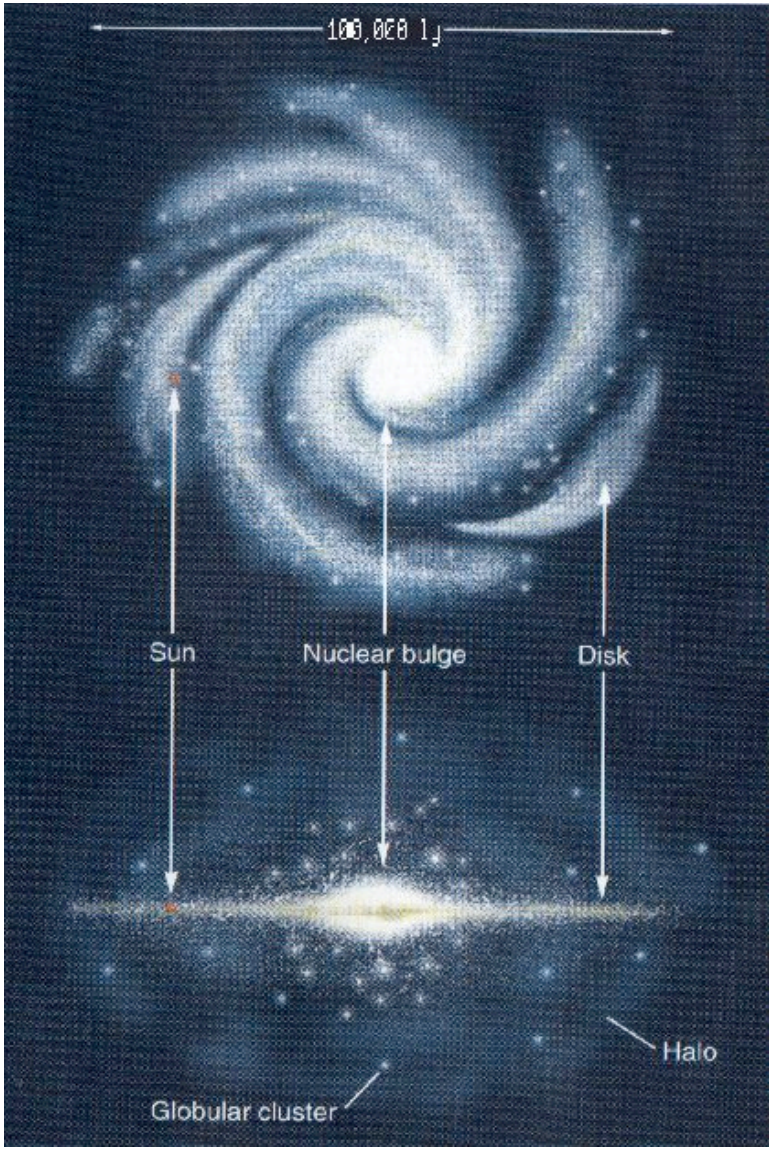
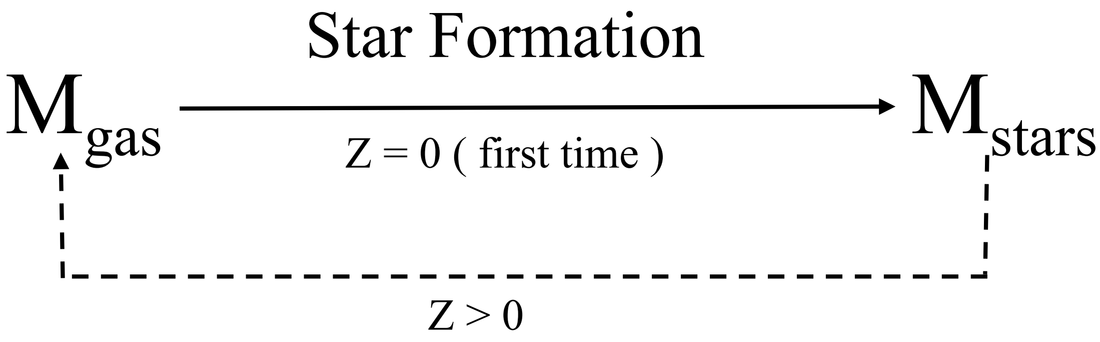
Lecture 8: Stellar Nucleosynthesis and Chemical Evolution of The Galaxy



- Chemical evolution of the Galaxy:
- Star Formation
- Nucleosynthesis in Stars
- Enrichment of the ISM (interstellar medium)
  - Supernova explosions
  - Planetary nebulae
  - Stellar winds

Recycling the ISM

Initially: $X = 0.75$ $Y = 0.25$ $Z = 0.0$



Each new generation of stars is born from gas with higher metalicity.

$X\downarrow$ $Y\uparrow$ $Z\uparrow$

Population III -- $Z = 0$ none seen!

Population II -- $Z \sim 10^{-3}$ (GCs, Halo stars)

Population I -- $Z \sim 0.02$ (Sun, Disk stars)

Enrichment of Primordial Abundances

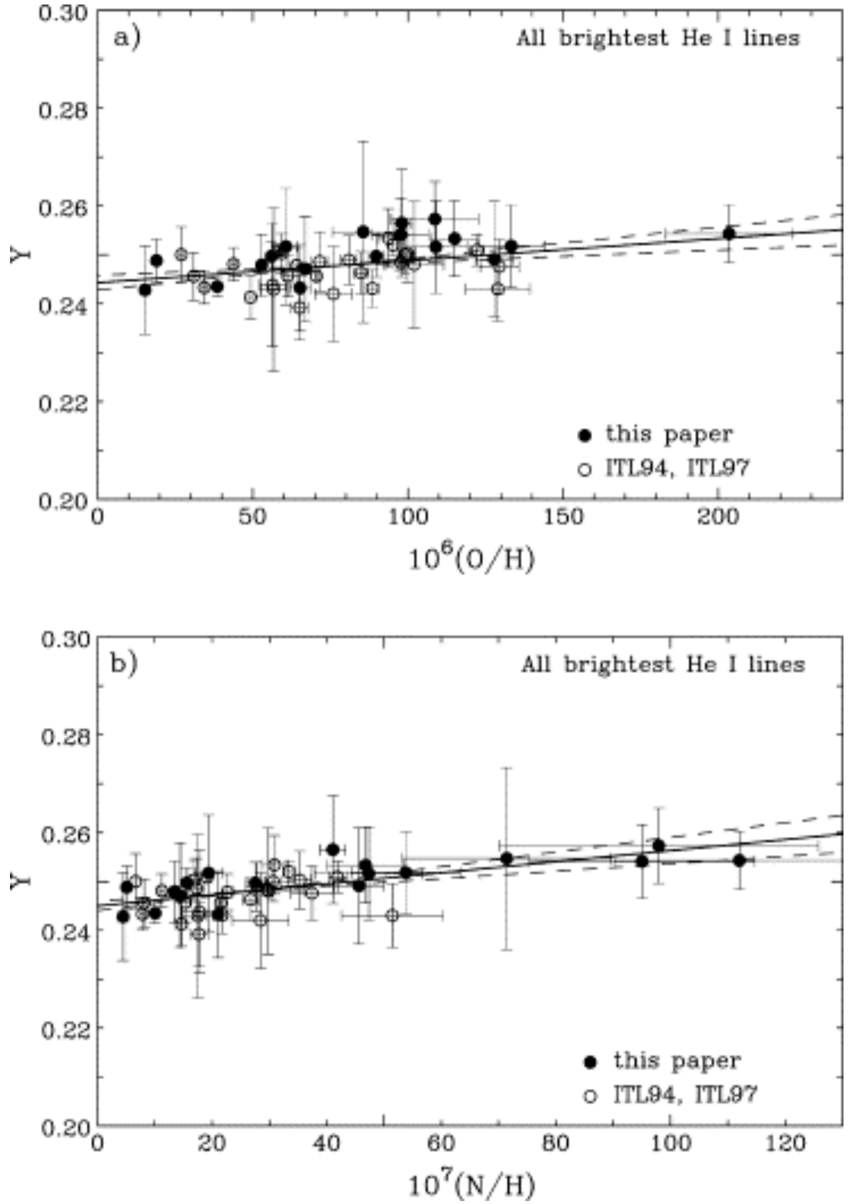
• Emission lines from H II regions in low-metalicity galaxies.

