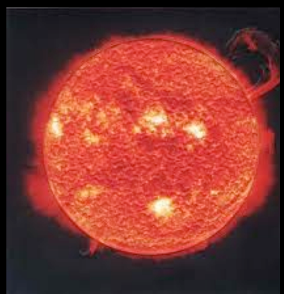
Oxygen in the Universe

Grażyna Stasińska

l'Observatoire de Paris

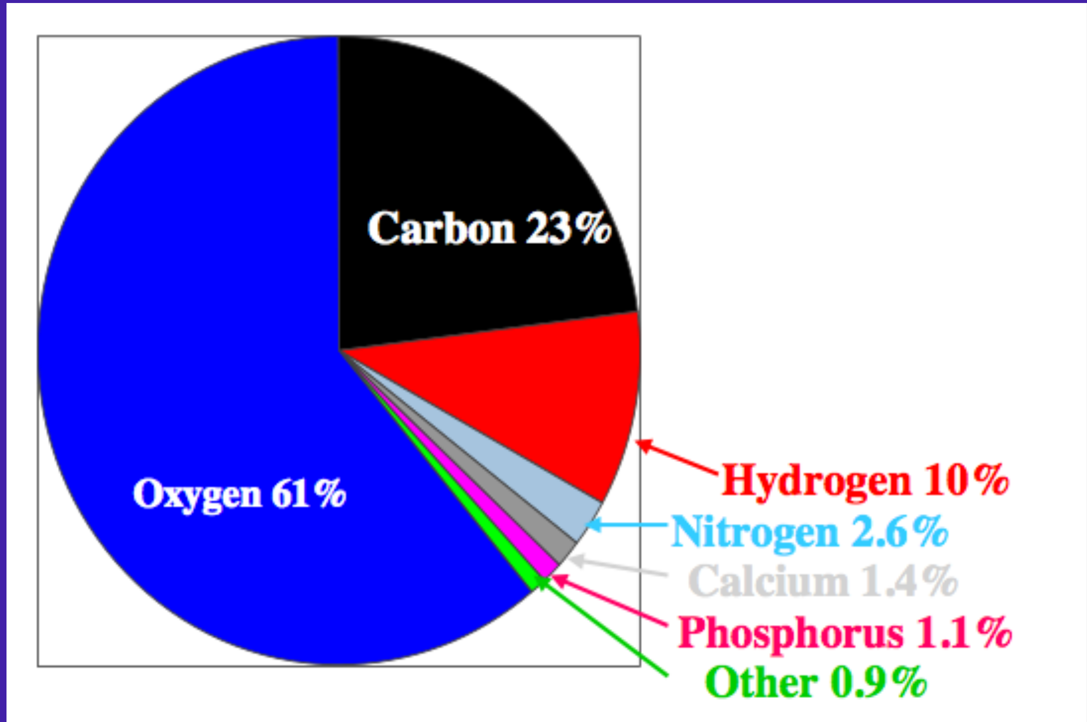






Oxygen in the human body

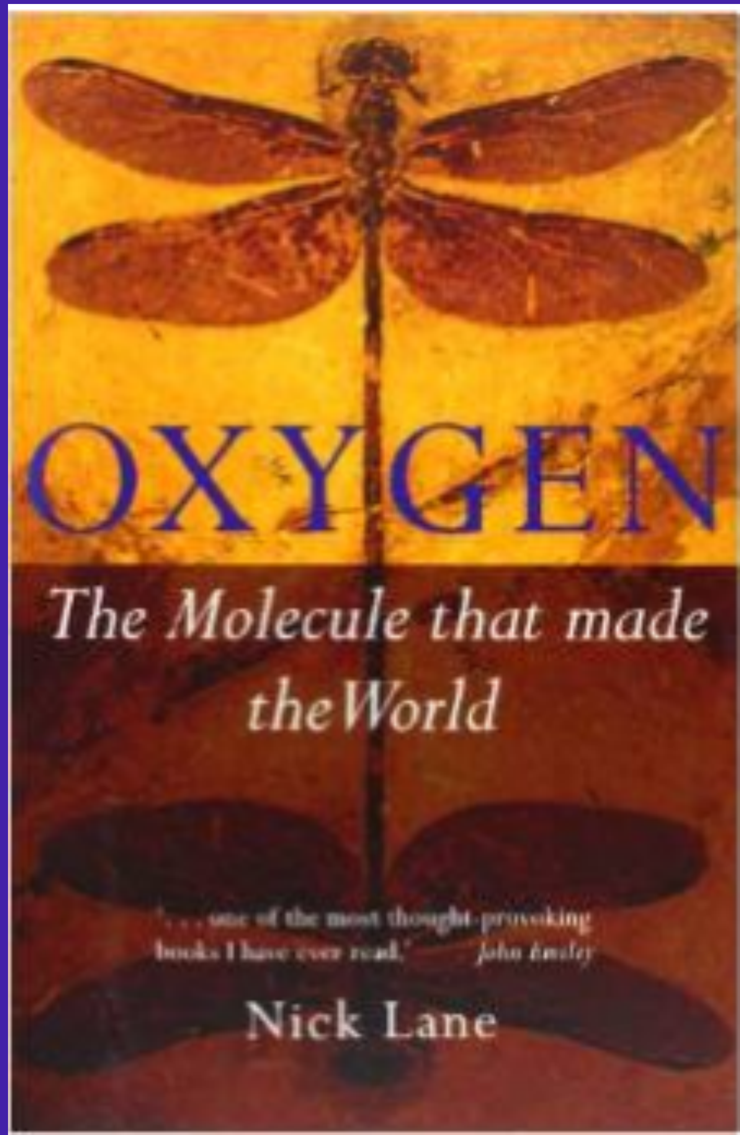
Oxygen constitutes
61% (by mass)
of the human body (Mainly H_2O)



