

# Observational Nuclear Astrophysics

(in four chapters)

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boron 5 <b>B</b> 10.811	carbon 6 <b>C</b> 12.011	nitrogen 7 <b>N</b> 14.007	oxygen 8 <b>O</b> 15.999	fluorine 9 <b>F</b> 18.998	helium 2 <b>He</b> 4.00260
aluminium 13 <b>Al</b> 26.982	silicon 14 <b>Si</b> 28.086	phosphorus 15 <b>P</b> 30.974	sulfur 16 <b>S</b> 32.065	chlorine 17 <b>Cl</b> 35.453	neon 10 <b>Ne</b> 20.180
gallium 31 <b>Ga</b> 69.723	germanium 32 <b>Ge</b> 72.61	arsenic 33 <b>As</b> 74.922	selenium 34 <b>Se</b> 78.96	bromine 35 <b>Br</b> 79.904	argon 18 <b>Ar</b> 39.948
indium 49 <b>In</b> 114.82	tin 50 <b>Sn</b> 118.71	antimony 51 <b>Sb</b> 121.76	tellurium 52 <b>Te</b> 127.60	iodine 53 <b>I</b> 126.90	krypton 36 <b>Kr</b> 83.80
thallium 81 <b>Tl</b> 204.38	lead 82 <b>Pb</b> 207.2	bismuth 83 <b>Bi</b> 208.98	polonium 84 <b>Po</b> [209]	astatine 85 <b>At</b> [210]	xenon 54 <b>Xe</b> 131.29
unununium 111 <b>Uuu</b> [272]	ununbium 112 <b>Uub</b> [277]	ununtrium 113 <b>Uut</b> [283]	ununquadium 114 <b>Uuq</b> [289]	ununpentium 115 <b>Uup</b> [295]	cadmium 48 <b>Cd</b> 112.41
	ds	rg	cn	nh	caesium 55 <b>Cs</b> 132.91
					barium 56 <b>Ba</b> 137.33
					lanthanum 57-70 *
					lutetium 71 <b>Lu</b> 174.967
					hafnium 72 <b>Hf</b> 178.49
					tantalum 73 <b>Ta</b> 180.95
					tungsten 74 <b>W</b> 183.84
					rhenium 75 <b>Re</b> 186.21
					osmium 76 <b>Os</b> 190.23
					iridium 77 <b>Ir</b> 192.22
					platinum 78 <b>Pt</b> 195.08
					gold 79 <b>Au</b> 196.97
					mercury 80 <b>Hg</b> 200.59
					unnilium 110 <b>Uun</b> [271]
					unnilium 111 <b>Uuu</b> [276]
					unnilium 112 <b>Uub</b> [282]
					unnilium 113 <b>Uut</b> [288]
					unnilium 114 <b>Uuq</b> [294]
					unnilium 115 <b>Uup</b> [300]
					unnilium 116 <b>Uuh</b> [306]
					unnilium 117 <b>Uus</b> [312]
					unnilium 118 <b>Uuo</b> [318]
					unnilium 119 <b>Uue</b> [324]

hydrogen 1 <b>H</b> 1.00794	beryllium 4 <b>Be</b> 9.0122
lithium 3 <b>Li</b> 6.941	magnesium 12 <b>Mg</b> 24.305
sodium 11 <b>Na</b> 22.990	calcium 20 <b>Ca</b> 40.078
potassium 19 <b>K</b> 39.098	strontium 38 <b>Sr</b> 87.62
rubidium 37 <b>Rb</b> 85.468	barium 56 <b>Ba</b> 137.33
cesium 55 <b>Cs</b> 132.91	radium 88 <b>Ra</b> [226]
francium 87 <b>Fr</b> [223]	

scandium 21 <b>Sc</b> 44.956	titanium 22 <b>Ti</b> 47.867	vanadium 23 <b>V</b> 50.942	chromium 24 <b>Cr</b> 51.996	manganese 25 <b>Mn</b> 54.938	iron 26 <b>Fe</b> 55.845	cobalt 27 <b>Co</b> 58.933	nickel 28 <b>Ni</b> 58.693	copper 29 <b>Cu</b> 63.546	zinc 30 <b>Zn</b> 65.39
yttrium 39 <b>Y</b> 88.906	zirconium 40 <b>Zr</b> 91.224	niobium 41 <b>Nb</b> 92.906	molybdenum 42 <b>Mo</b> 95.94	technetium 43 <b>Tc</b> [98]	ruthenium 44 <b>Ru</b> 101.07	rhodium 45 <b>Rh</b> 102.91	palladium 46 <b>Pd</b> 106.42	silver 47 <b>Ag</b> 107.87	cadmium 48 <b>Cd</b> 112.41
lutetium 71 <b>Lu</b> 174.967	hafnium 72 <b>Hf</b> 178.49	tantalum 73 <b>Ta</b> 180.95	tungsten 74 <b>W</b> 183.84	rhenium 75 <b>Re</b> 186.21	osmium 76 <b>Os</b> 190.23	iridium 77 <b>Ir</b> 192.22	platinum 78 <b>Pt</b> 195.08	gold 79 <b>Au</b> 196.97	mercury 80 <b>Hg</b> 200.59
lanthanum 57-70 *	actinium 89-102 * *	lawrencium 103 <b>Lr</b> [262]	rutherfordium 104 <b>Rf</b> [261]	dubnium 105 <b>Db</b> [262]	seaborgium 106 <b>Sg</b> [263]	bohrium 107 <b>Bh</b> [264]	hassium 108 <b>Hs</b> [265]	meitnerium 109 <b>Mt</b> [266]	unnilium 110 <b>Uun</b> [271]
									ununium 111 <b>Uuu</b> [276]
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									ununoctium 118 <b>Uuo</b> [318]
									ununnonium 119 <b>Uue</b> [324]

# Where do the elements come from?

“We are made  
of star stuff.”  
Carl Sagan



“It is the stars,  
The stars above us,  
govern our conditions”  
William Shakespeare



# Aim of this introductory lecture

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- **Acquire a qualitative overview, a framework, of the astrophysics you need to know**
- **Familiarize yourself with relevant astrophysical concepts and nomenclature**
- **Get inspired to read on...**

Other lectures later today/this week will give much more details on individual nuclear processes, astronomical messengers and astrophysical sources. And the nuclear part of the story...

# Further reading

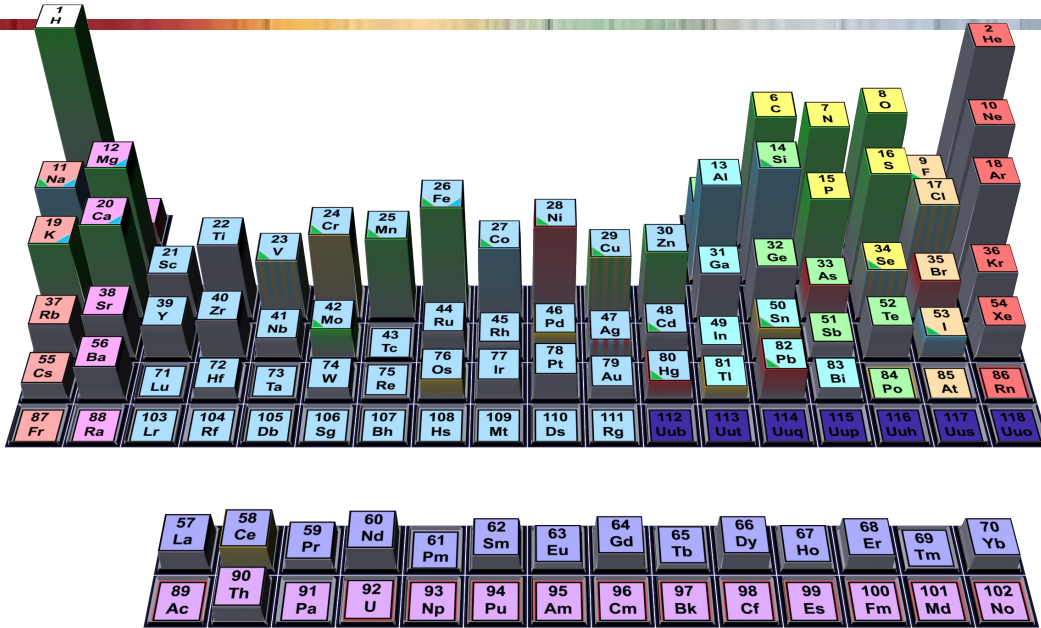
- **Burbidge, Burbidge, Fowler & Hoyle (1953)**, Synthesis of the Elements in Stars (**B2FH**)
- **Asplund (2005)**, New light on stellar abundance analyses: Departures from LTE and Homogeneity
- **Käppeler *et al.* (2011)**, The s process: Nuclear physics, stellar models, and observations
- **Johnson *et al.* (2020)**, The origin of the elements: a century of progress
- **Cowan *et al.* (2021)**, Origin of the heaviest elements: The rapid neutron-capture process
- **Diehl *et al.* (2022)**, Cosmic nucleosynthesis: A multi-messenger challenge
- + + + (talk to the Russbach lecturers about their favourite review paper!)

# SNAQs lectures

 <p>What is the state of the art in CNO related nuclear astrophysics?</p> <p>December 2022</p> <p>on indico</p>	 <p>Accurate abundances of chemical elements in stars: why and how?</p> <p>May 2022</p> <p>on indico</p>	 <p>Why is attracting high school students to nuclear astrophysics a win-win for everyone?</p> <p>April 2022</p> <p>on indico</p>	 <p>How to model a star in your laptop?</p> <p>February 2022</p> <p>on indico</p>
 <p>What is the link between radioactive nuclei and astrophysics?</p> <p>January 2022</p> <p>on indico</p>	 <p>Does Nuclear Astrophysics probe fundamental physics?</p> <p>December 2021</p> <p>on indico</p>	 <p>How to interpret stellar spectra?</p> <p>November 2021</p> <p>on indico</p>	 <p>How to study stars from underground laboratories and deep-sea samples?</p> <p>October 2021</p> <p>on indico</p>
 <p>What does nuclear physics do for astrophysics?</p> <p>June 2021</p> <p>on indico</p>	 <p>How can we query nature to determine nuclear inputs in the cosmos?</p> <p>May 2021</p> <p>on indico</p>	 <p>How to get from starlight to stellar abundances?</p> <p>April 2021</p> <p>on indico</p>	 <p>How do neutron star mergers impact r elements in the universe?</p> <p>March 2021</p> <p>on indico</p>
 <p>What do we need to know about nuclear astrophysics?</p> <p>February 2021</p> <p>on indico</p>			

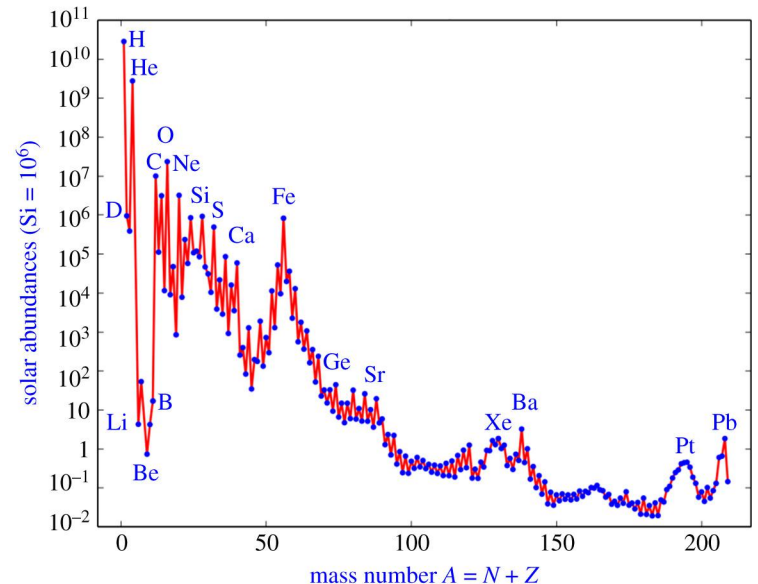
In particular, SNAQs 1, 3, 7 and 12.  
Check them out (<https://www.chetec-infra.eu/snaqs/>)!

# The NAP playground

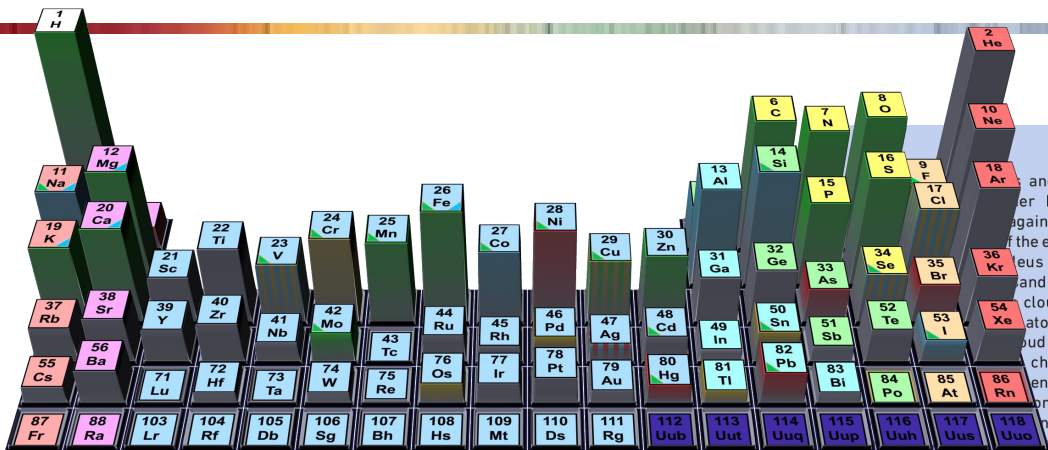


Features to be explained:

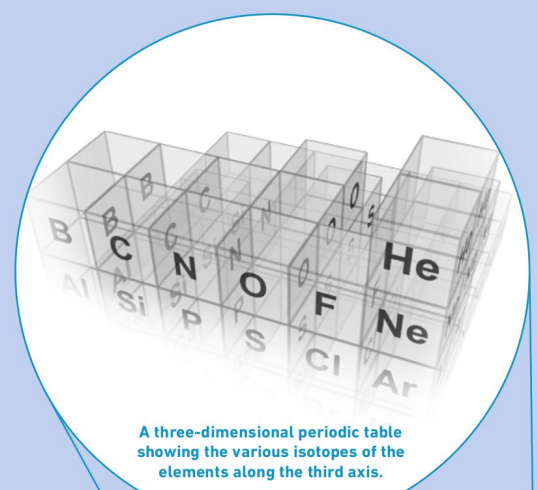
- very high abundances of H and He
- very low abundances of Li, Be and B
- high abundances of C, O, Ne, Mg Si, S and Ca
- high abundances in the Fe/Ni peak
- strong decline with  $A$  spanning  $> 12$  orders
- Ge/Sr, Xe/Ba & Pt/Pb double peaks



# The NAP playground



and number by the against the of the electric Heus is very and times cloud that atom. The cloud deter- chemical ent. The ons that number yety of isotopes, and these determine the characteristics of nuclear reactions. These reactions re-arrange the mix of isotopes and neutrons, thus cre- m existing nents, nu- ve unsta- from the gen and helium, elements such as carbon, oxygen, iron, and gold, and all their isotopes, are made.

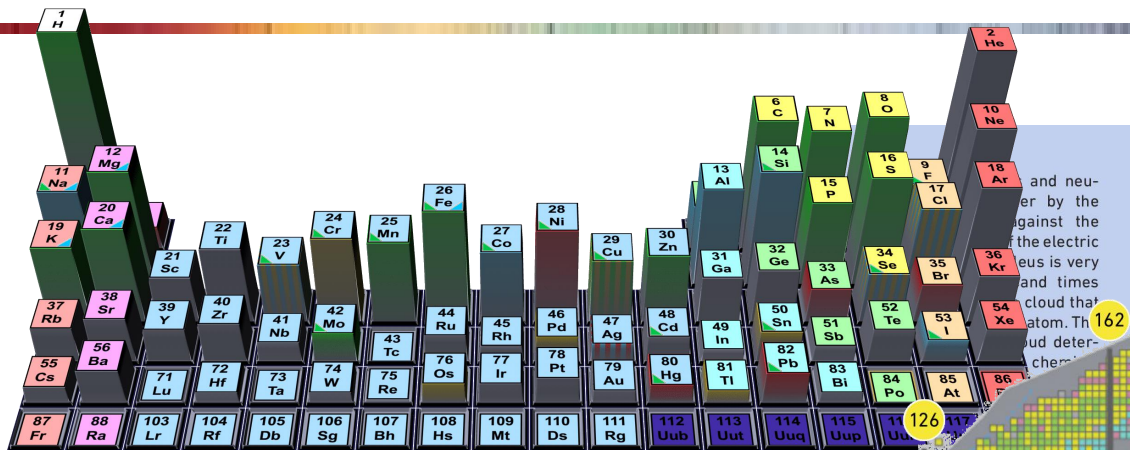


A three-dimensional periodic table showing the various isotopes of the elements along the third axis.

