Nuclear properties and the astrophysical *r* process

27th Jyväskylä Summer School

14.-18.8.2017

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Nuclear properties and the astrophysical *r* process

What is the astrophysical origin of the heaviest elements??

Class #	Subject
1	Introduction, chemical abundances
2	Origins of the elements up to the iron peak
3	Neutron capture nucleosynthesis, *r*-process dynamics
4	The r process: nuclear masses and lifetimes
5	The r process: neutron capture rates and fission

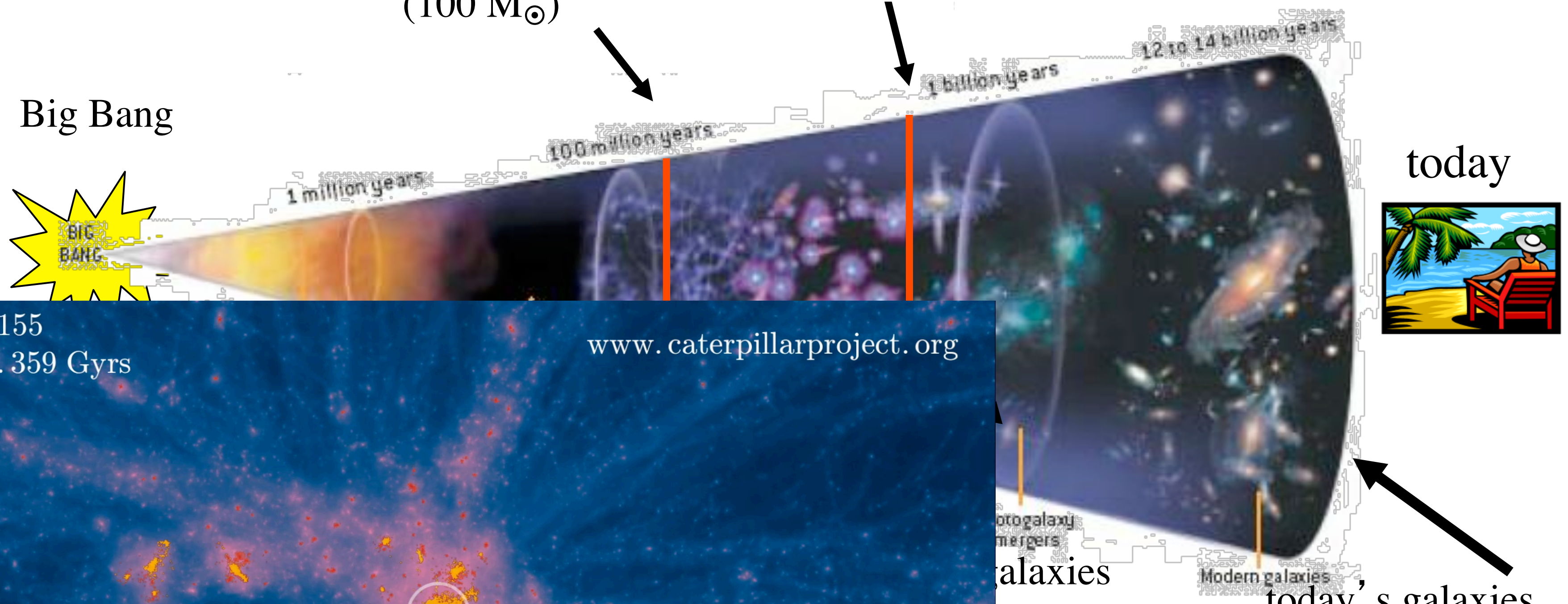
In preparation for the computational exercises that begin tomorrow…

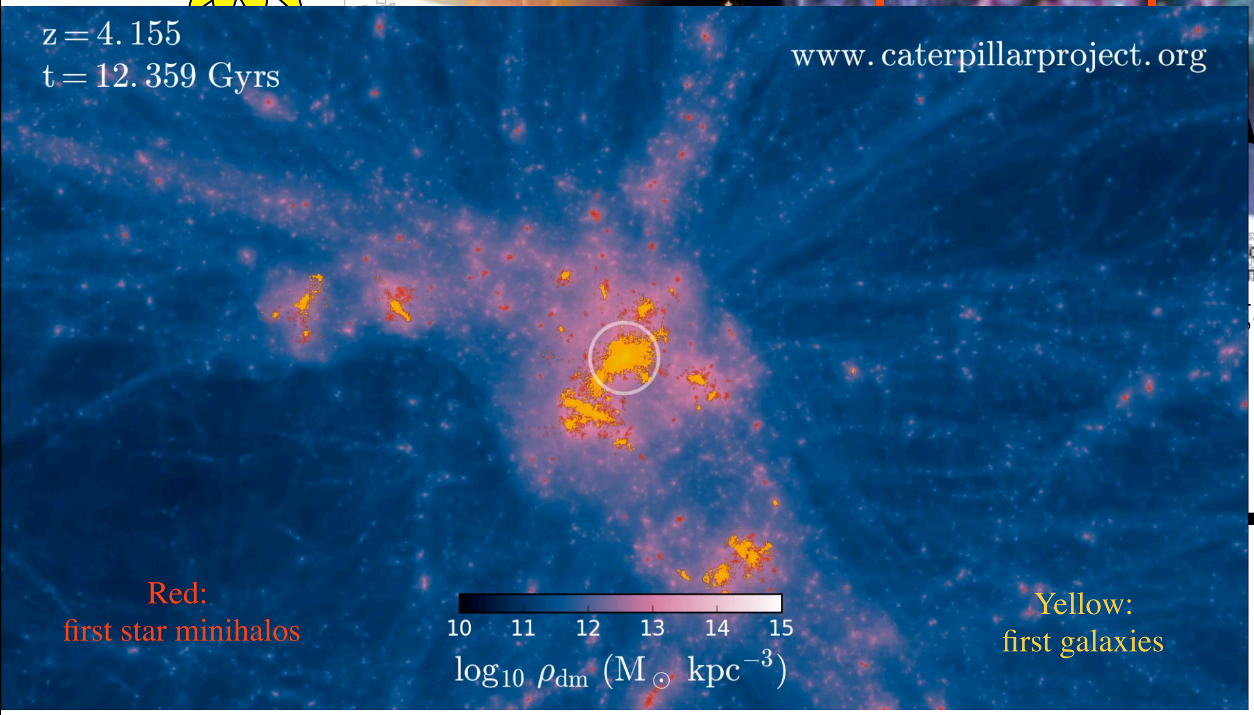
A – I have my own laptop with the appropriate compiler installed.

B – I have my own laptop but will need to install the necessary tools.

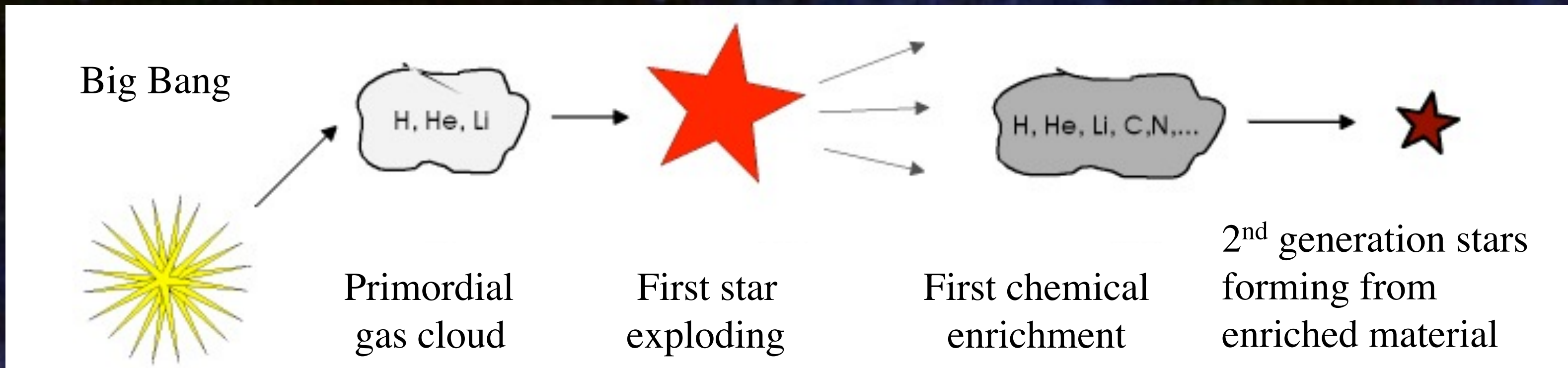
C – I do not have access to a laptop.

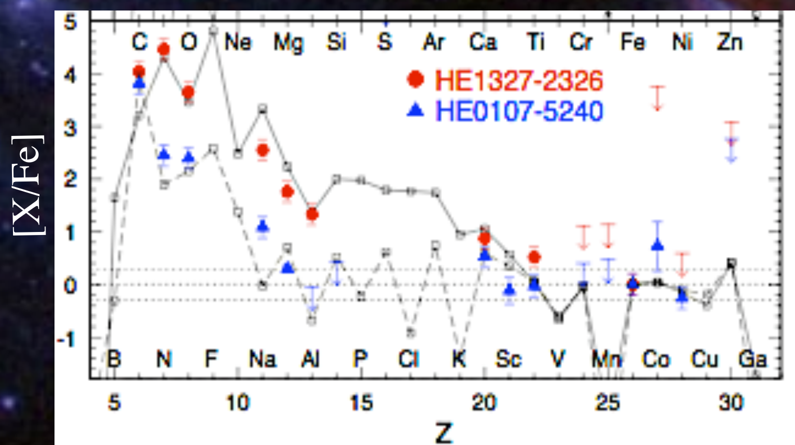
chemical evolution



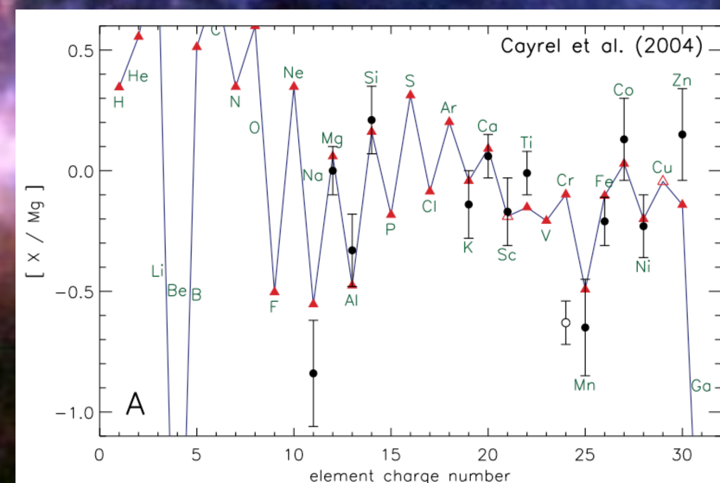


metal-poor stars and galactic chemical evolution





Tominaga et al. 2007



Heger & Woosley 2008

Why important?

Metal-poor stars provide the only available diagnosis for zero-metallicity Pop III nucleosynthesis and early chemical enrichment

Hydrogen core fusion changes the chemical composition of the core of a star. What happens to the chemical composition of the rest of the star?

A – We have no way to find out.

B – The chemical composition outside the core does not change much.

C – The same changes occur outside the core as within the core.

D – Any helium created in the core rises to the surface.

