# Phosphorus enrichment over the Milky Way disk observed with near-infrared spectra of Cepheids

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# Contents

- Introduction to stellar phosphorus abundances
- Objectives of our study
  - Cepheids are ideal targets for measuring phosphorus abundances
- Data and analysis with Subaru/IRD and Magellan/WINERED
- Some preliminary results

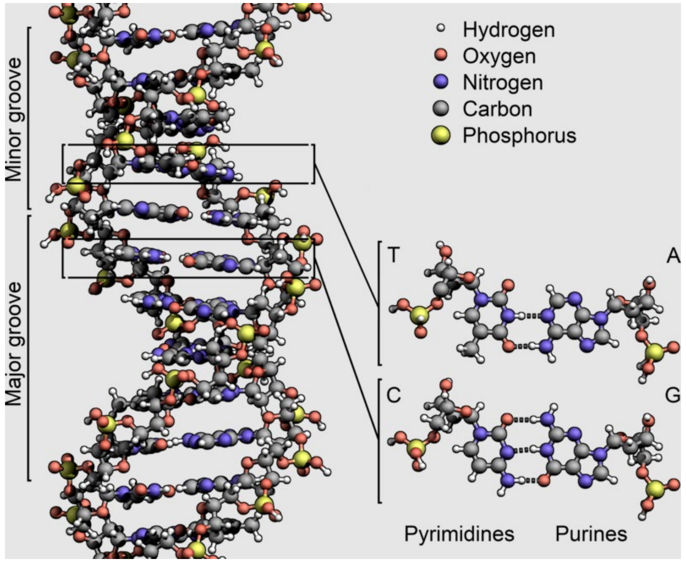
# Phosphorus

- 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

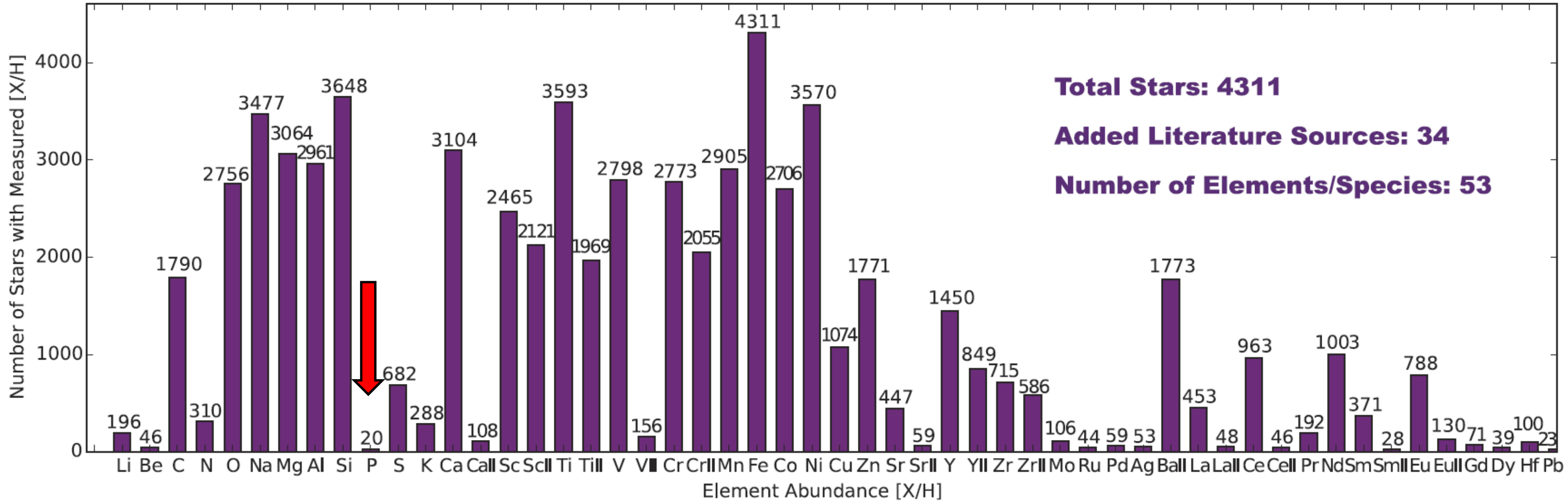
| COMPOUND | BIOCHEMICAL ROLE |
|---|---|
| Nucleic acids | Storage and transmission of genetic information |
| Nucleotides | Coenzymes; carriers of P; precursors in DNA and RNA synthesis |
| Phospholipids | Main characteristic components of cellular membranes |
| Sugar phosphates | Intermediate molecules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




DNA’s structure
(by Zephyris from Wikipedia)

# 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 only in **UV (2100～2600 Å, only from space)** and **near-IR (Y and H bands)**.



