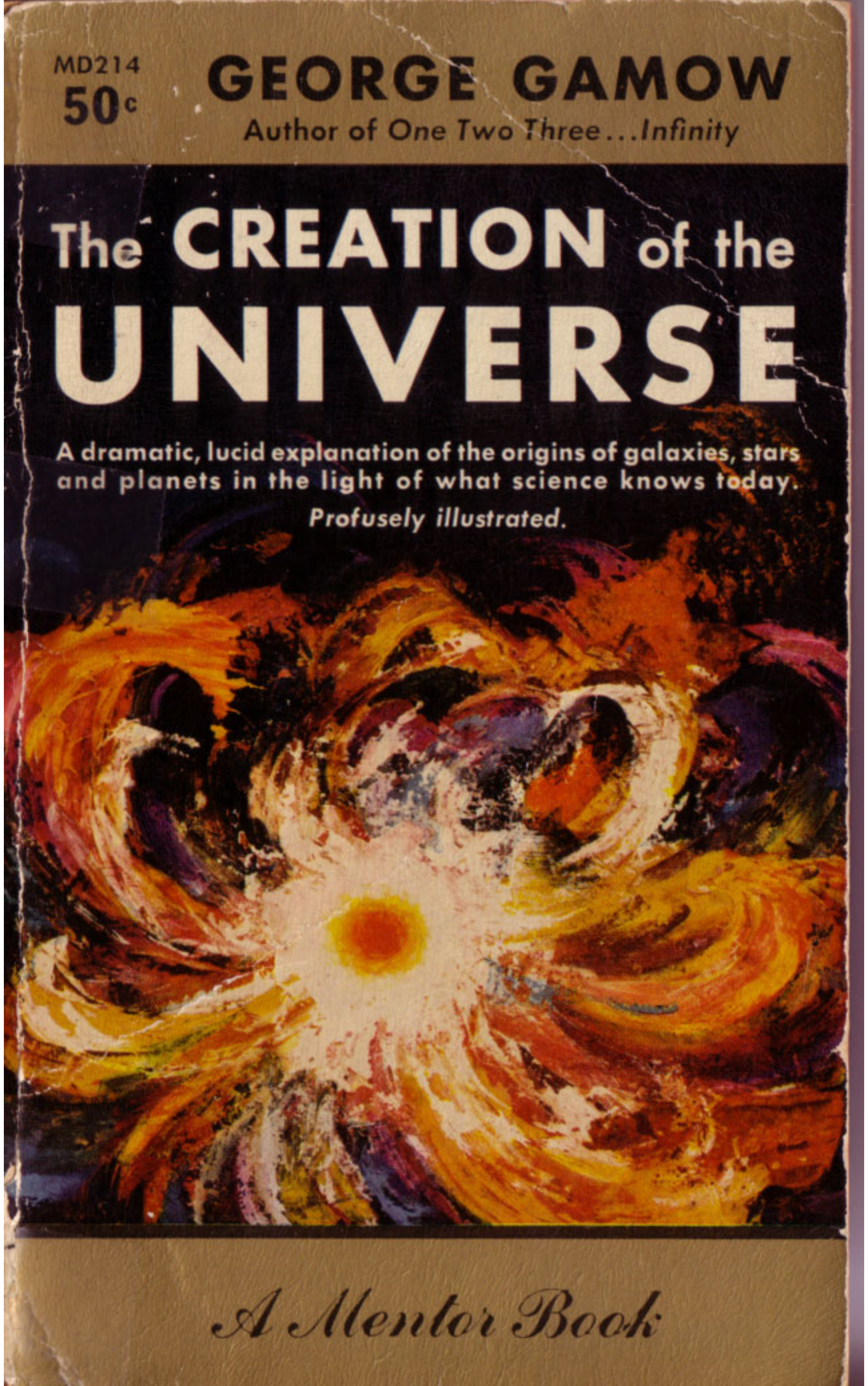
Nucleosynthesis: Building New Elements in the Cosmos

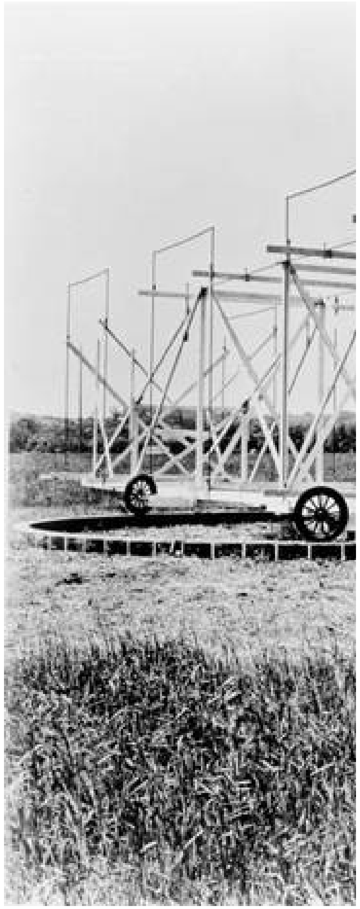
Prof. Jay Gallagher-- Astronomy

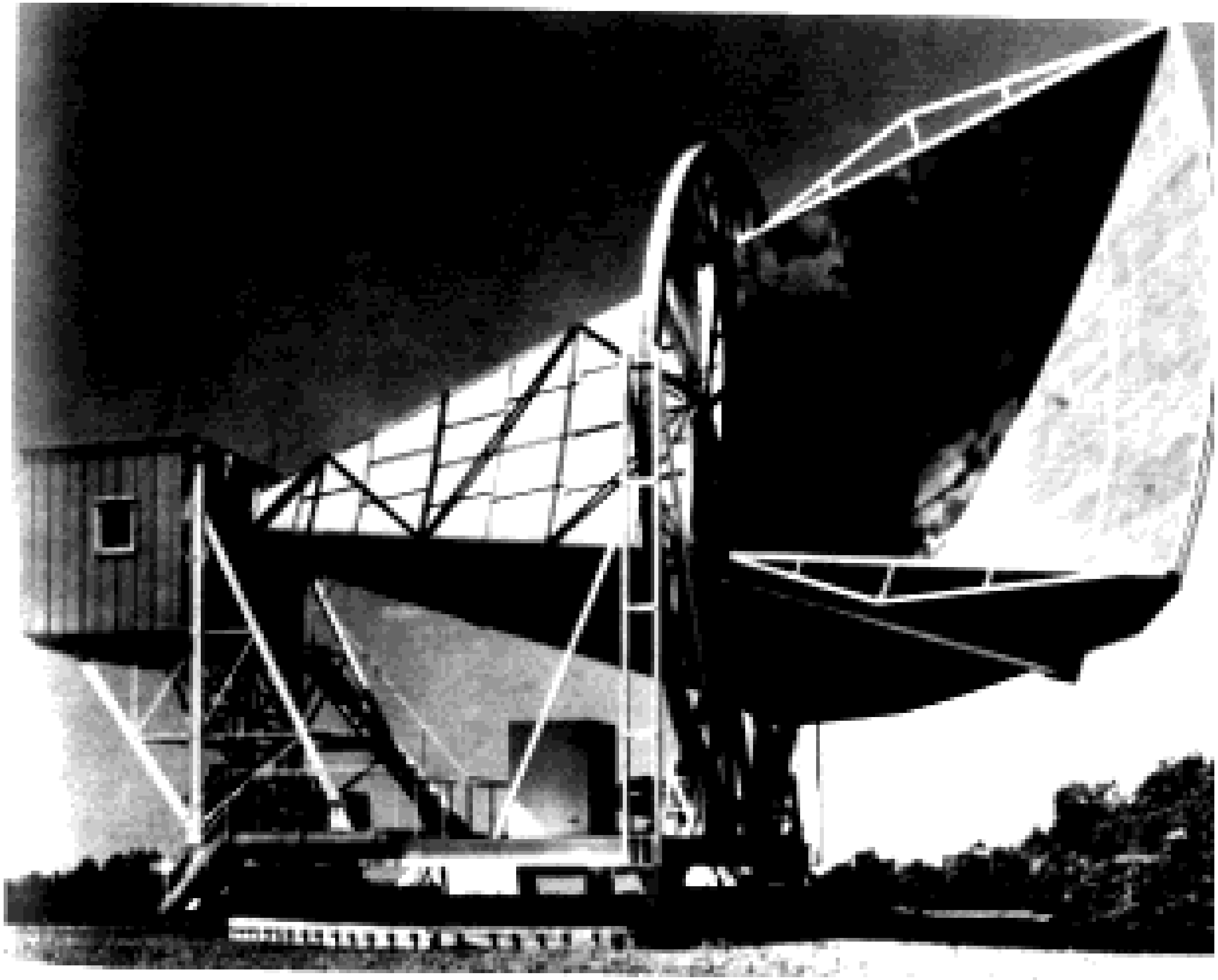
- Stars as natural thermonuclear reactors
- Basic nuclear burning processes
- Special nucleosynthesis processes:
  - Big Bang
  - Supernovae: r-process
  - Asymptotic giant branch (AGB) stars: s-process
  - Cosmic ray spallation
- Element dispersal
- (Special conditions in solar system formation-Schmidt)

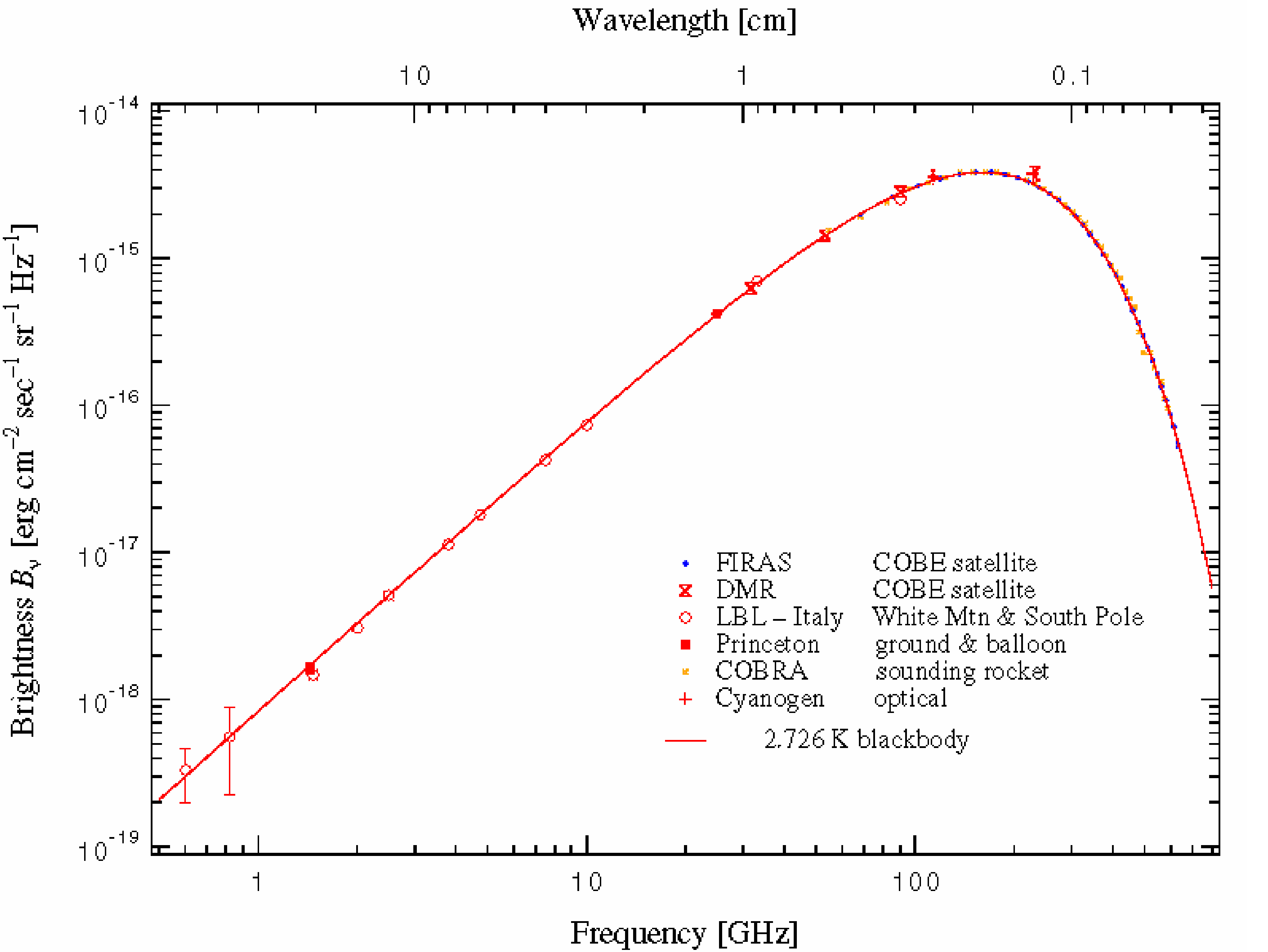
Hot Big Bang Model



Hot Big Bang Model







Wavelength [cm]
10
1
0.1
Brightness B_ν [erg cm^{-2} sec^{-1} sr^{-1} Hz^{-1}]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
FIRAS COBE satellite
DMR COBE satellite
LBL – Italy White Mtn & South Pole
Princeton ground & balloon
COBRA sounding rocket
Cyanogen optical
2.726 K blackbody
1
10
100
Frequency [GHz]

