STARS - S08

Wladimir (Wlad) Lyra
Brian Levine

AMNH After-School Program

American
Museum of
Natural
History

From last class

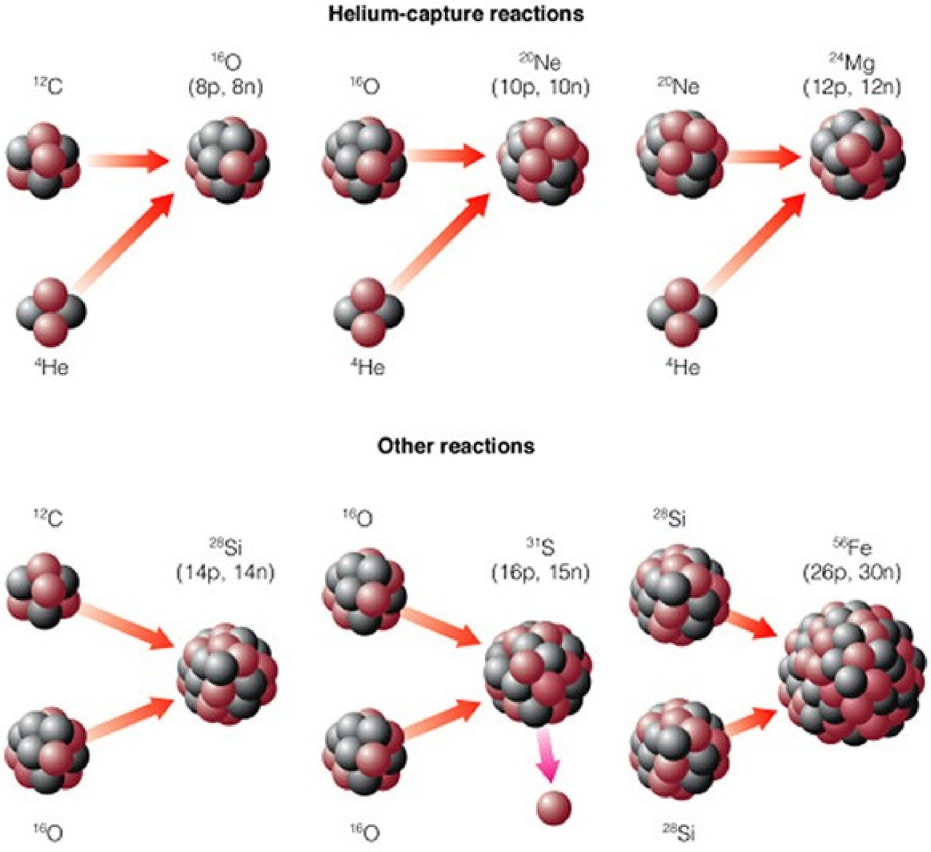
High mass stars have much hotter cores than low mass stars and get to fuse beyond Helium

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)



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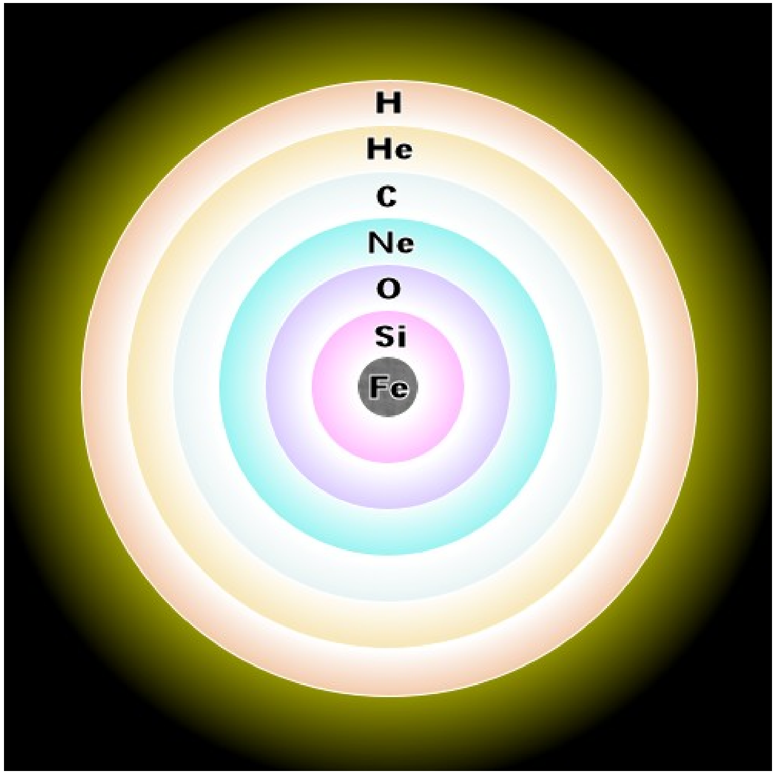

Onion-layer structure

From last class

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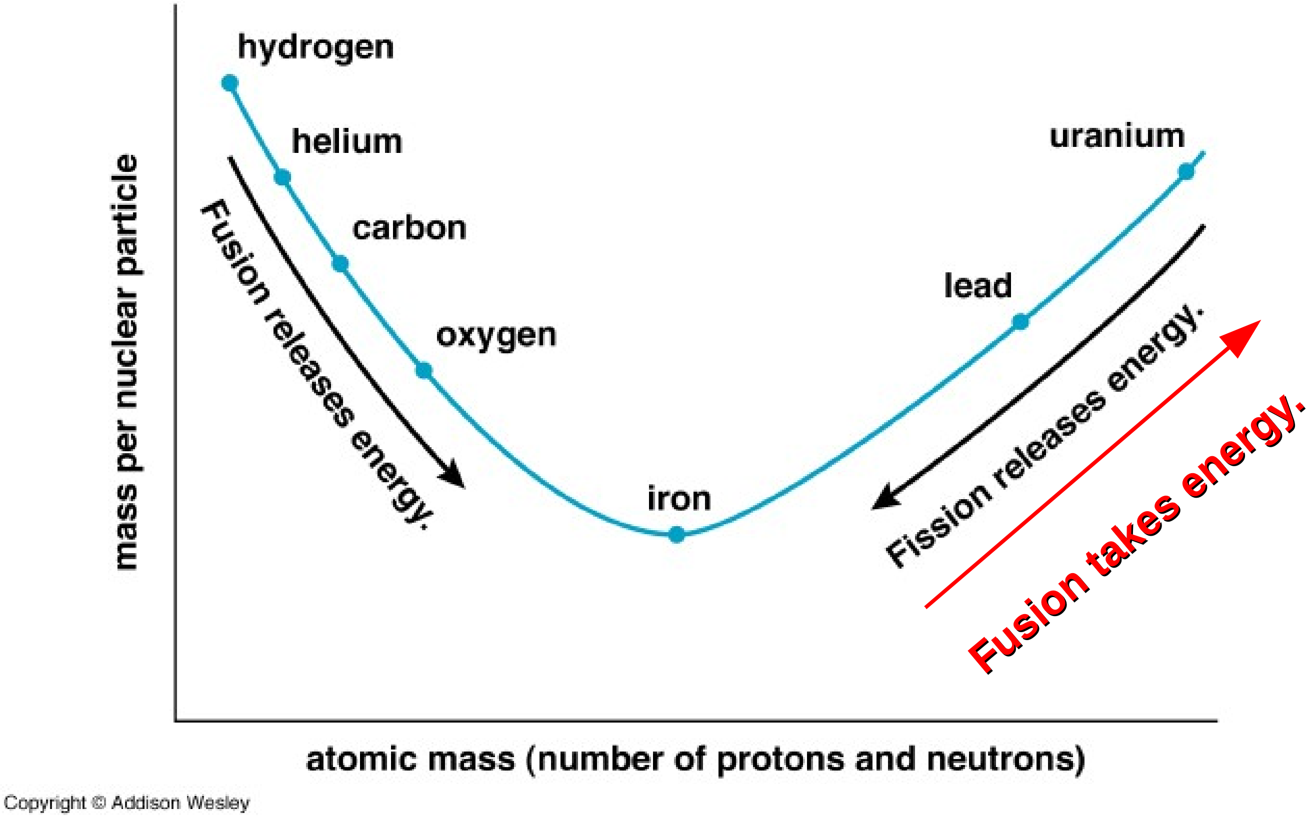

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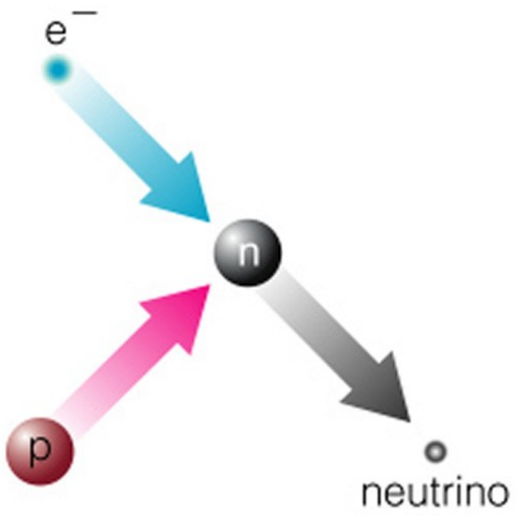

Proton + electron → neutron + neutrino

$$(p + e^- \rightarrow n + \nu)$$

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Beta decay

Neutron → Proton + electron + ***neutrino***

$(n \rightarrow p + e^- + \nu)$

Inverse Beta Decay

Proton + electron → neutron + ***neutrino***

$(p + e^- \rightarrow n + \nu)$

A flood of neutrinos!!

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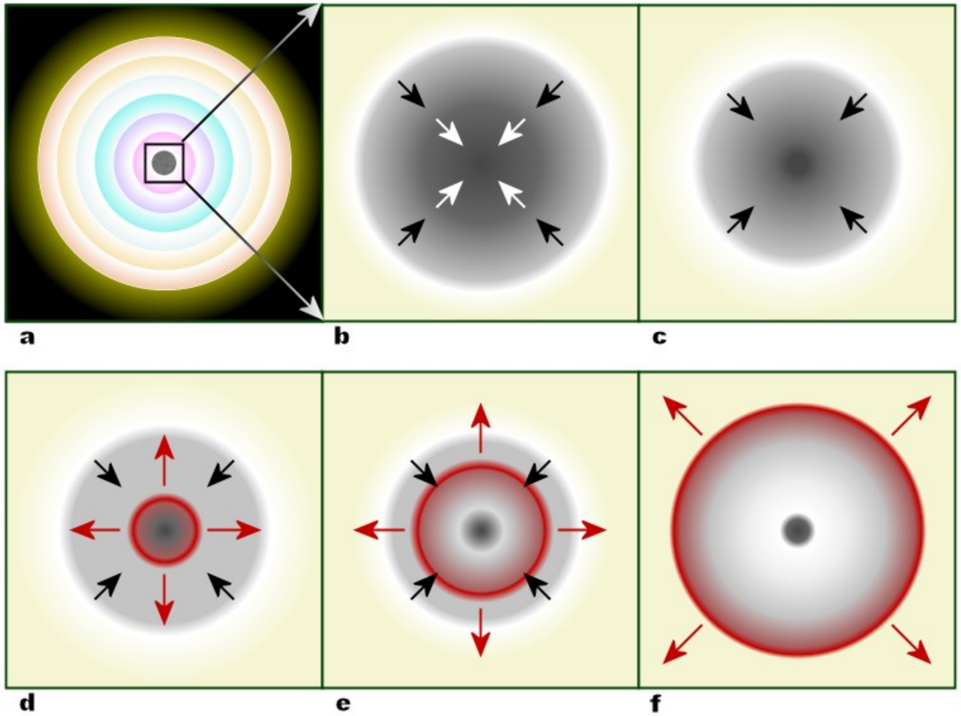

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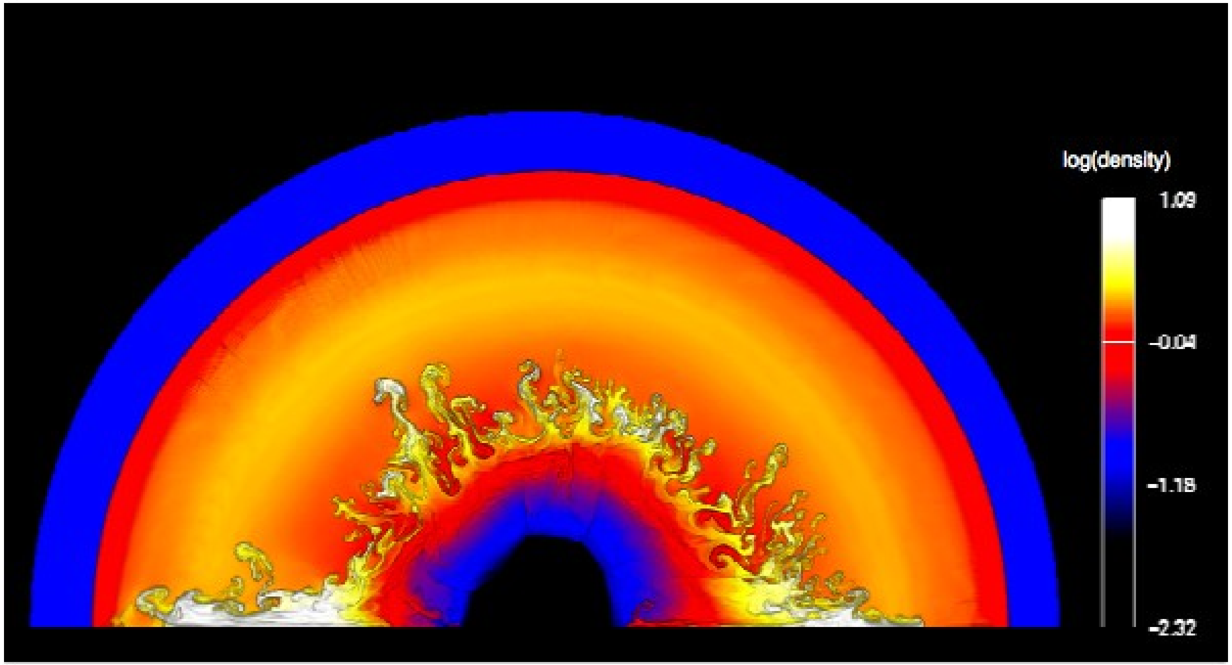

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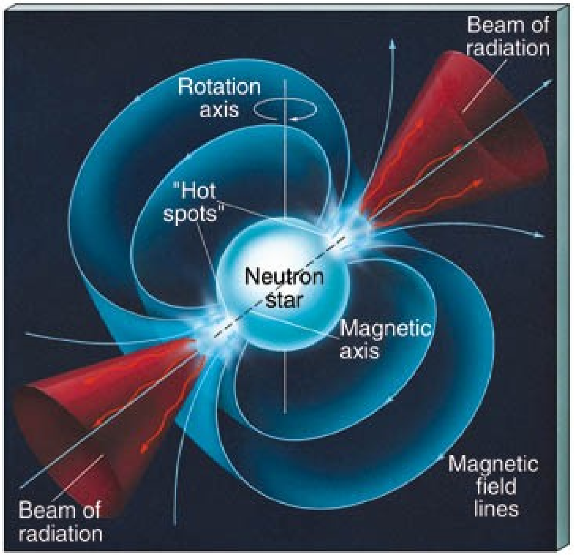
A few hours later, the shockwave reaches the surface. ***Boom!!***

From last class



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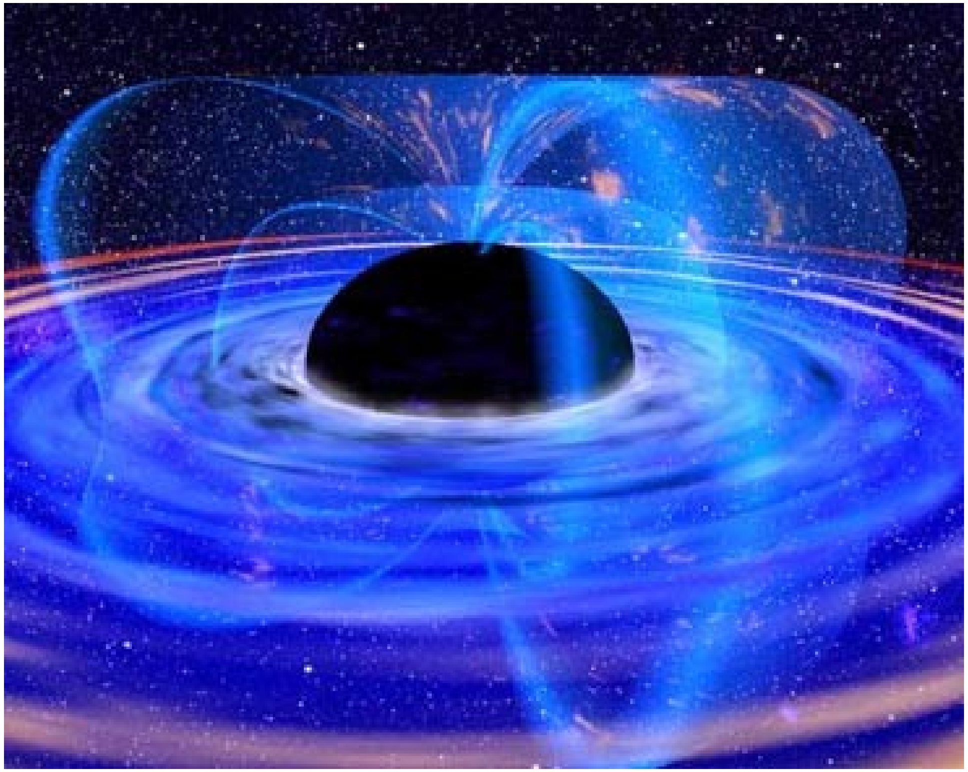

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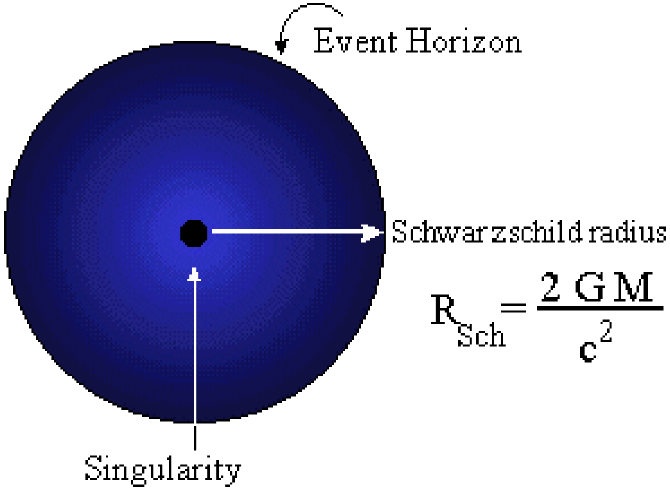
Black holes are simple stuff. They have “no hair”.