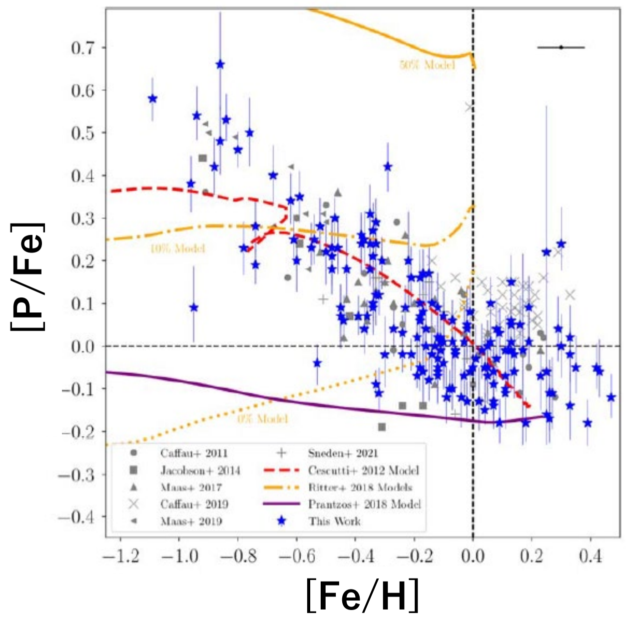

***Number of stars with each element measured in Hypatia Catalog 2.0 (FGK stars within 150 pc; Hinkel+14)***

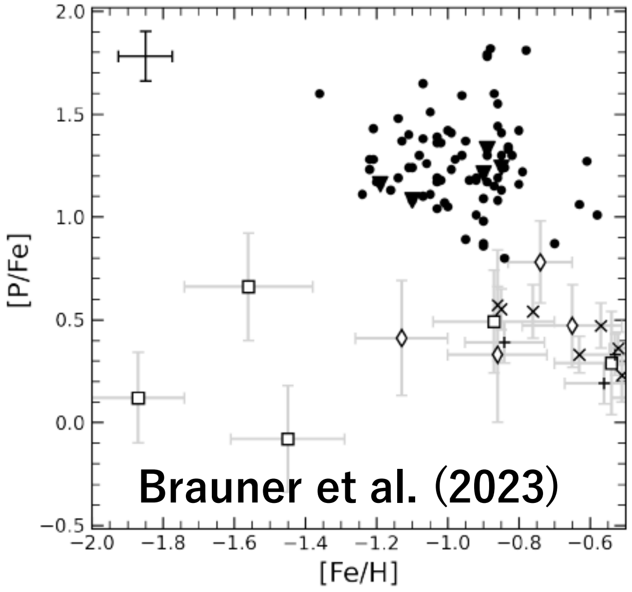
# P evolution – not established

- Previous data were limited to stars in the solar neighborhood
- Failure in explaining the [Fe/H]-[P/Fe] trend
  - Uncertainty in the yield of CCSN
  - Hard to explain high P in low-metal stars ([Fe/H] around -1).
- How to explain P-rich stars ([P/Fe]>1)?

- Brauner et al. (2023, 2024):
  - Main P synthesis – C burning shell in massive stars
  - Minor or no contribution from explosive synthesis in CCSN (Woosley & Weaver 1995), SN Ia (Leung & Nomoto 2018), or AGB stars (Karakas & Lugaro 2016)
  - Possible sites for fixing the inconsistency – Shell merger in massive stars (Ritter et al. 2018) , i-process and/or s-process in rotating massive stars (Brauner et al. 2024).

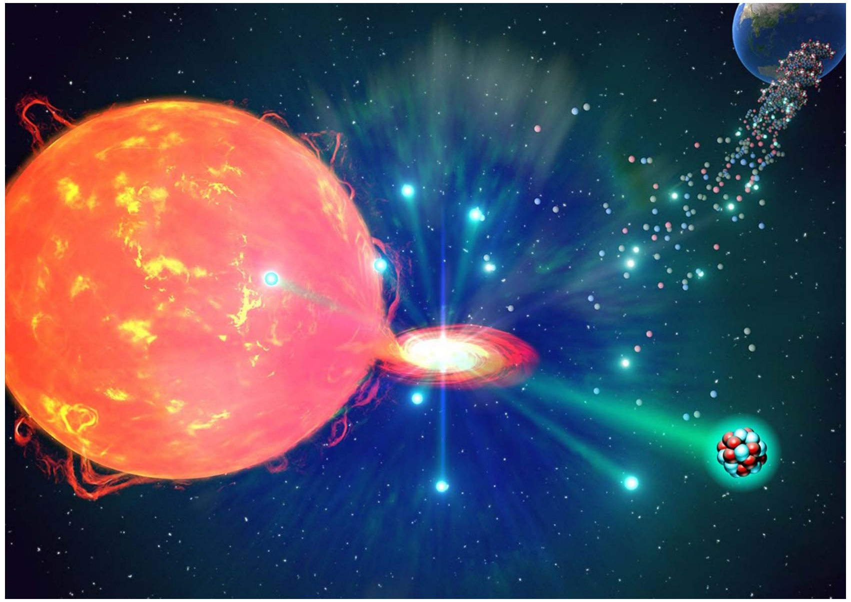
Maas et al. (2022)



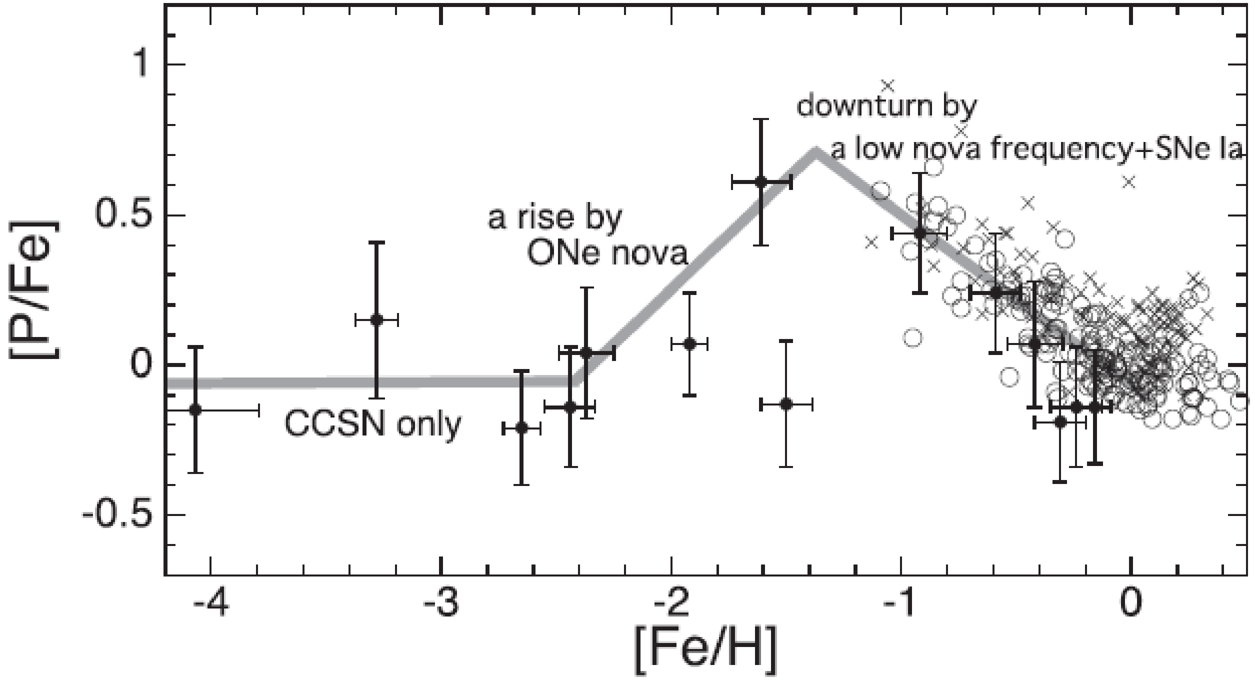



# Contribution of classical novae

- Bekki & Tsujimoto (2024) proposed the P evolution model with the contribution from ONe novae, which can reproduce the trend including very metal-poor stars from UV spectra.

