Stellar Abundances

I. Basic principles of stellar nucleosynthesis
II. Basic ingredients
III. Deciphering abundances
IV. A case study: LiBeB

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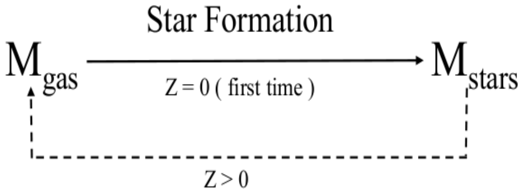
GREAT-ITN School, IAC - 2013

GCE: some basics

The history of the chemical composition of the Galaxy is dominated by the nucleosynthesis occurring in many generations of stars

Initially: $X=X_i$ (~0.75) $Y=Y_i$ (~0.25) $Z=Z_i$ (0.0)

- Elements are made in stars, ejected into the interstellar medium by stellar winds and supernova explosions.



Star Formation

M_{gas} → M_{stars}

Z = 0 (first time)

Z > 0

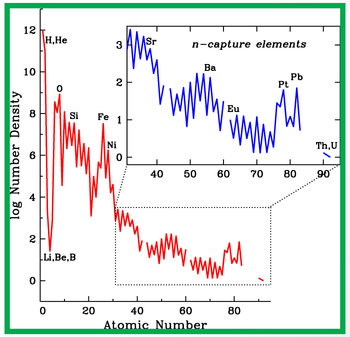
- Elements are mixed into the interstellar medium out of which new stars are formed. Each new stellar generation is born from gas with higher metallicity:

yield, IMF, SFR

X ↓ Y ↑ Z ↑

- The cycle repeats itself over billions of years

Chemical abundances in the solar system/ vicinity provide the richest information.



Budgets

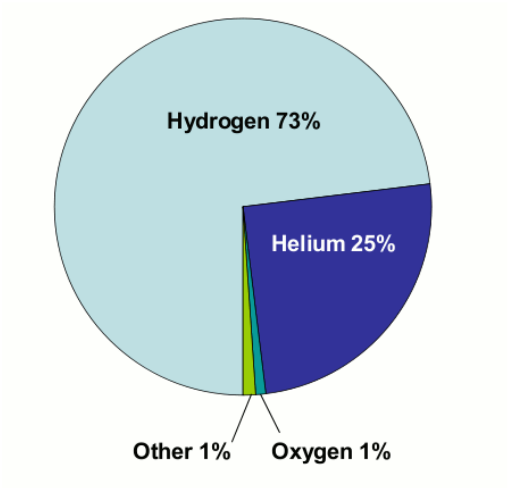
Chemical *vs.* *Cosmological*

H	X = 0.700
He	Y = 0.280
Metals	Z = 0.020

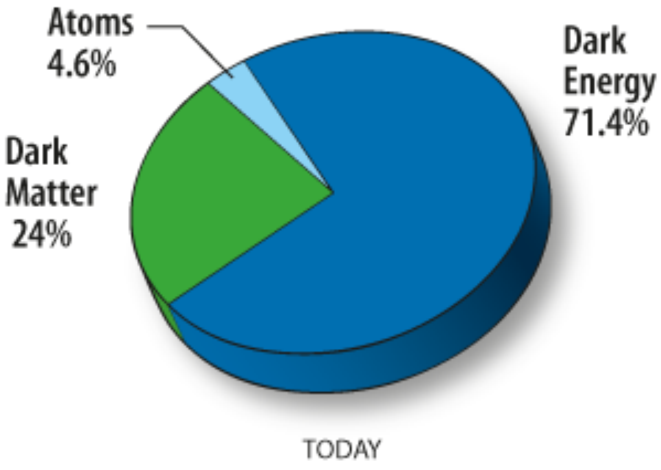
Dark energy	~70%
Dark matter	~25%
Baryons	~5%

- by mass
- young stars

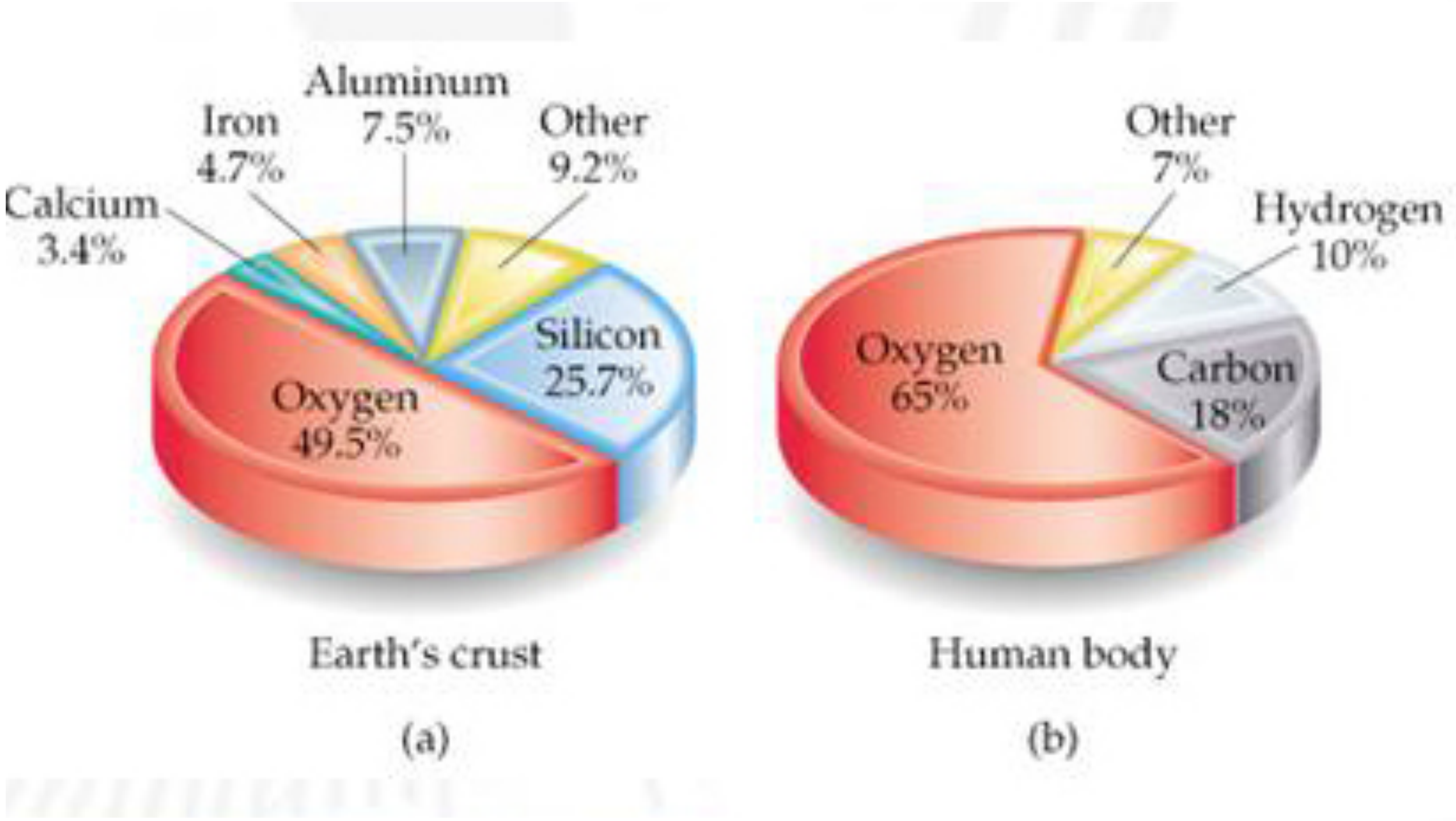
UNIVERSE



WMAP

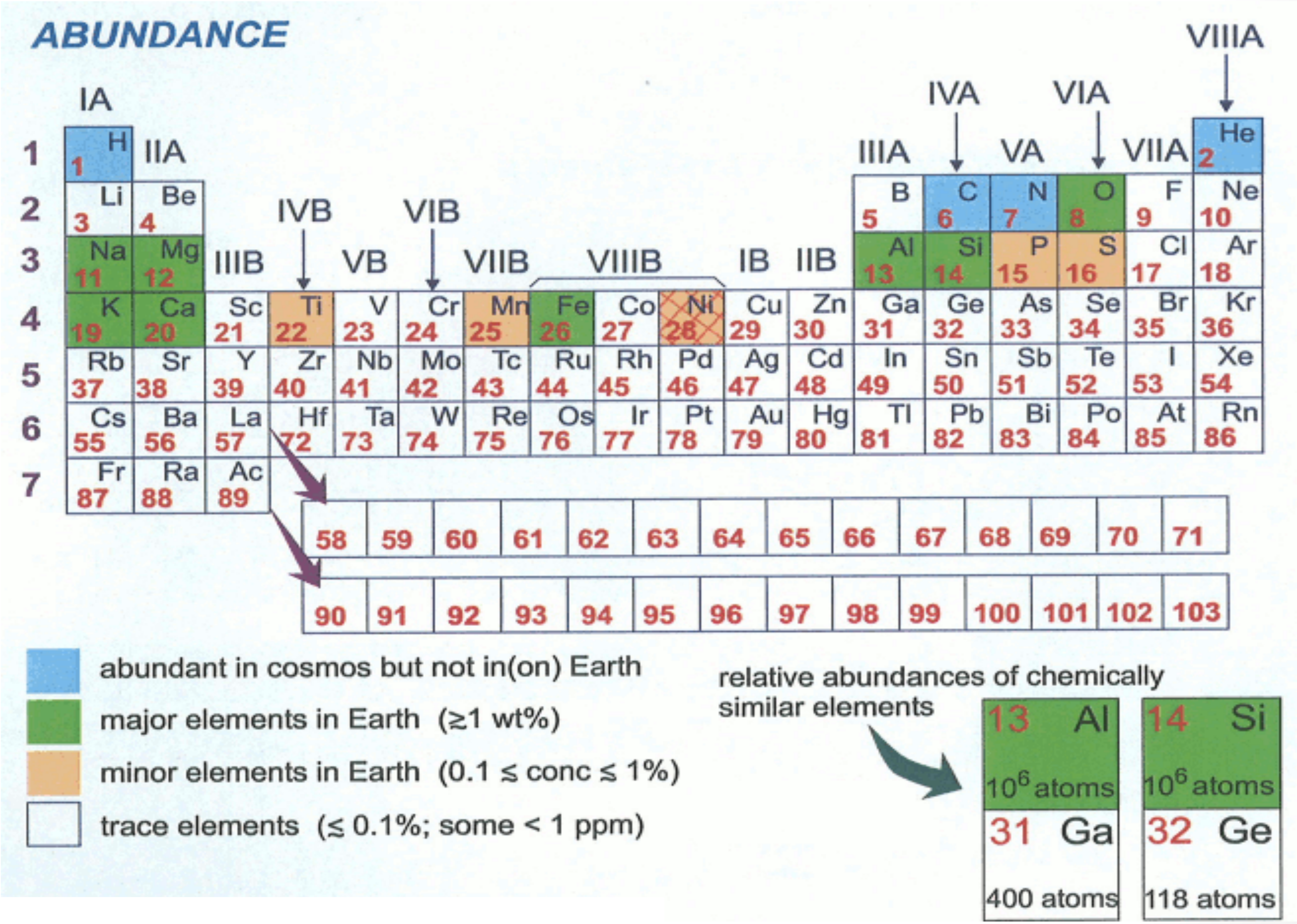


In comparison …



Different ways to sort and group the elements …

- By *abundance* here, there, or anywhere



🟦 abundant in cosmos but not in(on) Earth

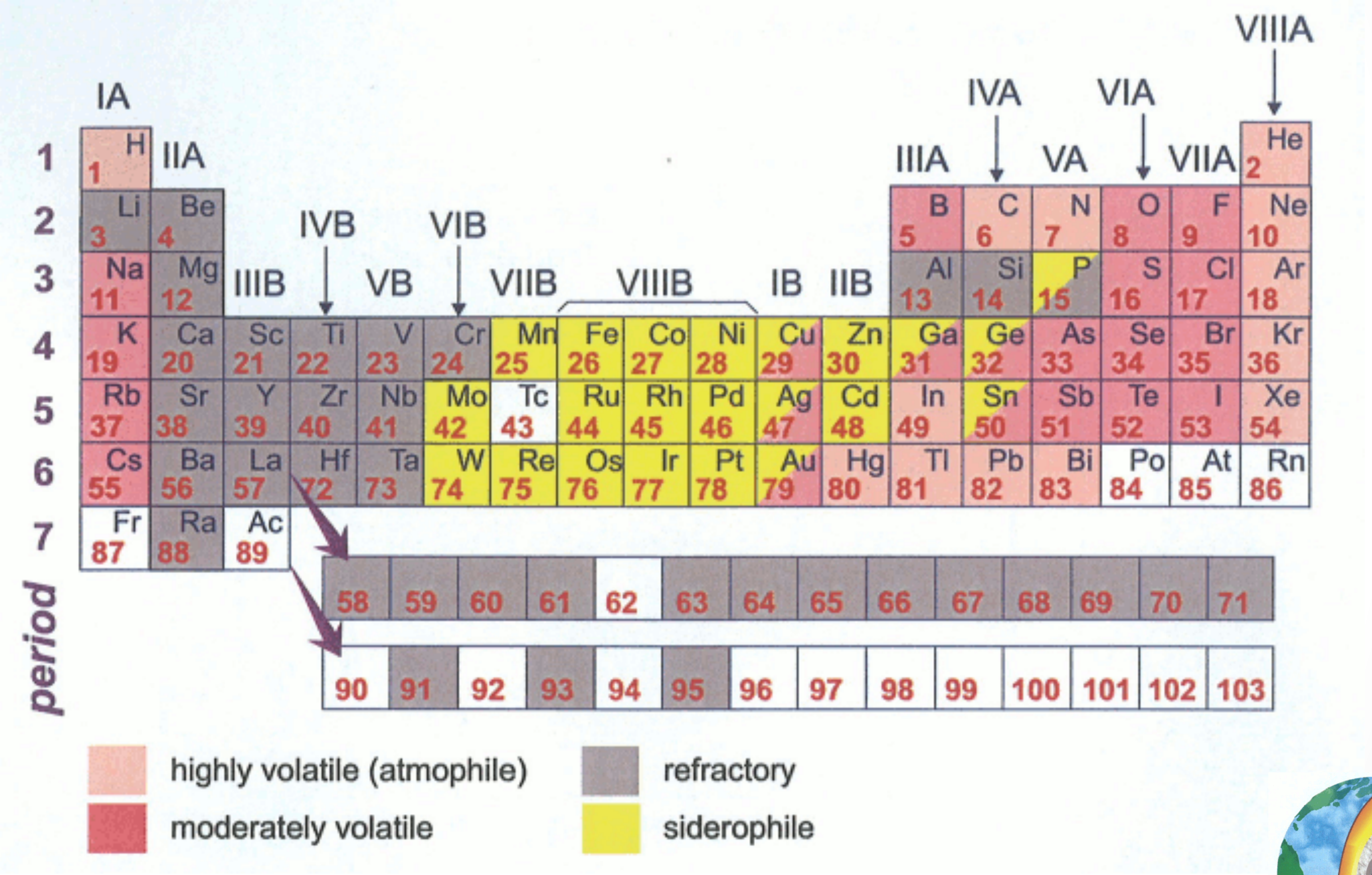
🟩 major elements in Earth (≥1 wt%)

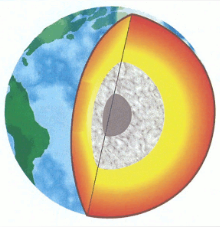
🟧 minor elements in Earth (0.1 ≤ conc ≤ 1%)

☐ trace elements (≤ 0.1%; some < 1 ppm)

Different ways to sort and group the elements …

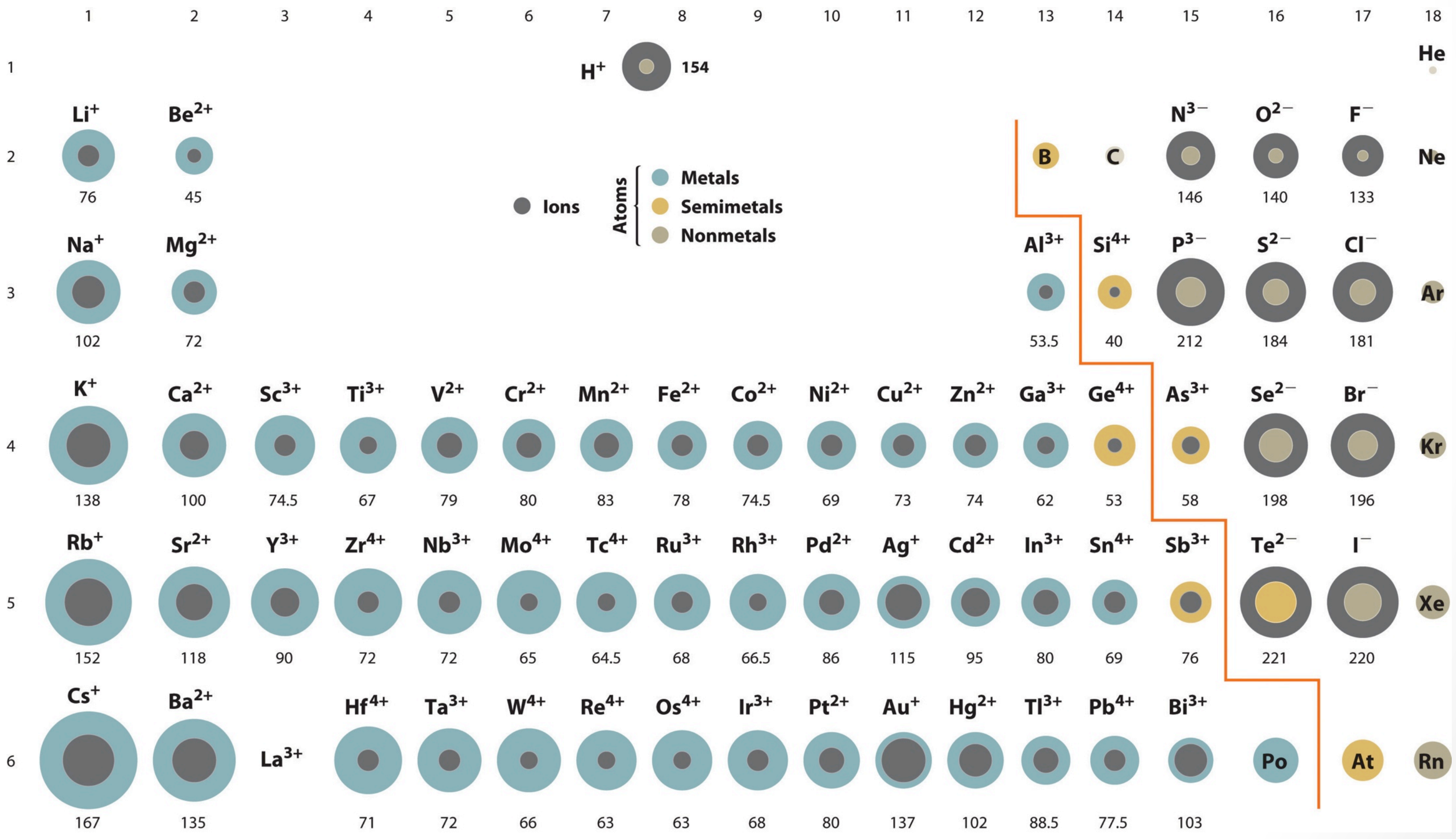
- *By volatility in gas-solid equilibria, i.e. by condensation temperature*
    - refractory, moderately volatile, highly volatile





