18th Russbach School on Nuclear Astrophysics, March 13-17, 2023

Observational Nuclear Astrophysics

(in four chapters)

Andreas Korn

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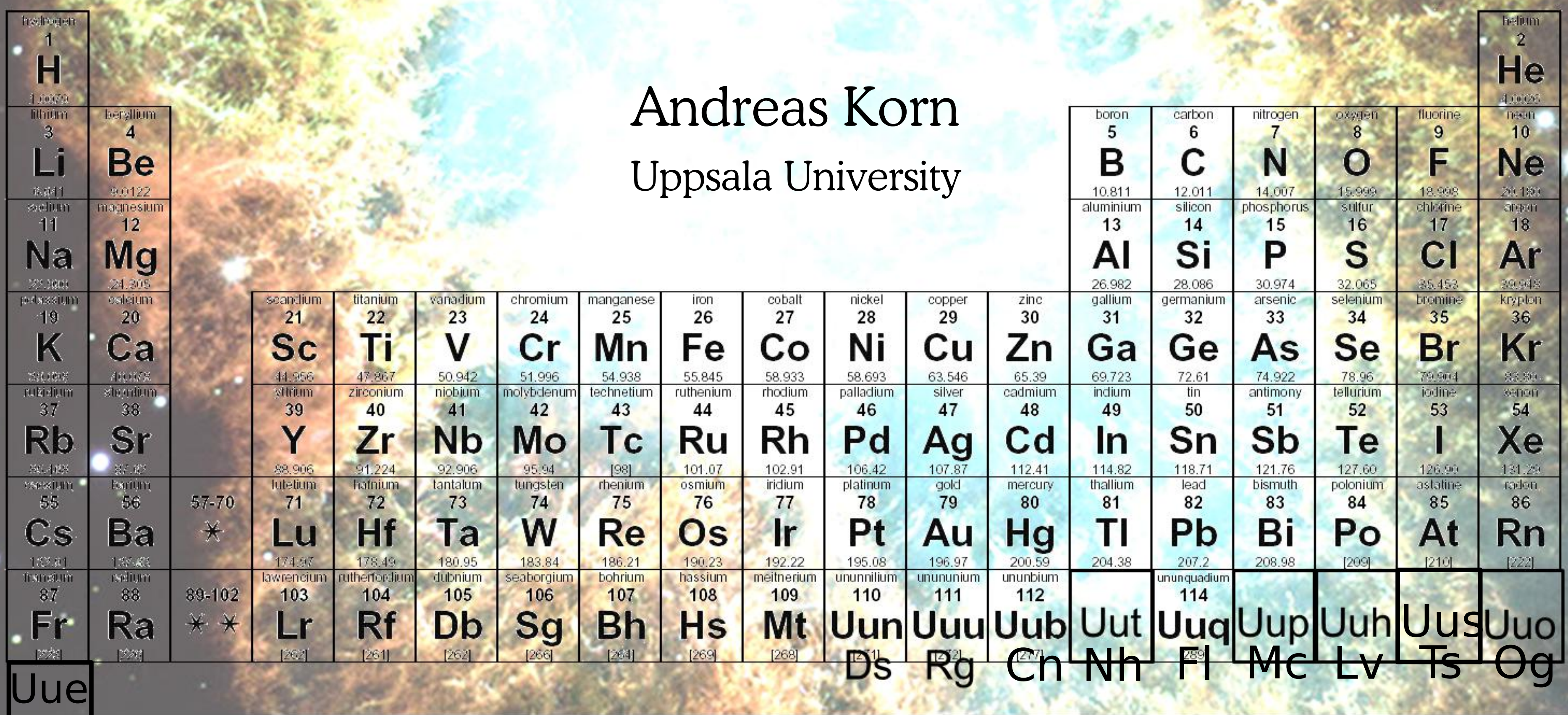
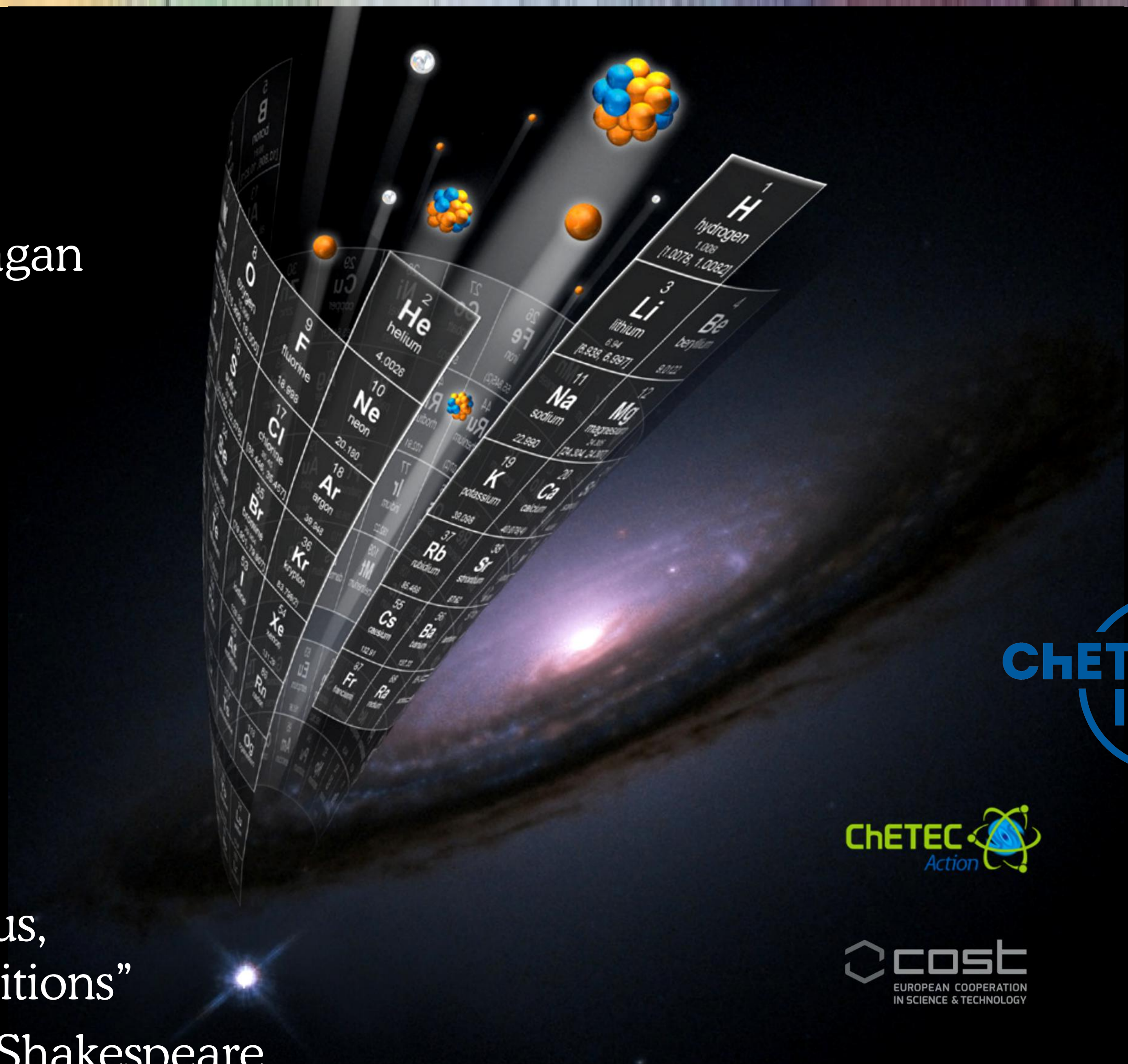


Where do the elements come from?

"We are made
of star stuff."
Carl Sagan



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

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Aim of this introductory lecture

- **Acquire a qualitative overview, a framework, of the astrophysics you need to know**
- **Familiarize yourself with relevant astro-physical 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

What is the state of the art in CNO related nuclear astrophysics?
December 2022
on indico

Accurate abundances of chemical elements in stars: why and how?
May 2022
on indico

Why is attracting high school students to nuclear astrophysics a win-win for everyone?
April 2022
on indico

How to model a star in your laptop?
February 2022
on indico

What is the link between radioactive nuclei and astrophysics?
January 2022
on indico

Does Nuclear Astrophysics probe fundamental physics?
December 2021
on indico

How to interpret stellar spectra?
November 2021
on indico

How to study stars from underground laboratories and deep-sea samples?
October 2021
on indico

What does nuclear physics do for astrophysics?
June 2021
on indico

How can we query nature to determine nuclear inputs in the cosmos?
May 2021
on indico

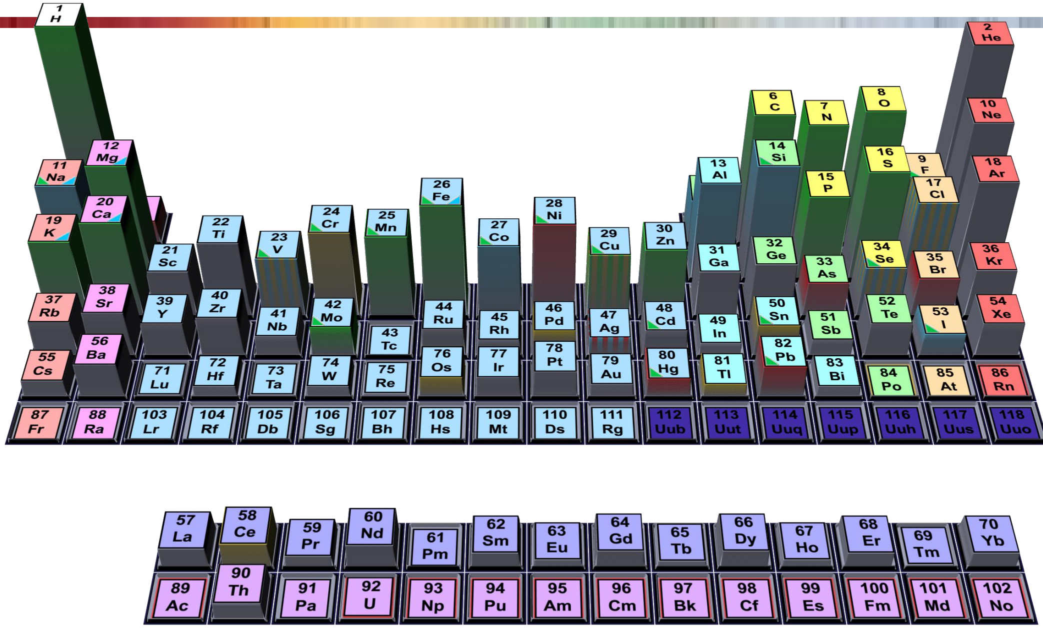
How to get from starlight to stellar abundances?
April 2021
on indico

How do neutron star mergers impact r elements in the universe?
March 2021
on indico

What do we need to know about nuclear astrophysics?
February 2021
on indico

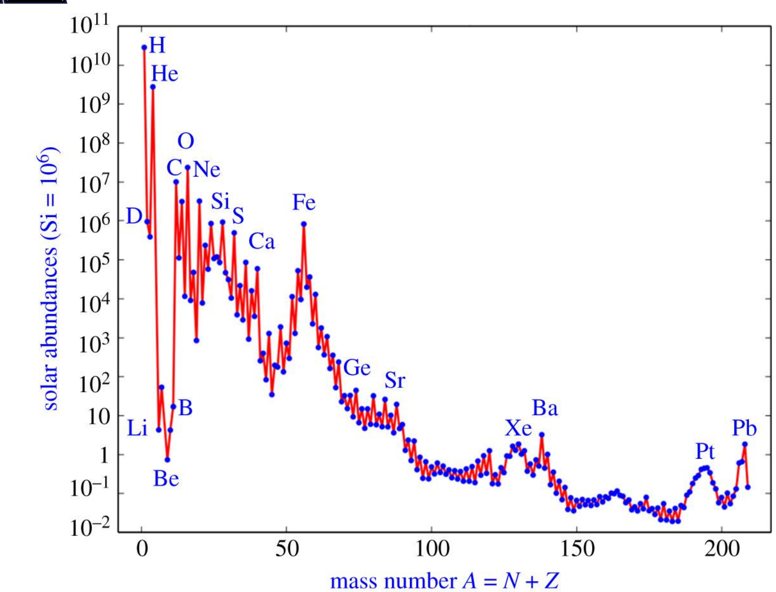
In particular, SNAQs **1**, **3**, **7** and **12**.
Check them out (https://www.chetec-infra.eu/snaqs/)!

