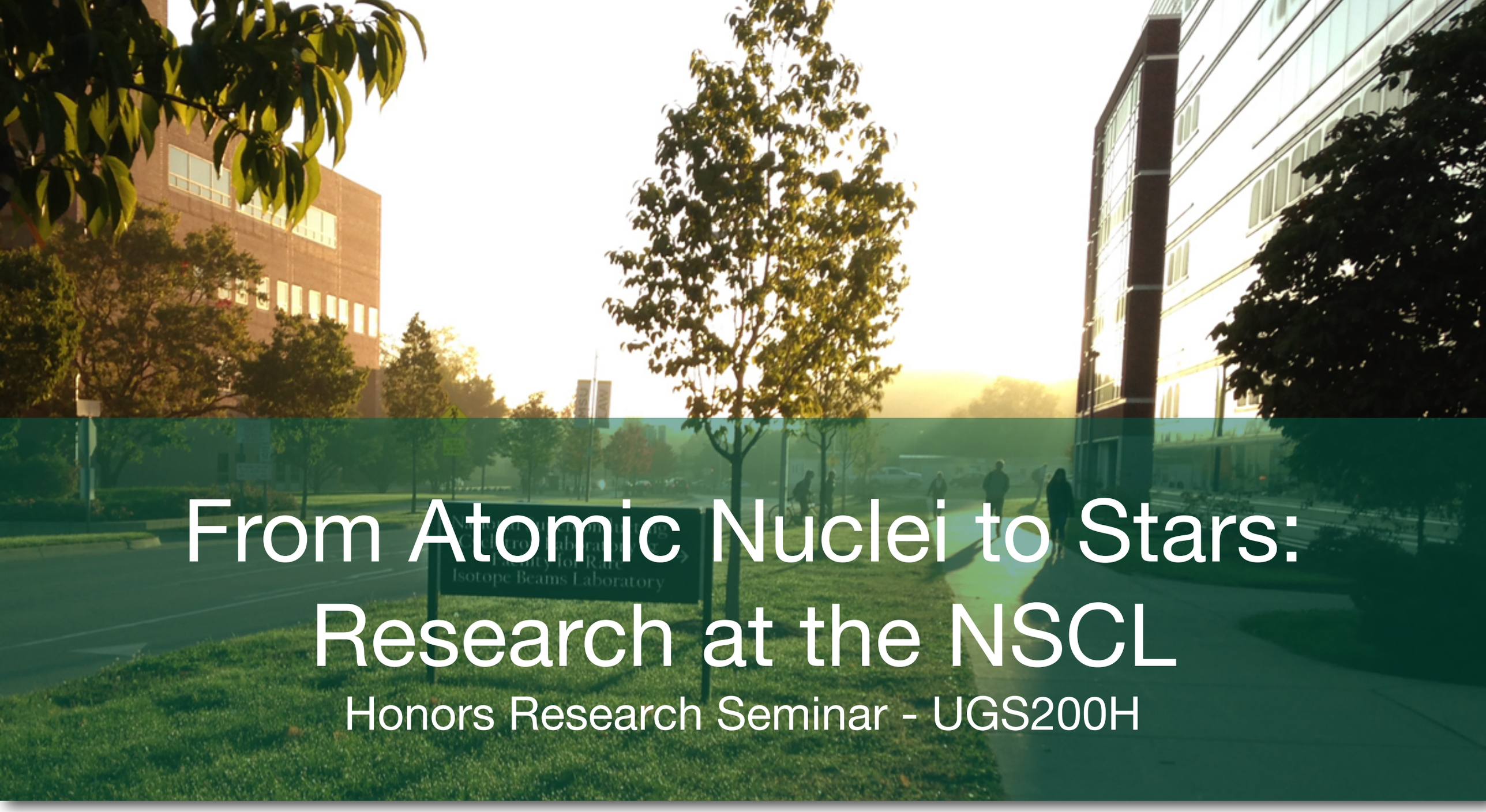

From Atomic Nuclei to Stars: Research at the NSCL

Honors Research Seminar - UGS200H

Heiko Hergert
National Superconducting Cyclotron Laboratory
& Department of Physics and Astronomy
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Faculty Supervisors



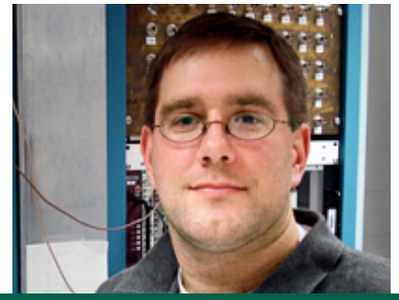






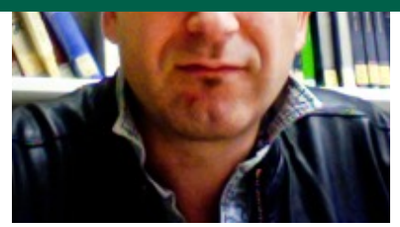
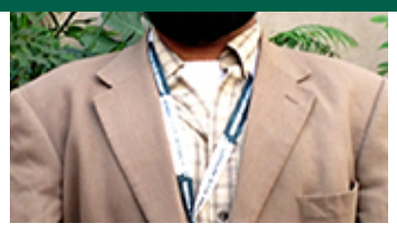
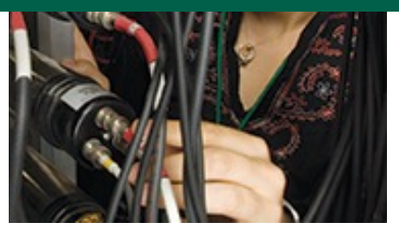
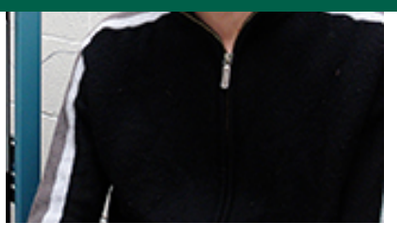
Faculty Supervisors





also see faculty websites:

www.nscl.msu.edu (NSCL/FRIB)

Course Overview

- 3 credit total (FS & SS), pass/no pass
- Course Organization:
  - 9/13 - 10/4: faculty presentations
  - 10/4 - mid-March: research (meet with supervisor on own schedule)
  - mid/late March (dates tba): student presentations
  - 4/5/18: presentations at University Undergraduate Research and Arts Forum (UURAF)
- HRS website (including presentations):
  - https://www.nscl.msu.edu/researchers/HRS.html

Faculty Presentation Schedule

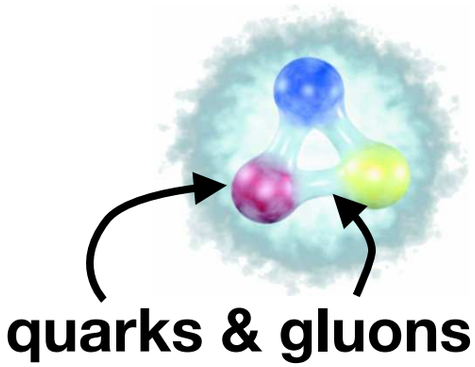
9/13	HH - intro
9/20	Jaideep Singh Artemis Spyrou Sean Liddick
9/27	Ryan Ringle Scott Bogner Remco Zegers
10/4	Andrea Shindler Gregory Severin

Some Materials

- Nuclear Physics Survey Course
  - https://people.nscl.msu.edu/~witek/Classes/PHY802/NuclPhys802-2016.html
- 2015 NSAC Long Range Plan: Reaching for the Horizon
  - http://science.energy.gov/~/media/np/nsac/pdf/docs/nuclear_science_low_res.pdf
- "Nuclear Physics: Exploring the Heart of Matter", National Research Council Report
  - http://www.nap.edu/catalog/13438/nuclear-physics-exploring-the-heart-of-matter
- JINA-CEE YouTube Channel
  - https://www.youtube.com/channel/UCTa4Bt0wQ6mYduyOCvsYR5A

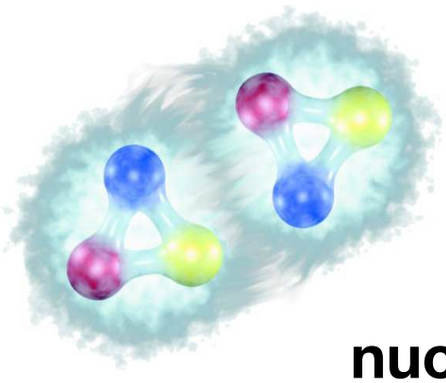
To Science!