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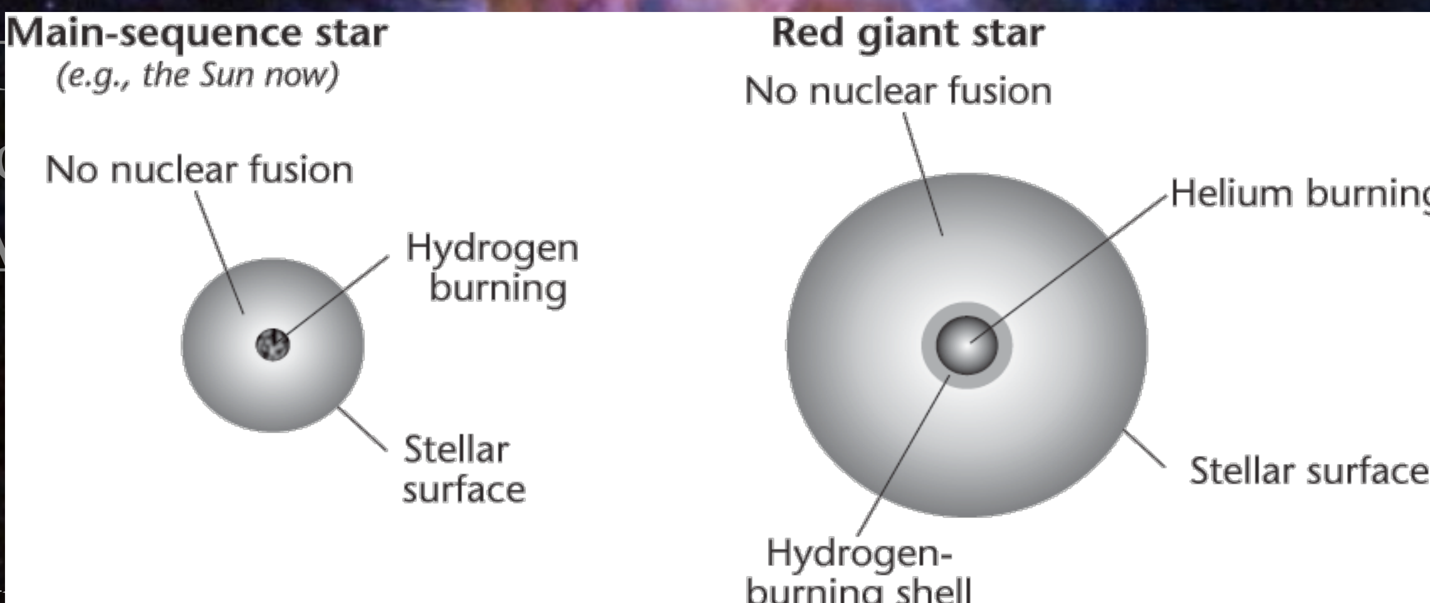
C – T … n the c…

D – A … e.



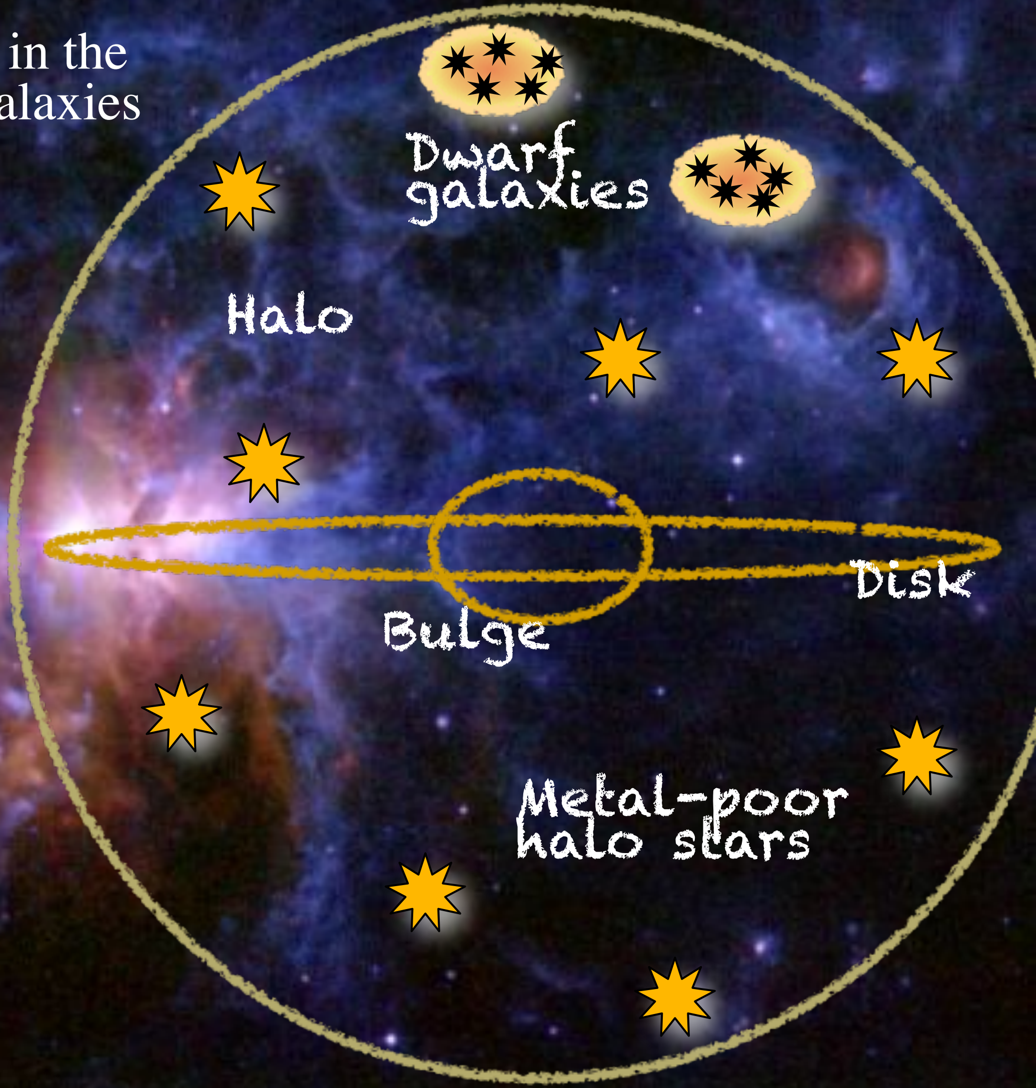
metal-poor stars and the Milky Way

Metal-poor stars are found in the halo, the bulge and in dwarf galaxies

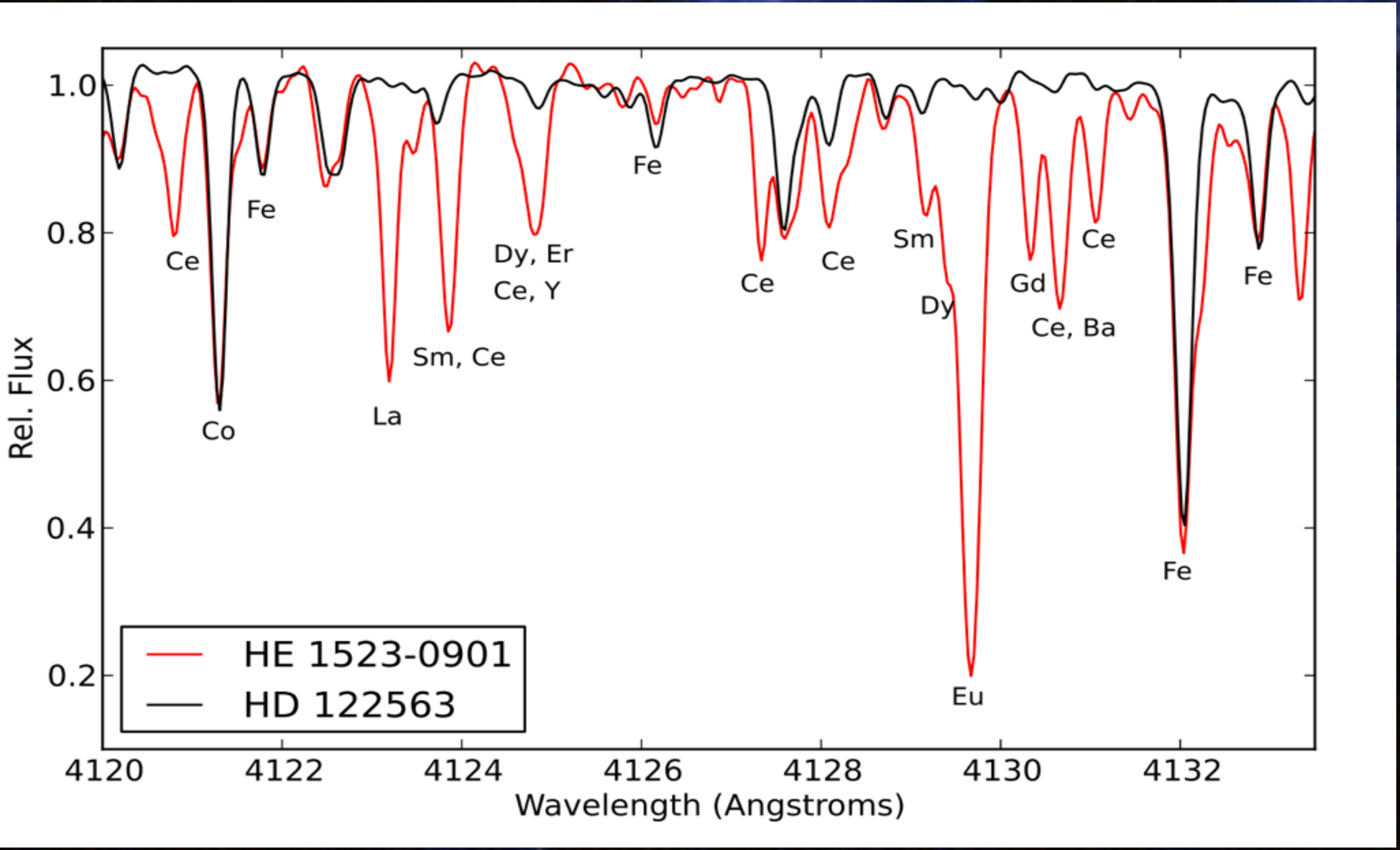
The disk and open and globular clusters do not contain stars with [Fe/H]<−2.3

