The Origin of the Elements

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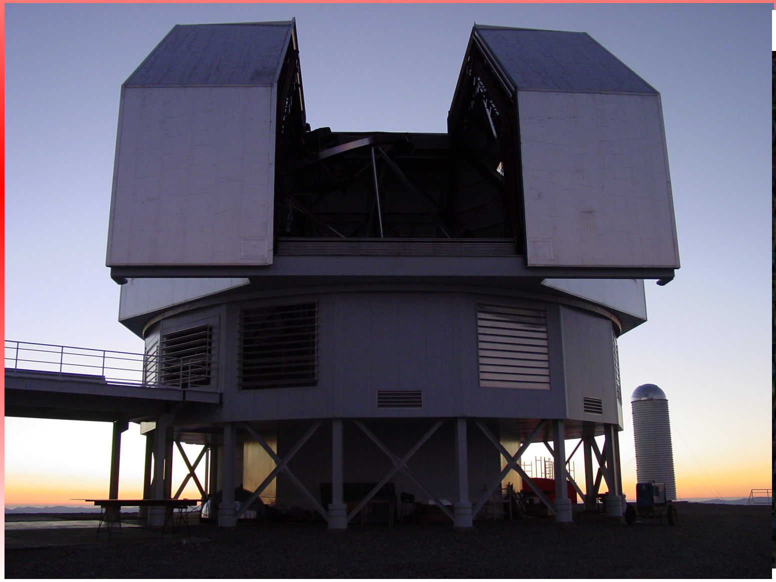
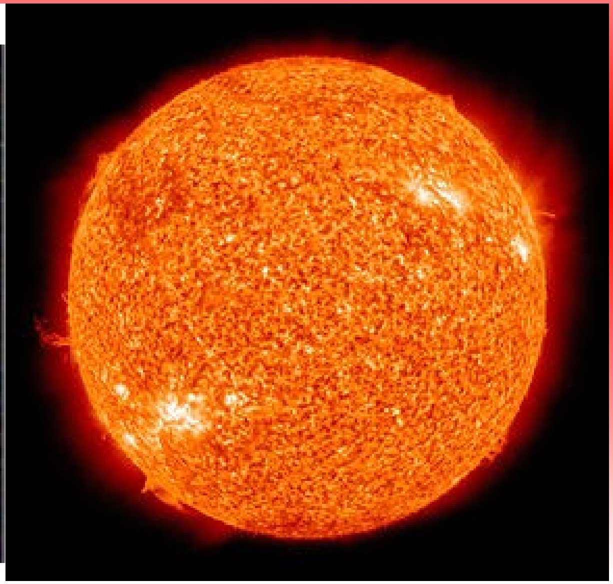
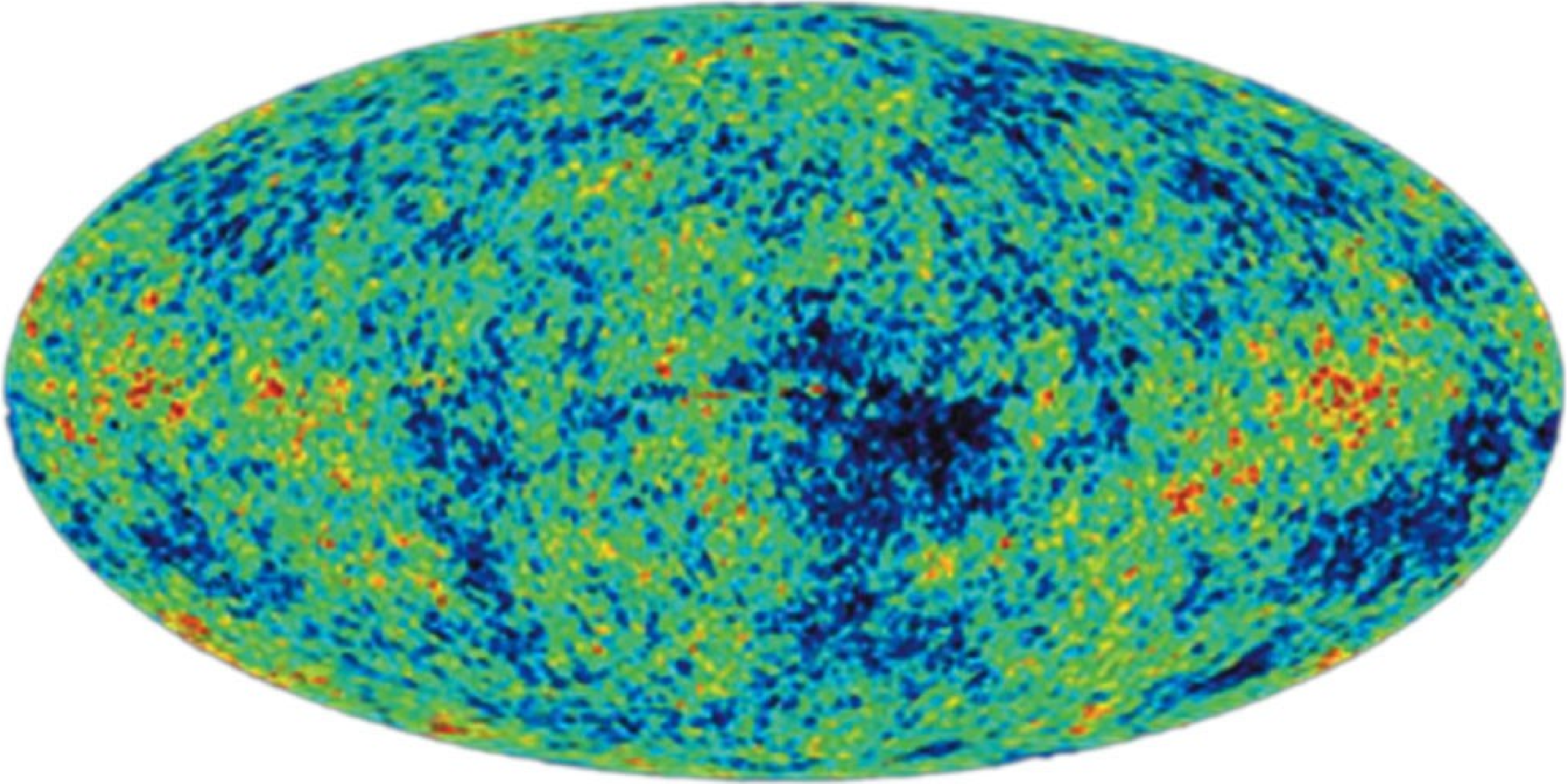
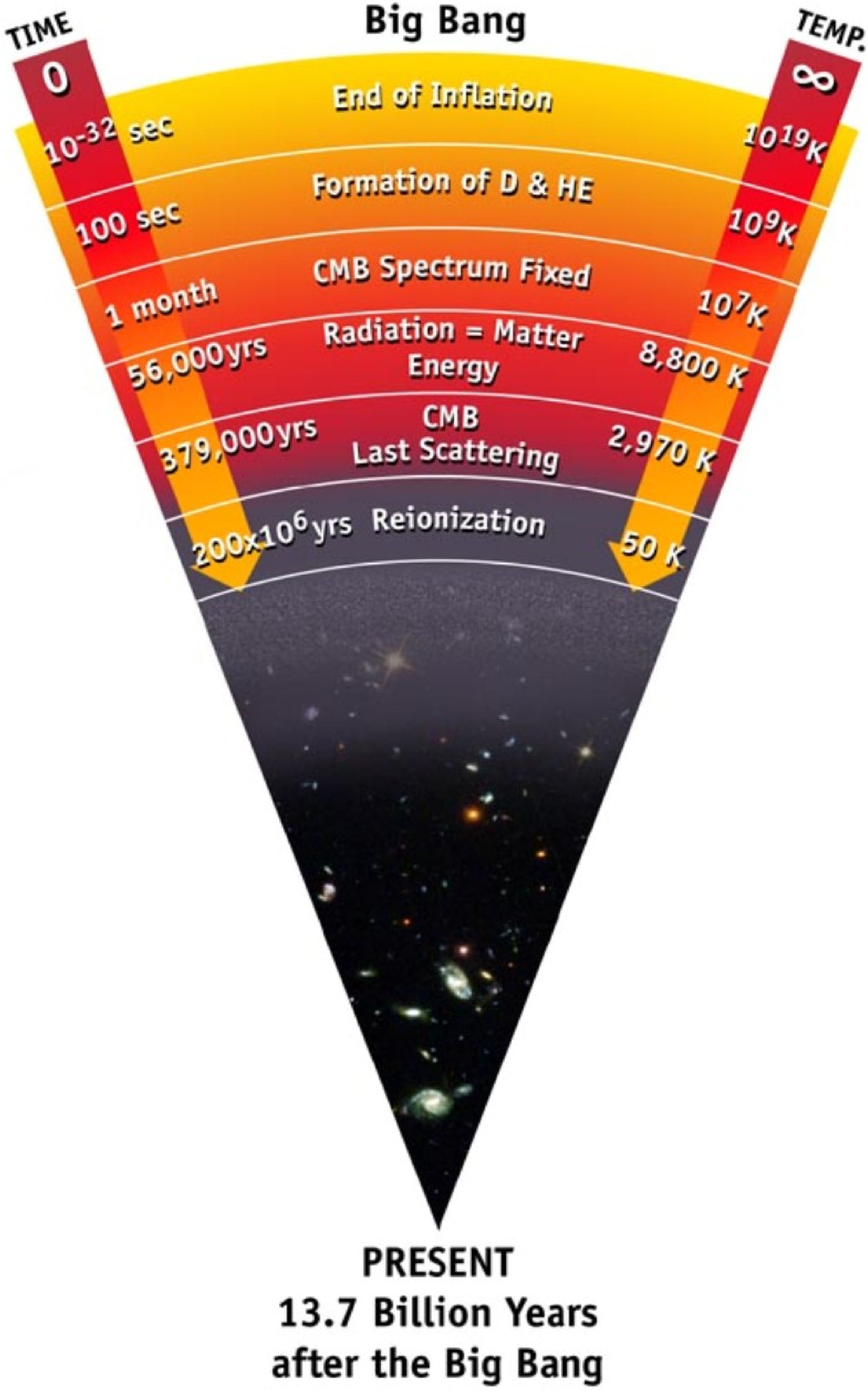




Public Astronomy Lecture Series
The University of Louisville
March 10, 2016

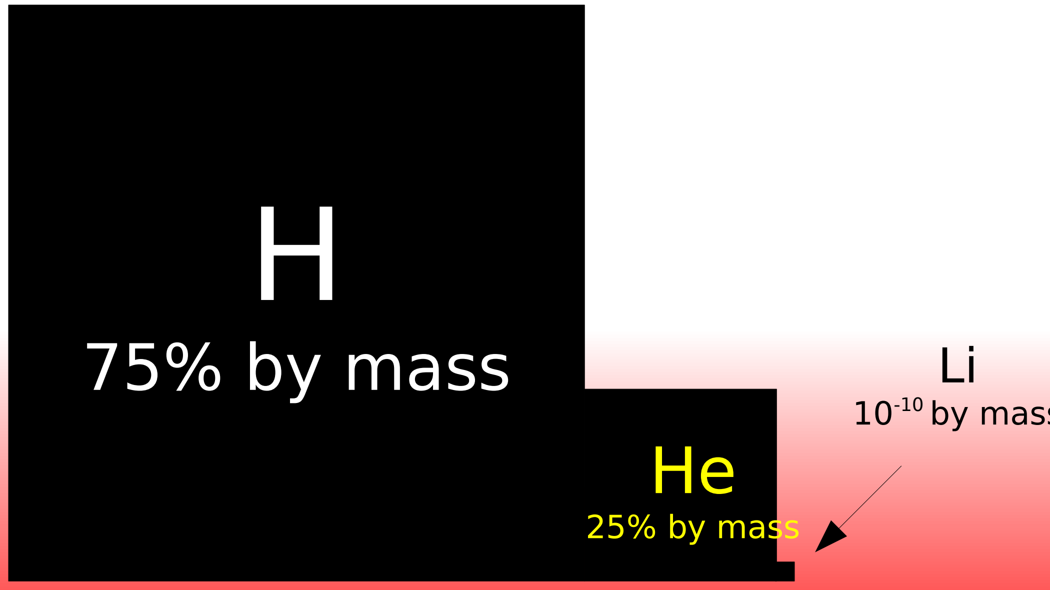


NASA's Wilkinson Microwave Anisotropy Probe (WMAP) Science Team



Big Bang
TIME
TEMP.
0
∞
End of Inflation
10-32 sec
1019K
Formation of D & HE
100 sec
109K
CMB Spectrum Fixed
1 month
107K
Radiation = Matter Energy
56,000yrs
8,800 K
CMB Last Scattering
379,000yrs
2,970 K
Reionization
200x106yrs
50 K
PRESENT
13.7 Billion Years
after the Big Bang

In the Big Bang the only elements formed were H, He, and tiny amounts of Li (and perhaps microscopic amounts of Be and B).



The Big Bang Periodic Table

All other elements have been made subsequently in stars and released back into the interstellar gas out of which new generations of stars are then formed.

Why only H, He, and tiny amounts of Li (and perhaps some Be, and B)?

The very early Universe is dominated by radiation, before the Universe cools and the density drops significantly particle and photon interactions prevent nuclei from forming.

At very early times (~1 sec) the number of protons and neutrons are approximately equal, but after this point neutrons due to their higher mass.

Thus neutrons are less likely to be formed by reactions of electrons with protons, in addition free neutrons decay so the neutron to proton ratio as nucleosynthesis starts is about 1/6.

So now there is more p's than n's, so we end up with more H than He (90% H by number)

Why don't we “cook” heavier elements at this time?

The Universe is rapidly getting less dense and cooler, so by the time we form a lot of He we have passed the time where we can fuse He to heavier elements.

