(and a chemically peculiar star)

Molybdenum in the Galactic disk and bulge

Rebecca Forsberg
Uppsala University – 27th April 2023

Who am I?

BSc in planet formation modelling
MSc and PhD in stellar spectroscopy
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Anders Johansen
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Science Communication internship
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Nils Ryde
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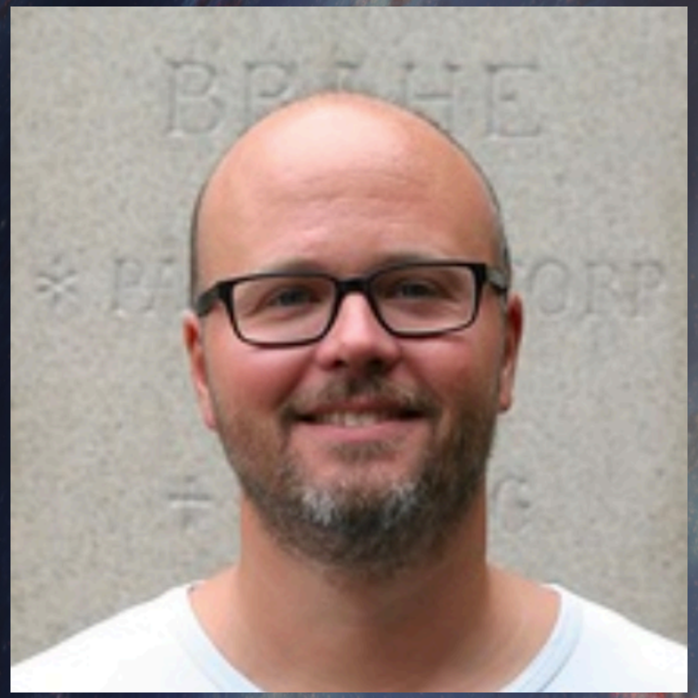


Henrik Jönsson
Malmö

POPULÄR Astronomi

Rebecca Forsberg
Uppsala University – 27th April 2023

Back to the Milky Way

- Forsberg at al. 2019
Zr, La, Ce and Eu in the bulge & disk

- Forsberg at al. 2022
Molybdenum in the bulge & disk

- Forsberg et al. 2023
R-process enriched star in the bulge

- Brief nucleosynthesis
- Stellar sample
- Abundance determination

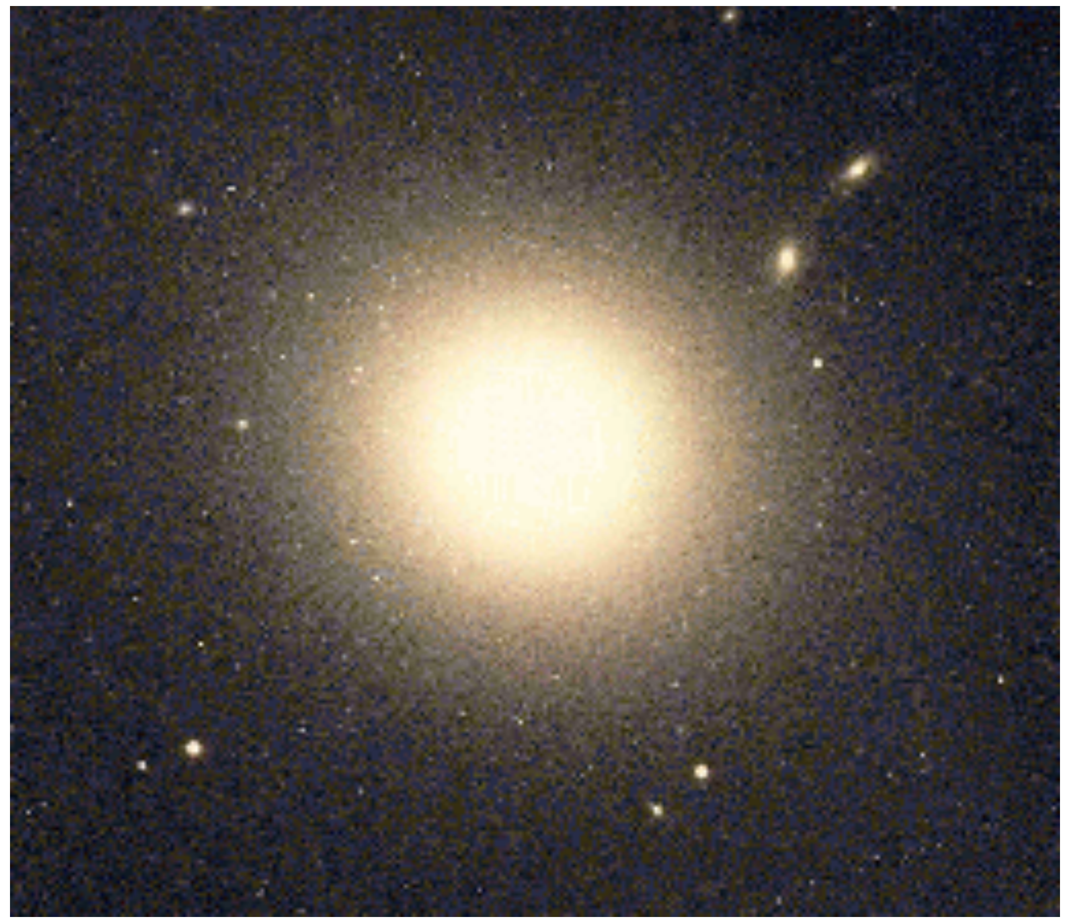
Rebecca Forsberg
Uppsala University – 27th April 2023

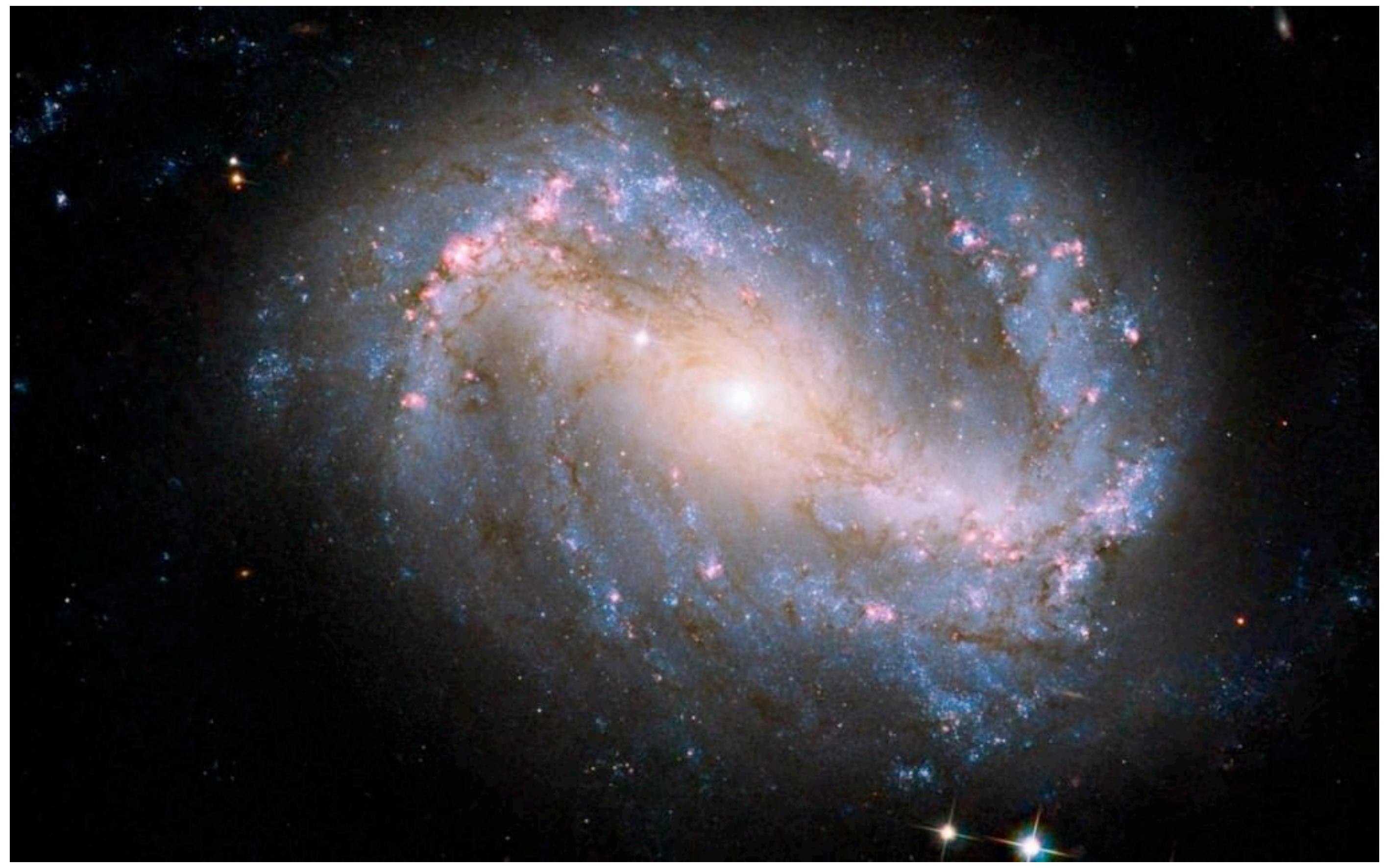
Why study neutron-capture elements in the Bulge?

- How did the bulge form, and what does it look like?

Classical, spherical, old vs. psuedo-bulge, younger

Higher SFR —> possibly higher r-process | Slower SFR —> similar to disk



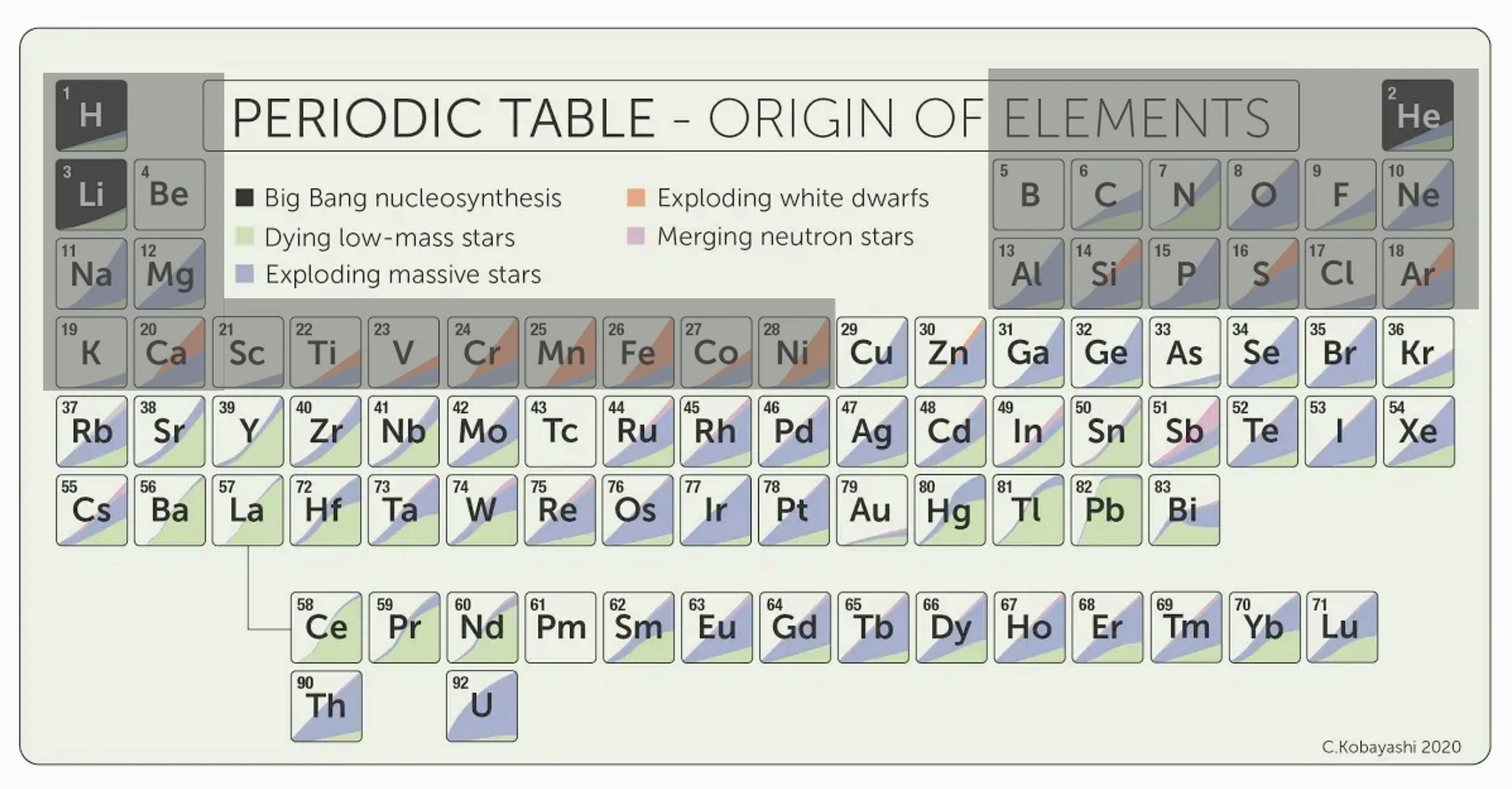


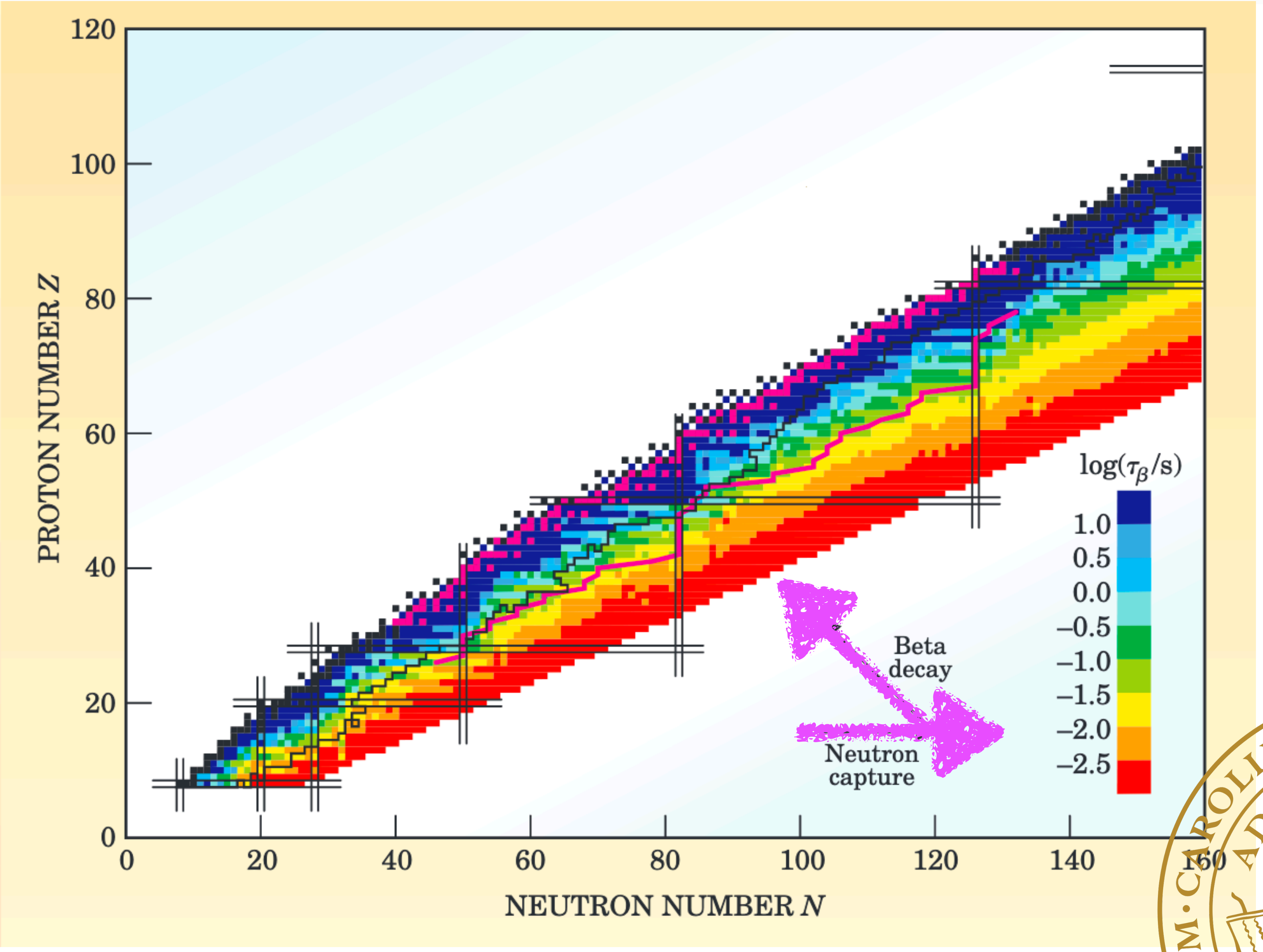
- Today, we consider the bulge to be much of a psuedo-bulge with a bar
- But is there a classical (r-rich) component in the bulge?