• From emission-line ratios, measure abundance ratios:

He/H, O/H, N/H, …

• Stellar nucleosynthesis increases He along with metal abundances.

• Find Y_p = 24.5% by extrapolating to zero metal abundance.



Star Formation in our Galaxy

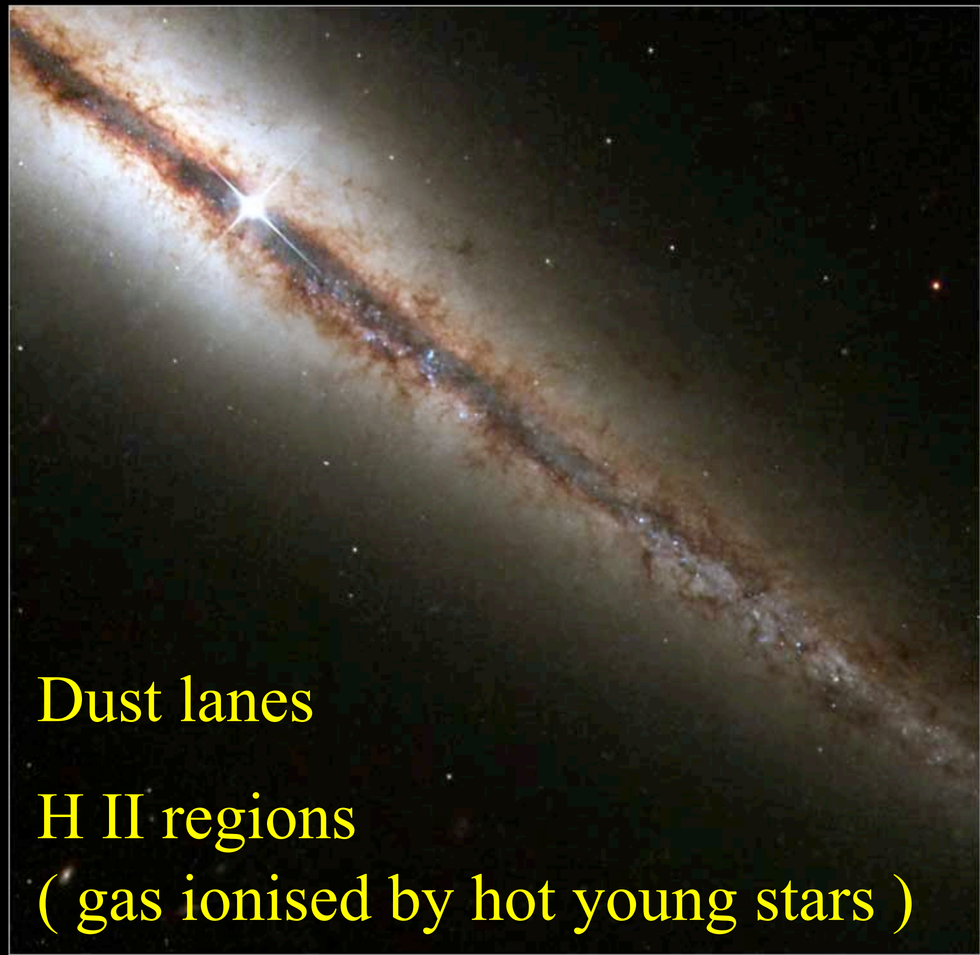
	Galaxy	Solar cylinder
Age	$t \sim 10$ - 15 Gyr	Surface area πR_0^2 $R_0 = 8.5$ kpc
Mass now in stars:	$\alpha\ M_S = 7 \times 10^{10}\ M_\odot$	$\alpha\, \Sigma_S \sim 45\ M_\odot\ pc^{-2}$
Mass now in gas:	$M_G \sim 7 \times 10^9\ M_\odot$	$\Sigma_G \sim 7 - 14\ M_\odot\ pc^{-2}$
Gas fraction:	$\mu = M_{G\,/}\ M_0 \sim 0.1$	$\mu \sim 0.14 - 0.25$
~ 90% of original gas has been converted to stars.		
Star formation depletes the gas:		
Average past SFR:	$M_S / t \sim (5 - 7)\ \alpha^{-1}\ M_\odot\ yr^{-1}$	$(3 - 4.5)\ \alpha^{-1}\ M_\odot\ Gyr^{-1} pc^{-2}$
Gas consumption time:	$M_G / (\alpha M_S / t) \sim 1$ Gyr	1.5 - 5 Gyr
Star formation could stop in as little as 1 Gyr		
Processes that restore the gas:		
AGB star winds + Planetary Nebulae:		$0.8\ M_\odot\ Gyr^{-1}\ pc^{-2}$
O stars winds:		$\sim 0.05\ M_\odot\ Gyr^{-1}\ pc^{-2}$
Supernovae:	$\sim 0.15\ M_\odot\ yr^{-1}$	$\sim 0.05\ M_\odot\ Gyr^{-1}\ pc^{-2}$
Total mass ejection from stars:		$\sim 1\ M_\odot\ Gyr^{-1}\ pc^{-2}$
Inflow from IGM	$< 2\ M_\odot\ yr^{-1}$	$< 1\ M_\odot\ Gyr^{-1}\ pc^{-2}$
Recycling (and inflow from IGM) extends the star formation era.		