Oxygen on Earth

Oxygen: The Molecule that Made the World

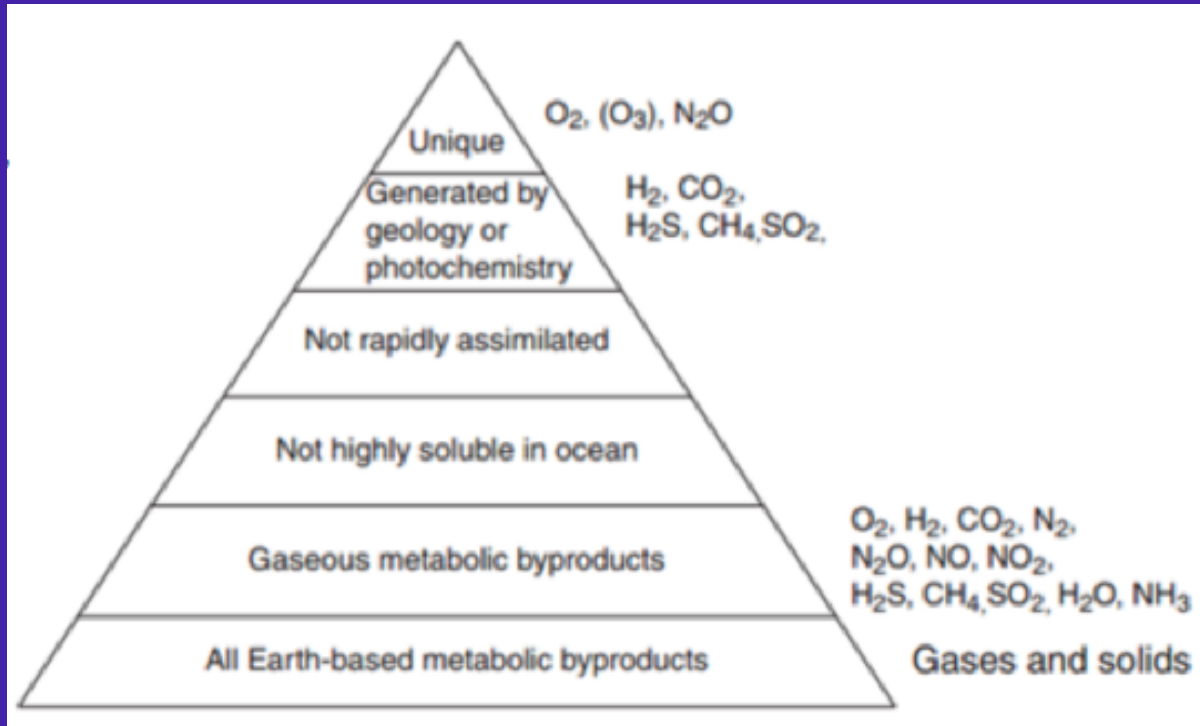
Nick Lane 2004



Oxygen and the search of life on exoplanets

- O_2 and other compounds of oxygen are a byproduct of life on Earth.
- They can be also be produced abiotically in small quantities, but their lifetime is short.
- Their detection in the atmosphere of an exoplanet would imply the presence of a source continually producing them
- life being the only present candidate

