Unravelling the chemical history of the Milky Way

Chiara Battistini
ZAH - LSW

Outline

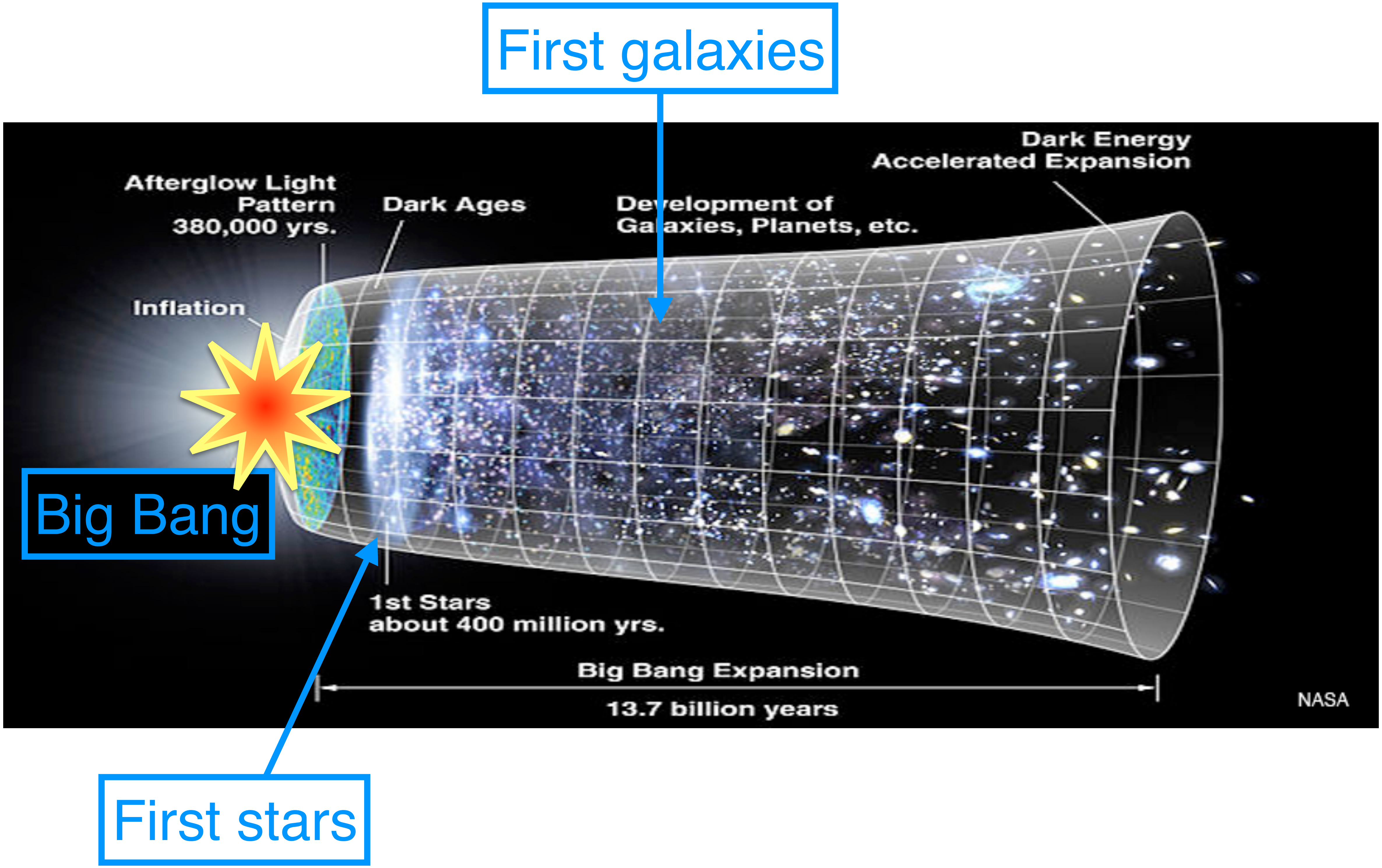
- Basics of stellar evolution
- Basics of abundance studies

First lecture

- Galactic components
- Galactic surveys

Second lecture

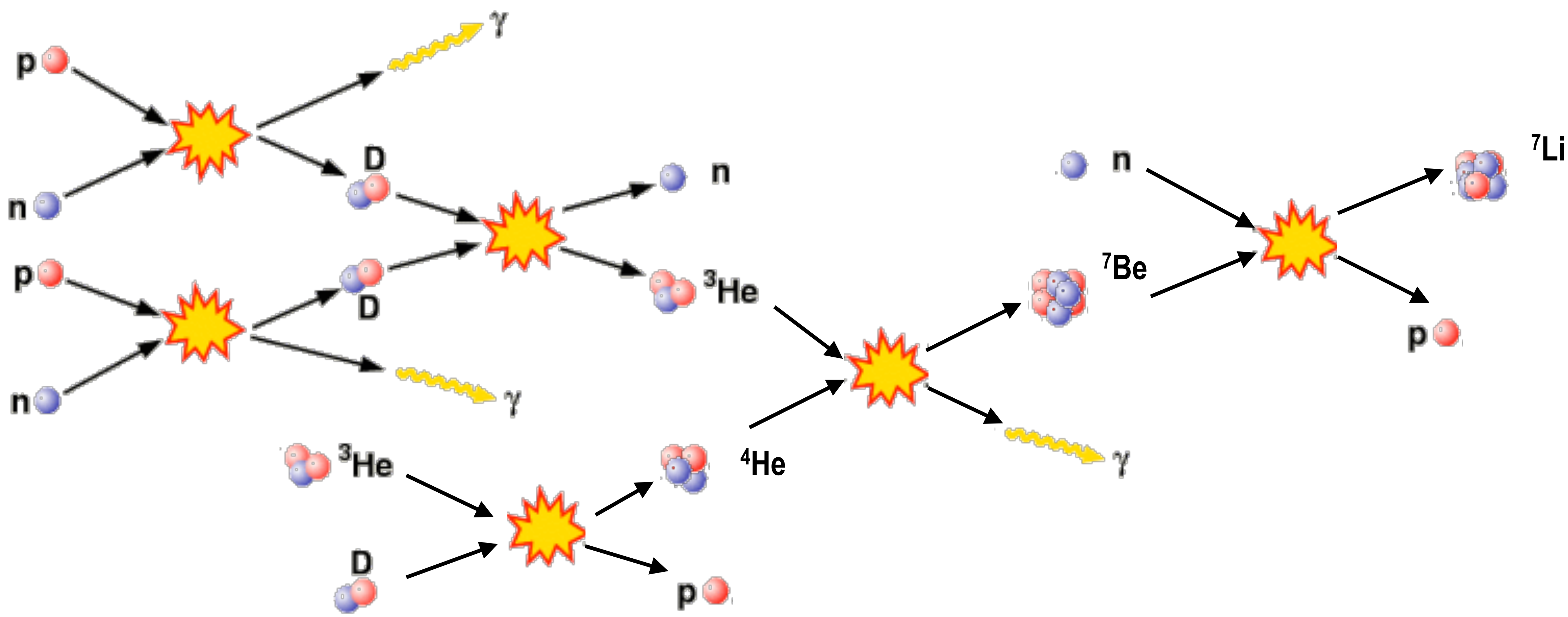
How everything formed…



Big Bang

Temperature extremely high (~10^{10} K)

After few minutes we had the formation of the first elements



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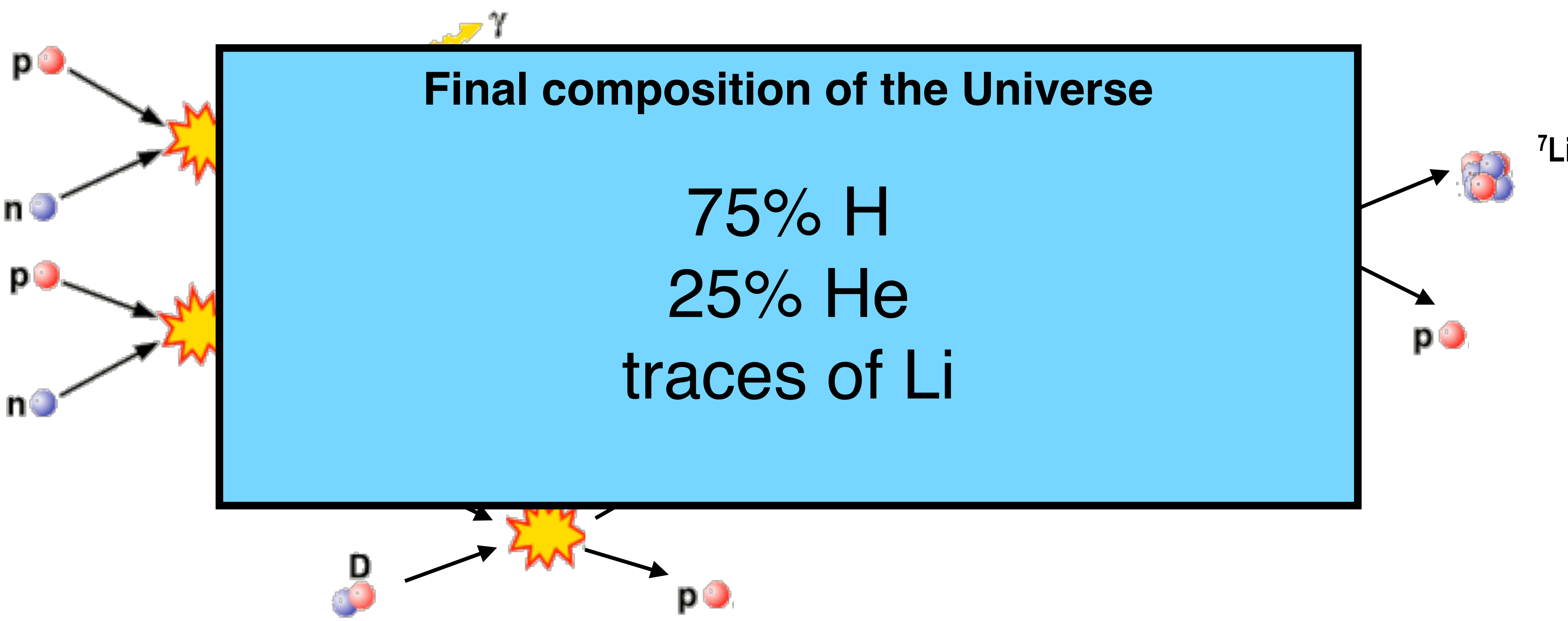
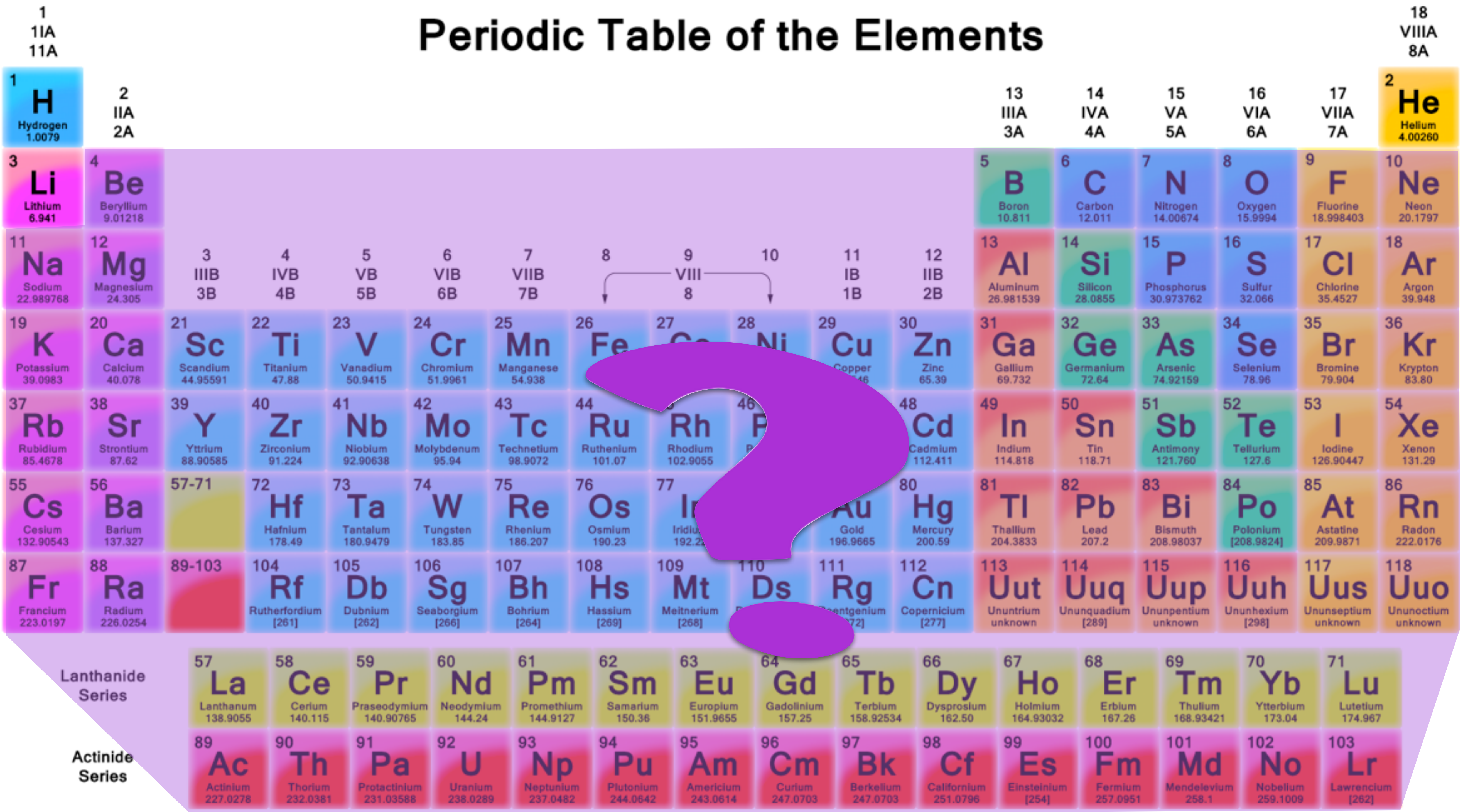


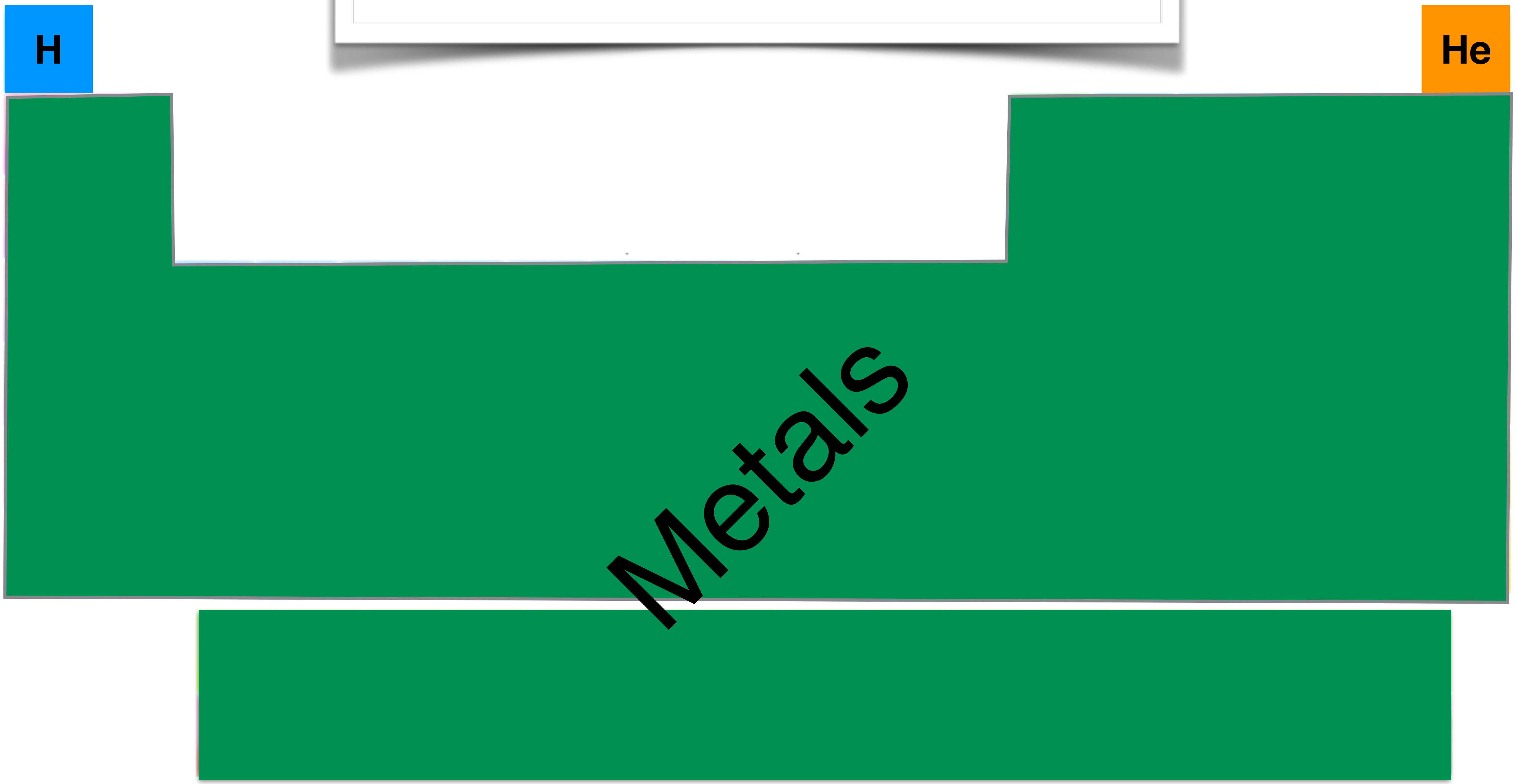
Final composition of the Universe

75% H
25% He
traces of Li



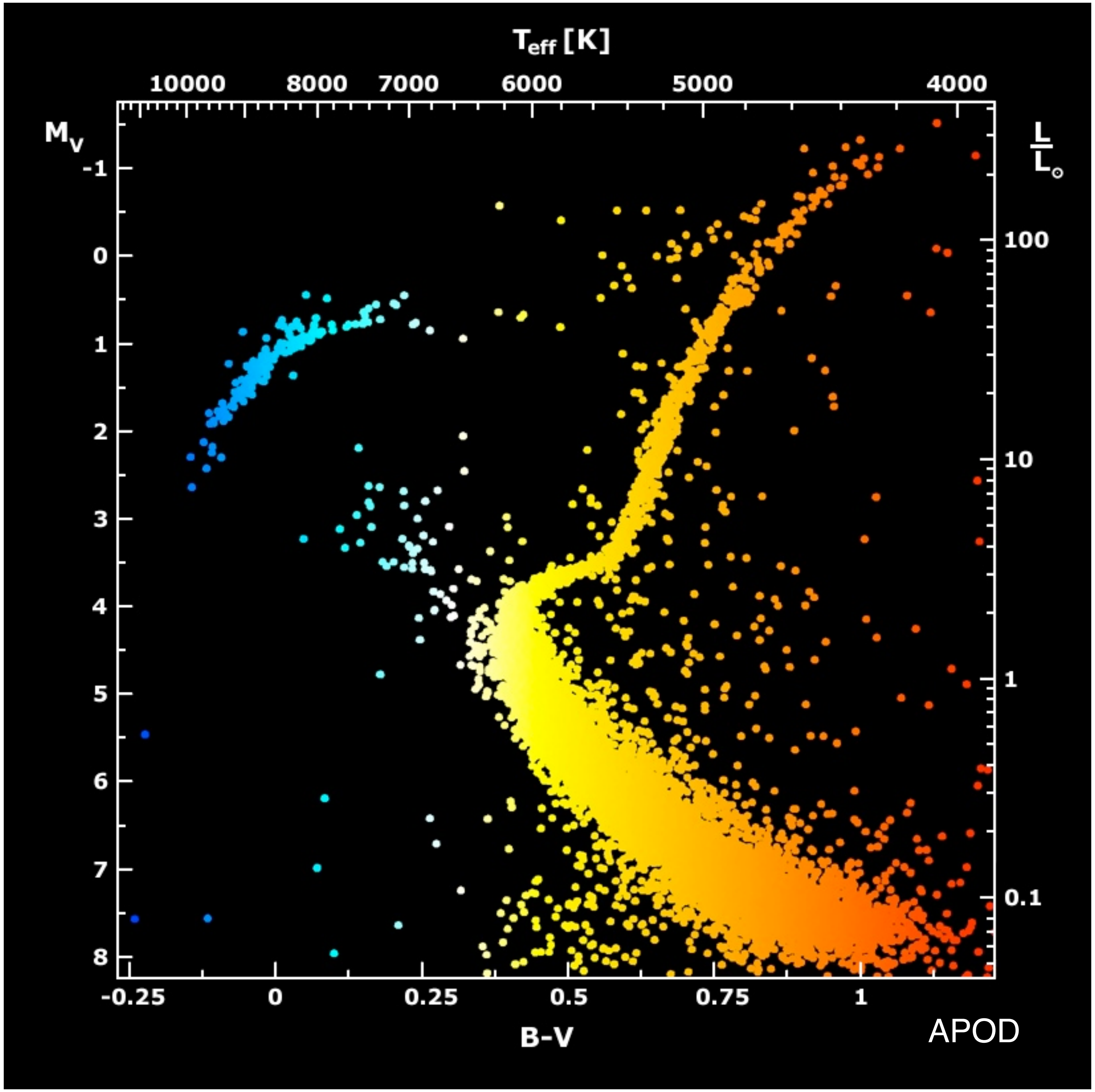
Periodic Table of the Elements
1 1IA 11A
2 IIA 2A
13 IIIA 3A
14 IVA 4A
15 VA 5A
16 VIA 6A
17 VIIA 7A
18 VIIIA 8A
3 IIIB 3B
4 IVB 4B
5 VB 5B
6 VIB 6B
7 VIIB 7B
8 9 10 VIII 8
11 IB 1B
12 IIB 2B
1 H Hydrogen 1.0079
2 He Helium 4.00260
3 Li Lithium 6.941
4 Be Beryllium 9.01218
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.00674
8 O Oxygen 15.9994
9 F Fluorine 18.998403
10 Ne Neon 20.1797
11 Na Sodium 22.989768
12 Mg Magnesium 24.305
13 Al Aluminum 26.981539
14 Si Silicon 28.0855
15 P Phosphorus 30.973762
16 S Sulfur 32.066
17 Cl Chlorine 35.4527
18 Ar Argon 39.948
19 K Potassium 39.0983
20 Ca Calcium 40.078
21 Sc Scandium 44.95591
22 Ti Titanium 47.88
23 V Vanadium 50.9415
24 Cr Chromium 51.9961
25 Mn Manganese 54.938
26
27
28
29 Cu
30 Zn Zinc 65.39
31 Ga Gallium 69.732
32 Ge Germanium 72.64
33 As Arsenic 74.92159
34 Se Selenium 78.96
35 Br Bromine 79.904
36 Kr Krypton 83.80
37 Rb Rubidium 85.4678
38 Sr Strontium 87.62
39 Y Yttrium 88.90585
40 Zr Zirconium 91.224
41 Nb Niobium 92.90638
42 Mo Molybdenum 95.94
43 Tc Technetium 98.9072
44 Ru Ruthenium 101.07
Rh Rhodium 102.9055
46
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.71
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.90447
54 Xe Xenon 131.29
55 Cs Cesium 132.90543
56 Ba Barium 137.327
57-71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.9479
74 W Tungsten 183.85
75 Re Rhenium 186.207
76 Os Osmium 190.23
77
Gold 196.9665
80 Hg Mercury 200.59
81 Tl Thallium 204.3833
82 Pb Lead 207.2
83 Bi Bismuth 208.98037
84 Po Polonium [208.9824]
85 At Astatine 209.9871
86 Rn Radon 222.0176
87 Fr Francium 223.0197
88 Ra Radium 226.0254
89-103
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [268]
110 Ds
111 Rg
112 Cn Copernicium [277]
113 Uut Ununtrium unknown
114 Uuq Ununquadium [289]
115 Uup Ununpentium unknown
116 Uuh Ununhexium [298]
117 Uus Ununseptium unknown
118 Uuo Ununoctium unknown
Lanthanide Series
57 La Lanthanum 138.9055
58 Ce Cerium 140.115
59 Pr Praseodymium 140.90765
60 Nd Neodymium 144.24
61 Pm Promethium 144.9127
62 Sm Samarium 150.36
63 Eu Europium 151.9655
64 Gd Gadolinium 157.25
65 Tb Terbium 158.92534
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93032
68 Er Erbium 167.26
69 Tm Thulium 168.93421
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
Actinide Series
89 Ac Actinium 227.0278
90 Th Thorium 232.0381
91 Pa Protactinium 231.03588
92 U Uranium 238.0289
93 Np Neptunium 237.0482
94 Pu Plutonium 244.0642
95 Am Americium 243.0614
96 Cm Curium 247.0703
97 Bk Berkelium 247.0703
98 Cf Californium 251.0796
99 Es Einsteinium [254]
100 Fm Fermium 257.0951
101 Md Mendelevium 258.1
102 No Nobelium 259.1009
103 Lr Lawrencium [262]

Table of the elements for astronomers

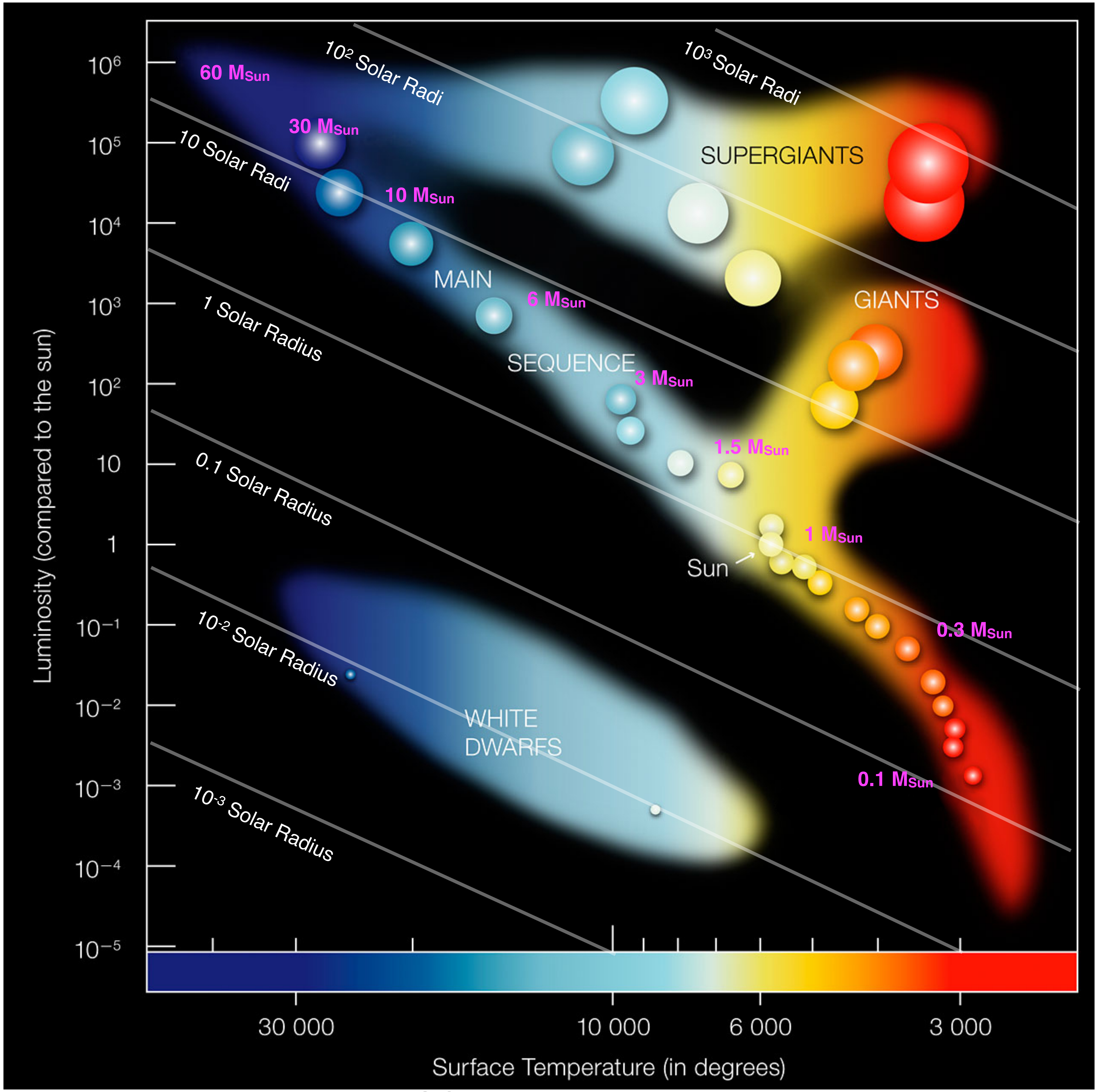



Stellar
evolution
ESO

Color-Magnitude diagram

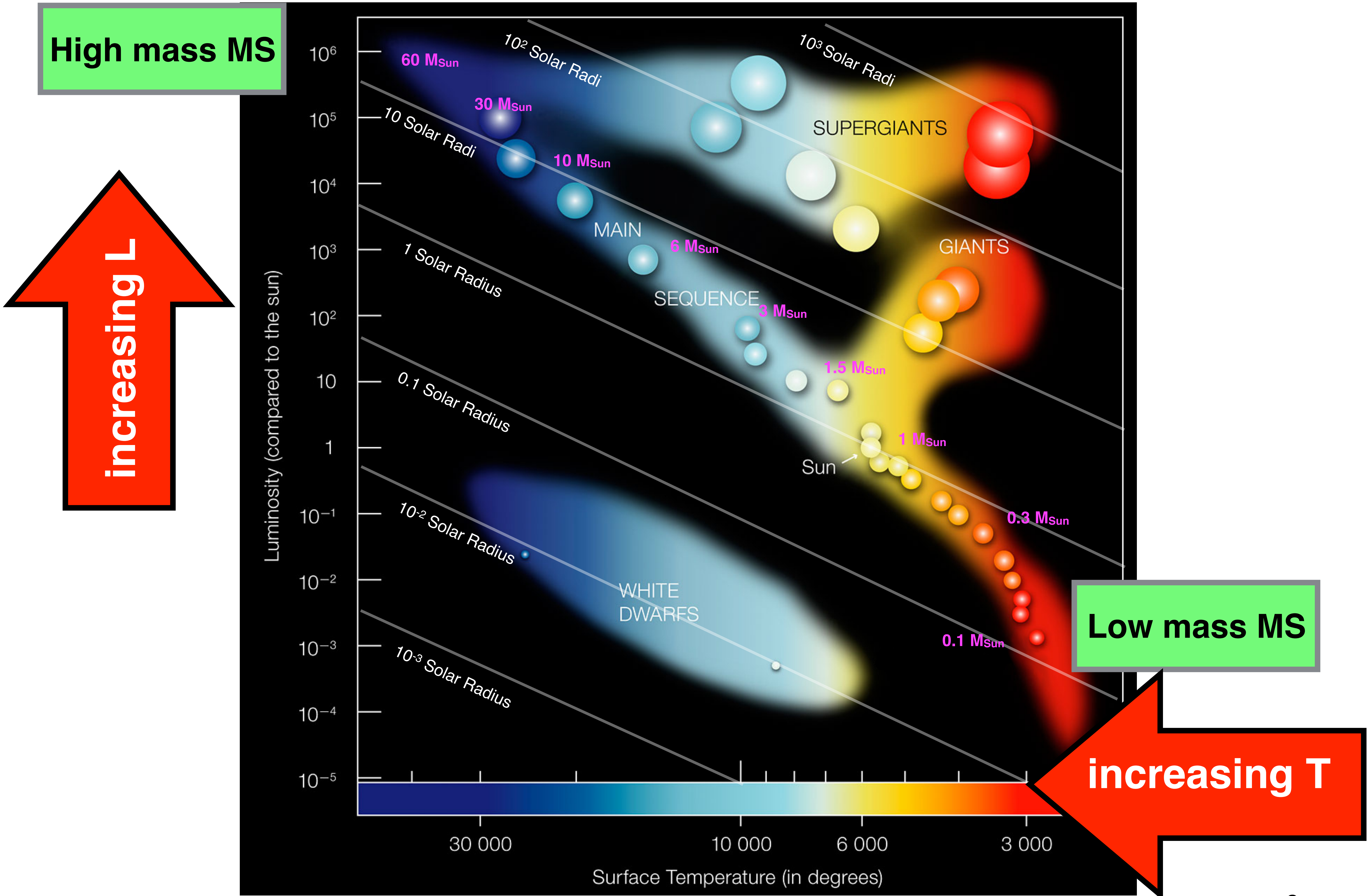


HR diagram



Luminosity (compared to the sun)
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
60 MSun
30 MSun
10 MSun
6 MSun
3 MSun
1.5 MSun
1 MSun
0.3 MSun
0.1 MSun
10^2 Solar Radi
10^3 Solar Radi
10 Solar Radi
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
Sun
WHITE
DWARFS
30 000
10 000
6 000
3 000
Surface Temperature (in degrees)

HR diagram


High mass MS
increasing L
Low mass MS
increasing T
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Luminosity (compared to the sun)
60 MSun
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SUPERGIANTS
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MAIN
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Sun
WHITE
DWARFS
30 000
10 000
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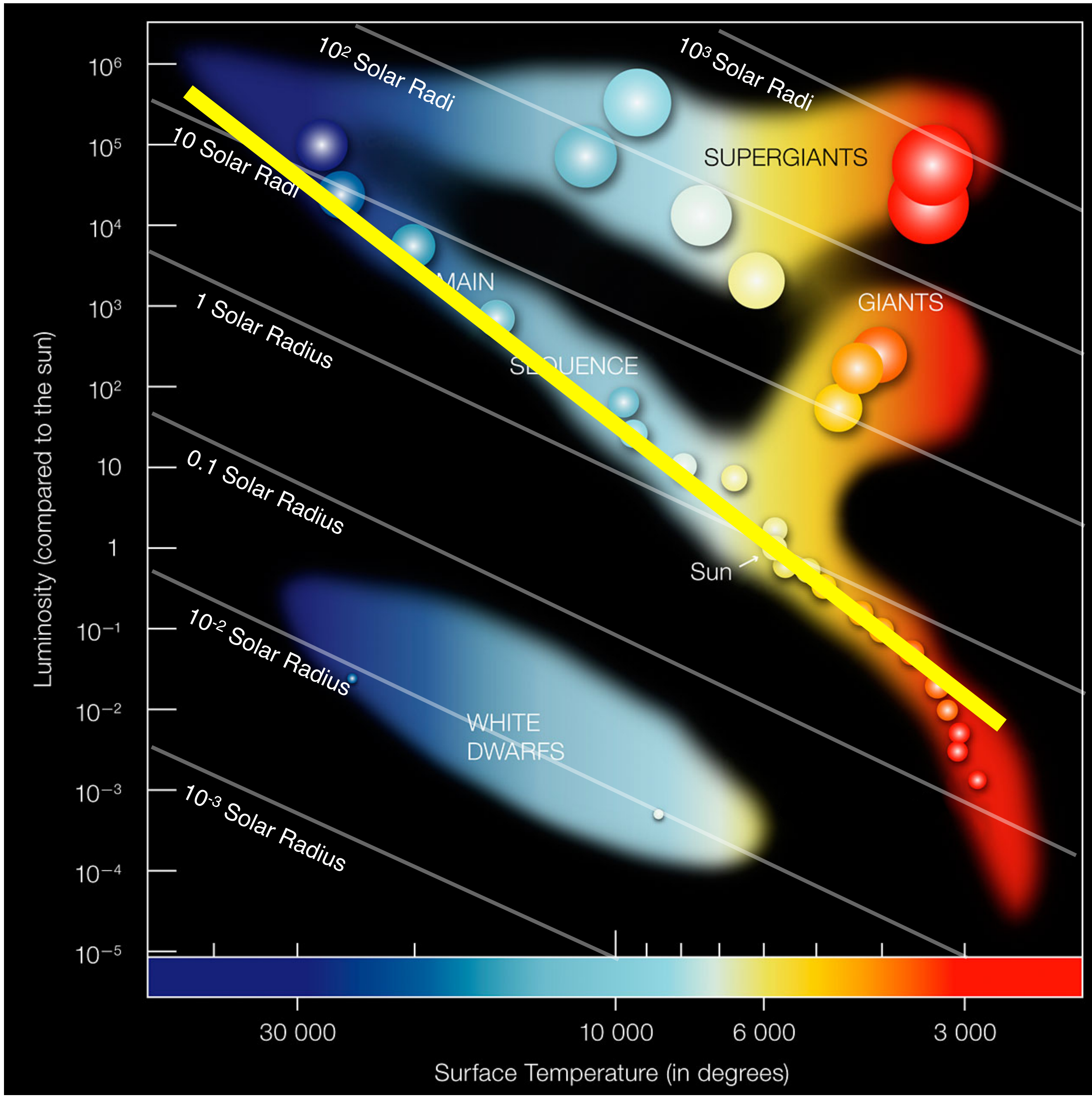
Mass-Luminosity relation



$$L \propto M_*^{\nu} \quad \nu = 3 - 5$$

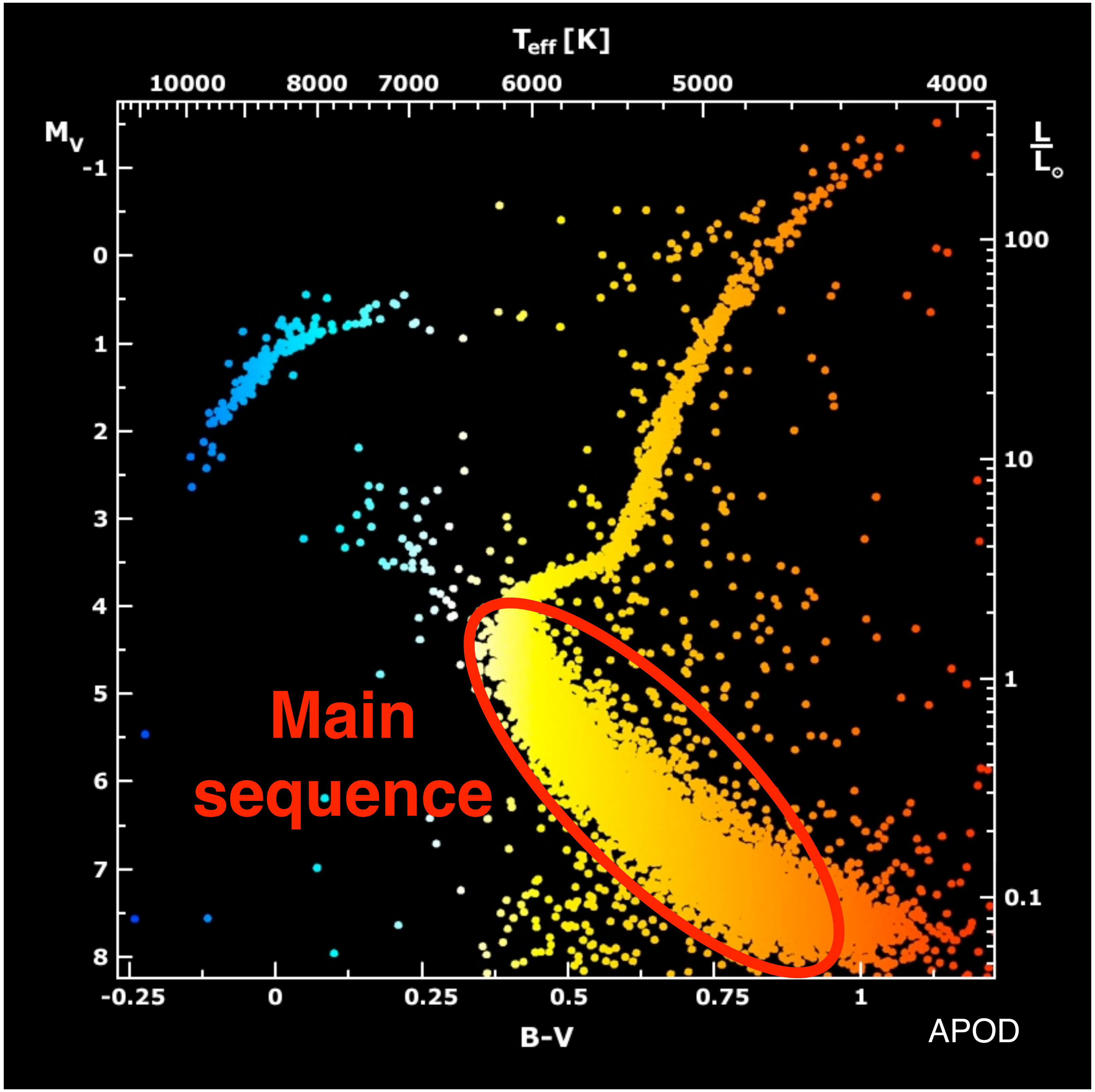
$$\tau_{MS} \propto \frac{M_*}{L} \propto M_*^{1-\nu}$$

$$M_* \nearrow \quad \tau_{MS} \searrow\searrow\searrow$$

$$M_* = 10 M_\odot \Longrightarrow \tau_{MS} \approx 10^8 yr$$

$$M_* = 1 M_\odot \Longrightarrow \tau_{MS} \approx 10^{10} yr$$

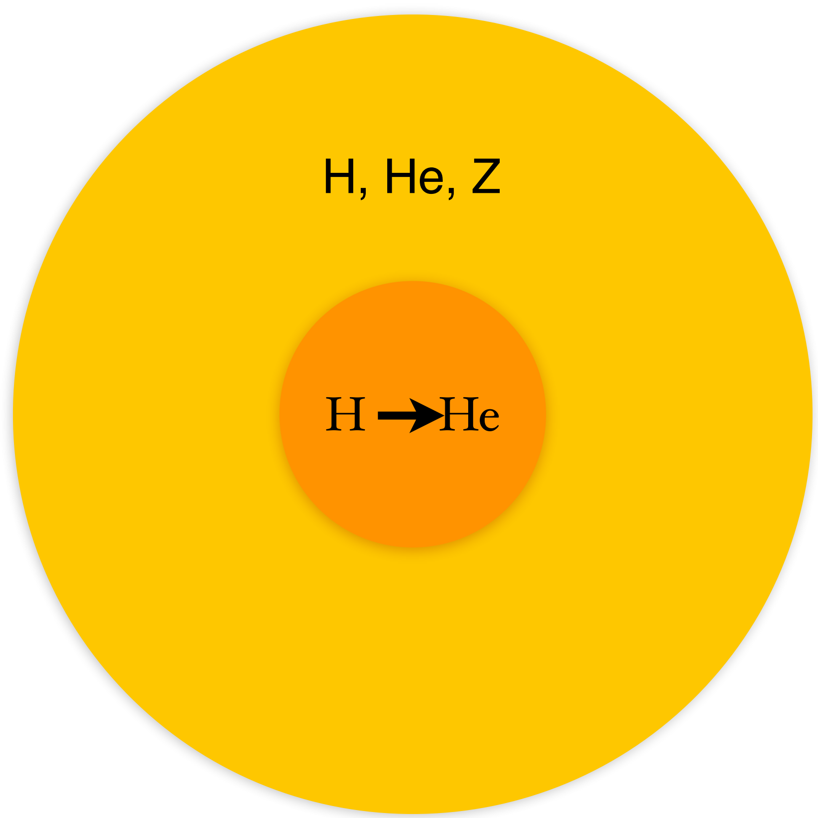
$$M_* = 0.1 M_\odot \Longrightarrow \tau_{MS} \approx 10^{12} yr$$



T_{eff} [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
$\frac{L}{L_\odot}$
100
10
1
0.1
-0.25
0
0.25
0.5
0.75
1
B-V
Main sequence
APOD

Main-sequence

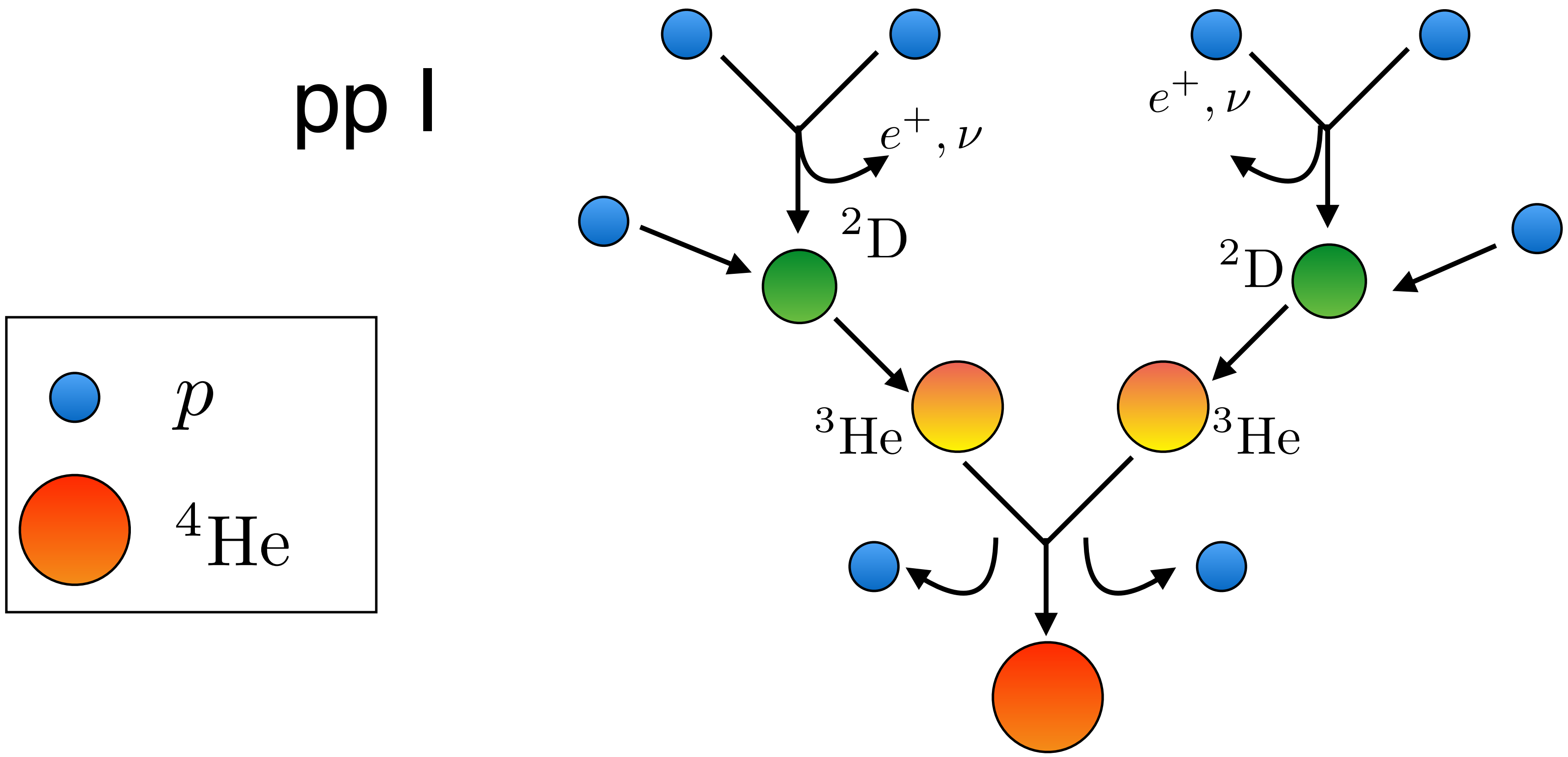
Star is in equilibrium
gravity = radiation pressure



$T_{core} = 10^7$ K

Sun-like stars

pp I



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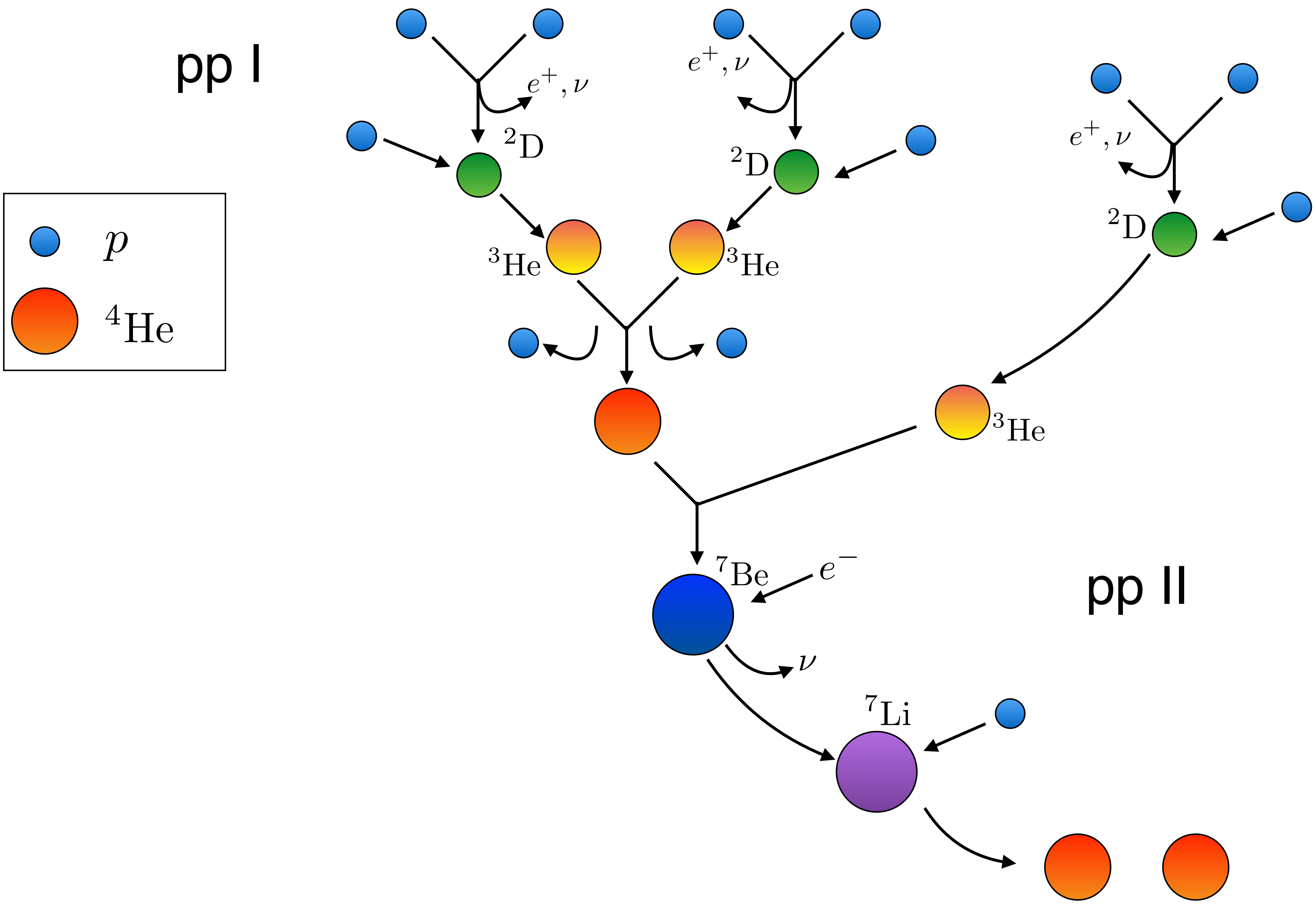

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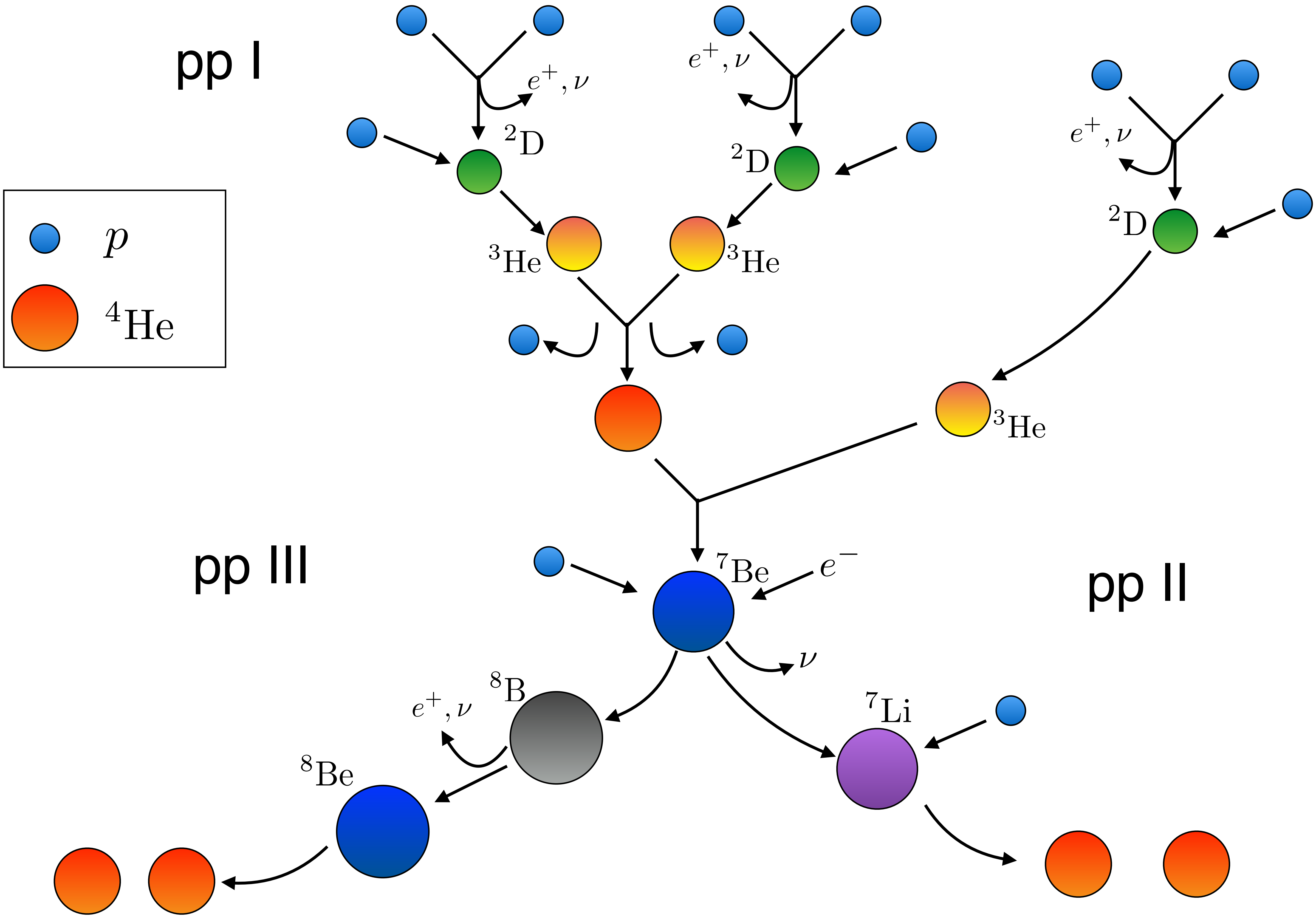

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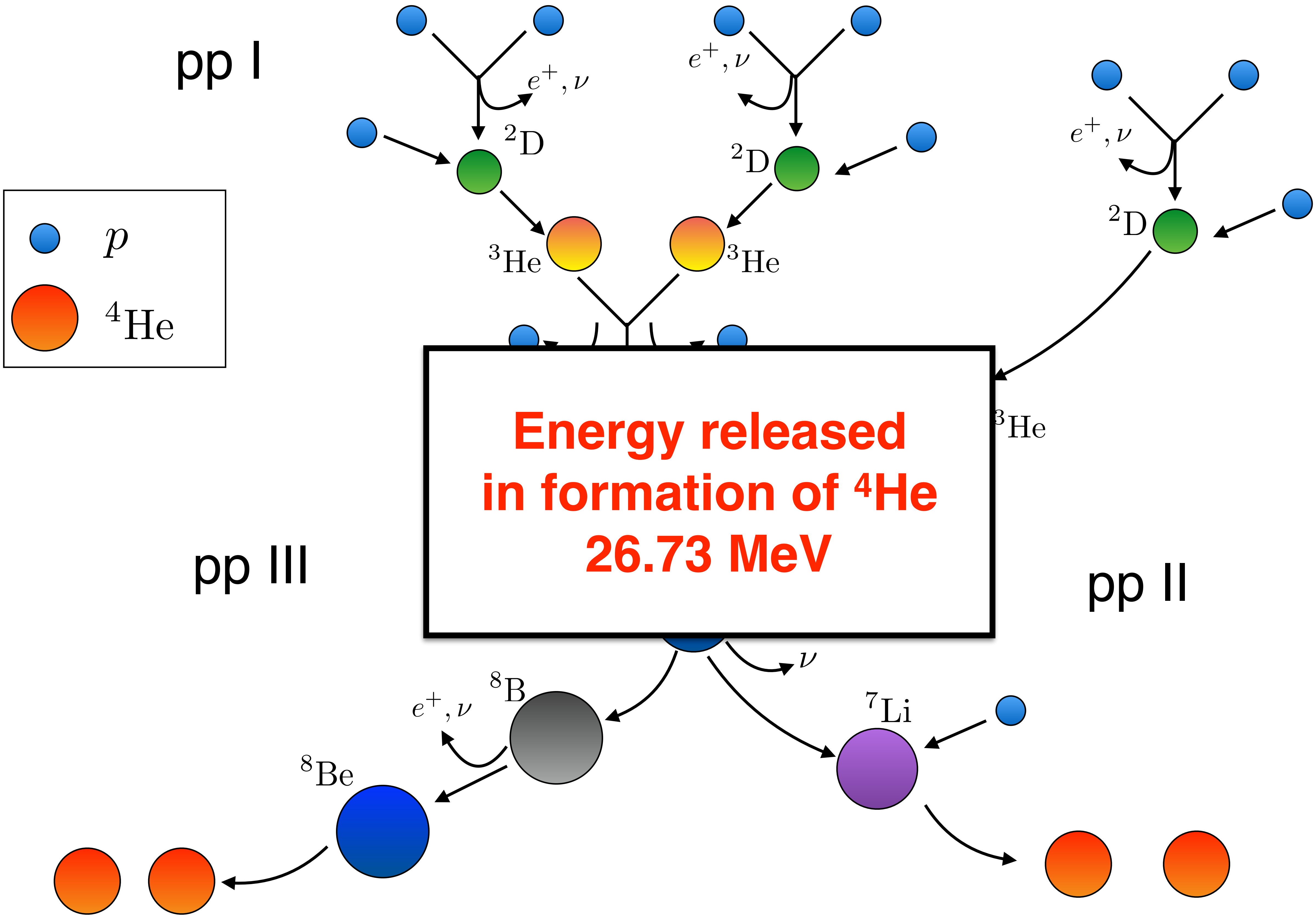


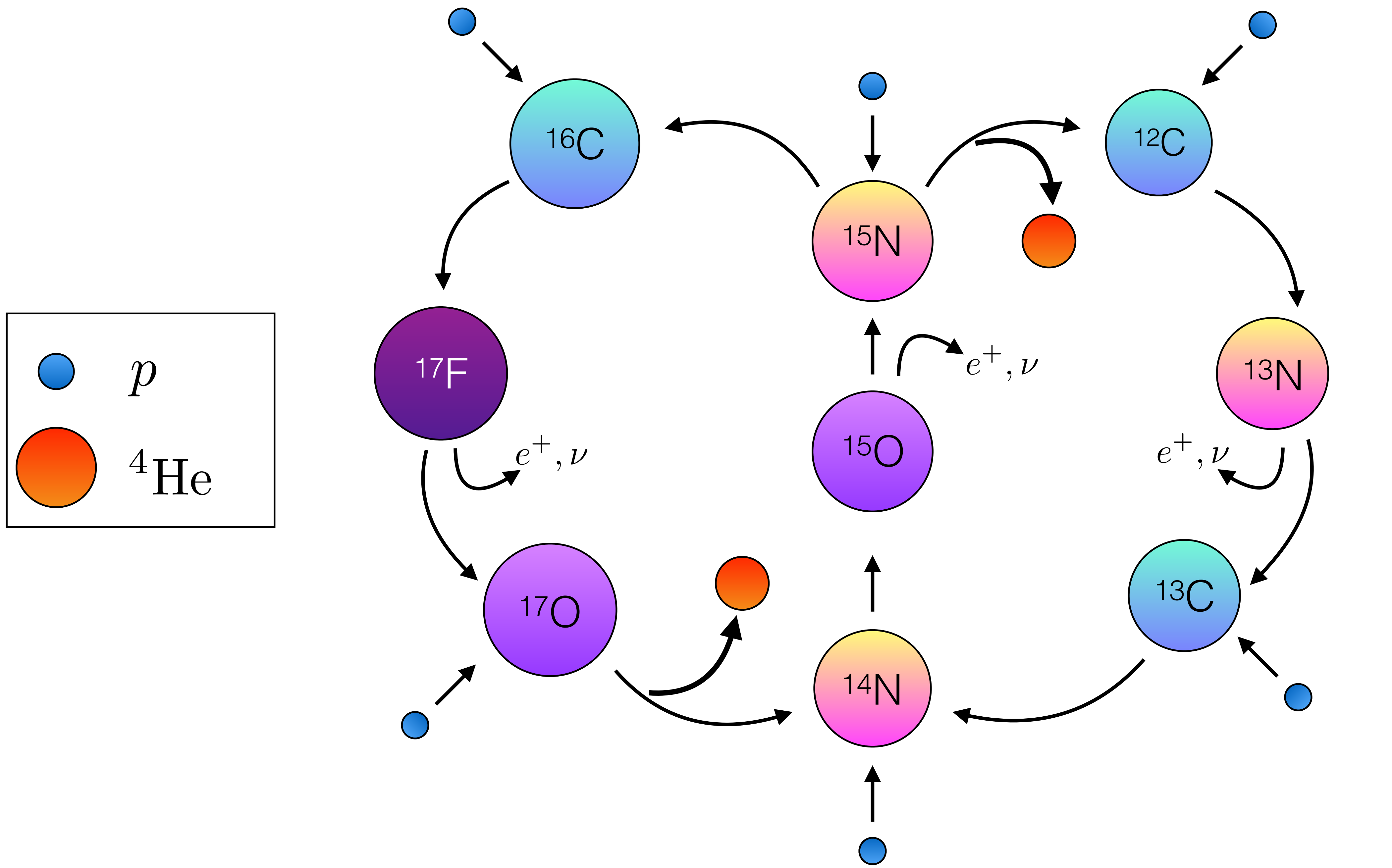
Energy released in formation of ^{4}He 26.73 MeV

Higher-mass stars

Higher quantity of “metals”

+

higher temperature in the centre (~ 2x10^7 K)



CNO cycle

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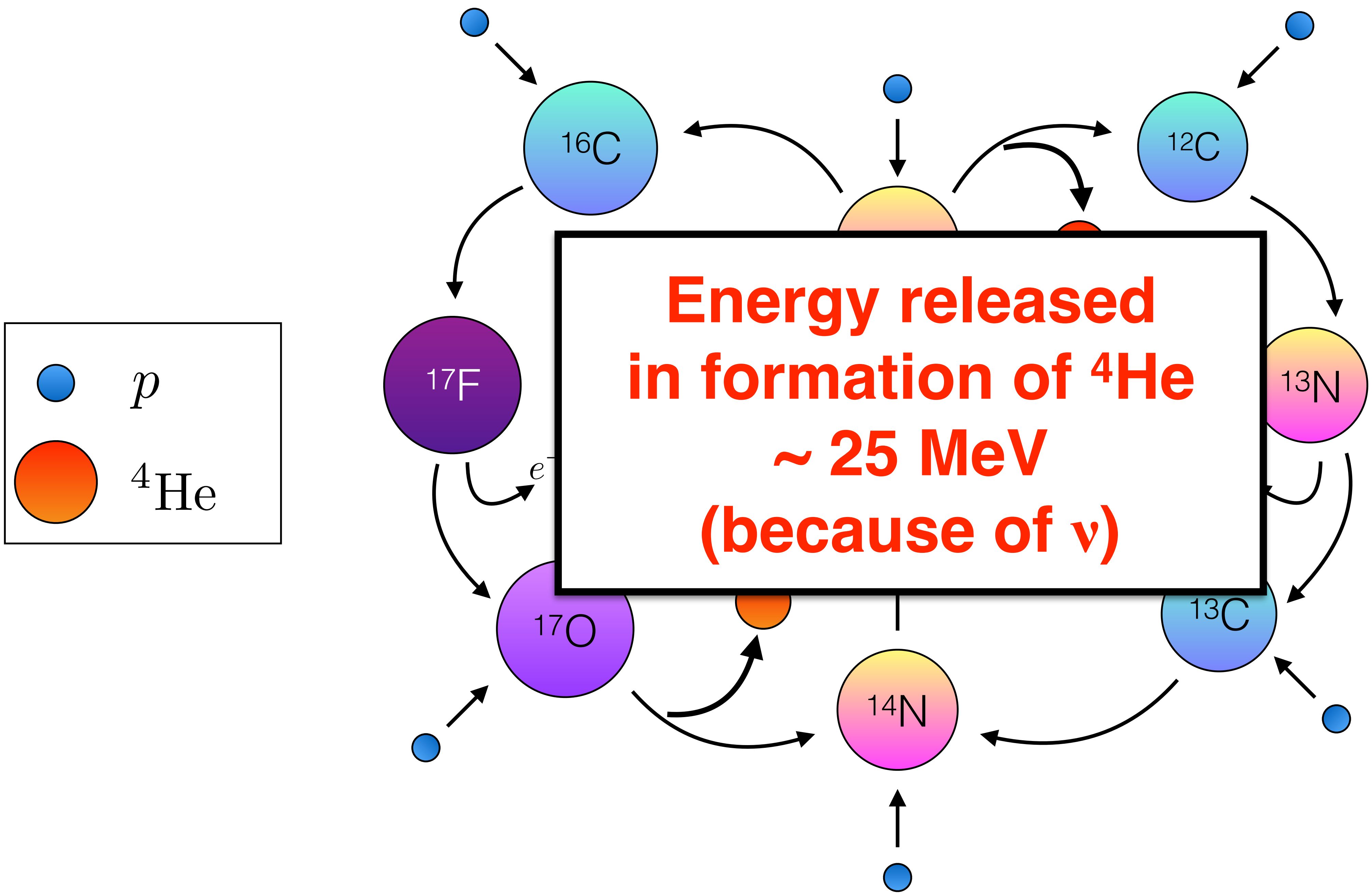
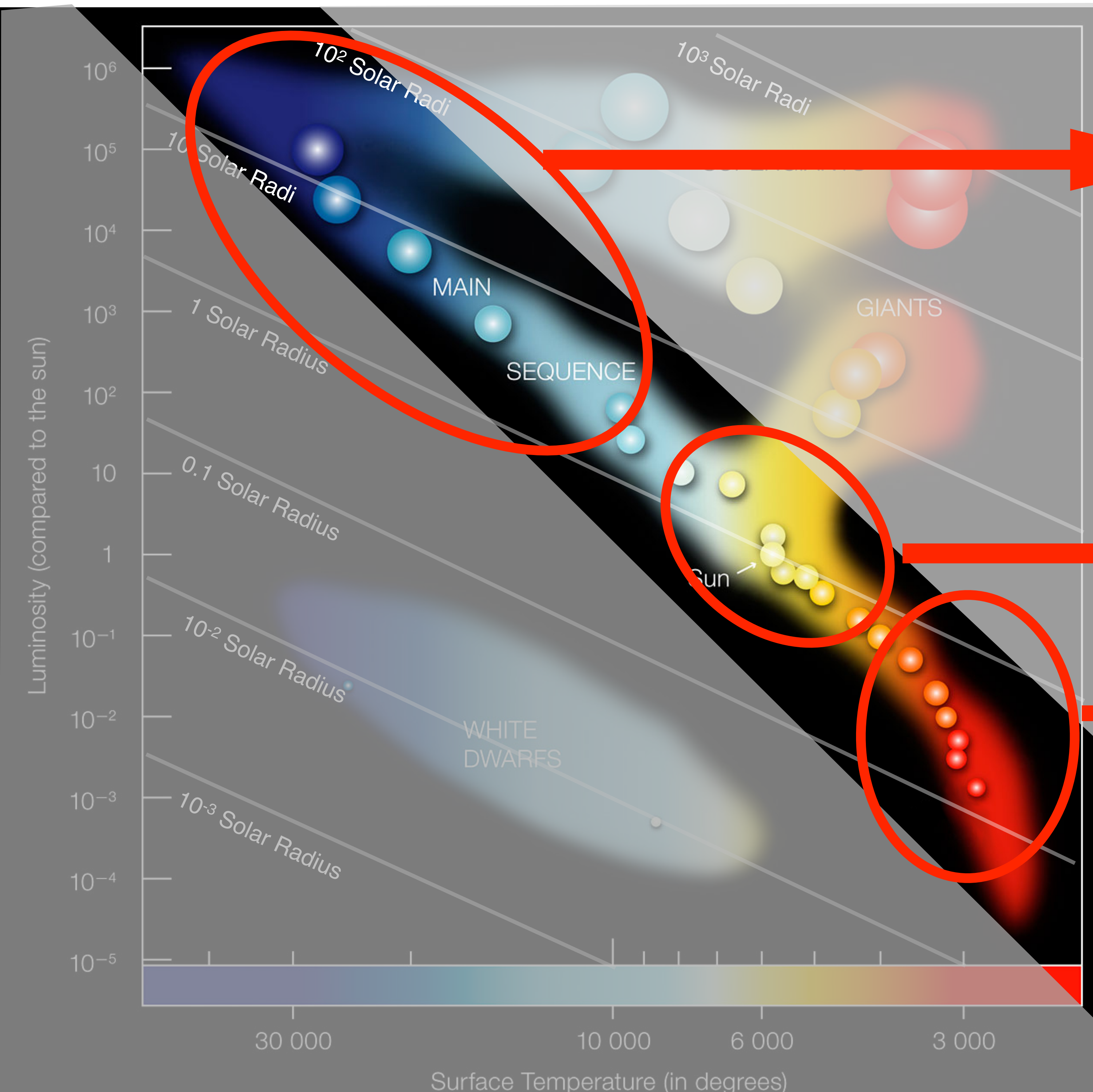
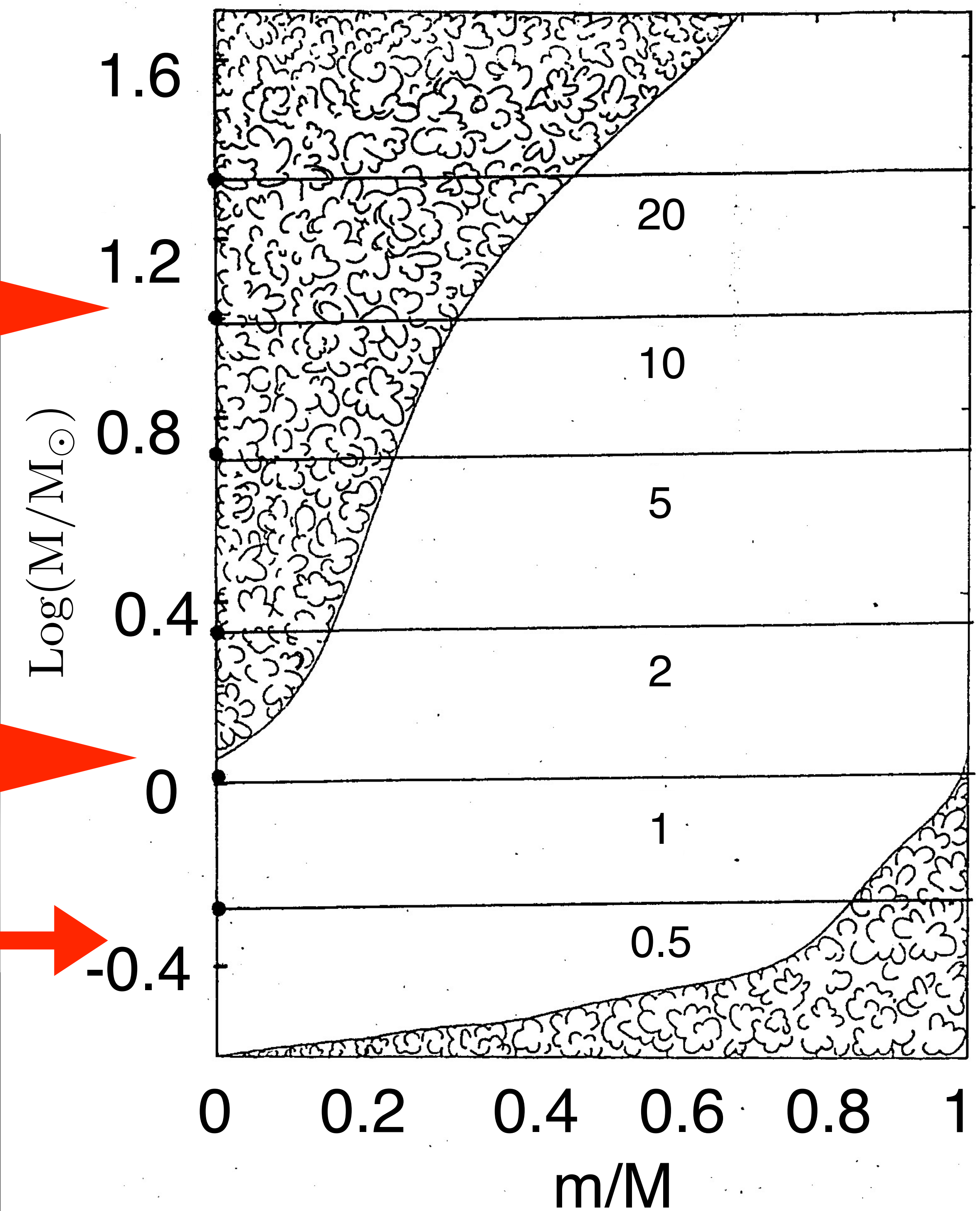


Energy released in formation of ^{4}He ~ 25 MeV (because of ν)

CNO cycle

Convection





adapted from Prialnik

End of Main Sequence

When the H in the center is exhausted...