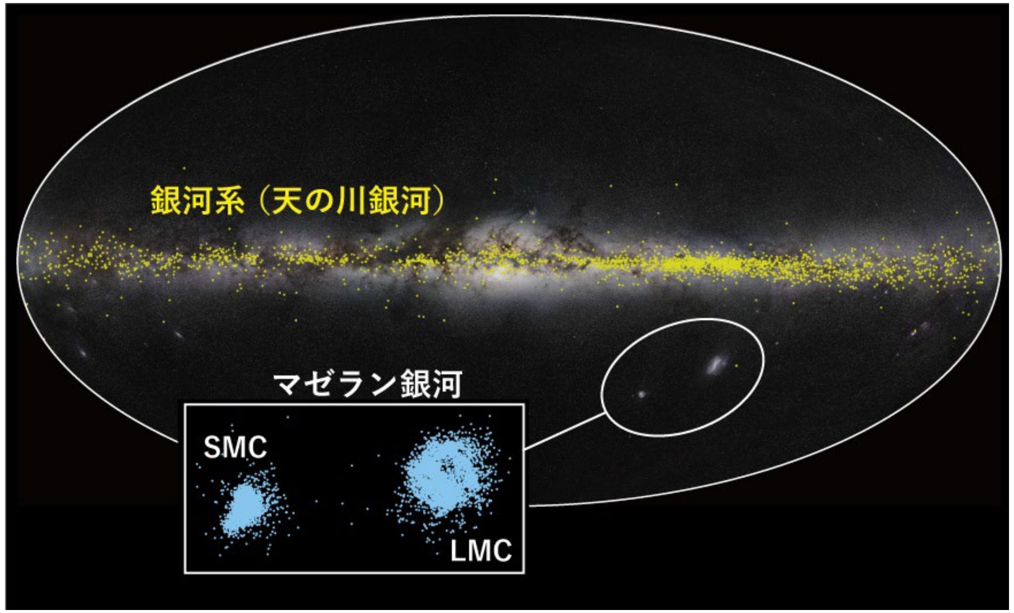


Bekki & Tsujimoto (2024, ApJL, 967, L1)



# Aims of our observations

- Identify the nucleosynthesis sites and establish the chemical enrichment model by measuring phosphorus in various samples
- Stellar systems
  - The Galactic disk – over a wide range of R(GC)
  - The Galactic bulge
  - Magellanic Clouds
- Tracers
  - Cepheids (young)
  - RR Lyrs (old)
  - Dwarfs/Giants (various ages)

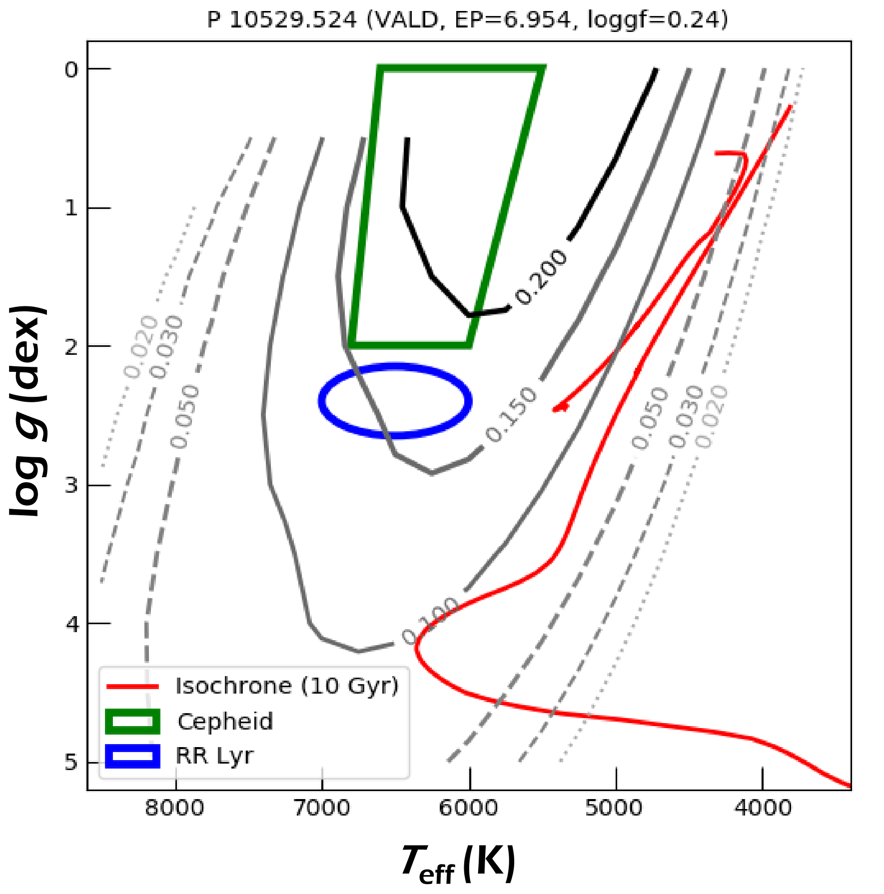



Thousands of Cepheids in the MW and LMC/SMC

# Cepheids as phosphorus tracers

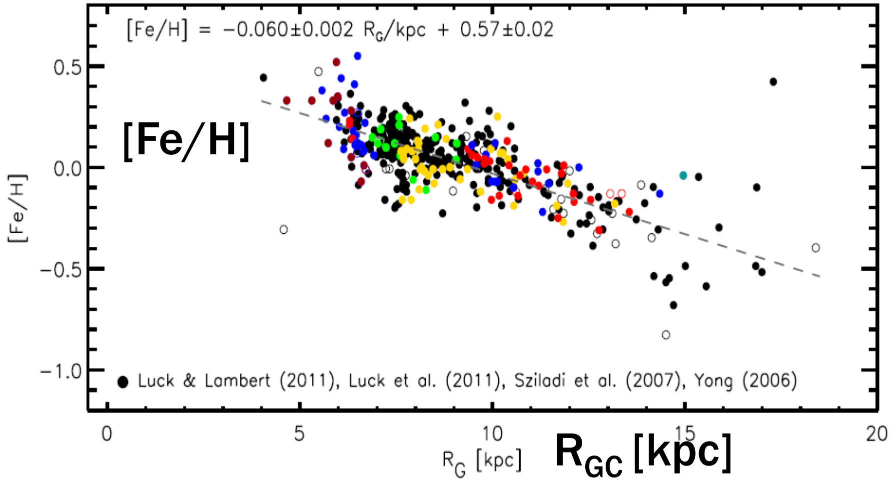
- Neutral P lines in NIR get strongest around ($T_{eff}$, log g) of Cepheids.
- We can measure Cepheids' P in almost the entire MW and nearby galaxies.
  - Most previous P measurements limited to within ~200 pc.
- FGK dwarfs and clump giants are good targets but with a smaller reach.