Nuclear Physics at Different Scales



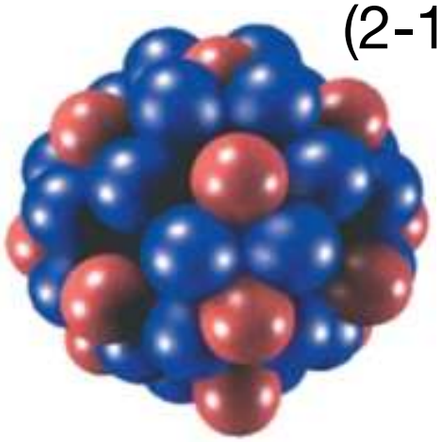
quarks & gluons

nucleons, baryons (gr. “heavy”)
& mesons (gr. “medium”(-mass))
(< **1 fm = 10^{-15} m**)

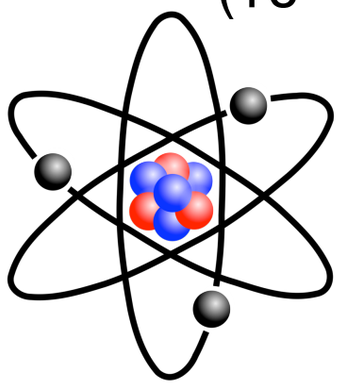


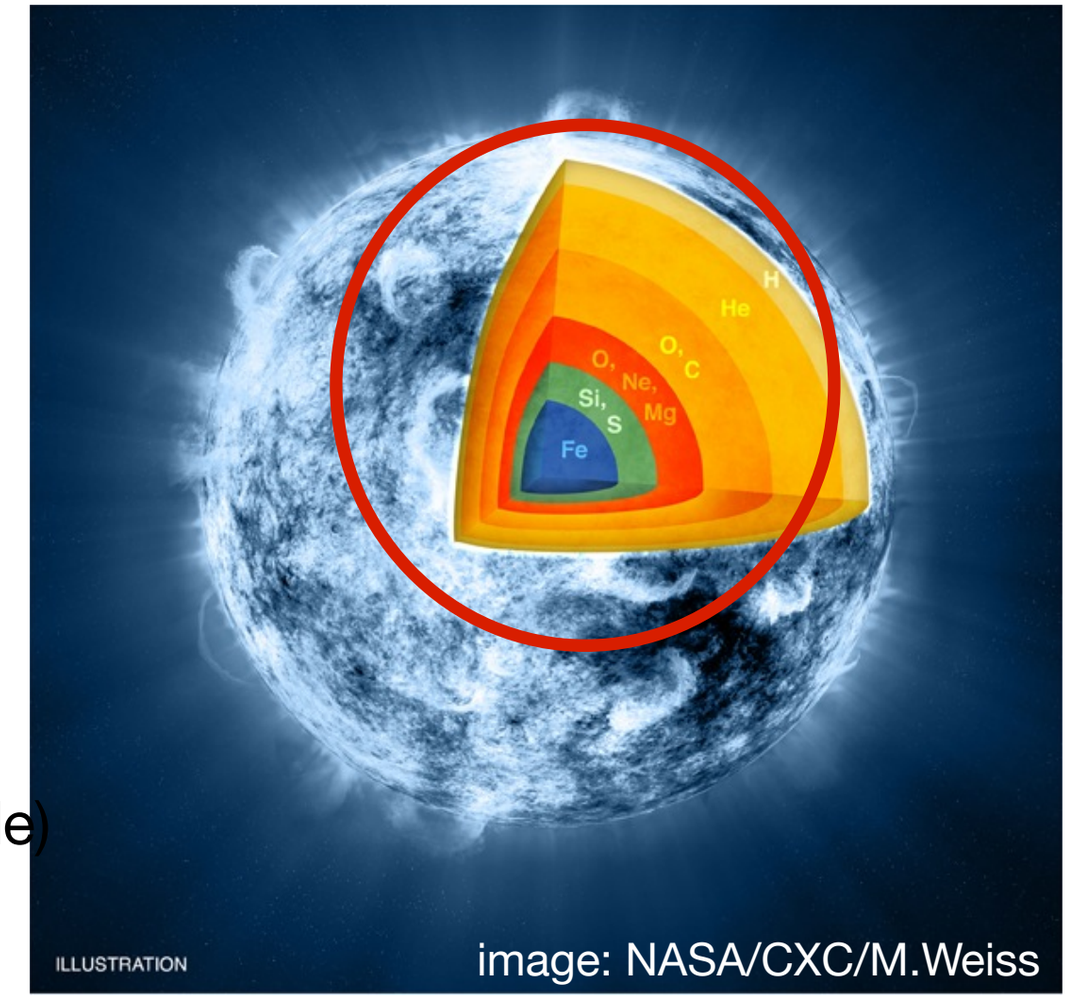
interacting nucleons
(1-2 fm)

nucleus
(2-10 fm)



atom
(nucleus not to scale)
(10^{5} -10^{6} fm)





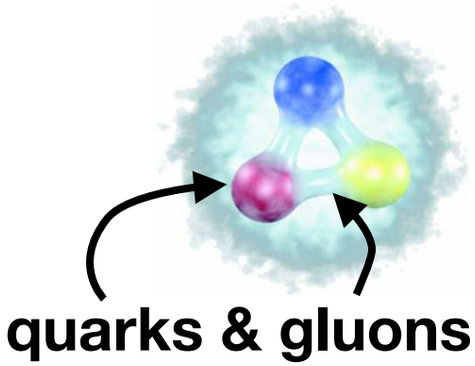
giant stars (10+ solar masses)
10^{9}-10^{10} m = 10^{24}-10^{25} fm

10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9}

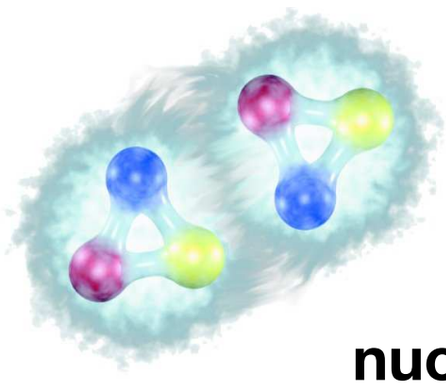
gamma rays | X-rays | visible light

Length Scale [m]

Nuclear Physics at Different Scales

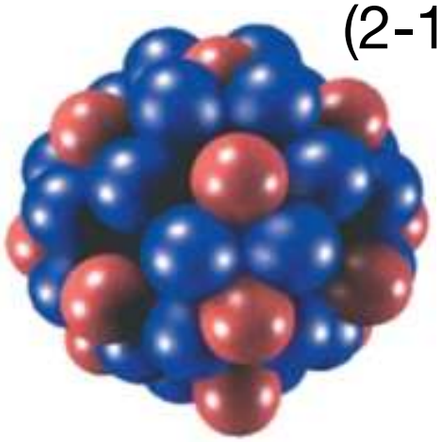


nucleons, baryons (gr. “heavy”)
& mesons (gr. “medium”(-mass))
(< **1 fm = 10^{-15} m**)