ISM in Spiral Galaxies

Whirlpool Galaxy • M51

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Edge-On Galaxy NGC 4013



Dust lanes

H II regions
(gas ionised by hot young stars)

Spiral shocks

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Shocks induce Star Formation

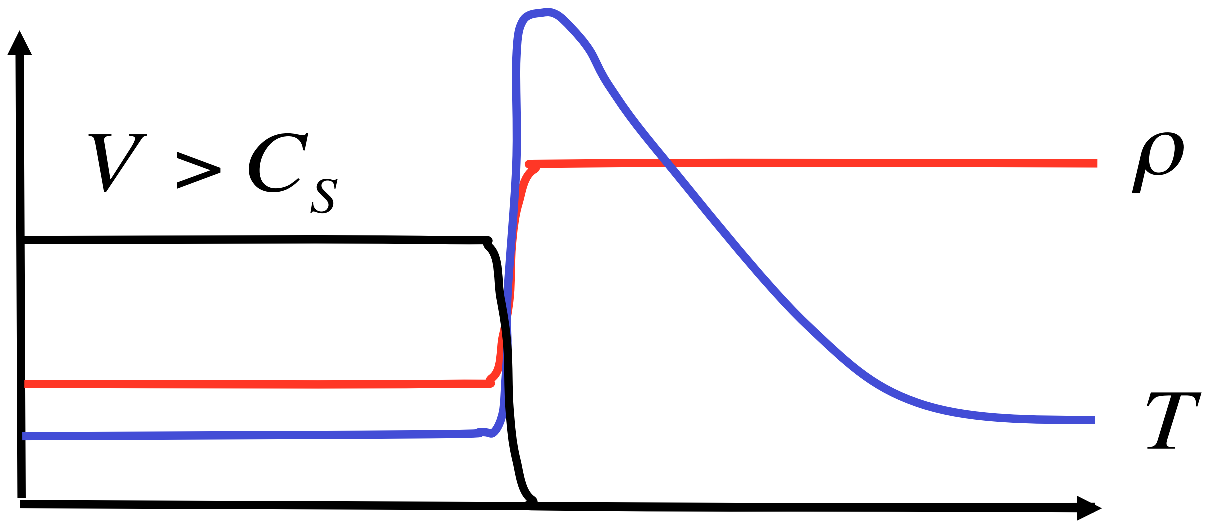
Shocks: supersonic collisions in gas.

Galaxy collisions, spiral arms, SN explosions.

Compress the ISM. Gas then cools.

Lower Jeans mass: $M_J \propto \rho^{-1/2} T^{3/2}$

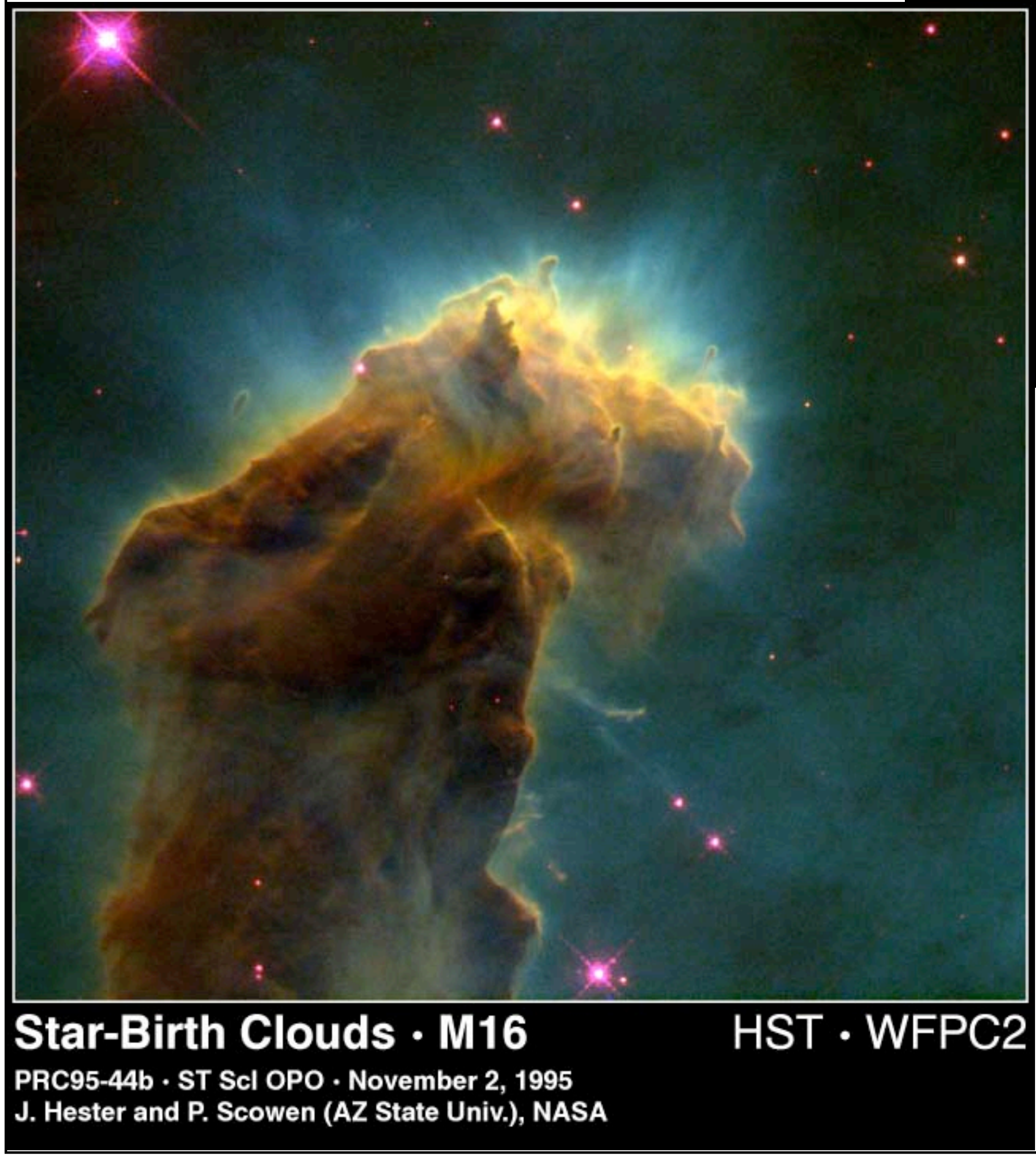
Overdense regions with $L > L_J$ collapse --> stars!



Energy per particle : $E \sim \frac{1}{2} m V^2 \quad \rightarrow \quad E \sim 3kT \sim m C_S^2$

The ISM

Star-forming regions in M16



Young Star Cluster

NGC 3603

Hubble Space Telescope • WFPC2

PRC99-20 • STScI OPO

Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington),
You-Hua Chu (University of Illinois, Urbana-Champaign) and NASA

Initial Mass Function (IMF)

Stars born in **clusters** with **wide range of masses**.

