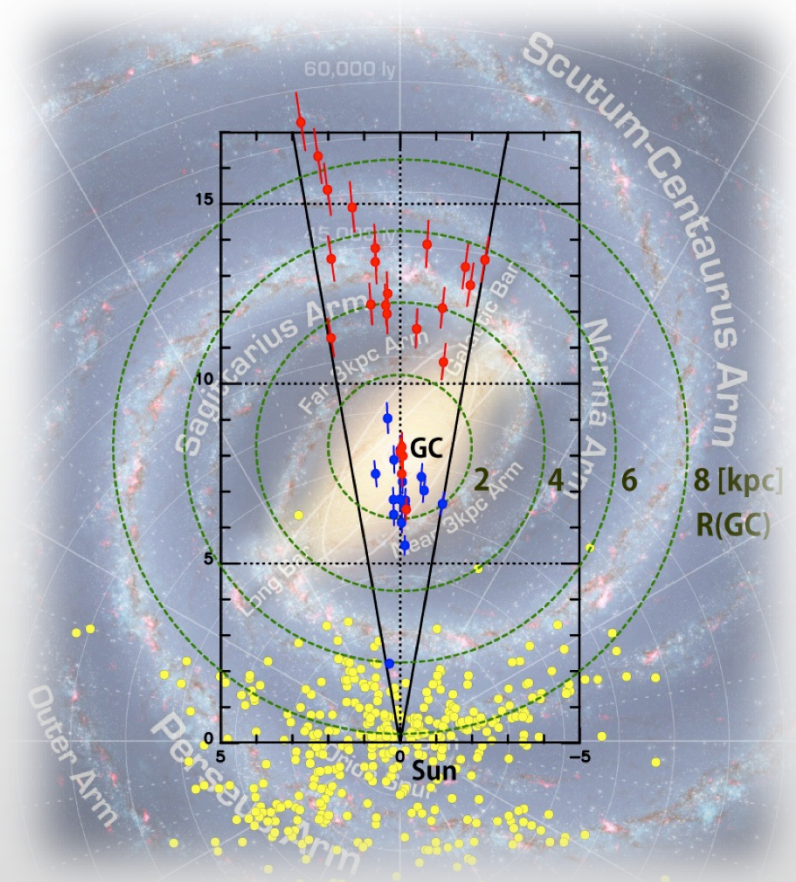


# Chemical and kinematic structure of the hidden part of the Milky Way

松永 典之

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(The University of Tokyo)



# Partly based on:

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- submitted to MNRAS

- N. Matsunaga, M. W. Feast, G. Bono, N. Kobayashi, L. Inno, T. Nagayama, S. Nishiyama, Y. Matsuoka & T. Nagata

- NM et al. 2015, *ApJ*, 799, id. 46

- Feast et al. 2014, *Nature*, 509, 342—344

- NM et al. 2013, *MNRAS*, 429, 385—397

- NM et al. 2011, *Nature*, 477, 188—190

In collaboration with W. Aoki, J. Baba, G. Bono, M. W. Feast, M. Fujii, K. Fukue, K. Genovali, I. S. Glass, S. Hamano, H. Hatano, Y. Ikeda, T. Kawadu, N. Kobayashi, S. Kondo, T. Nagata, T. Nagayama, S. Nishiyama, M. Tamura, T. Tsujimoto, R. Yamamoto

# What we want to do w/ U-Subaru

- Measuring Radial velocities and metallicities of selected tracers (pulsating stars) of the Milky Way
  - Typically only 1 Cepheids expected within the FOV
  - Targets will be faint enough, 12–18 VEGA mag in J, to require 8-m class telescopes.
- Characterizing surrounding stars around the tracers: reddening and stellar populations
  - Uncertainty in reddening law is a crucial (and nasty) problem when we study hidden regions of the Milky Way.

**Multi-object spectroscopy (eg. w/ MOIRCS) with ULTIMATE-Subaru is required.**

# Outline

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- Introduction

- Cepheids and their roles as distance and population tracers
- The need of large-scale surveys

- New Cepheids being found in our surveys

- IRSF/SIRIUS surveys towards the Galactic Center and Bulge
- Spectroscopic follow-ups with Subaru/IRCS

- The impact of uncertainty in the extinction law

- Comparison with Dekany et al. (2015a,b) who discovered distant Cepheids with VVV data toward the Bulge but disagree in the distribution of Cepheids; the extinction law is the key!

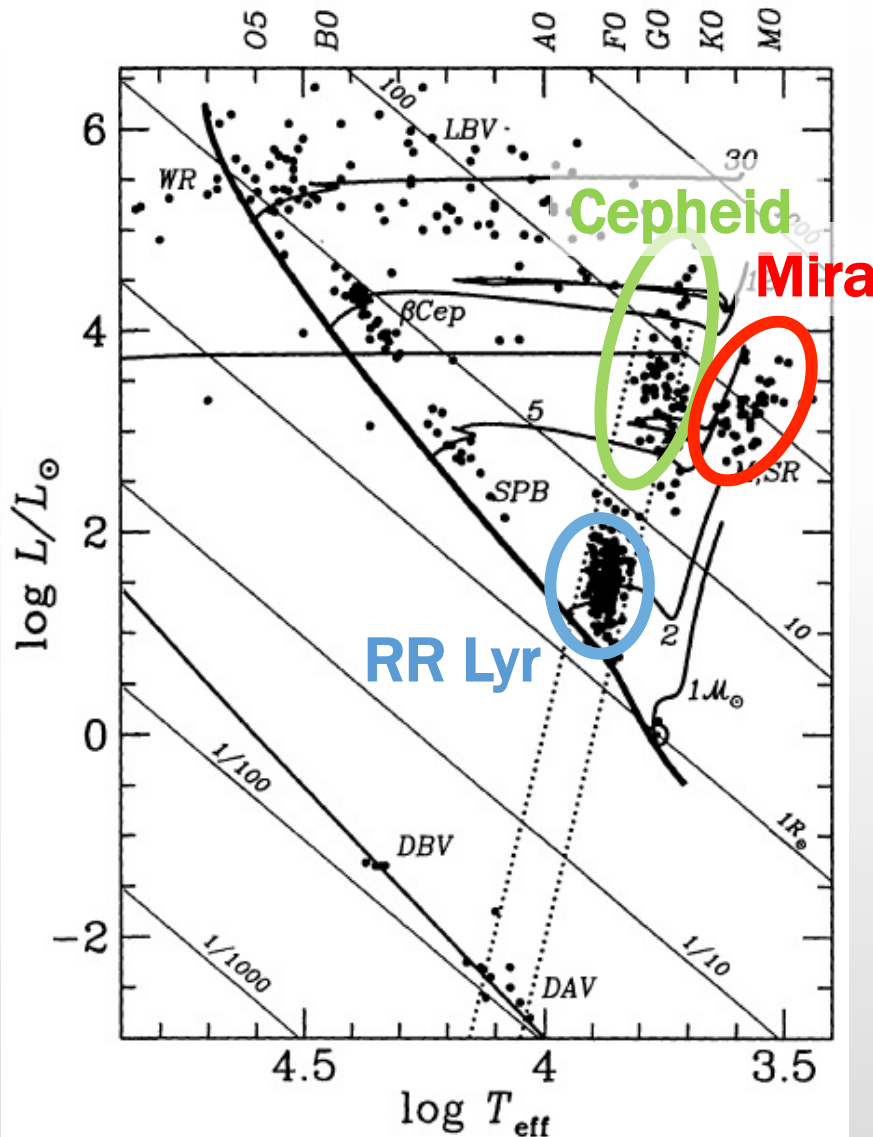
- ULTIMATE-Subaru

# Introduction

Cepheids and the need of infrared observations



# Cepheids and other variables



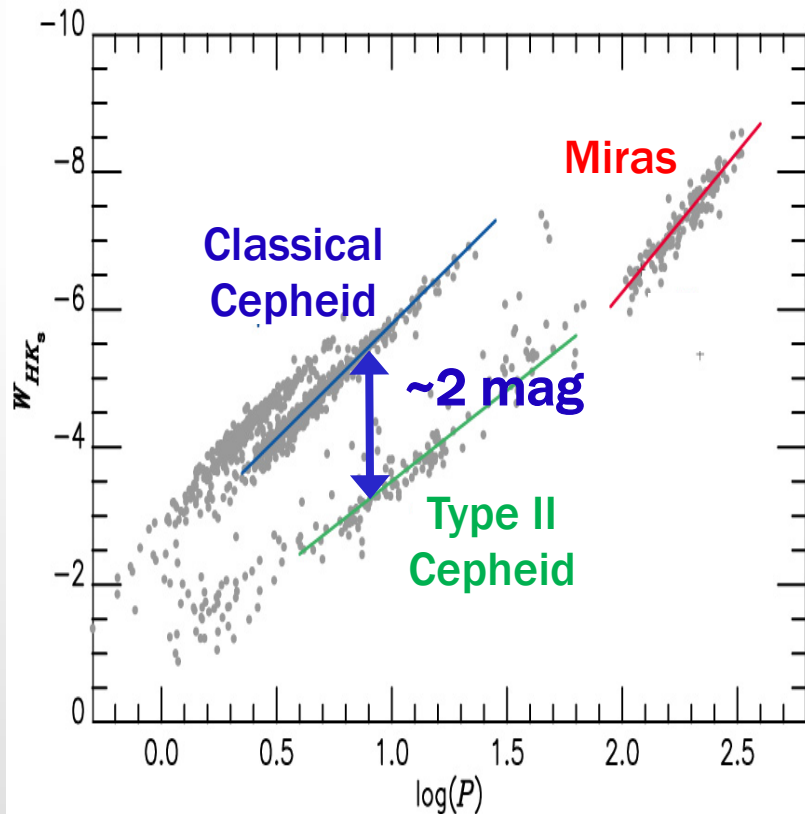
## • Cepheids

- in the Cepheid instability strip
- bright and periodic
- 2 types of Cepheids
  - classical Cep (10–300 Myr)
  - type II Cep (~10 Gyr)
- They are useful tracers of the Milky Way structure and evolution.