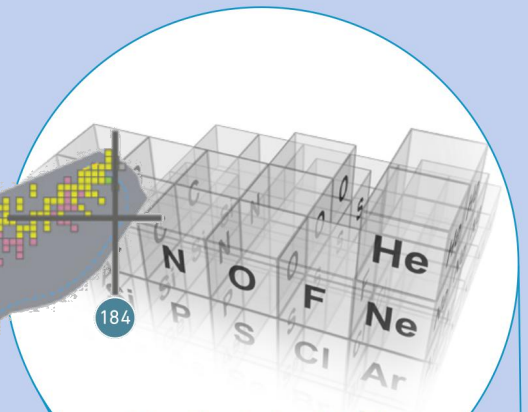
## IUPAC Periodic table of the elements

Key:																																																																									
atomic number	Symbol	name	standard atomic weight																																																																						
1	H	hydrogen	[1.0078, 1.0082]	2	He	helium	4.0026	3	Li	lithium	6.941	4	Be	beryllium	9.0122	5	B	boron	[10.806, 10.821]	6	C	carbon	[12.009, 12.012]	7	N	nitrogen	[14.006, 14.008]	8	O	oxygen	[15.999, 16.003]	9	F	fluorine	18.998	10	Ne	neon	20.180																																		
11	Na	sodium	[22.989, 22.990]	12	Mg	magnesium	[24.304, 24.305]	13	Al	aluminum	26.982	14	Si	silicon	[28.085, 28.086]	15	P	phosphorus	30.974	16	S	sulfur	[32.059, 32.076]	17	Cl	chlorine	[35.446, 35.453]	18	Ar	argon	39.948																																										
19	K	potassium	39.098	20	Ca	calcium	40.078	21	Sc	scandium	44.956	22	Ti	titanium	47.867	23	V	vanadium	50.942	24	Cr	chromium	51.996	25	Mn	manganese	54.938	26	Fe	iron	55.845	27	Co	cobalt	58.933	28	Ni	nickel	58.693	29	Cu	copper	63.546	30	Zn	zinc	65.38	31	Ga	gallium	69.723	32	Ge	germanium	72.630	33	As	arsenic	74.922	34	Se	selenium	78.9718	35	Br	bromine	[79.901, 79.904]	36	Kr	krypton	83.796		
37	Rb	rubidium	85.468	38	Sr	strontium	87.62	39	Y	yttrium	88.906	40	Zr	zirconium	91.224	41	Nb	niobium	92.906	42	Mo	molybdenum	95.94	43	Tc	technetium	[97.907, 97.907]	44	Ru	rhodium	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	121.757	52	Te	tellurium	[127.603, 127.603]	53	I	iodine	126.905	54	Xe	xenon	131.29		
55	Cs	caesium	132.91	56	Ba	barium	137.33	57-71	lanthanoids					72	Hf	hafnium	178.49	73	Ta	tantalum	180.948	74	W	tungsten	183.84	75	Re	rhenium	186.21	76	Os	osmium	190.23	77	Ir	iridium	192.22	78	Pt	platinum	195.08	79	Au	gold	196.967	80	Hg	mercury	[200.59, 200.59]	81	Tl	thallium	204.38	82	Pb	lead	207.2	83	Bi	bismuth	208.98	84	Po	polonium	[209, 209]	85	At	astatine	[210, 210]	86	Rn	radon	[222, 222]
87	Fr	francium	[223, 223]	88	Ra	radium	[226, 226]	89-103	actinoids					104	Rf	rutherfordium	261	105	Db	dubnium	262	106	Sg	seaborgium	263	107	Bh	bohrium	264	108	Hs	hassium	265	109	Mt	meitnerium	266	110	Ds	darmstadtium	267	111	Rg	roentgenium	268	112	Cn	copernicium	269	113	Nh	nihonium	270	114	Fl	flerovium	270	115	Mc	moscovium	271	116	Lv	livermorium	272	117	Ts	tennessine	273	118	Og	oganeson	274

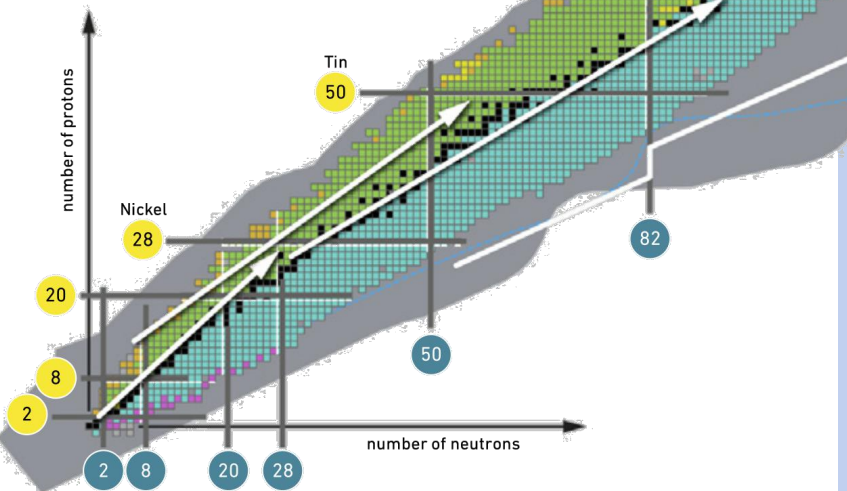
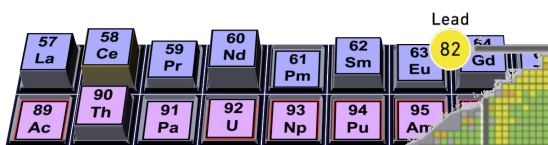
# The NAP playground



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A three-dimensional periodic table showing the various isotopes of the elements along the third axis.



IUPAC Periodic table of the elements

Key:		atomic number	
Symbol	name	name	standard atomic weight
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2	He	2	helium
3	Li	3	lithium
4	Be	4	beryllium
5	B	5	boron
6	C	6	carbon
7	N	7	nitrogen
8	O	8	oxygen
9	F	9	fluorine
10	Ne	10	neon
11	Na	11	sodium
12	Mg	12	magnesium
13	Al	13	aluminum
14	Si	14	silicon
15	P	15	phosphorus
16	S	16	sulfur
17	Cl	17	chlorine
18	Ar	18	argon
19	K	19	potassium
20	Ca	20	calcium
21	Sc	21	scandium
22	Ti	22	titanium
23	V	23	vanadium
24	Cr	24	chromium
25	Mn	25	manganese
26	Fe	26	iron
27	Co	27	cobalt
28	Ni	28	nickel
29	Cu	29	copper
30	Zn	30	zinc
31	Ga	31	gallium
32	Ge	32	germanium
33	As	33	arsenic
34	Se	34	selenium
35	Br	35	bromine
36	Kr	36	krypton
37	Rb	37	rubidium
38	Sr	38	strontium
39	Y	39	yttrium
40	Zr	40	zirconium
41	Nb	41	niobium
42	Mo	42	molybdenum
43	Tc	43	technetium
44	Ru	44	ruthenium
45	Rh	45	rhodium
46	Pd	46	palladium
47	Ag	47	silver
48	Cd	48	cadmium
49	In	49	indium
50	Sn	50	tin
51	Sb	51	antimony
52	Te	52	tellurium
53	I	53	iodine
54	Xe	54	xenon
55	Ba	56	barium
56	La	57-71	lanthanoids
57	Hf	72	hafnium
58	Ta	73	tantalum
59	W	74	wolframium
60	Re	75	rhenium
61	Os	76	osmium
62	Ir	77	iridium
63	Pt	78	platinum
64	Au	79	gold
65	Hg	80	mercury
66	Tl	81	thallium
67	Pb	82	lead
68	Bi	83	bismuth
69	Po	84	polonium
70	At	85	astatine
71	Rn	86	radon
72	Rf	87-103	rutherfordioids
73	Db	104	dubnium
74	Sg	105	seaborgium
75	Bh	106	bohrium
76	Hs	107	hassium
77	Mt	108	meitnerium
78	Ds	109	darmstadtium
79	Rg	110	roentgenium
80	Cn	111	copernicium
81	Nh	112	nihonium
82	Fl	113	flerovium
83	Mc	114	moscovium
84	Lv	115	livermorium
85	Ts	116	tennessine
86	Og	117	oganeson
87	Fr	118	francium
88	Ra	119	radium
89	Ac	120	actinoids
90	Th	91	thorium
91	Pa	92	protactinium
92	U	93	uranium
93	Np	94	neptunium
94	Pu	95	plutonium
95	Am	96	americium
96	Cm	97	curium
97	Bk	98	berkelium
98	Cf	99	californium
99	Es	100	einsteinium
100	Fm	101	fermium
101	Md	102	mendelevium
102	No	103	nobelium
103	Lr	104	lawrencium



# Where to collect elemental data

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**Earth** (geophysical processing, e.g. deuteration of oceanic water, ...)

**Moon & Mars** (surface bombarded by cosmic rays over 4.5 Gyr)

**meteorites and cosmic dust** (detailed isotopic information!; volatile elements depleted; see talks by Reto and Jenny)

**Sun** (photosphere, solar wind; solar modelling problem; a typical star?)

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**interstellar medium / HII regions** (isotopic information!; also gamma-ray lines from short-lived species like  $^{26}\text{Al}$ )

**starlight** (access to lots of elements!; mixing processes alter the composition of certain elements as stars evolve)

**stellar explosions** (supernova/kilonova lightcurves or “nebular” observations, e.g. SN1987A; hard to model, but progress is being made)

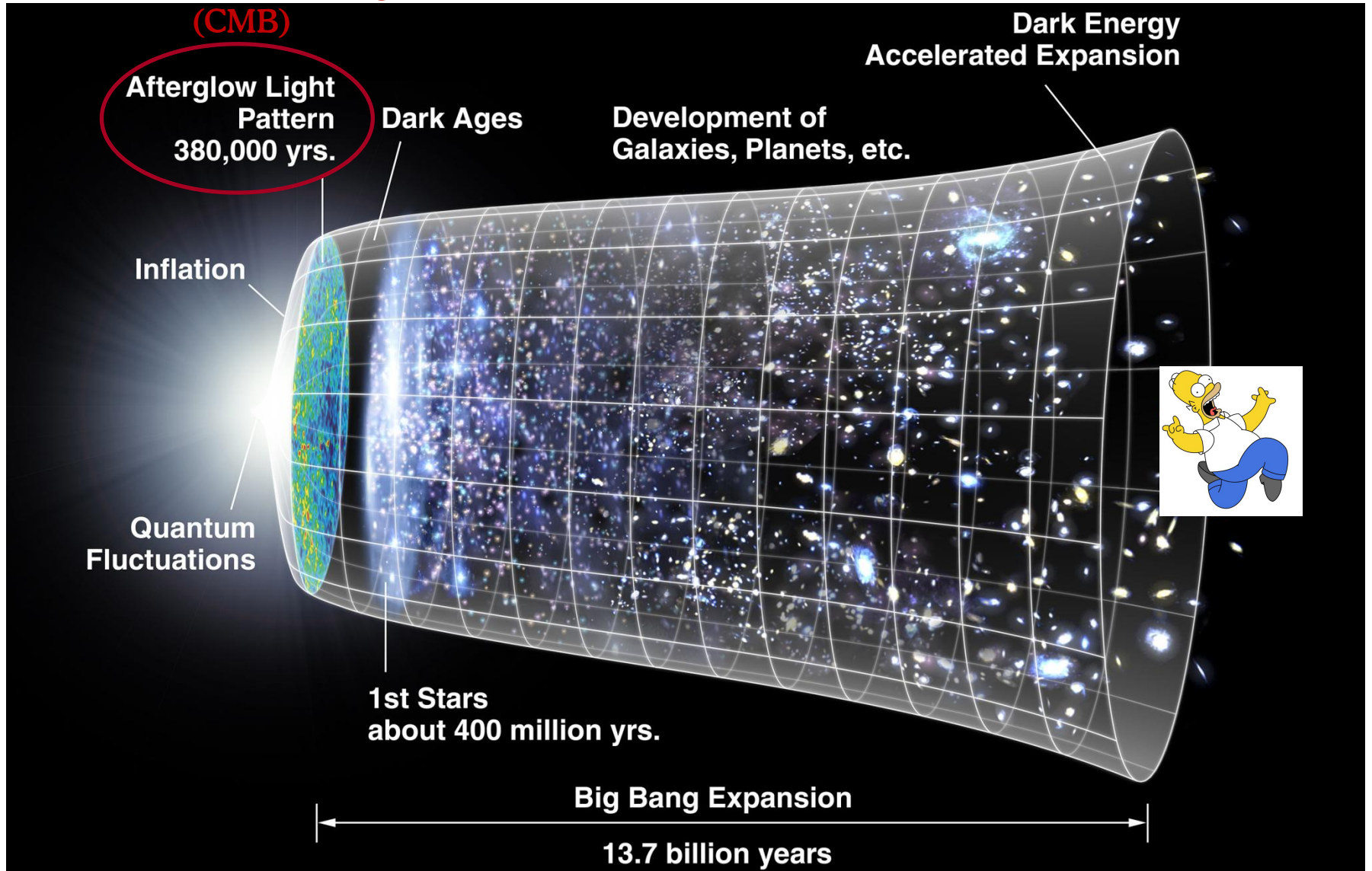


# I. Big Bang expansion and Big Bang Nucleosynthesis

We can observationally constrain the very first phase of element production just minutes after  $t=0$ . Amazing!