The NAP playground

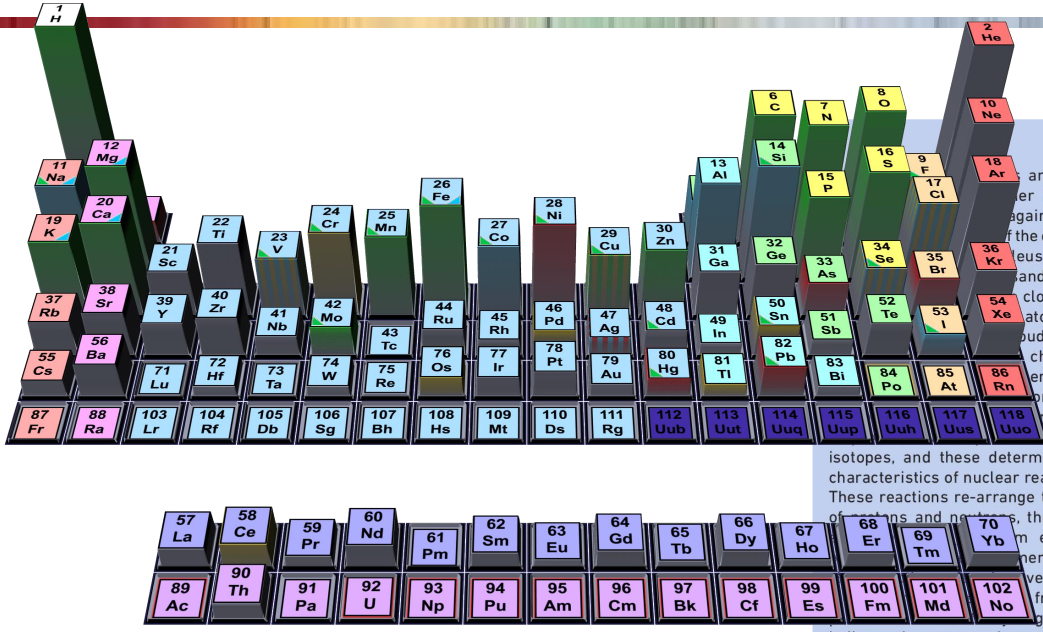


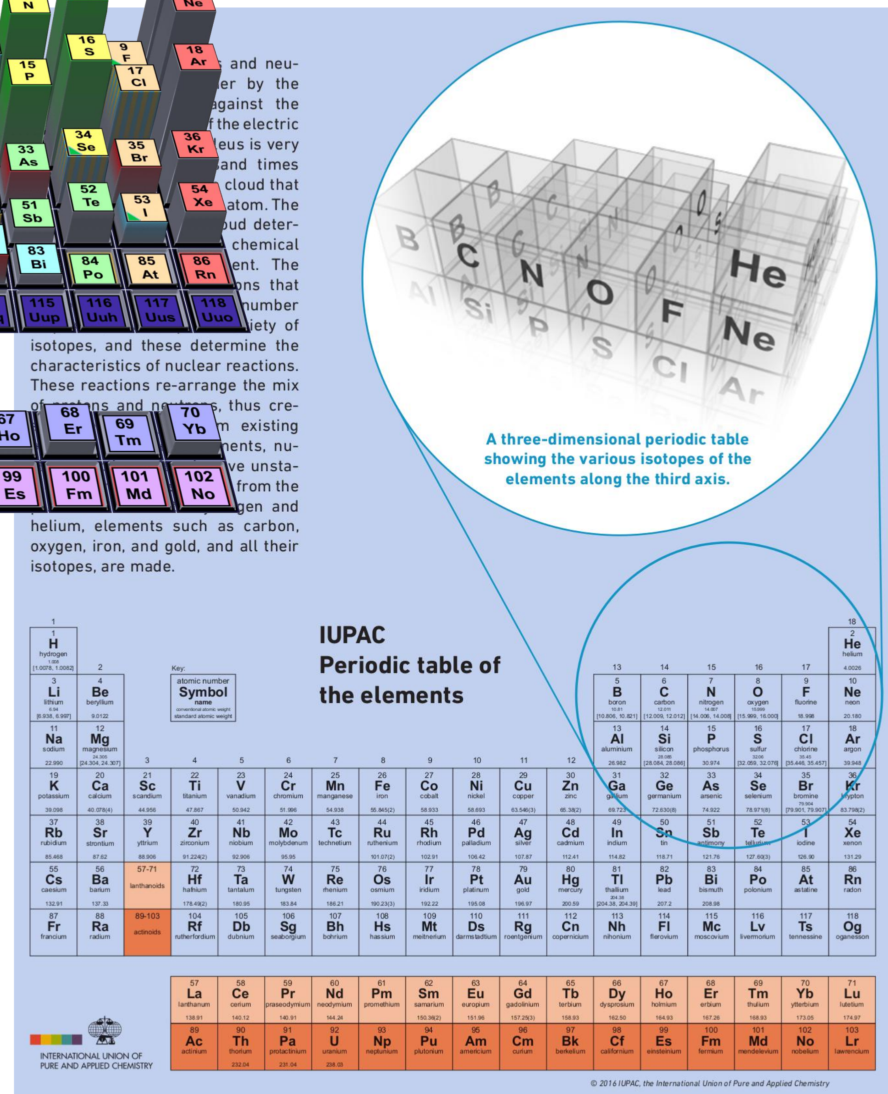
Features to be explained:

- 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 deline with *A* spanning >12 orders
- Ge/Sr, Xe/Ba & Pt/Pb double peaks

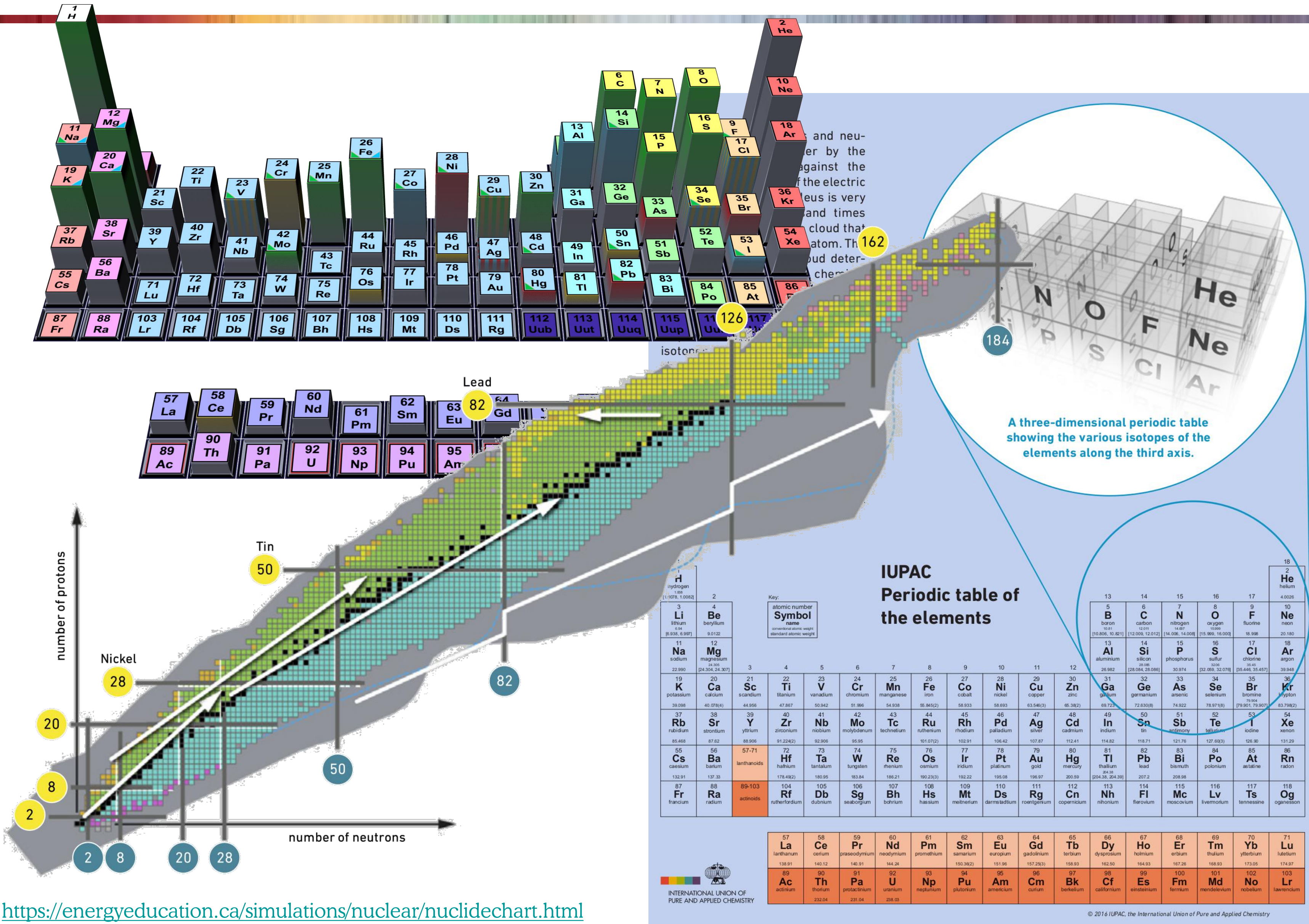


The NAP playground





The NAP playground



https://energyeducation.ca/simulations/nuclear/nuclidechart.html

COST ChETEC brochure (2021)

Where to collect elemental data

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}Al)

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

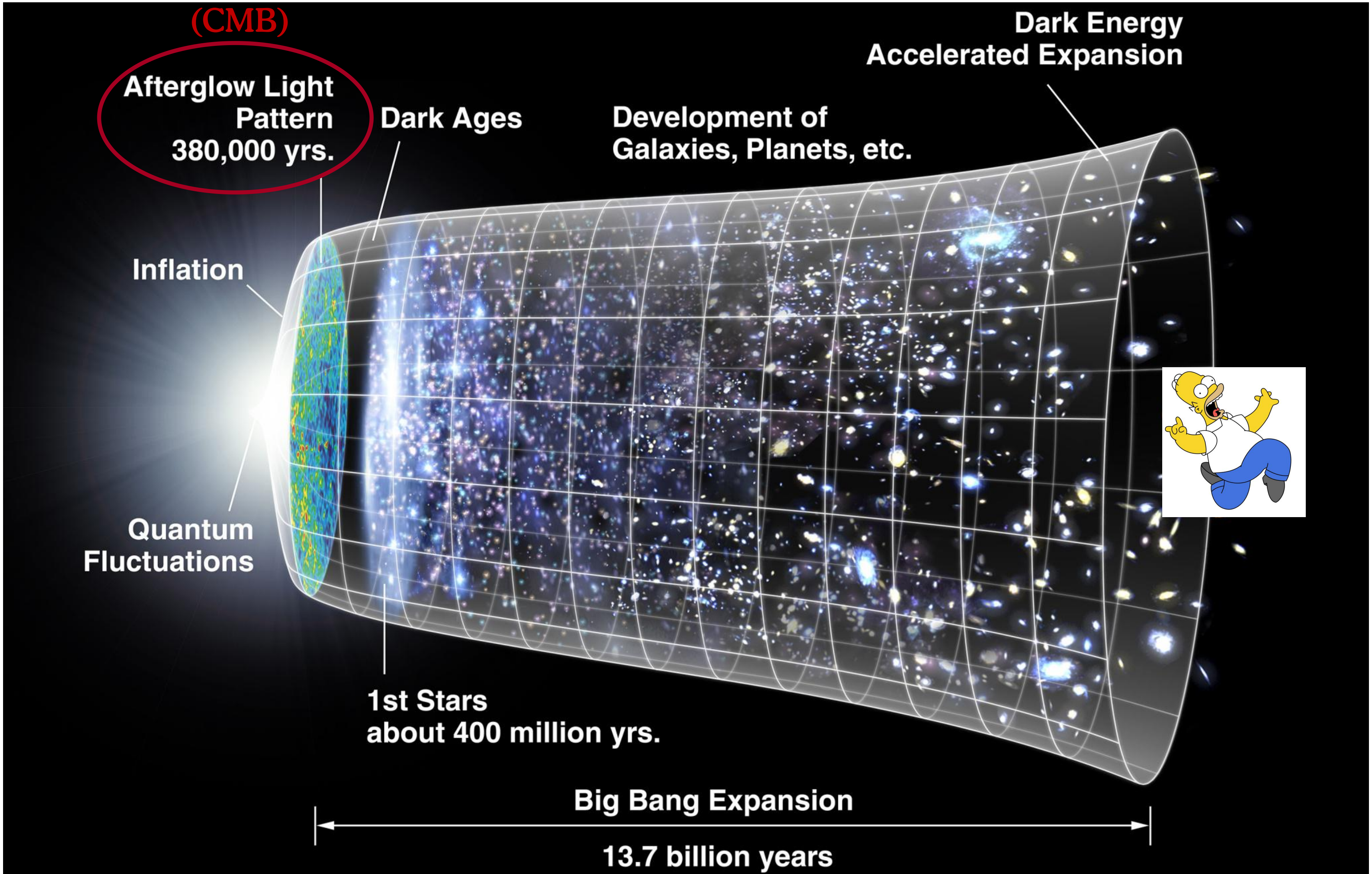
stellar explosions (supernova/kilonova lightcurves or “nebular” observations, e.g. SN1987A; hard to model, but progress is being made)

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!

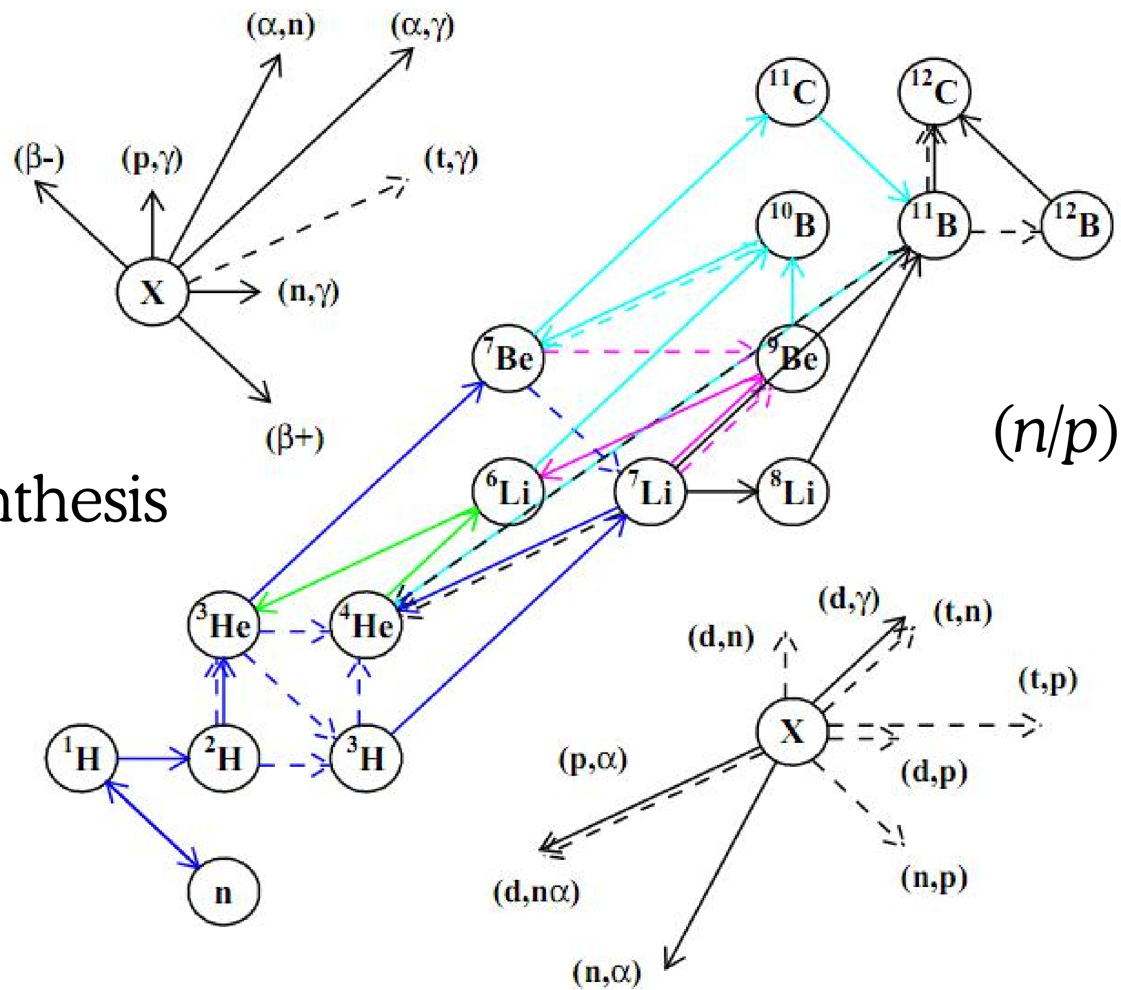
Cosmic time line

Cosmic microwave background (CMB)



Nucleosynthesis: from quarks to nuclei

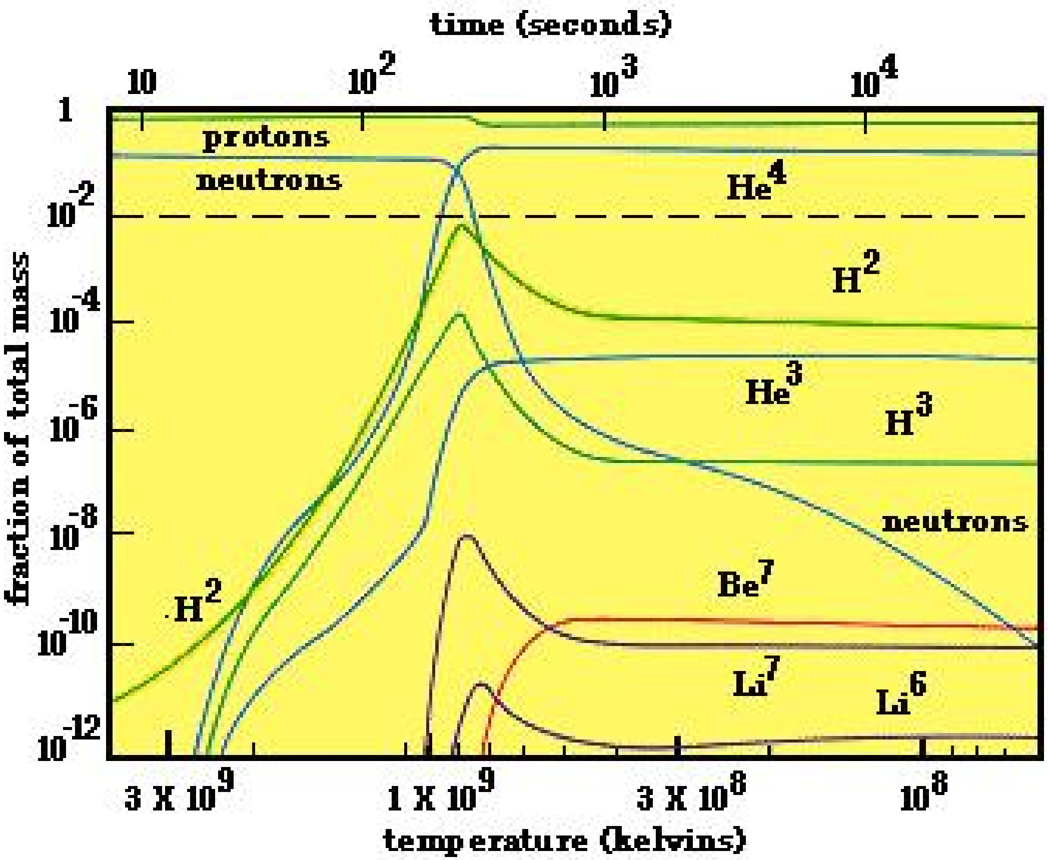
Seconds to minutes after the Big Bang, the Universum has the right temperature ($\approx 10^9$ K) to act as a as fusion reactor.