Contour of the strength of a P line (10529 Å) and the Cepehid instability strip

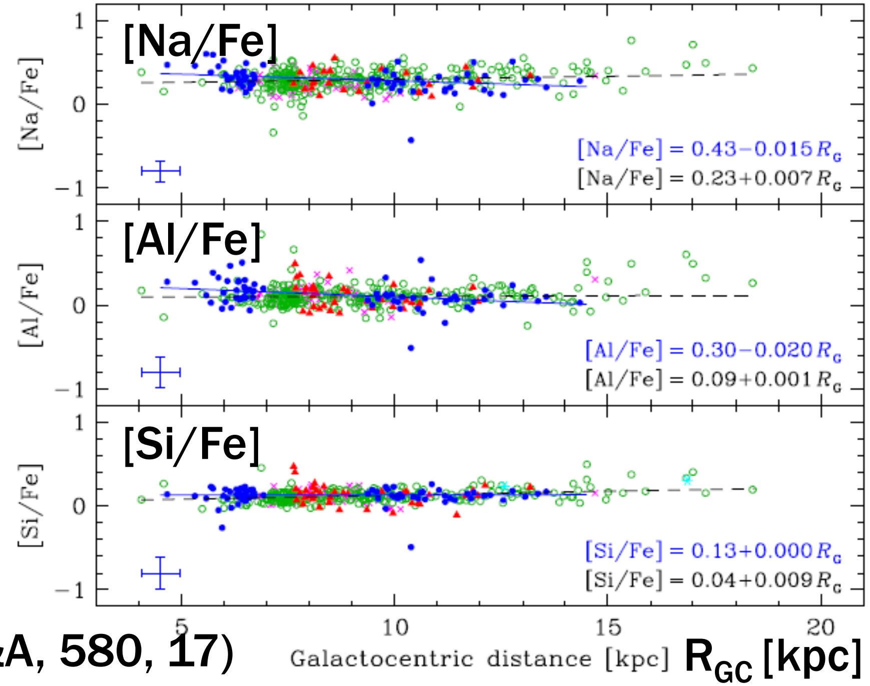


# Application of Cepheids as chemical tracers

- Clear and tight metallicity gradient traced by >400 Cepheids and almost no variation in [alpha/Fe] (Genovali et al. 2015), but significant slopes for neutron-capture elements (da Silva et al. 2016) and some other elements including sulfur [S/Fe] show the slope (da Silva+23).
- Almost no previous measurements of phosphorus



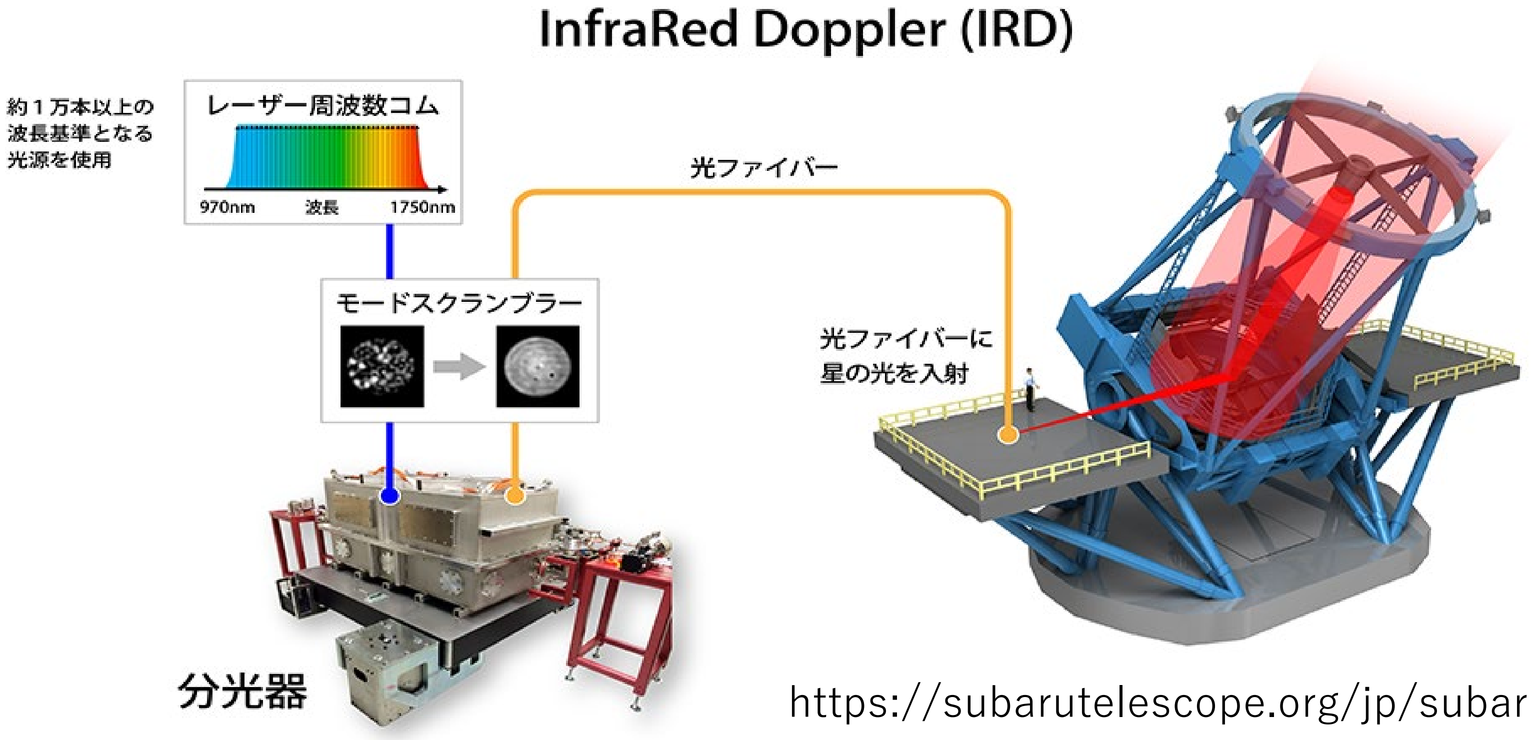

Genovali et al. (2014, A&A, 566, 37)