$$M_* = (\ 0.08\ -\ 100?\ )\ M_\odot$$

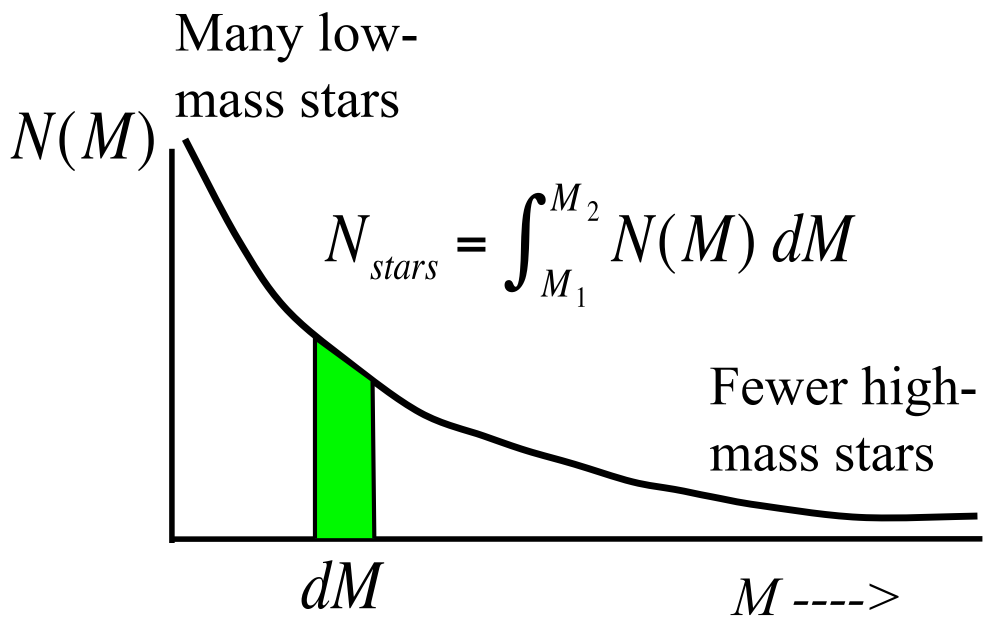
Brown dwarfs: $M < 0.08\ M_\odot$ (no H->He in core)

Max star mass: $\sim 100\ M_\odot$ (radiation pressure limit)

Salpeter IMF:

$$N(M) \propto M^{-7/3}$$

Holds in the solar neighbourhood, and many clusters. May be universal.



$$N_{stars} = \int_{M_1}^{M_2} N(M)\, dM$$

Role of Supernovae

Many low-mass stars. Long lives (> Hubble time).

A few ***high-mass stars***: Quickly go ***Supernova (SN)***, **enrich the ISM with *metals***.

$M_* > 8\ M_\odot$ SN => enrichment of ISM

$M_* < 8\ M_\odot$ retain most of their metals,
=> little enrichment of ISM

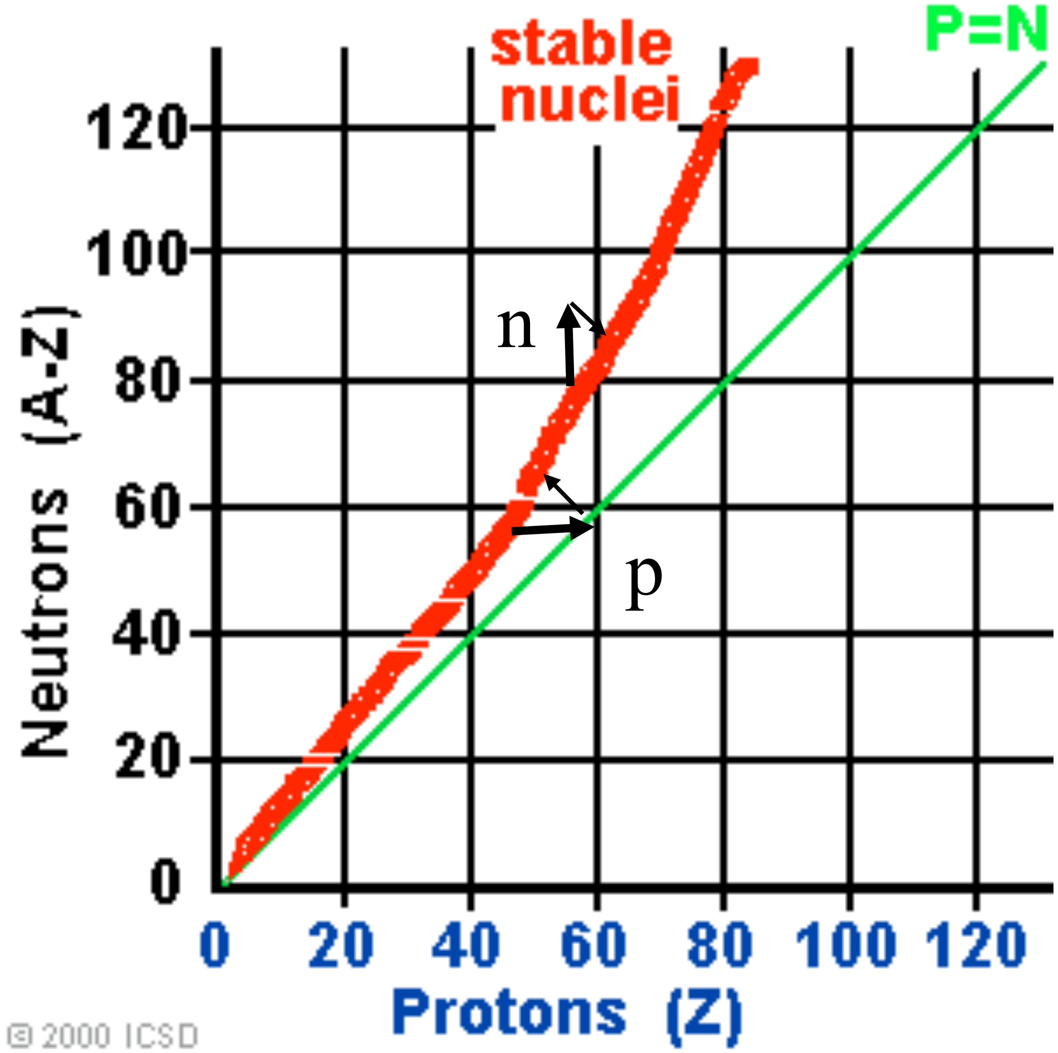
Intermediate mass stars: ($1 < M_*/M_\odot < 8$)
Make He, … C, N, O, …, Fe, but no SN.
Some ISM enrichment (*stellar wind, planetary nebulae*)
but ***most metals stay locked up in collapsed remnant***
(~ 0.5-0.8 $M_\odot$ *white dwarf*).

