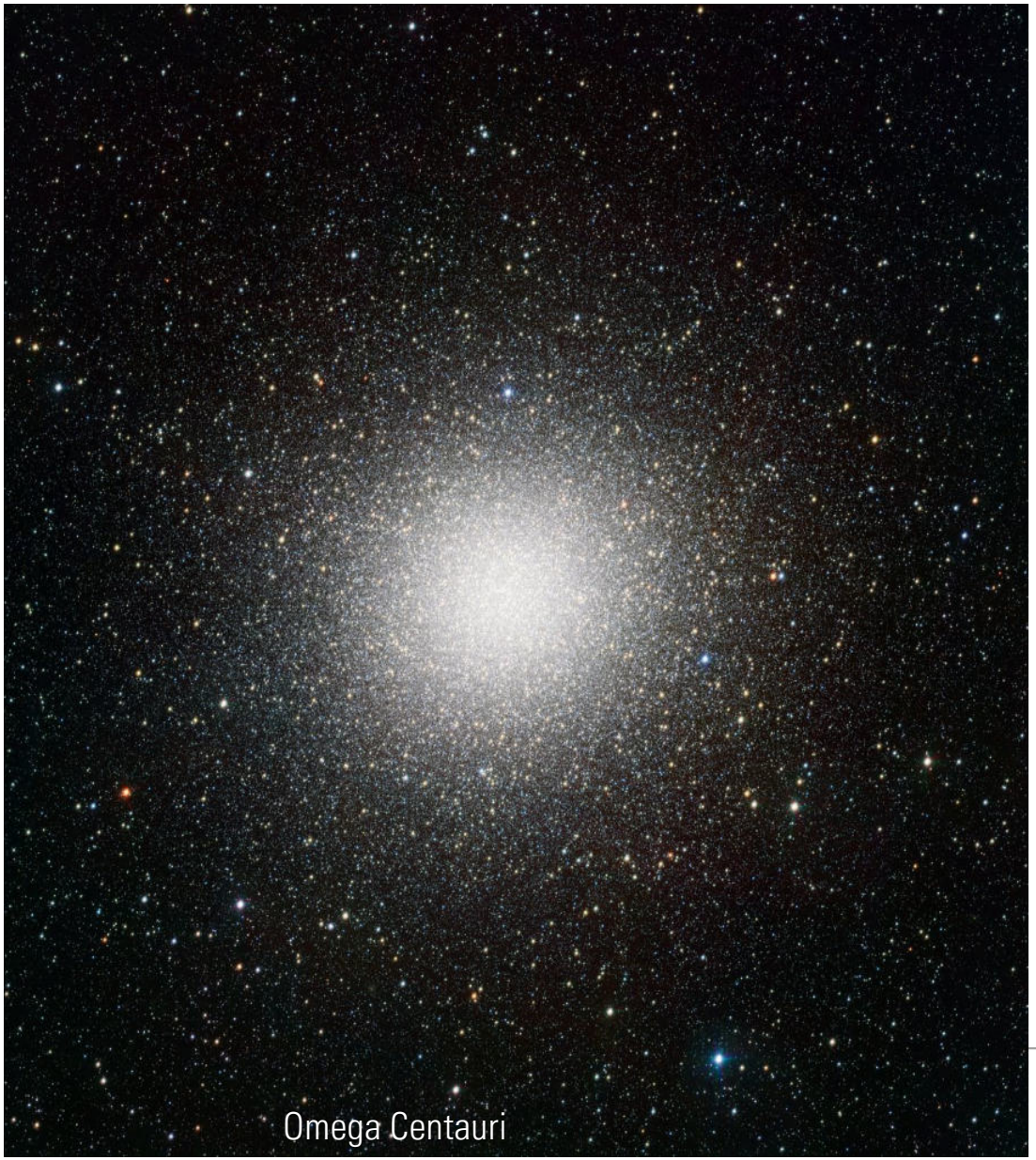
UNLOCKING THE UNIVERSE: HOW SCIENTISTS SEE THE INVISIBLE

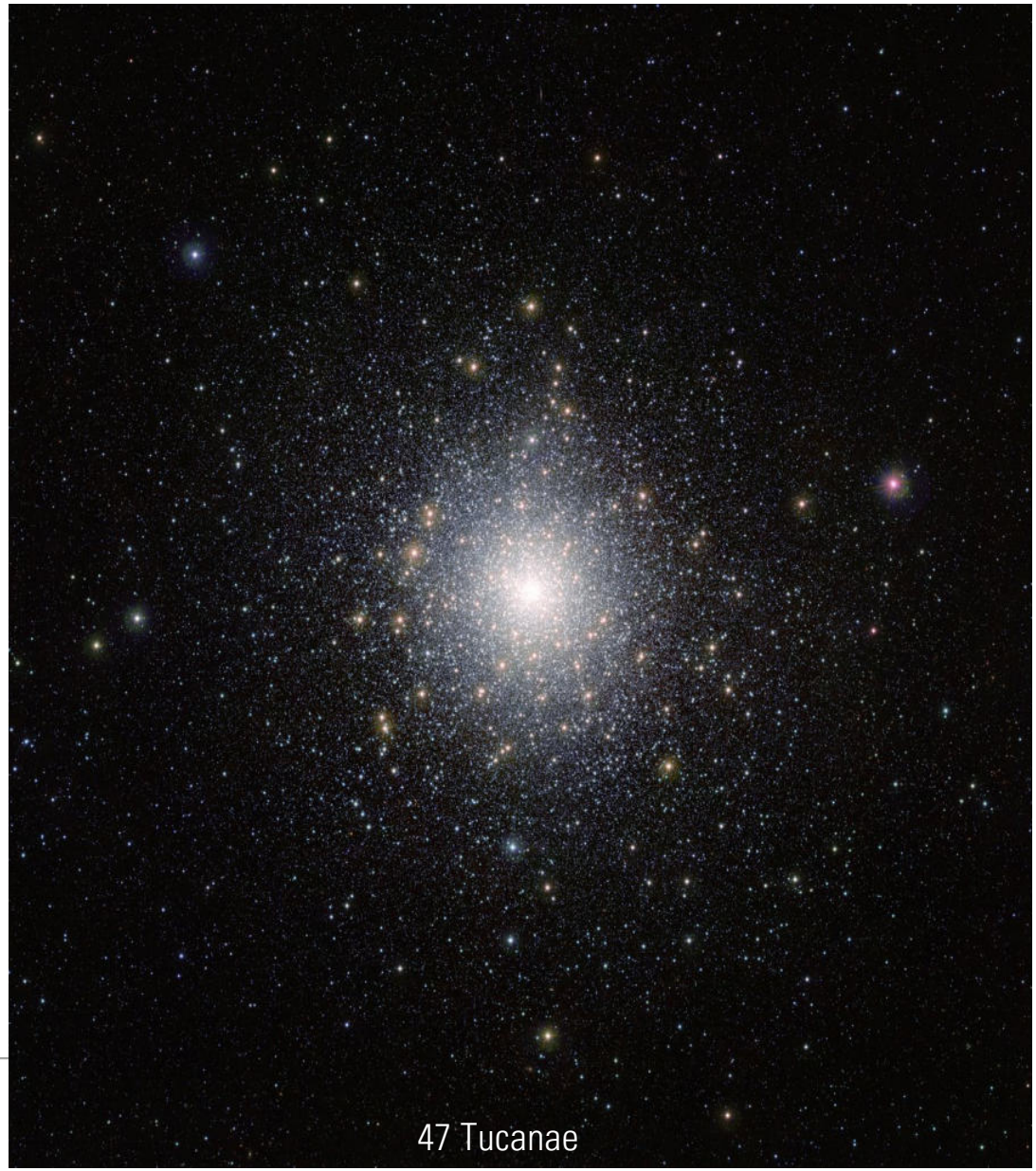


Francesca Primas

Photo credit: ESA/Gaia/DPAC; CC BY-SA 3.0 IGO. Acknowledgement: A. Moitinho.



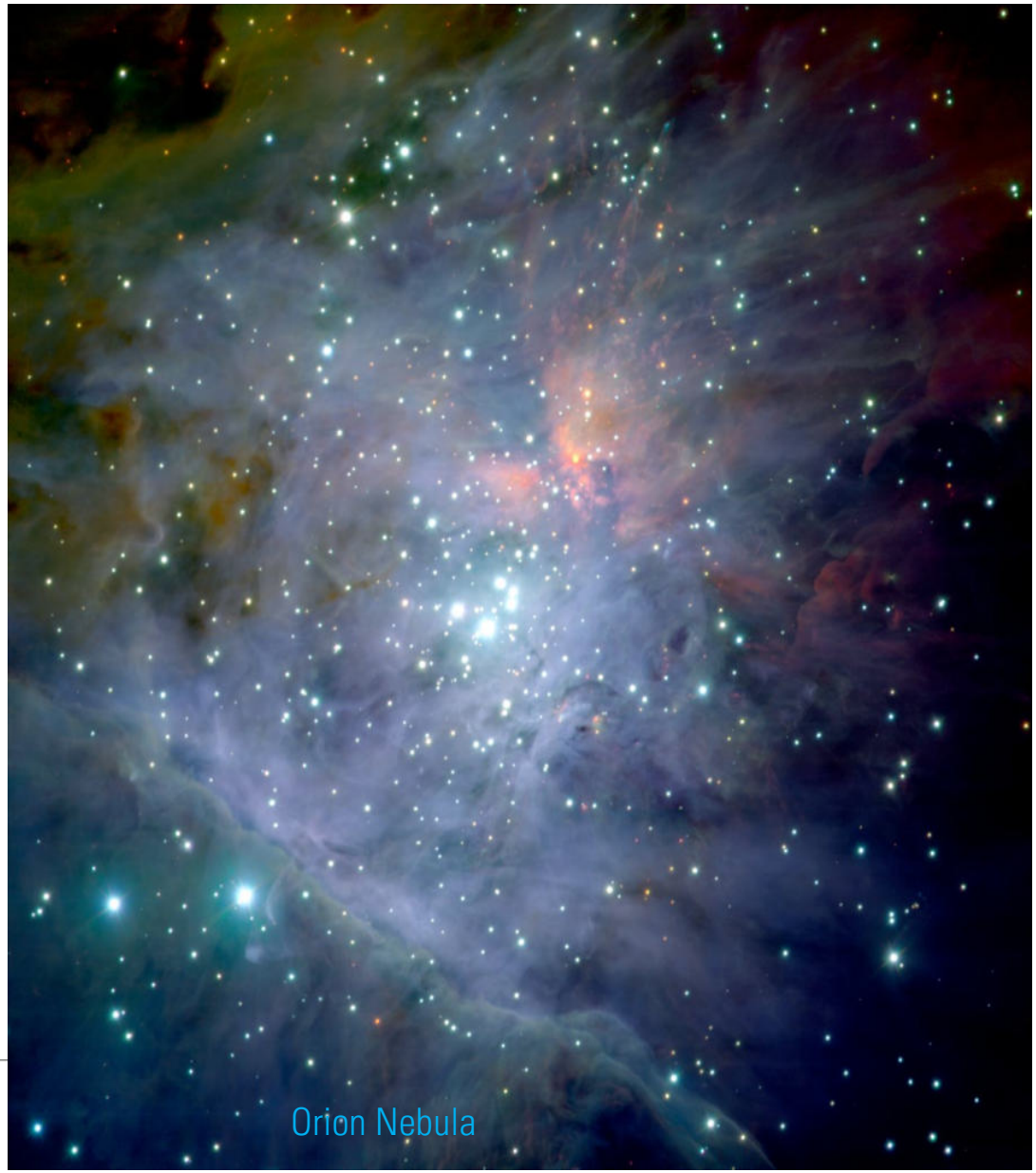
Omega Centauri



47 Tucanae



Tarantula – Large Magellanic Cloud



Orion Nebula



Cosmo Field



Hubble Ultra Deep Field

THE COSMIC HIERARCHY SEQUENCE – THEY ARE ALL MADE OF STARS

Stars → Star Clusters: hundreds to millions of stars are bound dynamically inside a single host galaxy.