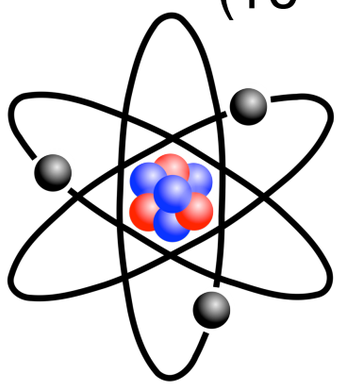


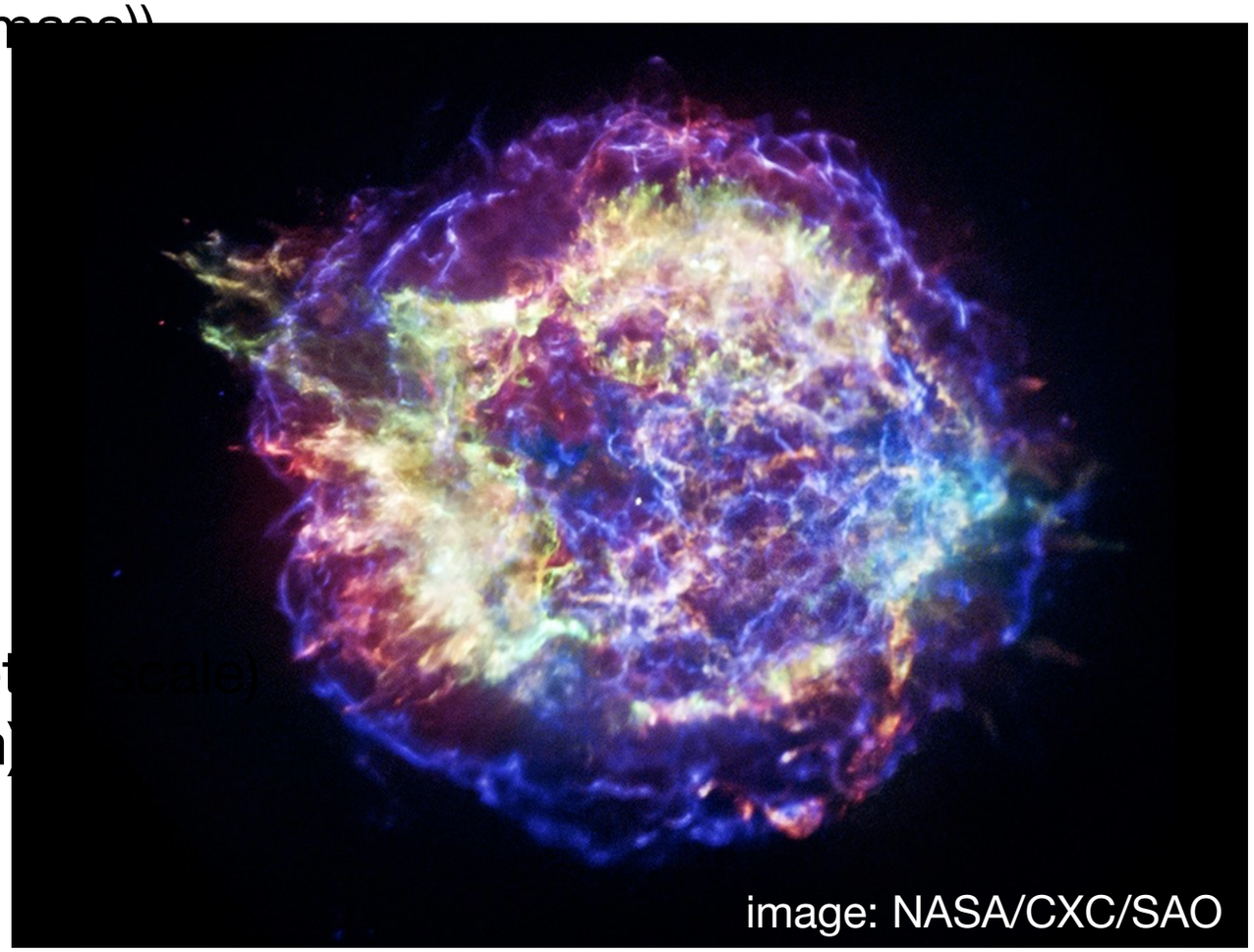
interacting nucleons
(1-2 fm)

nucleus
(2-10 fm)

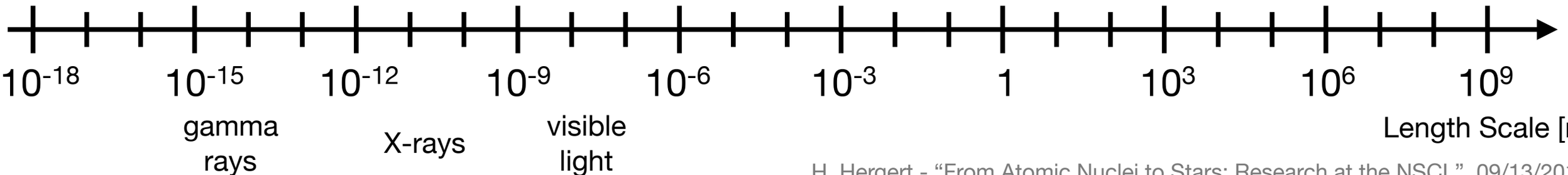


atom
(nucleus not to scale)
(10^5 -10^6 fm)

