Neutron-capture in the wild: finding r-process enhanced metal-poor stars in the Milky Way

Vinicius Placco

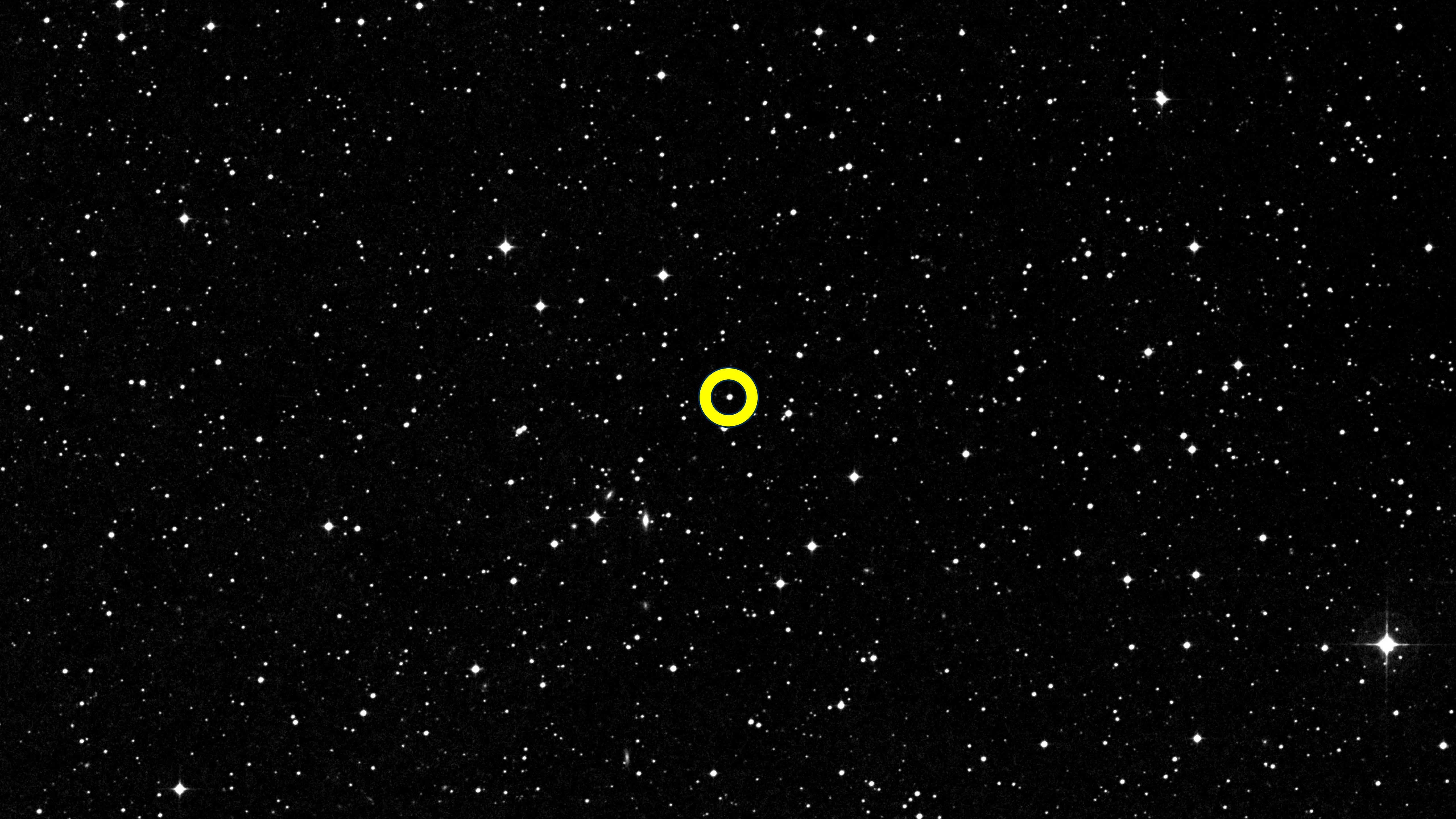
NSF NOIRLab

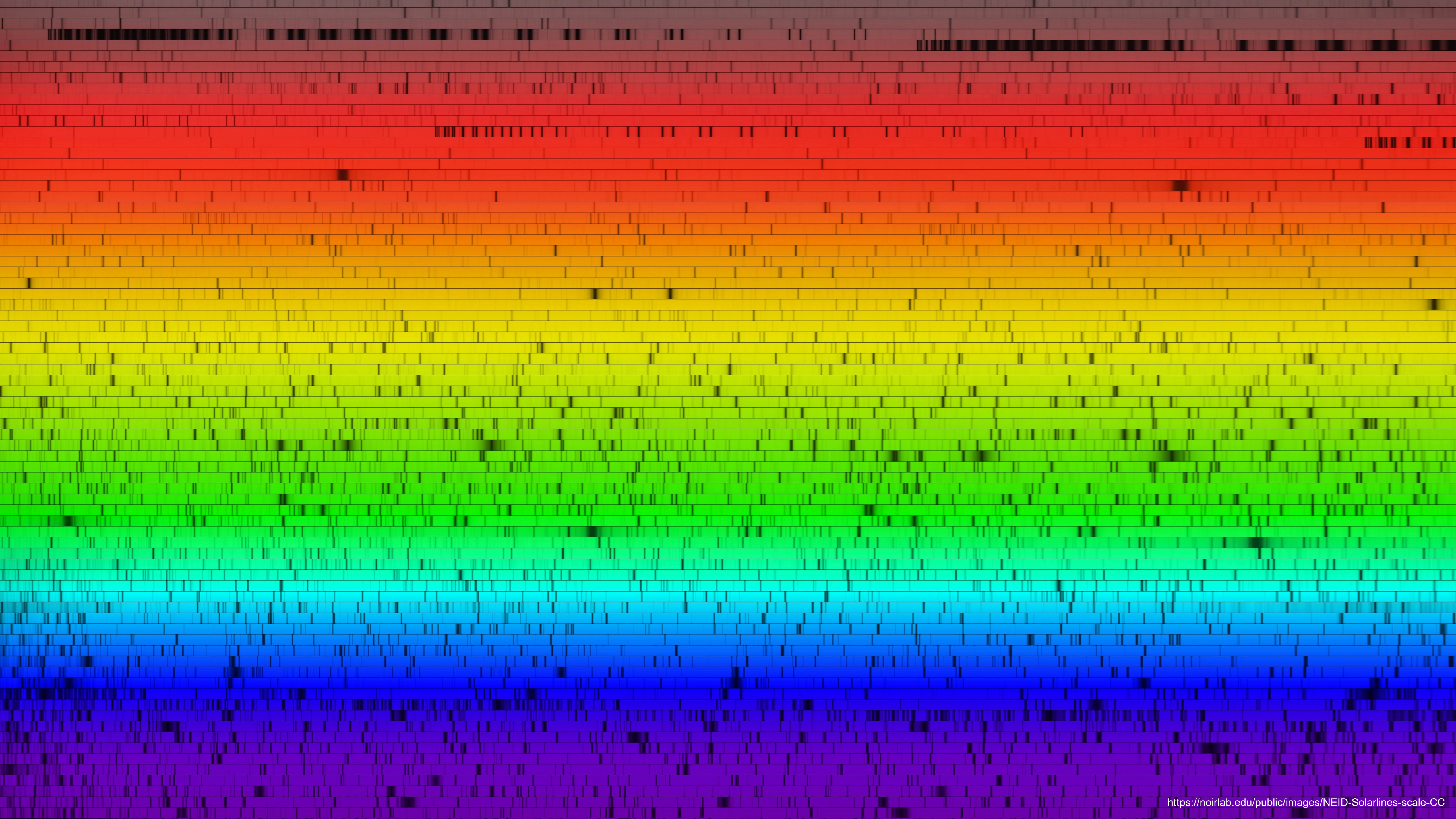
Neutron-capture in the wild: finding r-process enhanced metal-poor stars in the Milky Way and beyond!

“Going on a fishing expedition”

Vinicius Placco

NSF NOIRLab




https://noirlab.edu/public/images/NEID-Solarlines-scale-CC

Stellar Archaeology and Nucleosynthesis

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

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

https://skyandtelescope.org/wp-content/uploads/f2_Fowlerbirthday_FH-Library-500px.jpg
https://images.fineartamerica.com/images-medium-large-5/margaret-burbidge-lucinda-douglas-menzies.jpg

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https://ui.adsabs.harvard.edu/abs/1957RvMP...29..547B/abstract

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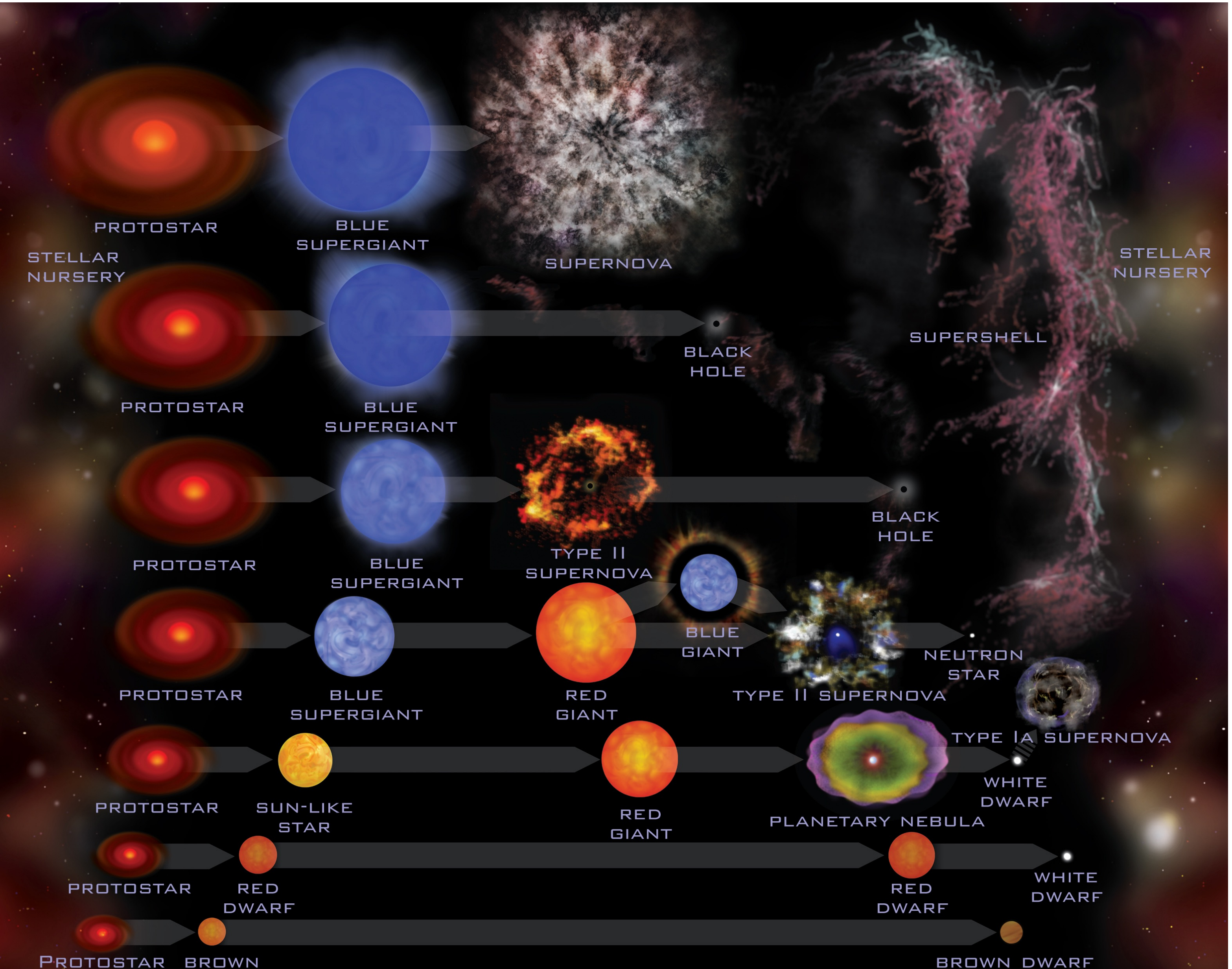
AURA

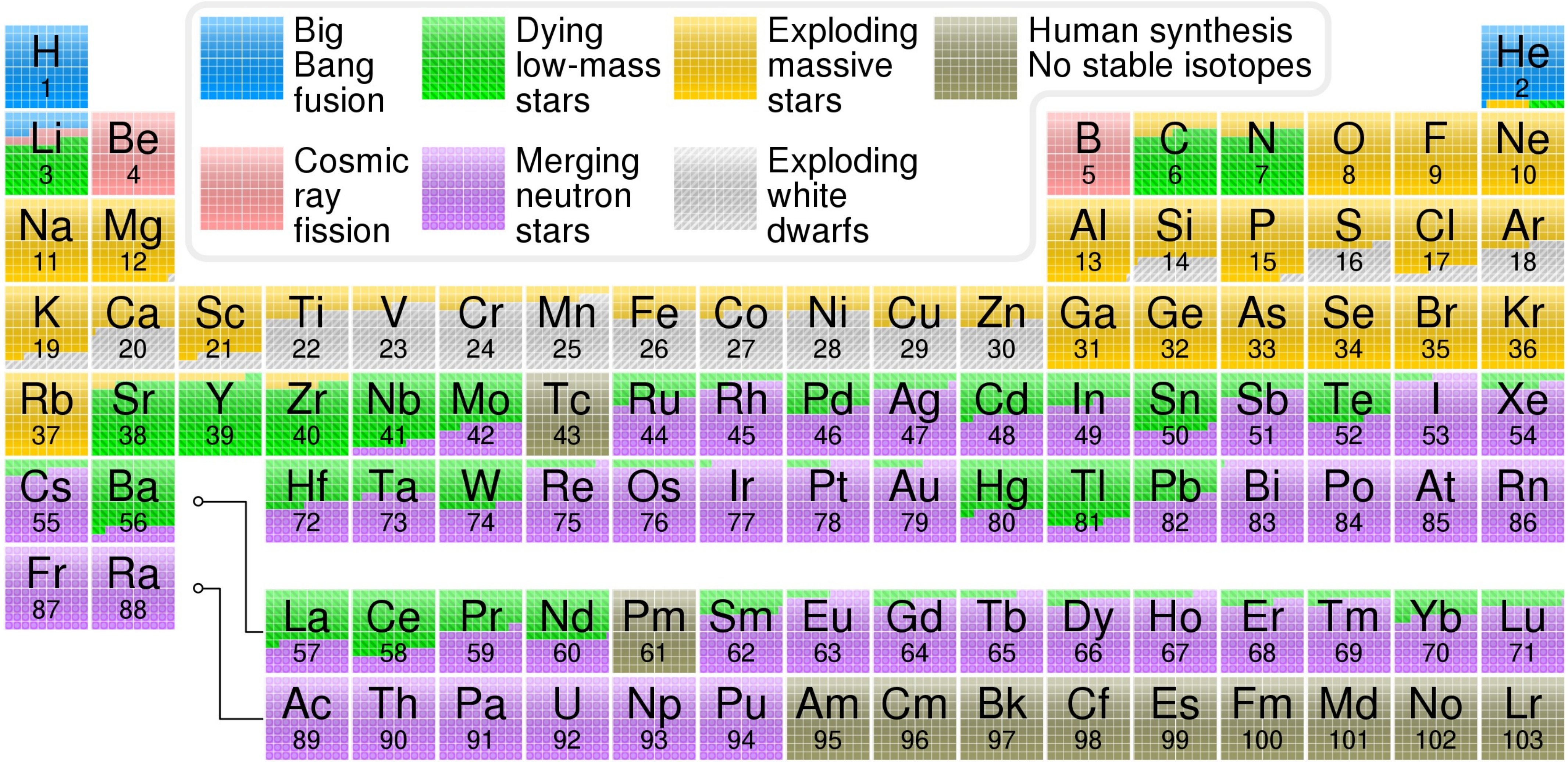
In nature - Stellar evolution



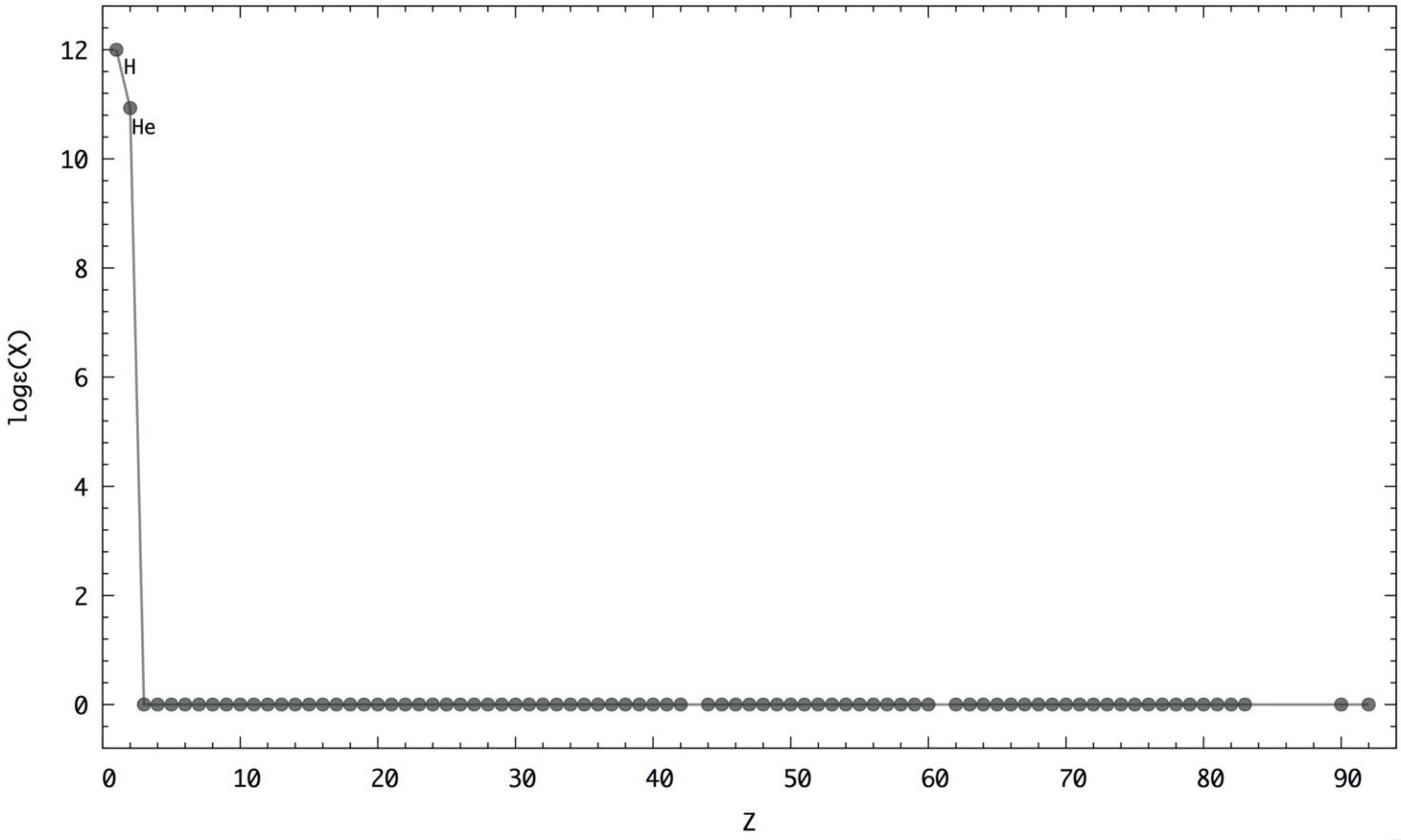
http://chandra.harvard.edu/edu/formal/stellar_ev/

https://webbtelescope.org/contents/media/images/2022/052/01GF423GBQSK6ANC89NTFJW8VM

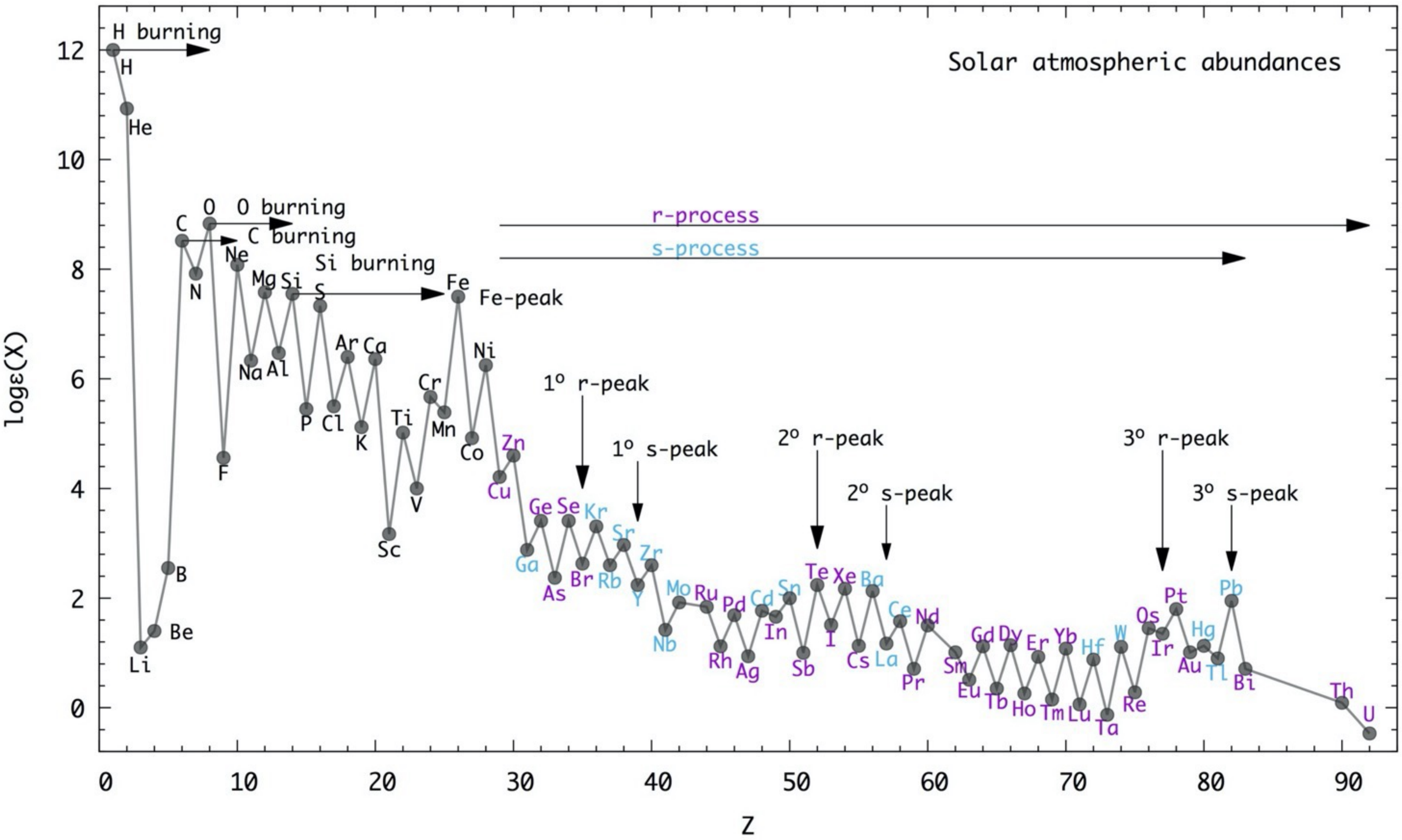
Stellar archaeology and the chemical evolution of the Universe (z = 0)



