

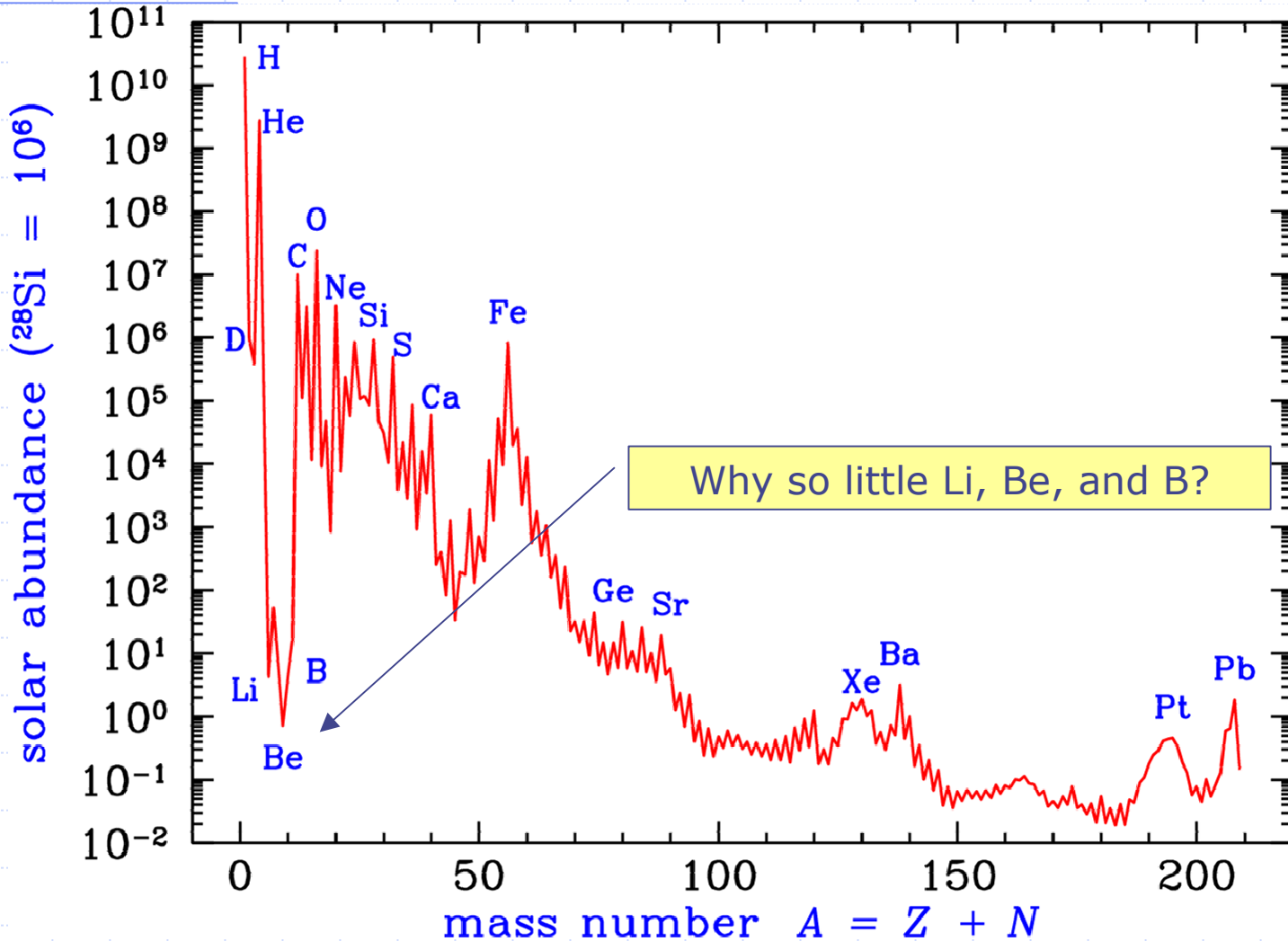
Cosmic Ray Nucleosynthesis

Aybüke Küpcü Yoldaş
MPE

Outline

- ◆ Why so low amount of LiBeB?
- ◆ Origin of LiBeB – Cosmic Ray Nucleosynthesis
- ◆ Origin of Cosmic Rays

