The Explosive Lives of Stars:
Producing Elements in the Cauldrons of the Cosmos

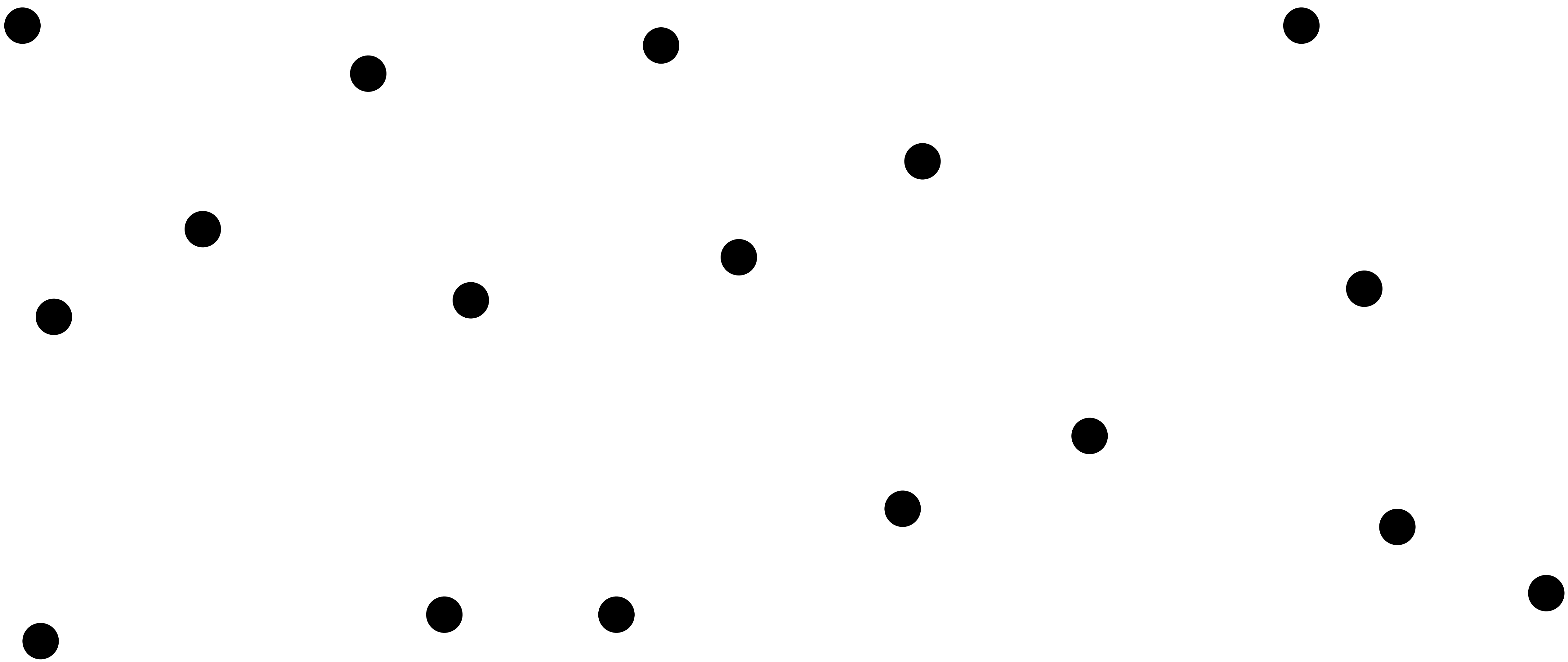
Catherine M. Deibel
Department of Physics & Astronomy
Louisiana State University

13.7 Billion (13,700,000,000) years ago the universe began with

THE BIG BANG

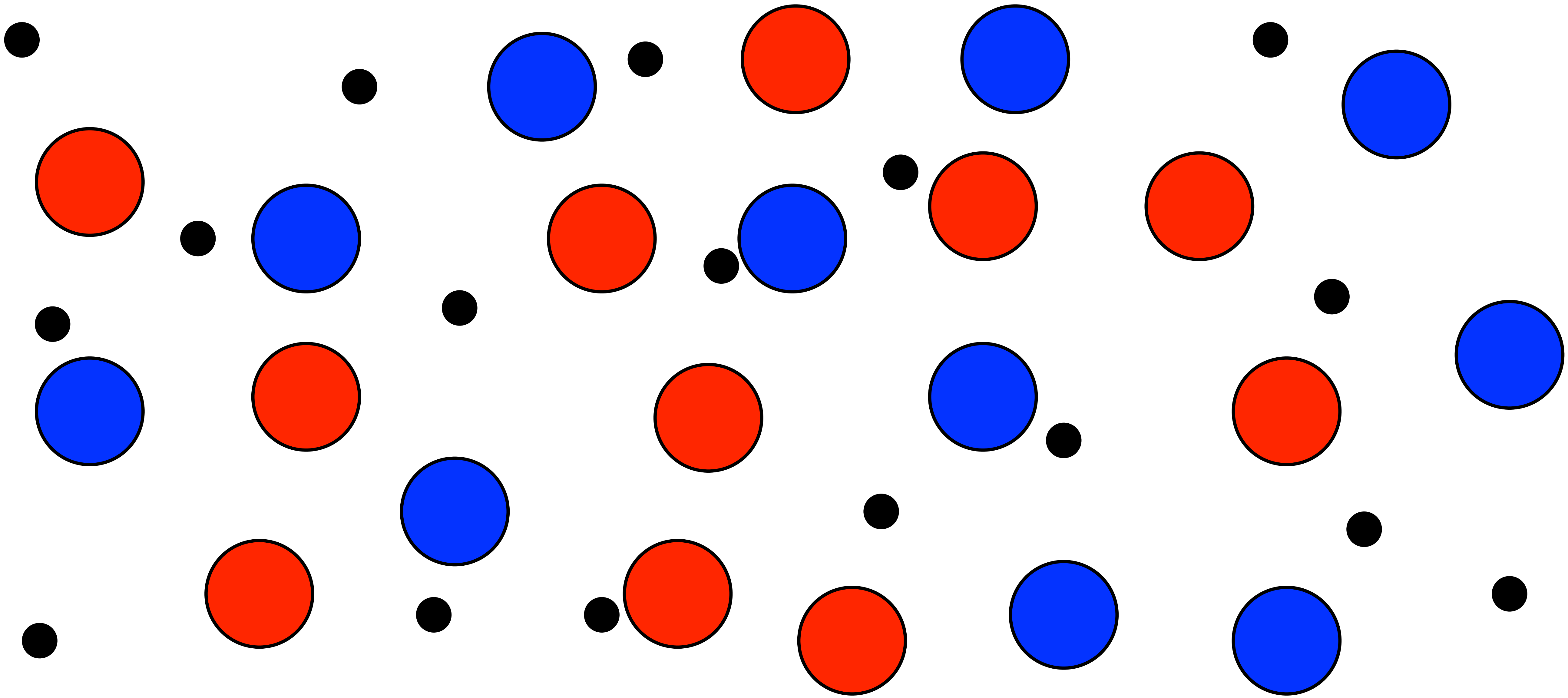
The first atoms

- A fraction (1/10,000,000,000,000,000,000,000,000,000,000,000) of a second after the BIG BANG electrons are created



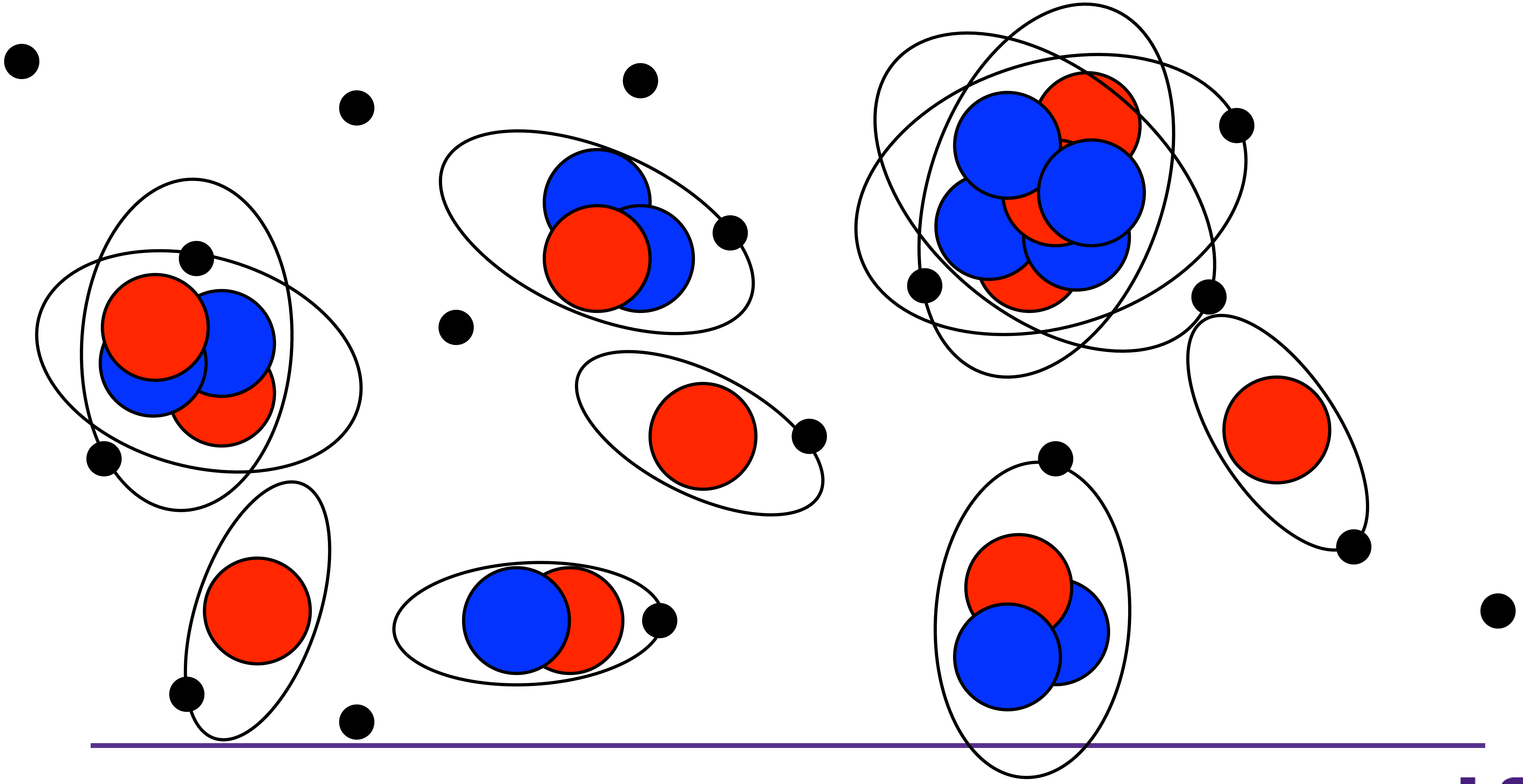
The first atoms

- One millionth of a second (.000001 seconds) after the BIG BANG protons and neutrons are formed

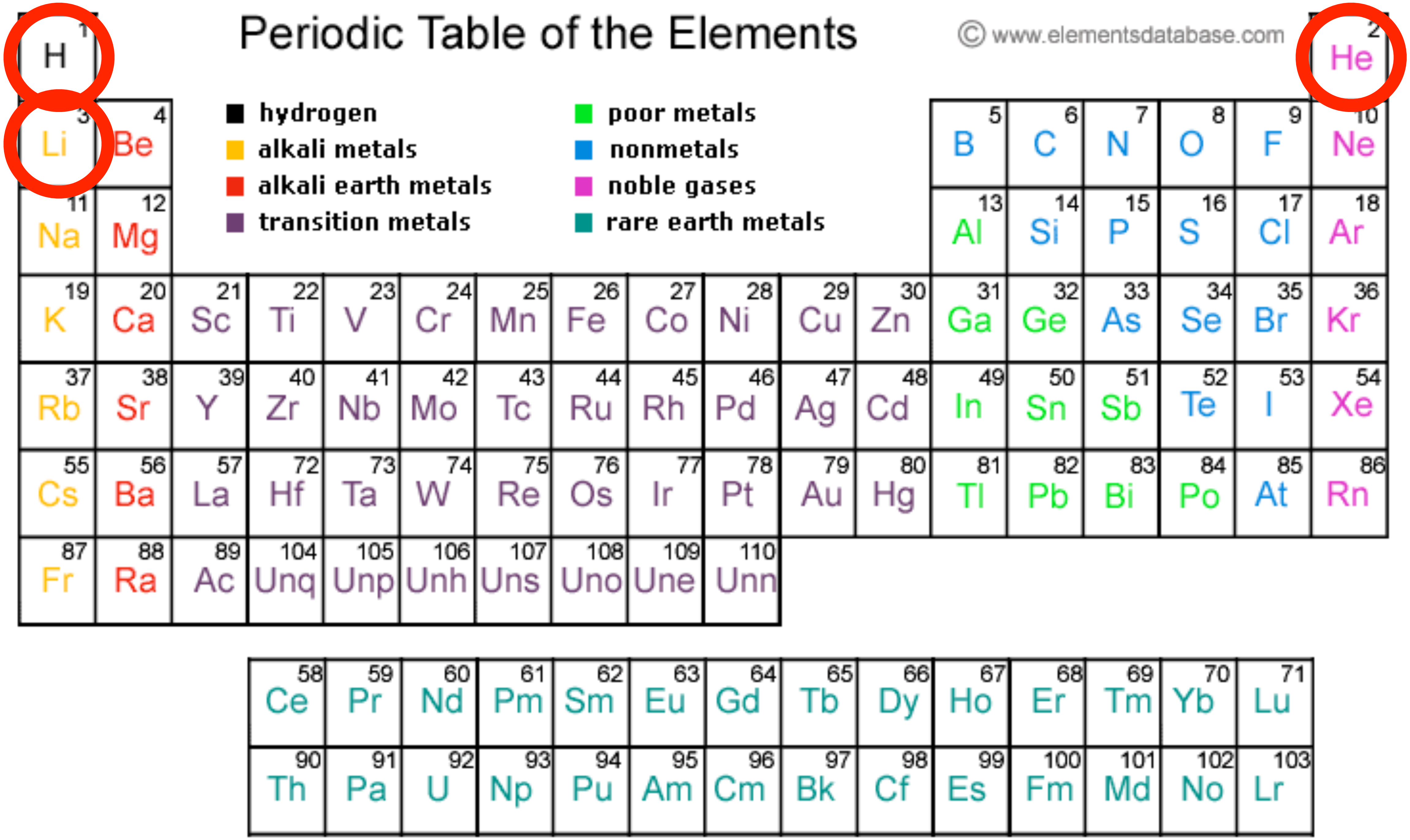


The first atoms

- 3 minutes after the BIG BANG the first atoms form



After the Big Bang



What about everything else?