Star is NOT in equilibrium

gravity > radiation pressure

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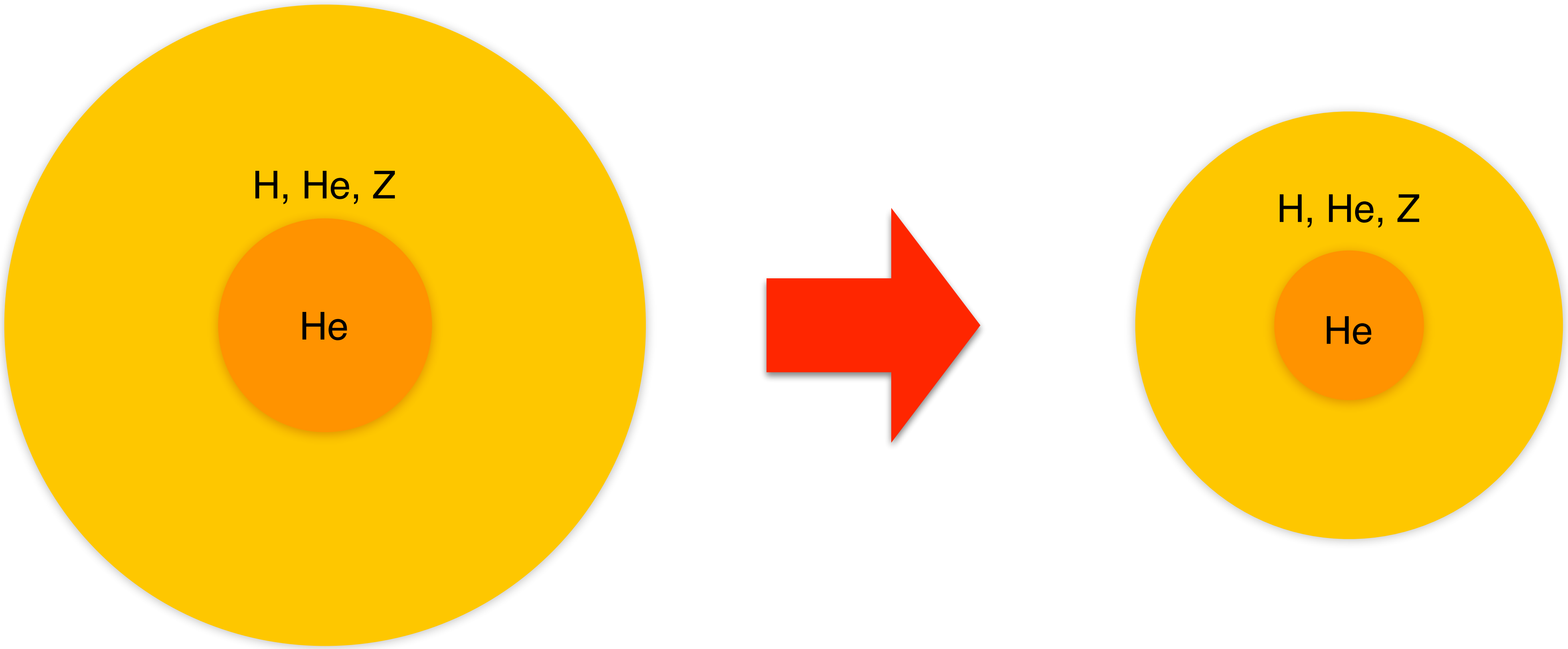

Red Giant Branch

Star contracts —> T increase toward the center

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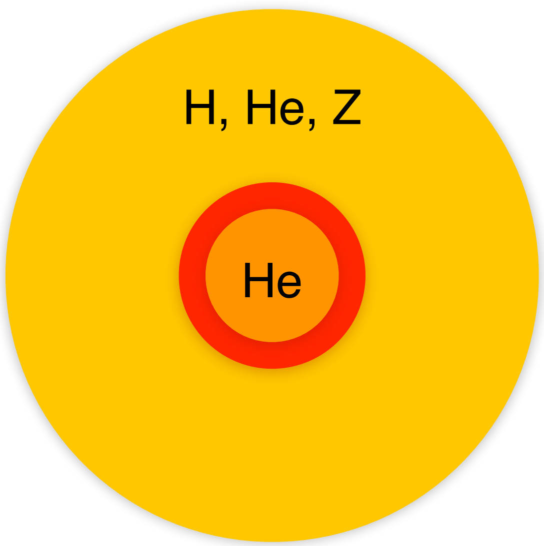

H ⟶ He

via CNO cycle

T_{shell} = 3x10^{7} K

Nuclear reactions in a small shell outside the center

Red Giant Branch

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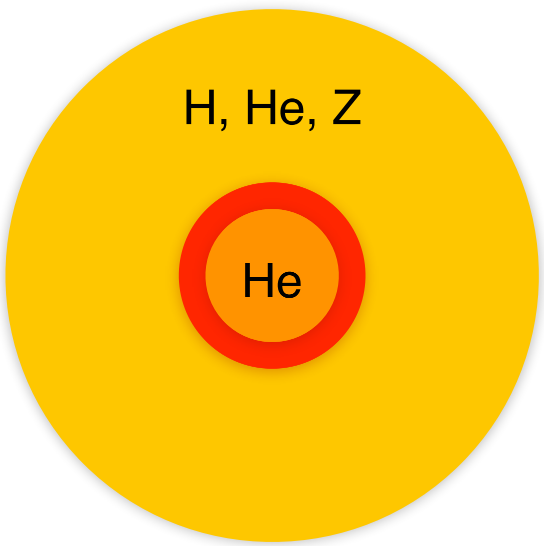

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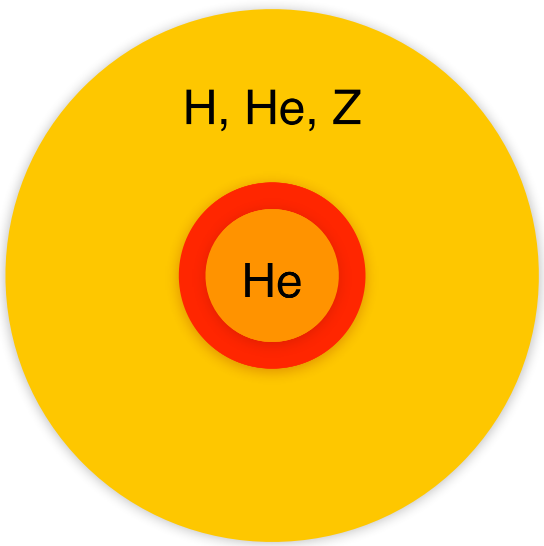

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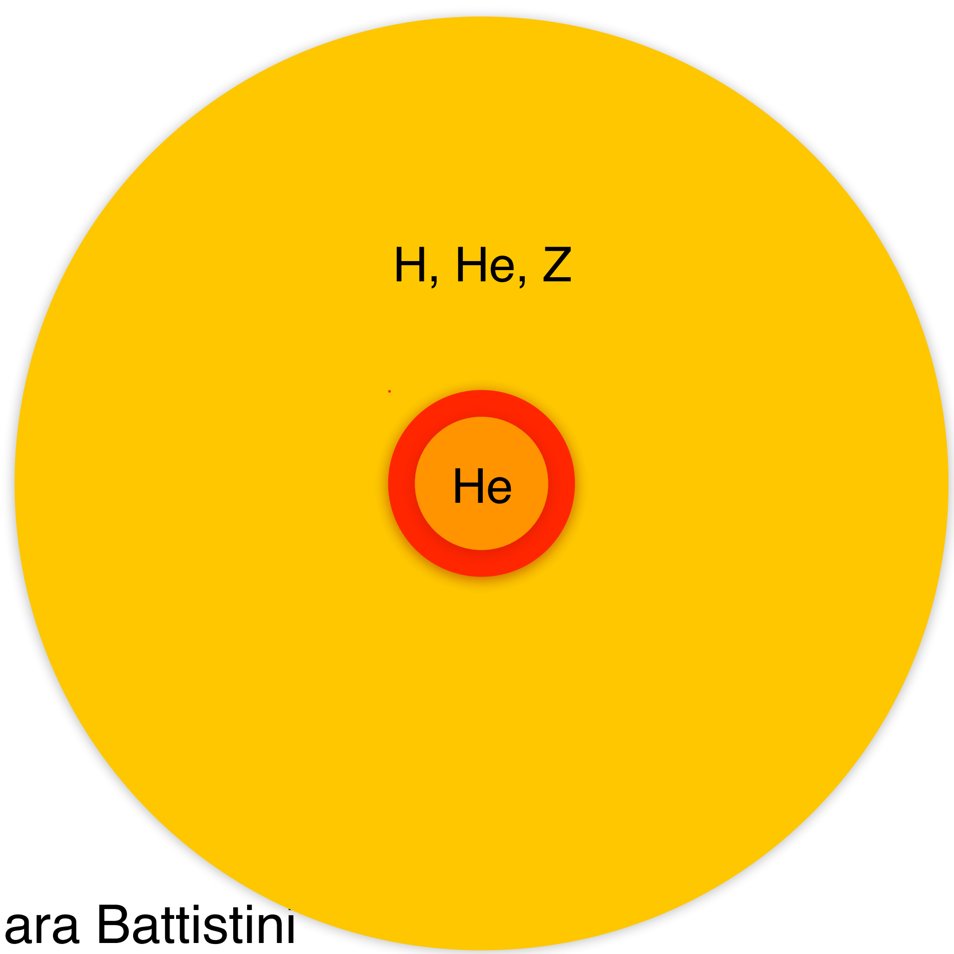

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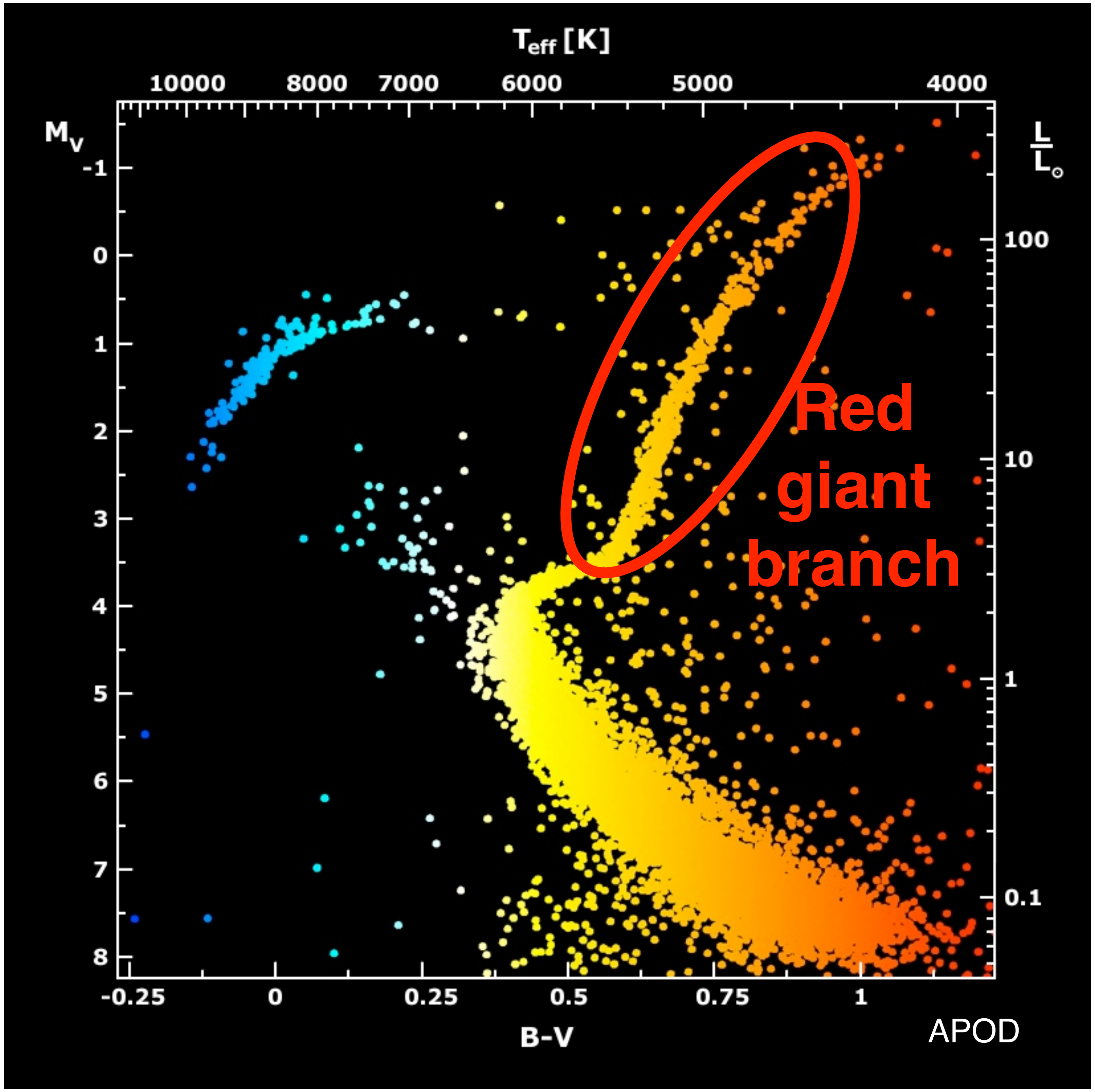
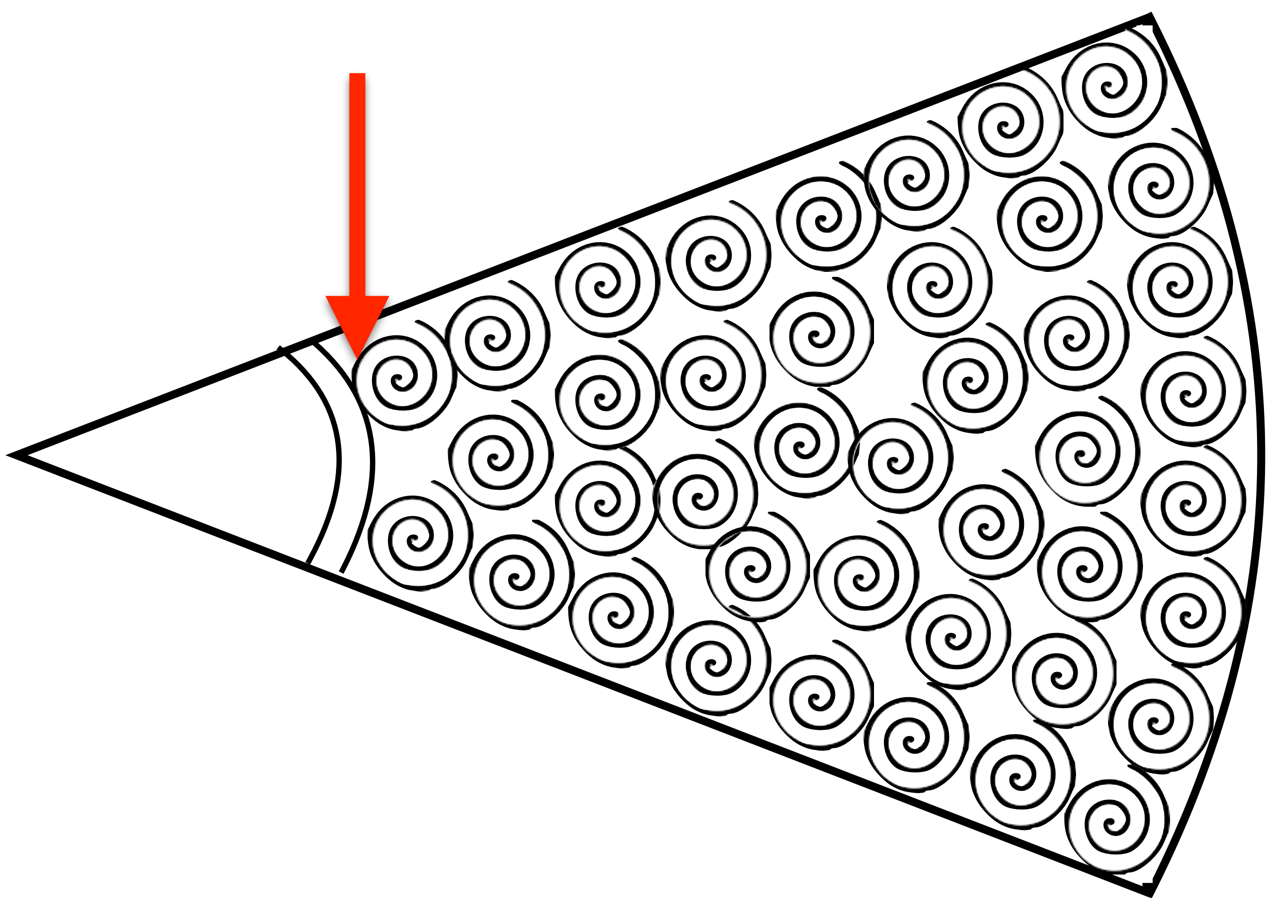

T_eff [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
L/L☉
100
10
1
0.1
-0.25
0
0.25
0.5
0.75
1
B-V
Red giant branch
APOD

Dredge-up

On RGB envelope become convective from just outside the H-shell burning up to surface.
The base of the convective envelope reaches layers where nuclear processes have taken place earlier so H-burning ashes make their way to surface (like He or N)



Mass loss

During RGB phase stars suffer from mass loss do to stellar winds.
The exact relation behind mass loss is still not clear (likely it has some dependency with metallicity)
—> more metal => more mass loss

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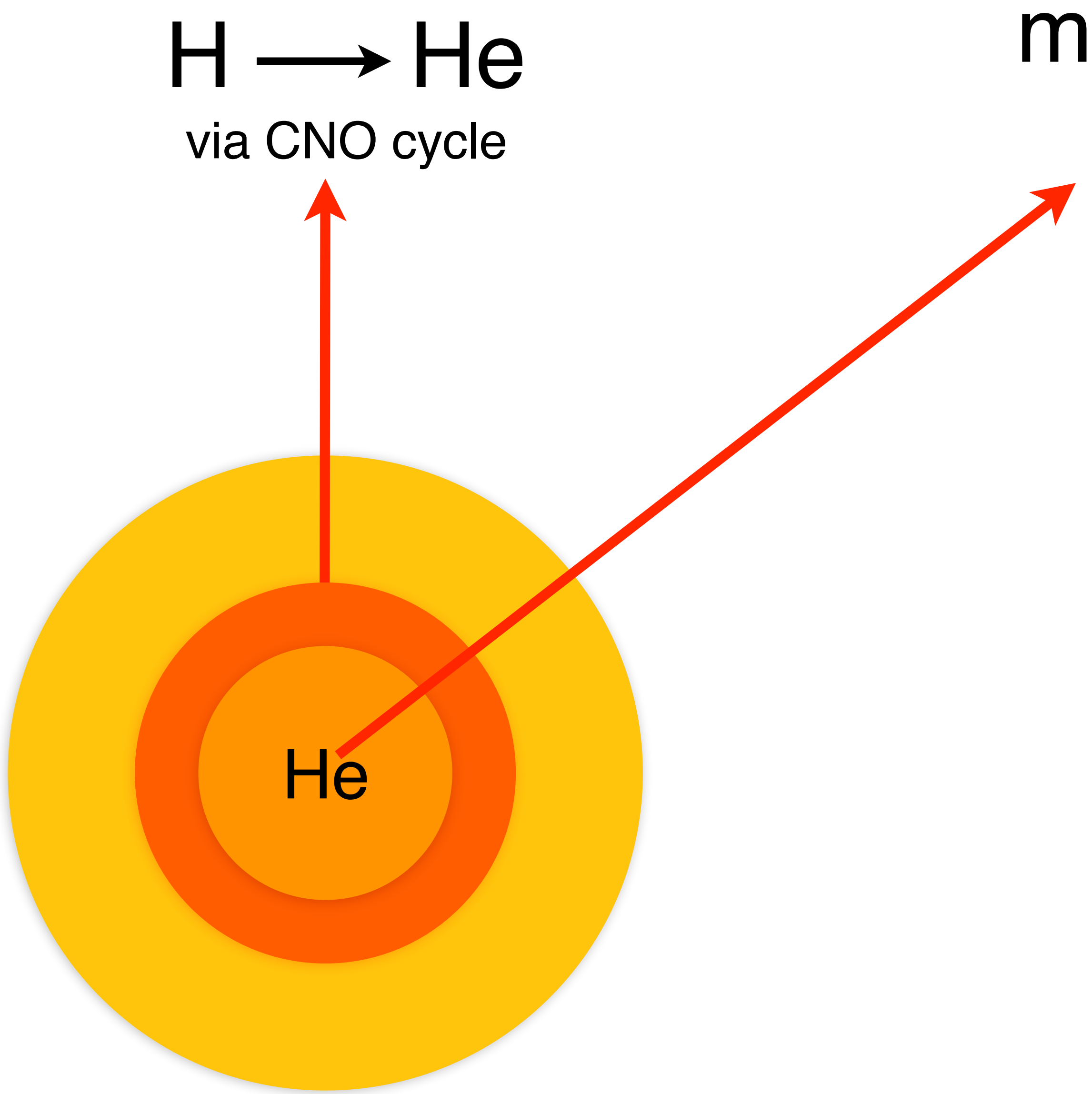
↓

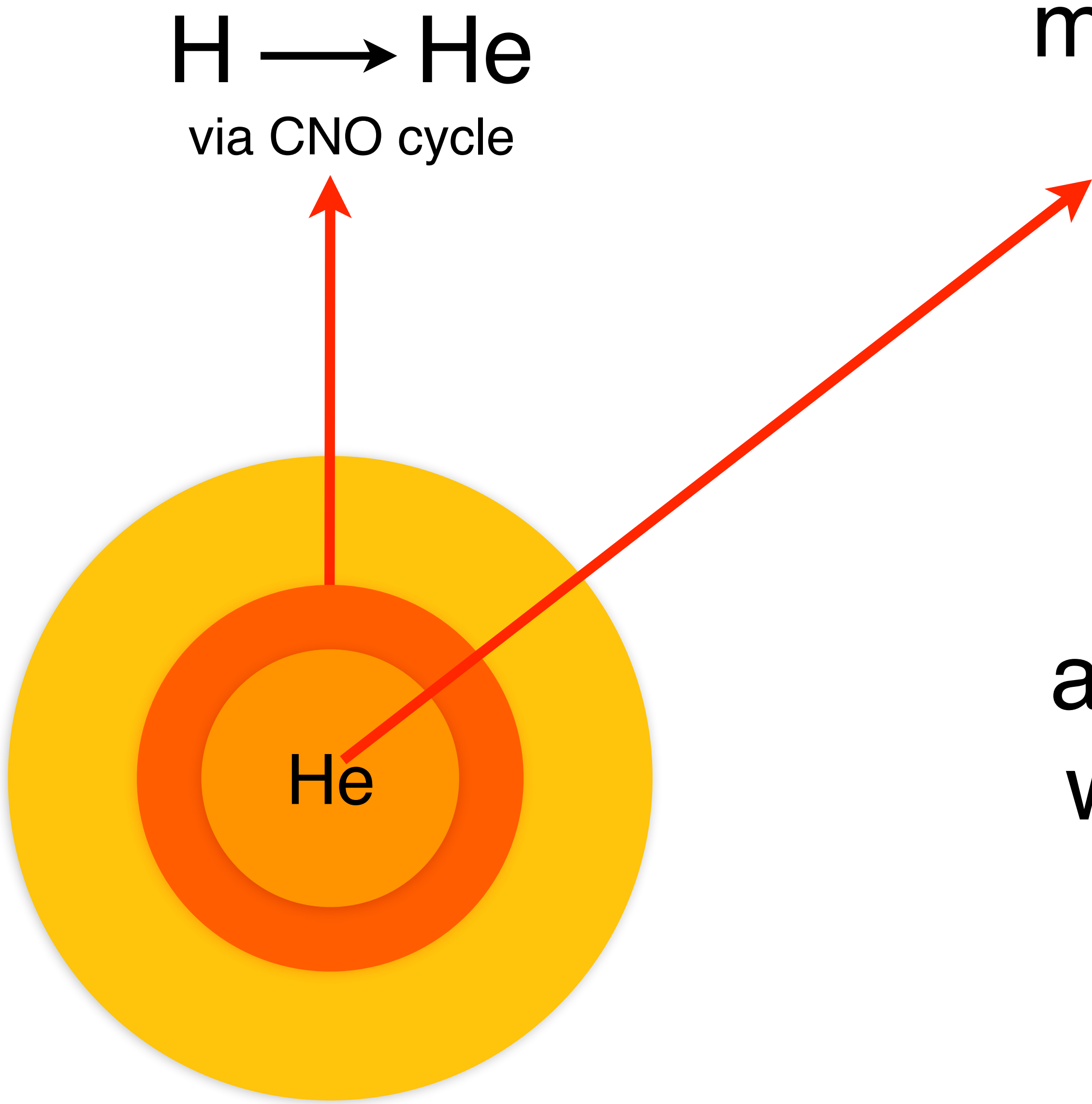
The amount of envelope still present in the star determines where the star will end up in the next evolutionary stage

End of RGB



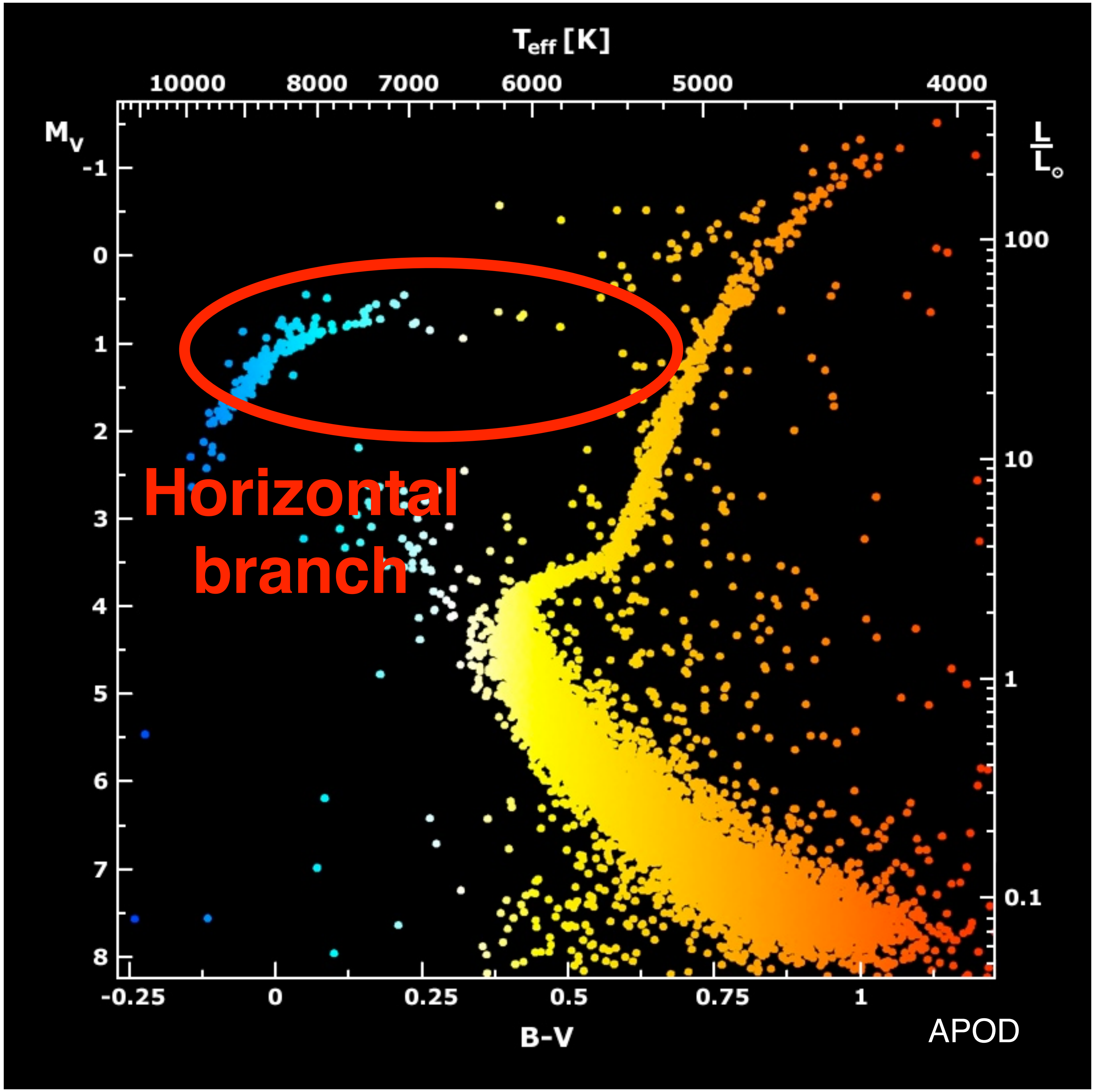
mass of He increases so also the density increases

End of RGB

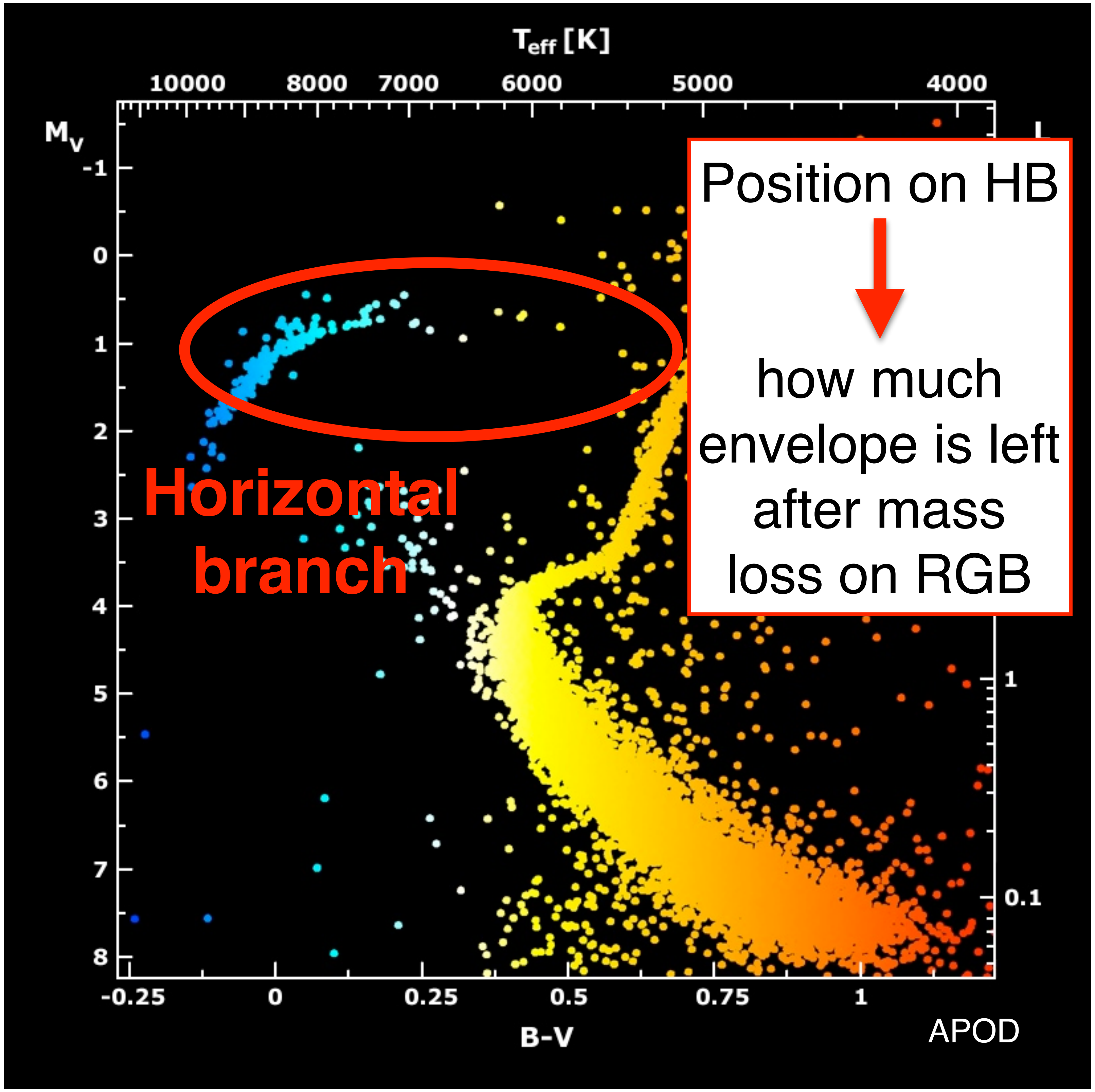


mass of He increases so also the density increases

at some point T in the center will be high enough to ignite He burning (~2×10^8 K)



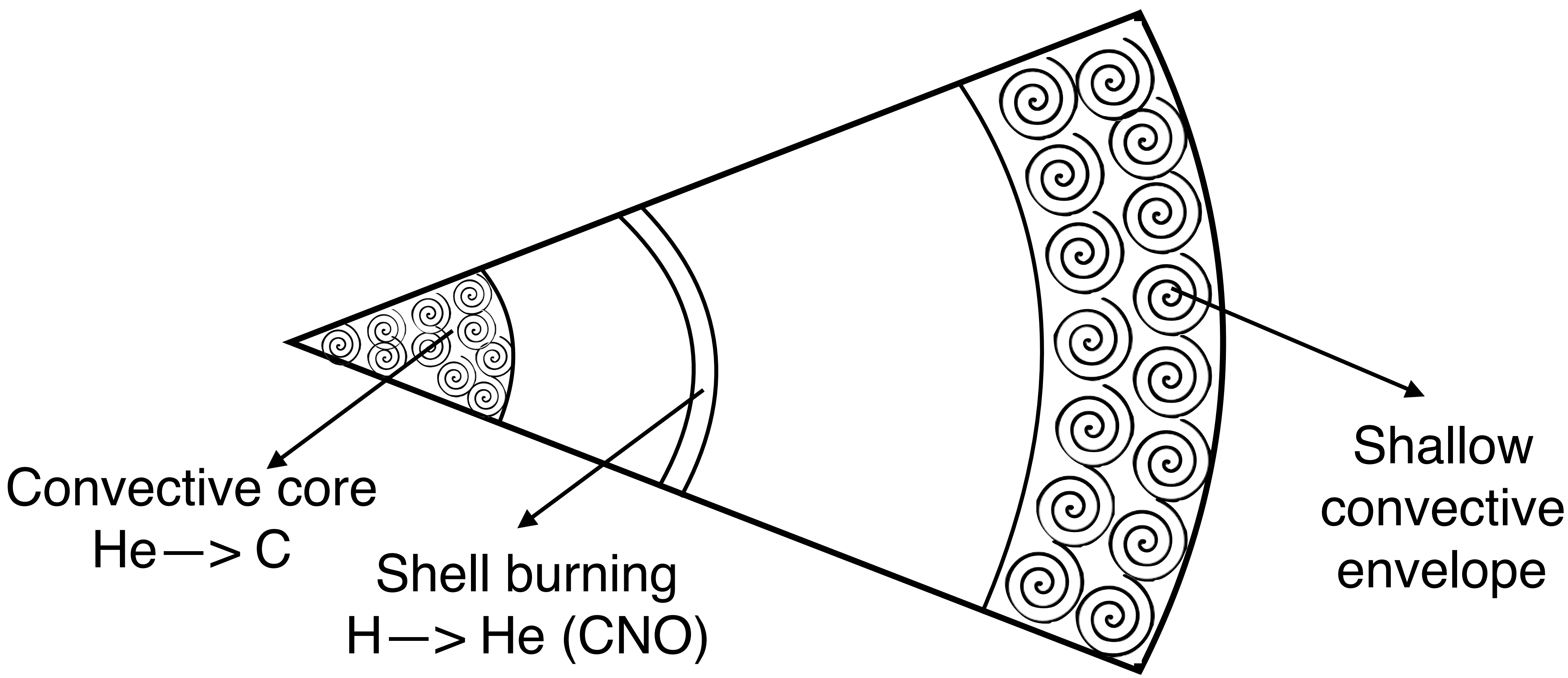
T_{eff} [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
$\frac{L}{L_\odot}$
100
10
1
0.1
Horizontal branch
-0.25
0
0.25
0.5
0.75
1
B-V
APOD


T_eff [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
-0.25
0
0.25
0.5
0.75
1
B-V
1
0.1
L
APOD
Horizontal branch
Position on HB
how much envelope is left after mass loss on RGB

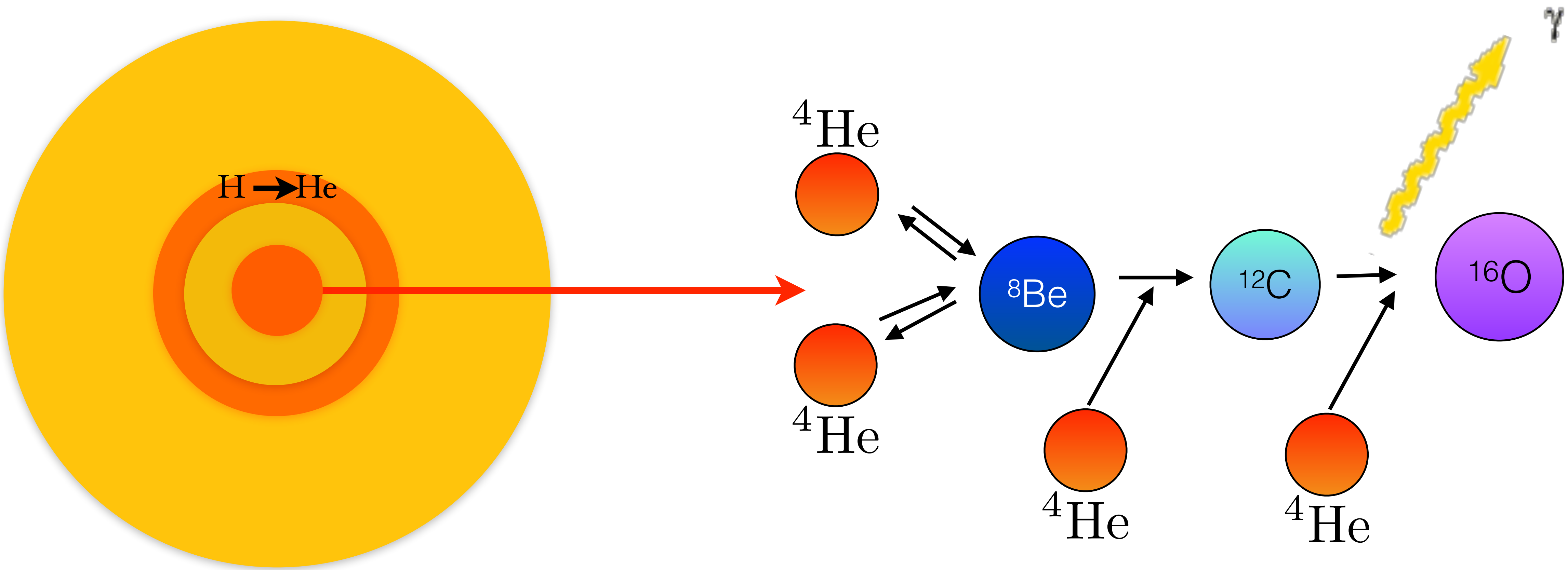
Horizontal Branch

Phase characterised by C production in the core

Timescale of stable He burning in the core is much shorter than MS —> ~10^8 yr for a Sun-like star



$T_{core} = 2x10^8$ K



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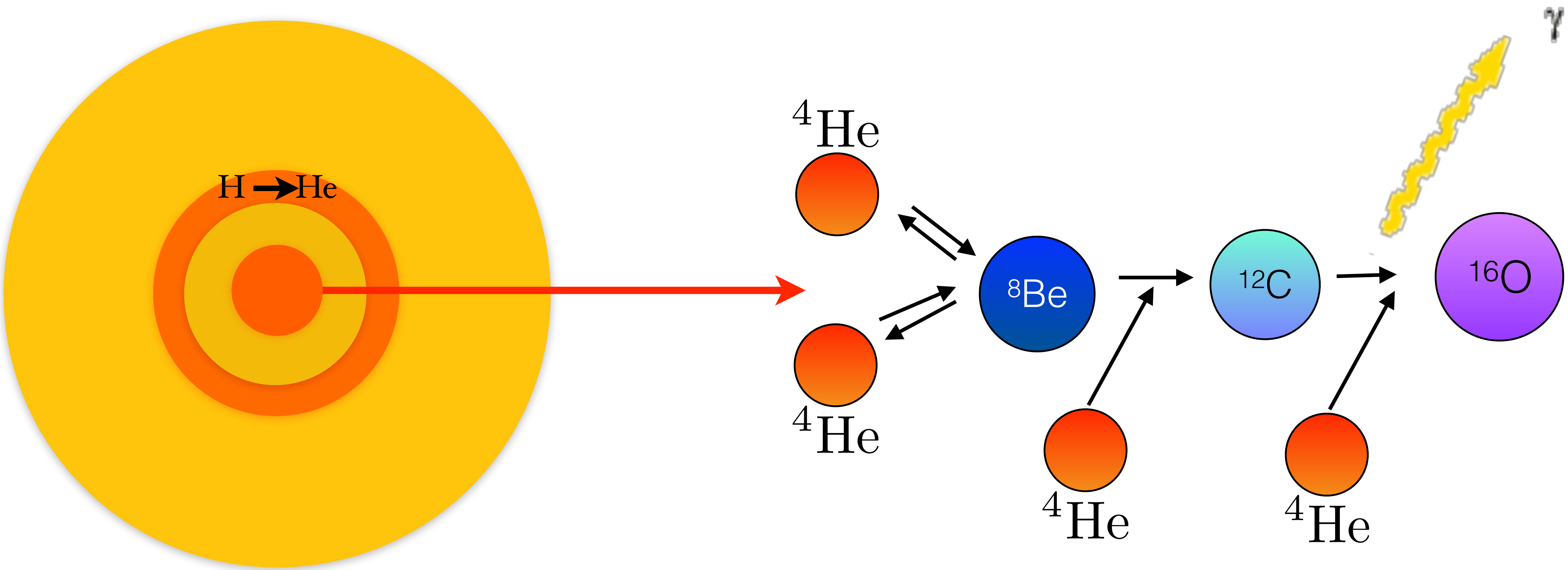
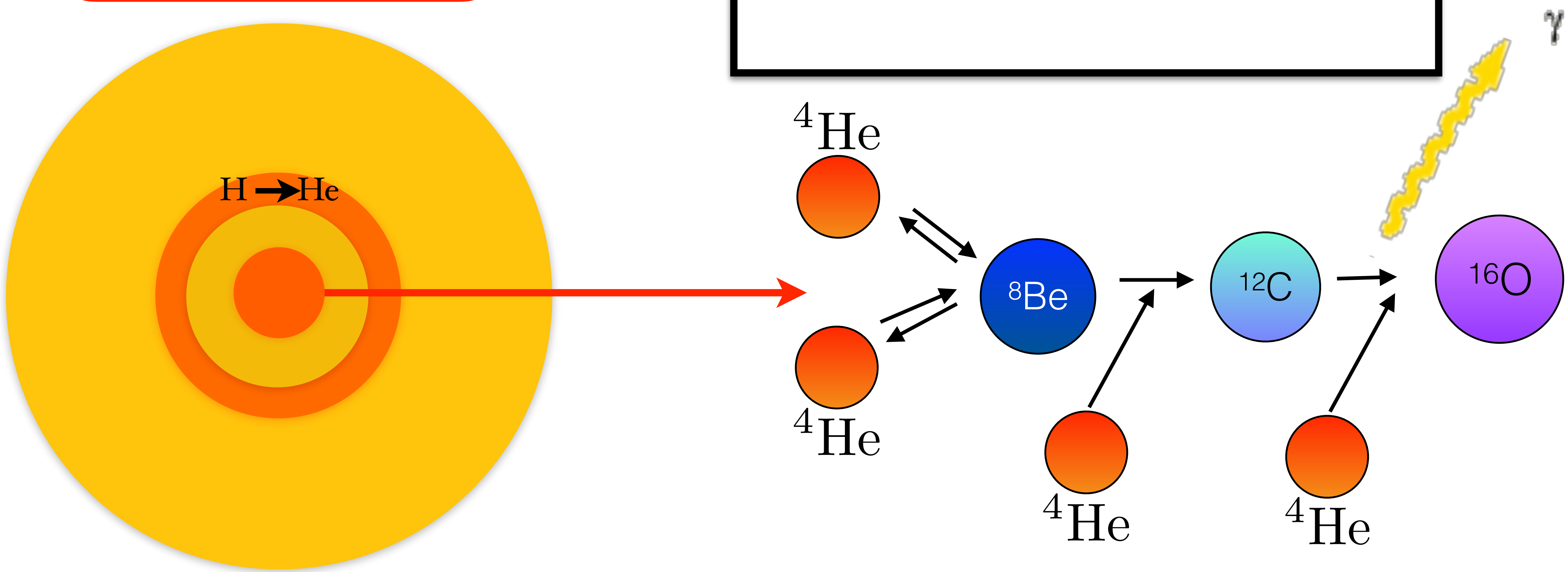


The core of the star now will be made by carbon and some oxygen (80% C and 20% O)

$T_{core} = 2x10^8$ K

Energy released in formation of C ~3 MeV



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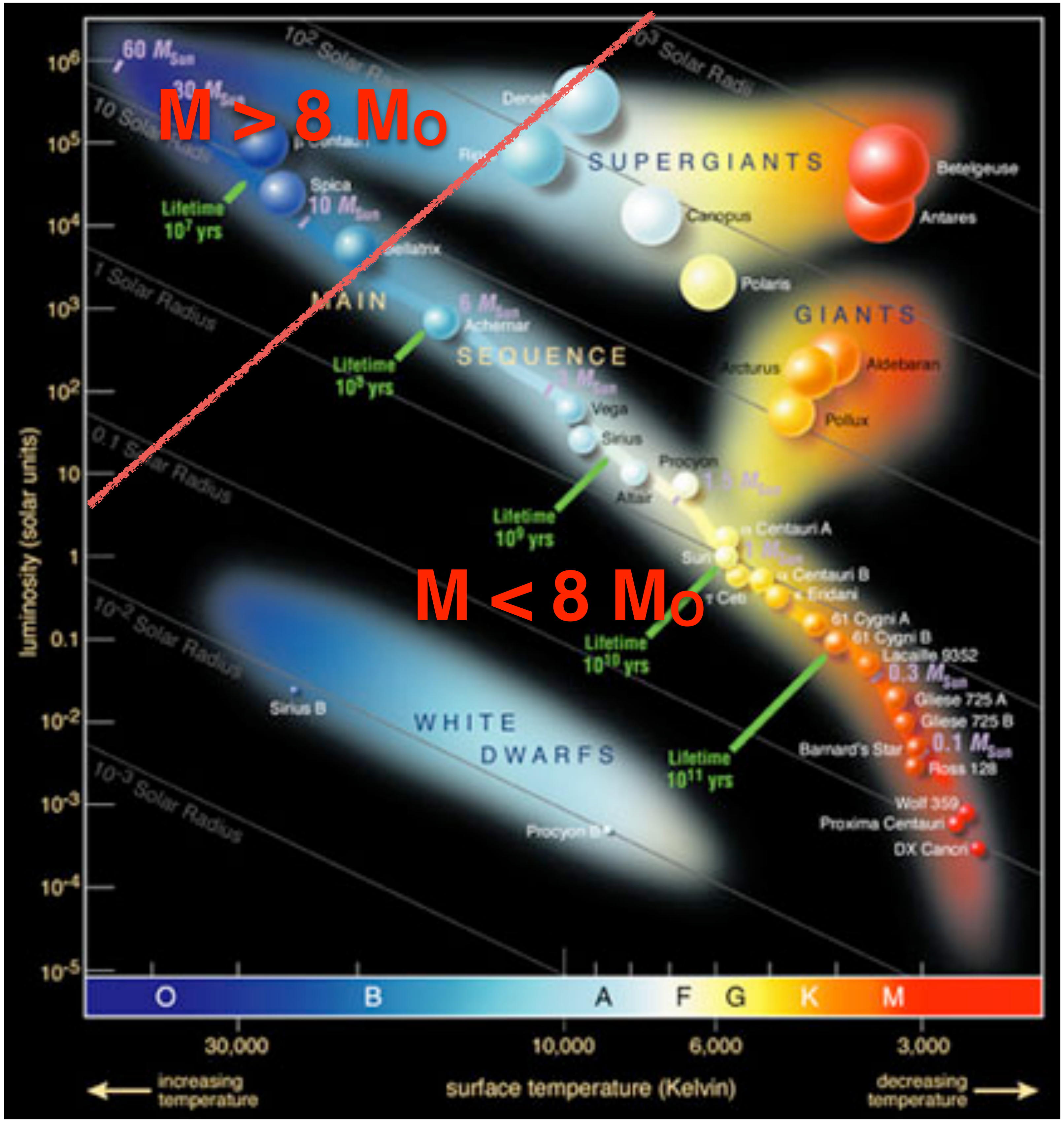
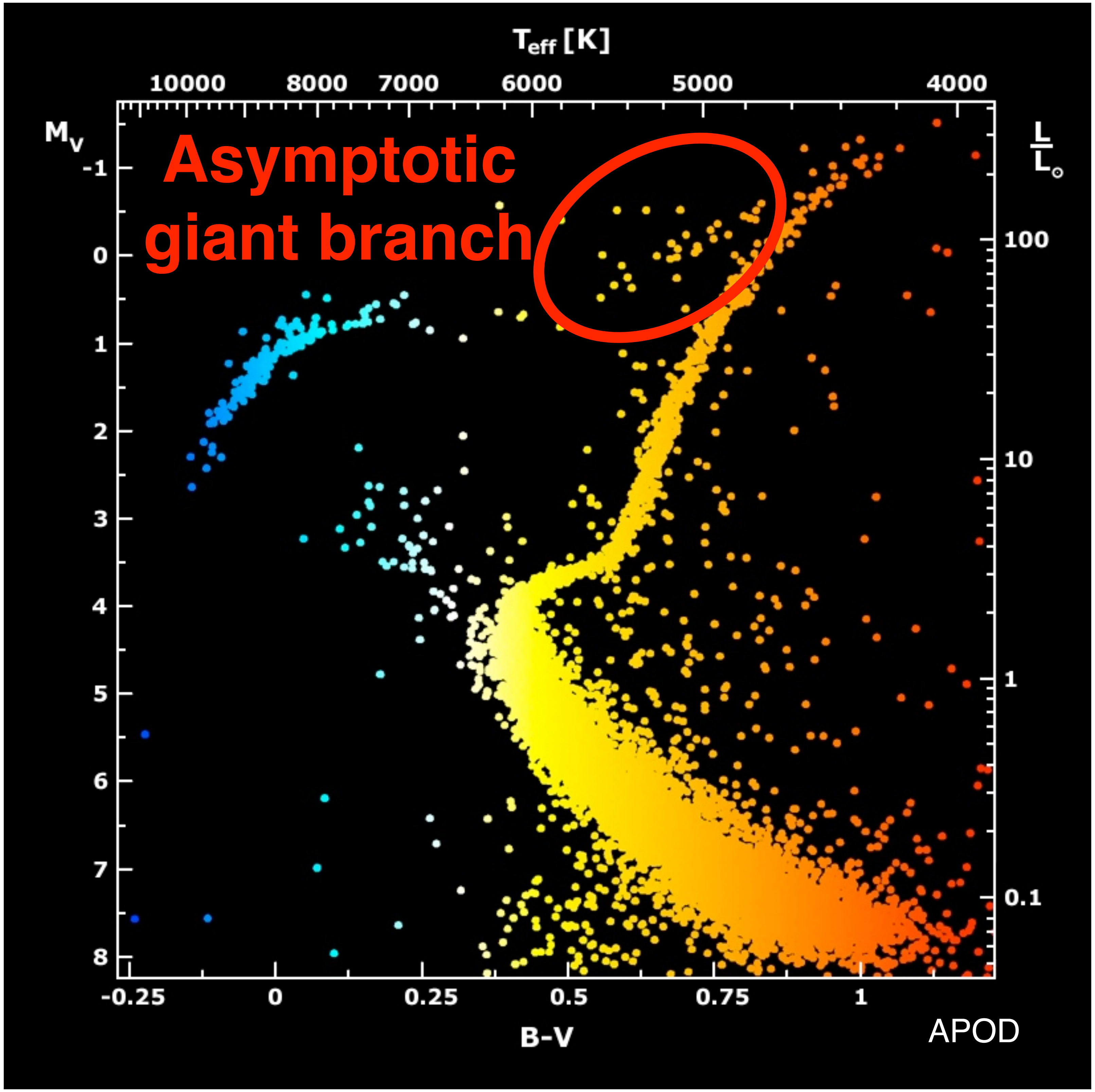
At this point we have to make a distinction…

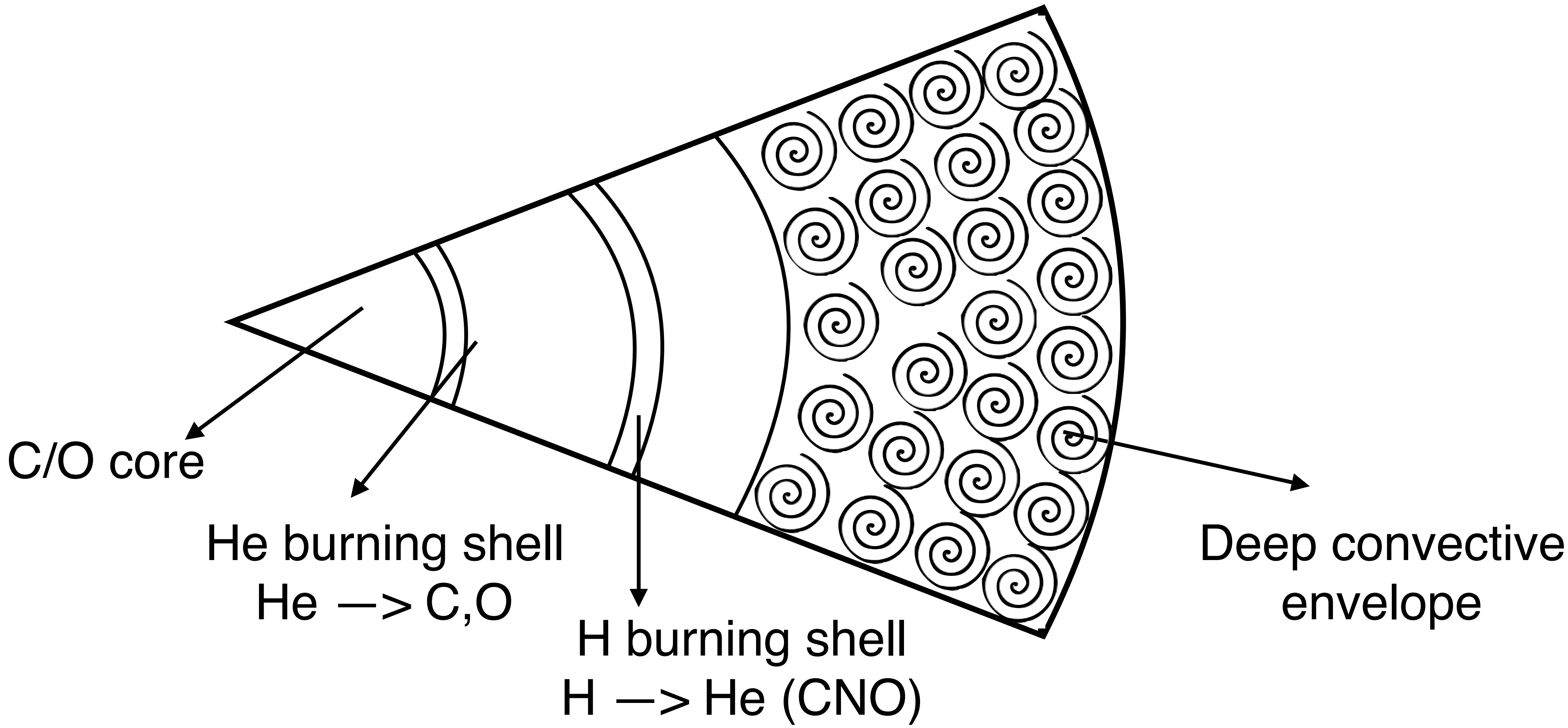




Teff [K]
10000
8000
7000
6000
5000
4000
Mv
-1
0
1
2
3
4
5
6
7
8
L/L⊙
100
10
1
0.1
Asymptotic
giant branch
-0.25
0
0.25
0.5
0.75
1
B-V
APOD

Stars with $M < 8\ M_0$

When He depletes in the centre
—> core contracts and heats up
—> He starts to burn in a shell at the C-O boundary
—> envelope expands and starts convection.



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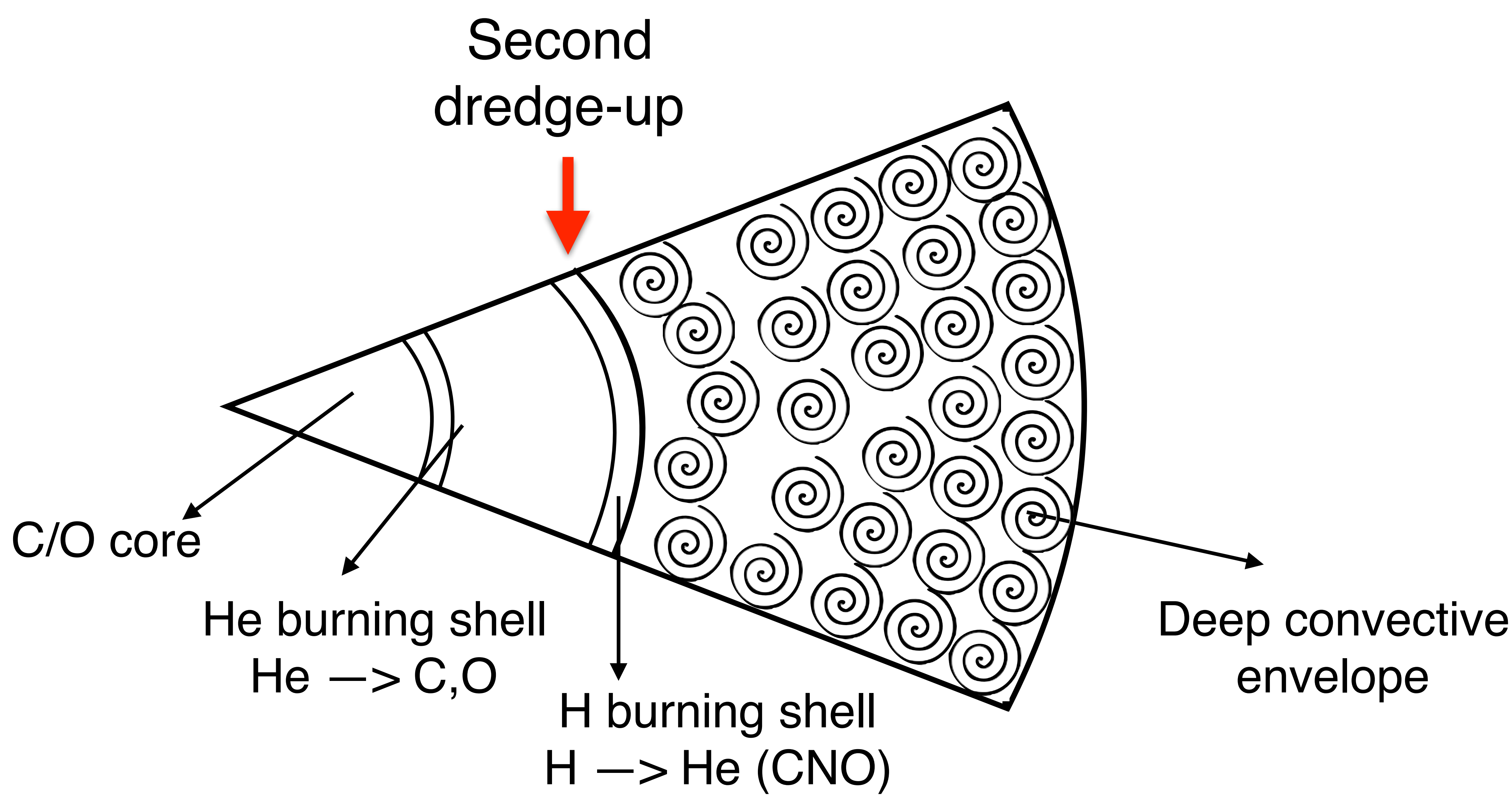

Thermal pulses

A thermally unstable configuration leads to a long series of thermal pulses because the two nuclear burning processes do not allow a steady state ==> **cycling process**

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1

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2. The He layer contracts and T rises igniting He shell

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3. Upper layers expand and cool, stopping the burning of the H-shell,
while the He-shell advances and catches up with the extinct H-shell

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4. H-shell reignites because of high T and He-shell stops

Thermal pulses

A thermally unstable configuration leads to a long series of thermal pulses because the two nuclear burning processes do not allow a steady state ==> **cycling process**

1. For most of the cycle H is burned in the external shell because the inner one is extinct
—> He layer grows in mass

2. The ... ell

3. Upp ... bur ... while the He-shell advances and catches up with the extinct H-shell

4. H-shell reignites because of high T and He-shell stops

One cycle is 100-1000 yr
+
growth of C-O core

Planetary nebula

Stars is now in the supergiant region of HR diagram

Planetary nebula

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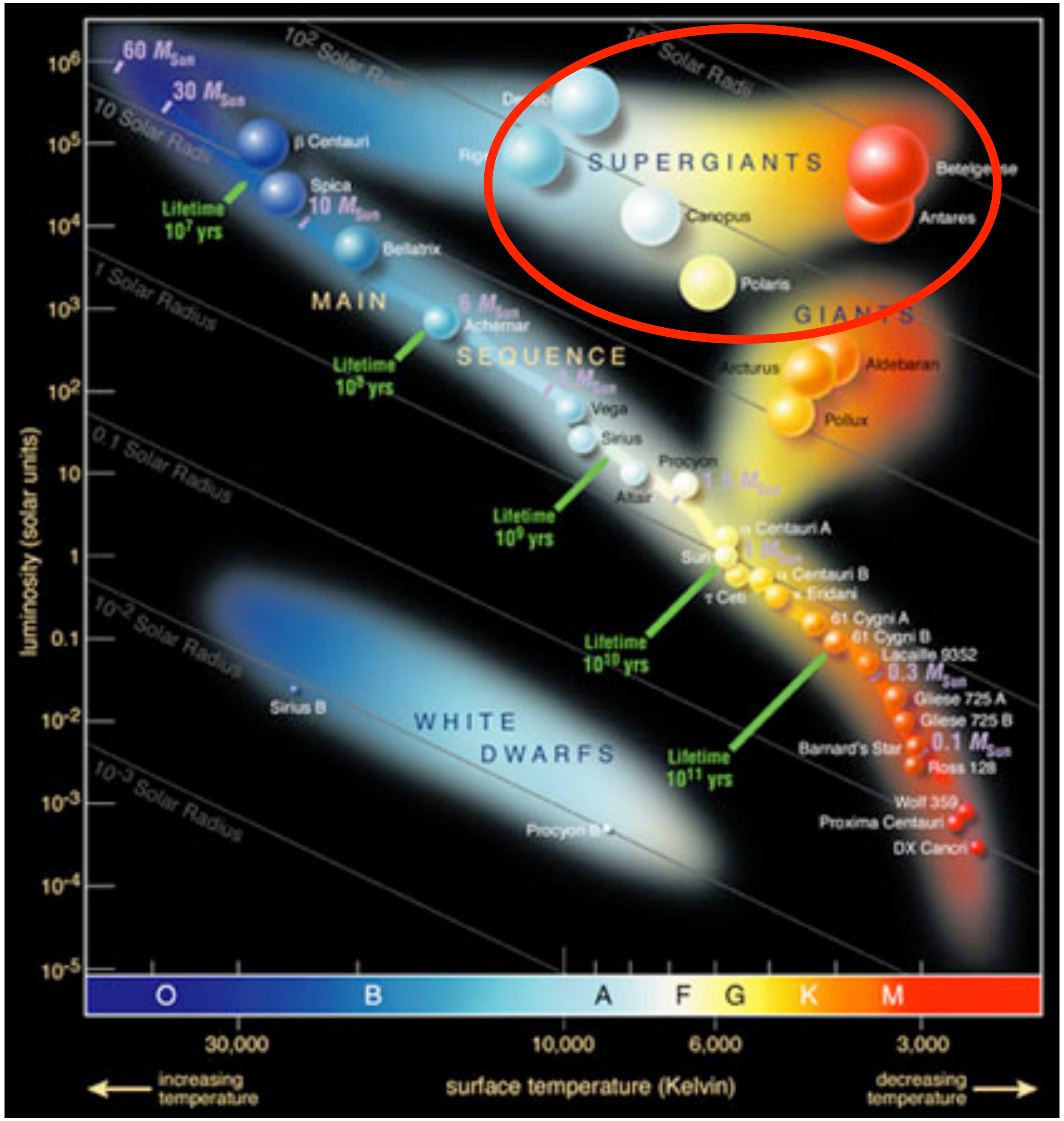

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↓

Envelope is loose and the wind is strong so it is shed away leaving a C-O core of 0.6-1.1 $M_\odot$

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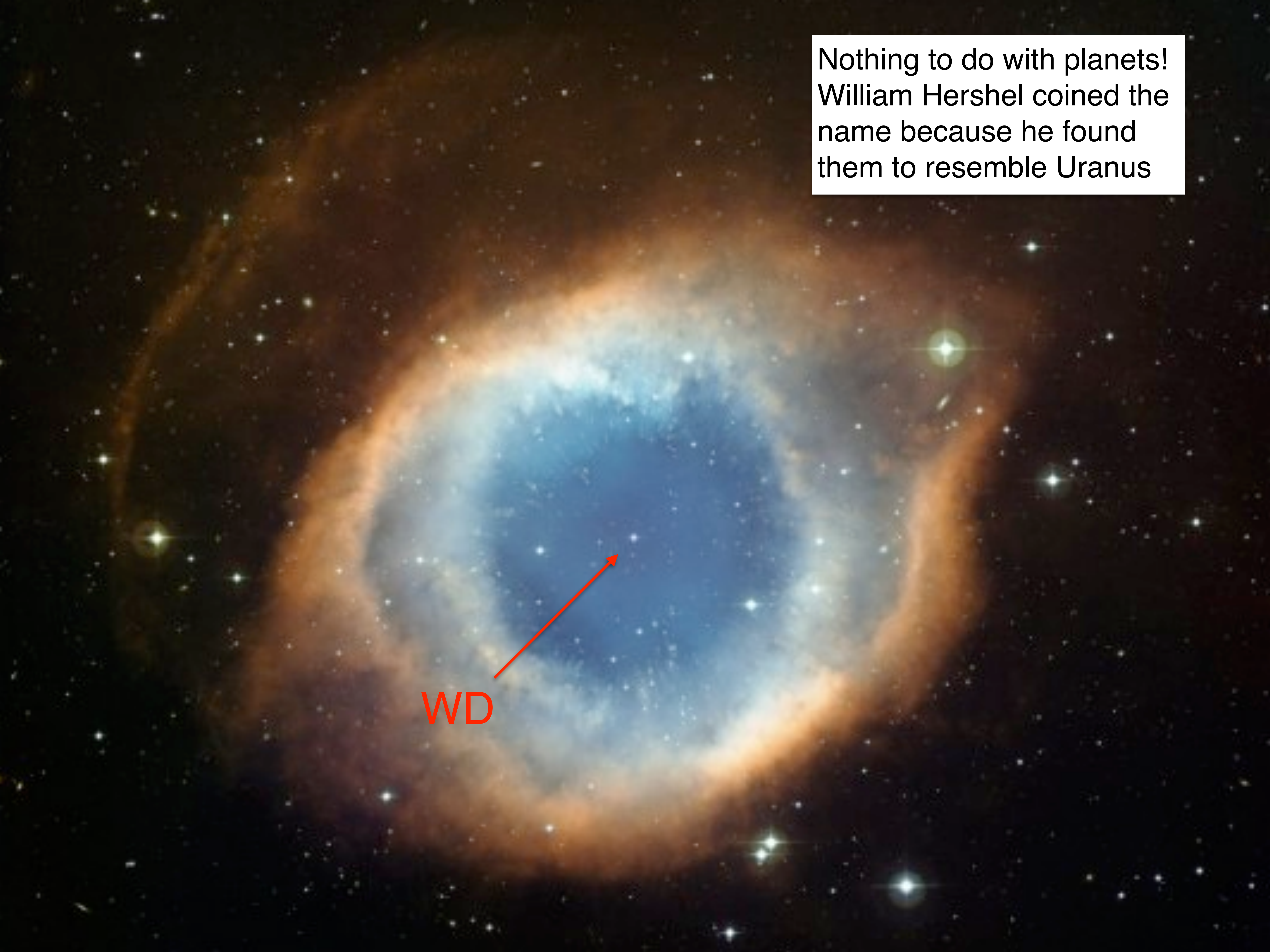
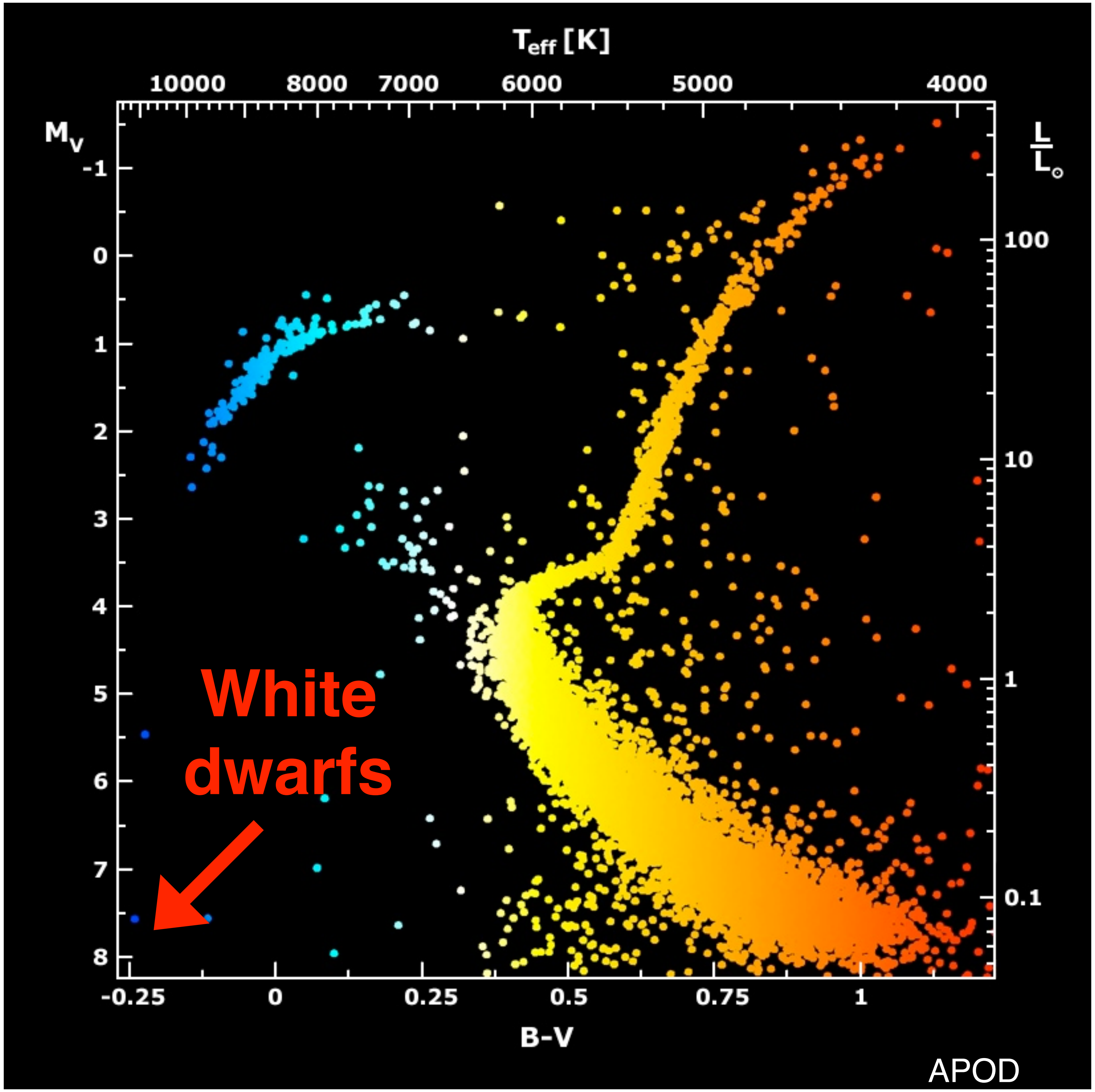
Planetary nebula
+
white dwarf


Nothing to do with planets! William Hershel coined the name because he found them to resemble Uranus
WD

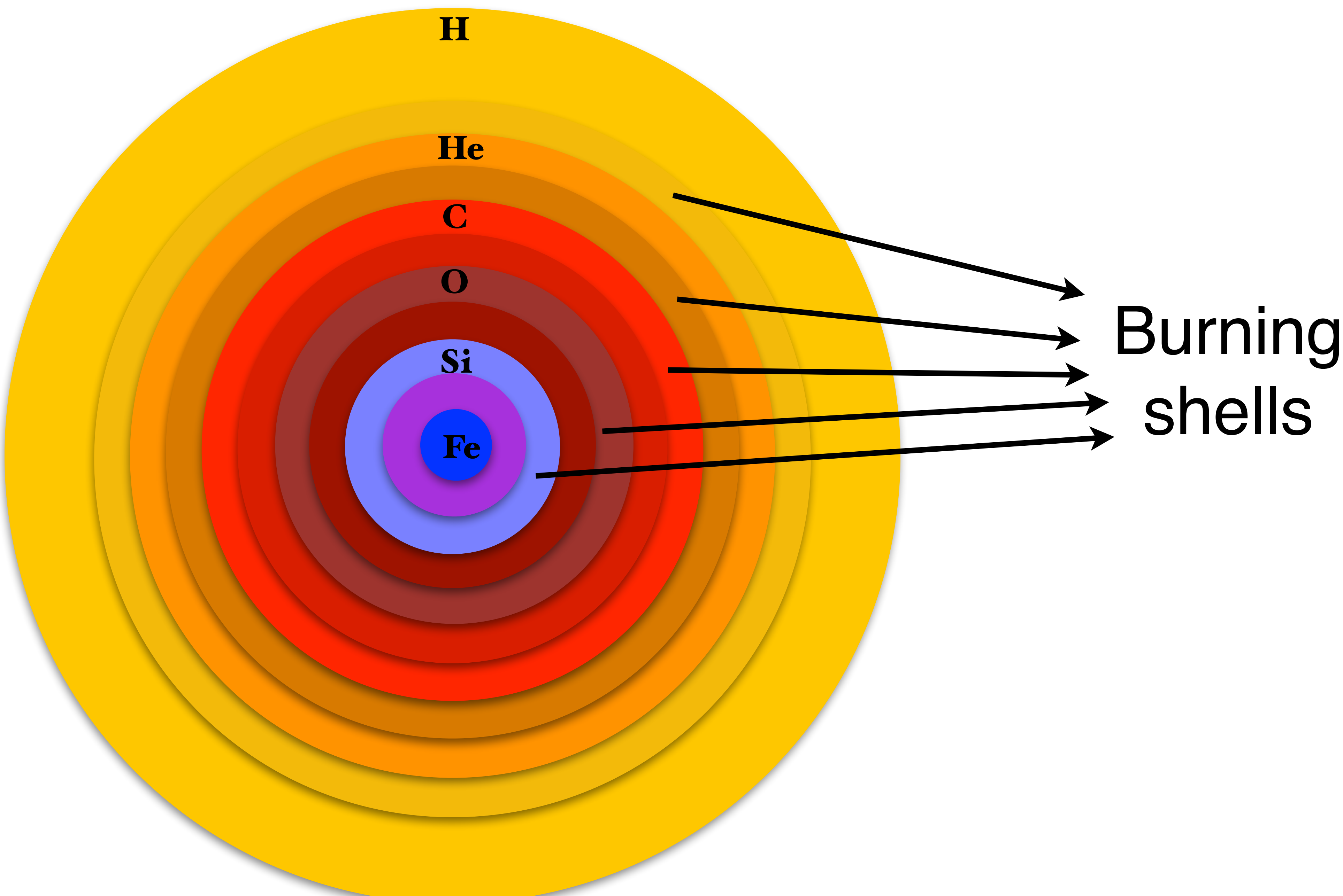


T_{eff} [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
$\frac{L}{L_\odot}$
100
10
1
0.1
-0.25
0
0.25
0.5
0.75
1
B-V
White dwarfs
APOD

High-mass stars

Fusion of elements continue after C burning ➡ "onion-like" structure

Silicon burning
$T_{core} \gtrsim 3 \times 10^9$ K



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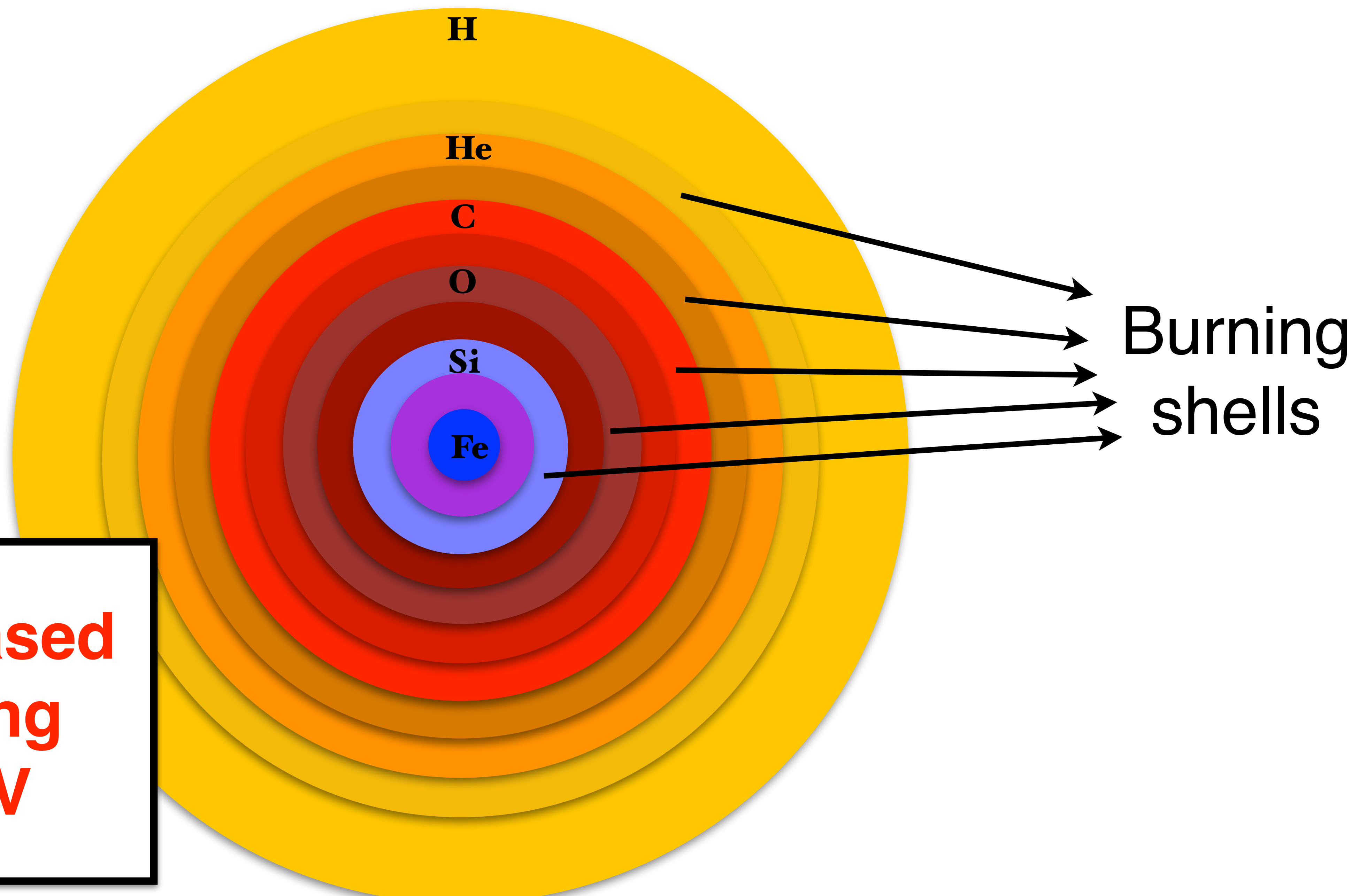

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Energy released in Si burning < 0.18 MeV

This is the end of the star

Now there is no way to get energy from fusion of Fe

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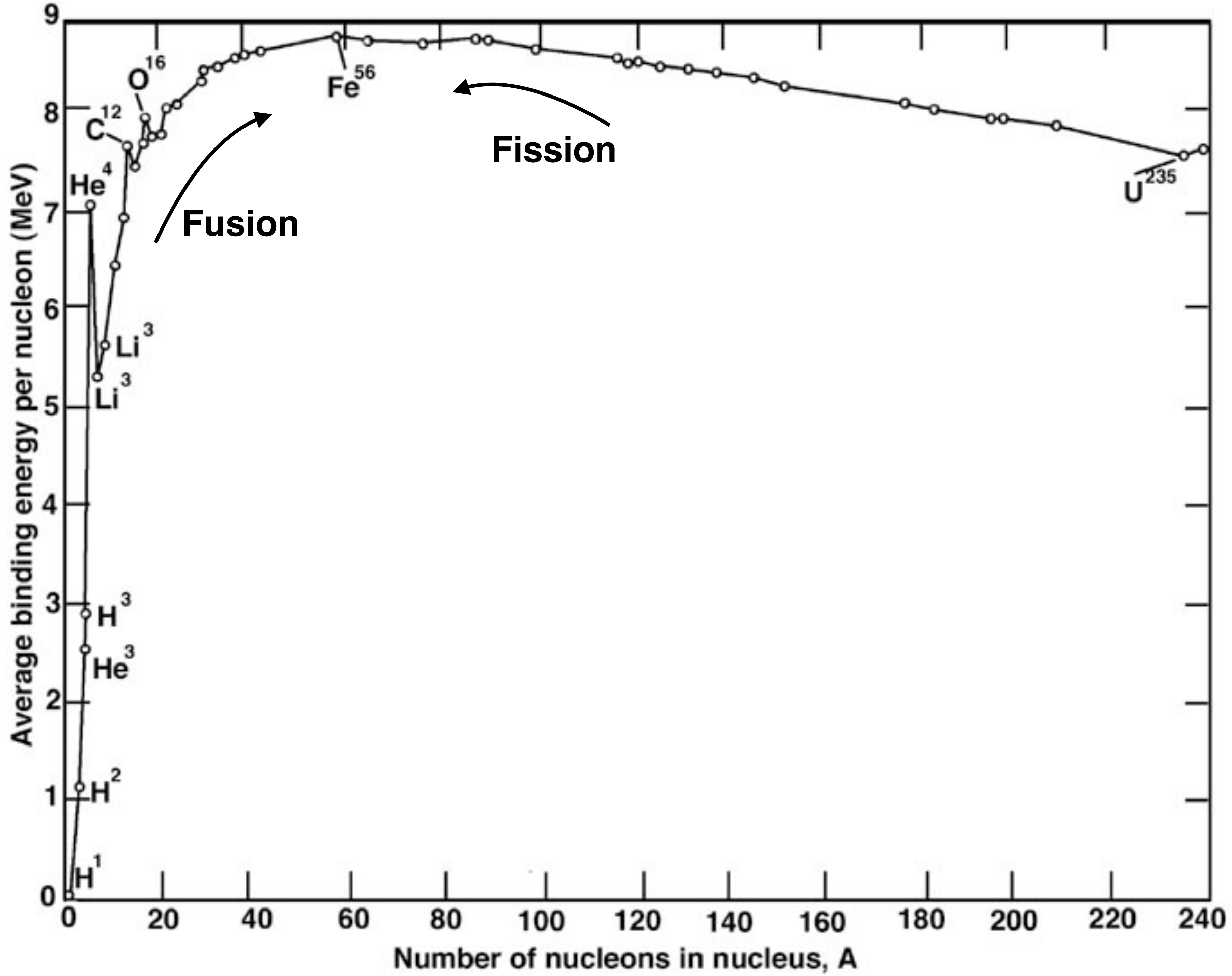

No production of energy via fusion but core continues to contract and increases temperature losing energy

photodisintegration

$$^{56}Fe + \gamma \longrightarrow 13\ ^{4}He + 4n$$

$$^{4}He + \gamma \longrightarrow 2\ H + 2n$$

Endotermic reactions

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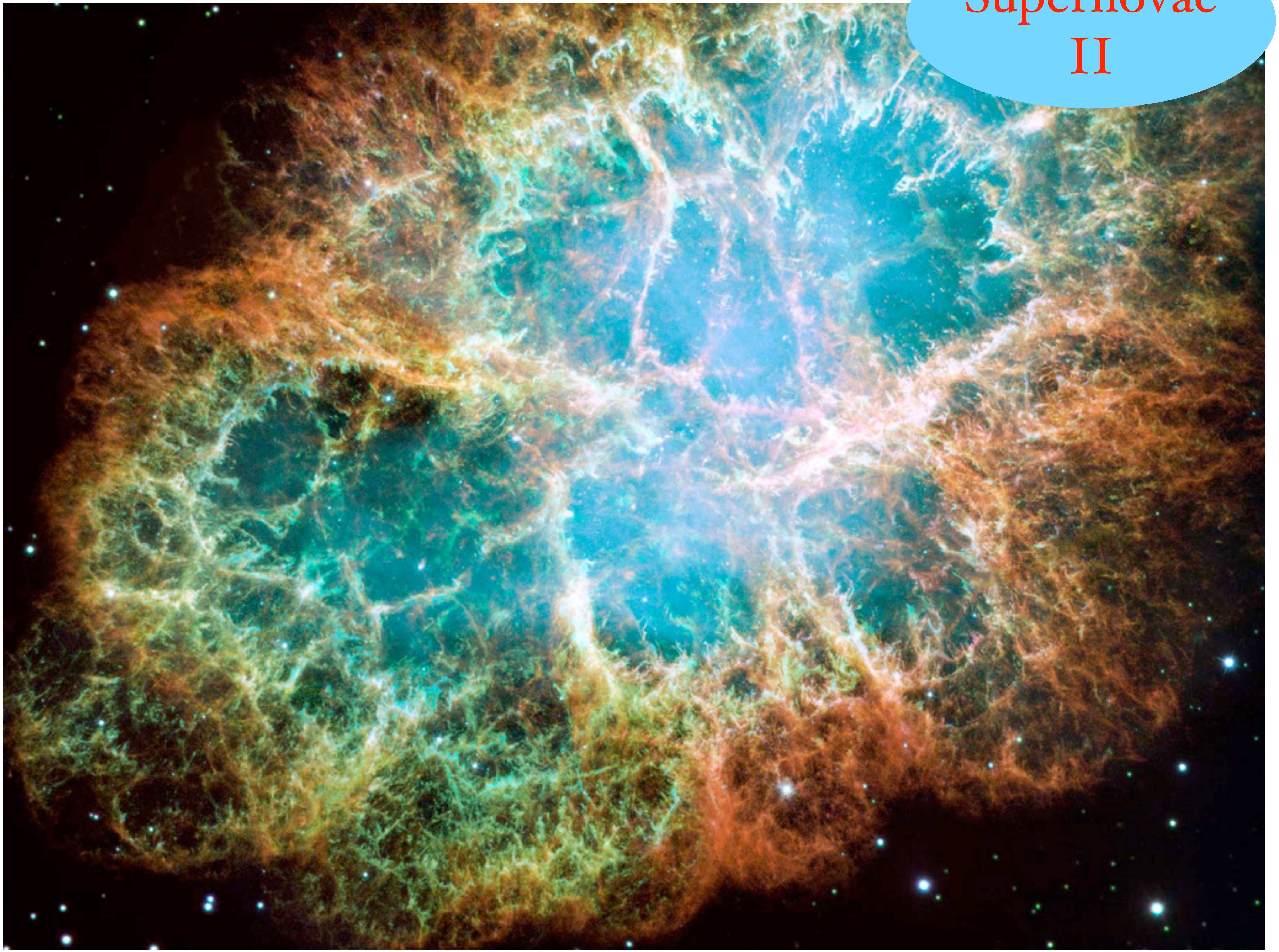
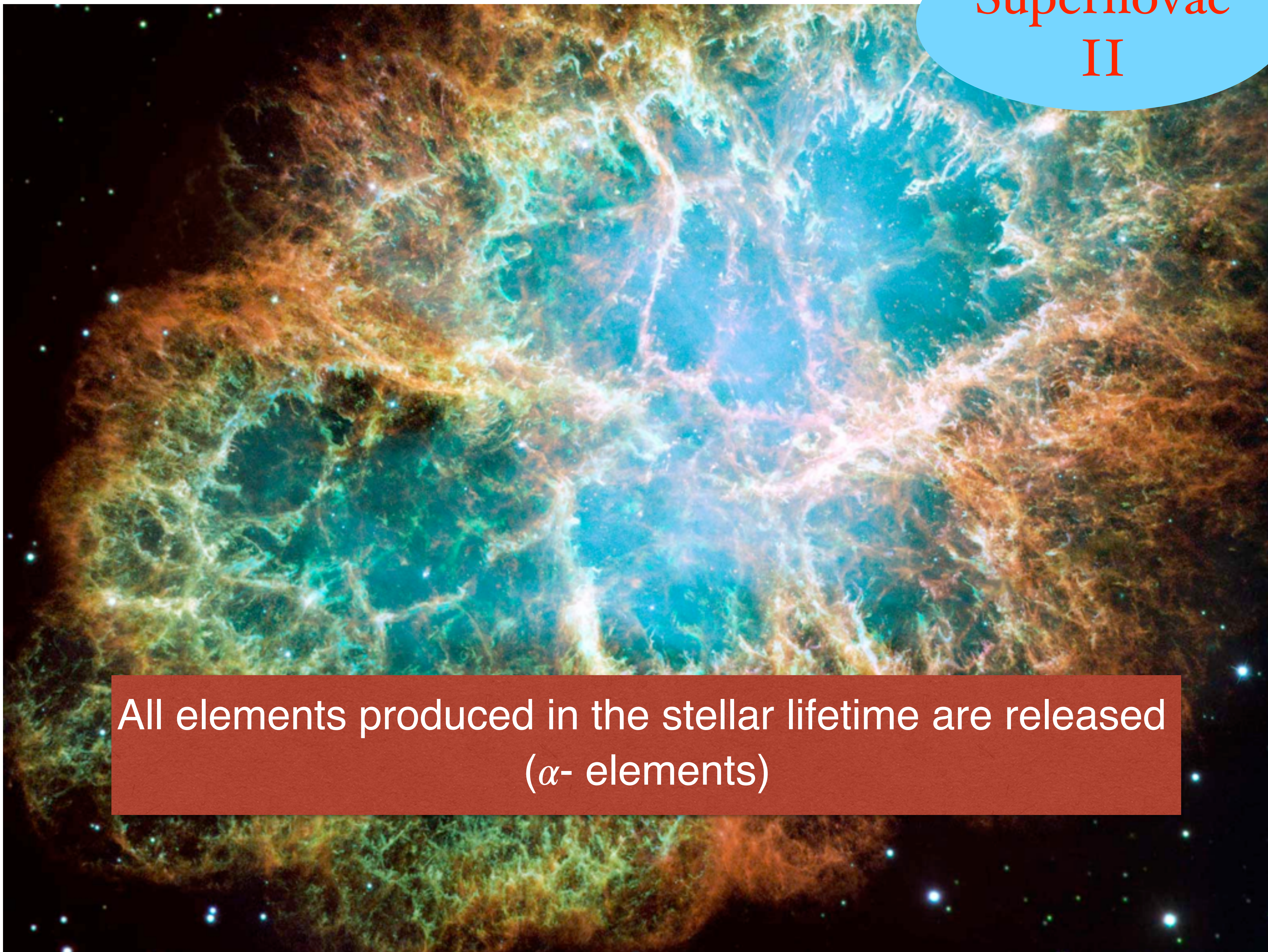
EXPLOSION!