Star Clusters → Galaxies: star clusters act as building blocks distributed throughout a galaxy's disk or halo.

Galaxies → Galaxy Clusters: individual galaxies aggregate along the high-density intersection nodes of the Cosmic Web, pooling into enormous clusters bound by an invisible scaffolding of dark matter.

Structure Type	Members Count	Physical Diameter Range	Key Characteristics
Star	1 (individual)	Sun: 1.4×10^6 km	The fundamental atomic factory of the universe; sustained by core nuclear fusion.
Star Cluster	$10^2 – 10^6$ stars	1 – 40 parsecs (3.2 - 130 light-years)	Gravitationally bound stellar families born from a single molecular cloud. Includes loose *open clusters* and dense *globular clusters*.
Galaxy	$10^7 – 10^{12}$ stars	1000 – 100000+ light-years	Massive isolated islands of stars, gas, dust, and dark matter. Can be spiral, elliptical, or irregular.
Galaxy Cluster	50 – 1000+ galaxies	1 – 5 Megaparsecs (3.2 – 16 million light-years)	The largest structures held together by their own gravity. Composed of galaxies, intense X-ray plasma, and up to 90% dark matter.

WHAT IS A STAR?

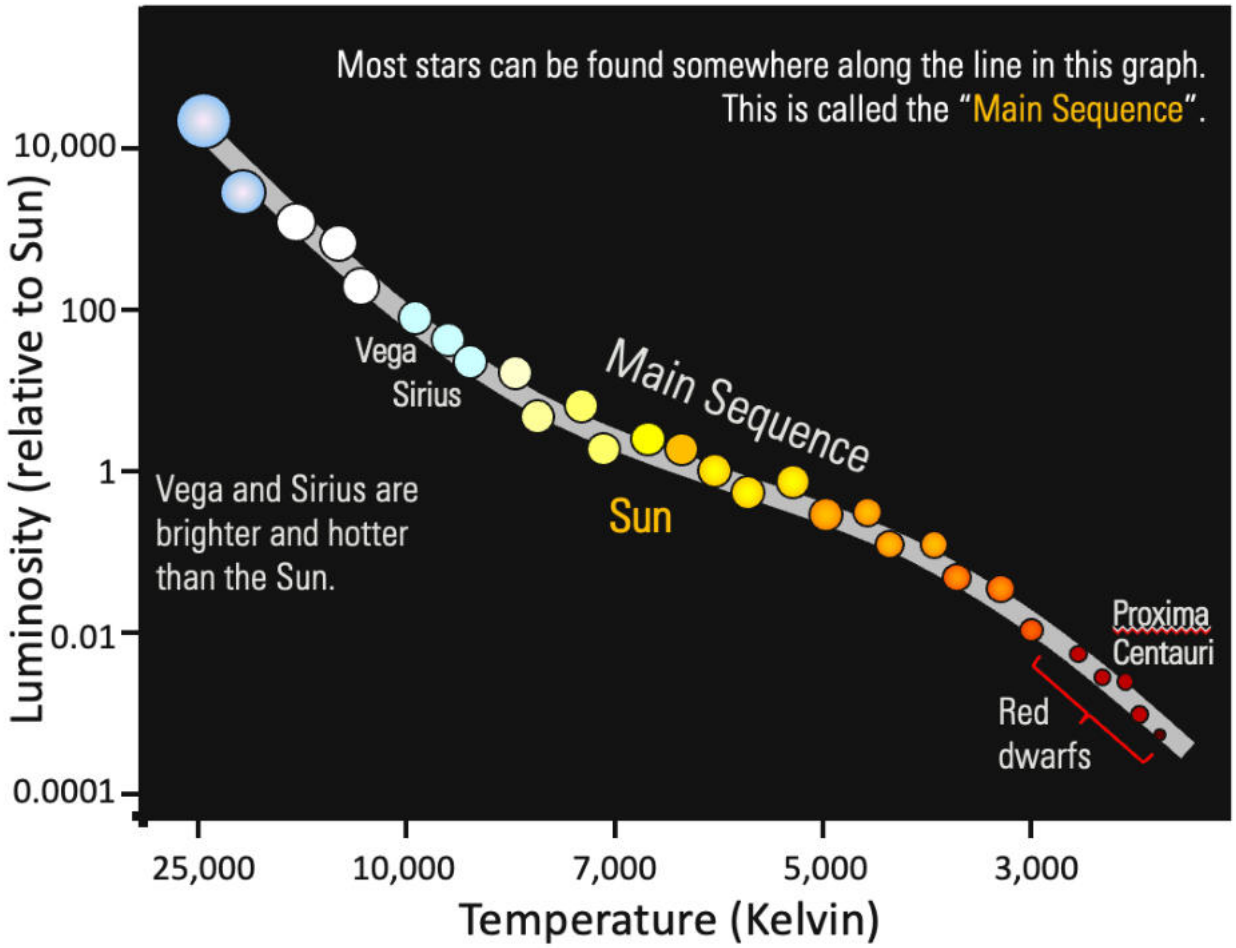
- A cloud of gas, mainly hydrogen and helium.
- The core is so hot and dense that nuclear fusion can occur.
  - This is where the energy comes from that makes the stars shine.
- The fusion converts light elements into heavier ones.
  - This is where all the atoms in your body have come from.

All stars are different

- Luminosity: how bright the star is, i.e. how much energy is being produced in the core
- Colour: the surface temperature of the star → red stars are cold, and blue stars are hot.



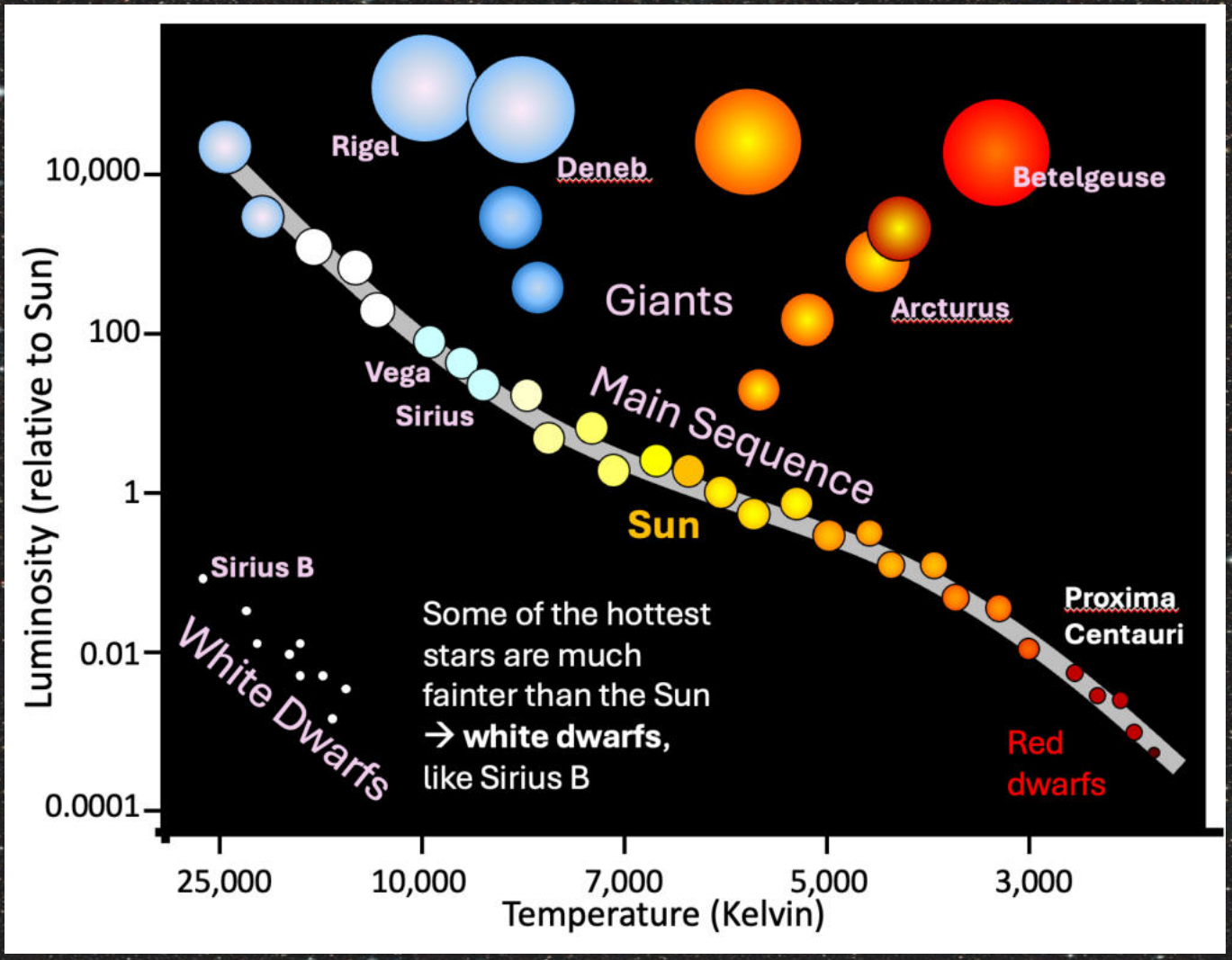
THE HERTZSPRUNG RUSSELL DIAGRAMME



We can compare stars by showing a graph of their temperature and luminosity.

Some stars are much cooler and less luminous, such as the closest star to the Sun, Proxima Centauri.

Even brighter than Betelgeuse are stars like Deneb and Rigel, which are much hotter. These are blue supergiants.



The bright star Betelgeuse is even more luminous than Aldebaran but is cooler.

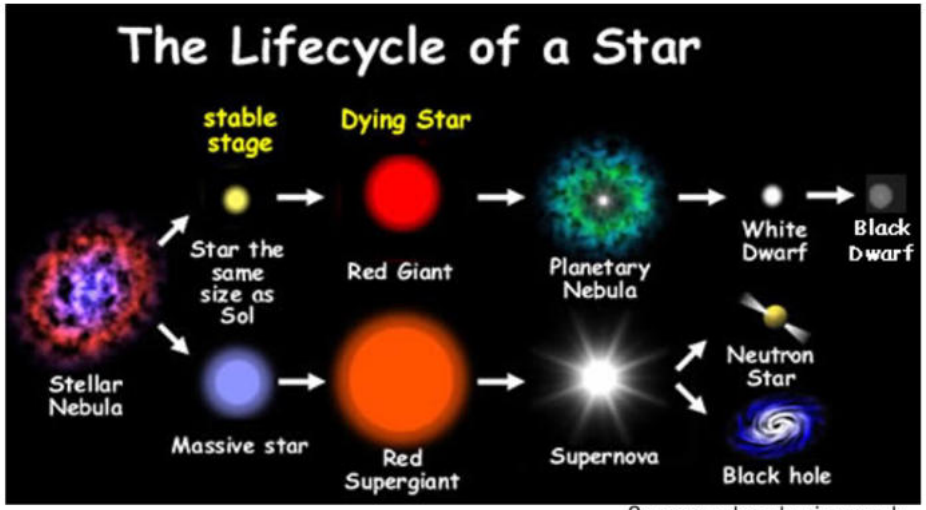
This makes it a red supergiant.

But not all stars lie on the main sequence. Some, such as Arcturus and Aldebaran, are much brighter than the Sun, but cooler.

These are red giant stars.

