Infrared access to hidden stellar populations in the Galactic bulge and disk

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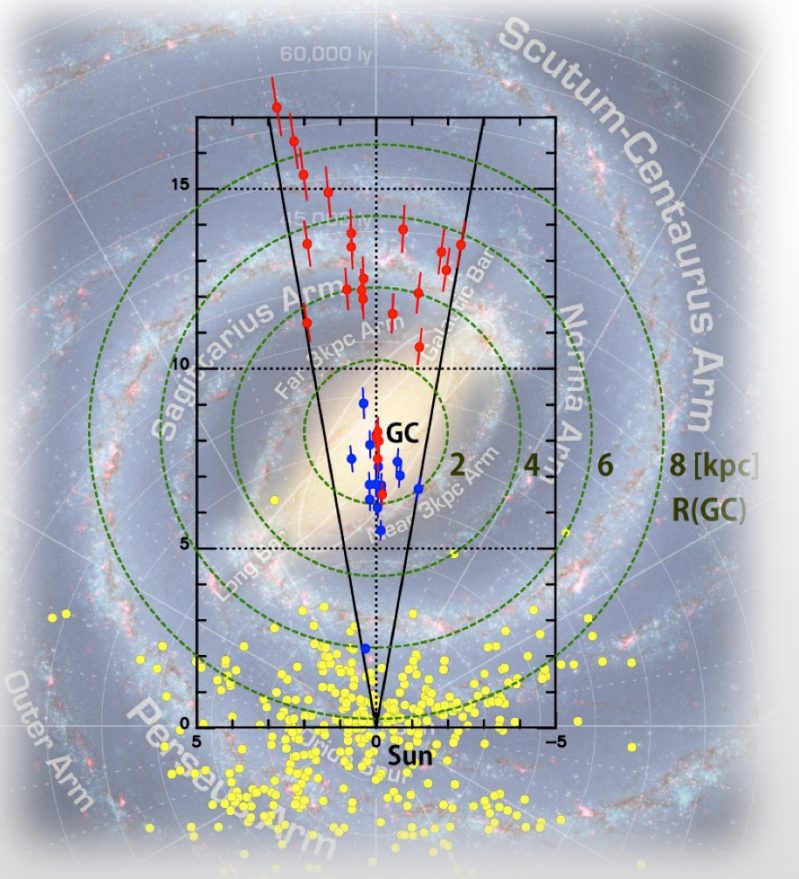

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Google earth

Outline

- Introduction
  - Variable stars as representatives of populations
  - The need of infrared observations
- Our recent results: spectroscopic
  - Kinematics of Cepheids in the Galactic bulge
- Our recent results: photometric
  - Cepheids in and beyond the Galactic bulge
- Future prospects
  - Near-IR spectroscopy with E-ELT

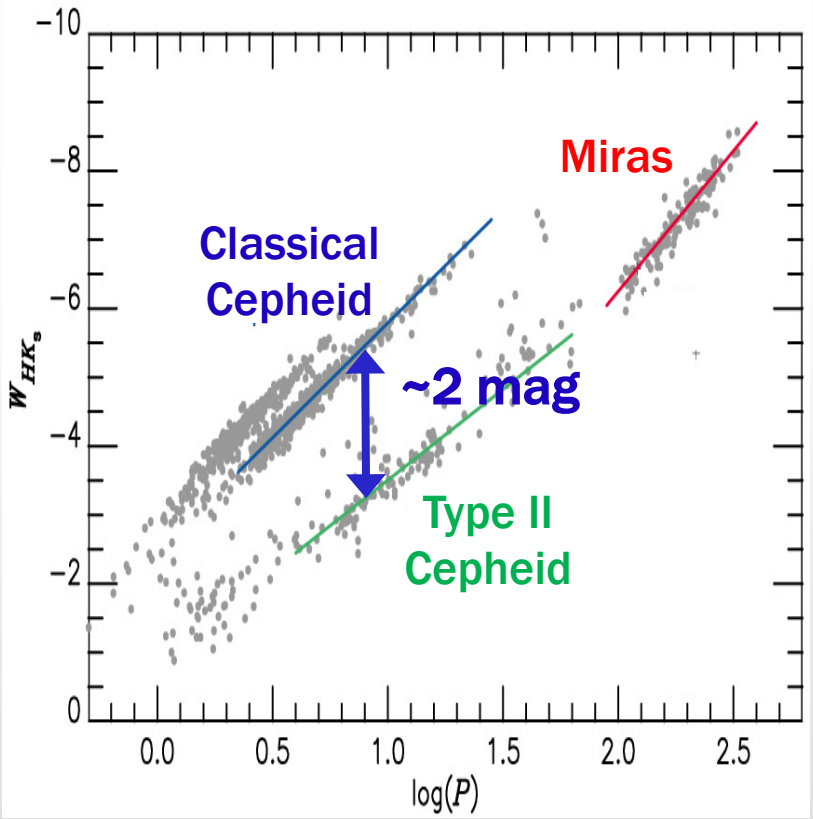
Infrared observations of variable stars are useful to study the Galaxy.

Introduction

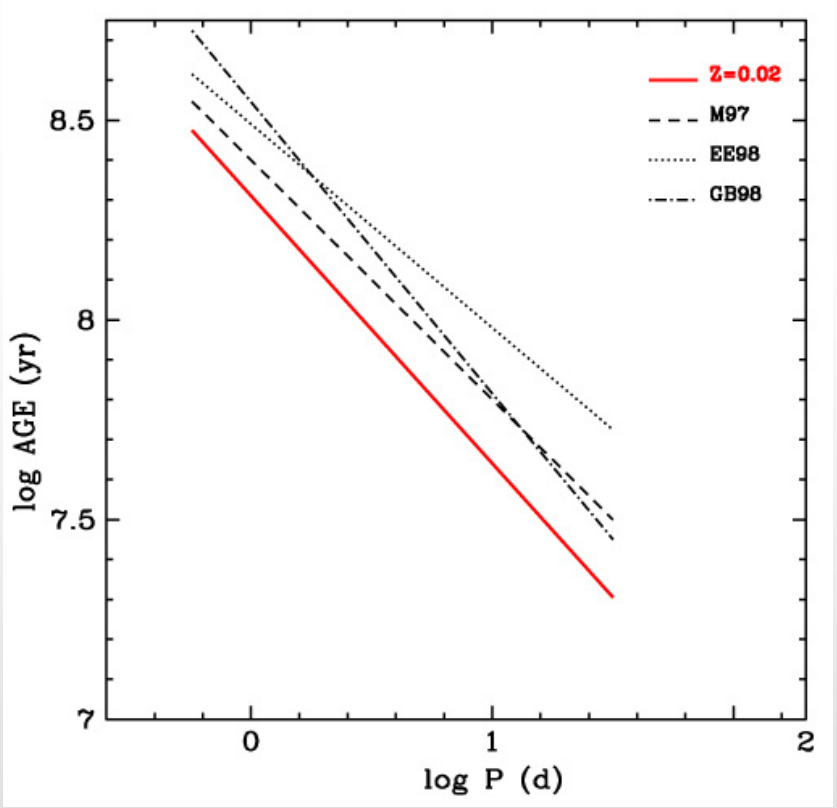
Variable stars and the need of infrared observations

Classical Cepheids as tracers

- P-L relation → distance
- Ages, kinematics and chamical abundances can be accurately determined, thus working as good



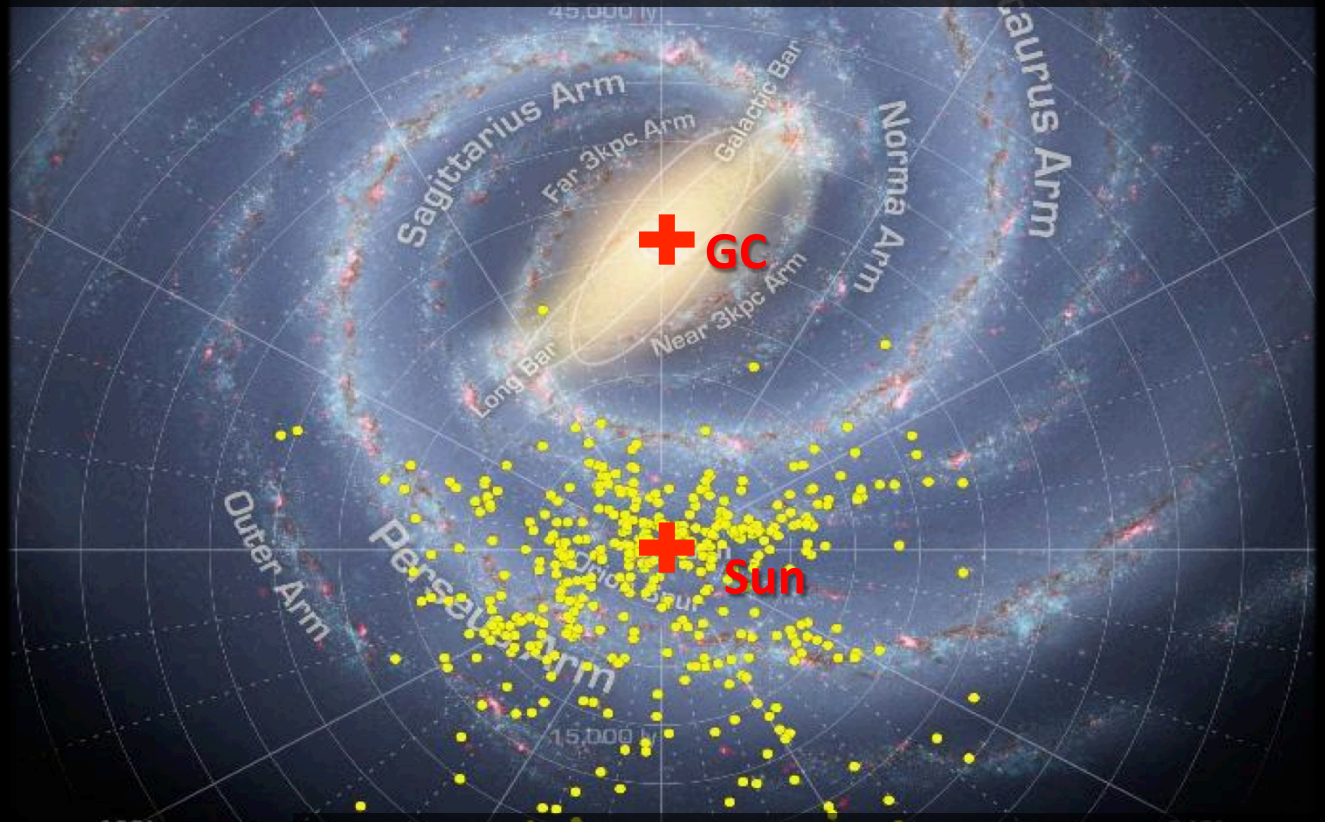
Near-IR P-L relations of LMC variables (Matsunaga, 2013)



Period-age relation (Bono et al. 2005)

Earlier status of Cepheid surveys

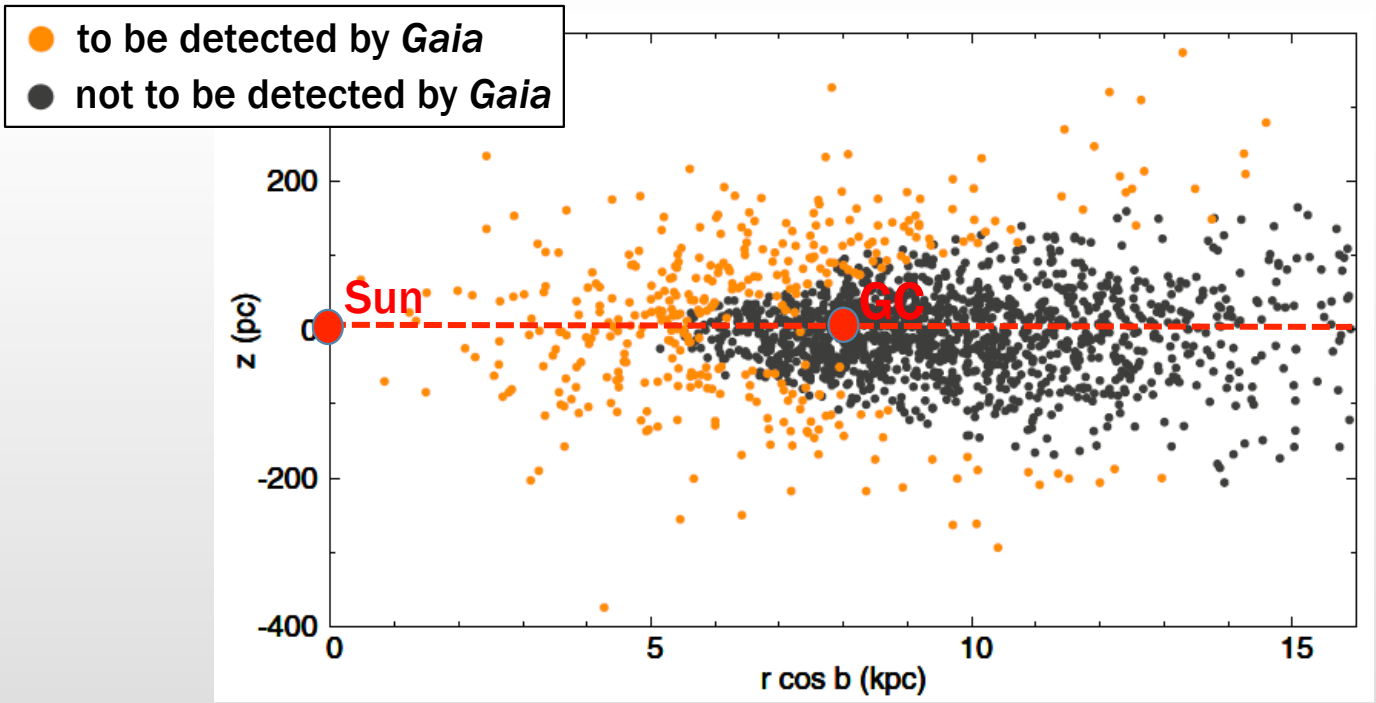
- Distant Cepheids in the Galactic disk are obscured.
- Many remain to be discovered (by infrared surveys).