Neutron capture

- Above iron-peak elements
- Formed by neutron-capture processes: $n \longrightarrow p + e + \nu$
- Beta-decay more likely than neutron-capture, slow process
- Beta-decay less likely than neutron capture, rapid process

—> put some constraints on where these processes can take place

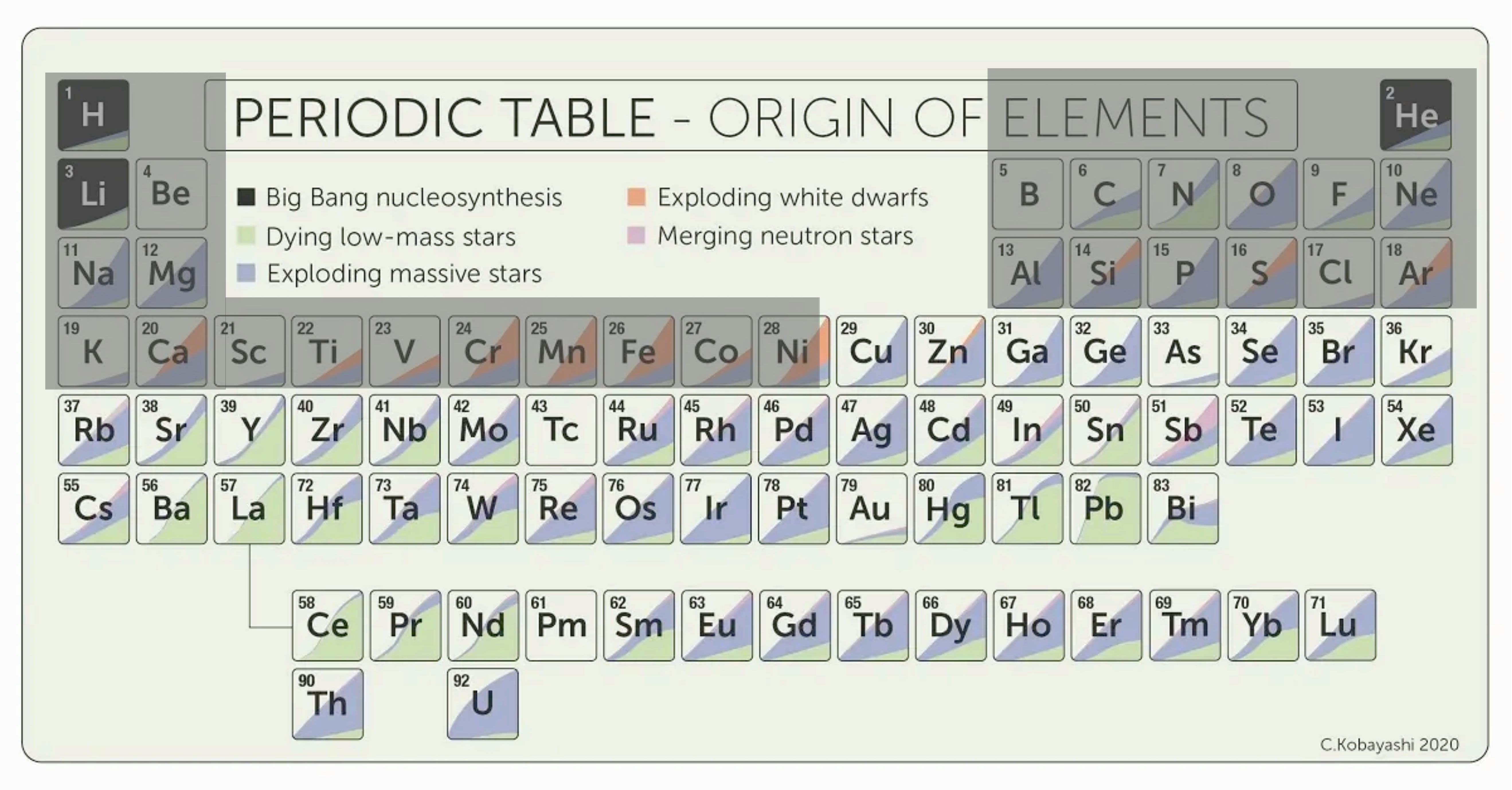




Neutron capture

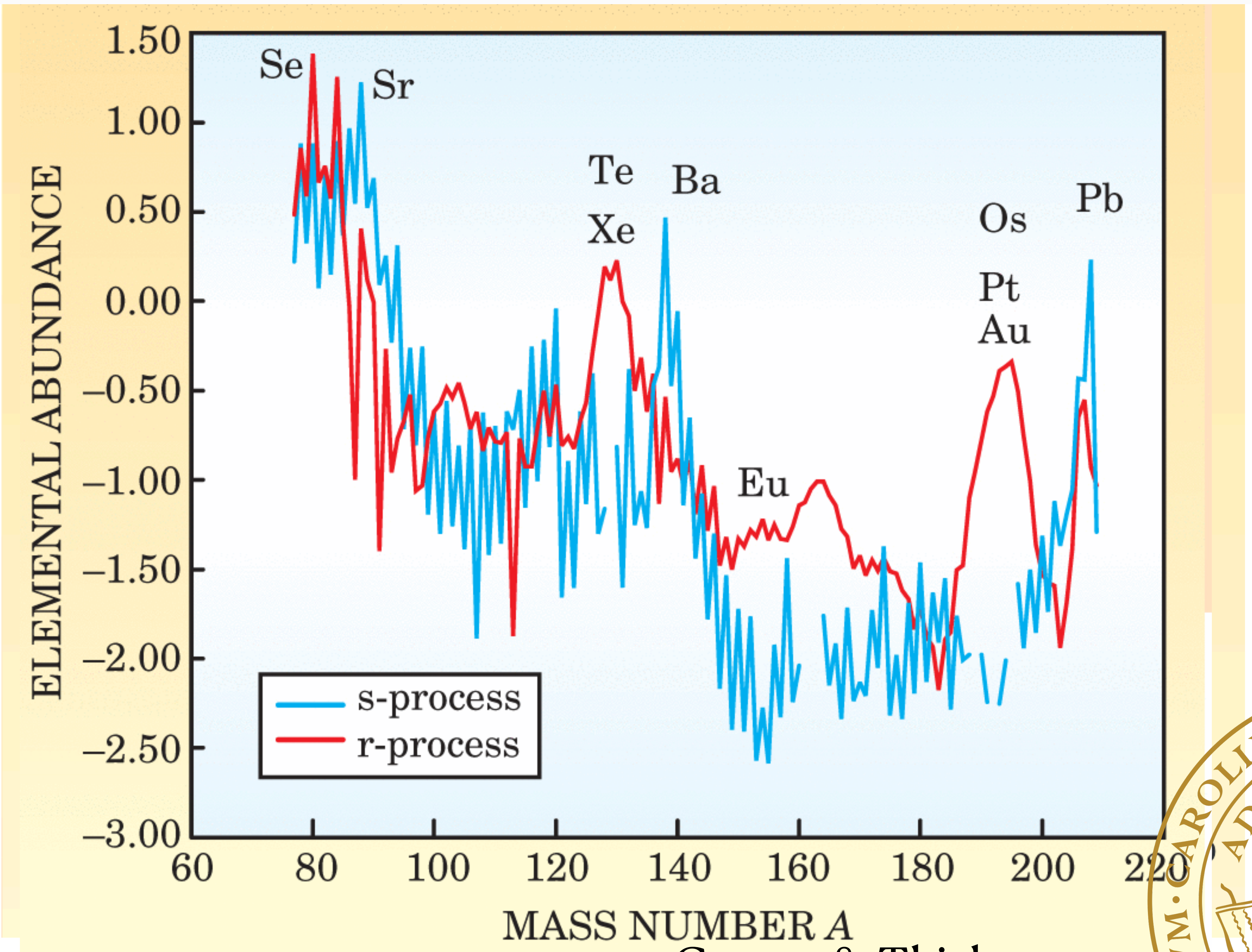
- The s-process takes place in
  - AGB stars during third dredge-up, n-source: $^{13}C(\alpha,n)^{16}O$
  - Massive stars, n-source: $^{22}Ne(\alpha,n)^{25}Mg$

  Karakas & Lattanzio 2014, Bisterzo et al. 2017



- Weak (Cu, Rb), main (Ba, La), strong (Tl, Pb)

- Still uncertainties on the effects of stellar rotation, the size of the ^{13}C-pocket, low-metallicity production…



Cowan & Thielemann 2004

Neutron capture

- The r-process takes place in
  - Neutron star mergers

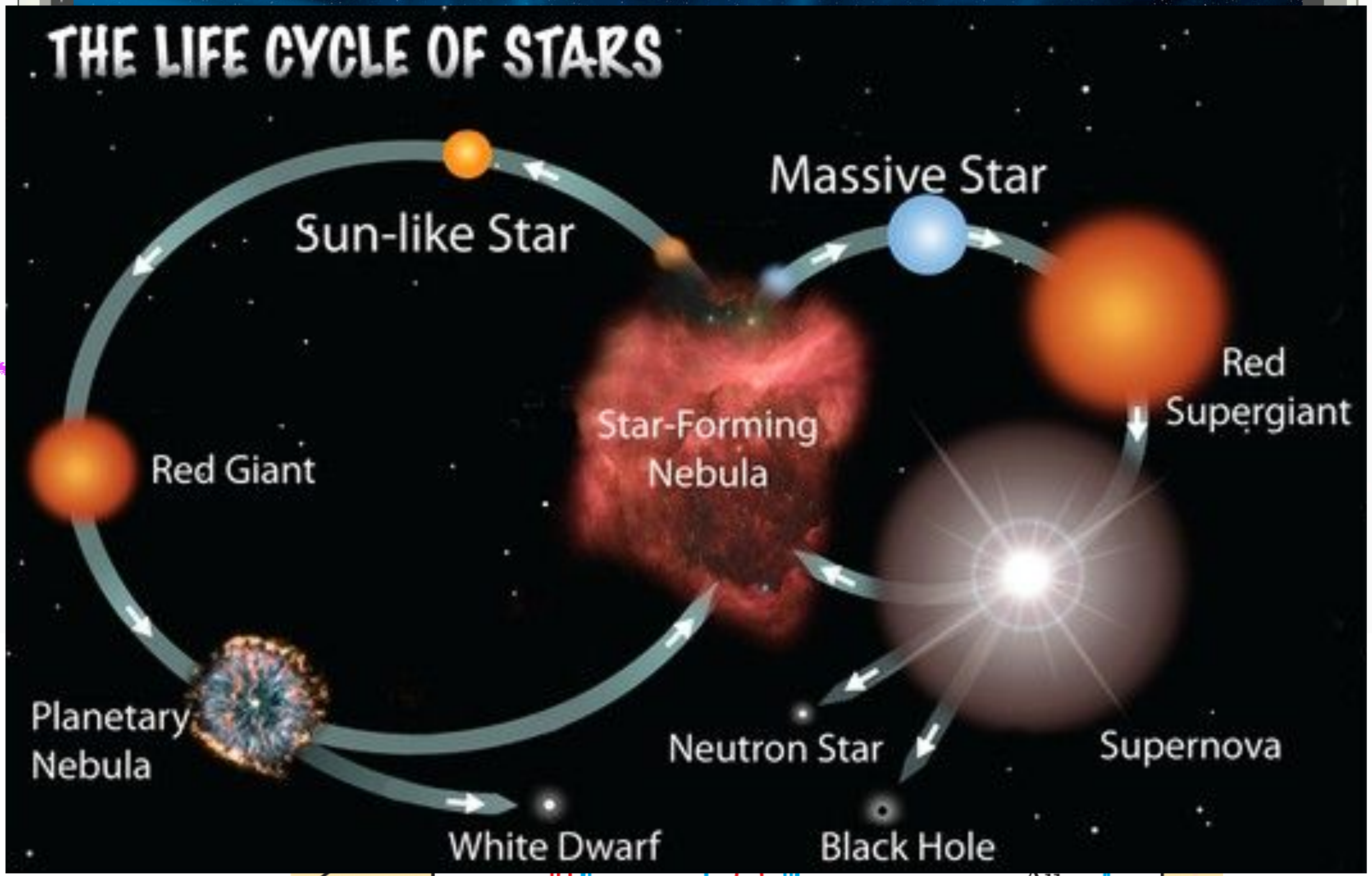
  Sneden et al. 2000, Thielemann et al. 2011, 2017
  Abbott et al.2017, Tanvir et al. 2017, Drout et al. 2017

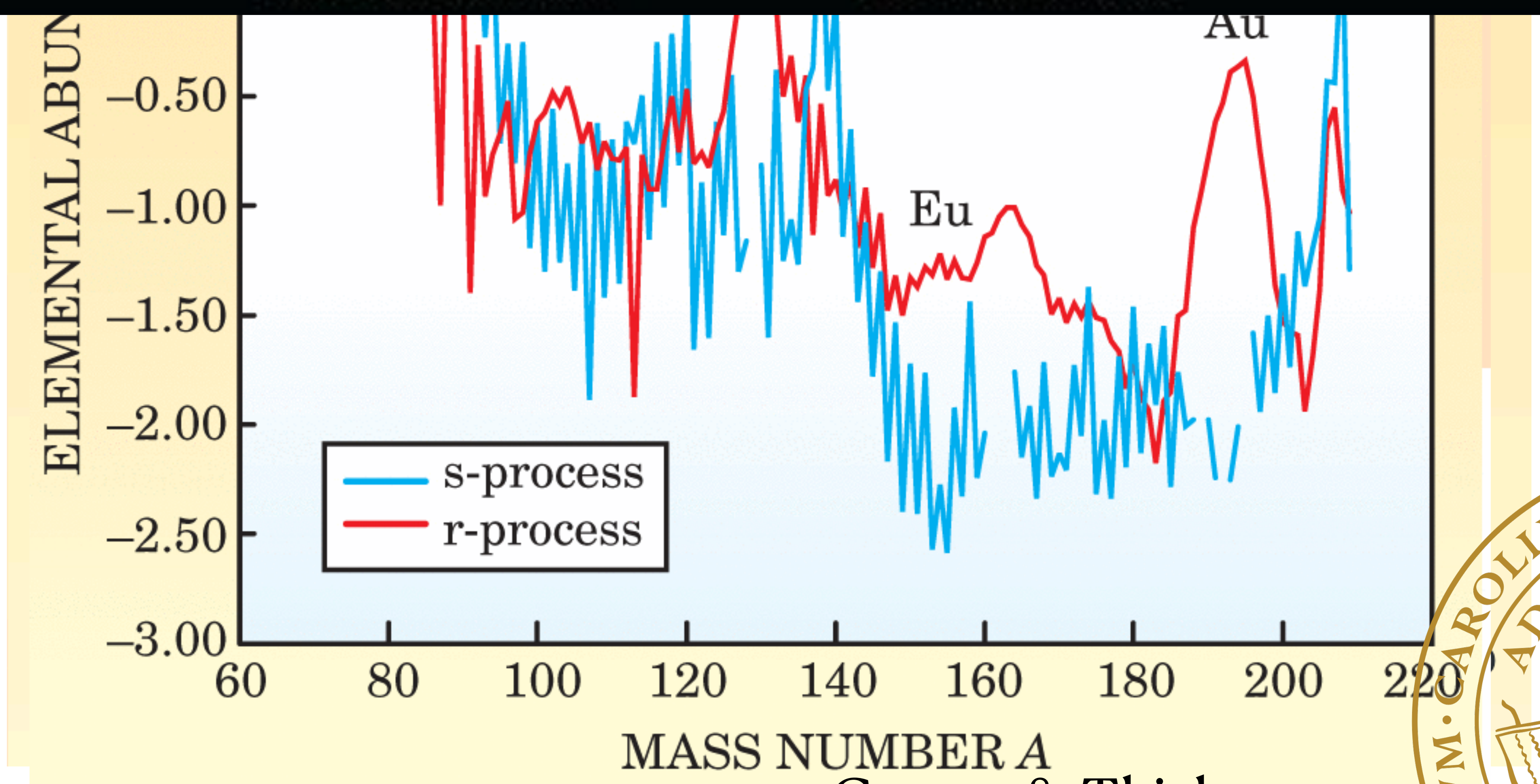
  - Various supernovae (CC, MR, EC)

  Côté et al.2019, Kajino et al. 2019,
  Kobayashi et al. 2020

Still uncertain!

