Infrared spectroscopy of Cepheids in the Galactic Center and more

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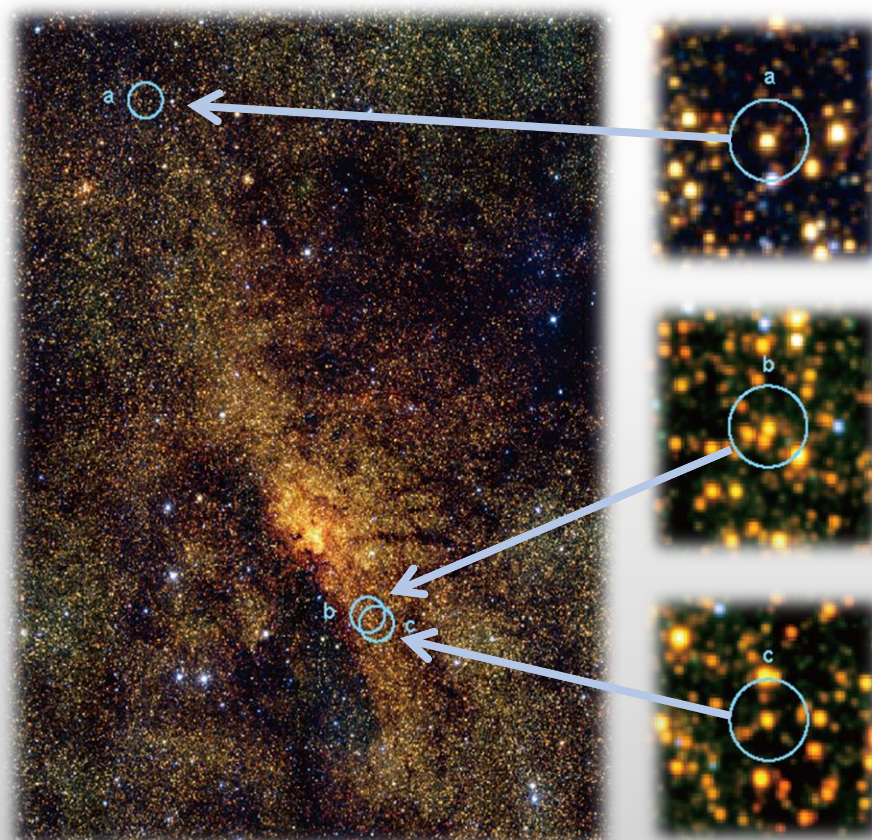

Collaborators

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Fukue-san

Outline

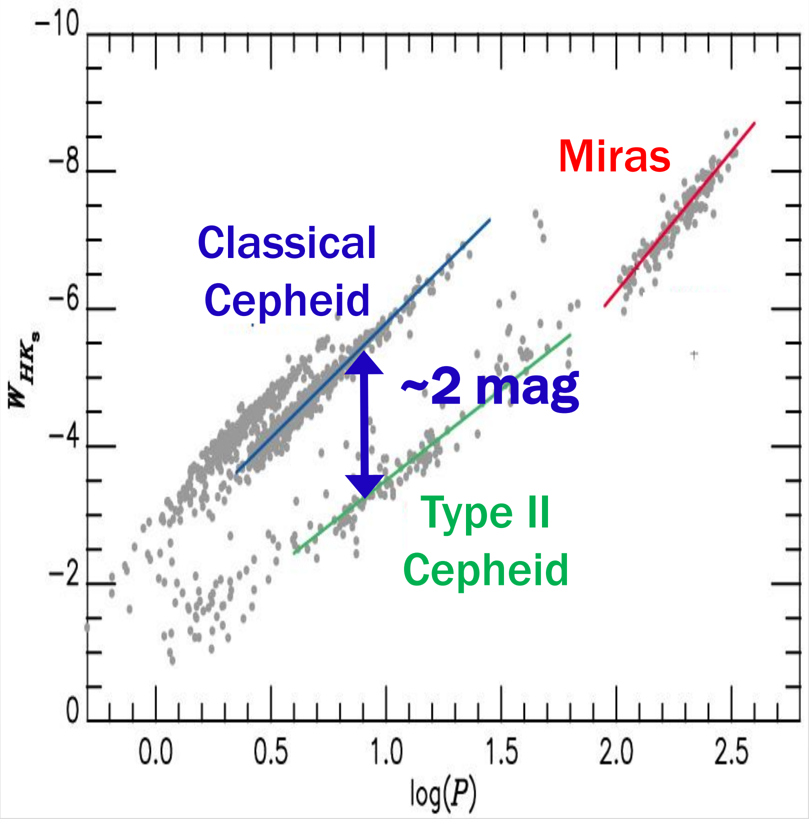
- Introduction
  - Importance of Cepheids to study the Galaxy
- Our goals and observations
  - What we would like to investigate with our Subaru/IRCS spectroscopic data.
- Analysis of IRCS H-band spectra for metallicity
  - Establishing the analysis methods and tools to measure [Fe/H] and other parameters with near-IR spectra
- Results for target Cepheids
  - [Fe/H] of the targets and the implications
- Summary and Future prospects

Introduction

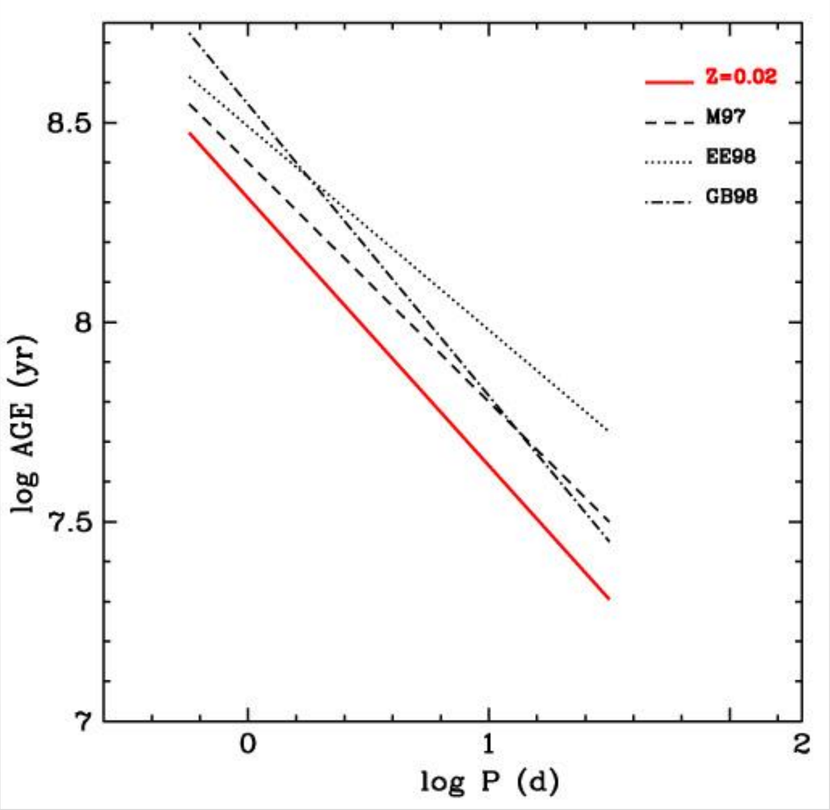
Cepheids as tracers of the Milky Way Galaxy

Classical Cepheids as tracers

- P-L relation → distance (accurate to 10% for each star)
- Ages, kinematics and chemical abundances can be accurately determined, thus working as good tracers.



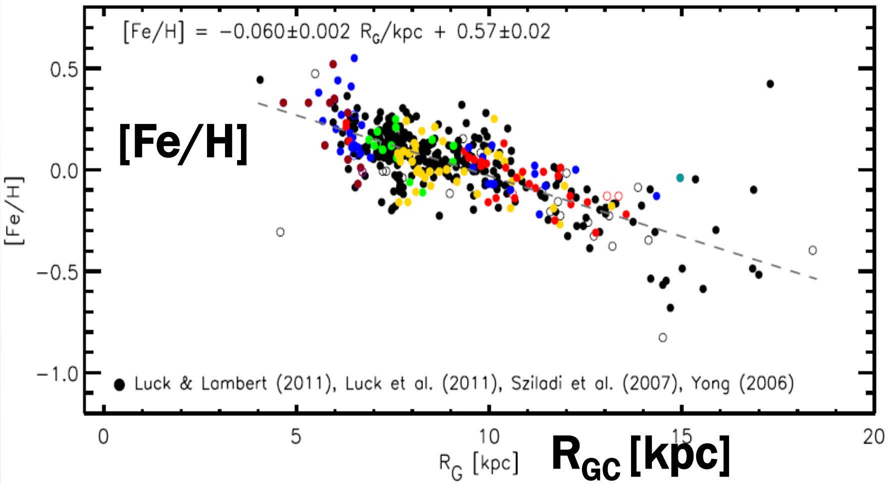
Near-IR P-L relations of LMC variables (Matsunaga, 2013)



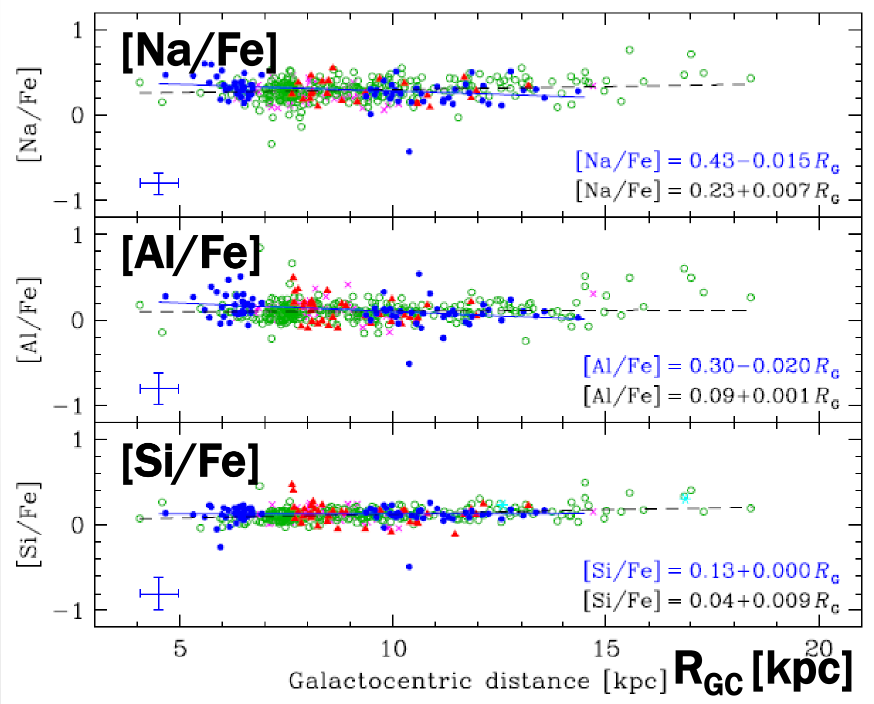
Period-age relation (Bono et al. 2005)

Cepheids as chemical tracers

- Genovali et al. (2013—2015), da Silva et al. (2016)
- 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).