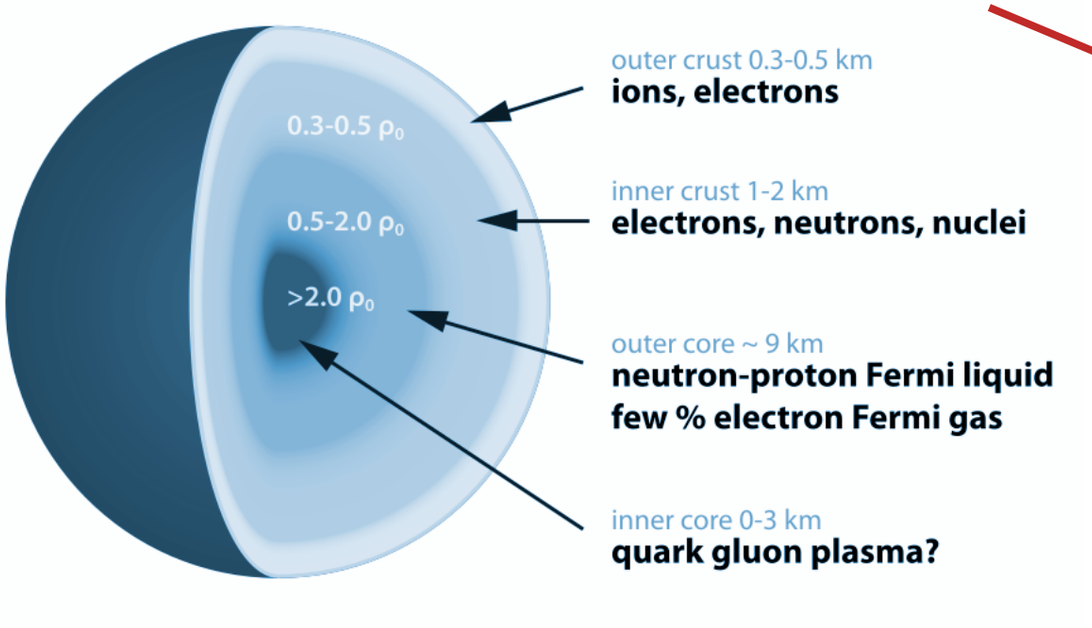




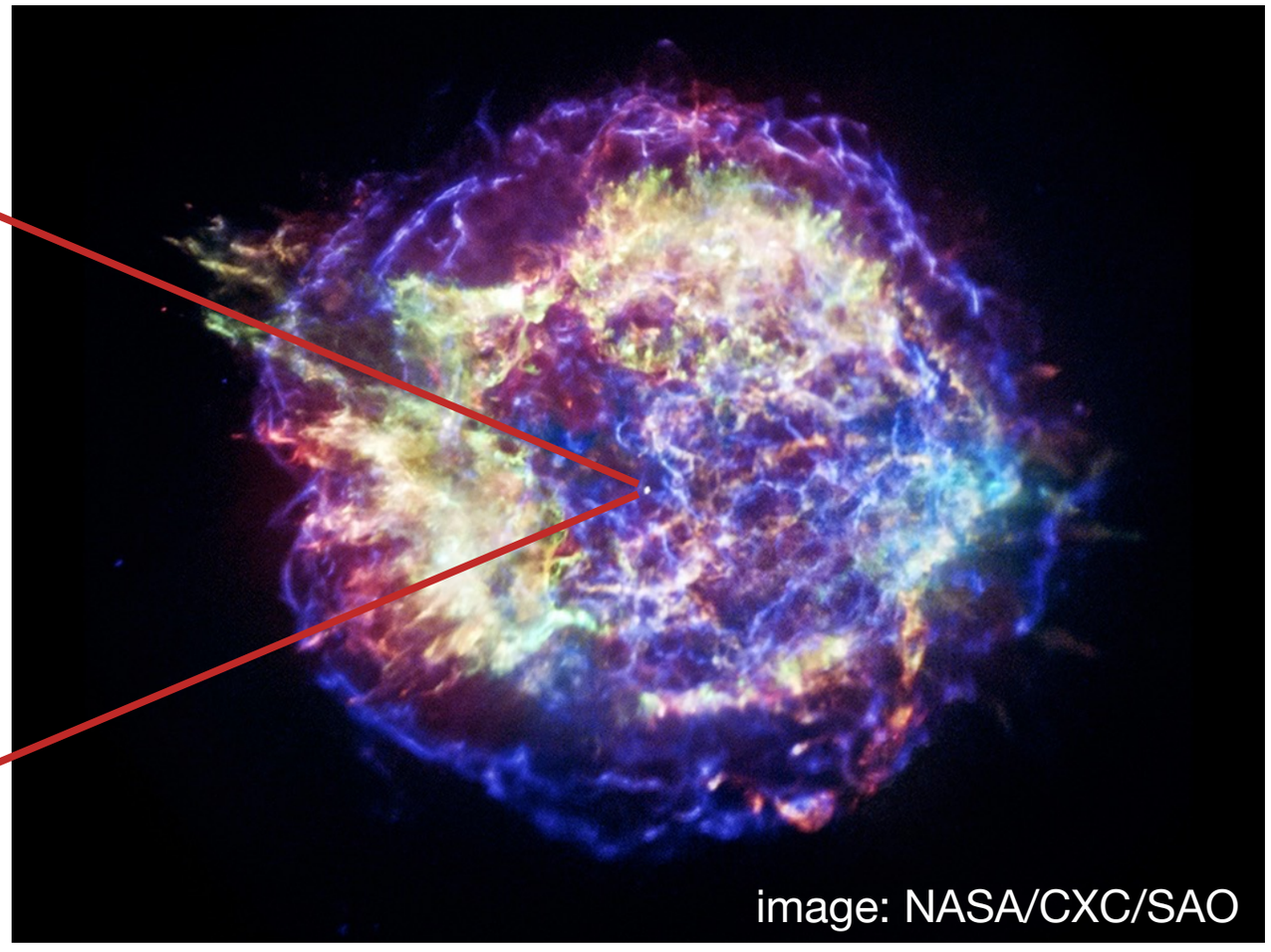
Cassiopeia A supernova (1947)



Nuclear Physics at Different Scales



neutron star
(15-20 km, but mass of our sun)



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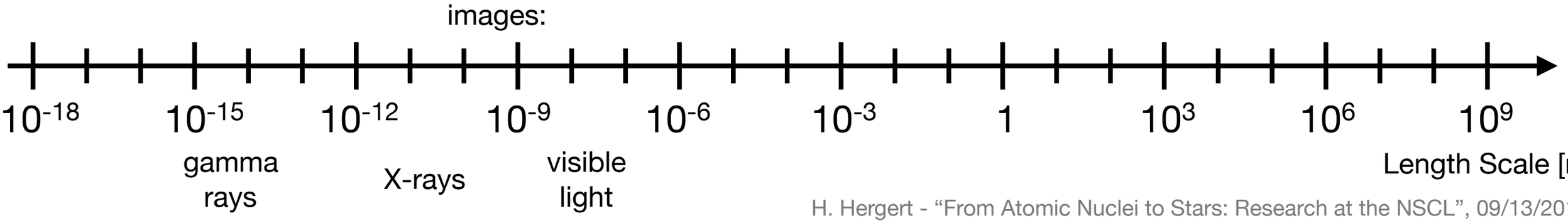
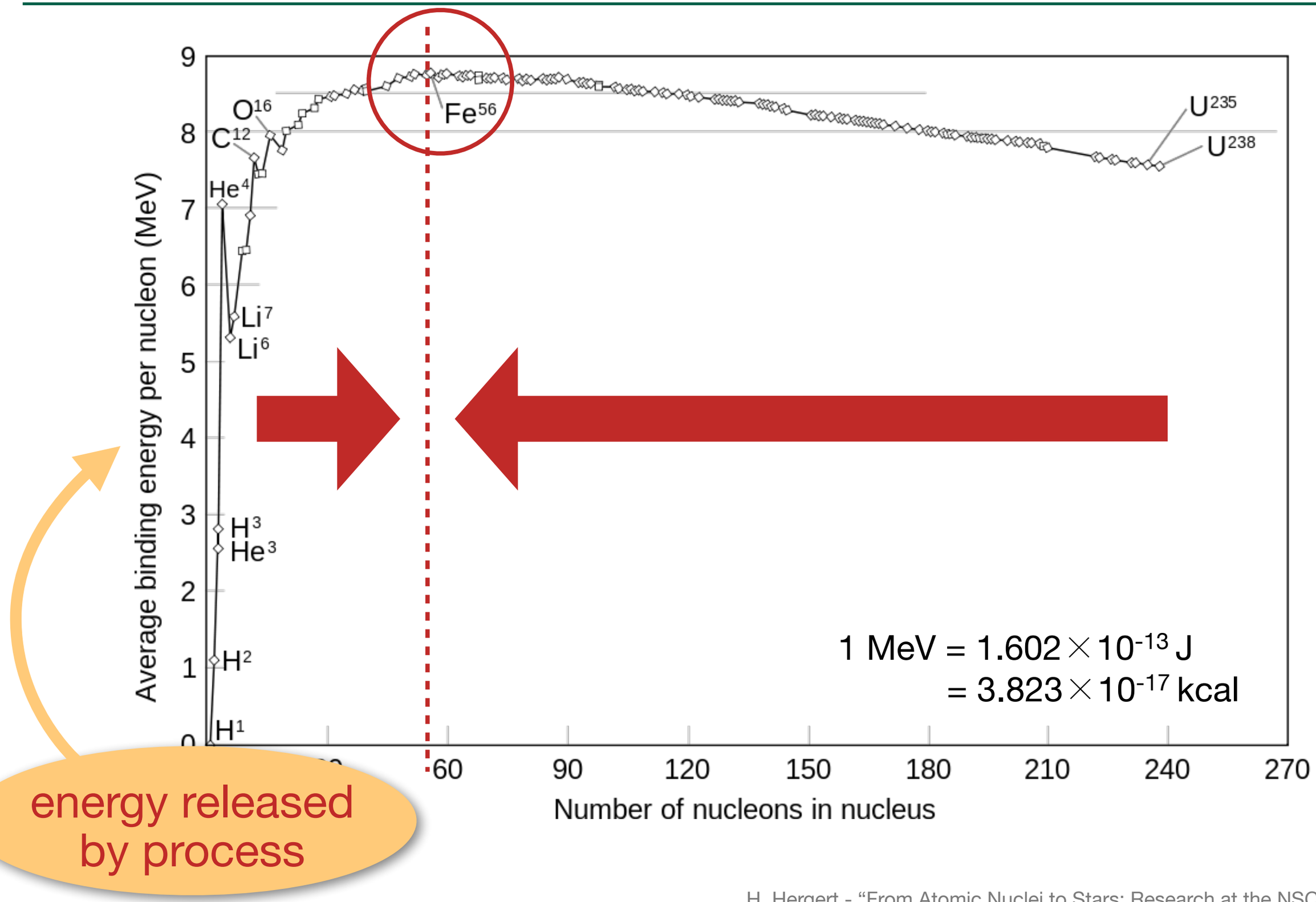