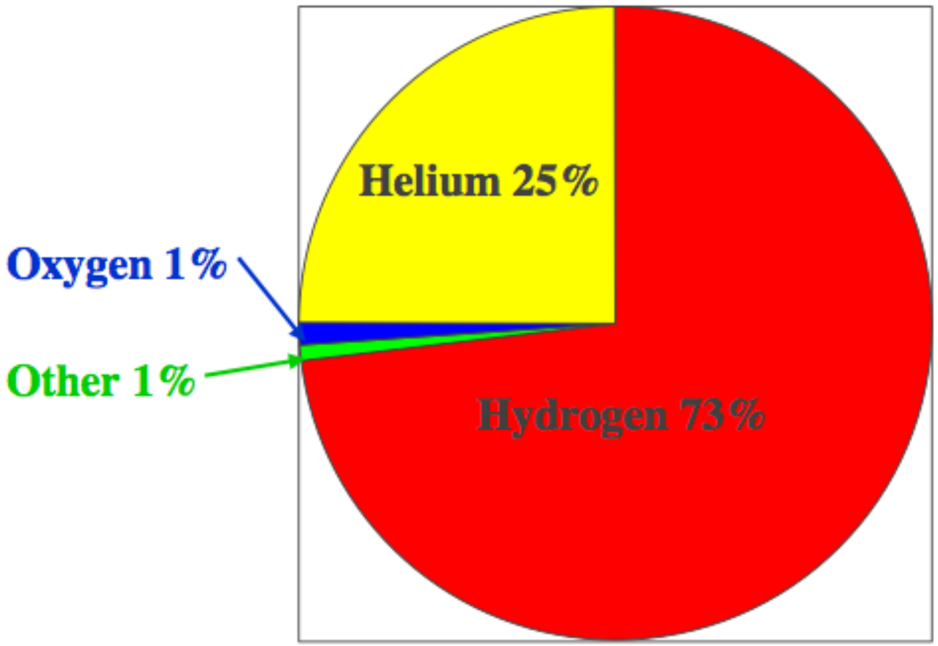
Possible biosignatures



Seager et al, 2012, ASTROBIOLOGY Volume 12

Oxygen in the Universe

Oxygen in the Universe

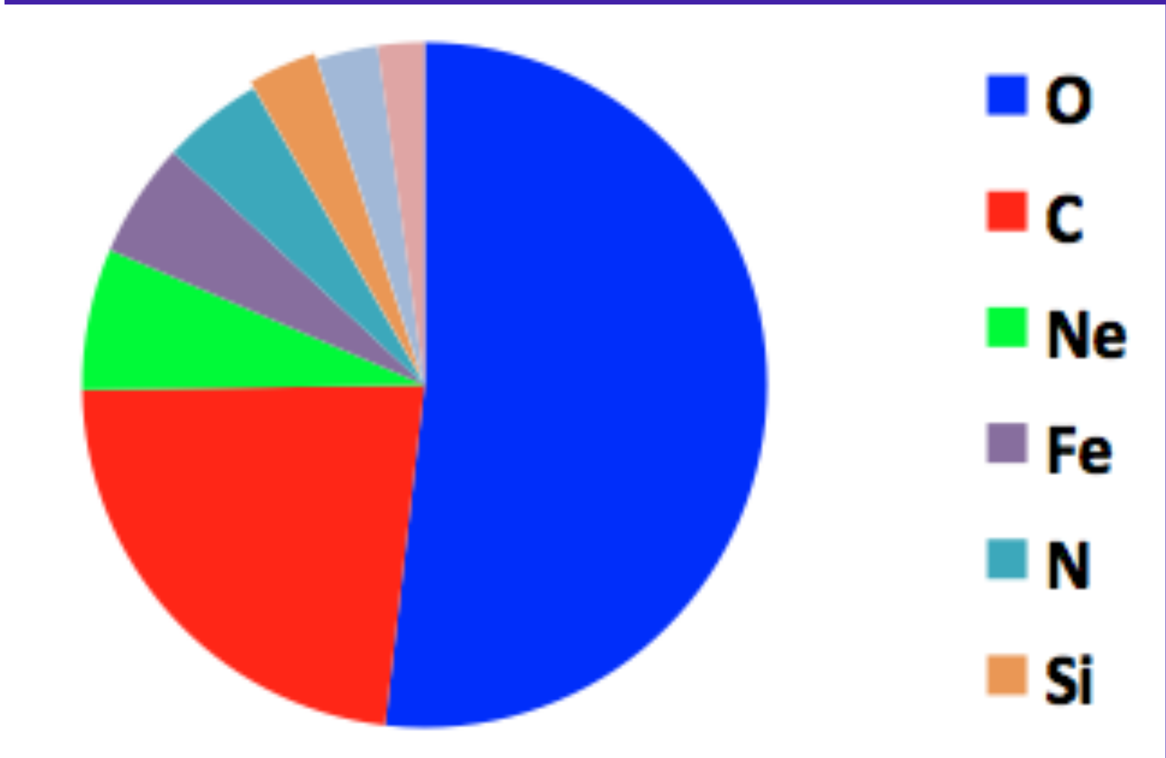


Oxygen represents only

1%

of the baryonic mass of the Universe

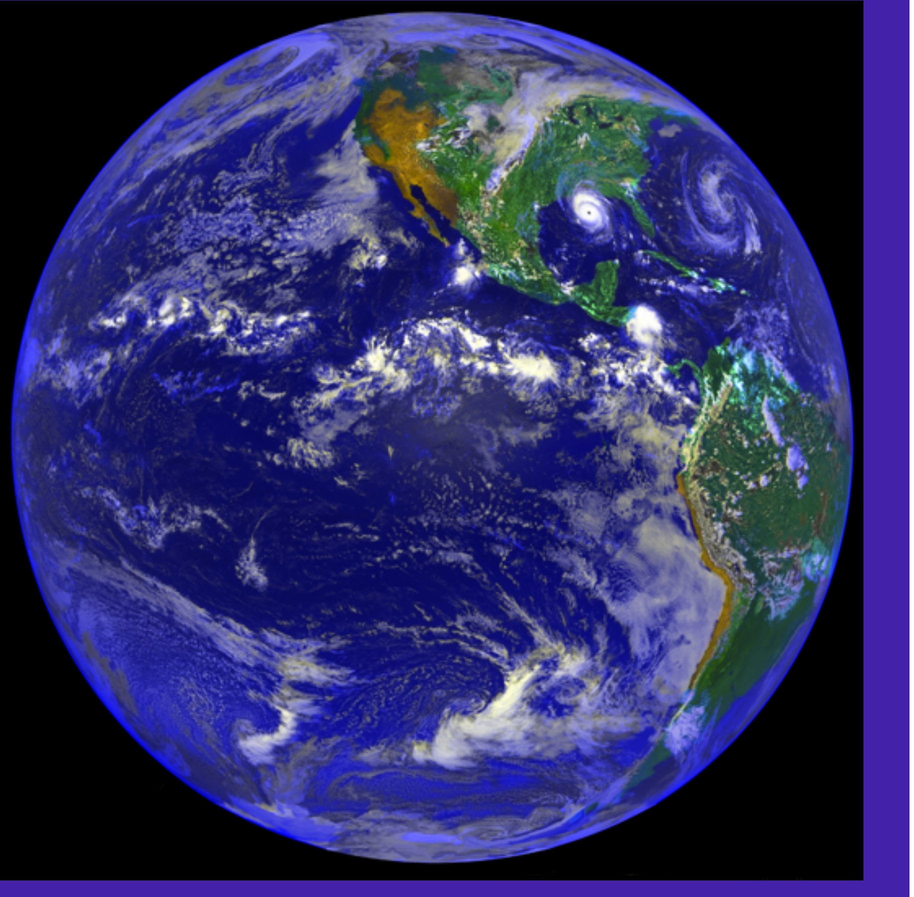
Oxygen in the Universe



Oxygen represents
half
of the ”metals” in the Universe

How did astronomers came to such numbers?

Oxygen on Earth



At the beginning of the XIXth century

- Alexander von Humboldt and Joseph Louis Gay-Lussac showed that water is composed of two parts hydrogen and one part oxygen.

- Louis Jacques Thénard had shown that the Earth rocks contained oxydes

We now know

that oxygen constitutes (by mass)

- 49 % of the Earth's crust (SiO_2)
- 88 % of the Oceans (H_2O)
- 23 % of the Earth's atmosphere (O_2)

Oxygen in meteorites

Jean-Baptiste Biot (1774-1862)
the origin of meteorites is extraterrestrial (1803)

meteories contain silicium, iron, megnesium .. and oxygen

météorite de l’Aigle

Les échantillons de pierres météoriques , dont il a été question dans ce mémoire, sont déposés au Muséum d'histoire naturelle. Le citoyen Thénard a bien voulu en analyser quelques-uns, et il a trouvé :

Silice	46
Fer oxidé	45
Magnésie	10
Nickel	2
Soufre, environ	5

108

Oxygen in the Sun ?

Wollaston 1802
first spectrum of the Sun

Fraunhofer 1814
first systematic study of the absorption lines

Kirchhoff & Bunsen 1860-1861
Fraunhofer lines have same wavelenghts as some heated metals

1863:
the Sun's atmosphere contains
hydrogen, sodium, iron, magnesium.

what about oxygen?

Oxygen in the Sun ?

1877Nature Draper,H. Discovery of Oxygen in the Sun by Photography, and a New Theory of the Solar Spectrum

1877Natur Meldola, R .Oxygen in the Sun

1878Obs Draper, H. Discovery of oxygen in the sun

1878MNRAS Draper, H. Researches on the existence of oxygen in the Sun

1878Natur 17 339 Draper, H. Oxygen in the Sun

1878Obs Schuster, A. On the presence of oxygen in the sun

1878Natur On the Presence of Dark Lines in the Solar Spectrum which Correspond Closely to the Lines of the Spectrum of Oxygen

1879AReg Draper, H. Correspondence - Oxygen in the Sun.

1879AReg Ranyard, A. C. Correspondence - Oxygen in the Sun.

1879MNRAS Schuster on the probable presence of oxygen in the solar chromosphere

1879MNRAS Draper, H. on the coincidence of the bright lines of the oxygen spectrum with bright lines in the solar spectrum

1879Obs Draper On the dark lines of O in the solar spectrum on the less refrangible side of G

1879Obs Maunder, E. W. Bright lines of oxygen in the solar spectrum

1879MNRAS Draper, J. C. on a photograph of the solar spectrum, showing dark lines of oxygen

all these are false detections!

The first detection of oxygen in the Sun

Runge & Paschen 1896

The O I 7777 lines are weak
and in a spectral zone not much
studied before

ASTROPHYSICAL JOURNAL

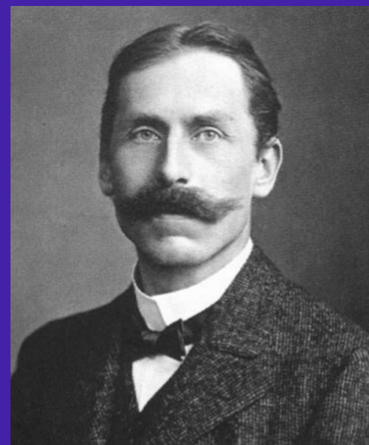
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME IV DECEMBER 1896 NUMBER 5

OXYGEN IN THE SUN.

By C. RUNGE and F. PASCHEN.

IN the spectrum of a vacuum tube filled with oxygen Piazzi Smyth discovered a line of wave-length about 7775.[1] This line we have lately found to consist of three components, of which the strongest is the most refrangible and the weakest the least refrangible. They seem to coincide with three lines of the same relative intensities in the solar spectrum.



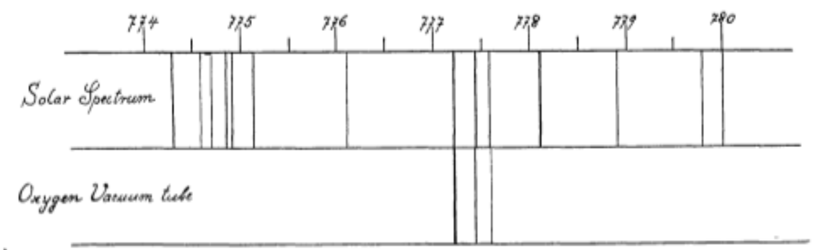


FIG. 1.

