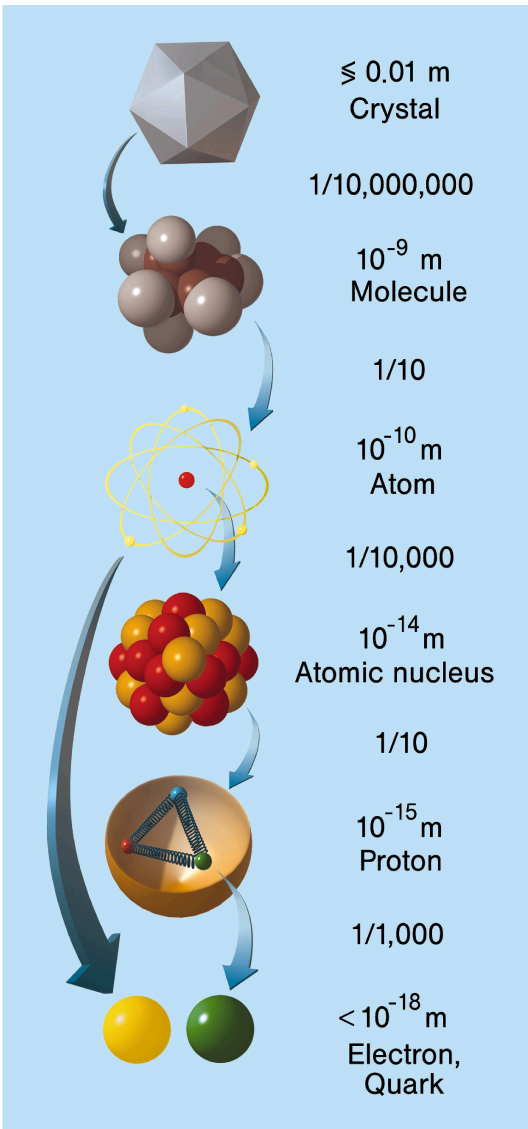
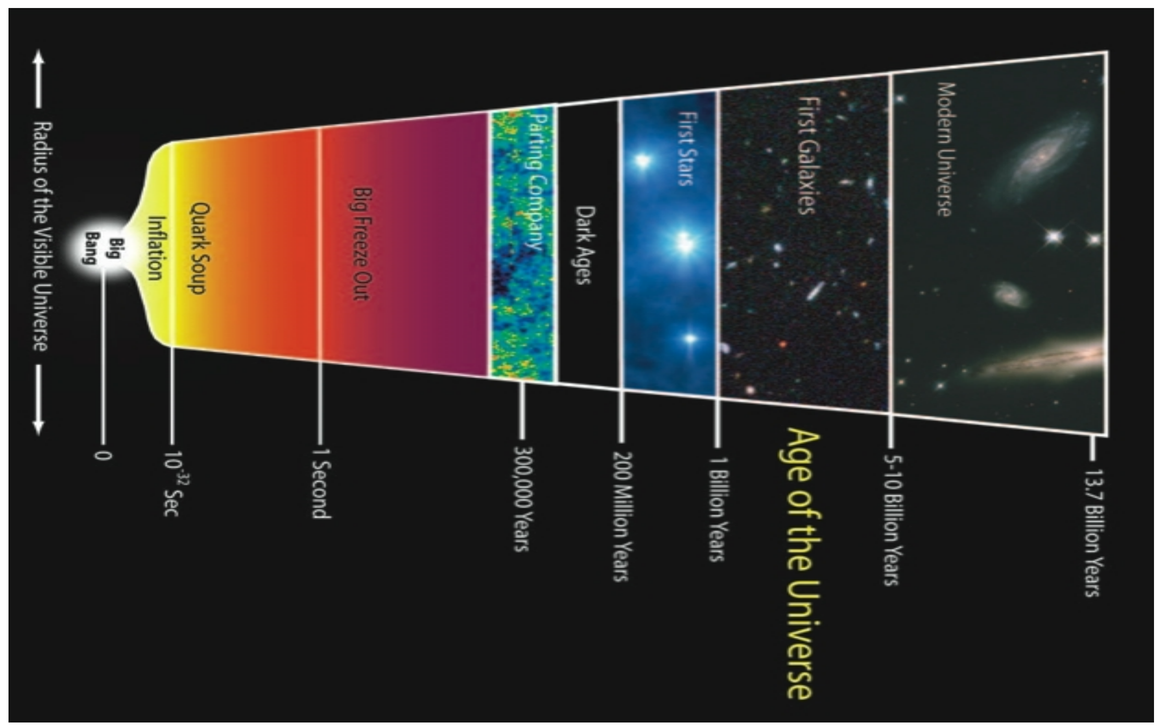
Nuclei in the Cosmos