Big Bang Nucleosynthesis network

$(n/p)_{\text{pre-BBN}} \approx 1/7$

Following BBN



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

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

We can observe D/H, ^{4}He/H and ^{7}Li/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: Ω_{DM} and Ω_{Λ}.

The strongest evidence for **D**ark **M**atter 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}He and a tad of D, ^{3}He and ^{7}Li.

NB

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

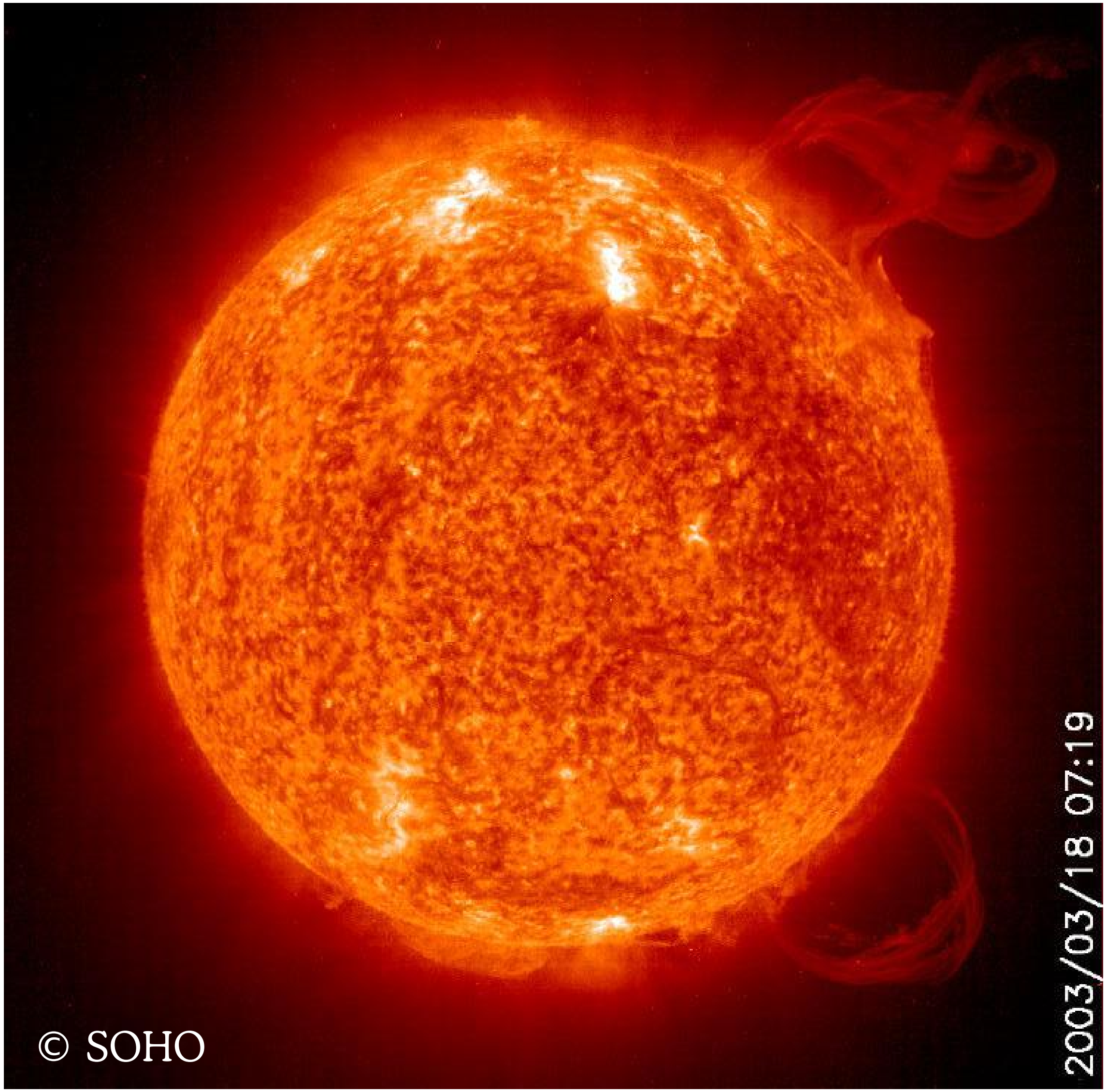
The theory of how stars produce ~all remaining elements of the periodic table was laid out in the seminal paper by Burbidge, Burbidge, Fowler & Hoyle (1953, B2FH).

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 $M_{Jupiter}$ (0.08 $M_\odot$)$< M <$ ~150 $M_\odot$

Right mass, but not yet fusing: PMS stars

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

Main sequence phase

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}C).**

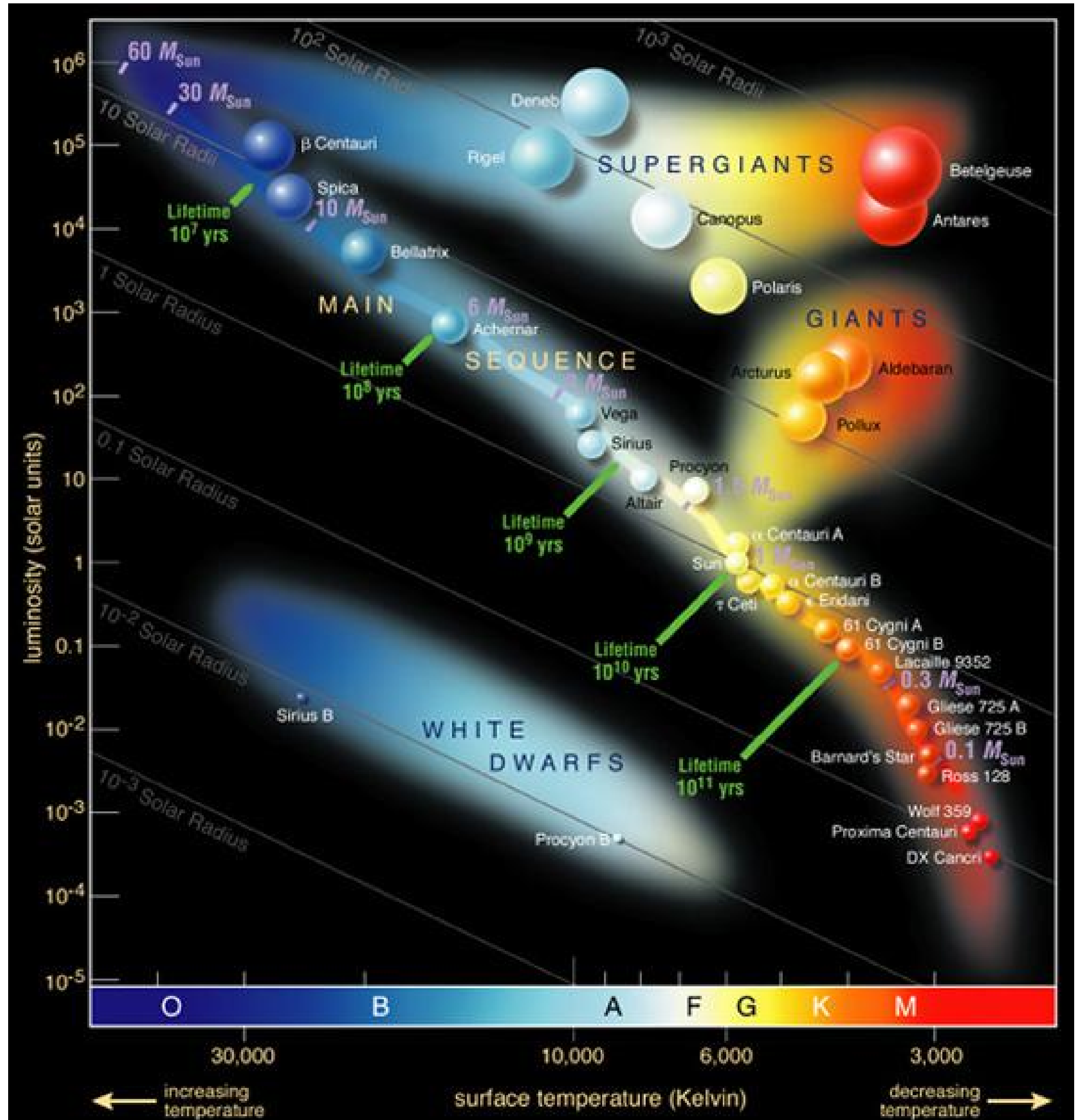
Stars move away from the MS once hydrogen in their core is exhausted ("turnoff point", TOP). The TOP is an important age indicator for stellar aggregates like clusters.

Surface temperatures, luminosities, radii

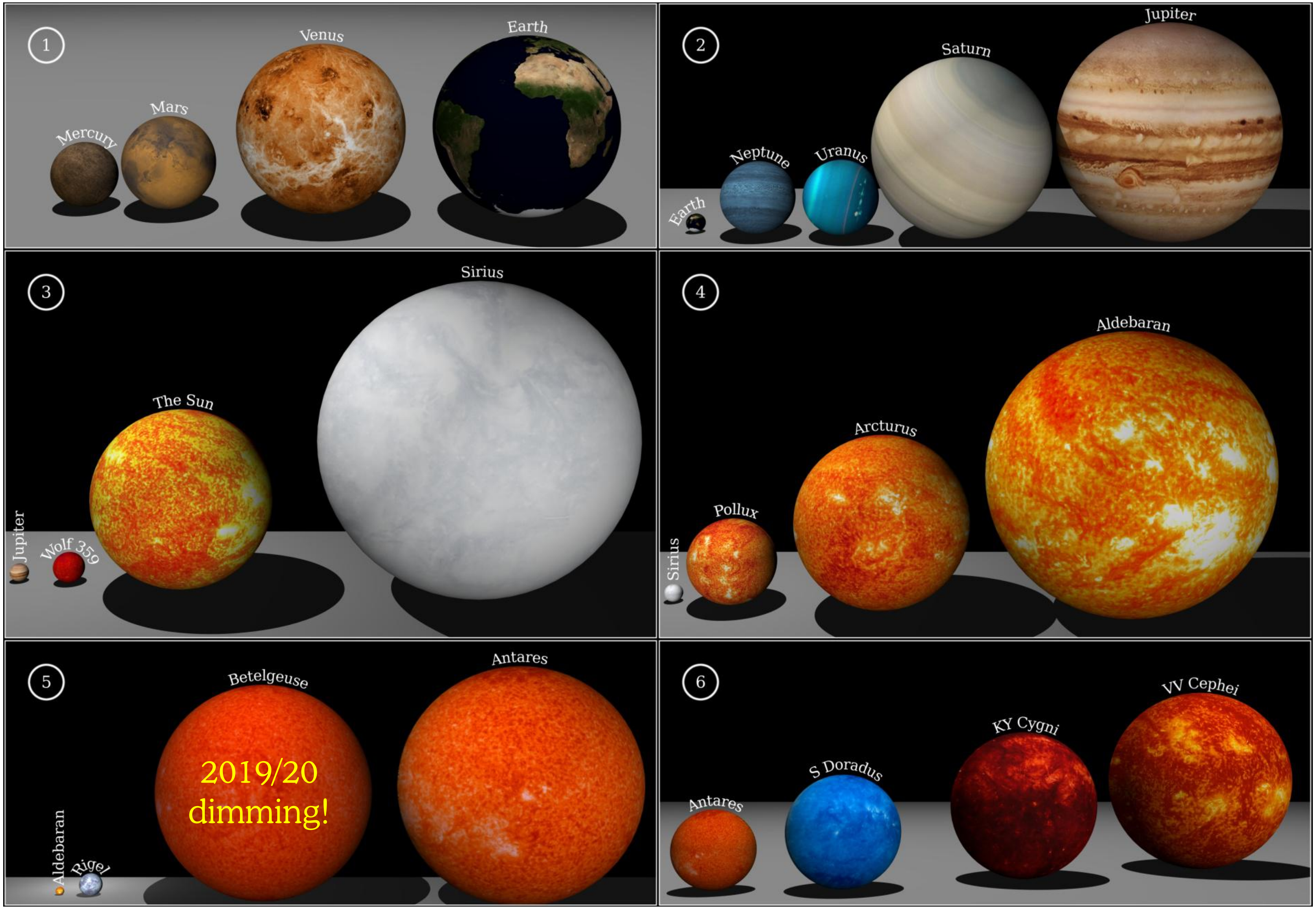
A **Hertzsprung-Russell diagram** shows the fundamental plane of stars in "observable" quantities: M_G vs $BP\text{–}RP$ or L vs T_{eff}.

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 that the Sun experience more advanced burning stages.