Supernovae II

Supernovae II



All elements produced in the stellar lifetime are released (α- elements)

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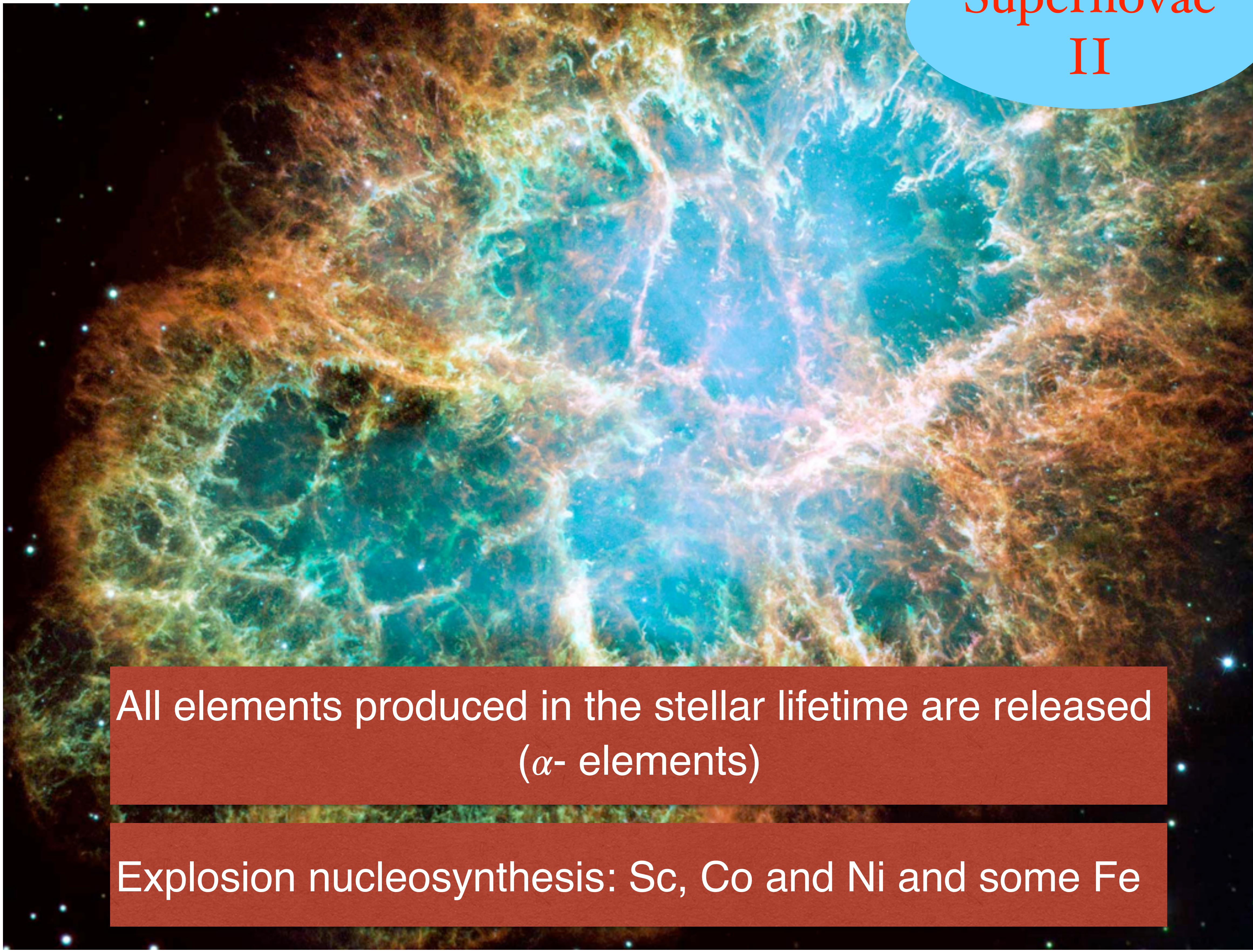


All elements produced in the stellar lifetime are released (α- elements)

Explosion nucleosynthesis: Sc, Co and Ni and some Fe

Depending on the mass of the progenitor
the remnant of a SN II will be

Neutron star

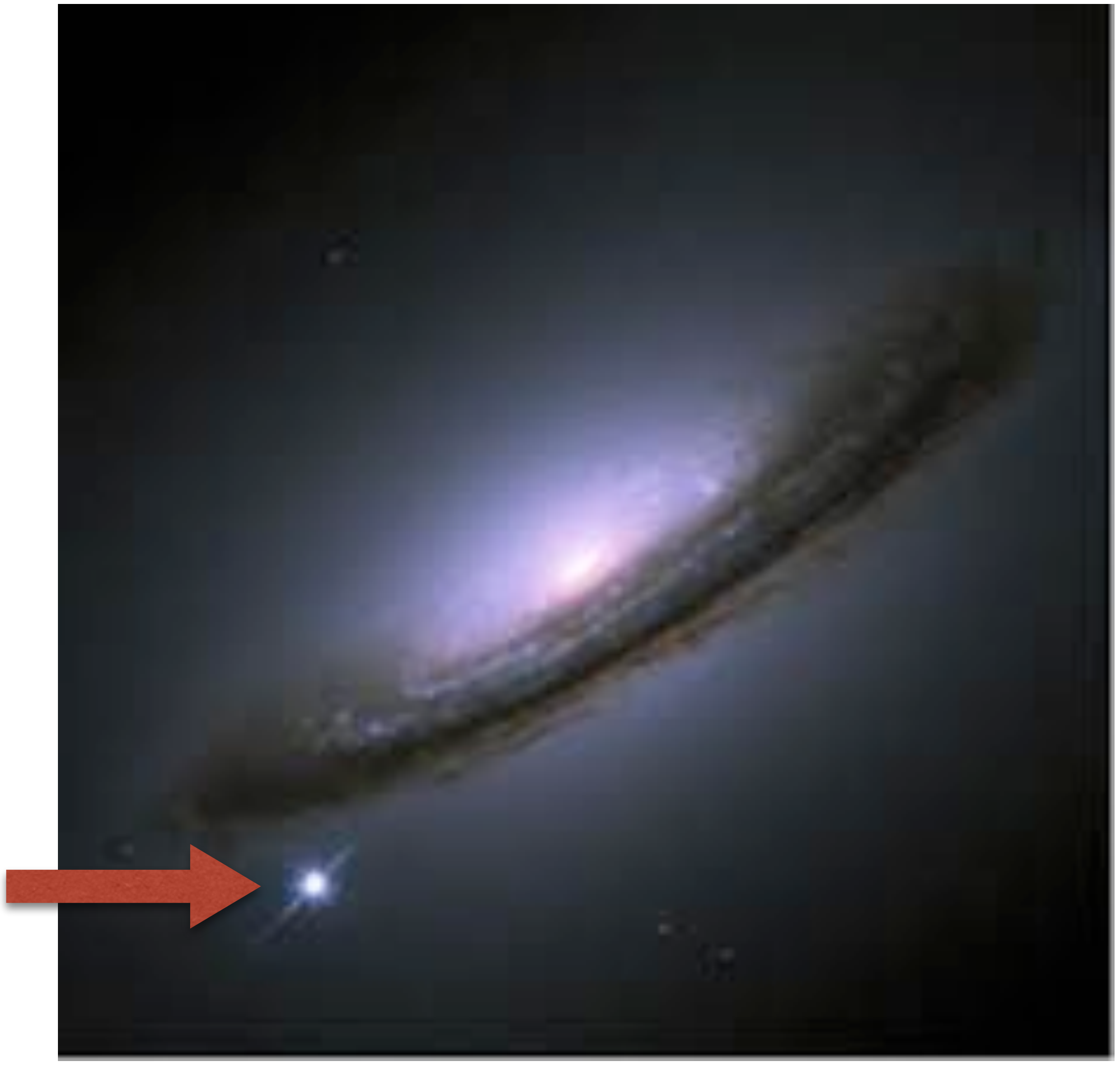
Stars with
$8M_\odot < M < 25M_\odot$

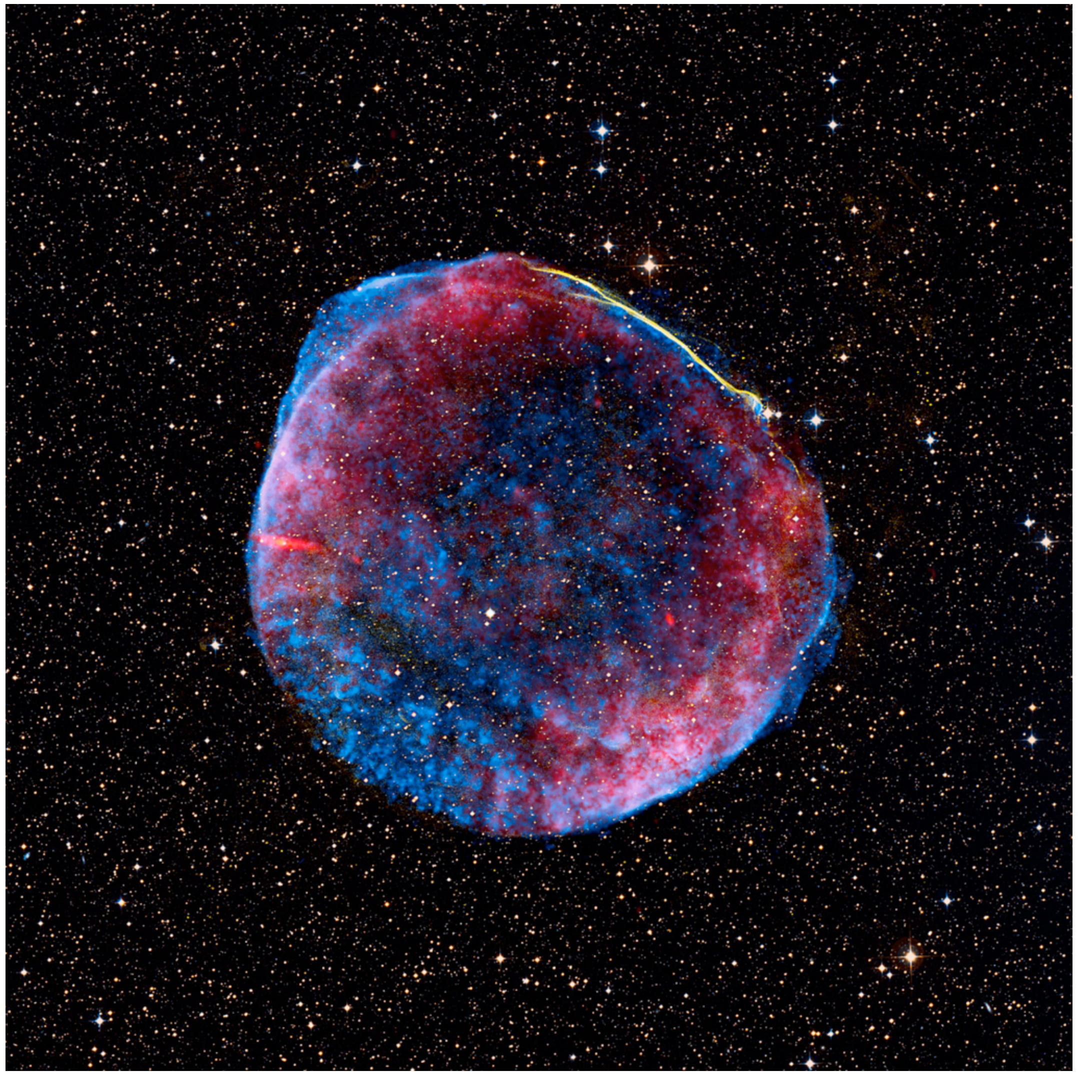
Black hole

Stars with
$M > 25M_\odot$

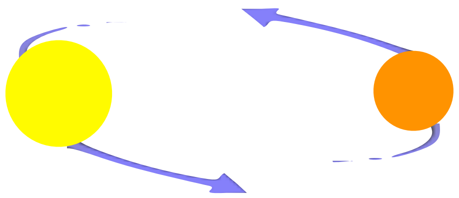
And what about the other elements close to Fe?

Supernovae Ia





Single degenerate scenario



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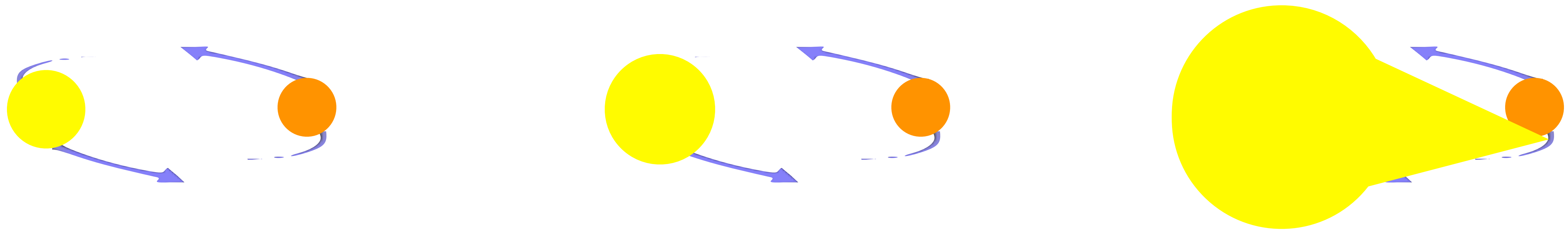

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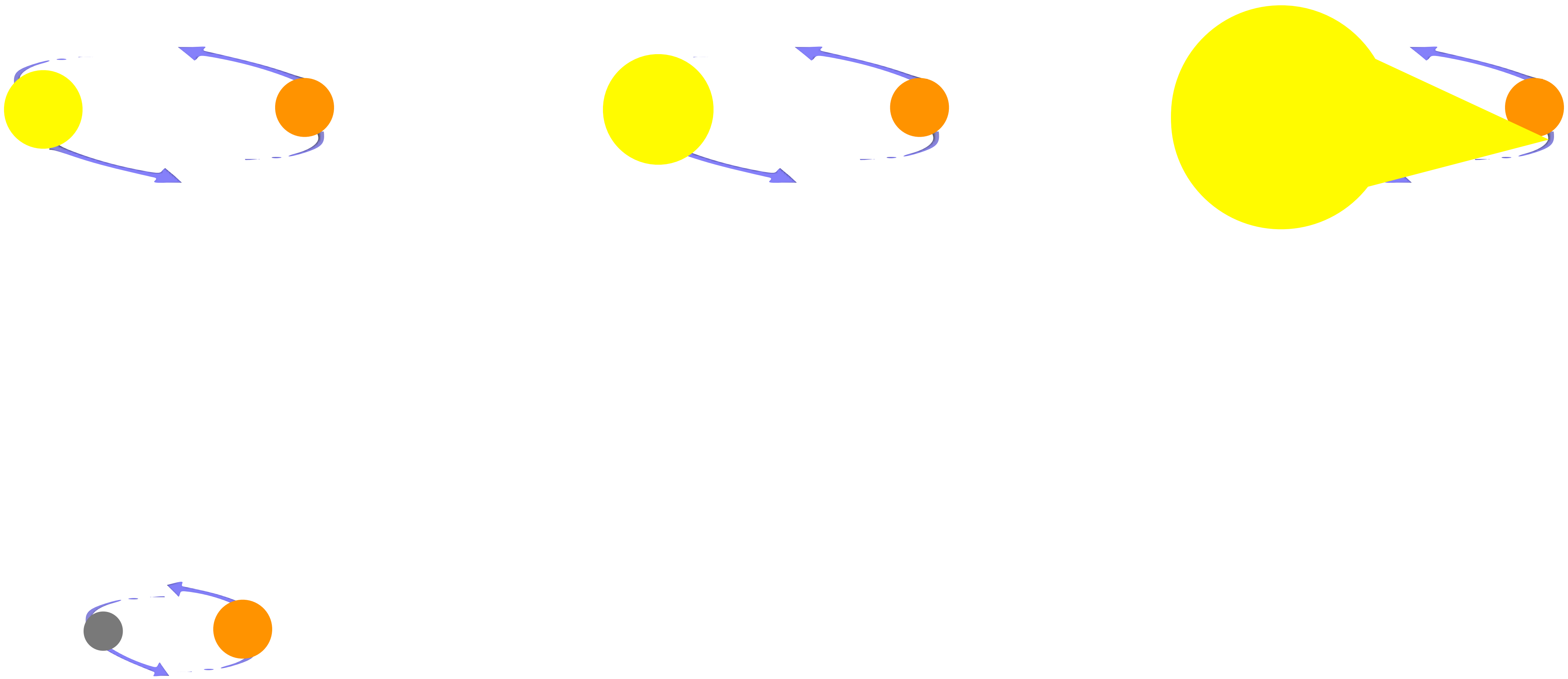

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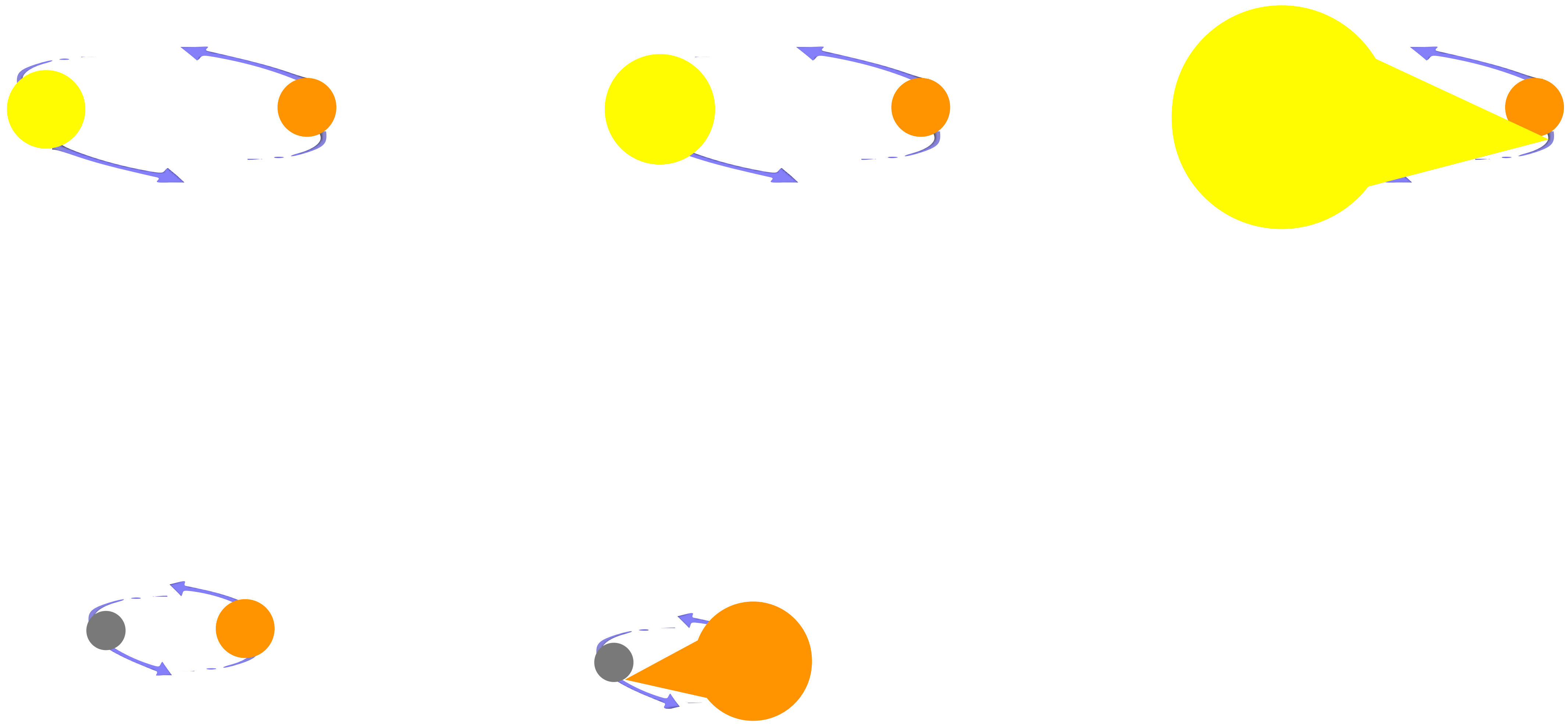

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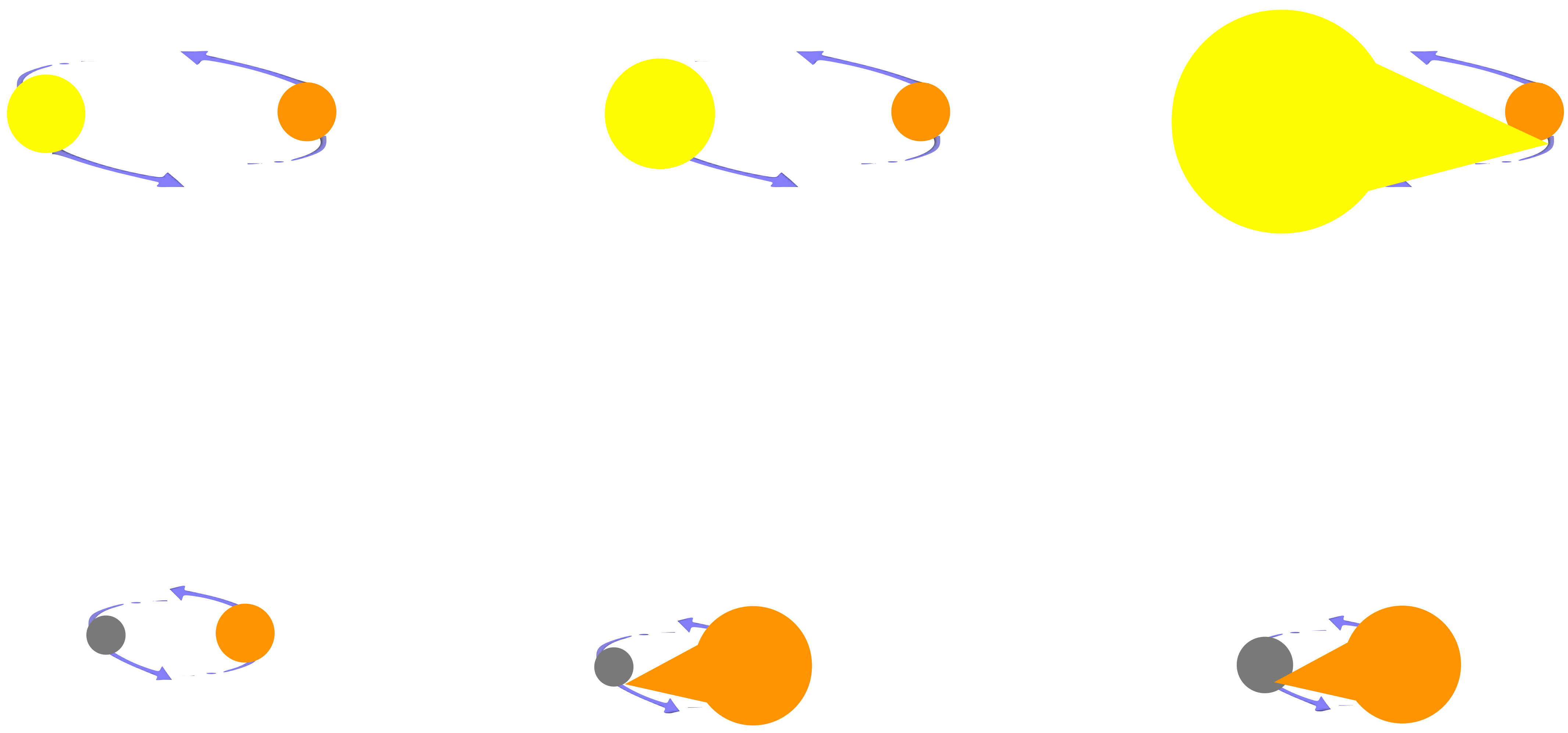

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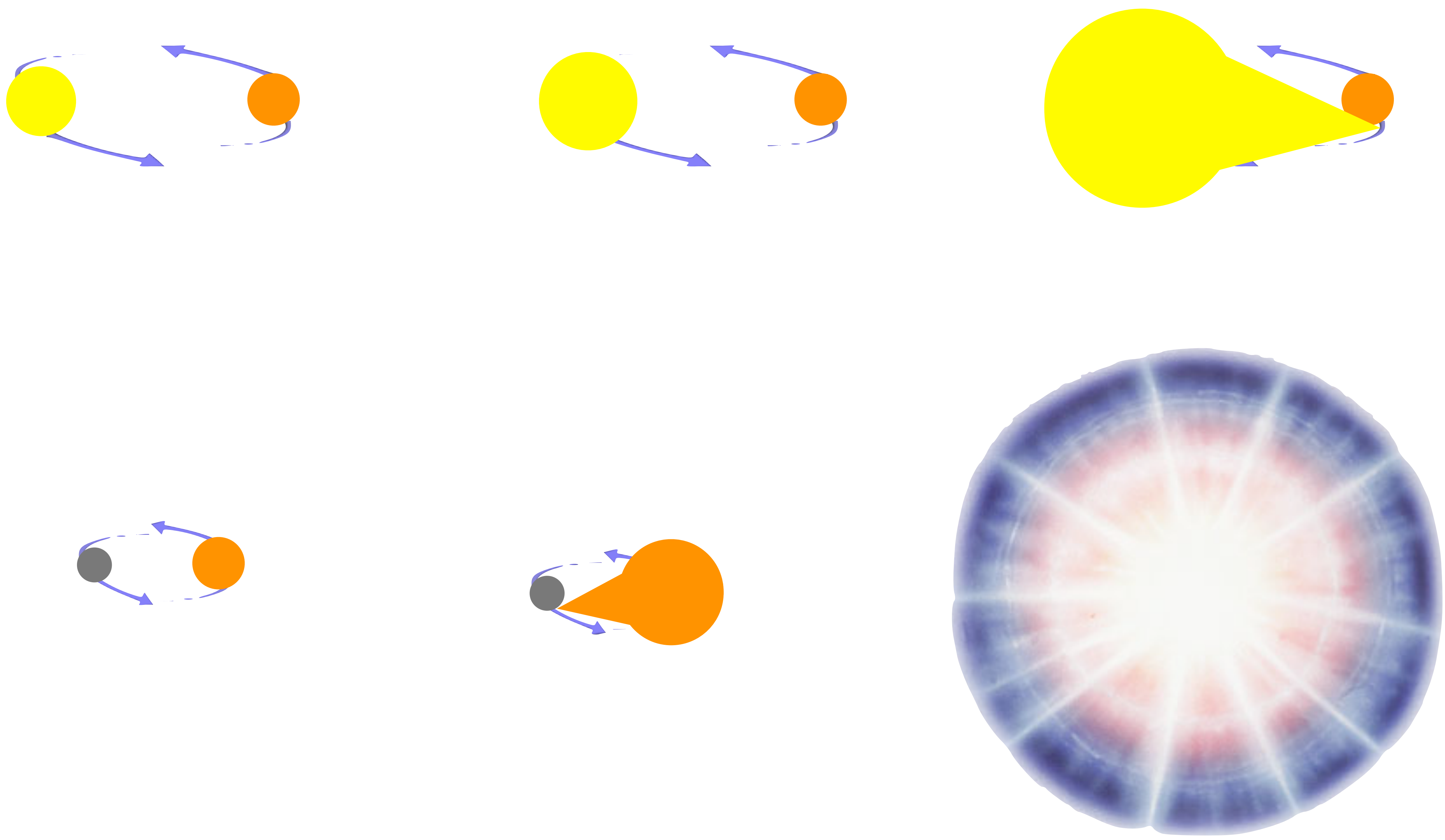

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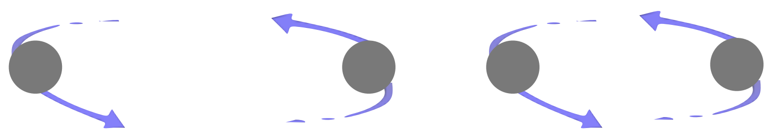

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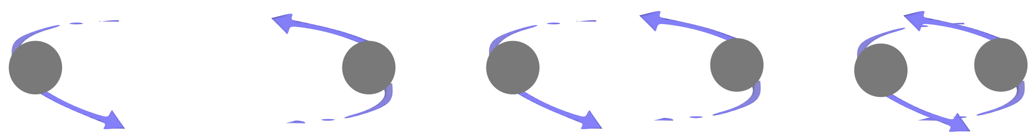

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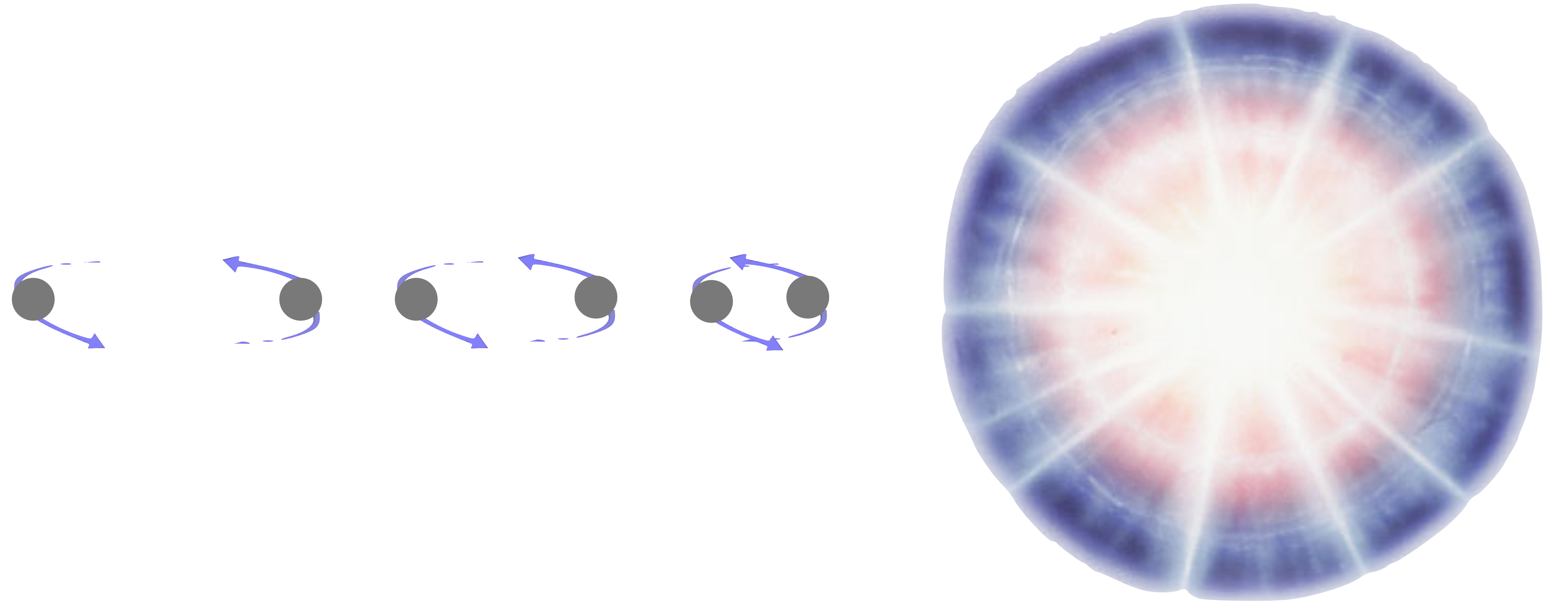

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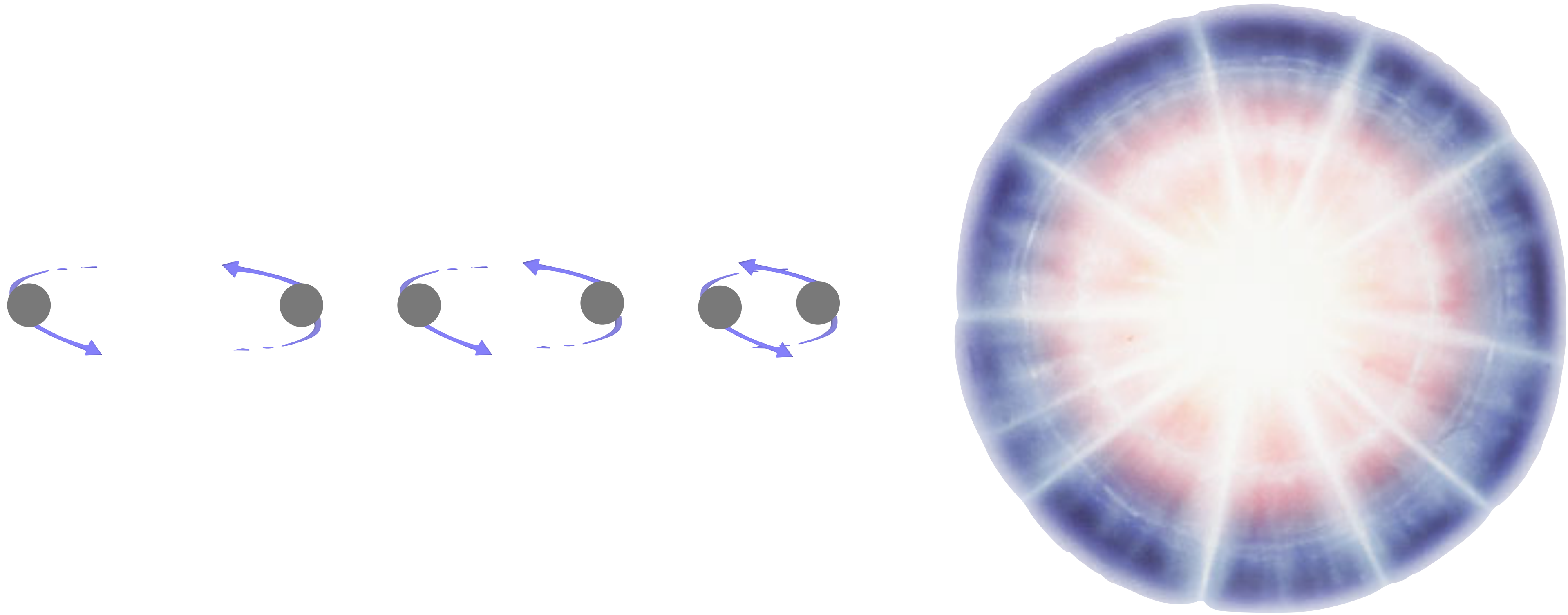
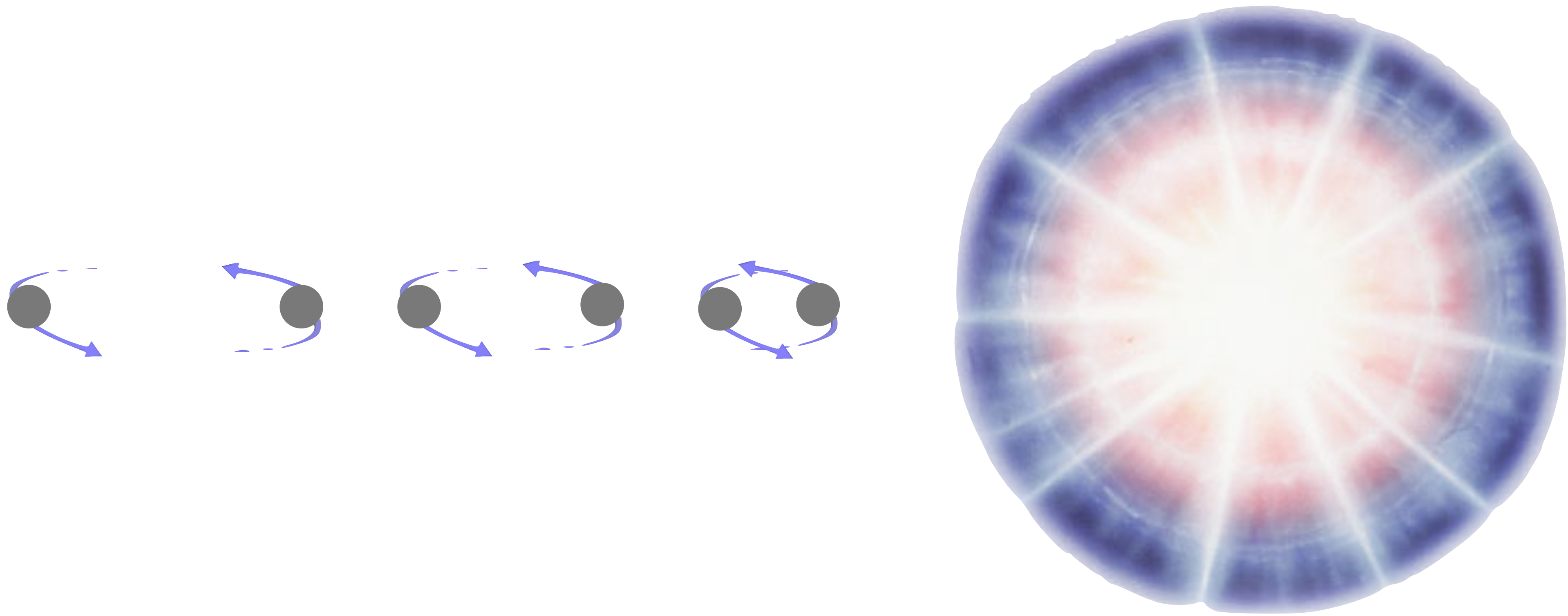


C ignition and a thermonuclear runaway causing a complete explosive disruption of the white dwarf

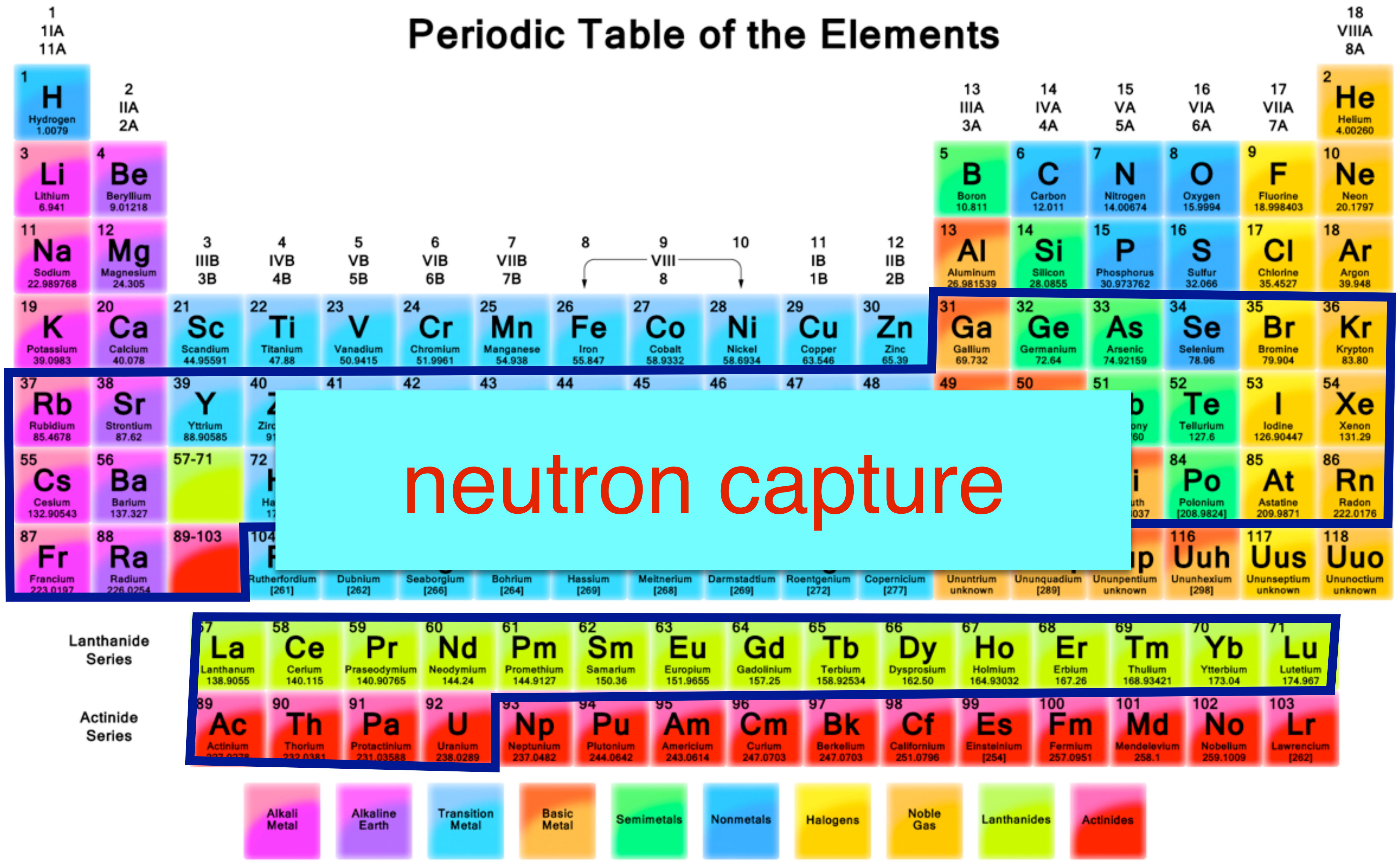
Double degenerate scenario



C ignition and a thermonuclear runaway causing a complete explosive disruption of the white dwarf

SN Ia nucleosynthesis: mainly Fe, Mn and some α elements

And all the other elements?



What is neutron capture?

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$$I(A,Z) + n \qquad I_1(A+1,Z)$$

$$I_1(A+1,Z) + n \qquad I_2(A+2,Z)$$

......

$$I_{N-1}(A+N-1,Z) + n \qquad I_N(A+N,Z)$$

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if I_N is stable the n capture can continue

if I_N (radioactive isotope) not stable $\longrightarrow$ decay

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New element

$$I_N(A+N,Z) \longrightarrow J(A+N,Z+1) + e^- + \overline{\nu}$$

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$$K(A+N,Z+2) \longrightarrow L(A+N,Z+3) + e^- + \bar{\nu}$$

....

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....

until a stable nucleus of mass A+N and
atomic number Z+M is produced

Different neutron processes

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Rapid neutron capture

r-elements derive from SN II (most probably)
due to the large amount of n during the explosion

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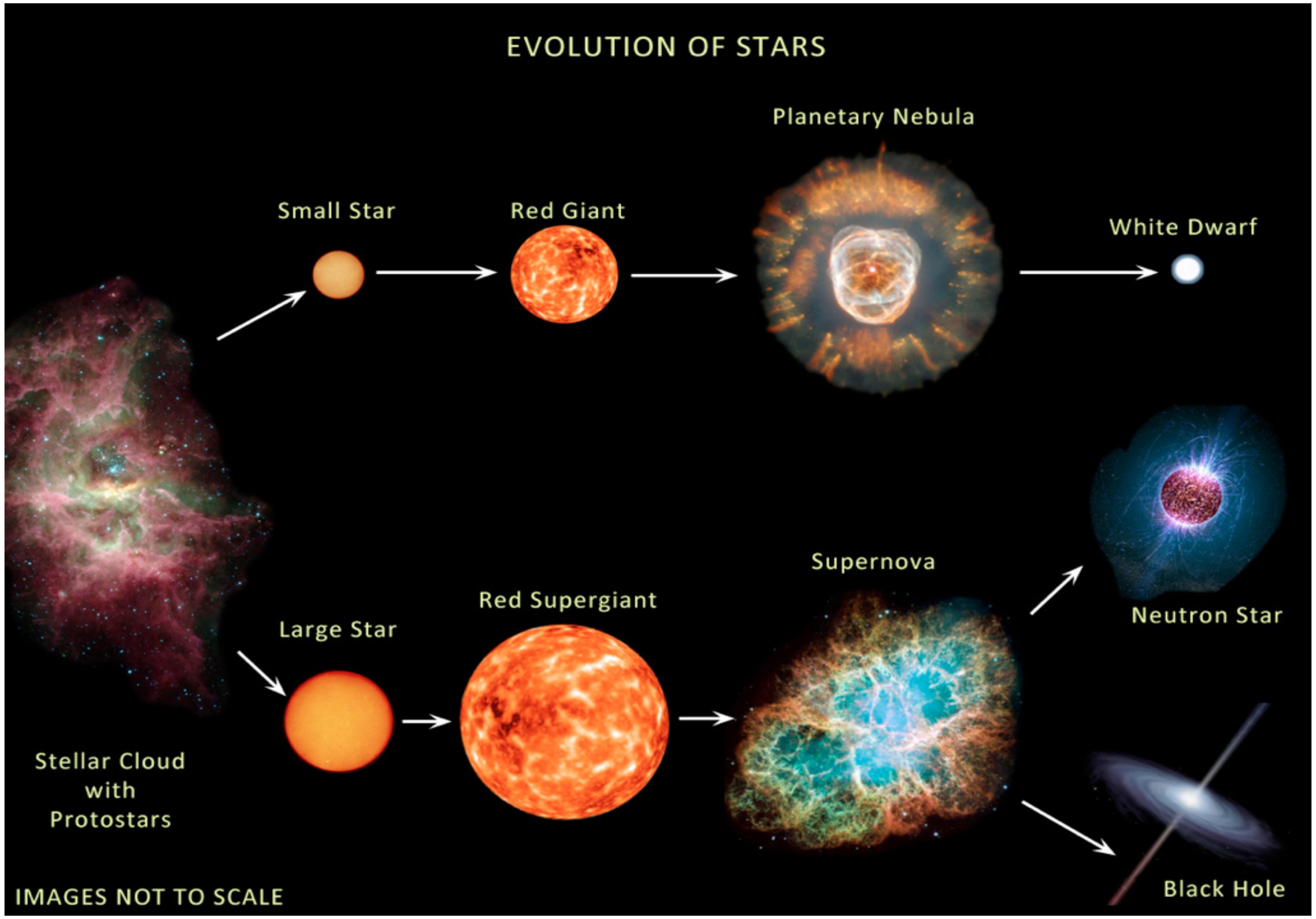
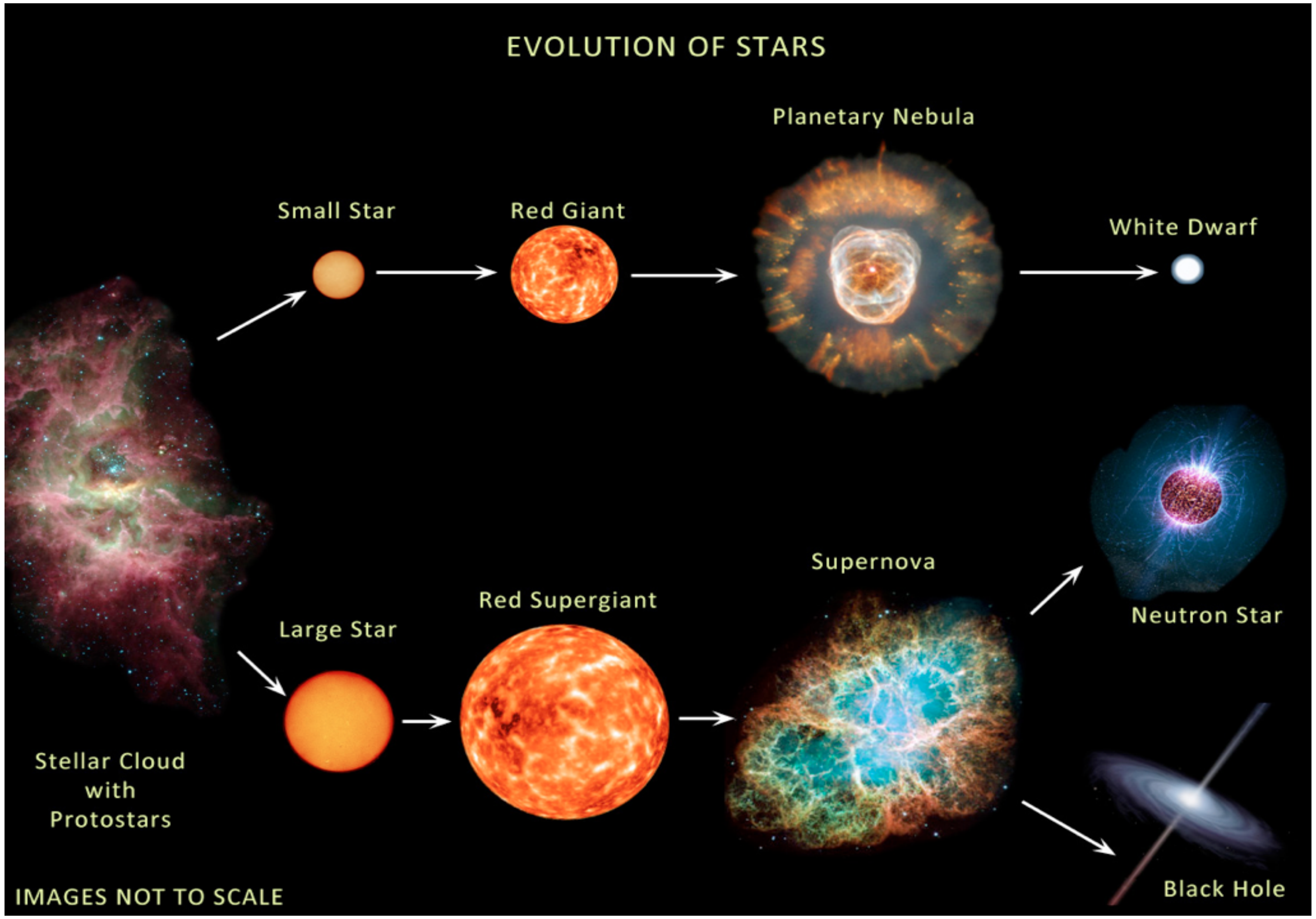
All the other elements are created in a combination
of the two processes, sometimes still unclear the proportion

Summary


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Neutron Star
Red Supergiant
Large Star
Stellar Cloud
with
Protostars
IMAGES NOT TO SCALE
Black Hole

Summary



Low mass stars produce: He, s-elements, Fe peak elements with SN Ia

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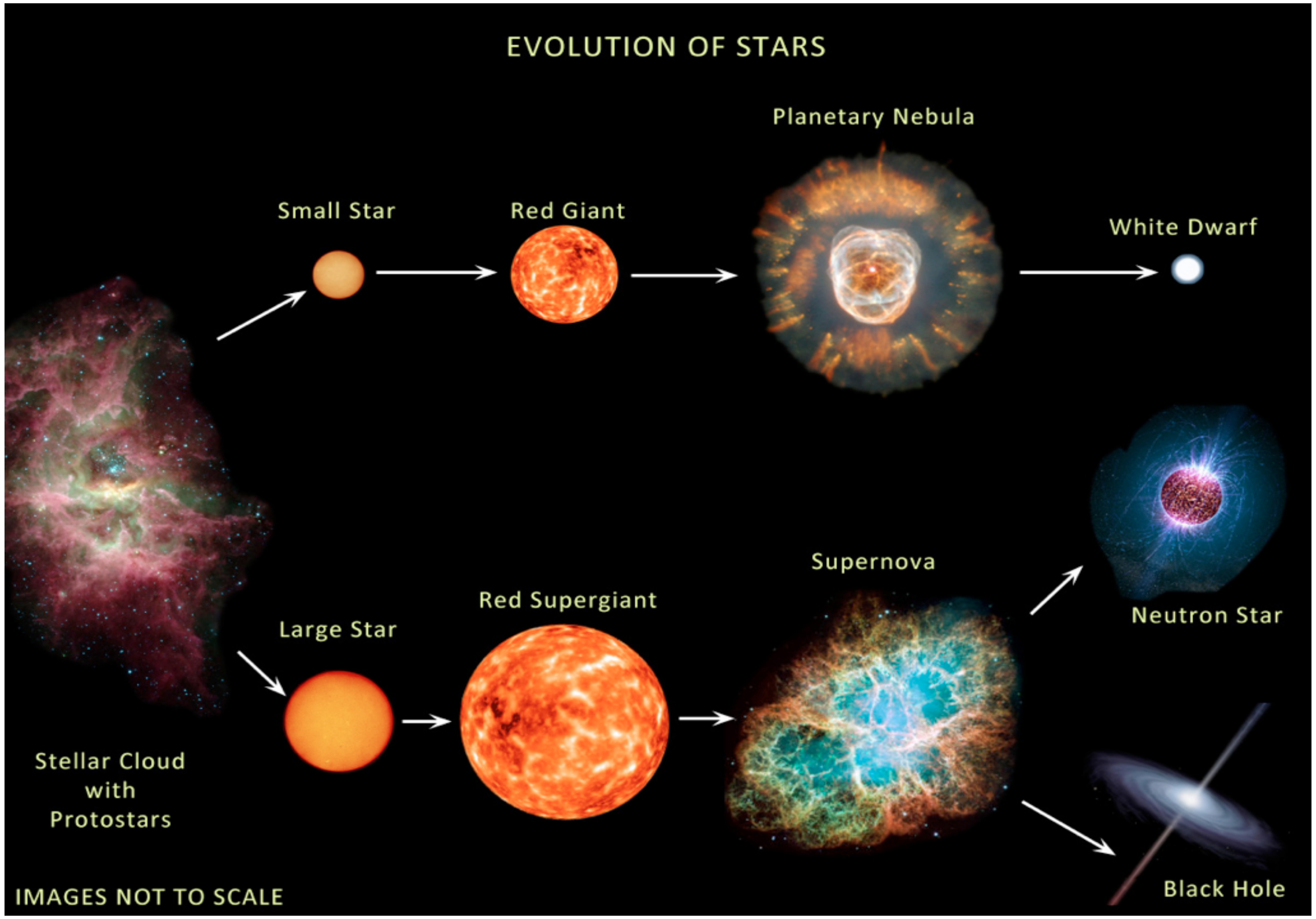


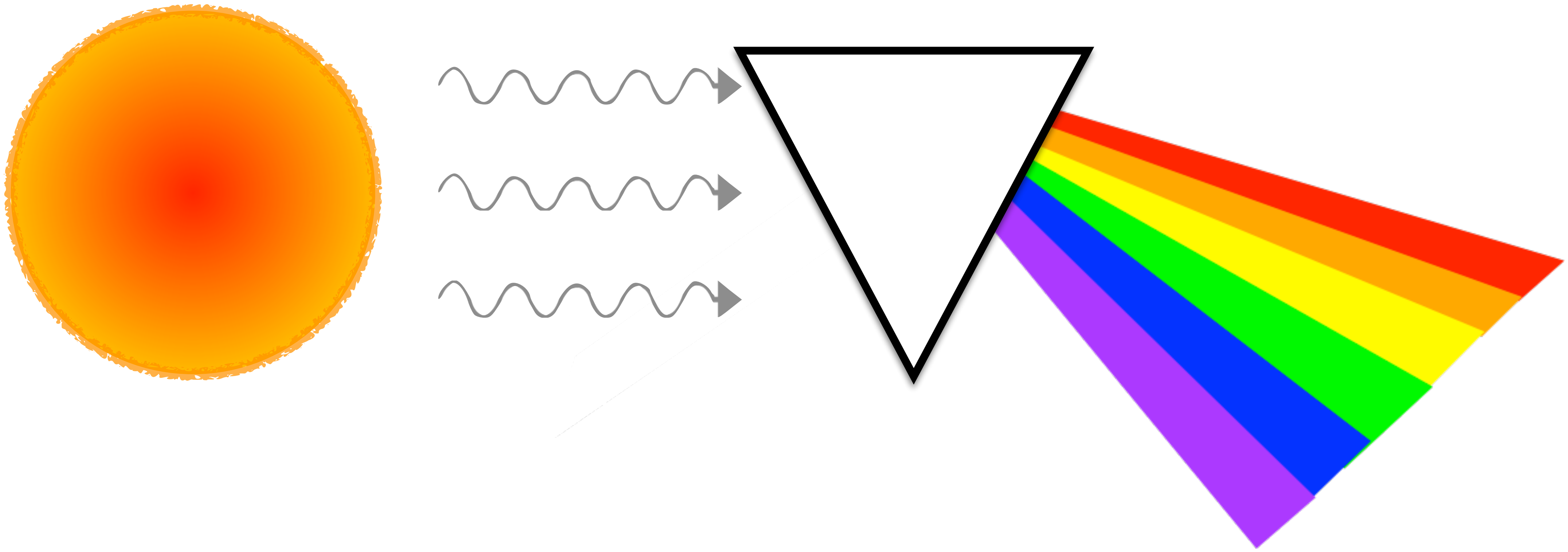
Low mass stars produce: He, s-elements, Fe peak elements with SN Ia

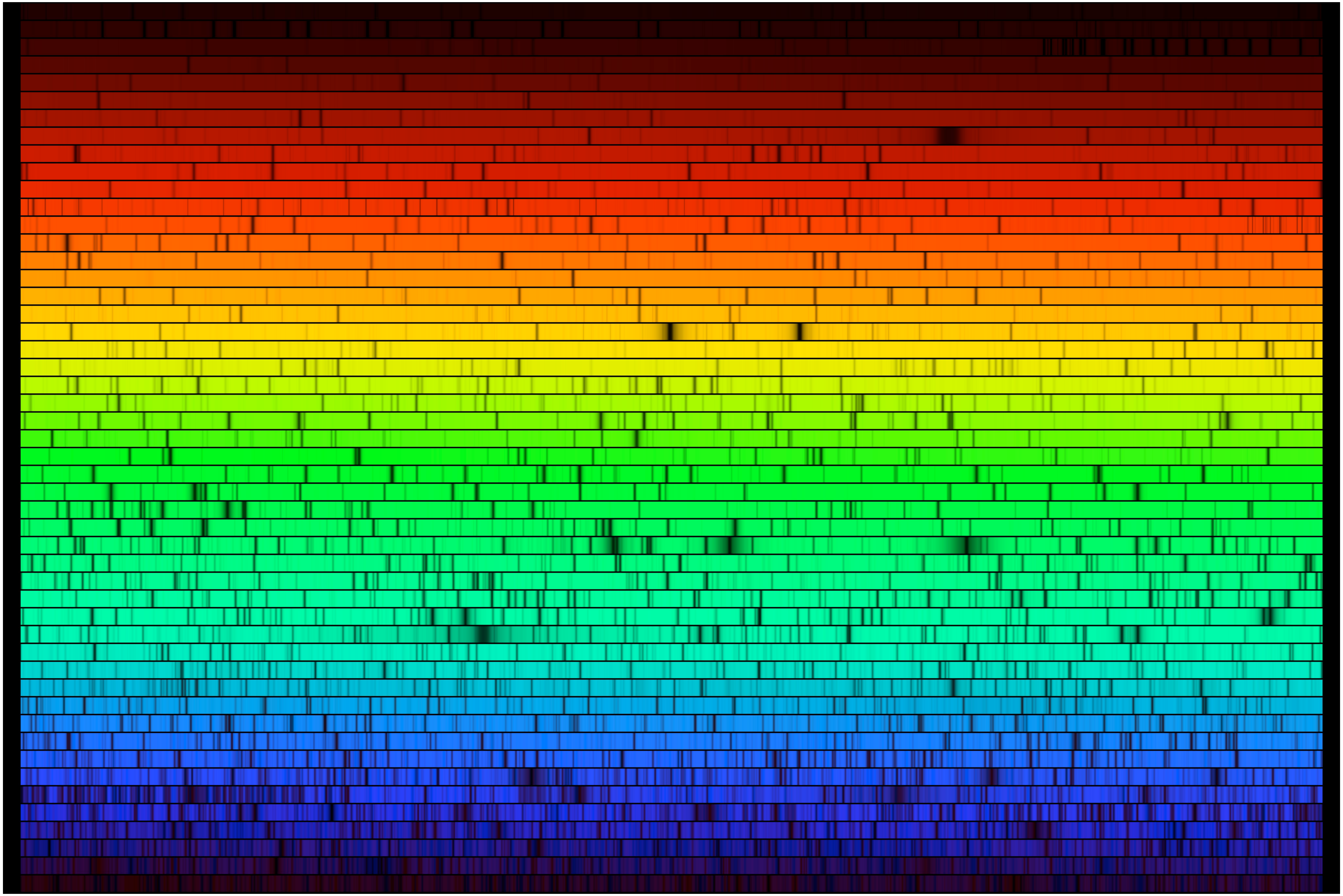
High mass stars produce: s-elements, r-elements, elements till Fe peak elements with SN II

Stellar spectroscopy

Stellar spectrum

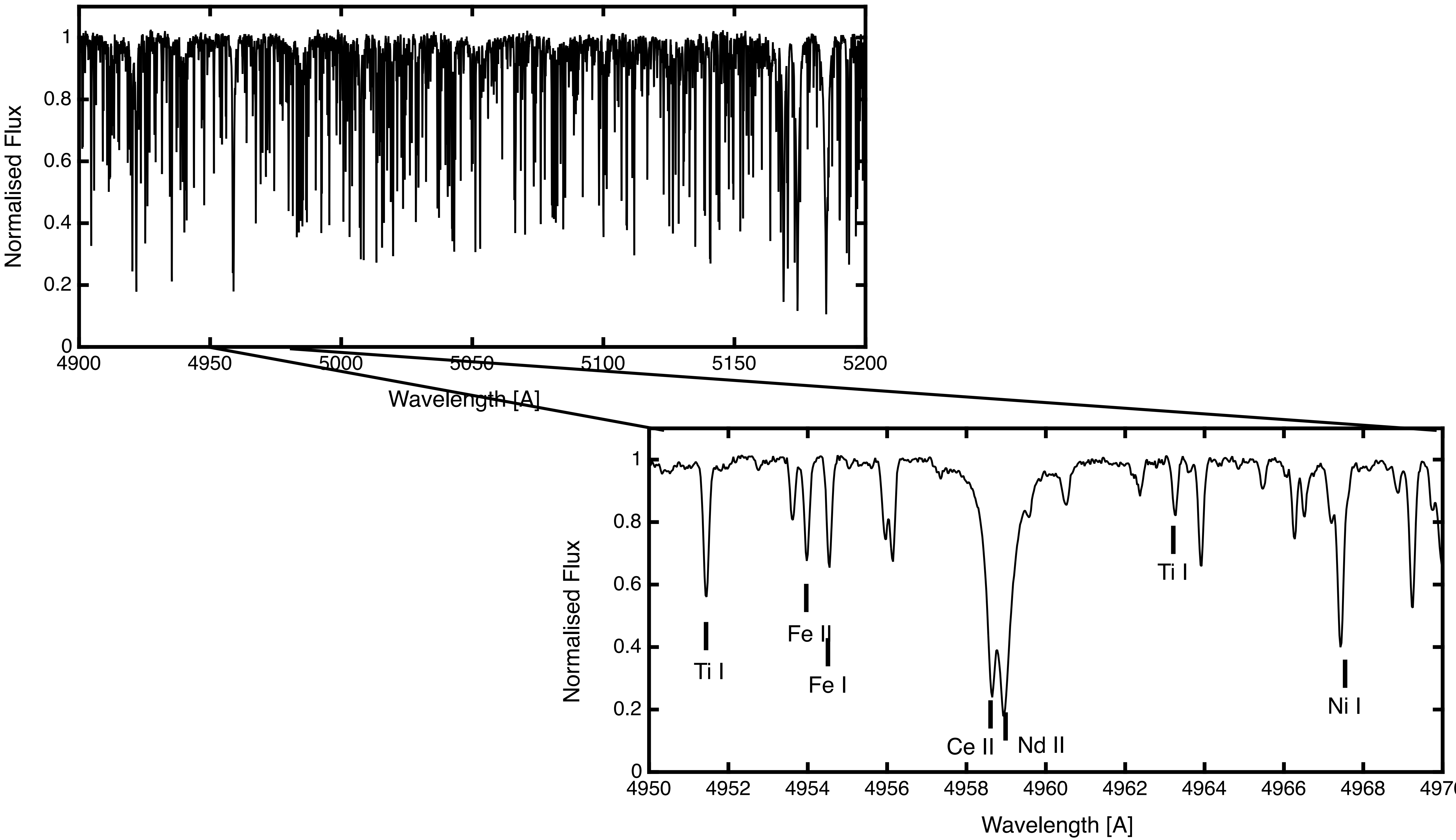
Stellar spectrum





High resolution solar spectrum

Abundance determination



Ingredients needed…

First approximation:
deeper the line => higher abundance

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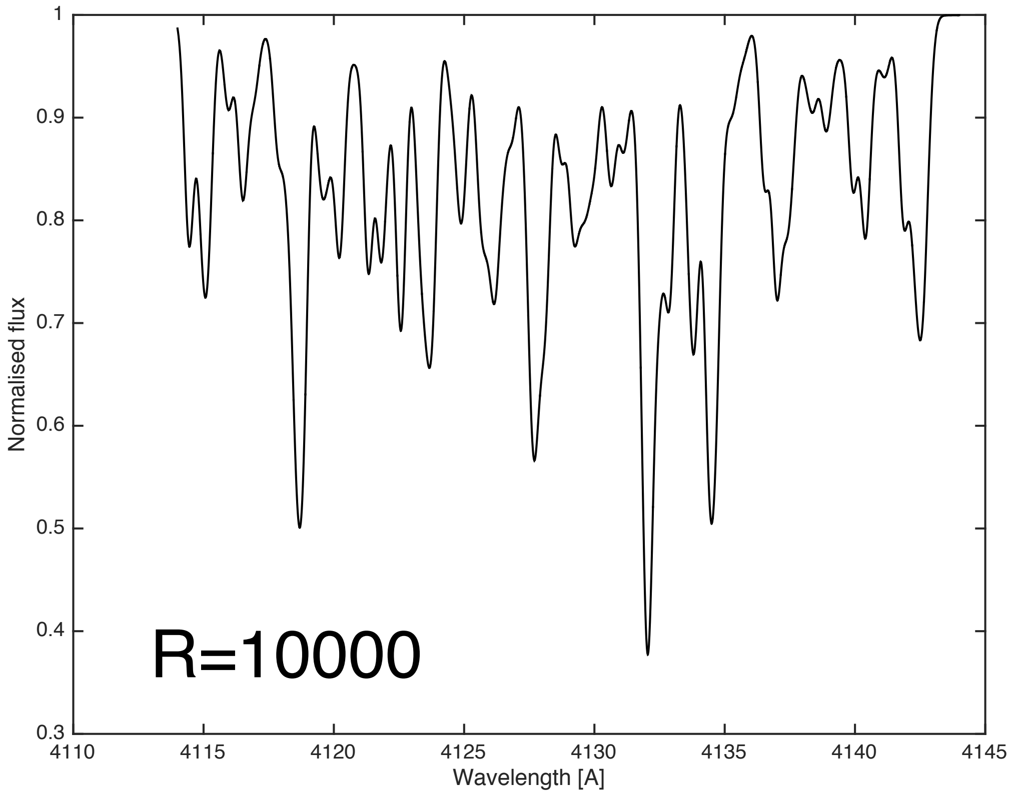
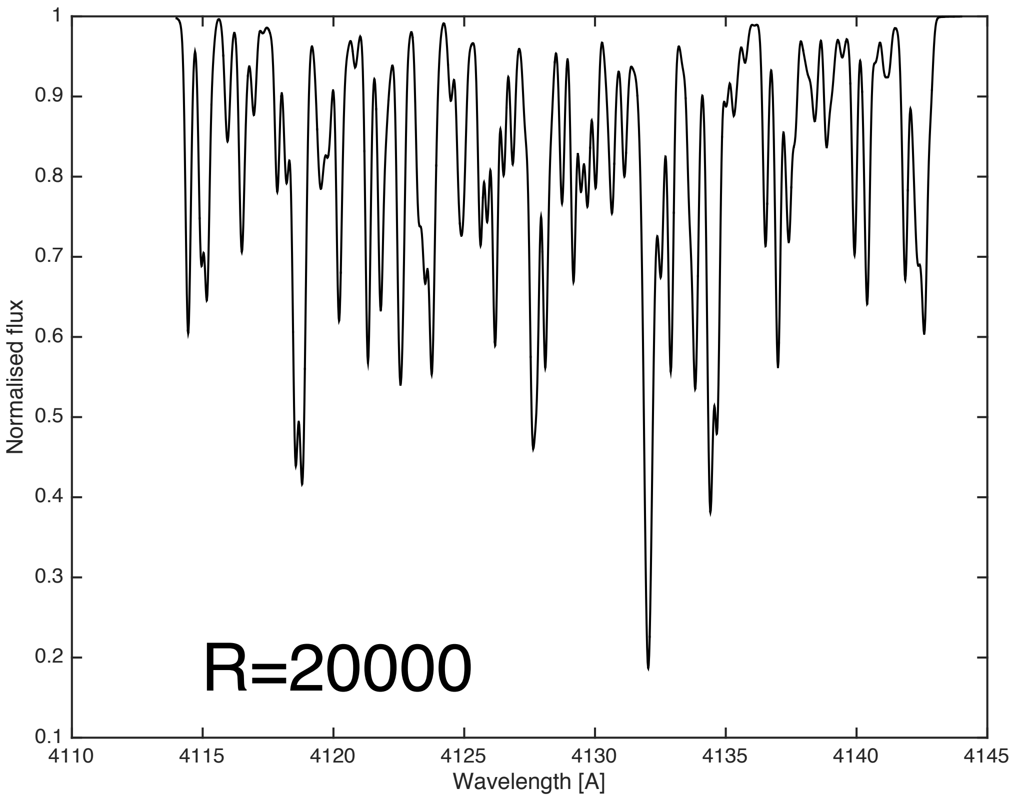
deeper the line => higher abundance

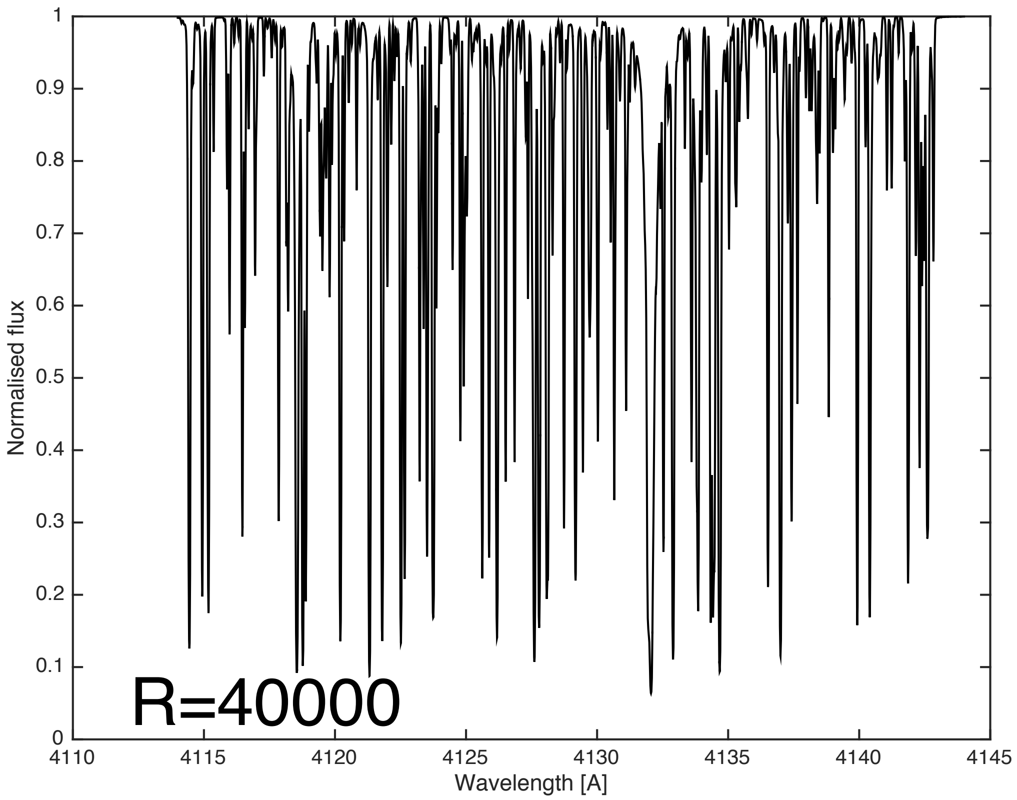
- High resolution spectra
- Determination of the stellar parameters
- Stellar atmosphere model
- Linelist (log gf, hfs, isotopic shift, blendings)

High resolution

Important to determine how well we can resolve close lines in the spectra







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Absorption lines in stellar spectra are influenced by stellar parameters

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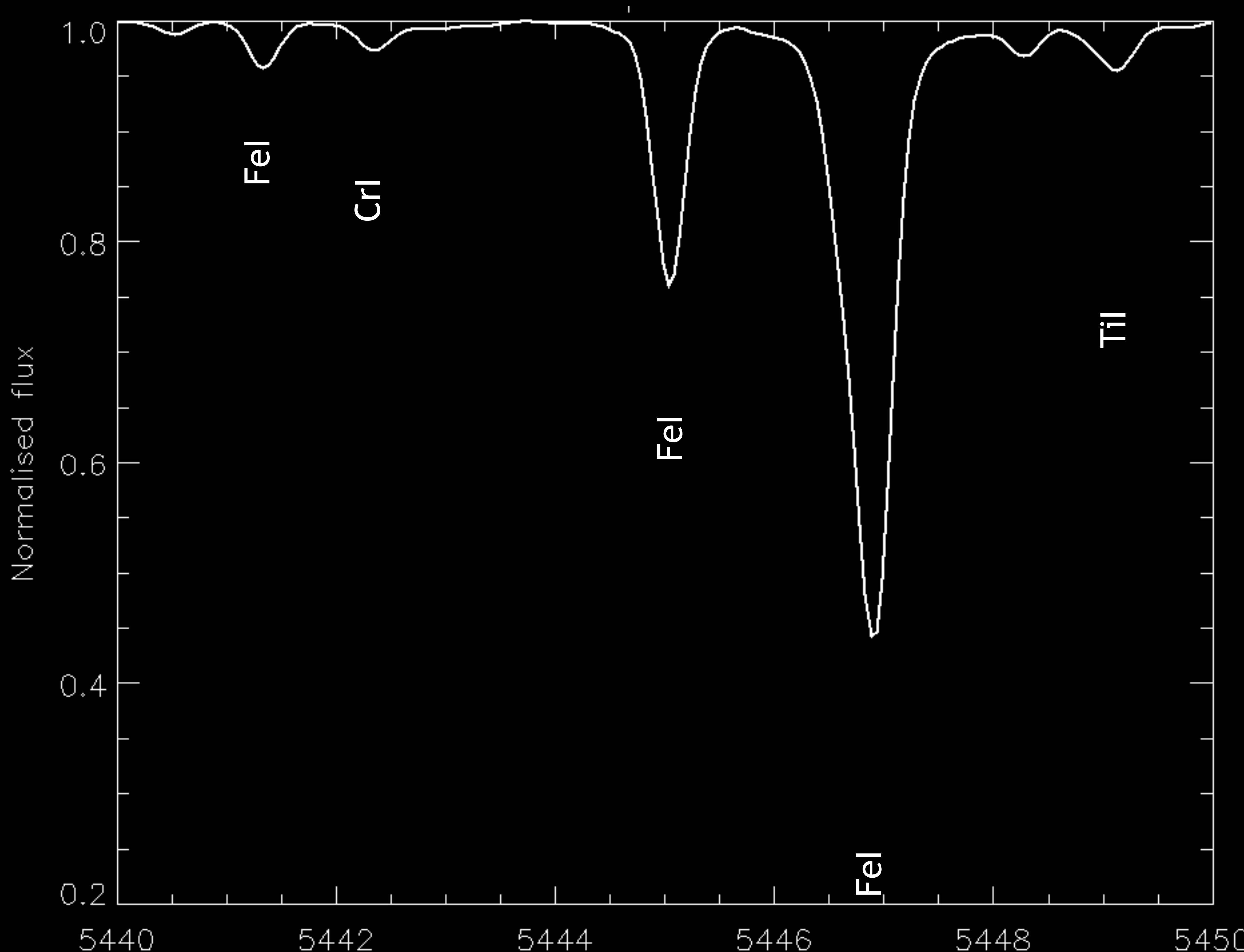
Metallicity
(first guess of [Fe/H])