# Cosmic time line

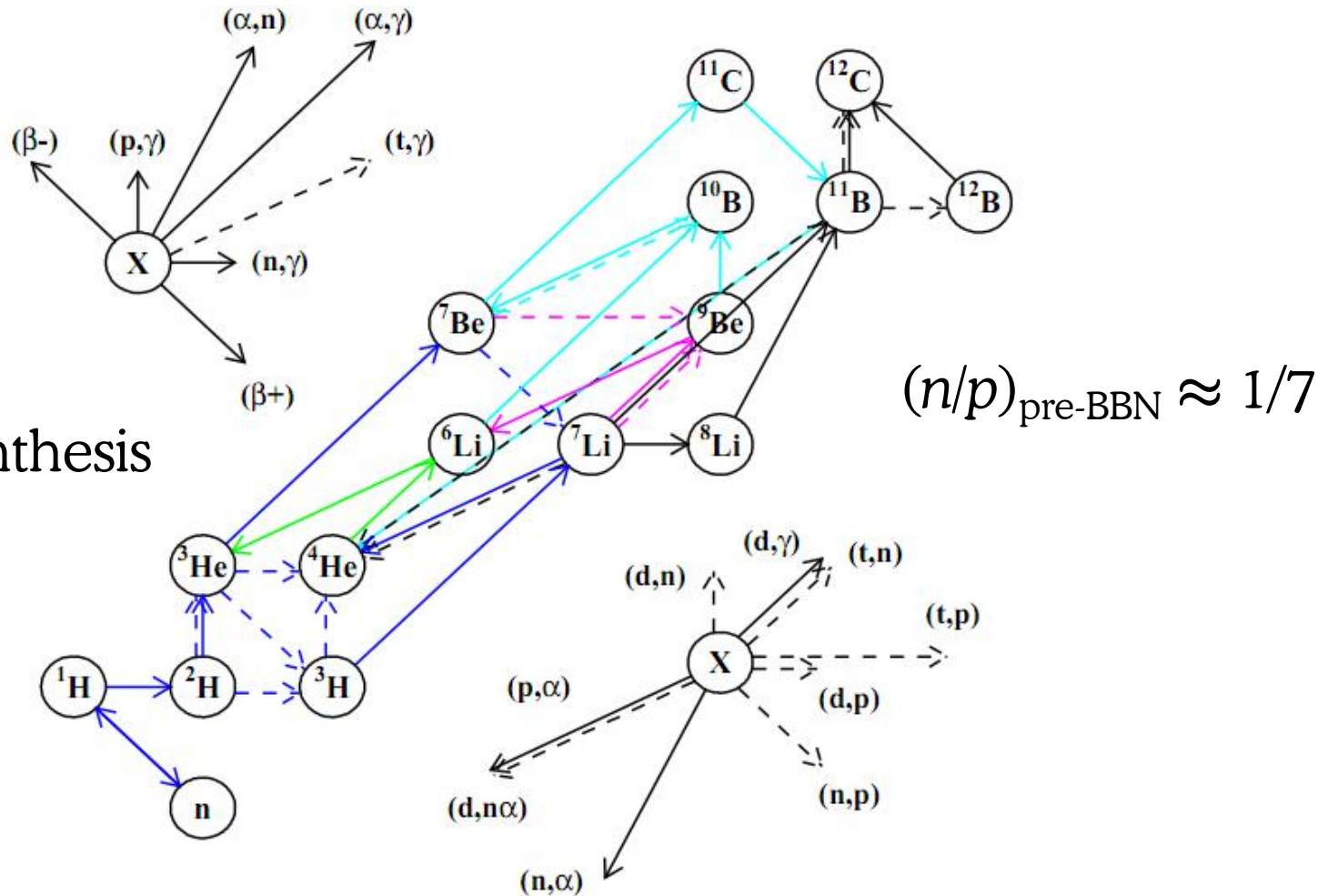
## Cosmic microwave background



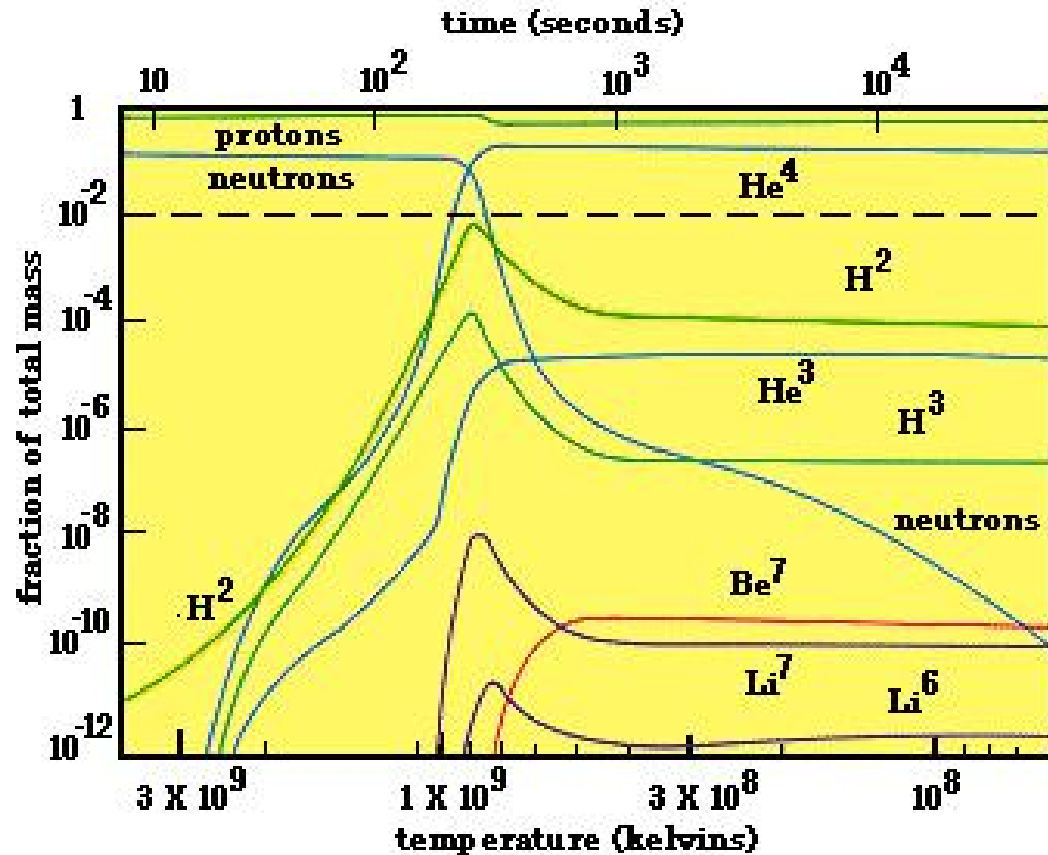
# Nucleosynthesis: from quarks to nuclei

Seconds to minutes after the Big Bang, the **Universe** has the right temperature ( $\approx 10^9$  K) to act as a **fusion reactor**.

Big Bang  
Nucleosynthesis  
network



# Following BBN



The expansion continues and the neutrons decay, quenching the fusion after a few minutes.

According to computations, highly accurate abundance ratios of hydrogen, helium, and lithium are predicted *essentially from first principles*.

We can observe  $D/H$ ,  ${}^4He/H$  and  ${}^7Li/H$  in little evolved objects. More on this tomorrow night. Stay put!

# Summary BBN

The Big Bang expansion theory can explain the evolution of the cosmos with two big unknown quantities:  $\Omega_{\text{DM}}$  and  $\Omega_{\Lambda}$ .

The strongest evidence for **Dark Matter** stems from detailed observations of CMB anisotropies, but other independent observations fit the same picture.

**During BBN, the first nuclei were produced:**

**75% H, 25%  $^4\text{He}$  and a tad of D,  $^3\text{He}$  and  $^7\text{Li}$ .**

# NB

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**Standard BBN in a homogeneous and isotropic Universe uniquely defines the nuclear (“chemical”) boundary condition for 14 Gyr of chemical evolution.**

The theory of how stars produce ~all remaining elements of the periodic table was laid out in the seminal paper by Burbidge, Burbidge, Fowler & Hoyle (1953, B2FH).



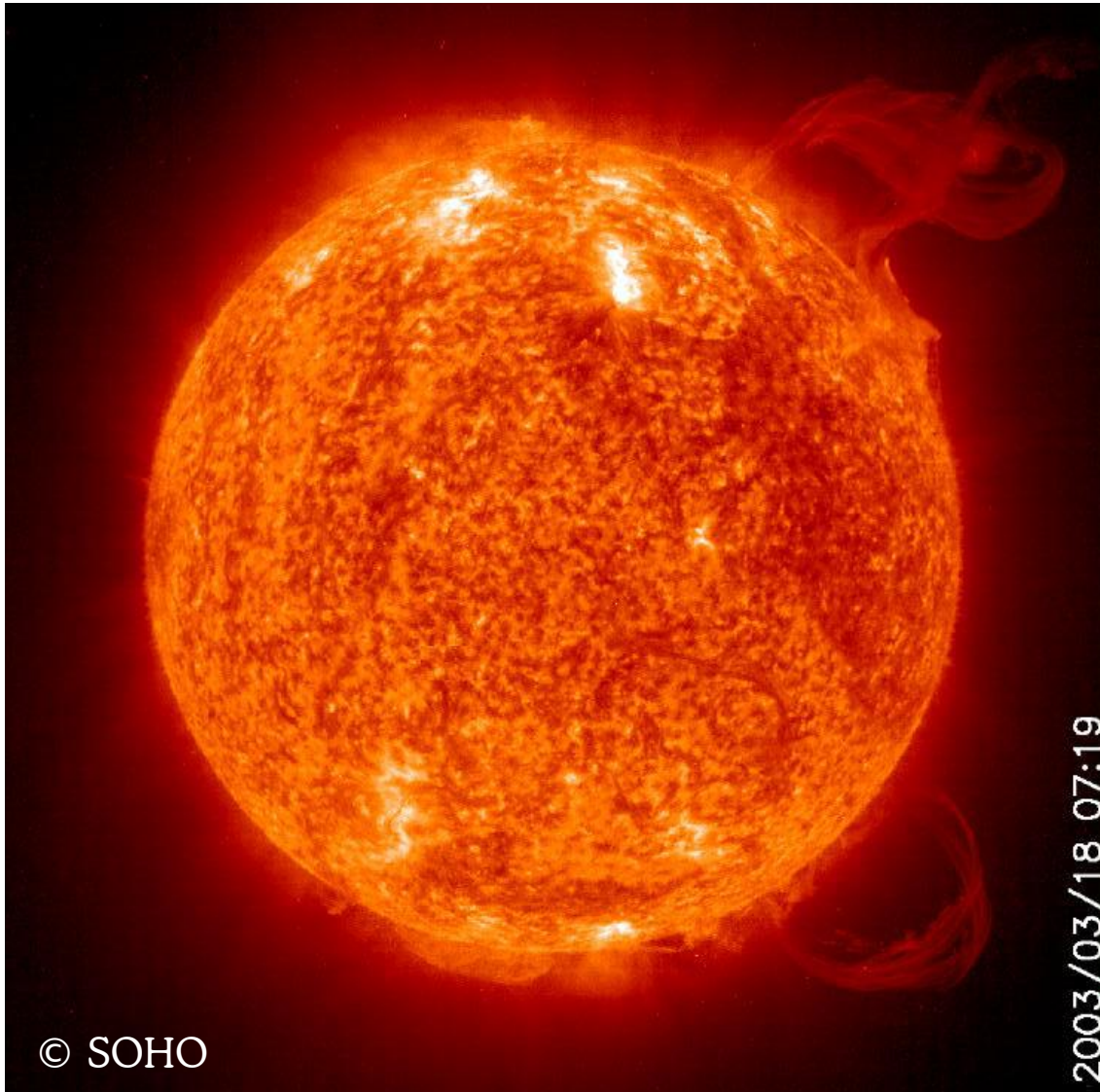


## II. Stars

the main source of cosmic abundance measurements *and* elements!

There is a natural focus on low-mass stars as they are long-lived and have rich atomic and molecular spectra. High-mass stars can constrain the *present-day* chemical evolution of the MW and extragalactic systems.

# Observables: stellar photons



Photons mainly originate from the stellar surface, a fairly thin (a few hundred km in the case of the sun) layer which we call the **stellar atmosphere**.

Unless there is significant exchange between the stellar interior and the atmosphere, the latter is a decent representation of the stellar material at birth. Mostly the case (with notable exceptions; more on this tomorrow). This is the foundation of **Galactic archaeology**.

# What is a star?

1930s: stars are powered by nuclear fusion  
(Bethe, Weizsäcker, following Eddington)

Thus, a star is a self-gravitating gas (plasma)  
sphere with nuclear fusion as its energy source.

Mass range:  $80 M_{\text{Jupiter}} (0.08 M_{\odot}) < M < \sim 150 M_{\odot}$

Right mass, but not yet fusing: PMS stars

Not fusing anymore: stellar remnant (WD, NS, BH)

# Main sequence phase

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All stars spend 80-90% of their lives on the main sequence (MS), i.e. for millions to billions of years depending on stellar mass.

Whilst on the MS, stars burn H to He in their cores (high-mass stars via CNO cycles).

*How do we know this for a fact?*

**Main product:** He (but also some N and  $^{13}\text{C}$ ).

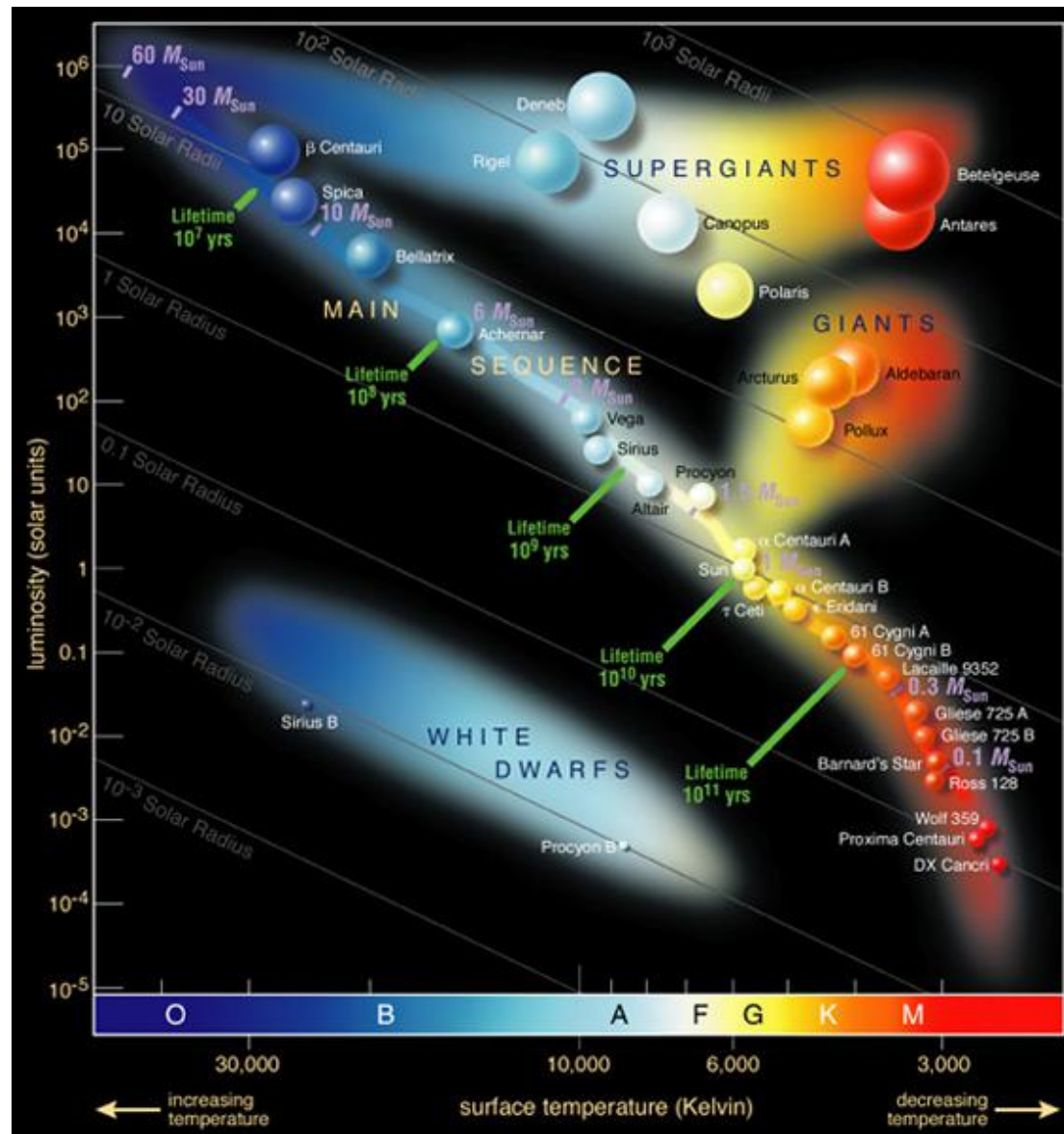
Stars move away from the MS once hydrogen in their core is exhausted (“turnoff point”, TOP). The TOP is an important age indicator for stellar aggregates like clusters.