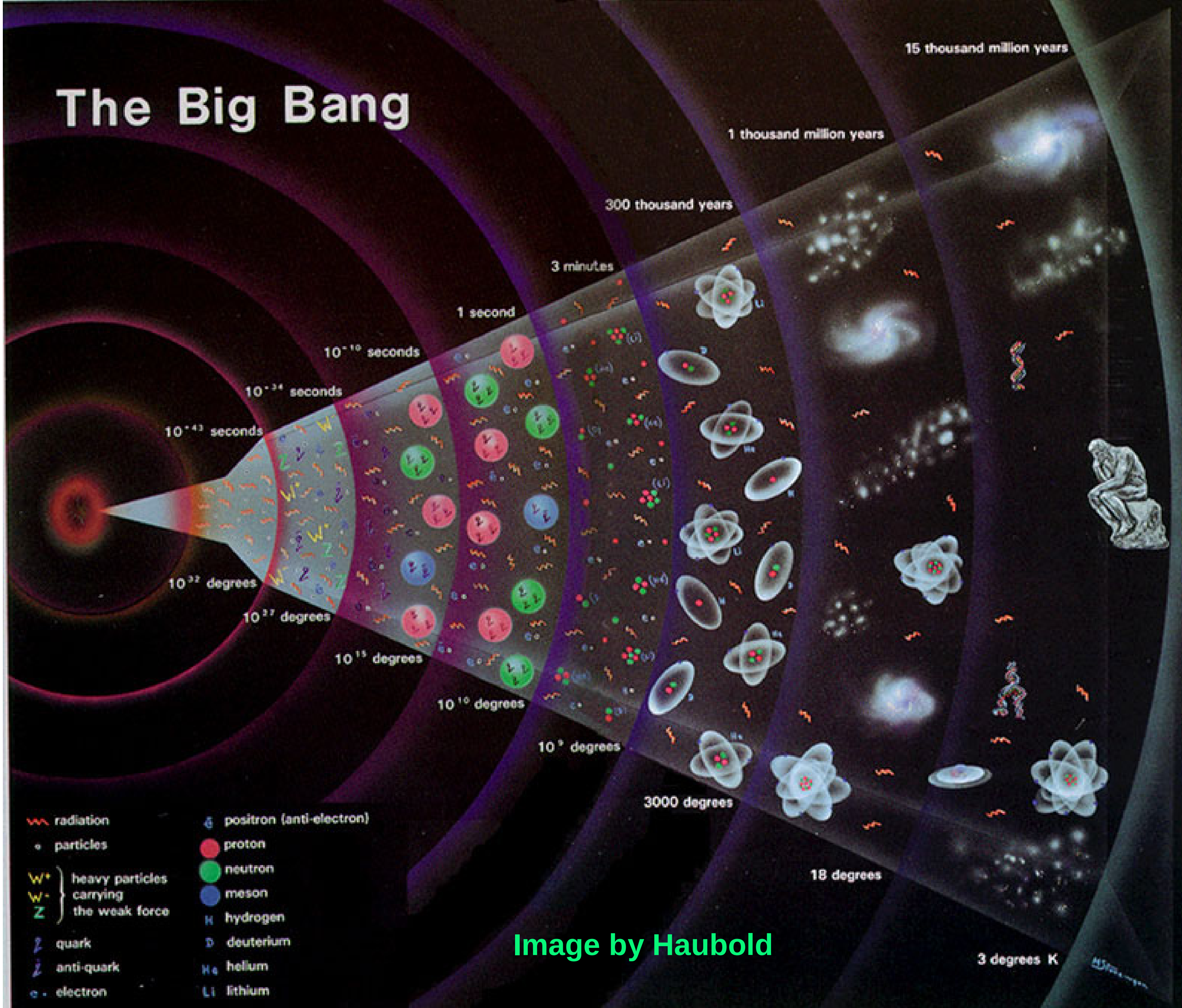


Image by Haubold

Thermal History of the Early Universe: from Equilibrium to H->He Burning

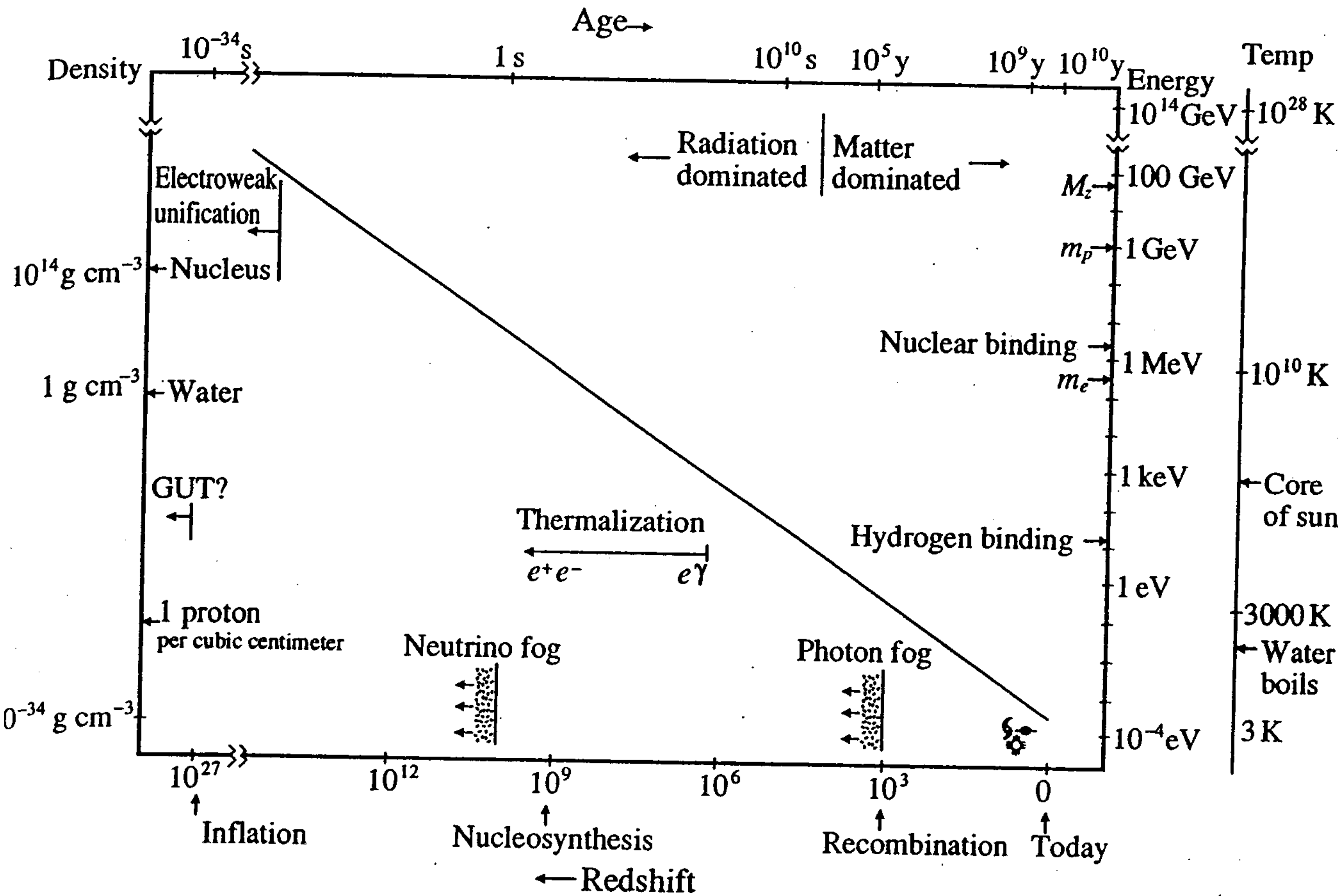
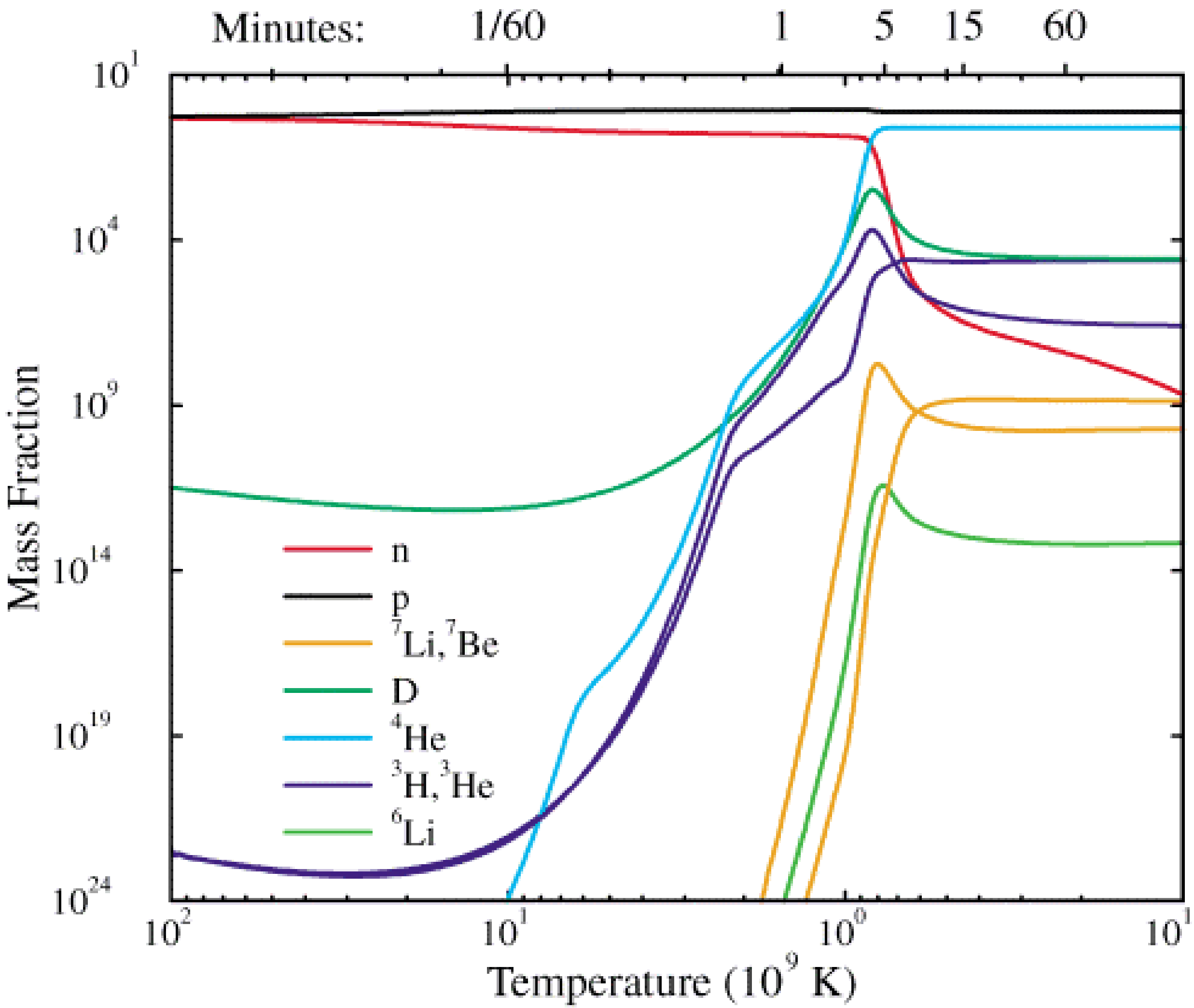


Figure 4.2 History of the universe showing significant events, particle interactions, and barriers in terms of the radiation temperature, energy, or energy density vs. time or redshift. The radiation behavior is exquisitely simple, yet packed with information as shown along the axes.

First nucleosynthesis in the cooling Universe: Production of ^{4}He from Free Neutrons



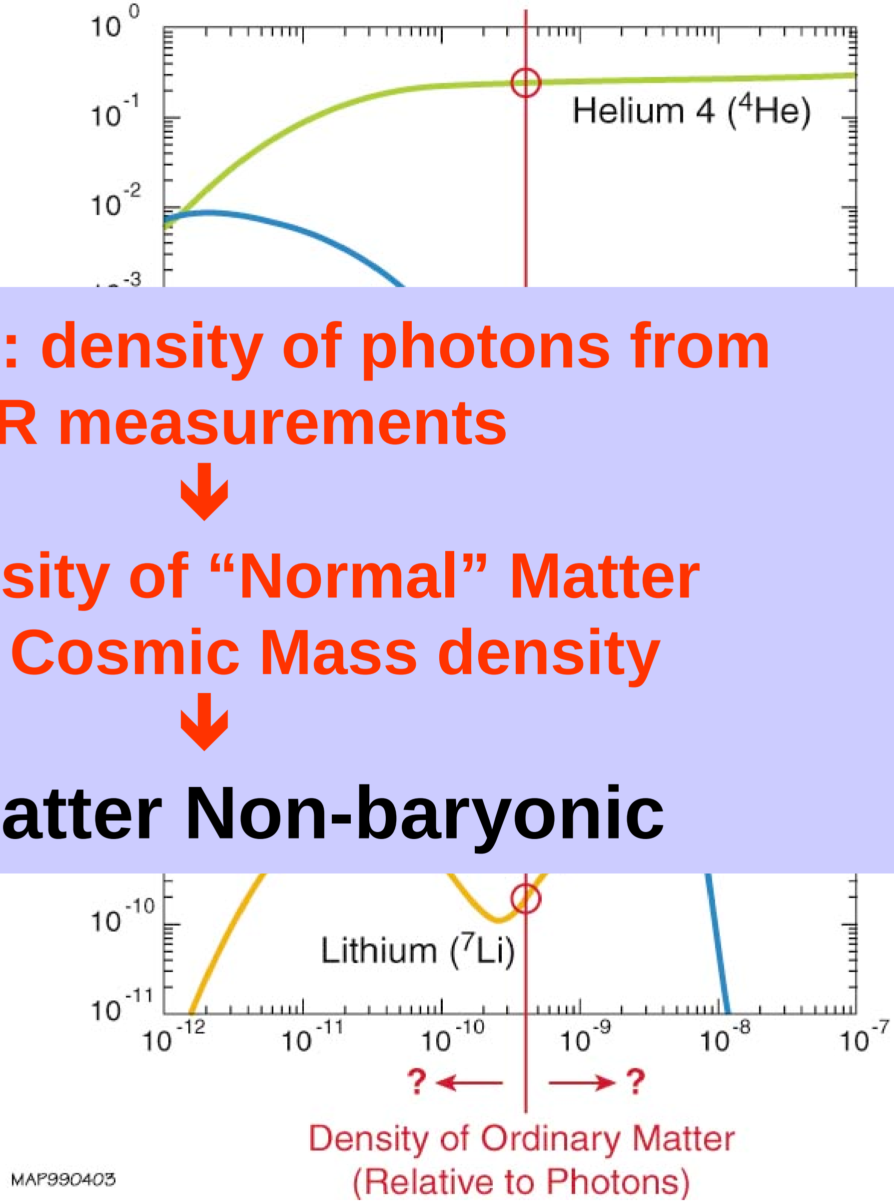
Products of Big Bang:

1. Helium

2. Deuterium

3. Lithium

But nucleosynthesis stopped by absence of stable element 8. All "metals" Z>8 must be made from H & He later.



Side benefit: density of photons from CBR measurements

↓

Total Density of "Normal" Matter <20% of Cosmic Mass density

↓

Most Matter Non-baryonic

But spectra of stars show lines

Of H, He, and heavier elements.

Stars contain “metals” ∴

Nucleosynthesis occurs outside of the big bang.

