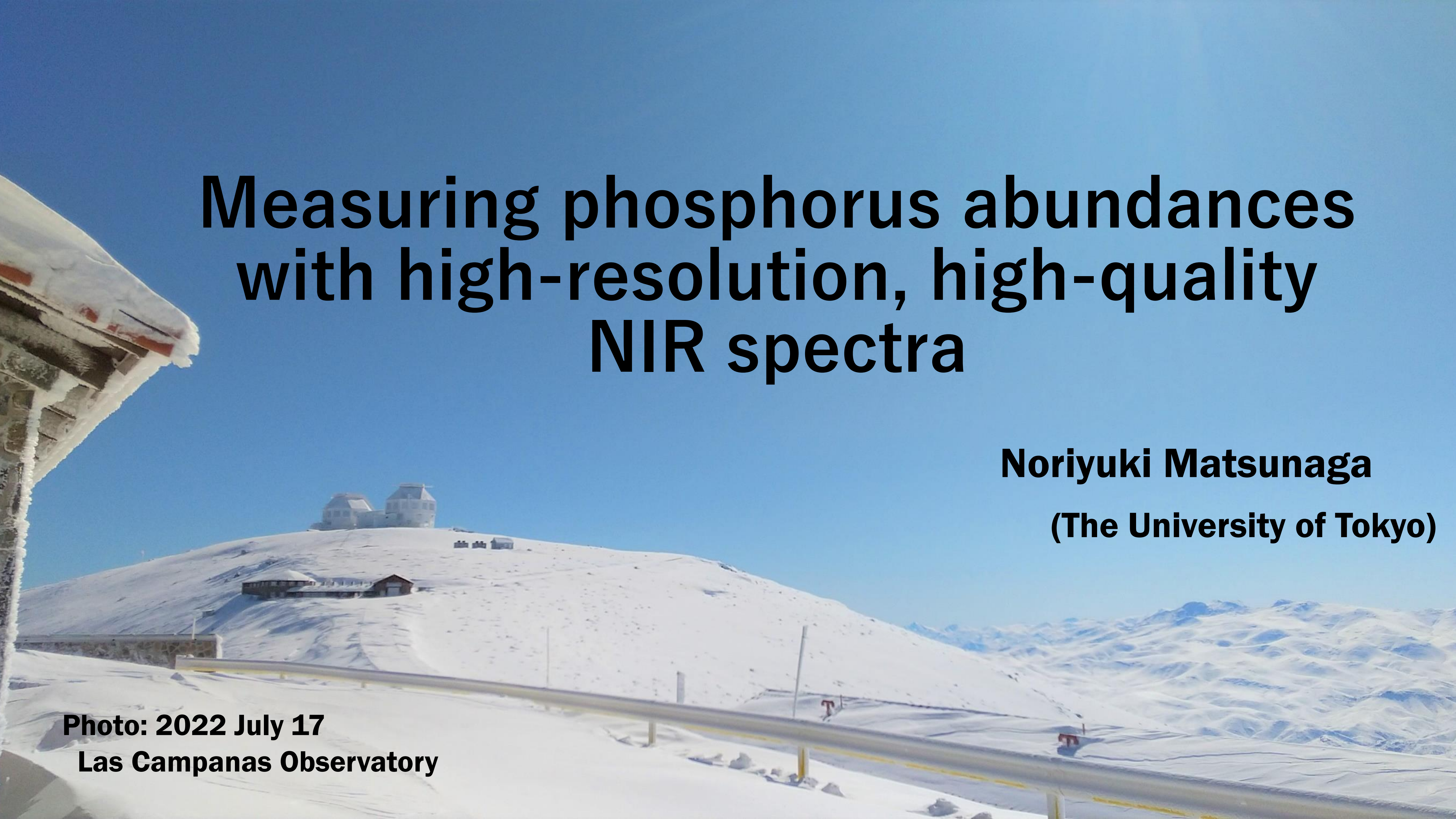
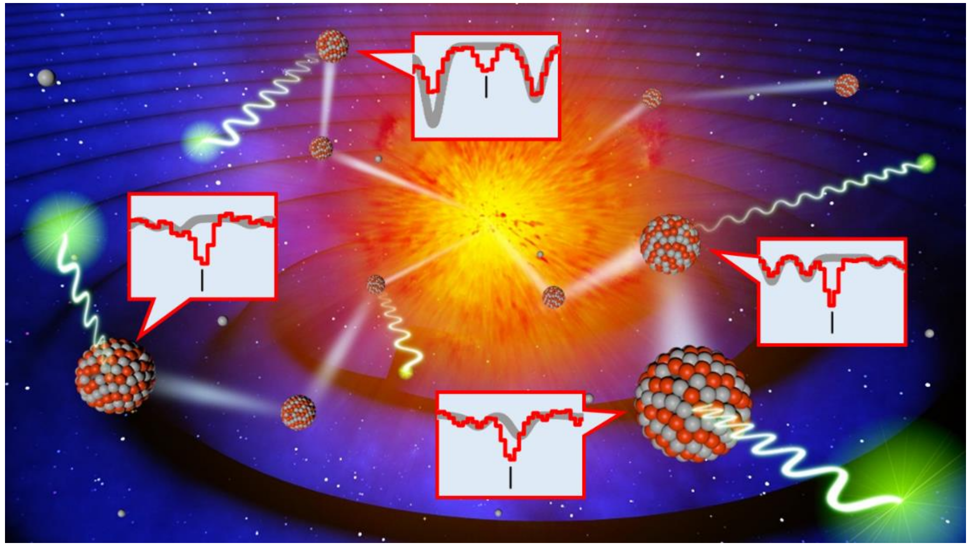


Measuring phosphorus abundances with high-resolution, high-quality NIR spectra

Noriyuki Matsunaga
(The University of Tokyo)

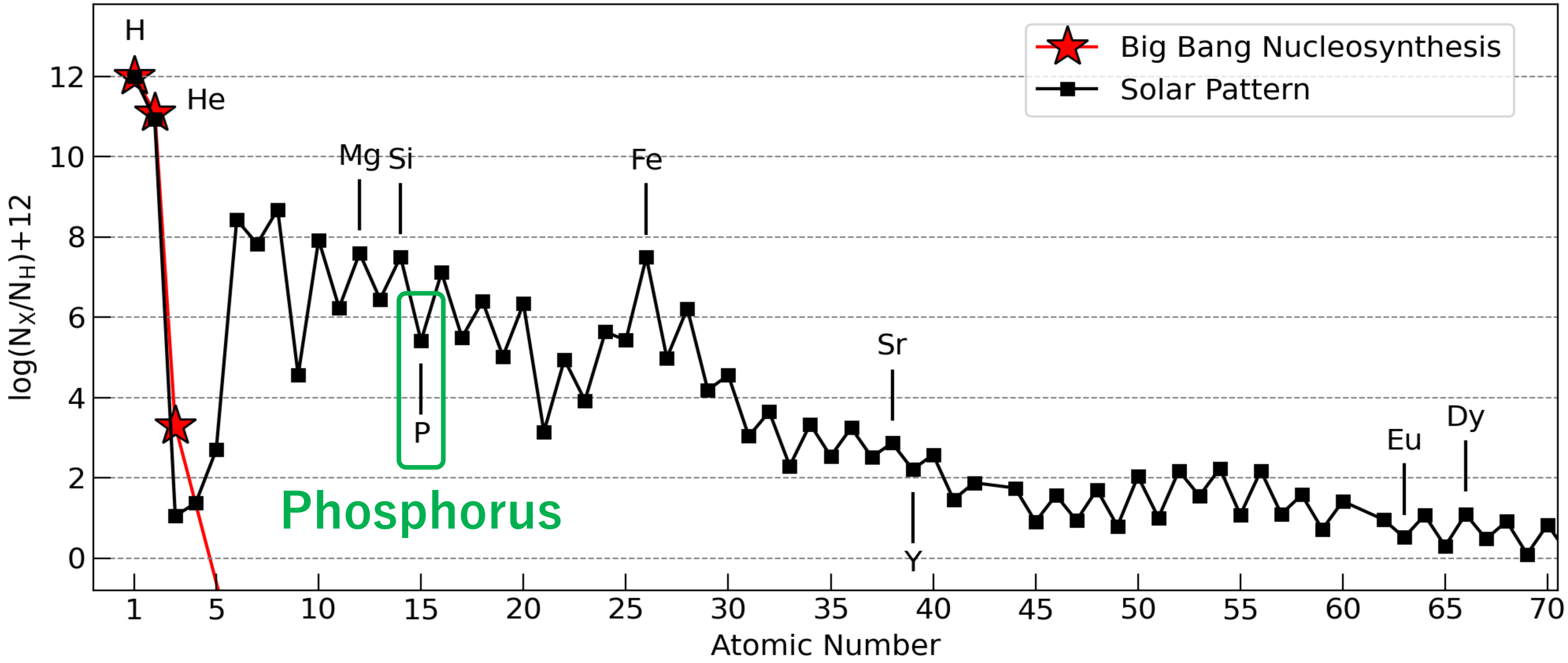
Photo: 2022 July 17
Las Campanas Observatory

Background and goals



Cosmic elementary abundance

After the Big Bang nucleosynthesis, astronomical objects like supernovae have synthesized all the heavy elements (heavier than Li).



