# ASTROPHYSIQUE II

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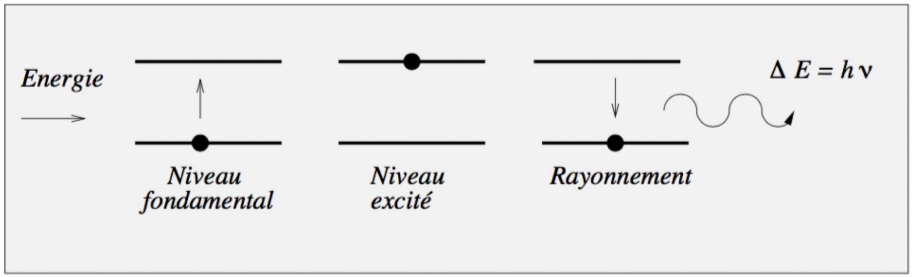
(Sept. 12 and a few other dates: Salvatore Taibi)

# ASTROPHYSICS II

## Interactions radiation-matter

Radiation originates from an electronic transition
between two energy states of a molecule or atom



# 1 Generalities on Radiation



Fondamental definitions

# 2 Radiative Energy Transfer



Macroscopic description

Absorption, Emission, and their balance

## 3 Absorption and Emission of Radiation

Towards building and interpreting a spectrum

**3.1** Electromagnetic Waves
**3.2** Absorption by a Harmonic Oscillator
**3.3** Absorption, Spontaneous Emission, and Induced Emission: Note on Einstein Coefficients
**3.4** Absorption by Spectral Lines
**3.5** Scattering by Free Electrons
**3.6** Photoionization or Bound-Free Absorption
**3.7** Hyperbolic Transitions: Free–Free Absorption and Bremsstrahlung
**3.8** Global Opacity in Stellar Medium
**3.9** Note on Equivalent Width, Curve of Growth, and Abundance Determination

Microscopic description

The variety of absorptions (physical mecanisms)

Chemical abundances // stellar parameters

## 4 Thermodynamic Properties

**4.1** Review of Statistical Physics
**4.2** Gases and Excited Atoms
**4.3** Ionization of Gases
**4.4** Molecular Weight and Pressure of Neutral, Partially or Completely Ionized Media
**4.5** Physical Properties of the Partially Ionized Medium
**4.6** Influence of the Physical State of Stellar Medium on Specific Heats. Adiabatic Exponents
**4.7** Specific Heats and Adiabatic Exponents for a Mixture of Perfect Gas and Radiation

Stellar interiors

End of life of stars – Extreme states of matter

## 5 Degenerate Gases

**5.1** Generalities
**5.2** Partially Degenerate Gas
**5.3** Completely Degenerate Gas
**5.4** Remarkable Consequences of the Law of Degenerate Gas
**5.5** Electrostatic Effects
**5.6** States of Matter in the log T vs. log ρ Plane

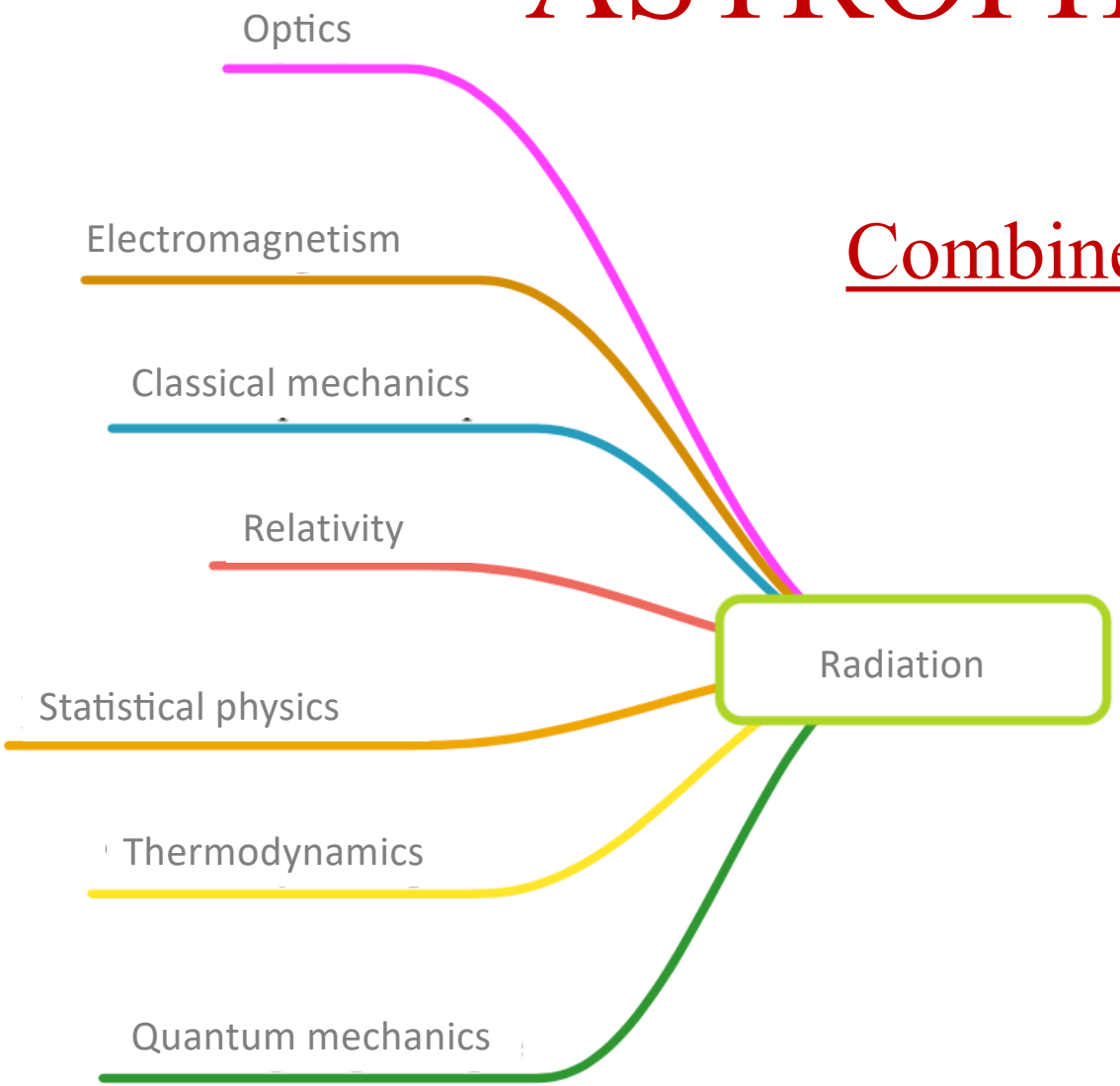
## 6 Nuclear Reactions

**6.1** General Definitions
**6.2** Non-Resonant Reactions
**6.3** Screening Effect
**6.4** Resonant Reactions

# Questions which ASTRO II will help you answer

- Under what physical conditions does a star radiate its energy?
- By what mechanisms are nuclear reactions initiated and sustained?
- Through which processes is energy transported from the stellar core to the surface?
- How is the stellar radiation distributed as a function of wavelength?
- What are the information encoded in the stellar spectra ?
- To which extent can the stellar chemical abundances be determined?
- Under what circumstances can a star undergo gravitational collapse or explode?

# ASTROPHICS II



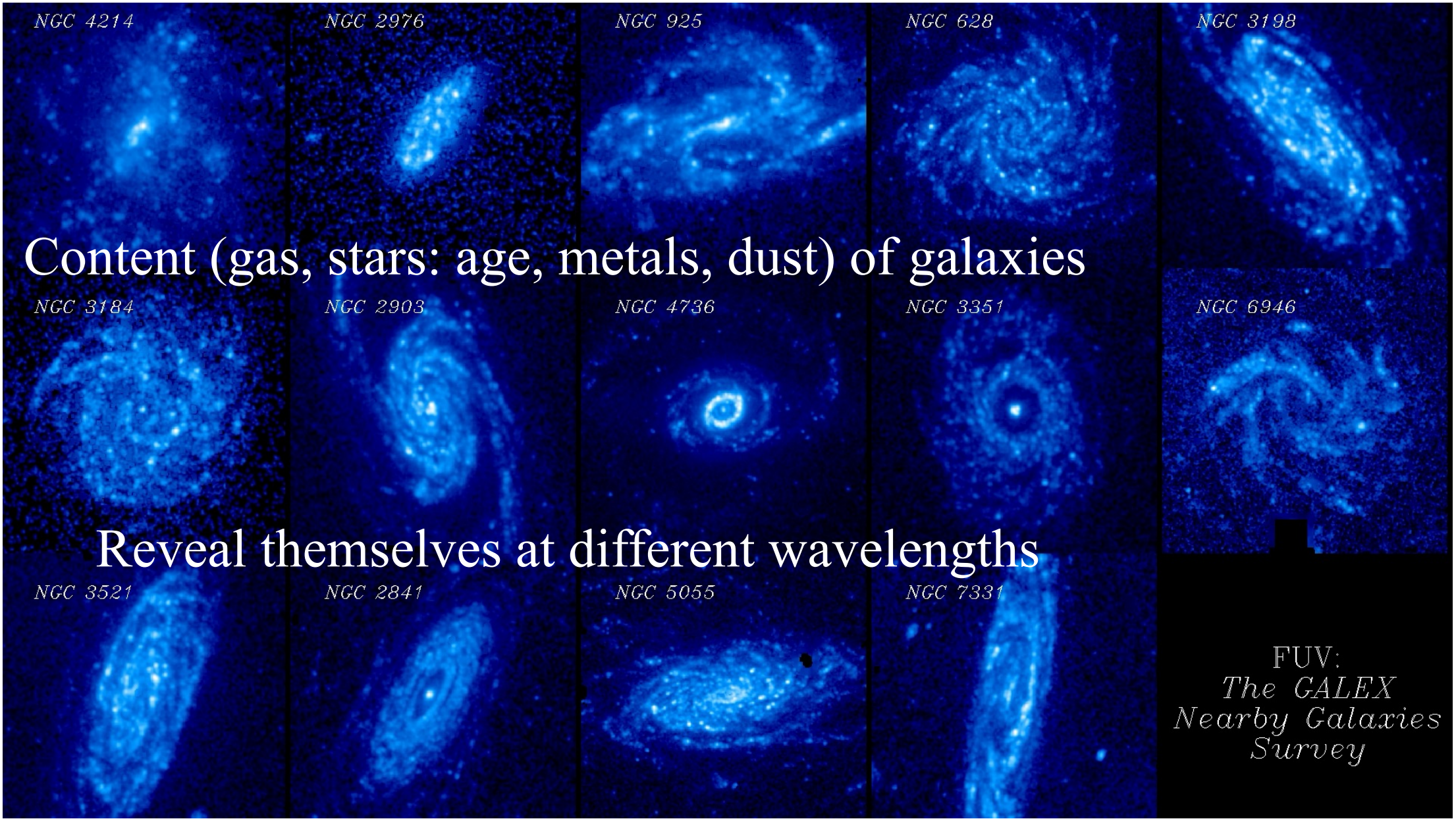

Combines different parts of physics

# Methods

ASTRO II includes a fair amount of equations

*You are very much encourage to redo the calculations by yourself, as they contain a lot of interesting information on physical framework and meaning of approximations.*


Everything we can access is light and must be interpreted


NGC 4214
NGC 2976
NGC 925
NGC 628
NGC 3198
Content (gas, stars: age, metals, dust) of galaxies
NGC 3184
NGC 2903
NGC 4736
NGC 3351
NGC 6946
Reveal themselves at different wavelengths
NGC 3521
NGC 2841
NGC 5055
NGC 7331
FUV:
The GALEX
Nearby Galaxies
Survey