We approximate *q* (and the opacity *κ*) as power laws in *ρ* and *T*:

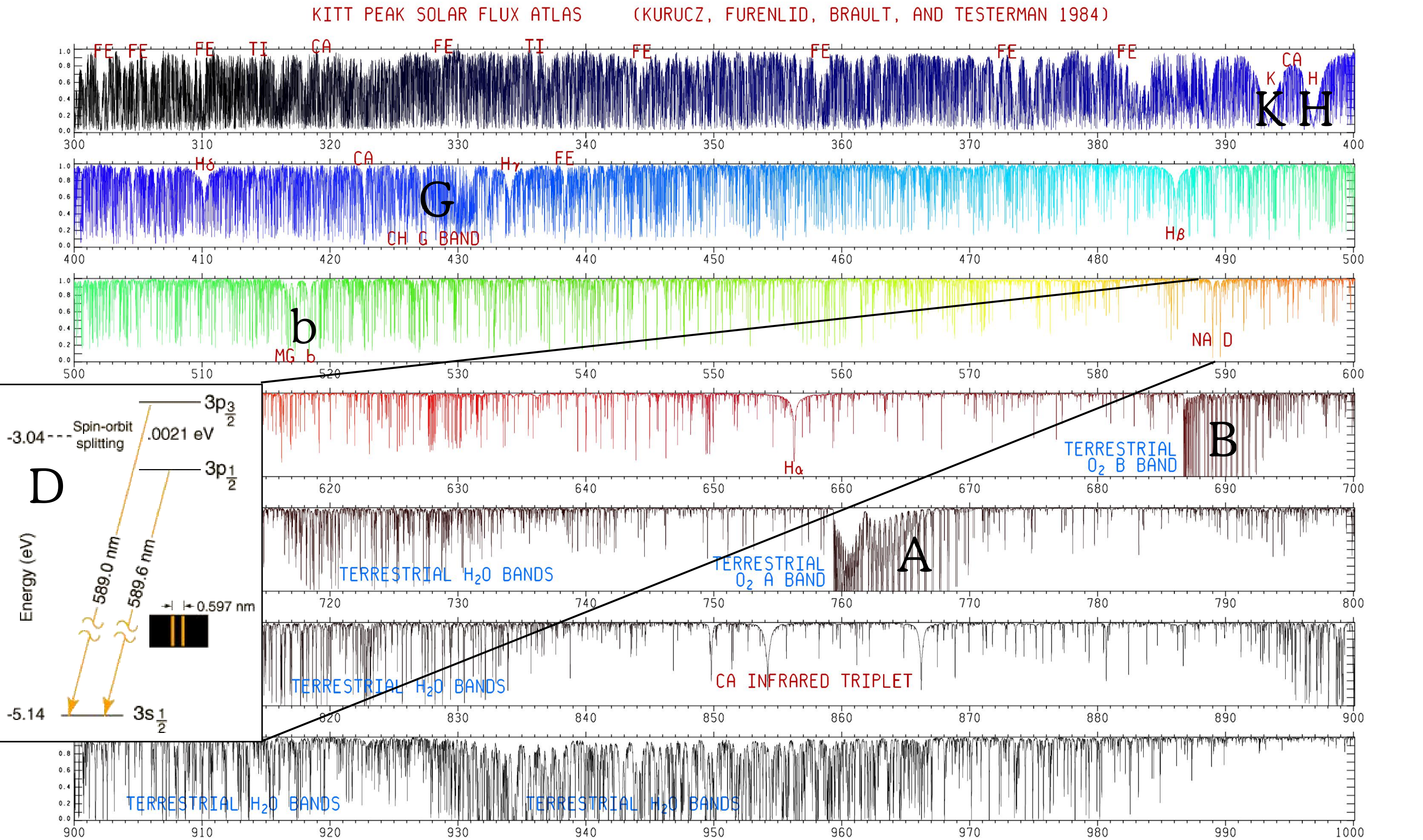
$$q \propto \rho^m T^n$$

energy released per unit mass

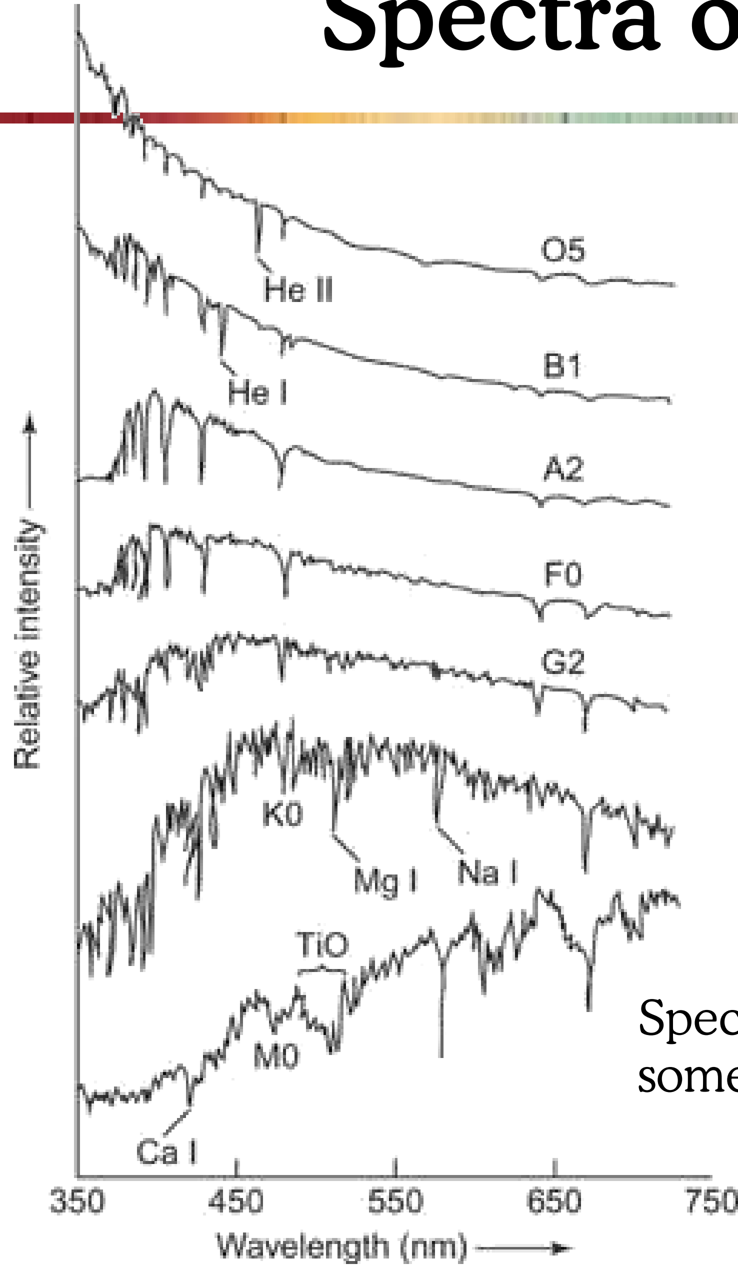
	m	n	main product(s)
p − p	1	4	He
CNO	1	20	He
3α	2	40	C, O
C	1	30	O,Ne,Na,Mg
O	1	45	Mg,S,P,Si

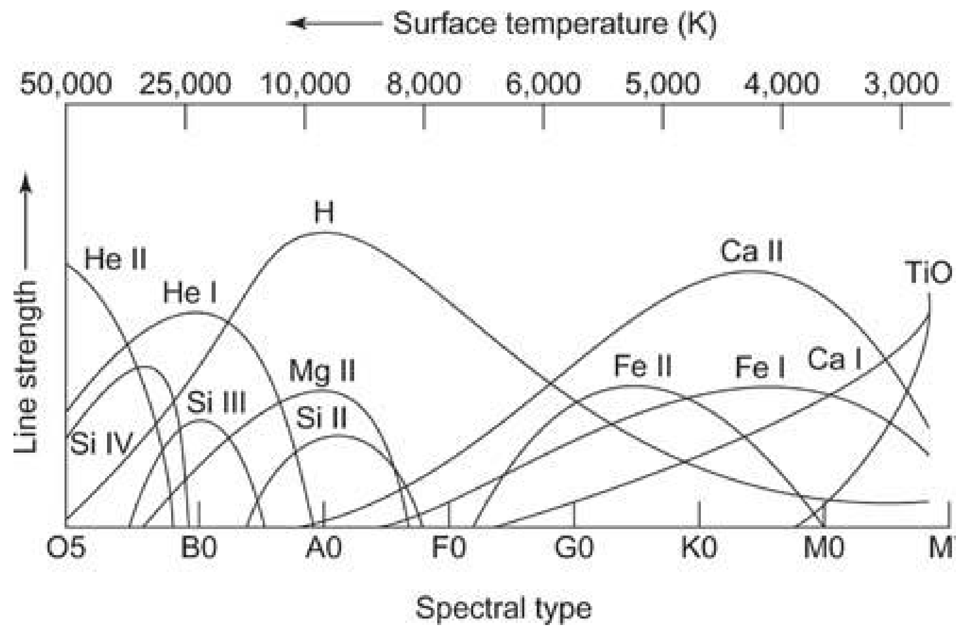
Cycles switch on *instantly* as they are ***very*** *T*-sensitive!

The solar spectrum



Spectra of different stars





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

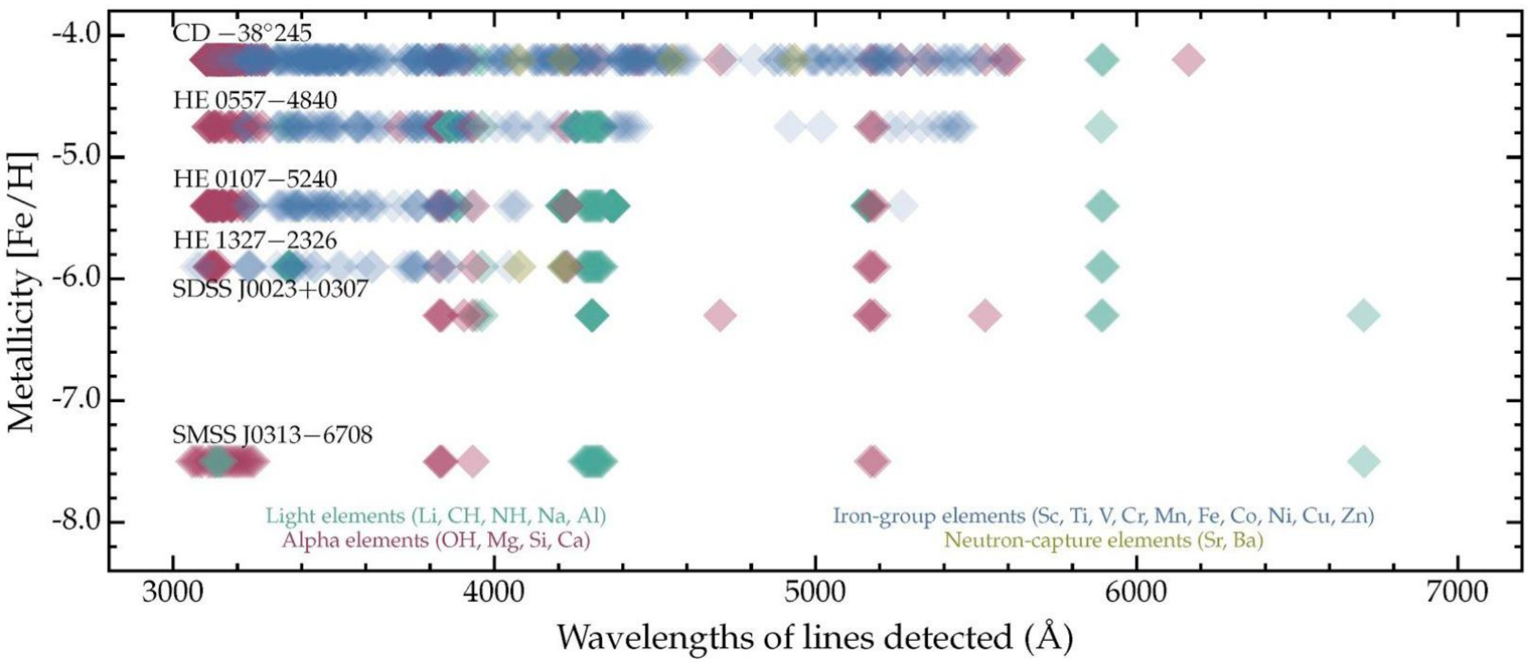
© CliffsNotes: Spectral Types

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.



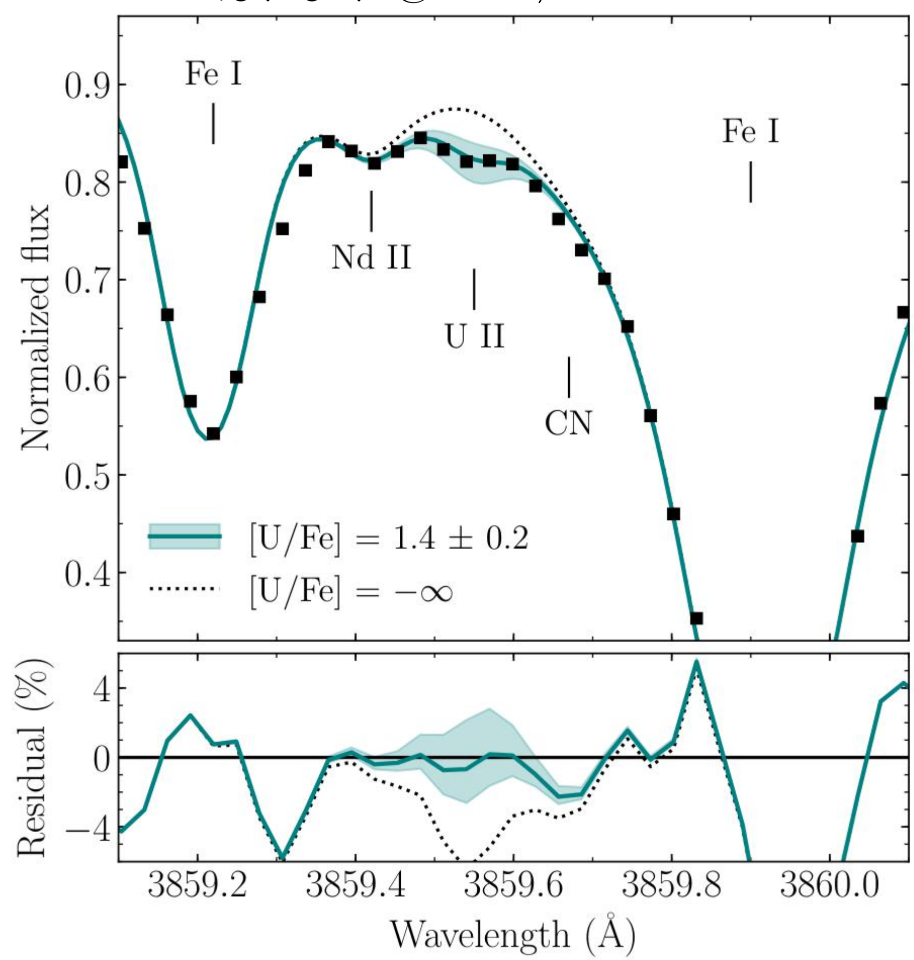
Roederer *et al.* (2019)

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 are 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).

