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The Origin of the Elements

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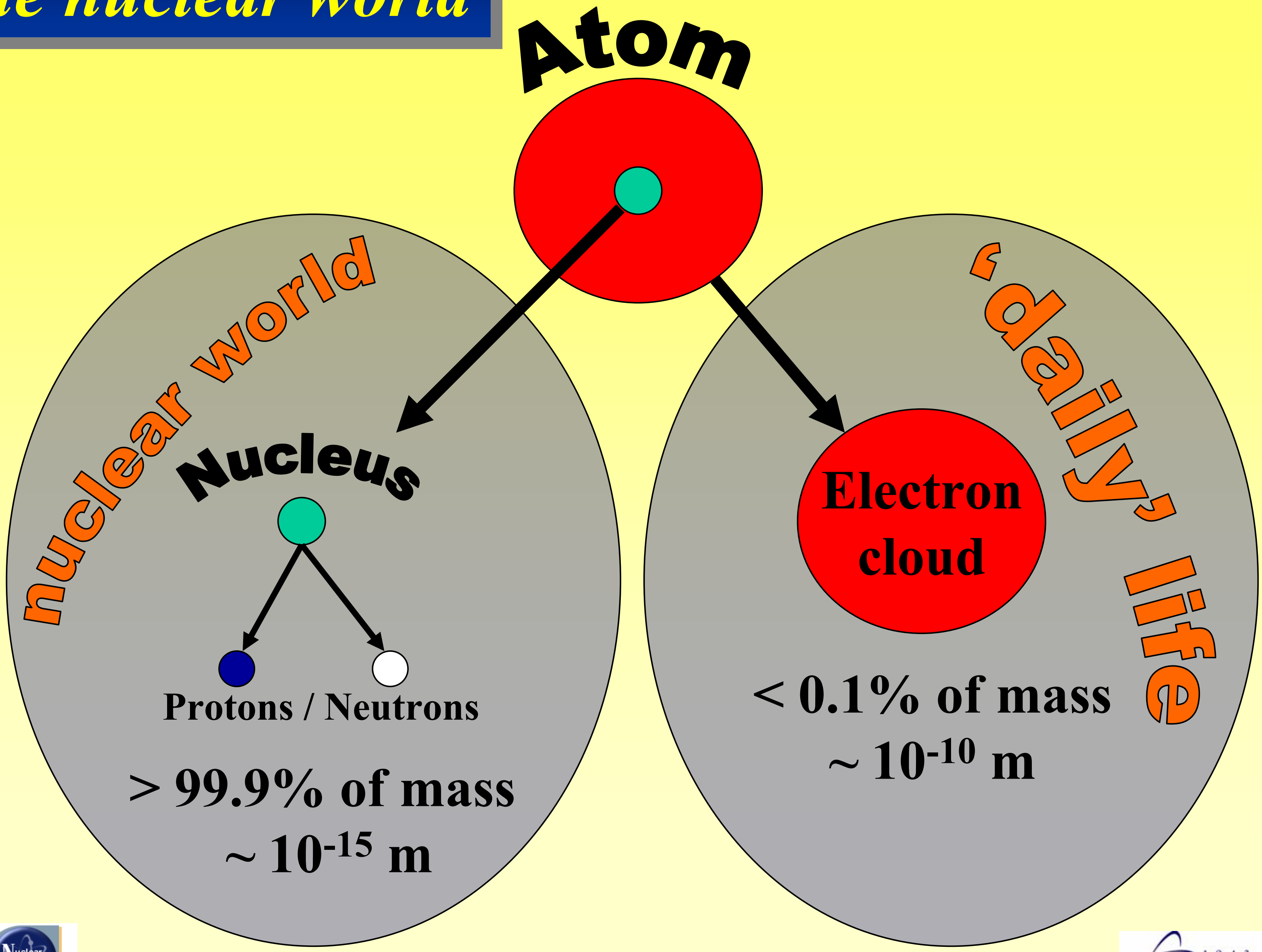
Outline

- Some terms (what do we want to explain?)
- Sources of information and how the picture developed
- Our present picture
- What's left to do?
- Summary

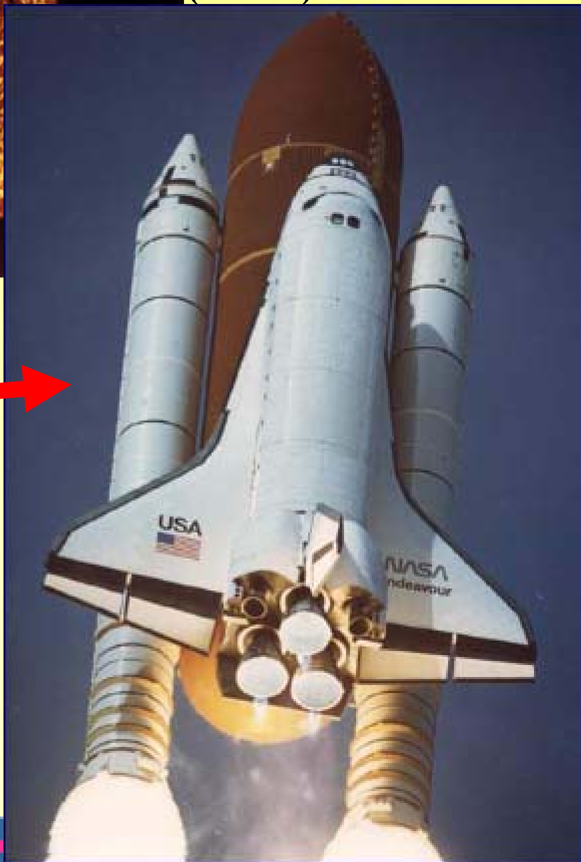
The nuclear world



Comparison: Nuclear/ Chemical Energy

- $4\ {}^{1}H + 2e^{-} \rightarrow {}^{4}He + 2\nu +$ **27 MeV**
- $Q \sim 6$ MeV/atom
- $Q \sim 1.5\times10^{11}$ Joules/gram

(NASA)