Phosphorus

- One of the main elements building up life, but measurements in astronomical objects have been limited.
- Nucleosynthesis process and responsible sites haven't been established well.
  - Mainly in massive stars: hydrostatic C, Ne burning and/or core-collapse supernovae
  - Contribution of Ia-type supernovae and classical novae?

Maciá et al. (2005)

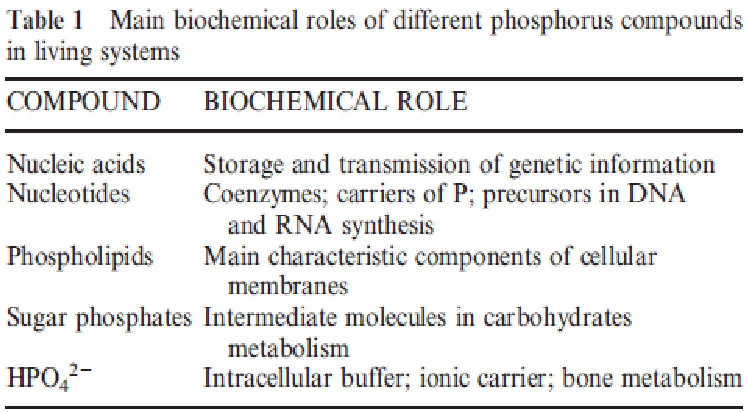
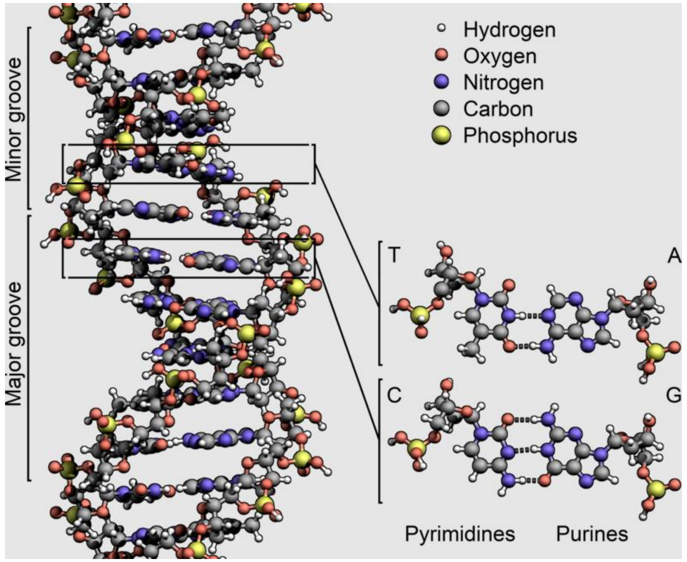


Table 1 Main biochemical roles of different phosphorus compounds in living systems

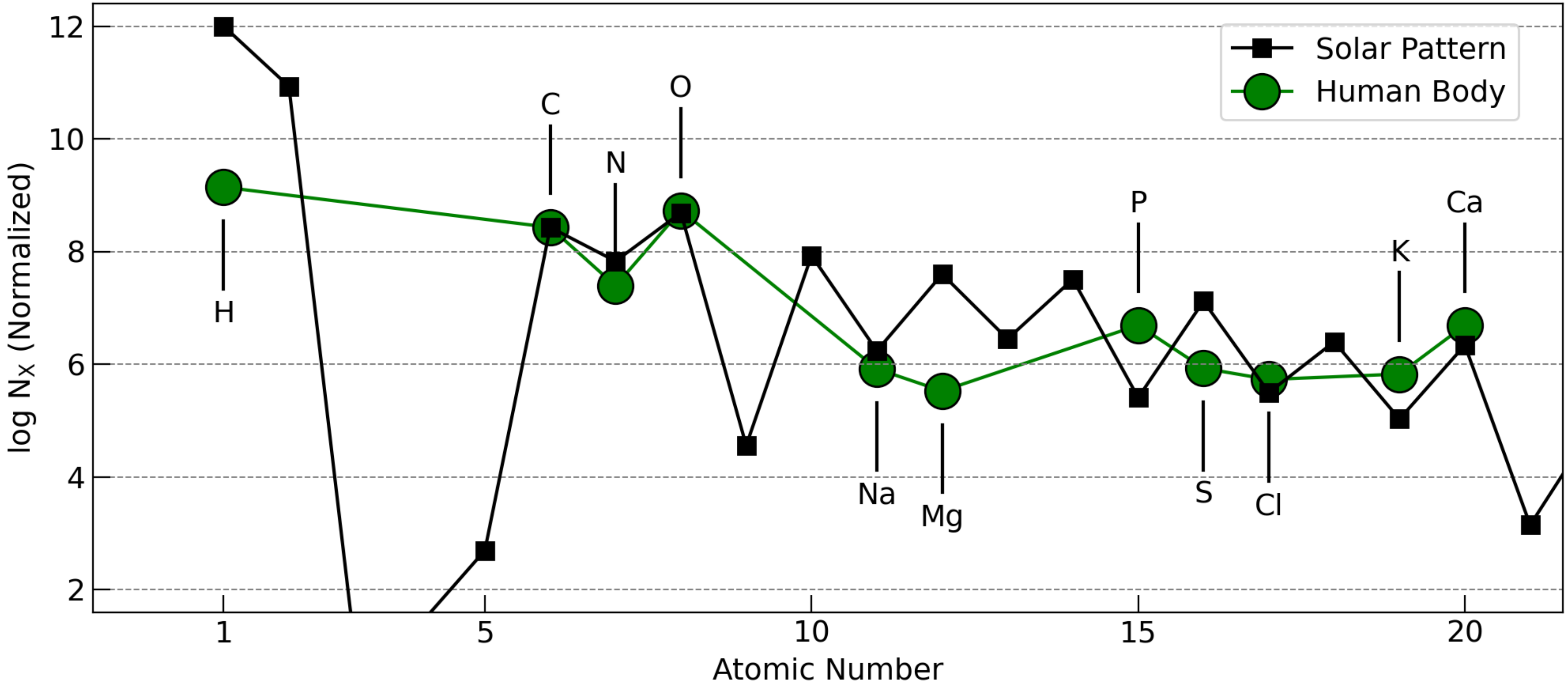
COMPOUND	BIOCHEMICAL ROLE
Nucleic acids	Storage and transmission of genetic information
Nucleotides	Coenzymes; carriers of P; precursors in DNA and RNA synthesis
Phospholipids	Main characteristic components of cellular membranes
Sugar phosphates	Intermediate molecules in carbohydrates metabolism
HPO_4^{2-}	Intracellular buffer; ionic carrier; bone metabolism



DNA's structure
(by Zephyris from Wikipedia)

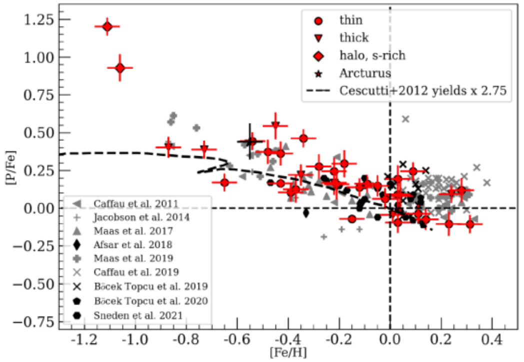
Concentration of phosphorus in life

- Phosphorus is 18th abundant in the universe but 5th abundant in life.