Stellar Nucleosynthesis

Add protons or neutrons,

then beta decay back

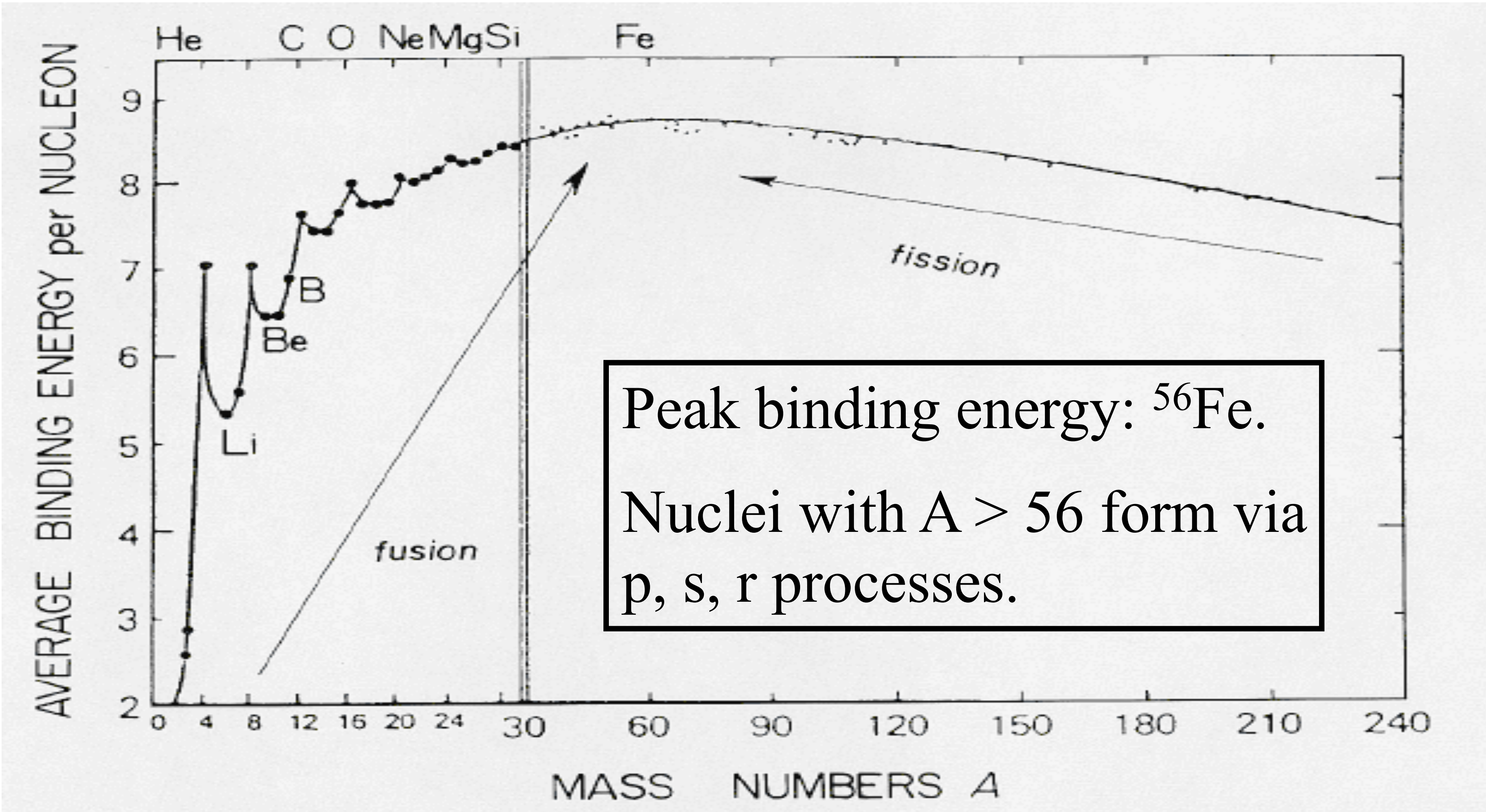
to ***valley of stability***.



Binding energy per nucleon

More stable if A is a multiple of 4:

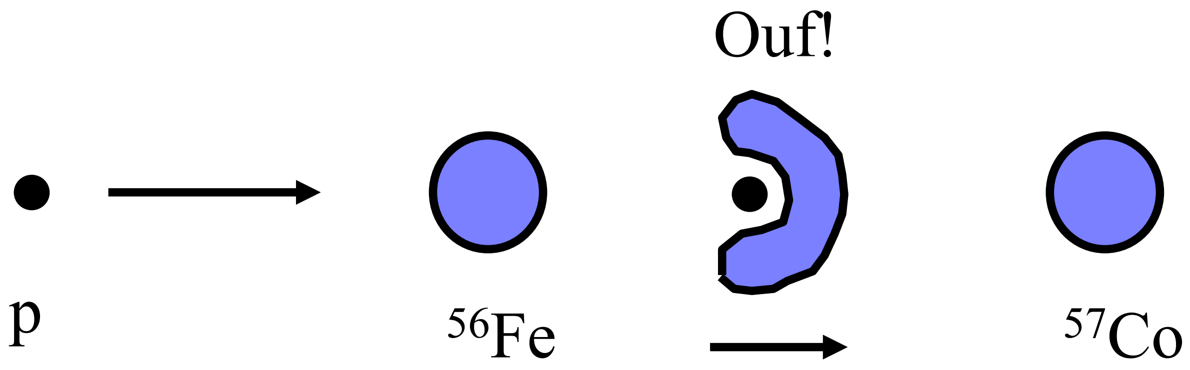
^{4}He ^{8}Be ^{12}C ^{16}O ^{20}Ne ^{24}Mg ^{28}Si …. ^{56}Fe



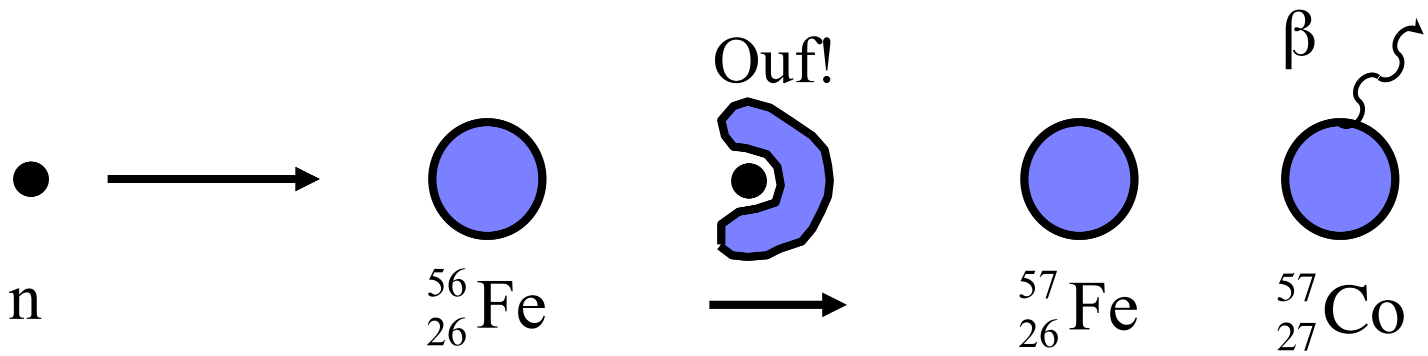
Peak binding energy: ^{56}Fe.

