The Origin of the Elements

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Outline:

1. What is an element?
2. Elements are made by nucleosynthesis in stars
3. How do we know the abundances of elements in stars:
    - Stellar spectra
    - Stellar dust particles in meteorites
4. Calculating the evolution of stars and the making of the elements
5. Scientists paradise: new data, lots of it!
6. Conclusions

What is an element

Basic building blocks of everything we see (breeze!) around us:

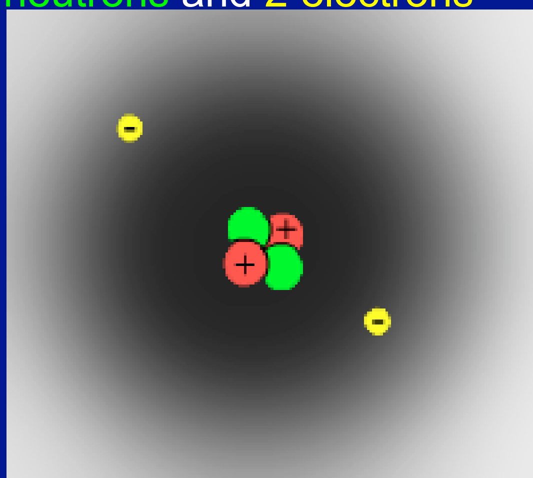
- o Air: nitrogen (N, 78.09%), oxygen (O, 20.95%), argon (Ar, 0.93), carbon dioxide (CO_2, 0.03), trace gases (0.003%)
- o Metals:
  - steel: alloy of iron (Fe) and less than 2% carbon (C)
  - bronze, brass: alloy of Tin (Sn) and copper (Cu)
- o Glass: mainly sand: silicon dioxide (SiO_2)
- o Water: hydrogen and oxygen: H_2O
- o The Sun (and most other stars): hydrogen (H, 0.76%), helium (He, 0.22%), and a little bit of everything else …

Everything else are 105 elements.

What is an element

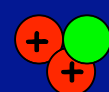
Material that consists of atoms with the same number of protons in the nucleus.

Helium atom model:
Nucleus with 2 protons, 2 neutrons and 2 electrons



A nucleus consists of protons and neutrons. Nuclei with the same number of protons are the same element. Elements have different isotopes with different neutron numbers.

<-- this is ^{4}He

This:  is ^{3}He

More elements and their proton/charge number:
C - 6, N - 7, O - 8, Ne (neon) - 10, Si - 14, Fe - 26, Pb (lead) 82

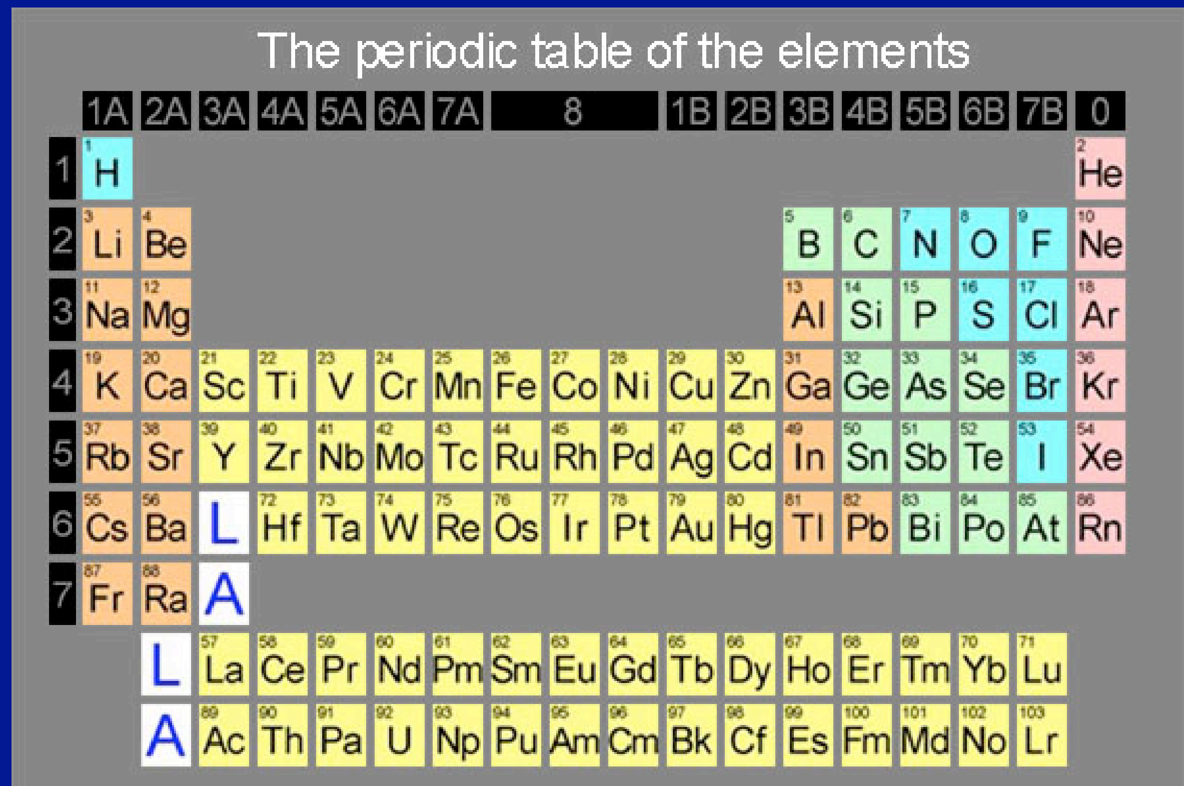
The stable isotopes of C: ^{12}C and ^{13}C

Bring order to this mess …

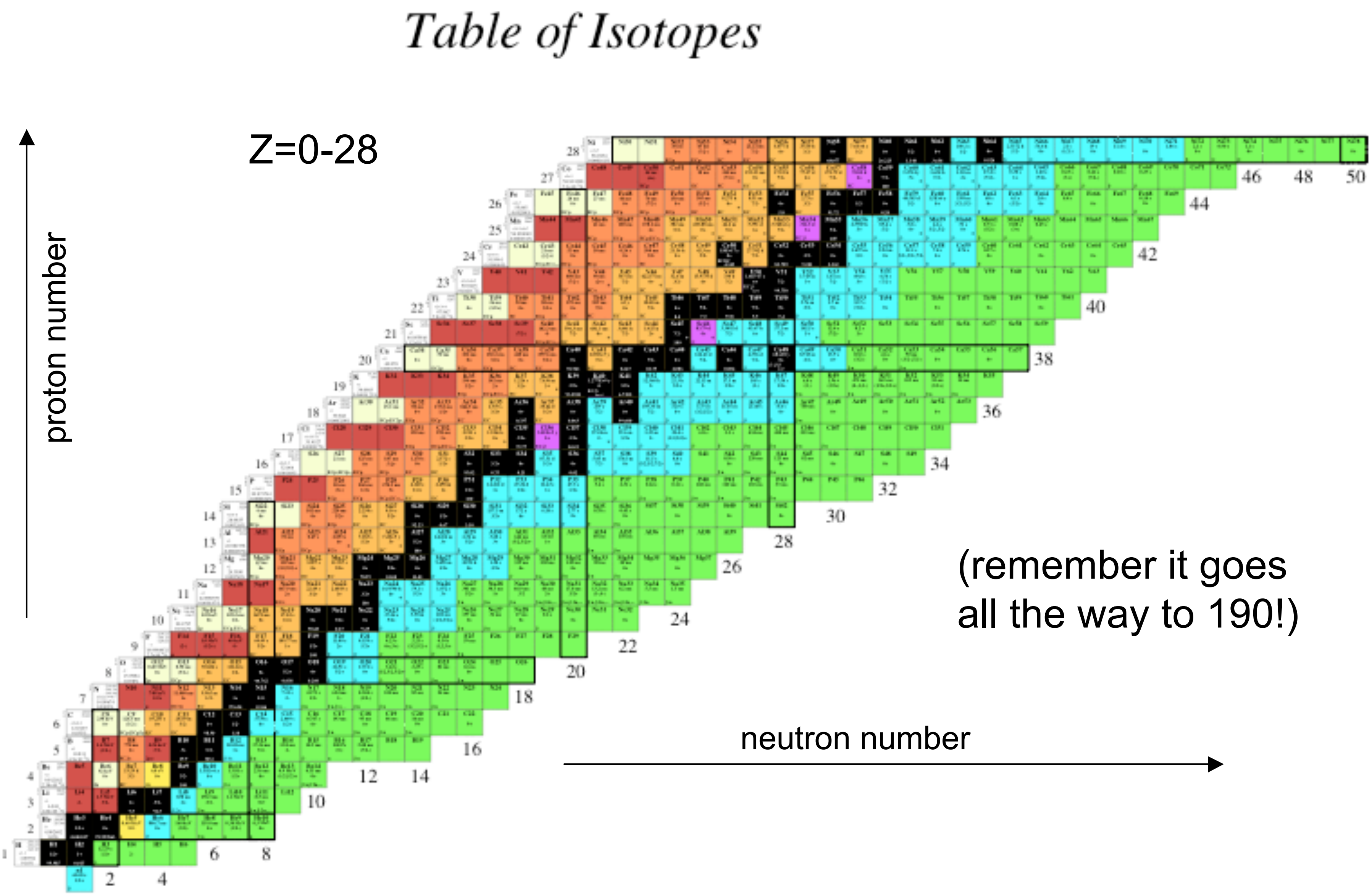
The periodic table

Order by number of electrons -> chemistry

Not suitable for nuclear (astro-) physics!!!

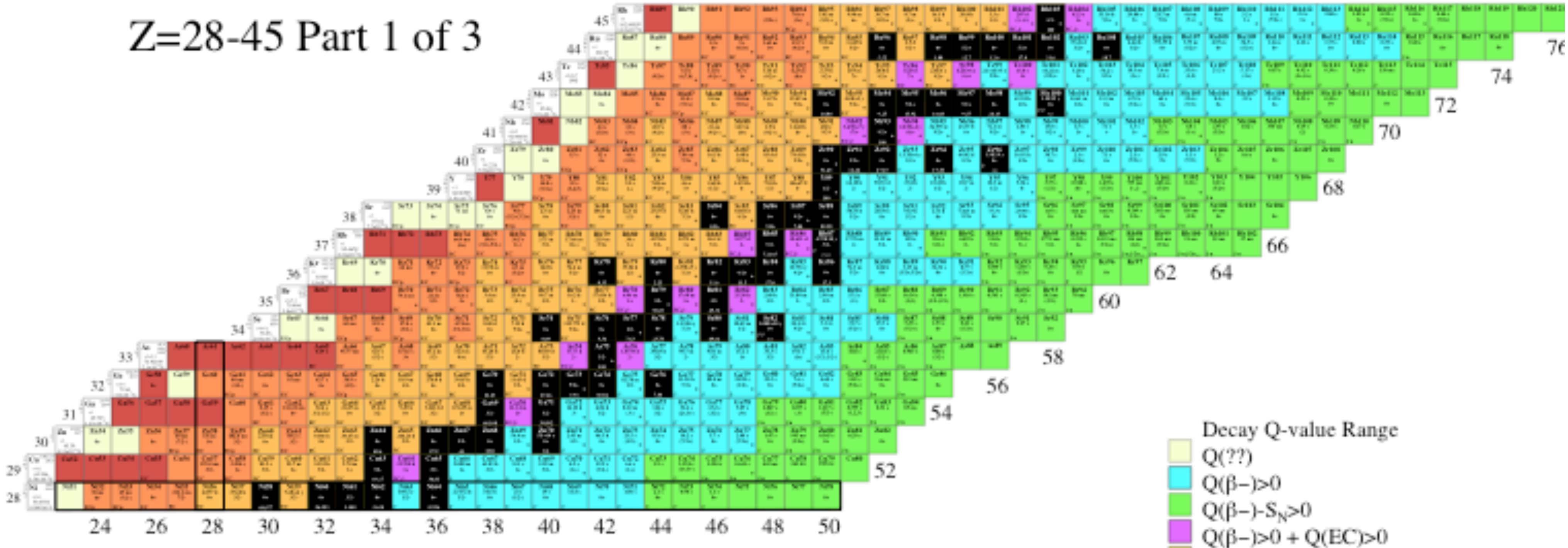


Bring order to this mess ...



(remember it goes all the way to 190!)

Z=28-45 Part 1 of 3



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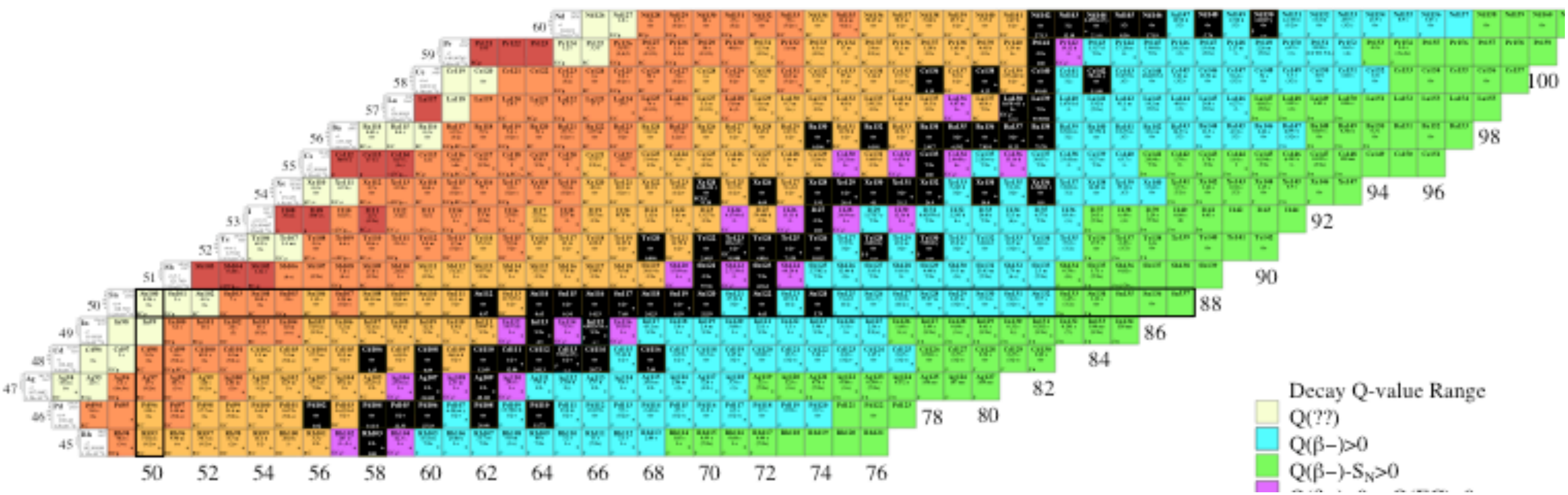
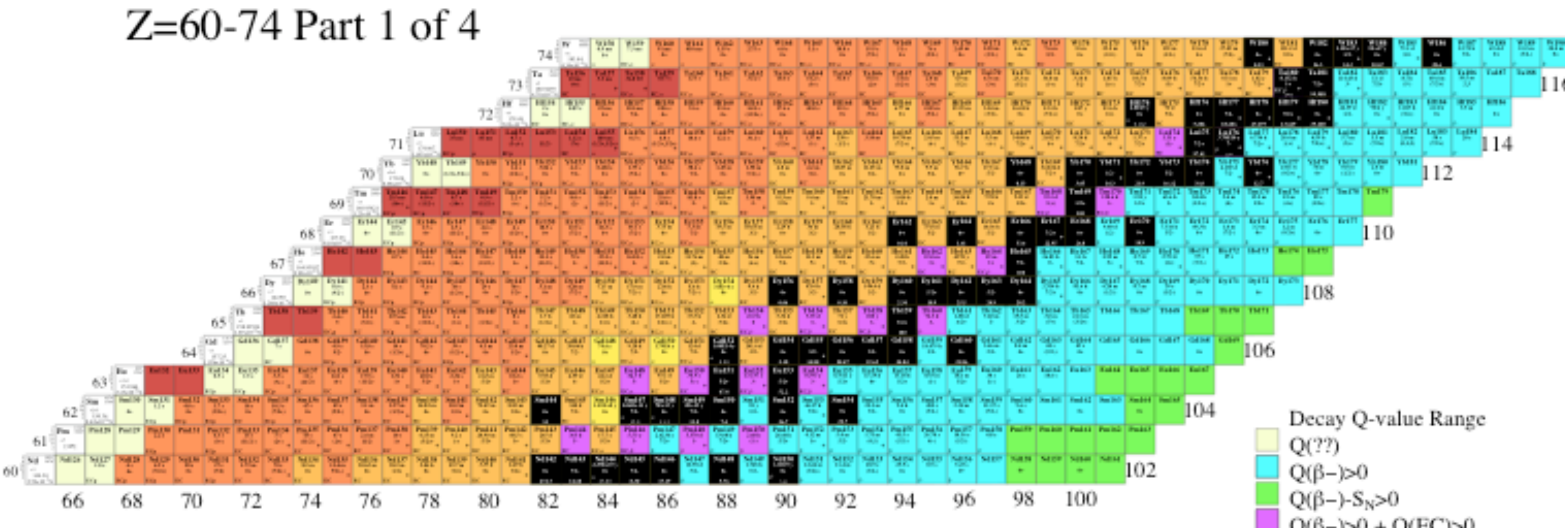
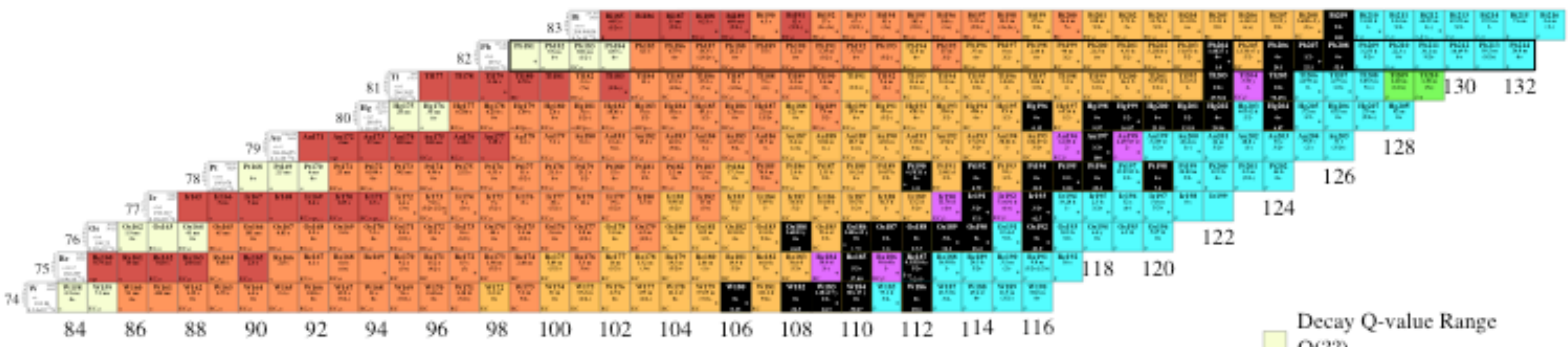
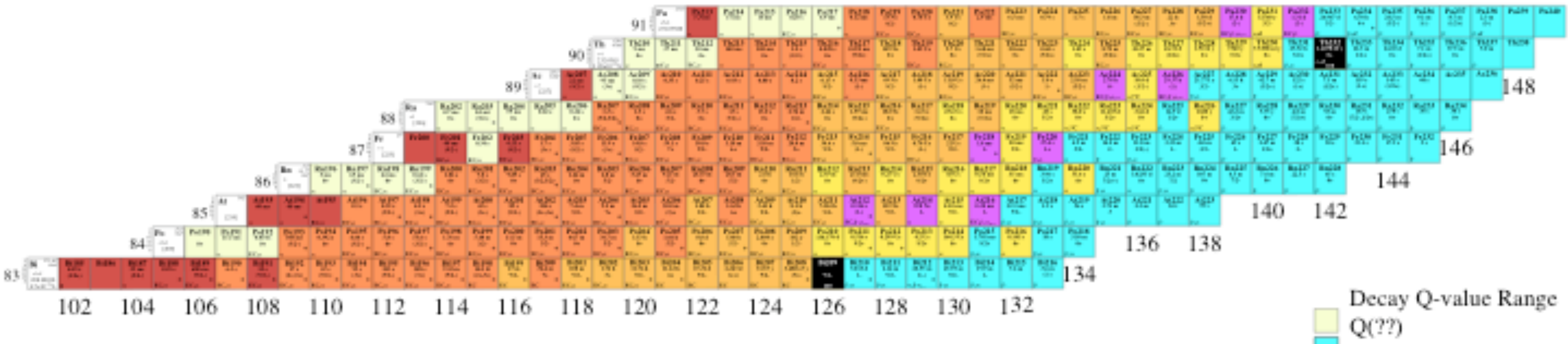