Aluminum (Al)

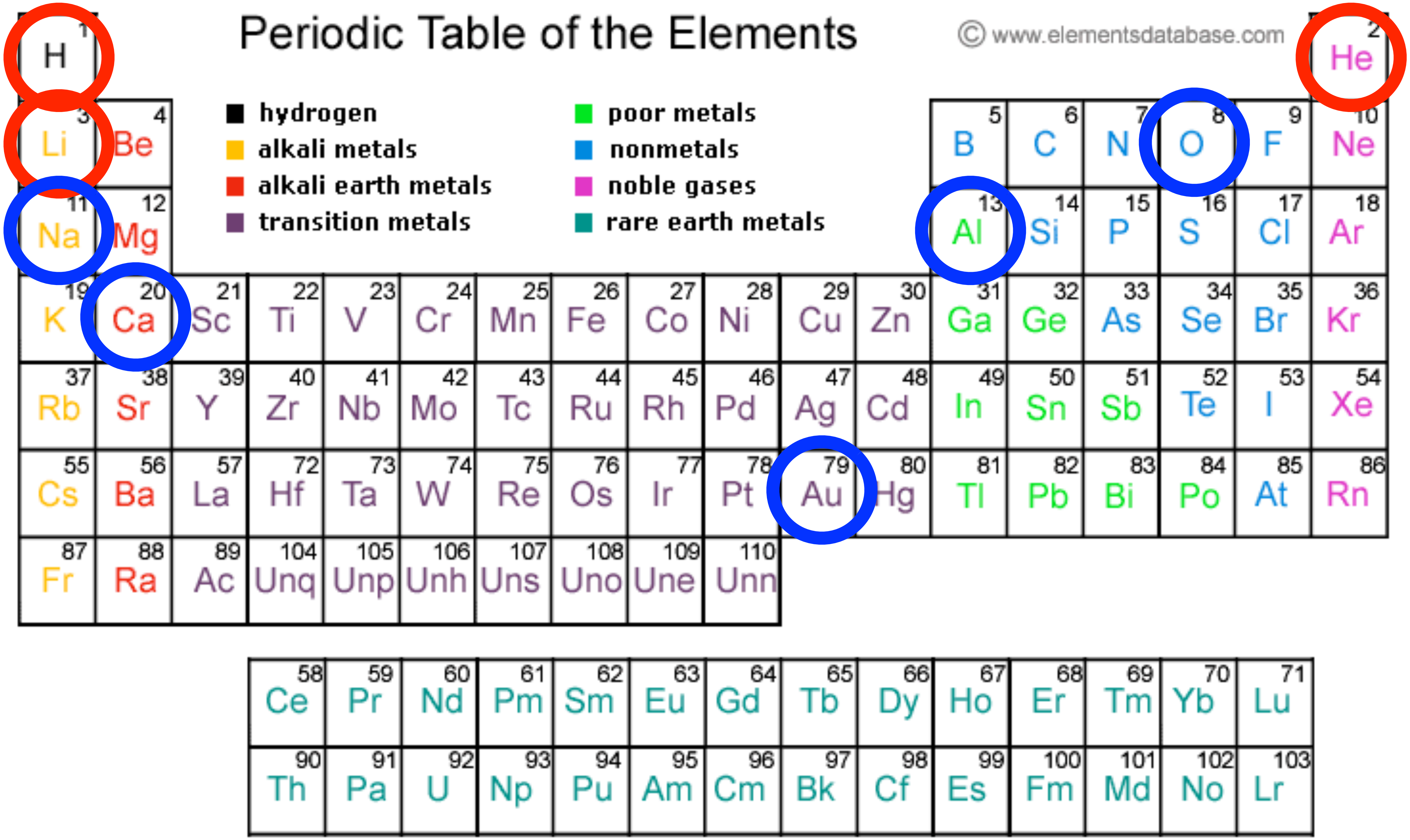
Sodium (Na)

Oxygen (O)
in water (H_2O)

Calcium (Ca)

Gold (Au)

Where does the rest of the Periodic Table come from?

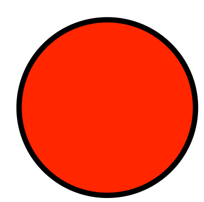


Beyond the Periodic Table . . .

- Adding or subtracting neutrons makes different ***isotopes***

- A hydrogen nucleus is one **proton**
  - Adding one **neutron** to hydrogen makes the ***isotope*** deuterium
  - Then adding one **proton** makes the ***isotope*** ^{3}He
  - Then adding one **neutron** makes the ***isotope*** ^{4}He

- Total number of protons (“atomic number”) = Z
- Total number of neutrons = N
- N + Z = A, “atomic mass number” or number of nucleons



^{1}H

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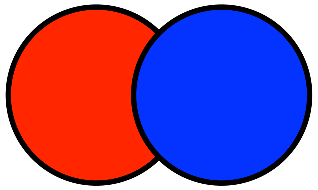

^{1}H	^{2}H

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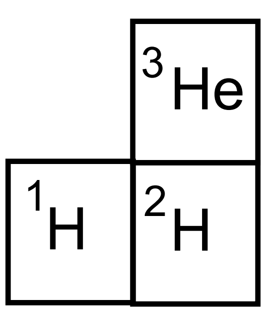

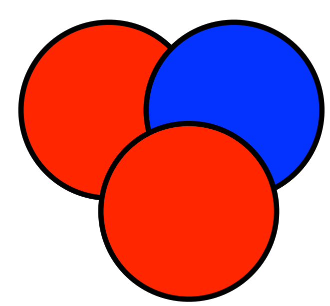

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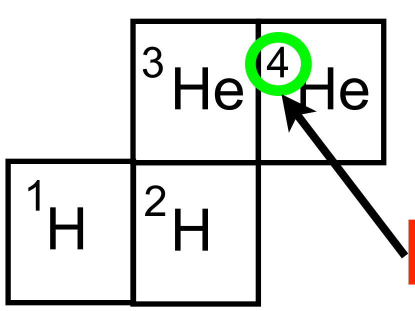
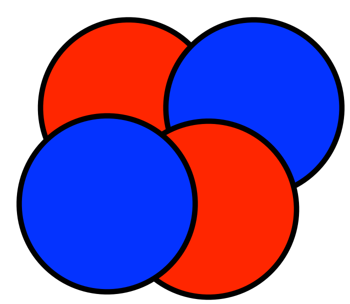