$$R_{Sch} = \frac{2\,G\,M}{c^2}$$

Let's summarize

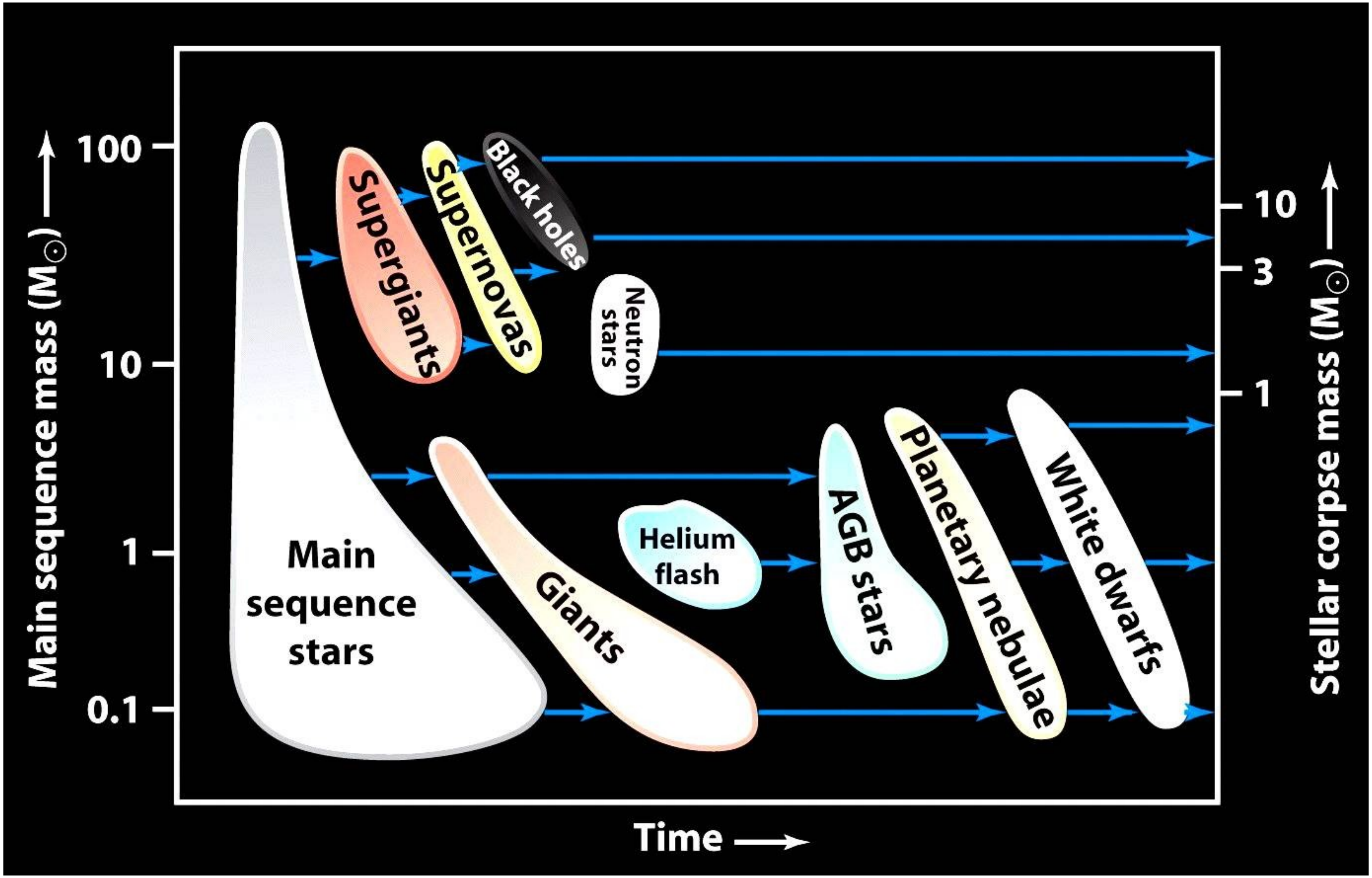
Stellar evolution summary

Higher mass stars develop onion-like structure of nuclear burning shells

Iron is a dead end. Fusion beyond it consumes energy

Urca se

The c ed.



Outline

- Nucleosynthesis
  - Neutron capture
    - S and R process

- Metals and Metallicity

- Chemical Enrichment of the Galaxy
  - Age-Metallicity Relationship
  - Galactic metallicity gradient

- Stellar Populations
  - Is there a difference between halo, bulge and disk stars?
  - Metal poor and metal rich stars

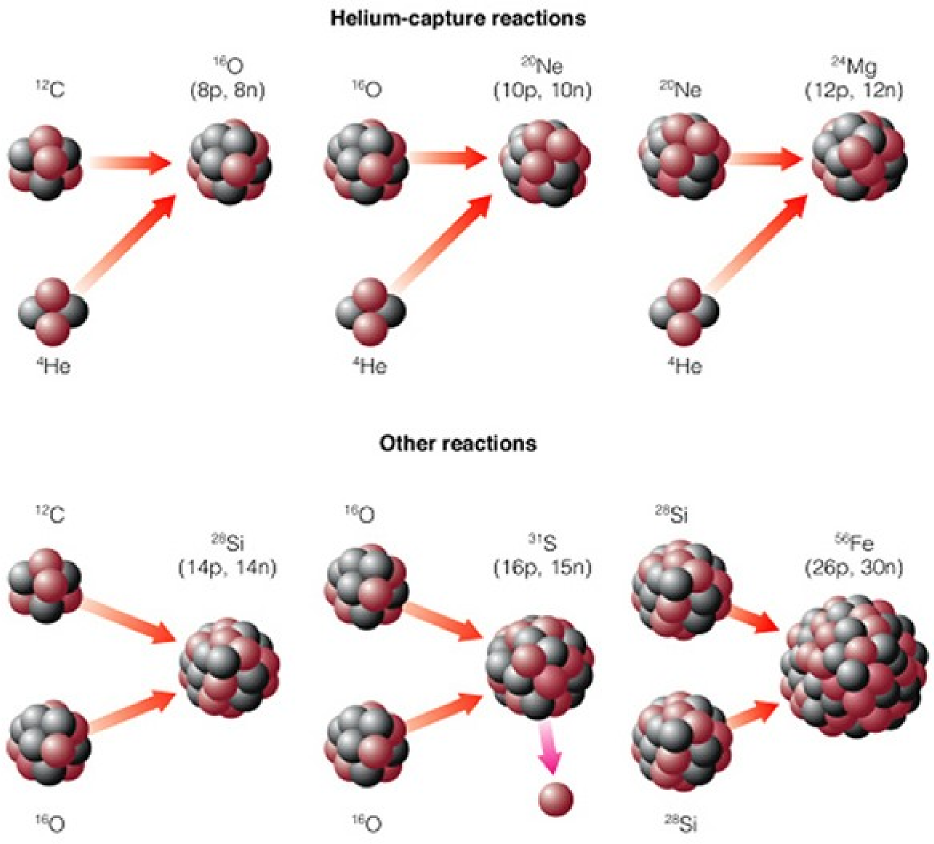
Nucleosynthesis

In the beginning there was Hydrogen and Helium

Low mass stars produce elements up to Carbon and Oxygen

High mass stars produce all the rest of the periodic table

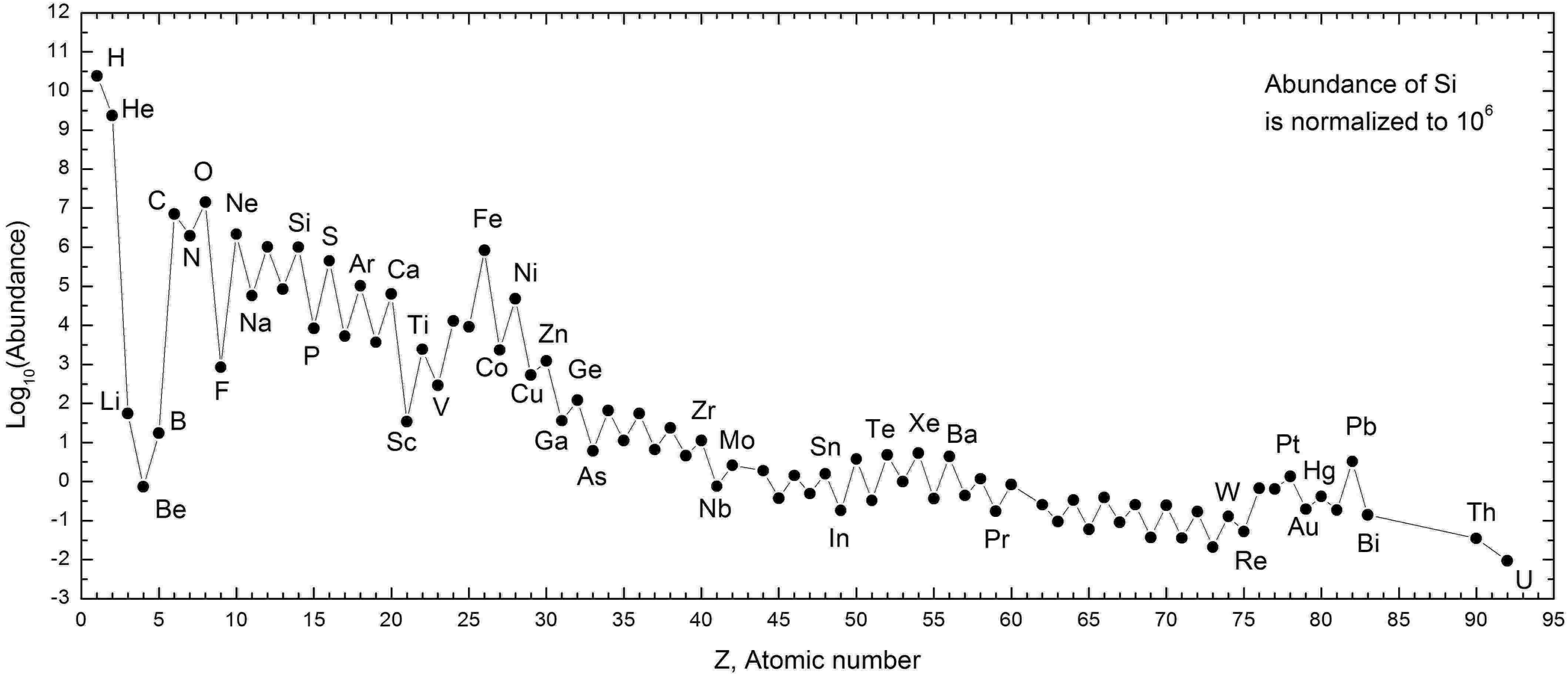
Up to Iron we have basically alpha reactions



Another look at the Sun's abundance pattern

Elements with even atomic number are more abundant than those with odd

An Iron peak.



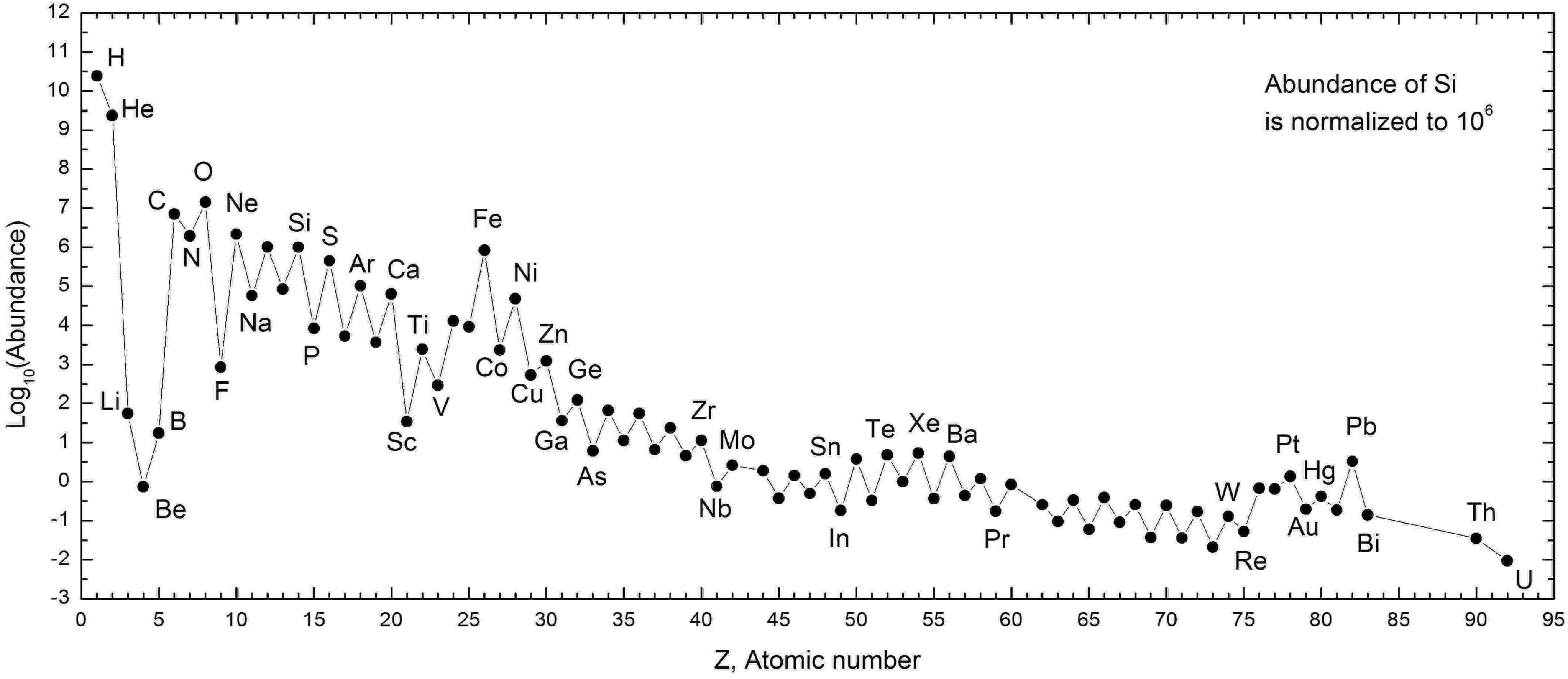
Another look at the Sun's abundance pattern

Elements with even atomic number are more abundant than those with odd

Elements are made by Helium (alpha) capture.

An Iron peak.

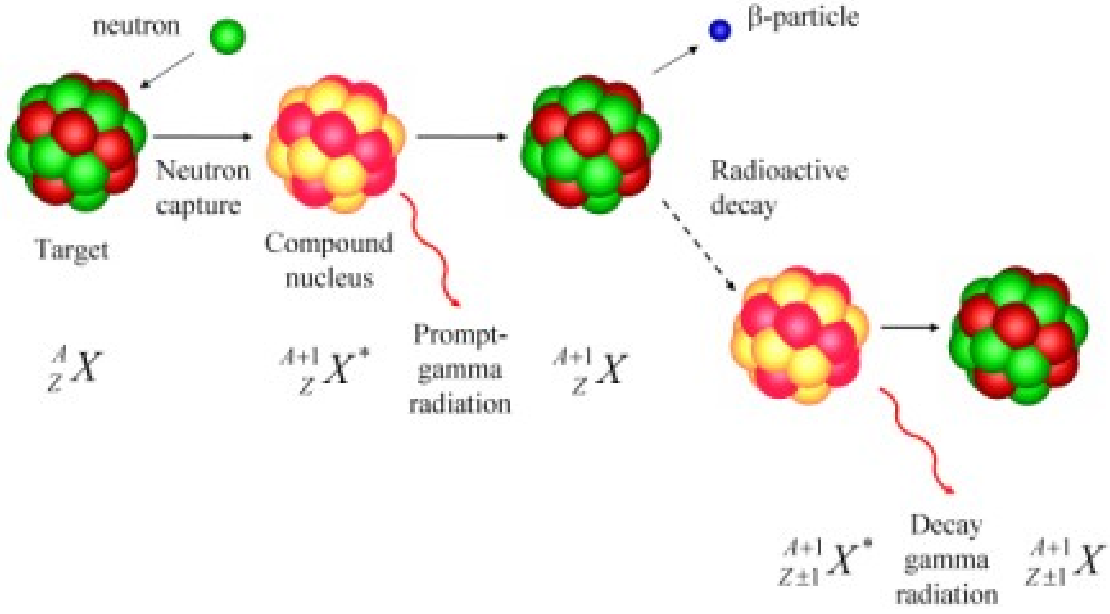
Expected, since Iron is the end of the fusion sequence.



