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U.S. DEPARTMENT OF ENERGY

Evaluations for medium- and high-mass nuclei for FUSION applications

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National Nuclear Data Center

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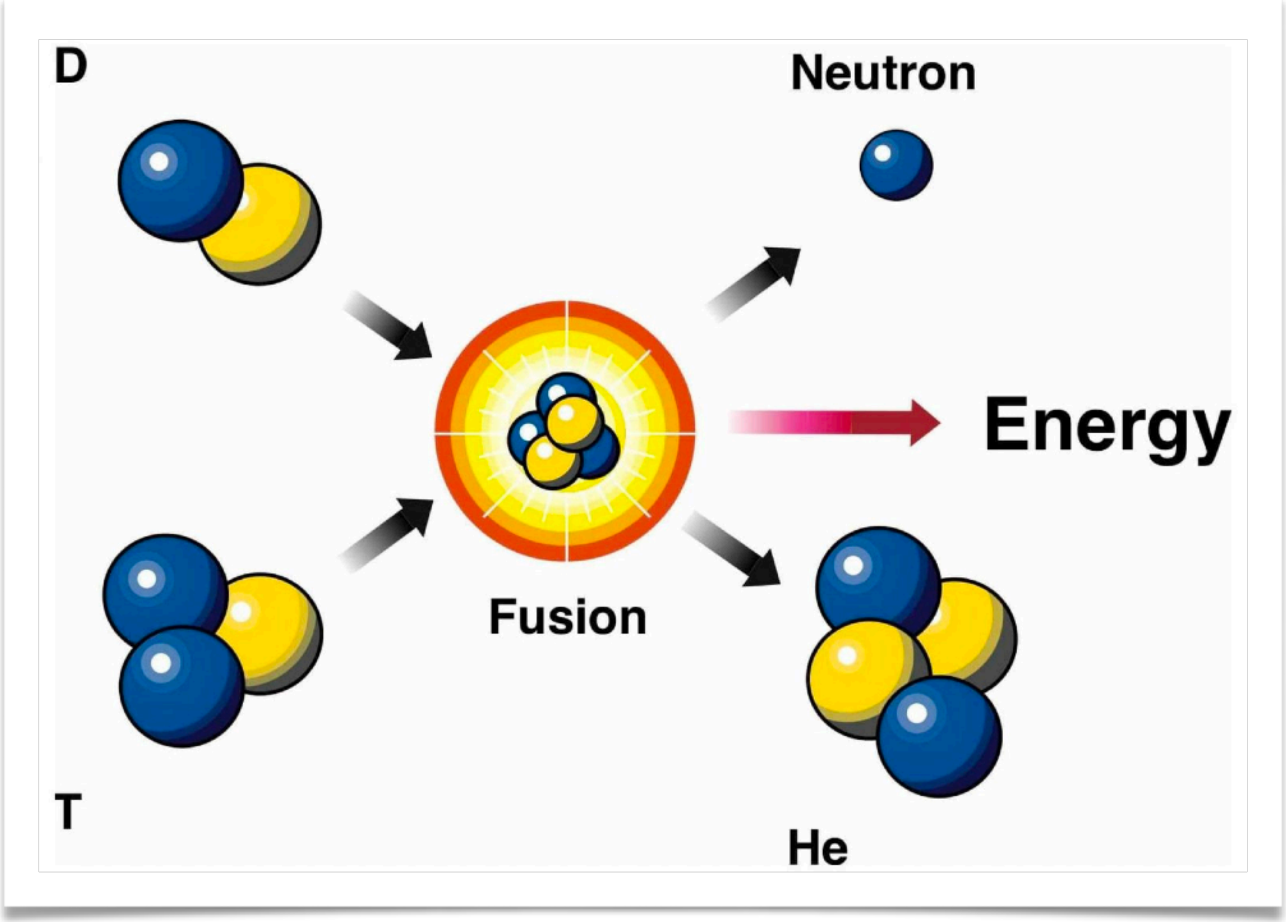
WANDA - Workshop for Applied Nuclear Data Activities

Fusion Neutronics session

Crystal City, VA - February 26-29, 2024

Outline

- ITER
- What's in ITER?
  - Which evaluations are relevant to ITER and other fusion applications?
- What are some of the challenges in evaluating these materials?
- Status of these evaluations in the ENDF/B library



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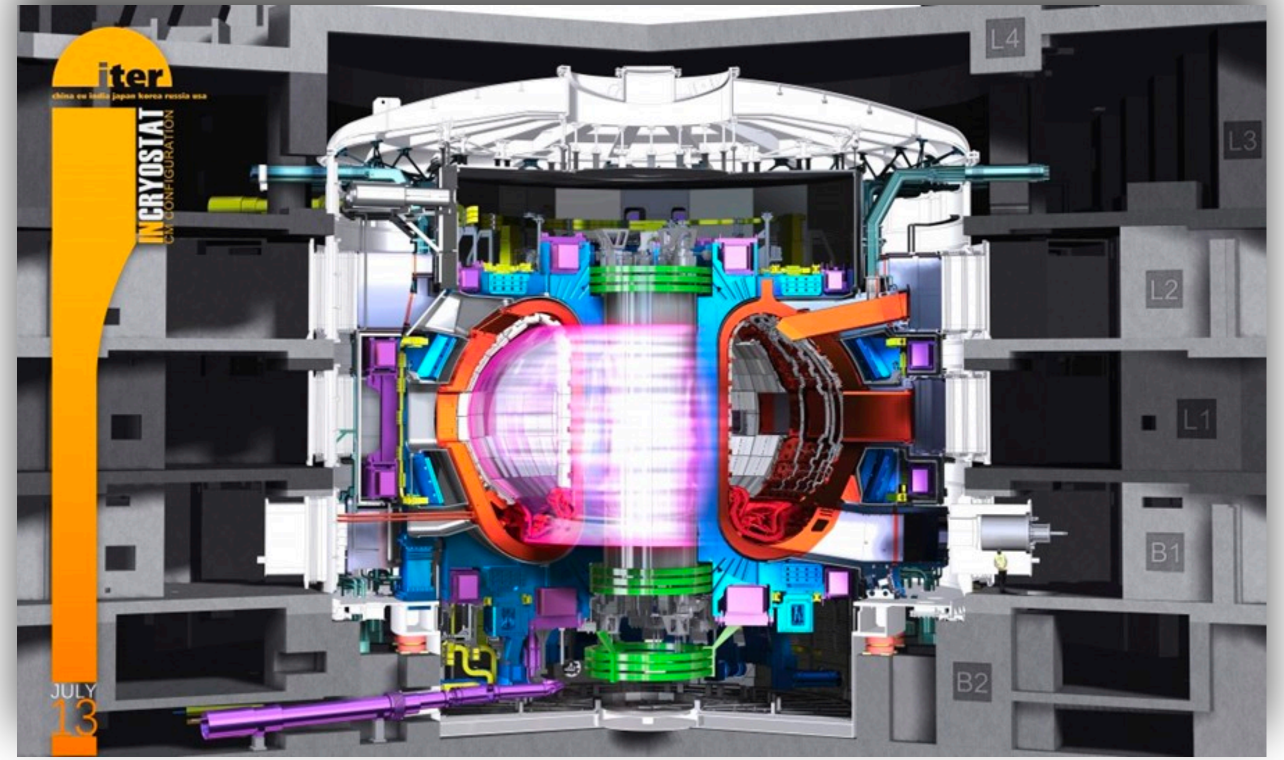
ITER

In southern France, 35 nations are collaborating to build the world's largest tokamak, a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy based on the same principle that powers our Sun and stars.*

- ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today.
- The experimental campaign that will be carried out at ITER is crucial to advancing fusion science and preparing the way for the fusion power plants of tomorrow.



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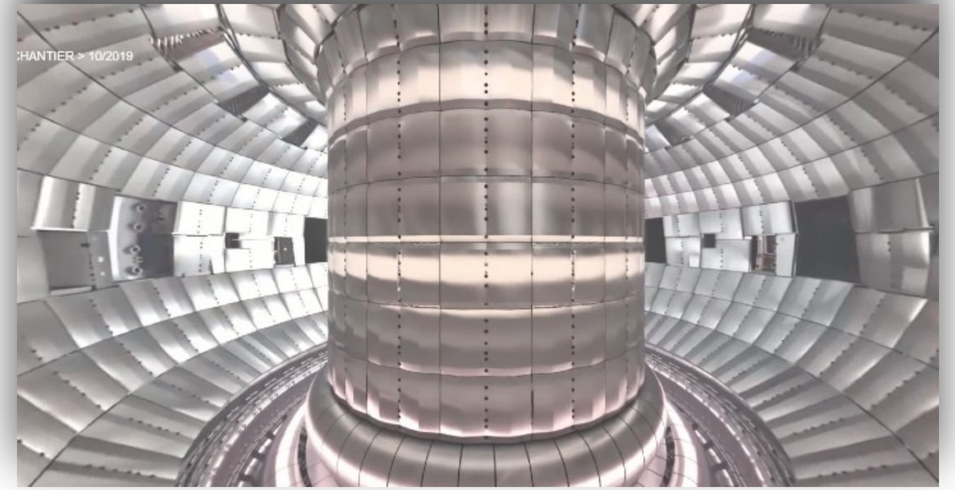
Text and pictures taken from www.iter.org

More pictures…



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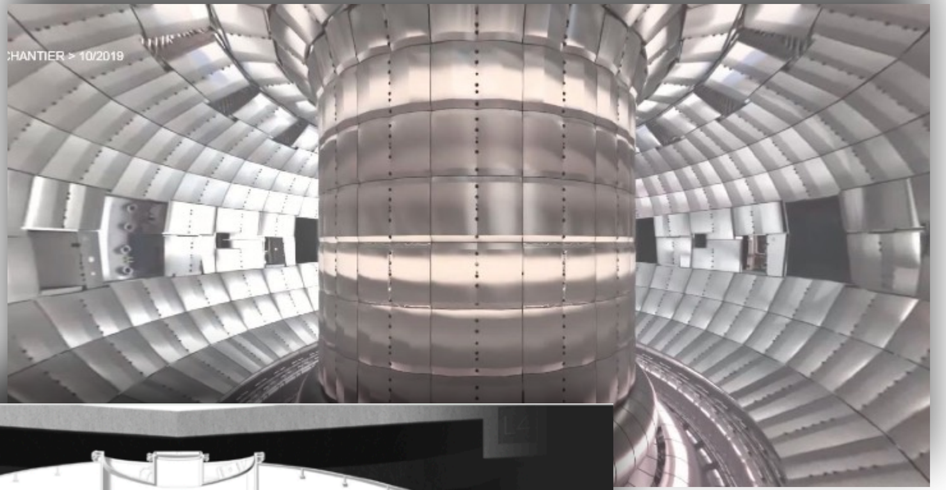

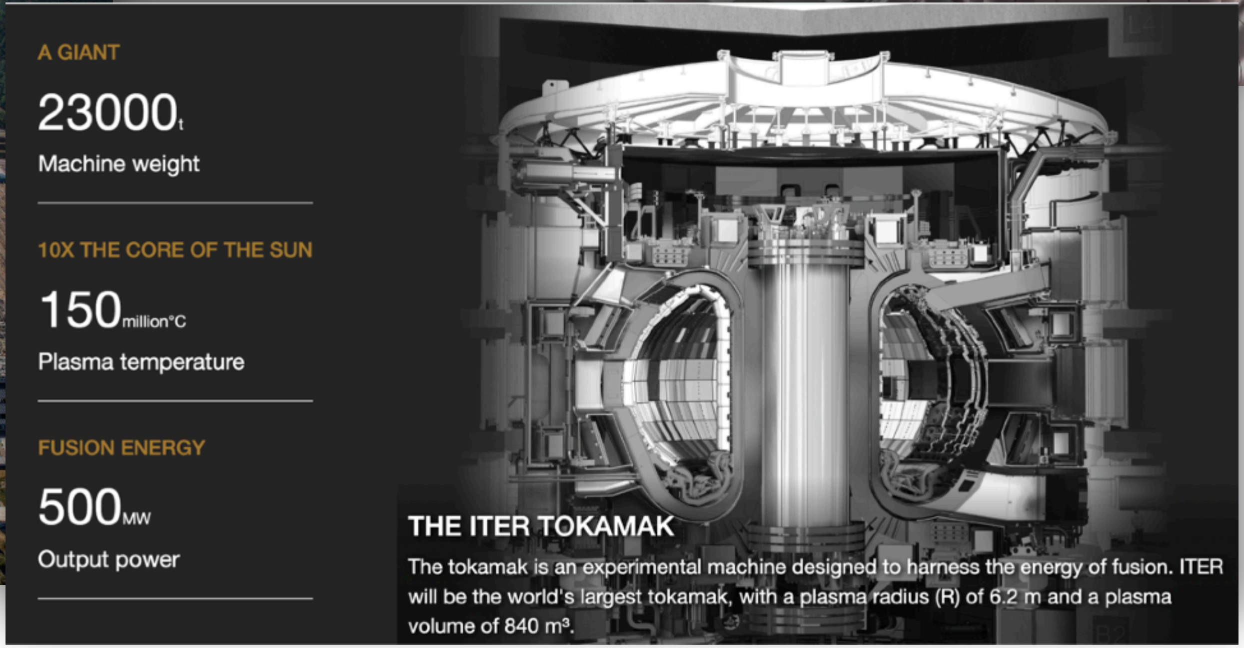

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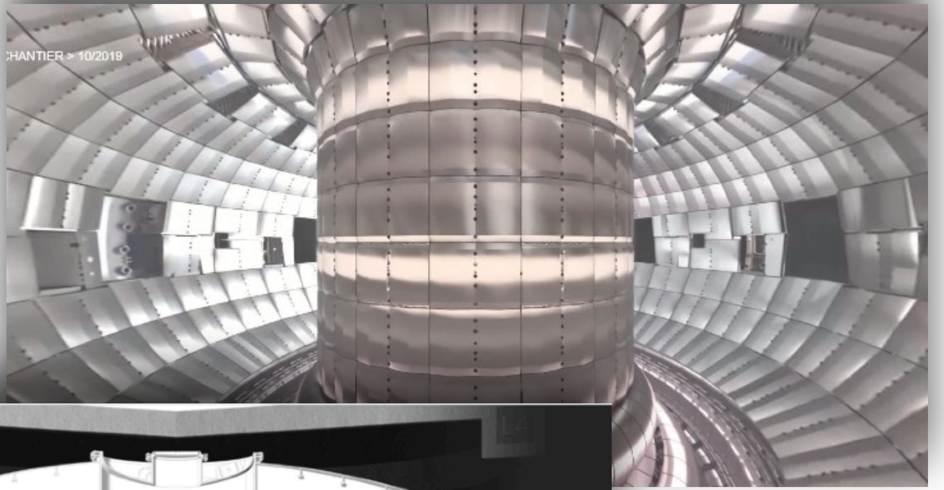

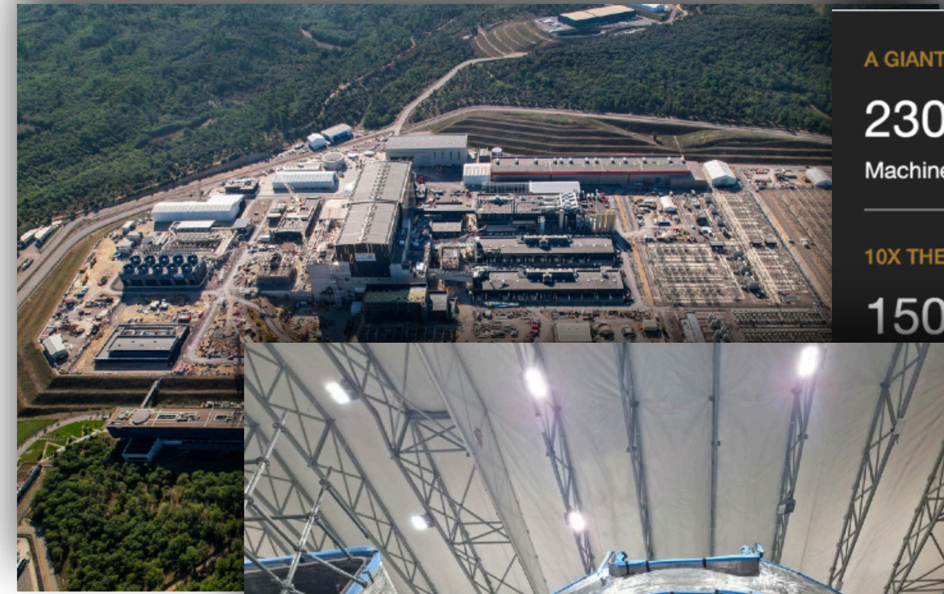

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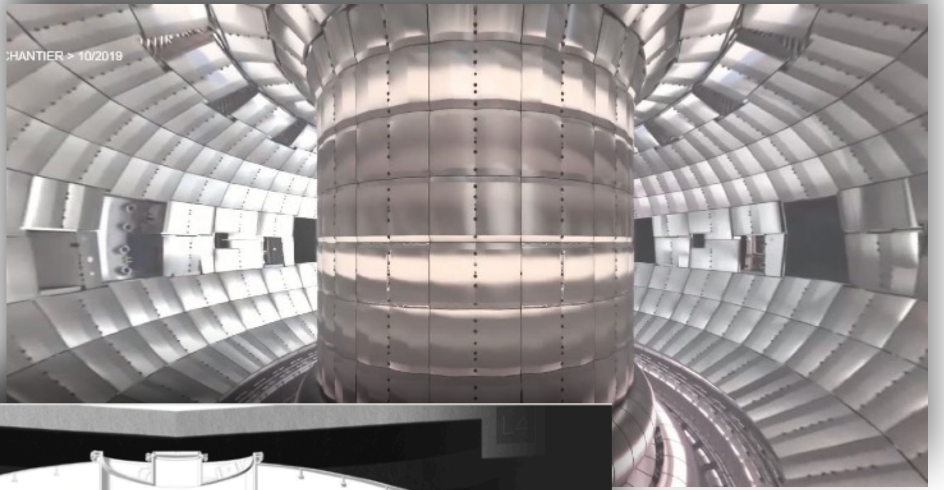

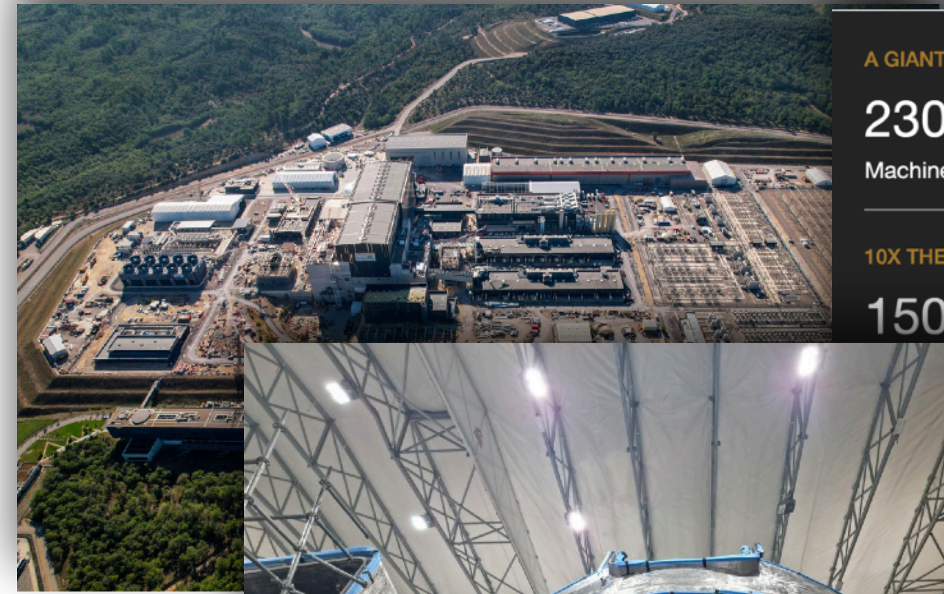

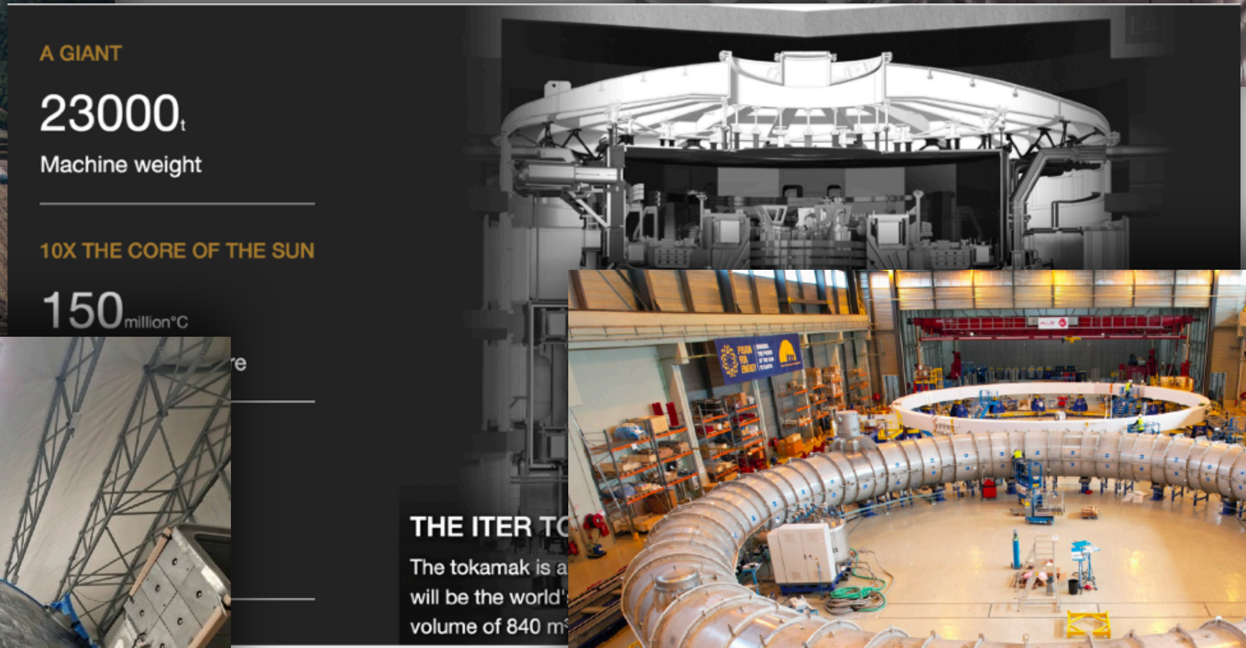

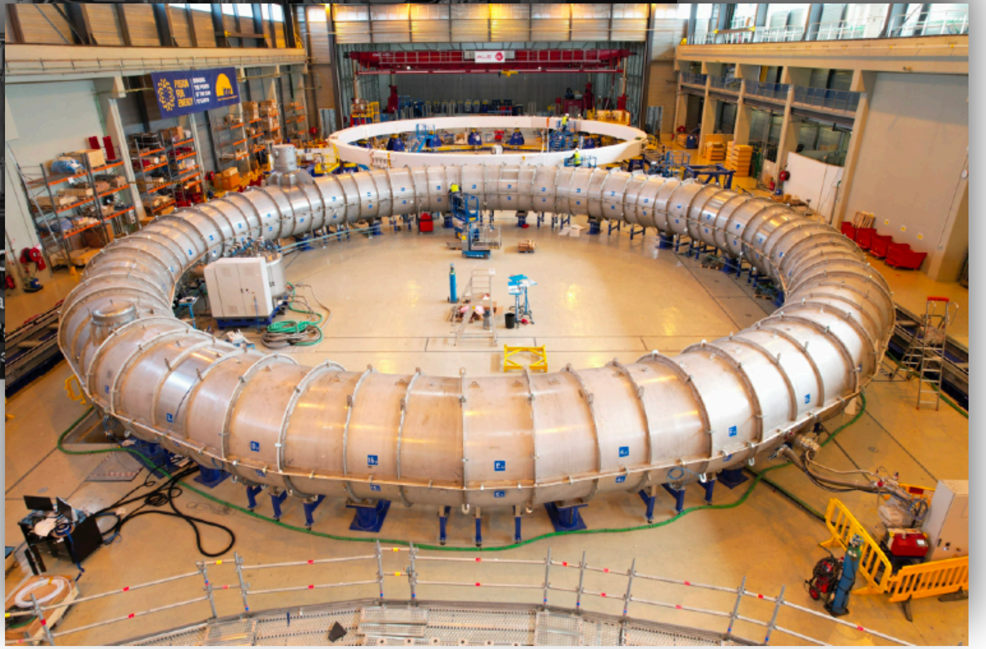

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Some pictures of my own tour to ITER