NGC 4214
NGC 2976
NGC 925
NGC 628
NGC 3198
emissions and absorptions can be interpreted
NGC 3184
NGC 2903
NGC 4736
NGC 3351
NGC 6946
NGC 3521
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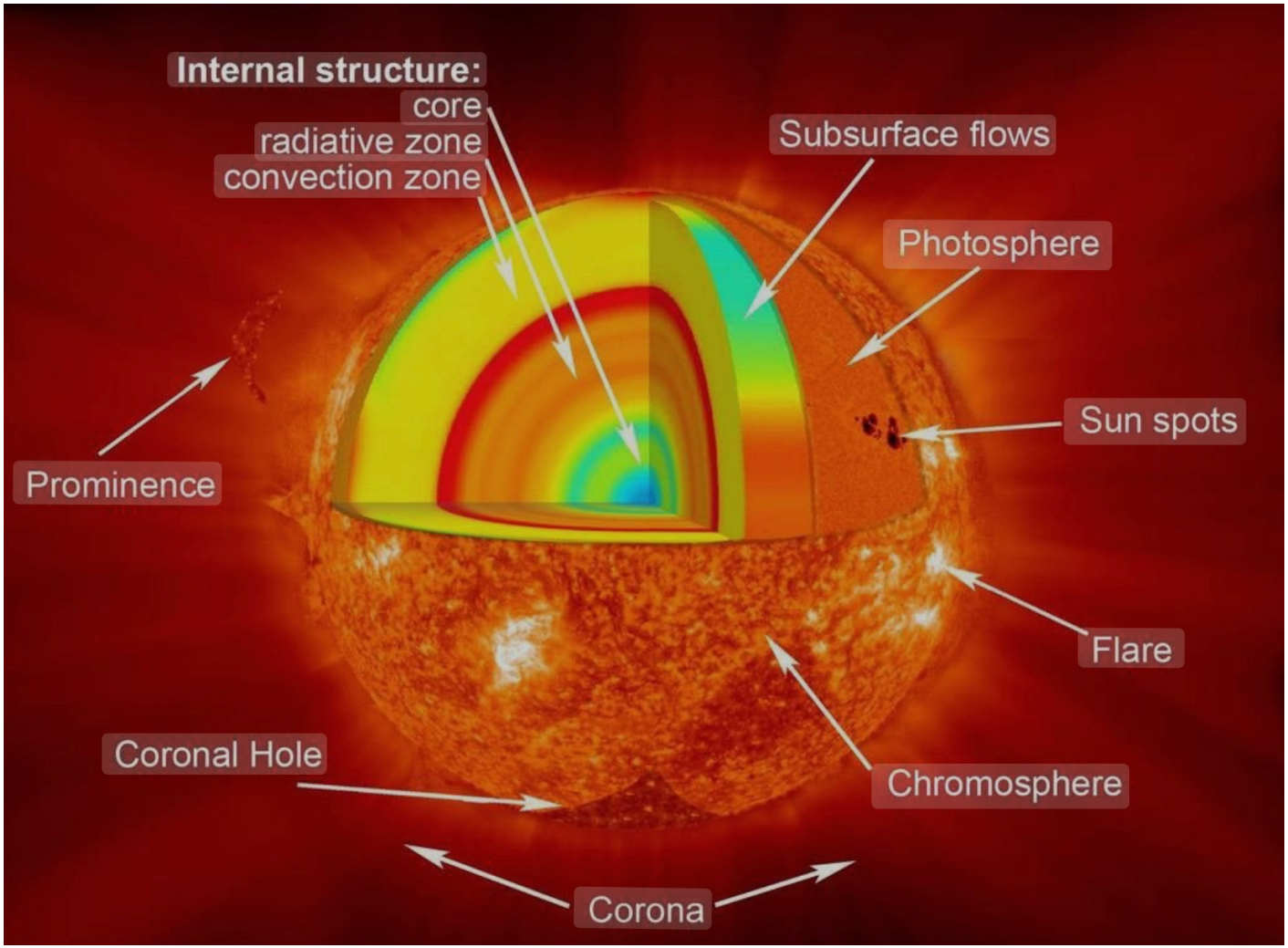
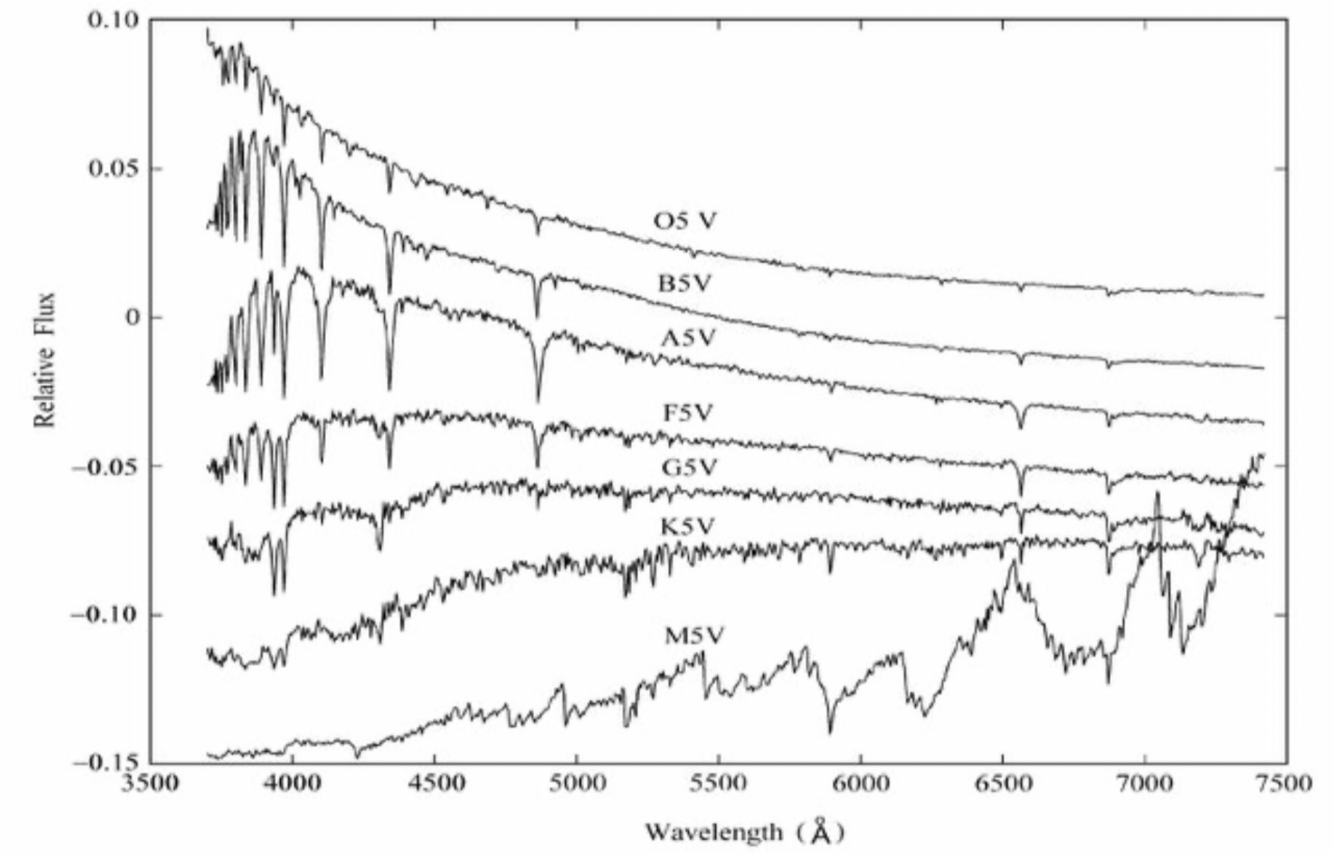
NGC 7331
THINGS:
The HI
Nearby Galaxy
Survey