Nucleosynthesis

Beyond the Iron peak, nucleosynthesis occurs by ***neutron capture*** and ***beta decay***

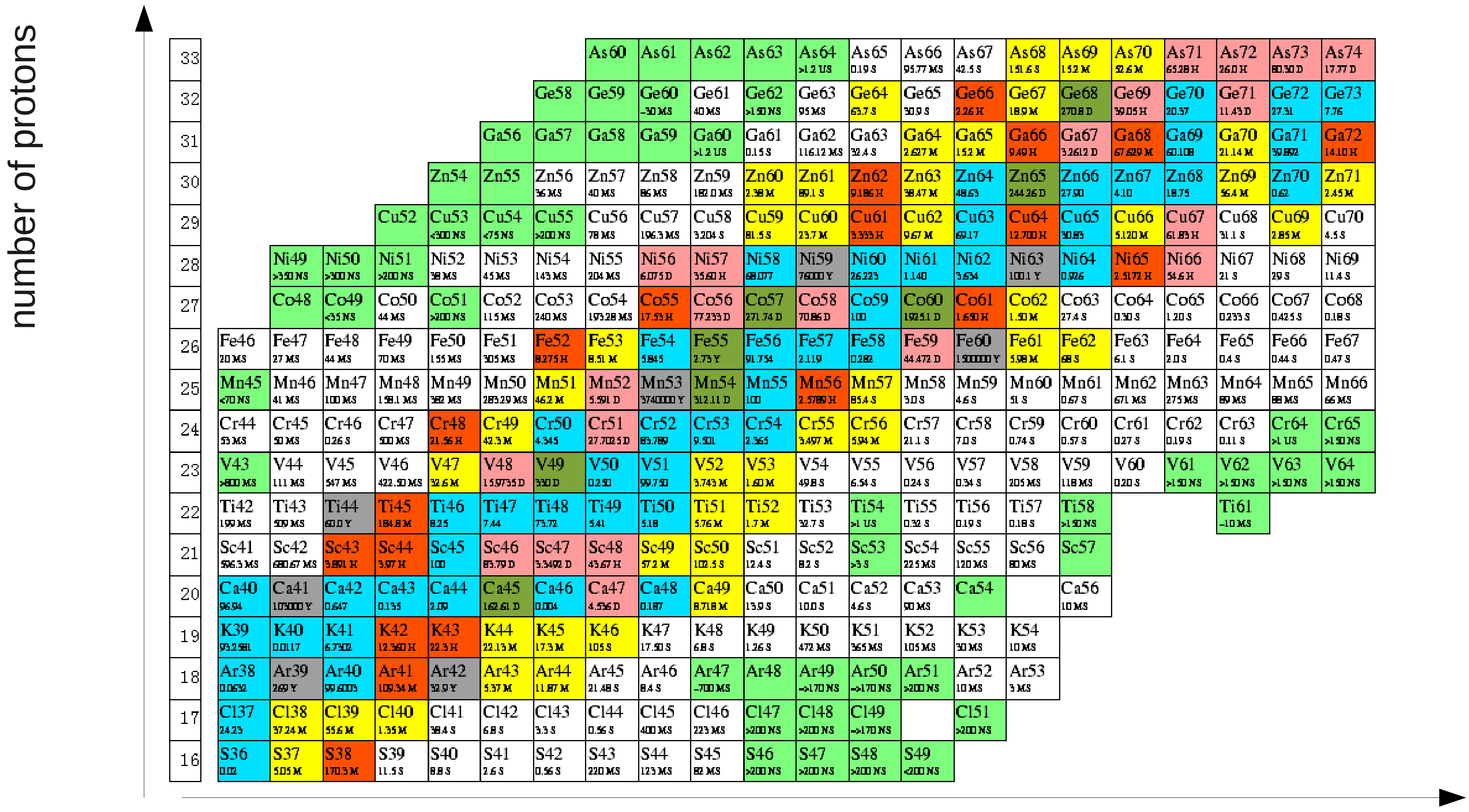
$$(n \rightarrow p + e^- + \nu)$$



Neutron capture produces isotopes
Neutron capture proceeds until the nuclide goes unstable (radioactive)

If a proton decays, the atomic number decreases
But if a neutron decays, the atomic number increases!

A chart of nuclides



33								As60	As61	As62	As63	As64 >1.2 US	As65 0.19 S	As66 95.77 MS	As67 42.5 S	As68 151.6 S	As69 15.2 M	As70 52.6 M	As71 65.28 H	As72 26.0 H	As73 80.30 D	As74 17.77 D
32							Ge58	Ge59	Ge60 –30 MS	Ge61 40 MS	Ge62 >150 NS	Ge63 95 MS	Ge64 63.7 S	Ge65 30.9 S	Ge66 2.26 H	Ge67 18.9 M	Ge68 270.8 D	Ge69 39.05 H	Ge70 20.37	Ge71 11.43 D	Ge72 27.31	Ge73 7.76
31						Ga56	Ga57	Ga58	Ga59	Ga60 >1.2 US	Ga61 0.15 S	Ga62 116.12 MS	Ga63 32.4 S	Ga64 2.627 M	Ga65 15.2 M	Ga66 9.49 H	Ga67 3.2612 D	Ga68 67.629 M	Ga69 60.108	Ga70 21.14 M	Ga71 39.892	Ga72 14.10 H
30					Zn54	Zn55	Zn56 36 MS	Zn57 40 MS	Zn58 86 MS	Zn59 182.0 MS	Zn60 2.38 M	Zn61 89.1 S	Zn62 9.186 H	Zn63 38.47 M	Zn64 48.63	Zn65 244.26 D	Zn66 27.90	Zn67 4.10	Zn68 18.75	Zn69 56.4 M	Zn70 0.62	Zn71 2.45 M
29				Cu52	Cu53 <300 NS	Cu54 <75 NS	Cu55 >200 NS	Cu56 78 MS	Cu57 196.3 MS	Cu58 3.204 S	Cu59 81.5 S	Cu60 23.7 M	Cu61 3.333 H	Cu62 9.67 M	Cu63 69.17	Cu64 12.700 H	Cu65 30.83	Cu66 5.120 M	Cu67 61.83 H	Cu68 31.1 S	Cu69 2.85 M	Cu70 4.5 S
28		Ni49 >350 NS	Ni50 >300 NS	Ni51 >200 NS	Ni52 38 MS	Ni53 45 MS	Ni54 143 MS	Ni55 204 MS	Ni56 6.075 D	Ni57 35.60 H	Ni58 68.077	Ni59 76000 Y	Ni60 26.223	Ni61 1.140	Ni62 3.634	Ni63 100.1 Y	Ni64 0.926	Ni65 2.5172 H	Ni66 54.6 H	Ni67 21 S	Ni68 29 S	Ni69 11.4 S
27		Co48	Co49 <35 NS	Co50 44 MS	Co51 >200 NS	Co52 115 MS	Co53 240 MS	Co54 193.28 MS	Co55 17.53 H	Co56 77.233 D	Co57 271.74 D	Co58 70.86 D	Co59 100	Co60 1925.1 D	Co61 1.650 H	Co62 1.50 M	Co63 27.4 S	Co64 0.30 S	Co65 1.20 S	Co66 0.233 S	Co67 0.425 S	Co68 0.18 S
26	Fe46 20 MS	Fe47 27 MS	Fe48 44 MS	Fe49 70 MS	Fe50 155 MS	Fe51 305 MS	Fe52 8.275 H	Fe53 8.51 M	Fe54 5.845	Fe55 2.73 Y	Fe56 91.754	Fe57 2.119	Fe58 0.282	Fe59 44.472 D	Fe60 1500000 Y	Fe61 5.98 M	Fe62 68 S	Fe63 6.1 S	Fe64 2.0 S	Fe65 0.4 S	Fe66 0.44 S	Fe67 0.47 S
25	Mn45 <70 NS	Mn46 41 MS	Mn47 100 MS	Mn48 158.1 MS	Mn49 382 MS	Mn50 283.29 MS	Mn51 46.2 M	Mn52 5.591 D	Mn53 3740000 Y	Mn54 312.11 D	Mn55 100	Mn56 2.5789 H	Mn57 85.4 S	Mn58 3.0 S	Mn59 4.6 S	Mn60 51 S	Mn61 0.67 S	Mn62 671 MS	Mn63 275 MS	Mn64 89 MS	Mn65 88 MS	Mn66 66 MS
24	Cr44 53 MS	Cr45 50 MS	Cr46 0.26 S	Cr47 500 MS	Cr48 21.56 H	Cr49 42.3 M	Cr50 4.345	Cr51 27.7025 D	Cr52 83.789	Cr53 9.501	Cr54 2.365	Cr55 3.497 M	Cr56 5.94 M	Cr57 21.1 S	Cr58 7.0 S	Cr59 0.74 S	Cr60 0.57 S	Cr61 0.27 S	Cr62 0.19 S	Cr63 0.11 S	Cr64 >1 US	Cr65 >150 NS
23	V43 >800 MS	V44 111 MS	V45 547 MS	V46 422.50 MS	V47 32.6 M	V48 15.9735 D	V49 330 D	V50 0.250	V51 99.750	V52 3.743 M	V53 1.60 M	V54 49.8 S	V55 6.54 S	V56 0.24 S	V57 0.34 S	V58 205 MS	V59 118 MS	V60 0.20 S	V61 >150 NS	V62 >150 NS	V63 >150 NS	V64 >150 NS
22	Ti42 199 MS	Ti43 509 MS	Ti44 60.0 Y	Ti45 184.8 M	Ti46 8.25	Ti47 7.44	Ti48 73.72	Ti49 5.41	Ti50 5.18	Ti51 5.76 M	Ti52 1.7 M	Ti53 32.7 S	Ti54 >1 US	Ti55 0.32 S	Ti56 0.19 S	Ti57 0.18 S	Ti58 >150 NS			Ti61 –10 MS		
21	Sc41 596.3 MS	Sc42 680.67 MS	Sc43 3.891 H	Sc44 3.97 H	Sc45 100	Sc46 83.79 D	Sc47 3.3492 D	Sc48 43.67 H	Sc49 57.2 M	Sc50 102.5 S	Sc51 12.4 S	Sc52 8.2 S	Sc53 >3 S	Sc54 22.5 MS	Sc55 120 MS	Sc56 80 MS	Sc57					
20	Ca40 96.94	Ca41 103000 Y	Ca42 0.647	Ca43 0.135	Ca44 2.09	Ca45 162.61 D	Ca46 0.004	Ca47 4.536 D	Ca48 0.187	Ca49 8.718 M	Ca50 13.9 S	Ca51 10.0 S	Ca52 4.6 S	Ca53 90 MS	Ca54		Ca56 10 MS					
19	K39 93.2581	K40 0.0117	K41 6.7302	K42 12.360 H	K43 22.3 H	K44 22.13 M	K45 17.3 M	K46 105 S	K47 17.50 S	K48 6.8 S	K49 1.26 S	K50 472 MS	K51 365 MS	K52 105 MS	K53 30 MS	K54 10 MS						
18	Ar38 0.0632	Ar39 269 Y	Ar40 99.6003	Ar41 109.34 M	Ar42 32.9 Y	Ar43 5.37 M	Ar44 11.87 M	Ar45 21.48 S	Ar46 8.4 S	Ar47 –700 MS	Ar48	Ar49 –>170 NS	Ar50 –>170 NS	Ar51 >200 NS	Ar52 10 MS	Ar53 3 MS						
17	Cl37 24.23	Cl38 37.24 M	Cl39 55.6 M	Cl40 1.35 M	Cl41 38.4 S	Cl42 6.8 S	Cl43 3.3 S	Cl44 0.56 S	Cl45 400 MS	Cl46 223 MS	Cl47 >200 NS	Cl48 >200 NS	Cl49 –>170 NS		Cl51 >200 NS							
16	S36 0.02	S37 5.05 M	S38 170.3 M	S39 11.5 S	S40 8.8 S	S41 2.6 S	S42 0.56 S	S43 220 MS	S44 123 MS	S45 82 MS	S46 >200 NS	S47 >200 NS	S48 >200 NS	S49 <200 NS								

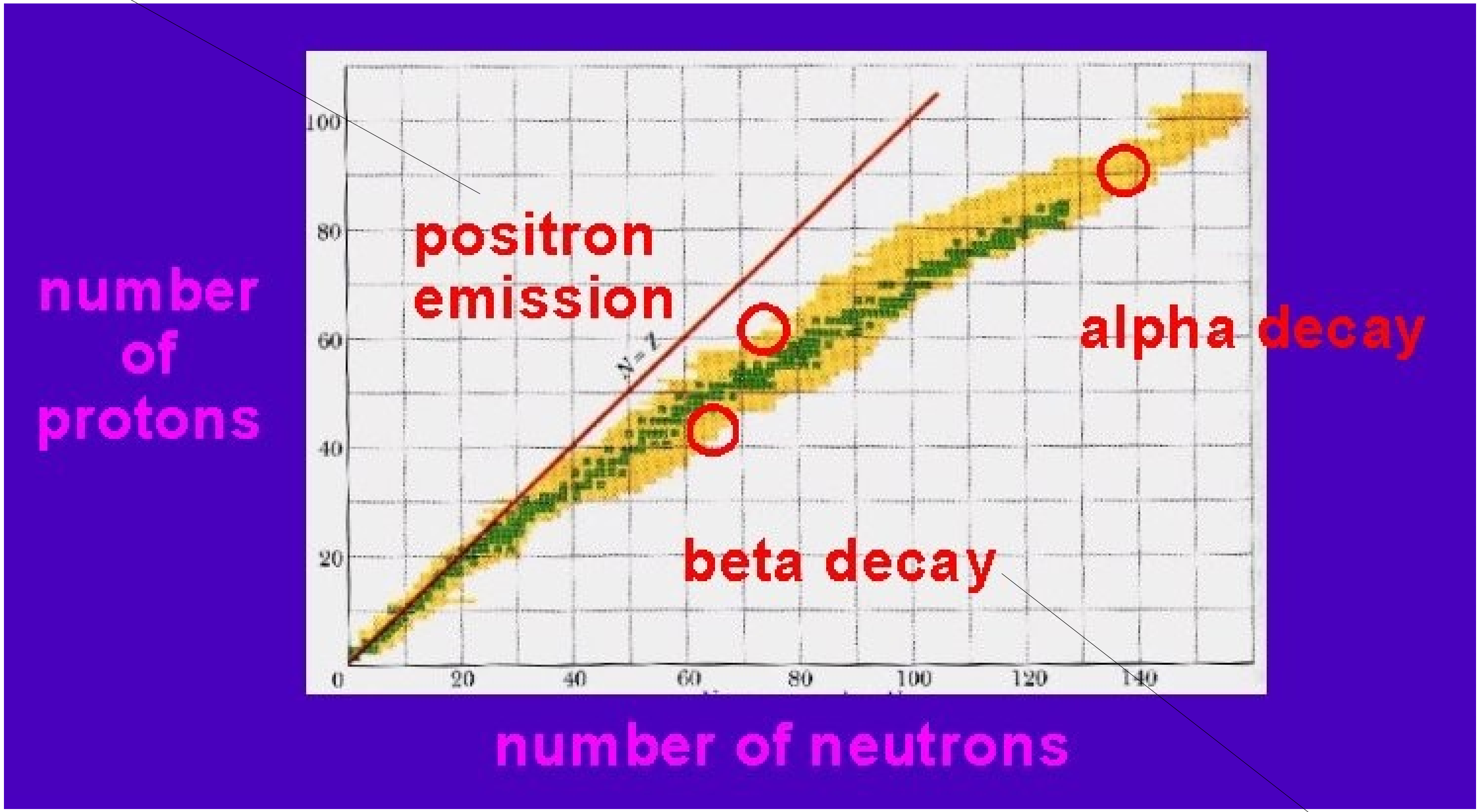
Color code represents lifetime

Blue: Stable

White: Unstable

Climbing the periodic table

Proton decays



Neutron decays

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Works up to bismuth (Z=83)

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AGB stars + Supernovae

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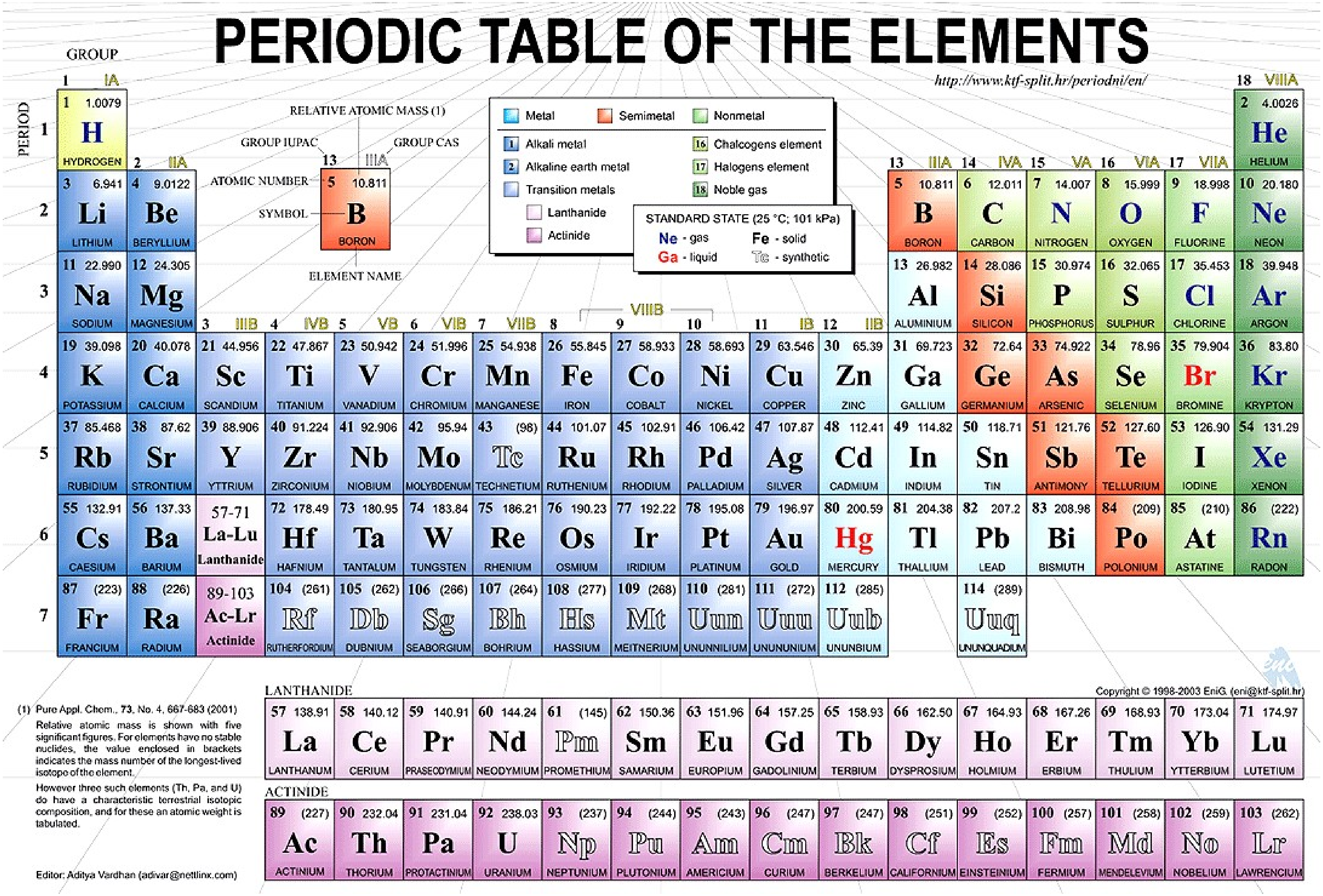
Really heavy stuff
All the way to Uranium

Where?
Supernovae



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

GROUP IUPAC 13, GROUP CAS IIIA
ATOMIC NUMBER 5, RELATIVE ATOMIC MASS (1) 10.811
SYMBOL B
ELEMENT NAME BORON

🟦 Metal	🟥 Semimetal	🟩 Nonmetal	
1 Alkali metal	16 Chalcogens element		
2 Alkaline earth metal	17 Halogens element		
Transition metals	18 Noble gas		
Lanthanide			
Actinide			

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netlinx.com)

Nucleosynthesis

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The process is classified according to the neutron flux

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(slow neutron capture)

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Where?
AGB stars + Supernovae