- calibrated photometry

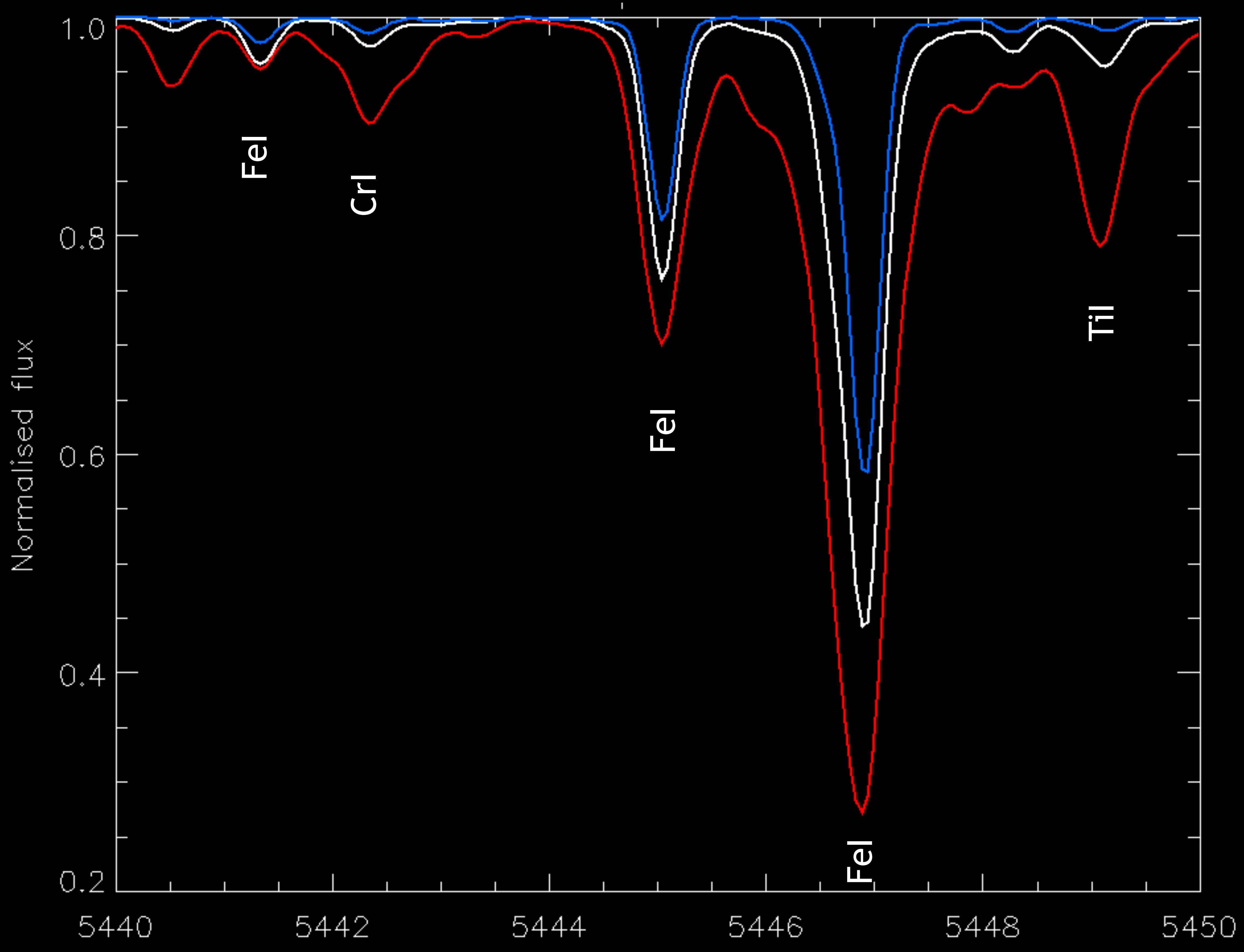
Temperature +-500K



Wavelength [Å]

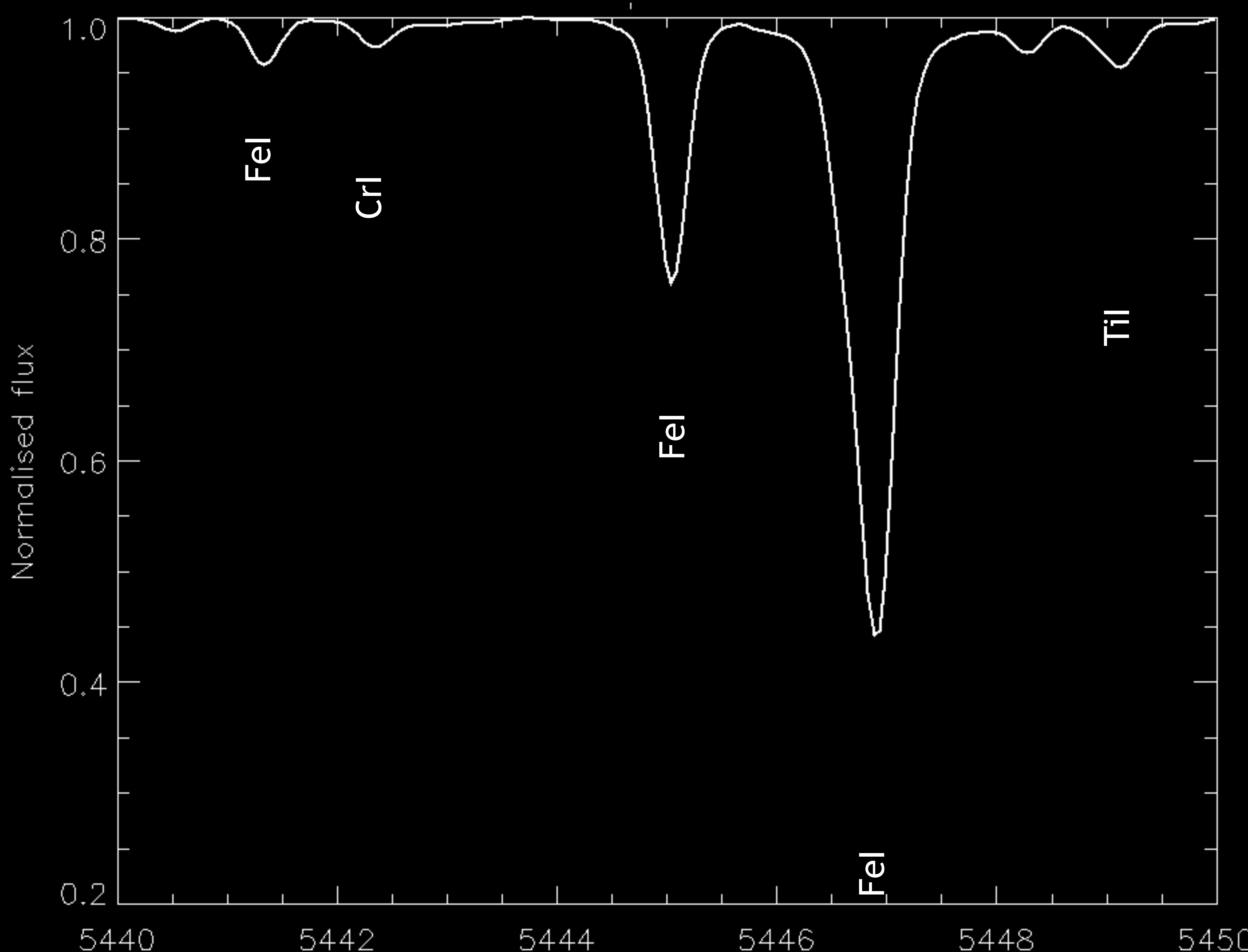
courtesy or Karin Lind

Temperature +-500K



courtesy or Karin Lind

Gravity +-1.0 dex



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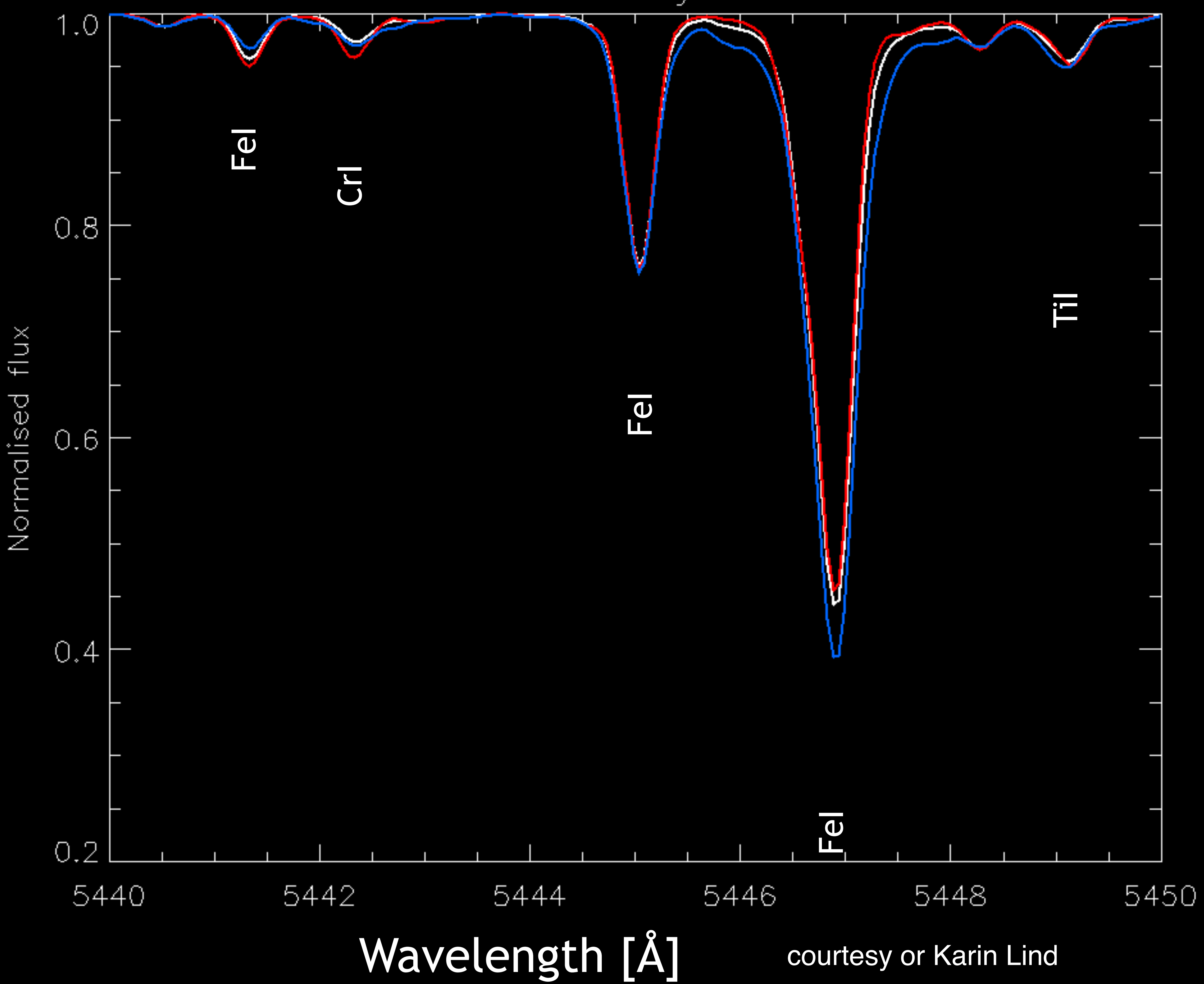
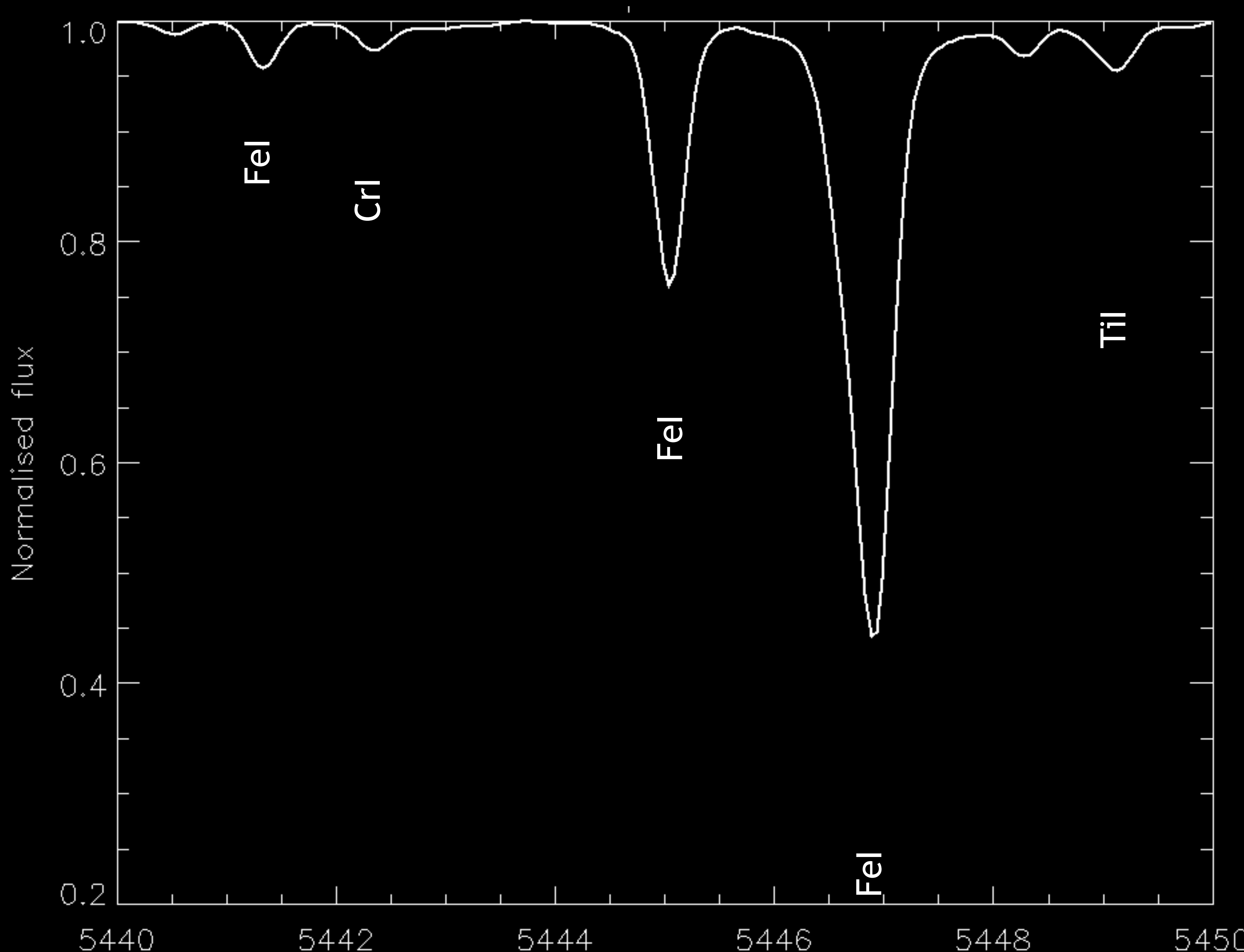


courtesy or Karin Lind

Metallicity +-0.3 dex



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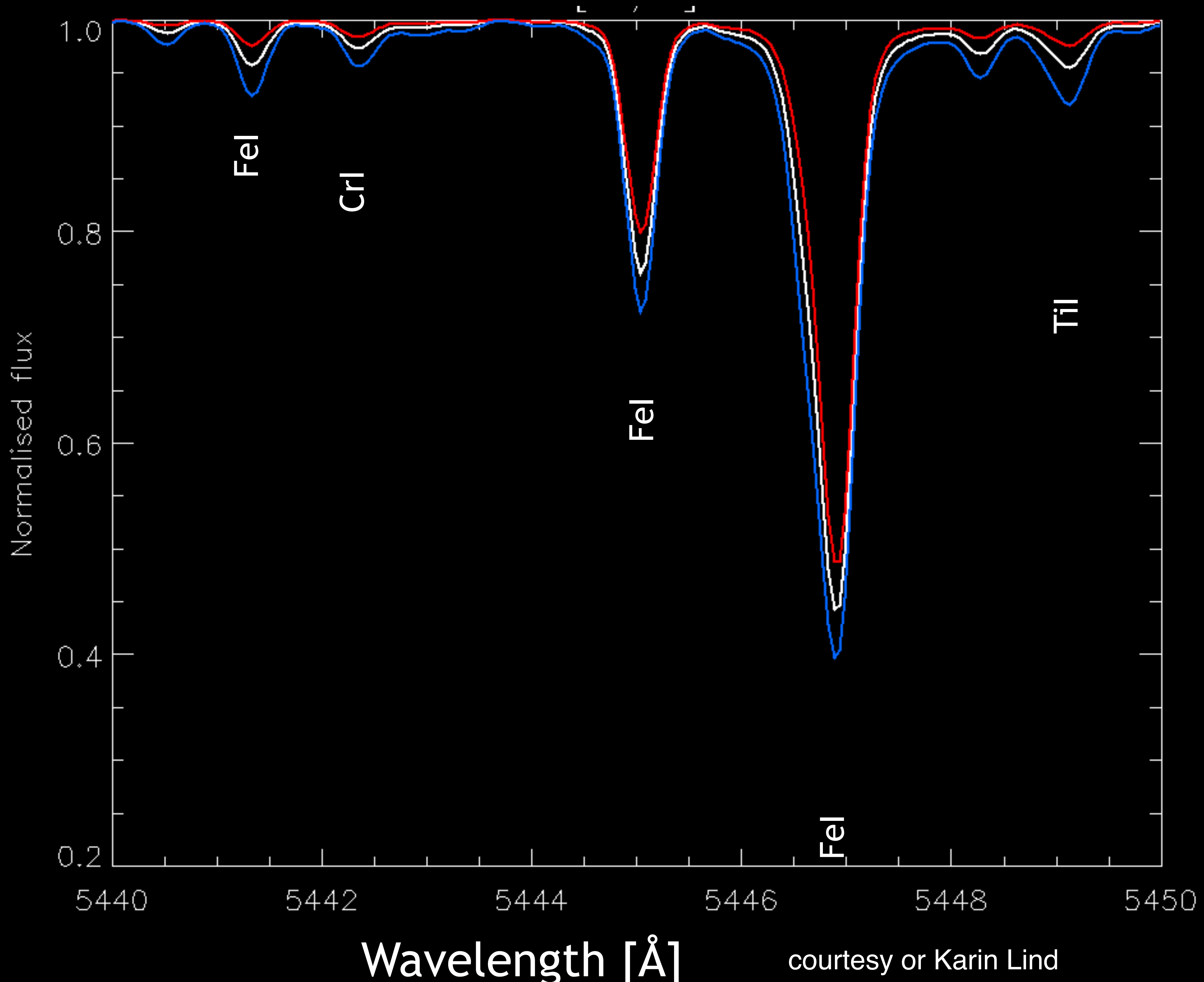
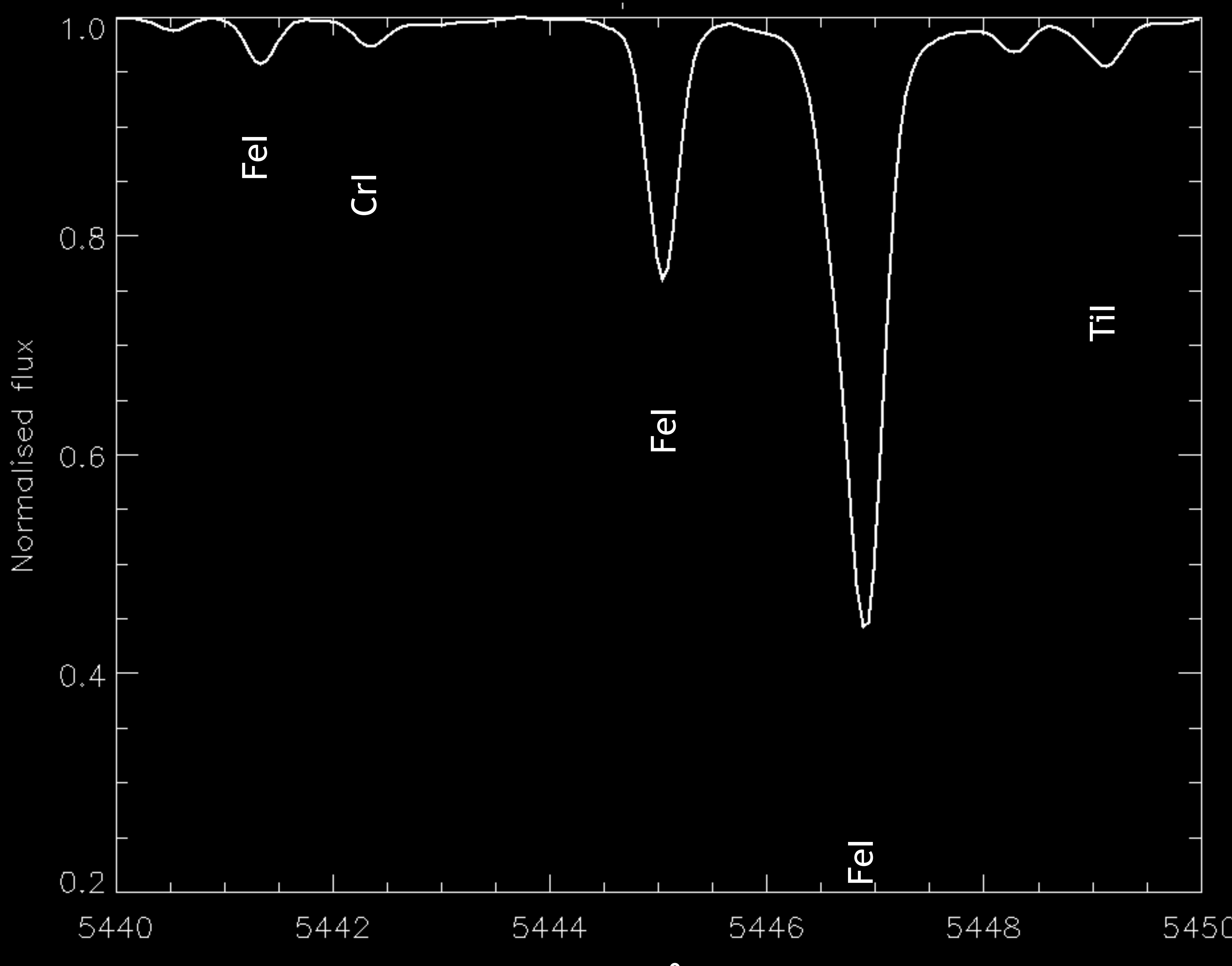


courtesy or Karin Lind

Temperature +-200K, logg+-1.0, Metallicity +-0.2 dex



courtesy or Karin Lind

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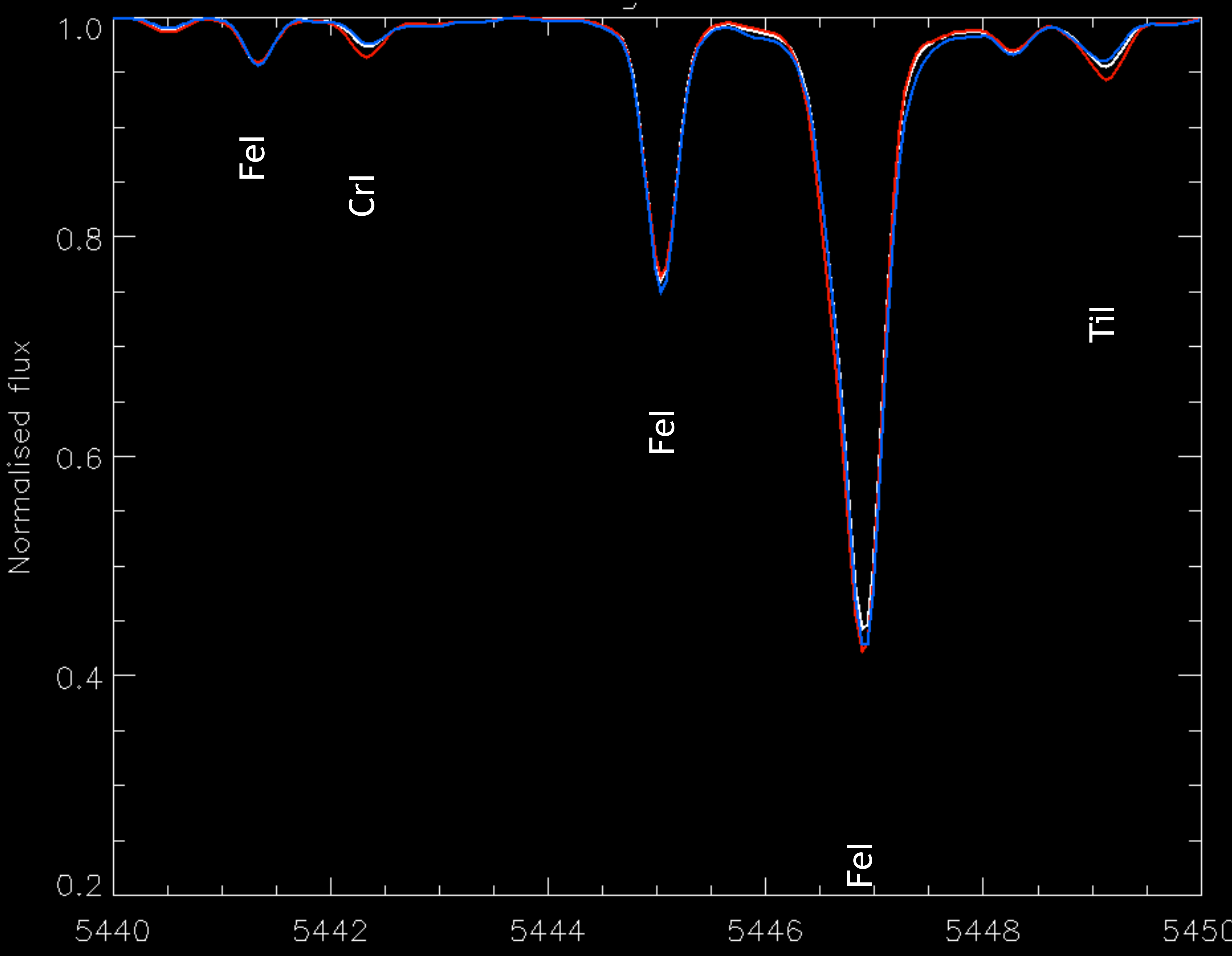
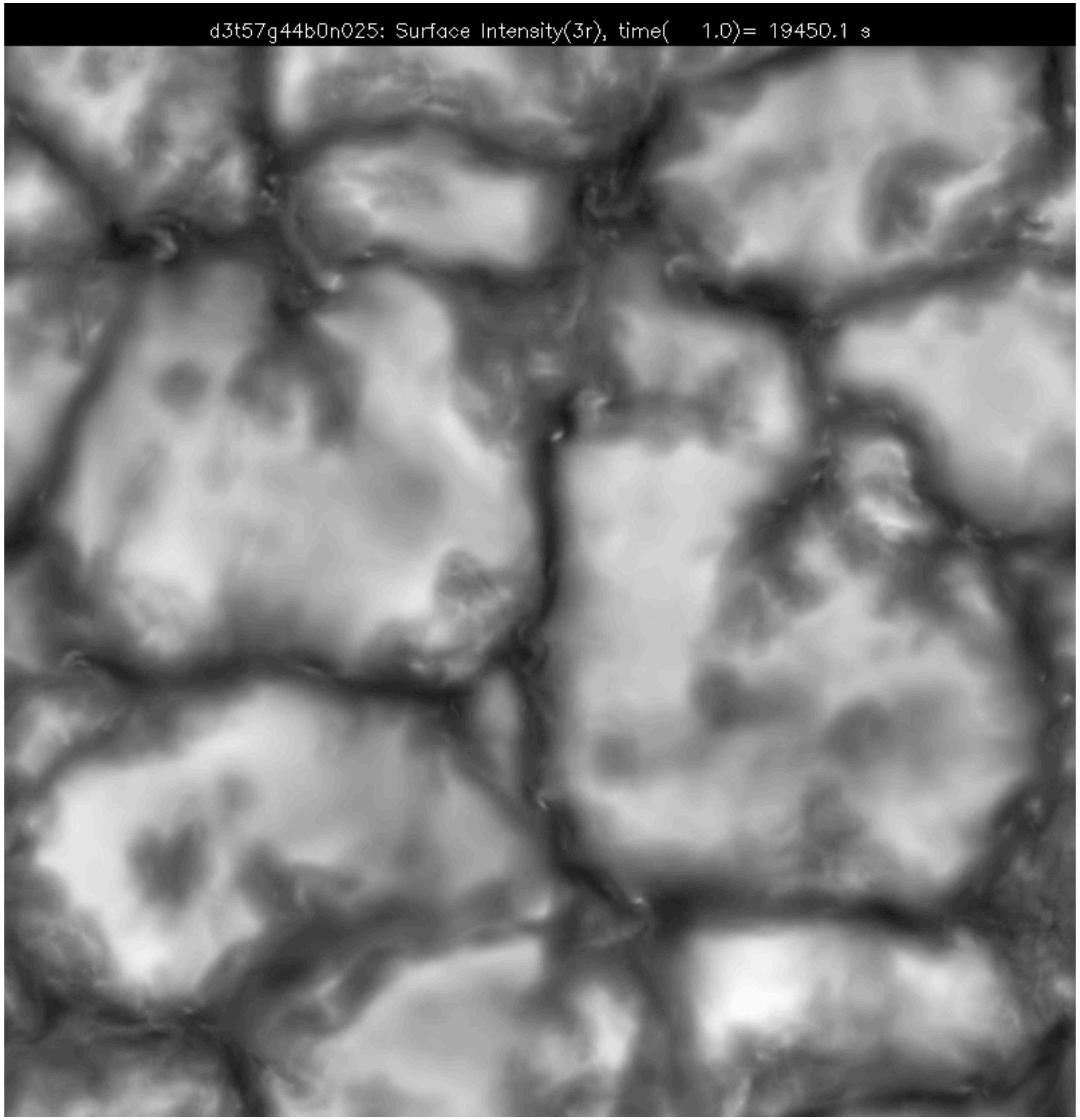


courtesy or Karin Lind

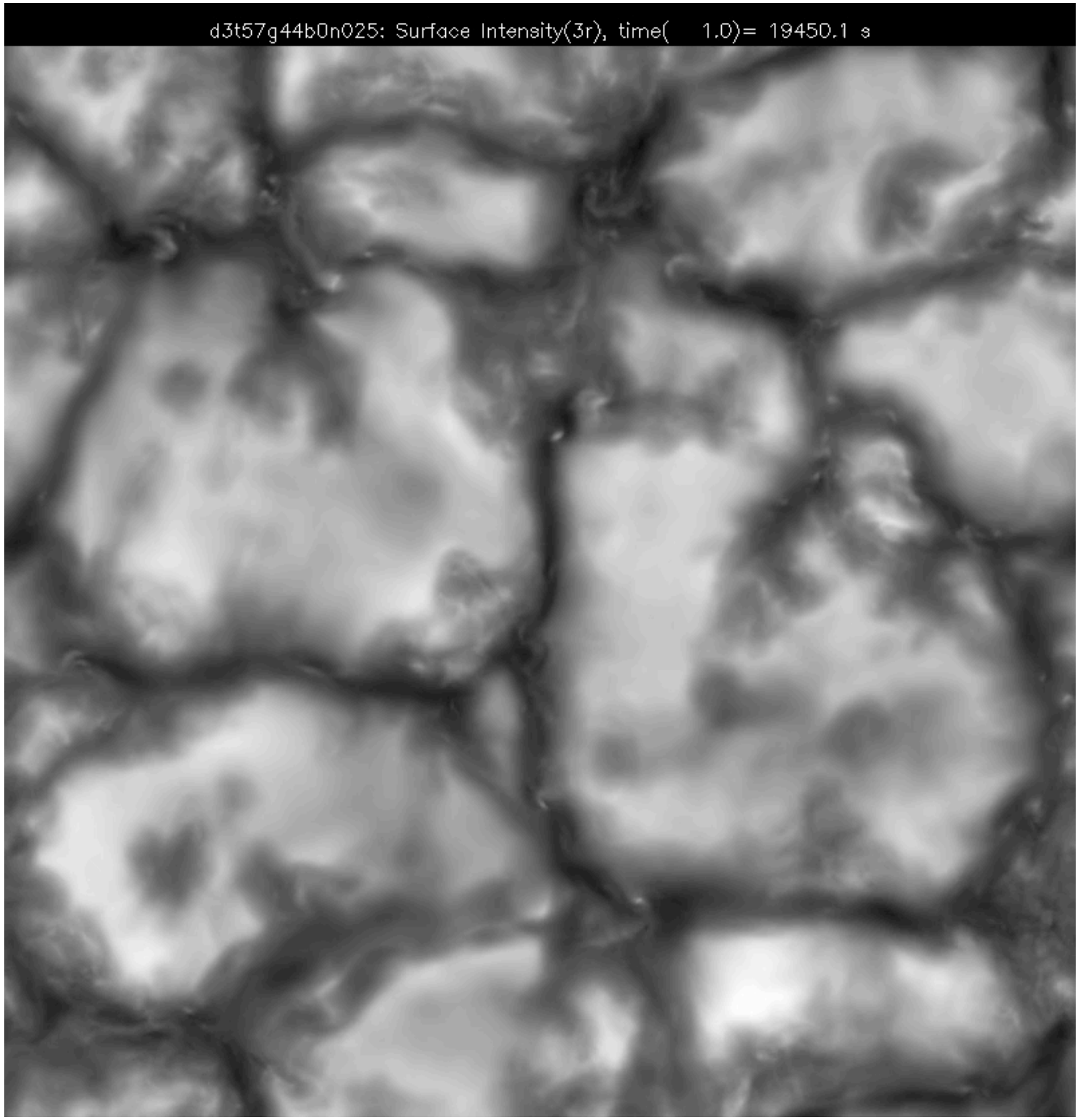
Stellar atmosphere model



credit: B. Freytag

Models are usually in 1D —> approximation!

Stellar atmosphere model



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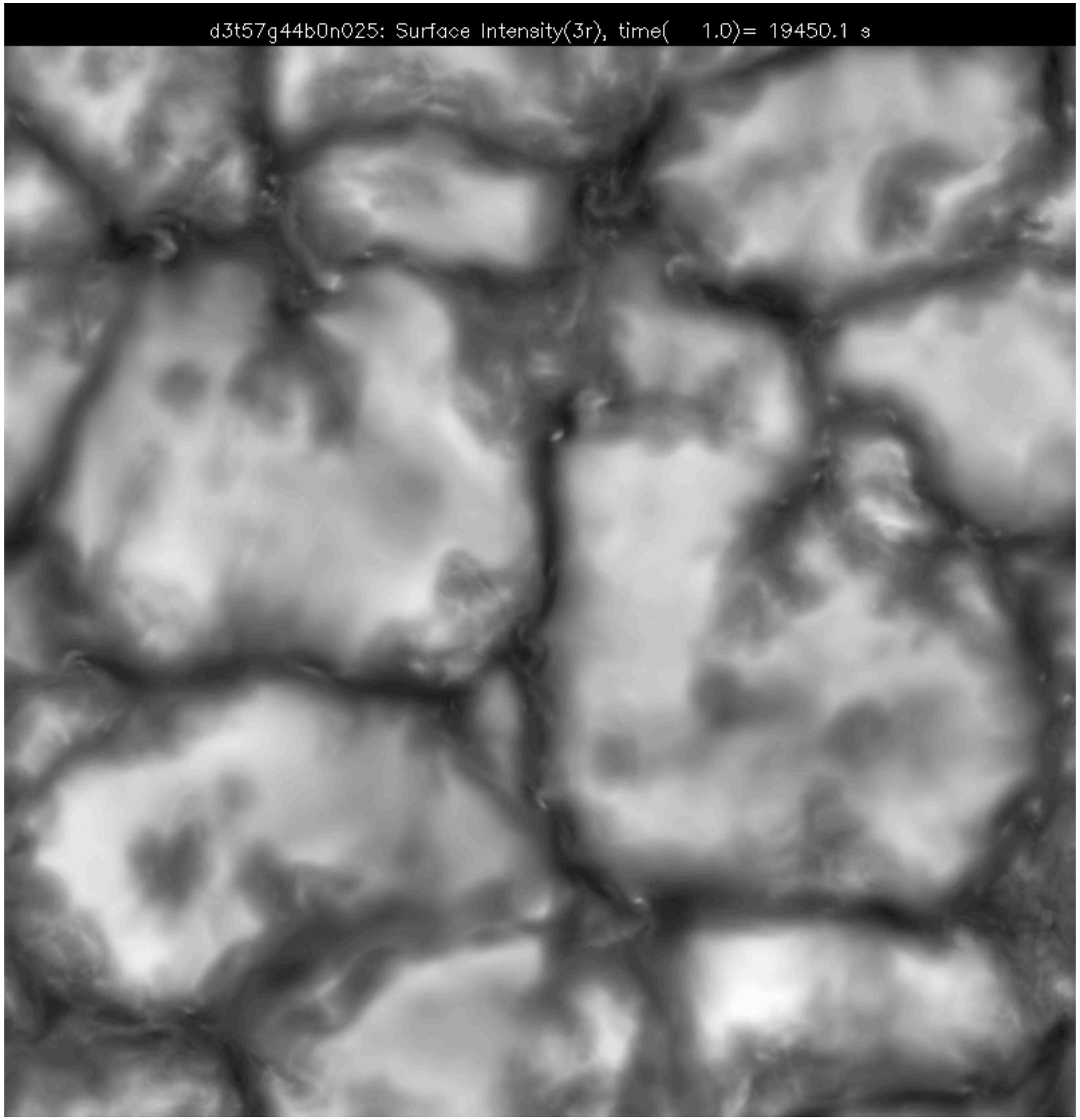

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Some 3D models available for some kind of stars
—> computationally heavy!

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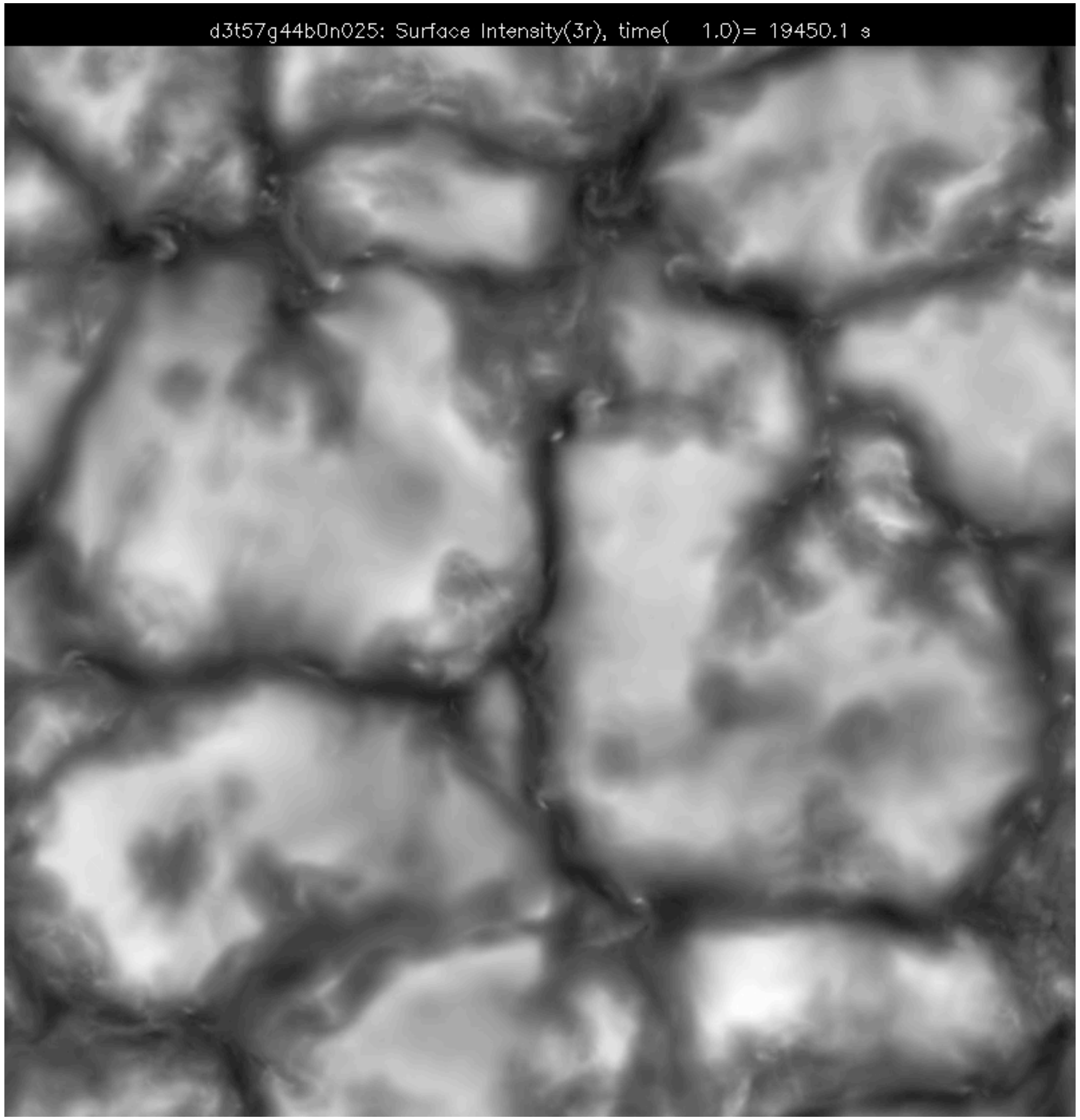

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<3D> models

Linelist

List of transitions lines in a certain wavelength region

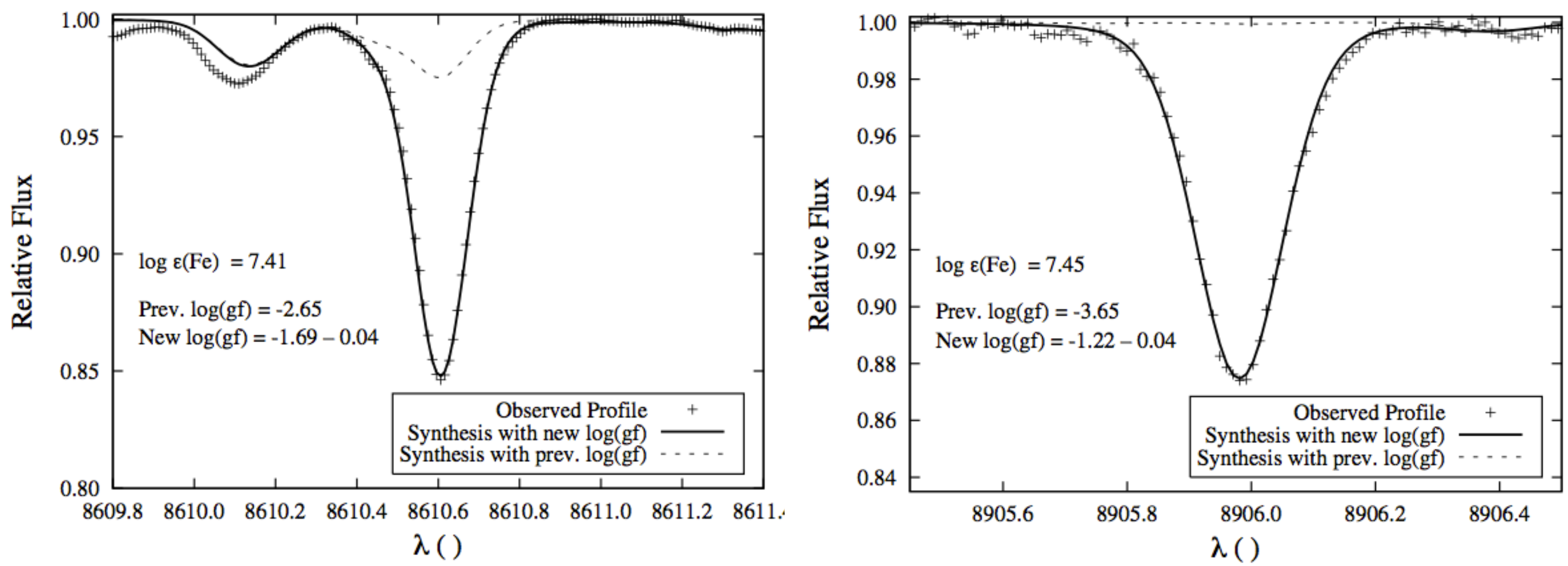
Why is it important?

- use the right atomic parameters to describe the spectral line(s) (especially log gf) of interest
- taking into account hyperfine splitting and/or isotopic shift in the line(s) of interest
- know all the transitions that can affect the region or the line of interest

Linelist I: atomic parameters

The oscillator strength (log gf) expresses the probability of absorption in transitions between energy levels of an atom or molecule

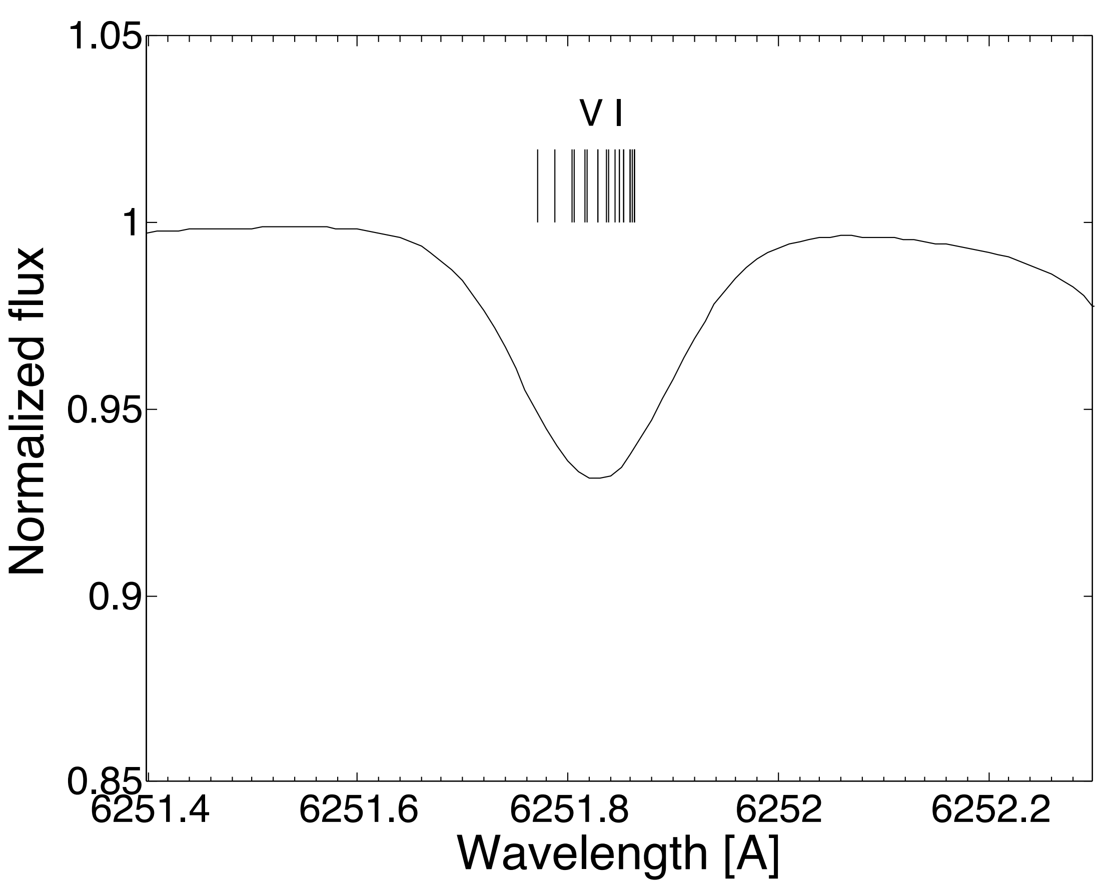
Important to know to correctly fit a line and get a correct abundance —> important lab work!

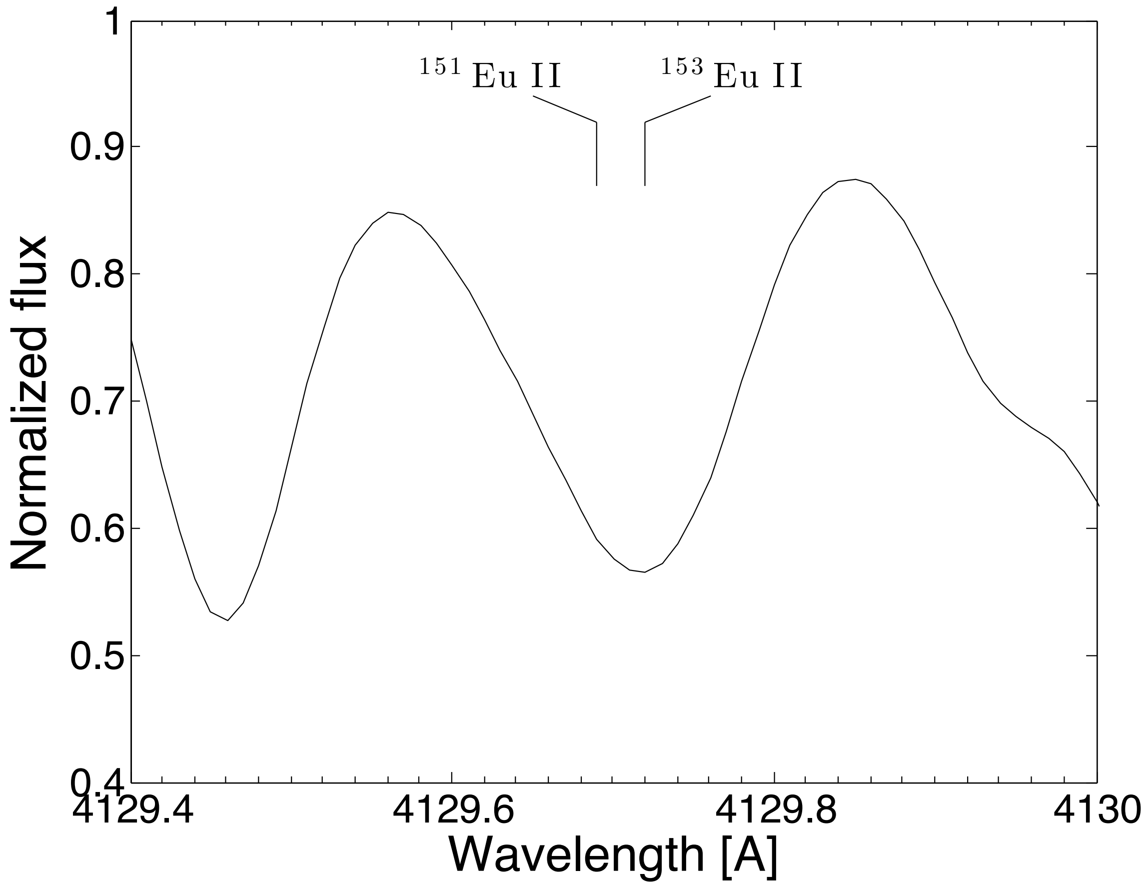


Ruffoni et al. (2014)

Linelist II: hfs + isotopic shift

Hyperfine splitting (hfs): interaction between the magnetic moment of the nucleus' spin and the magnetic moment of the electron's spin because the nucleus has an odd number of p and/or an odd number of n
—> <u>broaden the absorption line profile</u>
Isotopic shift: most elements have more than one isotope with different nuclear masses and charge distribution
—> <u>broaden the absorption line profile</u>



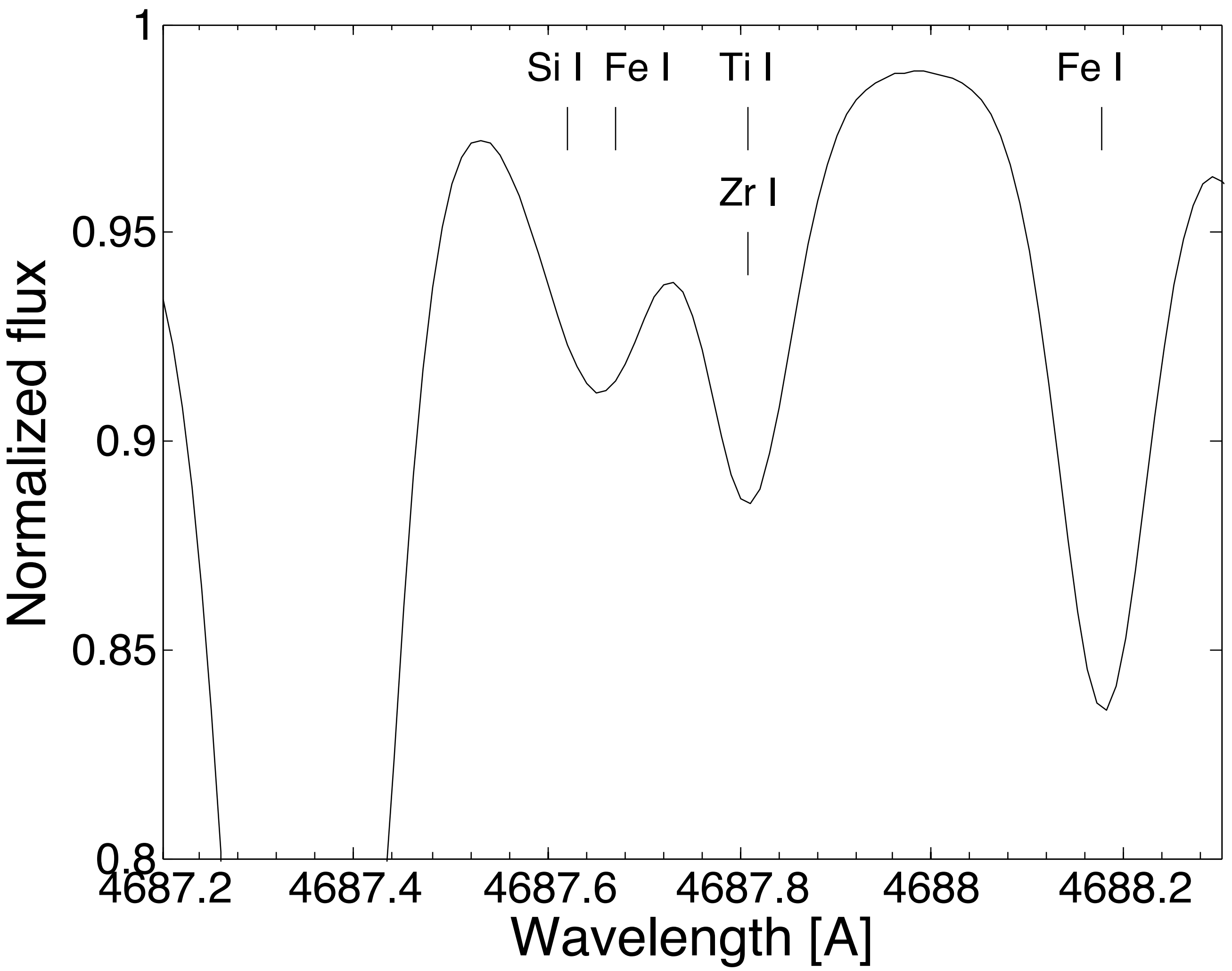


Linelist III: blendings

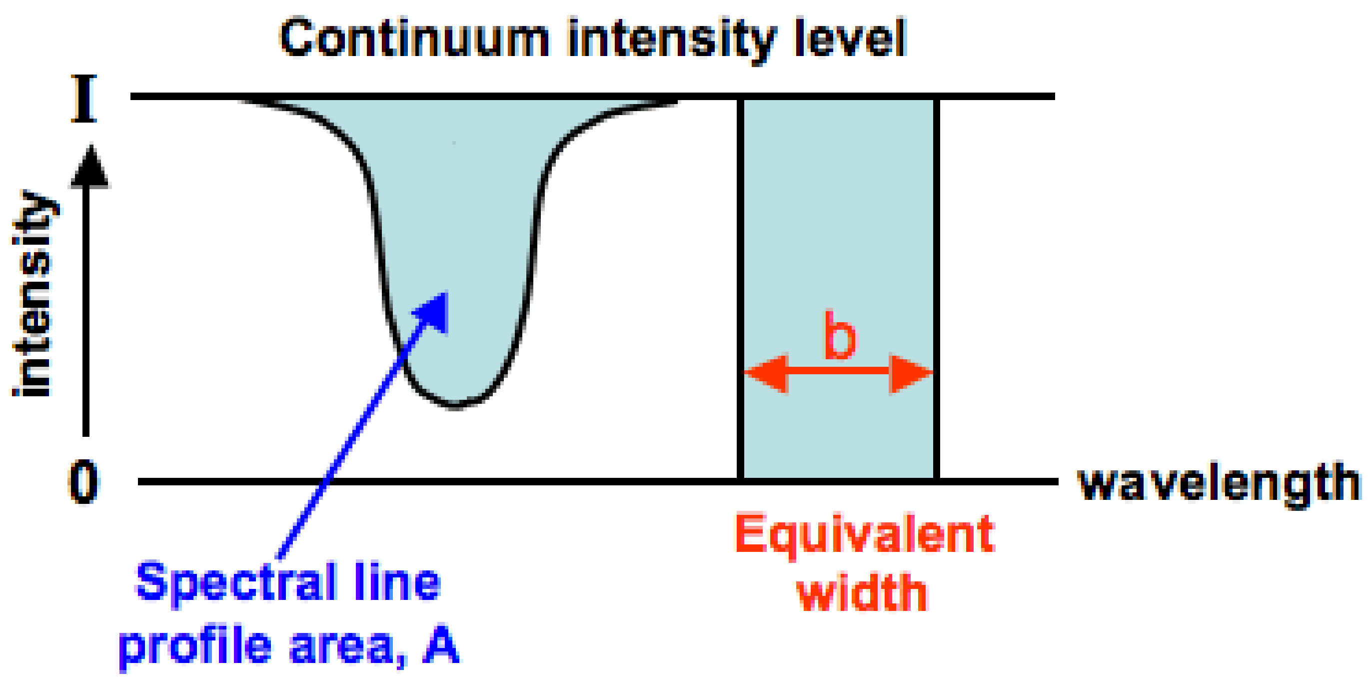
Several lines can be present in the wavelenght region of interest.

This is particulary true in the blue part of the spectrum where more transitions happen

Important to know which transition lines can affect the measurement of the line of interest



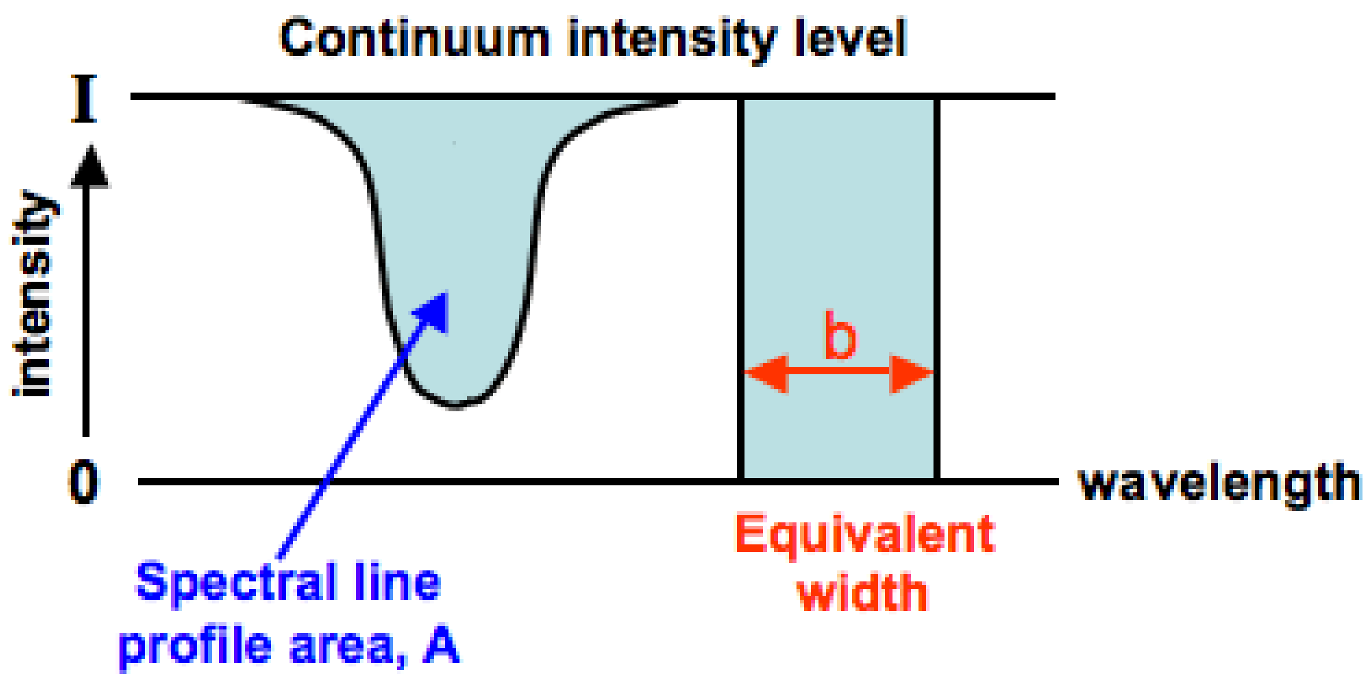
Abundance measurements



✓ **Pro:** more direct

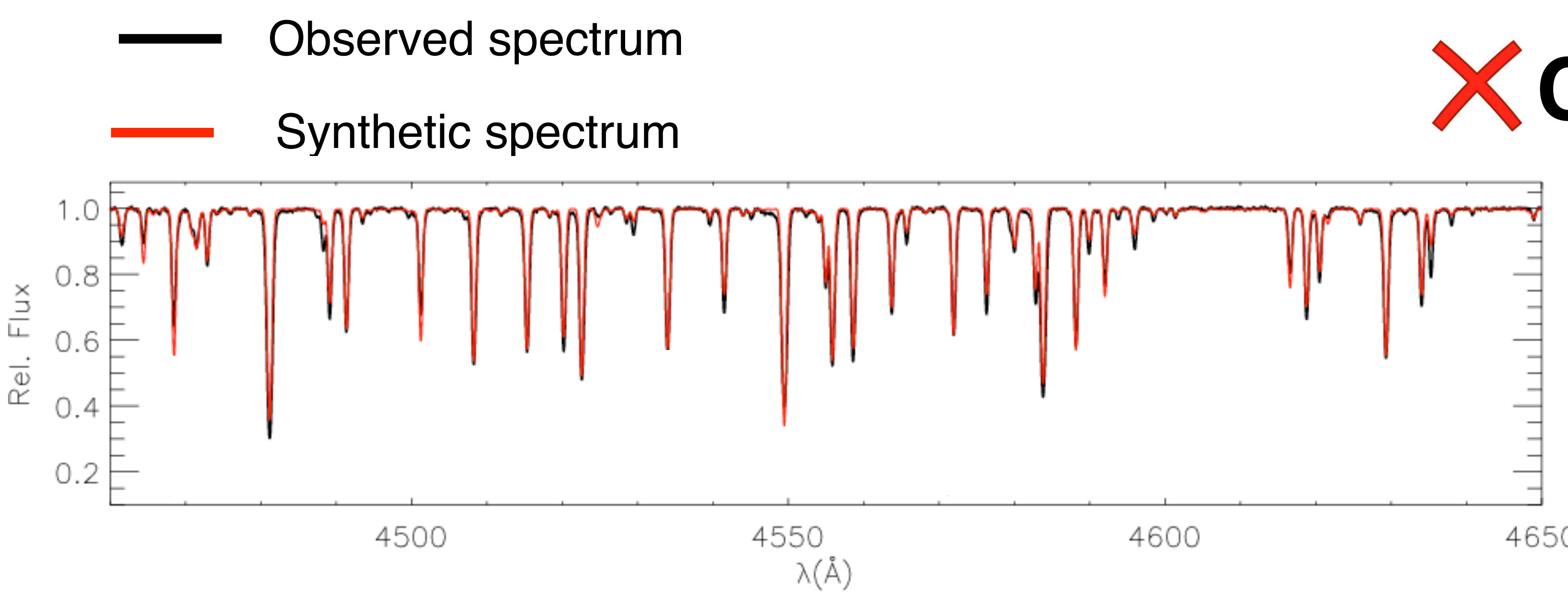
✗ **Cons:** more difficult to take care of blendings and hfs

Abundance measurements



✓ **Pro:** more direct

✗ **Cons:** more difficult to take care of blendings and hfs



✓ **Pro:** easier to work with hfs and blendings

✗ **Cons:** need good models

Abundance calculation

1. $\log \varepsilon(A) = \log (N_A/N_H)+12$

2. $[X / H] = \log_{10} (N_X / N_H)_\star - \log_{10} (N_X / N_H)_\odot$

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<u>Example</u>

$\log \varepsilon(Mg)_\star = 5.96$, $\log \varepsilon(Fe)_\star = 5.50$

$\log \varepsilon(Mg)_\odot = 7.60$, $\log \varepsilon(Fe)_\odot = 7.50$

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$$[\text{Mg} / \text{H}] = \text{Log } \varepsilon(\text{Mg})_\star - \text{Log } \varepsilon(\text{Mg})_\odot = -1.64$$

$$[\text{Fe} / \text{H}] = \text{Log } \varepsilon(\text{Fe})_\star - \text{Log } \varepsilon(\text{Fe})_\odot = -2.00$$

Abundance ratios

$$[X / \mathrm{H}] = \log_{10} (\mathrm{N}_X / \mathrm{N}_\mathrm{H})_\bigstar - \log_{10} (\mathrm{N}_X / \mathrm{N}_\mathrm{H})_\odot$$

Abundance ratios

$$[X / \mathrm{H}] = \log_{10} (N_X / N_H)_\star - \log_{10} (N_X / N_H)_\odot$$

One important abundance is [Fe/H], that can be derived as:

$$[\mathrm{Fe} / \mathrm{H}] = \mathrm{Log}\ \varepsilon(\mathrm{Fe})_\star - \mathrm{Log}\ \varepsilon(\mathrm{Fe})_\odot$$

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One important abundance is [Fe/H], that can be derived as:

$$[Fe / H] = \text{Log}\ \varepsilon(Fe)_\star - \text{Log}\ \varepsilon(Fe)_\odot$$

If you want to relate another element, like for example Mg, with Fe then you have:

$$[Mg / H] = \text{Log}\ \varepsilon(Mg)_\star - \text{Log}\ \varepsilon(Mg)_\odot$$

$$[Mg / Fe] = [Mg / H] - [Fe / H]$$

Abundance plots

We saw that different elements are produced in different moments during stellar evolution

SN II —> α-elements, r-process elements

SN Ia —> iron-peak elements

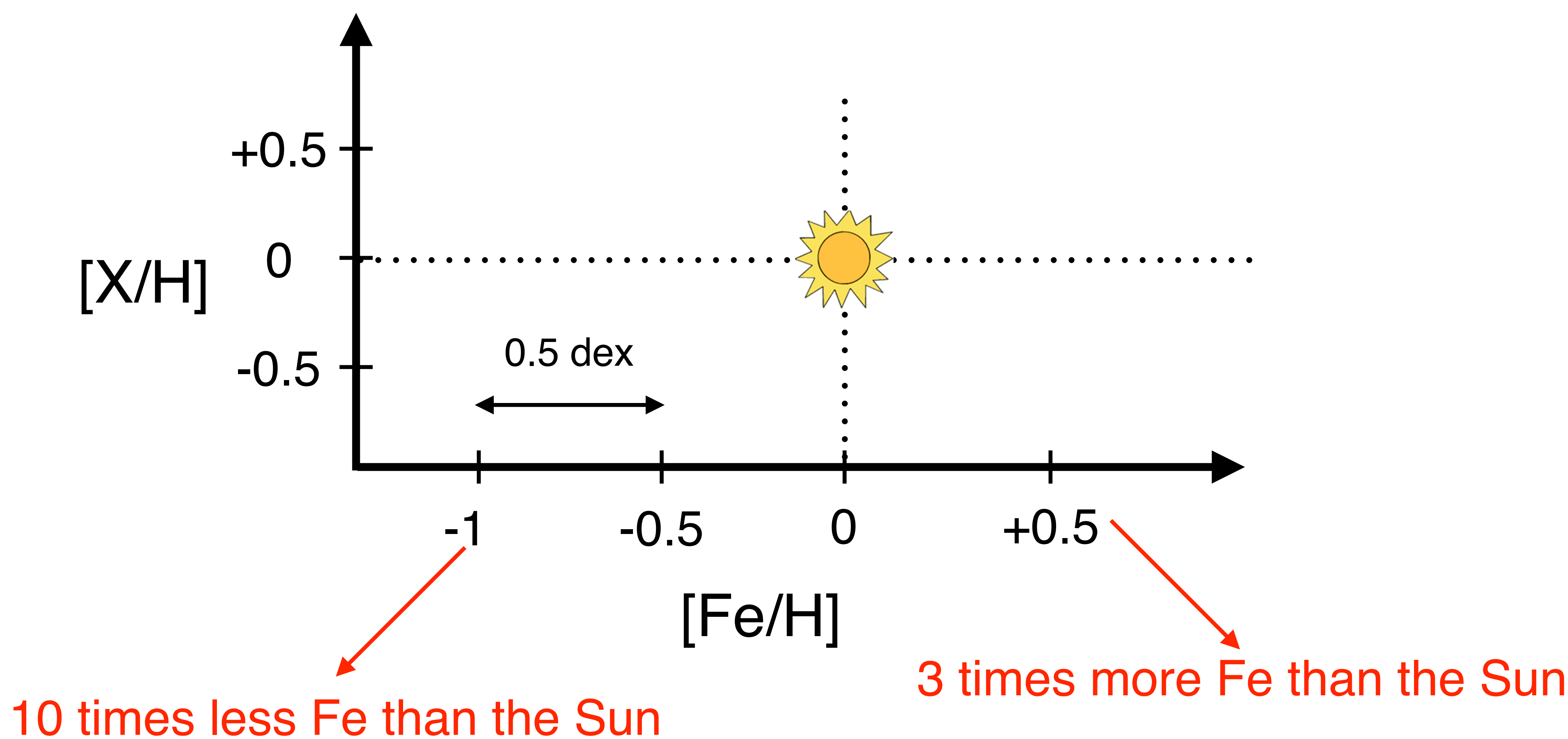
AGB —> s-process elements

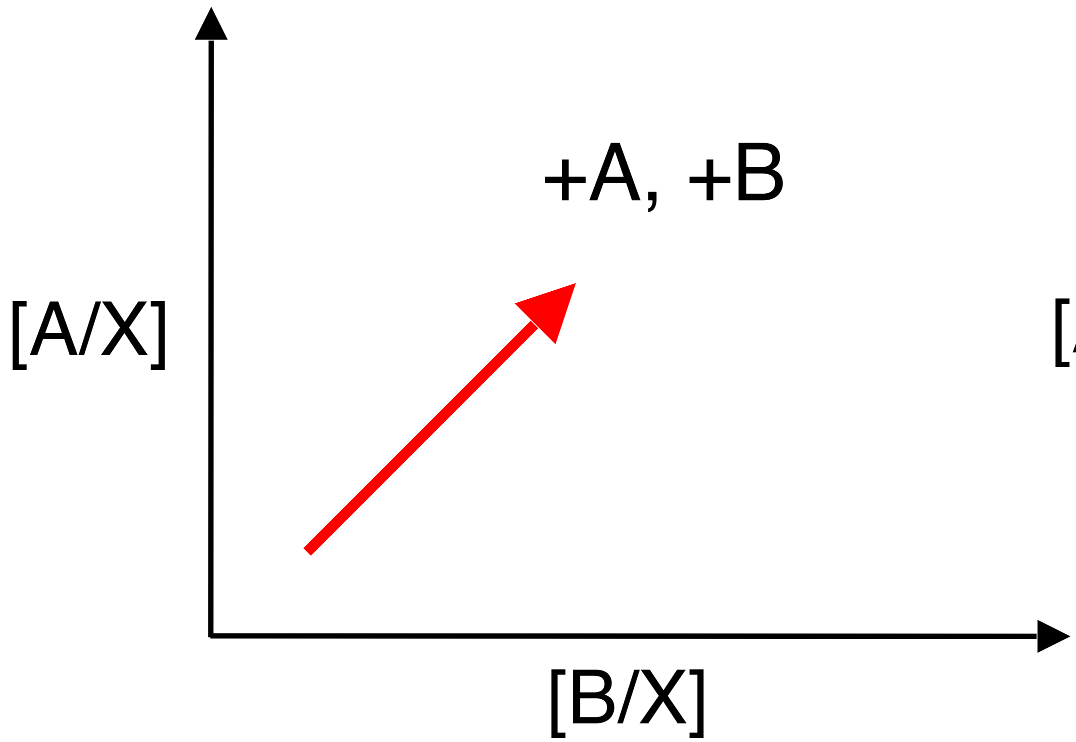
The comparison of abundances of different elements can give us information about production sites and chemical evolution

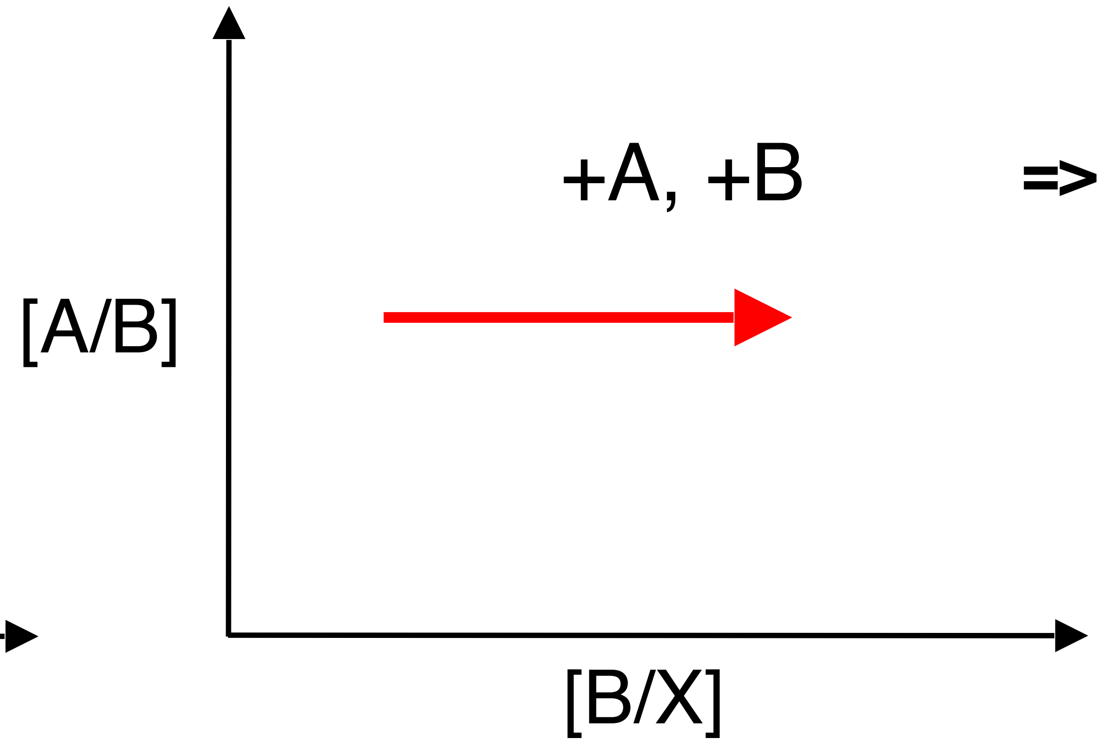
Abundance plot

Comparison of two different abundance ratios

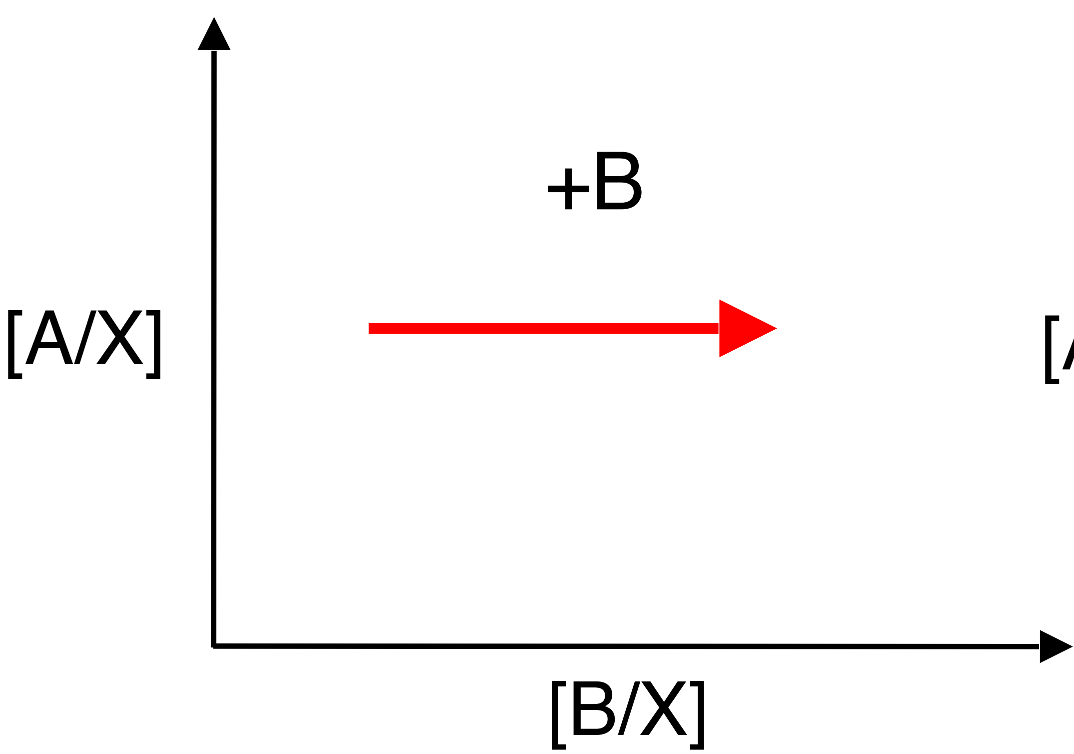
Values are in logarithmic scale with Sun as reference

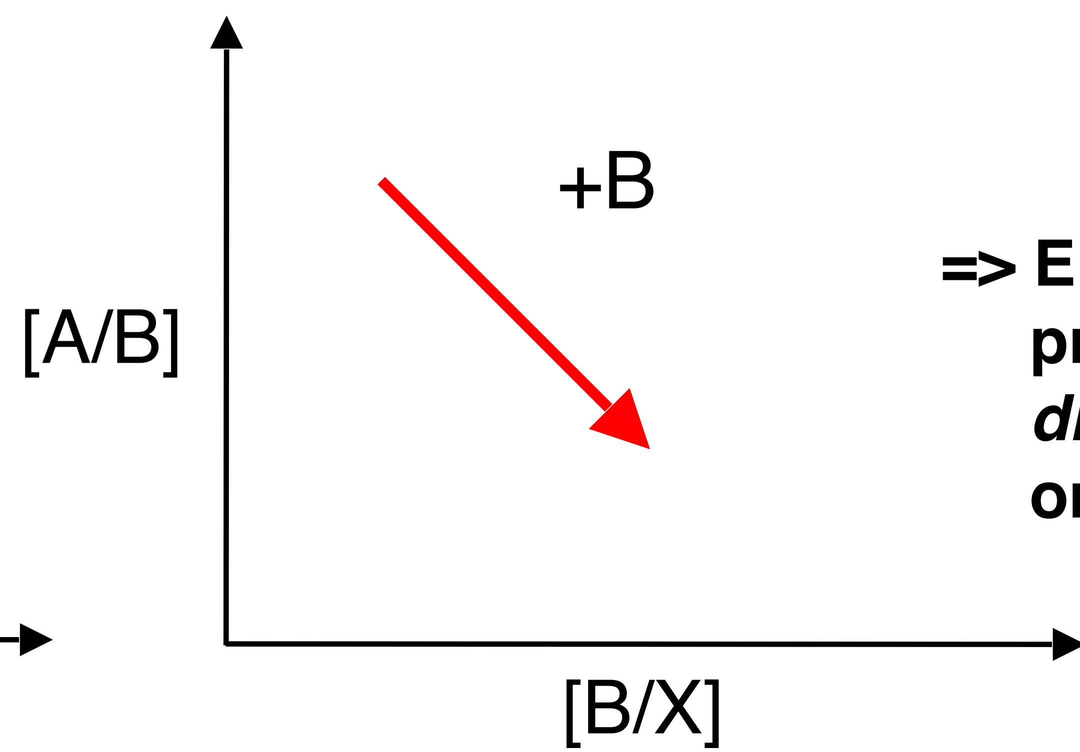






=> Elements A, B produced in the *same* process or site.





=> Elements A, B produced in *different* processes or sites.