- When and where were all the known nuclei existing naturally on Earth produced?
- What kind of nuclear reactions are involved?
- What kind of stellar or galactic or Big Bang environments provide these reactions?
- How can we learn more about this with experiments on Earth?

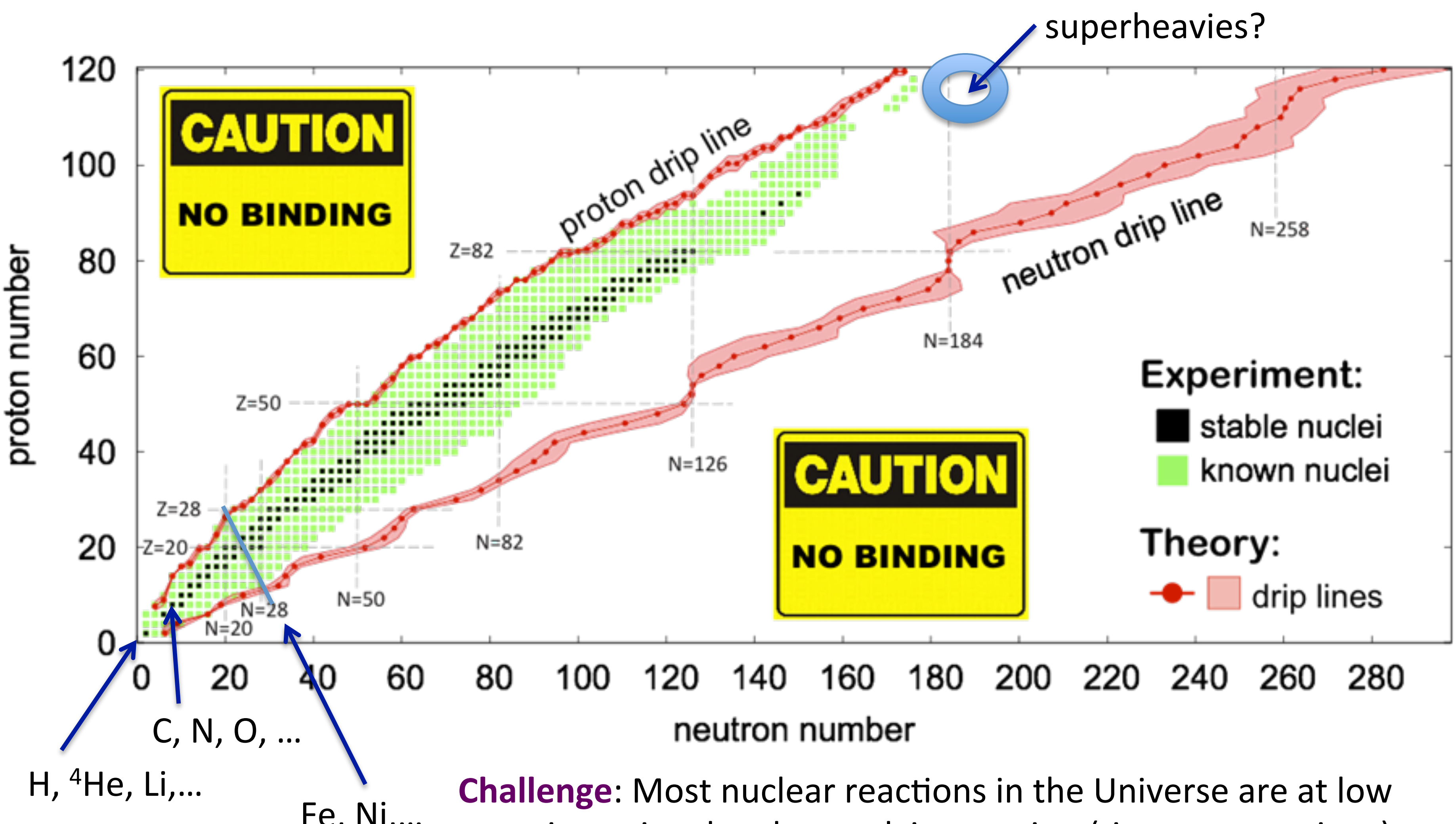
The Structure of Matter



- What **nuclei** is the Universe made off?
- What nuclei where there in the beginning (right after the big bang)?