Pictures courtesy of G. Nobre

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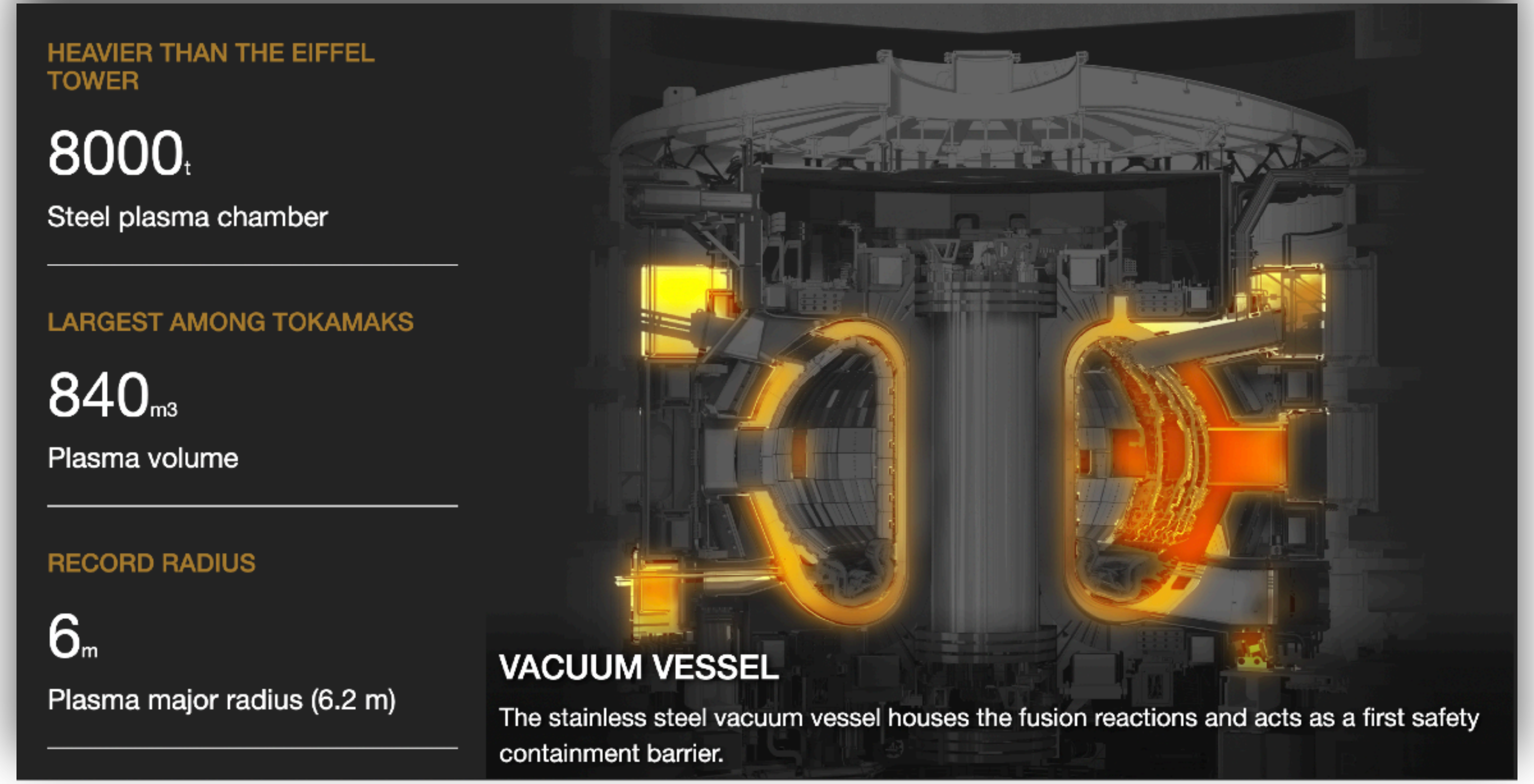
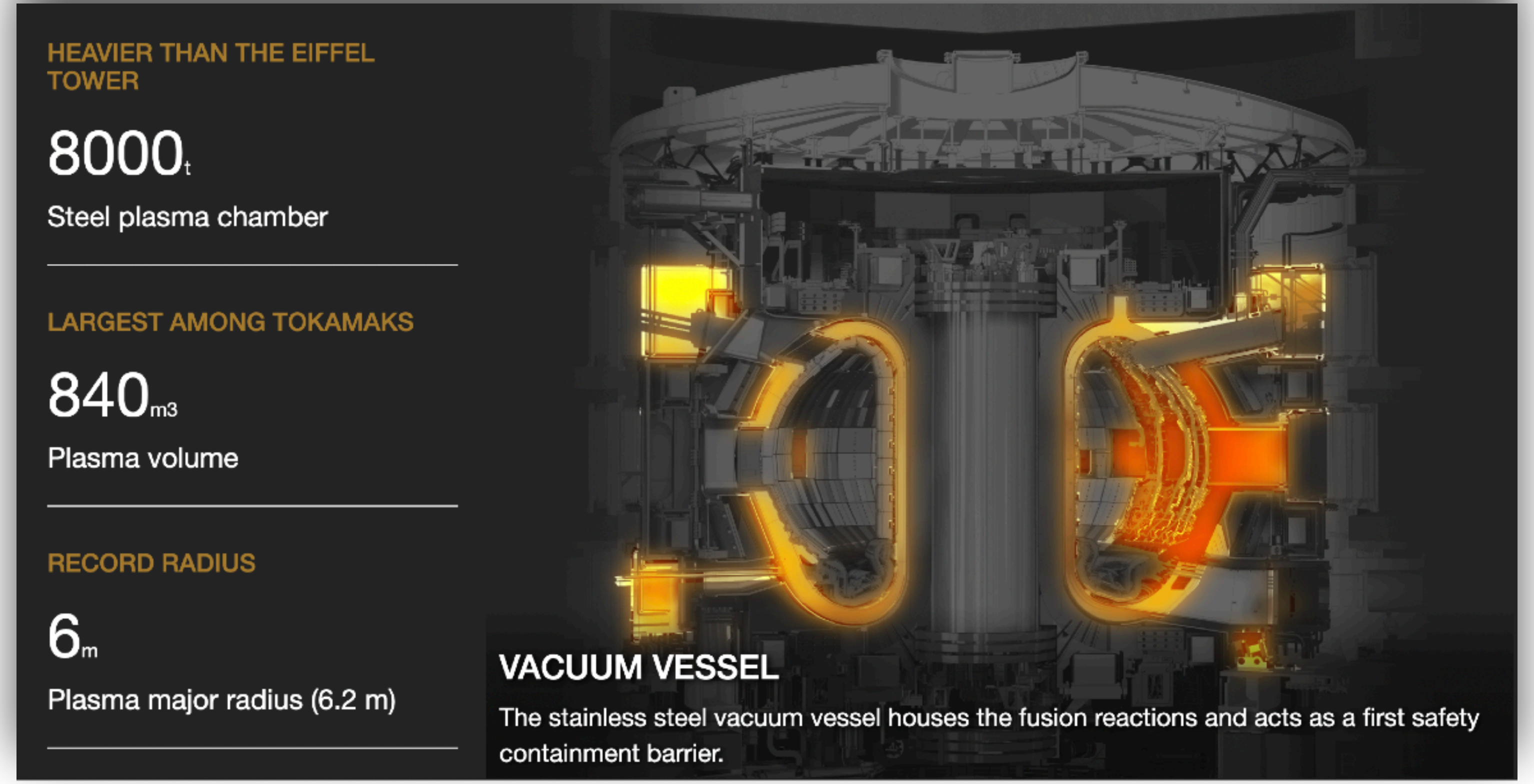
Looking into the details…



Looking into the details…

- Identifying materials relevant to neutronics



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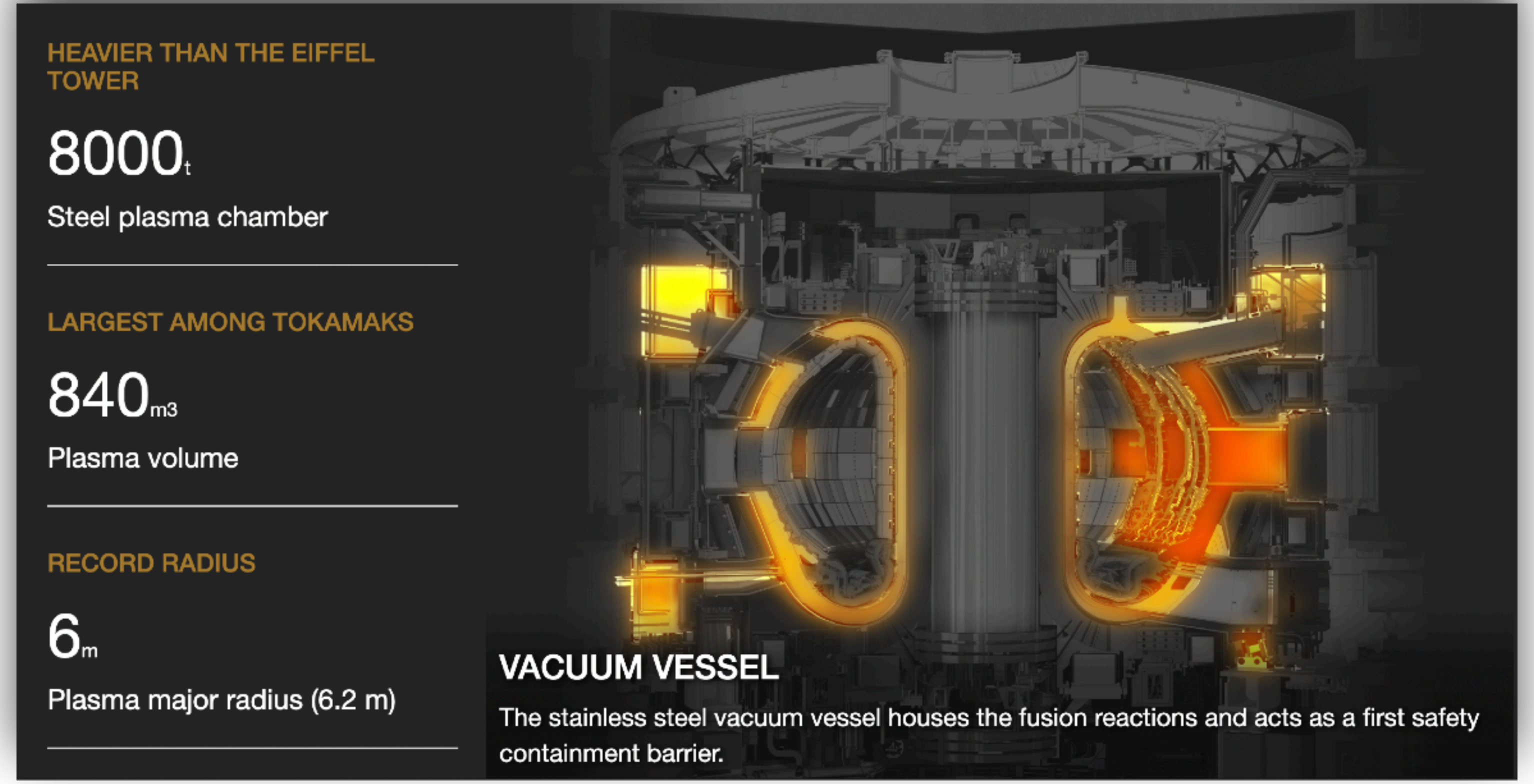
Looking into the details…

- Identifying materials relevant to neutronics
- Structural materials
    - Stainless Steel
    - Various steel alloys have the same elements in different proportions



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Looking into the details…

- Identifying materials relevant to neutronics
- Structural materials
    - Stainless Steel
    - Various steel alloys have the same elements in different proportions
- Niobium-tin strands in magnets

HEAVIER THAN THE EIFFEL TOWER

8000t

Steel plasma chamber

LARGEST AMONG TOKAMAKS

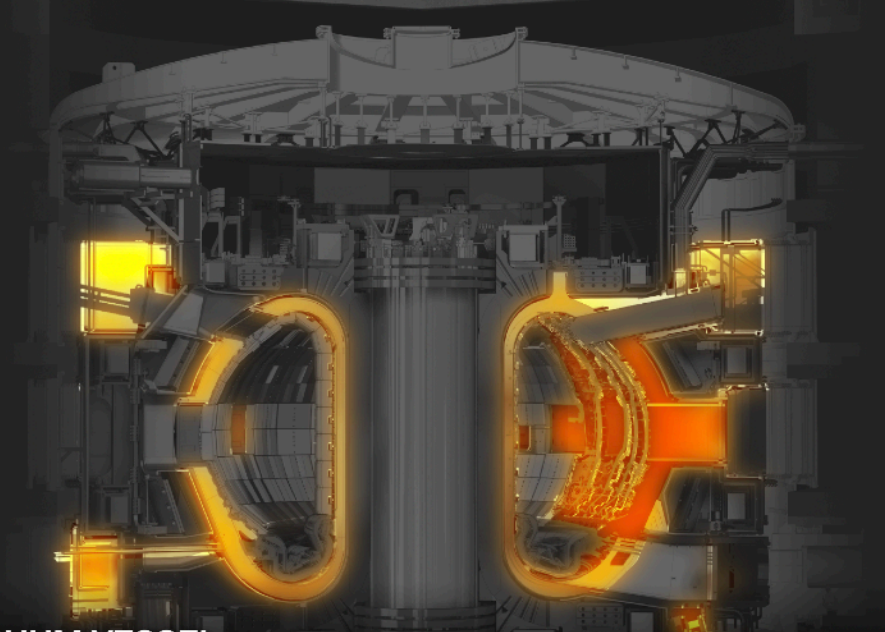
840m3

Plasma volume

RECORD RADIUS

6m

Plasma major radius (6.2 m)



VACUUM VESSEL

The stainless steel vacuum vessel houses the fusion reactions and acts as a first safety containment barrier.

100,000 KILOMETRES

100,000 kilometres of niobium-tin (Nb3Sn) superconducting strands are necessary for ITER's toroidal field magnets. Fabricated by suppliers in six ITER Domestic Agencies—China, Europe, Japan, Korea, Russia and the USA—production began in 2009 and ended in 2014. Over 400 tonnes of this multifilament wire has been produced for ITER at a rate of about 150 tonnes/year, a spectacular increase in worldwide production capacity (estimated, before the scale-up for ITER, at a maximum of 15 tonnes/year). Stretched end to end, the Nb3Sn strand produced for ITER would wrap around the Earth at the equator twice.

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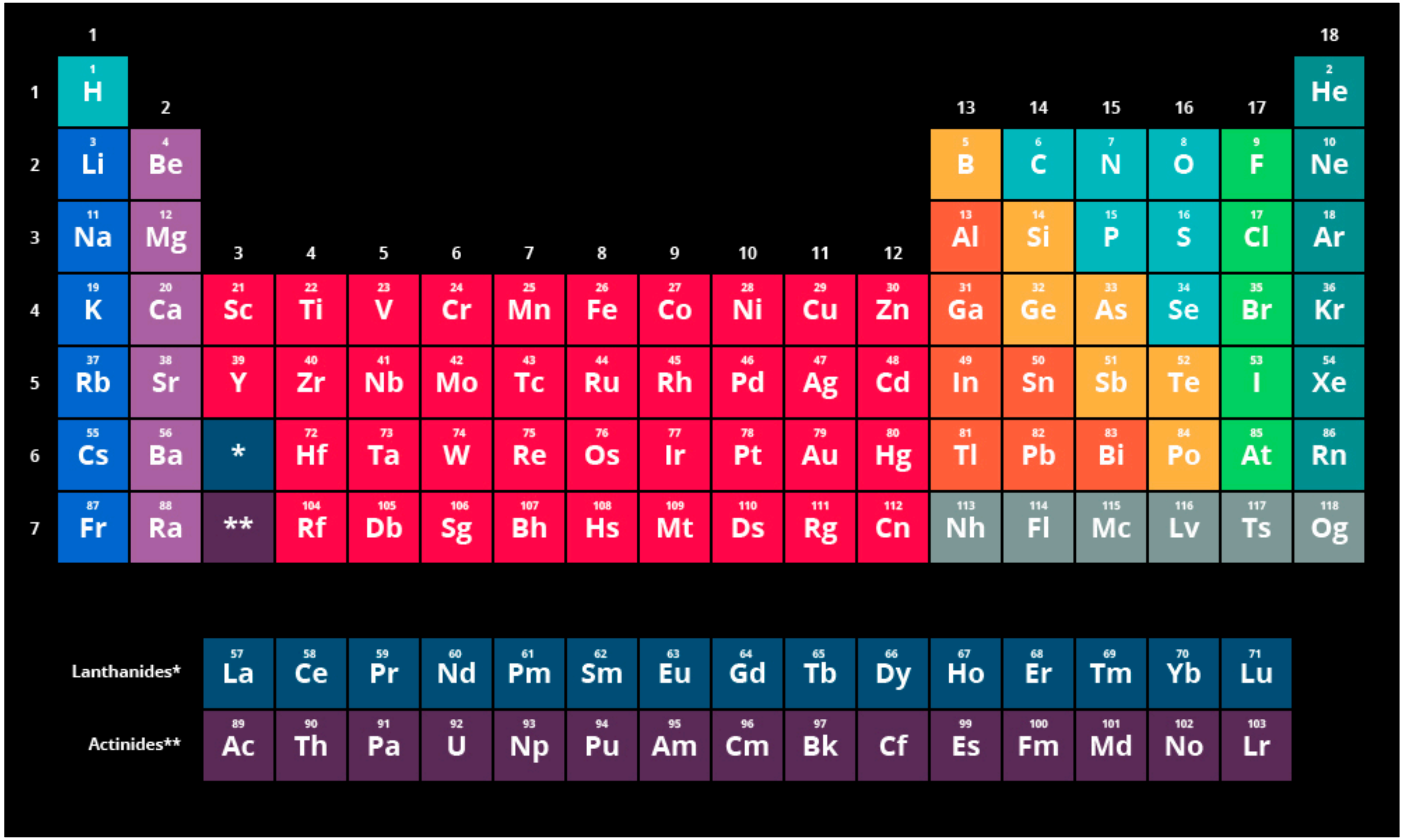
Nuclei relevant for neutron transport and/or activation at ITER (in our mass range)



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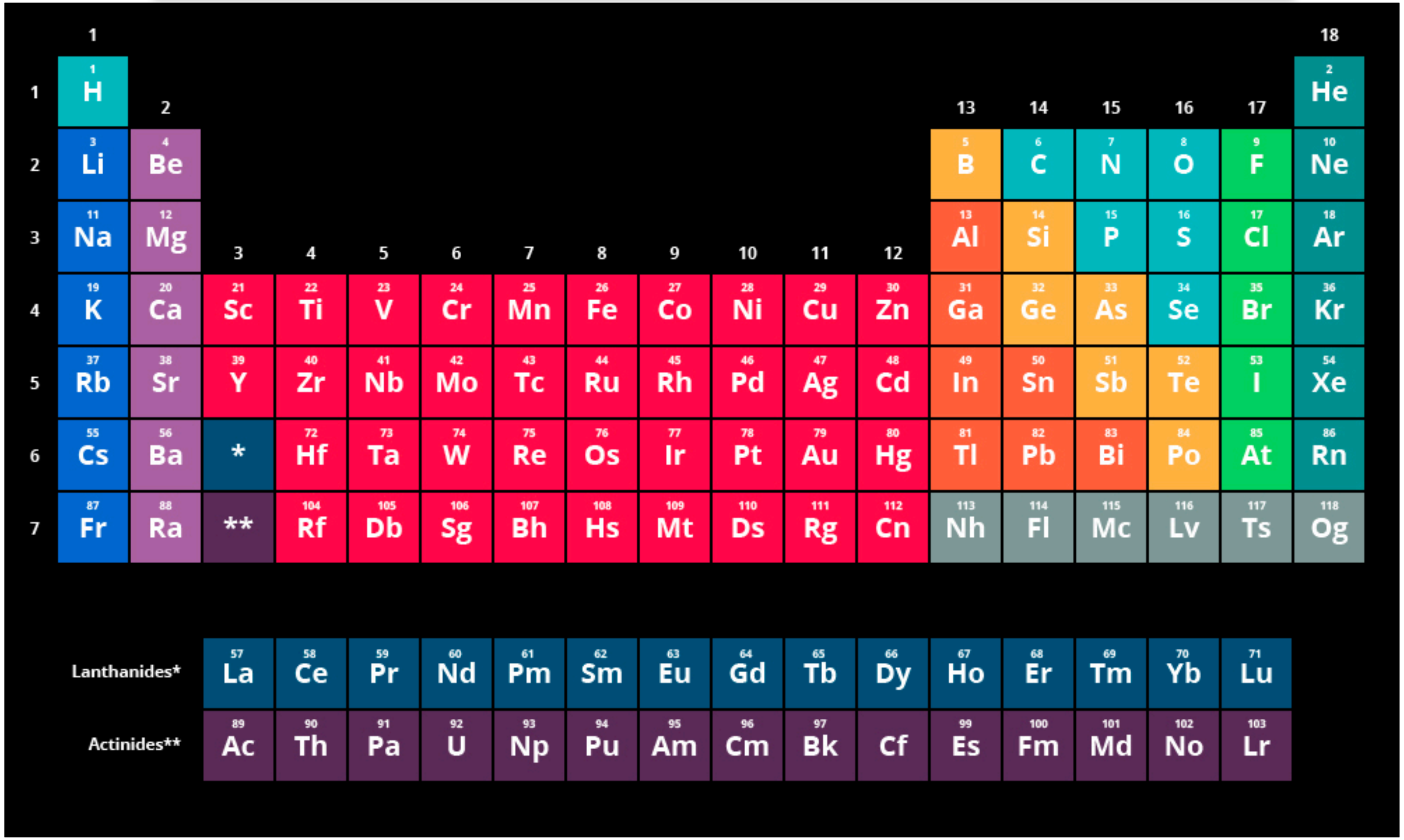
Fe, C, **Mn**, **Ni**, **Cr**, **Mo**, P, S, **Si**, **Cu**, **Ta**, **Ti**, B, **Nb**, **Co**, **V**, Al, **Sn**