Nuclear Binding Energy



Fusion vs. Fission

Fusion

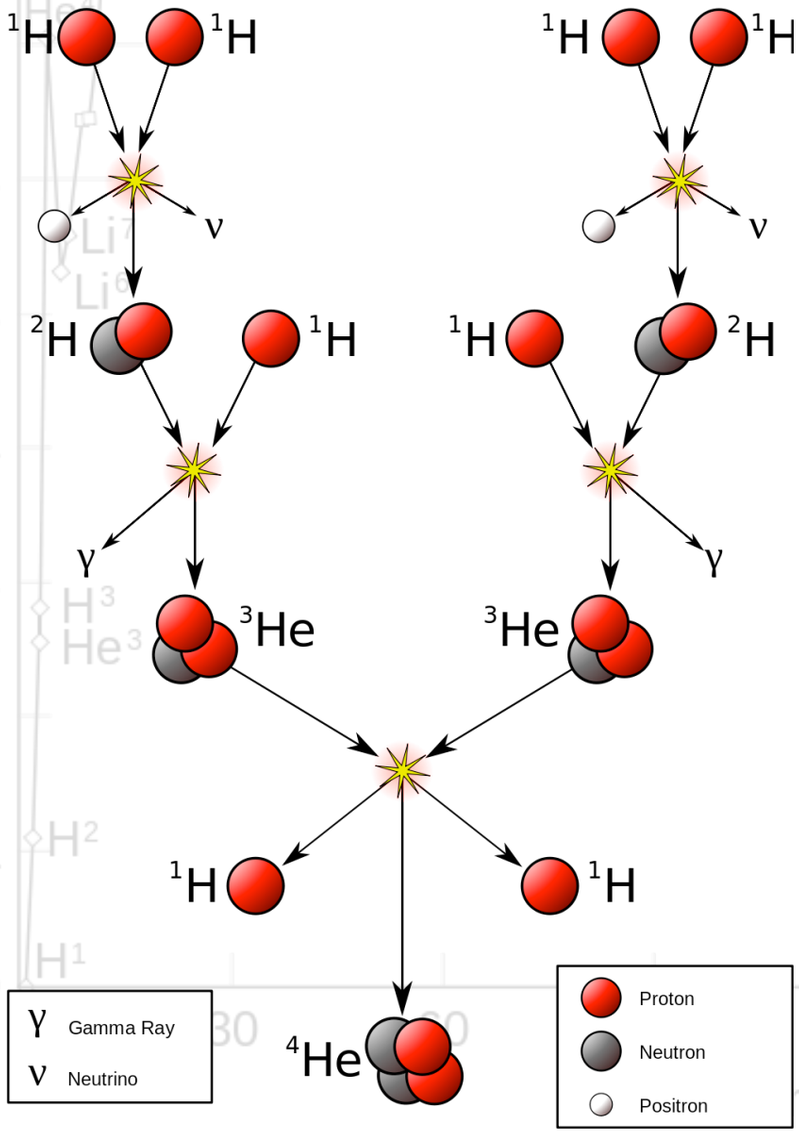
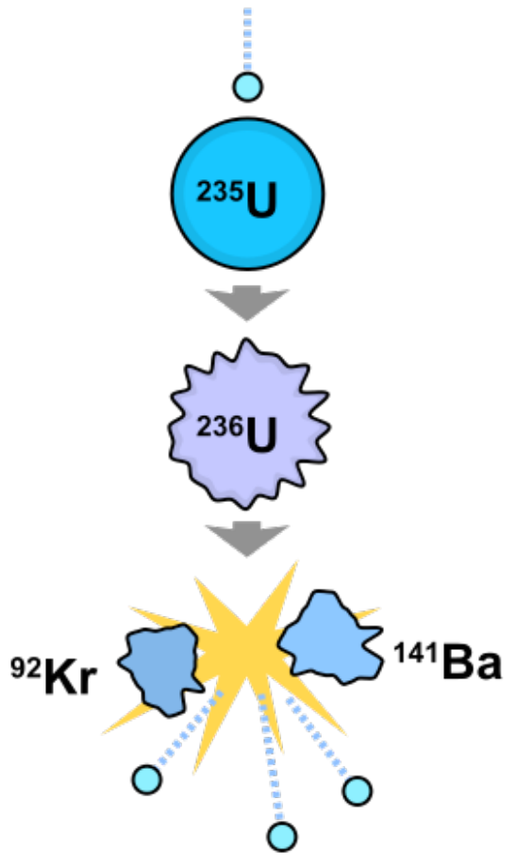


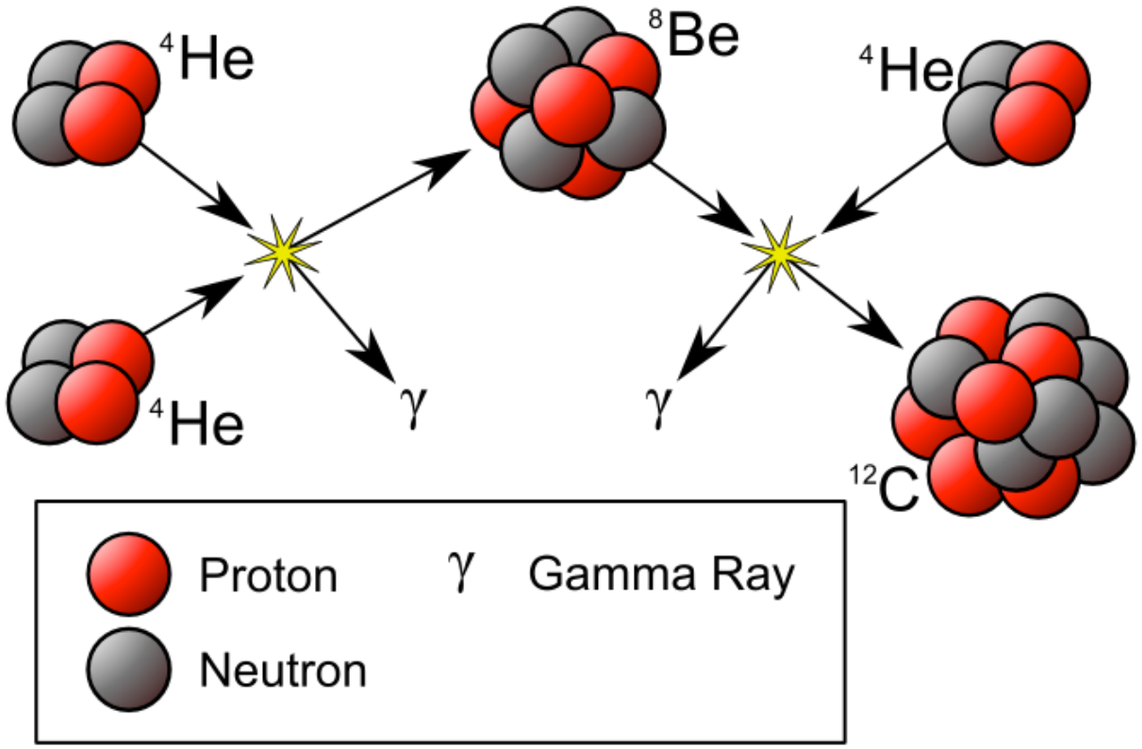
image: User:Borb@Wikimedia Commons, CC BY-SA 3.0