- When and how did nuclei important for life form?
- Where do heavy nuclei come from?

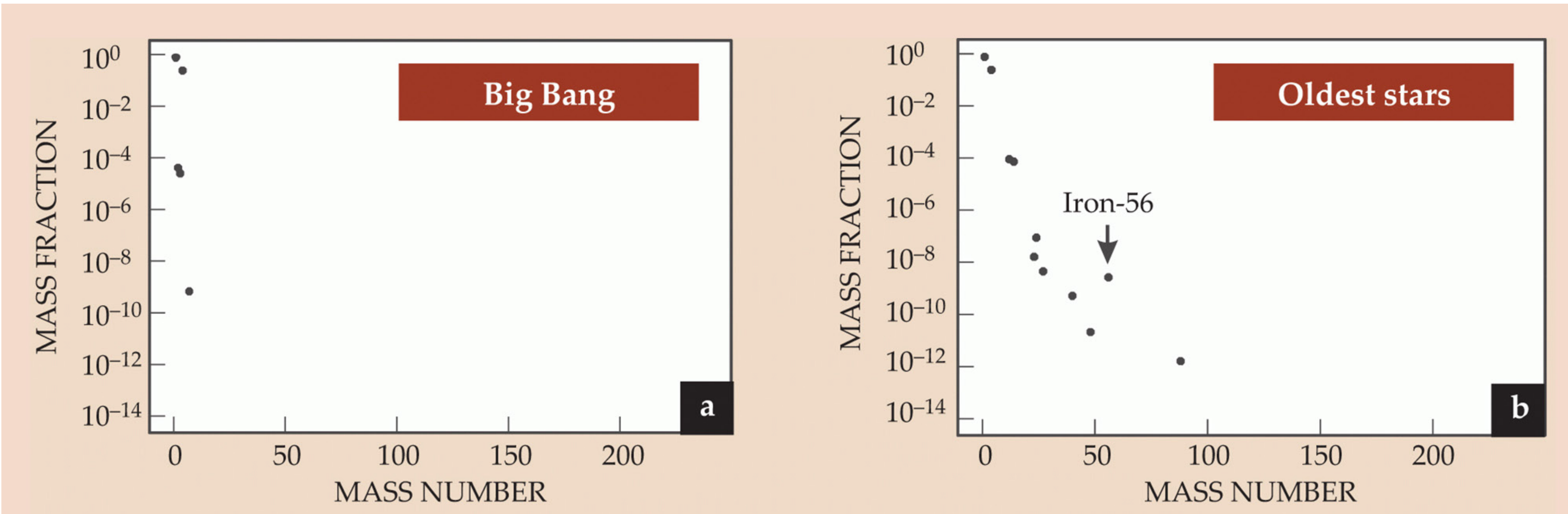


All the nuclei in the universe



Challenge: Most nuclear reactions in the Universe are at low energies or involve the weak interaction (tiny cross sections) => Experiments and Theory are HARD! (subtle effects play big role!)

Where does ^{4}He come from ?