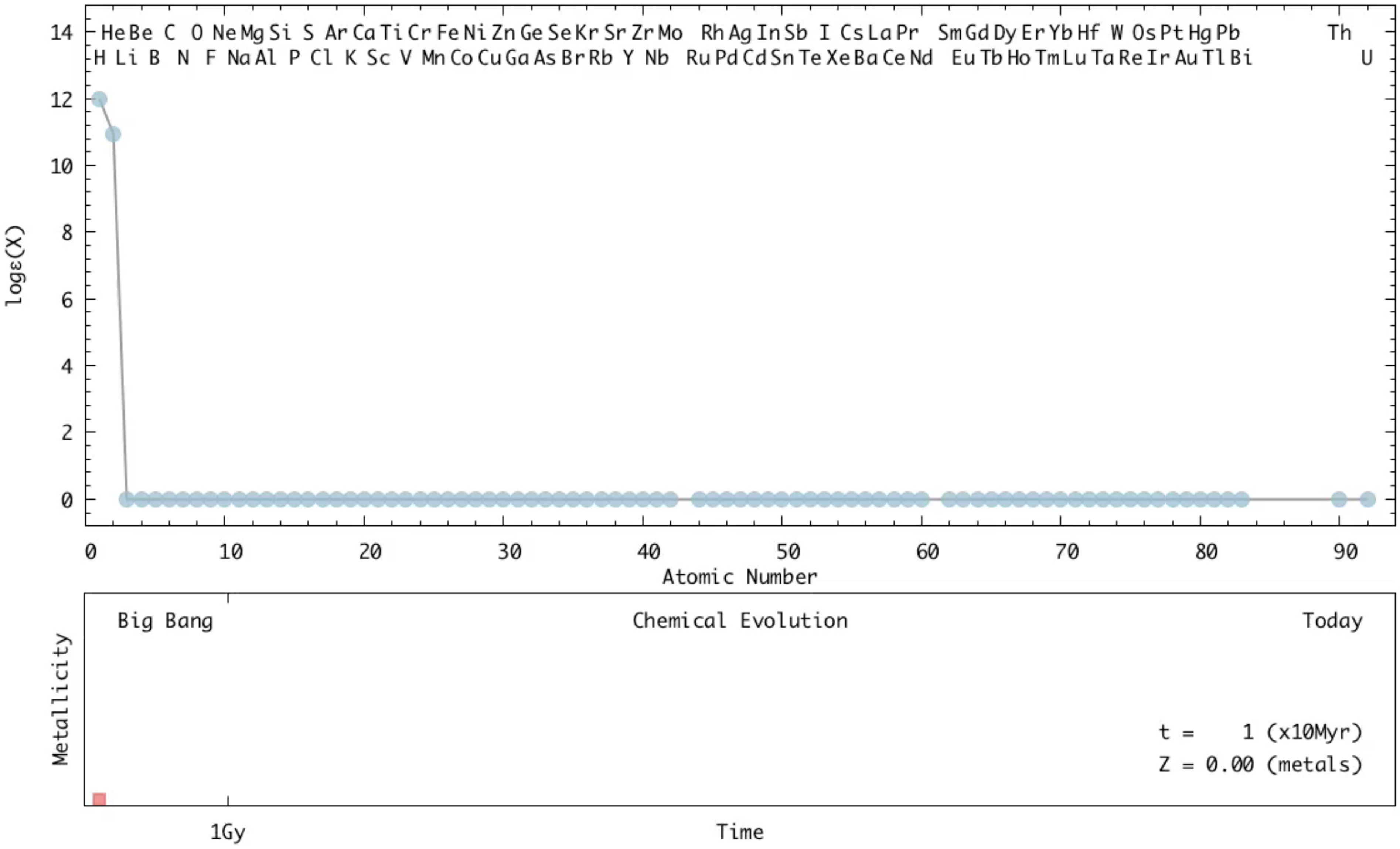
r-process in our backyard



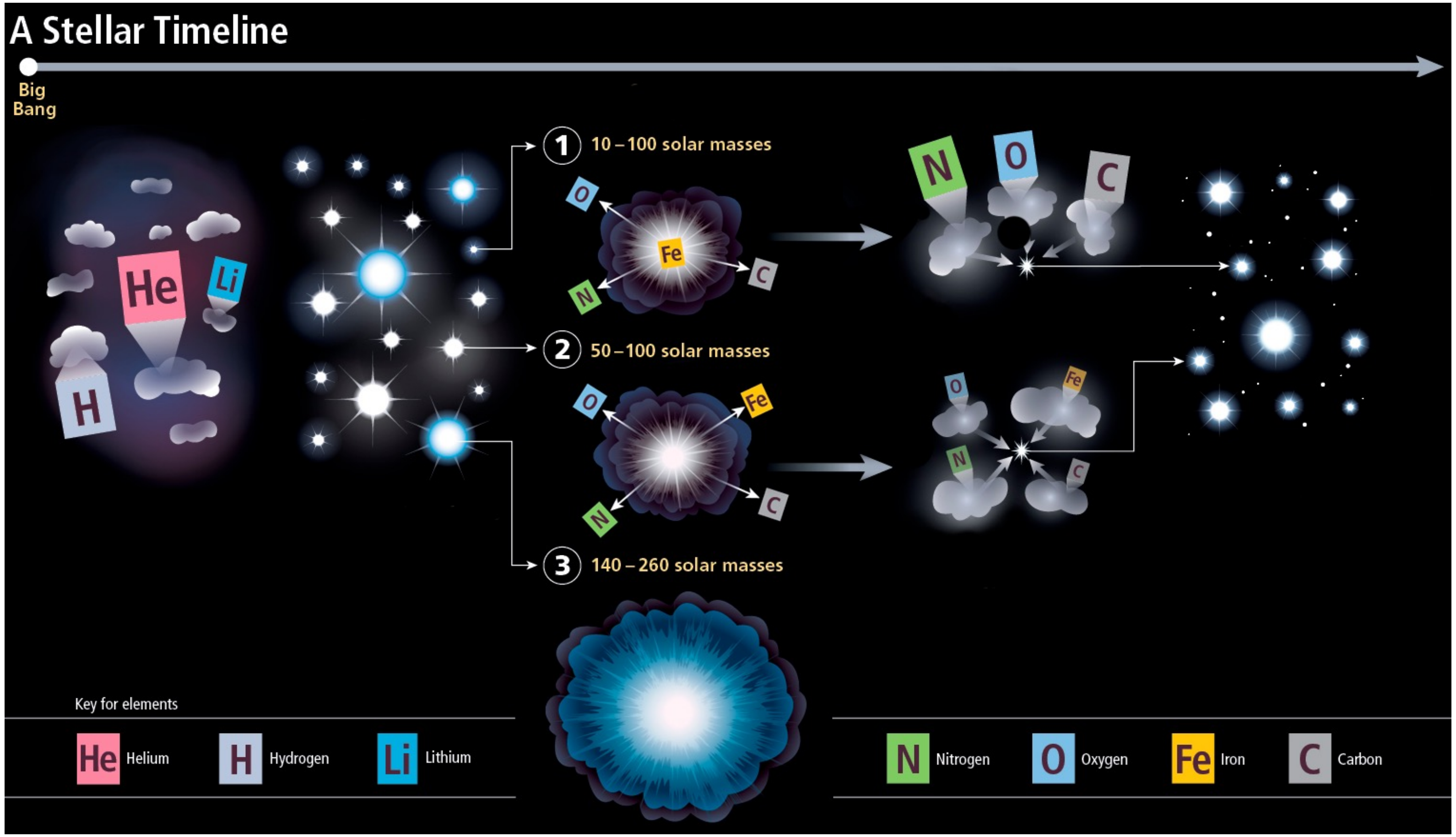
r-process in our backyard



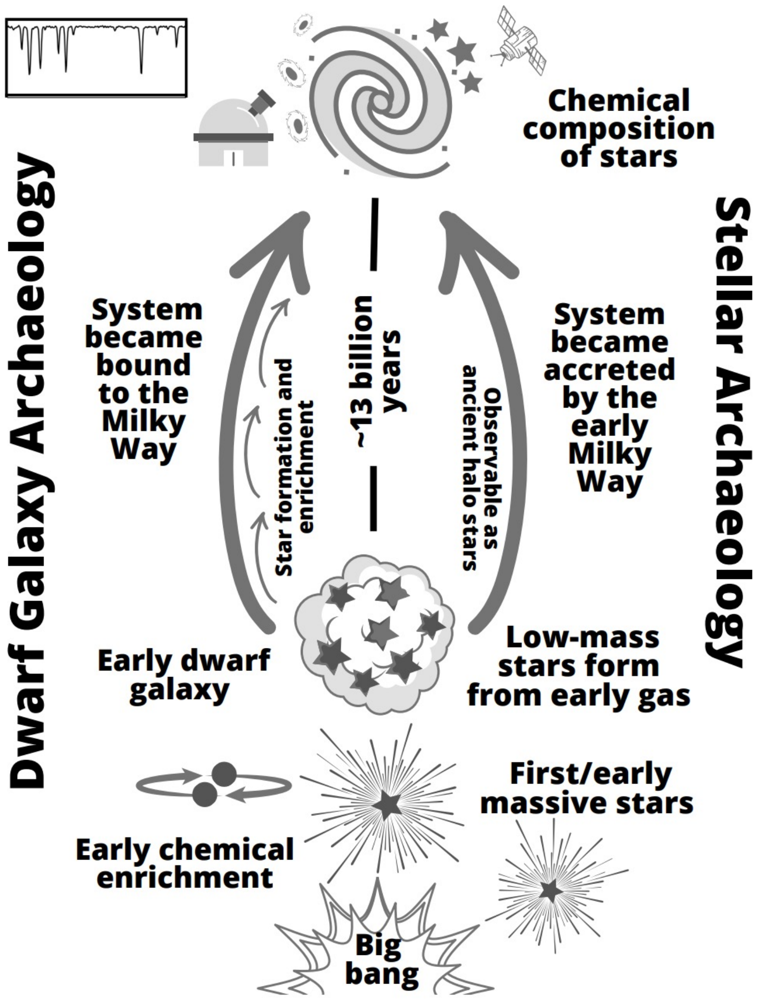
Chemical time machine



“Near field cosmology” (a.k.a. the next best thing)



Credits: Discover Magazine / Elisa Arizono



Frebel & Ji 2023

r-process enhanced metal-poor stars:

when/how were they first formed?

how do they look like?

where do we find them?

how do we find more?

the curious case of J1424-2542

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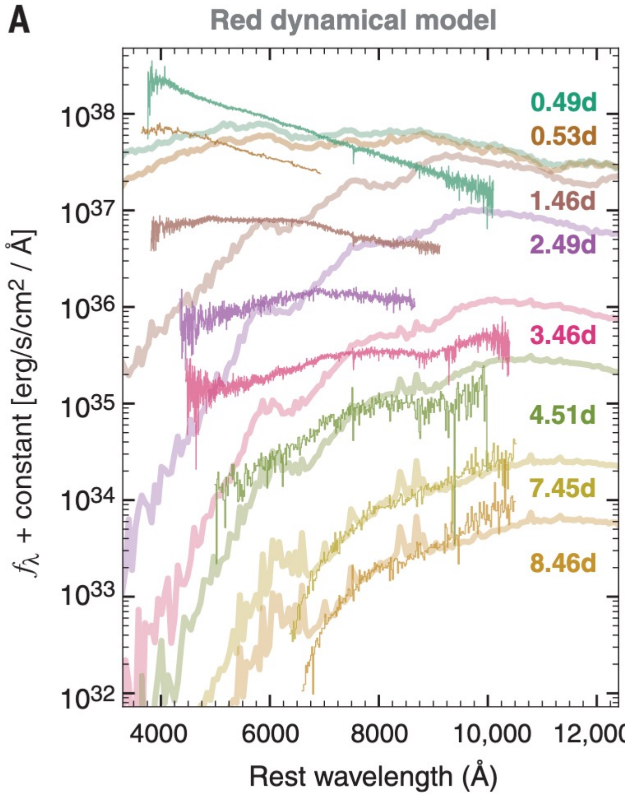
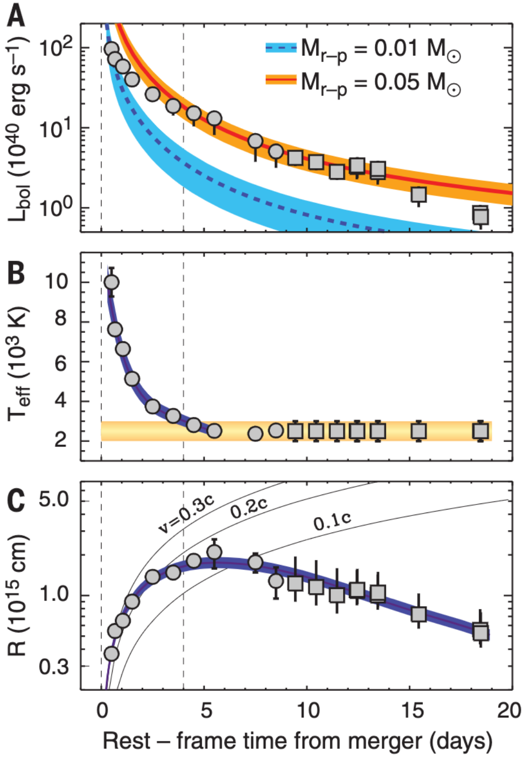
What is the culprit?

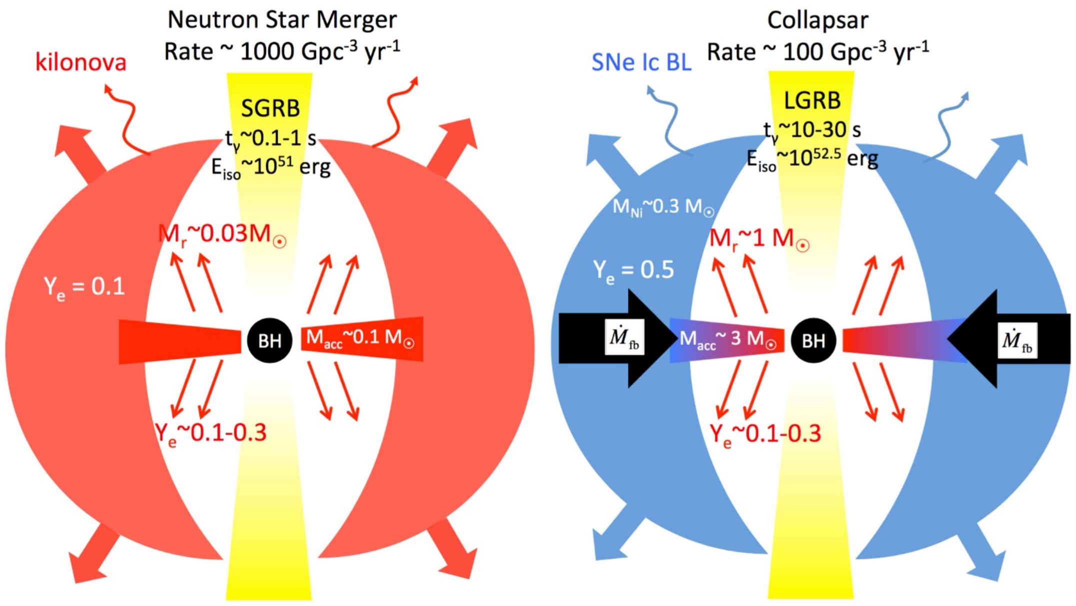
Neutron Star Merger: GW170817 → SSS17a

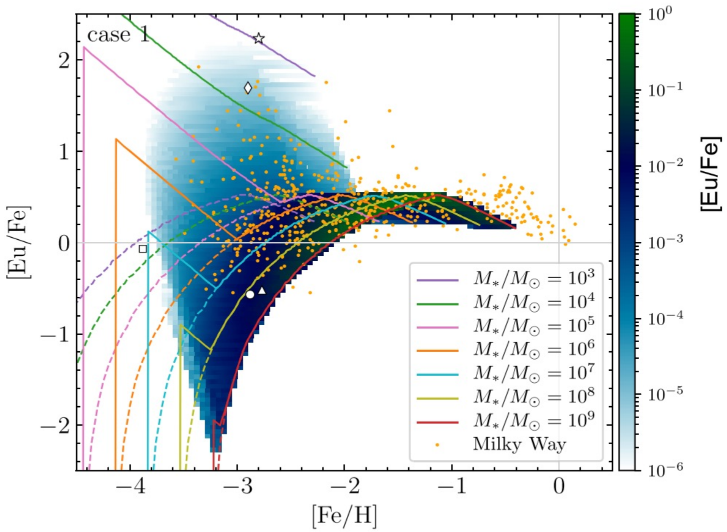


Shappee+2017

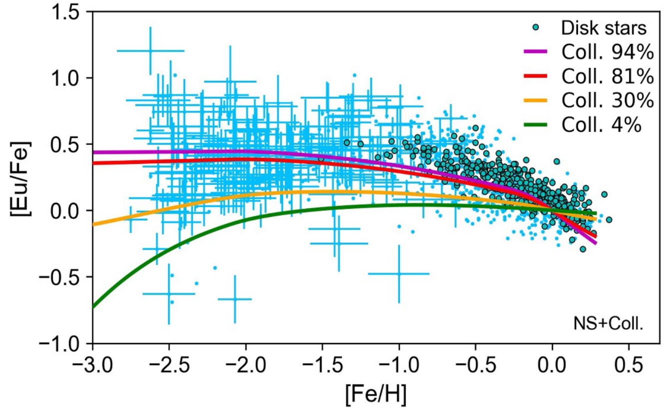


Drout+2017





Wanajo+2021



Siegel+2019

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Collapsars: supernova-triggering collapse of rapidly rotating massive stars

The culprit and the evidence

Table 2 Nucleosynthesis processes that can contribute neutron-capture elements

Process	Conditions	Elements produced	Y_e	Astrophysical sites
Terminal QSE[a]	Insufficiently neutron rich; α, neutron, proton capture and reverse; expansion from hot, dense state	Sr → Ag	<0.5	Standard proto–neutron star wind in core-collapse supernovae; shock-heated/disk ejecta
νp-process	Proton rich, $\bar{\nu}_e$ rich; QSE and $\bar{\nu}_e$ capture	Sr → Ag	>0.5	Standard proto–neutron star wind in core-collapse supernovae; shock-heated/disk ejecta
Limited r-process[b]	Neutron-to-seed ratio ≪100; QSE and (limited) neutron capture; no fission cycling	Sr → Ba (limited production) toward Ba	<0.5	Modified proto–neutron star wind; neutron star merger: disk (after merger, viscous/wind timescales); shock-heated ejecta (during merger, dynamical timescales)
Main r-process	Neutron-to-seed ratio >100; QSE and neutron capture; any fission cycling	Ba→ U	<0.2	Neutron star merger: tidal ejecta (during interaction); dynamical ejecta (during merger)
Robust (main) r-process	Neutron-to-seed ratio >100; QSE and neutron capture; fission cycling limit	Ba → U	<0.2	Neutron star merger: tidal ejecta (during interaction); dynamical ejecta (during merger)

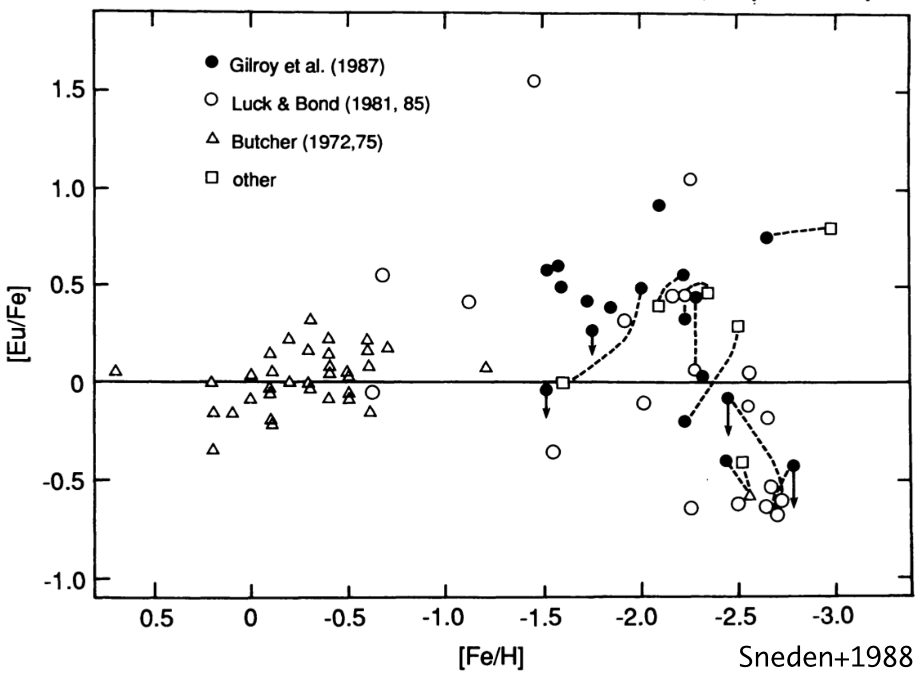
[a]Quasi-statistical equilibrium; see Reference 104 for a detailed description and treatment.
[b]Often referred to as the weak r-process or the light-element primary process (LEPP). However, the term "weak" does not well describe the nature of the underlying r-process physics, and "LEPP" does not refer to a specific nuclear physics process.

Frebel 2018

Property	Evidence from Metal-Poor Halo Stars	Evidence from Dwarf Galaxies
Rate	Rare: large [Eu/Fe] scatter	Rare: fraction of ultra-faint dwarf galaxies with r-process; $\sim 10^{-3}$ that of core-collapse supernovae
Yield	Ambiguous due to unknown dilution mass and metal-poor star formation site	At least one prolific r-process site $M_r \gtrsim 10^{-2} M_\odot$
Delay Time	Likely have prompt sources and may have delayed sources	Must have both prompt and delayed sources
Composition	Universal pattern from 2nd to 3rd peak Variations in relative abundance of 1st peak and actinides	Consistent with halo stars

Table 3: Summary of Evidence for R-process Site(s)

Frebel & Ji 2023



Sneden+1988

r-process enhanced metal-poor stars:

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how do we find more?

the curious case of J1424-2542

The r-process signature: find europium!

Lunt 1907

On the Presence of Europium in Stars.

By Joseph Lunt, B.Sc., F.I.C., Assistant at the Royal Observatory, Cape of Good Hope.

(Communicated by Sir David Gill, K.C.B., F.R.S., H.M. Astronomer. Received January 2,—Read January 24, 1907.)