Nuclei with A > 56 form via p, s, r processes.

p-process: Proton capture:



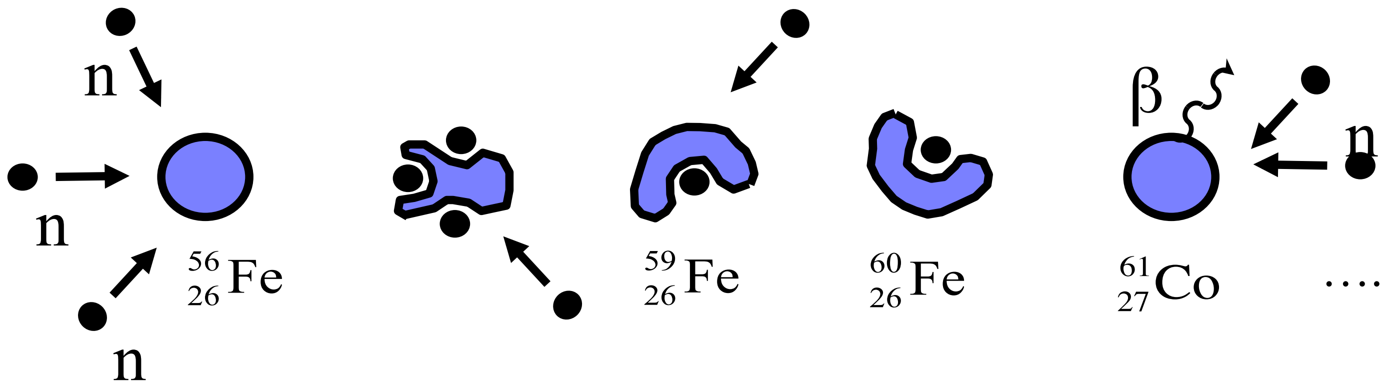
s-process: Slow neutron capture:



Absorb n^0, then … later … emit e^- (β-particle).

Repeat. Progress up the *valley of stability*.

r-process: Rapid neutron capture:



High n^0 flux: absorb many n^0s before β emission.

These processes require energy.
Occur only at high ρ & T :

Core & shell burning: p & s process

Supernovae: p & r process

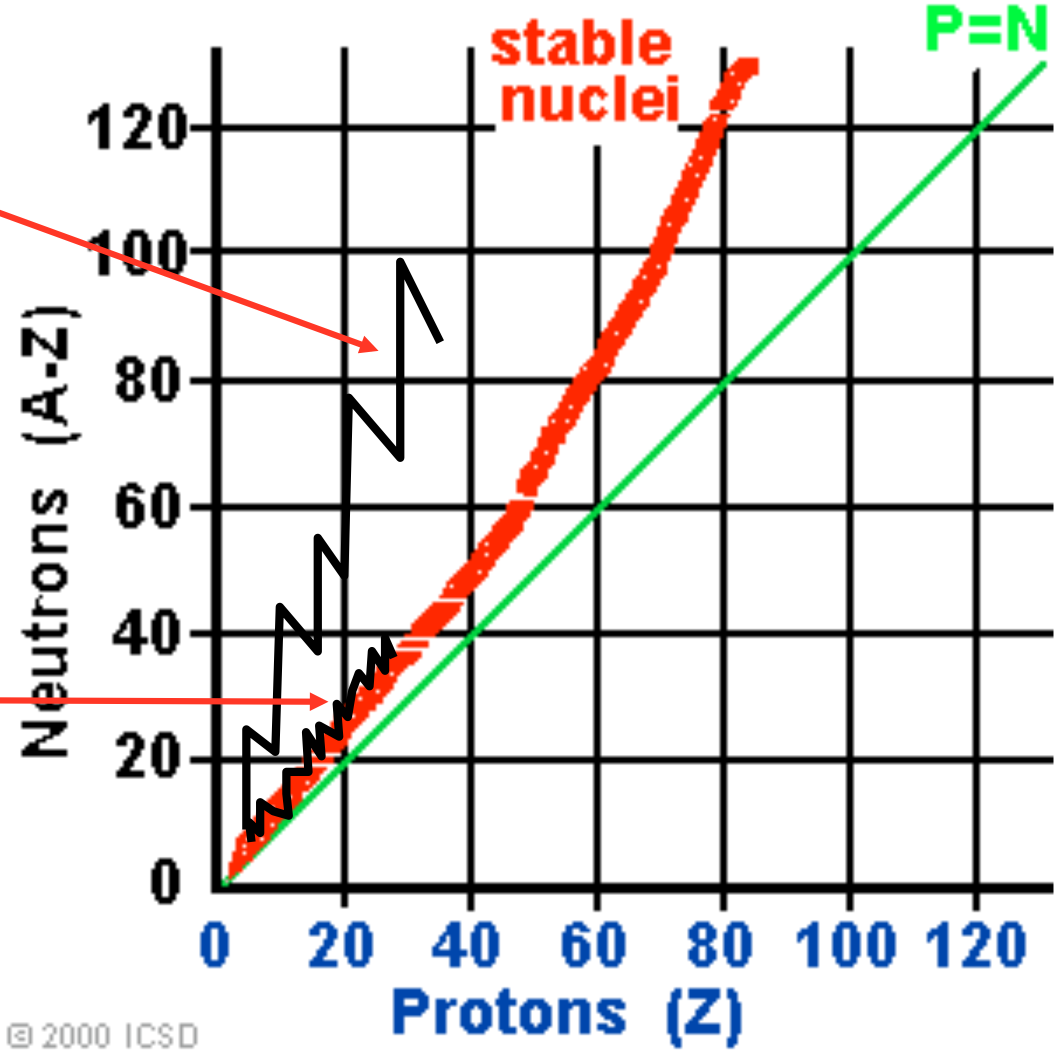
Neutron Capture: Speed Matters

r-process

departs from

valley of stability

s-process



Stellar Nucleosynthesis

Main processes (fusion):

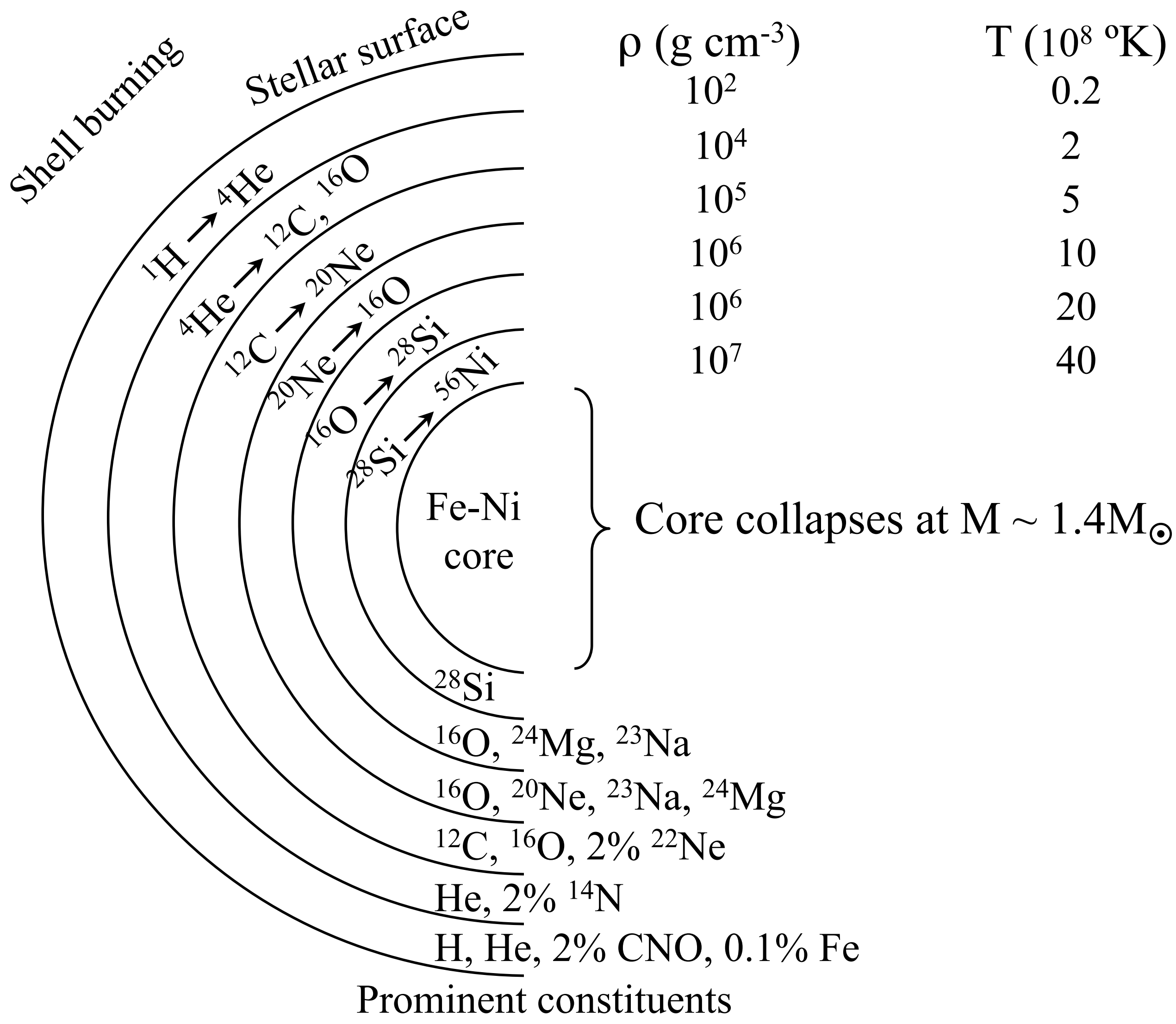
pp-chain	➔	^4He	H-burning
[also CNO-cycle	➔	^4He	in metal rich stars]