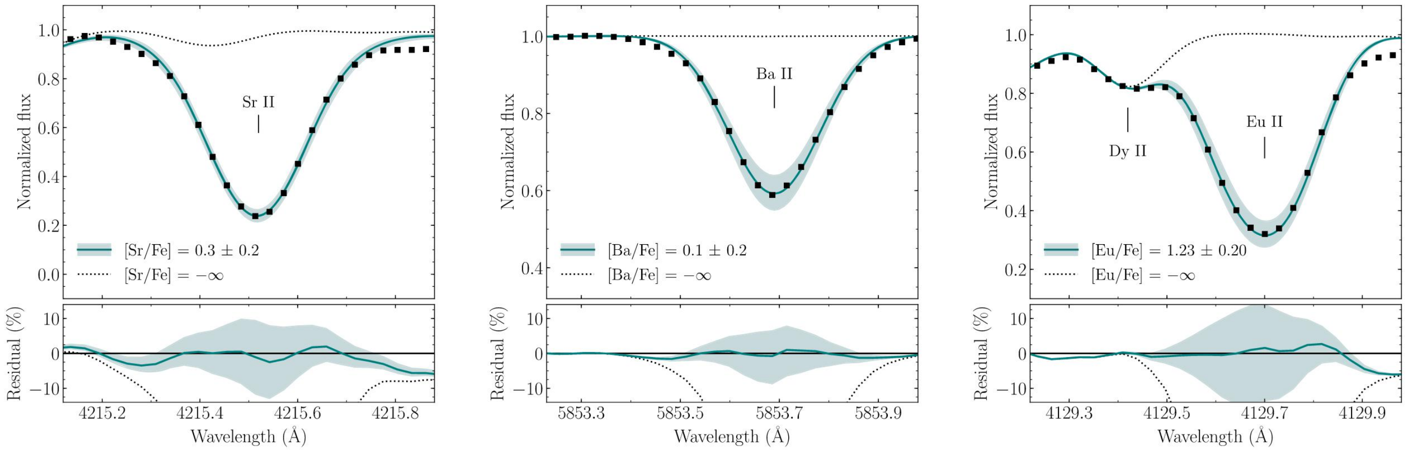
J0954+5246 @ R=60,000 and SNR~100



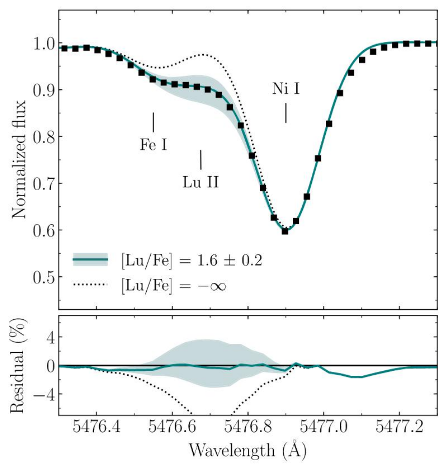
Holmbeck *et al.* (2018)

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

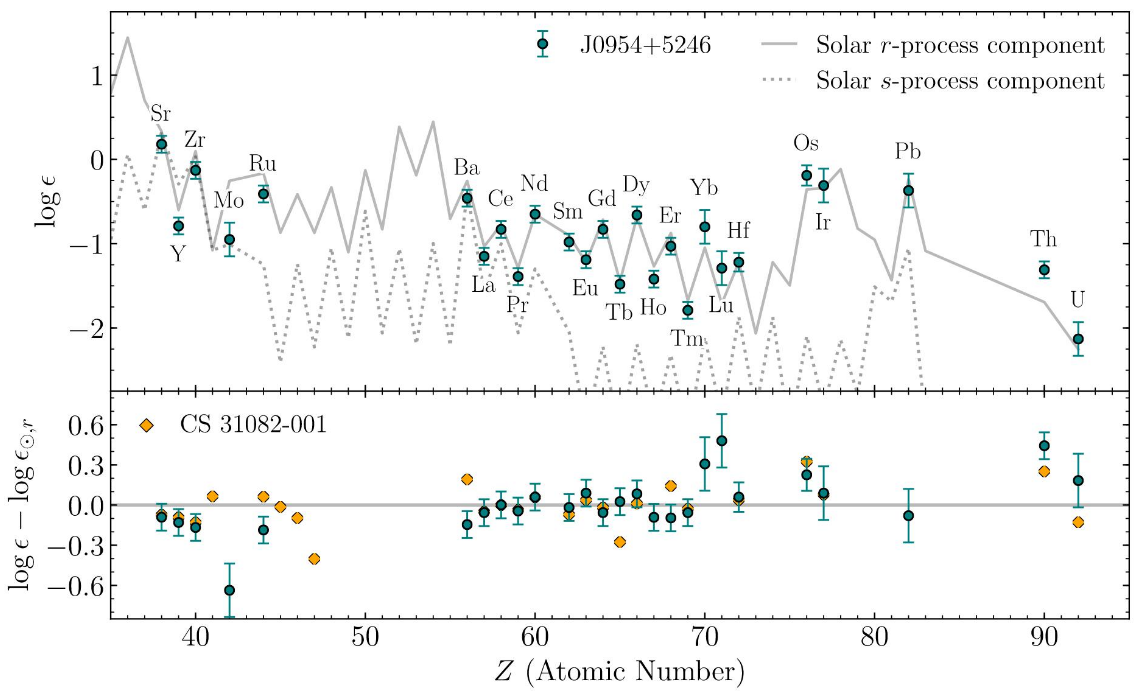
Good spectra + good models = good results



An almost perfect solar r-process pattern! Almost…



Model ***all*** known lines!



Holmbeck *et al.* (2018)

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)

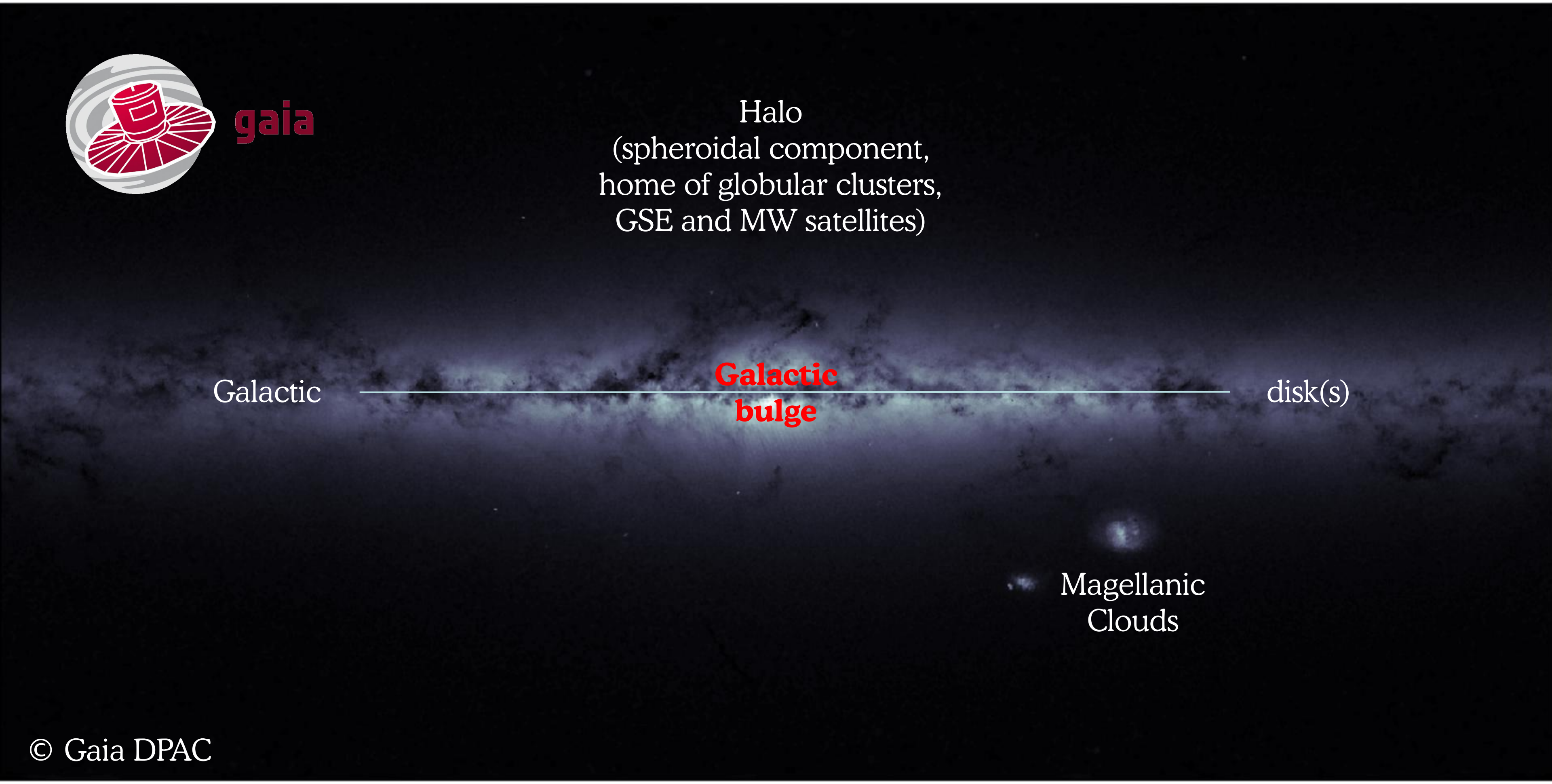
The 12 scale: $\log \varepsilon(M) = \log (n_M / n_H) + 12$

example: $\log \varepsilon(O)_\odot \approx 8.7$ 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

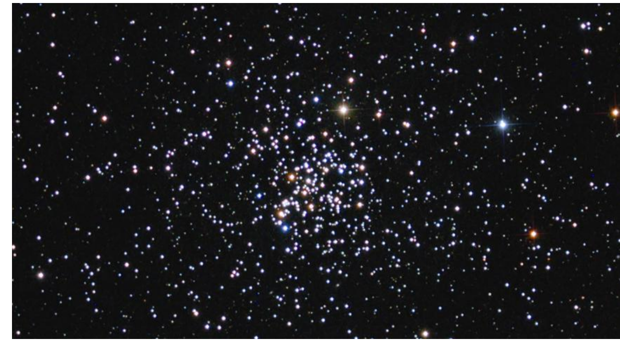


Star *density* map, assembled by Gaia

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

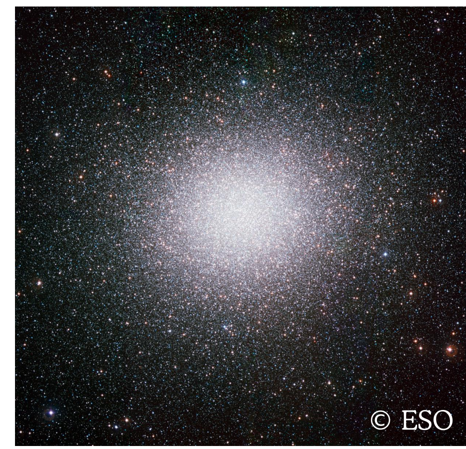
The role of environment

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…)!

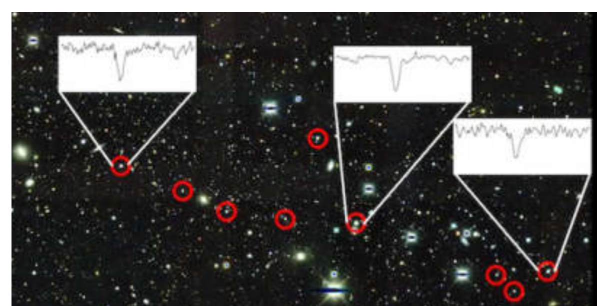


© Greg Noel

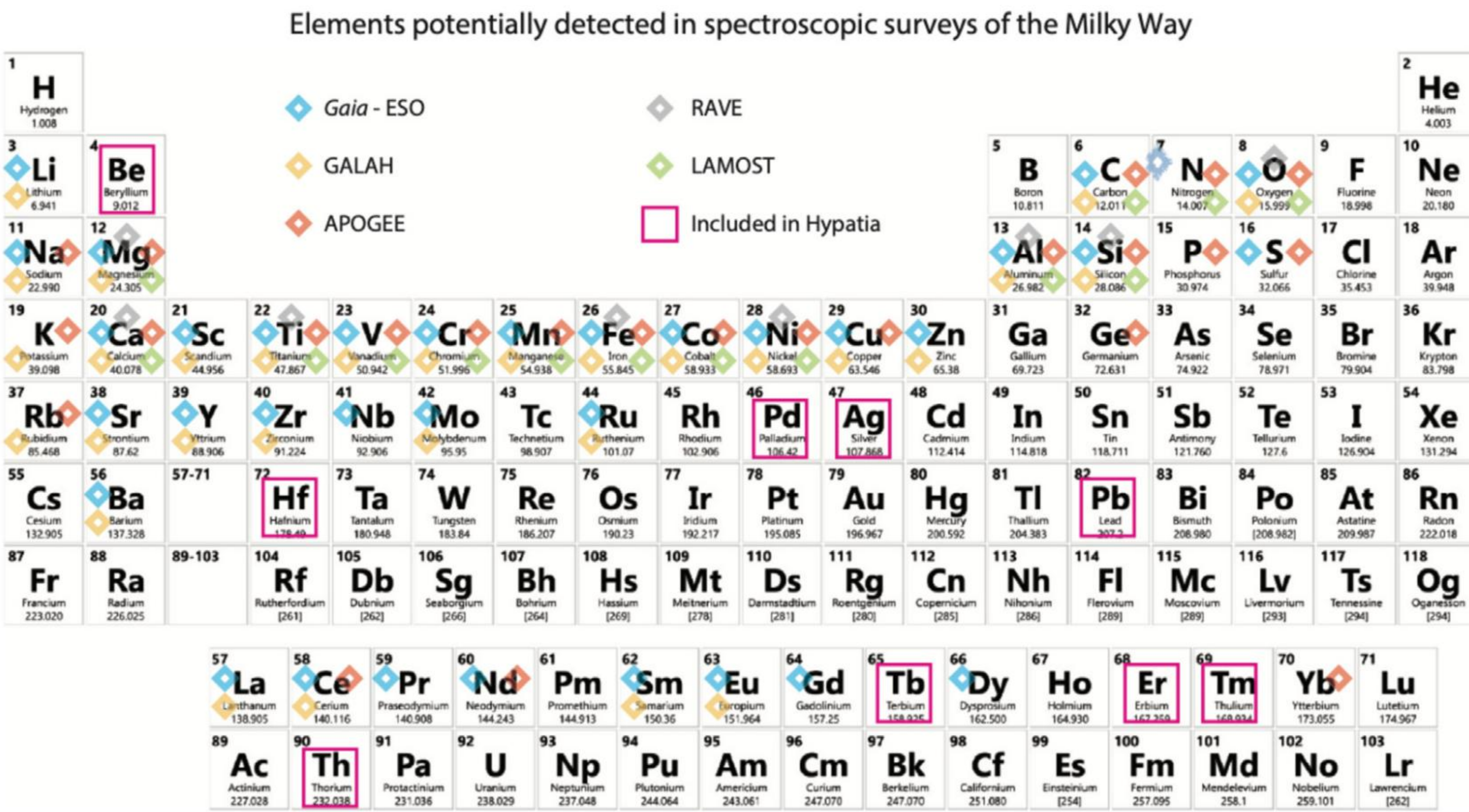
Globular clusters: very old, very complex, unexplained! See e.g. Milone *et al*. (2017) for chromosome-map analysis. HRD construction: https://youtu.be/HWQslu4S5eQ



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



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): [Fe/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

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 **α** elements (O + $n \cdot {}^{4}He$, up to Ca) and kilonovae (merging neutron stars) r-process elements.