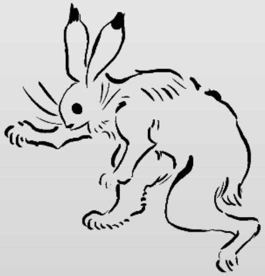
Genovali et al. (2014, A&A, 566, 37)



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

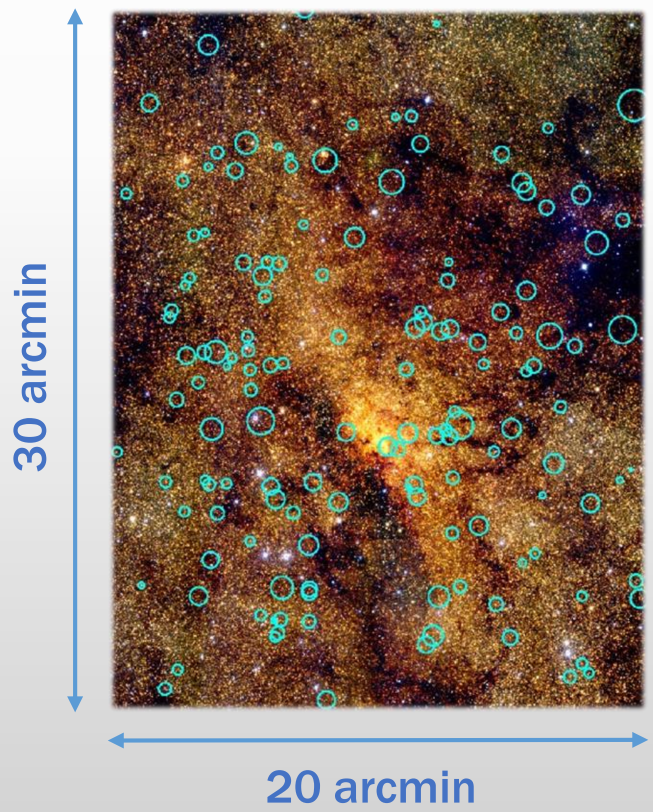
Our goals and observations

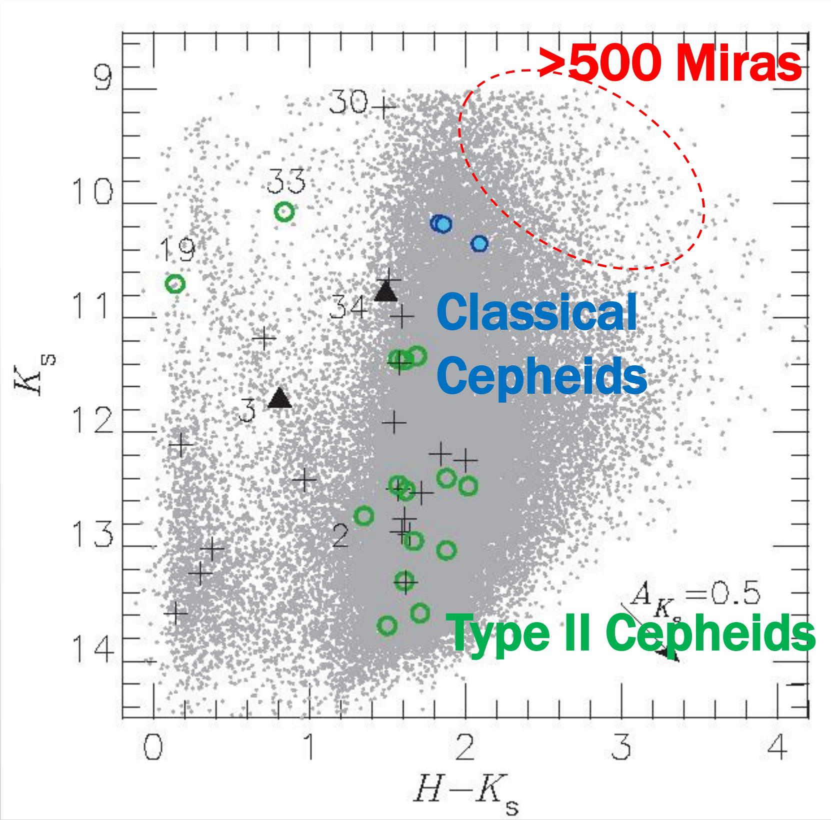
Cepheids we found in the Galactic Center and
what we like to study with H-band spectra
from Subaru/IRCS



IRSF survey of the Galactic Center

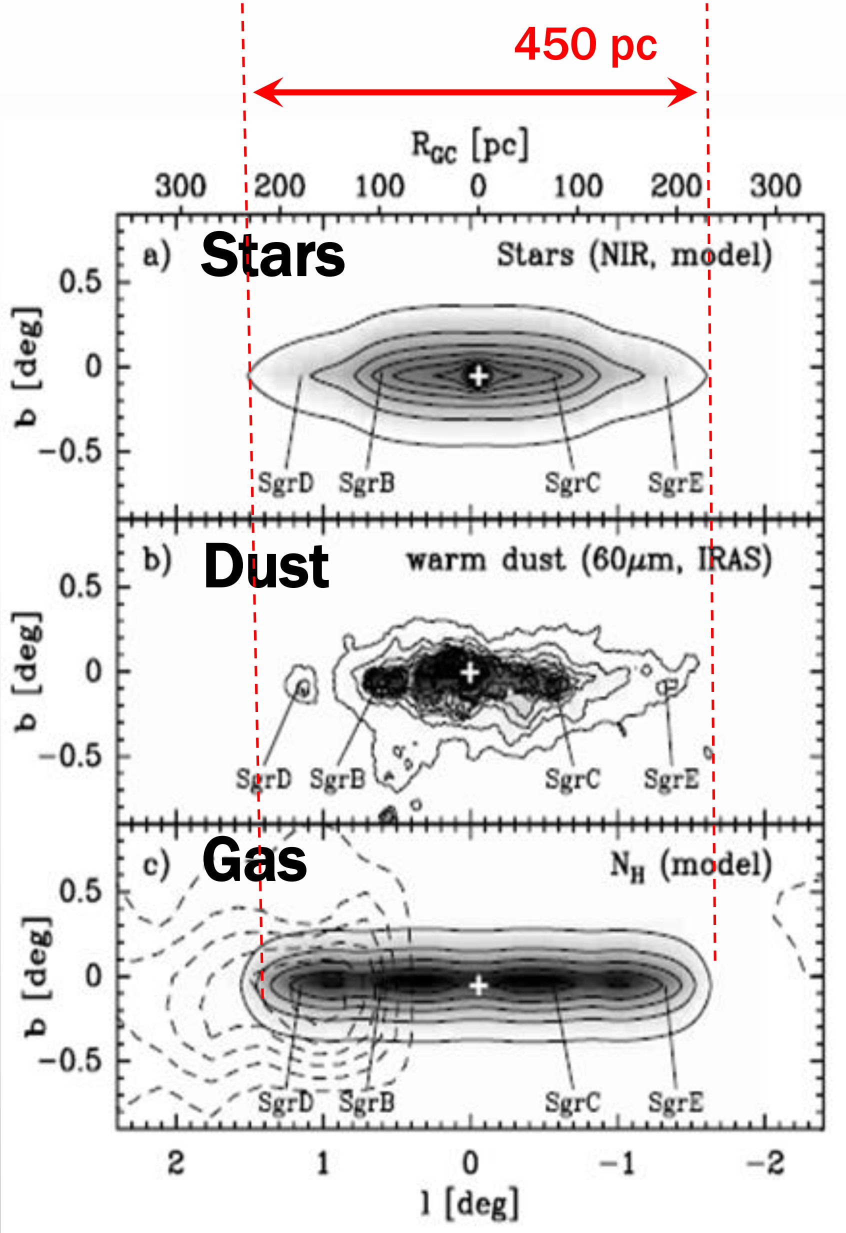
- We discovered 4 classical Cepheids (Matsunaga et al. 2011, 2013, 2015) along with other variable stars (eg >500 Miras).
- IRSF 1.4-m telescope and SIRIUS *JHKs*-band camera





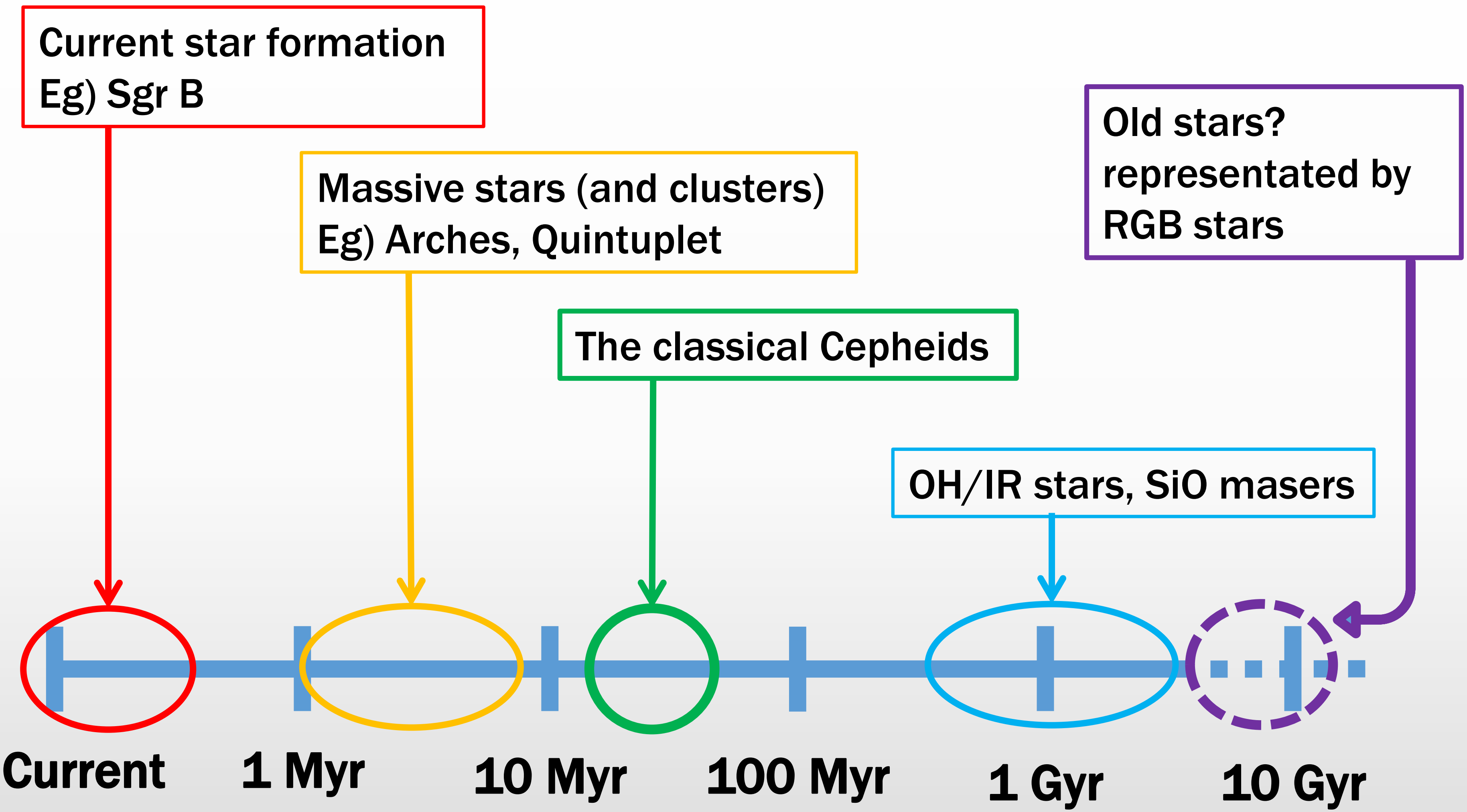
The Nuclear Stellar Disk

- A disk-like system where stars coexist with gas/dust (Central Molecular Zone)
- Young stars exist in contrast to the Bulge dominated by old stars, ~10 Gyr.
- Our 4 Cepheids considered to be within this disk.