Genovali et al. (2015, A&A, 580, 17)

# IRD@Subaru

- YJH-band high-resolution spectrograph (PI: Tamura & Kotani)
  - R=70,000
  - Very stable and accurate wavelength calibration with laser frequency comb



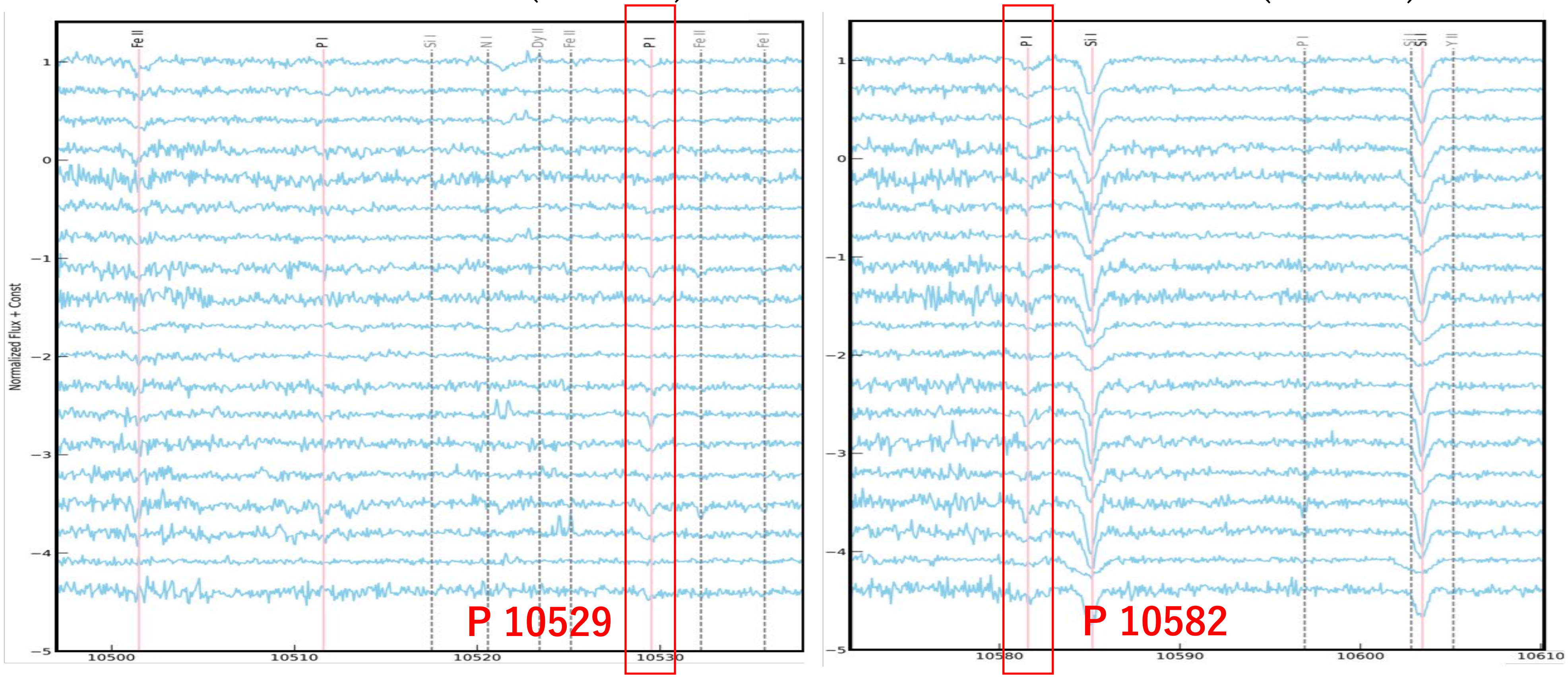

https://subarutelescope.org/jp/subaru2/instrument/ird/

# IRD observations for P and other elements

| ID | Targets | Night(s) | Data |
| --- | --- | --- | --- |
| S22B-104 | Ceps in the outer Disk | 10/10+11 (2n) | 8 outer-disk Ceps, but S/N too low for P |
| S23A-021 | Ceps in the inner Disk | 3/23+6/16 (1n) | ~30 inner-disk Ceps with good quality |
| S24A-024 | Metal-rich RR Lyrs | 3/7+6/8 (1n) | ~20 RR Lyrs with good quality |

# Phosphorus in metal-rich RR Lyrs from S24A

Part of order 140 (Y-band) Part of order 139 (Y-band)




- Generally speaking, RR Lyrs are ~10 Gyr old, but some recent studies claim metal-rich RR Lyrs ([Fe/H]>-1) are younger (a few Gyr).

# WINERED


- Near-IR: **0.91—1.35 μm** (zYJ bands)
- Resolution: **28,000** (WIDE) or **~70,000** (HIRES)
- High S/N ratio: **~500**, routinely for bright targets
- High efficiency: **50 %**
- We started observations with Magellan 6.5m at LCO
- Limits (expected): **J=14.2** (S/N=100) or **15.8** (S/N=30) with 1hr for WIDE mode w. Magellan 6.5m

| | |
|---|---|
| **Home Page** | https://merlot.kyoto-su.ac.jp/LIH/WINERED/ |
| **ETC** | https://merlot.kyoto-su.ac.jp/WINERED/ETC/ |