THE COSMIC RECYCLING PROGRAM

The history of the chemical composition of a galaxy is dominated by the nucleosynthesis occurring in many generations of stars



Source: cyberphysics.co.uk

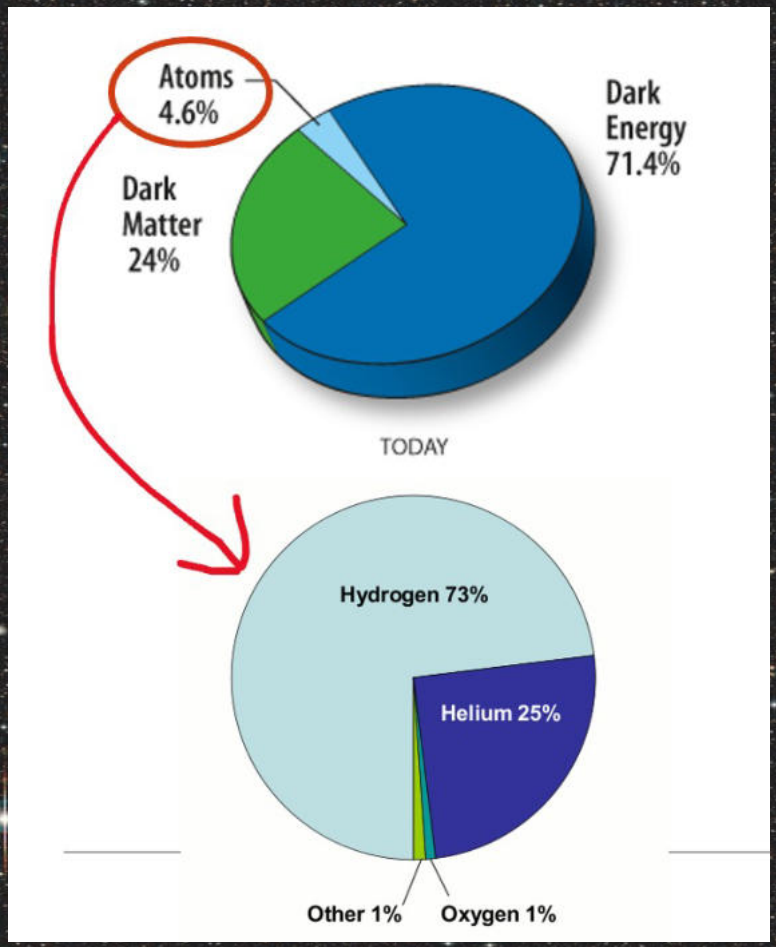
Elements trapped inside a living star need to escape!

When massive stars run out of fuel, they collapse and explode as **Supernovae:**

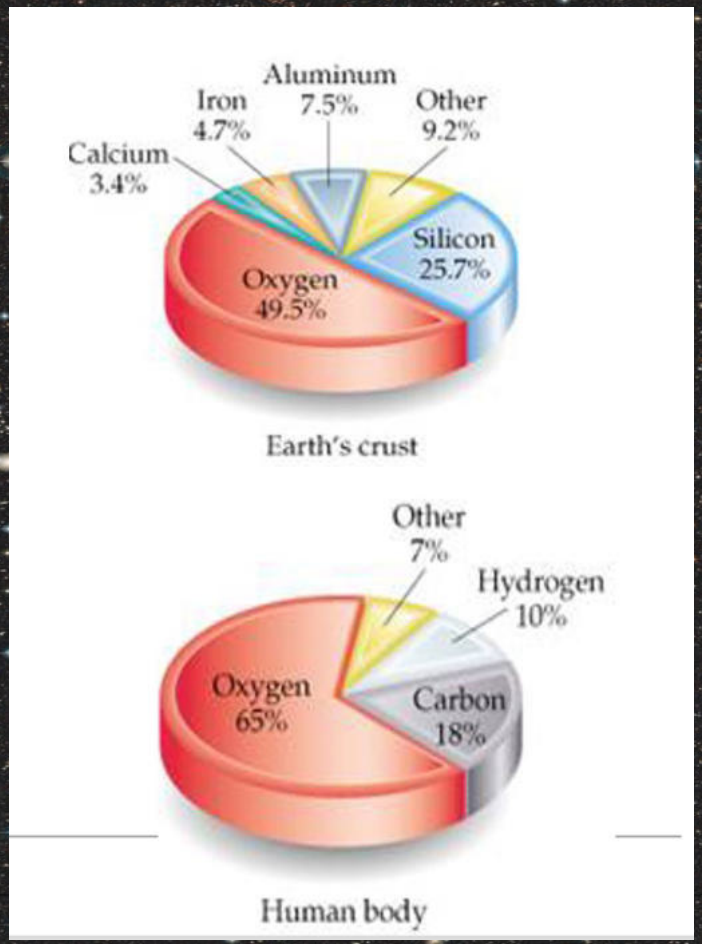
→ They instantly blast the elements cooked inside the star out into deep space.
→ The extreme energy of the explosion itself forces atoms together, forging elements heavier than iron.

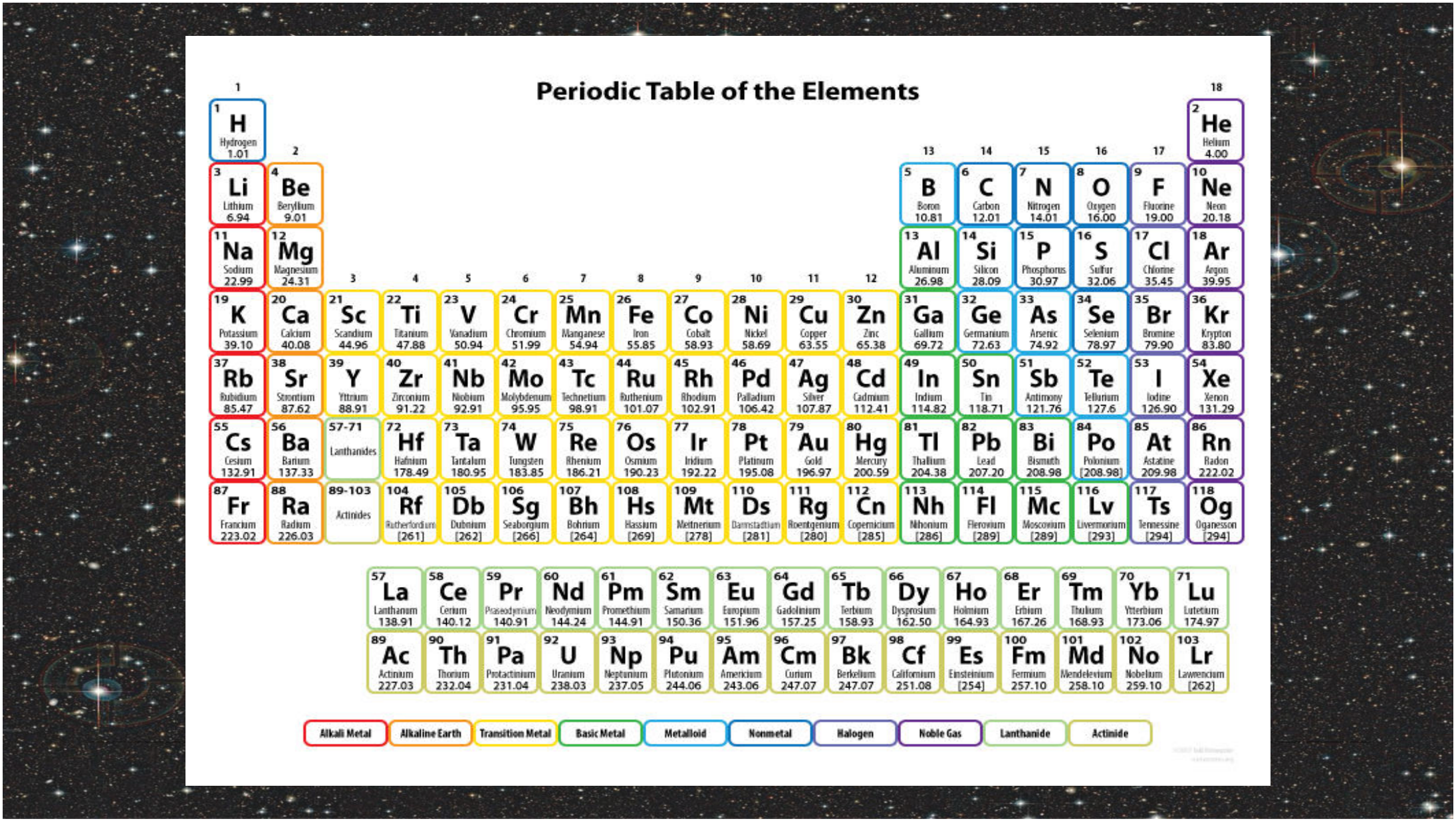
This enriched dust mixes into interstellar gas clouds. The next generation of stars forms from this "polluted" gas, starting the cycle over again, but with more raw materials.

WHAT IS THE UNIVERSE MADE OF



WHAT ARE "WE" MADE OF

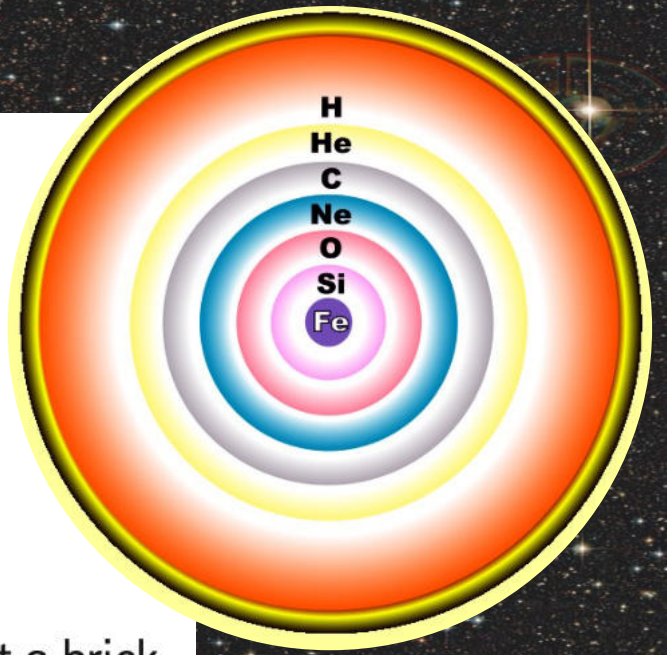



Periodic Table of the Elements
1 H Hydrogen 1.01
2 He Helium 4.00
3 Li Lithium 6.94
4 Be Beryllium 9.01
5 B Boron 10.81
6 C Carbon 12.01
7 N Nitrogen 14.01
8 O Oxygen 16.00
9 F Fluorine 19.00
10 Ne Neon 20.18
11 Na Sodium 22.99
12 Mg Magnesium 24.31
13 Al Aluminum 26.98
14 Si Silicon 28.09
15 P Phosphorus 30.97
16 S Sulfur 32.06
17 Cl Chlorine 35.45
18 Ar Argon 39.95
19 K Potassium 39.10
20 Ca Calcium 40.08
21 Sc Scandium 44.96
22 Ti Titanium 47.88
23 V Vanadium 50.94
24 Cr Chromium 51.99
25 Mn Manganese 54.94
26 Fe Iron 55.85
27 Co Cobalt 58.93
28 Ni Nickel 58.69
29 Cu Copper 63.55
30 Zn Zinc 65.38
31 Ga Gallium 69.72
32 Ge Germanium 72.63
33 As Arsenic 74.92
34 Se Selenium 78.97
35 Br Bromine 79.90
36 Kr Krypton 83.80
37 Rb Rubidium 85.47
38 Sr Strontium 87.62
39 Y Yttrium 88.91
40 Zr Zirconium 91.22
41 Nb Niobium 92.91
42 Mo Molybdenum 95.95
43 Tc Technetium 98.91
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.91
46 Pd Palladium 106.42
47 Ag Silver 107.87
48 Cd Cadmium 112.41
49 In Indium 114.82
50 Sn Tin 118.71
51 Sb Antimony 121.76
52 Te Tellurium 127.6
53 I Iodine 126.90
54 Xe Xenon 131.29
55 Cs Cesium 132.91
56 Ba Barium 137.33
57-71 Lanthanides
72 Hf Hafnium 178.49
73 Ta Tantalum 180.95
74 W Tungsten 183.85
75 Re Rhenium 186.21
76 Os Osmium 190.23
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.97
80 Hg Mercury 200.59
81 Tl Thallium 204.38
82 Pb Lead 207.20
83 Bi Bismuth 208.98
84 Po Polonium [208.98]
85 At Astatine 209.98
86 Rn Radon 222.02
87 Fr Francium 223.02
88 Ra Radium 226.03
89-103 Actinides
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [278]
110 Ds Darmstadtium [281]
111 Rg Roentgenium [280]
112 Cn Copernicium [285]
113 Nh Nihonium [286]
114 Fl Flerovium [289]
115 Mc Moscovium [289]
116 Lv Livermorium [293]
117 Ts Tennessine [294]
118 Og Oganesson [294]
57 La Lanthanum 138.91
58 Ce Cerium 140.12
59 Pr Praseodymium 140.91
60 Nd Neodymium 144.24
61 Pm Promethium 144.91
62 Sm Samarium 150.36
63 Eu Europium 151.96
64 Gd Gadolinium 157.25
65 Tb Terbium 158.93
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93
68 Er Erbium 167.26
69 Tm Thulium 168.93
70 Yb Ytterbium 173.06
71 Lu Lutetium 174.97
89 Ac Actinium 227.03
90 Th Thorium 232.04
91 Pa Protactinium 231.04
92 U Uranium 238.03
93 Np Neptunium 237.05
94 Pu Plutonium 244.06
95 Am Americium 243.06
96 Cm Curium 247.07
97 Bk Berkelium 247.07
98 Cf Californium 251.08
99 Es Einsteinium [254]
100 Fm Fermium 257.10
101 Md Mendelevium 258.10
102 No Nobelium 259.10
103 Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Metalloid
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide

THE COSMIC STARTER PACK (THE BIG BANG)

In the beginning, the Big Bang cooked up the universe's starter pack:

- ~75% Hydrogen
- ~25% Helium
- + a tiny pinch of Lithium.