Launhardt et al. 2002

Stellar populations in the Nuclear Disk



Our target Cepheids are the only objects aged ~25 Myr which have been identified in this region.

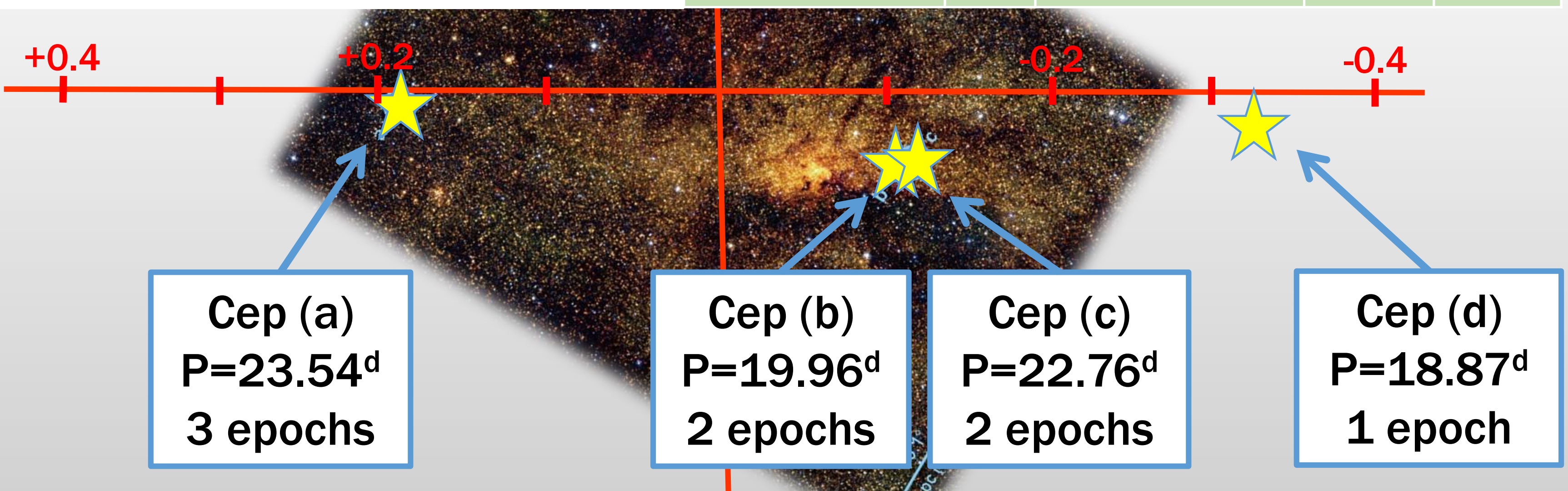
Goals of IRCS spectroscopy

- Kinematics of the Cepheids
  - Confirm their membership to the Nuclear Stellar Disk by comparing radial velocities with those of gas and other stars.
  - (Proper motions from images separated by a few years would give a stronger result.)
- Chemical abundances of the Cepheids
  - Study chemical evolution of the Nuclear Stellar Disk and gas supply to the Central Molecular Zone

Observations in 2010—2012

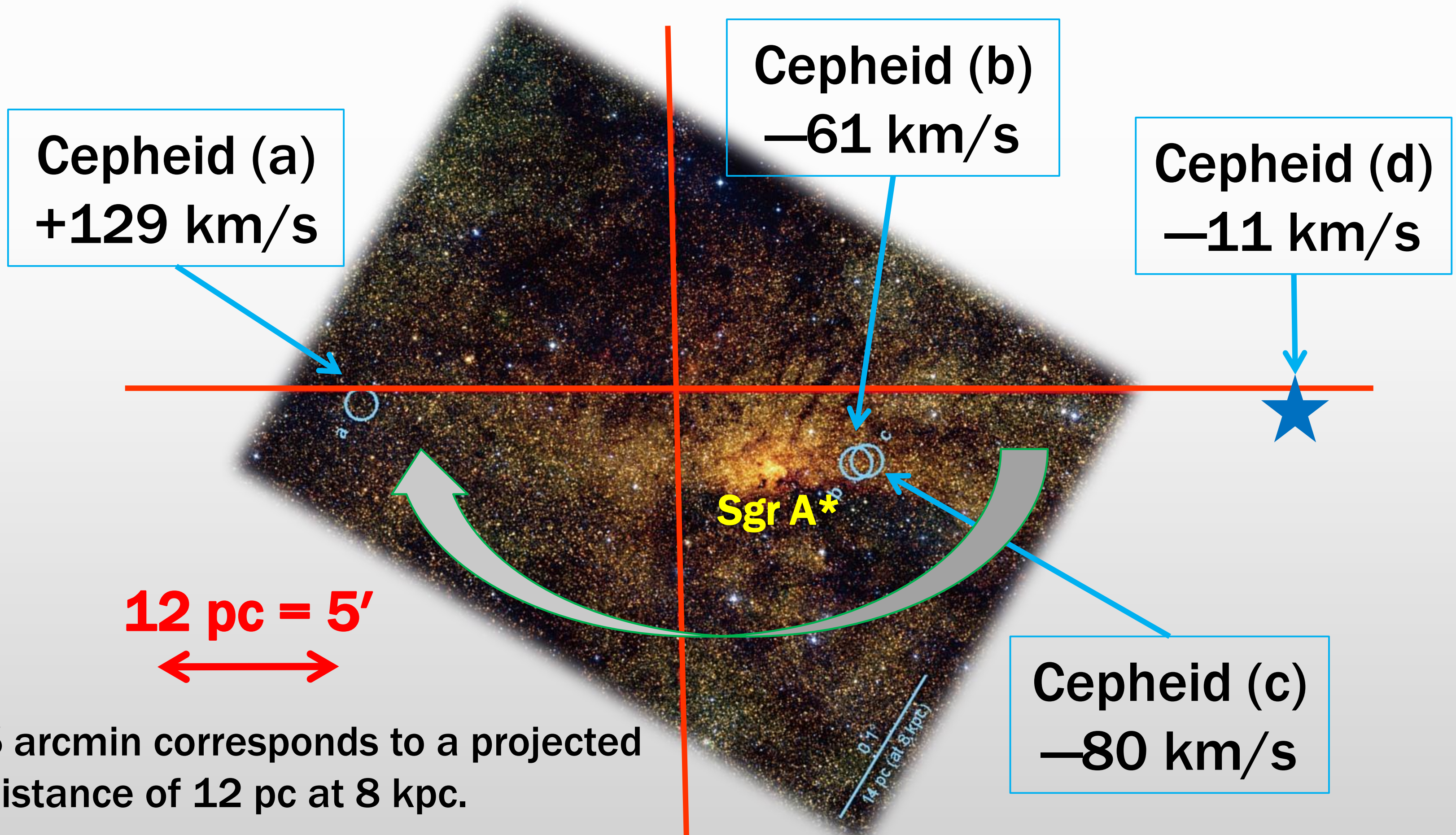
- Subaru/IRCS + AO188
  - H- (or K-) band
  - R=λ/Δλ~20,000
- 4 Cepheids reported in Matsunaga et al. (2011, 2013, 2015).
- We also observed 10 standard stars and 2 well-studied Cepheids (δ Cep and X Cyg).

Date	λ	Integration	S/N	Obj.
2010/06/20	*K*	300 sec × 8	~25	(a)
2012/05/25	*H*	300 sec × 12	~20	(a)
2012/05/25	*H*	300 sec × 10	~20	(b)
2012/05/25	*H*	300 sec × 12	~20	(c)
2012/07/26	*H*	300 sec × 14	42	(a)
2012/07/26	*H*	300 sec × 12	55	(b)
2012/07/27	*H*	300 sec × 12	35	(c)
2012/07/27	*H*	300 sec × 8	36	(d)