Chemical enrichment

Chemical enrichment

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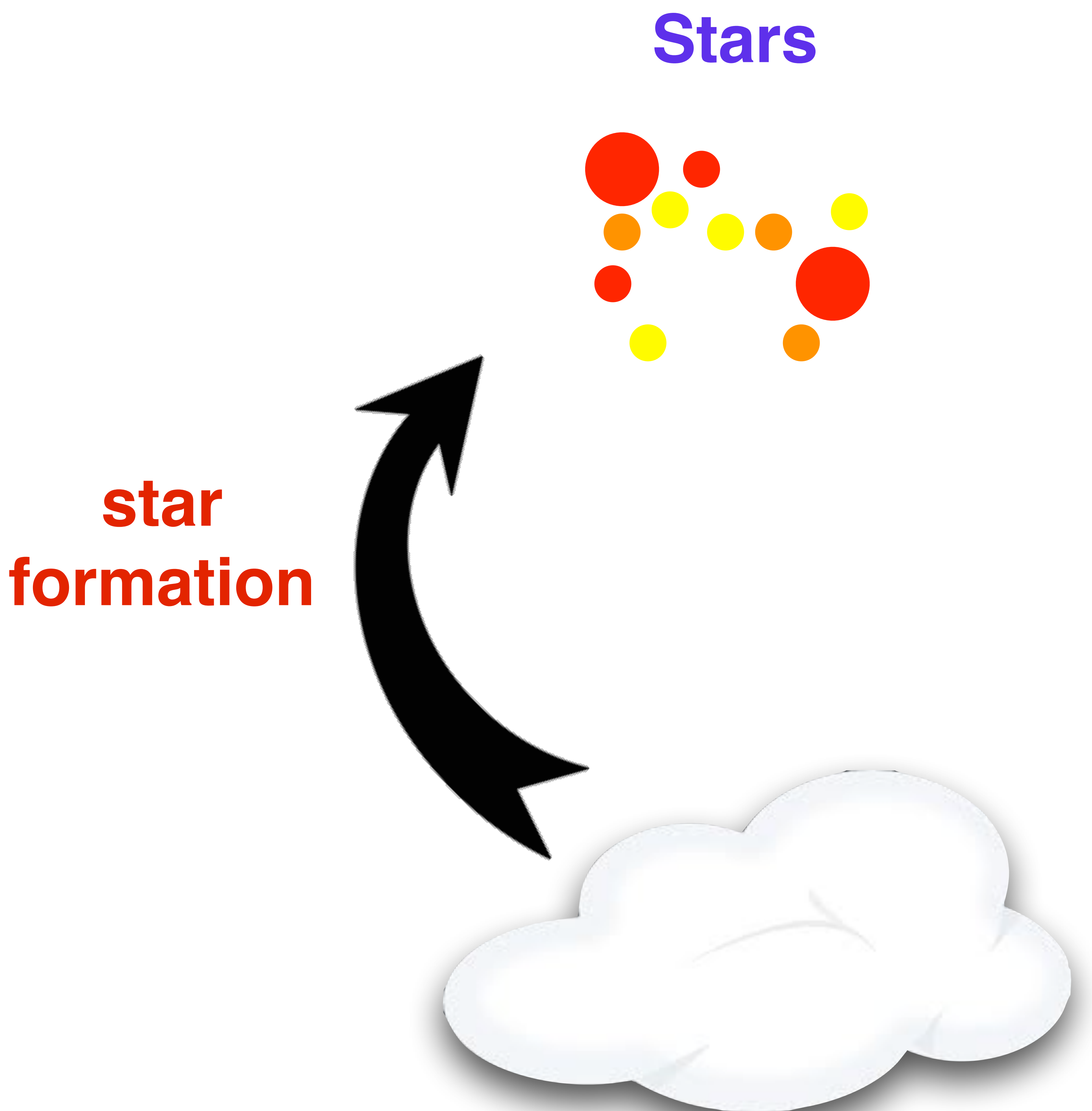
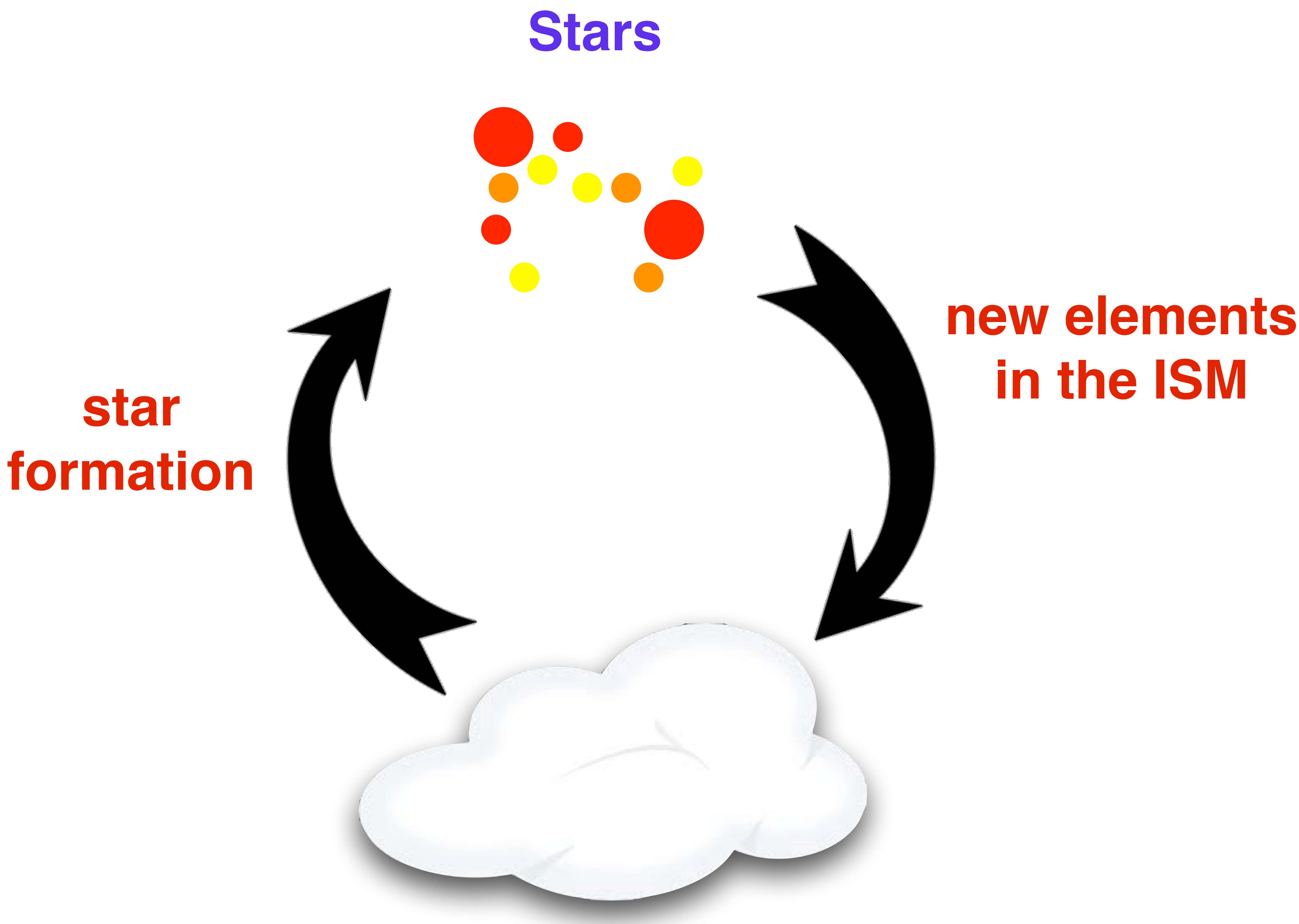
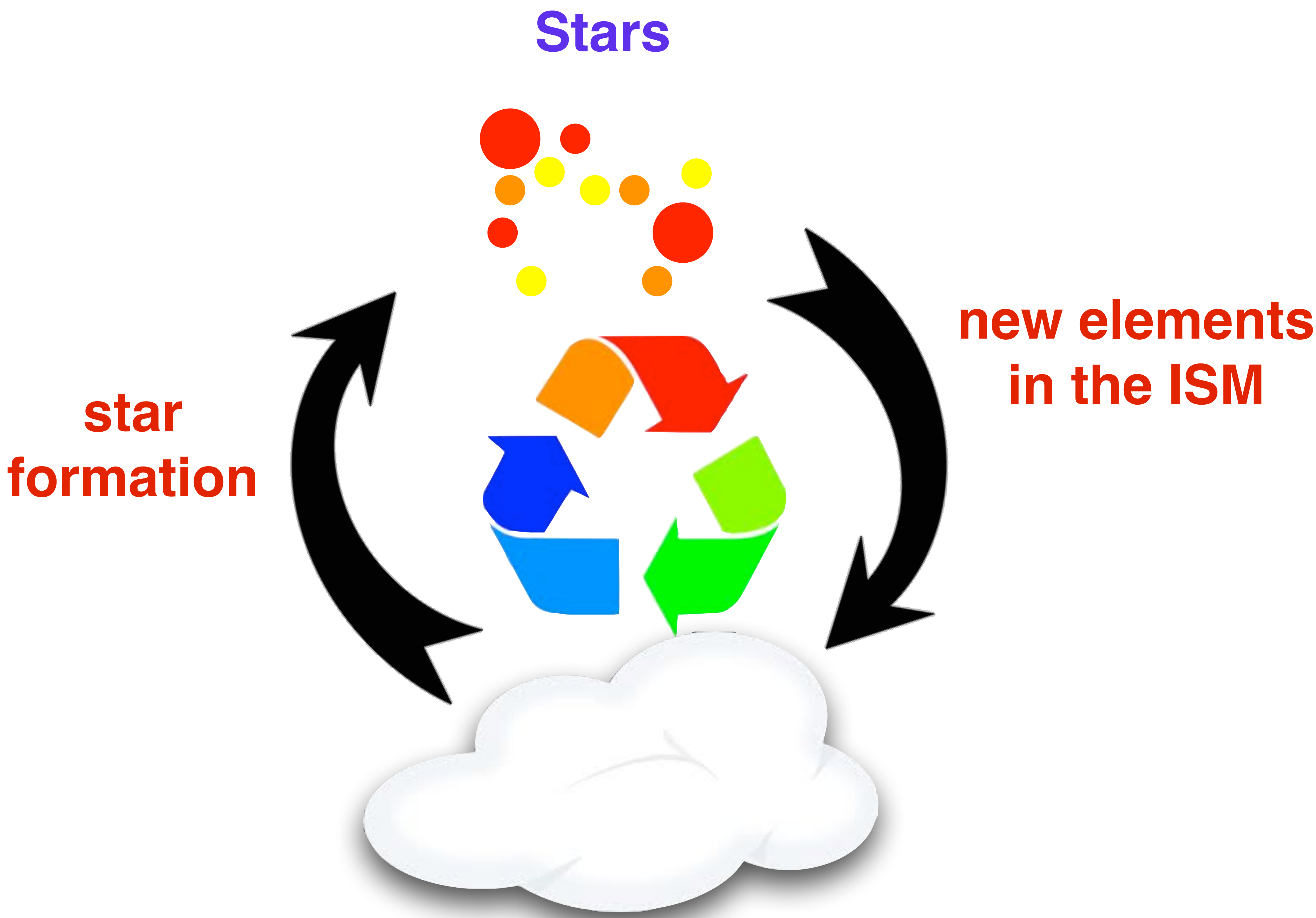


Chemical enrichment



Chemical enrichment



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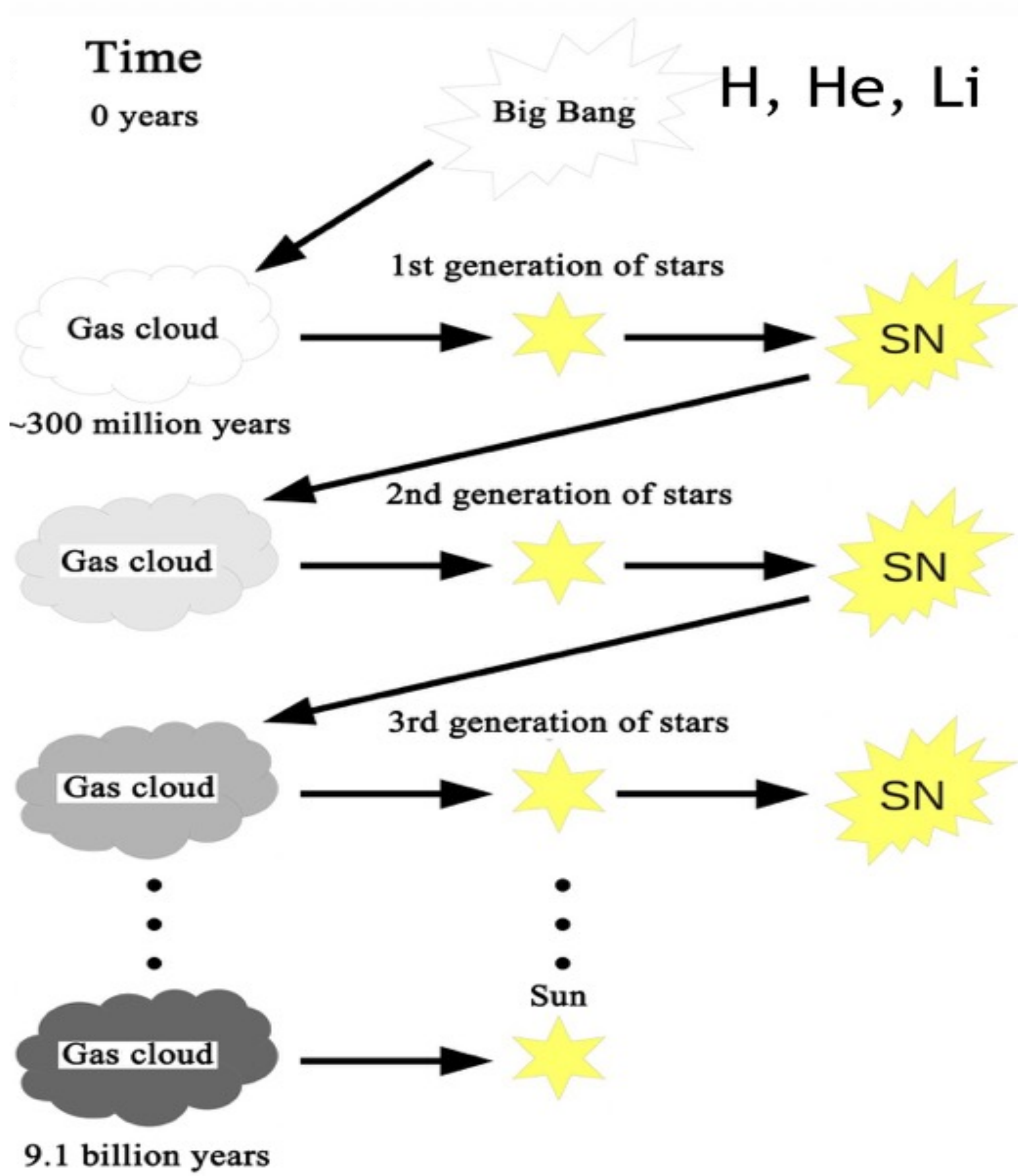


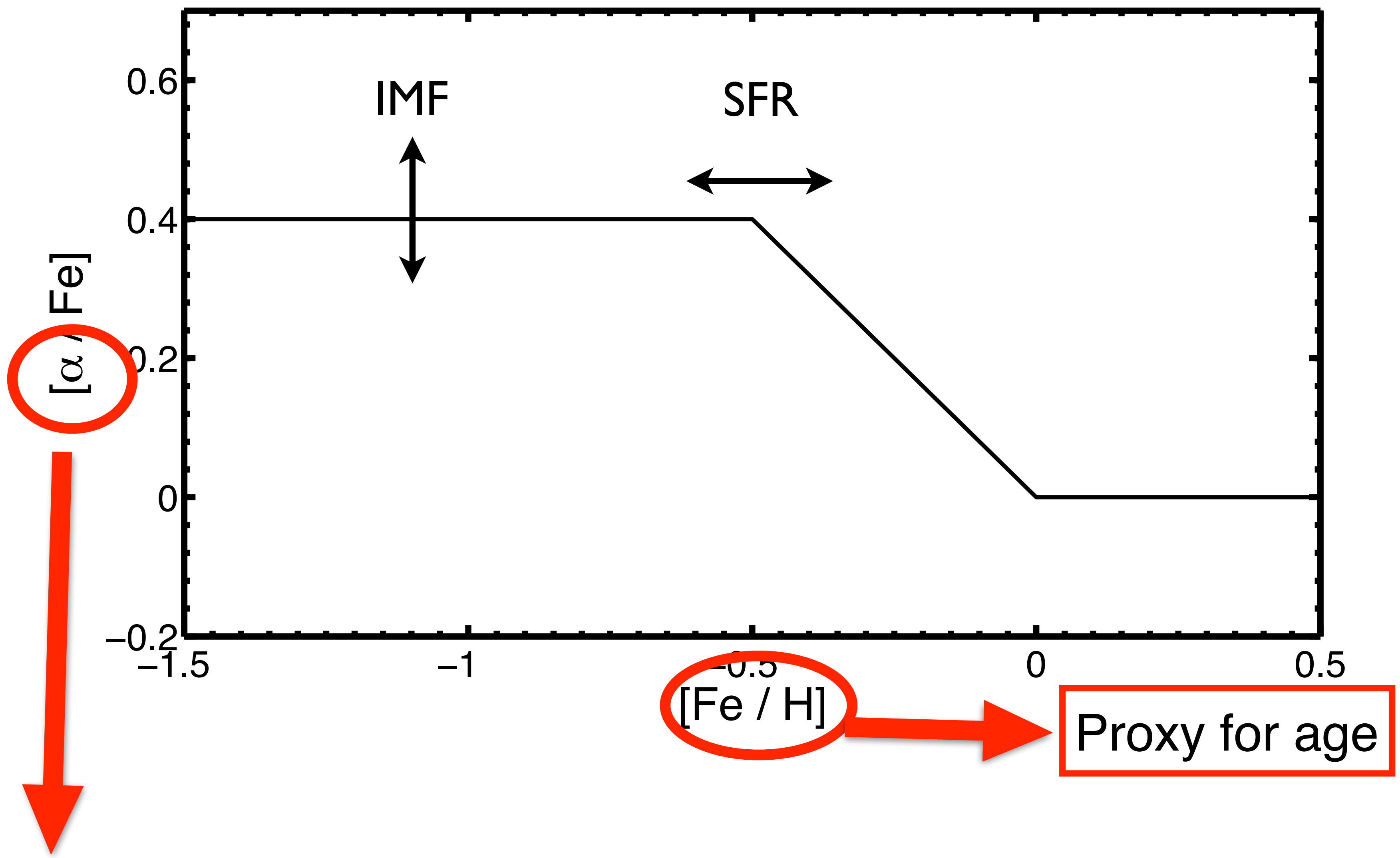
Star formation: important concepts

- Star formation rate (SFR) how much gas is transformed in stars. Expressed in solar masses/yr.

- Initial mass function (IMF) how many stars of different masses are produced with a defined amount of gas.

- Star formation history (SFH) study of the different past episodes of star formation that a system underwent.

Star formation history

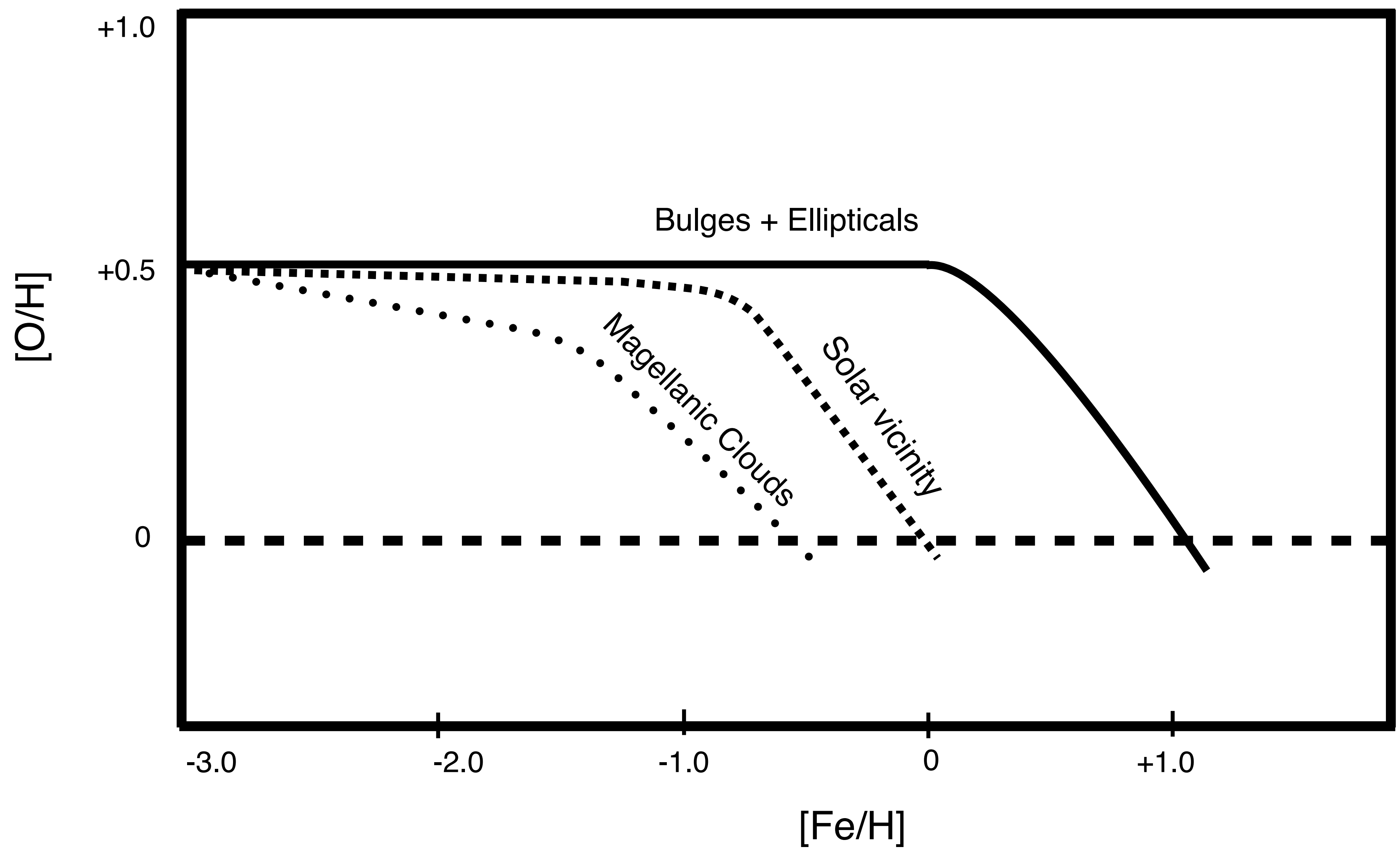


With α elements we refer to

Mg, Ca, Si, O, Ti

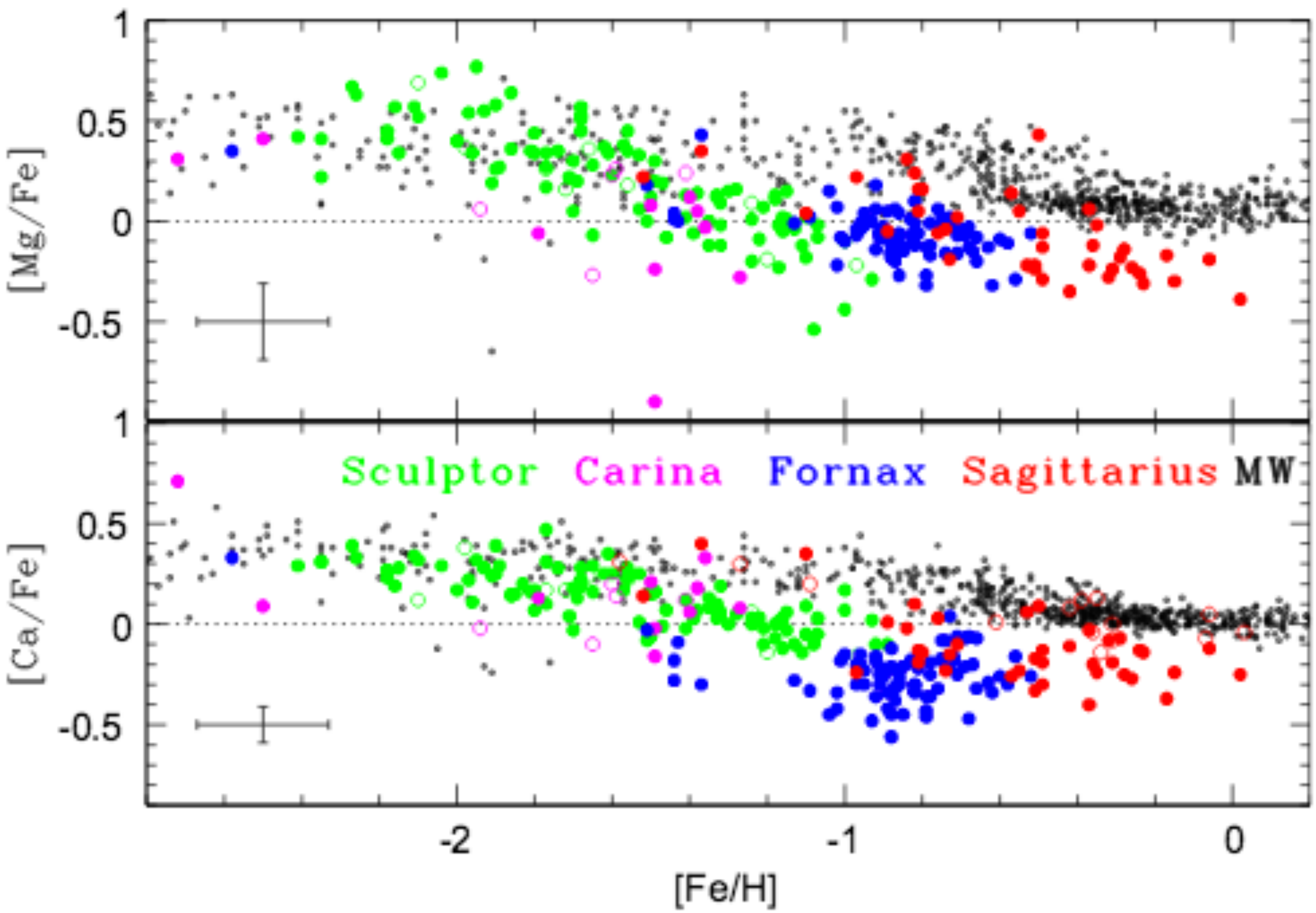
Reminder: α elements are mainly produced in SNII events

Example



+1.0
+0.5
0
[O/H]
Bulges + Ellipticals
Magellanic Clouds
Solar vicinity
-3.0
-2.0
-1.0
0
+1.0
[Fe/H]

Reality

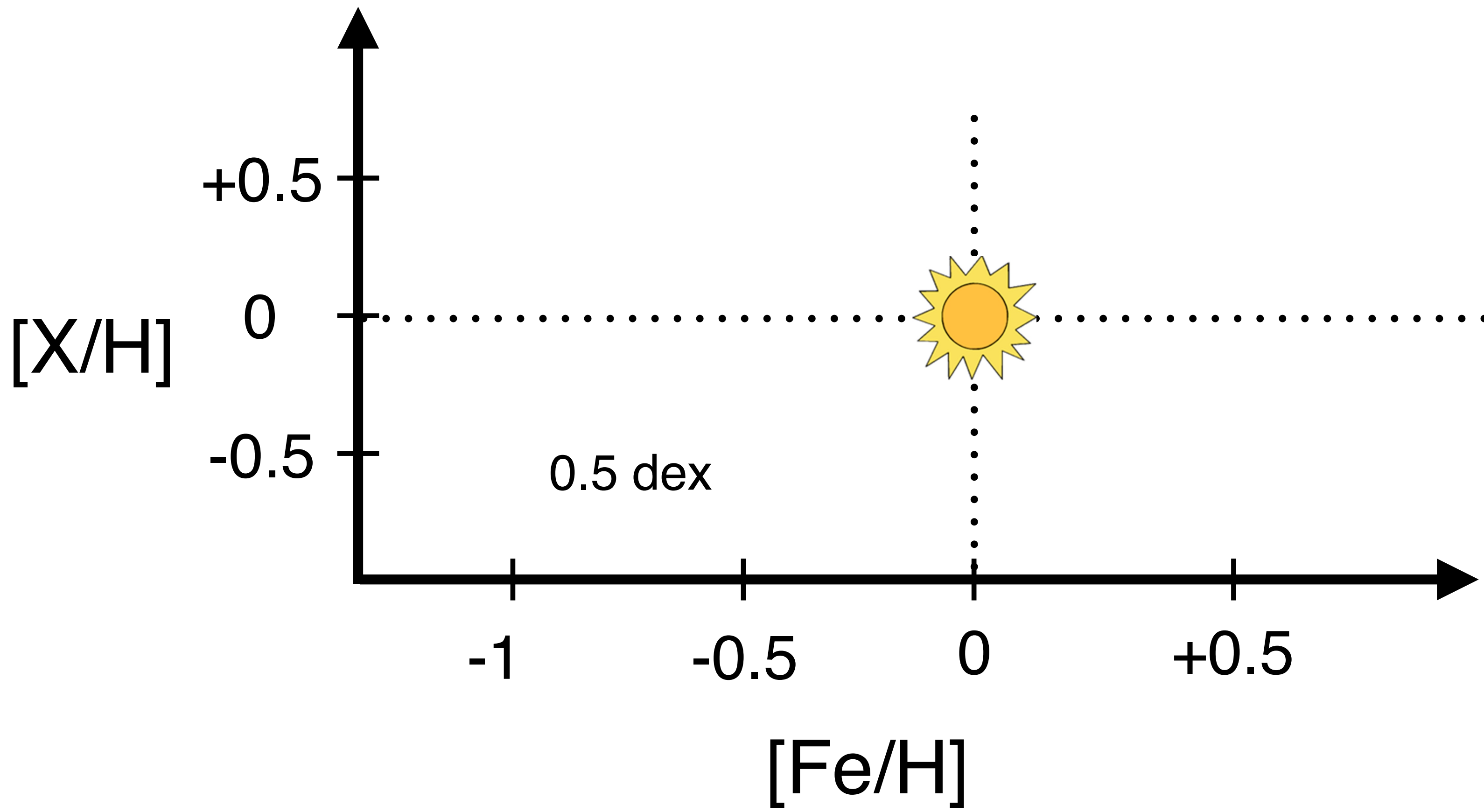


Tolstoy et al. (2009)

The Milky Way

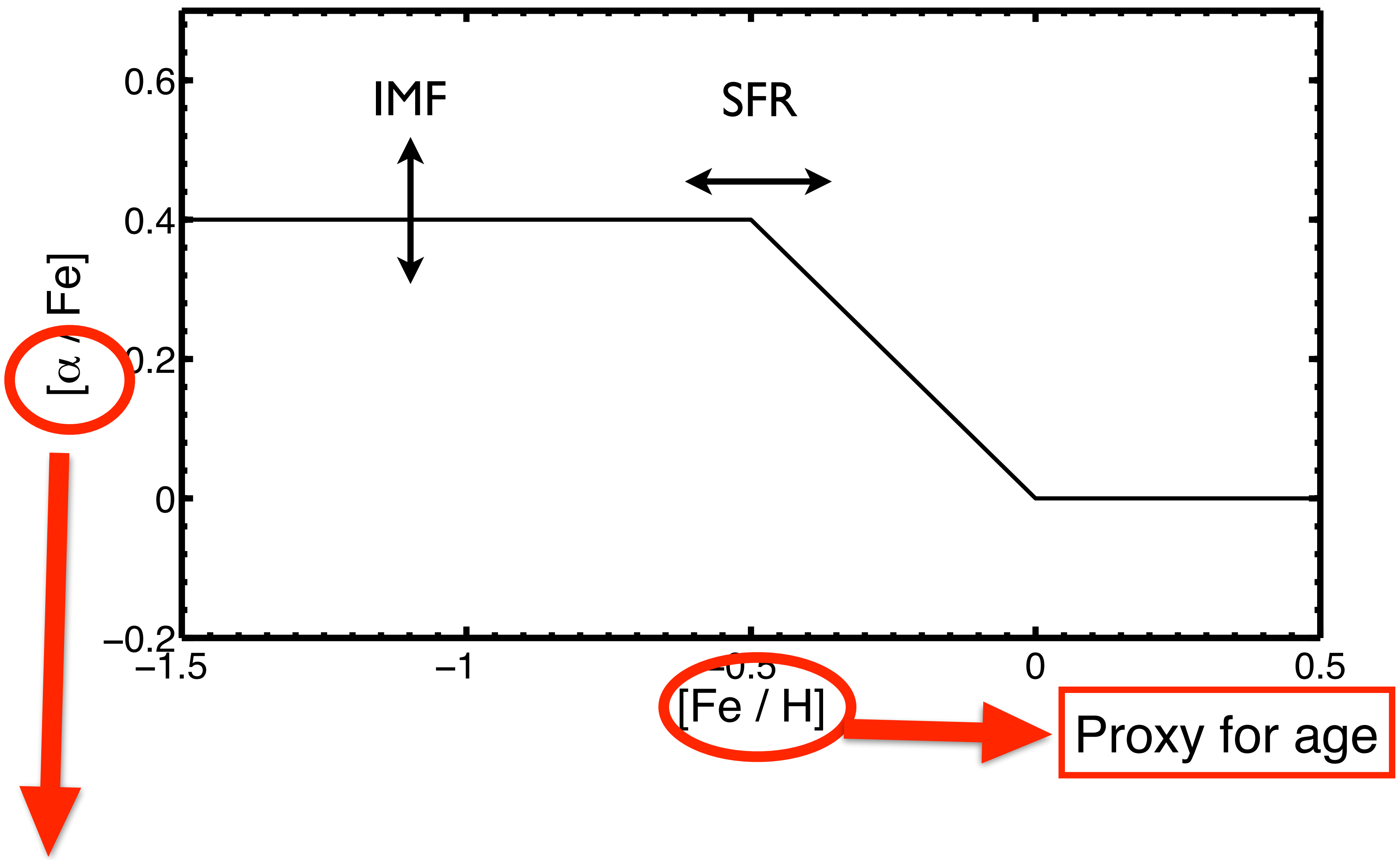
Small recap

SN II —> α-elements, r-process elements
SN Ia —> iron-peak elements
AGB —> s-process elements



$$[Fe / H] = \log \varepsilon(Fe)_{\star} - \log \varepsilon(Fe)_{\odot}$$

Star formation history



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Structure of the Milky Way

artistic impression of MW seen face-on

Total mass ~ few 10^{11} $M_\odot$

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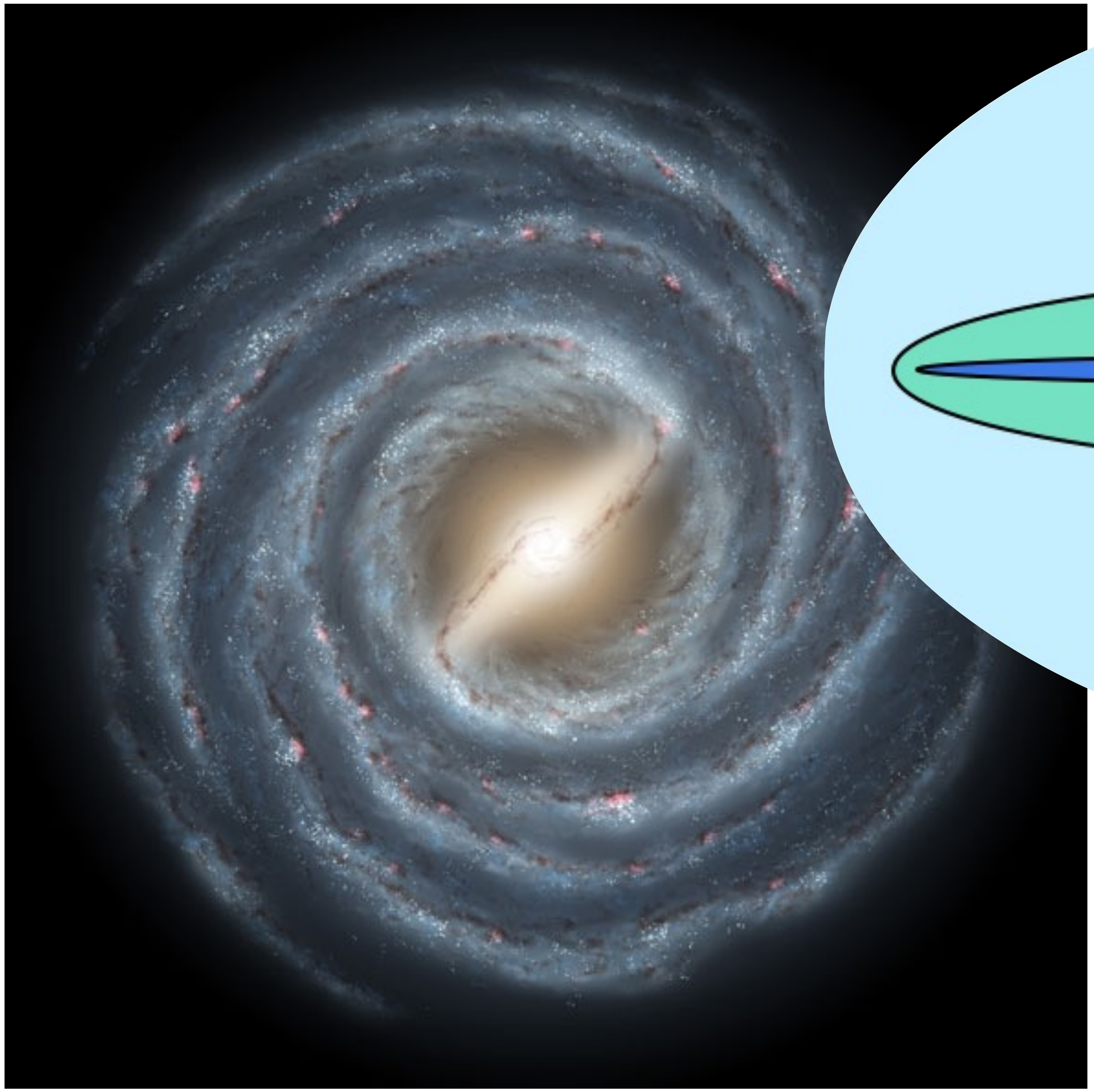

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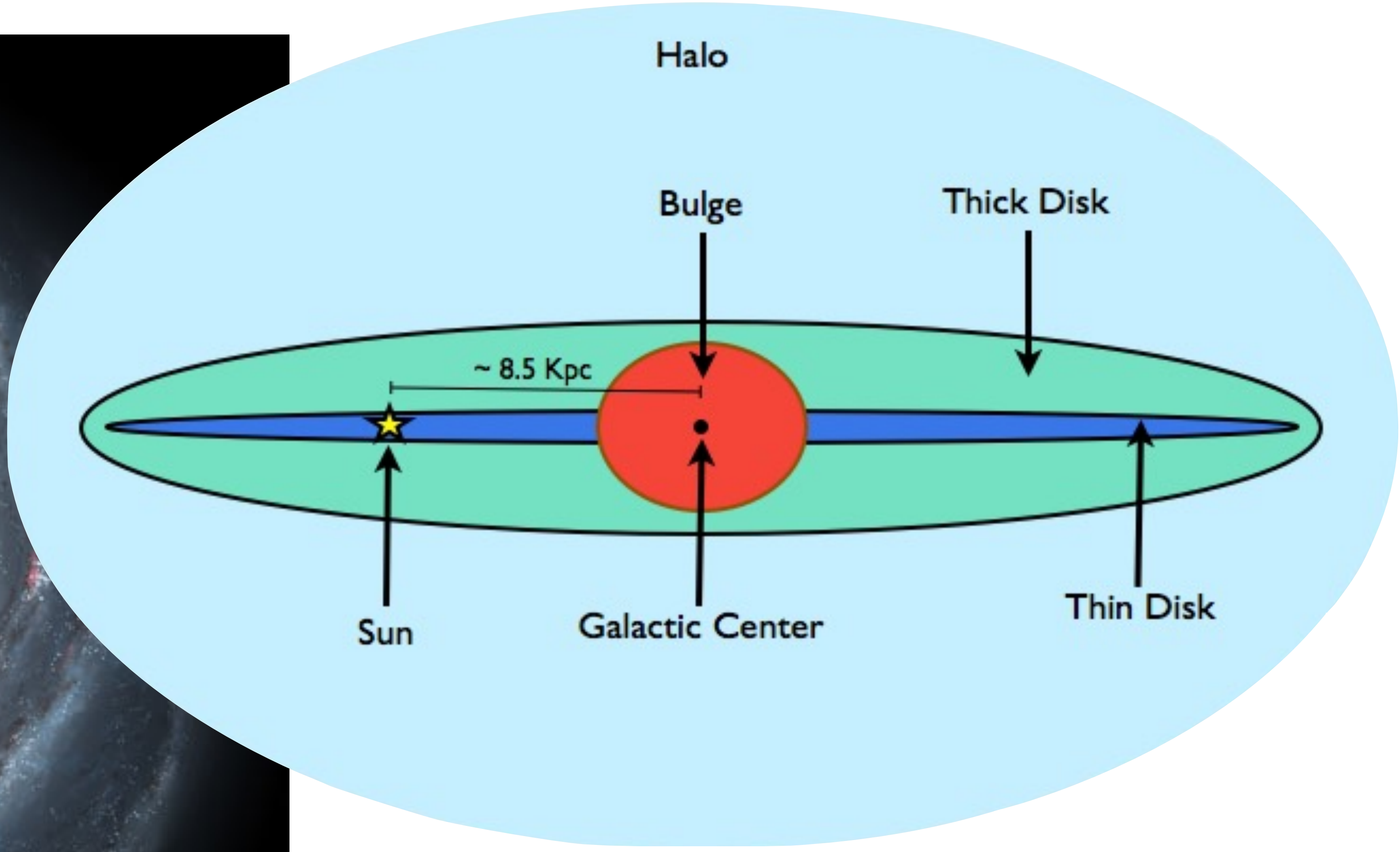

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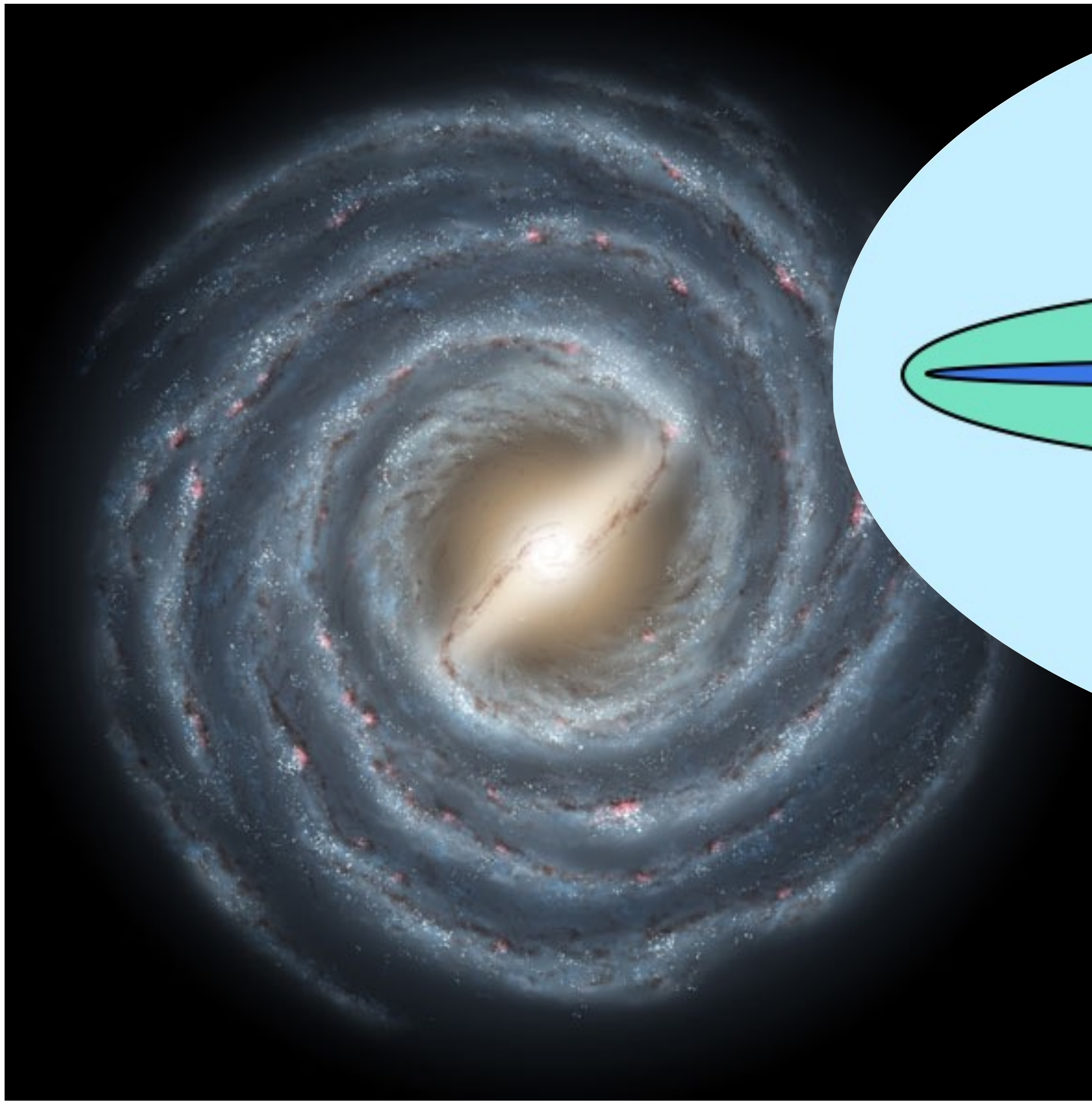

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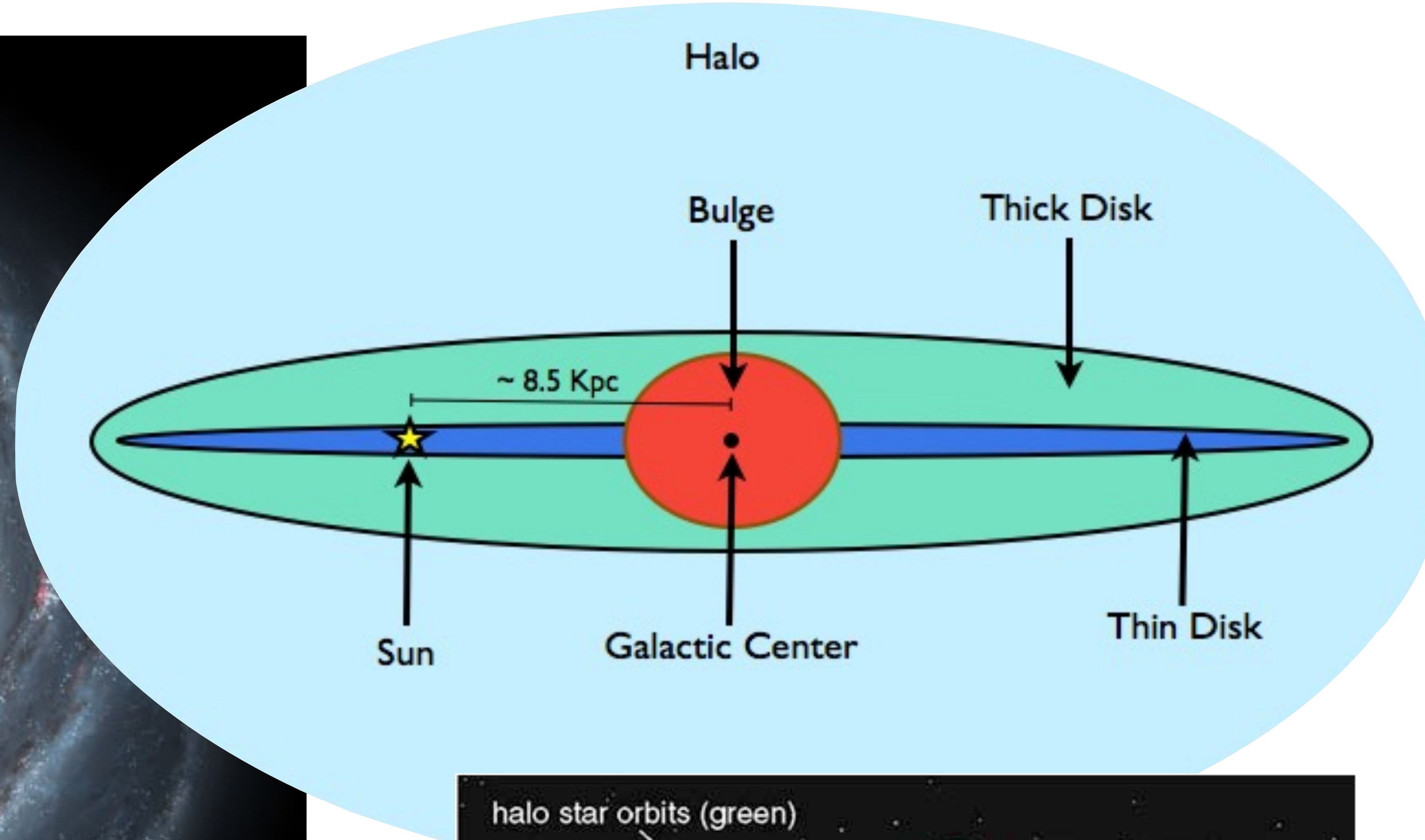

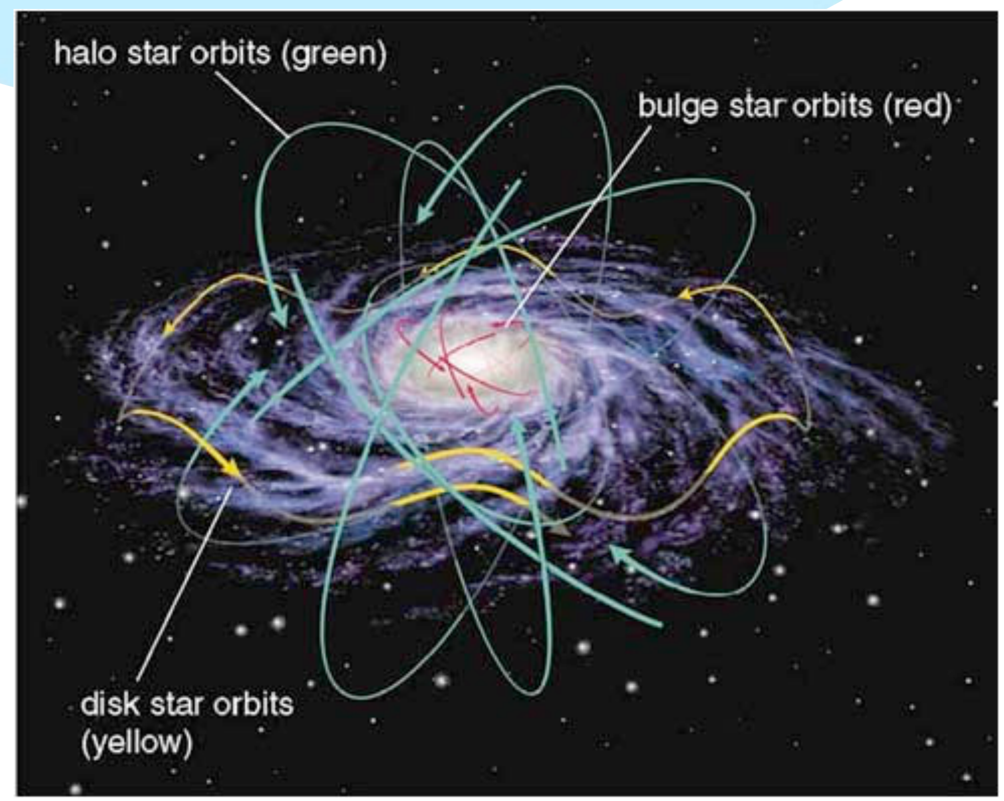

source supernovacondensate.net

Total mass ~ few 10^{11} $M_\odot$

Characteristics

The different components of the Milky Way have different properties regarding chemical abundances and kinematics

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↓

Possible to reveal the past history of formation and evolution of the Milky Way because chemical patterns might store fossil records of the physical characteristics of the ISM at the time and place of their birth and the physical processes which affect them

Different observables

- **DWARF STARS** (like the Sun)

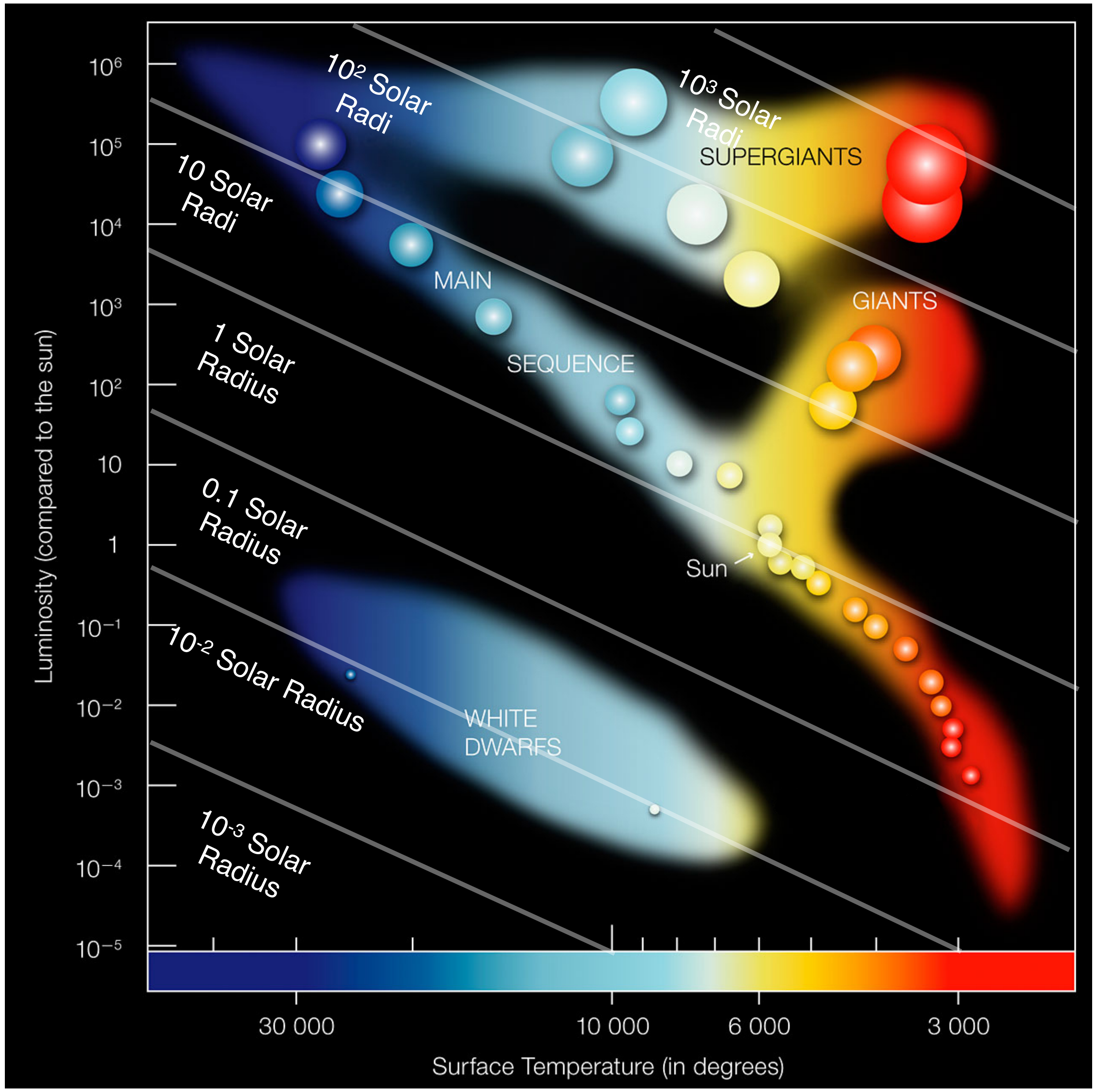
✓ **Pro:** atm composition preserved easy abundance

✗ **Cons:** not very bright so they are not observable too far

- **GIANT STARS**

✓ **Pro:** brighter, so can be observed further away

✗ **Cons:** atm composition can also be not the original



Each component has its best (or only) way to be observed!

Halo

T. Beers, Nature 486, 38–40

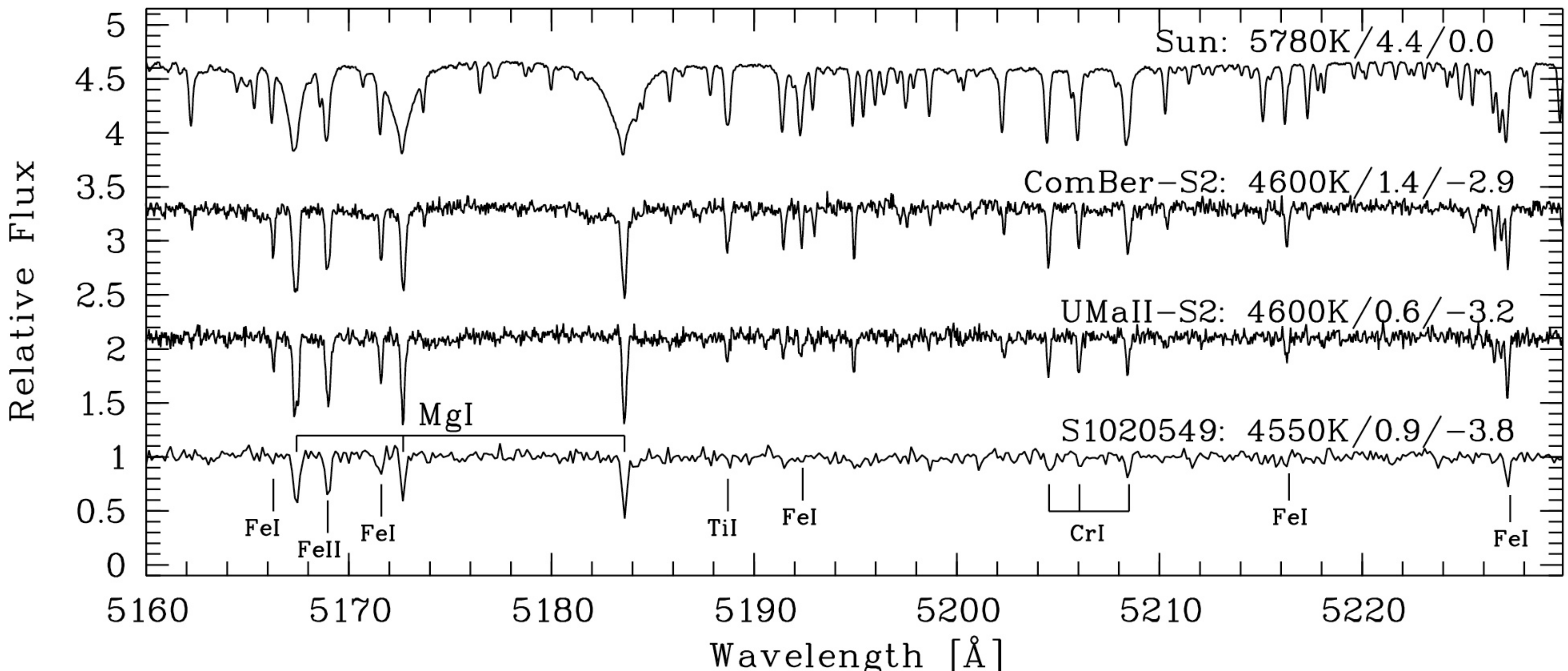
Halo

T. Be[illegible] Nature 486, 38–40

Halo

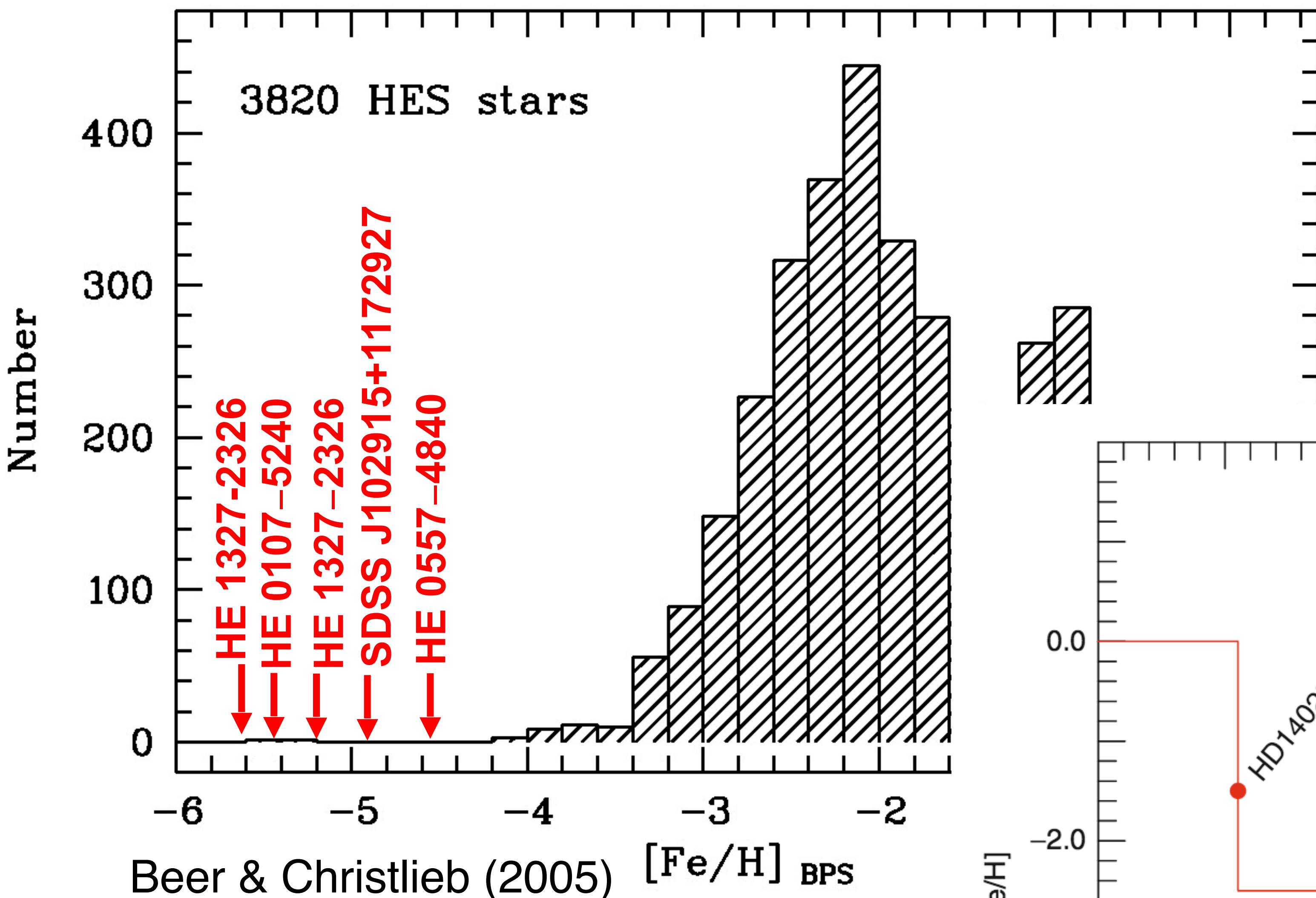
- Spherical component around Milky Way disk (100-200 kpc)
- Low star density
- Contains the oldest and the most metal-poor stars of the Galaxy (main population has [Fe/H] $<$ -1)
- Contains the relics of accretion events

Metal-poor stars

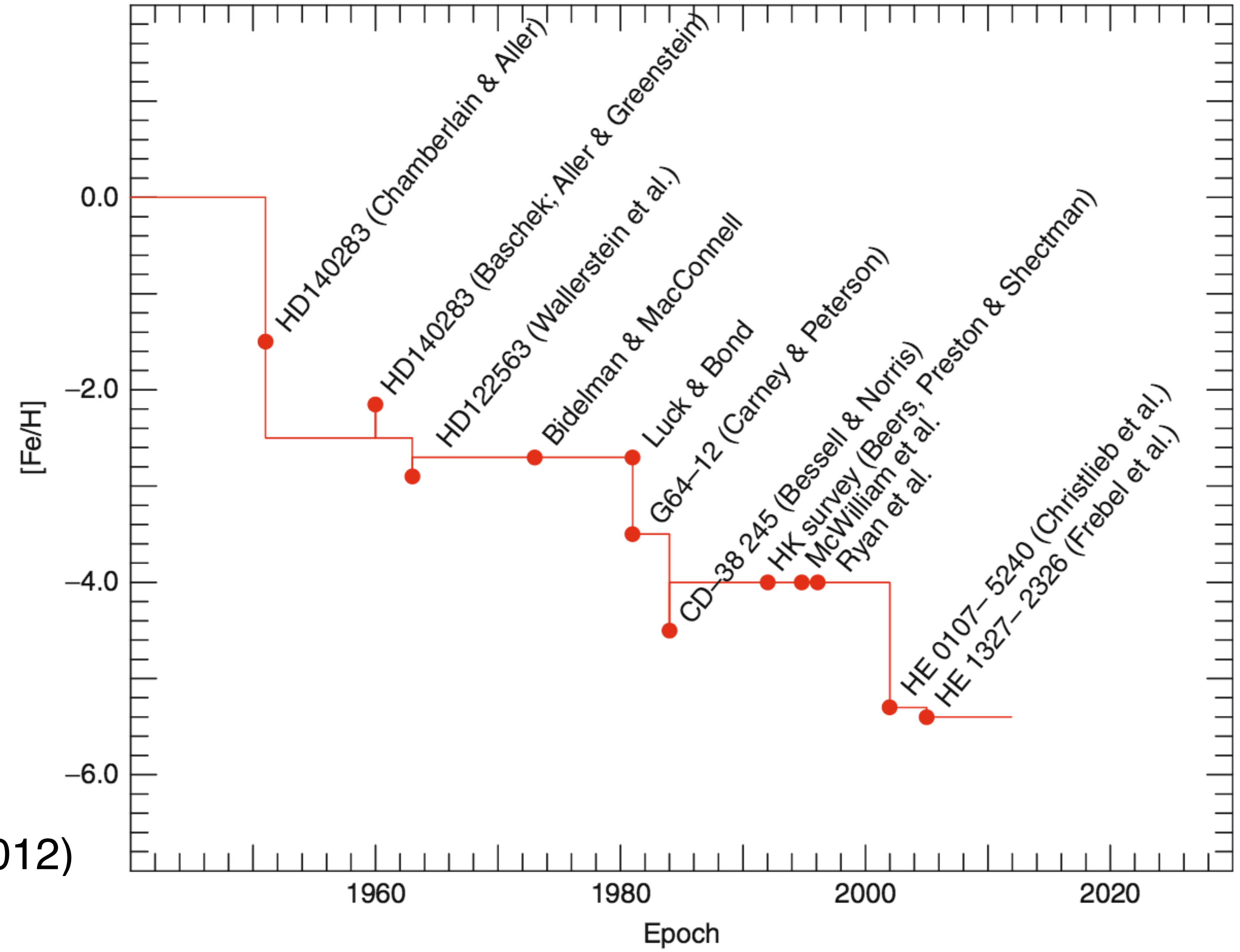


Frebel et al. (2010)

Metal-poor stars

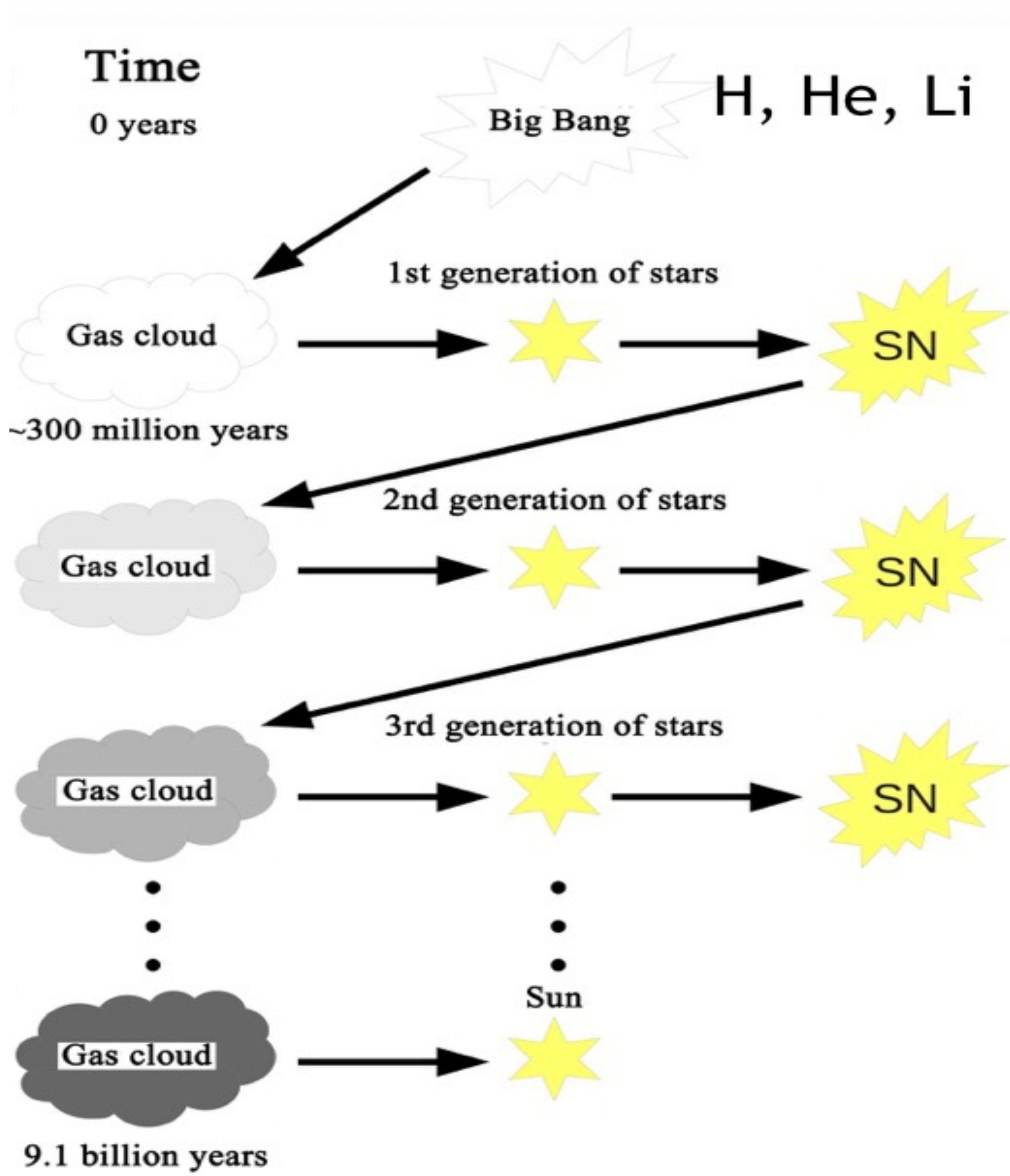


Beer & Christlieb (2005)

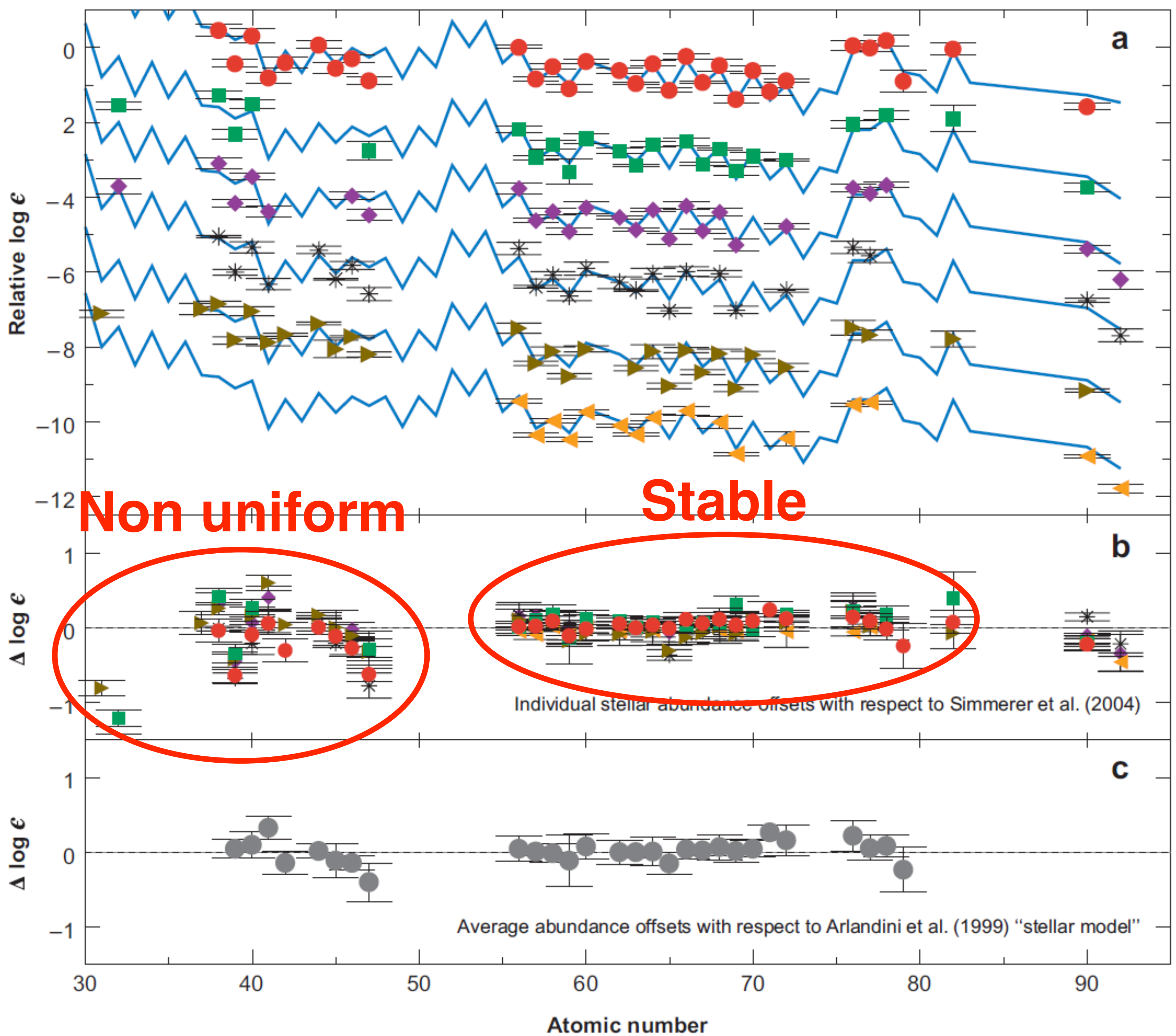


Frebel & Norris (2012)

Why are they important?



Understanding nucleosynthesis

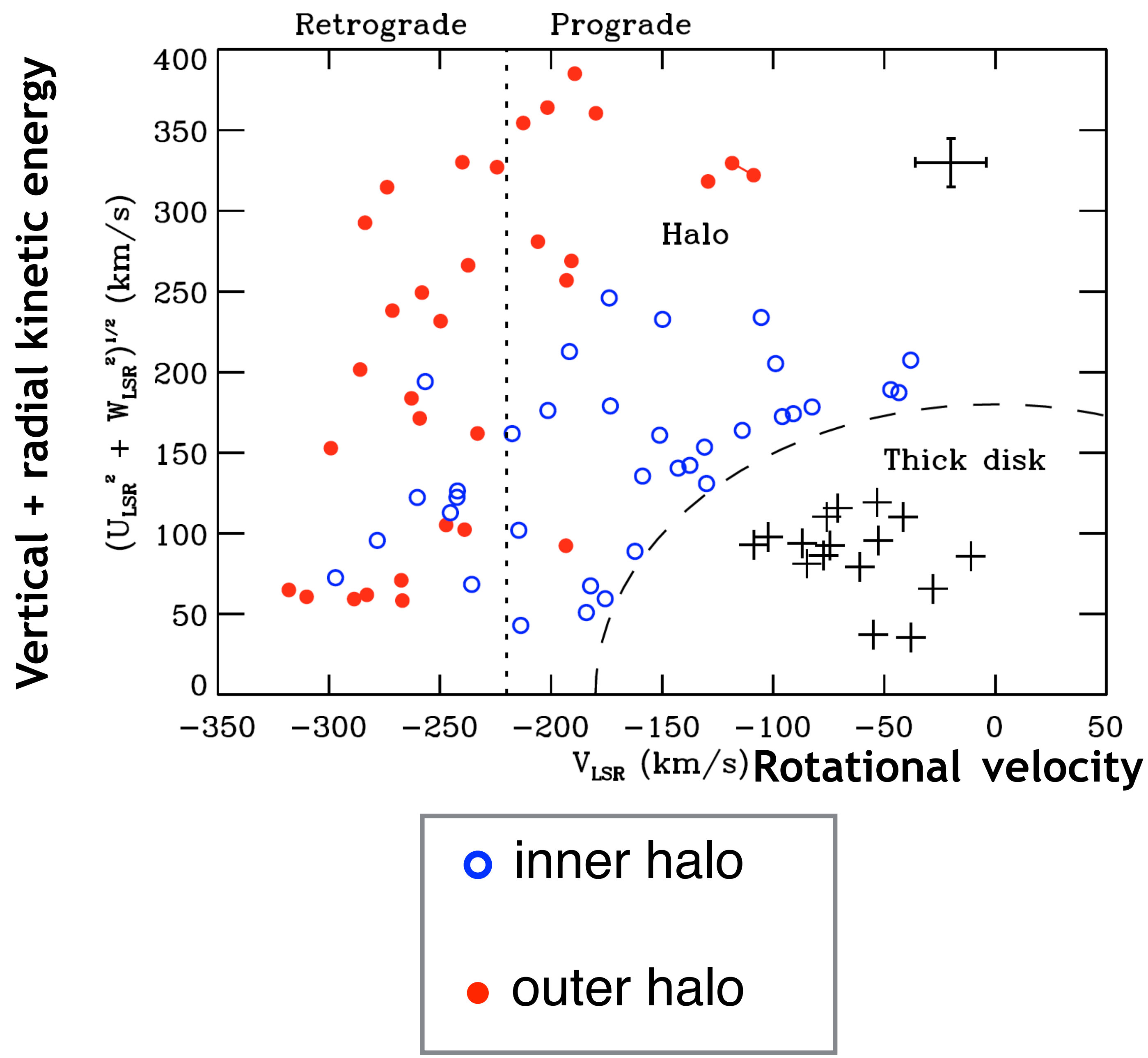


Sneden, Cowan & Gallino (2008)

Dual halo

Inner component: 0 or some pro-grade rotation, stars originated in situ.

Outer component: large majority of the mass of the halo, more metal-poor with retrograde rotation, probably accreted.