=> Origin of halo and bulge stars is actually unknown

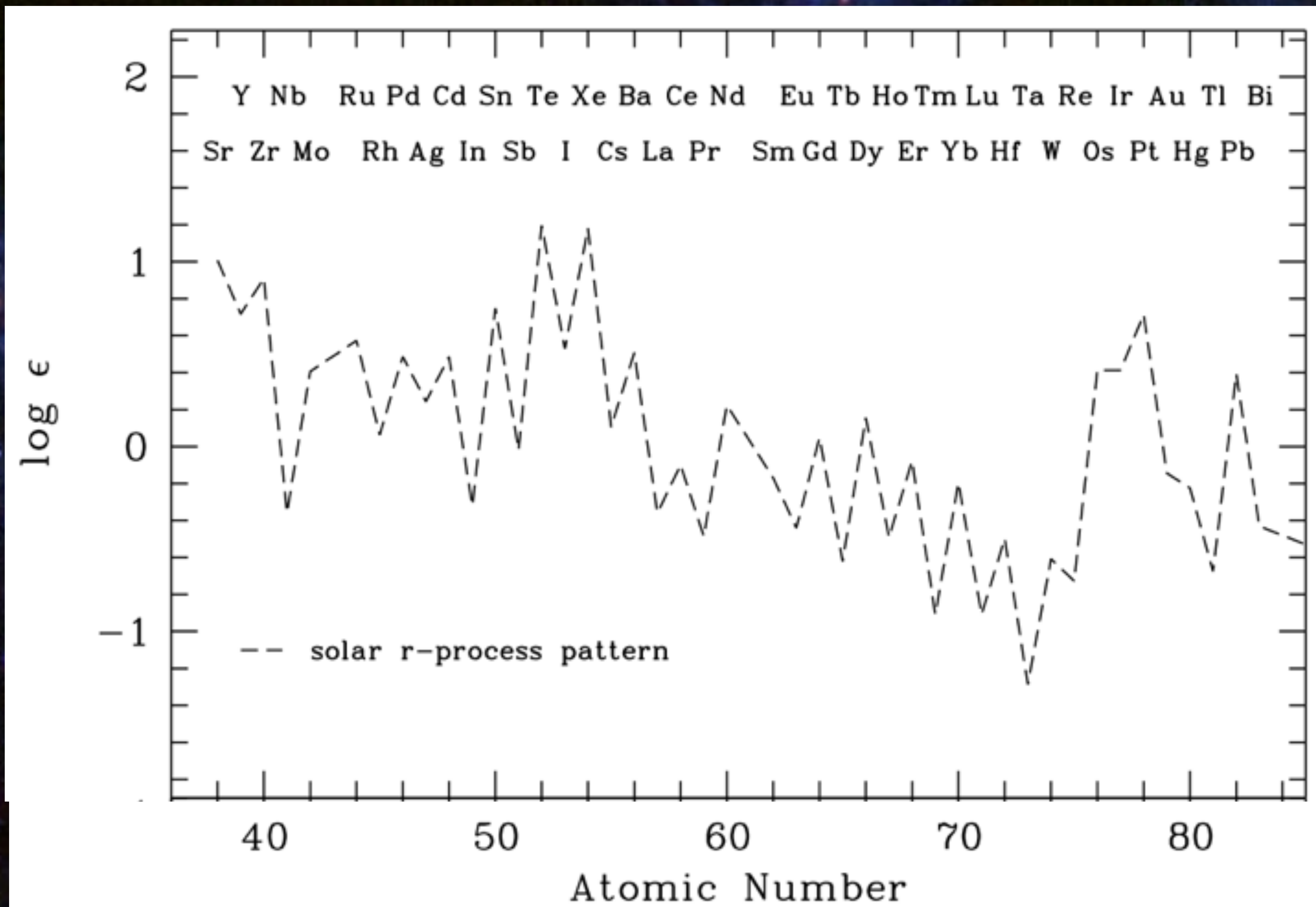
=> Trace chemical signature of their birth gas cloud wherever they formed



metal-poor stars and the *r* process



elemental solar *r*-process pattern



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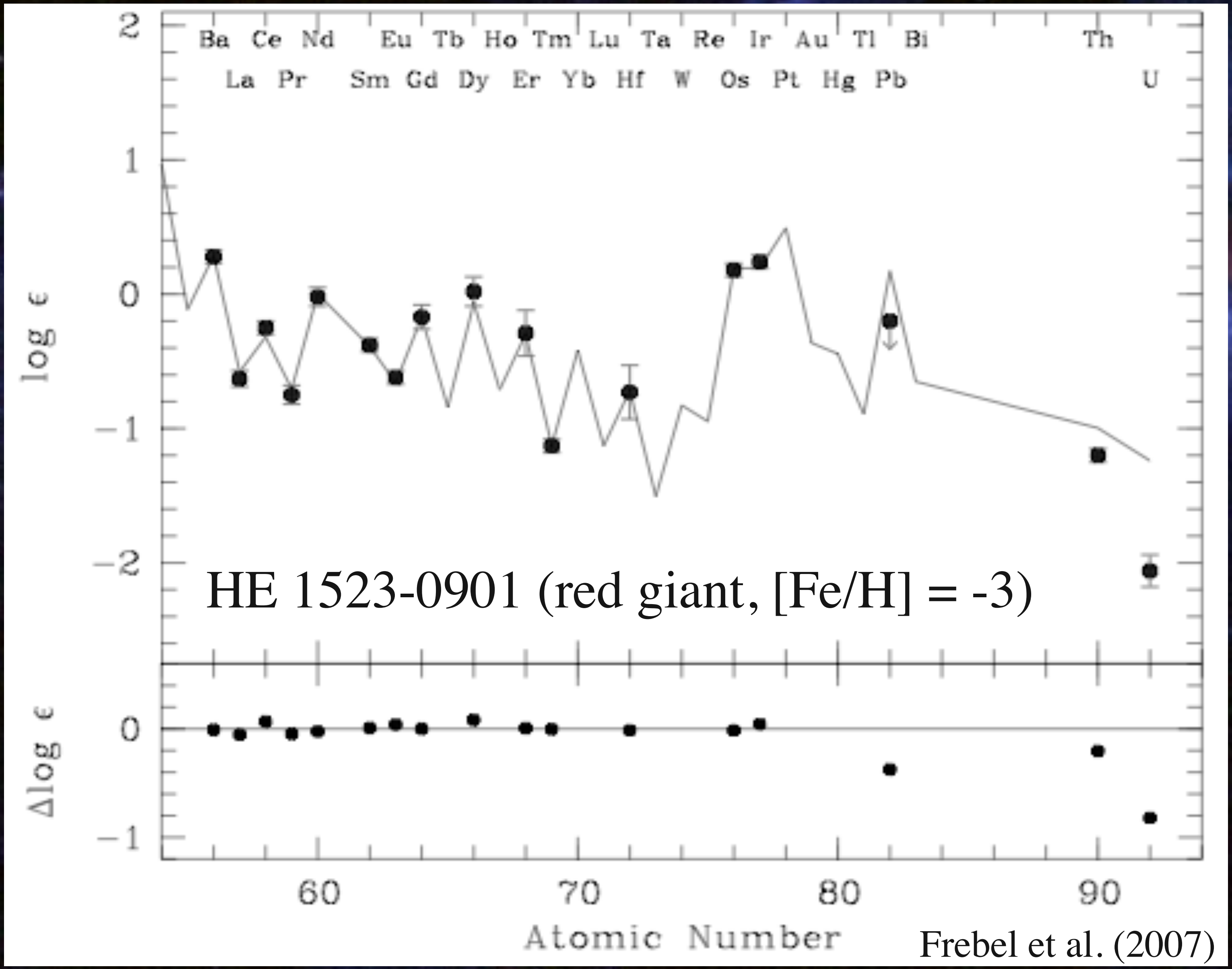

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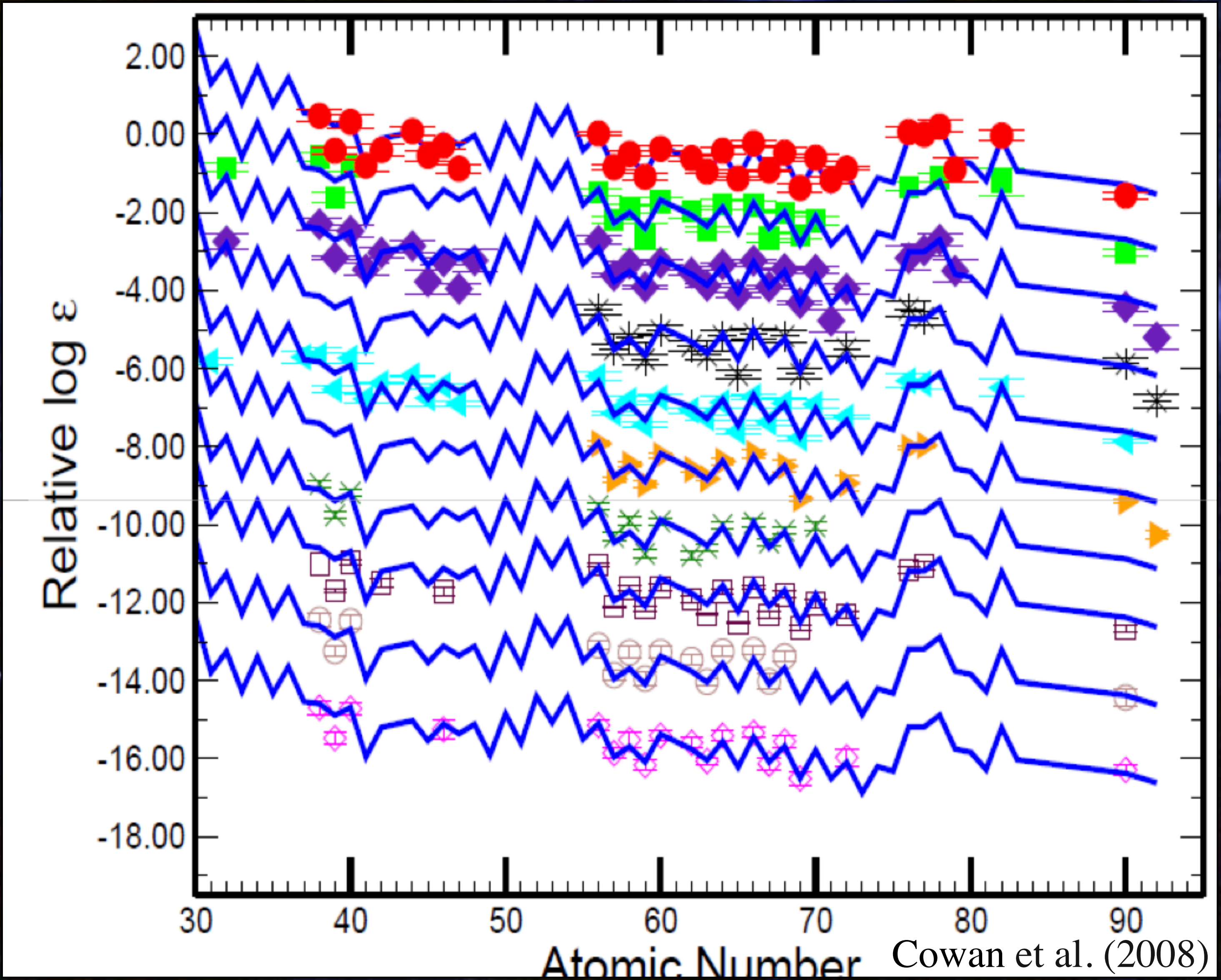
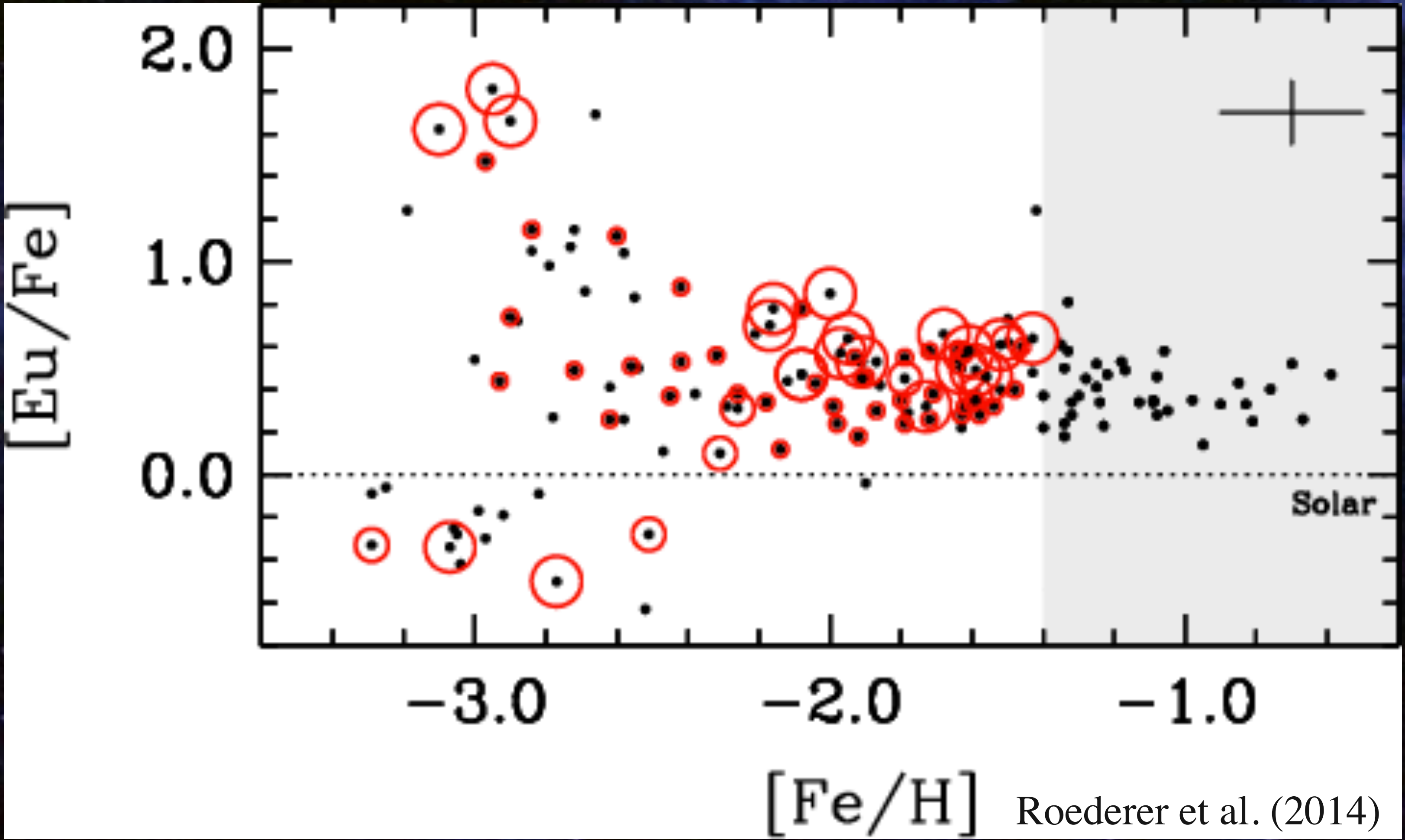