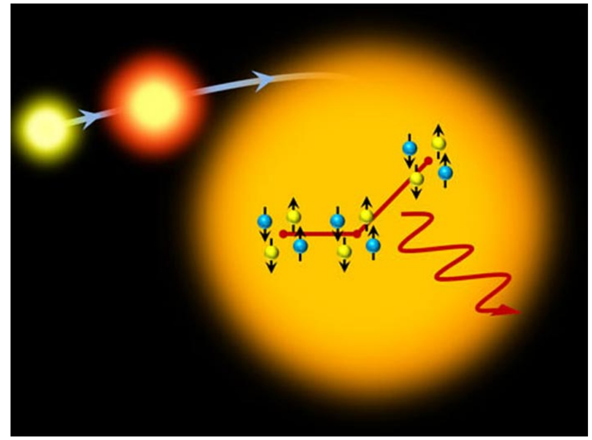
First “3” minutes:

- quarks fuse to p, n (everything else decays)
- p+n = d, d+p=^{3}He, ^{3}He+n = ^{4}He
- Competes with n decay (15 min) => observed abundance = test of Big Bang models
- Smattering of Li,…

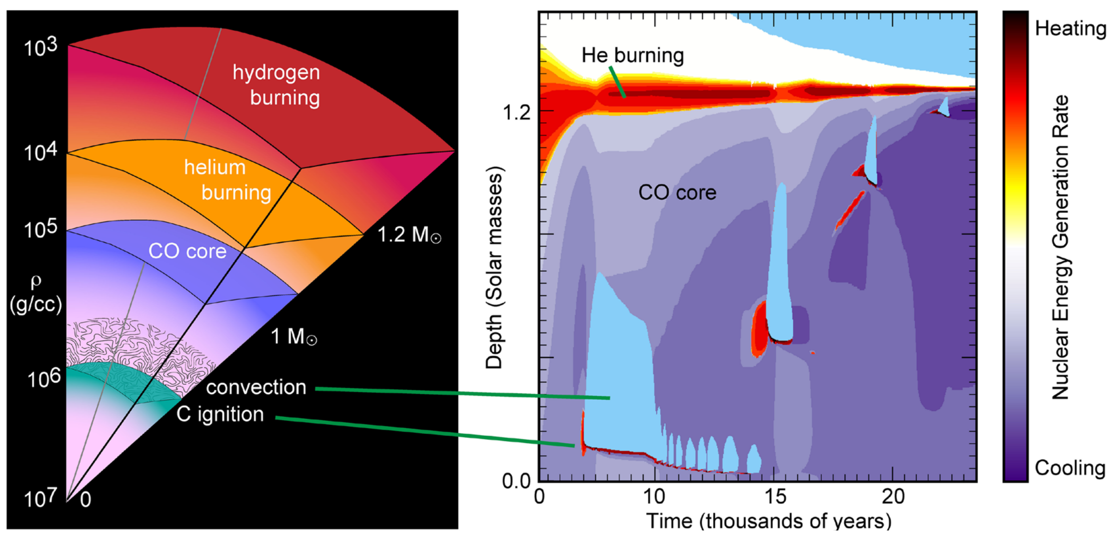
“Ordinary” nucleosynthesis in stars (like the sun):