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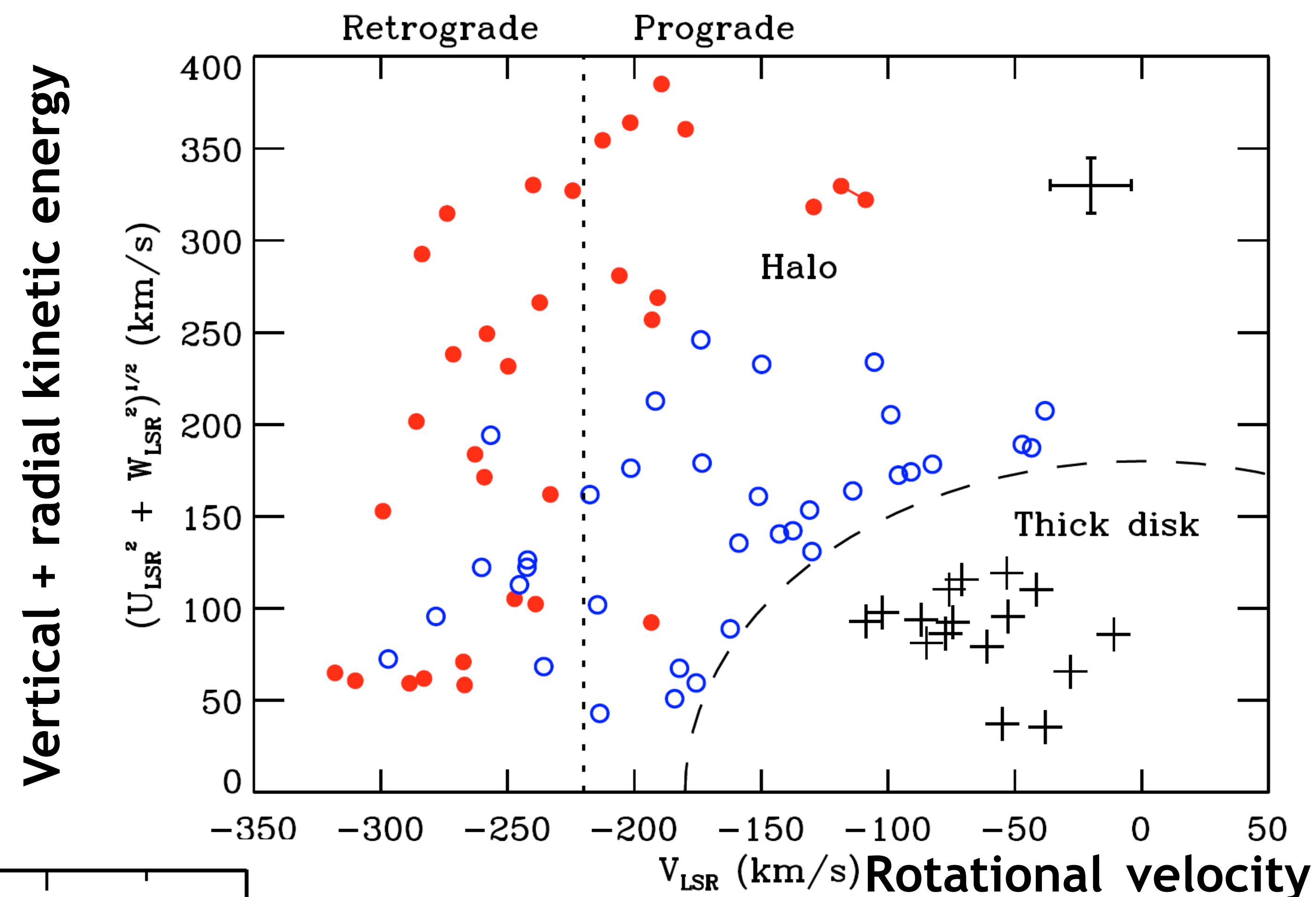

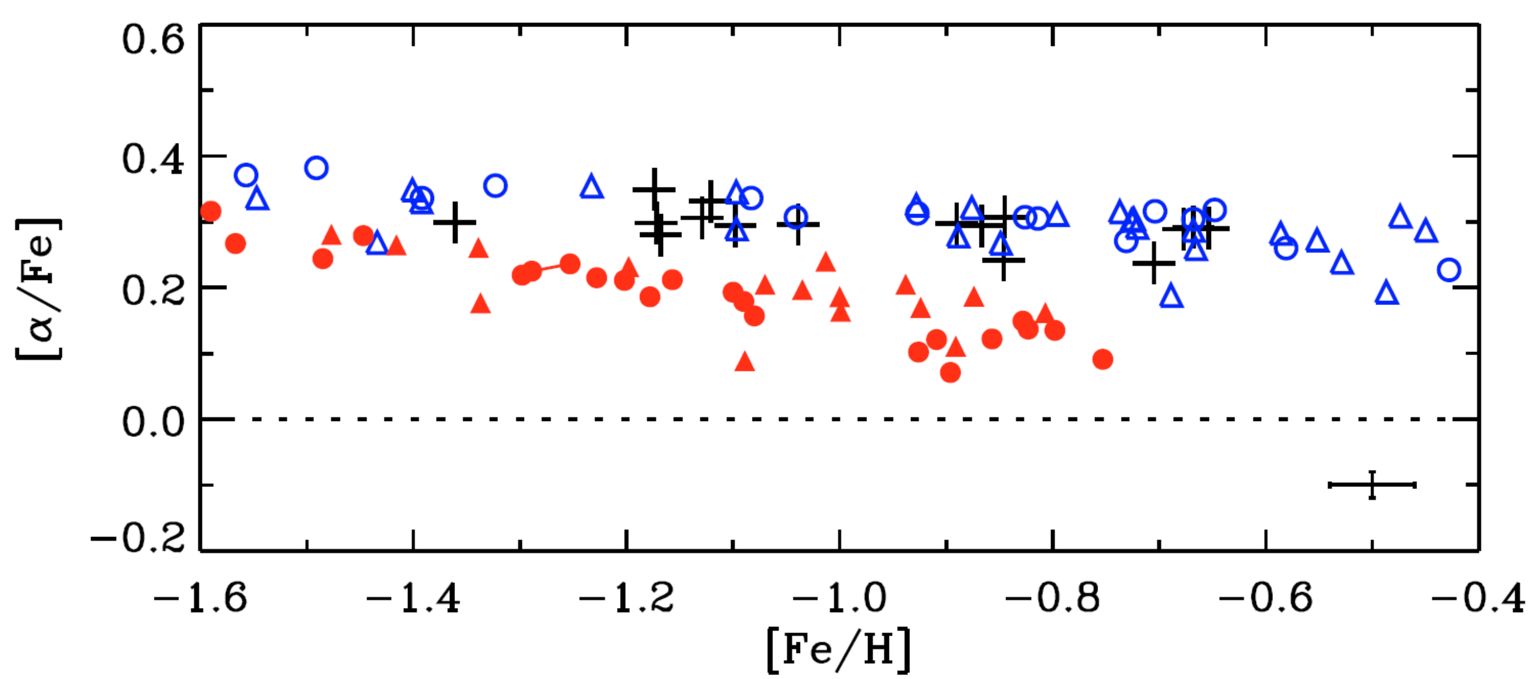

Nissen & Schuster (2010)

inner halo

outer halo

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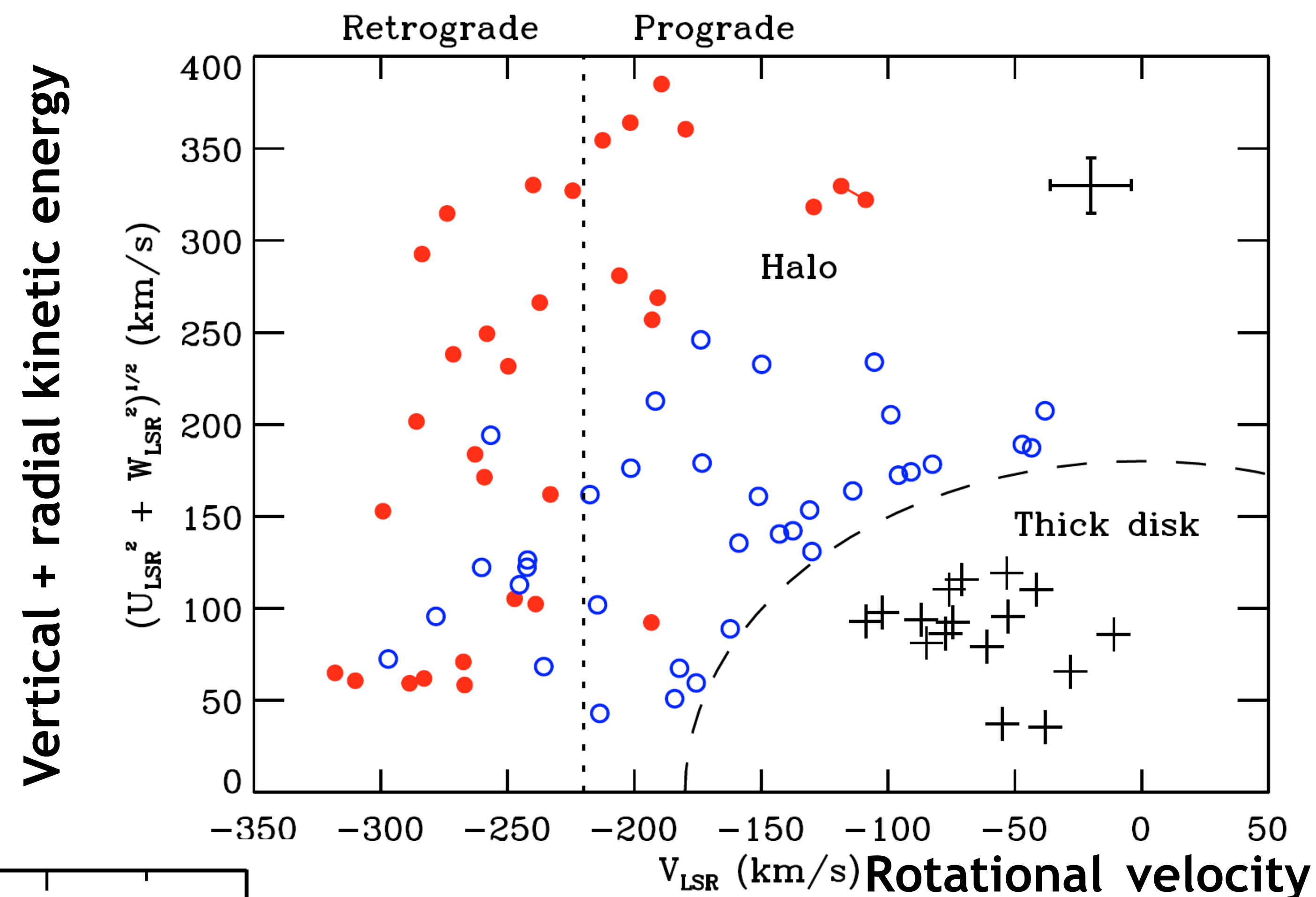

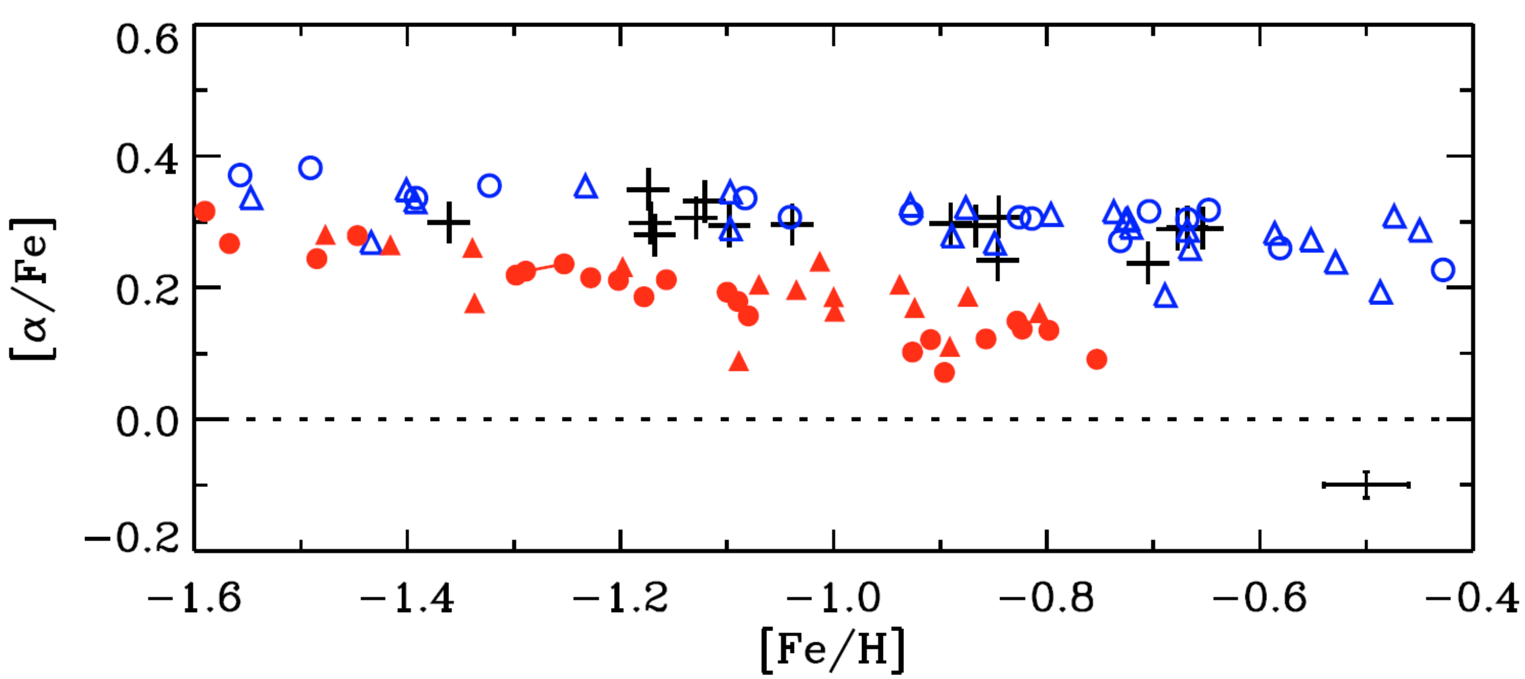

Nissen & Schuster (2010)

inner halo

outer halo

Difference is ~ 0.1dex
—> more stars and better measurements needed

Stellar streams

In the halo there is presence of kinematic substructures, evidence of past merging events

—> **streams** → disrupted satellites should still mantain certain clumpiness in configuration and velocity space

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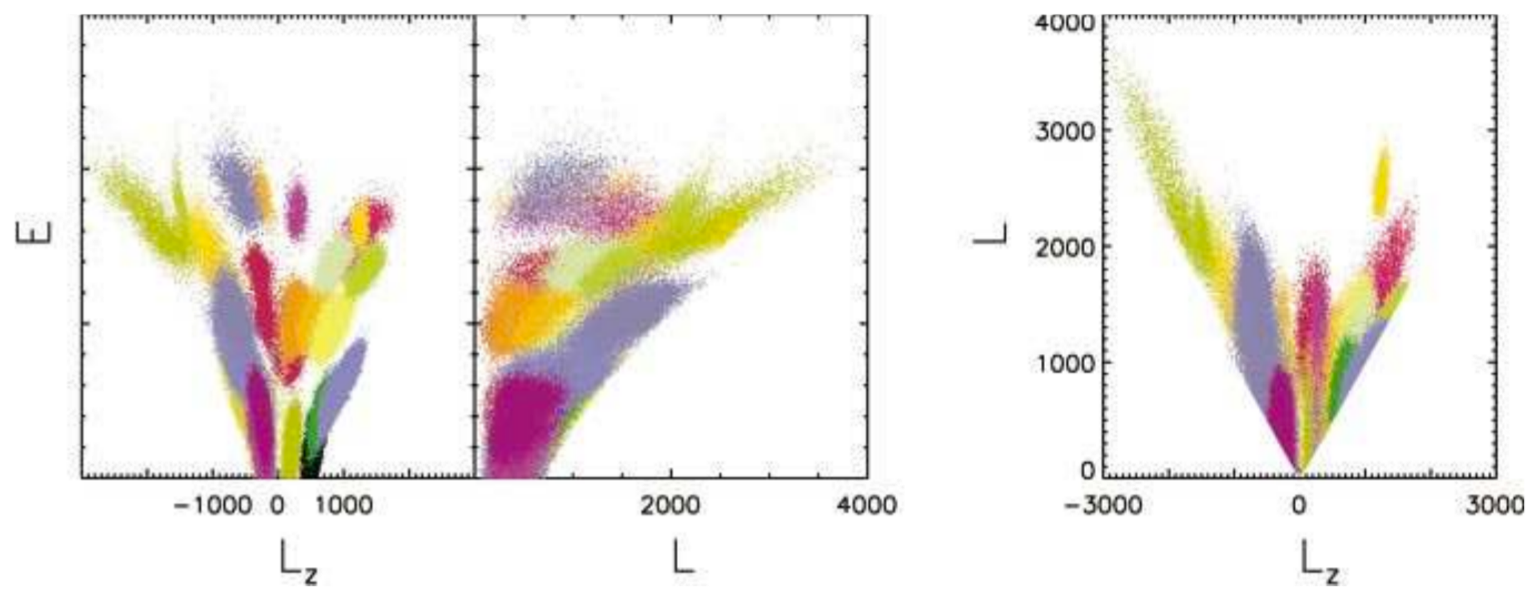

Simulation of how stars from different satellites would keep kinematics info after 12 Gyr from accretion

Helmi & de Zeeuw (2000)

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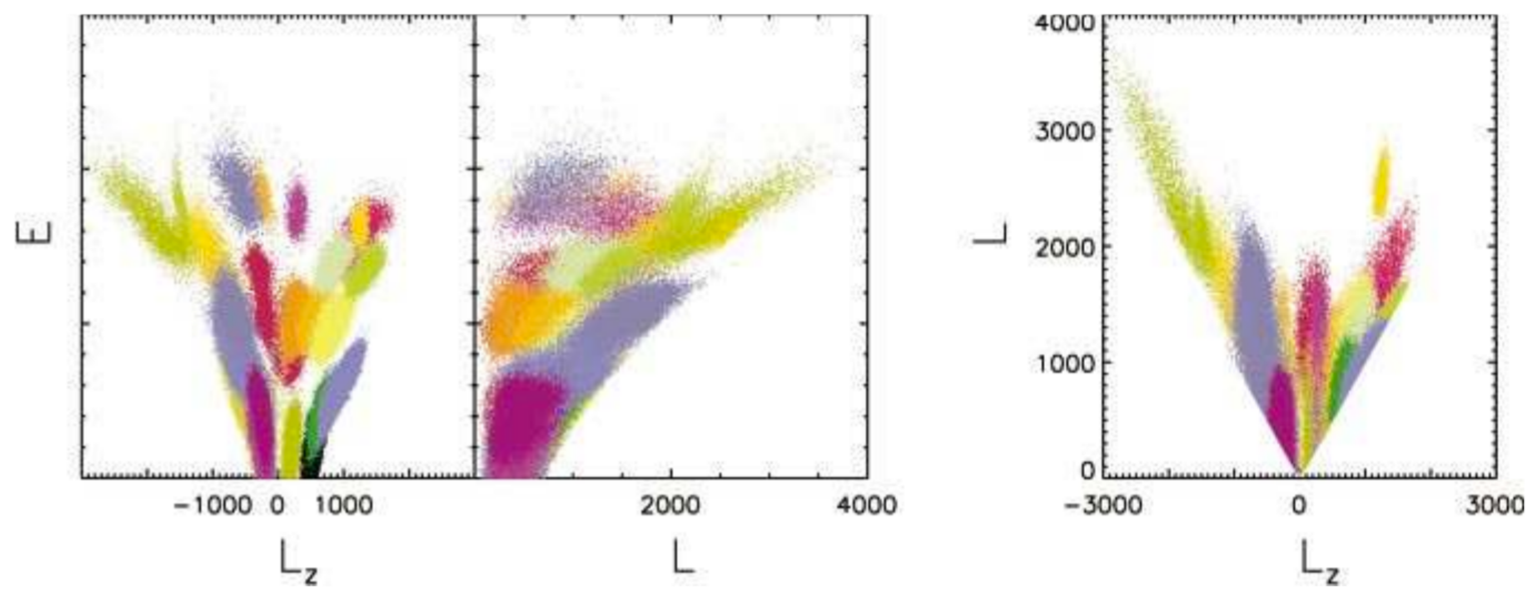

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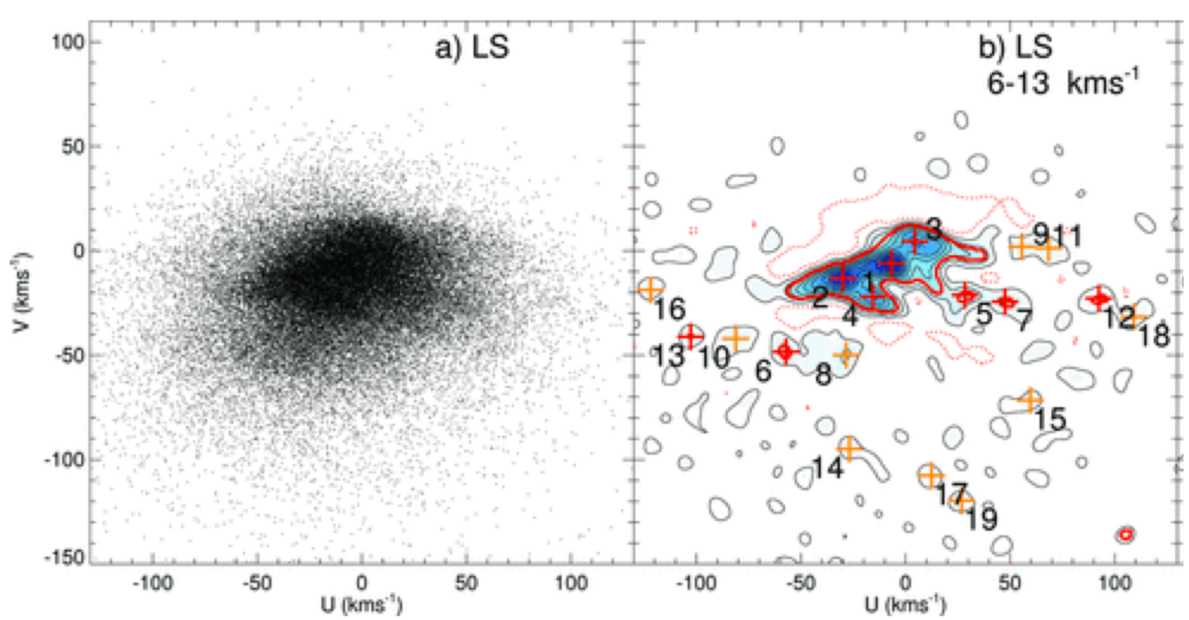
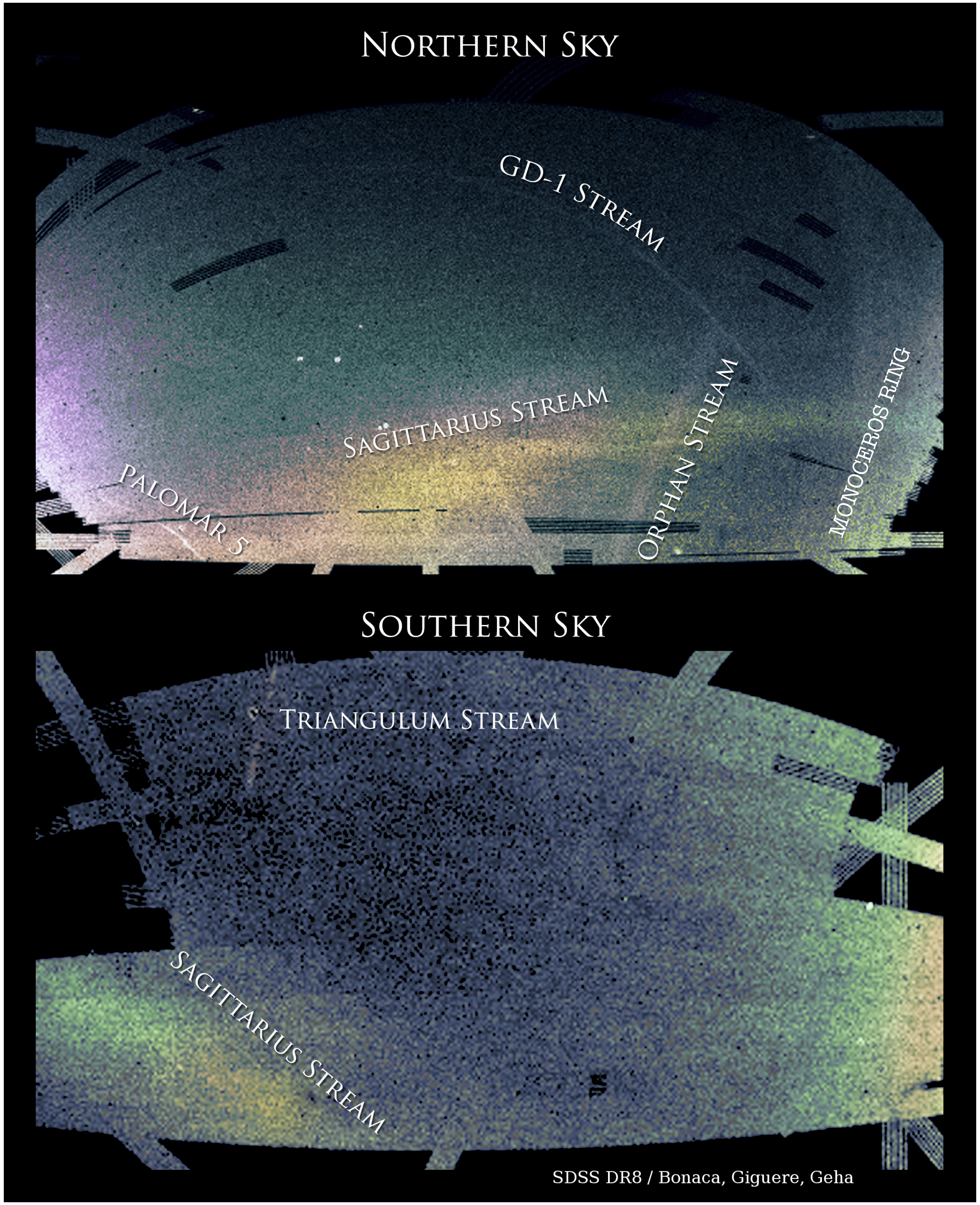


Real data

Antoja et al. (2012)

Stellar streams



Color = distance of the stars
Intensity = density of stars

Structures visible in this map:

- Sagittarius dwarf galaxy
- a smaller 'orphan' stream crossing the Sagittarius streams
- 'Monoceros Ring' that encircles the Milky Way disk
- trails of stars being stripped from the globular cluster Palomar 5

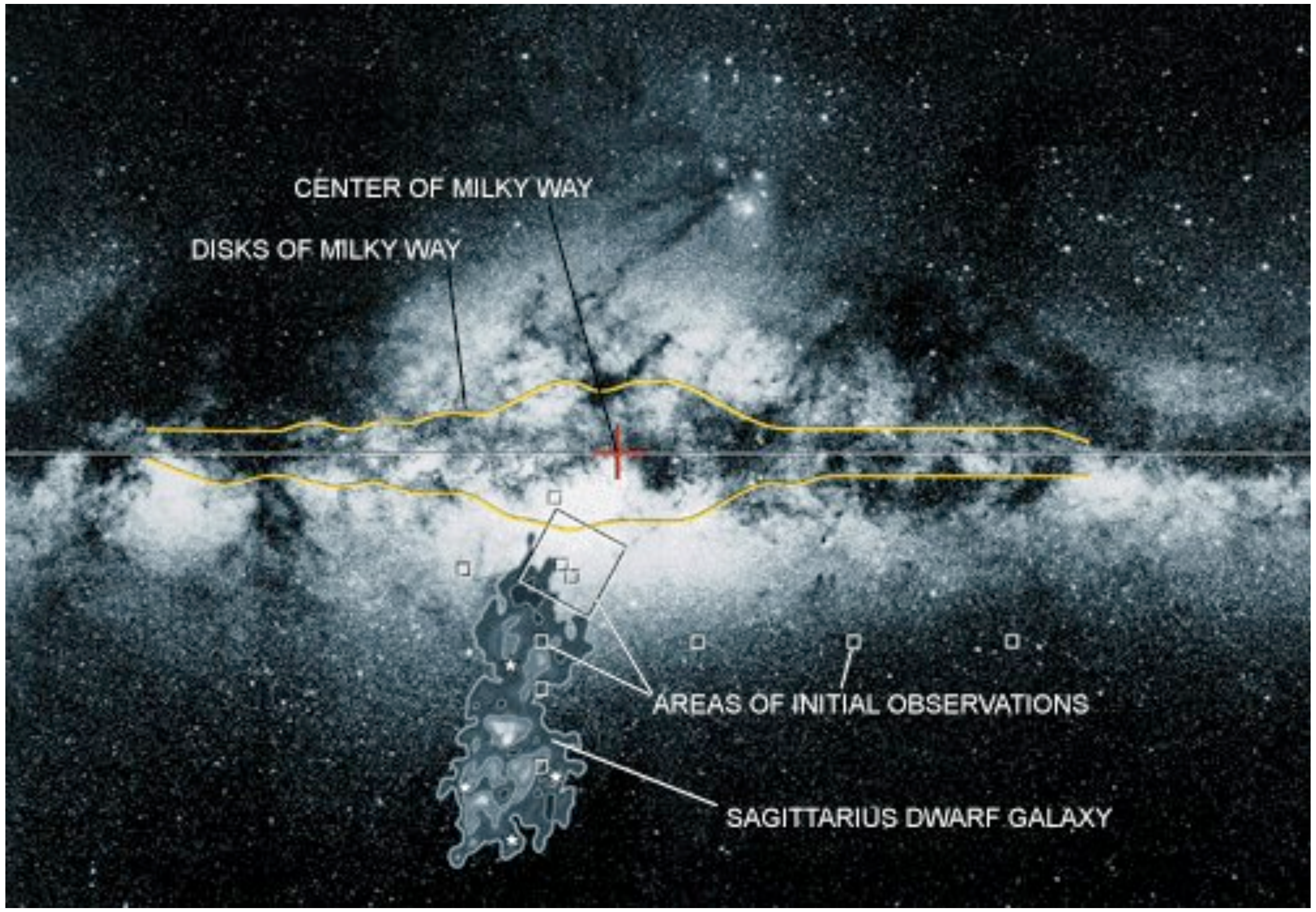
Sagittarius dwarf

Discovered in 1994

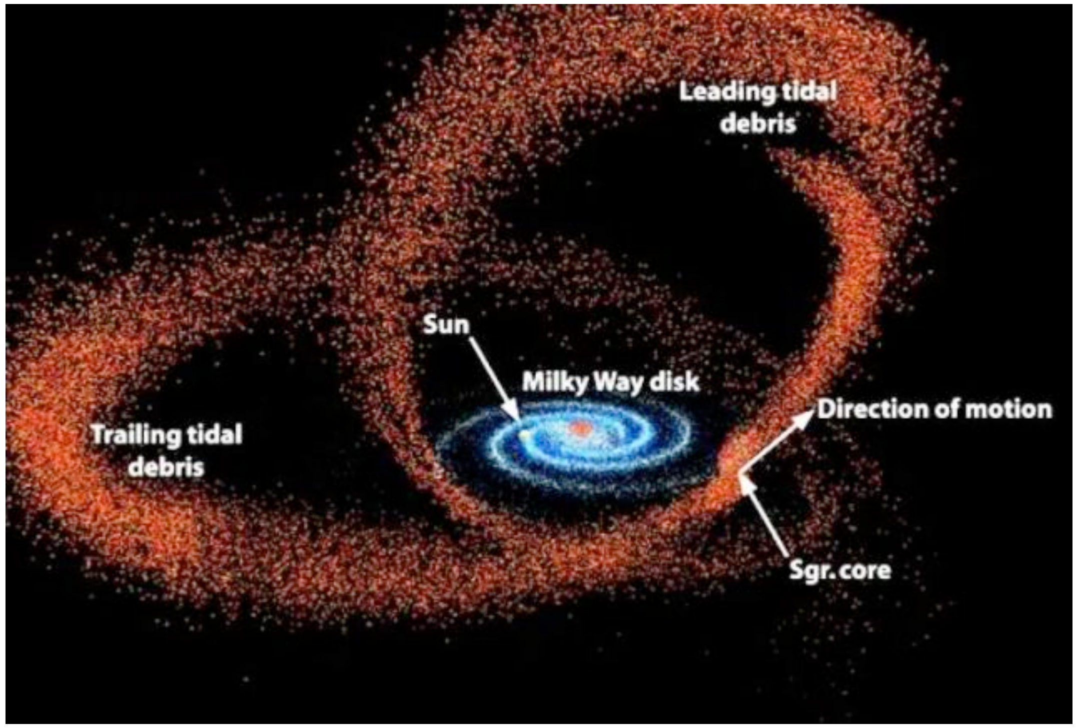
Covers a large fraction of the sky but it is on the opposite site of the bulge so faint

Looping structure

At least 4 globular clusters are associated with it
—> important M54, considered the nucleous of it



credit (Rosie Wyse/JHU)



Some standing issues…

1) how metal-poor are the most metal-poor stars, how many?

2) how many past accretion events the MW experienced?

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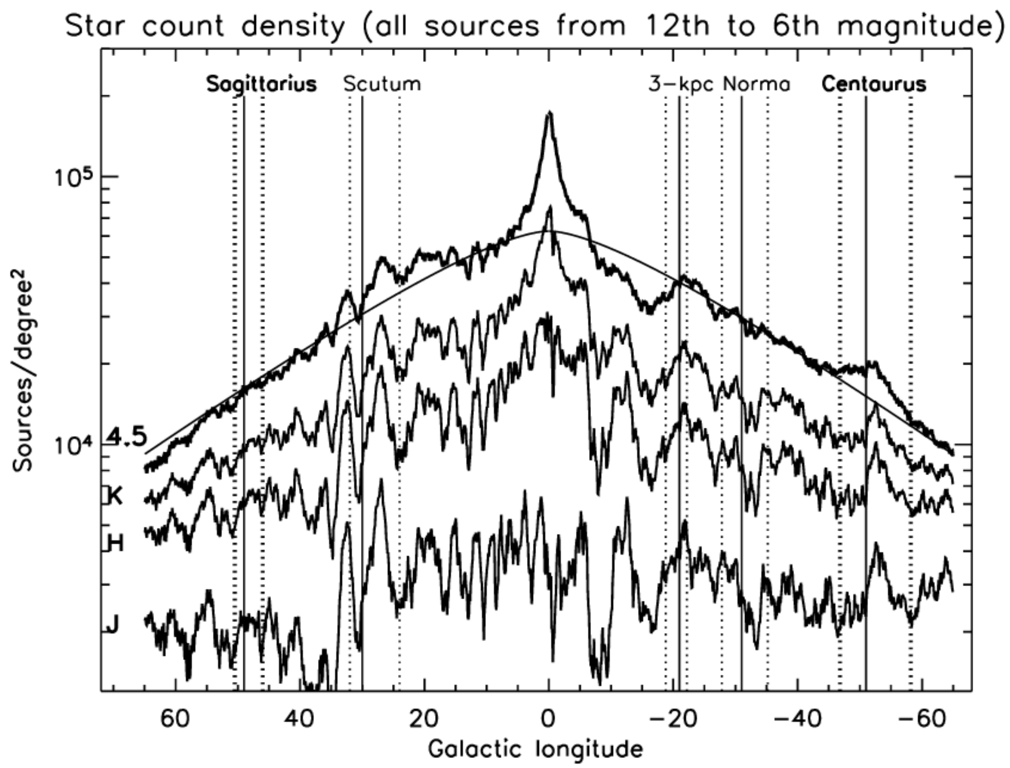
↓

More observations needed!!!

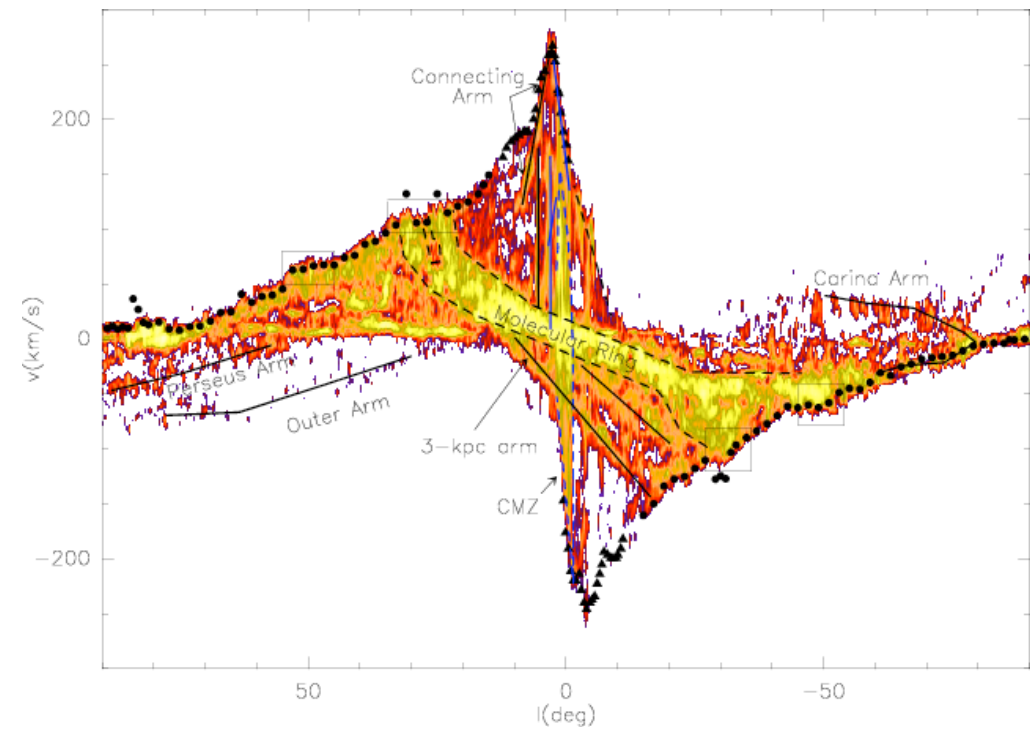
Disk

Disk

- Flattened component (50 kpc across and few kpc thick)
- Presence of spiral arms and gas

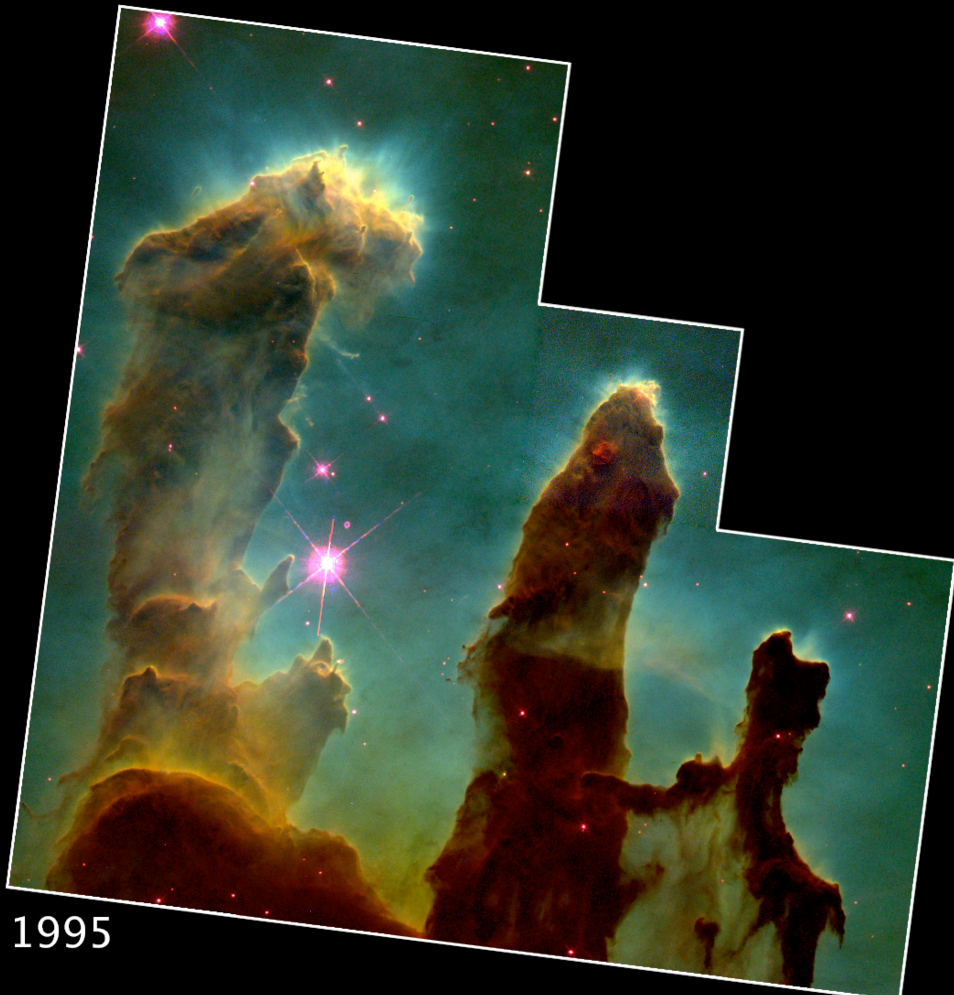


Churchwell et al. (2009)



Rodriguez-Fernandez (2011)

- Star formation is present nowadays (~ 3 solar masses per year)



1995

2014

M16 ▪ Eagle Nebula

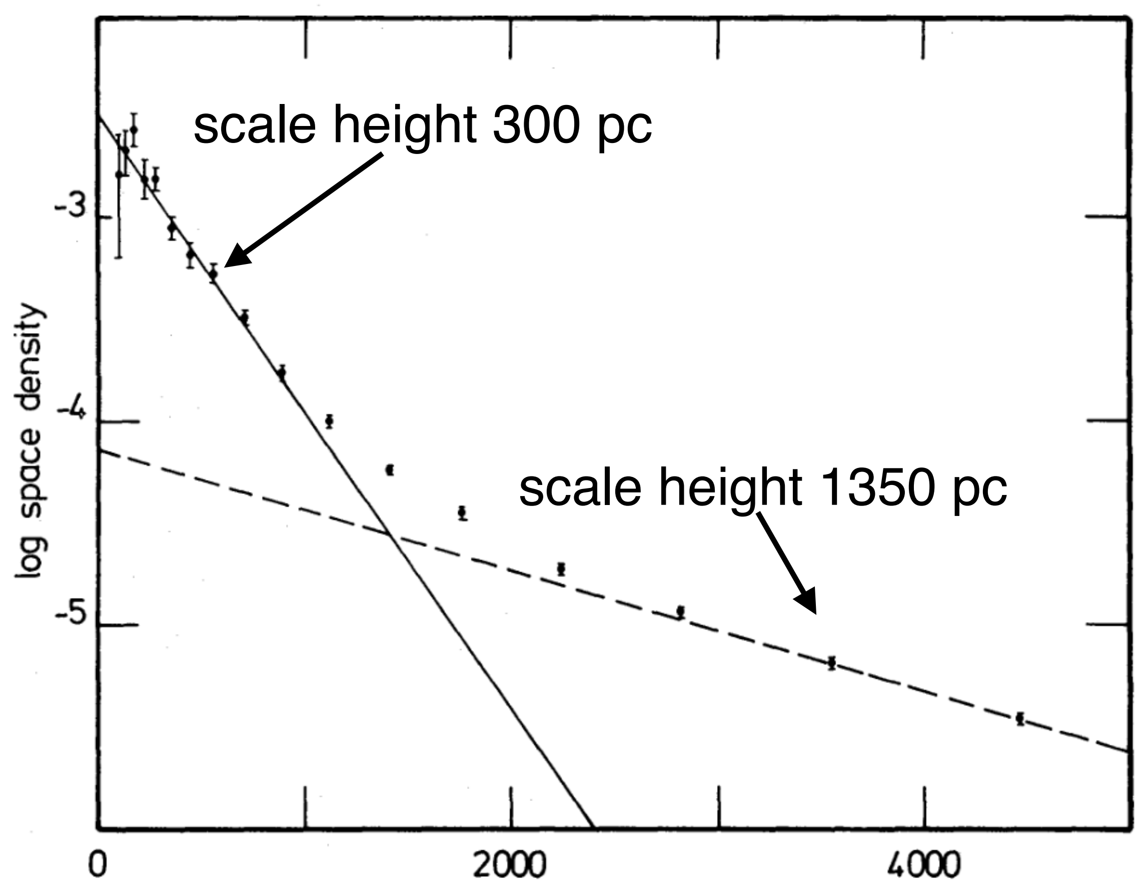
Hubble Space Telescope ▪ WFPC2 ▪ WFC3/UVIS

STScI-PRC15-01a

Disk structure

Gilmore & Reid in 1983 introduce the concept of **thin** and **thick disk**

The number density of stars above the plane cannot be represented with a single exponential but with two
—> **thin and thick disk**



Gilmore & Read (1983)

From studies in the Solar Neighbourhood, these two components have different kinematic and chemical properties

Disk kinematics

Thin and thick disk populations can be divided considering their kinematics.
BUT: assuming that their characteristics are the same also outside the solar neighbourhood (spiral arms or molecular clouds interactions can modify kinematics…)

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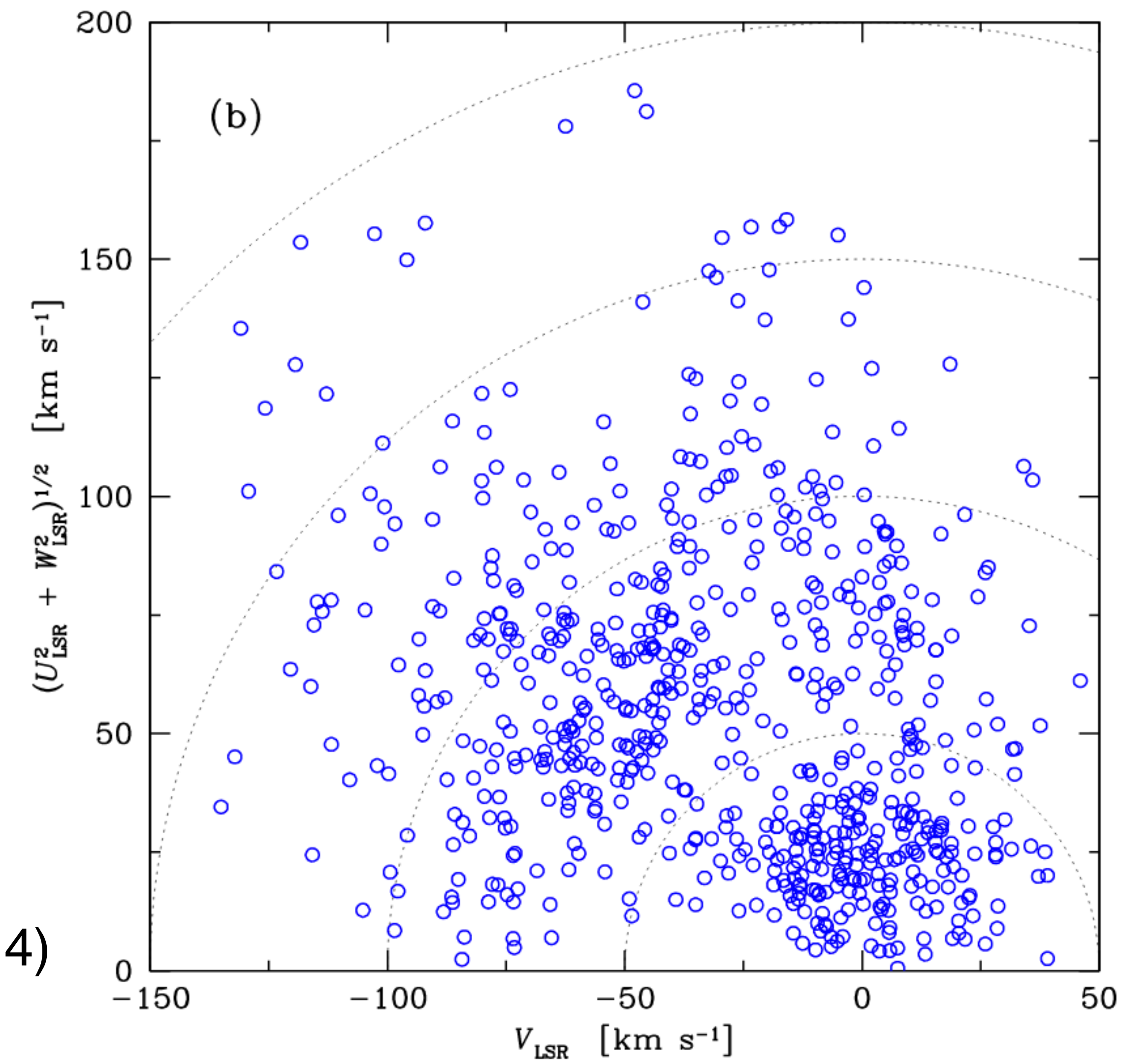

Bensby et al. (2014)

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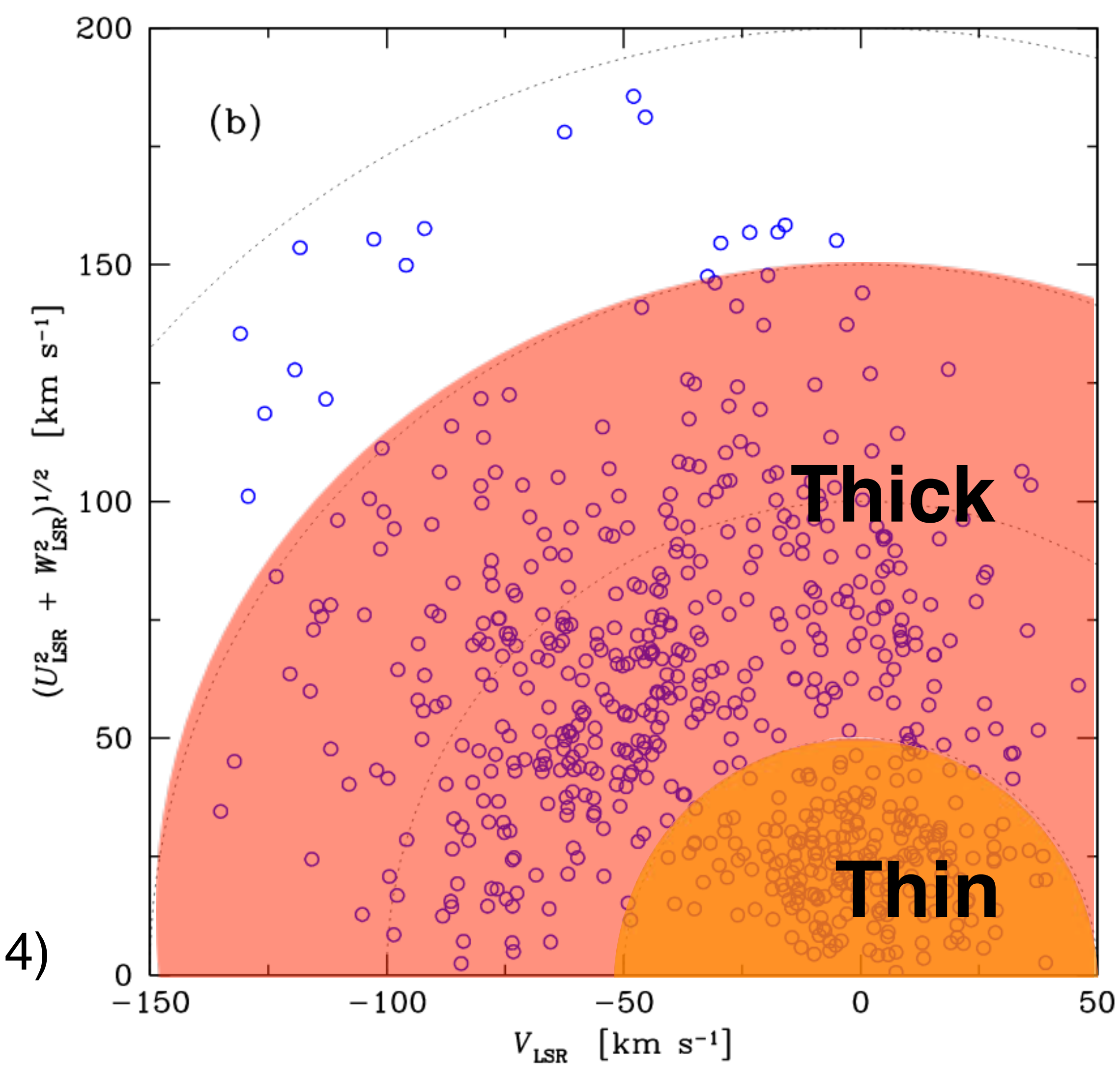
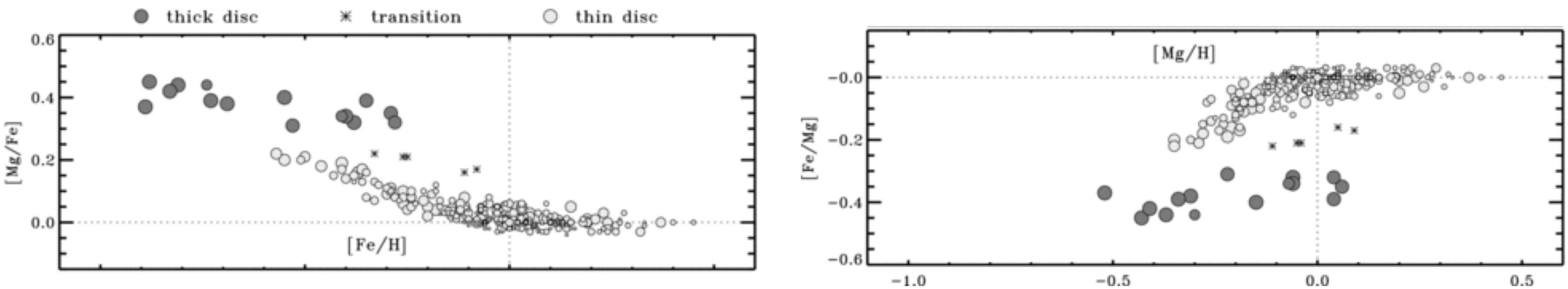


Bensby et al. (2014)

Disk abundances

Very detailed abundances for sphere of 25 pc around the Sun



Fuhrmann (2011)

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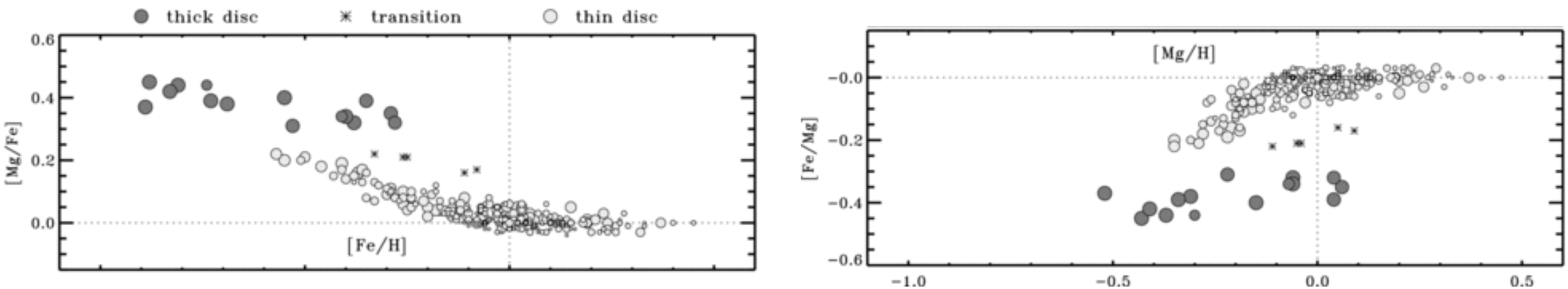

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Most of the abundances for the disk are from 1-2 kpc around the Sun

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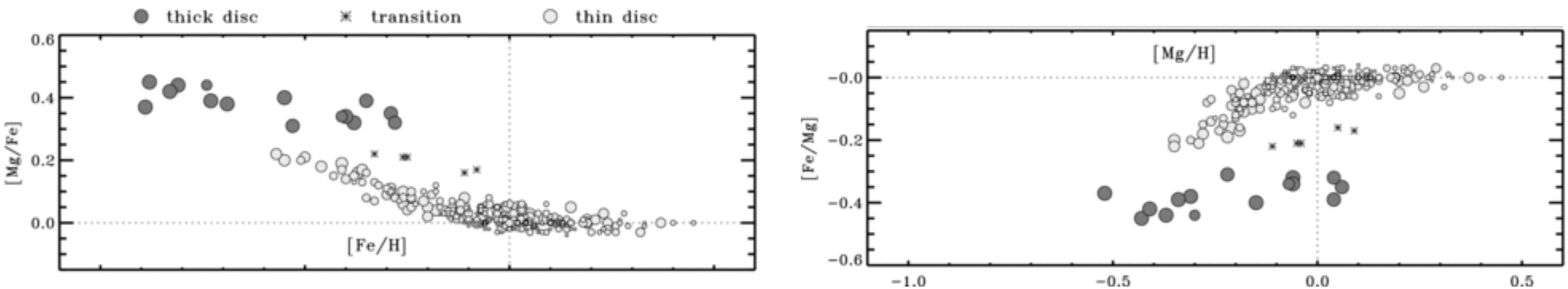

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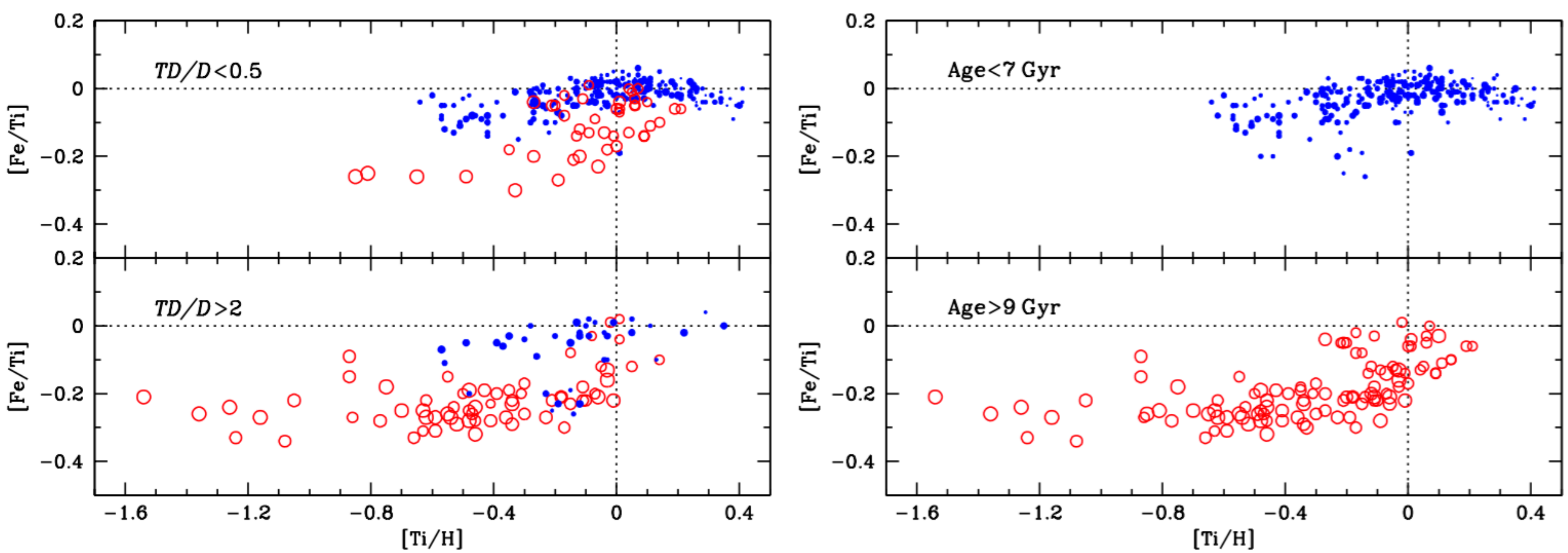
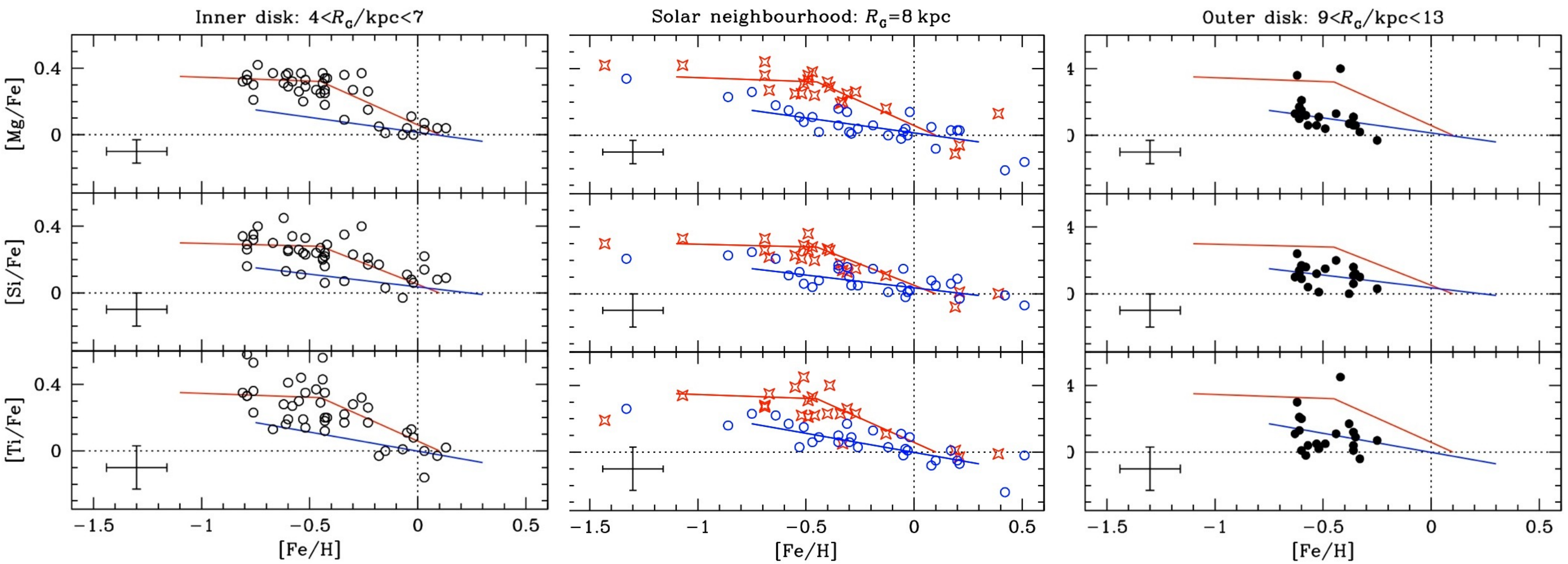
Bensby et al. (2014)



Other regions of the disk..?



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Chemical tagging

If disk is formed by stars born in clusters that then got distrupted
—> stars from the same cluster should share the same kinematics
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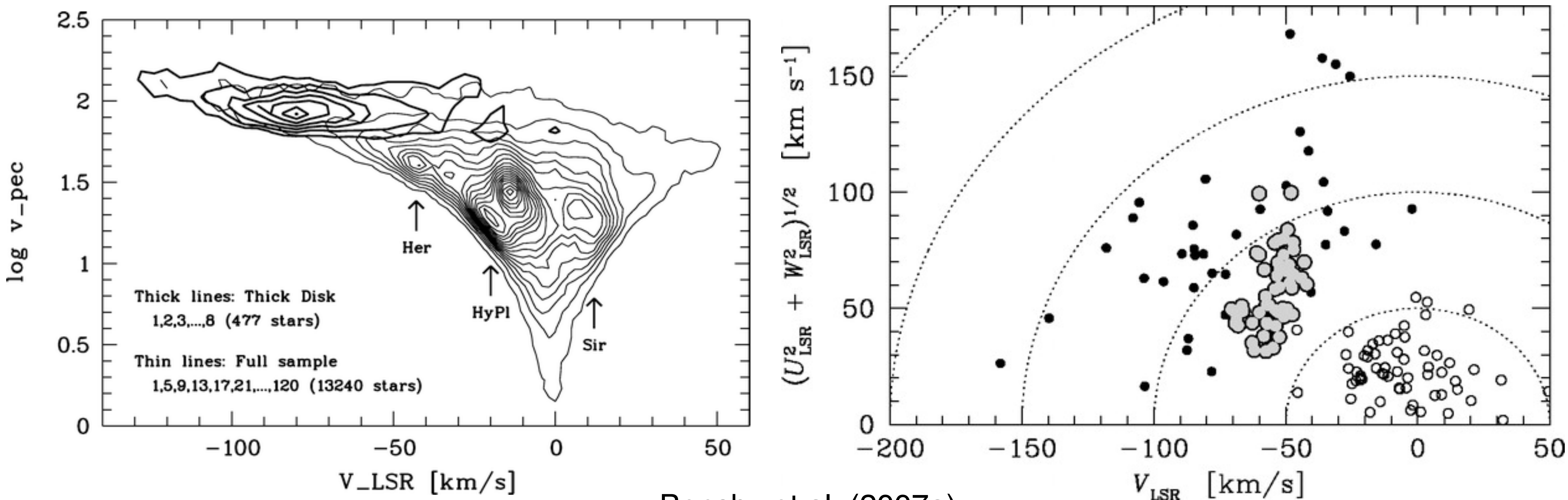
Not all the groups sharing the same kinematics are from dissolved cluster but they are clumped together from interaction with spirals or bar (for example the Hayades or Hercules streams).



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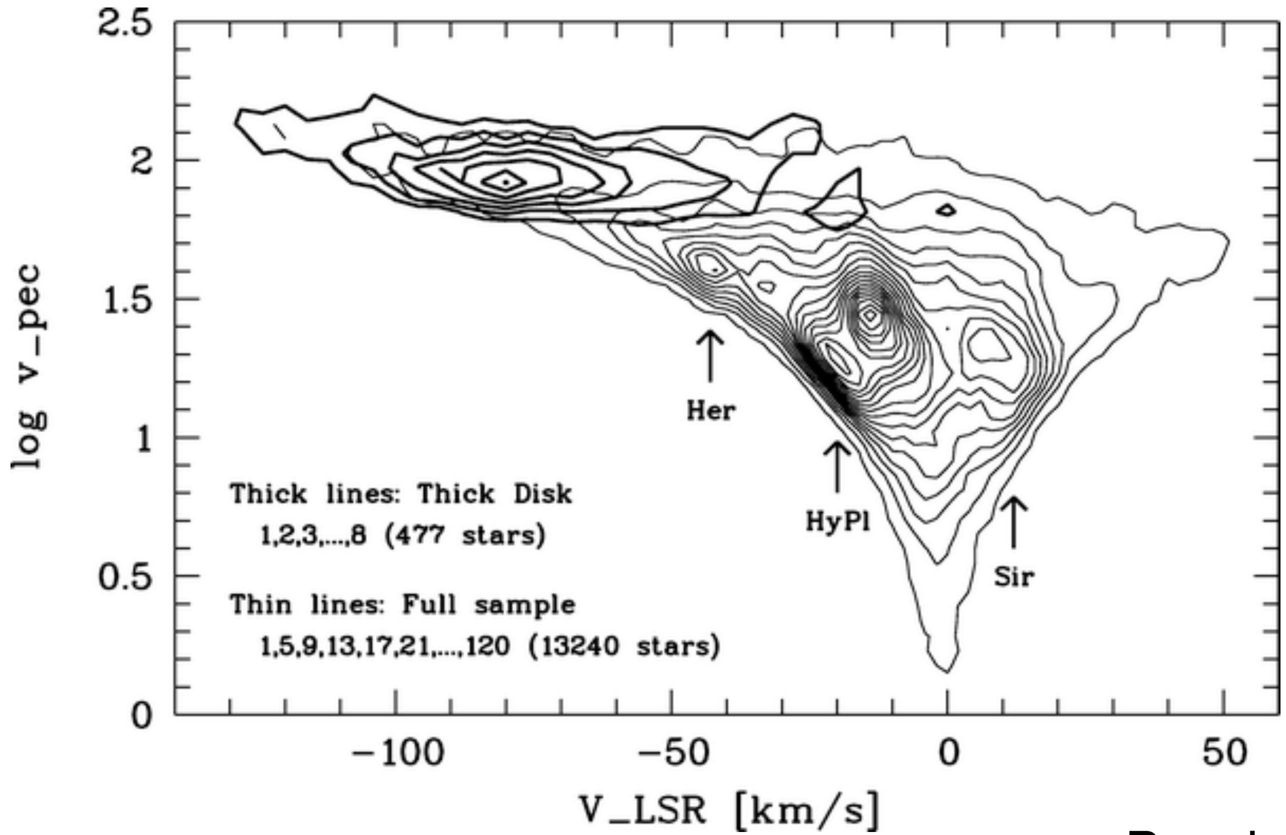
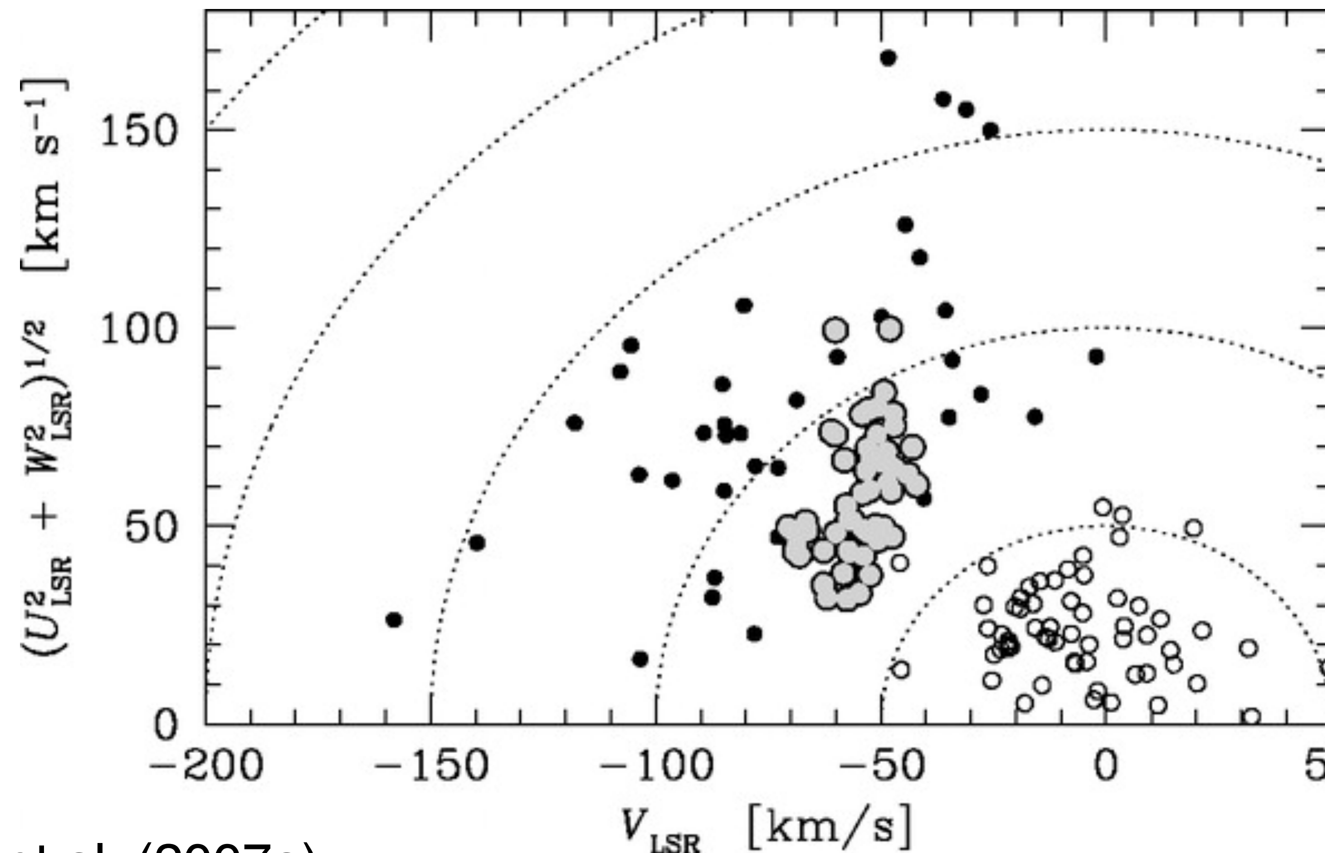
Chemical tagging to determine if stars are coming from the same original disrupted cluster.





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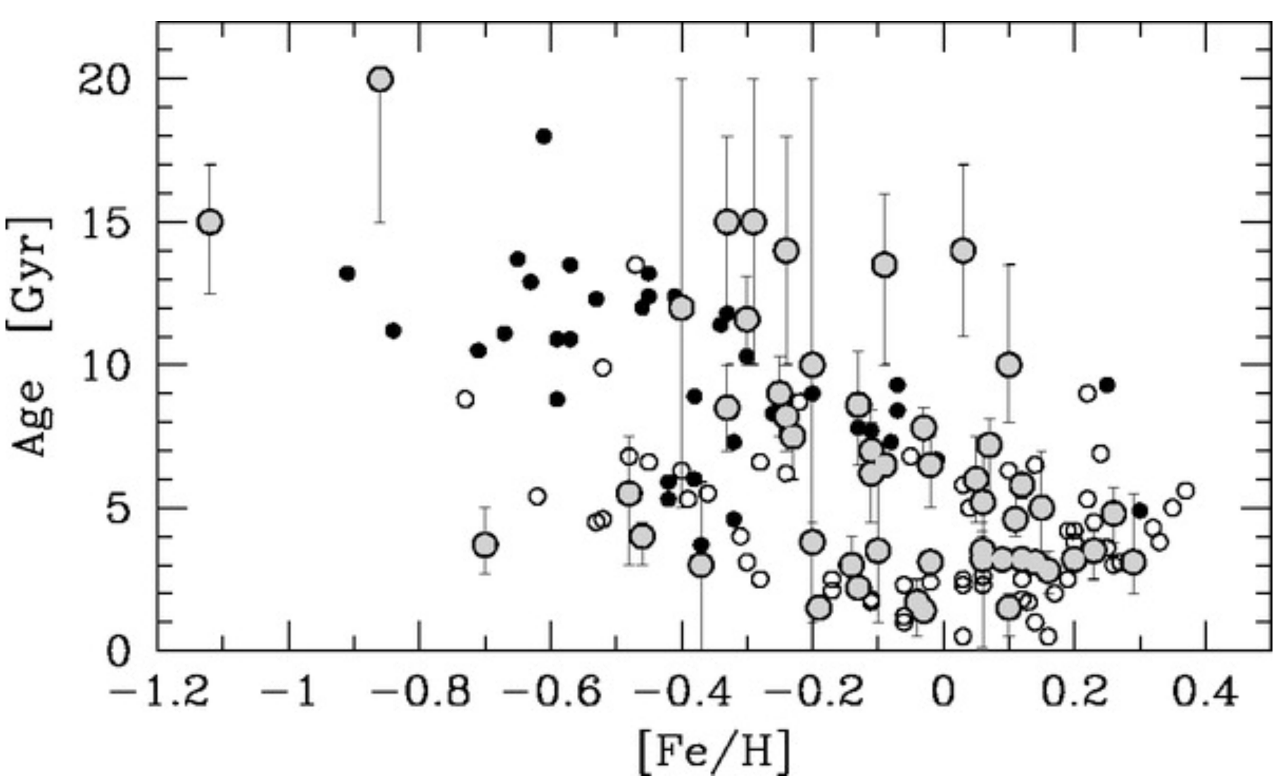

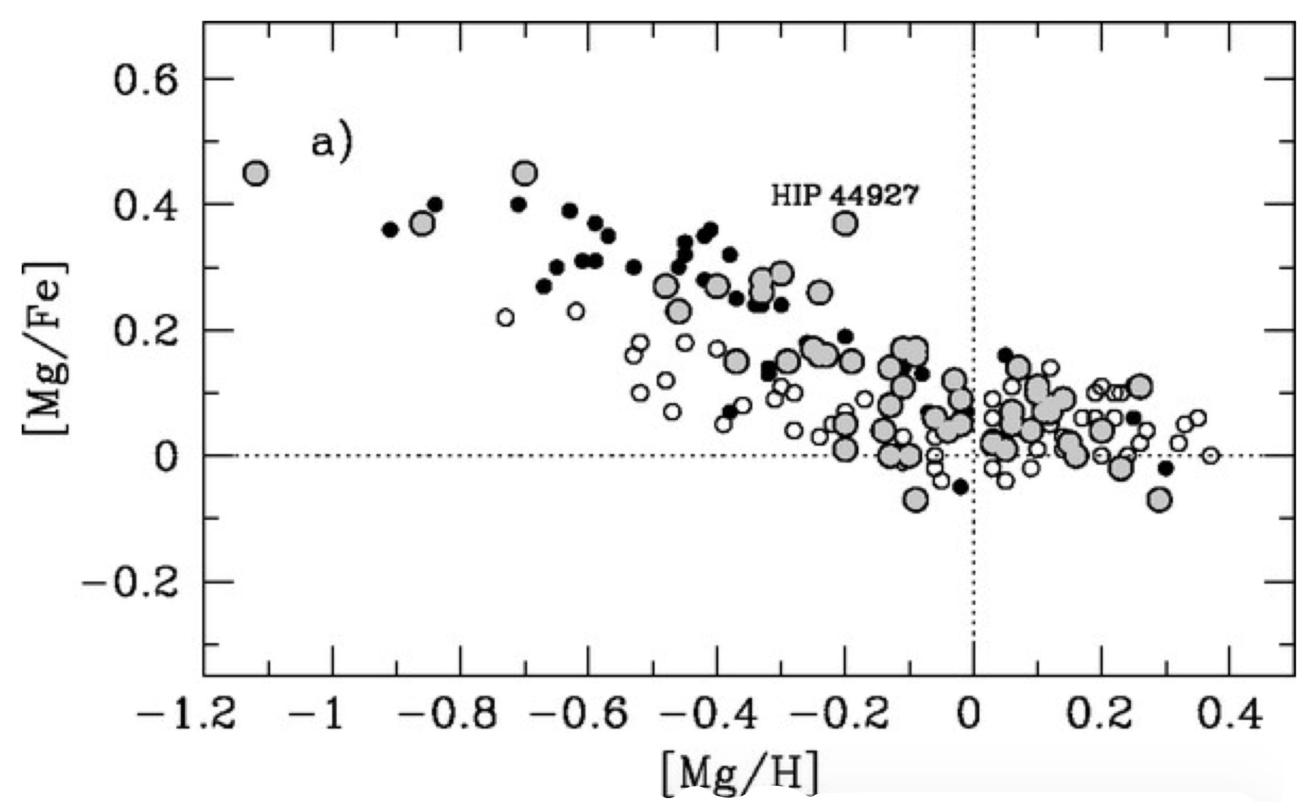

Some standing issues…

1) is thin and thick distinction still valid at different radius?

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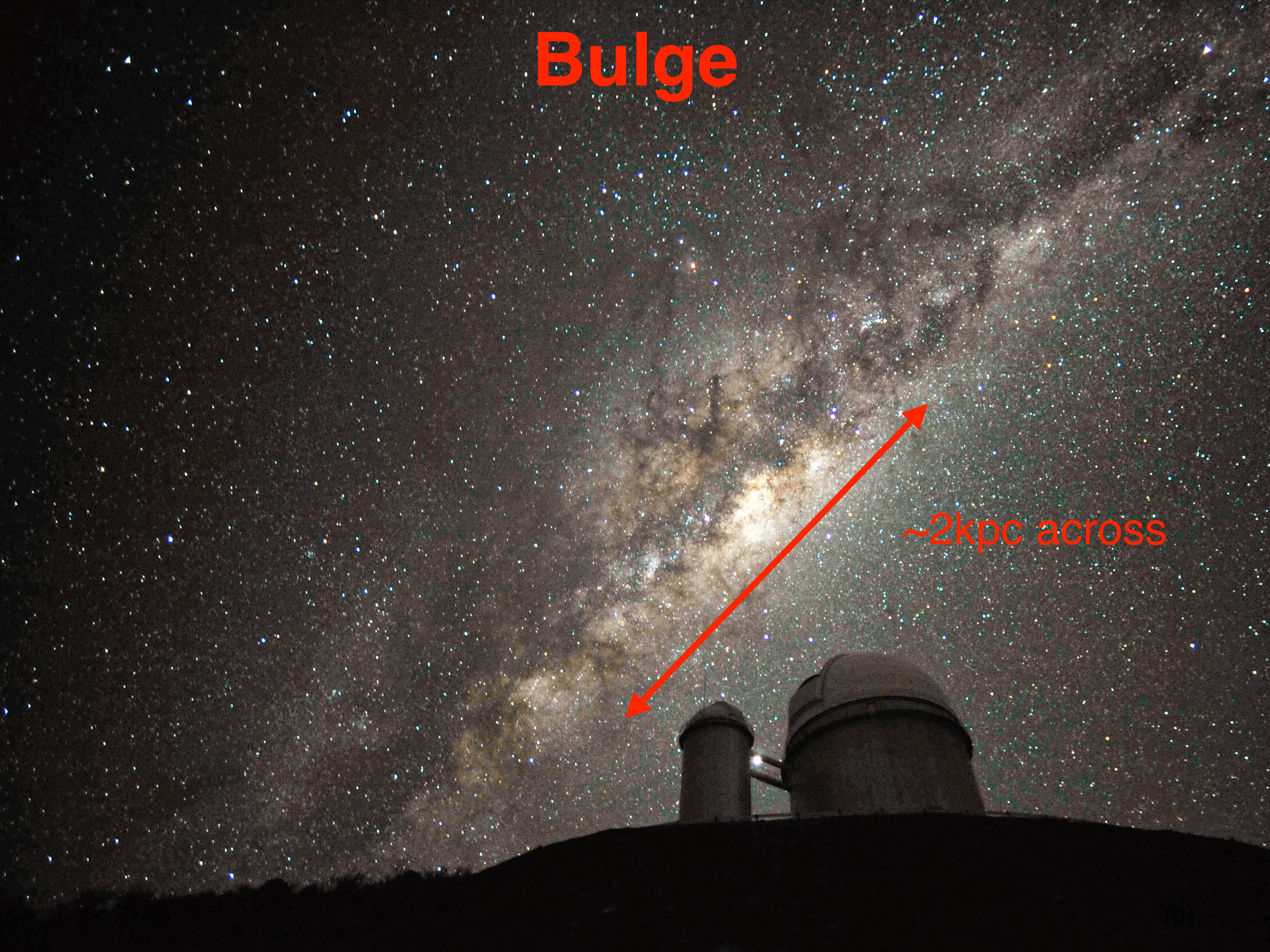
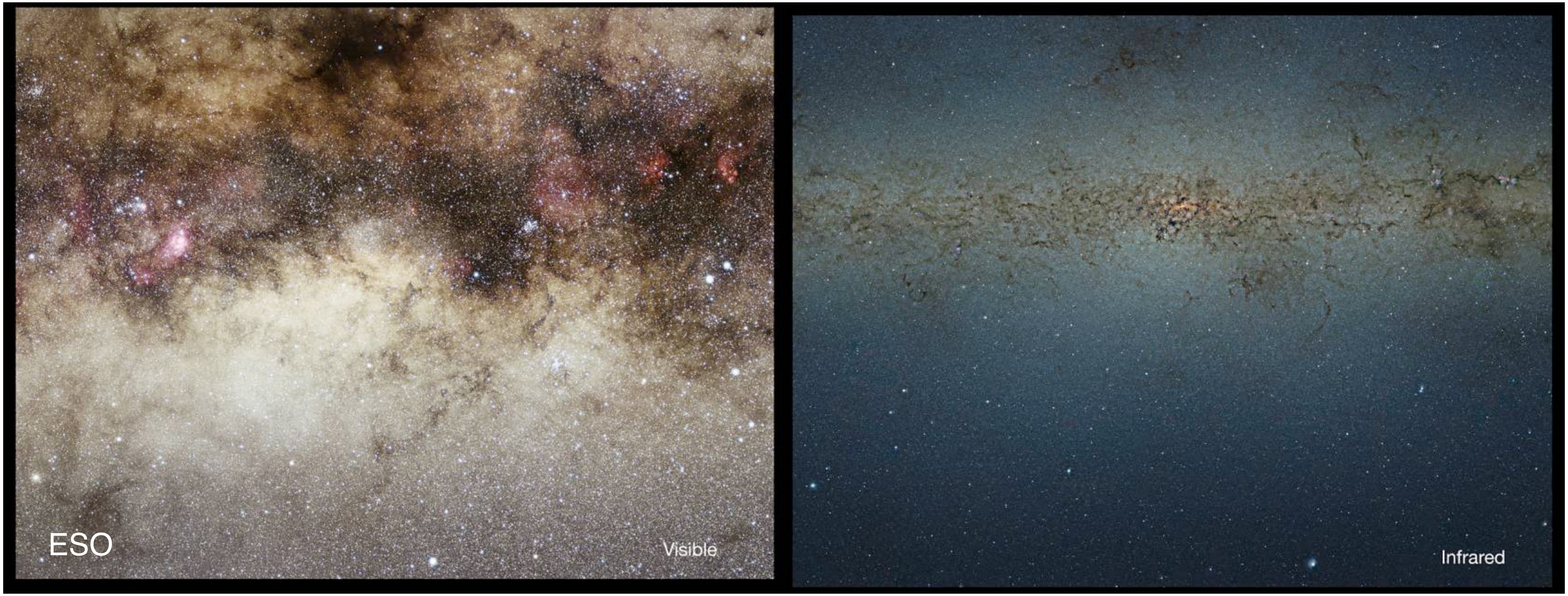
More observations needed!!!