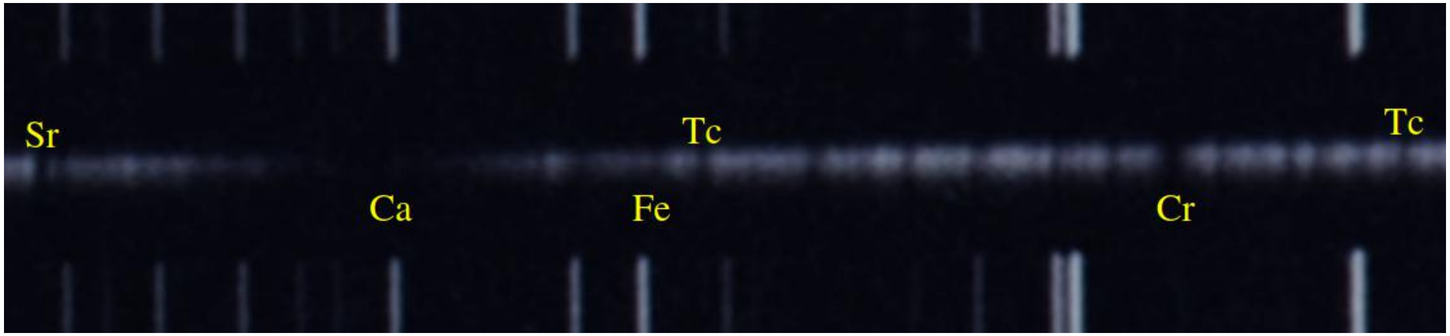
Some explosions produce nucleids on the proton-rich side of the valley of stability through a p process. Processes involving neutrinos are also expected to contribute (**ν**-process/**ν**p-process). +++

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 β decays.

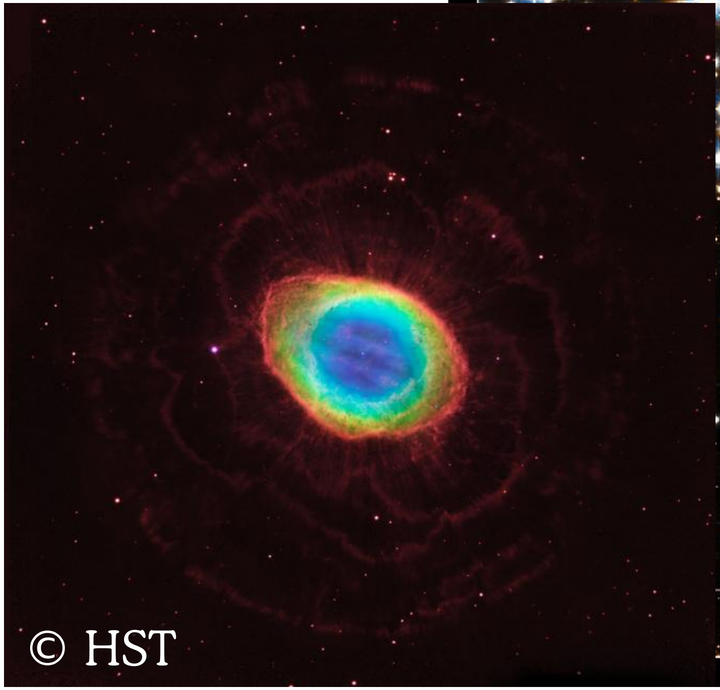
The smoking gun of this process is the detection of Tc (Merrill 1952) in the spectra of cool AGB stars: this element has no stable isotope, i.e. it must have been produced in the past few Myr.



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

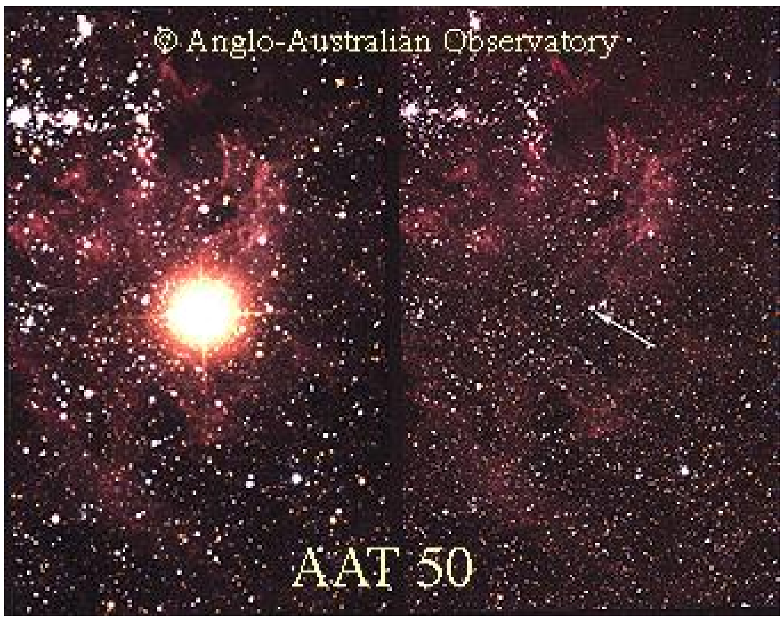
These stars occupy the same *L* regime as AGB stars, but are significantly hotter. As radiation pressure goes with the fourth power of *T*, radiation-driven mass loss is strong in these stars and will significantly affect their evolution (prime example: Wolf-Rayet stars).

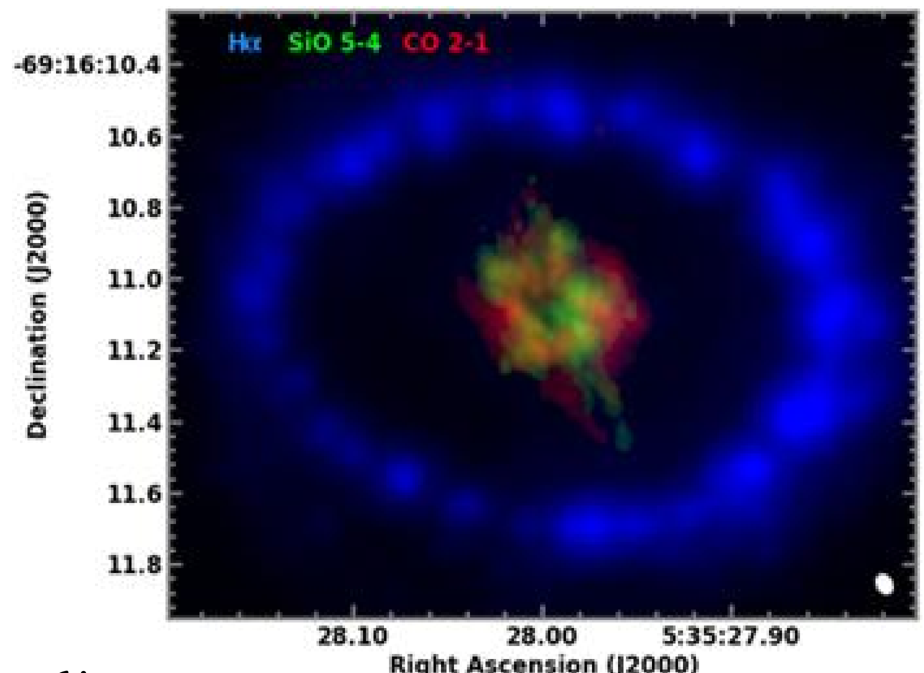
High-mass stars move more or less horizontally across the HRD, at constant *L*. They may explode either in the blue or the red part, as blue or red supergiants. The SN (type II) explosion was long believed to be the site of the **r** (*rapid* neutron-capture) **process** producing ≈half of the stable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



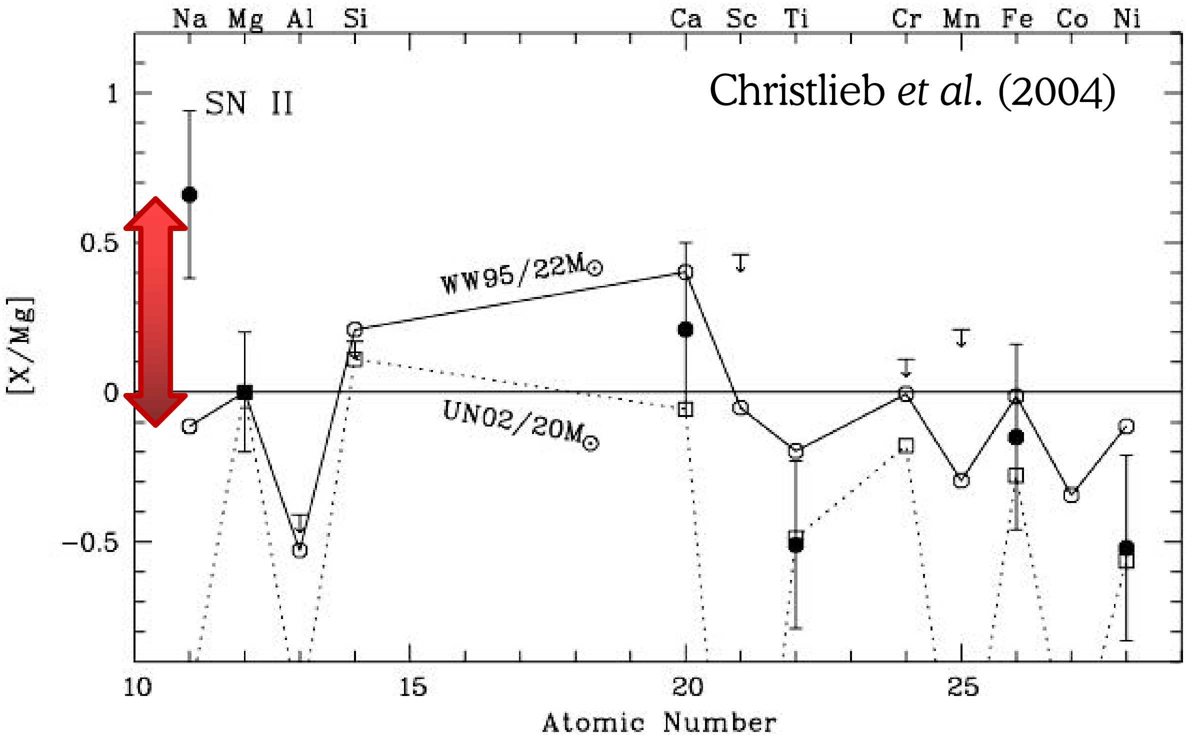


...plus some 20 νs detected!

Abellán *et al.* (2017)

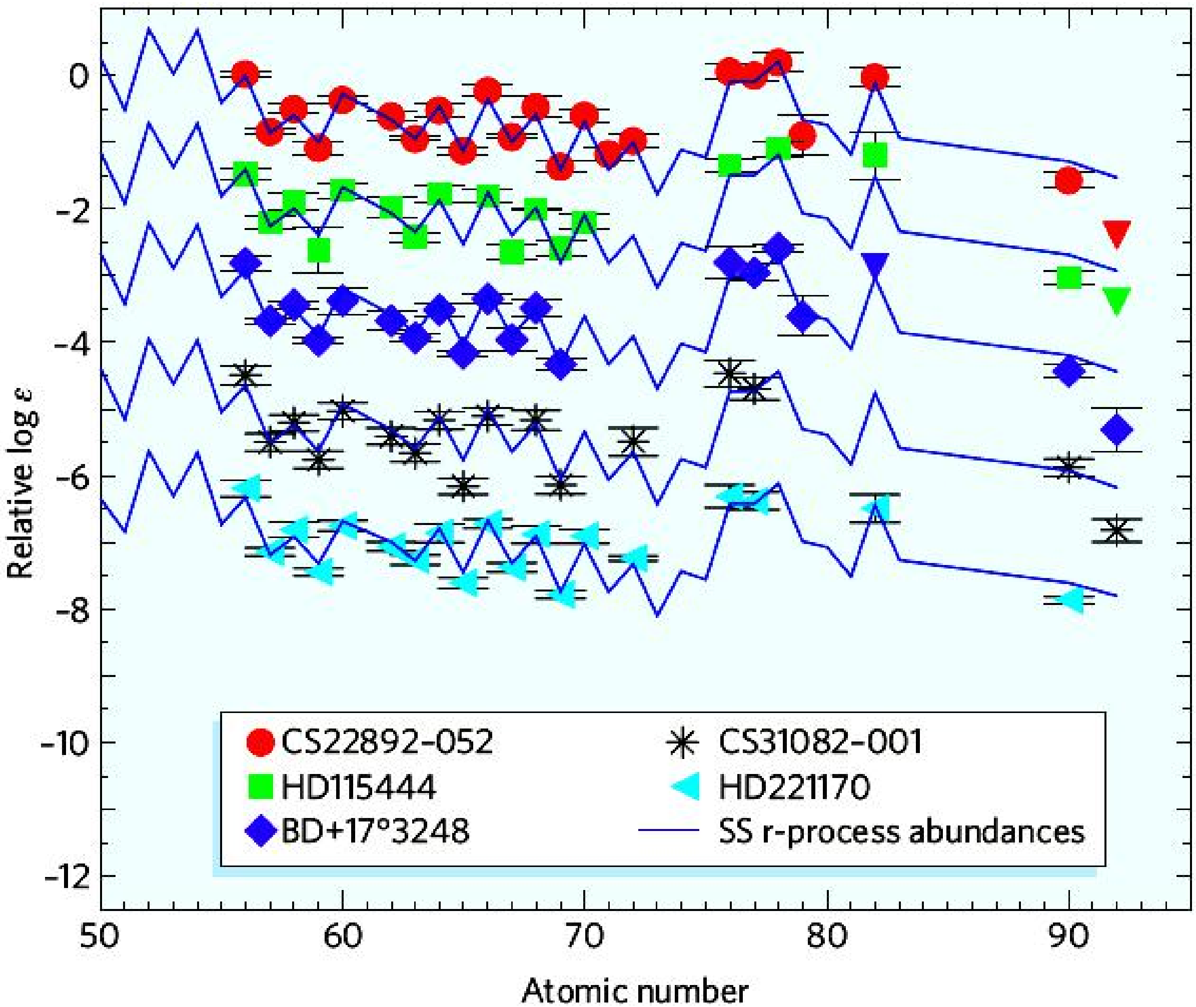
SN *yields*

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, ν 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)

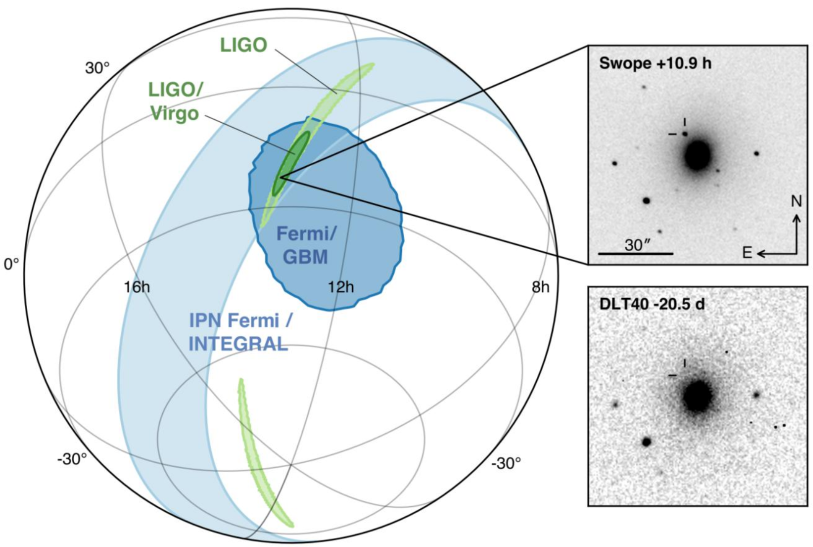
See Gabriel's talk.