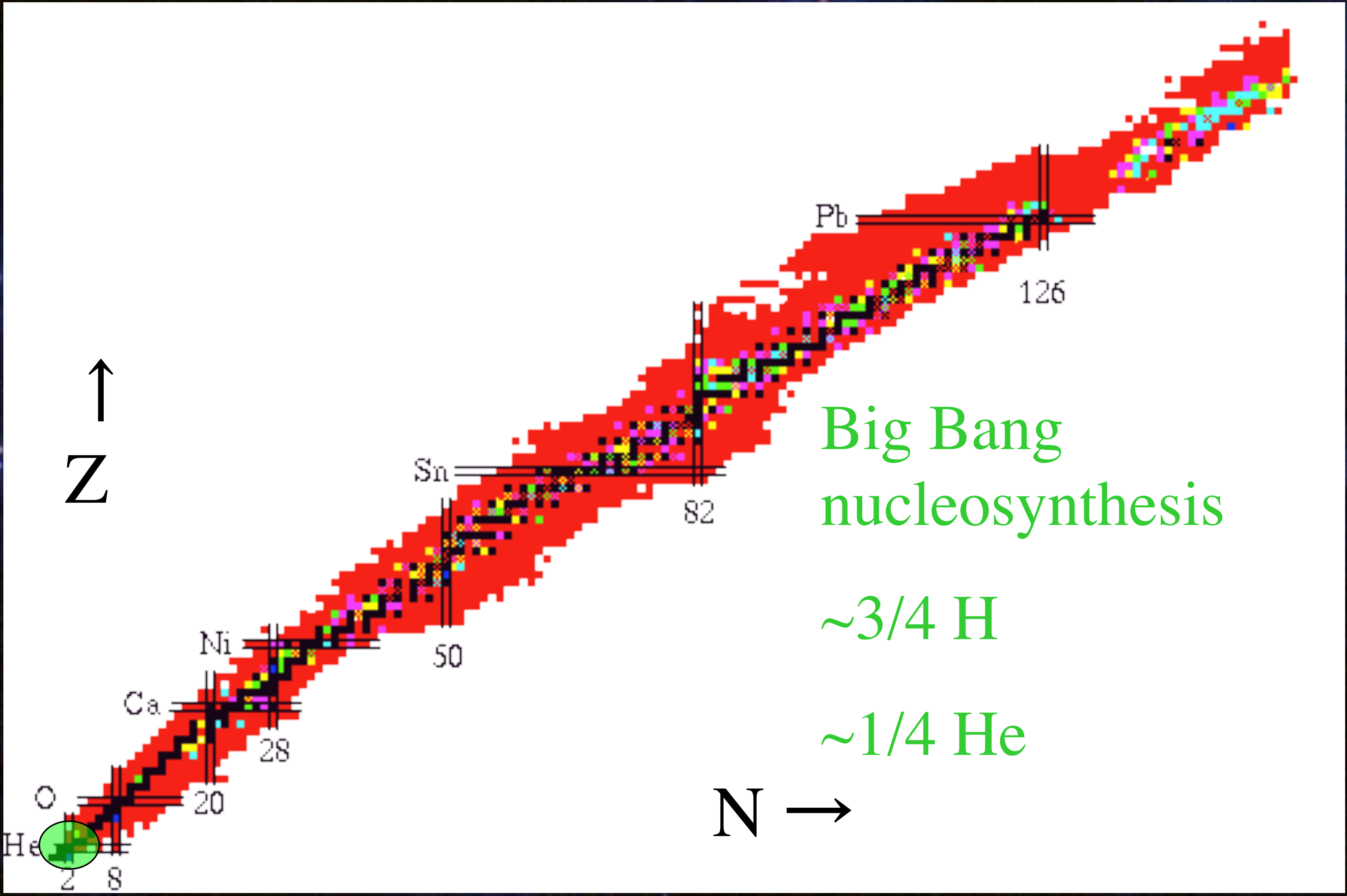
Cowan et al. (2008)

metal-poor stars and the *r* process



Roederer et al. (2014)

chart of the nuclides



Big Bang nucleosynthesis

~3/4 H

~1/4 He

Could ^{4}He, ~25% by mass, be generated by stellar burning during the lifetime of our galaxy?

Estimate the percentage of the Sun's mass that has been converted from p to ^{4}He so far, and use the result to argue the bulk of the ^{4}He in our galaxy is primordial.

Note the average amount of solar radiation received by the Earth's atmosphere is 1370 W/m^2.

Sun's luminosity:

$(1370\ \mathrm{W/m^2})(4\pi d^2) = 3.8 \times 10^{26}\ \mathrm{J/s}$

energy recieved on Earth

Earth-Sun distance $= 1.49 \times 10^{11}$ m

Convert to MeV/s $\rightarrow$ 2.4×10^{39} MeV/s

Fusion of 4 protons to ^{4}He releases ~ 25 MeV

energy release per proton ~ 25 MeV/4

~ 4×10^{38} p consumed per second

Sun's mass ~ 1.99×10^{30} kg

mass of p ~ 1.67×10^{-27} kg

$\rightarrow$ Sun has roughly 1.2×10^{57} p

Total number of protons consumed so far in Sun's ~ 5 billion year lifetime

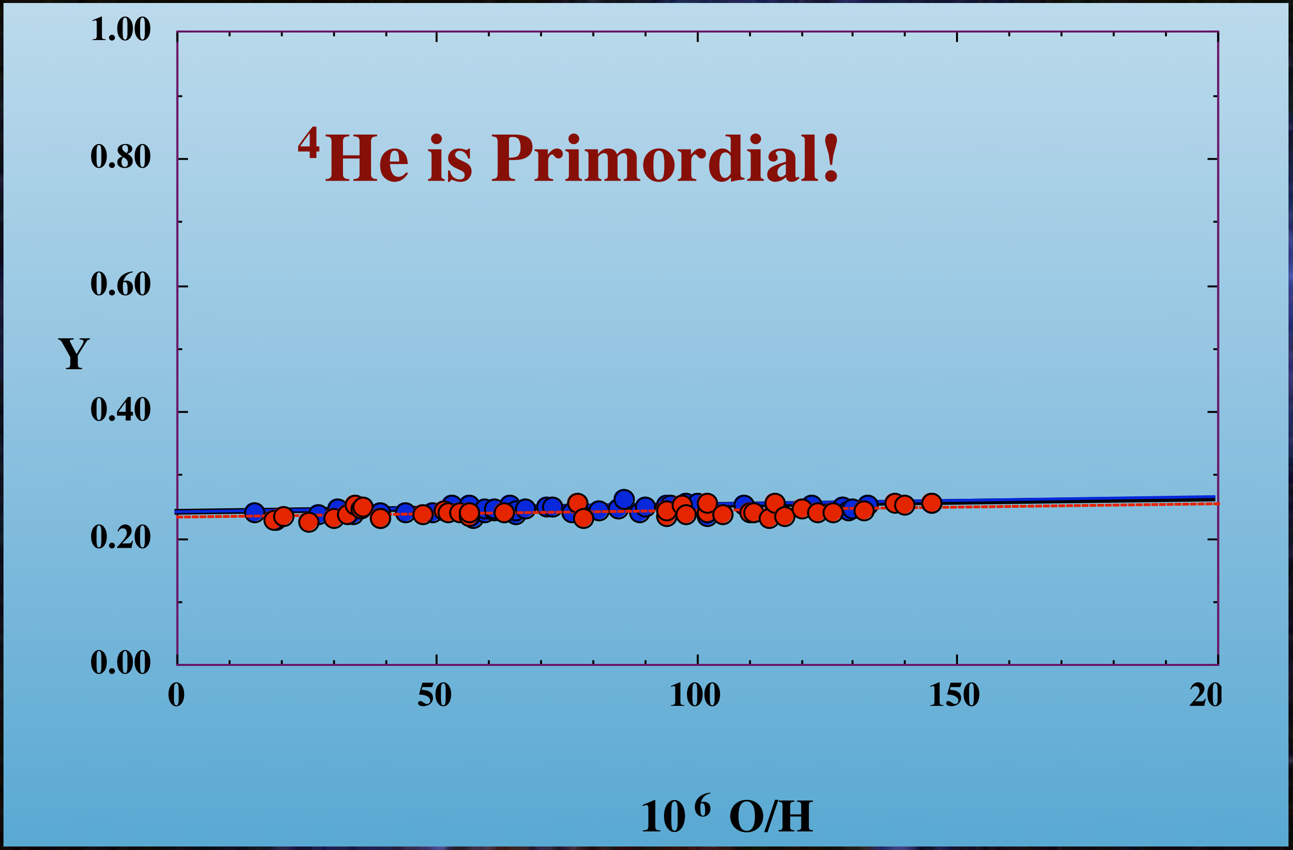
$(3.15 \times 10^7\ \mathrm{s/year})(5 \times 10^9\ \mathrm{years})(4. \times 10^{38}\ \mathrm{p/s})$