# Surface temperatures, luminosities, radii

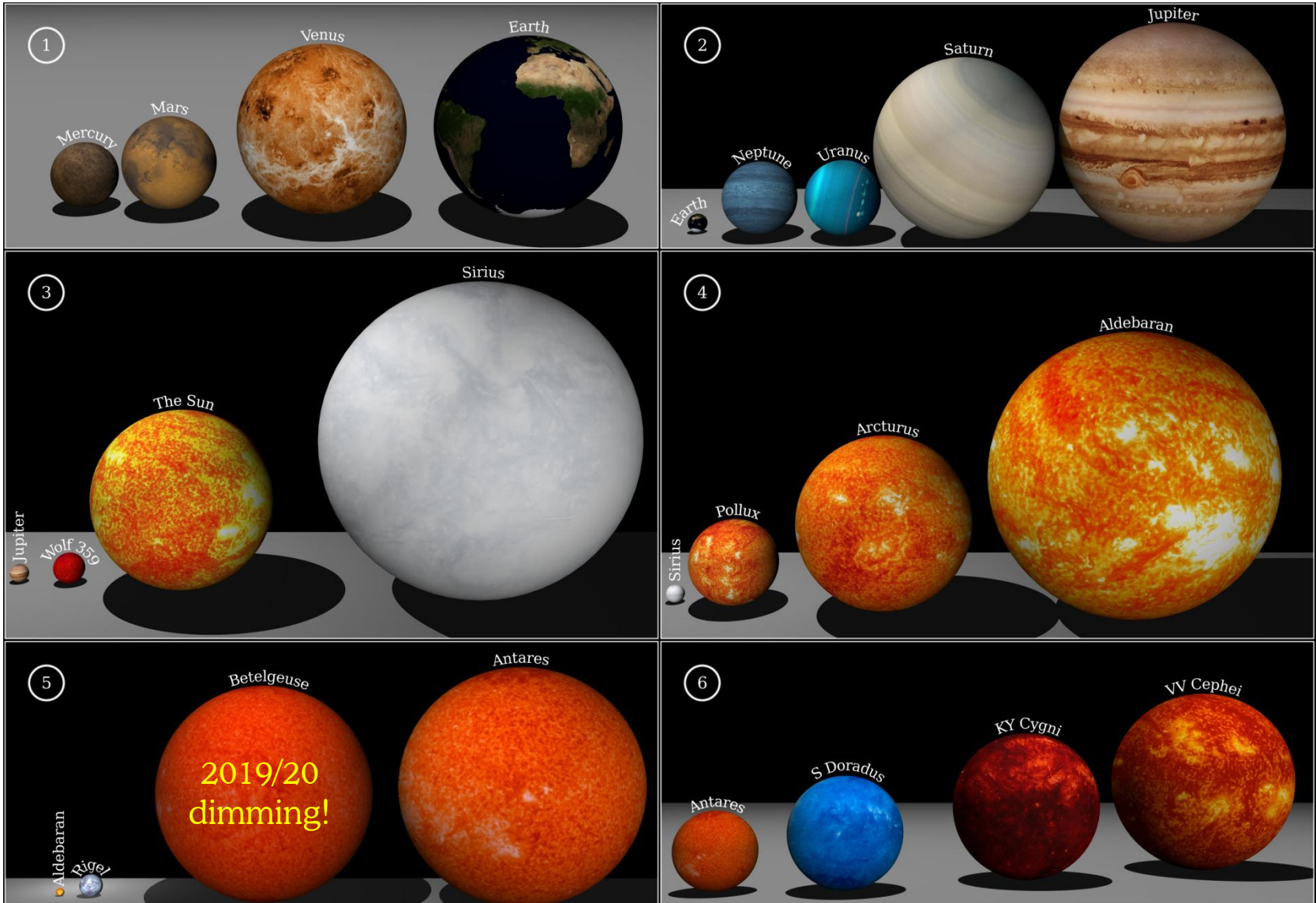
A **Hertzsprung-Russell diagram** shows the fundamental plane of stars in “observable” quantities:  $M_G$  vs  $BP-RP$  or  $L$  vs  $T_{\text{eff}}$ .

The main sequence (MS) is inclined with respect to loci of constant radius: upper-MS stars (OB-type) are much more luminous, because they are hotter and larger.

White dwarfs (WD) are stellar remnants, not stars.



# The zoo of stars



# Nuclear energy release

Various nuclear processes can power stars. All stars either run the  $p$ - $p$  chains or the CNO cycles. Stars more massive than the Sun experience more advanced burning stages.

We approximate  $q$  (and the opacity  $\kappa$ ) as power laws in  $\rho$  and  $T$ :

$$q \propto \rho^m T^n$$

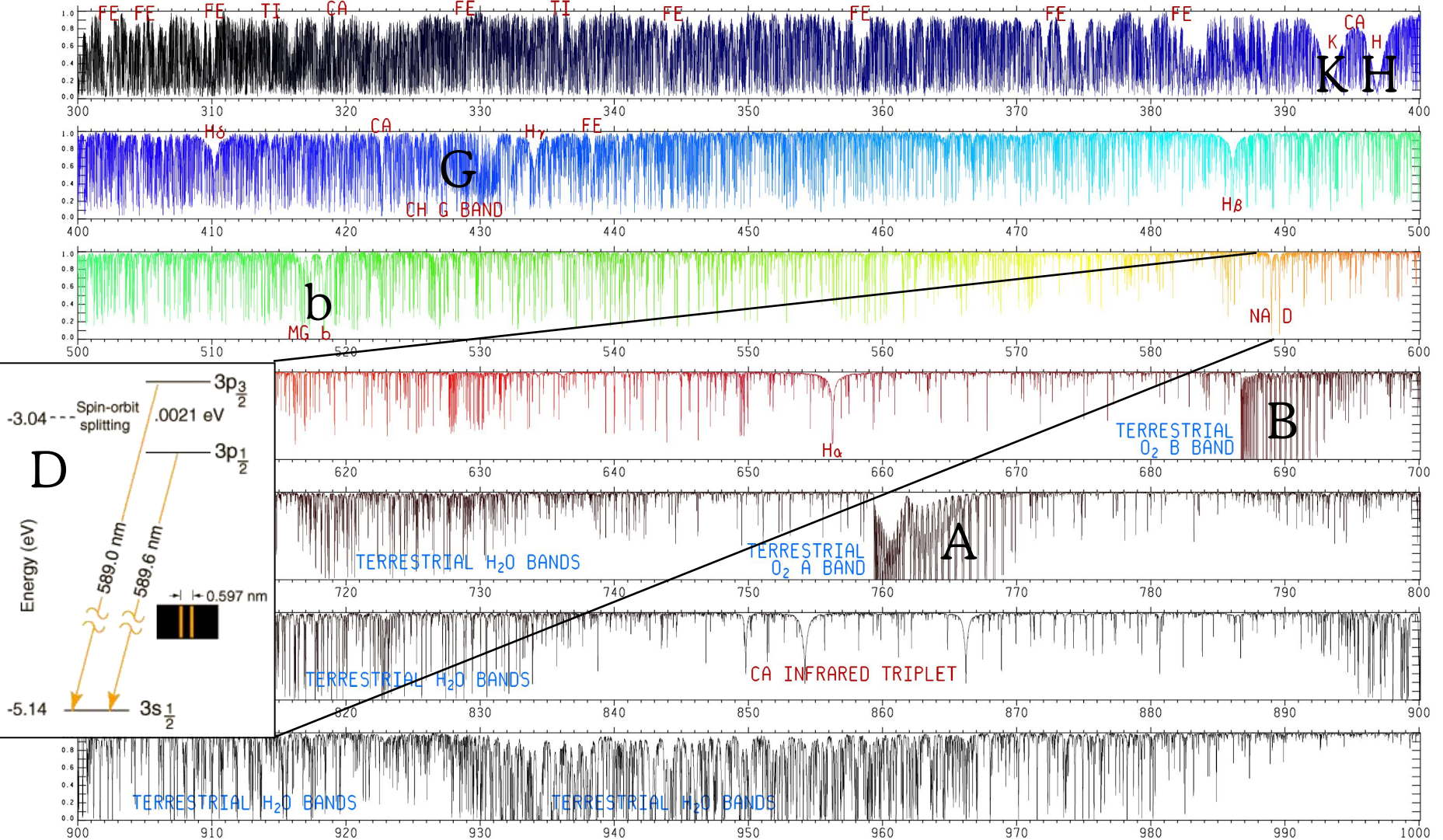
energy released  
per unit mass

	$m$	$n$	main product(s)
p – p	1	4	He
CNO	1	20	He
$3\alpha$	2	40	C, O
C	1	30	O,Ne,Na,Mg
O	1	45	Mg,S,P,Si

Cycles switch on *instantly* as they are *very*  $T$ -sensitive!

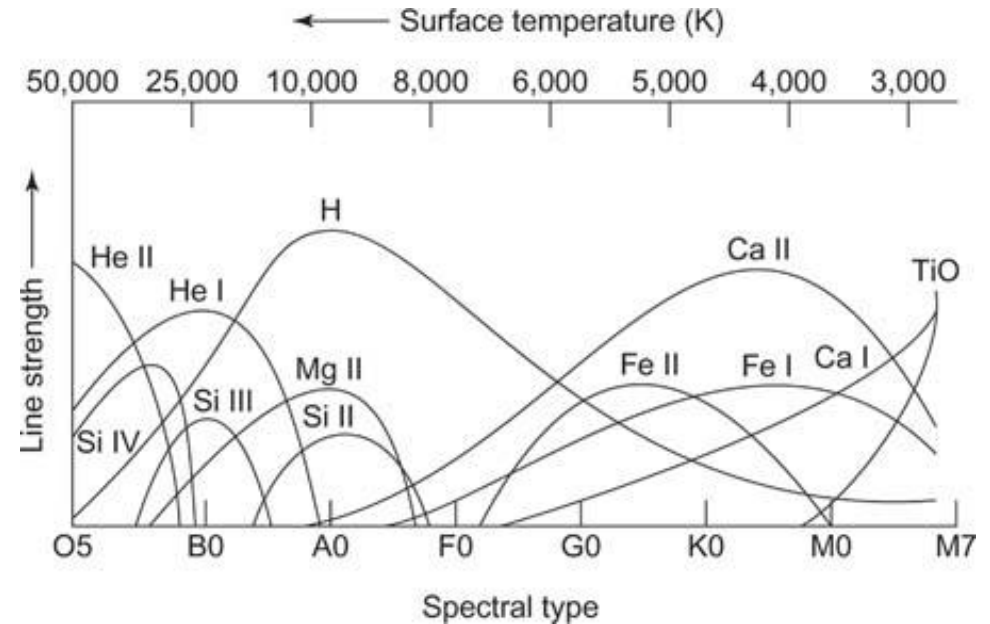
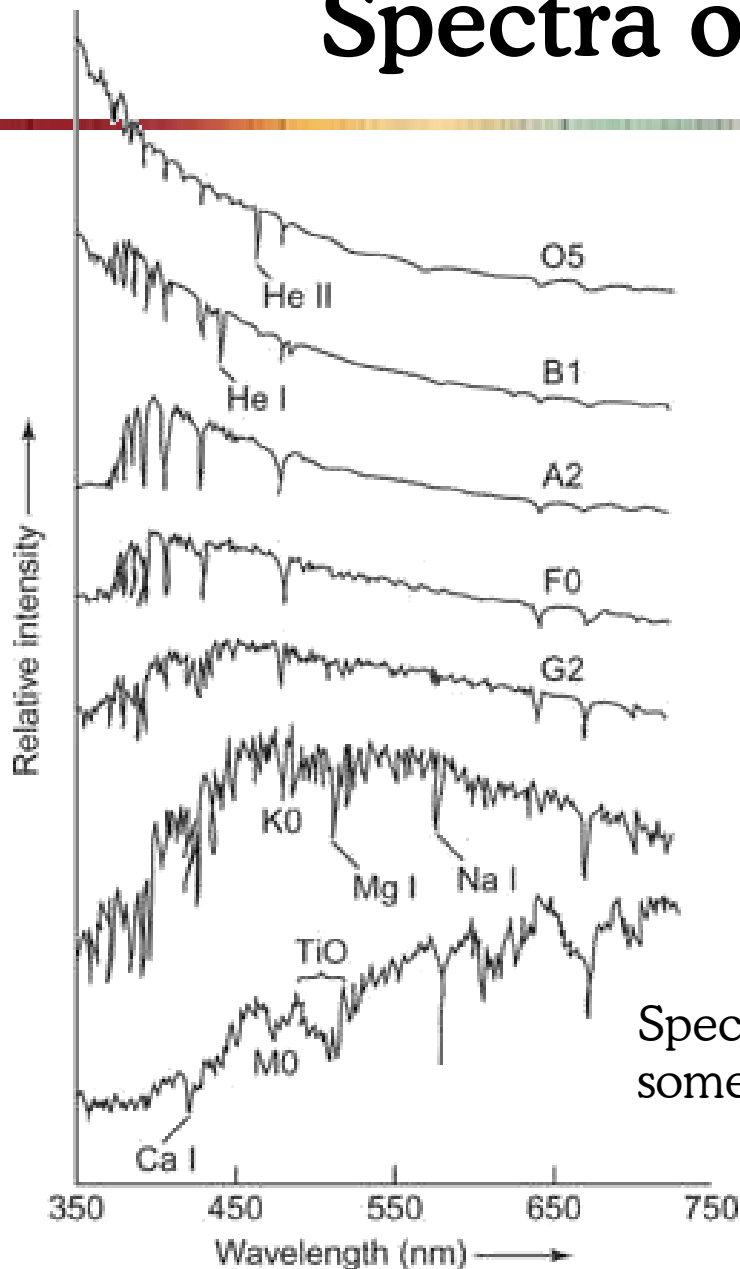
# The solar spectrum

KITT PEAK SOLAR FLUX ATLAS (KURUCZ, FURENLID, BRAULT, AND TESTERMAN 1984)





# Spectra of different stars



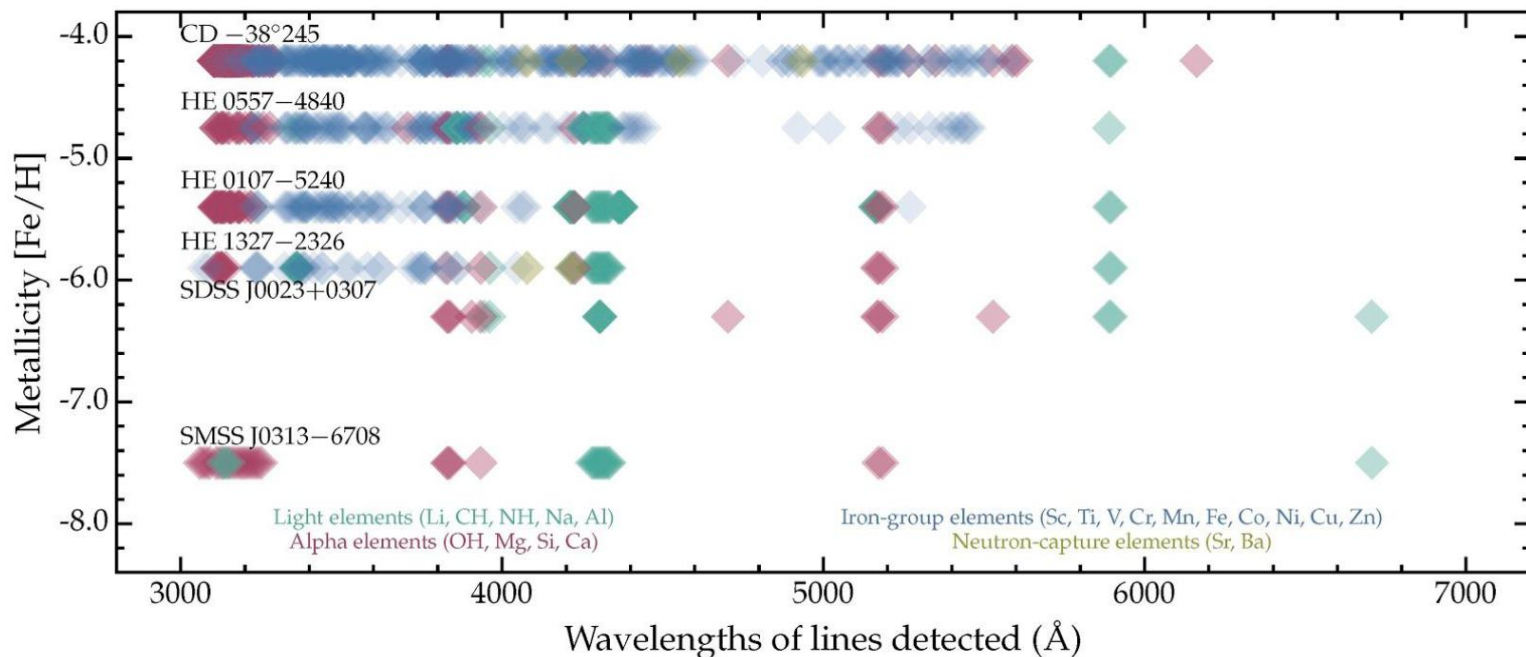
Spectra of low-mass stars (GKM) allow to probe some isotopic ratios, e.g.  $^{24,25,26}\text{Mg}$  (Yong *et al.* 2003)

# Where stars have their spectral lines

Metal-rich stars (like the sun) have so many lines that observations in the blue or UV spectral region can be difficult.

Metal-poor stars have significantly reduced line densities which makes observations in the blue/UV a necessity, especially for rare species.

For more details on this, see Camilla's talk.