Different ways to sort and group the elements …

- *By compatibility (solid/melt concentration ratio) in igneous processes*
  - compatible, incompatible, very incompatible; generally functions of charge and ionic radius…related to position in periodic table in systematic ways

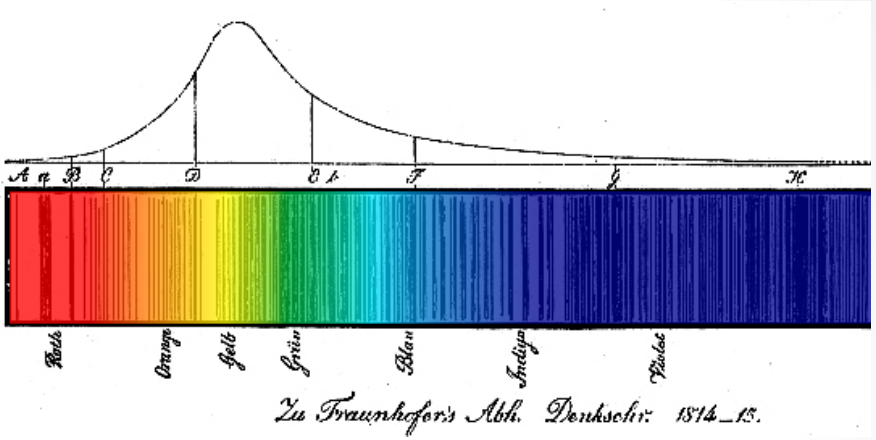


Different ways to sort and group the elements …

- *By nucleosynthetic origin and nuclear properties*
    - primordial, H-, He-, C-, Ne-, Si-burning, RG processes, n-captures
    - stable, long-lived or short-lived radioactive

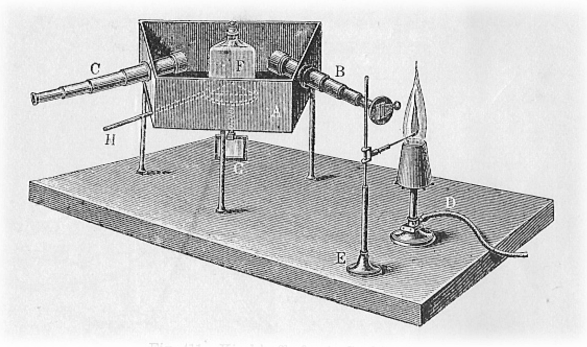
Big Bang
CR spallation
H-burning (hydro)
H-burning (expl)
He-burning
C-burning
O-burning
Ne-burning
Expl. Nucleosyn.
NSE
s-process
r-process

Let's start (almost) from the beginning …

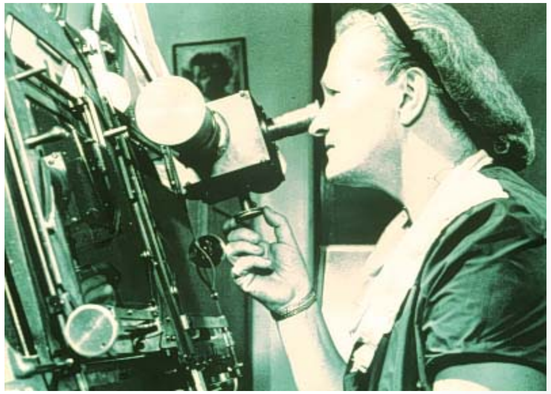


1802 First notice of dark bands
Wollaston

1817 Absorption lines detected in the solar spectrum
Fraunhofer

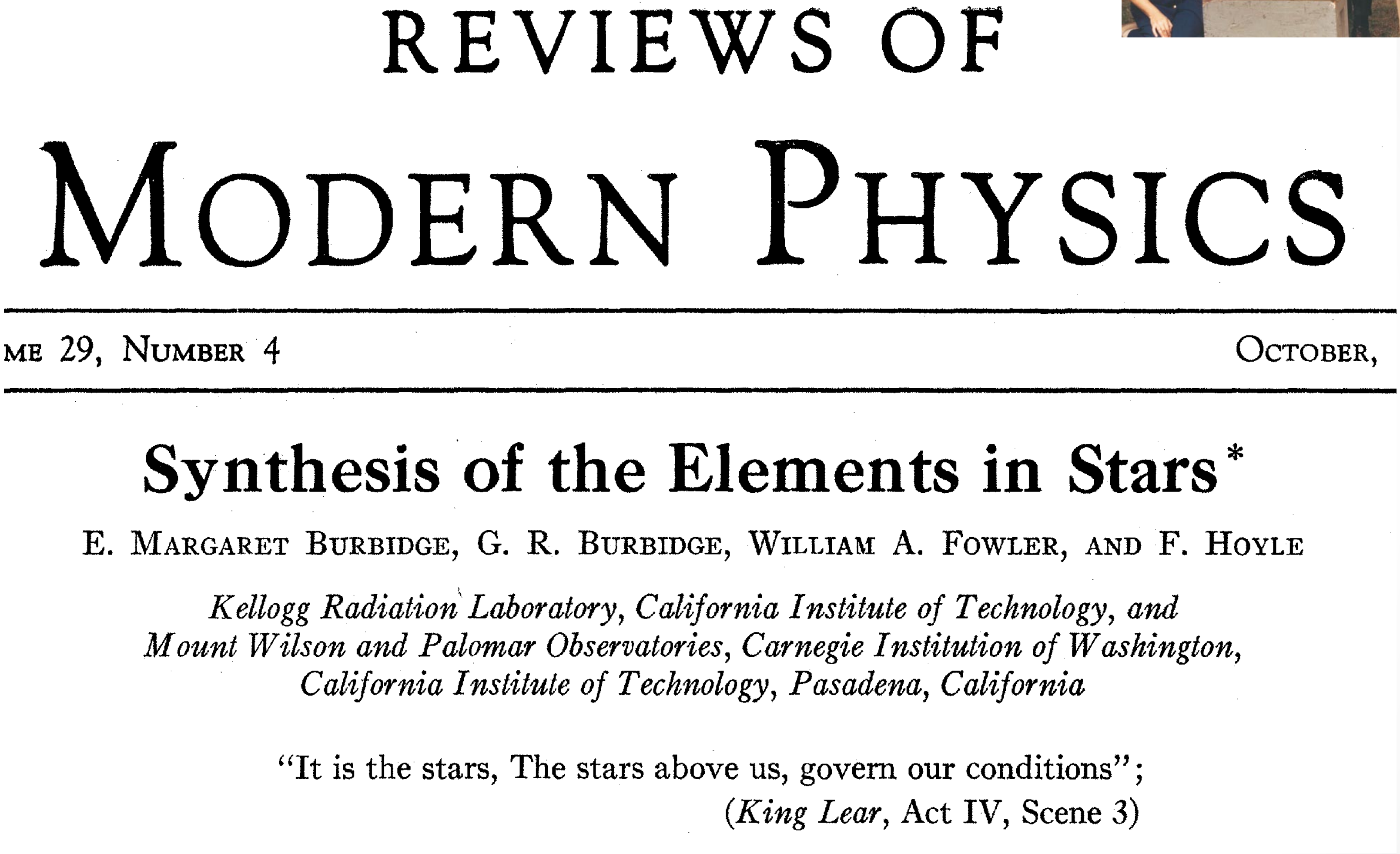


1859 Every chemical element has its own spectral lines
Kirchhoff



1925 Stars are mostly Hydrogen and Helium
Payne[-Gaposchkin]

The 1957 milestone



REVIEWS OF

MODERN PHYSICS

ME 29, NUMBER 4 OCTOBER,

Synthesis of the Elements in Stars*

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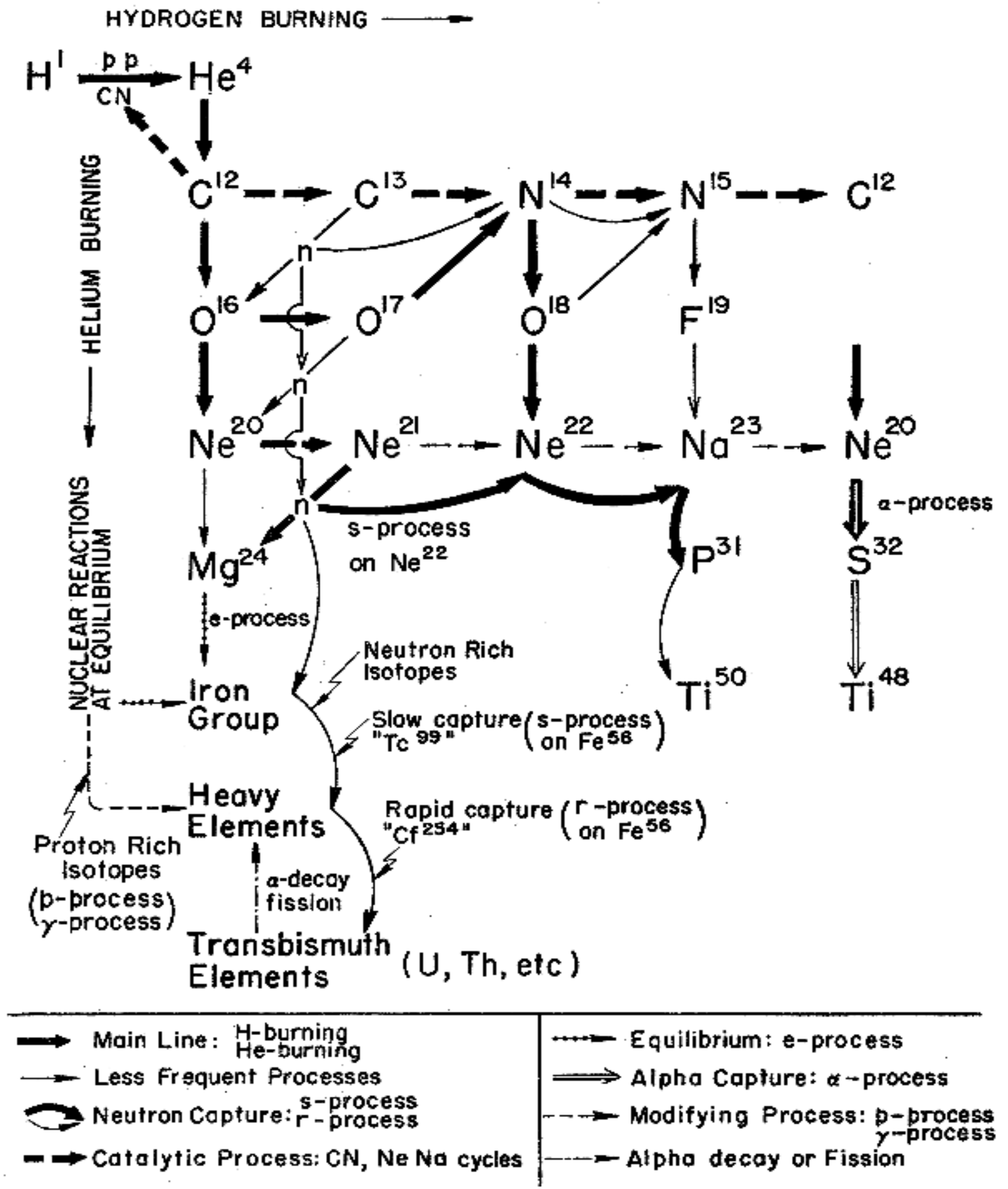
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

B^{2}FH – 1957

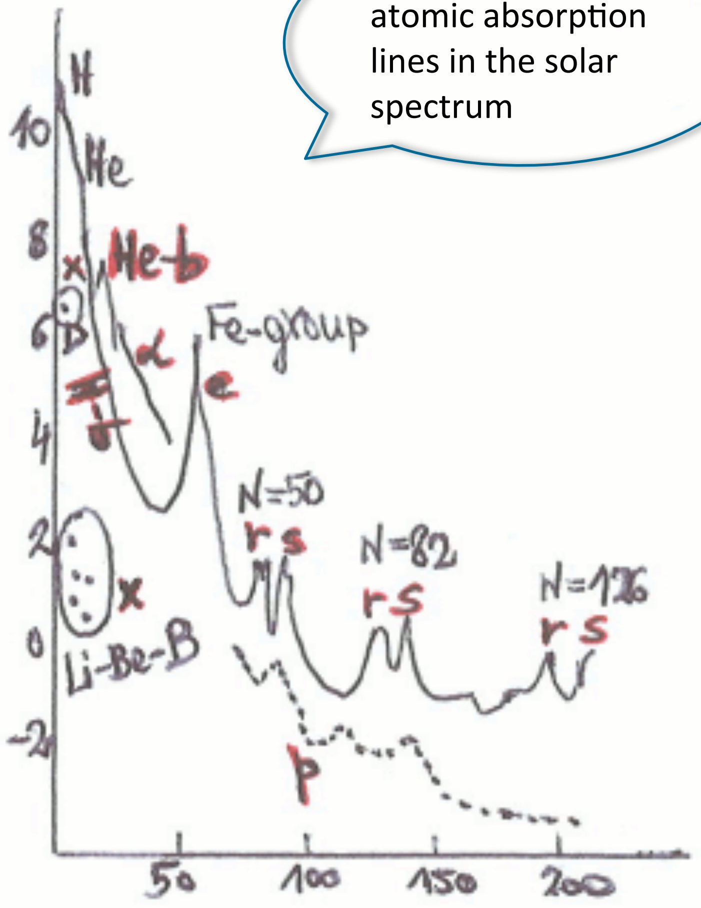

HYDROGEN BURNING
H¹
p p
CN
He⁴
HELIUM BURNING
C¹²
C¹³
N¹⁴
N¹⁵
C¹²
n
O¹⁶
O¹⁷
O¹⁸
F¹⁹
n
Ne²⁰
Ne²¹
Ne²²
Na²³
Ne²⁰
n
α-process
s-process
on Ne²²
Mg²⁴
P³¹
S³²
NUCLEAR REACTIONS
AT EQUILIBRIUM
e-process
Neutron Rich
Isotopes
Ti⁵⁰
Ti⁴⁸
Iron
Group
Slow capture (s-process on Fe⁵⁶)
"Tc 99"
Heavy
Elements
Rapid capture (r-process on Fe⁵⁶)
"Cf 254"
Proton Rich
Isotopes
(p-process γ-process)
α-decay
fission
Transbismuth
Elements
(U, Th, etc)
Main Line: H-burning He-burning
Less Frequent Processes
Neutron Capture: s-process r-process
Catalytic Process: CN, Ne Na cycles
Equilibrium: e-process
Alpha Capture: α-process
Modifying Process: p-process γ-process
Alpha decay or Fission

B^2FH – 1957

- Hydrogen burning: responsible for majority of energy production in stars – all cycles synthesizing He from H + isotopes of C,N,O,F,Ne and Na (not produced in He+α)
- Helium burning: responsible for synthesis of C from He + production of O^{16}, Ne^{20} and maybe Mg^{24} with extra α-s
- The α process: adding α particles to Ne^{20} to form Mg^{24}, Si^{28}, S^{32}, A^{36}, Ca^{40} (and probably Ca^{44} and Ti^{48})
- The *e* process: the equilibrium process (very high T and ρ) makes the iron-group (V,Cr,Mn,Fe,Co,Ni)
- The *s* process: n-capture with emission of (n,γ) on a long timescale (100yrs-10^5yrs/n-capture); 23<A<46 + good fraction of 63<A<209; abundance peaks at A=90,138 and 208
- The *r* process: n-capture on short timescales (0.01-10s); large fraction 70<A<209 + U,Th + some light isotopes; abundance peaks at A=80,130,194
- The *p* process: p-capture with emission of (p,γ) or (γ,n); responsible for p-rich isotopes, with very low abundances
- The ***x* process**: synthesis of D,Li,Be,B (unstable at $T_{int,}$ thus requiring regions of low T and ρ)

… and the νp process

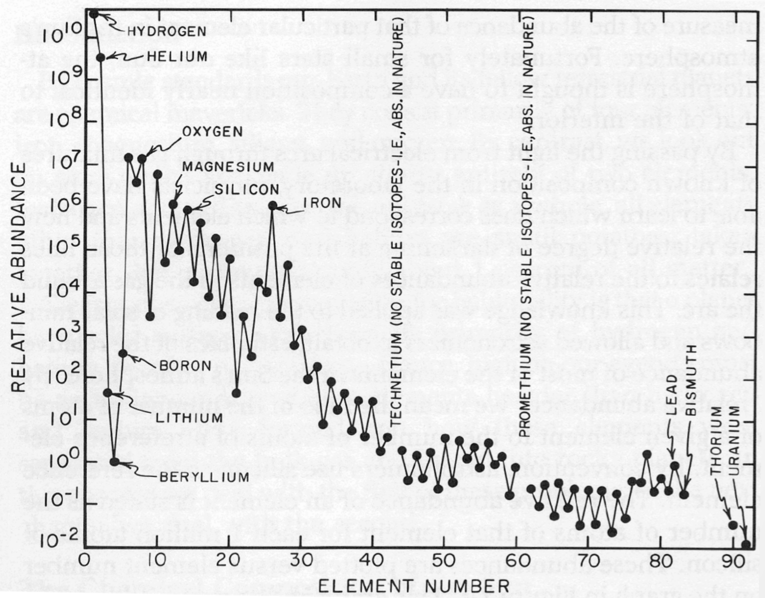
B^{2}FH: Atomic abundances curve as a function of atomic weight



from observation of atomic absorption lines in the solar spectrum

Notes

- H most abundant, then general decrease till U (least abundant)
- Big negative anomaly at Be, B, Li
- Moderate positive anomaly around Fe
- Sawtooth pattern from odd-even effect



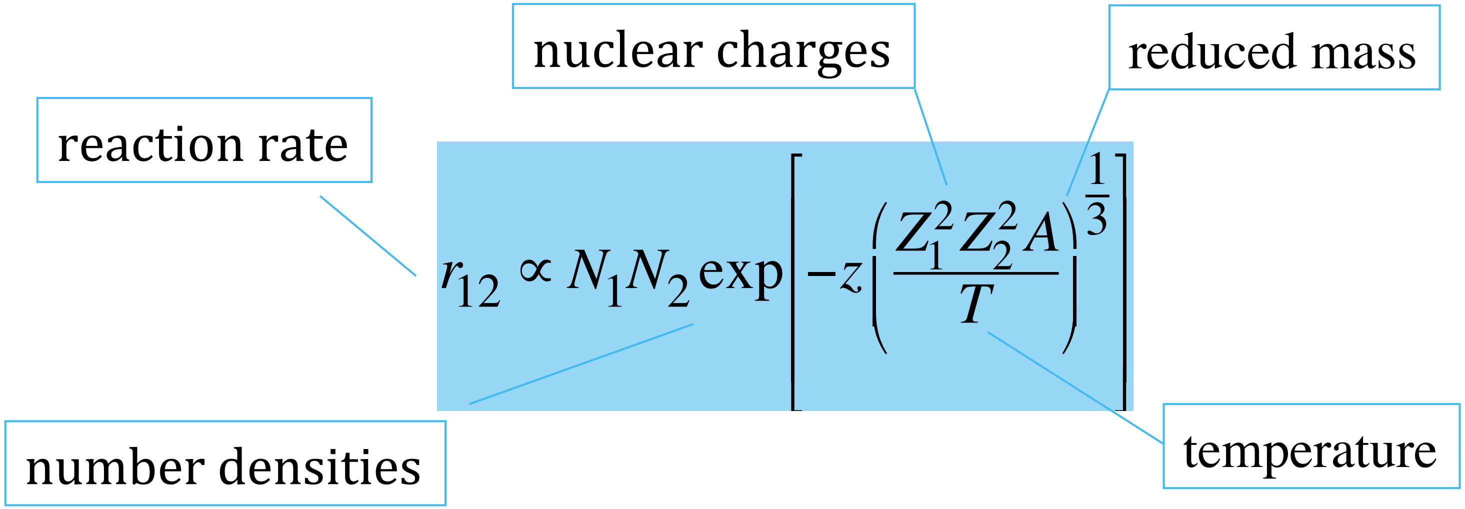
Successful model of nuclear origins needs to explain all these features in the abundance pattern!