~ 0.63×10^{56} p

$0.63/12$ ~ 5.3% of Sun's mass

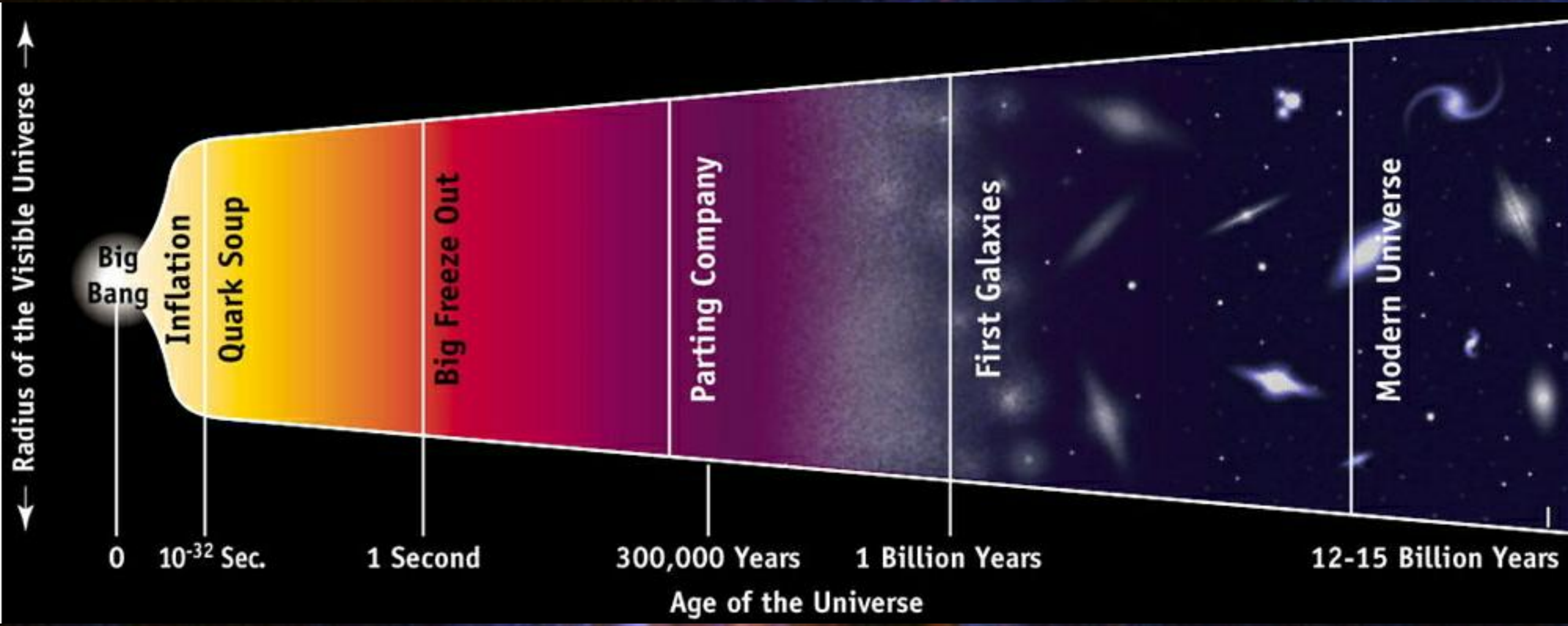
not enough, and locked in core!

helium in extragalactic metal-poor HII regions

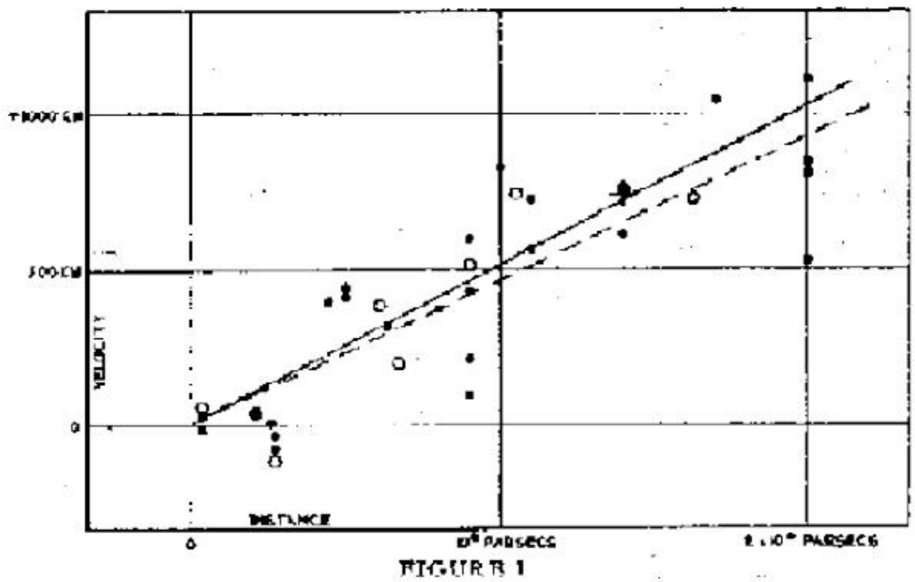


shows no correlation with metallicity

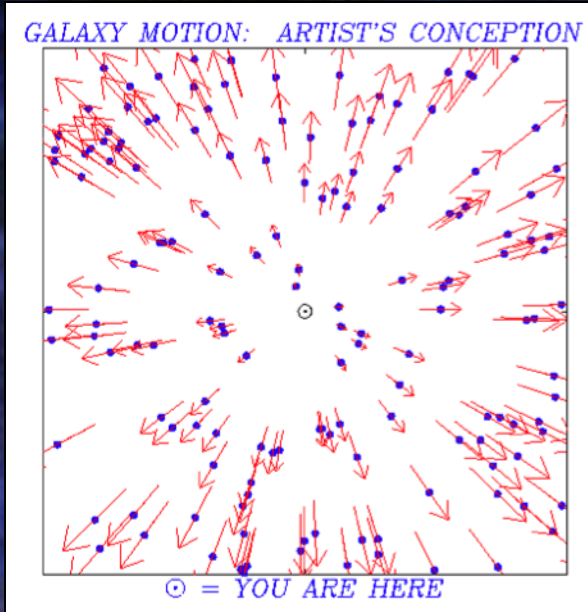
cosmology in brief



Hubble expansion



Hubble's original 1929 data, from which a linear velocity-distance relation was proposed.



$\vec{v} = H\,\vec{r}$

$\vec{v}$ galaxy's recessional velocity

$\vec{r}$ distance between galaxy and observer

H Hubble's constant

Hubble's Law is a natural result of an expansion that is isotropic and homogeneous

Which of the following are moving apart due to the expansion of the universe?

A – two hydrogen atoms in the interstellar medium

B – two stars in a galaxy

C – two widely separated galaxies

D – all of the above

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According to modern cosmology, the universe will:

A – continue to expand forever at the rate observed today

B – slow its expansion

C – reverse its expansion into a ‘big crunch’