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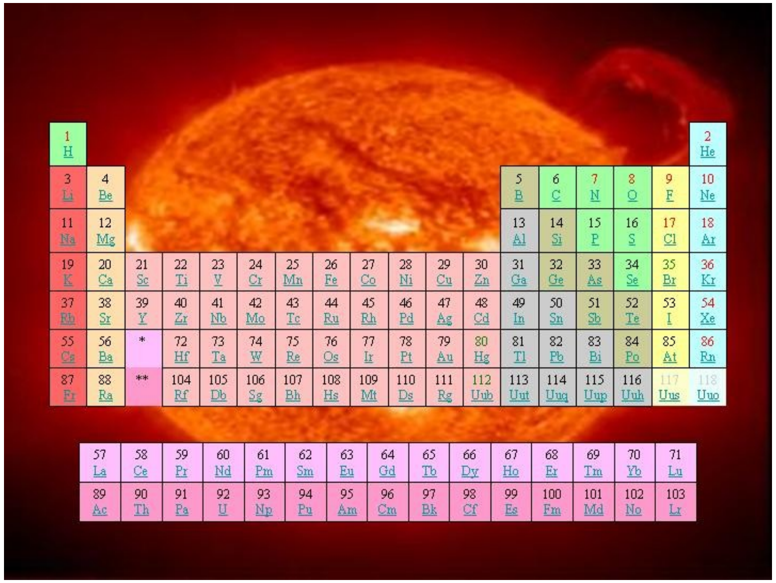
Supernovae

Nucleosynthesis

Element	# of Protons	Site
H	1	Big Bang
He, C, O	2,6,8	Big Bang + Low and High Mass stars
Ne - Fe	10-26	High mass stars
Co - Bi	27-83	S and R process, ABG and SN
Po - U	84-92	R process in SN



Chemical Enrichment of the Galaxy

In the beginning there was
Hydrogen and Helium

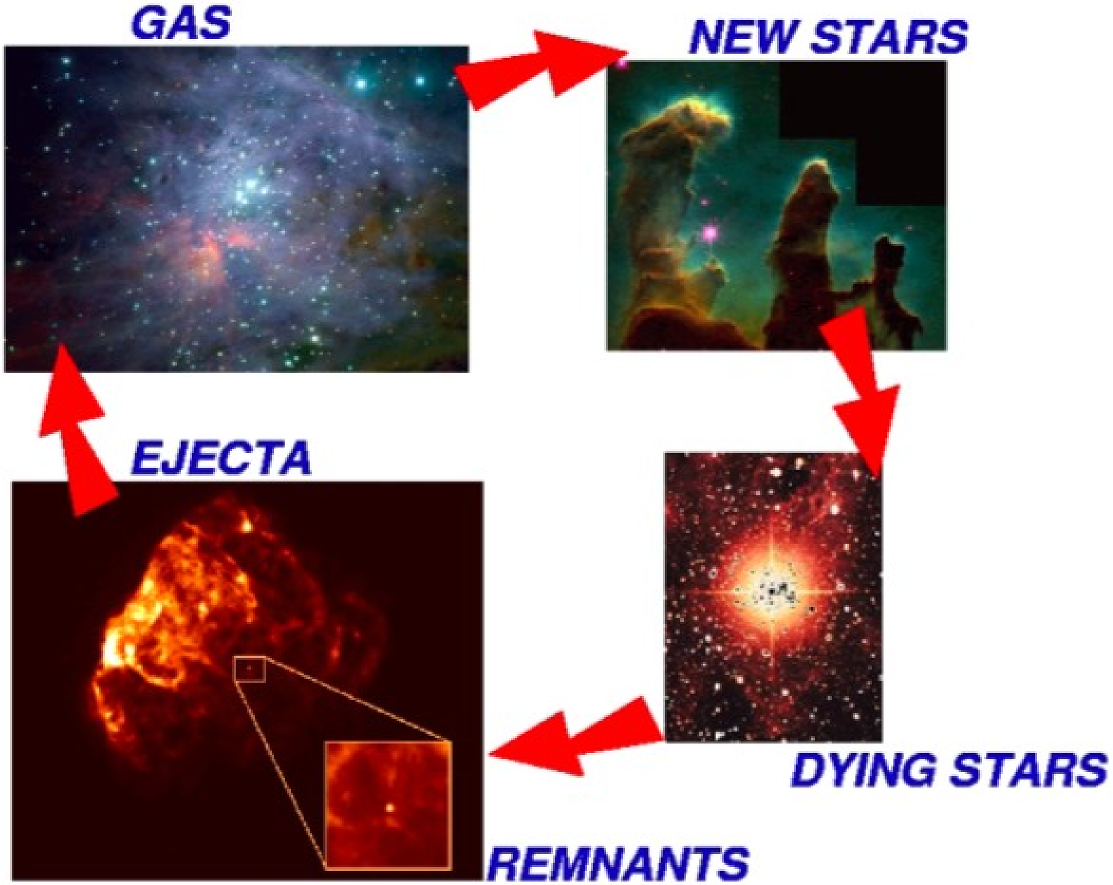
Stars form

Planetary Nebulae and **Supernovae** eject gas **enriched in metals** into the ISM

Recycling of matter

Remember, supernovae are massive stars, they live shortly (10 Myr or less). The SN recycling is practically instantaneous!

New generations of stars are enriched in metals.



Chemical Enrichment of the Galaxy

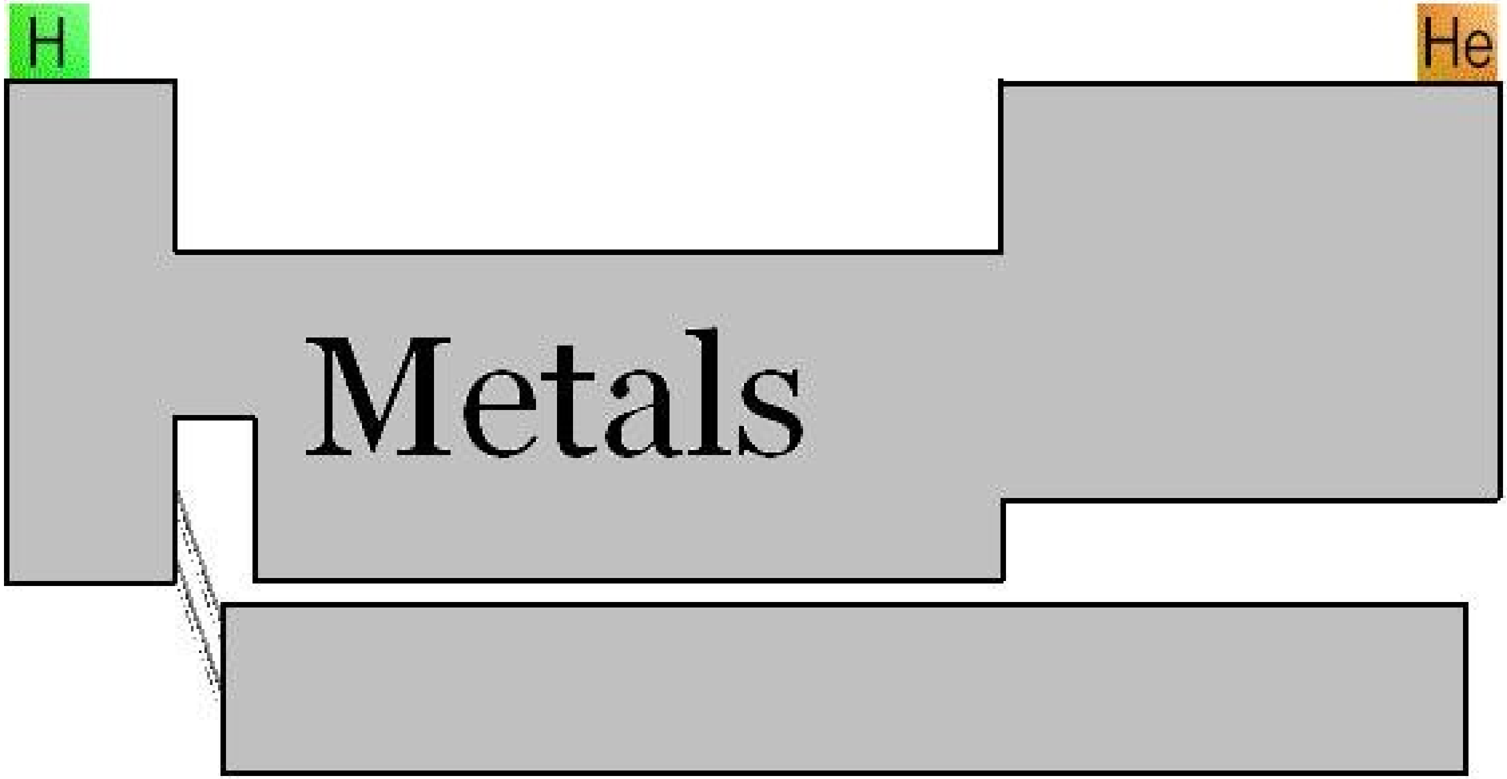
Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

The Astronomer's Periodic Table



Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

X: Hydrogen abundance
Y: Helium abundance
Z: All the rest (i.e., abundance of metals)

$$X+Y+Z=1$$

Sun: X=0.749, Y=0.238, Z=0.013

Some astrochemistry jargon

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The Astronomer's *Simplified* Periodic Table

H	He	Z

Some astrochemistry jargon

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Metallicity

Iron abundance (normalized to solar)

$$[Fe/H] = \log\left(\frac{N_{Fe}}{N_H}\right)_{\star} - \log\left(\frac{N_{Fe}}{N_H}\right)_{\odot}$$

Sun: [Fe/H] = 0.0

Metallicity

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$$[Fe/H] = \log\left(\frac{N_{Fe}}{N_H}\right)_{\star} - \log\left(\frac{N_{Fe}}{N_H}\right)_{\odot}$$

Sun: [Fe/H] = 0.0

Negative → Less metals than the Sun

Positive → More metals than the Sun

Chemical Enrichment of the Galaxy

In the beginning there was
Hydrogen and Helium

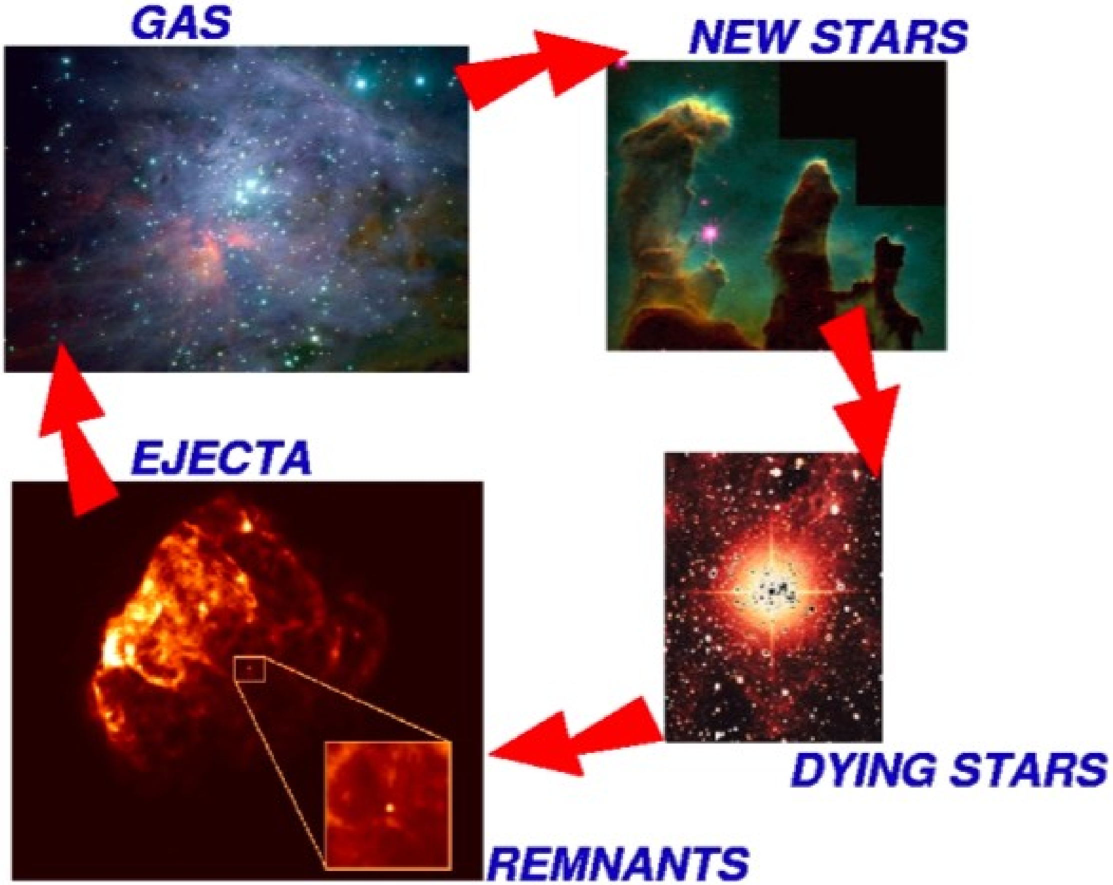
Stars form

Planetary Nebulae and **Supernovae** eject gas **enriched in metals** into the ISM

Recycling of matter

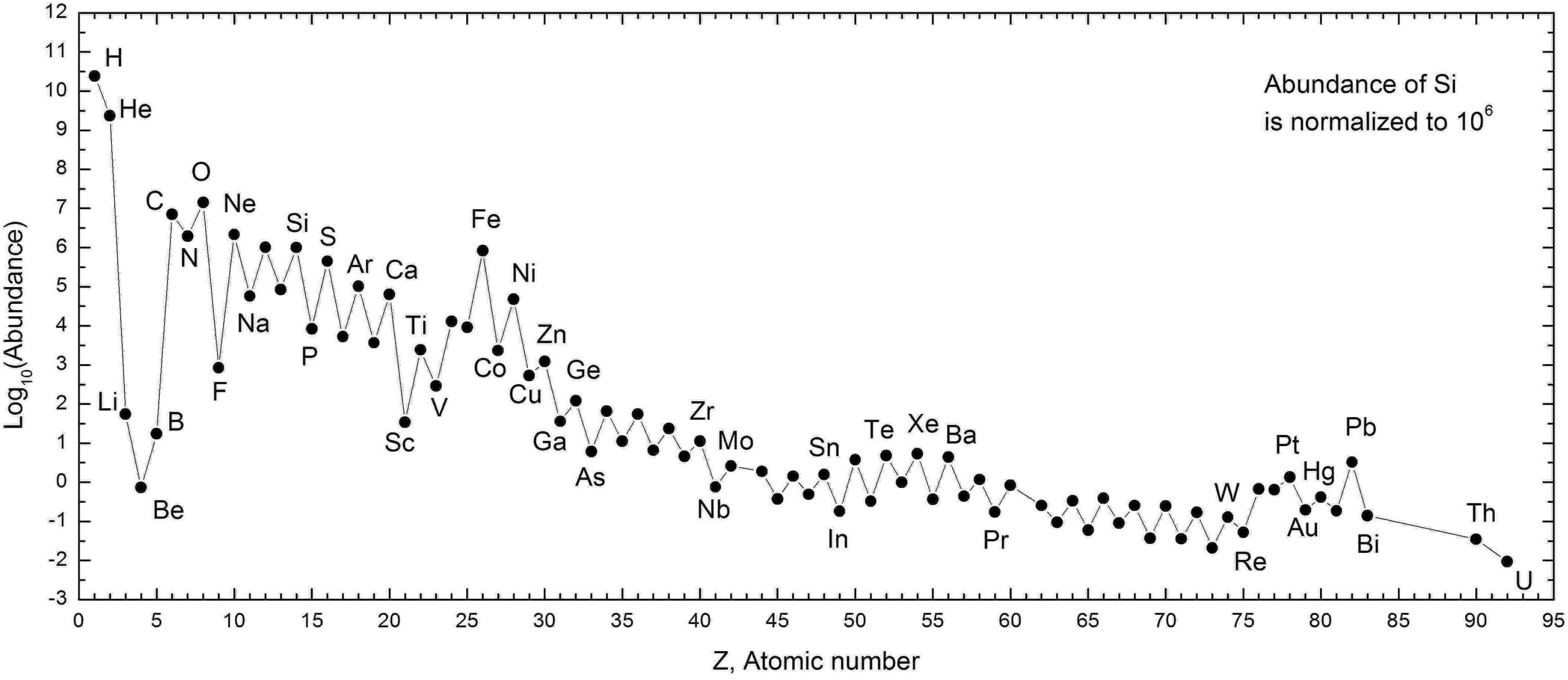
Remember, supernovae are massive stars, they live shortly (10 Myr or less). The SN recycling is practically instantaneous!

New generations of stars are enriched in metals.



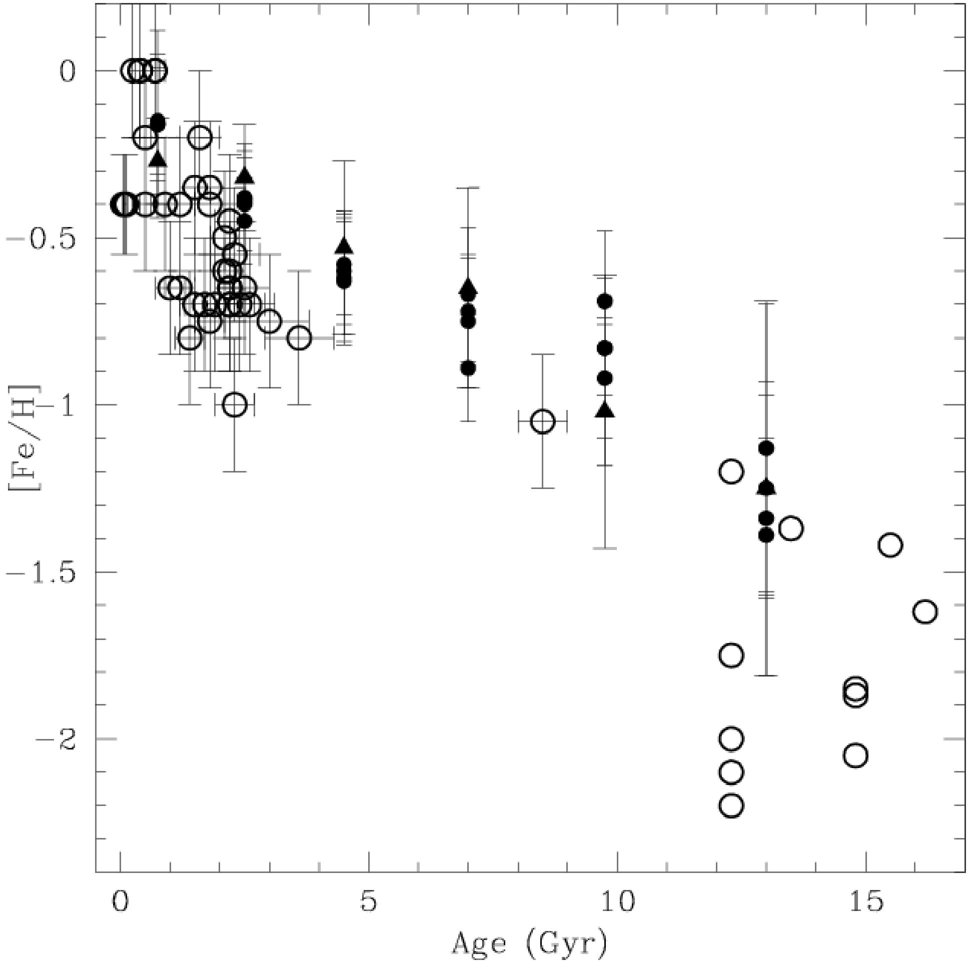
Insight

The Sun (or stars in general) do NOT self-enrich its atmosphere. They were formed out of gas that already contained those elements.