Phosphorus evolution in Galaxy

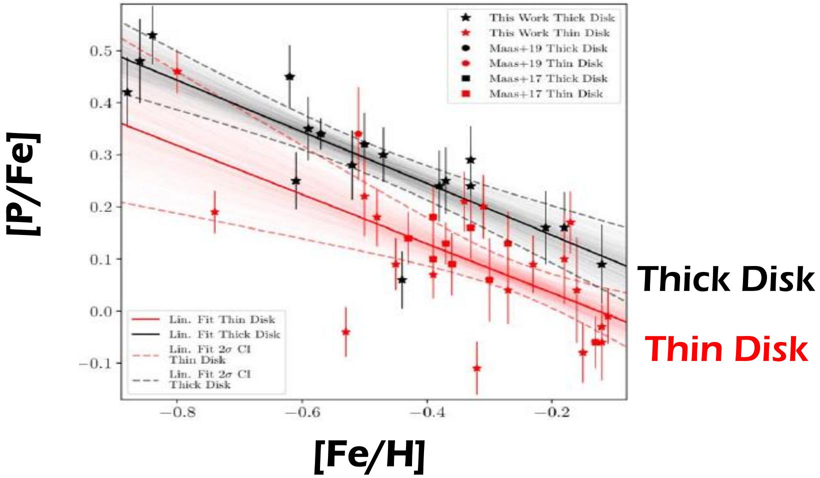
- Number of measurements still limited and targets are mainly within ~200 pc.
- The trends looks similar to **α**, but large uncertainties remain.
  - Artificial offsets in log gf needed to match [P/Fe] with [**α**/**Fe**].

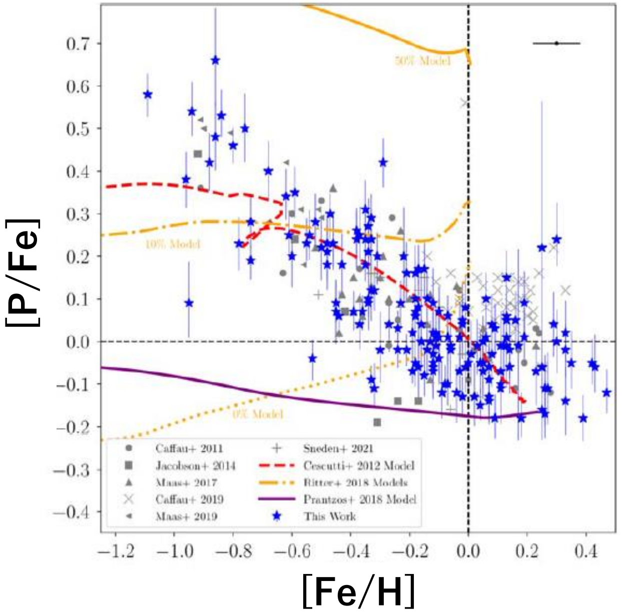


Nandakumar et al. (2022)

Maas et al. (2022)

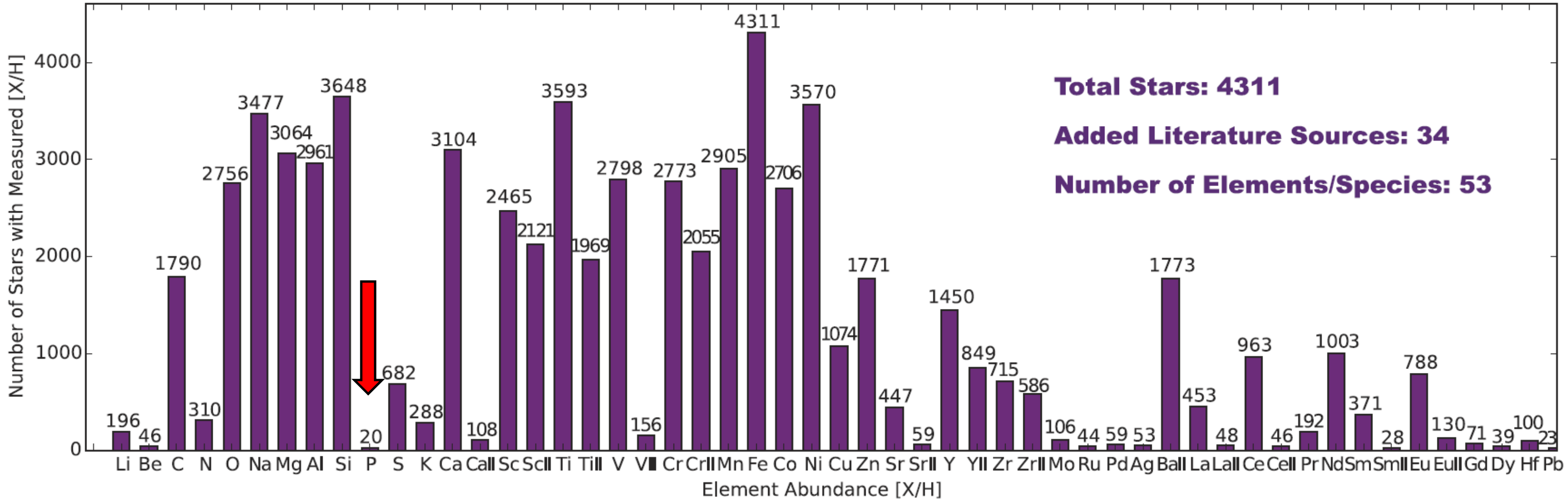
163 FGK-type stars with Y-band spectra (HPF@HET)





Observational limitation

- No neutral phosphorus line in optical spectra.
  - Ionic P lines in hot stars and chemically peculiar stars are observed, but not simple to use them.
- Found in late-type stars are only in UV (2100～2600 Å) and near-IR (Y and H bands).

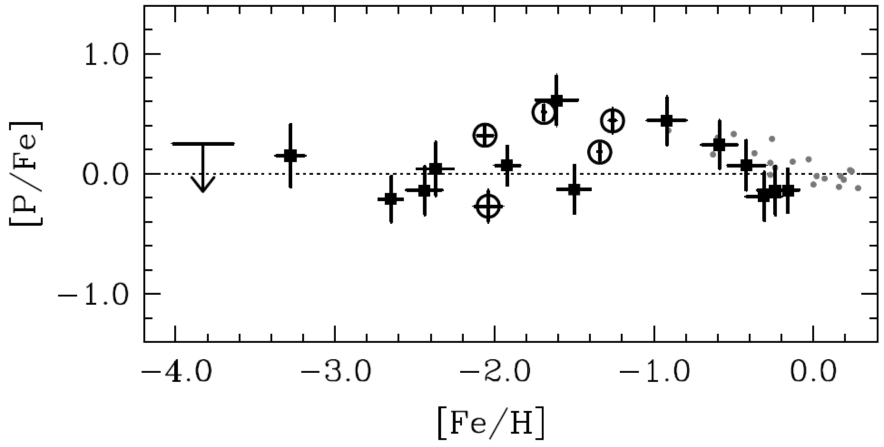


Number of stars with each element measured in Hypatia Catalog 2.0 (FGK stars within 150 pc; Hinkel+14)

P lines in UV

- UV neutral P lines (2100~2600 Å) can be detected even in extremely metal-poor stars.
- No observational access from the ground.