# Stellar photosphere: a definition

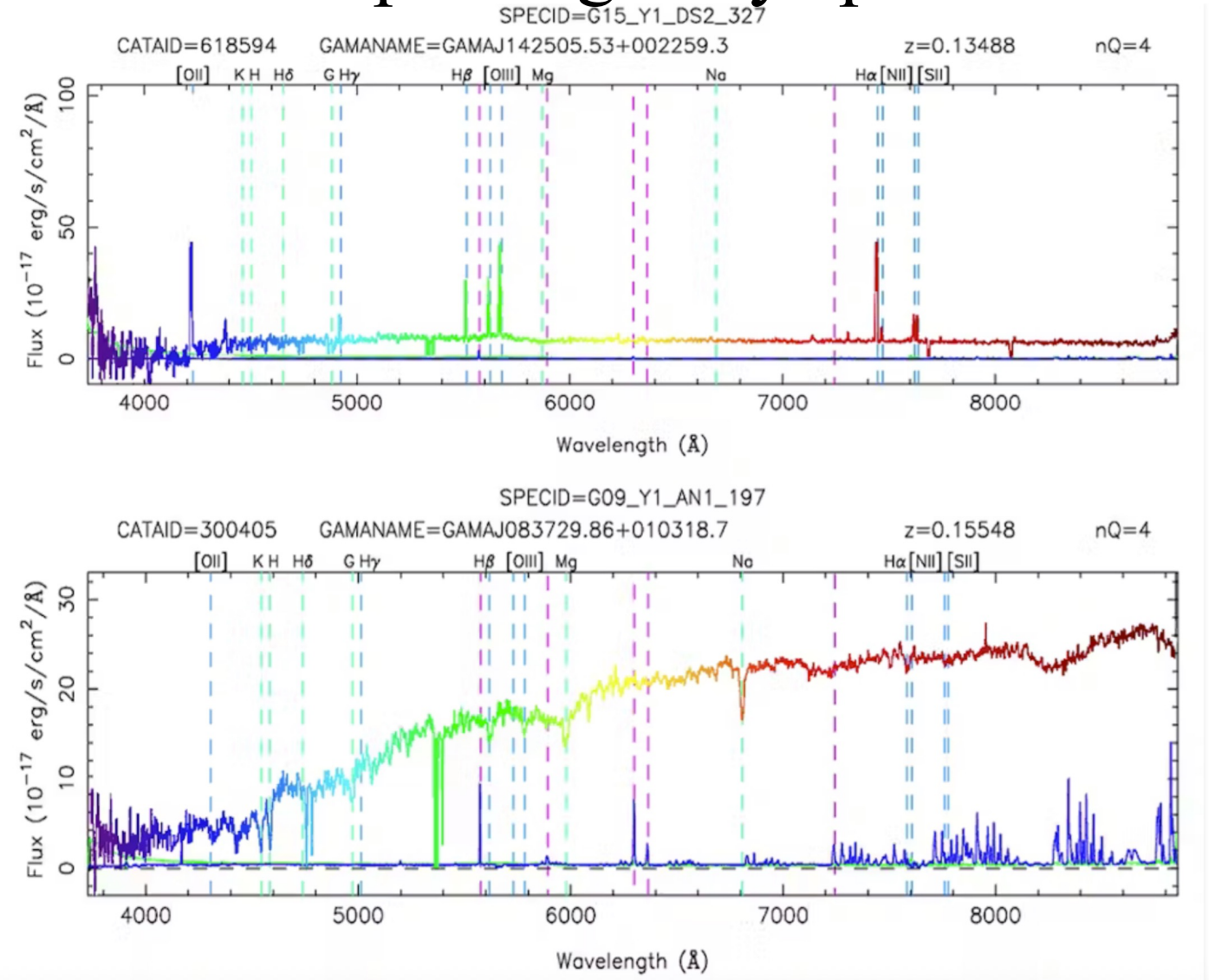



*Transition from interior to ISM*
*Layer from which we receive photons*

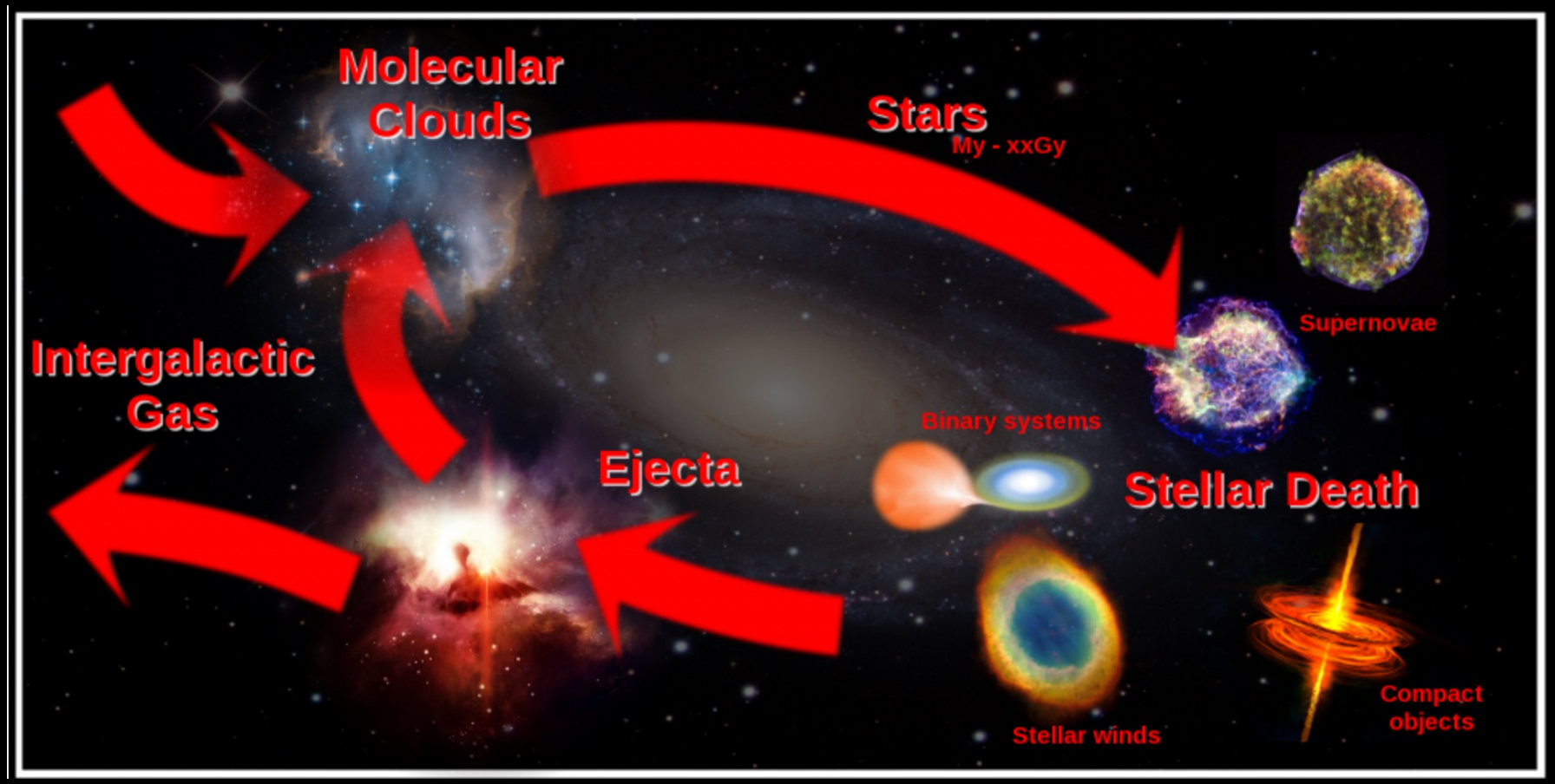
# Example of stellar spectra



# Example of galaxy spectra



# Matter (baryons) cycle in galaxies



# How can we model this cycle?

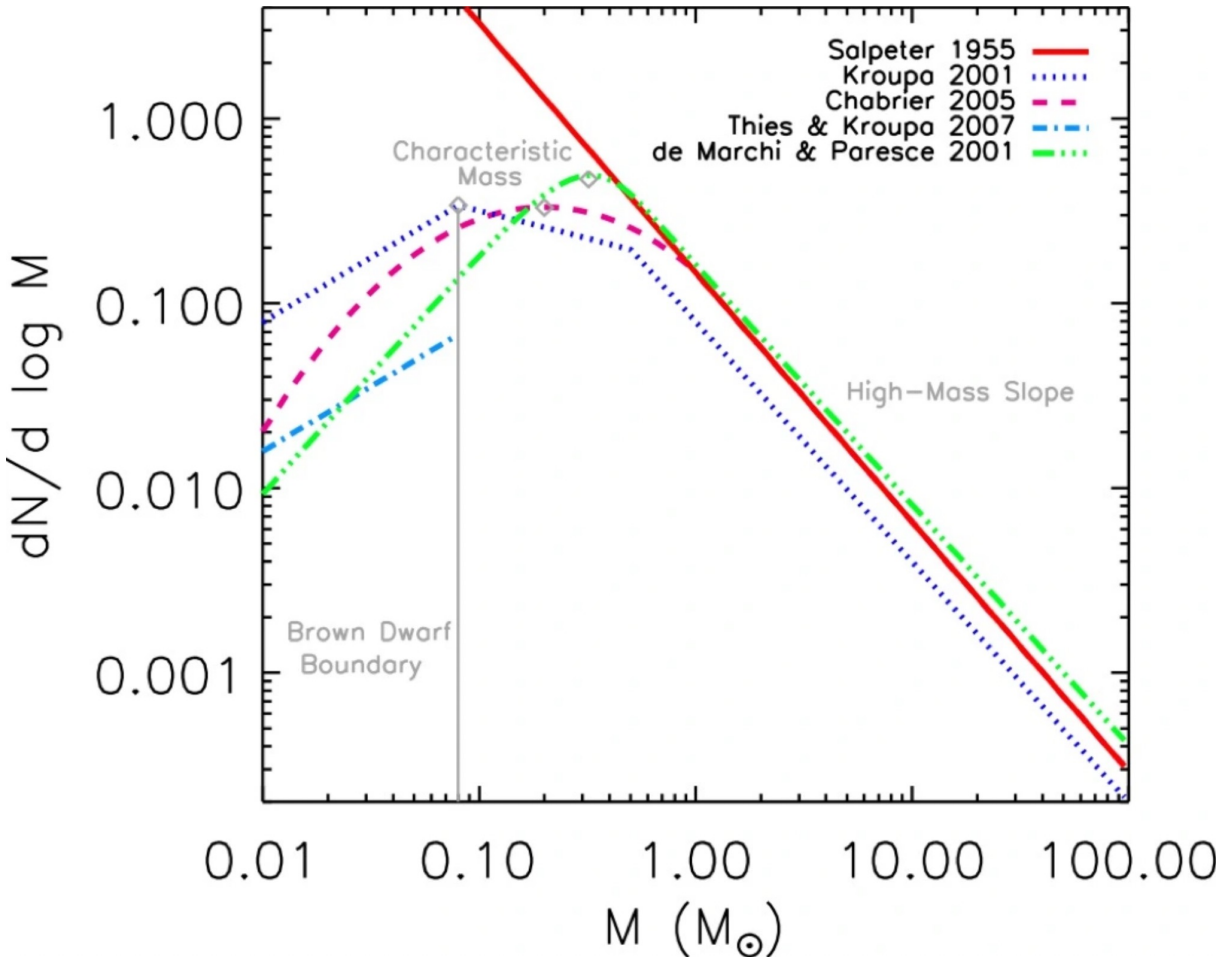
- One needs to parametrize the transformation between gas and stars : Star Formation Rate (SFR)

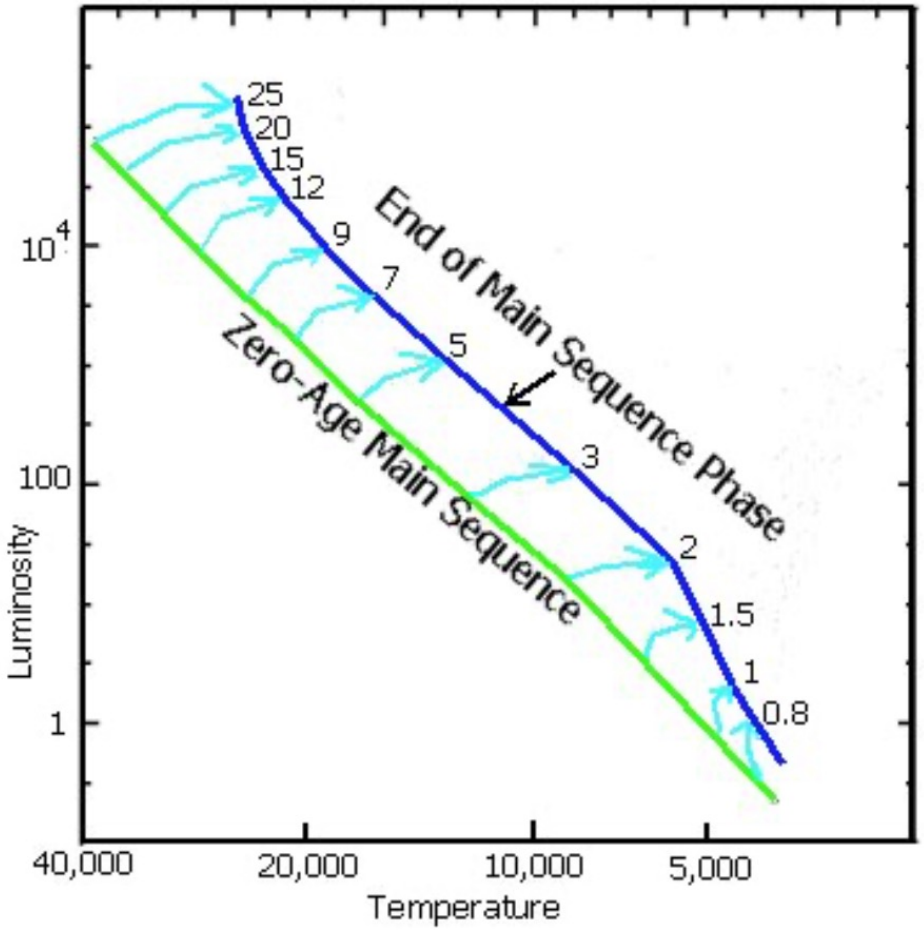
  Units: solar masses per year

- These newly formed stars form with a distribution in mass : the initial mass function (IMF)

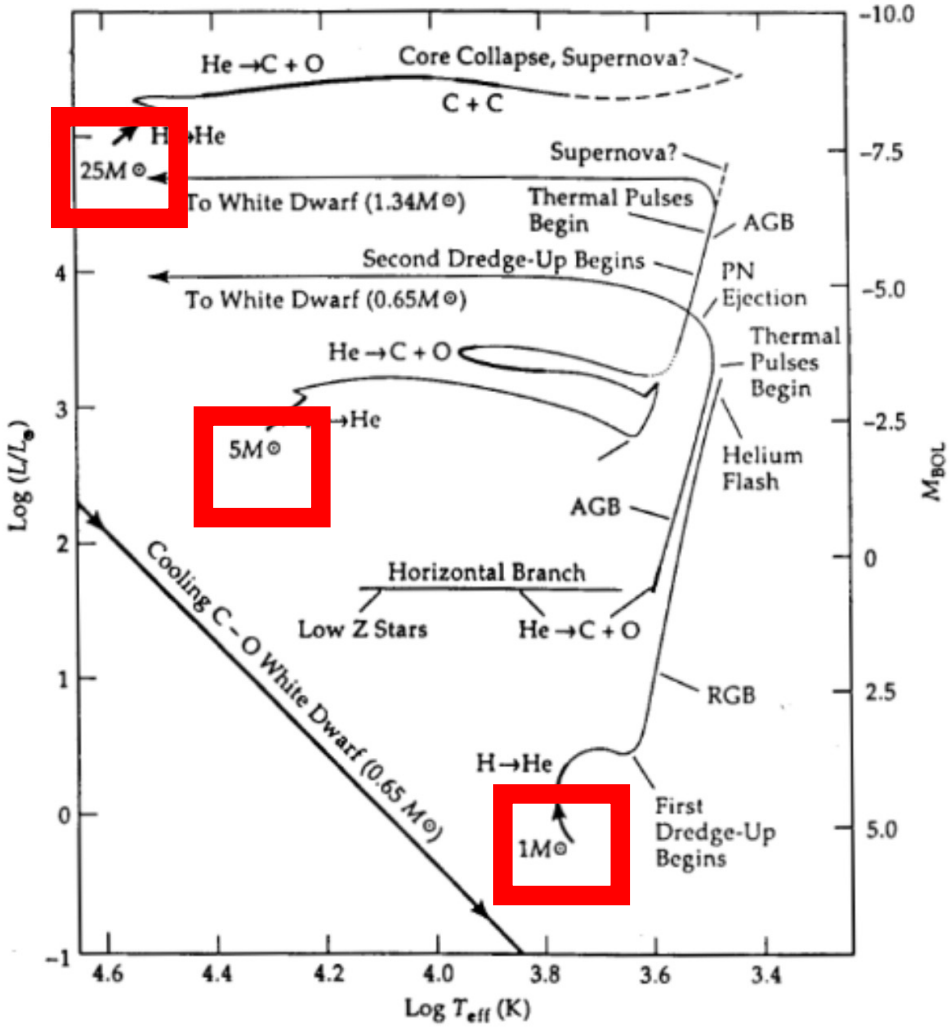
- One then follows the evolution of stars, depending on their mass, their return to the interstellar medium can come from explosions or winds. Even the exploding stars (supernovae) leave a certain fraction of matter behind, called “remnants”.