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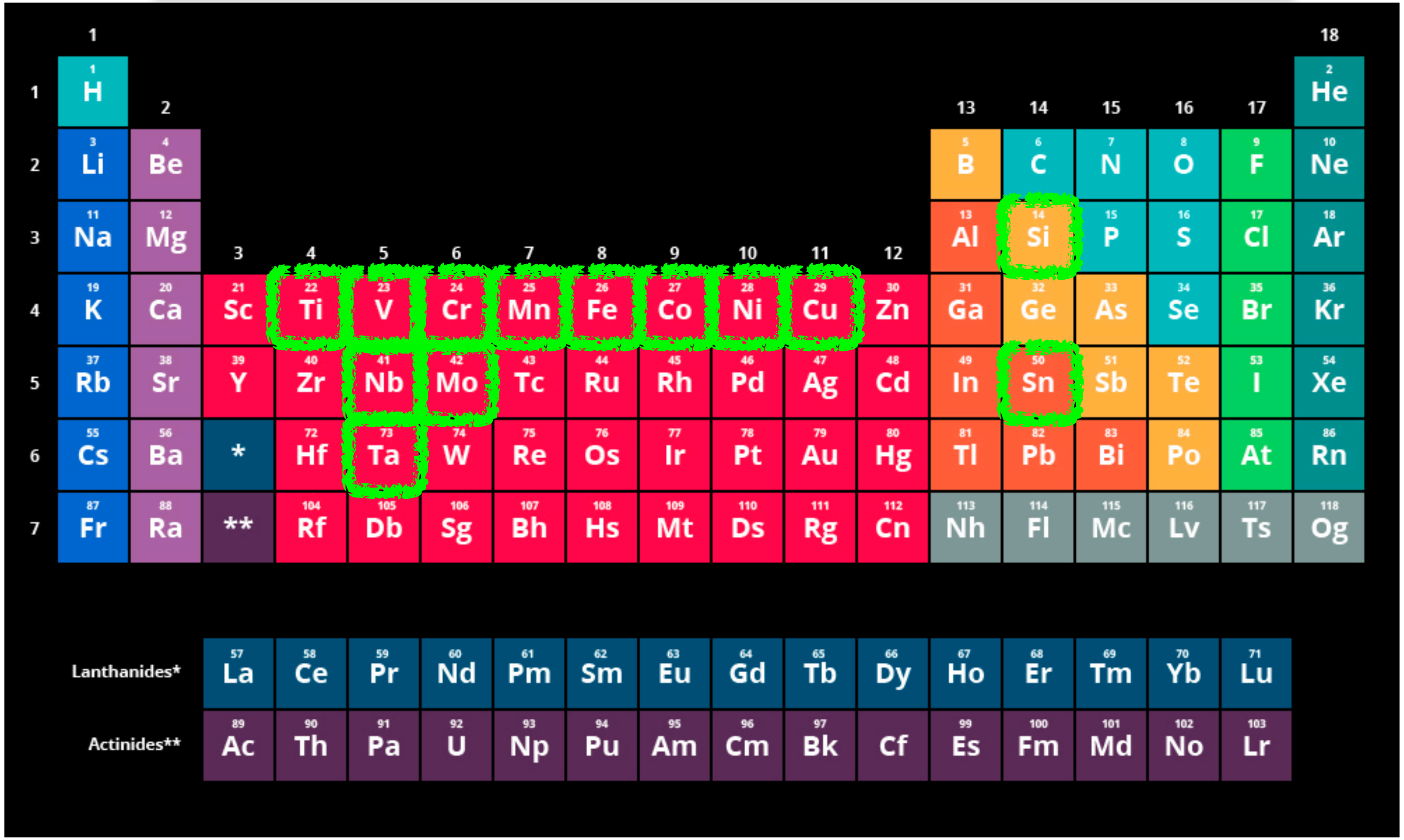

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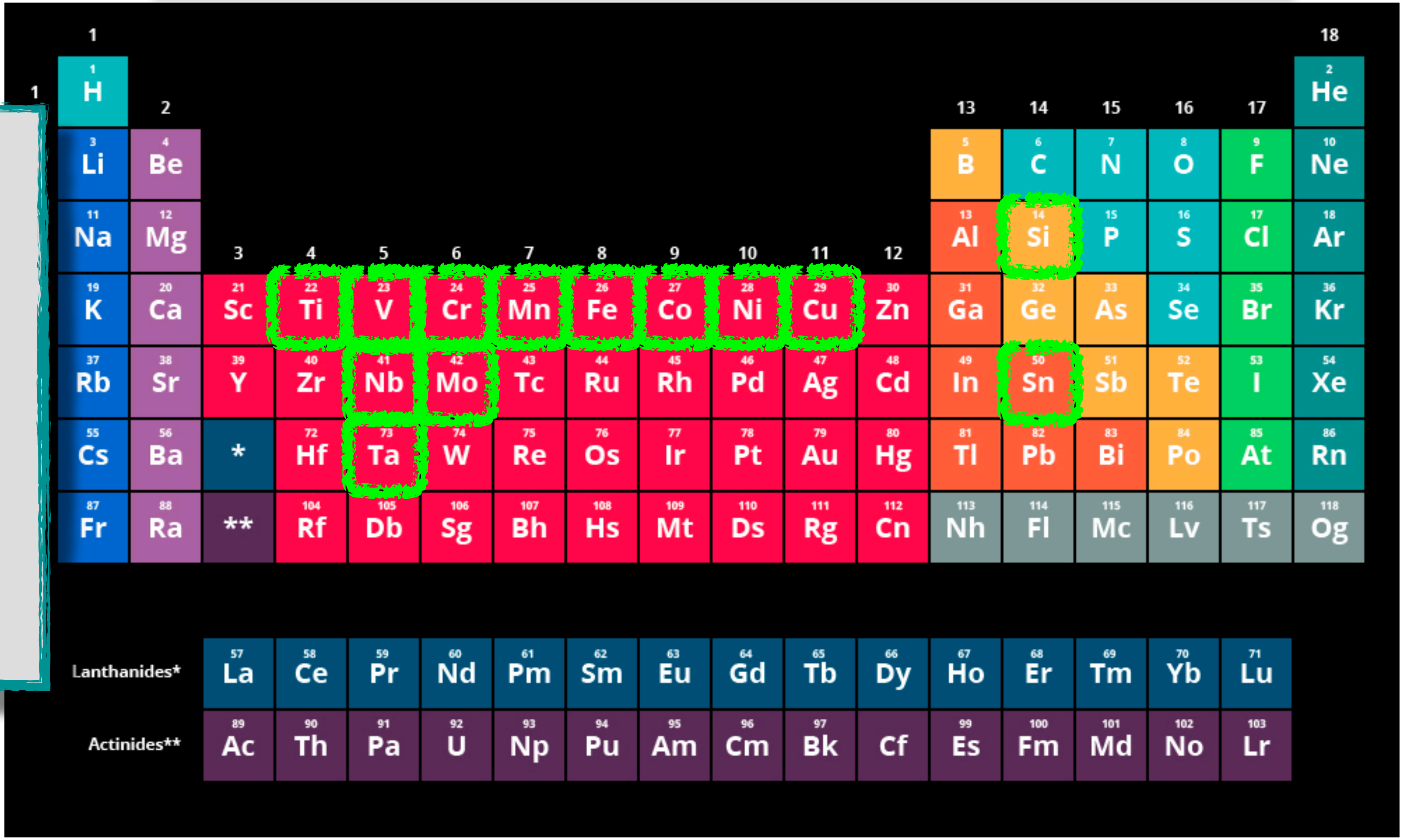
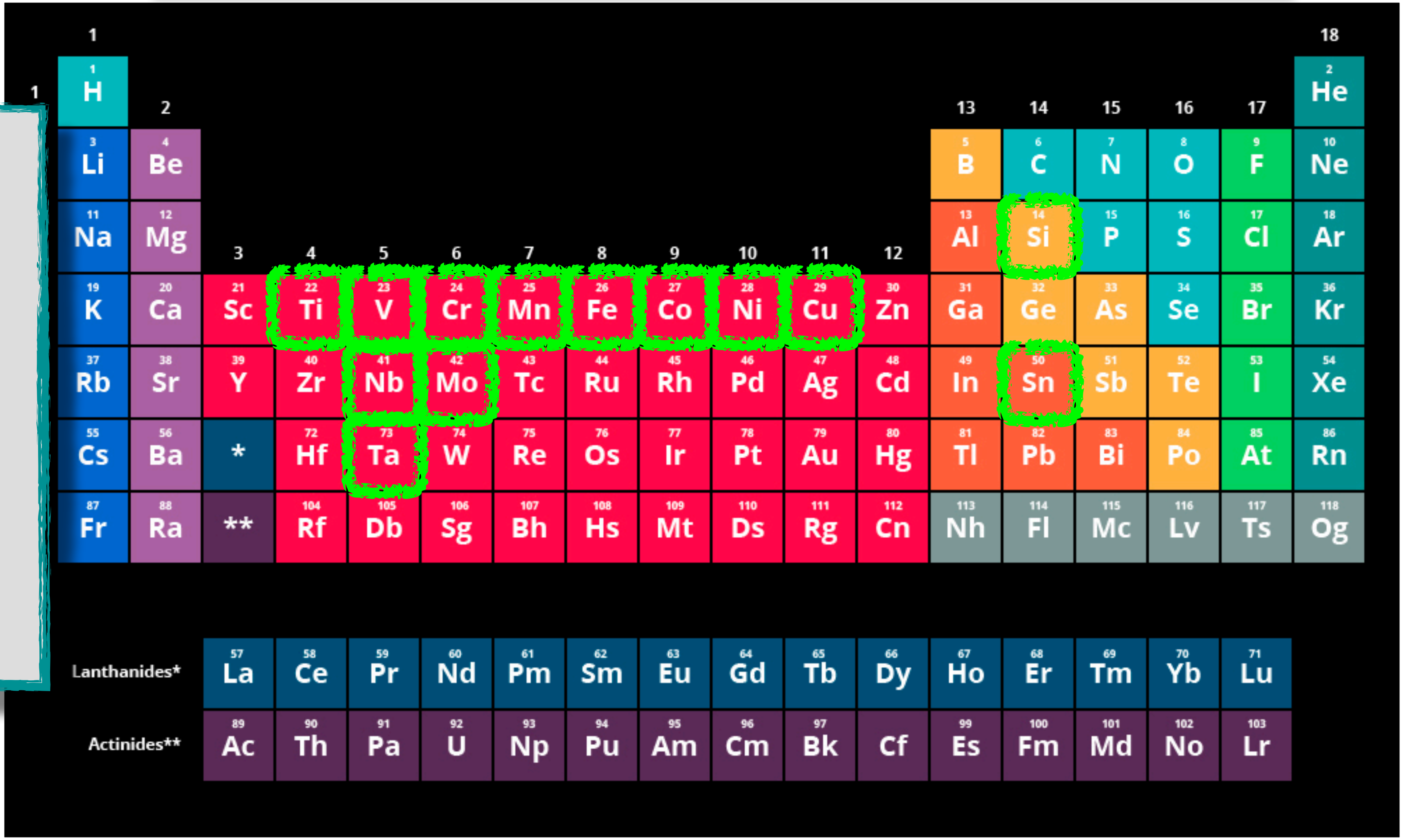


- Mostly structural materials!

Nuclei relevant for neutron transport and/or activation at ITER (in our mass range)

Fe, C, **Mn**, **Ni**, **Cr**, **Mo**, P, S, **Si**, **Cu**, **Ta**, **Ti**, B, **Nb**, **Co**, **V**, Al, **Sn**

- Mostly structural materials!
- Why are structural materials used as structural materials in nuclear applications?



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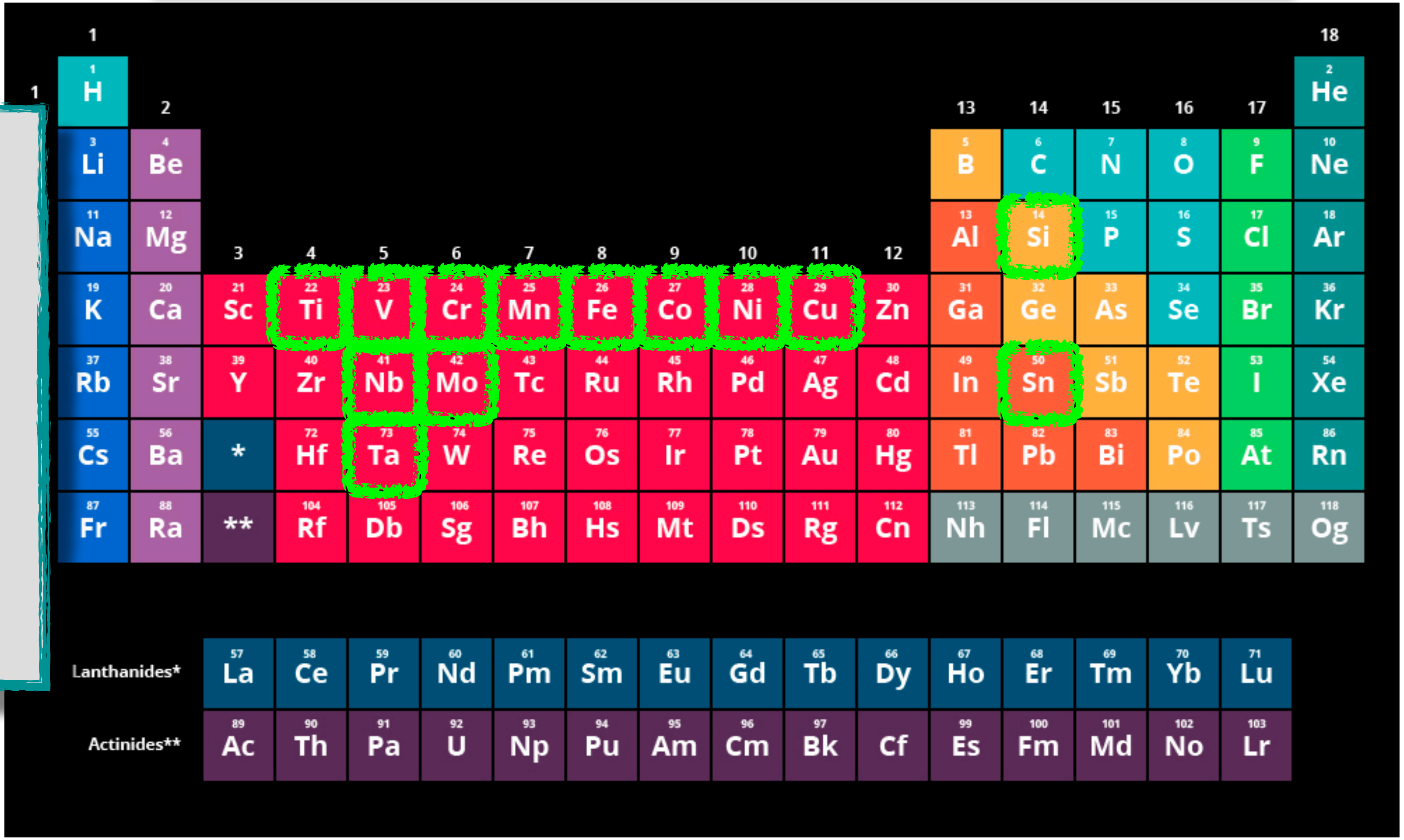

- Mostly structural materials!
- Why are structural materials used as structural materials in nuclear applications?
- Or, why do people like building stuff with this?

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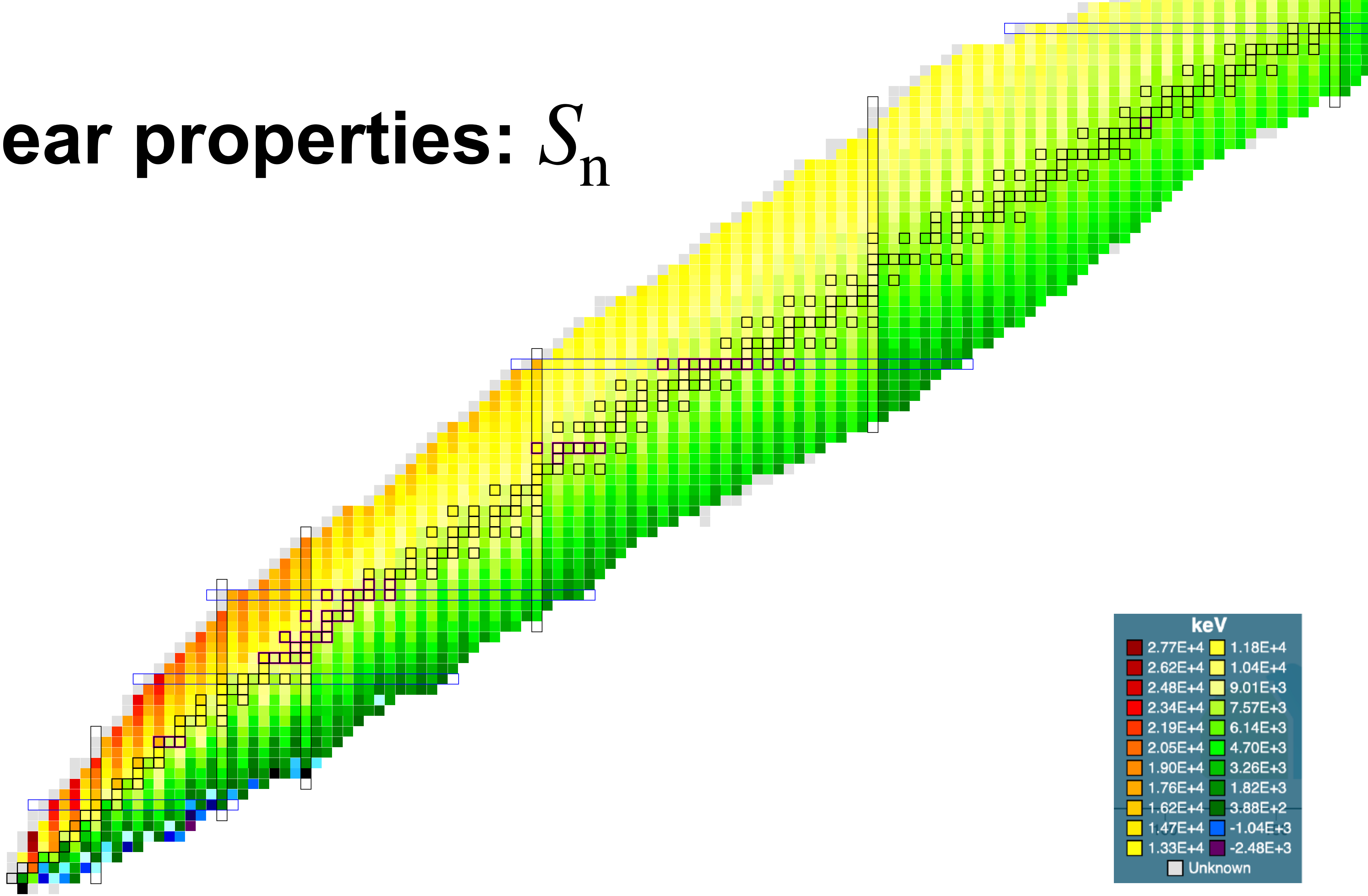
Nuclear properties: S_n