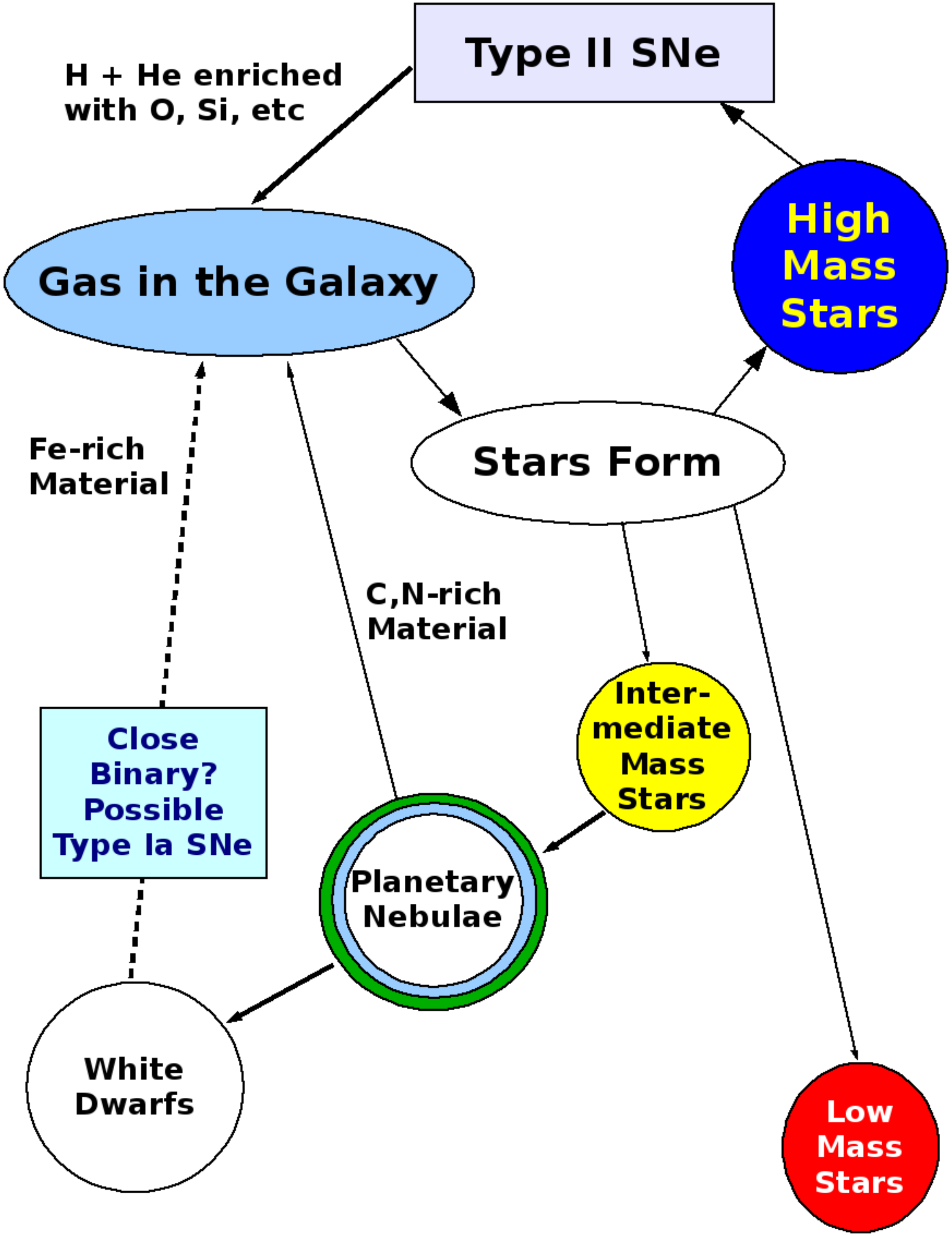
In addition there is another block.

This is because to make Carbon we need 3 Helium nuclei to combine. However the intermediate step of 2 Heliums combining is Be^{8} an extremely unstable nucleus which decays in $6x10^{-17}$ seconds. The triple alpha process to use 3 He nuclei has a long timescale (10's of thousands of years).

The Star-Gas Cycle

This figure shows a "cartoon" of the Star-Gas Cycle.

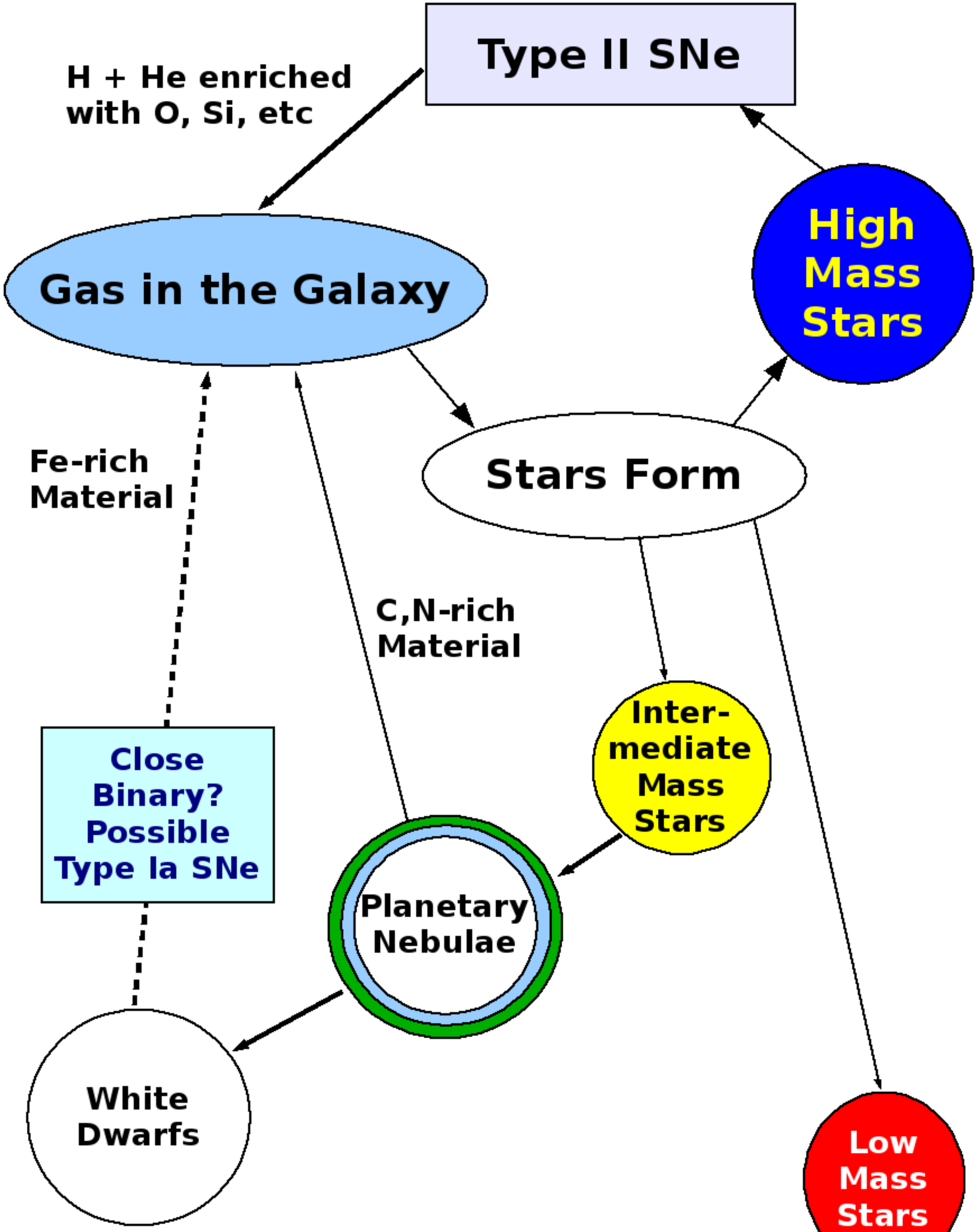
Interstellar gas and (after it is enriched by stars) dust cools, and eventually stars form, then what happens depends on the mass of the star.



The Star-Gas Cycle

The primary source of elements like O, Ne, Mg, Si, S, Ar, Ca and Ti is massive stars (>8 Solar masses) which explode as Type-II SNe.

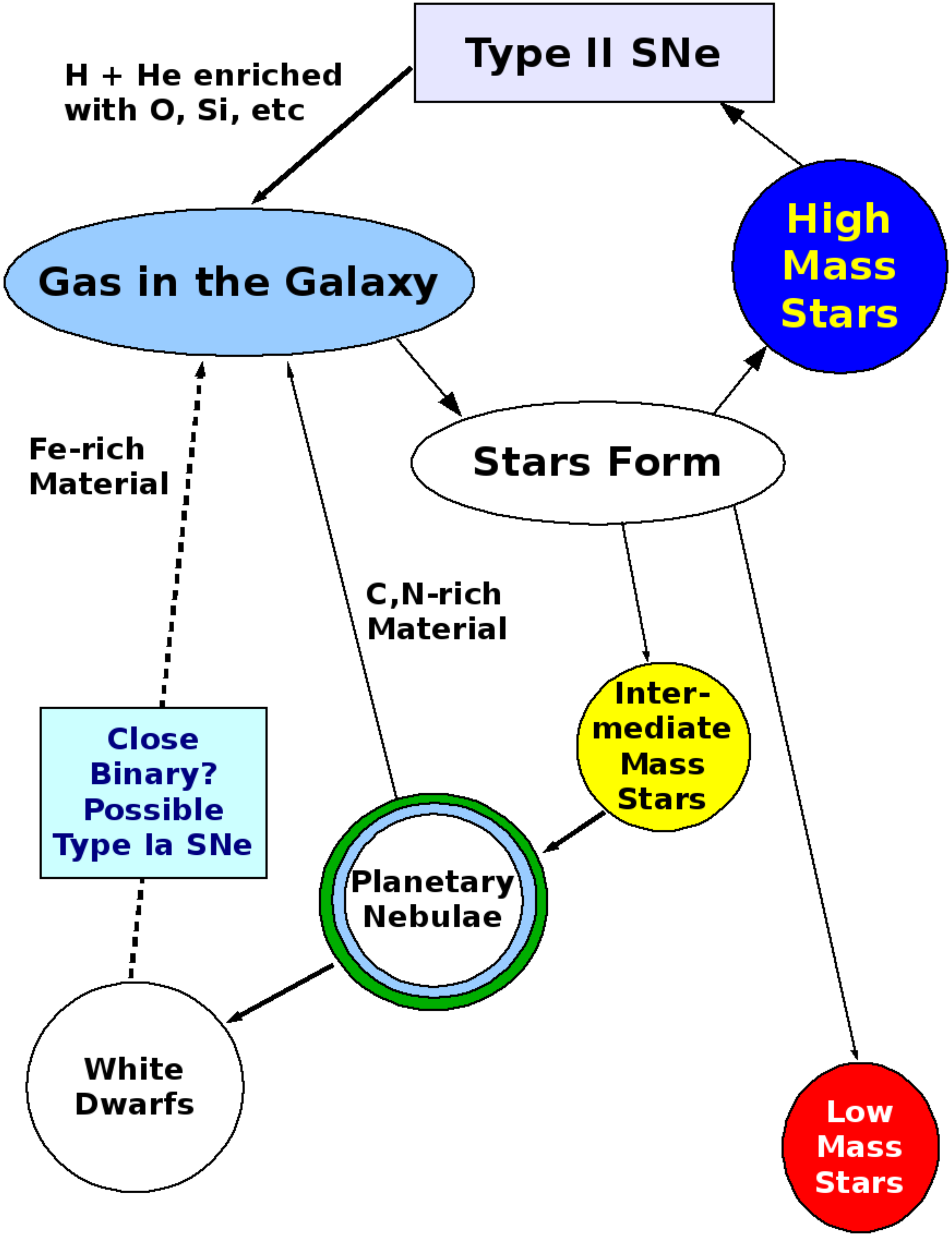
The odd-Z (odd number of proton) elements like Na, Al, P, Cl, K, Sc are also produced but in smaller amounts than their even-Z neighbors.



The Star-Gas Cycle

The primary source of C and N is intermediate mass stars (0.8 to 8 Solar masses) which at the end of their lives fuse He into heavier elements and then eject this enriched material as a planetary nebula.

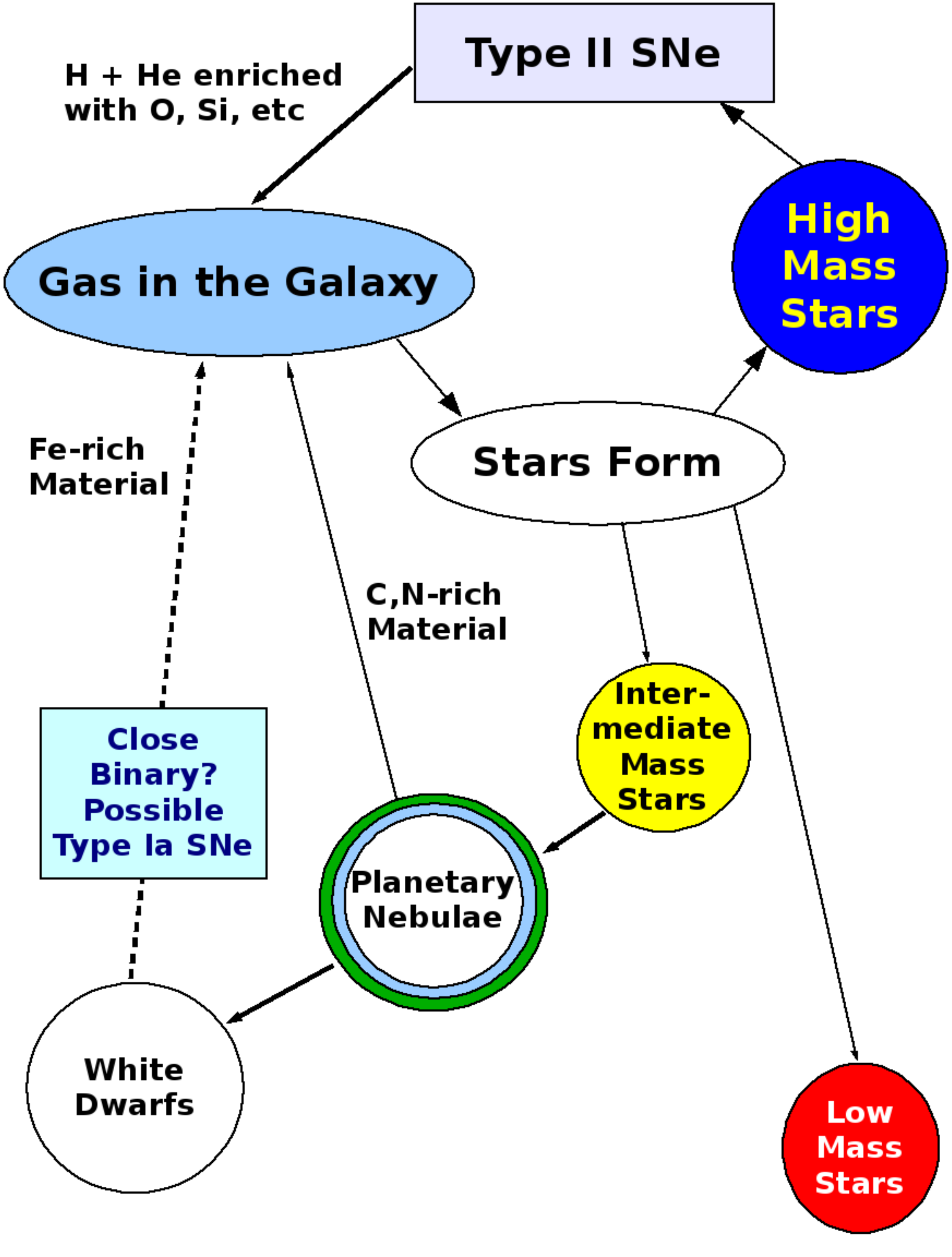
This will be the fate of the Sun in about 5.5 billion years.