Bring order to this mess …

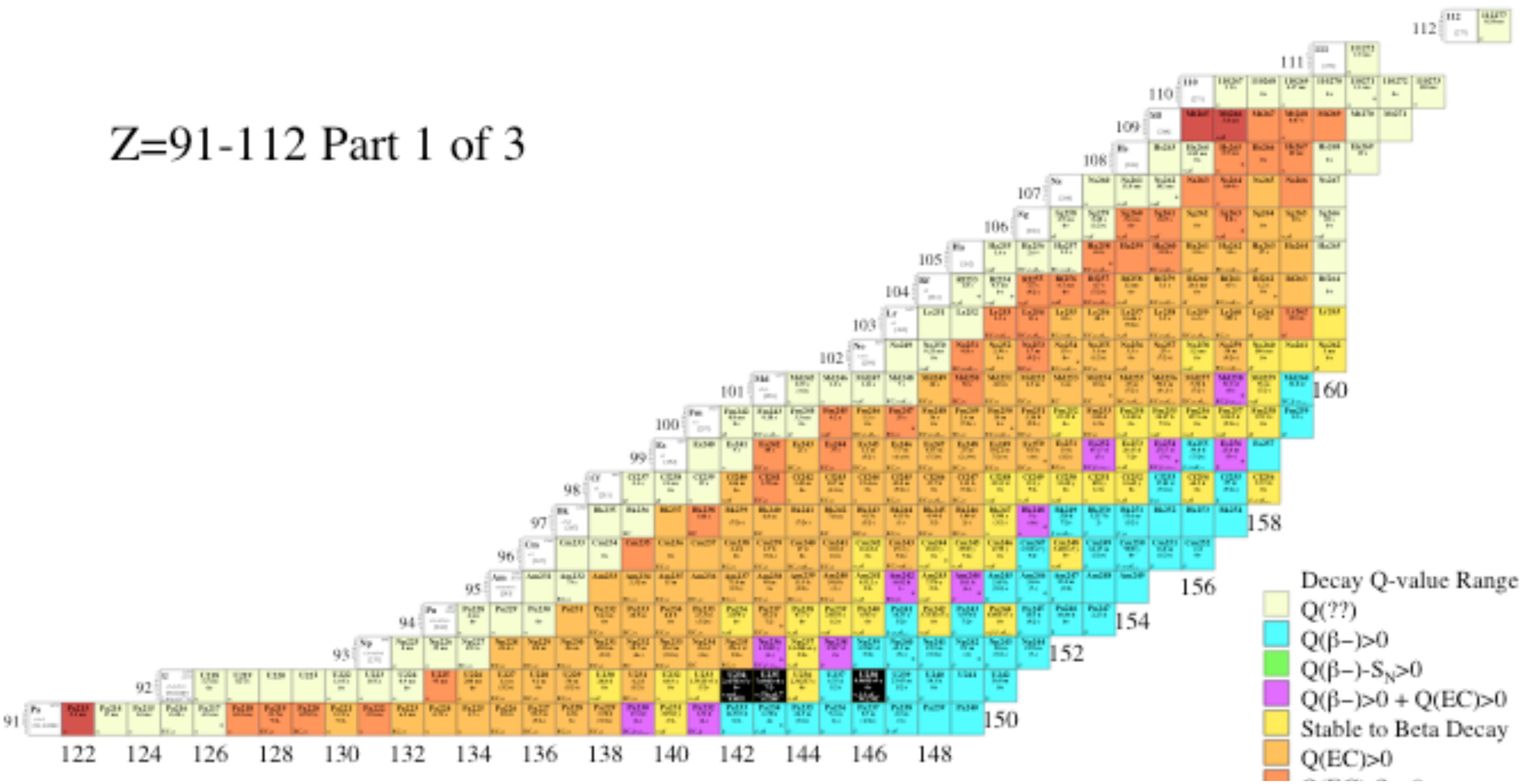




Z=83-91 Part 1 of 3



Z=91-112 Part 1 of 3



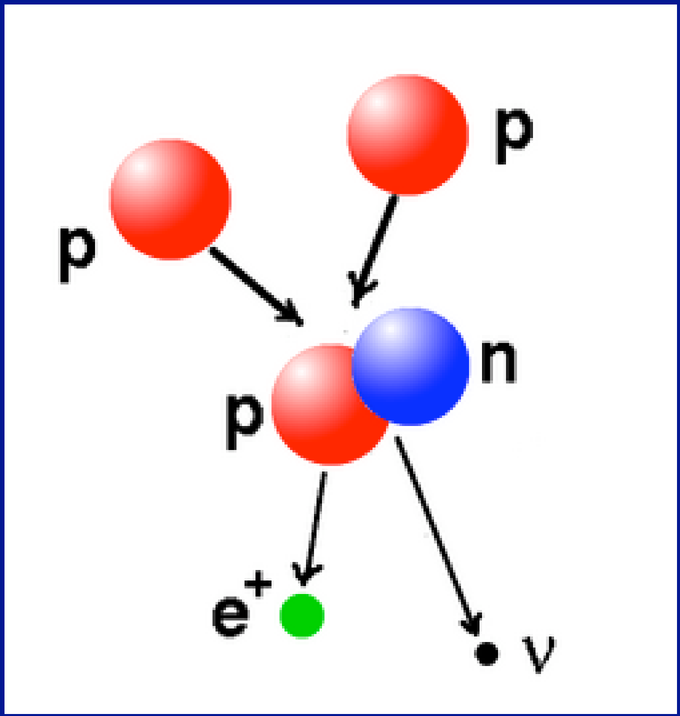
Elements are made by nucleosynthesis in stars*

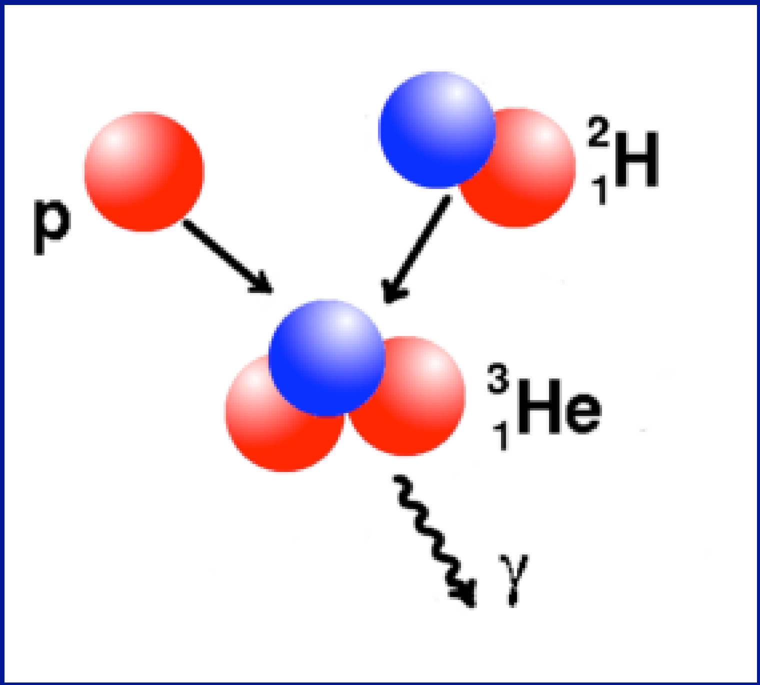
Nucleosynthesis: Creating new nuclei by nuclear fusion of fission

High temperature required!!!

For example:

$p + p \rightarrow {}^{2}H + e^{+} + \nu + 1.02MeV$ $p + {}^{2}H \rightarrow {}^{3}He + \gamma + 5.49MeV$





*OK, not exactly true: H and the vast majority of He (both ^{3}He and ^{4}He) and Li is made in the Big Ban

Elements are made by nucleosynthesis in stars

And so on …:

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

…..

```
Title: Evolution and Yields of Extremely Metal Poor Intermediate Mass Stars
Author: Herwig F.
Table: Reaction network
================================================================================
Byte-by-byte Description of file: datafile1.txt
--------------------------------------------------------------------------------
   Bytes Format Units   Label  Explanations
--------------------------------------------------------------------------------
   1- 37 A37    ---     Type   Type
  39- 41 I3     ---     ID     Identification number
  43- 79 A37    ---     React  Reaction description
      81 A1     ---   r_React  Reference for React (1)
--------------------------------------------------------------------------------
Note (1):
    1 = NACRE adotped;
    2 = Horiguchi et al. (1996);
    3 = Caughlan & Fowler (1988);
    4 = Iliadis et al. (2001);
    5 = Bao et al. (2000a);
    6 = Beer et al. (2001);
    7 = Bao et al. (2000b);
    8 = Hauser-Feshbach (Jorissen & Gorely 2001);
    9 = see Jorissen & Goriely (2001);
    a = Wiescher et al. (1990);
    b = Koehler & O'Brien (1989);
    c = Takahashi Yokoi (1987);
    d = Goriely (1999);
    e = Hauser-Feshbach (Jorissen & Gorely 2001).
--------------------------------------------------------------------------------
p-capture reactions                       1  2 PROT  (  0 OOOOO,  0 OOOOO)  1 DEUT   1
p-capture reactions                       2  1 DEUT  (  1 PROT ,  0 OOOOO)  1 HE 3   1
p-capture reactions                       6  1 LI 7  (  1 PROT ,  0 OOOOO)  2 HE 4   1
p-capture reactions                       7  1 BE 7  (  1 PROT ,  0 OOOOO)  1 B 8    1
p-capture reactions                      10  1 C 12  (  1 PROT ,  0 OOOOO)  1 N 13   1
p-capture reactions                      11  1 C 13  (  1 PROT ,  0 OOOOO)  1 N 14   1
p-capture reactions                      12  1 N 14  (  1 PROT ,  0 OOOOO)  1 O 15   1
p-capture reactions                      13  1 N 15  (  1 PROT ,  1 HE  4)  1 C 12   1
p-capture reactions                      14  1 N 15  (  1 PROT ,  0 OOOOO)  1 O 16   1
p-capture reactions                      15  1 O 16  (  1 PROT ,  0 OOOOO)  1 F 17   1
p-capture reactions                      16  1 O 17  (  1 PROT ,  1 HE  4)  1 N 14   1
p-capture reactions                      17  1 O 17  (  1 PROT ,  0 OOOOO)  1 F 18   1
p-capture reactions                      18  1 O 18  (  1 PROT ,  1 HE  4)  1 N 15   1
p-capture reactions                      19  1 O 18  (  1 PROT ,  0 OOOOO)  1 F 19   1
p-capture reactions                      20  1 F 19  (  1 PROT ,  1 HE  4)  1 O 16   1
p-capture reactions                      21  1 F 19  (  1 PROT ,  0 OOOOO)  1 NE 20  1
p-capture reactions                      22  1 NE 20 (  1 PROT ,  0 OOOOO)  1 NA 21  1