Kinematics of the Cepheids

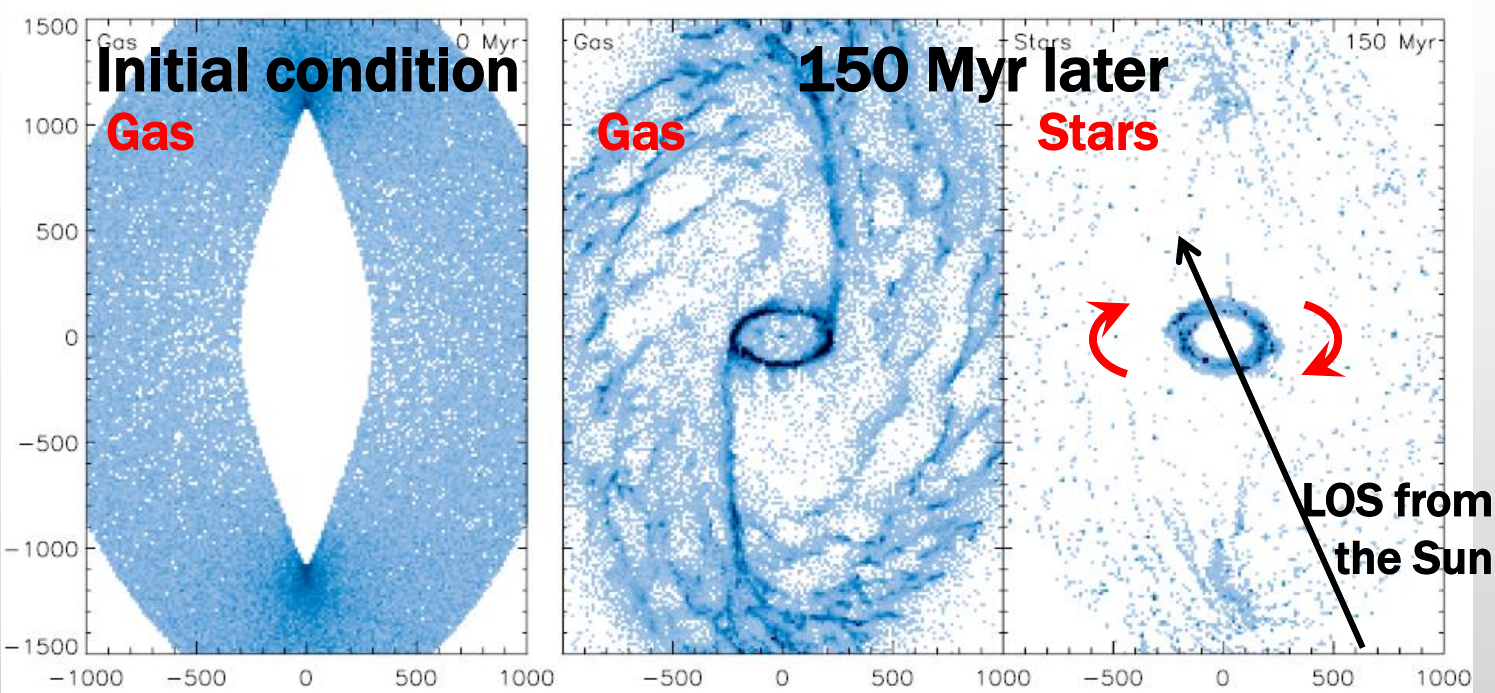
- Matsunaga et al. (2015, ApJ, 799, 46)
- Radial velocities (V_{LSR}) Consistent with the rotation of the Nuclear Disk.



5 arcmin corresponds to a projected distance of 12 pc at 8 kpc.

In context of chemical evolution

- Chemistry of the targes may tell us the origin(s) of gas in the Central Molecular Zone.
- 3 possible origins
  - Gas in the inner Disk falling through the Bar—**metal-rich**
  - Gas being lost by old evolved stars in the Bulge—**around solar**
  - (High-velocity) clouds in the Halo—**metal-poor**



N-body/SPH simulation by Kim et al. (2011)

Analysis of IRCS H-band spectra for metallicity

Establishing analysis methods and tools using spectra of standard stars

Chemical analysis with H-band high-resolution specrtra

- Still state of the art
  - line information (identification, strengths)
  - how to derive various parameters (T_{eff}, log g, metals)
- APOGEE (Majewski et al. 2015, and a lot more)
  - Providing many fundamental results to enable the accurate chemical analysis with H-band spectra in the recent couple of years.
  - Similar resolution to our H-band data, but slightly narrower wavelength coverage.
  - Our analysis has been developed independently.

Overview: Steps

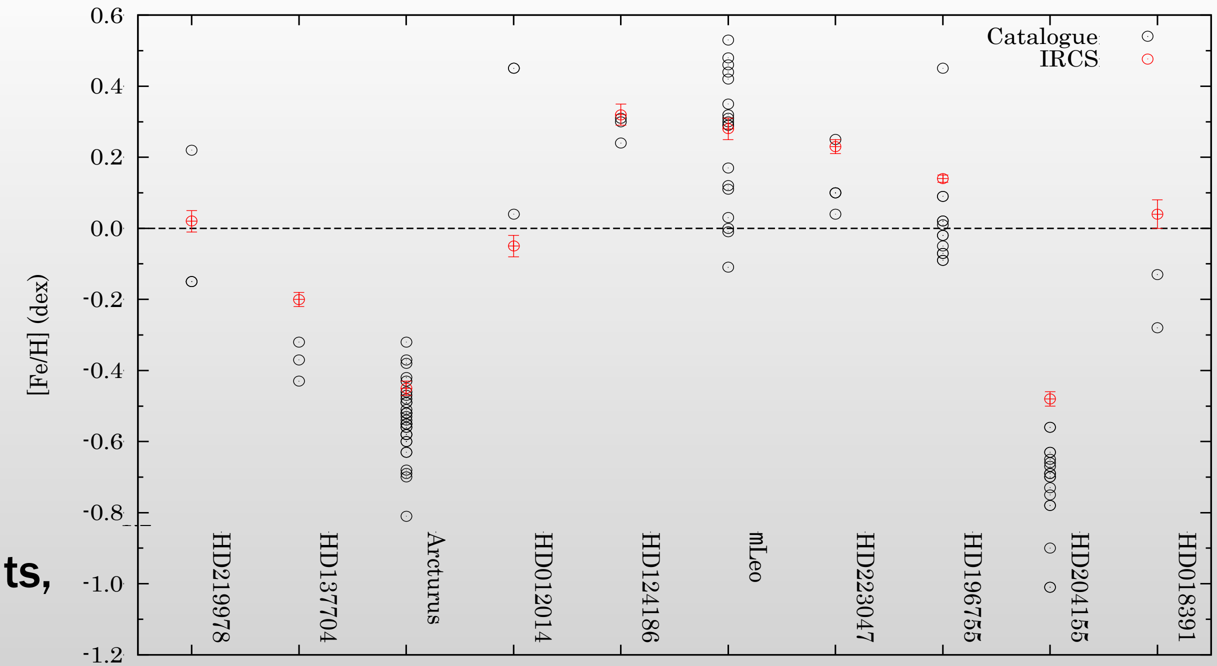
- For metallicity standard stars
  - Reproducing the known metallicities of 10 standards to verify analysis tool and line information
  - Finding a temperature indicator (line-depth ratio method)
- For standard Cepheids
  - Reproducing the known temperatures and metallicities of 2 Cepheids (δ Cep and X Cyg) to check the methods
- For 4 target Cepheids
  - Deriving the temperatures and metallicities

Tools and basic data

- SPTOOL (by Y. Takeda)
  - SPSHOW – synthesizing and displaying model spectra
  - MPFIT – measuring abundances
  - We combined SPTOOL tasks to effeciently determine microtubulence and metallicity.
- Stellar atmosphere models (by Kurucz)
- Line lists
  - Atomic : Melendez & Barbuy (1999)
  - Molecular : Kurucz (http://kurucz.harvard.edu/)
  - including wavelengths, excitation potentials, and strengths

[Fe/H] measurements for standards

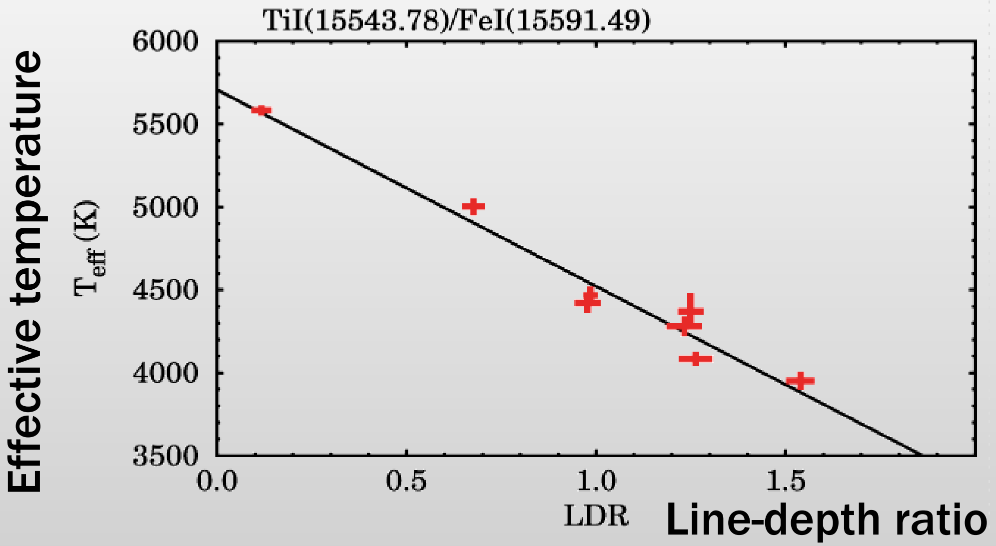
- We selected 95 (relatively unblended) Fe I lines.
- Microturbulences are determined by balancing between [Fe/H] values from strong and weak lines.
- Derived [Fe/H], standard errors of 0.03 dex, agree very well with literature values.



Comparisons of [Fe/H] of 10 standard stars; red—our results, and black—literature values.

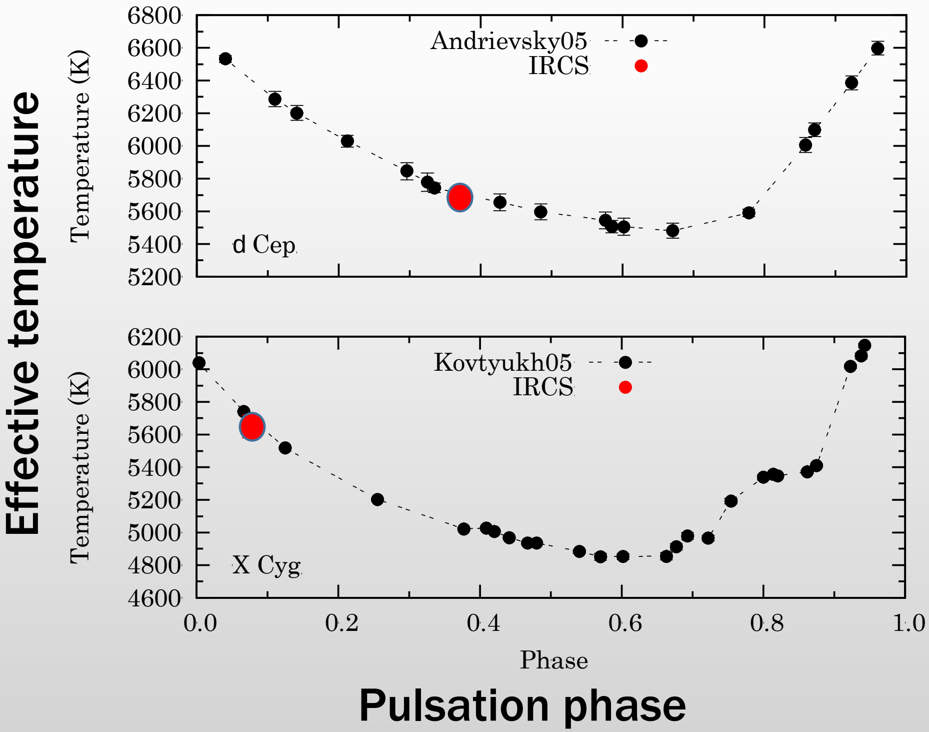
Line-depth ratios (LDRs) as a thermometer