Roederer et al. (2014)



HST/STIS

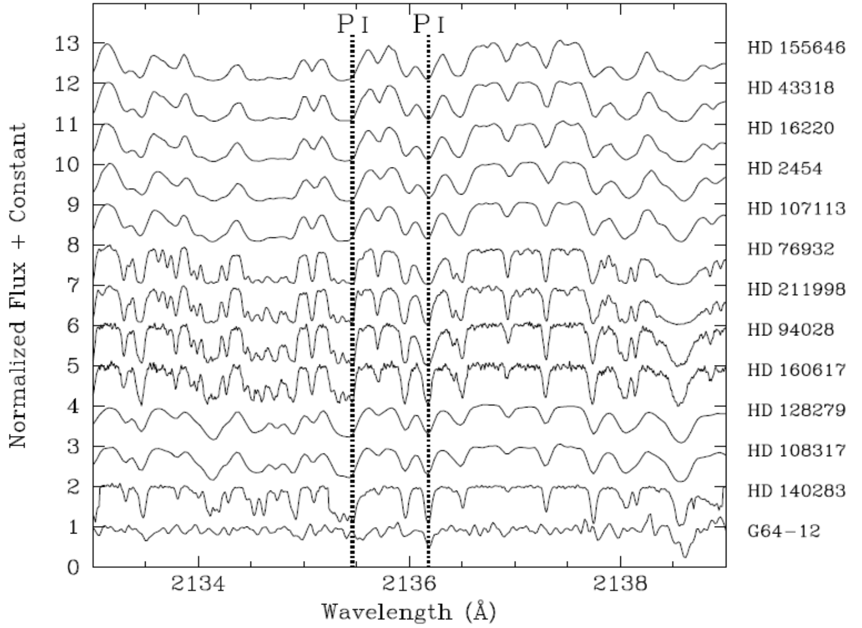
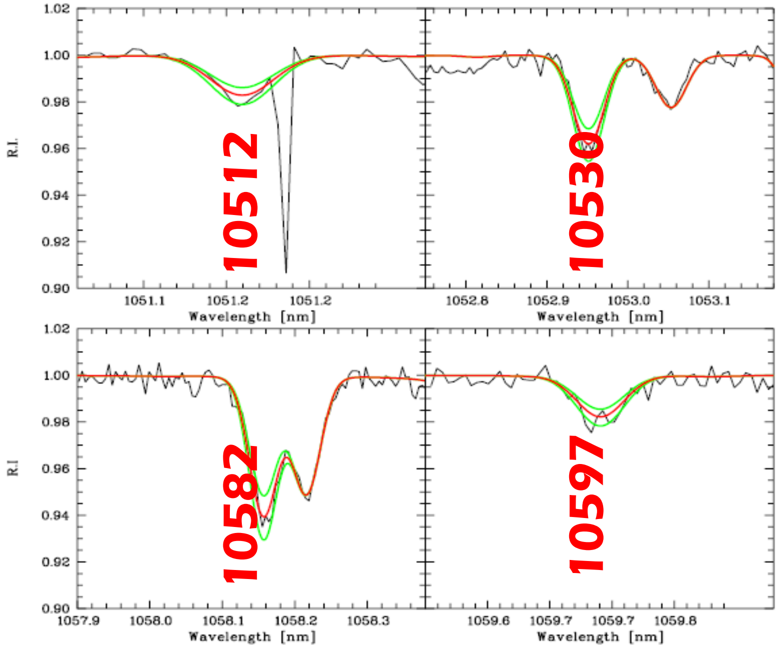


Figure 1. Spectral region surrounding the P I 2135.46 and 2136.18 Å lines. The STIS spectra have been shifted vertically by adding a constant to the normalized flux values. The stars are ordered by decreasing metallicity from top to bottom. The relatively clean region of continuum from 2136.6–2136.8 Å, which we use to match our observed and synthetic spectra (see Section 6), is apparent.

P lines in Y and H bands

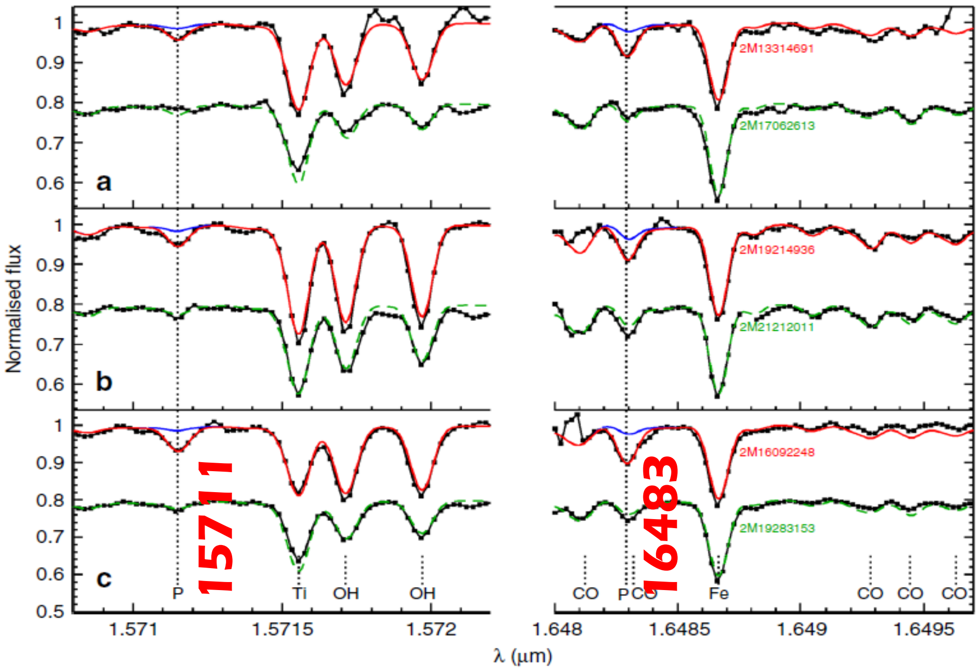
- A few lines in each of Y and H
- All of them are shallow, requiring S/N~100 even for solar-metal stars.

Y band



Caffau et al. (2011)

H band

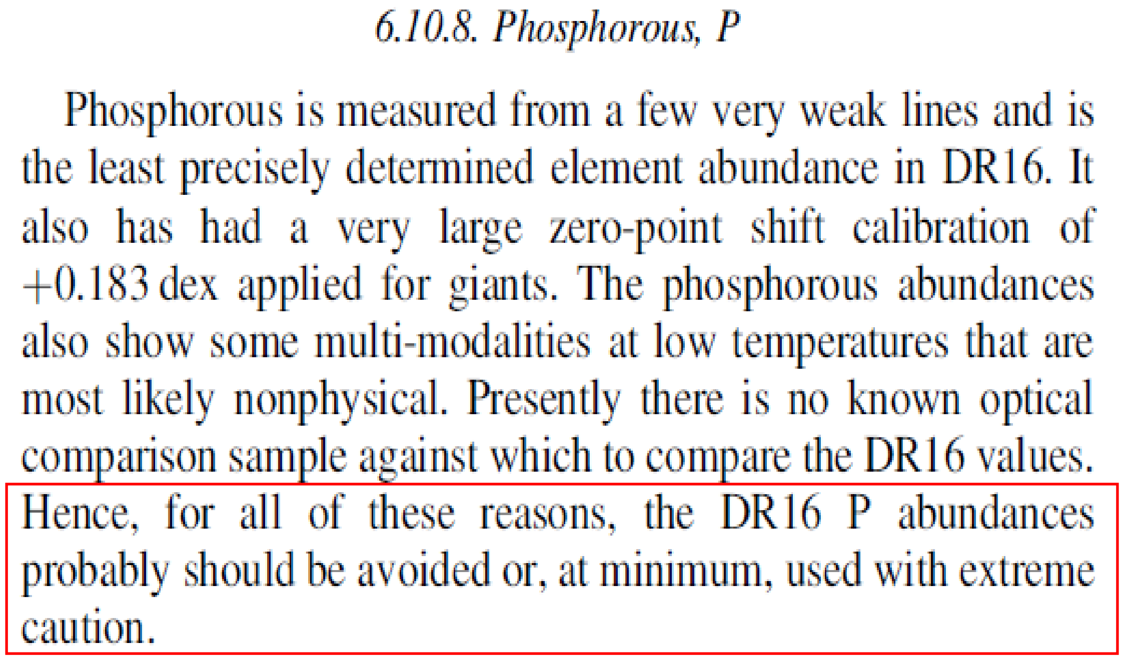


Masseron et al. (2020)

Phosphorus in APOGEE

P abundances given in DR16 but with low precision.