p-capture reactions                      23  1 NE 21 (  1 PROT ,  0 OOOOO)  1 NA 22  1
p-capture reactions                      26  1 NA 22 (  1 PROT ,  0 OOOOO)  1 MG 23  1
p-capture reactions                      30  1 MG 25 (  1 PROT ,  0 OOOOO)  1 AL 26g 1
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Elements are made by nucleosynthesis in stars

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p-capture reactions                          33 1 AL 26g( 1 PROT , 0 OOOOO)  1 SI 27   4
p-capture reactions                          35 1 AL 27 ( 1 PROT , 1 HE   4)  1 MG 24   1
p-capture reactions                          37 1 SI 28 ( 1 PROT , 0 OOOOO)  1 P 29    1
p-capture reactions                          38 1 SI 29 ( 1 PROT , 0 OOOOO)  1 P 30    1
p-capture reactions                          39 1 SI 30 ( 1 PROT , 0 OOOOO)  1 P 31    1
p-capture reactions                          63 1 NE 22 ( 1 PROT , 0 OOOOO)  1 NA 23   1
p-capture reactions                          65 1 NA 23 ( 1 PROT , 0 OOOOO)  1 MG 24   1
p-capture reactions                          66 1 NA 23 ( 1 PROT , 1 HE   4)  1 NE 20   1
p-capture reactions                          69 1 MG 24 ( 1 PROT , 0 OOOOO)  1 AL 25   1
p-capture reactions                          70 1 MG 25 ( 1 PROT , 0 OOOOO)  1 AL 26   1
p-capture reactions                          72 1 MG 26 ( 1 PROT , 0 OOOOO)  1 AL 27   1
p-capture reactions                          73 1 AL 27 ( 1 PROT , 0 OOOOO)  1 SI 28   1
p-capture reactions                          74 1 AL 27 ( 1 PROT , 1 HE   4)  1 MG 24   1
p-capture reactions                          79 1 B 11  ( 1 PROT , 0 OOOOO)  3 HE 4    1
p-capture reactions                          81 1 C 14  ( 1 PROT , 0 OOOOO)  1 N 15    a
p-capture reactions                          92 1 N 13  ( 1 PROT , 0 OOOOO)  1 O 14    1
p-capture reactions                         101 1 P 31  ( 1 PROT , 0 OOOOO)  1 S 32    4
{alpha} - and ^3^He-capture reactions         3 2 HE 3  ( 0 OOOOO, 2 PROT )  1 HE 4    1
{alpha} - and ^3^He-capture reactions         4 1 HE 4  ( 1 HE   3, 0 OOOOO)  1 BE 7    1
{alpha} - and ^3^He-capture reactions        40 3 HE 4  ( 0 OOOOO, 0 OOOOO)  1 C 12    1
{alpha} - and ^3^He-capture reactions        41 1 C 12  ( 1 HE   4, 0 OOOOO)  1 O 16    1
{alpha} - and ^3^He-capture reactions        42 1 C 13  ( 1 HE   4, 1 NEUT )  1 O 16    1
{alpha} - and ^3^He-capture reactions        43 1 N 14  ( 1 HE   4, 0 OOOOO)  1 F 18    1
{alpha} - and ^3^He-capture reactions        44 1 O 16  ( 1 HE   4, 0 OOOOO)  1 NE 20   1
{alpha} - and ^3^He-capture reactions        45 1 O 18  ( 1 HE   4, 0 OOOOO)  1 NE 22   1
{alpha} - and ^3^He-capture reactions        46 1 NE 20 ( 1 HE   4, 0 OOOOO)  1 MG 24   1