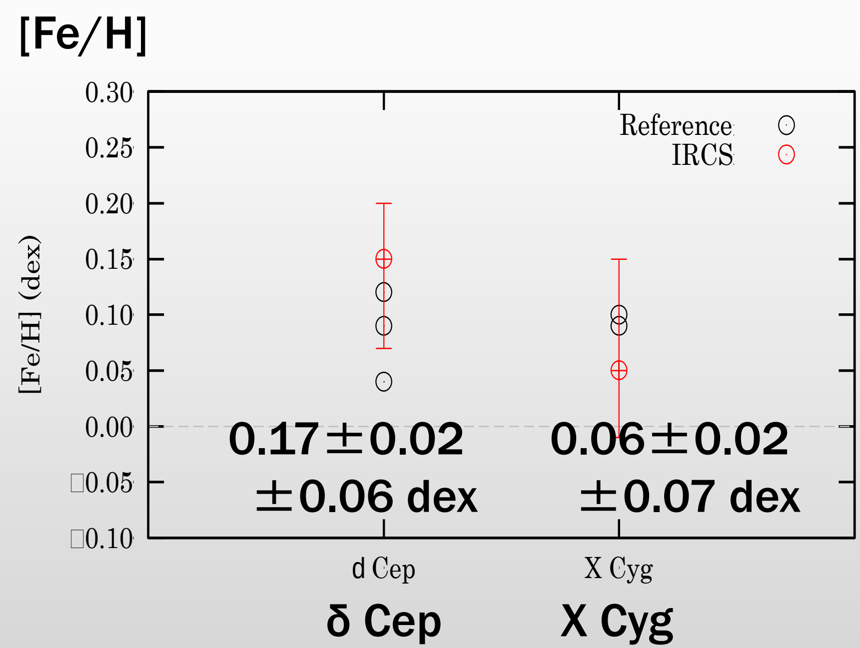
- Fukue et al. (2015, ApJ, 812, 64)
- Combinations of lines with different excitation potential are sensitive to stellar temperature.
  - Low-excitation potential (< 4eV) – relatively insensitive to $T_{\rm eff}$ variation
  - High-excitation potential (5—7 eV) – strong dependency on $T_{\rm eff}$
- Based on IRCS spectra of 8 standard stars with known $T_{\rm eff}$, we derived 9 LDR-$T_{\rm eff}$ relations (for the first time in H-band).
- Because of the very large foreground extinction for our targets, this method is crucial to determine their temperatures.



Analysis for standard Cepheids

- T_{eff} and [Fe/H] of well-studied Cepheids, δ Cep and X Cyg
- LDR method gives temperatures consistent with the observed phases.
- A typical gravity for Cepheids with P=20 days, log g=1.3±0.5 dex, is assumed.
- Derived [Fe/H] also agrees with literature values within 0.05 dex.





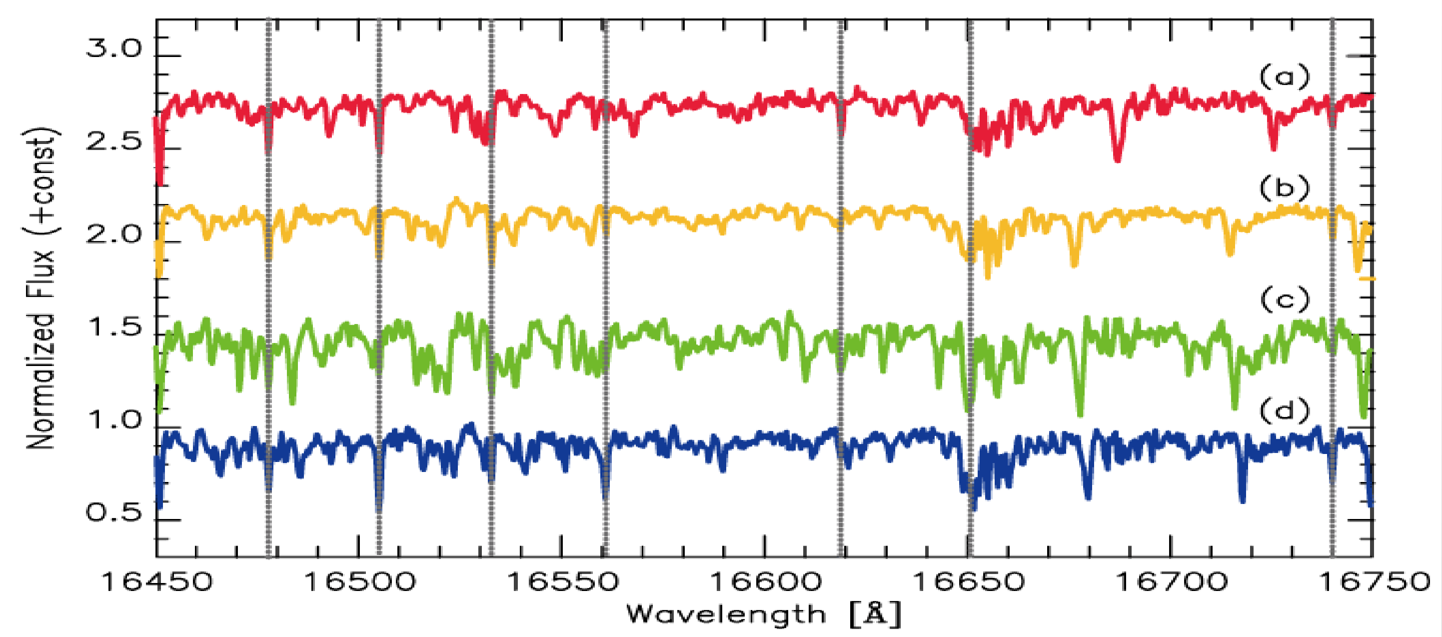
Results for target Cepheids

[Fe/H] of Cepheids in the Nuclear Stellar Disk
and their implications

Data to use for the targets

- Subaru/IRCS + AO188
  - H-band
  - R=λ/Δλ~20,000
- Relatively higher-S/N spectra takend in 2012 are used for chemical analysis (but S/N=35~55)

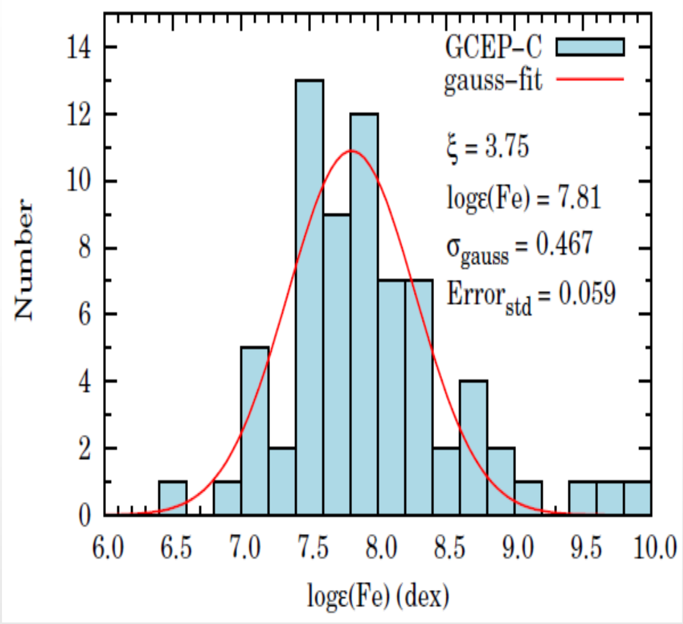
Object	Date	λ	Integration	S/N
GCC-a	2012/07/26	*H*	300 sec × 14	42
GCC-b	2012/07/26	*H*	300 sec × 12	55
GCC-c	2012/07/27	*H*	300 sec × 12	35
GCC-d	2012/07/27	*H*	300 sec × 8	36



T_{eff} and [Fe/H] of the targets

- Although the accuracy is limited by low S/N (35—55), T_{eff} and [Fe/H] are reasonably constrained.

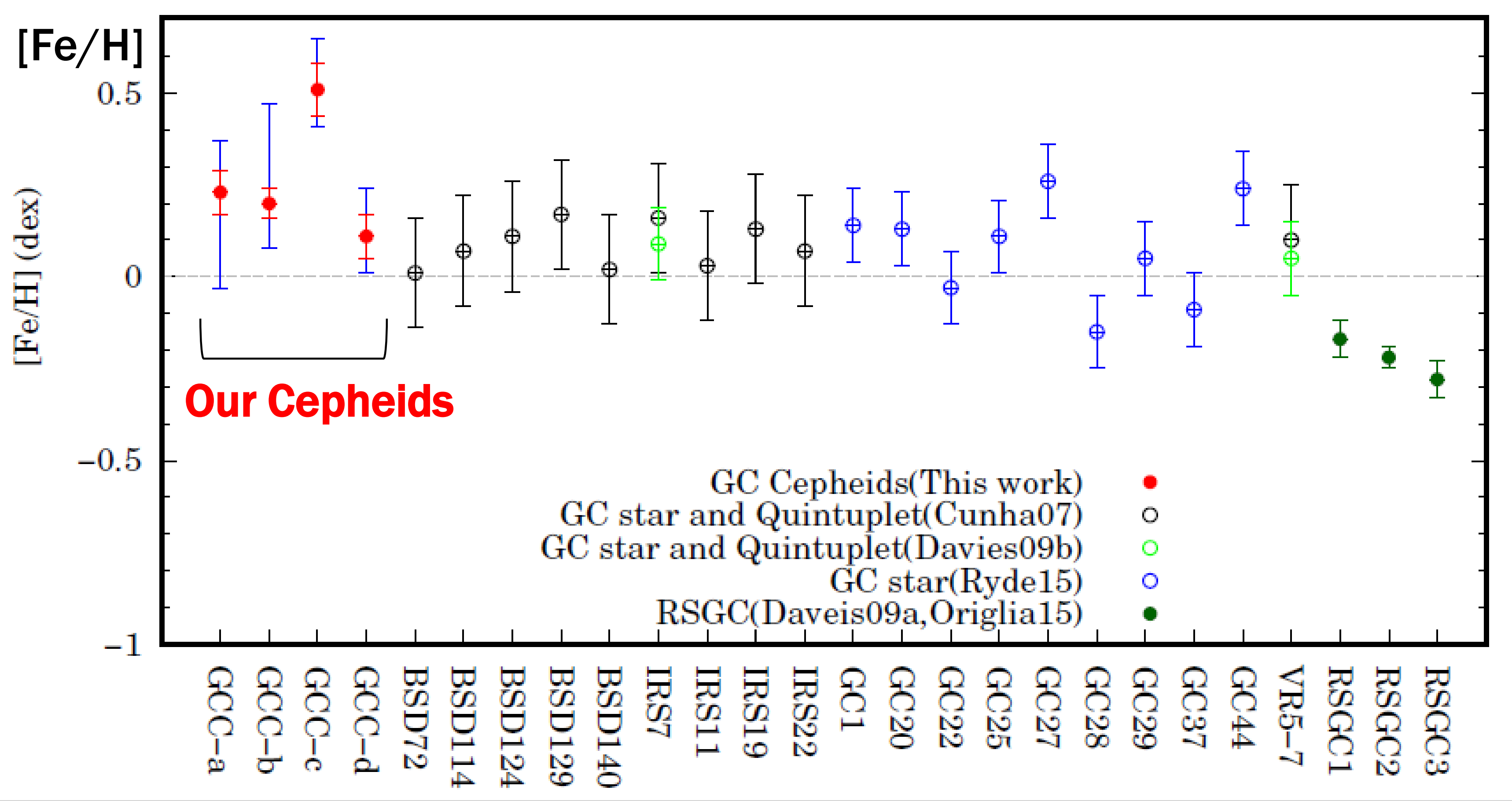
Object	T_{eff}(K)	[Fe/H] (dex)
GCC-a	5300±290	**0.23**±$0.06^{+0.14}_{-0.26}$
GCC-b	5250±250	**0.20**±$0.04^{+0.27}_{-0.12}$
GCC-c	4780±160	**0.51**±$0.07^{+0.14}_{-0.10}$
GCC-d	5000±120	**0.11**±$0.06^{+0.13}_{-0.10}$



Important—this result is preliminary, in particular, for the case of GCC-c, [Fe/H]~+0.5 dex. In such a high-metal regime, T_{eff} from LDR can be altered due to metallicity effect on the LDR method.