Measuring elements originating from the s-process and the r-process can give signatures of these events historically in the Galaxy

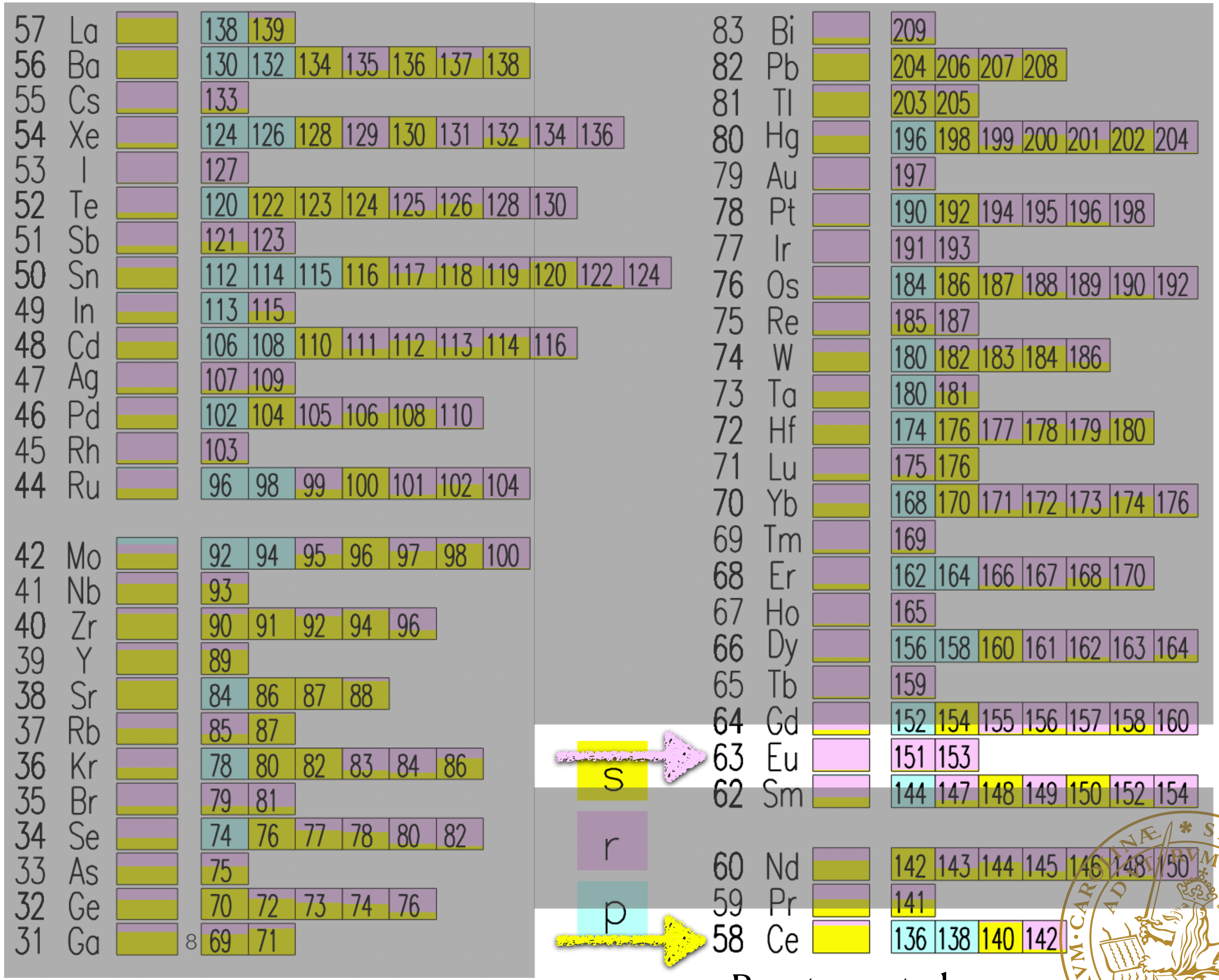




Cowan & Thielemann 2004

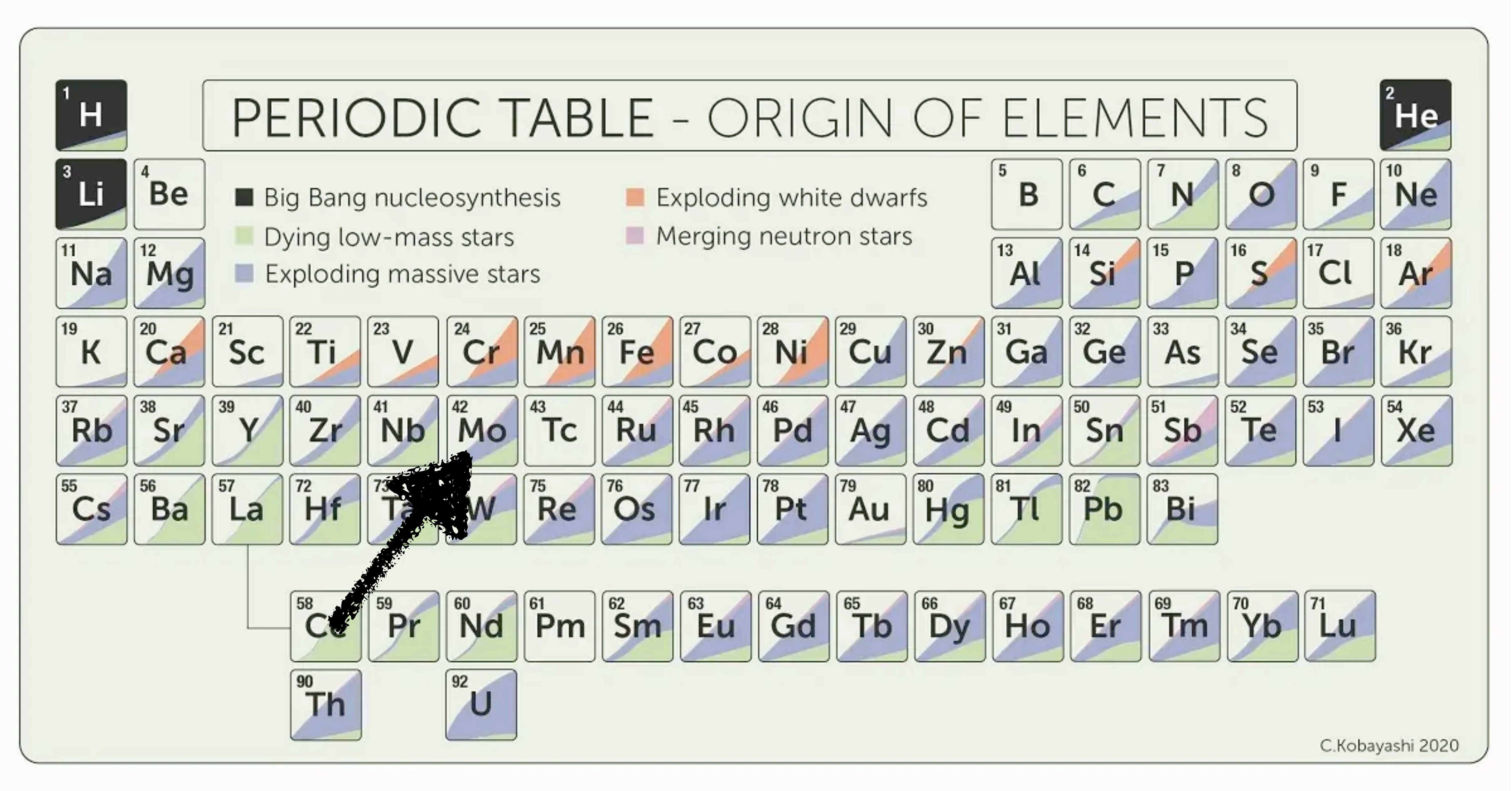
It's really about isotopes

Talk about *dominated* production from either process

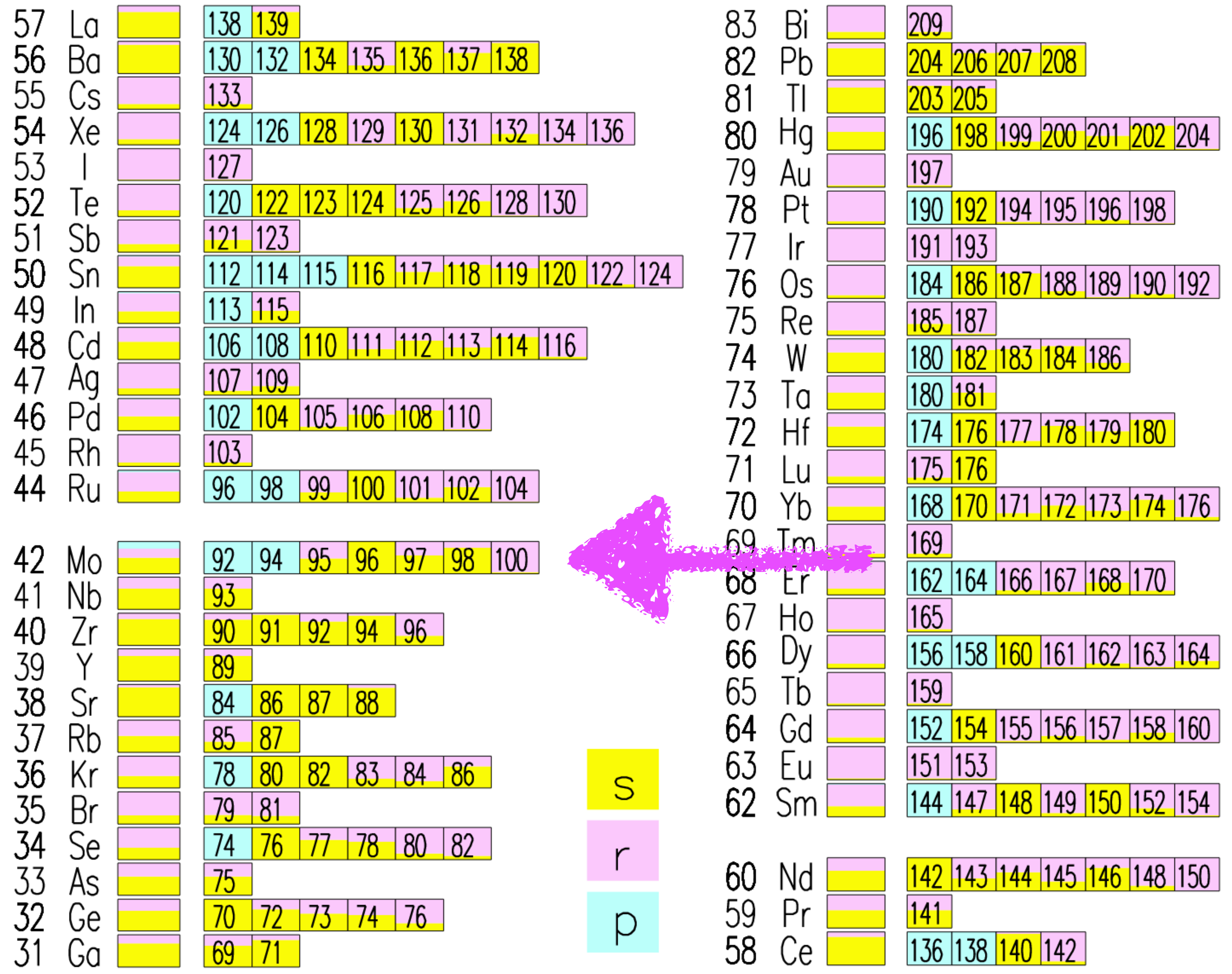


Prantzos et al. 2020

The case of molybdenum



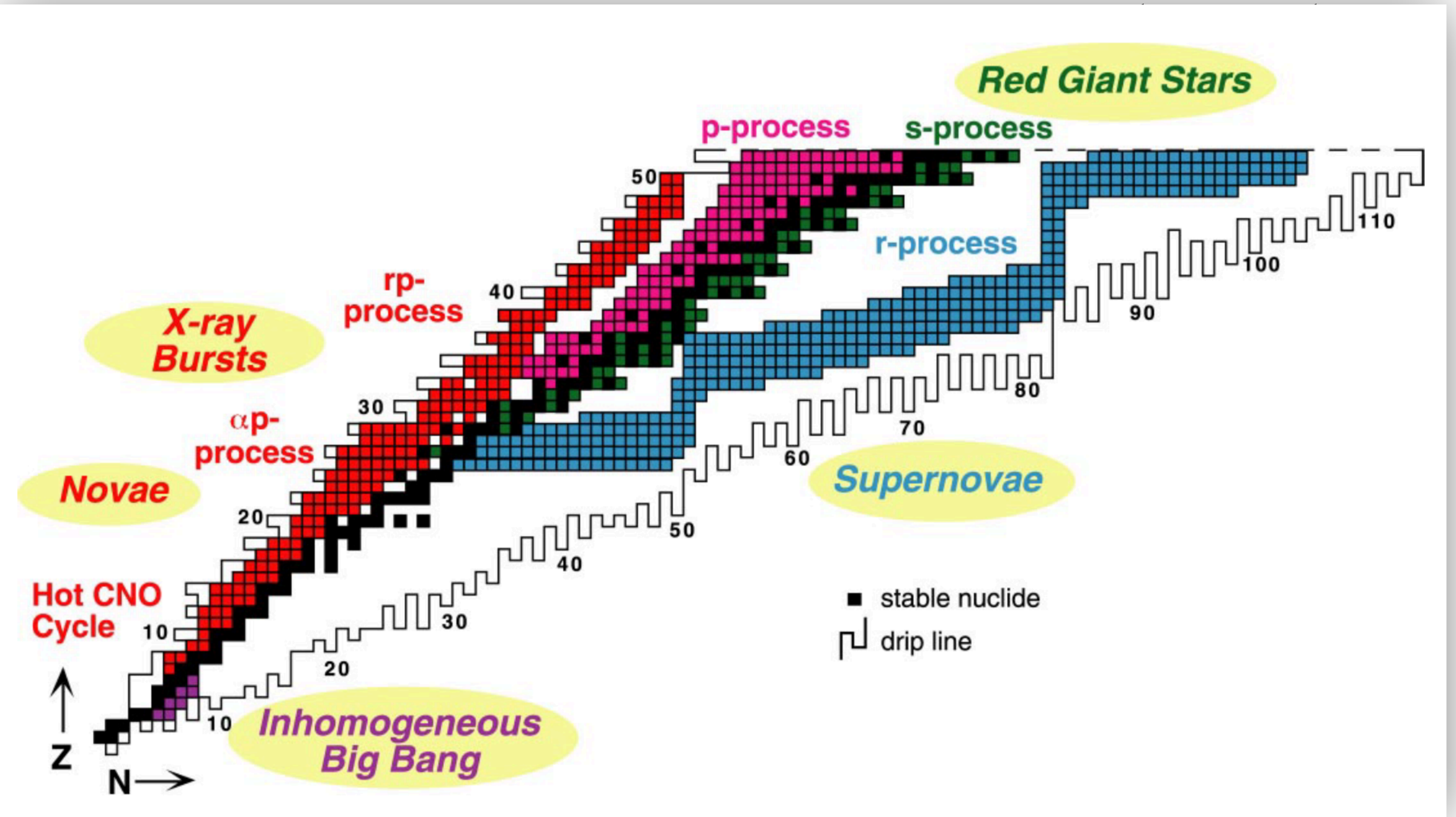
50% s-process, 25% r-process, 25 % p-process



Prantzos et al. 2020

The p-process

- 35 proton rich isotopes from the p-process (Burbidge et al. 1957, Rauscher et al. 2013)
- Not necessarily proton capture...



Photodisintegration of heavy isotopes in the O/Ne-shell of massive stars during CC SNe explosions, γ-process

Neutrino winds, SNe, ν-process

Should behave like a typical alpha- and iron-peak element

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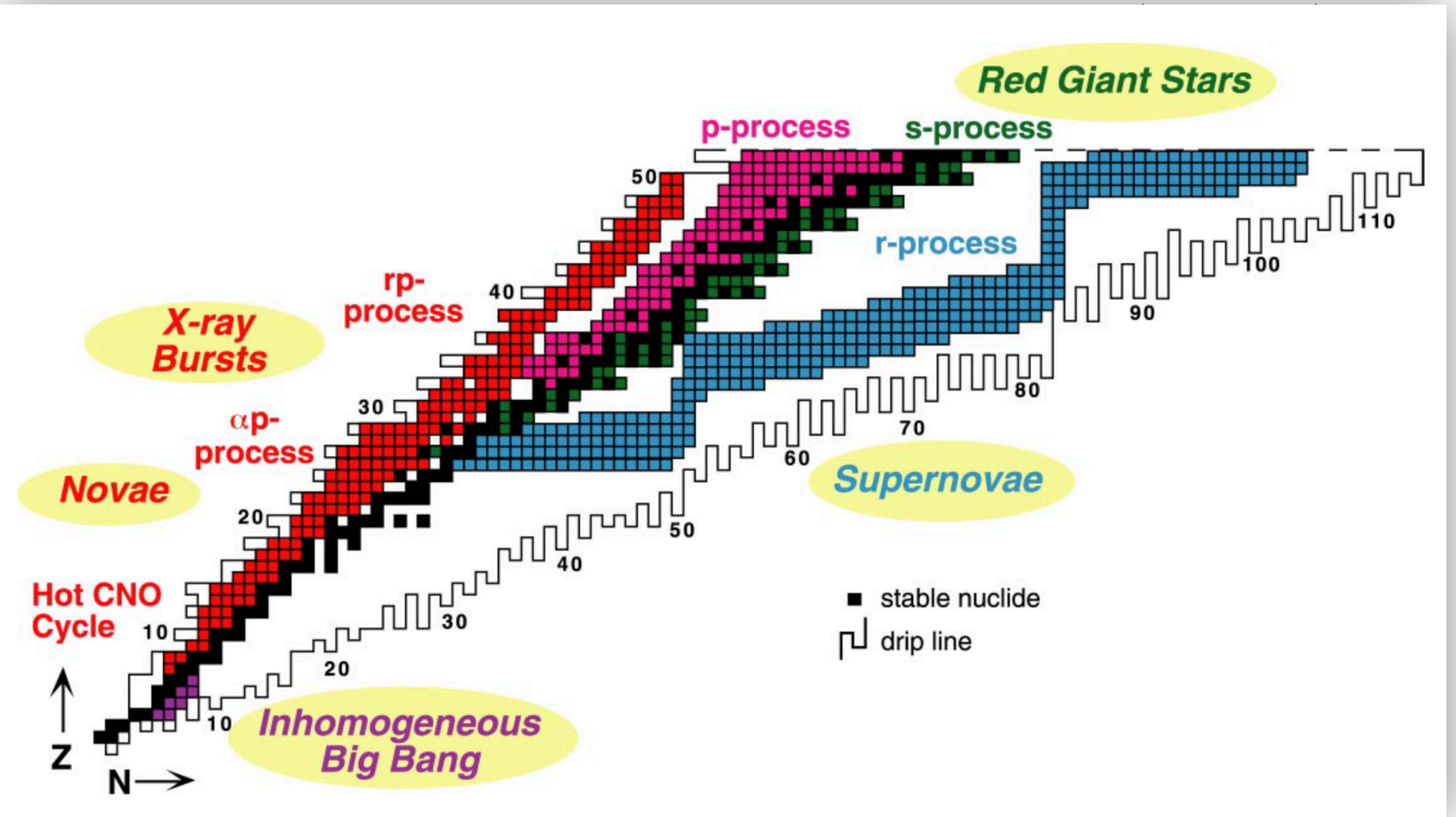