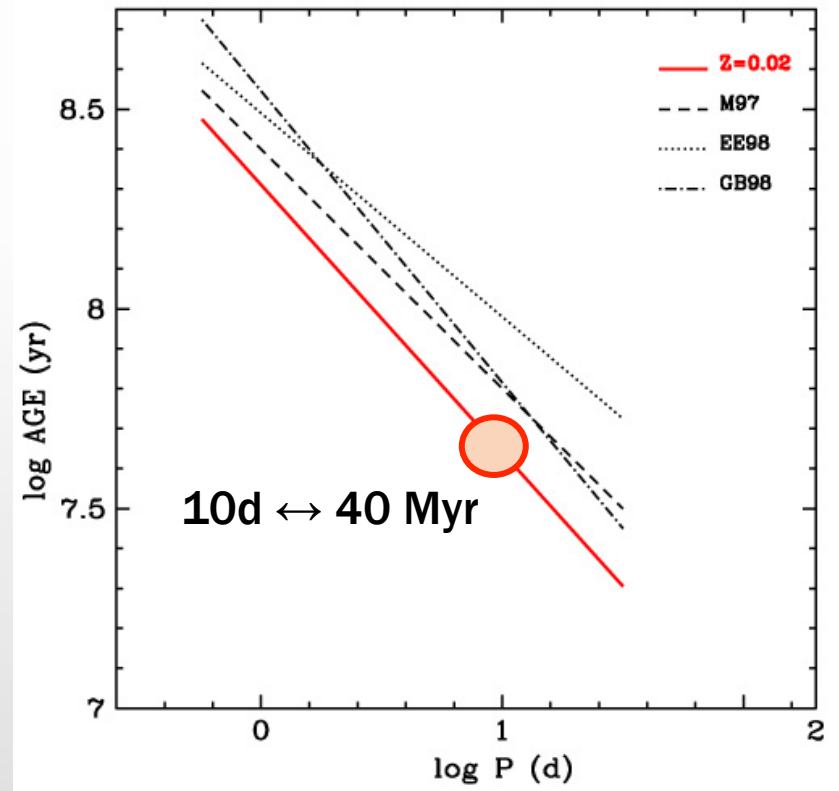
Distribution of variable stars across the H-R diagram (Gautschy & Saio, 1995)

# Classical Cepheids as tracers

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



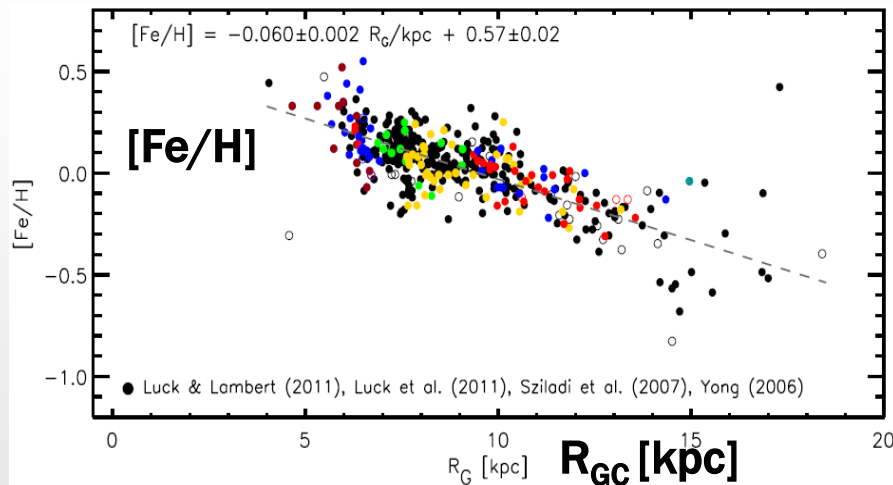
Near-IR P-L relations of LMC variables (Matsunaga, 2013)



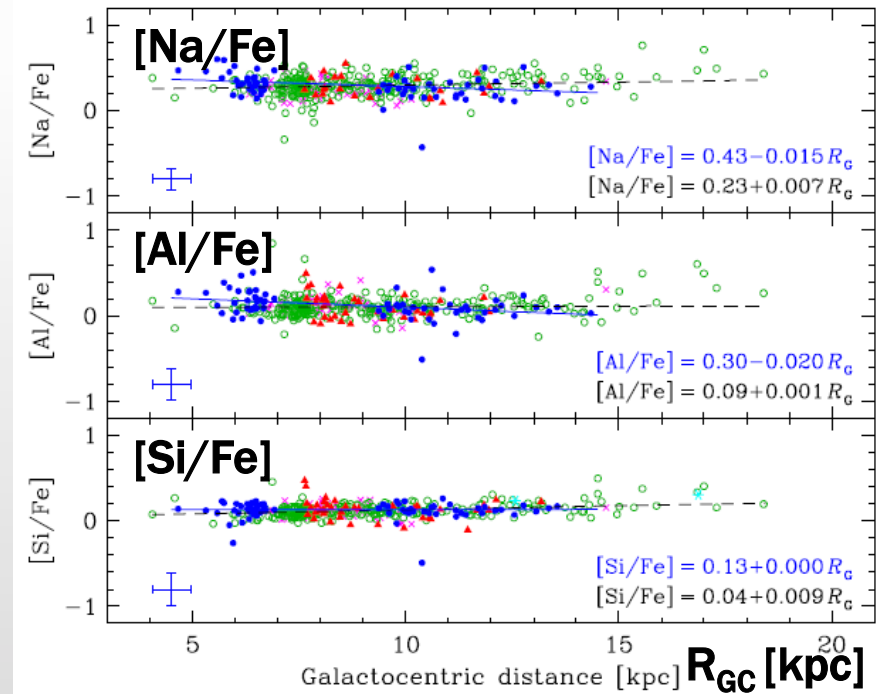
Period-age relation (Bono et al. 2005)

# 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)

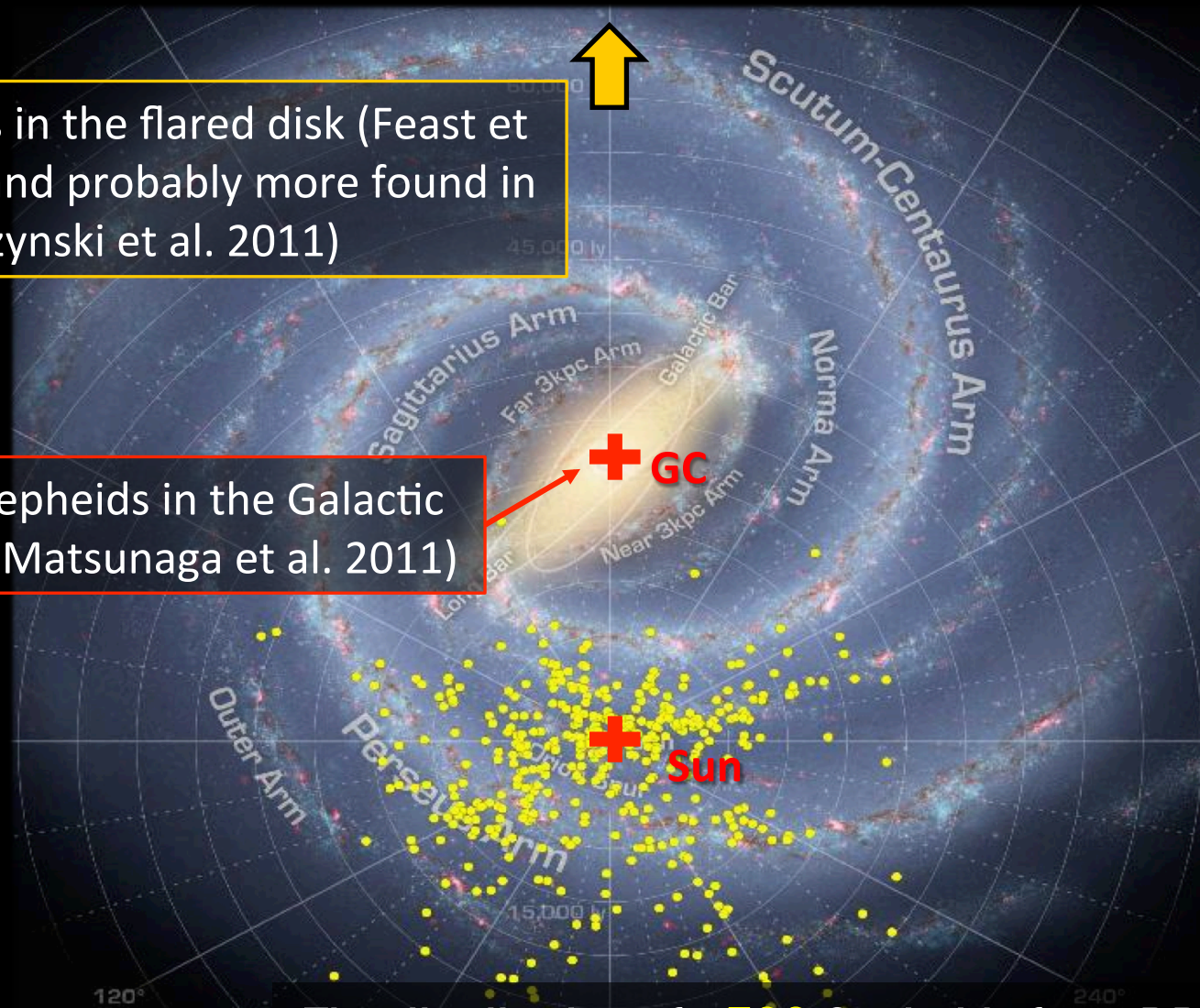


Genovali et al. (2015, A&A, 580, 17)

# Earlier surveys of classical Cepheids

5 Cepheids in the flared disk (Feast et al. 2014), and probably more found in OGLE (Soszynski et al. 2011)

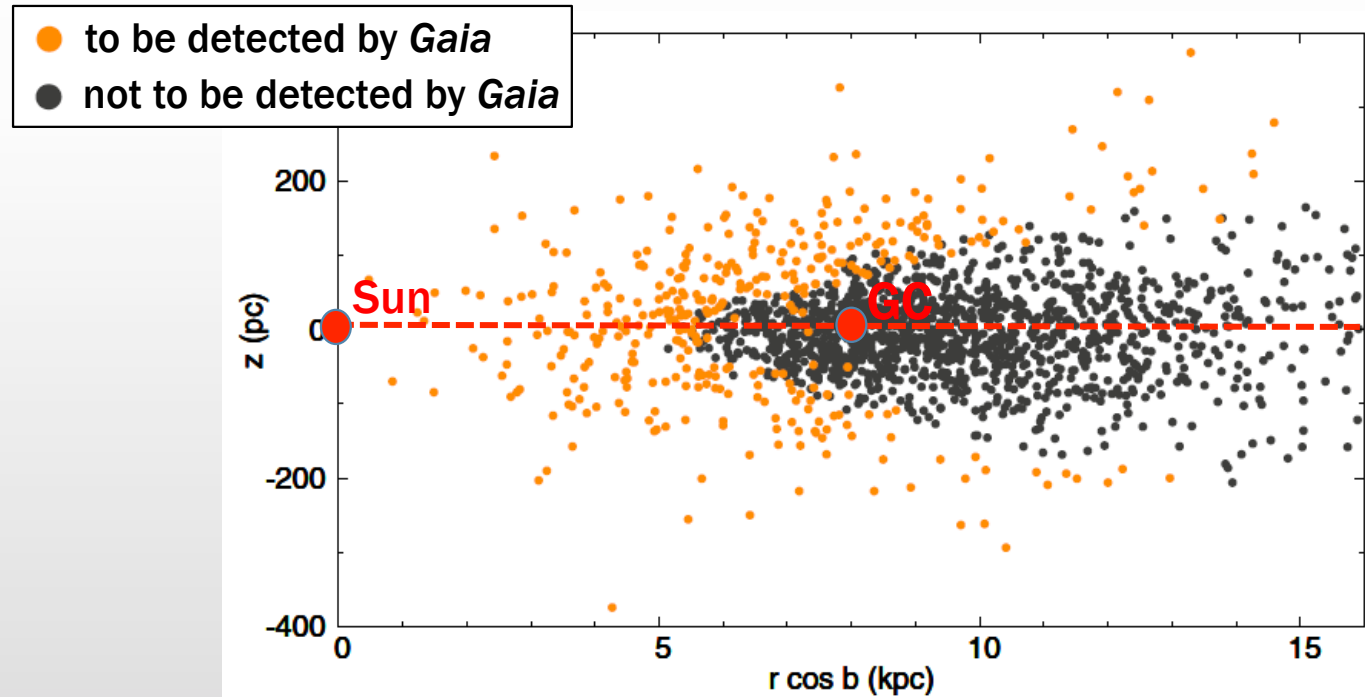
Three Cepheids in the Galactic Center (Matsunaga et al. 2011)



The distribution of **~500** Cepheids from DDO database:  
<http://www.astro.utoronto.ca/DDO/research/cepheids/>  
overlaid on the illustration by GLIMPSE project (2008)

# Cepheids waiting to be discovered

- Windmark et al. 2011, A&A, 530, A76
  - A simple exponential-disk model:  $f(R,z) = \exp(-R/3.5\text{kpc}) \text{sech}(z/z_0)$
  - 20,000 Cepheids predicted
  - 9,000 Cepheids may be detected by Gaia.