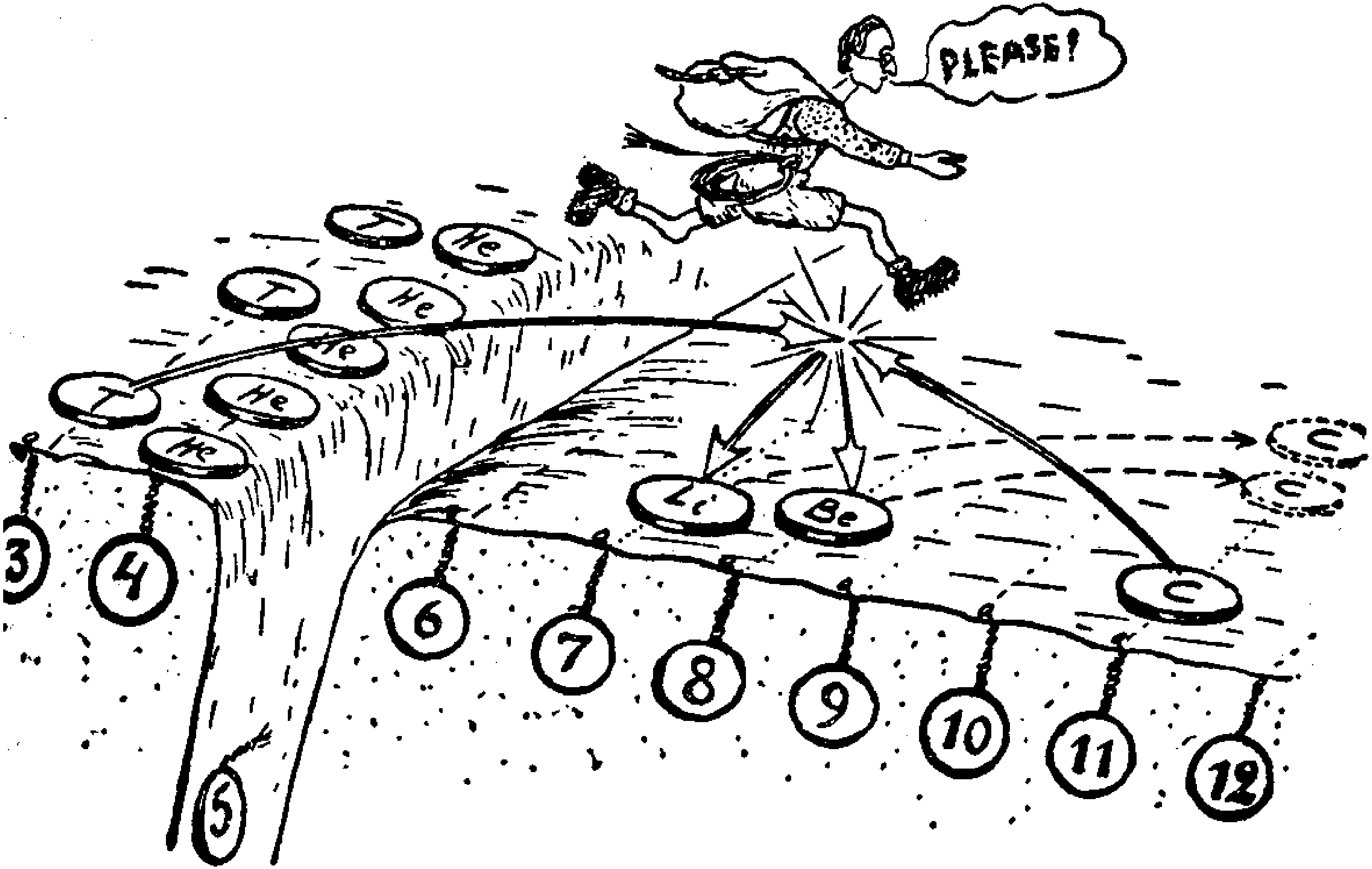


Fig. 17. Wigner's proposal as to how to jump across the mass 5 crevasse

Stellar spectra--Line strengths + models = abundances

Dark regions are absorption lines where light is intercepted by specific species of atoms

Spectrum is light sorted by wavelength--this example covers the visible region where most lines from Fe-peak elements

3.5-M WIYN Telescope

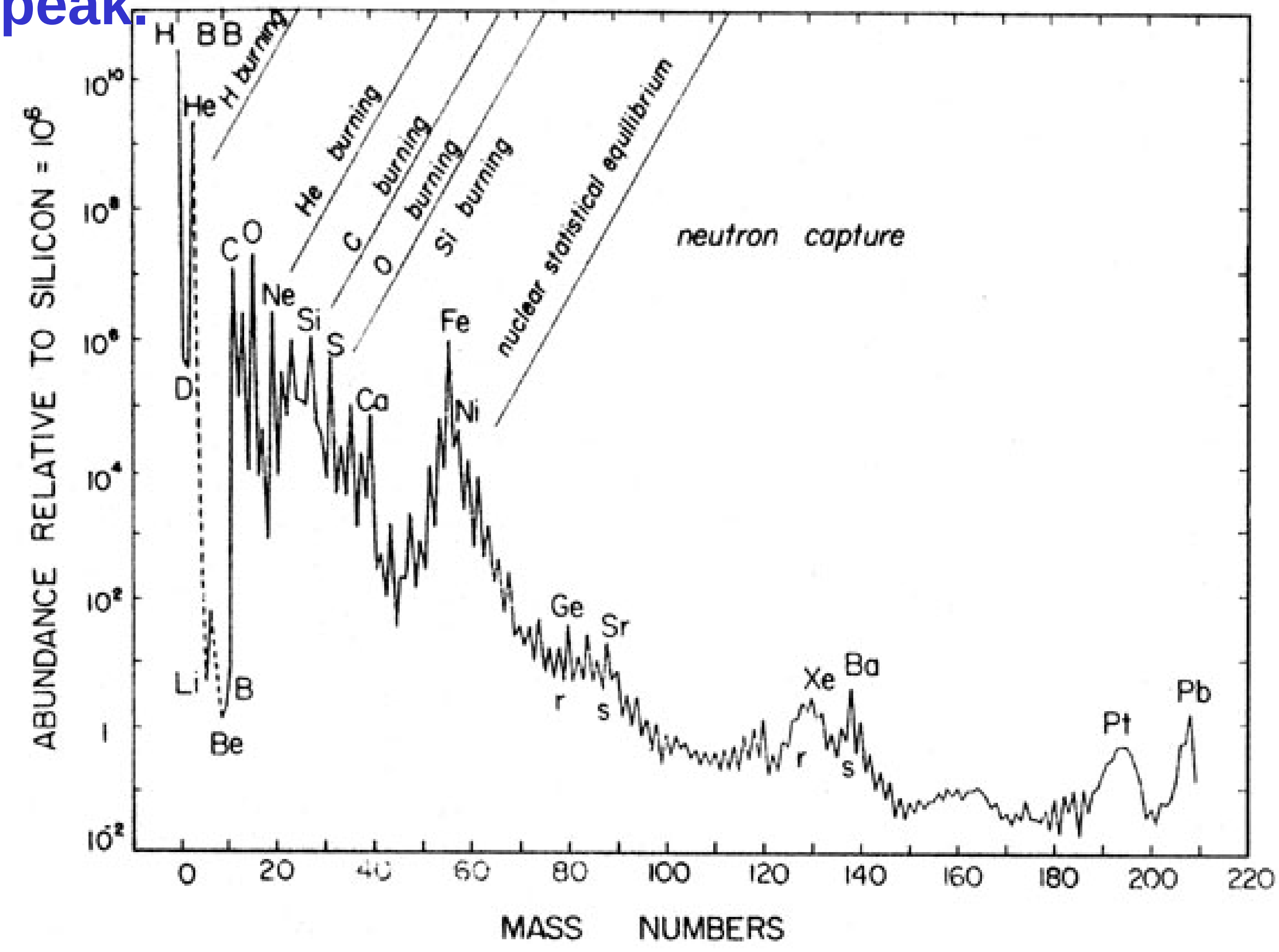
Spectroscopy drives astronomers to higher performance and larger telescopes.

Globular stars cluster: oldest coeval groupings of stars (12 Gyr) have low metals-->>heavy elements produced by **STARS**!

Ages of stars can best be determined for systems of stars that formed at the same time.

Lagoon nebula: Gas ionized by young, hot stars with high masses (20-100 x Sun) cools by atomic emission from α-elements: N,O,Ne,S, allowing their abundances to be measured from spectra of the nebula.

Cosmic abundances--most “metals”=CNO + Fe peak.



Pagel, Nucleosynthesis and Chemical Evolution of Galaxies

Classifying stars by their nuclear burning characteristics

- low mass, $\leq$ 2 Msun; H->C, white dwarf remnants

- intermediate mass, 2-8 Msun H->C/O/Ne, white dwarf remnants. Slow neutron captures during late evolution as "asymptotic giant" stars. C from He, N from CNO cycle burning.

- binary star evolution yields type I supernovae from intermediate mass stars; Fe-peak elements.

- massive 8-30 Msun; H->Fe; type II supernovae, neutron star remnants, α-elements, O-Ca, & r-process elements.

- very massive 30-100+ Msun, type II supernovae, black hole remnants, r-process

Nuclear mass defects & nuclear energy:

$$\Delta M_n = M_n - ZM_p - NM_n$$

$$\Delta E = \Delta M_n c^2$$

Conversion of mass to energy

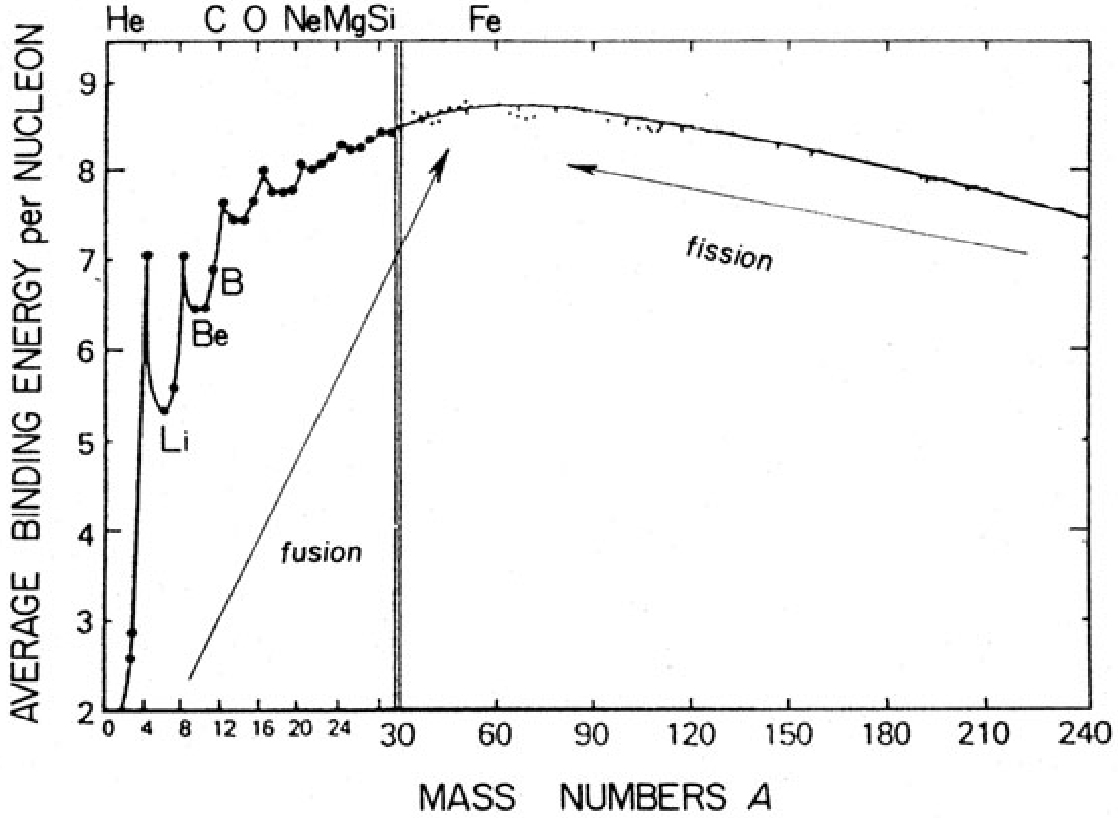
Nucl.	Total Binding E (MeV)	Binding E/A (Mev)
He(2p,2n)	-28.3	-7.07
C(6p,6n)	-92.16	-7.68
O(8p,8n)	-127.62	-7.98
Ca(20p,20n)	-342.05	-8.55
Fe(26p,30n)	-492.26	-8.79
U(92p,146n)	-1801.70	-7.57

Fusion releases

Energy only to near Fe-peak

Binding energy/nucleon: 80% of energy in H->>He

Thus most fusion energy is released in the H-> He step of the process.



Star as a perfect gas sphere:

$\Delta U = -1/2\Delta\Omega$ grav contraction heats star

Equations of stellar structure:

$dp/dr = -Gm\rho/r^2$ pressure equilibrium

$dm/dr = 4\pi\rho r^2$ mass conservation

$Power = L = -4\pi r^2(ac/3\rho\kappa)[\frac{d}{dT}(T^4)]$ radiation diffusion

$\varepsilon = dL/dm$ conservation of energy

Basic physics:

$$U_{elec} = Z_1 Z_2 e^2 / r^2 = 550 keV \; for \; r = r(p)$$

$$\Rightarrow U_{elec} = E_{th} \;\; for \; T = 6x10^9 K \quad (E_{th} = 0.086 T_6 \; keV)$$

$$but \; T(0) \approx (m_p G / k)(M / R) \approx 10^7 K$$

Electric repulsion dominates!!!

Solution: quantum mechanical effects:

$$P = \exp(-2\pi\eta) \; probability \; to \; tunnel \; where$$

$$2\pi\eta = 31.3 Z_1 Z_2 (\mu / E)^{1/2} \;\; \mu \; in \; amu; E \; keV$$

$$\rightarrow \sigma(E) \propto (1/E) \exp(-2\pi\eta) S(E)$$

Thermonuclear reactions can occur at stellar core temperatures

The proton-proton cycle is the first major H-burning process and occurs at the lowest central temperatures in stars. It consists of 3 distinct channels: PPI, PPII, & PPIII.

Hydrogen burning

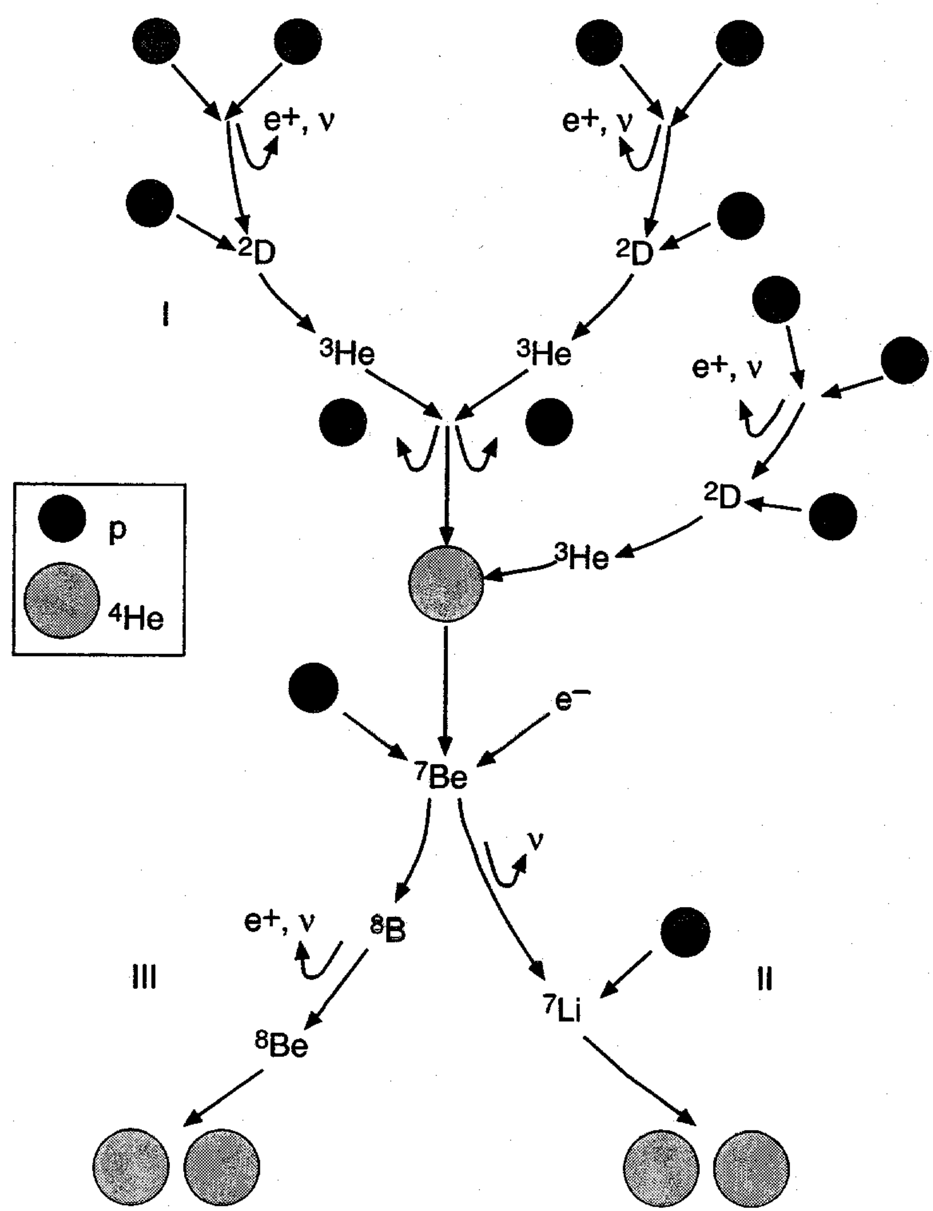


Figure 4.3 The nuclear reactions of the *p–p* I, II, and III chains.