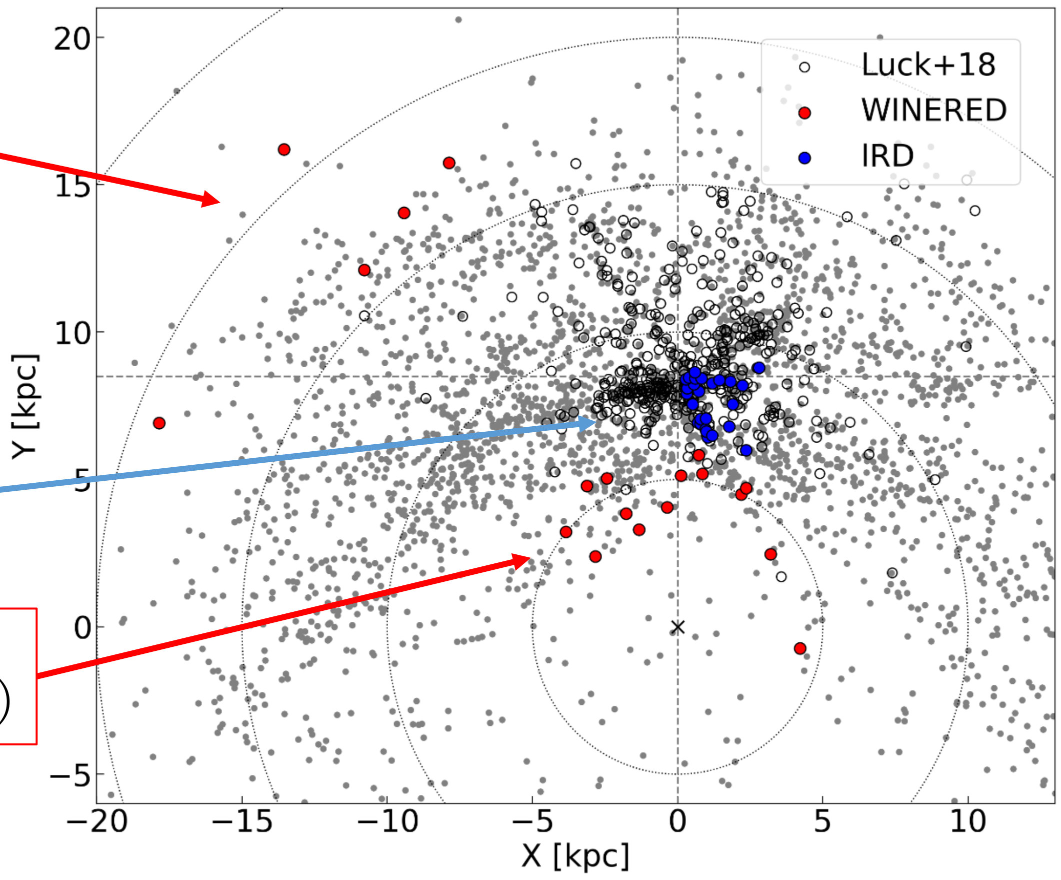
# Current sample of Cepheids in the MW disk

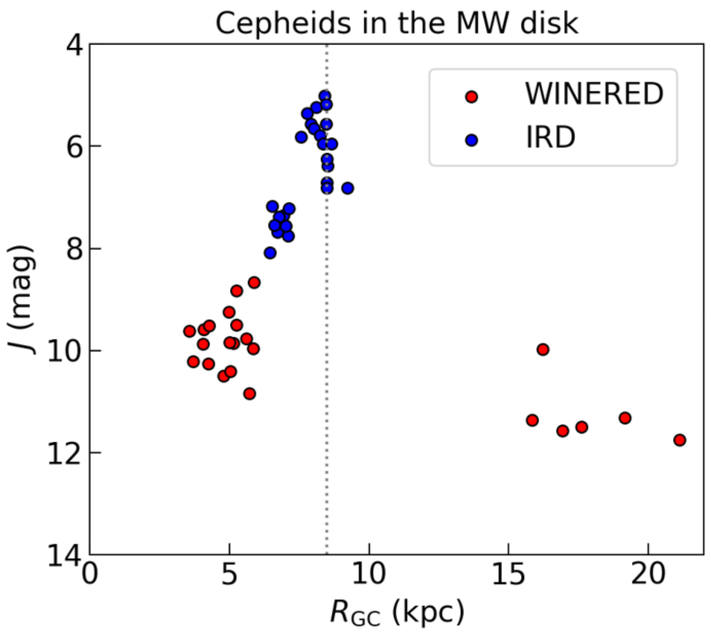
- Covering a wide range of R(GC), 3.5—21 kpc.
  - So far, we used Subaru/IRD for nearby bright Cepheids.

5 Ceps in the outer disk (WINERED)

~30 Ceps in the inner disk (IRD)

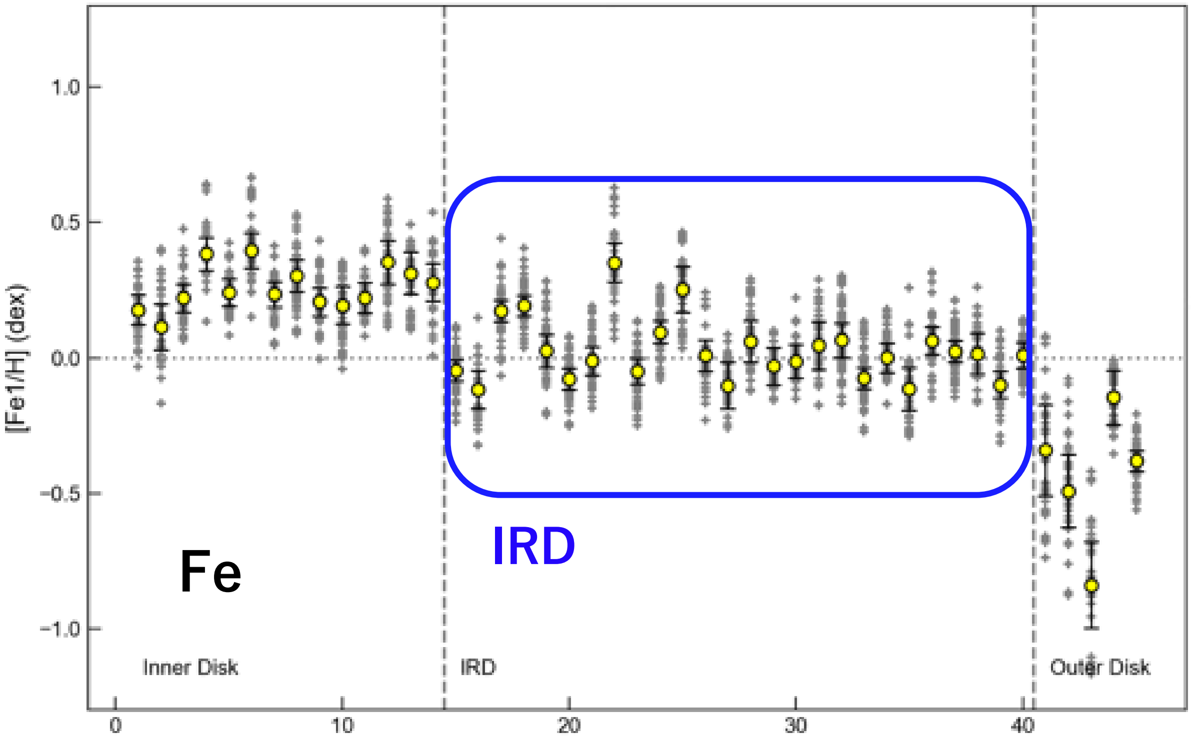
16 Ceps in the inner disk (WINERED, Matsunaga+23)