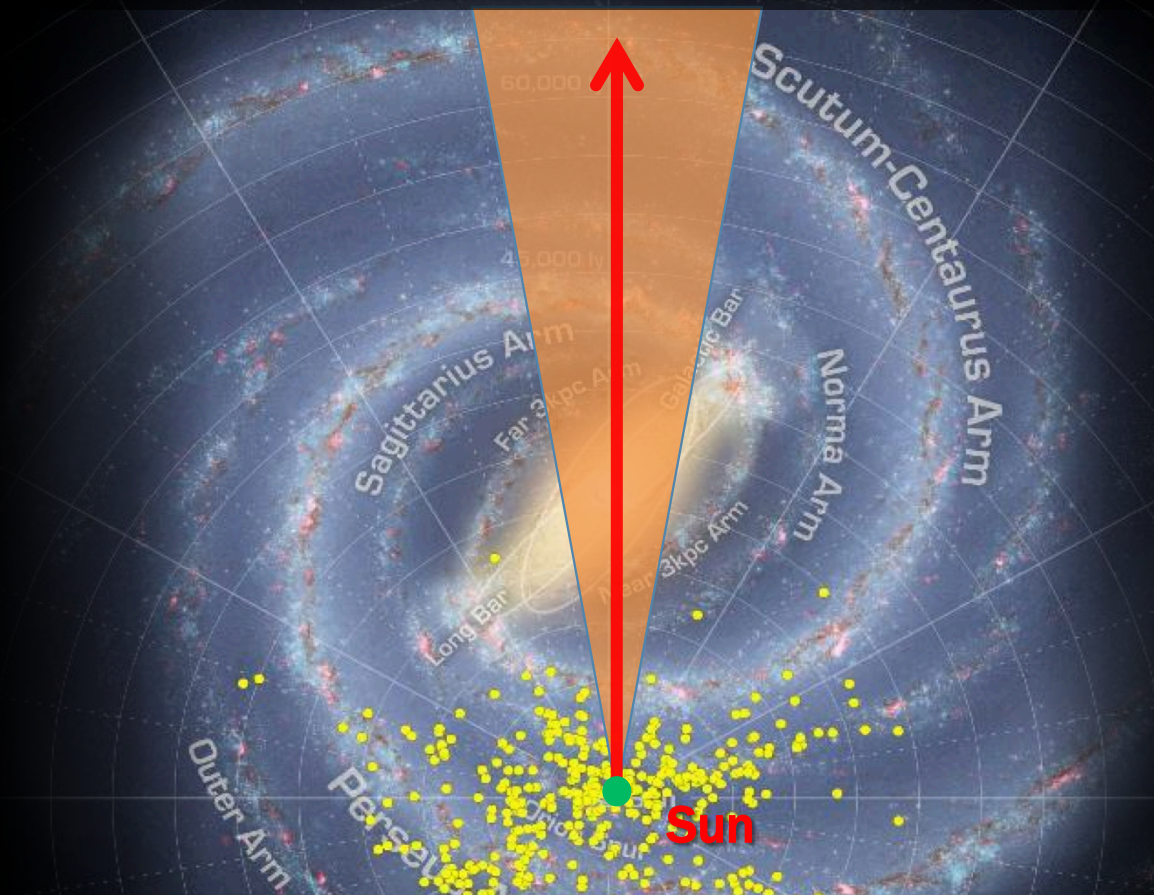
Simulation of Cepheids to be detected by *Gaia* (Windmark et al. 2011)

# **New Cepheids being found in our surveys**



Infrared surveys are revealing new tracers  
of the hidden part of the Milky Way



# IRSF surveys toward the GC and bulge



- **IRSF** 1.4-m telescope in South Africa
- **SIRIUS** JHKs 3-band imager

Region	range	#(FOVs)	Area	Obs. Duration	#(Obs)
 Center	$\ell=0$	12	0.17 deg <sup>2</sup>	2001–2008	~90
 Bulge	$-10 < \ell < +10$	142	2.3 deg <sup>2</sup>	2007–2012	~30

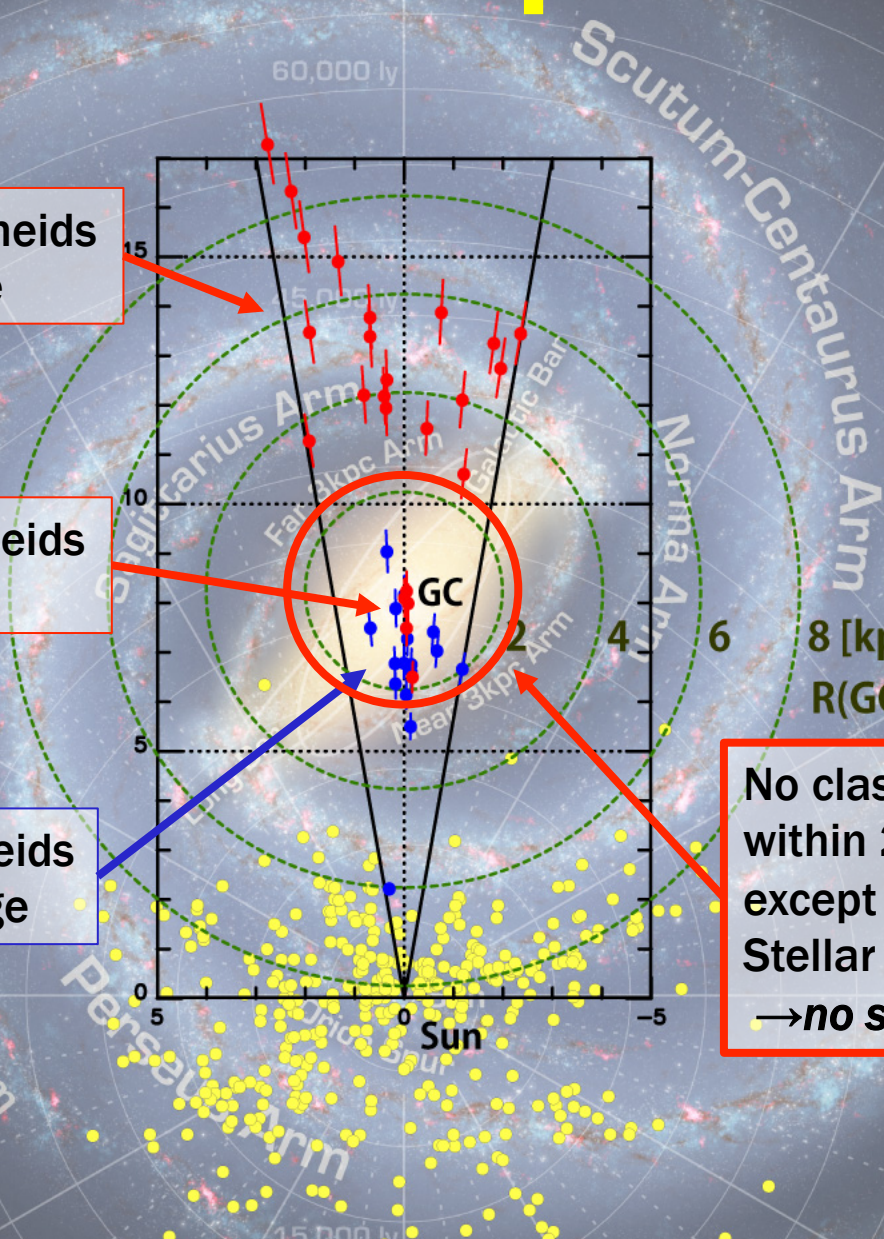
# Distribution of Cepheids found

25 classical Cepheids beyond the bulge

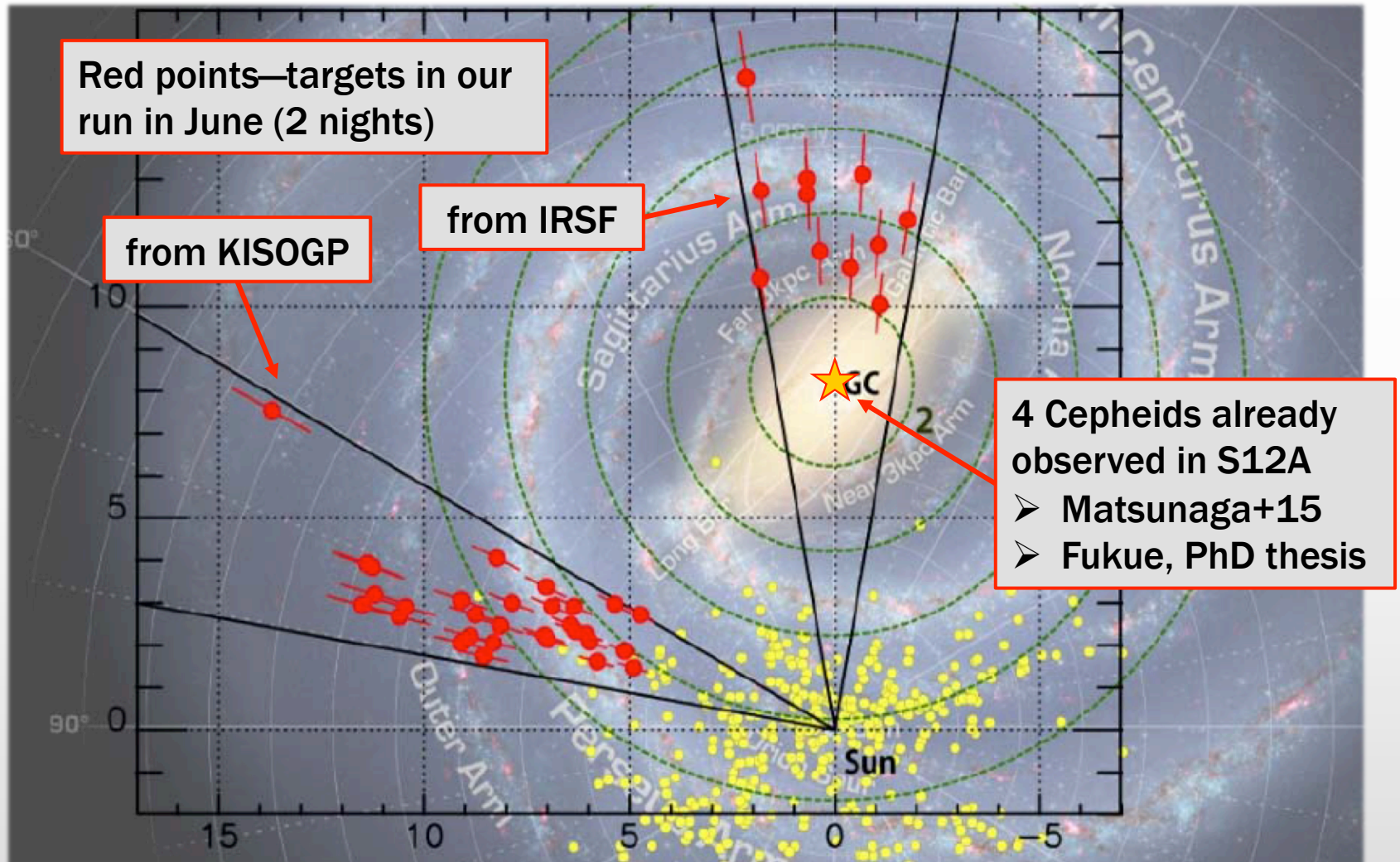
4 classical Cepheids around the GC

16 type II Cepheids around the bulge

No classical Cepheids within 2.5 kpc of the GC except 4 in the Nuclear Stellar Disk ( $|\ell| < 2^\circ$ )  
→ no simple exp. disk