In measures of the radial velocity of α Boötis and β Geminorum, the results for the calcium line at λ 4435·851 (Rowland) are discordant. In both stars, in measures made independently by Mr. Goatcher and the author, the value for this line is too low (positive). The following are the figures :—

The assumption was made that some line of unknown origin was blended with the Ca line in these stars. On consulting Exner and Haschek's "Haupttabelle," europium was indicated as the disturbing element, a line of intensity 30 being recorded at λ 4435·75.

On comparing the spectrum of α Boötis with a solar spectrum (daylight), both taken with the same instrument, by placing the negatives film to film and adjusting the lines to coincidence, it was found that the indications of the presence of europium, already noted, were confirmed.

The two strong lines at λ 4129·90 and λ 4205·20 happen to fall on groups of faint lines in the solar spectrum which are unresolved and appear as shadings with the dispersion employed.

As there is such strong evidence of the existence of europium in celestial bodies, it would appear remarkable if the closely allied elements of the rare-earths, particularly samarium and gadolinium, were absent. Professor Dyson records the following rare-earth metals as present, with more or less certainty, in the chromosphere, viz. :—

La, Ce, Pr, Nd, Sa, Eu, Gd, Yb, Y.

Some of these elements, *e.g.*, La, Ce, Nd, Yb, Y are without doubt responsible for lines in the solar spectrum.

The present paper suggests that if the lines of europium are so much more pronounced in the spectra of the more advanced solar stars, such as α Boötis, than in the solar stars proper, the rare-earth metals as a group may possibly account for many of the striking differences to be observed between them.

Baxandall 1913

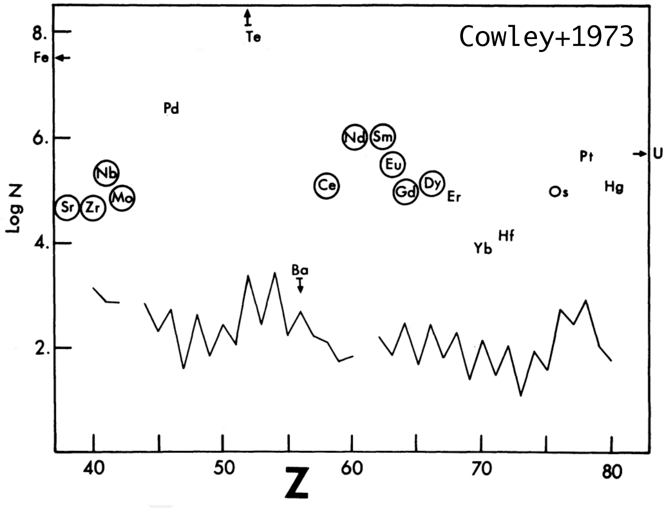
On the Occurrence of Europium Lines in Stellar Spectra.

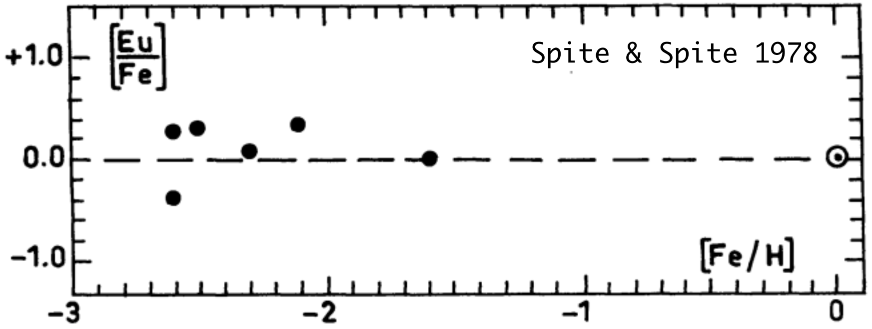
By F. E. Baxandall, A.R.C.Sc.

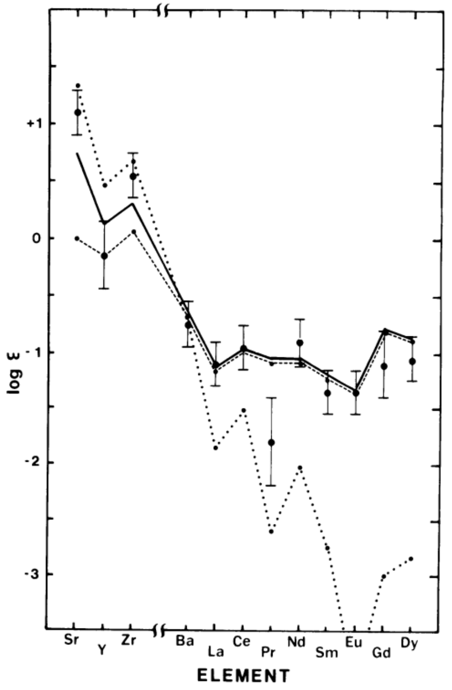
(*Communicated by Professor Newall.*)

In a letter to *The Observatory*, dated October 18, it was pointed out that several lines which Professor Belopolsky * has shown to have a periodic variation in intensity in the spectrum of α Canum Venaticorum, agreed very closely in wave-length with the strongest lines of europium, and that this suggested a real identity between the two sets of lines. The facts may be concisely re-stated here for convenience of reference. The following table gives a comparison of the wave-lengths of lines in Belopolsky's list for α Canum Venaticorum, and those of the strongest lines of europium as given by Exner and Haschek in the same region of spectrum.

Strongest Europium Lines (Exner and Haschek.) λ.	Intensity. Spark.	Arc.	α Canum Venaticorum Lines (Belopolsky). λ.	Diff. in λ.	Remarks.
3930·65	50	50	3930·67	0·02	...
3972·16	50	50	...	...	Hε would mask this line in star.
4129·90	100	100	4130·04	0·14	...
4205·20	50	100	4205·20	0·00	...
4435·75	30	50	4435·77	0·02	Stellar line partly due to Ca 4435·85.







Sneden & Pilachowski 1985

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Metal-poor, but with lots of (heavy) metals…

Definition:

Sun: [Fe/H]=0 and [Eu/Fe]=0

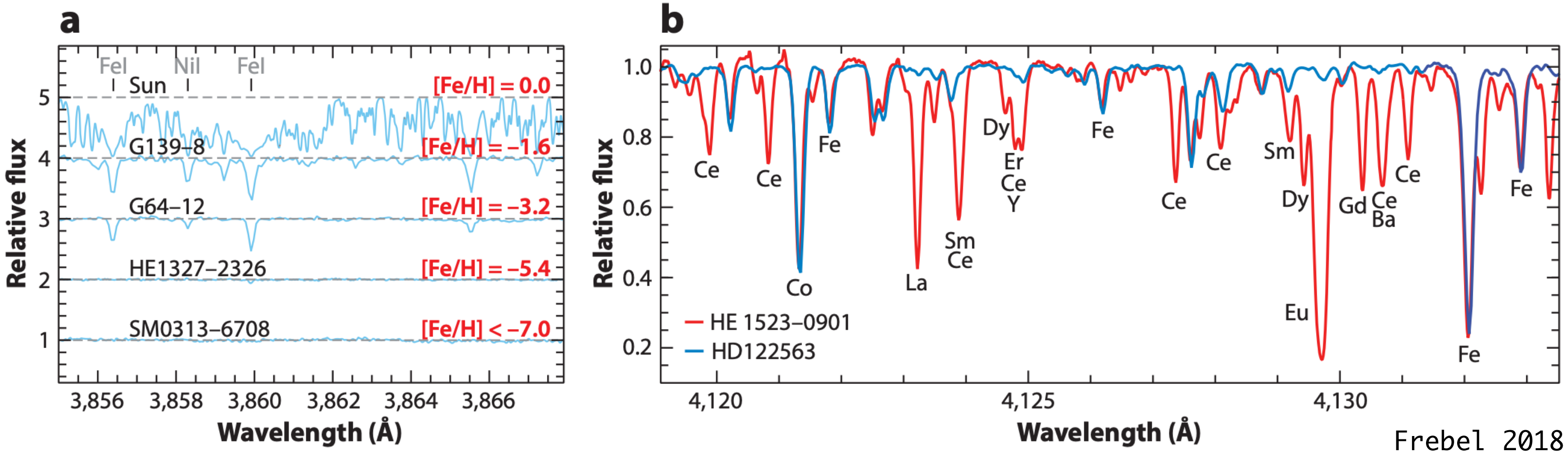
Metal-poor: [Fe/H] < -1

r-I:
- [Fe/H] < -1
- 0.3 < [Eu/Fe] < 0.7
- [Ba/Eu] < 0.0

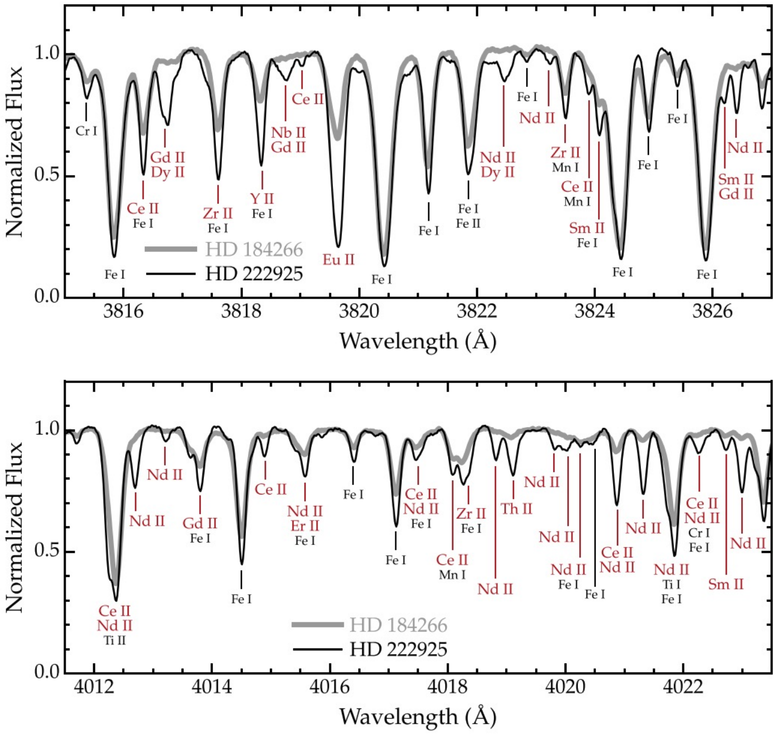
r-II:
- [Fe/H] < -1
- [Eu/Fe] > 0.7 (>1.0)
- [Ba/Eu] < 0.0

r-III:
- [Fe/H] < -1
- [Eu/Fe] > 2.0
- [Ba/Eu] < 0.0

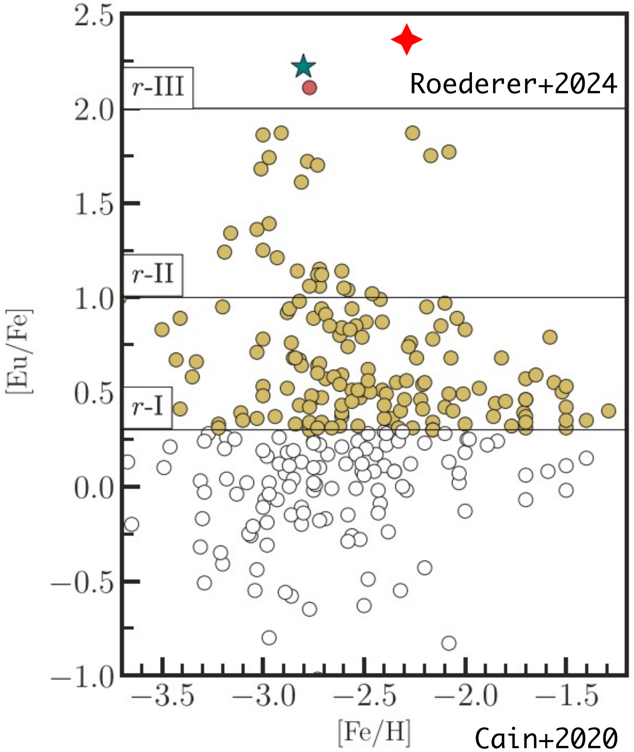
Frebel 2018, Cain+2020, Holmbeck+2020



Frebel 2018



Roederer+2018



Cain+2020

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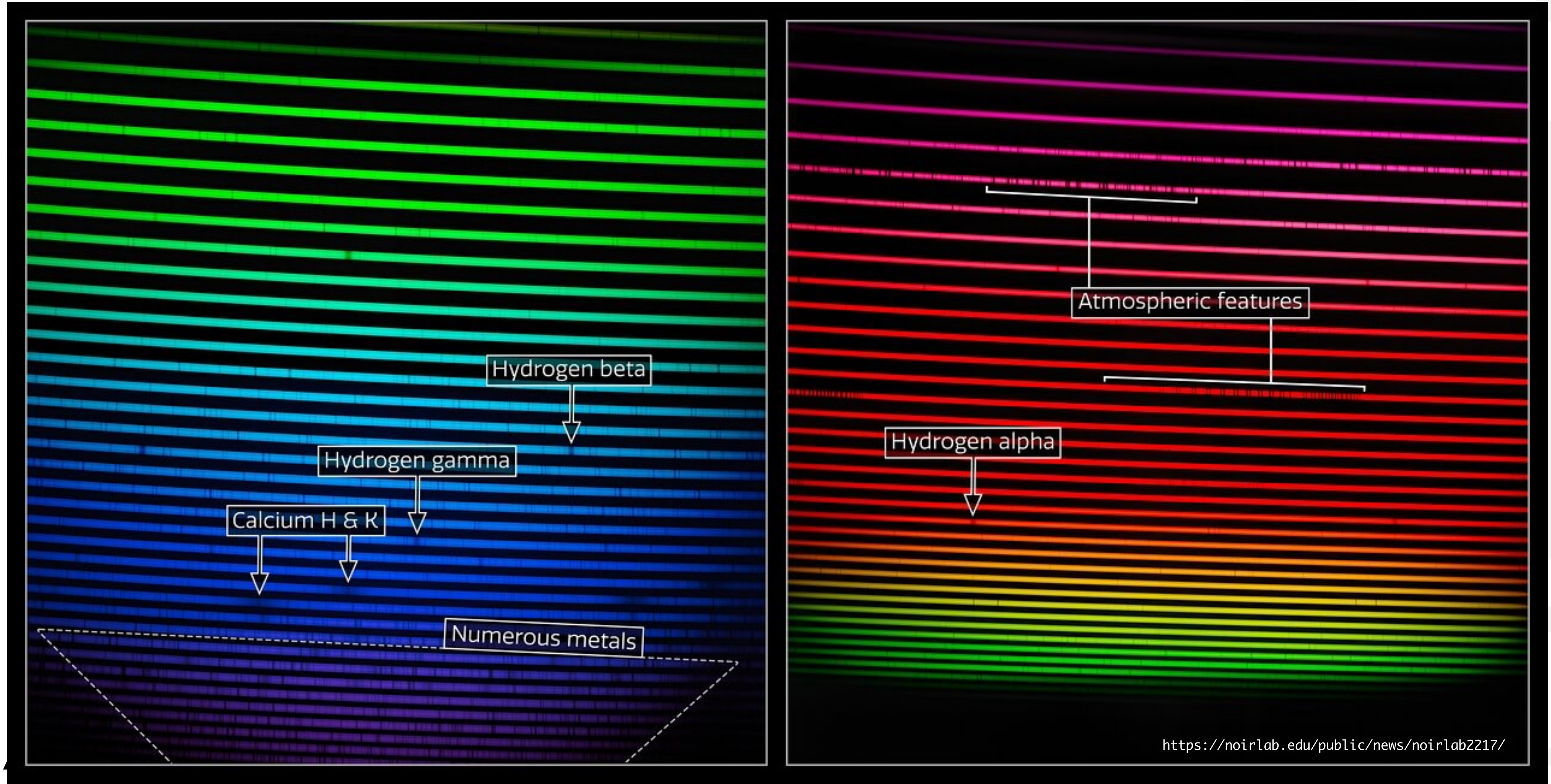
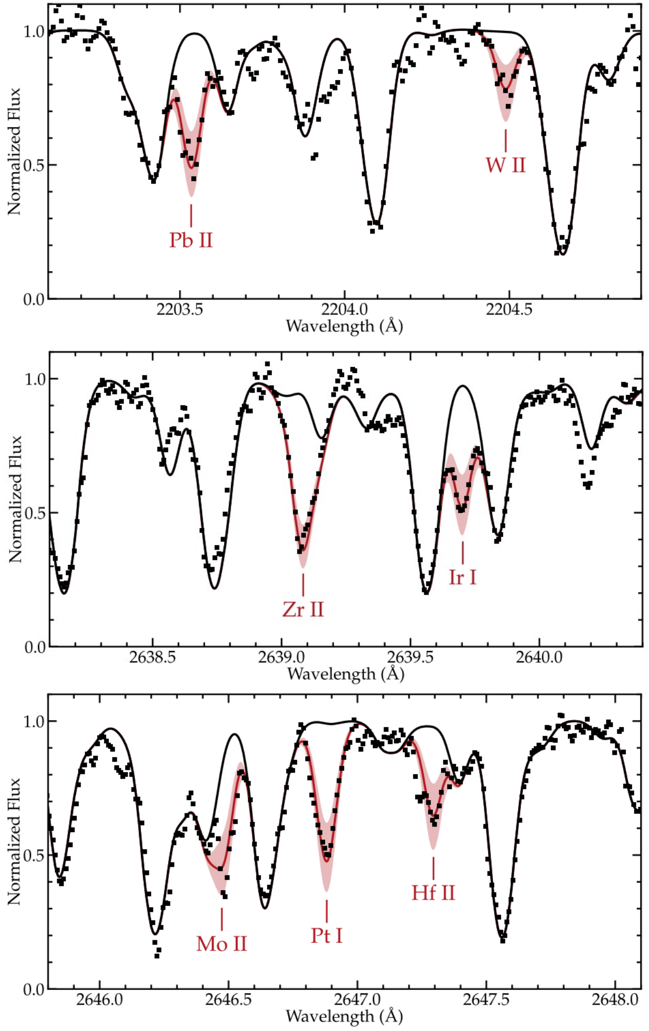
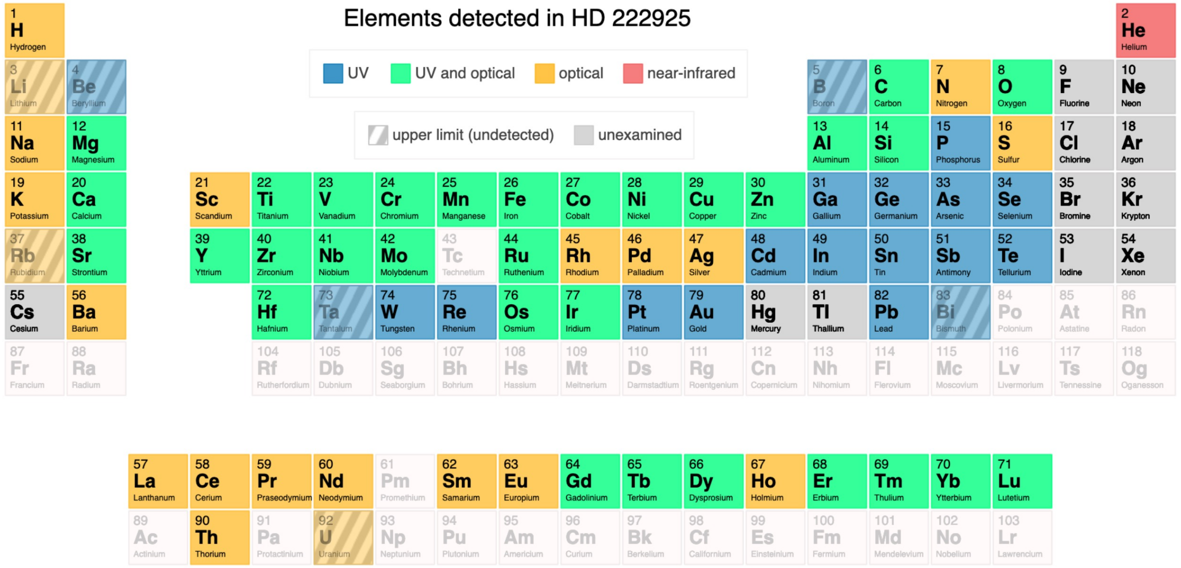
The new standard: HD222925

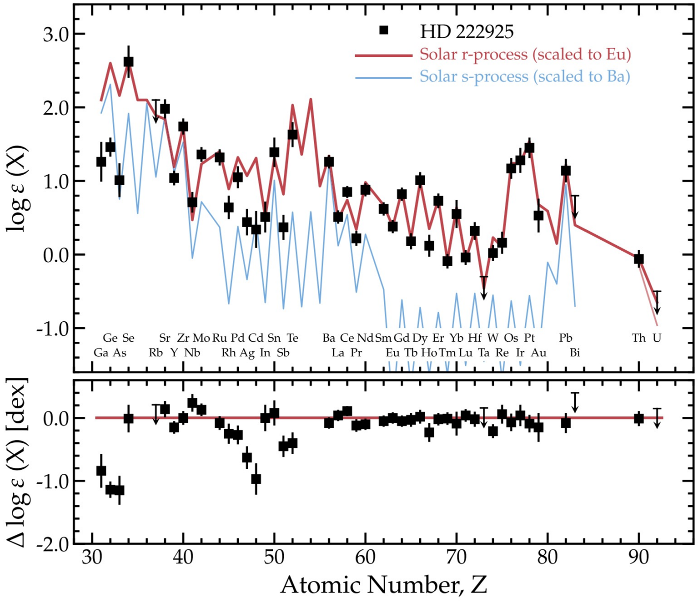


The new standard: HD222925 (63 metals detected)

1,305 lines measured (UV + optical)







Roederer+2018, Roederer+2022

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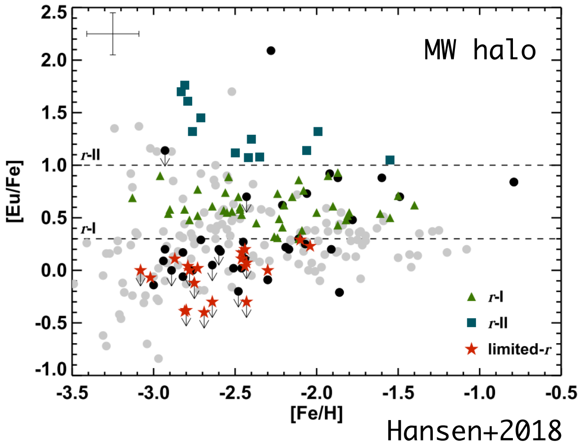
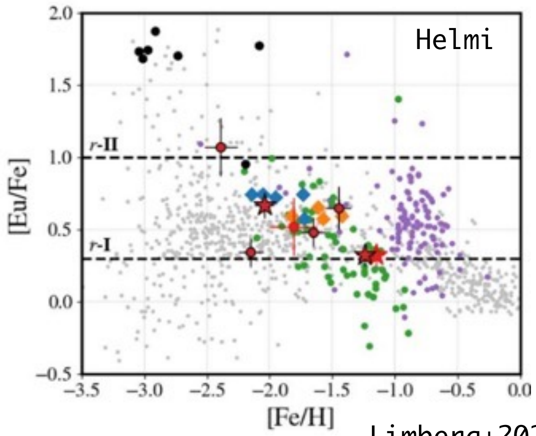
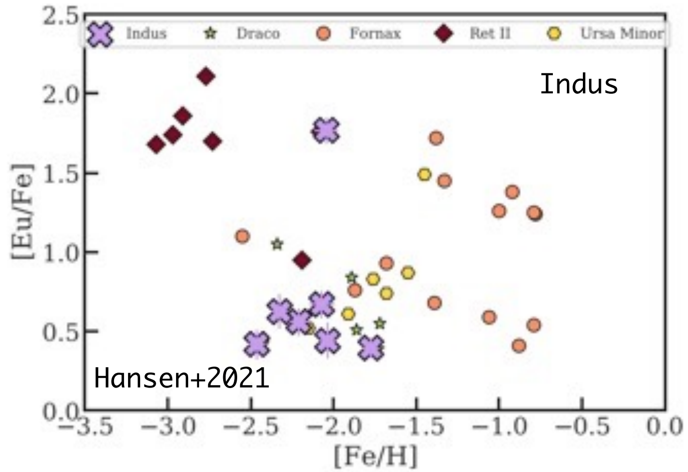
R-process in the MW and beyond* → chemistry and dynamics