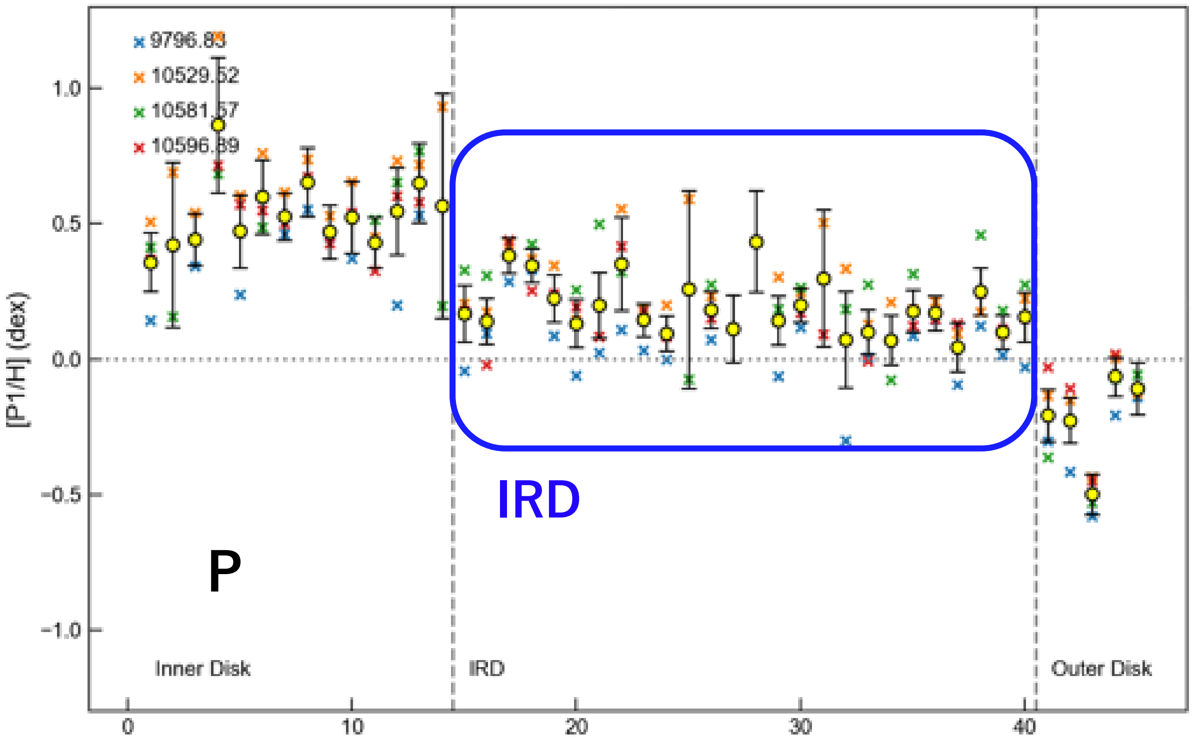


# Work in progress: checking measurements…

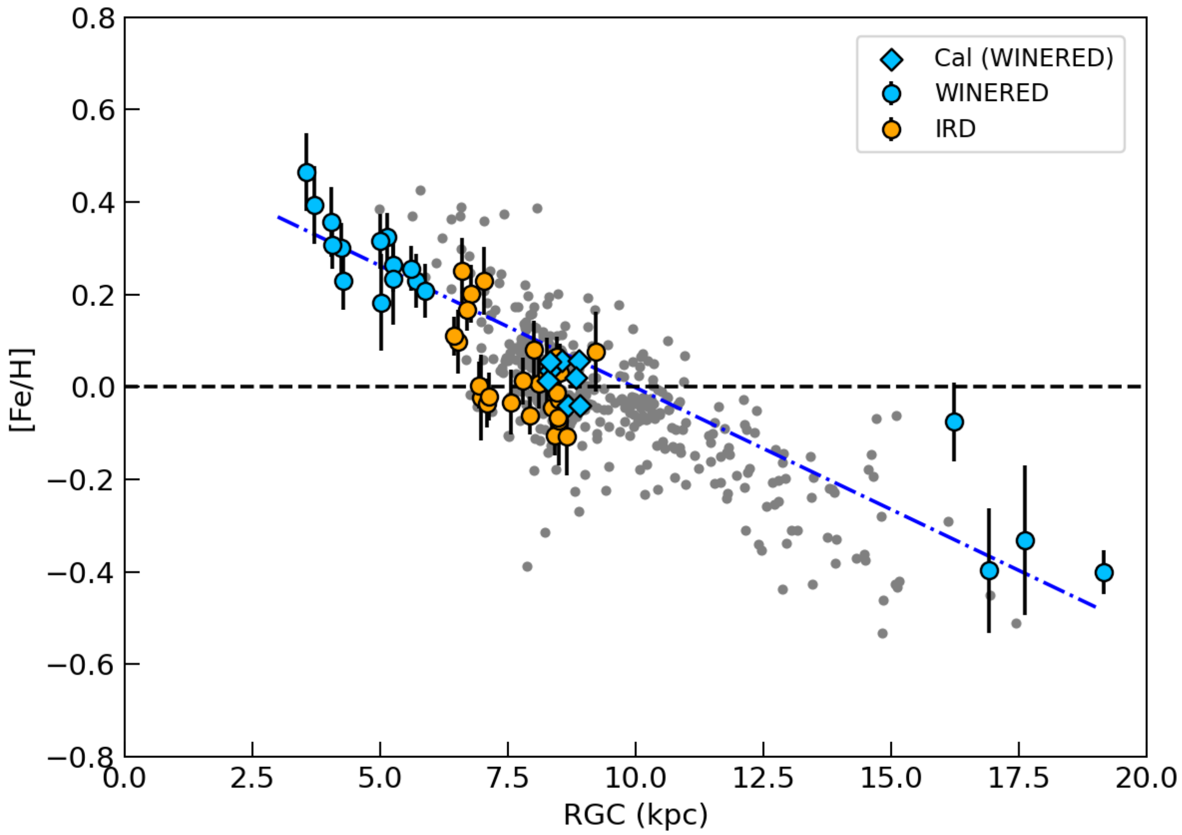
- IRD and WINERED measurements look both good and consistent as we see on [Fe/H]-[X/Fe] diagrams (in next slides).
  - Precision: Fe – 0.05~0.09 dex (30-40 lines), P – 0.06—0.12 dex (3—4 lines)