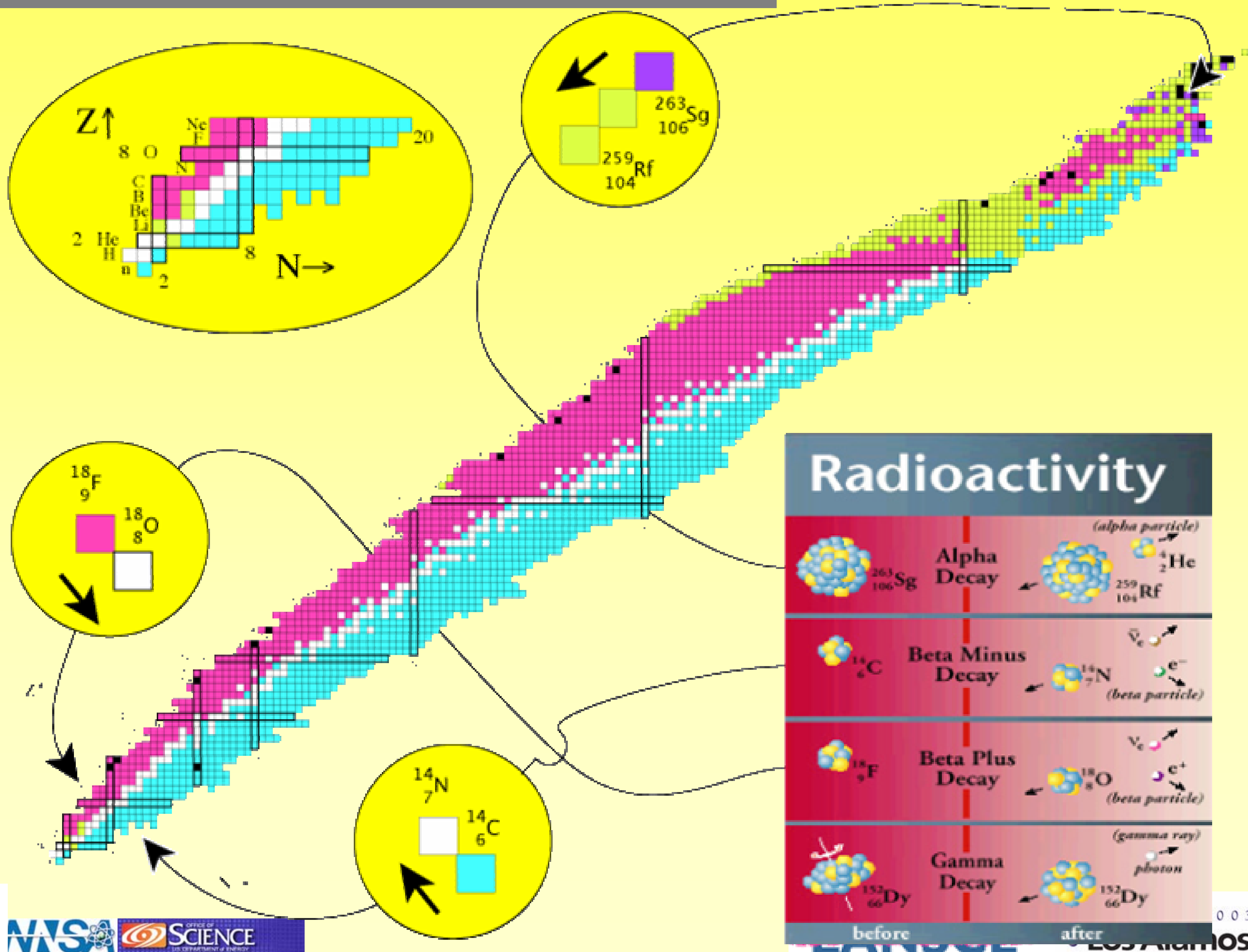


- $2\ H_2 + O_2 \rightarrow 2\ H_2O$
- $Q = 1.5\times10^{5}$ Joules/gram

1 g ⇔ 1000 kg

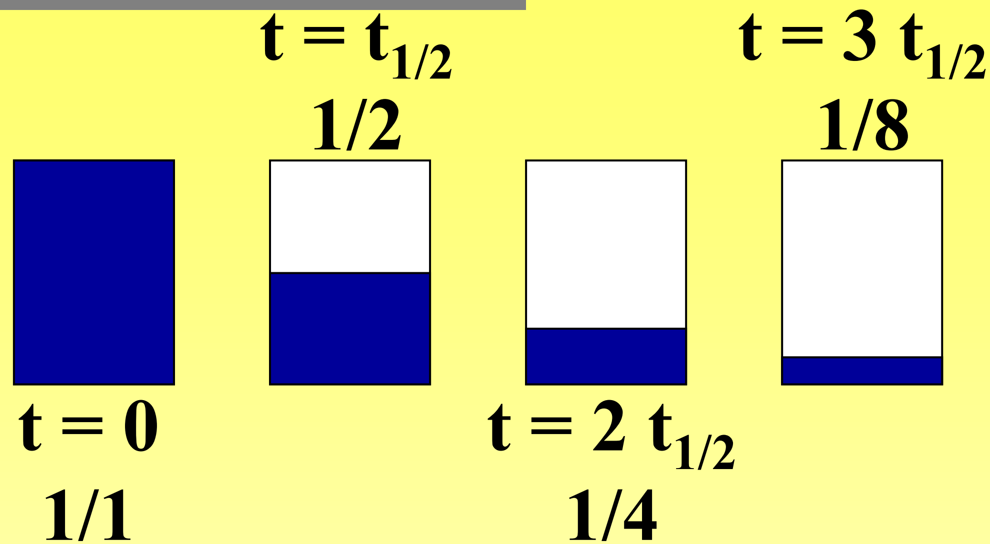
(1 oz ⇔ 25 tons)

Radioactive Decay - Types



Radioactive Decay - Times

- Half-life concept:



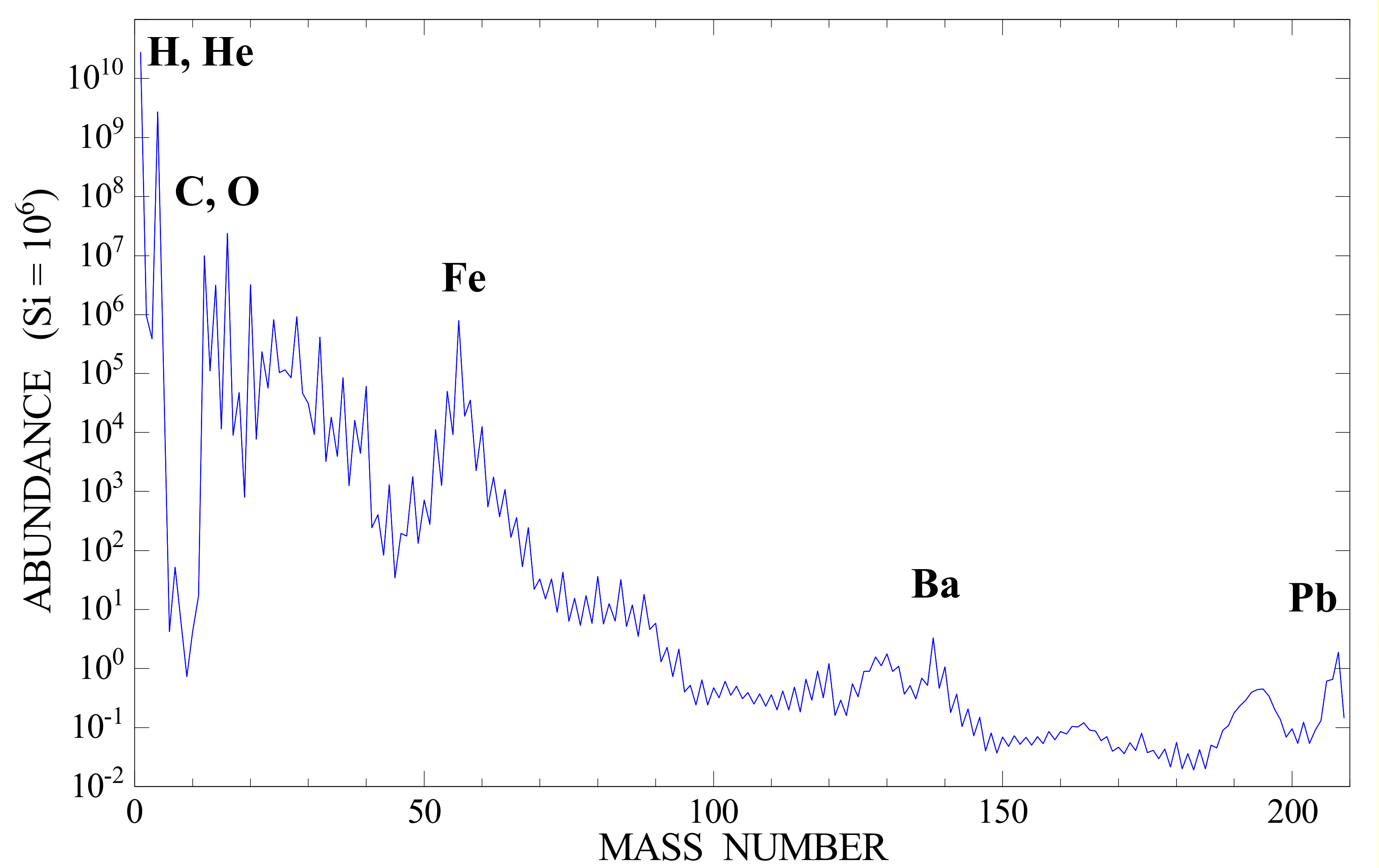
Half-life ranges:

- 'nuclear states' 10^{-15} s
- 'unstable isotopes' 10^{-6} s .. 10^{9} years
- 'metastable isotopes' 10^{9} .. 10^{19} years
- stable

Ages:

- Universe: 13.7 10^{9} years
- Solar system (sun): 4.5 10^{9} years

solar abundance distribution



Observation of galaxies

Edwin Hubble

Hubble's law:

Velocity / Distance = constant

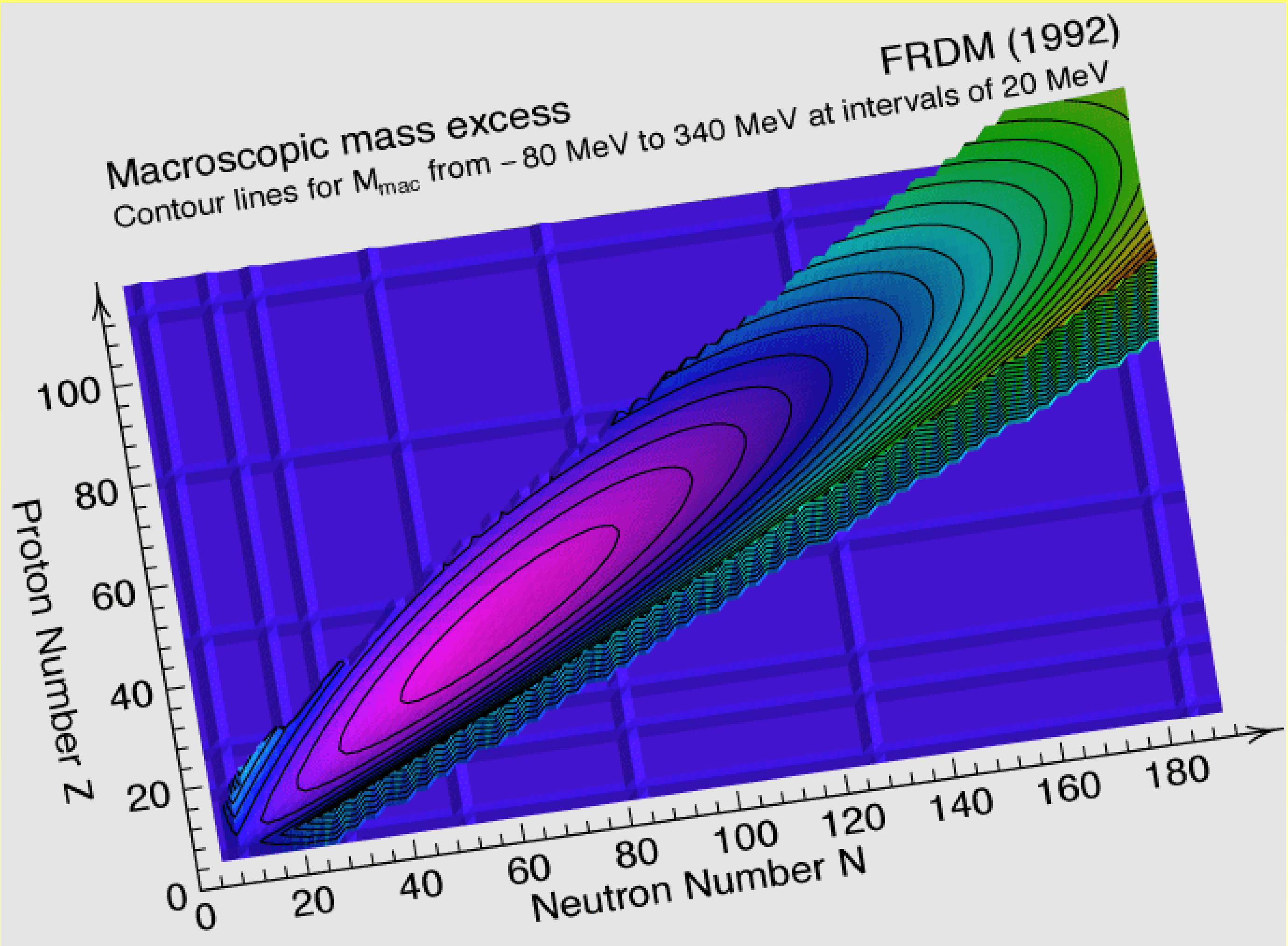
Interpretation/Consequences:

- the entire universe is expanding
- there was a time of 'zero distance', a beginning
- **'big bang' theory** is broadly accepted
- time since big bang 10 .. 100 10^9 years

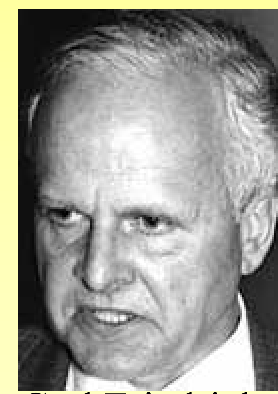
E.P. Hubble, Proc. Nat. Ac. Sci. **15**, 168 (1929)

Nuclear Masses

Sources of Information



Hans Bethe



Carl Friedrich v. Weizsäcker

Historically: Bethe – Weizsäcker mass formula (1920's)

Observation of stars

Why/how do they shine?

- Distance/luminosity known
- Gravitational energy **not** enough!
- Bethe – Weizsäcker mass formula known

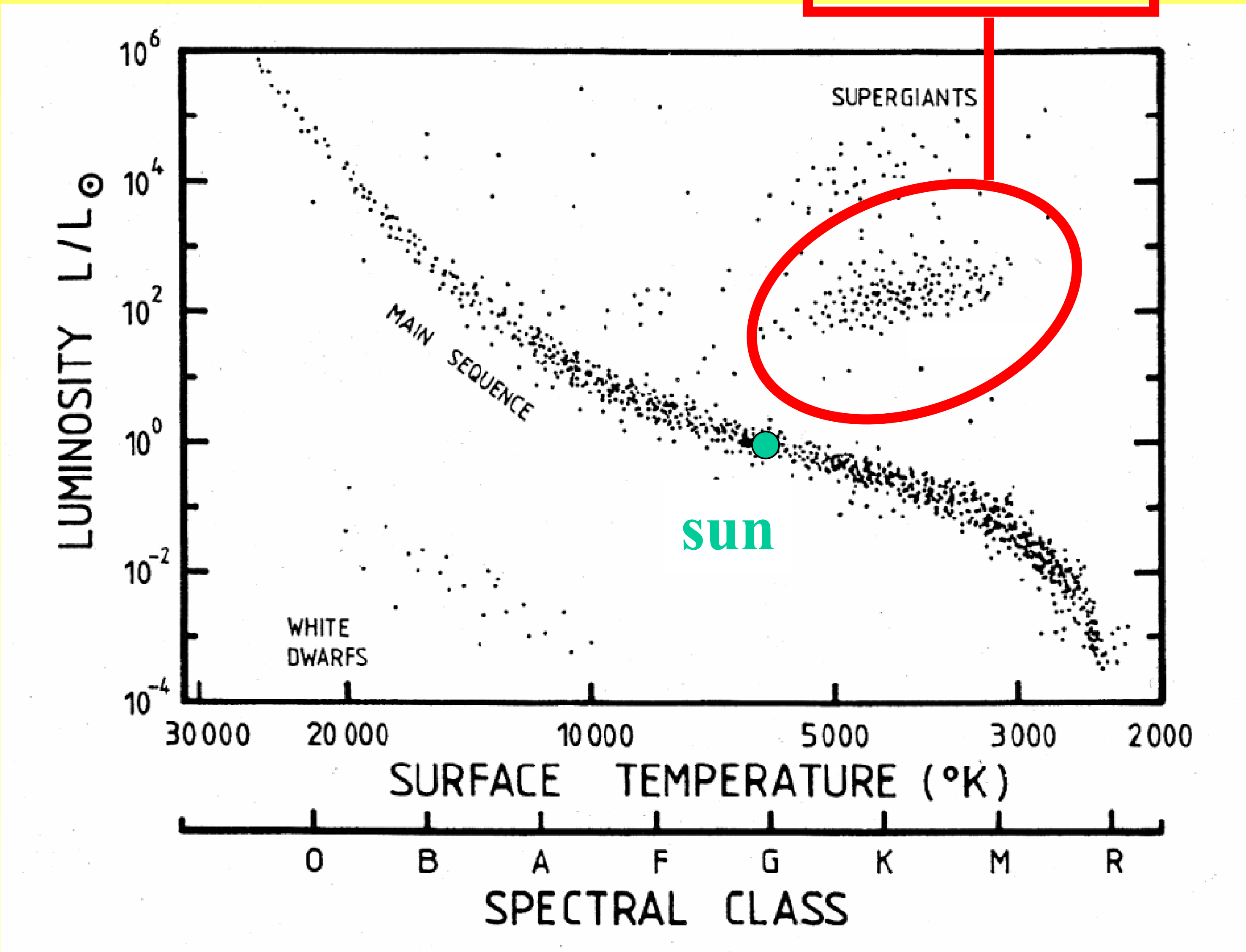
Energy source nuclear!!