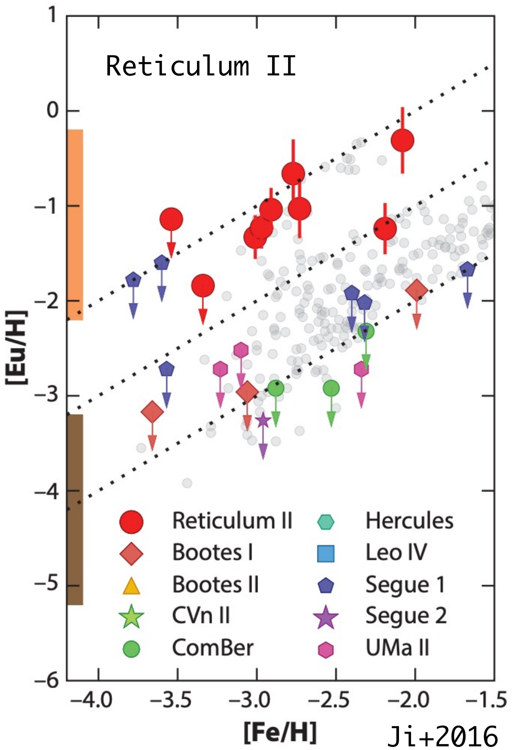


Hansen+2018

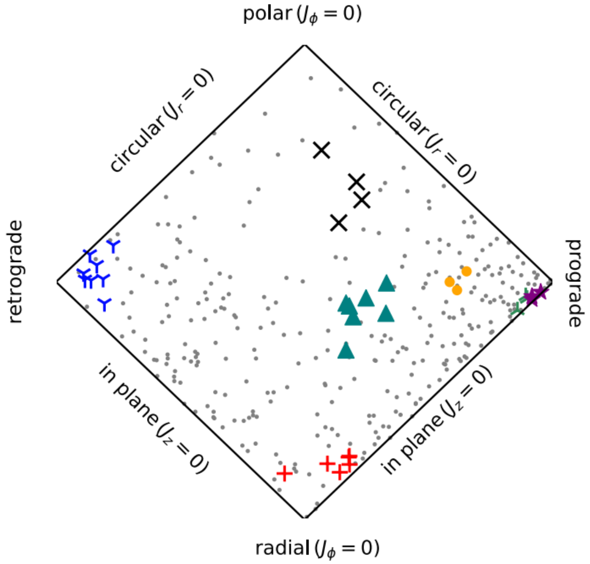


Limberg+2021

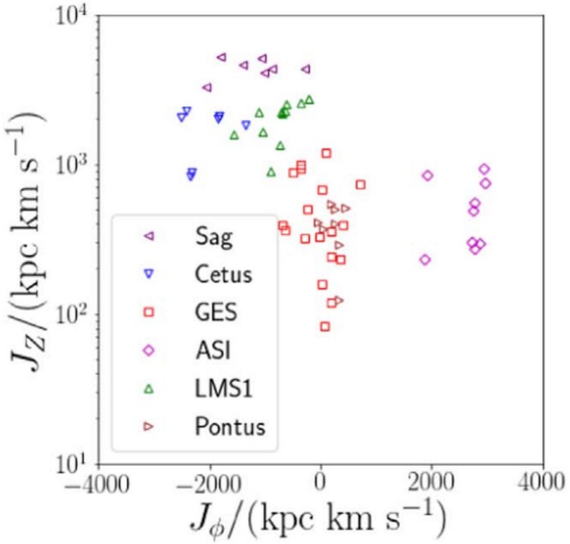




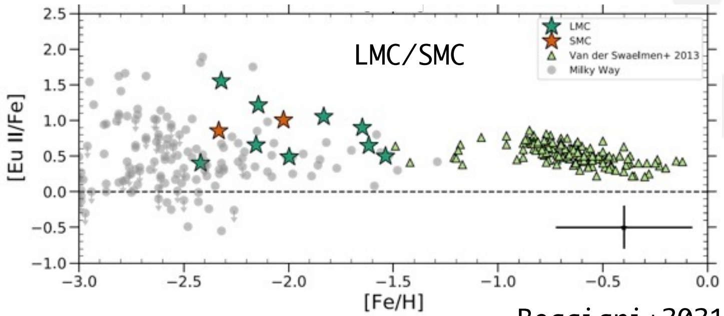
Ji+2016
Frebel 2018



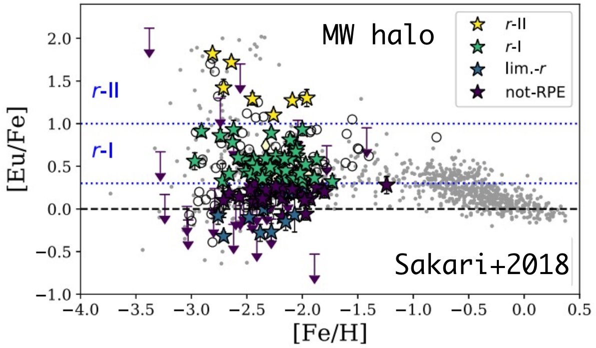
Gudin+2021

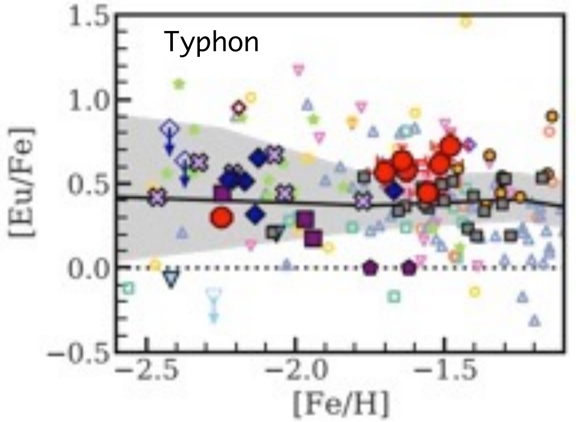


Hattori+2023



Reggiani+2021





Ji+2023

*stellar streams, ultra faint dwarf galaxies, classical dwarfs…

The R-process Alliance

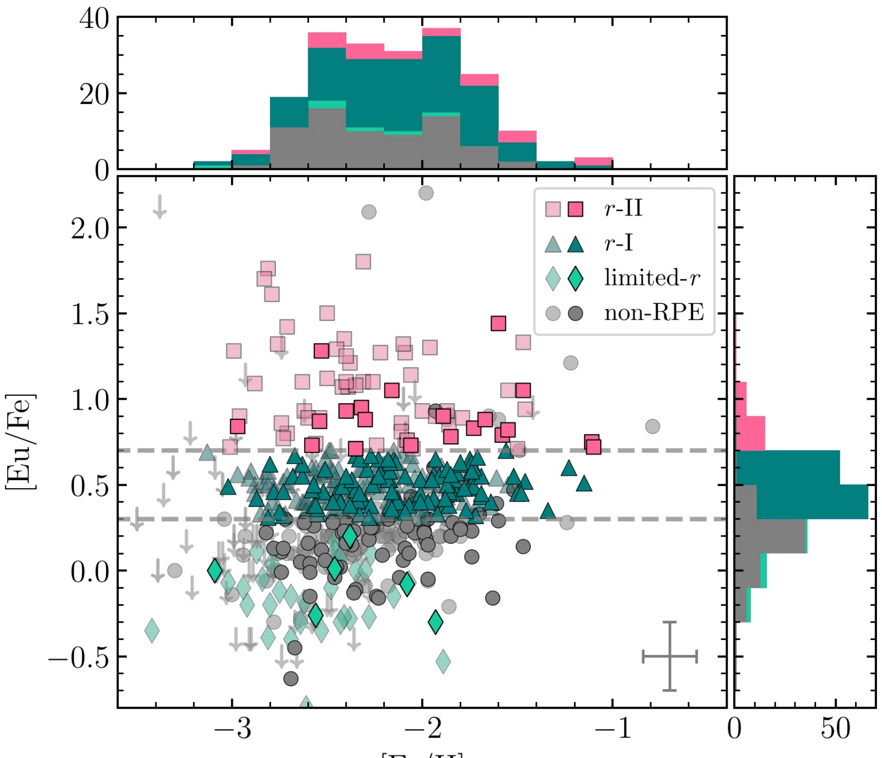
R-Process Alliance

Our goals

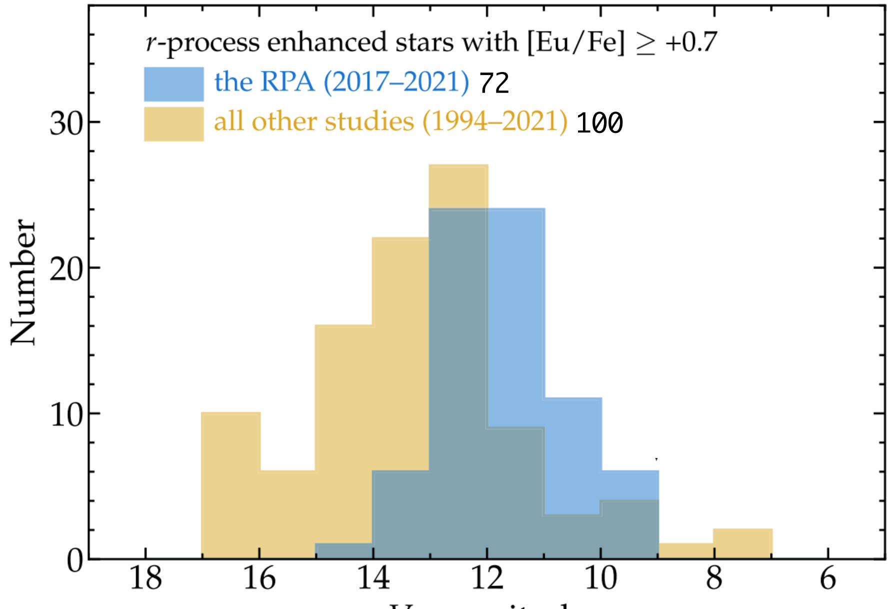
Split into five main "Phases," the RPA aims to provide a robust, homogeneously analyzed database of metal-poor stars and quantify their *r*-process enrichment. This data set will be used to motivate studies of yields from *r*-process sites, Galactic Chemical Evolution, and nuclear data.

Since 2017:

- Five data releases
- 647 stars published
- Homogeneous analysis of over 2,000 stars is coming soon!



Holmbeck+2020



Roederer+2022

Publications:

- Placco+2017
- Cain+2018
- Gull+2018
- Hansen+2018
- Holmbeck+2018
- Placco+2018
- Roederer+2018
- Sakari+2018a
- Sakari+2018b
- Placco+2019
- Sakari+2019
- Cain+2020
- Ezzeddine+2020
- Holmbeck+2020
- Placco+2020
- Gudin+2021
- Roederer+2022a
- Roederer+2022b
- Shank+2023
- Bandyopadhyay+2024
- Roederer+2024
- Shah+2024
- Xylakis+2024
- Hansen+2025
- Hirai+2025

https://sites.google.com/view/rprocessalliance/

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AURA

How do we (effectively) choose targets?

An image is worth a thousand words

https://space-facts.com/galaxies/andromeda/

The estimated distance of the Andromeda Galaxy from our own was doubled in 1953 when it was discovered that there is another, dimmer type of Cepheid variable star. In the 1990s, measurements of both standard red giants as well as red clump stars from the *Hipparcos* satellite measurements were used to calibrate the Cepheid distances.[41][42]

Formation and history[edit]

The Andromeda Galaxy was formed roughly 10 billion years ago from the collision and subsequent merger of smaller protogalaxies.[43]

This violent collision formed most of the galaxy's (metal-rich) galactic halo and extended disk. During this epoch, its rate of star formation would have been very high, to the point of becoming a luminous infrared galaxy for roughly 100 million years. Andromeda and the Triangulum Galaxy had a very close passage 2–4 billion years ago. This event produced high rates of star formation across the Andromeda Galaxy's disk—even some globular clusters—and disturbed M33's outer disk.

Over the past 2 billion years, star formation throughout Andromeda's disk is thought to have decreased to the point of near-inactivity. There have been interactions with satellite galaxies like M32, M110, or others that have already been absorbed by Andromeda Galaxy. These interactions have formed structures like Andromeda's Giant Stellar Stream. A galactic merger roughly 100 million years ago is believed to be responsible for a counter-rotating disk of gas found in the center of Andromeda as well as the presence there of a relatively young (100 million yr) stellar population

Distance estimate[edit]

At least four distinct techniques have been used to estimate distances from Earth to the Andromeda Galaxy. In 2003, using the infrared surface brightness fluctuations (I-SBF) and adjusting for the new period-luminosity value and a metallicity correction of −0.2 mag dex^{-1} in (O/H), an estimate of 2.57 ± 0.06 million light-years ($1.625 \times 10^{11} \pm 3.8 \times 10^9$ astronomical units) was derived. A 2004 Cepheid variable method estimated the distance to be 2.51 ± 0.13 million light-years (770 ± 40 kpc).[2][3] In 2005, an eclipsing binary star was discovered in the Andromeda Galaxy. The binary[c] is two hot blue stars of types O and B. By studying the eclipses of the stars, astronomers were able to measure their sizes. Knowing the sizes and temperatures of the stars, they were able to measure their absolute magnitude. When the visual and absolute magnitudes are known, the distance to the star can be calculated. The stars lie at a distance of $2.52 \times 10^6 \pm 0.14 \times 10^6$ ly ($1.594 \times 10^{11} \pm 8.9 \times 10^9$ AU) and the whole Andromeda Galaxy at about 2.5×10^6 ly (1.6×10^{11} AU).[4] This new value is in excellent agreement with the previous, independent Cepheid-based distance value. The TRGB method was also used in 2005 giving a distance of $2.56 \times 10^6 \pm 0.08 \times 10^6$ ly ($1.619 \times 10^{11} \pm 5.1 \times 10^9$ AU).[5] Averaged together, these distance estimates give a value of $2.54 \times 10^6 \pm 0.11 \times 10^6$ ly ($1.606 \times 10^{11} \pm 7.0 \times 10^9$ AU).[a] And, from this, the diameter of Andromeda at the widest point is estimated to be 220 ± 3 kly (67,450 ± 920 pc). This is equivalent to an apparent 4.96° angle in the sky.

Mass estimates[edit]

Until 2018, mass estimates for the Andromeda Galaxy's halo (including dark matter) gave a value of approximately $1.5 \times 10^{12}\ M_\odot$,[15] compared to $8 \times 10^{11}\ M_\odot$ for the Milky Way. This contradicted earlier measurements that seemed to indicate that the Andromeda Galaxy and Milky Way are almost equal in mass. In 2018, the equality of mass was re-established by radio results as approximately $8 \times 10^{11}\ M_\odot$[45] [46] [47] [48] In 2006, Andromeda Galaxy's spheroid was determined to have a higher stellar density than that of the Milky Way,[49] and its galactic stellar disk was estimated at about twice the diameter of that of the Milky Way.[10] The total mass of Andromeda Galaxy is estimated to be between $8 \times 10^{11}\ M_\odot$[45] and $1.1 \times 10^{12}\ M_\odot$.[50][51] The stellar mass of M31 is $10\text{-}15 \times 10^{10}\ M_\odot$, with 30% of that mass in the central bulge, 56% in the disk, and the remaining 14% in the stellar halo.[52] The radio results (similar mass to Milky Way galaxy) should be taken as likeliest as of 2018, although clearly this matter is still under active investigation by a number of research groups worldwide.

As of 2019, current calculations based on escape velocity and dynamical mass measurements put the Andromeda Galaxy at $0.8 \times 10^{12}\ M_\odot$,[53] which is only half of the Milky Way's newer mass, calculated in 2019 at $1.5 \times 10^{12}\ M_\odot$.[54][55][56]

In addition to stars, Andromeda Galaxy's interstellar medium contains at least $7.2 \times 10^9\ M_\odot$[57] in the form of neutral hydrogen, at least $3.4 \times 10^8\ M_\odot$ as molecular hydrogen (within its innermost 10 kiloparsecs), and $5.4 \times 10^7\ M_\odot$ of dust.[58]

Andromeda Galaxy is surrounded by a massive halo of hot gas that is estimated to contain half the mass of the stars in the galaxy. The nearly invisible halo stretches about a million light-years from its host galaxy, halfway to our Milky Way galaxy. Simulations of galaxies indicate the halo formed at the same time as the Andromeda Galaxy. The halo is enriched in elements heavier than hydrogen and helium, formed from supernovae and its properties are those expected for a galaxy that lies in the "green valley" of the Galaxy color–magnitude diagram (see below). Supernovae erupt in Andromeda Galaxy's star-filled disk and eject these heavier elements into space. Over Andromeda Galaxy's lifetime, nearly half of the heavy elements made by its stars have been ejected far beyond the galaxy's 200,000-light-year-diameter stellar disk.[59][60][61][62]

Luminosity estimates[edit]

Compared to the Milky Way, the Andromeda Galaxy appears to have predominantly older stars with ages $>7 \times 10^9$ years.[52][clarification needed] The estimated luminosity of Andromeda Galaxy, $\sim 2.6 \times 10^{10}\ L_\odot$, is about 25% higher than that of our own galaxy.[63] However, the galaxy has a high inclination as seen from Earth and its interstellar dust absorbs an unknown amount of light, so it is difficult to estimate its actual brightness and other authors have given other values for the luminosity of the Andromeda Galaxy (some authors even propose it is the second-brightest galaxy within a radius of 10 mega-parsecs of the Milky Way, after the Sombrero Galaxy,[64] with an absolute magnitude of around -22.21[d] or close[65]).

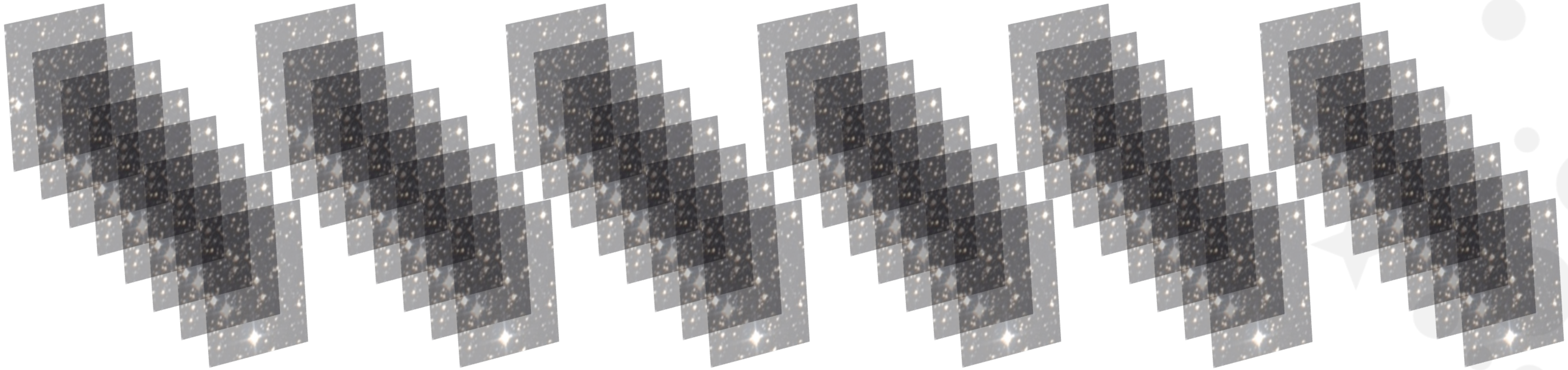
An estimation done with the help of Spitzer Space Telescope published in 2010 suggests an absolute magnitude (in the blue) of −20.89 (that with a color index of +0.63 translates to an absolute visual magnitude of −21.52,[b] compared to −20.9 for the Milky Way), and a total luminosity in that wavelength of $3.64 \times 10^{10}\ L_\odot$.[66]

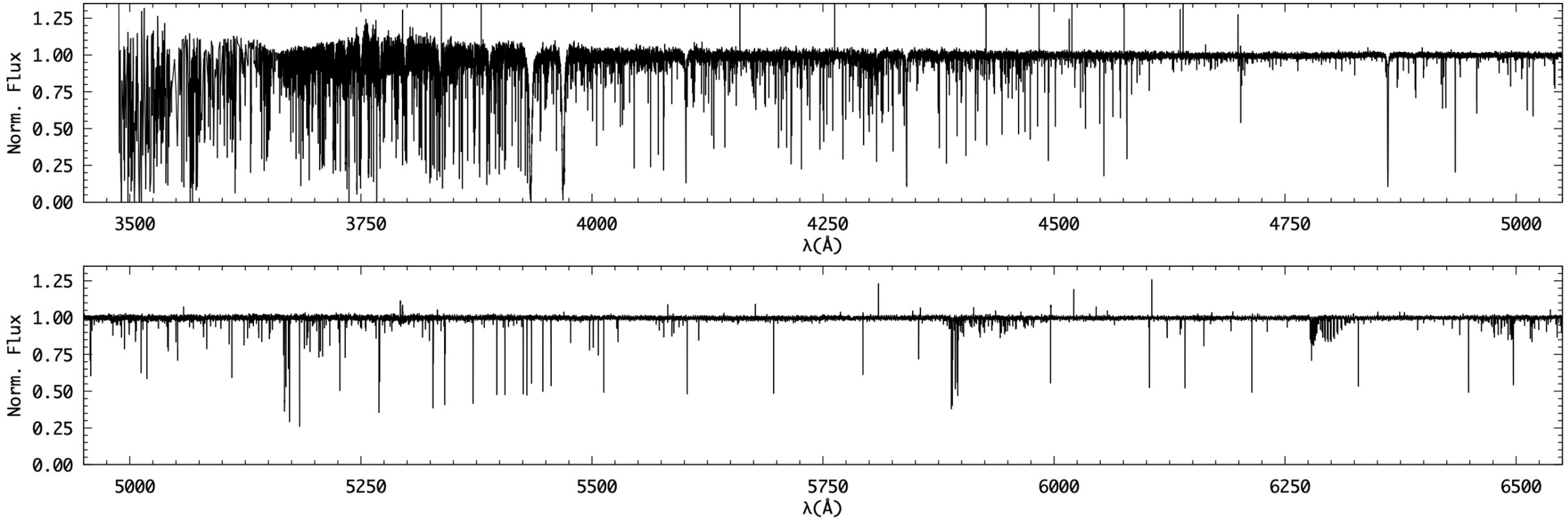
The rate of star formation in the Milky Way is much higher, with Andromeda Galaxy producing only about one solar mass per year compared to 3–5 solar masses for the Milky Way. The rate of novae in the Milky Way is also double that of Andromeda Galaxy.[67] This suggests that the latter once experienced a great star formation phase, but is now in a relative state of quiescence, whereas the Milky Way is experiencing more active star formation.[63] Should this continue, the luminosity of the Milky Way may eventually overtake that of Andromeda Galaxy.