→How do we get the other elements? Nuclear Fusion.

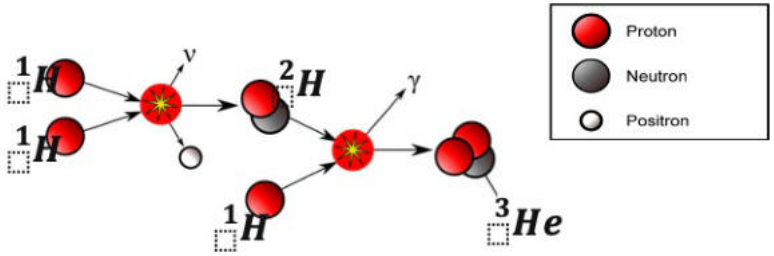
→Stars can happily fuse light elements into heavier ones, but they hit a brick wall at **Iron (^{56}Fe)**. Fusing iron requires more energy than it releases, effectively shutting down the star's engine.

BTW: Astronomers call every single element heavier than Helium a "metal".

NUCLEAR FUSION

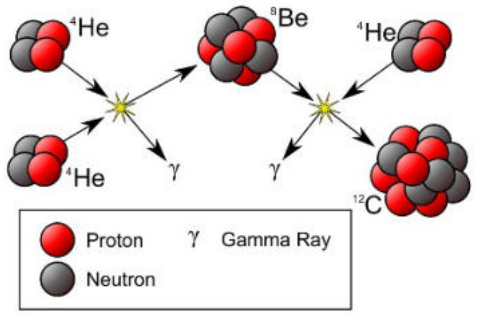
The luminosity of a star is powered by nuclear fusion taking place in the centre of the star converting hydrogen into helium.

- Temperature and density must be high enough.
- At T>4 million Kelvin hydrogen nuclei fuse into helium.



As the H runs out, the energy released from fusion decreases and the forces are now unbalanced.

If the star is massive enough, the core temperature increases until helium fusion starts (when T > 100 million Kelvin, 3 Helium nuclei can be fused together to produce 1 carbon nucleus)



THE 1957 MILESTONE (THE B²FH PAPER)

REVIEWS OF
MODERN PHYSICS

ME 29, NUMBER 4 OCTOBER,

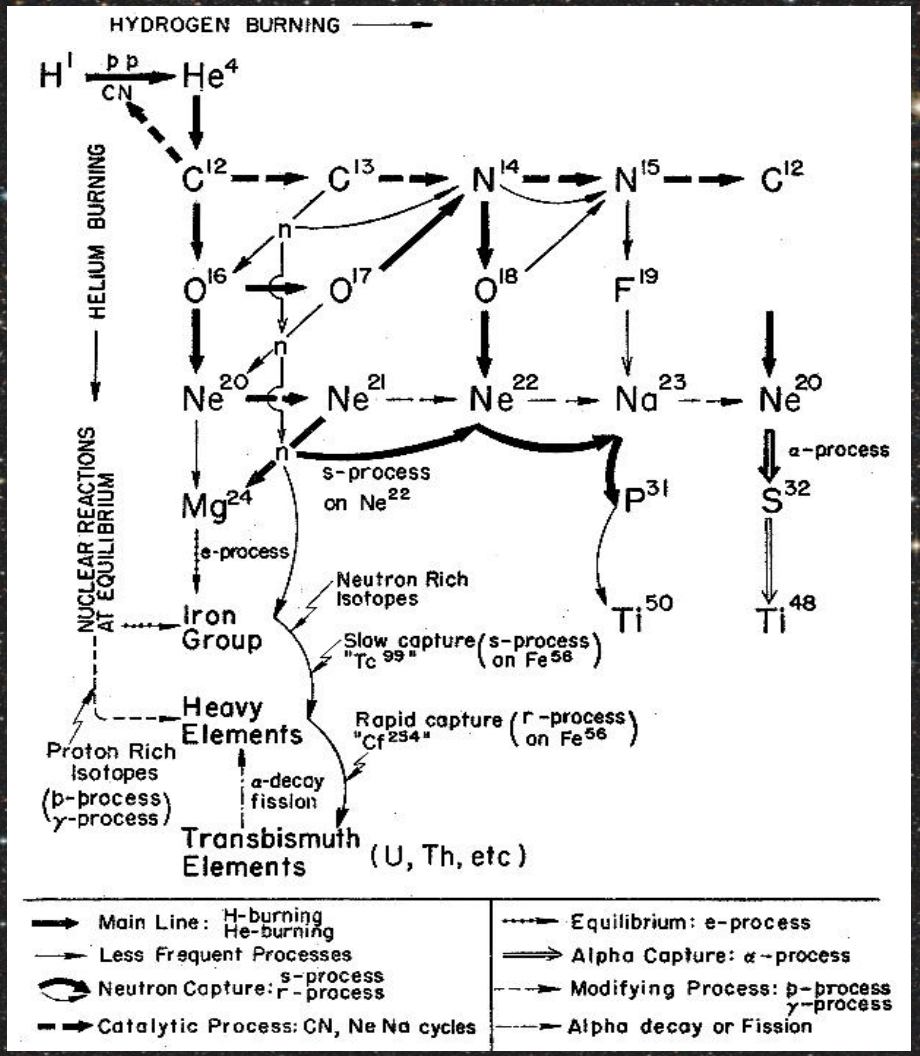
Synthesis of the Elements in Stars*

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

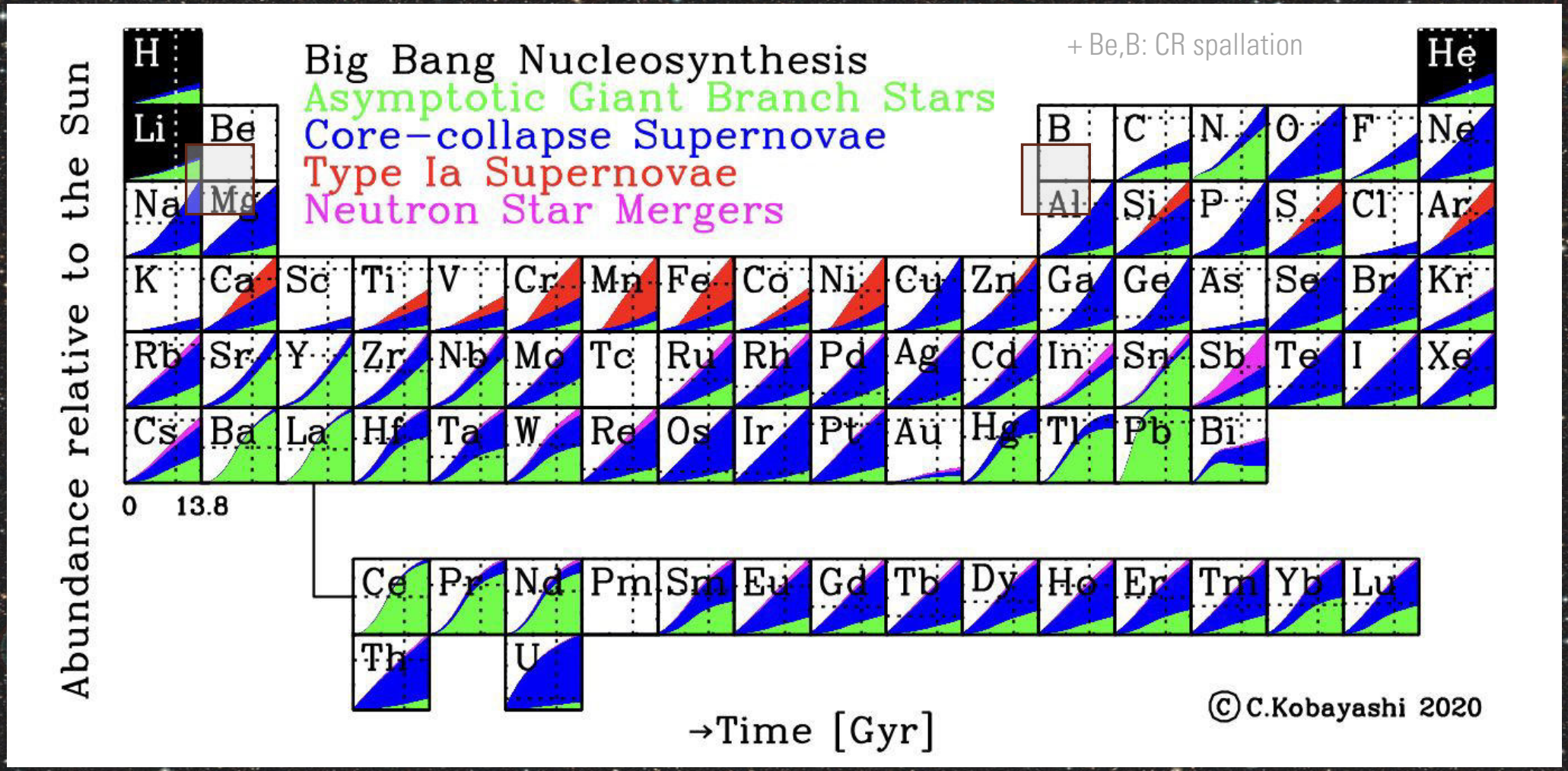
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)



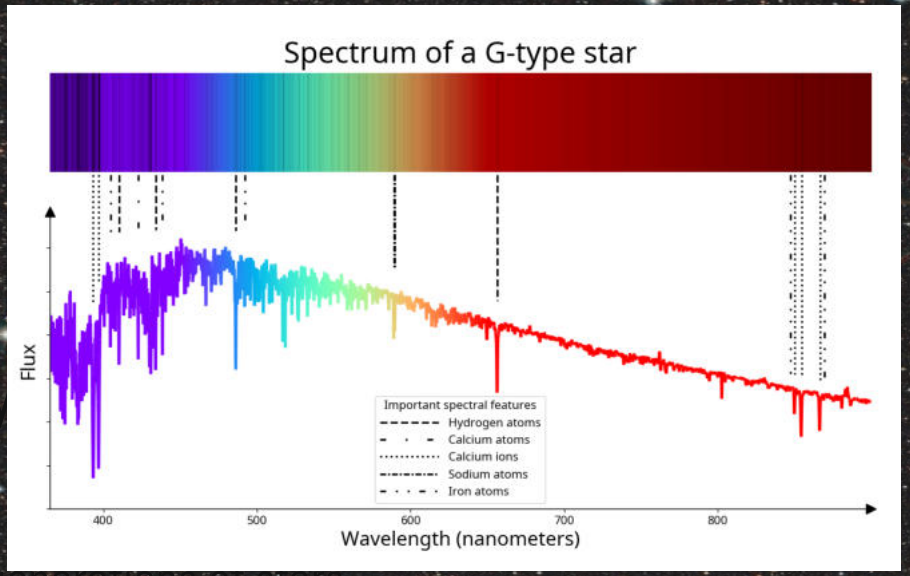


OTHER WAYS TO REPRESENT THE PERIODIC TABLE ...