Fission



Nucleosynthesis

“We are made of star stuff.” - Carl Sagan, *Cosmos*



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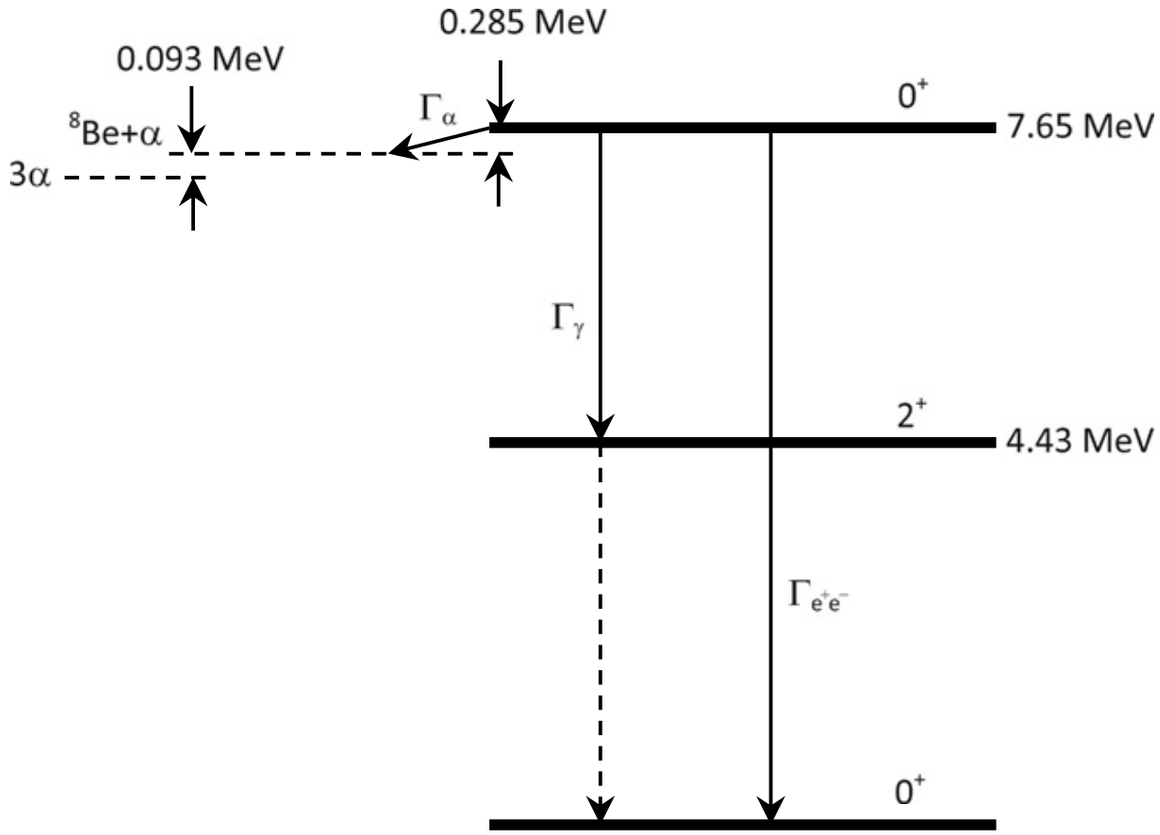


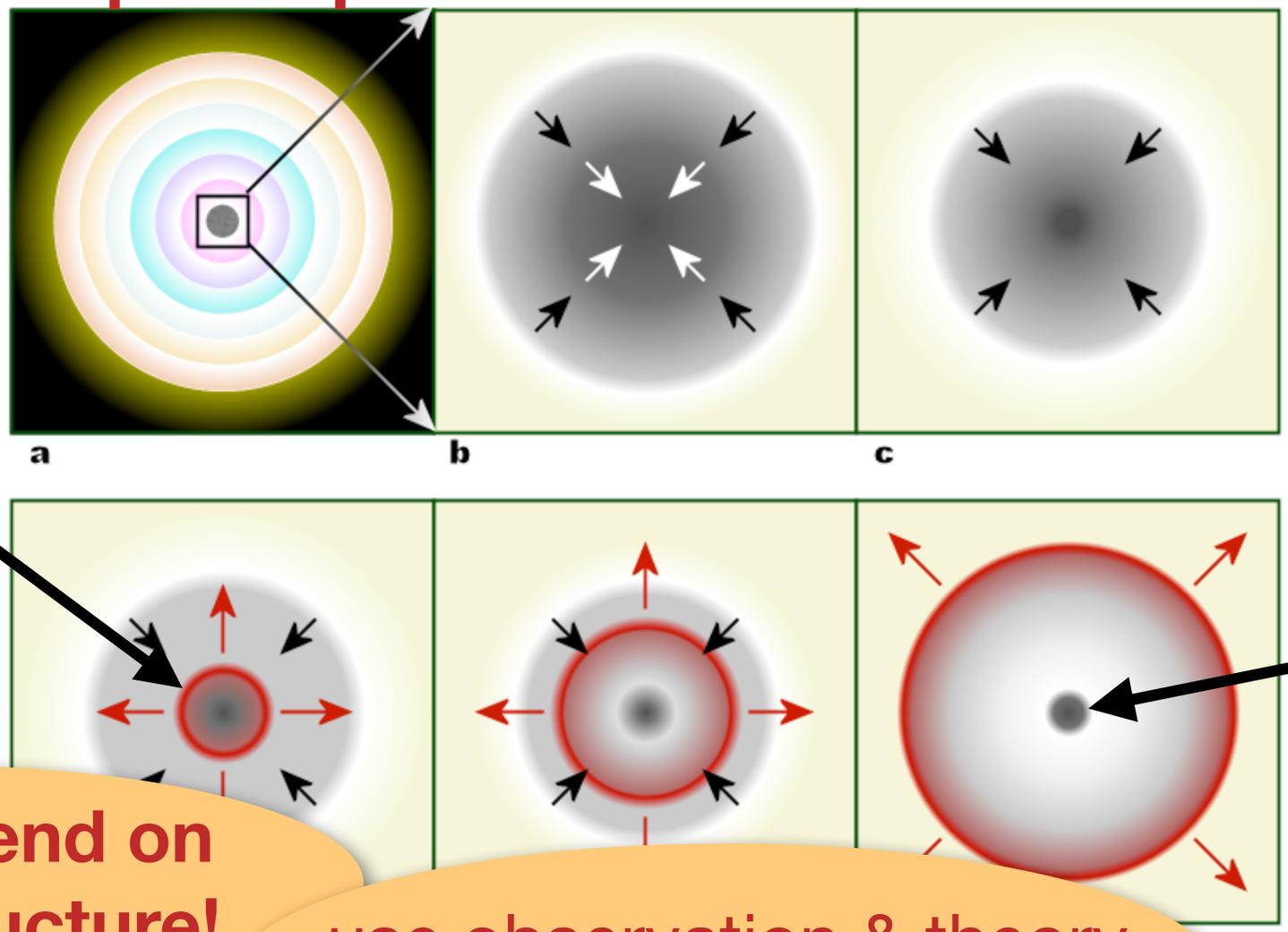
from: M. Freer, H. Fynbo,
Prog. Part. Nucl. Phys. 78, 1 (2014)

- **F. Hoyle** (~1952): excited 0^+ state in ^{12}C to explain the abundance of carbon in the observable universe
- state found & properties confirmed by 1957

Supernovae

- **heavy elements** (beyond iron) are produced in old, carbon-burning giant stars (~2-10 solar masses) or **supernovae**
- **core collapse supernova** scenario:

shockwave, "bounce"