H. Bethe, C. Critchfield, Phys. Rev. **54**, 248 (1938)
C. von Weizsäcker, Physikalische Zeitschrift **39**, 639 (1938)

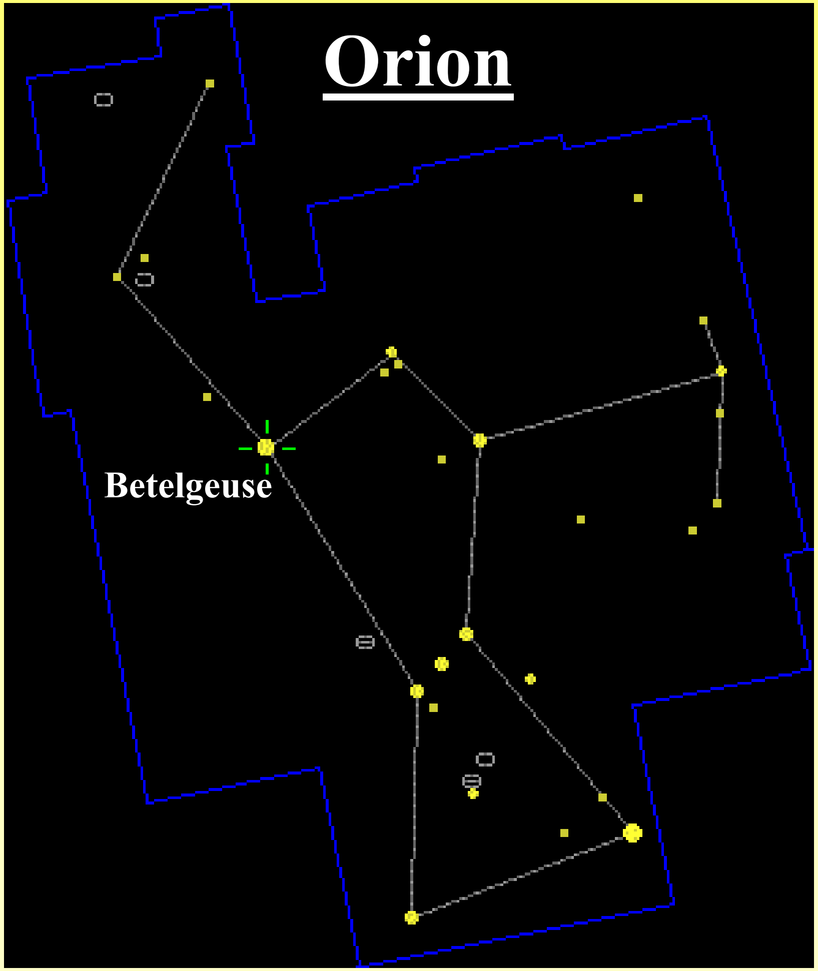
HR - diagram

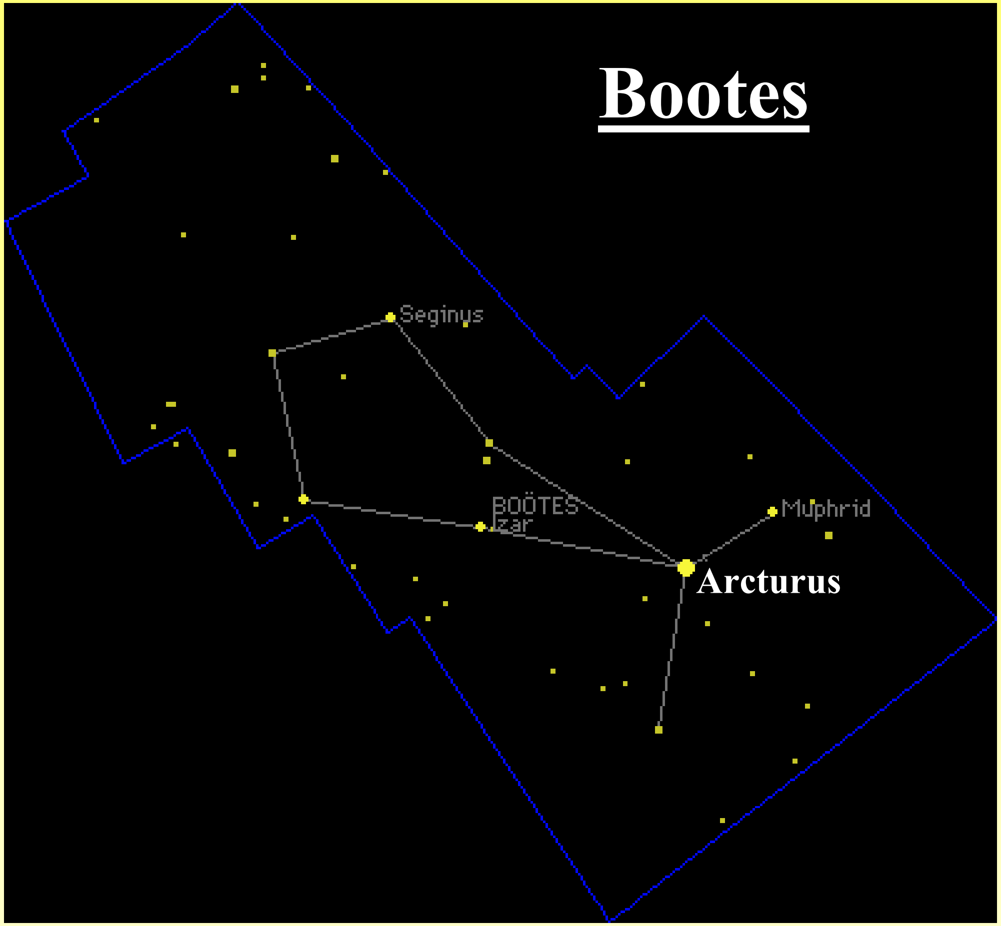
Sources of Information

Red Giants



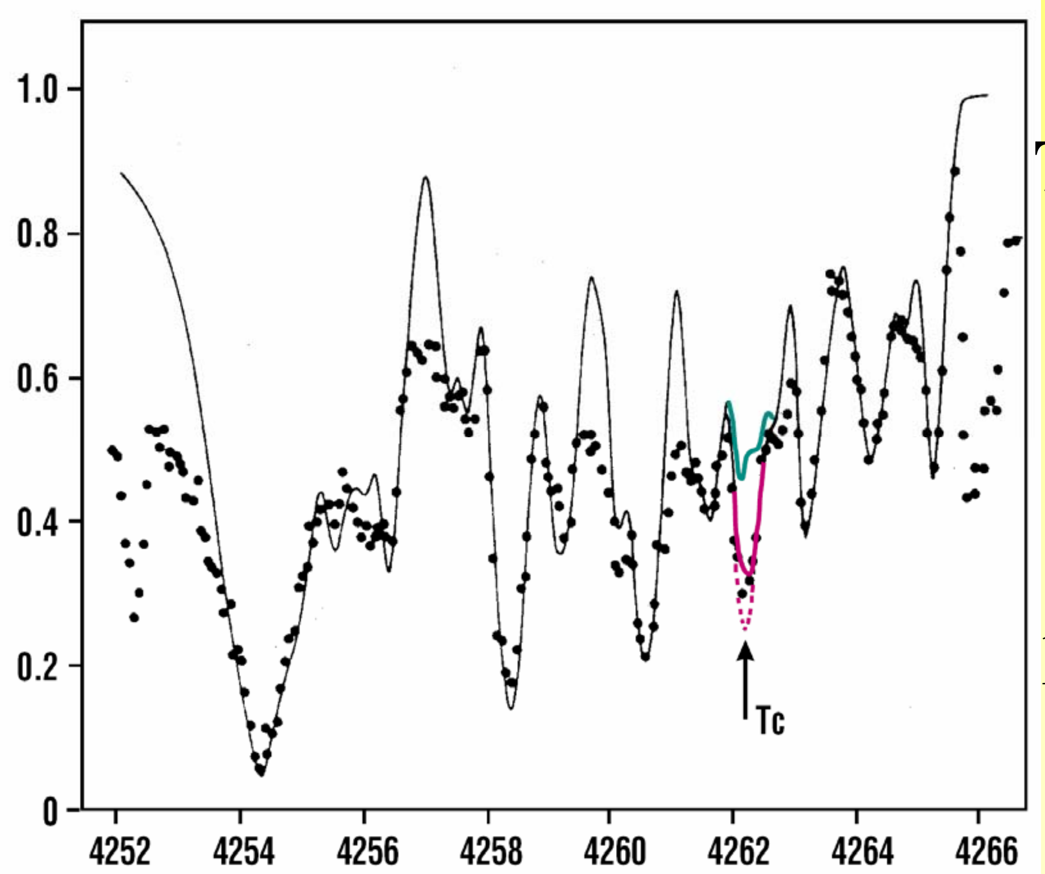
Red Giants – easy to spot





Stellar spectra

Paul W. Merrill



Tc in stellar atmospheres!!

Half-lives < 10^7 years

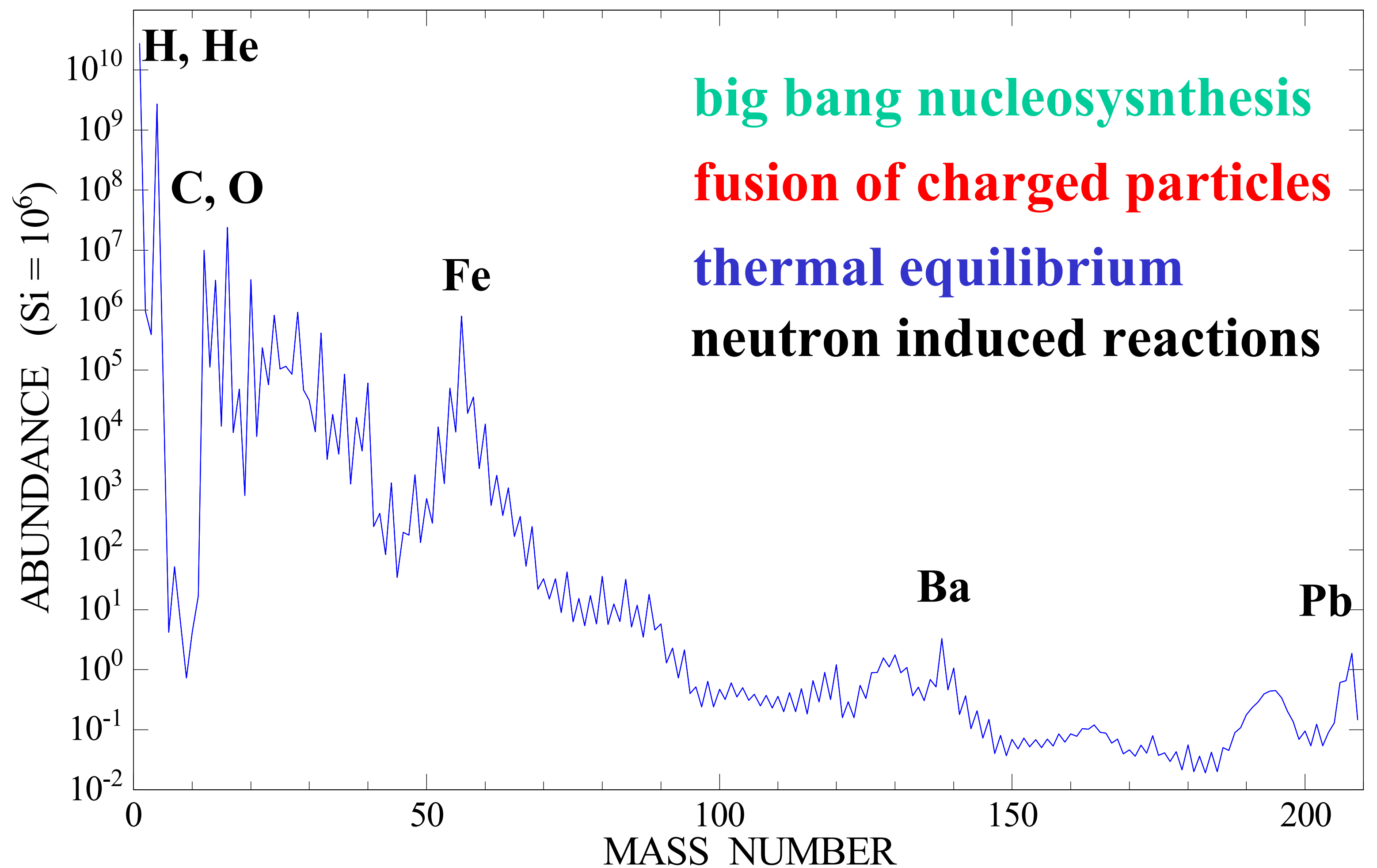
Consequences:

- Tc produced in Red Giants
- all heavy elements are produced in stars

P. Merrill, Science **115**, 484 (1952)

solar abundance distribution

Present Picture



William Fowler
Nobel Price 1983

E. Burbidge, G. Burbidge, W. Fowler, F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957)

Very light elements – ashes of big bang

Present Picture

10^0 .. 10^3 s after big bang

Recombination of protons, neutrons to light nuclei

Problem: Not enough time to bridge stability gap at **A = 5, 8**

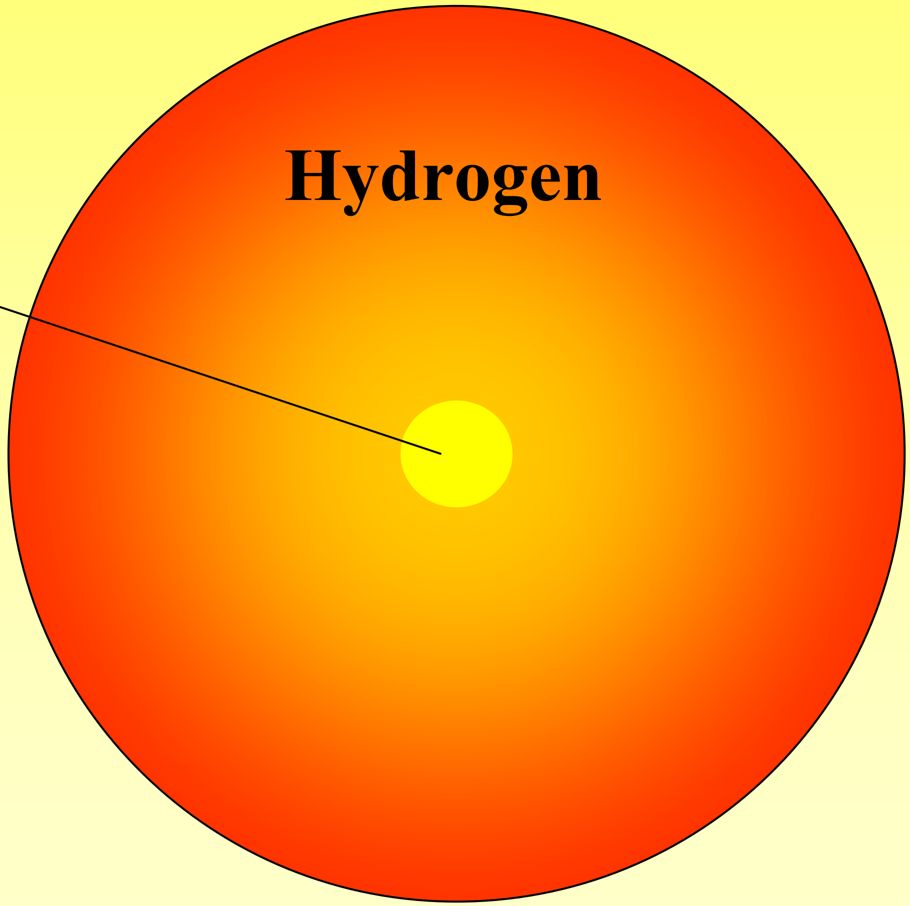
Nuclide	Mass fraction
^1H	**0.75**
^2H	$2.5\ 10^{-5}$
^3He	$4.2\ 10^{-5}$
^4He	**0.23**
$^{6,7}Li$	$<10^{-11}$

Between Carbon and Iron

Present Picture

First stars: 10^{16} s (500 10^{6} years) after big bang

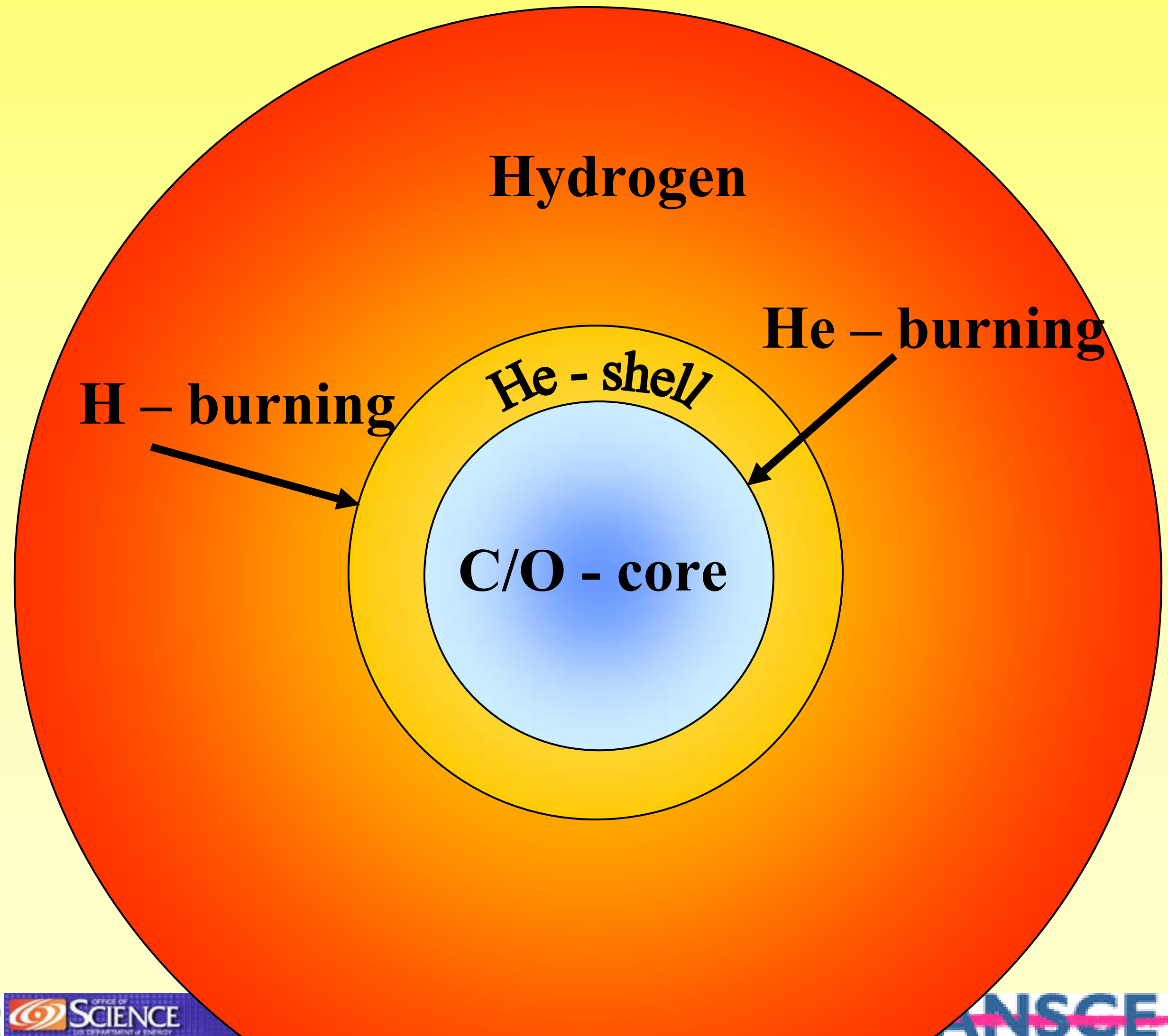
Hydrogen core burning (main sequence) (H → He)



Between Carbon and Iron

Present Picture

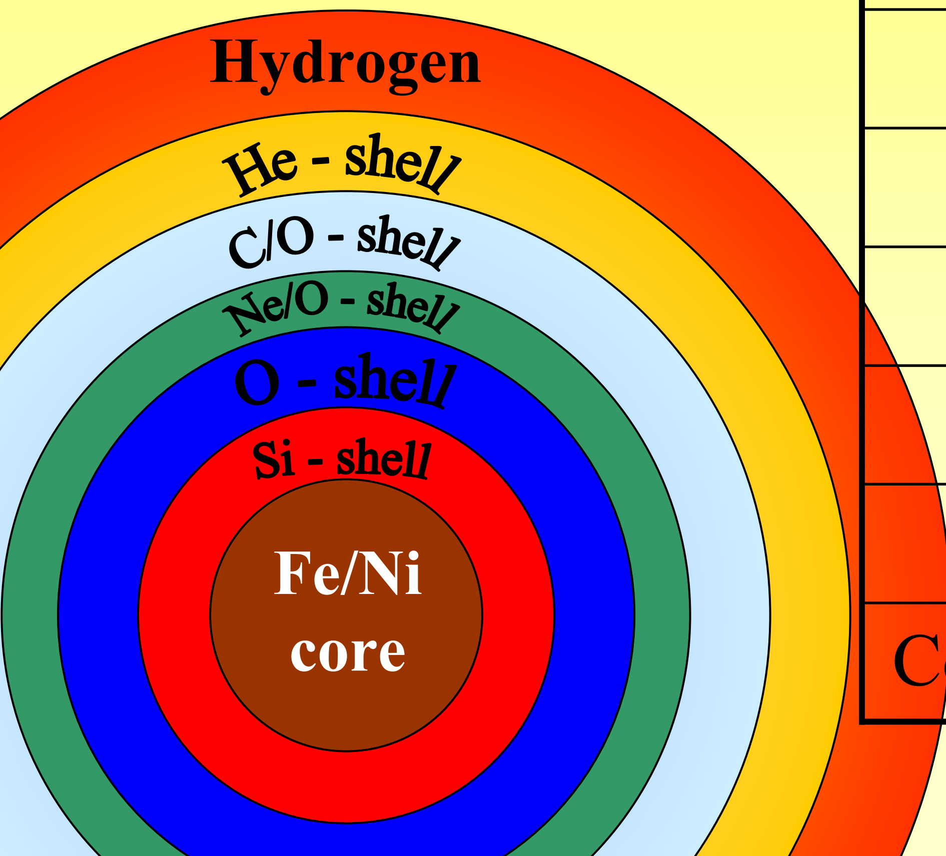
later stage: H, He shell burning, maybe C – core burning