The first determination of elemental abundances in stars

Cecilia Payne (1900-1979)

Her thesis (**1925**) laid the basis of quantitative analysis of stellar spectra:

- intensities of absorption lines are complicated function of temperature, pressure and atomic data.
- weak lines do not necessarily indicate small abundances

Element	Abundance of atoms Stellar	Abundance of atoms Terrestrial
Oxygen	45	54
Silicon	16	6
Aluminum	5	4
Sodium	6	2
Calcium	3	1.5
Iron	2.5	1

The abundances of oxygen in the Sun

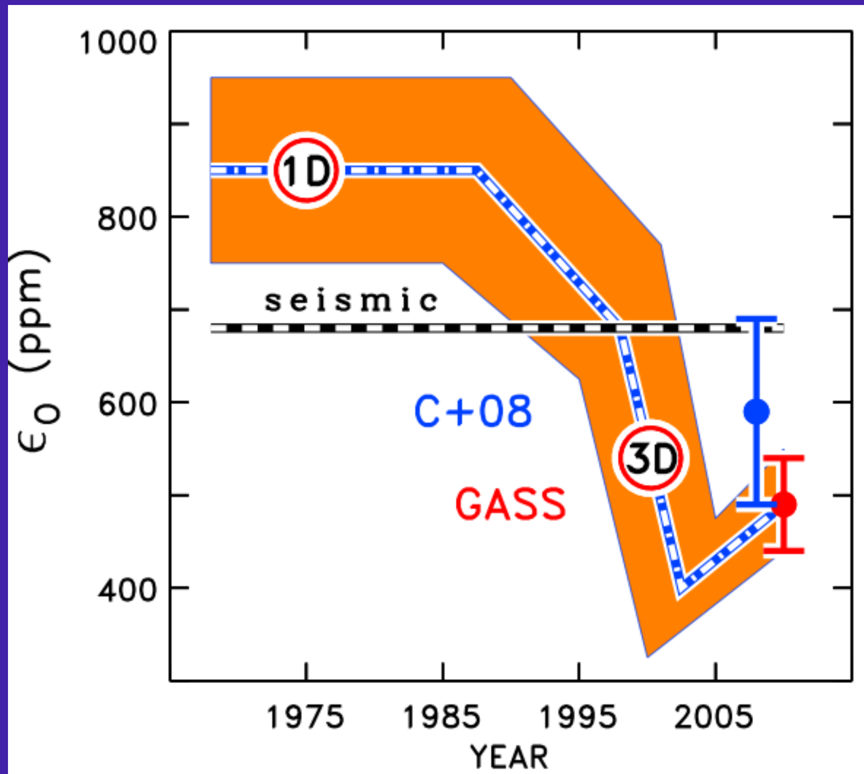
From atmospheric studies

in units of 12 + log O/H (by number)

Payne 1925	8
Russell 1929	9.5:
Hunaerts 1947	9.23
Bowen 1948	8.2
Unsold 1948	8.73
Class 1950	8.65
Goldberg 1960	8.96
Lambert 1968	8.77
Nikolaides 1973	8.93
Lambert 1978	8.92
Anders Grevesse 1989	8.93
Grevesse Sauval 1998	8.83
Allende Prieto 2001	8.69
Asplund 2009	8.69
Caffau Ludwig 2011	8.76
Villante 2014	8.89
Socas-Navarro 2014	8.9 – 8.7 !!!

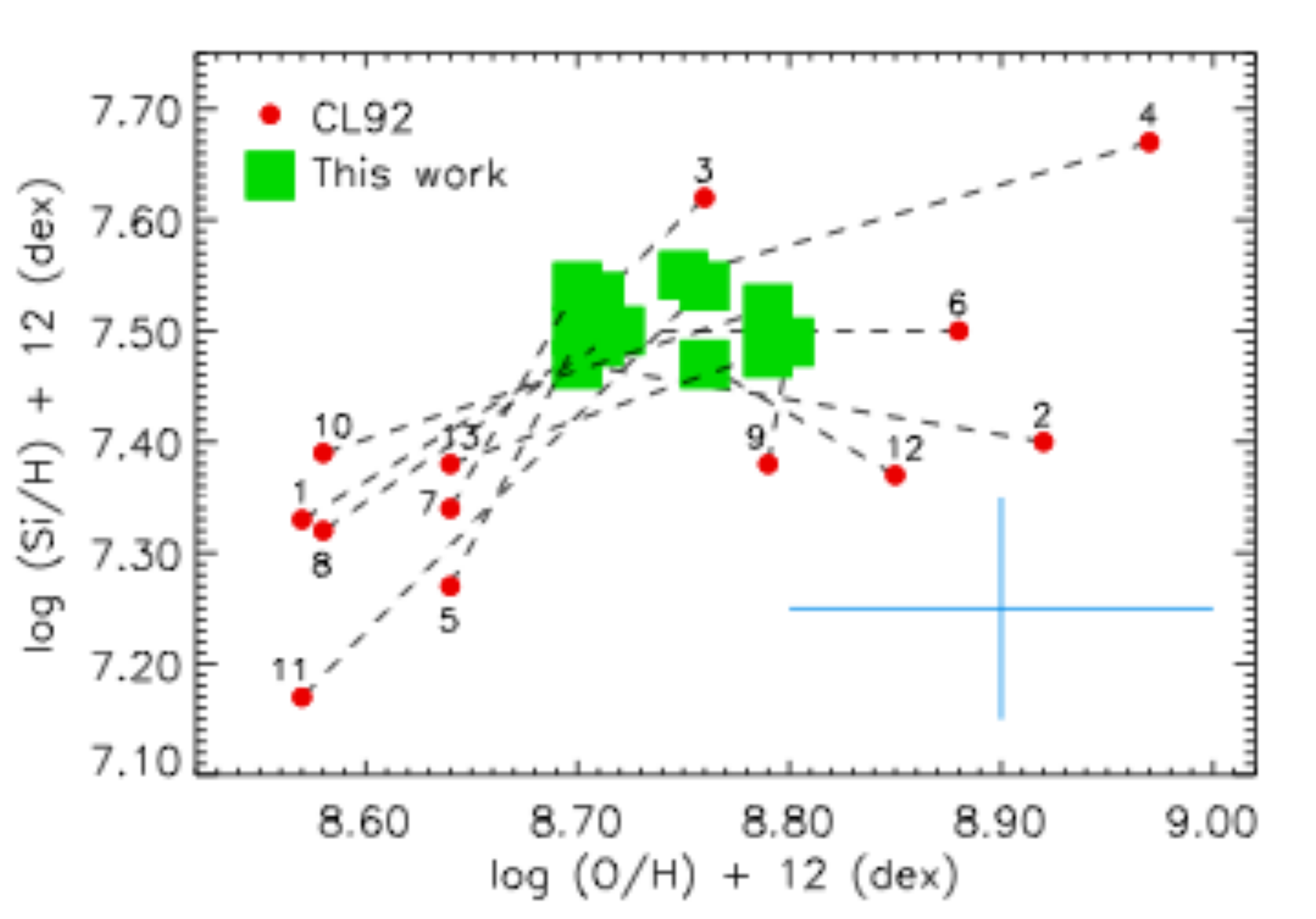
The oxygen crisis

Discrepancy between atmospheric abundances and results from helioseismology



About to be solved?
back to high solar oxygen abundance?

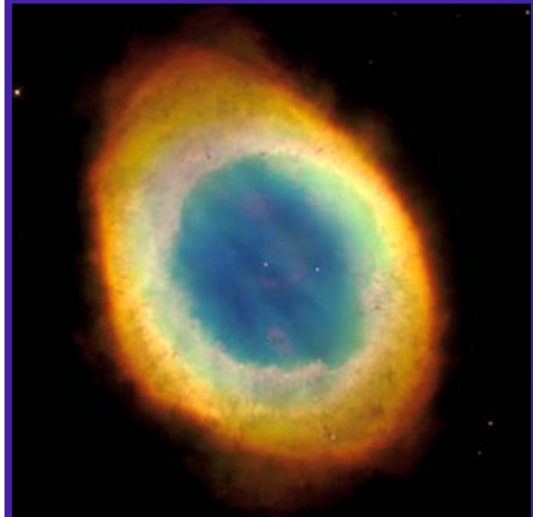
Oxygen abundance determinations in hot stars