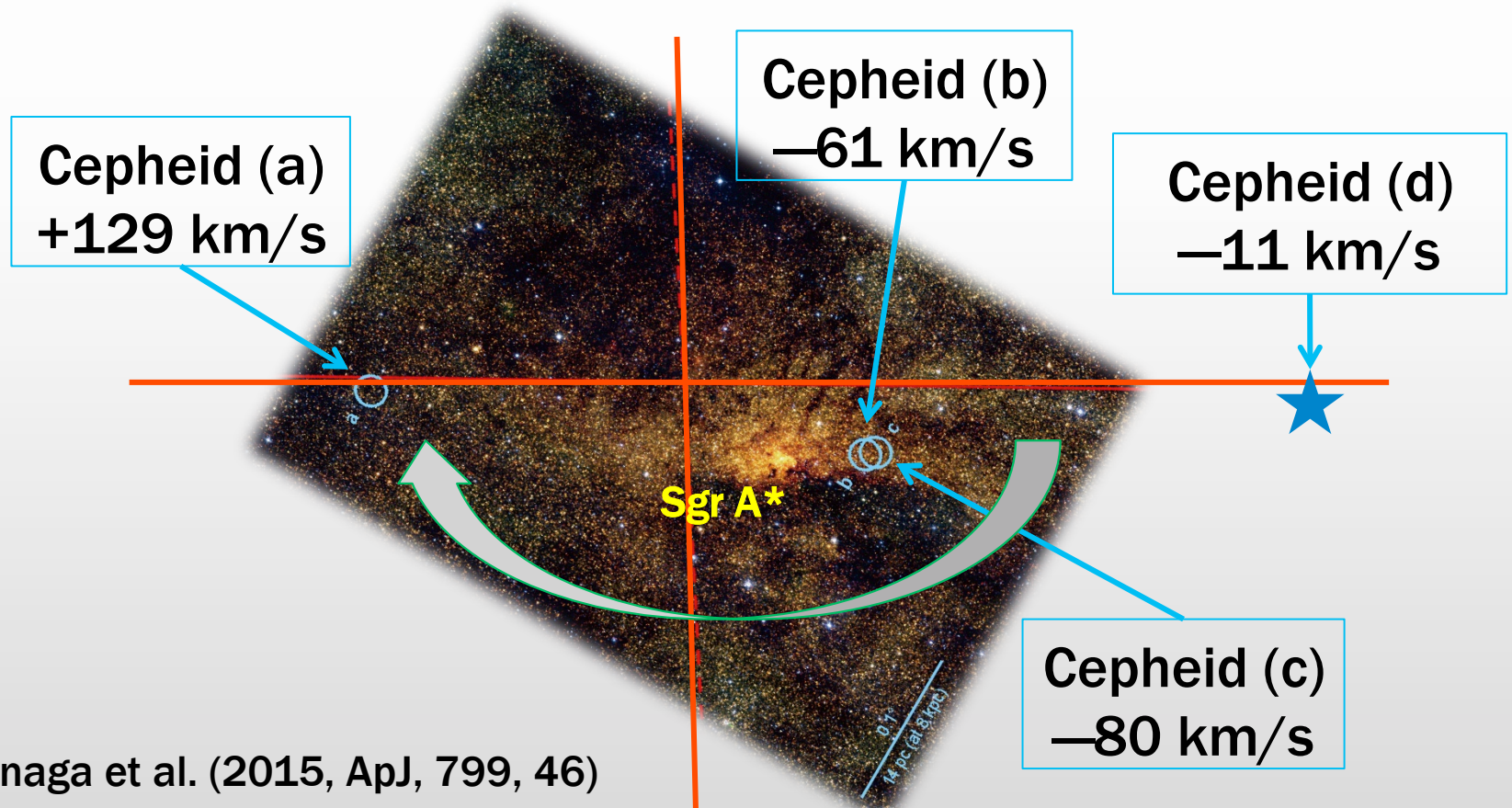


# Spectroscopic follow-up w/ Subaru



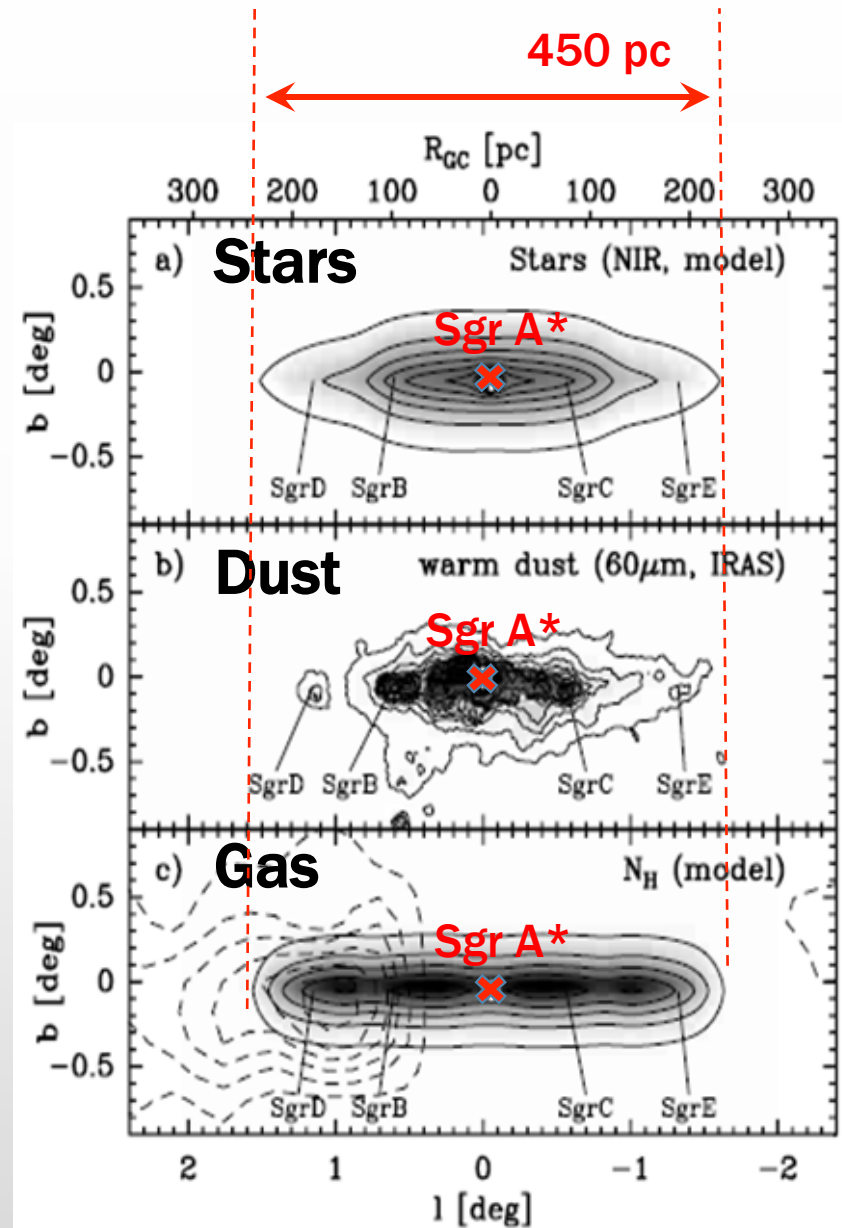
# Kinematics of the 4 GC Cepheids

- Subaru/IRCS+A0188 in 2012: *H*-band,  $R=20,000$
- Consistent with the rotation in the Nuclear Disk.
  - Unless they belong to the disk, such velocities are unexpected.
- Chemical analysis by Fukue (PhD thesis, 2016 Mar)



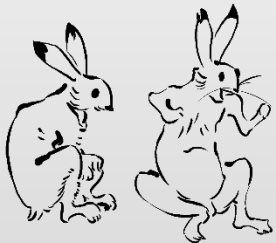
# The Nuclear Stellar Disk

- A disk-like system where stars coexist with gas/dust (Central Molecular Zone)
- Young stars are found to be rotating within the Disk.
  - Arches, Quintuplet ( $\sim 5$  Myr)
  - Mira-related objects: OH/IR stars, SiO masers (100 Myr—3 Gyr)
  - ongoing star formation
- Classical Cepheids belong to this NSD rather than the Bulge.