The distribution of ~500 Cepheids from DDO database:
http://www.astro.utronto.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: $f(R,z)=\exp(R/3.5\text{kpc})\,\mathrm{sech}(z/z_0)$
  - 20,000 Cepheids predicted
  - 9,000 Cepheids may be detected by Gaia.



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

Section summary

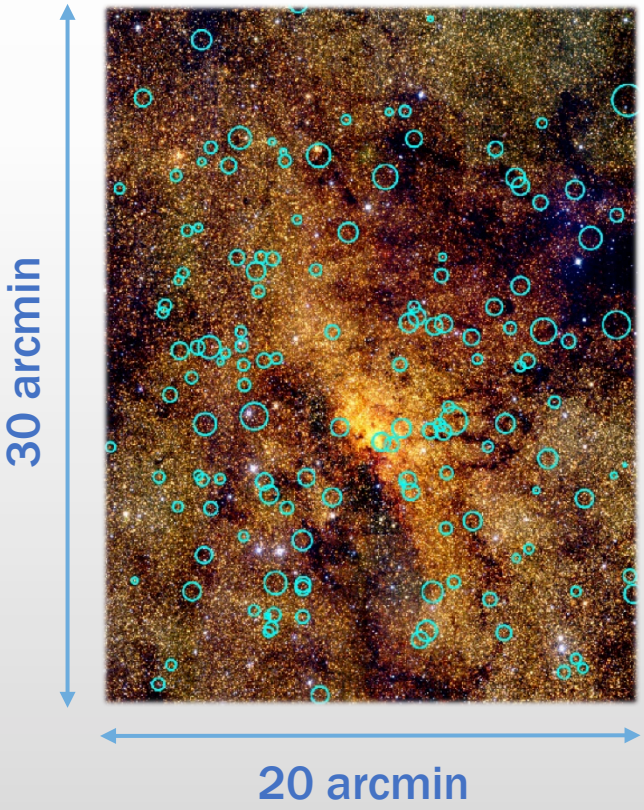
- Variable stars, in particular classical Cepheids, are useful tracers of the Galaxy.
- The objects hidden in the Galactic plane should be found and studied by infrared observations.

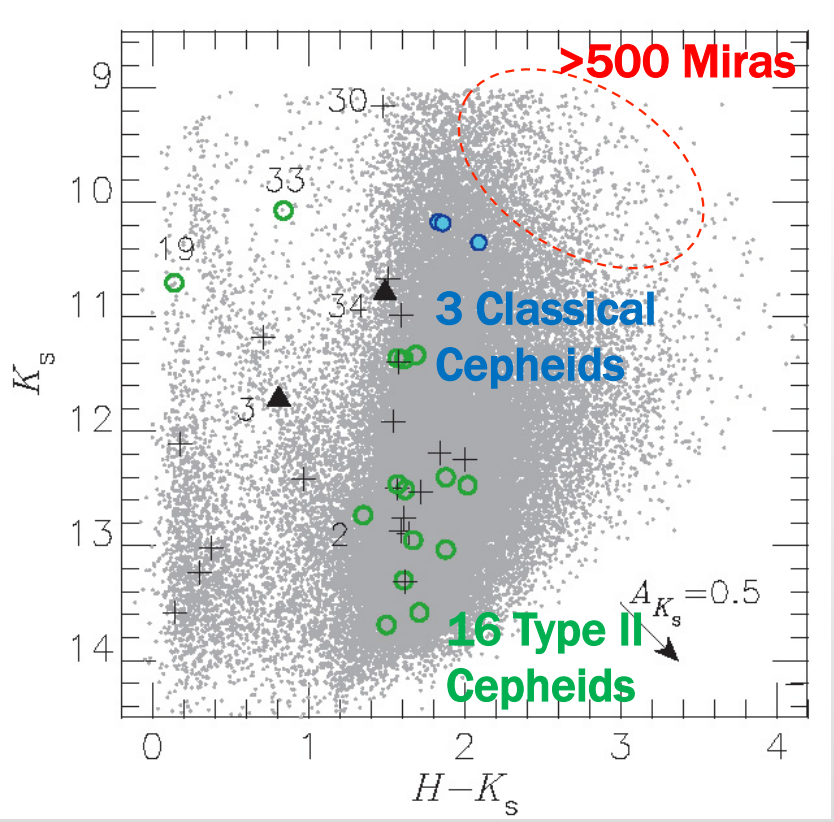
Kinematics of Cepheids in the Nuclear Disk

Radial velocities of Cepheids from infrared spectra

IRSF survey of the Galactic Center

- IRSF 1.4-m telescope and SIRIUS *JHKs*-band camera
- With the 8-yr survey for 30min×20min around the GC, we detected 3 classical Cepheids, 16 type II Cepheids, and >500 Miras (Matsunaga et al. 2009, 2011, 2013).

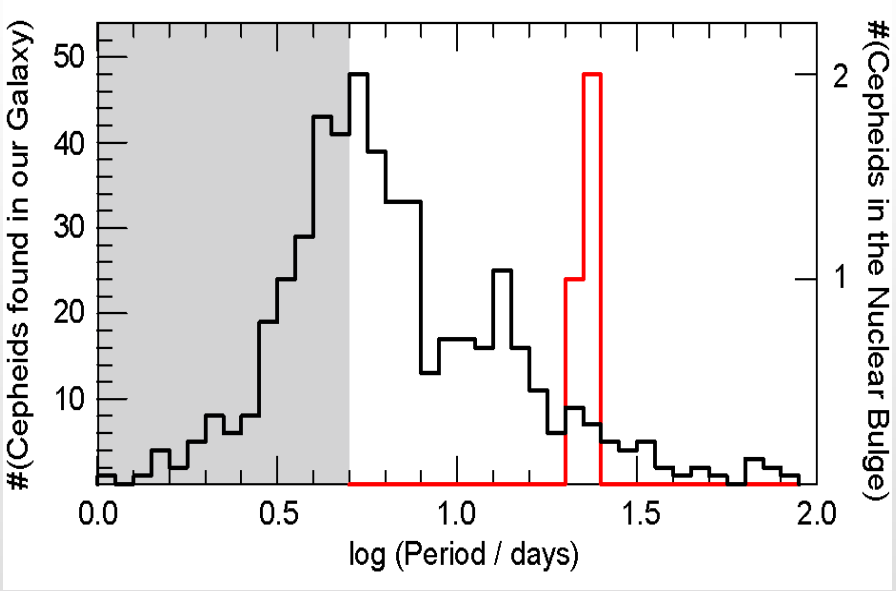




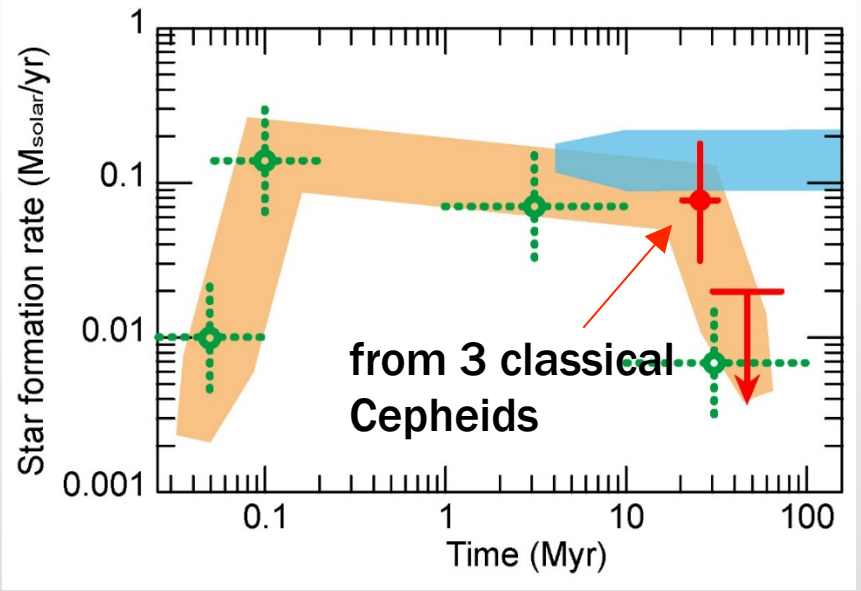
Discovery of classical Cepheids

- All the 3 classical Cepheids are located at the distance of 8 kpc and have *P*~20 days corresponding to 25 Myr.
- They are considered to be within the Nuclear Stellar Disk, and Matsunaga et al. (2011) discussed star formation history therein.

Matsunaga et al. (2011, *Nature*, 477, 188)



Period histogram of nearby Cepheids (black) and those around the GC (red)

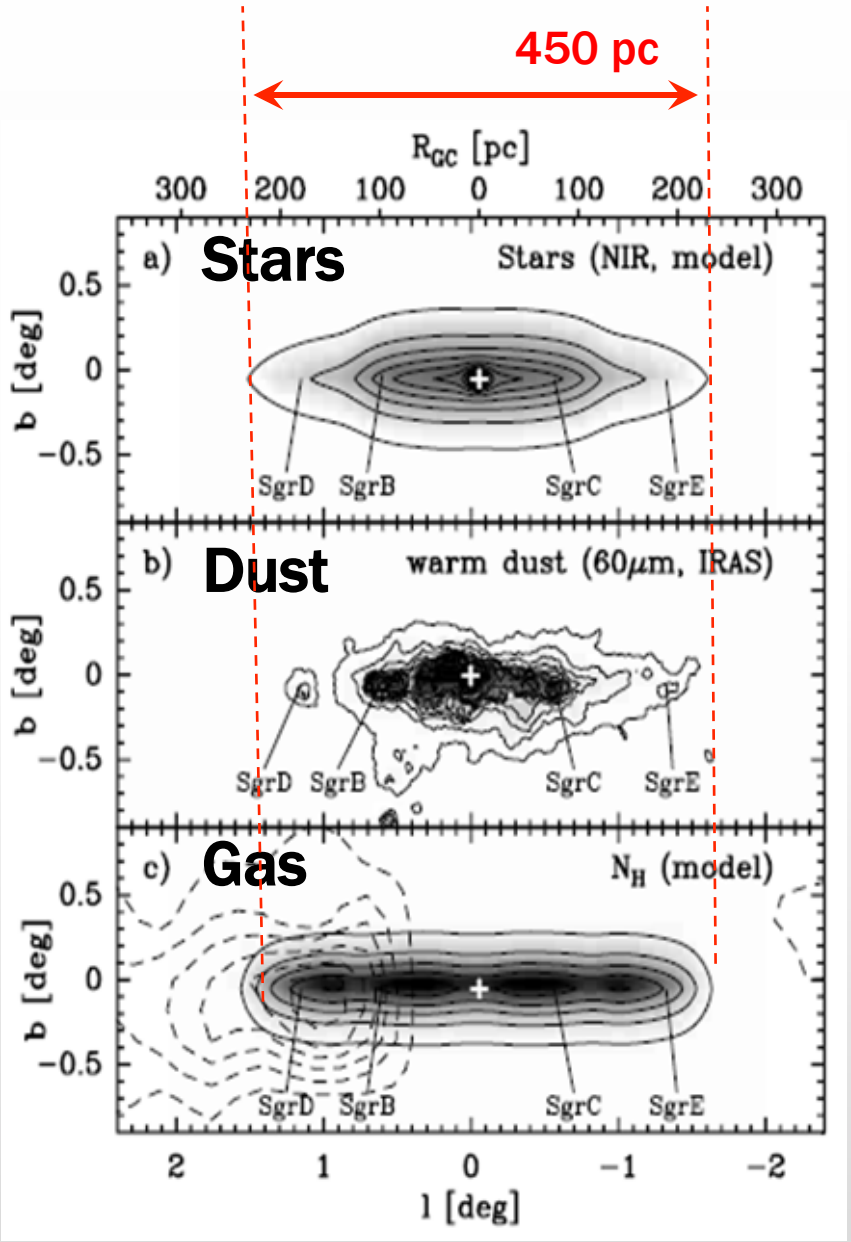


Star formation history inferred from the Cepheids and other objects

The Nuclear Stellar Disk

- Revealed by infrared observations in 1990s.
- A disk-like system where stars coexist with gas/dust (Central Molecular Zone)
- Relatively young stars are found to be rotating within the Disk.
  - Arches, Quintuplet (~5Myr)
  - OH/IR stars, SiO masers (100 Myr—3 Gyr)