According to recent studies, the Andromeda Galaxy lies in what in the Galaxy color–magnitude diagram is known as the "green valley," a region populated by galaxies like the Milky Way in transition from the "blue cloud" (galaxies actively forming new stars) to the "red sequence" (galaxies that lack star formation). Star formation activity in green valley galaxies is slowing as they run out of star-forming gas in the interstellar medium. In simulated galaxies with similar properties to Andromeda Galaxy, star formation is expected to extinguish within about five billion years from the now, even accounting for the expected, short-term increase in the rate of star formation due to the collision between Andromeda Galaxy and the Milky Way.[68]

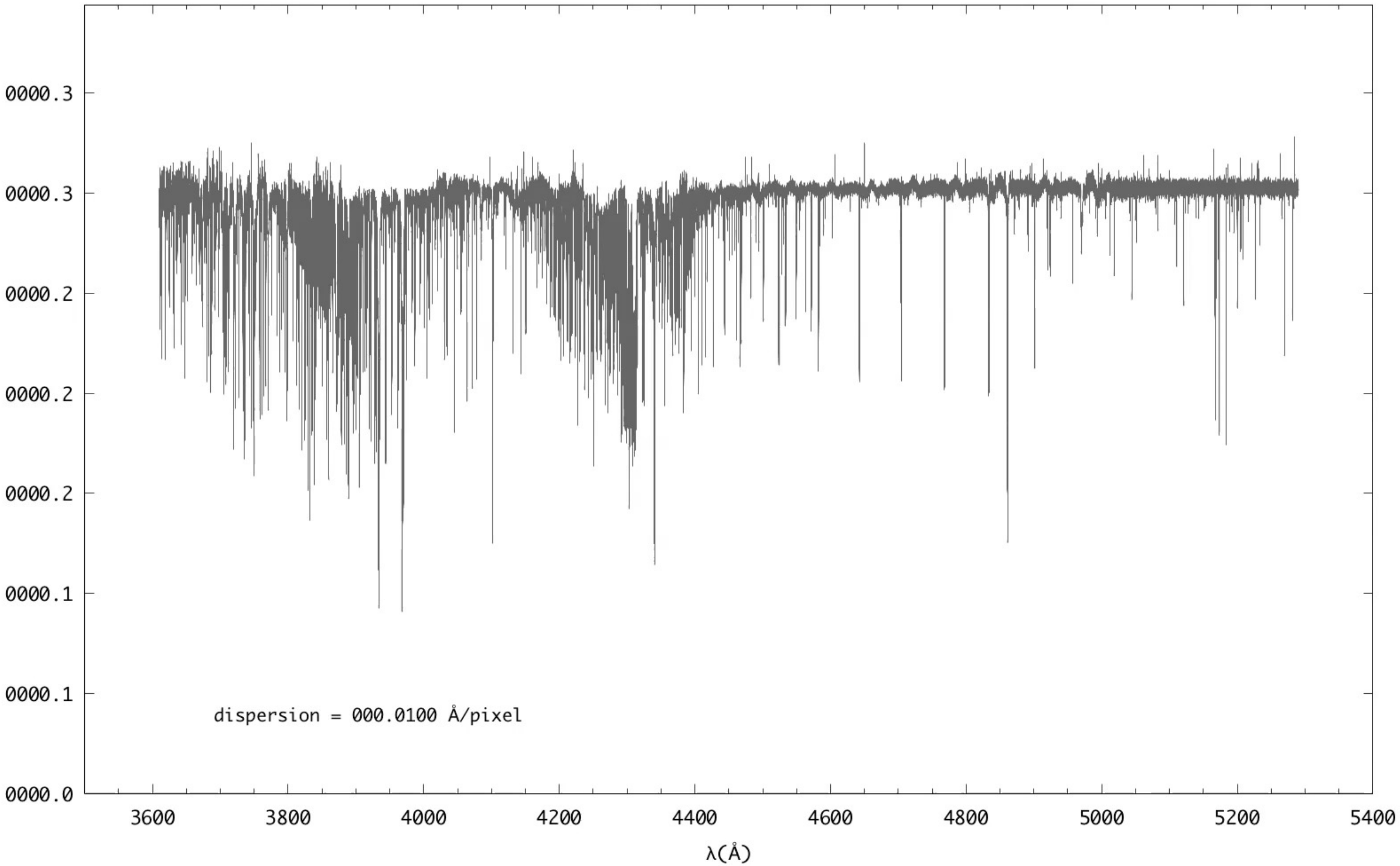
https://en.wikipedia.org/wiki/Andromeda_Galaxy

A spectrum is worth $\underline{n}$ images, where $\underline{n} = \frac{(\lambda_{red} - \lambda_{blue})}{\Delta\lambda}$



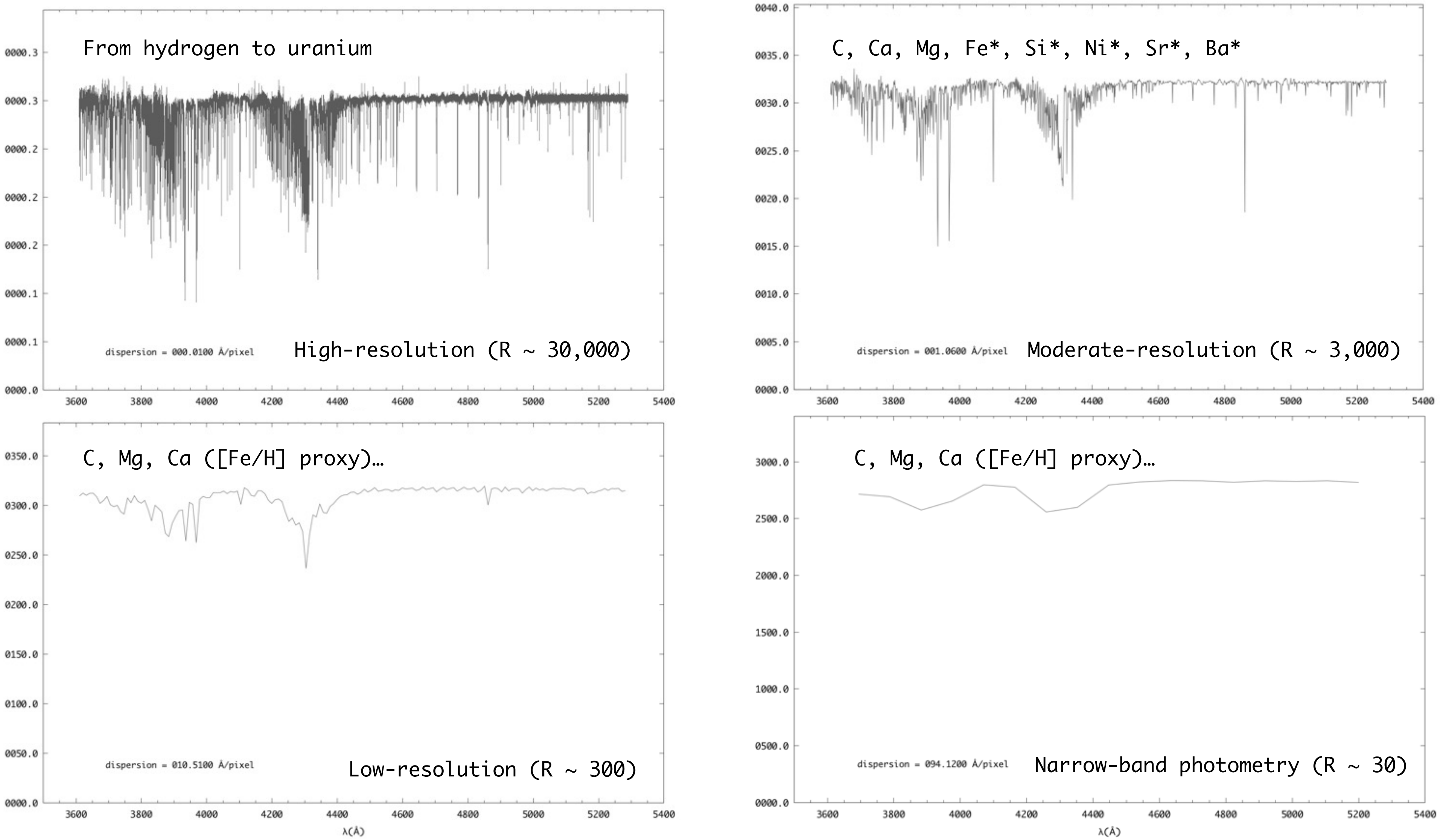


The effect of resolution - what is the ideal *n*?



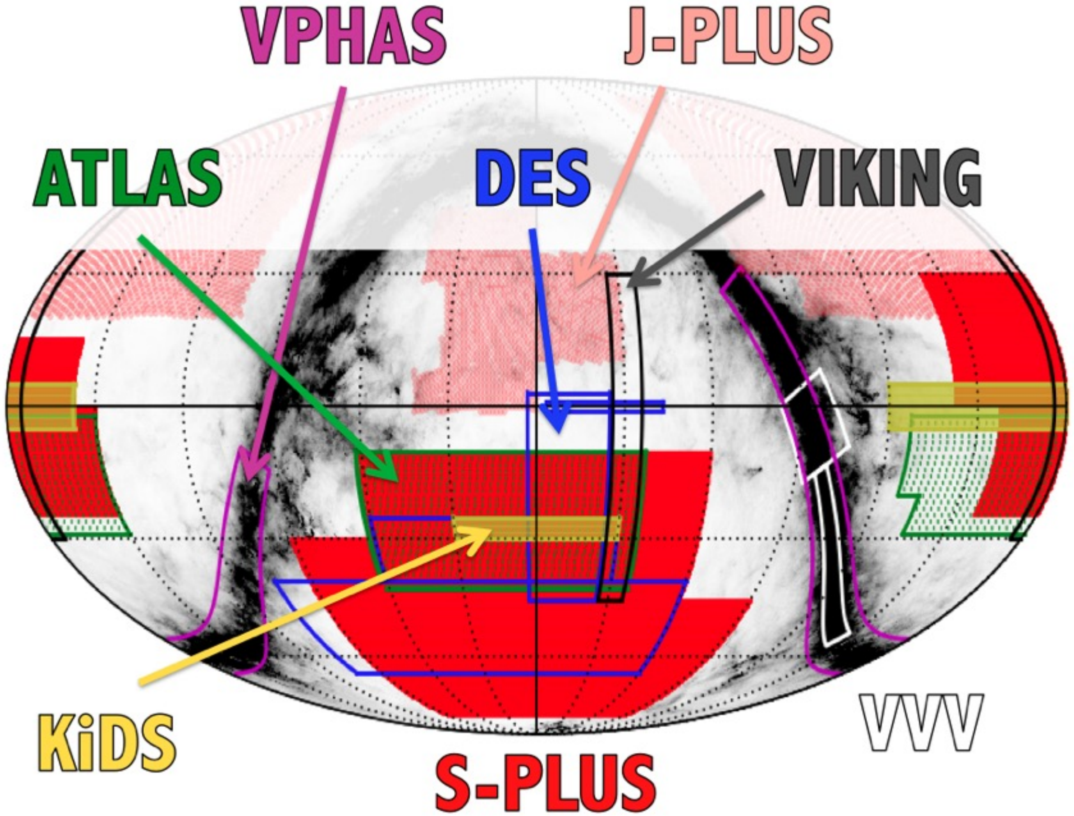
From R~30 to R~30,000

(finding the ideal *n* to determine chemical abundances)



How about observing “everything”?

J-PLUS (Javalambre Photometric Local Universe Survey)
S-PLUS (Southern Photometric Local Universe Survey)



T80 N/S: 80cm
FOV: 2 deg^2
Footprint: 17,000 deg^2 (N/S)

Cenarro+2019
Mendes de Oliveira+2019

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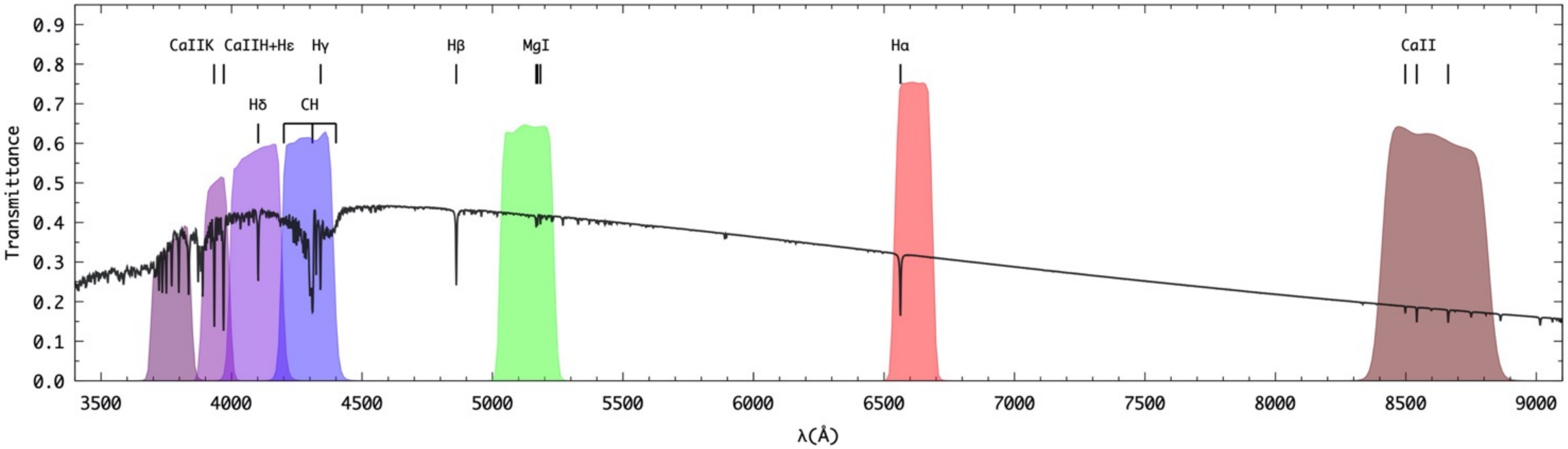
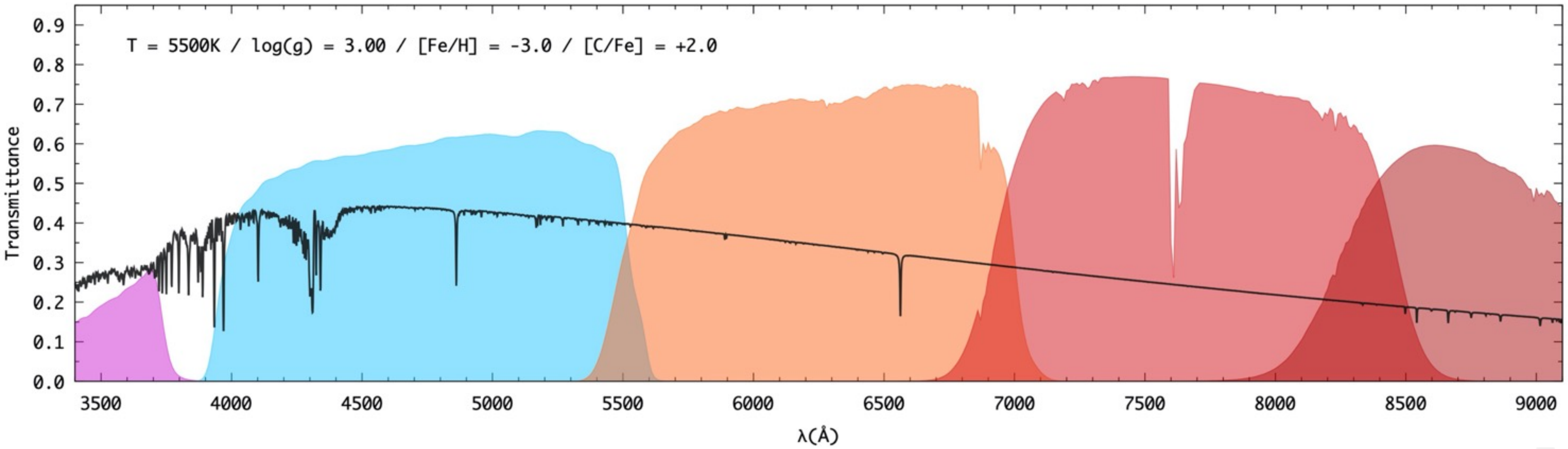
S-PLUS/J-PLUS (Filter system)





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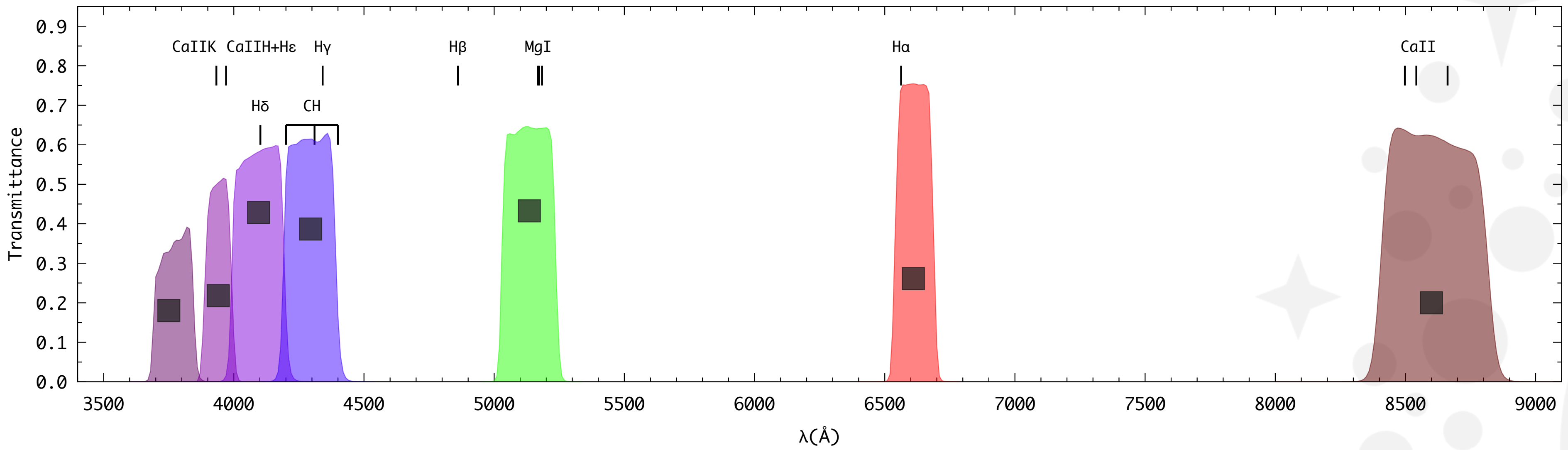
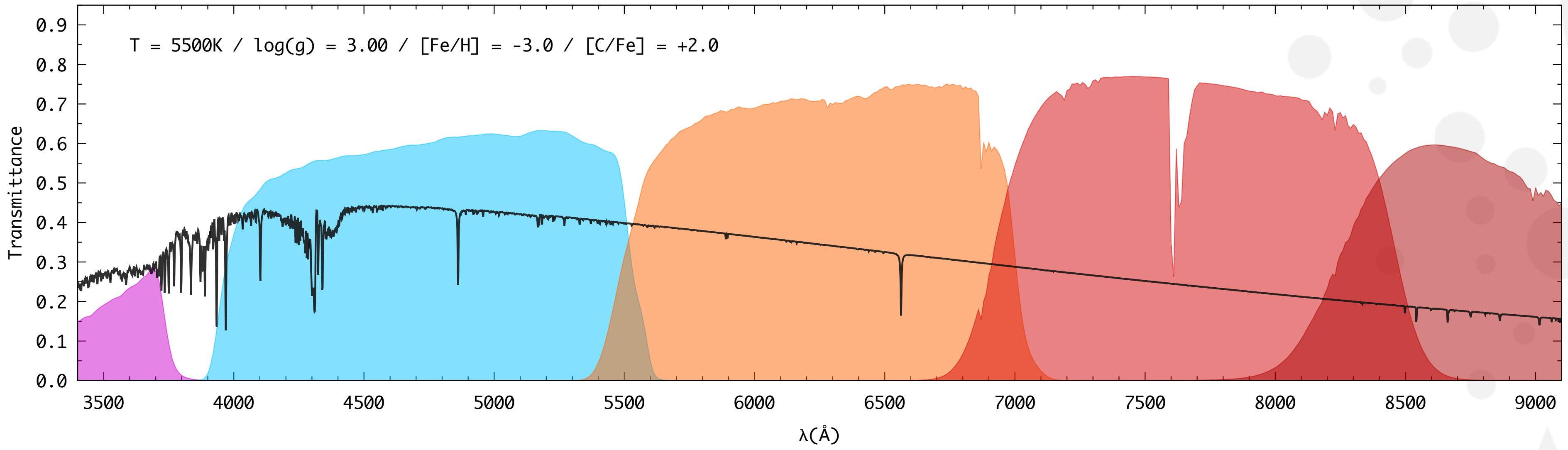
S-PLUS/J-PLUS (Filter system)