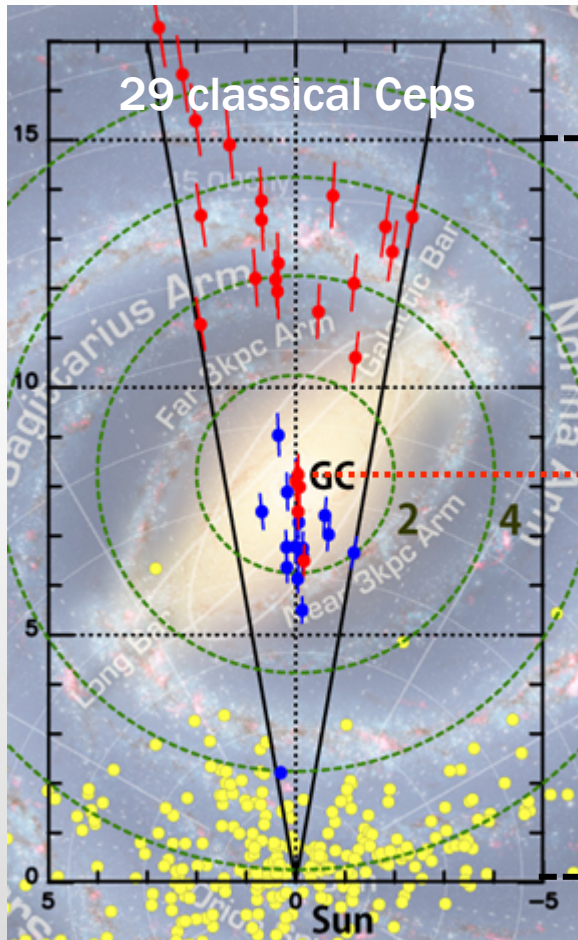
# **The impact of uncertainty in the extinction law**

Comparison with Dekany et al. (2015)

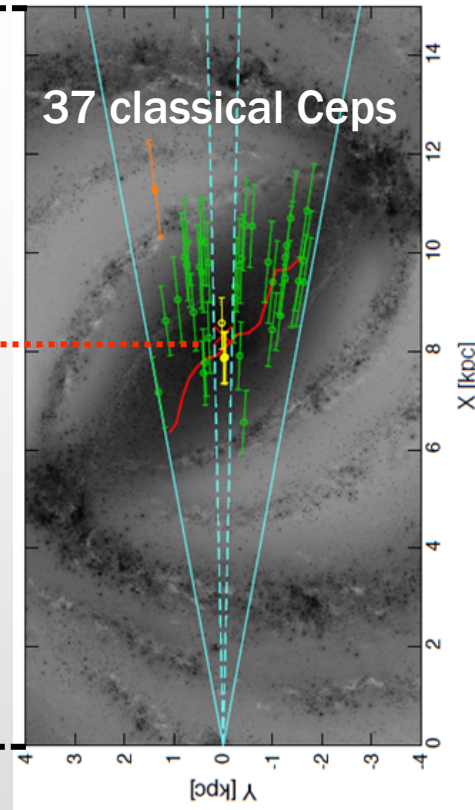


# A different map by Dekany+15

- Dekany et al. (2015) found ‘an inner thin disk of Classical Cepheids surrounding the Galactic Center’ using data from VVV (VISTA Variables in the Via Lactea)

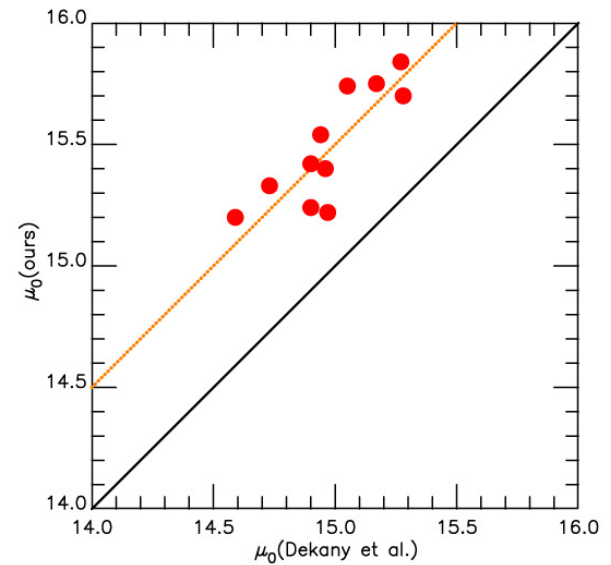


Our work



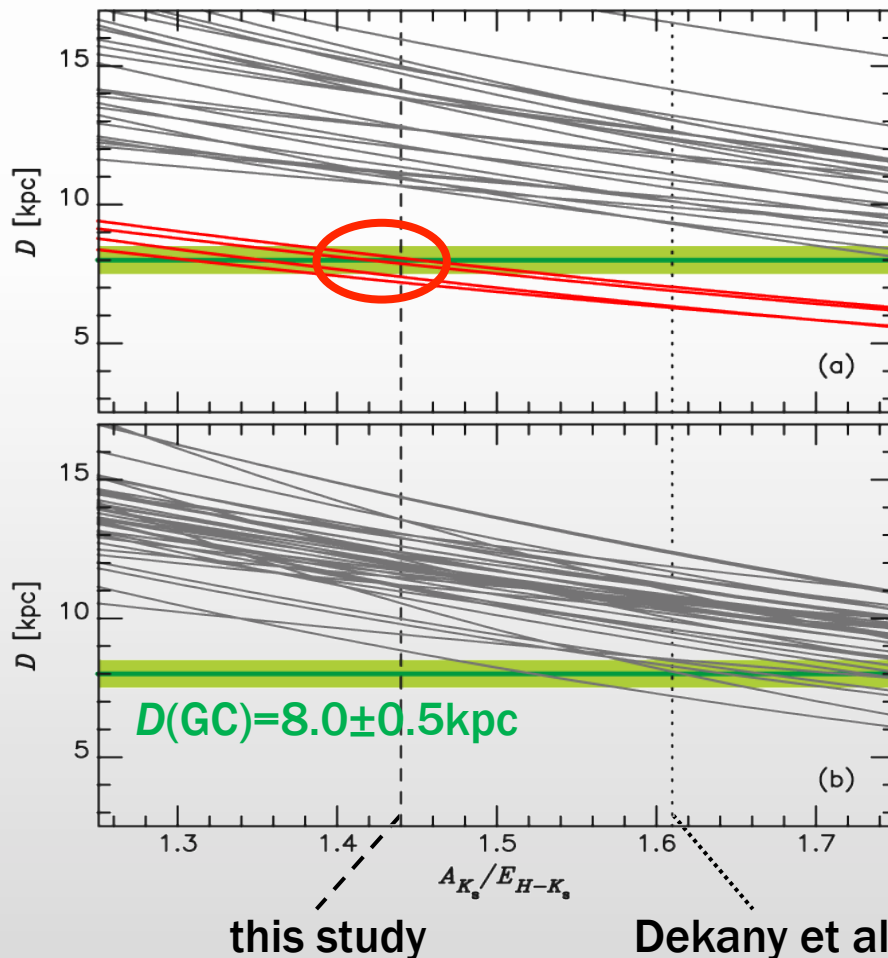
Dekany et al. (2015)

11 Cepheids are common, and  $\mu_0(\text{ours})$  are systematically larger than  $\mu_0(\text{Dekany et al.})$ .



# The impact of $A(K_s)/E(H-K_s)$

- Different  $A(K_s)/E(H-K_s)$  values were used: 1.44 in our works and 1.61 in Dekany et al. (2015ab), which leads to significantly different distances.



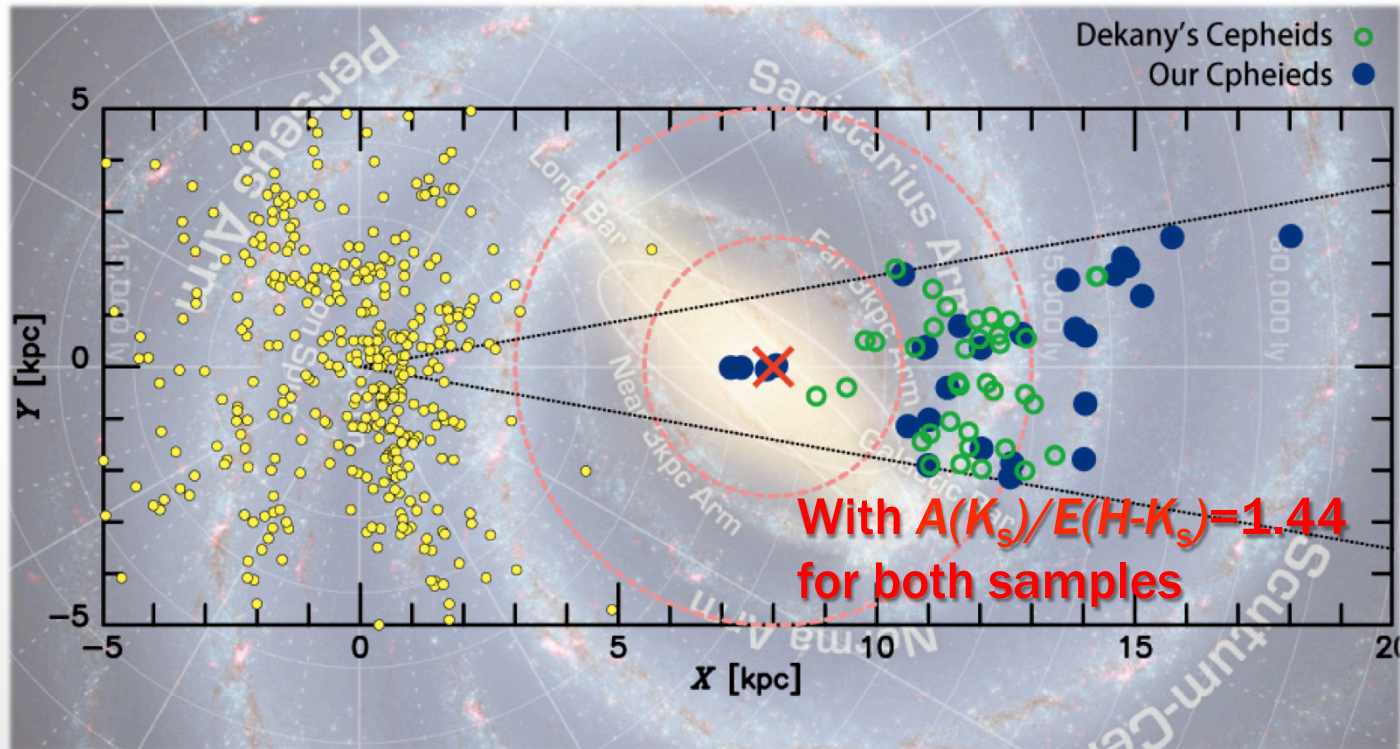
← For our Cepheids  
**red**—4 Cepheids in the NSD

*The memberships have been also supported by the radial velocities.*

← For Cepheids in Dekany et al. (2015)

These Cepheids typically have  $E(H-K_s) \sim 2$ .

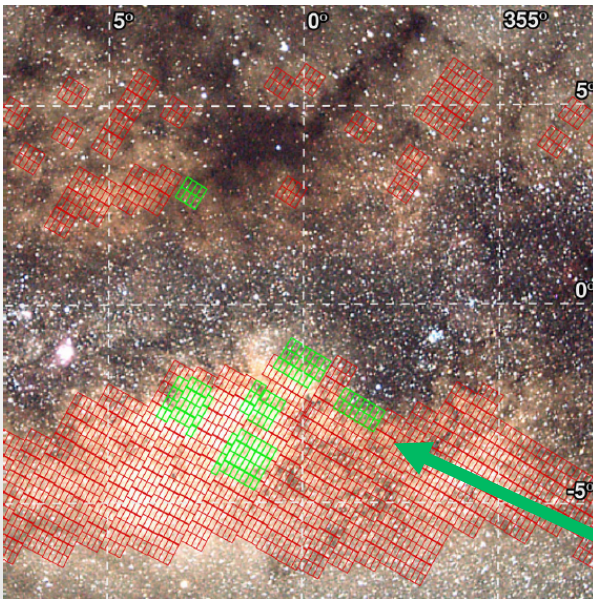
# A lack of young stars in the inner part of the disk



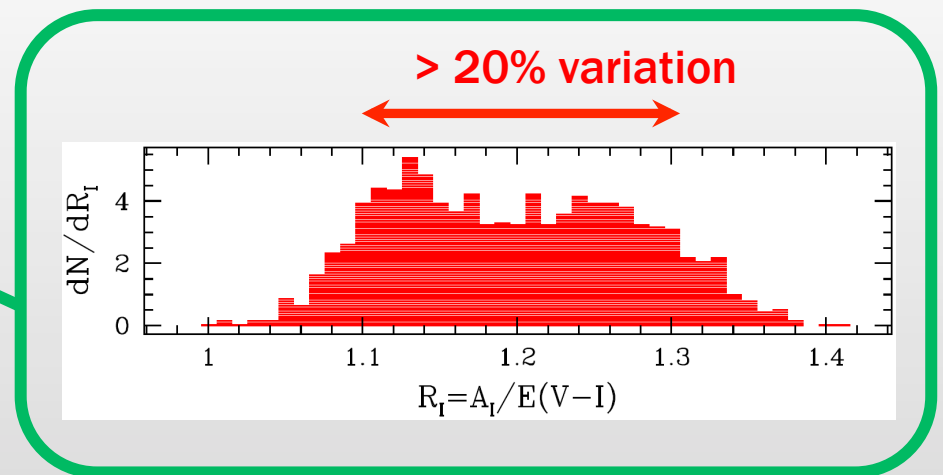
- Very few, if any, Cepheids within  $\sim 2.5$  kpc of the Galactic Center except those in the NSD.
- HII regions also show the similar void (e.g. Anderson et al. 2011, ApJS, 194, 32).