Solar Abundances



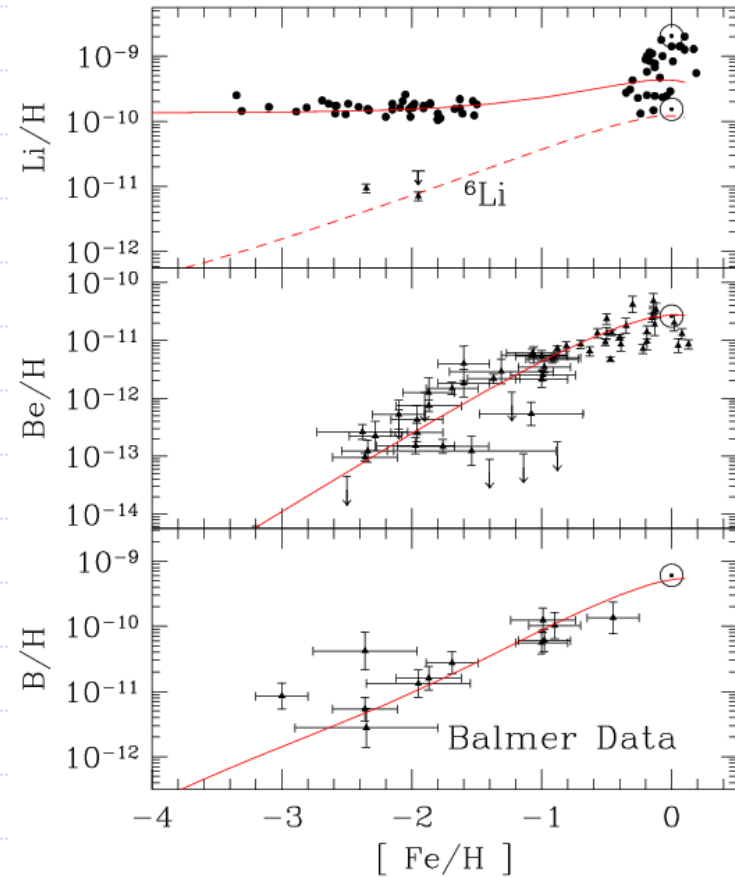
Why little amount of LiBeB?

- ◆ Easily split into other elements
- ◆ Destroyed in stellar interiors
- ◆ Stability gaps at mass numbers 5 – 8:
He-burning bypasses LiBeB through ^{12}C
BBN can only produce ^7Li
 - Fragile

Big-Bang Nucleosynthesis ?

- ◆ Plateau at low Fe
 - constant abundance at early times
 - ${}^7\text{Li}$ is primordial
- ◆ No plateau for Be and B:
 - Not primordial
 - Made by Galactic processes