Origin of atoms in the solar system

- Two sources of nuclei: nucleosynthesis in the **BIG BANG** and in **STARS**
- The Big Bang made only H and He (and some Li)
- All other nuclei are created/produced in stars, by 3 essential kinds of processes:
  - Nuclear burning (fusion): PP cycles, CNO bi-cycle, He-, C-, O-, Si-burnings … makes atoms up to ^{40}Ca, but no heavier
    - These processes happen in Main Sequence stars and in Red Giants
  - Photodisintegration: when thermal radiation reaches γ-ray energies it drives rapid nuclear rearrangements creating everything up to ^{56}Fe, but nothing heavier
  - Neutron irradiation: most nuclei heavier than ^{56}Fe are generated by neutron-captures, which follow two paths depending on *n*-flux:
    - The *s-process*, in which neutron addition is **s**low compared to b-decay
    - The *r-process*, in which neutron addition is **r**apid compared to b-decay (only in SN)
  - Proton irradiation: some low-abundance nuclei are made by an *s*-process-like addition of protons rather than neutrons (*p*-process)

Stellar Nucleosynthesis

- Until stars form, there is nothing except H and He (and some Li)
- Gravitational instabilities develop which lead to formation of galaxies and collapse of molecular clouds to form stars
- At sufficient temperature and density (~10^7 K), nuclear fusion begins in star cores
- Due to Coulomb repulsion between positively charged nuclei, non-resonant nuclear reaction rates obey a law of the form:



$$r_{12} \propto N_1 N_2 \exp\left[-z\left(\frac{Z_1^2 Z_2^2 A}{T}\right)^{\frac{1}{3}}\right]$$

reaction rate

nuclear charges

reduced mass

number densities

temperature

So reaction is fastest between most abundant, least charged pairs of nuclei, and increase in T is needed to make slower reactions significant

Hydrostatic H-burning

Sun (T=15.6 MK), stellar core (T=8-55 MK),
shell of AGB stars (T=45-100 MK)

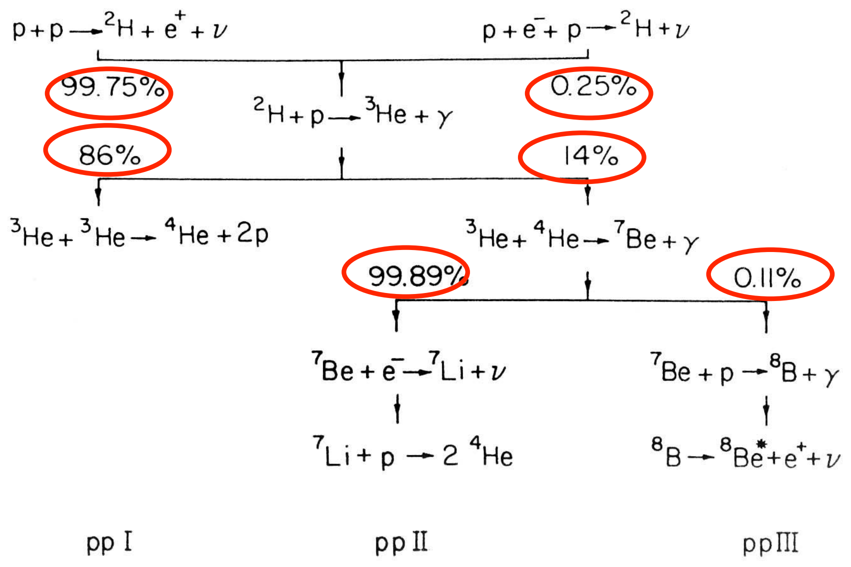
- At the starts, none of the 2-particle reactions between H and He is stable:
  - $^{1}H + {}^{1}H = {}^{2}He$ (unstable) $= {}^{1}H + {}^{1}H$
  - $^{1}H + {}^{4}He = {}^{5}Li$ (unstable) $= {}^{1}H + {}^{4}He$
  - $^{4}He + {}^{4}He = {}^{8}Be$ (unstable) $= {}^{4}He + {}^{4}He$
- 1939: Hans Bethe shows how H-burning can begin with the <u>exothermic</u> formation of D:
  - $^{1}H + {}^{1}H = {}^{2}D + \beta^{+} + \nu + 1.442$ MeV
- This reaction initiates the PP-I chain:

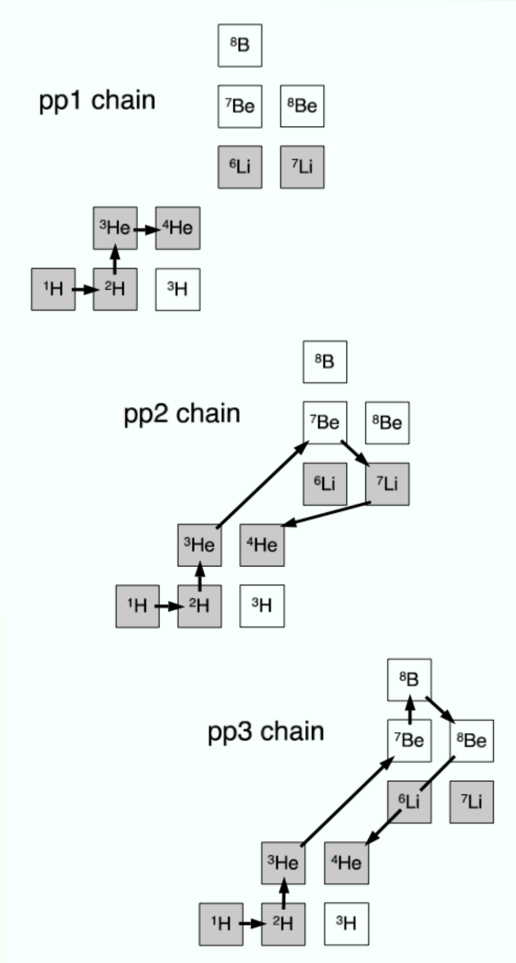
$$\boxed{\begin{array}{c} 2\,({}^{1}H + {}^{1}H = {}^{2}D + \beta^{+} + \nu) \\ 2\,({}^{1}H + {}^{2}D = {}^{3}He + \gamma) \\ {}^{3}He + {}^{3}He = {}^{4}He + 2\,{}^{1}H \\ \hline \text{Net: } 4\,{}^{1}H = {}^{4}He + 2\,\nu + \gamma \end{array}}$$

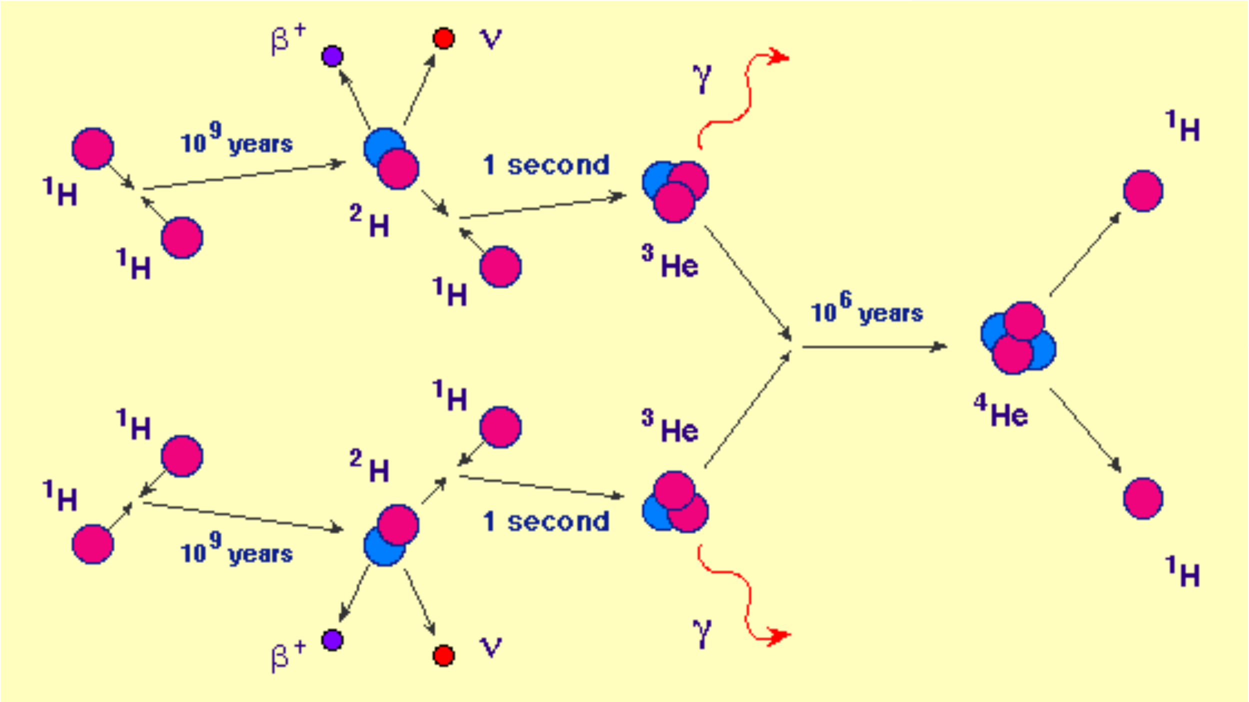
+ 26.7 MeV

$^{2}D/^{1}H$ quickly approaches equilibrium value, but 10^{13} times << than the terrestrial value…

PP-chain: main reactions, importance, lifetimes

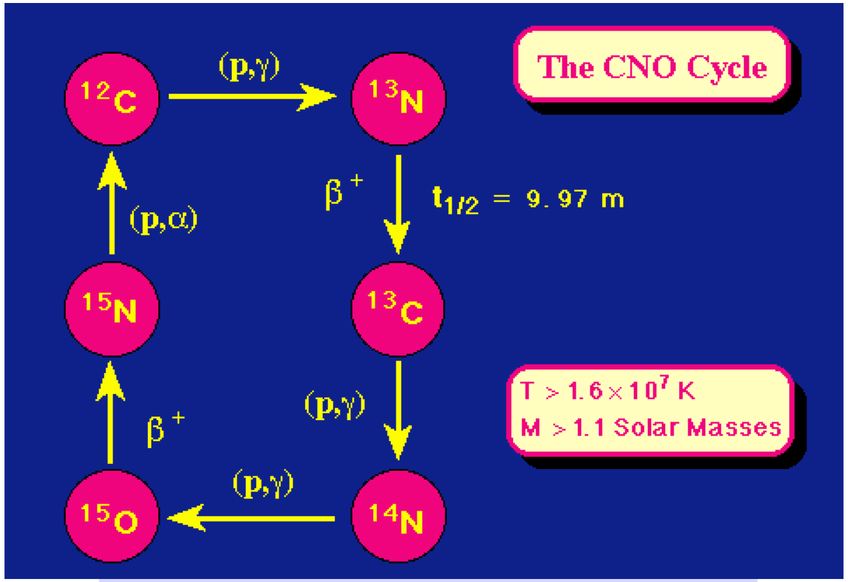






90% of Sun’s energy produced by pp1 chain

CNO-cycle



$^{15}N(p,\gamma)^{16}O \qquad ^{16}O(p,\gamma)^{17}F$

$^{17}F \rightarrow ^{17}O + e^+ + \nu$

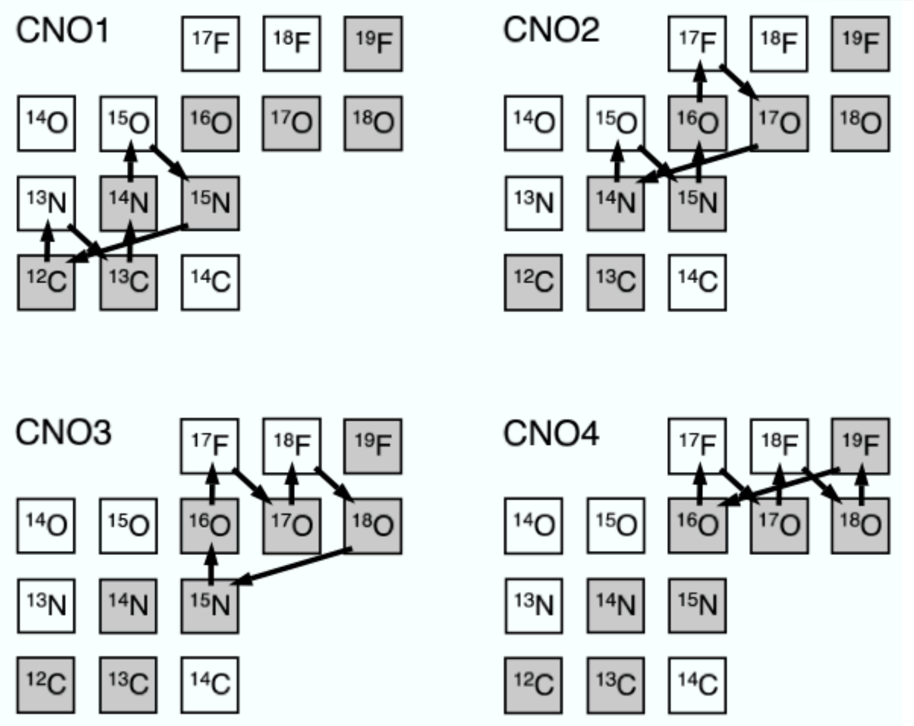
$^{17}O(p,\alpha)^{14}N \quad \rightarrow \quad \text{refuels CN}$

$^{17}O(p,\gamma)^{18}F$

$^{18}F \rightarrow ^{18}O + e^+ + \nu$

$^{18}O(p,\alpha)^{15}N \quad \rightarrow \quad \text{refuels CN}$

$^{18}O(p,\gamma)^{19}F \qquad ^{19}F(p,\alpha)^{16}O$

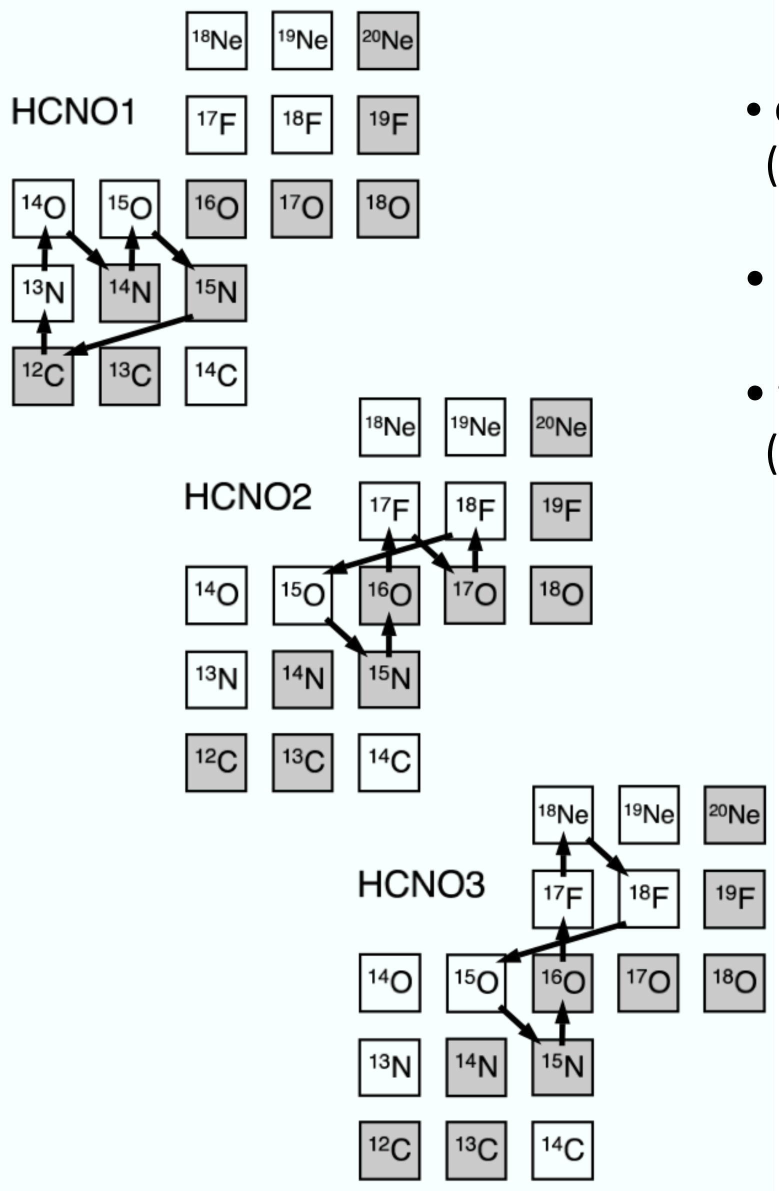


- T>20 MK: CNO1 faster than pp1

CNO cycles in AGB stars: main source of ^{13}C and ^{14}N in Universe

Explosive H-burning

Classical novae (T=100-400 MK)



- energy generation depends on β-decays ("β-limited CNO cycle")
- most abundant nuclides: ^{14}O, ^{15}O
- time for one HCNO1 cycle: 278 s (operates far from equilibrium)

He-burning

- If ^1H becomes so depleted that $^1H+^1H$ collisions become too rare to drive PP-I chain fast enough to maintain thermal pressure (after ~10^6 yr in a red giant star), the core collapses, temperature rises and at ~2×10^8 K, He-burning becomes possible