D – expand at an accelerating rate

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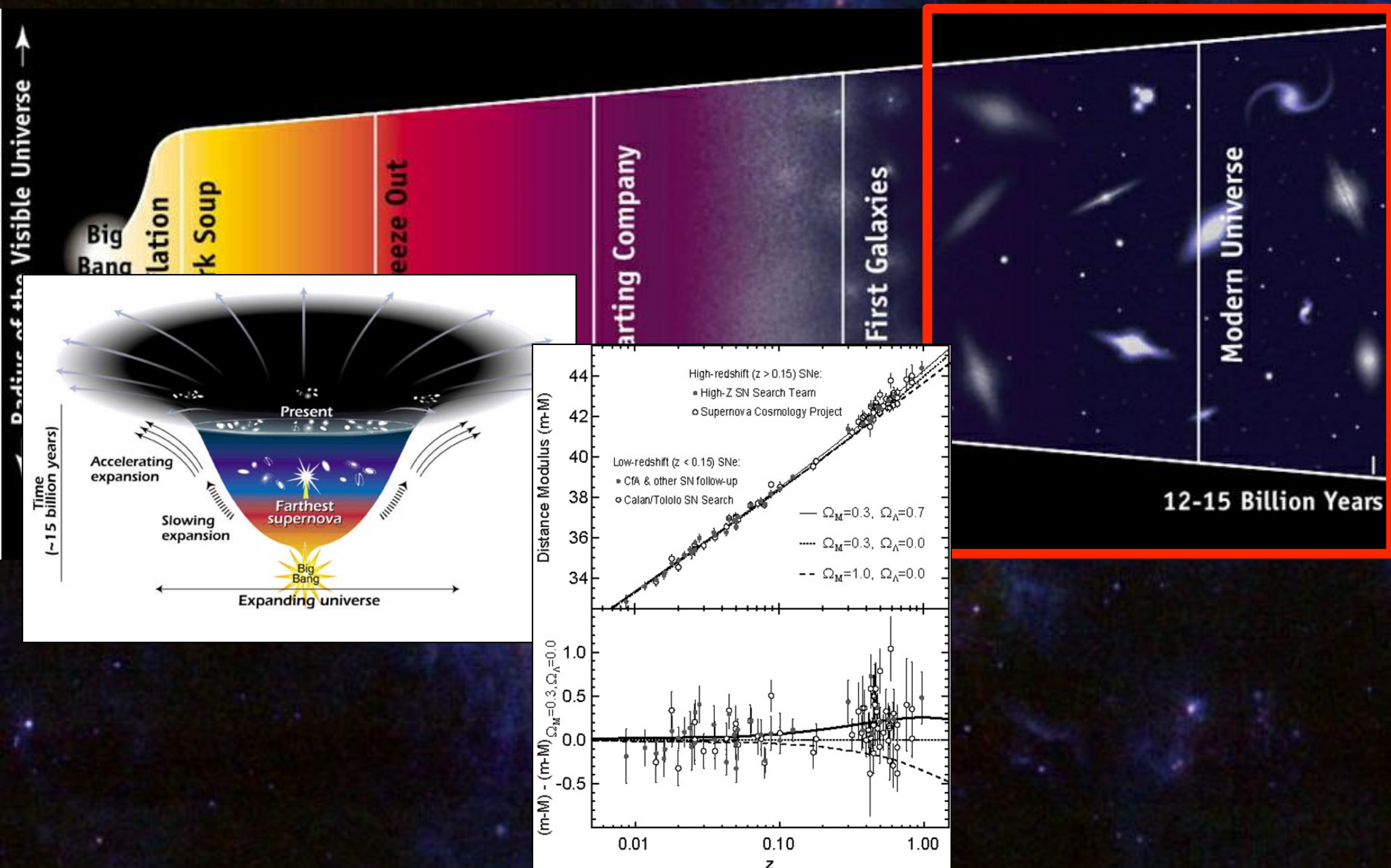
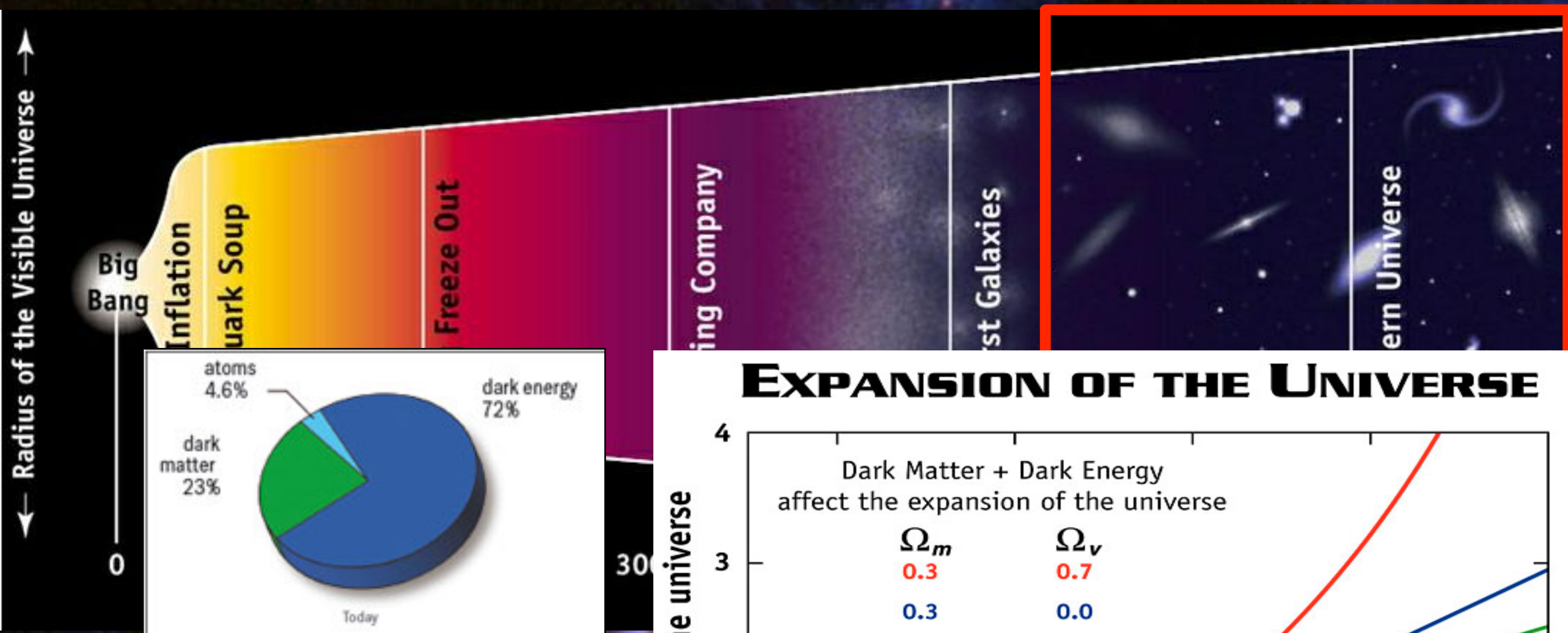
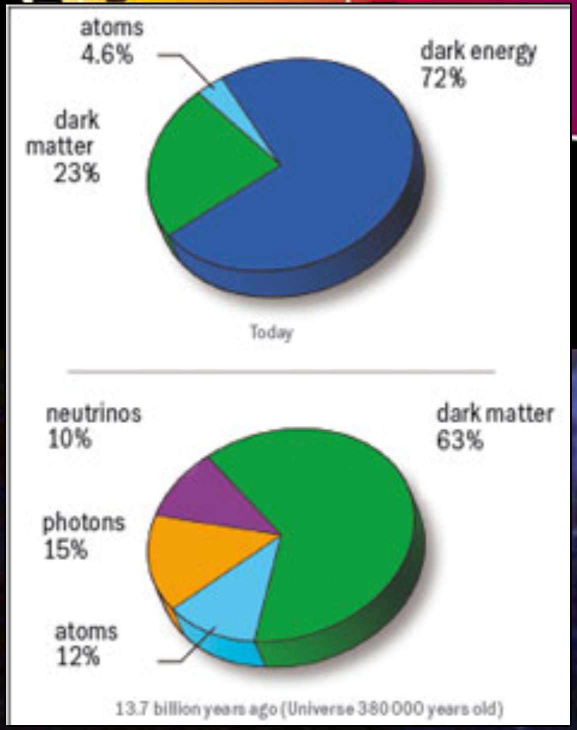
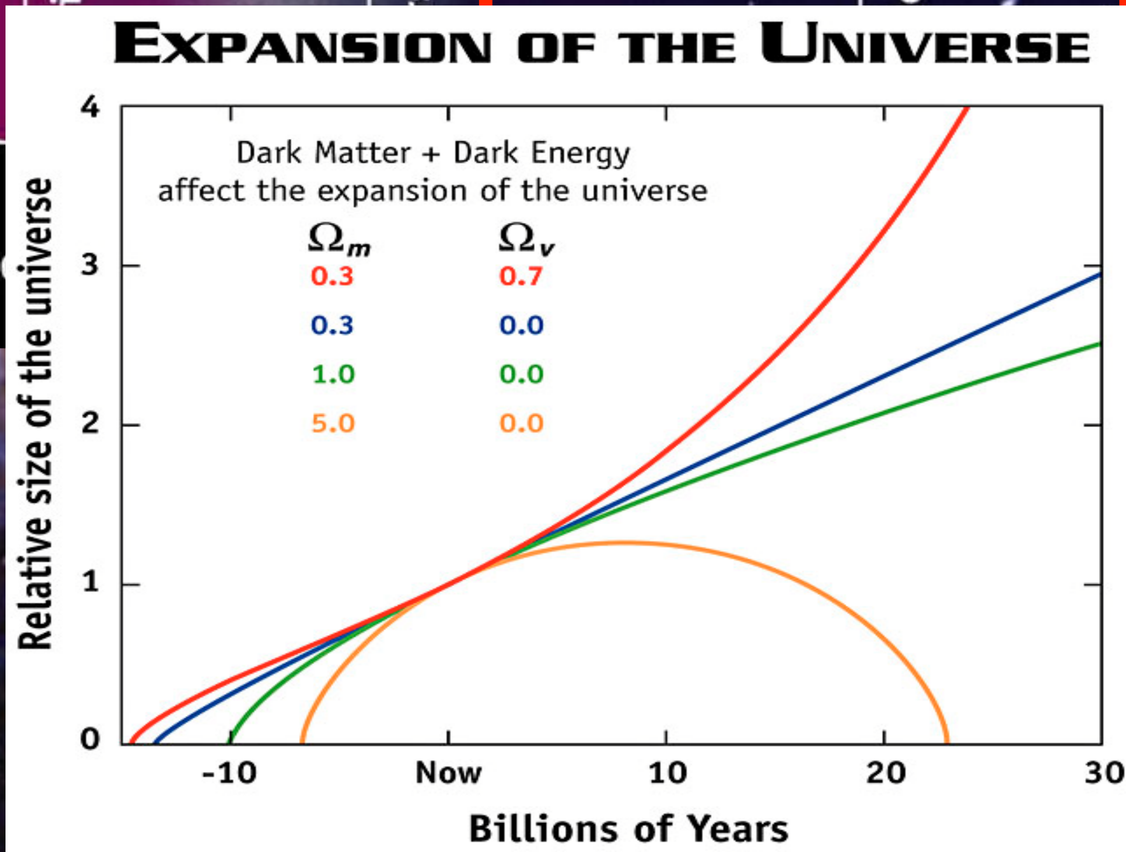


Hubble expansion and dark energy







As photons travel through our expanding universe over billions of years, what happens to them?

A – Their wavelength decreases.

B – Their wavelength increases.

C – Their velocity slows down.

D – Their energy increases.

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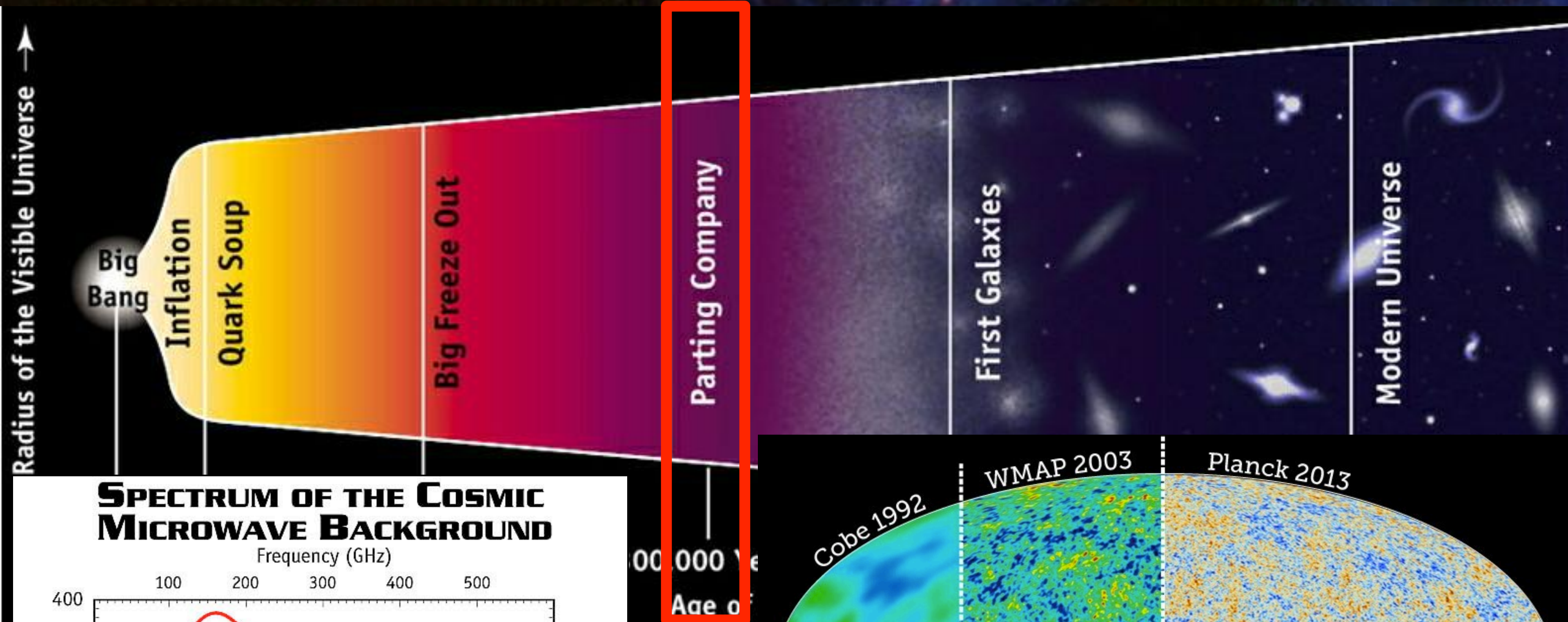
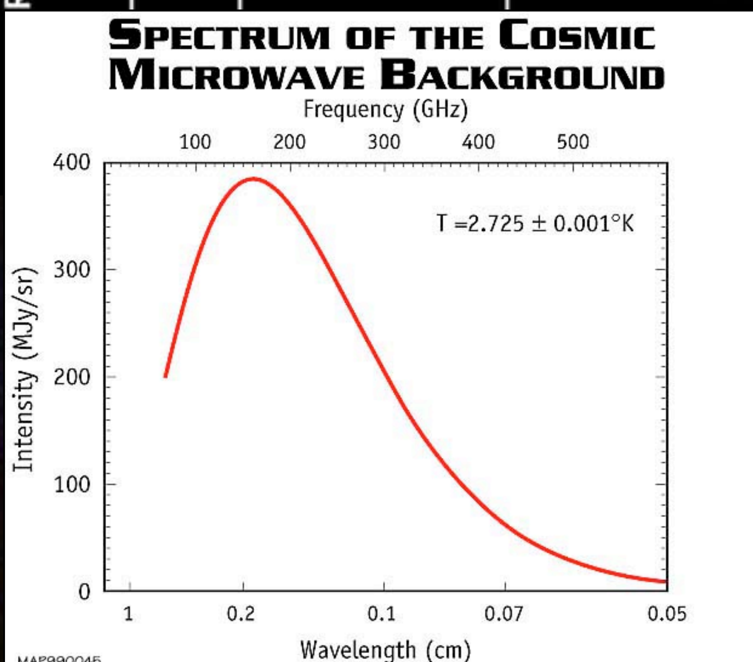
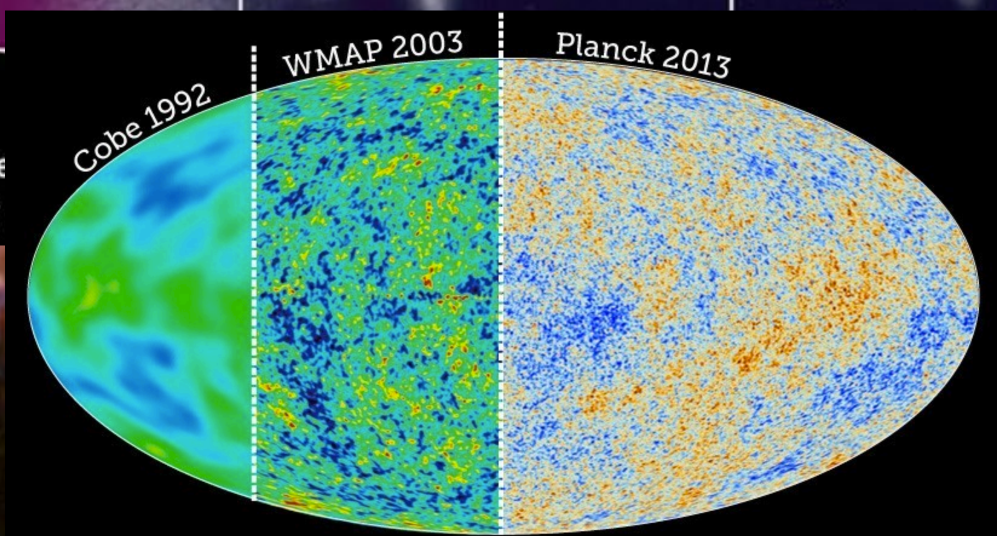
cosmic microwave background radiation