Jonsson et al. (2020)

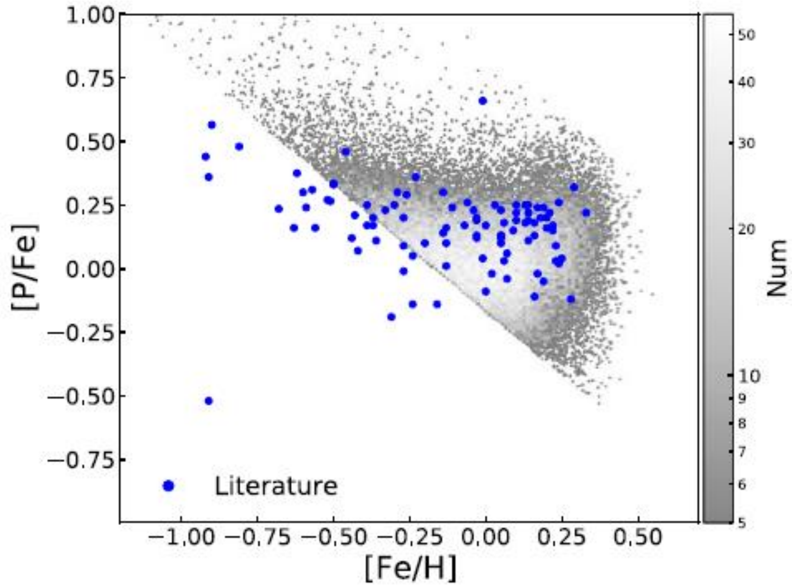


6.10.8. Phosphorous, P

Phosphorous is measured from a few very weak lines and is the least precisely determined element abundance in DR16. It also has had a very large zero-point shift calibration of +0.183 dex applied for giants. The phosphorous abundances also show some multi-modalities at low temperatures that are most likely nonphysical. Presently there is no known optical comparison sample against which to compare the DR16 values. Hence, for all of these reasons, the DR16 P abundances probably should be avoided or, at minimum, used with extreme caution.

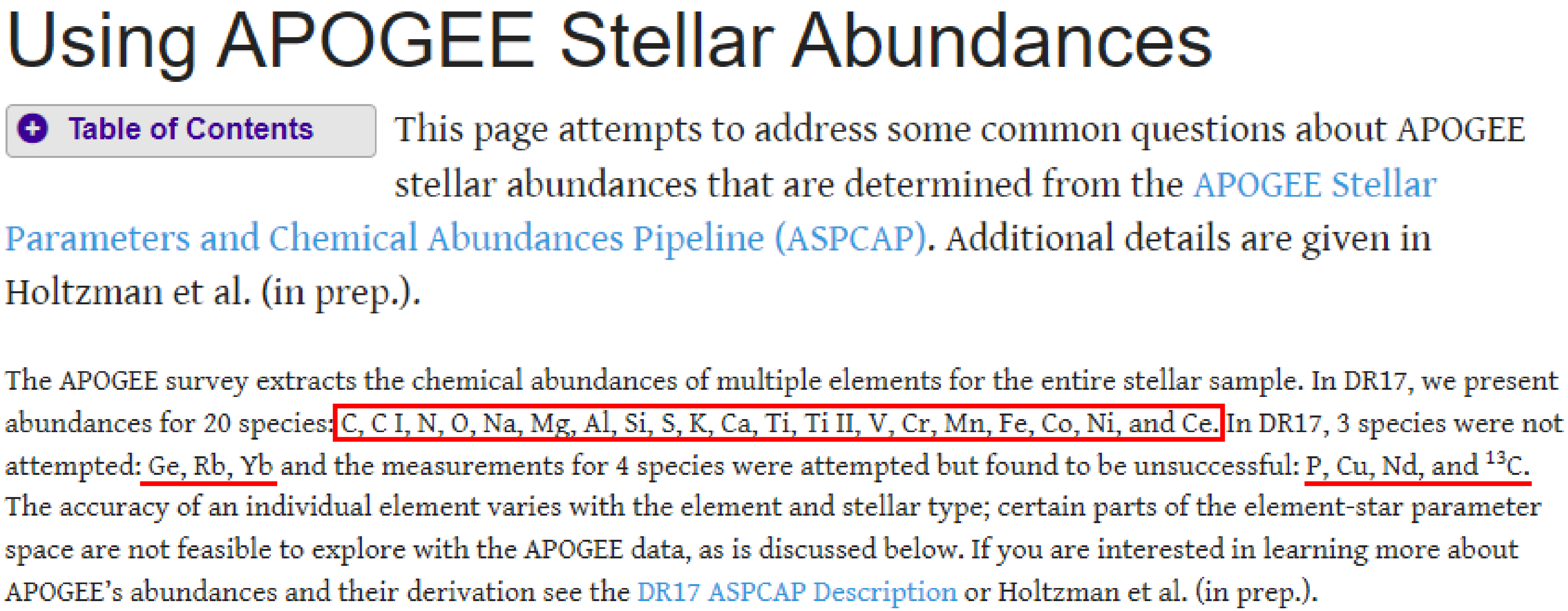
Hayes et al. (2022)

- Improvements in handling weak lines in the APOGEE spectra, but the precision is still unclear.



Phosphorus in APOGEE (DR17)

Phosphorus and some elements excluded in DR17.



Using APOGEE Stellar Abundances

This page attempts to address some common questions about APOGEE stellar abundances that are determined from the APOGEE Stellar Parameters and Chemical Abundances Pipeline (ASPCAP). Additional details are given in Holtzman et al. (in prep.).

The APOGEE survey extracts the chemical abundances of multiple elements for the entire stellar sample. In DR17, we present abundances for 20 species: C, C I, N, O, Na, Mg, Al, Si, S, K, Ca, Ti, Ti II, V, Cr, Mn, Fe, Co, Ni, and Ce. In DR17, 3 species were not attempted: Ge, Rb, Yb and the measurements for 4 species were attempted but found to be unsuccessful: P, Cu, Nd, and ^{13}C. The accuracy of an individual element varies with the element and stellar type; certain parts of the element-star parameter space are not feasible to explore with the APOGEE data, as is discussed below. If you are interested in learning more about APOGEE's abundances and their derivation see the DR17 ASPCAP Description or Holtzman et al. (in prep.).

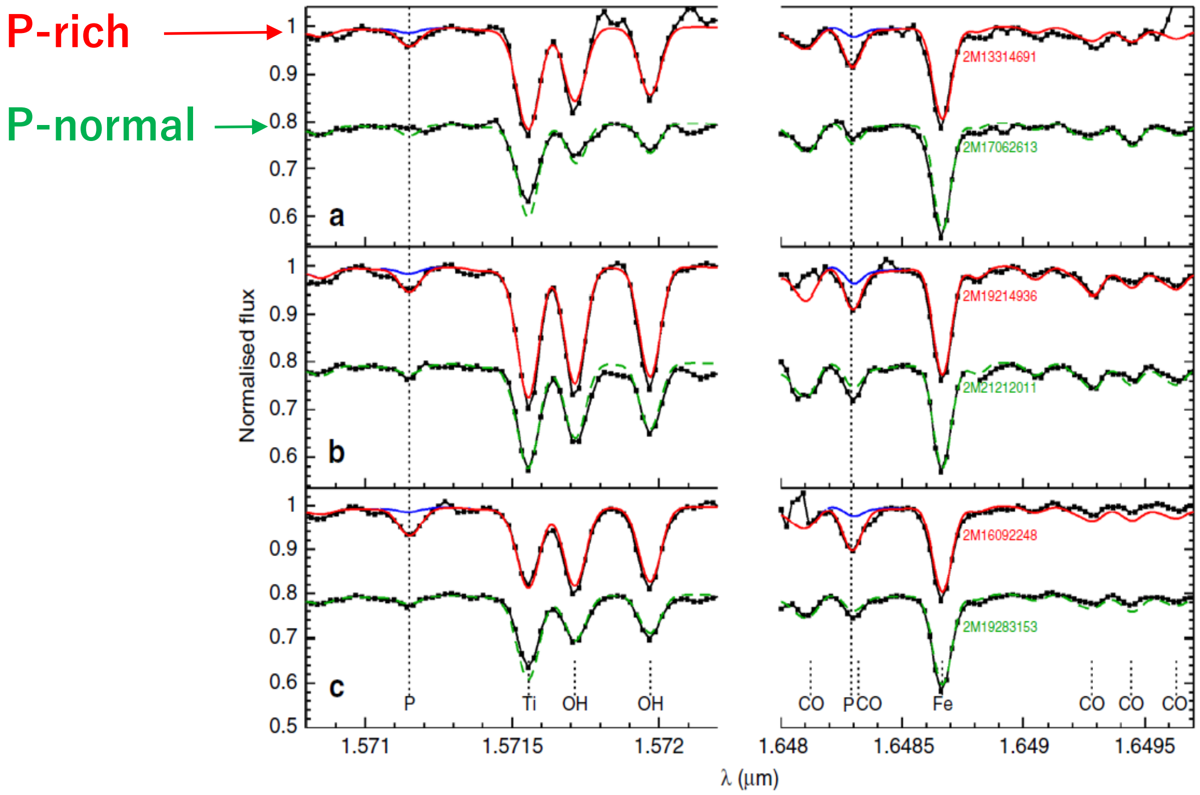
Elements seen in Cepheids' YJ-band (WINERED) spectra
– C, Mg, Si, P, S, Ca, Ti, Cr, Fe, Y, Sr, Eu, Dy (+α)