+ongoing star formation

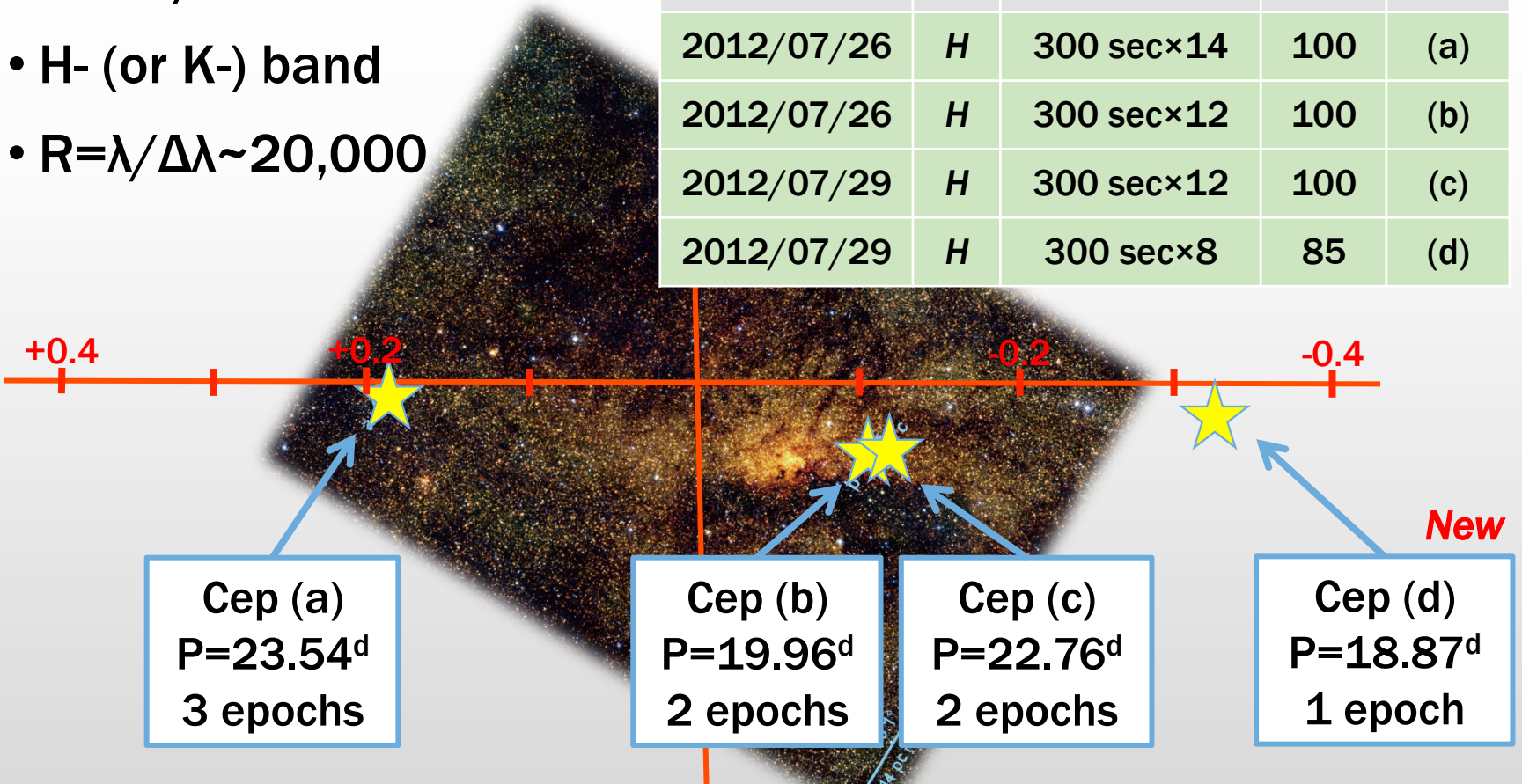


Launhardt et al. 2002

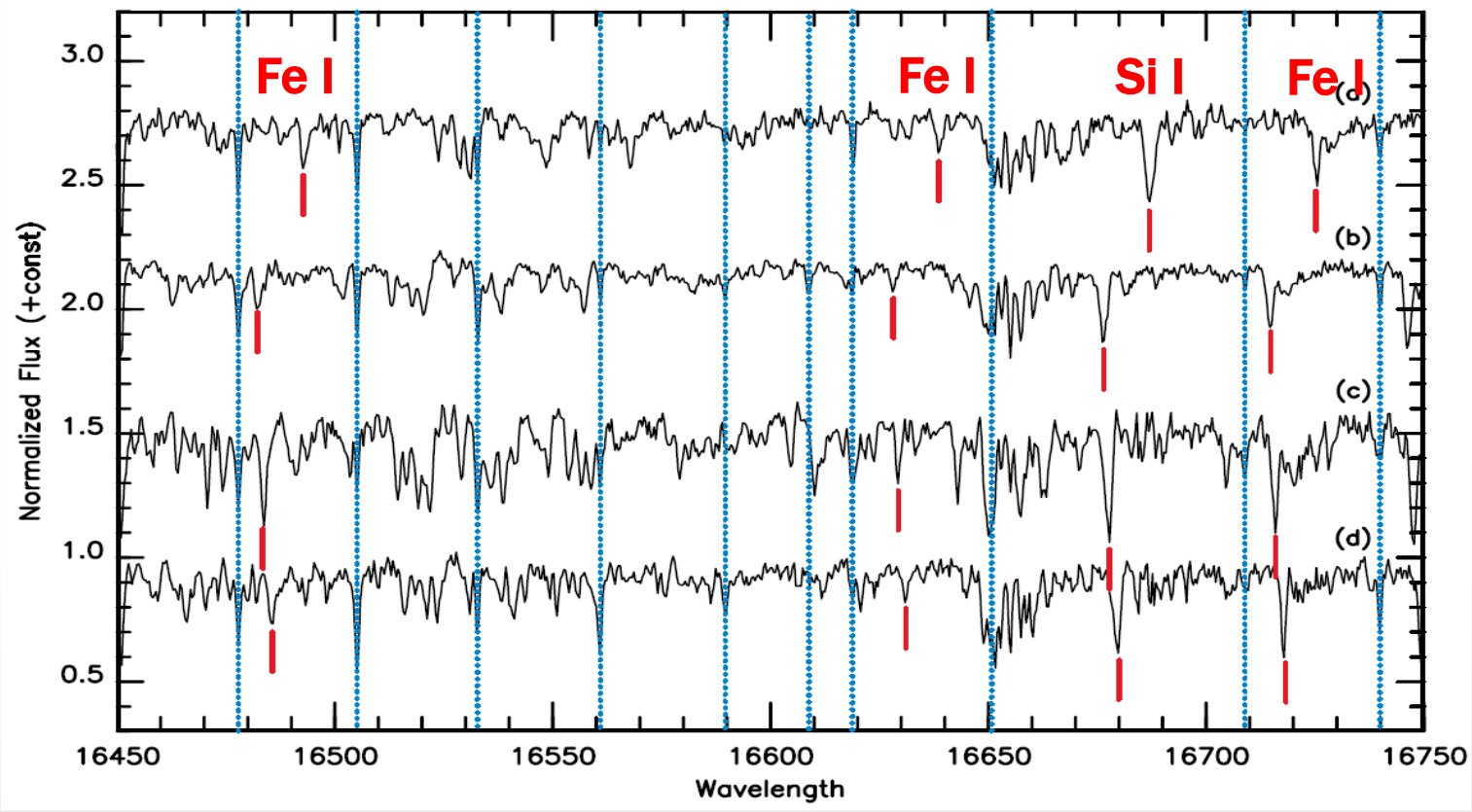
Spectroscopic observations

- 3 Cepheids reported in 2011 and 1 additional Cepheid newly found.
- Subaru/IRCS + AO188
  - H- (or K-) band
  - R=λ/Δλ~20,000

Date	λ	Integration	S/N	Obj.
2010/06/20	*K*	300 sec×8	45	(a)
2012/05/25	*H*	300 sec×12	25	(a)
2012/05/25	*H*	300 sec×10	25	(b)
2012/05/25	*H*	300 sec×12	25	(c)
2012/07/26	*H*	300 sec×14	100	(a)
2012/07/26	*H*	300 sec×12	100	(b)
2012/07/29	*H*	300 sec×12	100	(c)
2012/07/29	*H*	300 sec×8	85	(d)



Subaru/IRCS Spectra of the Cepheids



Cepheid (a)

Cepheid (b)

Cepheid (c)

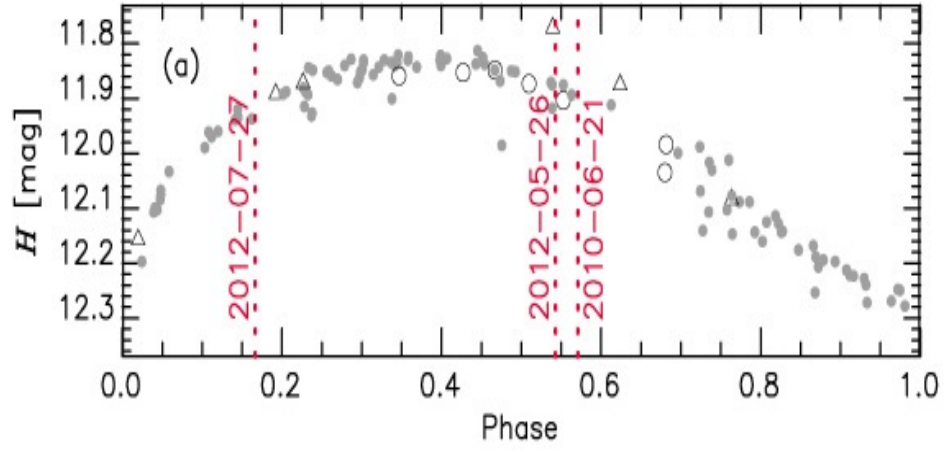
Cepheid (d)

H-band spectra ($R=\lambda/\Delta\lambda\sim20{,}000$) of the 4 Cepheids taken in 2012 July

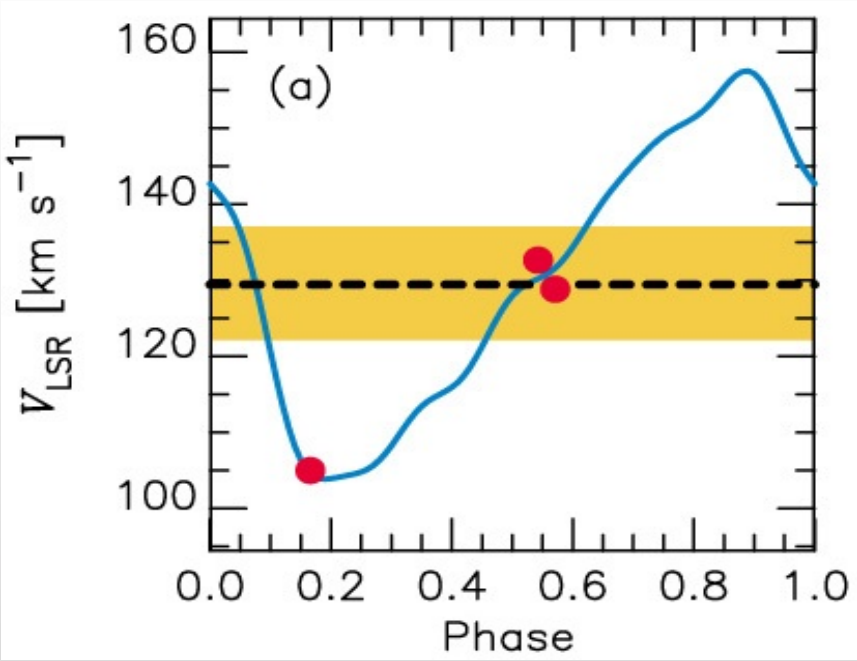
- Dozens of metallic absorption lines exist.
- Significantly different radial velocities observed.
- Velocities obtained with the cross-correlation method.

Correction of the pulsational effect

- Using an *H*-band light curve
  - To determine the phase of each spectrum
  - To predict a velocity curve based on templates we constructed using the data for 11 nearby Cepheids with P~20 d compiled by M. Groenewegen (2011).
- Comparing a predicted velocity curve with the measured velocities to estimate a mean.

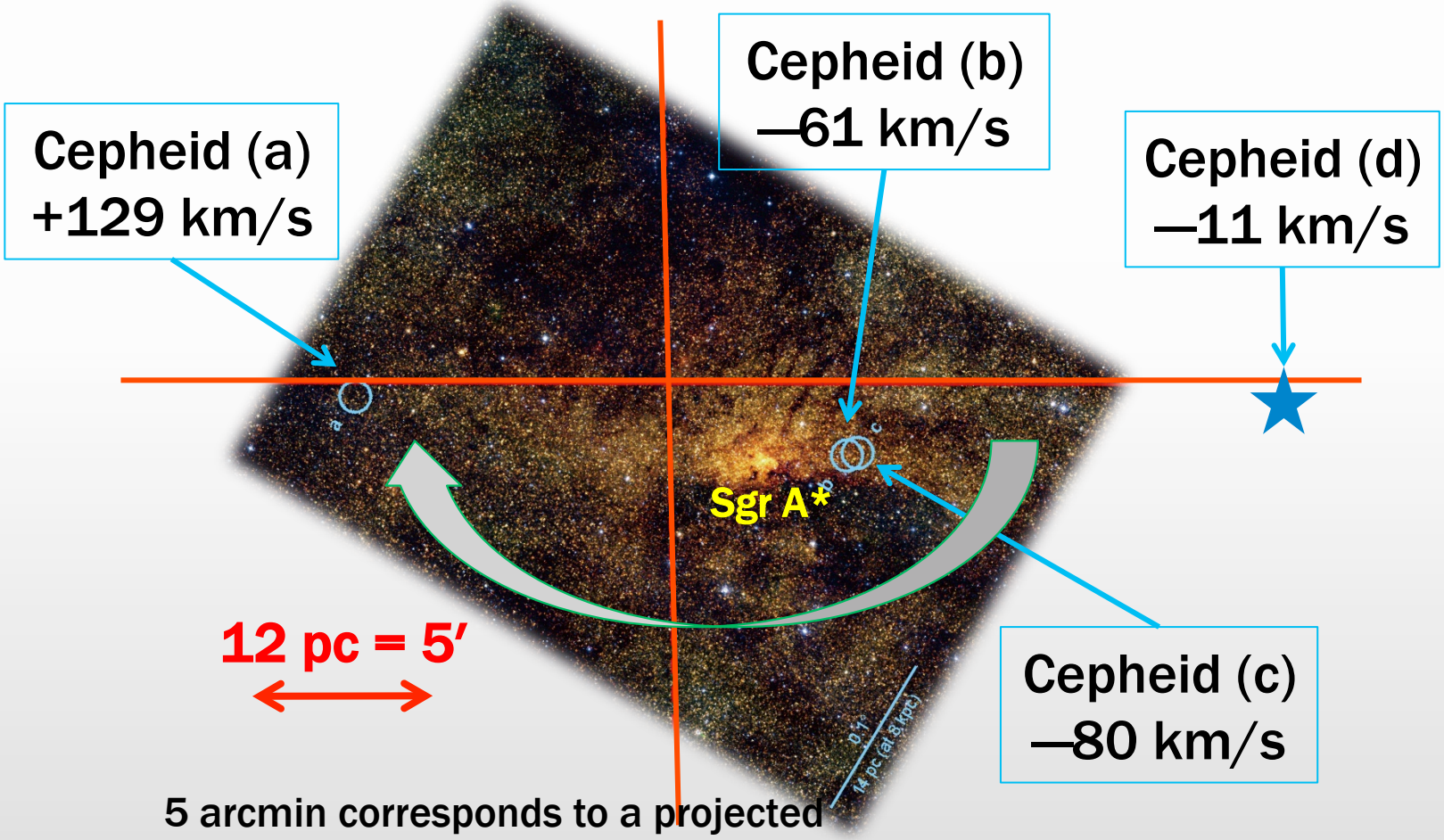


The H-band light curve (↑) and the predicted velocity curve (→) of the object (a).