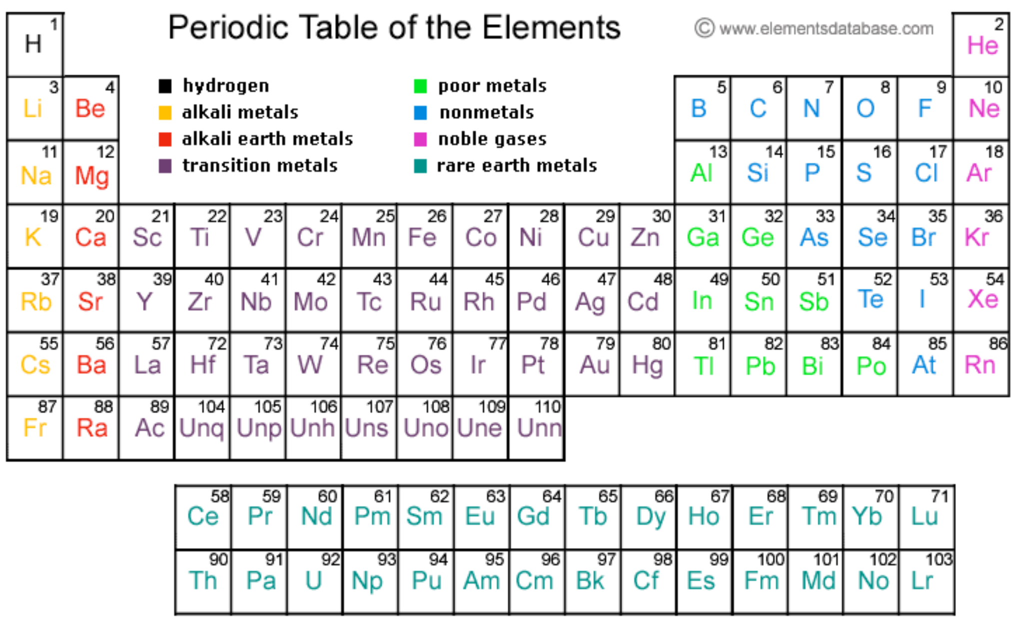
protons + neutrons

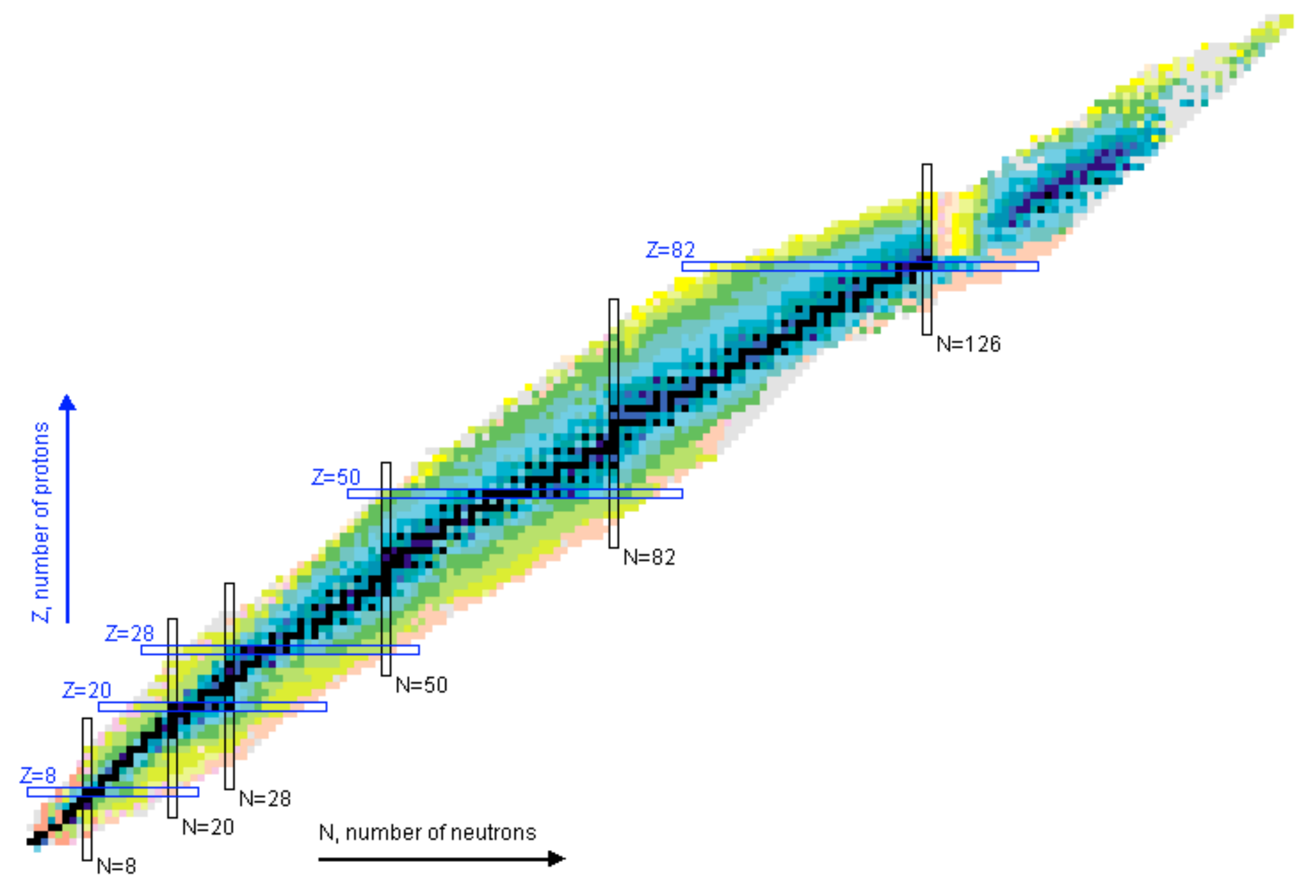


^{A}X or $^{A}_{Z}X$

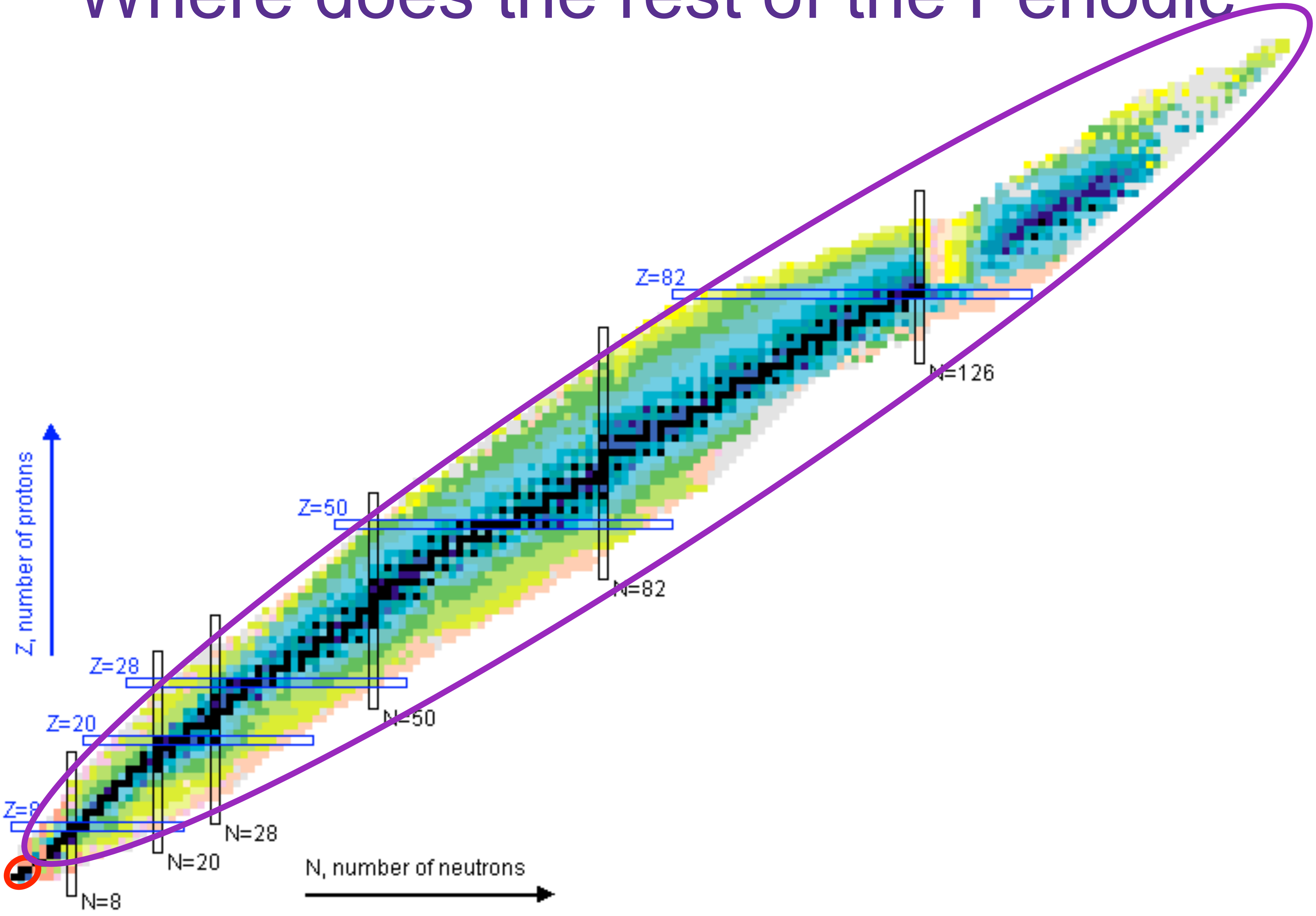
Beyond the Periodic Table . . .

- Keep adding protons and neutrons to make **thousands** of ***isotopes***





Where does the rest of the Periodic



Where does the rest of the Periodic

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

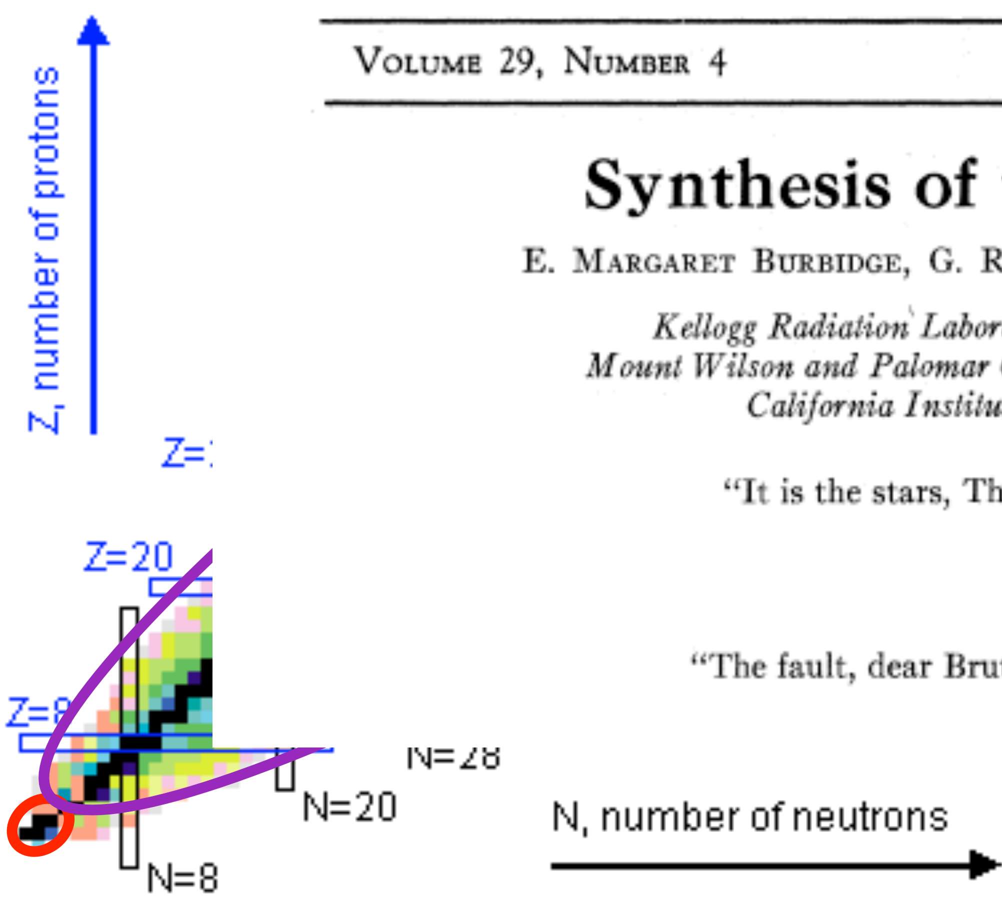
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

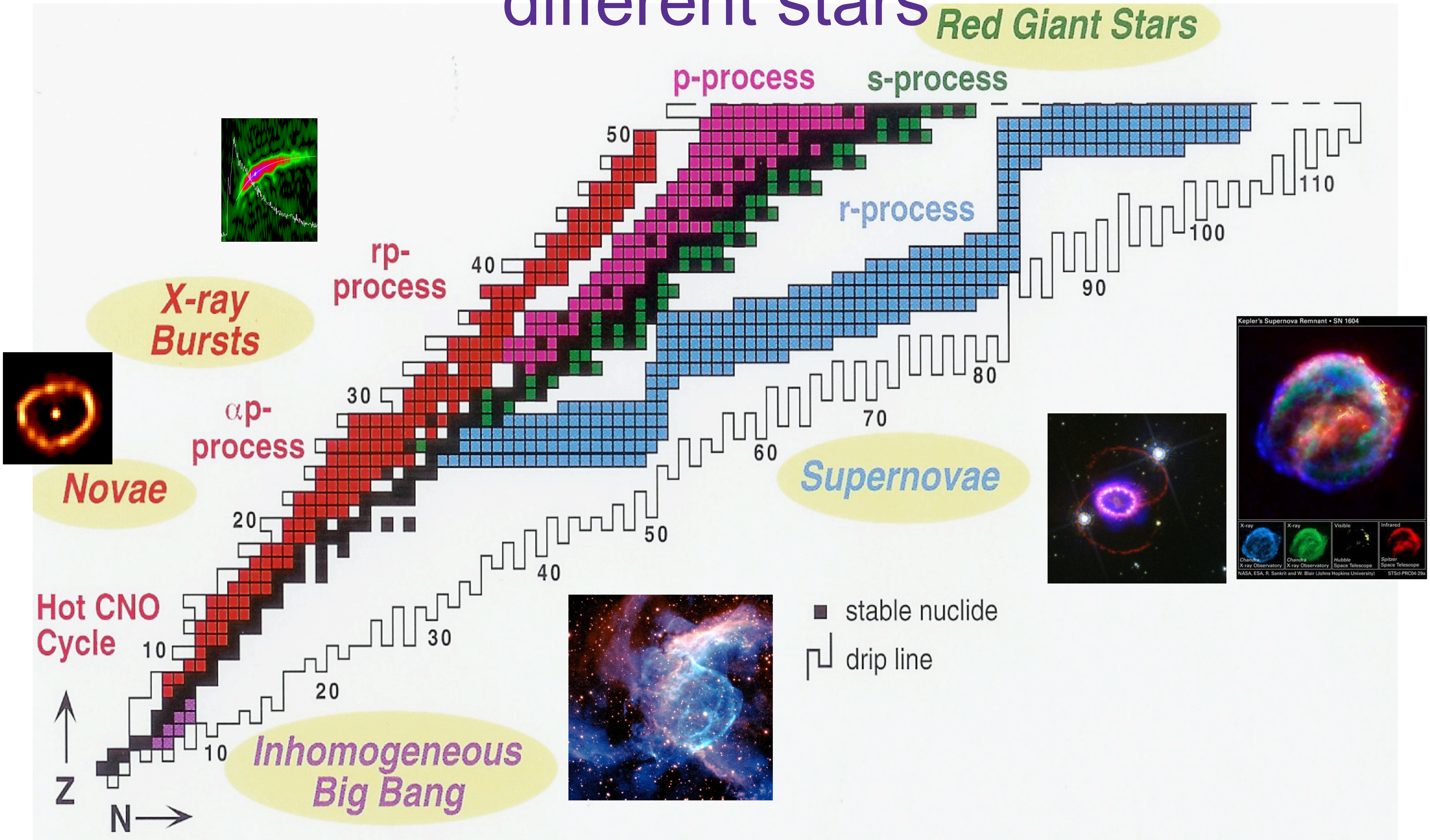
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)