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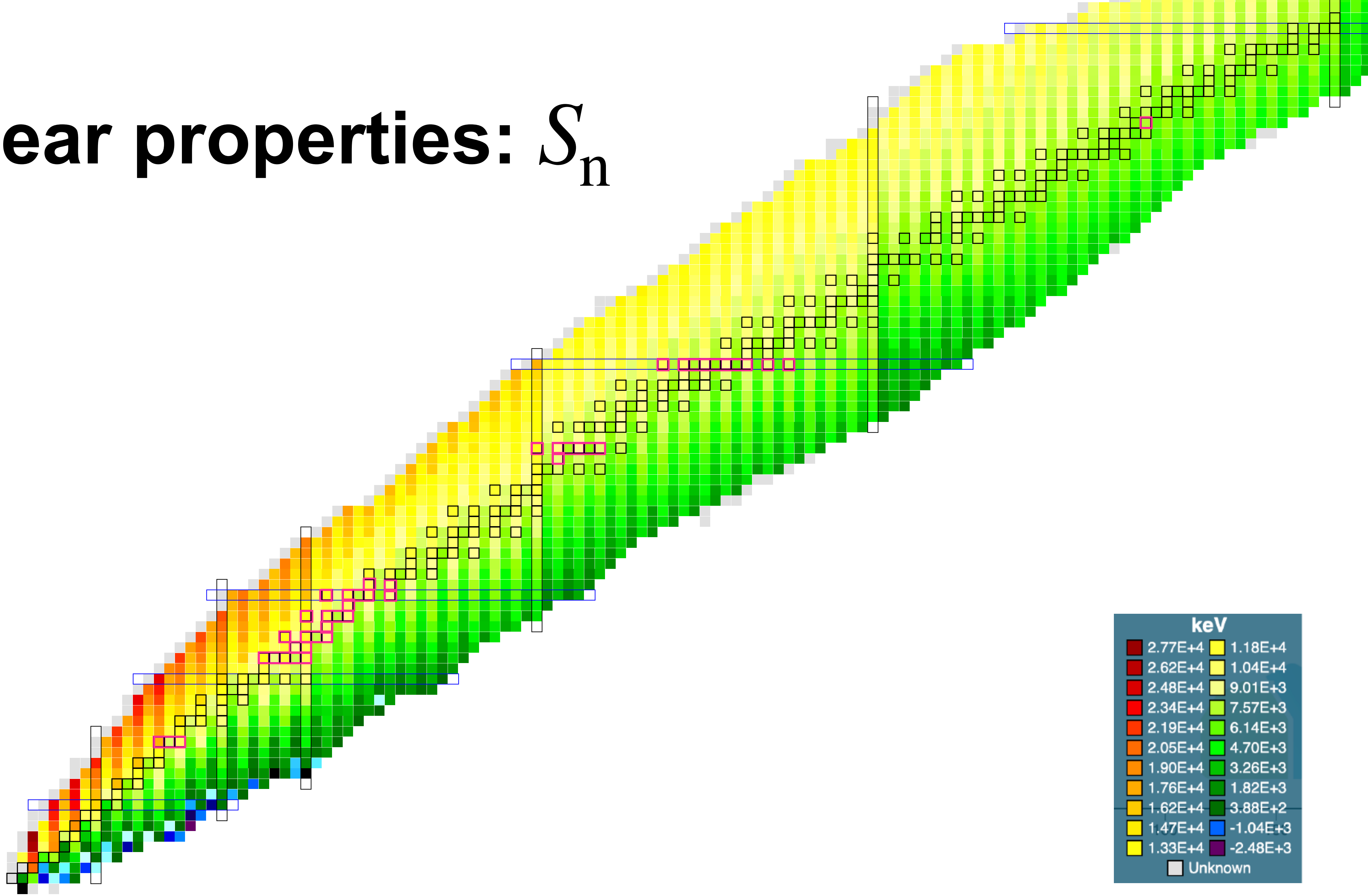
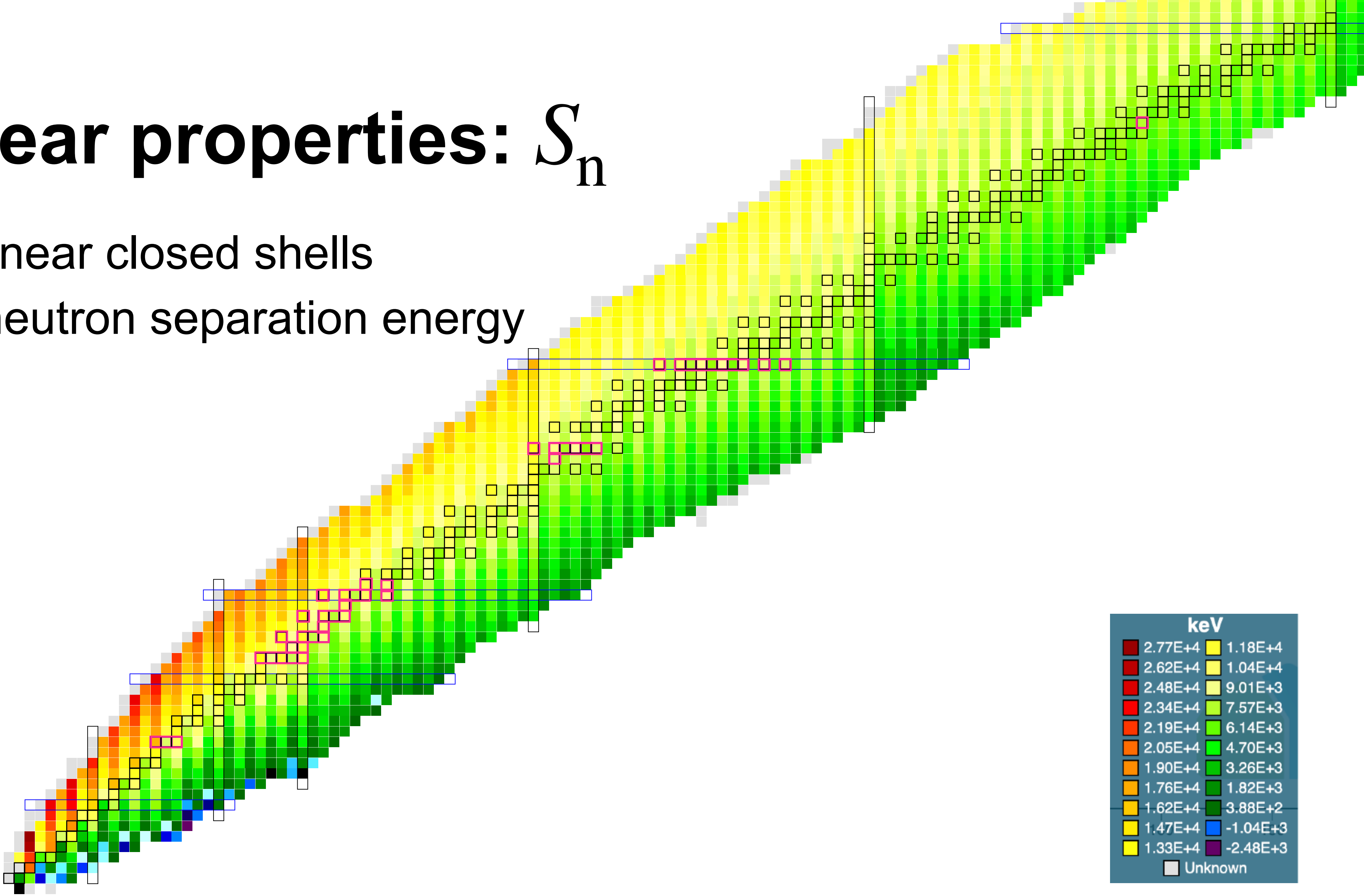


Nuclear properties: S_n

- On or near closed shells
- High neutron separation energy



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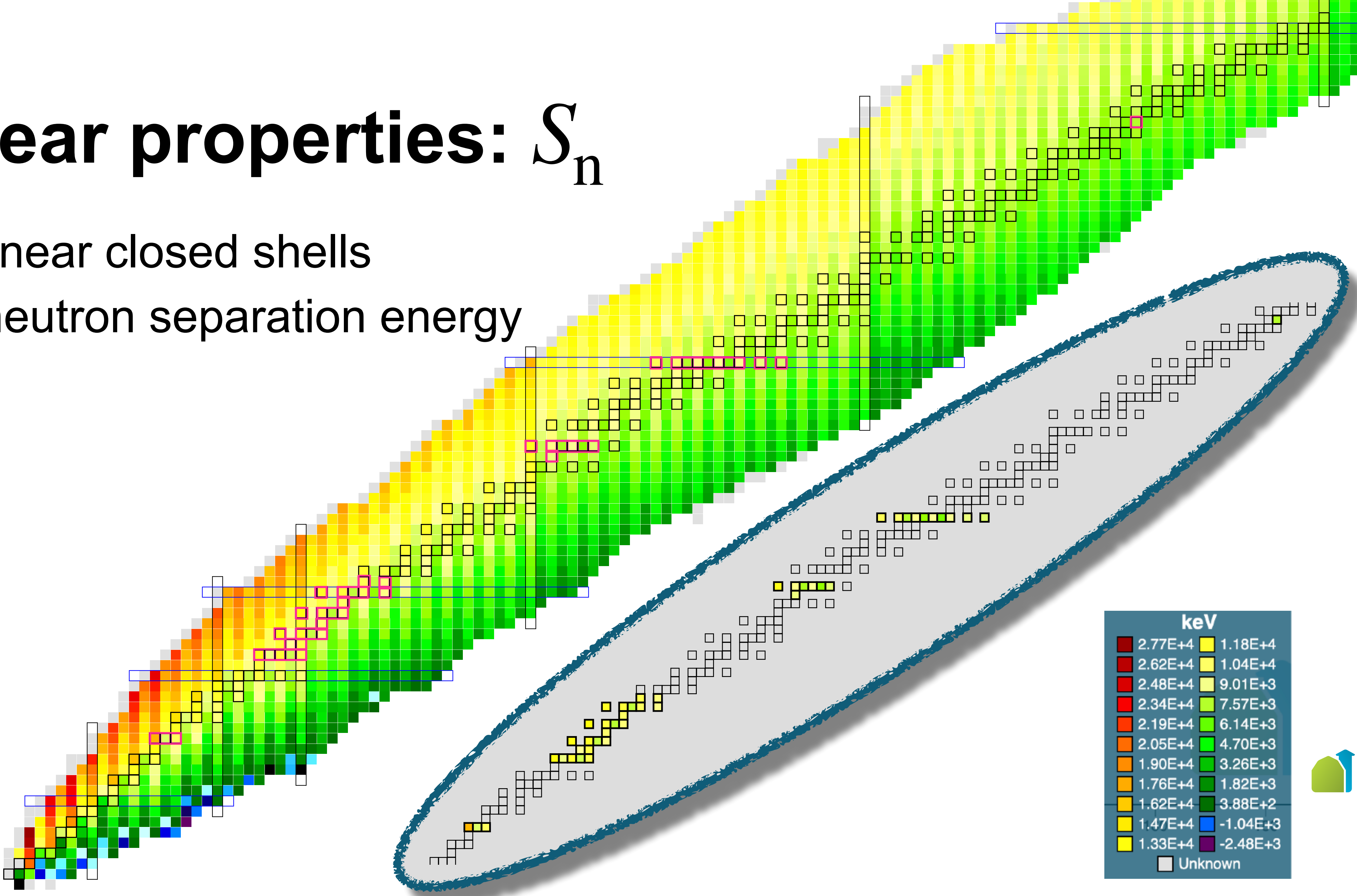
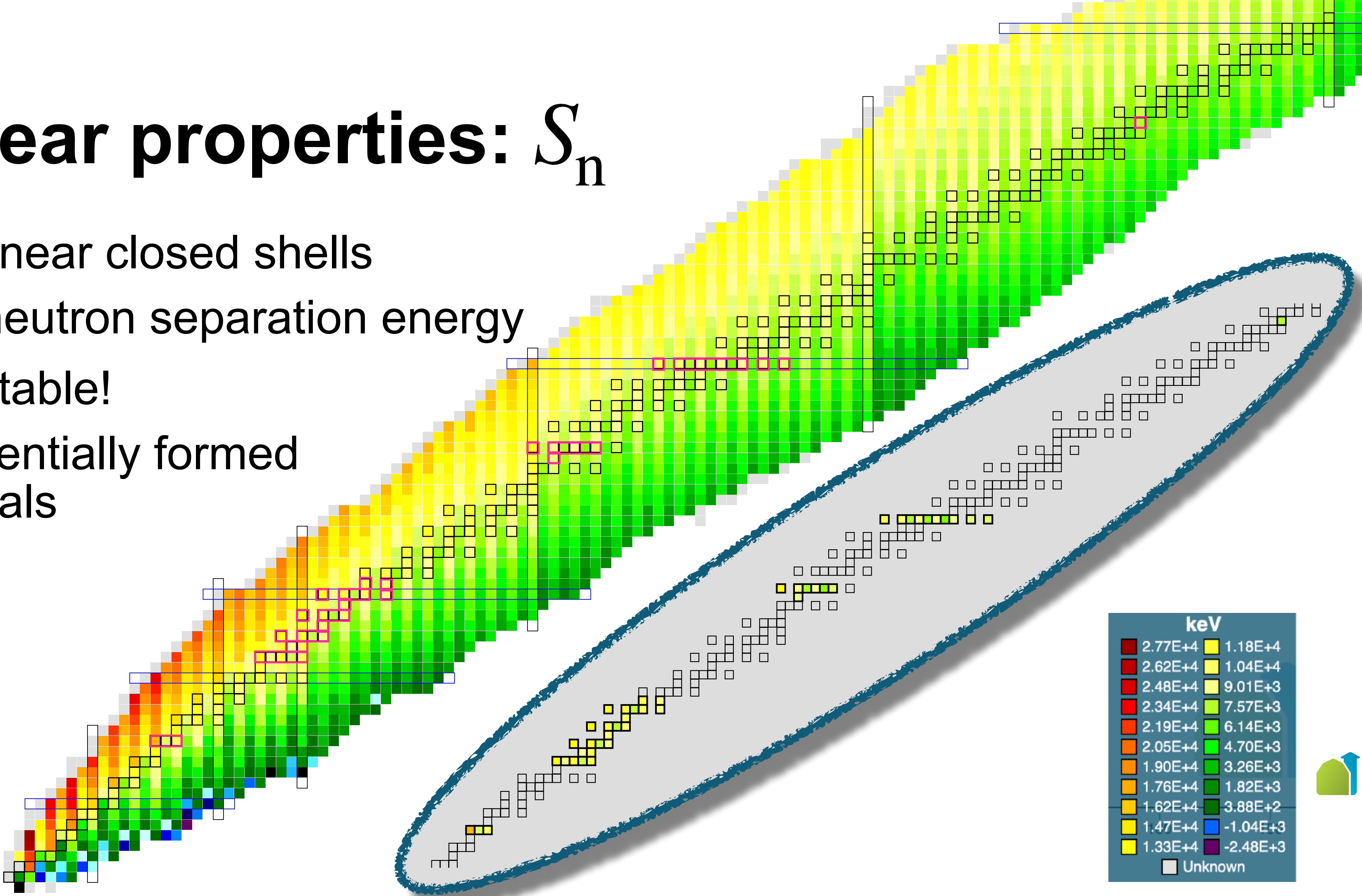


Nuclear properties: S_n

- On or near closed shells
- High neutron separation energy
- Very stable!
- Preferentially formed materials



Nuclear properties: S_n

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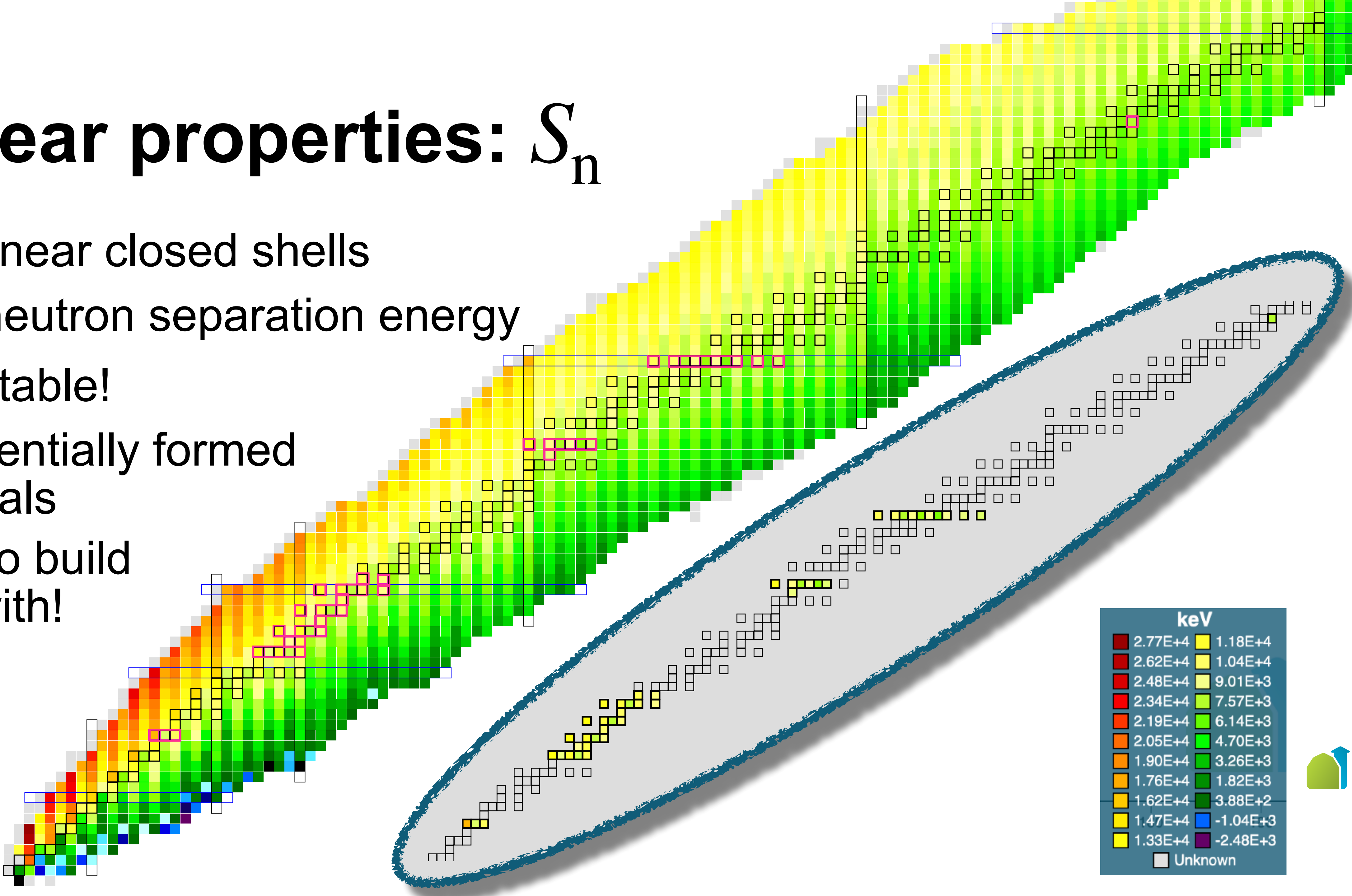
- Ideal to build stuff with!



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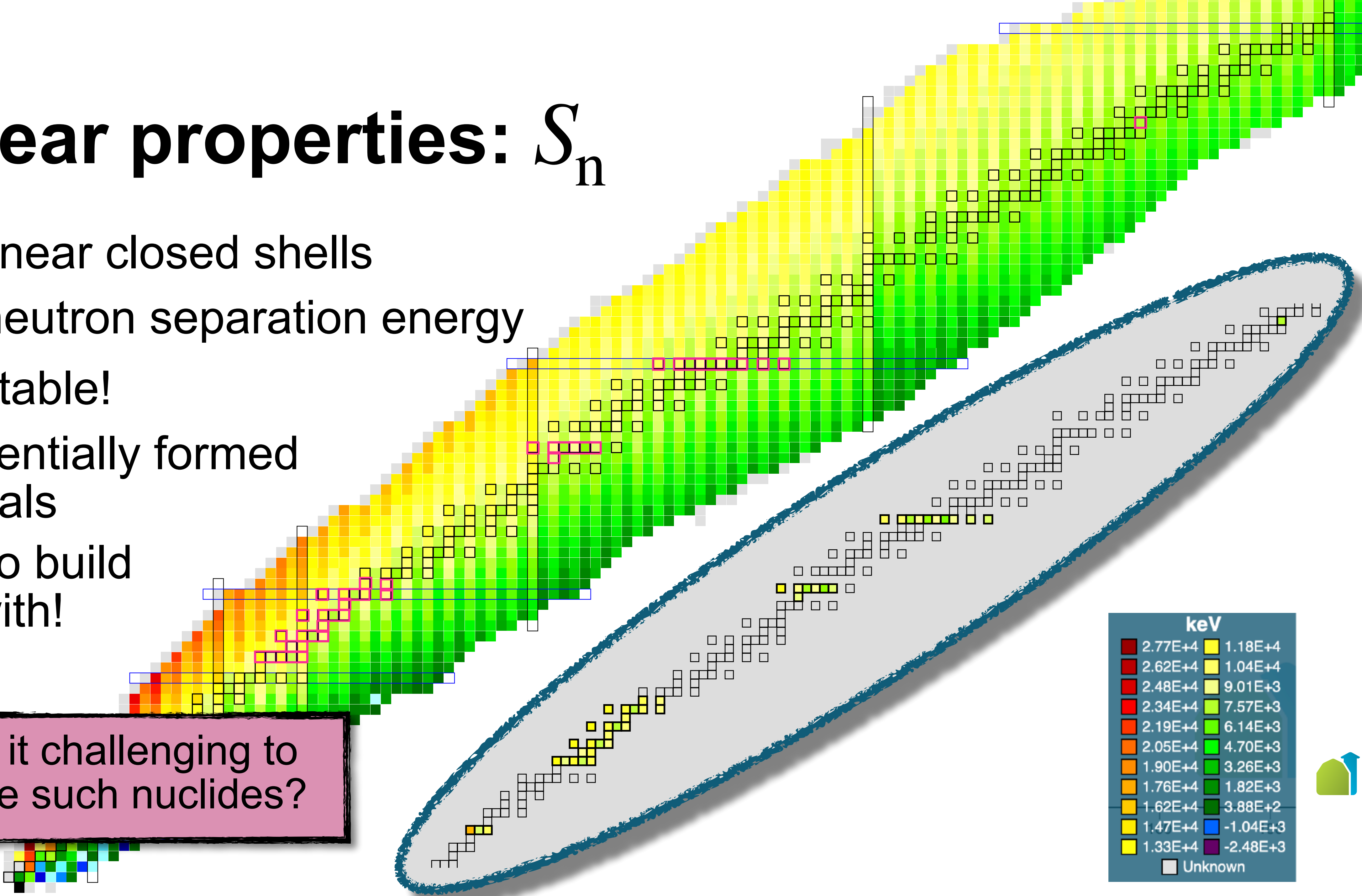

Why is it challenging to evaluate such nuclides?