The Star-Gas Cycle

The majority of the Fe and elements near Fe such as Cr, Mn, Co, Ni, Cu, and Zn are primarily formed when white dwarfs explode as Type-Ia SNe.

Type-II SNe also contribute some of these elements.



The Star-Gas Cycle

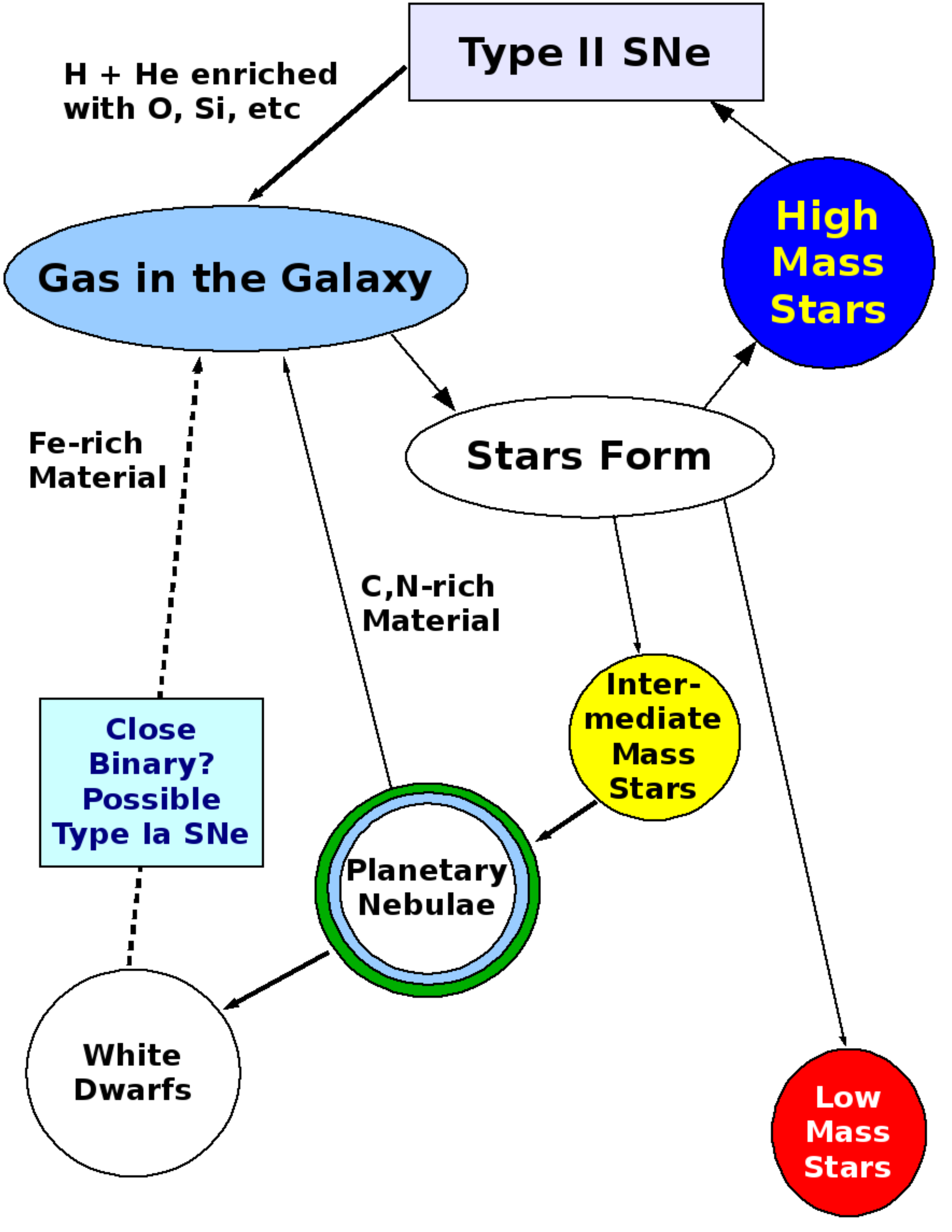
What about heavier elements (masses greater than iron)?

These are primarily made via the:

1) s-process – slow build up on neutrons in seed nuclei with beta-decay (mostly intermediate mass)

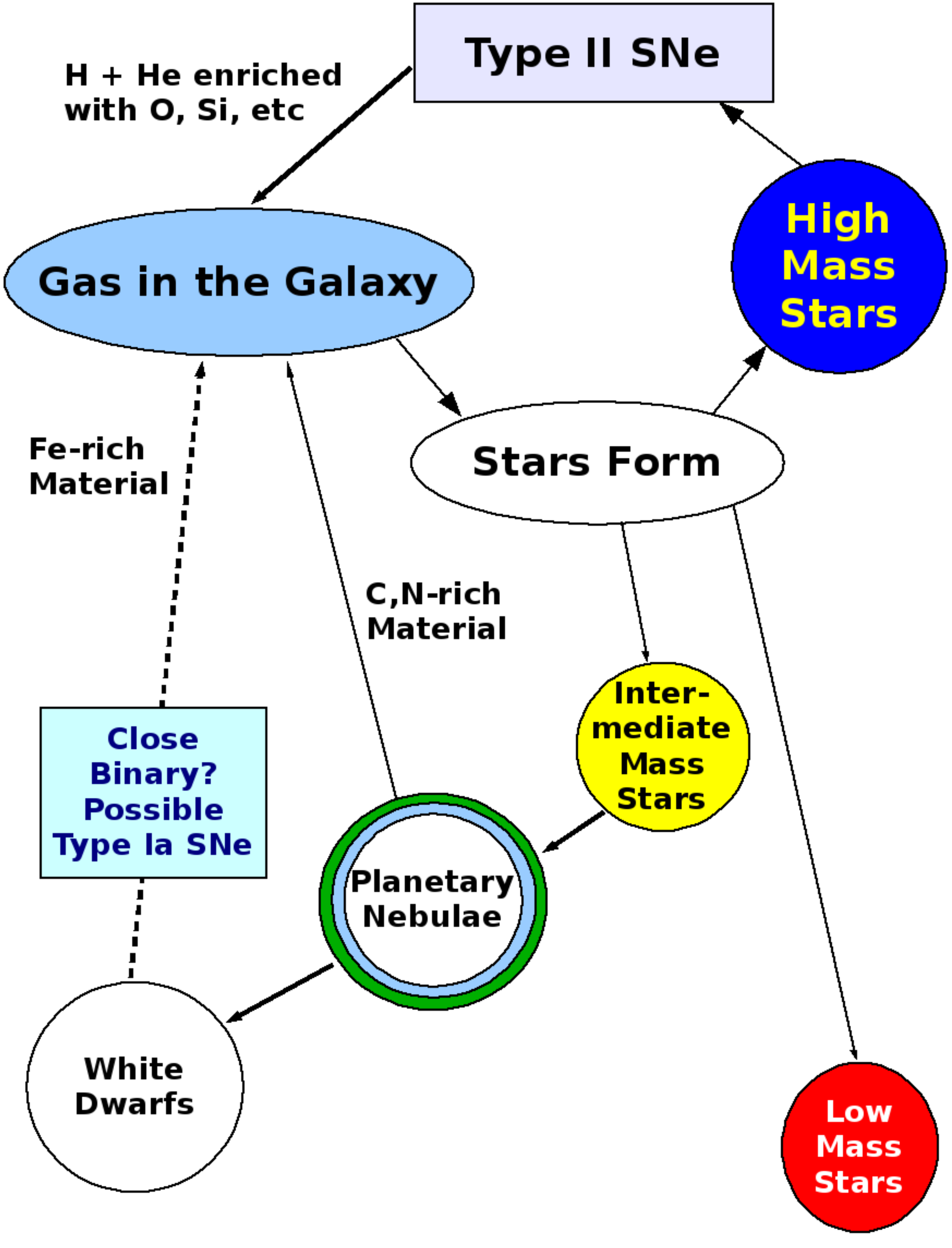
2) r-process – rapid neutron capture (supernovae)

These require seed nuclei.



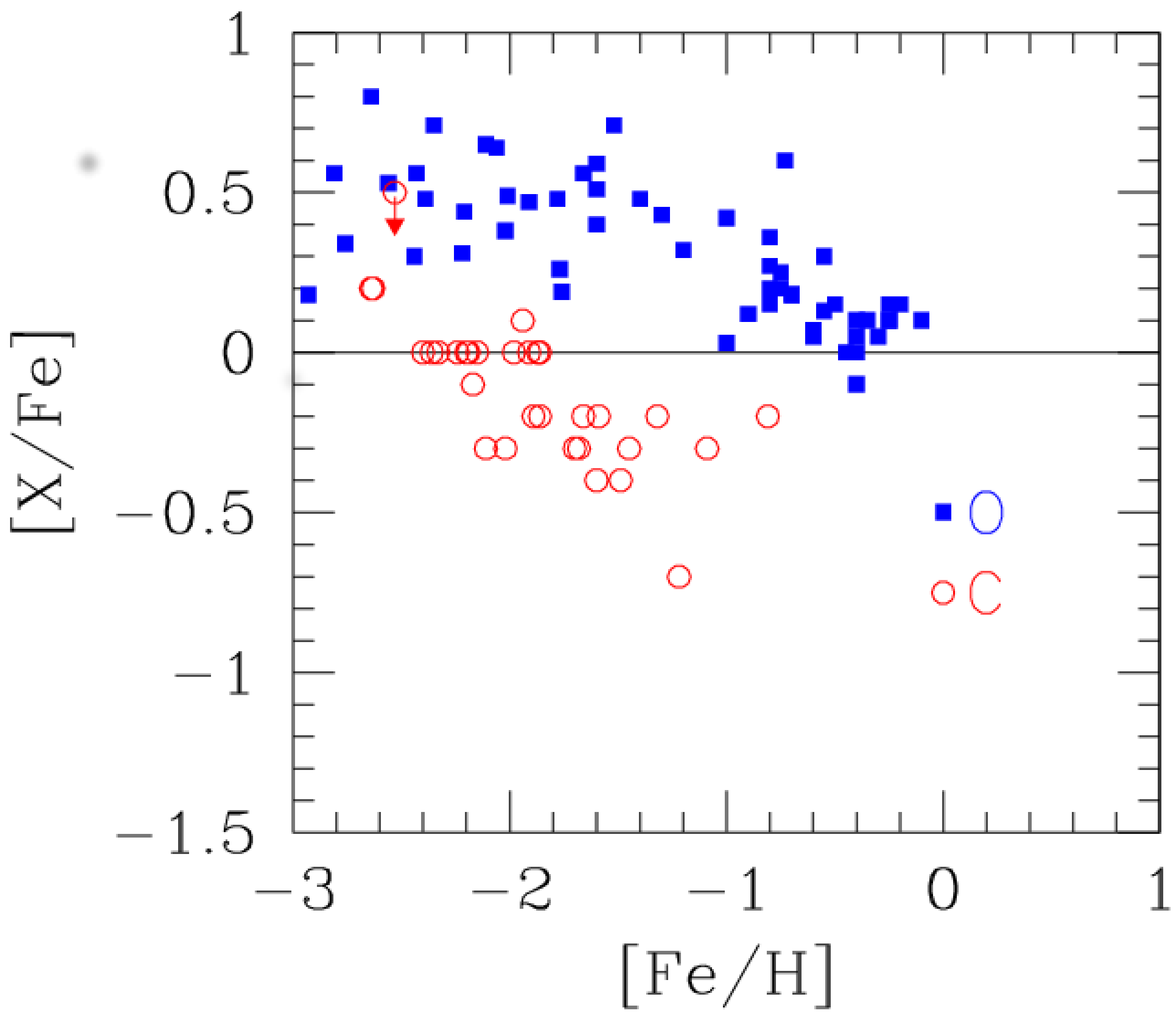
The Star-Gas Cycle

Low mass stars (<0.8 Solar masses) have lifetimes that are longer than the age of the Universe and act as sinks for interstellar gas.