Si and O abundances in the solar vicinity Simon-Diaz 2009

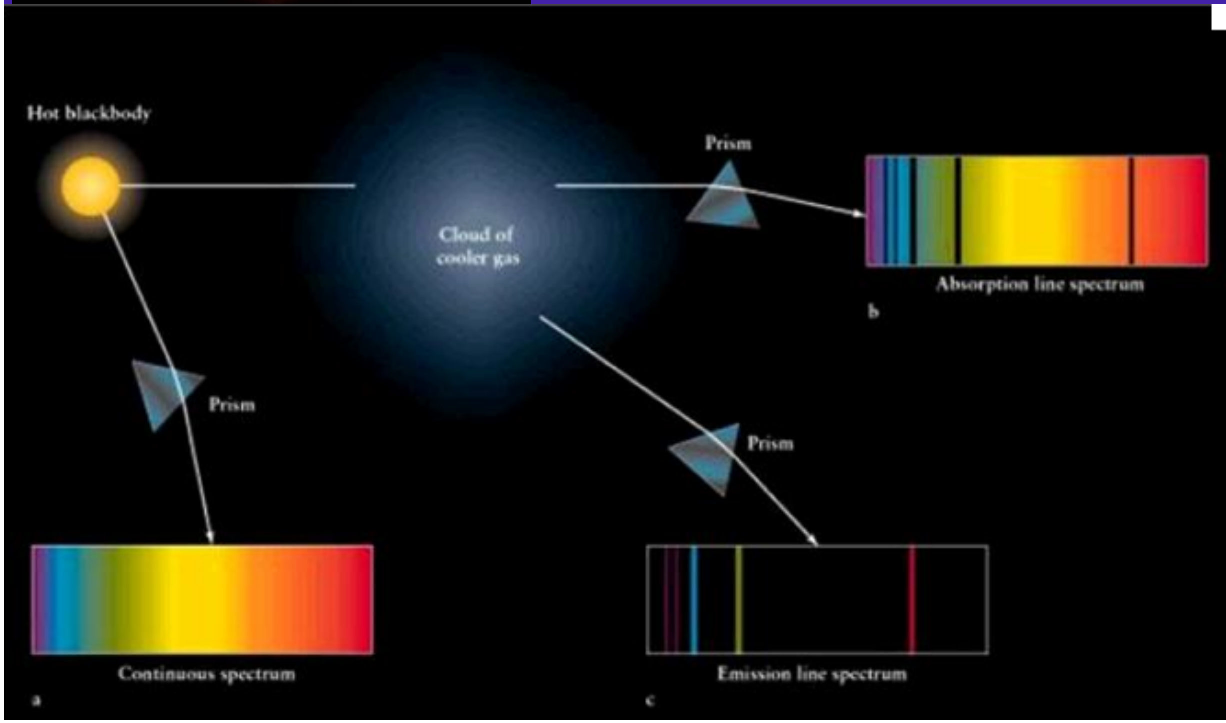
- use different techniques than determinations in solar-type stars
- rely on more lines
- have much improved in recent years

Oxygen abundances in ionized nebulae



A planetary nebula
nebula ejected by an ageing solar-type star and ionized by it

An HII region
a nebular zone ionized by recently formed massive stars



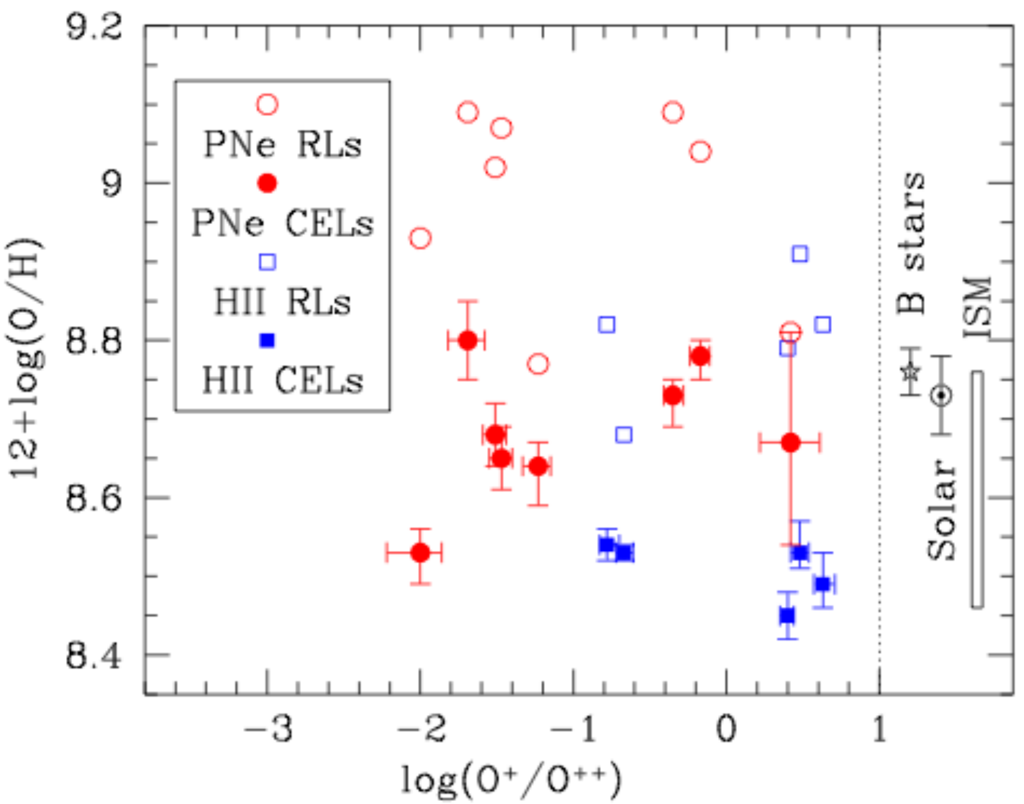
In both cases

- gas is very diluted (~1000 cm^3)
- one observes lines in emission
- the lines are produced
  by collisional excitation followed
  by radiative deexcitation,
  or by recombination
- abundance determination methods are very different from stellar ones

Oxygen abundances in ionized nebulae

Advantages of ionized nebulae to probe the oxygen abundance

- In principle, methods to derive abundances in nebulae are straightforward
- Emission lines are easily detected evec at large distances
- Ionized nebulae are used to probe abundances in distant galaxies