Between Carbon and Iron

Present Picture

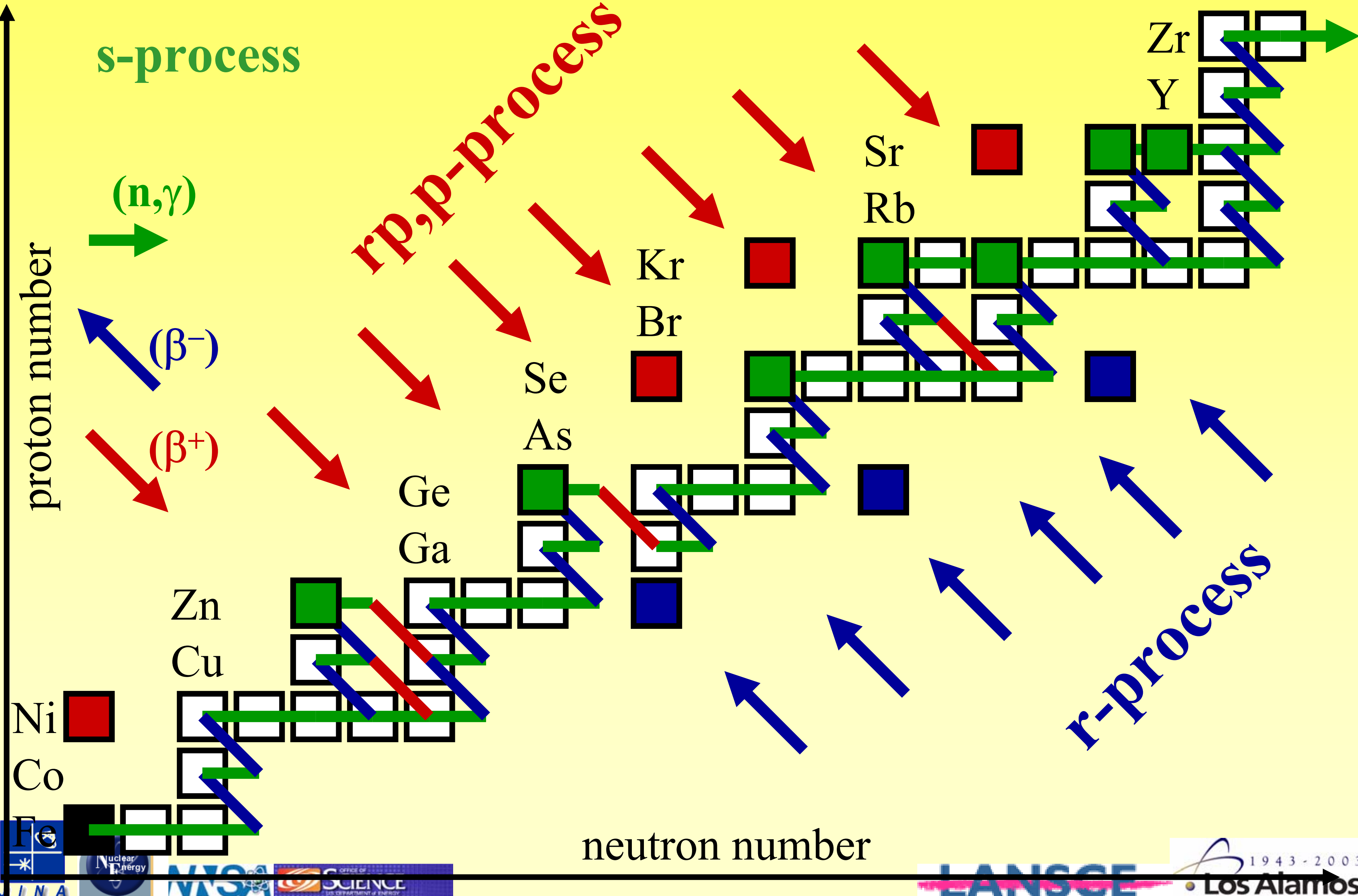
Onion-shell structure before collapse



Burning stage	Time	Temp. GK	Dens. g/cm^3
H	7 My	0.06	5
He	0.5 My	0.23	$7\ 10^2$
C	600 y	0.93	$2\ 10^5$
Ne	1 y	1.7	$4\ 10^6$
O	0.5 y	2.3	$1\ 10^7$
Si	1 d	4.1	$3\ 10^7$
Collaps	~ s	8.1	$3\ 10^9$

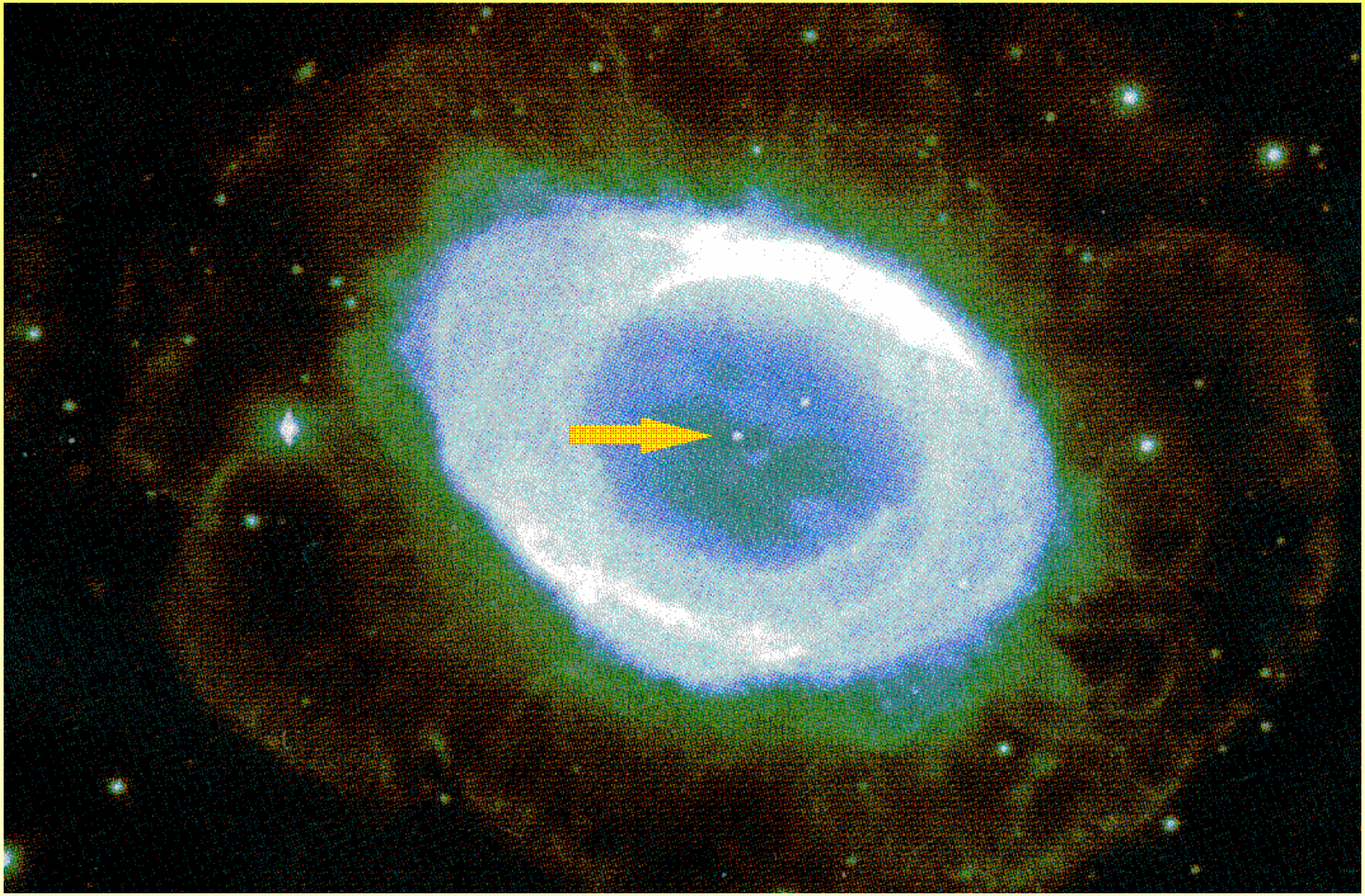
Beyond Iron - byproducts

Present Picture



Present Picture

The stellar site



Meteorites - Hints falling from the sky

Von dem donnerstein gefallē jm xcij. iar: vor Ensisheim.