At higher temperatures, H->He via the CNO cycle which depletes O and enhances the N abundances. The CNO cycle dominates H-burning for stars slightly more massive than the Sun.

Conversion of ^{12}C into ^{14}N

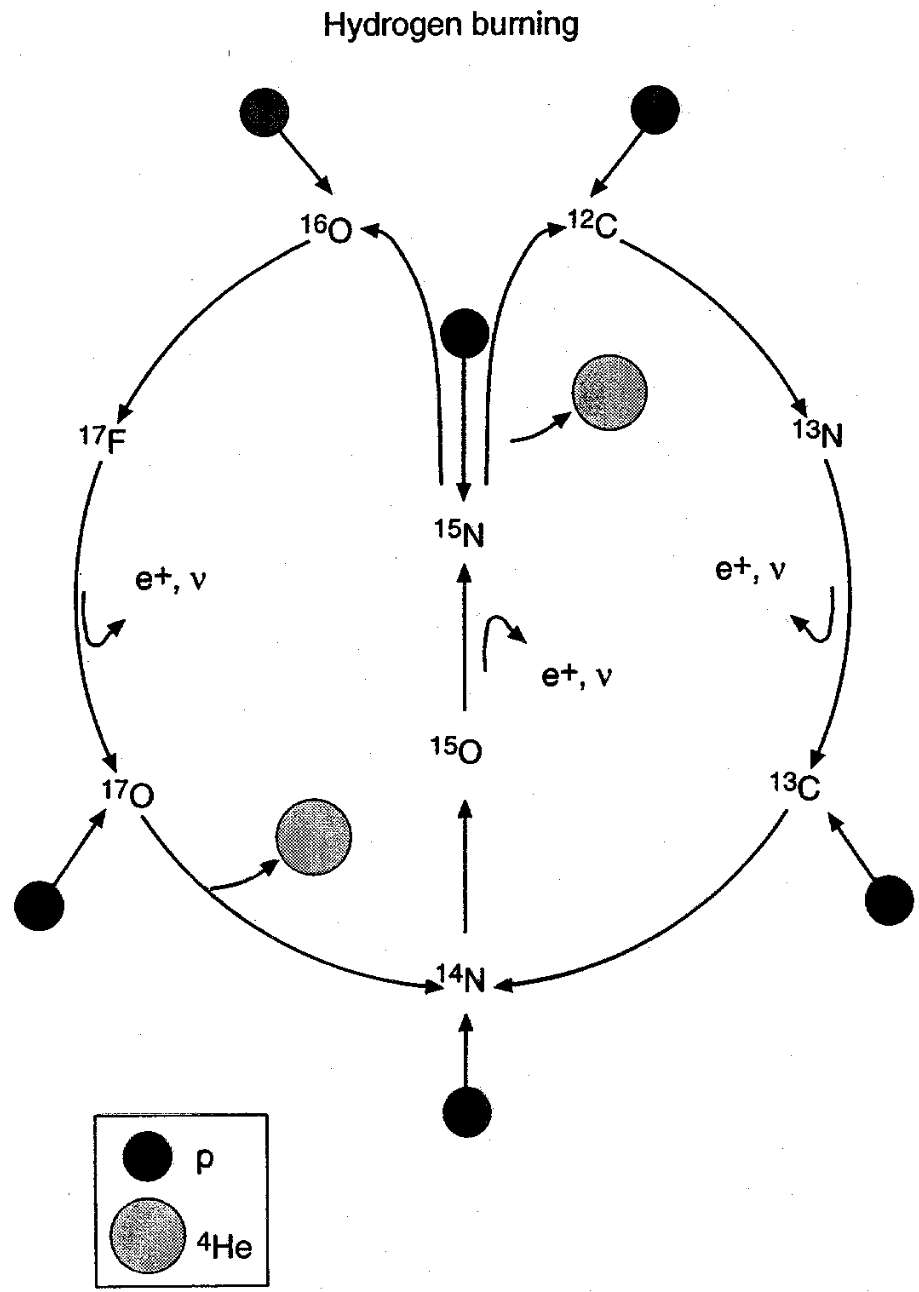


Figure 4.4 The nuclear reactions of the CNO bi-cycle.

This diagram shows how abundances vary with time during the CNO cycle. Note how the N abundance increases as this cycle operates over long times

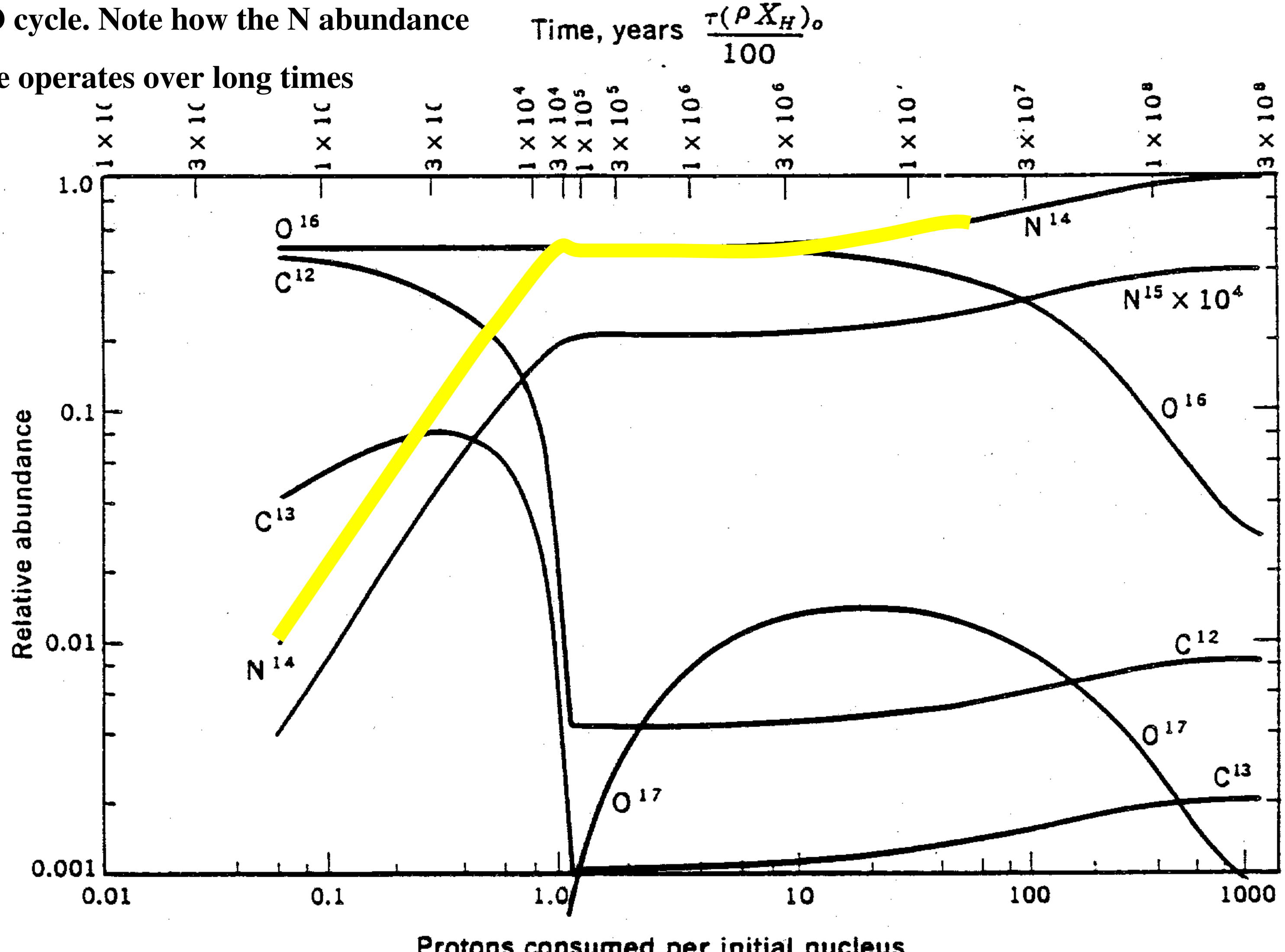
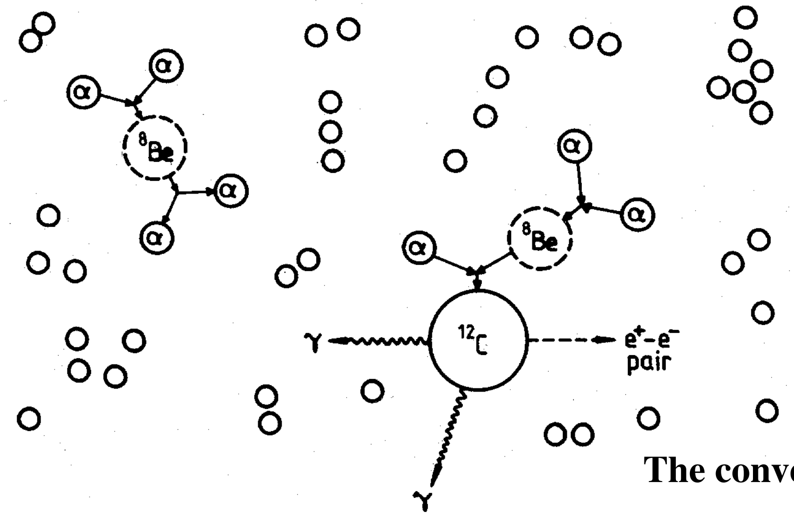


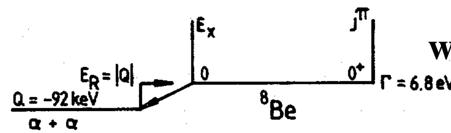
Fig. 5-15 The approach to equilibrium in the CNO bi-cycle as a function of the number of protons captured per initial CNO nucleus. This particular calculation started with equal concentrations of C^{12} and O^{16}. [*After G. R. Caughlan, Astrophys. J.*, **141**:688 (1965). *By permission of The University of Chicago Press. Copyright* 1964 *by The University of Chicago.*]

THE TRIPLE-ALPHA PROCESS



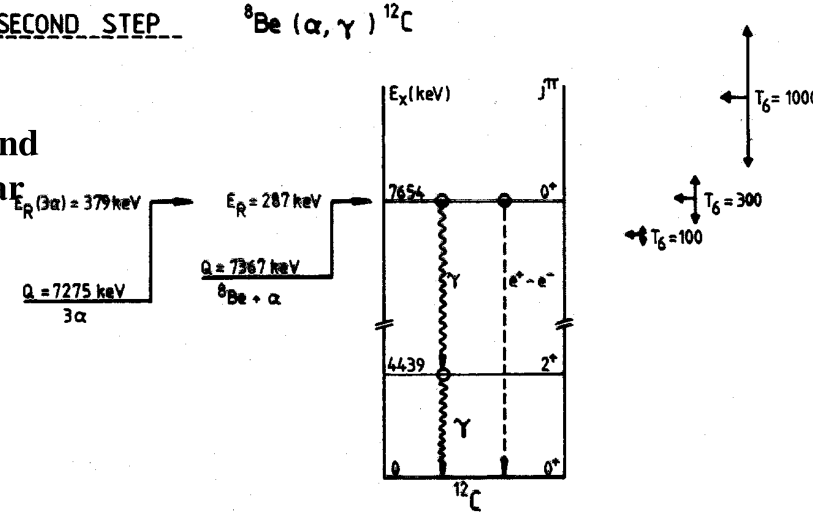
The conversion of He->C is tricky because no stable A=8 nucleus exists. Instead, the triple alpha process involves 3 fast collisions which go directly to C.