WD-associated
Travaglio et al. 2011, 2015

Mass accreting WD, γ-process

γ + p-capture process in sub-C-mass WD, pn- process

Should behave like a typical iron-peak element

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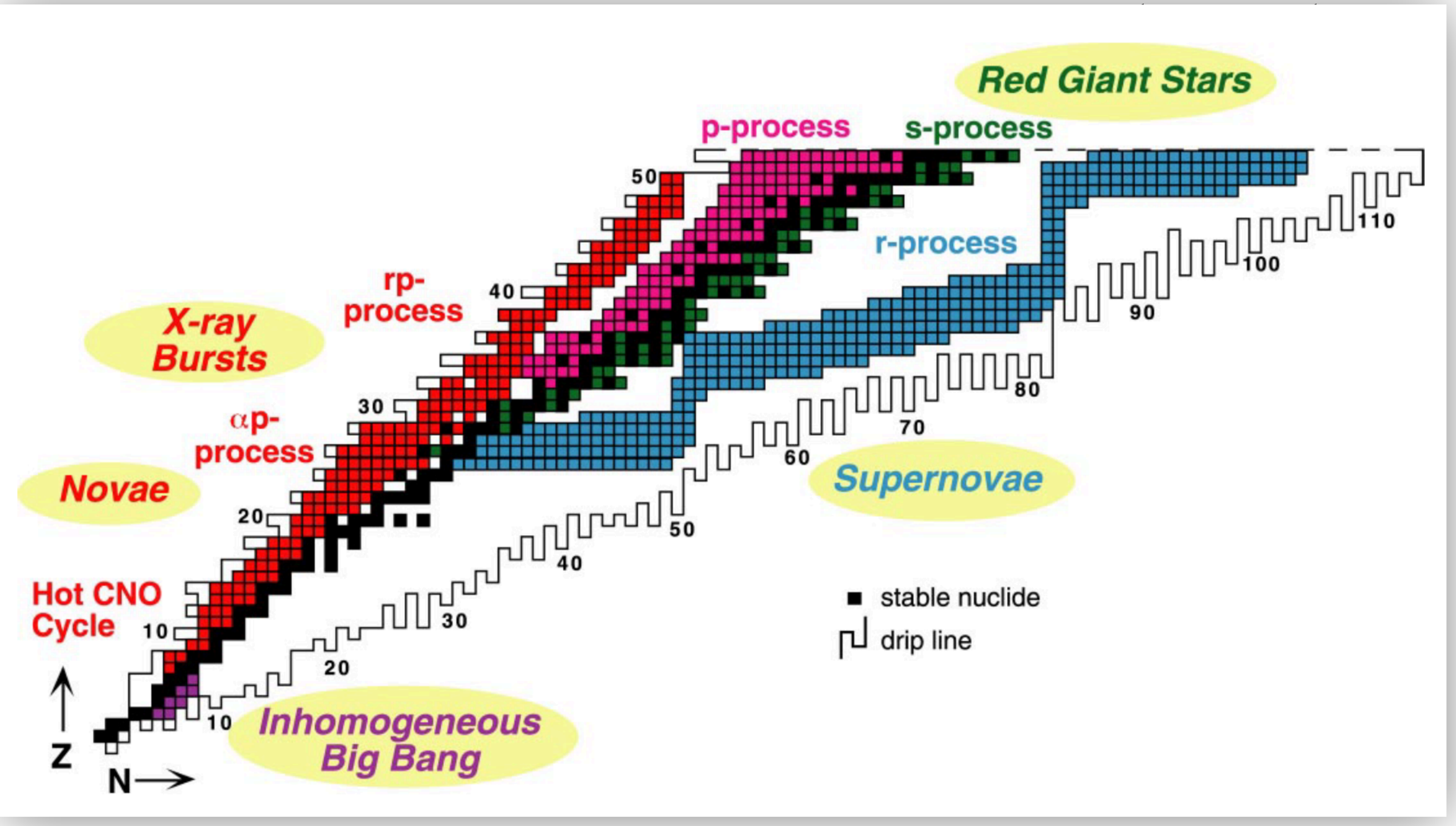
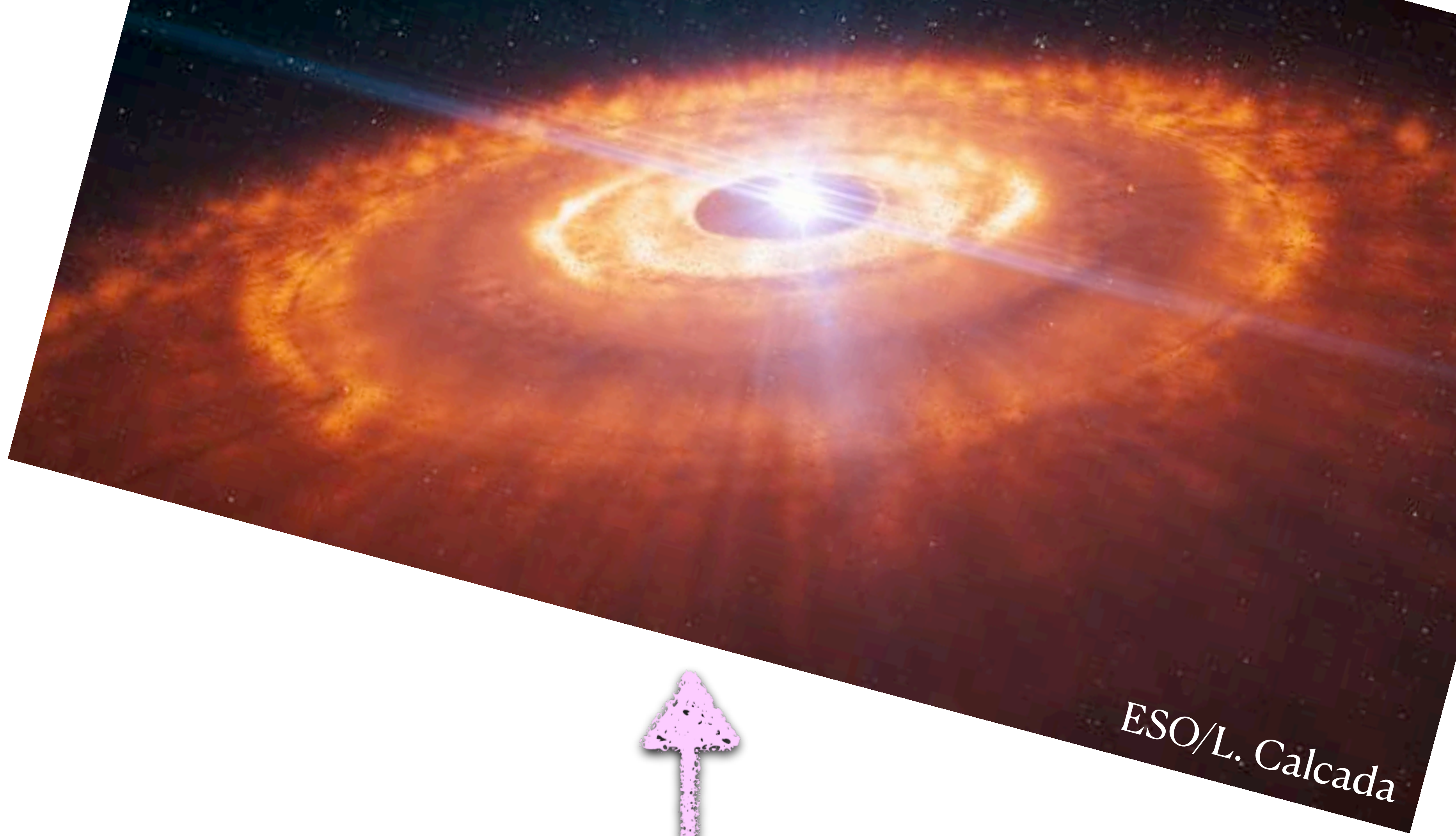


H+He burning on mass accreting neutron stars (rp-process)

Don't know what this would look like!

The case of molybdenum –
a conundrum for planet-formation community

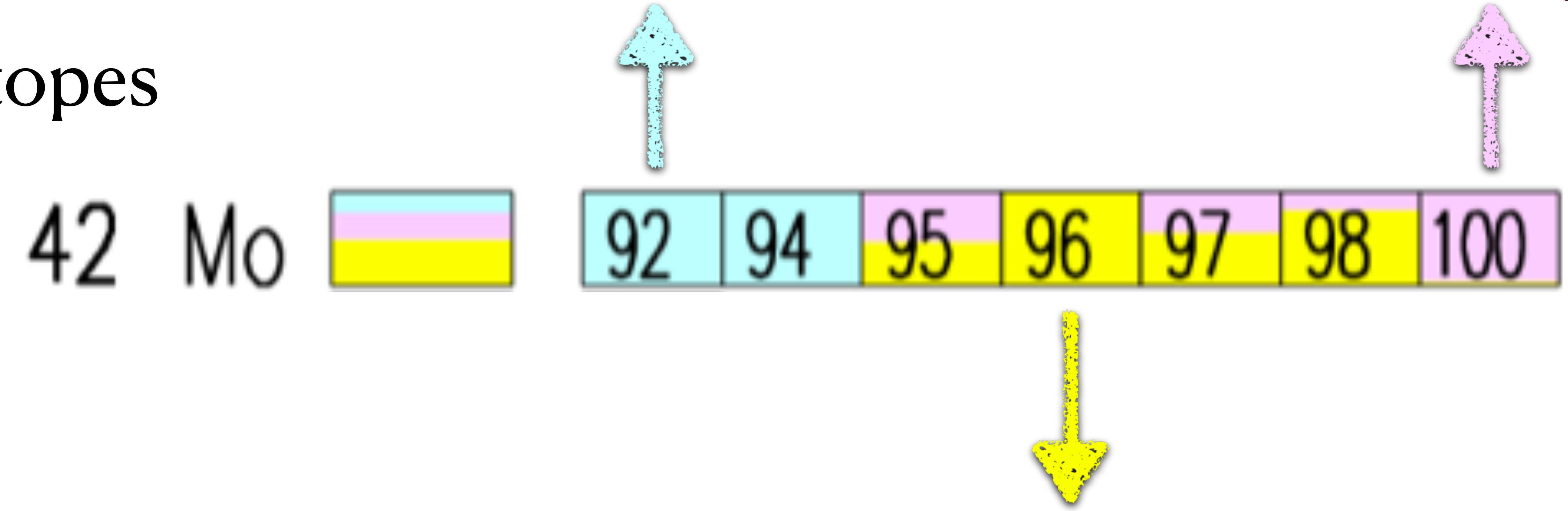


In solar system meteorites...

- Excess of Mo p- and r-isotopes
- Deficit of Mo s-isotope

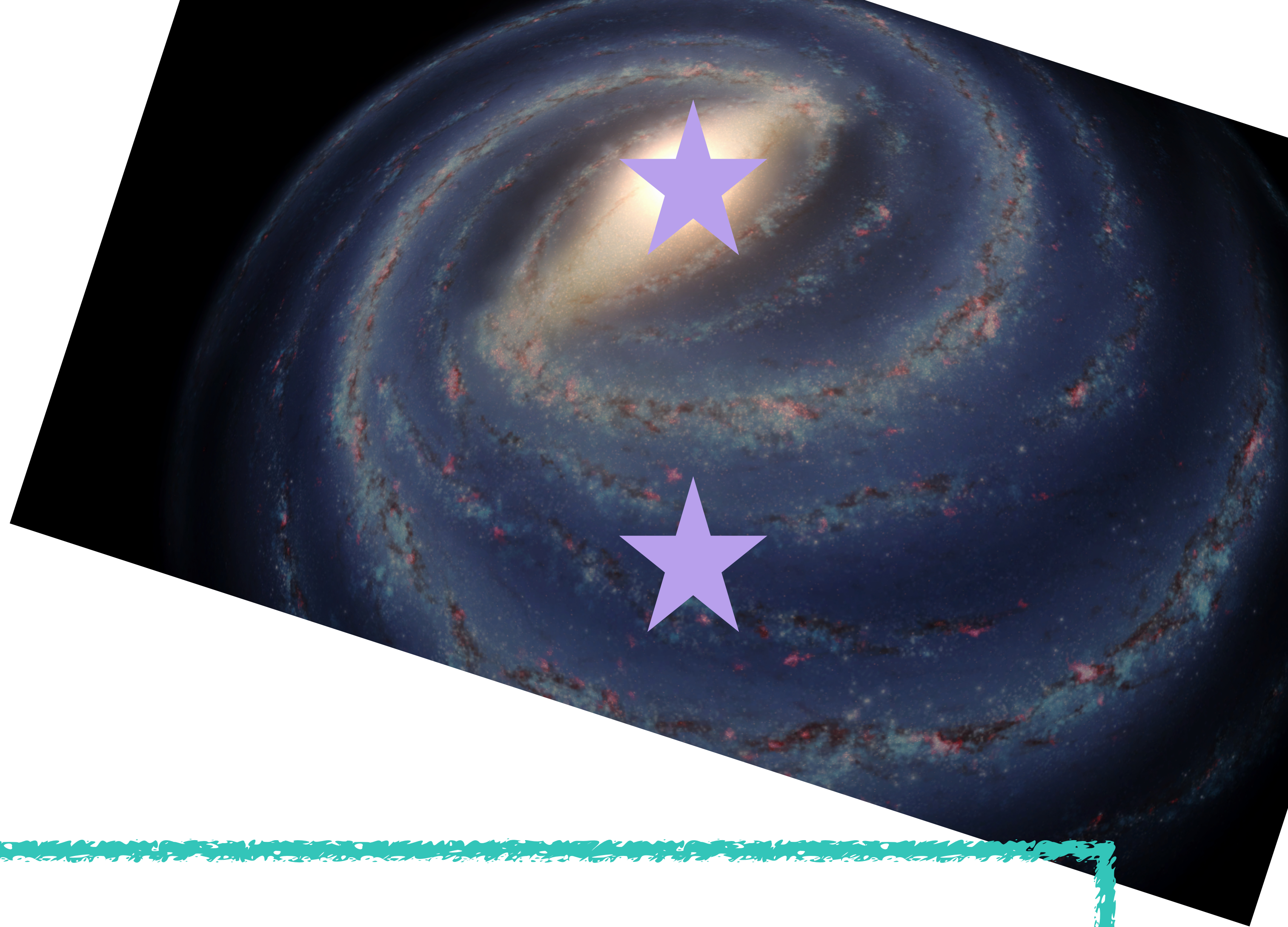
...relative to the Earth

Burkhardt et al. 2011,
Budde et al. 2016, 2019



- To understand the p-process, Mo is the element to study

The Jönsson series



Abundances of disk and bulge giants from high-resolution optical spectra

I. O, Mg, Ca, and Ti in the solar neighborhood and *Kepler* field samples★,★★

H. Jönsson[1,2,3], N. Ryde[1], T. Nordlander[4], A. Pehlivan Rhodin[1,5], H. Hartman[1,5], P. Jönsson[5], and K. Eriksson[4]

Abundances of disk and bulge giants from high-resolution optical spectra

II. O, Mg, Ca, and Ti in the bulge sample★

H. Jönsson[1,2,3], N. Ryde[1], M. Schultheis[4], and M. Zoccali[5,6]

Abundances of disk and bulge giants from high-resolution optical spectra

III. Sc, V, Cr, Mn, Co, Ni★,★★

M. Lomaeva[1], H. Jönsson[1], N. Ryde[1], M. Schultheis[2], and B. Thorsbro[1]

Abundances of disk and bulge giants from high-resolution optical spectra

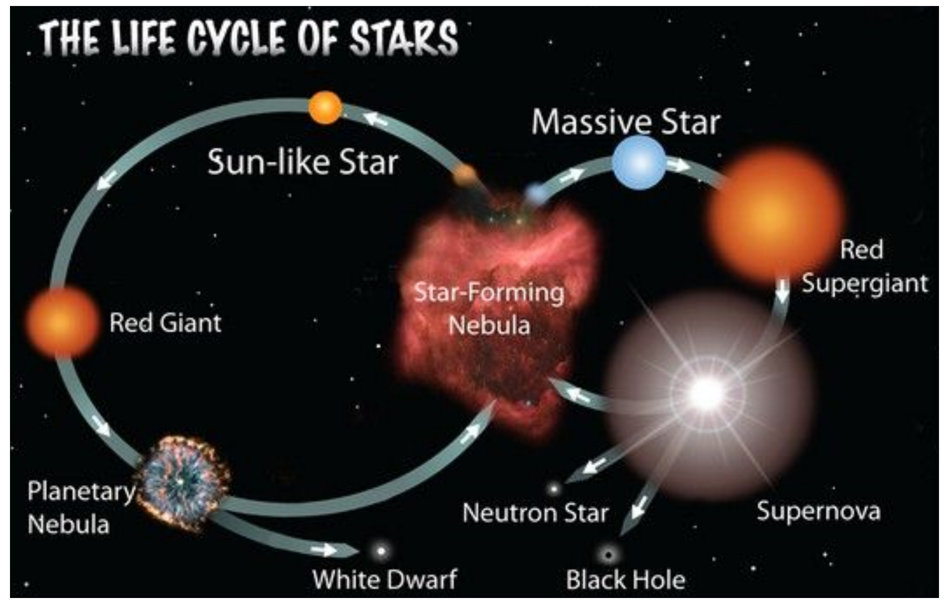
IV. Zr, La, Ce, Eu★,★★

R. Forsberg[1], H. Jönsson[1,2], N. Ryde[1,3], and F. Matteucci[4,5,6]

Abundances of disk and bulge giants from high-resolution optical spectra

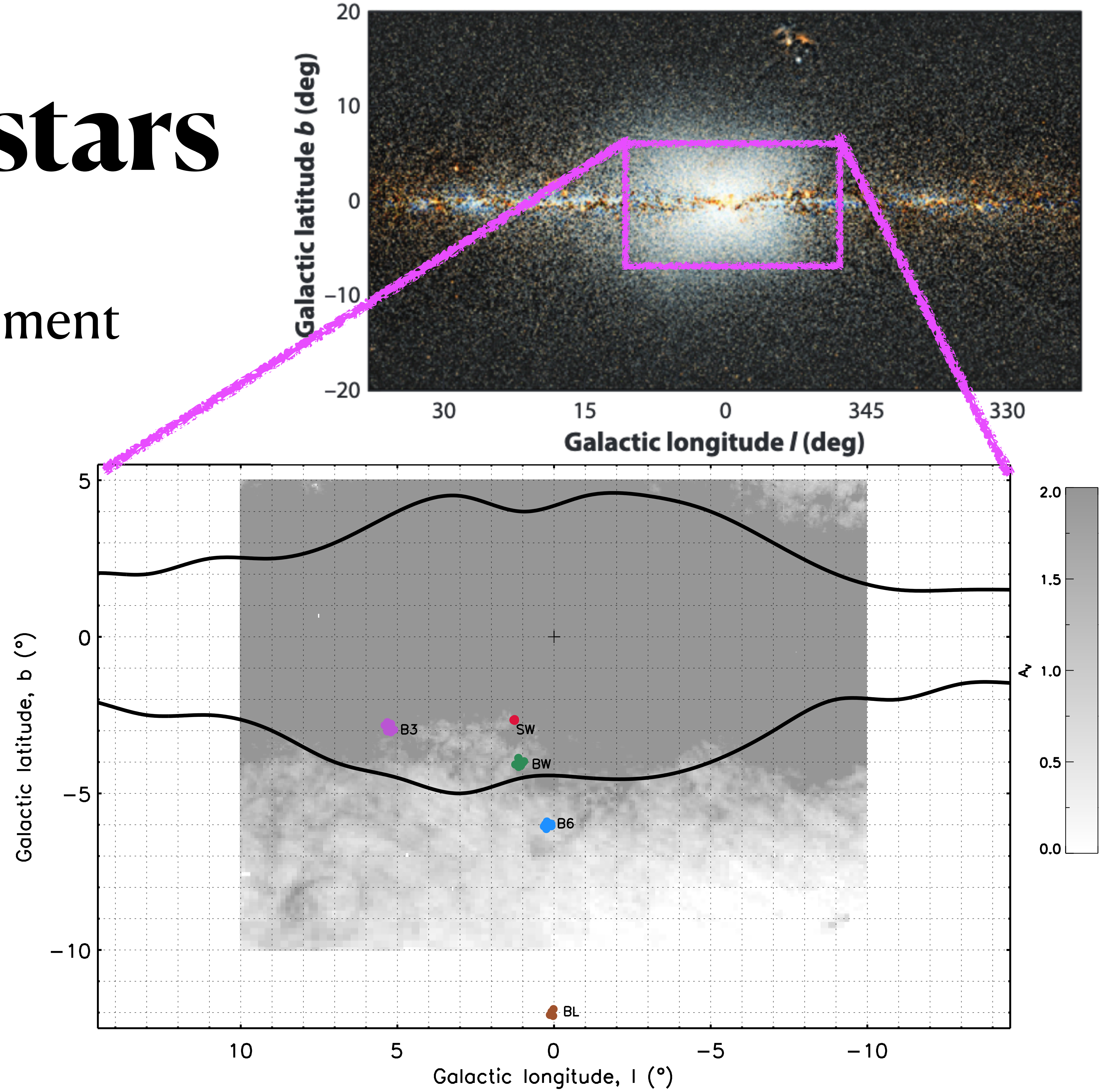
V. Molybdenum: The p-process element★,★★

