when-will-we-reach-end-periodic-table-180957851/

Testing the fundamental symmetries of nature



Specific nuclei offer new opportunities for precision tests of:

- CP and P violation
- Unitarity of the CKM matrix
- …

How will we turn experimental signals into precise information on physics beyond the standard model?

Are the fundamental interactions that are basic to the structure of matter fully understood?

Rare isotopes with enhanced sensitivity to fundamental symmetries provide opportunities for discovering new physics beyond the Standard Model

Experimental tests of the Standard Model

- Searches of atomic EDM in rare isotopes
- Tests of parity violation (anapole moment of Fr)
- Studies of superallowed β decays in N≈Z nuclei to test the CKM matrix unitarity
- β-ν angular correlation for the search of exotic scalar and tensor couplings
- Measurement of asymmetry-longitudinal polarization correlation in β decay to test deviations from maximal parity violation

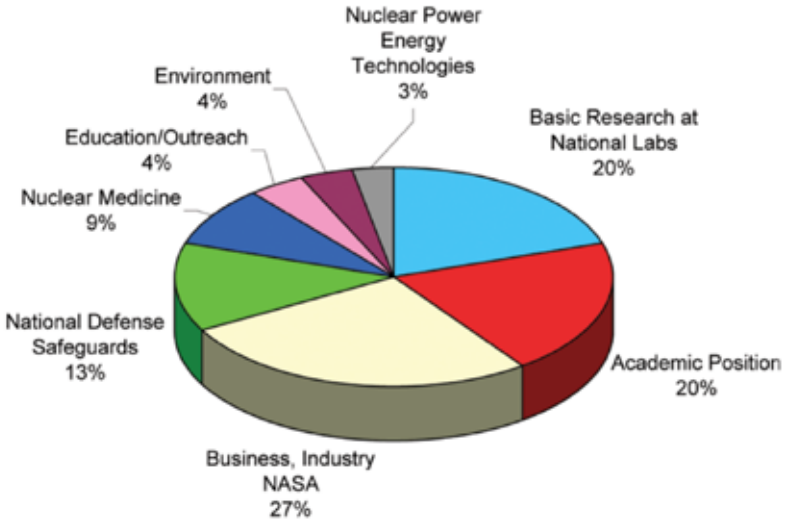
Nuclear structure calculations relevant to SM tests

- Isospin mixing corrections for superallowed beta decays
- Calculations of nuclear anapole moments for parity violation tests
- Calculations of Schiff moments for atomic EDM searches
- Calculations of nuclear $2\nu\beta\beta$ and $0\nu\beta\beta$ matrix elements and comparison with observables

Societal Benefits

- Energy, transmutation of waste…
- Medical and biological research
- Materials science
- Environmental science
- Stockpile stewardship
- Security
- …

http://science.energy.gov/~/media/np/pdf/Accelerating_Innovation_9_01142011.pdf



The pie chart above shows that many scientists who receive Ph.D.s in nuclear science go on to apply their knowledge working in professions outside the field after five to 10 years.

What are the next medically viable radioisotopes required for enhanced and targeted treatment and functional diagnosis?