Nuclear properties: S_n

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- Very stable!
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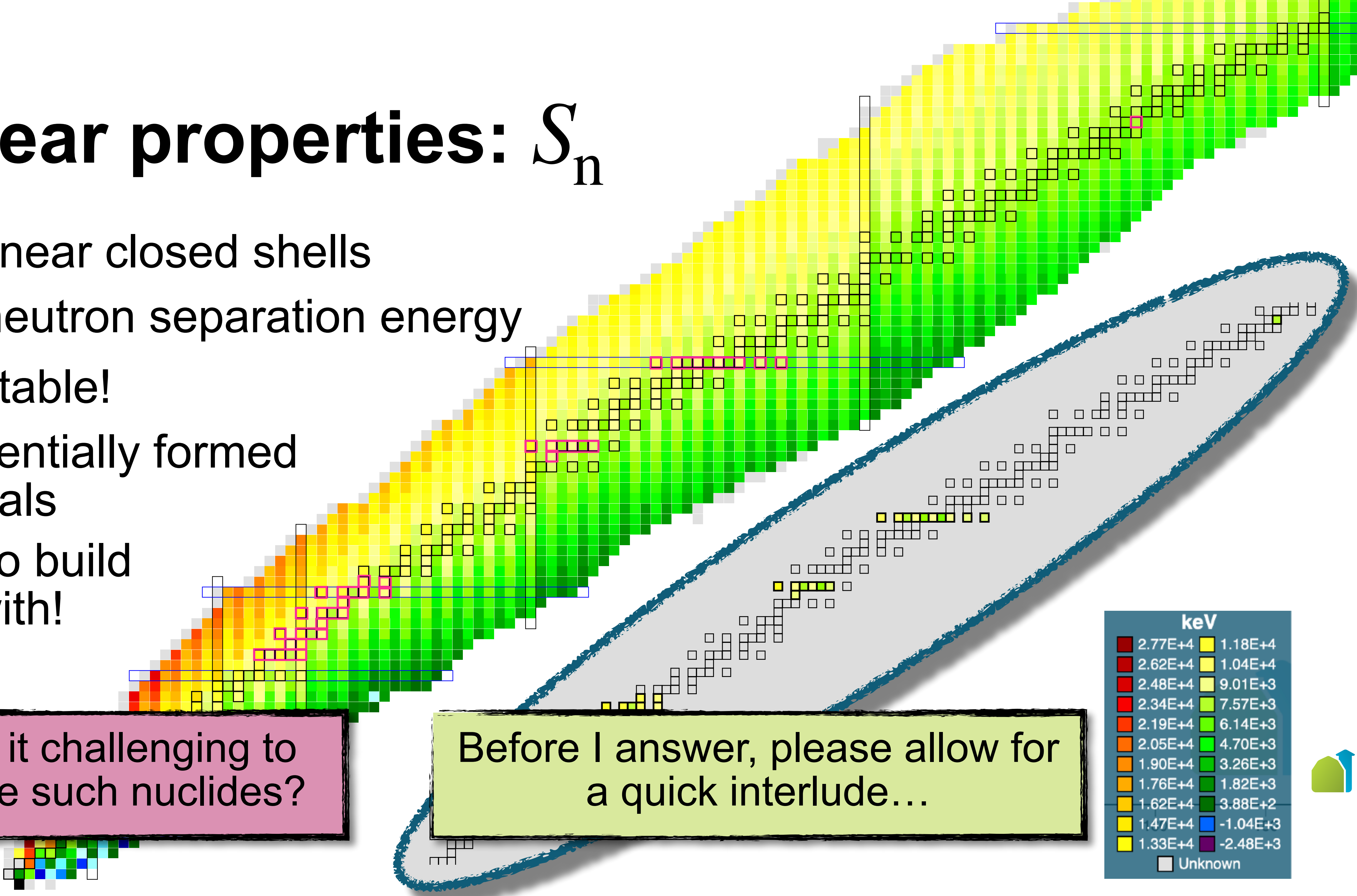
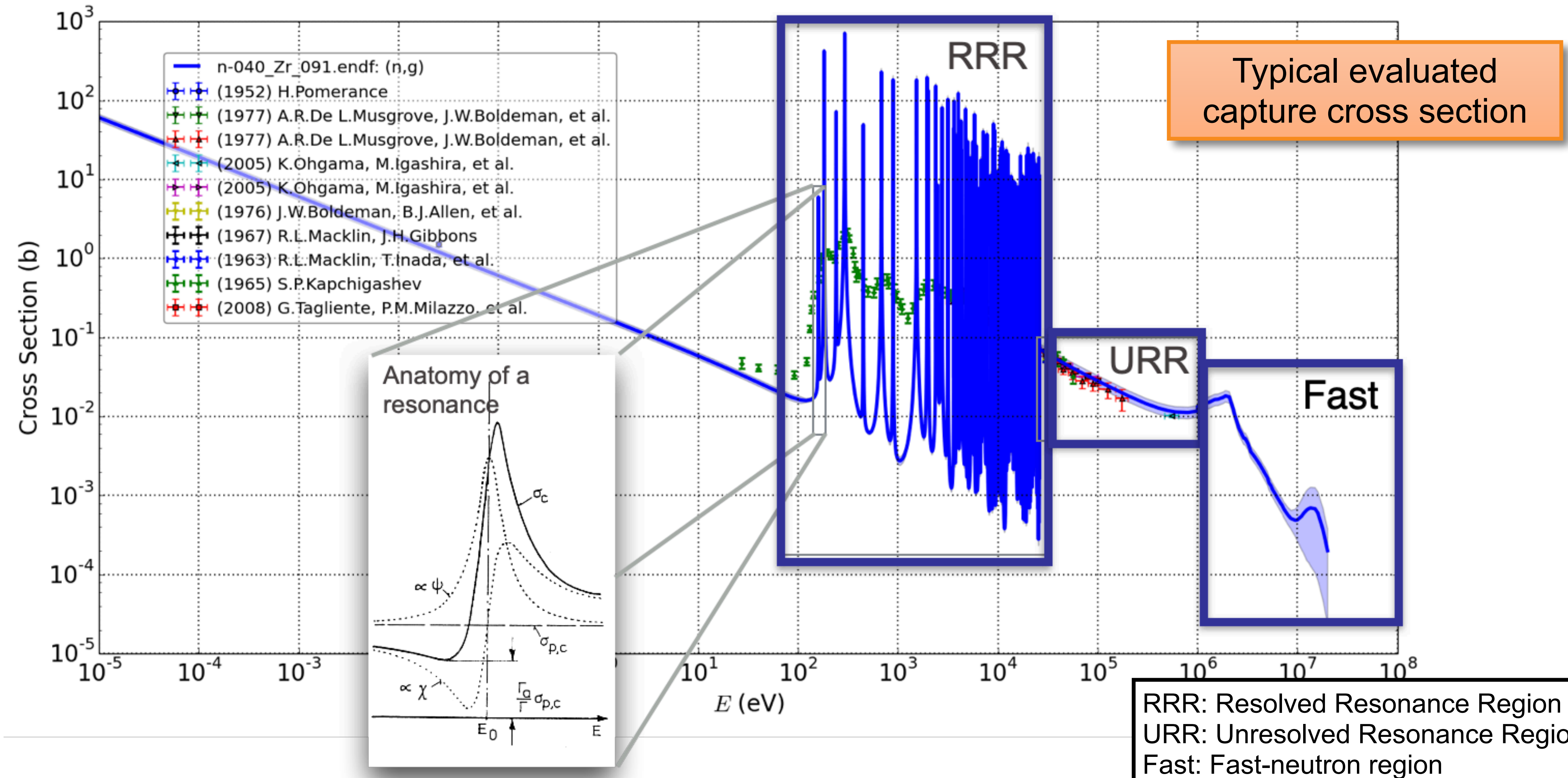


Why is it challenging to evaluate such nuclides?

Before I answer, please allow for a quick interlude…

Cross sections can be split in different regions



RRR: Resolved Resonance Region
URR: Unresolved Resonance Region
Fast: Fast-neutron region

Characterizing the different energy regions

D → resonance spacing
Γ → resonance width
ΔE → experimental resolution

- RRR:
  - Resonances can be individually resolved
  - Resonances parametrized individually (R-matrix)

$$\frac{\langle \Gamma \rangle}{\langle D \rangle} \rightarrow \text{small}$$

- URR:
  - Resonances cannot be experimentally resolved from one another
  - Description based on average cross sections and probability distributions

$$\frac{\langle \Gamma \rangle}{\langle D \rangle} \approx 1; \frac{\Delta E}{\langle D \rangle} \rightarrow \text{big}$$

- Fast:
  - Resonances are so wide and so close together that they average each other out
  - Measured cross section is smooth

$$\frac{\langle \Gamma \rangle}{\langle D \rangle} \rightarrow \text{big}$$

Example of opposite case to the nuclei discussed here

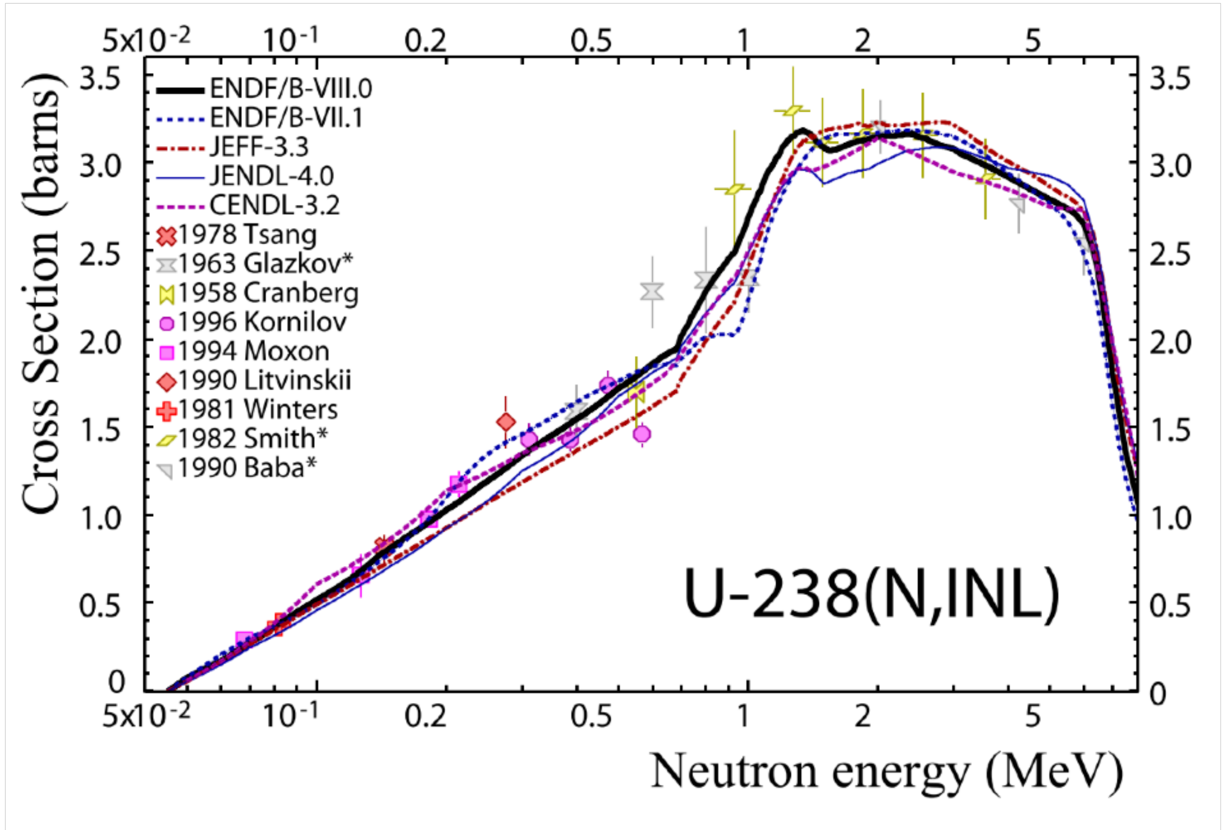


FIG. 1. Evaluated [21–26] and experimental ^{238}U inelastic scattering cross section data [7,8,10–16]. The experimental data marked with * have been corrected using model calculations.

*Taken from Kerveno et al., PRC**104**, 044605 (2021)*

- Fast neutron region starts at really low energies
- Cross sections are smooth down to very low energy

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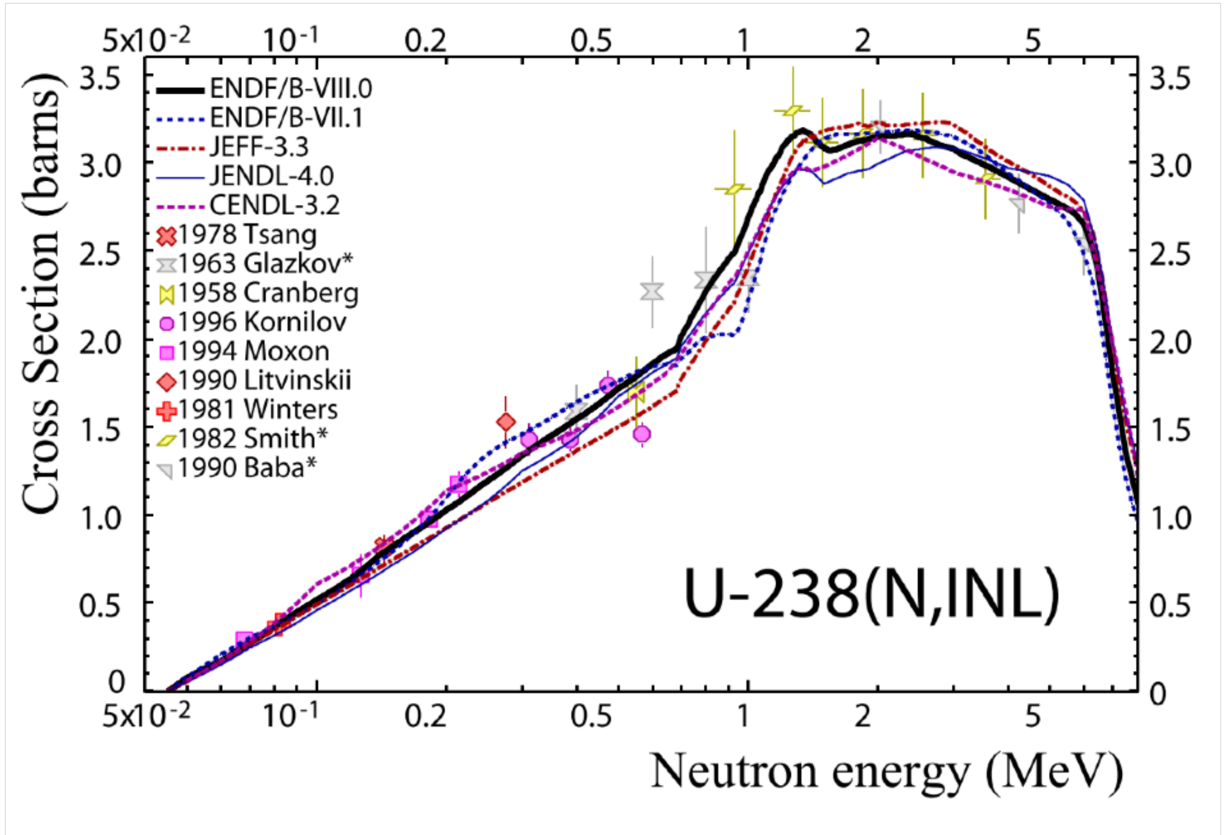

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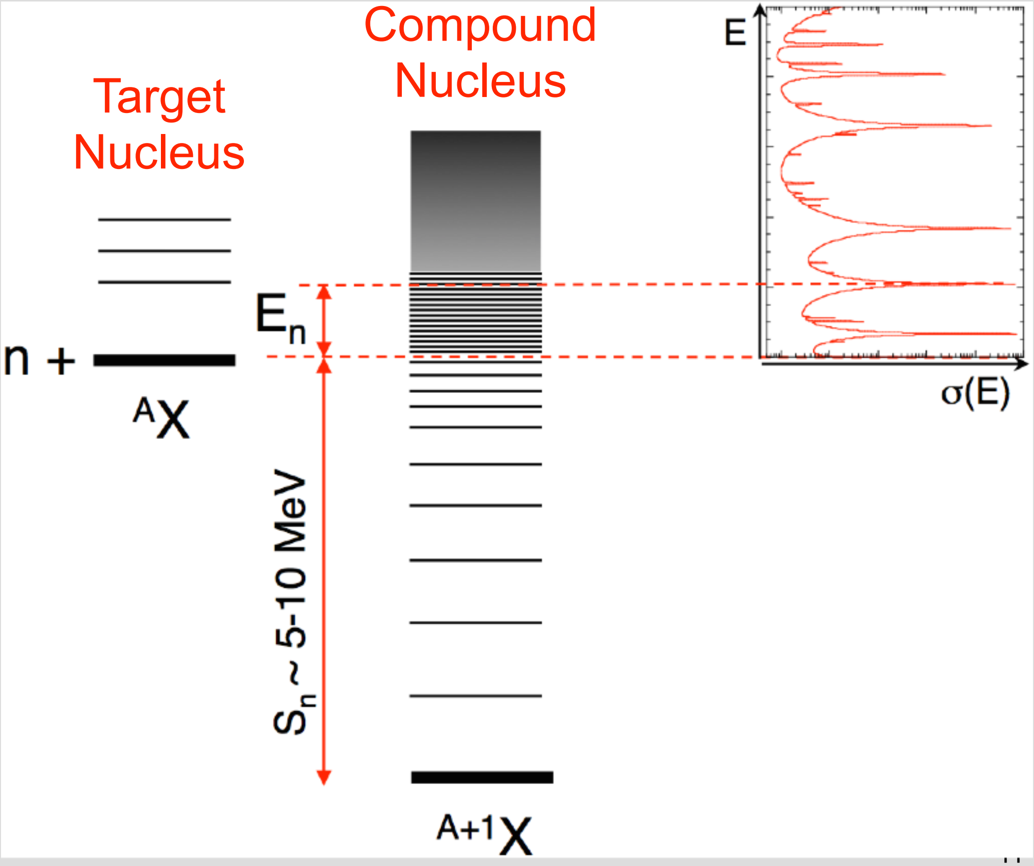

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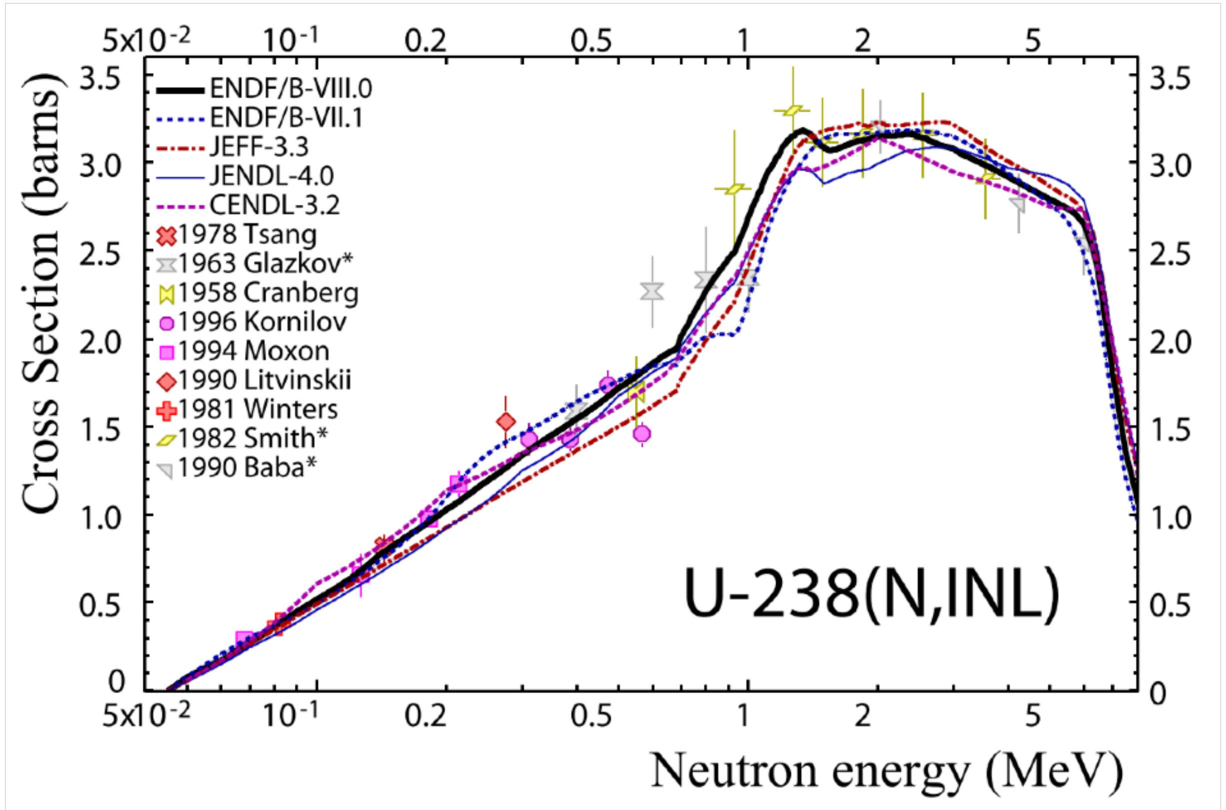