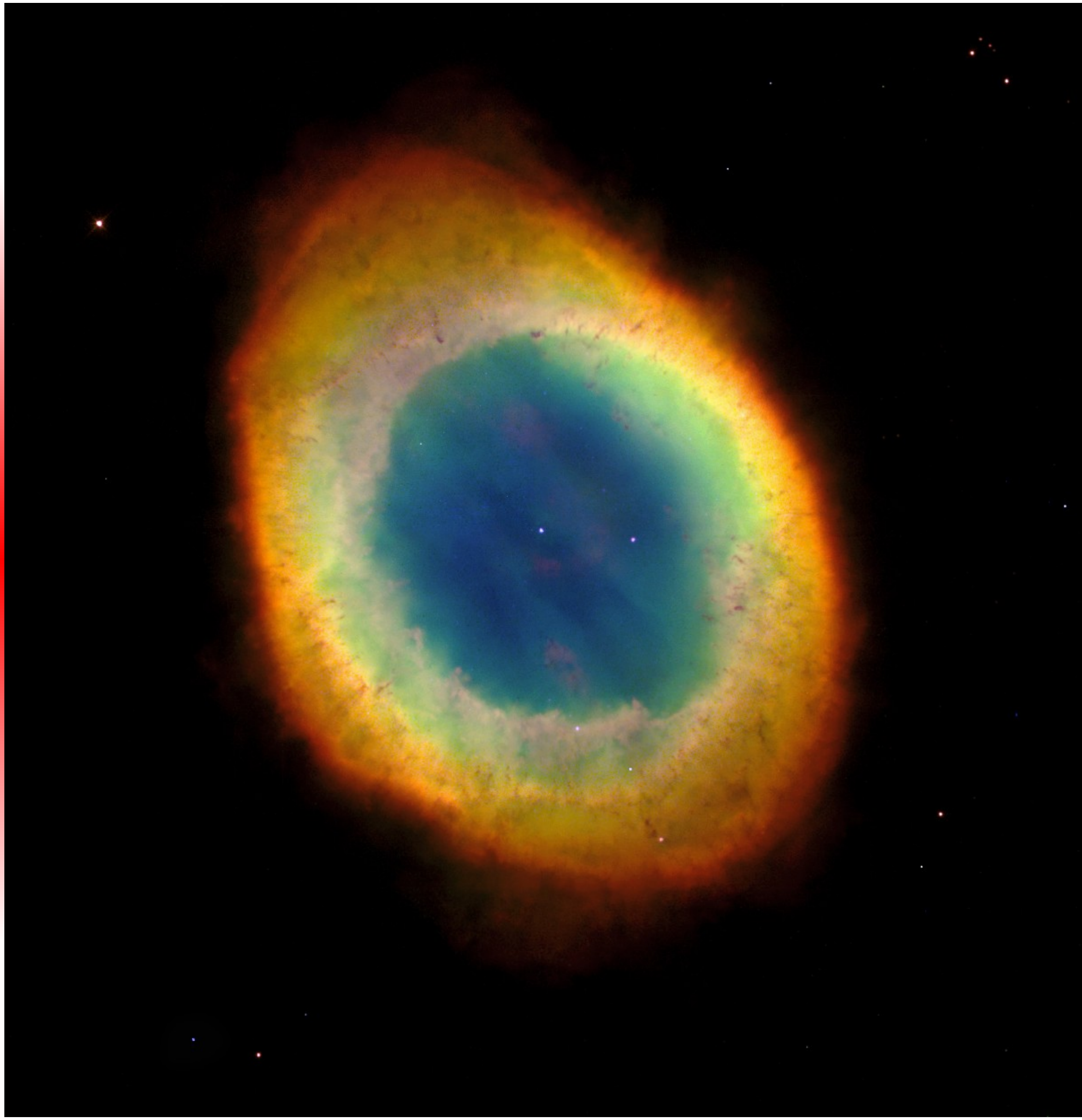


The relative abundances of the elements in Galactic stars reflect their origins.

For example, the bulk of elements such as O, Si, and S comes from Type-II SNe.



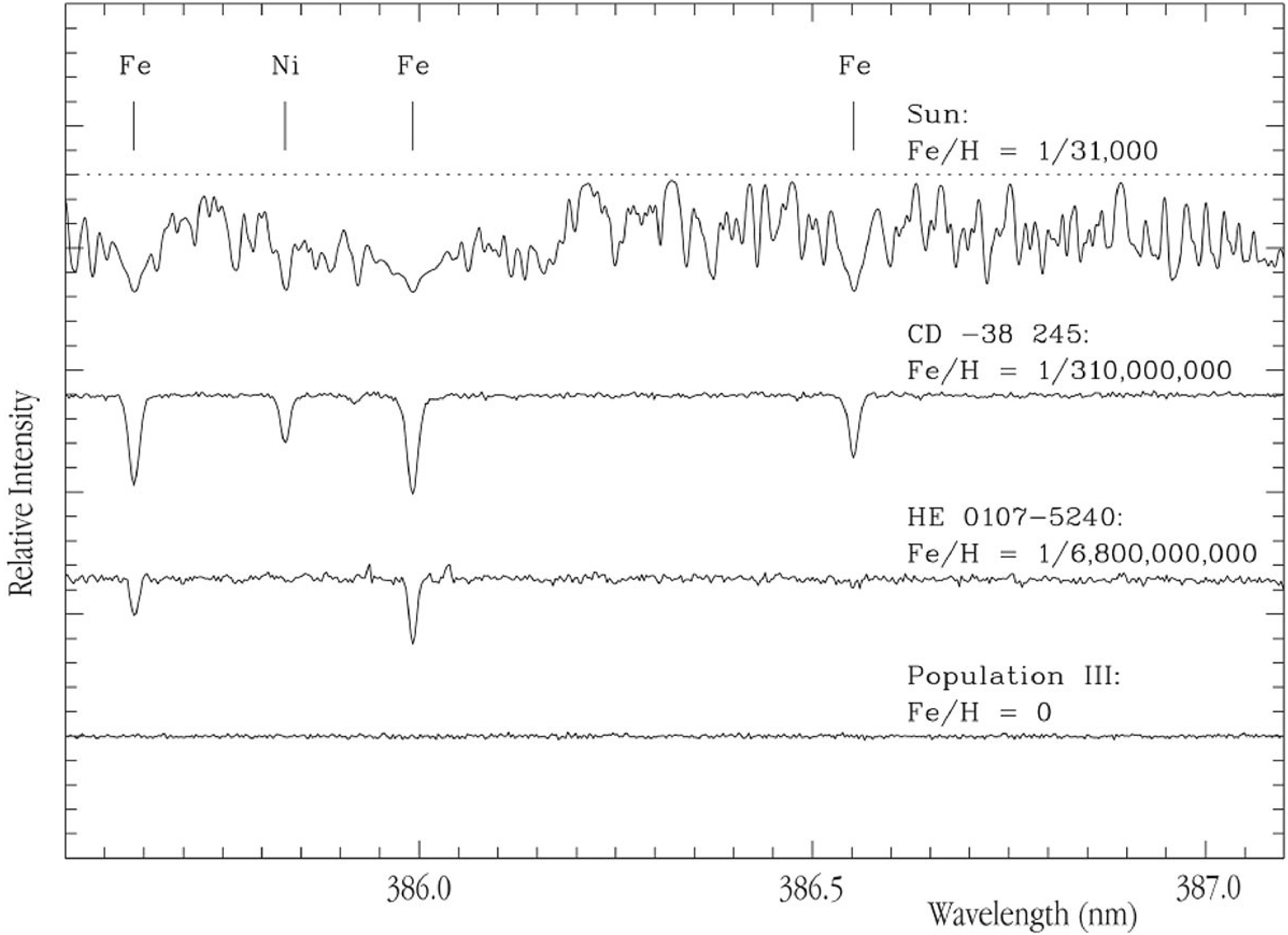
In order to study the origin of the elements we must construct models of stellar evolution and the processes that expel the products of nuclear fusion (novae, supernovae and stellar winds).



How can we study the build up of the elements in the Galaxy?

We study the abundances in Galactic stars as a function of age. Until the last stages of stellar evolution the composition of the atmospheres of stars are unchanged from when they formed.

Thus we can track the elemental abundances as a function of age.



Spectra of Stars with Different Metal Content

ESO PR Photo 25b/02 (30 October 2002)

How can we study the build up of the elements in the Universe?

1) study the abundances in Galactic stars as a function of age.

2)measure the average star formation history using deep imaging and redshift surveys - then infer the evolution of the elements.

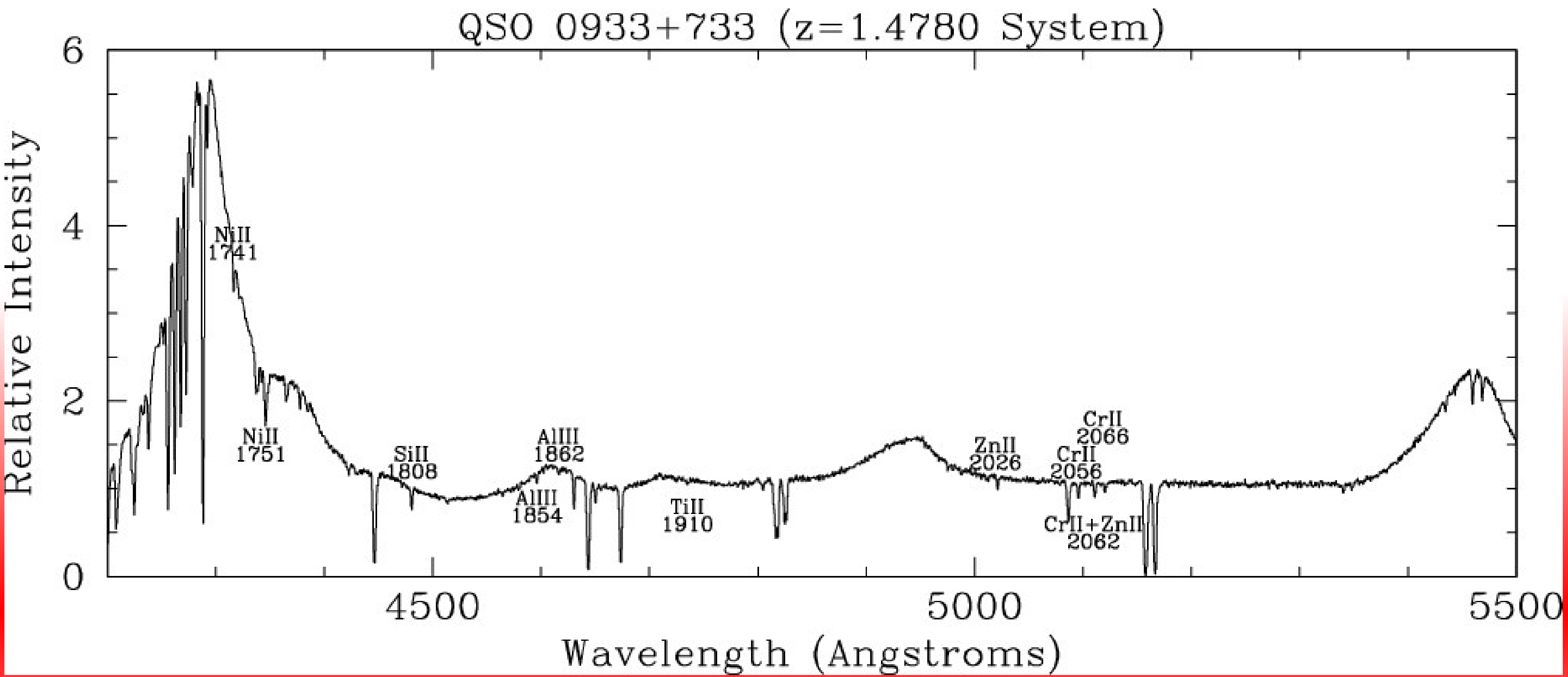
3) directly measure abundances in samples of galaxies at high redshifts.

All methods have limitations:

1) Galactic stars only tell us about our Galaxy.

2) The inferred abundances depend on details including the assumed stellar mass distribution, dust properties, gas recycling timescales, etc.

3)High redshift galaxies are faint, and it is difficult to obtain useful spectra in many (even most) cases. Also the interpretation of the spectra requires many assumptions (ex. stellar populations, dust content, etc).



There is another method to directly measure abundances in galaxies by using the absorption lines which can be seen in the spectra of QSOs due to foreground galaxies.

The technique that my collaborators and I use is to take spectra of quasars (QSOs), the bright point-like emission from gas falling into super-massive black holes in the center of galaxies.

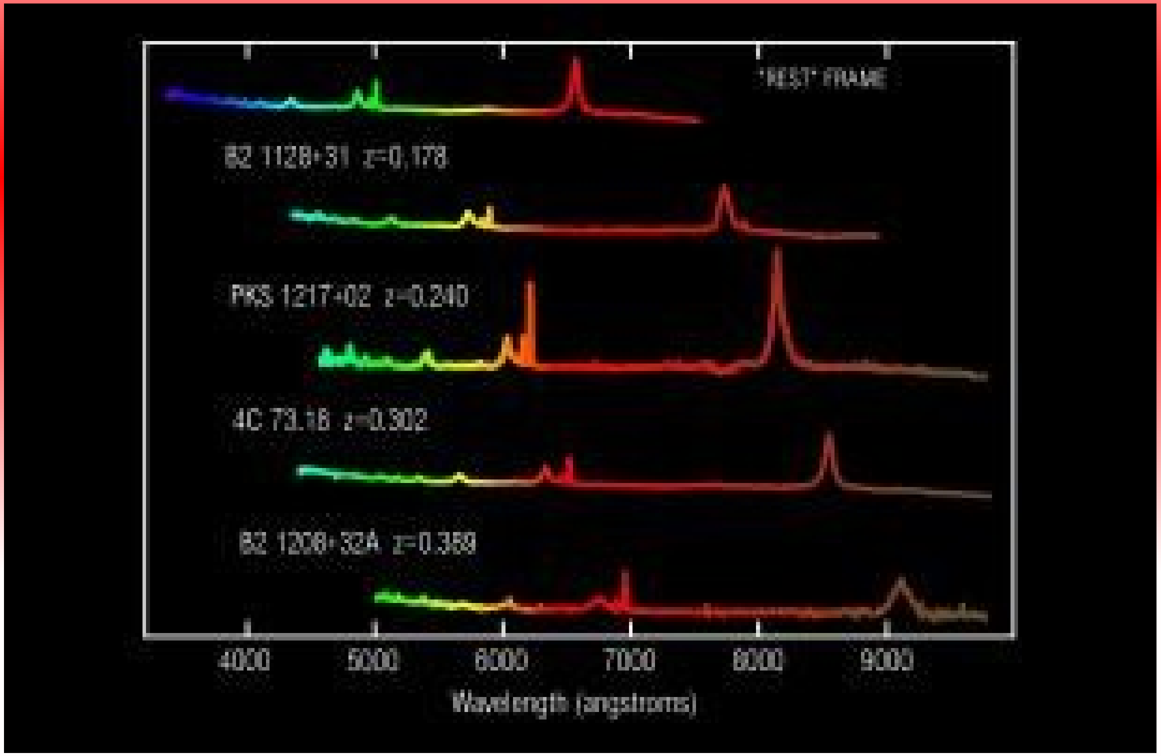


Image courtesy of KPNO (C. Pilachowski, M. Corbin/NOAO/AURA/NSF)

Since QSOs occur at different redshifts we can sample galaxies at different redshifts which correspond to different ages since the Big Bang.