M / $M_\odot$	Fuel	Products	T / 10^8 K
0.08	H	He	0.2
1.0	He	C, O	2
1.4	C	O, Ne, Na	8
5	Ne	O, Mg	15
10	O	Mg … S	20
20	Si	Fe …	30
> 8	Supernovae	all!	

Pre-Supernova "Onion Skin" Structure

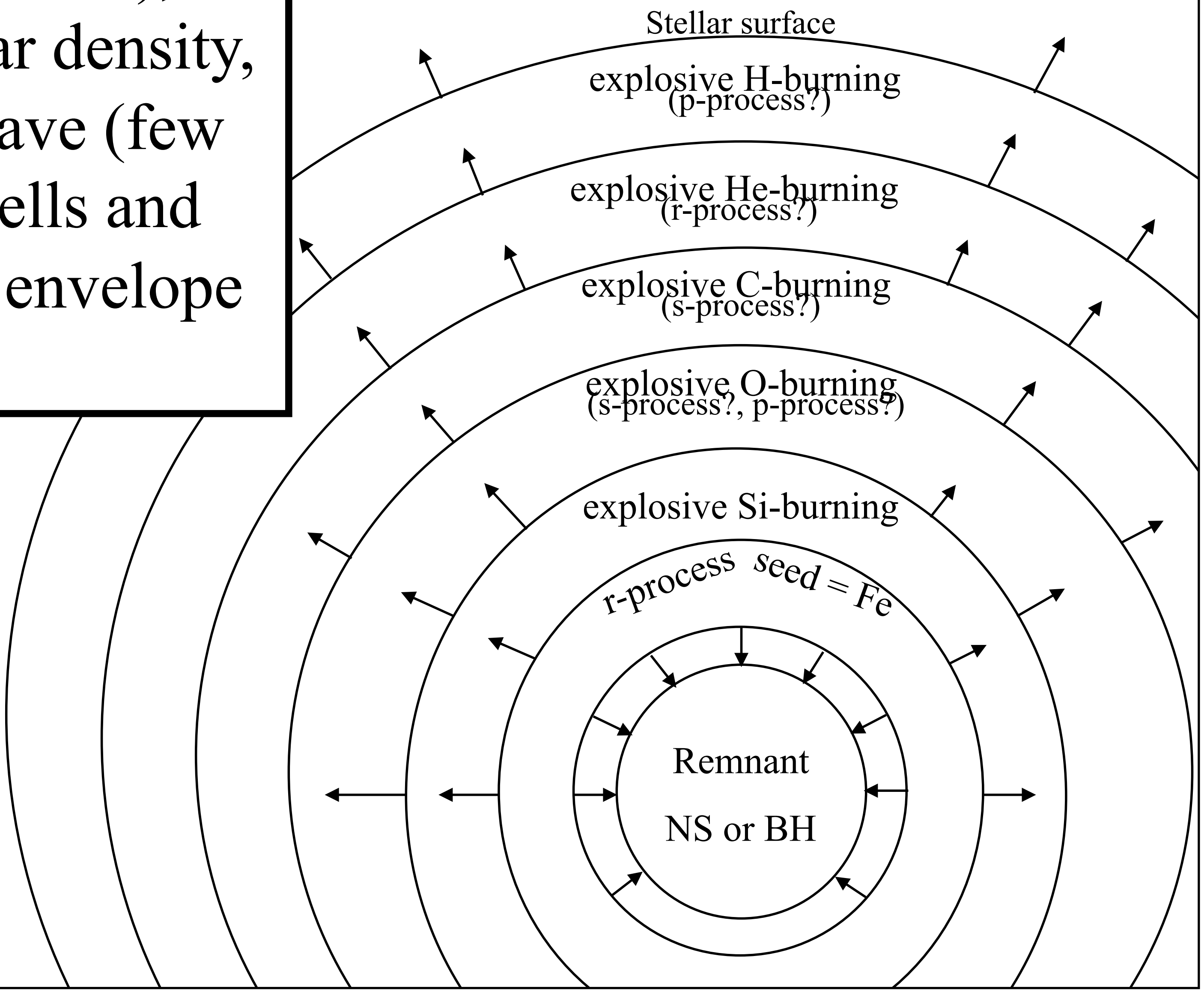
Heavy elements settle into layers. Shell burning at interfaces.