# Initial mass function (IMF)

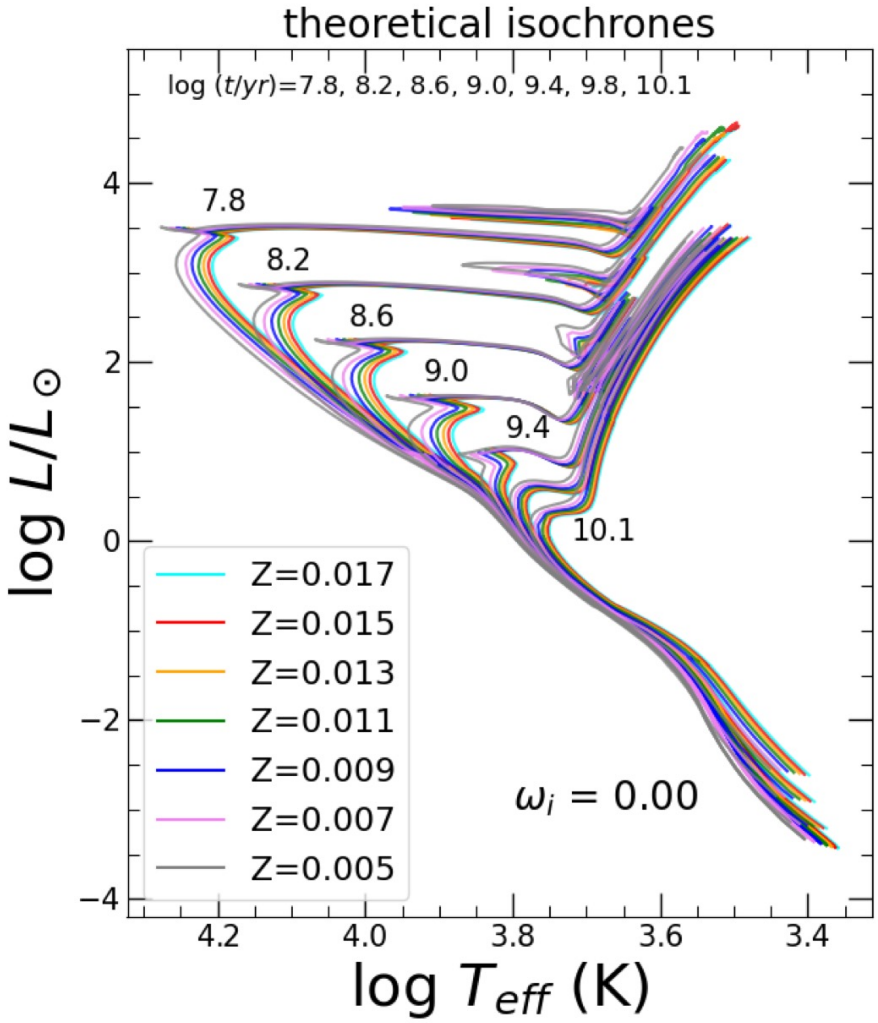


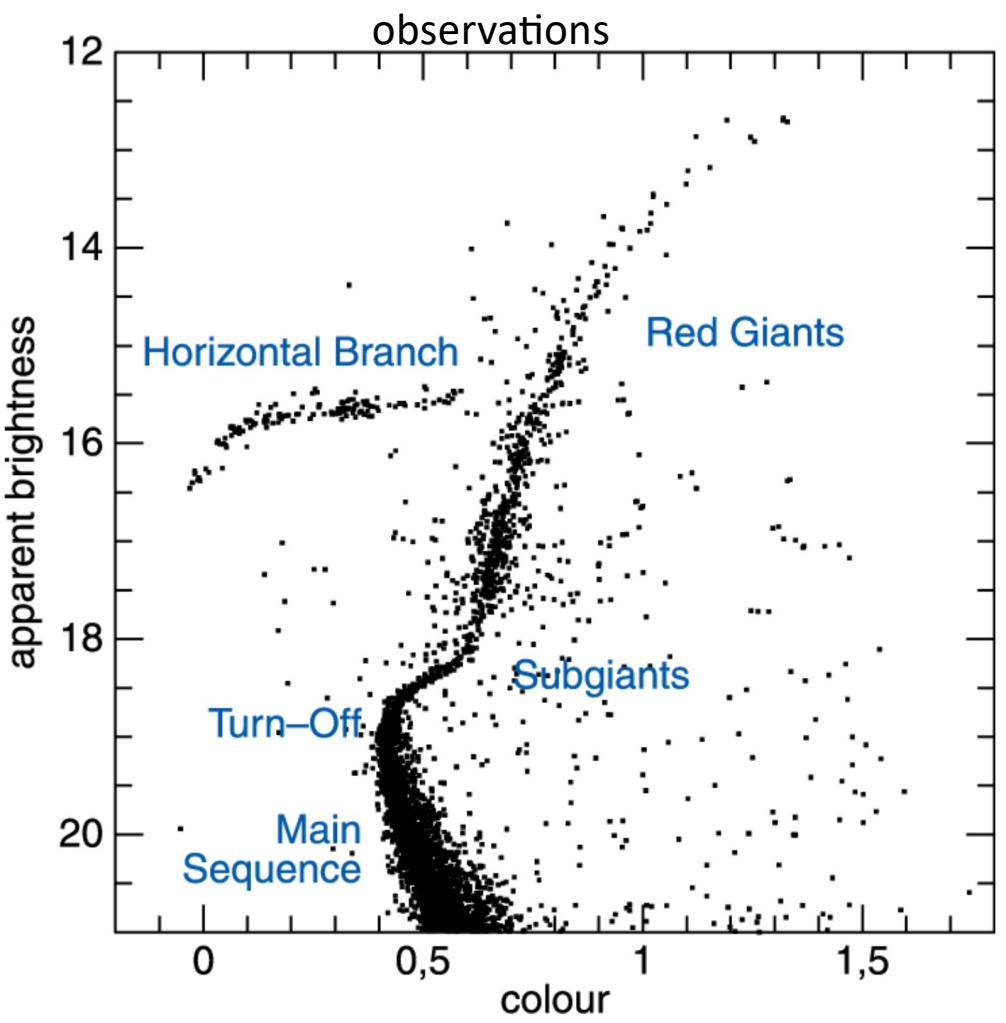



# Stellar evolutionary track



# Isochrones – colour-magnitude diagrams



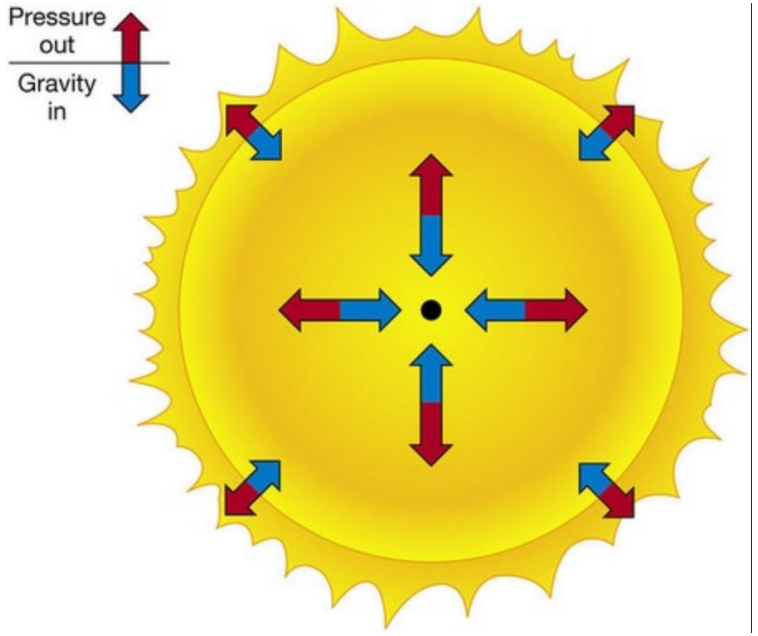



## While Stars Are on the Main Sequence

•What holds stars up? Equilibrium between thermal pressure and gravity (and radiation pressure in massive stars); lasts for 90% of their life: 10 Gyr for the Sun, more for smaller stars.

•How is the energy produced? Between the time when $T > 10$ million K and when they run out of H, He production in the core, by the proton-proton chain ($T < 20$ million K) or CNO cycle (dominant at $T > 20$ million K).

•How does the energy get out? Radiation and convection, like in the Sun; May take a million years to reach the surface; In very low mass stars, deep convection zone and intense flare activity; In high-mass stars, no convection near the surface.



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***p-p chain***

| pp I | pp II | pp III |
|---|---|---|
| $^1H + {}^1H \rightarrow {}^2D + e^+ + \nu_e$ | $^3He + {}^4He \rightarrow {}^7Be + \gamma$ | $^3He + {}^4He \rightarrow {}^7Be + \gamma$ |
| $^2D + {}^1H \rightarrow {}^3He + \gamma$ | $^7Be + e^- \rightarrow {}^7Li + \nu_e$ | $^7Be + {}^1H \rightarrow {}^8B + \gamma$ |
| $^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$ | $^7Li + {}^1H \rightarrow {}^4He + {}^4He$ | $^8B \rightarrow {}^8Be + e^+ + \nu_e$ |
| | | $^8Be \rightarrow {}^4He + {}^4He$ |

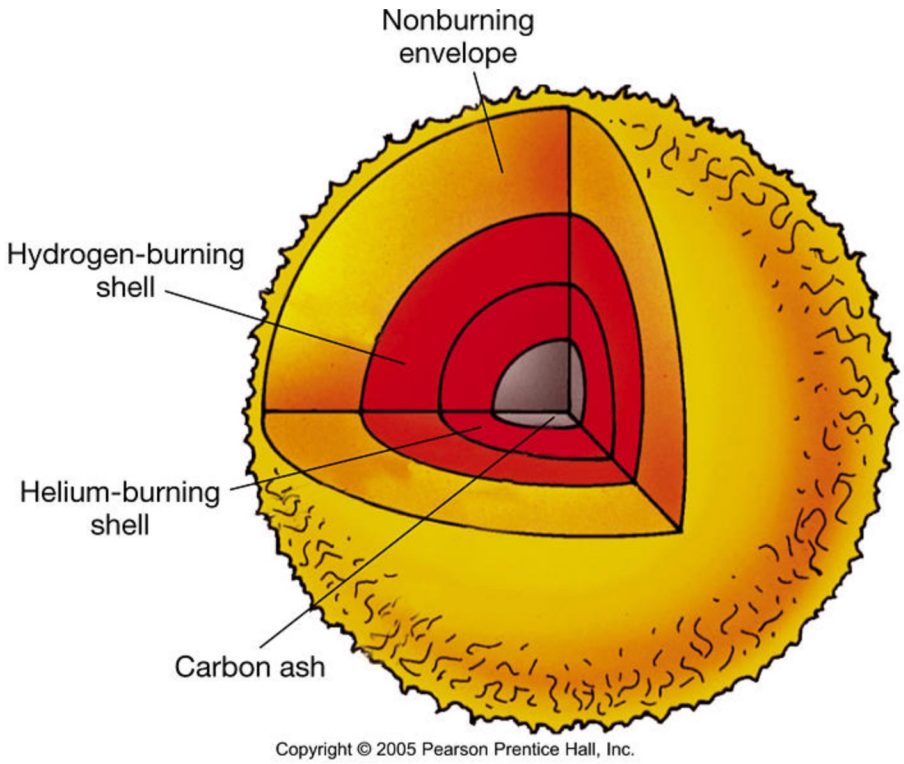
***CNO cycle***

| CN cycle | NO cycle |
|---|---|
| $^{12}C + {}^1H \rightarrow {}^{13}N + \gamma$ | $^{15}N + {}^1H \rightarrow {}^{16}O + \gamma$ |
| $^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$ | $^{16}O + {}^1H \rightarrow {}^{17}F + \gamma$ |
| $^{13}C + {}^1H \rightarrow {}^{14}N + \gamma$ | $^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$ |
| $^{14}N + {}^1H \rightarrow {}^{15}O + \gamma$ | $^{17}O + {}^1H \rightarrow {}^{14}N + {}^4He$ |
| $^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$ | |
| $^{15}N + {}^1H \rightarrow {}^{12}C + {}^4He$ | |

**After the Main Sequence**

## Evolution of Low-Mass Stars ($M$ < 10 solar masses)

•H shell burning production: H depleted in the core, He core shrinks; $T$ rises around the core, energy production by H fusion continues at a faster rate in a shell, and the star becomes brighter.
•Star growth: Envelope expands so it cools down, while the core shrinks and heats up; > Subgiant and red giant branch, with red giant winds.
•Very-low-mass stars: They end their lives as He white dwarfs (with electron degeneracy pressure maintaining their size).
•Sunlike stars: He burning to C in the core starts with a flash when $T = 10^8$ K; The core expands and the luminosity decreases, as the star moves to the horizontal branch of the HR diagram.
•He shell burning: He depleted, C core shrinks, $T$ rises, faster fusion, envelope expands > Double-shell burning and asymptotic giant branch.