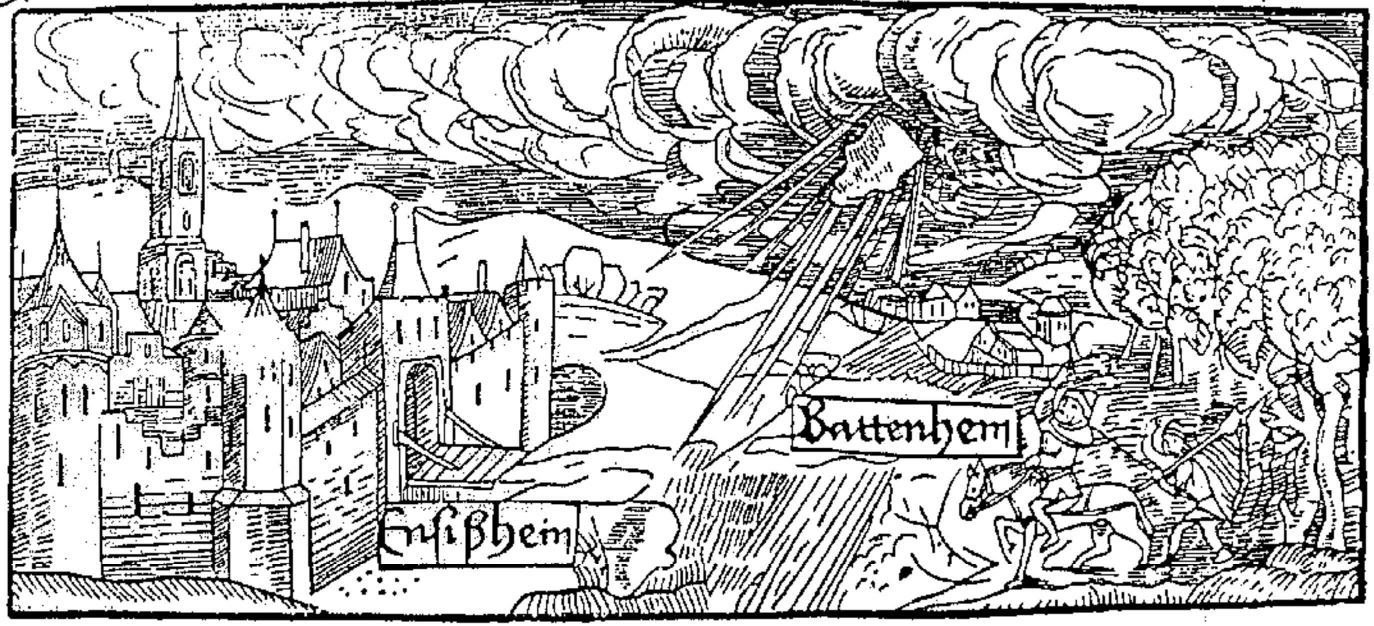
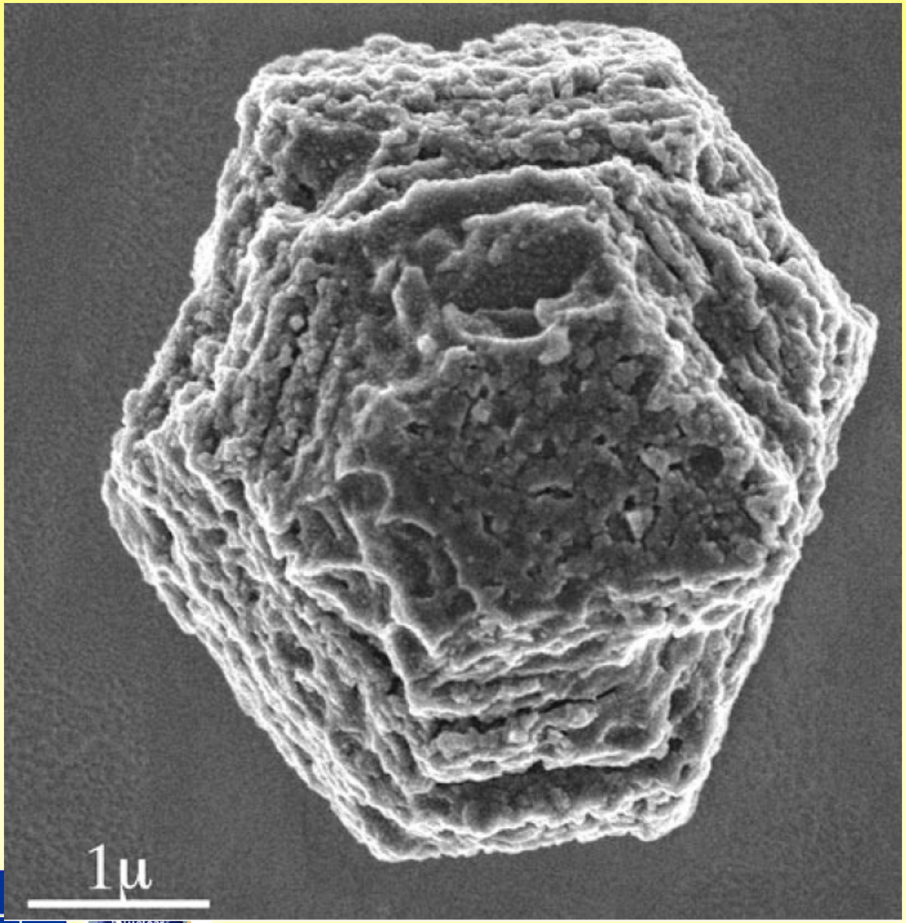
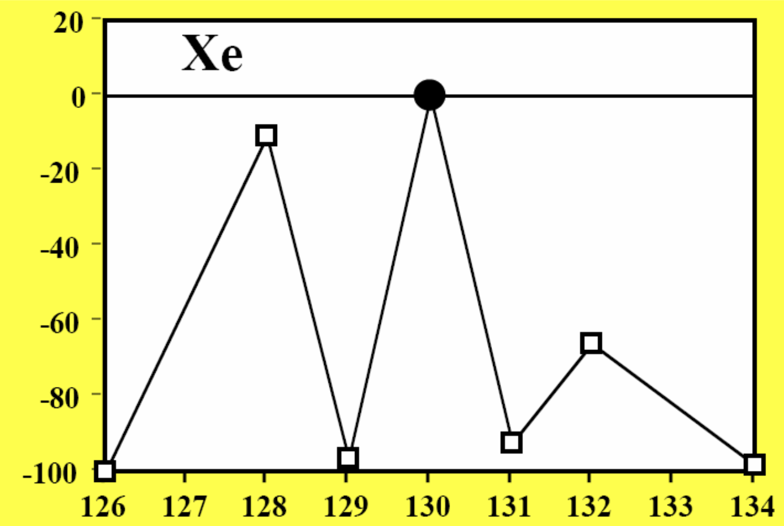


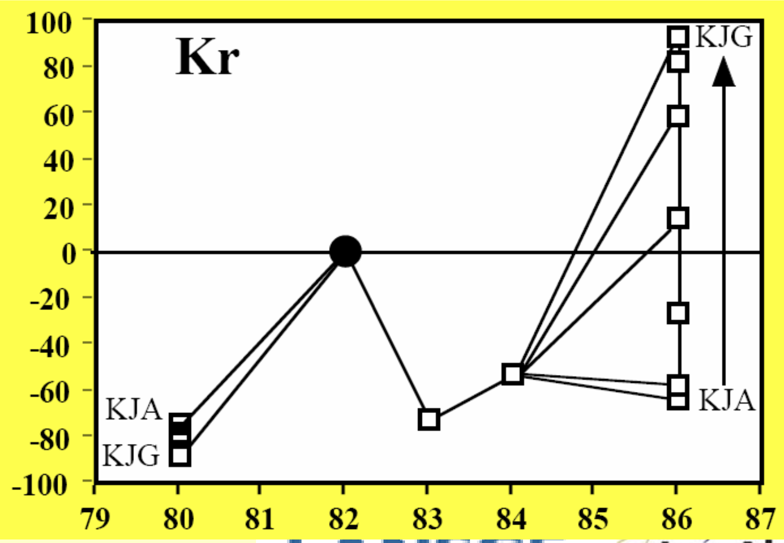
Figure I-2. Woodcut depicting the fall of the Ensisheim LL chondrite on 7 November 1492. A literal translation of the German caption (by Sebastian Brant) is "of the thunder-stone (that) fell in xcii (92) year outside of Ensisheim." This meteorite, which is preserved in the city hall of Ensisheim, Alsace, is the oldest recorded fall from which material is still available.

Presolar grains: Left-overs from stellar events

(E. Zinner, WUSTL)