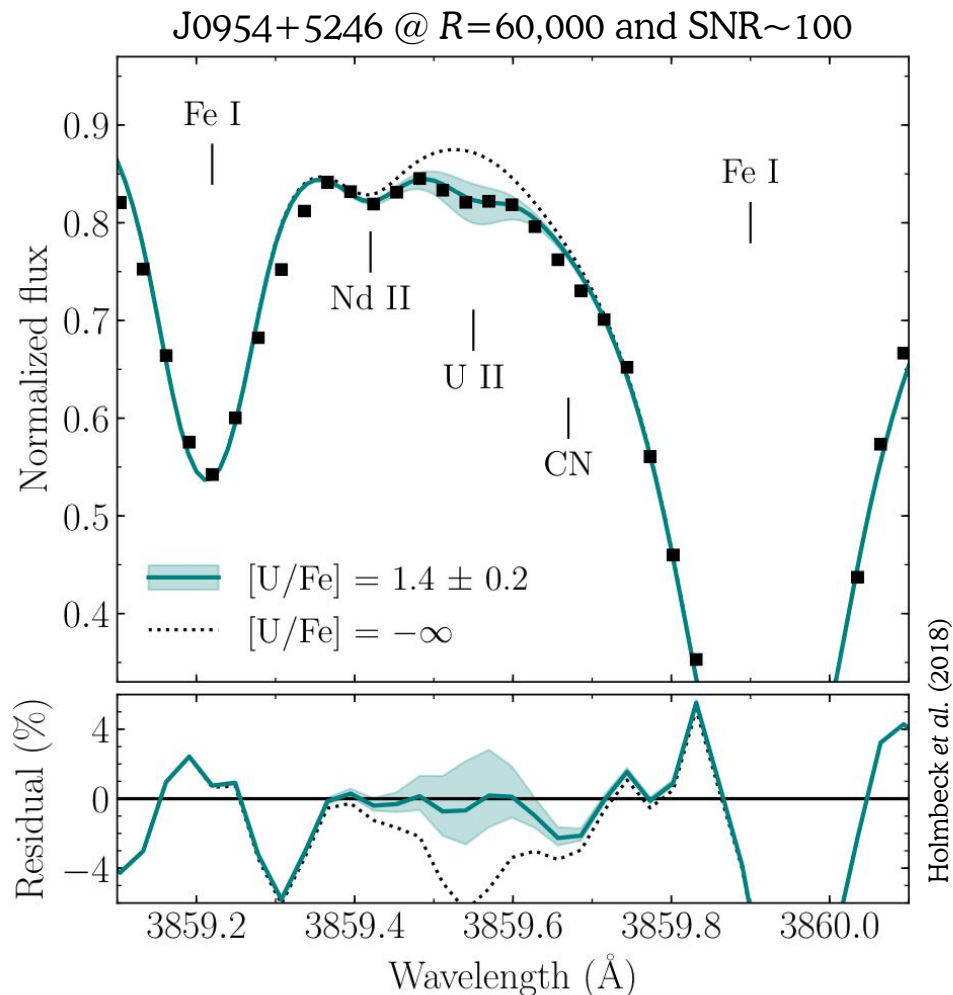


Roederer et al. (2019)

# Modelling stellar spectra

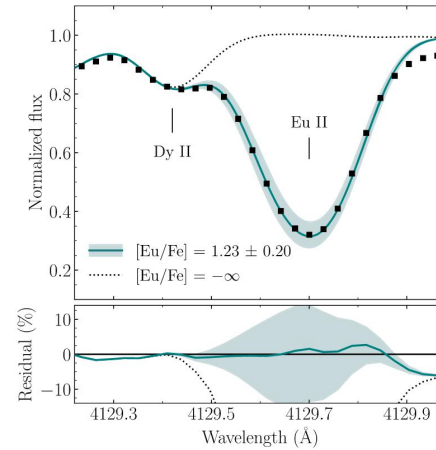
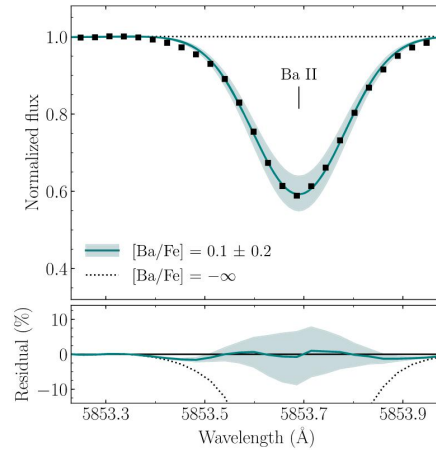
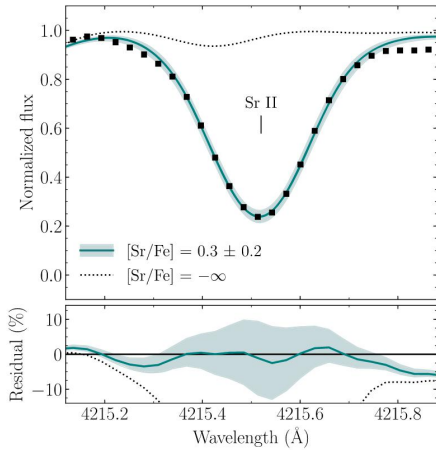
We can observe elements from H to U. Modelling is mature, but classical (1970s+) assumptions (1D, LTE) can lead to biased results, in particular for metal-poor stars the atmospheres of which do not resemble 1D models and high UV fluxes drive line formation away from LTE.

With NLTE (3D) modelling, accuracies of 0.1 dex (25%) in  $[X/H]$  are now achievable (given good spectral data).

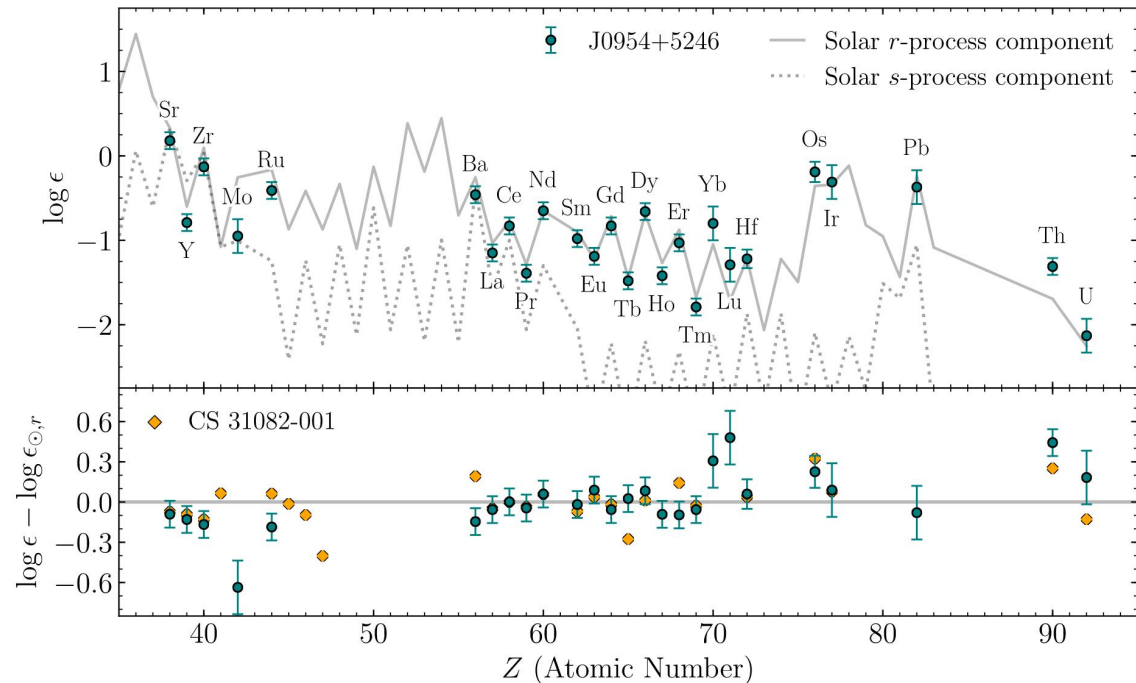
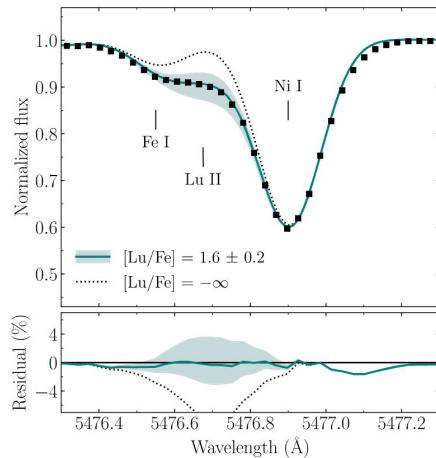


See Asplund (2005) and SNAQs talks by Andy Gallagher (AIP) & Anish Amarsi (UU)!

# Good spectra + good models = good results



An almost perfect solar *r*-process pattern!  
Almost...



Model *all* known lines!

# Get the nomenclature right!

**mass fractions:** let  $X$ ,  $Y$ ,  $Z$  denote the mass-weighted abundances of H, He and all other elements (“metals”), respectively, normalized to unity ( $X + Y + Z = 1$ ).

example:  $X_{\odot} = 0.744$ ,  $Y_{\odot} = 0.242$ ,  $Z_{\odot} = 0.014$

(Asplund, Amarsi & Grevesse 2021)

**The 12 scale:**  $\log \epsilon(M) = \log (n_M / n_H) + 12$

example:  $\log \epsilon(O)_{\odot} \approx 8.7$  dex, i.e., oxygen, the most abundant metal, is 2000 times less abundant than H in the Sun (Asplund, Amarsi & Grevesse 2021)

**Square-bracket scale:**  $[M/H] = \log (n_M / n_H)_* - \log (n_M / n_H)_{\odot}$

example:  $[Fe/H]_{HE0107-5240} = -5.3$  dex, i.e., this star has an iron abundance a factor of 200 000 below the Sun (Christlieb *et al.* 2002)

# The Milky Way



gaia

Halo  
(spheroidal component,  
home of globular clusters,  
GSE and MW satellites)

Galactic

**Galactic  
bulge**

disk(s)

Magellanic  
Clouds

© Gaia DPAC

Star *density* map, assembled by Gaia

For GSE, Gaia's main MW-evolution discovery, see Helmi *et al.* (2018).

# The role of environment

**Open clusters:** youngish (0-6 Gyr) and fairly simple. Excellent objects to test one's analysis methods *and* study stellar evolution. There are many details left to understand (dredge-up, role of rotation...)!



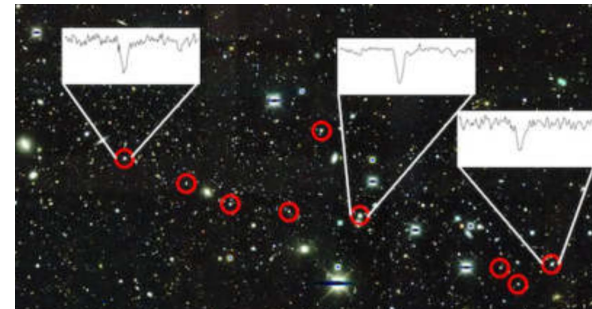
© Greg Noel

**Globular clusters:** very old, very complex, unexplained! See e.g. Milone *et al.* (2017) for chromosome-map analysis. HRD construction: <https://youtu.be/HWQslu4S5eQ>



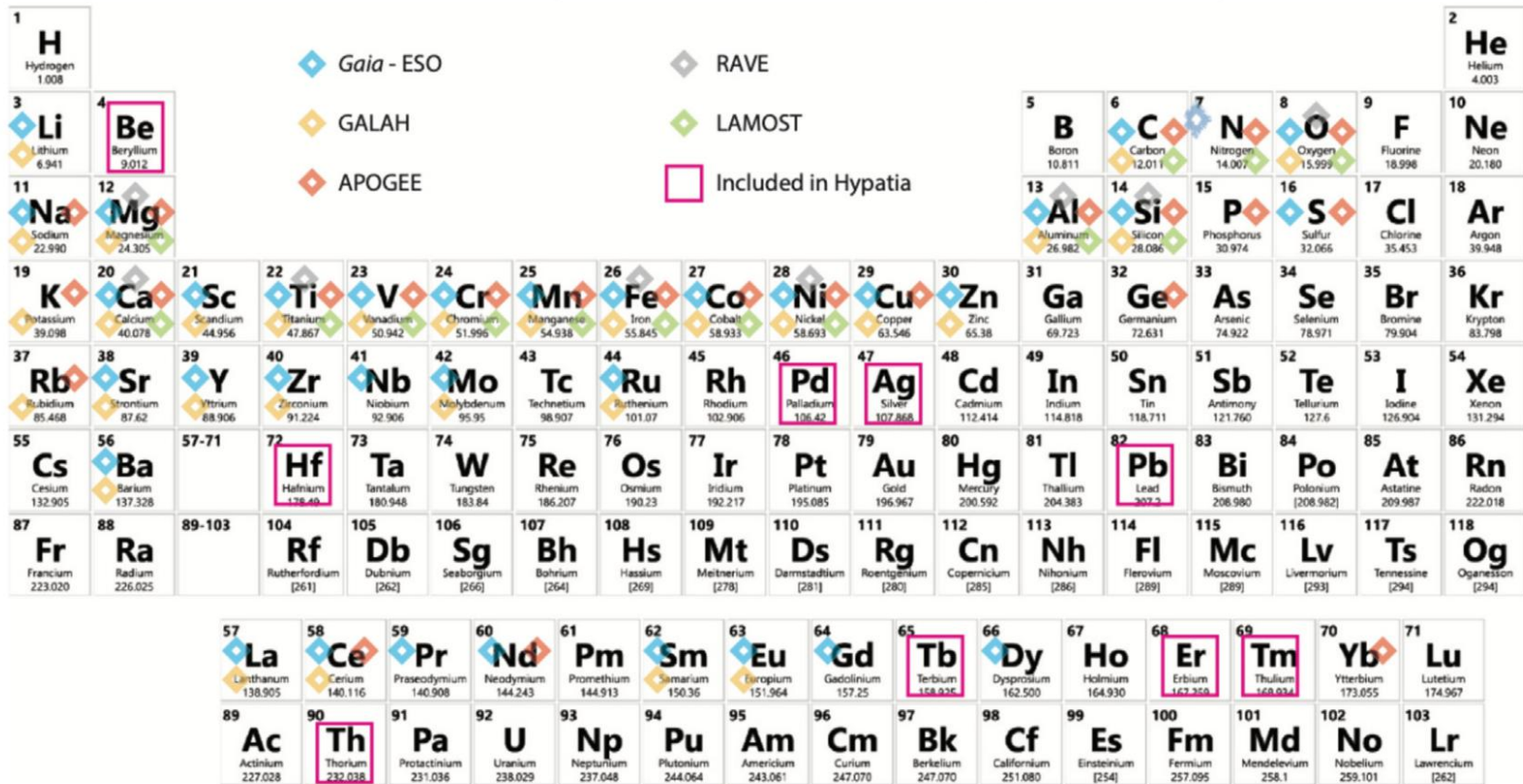
© ESO

**MW satellite galaxies**, e.g. dSph galaxies: remnants of the hierarchical structure formation of the MW. Some have totally unique abundance patterns constraining individual enrichment events (see e.g. Ji *et al.* (2016) on Reticulum II).



# Deep and wide stellar surveys

Elements potentially detected in spectroscopic surveys of the Milky Way



Jofré et al. (2019)

And the near future will see surveys with *tens of millions* of spectra: **WEAVE** (N) and **4MOST** (S). Plus **Gaia-RVS**! See Johannes' talk on a widely used spectroscopic tool (pySME).



# The holy grail: Population III

The very first generation of stars, Pop III, only consisting of H and He, is to date unobserved.

Presumably exclusively high-mass (cooling primordial gas is difficult!) and thus short-lived.

Maybe not, we may have to sample the MW halo in greater depth. The metallicity distribution function drops very steeply (factor 100 for factor of 10 in metal content).

Pop III stars enriched **extreme Pop II** with the first metals which offers **an indirect way of studying Pop III SNe**.

For the most extreme example, see Keller *et al.* (2014):  $[\text{Fe}/\text{H}] < -7.5$  and an abundance pattern anything but solar!

See also Welch *et al.* (2022) for a highly magnified massive star (binary) at  $z \sim 6$ . Wow!

# Summary Stars

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We have seen that there are all kinds of stars. They differ drastically in shapes and sizes ( $M$ ,  $R$ ). **Mass is a star's most fundamental parameter.** All stars fuse nuclei in different burning stages. All initially fuse H to He in either the ***pp* chains** or the **CNO cycles**. Late stages of evolution can produce rather heavy elements (Sect. III).

So how are the elements beyond the iron peak created?

# III. Stellar endgames

Dying low-mass stars produce **s-process elements** with peaks at the neutron magic numbers, as well as lithium.

SNe type II (core-collapse of massive stars) produce  **$\alpha$  elements** ( $O + n \cdot {}^4\text{He}$ , up to Ca) and kilonovae (merging neutron stars) **r-process elements**.