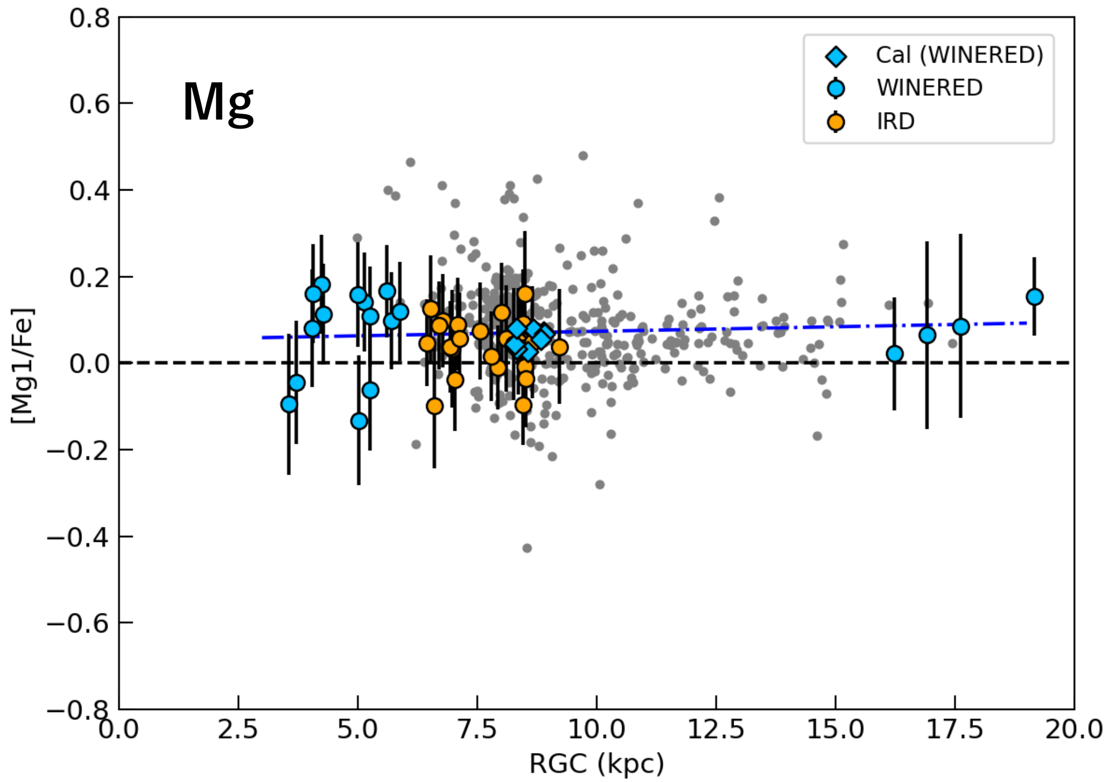
# Work in progress: metallicity gradient

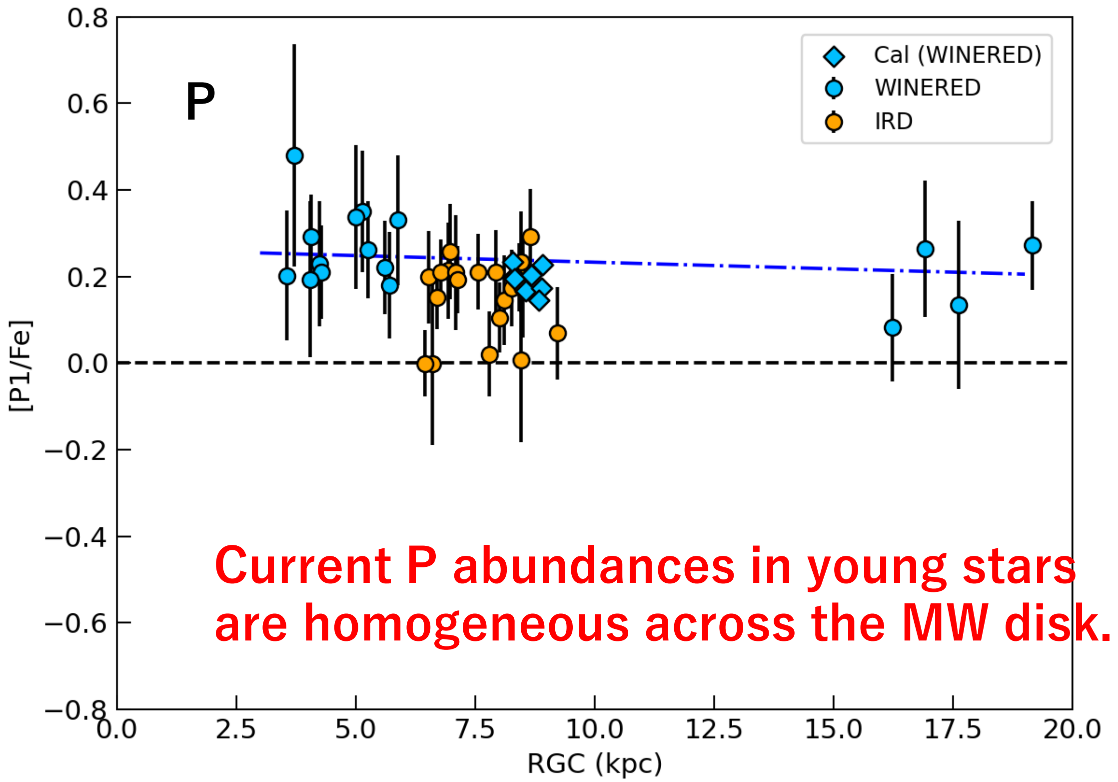
- Consistent with previous works
  - Linear including the innermost region (Matsunaga+23)
  - Sample in the outer disk is still small.



# Work in progress: abundance-ratio gradient

- Almost flat in [X/Fe] except for Y; i.e. [X/H] shows the same slope as [Fe/H]
  - Consistent with previous results for $5.5 < R_{GC} < 15$ kpc. Tilted in [Y/Fe]



# Summary

- Phosphorus measurements have been limited to small samples in the solar neighborhood.
- We are extending the measurements:
  - Cepheids over a wide range of the Galactic disk
  - Cepheids in the Magellanic Clouds
  - And various other tracers including RR Lyrs, P-rich stars, and solar twins.
- Trying to establish the nucleosynthesis sites of phosphorus and models of galactic chemical evolution.
  - Calculation of galactic evolution being updated by Takuji Tsujimoto (NAOJ)