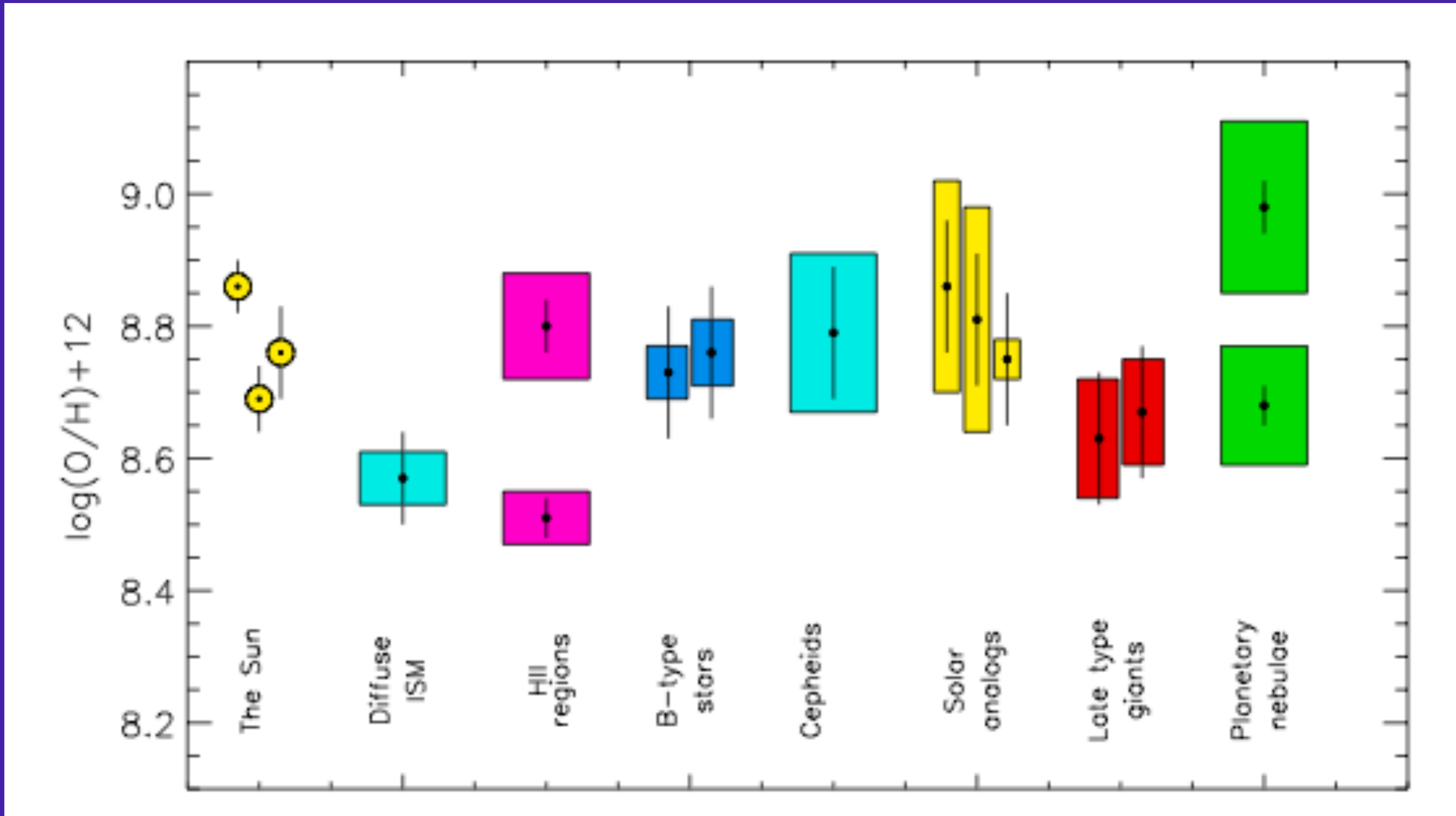


An important caveat

Collisionally excited lines (CEL) and recombination lines (RL) give results differing by a factor of ~2

abundances as a function of excitation in planetary nebulae and HII regions of the solar vicinity
Rodriguez & Delgado Inglada 2011

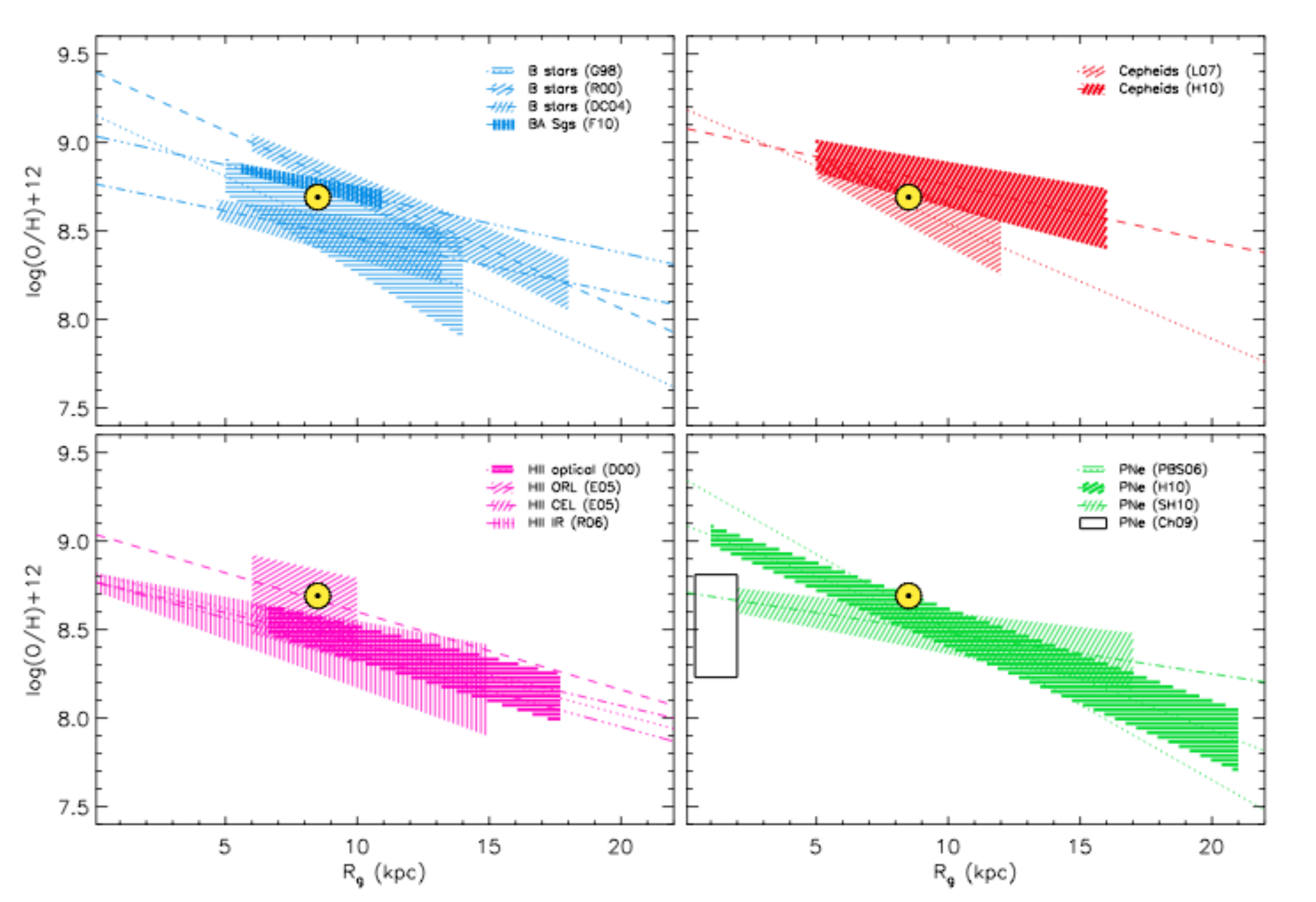
Summary of the oxygen abundance in the solar vicinity