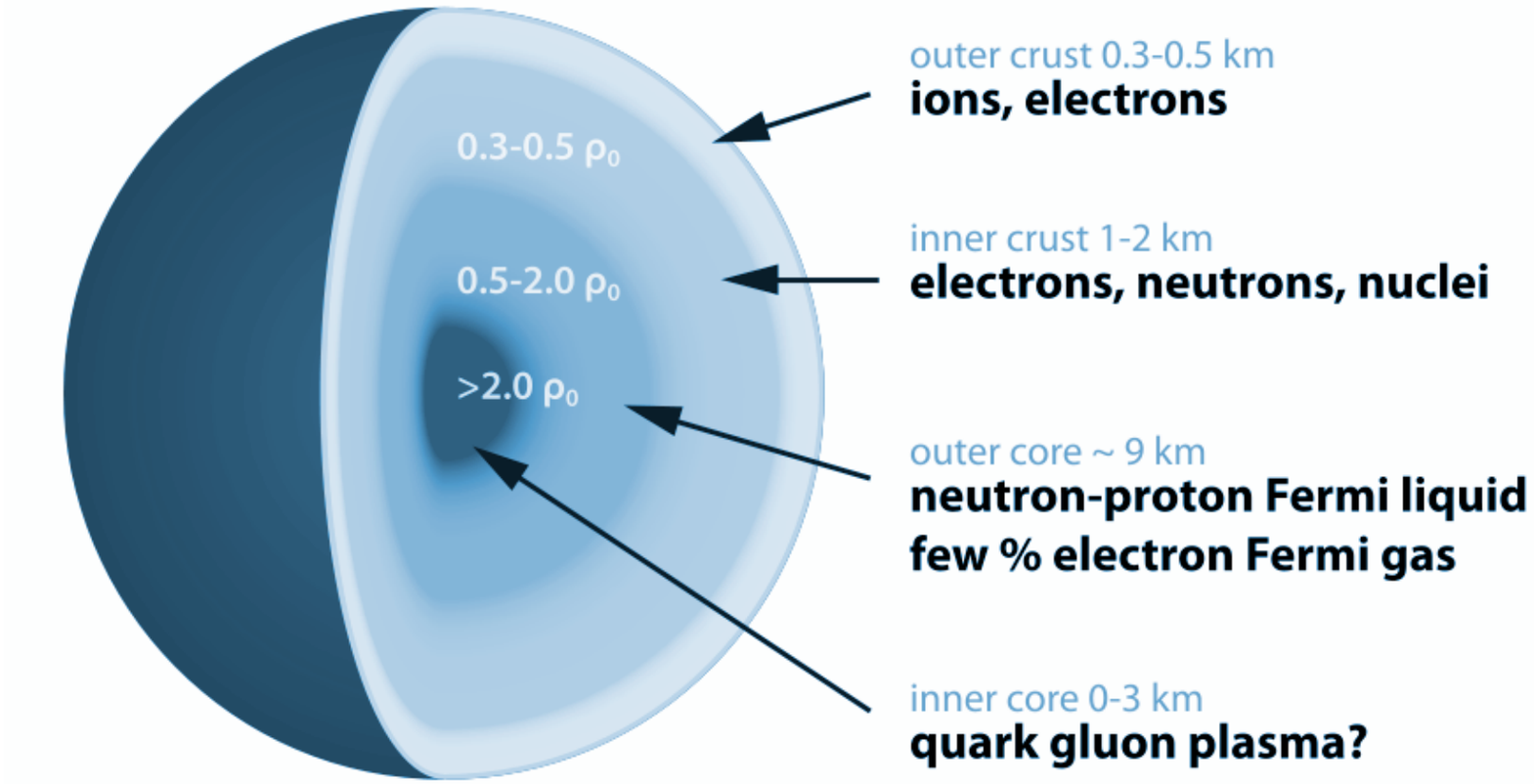


remnant neutron star or black hole

details depend on nuclear structure!

use observation & theory to learn about progenitor

Neutron Stars



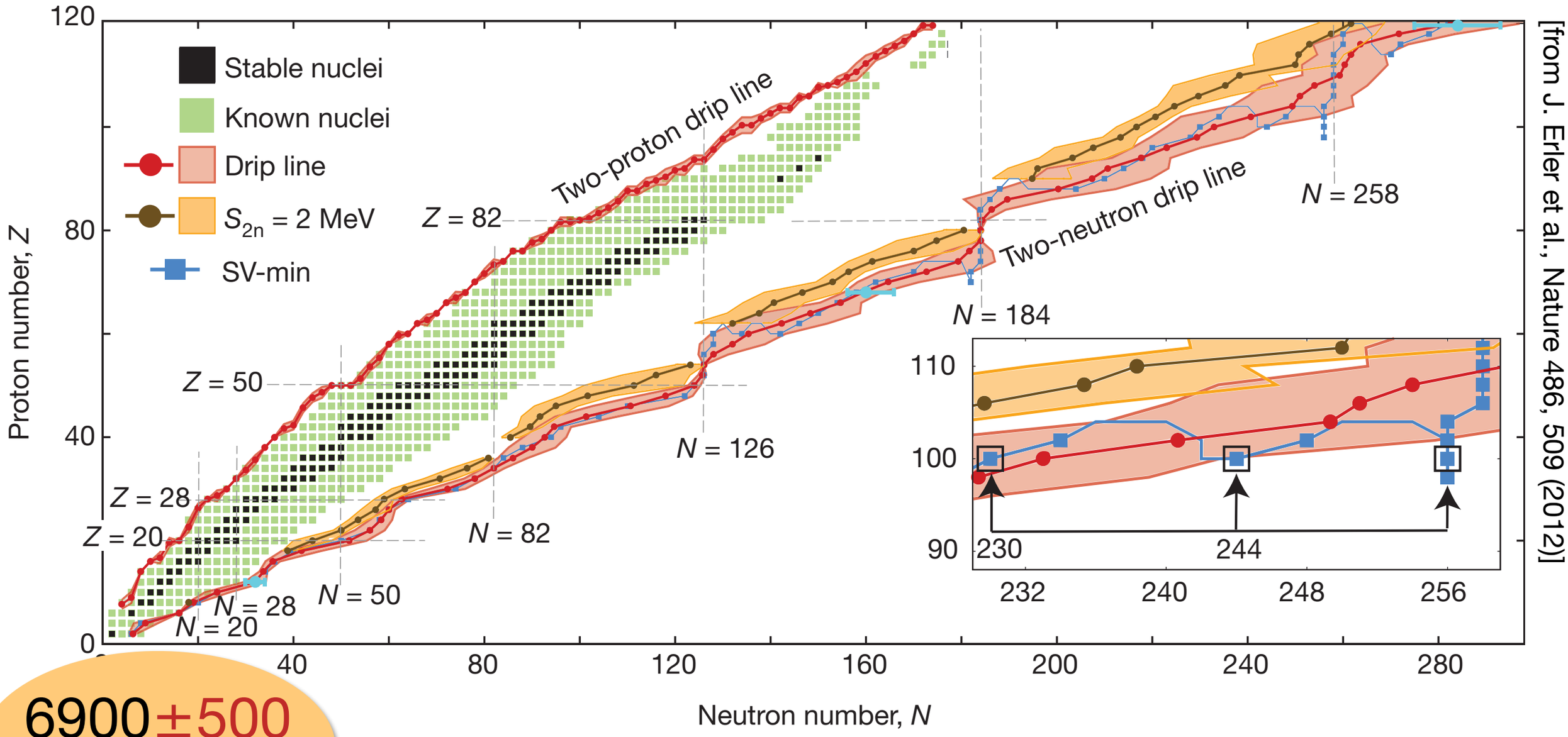
- a **“gigantic nucleus”**: 15-20 km radius (vs. ~ 2-10 fm), as heavy as our sun (2×10^{30} kg)
- **stability** against gravitational collapse depends on **nuclear matter properties**
- **constrained by astronomical observations**

Neutron Star Mergers

Panel discussion on the impact of the NSM GW170817:

- https://www.youtube.com/watch?v=CxxmaLx-4e0&t=2s

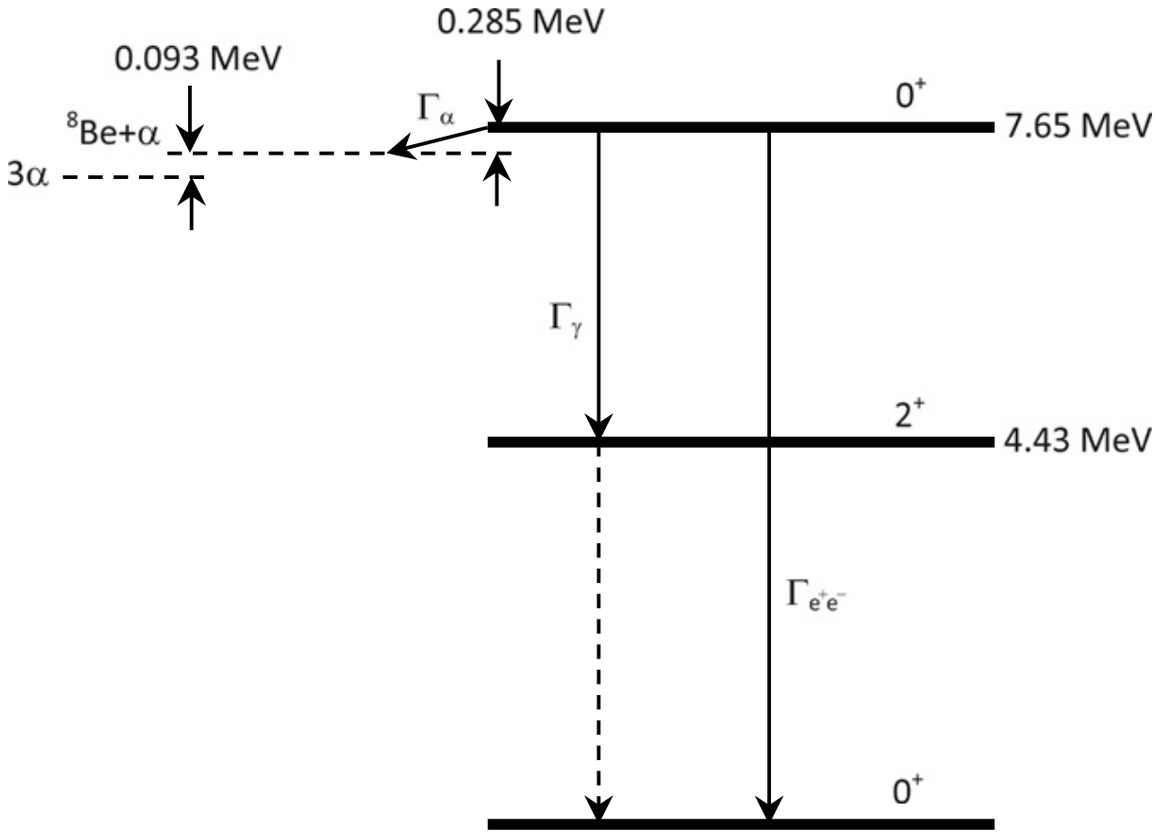
What are the Limits of Nuclear Existence?