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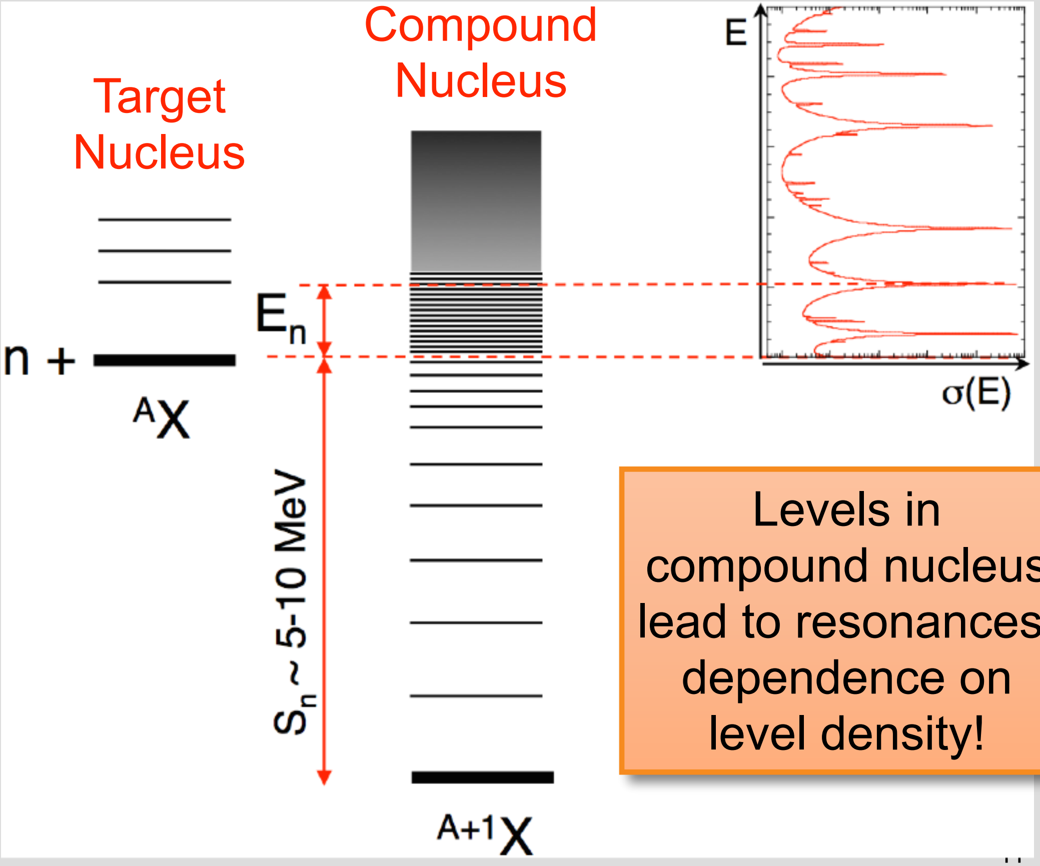
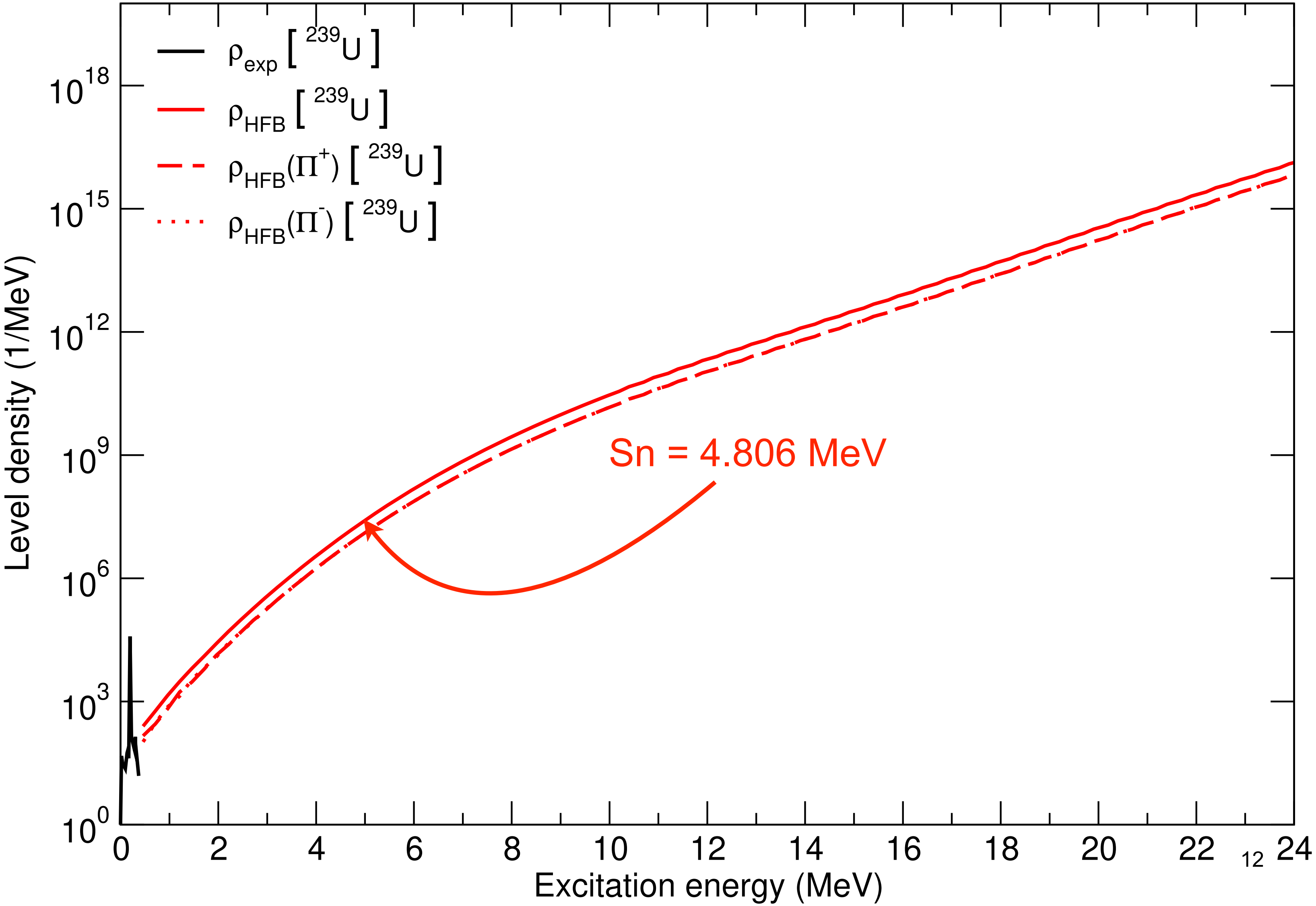


Levels in compound nucleus lead to resonances: dependence on level density!

Challenges for nuclei discussed here: Low Nuclear Level Densities

- For scattering off ^{238}U:
  - So many levels even at "0" neutron energy
  - Resonance region ends at 20keV



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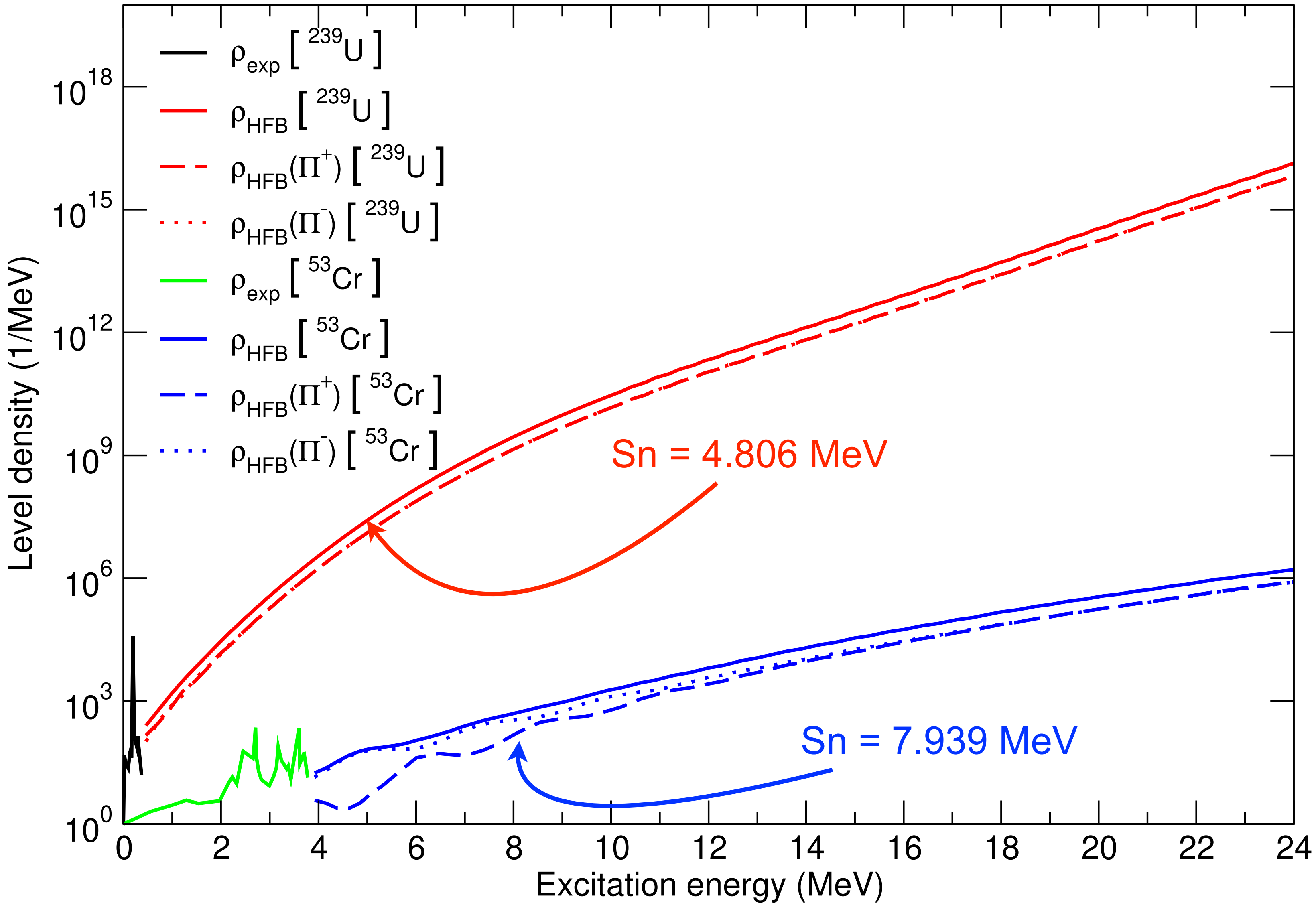
- For ^{52}Cr:
    - Even a few MeV above “0” neutron energy there’s a factor of 10^7 fewer levels in compound nucleus
    - Cross-section fluctuations extend to much higher energy



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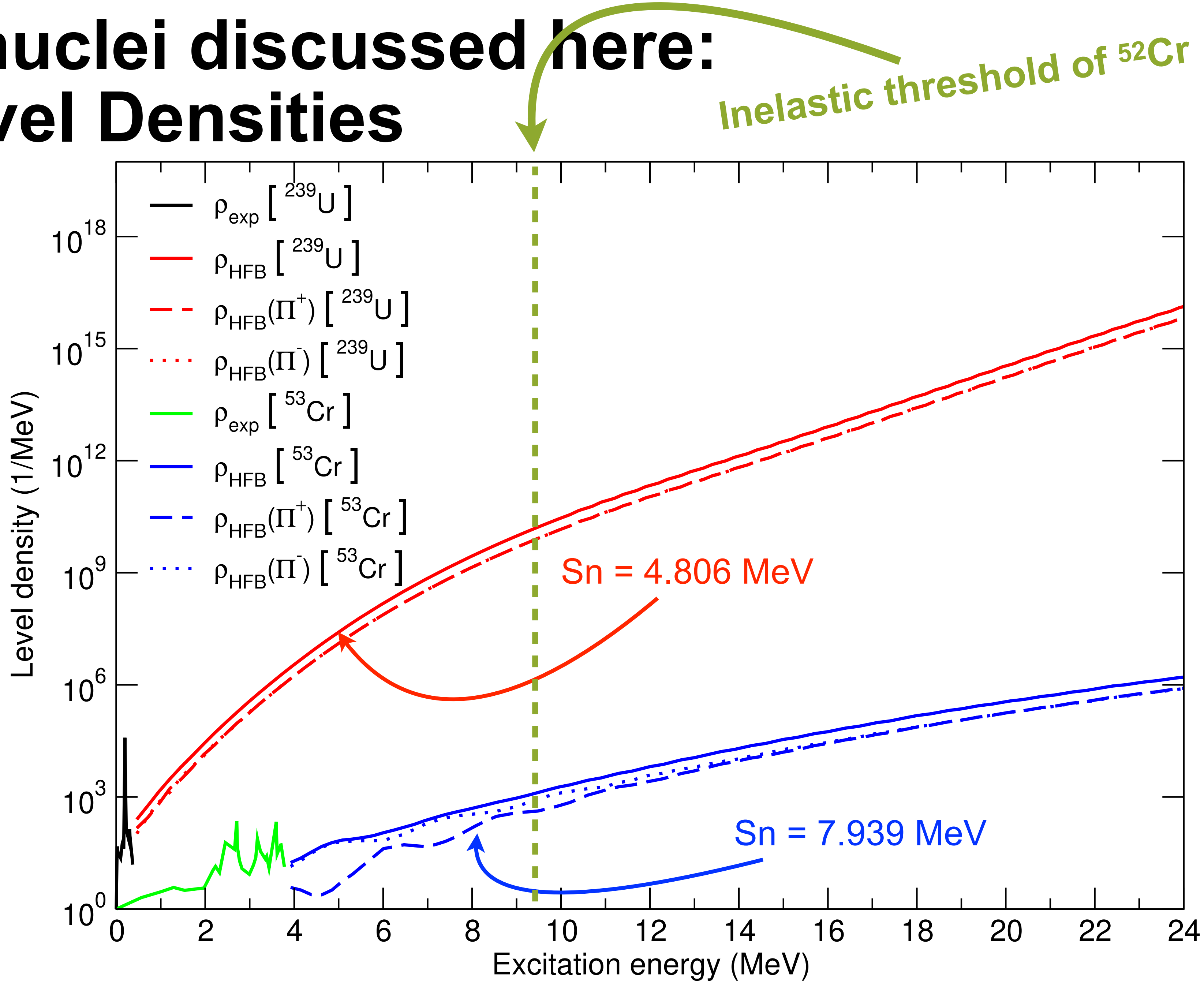

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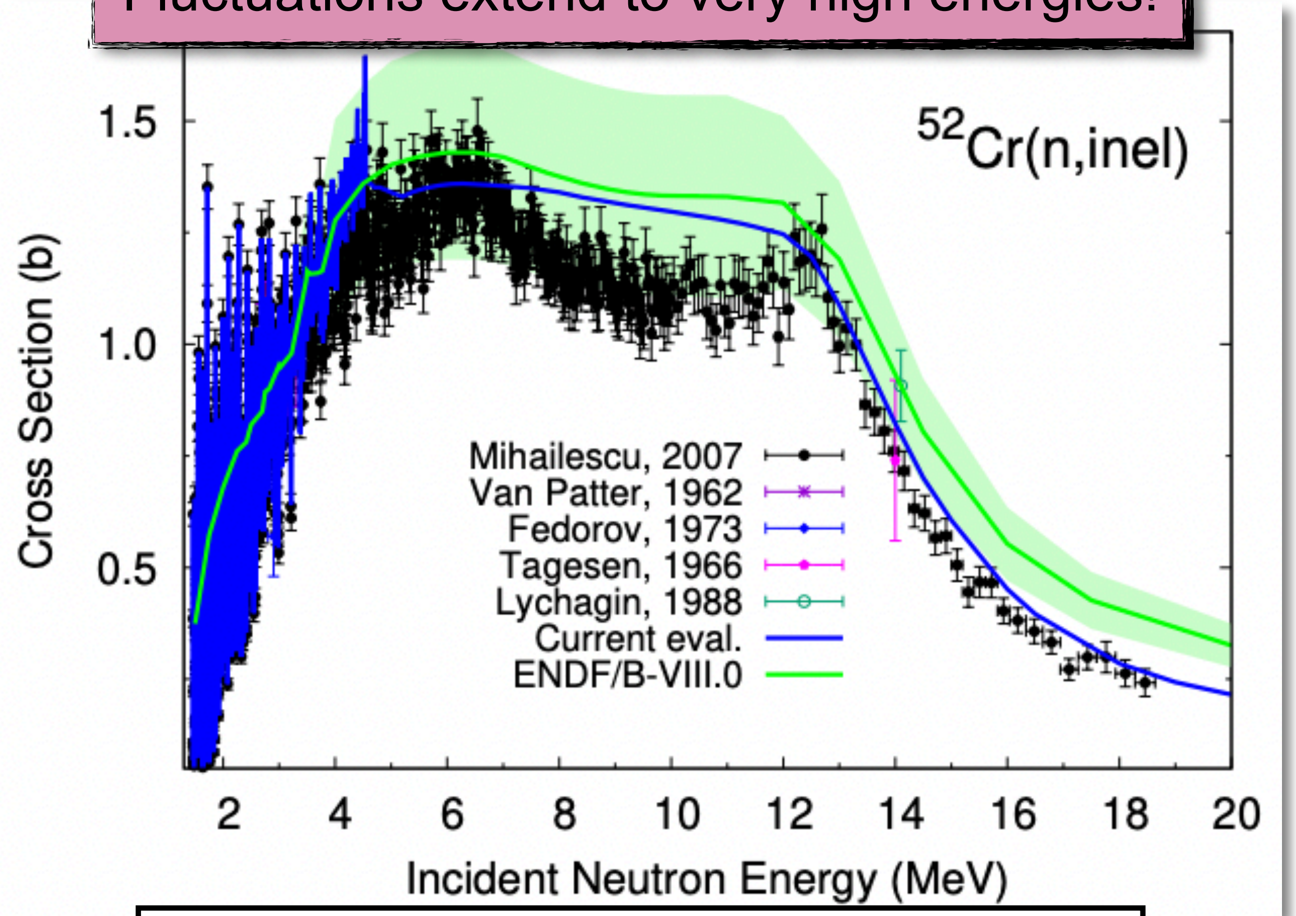

From latest ENDF/B chromium evaluation: Nuclear Data Sheets 173 (2021) 1-41

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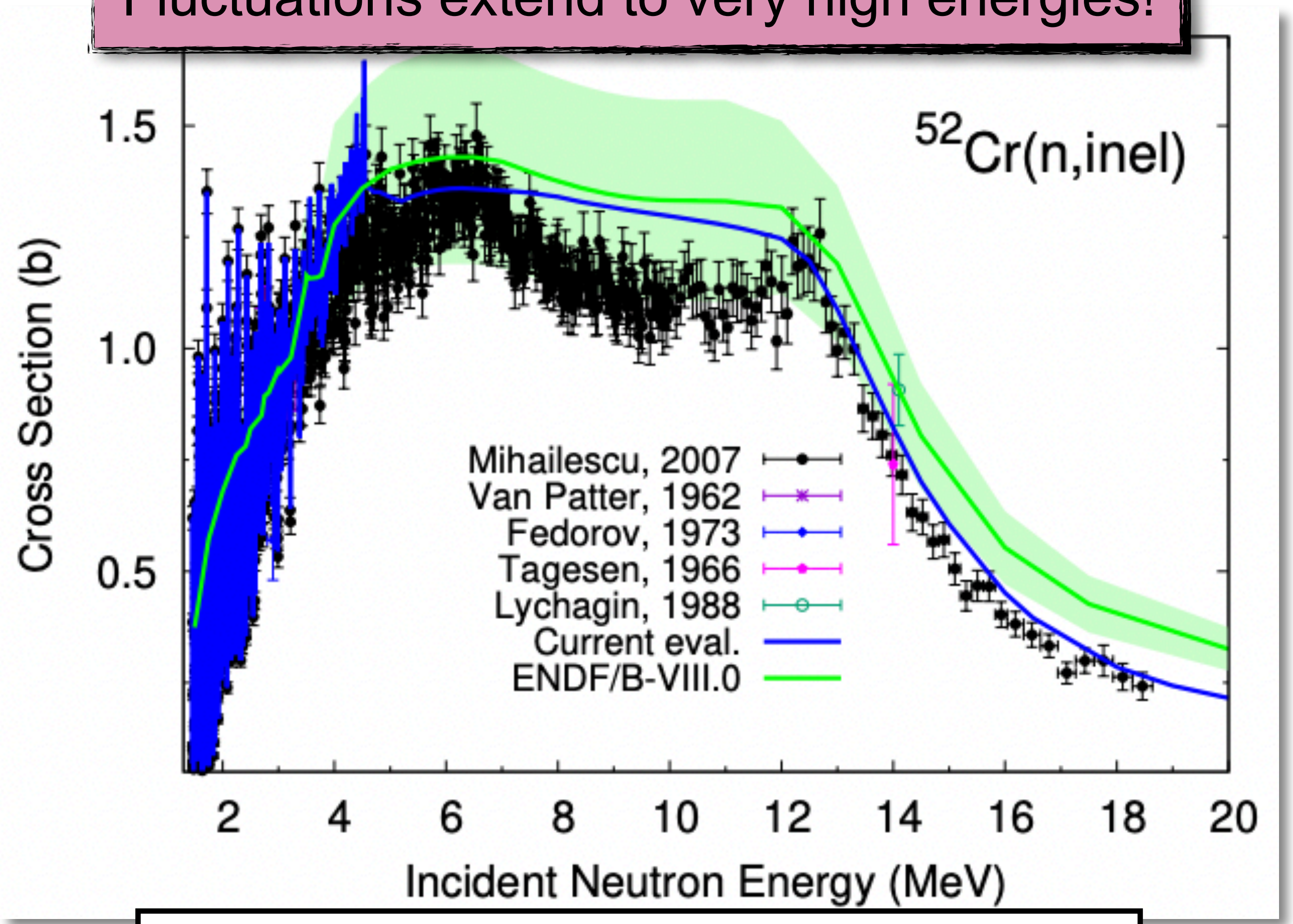
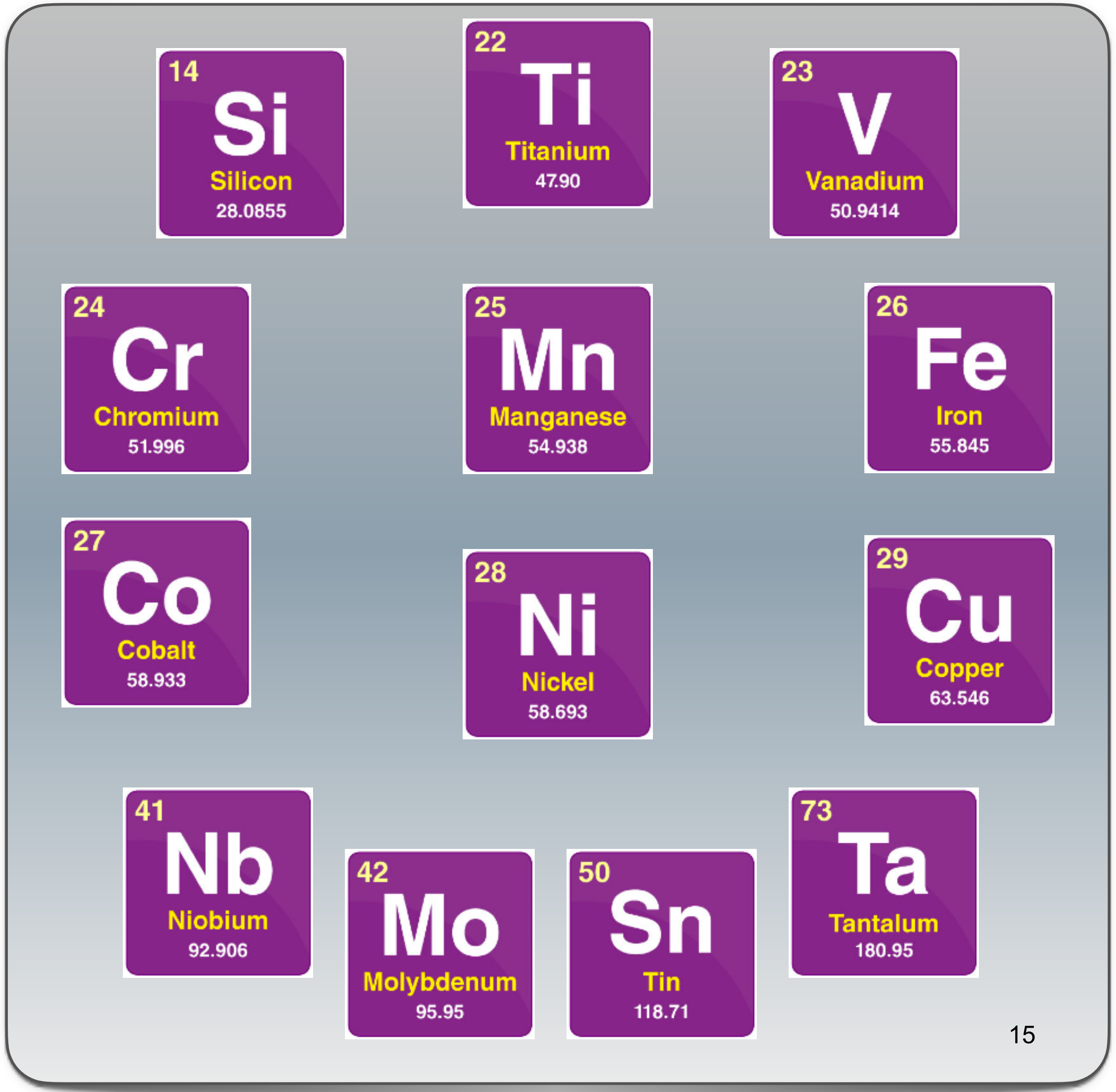


From latest ENDF/B chromium evaluation: Nuclear Data Sheets 173 (2021) 1-41

- No single approach is fully applicable:
  - Cannot use R-matrix like with standalone resonances
  - Cannot use probability distributions as in URR
  - Cannot simply use smooth models from fast regions
- Delicate combination of approaches, model and data
  - E.g., not fully spherical nuclei, not deformed: soft-rotor potentials

Current status in ENDF/B library

- Recently evaluated (VIII.1)
- Not-so recently evaluated (VIII.0)
- Would benefit from additional evaluation effort
- Needing some crucial evaluation work
- Old evaluations, need new effort!