R. Forsberg[1], N. Ryde[1], H. Jönsson[2], R. M. Rich[3], and A. Johansen[1,4]



Investigate using stars

WISE mikrometer obs. of Bulge region (Ness & Lang 2016)



- Stars carry chemical fingerprint of the formation environment

- 291 disk giants, FIES at the Nordic Optical Telescope
- FIES: ~~4000 - 7000~~ Å, S/N ~ 100

5800 - 6800 Å

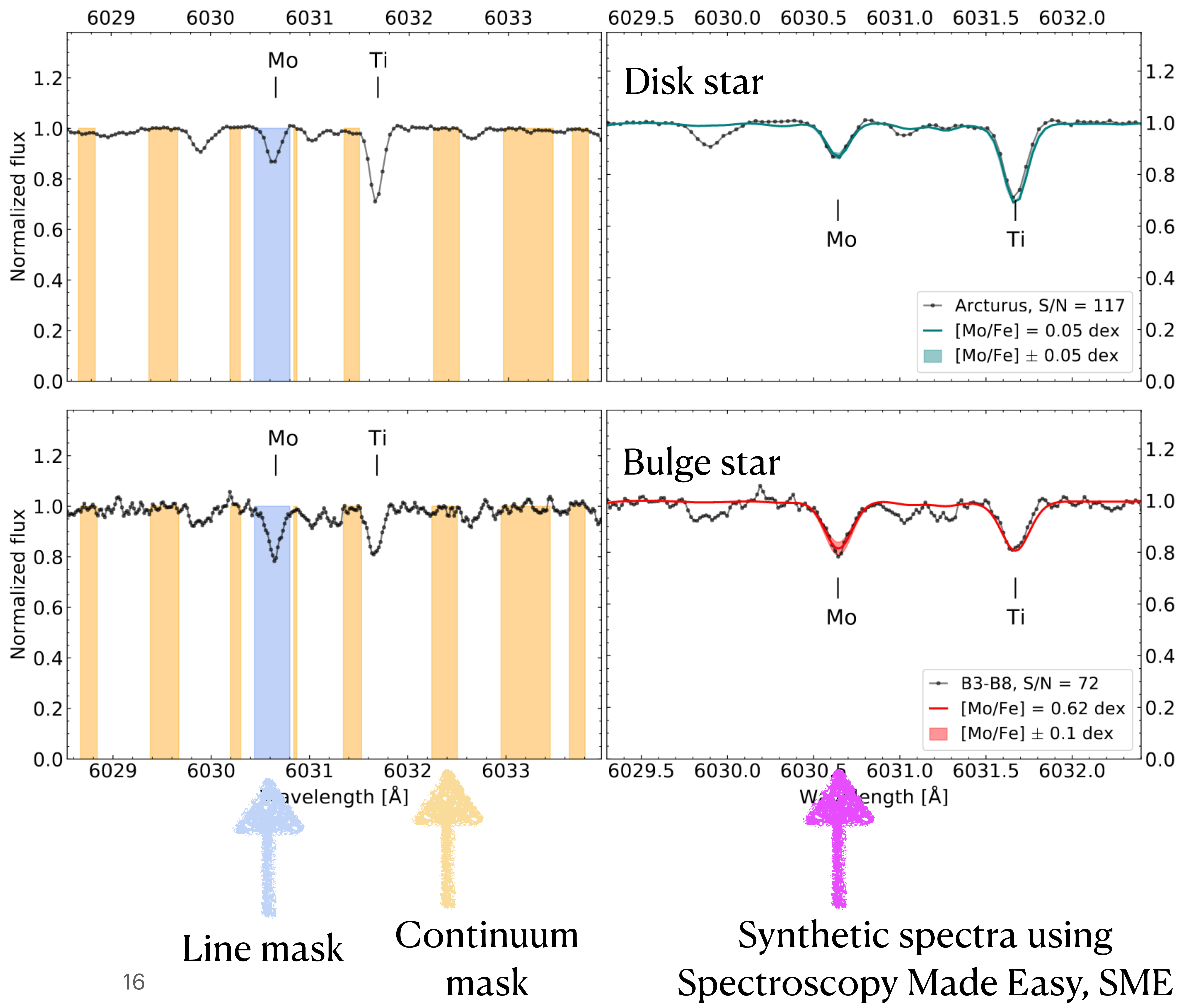
- 45 bulge giants, UVES (ESO's VLT, Zoccali+06)
- UVES: 5800-6800 Å, S/N ~ 50

Differential comparison between disk and bulge

Determining the abundance of Mo

- Use Spectroscopy Made Easy
  (SME, Valenti & Piskunov & 1996, 2017)
  to create synthetic spectra
  - Model atmosphere
    MARCS, Gustafsson et al. 2008
  - Stellar parameters
  - Atomic data
    Gaia-ESO, Heiter et al. 2021
  - Continuum & line masks:
    patience!

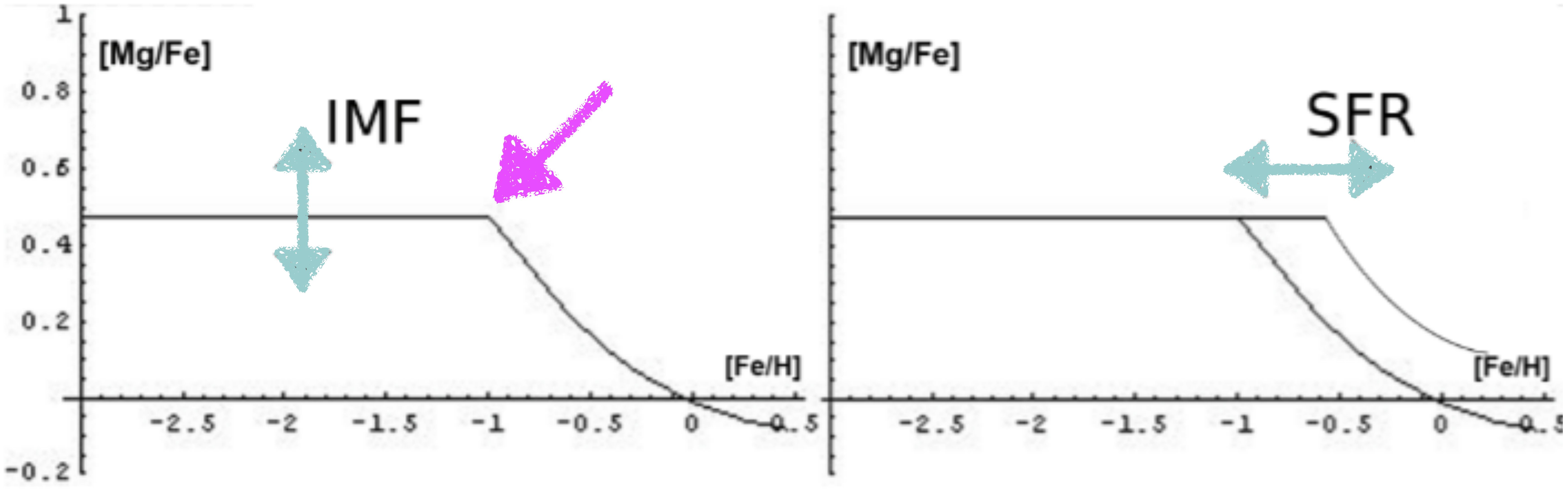
- Mo 6030 Å,
  - no HFS, IS but not resolvable
  - assume LTE



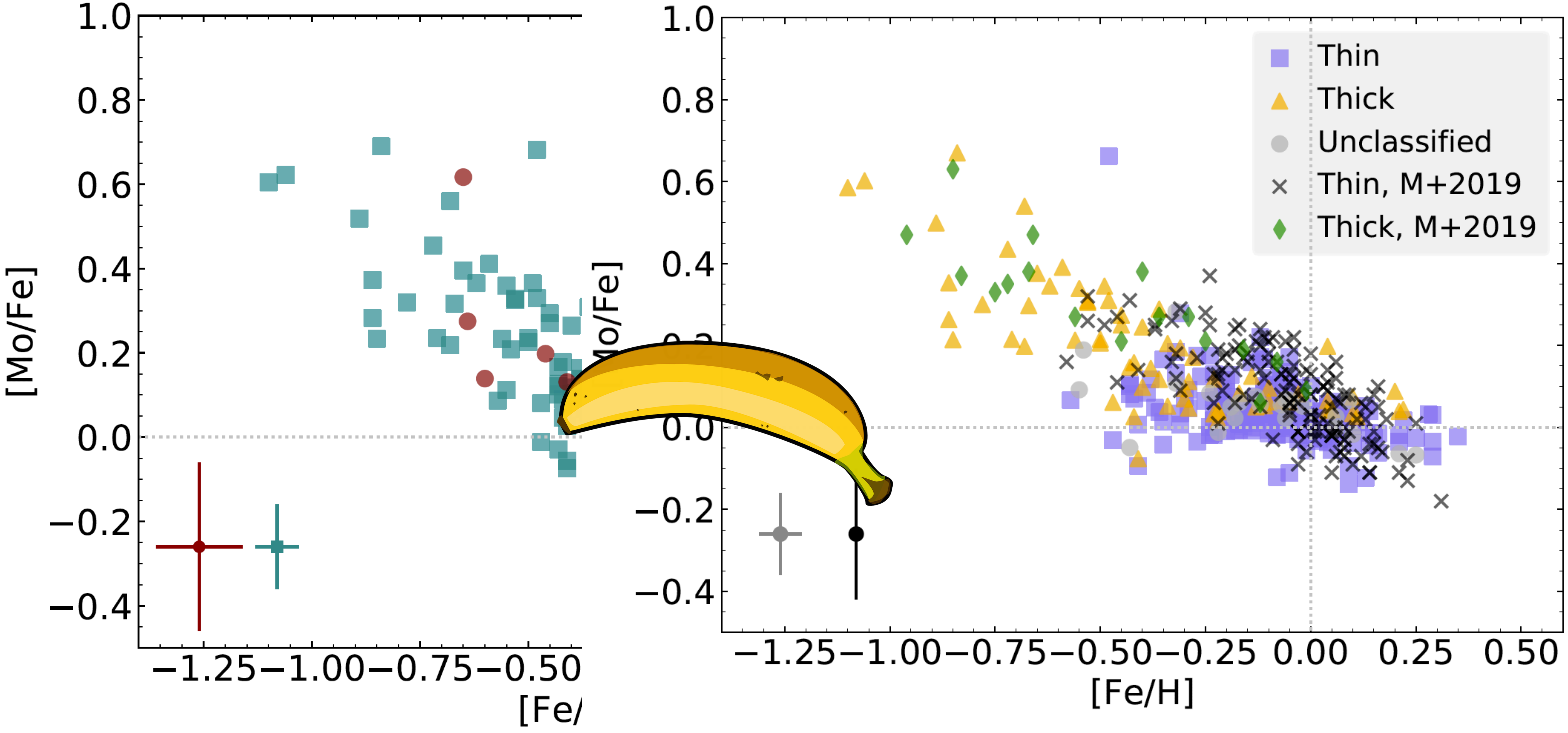
Reminder on how to read abundance plots

- Mg produced in SNe II
  Fe produced in SNe II and SNe Ia (white dwarf origin)
- Initial Mass Function (IMF)
- Star Formation Rate (SFR)