FIRST STEP: $\alpha + \alpha \rightleftharpoons {}^{8}Be$

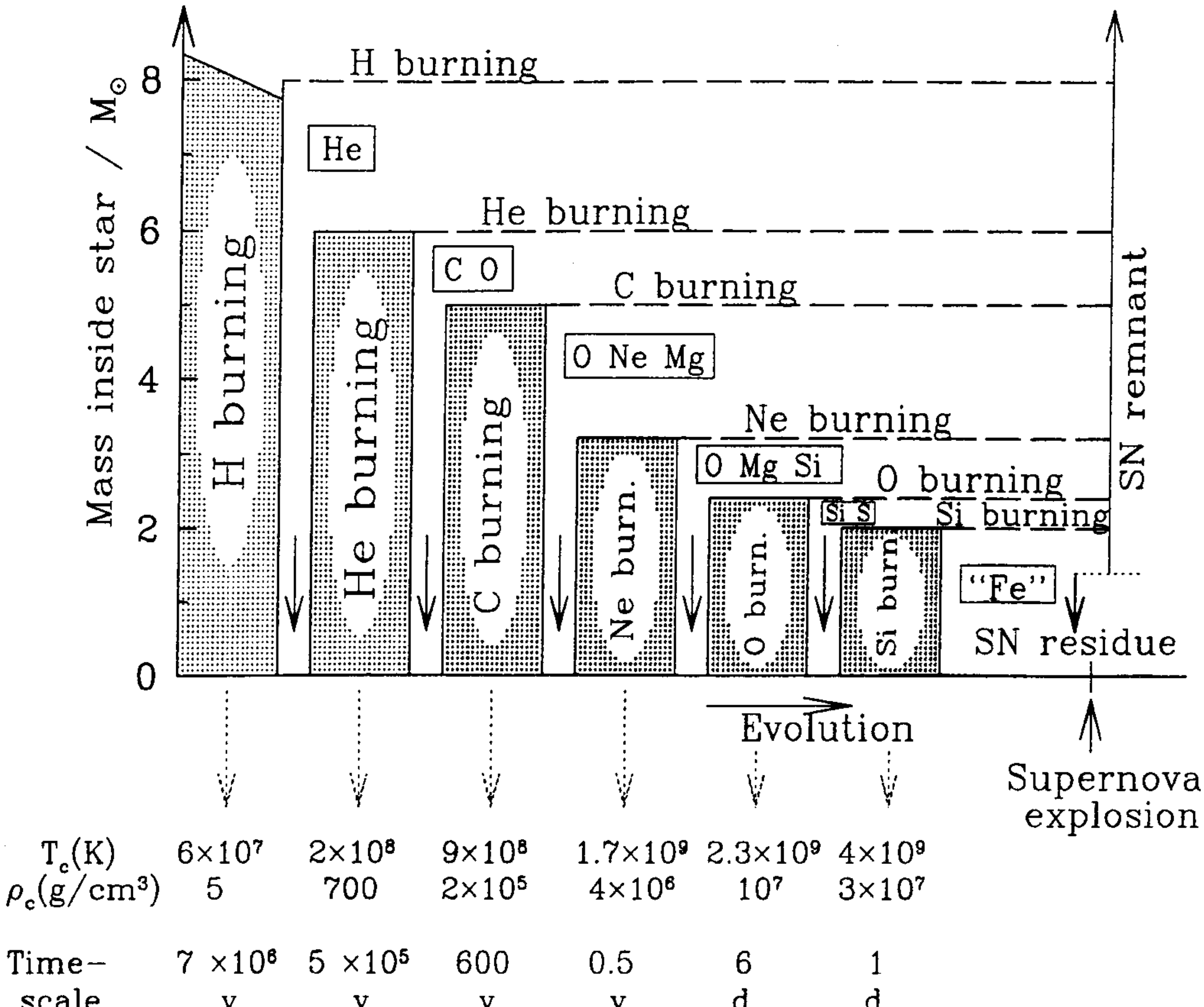


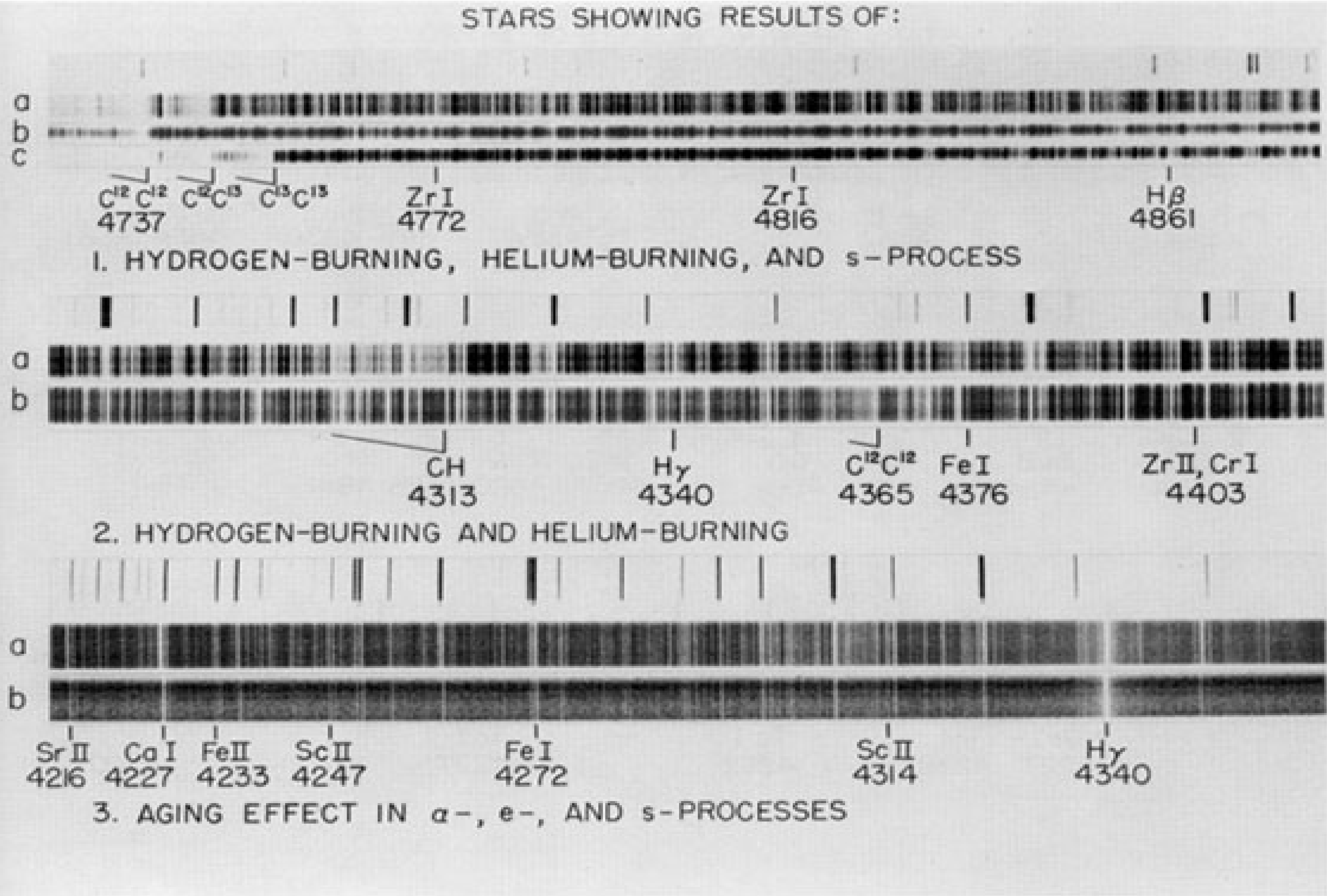
The success of the 3-alpha process rests on the presence of an excited nuclear state of C, which was hypothesized to exist by F. Hoyle and is the physical key to much of stellar nucleosynthesis.

SECOND STEP $^{8}Be(\alpha, \gamma)^{12}C$



Stellar Nuclear burning phases: Element Synthesis as Nuclear Ashes

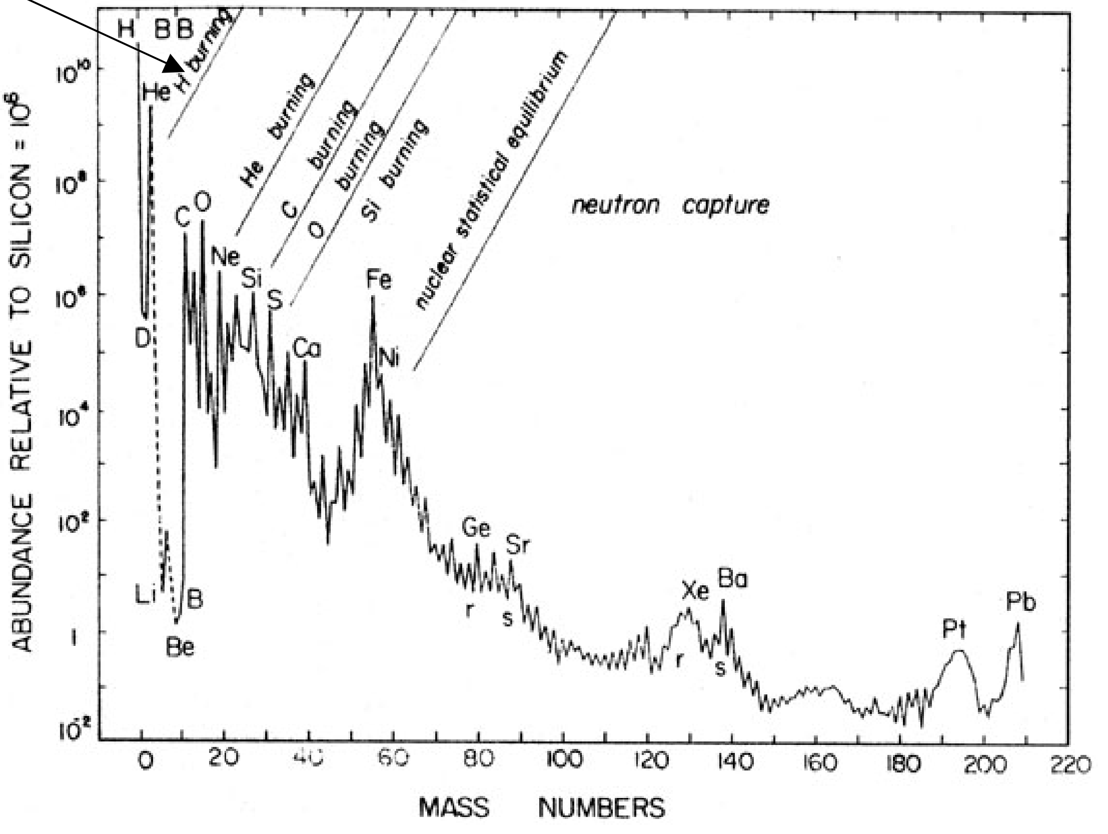




Pagel, Nucleosynthesis and Chemical Evolution...

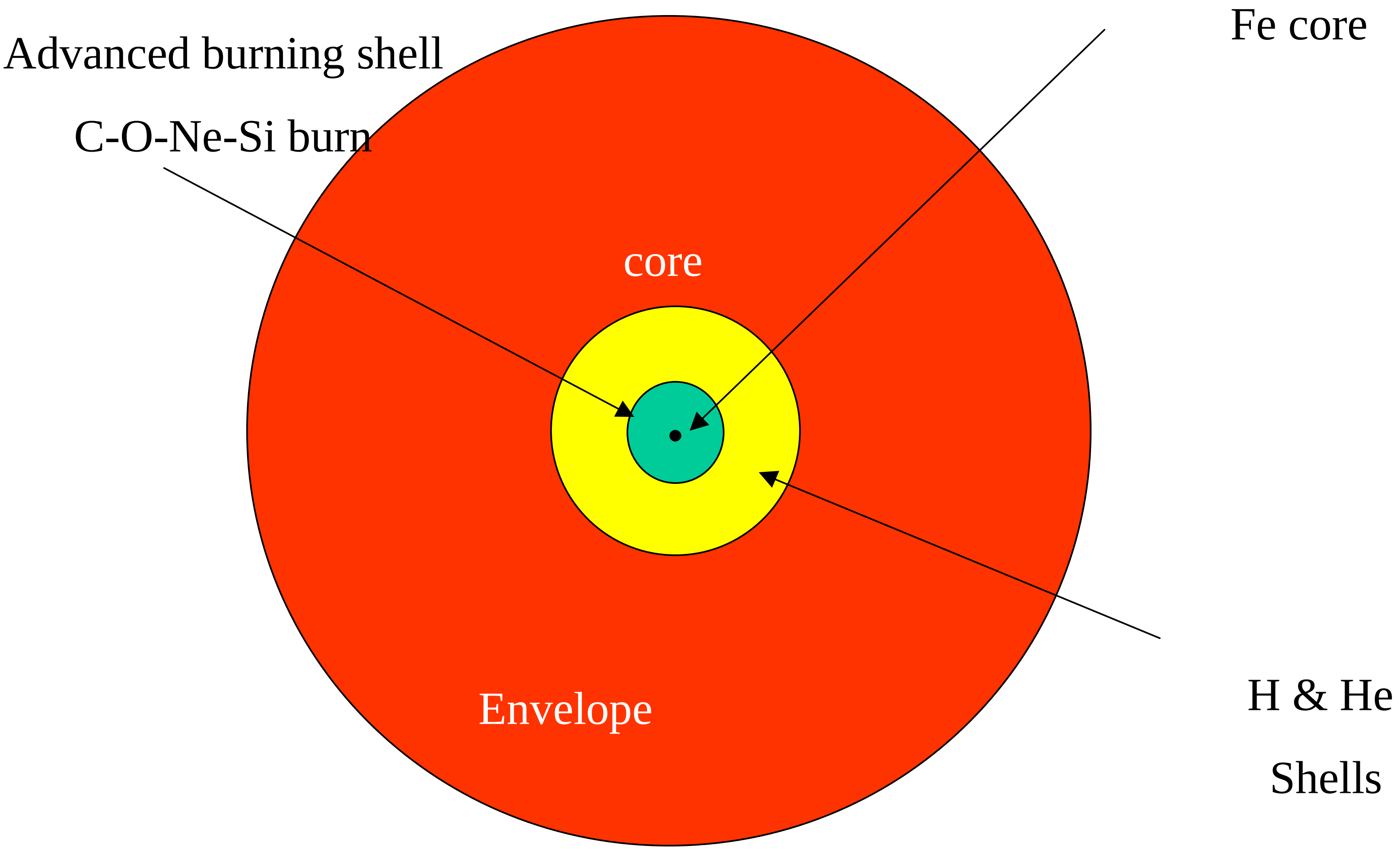
Cosmic abundances--most "metals"=CNO + Fe peak.