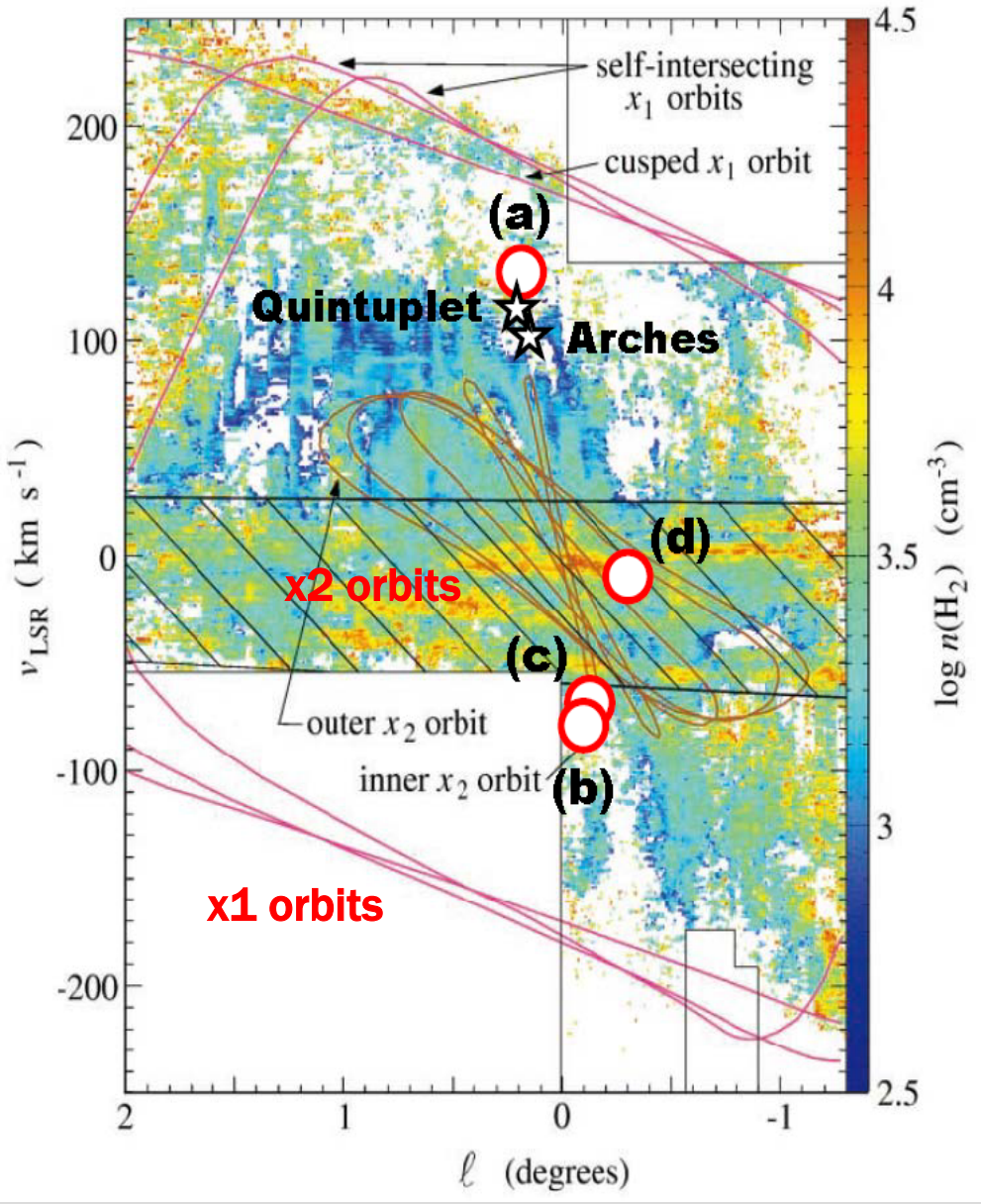
Velocities (V_{LSR}) of the Cepheids

- Consistent with the rotation of the Nuclear Disk.



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

Discussion



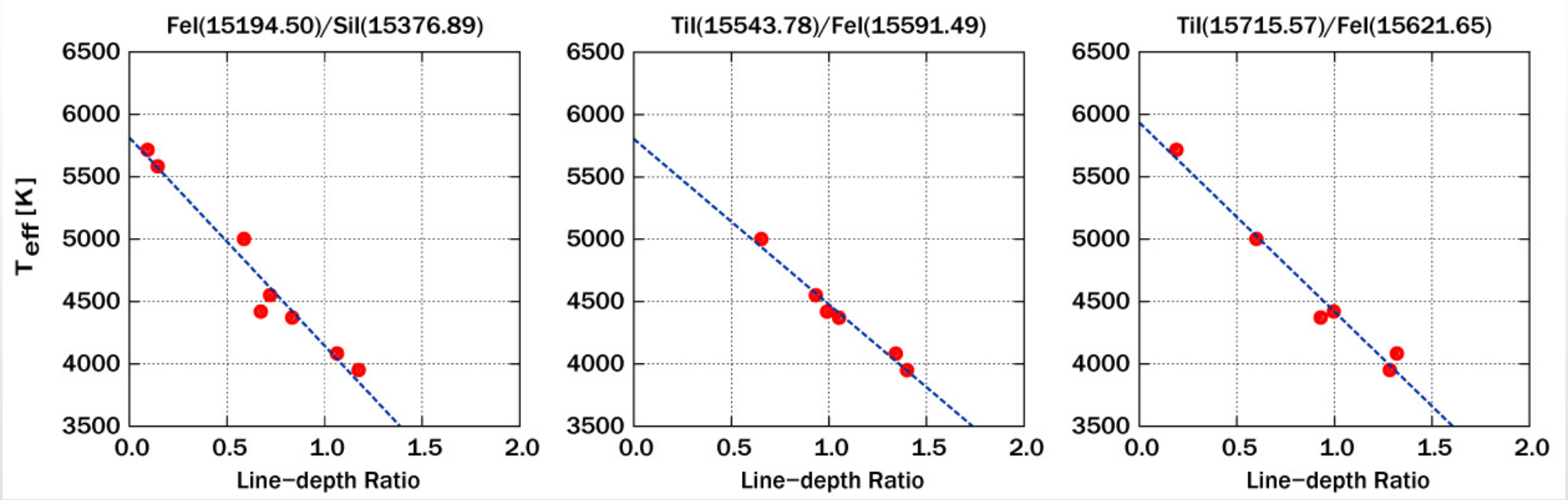
- Consistent with the rotation of the Nuclear Stellar Disk.
  - (b), (c), (d)—consistent with x2 orbits.
  - (a)—velocity is larger than expected for closed x2 orbits. This object may be in a transitional orbit like Arches and Quintuplet clusters (Stolte et al. 2008, 2014).
- Proper motions should be measured in the future.

V(LSR) of Cepehids and clusters are overplotted on the *l-v* diagram of CO gas (Stark et al. 2004).

Abundances of the Cepheids?

- Analysis in progress...
- We have constructed the method of line-depth retios to determine $T_{\rm eff}$ with the *H*-band spectra, and estimated $T_{\rm eff}$ of the Cepheids.

Examples of line-depth ratio vs $T_{\rm eff}$ relations



See the posters by K. Fukue and also R. Yamamoto!

Section summary

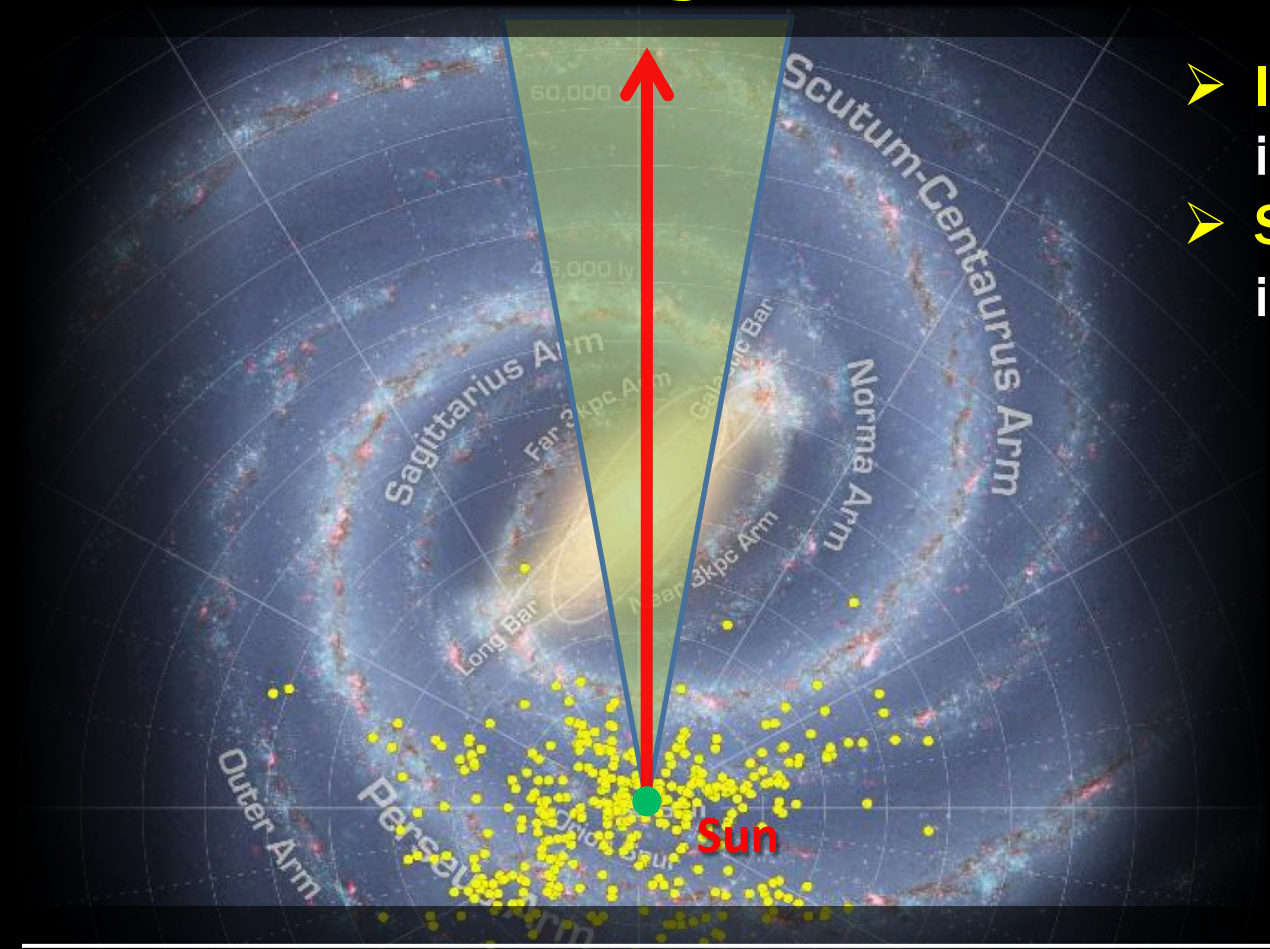
- Exploring *H*-band spectra in order to study kinematics and abundances of highly reddened objects
  - Radial velocity by the cross correlation method
  - Effective temperature by the line-depth-ratio method
  - Abundance analysis: in progress
- We confirmed that the Cepheids around the GC are rotating within the Nuclear Stellar Disk.