GALACTIC ARCHEOLOGY

The stars are our fossils.



By using telescopes to split starlight into a barcode (spectroscopy), we can read exactly what elements a star is made of.

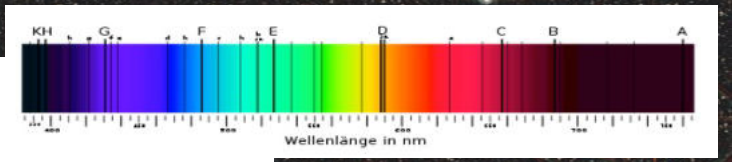
The universe doesn't enrich itself all at once, it evolves. It takes generations of stars.

Old stars formed early in the universe have almost no "metals" (low metallicity).

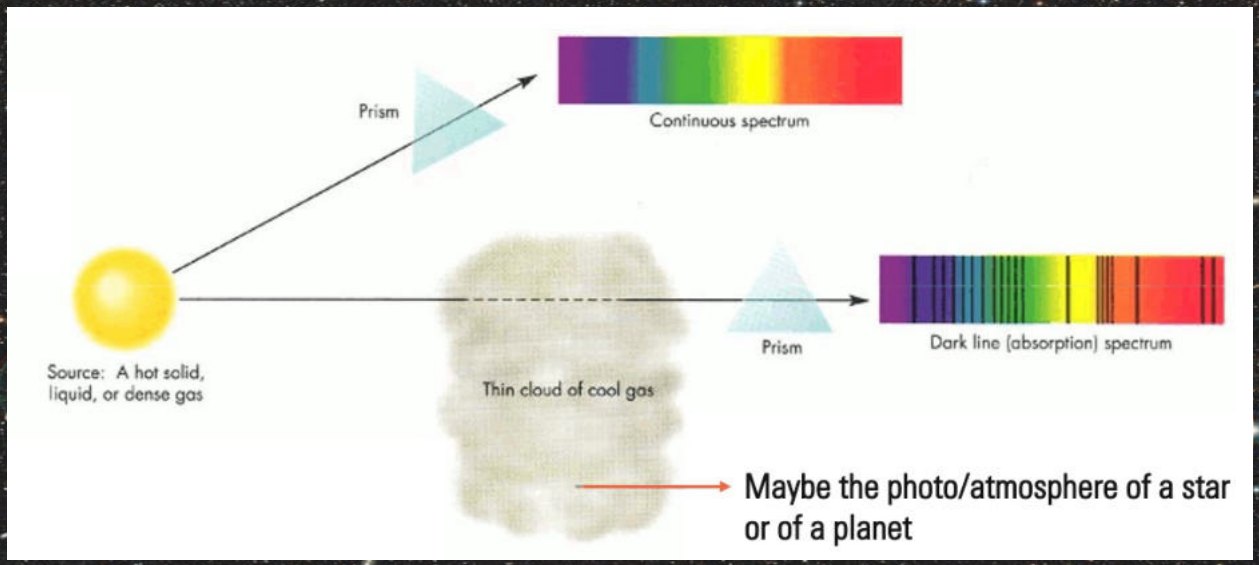
Short-lived massive stars eject elements like Oxygen and Magnesium immediately. Iron takes longer because it largely relies on lower-mass binary stars.

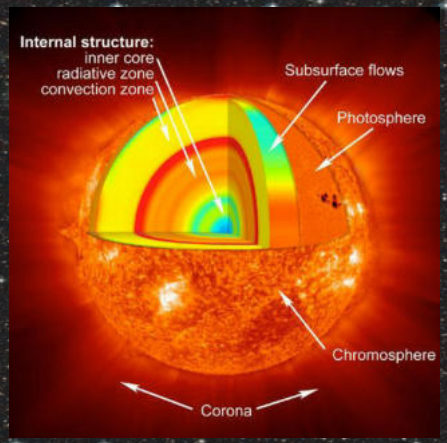
Our Sun was born late in the game, inheriting a highly enriched cocktail of elements.

WHAT INFORMATION DOES THE OBSERVED FLUX CARRY?

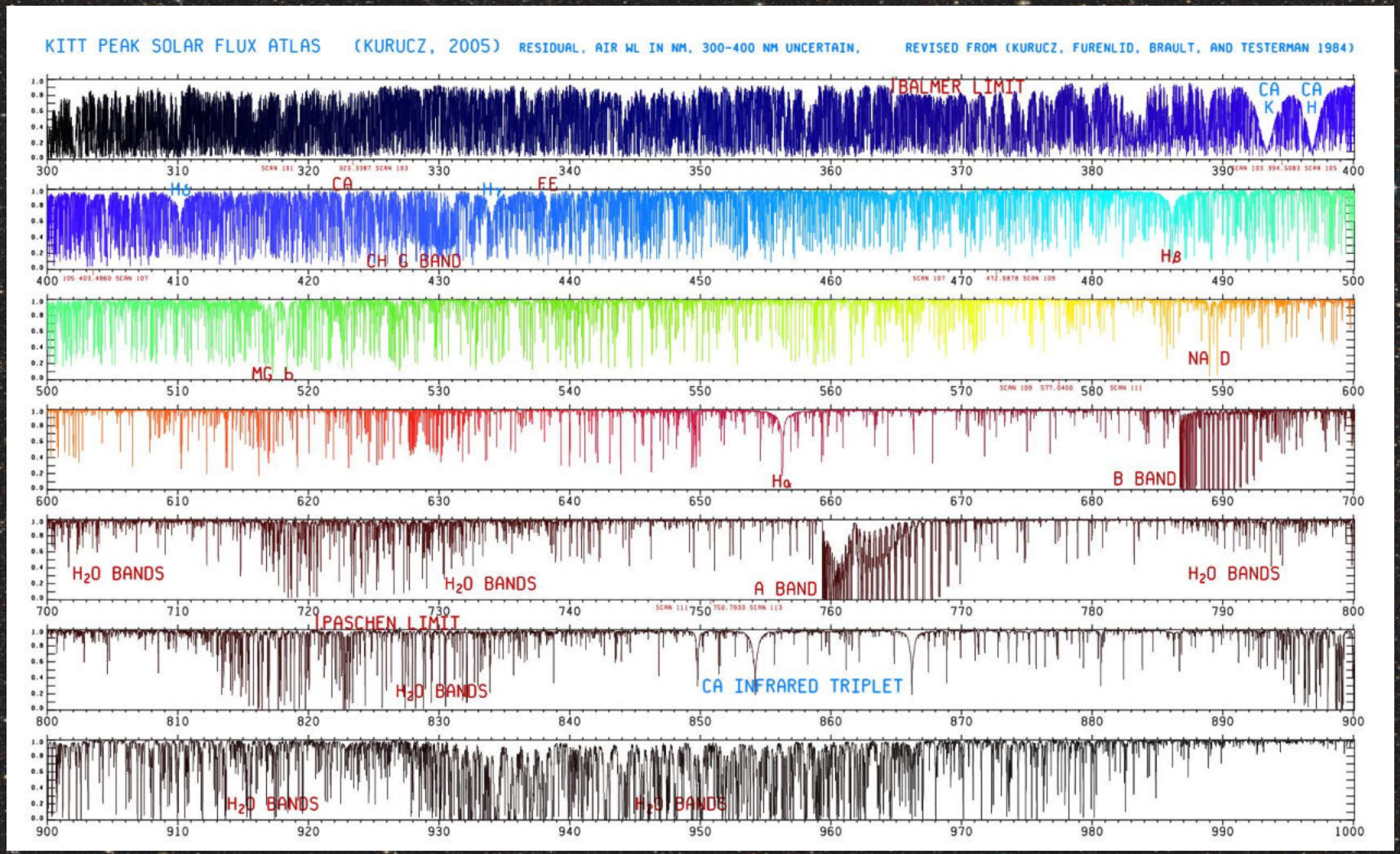


- Absorption-line spectrum
- Lines occur when an atom absorbs a photon with exactly the same energy necessary to make a jump to a higher orbital
- Emergent flux carries information about physical conditions in photosphere
- The energy of photons depends on the types of stars → their effective temperature



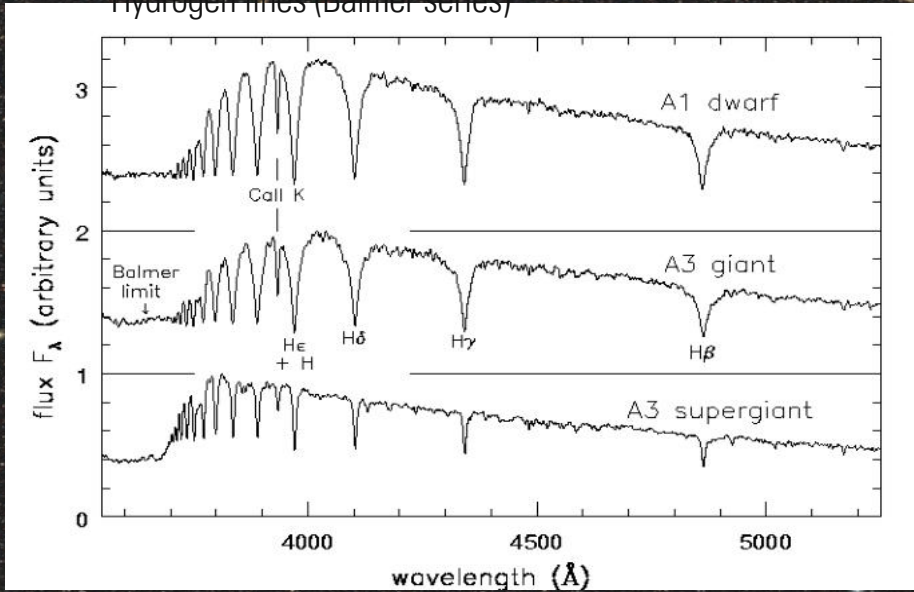


THE SOLAR SPECTRUM

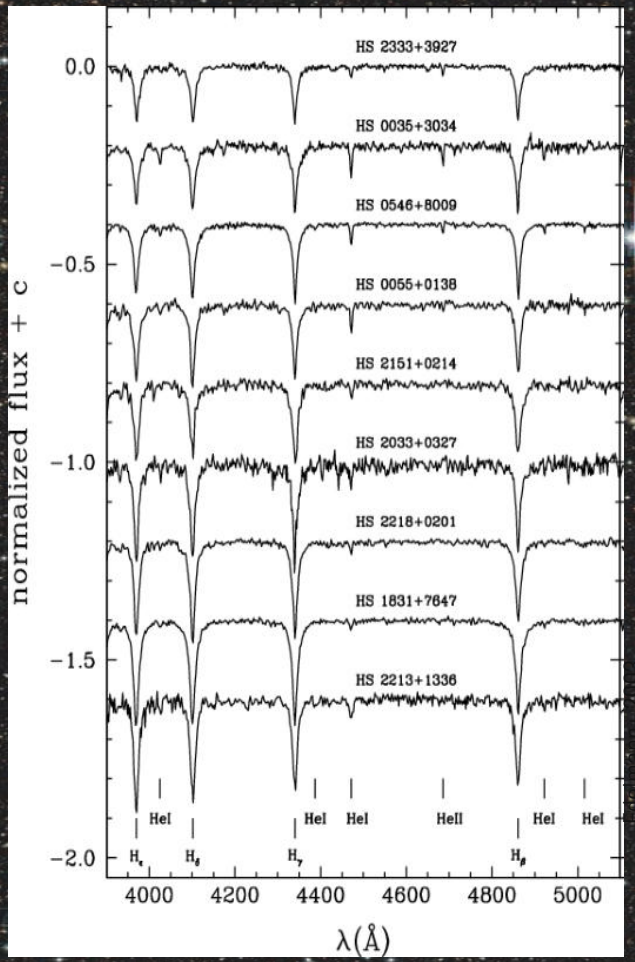


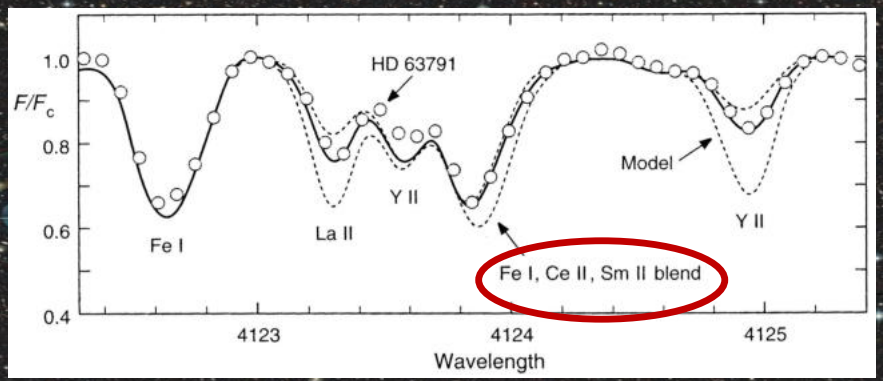
SOME EXAMPLES OF ABSORPTION LINES

Hydrogen lines (Balmer series)



Helium lines





THE POWER OF STELLAR ABUNDANCES

A key abundance ratio!