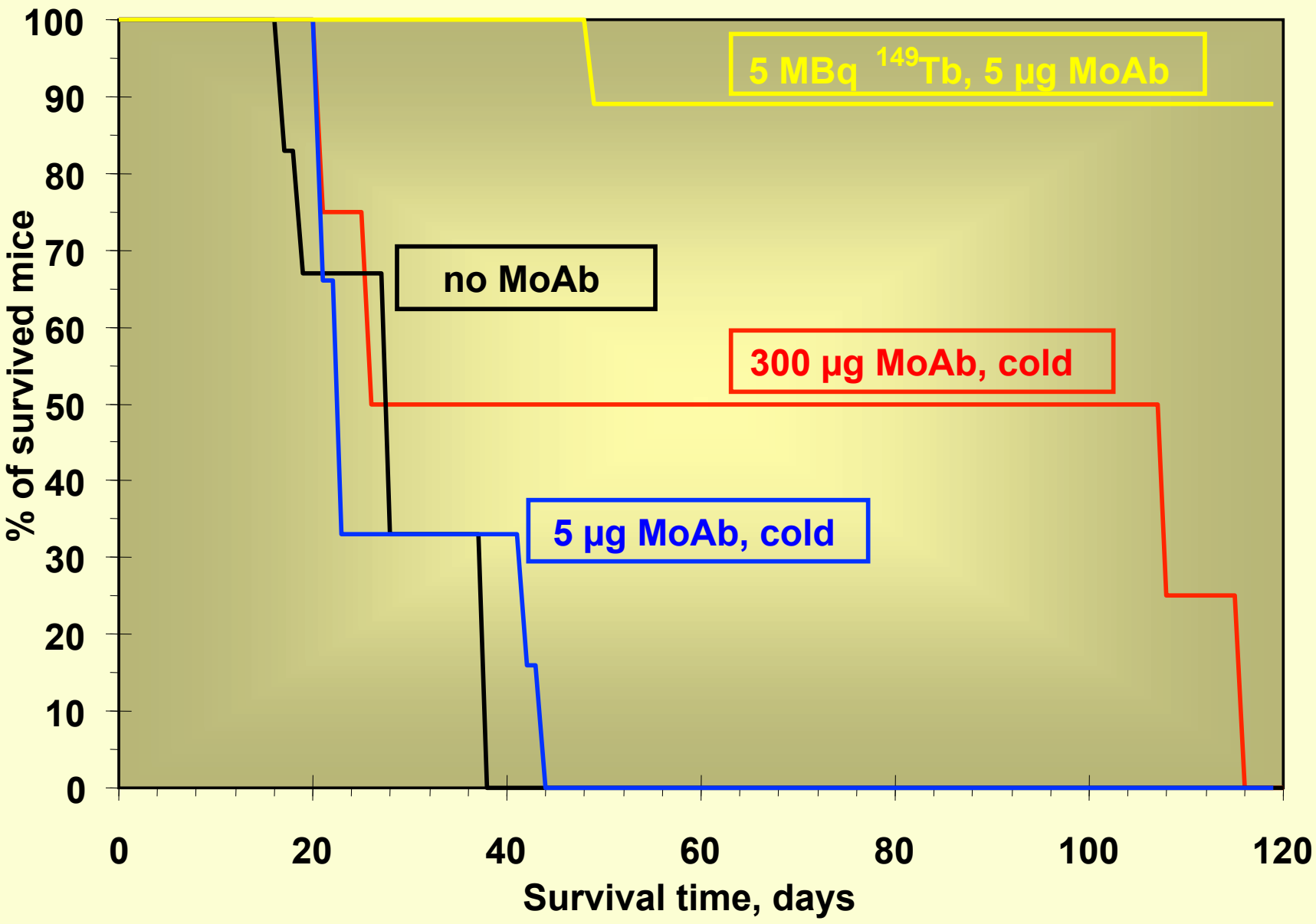
Example: Targeted Alpha Therapy in vivo

The radionuclide ^{149}Tb decays to alpha particles 17 percent of the time and has a half-life of 4.1 hours, which is conveniently longer than some other alpha-emitting radionuclides. Low-energy alpha particles, such as in ^{149}Tb decays, have been shown to be very efficient in killing cells, and their short range means that minimal damage is caused in the neighborhood of the target cells.

α-knife!

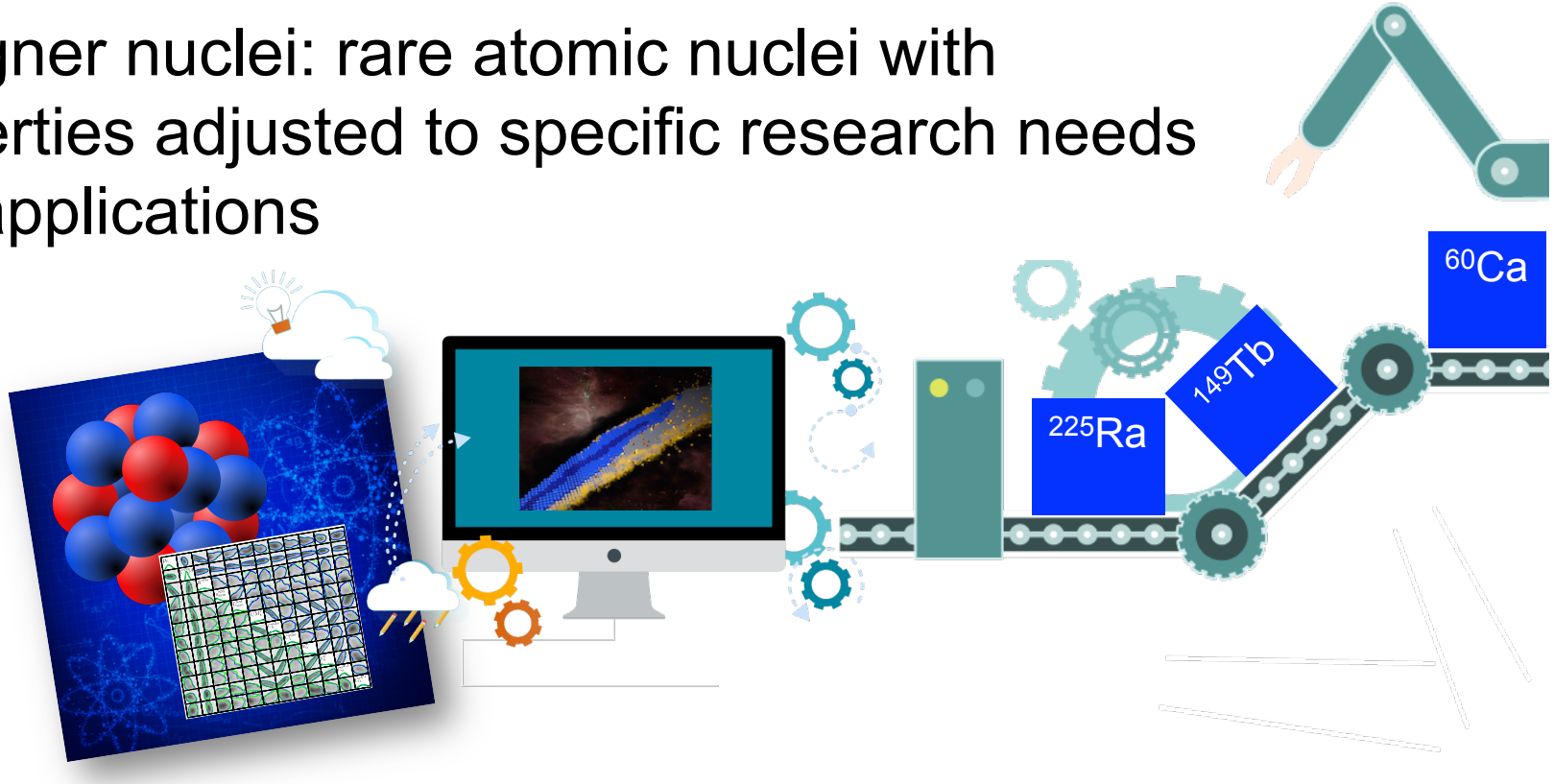
First in vivo experiment to demonstrate the efficiency of alpha targeted therapy using ^{149}Tb produced at ISOLDE, CERN