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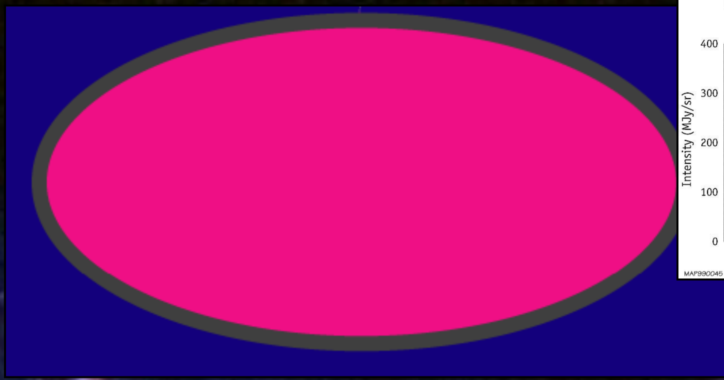

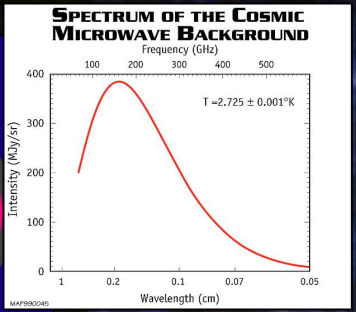

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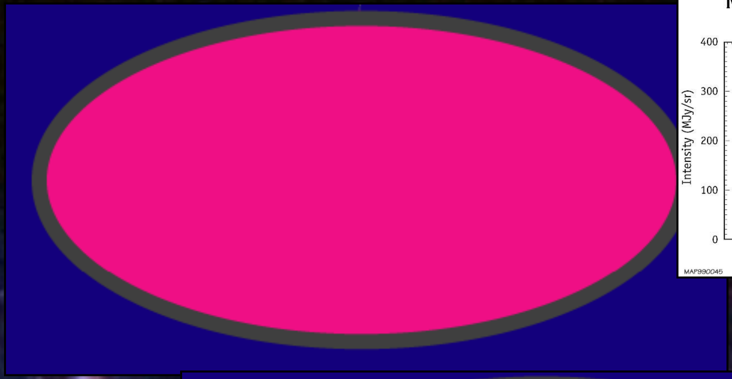

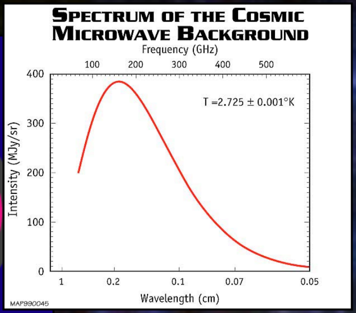

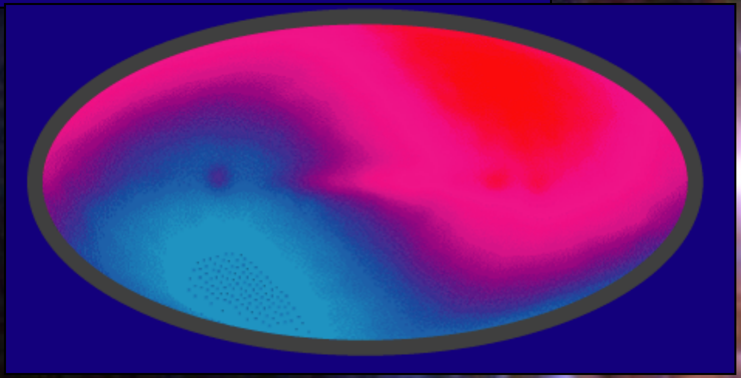

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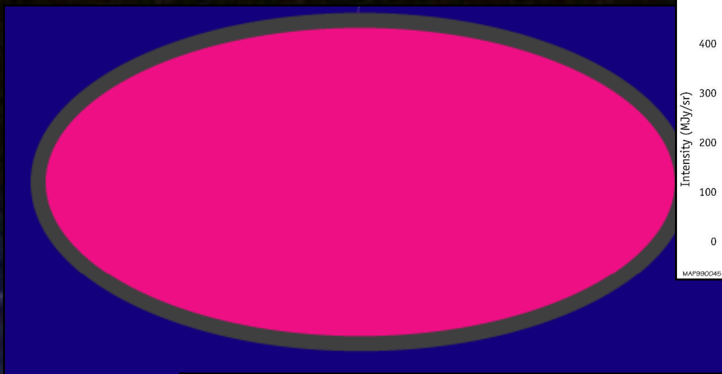