Different Nuclei are produced in different stars

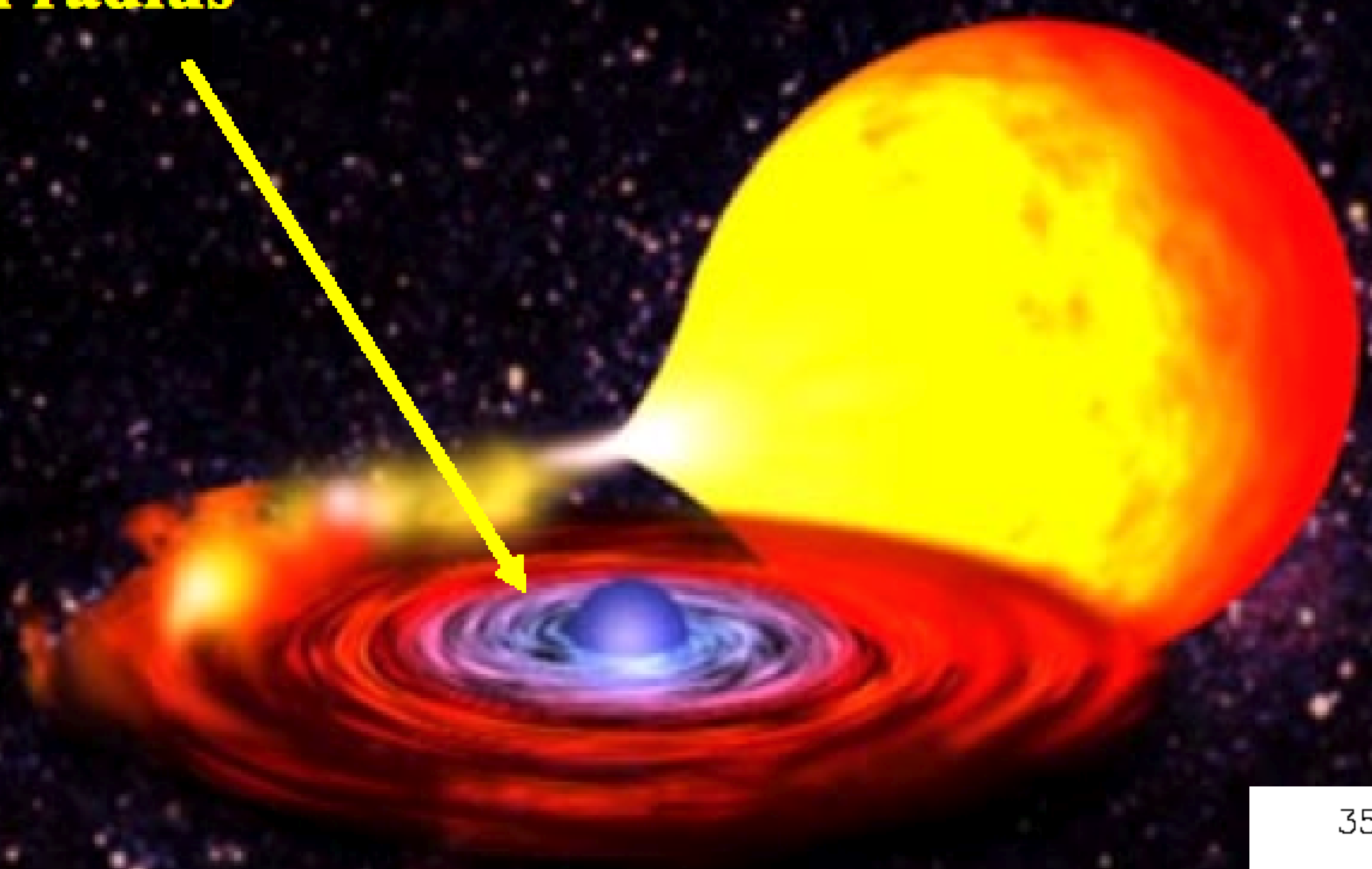


LSU

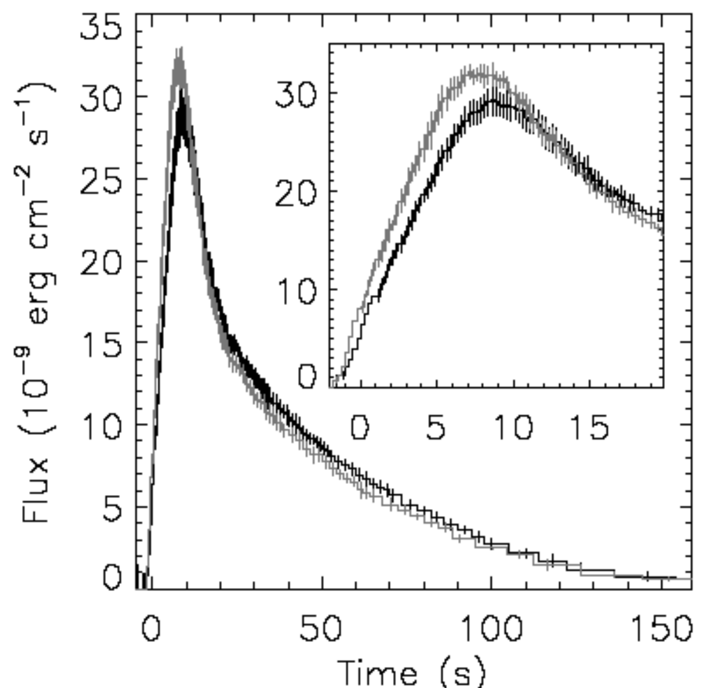
Type I X-Ray Bursts (XRBs)

Neutron stars:
1.4 M_o, 10 km radius

Normal star



Accretion rate ~ $10^{-8}/10^{-10}$ M_o/year
Peak x-ray burst temperature ~ 1.5 GK
Recurrence rate ~ hours to days
Burst duration of 10 – 100 s
Observed x-ray outburst ~10^{39} – 10^{40} ergs



D.K. Galloway *et al.*, ApJ **601** 466

Neutron Stars

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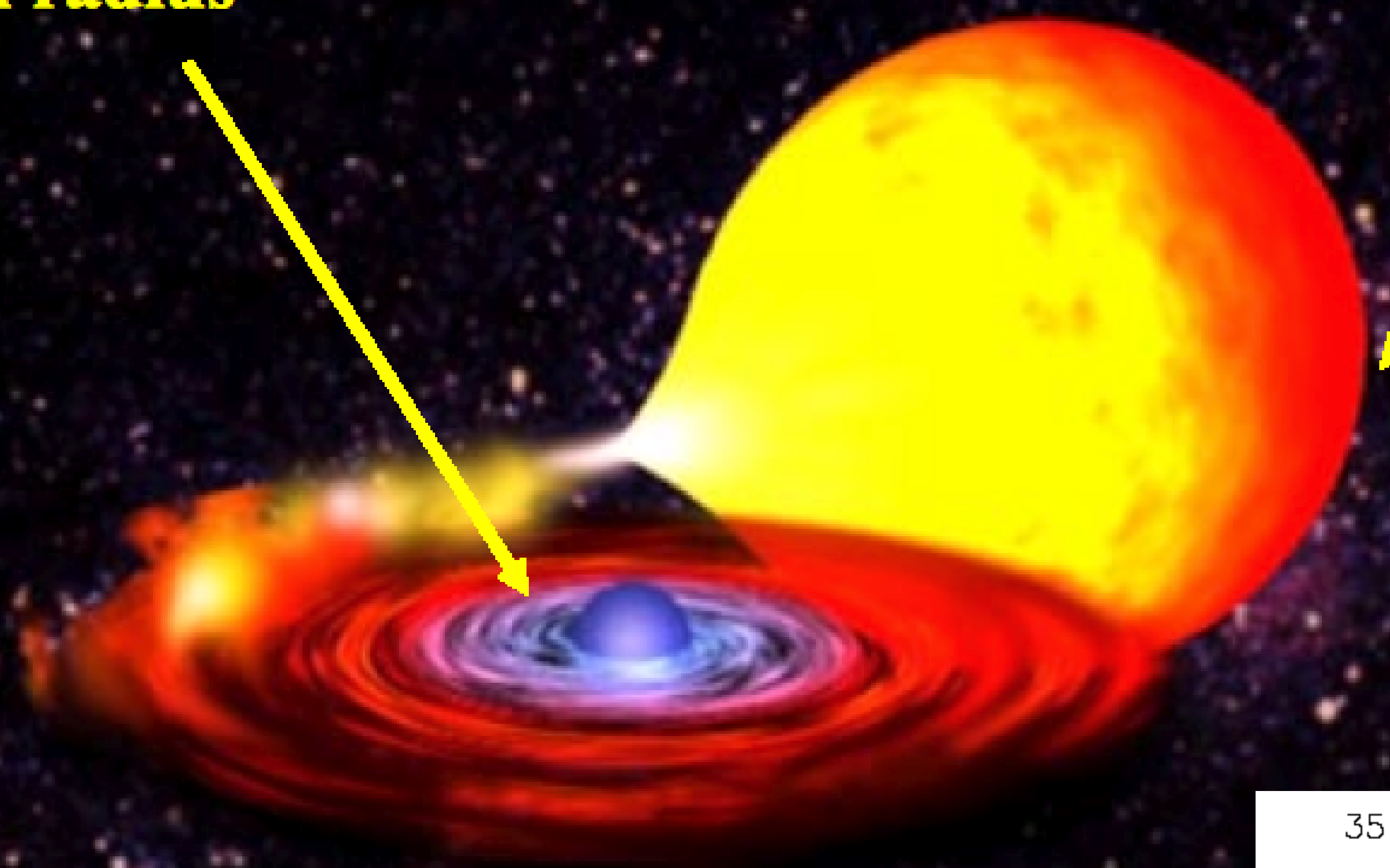

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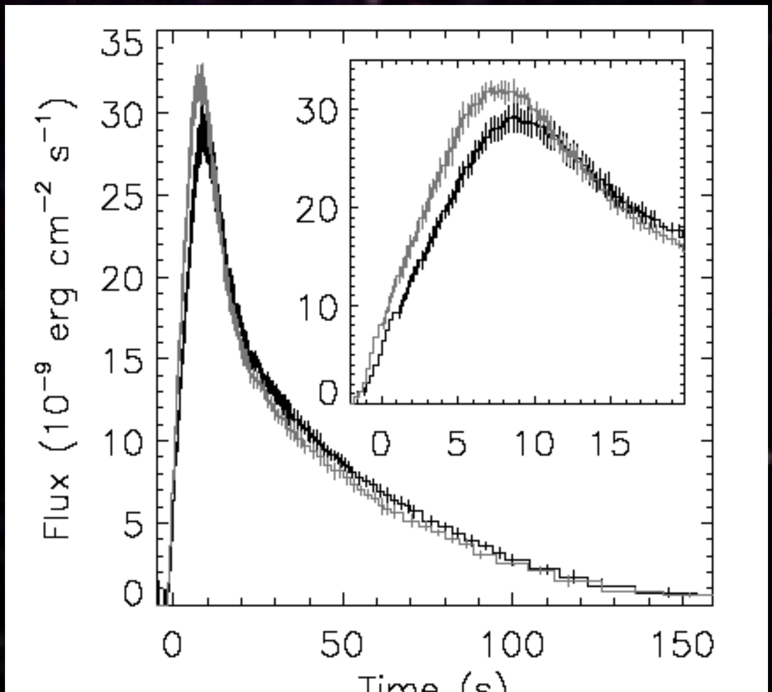


D.K. Galloway *et al.*, ApJ **601** 466

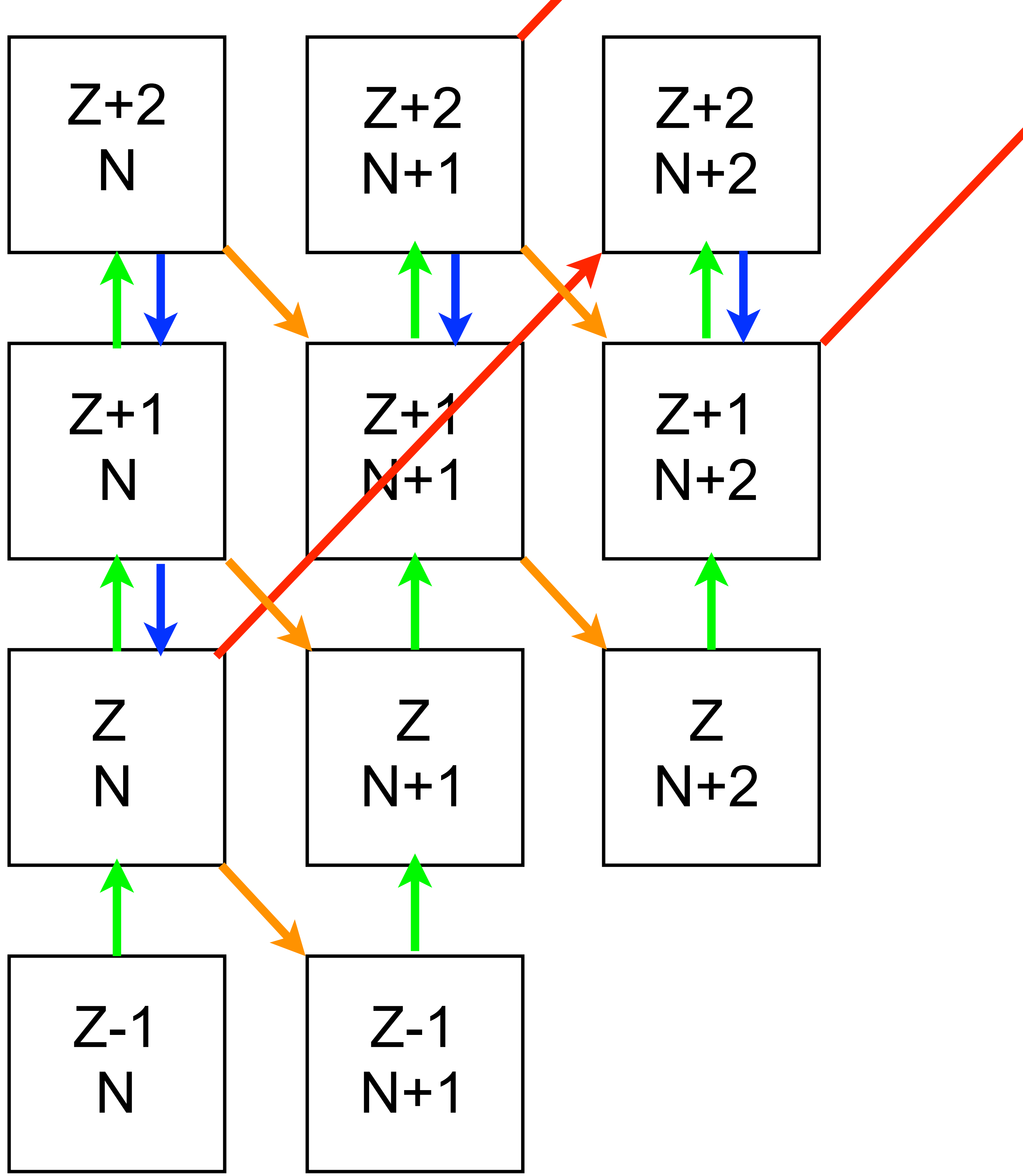
X-Ray Burst Nucleosynthesis

Proton capture:
(p,γ)