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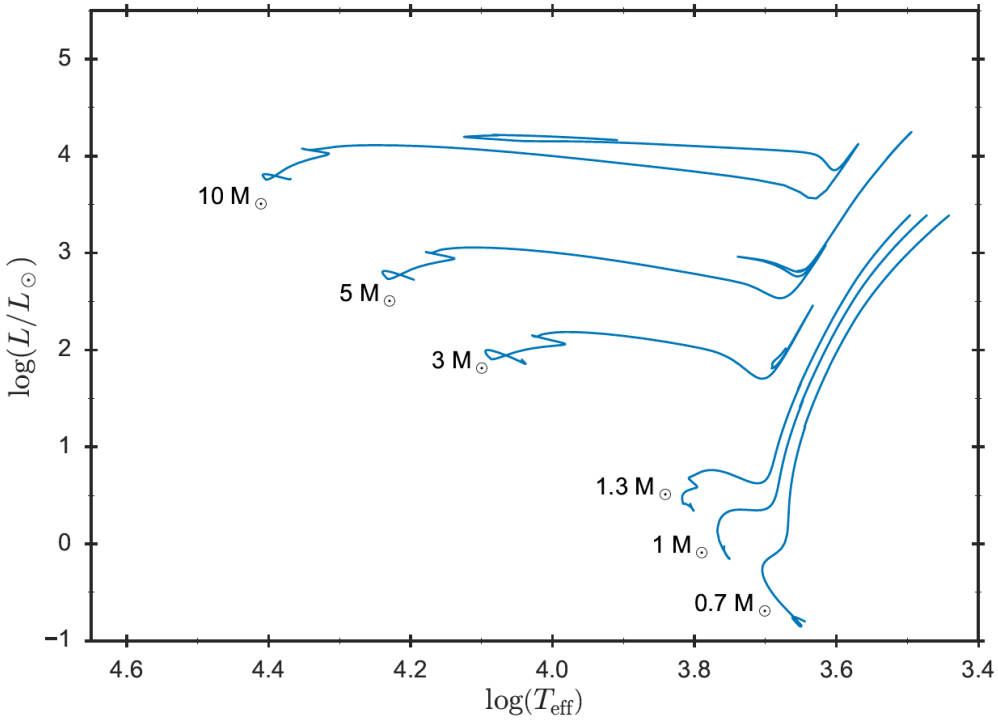



**Fig. 1** Hertzsprung-Russell Diagram plotted for different masses at a fixed chemical composition of $Y = 0.28$ and $Z = 0.02$. The tracks cover the evolution from the beginning of the main sequence to the red giant phase or, for $M \geq 3.0\ M_\odot$, also the helium burning phase.

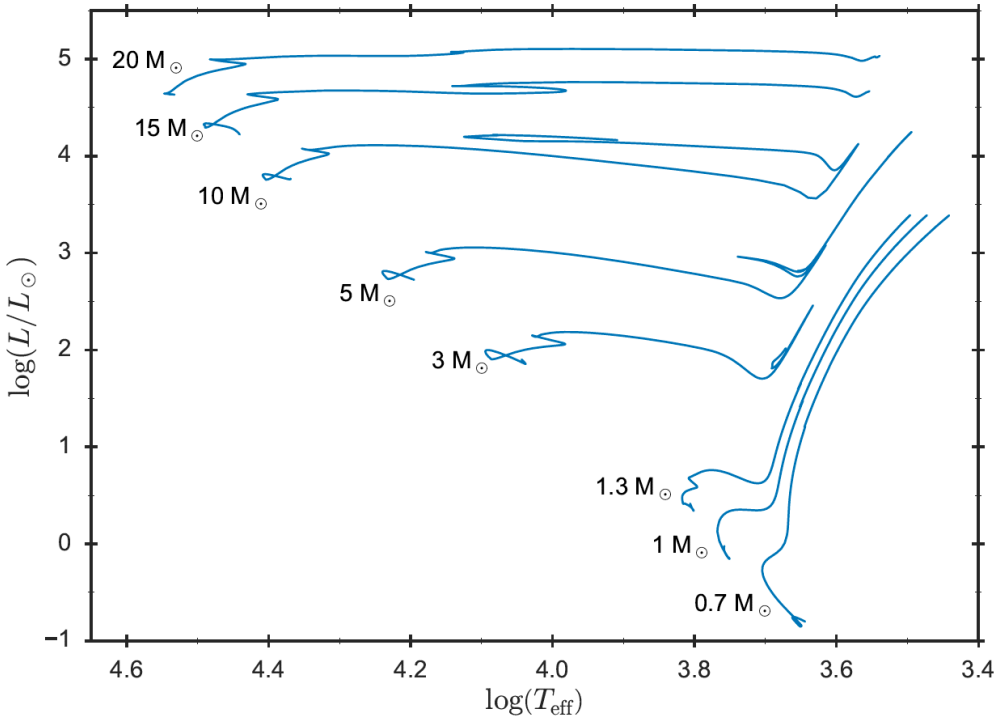
## Evolution of High-Mass Stars

Heavier, bigger stars lead a much shorter, more violent life.

•Faster changes: The more massive the star, the faster the p-p chain proceeds; [and at the higher *T* the presence of C, N and O accelerates H fusion (CNO cycle)].

•Phases: H shell burning; gradual onset of He burning in the core; He shell burning; ... Intermediate mass stars stop here.

•C burning in the core: It requires a temperature of 600 MK, or an initial mass of 8 suns; Produces heavier elements; Last significant process is Si burning and Fe piling up in the core; Fe cannot fuse.

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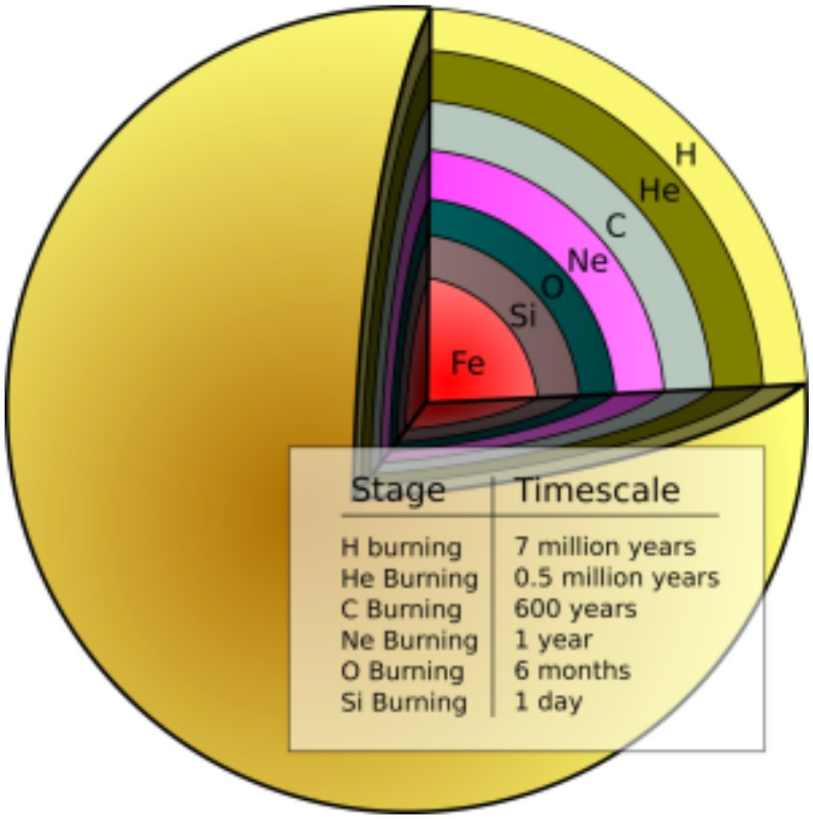
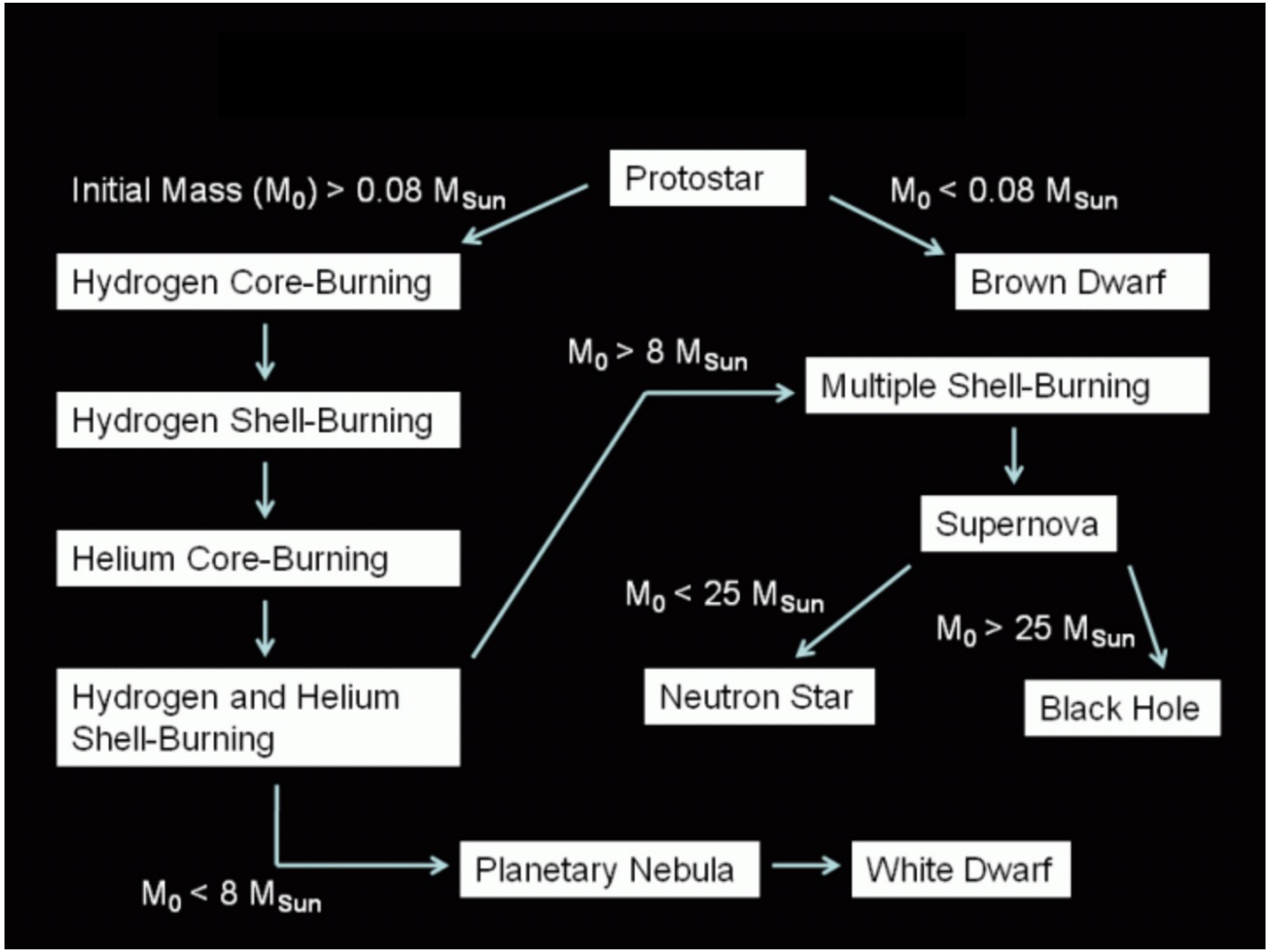
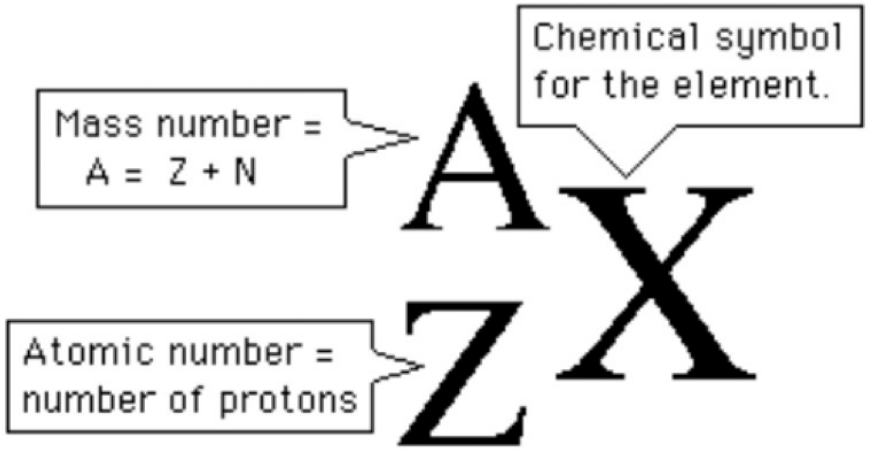