Bulge


Bulge
~2kpc across

Observations of the bulge

Observations of the bulge



Dust is transparent to infrared emissions

Extinction map, how much extinction in visible vs IR

Bulge structure

Three main components:

BOXY BAR: ~300pc vertical scale height, 2-3 kpc radius that likely hosts an X-shaped structure visible away from the plane

LONG BAR: thin ~100pc scale height and it lies in the plane, —> still not clear if it is part of the main bar or not.

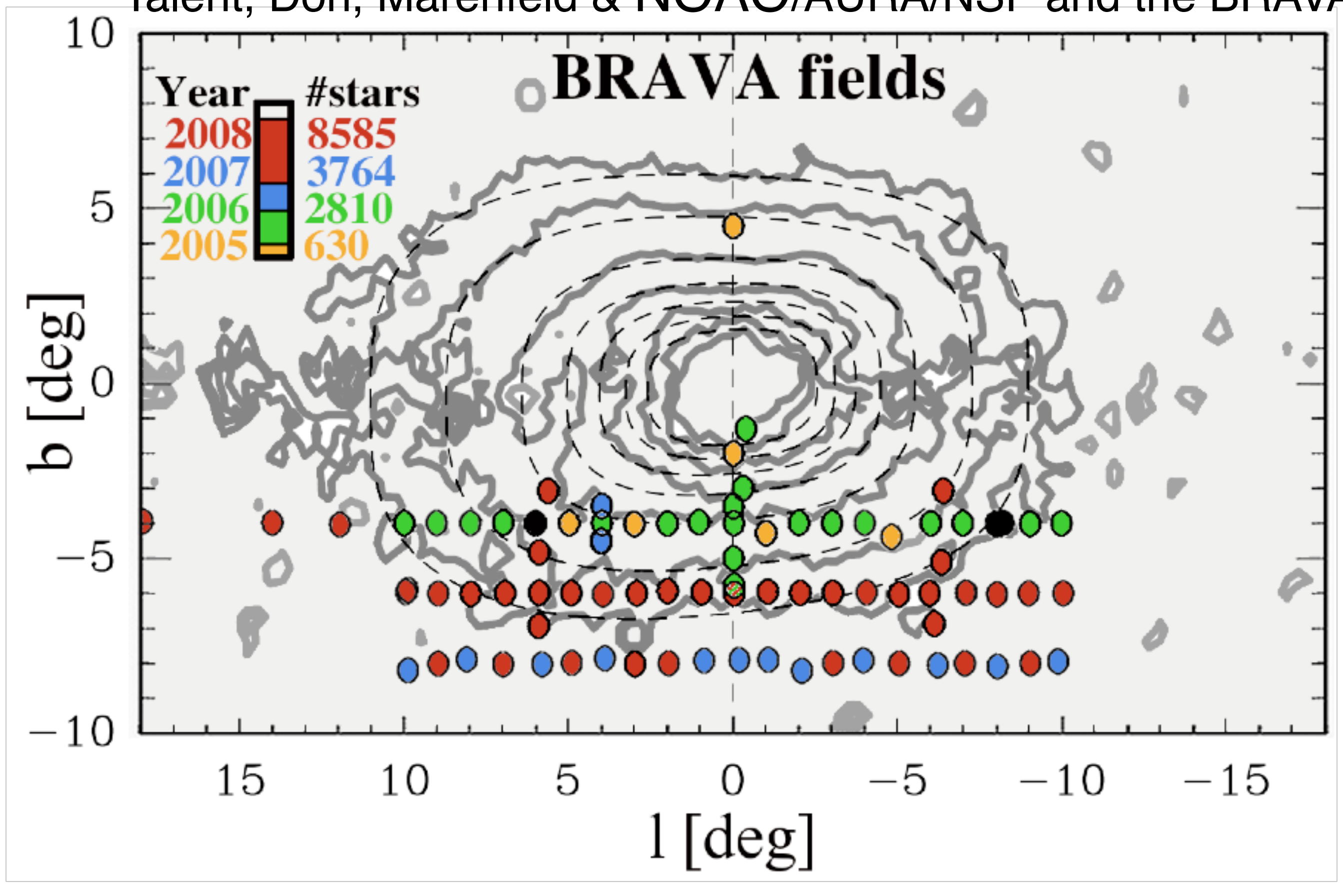
NUCLEAR BAR or DISK (debated): ~100pc

Bulge structure

Studies based on gas and stars to investigate the rotation of the bulge

NO “solid body” rotation, but cylindrical rotation like a pseudobulge

Talent, Don, Marenfeld & NOAO/AURA/NSF and the BRAVA Project



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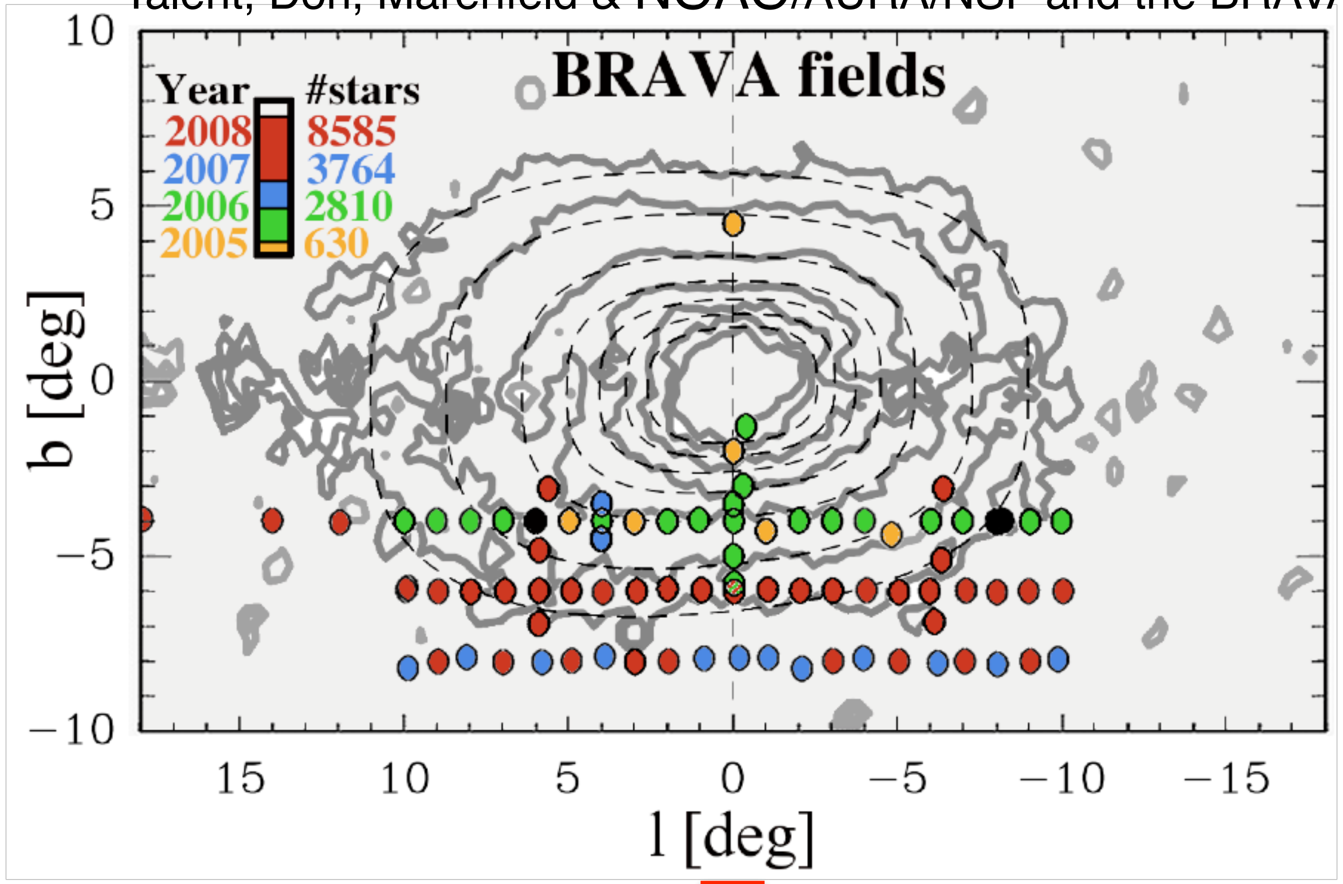
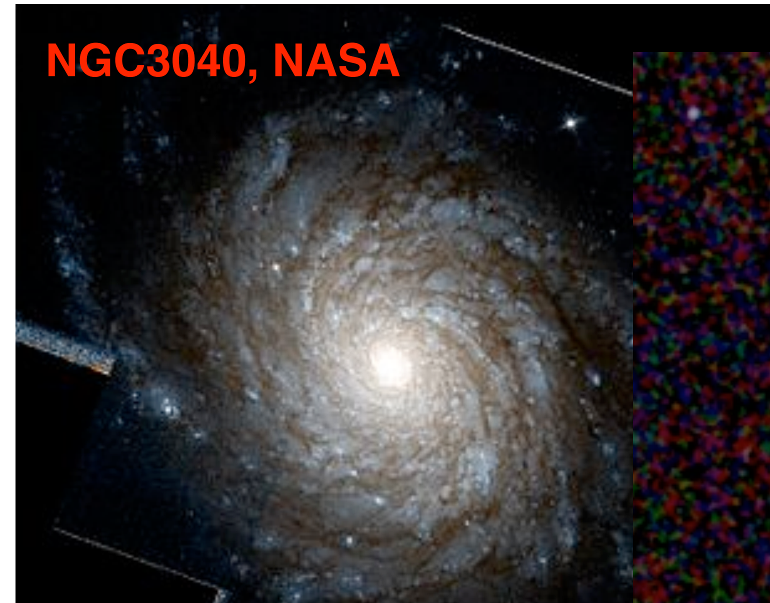


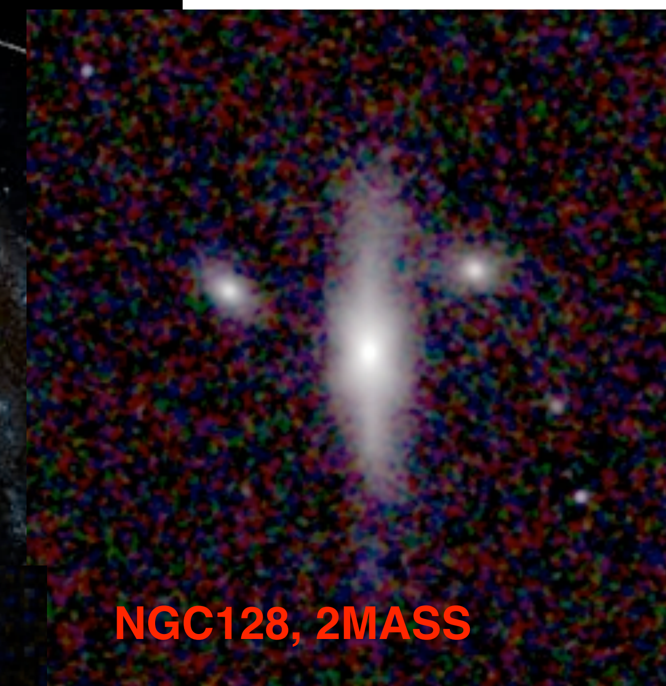
RV consistent with bulge formed from a bar that has undergone buckling

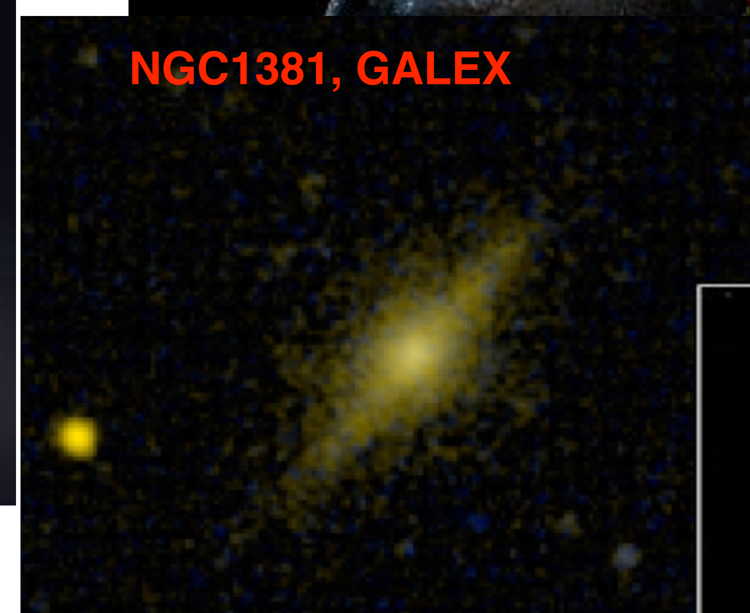
Bulge in other galaxies

Classical

Pseudobulge

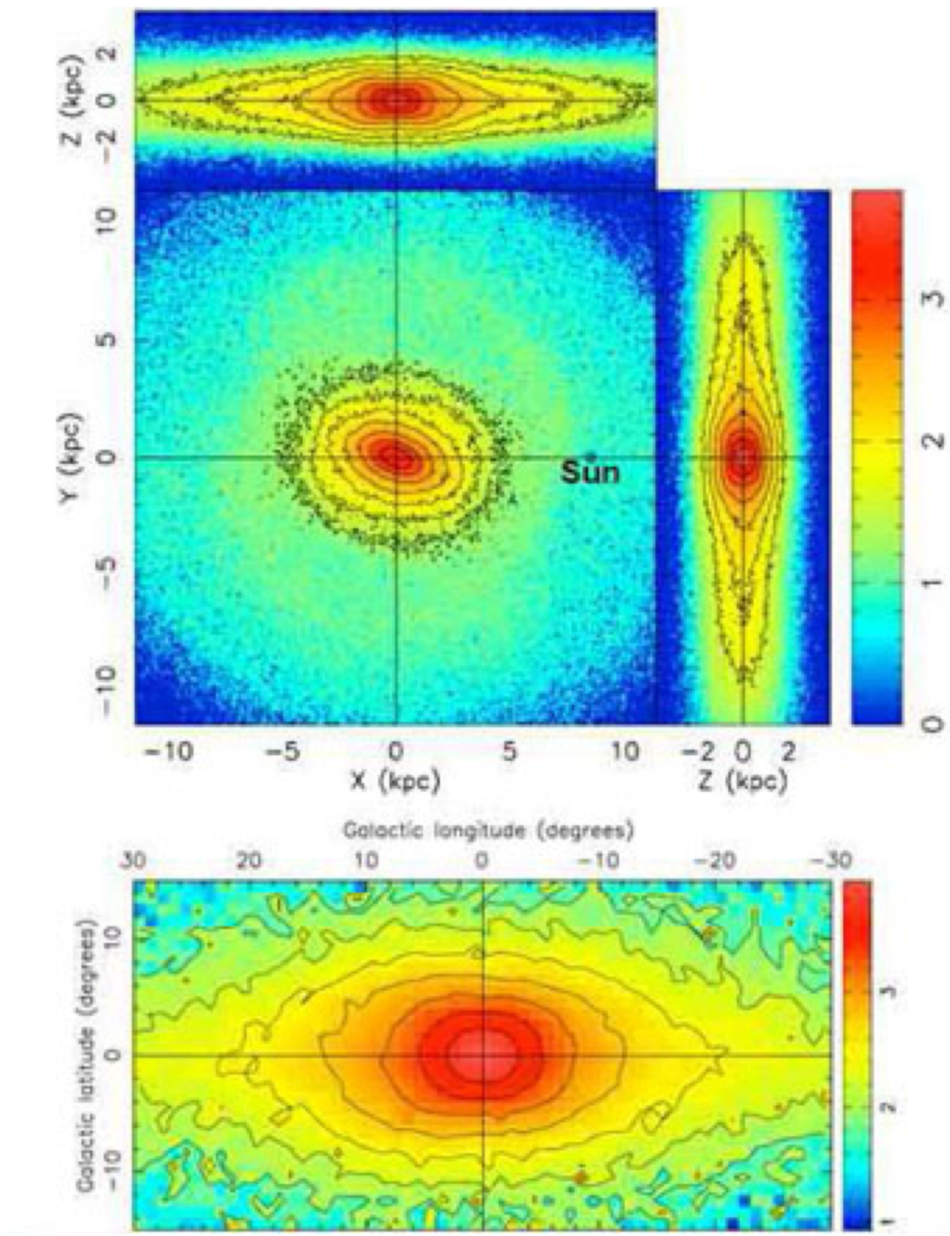




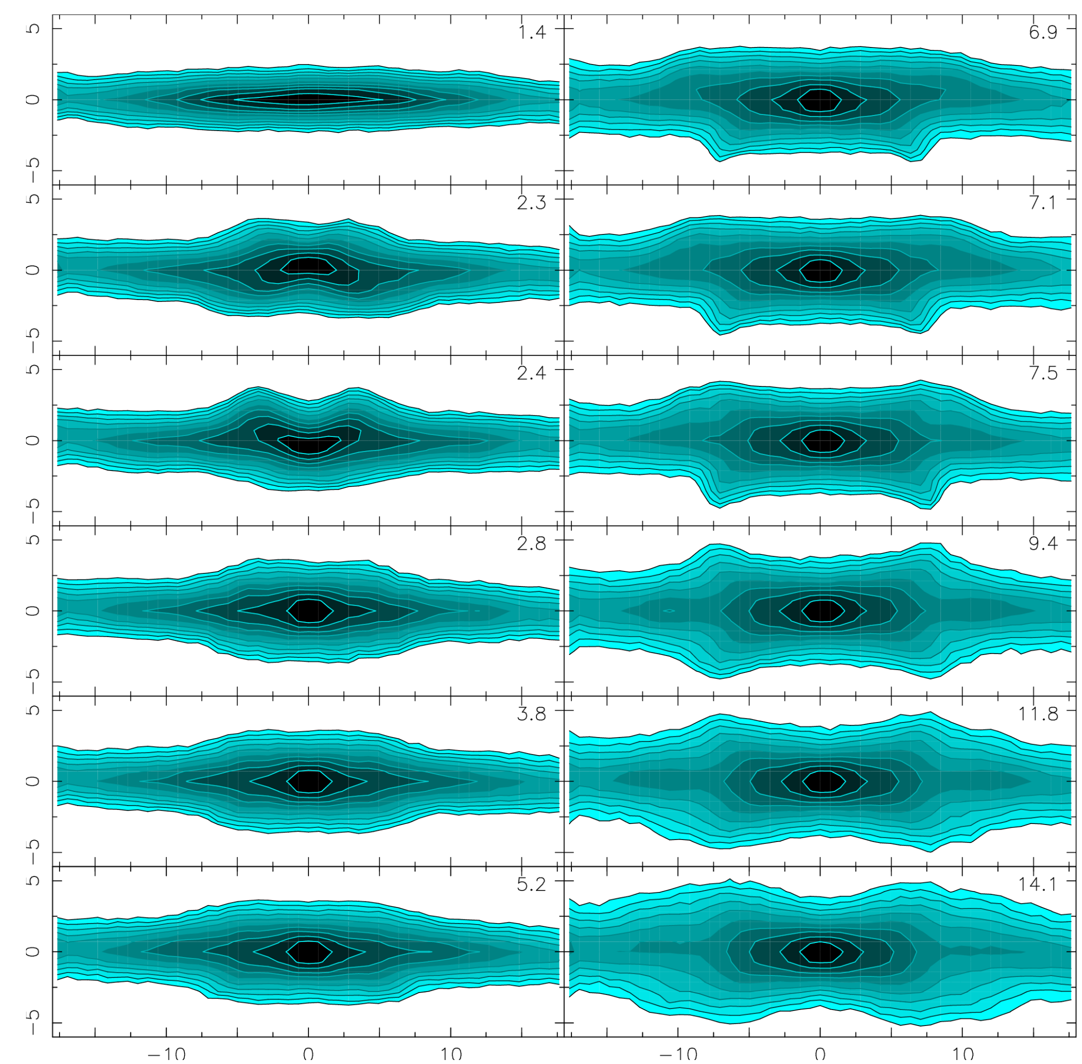


Bulge formation

Scenario of secular evolution of a massive disk that buckles into a bar



Shen et al. (2010)



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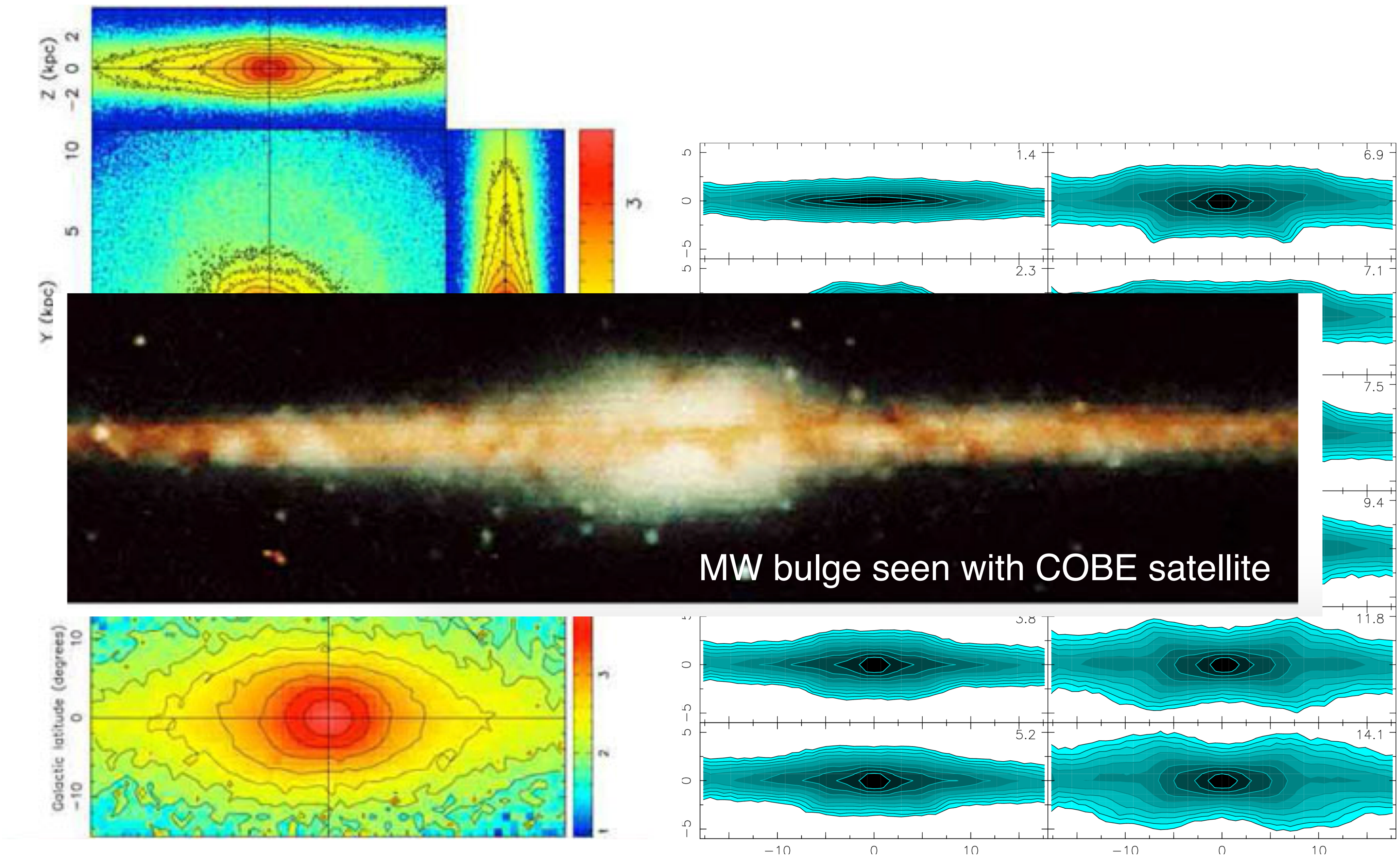

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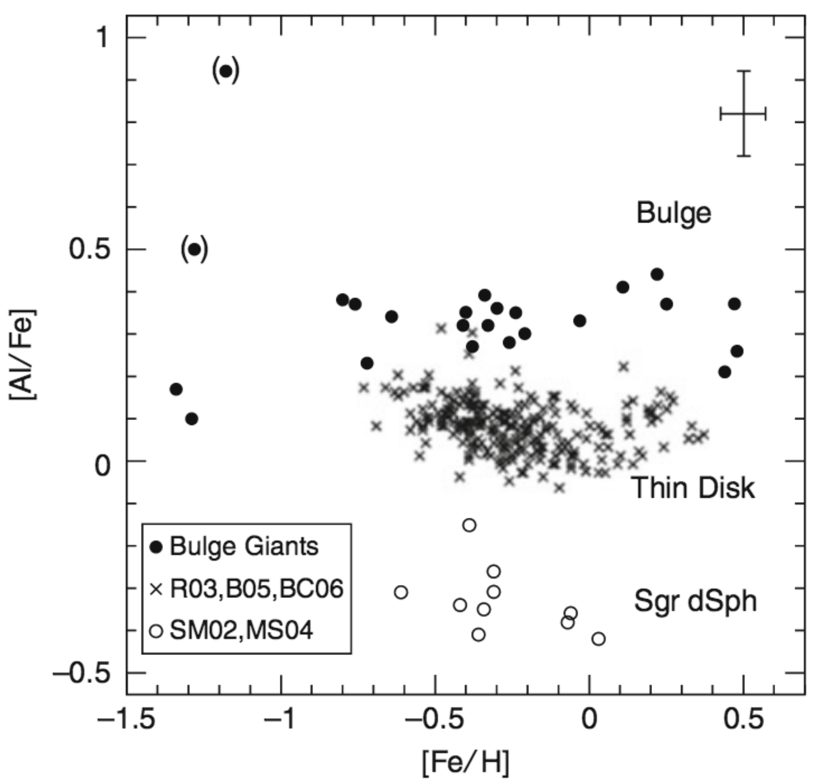
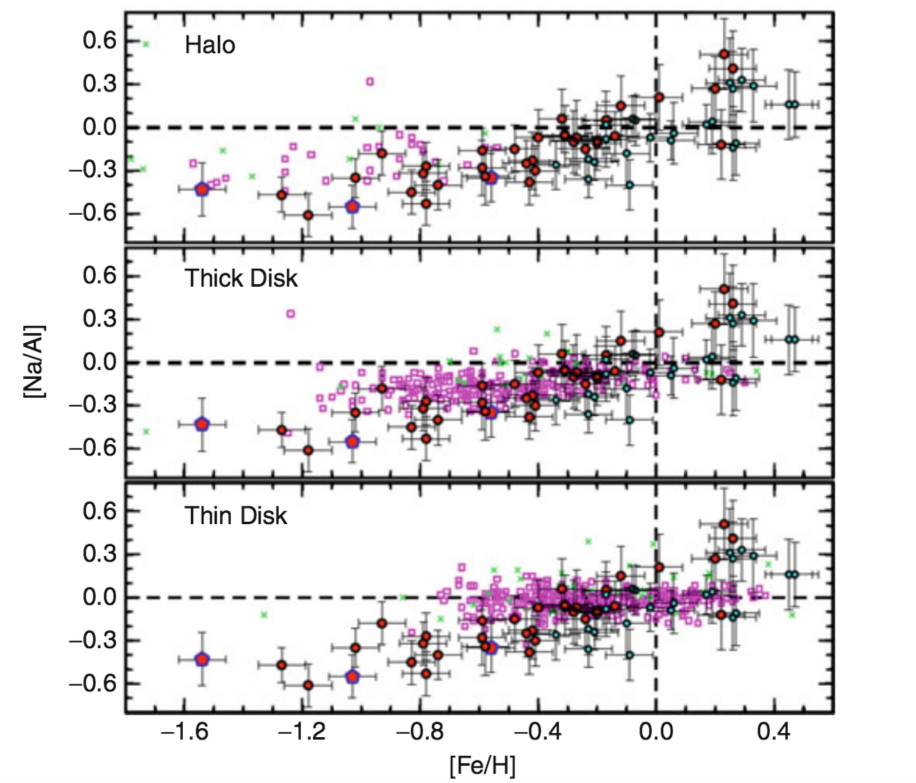


Fulbright et al. (2007)



Johnson et al. (2012a)

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Hint for rapid star formation and fast enrichment is given also from heavy metals

⬇

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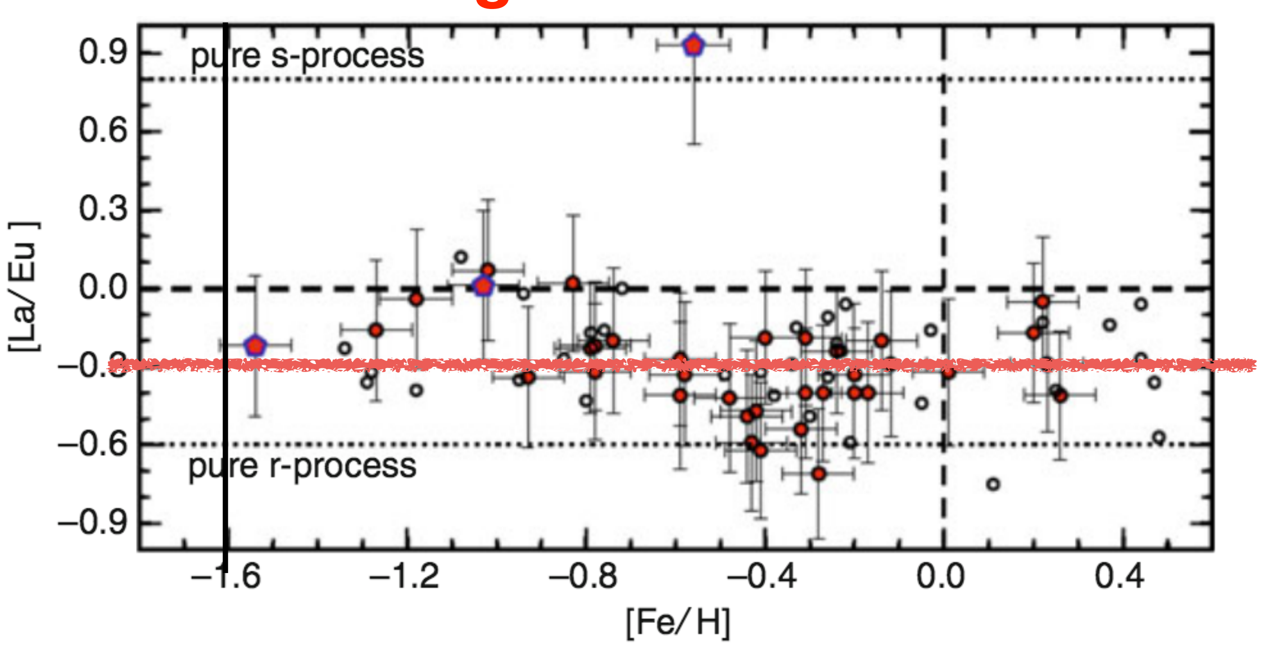
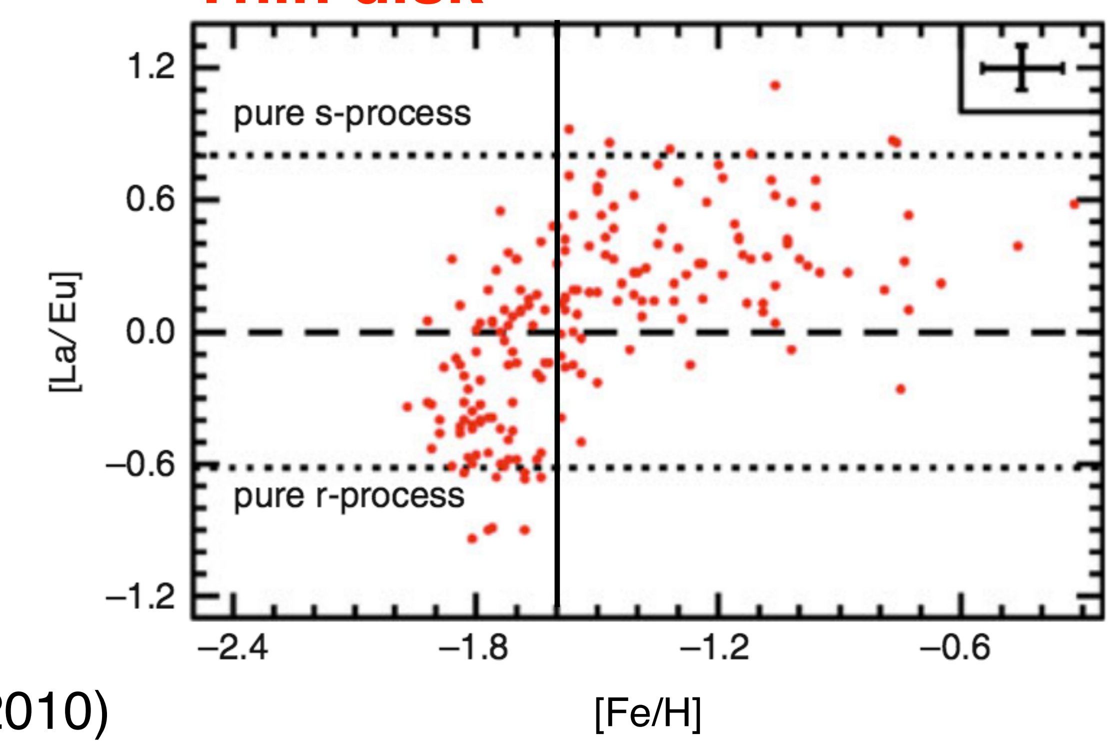
Giant bulge stars

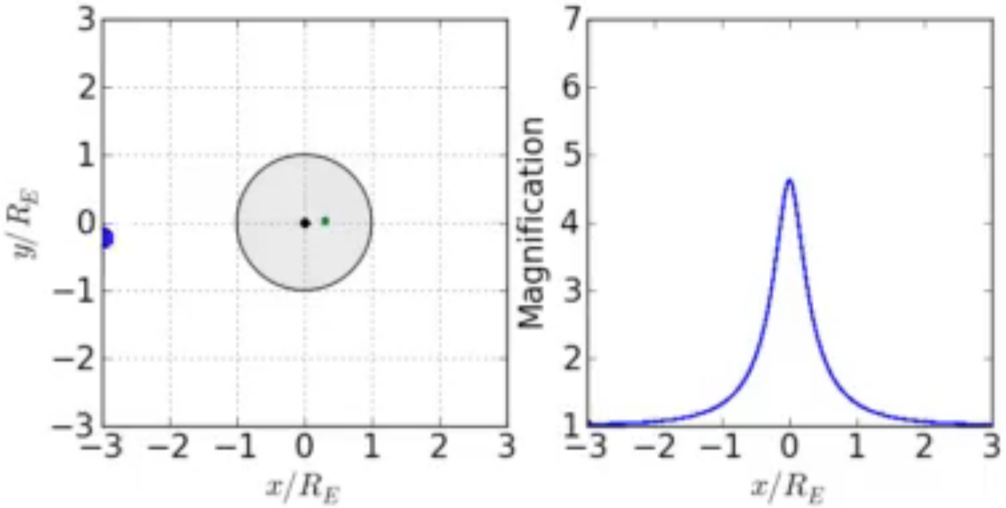


Thin disk

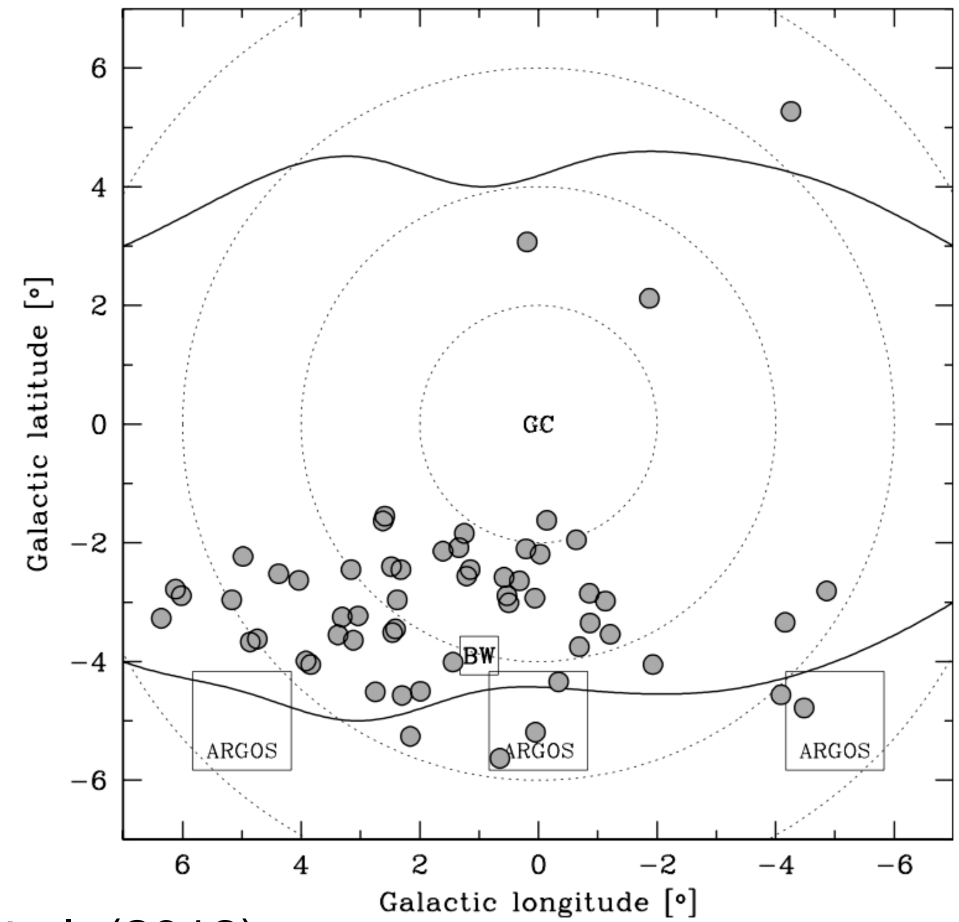


Johnson & Pilachowski (2010)

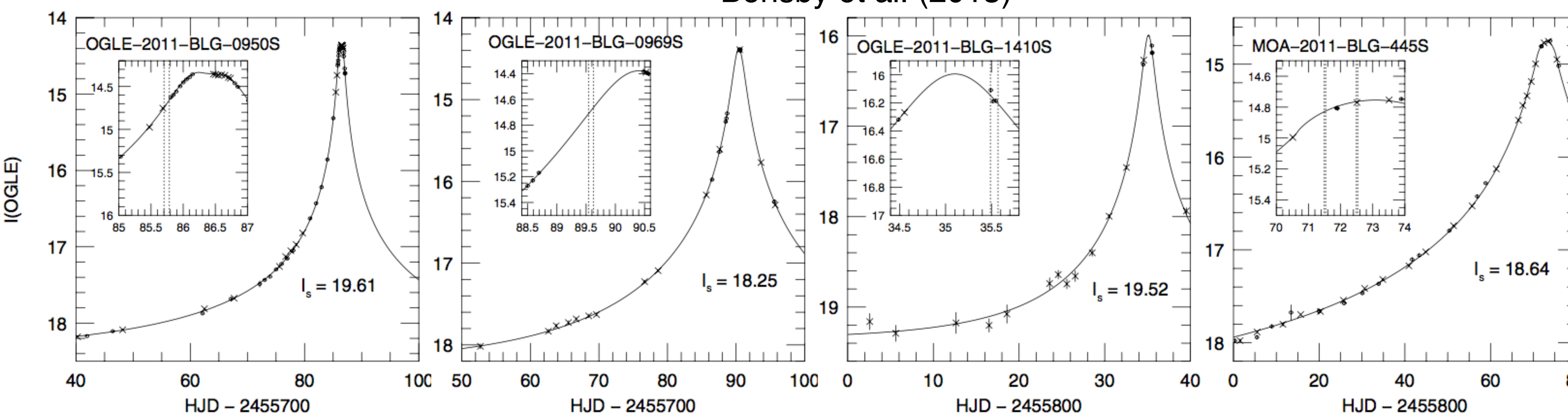
Microlensed dwarfs



credit RoboNet



Bensby et al. (2013)



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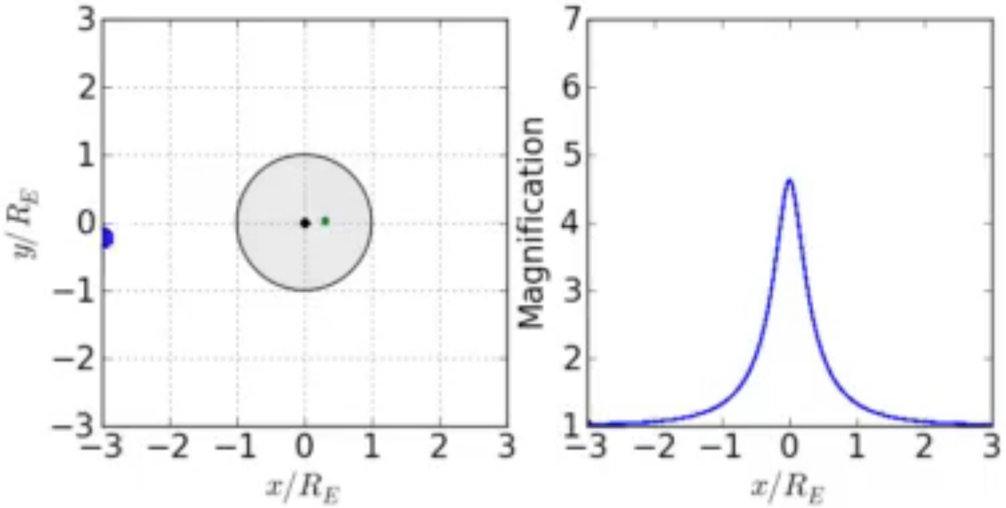

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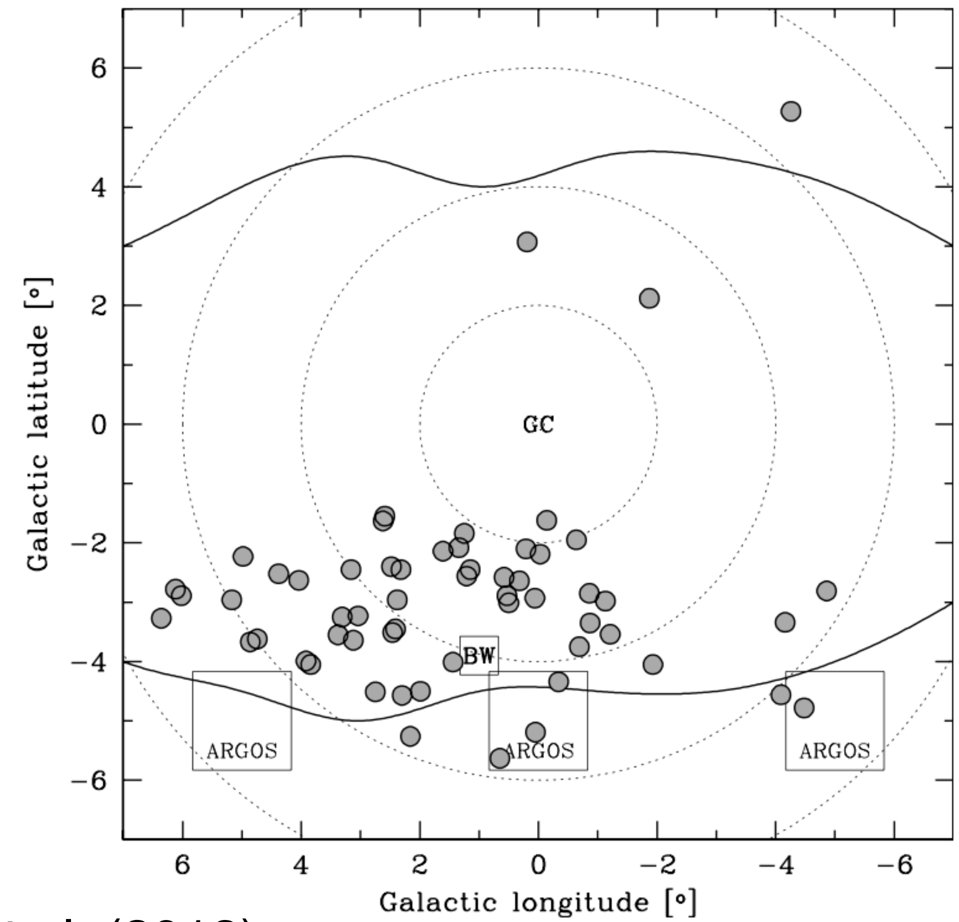

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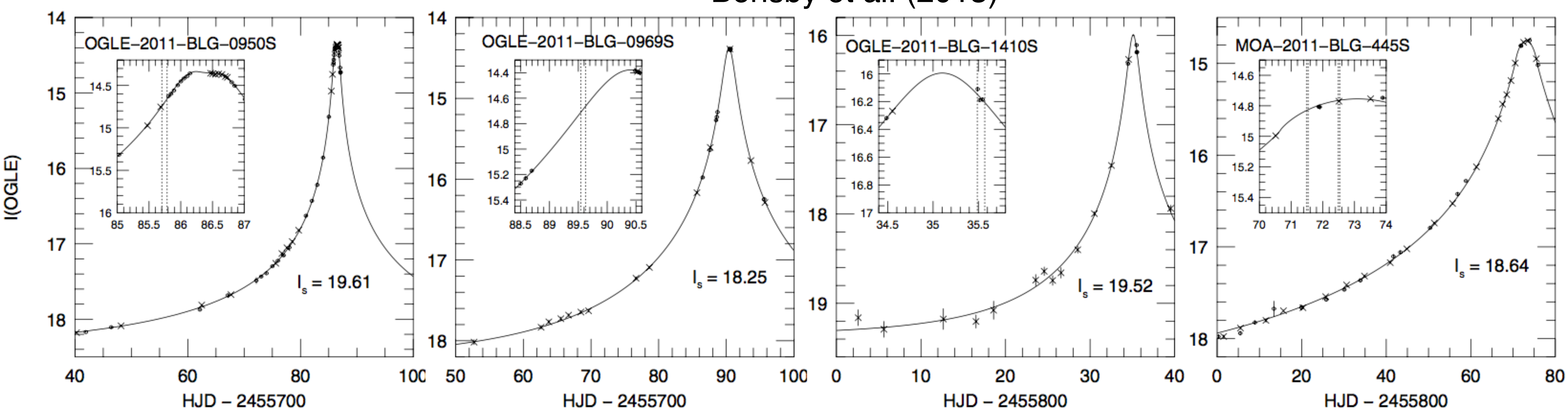
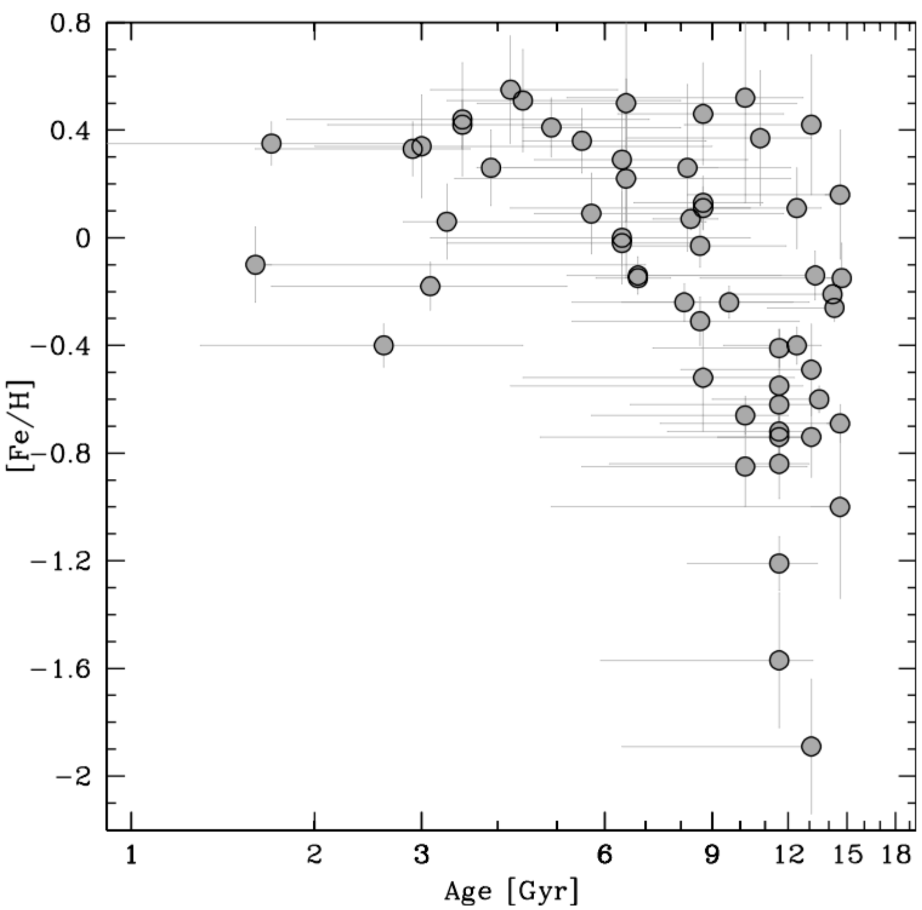
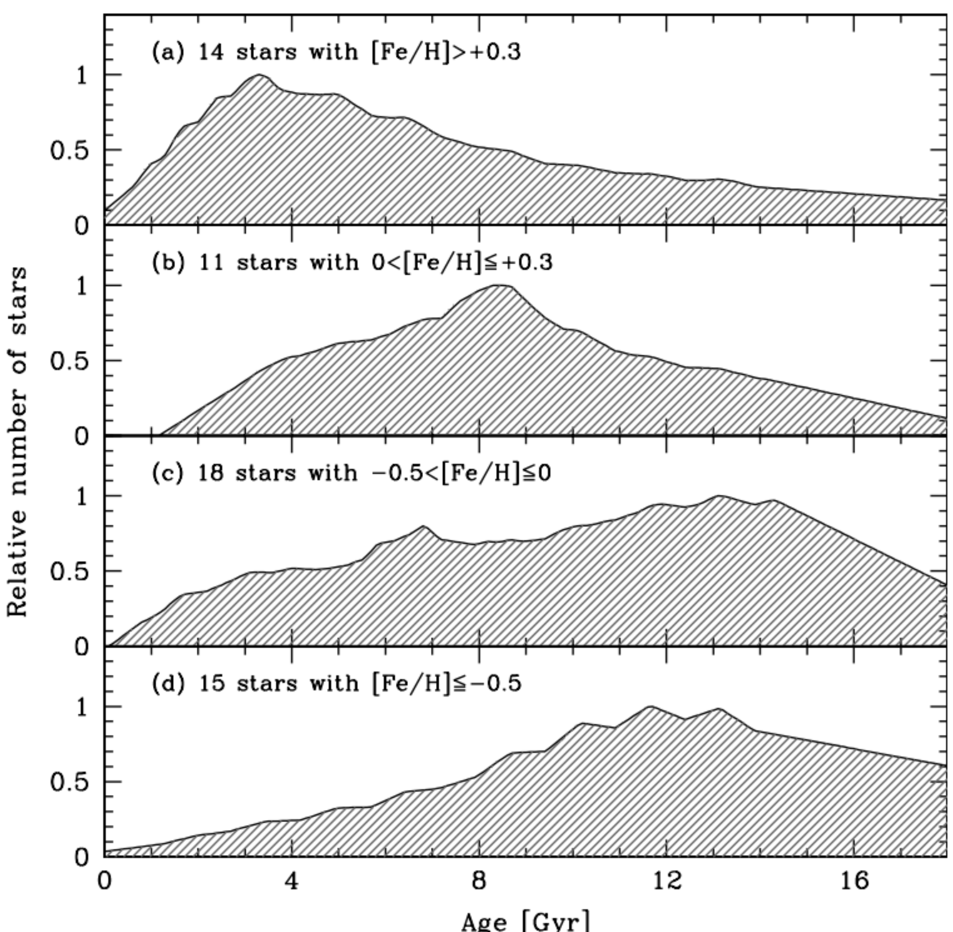


Intermediate age population

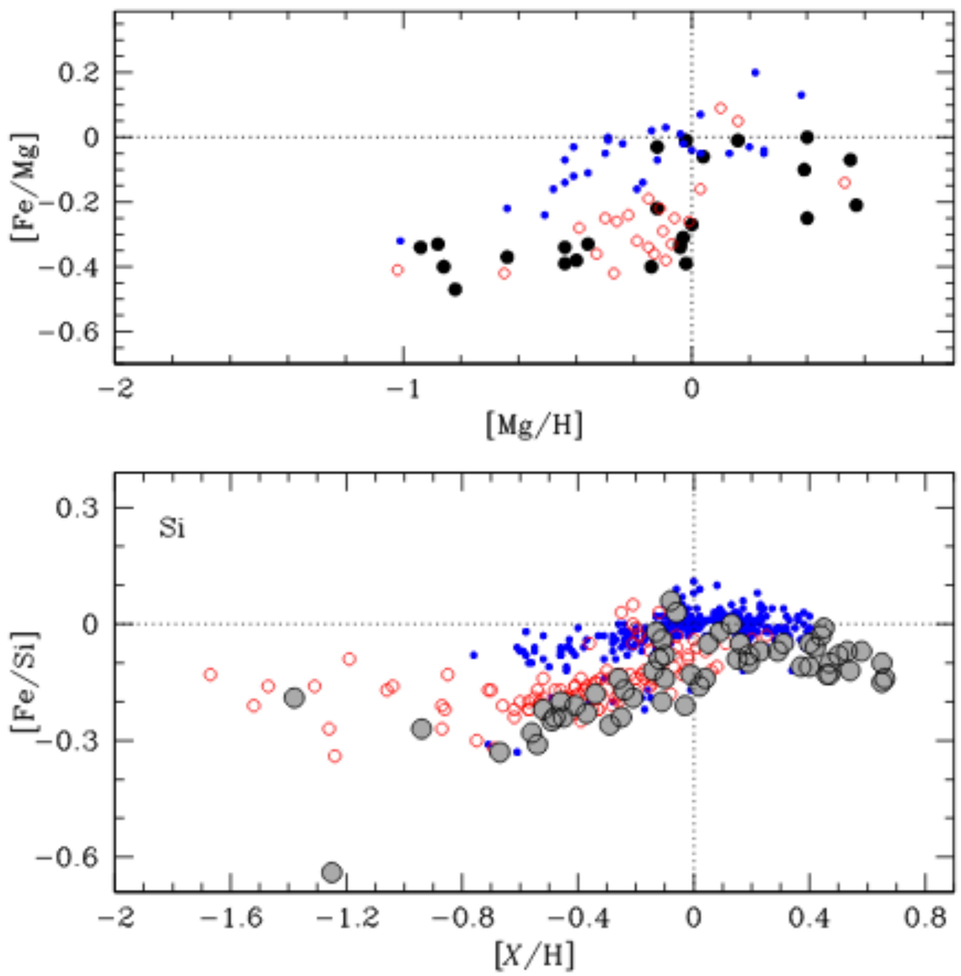
Population dominated by old stellar ages, but dwarfs point to a intermediate age component present in the bulge

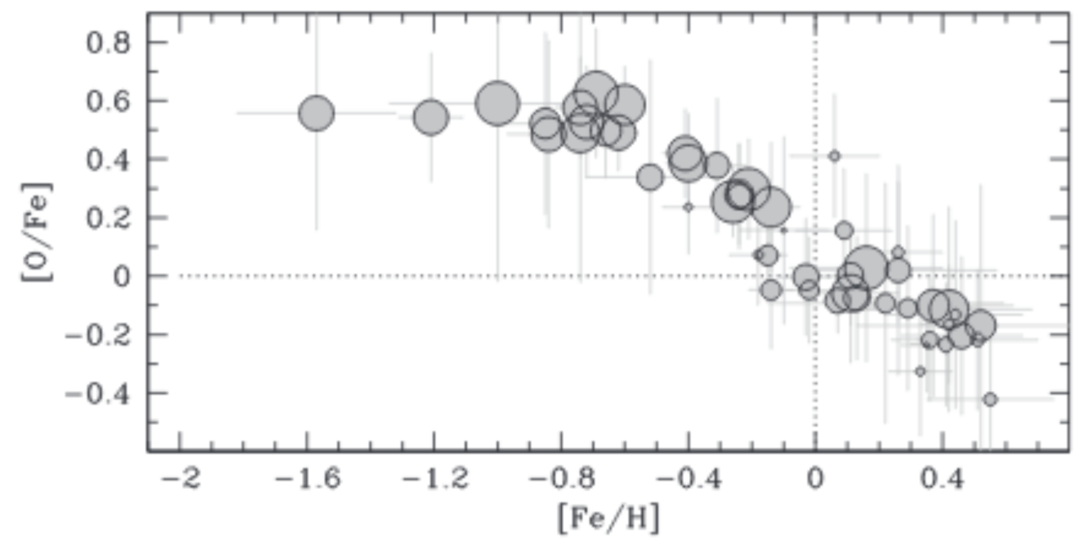




Bensby et al. (2013)

Abundances bulge dwarfs





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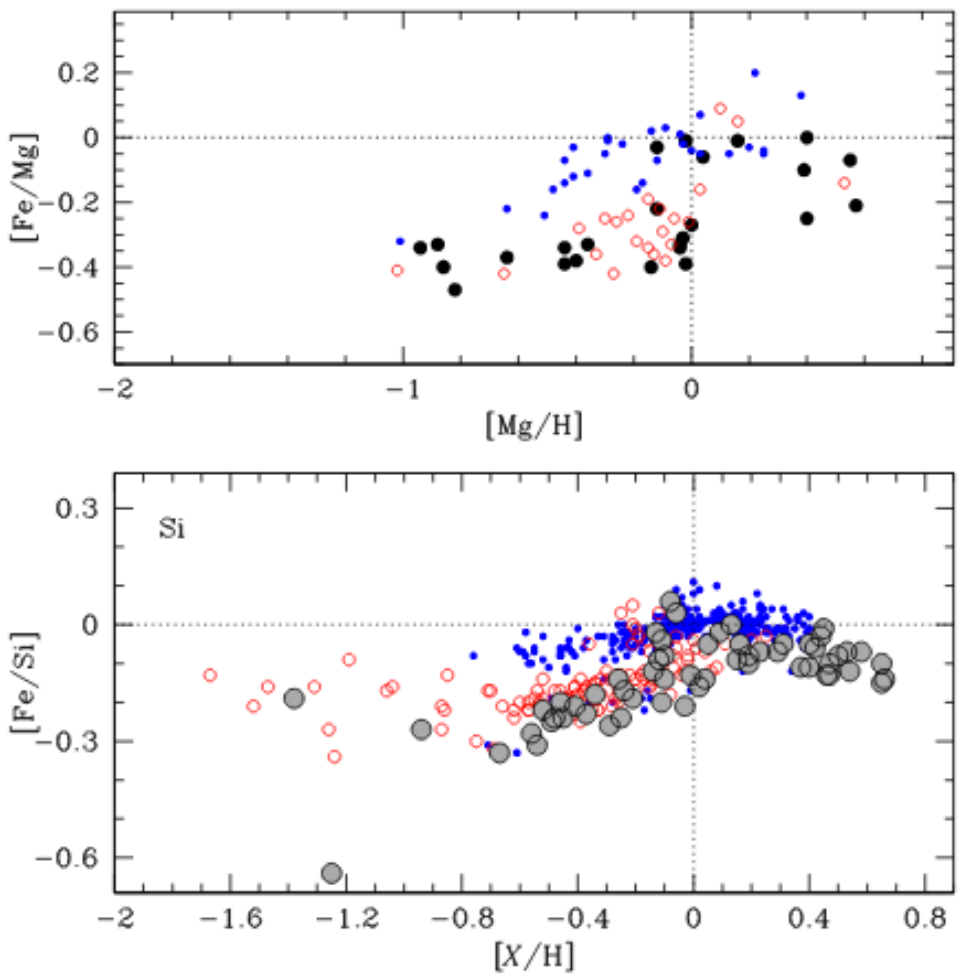

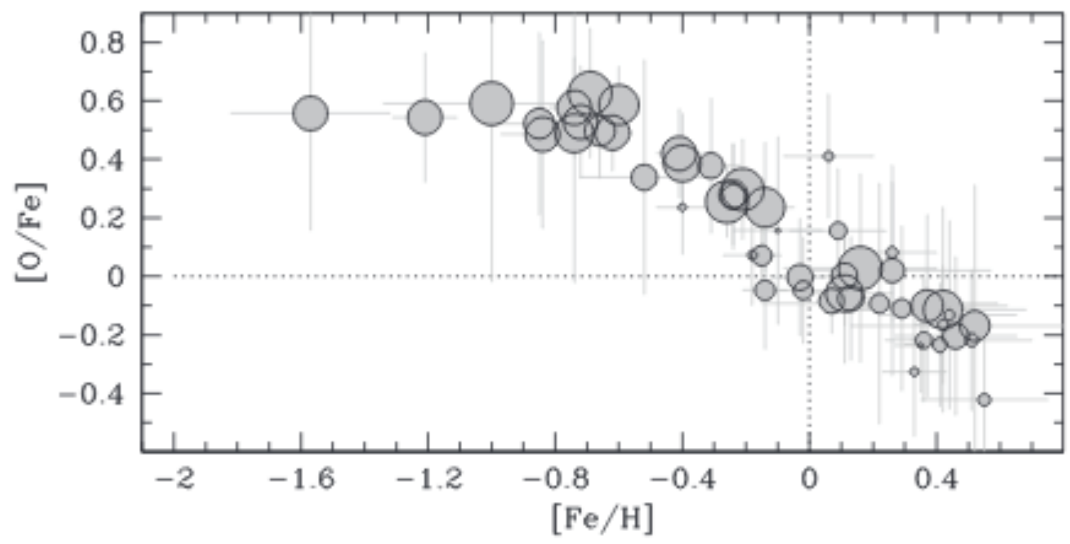

Bensby et al. (2013)

BUT…

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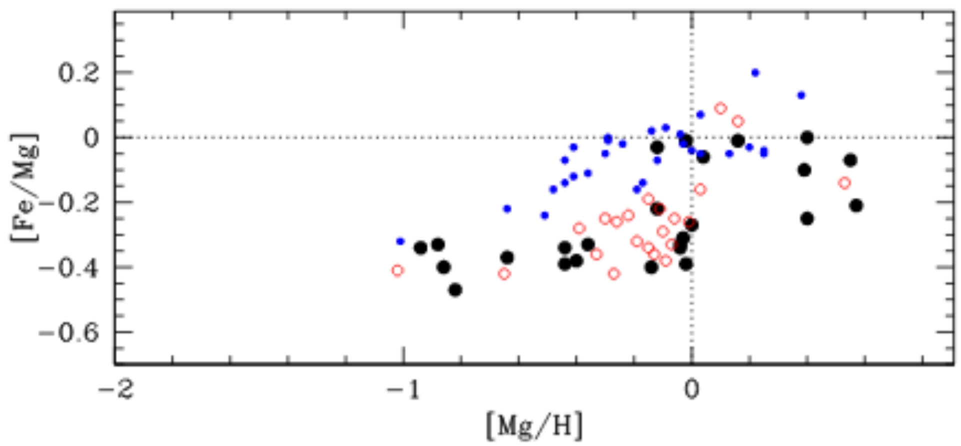

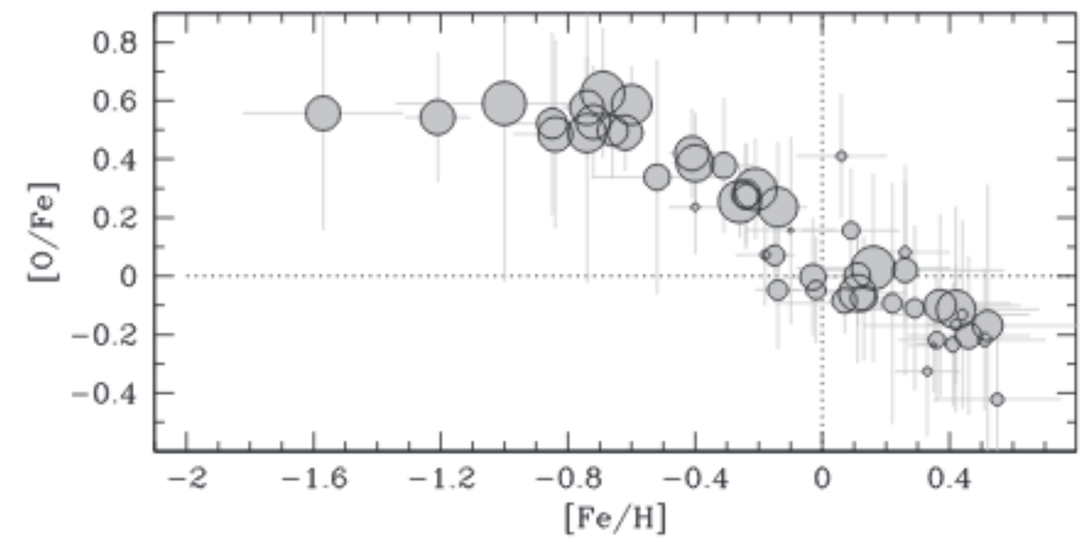

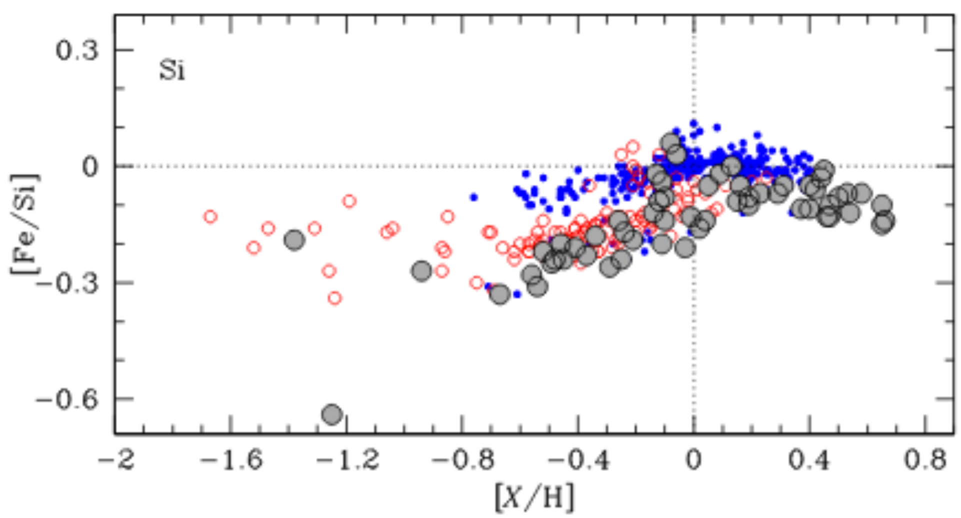

Bensby et al. (2013)

Ryde et al. (2015), Bensby et al. (2011), (2013)

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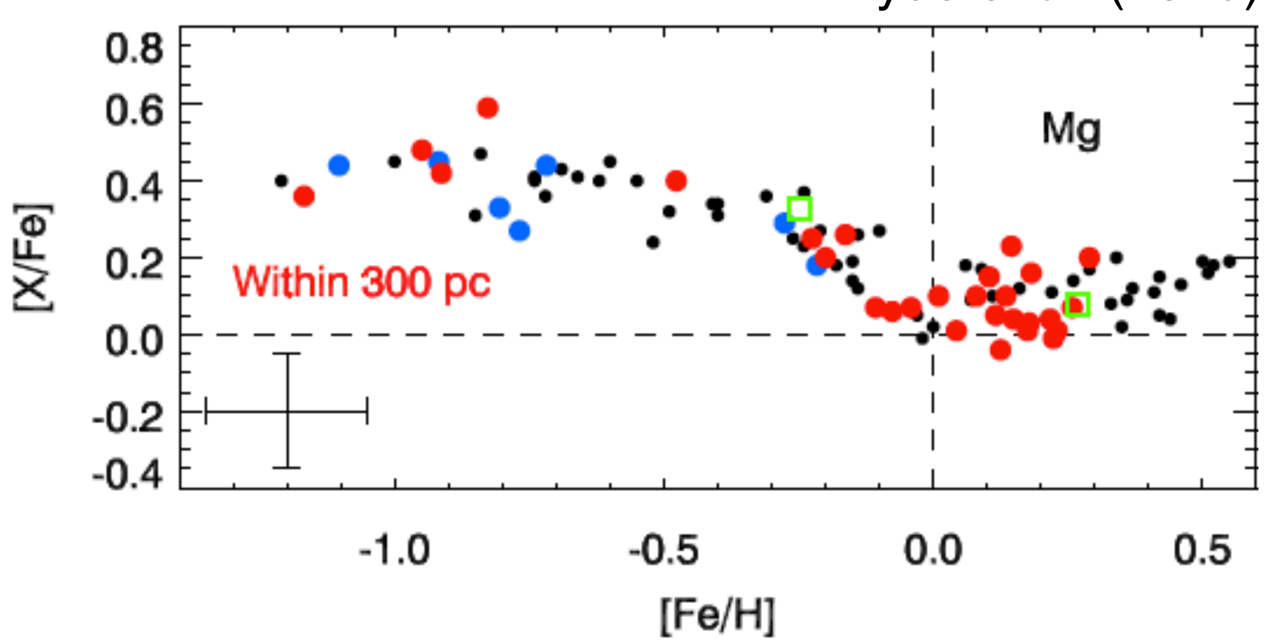
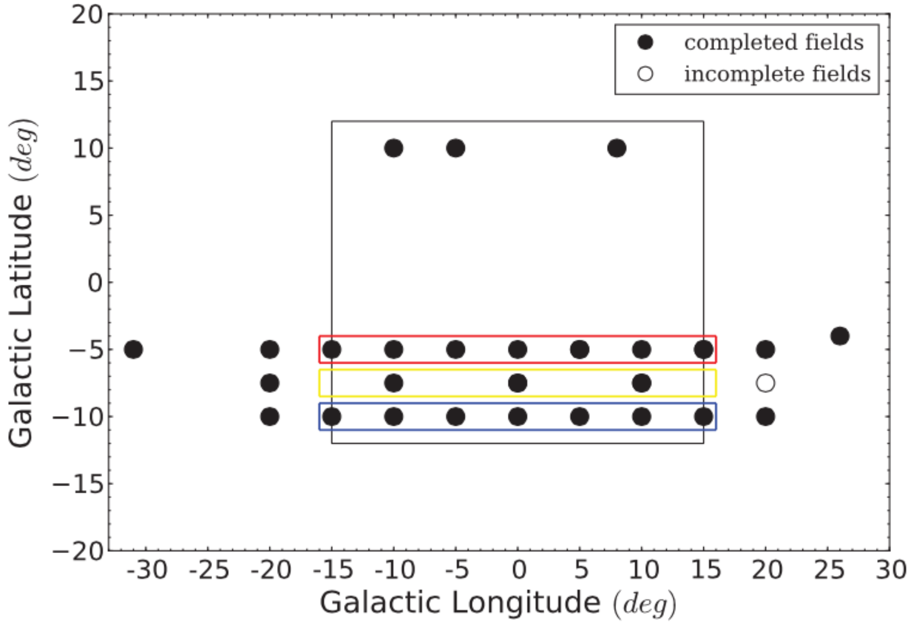


Which one is right?

How many bulge populations?



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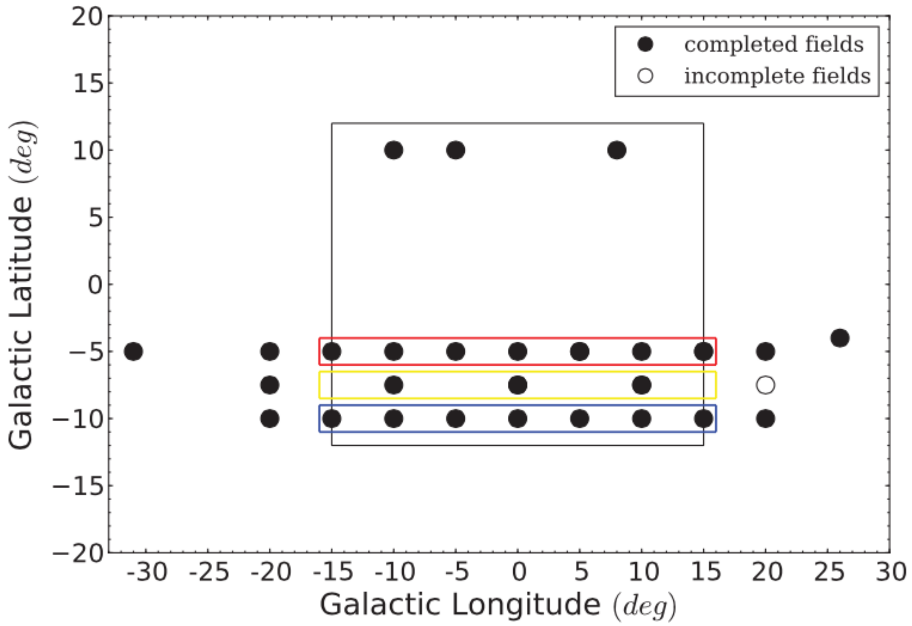

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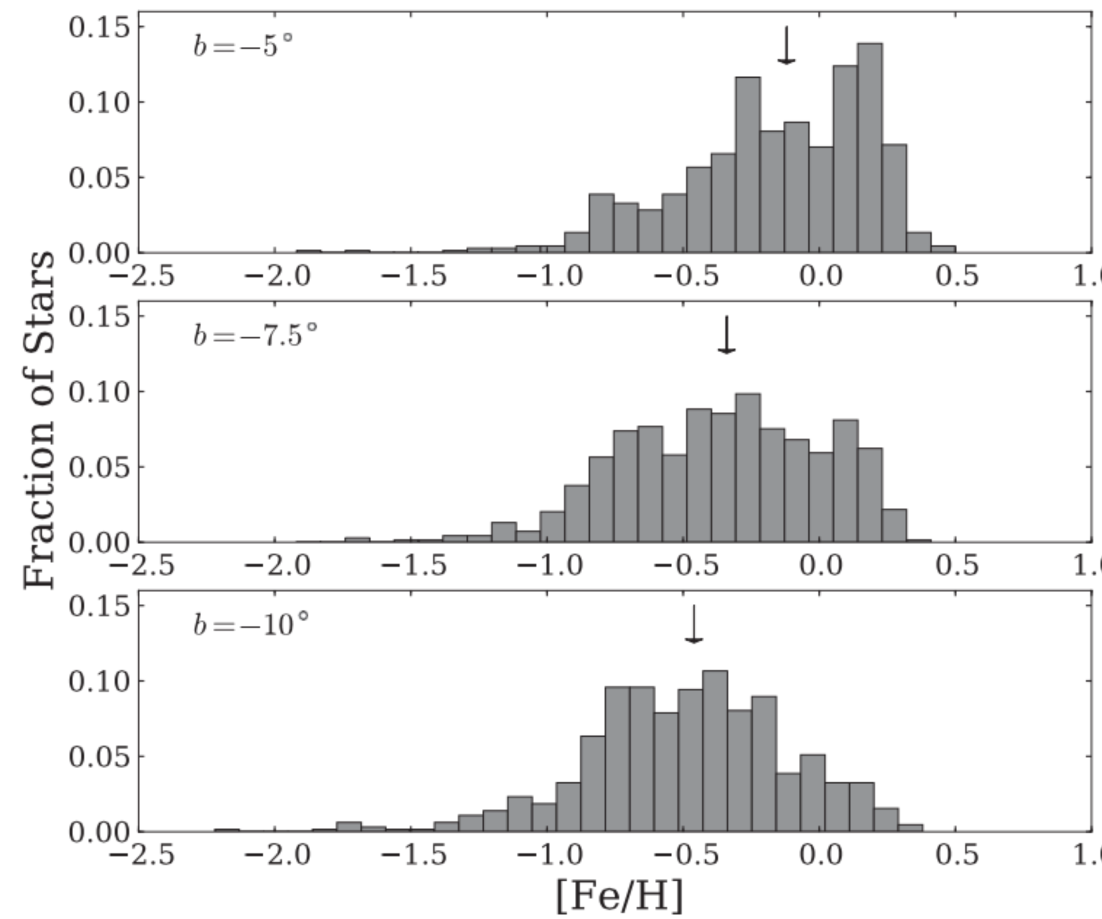
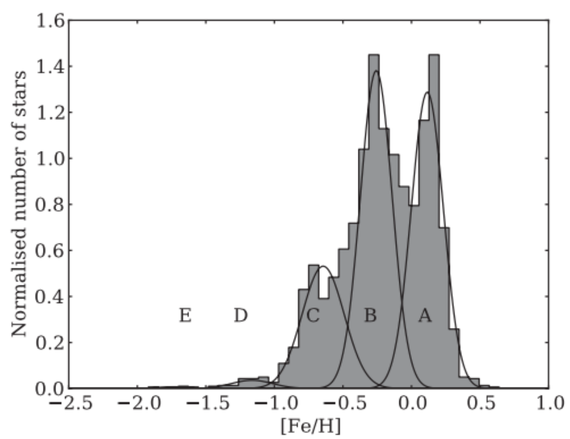
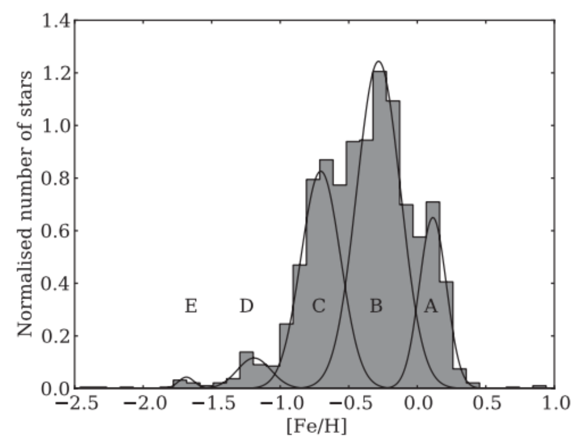
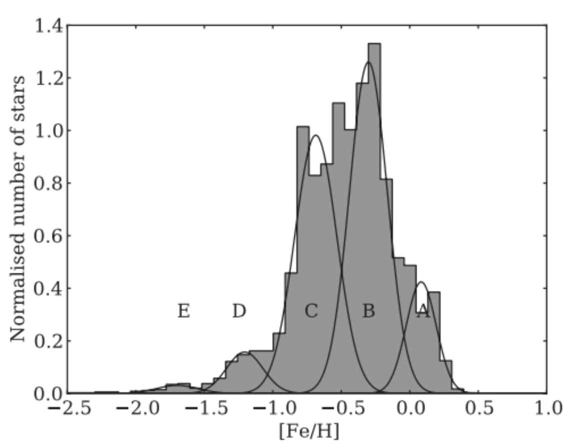




(a) $l \pm 15^\circ, b = -5^\circ$

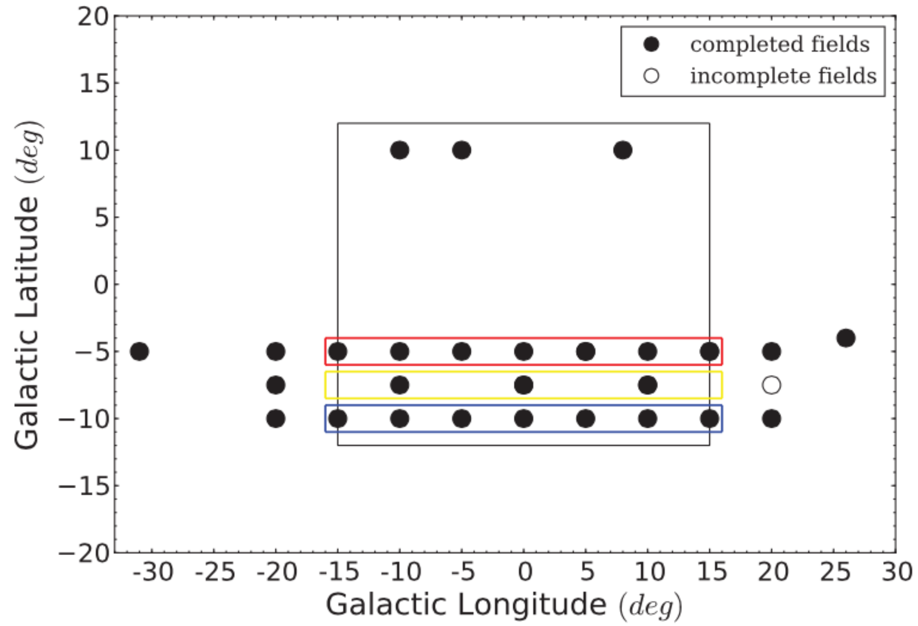


(b) $l \pm 15^\circ, b = -7.5^\circ$

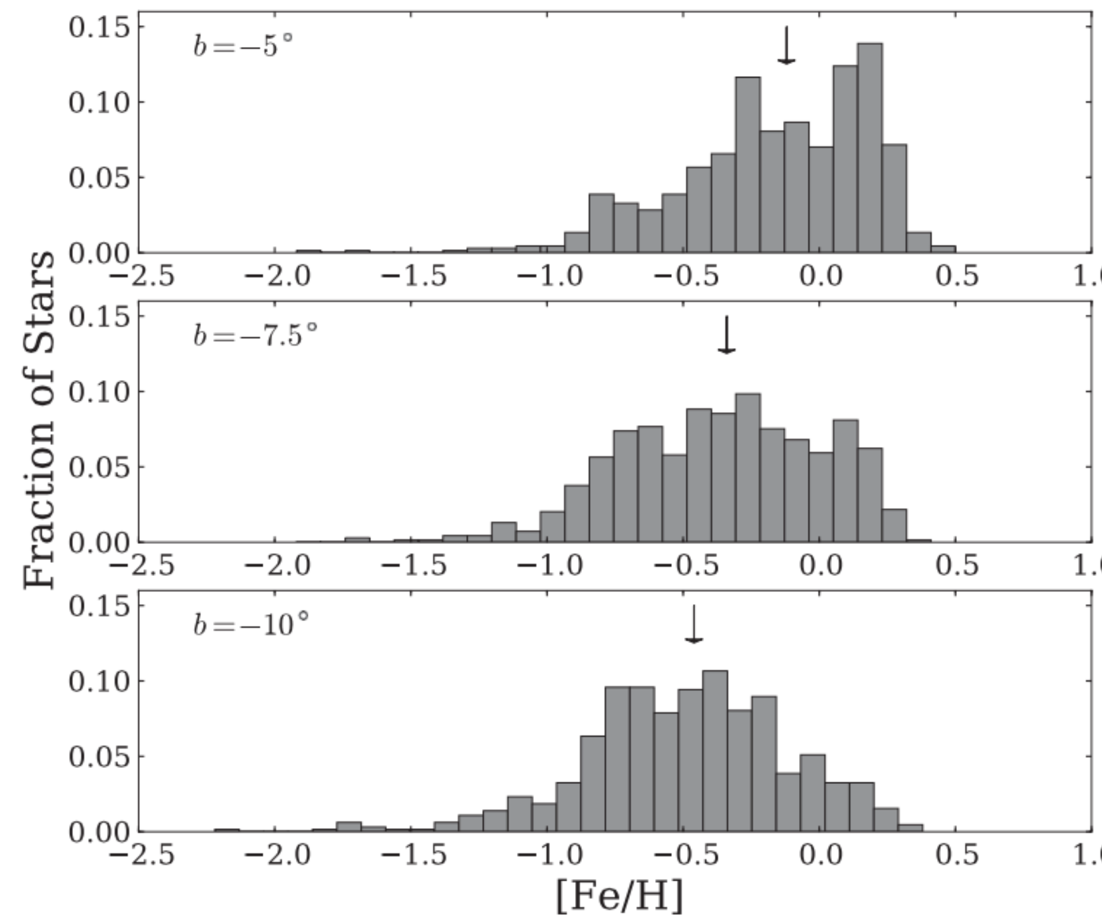


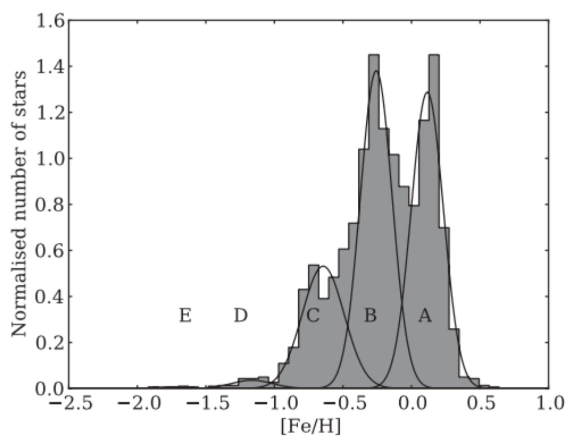
(c) $l \pm 15^\circ, b = -10^\circ$

How many bulge populations?