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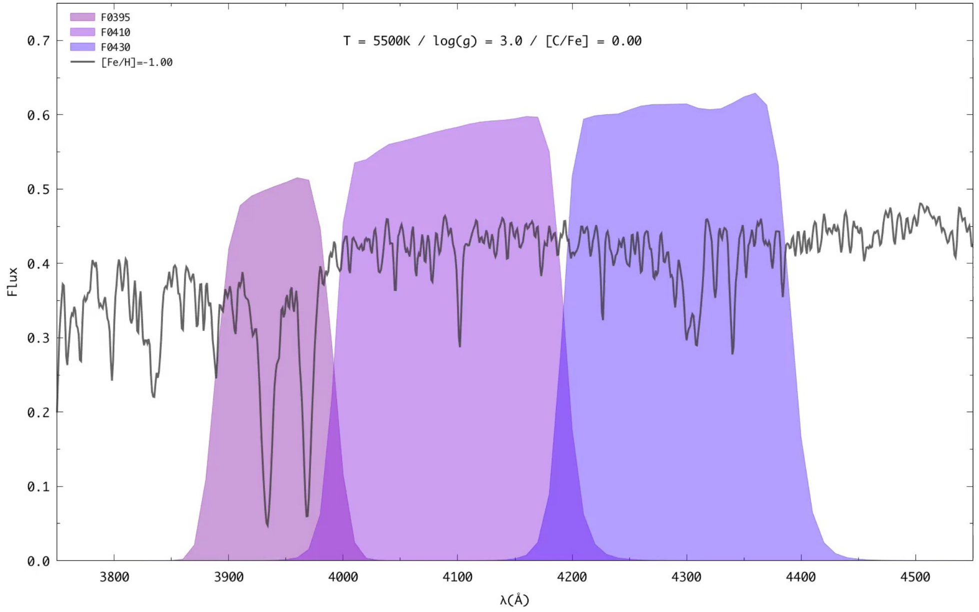
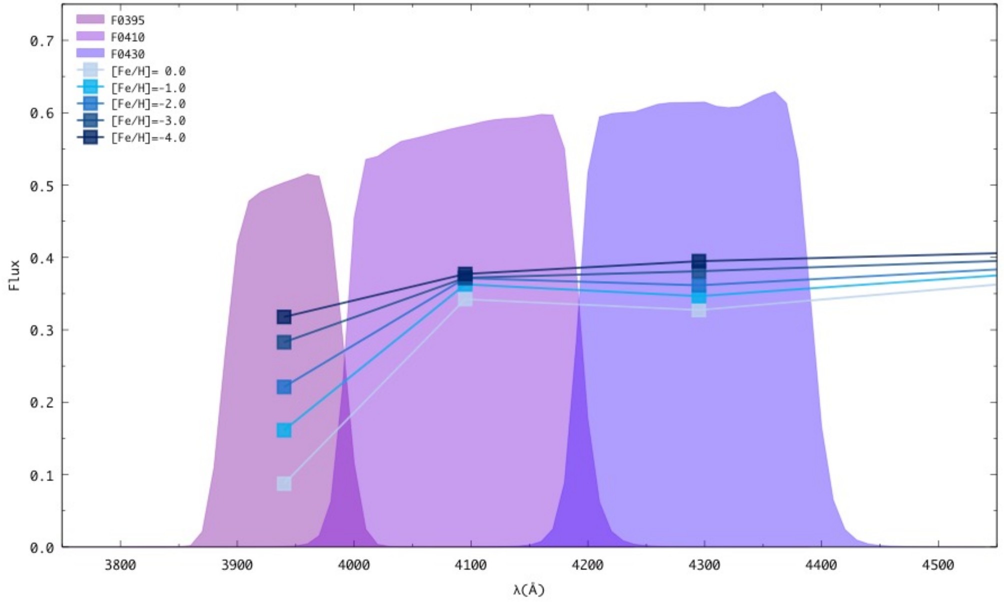
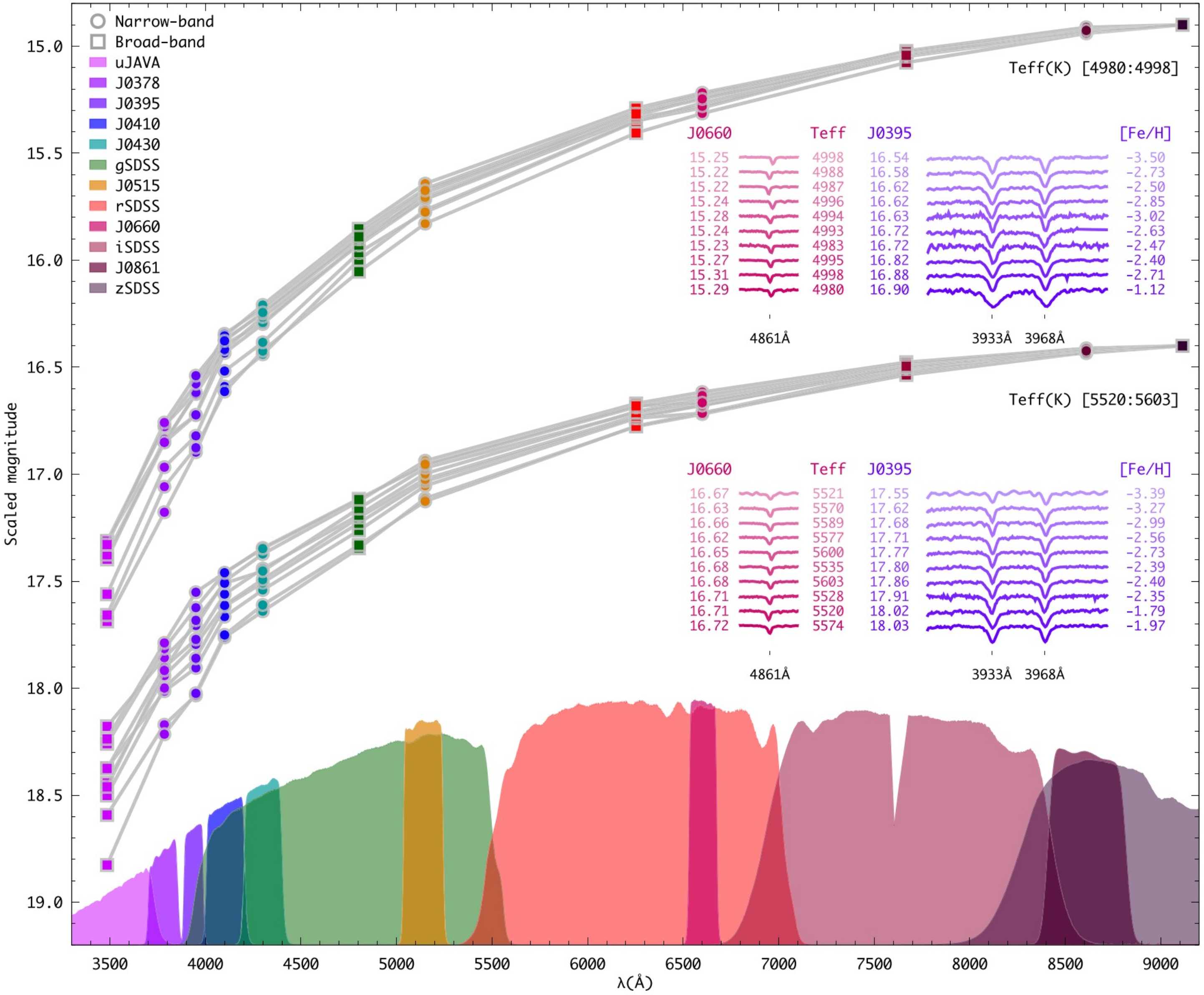
How do changes in [Fe/H] affect fluxes?



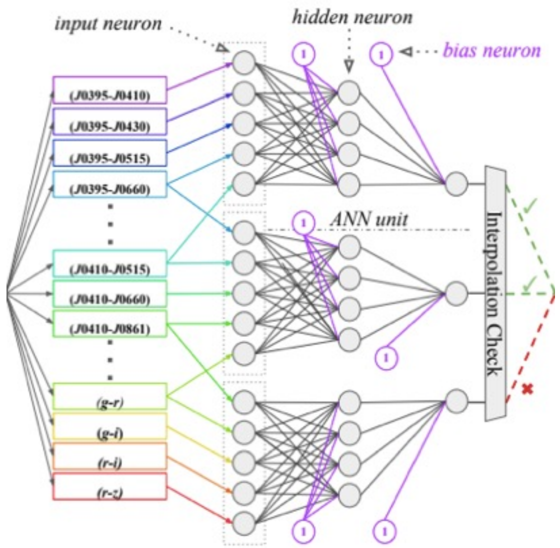


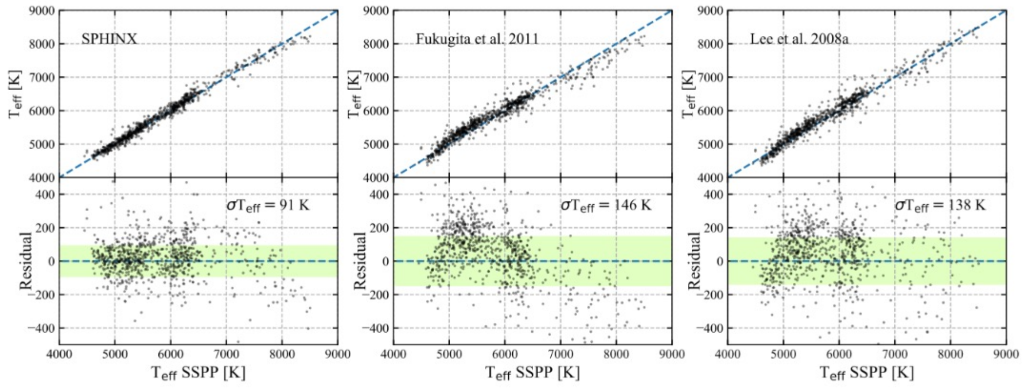


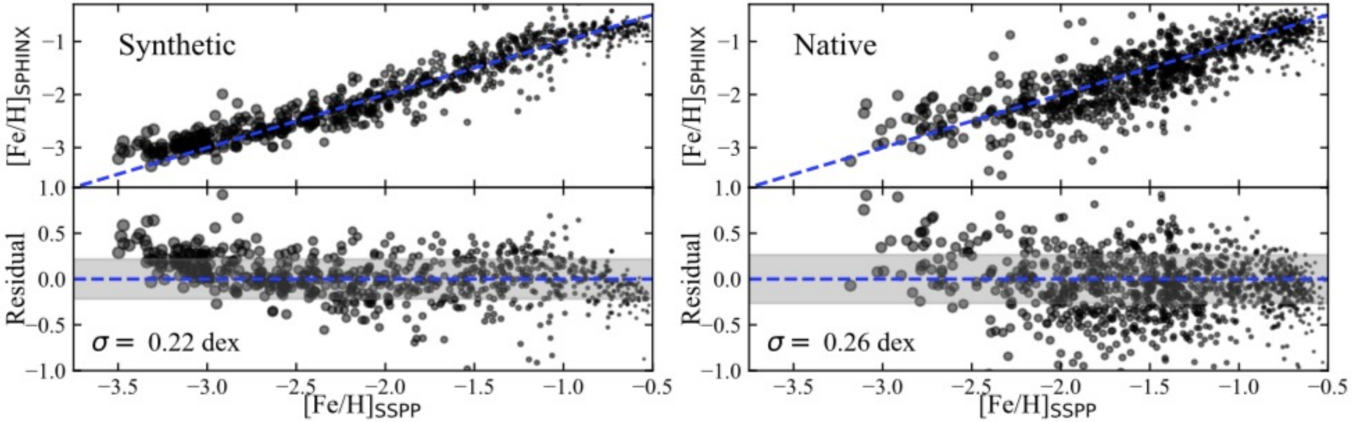
Placco+2022

Artificial Neural Networks

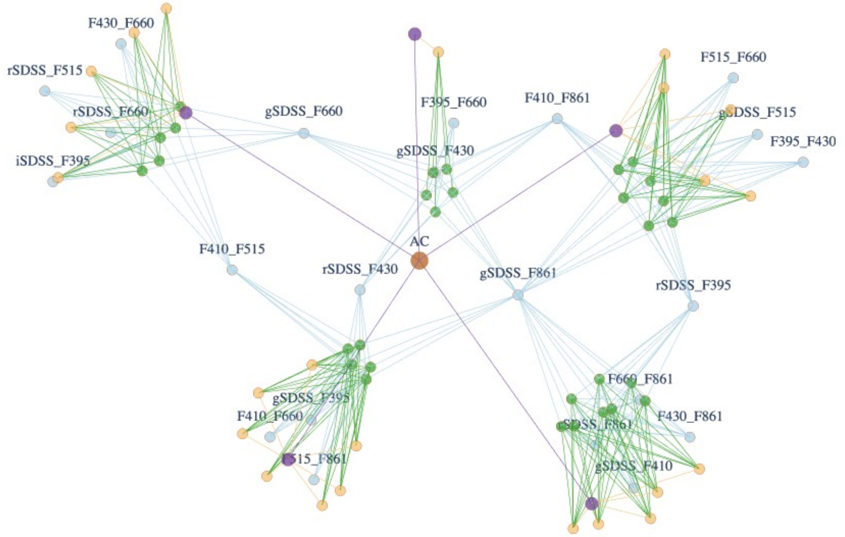
Determine T_{eff}, [Fe/H], and [C/Fe]

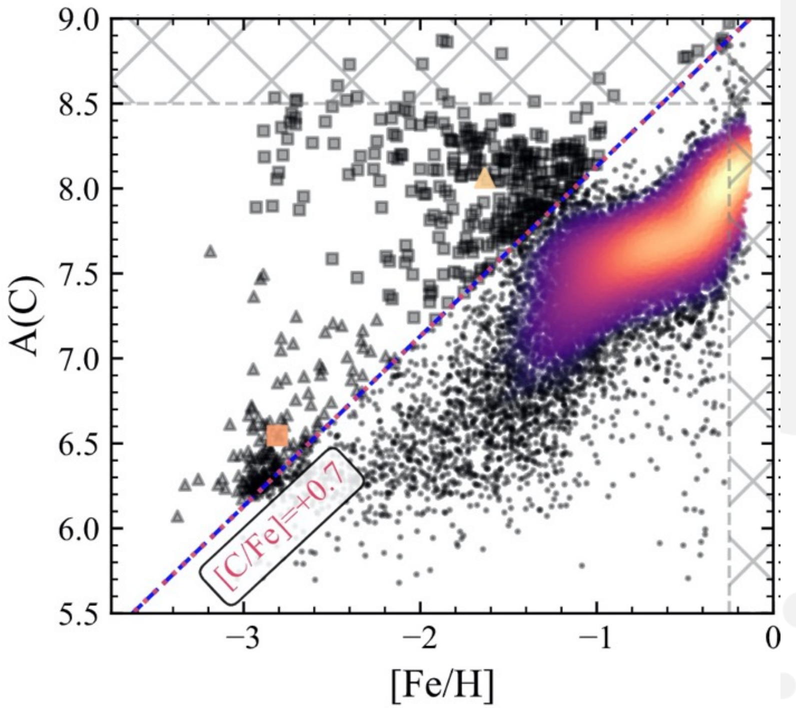






Whitten, Placco, JPLUS Collab+2019





Whitten, Placco, SPLUS Collab+2021

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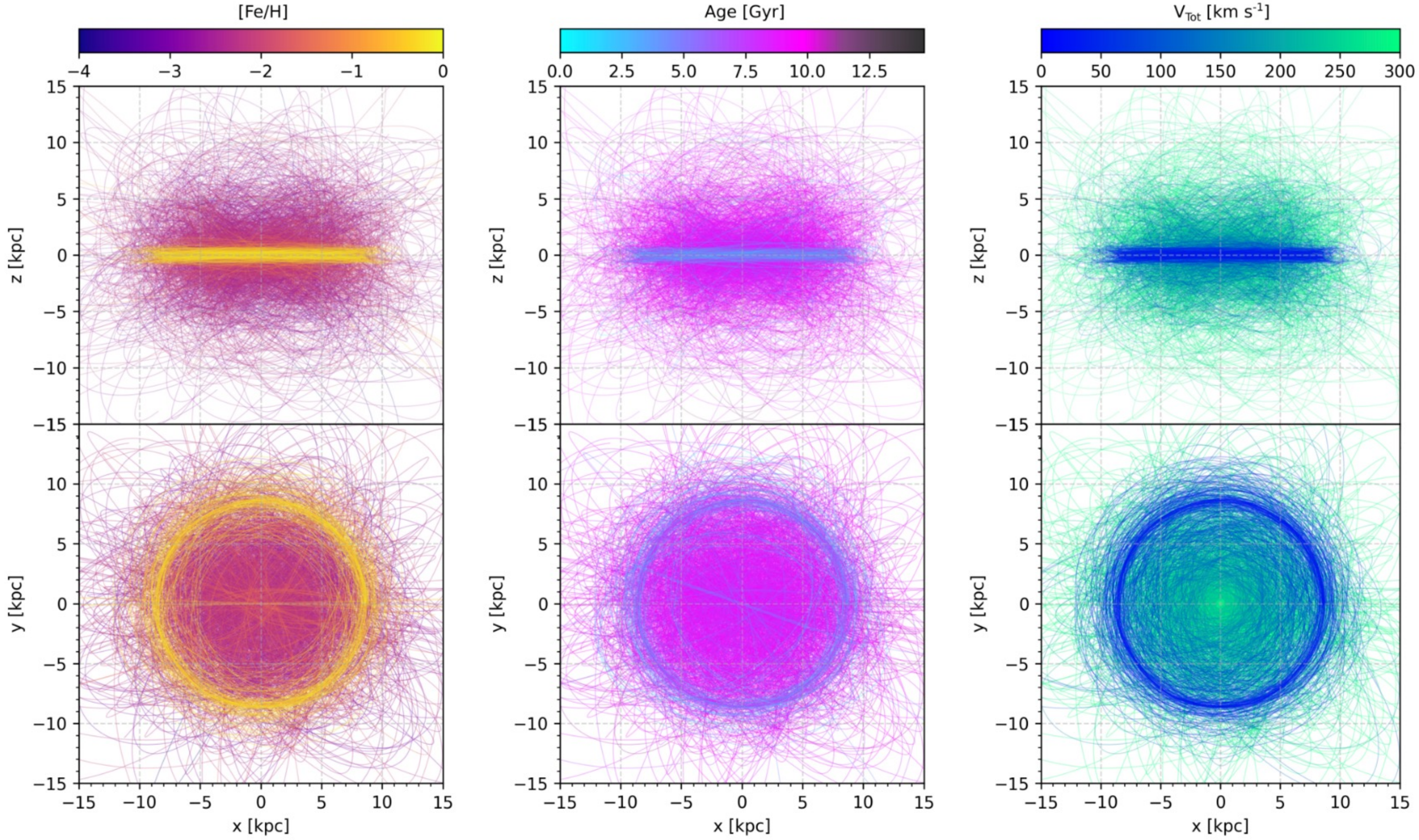
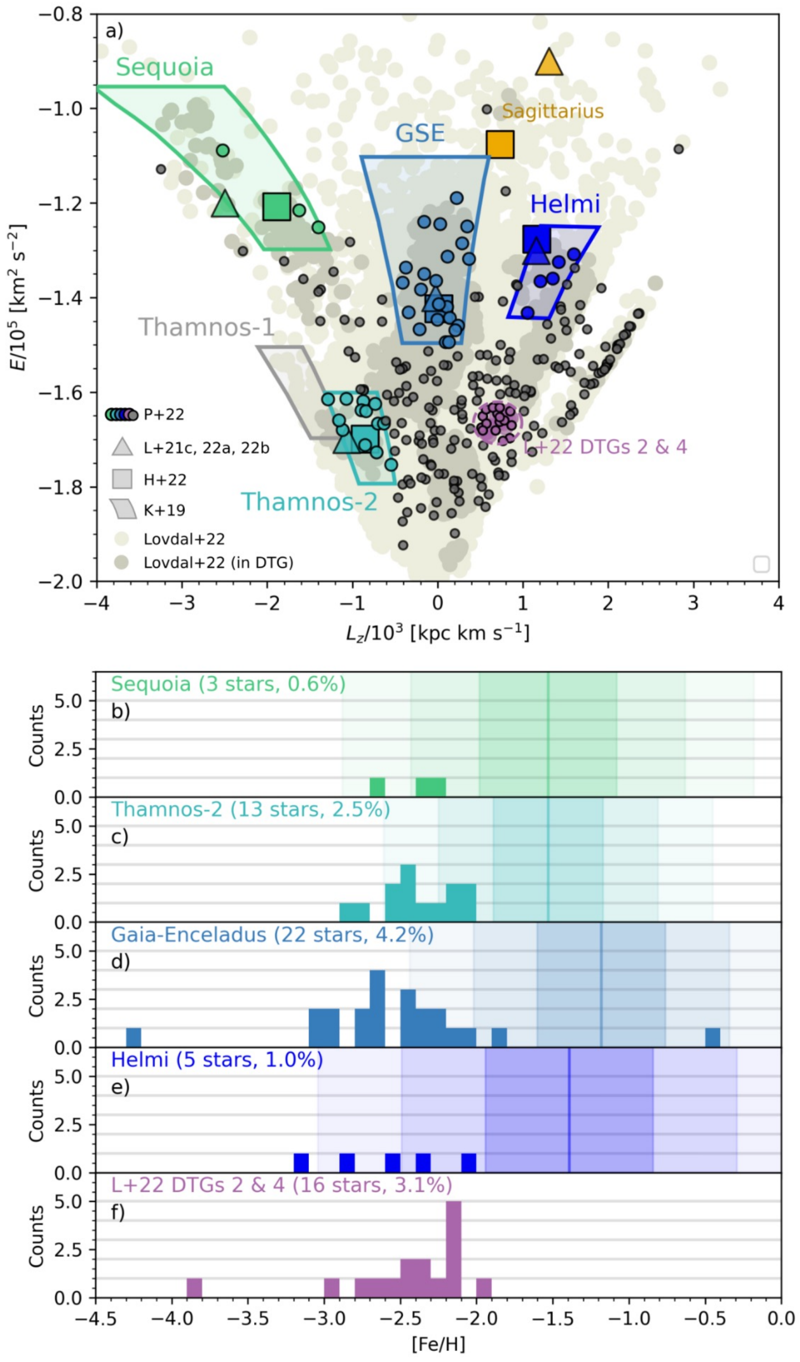
NSF NOIRLab

Chemodynamical Properties and Ages





Find r-process → Select old, low-mass, low-[Fe/H], low-carbon, giant stars

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Almeida-Fernandes, Placco+2023

r-process enhanced metal-poor stars:

when/how were they first formed?

how do they look like?

where do we find them?

how do we find more?

the curious case of J1424-2542

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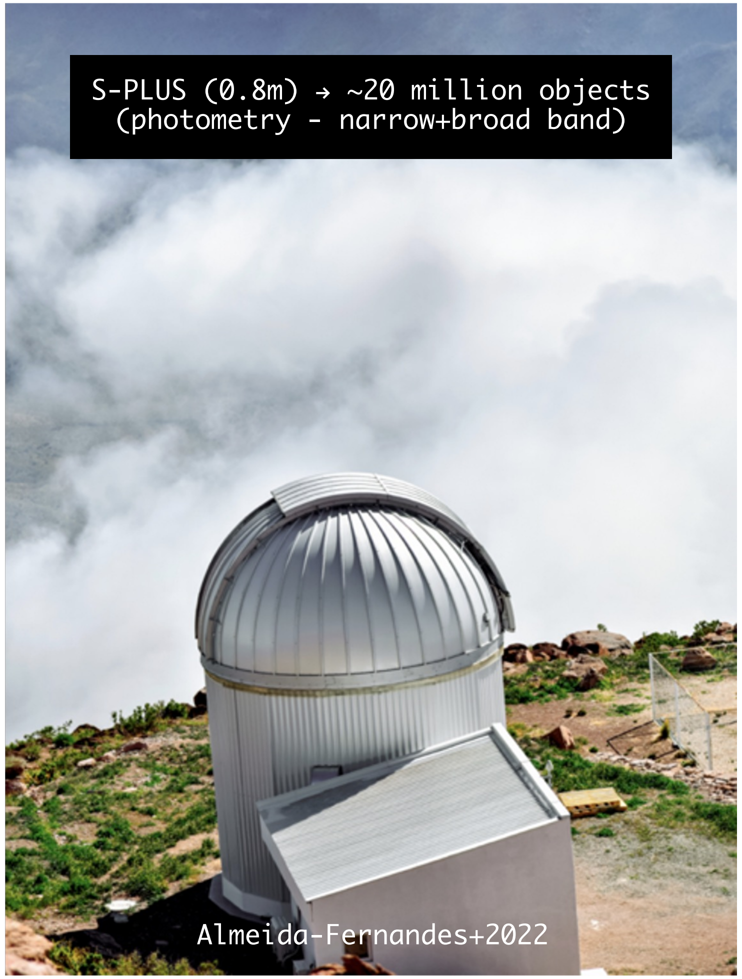
The power in numbers