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{Sun}}$$



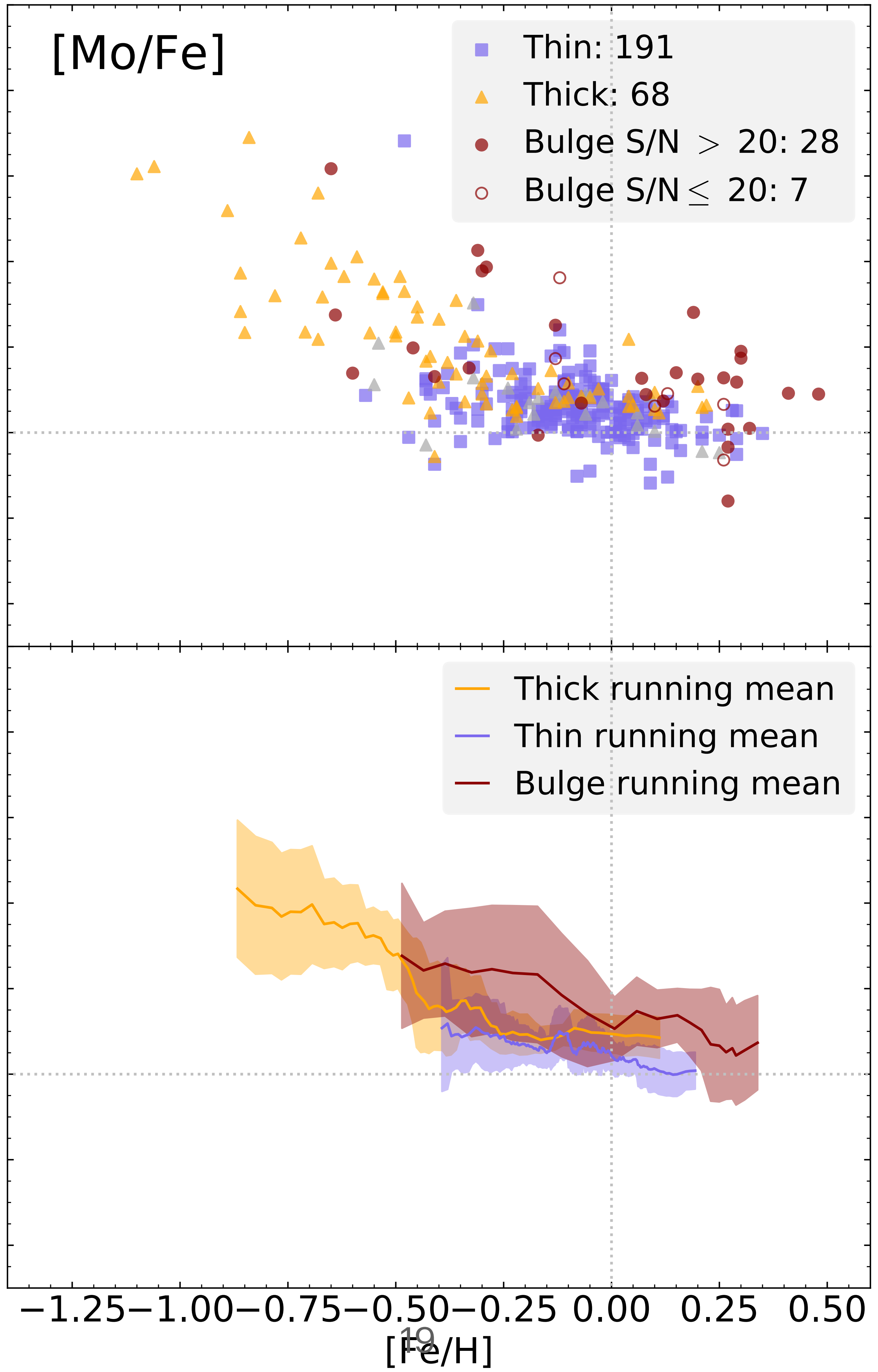
The Mo abundances



183 dwarf stars
Mishenina et al. 2019

Molybdenum in the Disk + Bulge

Forsberg et al. 2019,
s-process



Forsberg et al. 2019,
r-process

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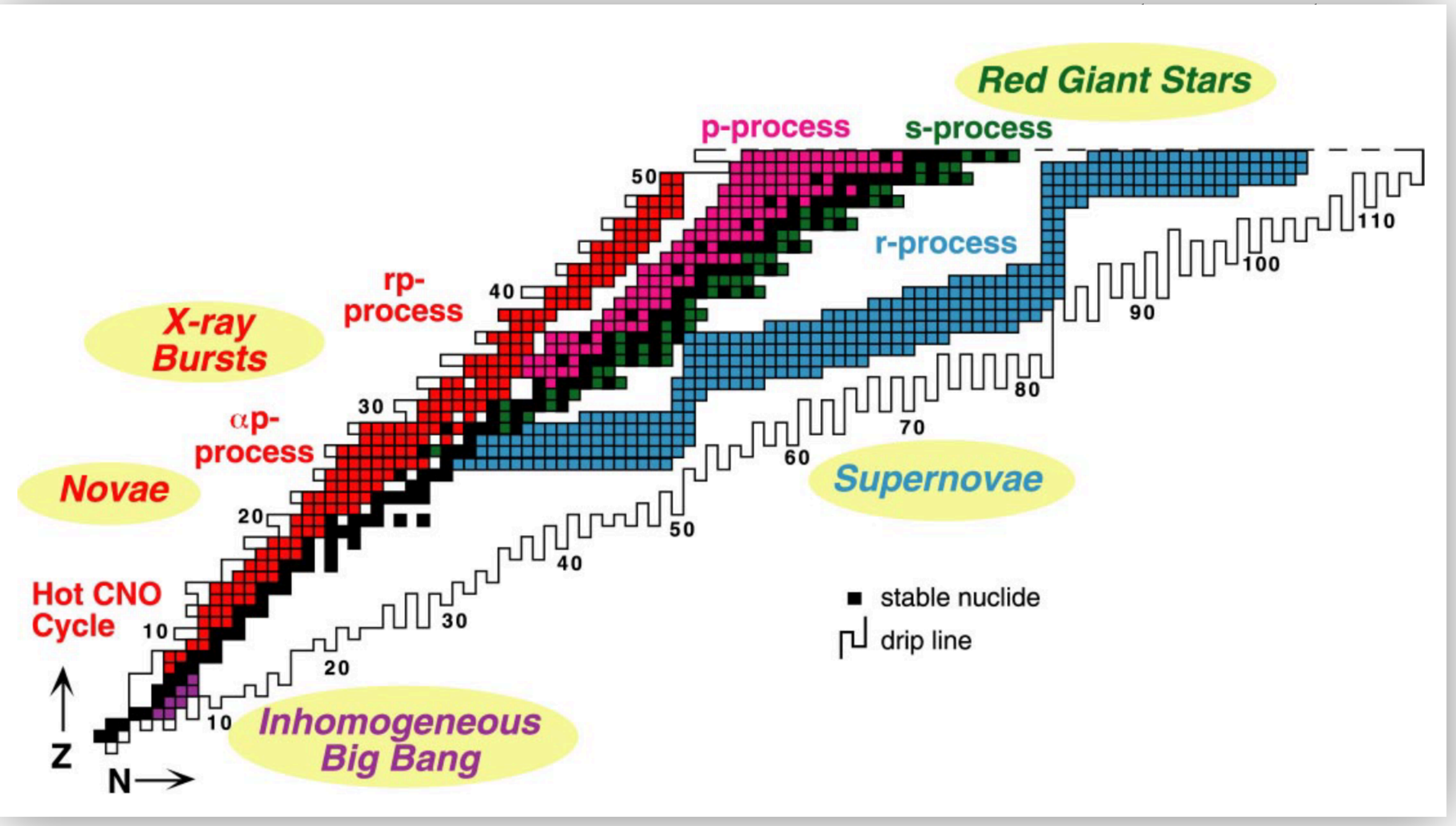


~~For WD or SNe origin: should behave like a typical alpha- and iron-peak element~~

~~Do not see a difference in disk/bulge in these elements!~~

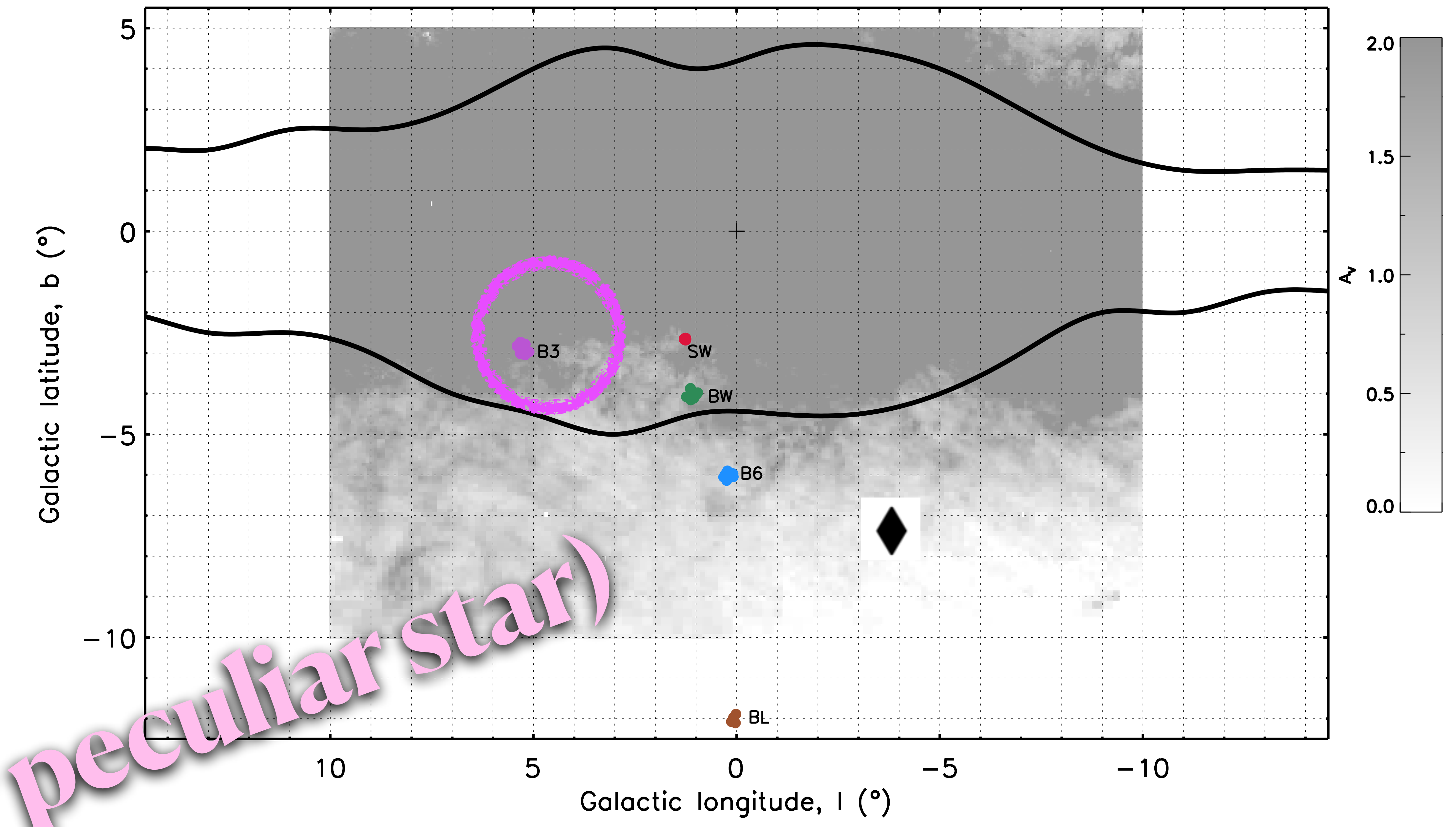
H+He burning on mass accreting neutron stars (rp-process)

But why would we see that in the bulge…?

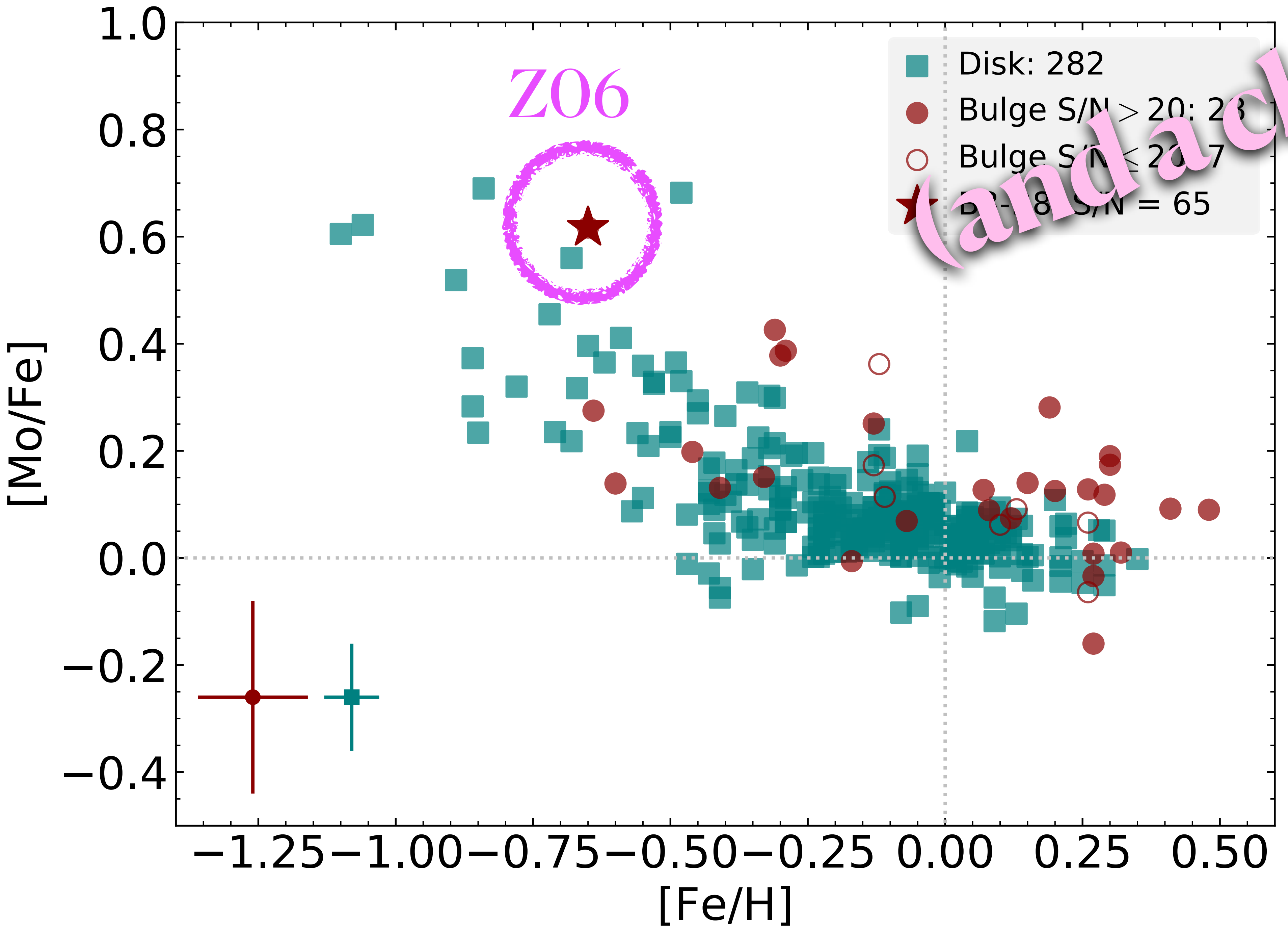
First *r*-process enhanced star confirmed as a member of the Galactic bulge

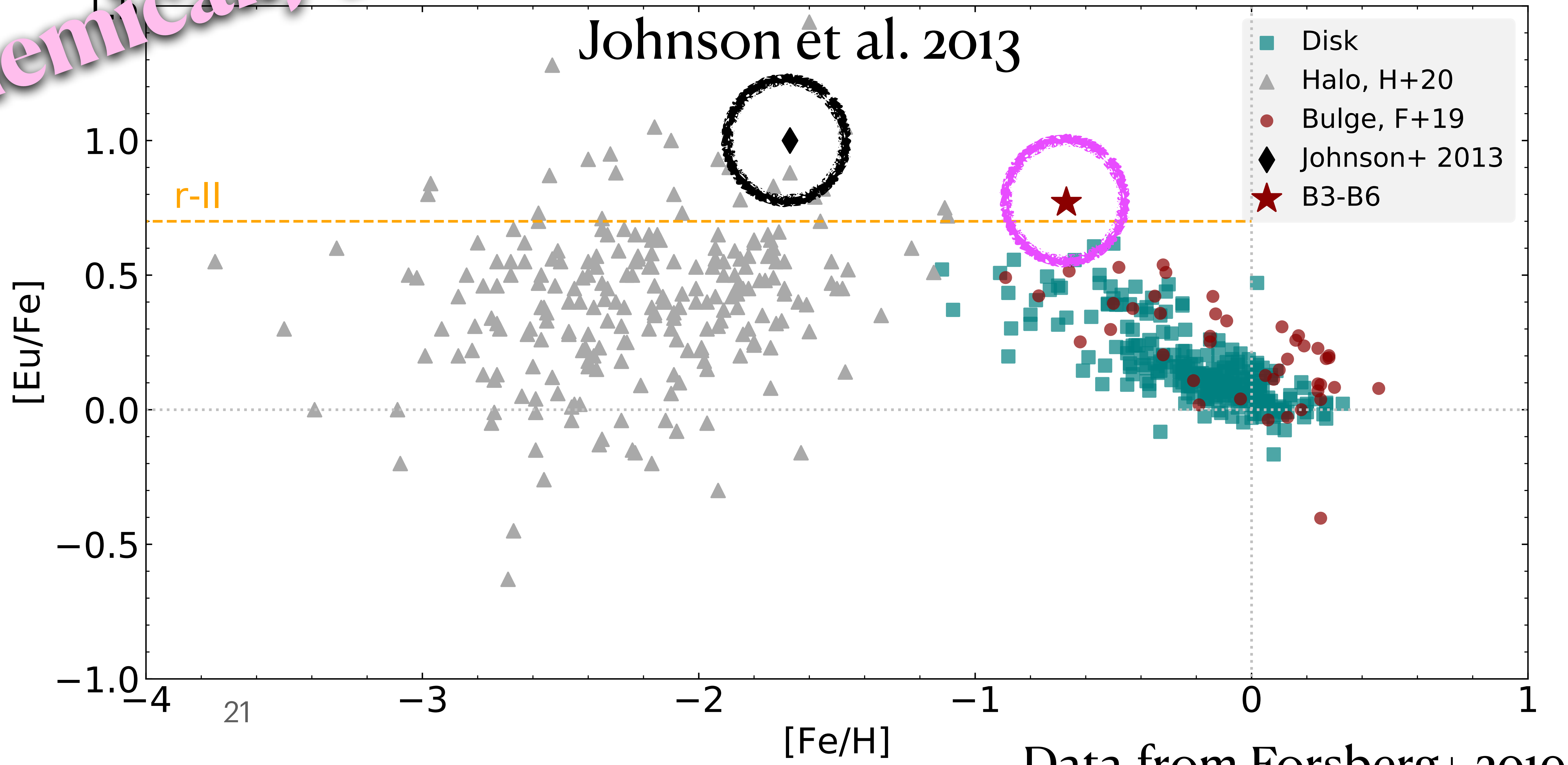
R. Forsberg[1], R. M. Rich[2,3], N. Nieuwmunster[1,3], H. Jönsson[4], M. Schultheis[3], N. Ryde[1], and B. Thorsbro[1,5]

- What are these? In literature [Eu/Fe] > 0.7 (Holmbeck et al. 2020, r-process alliance)
- Some 300 have been observed in disk + halo



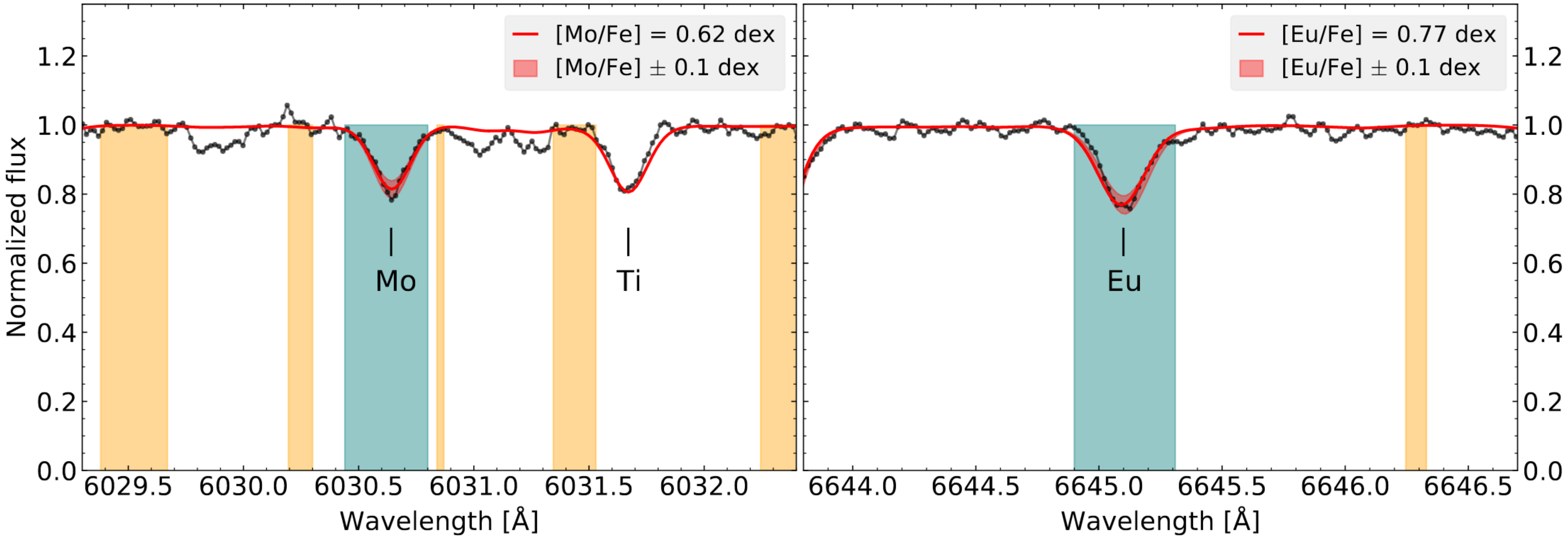
(and a chemically peculiar star)