Comparison with literature

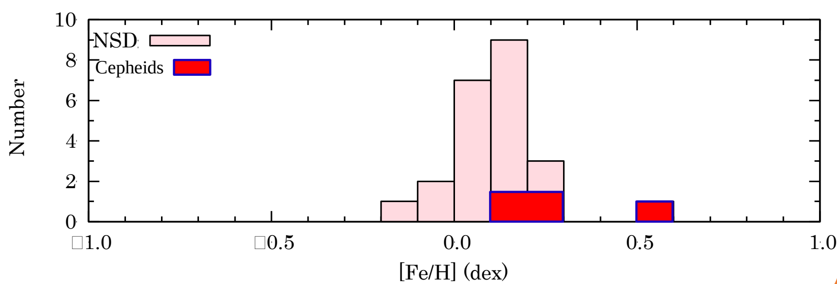
- All the previous measurements indicates [Fe/H] around the solar, -0.2~+0.2 dex, regardless of ages of tracers.
- 3 Cepheids have [Fe/H] similar to the other tracers, while 1 (GCC-c) have a significantly higher [Fe/H], +0.5 dex.



Metallicities of relevant systems

Most stars including 3 Cepheids seem to favor <[Fe/H]> of stars in the *Bulge*, but gas from the inner *Disk* may be also responsible.

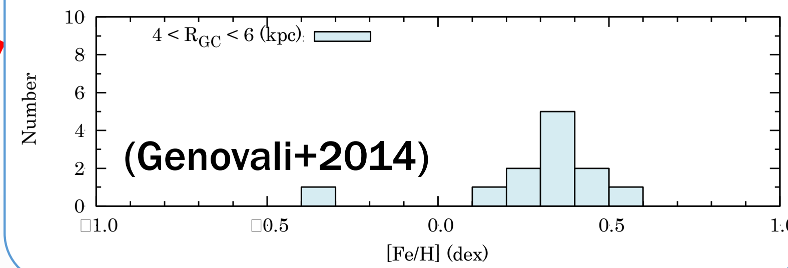
Stars in the *Nuclear Stellar Disk*
<[F/H]>= **+0.07** dex



Halo gas is too metal-poor to produce stars in the NSD.

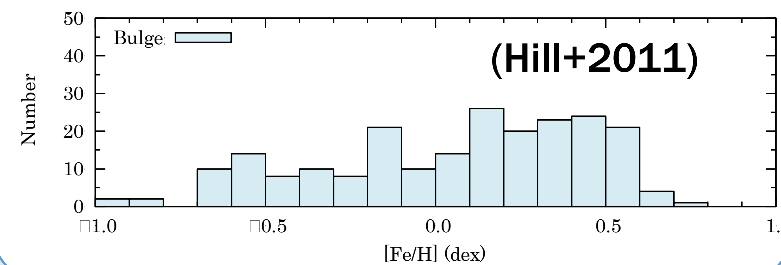
Gas from the inner *Disk*?

Cepheids in the innermost part of the *Disk*, R_{GC}=4~6kpc: <[Fe/H]>= **+0.3**



Gas recycling within the *Bulge*?

Red clump stars in the *Bulge*:
<[Fe/H]>= **+0.0** dex



Gas fall from the *Halo*?

High velocity clouds in the *Halo*
eg) [Fe/H] ~ **–0.7dex** (Richter+2015)

Implications and drawbacks

- Implications
  - Mass-loss gas from stars in the Bulge may be the main source of gas and star formation in the Nuclear Stellar Disk (or the Central Molecular Zone) (see also Cunha+2007).
  - One of our Cepheids, GCC-c, has a significantly higher [Fe/H] than other stars. [Fe/H]=+0.5 favors gas fueling from the inner Disk.
- Drawbacks
  - The S/N of our spectra are low, at around the lower limit of quality required for reasonable [Fe/H] measurements.
  - The number of stars and [Fe/H] measurements are still limited both for the NSD and for the inner Disk.

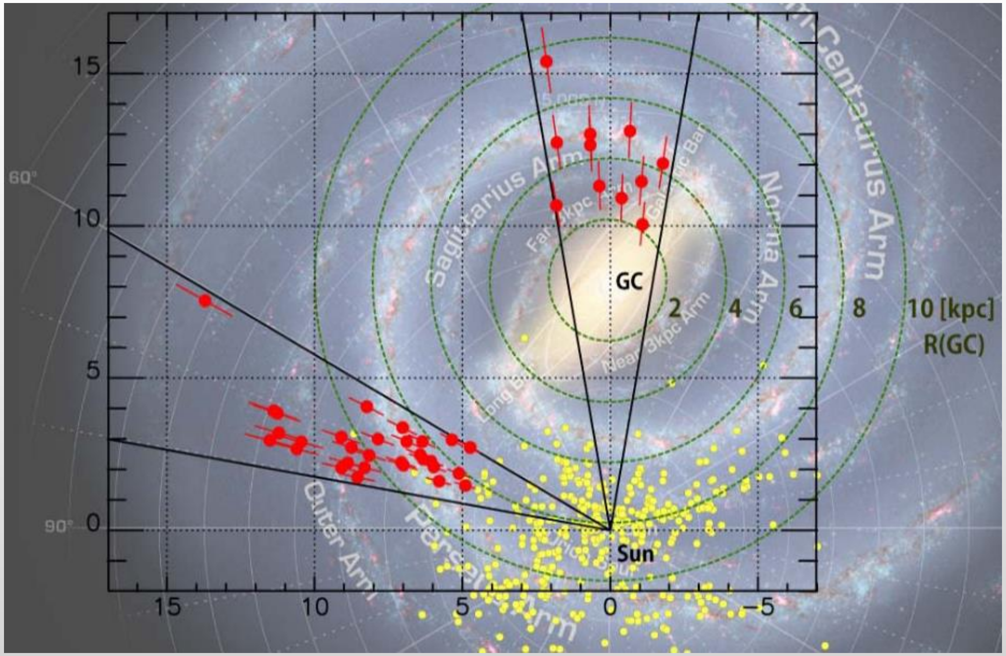
Summary

- IRCS results of velocities and [Fe/H] of 4 Cepheids in the Nuclear Stellar Disk
- We have developed chemical abundance analysis for H-band spectra.
  - Line-depth ratio (LDR) method for T_{eff} (Fukue et al. 2015)
  - 95 Fe I lines to use for [Fe/H]
- [Fe/H] of Cepheids in the Nuclear Stellar Disk
  - 3 Cepheids consistent with enrichment by gas lost by low-mass evolved stars in the Bulge, while 1 may give the first evidence of metal-rich gas fallen from the inner Disk.

Future prospects

- Abundances of other elements would give further insights into chemical evolution.
- More Cepheids are being discovered in recent surveys (eg. KISOGP; VVV—Dekany et al. 2015ab).
- Other near-IR spectrographs, eg WINERED and GIANO, will be also useful to make similar measurements.

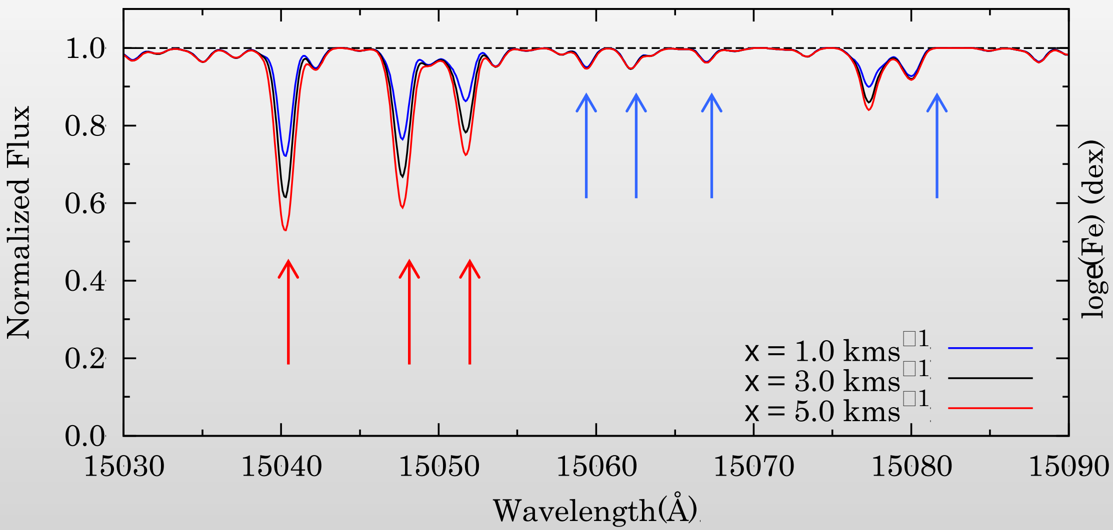
Targets in our S16A run (2 nights) which are located in uncultivated regions of the Galactic disk.