New IRSF Survey:

$-10° < l < 10°$, $b = 0°$

Search for variables in the bulge and beyond

IRSF surveys: Center and Bulge



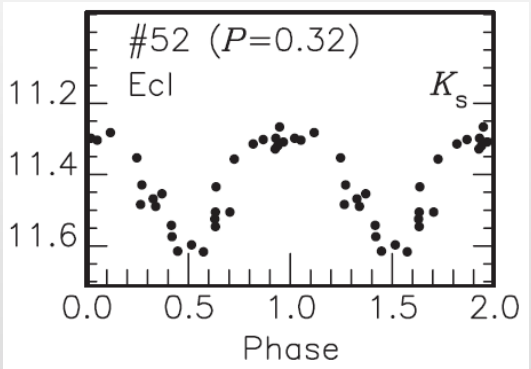
- IRSF 1.4-m telescope in South Africa
- SIRIUS JHKs 3-band imager

Region	range	#(FOVs)	Area	Obs. Duration	#(Obs)
Center	ℓ=0	12	0.17 deg^2	2001—2008	90
Bulge	-10<ℓ<+10	142	2.3 deg^2	2007—2012	30

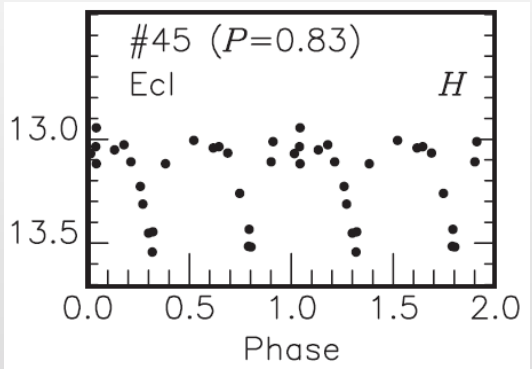
Variable stars detected

- More than 5,000 variable stars are found.
- 96 variable stars with *P* shorter than 60 days.
  - 3 are classical Cepheids already reported in 2011
  - 3 were reported as variable stars before by other groups; All are eclipsing binaries.
    - WY Sgr (*P*=4.67 d), HV10266 (*P* unreported), Sokolovsky+09 #1 (*P*=0.82 d)
  - Some eclipsing binaries have X-ray signals reported.

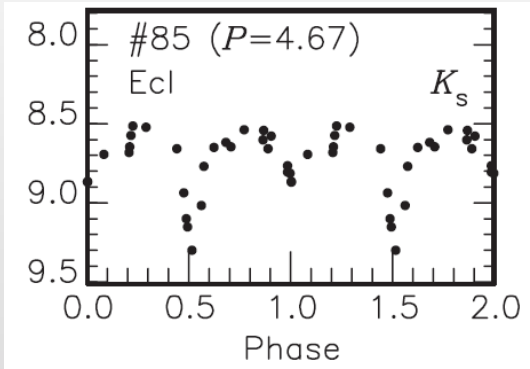
Previously known eclipsing binaries



HV10266



Sokolovsky+09 #1

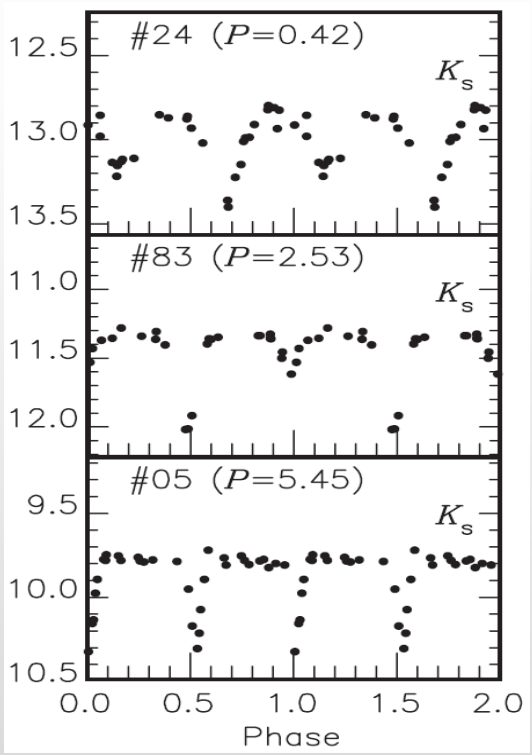


WY Sgr

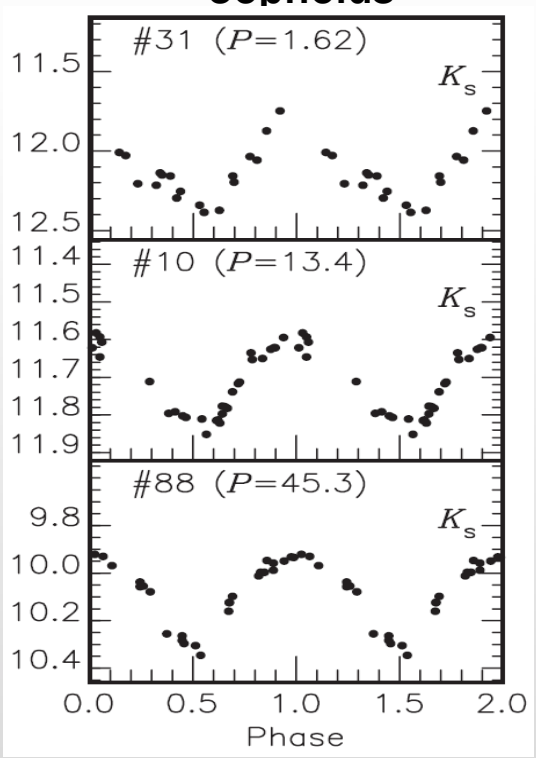
Examples of light curves

- In most cases, light curves indicate whether the variables are eclipsing binaries or pulsating stars.
- Examined by eye, and Fourier parameters are investigated for classification.

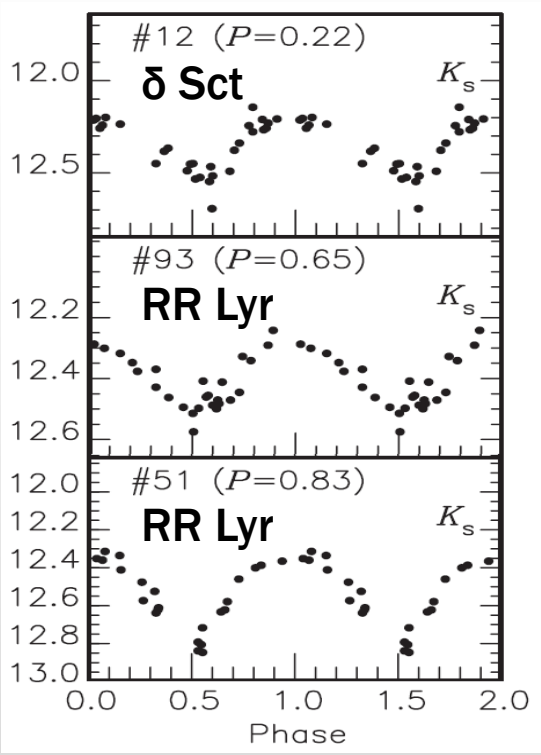
Binaries



Cepheids

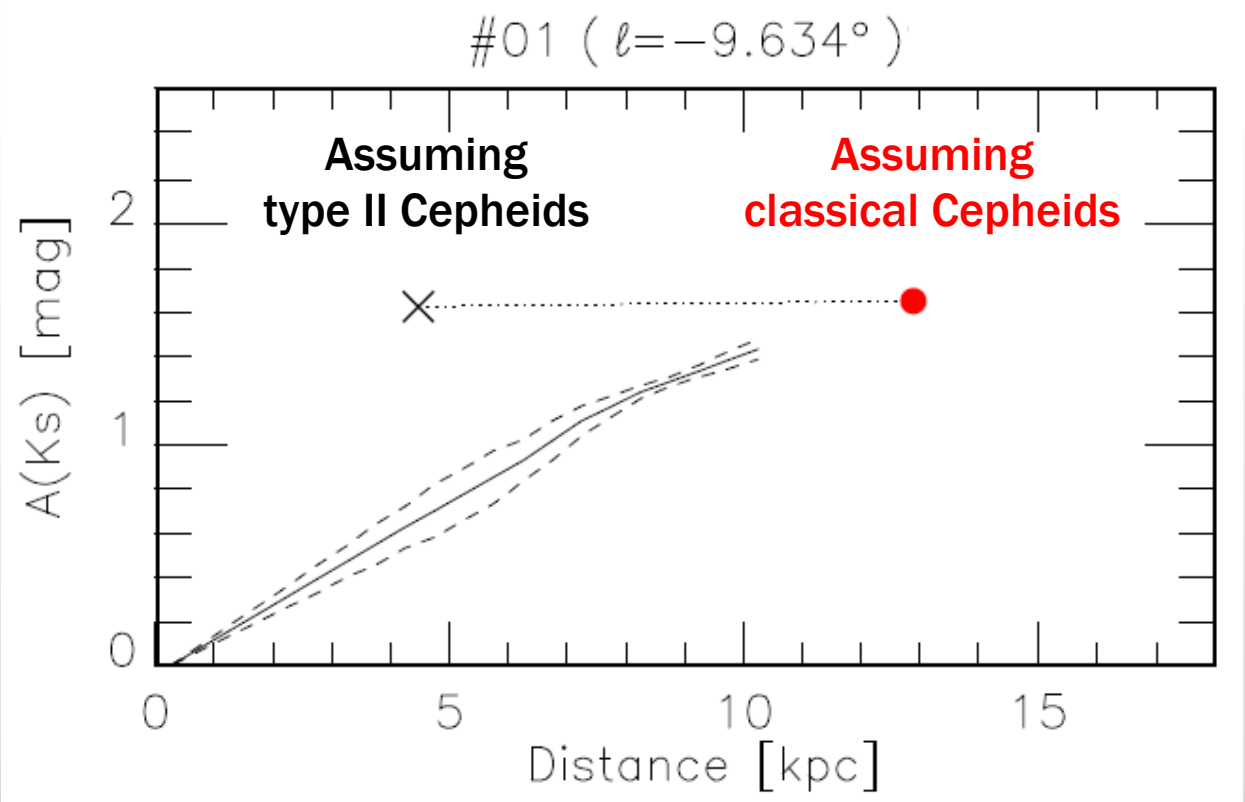


Others

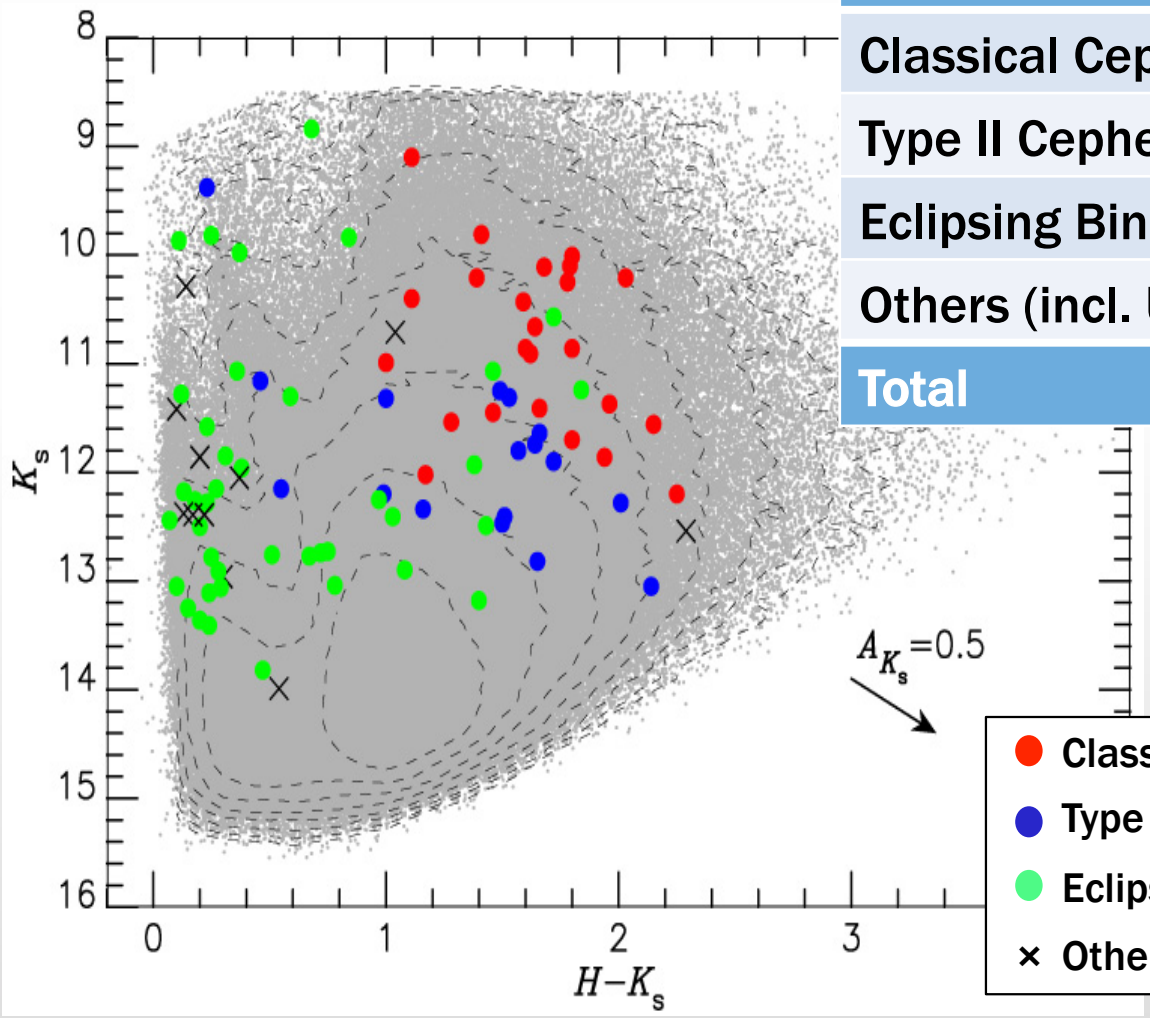


Dividing classical/type II Cepheids

- It is not always easy to discriminate between IR light curves of two kinds of Cepheids.
- 3D extinction map (Schultheis et al. 2014) is found useful to determine two types of Cepheids.