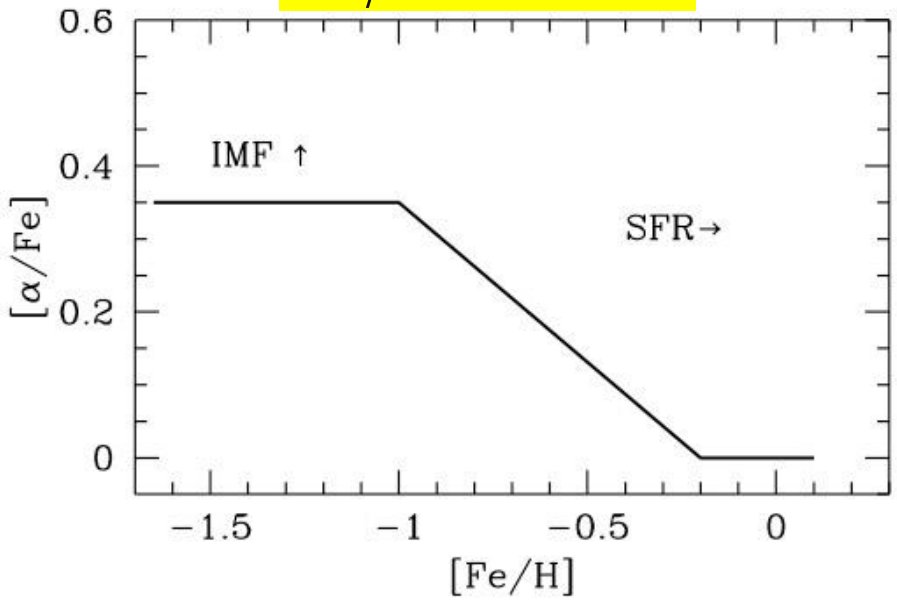
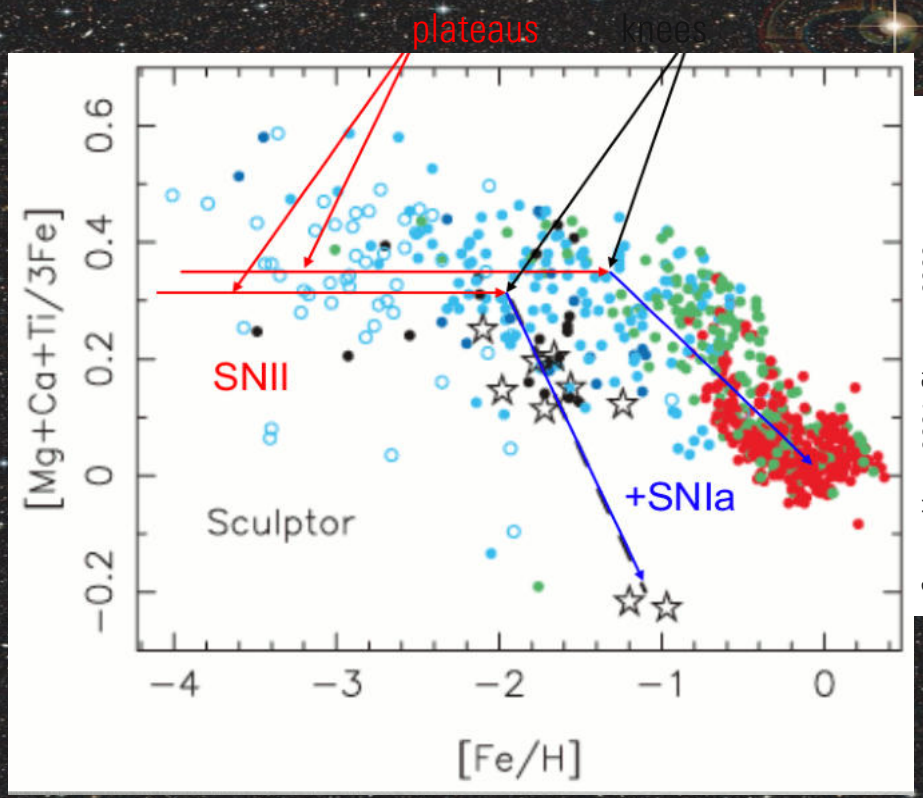
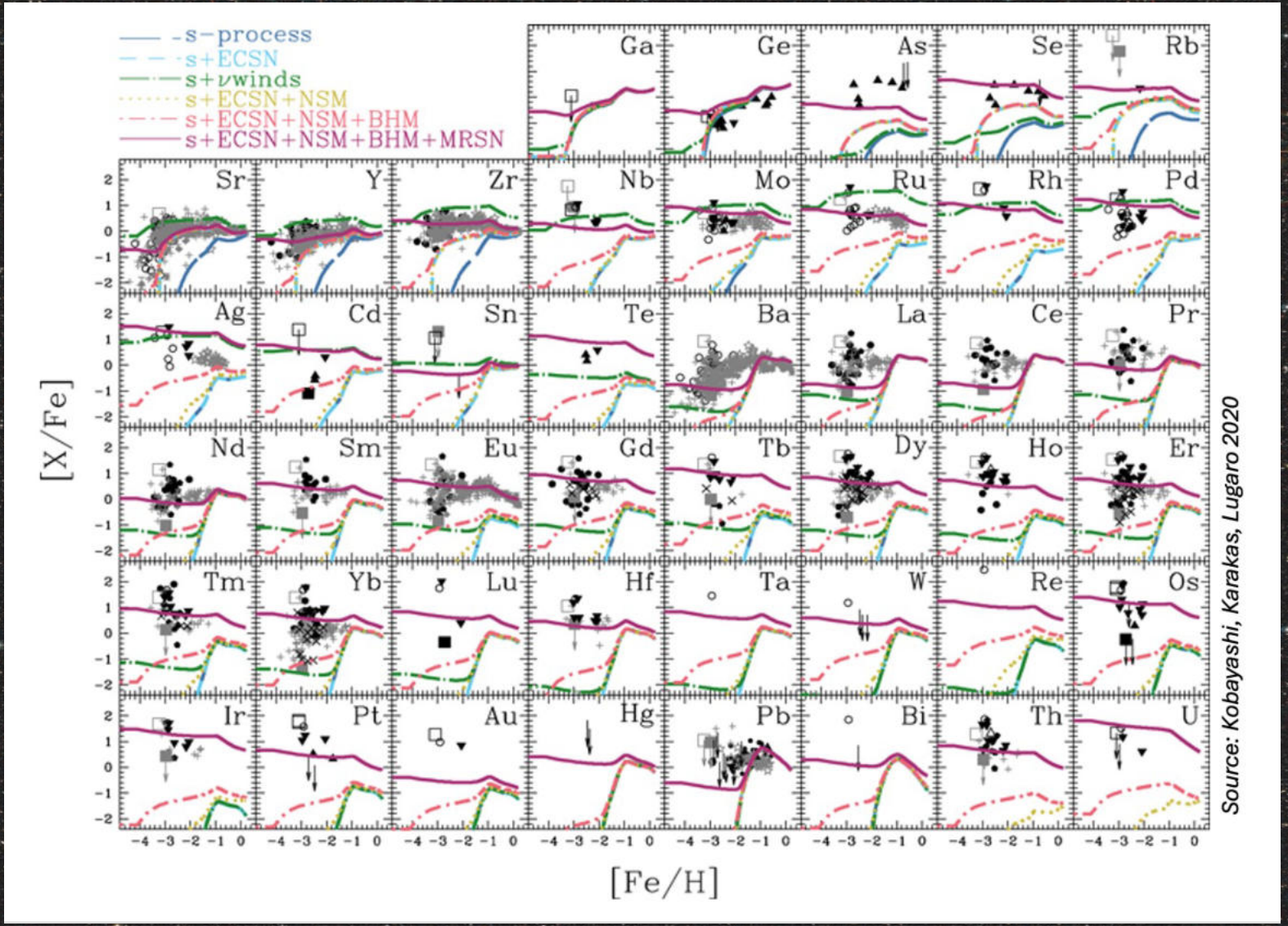


Figure 1 A schematic diagram of the trend of α-element abundance with metallicity. Increased initial mass function and star formation rate affect the trend in the directions indicated. The knee in the diagram is thought to be due to the onset of type Ia supernovae (SN Ia).