{alpha} - and ^3^He-capture reactions        48 1 NE 21 ( 1 HE   4, 1 NEUT )  1 MG 24   1
{alpha} - and ^3^He-capture reactions        49 1 NE 22 ( 1 HE   4, 0 OOOOO)  1 MG 26   1
{alpha} - and ^3^He-capture reactions        50 1 NE 22 ( 1 HE   4, 1 NEUT )  1 MG 25   1
{alpha} - and ^3^He-capture reactions        53 1 MG 24 ( 1 HE   4, 0 OOOOO)  1 SI 28   3
{alpha} - and ^3^He-capture reactions        61 1 NE 20 ( 1 HE   4, 1 PROT )  1 NA 23   1
{alpha} - and ^3^He-capture reactions        67 1 NA 23 ( 1 HE   4, 1 PROT )  1 MG 26   8
{alpha} - and ^3^He-capture reactions        68 1 MG 24 ( 1 HE   4, 1 PROT )  1 AL 27   1
{alpha} - and ^3^He-capture reactions        71 1 MG 25 ( 1 HE   4, 1 NEUT )  1 SI 28   1
{alpha} - and ^3^He-capture reactions        75 1 BE 7  ( 1 HE   4, 0 OOOOO)  1 C 11    1
{alpha} - and ^3^He-capture reactions        76 1 LI 7  ( 1 HE   4, 0 OOOOO)  1 B 11    1
{alpha} - and ^3^He-capture reactions        78 1 B 11  ( 1 HE   4, 1 NEUT )  1 N 14    3
{alpha} - and ^3^He-capture reactions        80 1 C 14  ( 1 HE   4, 0 OOOOO)  1 O 18    9
{alpha} - and ^3^He-capture reactions        82 1 N 15  ( 1 HE   4, 0 OOOOO)  1 F 19    1
{alpha} - and ^3^He-capture reactions        83 1 O 17  ( 1 HE   4, 0 OOOOO)  1 NE 21   3
{alpha} - and ^3^He-capture reactions        84 1 O 17  ( 1 HE   4, 1 NEUT )  1 NE 20   1
n-capture reactions                          31 1 AL 26g( 1 NEUT , 1 PROT )  1 MG 26   3
n-capture reactions                          32 1 AL 26g( 1 NEUT , 1 HE   4)  1 NA 23   3
n-capture reactions                          36 1 BE 7  ( 1 NEUT , 1 PROT )  1 LI 7    0
n-capture reactions                          47 1 NE 20 ( 1 NEUT , 0 OOOOO)  1 NE 21   5
n-capture reactions                          51 1 NE 22 ( 1 NEUT , 0 OOOOO)  1 NA 23   6
n-capture reactions                          52 1 NA 23 ( 1 NEUT , 0 OOOOO)  1 MG 24   5
n-capture reactions                          54 1 MG 24 ( 1 NEUT , 0 OOOOO)  1 MG 25   5
n-capture reactions                          55 1 MG 25 ( 1 NEUT , 0 OOOOO)  1 MG 26   5
n-capture reactions                          56 1 MG 26 ( 1 NEUT , 0 OOOOO)  1 AL 27   5
n-capture reactions                          57 1 AL 27 ( 1 NEUT , 0 OOOOO)  1 SI 28   5
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n-capture reactions                    58 1 C 12  ( 1 NEUT , 0 OOOO
n-capture reactions                    62 1 NE 21 ( 1 NEUT , 0 OOOO
n-capture reactions                    64 1 NE 22 ( 1 NEUT , 0 OOOO
n-capture reactions                    85 1 N 14  ( 1 NEUT , 1 PROT
n-capture reactions                    86 1 SI 28 ( 1 NEUT , 0 OOOO
n-capture reactions                    87 1 SI 29 ( 1 NEUT , 0 OOOO
n-capture reactions                    88 1 SI 30 ( 1 NEUT , 0 OOOO
n-capture reactions                    89 1 N 14  ( 1 NEUT , 0 OOOO