6900±500 nuclei (?)

A Discovery Machine

A Bit of Theory



Why are only certain *discrete* excitation energies observed?

Quantum Physics!

A Bit of Theory

- (stationary) many-body **Schrödinger equation**:

$$H \left| \Psi \right\rangle = E \left| \Psi \right\rangle$$

- $\left| \Psi \right\rangle$ encodes the **state** (aka wave function) of the system
- **Hamiltonian *H*** describes the interactions between nucleons
- E is just a number

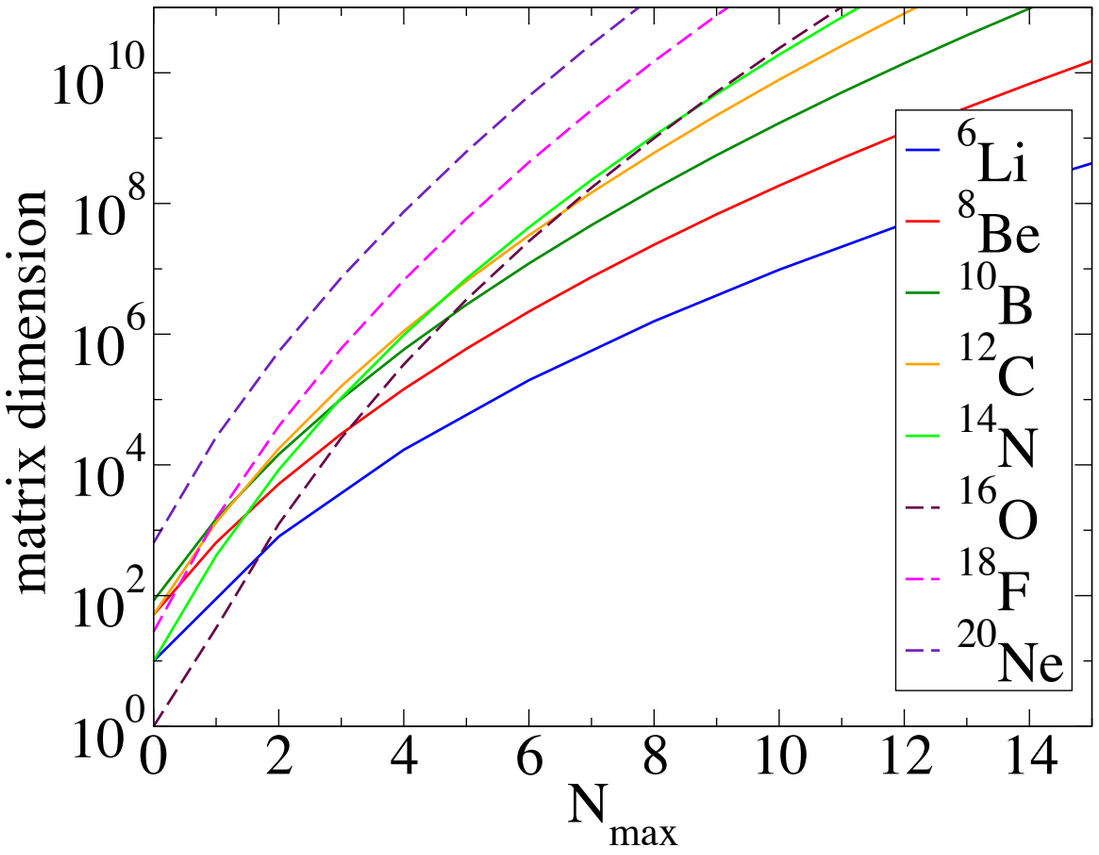
A Bit of Theory

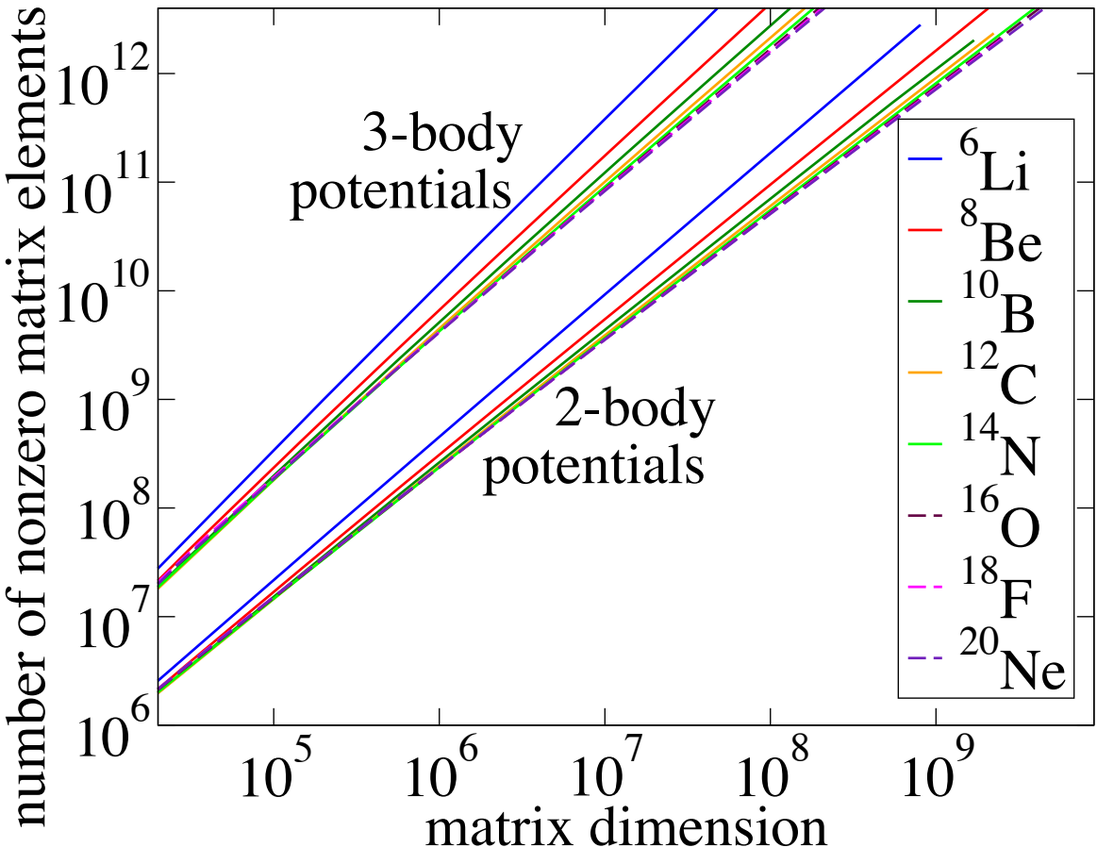
- represent $|\Psi\rangle$ and *H* as a vector and a matrix:

$$\mathbf{H}\vec{\psi} = E\vec{\psi}$$

- This is an **eigenvalue problem!**
- yields **allowed energies** for nuclear ground (lowest eigenvalue) and excited states (everything else)
- **eigenvectors** represent the corresponding wave functions

Basis Size “Explosion”





from: C. Yang, H. M. Aktulga, P. Maris, E. Ng, J. Vary, Proceedings of NTSE-2013

- **constructing and storing full *H* matrix is impossible**
- matrices are **sparse** (many entries are zero), but problem is still **hard**

Theory's Discovery Machines