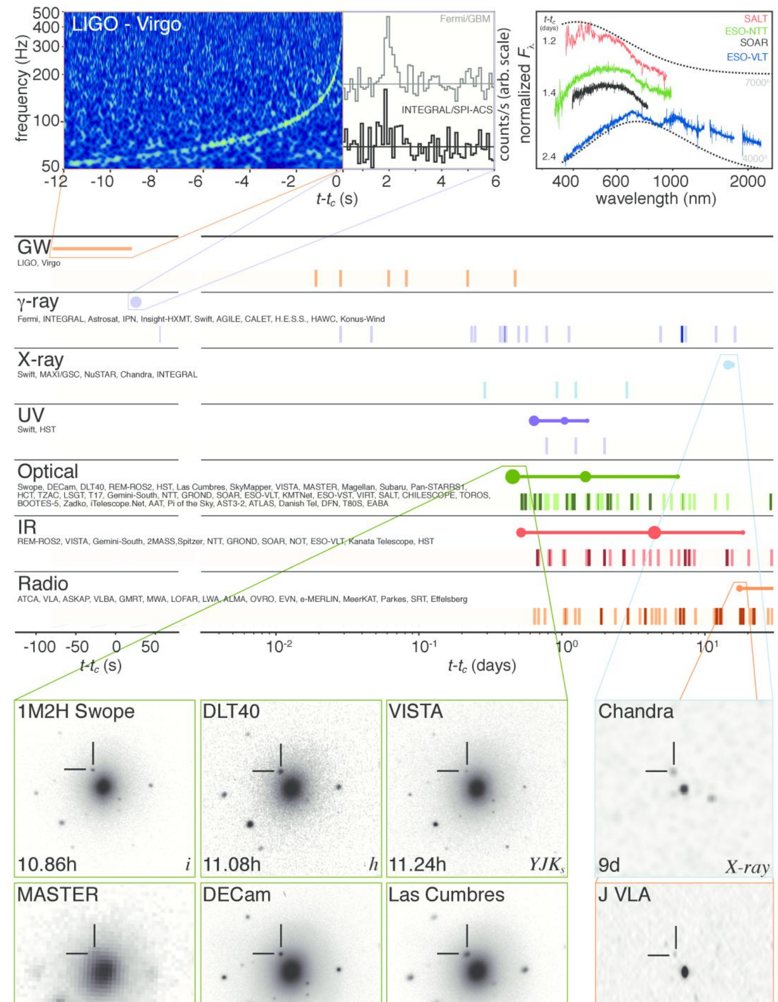
How can it be universal?

Neutron star mergers: finally confirmed

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

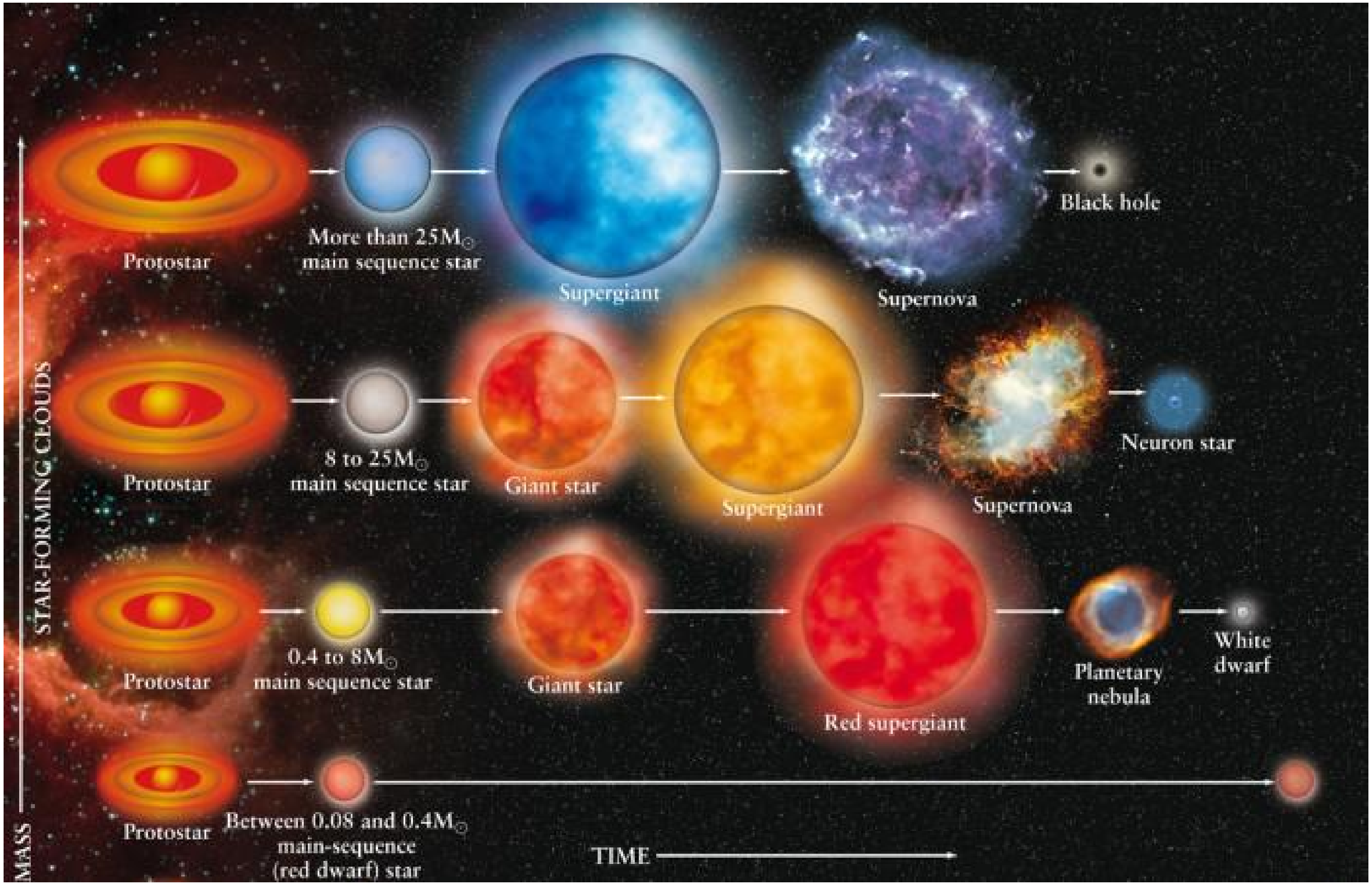
LIGO *et al.* (2017), *The Multi-messenger Paper*





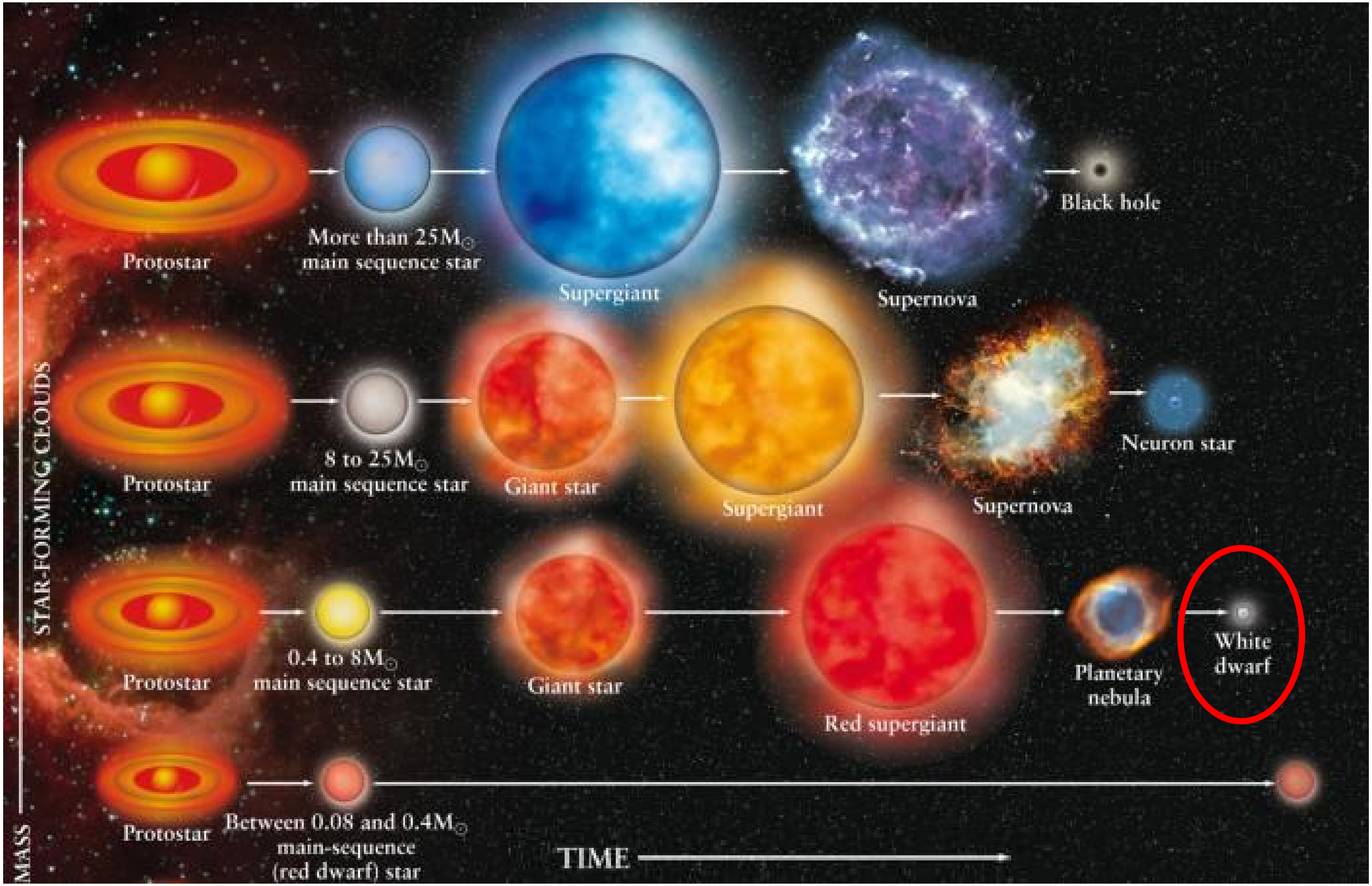
A confirmed source of **r-process elements**!

Summary

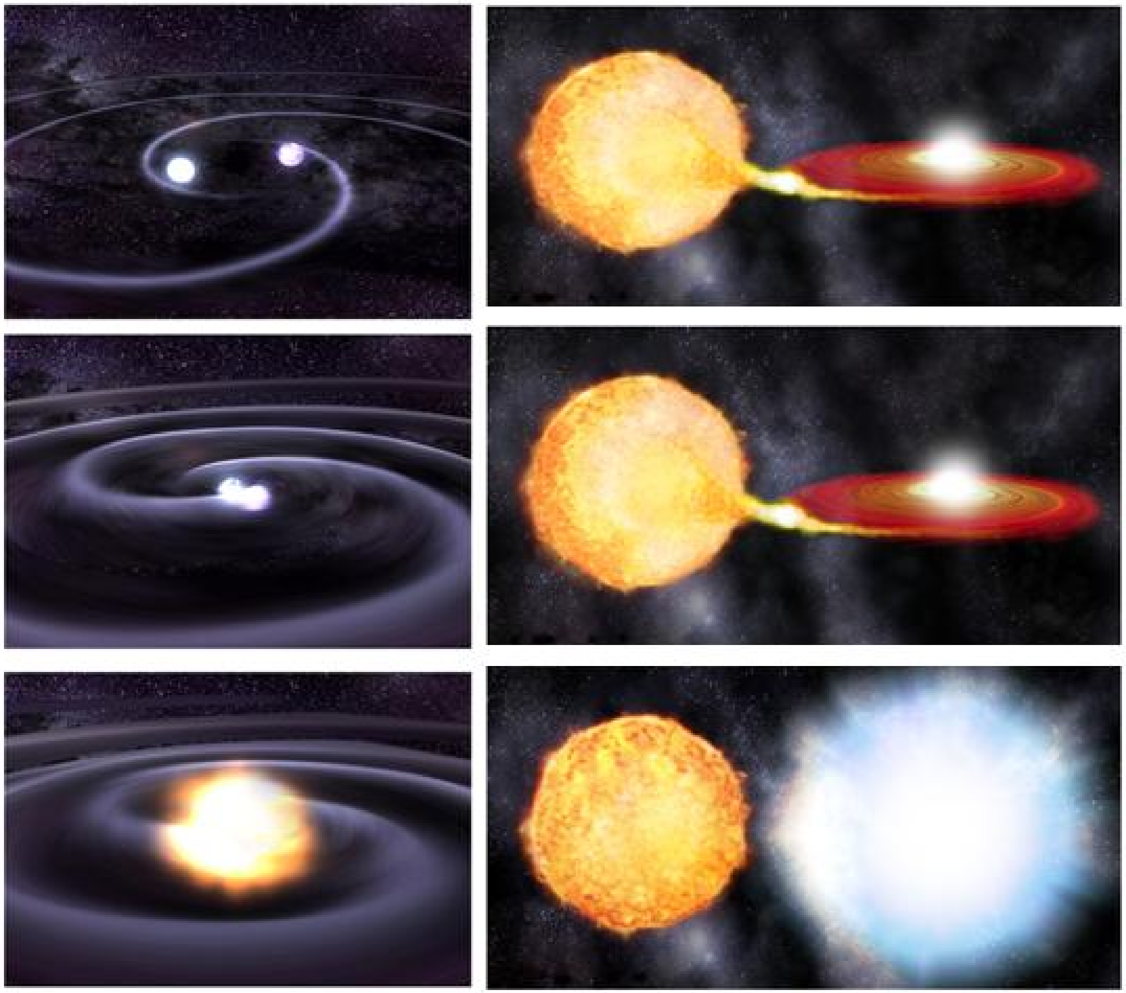


But what about binary/multiple systems?