n-capture reactions                    90 1 O 16  ( 1 NEUT , 0 OOOO
n-capture reactions                    93 1 FE 56 ( 1 NEUT , 0 OOOO
n-capture reactions                    94 1 FE 57 ( 1 NEUT , 0 OOOO
n-capture reactions                    95 1 FE 58 ( 1 NEUT , 0 OOOO
n-capture reactions                    96 1 CO 59 ( 1 NEUT , 0 OOOO
n-capture reactions                    97 1 NI 60 ( 1 NEUT , 0 OOOO
n-capture reactions                    98 1 NI 61 ( 1 NEUT , 0 OOOO
n-capture reactions                   100 1 P 31  ( 1 NEUT , 0 OOOO
n-capture reactions                   106 1 NI 58 ( 1 NEUT , 0 OOOO
n-capture reactions                   107 1 NI 59 ( 1 NEUT , 0 OOOO
n-capture reactions                   108 1 NI 59 ( 1 NEUT , 1 PROT
{beta} -decay and e^-^-captures         5 1 BE 7  ( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures         8 1 B 8   ( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures         9 1 B 8   ( 0 OOOOO, 1 PROT
{beta} -decay and e^-^-captures        25 1 NA 22 ( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures        34 1 AL 26g( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures        77 1 C 11  ( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures        91 1 N 13  ( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures       104 1 C 14  ( 0 OOOOO, 0 OOOO
{beta} -decay and e^-^-captures       105 1 NI 59 ( 0 OOOOO, 0 OOOO
C-burning                              59 2 C 12  ( 0 OOOOO, 1 PROT
C-burning                              60 2 C 12  ( 0 OOOOO, 1 HE
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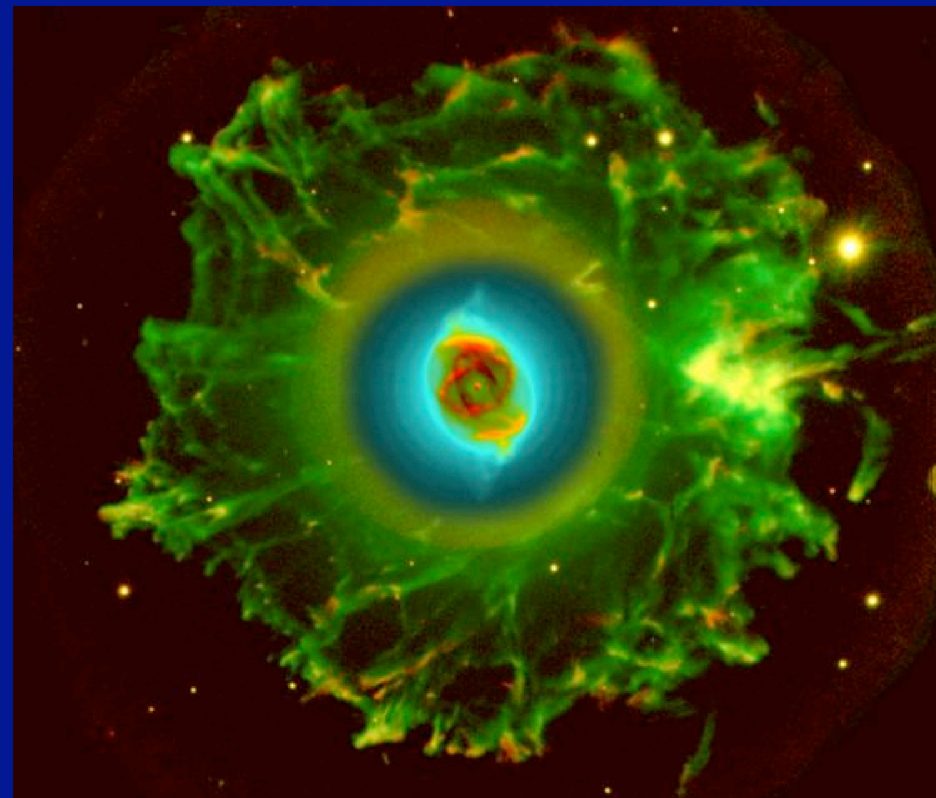
How do we know the abundances of elements in stars

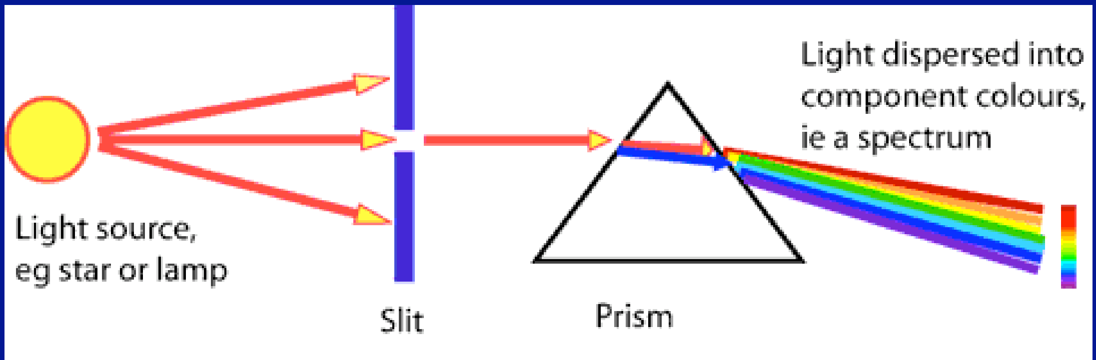
Little Ghost Nebula (NGC 6369), ionized oxygen, hydrogen, and nitrogen atoms are colored blue, green, and red



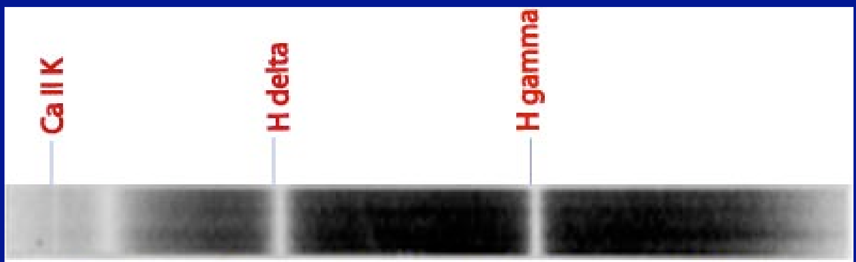
Cat's Eye Nebula (NGC 6543), emission from nitrogen atoms as red and oxygen atoms as green and blue shades.

How do we know the abundances of elements in stars

1. Stellar spectroscopy:



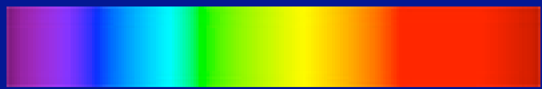
Dispersion of light through a prism



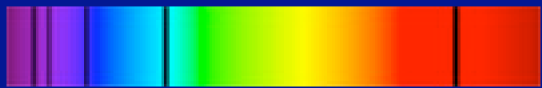
Photographic spectrum for Alpha Lyrae, an A0 V star

Types of spectra:

Continuous (or continuum):



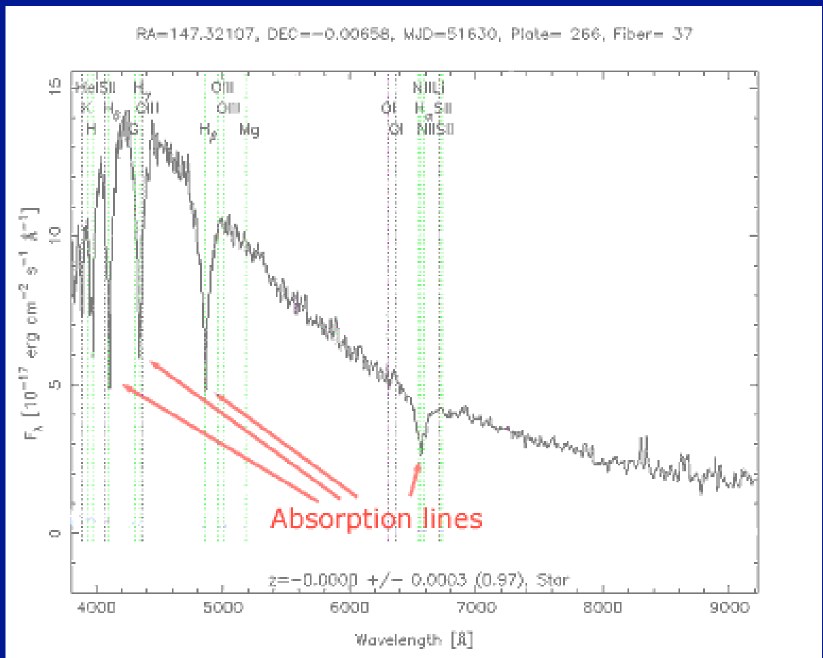
Absorption (dark line):



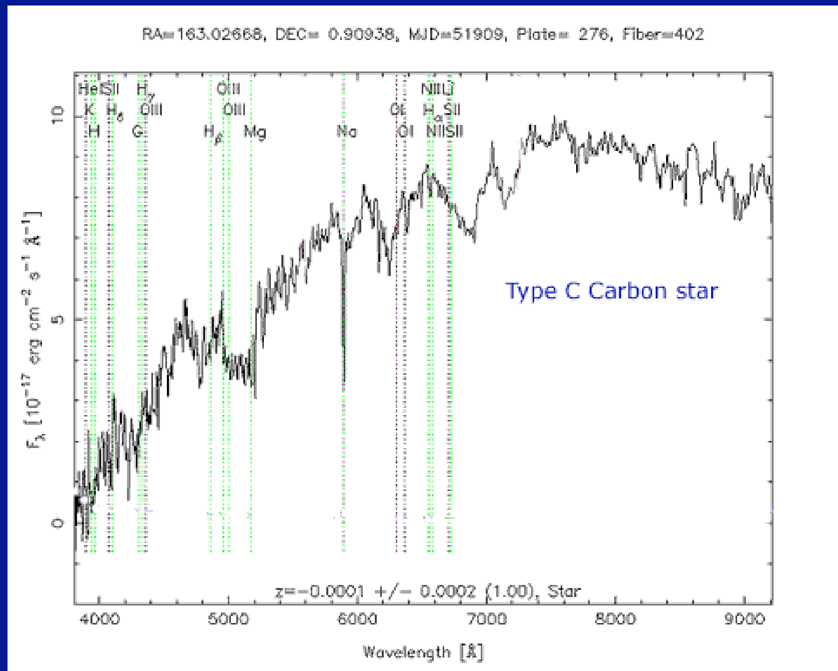
Emission (bright line):

How do we know the abundances of elements in stars

A-type main sequence Star, hot: H-burning in the core



Giant star: C-rich, cool, inert C/O core, He- and H-shell burning



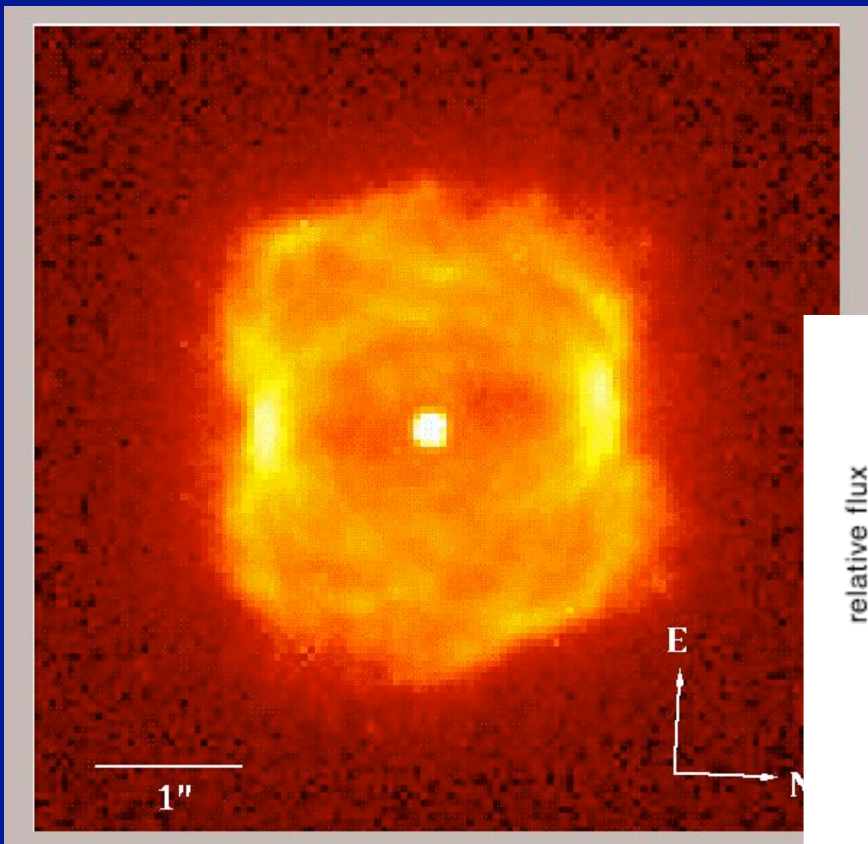
Some exotic stars:
hot H-poor central stars of planetary nebulae

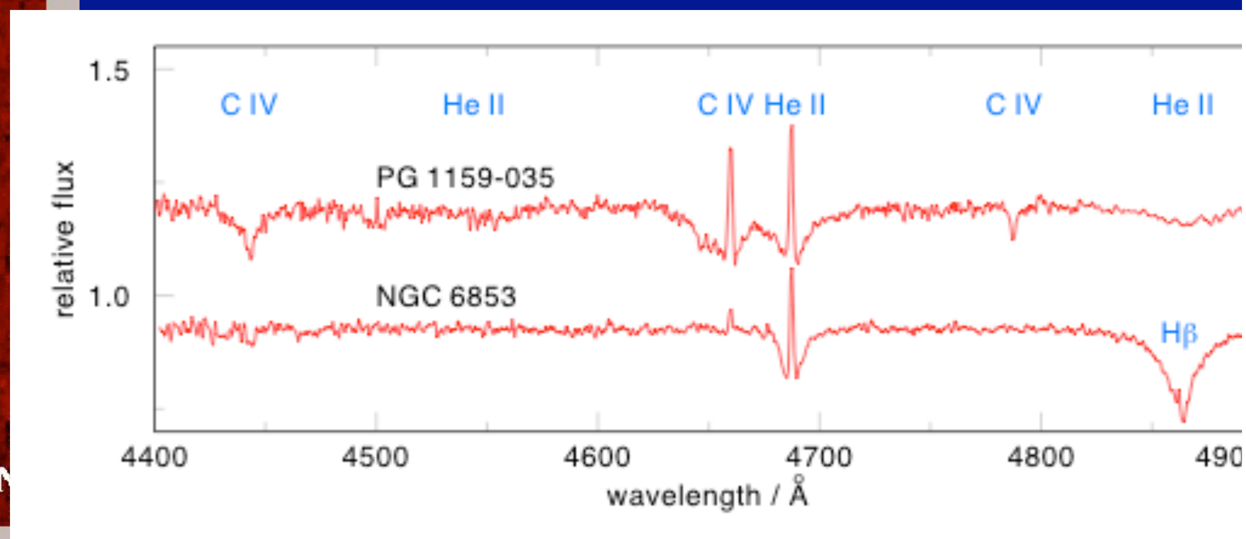
PN M4-18