- It's a 2-steps reaction: $^4He + ^4He \rightarrow ^8Be$

  requires particle velocities high enough that the reaction rate

$$^4He + ^8Be = ^{12}C + \gamma$$

  exceeds the decay rate of ^8Be (half-life 2.6×10^{-16} s!), despite the large Coulomb repulsion: $Z_1^2 Z_2^2 = 64$

When ^4He runs out, another core collapse heats up the core enough to initiate C-burning
This continues up through Si-burning
This type of nuclear burnings produce all the α-particle nuclides: ^4He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca
Smaller quantities of ^{14}N, ^{15}N, ^{13}C, Na, P also result
Explains excesses of α-particle nuclei up to ^{40}Ca, if solar system contains matter expelled from red giants

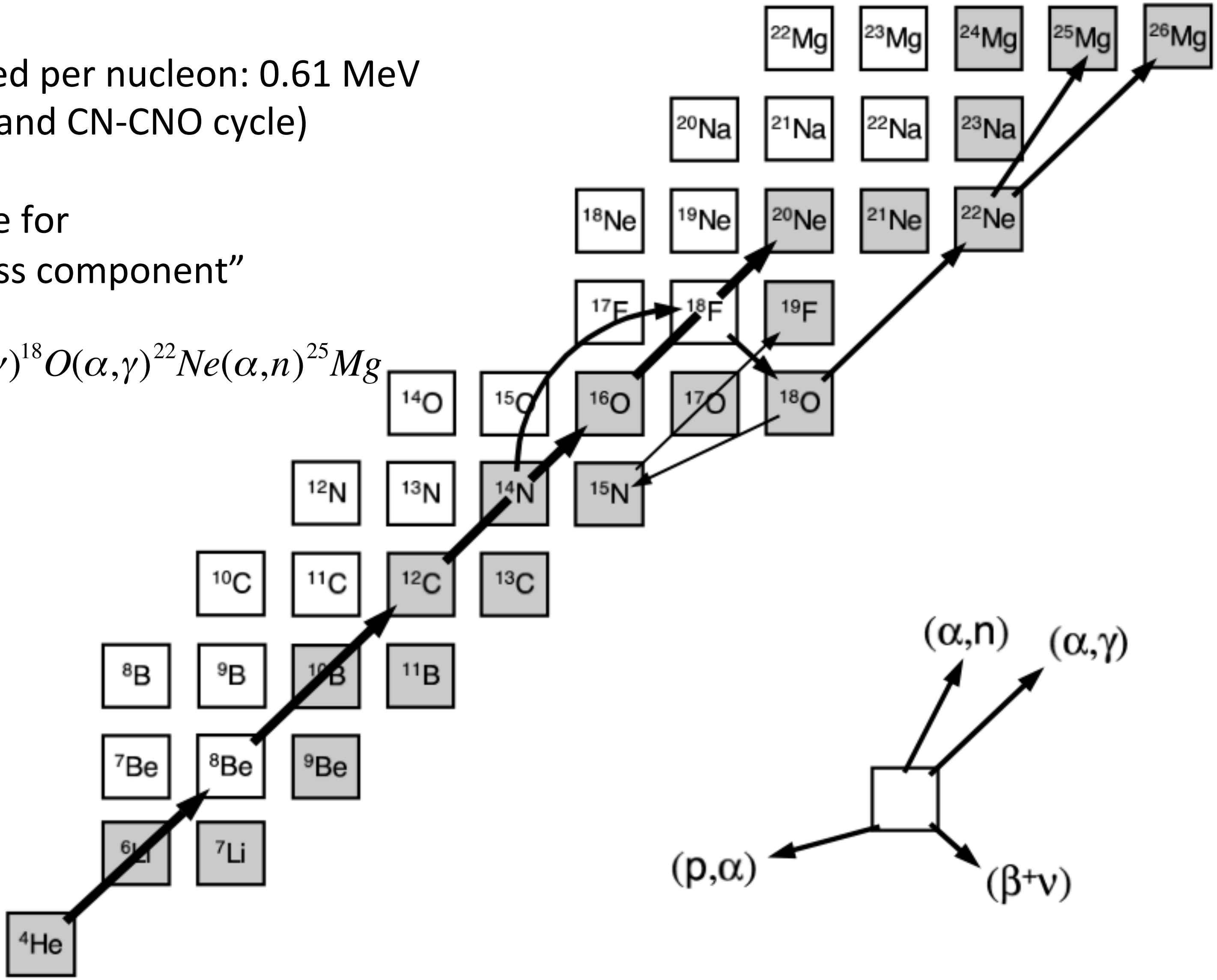
He-burning: 3α→ C

Massive stars (T=100-400 MK)

Energy liberated per nucleon: 0.61 MeV
(~1/12 of PP-I and CN-CNO cycle)

neutron source for
“weak s-process component”

$$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$$

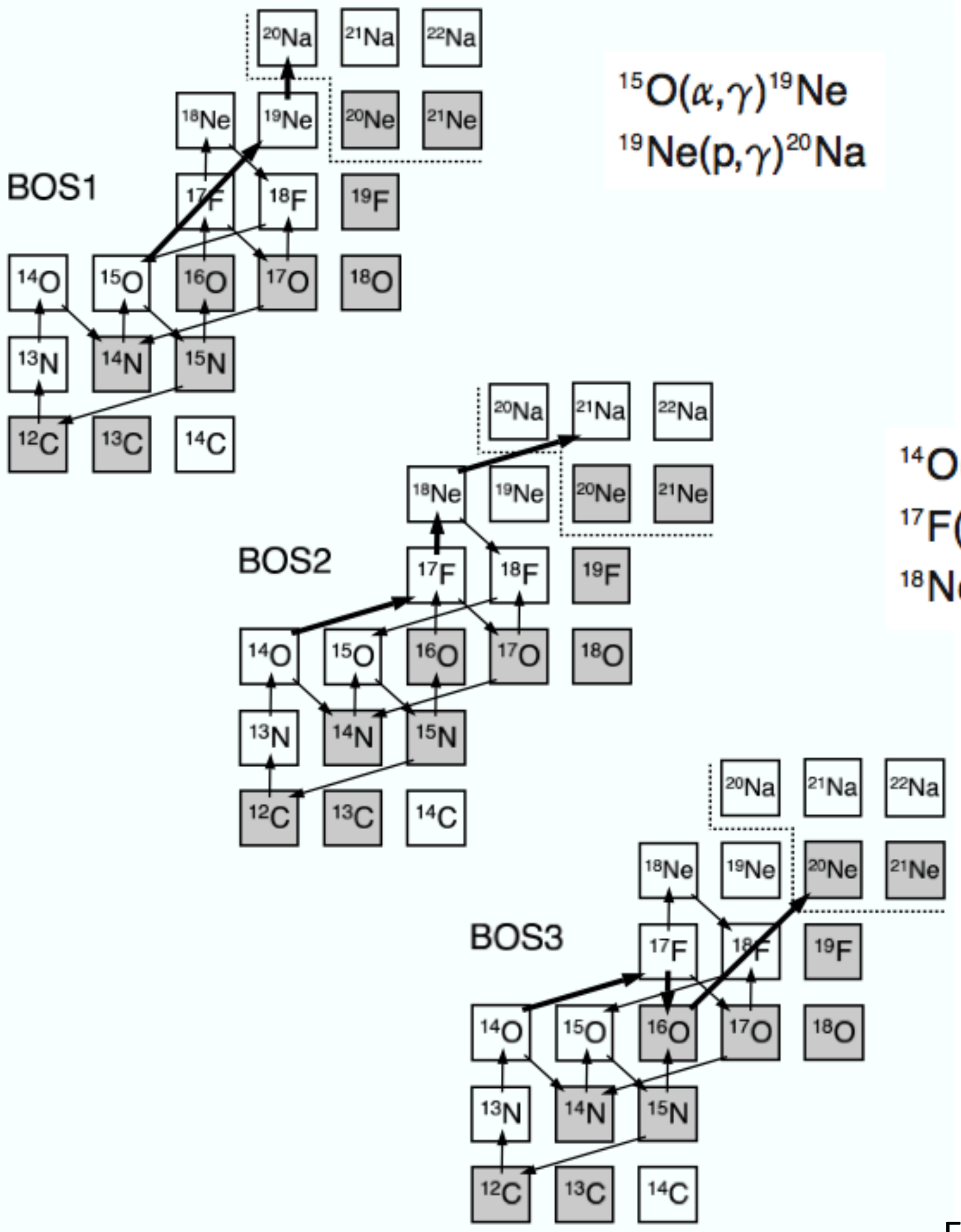


Main source of ^{12}C, ^{16}O, ^{18}O, ^{22}Ne in Universe

Explosive He-burning

Type I X-ray bursts (T>500 MK)

BOS = Break-Out Sequence



$^{15}O(\alpha,\gamma)^{19}Ne$

$^{19}Ne(p,\gamma)^{20}Na$

$^{14}O(\alpha,p)^{17}F$

$^{17}F(p,\gamma)^{18}Ne$

$^{18}Ne(\alpha,p)^{21}Na$

$^{14}O(\alpha,p)^{17}F$

$^{17}F(\gamma,p)^{16}O$

$^{16}O(\alpha,\gamma)^{20}Ne$

Experiments with radioactive ion beams

C-burning

core (T=0.6-1.0 GK)
ρ=10^5 g/cm^3

- Primary reactions

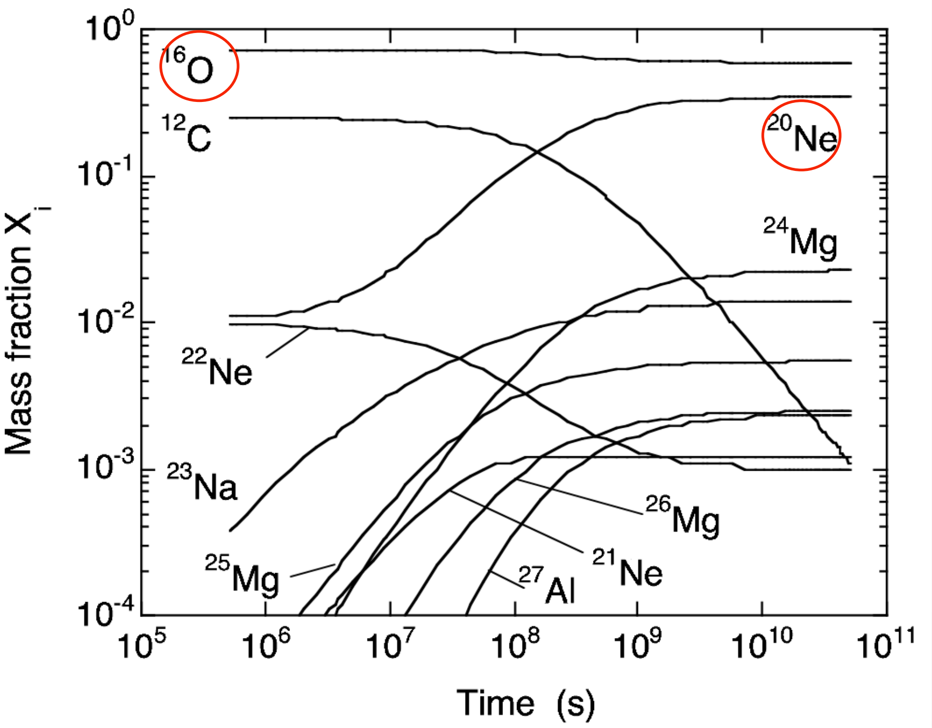
$^{12}C(^{12}C,p)^{23}Na$	2.23MeV
$^{12}C(^{12}C,\alpha)^{20}Ne$	4.62MeV
$^{12}C(^{12}C,n)^{23}Mg$	-2.60MeV
$^{12}C(^{12}C,\gamma)^{24}Mg$	13.93MeV
$^{12}C(^{12}C,\alpha)^{24}Mg$	4.68MeV

+ several secondary reactions
$^{25}Mg(p,\gamma)^{26}Al$

- Companion reactions:
  - $^{12}C(^{4}He,\gamma)^{16}O$
  - $^{16}O(^{4}He,\gamma)^{20}Ne$
  - $^{20}Ne(^{4}He,\gamma)^{24}Mg$

- Ashes: ^{16}O, ^{20}Ne

New p, n and α-particles are created
Heavy elements start being synthesized



Important source of $^{20,21}Ne$, ^{23}Na, ^{24}Mg, ^{27}Al in Universe

Ne-burning (photo-dissociation)

core (T=1.2-1.8 GK)
$\rho=5\times10^6$ g/cm^3

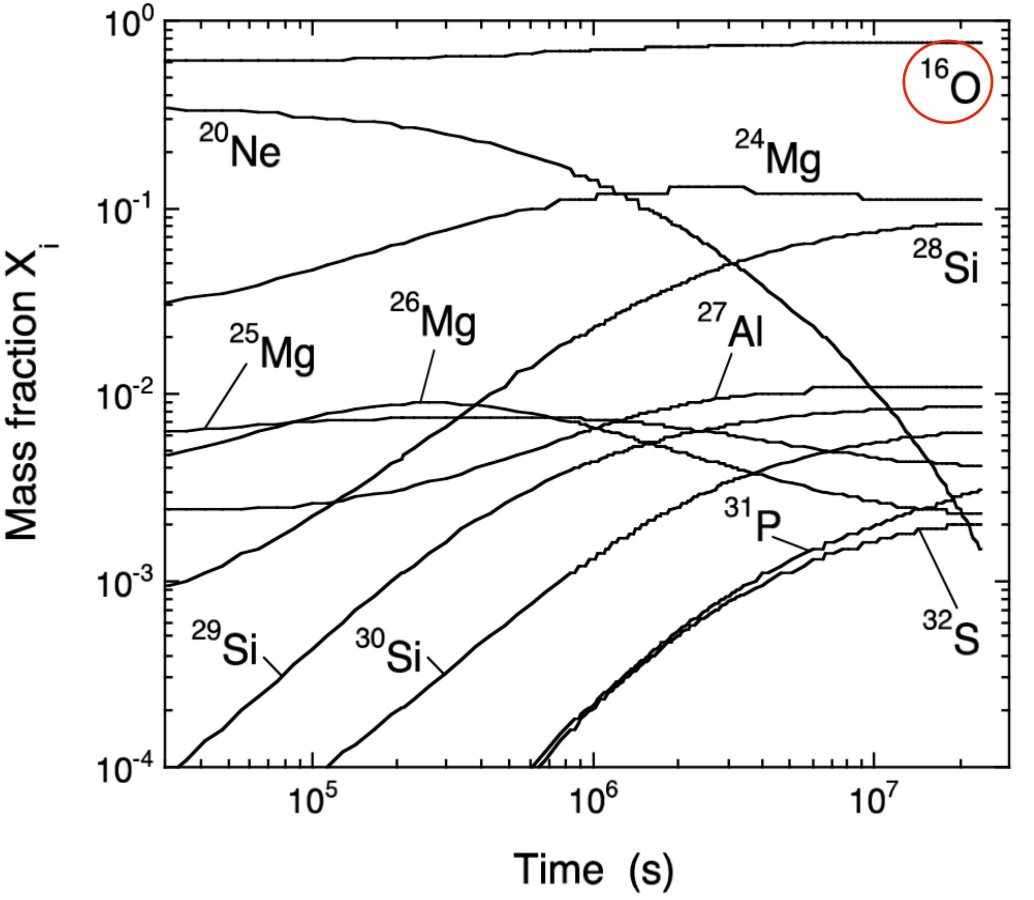
It proceeds by a combination of photo-disintegrations and α captures

- Primary reaction
  - $^{20}Ne(\gamma,\alpha)^{16}O$ (Q=-4.73 MeV)

- Secondary reactions
  - $^{20}Ne(\alpha,\gamma)^{24}Mg(\alpha,\gamma)^{28}Si$

  + more

- Ashes: ^{16}O



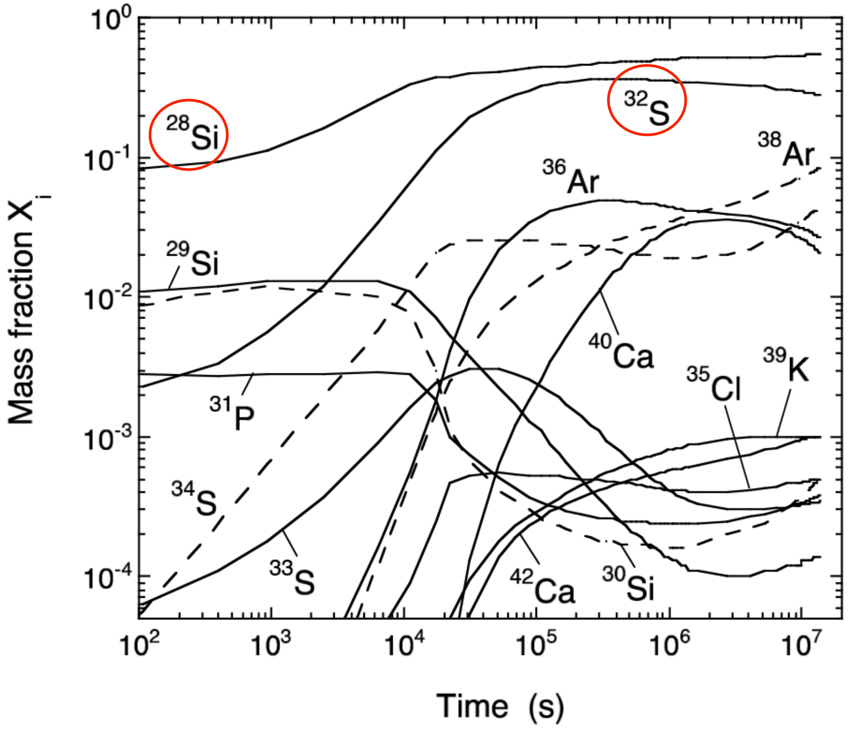
For the first time photo-dissociation becomes important

O-burning

core (T=1.5-2.7 GK)
$\rho=3\times10^6$ g/cm^3

- Primary reactions

$^{16}O(^{16}O,\gamma)^{32}S$	16.539MeV
$^{16}O(^{16}O,p)^{31}P$	7.676MeV
$^{16}O(^{16}O,n)^{31}S$	1.459MeV
$^{16}O(^{16}O,\alpha)^{28}Si$	9.593MeV
$^{16}O(^{16}O,2\alpha)^{24}Mg$	-0.393MeV
$^{16}O(^{16}O,2p)^{30}Si$	0.424MeV



- Followed by
  - $^{31}P(p,\alpha)\,^{28}Si$
  - $^{24}Mg(\alpha,\gamma)\,^{28}Si$
  - $^{28}Si(\alpha,\gamma)\,^{32}S$