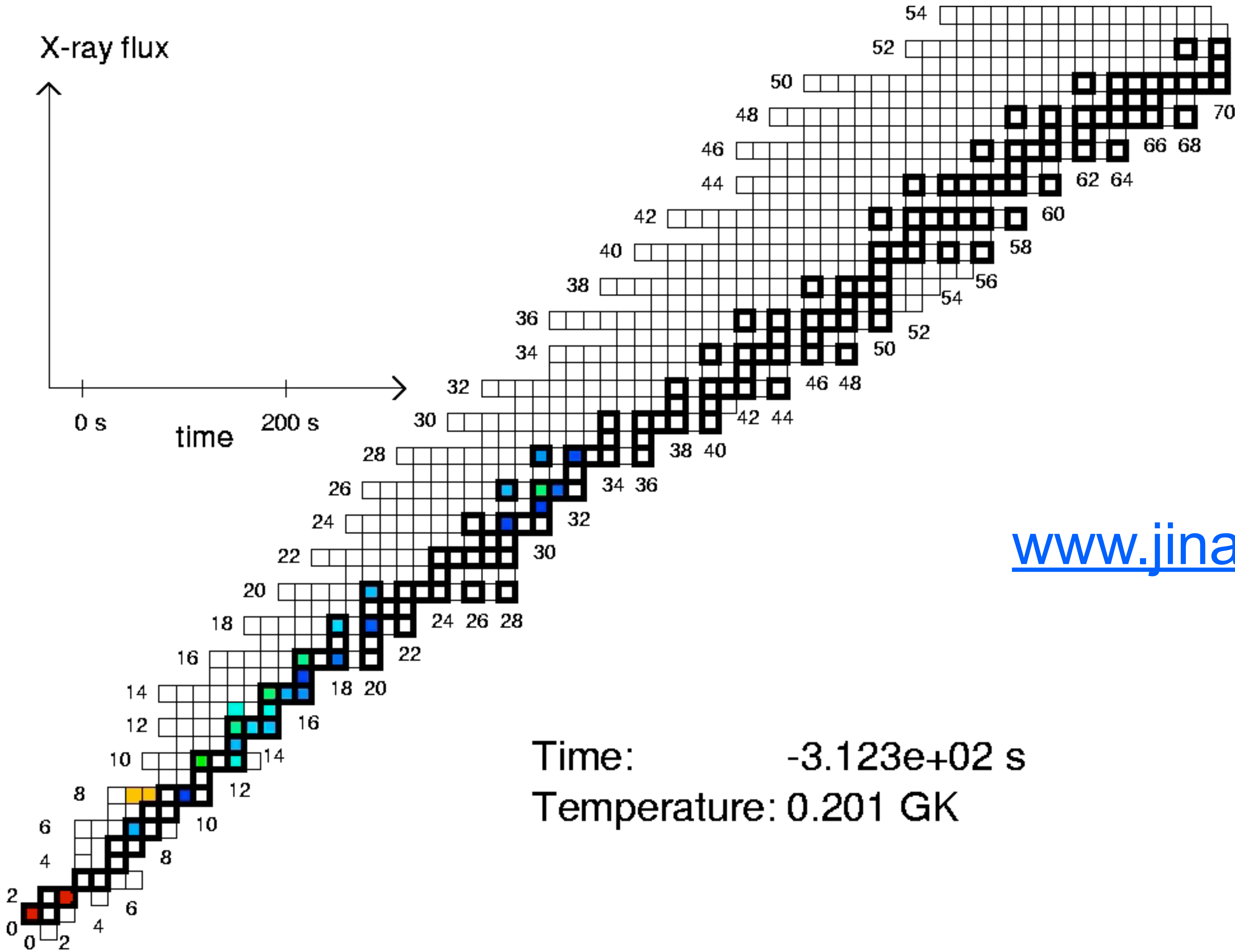
Proton decay:
(γ,p)

Beta decay:
(β^+)

Alpha capture:
(α,γ)
(α,p)



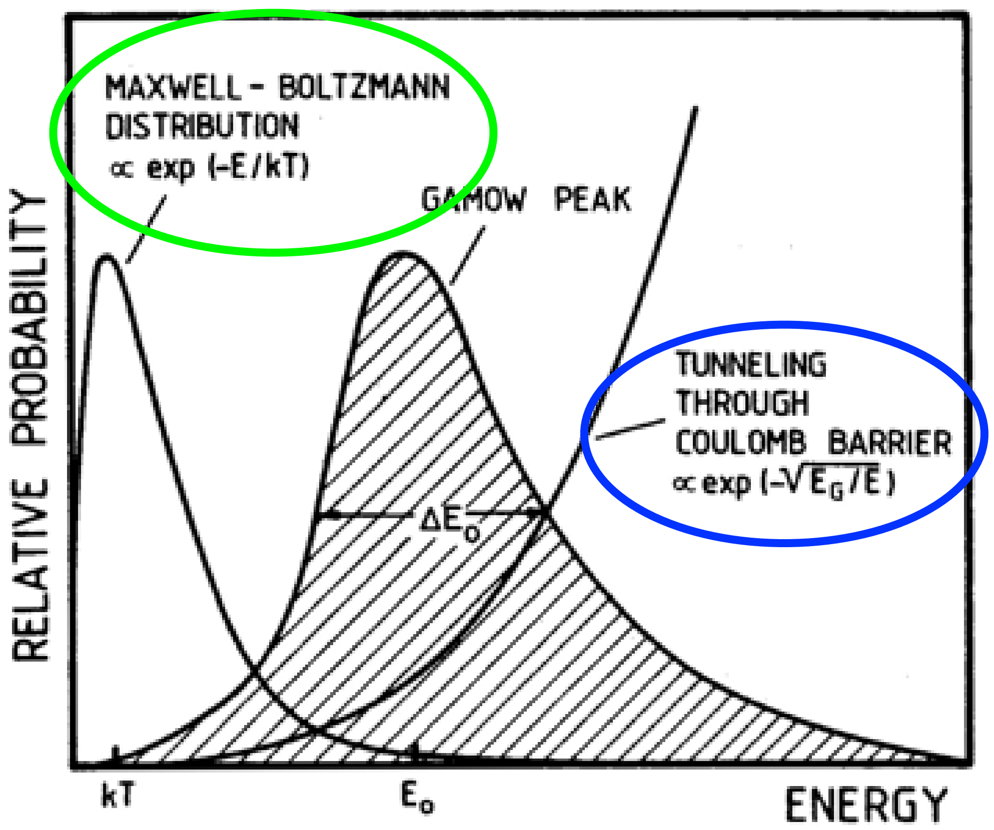
X-Ray Burst Nucleosynthesis



www.jinaweb.org

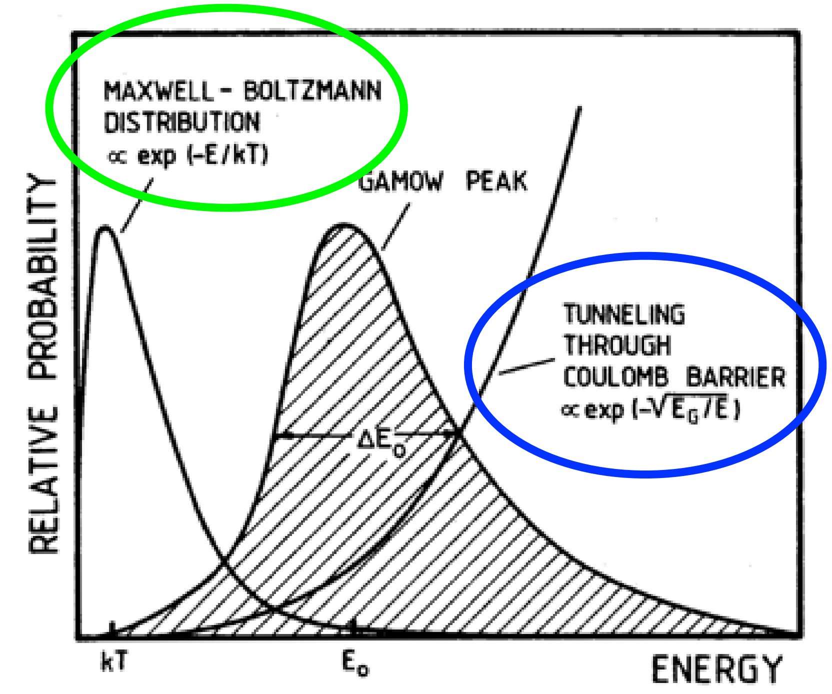
How do nuclei react?

- What is a **reaction rate**?
  (i.e. What is the **probability** of two nuclei reacting in the stellar plasma?)
- Thermal distribution of nuclei in stellar plasma:
  Maxwell-Boltzmann distribution
- The probability of the interaction between two nuclei:
  nuclear cross section
- **Temperature dependent** – different temperatures in stars probe different energies in nucleus



Reaction Rates

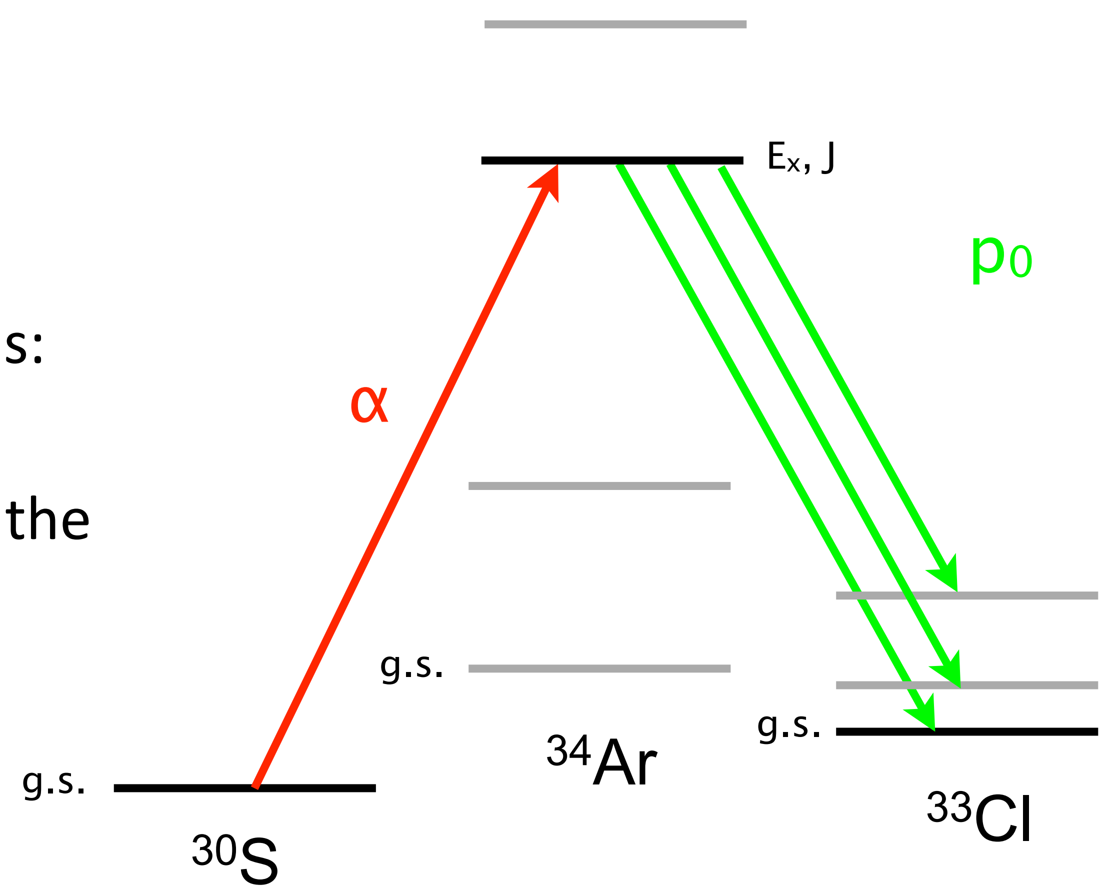
- Folding the **Maxwell-Boltzmann distribution** in with the **nuclear cross section** gives the **reaction rate**



- For resonant reaction rates:
  - $\propto$ exp(−E)
  - $\propto$ nuclear spin, J
  - $\propto$ nuclear widths, Γ

- Two ways to study reactions rates and cross sections:
  - Directly- measuring the reaction rate itself
  - Indirectly- determining different components of the reaction rate

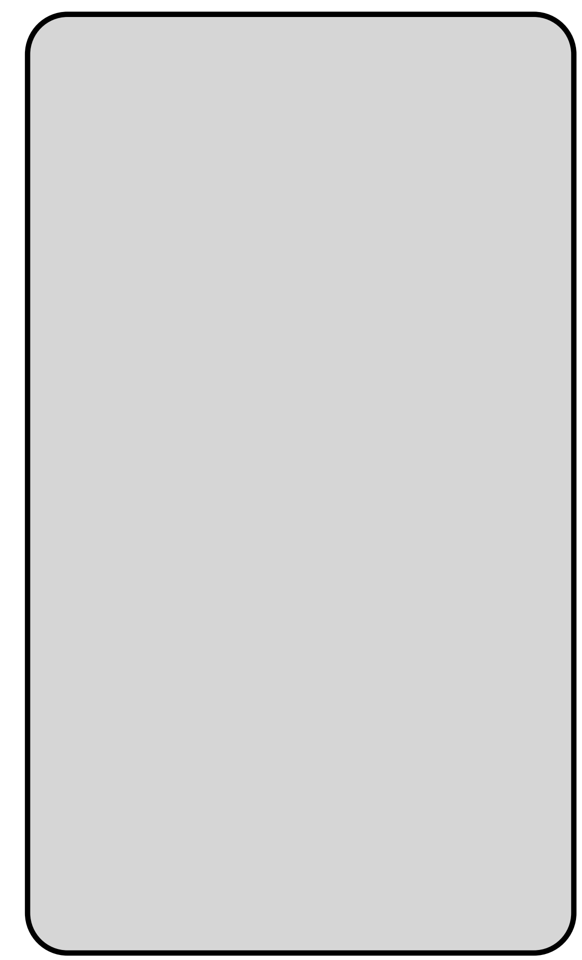
- e.g. $^{30}S(\alpha,p)^{33}Cl$

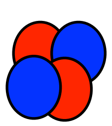


Studying Nuclear Reactions in the Laboratory

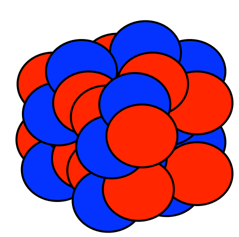
- Using accelerators with different types of detectors we can measure what nuclear reactions happen in stars
- A particle beam is accelerated and impinges on a target
- Outgoing particles are detected