Age-Metallicity Relationship

The **overall metallicity** of the Galaxy **increases in time**
as successive generations of stars enrich the ISM

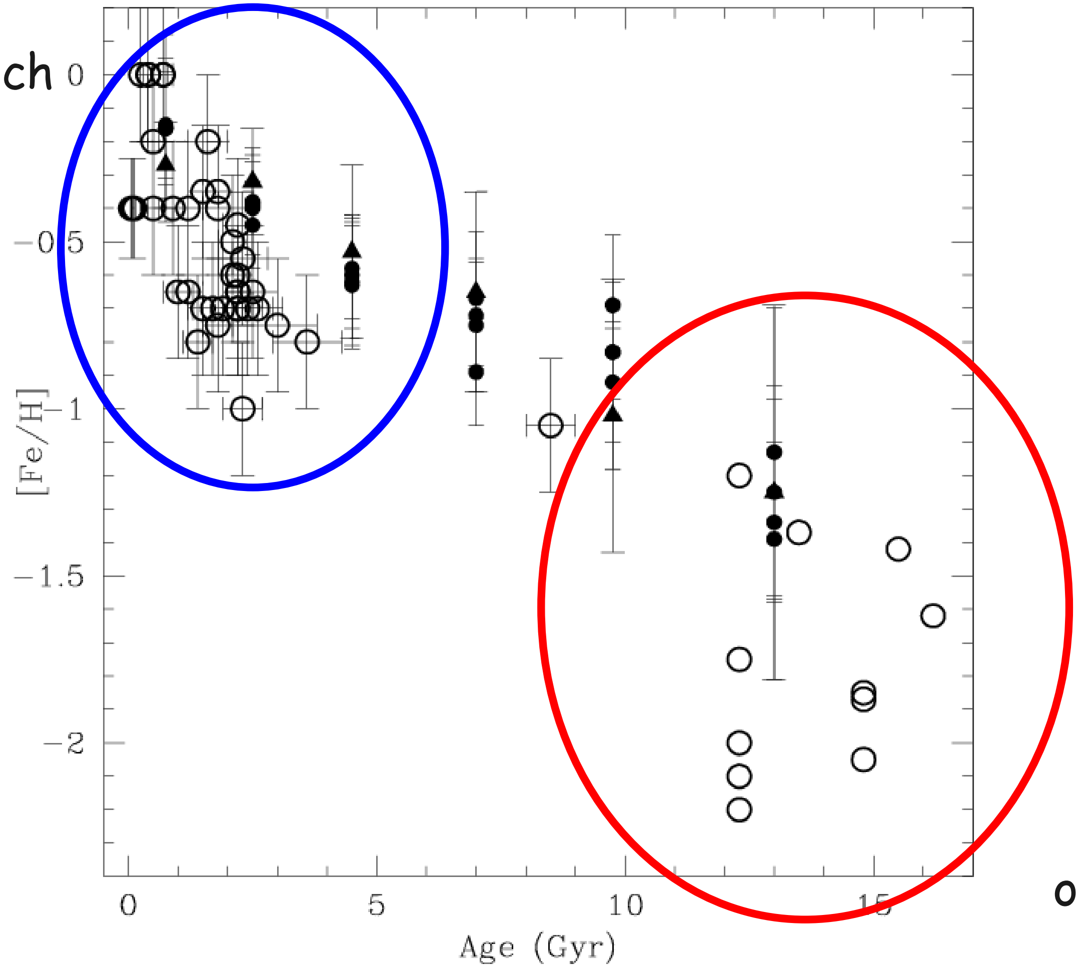


Age of the stars

Stellar Populations

More old terminology we are stuck with

Population I
young and metal-rich

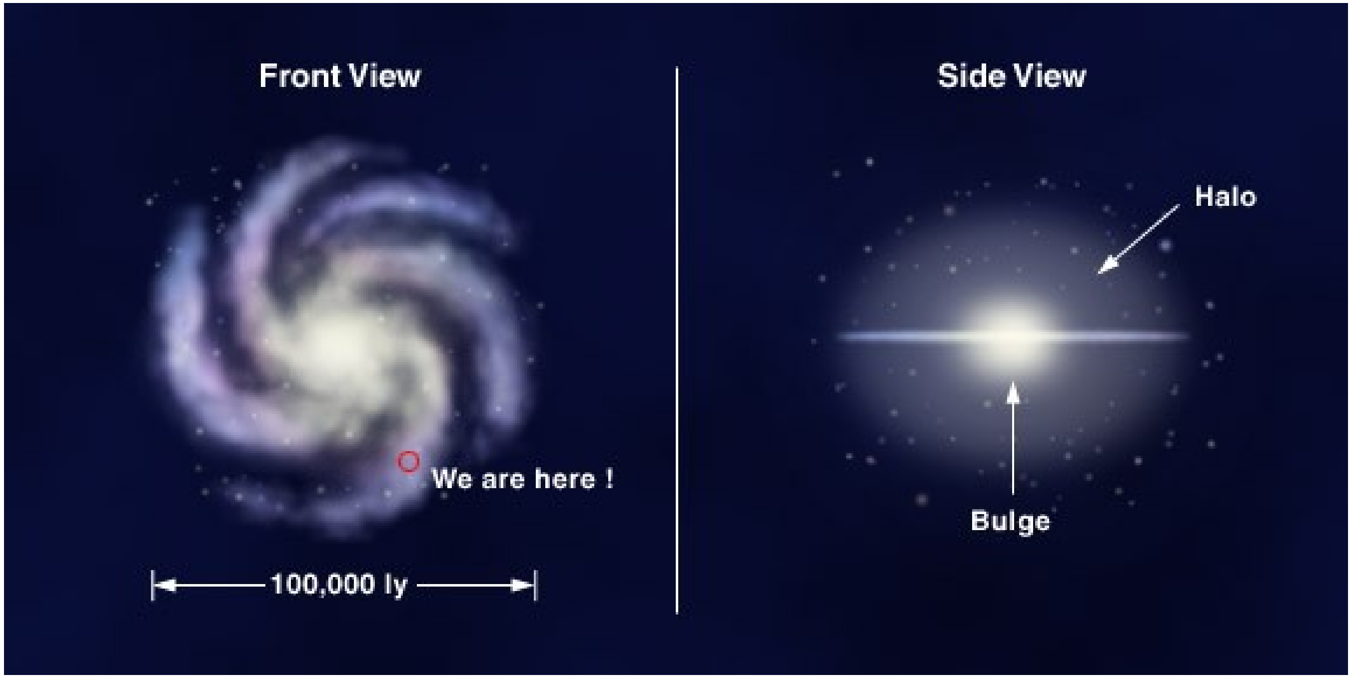


Population II
old and metal-poor

Age of the stars

Stellar Populations

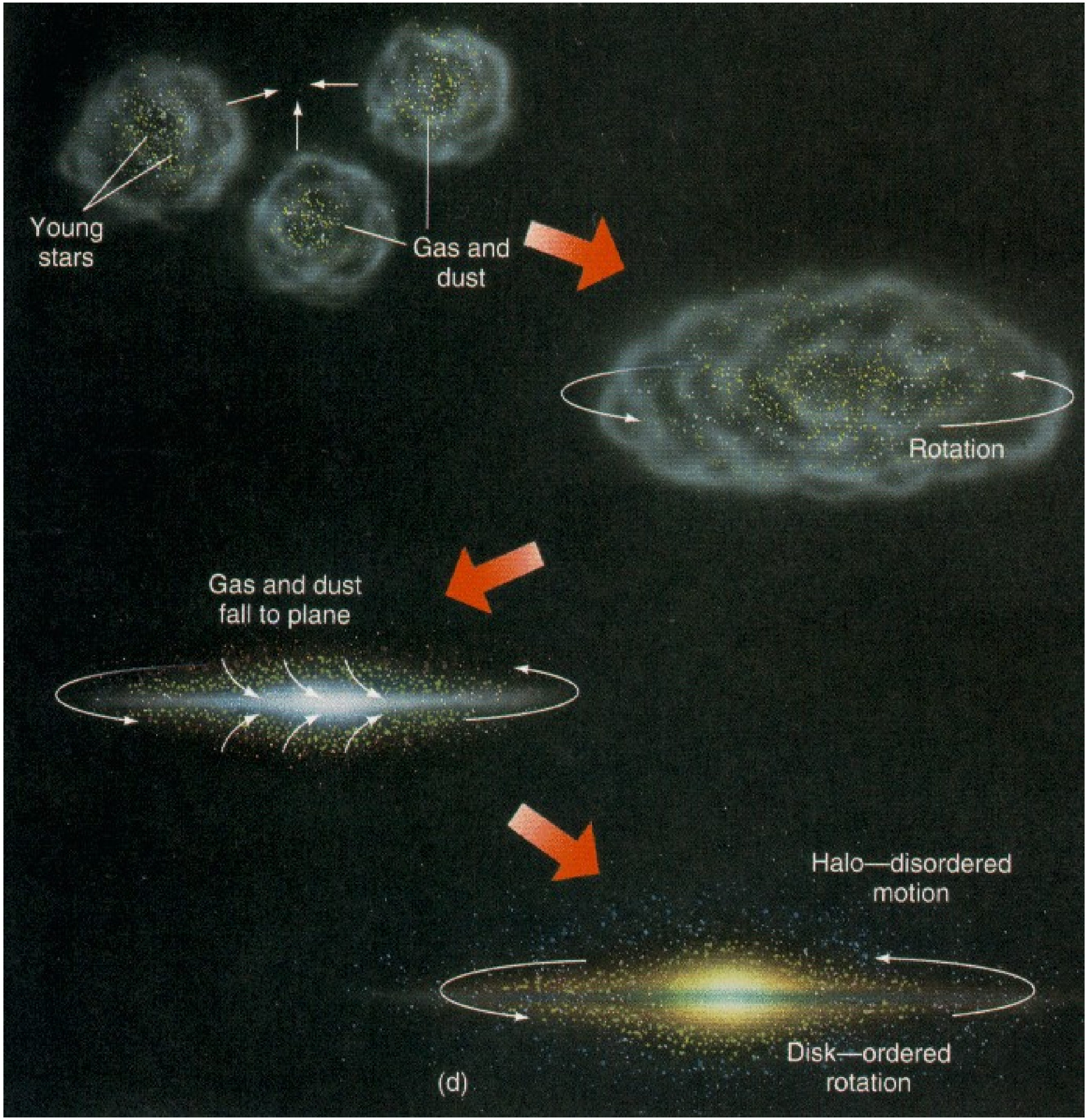
Where do we find the different populations?



Galactic Structure

Bulge
Halo
Disk

Galaxy formation



The **Halo** is the first structure that forms, during the collapse of the original cloud

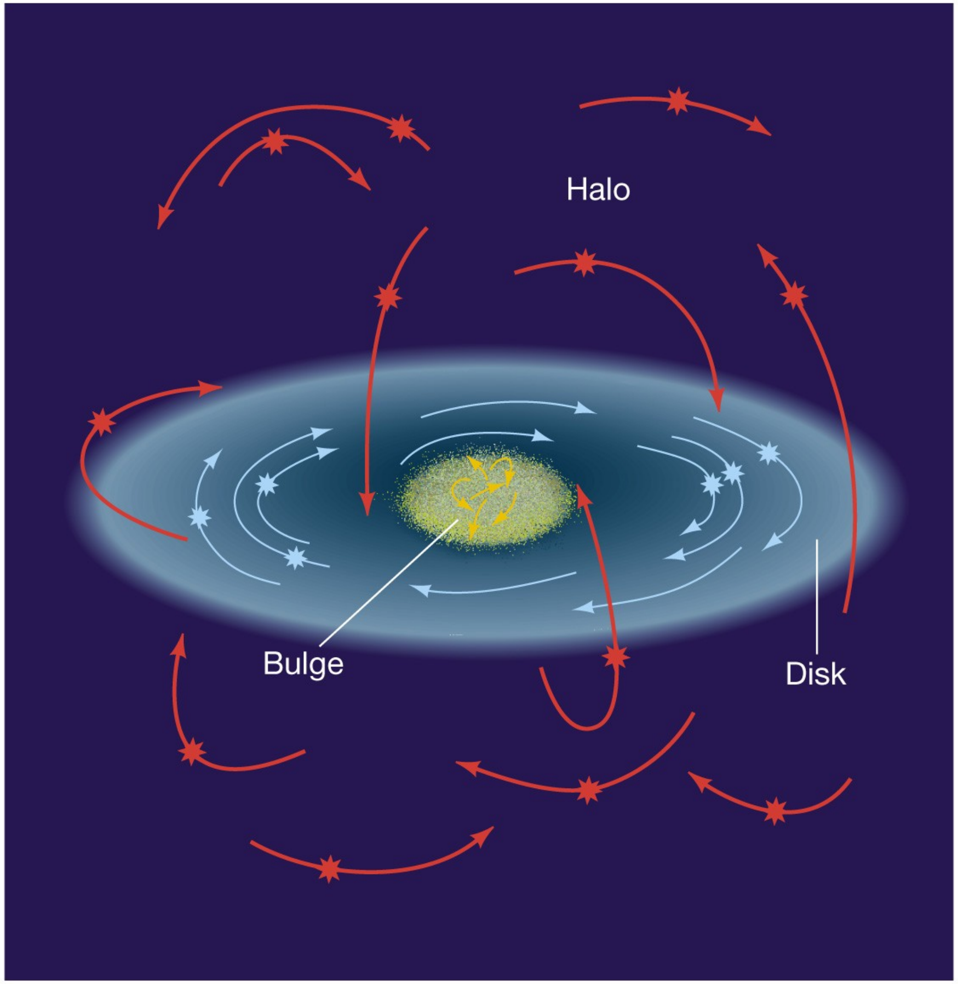
The **Disk** forms later, as the gas settles

Halo: disordered motion
Disk: ordered motion

Stellar Populations

Population II
old and metal-poor
Halo Stars

Star formation ceased long ago

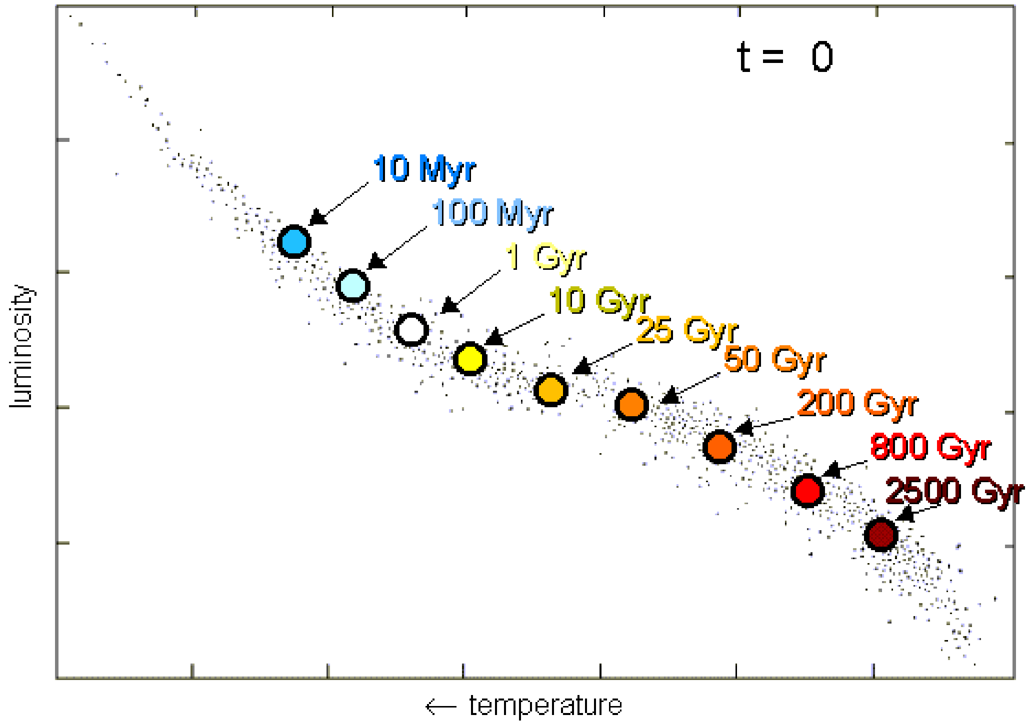


Population I
young and metal-rich

Disk Stars

Star formation is ongoing

Insight



Blue stars are invariably young

Red stars are usually (but not always) old

Example of Population I – Young Open Clusters

Open Clusters are usually young

Why? Because they are formed in the ***disk***, and are subject to Galactic tides!
(there is a lot of gas around)

They are disrupted in a few orbits
They retain their physical integrity only for a few millions of years, before the stars disperse
Still hanging around their birthplaces – the **Spiral Arms**

All disk stars (the Sun included) were born in Open Clusters

The Pleiades

Are there old open clusters?