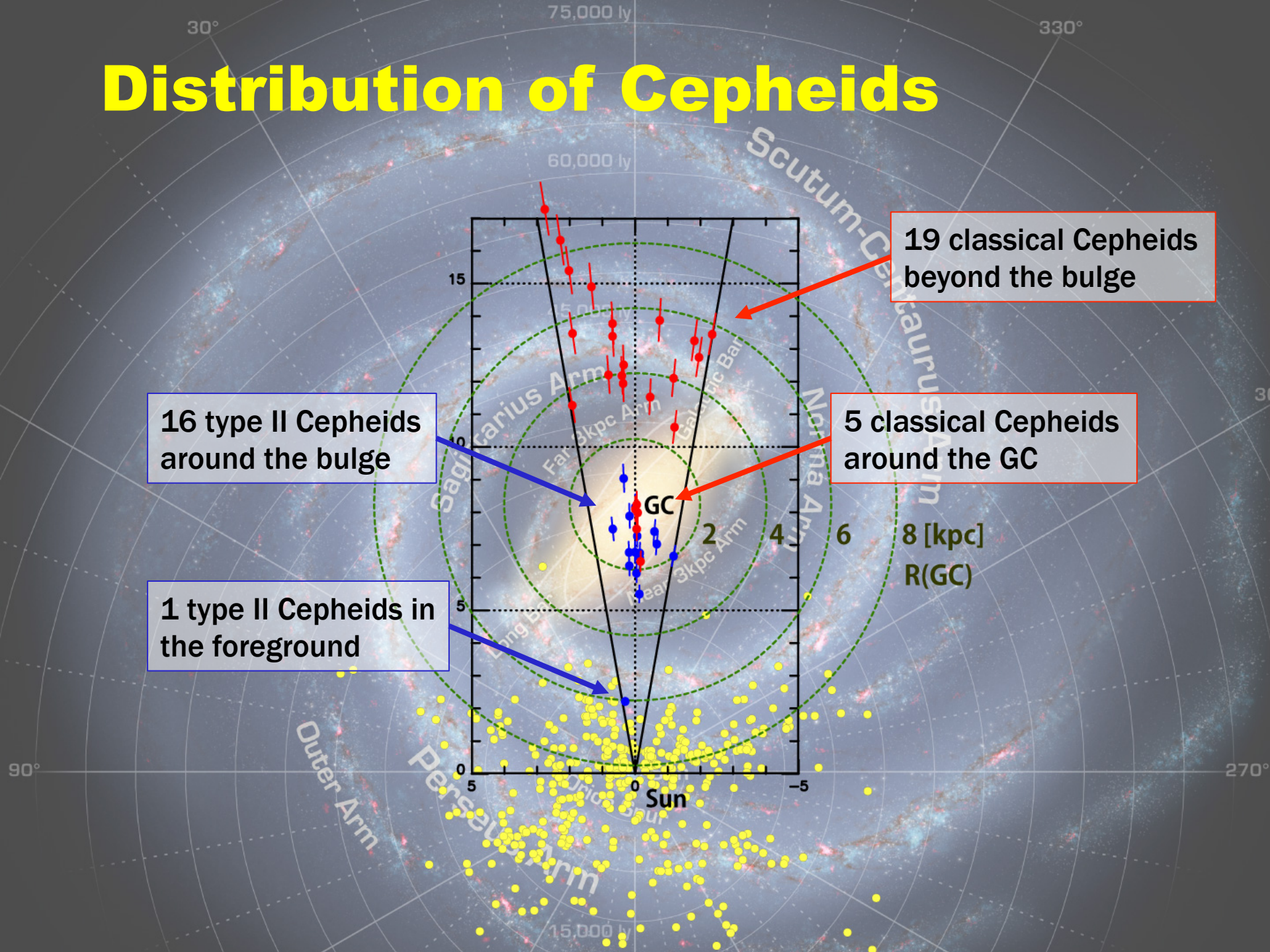
Classification



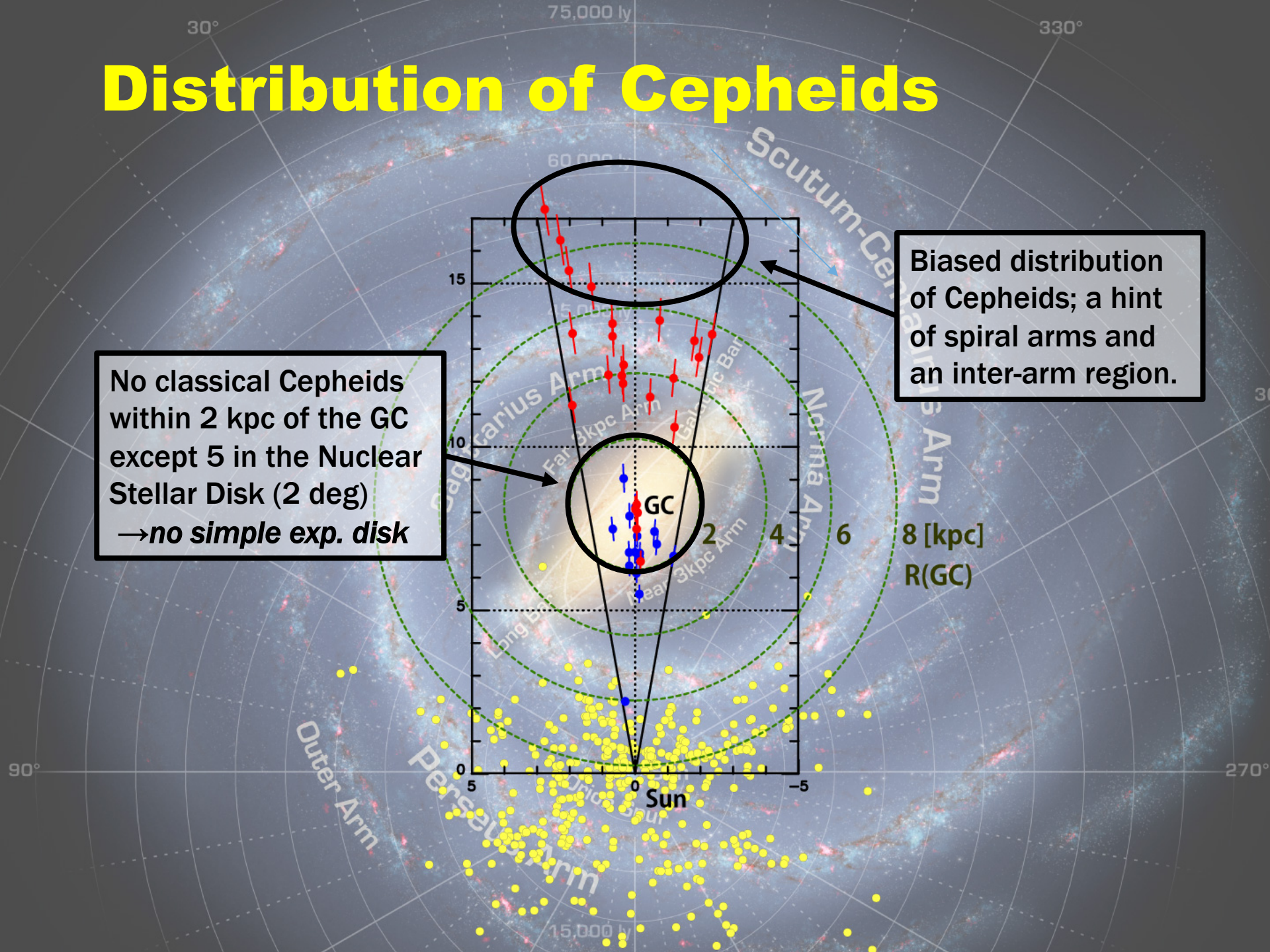
Type	Number
Classical Cepheids	24†
Type II Cepheids	17
Eclipsing Binary Systems	43
Others (incl. Unclassified)	12
Total	**96**

† 3 were those already reported in 2011.

Distribution of Cepheids



Distribution of Cepheids



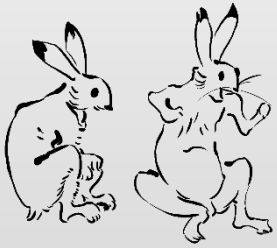
Section summary

- IRSF survey towards the bulge: $|\ell| < 10°$, $b = 0°$
- We discovered:
  - 5 classical Cepheids in the Nuclear Stellar Disk,
  - ~20 classical Cepheids beyond the bulge,
  - dozens of type II Cepheids in the bulge,
  - and ~5,000 long-period variables

Future prospects

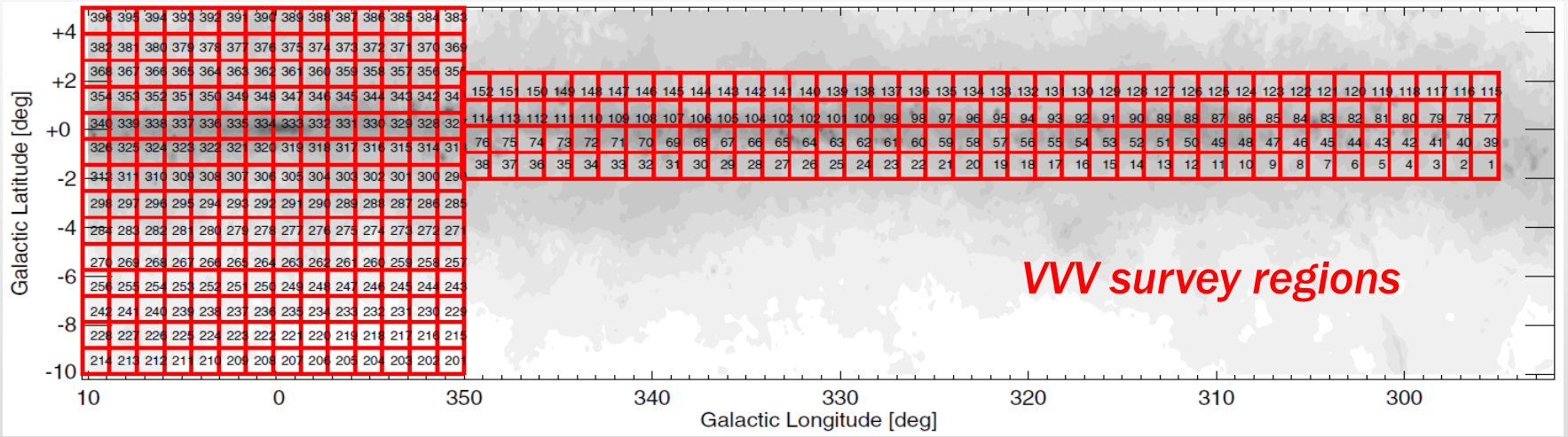
Find (photometric surveys), and

look more closely (spectroscopy)



Photometric surveys

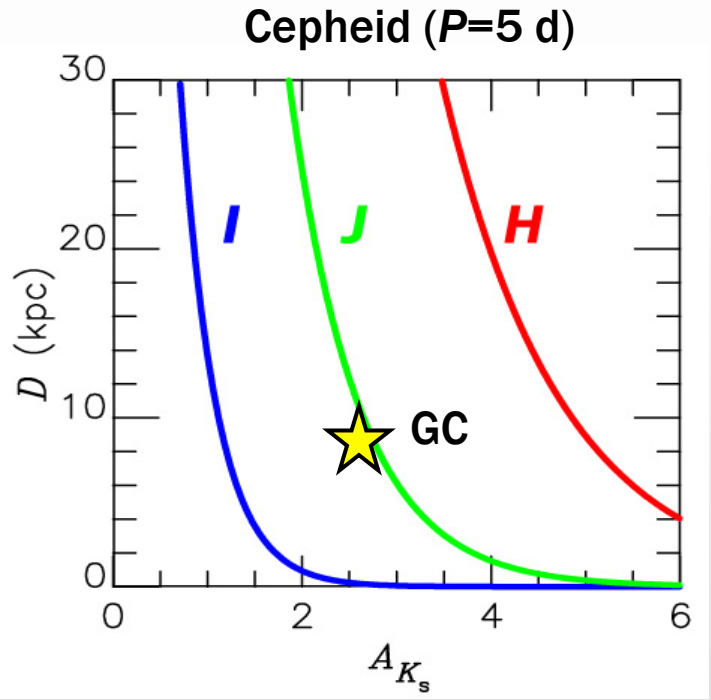
- Large-scale systematic surveys will discover a huge numbers of variable stars (as *OGLE* already started).
- *VISTA-VVV*: *Ks*-band (*Ks*<17^{mag}) monitoring for the bulge (100 epochs) and disk (60 epochs) in 5 years.
- *Gaia*: in the optical, still many Cepheids to be found in less obscured regions (Windmark et al. 2011)
- *ZTF, LSST, …*



Saito et al. (2012, A&A, 537, A107)

Spectroscopy

- HIRES being planned for E-ELT (www.hires-eelt.org)
  - R=130,000
  - *H*=17.6 VEGA mag (S/N=50, 2hr; courtesy of L. Origlia)
  - ***H***-band (or ***J***-band) spectroscopy needed rather than ***I***-band.



Maximum A(K) value with which a Cepheid (P=5d) can be observed.