- The abundances roughly agree (the solar vicinity seems chemically homogeneous)
- However, several problems subsist

compilation Stasinska et al 2012

The oxygen abundance varies within the galaxies



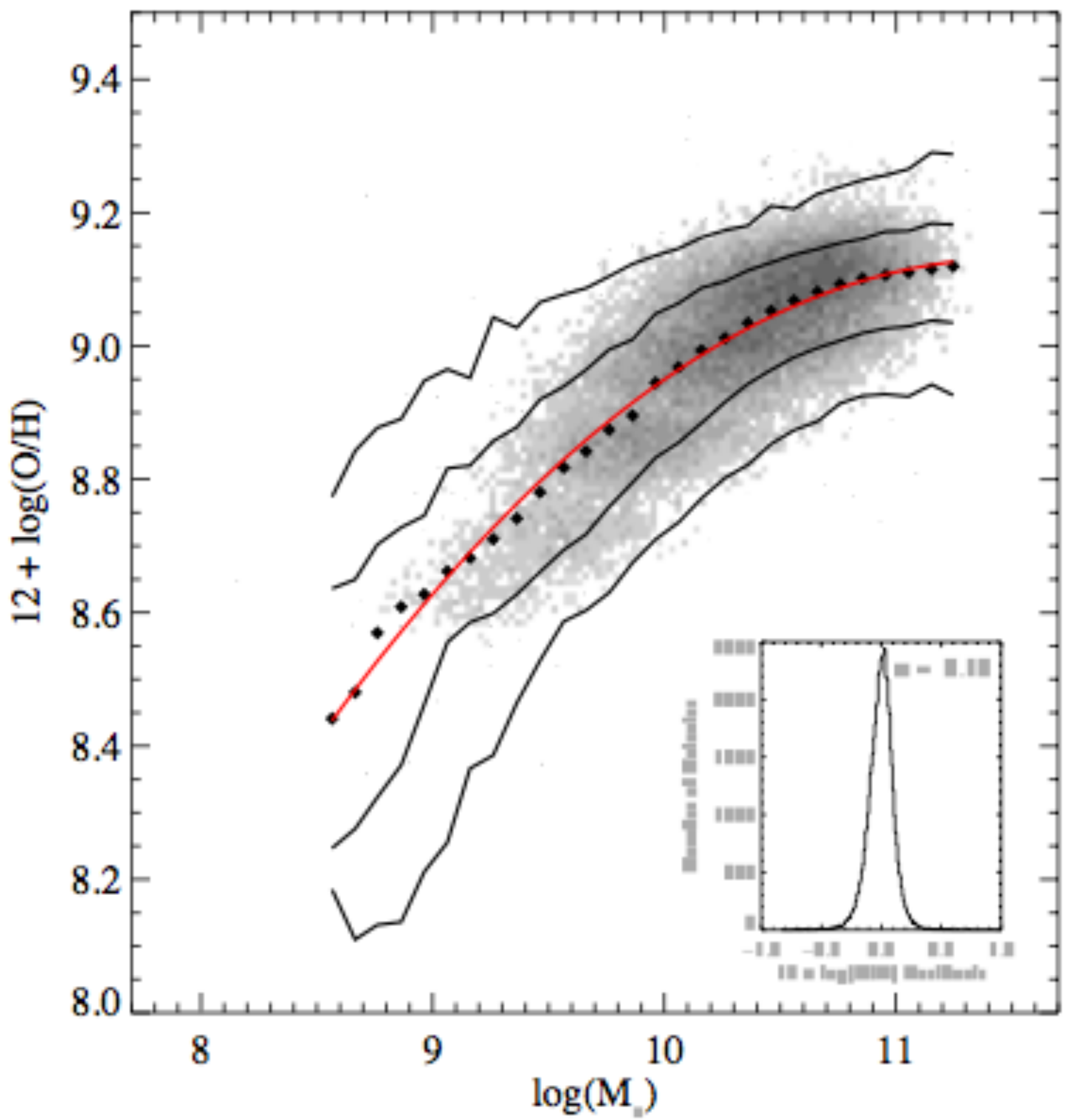
Radial distribution of the oxygen abundance in the Milky Way Galaxy for

- Young stars
- Cepheids
- HII regions
- Planetary Nebulae

There is typically a factor of 10 difference between the innermost zone and the outermost zones

Compilation from Stasinska et al. 2012

The oxygen abundances vary among the galaxies



The « mass-metallicity relation »

I.e. the relation between the total mass of the stars in the galaxies and the average oxygen abundance in their nebulae

Tremonti et al 2004
Determination for 53,000 galaxies from the Sloan Digital Sky Survey

Where does the oxygen com from?

The development of the argumentation

Rutherford (1907)
radioactive dating of terrestrial rocks shows that the Earth is at least one billion years old, therefore the Sun should also be that old.

Russell (1919)
If stars were shining only due to gravitational contraction, their lifetime would be about 1 million years.
Thus another source of energy must be present in stars.

Jeans (1907)
A star contracting under its own gravity reaches a temperature of about 1 million degrees

Atkinson & Houtermans (1929)
At such temperatures, some nuclear fusion reactions can occur and generate energy

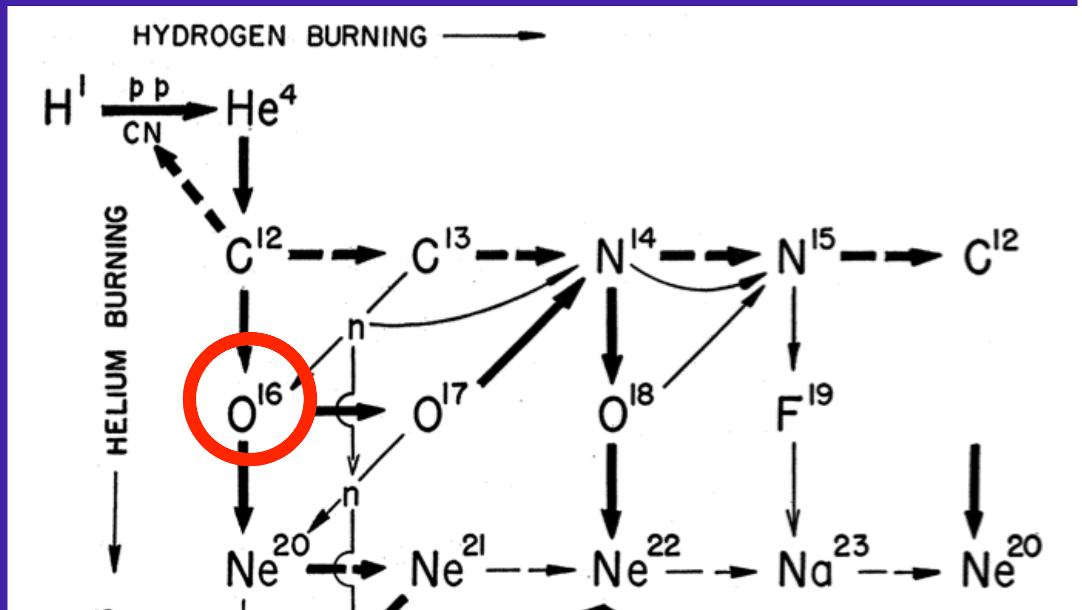
Atkinson (1931) Is the first to suggest that stellar nucleosynthesis is the main energy source in stars and that it transforms the simplest atoms into more complex ones by subsequent addition of protons