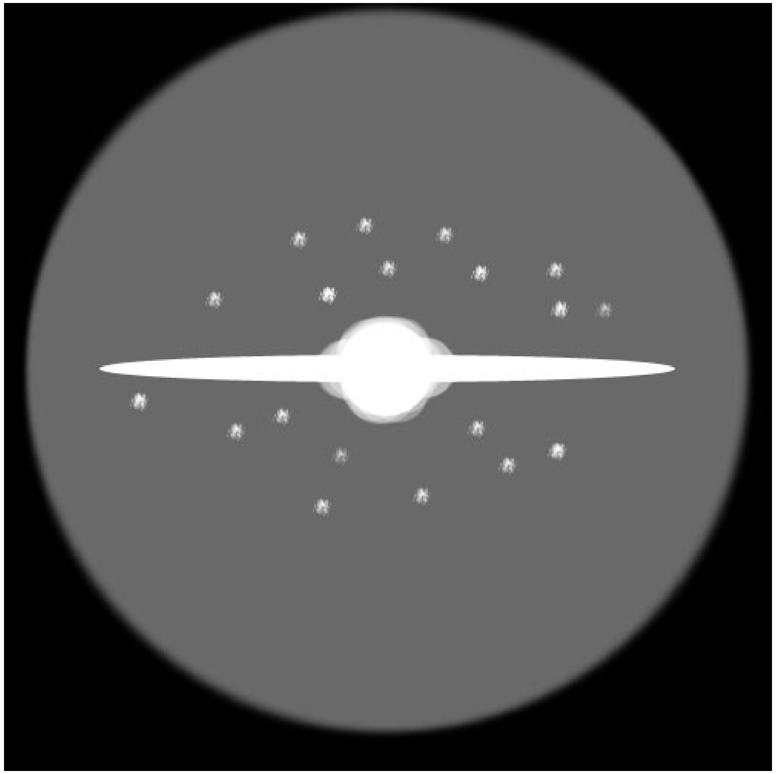
Yes, **M67**, for instance, which is **4 Gyr old**

It is an open cluster that is **massive** enough to remain gravitationally bound

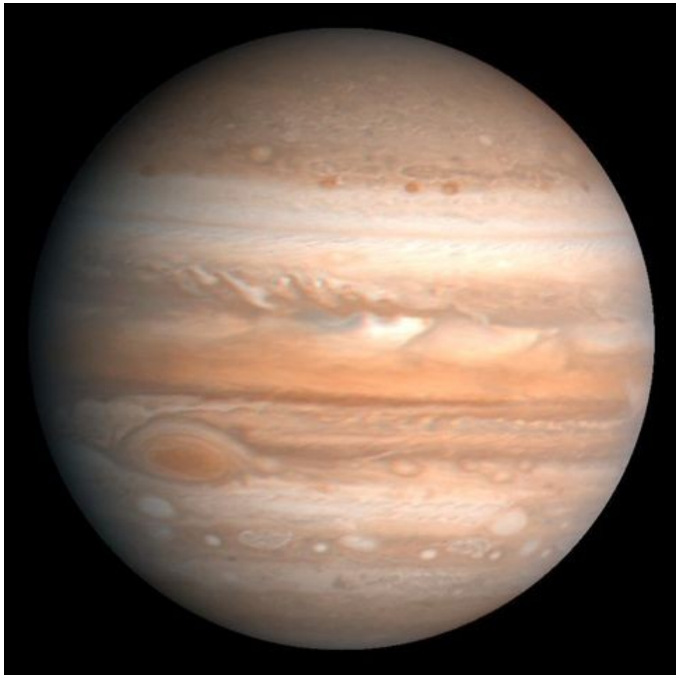
Example of Population II – Globular Clusters

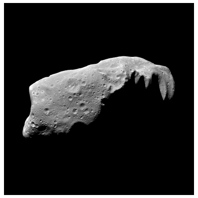
Globular clusters are old systems of stars in the Halo

They are spherical (globular) because they are massive
Gravity could shape the system into a spherical configuration



A “mass-sphericity” analogy...





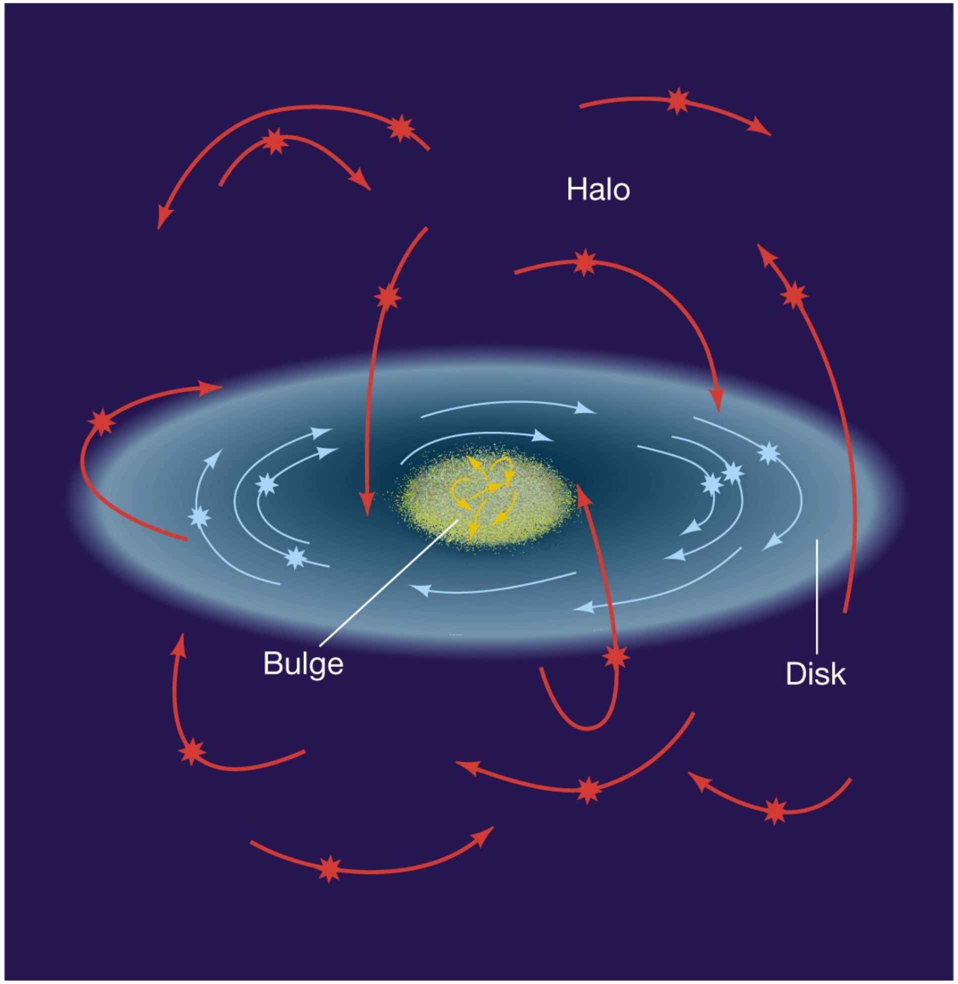
Stellar Populations

Population II

old and metal-poor

Halo Stars

Star formation ceased long ago



Population I

young and metal-rich

Disk Stars

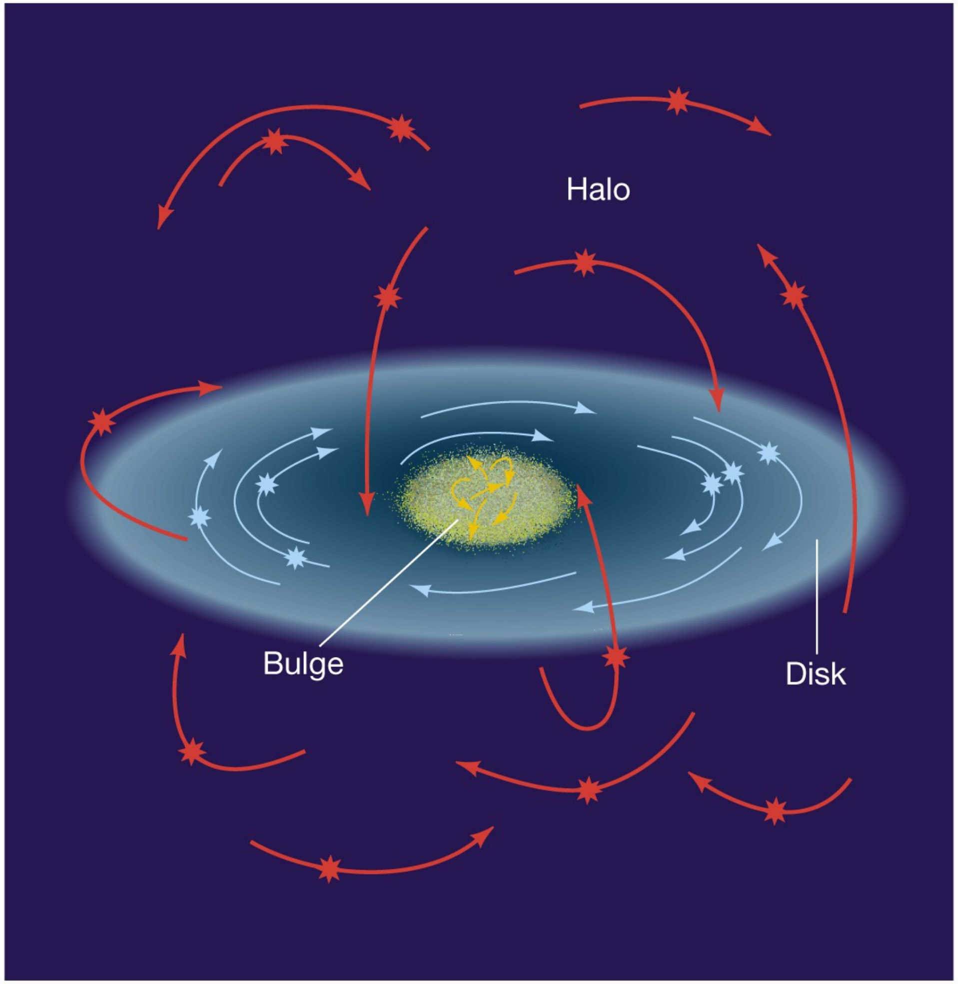
Star formation is ongoing

Stellar Populations

How about the Bulge??

Population II
old and metal-poor
Halo Stars

Star formation ceased long ago



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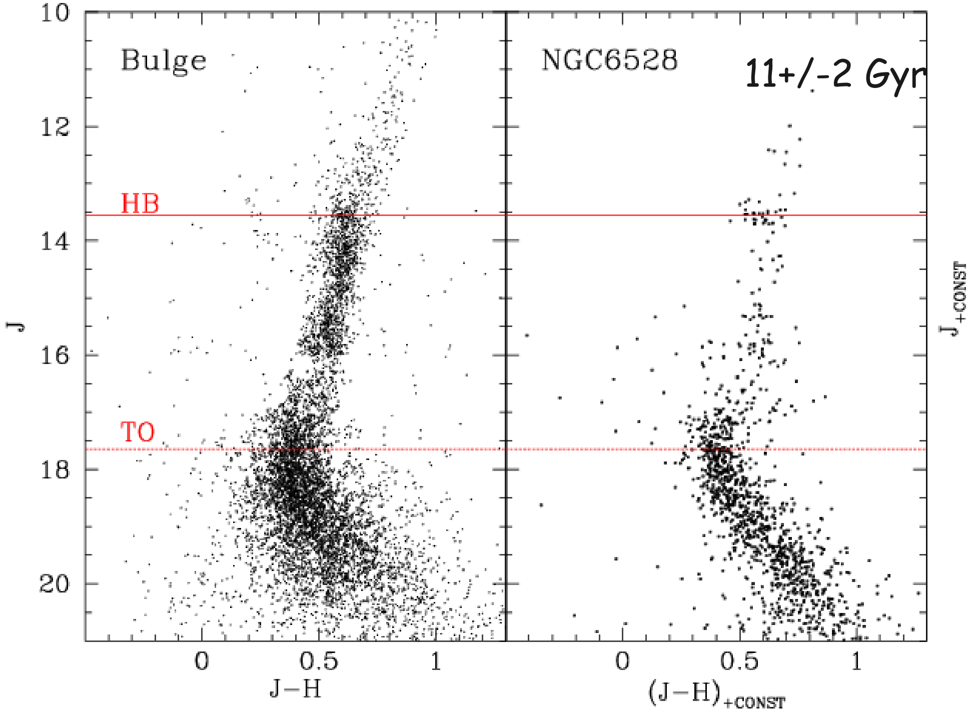
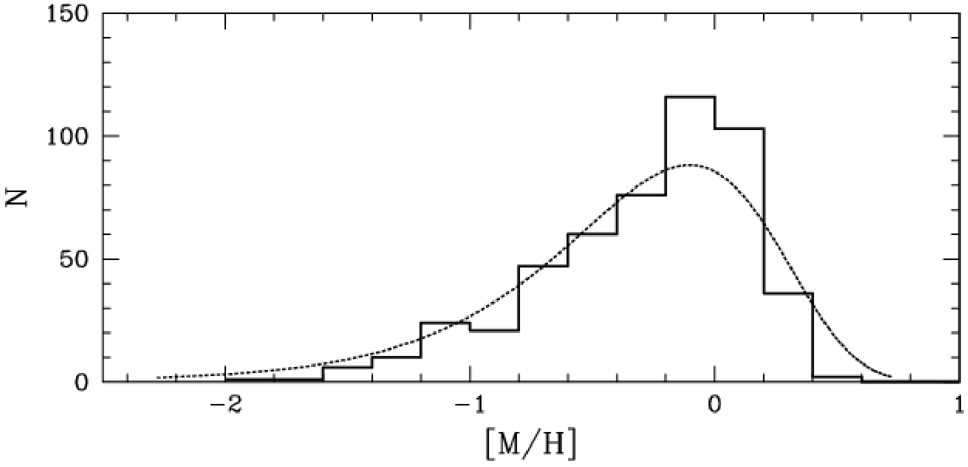
Stellar Populations



Metallicity Distribution of the Bulge



Bulge stars are old and metal rich

The Bulge is an old structure,
but quite dense

Star formation rate (SFR) is proportional to the density

More gas, more stars....

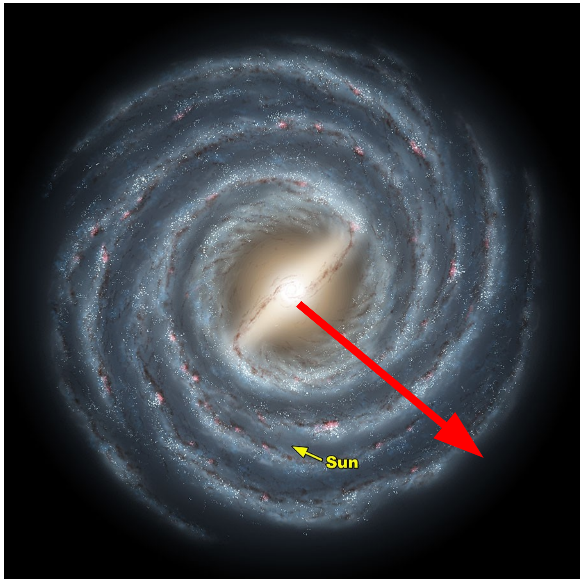
So, the chemical enrichment was fast!!

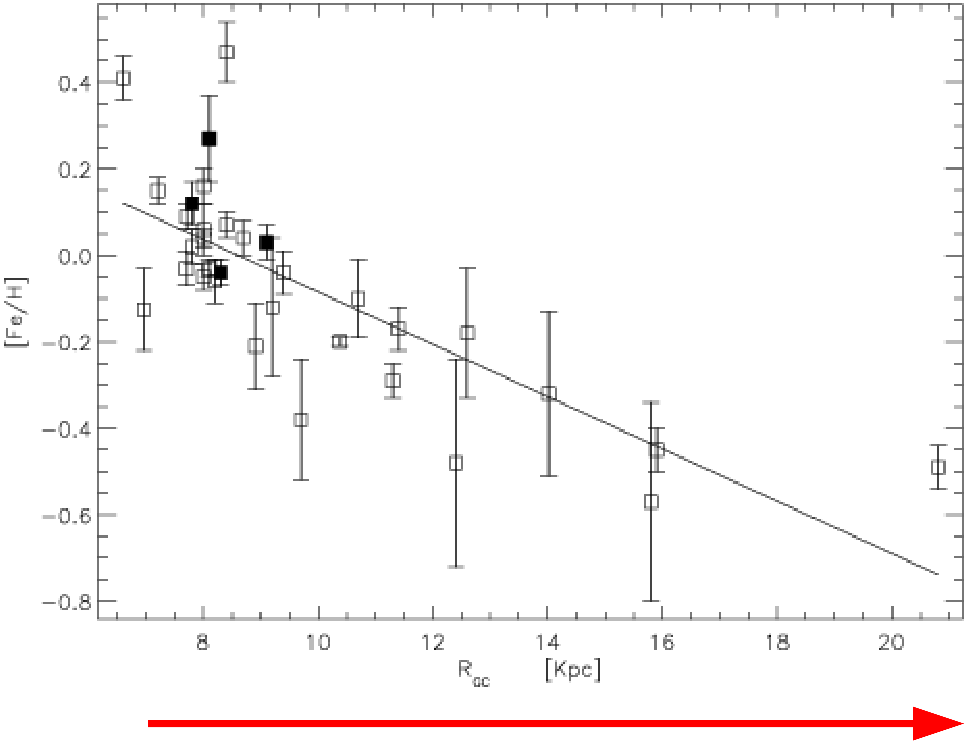
The Galactic Radial Metallicity Gradient

Star formation rate (SFR) is proportional to the density

A galaxy's density decreases with radius
So, the SFR decreases with radius

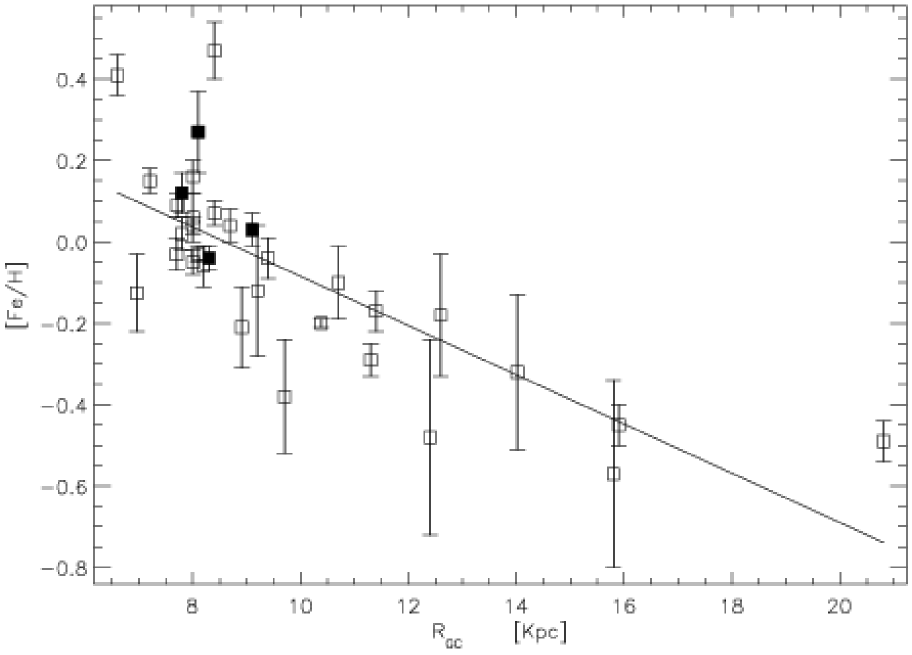
Central part (Bulge) → High gas density → Fast chemical enrichment
Outer disk → Low gas density → Slow chemical enrichment





Stellar Populations
Why we shouldn't use the terminology

Population I - young and metal-rich
Population II – old and metal-poor



There exists **old metal rich stars** (bulge)

As well as **young metal poor stars** (outer disk)

Use of “stellar populations” is **discouraged**.