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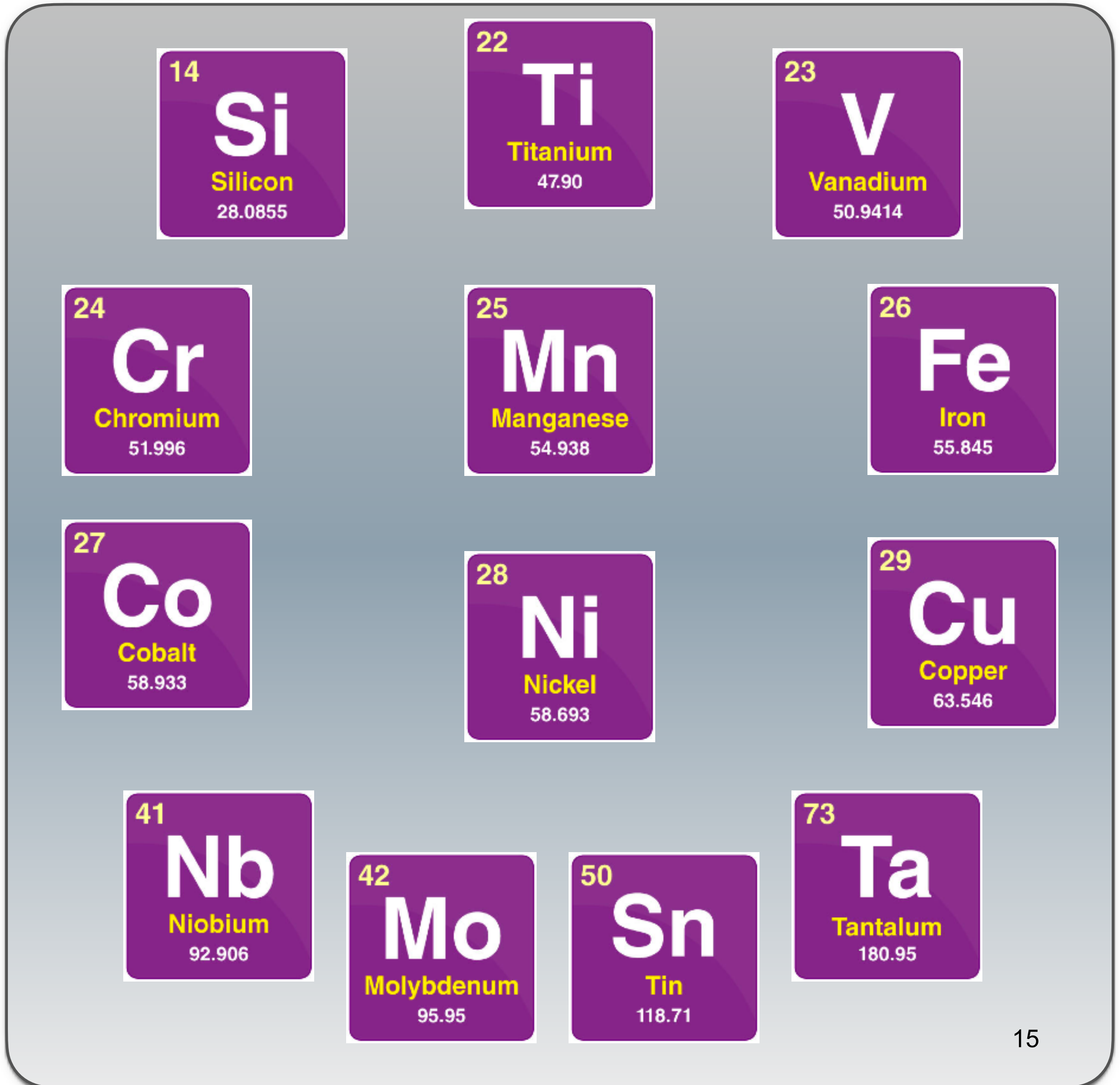

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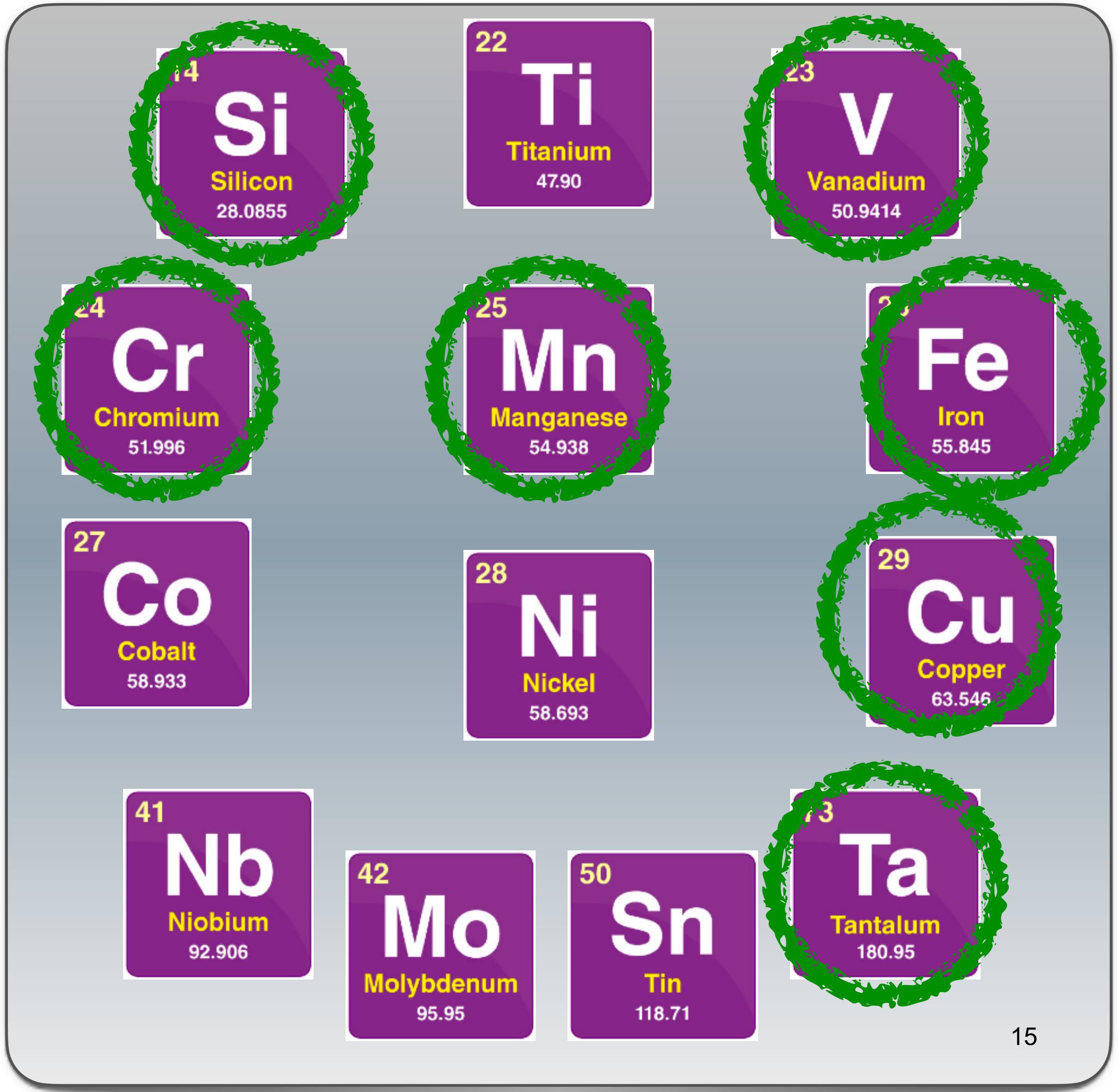

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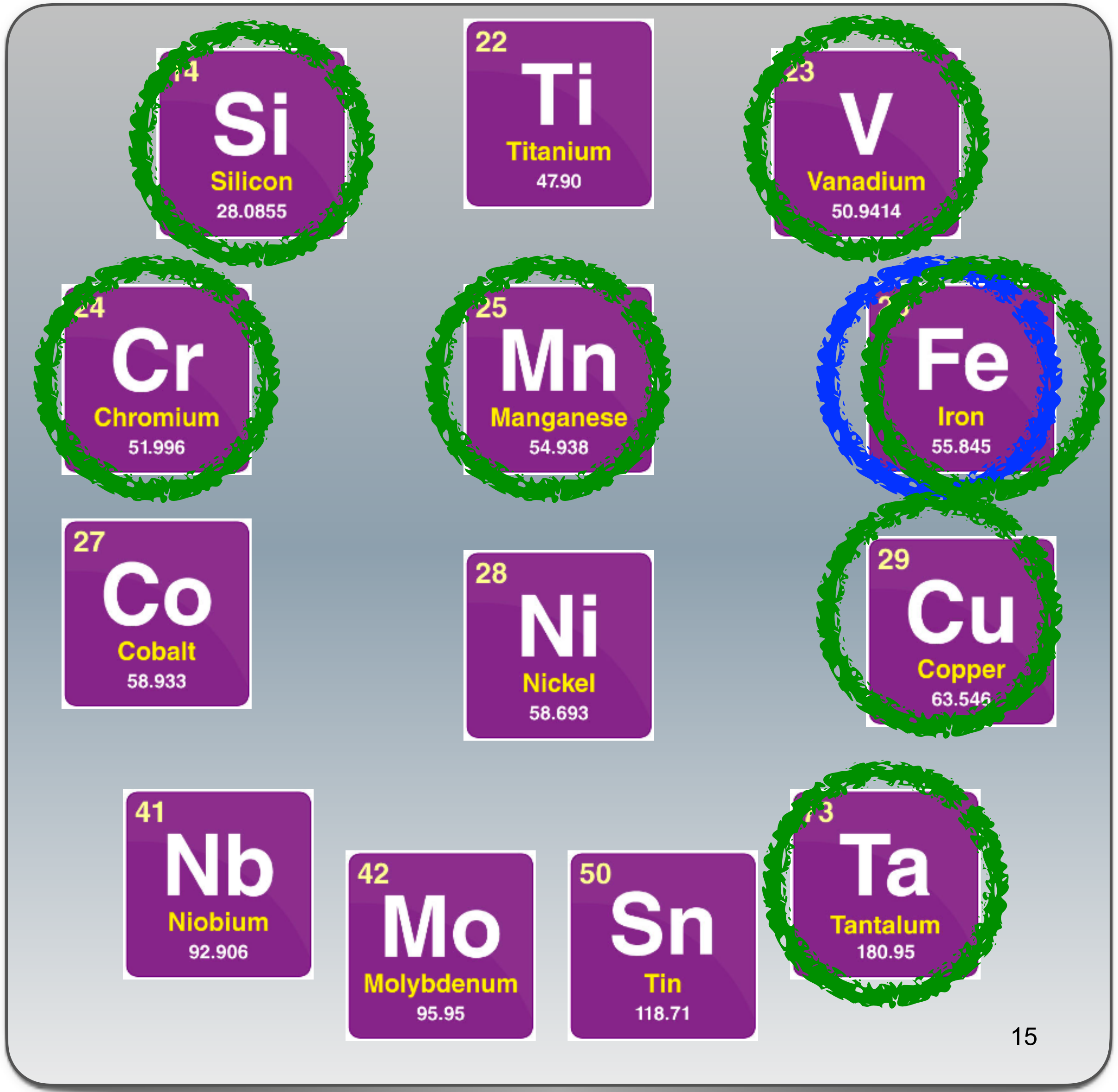

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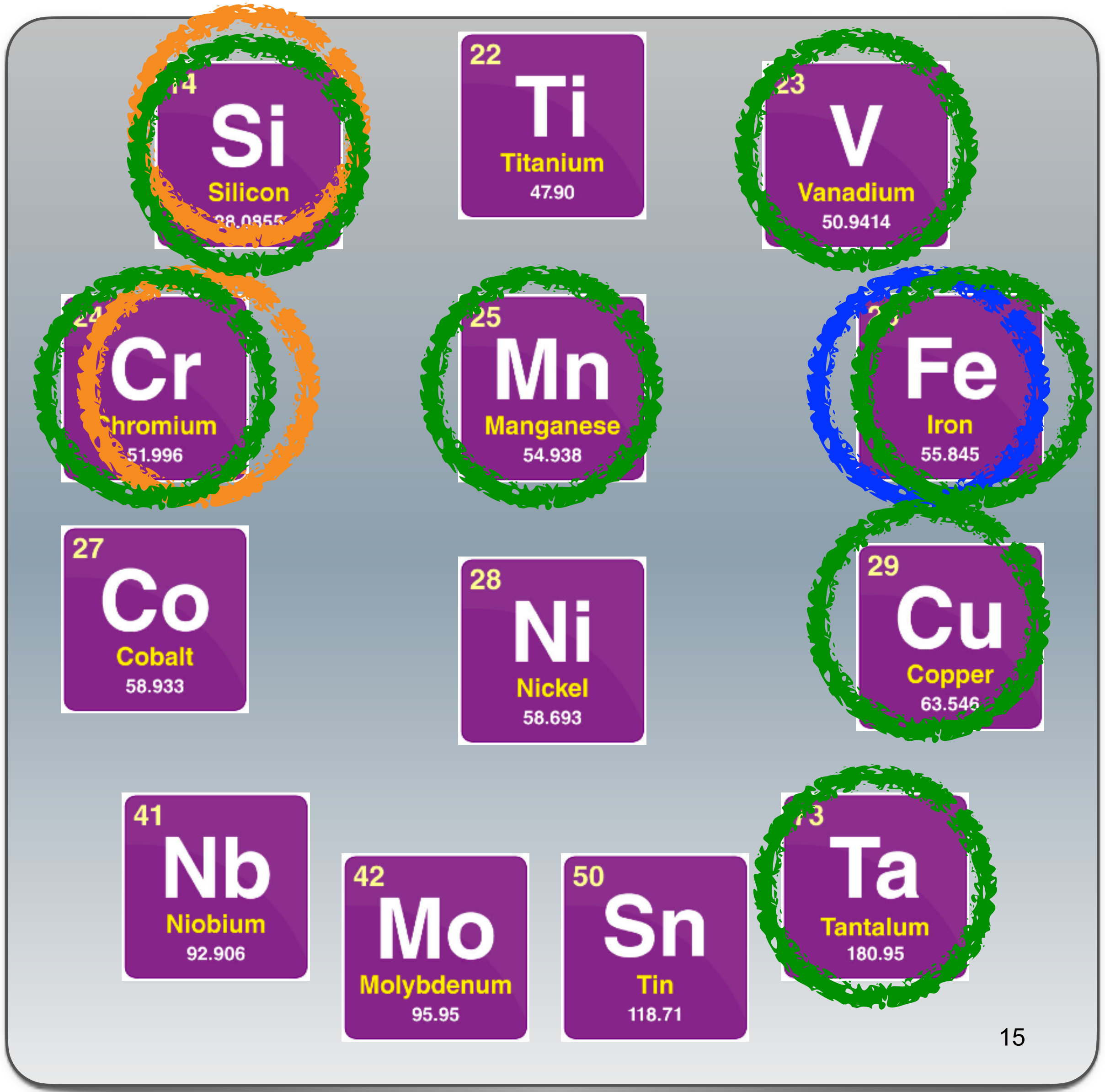

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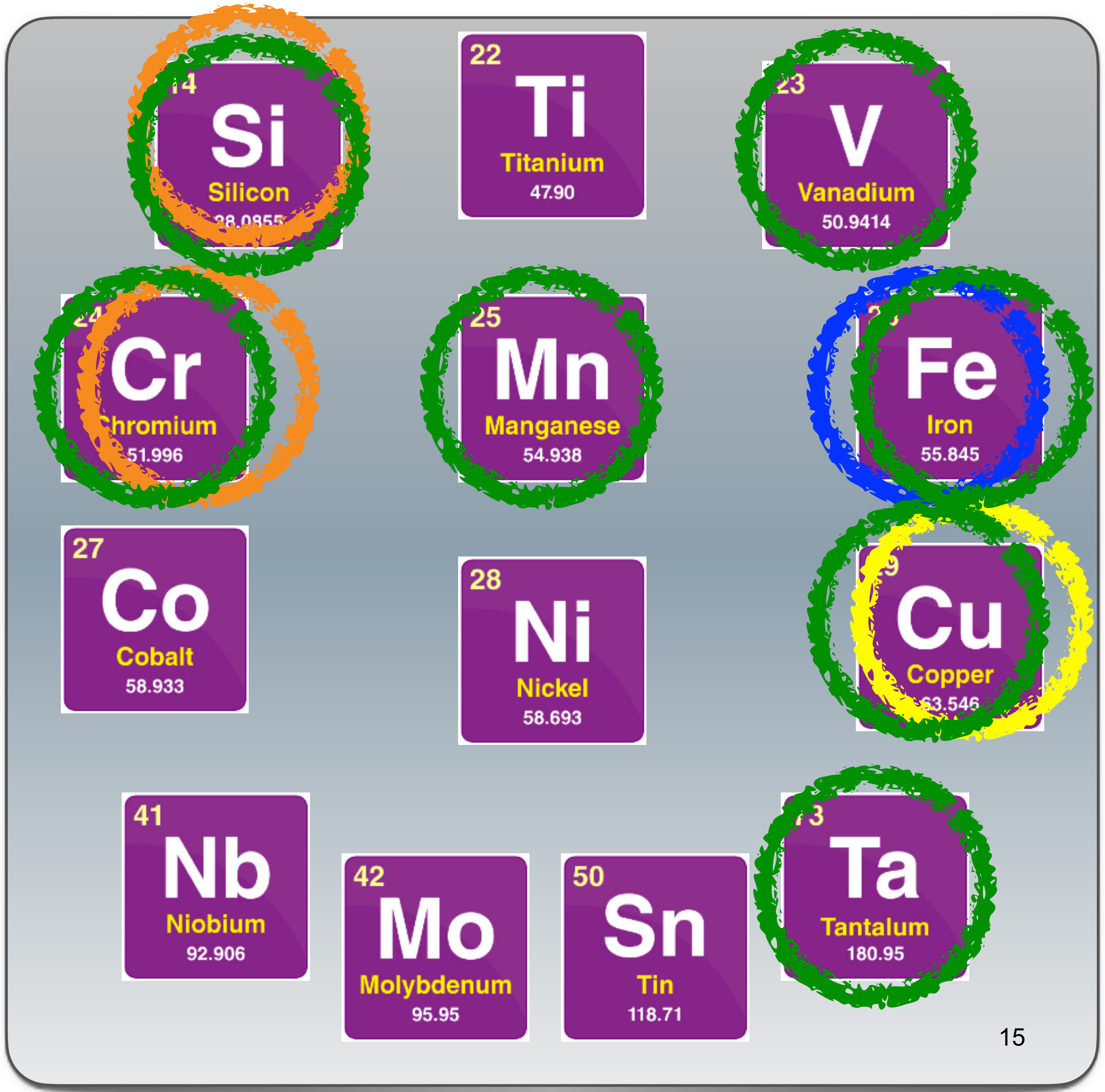