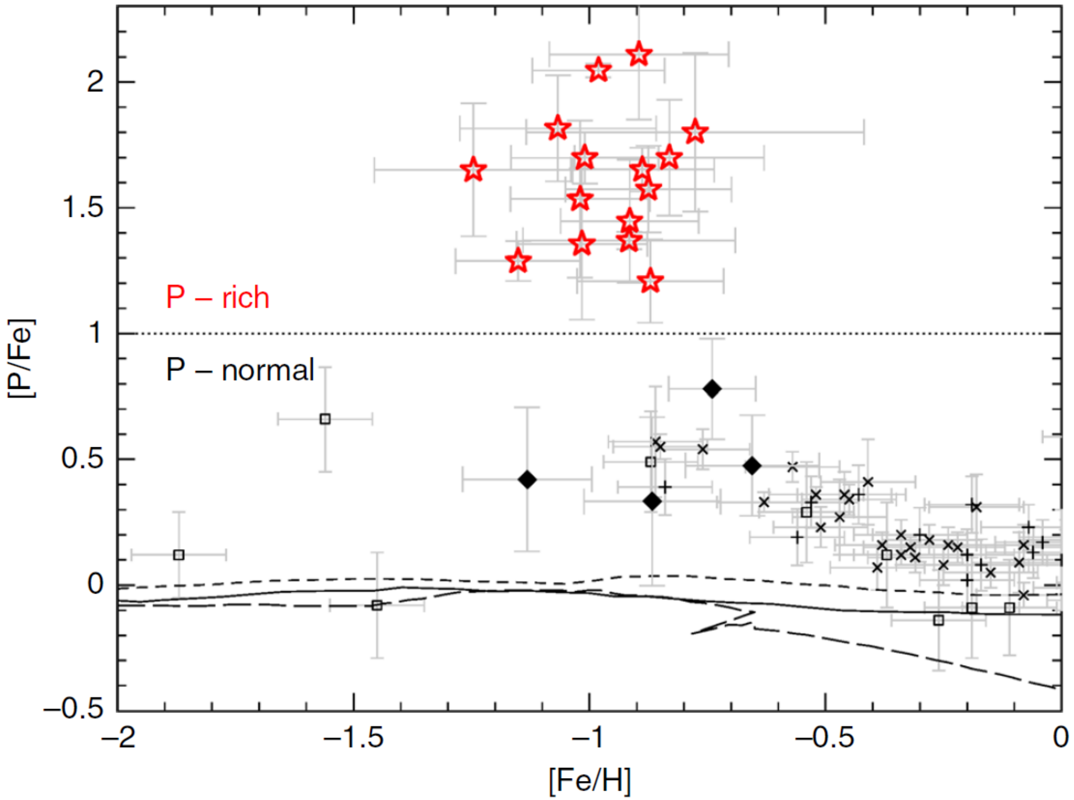
P-rich stars

Discovered using APOGEE data

- P lines should be too weak around [Fe/H]=−1 but clearly visible in P-rich stars.

Masseron et al. (2020)

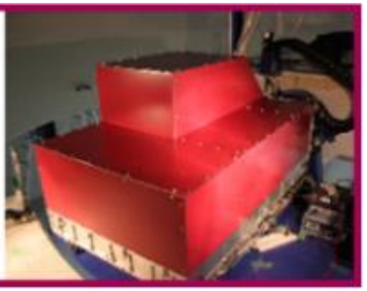




What should be studied

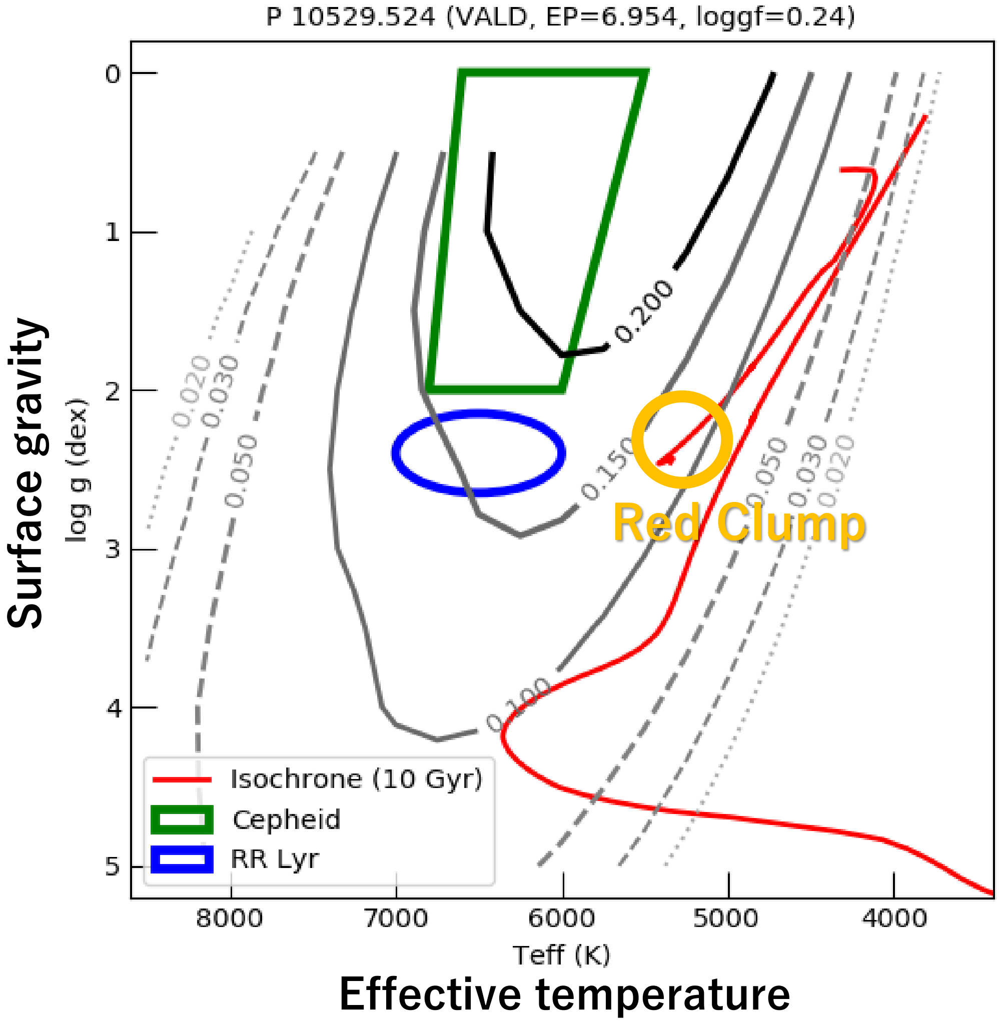
- Confirmation/calibration of loggf and measured [P/H]
  - Clusters with both Cepheids and red clumps would be useful for checking systematics.
- Measure P abundances in different regions of the Galaxy and nearby galaxies
  - How P has been produced in different systems
- Determine the synthesis process in various sources (SN II, SN Ia, novae, etc, with different metallicities) and calibrate the yield
- Application to astrochemistry and astrobiology
  - Give the P abundance at each site as an input to the calculation of interstellar chemical reactions
  - How much P is available on exoplanets

WINERED observations



Good P tracer: Cepheids

- Relatively young pulsating stars (20～300 Myr) in the Cepheid instability strip
- Cosmic distance indicator thanks to period-luminosity relation and a good tracer of stellar populations.
- NIR phosphorus absorption lines get most prominent in stars at around Teff=6000 K, corresponding to the Cepheid instability strip.