# Schematic view of stellar evolution



# Chemical elements



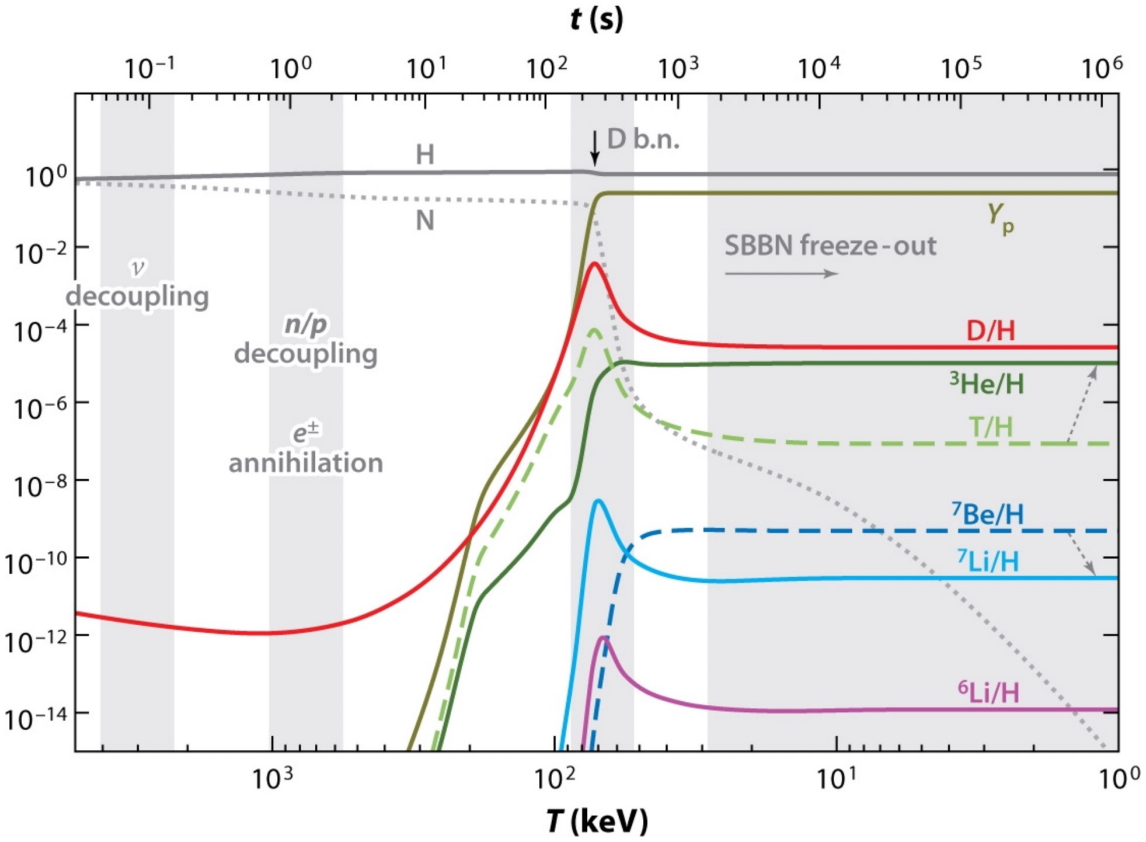

A : the total count of protons and neutrons in an atom's nucleus, calculated as A = Z (protons) + N (neutrons).

The mass number identifies a specific isotope of an element, which are atoms of the same element with different numbers of neutrons.

Z: Atomic number or nuclear charge of a chemical element is the charge number of its atomic nucleus.
For ordinary nuclei composed of protons and neutrons, this is equal to the proton number ($n_p$) or the number of protons found in the nucleus of every atom of that element.

# Let's refresh everyone's memroy

(see moodle as well)




Big Bang:

Deuterium, Lithium, Berylium, Helium

All other elements are formed in stars
(some such as Li can be destroyed)

# Scales for Chemical abundances

**Fraction of mass :** X, Y et Z

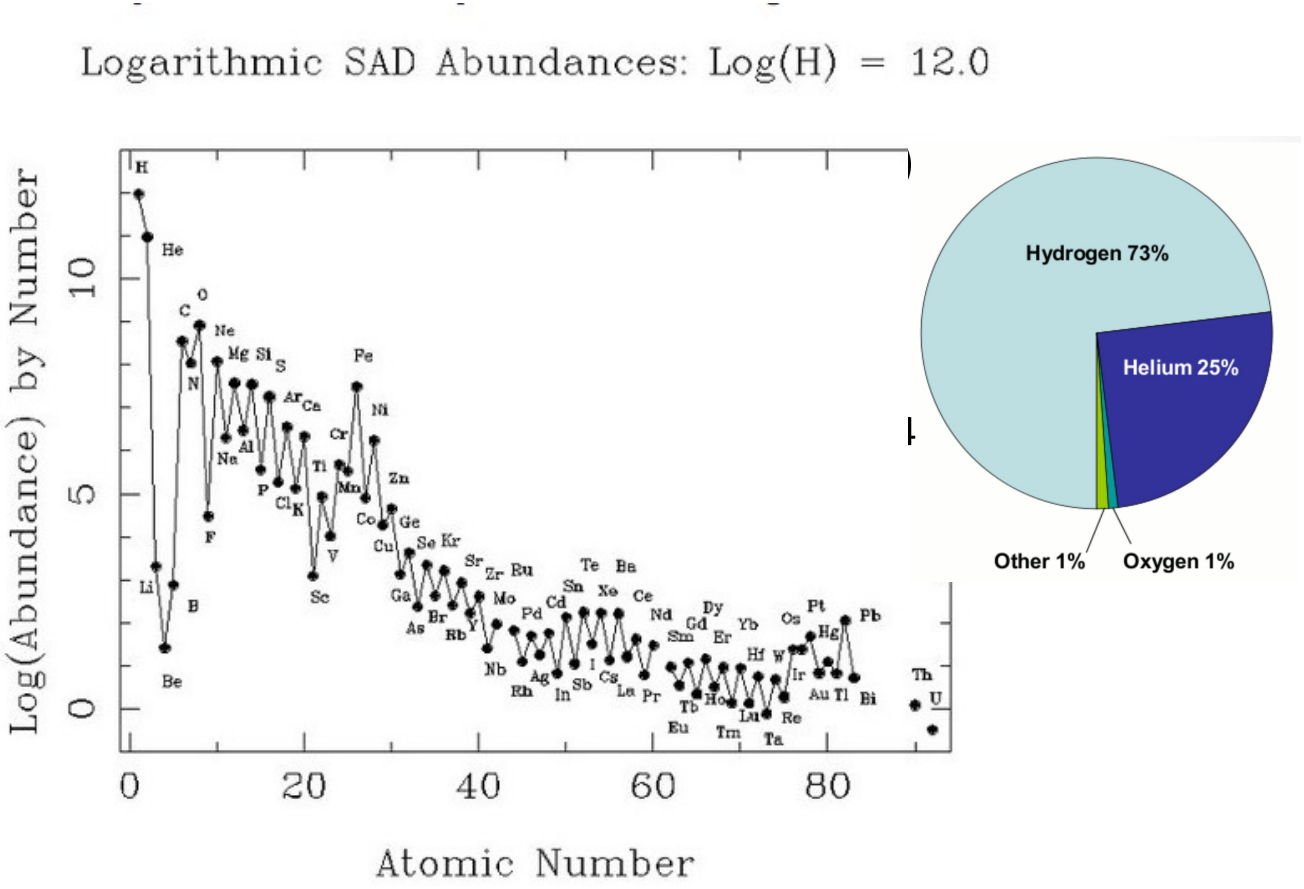
The mass fractions of hydrogen and helium are called **"X"** and **"Y"**, respectively. The symbol **"Z"** represents the mass fraction of all the other elements heavier than helium (from Li to U).
Astronomers group all the heavier elements together because they account for only about **Z = 0.0148** of the Sun, whereas hydrogen has **X = 0.7389** and helium **Y = 0.2463**.

**Scale 12** : Logarithm of the ratio of the number density of an element to the number density of hydrogen being set to 12.
Used because hydrogen is the most abundant element in the cosmos, and it provides manageable numbers

$$\log \varepsilon(X) = \log (nX/\ nH) + 12 \qquad (\log \varepsilon(H) \equiv 12)$$

**Log Scale**: $[X/H] = \log (nX/\ nH)^* - \log (nX/\ nH)_{sun}$

# Present-day solar photosphere elemental abundances







Lodder 2009

Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

| Z | Element | Photosphere | Meteorites | Z | Element | Photosphere | Meteorites |
|---|---|---|---|---|---|---|---|
| 1 | H | 12.00 | 8.22 ± 0.04 | 44 | Ru | 1.75 ± 0.08 | 1.76 ± 0.03 |
| 2 | He | [10.93 ± 0.01] | 1.29 | 45 | Rh | 0.91 ± 0.10 | 1.06 ± 0.04 |
| 3 | Li | 1.05 ± 0.10 | 3.26 ± 0.05 | 46 | Pd | 1.57 ± 0.10 | 1.65 ± 0.02 |
| 4 | Be | 1.38 ± 0.09 | 1.30 ± 0.03 | 47 | Ag | 0.94 ± 0.10 | 1.20 ± 0.02 |
| 5 | B | 2.70 ± 0.20 | 2.79 ± 0.04 | 48 | Cd | | 1.71 ± 0.03 |
| 6 | C | 8.43 ± 0.05 | 7.39 ± 0.04 | 49 | In | 0.80 ± 0.20 | 0.76 ± 0.03 |
| 7 | N | 7.83 ± 0.05 | 6.26 ± 0.06 | 50 | Sn | 2.04 ± 0.10 | 2.07 ± 0.06 |
| 8 | O | 8.69 ± 0.05 | 8.40 ± 0.04 | 51 | Sb | | 1.01 ± 0.06 |
| 9 | F | 4.56 ± 0.30 | 4.42 ± 0.06 | 52 | Te | | 2.18 ± 0.03 |
| 10 | Ne | [7.93 ± 0.10] | −1.12 | 53 | I | | 1.55 ± 0.08 |
| 11 | Na | 6.24 ± 0.04 | 6.27 ± 0.02 | 54 | Xe | [2.24 ± 0.06] | −1.95 |
| 12 | Mg | 7.60 ± 0.04 | 7.53 ± 0.01 | 55 | Cs | | 1.08 ± 0.02 |
| 13 | Al | 6.45 ± 0.03 | 6.43 ± 0.01 | 56 | Ba | 2.18 ± 0.09 | 2.18 ± 0.03 |
| 14 | Si | 7.51 ± 0.03 | 7.51 ± 0.01 | 57 | La | 1.10 ± 0.04 | 1.17 ± 0.02 |
| 15 | P | 5.41 ± 0.03 | 5.43 ± 0.04 | 58 | Ce | 1.58 ± 0.04 | 1.58 ± 0.02 |
| 16 | S | 7.12 ± 0.03 | 7.15 ± 0.02 | 59 | Pr | 0.72 ± 0.04 | 0.76 ± 0.03 |
| 17 | Cl | 5.50 ± 0.30 | 5.23 ± 0.06 | 60 | Nd | 1.42 ± 0.04 | 1.45 ± 0.02 |
| 18 | Ar | [6.40 ± 0.13] | −0.50 | 62 | Sm | 0.96 ± 0.04 | 0.94 ± 0.02 |
| 19 | K | 5.03 ± 0.09 | 5.08 ± 0.02 | 63 | Eu | 0.52 ± 0.04 | 0.51 ± 0.02 |
| 20 | Ca | 6.34 ± 0.04 | 6.29 ± 0.02 | 64 | Gd | 1.07 ± 0.04 | 1.05 ± 0.02 |
| 21 | Sc | 3.15 ± 0.04 | 3.05 ± 0.02 | 65 | Tb | 0.30 ± 0.10 | 0.32 ± 0.03 |
| 22 | Ti | 4.95 ± 0.05 | 4.91 ± 0.03 | 66 | Dy | 1.10 ± 0.04 | 1.13 ± 0.02 |
| 23 | V | 3.93 ± 0.08 | 3.96 ± 0.02 | 67 | Ho | 0.48 ± 0.11 | 0.47 ± 0.03 |
| 24 | Cr | 5.64 ± 0.04 | 5.64 ± 0.01 | 68 | Er | 0.92 ± 0.05 | 0.92 ± 0.02 |
| 25 | Mn | 5.43 ± 0.04 | 5.48 ± 0.01 | 69 | Tm | 0.10 ± 0.04 | 0.12 ± 0.03 |
| 26 | Fe | 7.50 ± 0.04 | 7.45 ± 0.01 | 70 | Yb | 0.84 ± 0.11 | 0.92 ± 0.02 |
| 27 | Co | 4.99 ± 0.07 | 4.87 ± 0.01 | 71 | Lu | 0.10 ± 0.09 | 0.09 ± 0.02 |
| 28 | Ni | 6.22 ± 0.04 | 6.20 ± 0.01 | 72 | Hf | 0.85 ± 0.04 | 0.71 ± 0.02 |
| 29 | Cu | 4.19 ± 0.04 | 4.25 ± 0.04 | 73 | Ta | | −0.12 ± 0.04 |
| 30 | Zn | 4.56 ± 0.05 | 4.63 ± 0.04 | 74 | W | 0.85 ± 0.12 | 0.65 ± 0.04 |
| 31 | Ga | 3.04 ± 0.09 | 3.08 ± 0.02 | 75 | Re | | 0.26 ± 0.04 |
| 32 | Ge | 3.65 ± 0.10 | 3.58 ± 0.04 | 76 | Os | 1.40 ± 0.08 | 1.35 ± 0.03 |
| 33 | As | | 2.30 ± 0.04 | 77 | Ir | 1.38 ± 0.07 | 1.32 ± 0.02 |
| 34 | Se | | 3.34 ± 0.03 | 78 | Pt | | 1.62 ± 0.03 |
| 35 | Br | | 2.54 ± 0.06 | 79 | Au | 0.92 ± 0.10 | 0.80 ± 0.04 |
| 36 | Kr | [3.25 ± 0.06] | −2.27 | 80 | Hg | | 1.17 ± 0.08 |
| 37 | Rb | 2.52 ± 0.10 | 2.36 ± 0.03 | 81 | Tl | 0.90 ± 0.20 | 0.77 ± 0.03 |
| 38 | Sr | 2.87 ± 0.07 | 2.88 ± 0.03 | 82 | Pb | 1.75 ± 0.10 | 2.04 ± 0.03 |
| 39 | Y | 2.21 ± 0.05 | 2.17 ± 0.04 | 83 | Bi | | 0.65 ± 0.04 |
| 40 | Zr | 2.58 ± 0.04 | 2.53 ± 0.04 | 90 | Th | 0.02 ± 0.10 | 0.06 ± 0.03 |
| 41 | Nb | 1.46 ± 0.04 | 1.41 ± 0.04 | 92 | U | | −0.54 ± 0.03 |
| 42 | Mo | 1.88 ± 0.08 | 1.94 ± 0.04 | | | | |