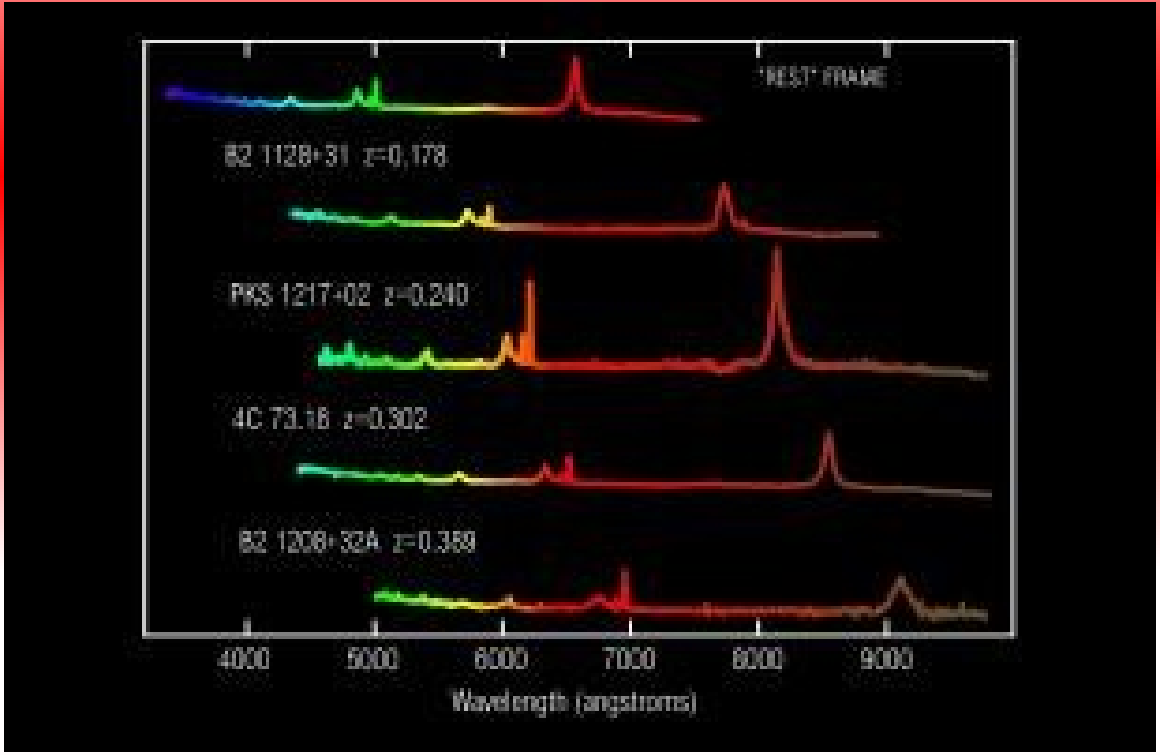
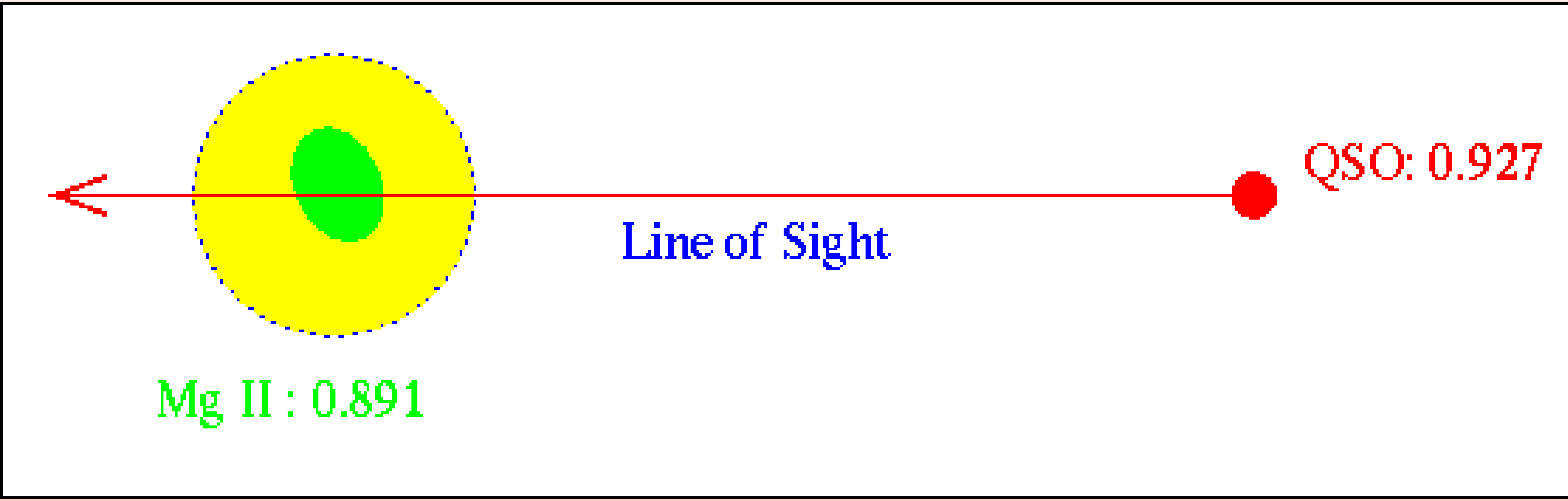


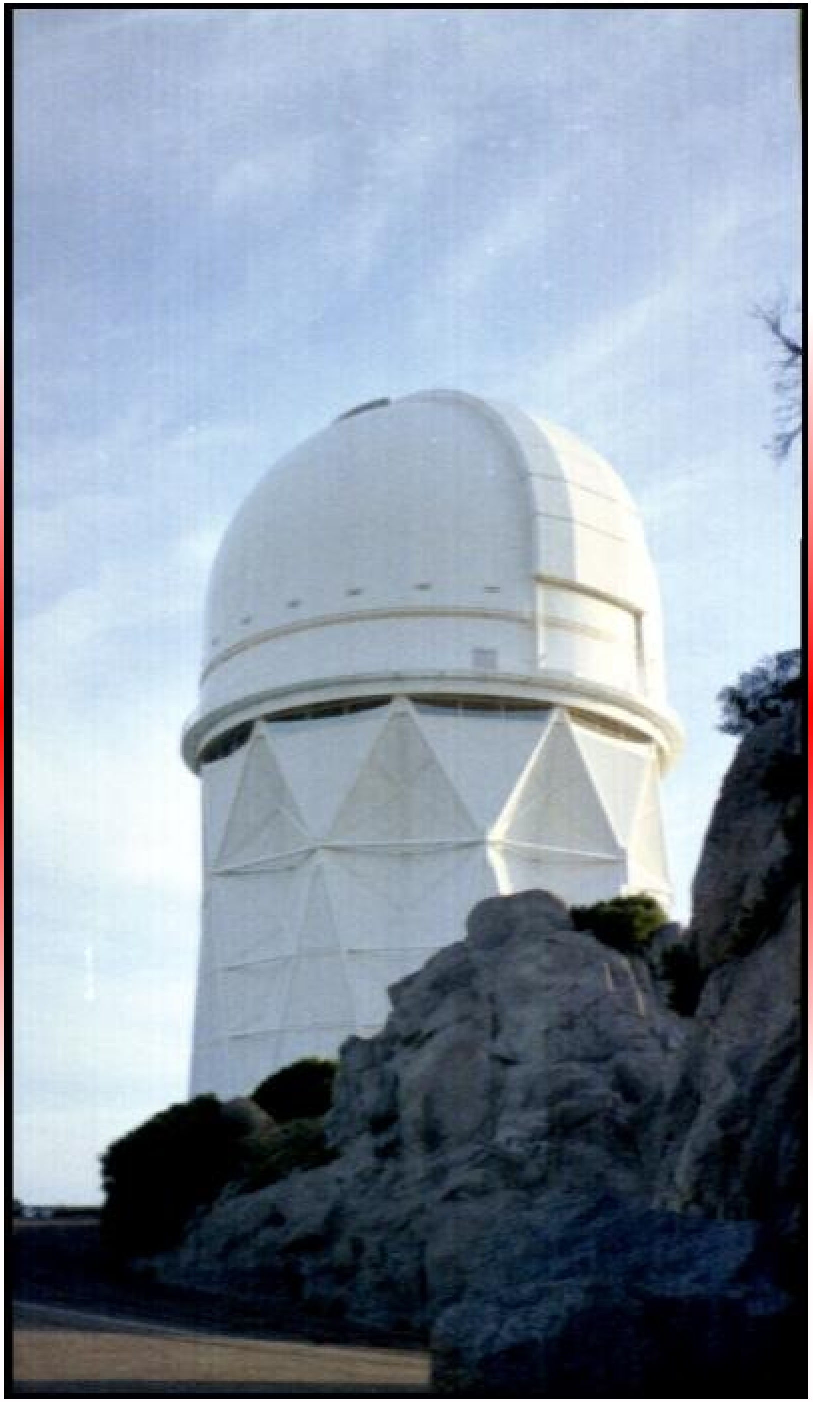
Image courtesy of KPNO (C. Pilachowski, M. Corbin/NOAO/AURA/NSF)



Schematic view of a QSO absorption line system (Chris Churchill, NMSU).

Some Advantages of QSO Absorbers:

1) QSOs are bright point sources.
2) Abundances of many elements can be measured.
3) The galaxies selected are not biased by their luminosities, so galaxies with low amounts of star formation can be probed.



Some Disadvantages of QSO Absorbers:

1) Obscuration due to foreground dust may remove the highest abundance systems (although this can be tested).
2) The galaxy sample is biased toward objects with large gas contents and/or extents.

And the Big Disadvantage:

3) Galaxies without gas (either because they have converted it all into stars and/or they have ejected it due to SNe and stellar winds do not show up in these surveys (although the expelled gas will).

Additional information one gets from studies of QSO absorbers:

1) a measure of the abundance scatter as a function of redshift.
2) information on the composition of dust grains in other galaxies.
3) their physical conditions (density, temperature, ionization fraction, etc).
4) a measure of the relative contributions of Type-I SNe, Type-II SNe and AGB stars to the abundances in different galaxies.

Local Benchmarks

Spectroscopic observations of interstellar sight lines in the Galaxy and in the Magellanic Clouds yield information on dust composition, ionization ratios, densities, and temperatures for comparison to these absorption selected galaxies.

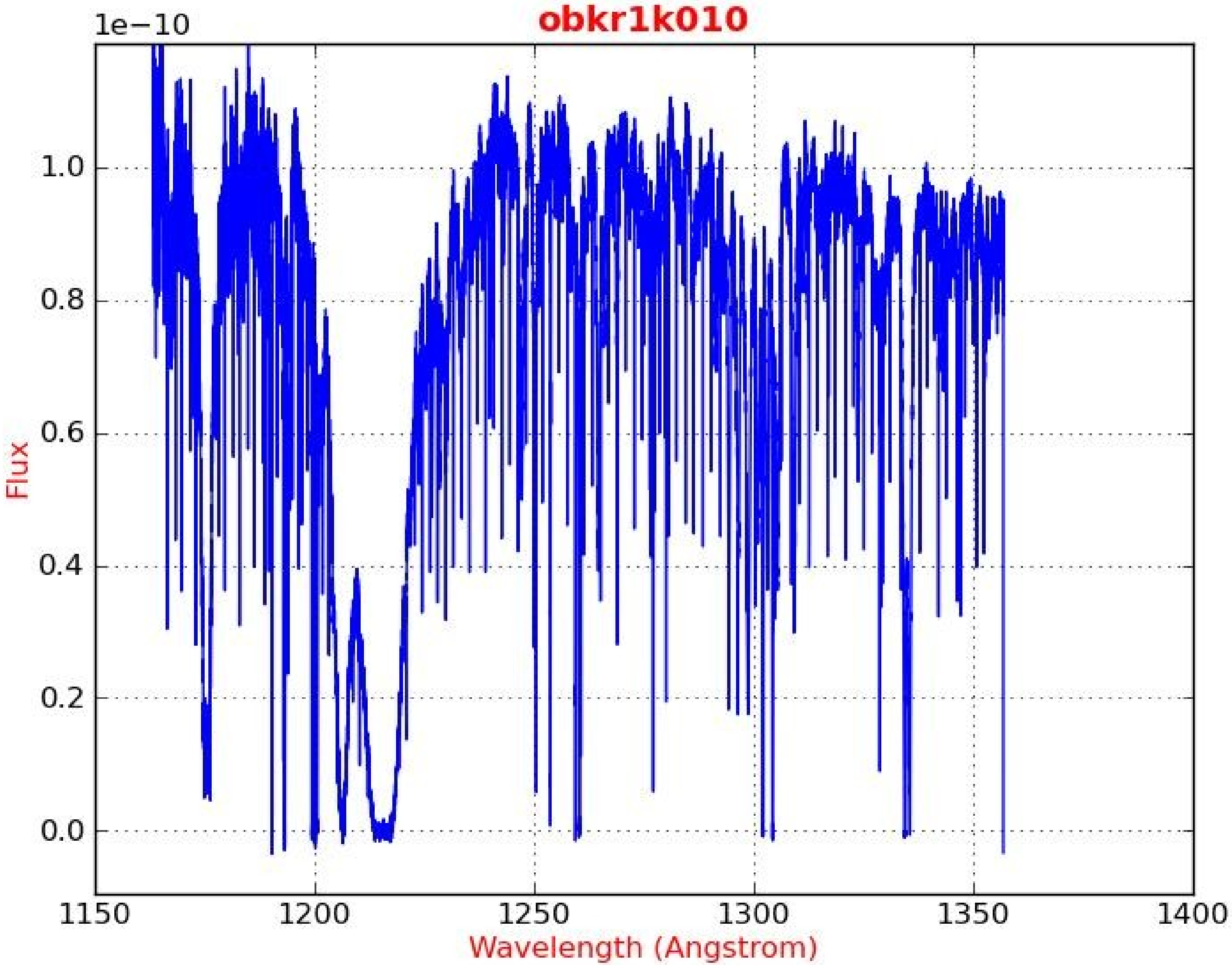
Stellar abundance studies allow one to identify elemental abundance ratios which are tracers of various nucleo-synthetic sources (Type I and II Sne and AGB stars).