Wavelength	I	J	H
A(K) limit for 10 kpc	1.2	3.6	4.8
A(K) limit for 20 kpc	0.8	2.2	3.9

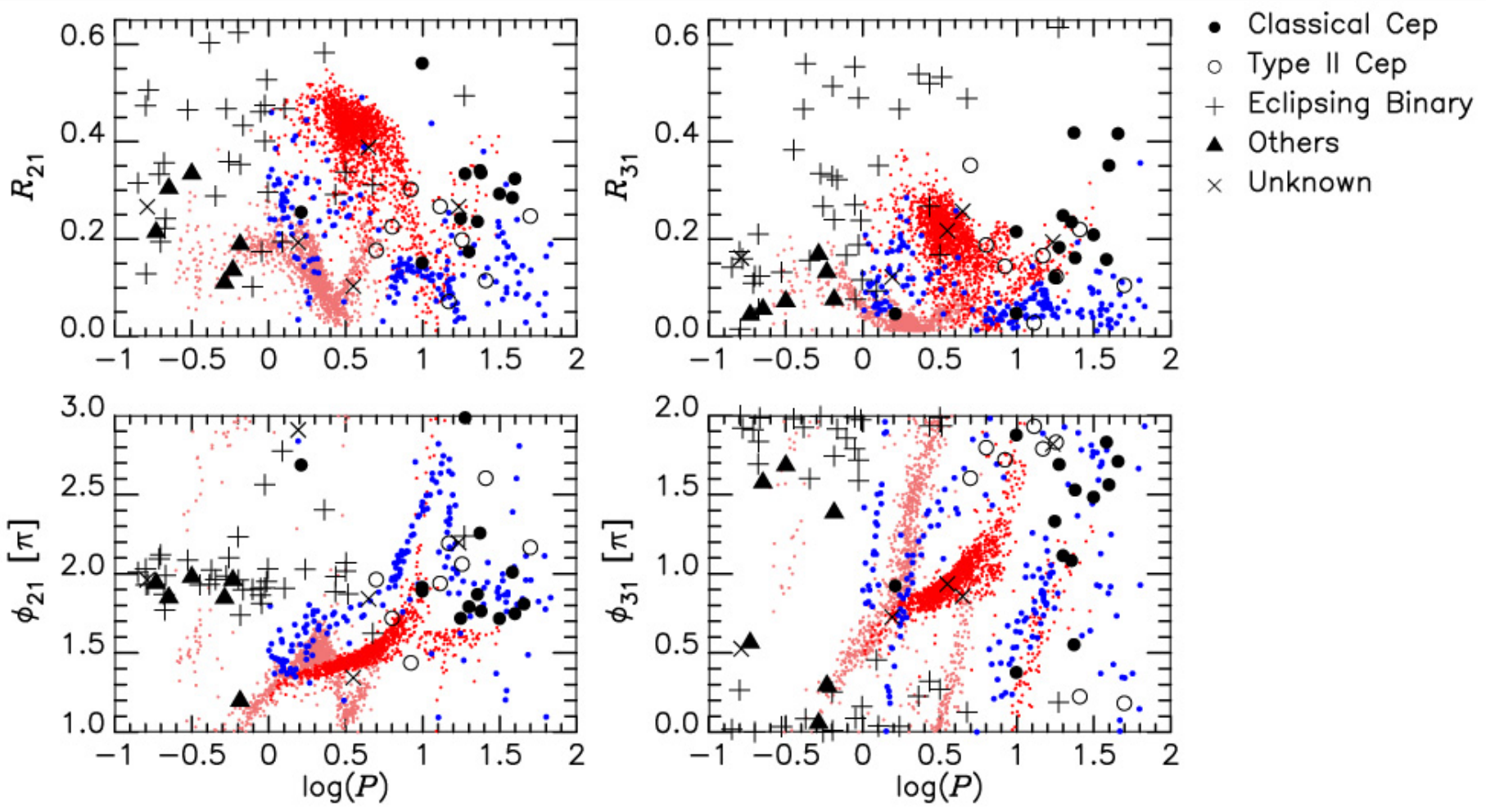
Limit distances at which spectra can be taken as functions of extinction ($A\downarrow\lambda \propto \lambda\uparrow -2$ extinction law assumed).

Summary

- Our recent results—examples of infrared observations of obscured variable stars
  - Kinematics of Cepheids within the Nuclear Disk (R_{GC}<300pc).
  - Distant Cepheids behind the Galactic bulge found.
- Take-away message
  - Variable stars are useful and important tracers, and infrared observations are necessary to study the populations hidden in the Milky Way.

End

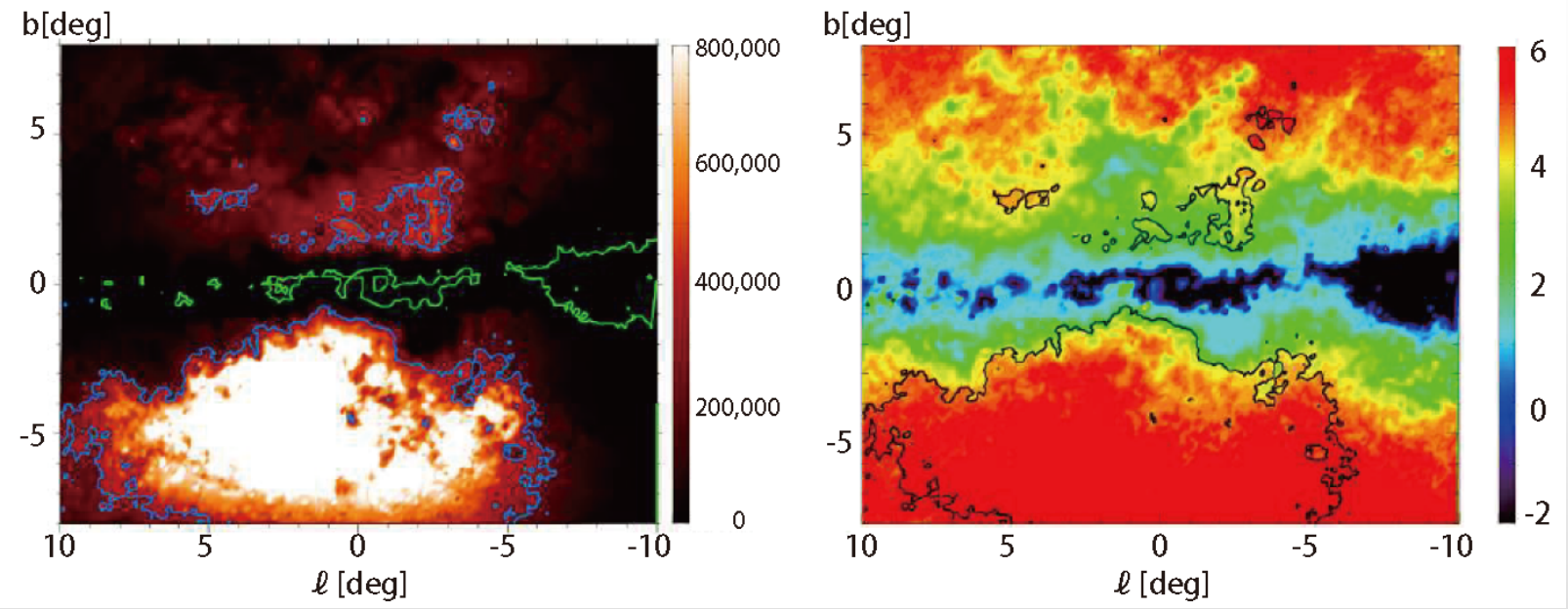
Fourier parameters



Stellar populations behind the veil

- The bulge and disk, the main body of the Galaxy, is obscured by the interstellar extinction.
- Infrared observations are necessary.

Stellar population to be detected in *Gaia* (Reyle et al. 2008)

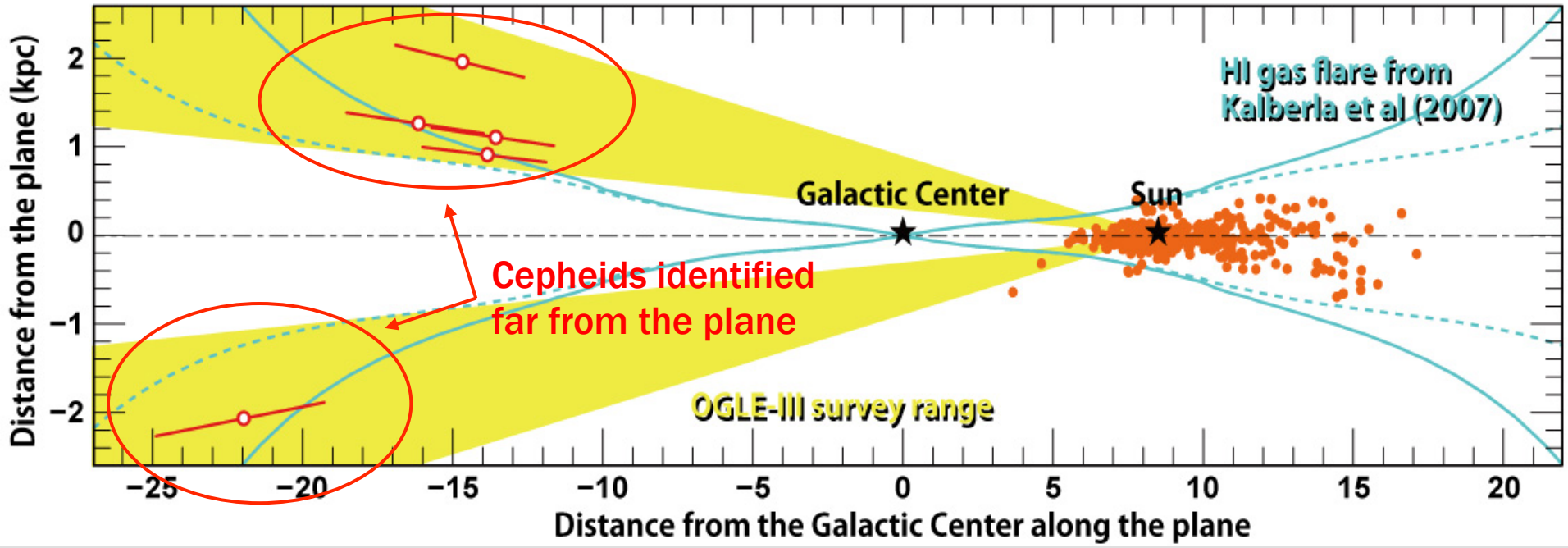


Stellar density of the bulge seen down to G=20

Absolute magnitude M_V just reached at G=20

Feast et al. 2014, *Nature* 509, 342

- We discovered Cepheids in the flared part of the disk.
- They belong to the disk (rather than the helo) because
  - they are young (~100 Myr old),
  - their kinematics are consistent with the disk rotation model.



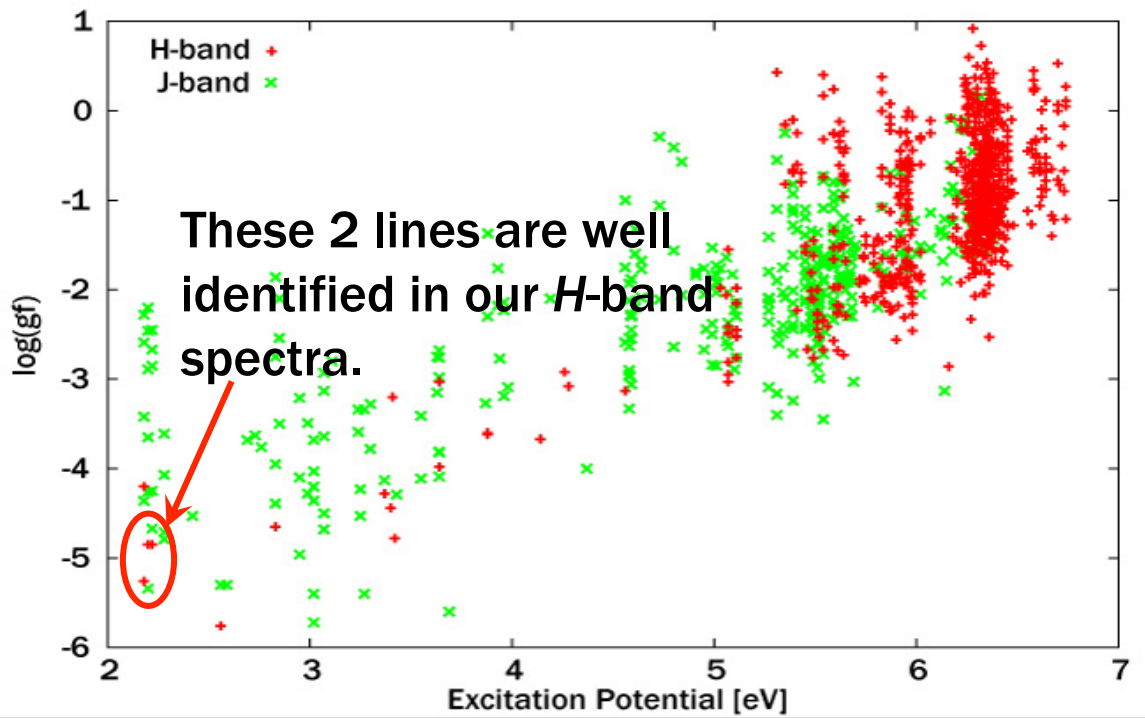
Variable stars in the *Gaia* era

- With accurate parallaxes, *Gaia* can build a map of billions of normal stars in the Milky Way.
  - Distance up to 10 kpc with the 10% accuracy