EJECTA NUCLEOSYNTHESIS

SNeIa

| Species | W7 |
|---|---|
| 12C | 4.83E-02 |
| 13C | 1.40E-06 |
| 14N | 1.16E-06 |
| 15N | 1.32E-09 |
| 16O | 1.43E-01 |
| 17O | 3.54E-08 |
| 18O | 8.25E-10 |
| 19F | 5.67E-10 |
| 20Ne | 2.02E-03 |
| 21Ne | 8.46E-06 |
| 22Ne | 2.49E-03 |
| 23Na | 6.32E-05 |
| 24Mg | 8.50E-03 |
| 25Mg | 4.05E-05 |
| 26Mg | 3.18E-05 |
| 27Al | 9.86E-04 |
| 28Si | 1.50E-01 |
| 29Si | 8.61E-04 |
| 30Si | 1.74E-03 |
| 31P | 4.18E-04 |
| 32S | 8.41E-02 |
| 33S | 4.50E-04 |
| 34S | 1.90E-03 |
| 36S | 3.15E-07 |
| 35Cl | 1.34E-04 |
| 37Cl | 3.98E-05 |
| 36Ar | 1.49E-02 |
| 38Ar | 1.06E-03 |
| 40Ar | 1.26E-08 |
| 39K | 8.52E-05 |
| 41K | 7.44E-06 |
| 40Ca | 1.23E-02 |
| 42Ca | 3.52E-05 |
| 43Ca | 1.03E-07 |
| 44Ca | 8.86E-06 |
| 46Ca | 1.99E-09 |
| 48Ca | 7.10E-12 |

SNeII

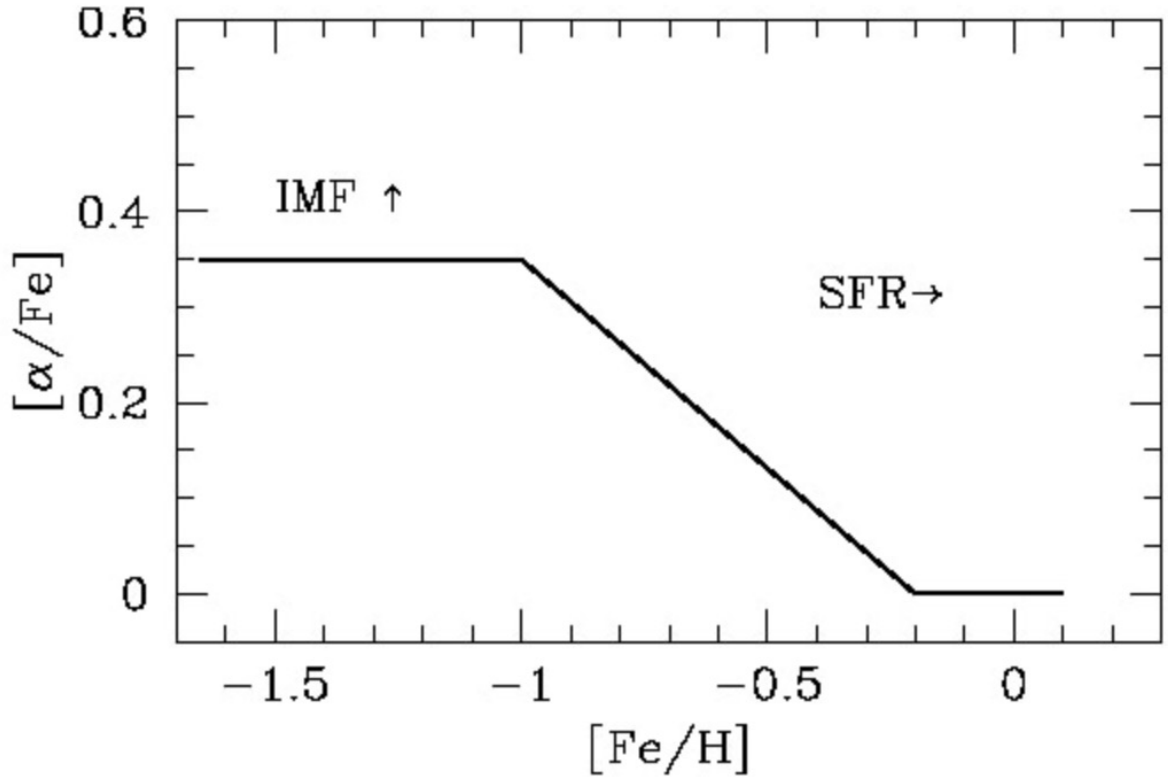
| Species | 13 | 15 | 18 | 20 | 25 | 40 | 70 |
|---|---|---|---|---|---|---|---|
| 12 C | 2.68E-03 | 8.26E-02 | 1.65E-01 | 1.14E-01 | 1.48E-01 | 1.48E-01 | 4.67E-01 |
| 13 C | 9.47E-09 | 4.97E-10 | 7.73E-10 | 1.17E-10 | 1.03E-08 | 3.02E-10 | 2.57E-10 |
| 14 N | 3.75E-08 | 5.37E-03 | 3.39E-03 | 2.72E-03 | 9.53E-04 | 7.08E-05 | 7.68E-03 |
| 15 N | 2.08E-08 | 1.36E-10 | 9.05E-08 | 6.48E-10 | 1.04E-08 | 1.19E-08 | 2.36E-10 |
| 16 O | 1.51E-01 | 3.55E-01 | 7.92E-01 | 1.48E+00 | 2.99E+00 | 9.11E+00 | 2.14E+01 |
| 17 O | 6.07E-08 | 4.41E-09 | 4.01E-07 | 9.86E-09 | 7.86E-08 | 3.13E-07 | 6.64E-10 |
| 18 O | 9.44E-09 | 1.35E-02 | 8.67E-03 | 8.68E-03 | 6.69E-03 | 1.79E-06 | 3.80E-03 |
| 19 F | 8.06E-10 | 2.12E-11 | 7.67E-09 | 7.84E-11 | 8.17E-10 | 7.38E-10 | 2.63E-15 |
| 20 Ne | 2.25E-02 | 2.08E-02 | 1.61E-01 | 2.29E-01 | 5.94E-01 | 6.58E-01 | 2.00E+00 |
| 21 Ne | 2.08E-04 | 3.93E-05 | 2.19E-03 | 3.03E-04 | 3.22E-03 | 2.36E-03 | 1.14E-02 |
| 22 Ne | 1.01E-04 | 1.25E-02 | 2.74E-02 | 2.93E-02 | 3.39E-02 | 5.66E-02 | 5.23E-02 |
| 23 Na | 7.27E-04 | 1.53E-04 | 7.25E-03 | 1.15E-03 | 1.81E-02 | 2.37E-02 | 6.98E-02 |
| 24 Mg | 9.23E-03 | 3.16E-02 | 3.62E-02 | 1.47E-01 | 1.59E-01 | 3.54E-01 | 7.87E-01 |
| 25 Mg | 1.38E-03 | 2.55E-03 | 7.54E-03 | 1.85E-02 | 3.92E-02 | 4.81E-02 | 1.01E-01 |
| 26 Mg | 8.96E-04 | 2.03E-03 | 5.94E-03 | 1.74E-02 | 3.17E-02 | 1.07E-01 | 2.91E-01 |
| 27 Al | 1.04E-03 | 4.01E-03 | 5.44E-03 | 1.55E-02 | 1.95E-02 | 8.05E-02 | 1.44E-01 |
| 28 Si | 6.68E-02 | 7.16E-02 | 8.69E-02 | 8.50E-02 | 1.03E-01 | 4.29E-01 | 7.55E-01 |
| 29 Si | 7.99E-04 | 3.25E-03 | 1.76E-03 | 9.80E-03 | 6.97E-03 | 5.43E-02 | 1.08E-01 |
| 30 Si | 1.87E-03 | 4.04E-03 | 3.33E-03 | 7.19E-03 | 6.81E-03 | 4.32E-02 | 1.00E-01 |
| 31 P | 2.95E-04 | 6.55E-04 | 4.11E-04 | 1.05E-03 | 9.02E-04 | 5.99E-03 | 2.57E-02 |
| 32 S | 1.46E-02 | 3.01E-02 | 3.76E-02 | 2.29E-02 | 3.84E-02 | 1.77E-01 | 2.05E-01 |
| 33 S | 1.19E-04 | 9.60E-05 | 1.48E-04 | 8.84E-05 | 2.20E-04 | 7.49E-04 | 1.02E-03 |
| 34 S | 1.83E-03 | 1.49E-03 | 1.89E-03 | 1.26E-03 | 2.77E-03 | 1.14E-02 | 1.98E-02 |
| 36 S | 3.04E-07 | 3.34E-07 | 8.08E-07 | 4.23E-07 | 7.51E-07 | 1.40E-05 | 2.17E-06 |
| 35 Cl | 3.70E-05 | 3.45E-05 | 8.95E-05 | 6.05E-05 | 6.72E-05 | 4.75E-04 | 1.76E-03 |
| 37 Cl | 6.73E-06 | 9.60E-06 | 1.04E-05 | 4.96E-06 | 1.32E-05 | 1.17E-04 | 1.01E-04 |
| 36 Ar | 2.36E-03 | 5.63E-03 | 6.13E-03 | 3.78E-03 | 6.71E-03 | 3.11E-02 | 2.92E-02 |
| 38 Ar | 4.85E-04 | 6.49E-04 | 6.29E-04 | 3.25E-04 | 7.24E-04 | 9.14E-03 | 6.16E-03 |
| 40 Ar | 4.82E-09 | 3.24E-09 | 1.42E-08 | 4.65E-09 | 8.92E-09 | 1.74E-07 | 5.07E-08 |
| 39 K | 1.95E-05 | 3.31E-05 | 3.66E-05 | 3.24E-05 | 3.47E-05 | 3.83E-04 | 3.84E-04 |
| 41 K | 1.42E-06 | 2.37E-06 | 2.23E-06 | 1.28E-06 | 2.79E-06 | 3.43E-05 | 2.84E-05 |
| 40 Ca | 2.53E-03 | 5.29E-03 | 5.11E-03 | 3.25E-03 | 6.15E-03 | 2.56E-02 | 2.14E-02 |
| 42 Ca | 1.02E-05 | 1.63E-05 | 1.45E-05 | 9.45E-06 | 1.77E-05 | 3.13E-04 | 1.64E-04 |
| 43 Ca | 1.91E-06 | 1.30E-06 | 3.99E-07 | 3.38E-06 | 2.78E-07 | 4.02E-07 | 4.09E-06 |
| 44 Ca | 1.22E-04 | 7.49E-05 | 1.43E-05 | 9.15E-05 | 2.11E-05 | 2.00E-05 | 2.97E-04 |
| 46 Ca | 2.06E-10 | 6.23E-11 | 3.23E-11 | 1.12E-11 | 2.60E-10 | 4.39E-10 | 2.23E-10 |
| 48 Ca | 1.13E-13 | 3.99E-16 | 1.07E-15 | 2.41E-16 | 1.70E-14 | 2.48E-13 | 2.36E-14 |

SNeIa

| | |
|---|---|
| 45Sc | 2.47E-07 |
| 46Ti | 1.71E-05 |
| 47Ti | 6.04E-07 |
| 48Ti | 2.03E-04 |
| 49Ti | 1.69E-05 |
| 50Ti | 1.26E-05 |
| 50V | 8.28E-09 |
| 51V | 5.15E-05 |
| 50Cr | 2.71E-04 |
| 52Cr | 5.15E-03 |
| 53Cr | 7.85E-04 |
| 54Cr | 1.90E-04 |
| 55Mn | 8.23E-03 |
| 54Fe | 1.04E-01 |
| 56Fe | 6.13E-01 |
| 57Fe | 2.55E-02 |
| 58Fe | 9.63E-04 |
| 59Co | 1.02E-03 |
| 58Ni | 1.28E-01 |
| 60Ni | 1.05E-02 |
| 61Ni | 2.51E-04 |
| 62Ni | 2.66E-03 |
| 64Ni | 1.31E-06 |
| 63Cu | 1.79E-06 |
| 65Cu | 6.83E-07 |
| 64Zn | 1.22E-05 |
| 66Zn | 2.12E-05 |
| 67Zn | 1.34E-08 |
| 68Zn | 1.02E-08 |