$p+p = d + e^{+} + \nu \rightarrow {}^{4}$He, …

C, N, O: Elements for Life

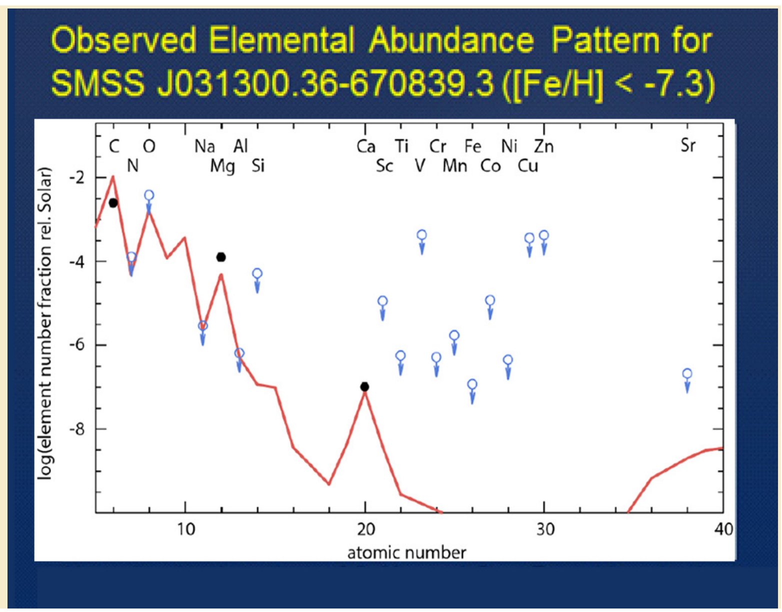


- How do you form C?
  - Core runs out of H fuel, compacts and heats up
  - “Helium burning”: $\alpha + \alpha + \alpha = {}^{12}C$
  - $\alpha + \alpha = {}^{8}Be$? Unbound! => Crucial importance of Hoyle state (3-dim structure recently discovered)
- From C to oxygen
- Other elements

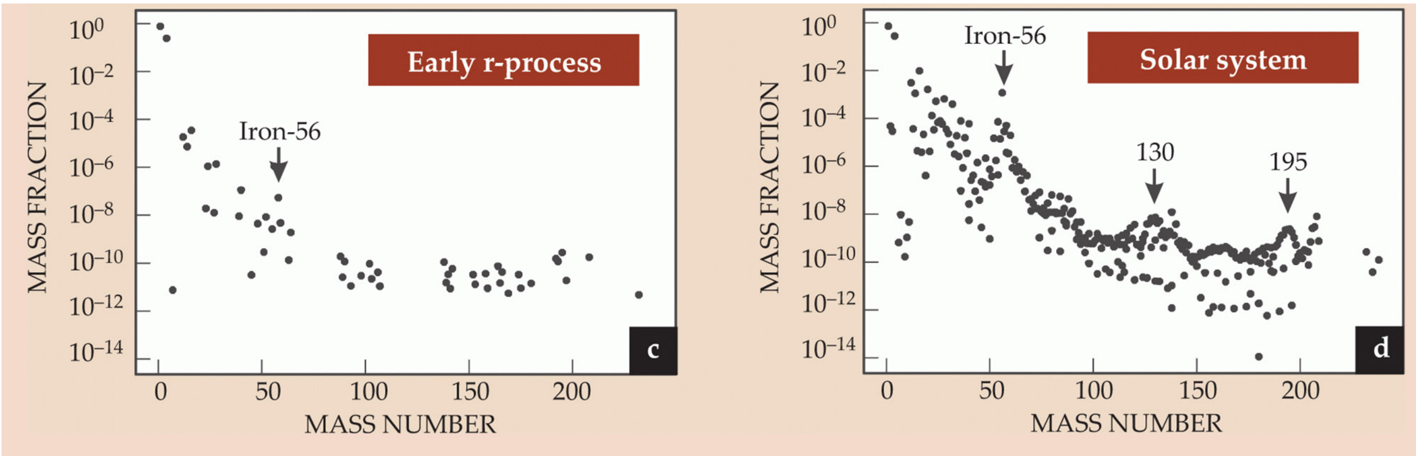


C, N, O: Elements for Life

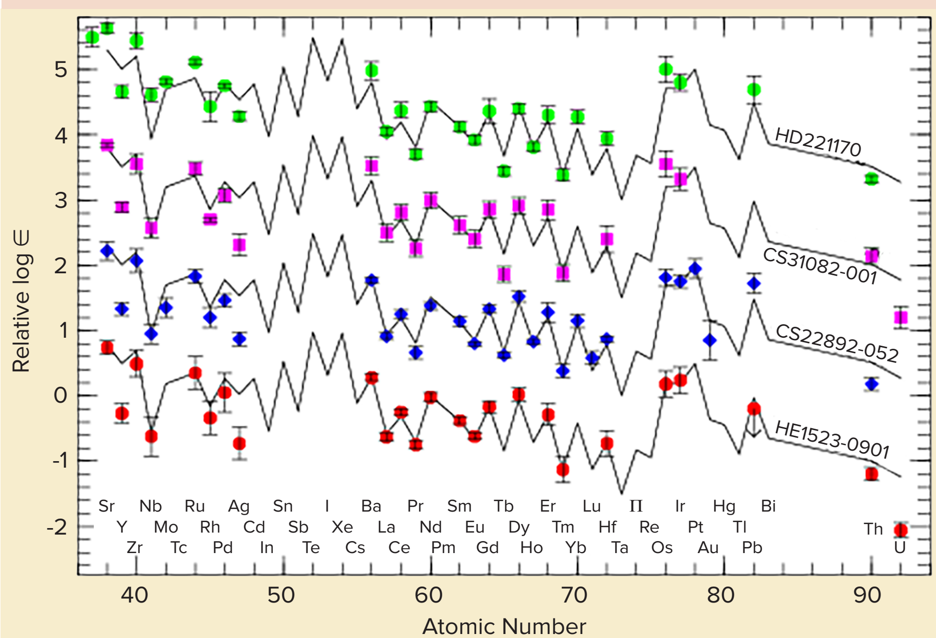
- Carbon/Oxygen ratio in our universe?
- What reaction do we need to study?
- What is the problem?
- What do we need to study it?