BBN produces very small amount of ${}^6\text{Li}$, Be, B

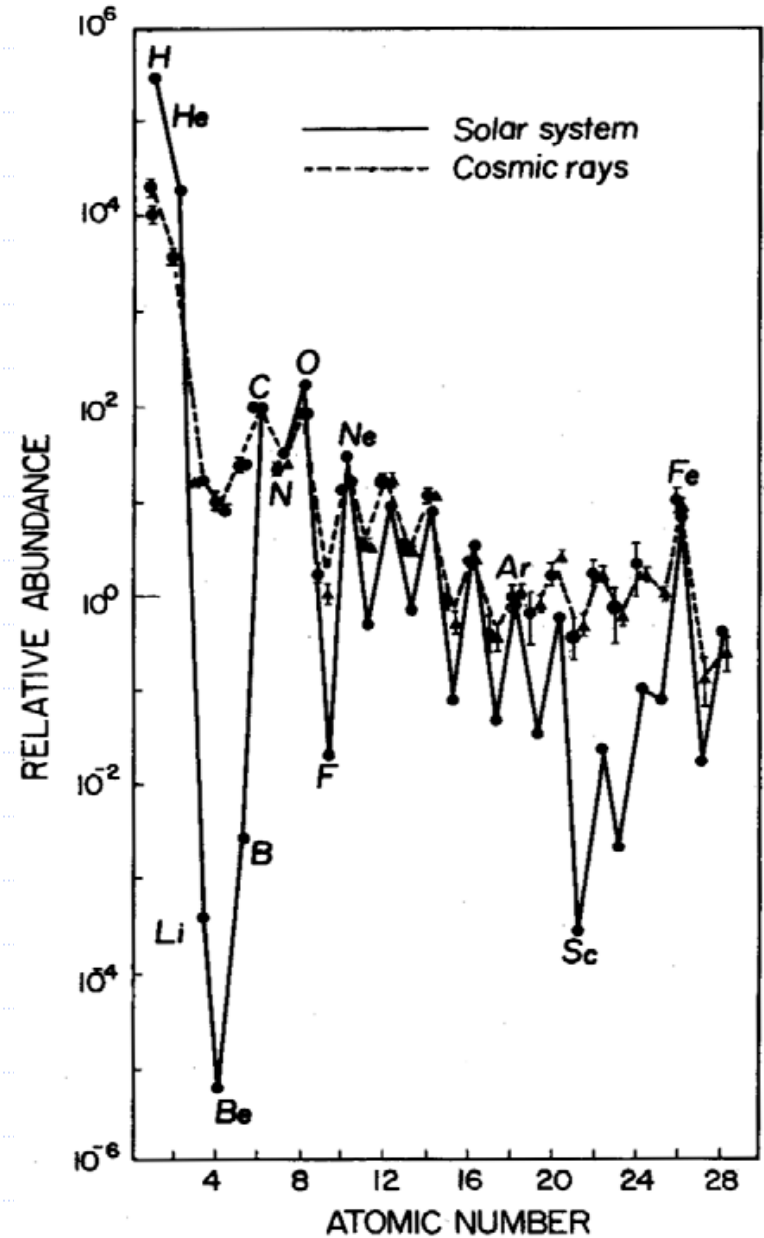


Cosmic Rays ?

- ◆ Bare, very energetic nuclei stripped from electrons
- ◆ Power-law energy spectrum
- ◆ Isotropic distribution
- ◆ ISM like composition with some exceptions

Cosmic Rays ?

- ◆ $\text{LiBeB/CNO} = 10^{-6}$ in standard abundances
- ◆ $\text{LiBeB/CNO} = 0.25$ in galactic cosmic rays
- LiBeB are $\sim 10^6$ more abundant in cosmic rays