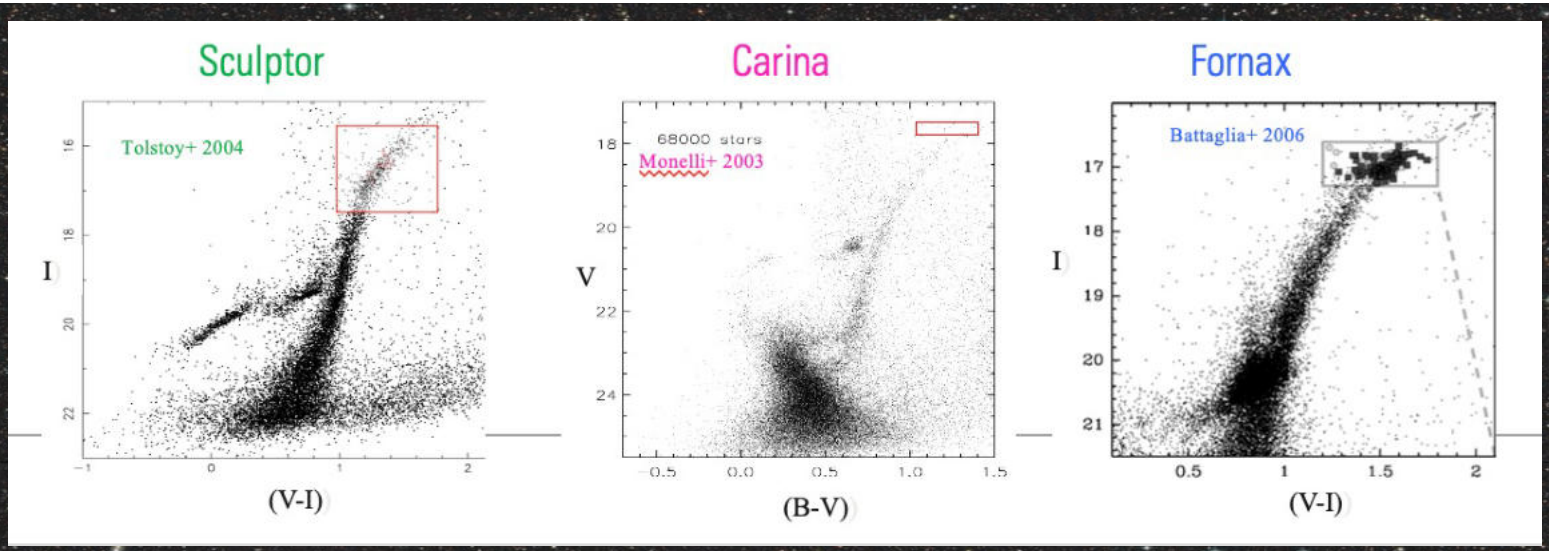
Source: Venn+2004, Shetrone 2003

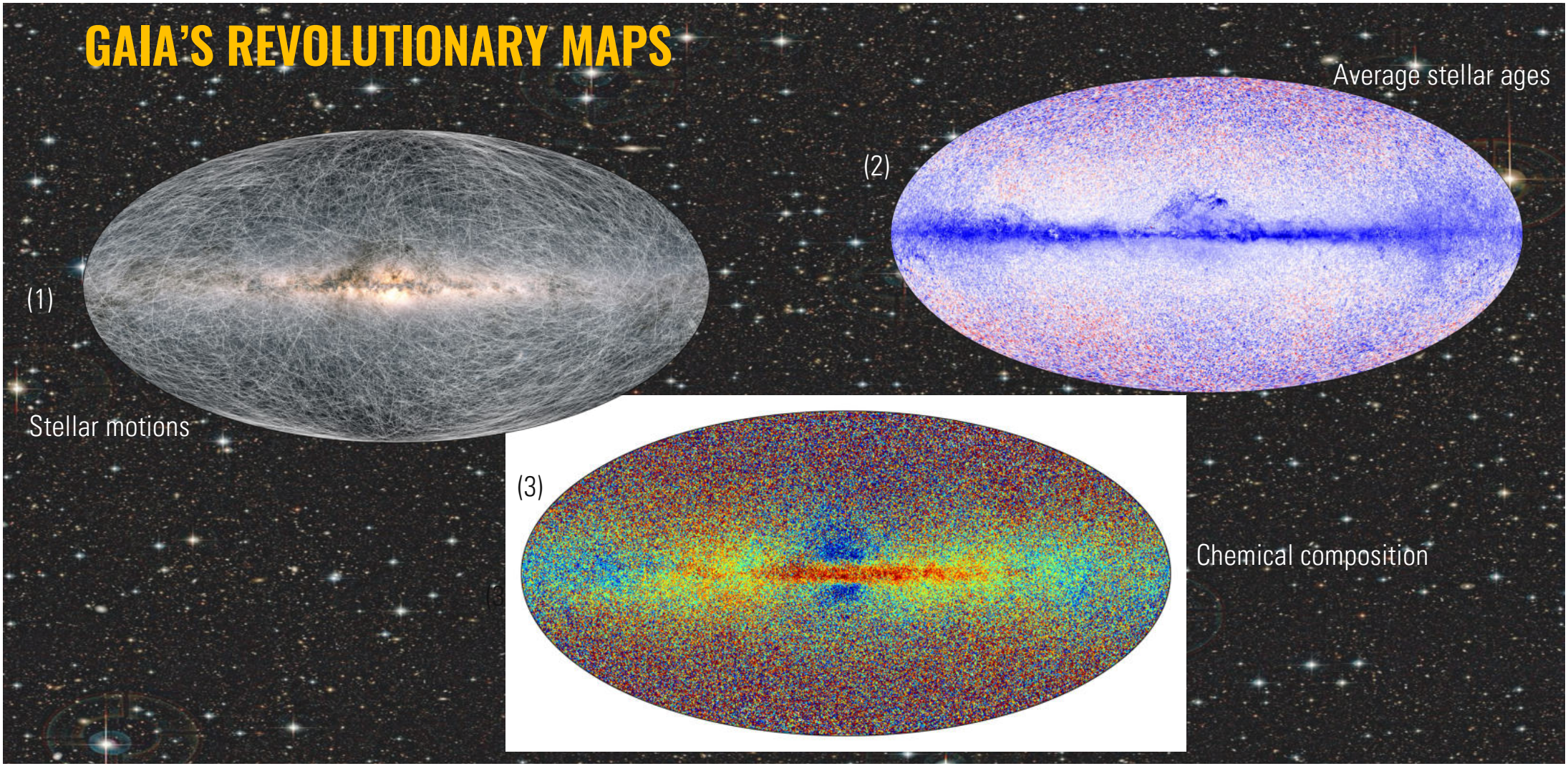
GCE MODELING



HOW REPRESENTATIVE IS THE MILKY WAY?







Credits:

(1) ESA/Gaia/DPAC, CC BY-SA 3.0 IGO. Ack: the image was created by A.Brown, based on an idea from S. Jordan, and with inputs from T. Roegiers, X. Luri, E. Masana, and T. Prusti.

(2) ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: created by O.Creevey, M. Fouesneau, and the Gaia group at MPIA

(3) Gaia Data Release 3: Chemical cartography of the Milky Way by Gaia Collaboration et al. 2022. CC BY-SA 3.0 IGO.

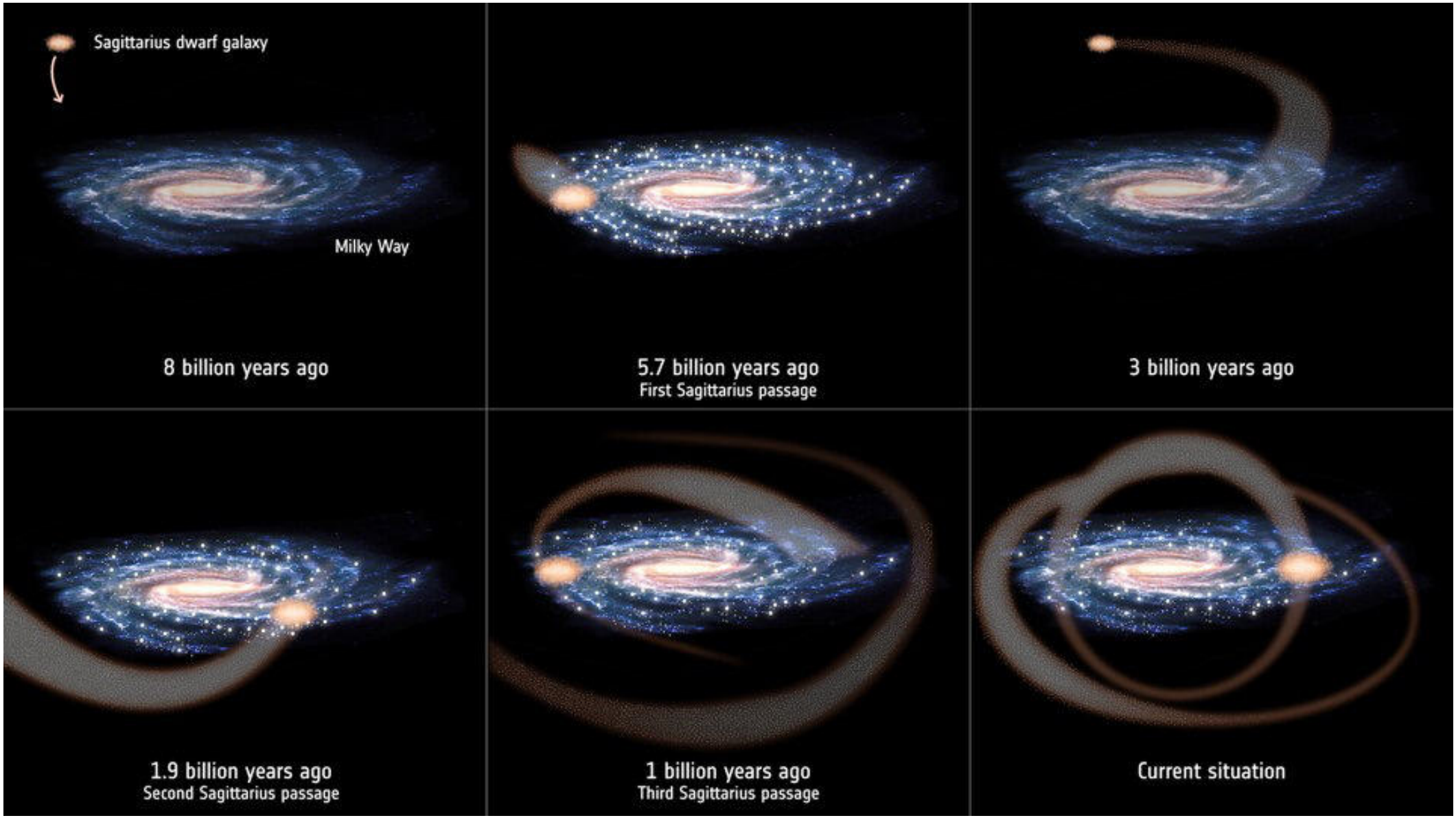
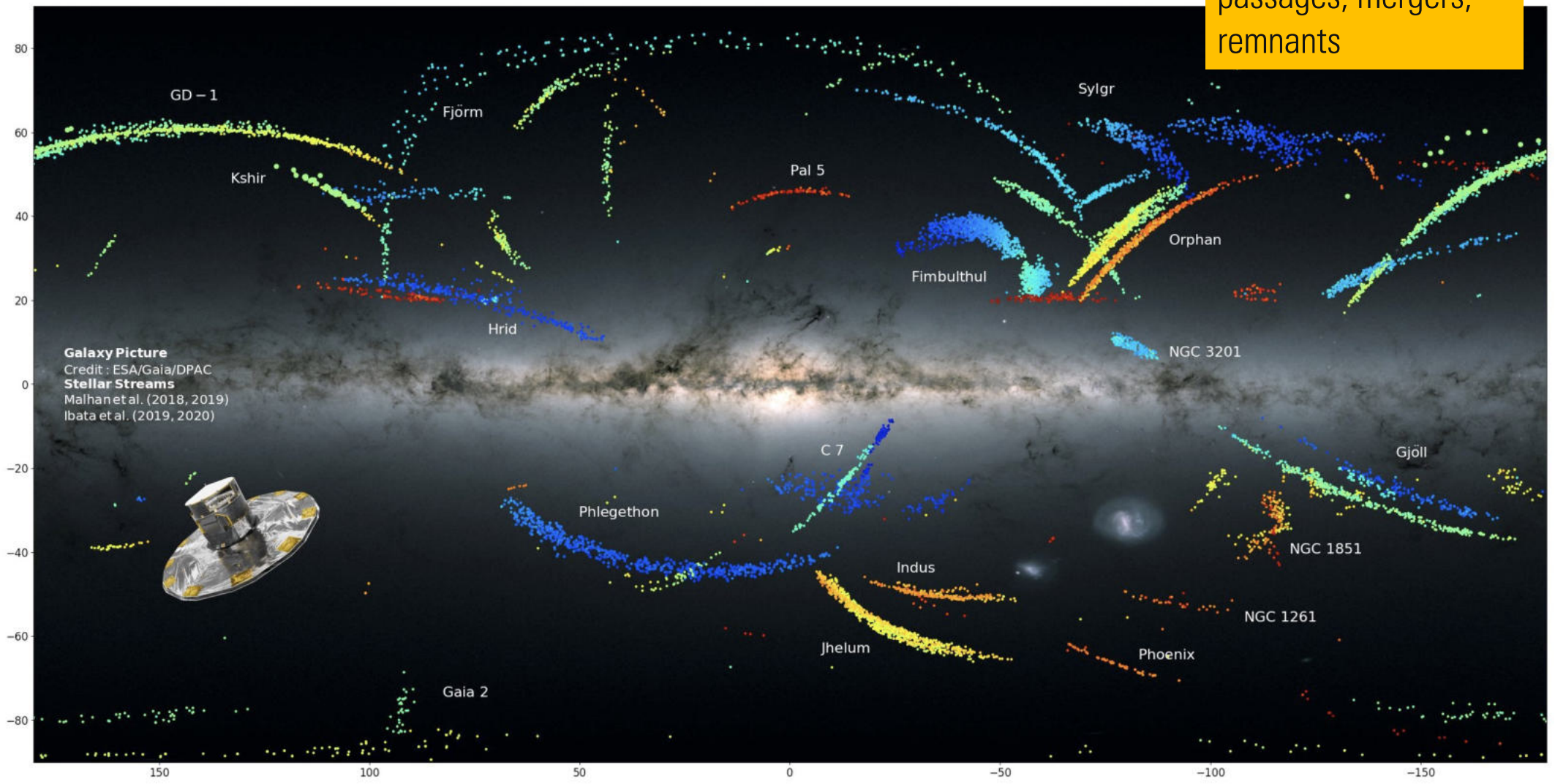