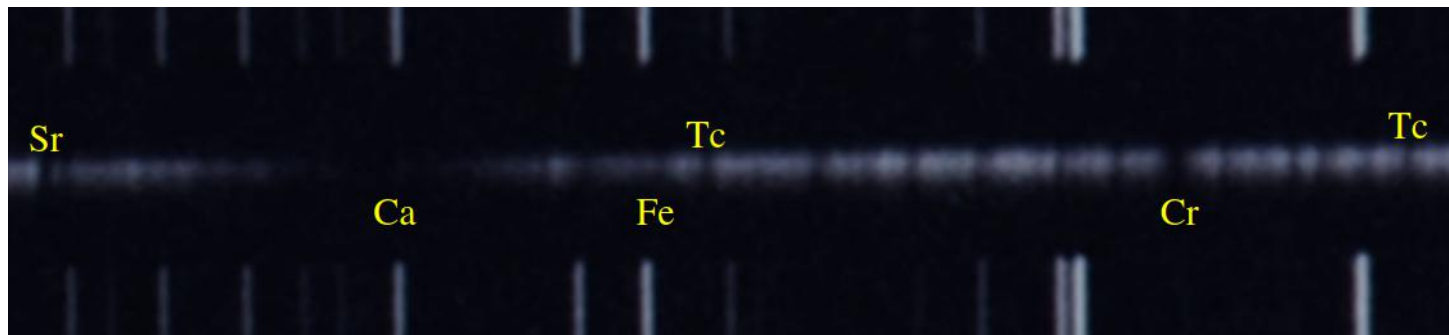
Some explosions produce nucleids on the proton-rich side of the valley of stability through a **p process**. Processes involving neutrinos are also expected to contribute ( **$\nu$ -process/ $\nu$ p-process**). + + +

Finally, **SNe type Ia** (thermonuclear deflagrations of white dwarfs) **contribute significantly to the iron peak**.

# Neutron-capture processes in AGB stars

Low- and intermediate-mass evolved (asymptotic giant branch, AGB) stars manage to create neutron-rich condition in their interiors which lead to the successive build-up of heavier elements. This process is referred to as the **s (slow neutron capture) process**, as it proceeds close to the valley of stability in competition with  $\beta$  decays.

The smoking gun of this process is the detection of Tc (Merrill 1952) in the spectra of cool AGB stars: this element has no stable isotope, i.e. it must have been produced in the past few Myr.



See Sergio's and Marco's talk tomorrow.

# The demise of low-mass stars

From Planetary  
Nebulae (PNe)  
to White Dwarfs  
(WDs).  
WDs in binaries  
can go SN!



# Stars with $M \approx 8 M_{\odot}$ or more

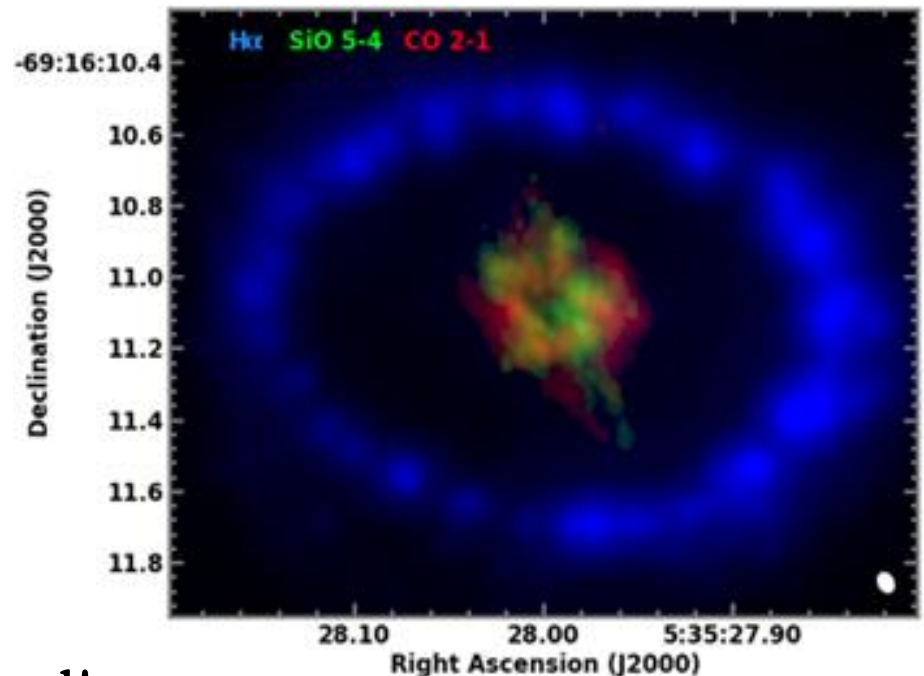
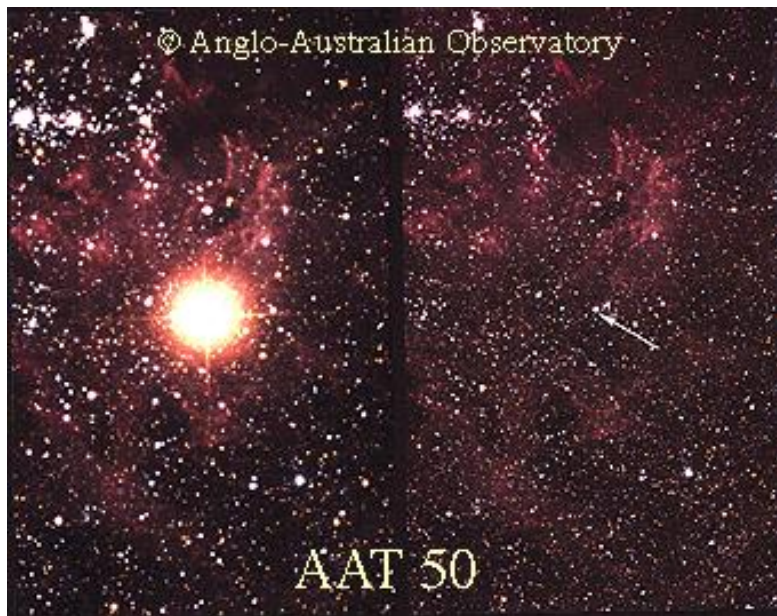
These stars occupy the same  $L$  regime as AGB stars, but are significantly hotter. As radiation pressure goes with the fourth power of  $T$ , radiation-driven mass loss is strong in these stars and will significantly affect their evolution (prime example: Wolf-Rayet stars).

High-mass stars move more or less horizontally across the HRD, at constant  $L$ . They may explode either in the blue or the red part, as blue or red supergiants. The SN (type II) explosion was long believed to be the site of the ***r* (rapid neutron-capture) process** producing  $\approx$  half of the stable nuclei beyond the iron peak, plus U and Th.

Example: Eu(ropium) in the Solar System is 94% *r* (Arlandini et al. 1999)

# SN 1987A

The supernova (type IIp) we have been able to follow in greatest detail. The progenitor was an inconspicuous B3 supergiant.

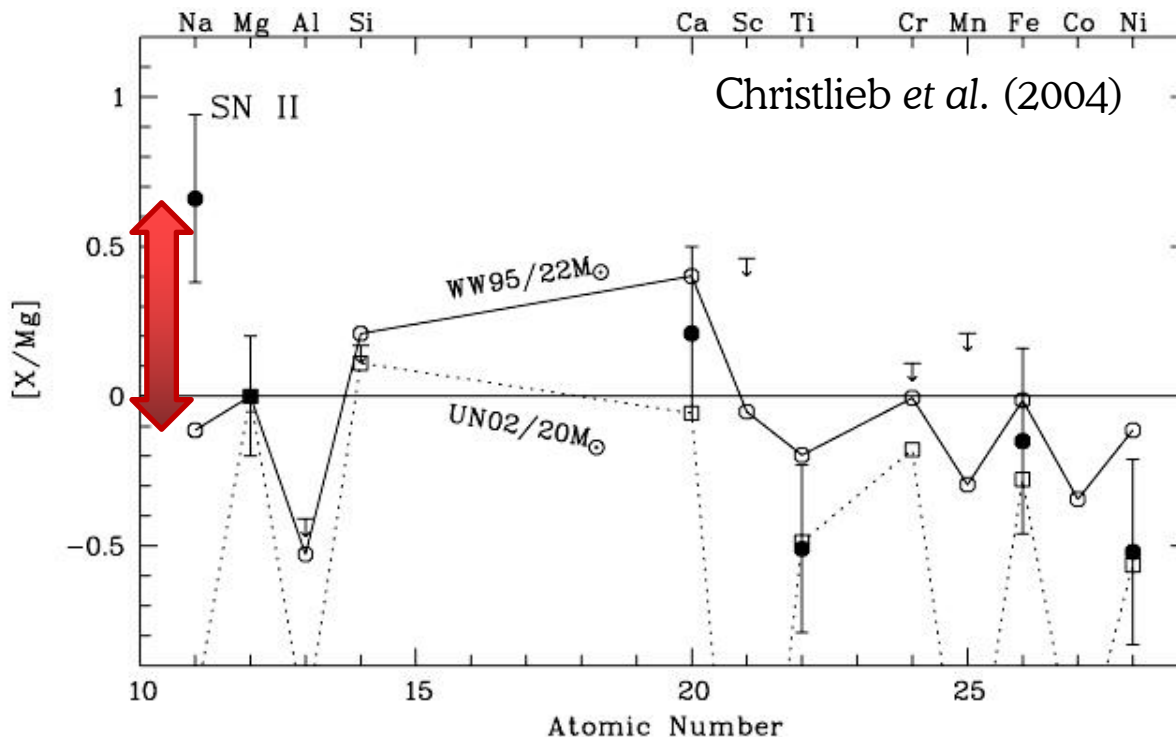


...plus some 20  $\nu$ s detected!

Abellán *et al.* (2017)

# SN yields

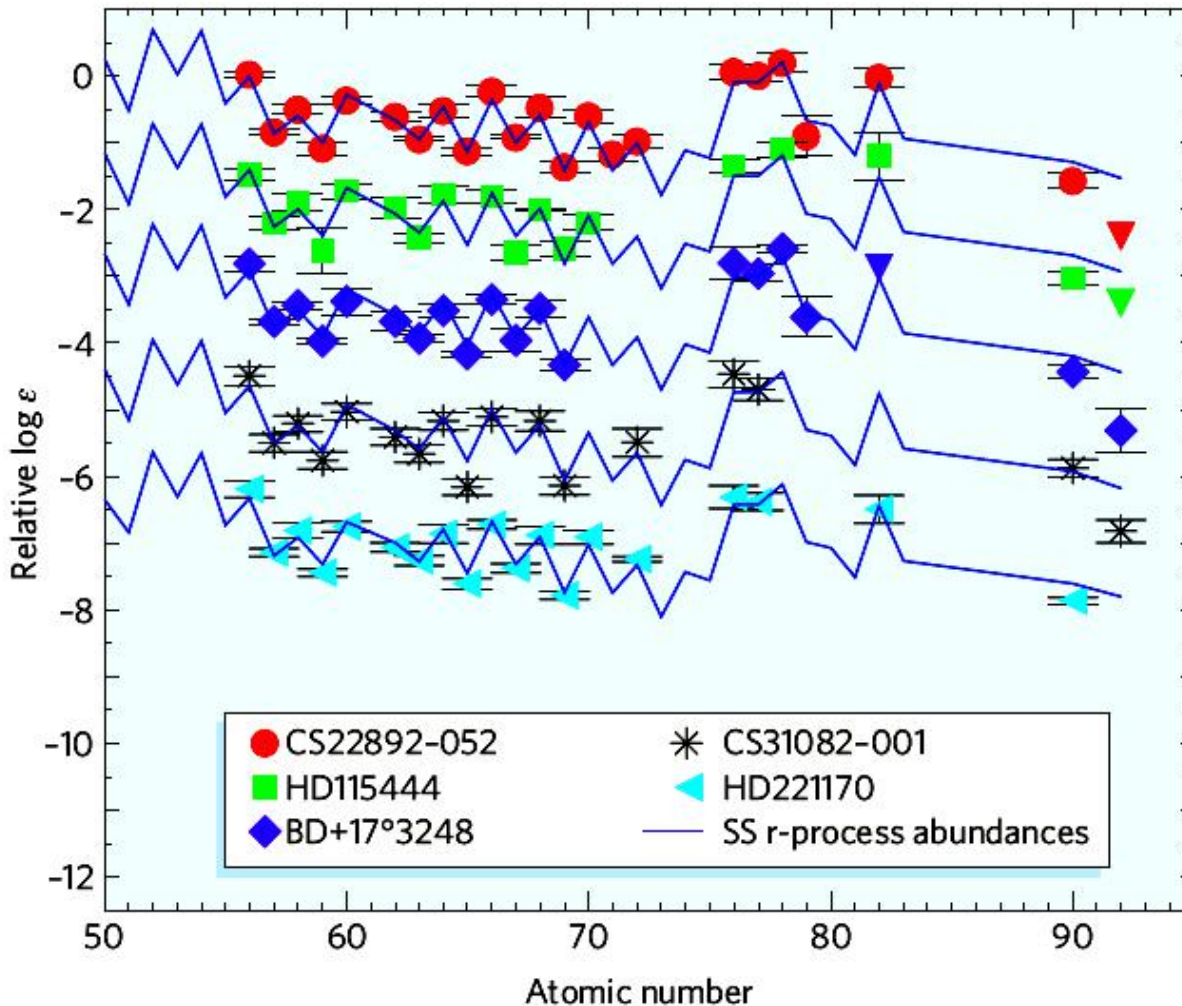
The elemental output of a star. Depends critically on the mass of the SN progenitor (roughly  $8 M_{\odot} < M < 50 M_{\odot}$ ) and the physical modelling. Many free parameters (mixing, mass cut, fallback,  $\nu$  physics), nonetheless some successes:



Important to have more measured abundances as constraints than tunable parameters in the model!



# Is the r process universal?



Cowan & Sneden (2006)

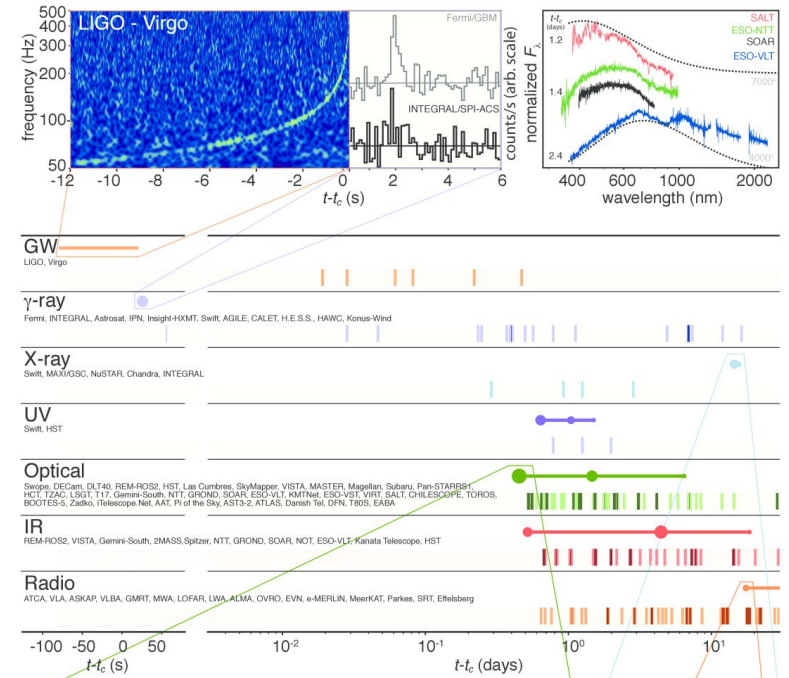
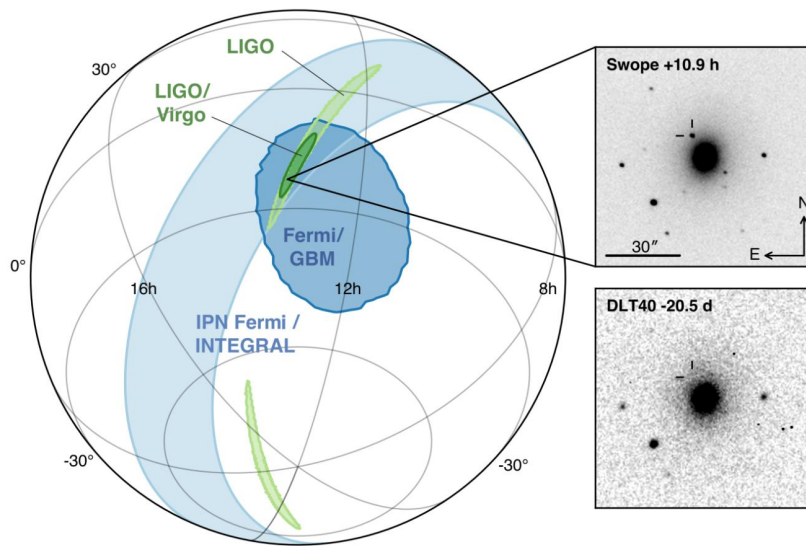
See  
Gabriel's talk.