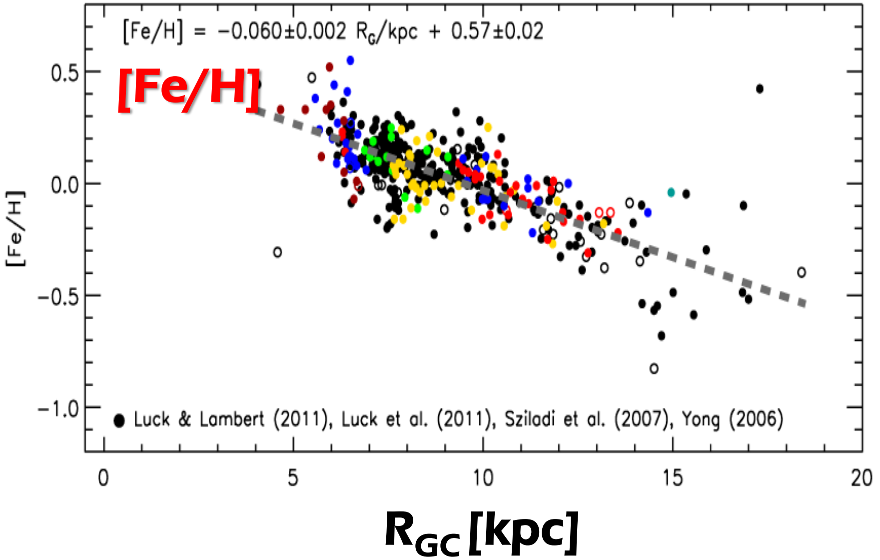


Contour: depth of a phosphorus absorption line (10529.5 AA) showing the dependency on the effective temperature and surface gravity.

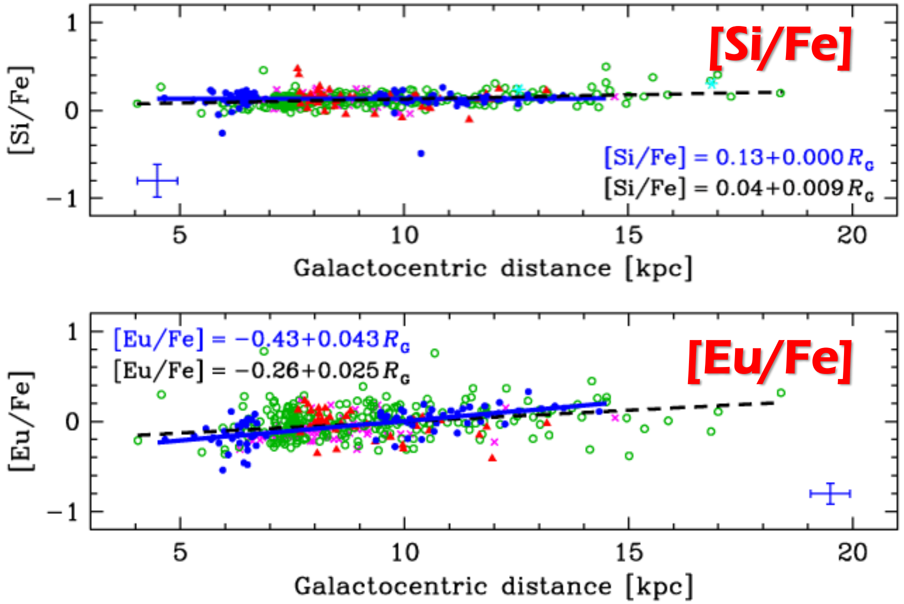
Cepheids as chemical tracers

- Clear metallicity gradient traced by >400 Ceps
  - Almost no variation in [alpha/Fe] (Genovali+20)
  - Significant slope for n-capture elements (da Silva+16)

Genovali et al. (2014)

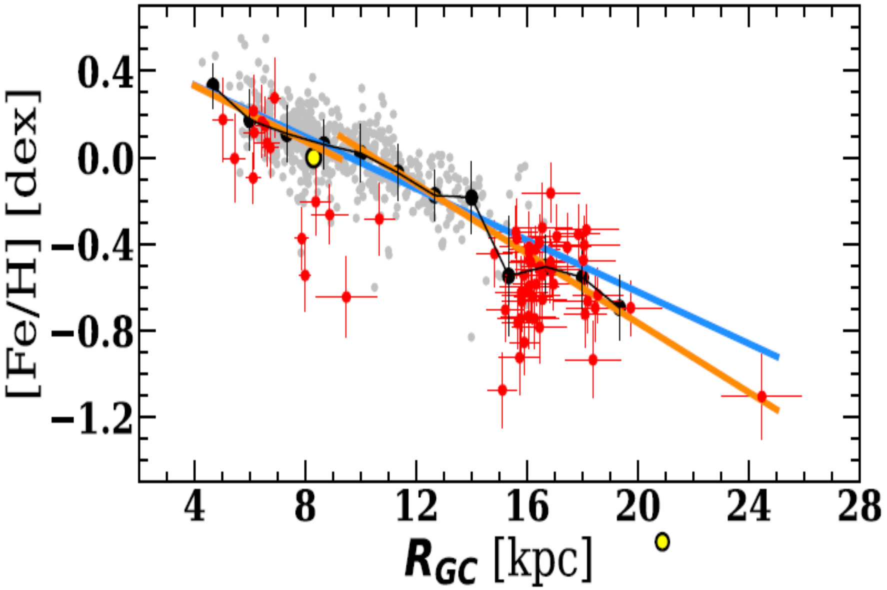


Top: Genovali et al. (2015)
Bottom: da Silva et al. (2016)

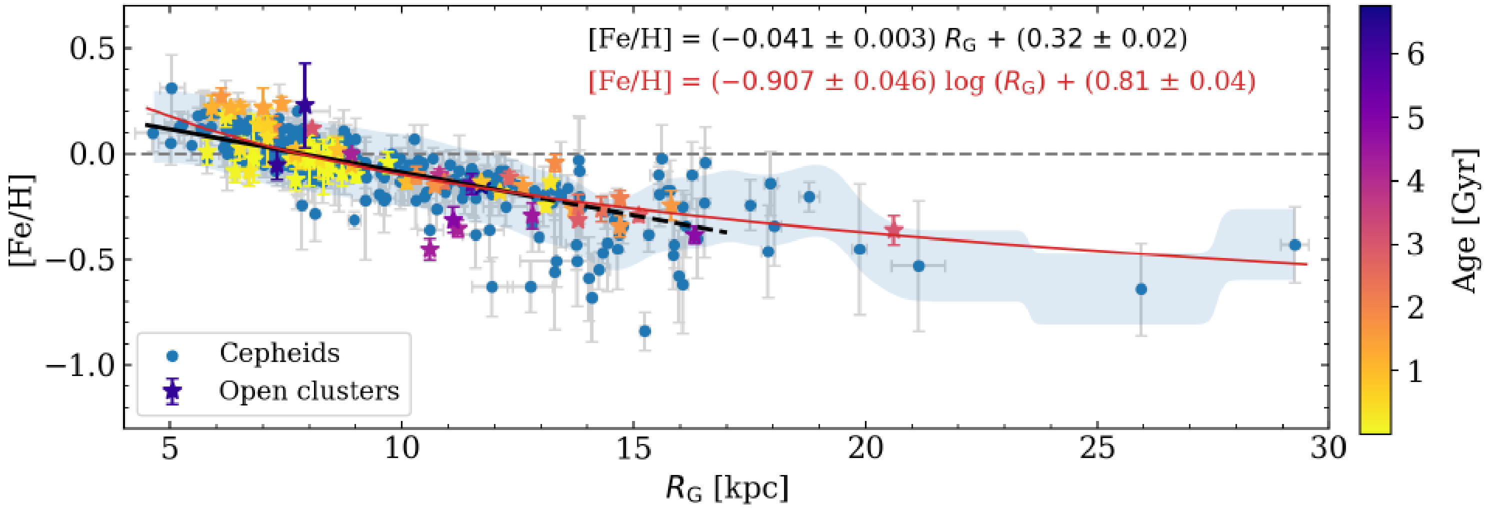


New Cepheids sample covering the entire MW disk

- Samples limited to $5 < R_{\mathrm{GC}} < 15$ kpc until recently
  - New sensitive spectroscopic data required to extend the R_{GC} range