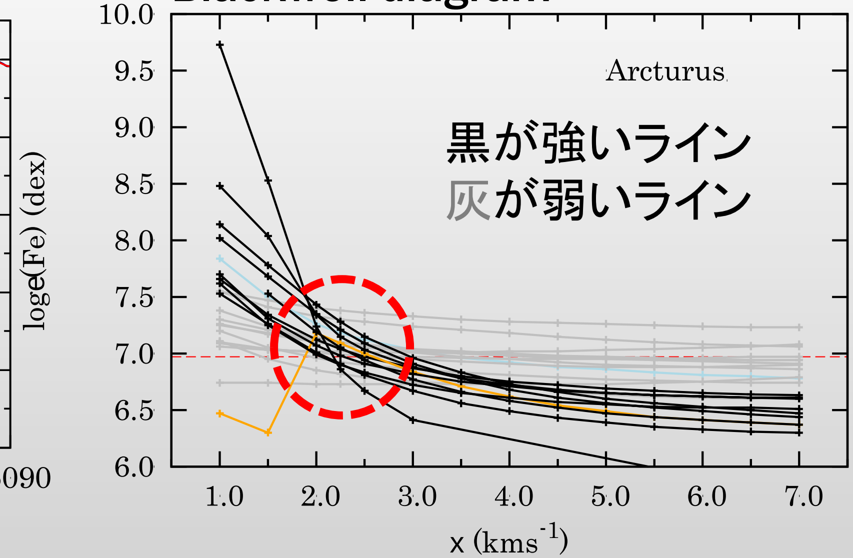
End

ミクロ乱流ξの決定

- **ミクロ乱流ξ**
  - ライン形成領域における微小な非熱的成分
  - サチレーションするような強いラインほどξの影響が大きく、吸収の浅い弱いラインはξへはほとんど依存しない。
- **Blackwell diagram (Saffe & Levato 2004)**
  - 強いラインと弱いラインのそれぞれで導出された金属量の分散が最小になるξを探す方法。
  - IRCSでの決定精度：~0.5km/s

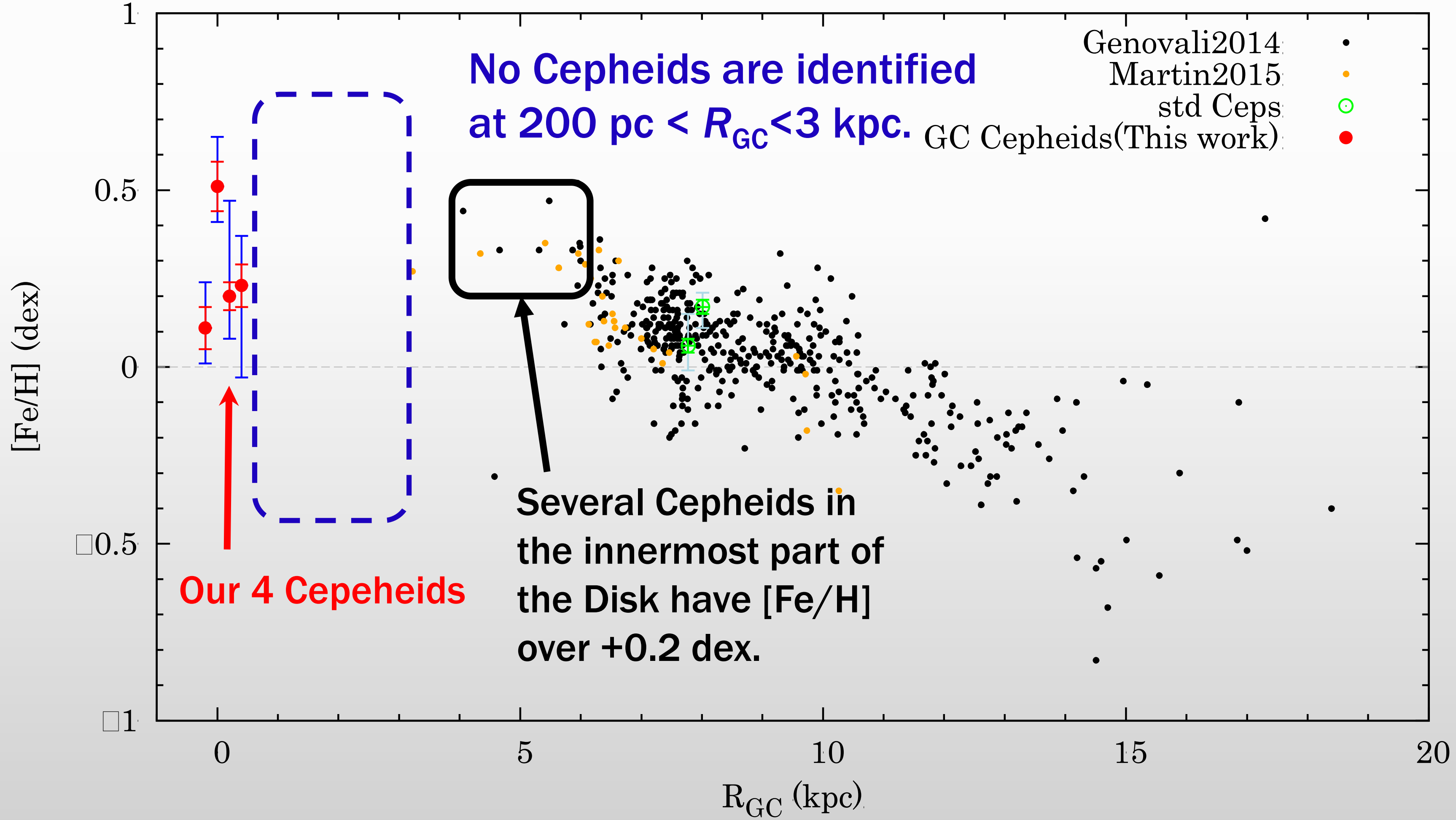


Blackwell diagram

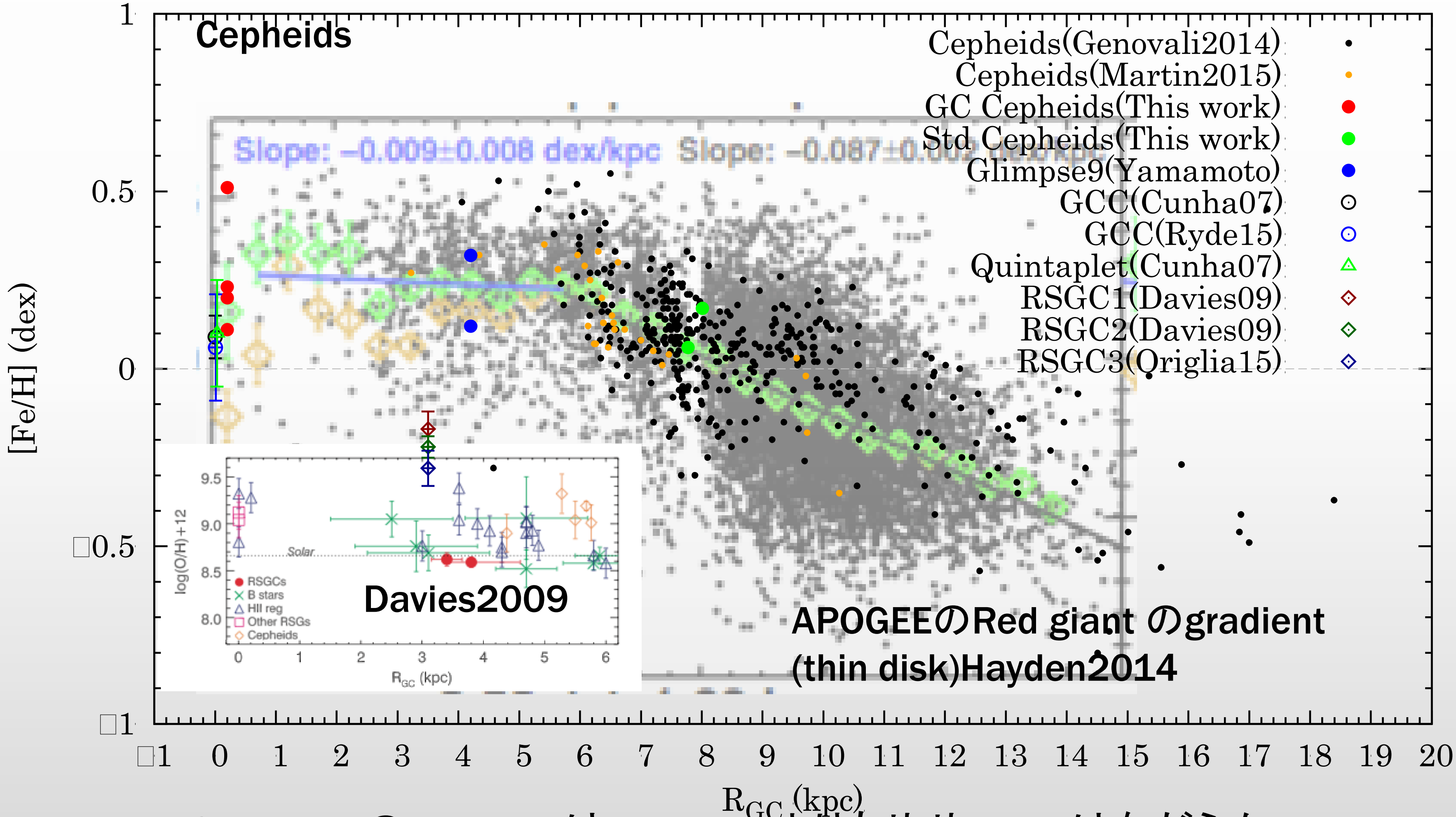


Comparison with other Cepheids in the Disk

- 3 Cepheids with [Fe/H] ~ 0.1—0.2 dex are not so metal-rich as several Cepheids in the innermost part of the Disk, but the number of the Cepheids in the inner Disk is very limited.



金属量分布の比較



- Cepheidsのgradientはred giantよりもややslopeはなだらか
- Glimpse9やRSGCなどclusterのある領域にはHII領域が付随

バルジの星の金属量

Ryde2015

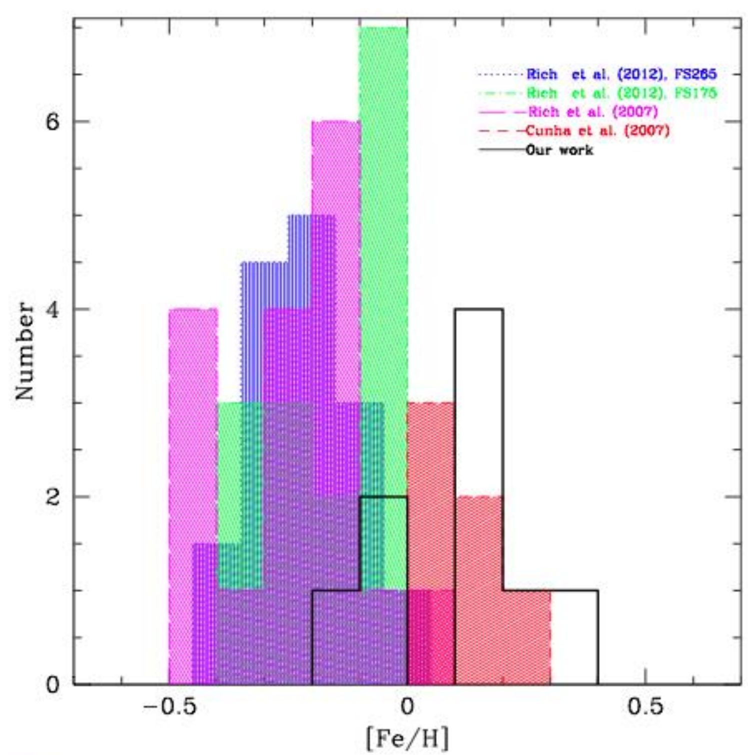


Fig. 6. Histogram of our metallicities in black with a mean of [Fe/H] = 0.11 and a standard deviation of 0.15. The red histogram shows the metallicities of the Galactic centre giants of Cunha et al. (2007). For comparison we show the field of Rich et al. (2007) located at $(l,b) = (0°, -1°)$ in magenta, the field at $(0°, -1.75°)$ in green (Rich et al. 2012), and the field at $(1°, -2.65°)$ in blue (Rich et al. 2012).