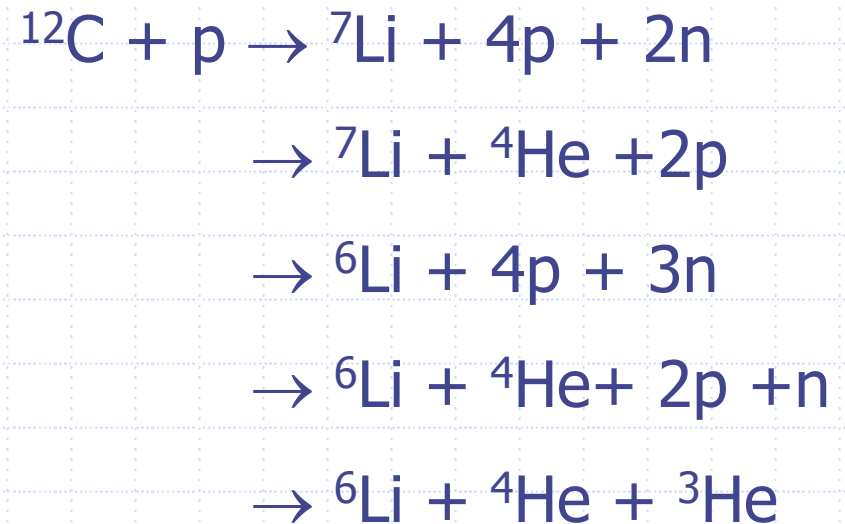
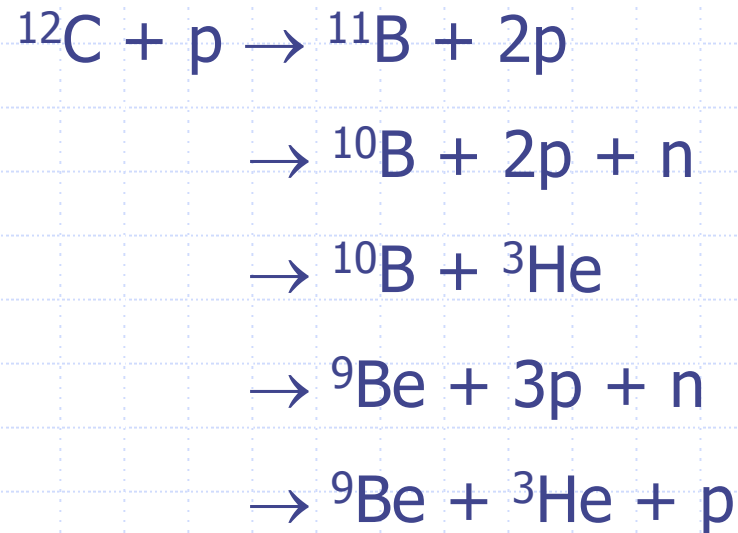
Spallation



cosmic rays + CNO
(p)

→

LiBeB



Spallation

- ◆ Energies greater than ~ 10 MeV needed
 - cosmic rays
- ◆ Breaking up of interstellar CNO as a result of energetic collisions with cosmic ray protons is a **secondary** process:

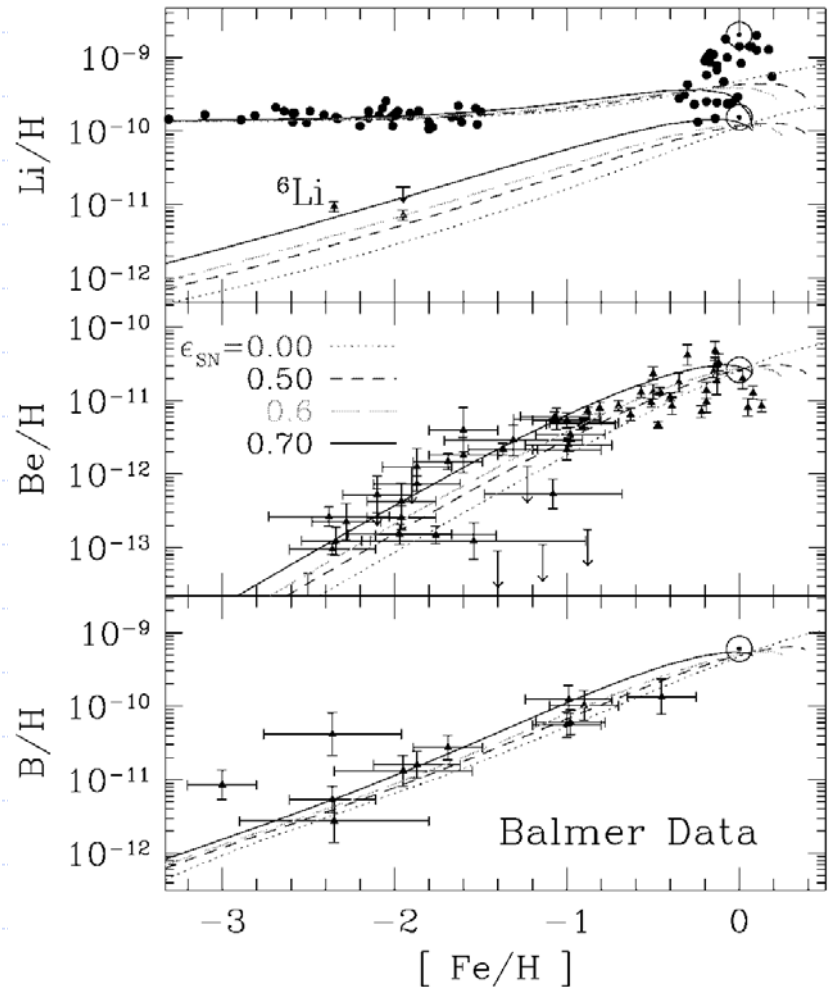
It depends on both the abundance of interstellar CNO which are primary nucleosynthesis products, and the cosmic ray flux which is accelerated by and hence depends on SNII rate.