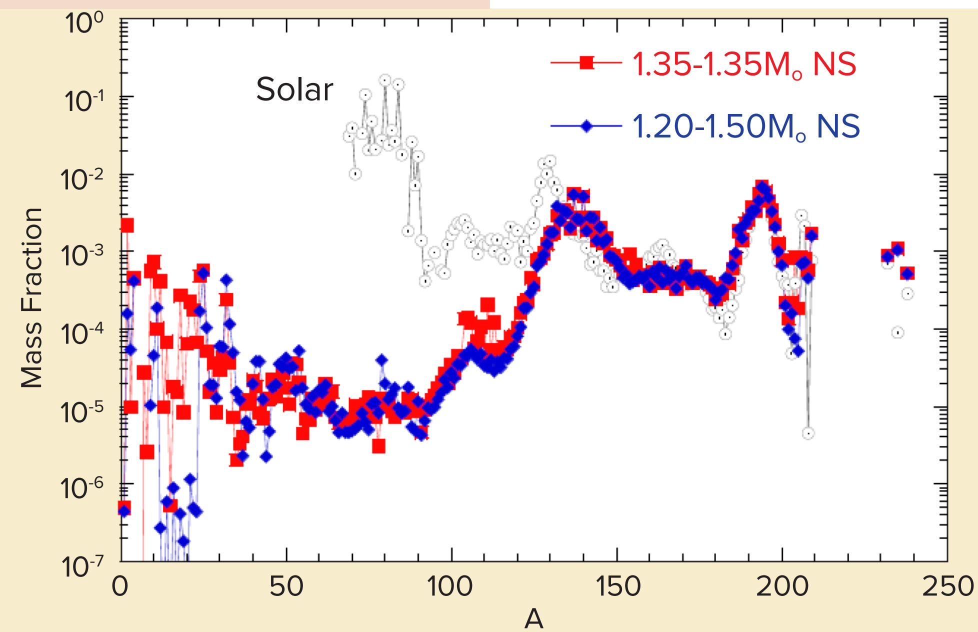


Heavier elements – the r process



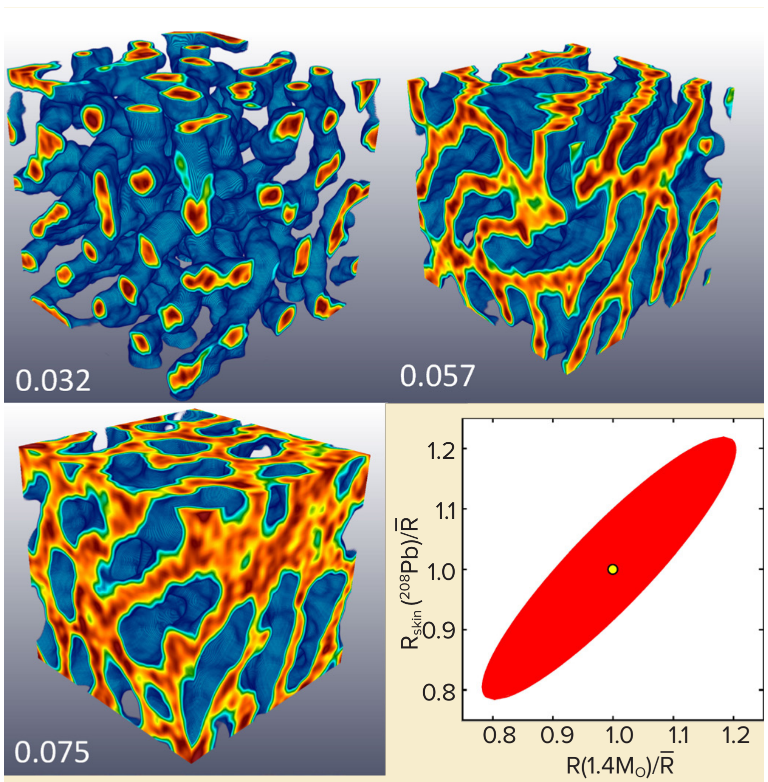
- What is the r-process?
- What kind of nuclei do we need to study to understand it?
- What are possible sites for it?
- How can LIGO help?