*How can it be universal?*

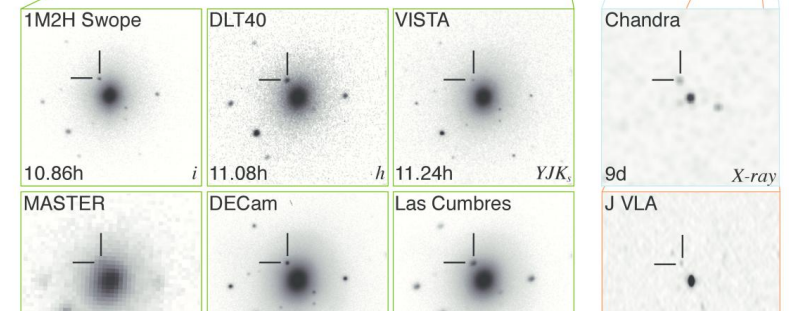
# Neutron star mergers: finally confirmed

## GW170817 plus GRB170817A (~1.7 s later) plus optical follow-up

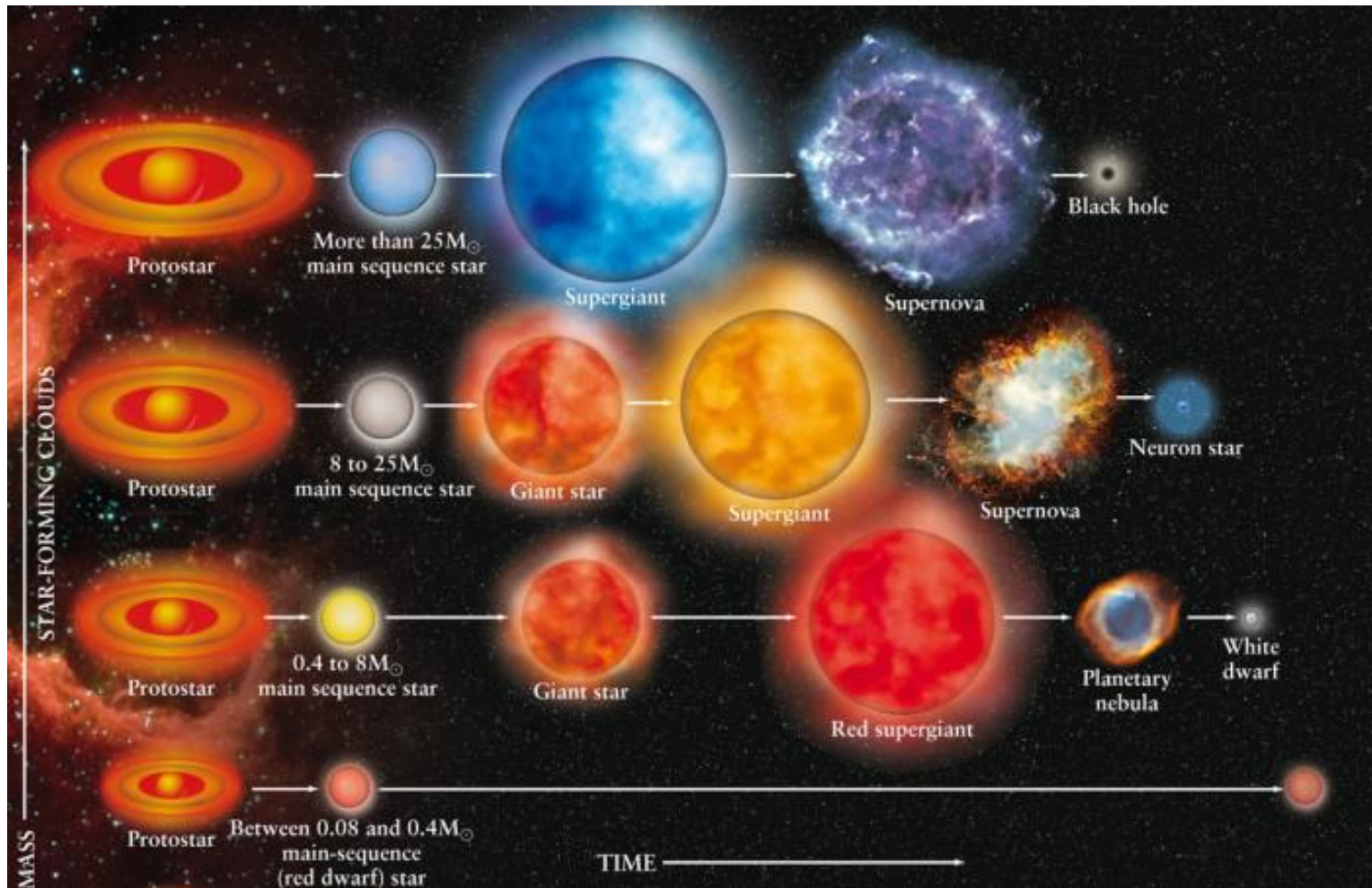
LIGO et al. (2017),  
The Multi-messenger Paper



A confirmed source of  
**r-process elements!**

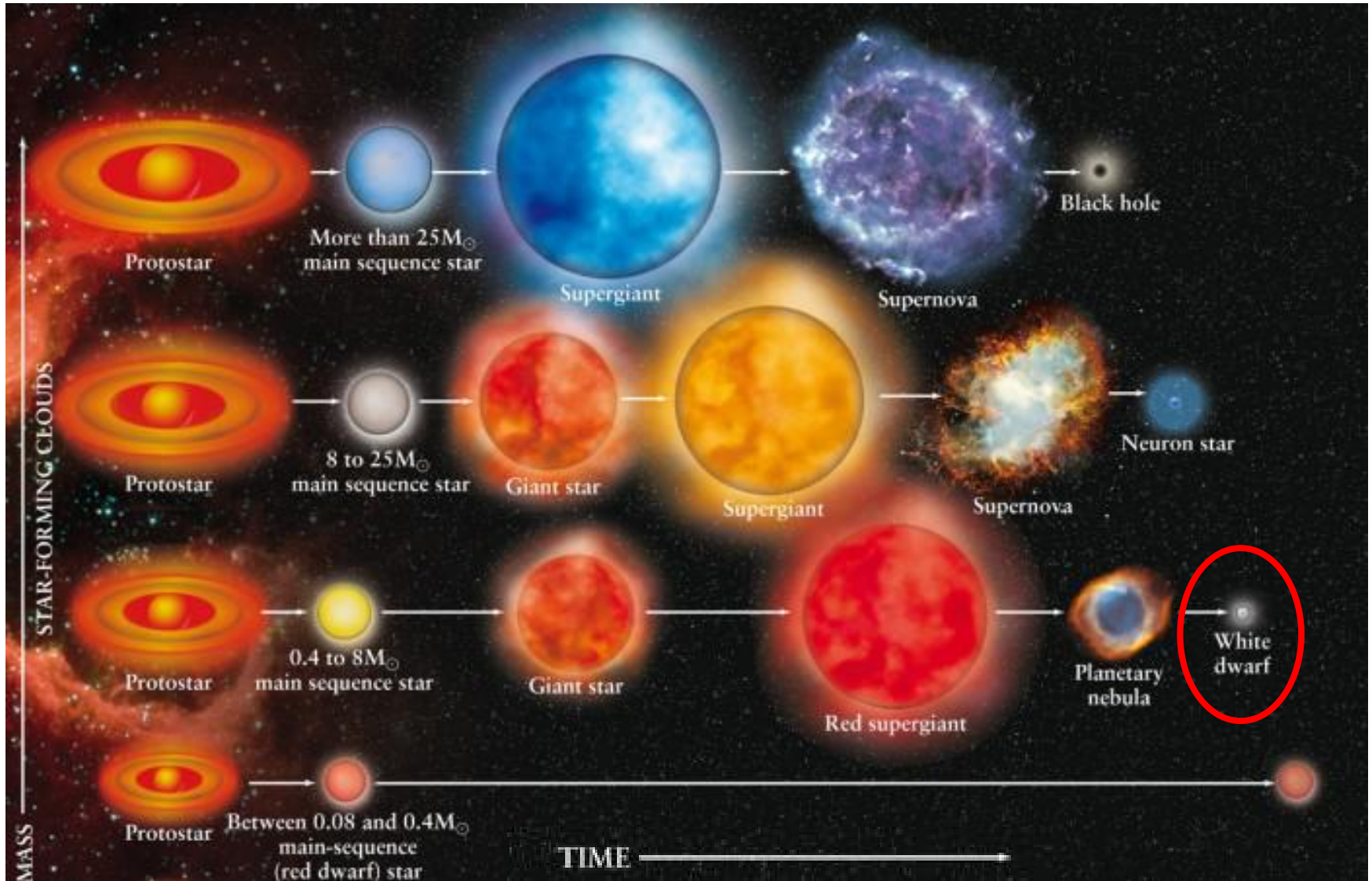


# Summary

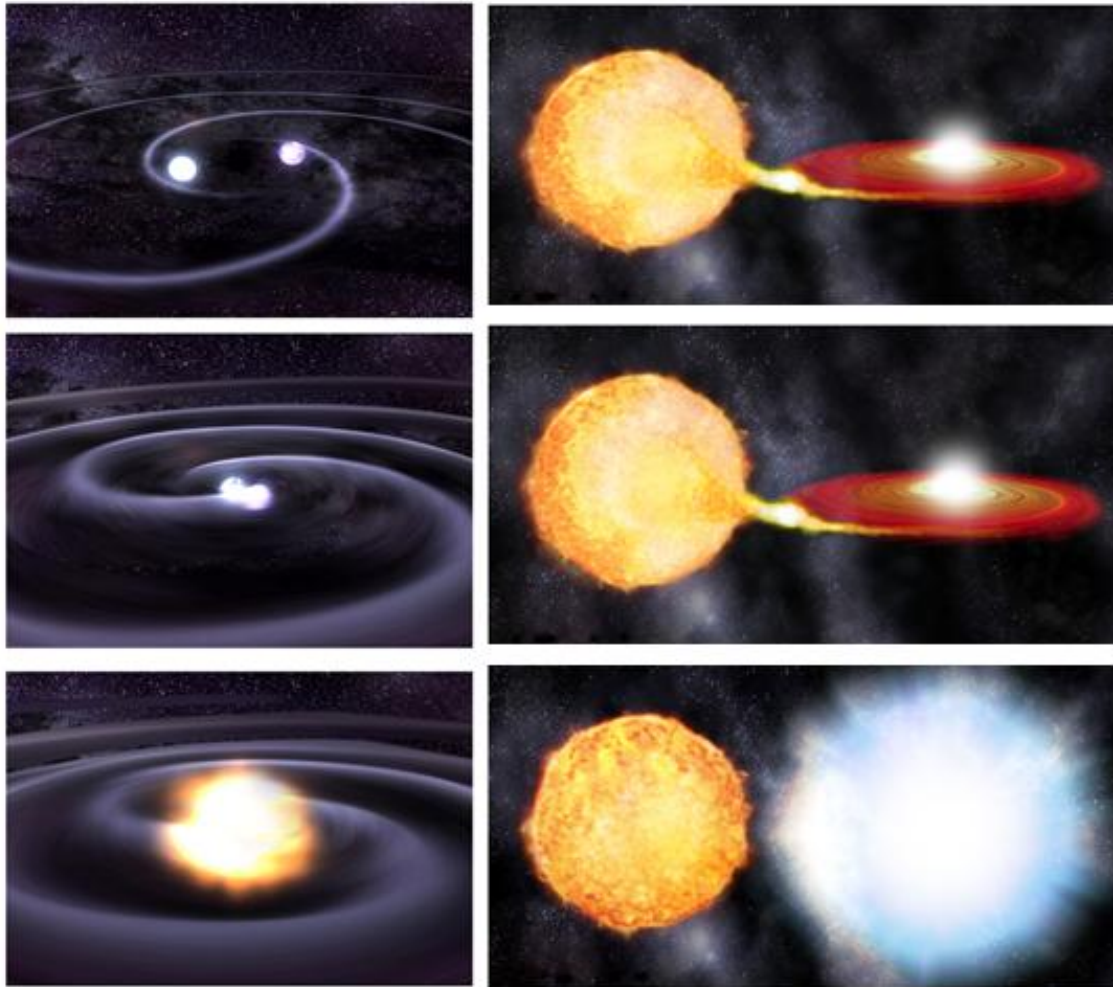


But what about binary/multiple systems?

# How to make a SN type Ia



# Two scenarios for SN Ia



Merger of two white dwarfs  
and/or  
mass accretion from a non-  
WD companion  
leads to  
 $M_{\text{WD}} > M_{\text{Chandrasekhar}}$

which results in a  
detonation/deflagration  
( $E \approx 10^{51}$  erg). Takes time!

In absolute terms, a Type Ia  
SN yields less O, Mg and Fe,  
compared to a SN Type II.  
In relative terms, it yields  
more Fe than O and Mg.

$$M_{\text{Ni}} \approx 0.5 M_{\odot} \text{ (Childress et al. 2015)}$$

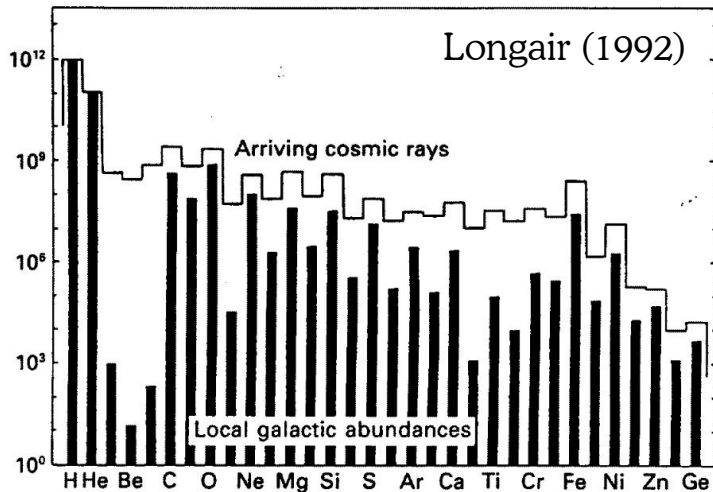
## IV. Cosmic rays

B2FH did not manage to explain the origin of the light elements  ${}^6,7\text{Li}$ ,  ${}^9\text{Be}$  and  ${}^{10,11}\text{B}$ .

They assigned an unknown ( $X$ ) process to it.

Now we know that these isoptopes can be produced in interactions of cosmic rays with the interstellar medium (ISM).