Evolution of LiBeB

- ◆ The evolution of LiBeB is traced in terms of comparison with Fe.
- ◆ Expectations from standard cosmic ray nucleosynthesis theory: a quadratic relation due to the "secondary" nature of LiBeB production

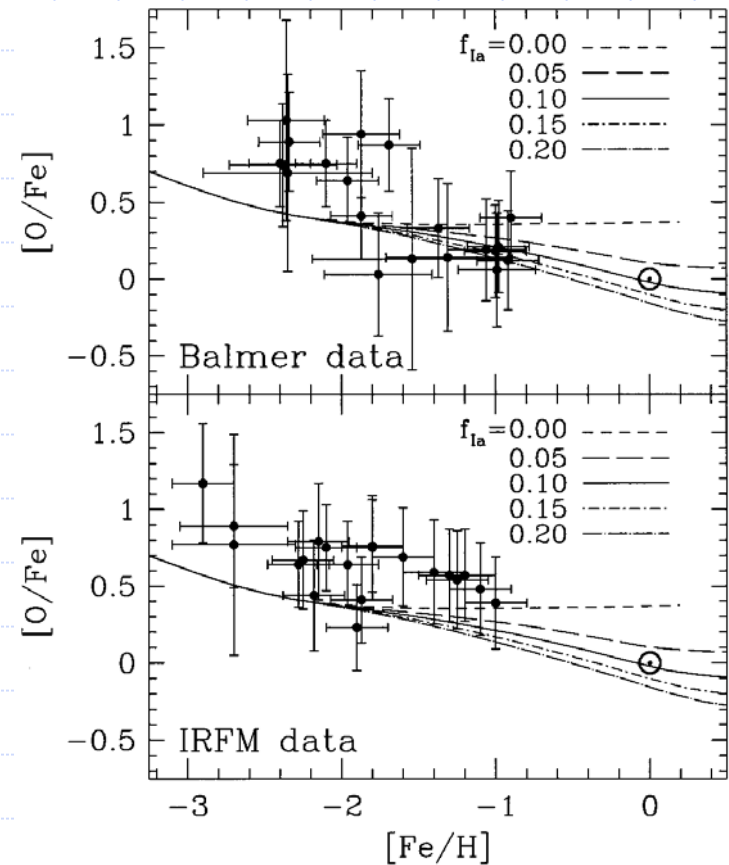
Secondary ?

- ◆ Notation:
 $[Fe/H] = \log(Fe/H) - \log(Fe/H)_{\text{sun}}$
- ◆ Linearity instead of a quadratic relation as expected from originating as “secondary” products
- ◆ Do we need an additional “primary” component?