Bensby2013

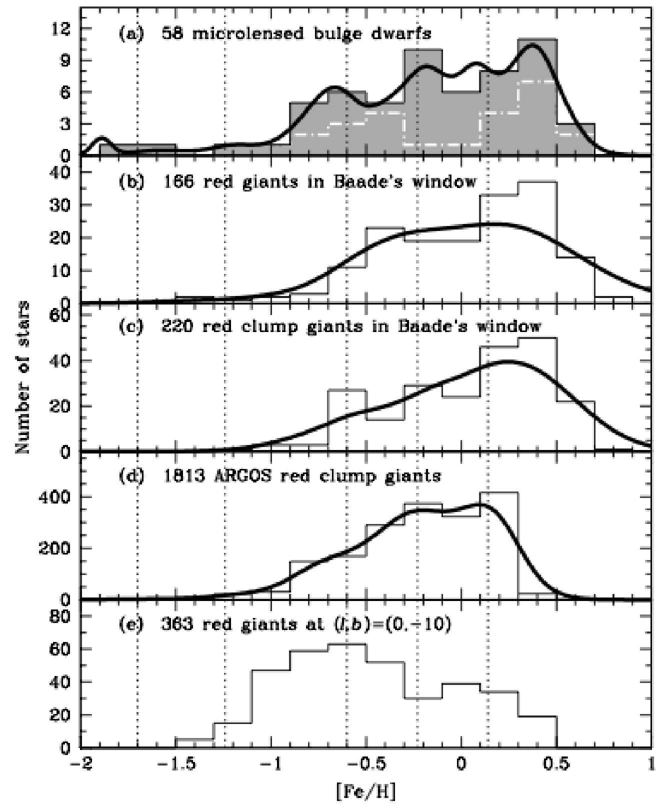
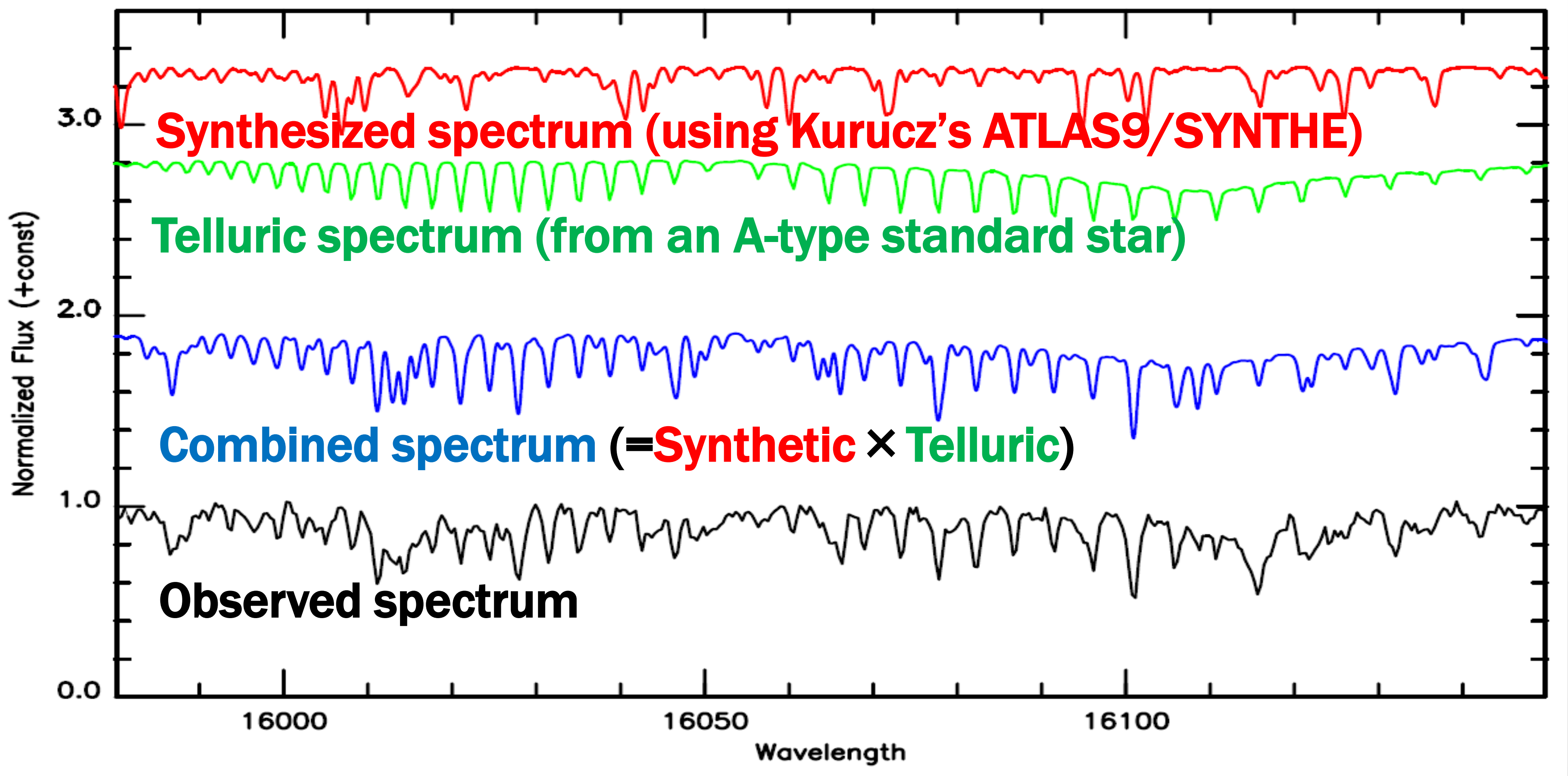


Fig. 12. a) Metallicity distribution for the microlensed dwarf sample (white dashed line shows the distribution of the 26 microlensed dwarf stars from Bensby et al. 2011); **b)** 166 red giant stars in Baade's window from Hill et al. (2011); **c)** 220 red clump stars in Baade's window from Hill et al. (2011); **d)** 1813 red giant stars with from the ARGOS survey fields at $(l, b) = (0, -5), (5, -5), (-5, -5)$ from Ness et al. (submitted). **e)** 363 red giants at $(l, b) = (0, -10)$ from Uttenthaler et al. (2012); The curved lines in **a)**–**d)** represent generalised histograms. Dotted vertical lines mark the peaks claimed by Ness et al. (submitted) in **d**).

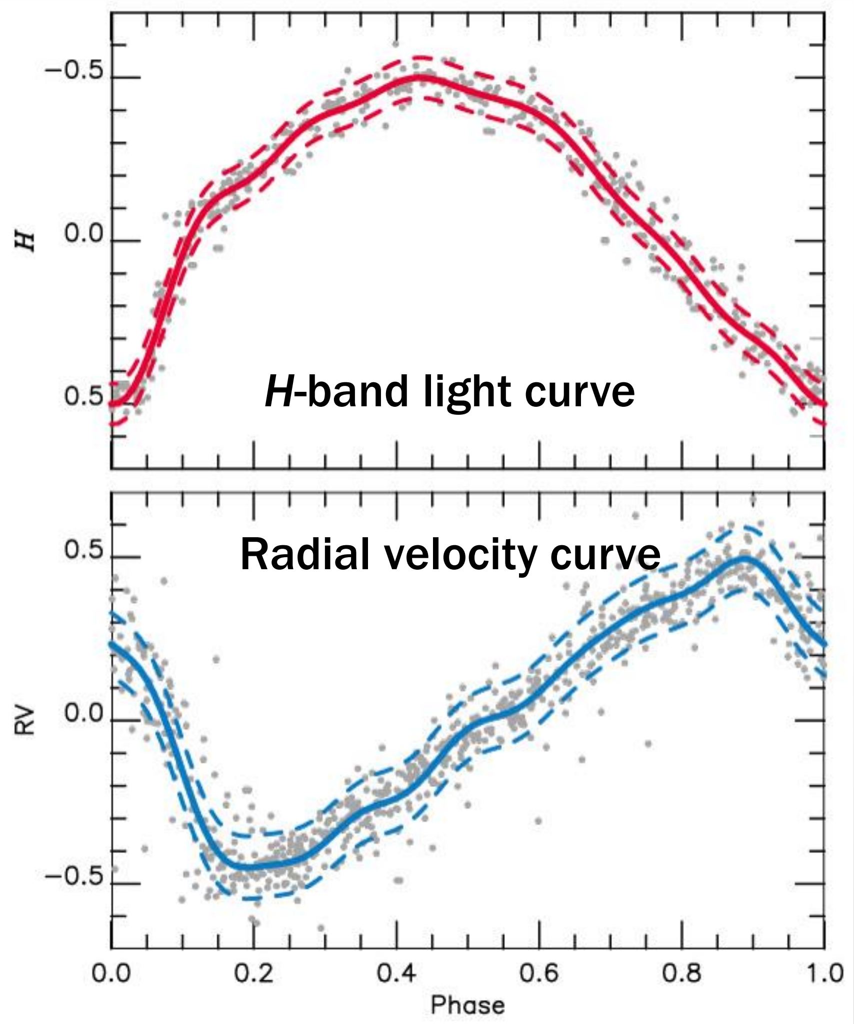
Estimating radial velocities

- Comparing **Observed** spectra are with **Combined** spectra (=**Synthesized** × **Telluric**)
- Finding velocities which give the best matches between the Observed and Combined spectra



Light curve and velocity curve templates

- *H*-band light and velocity curves of 11 Cepheids with *P*~20 days are conbined.
  - Data compiled by Groenewegen (2011)
- These templates enable us to predict the velocity curve from the light curve.



(Pulsation-corrected) mean velocities

- Typical uncertainties are roughly ±5km/s.