- Ashes: ^{28}Si, ^{32}S

Si-burning

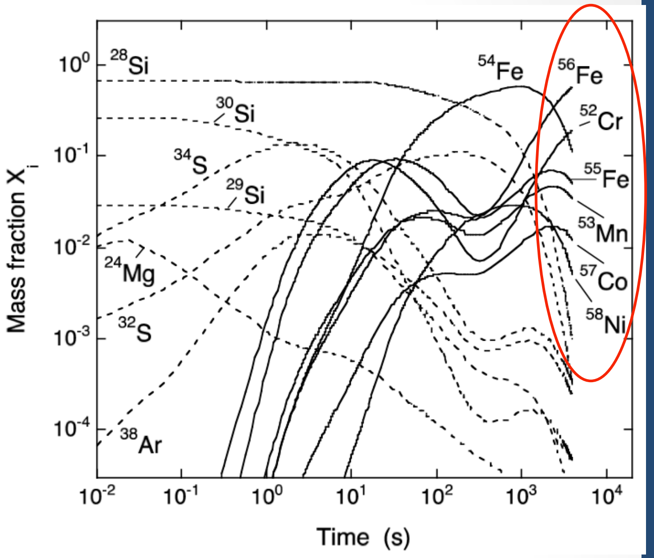
core (T=2.8-4.1 GK)
$\rho=3\times10^7$ g/cm^3

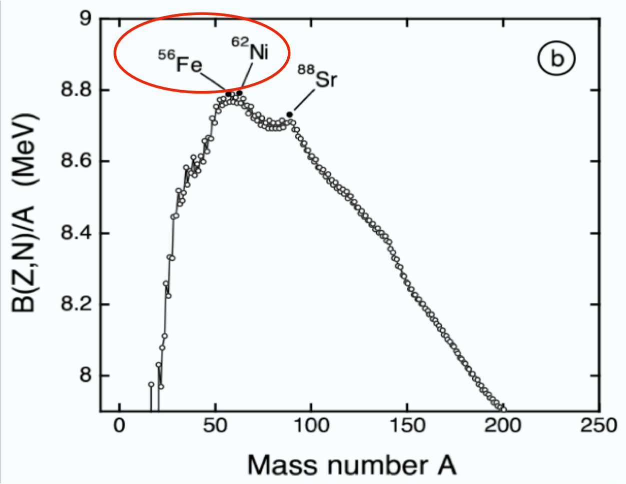
“Photodisintegration rearrangement”

- Destruction of less tightly bound species and capture of released p, n, α to synthesize more tightly bound species
- It begins with:

  ^{28}Si(γ,α)^{24}Mg(γ,α)^{20}Ne(γ,α)…

- A sort of equilibrium condition is established in which Si is converted into elements of the Fe-group (for which the binding energy/nucleon is maximum)
- Ashes: ^{56}Fe … “iron peak”

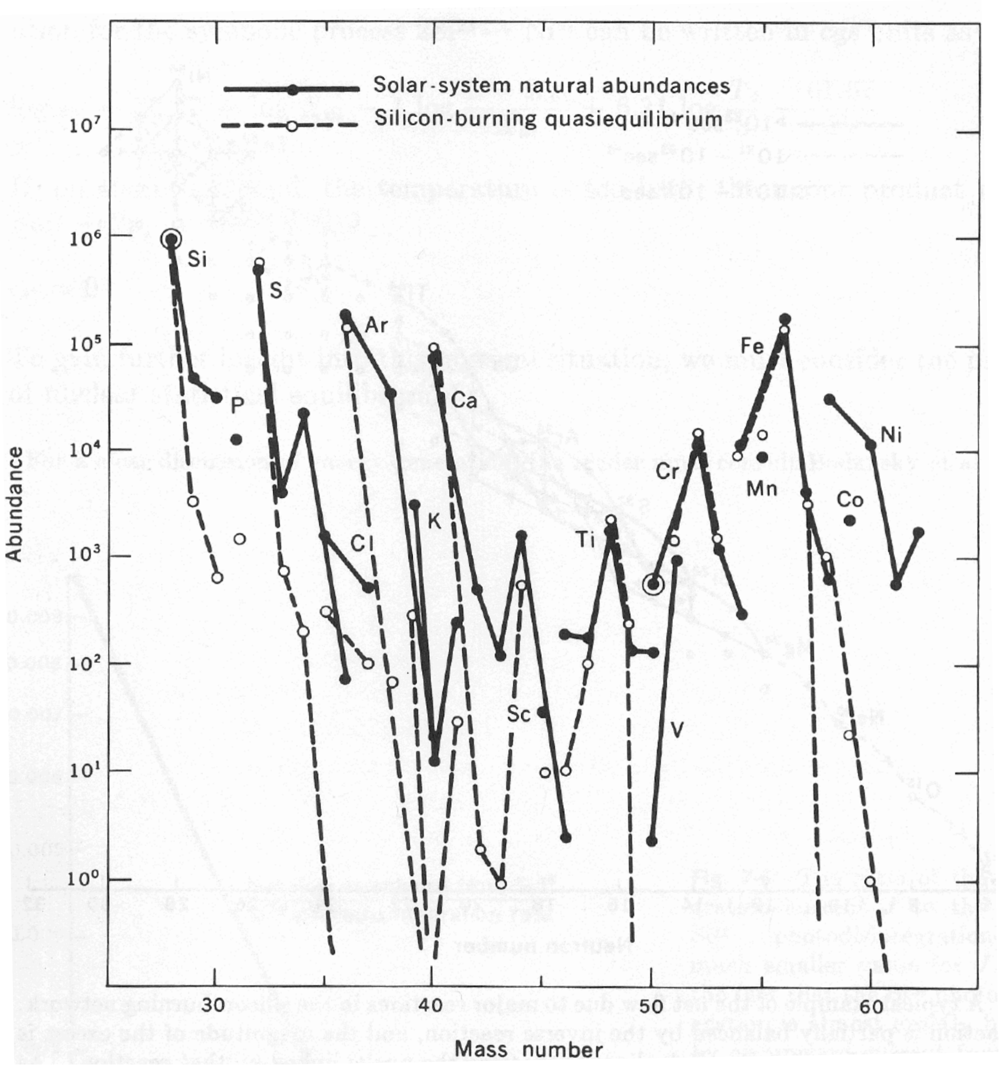




End of the nuclear exo-energetic history of a star
End of nuclear reactions as large scale energy sources

Nuclear Statistical Equilibrium

Approach to nuclear statistical equilibrium makes definite predictions about abundance of species in the Si-to-Fe range, and provides a natural mechanism for the high nuclear binding energy of the Fe group to be translated into the peak in the solar abundance pattern



Abundance of any nuclide in NSE is determined by:

temperature, density, n-excess

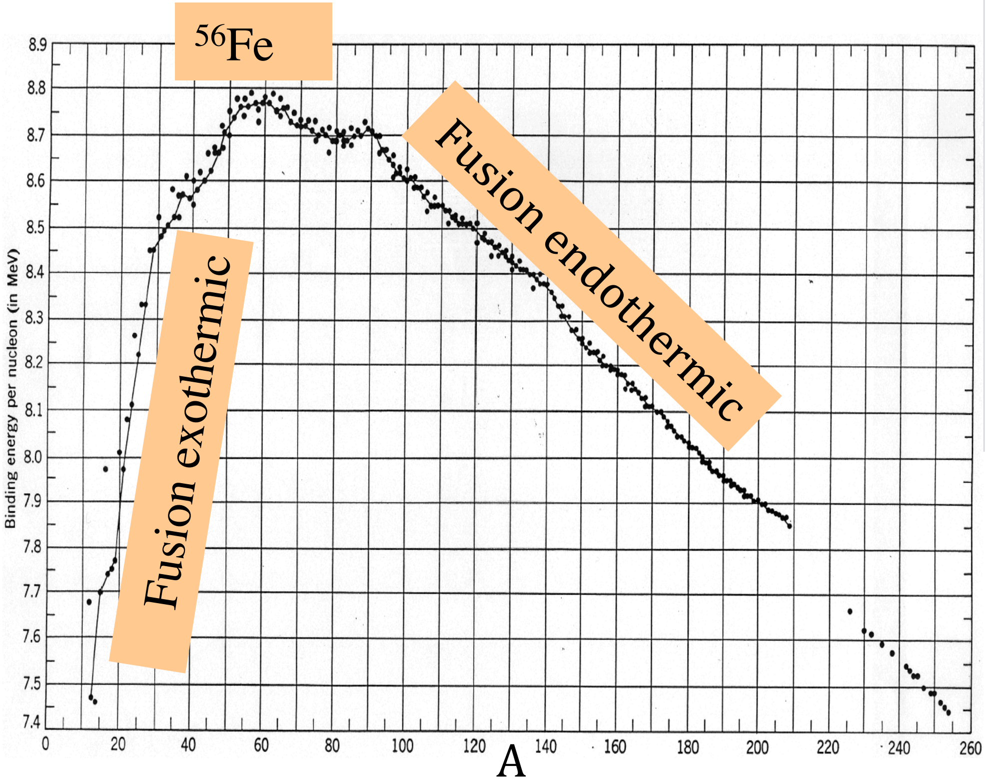
$$\eta \equiv \sum_i \frac{(N_i - Z_i)}{M_i} X_i$$

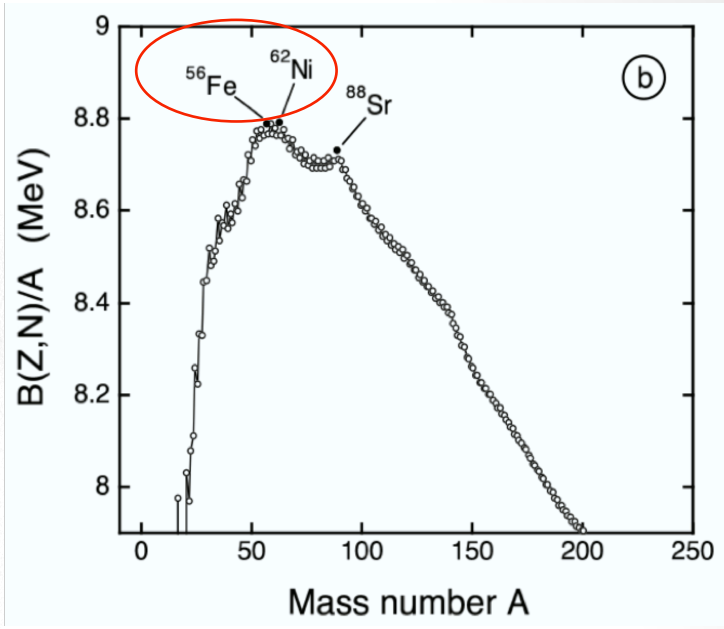
N_i, Z_i, M_i : number of n, p; atomic mass

M_i, X_i : atomic mass, mass fraction

MODEL: prediction of abundance pattern after 10s of Si-burning at $T \sim 4.2 \times 10^9$ K

Nuclear binding energy





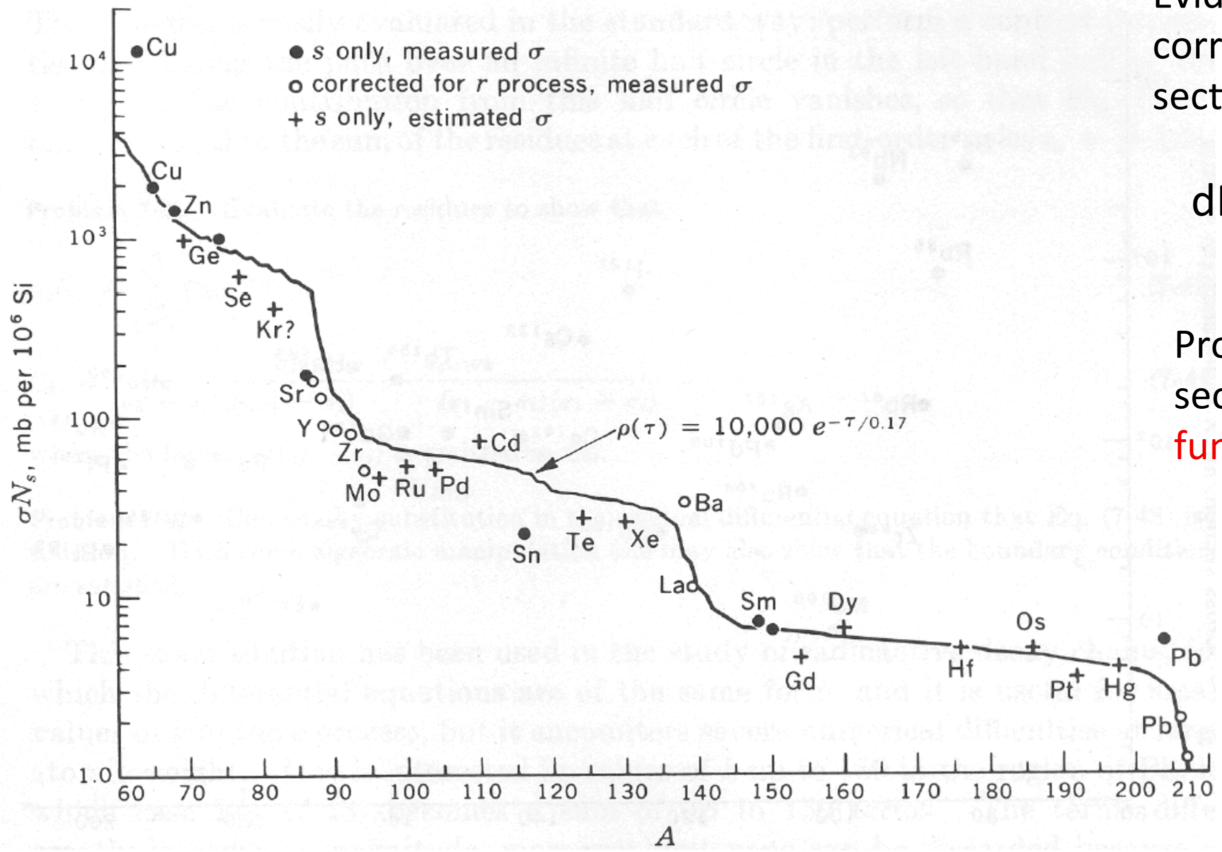
In principle, nuclear burning by fusion can continue only up to ^{56}Fe, the nucleus with the greatest binding energy per nucleon.

H-burning is by far the most effective means of converting mass into energy!

Neutron captures

- Although Coulomb repulsion prevents reactions between massive charged nuclei at solar temperatures, *neutrons* have no charge and neutron capture reactions can proceed even at room temperature

- When nuclear reactions in stars liberate a flux of *neutrons*, they are captured by nuclei in proportion to their *neutron capture cross-section*



Evidence comes from abundance correlation with *n*-capture cross-section:

$$dN_A/d\tau = -\sigma_A N_A + \sigma_{A-1} N_{A-1}$$

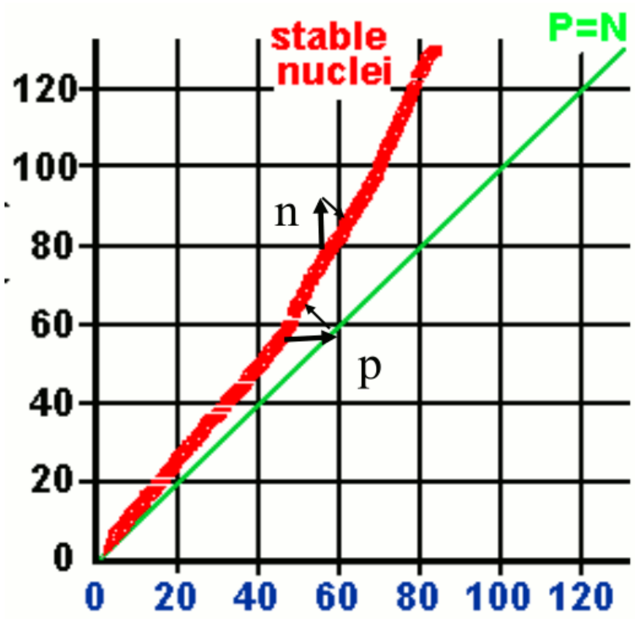
Product of abundance and cross-section σN is a smoothly varying function

Neutron capture processes

- If neutron flux is slow compared to β-decay times, nuclei follow the valley of stability and make *s*-process nuclei

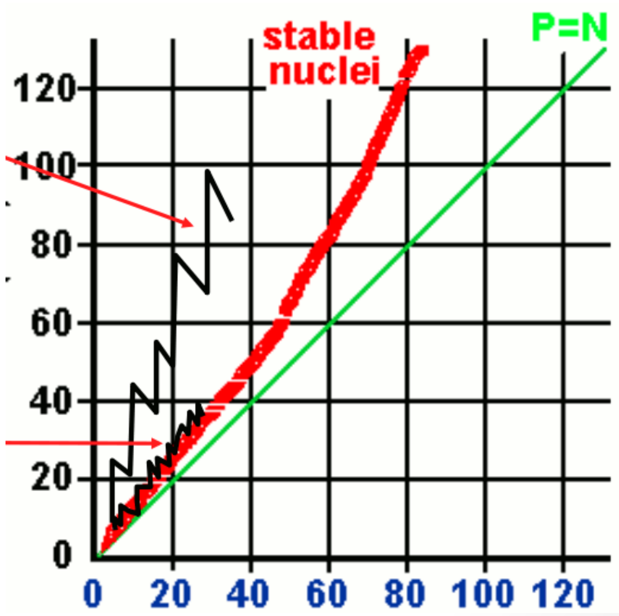
- If neutron flux is so fast that repeated captures occur before β-decay, nuclei on the neutron dripline (where the capture rate goes to zero) are made, which subsequently decay back to first stable nuclide on each isobar. These make the *r*-process (*r* = rapid)
  - These require energy and occur only at high T and ρ:

Core+shell burning	p- & s-process
Supernovae	p- & r-process



r-process departs from stability valley

s-process



s- and *r*-processes

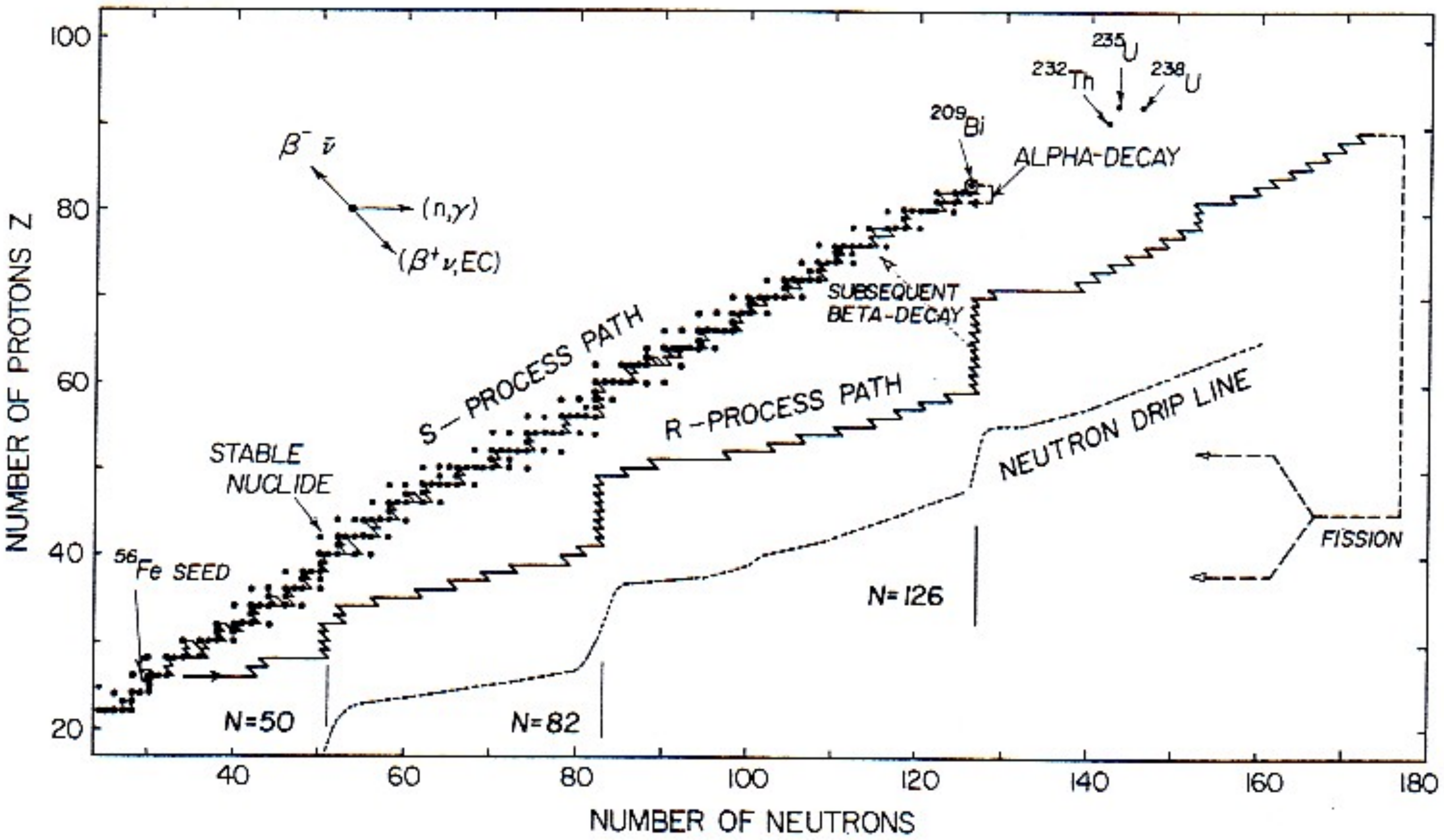


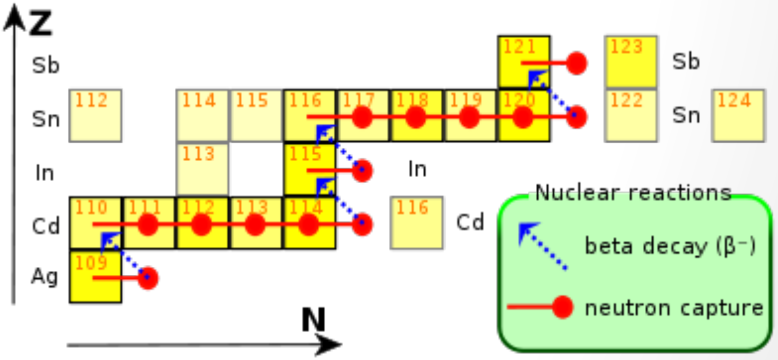
Fig. 6.9. Neutron capture paths in the N, Z plane. The r-process path was calculated for a temperature of 10^9 K and a neutron density of 10^{24} cm^{-3} (Seeger, Fowler & Clayton 1965). The dotted curve shows a possible location of the neutron drip line after Uno, Tachibana & Yamada (1992). Adapted from Rolfs & Rodney (1988).

s-process basics

- Neutron densities in the order of 10^{6}-10^{11}cm^{-3}
- Neutron capture rates much lower than beta decay rates
- After each neutron capture, the product nucleus has time to decay if it is unstable
- Moves along the valley of stability: n-captures increase the mass number through (n,γ) reactions
- Process timescales in the order of years
- Final abundances depend on the site observed

- The s-process network goes up to ^{209}Bi. As there are no stable nuclei with A>209, neutron capture will lead back to the previous *s*-process elements by alpha decay of the capture products

- Magnic neutron numbers produce three major peaks in the abundance distribution:
  - N=50 (Sr/Y/Zr): “ls” (light-s) peak
  - N=82 (Ba/La/Ce/Pr/Nd): “hs” (heavy-s) peak
  - N=126 (Pb/Bi) : Pb peak



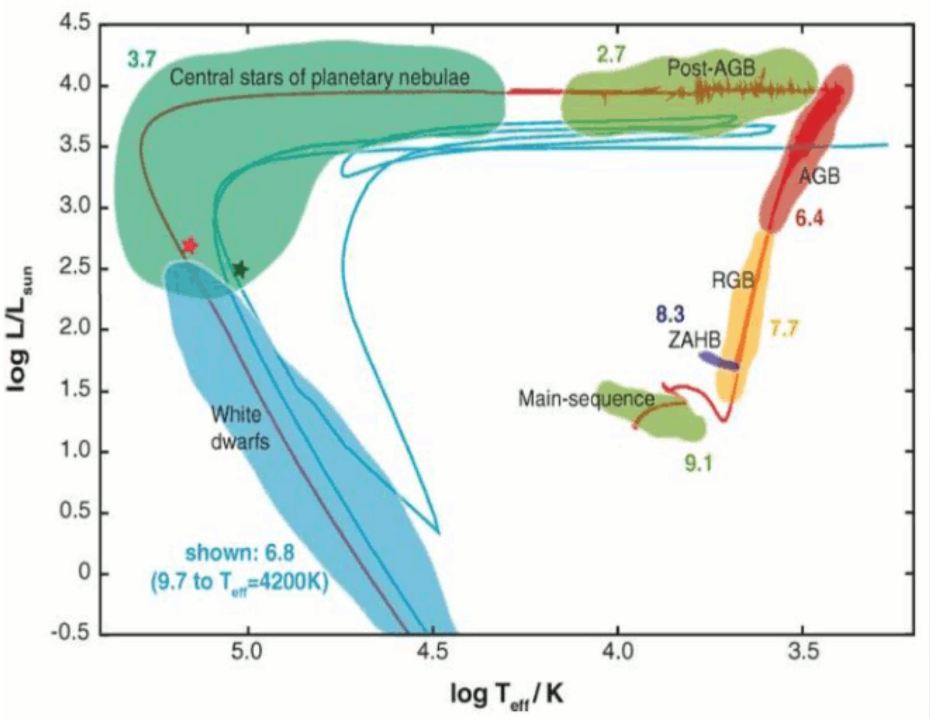
s-process components and sites

- Weak component: in massive stars during He/C core burning
  - Neutron source: 22Ne(α,n)25Mg
  - Reaches up to A<80
- Main component: in thermally pulsating AGB stars
  - Majority of observed abundances
  - Neutron sources: ^{13}C(α,n)^{16}O; ^{22}Ne(α,n)^{25}Mg

AGB: Asymptotic Giant Branch

M ~1.8 M $_{\text{sun}}$

after H/He-core burnings are exhausted

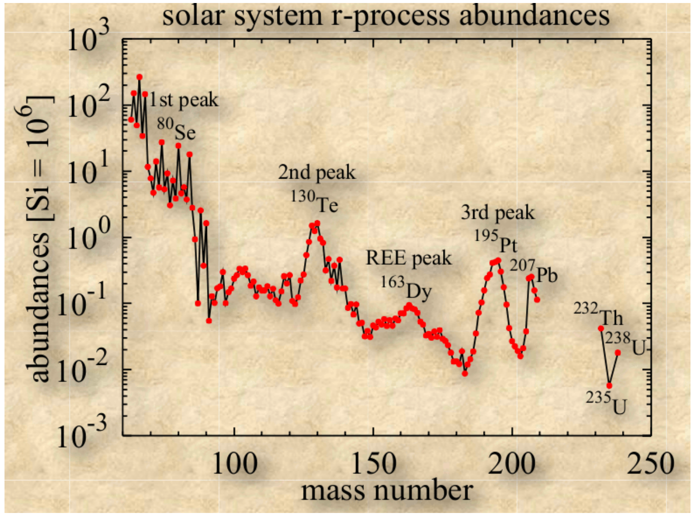


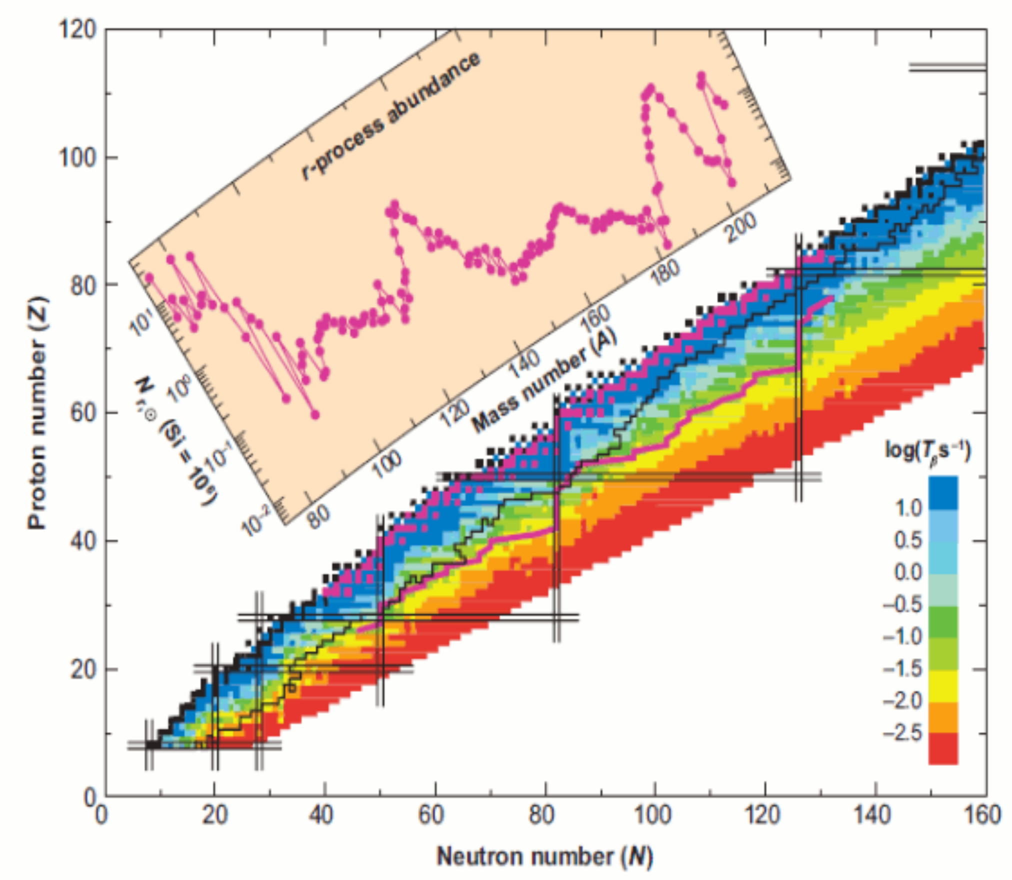
Source: Goblirsch 2010

r-process basics

- High neutron densities ($>10^{20}$cm^{-3}) → sites!
- Very short time scales (seconds)
- Moves on the neutron rich side of the valley of stability

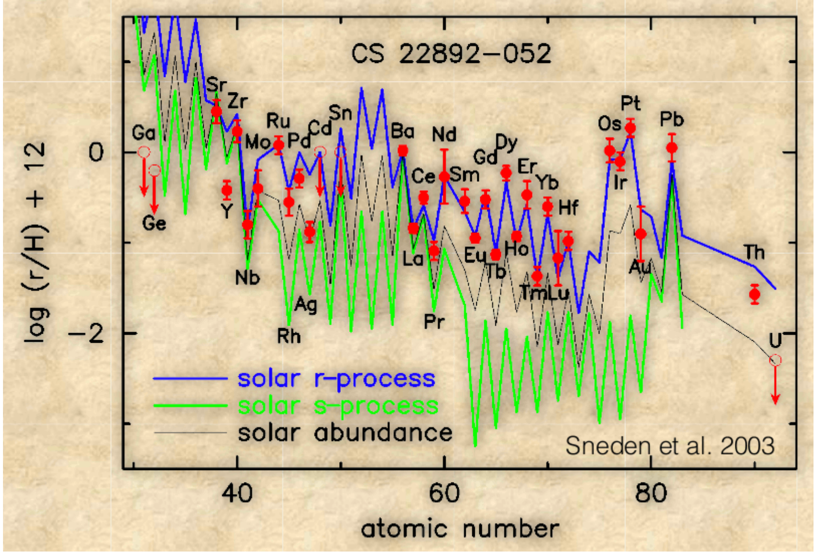
- Stable nuclides reached through beta decay chains after the neutron exposure

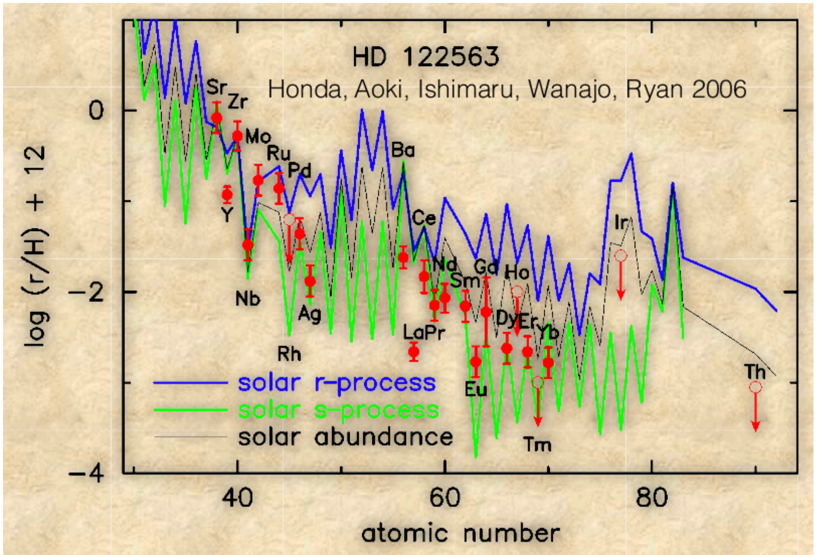




Source: Wanajo 2011

r-process





Final abundances very uniform
in ‘all’ stars

but …

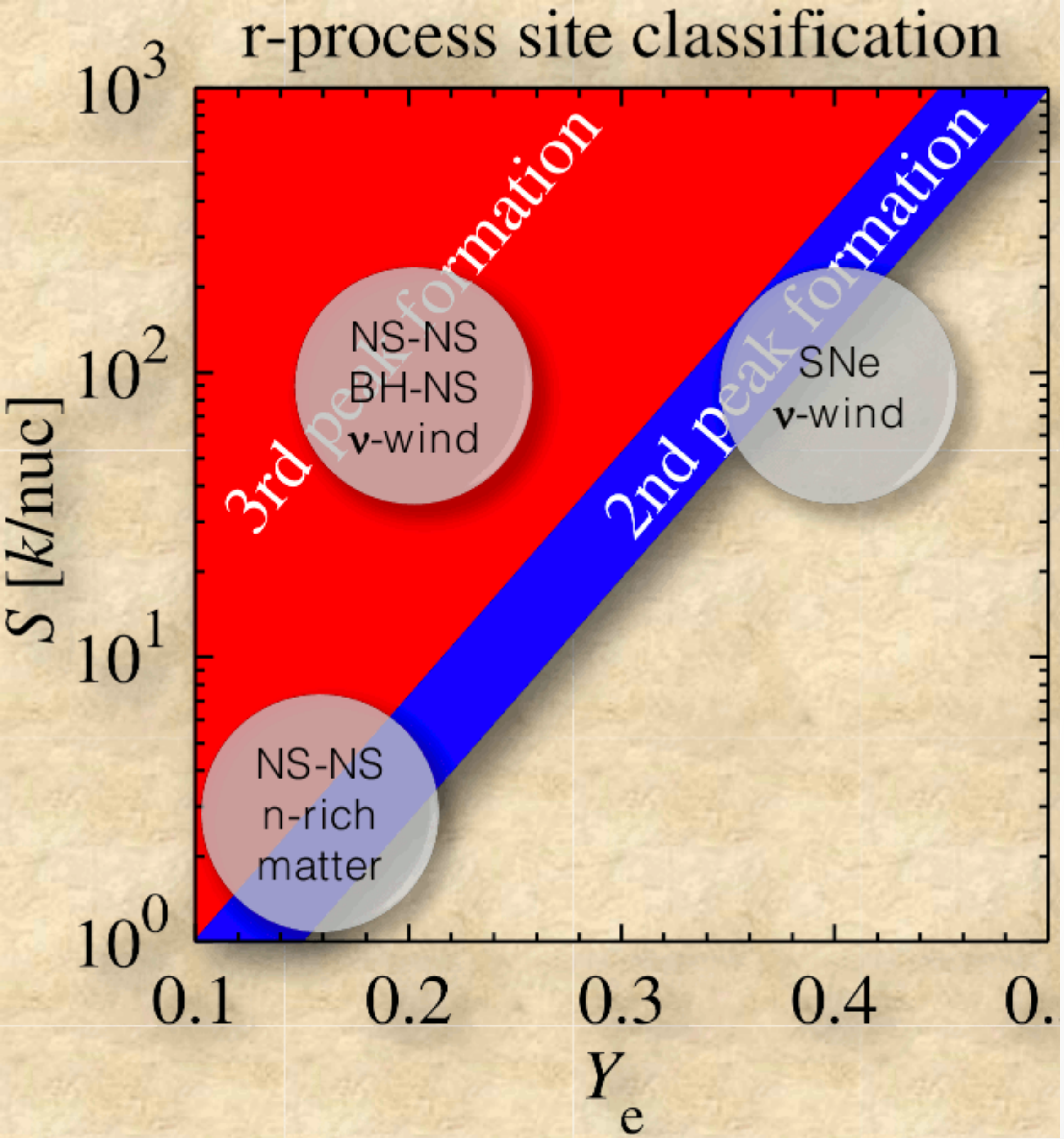
Also the r-process likely comes in at least two versions:

- weak
- main/strong

Source: Wanajo 2011

r-process sites

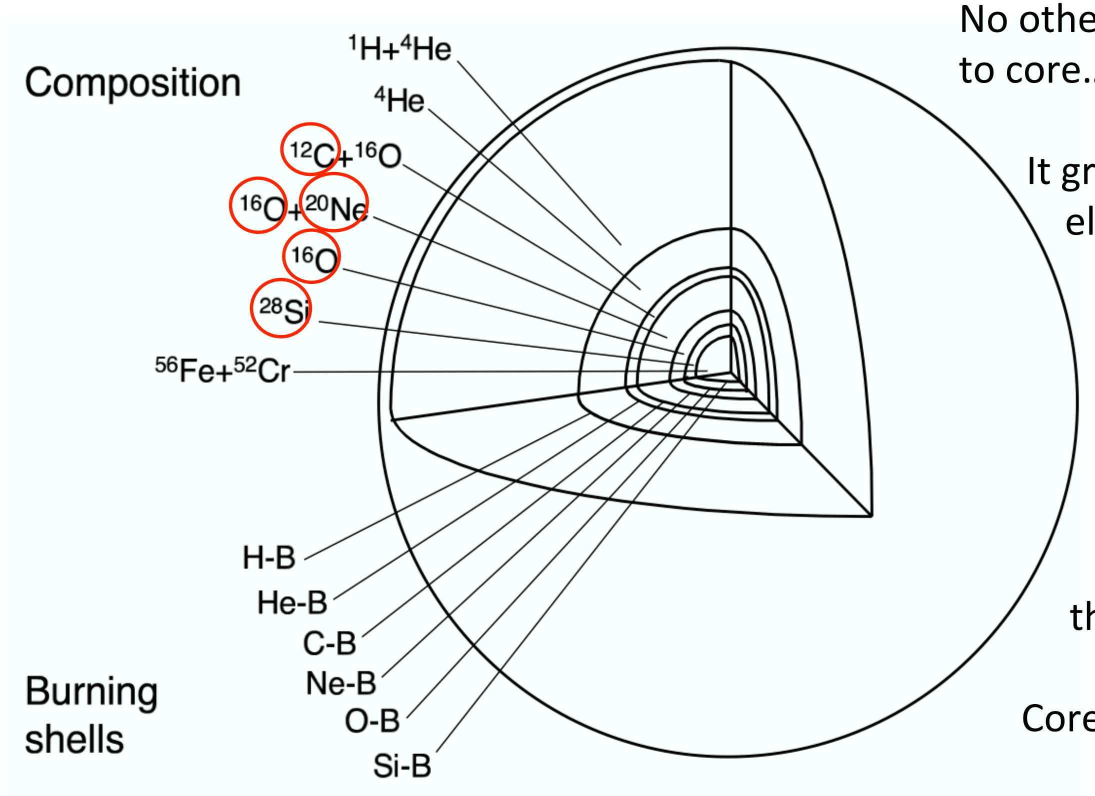
best bets

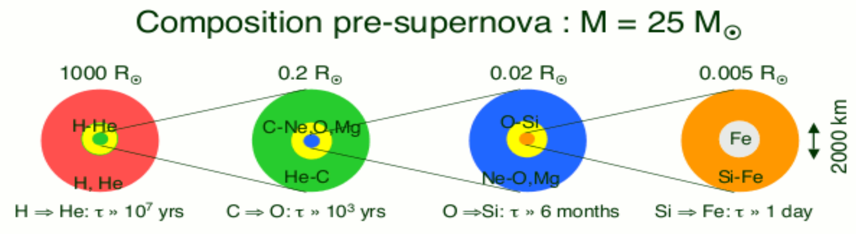


Source: Wanajo 2011

Structure of massive pre-supernova star

(after Si exhaustion in core)





No other nuclear energy source is available to core…

It grows in mass; when it exceeds1.4M_{sun}, electron degeneracy pressure is unable to counteract gravity:

(i) e^--capture on Fe-peak nuclei removes e^-, thus decreasing pressure

(ii) NSE composition shifts to lighter nuclei (less stable!) removing energy, thus decreasing pressure

Core collapses in free fall…

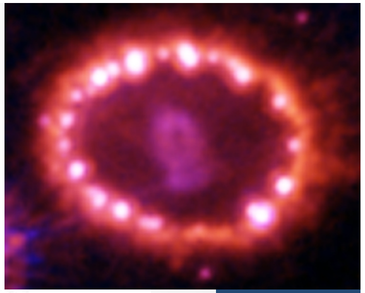
At $\rho=10^{14}$ g/cm^3, nuclei and nucleons feel short-range nuclear force (repulsive at very short r)

Part of core rebounds, producing an outward moving shock wave…

Composition of layers dominated by more stable nuclei (A multiple of 4)

Explosive Si-burning

(T=4-5 GK)



High T and ρ reached in inner ^{28}Si layer because of outgoing shock wave
Matter cools when shock moves outwards
NSE → non-NSE

If NSE is terminated by lack of α-particles

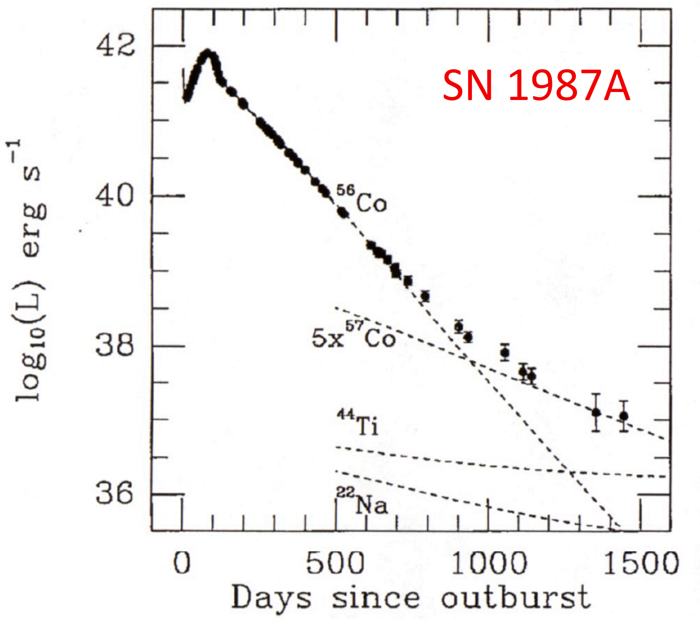
"α-particle-poor freeze-out"

then ejected abundances are close to those derived from NSE (mainly ^{56}Ni since $\eta \approx 0$)

If NSE is terminated by excess of α-particles

"α-rich freeze-out"

then ejected abundances change somewhat from NSE (although still mainly ^{56}Ni for $\eta \approx 0$; also ^{44}Ti)



$$^{56}\text{Ni} \xrightarrow{T_{1/2}=6.1\text{ d}} {}^{56}\text{Co} \xrightarrow{T_{1/2}=77.3\text{ d}} {}^{56}\text{Fe}\ \text{(stable)}$$

$m(^{56}\text{Ni}) = 0.07 \pm 0.01\ M_{\text{sun}}$

Nucleosynthesis now depends critically on ρ, expansion time scale and n, p, α abundances

Explosive O-burning

(T=3-4 GK)

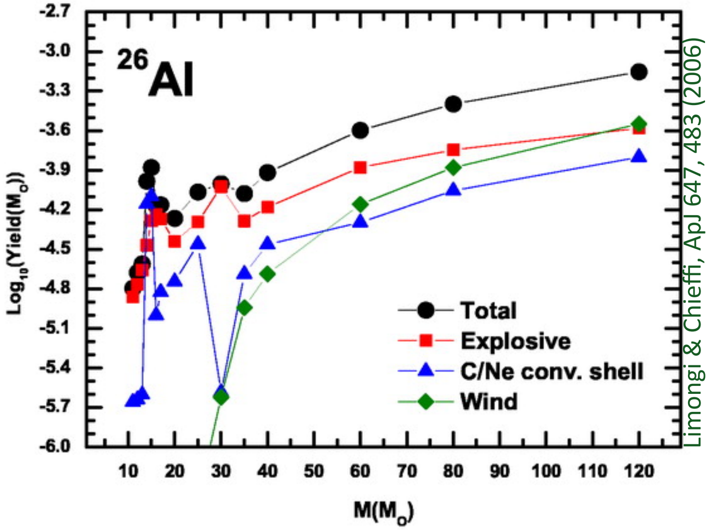
- Quasi-equilibrium clusters form during nucleosynthesis
- Nucleosynthesis similar to hydrostatic O-burning

Main source of ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca (“α-elements”) in Universe

Explosive C- and Ne-burnings

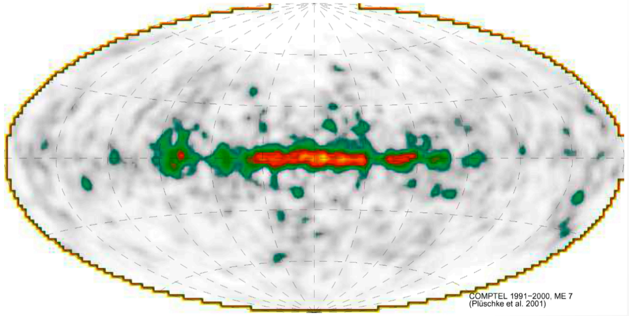
(T=2-3 GK)

Nucleosynthesis similar to hydrostatic C- and Ne-burnings



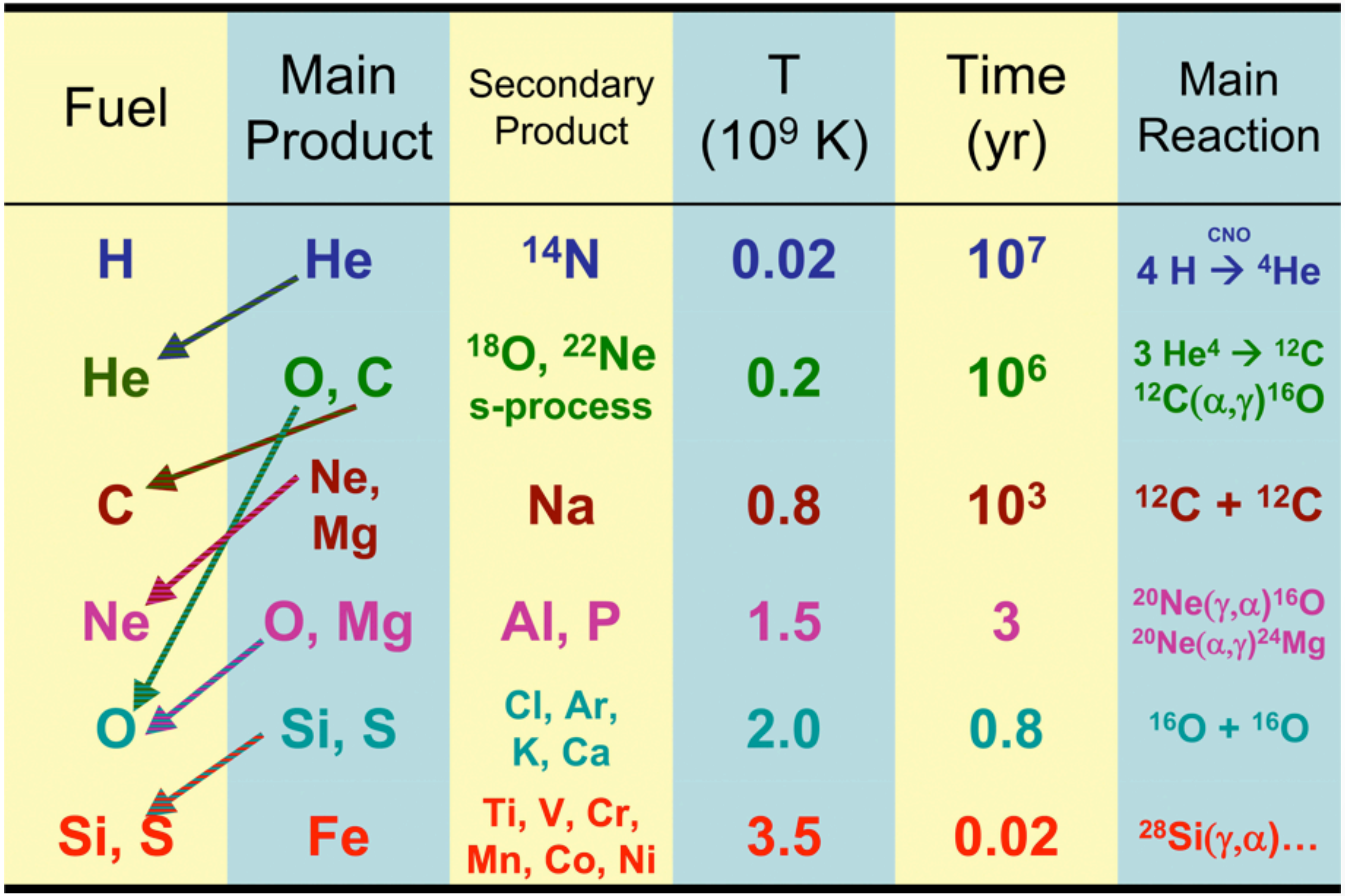
Limongi & Chieffi, ApJ 647, 483 (2006)

COMPTEL map (1.8MeV)



Predicted to be main source of ^{26}Al

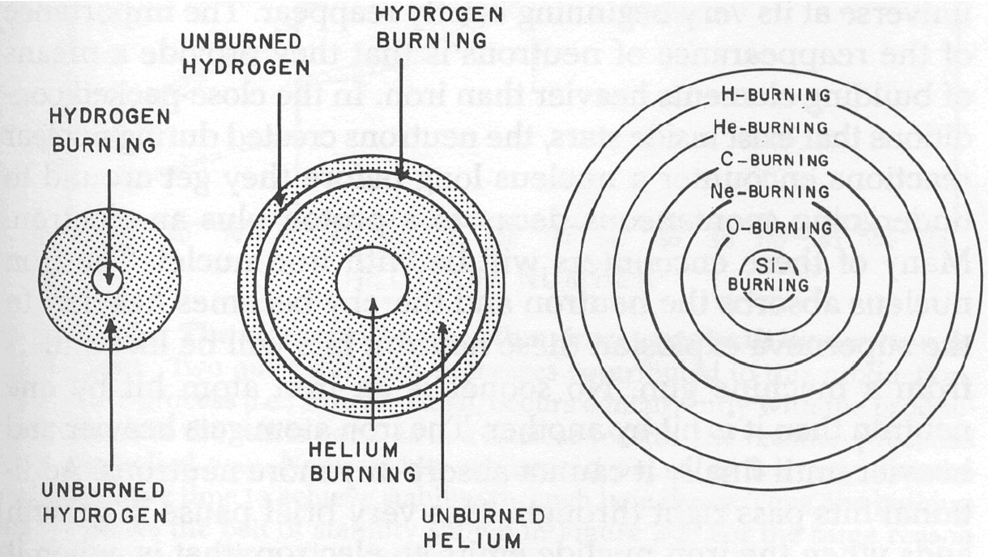
Stellar nucleosynthesis: a recap



Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

Source: Alex Heger

Stellar nucleosynthesis: hydrostatic and explosive



Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60×10^6 °K
Helium-Burning	He	C, O	200×10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800×10^6 °K
Neon-Burning	Ne	O, Mg	1500×10^6 °K
Oxygen-Burning	O	Mg to S	2000×10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000×10^6 °K

Each nuclear step requires a minimum mass (or core mass) to occur:

- H-burning $M > 0.05\ M_{sun}$
- He-burning $M_{He} = 0.5\ M_{sun}$ $(M < 2.2\ M_{sun})$
- C-burning $M < 9\ M_{sun}$ or $M_{CO} = 1.44\ M_{sun}$

Those limits are set by the competing effect of heating by gravitational contraction and onset of electron degeneracy at increasing density

Stellar nucleosynthesis: dependence on mass

M/M_{sun}	**Fuel**	**Products**	**$T/10^8K$**
0.08	H	He	0.2
1.0	He	C, O	2 **AGB**
1.4	C	O, Ne, Na	8
5	Ne	O, Mg	15
10	O	Mg … S	20
20	Si	Fe …	30
>8	SNe	All!	

Not all stars undergo the complete sequence, but, depending on their mass, they may stop before He-burning, C-burning. Only massive stars go straight up to the end.

Nucleosynthesis in low-intermediate mass stars

- Low-mass stars ignite core He-burning in degenerate conditions ($M < 2.2\ M_{sun}$)

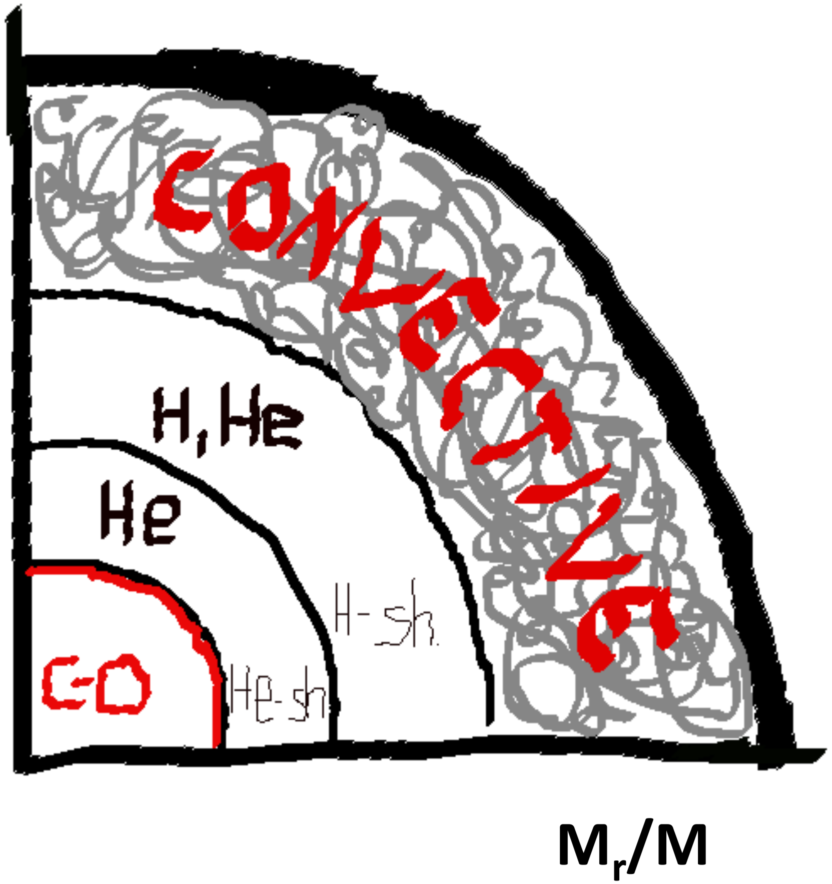
- Intermediate-mass stars ignite He-burning in non-degenerate conditions, but develop strongly degenerate CO cores ($2.2\ M_{sun} < M < 8\ M_{sun}$).

- In these stars C-ignition fails unless the CO core mass reaches $M_{ch} = 1.4\ M_{sun}$

- All these stars go through the AGB phase.

AGB phase

Typical structure *at start*



Following central He-exhaustion, the star now has:

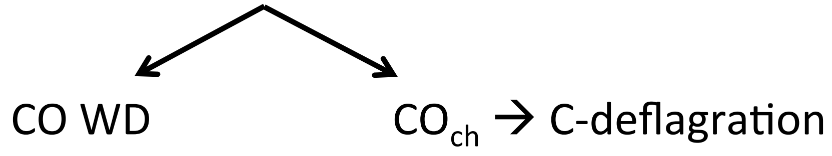
- A contracting, degenerate CO core;
- Two burning shells;
- An expanding convective envelope;
- The star climbs the Hayashi track and looses mass by stellar wind.