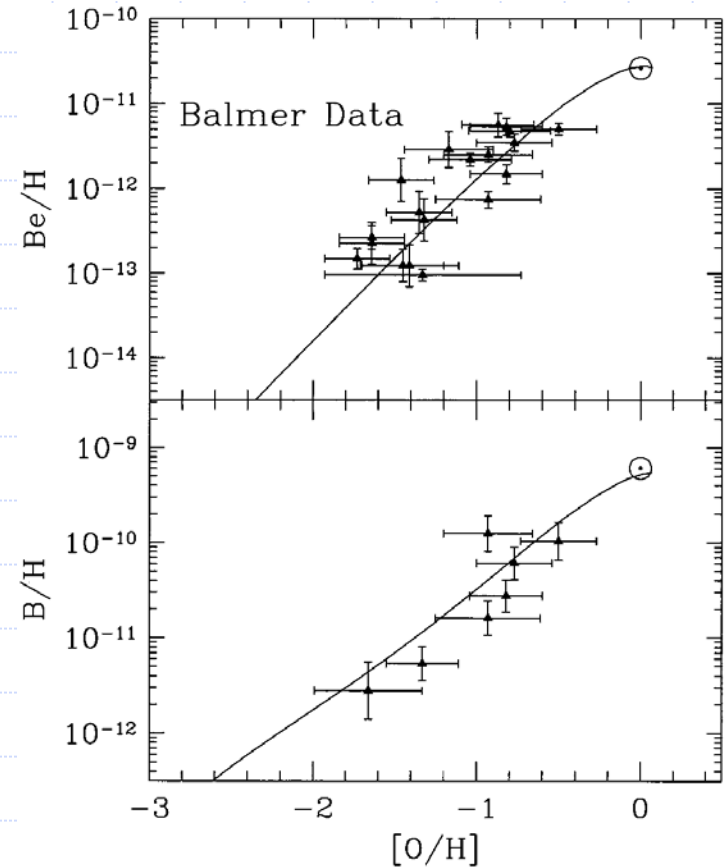
Fe or O ?

- ◆ O/Fe is not constant ?
 - O/Fe increase toward low metallicity.
- ◆ Fe cannot trace LiBeB evolution, but O.



BeB versus O

- ◆ More quadratic: somewhere between linearity and quadraticity
- ◆ More data + maybe a "primary" component from neutrino process (for B)



Neutrino Process

- ◆ Neutrino flux from supernova colliding inelastically with Carbon and Helium shells
- ◆ Primary process
- ◆ Produces ^{11}B and ^7Li
but cannot produce Be and ^6Li , ^{10}B
 - Cannot be the only process

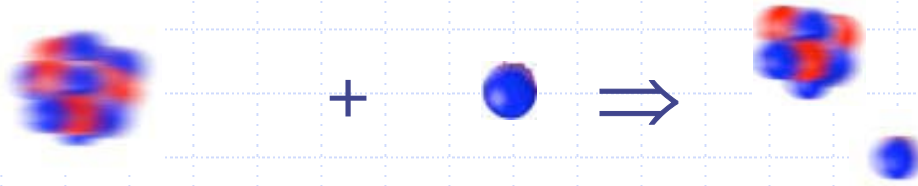
Problems and Uncertainties

- ◆ Cross-sections
 - measured at earth but extrapolations
- ◆ Spectra (energy dependence) of source and target
 - for cosmic rays: measurements from meteorites and from ISM (but effected by Sun) plus a high ^{22}Ne abundance (by 4.5)
 - for target: model dependent
- ◆ Chemical evolution models

Problems of standard CR theory

- ◆ Non-quadratic proportionality of $\log(\text{Be}/\text{H})$ and $\log(\text{B}/\text{H})$ to $[\text{Fe}/\text{H}]$
 - “primary” process needed ?
- ◆ O or Fe :
 - little O data
 - Different O lines lead to different O/H abundances
 - Mg, Si, Ca, S, Ti show a plateau from $[\text{Fe}/\text{H}] = -4$ to -1 , why O different ?