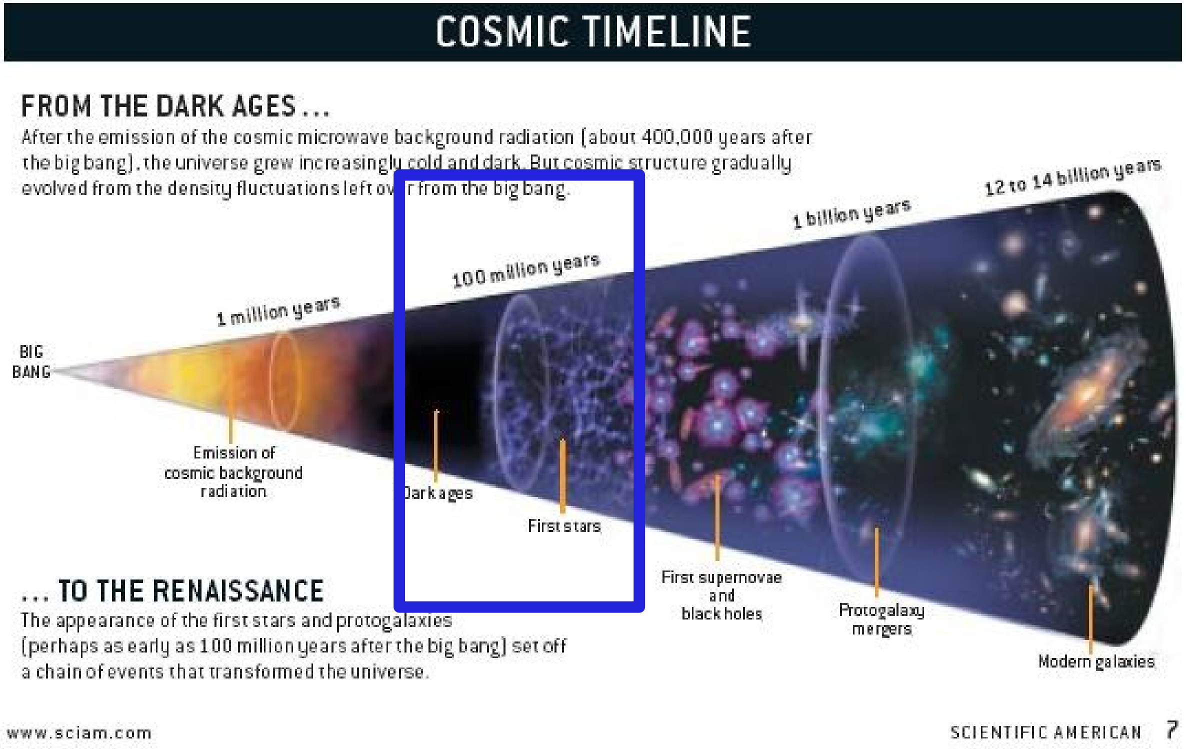
Use *age* and *metallicity* when you can.

Exception to the rule – Pop III stars

Pop I – metal rich, young

Pop II – metal poor, old

Pop III – metal free, extinct



COSMIC TIMELINE

FROM THE DARK AGES ...

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left ov r from the big bang.

... TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

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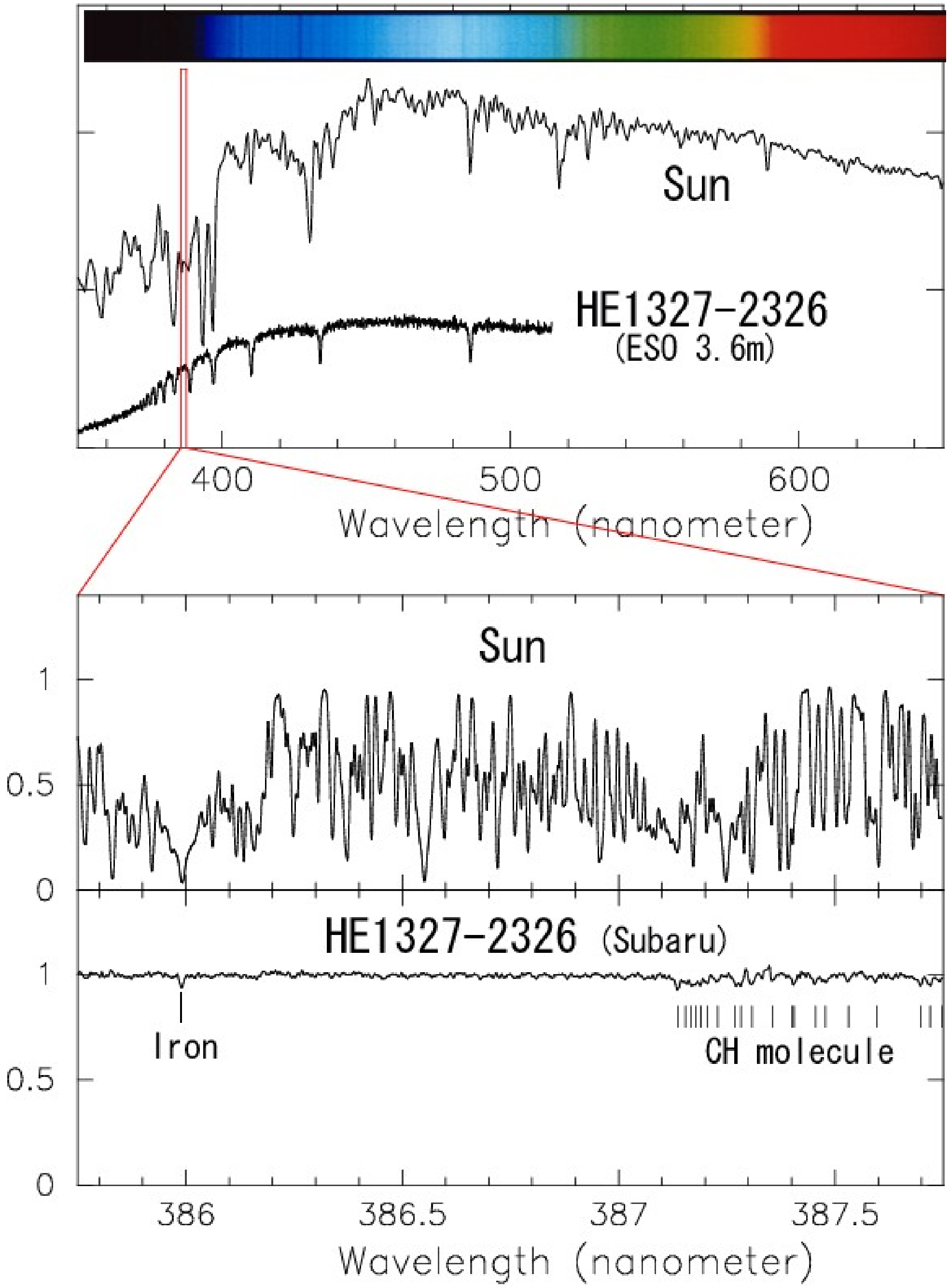
The First Stars

Purely Hydrogen and Helium, nothing else.

We cannot see them since they are gone.

But... the second generation of stars may still be around

Very metal poor stars – HE 1327-2326



[Fe/H] = -5.2

How much less iron than the Sun?
300,000 times less

Let's summarize

Beyond the Iron peak, nucleosynthesis occurs by ***neutron capture*** and ***beta decay***

$$(n \rightarrow p + e^{-} + \nu)$$

The process is classified according to the neutron flux

S-process

(slow neutron capture)

Neutron capture occurs
slower
than beta decay

Works up to bismuth (Z=83)

Where?
AGB stars + Supernovae

R-process

(rapid neutron capture)

Neutron capture occurs
faster
than beta decay

Really heavy stuff
All the way to Uranium

Where?
Supernovae

Let's Summarize

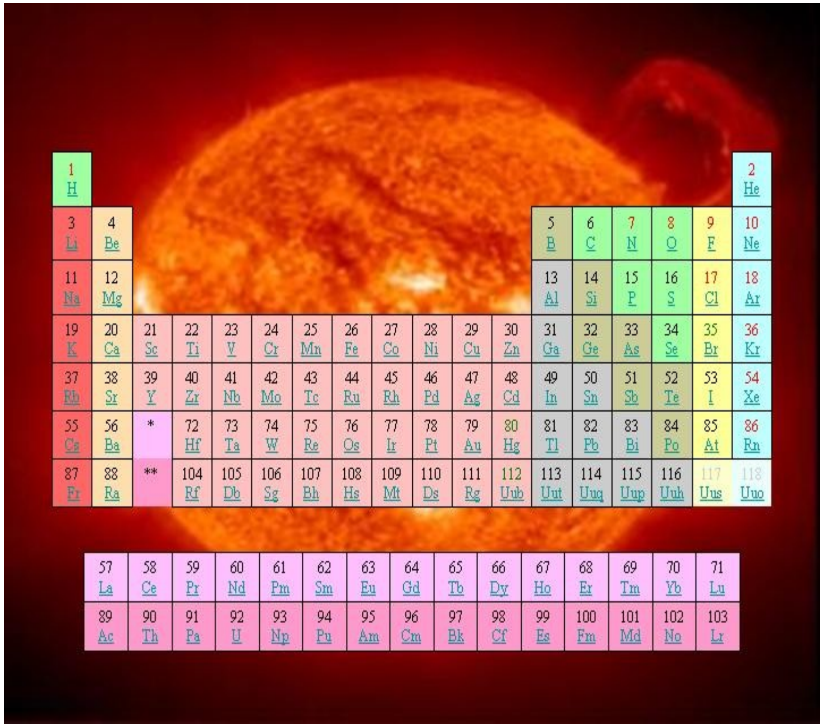
Element	**# of Protons**	**Site**
H	1	Big Bang
He, C, O	2,6,8	Big Bang + Low and High Mass stars
Ne - Fe	10-26	High mass stars
Co - Bi	27-83	S and R process, ABG and SN
Po - U	84-92	R process in SN

Hi s

Urca proces e collapse
The core coll e triggered.
The s path

Remna nass.
Black holes are simple stuff. They have "no hair".

Nucleosynthesis: Stars are where the periodic table is cooked



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Let's summarize

Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

X: Hydrogen abundance
Y: Helium abundance
Z: All the rest (i.e., abundance of metals)

X+Y+Z=1

Sun: X=0.749, Y=0.238, Z=0.013

Metallicity

Iron abundance (normalized to solar)

$$[Fe/H] = \log\left(\frac{N_{Fe}}{N_H}\right)_{\star} - \log\left(\frac{N_{Fe}}{N_H}\right)_{\odot}$$

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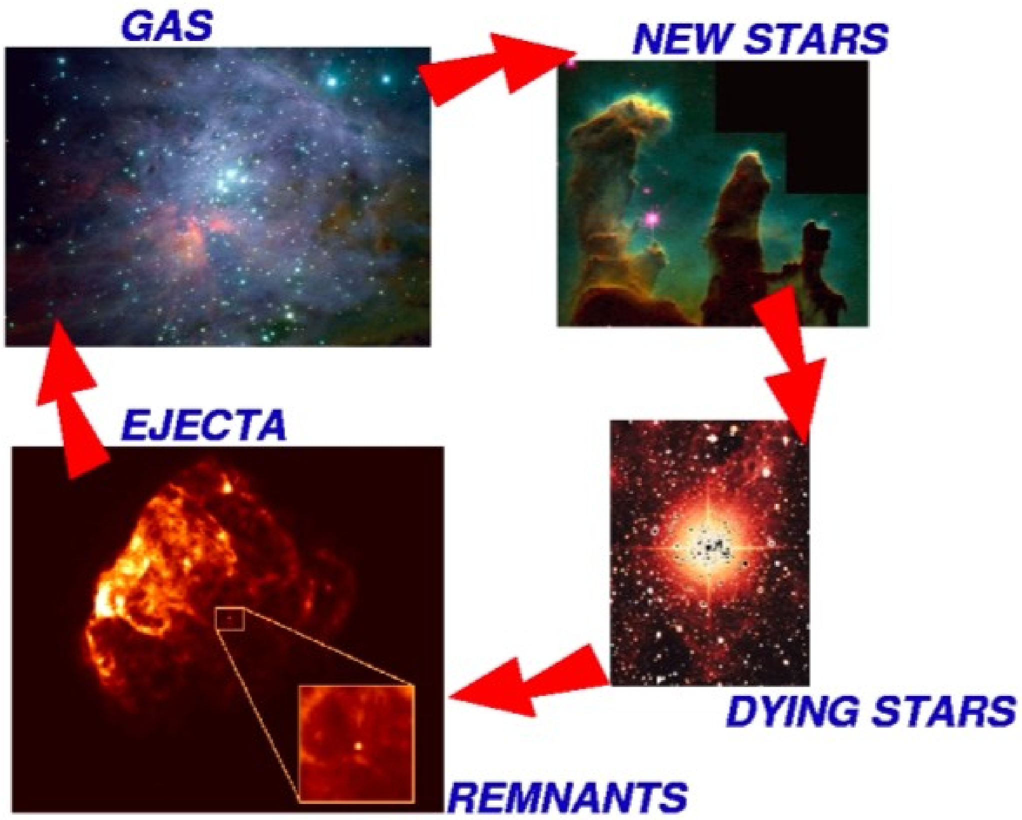
Let's summarize

Some astrochemistry jargon

Successive generations of stars enrich the Galaxy in metals



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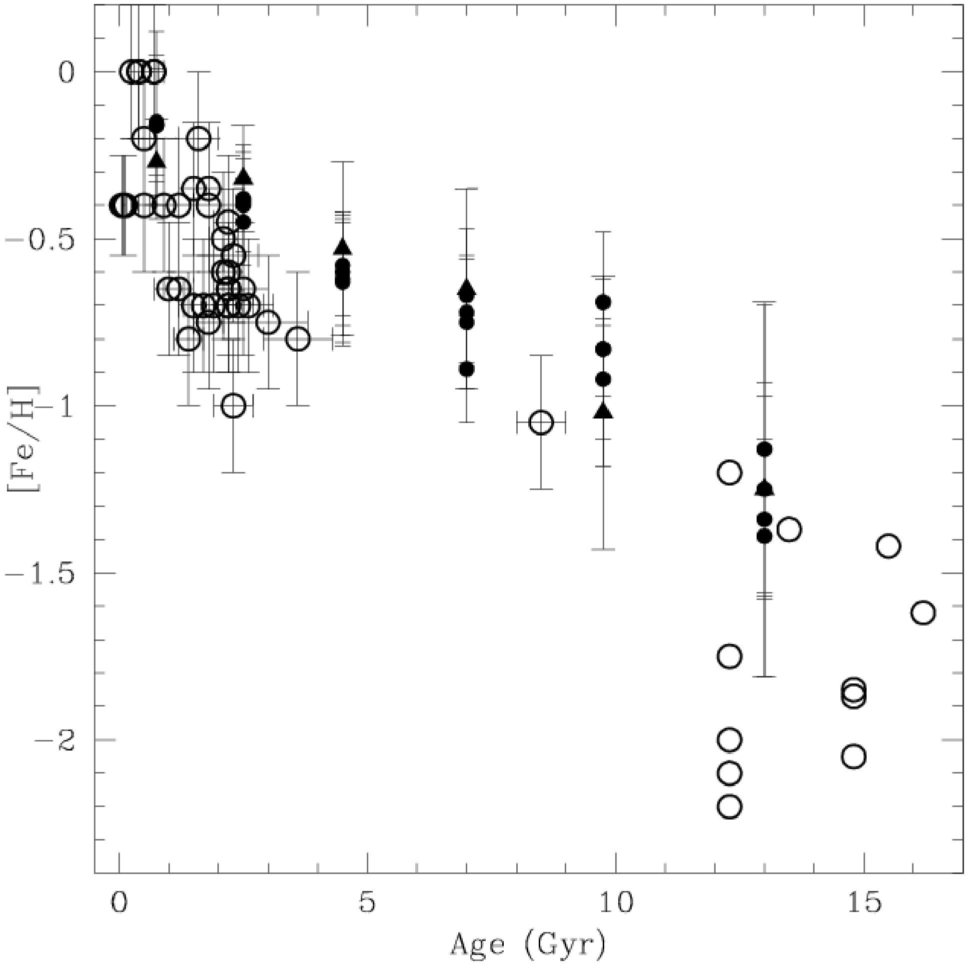
Some astrochemistry jargon