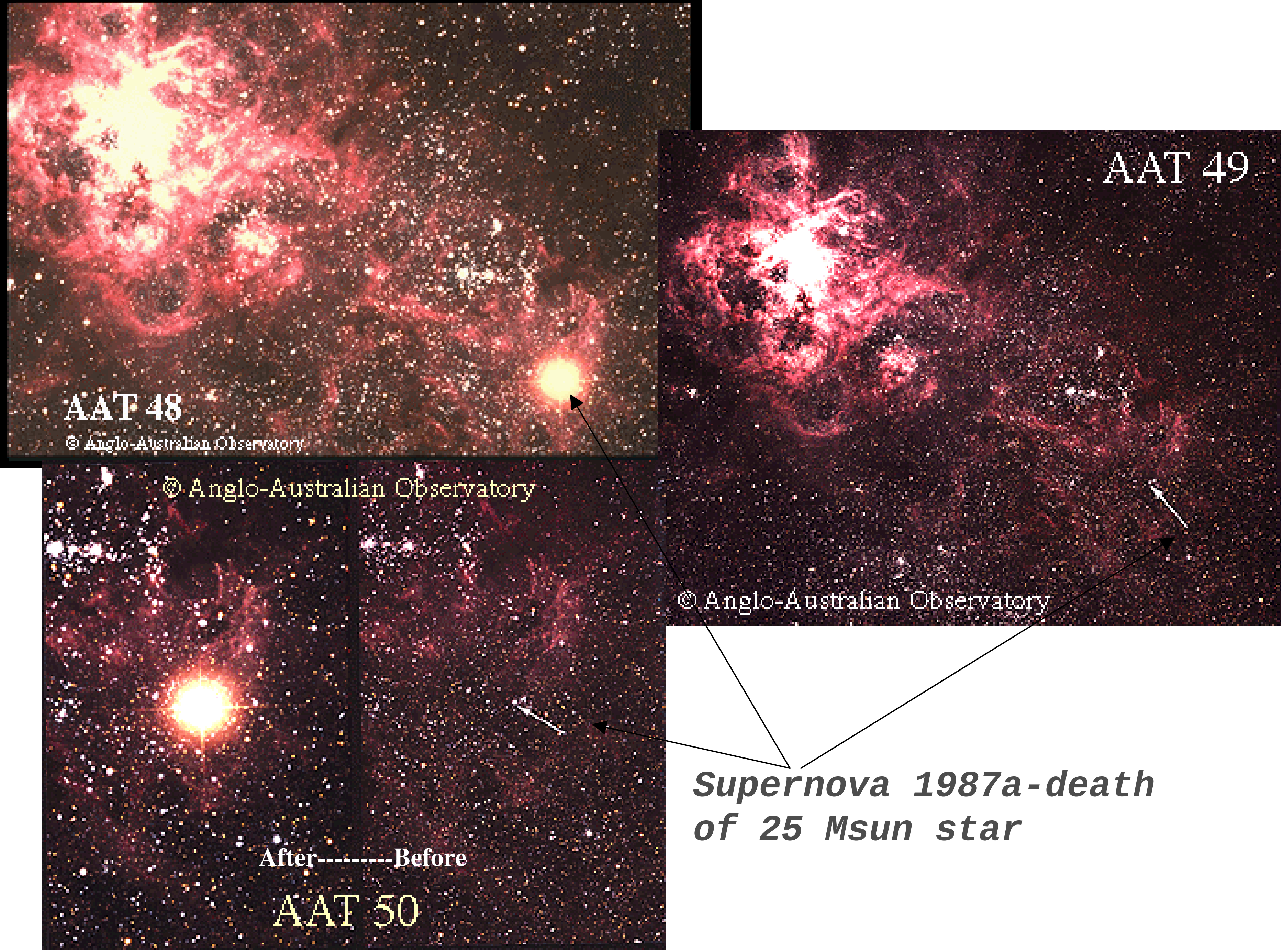
H-burning processes



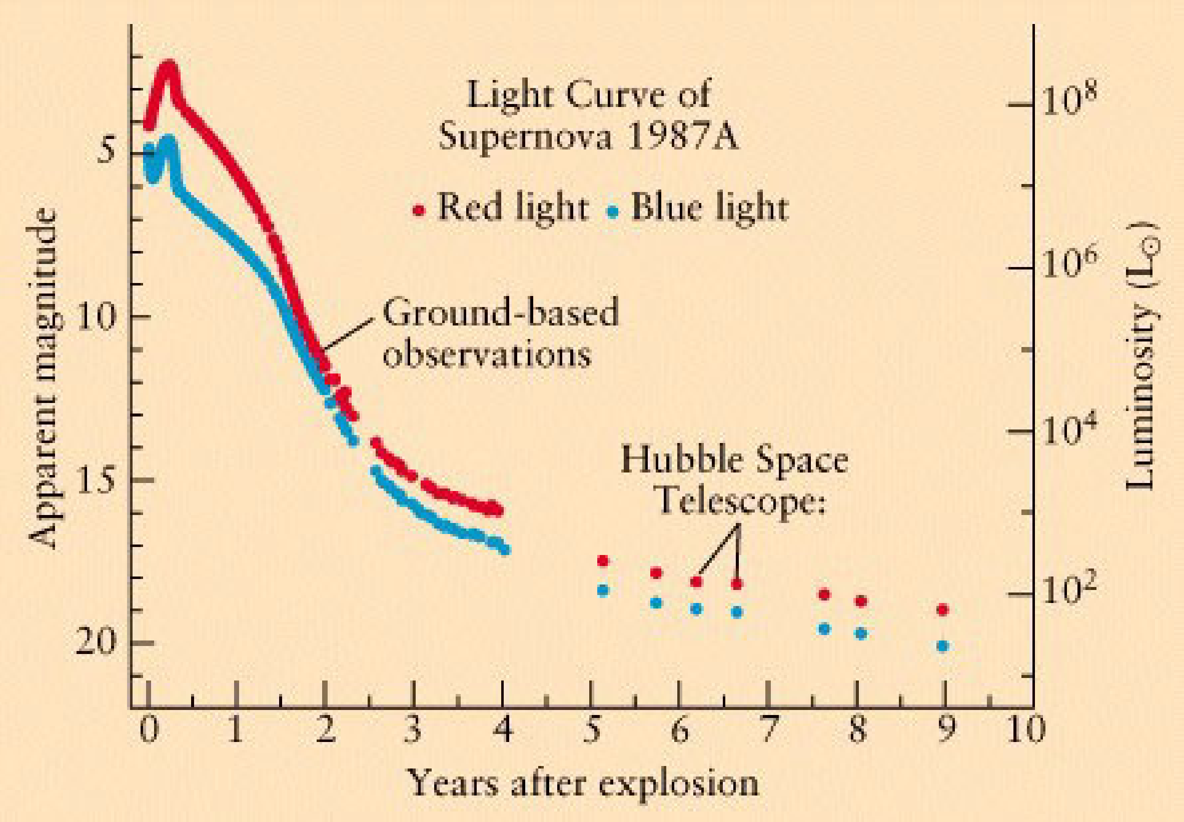
Pagel, Nucleosynthesis and Chemical Evolution of Galaxies

Pre-supernova Massive Star



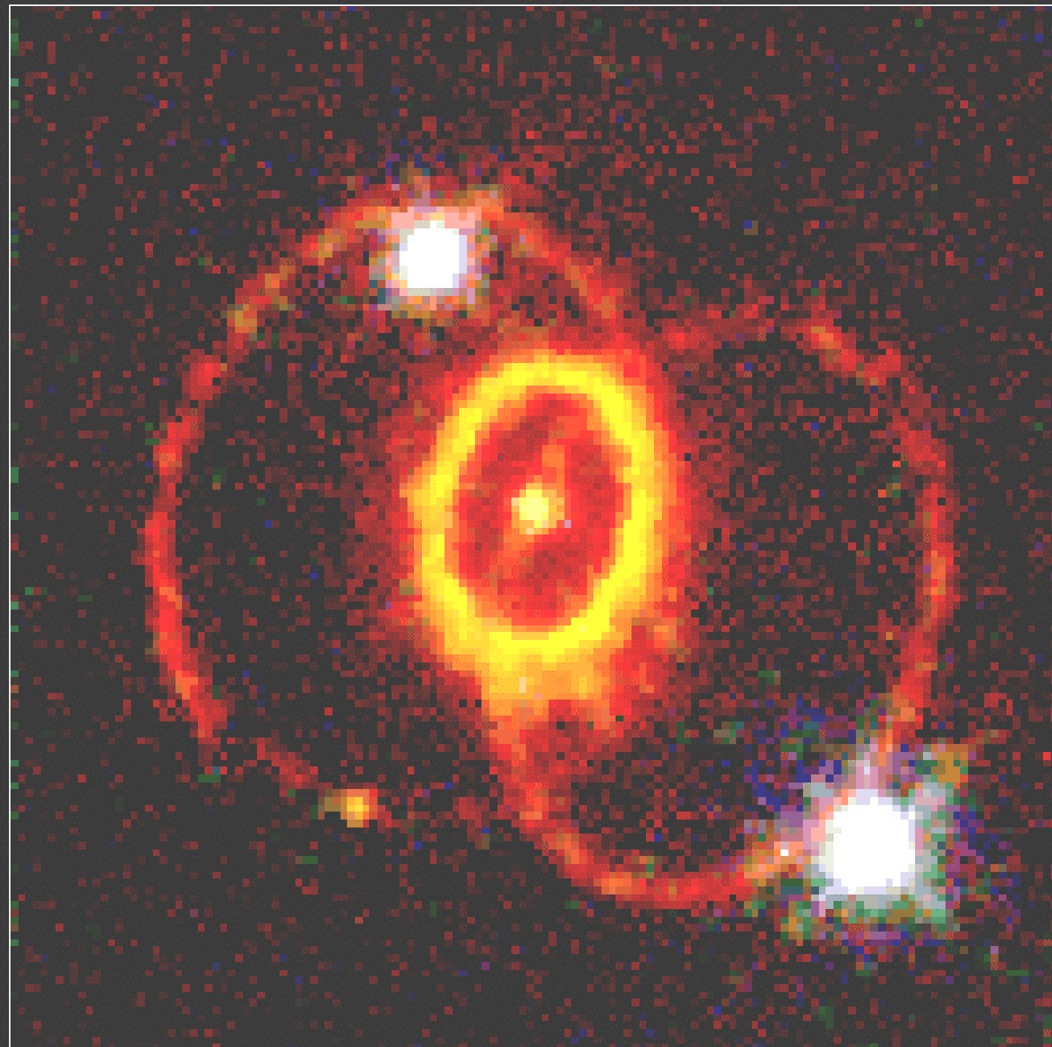


Supernova 1987a-death of 25 Msun star



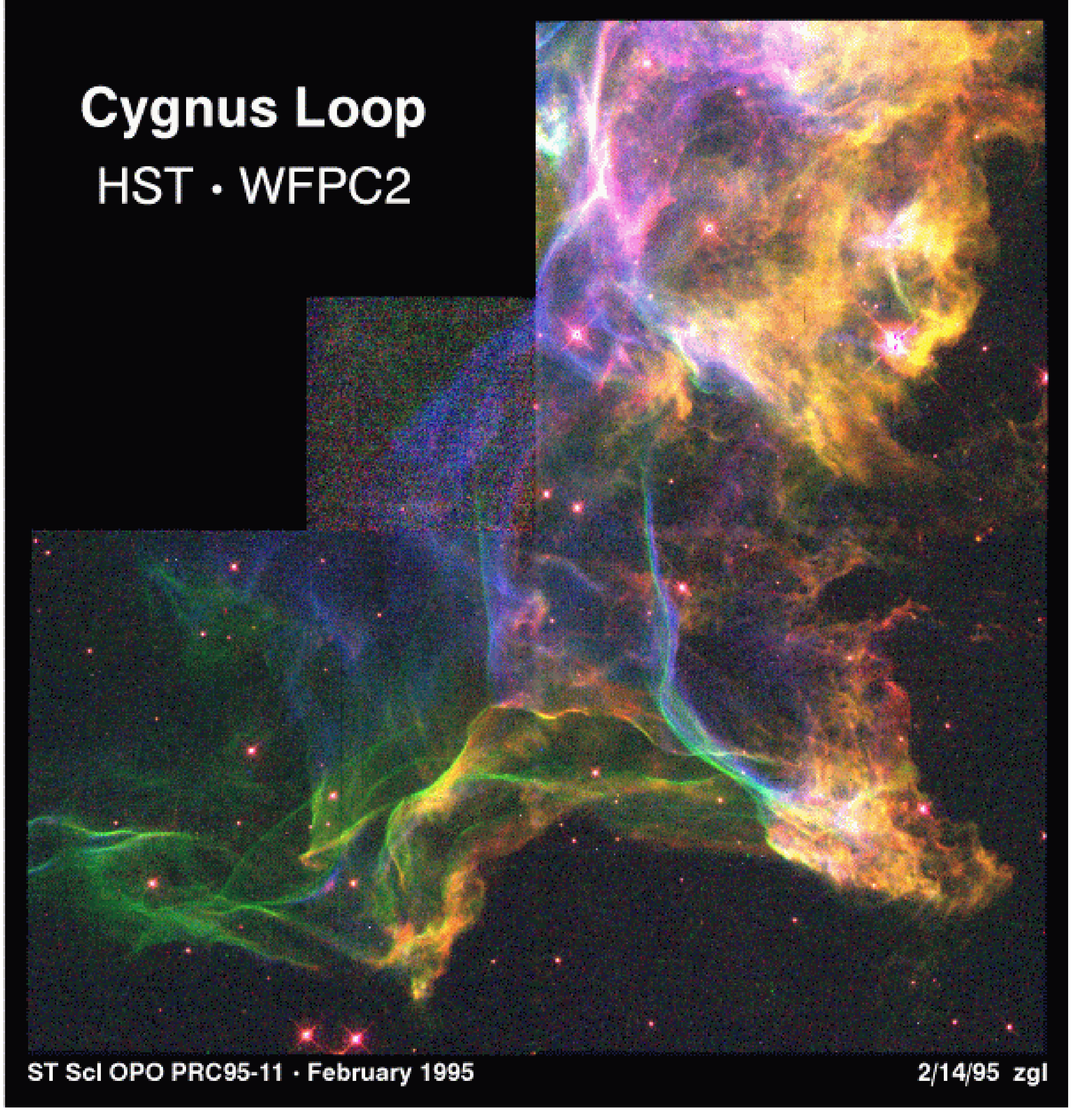
Light Curve of
Supernova 1987A
Red light
Blue light
Ground-based
observations
Hubble Space
Telescope:
Apparent magnitude
5
10
15
20
Luminosity ($L_\odot$)
10^8
10^6
10^4
10^2
0
1
2
3
4
5
6
7
8
9
10
Years after explosion