DETECTOR





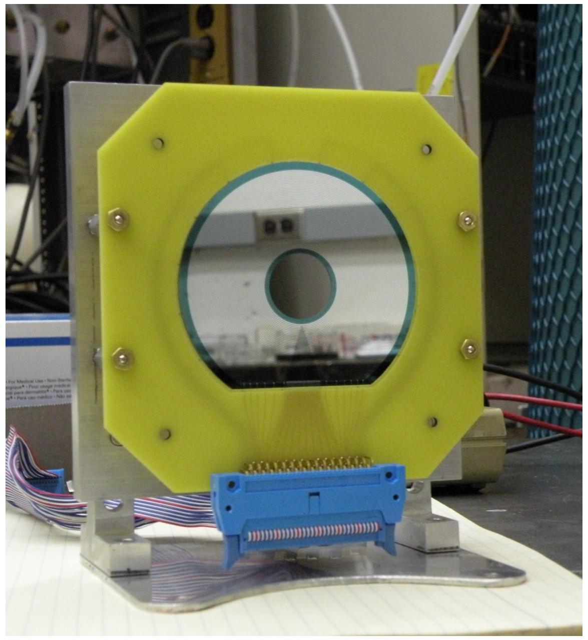
beam →



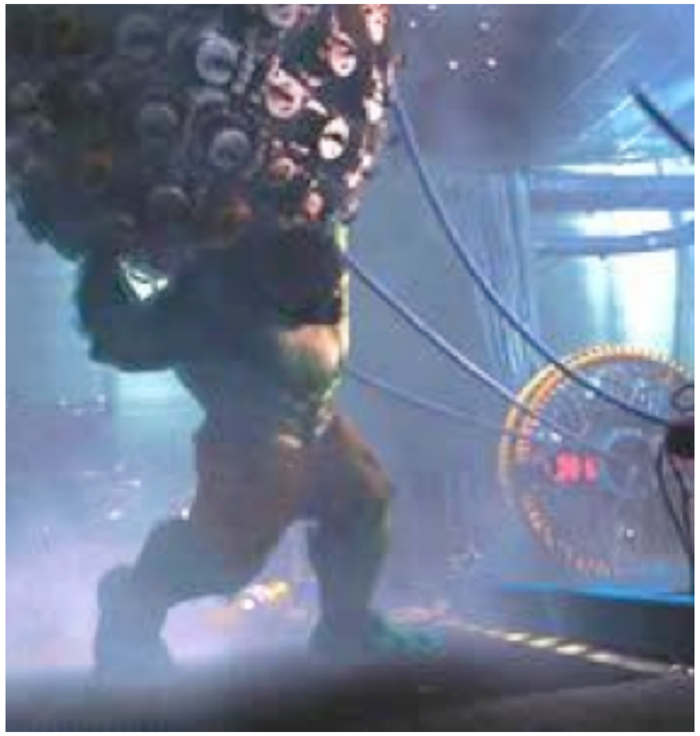
target

Studying Nuclear Reactions in the Laboratory

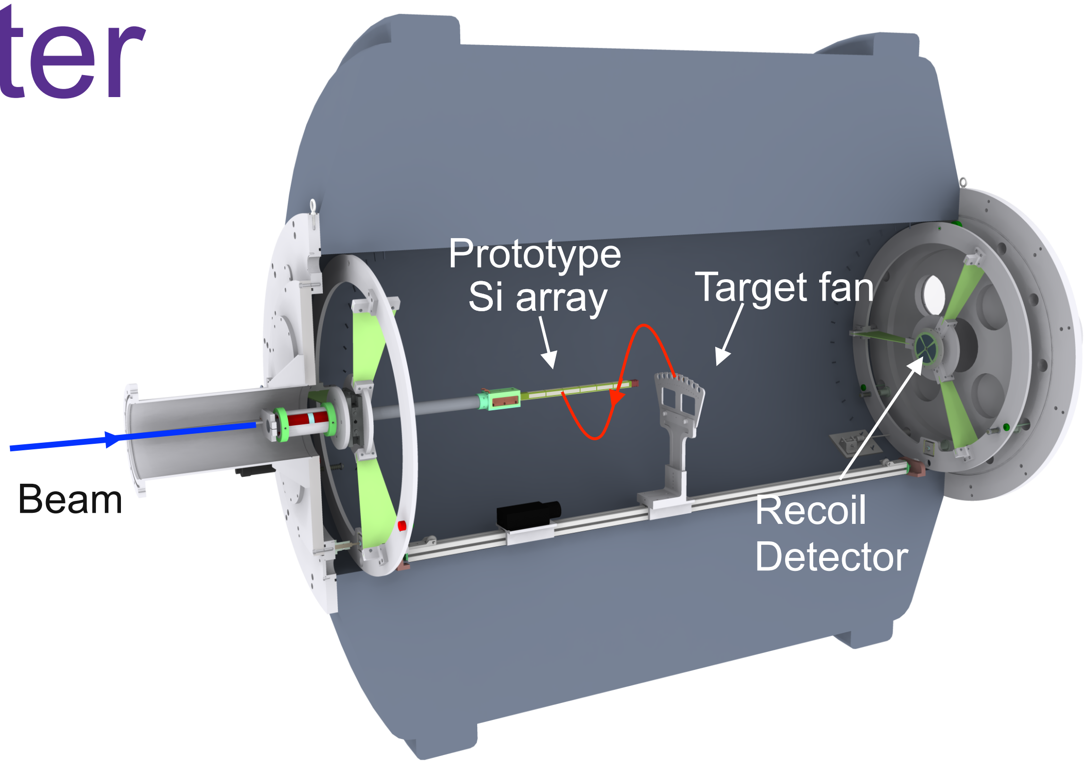
- Charged particles can be manipulated by magnetic fields and separated by
  - charge
  - mass
  - energy



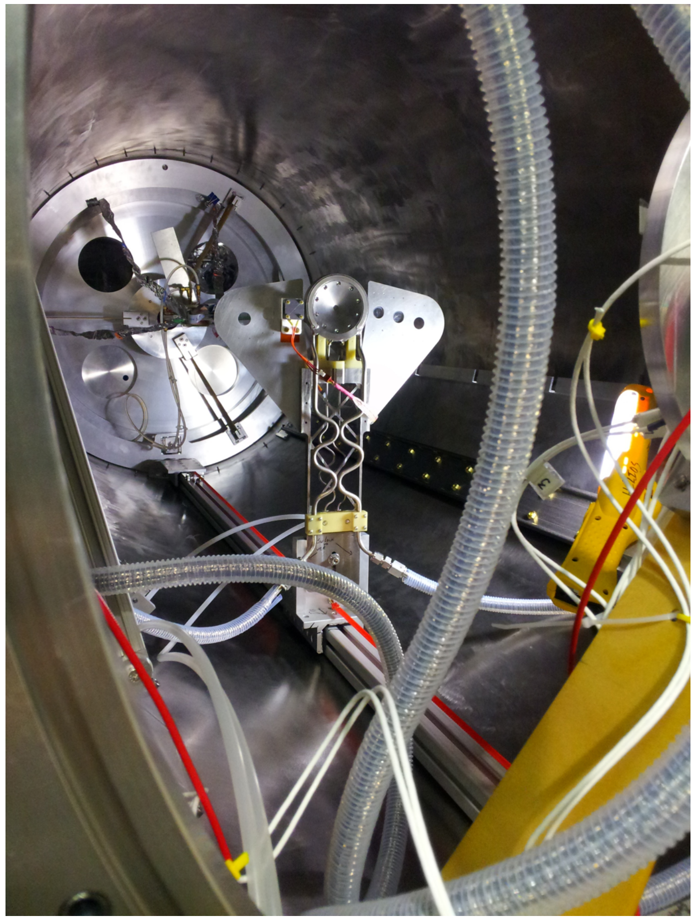
- Detected using
  - ionization chambers
  - silicon detectors
  - CsI detectors
  - gamma detectors



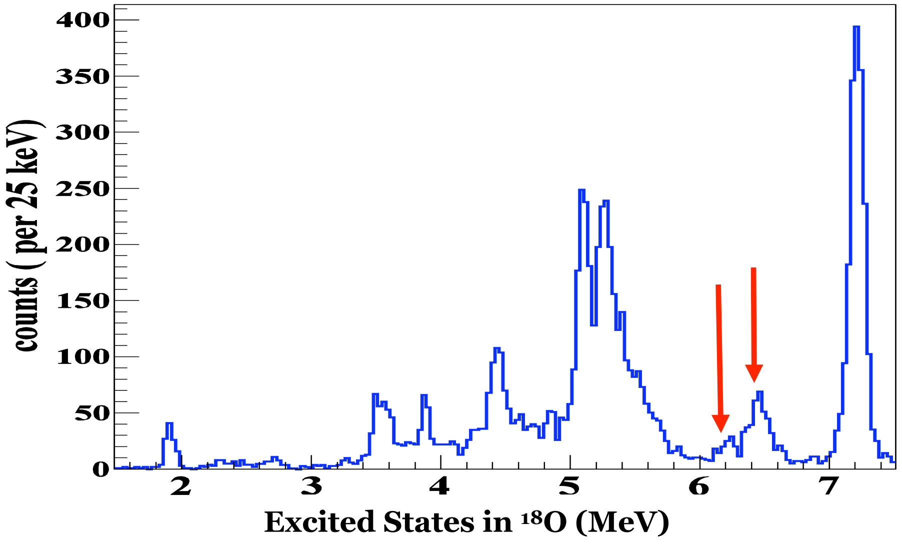
HELIcal Orbit Spectrometer



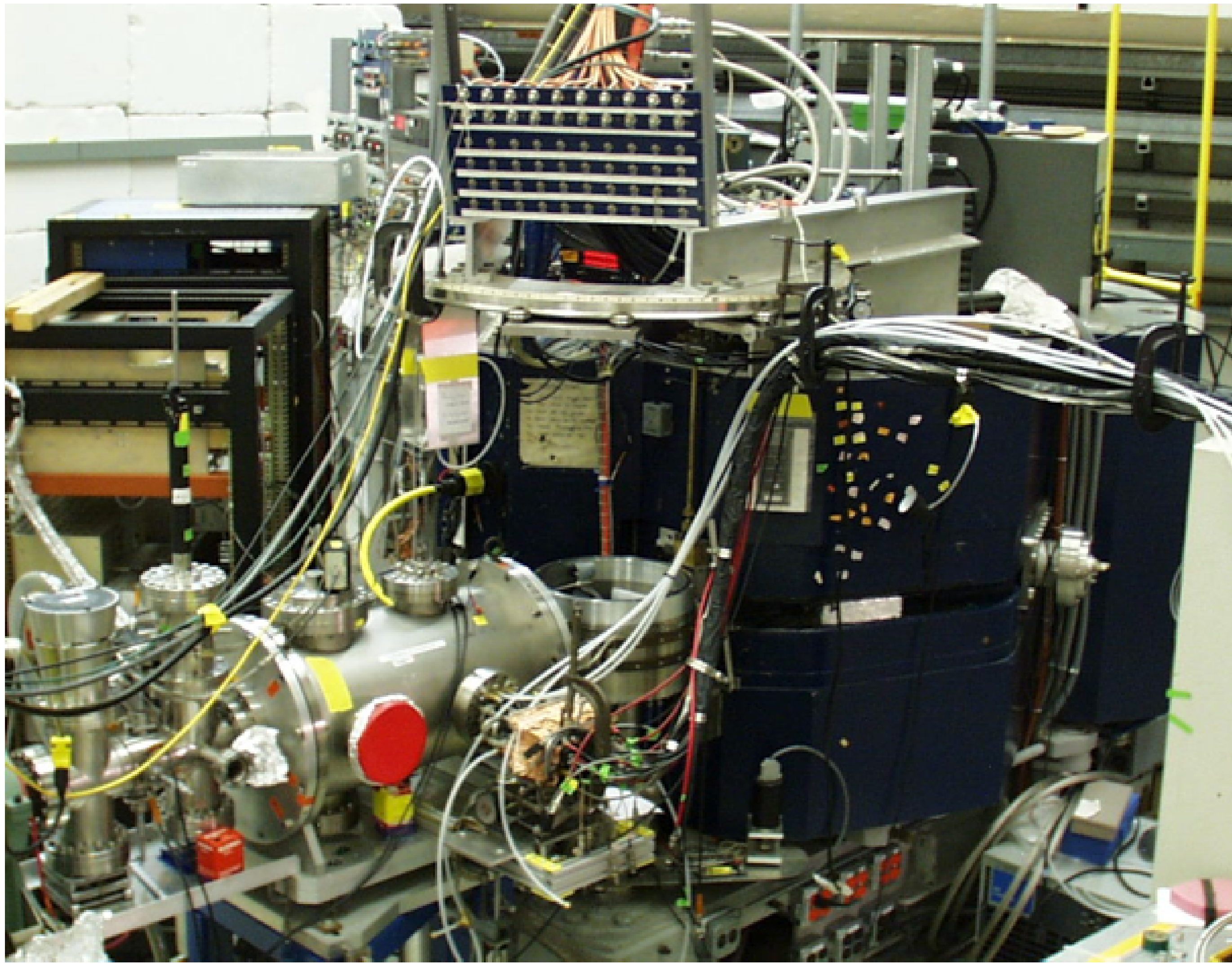
- Beam of radioactive nuclei directed through center of solenoid
- Impinges on a target of light nuclei (e.g. hydrogen, helium, etc.)
- Reaction products measured by detectors
- Reaction products tell us:
  - excitation energy levels
  - spins of levels
  - reaction rate information