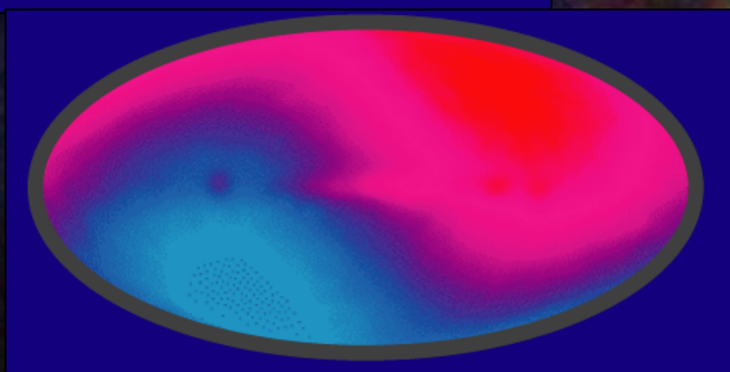

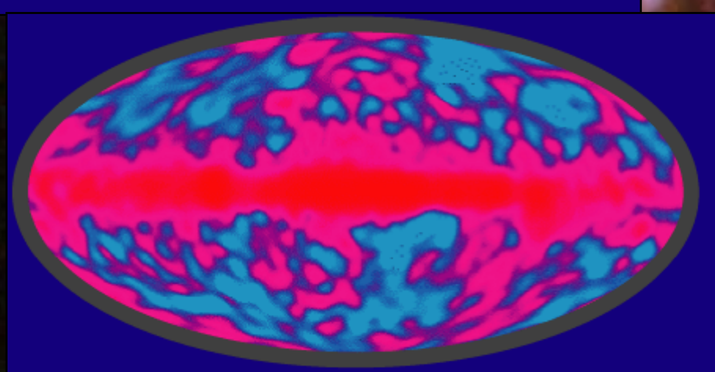

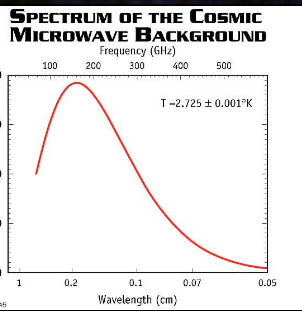

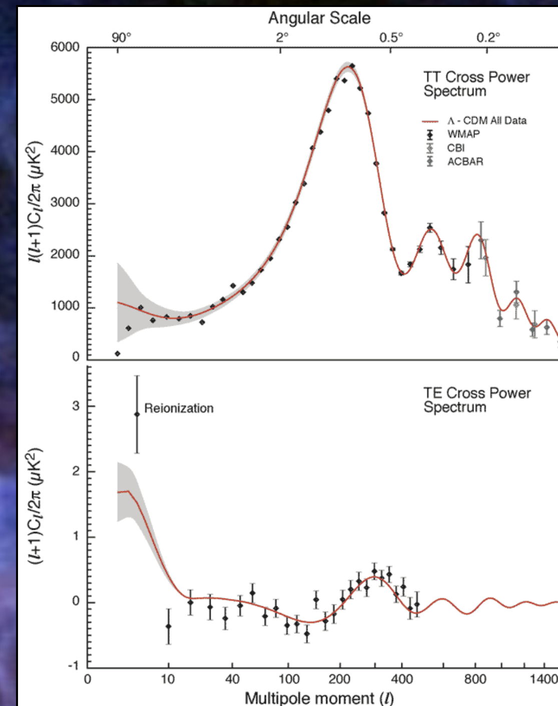

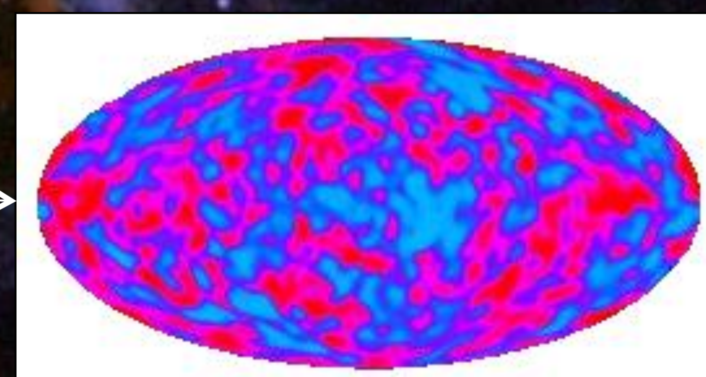

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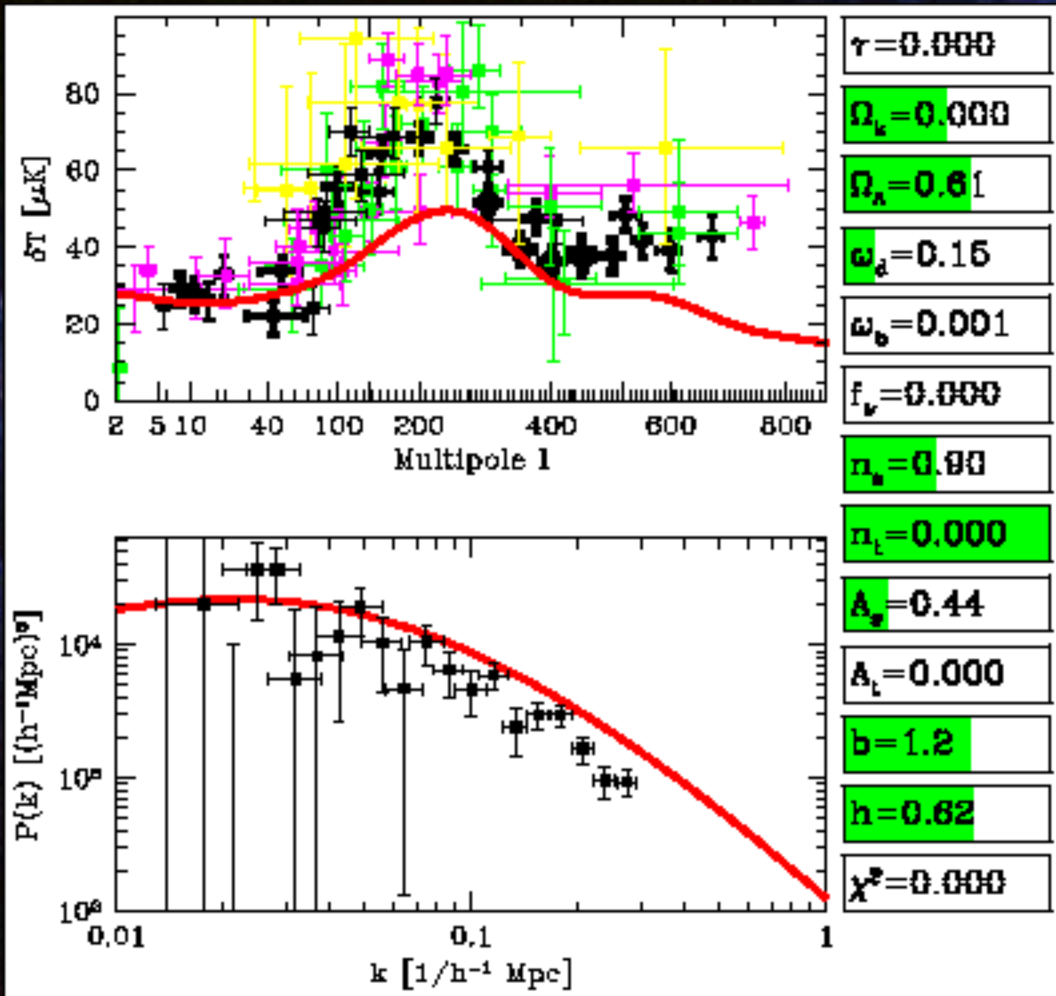
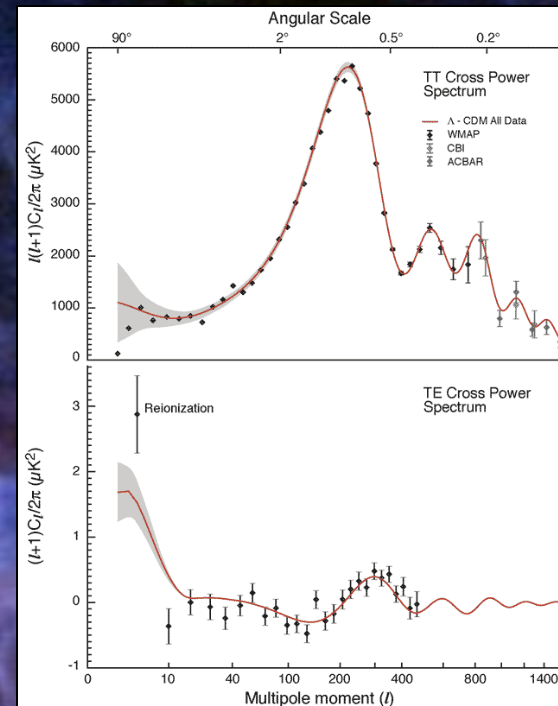
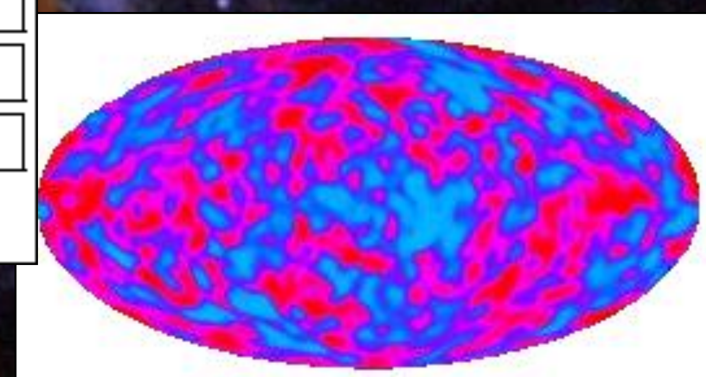
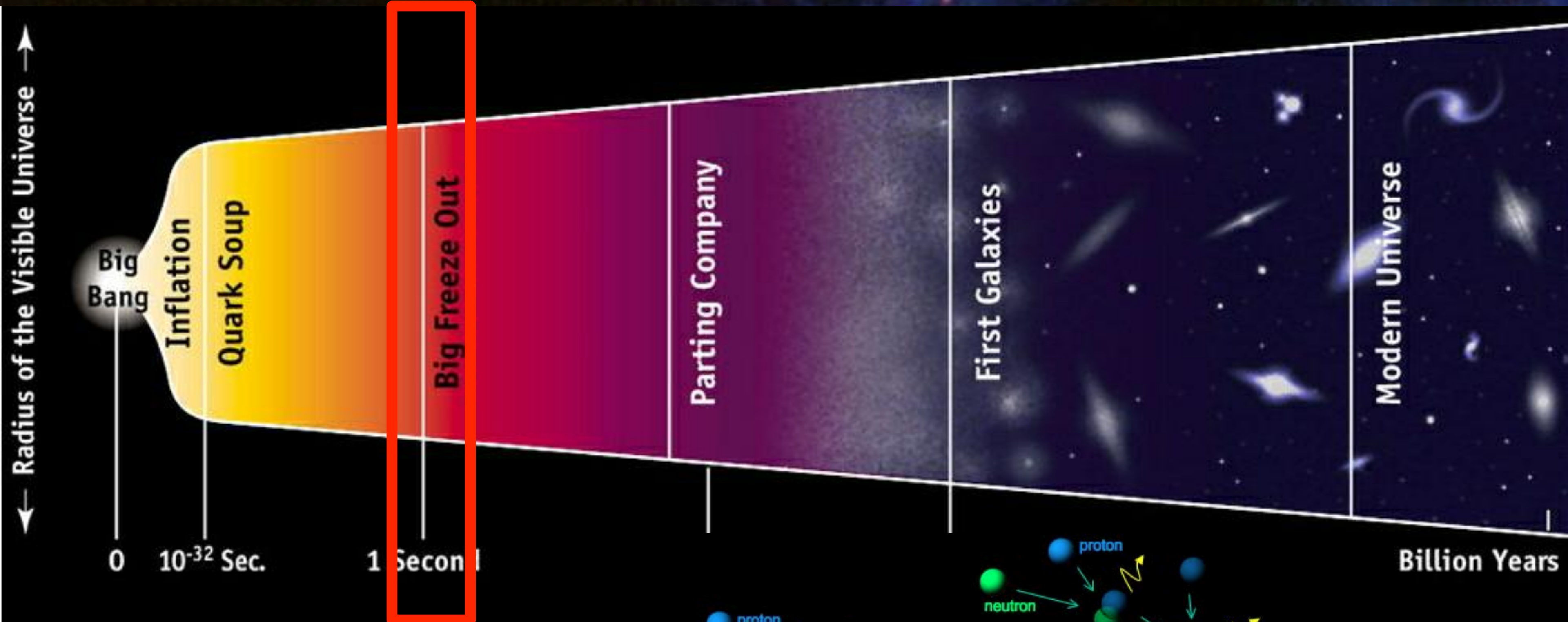


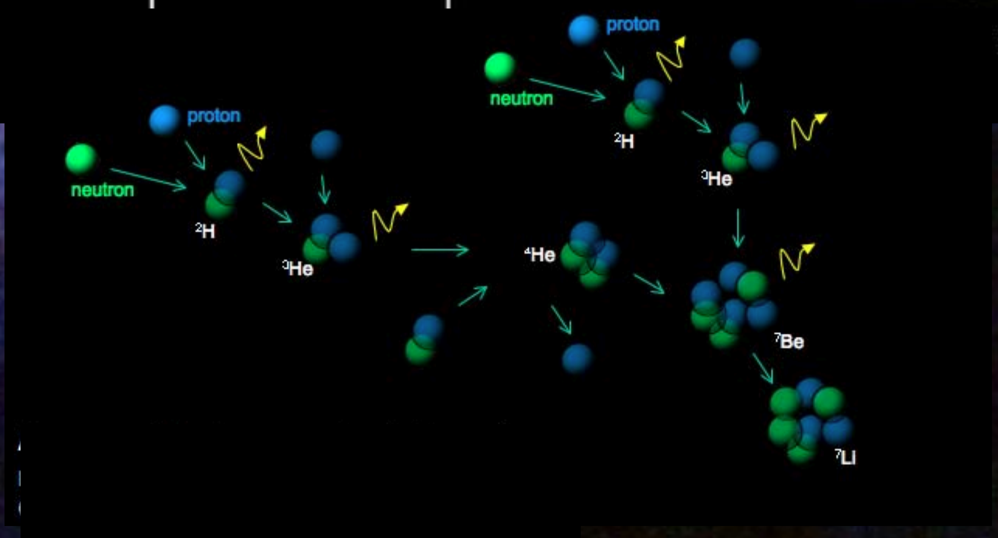




Max’s Cosmic Cinema
http://space.mit.edu/home/tegmark/cmb/movies.html

big bang nucleosynthesis





BBN: the conditions

space – homogeneous, isotropic

hot, radiation dominated $\rho_{\text{early}} \approx \rho_{\text{radiation}} \propto T_\gamma^{\,4}$

dark matter, dark energy present but not interacting

adiabatic expansion with fixed baryon-to-photon ratio

$$T = \frac{T_0}{a} \qquad \eta = \frac{n_b}{n_\gamma}$$

composition

$$\gamma,\ e^-,\ e^+,\ \nu,\ \bar{\nu},\ p,\ n$$

back-of-the-envelope BBN

Reactions coupling radiation and matter are initially in equilibrium

$$\gamma + \gamma \leftrightarrow e^- + e^+ \leftrightarrow \nu + \bar{\nu}$$

$$p + e^- \leftrightarrow \nu_e + n$$

$$n + e^+ \leftrightarrow \bar{\nu}_e + p$$

back-of-the-envelope BBN

Reactions coupling radiation and matter are initially in equilibrium

and so the neutron-to-proton ratio can be calculated as

$$\frac{n_n}{n_p} = e^{-Q/kT}, \text{ where } Q = (m_n - m_p)c^2 = 1.293 \text{ MeV}$$

As the temperature falls, so do the interaction rates
Weak equilibrium fails when T~10^{10} K, so the neutron-to-proton ratio is 'frozen' at:

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$$\frac{n_n}{n_p} = e^{-Q/kT} = e^{-(1.293\text{ MeV})/(8.617\times10^{-11}\text{ MeV/K}\cdot10^{10}\text{ K})} \approx 0.223$$

Composition is therefore ~223 n for every 1000 p

back-of-the-envelope BBN

At T~10^{10} K, still too hot for deuterium to form:

$$p + n \leftrightarrow d + \gamma$$

Below T~10^9 K, the reverse reaction slows, and deuterium can survive.
From T~10^{10} K to T~10^9 K, roughly 176 s have passed, and the composition has evolved due to the decay of the neutron:

back-of-the-envelope BBN

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From T~10^{10} K to T~10^{9} K, roughly 176 s have passed, and the composition has evolved due to the decay of the neutron:

$$N_n = 223e^{-t/\tau} = 223e^{-176/885.7} = 183 \text{ neutrons remaining}$$

$$N_p = 1000 + (223 - 183) = 1040 \text{ protons}$$

If we now assume all of the neutrons combine with an equal number of protons to make deuterium, and that all of the deuterium combines to ^{4}He, we can estimate the mass fraction of helium as:

$$X_{\mathrm{He}} \sim \frac{4N_{\mathrm{He}}}{N_p + 4N_{\mathrm{He}}} \sim \frac{4(91)}{858 + 4(91)} \sim 0.298$$

Why does big bang nucleosynthesis fail to reach iron?

A – By the time deuterium is made and alpha particles assemble, the temperature and density are too low.

B – No stable nuclei exist for A=5 and A=8.

C – High energy photons block production of nuclei heavier than lithium/beryllium/boron.

D – It doesn't – a small amount of iron group and other heavy elements are made in BBN.

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