G.-J. Beyer et al. Eur. J. Nucl. Med. and Molecular Imaging **33**, 547 (2004)


Survival of mice…
5 MBq 149Tb, 5 µg MoAb
no MoAb
300 µg MoAb, cold
5 µg MoAb, cold
% of survived mice
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Survival time, days

Some nuclei are more important than others

Designer nuclei: rare atomic nuclei with properties adjusted to specific research needs and applications



CONCEPT PREDICTION FABRICATION

http://iopscience.iop.org/article/10.1088/0954-3899/43/4/044002

Philip Bredesen, Governor of Tennessee 2003-2011, PAC05 welcome address

(he earned a bachelor's degree in **physics** in 1967 from Harvard University in 1967)

"People who truly understand something, who truly have command of a subject, can explain it at some level to anyone who asks and is willing to try to understand an answer. The point is that if you were asked about something and had to resort to that's all very complicated and until you take a course in differential equations and then give me a blackboard I can't possibly make you understand, that that was more often a signal of a failure of the physicist to have a real command of the issue than of the failure of the person asking the question.

I have adapted it to my own life is the **"Walmart Test."** When I propose to take some course of action in the public sector, I do a thought experiment and imagine how I will explain it to the Walmart checkout person. Let me clear that I don't mean in any way dumbing-down the idea, I mean taking the principle that if I understand well enough what I am doing, I can cogently explain it to another human being with a different reference point. If I can successfully do this thought experiment, I have the makings of a plan."

What about YOU?

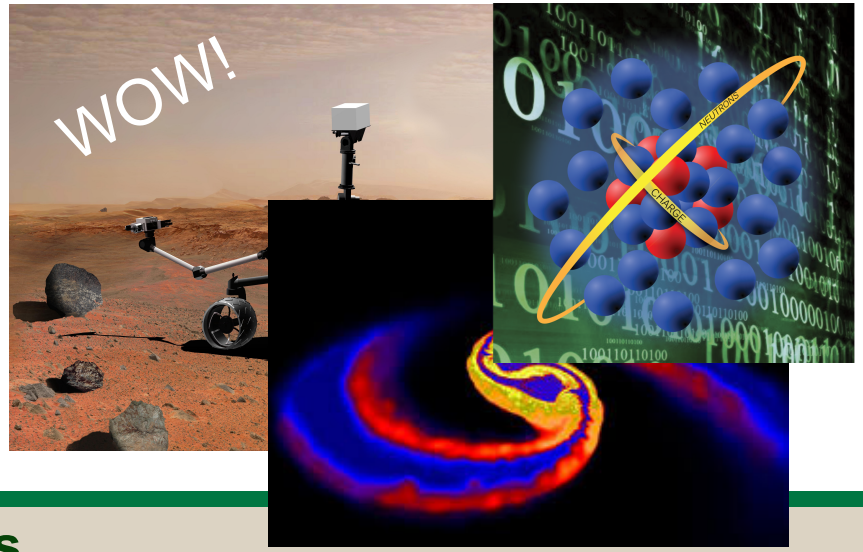
Philip Bredesen, cont.

Big science has had a great run for the last 60 years: Manhattan project, Sputnik and space exploration, the explosion and excitement of particle physics and accelerator; the rationale was obvious and easy. But those rationales are getting long in the tooth now, and need to be reinvigorated.

(...) the reality is that resources are scarce, the reality is that big science needs resources that only the government can supply, and the reality is that those scarce resources will go to those things that ordinary citizens think are important to themselves and to their children and to our nation. That's our job, to remake that connection in the 21st century.

There's nothing wrong or demeaning in this; even Michelangelo had patrons who had a seat at the table and needed to be satisfied.

Importance of Basic Research



FRIB will offer tremendous opportunities for WOW! moments