# The extinction law still matters

- May be spatially variable
  - although it is not established...
  - Extinction towards the bulge may be non-standard...



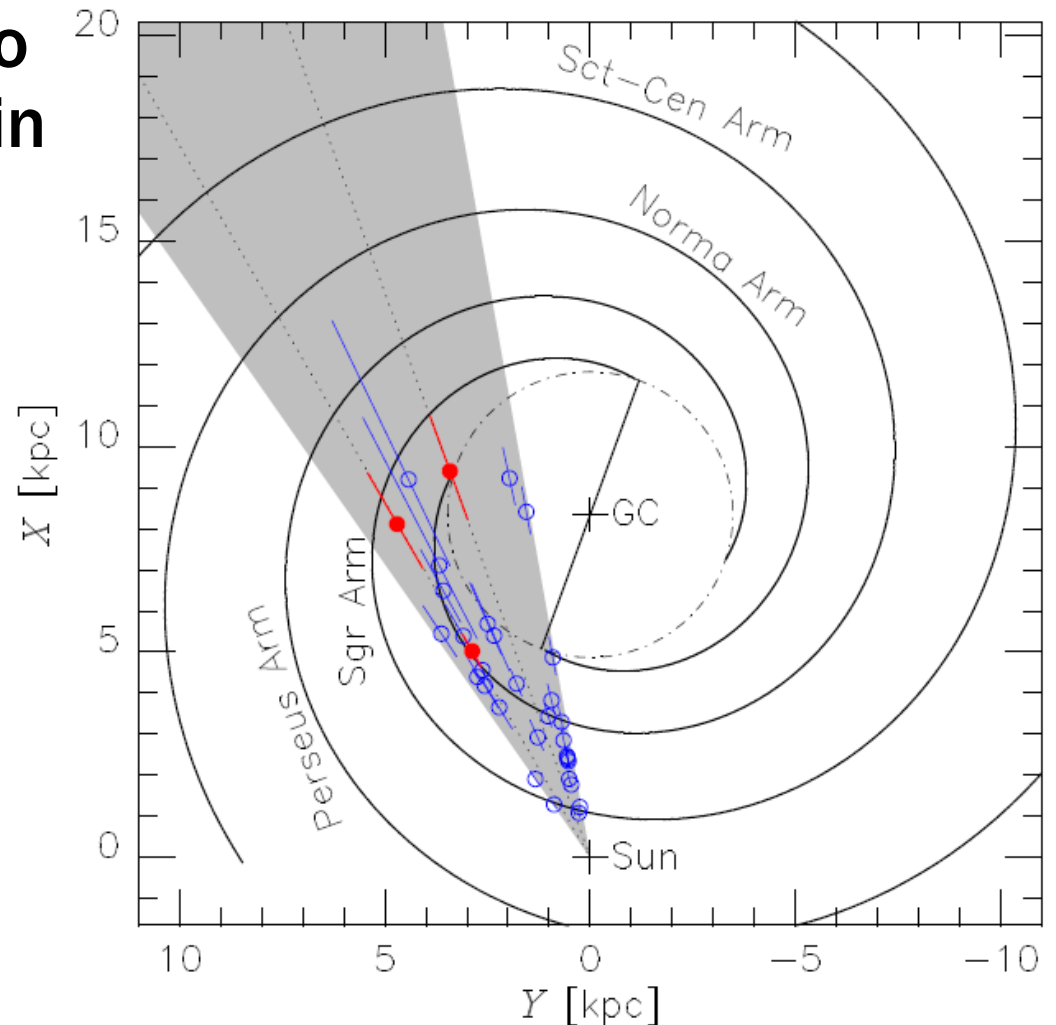
Nataf et al. (2016,  
MNRAS, 456, 2692)



# The extinction law still matters

- An error of 0.1 in  $A(K_s)/E(H-K_s)$  leads to an error of 0.3 mag in distance modulus.

**Red**—new Cepheids  
**Blue**—SF regions with maser parallax



# Future prospects

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- **Photometry**

- OGLE, VVV, Gaia, LSST, WFIRST, and other surveys will discover a lot more Cepheids and other kinds of variables across the Galactic disk.
- Characterizing the interstellar extinction is an urgent task.

- **Spectroscopy**

- Abundances of other elements would give further insights into chemical evolution.
- Other near-IR spectrographs, eg WINERED and GIANO, will be also useful to make similar measurements.

# **ULTIMATE-Subaru**

Multi-object spectroscopic observations would be very useful to study the hidden part of the MW



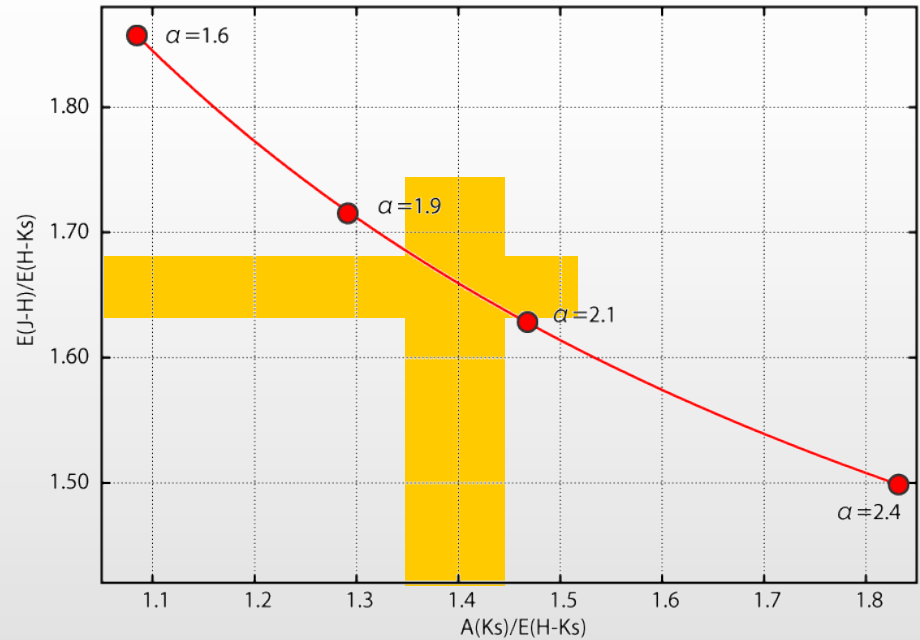
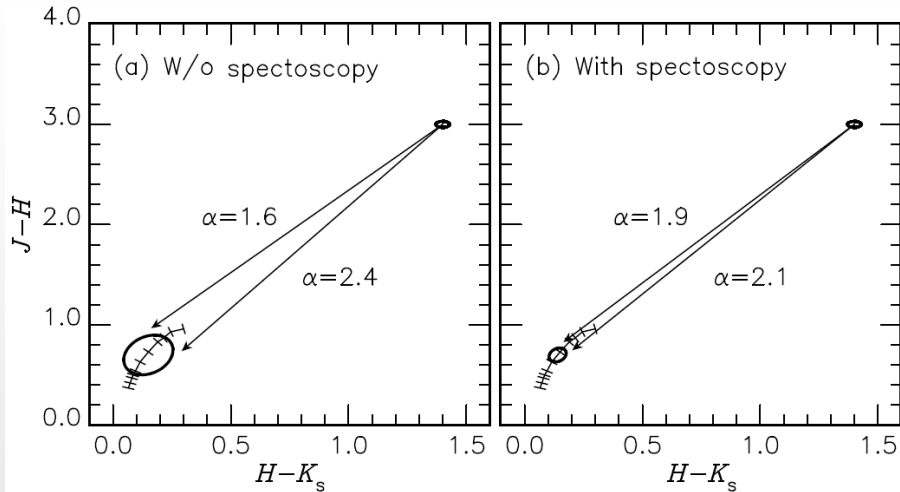
# What we want to do w/ U-Subaru

- Measuring Radial velocities and metallicities of selected tracers (pulsating stars) of the Milky Way
  - Typically only 1 Cepheids expected within the FOV
  - Targets will be faint enough, 12–18 VEGA mag in J, to require 8-m class telescopes.
- Characterizing surrounding stars around the tracers: reddening and stellar populations
  - Uncertainty in reddening law is a crucial (and nasty) problem when we study hidden regions of the Milky Way.

**Multi-object spectroscopy (eg. w/ MOIRCS) with ULTIMATE-Subaru is required.**

# An idea to determine $A(K_s)/E(H-K_s)$

- Determine spectral types of surrounding stars in individual lines of sight, and then determine the slope of the reddening vector accurately.
  - Nishiyama-san's work (2006;  $\alpha=1.99\pm 0.02$ ) was possible because they could use red clump stars in the bulge

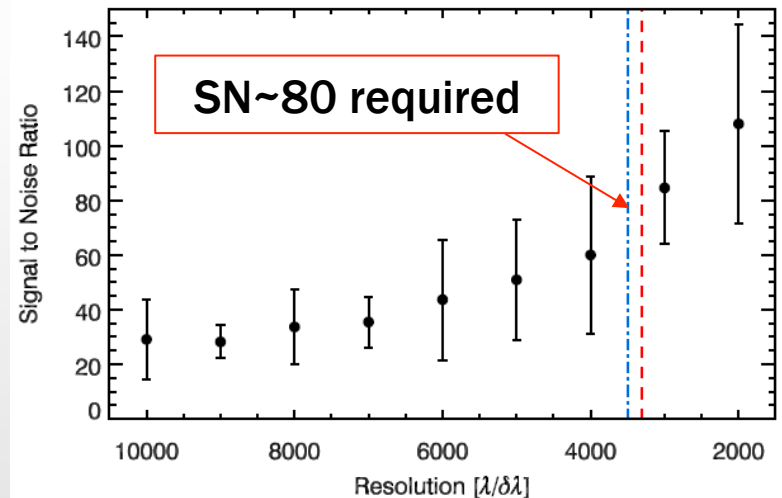
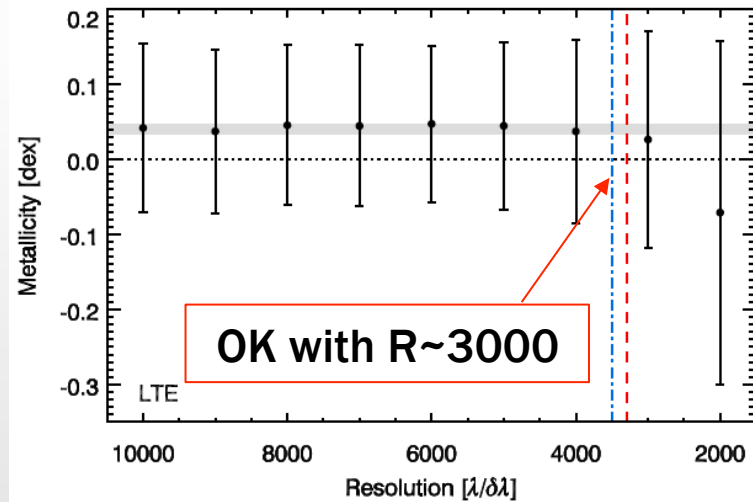


Wang & Jiang (2014) used a similar method: selecting K-type giants based on APOGEE spectra to study the extinction ratio  $E(J-H)/E(J-K_s)$ .