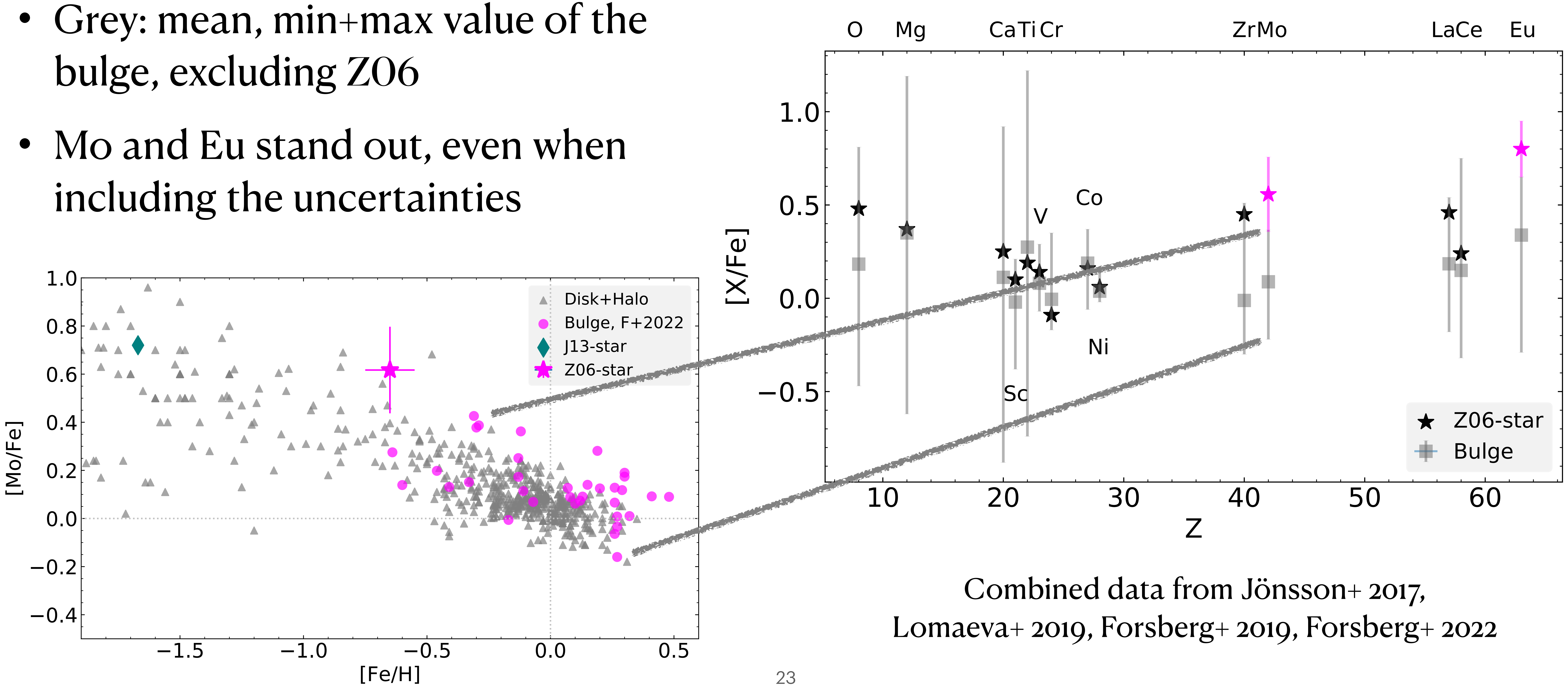
Data from Forsberg+ 2019

Z06 in Mo and Eu



Z06 in 14 elements from Jönsson series

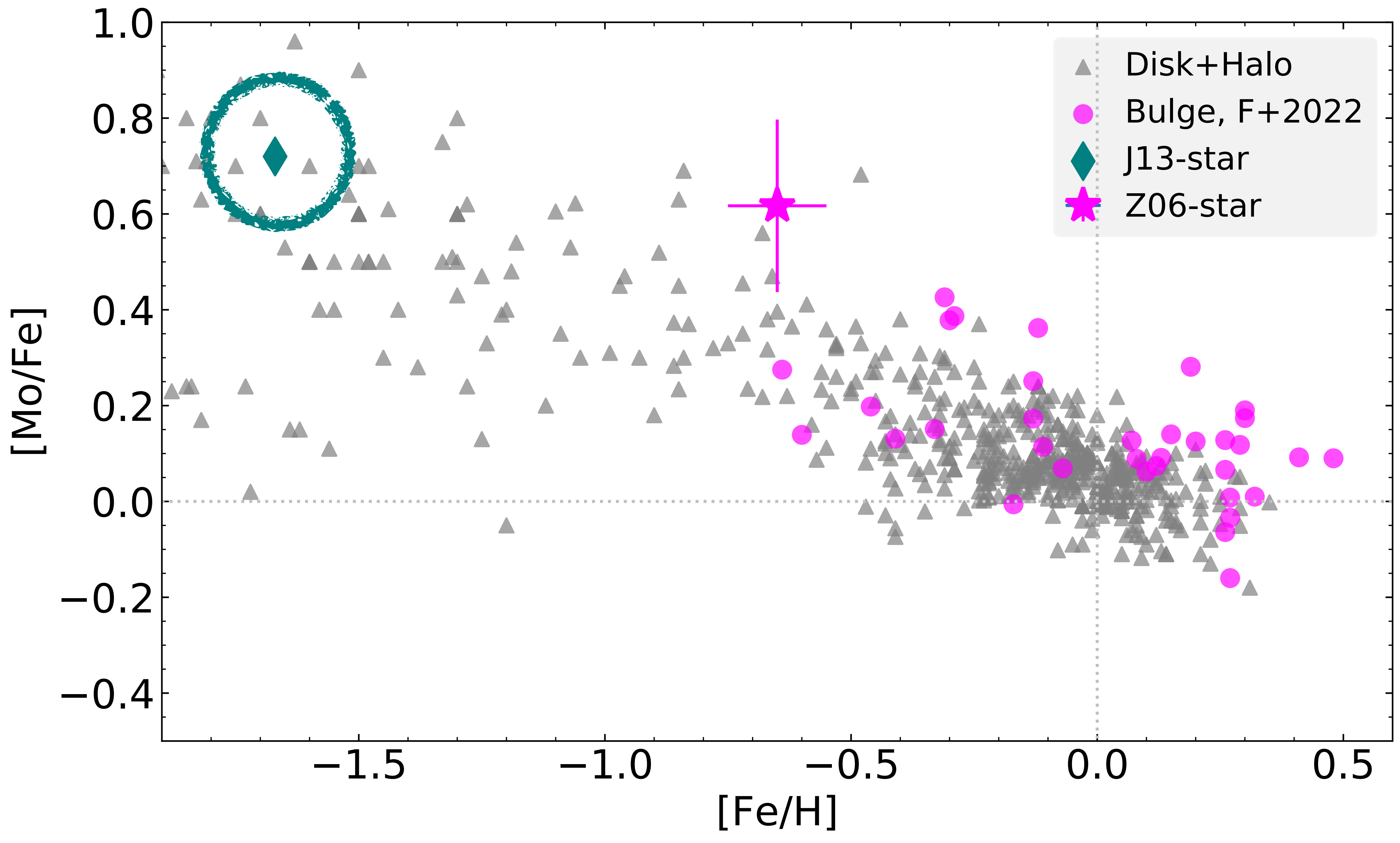
- Grey: mean, min+max value of the bulge, excluding Z06
- Mo and Eu stand out, even when including the uncertainties

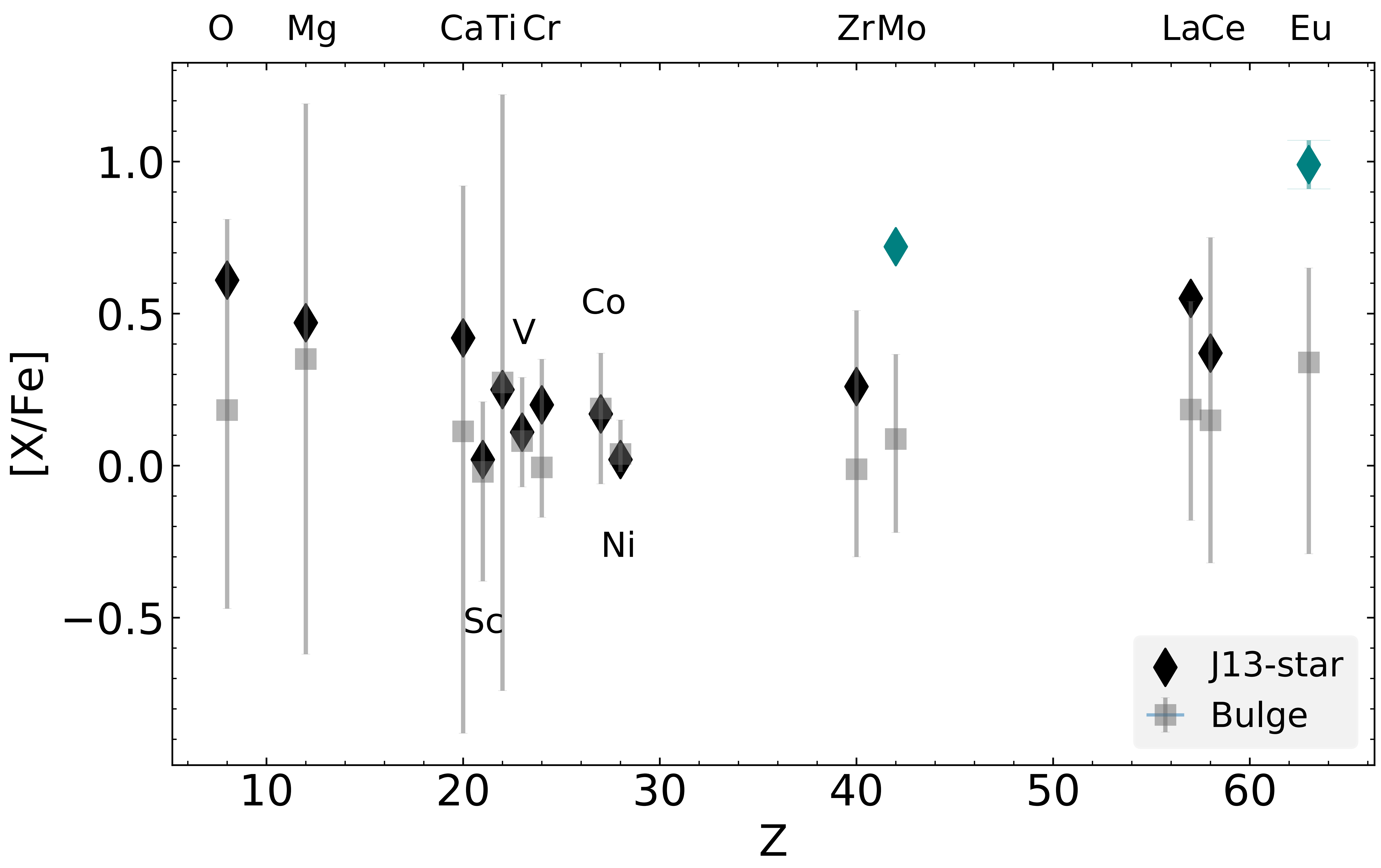


Combined data from Jönsson+ 2017, Lomaeva+ 2019, Forsberg+ 2019, Forsberg+ 2022

J13 star in 14 elements, Johnson et al. 2013

- Grey: mean, min+max value of the bulge, excluding J13
- Mo and Eu stand out





Data from Johnson+ 2013, Jönsson+ 2017, Lomaeva+ 2019, Forsberg+ 2019, Forsberg+ 2022

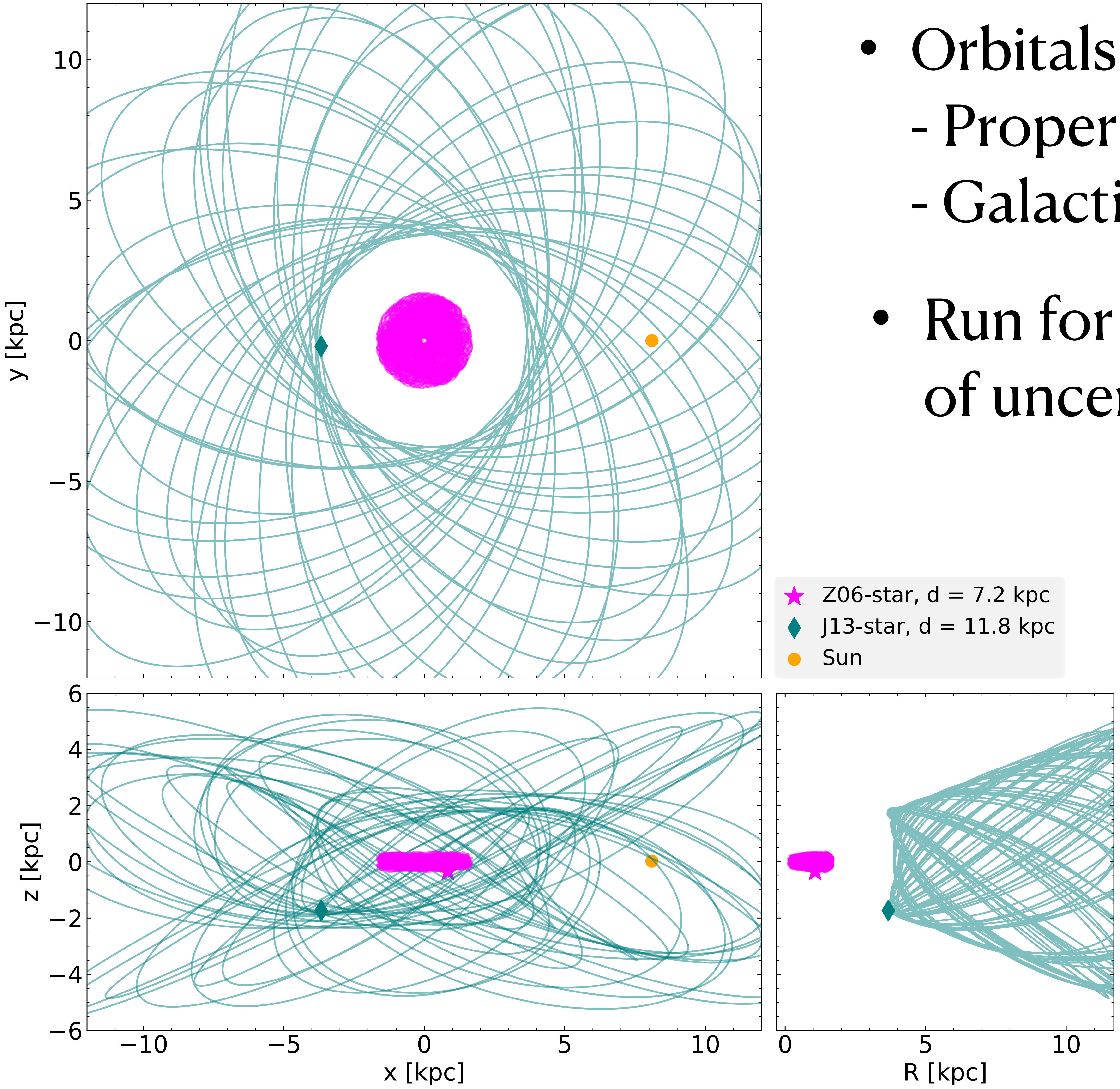
Bulge membership?

Mathias Schulteis in Nice

- Calculate spectrophotometric distances (following APOGEE, Majeski et al. 2017, Rojas-Arriagada et al. 2017a,b)
  —> by comparing to theoretical isochrones (PARSEC, Bressan et al. 2012, Marigo et al. 2017)
  to obtain the (probable) absolute magnitudes
  —> compare to the observed photometry to estimate line-of-sigh reddening and distances

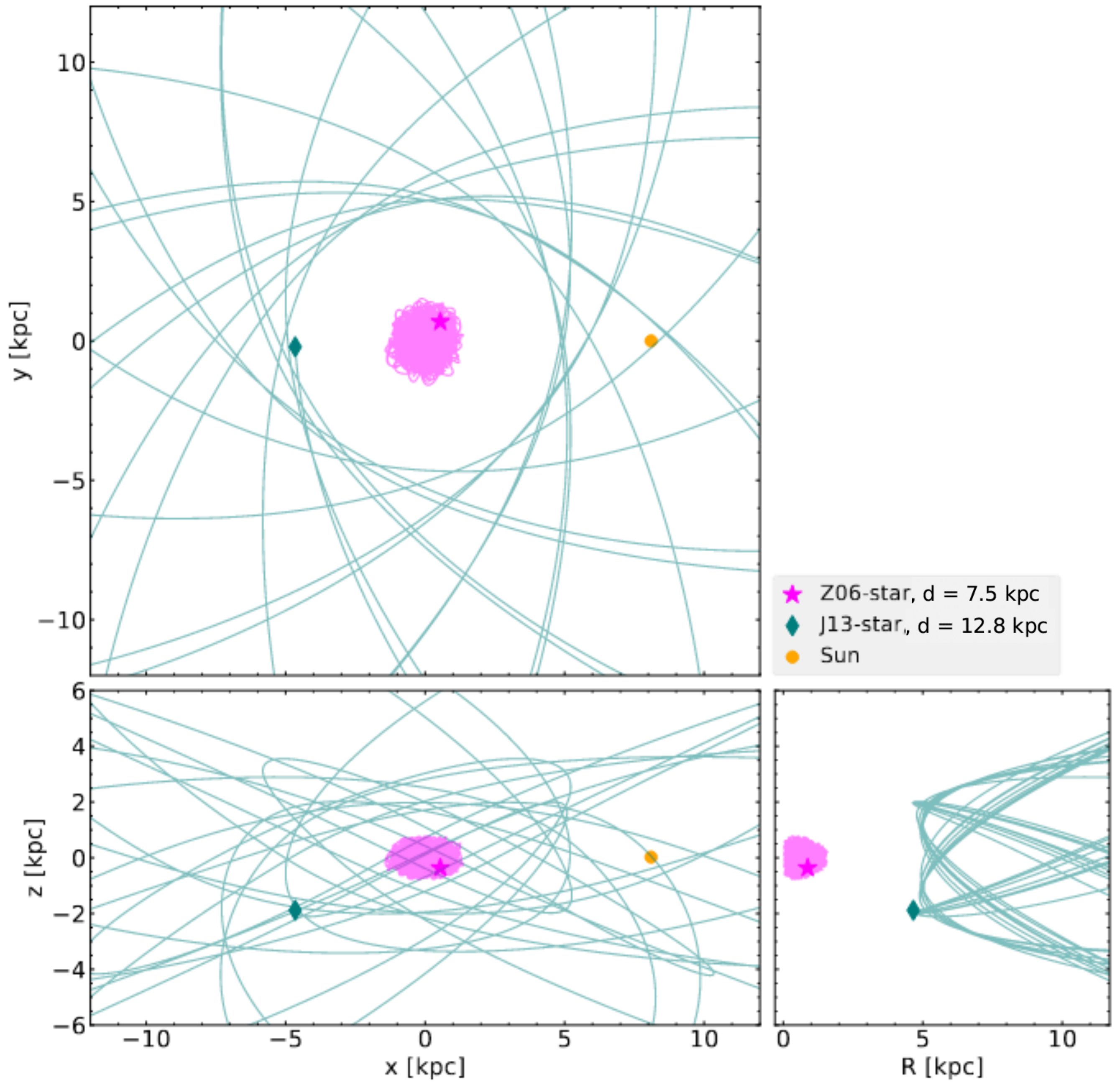
Properties	J13-star	Z06-star
(l,b) [deg]	(-1.0, -8.4)	(5.2, -2.8)
RA [deg]	274.438	272.10
Dec [deg]	-33.890	-25.812
J mag	11.686	12.255
H mag	11.034	11.395
K mag	10.955	11.130
Distance [kpc]	11.8 ± 1.0	7.2 ± 0.3
pm(ra) [mas/yr]	-3.734±0.023	-0.304 ±0.052
pm(dec) [mas/yr]	-9.512 ±0.018	-2.601 ±0.036
RV [km/s]	-16	-36