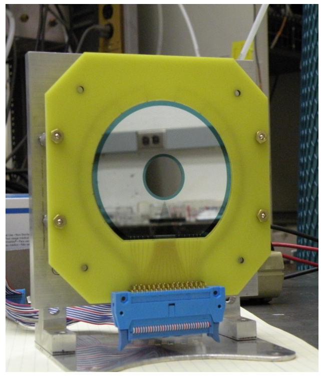


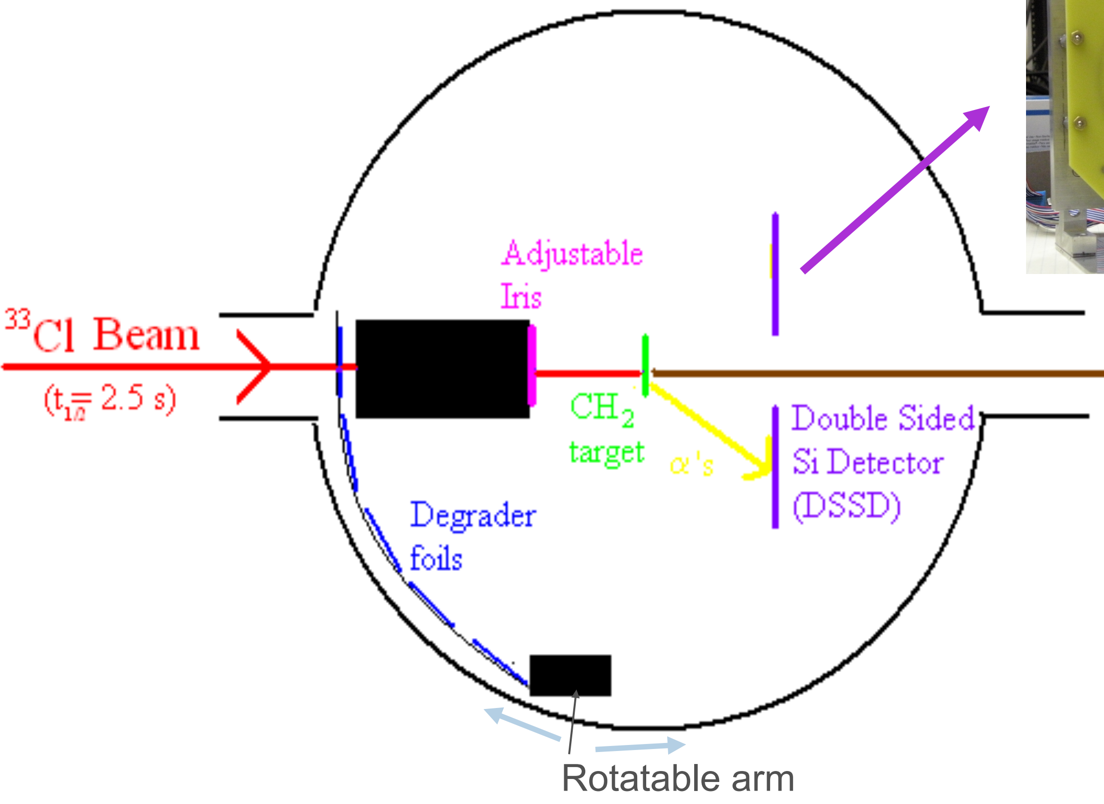
States in ^{18}O from $^{14}O(^{6}Li,d)^{18}O$

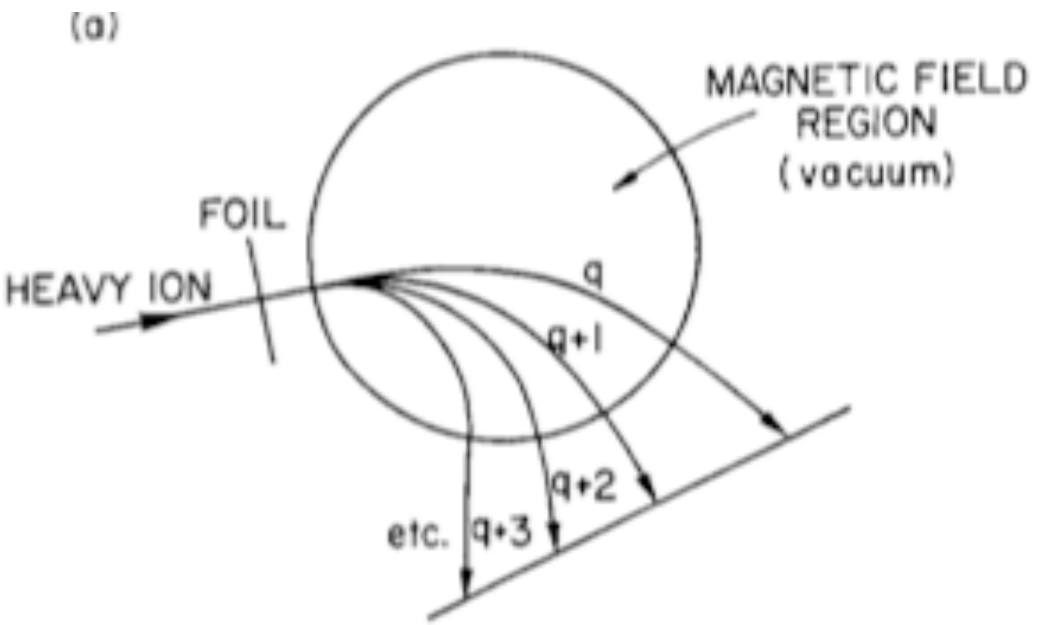


^{33}Cl(p,α)^{30}S Measurement



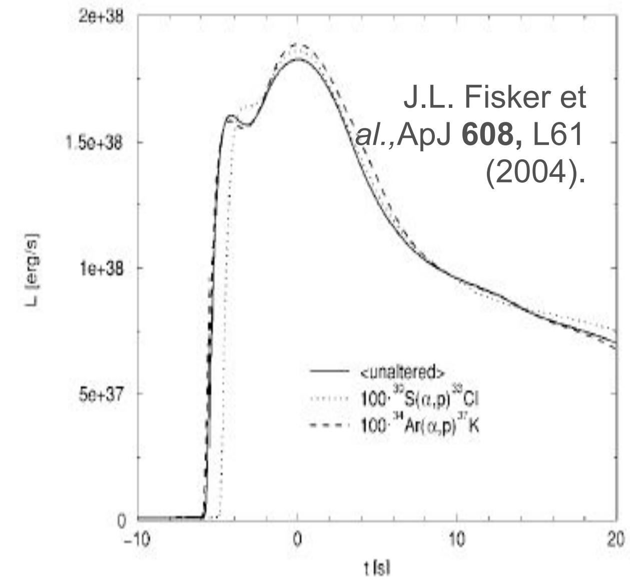




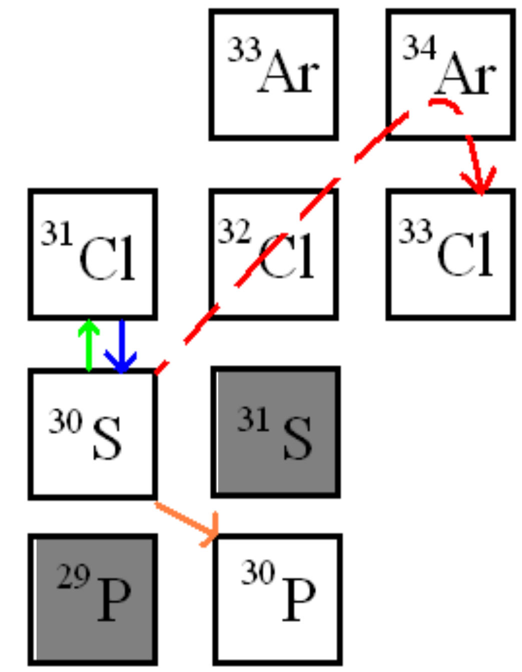


(α,*p*)-process waiting points: $^{30}S(\alpha,p)^{33}Cl$ Measurement

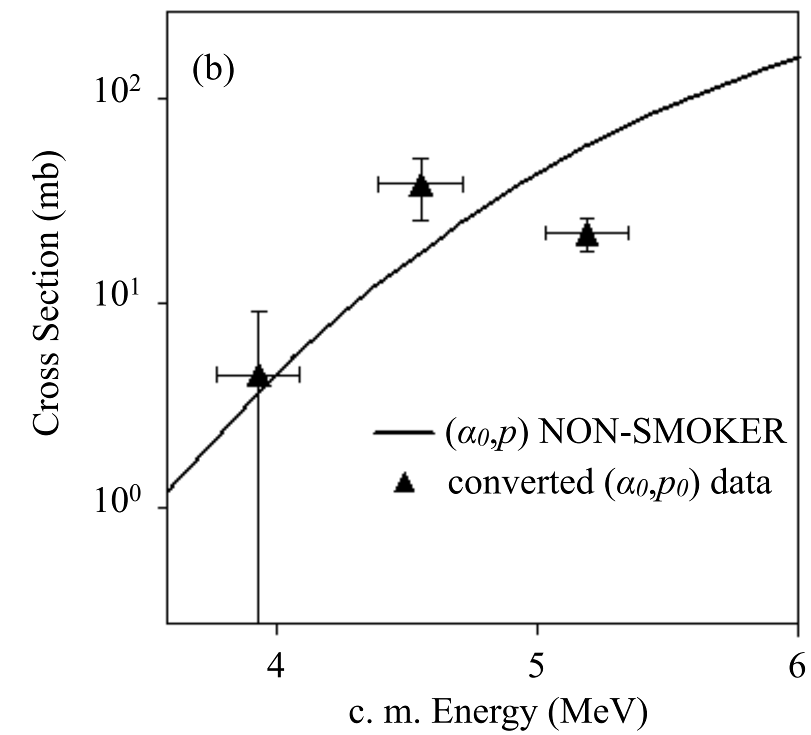
- (α,*p*) reactions on waiting points (^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar) may have significant effects on type I X-ray bursts
  - final elemental abundances
  - energy generation
  - double-peaked luminosity profiles



J.L. Fisker et *al.*,ApJ **608,** L61 (2004).



$^{30}S(\alpha_0,p)^{33}Cl$



C.M. Deibel ett *al*, submitted (2011).

- Measured cross sections (probability of reacting) larger than theoretical predictions:
  - reaction rate is bigger!