Trentin+23 (using UVES@VLT)



da Silva+23 (using a large collection of high-resolution spectra, discussed in Giuseppe's talk)

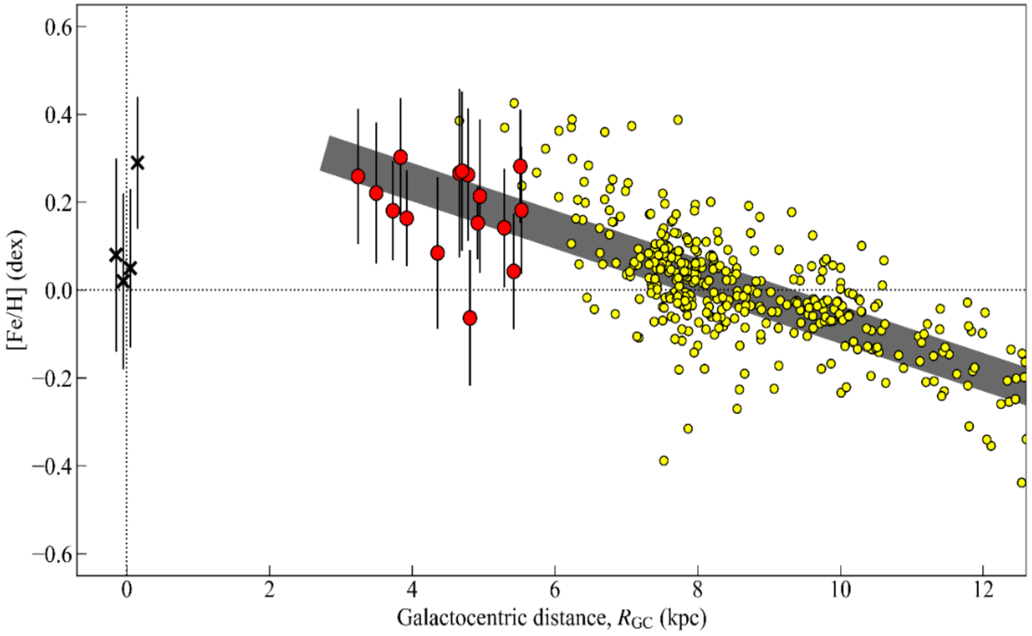
WINERED

- Near-infrared high-resolution spectrograph
  - Resolution λ/Δλ= 28000, covering 0.91～1.34 μm (HIRES modes with λ/Δλ= 70000 with narrower coverages
  - Started the operation with 6.5m Magellan telescope at Las Campanas Observatory (Chile)
- World-leading high sensitivity, 50%
  - Detecting the signal of half of the photon reaching the entrance of spectrograph (5～30% for other spectrographs)

Recent WINERED observations

- 2022 September – First light with Magellan telescope (mainly technical feasibility check)
- 2023 June – The first scientific runs
  - Mainly targets in the Milky Way
  - Matsunaga+23 (ApJ) : [Fe/H] of 16 Cepheids in the inner MW disk.
- 2023 October – Supported by this grant
  - Cepheids in the Magellanic Clouds
- 2024 April – Next run scheduled

Matsunaga et al. (2023)
Cepheids in the inner MW disk



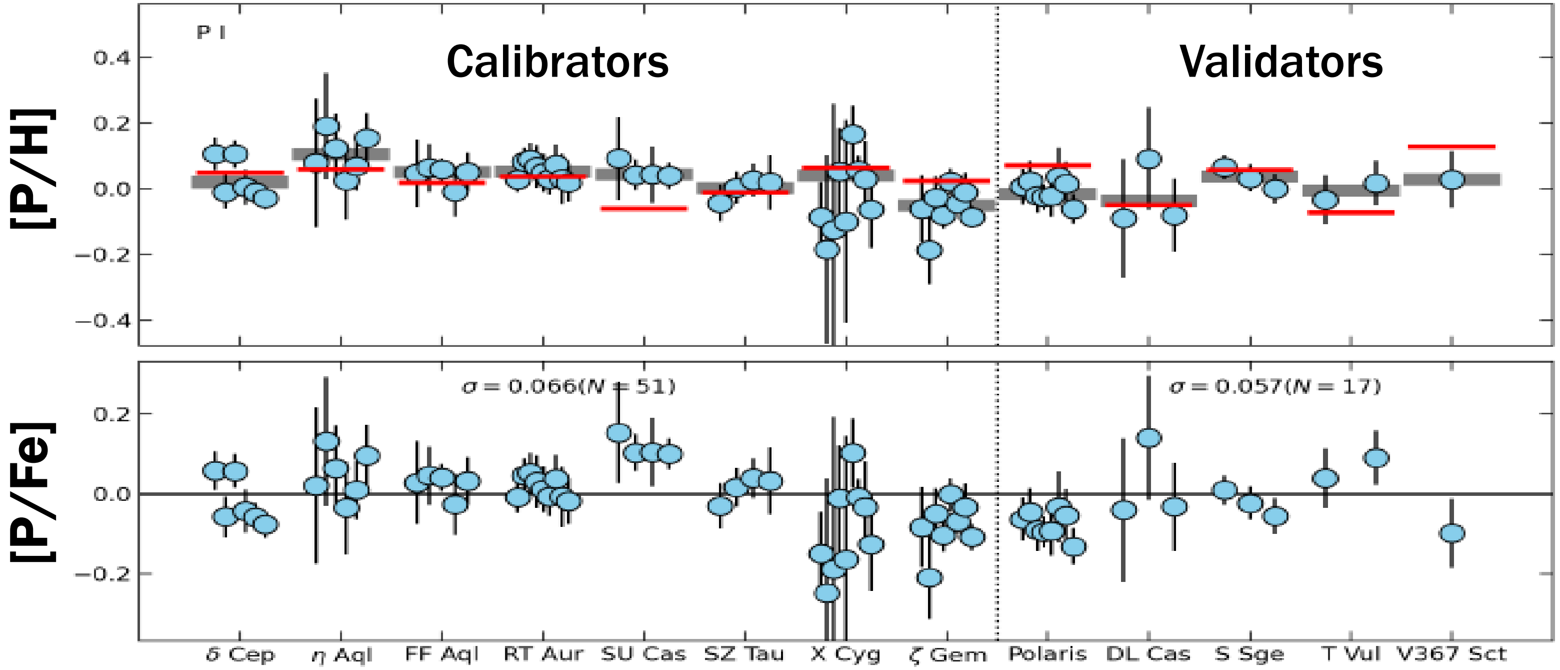
X-axis R_{GC} – Galactocentric distance (kpc)
Y-axis [Fe/H] – metallicity

PhD project by Scarlet S. Elgueta

- *Completed in 2022 Mar*
- Time-series **YJ-band** (WINERED) spectra of well-known Cepheids to establish the abundance analysis with the precision as high as optical spectroscopy, ~0.1 dex
- Establishing the line lists of various elements: Si I, P I, S I, Ca I, Ca II, Fe I, Fe II, Zn I, Y II, Dy II.

Result on phosphorus

- 7 lines in the Y band allows the abundance measurements with the precision ~0.07 dex.
  - Internal precision confirmed to be high, but the accuracy on the absolute scale remains to be checked.



Elgueta (2022, PhD thesis)
See also arXiv:2307.00158

Lines confirmed in the recent analysis

- An updated analysis to include all available elements in progress
- Elements with 5 or more lines in the YJ band

Species	C 1	Mg 1	Si 1	P 1	Ca 1	Ti 1	Fe 1	Fe 2	Ni 1
VALD	14	7	41	6	10	7	75	9	8
MB99	23	5	35	5	10	6	60	6	7

- Elements with fewer lines
    - O1, Na 1, Mg 2, S 1, K 1, Ca 2, Cr 1, Mn 1, Zn 1, Y 2, Eu 2

Arabic numbers used instead of roman numbers
for the neutral (=1) or 1st ionization (=2) status.

Summary

- Phosphorus is an important but unexplored elements. Broad interests include the contexts of astrobiology and astrochemistry.
- Stellar phosphorus abundances require high-resolution ($R \geq 20000$) and high-quality ($S/N > 70$) NIR spectra.
- Magellan/WINERED can reach Cepheids over a wide range of the Galactic disk and those in the Magellanic Clouds.