abundances of the central star:

(H,He,C,O) = (<0.02,0.46,0.50,0.08)

Sun: (0.70, 0.28,0.003,0.008)





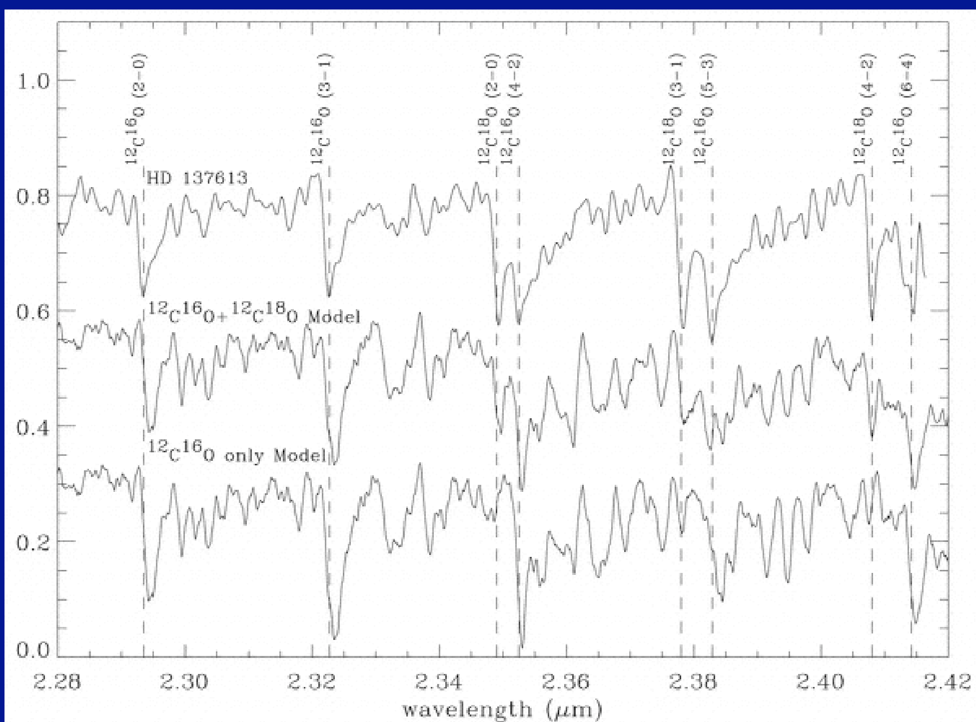
Hubble Space Telescope image Spectroscopy at 3.5m telescope Calar Alto, Spa

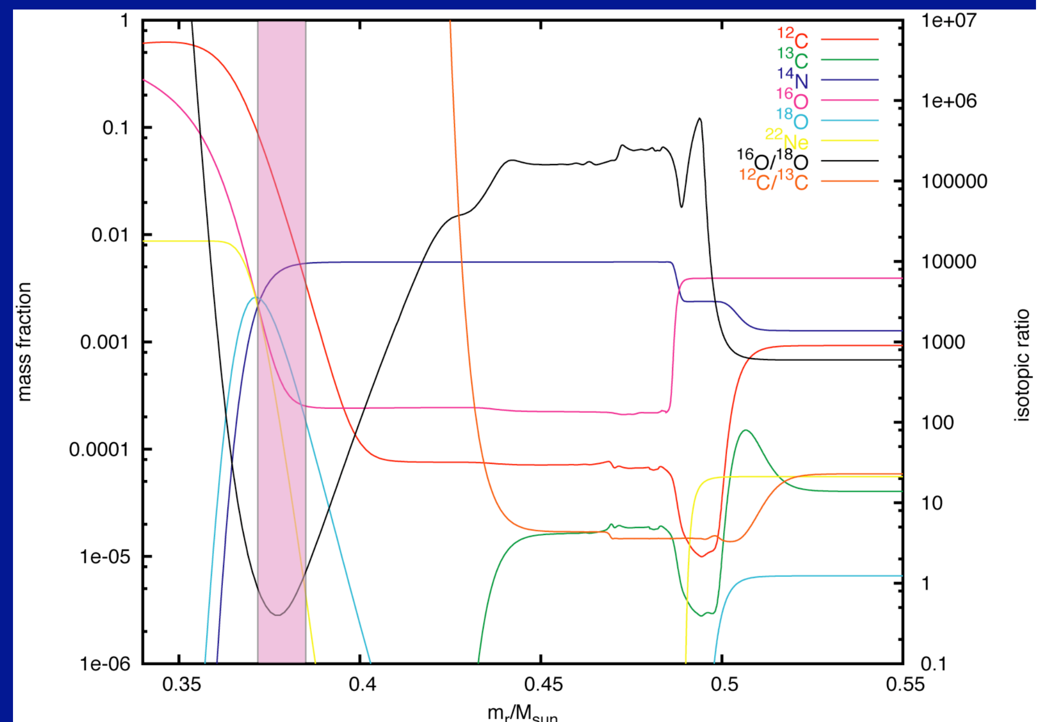
Some exotic stars: A H-deficient ^{18}O-rich C-star

	$^{16}O/^{18}O$
HD 137613	< 1.0
Sun	440

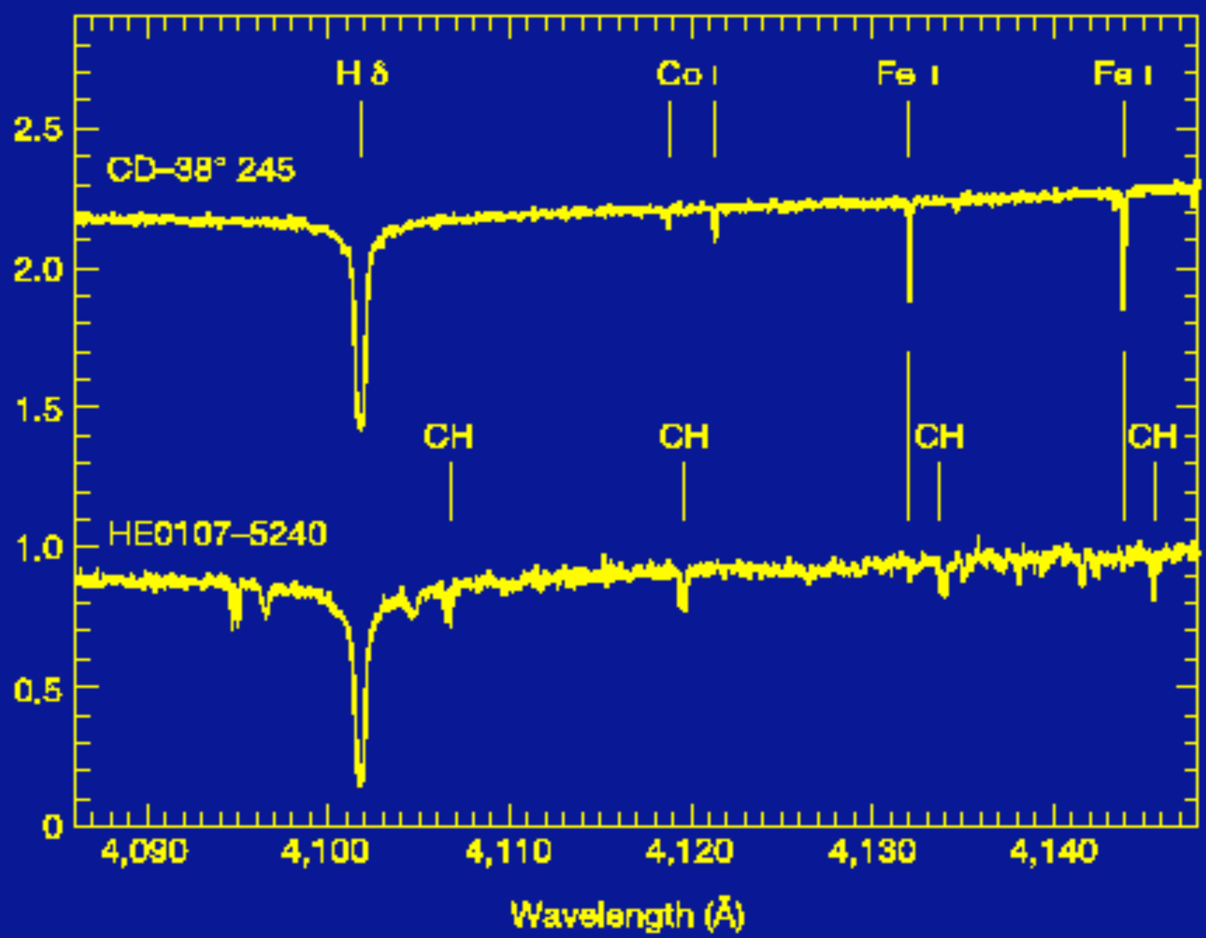
Abundance profile in the interior of a $2M_{\odot}$ stellar model after the completion of H-core and He-core burning.

HD 137513





The most metal-poor star: Messenger from the early universe

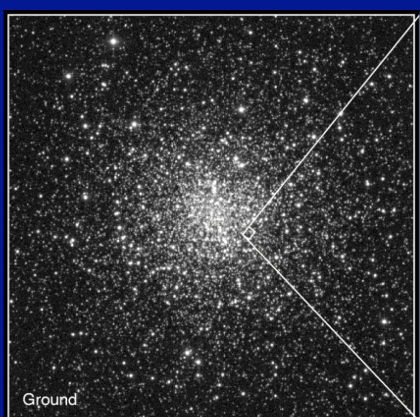


Metal content 100.000 times smaller than in the sun: [Fe/H] = -5.3

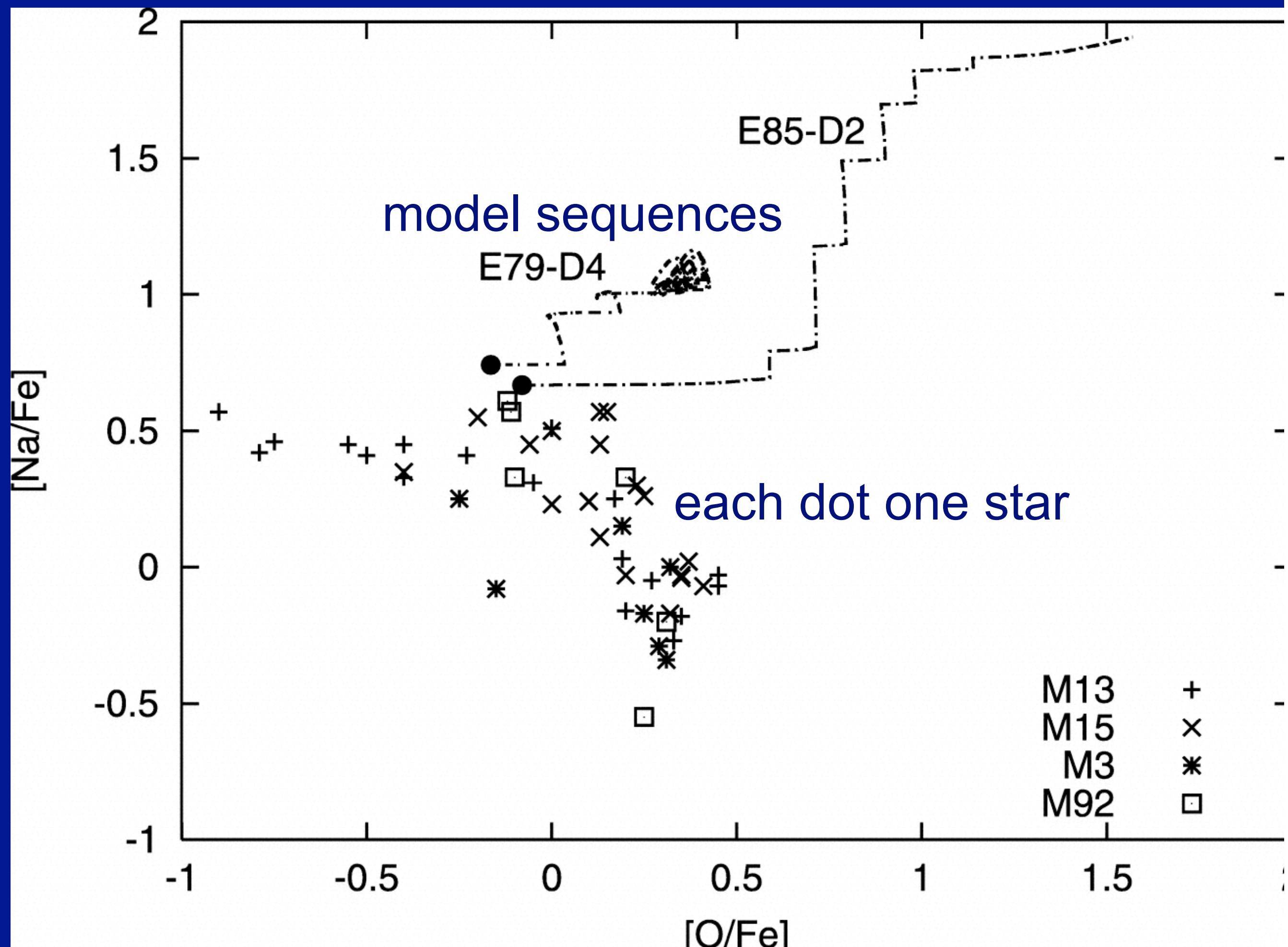
This star has formed shortly after the Big Bang when the Universe was young.

Abundances of many stars in one population:

The O-Na anti-correlation in globular cluster stars

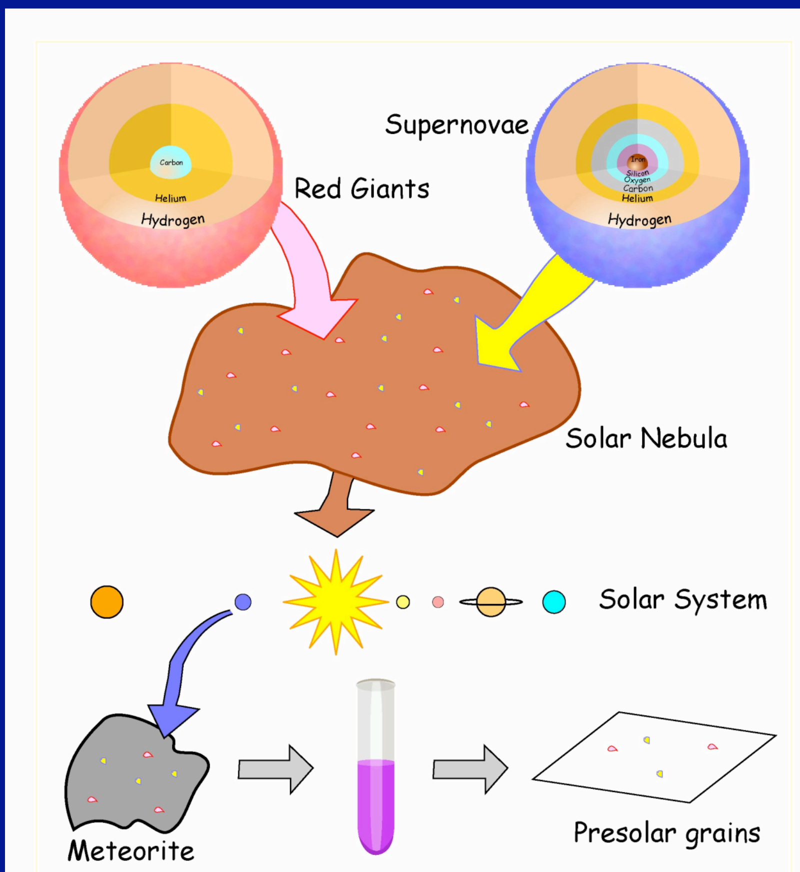


M4

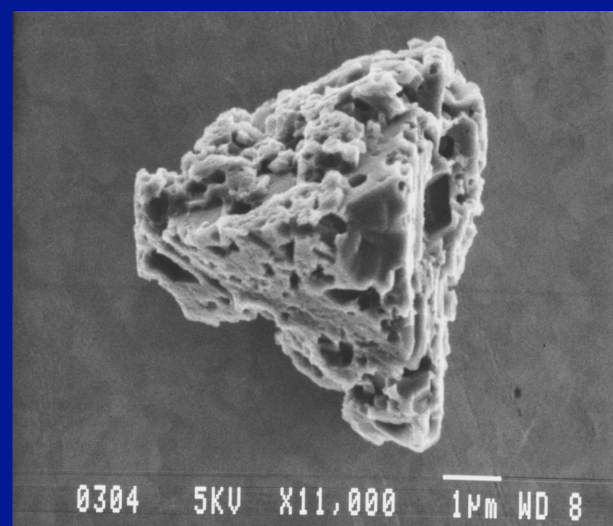


Stellar isotopic abundances from pre-solar grains:

Dust forms in the cool mass-loss outflows of stars and the supernova debris.

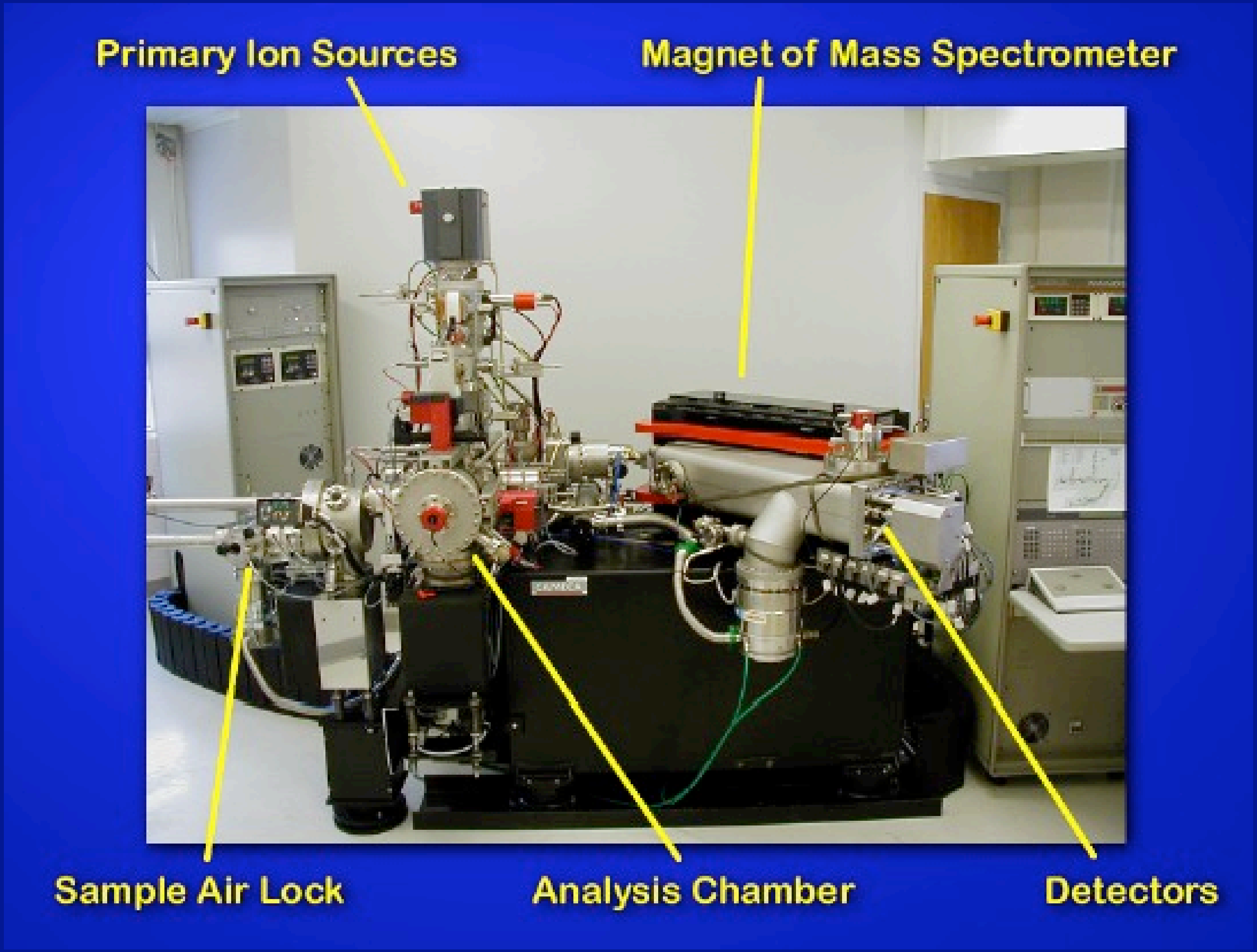


Individual dust grains extracted from primitive meteorites can be associated with their individual site of origin around one star ... tracing that star's individual isotopic signature.



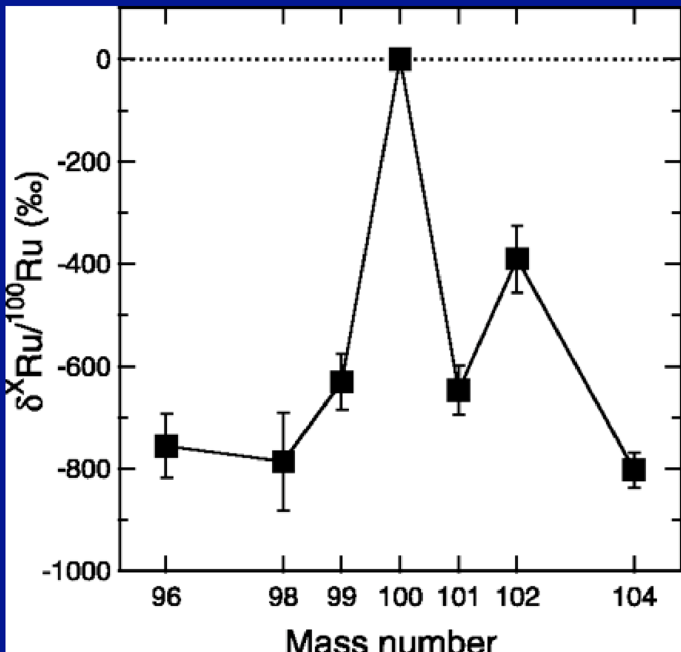
Stellar isotopic abundances from pre-solar grains:

The nano-SIMS: nano-meter secondary ion-mass spectroscopy



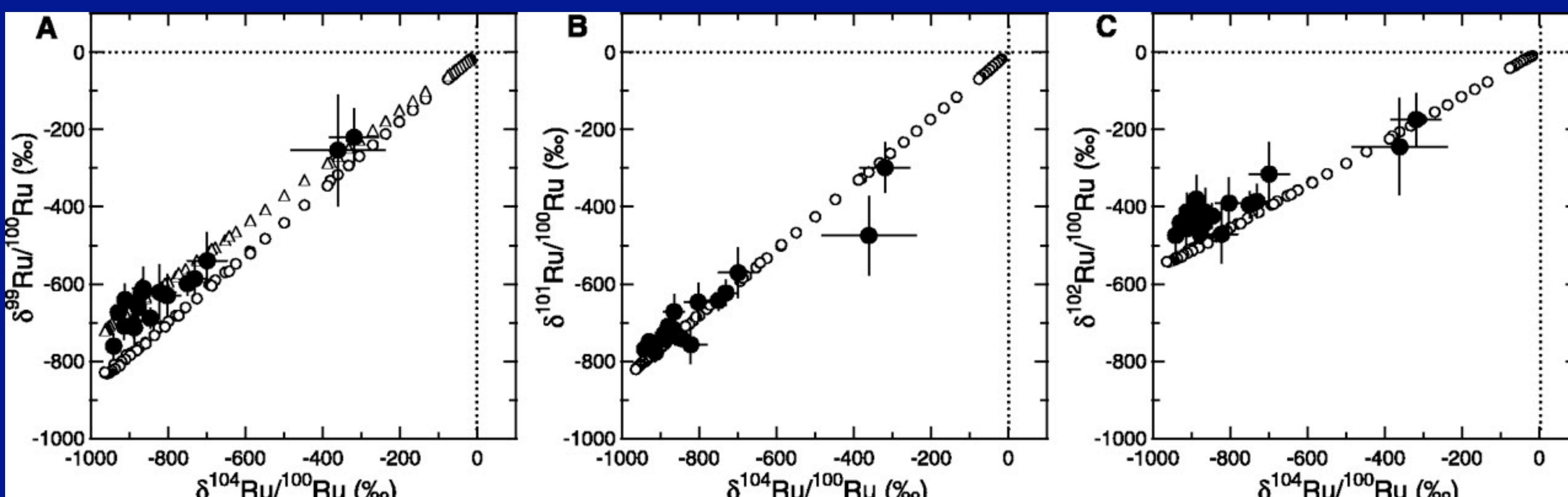
One at Washington University, St. Louis, one at Max-Planck Insitut for cosmo-chemistry in Mainz, Germany.

Stellar isotopic abundances from pre-solar grains:



Extinct Technetium in Silicon Carbide Stardust Grains: Implications for Stellar Nucleosynthesis

Savina etal. 2004, Science 303, 649



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3. How do we know the abundances of elements in stars:
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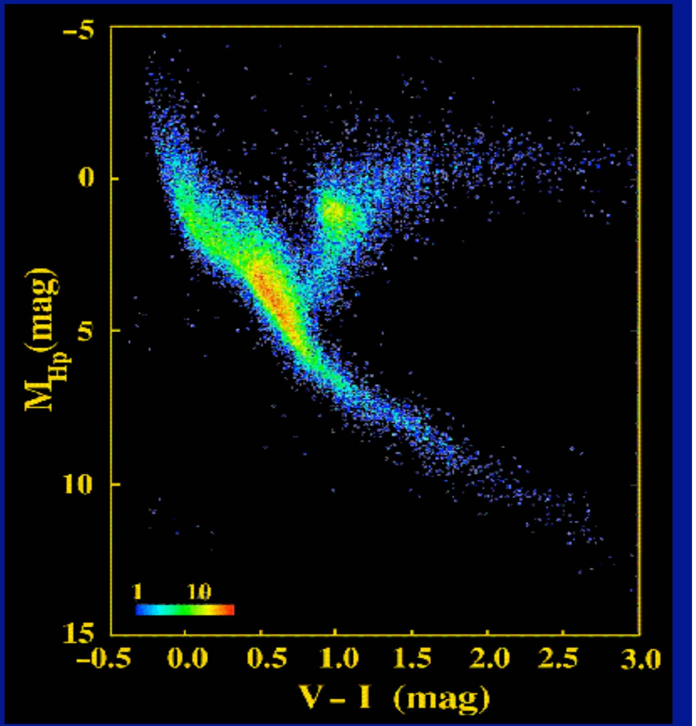
4. Calculating the evolution of stars and the making of the elements
5. Scientists paradise: new data, lots of it!
6. Conclusions

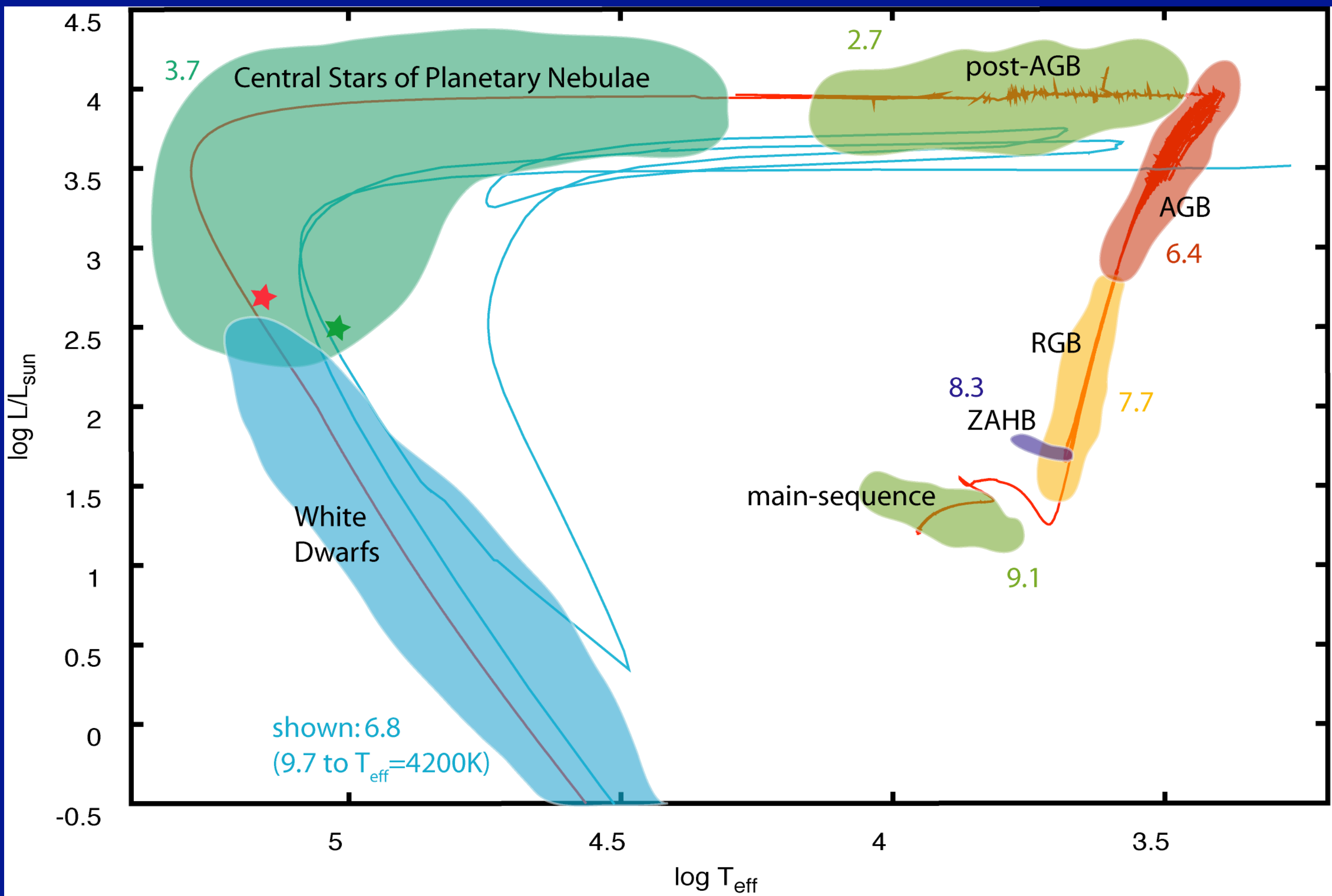
1D evolution of stellar structure

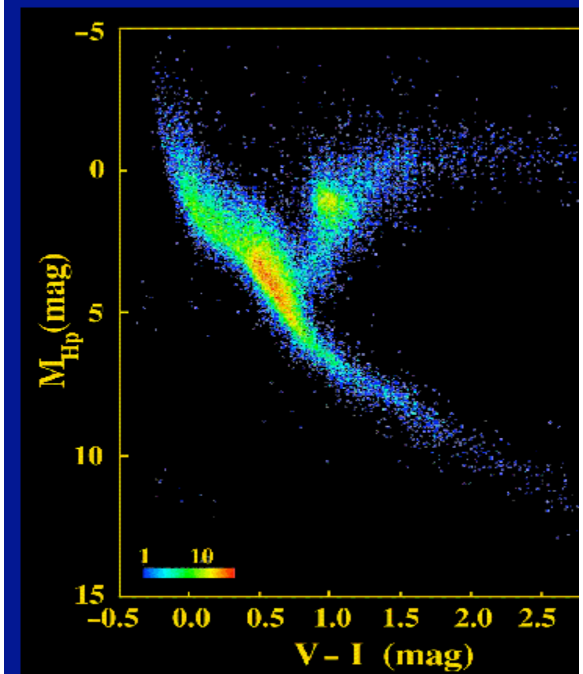
Time sequence of stellar models, each model:

- Spherically symmetric
- Governing equations:
  - mass conservation
  - hydrostatic equilibrium
  - energy equation
  - energy transport
- Material properties
  - opacities
  - equation of state (EOS)
- Mixing, for example due to convection
- Nucleosynthesis
- Evolution through the complete life cycle of stars

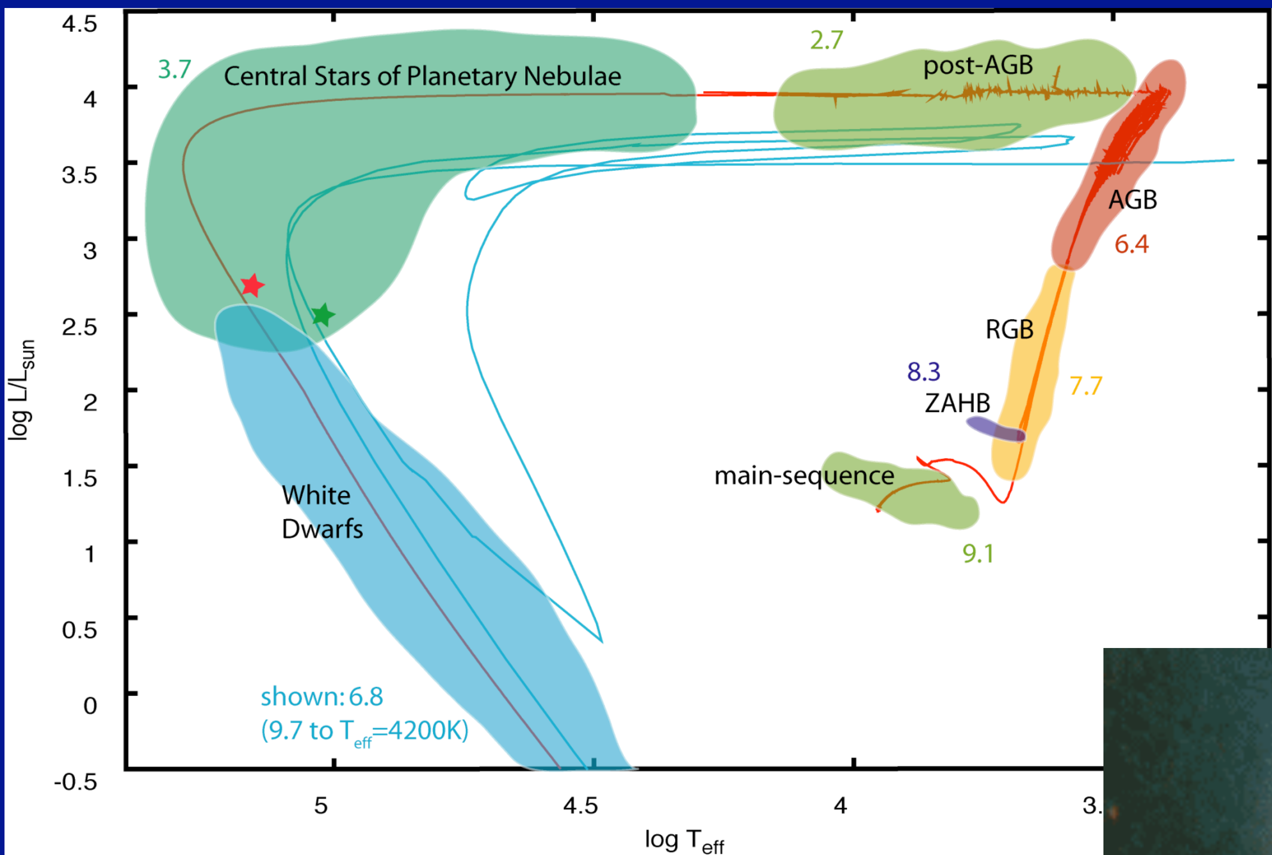


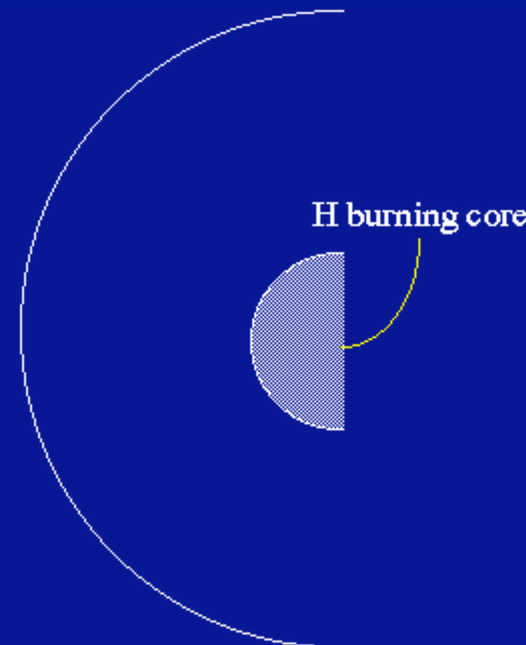
The life cycle of stars: Evolving through a succession of stages