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

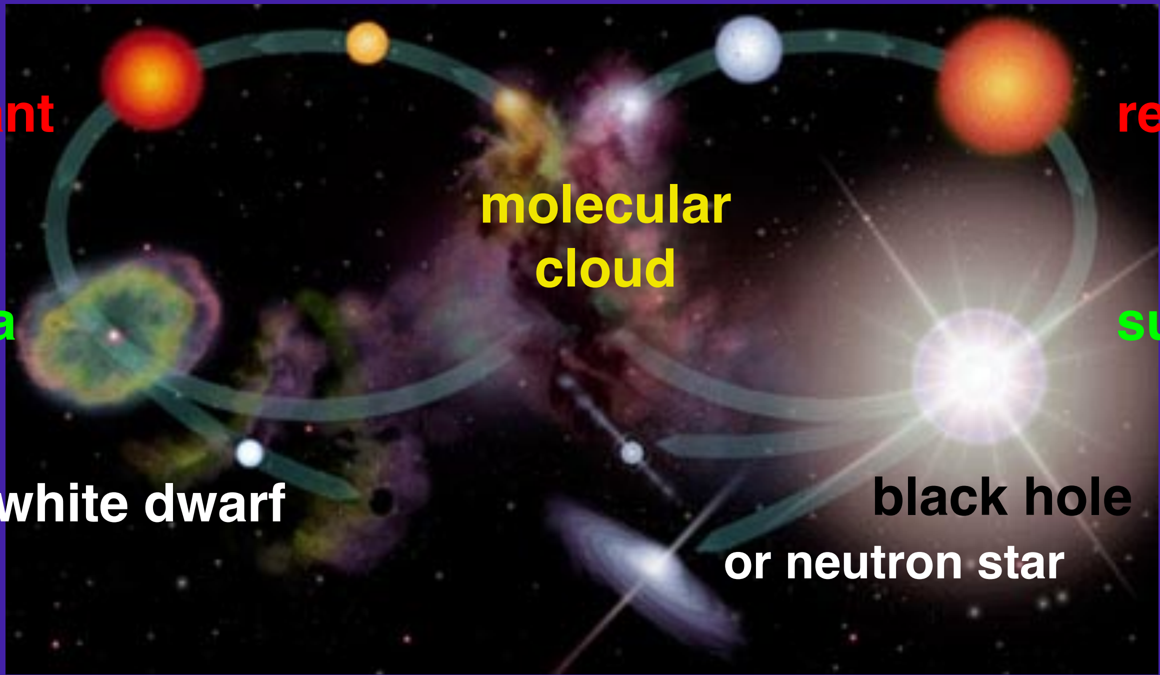
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE



Burbidge, Burbidge, Fowler & Hoyle (1957)
The cornerstone paper
on stellar nucleosynthesis

Stellar cycles

low mass star — high mass star



the cycle takes one billion years — the cycle takes 10 million years

The recently synthesized elements are

- ejected into the interstellar medium and enrich future generations of stars
- or trapped forever in stellar remnants

The oxygen that we see in galaxies comes from high mass stars

The evolution of oxygen in galaxies

Definitions

s: mass of stars
g: mass of gas
a: fraction of mass formed into stars and not returned to the interstellar medium (ISM)
z: mass of oxygen nuclei in the gas with respect to the mass of H nuclei
p: the « yield »: mass of oxygen formed in stars and returned to the ISM divided by a

In the « closed box model »

- the solution of the equations of conservation is

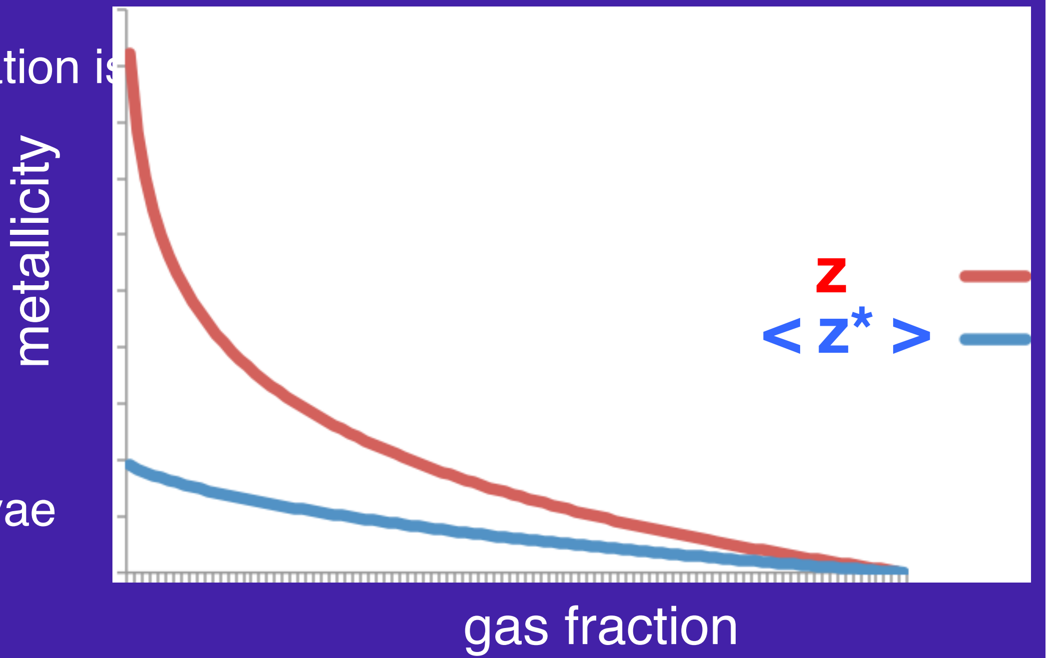
$z = p \ln (1 / f)$
where $f = g / (g+as)$

- the mean stellar « metallicity » is

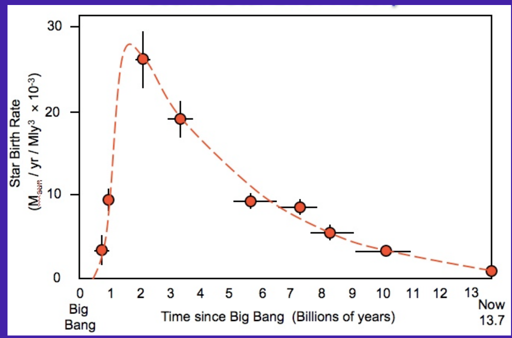
$< z^* > = p - p (f \ln(1 / f)) / (1-f)$

More realistic models of galaxies

- Outflow of enriched gas due to supernovae
- Inflow of metal-poor gas



The global budget of oxygen in the Universe



Madau et al 1996

Theoretical estimation

from
- the star formation history of the galaxies in the Universe
- and the production rate of oxygen nuclei in stars

one can estimate the total amount of oxygen produced since the Big Bang
- hidden in stars
- or present in the interstellar medium

Observational inventory

in stars
- stellar population studies in galaxies give the total mass of stars (including stellar remnants)
- nucleosynthesis (theory and experiment) gives the amount of oxygen hidden in stars

In the interstellar medium
- emission lines in nebulae and
- absorption lines produced in galaxies in front of quasars

allow one to measure the O/H ratio
- The total mass hydrogen can be estimated from hydrogen line studies

The missing « metal » problem

Pagel 1999, Pettini 1999

- Metals locked in stars represent only 10% of the metals « visible » in galaxies
- Adding up all the metals observed acounts for only 10% of the expected value
- The missing metals could actually be stored in hot gas in galactic haloes or expelled from galaxies by galactic winds and found in clusters of galaxies

Shull et al 2014

- Observed the hot gas of the intergalactic medium (OVI lines in absorption in front of quasars) together with the « warm » gas
- The amount of metals in the hot gas is twice that in the warm gas
- Metals in hot+warm phases represent only 10% of the whole metal production

But they conclude

- Given the uncertainties in star formation histories and metal production
- and the existence of various metal reservoirs (stars, galaxy halos, intra cluster gas)
- there is probably no compelling reason to require a missing metals problem.

Summary

Oxygen constitutes

- 1% of the total baryonic mass in the Universe
- one half of the total mass of metals

Oxygen is formed in stars

- Massive stars explode and enrich the interstellar medium in newly produced oxygen
- Oxygen synthesized in low-mass stars is forever locked in their degenerate cores

What we still need to understand

- Abundance discrepancies in nebulae (factor 2)
- Solar crisis (factor 2)
- Missing oxygen (factor 10?)