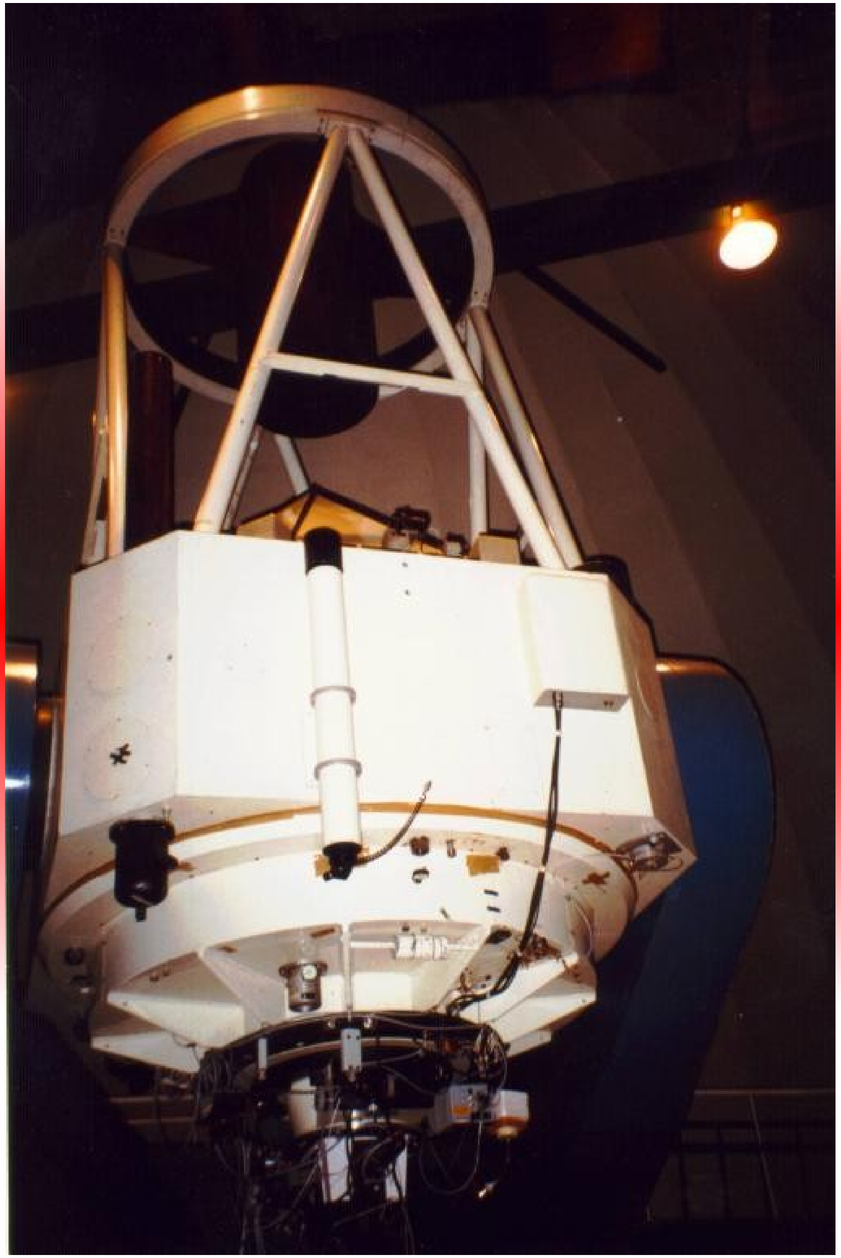
Local Benchmarks

With collaborators I have worked to sample the interstellar gas toward approximately 200 stars using the Hubble Space Telescope (plus about 20 stars with the Far Ultraviolet Spectroscopic Explorer) to study the abundances and physical conditions in interstellar gas in our Galaxy and the nearby Magellanic Clouds.

Elements studied include H, C, N, O, Na, Mg, Si, P, S, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Kr, Cd, Sn, Pb

Local Benchmarks

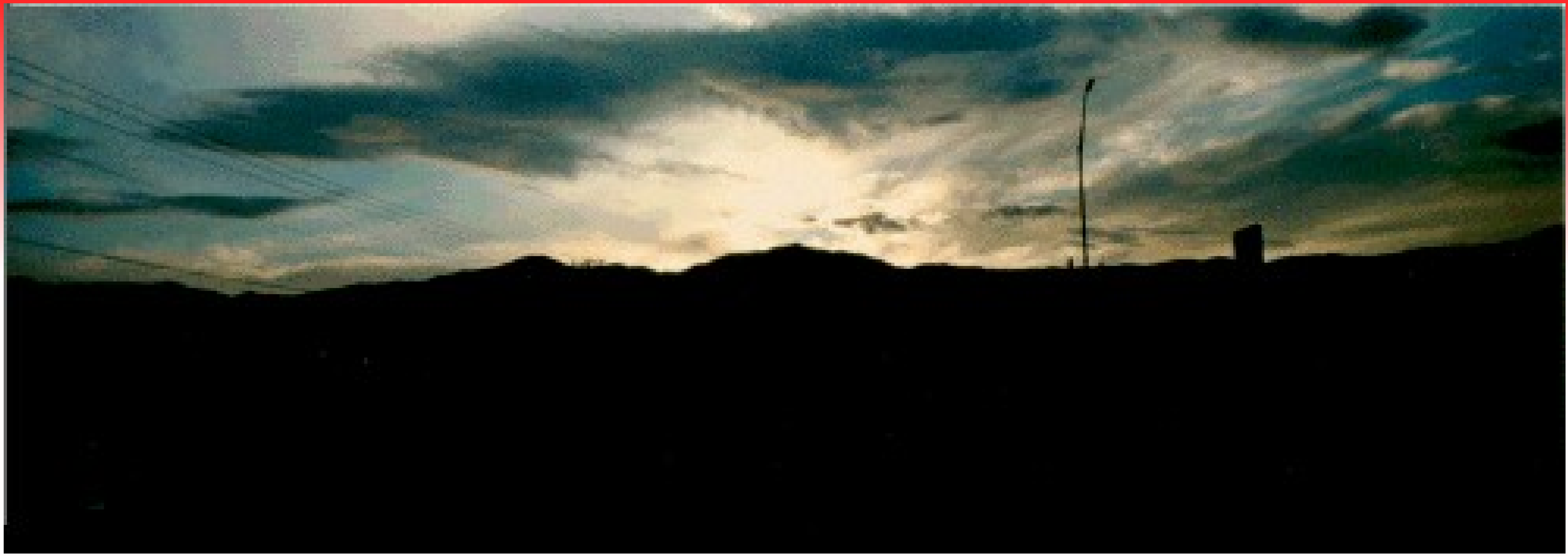


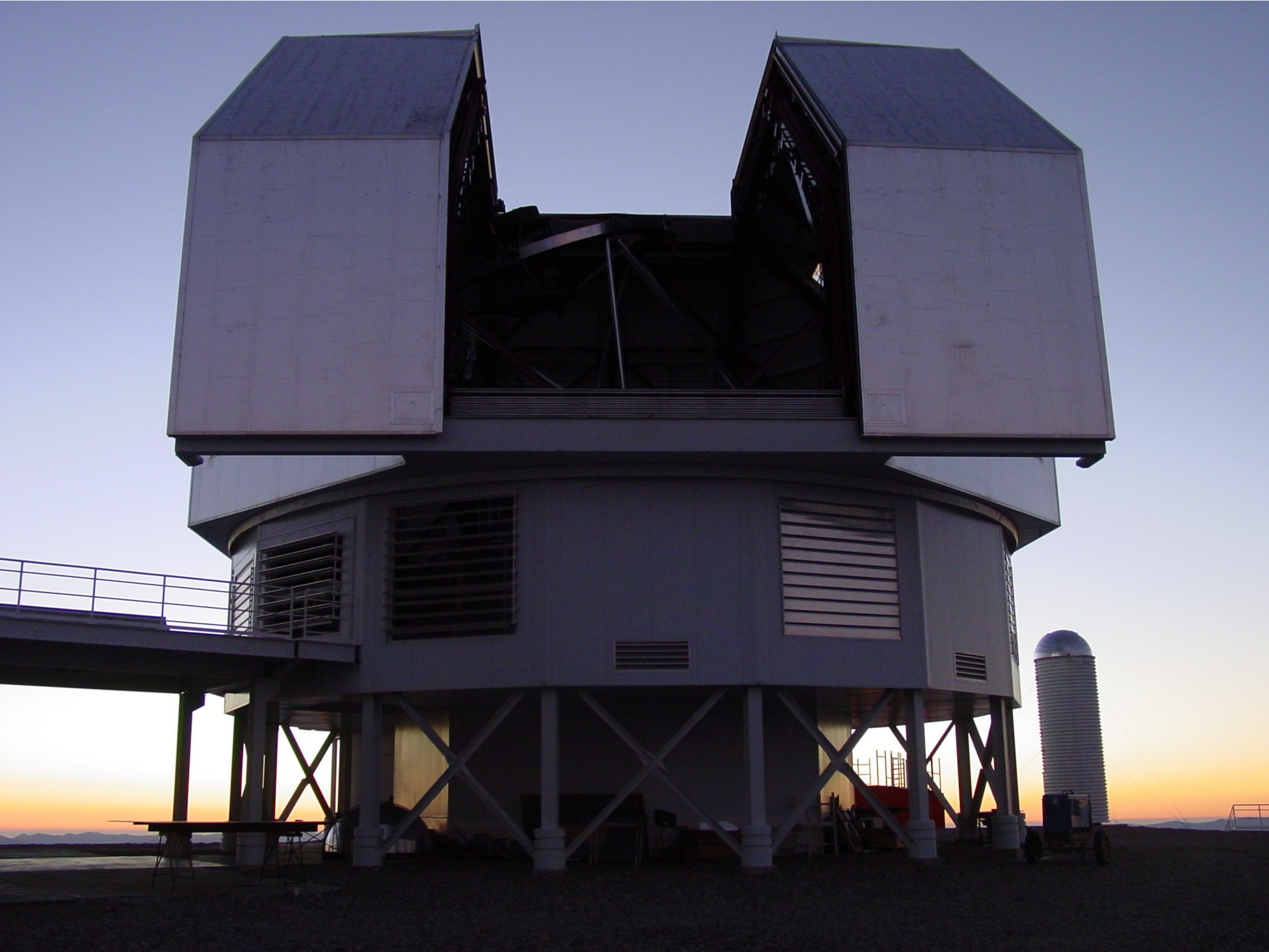


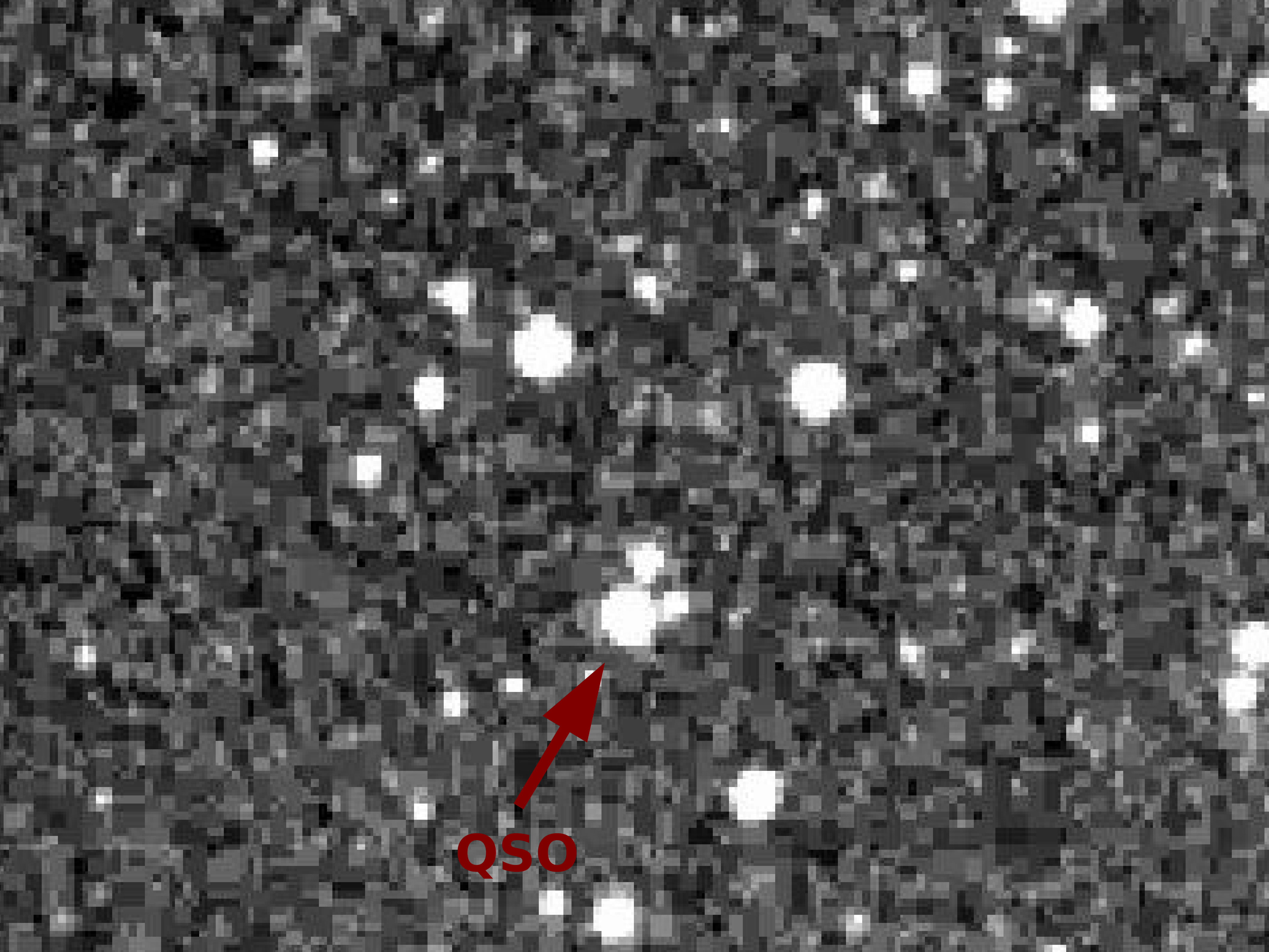
Dust composition can be measured by comparing the abundances of elements not found in dust in the Galaxy and Magellanic Clouds (ex. S and Zn) to elements with the same origin that are found in dust (ex. Si and Fe).