# Which waveband to go

- **J band** seems to be the best window unless higher resolution ( $R \sim 20,000$ ) is available.

Waveband	For Chemical analysis	Effect of reddening
J	$R \sim 3,000$ allowed	Large (3.5—9 mag in J)
H (or longer)	$R \sim 20,000$ required	Smaller (2—5 mag in H)



Gazak et al. (2014, ApJ, 788, 58)

- Decreasing the  $R$  to  $\sim 3,000$  doesn't greatly degrade metallicity measurements.
- Their targets are RSGs, a similar simulation should be done for warmer stars.

# Summary

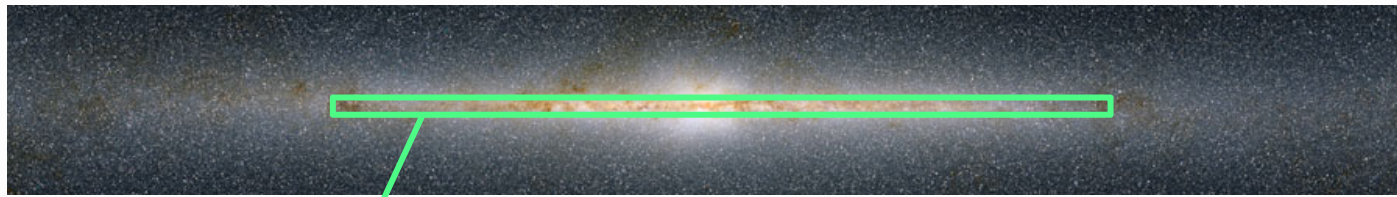
- **New (infrared) surveys are revealing stellar tracers of the hidden part of the Milky Way.**
  - **Uncertainty in the reddening law is a crucial problem in studying their distribution.**
- **Spectroscopic follow-ups will be useful for:**
  - **studying kinematics and chemical abundances of the stellar tracers (and surrounding stars)**
  - **characterizing the reddening law toward regions around individual tracers**

**End**

# Very rough estimate

- Typically we expect only one Cepheid(s) in FOV of ULTIMATE-Subaru.

2MASS



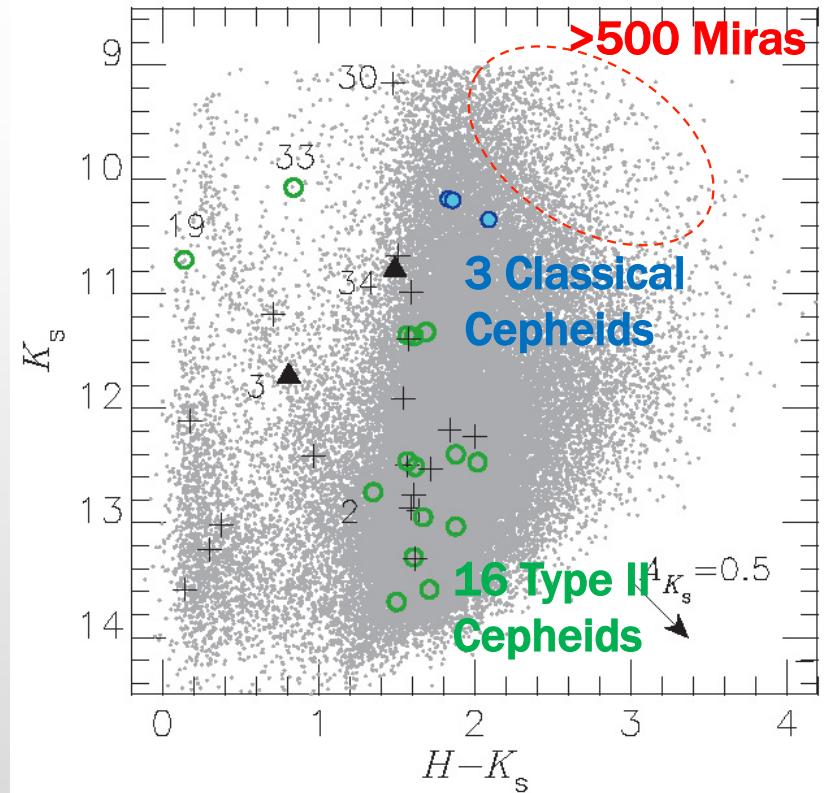
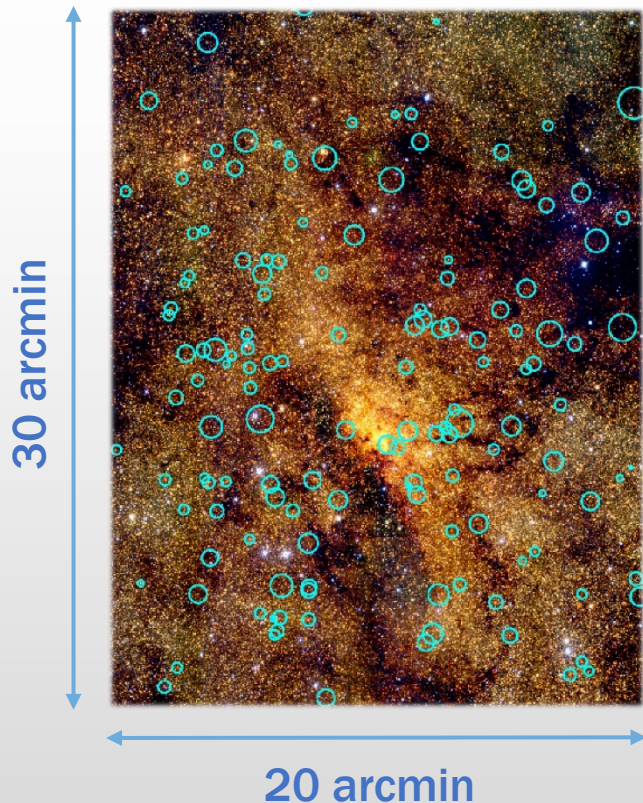
2,000 in  $180^{\text{deg}}$  times  $2^{\text{deg}}$  gives the density of  $5.5 \text{ deg}^{-2} = 0.15$  in a 10 arc-minute square.

# **Other U-Subaru instruments**

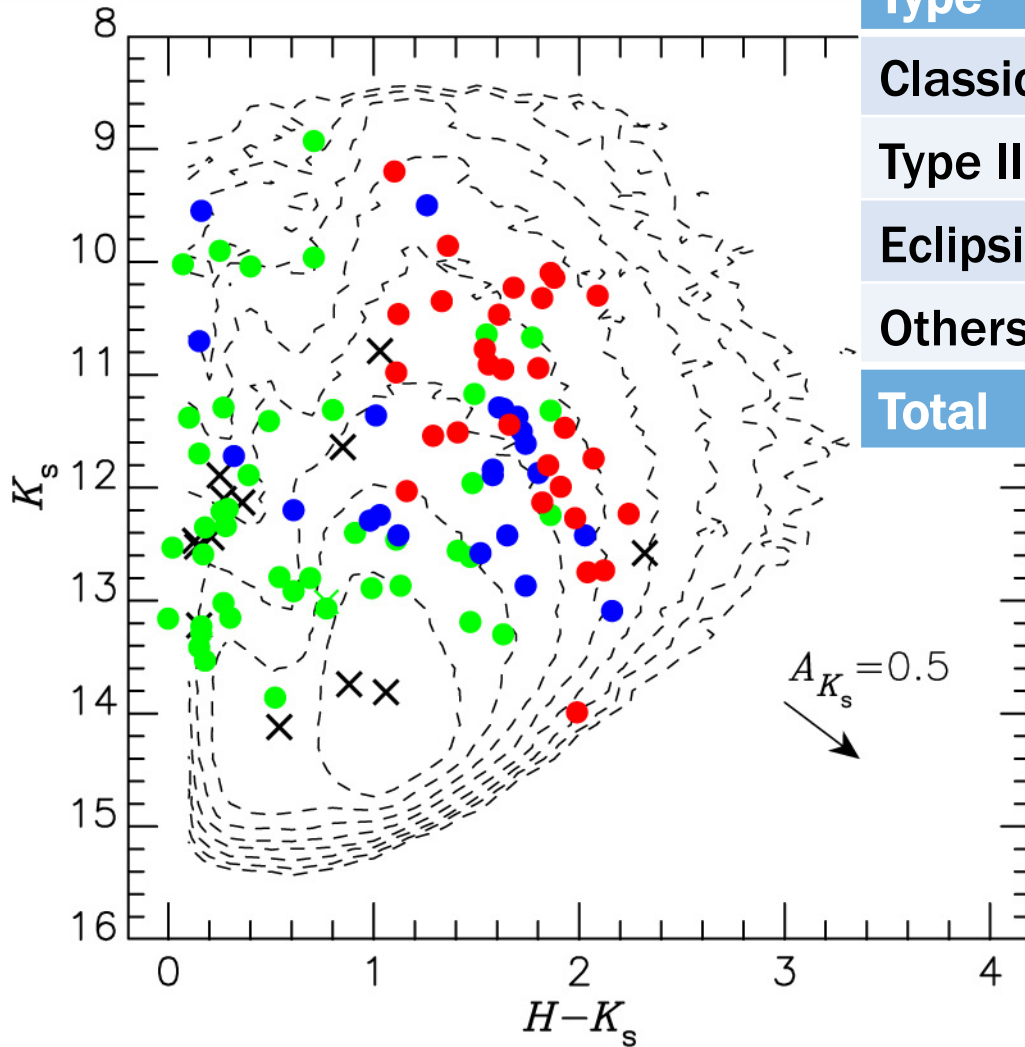
- **WFC (wide-field and accurate photometry) would be useful. However:**
  - **Our targets are relatively bright for photometry.**
  - **For the comprehensive study (which I discussed here) on stellar populations in a large area of the MW, we want systematic datasets with the same instrument to avoid filter differences.**
- **IFU will be not necessary for our topics.**

# The survey toward the Center

Miras	549	Matsunaga et al. (2009)
Other long-period variables	815	
Classical Cepheids	3	Matsunaga et al. (2011)
Type II Cepheids	16	Matsunaga et al. (2013)
Other short-period variables	26	



# From the new survey ( $\pm 10^{\text{deg}}$ in $\ell$ )



Type	Number
Classical Cepheids	29 <sup>†</sup>
Type II Cepheids	24
Eclipsing Binary Systems	47
Others (incl. Unclassified)	18
<b>Total</b>	<b>118</b>

<sup>†</sup> including 4 NSD classical Cepheids already discussed.