Successive generations of stars enrich the Galaxy in metals

An age-metallicity relation can be traced



Age of the stars

Let's summarize

Some astrochemistry jargon

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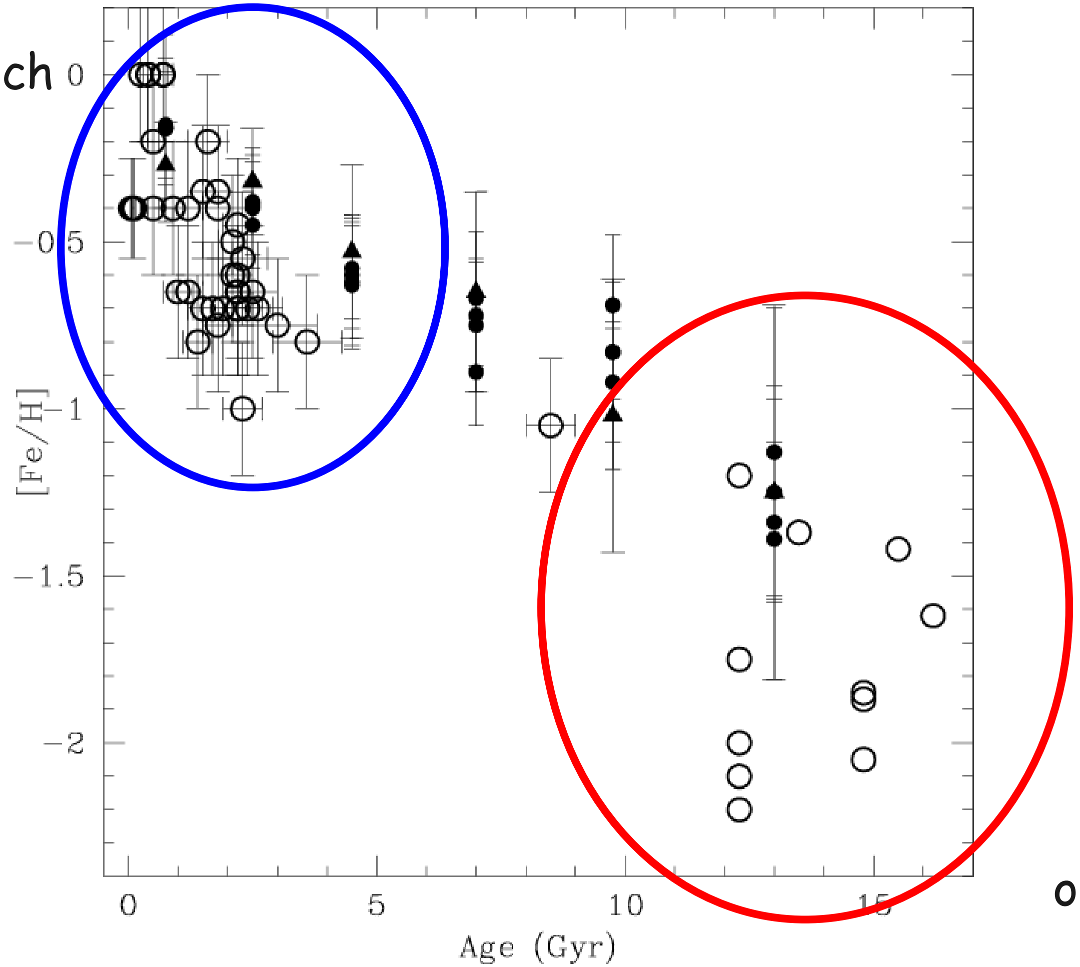
Population I

young and metal-rich



Population II

old and metal-poor

Age of the stars

Let's summarize

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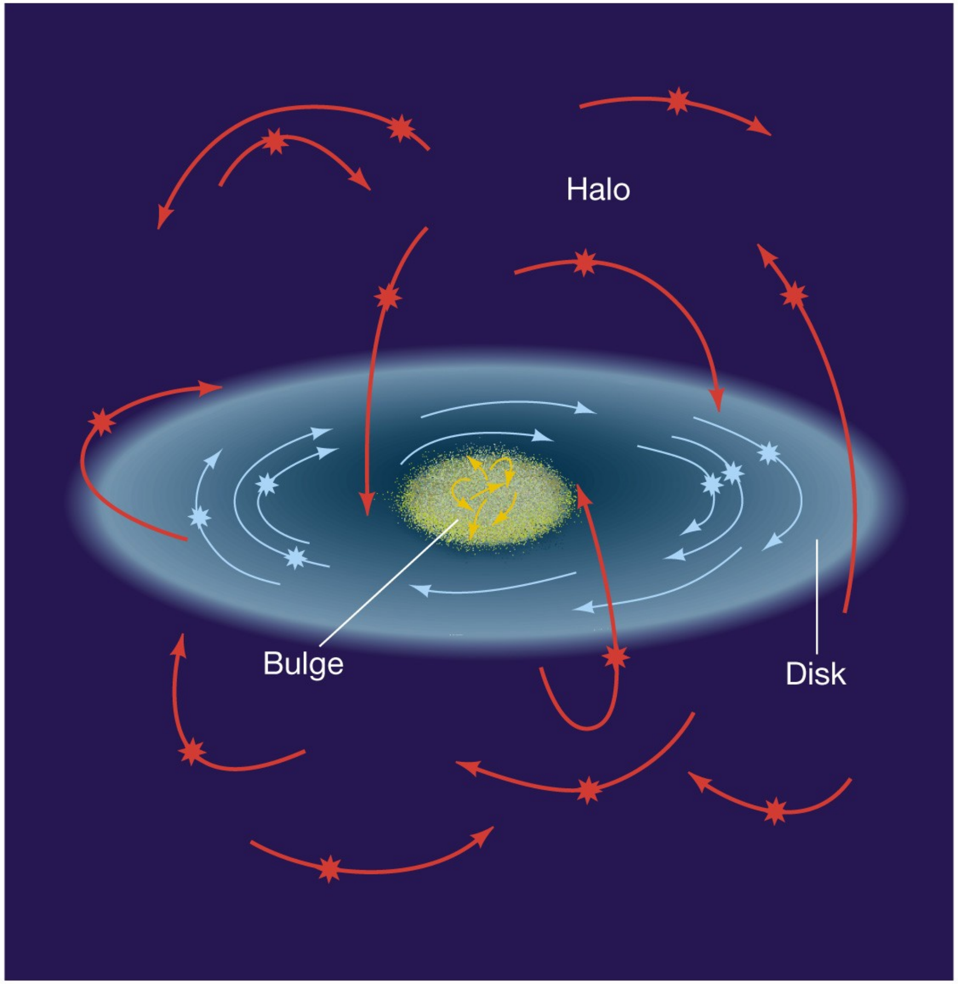
Pop I - Disk stars ; Pop II - Halo stars

Population II

old and metal-poor

Halo Stars

Star formation ceased long ago



Population I

young and metal-rich

Disk Stars

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Let's summarize

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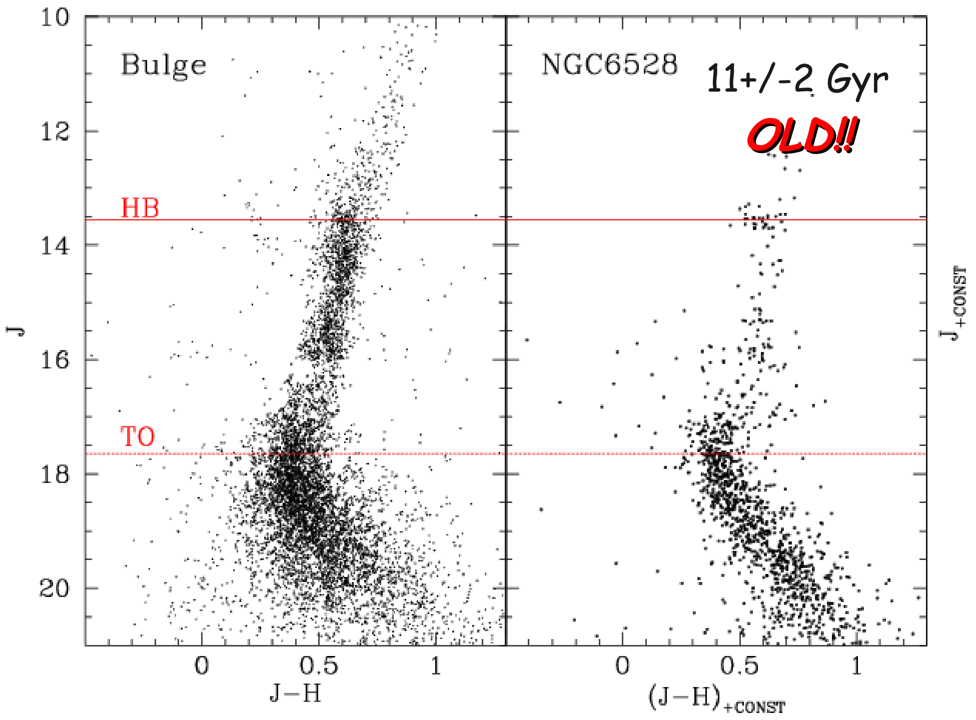
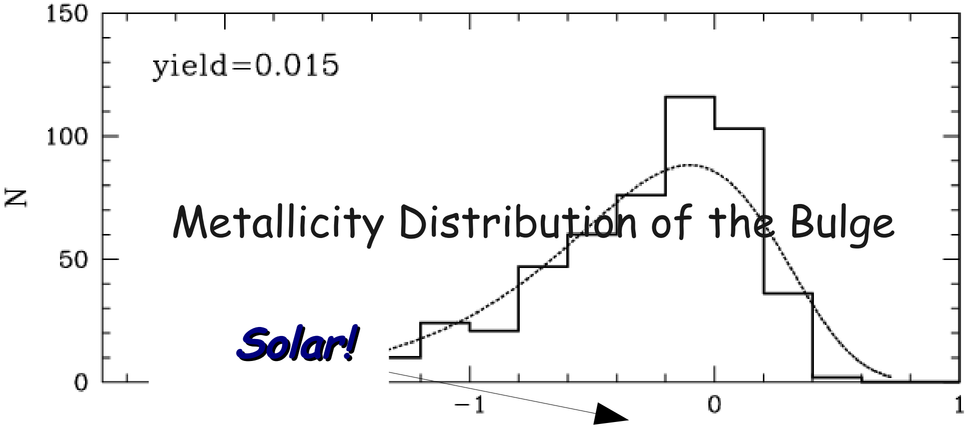
Age of the Bulge



11+/-2 Gyr

OLD!!



Metallicity Distribution of the Bulge

Solar!

Let's summarize

Some astrochemistry jargon

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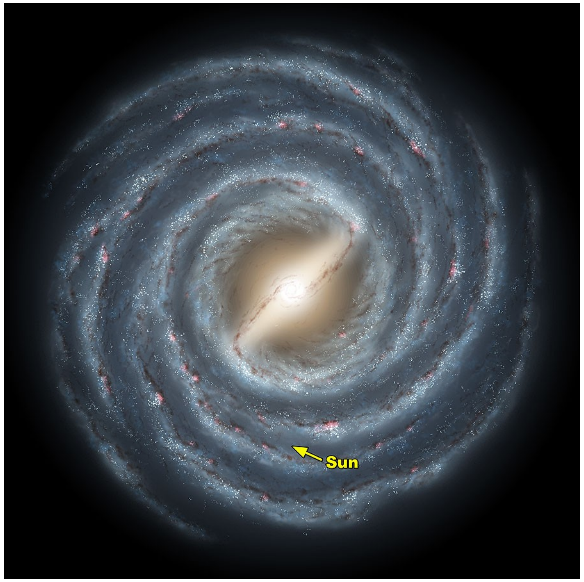

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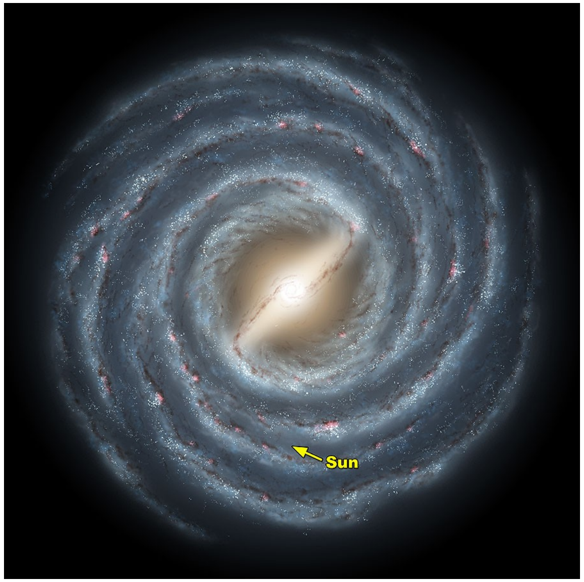
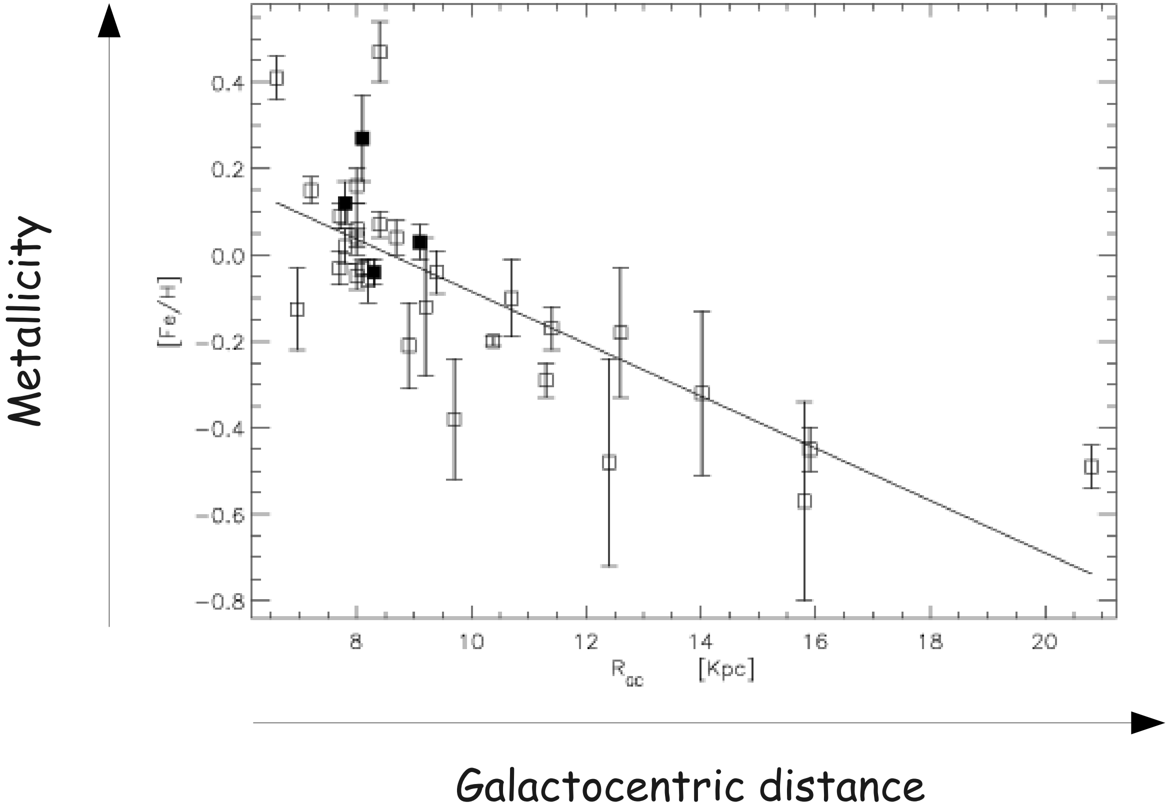
The Galaxy has a radial metallicity gradient





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Successive ge xy in metals

An o ed

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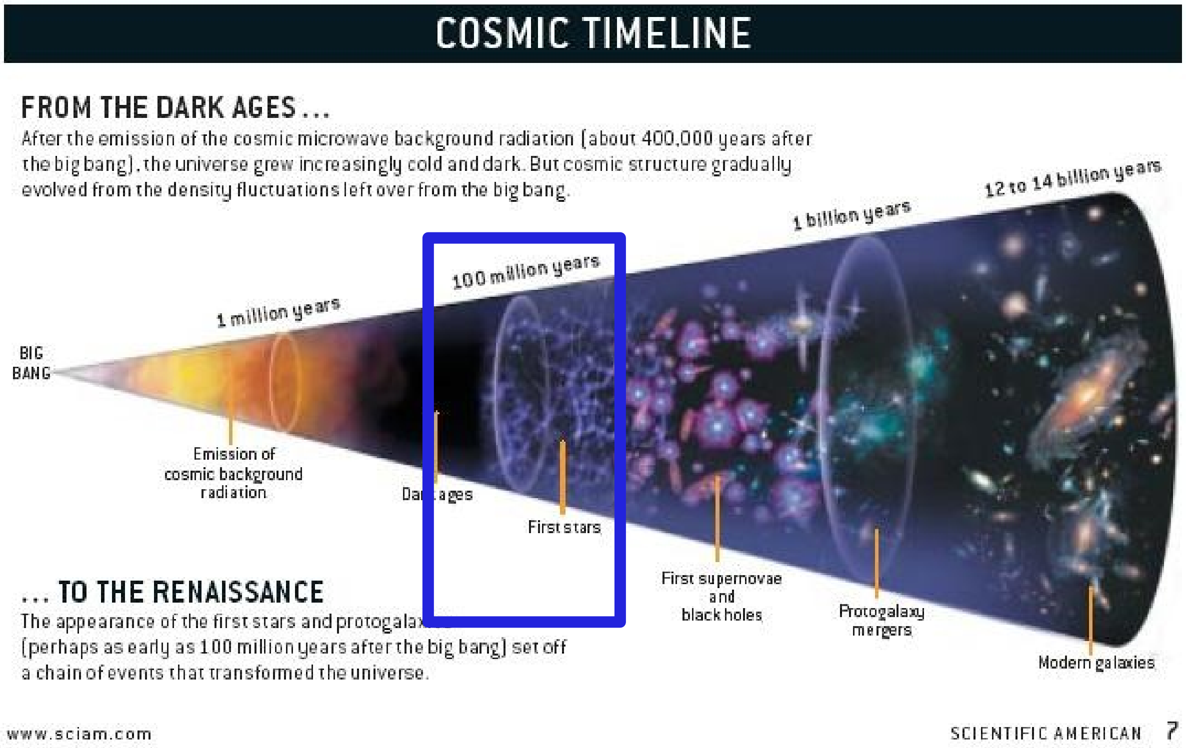
Pop III – metal free, extinct

Population III stars – Metal free, the first stars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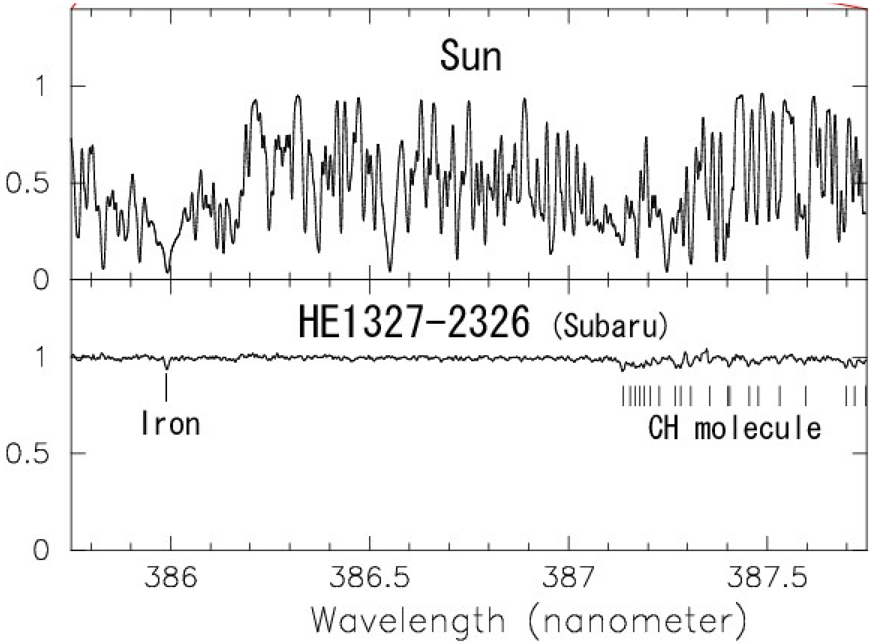
Population III stars – Metal free, the first stars

HE 1327-2326: The most metal poor star ever found



[Fe/H] = -5.2

300,000 times less Iron than the Sun