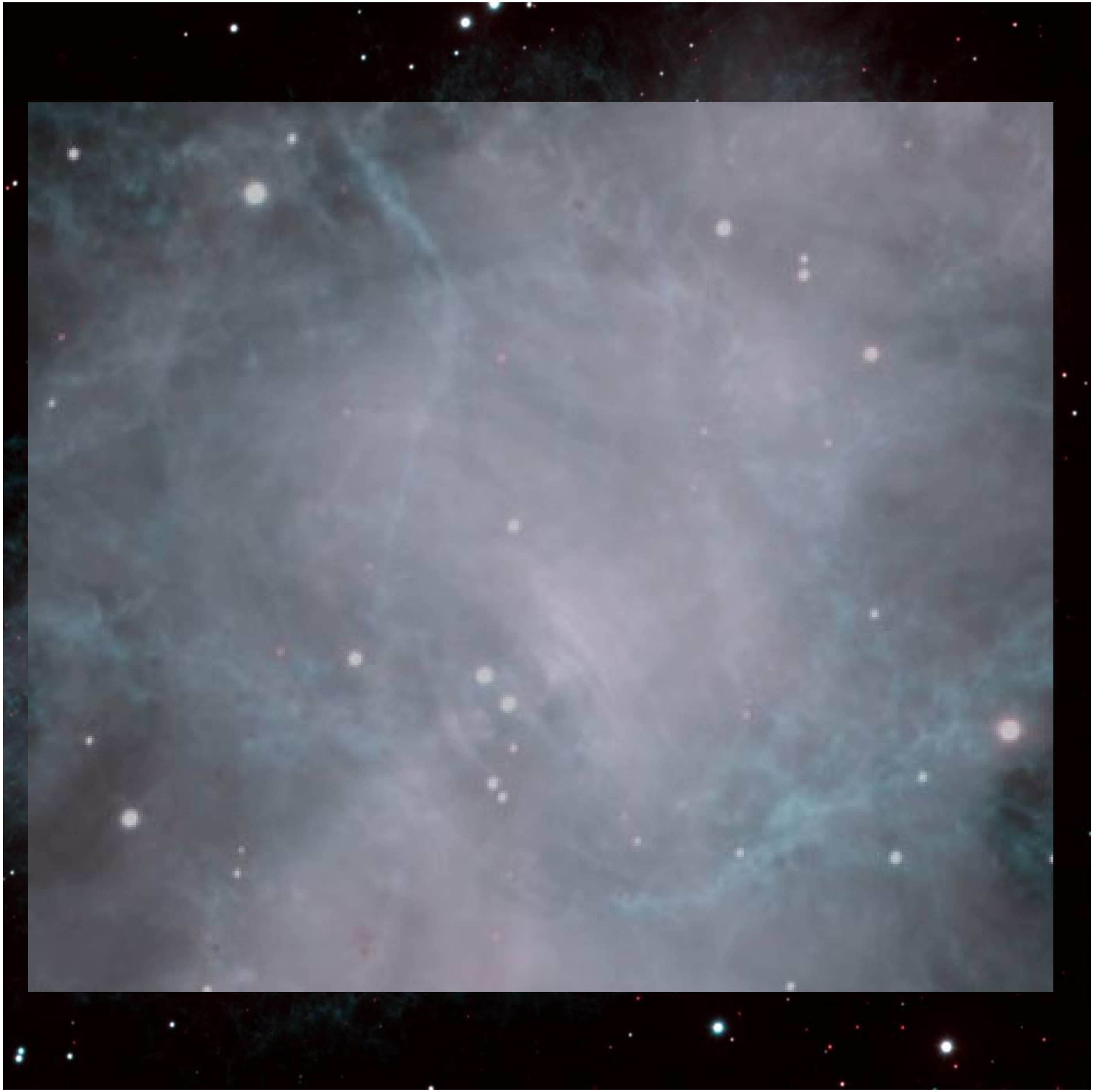
Supernova 1987A Rings



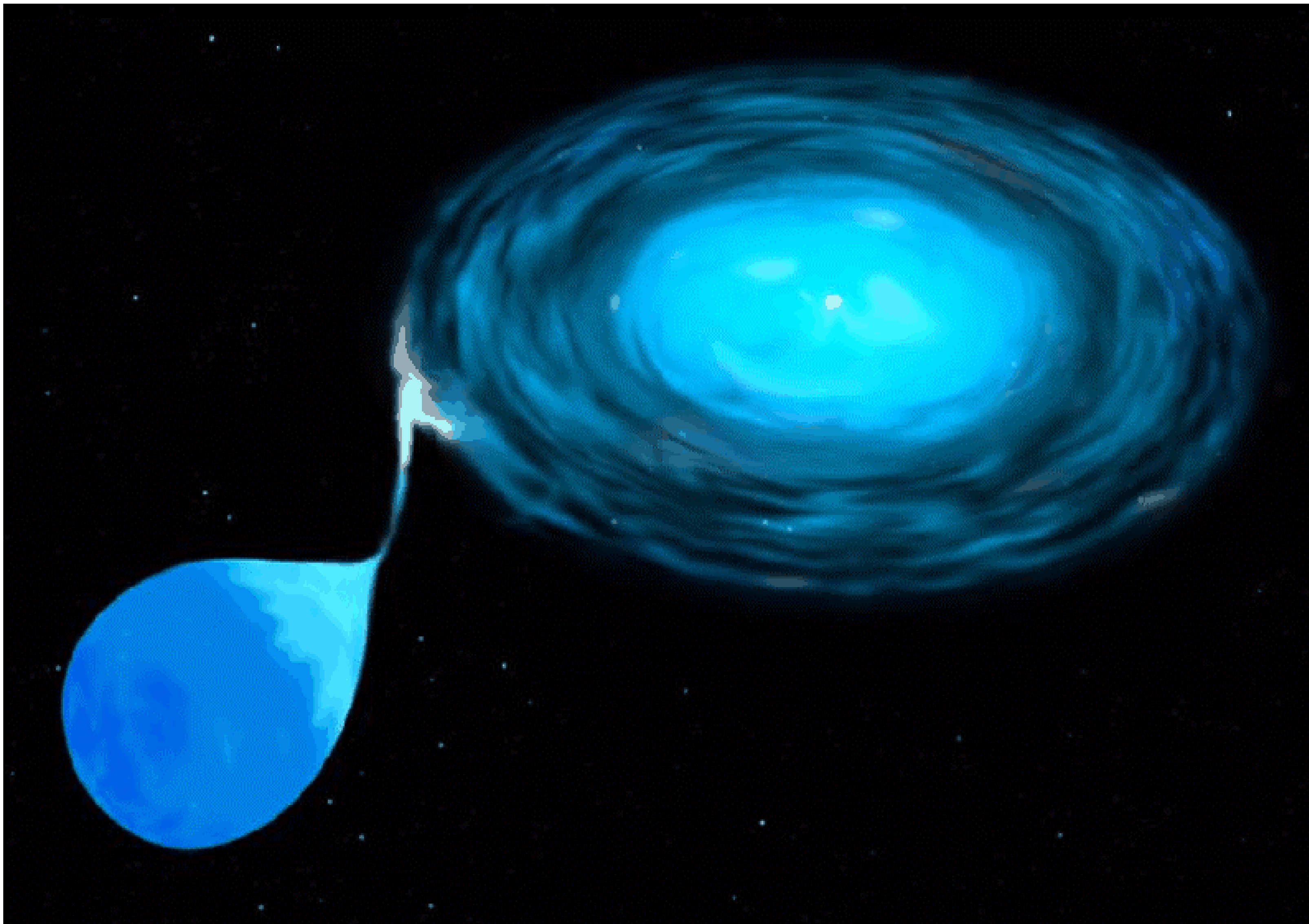
Hubble Space Telescope
Wide Field Planetary Camera 2

SPACE
TELESCOPE
SCIENCE
INSTITUTE


Cygnus Loop
HST • WFPC2
ST ScI OPO PRC95-11 • February 1995
2/14/95 zgl

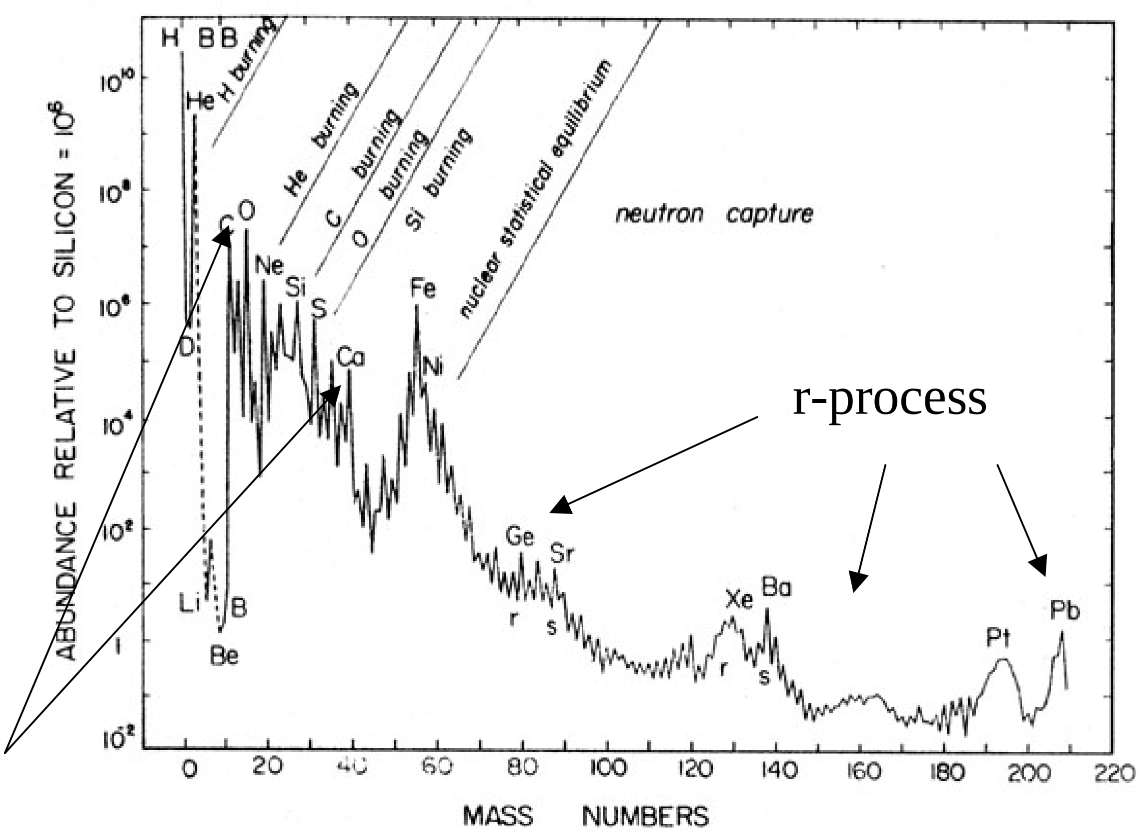


Binary star mass transfer--overload white dwarf. One path to type I supernovae in which much of the Fe-peak is synthesized.



Cosmic abundances--most “metals”=CNO + Fe peak.

The r-process=rapid capture of neutrons onto Fe seed nuclei--makes some very heavy elements above Fe-peak

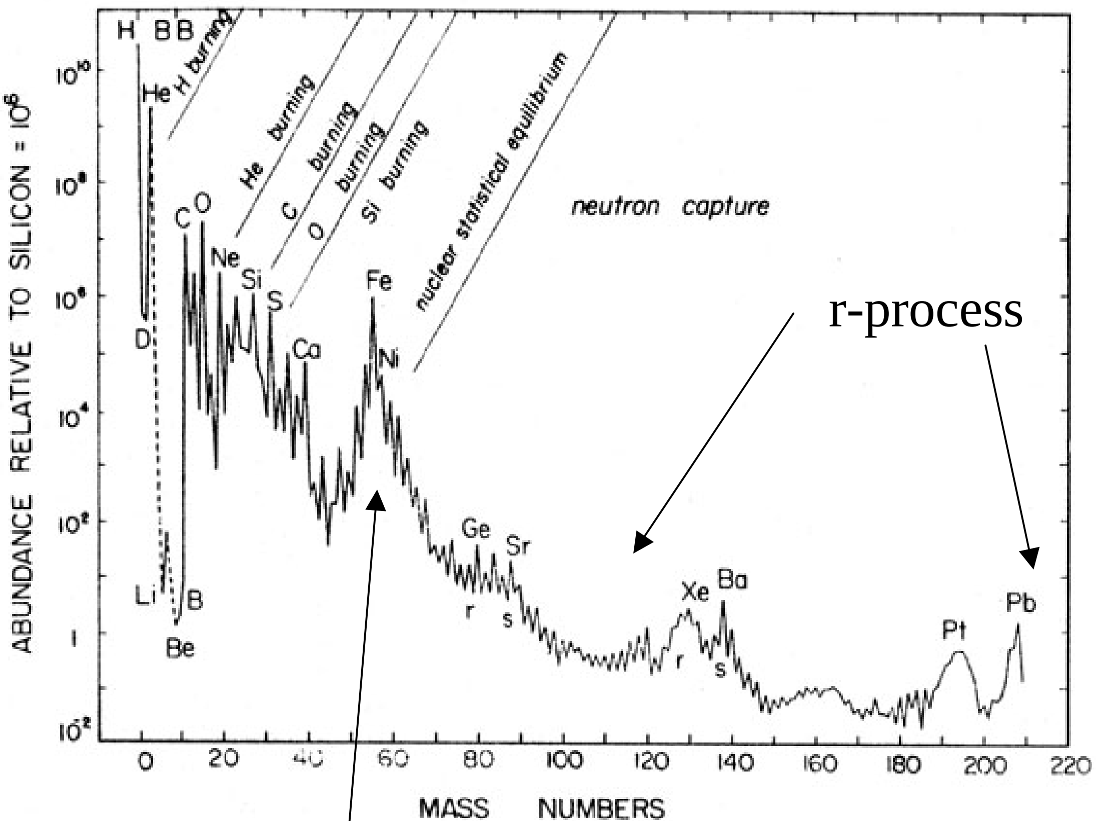


Massive star supernovae-->

α-elements O,Ne,Si, Ca

Pagel, Nucleosynthesis and Chemical Evolution of Galaxies

Cosmic abundances--most "metals"=CNO + Fe peak.

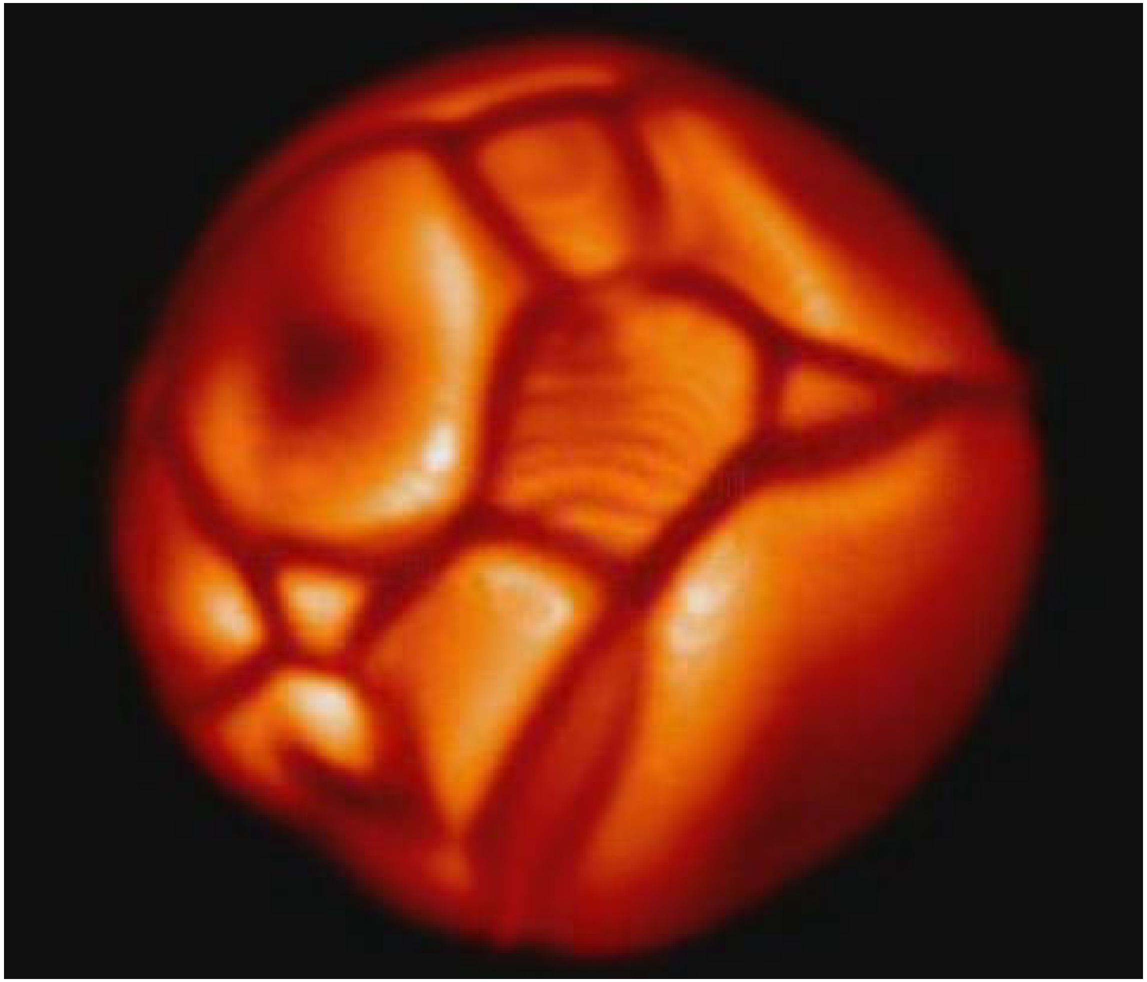


r-process

Low mass supernovae-->>"iron peak"