SNeII

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 45 Sc | 4.26E-08 | 7.44E-08 | 1.18E-07 | 1.04E-07 | 8.96E-08 | 1.53E-06 | 2.78E-06 |
| 46 Ti | 2.56E-06 | 6.26E-06 | 6.72E-06 | 6.81E-06 | 6.84E-06 | 3.56E-05 | 1.44E-05 |
| 47 Ti | 5.13E-06 | 3.75E-06 | 3.11E-07 | 1.73E-06 | 9.11E-07 | 9.74E-07 | 6.26E-07 |
| 48 Ti | 1.68E-04 | 1.58E-04 | 8.59E-05 | 1.85E-04 | 8.98E-05 | 1.58E-04 | 1.42E-04 |
| 49 Ti | 3.45E-06 | 6.10E-06 | 7.54E-06 | 4.89E-06 | 6.01E-06 | 2.17E-05 | 6.97E-06 |
| 50 Ti | 3.56E-10 | 1.21E-09 | 1.17E-10 | 1.12E-10 | 5.90E-10 | 2.00E-10 | 2.56E-10 |
| 50 V | 8.65E-10 | 8.57E-10 | 4.64E-10 | 2.15E-10 | 7.99E-10 | 2.14E-09 | 1.52E-09 |
| 51 V | 9.34E-06 | 1.25E-05 | 1.25E-05 | 6.40E-06 | 9.96E-06 | 2.73E-05 | 1.15E-05 |
| 50 Cr | 2.30E-05 | 5.15E-05 | 7.49E-05 | 3.54E-05 | 5.01E-05 | 1.49E-04 | 1.01E-04 |
| 52 Cr | 1.15E-03 | 1.36E-03 | 1.44E-03 | 8.64E-04 | 1.31E-03 | 2.77E-03 | 6.86E-04 |
| 53 Cr | 9.34E-05 | 1.35E-04 | 1.50E-04 | 7.12E-05 | 1.39E-04 | 3.56E-04 | 1.00E-04 |
| 54 Cr | 3.35E-08 | 4.09E-08 | 2.53E-08 | 6.26E-09 | 2.41E-08 | 2.81E-08 | 7.61E-08 |
| 55 Mn | 3.65E-04 | 4.74E-04 | 5.48E-04 | 2.27E-04 | 5.02E-04 | 8.41E-04 | 3.64E-04 |
| 54 Fe | 2.10E-03 | 4.49E-03 | 6.04E-03 | 2.52E-03 | 4.81E-03 | 9.17E-03 | 5.81E-03 |
| 56 Fe | 1.50E-01 | 1.44E-01 | 7.57E-02 | 7.32E-02 | 5.24E-02 | 7.50E-02 | 7.50E-02 |
| 57 Fe | 4.86E-03 | 4.90E-03 | 2.17E-03 | 3.07E-03 | 1.16E-03 | 2.29E-03 | 3.83E-03 |
| 58 Fe | 3.93E-09 | 1.27E-08 | 1.37E-08 | 3.70E-09 | 8.34E-09 | 1.29E-08 | 4.17E-08 |
| 59 Co | 1.39E-04 | 1.22E-04 | 4.82E-05 | 1.31E-04 | 2.19E-05 | 2.51E-05 | 1.59E-04 |
| 58 Ni | 5.82E-03 | 7.50E-03 | 3.08E-03 | 3.71E-03 | 1.33E-03 | 3.31E-03 | 9.25E-03 |
| 60 Ni | 3.72E-03 | 3.36E-03 | 8.71E-04 | 2.18E-03 | 6.67E-04 | 3.88E-04 | 1.77E-03 |
| 61 Ni | 1.58E-04 | 1.43E-04 | 4.77E-05 | 1.59E-04 | 2.75E-05 | 2.57E-05 | 1.55E-04 |
| 62 Ni | 1.05E-03 | 9.50E-04 | 2.52E-04 | 7.26E-04 | 1.70E-04 | 1.11E-04 | 1.28E-03 |
| 64 Ni | 2.02E-15 | 4.28E-15 | 2.93E-16 | 2.06E-15 | 6.08E-15 | 6.49E-16 | 4.33E-12 |
| 63 Cu | 1.18E-06 | 1.01E-06 | 4.32E-07 | 3.00E-06 | 1.50E-07 | 1.62E-07 | 9.09E-06 |
| 65 Cu | 9.11E-07 | 7.17E-07 | 8.40E-08 | 7.02E-07 | 1.42E-07 | 1.89E-08 | 5.34E-07 |
| 64 Zn | 2.14E-05 | 1.99E-05 | 3.89E-06 | 1.78E-05 | 3.10E-06 | 8.79E-07 | 1.02E-05 |
| 66 Zn | 1.63E-05 | 1.30E-05 | 4.47E-06 | 2.08E-05 | 2.58E-06 | 9.99E-07 | 3.09E-05 |
| 67 Zn | 2.13E-08 | 1.54E-08 | 3.39E-09 | 6.39E-08 | 2.95E-09 | 2.51E-10 | 1.95E-07 |
| 68 Zn | 6.63E-09 | 7.35E-09 | 8.36E-10 | 5.33E-09 | 9.29E-10 | 1.20E-10 | 9.51E-08 |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[α/Fe]
IMF ↑
SFR→
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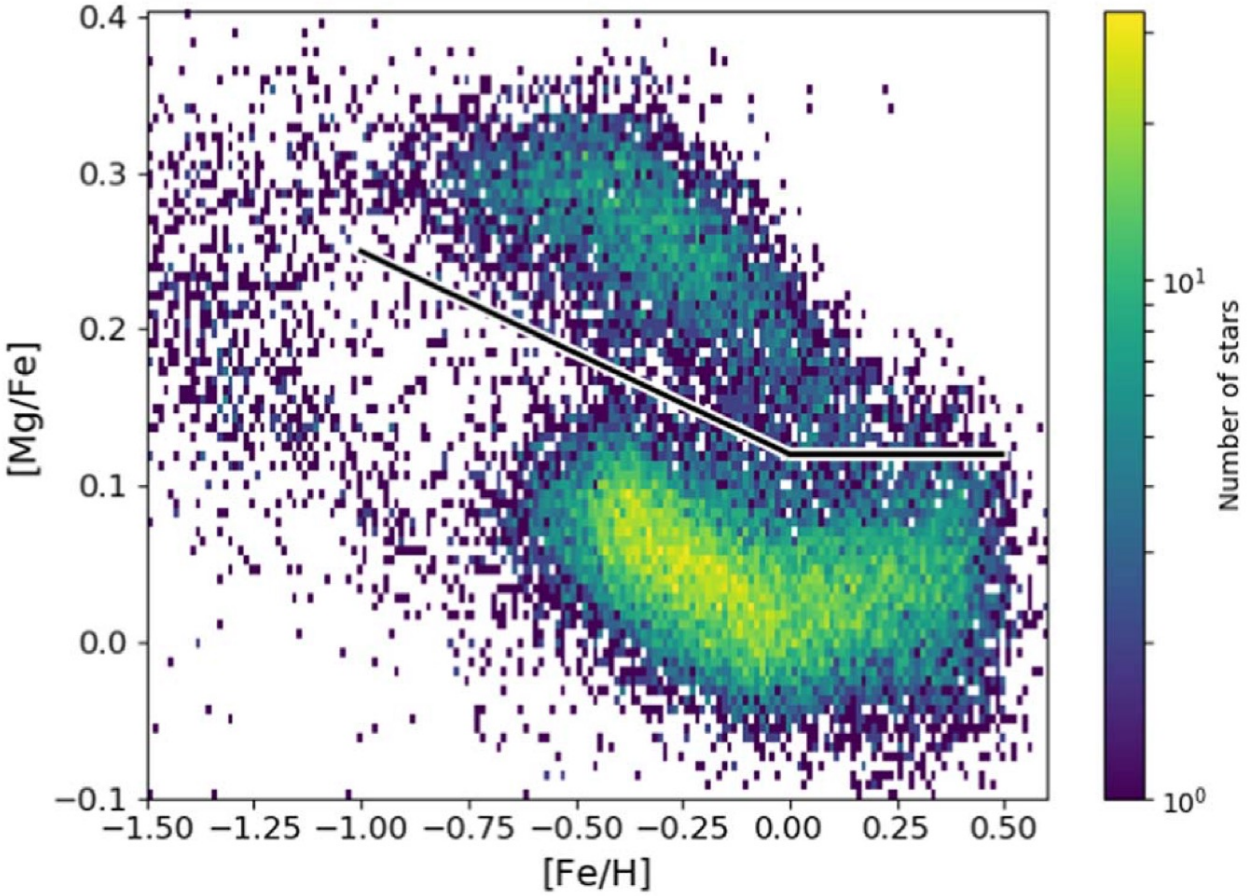
[Fe/H]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[Fe/H]
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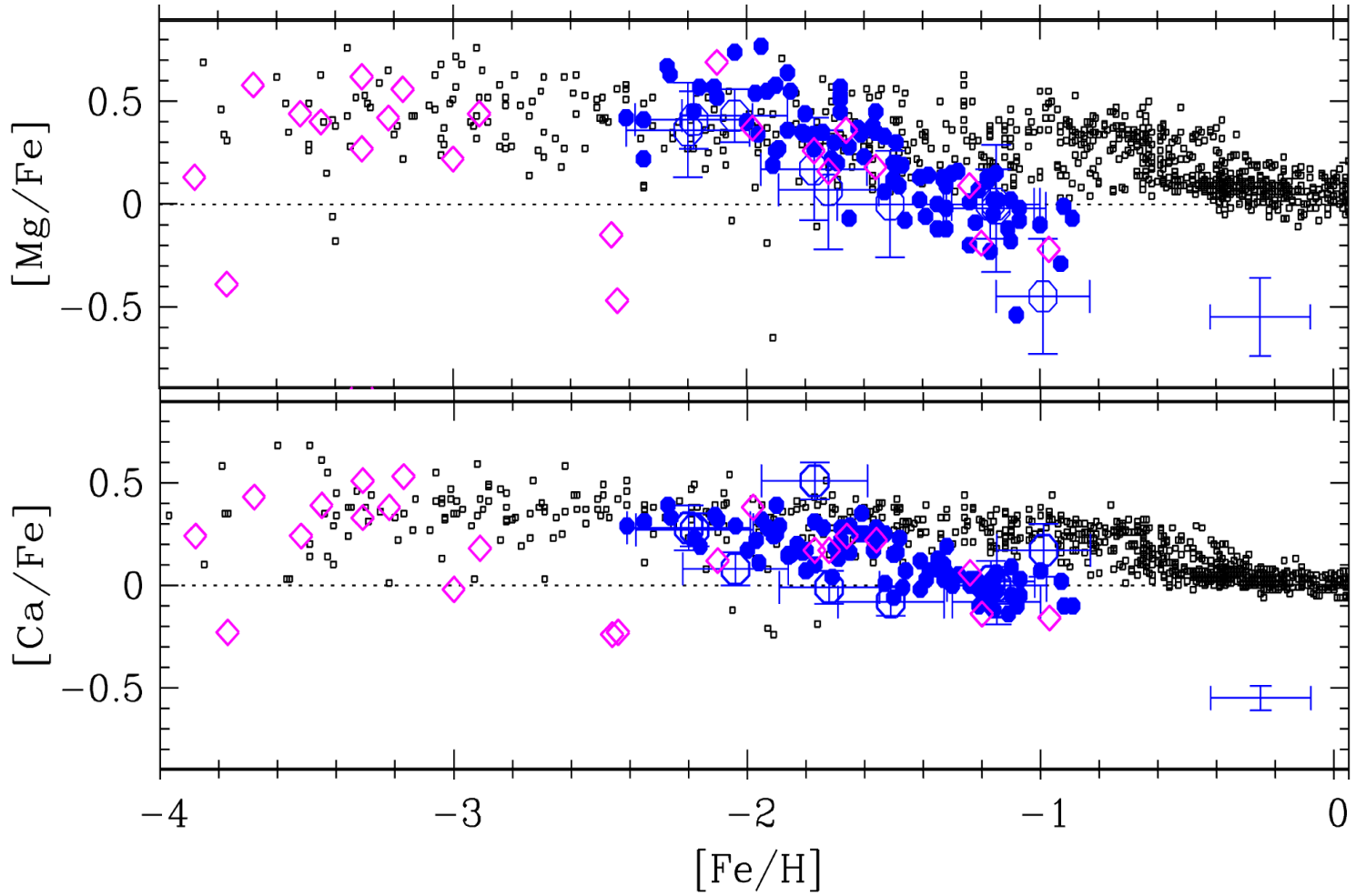
$10^0$
Number of stars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−1
0
[Fe/H]