- Classical Cepheids
- Type II Cepheids
- Eclipsing binaries
- × Others


# $A(K_s)/E(H-K_s)$


- $(\mu_{0,K_s}, A_{K_s})$  are derived with two-band magnitudes and PLRs.


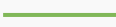
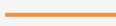
From the extinction law

$$A_{K_s} = \frac{A_{K_s}}{E(H-K_s)} \{ (H-K_s) - (M_H - M_{K_s}) \}$$


  
 $\mu_{0,K_s}$


  
 $K_s - M_{K_s}$


  
 $-A_{K_s}$

 observed  
 from PLR  
 unknown

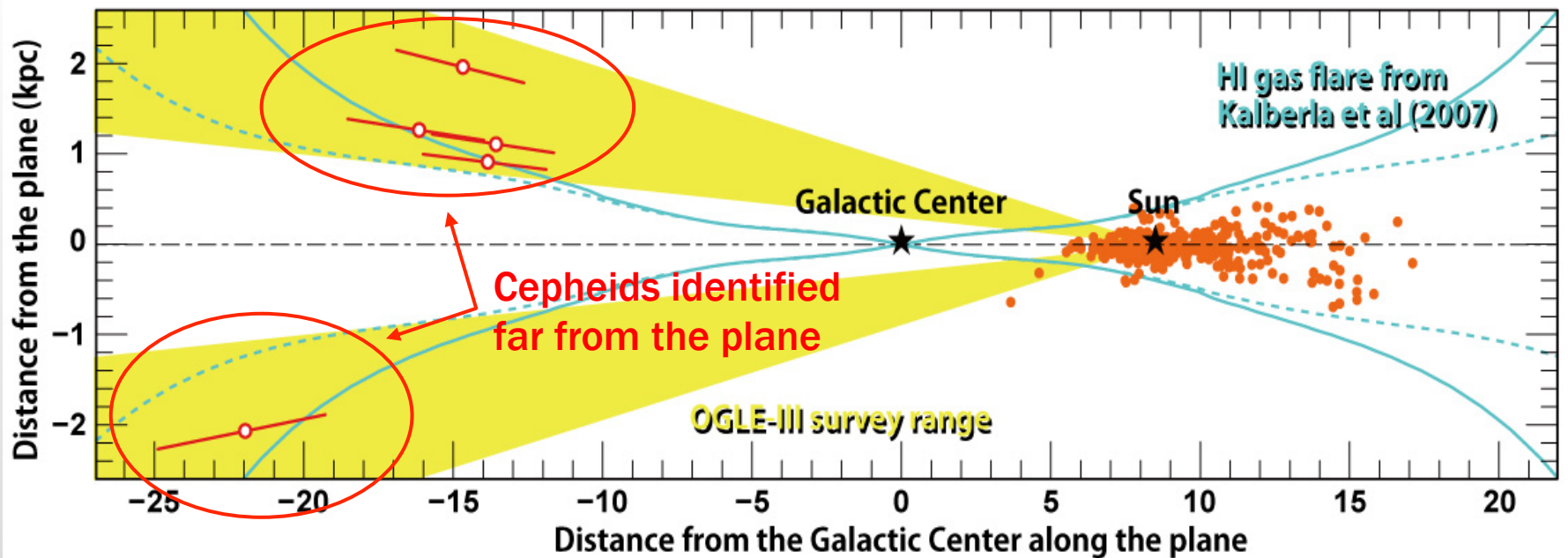
- $E(H-K_s) = 1.5-2$  for stars around the Galactic Center

- $A(K_s)/E(H-K_s) = 1.44 \Rightarrow A(K_s) = 2.16-2.88$
- $A(K_s)/E(H-K_s) = 1.61 \Rightarrow A(K_s) = 2.42-3.22$

} ~0.3 mag

# 5 Cepheids in the disk flare

- Feast et al. 2014, *Nature* 509, 342
- Identified among OGLE-III Cepheids toward the bulge (Soszynski et al. 2011, *AcA*, 61, 285).
- The first stars ever confirmed to be in the disk flare.
- They belong to the disk (rather than the halo).
  - The kinematics are consistent with the disk rotation.



# Differences in analysis

	This work	Dekany et al. (2015a,b)
Photometry	Our IRSF/SIRIUS phot.	VVV photometry (Ks means and H-Ks single-epoch colors)
PLR	Matsunaga+13	Monson+12
Extinction law	AKs/E(H-Ks)= <b>1.44</b> from Nishiyama+06 (for IRSF/SIRIUS)	AKs/E(H-Ks)= <b>1.61</b> from Nishiyama+09 (for 2MASS)

**Table 1**

The Wavelength Dependence of the Interstellar Extinction in the IRSF/SIRIUS (*J*, *H*, *K<sub>S</sub>*; Similar to the MKO Filter System), SST/IRAC ([3.6], [4.5], [5.8], [8.0]) and 2MASS (*J*<sub>2MASS</sub>, *H*<sub>2MASS</sub>, *K<sub>S</sub>2MASS*) Bands

3.5exband	Wavelength [ $\mu\text{m}$ ]	$A_{K_S}/E_{K_S-\lambda}$ <sup>a</sup>	$A_\lambda/A_{K_S}$ <sup>b</sup>
<i>J</i>	1.25 <sup>c</sup>	...	$3.02 \pm 0.04$ <sup>e</sup>
<i>H</i>	1.63 <sup>c</sup>	...	$1.73 \pm 0.03$ <sup>e</sup>
<i>K<sub>S</sub></i>	2.14 <sup>c</sup>	...	1.0
[3.6]	3.545 <sup>d</sup>	$2.01 \pm 0.04$	$0.50 \pm 0.01$
[4.5]	4.442 <sup>d</sup>	$1.64 \pm 0.02$	$0.39 \pm 0.01$
[5.8]	5.675 <sup>d</sup>	$1.56 \pm 0.03$	$0.36 \pm 0.01$
[8.0]	7.760 <sup>d</sup>	$1.74 \pm 0.04$	$0.43 \pm 0.01$
<i>J</i> <sub>2MASS</sub>	1.240 <sup>d</sup>	$-0.528 \pm 0.015$	$2.89 \pm 0.08$
<i>H</i> <sub>2MASS</sub>	1.664 <sup>d</sup>	$-1.61 \pm 0.04$	$1.62 \pm 0.04$
<i>K<sub>S</sub>2MASS</i>	2.164 <sup>d</sup>	$-(0.012 \pm 0.002)^{-1}$	$1.012 \pm 0.002$

**Notes.** <sup>a</sup> The ratio of total-to-selective extinction derived from the slopes in Figure 5 and 6. <sup>b</sup> The relative extinction to the *K<sub>S</sub>* band (IRSF/SIRIUS system). <sup>c</sup> The mean effective wavelengths of the SIRIUS filters (see Section 5.1; Nishiyama et al. 2006). <sup>d</sup> The isophotal wavelengths of the 2MASS and IRAC filters (see Table 1; Indebetouw et al. 2005). <sup>e</sup> From Nishiyama et al. (2006).

The absolute  $A(K_s)$  extinction is determined by assuming the extinction curve found by Nishiyama et al. (2009). By transforming their absolute-to-selective extinction ratios from the 2MASS to the VISTA system using the equations given by CASU<sup>9</sup>, we obtain:

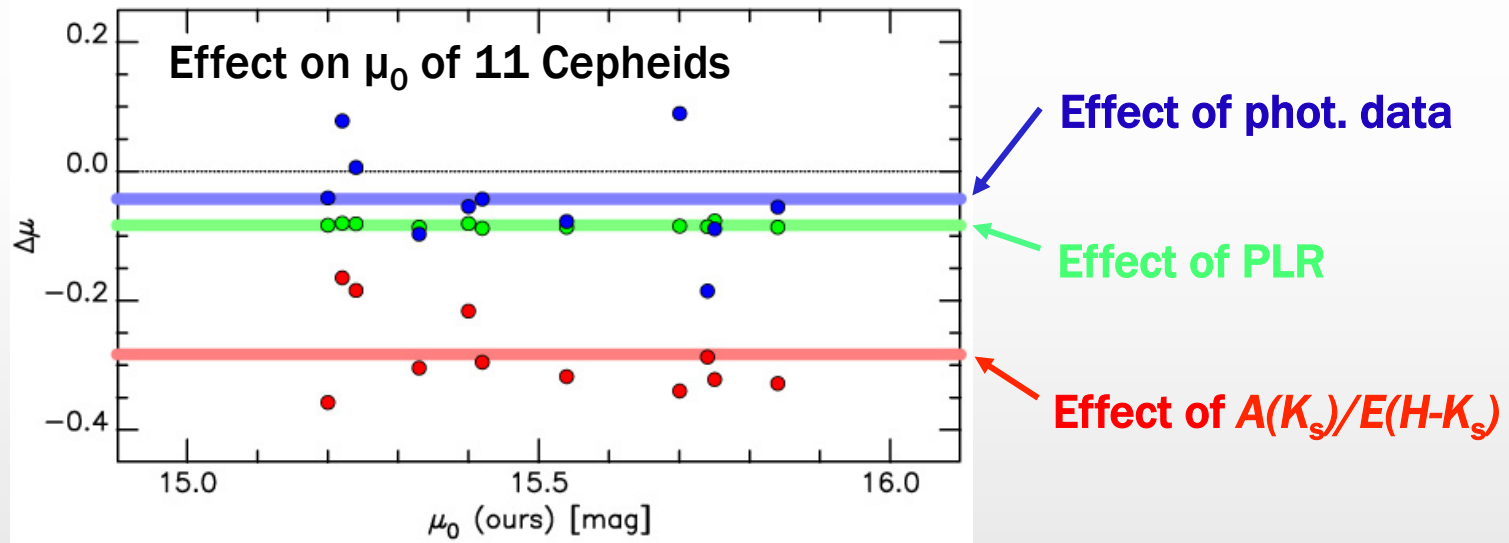
$$A(K_s) = 1.63 \times E(H - K_s). \quad (2)$$

Dekany et al. (2015)

Nishiyama et al. (2009)

# What causes the difference?

Item	Our work	Dekany et al.	$\langle \Delta\mu \rangle$	$\sigma_{\Delta\mu}$
Photometric data	IRSF/SIRIUS	VVV	-0.04	0.08
P-L relation	Matsunaga+13	Monson+12	-0.08	0.00
$A(K_s)/E(H-K_s)$	1.44	1.61	-0.28	0.07



- The offset is mainly caused by  $A(K_s)/E(H-K_s)$ .
- The scatter is attributed to photometric data and  $A(K_s)/E(H-K_s)$ .