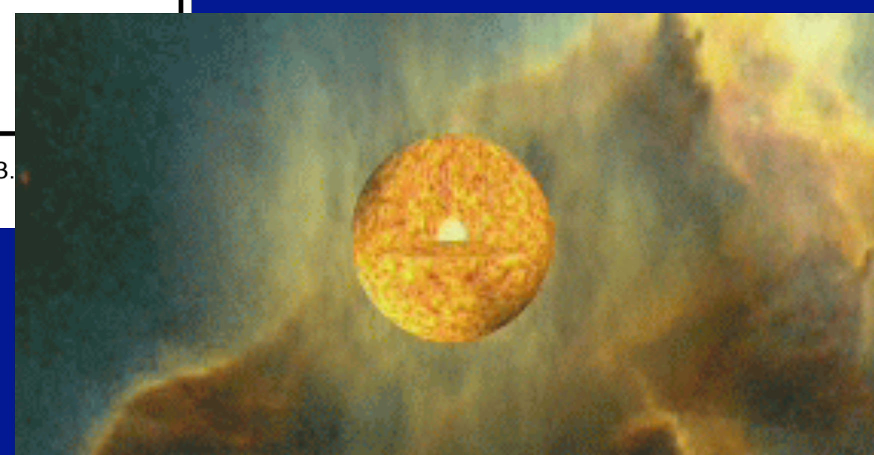




The life cycle of stars: main sequence - H-core burning

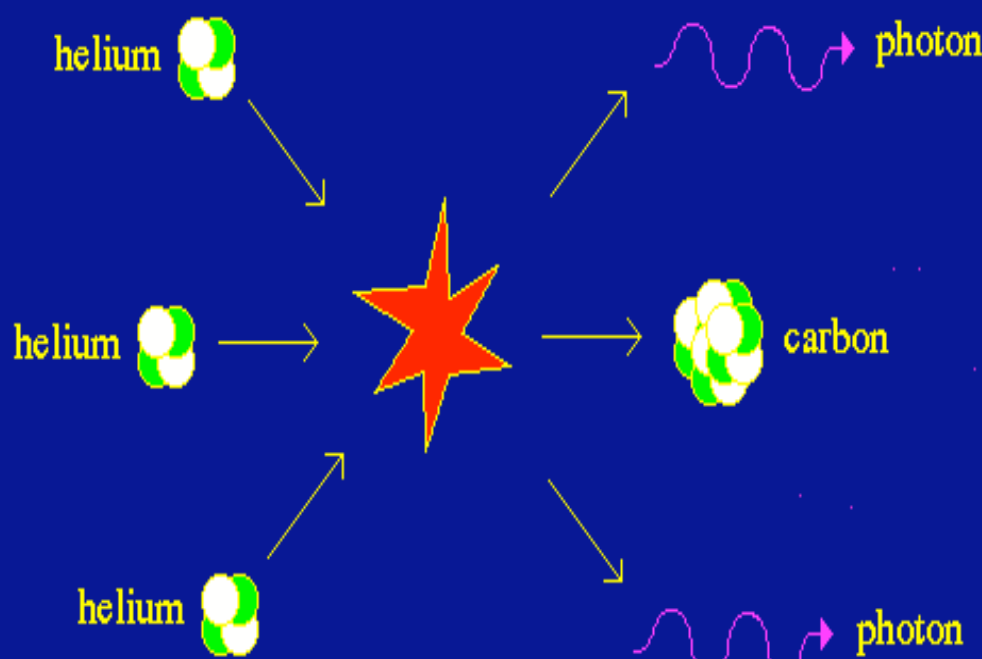


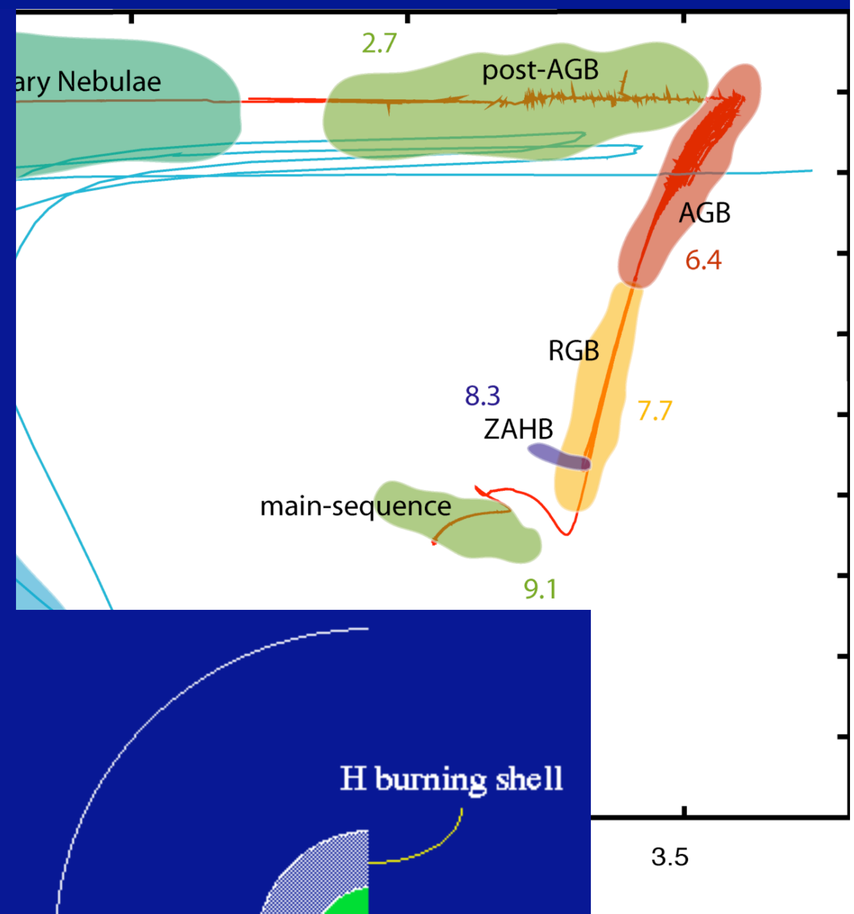


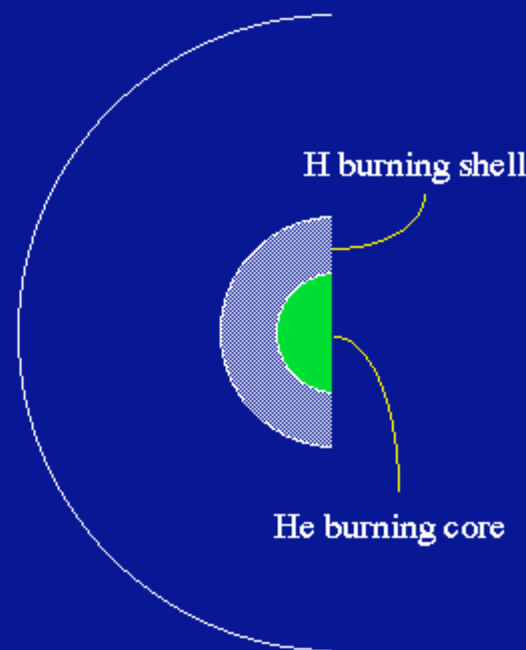


The life cycle of stars: ZAHB - He-core burning

$$^{4}He_{2} + {}^{4}He_{2} + {}^{4}He_{2} \rightarrow {}^{12}C_{6} + \gamma + \gamma$$



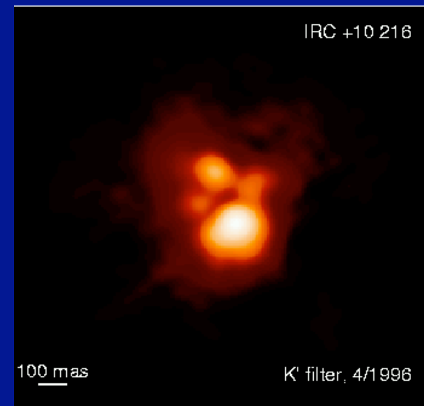




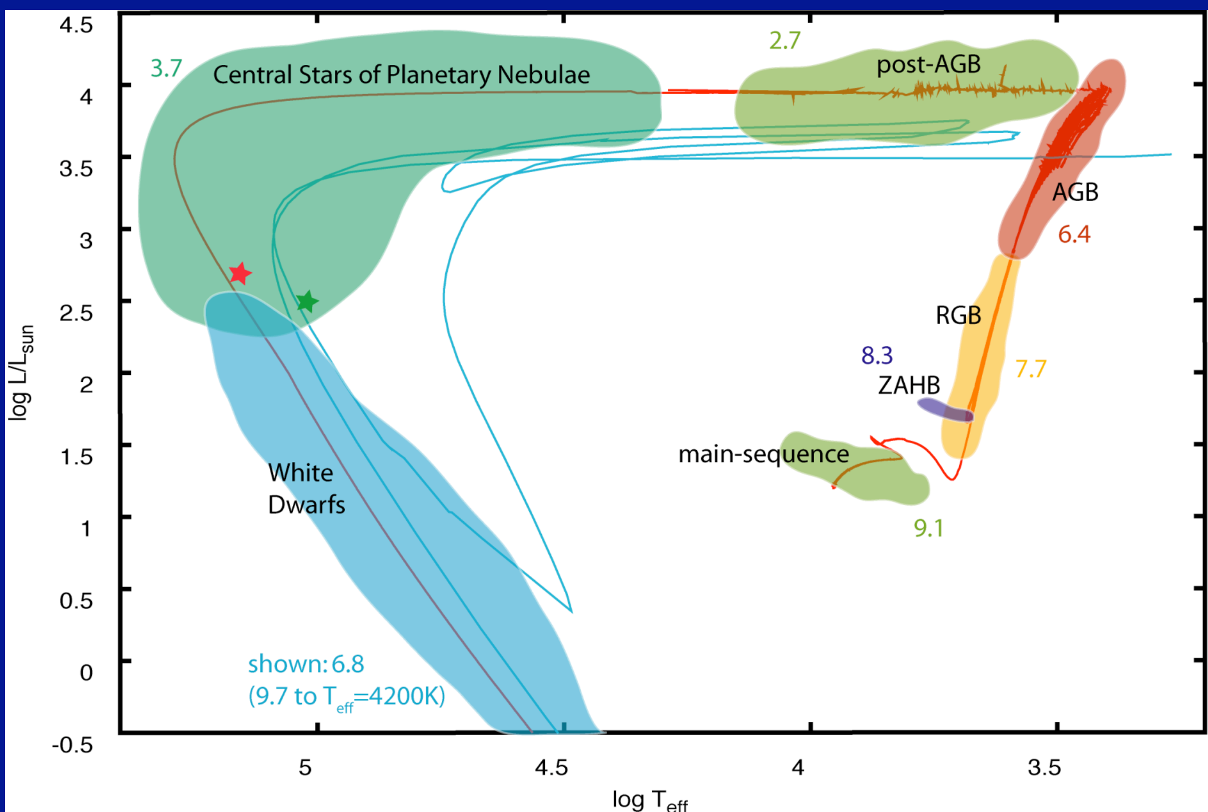
The life cycle of stars:

Asymptotic Giant Branch

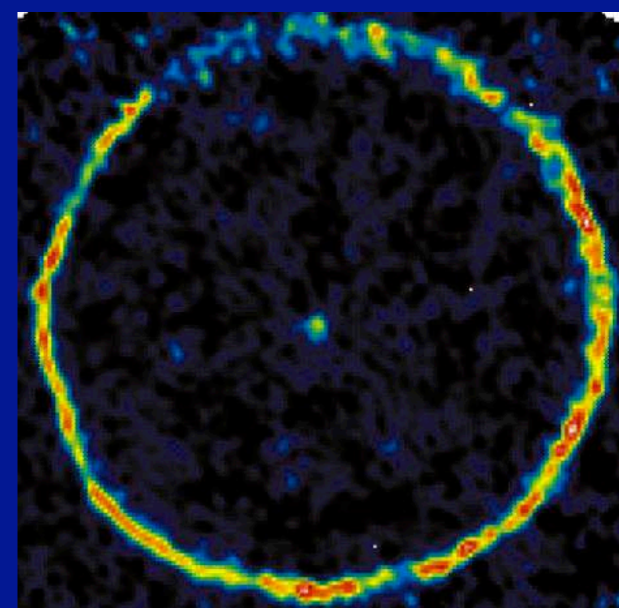
H- and He-shell burning



Interferometric image of AGB C-star IRC 10+216

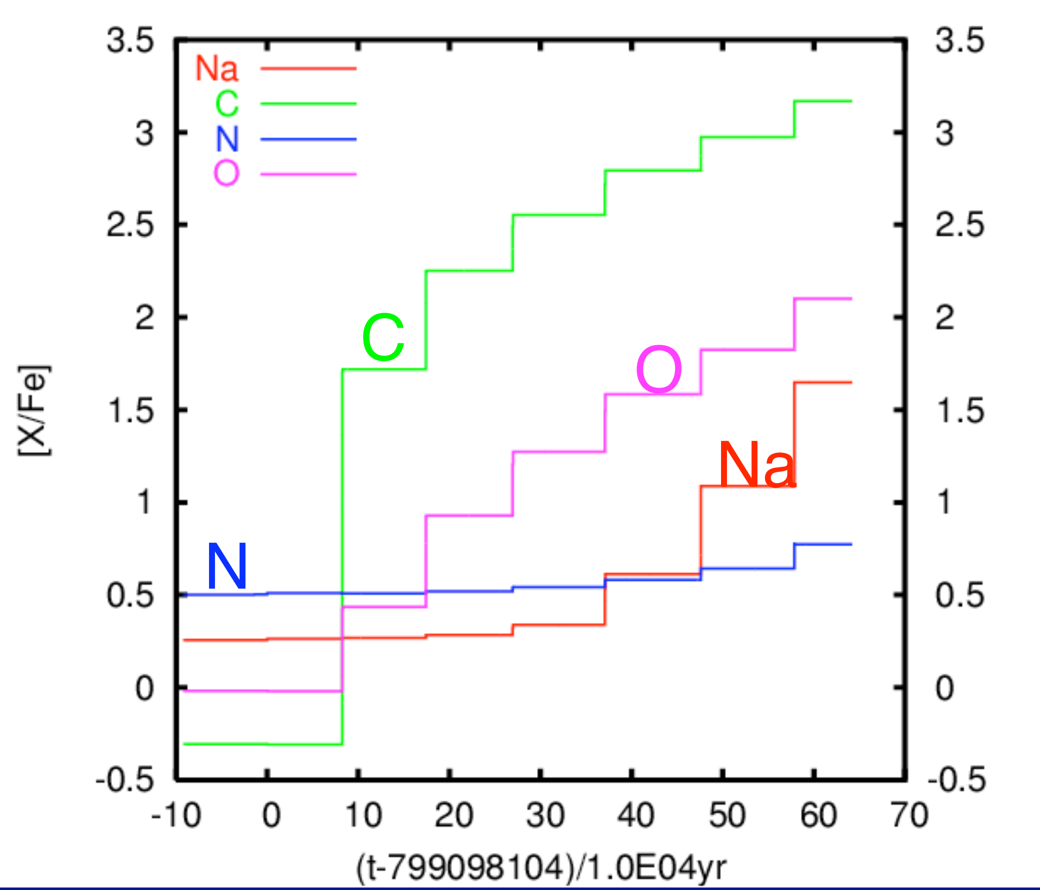


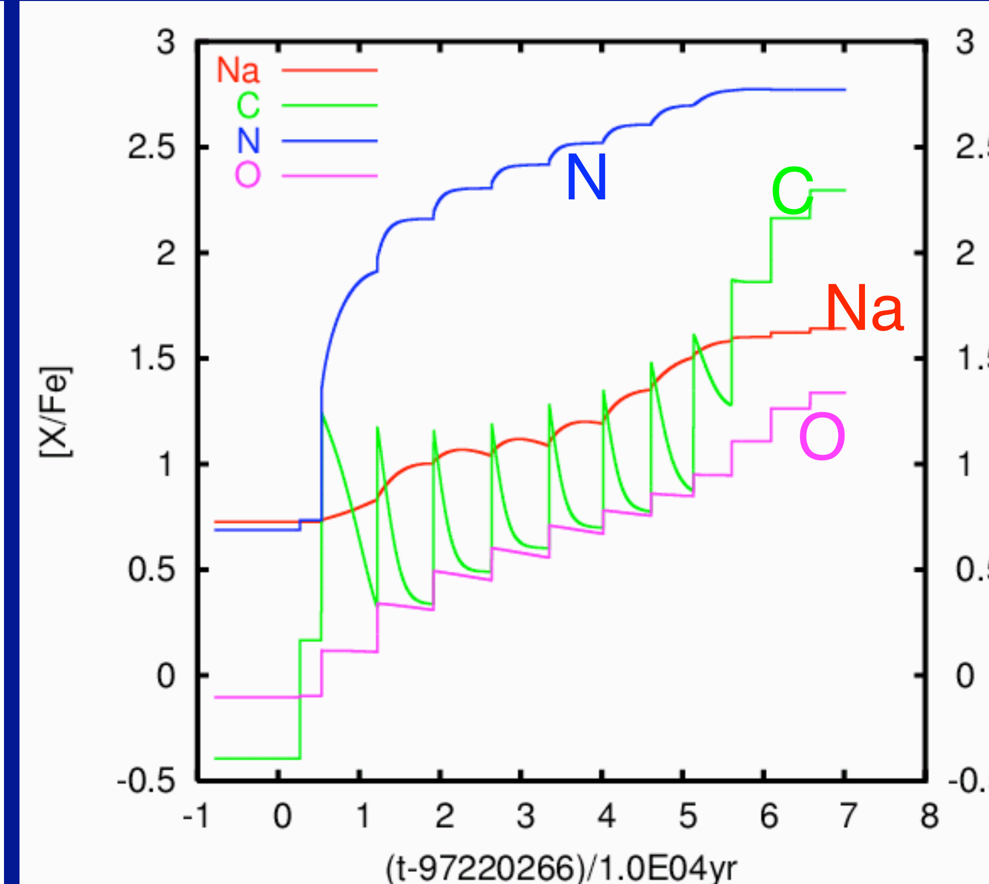
Radio emission of CO arou
AGB star TT Cygni



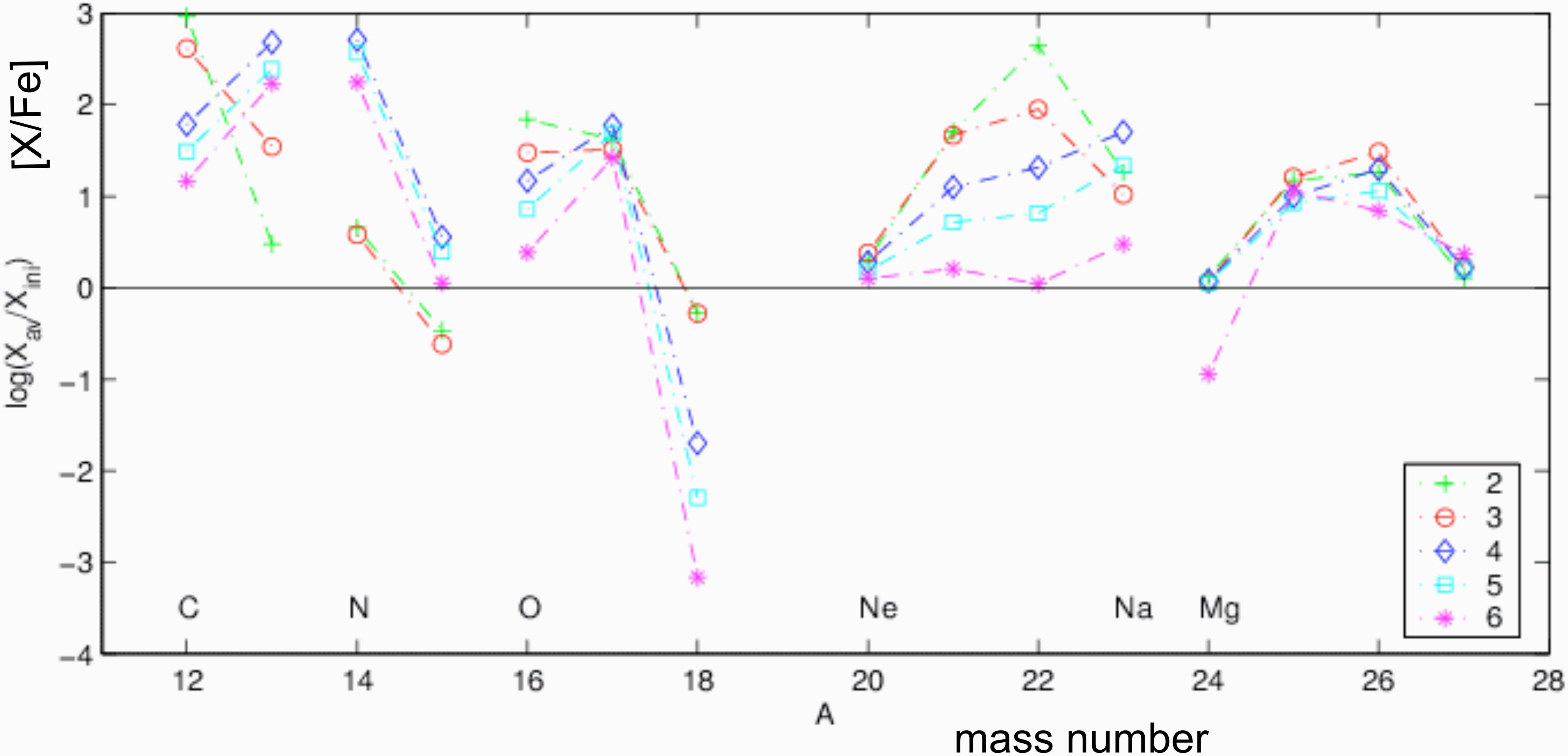
Surface Abundance Evolution of AGB stars with low metal content:

initial mass:	$2M_\odot$	$5M_\odot$
ejecta released after:	0.8Gyr	0.1Gyr



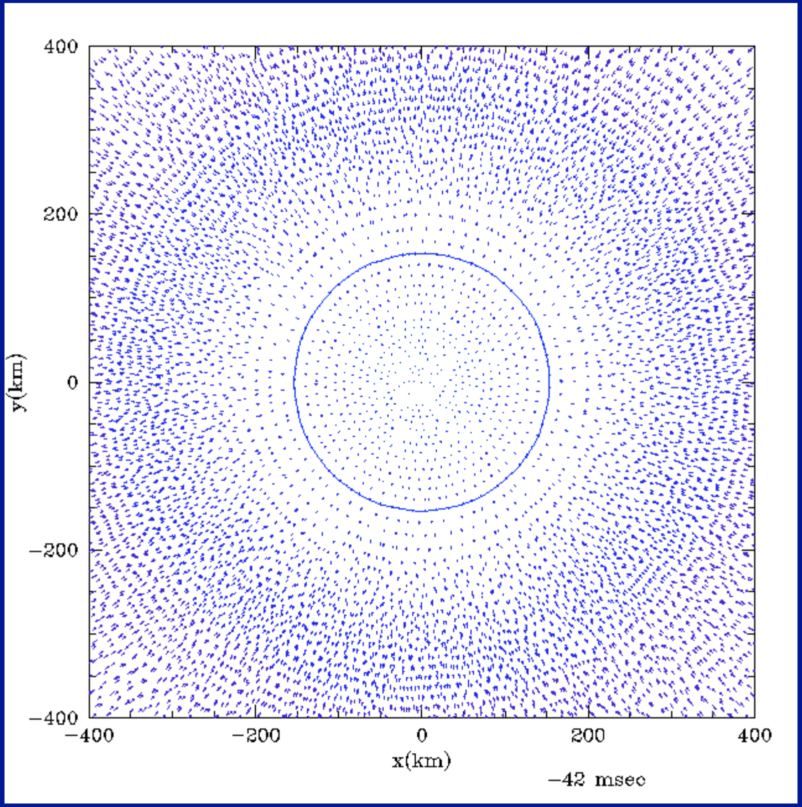


Nuclear production of very low-metallicity AGB stars

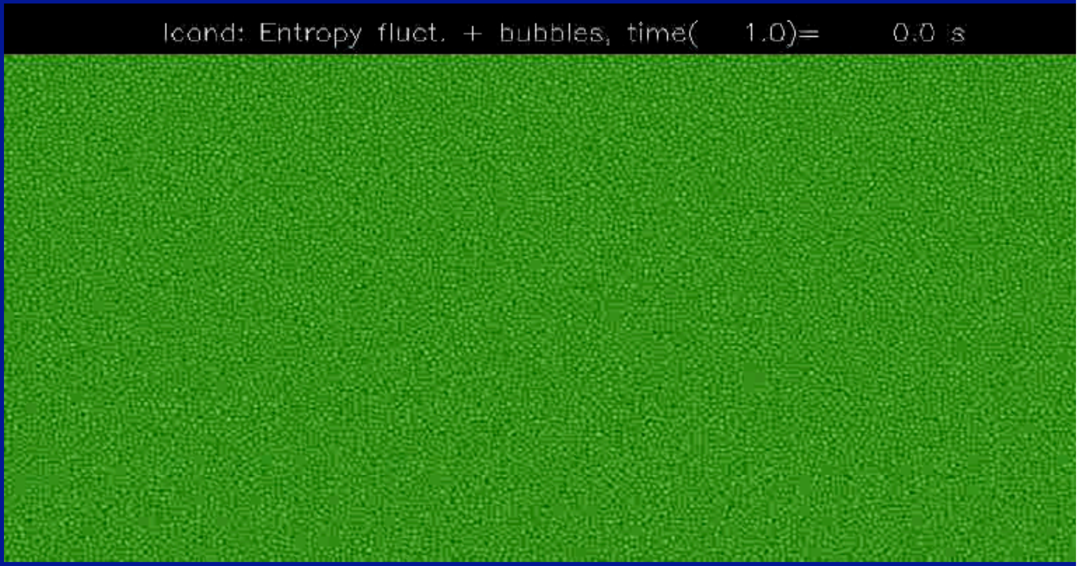


Multi-dimensional simulations:

3D core-collapse supernova simulation with smoothed-particle hydrodynamics



2D He-shell flash convection simulation with grid-hydro code



Outline:

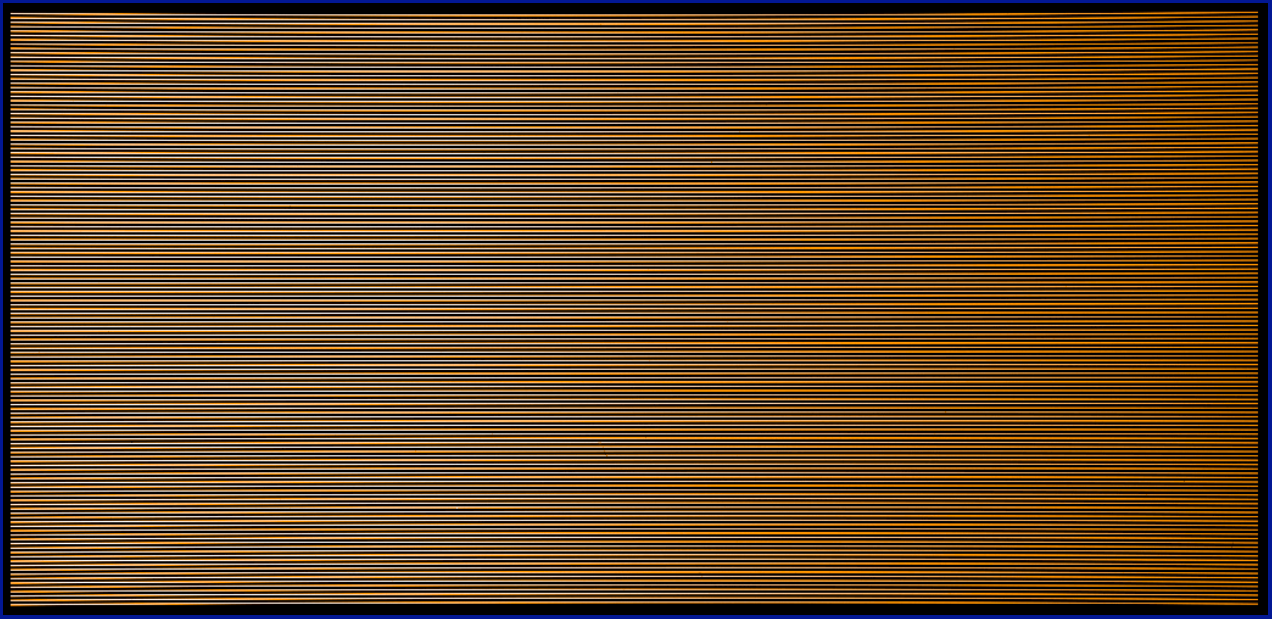
1. What is an element?
2. Elements are made by nucleosynthesis in stars
3. How do we know the abundances of elements in stars:
    - Stellar spectra
    - Stellar dust particles in meteorites
4. Calculating the evolution of stars and the making of the elements
5. Scientists paradise: new data, lots of it!
6. Conclusions

New data - new question - new fun!

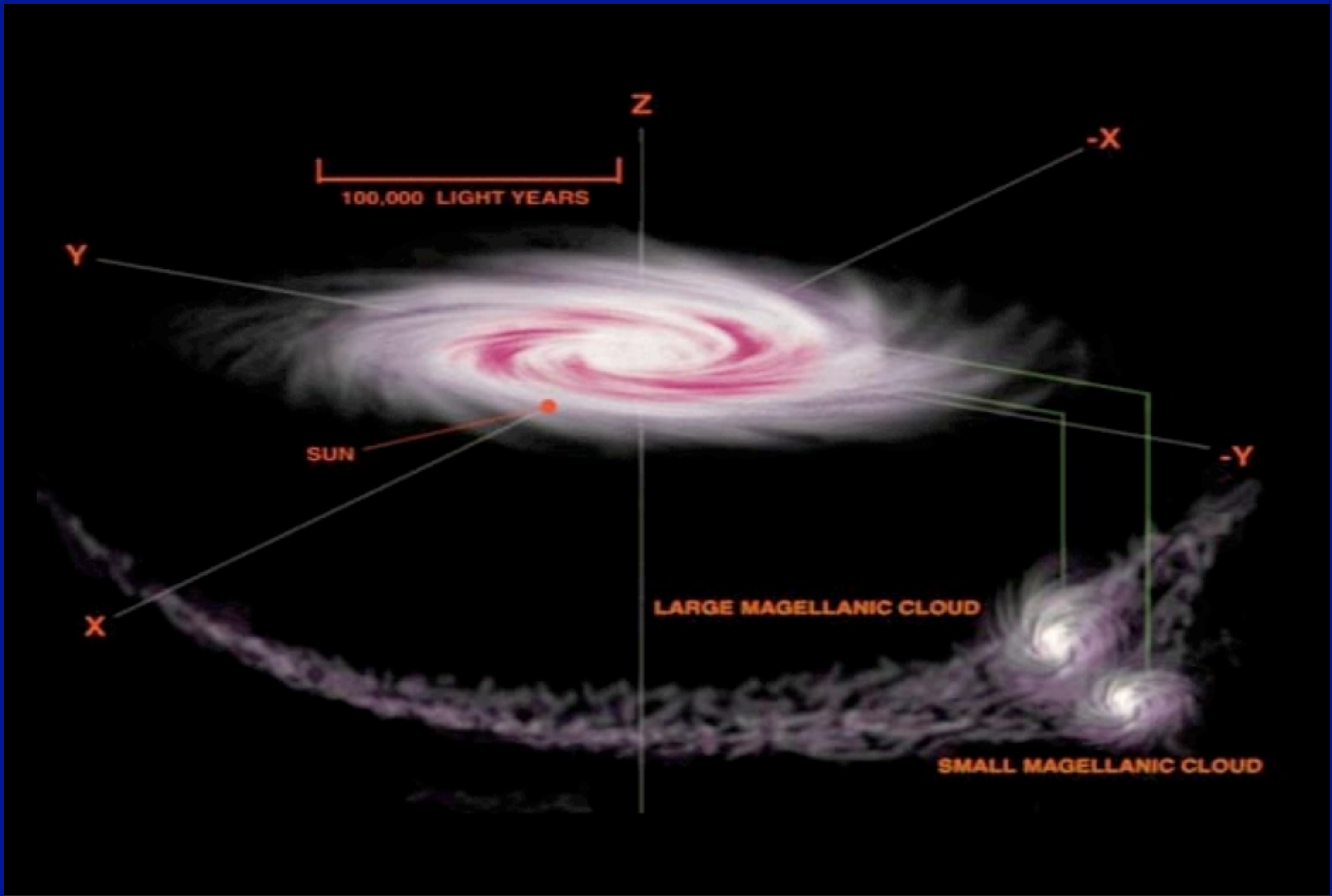
New kid on the block:
Fiber-optics multi-object spectroscopy

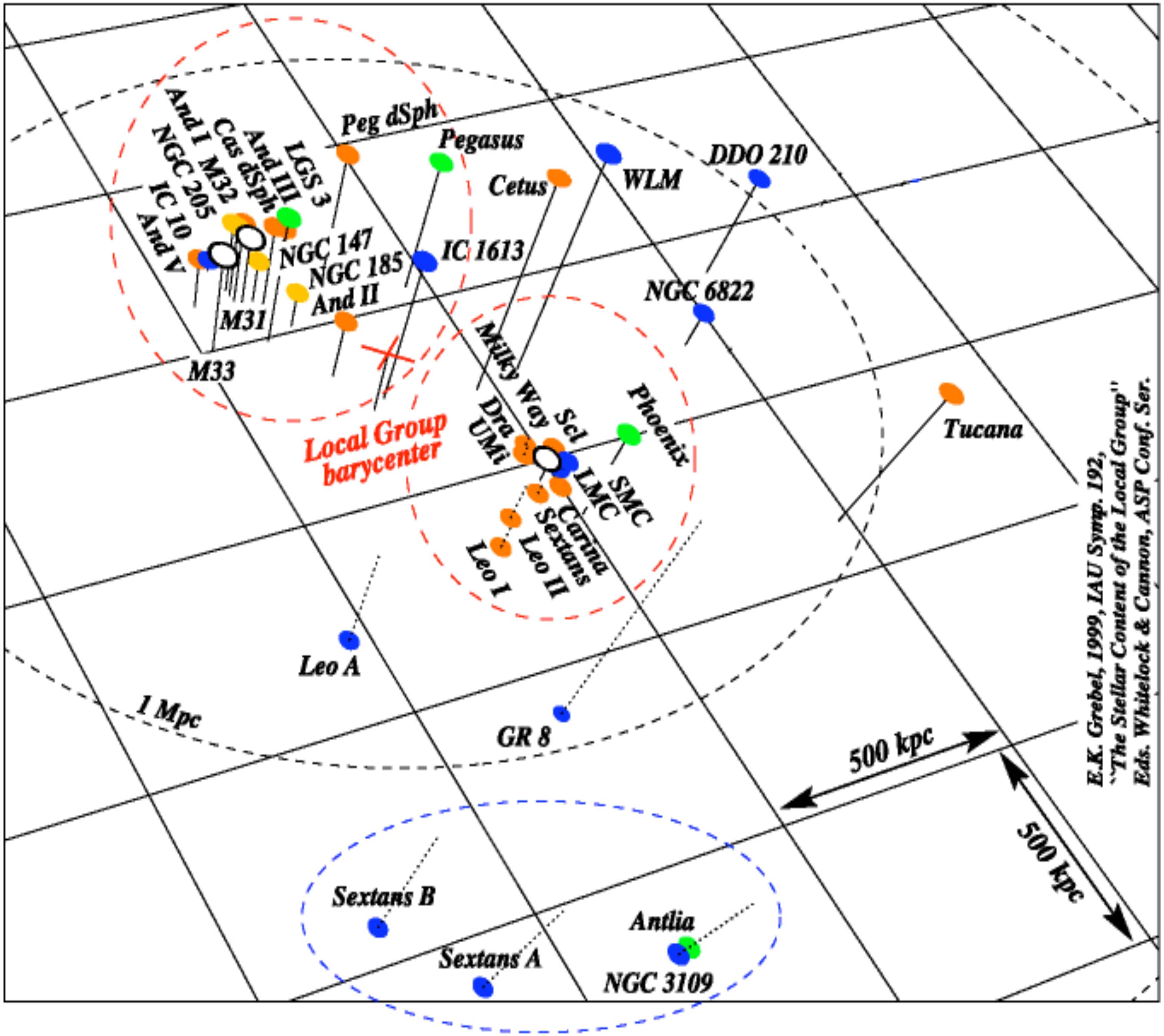
FLAMES at the Very Large Telescope (VLT, ESO)

100's to 100's of spectra in one shot for stars in the field of view.



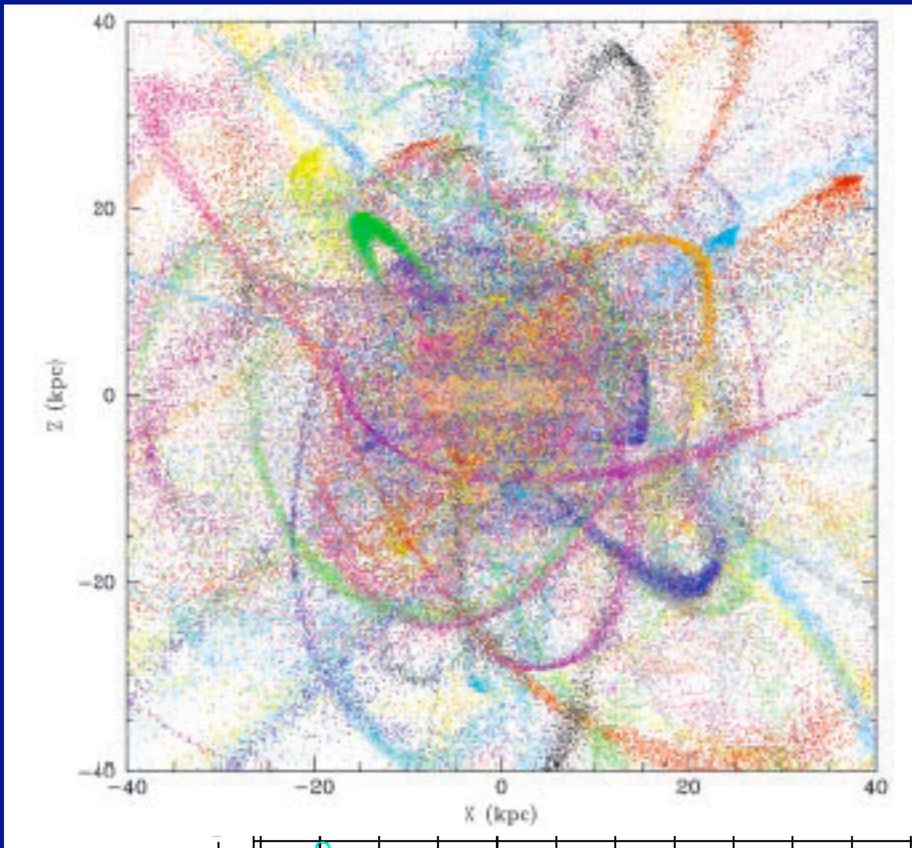
The Milky Way and it's neighbours:





Peg dSph
Pegasus
Cetus
WLM
DDO 210
LGS 3
And III
Cas dSph
And I
M32
NGC 205
IC 10
And V
NGC 147
NGC 185
And II
IC 1613
M31
M33
NGC 6822
Local Group barycenter
Milky Way
Dra
UMi
Scl
Phoenix
LMC
SMC
Carina
Sextans
Leo II
Leo I
Tucana
Leo A
1 Mpc
GR 8
500 kpc
500 kpc
E.K. Grebel, 1999, IAU Symp. 192,
"The Stellar Content of the Local Group"
Eds. Whitelock & Cannon, ASP Conf. Ser.
Sextans B
Sextans A
Antlia
NGC 3109

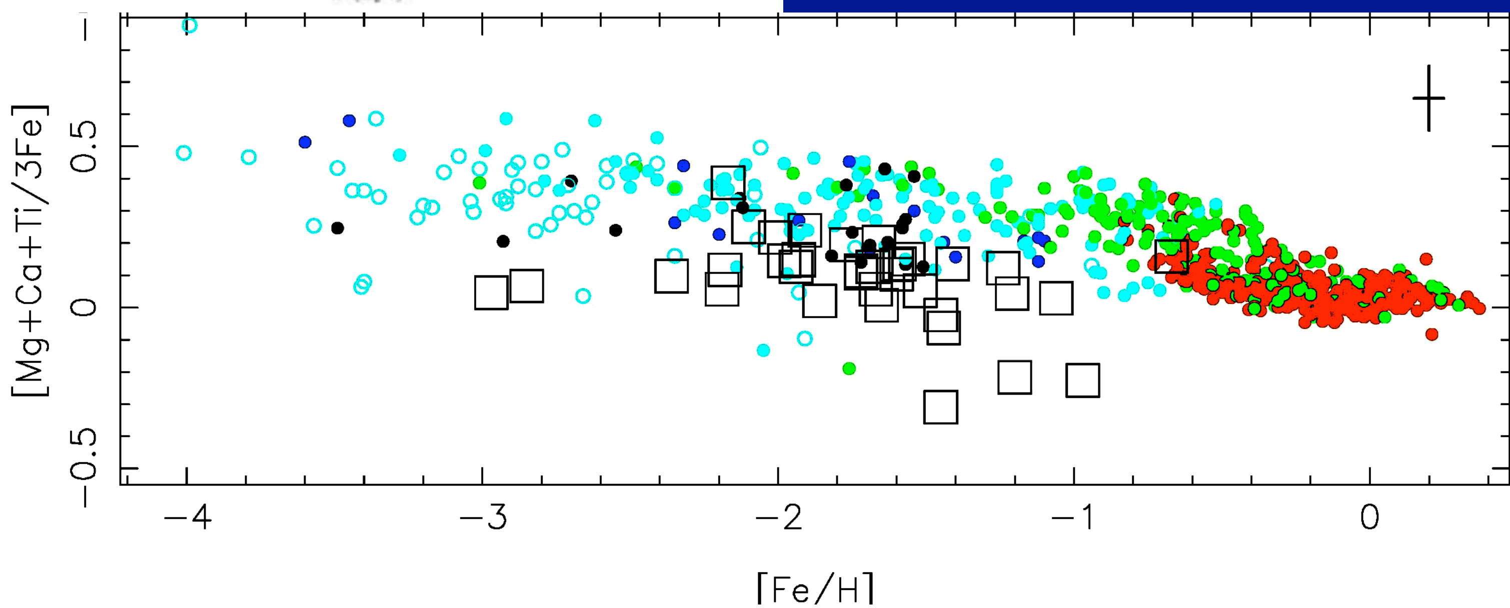
New data - new question - new fun!



Framework: Galaxy is the result of a long history of merging events.

<- A simulation of the baryon halo built up through accretion of 100 satellite galaxies.

(Bland-Hawthorn & Freeman, Science 287, 2000)



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