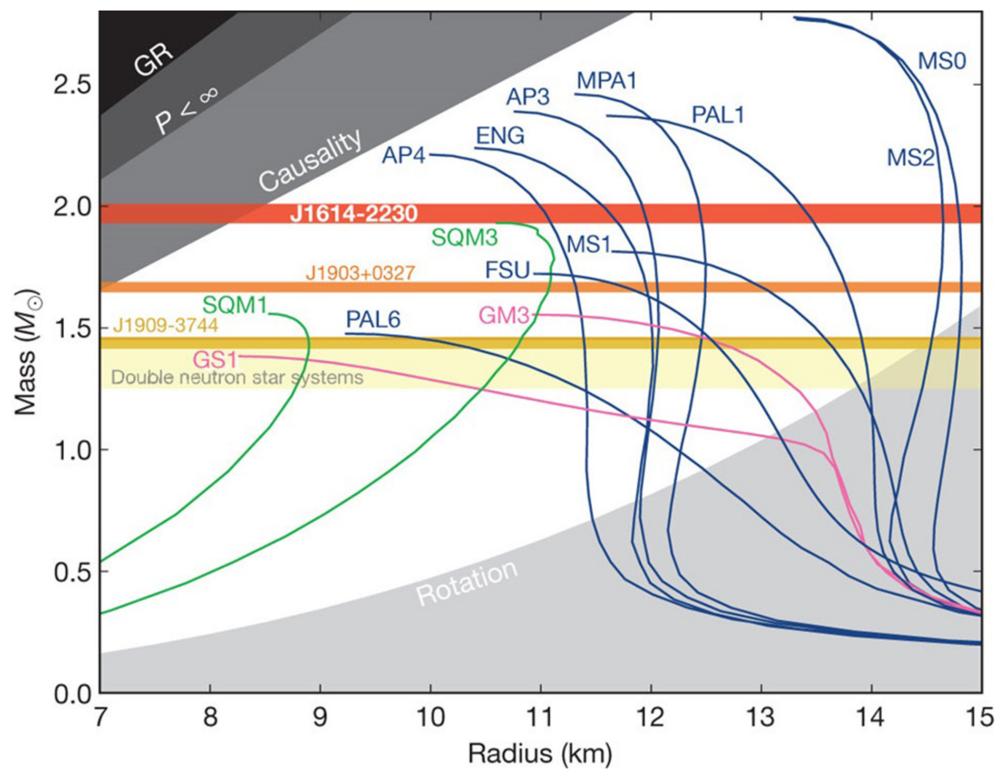




Neutron Stars and Nuclear Pasta

n stars = End states of star collapse for stars > several solar masses (supernovae)
Gigantic nuclei: $A = 10^{57}$ (but superdense core due to gravity >> nuclear force!)





models of neutron stars + observed masses

Nuclear Pasta
(crust of n star)

Measuring the n radius of lead to predict the radius of a n star

Summary

- Much already known about nuclear processes in the universe
- Still more information needed: cross sections of very rare processes, properties for very exotic nuclei, equation of state of nuclear matter, r-process sites,…
- Tools: low energy accelerators (future: underground!), rare isotope facilities (FRIB!), parity violating electron scattering (JLab), LIGO