# Cosmic-ray spallation

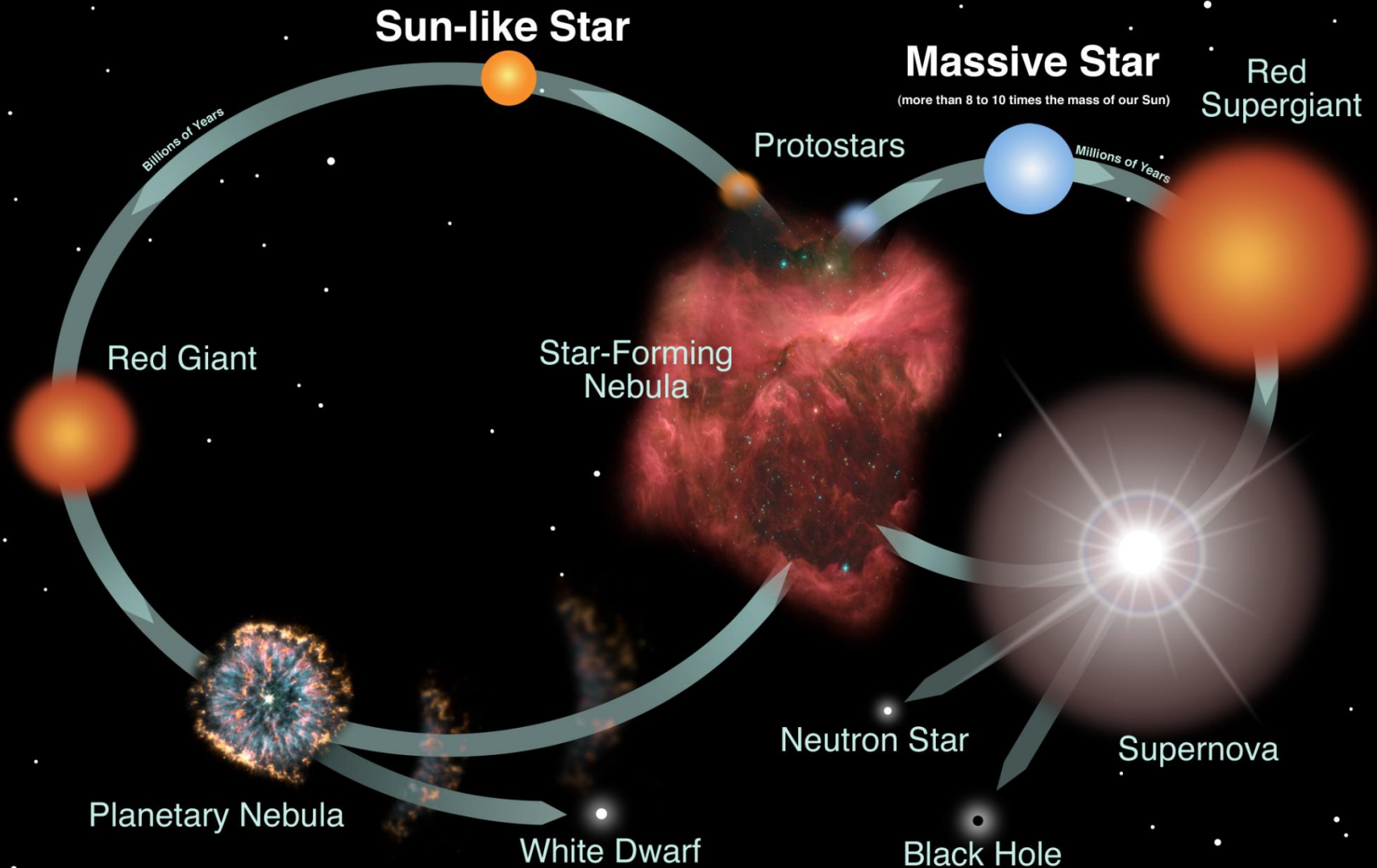


Li, Be and B are relatively fragile nuclei which generally speaking do not survive the conditions of stellar interiors ( $T > 10^6$  K).

As is evident from the cosmic rays arriving at earth, LiBeB nuclei can be produced through spallation (and fusion) reactions with nuclei in the interstellar medium. These reactions contribute to the gradual build-up of  ${}^7\text{Li}$  in the MW (above  $[\text{Fe}/\text{H}] \sim -1$ ). Be and B are less well studied in Galactic stars (hard-to-observe UV lines).

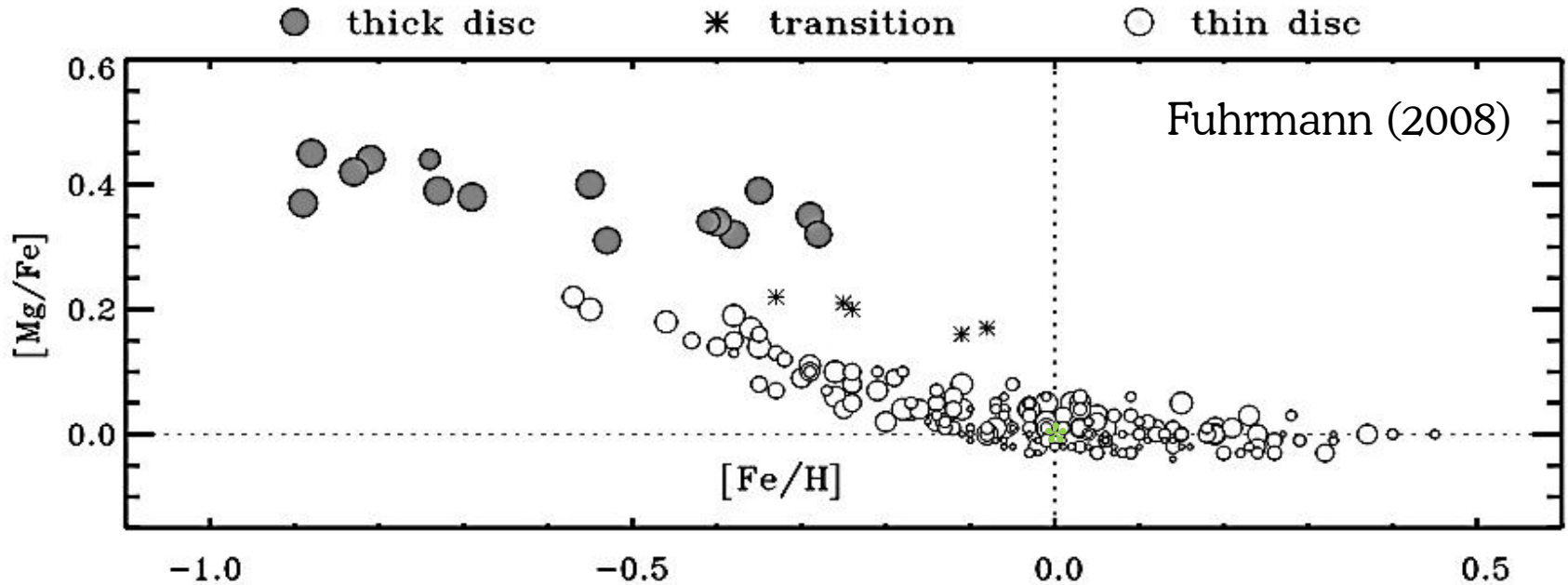
# Cosmic Matter Cycle

©·NASA





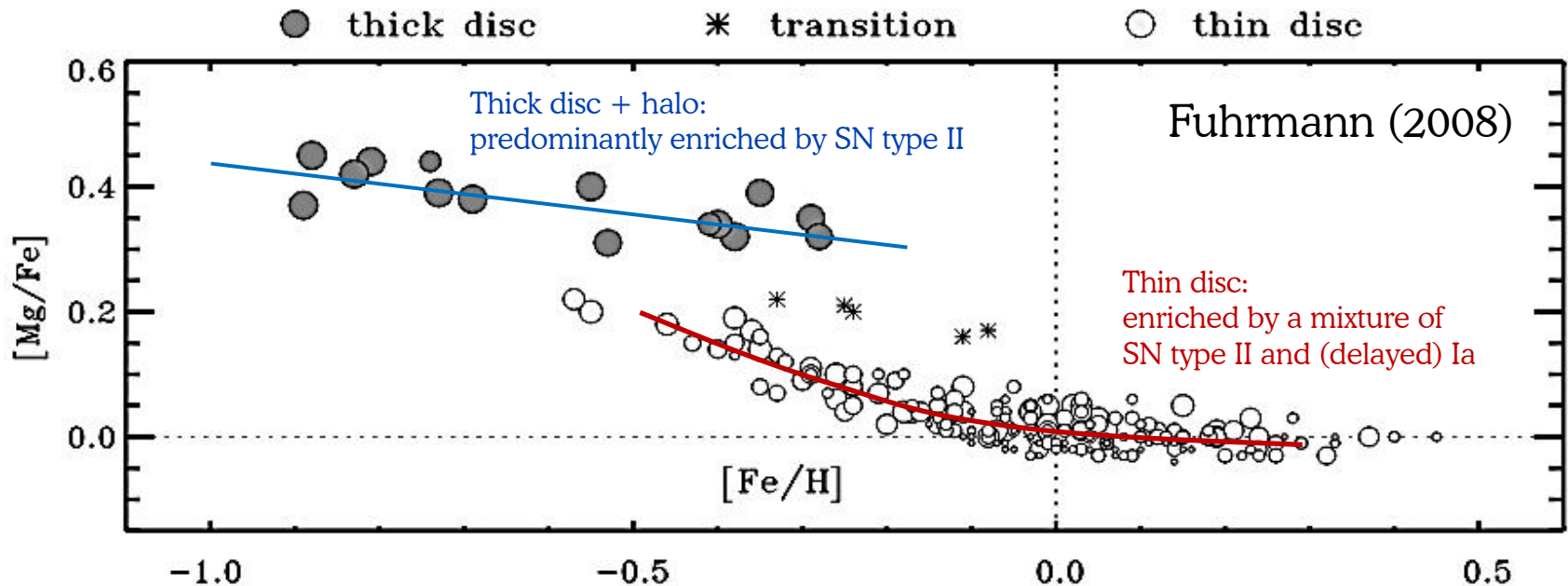
# The Solar neighbourhood (25 pc)



The Sun (\*) is a normal, albeit fairly high-mass, thin-disk star.

No bulge and very few halo stars (not shown here) within 25 pc.

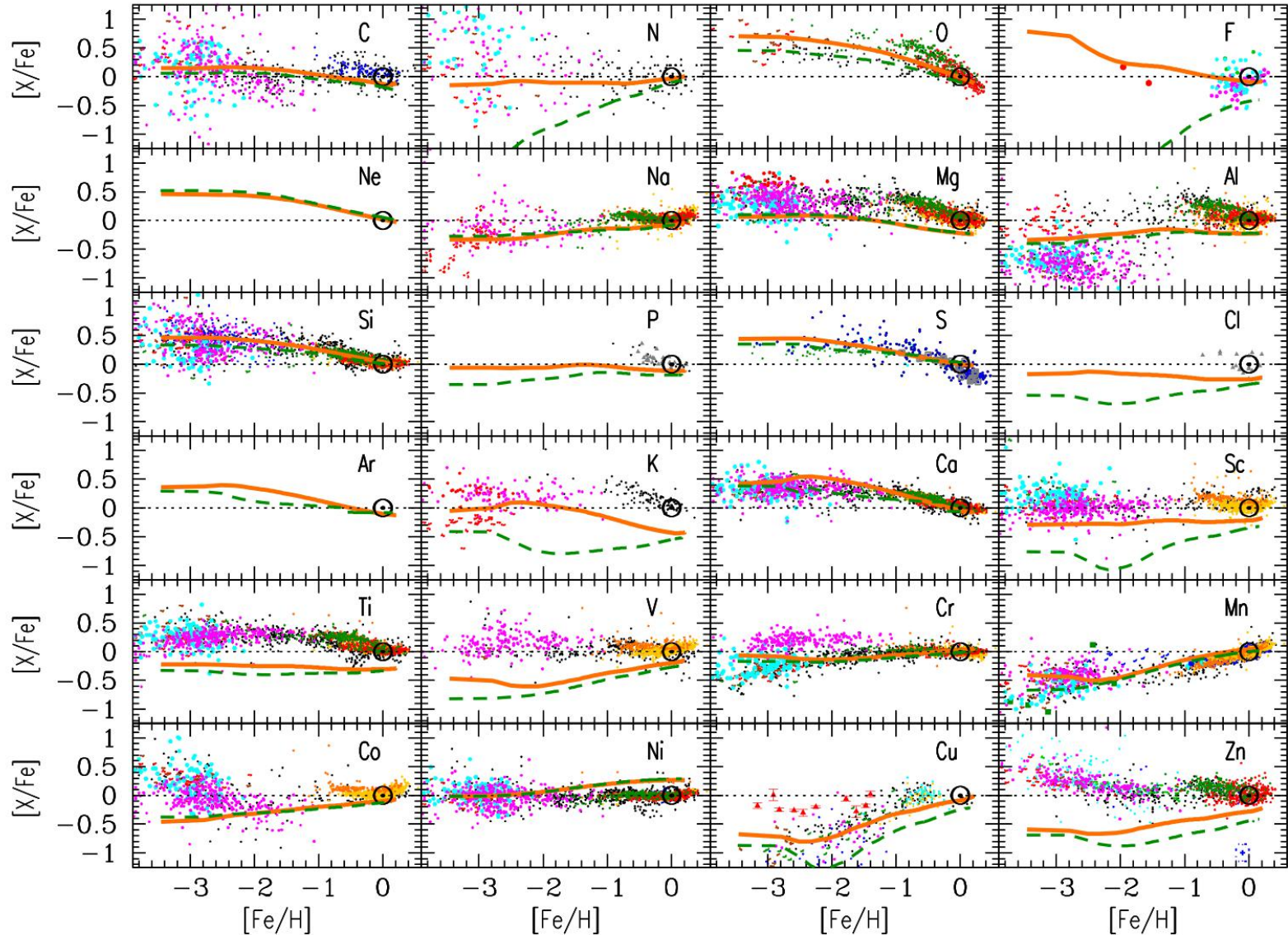
# The Solar neighbourhood (25 pc)



This is the most fundamental distinction between Galactic stellar populations (Tinsley 1979). It comes down to enrichment timescales.

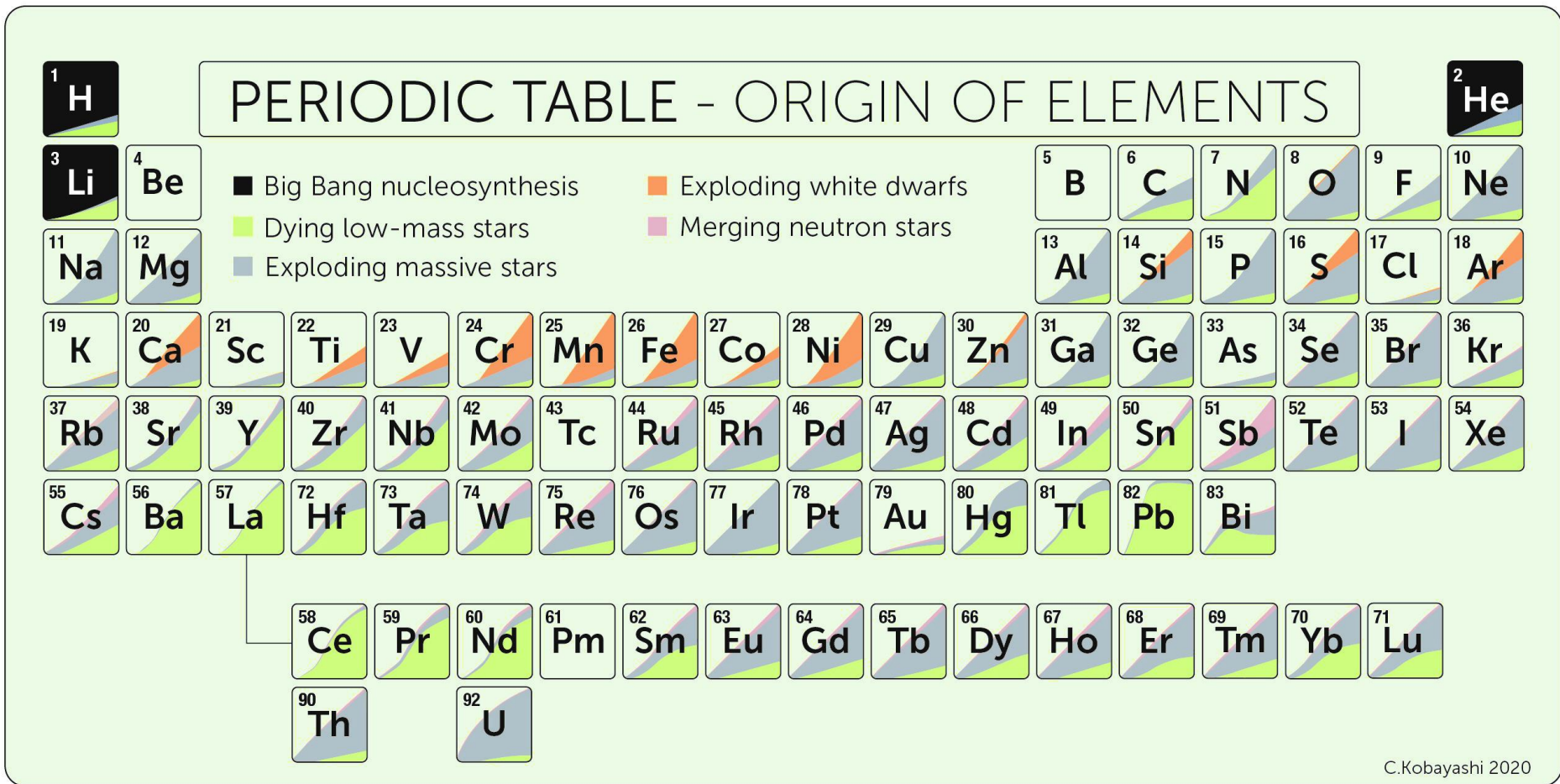
# Evolving the elements

See talks by Vanessa, Gabriele and Benjamin.



Prantzos et al. (2018)

# Summary periodic evolution table



C.Kobayashi 2020