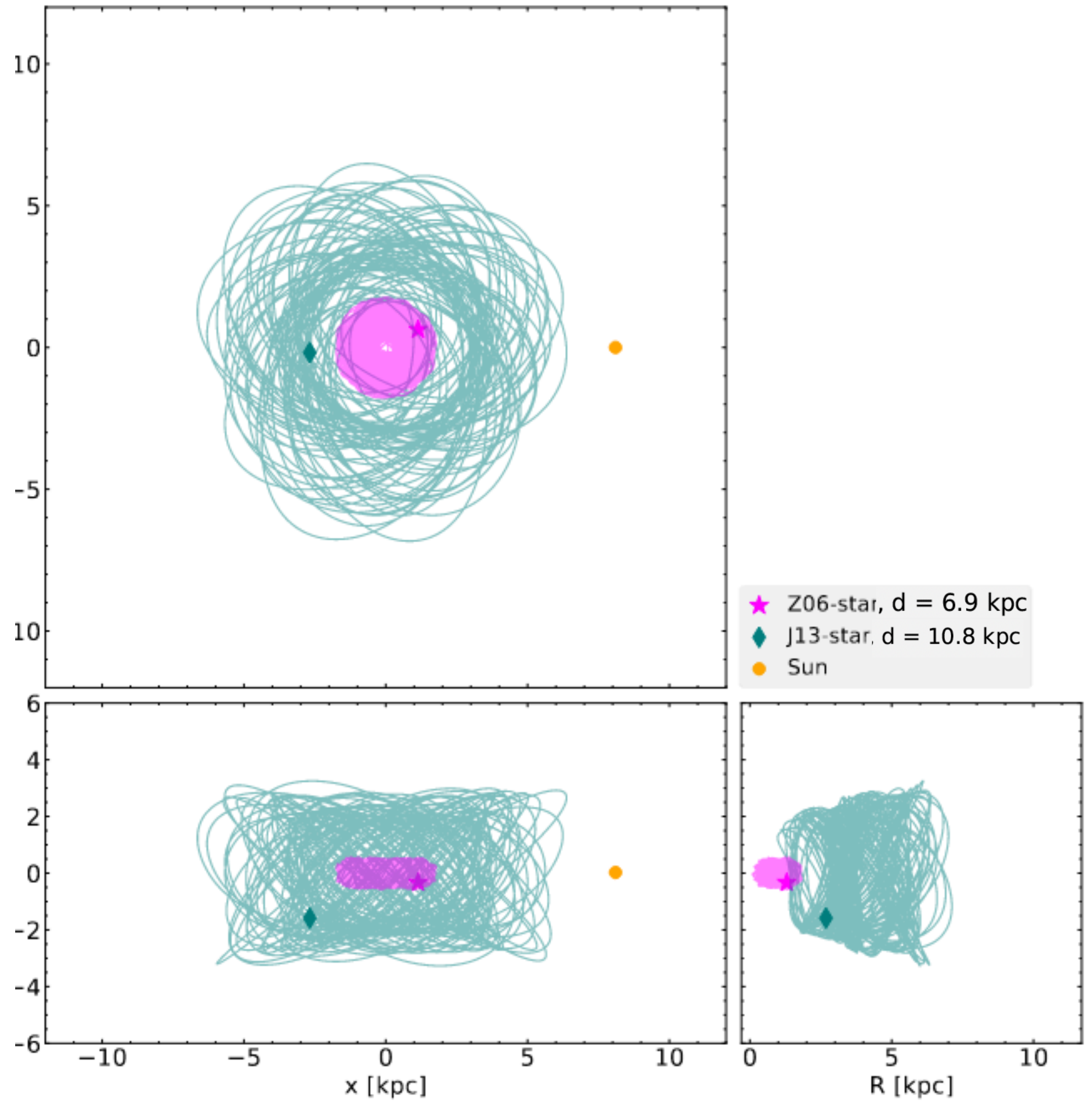
Bulge membership



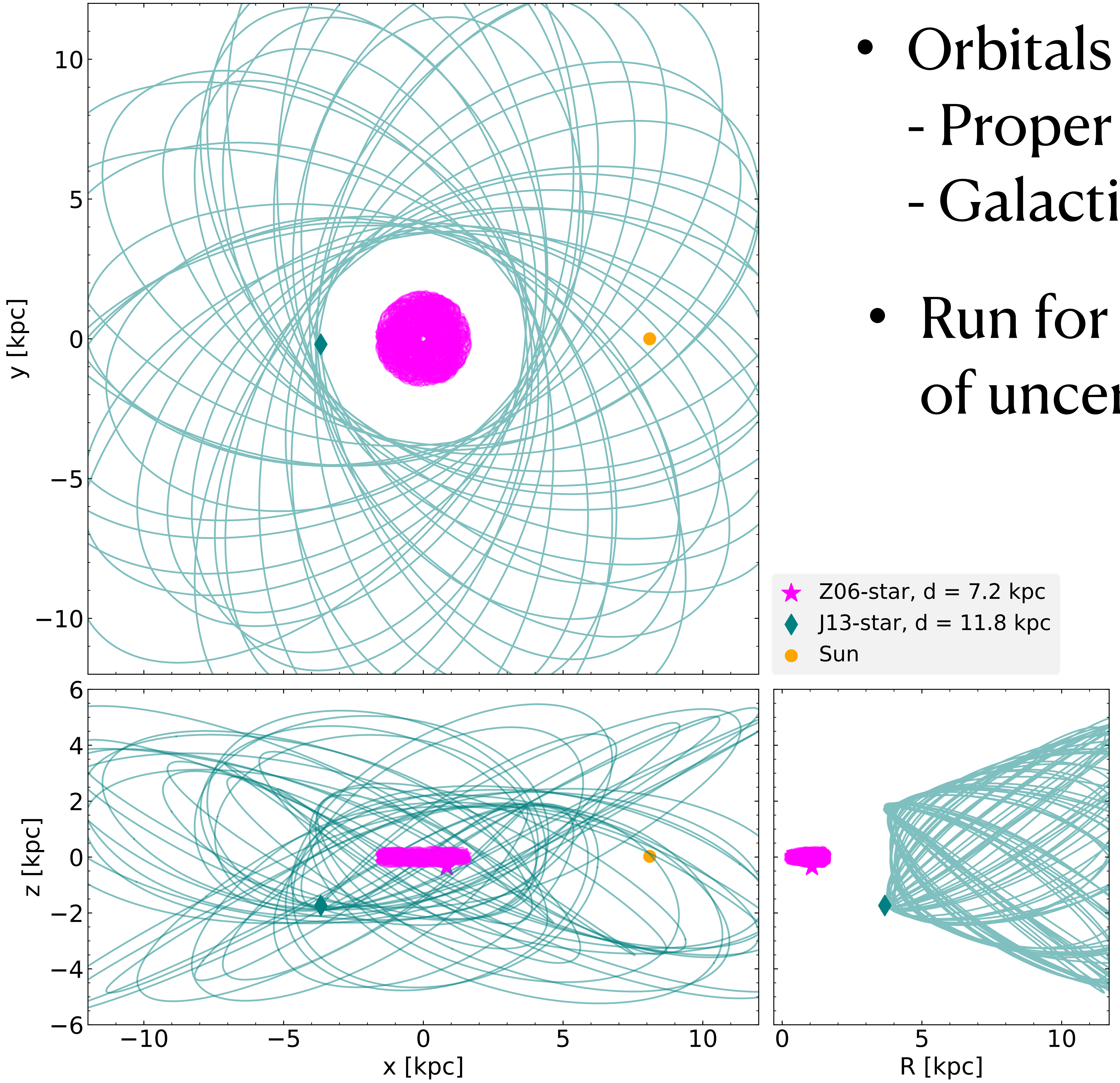
- Orbitals using galpy (Bovy 2015)
  - Proper motions Gaia DR3, RV from spectroscopy
  - Galactic potential: disk + bar (MW2014 disk, Dehnen bar)

- Run for 10 billion years, also with the most extreme cases of uncertainty in distance, PM





Bulge membership



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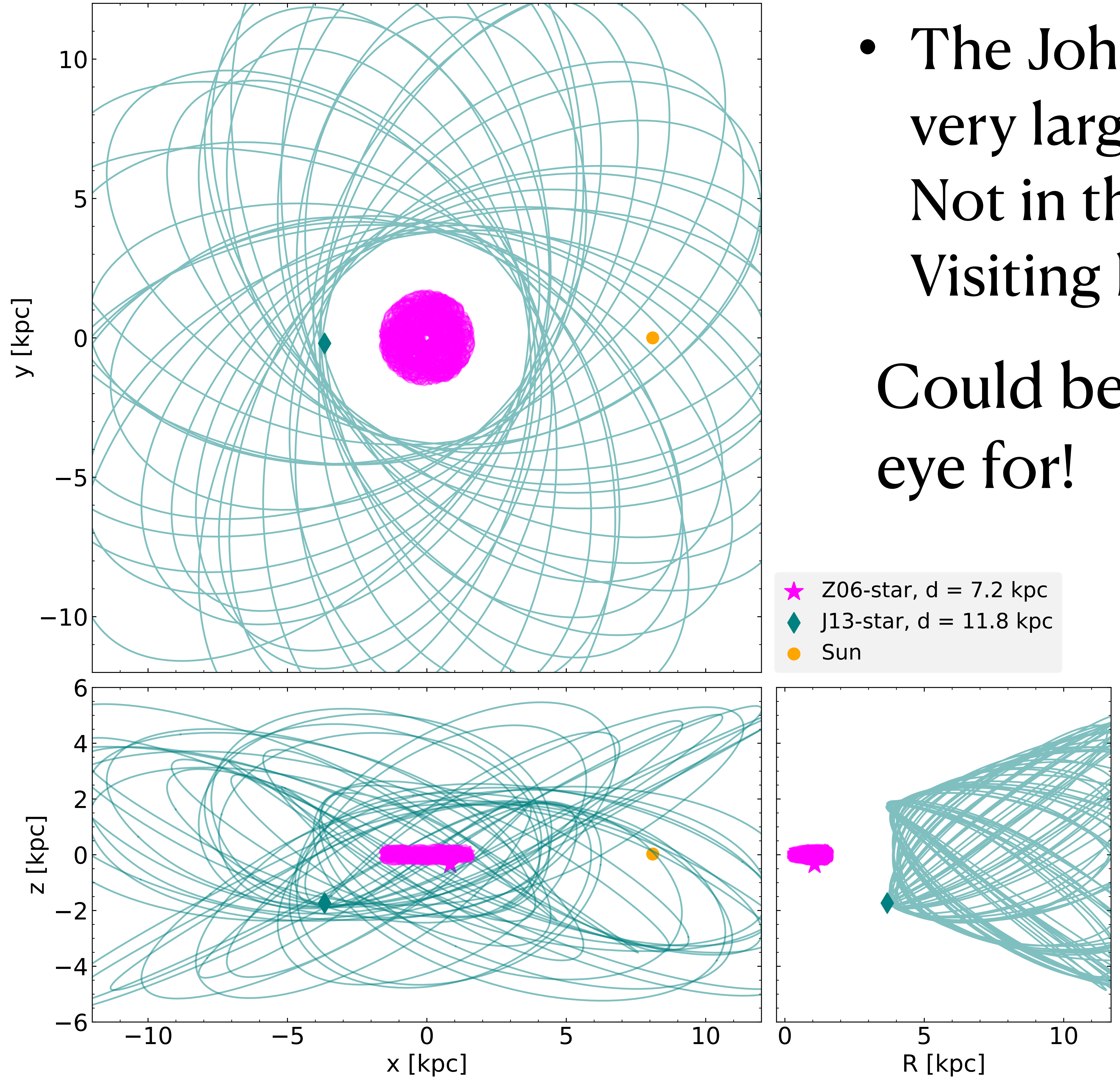
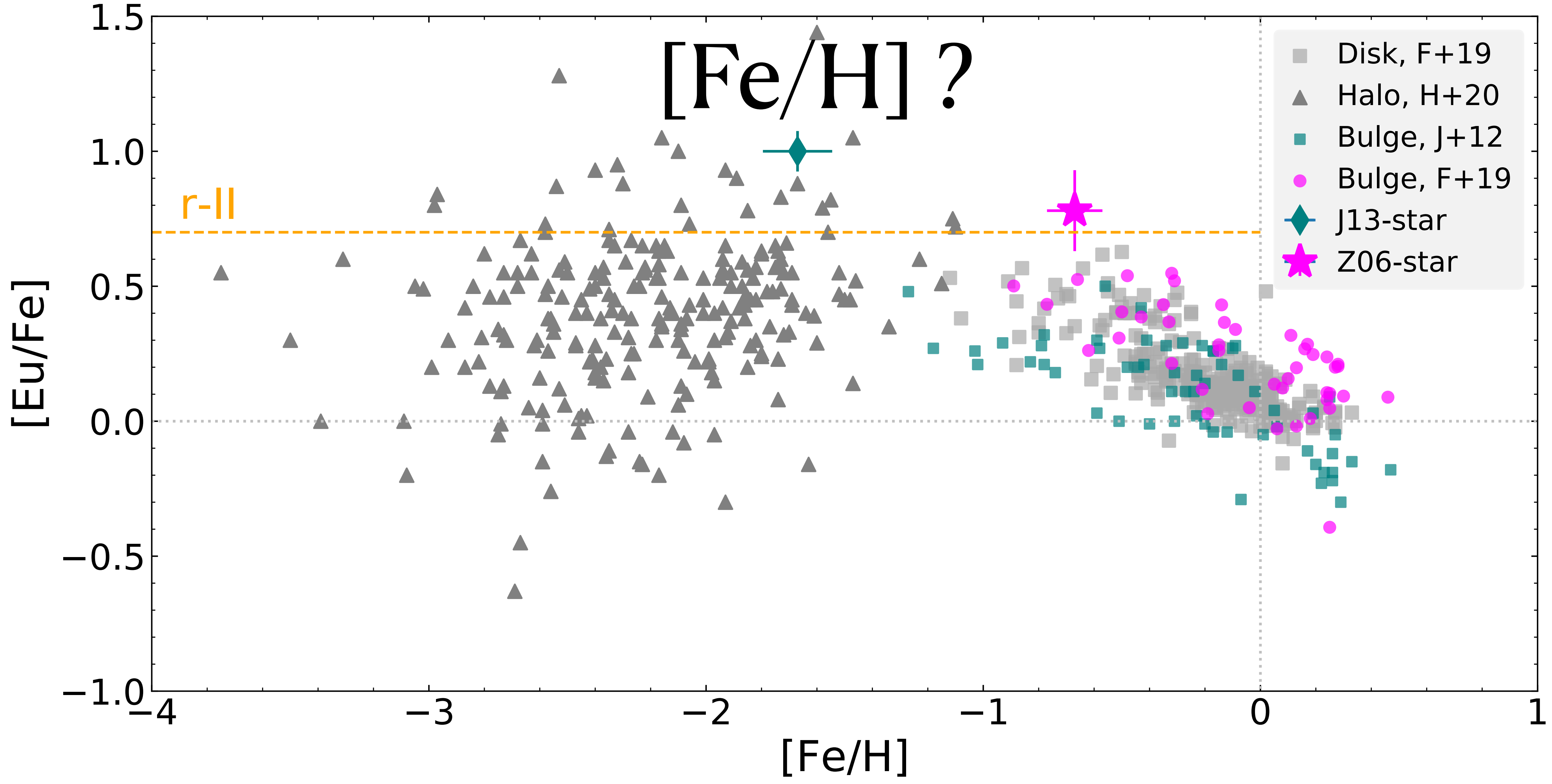
Bulge membership



- The Johnson+13 star found at 12 kpc away from Sun gives very large orbits
  Not in the bulge?
  Visiting halo/thick disk star?

Could be interesting group of stars to keep an open eye for!



Concluding remarks

- We are still not sure how and where all elements are formed
- Studying a variety of elements are key when studying and trying to understand our Galaxy
- Measured Mo from high-resolution giant spectra in the Disk, for the first time in the Bulge
- Find a chemically-peculiar star in the Bulge, that could be a part of an old, classical bulge

Thank you!

Rebecca Forsberg
Uppsala University – 27th April 2023