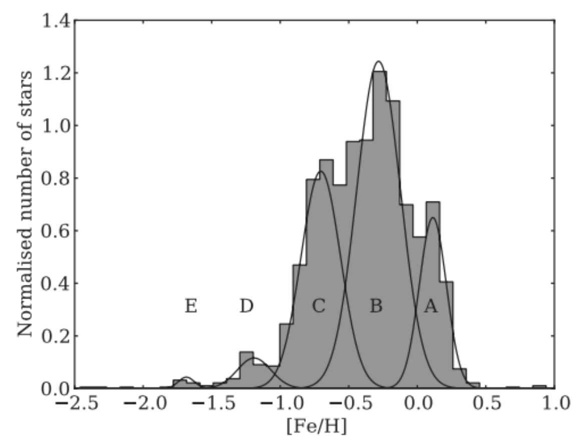


Ness et al. (2012)





(a) $l \pm 15°, b = -5°$



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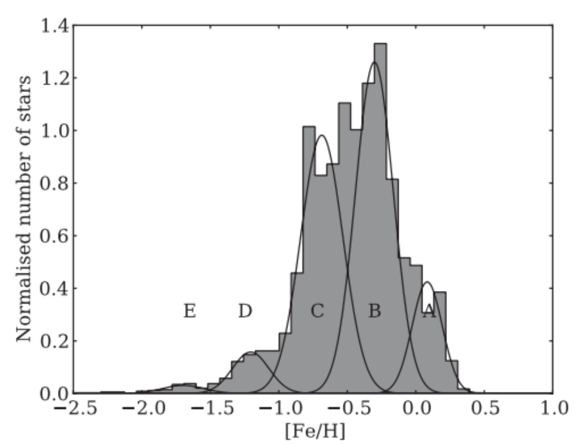

(c) $l \pm 15°, b = -10°$

A: [Fe/H] ~ +0.15 boxy-bulge component, concentrated towards the plane
B: [Fe/H] ~ -0.25, vertically thicker boxy-bulge
C: [Fe/H] ~ -0.70, inner thick disk
D: [Fe/H] ~ -1.20, tentatively a metal-poor thick disk
E: inner Galactic halo

Some standing issues…

1)metal-poor bulge has different pattern from thick disk?

2)how much fraction (significant?) of metal-rich pop is young?

3) bulge has distinct chemodynamical subpop based on structure, kinematics, ecc.. ?

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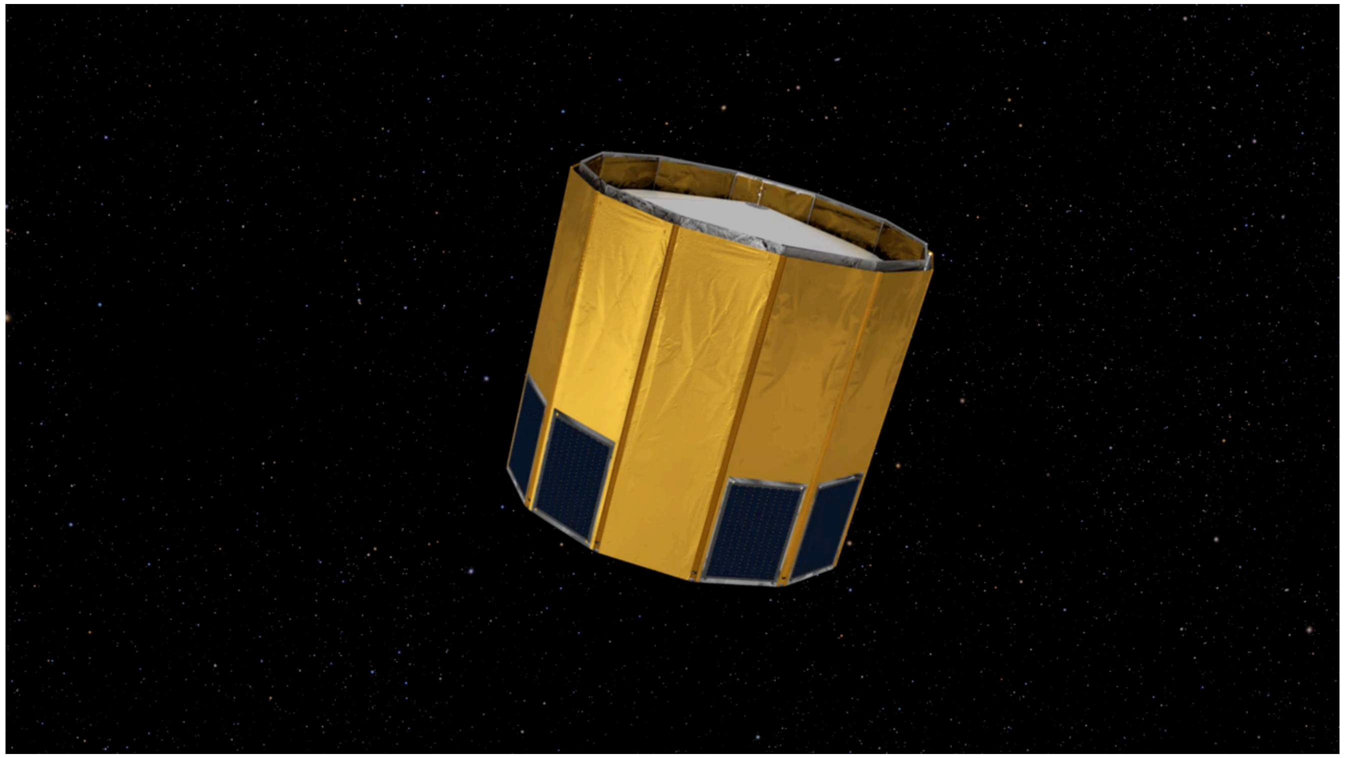
More observations needed!!!

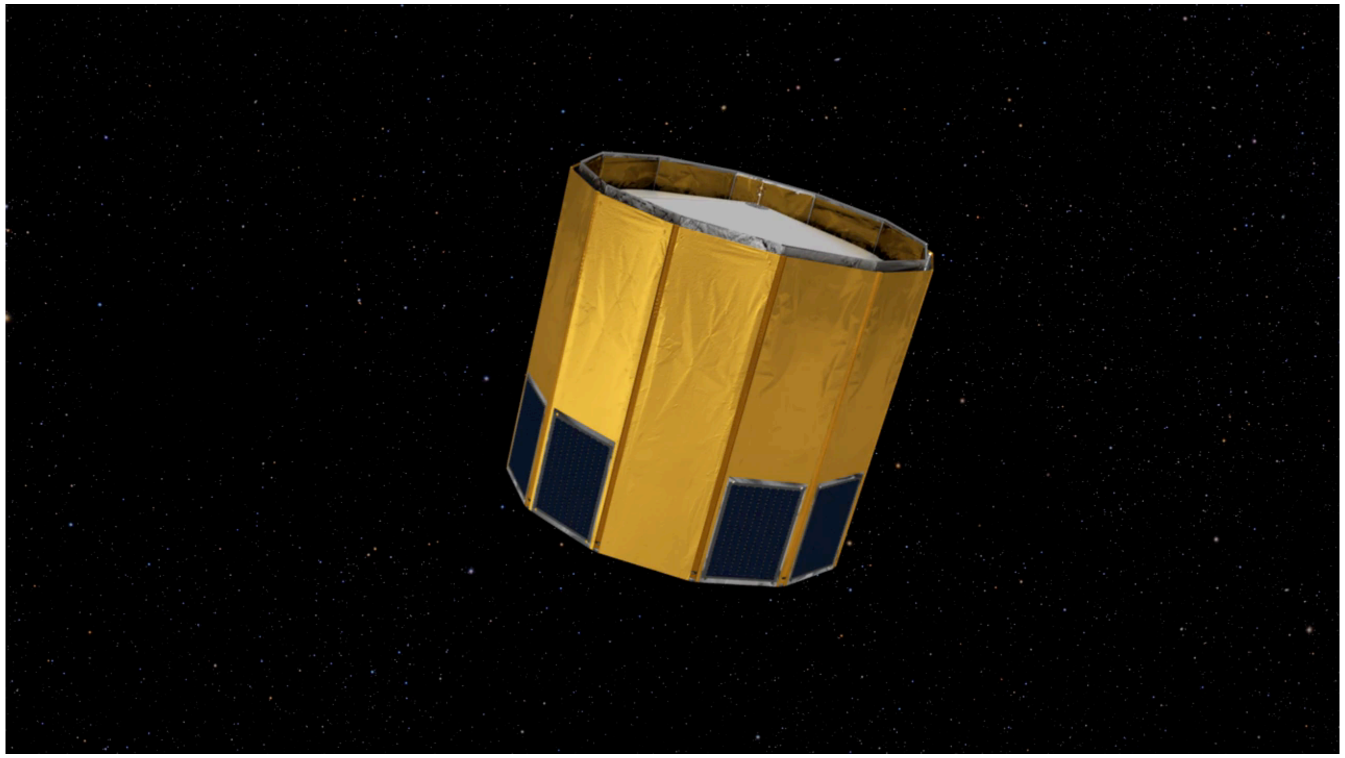
Age of Galactic surveys

Gaia



The all-sky survey of about one billion stars

Gaia



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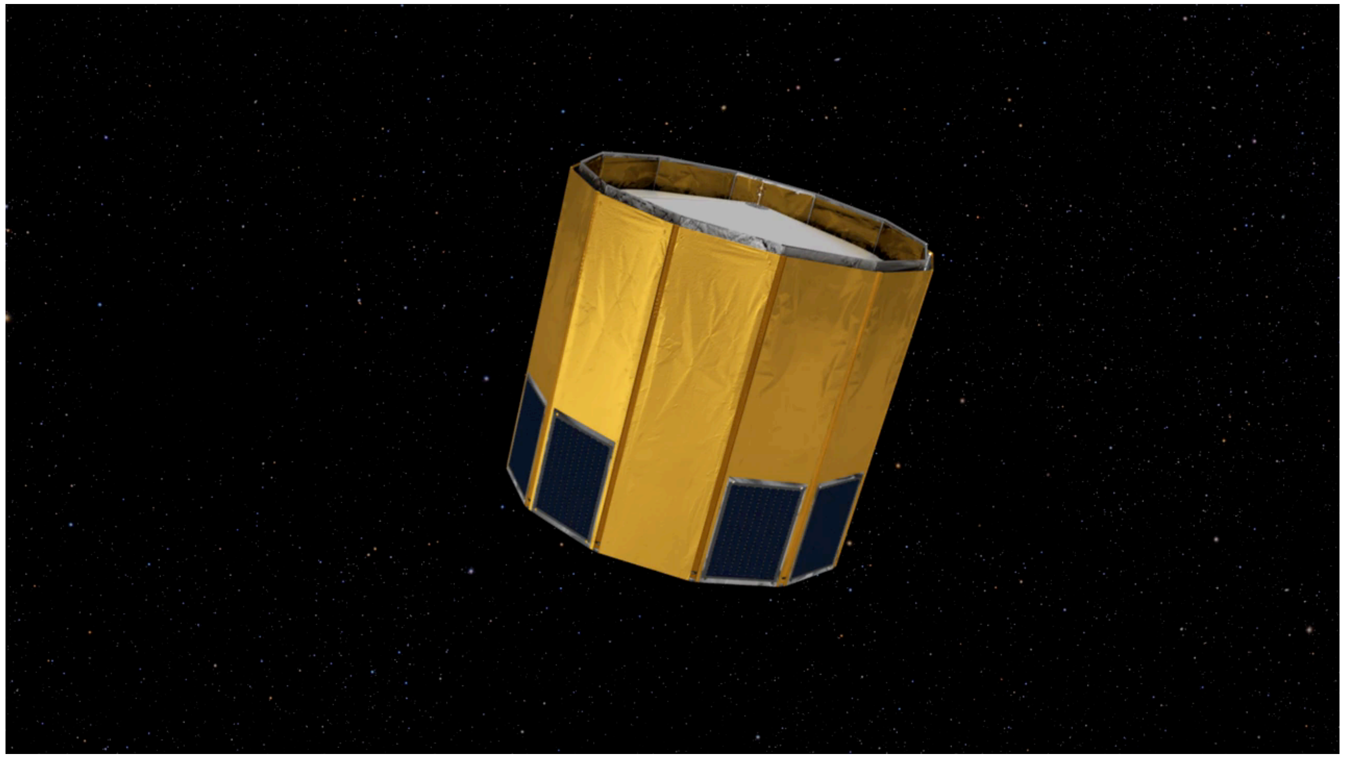


The all-sky survey of about one billion stars

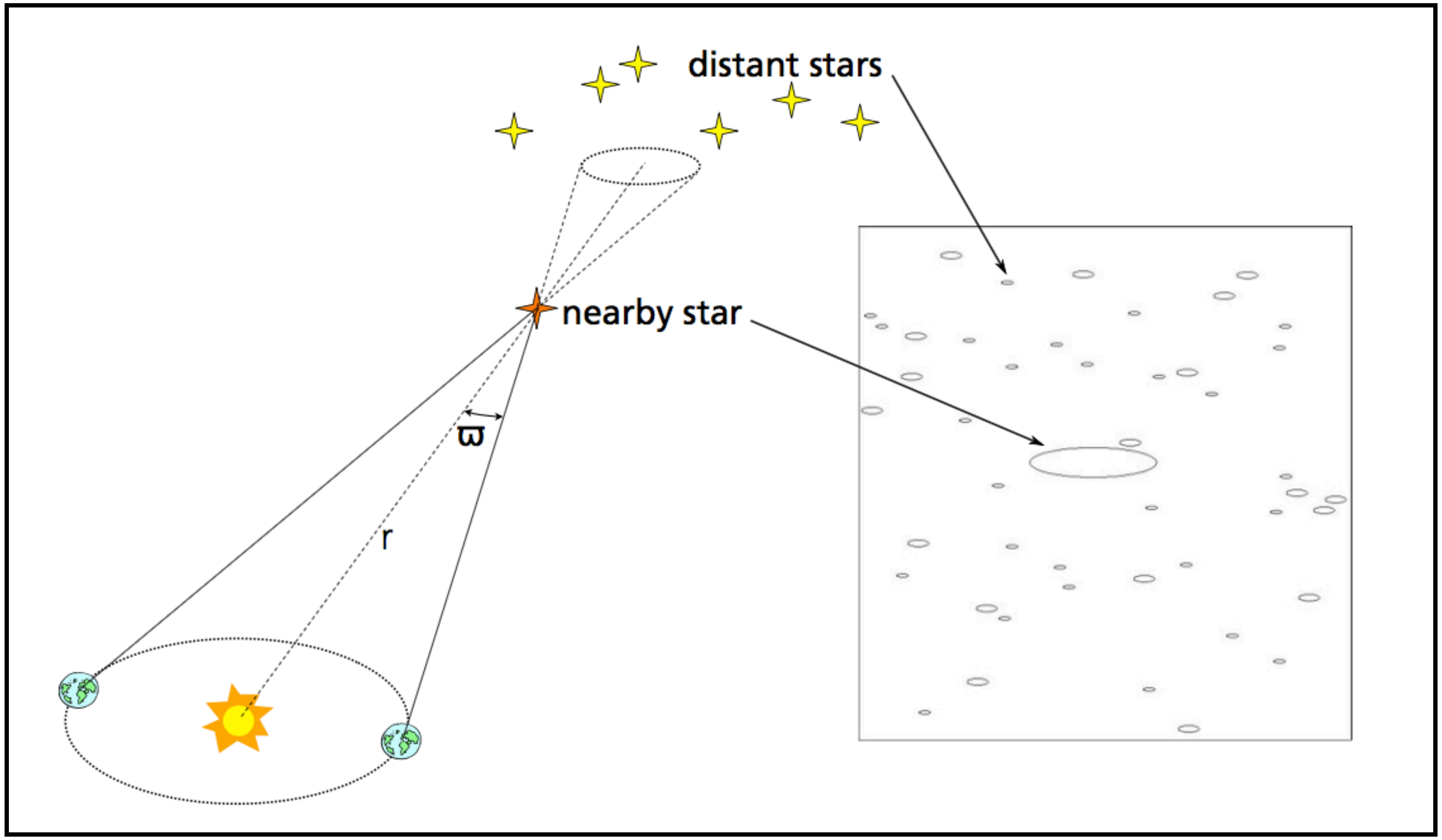
ASTROMETRY → measurements of stellar position, parallax and proper motion

PHOTOMETRY → measurement of magnitudes in different bands and epochs

SPECTROSCOPY → acquisition of radial velocities and astrophysical parameters

How Gaia works

Gaia measures parallaxes of stars



How Gaia works

Gaia measures parallaxes of stars

Simulations of the real parallax effect, 150000x exaggerated" (D.Michalik & Stellarium)

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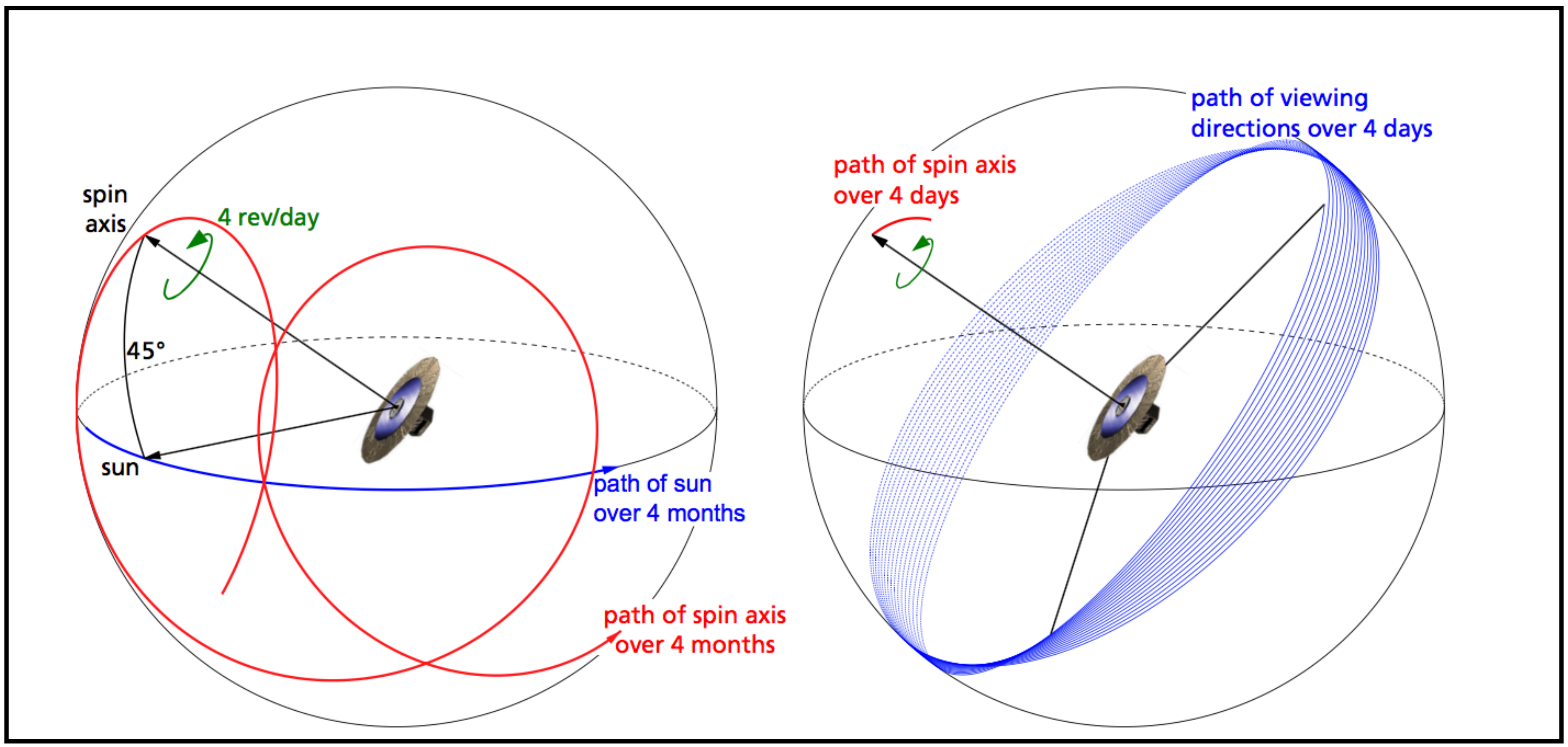
Gaia is spinning slowly to make four complete rotations per day pointing at two different portions of the sky (separated by 106.5º).
Meanwhile its spin axis precesses around the Sun with a period of about 64 days.
The spacecraft spin axis makes an angle of 45° with the Sun direction ensuring that the payload is shaded.



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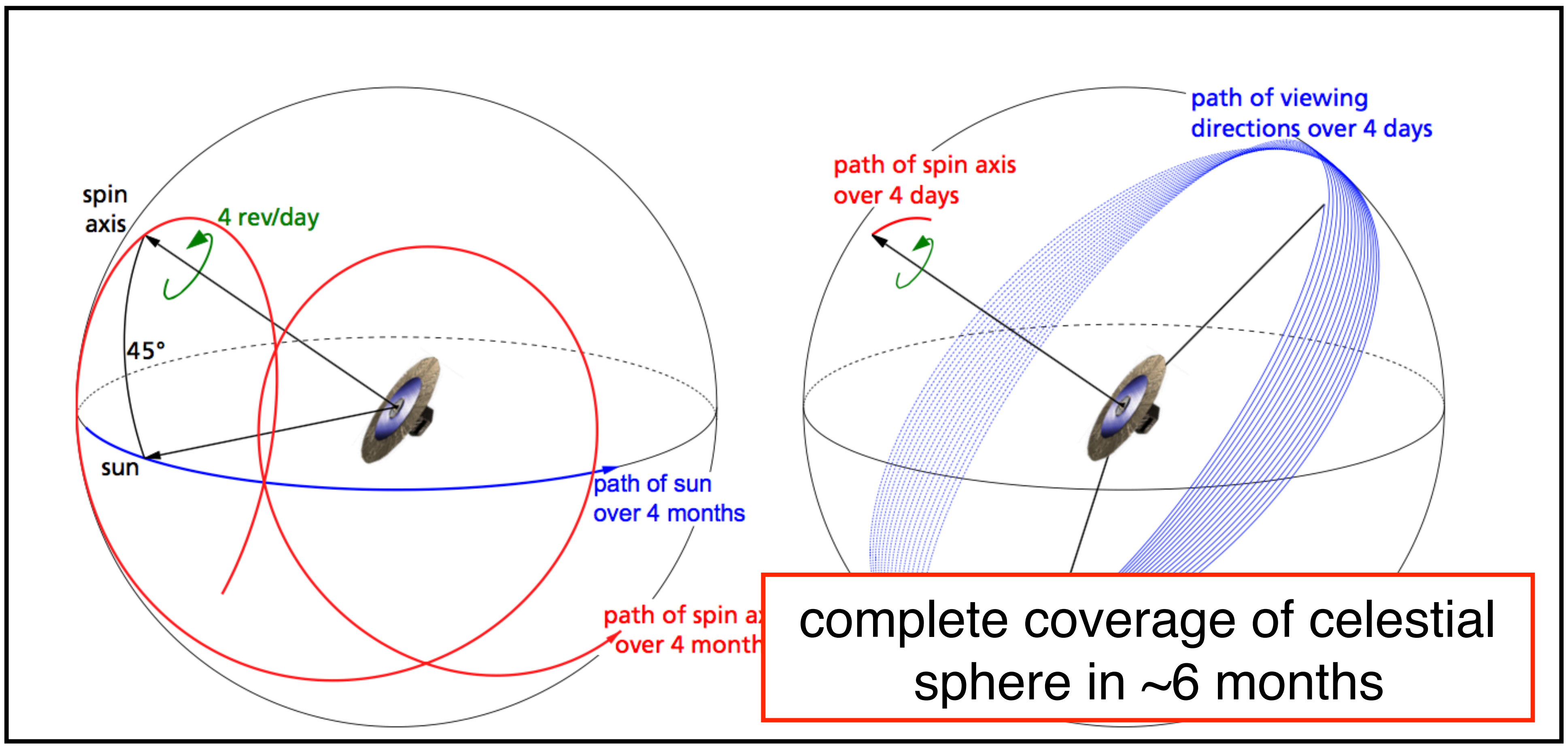

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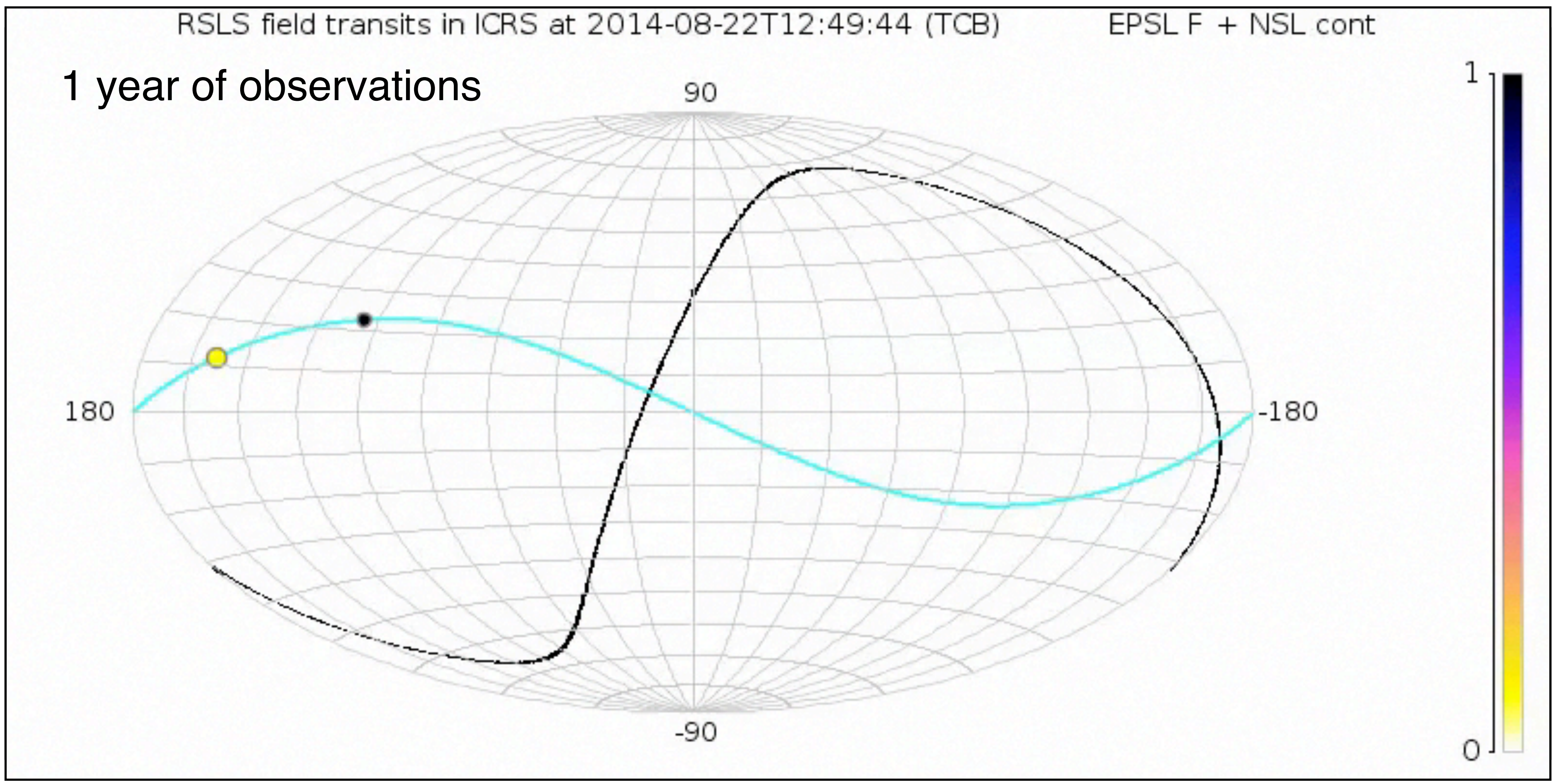

credit D. Michalik & Gaia DPAC

How Gaia works

Gaia is spinning slowly to make four complete rotations per day pointing at two different portions of the sky (separated by 106.5º).
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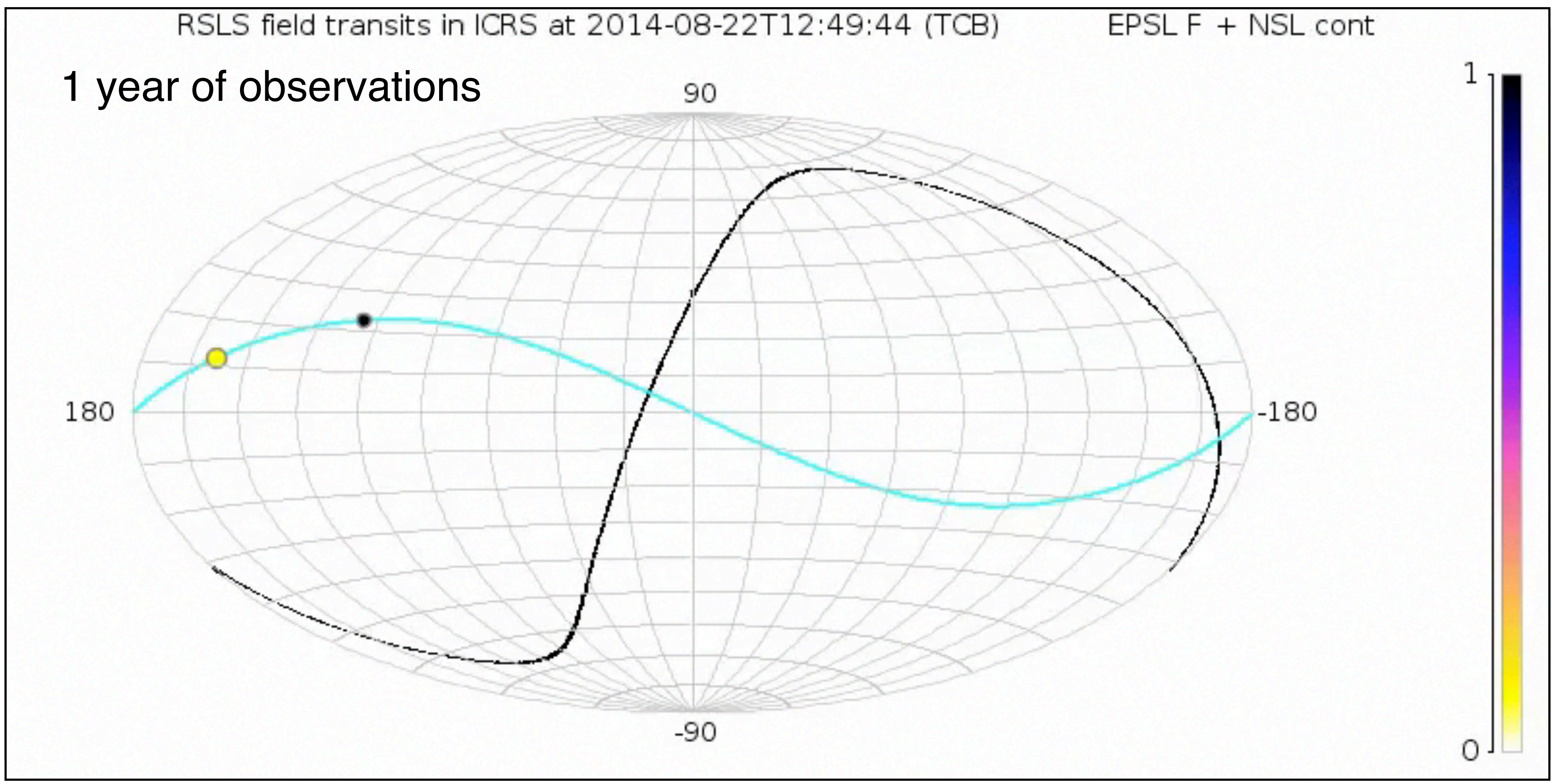

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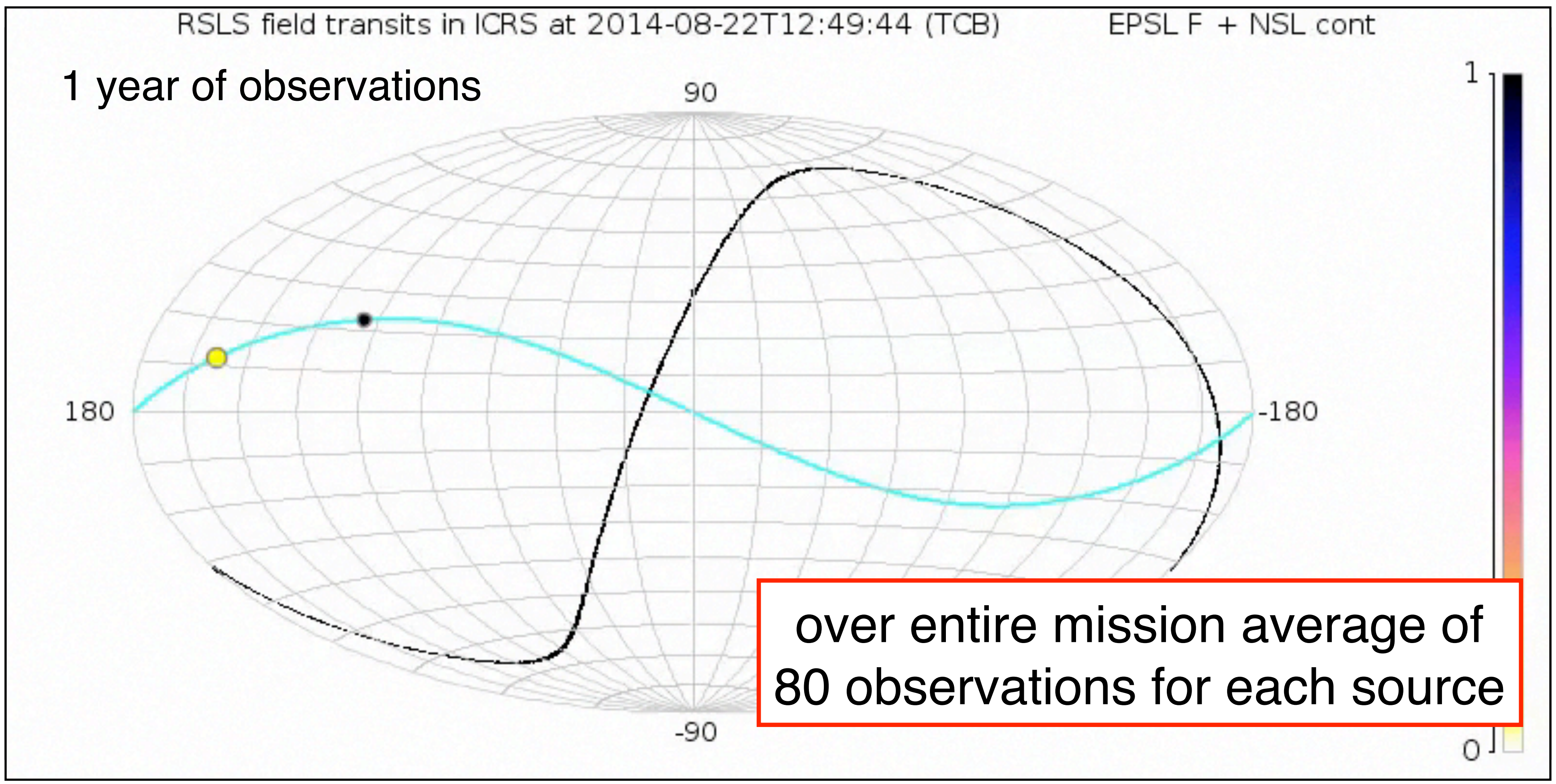
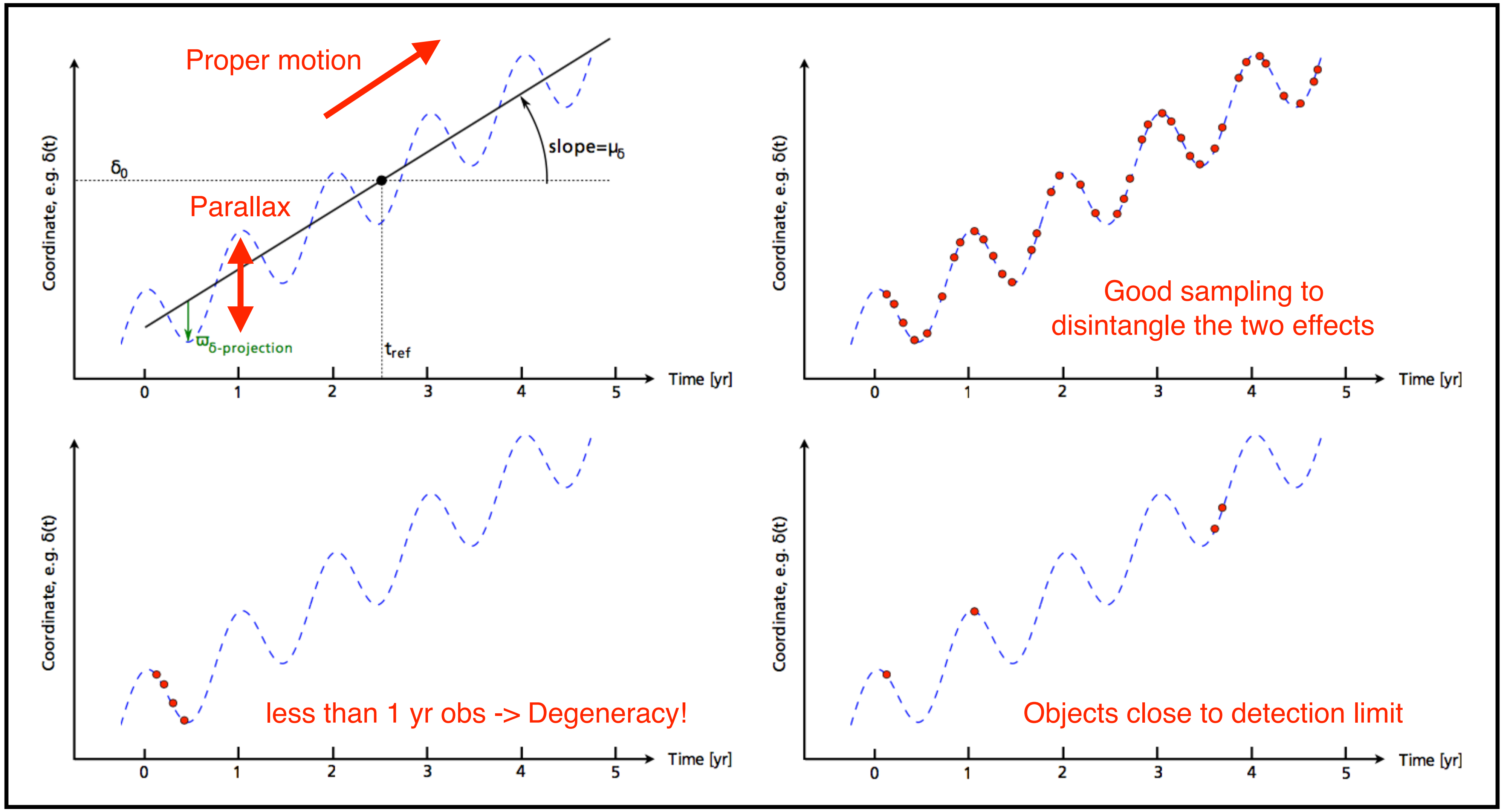


credit D. Michalik & Gaia DPAC

How Gaia works

Gaia is providing systematic and repeating observation of star positions in two fields of view.
This scanning strategy builds up an interlocking grid of positions, providing absolute values of the stellar positions and motions.



credit D. Michalik & L. Lindegren

To have a feeling…

Alpha Centauri

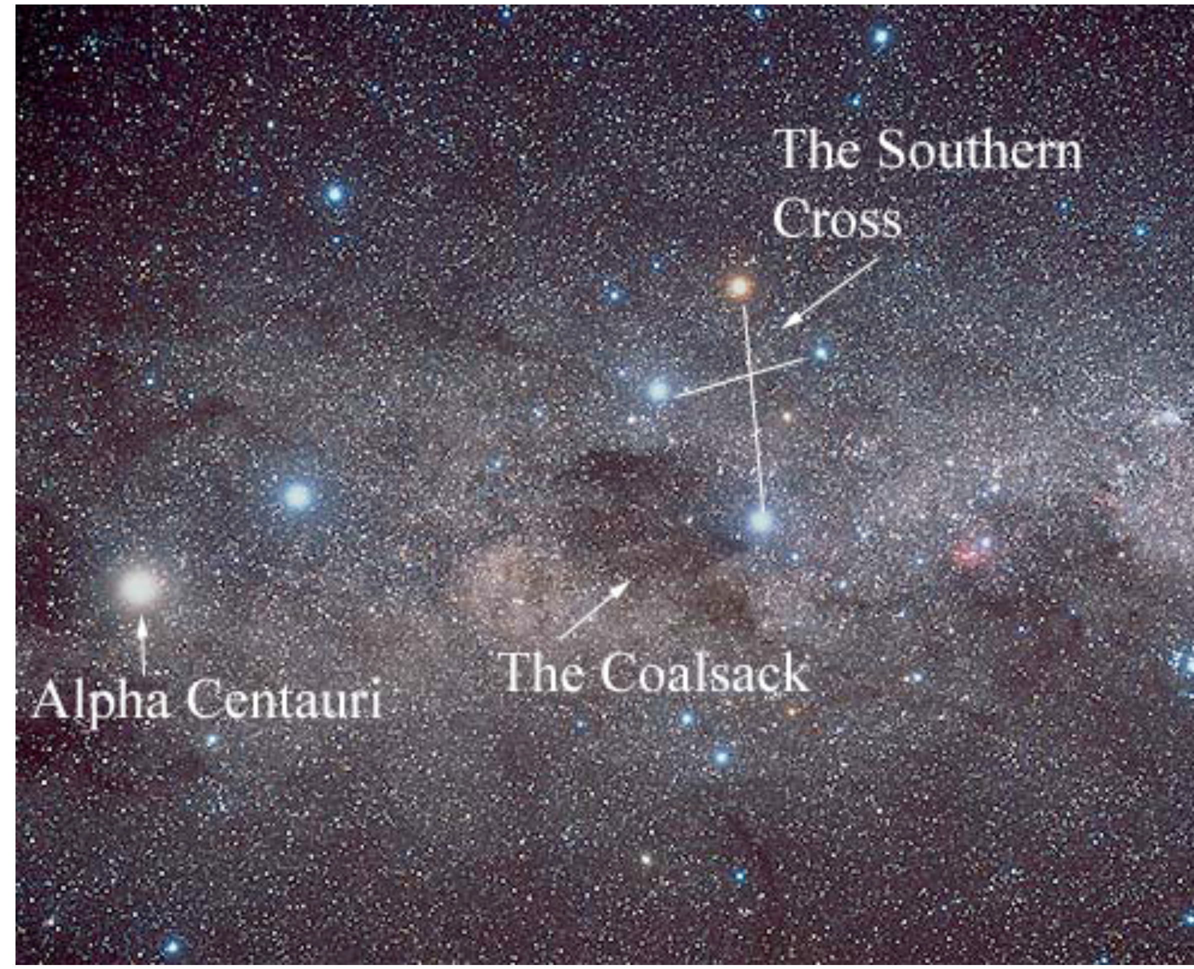
parallax 0.75”

~2500 times smaller than angular size of Moon (~0.5°)

1°= 3600”

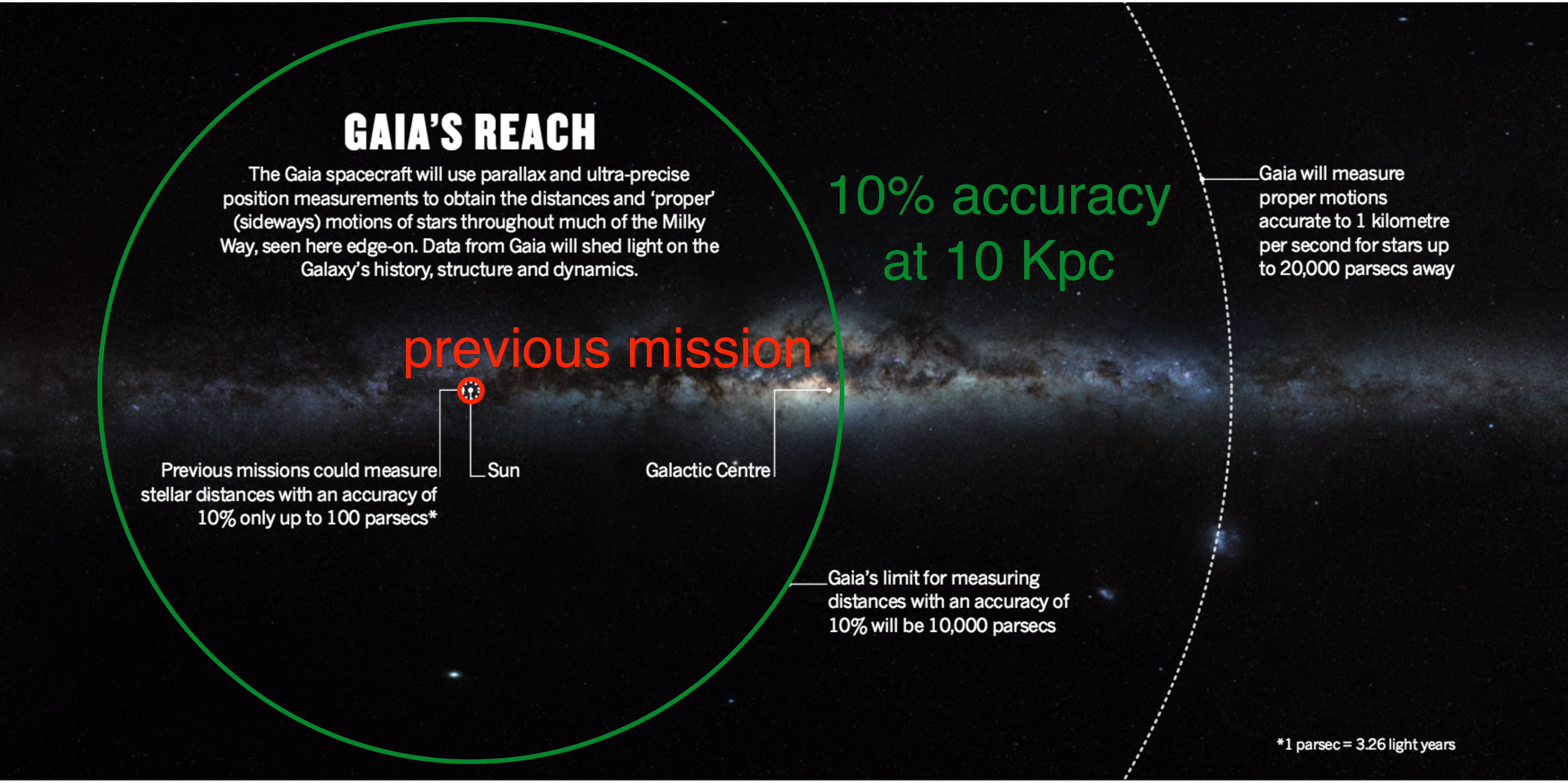
4.37 ly, 271000 times Earth-Sun distance (150 million km, 1 AU)

Stars in our Galaxy up to 20000 times further away



Akira Fujii / David Malin image

Gaia's view



modified from ESA

Gaia's view

	Mag limit in G	# of stars
Micro-arcsecond astrometry	~20	> 1000 millions stars
Radial velocities	16	~150 million stars
Stellar Parameters	12	~5 millions stars
Elemental abundances	11	~2 millions stars

Gaia's view

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Gaia

2-D → 3-D → 5-D

Position | Parallax | Proper Motions

Ultra-precision, over years | Distance | Transverse velocities

Gaia’s timeline

First release	Summer 2016	• Positions and G mag for stars with acceptable formal standard errors • 5 param solution for stars in common with Tycho-2 catalogue
Second release	Summer 2017	• 5 parameters astrometic solution single-stars • Photometry + errors for sources with verified astrophysical parameters • Mean RV for sources with no RV variations

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Final release	2022 (TBC)	• Full astrometric, photometric, and radial-velocity catalogues. • All available variable-star and non-single-star solutions. • Source classifications (probabilities) • An exo-planet list. • All epoch and transit data for all sources.

Gaia's timeline

First release	Summer 2016	• Positions and G mag for stars with acceptable formal standard errors cho-2 catalogue
Second release		astrophysical
Final release		ocity catalogues. solutions.

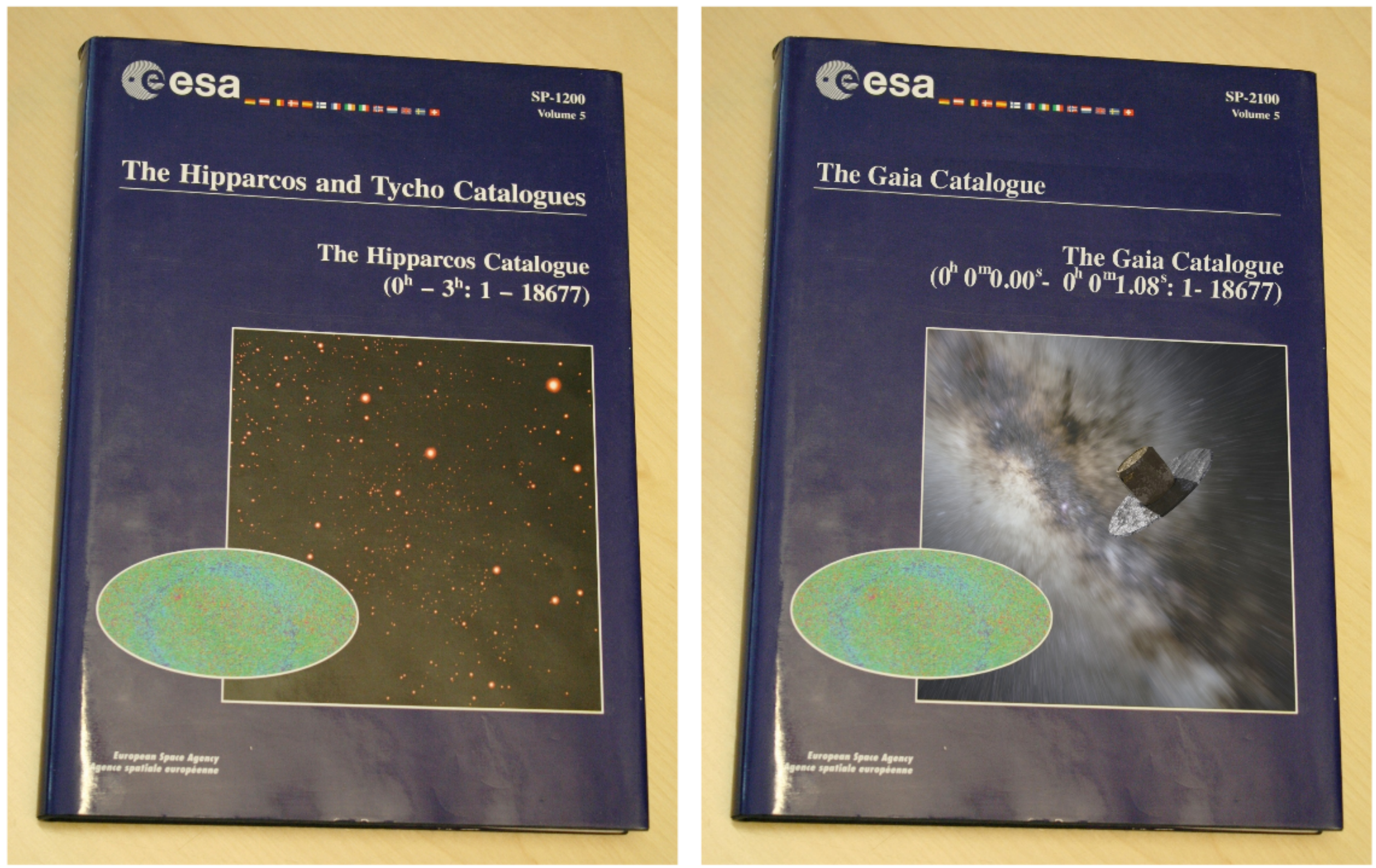
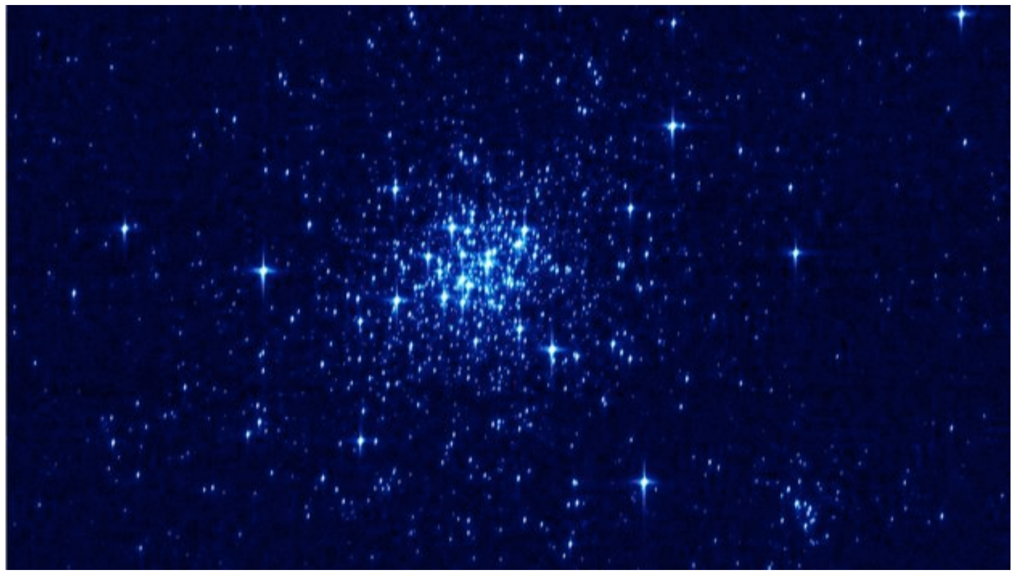


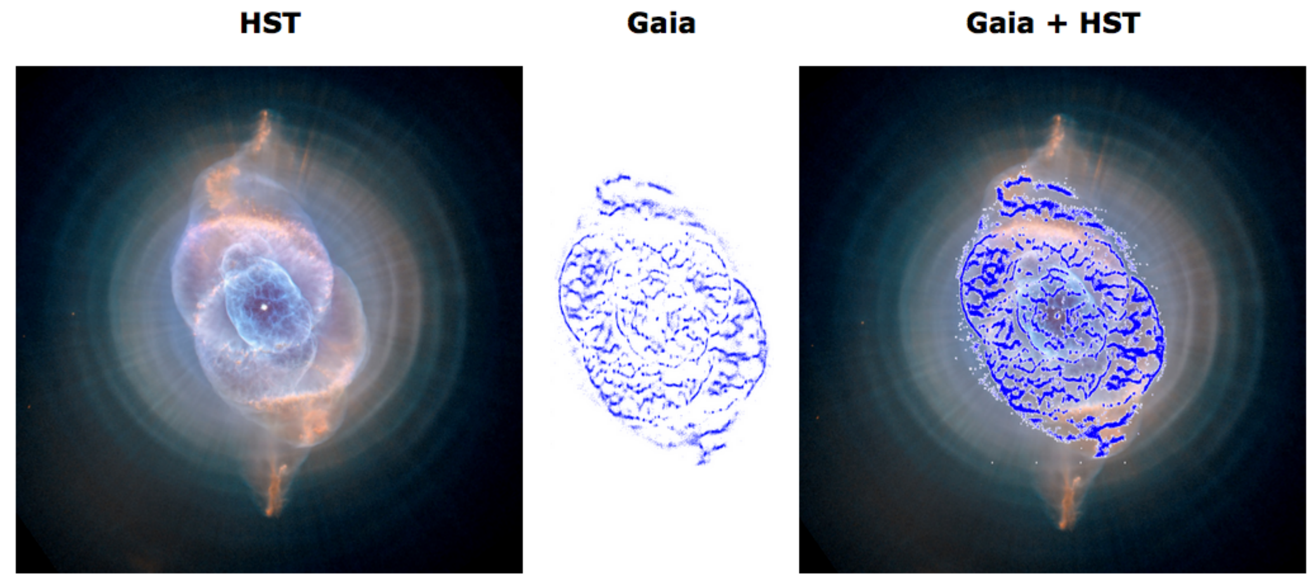
Figure 1.1: Comparison of the Hipparcos and Gaia catalogues. **Left:** The first volume (out of five) of astrometric data in the Hipparcos Catalogue, in total containing the five astrometric parameters of nearly 120 000 sources. **Right:** (Hypothetical) Gaia astrometric data, volume 1 out of 50 000, in total containing the astrometric parameters of ~1 000 000 000 sources.

credit B.Holl

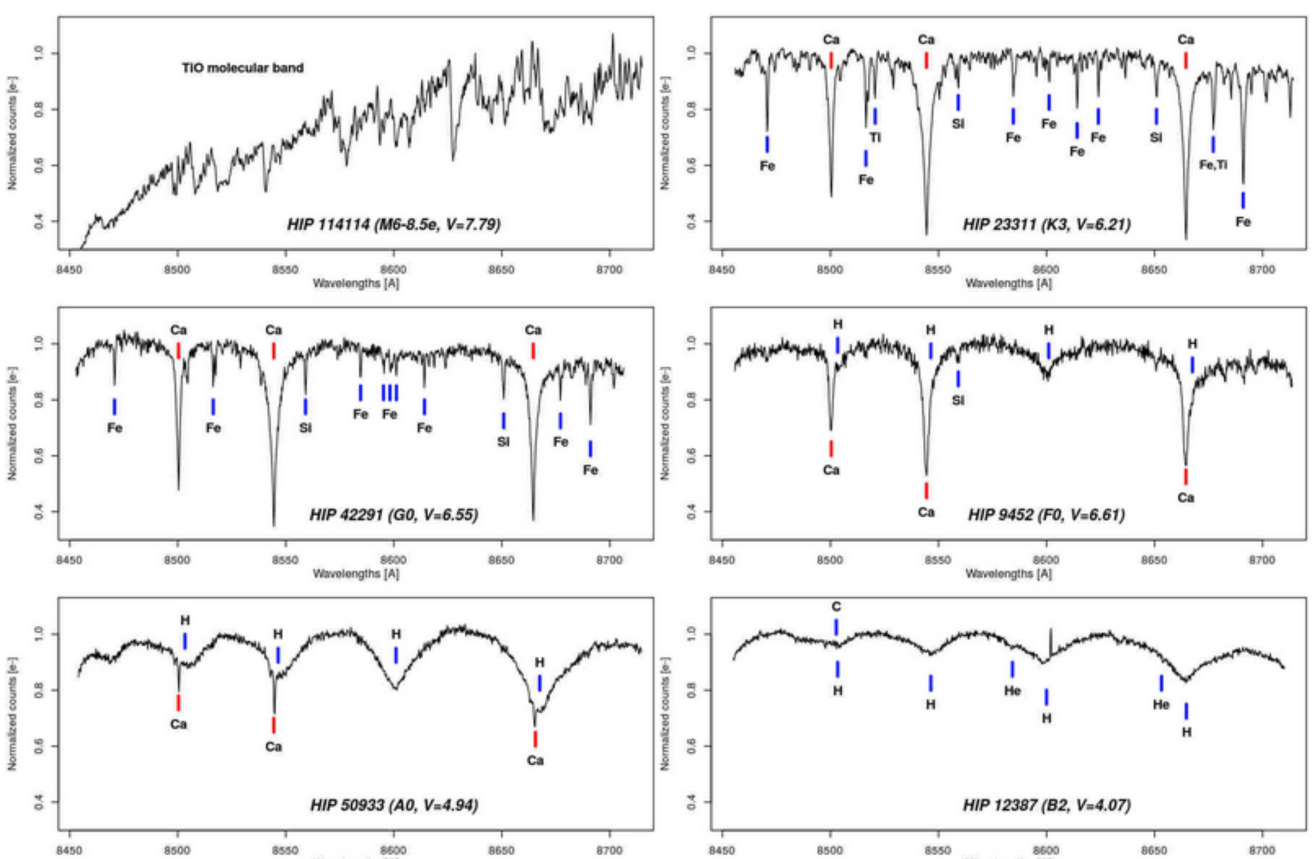
Some images from Gaia



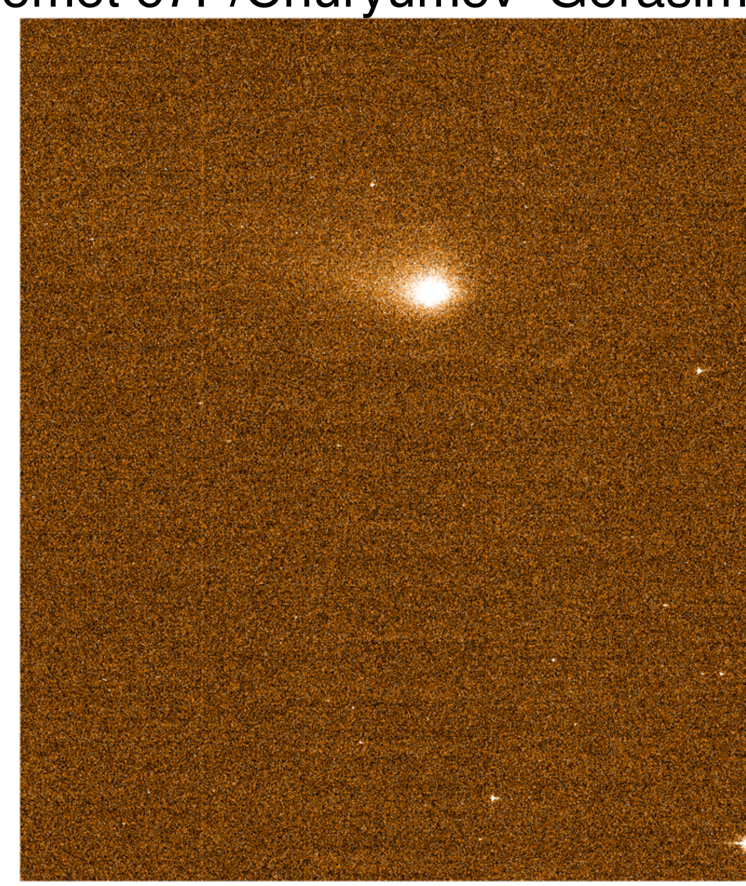
NGC1818

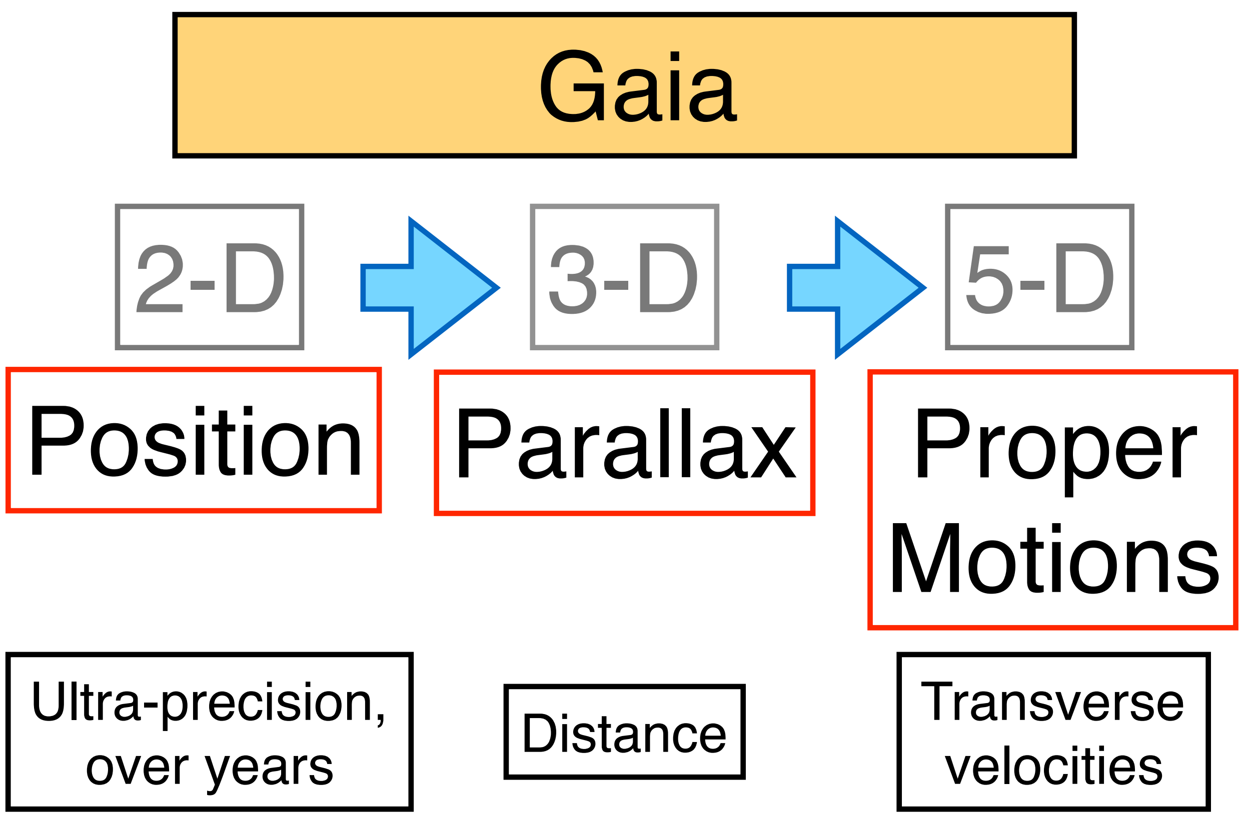


Cat's Eye Nebula



Comet 67P/Churyumov–Gerasimenko




Gaia
2-D
3-D
5-D
Position
Parallax
Proper Motions
Ultra-precision, over years
Distance
Transverse velocities

Gaia			Spectroscopic Surveys	
2-D →	3-D →	5-D →	6-D →	>12-D
Position	Parallax	Proper Motions	Spectrum	Astrophysical parameters
Ultra-precision, over years	Distance	Transverse velocities	Radial velocity + abundances	Ages, histories, astrophysics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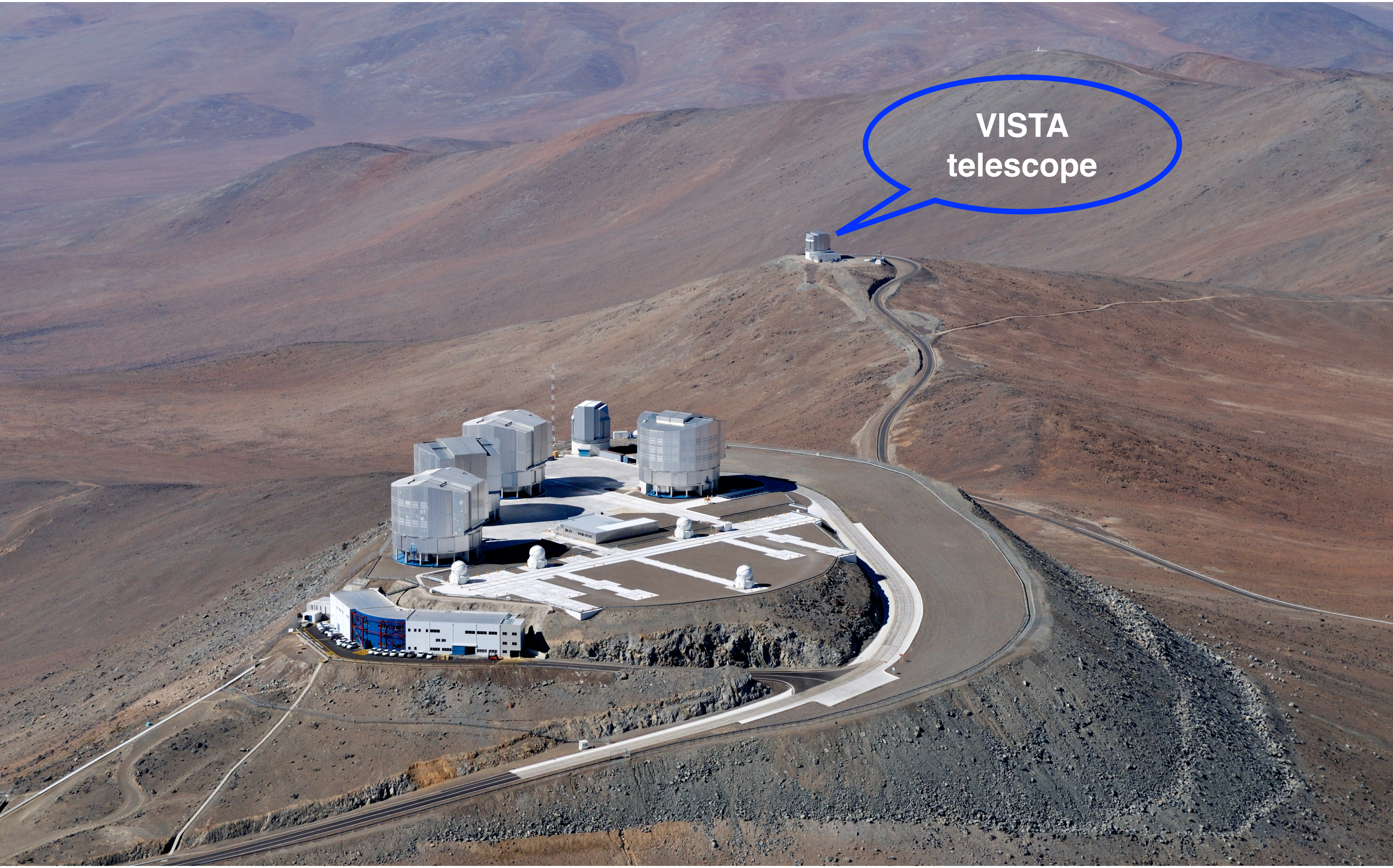
Survey strategy



Survey strategy

Galactic surveys

- Galactic Halo Low Resolution
- Galactic Halo High Resolution
- Galactic Disk-Bulge Low Resolution
- Galactic Disk-Bulge High Resolution

Extra Galactic surveys

- Galactic Clusters
- AGN
- Galaxy Evolution (WAVES)
- Cosmology Redshift

Community surveys

Chilean Community

Supposed start: 2021

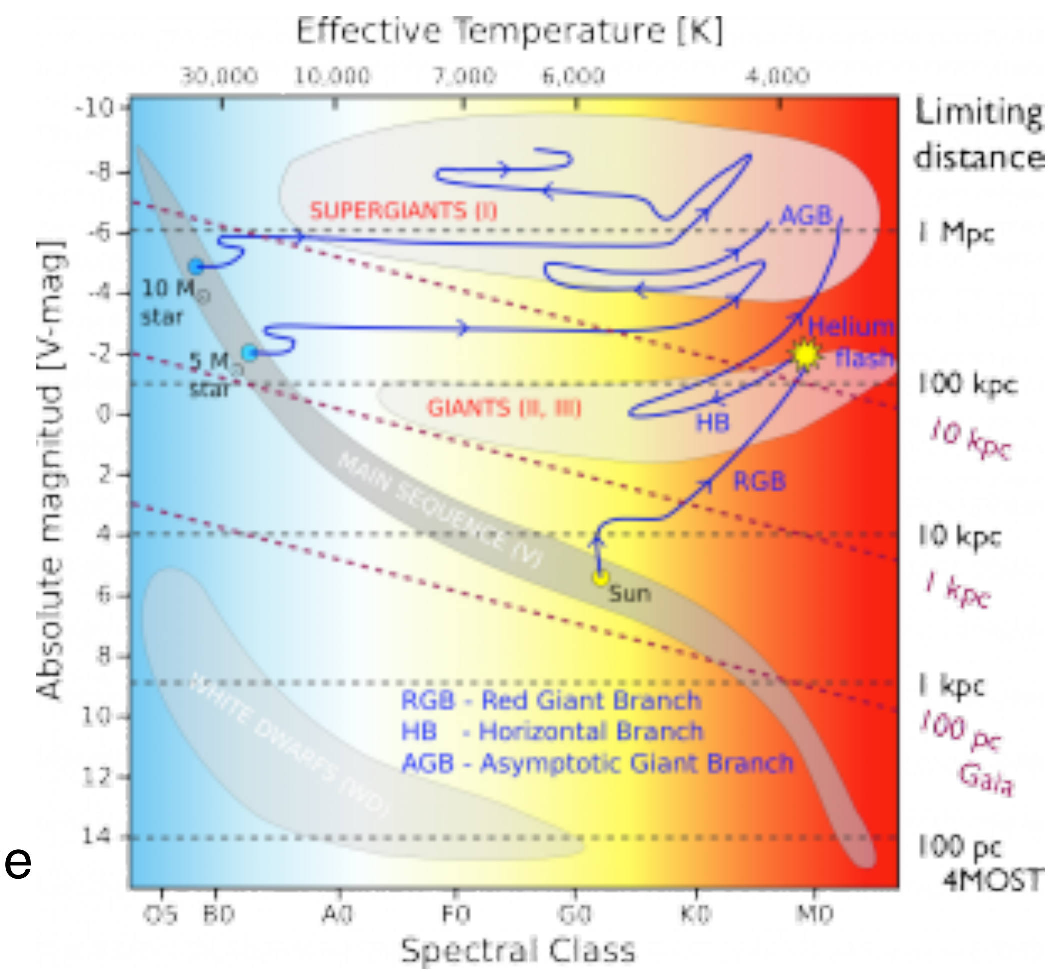
Specifications

Specification	Requirement	Goal	Design
Field-of-View in hexagon	>4 degree^2	>5 degree^2	4.1 degree^2
Fibre multiplex per pointing	>1500	>2400	2436
Low-Resolution Spectrograph (LRS)			
Fibre multiplex	>800	>1500	1624
Spectral resolution	R> 5000	R>7500 @800nm	R>5000–7000
Wavelength coverage	400–885 nm	390–950 nm	390–950 nm
High-Resolution Spectrograph (HRS)			
Fibre multiplex	>800	>800	812
Spectral resolution	R>18,000	R>20,000	R>18,000
Wavelength coverage	392.8–435.5, 521–571 & 610–675.5 nm	392–460, 521–571 & 606–683 nm	392.6–436, 515–573.7 & 608–676 nm
Photon detecting percentage (in 1.0 arcsec seeing)	>15%	>20%	>15%
Spectral crosstalk (after data reduction)	<0.05%	<0.02%	TBD
Fibre aperture diameter	1.4″±0.1″	1.4″±0.1″	1.4″±0.1″
Observing efficiency	Overhead < 20%	Overhead < 10%	<15%
Available sky area (Zenith angle)	10–52 degree	4–70 degree	4–60 degree

from 4MOST webpage

Goals for Galactic science

- Determine the 3D Galactic potential and its substructure
- Discern the dynamical structure of the Milky Way disc and measure the influence of its bar and spiral arms
- Understand Galactic assembly history through chemo-dynamical substructure and abundance pattern labelling
- Find thousands of extremely metal-poor stars to constrain early galaxy formation and the nature of the first stellar generations in the Universe.



from 4MOST webpage

Difficulties

Very ambitious project:

- since the high number of stars that will be observed there is need of fast pipeline to analyse the spectra

- define a well designed strategy to optimise observations and to permit a parallel evolution of the surveys

- many people involved —> developping good comunication channels

Conclusion

Most of the standing questions that we have about the history of the Milky Way could be answered by observing more stars

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Next surveys are going to provide all the information that we are waiting for!

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↓

Next surveys are going to provide all the information that we are waiting for!

This is a very exciting moment for Galactic Archeology!


Thank you!