Photo: ©ESA (Sagittarius collisions trigger star formation in Milky Way)

GAIA MISSION: DECIPHERING THE FORMATION OF THE MW

An intriguing story of passages, mergers, remnants

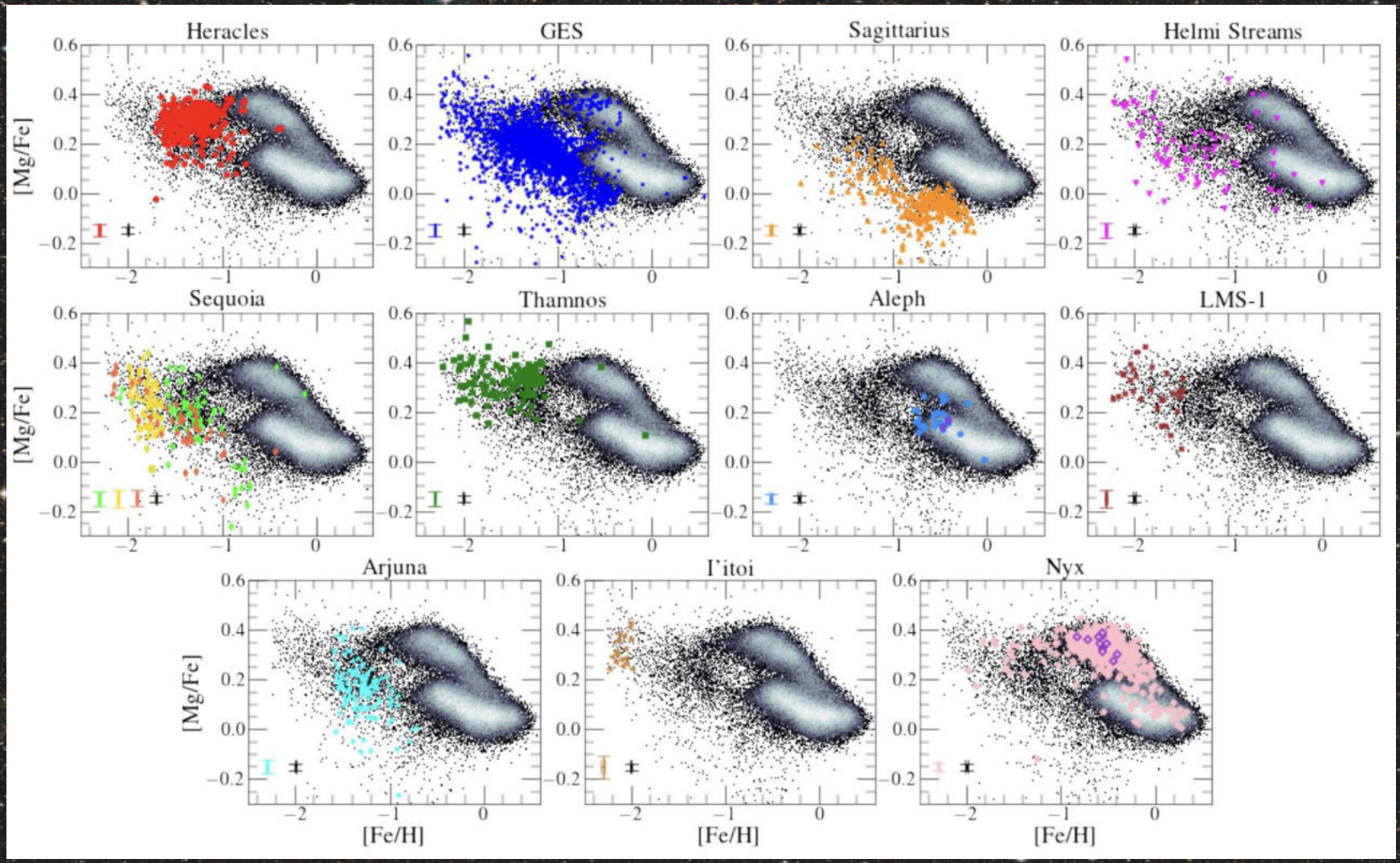


Malhan+2021

THE MW ACCRETION HISTORY

Chemical abundances help reveal nature of halo substructures: [Mg/Fe] vs [Fe/H]

[Mg/Fe]



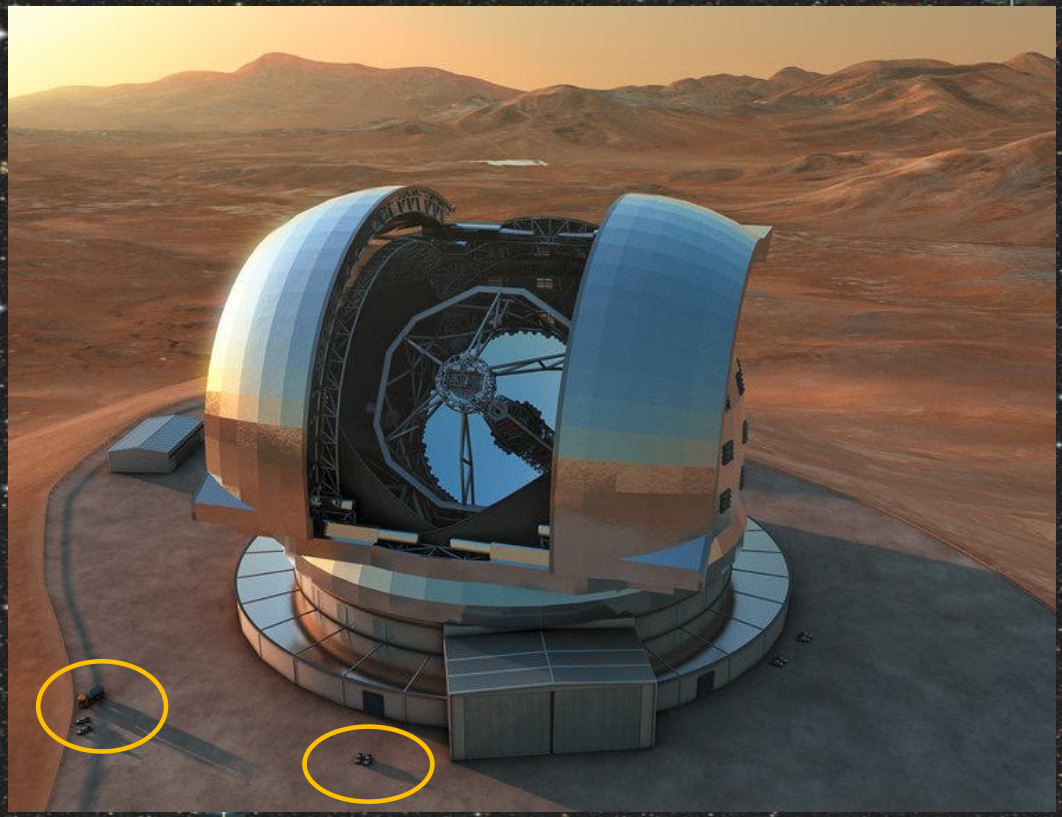
Data source: APOGEE

Source: Horta+23

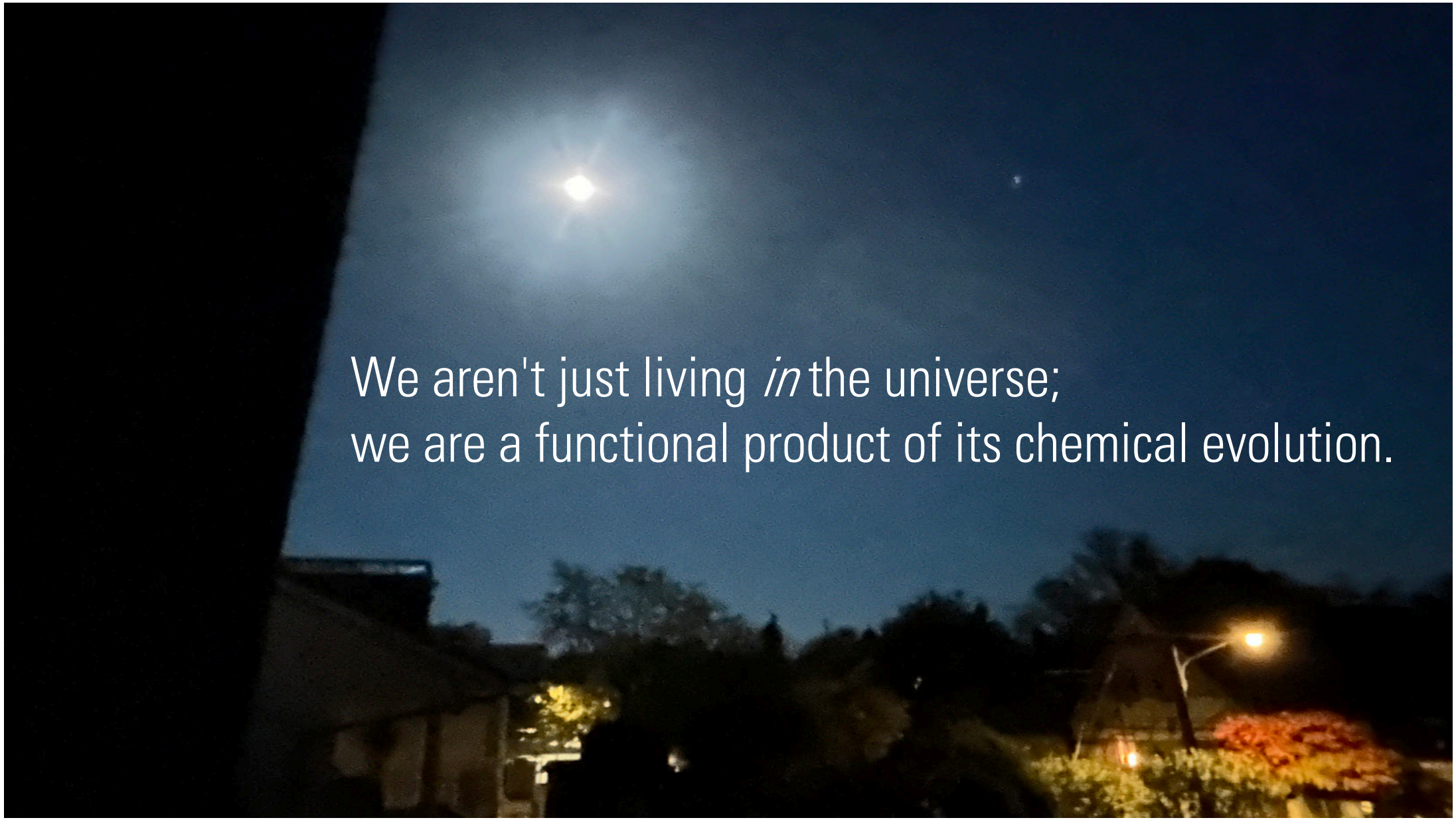
WHAT COMES NEXT

Many more millions of stars coming soon …

The ELT = Extremely Large Telescope



Source: Hill 2024 IAUS396


We aren't just living *in* the universe;
we are a functional product of its chemical evolution.