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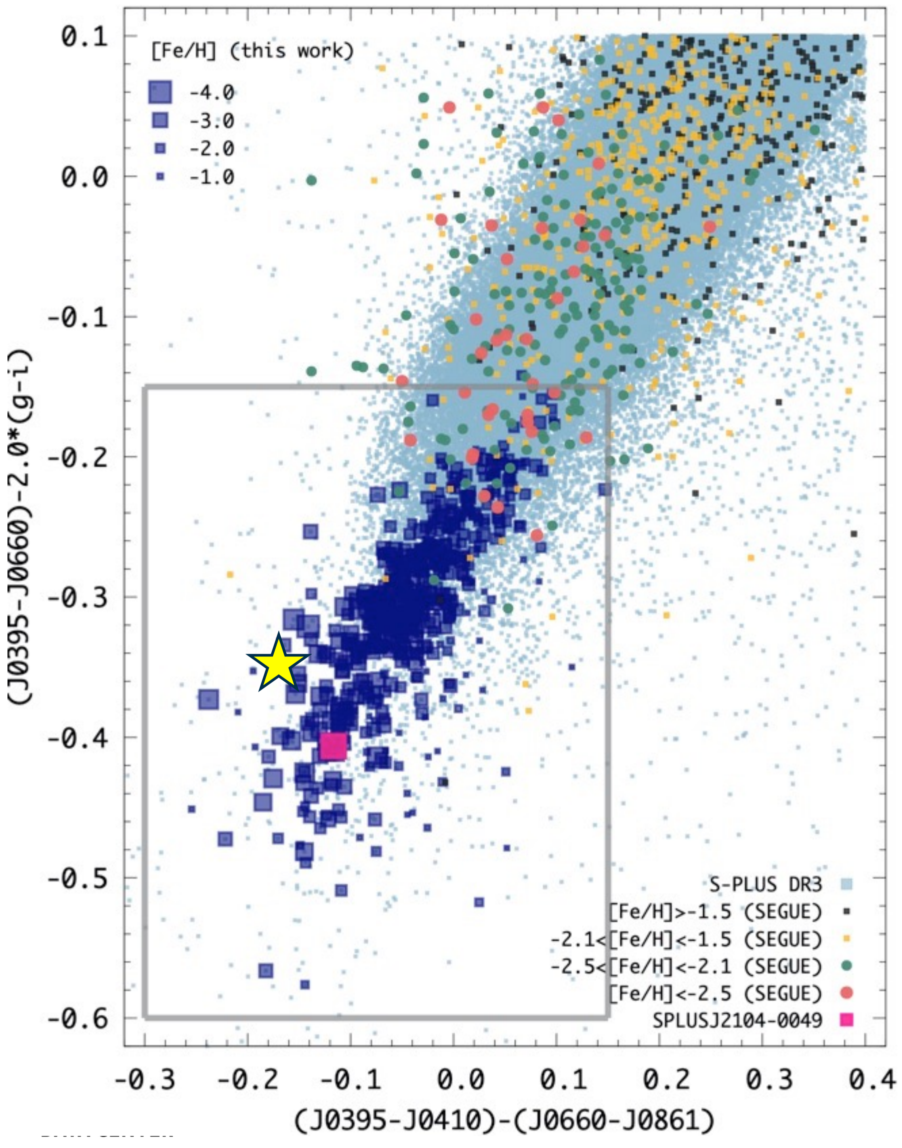
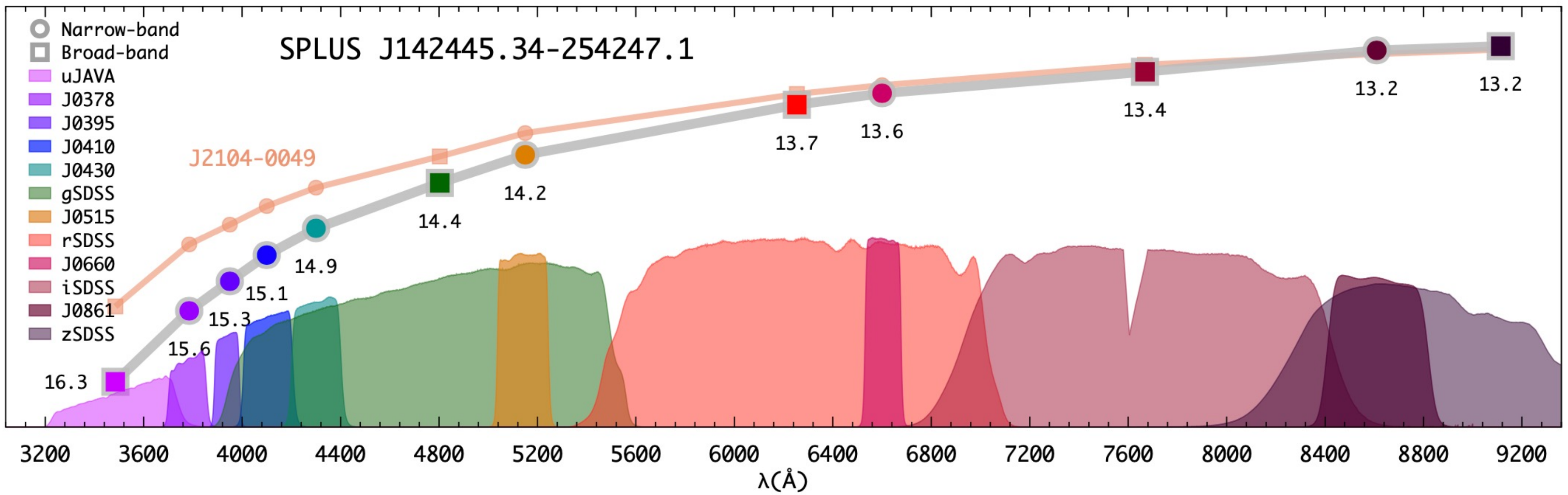
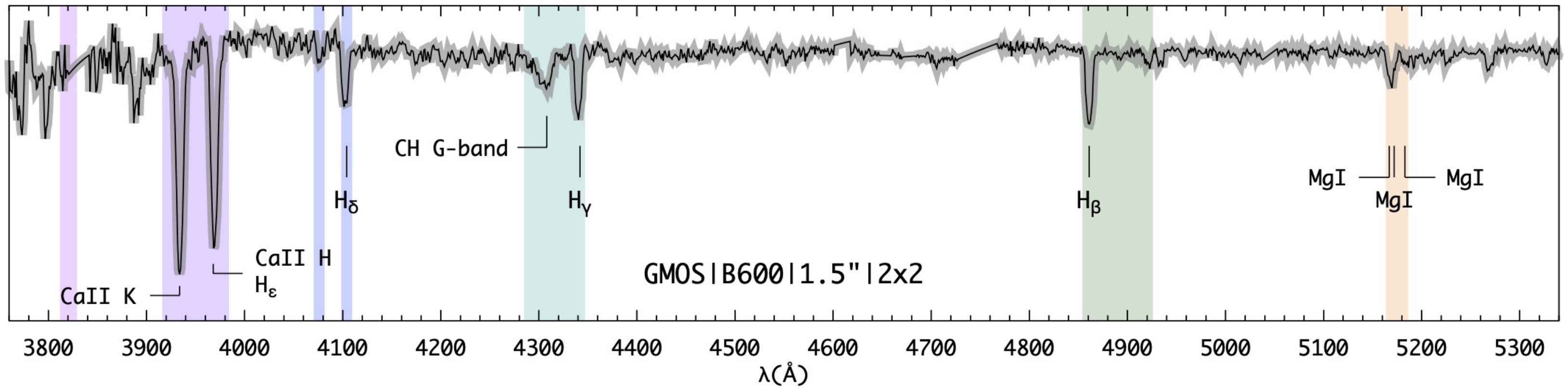
SPLUS J1424-2542 (g=14.4) – as “boring” as a star can be…







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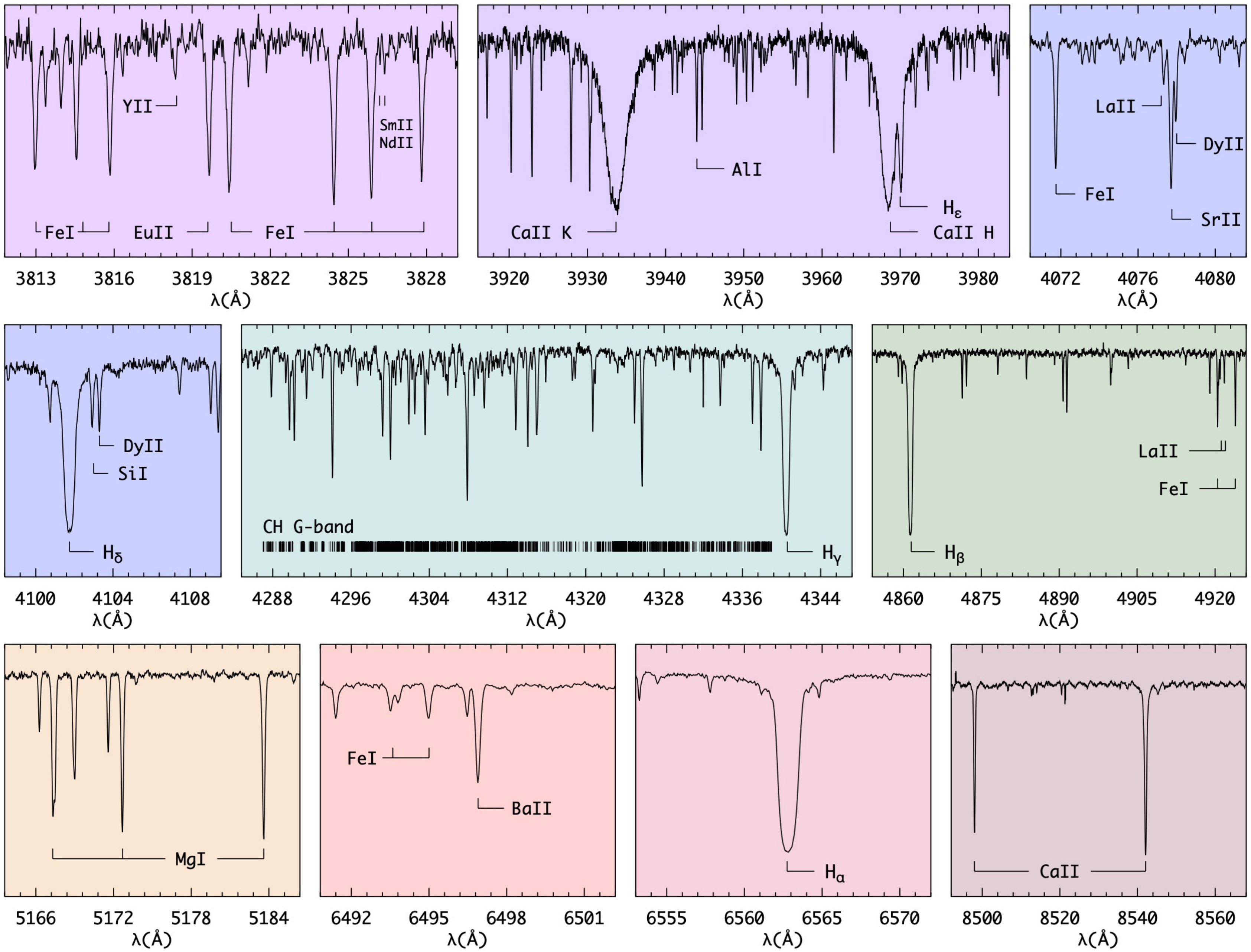
SPLUS J1424-2542 → What GHOST revealed

Stellar parameters:

- T_{eff}: 4762
- logg: 1.58
- [Fe/H]: -3.39

Chemical abundances:

- 36 elements (C to Th)
- 308 absorption features



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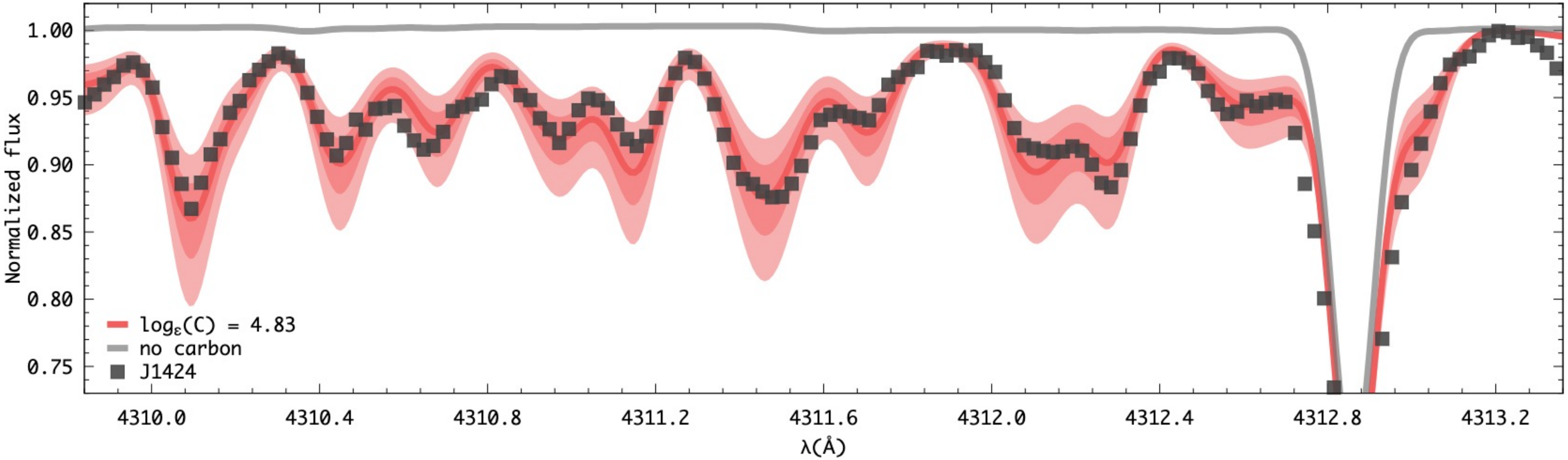
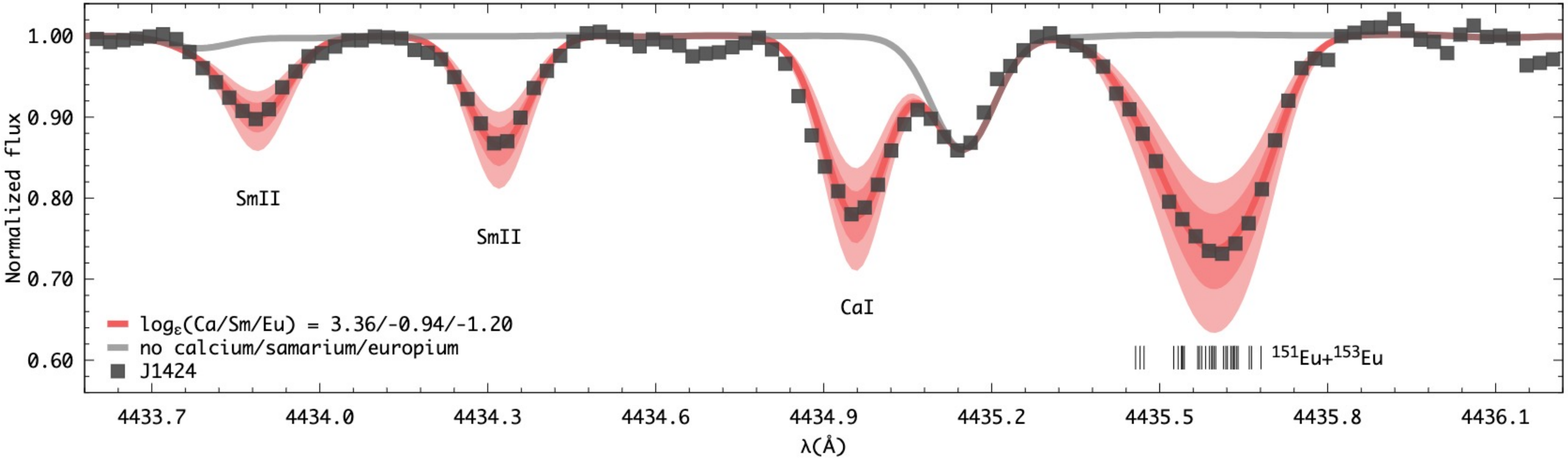
SPLUS J1424-2542 → Getting chemical abundances





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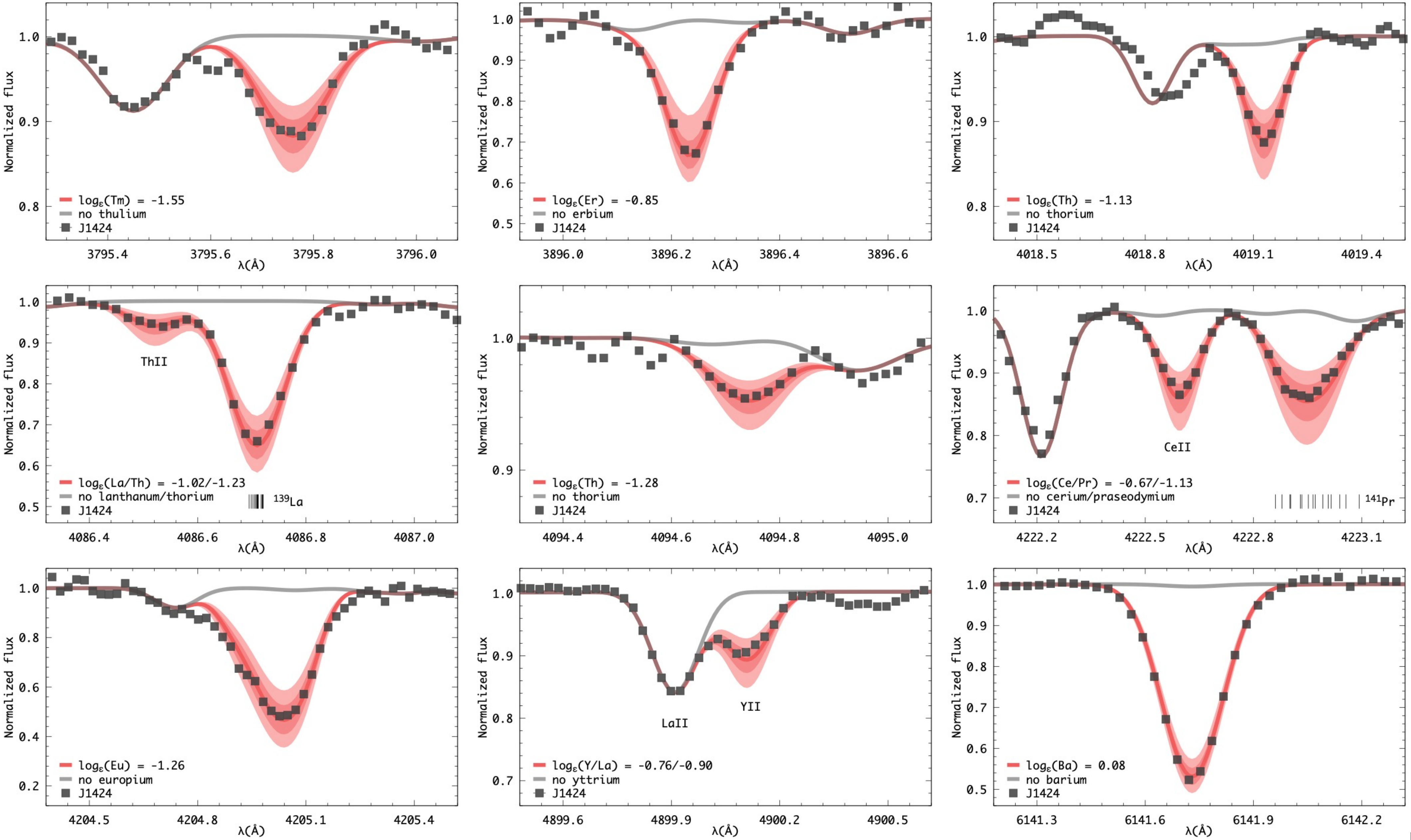
SPLUS J1424-2542 → Getting chemical abundances



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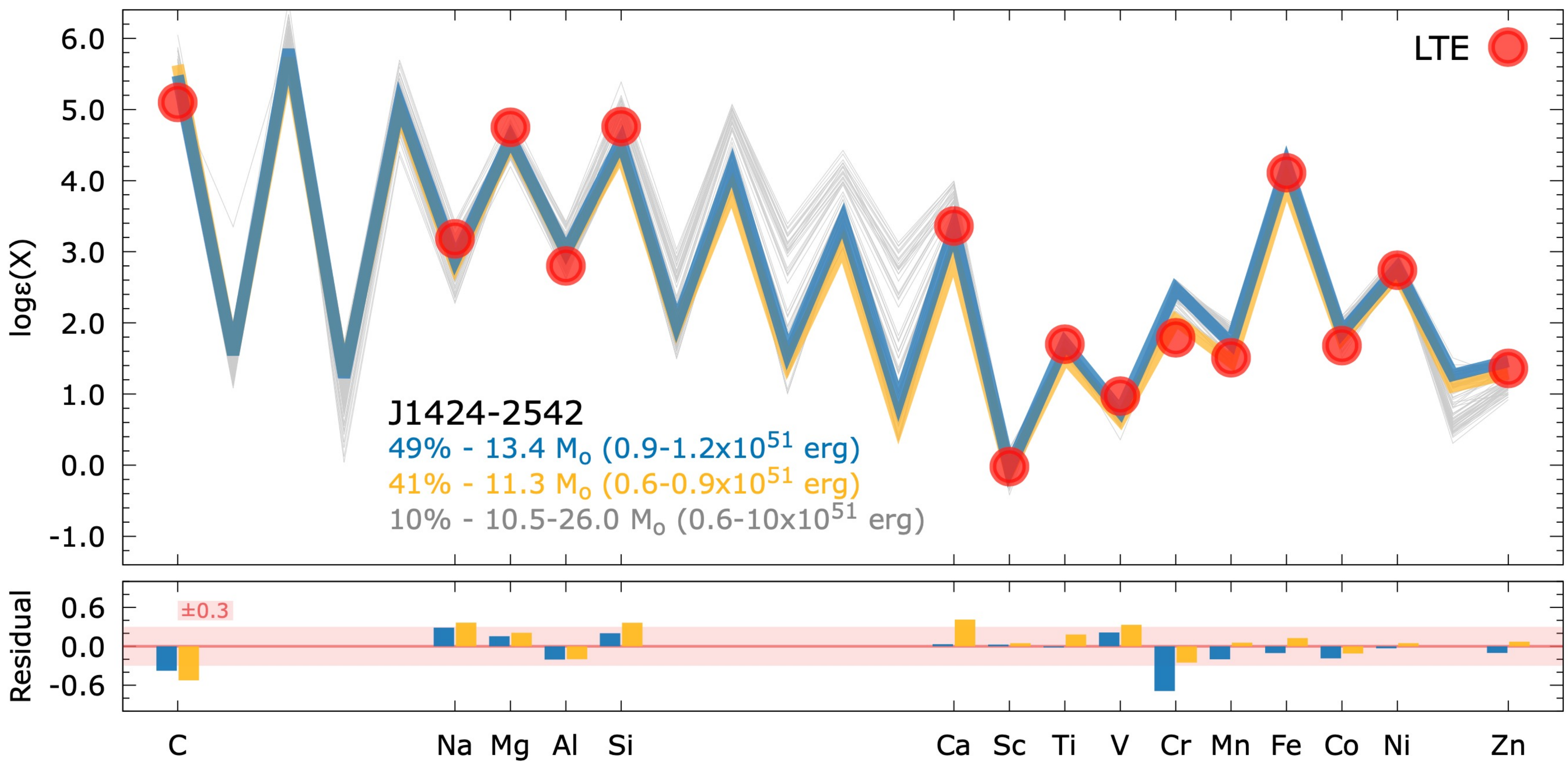
SPLUS J1424-2542 → light-element abundances vs. Pop III SN yields