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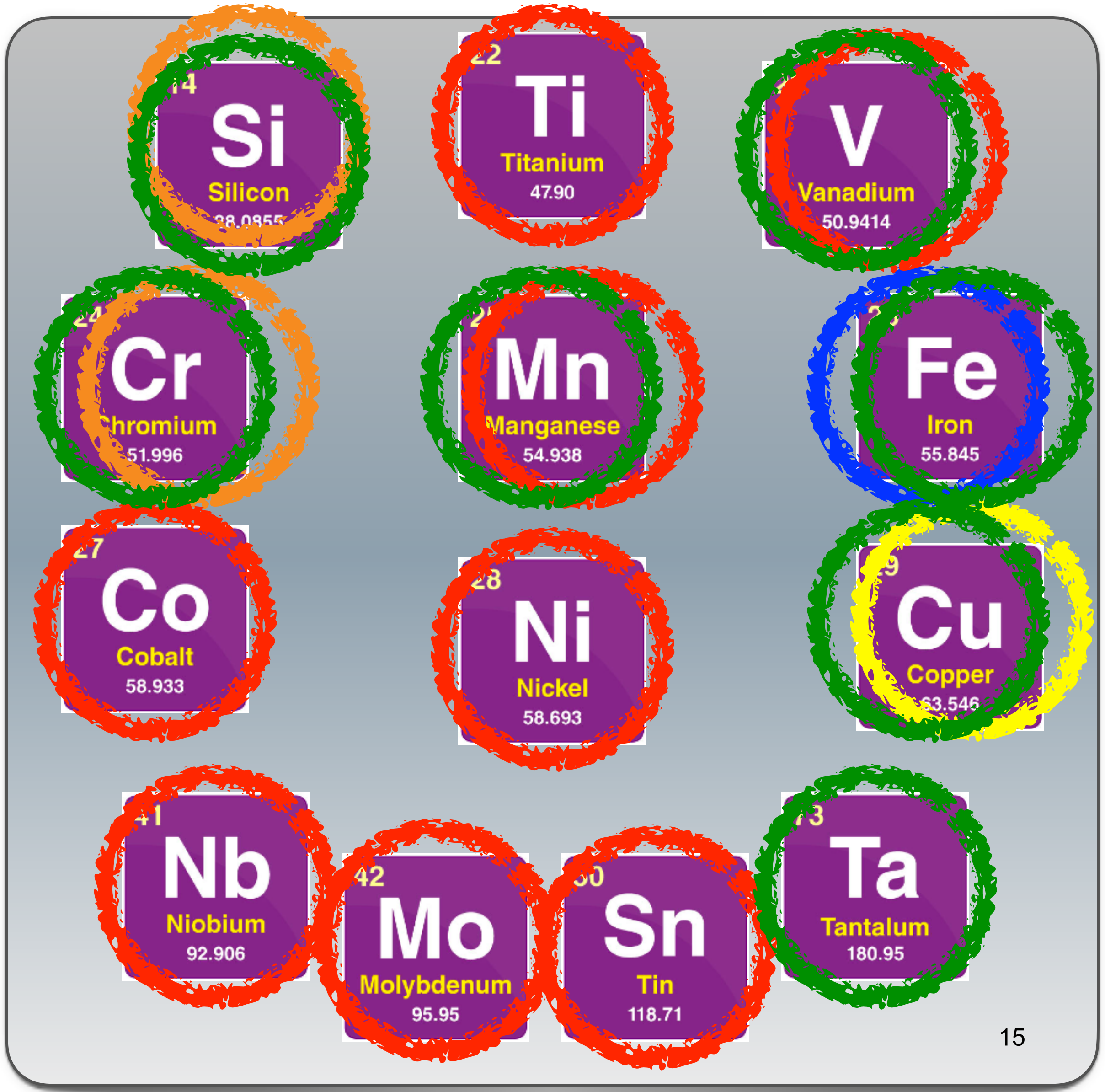

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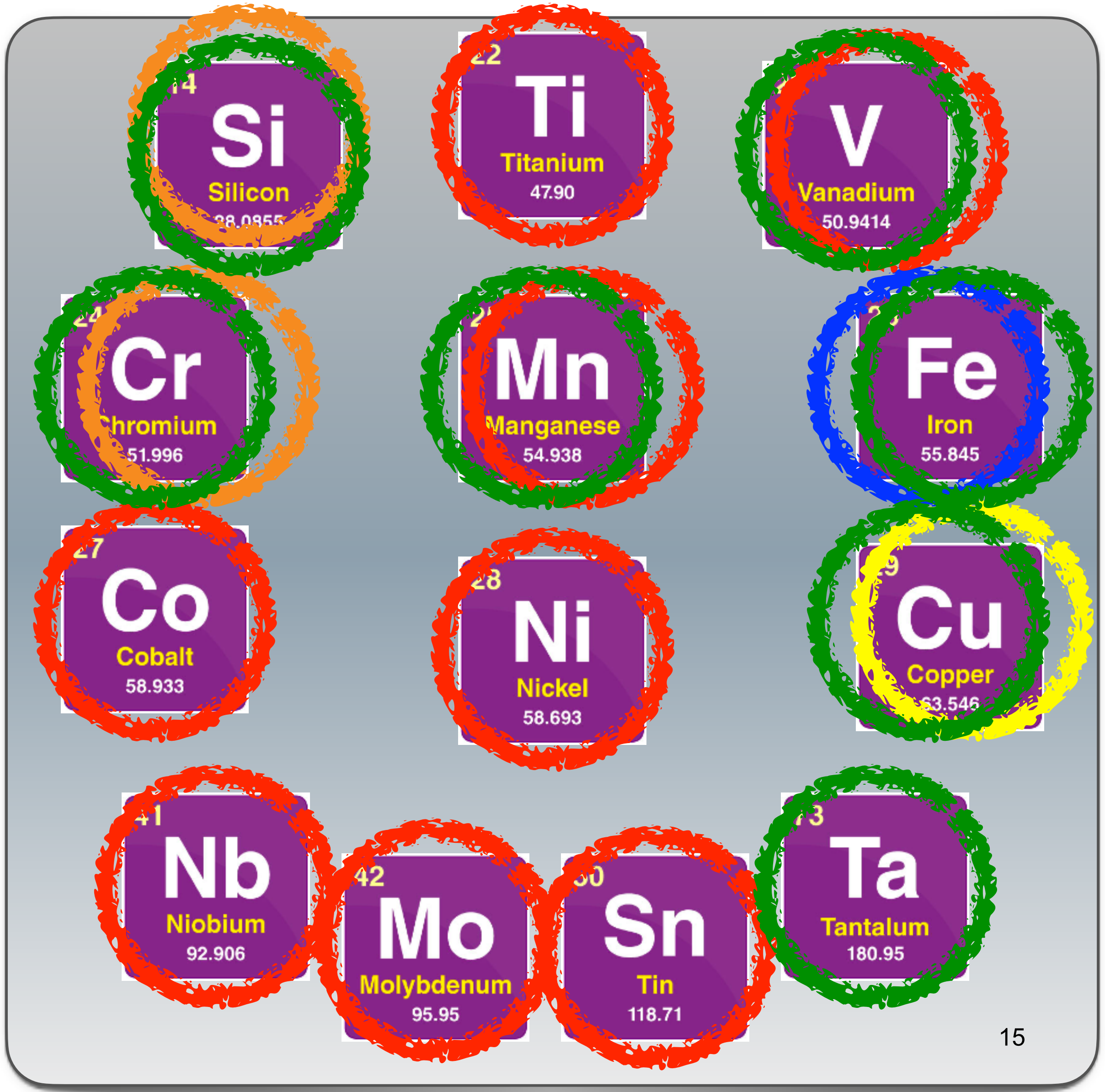
- **What do we need?**



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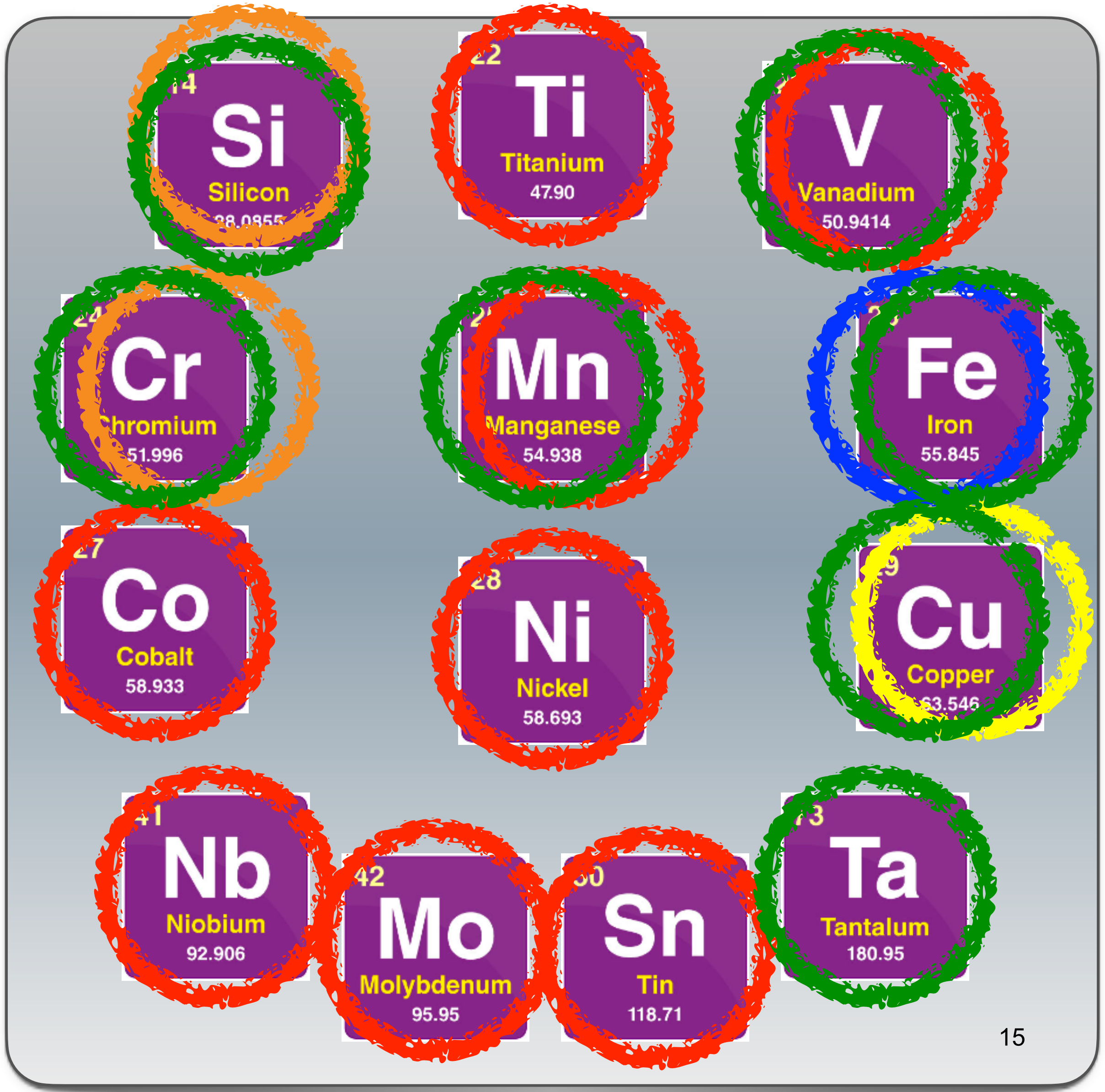
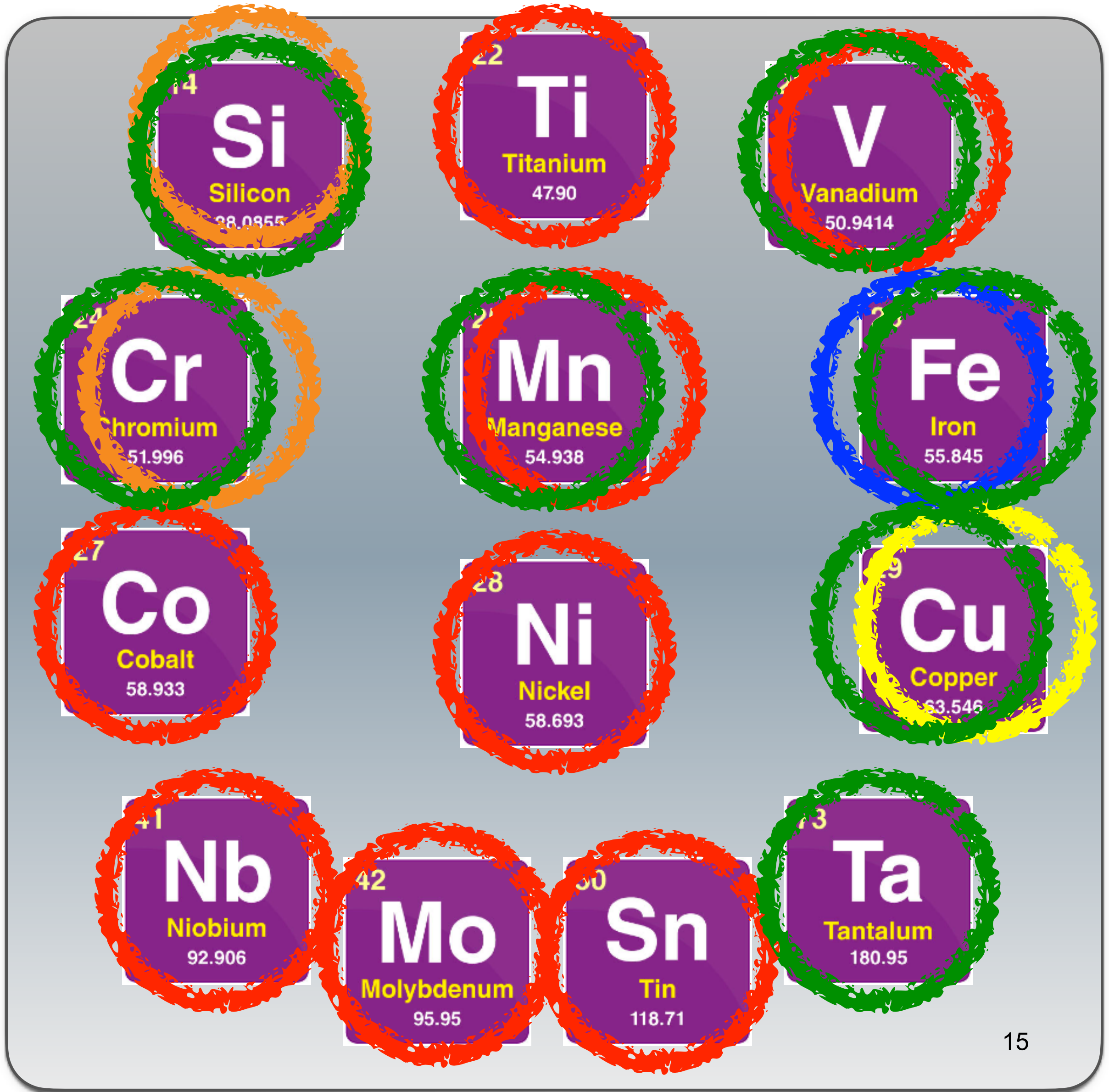


- **What do we need?**
  - *Evaluations, evaluations, evaluations!*

Current status in ENDF/B library

- Recently evaluated (VIII.1)
- Not-so recently evaluated (VIII.0)
- Would benefit from additional evaluation effort
- Needing some crucial evaluation work
- Old evaluations, need new effort!

- **What do we need?**
  - *Evaluations, evaluations, evaluations!*
- **How do we get them?**



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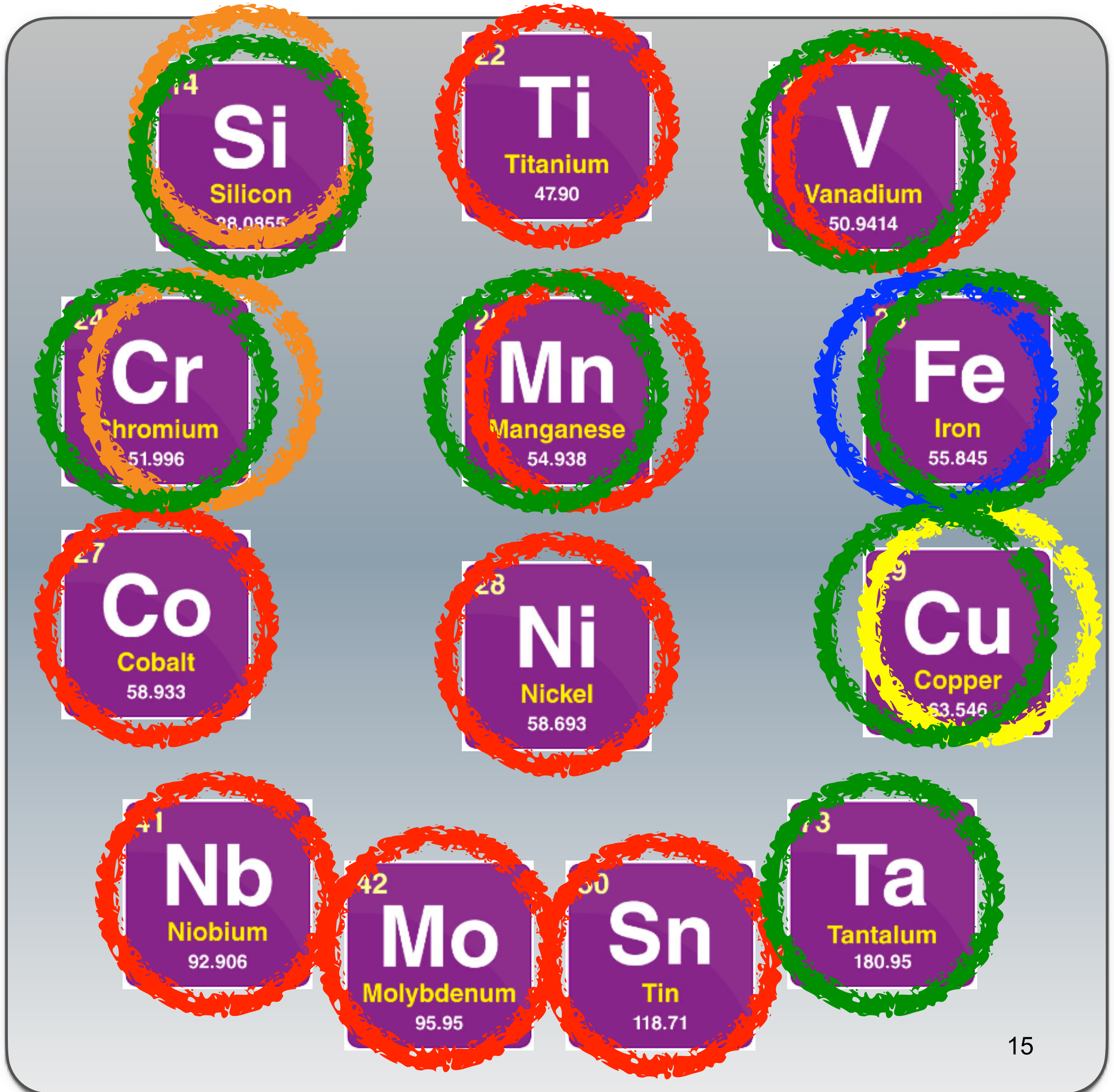
Current status in ENDF/B library

- Recently evaluated (VIII.1) — green
- Not-so recently evaluated (VIII.0) — blue
- Would benefit from additional evaluation effort — orange
- Needing some crucial evaluation work — yellow
- Old evaluations, need new effort! — red



- **What do we need?**
  - *Evaluations, evaluations, evaluations!*
- **How do we get them?**
  - *Evaluators, evaluators, evaluators!*

Acknowledgements

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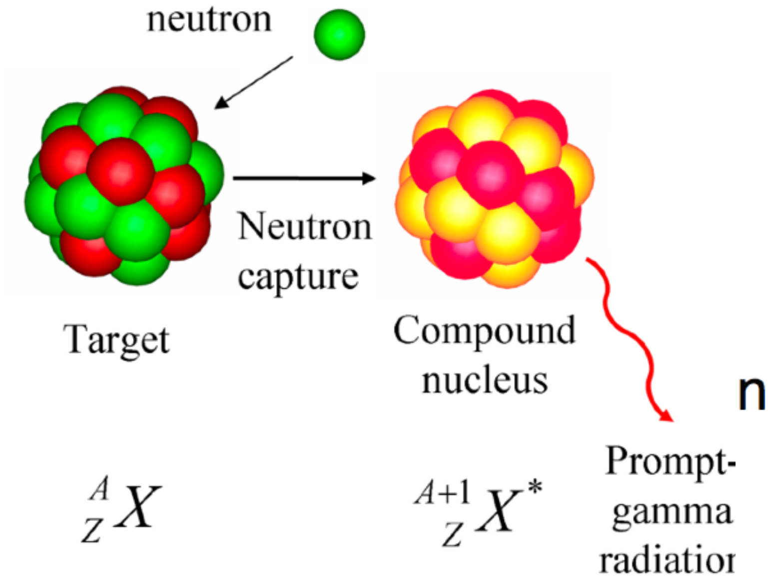
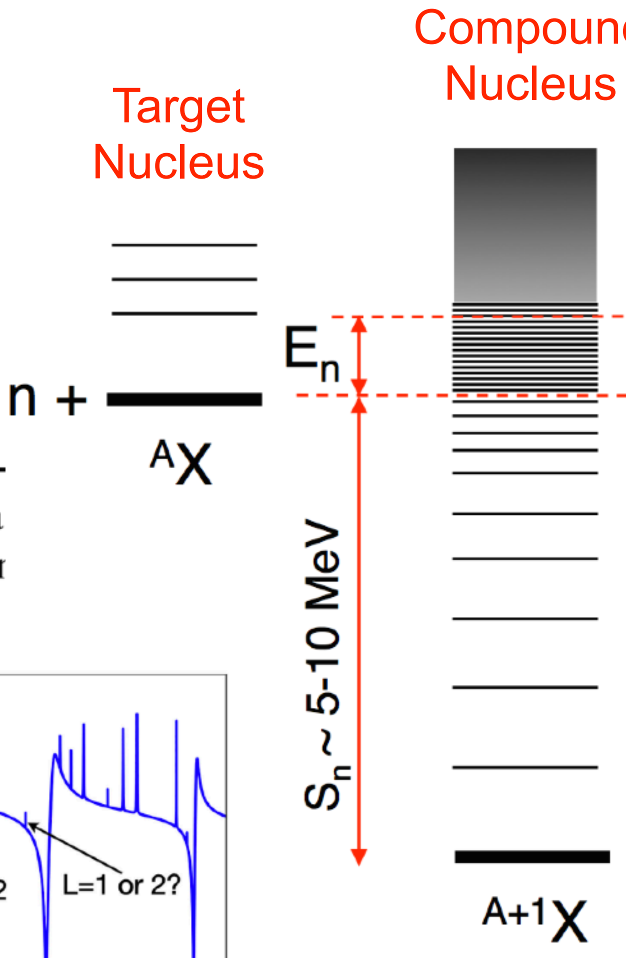
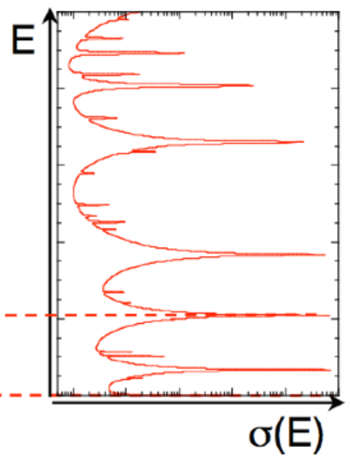
Backup

What are neutron resonances, after all?







D → resonance spacing
Γ → resonance width