Standard cosmic ray model revised



Cosmic rays + p \rightarrow LiBeB
(CNO)

- ◆ Primary process: does not need CNO in ISM
- ◆ ..but where did the CNO as cosmic rays originated ?
 - superbubbles theory

Standard cosmic ray model revised – Superbubbles

- ◆ Superbubbles: interacting winds from many massive stars and their supernovae explosions
- ◆ Superbubble model: new SNe accelerate the ejecta of previous SNe
 - supplies CNO
 - explains high ^{22}Ne abundance
 - does not need very high energies
 - does not need very short time-scales

Origin of Cosmic Rays

◆ Interstellar medium ?

- Non-quadratic LiBeB trend
- ^{22}Ne excess

◆ From newly exploded supernova ?

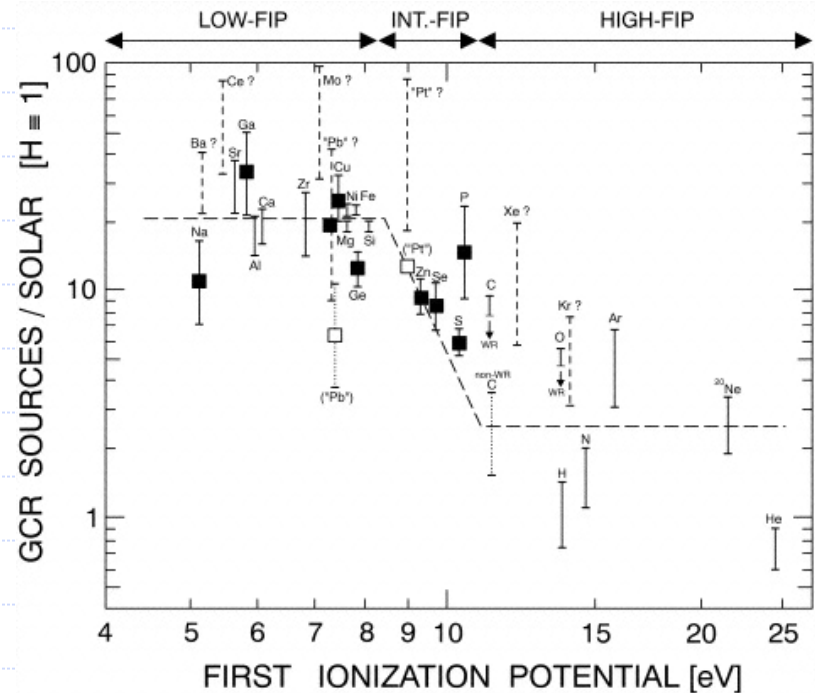
- low amount of ^{20}Ne compared to Mg, Al (all largely from C-burning)
- low amount of S and Ar compared to Si and Ca (all from O- and Si-burning)

◆ Wolf-Rayet star wind ?

◆ Superbubbles ?

Composition of Cosmic Rays

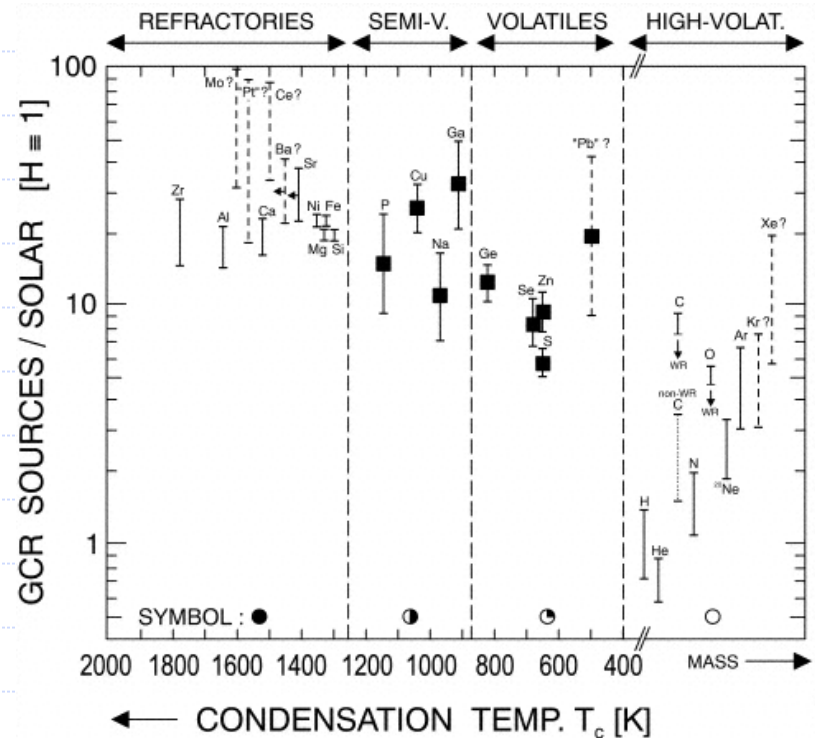
- ◆ Easily ionised elements ($FIP \leq 8.5$ eV) are a factor of ~ 5 more abundant than high FIP elements ($FIP \geq 11$ eV)