How to make a SN type Ia



Two scenarios for SN Ia



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

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

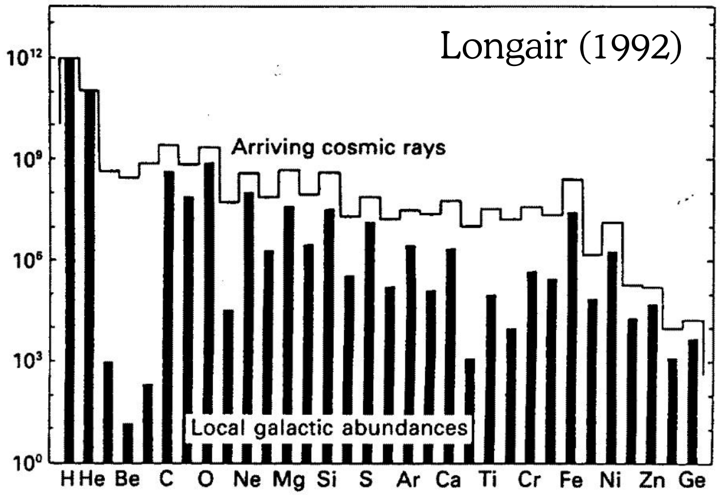
which results in a detonation/deflagration ($E \approx 10^{51}$ erg). Takes time!

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.

IV. Cosmic rays

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

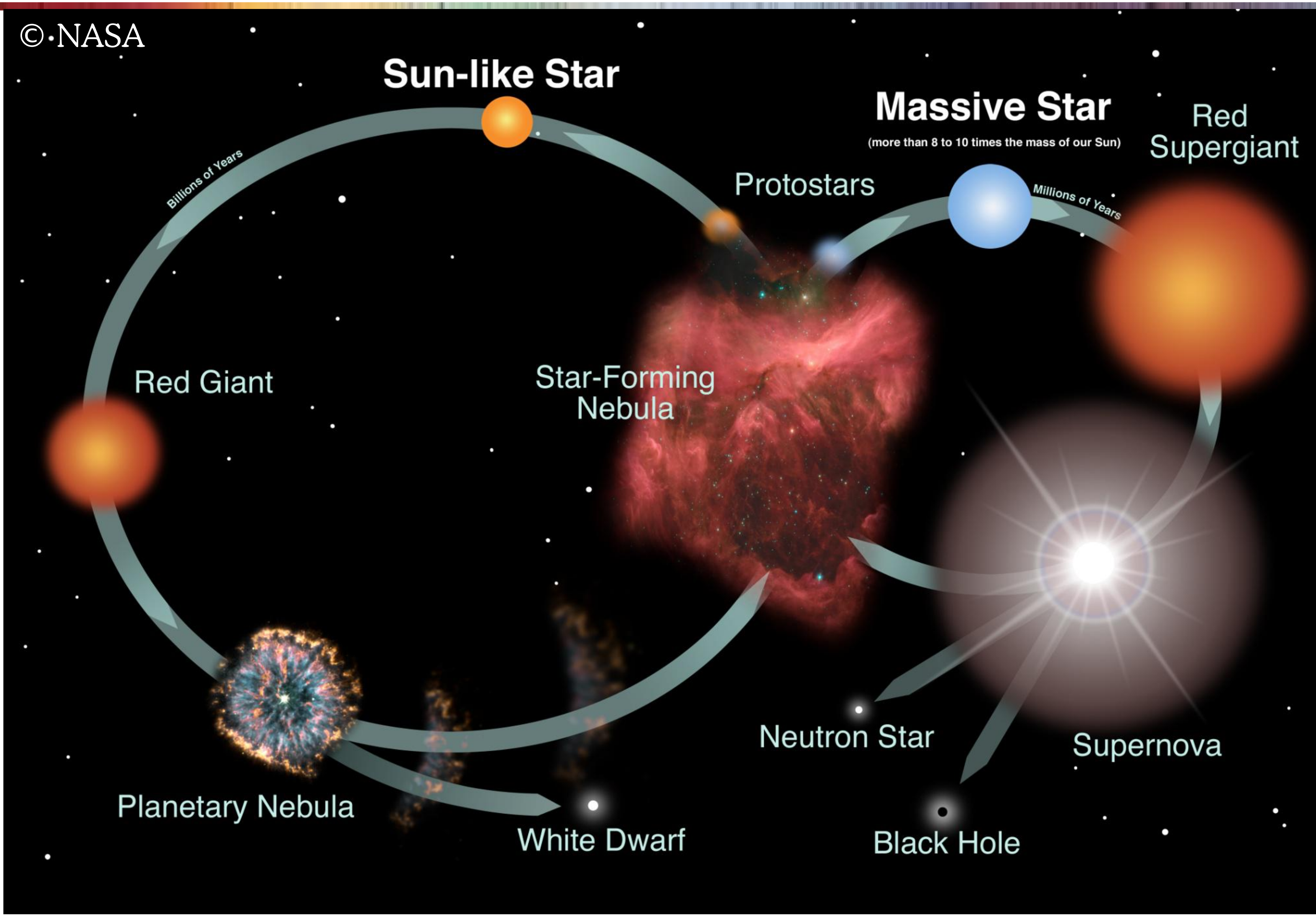
Cosmic-ray spallation



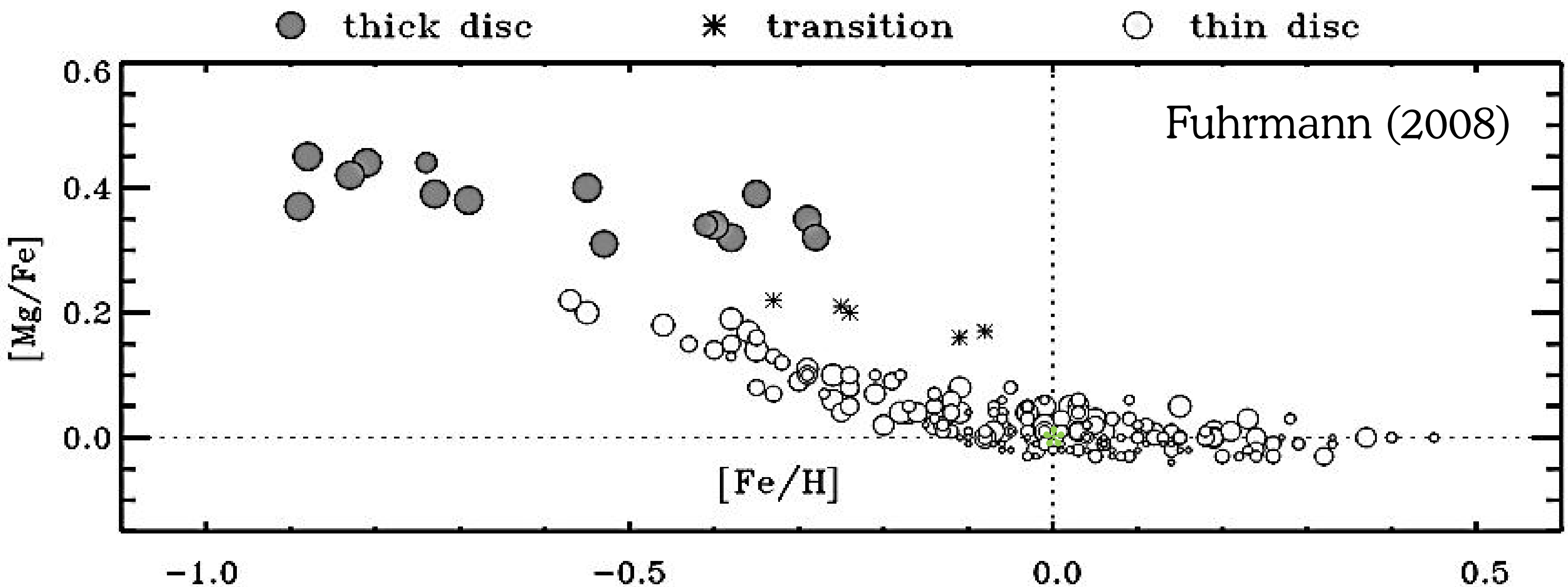
Li, Be and B are relatively fragile nuclei which generally speaking do not survive the conditions of stellar interiors ($T > 10^6$ K).

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}Li in the MW (above [Fe/H]~ -1). Be and B are less well studied in Galactic stars (hard-to-observe UV lines).

Cosmic Matter Cycle



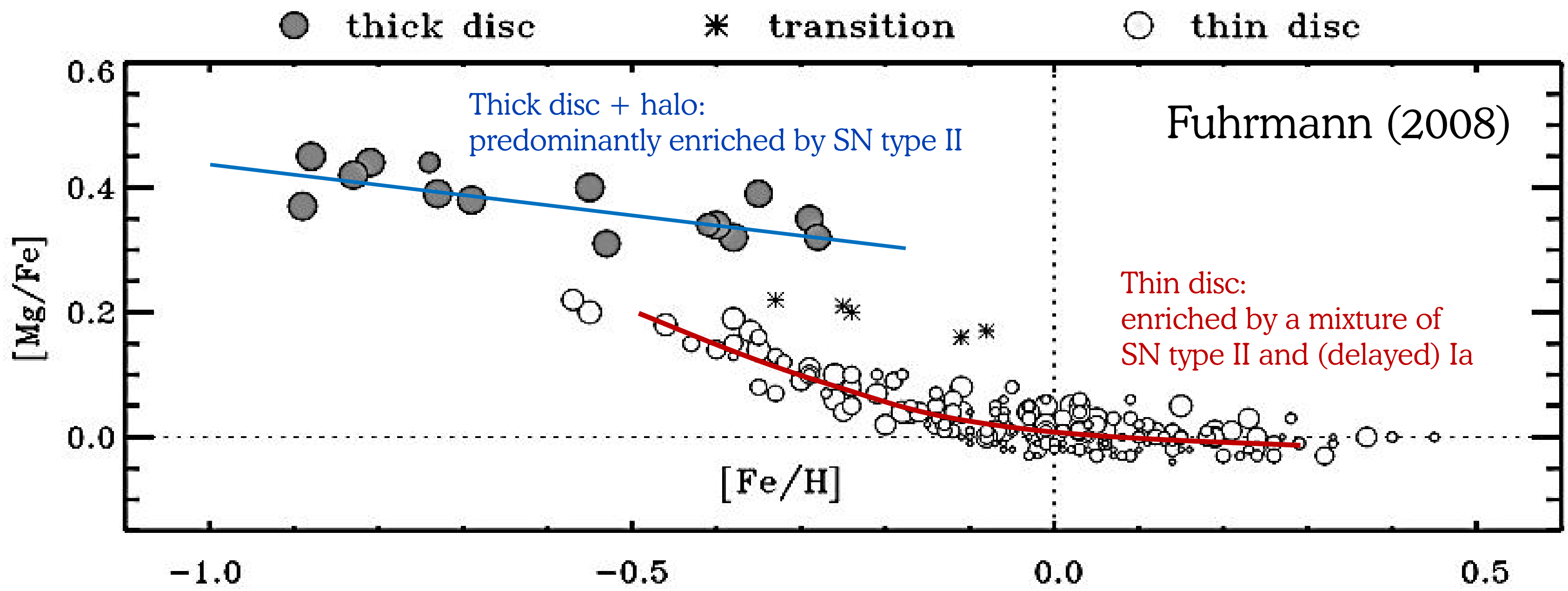
The Solar neighbourhood (25 pc)



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.

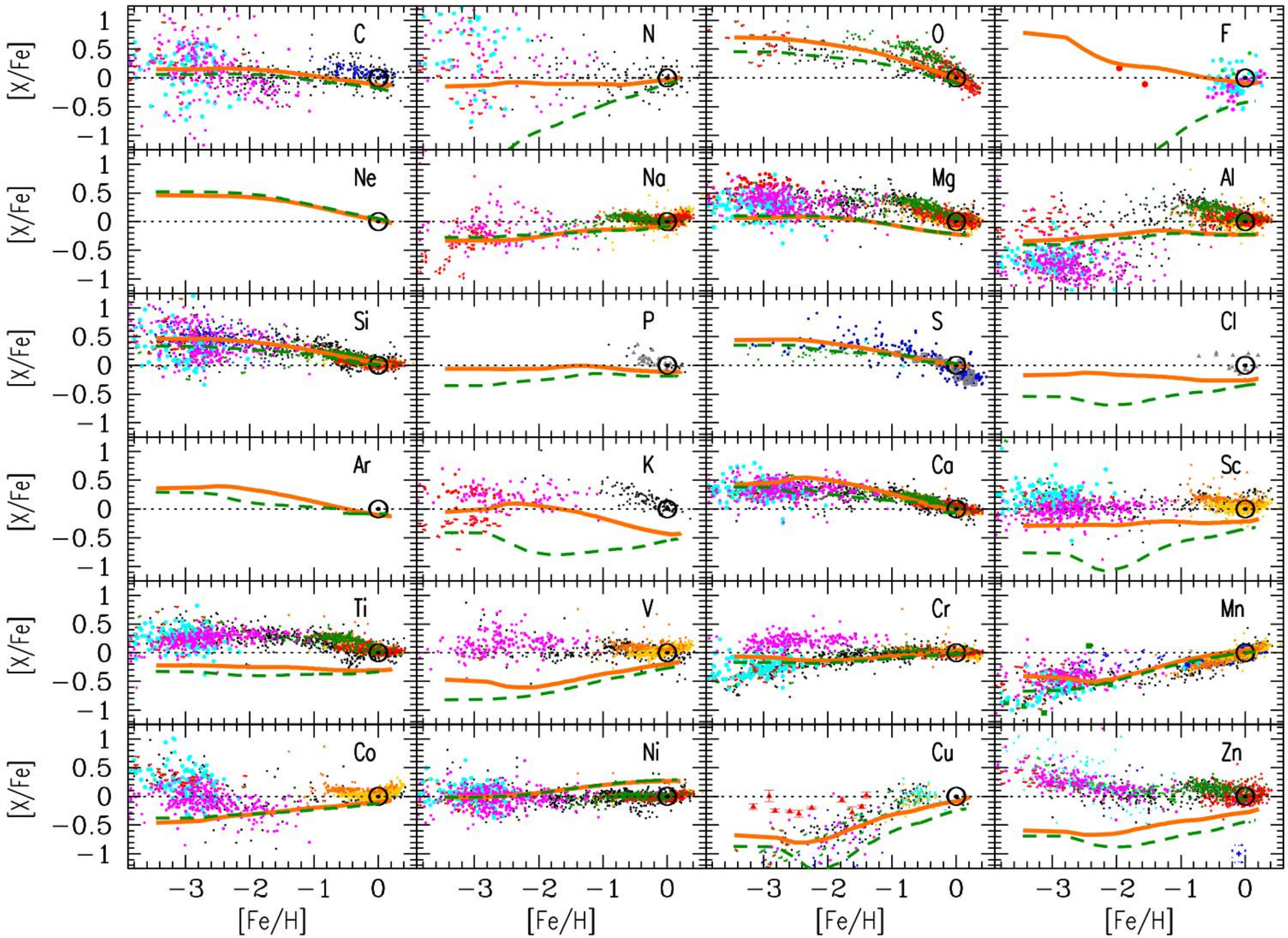
The Solar neighbourhood (25 pc)



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