The amount of dust can be inferred from the fraction of Si and Fe which must be in dust.

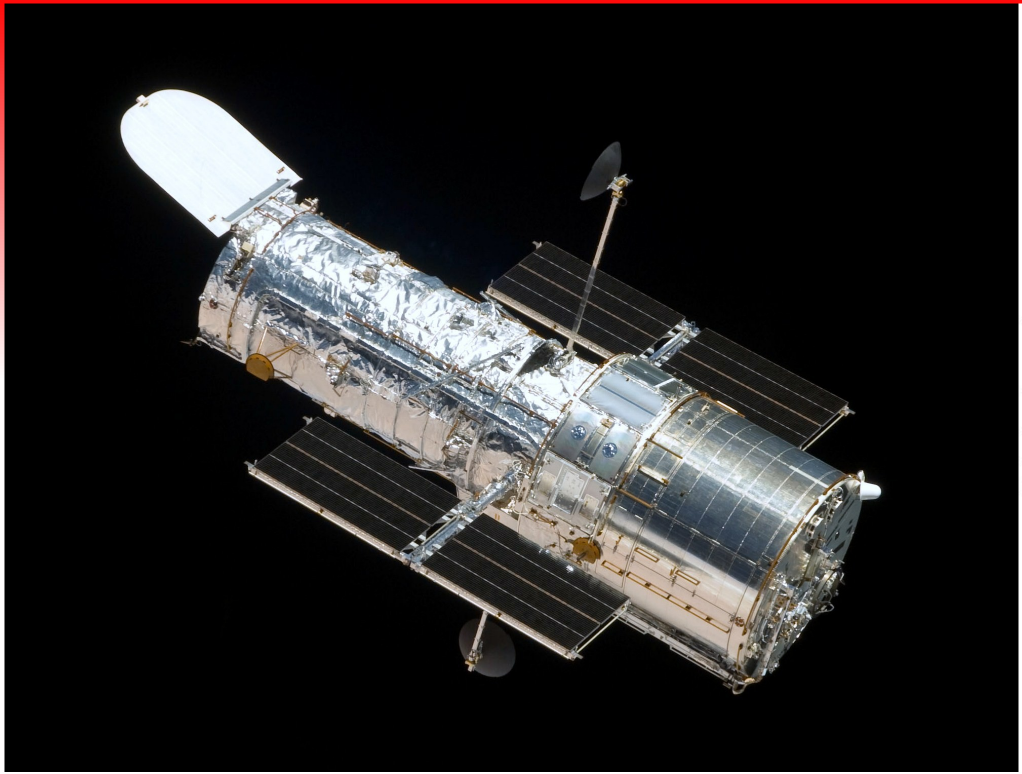
Even for the brightest QSOs, abundance measurements in even a single foreground galaxy can take several hours on the largest telescopes, thus large samples have only recently been measured.

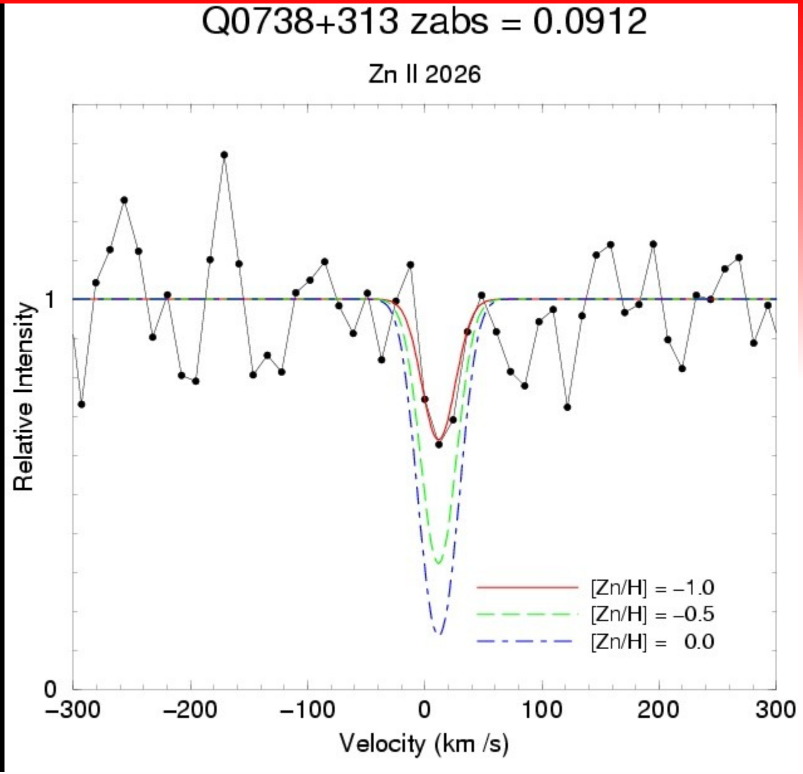




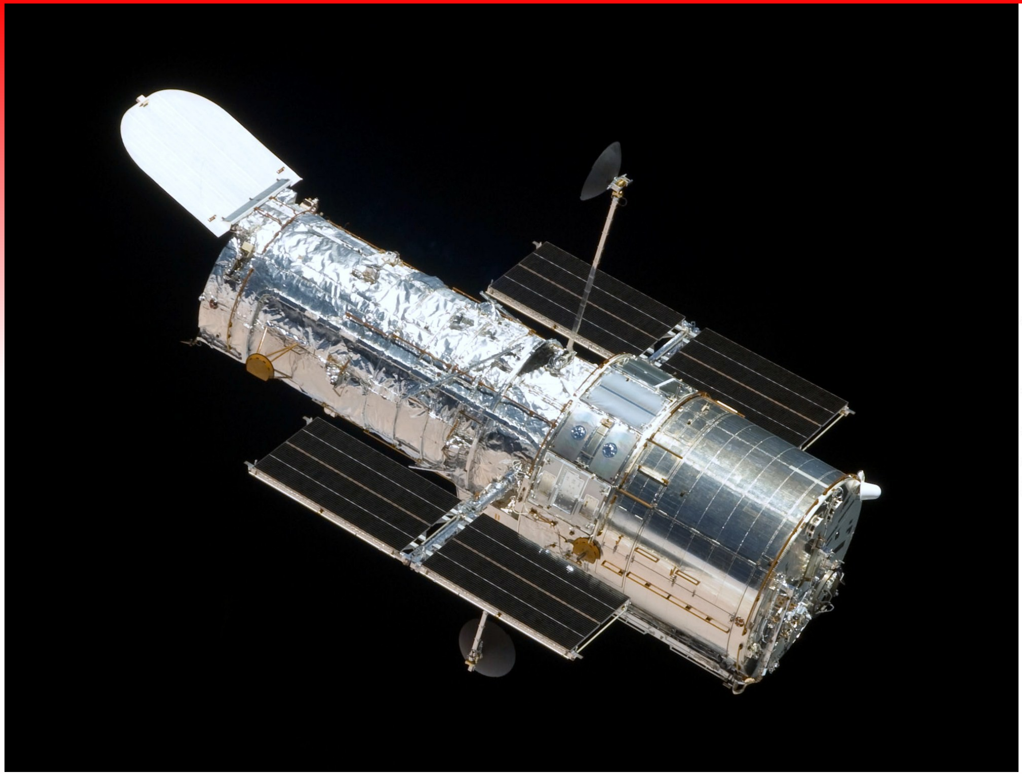

QSO

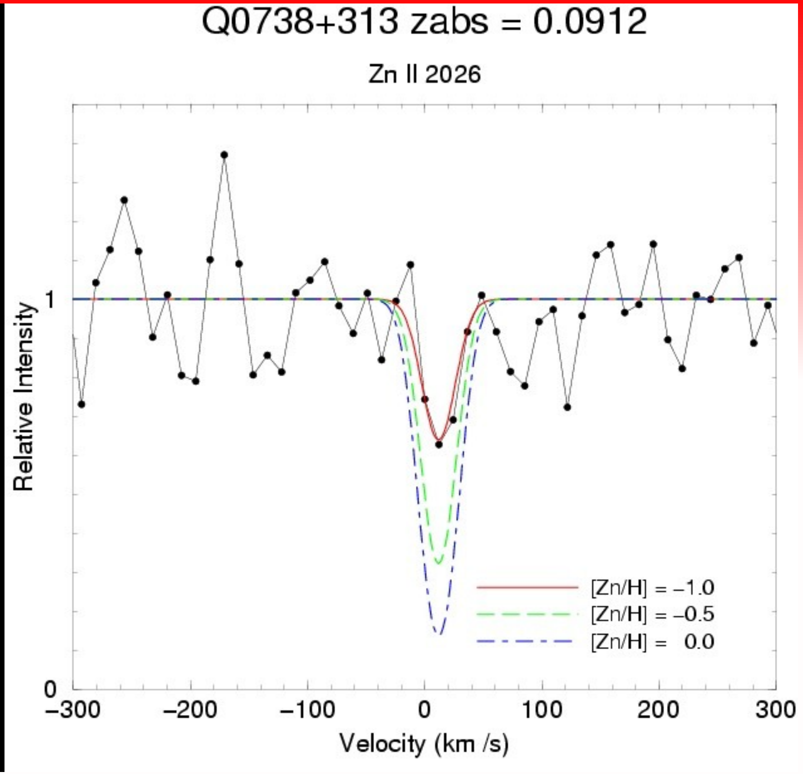
The lines we wish to study lie in the rest frame ultra-violet portion of the spectrum, so until galaxies are at high enough redshifts these lines do not lie in the optical and thus we must use a space based telescope namely the Hubble Space Telescope.





However the Hubble Space Telescope is only 2.5 meters in diameter and can only observe the very brightest QSOs.





Sample absorption lines from Magellan/MIKE observations of Q1224+0037.

This galaxy has abundances ~0.025x Solar.

These data took 1.5 hours to obtain.