Meyer, Drury & Ellison 1997

Composition of Cosmic Rays

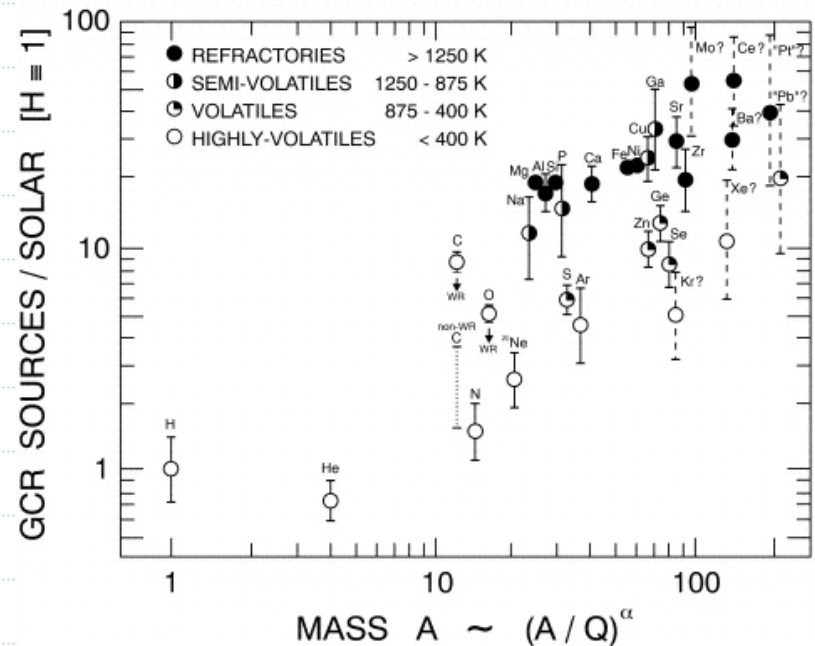
- ◆ FIP or volatility: enhancement of refractory elements relative to volatile ones



Meyer, Drury & Ellison 1997

Composition of Cosmic Rays

- ◆ Among the volatiles, enhancement of heavier elements relative to lighter ones
- ◆ Acceleration of interstellar/circumstellar matter in gas-phase or as dust by supernova shock waves



Meyer, Drury & Ellison 1997

Origin of Cosmic Rays

- ◆ ^{59}Ni is a product of explosive nucleosynthesis and is unstable: $\tau = 1.1 \times 10^5 \text{ yr} \rightarrow ^{59}\text{Co}$ (through e^- capture)
- ◆ Among galactic cosmic rays, $^{59}\text{Ni}/^{60}\text{Ni} \sim 0 \rightarrow$ must have decayed before acceleration (of ^{59}Co)
 - time delay $> 10^5 \text{ yr}$

Summary

Origin of LiBeB:

- ◆ Be, ^{10}B , ^6Li mostly from cosmic ray spallation
- ◆ ^7Li from BBN and maybe some from neutrino processes together with some ^{11}B

Origin of Cosmic rays:

- ◆ ISM or wind + supernova(e)

Bibliography

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