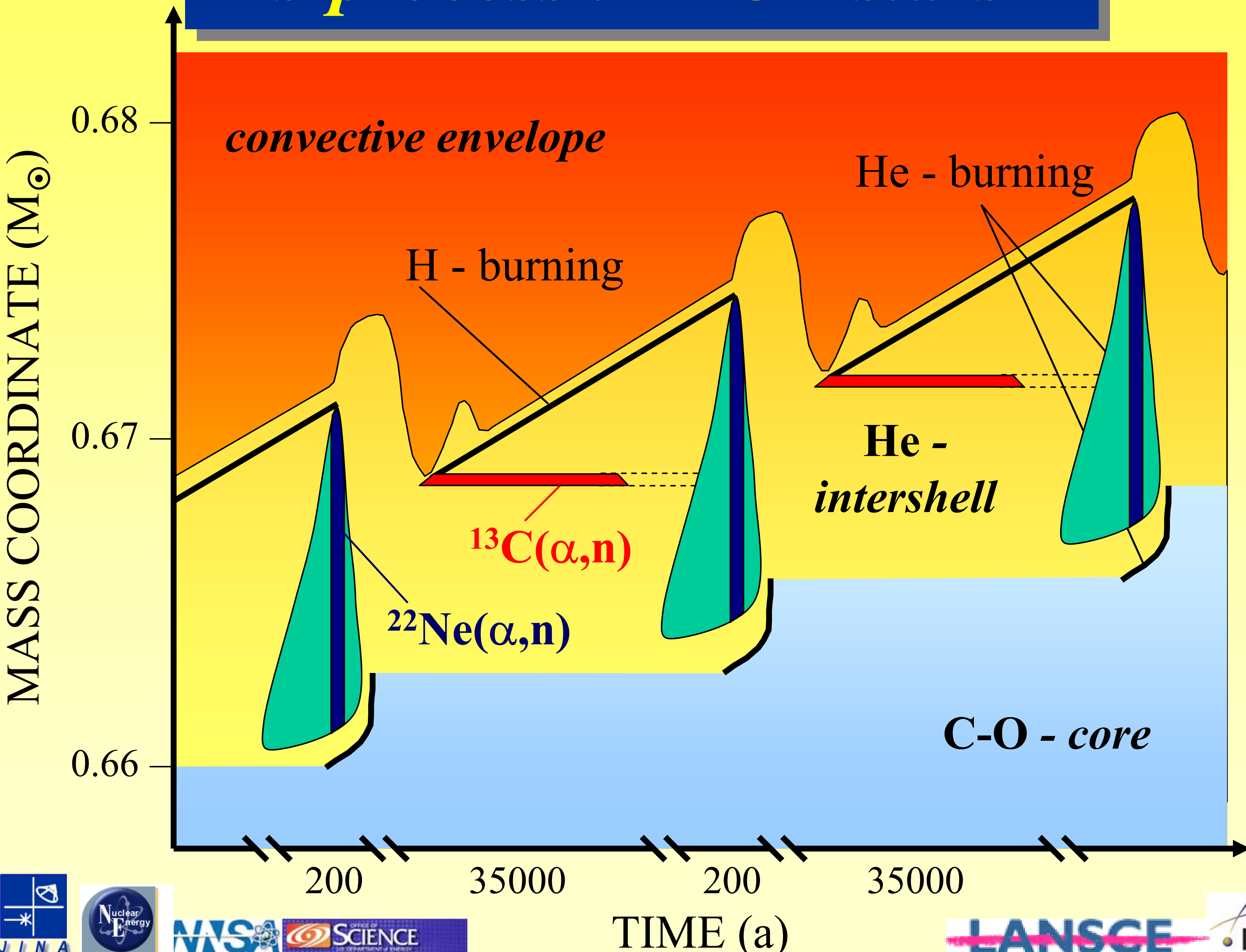






s-process in AGB stars

Open questions

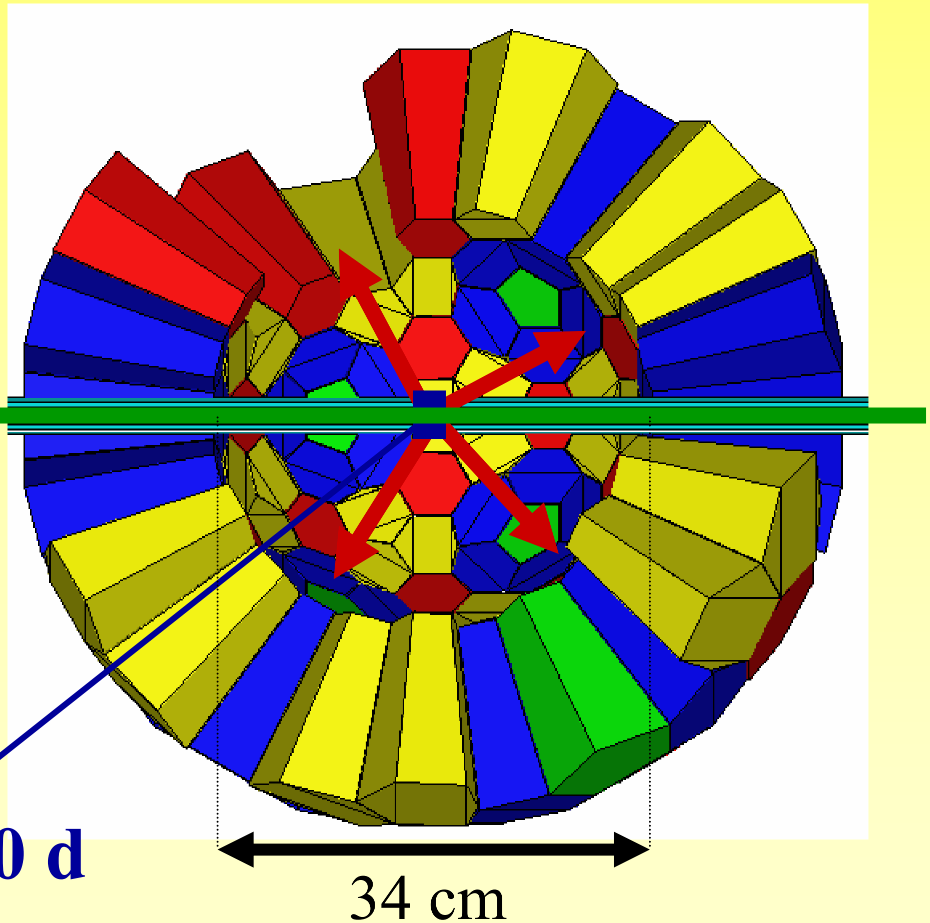


What's needed?

- Reaction rates
  - Neutron induced
  - Charged particles
- Half-lives
- Masses
- Observational data of faint stars
- More isotopic information (grains)

Detector for Advanced Neutron Capture Experiments

collimated neutrons beam



sample
$t_{1/2} > 100$ d
$m \sim 1$ mg

neutrons:

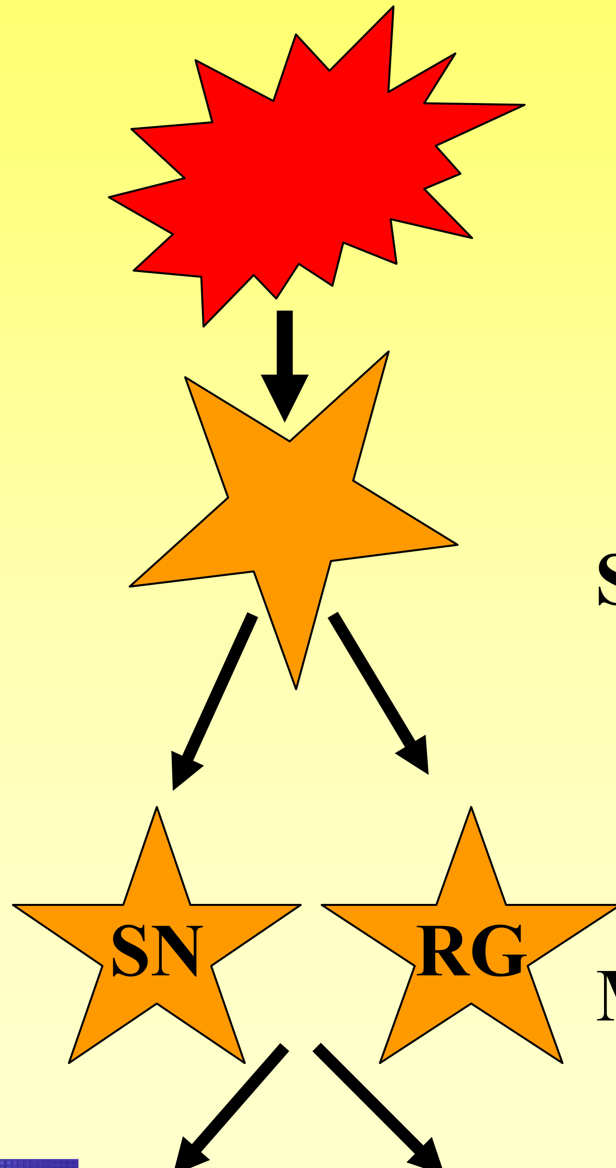
- spallation source
- thermal .. 500 keV
- 20 m flight path
- $3\ 10^5$ n/s/cm^2/decade

γ-Detector:

- 160 BaF_2 crystals
- 4 different shapes
- R_i=17 cm, R_a=32 cm
- 7 cm ^{6}LiH inside
- $\varepsilon_\gamma \approx$ 90 %
- $\varepsilon_{casc} \approx$ 98 %

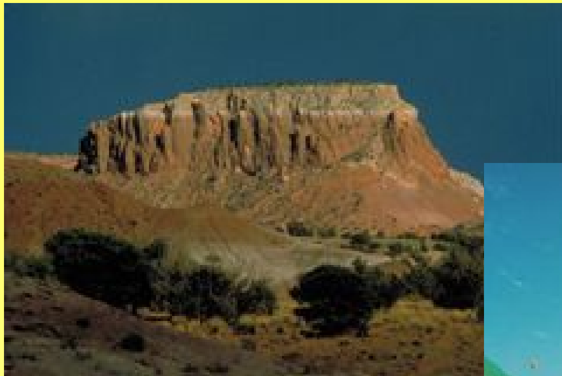
Summary - Recycling of elements

Big Bang — **H, He, Li**

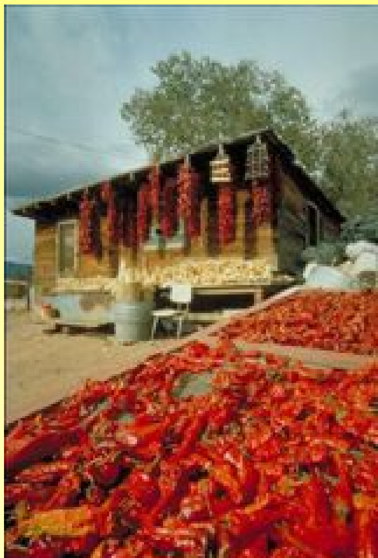


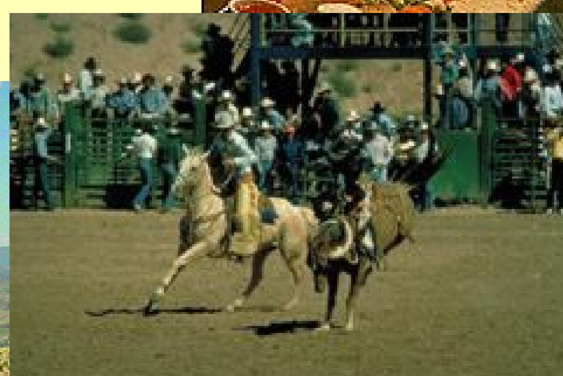
First generation of (heavy) stars — **C … Fe, Iron peak, Some heavy elements**

later generation of stars — **C … Fe, Iron peak, More heavy elements**



Enjoy New Mexico!!





1943 - 2003 Los Alamos