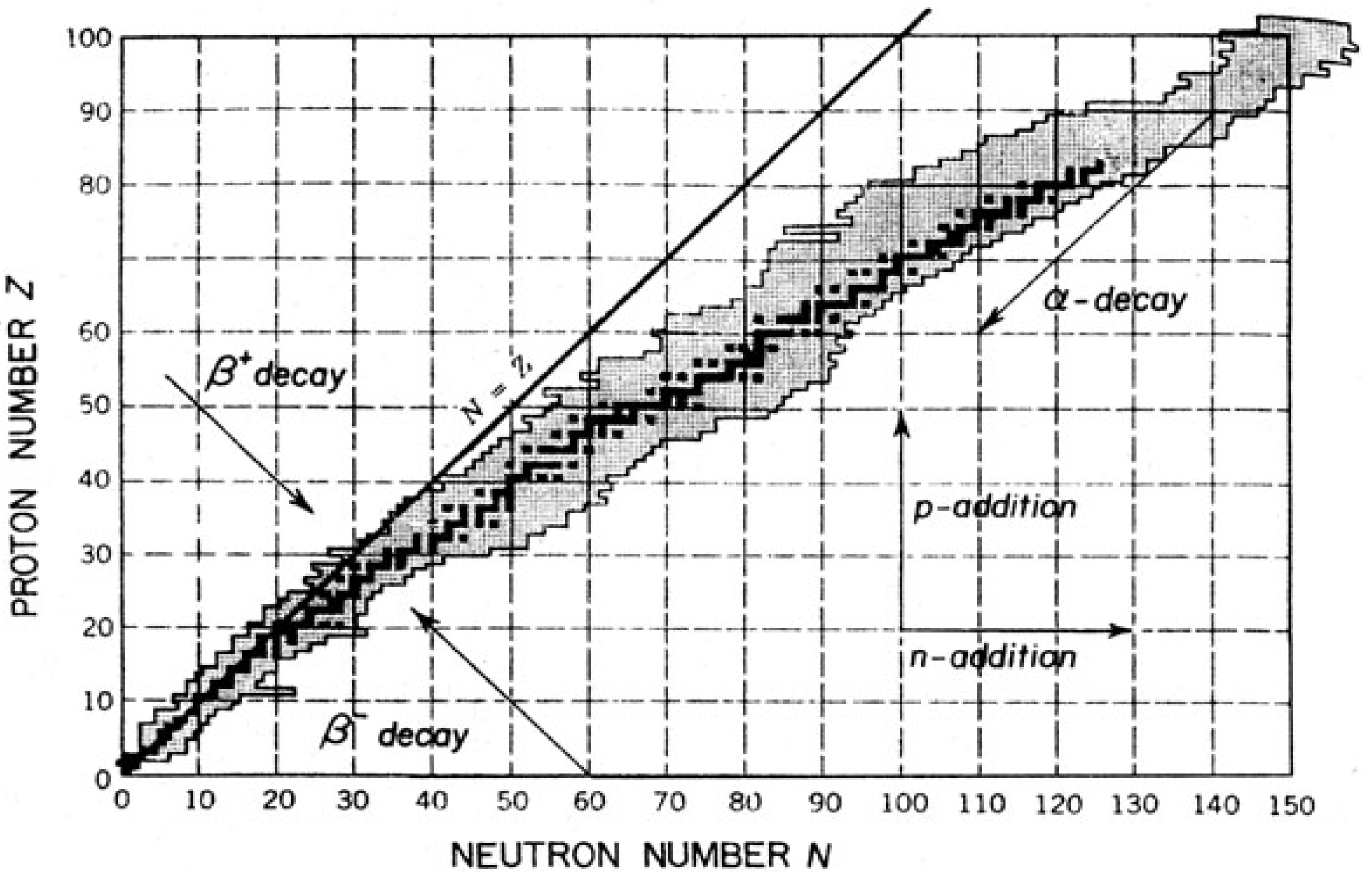
Pagel, Nucleosynthesis and Chemical Evolution of Galaxies

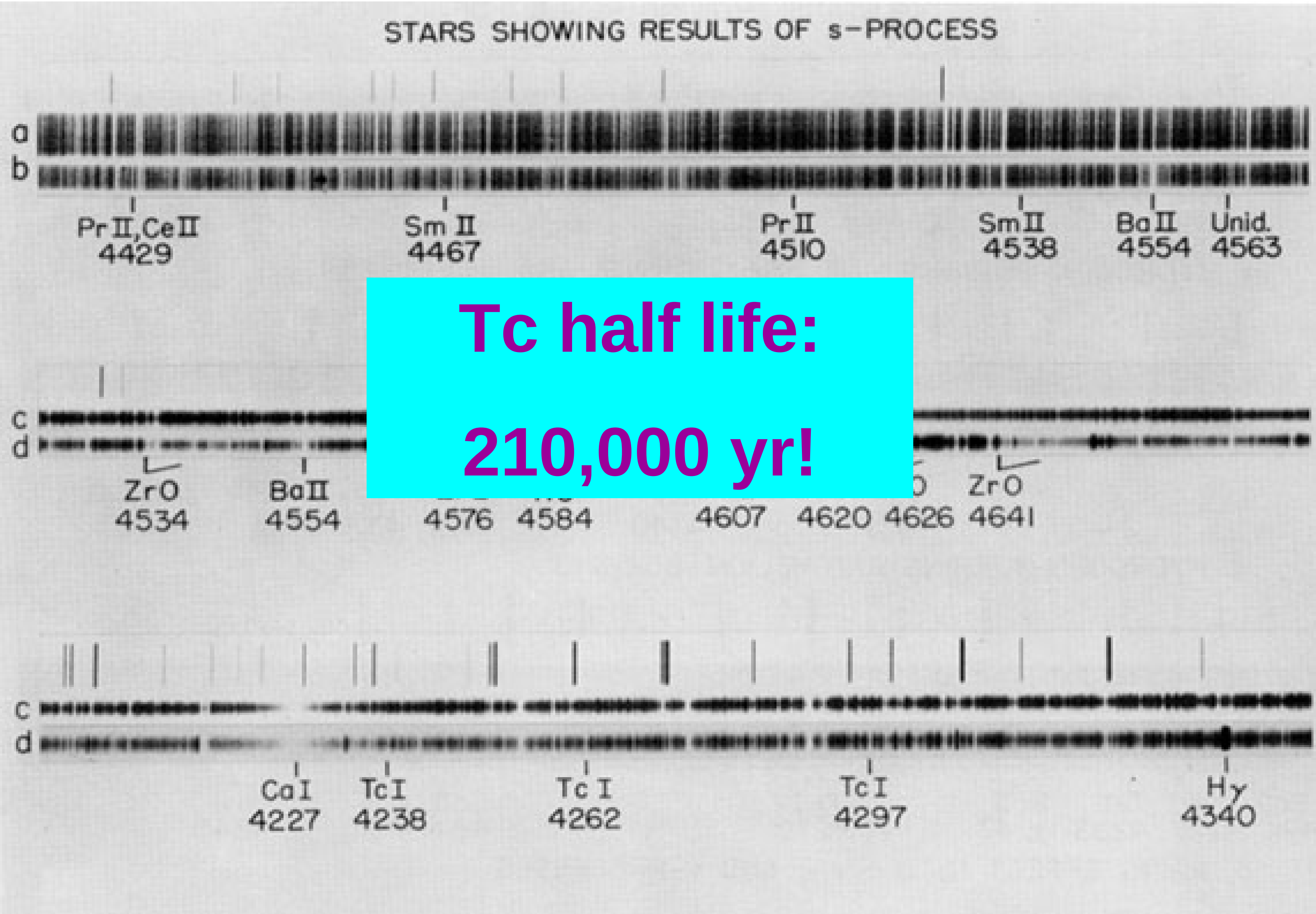
Red intermediate mass asymptotic giant star with complex atmosphere e.g., Betelgeuse in **Orion**



Synthesis of elements of by capture/decay

The s-process is slow neutron capture--elements have time to decay. This occurs in dying moderate mass red stars.





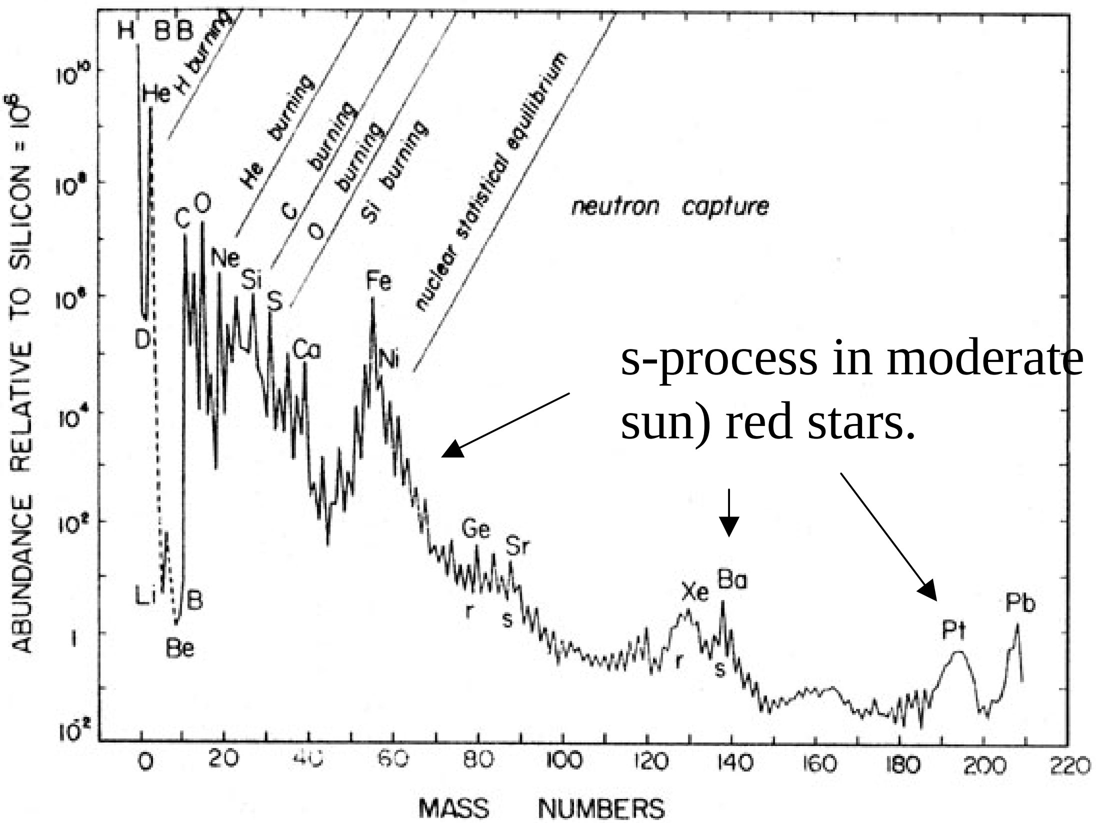
Tc half life:

210,000 yr!

Pagel, Nucleosynthesis and Chemical Evolution...

A young planetary nebula showing interaction with remnants of the cool star’s outer layers.

Cosmic abundances--most "metals"=CNO + Fe peak.

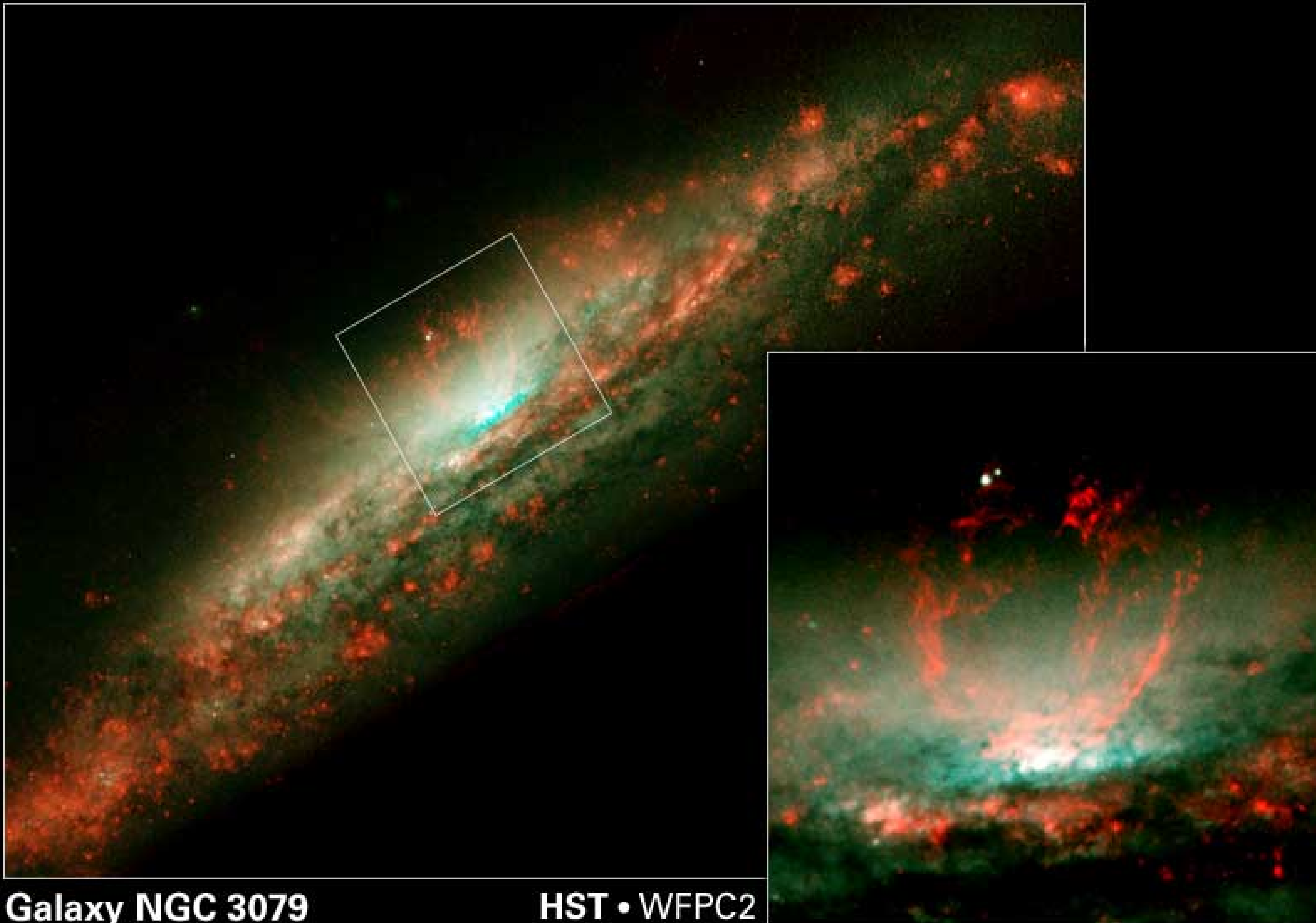


s-process in moderate (2-8 M-sun) red stars.

Pagel, Nucleosynthesis and Chemical Evolution of Galaxies


Planets form from star ashes

Planetary nebula around dying star--^{14}N + s-process?



Galaxy NGC 3079 **HST • WFPC2**

NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28