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

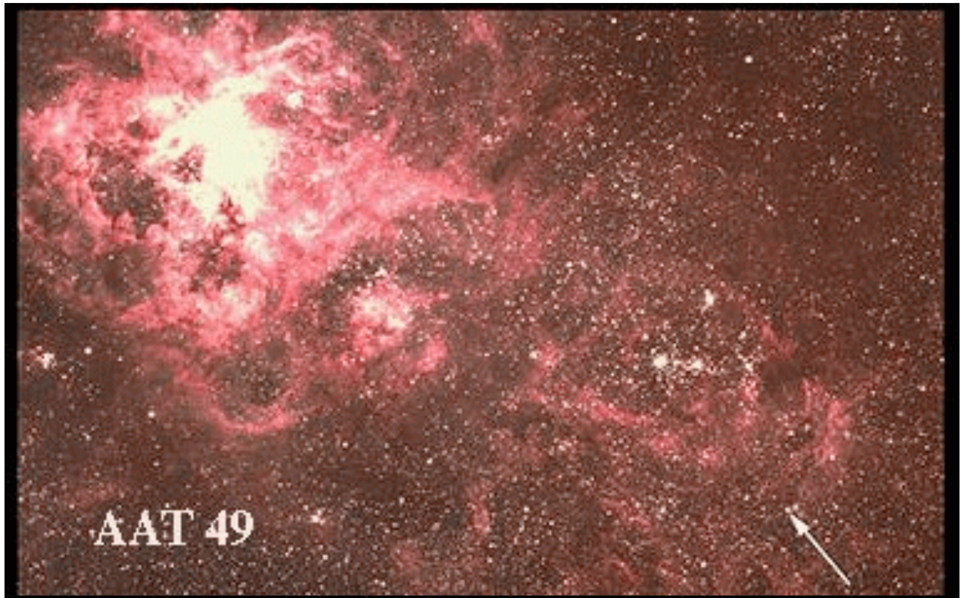


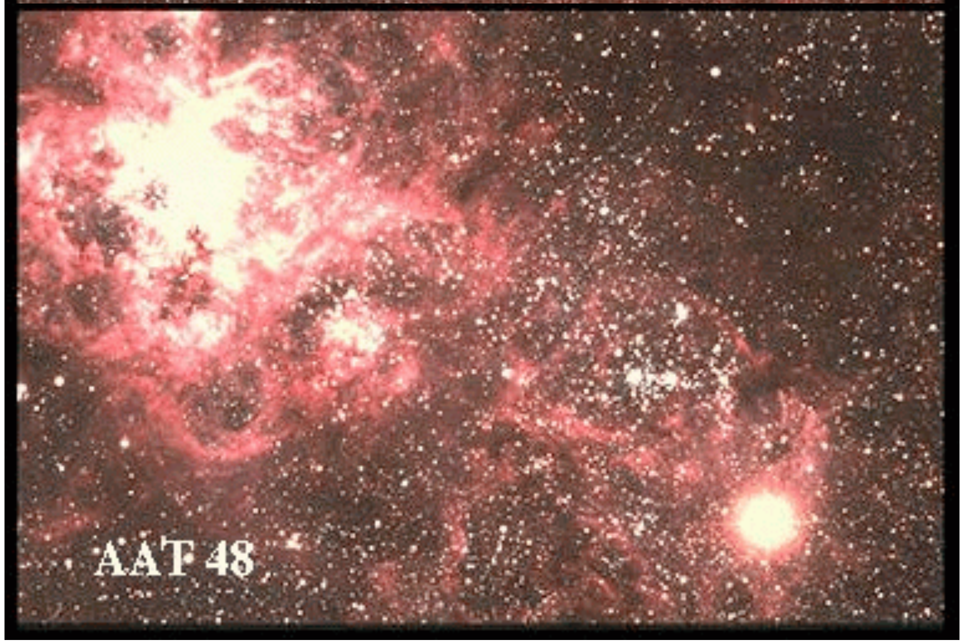
Exploding Supernova Ejecta

Core collapse (few ms), bounces at nuclear density, outward shock wave (few hours), ignites shells and expels the stellar envelope ($V>10^4$ km/s).



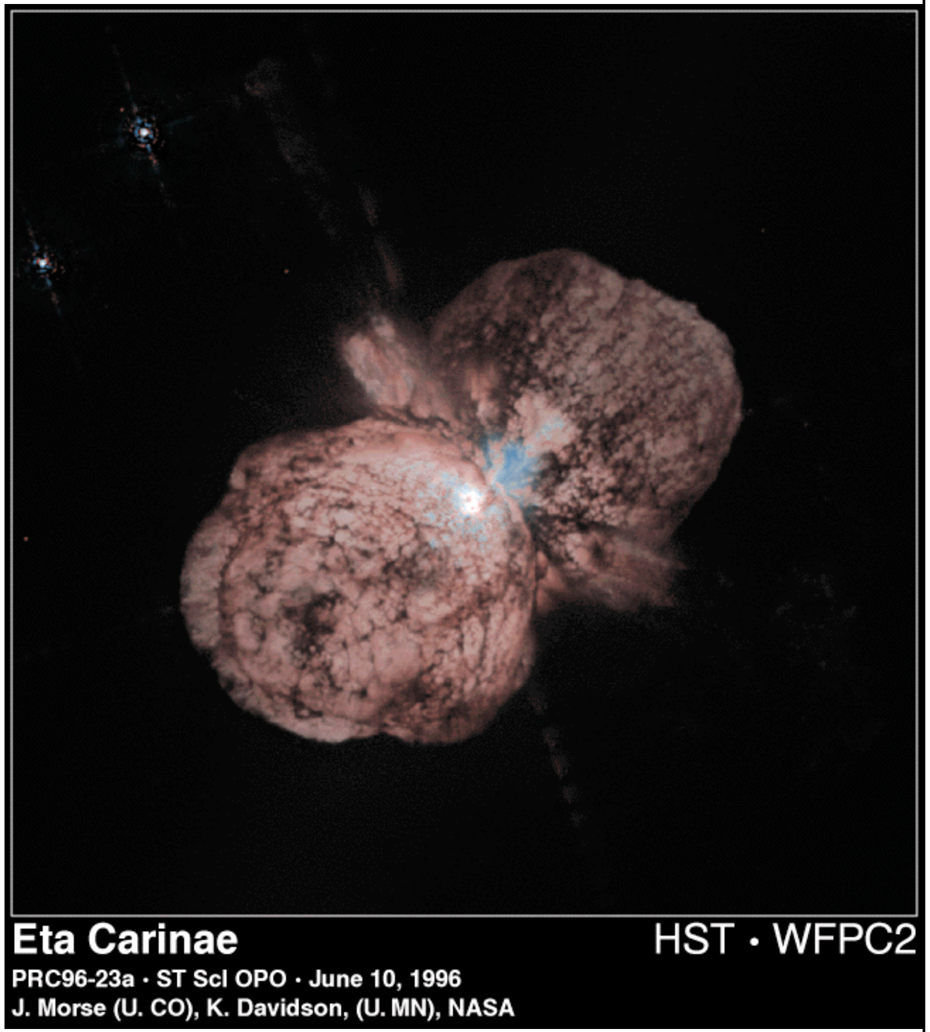
SN 1987A in LMC





Hot star winds also enrich the ISM

- ***Stellar winds:*** radiation pressure blows gas from the surfaces of hot massive stars.
- Can be very eruptive!



l-process: Spallation

D, Li, Be, B are destroyed in stars:
Low binding energies, burn quickly to heavier nuclei.
(Li convects to the core and is destroyed, depleting gradually at star surface, used to estimate ages of low-mass stars).

But, we observe D close to Big Bang predictions, and often higher abundances of Li, Be, B.

Must be produced somewhere after the Big Bang.

l-process (*spallation*):

Accelerate a nucleus to $V \sim c$ (i.e. cosmic rays)
Collide with a heavy nucleus.
Splits yield some Li, Be, B as fragments.

Nucleosynthesis Flowchart