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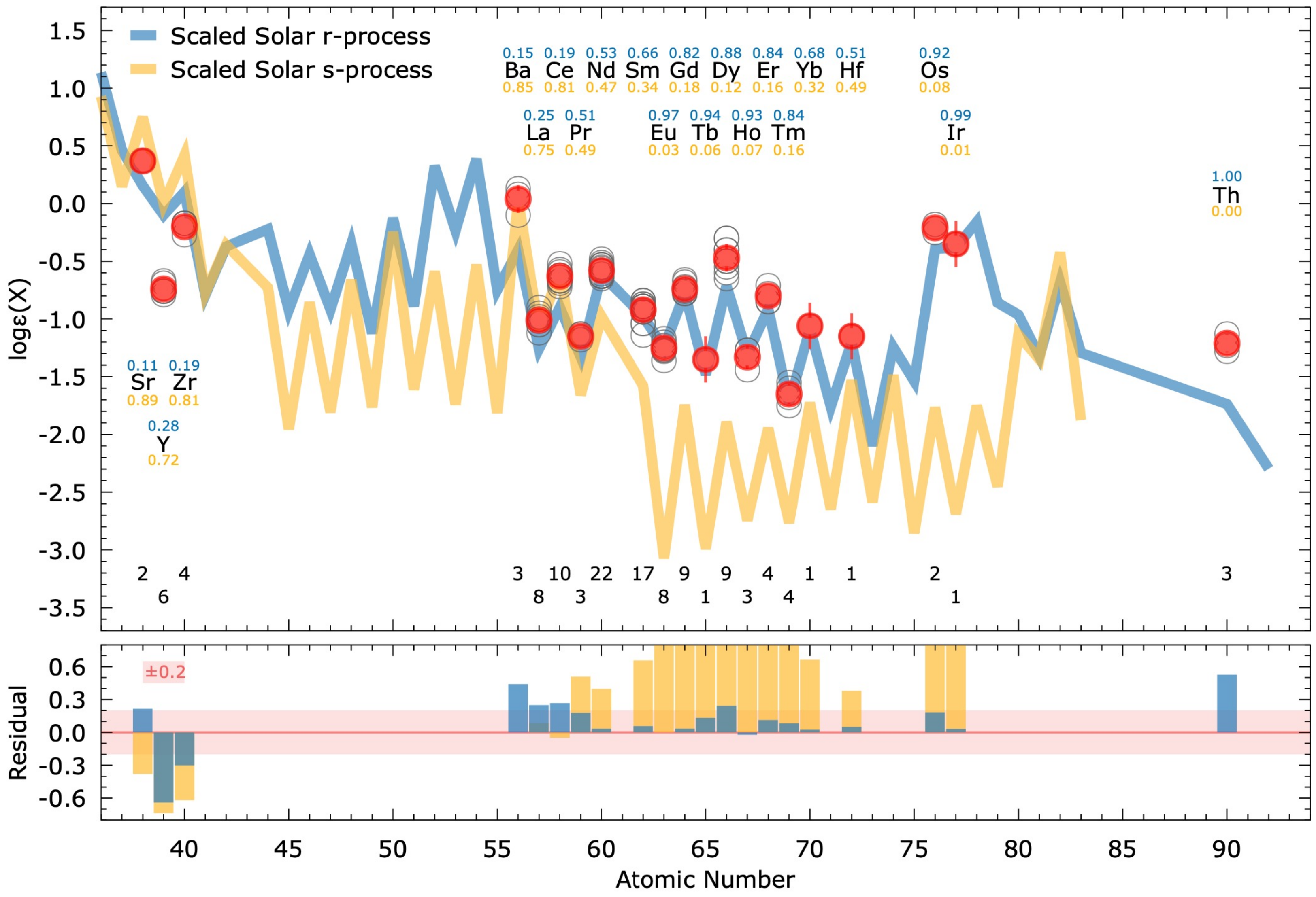
SPLUS J1424-2542 → heavy-element abundances vs. Solar System



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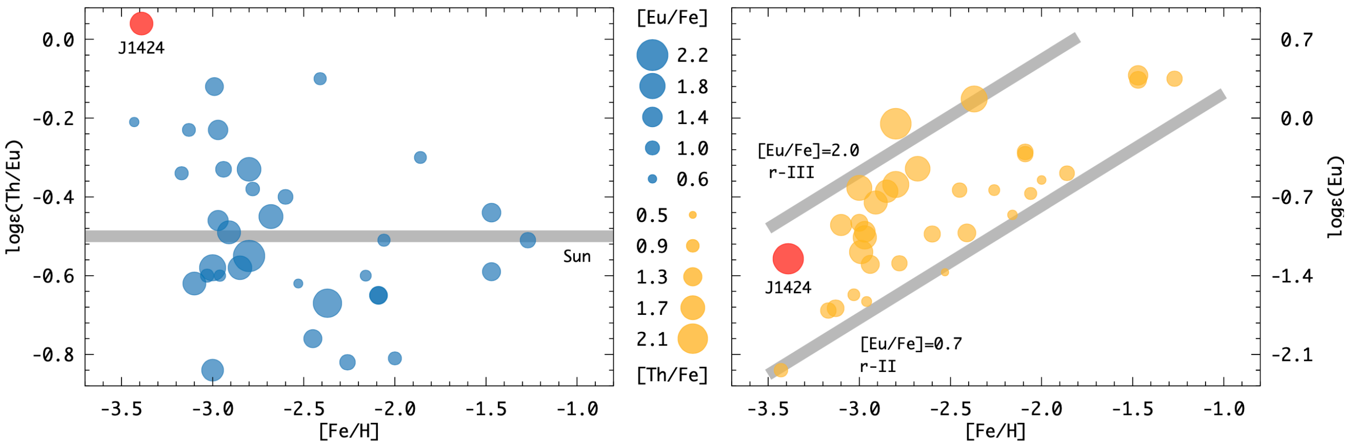
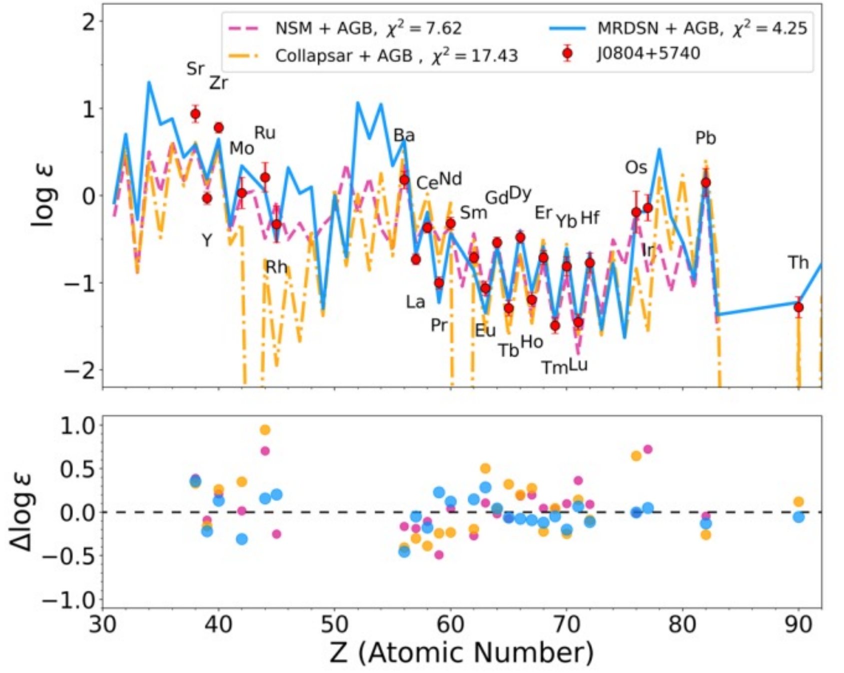
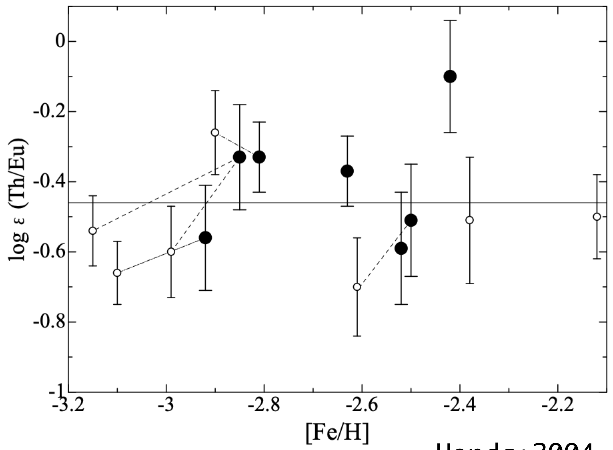
SPLUS J1424-2542 → Actinide-boost!



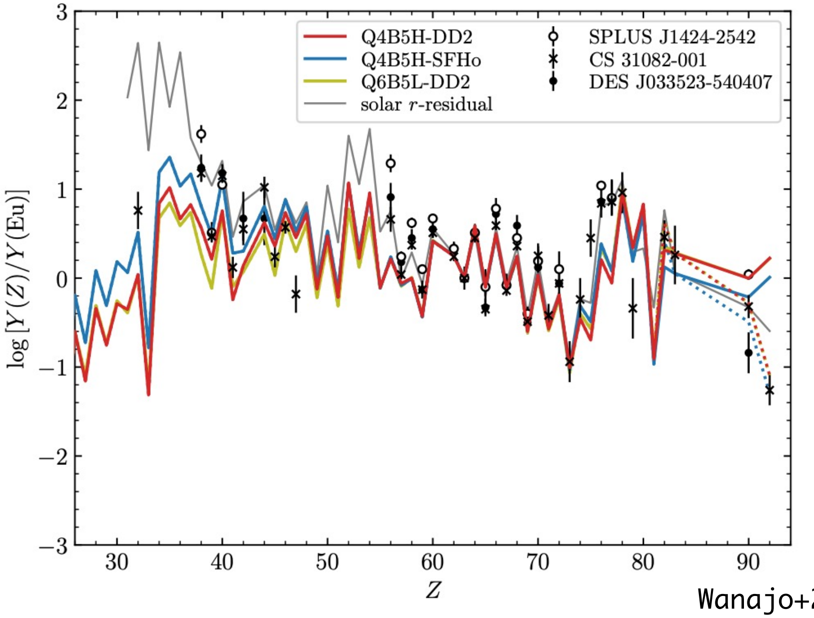
Placco+2023

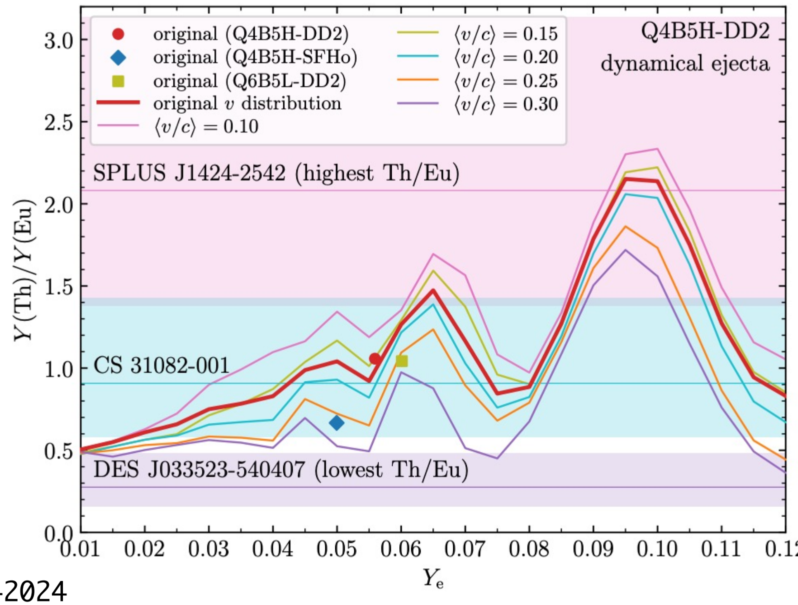


Lin+2025



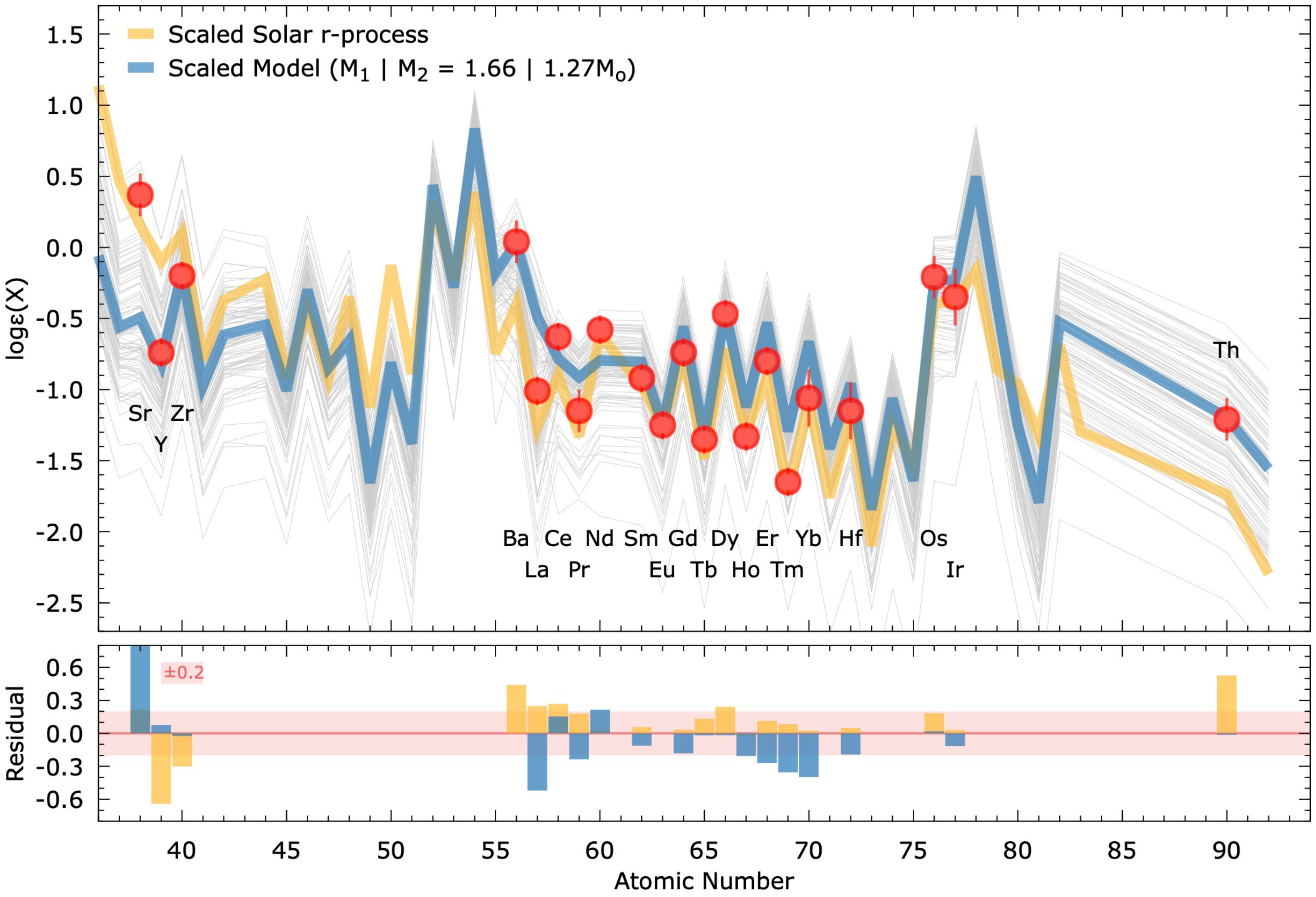
Honda+2004





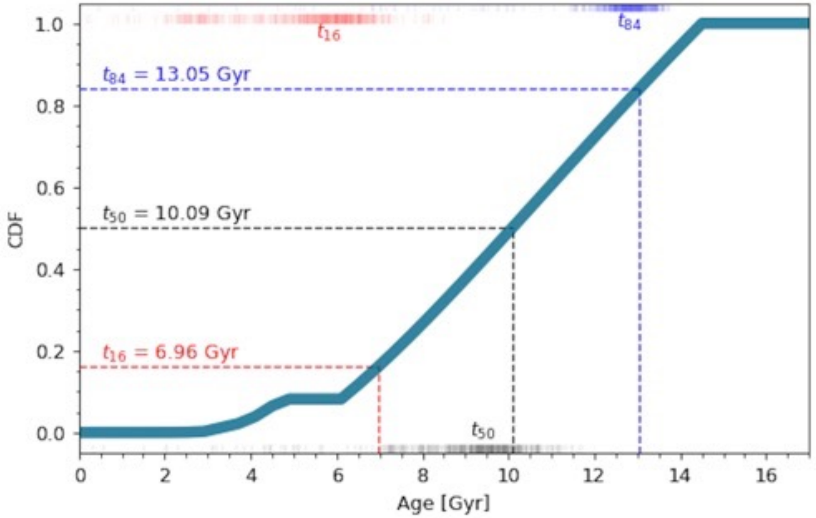
Wanajo+2024

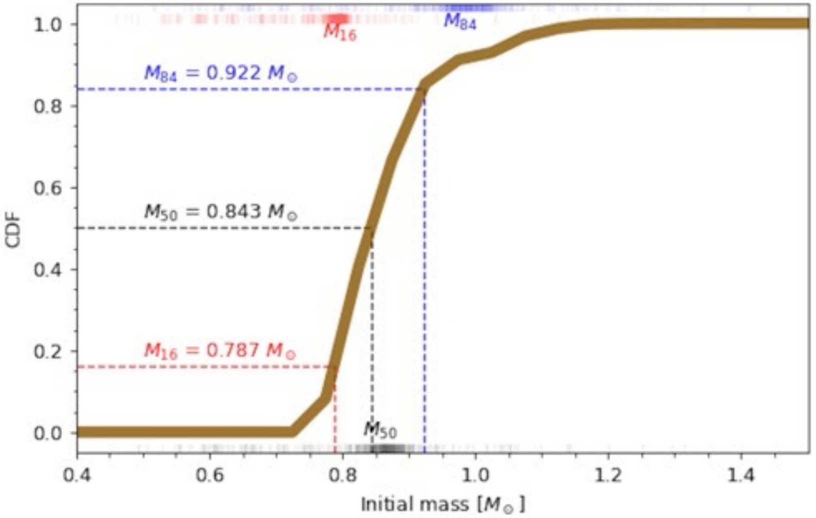
SPLUS J1424-2542 → heavy-element abundances vs. neutron star merger

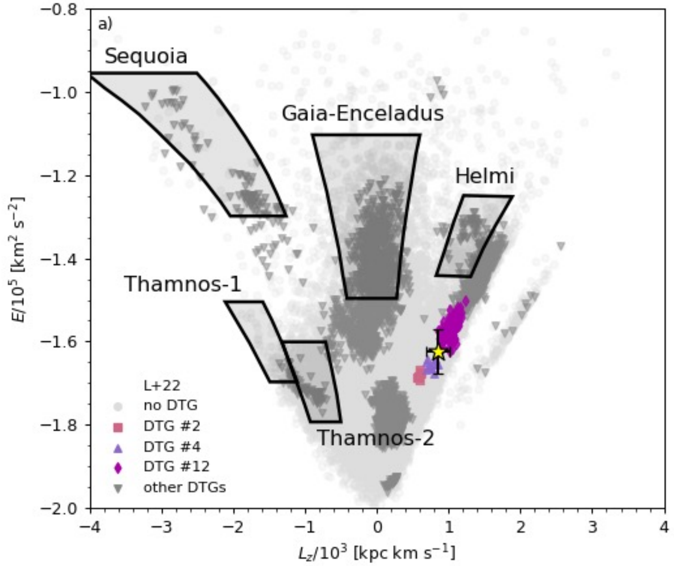


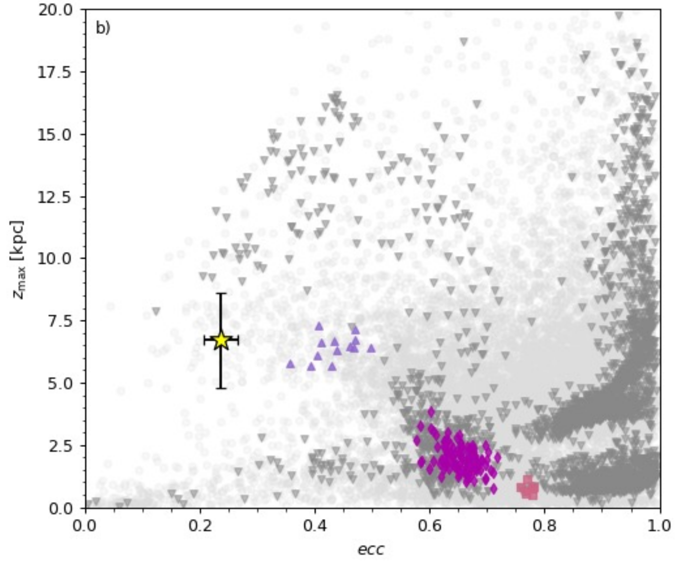
Placco+2023

SPLUS J1424-2542 → age, mass, and kinematics









Placco+2023

What now?

R-Process Enhanced Stars

- Galactic chemical evolution
- Address frequencies of NS+NS mergers and Collapsars

J1424-2542

- Old, low-mass, halo star
- Help constrain Actinide-boost phenomena
- Two progenitors?
    - SN explosion of a 13.4 $M_{\odot}$ Pop. III star +
    - Neutron star merger (1.66 $M_{\odot}$ + 1.27 $M_{\odot}$)

Moving forward

- Statistics, statistics, statistics
- Homogeneous samples and analyses
- Modelers: talk to your observer friends!
- Observers: talk to your modeler friends!

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credit: Babak Tafreshi /NOIRLab/AURA/NSF