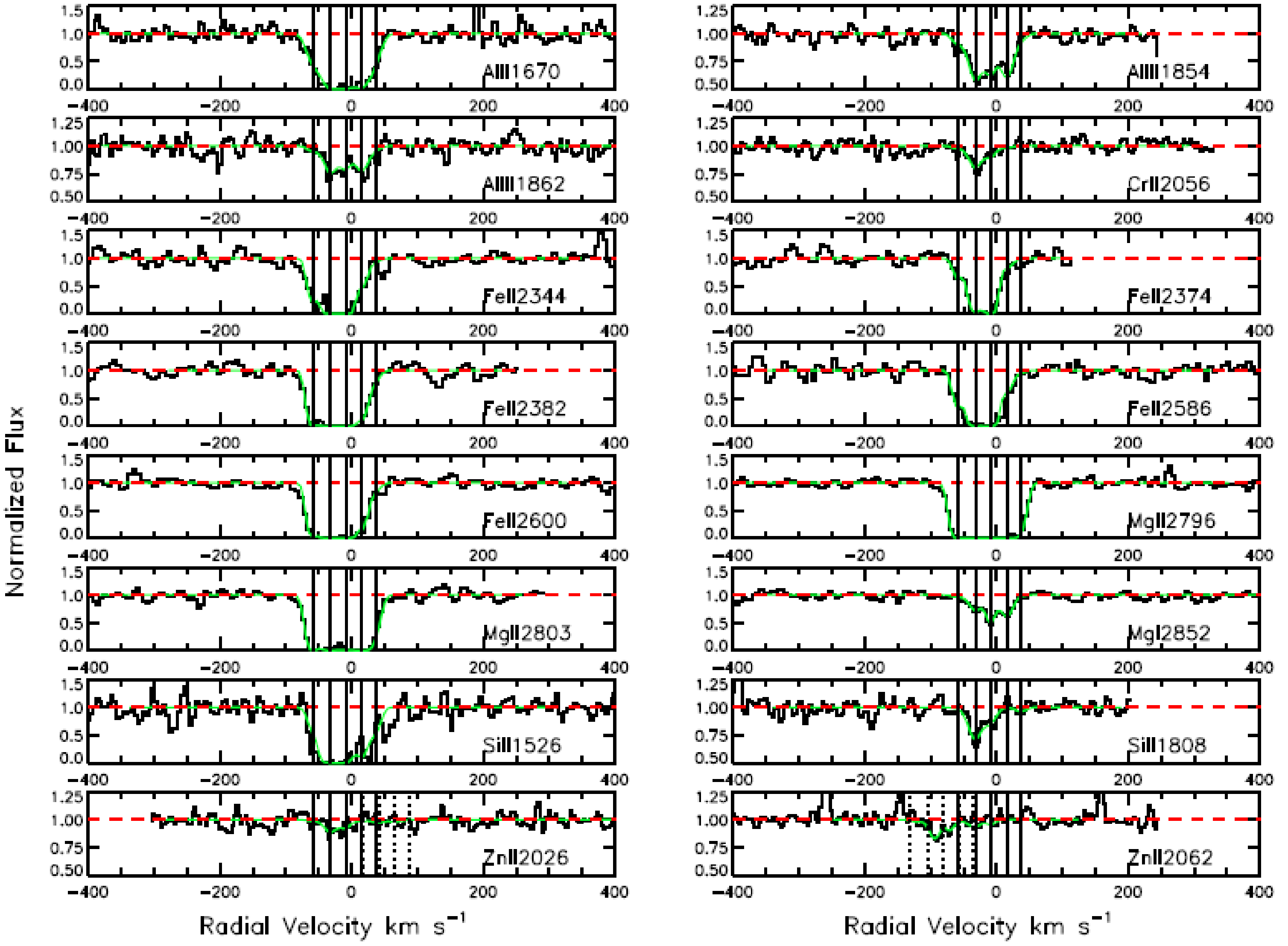
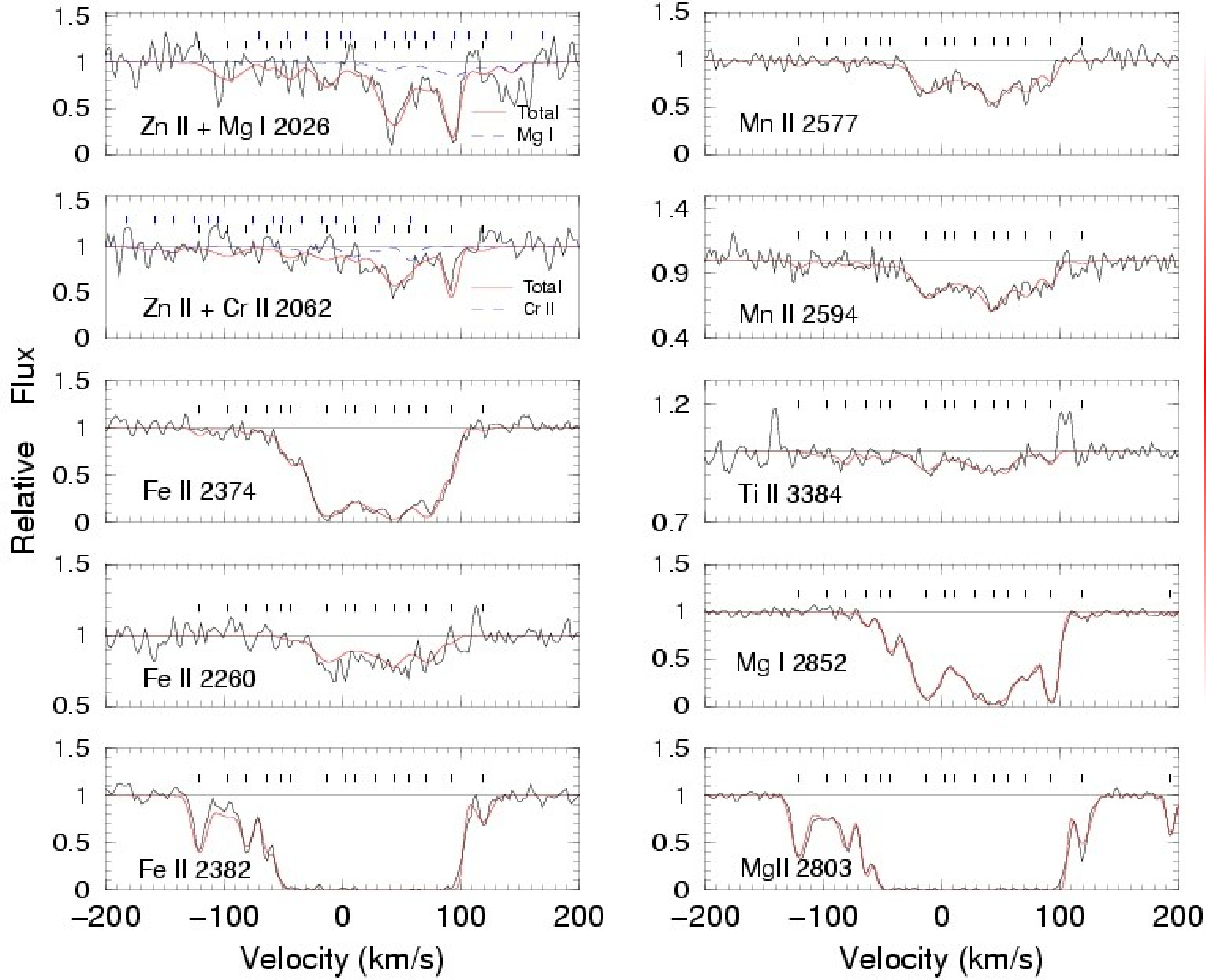


Figure 6. The same as fig.1, but for the z=1.2346 system in the spectrum of Q1224+0037

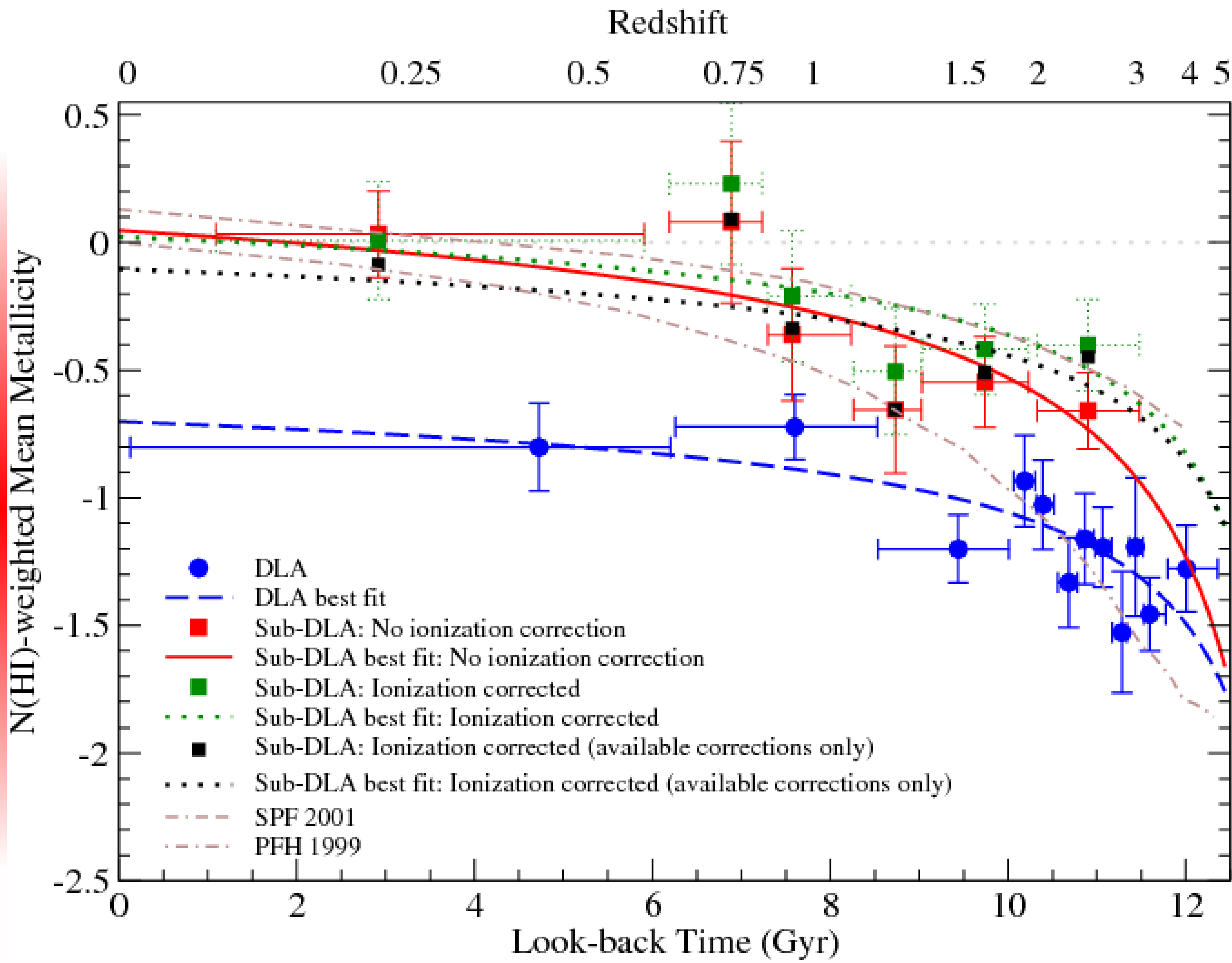
Sample absorption lines from VLT/UVES observations of SDSS J1323-0021.

When observed (March 2005) this was the most metal-rich system known, ~4x Solar.

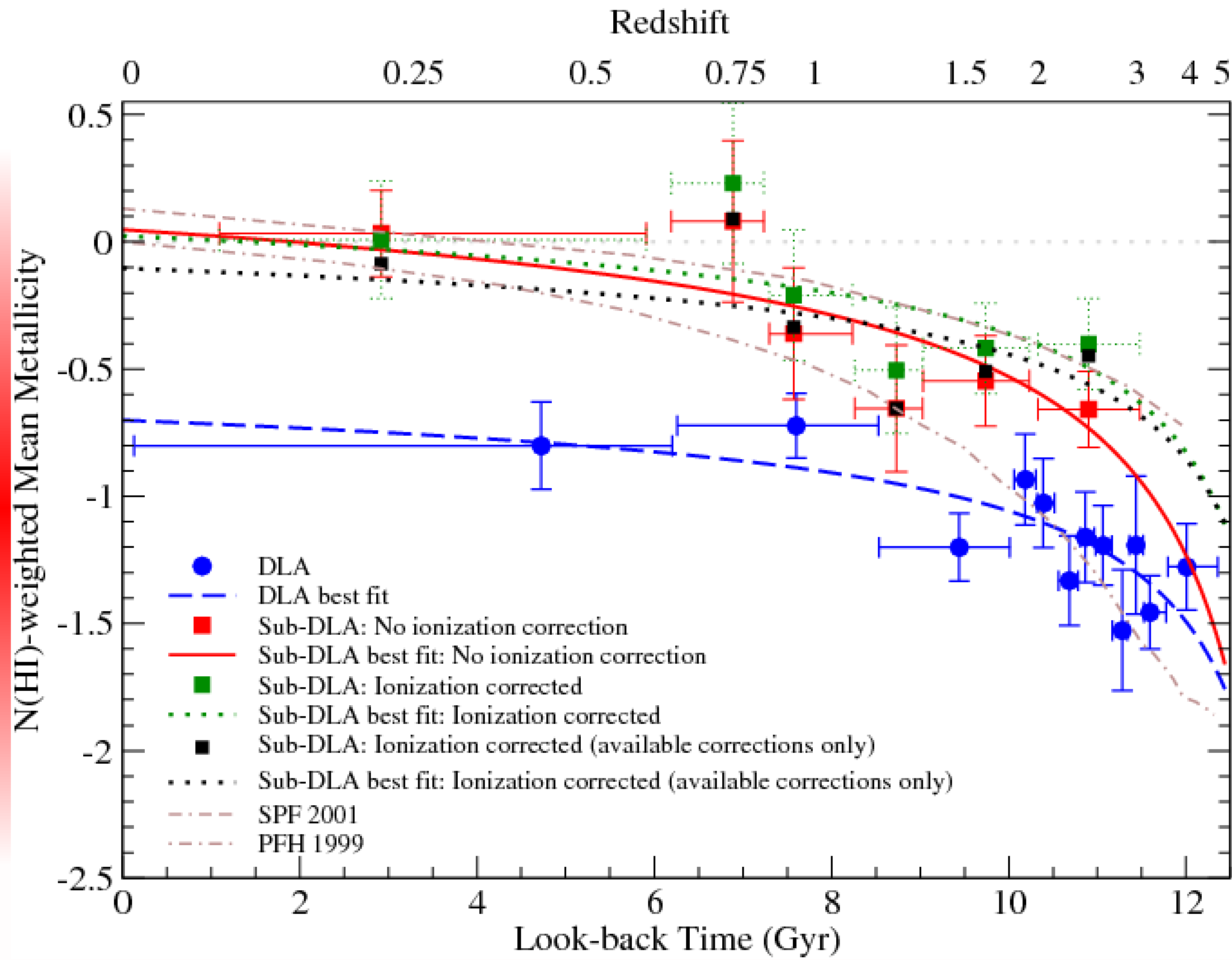
It took 3.2 hours for this one object.



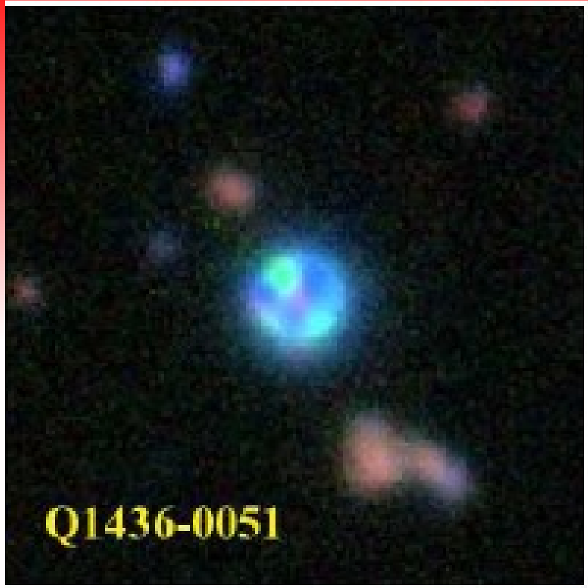
Observations of slightly less gas-rich systems have shown that their abundances are significantly higher than gas rich systems.



Perhaps because they have converted more gas into stars (and thus have had more SNe).



This seems to make sense, gas-rich systems may not have converted much of their mass to stars, while the slightly less gas-rich objects may be galaxies where more material has formed stars and thus elements heavier than H and He.



What does this mean?

We can tie theoretical models of galaxy formation, imaging observations of galaxies and observations of the gas content of galaxies into a coherent picture of how the heavy elements (and then planets and life forms) evolve with time.