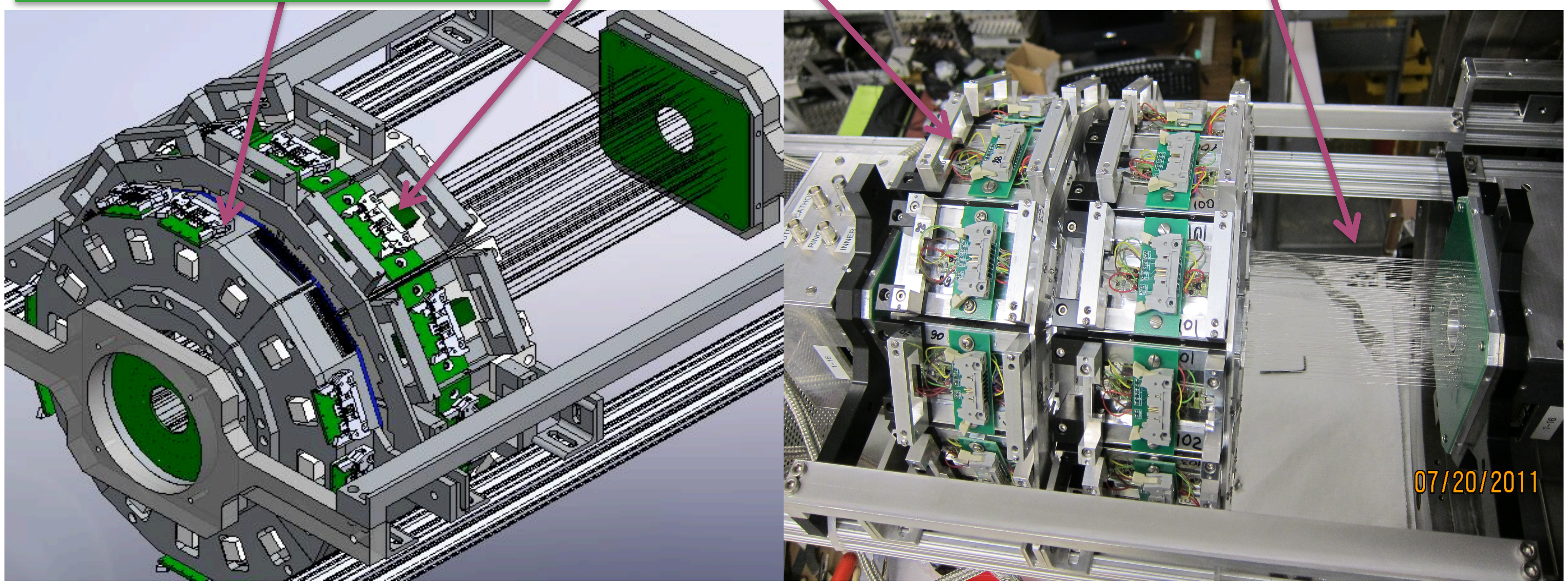
Experiments for X-ray bursts

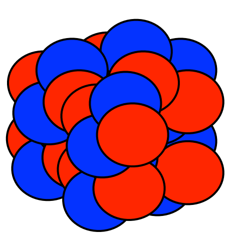
Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN)

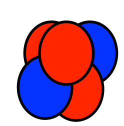
Up to 3 rings of 12 modules in barrel formation

Annular array for forward/ backward angles

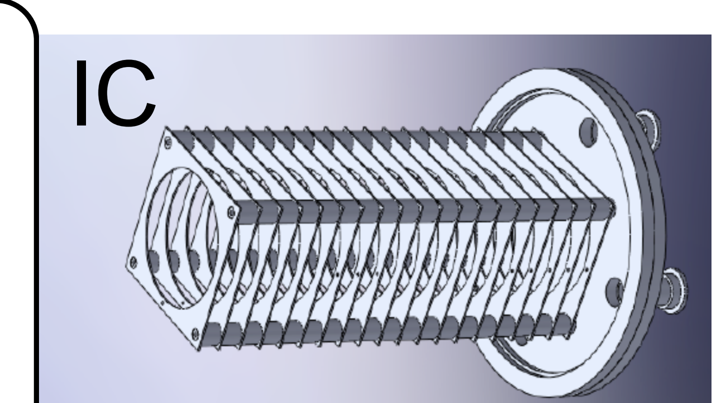
Active target+detector
Annular gas proportional counter surrounds beam axis







ANASEN

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COLOMBIA
PERU
BRAZIL
BOLIVIA
ARGENTINA
ICELAND
SWEDEN
FINLAND
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FRANCE
SPAIN
ITALY
UKRAINE
ROMANIA
GREECE
TURKEY
RUSSIA
KAZAKHSTAN
MONGOLIA
CHINA
SYRIA
IRAQ
IRAN
SAUDI ARABIA
YEMEN
OMAN
INDIA
PAKISTAN
THAILAND
ALGERIA
LIBYA
EGYPT
MALI
NIGER
CHAD
SUDAN
ERITREA
ETHIOPIA
NIGERIA
CENTRAL AFRICAN REPUBLIC
SOMALIA
UGANDA
KENYA
DEMOCRATIC REPUBLIC OF THE CONGO
TANZANIA
ANGOLA
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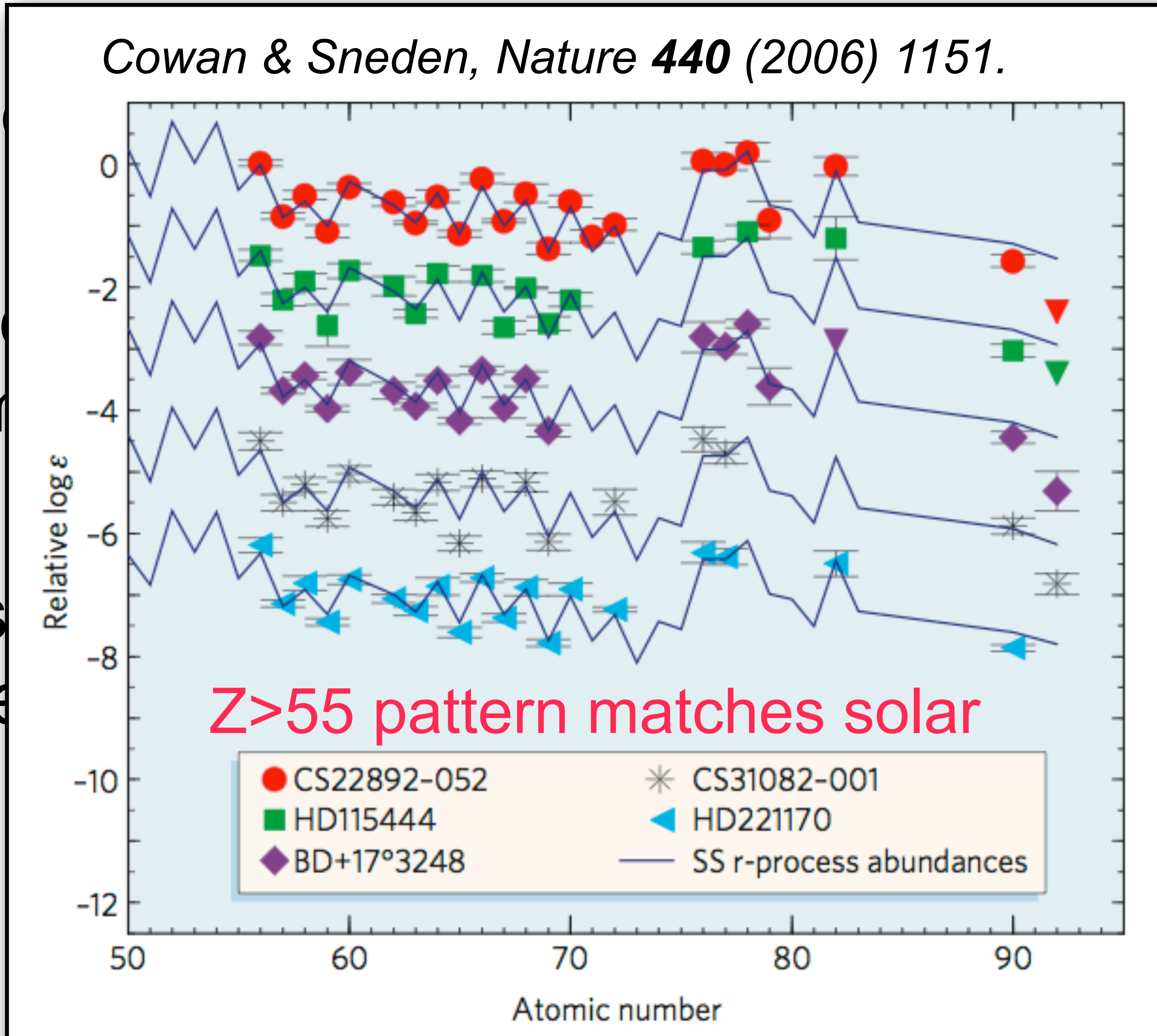
Embarrassing truths about NA
a.k.a. why we stay employed

- Sup
- We
elem
- Mos
have

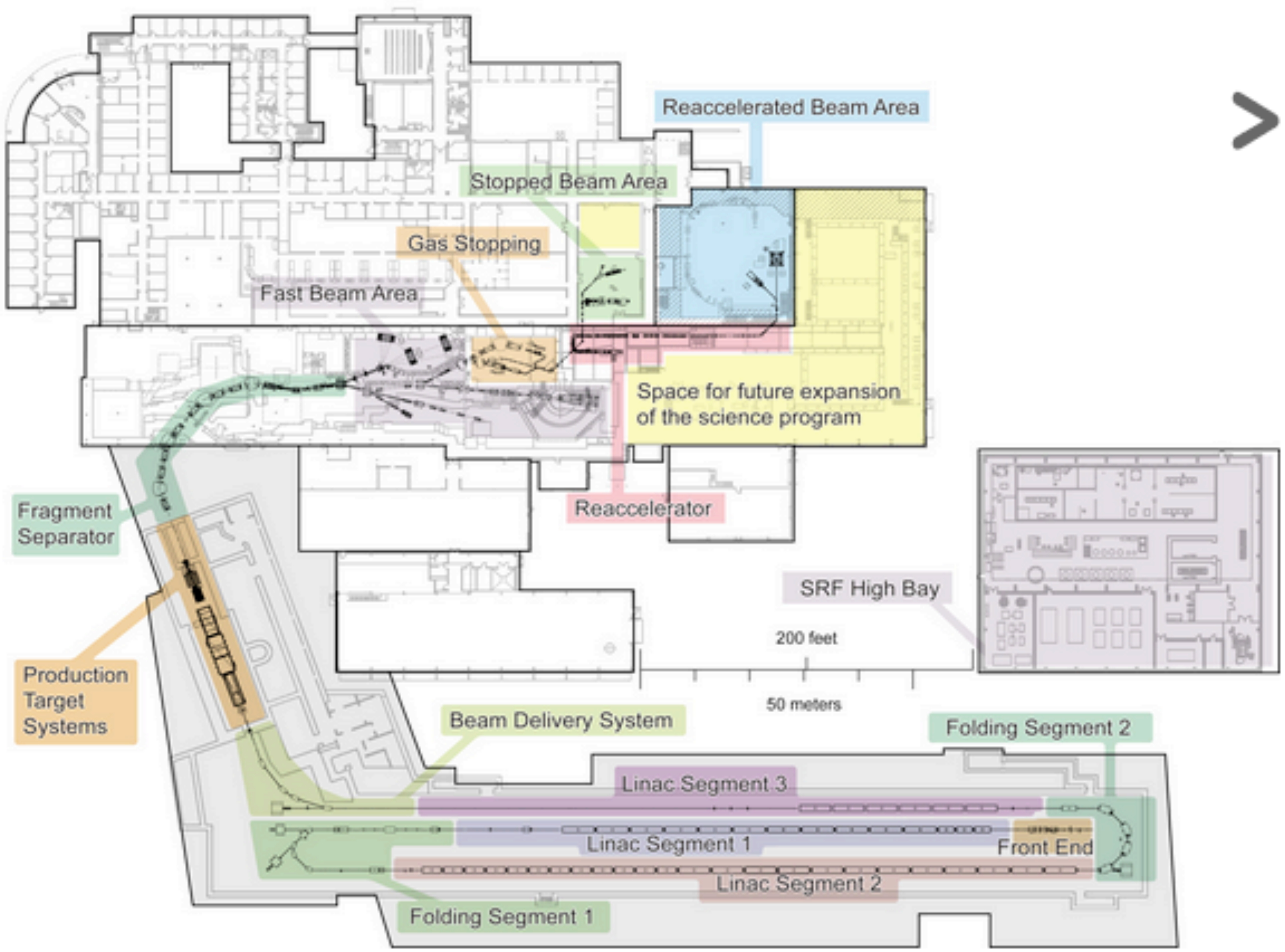


Embarrassing truths about NA
a.k.a. why we stay employed

- Supernova models don't explode
- We don't know where all the heavy elements are made
- Most reactions that happen in stars have not been studied
- But the future is bright . . .

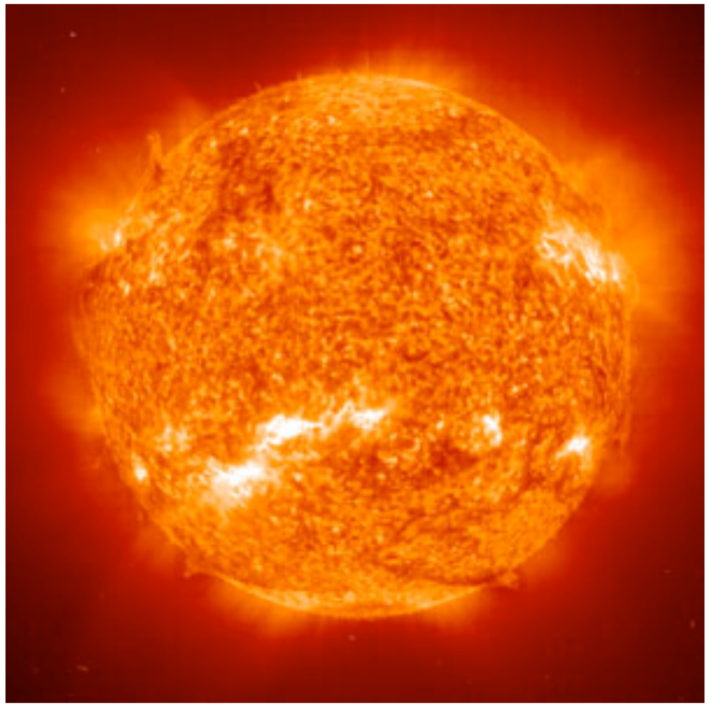
Embarrassing truths about NA

a.k.a. why we stay employed



Layout of the accelerator and experimental systems and the experimental areas of the Facility for Rare Isotope Beams.
Image 2 of 3

>



FACILITY FOR RARE ISOTOPE BEAMS

Thanks!


Rascoe
Blackmon
Williams
Gardiner
Zganjar
Lai
Lauer
Macon
Linhardt
Afanasieva