- The two shells get spatially very close and thermally coupled, separated by a thin layer of matter
- The He-shell becomes thermally unstable and undergoes periodical pulses of strong activity

AGB phase: general considerations

During the thermal cycles:

- nuclear shell increases the mass of the CO core (more and more e^- degenerate)
- mass loss by stellar wind continuously decreases the mass of the external envelope until it is completely expelled.



CO WD

CO_{ch} → C-deflagration

Number of cycles depends on envelope mass wrt to core and total mass:

- Low-mass AGBs have small envelopes, hence a few cycles
- Intermediate-mass stars have bigger envelopes, hence more cycles

Every cycle may bring some C to the surface.

The intershell region can become a good site for *s*-process nucleosynthesis.

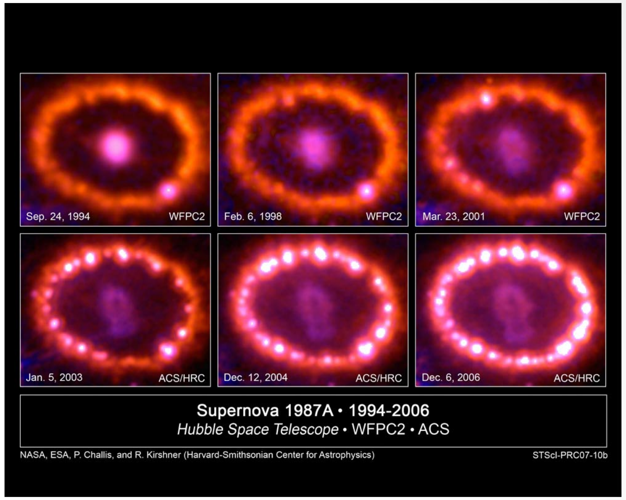
AGB stars are major producers of Carbon in the Universe!

Nucleosynthesis in massive stars

The structure of the star in the core (inside the H-burning shell) is rather well known. But not in the envelope.

Burning	**Temperature** 10^6 K	**Density** g/cm^3	**Lifetime** years
Hydrogen	37	3.8	7.3×10^6
Helium	180	620	720 000
Carbon	720	6.4×10^5	320
Neon	1200	$>10^6$	<10
Oxygen	1800	1.3×10^7	~0.5
Silicon	3400	1.1×10^8	<1 day
Collapse	8300	$>3.4\times10^9$	0.45 sec
Neutron Star	<8000	$>1.4\times10^{14}$	–

Supernova Types



Supernova 1987A • 1994-2006
Hubble Space Telescope • WFPC2 • ACS

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC07-10b

SN Type	**pre-SN stellar structure**
IIp	> $2M_{sun}$ H envelope
IIL	< $2M_{sun}$ H envelope
Ib/c	No H envelope

Type Ib/c He core mass at explosion	**Explosion energy**	**Display**
> $15M_{sun}$	direct collapse	none
~15 … $8M_{sun}$	weak	dim
~8 … $5M_{sun}$	strong	dim
< $5M_{sun}$	strong	bright

What blows up?

CO White Dwarf → **SN Ia** (E~1Bethe=10^{51} erg)

MgNeO White Dwarf, accretion → AIC*, **faint SN**

AGB SN star → EC** SN

‘normal’ SN (Fe CC***) → Type Ib/c

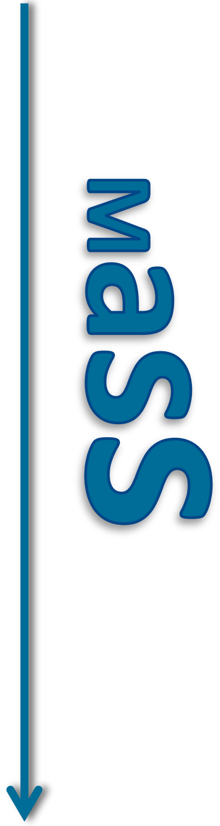
‘Collapsar’, GRB → broad line Ib/a SN, ‘**hypernova**’

Pulsational pair SN → multiple, nested Type I/II SN

Very massive stars → **pair SN**, <~100B

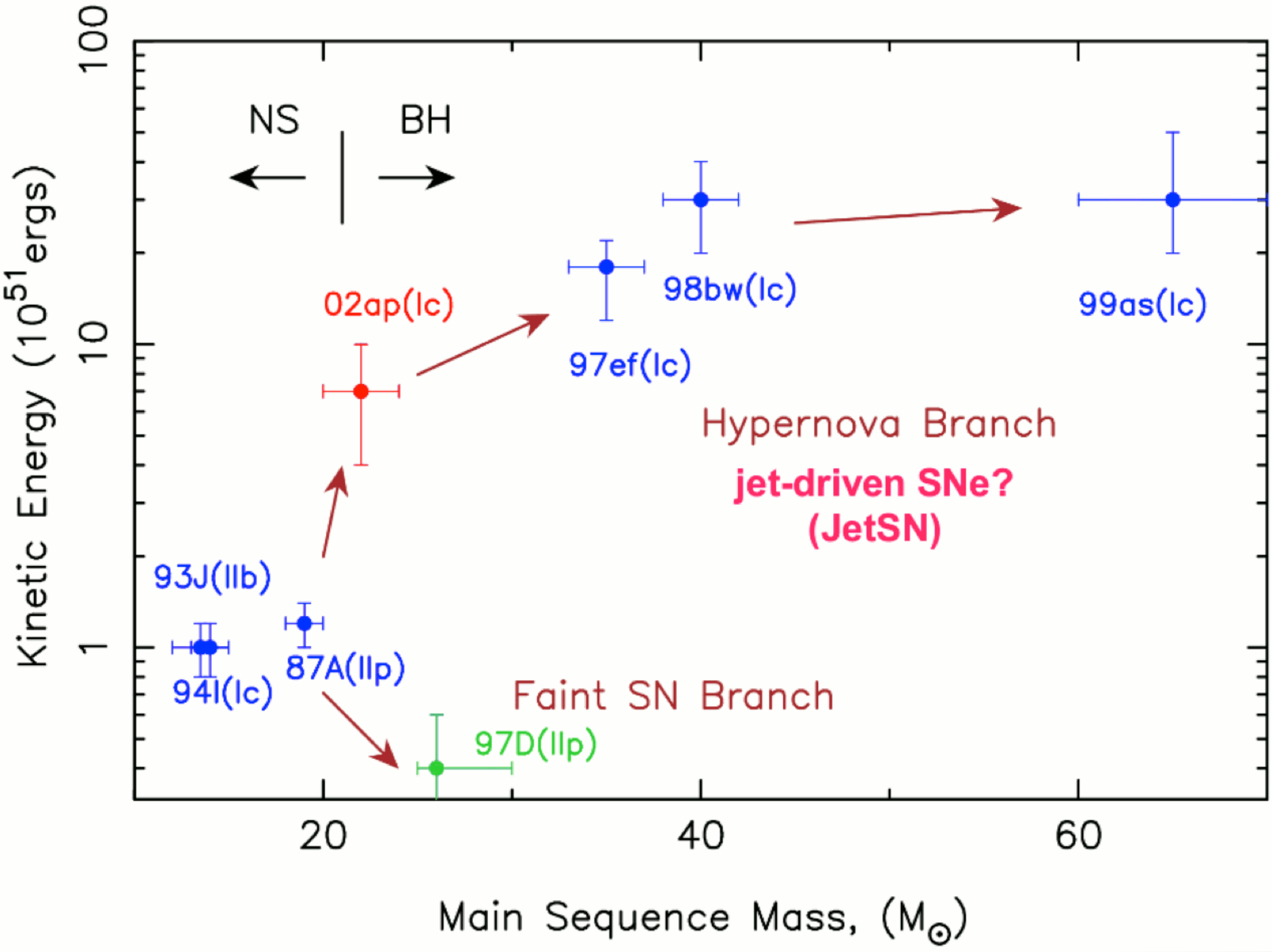
Very massive collapsar → IMBH, SN, hard transient

Supermassive stars → >~100000 B SN or SMBH



*AIC=Accretion Induced Collapse
**EC=Electron Capture
***CC=Core Collapse

Source: Alex Heger



Source: Nomoto

SN Ia

~15% of supernovae are type Ia SN

If WD accretes mass from close companion it might exceed the Chandrasekhar limit

→ Carbon ignites under degenerate conditions (thermonuclear runaway → 50% into Fe)
→ The released energy causes the WD to explode as SN Ia

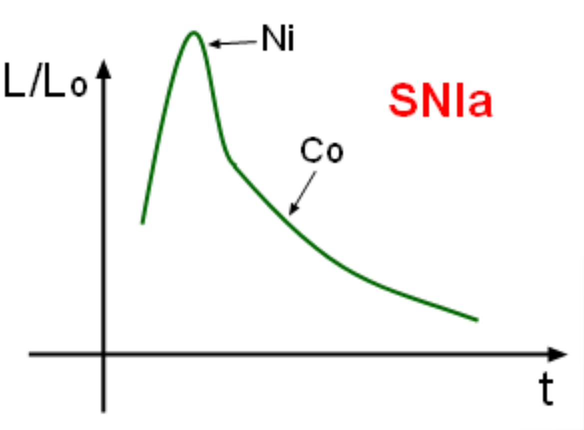
Characteristics:

No prominent H lines

Decline of c.o.l. dominated by radioactive decay:

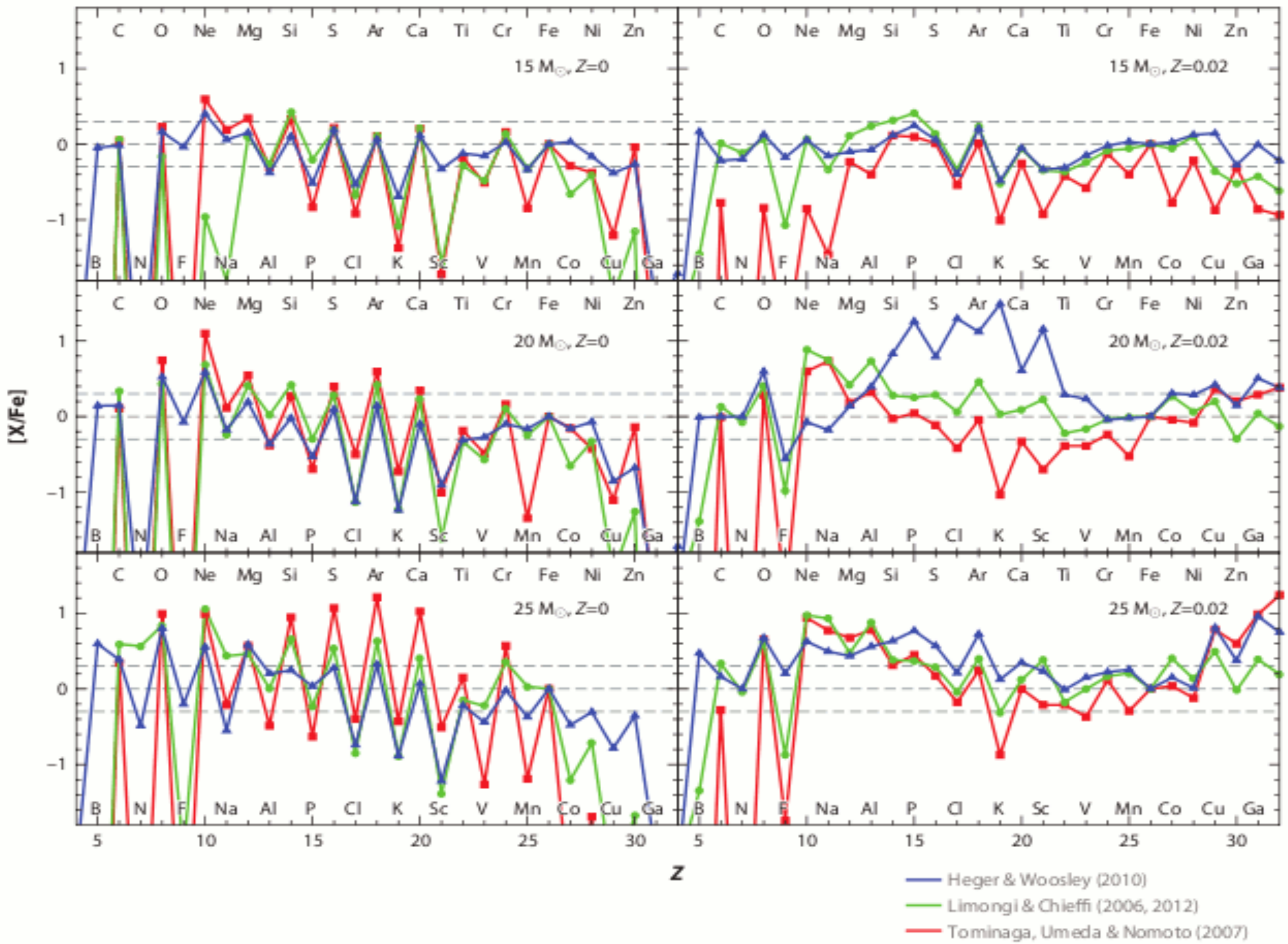
$^{56}_{28}Ni \rightarrow {}^{56}_{27}Co \rightarrow {}^{56}_{26}Fe$

No remnant left



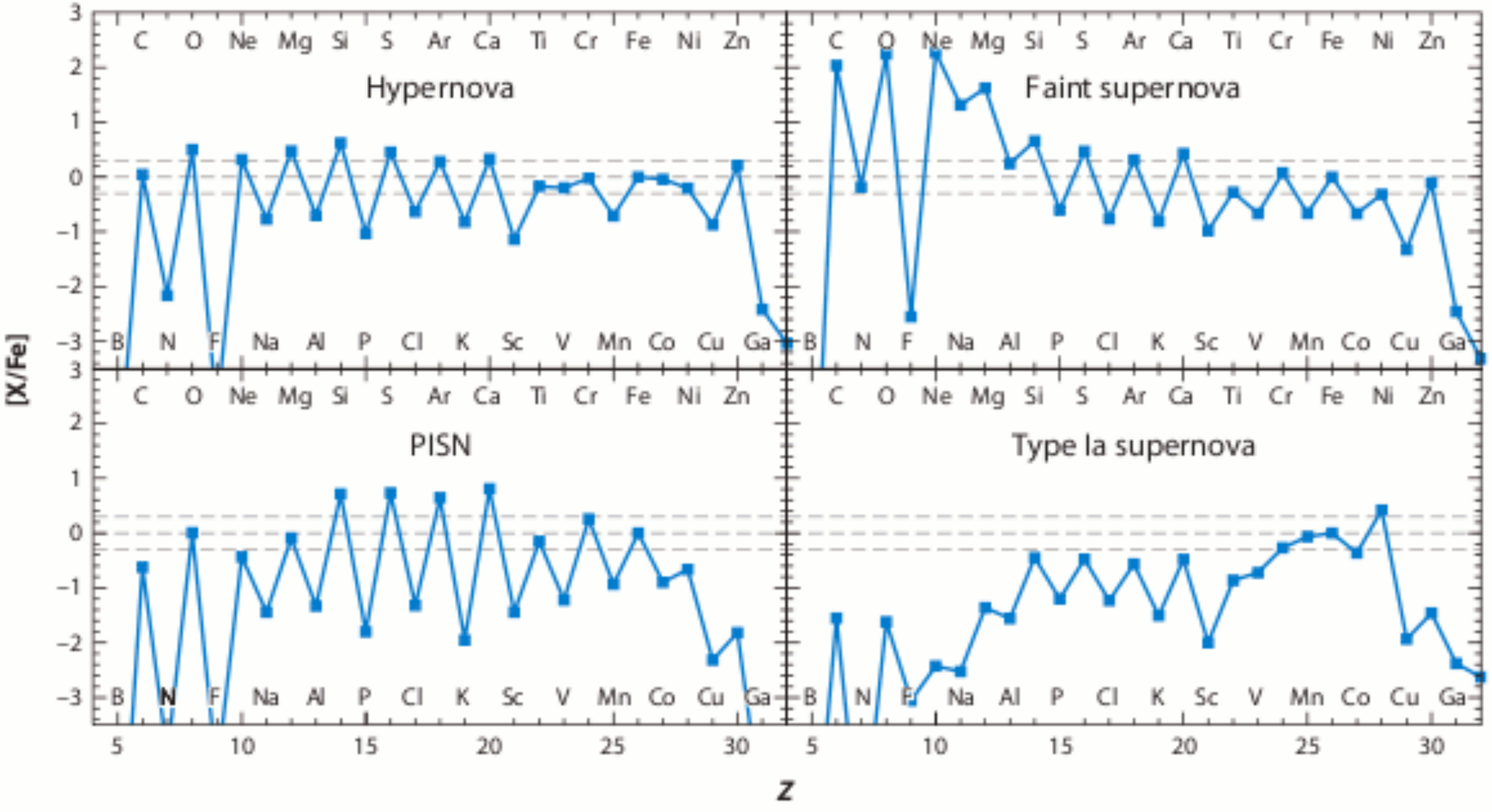
Main source of Fe in the Universe

And now ?



Source: Nomoto, Kobayashi & Tominaga 2013

Testing the different types



Source: Nomoto, Kobayashi & Tominaga 2013

Elements production & destruction

- ^{1}H created by Big Bang and destroyed in/by stars
- ^{2}H, ^{3}He, ^{4}He, ^{7}Li produced by Big Bang (Li also in/by stars)
- ^{2}H always destroyed in/by stars
- ^{3}He mostly destroyed but some production in/by stars
- ^{4}He produced by Big Bang and also in/by stars (1-100 M_{sun})
- ^{7}Li likely produced in/by AGB stars, Novae and SNII
- ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B produced by CR spallation (^{11}B maybe also by ν–spallation)
- ^{12}C produced by He-burning in intermediate/high-mass stars
- ^{13}C produced during quiescent and explosive H-burning (can be primary)
- ^{14}N produced during quiescent H-burning (cold CNO) in low/intermediate-mass stars (can be primary)
- ^{15}N produced during explosive H-burning in SN and Novae

Elements production & destruction – ctd.

- ^{16}O produced during He-burning in massive stars
- ^{17}O produced by cold CNO in low/intermediate-mass stars
- ^{18}O produced rom destruction of N via N(α,γ)F(β)O in He-burning regions; restored by SN II; some production also in quiescent and explosive H-burning
- ^{20}Ne, ^{24}Mg produced by C-burning in massive stars + C-deflagration in SN Ia; Mg also in quiescent and explosive Ne-burning
- ^{28}Si, ^{32}S produced during quiescent and explosive O-burning in massive stars + C-deflagration
- ^{40}Ca produced in explosive O- and Si-burnings in massive stars + C-deflagration in CO WDs
- ^{56}Fe produced during quiescent and explosive Si-burning in massive stars + CO-deflagration in CO WDs
- *s*-process elements produced during He-burning in massive stars via ^{22}Ne(α,γ)^{25}Mg (A<90) + He-flashes via ^{13}C(α,n)^{16}O (A>90) in AGB stars
- *r*-process elements produced in explosive He-, C-, O-, Si-burnings in SN II