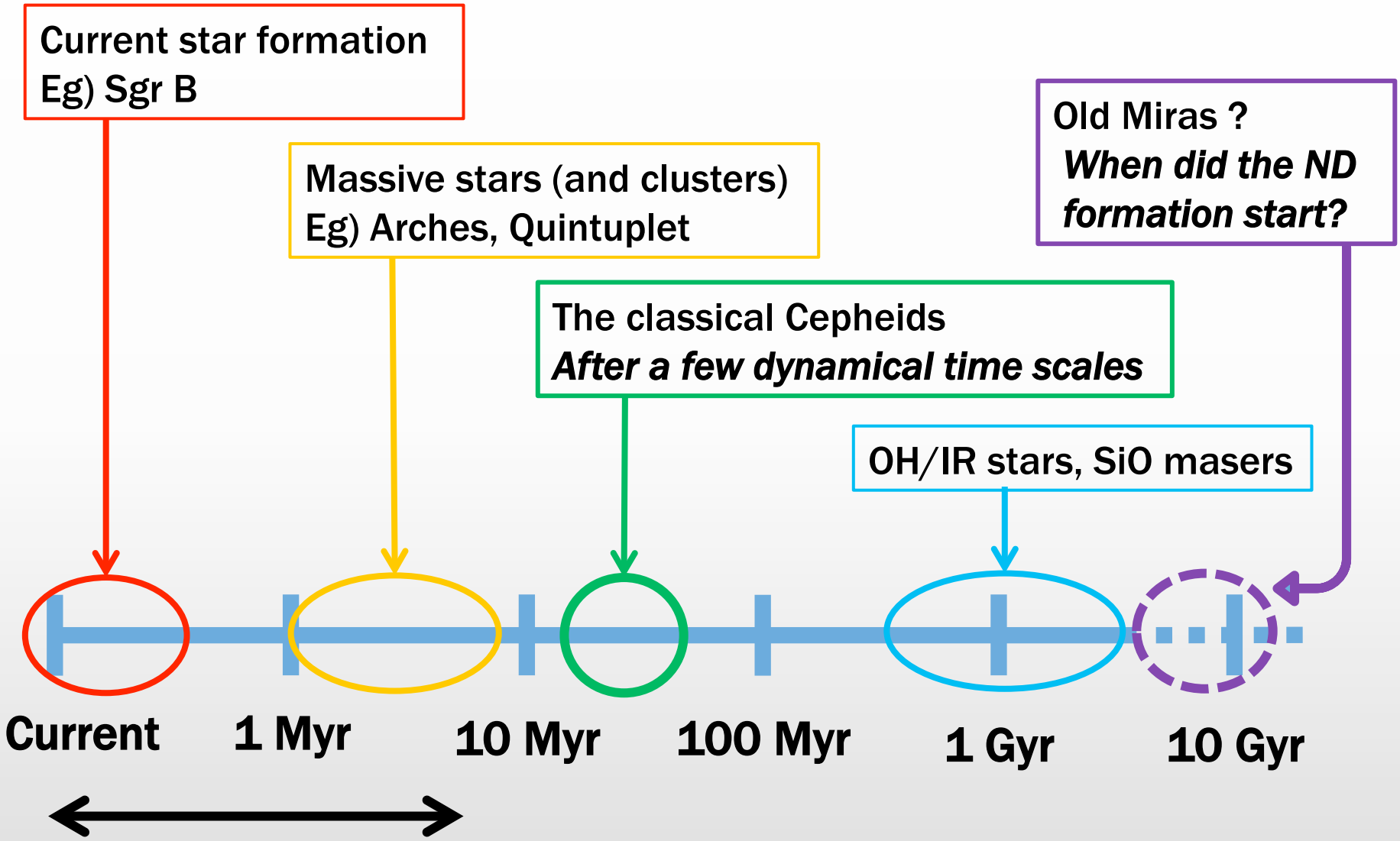
- (Infrared) observations of variable stars will be still important for studying the Milky Way:
  - A larger range of distance can be obtained to the 10% level.
  - Obscured objects in the disk can be observed (in the IR).
  - Ages of variable stars are accurately determined.
    - Direct indicator of stellar population

A disadvantage in *H*-band spectroscopy?

- No Fe II (ionized) lines identified
- Only a few lines with low excitation potential
  (Melendez & Barbuy, 1999, ApJS, 124, 527)
- These lines are useful in estimating temperatures.

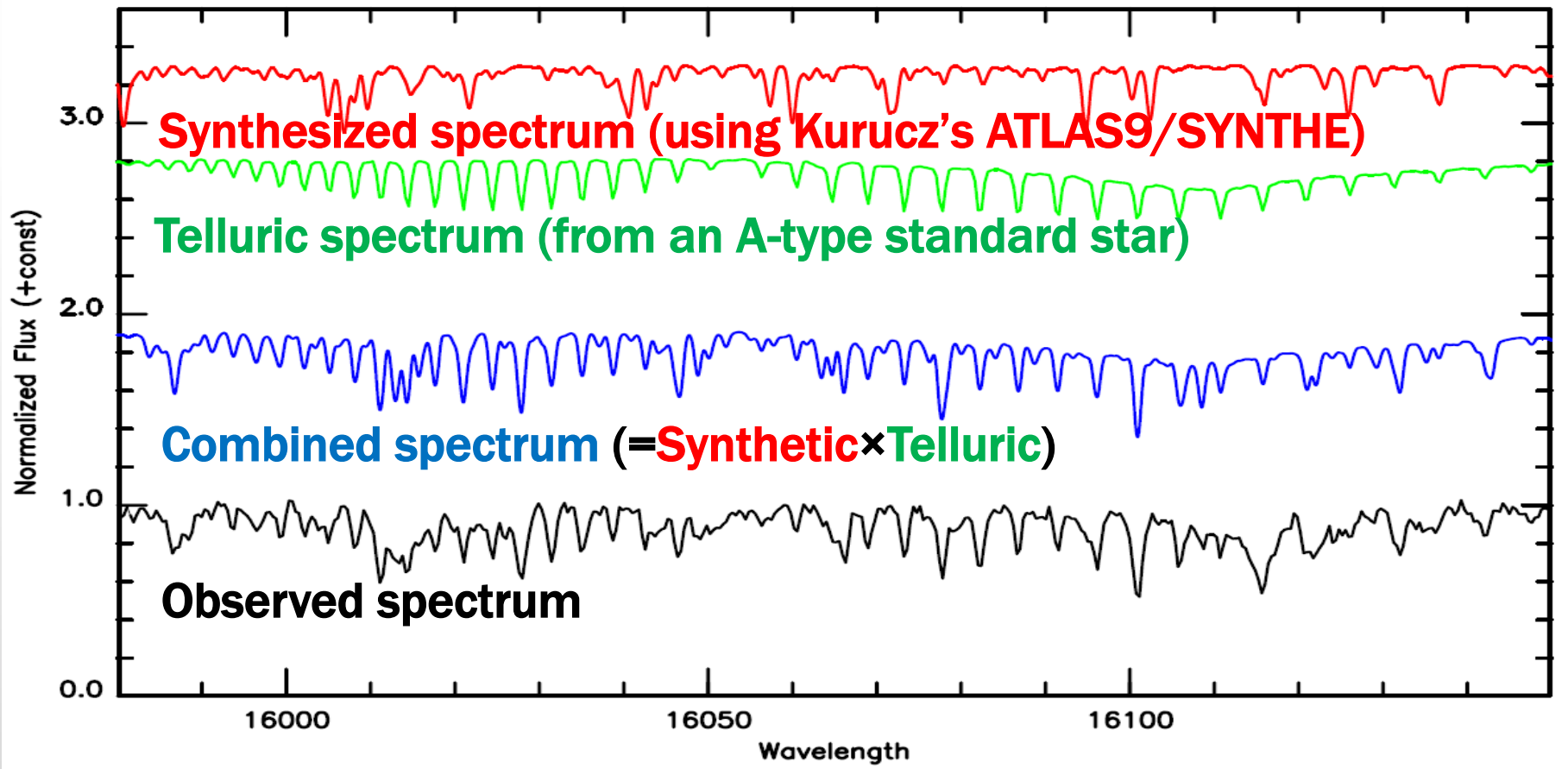


Stellar populations in the Nuclear Disk



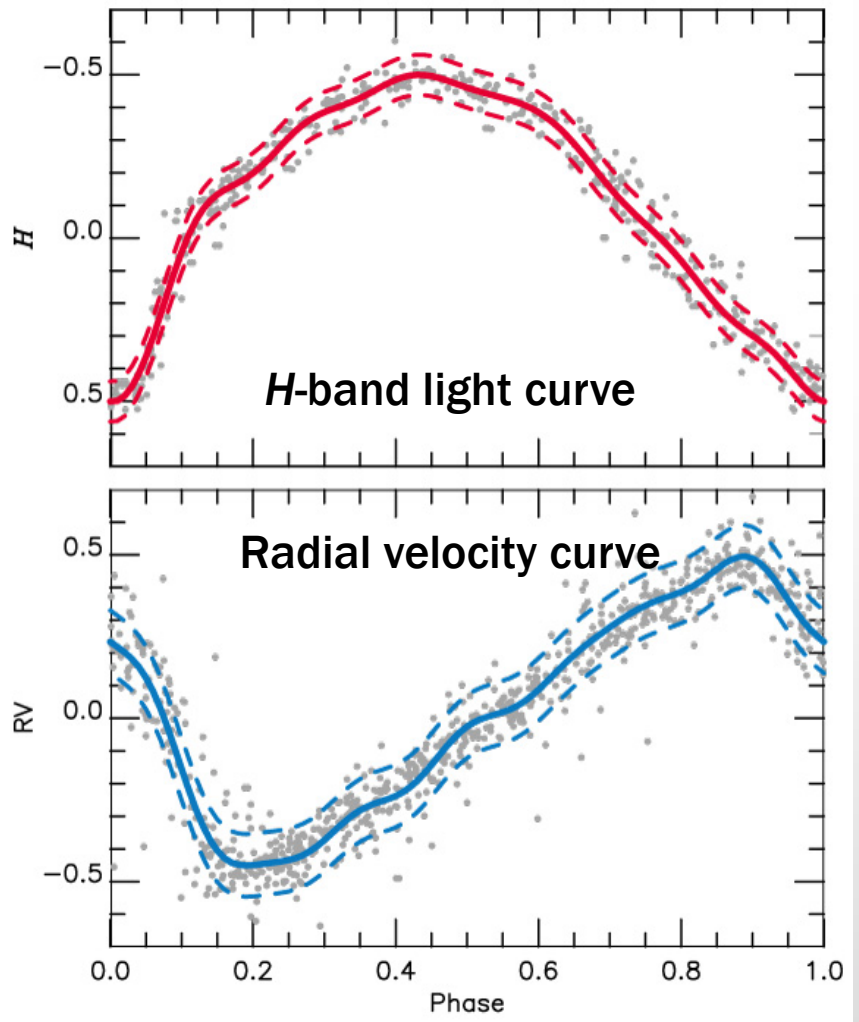
Estimating radial velocities

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



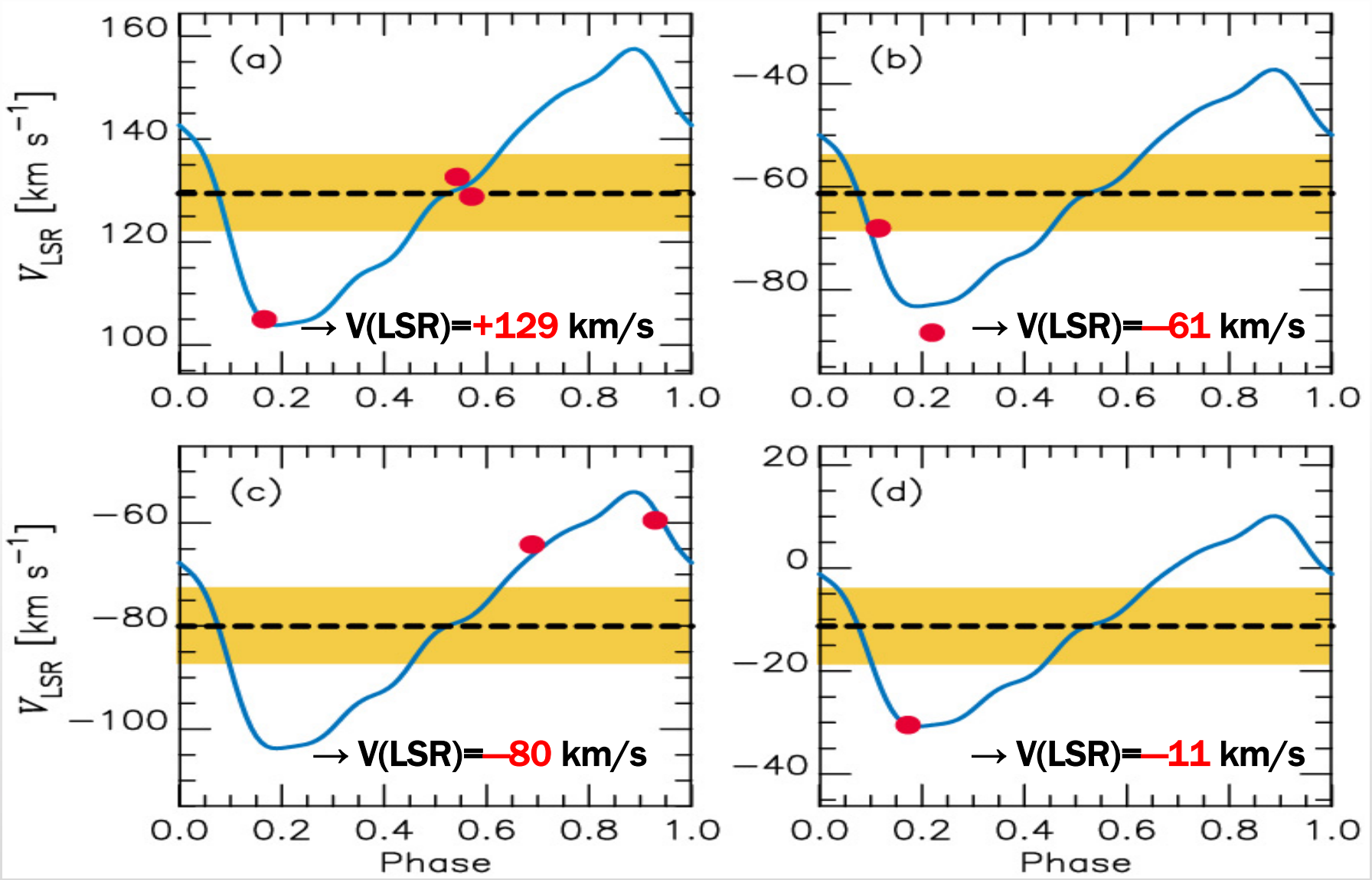
Light curve and velocity curve templates

- *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

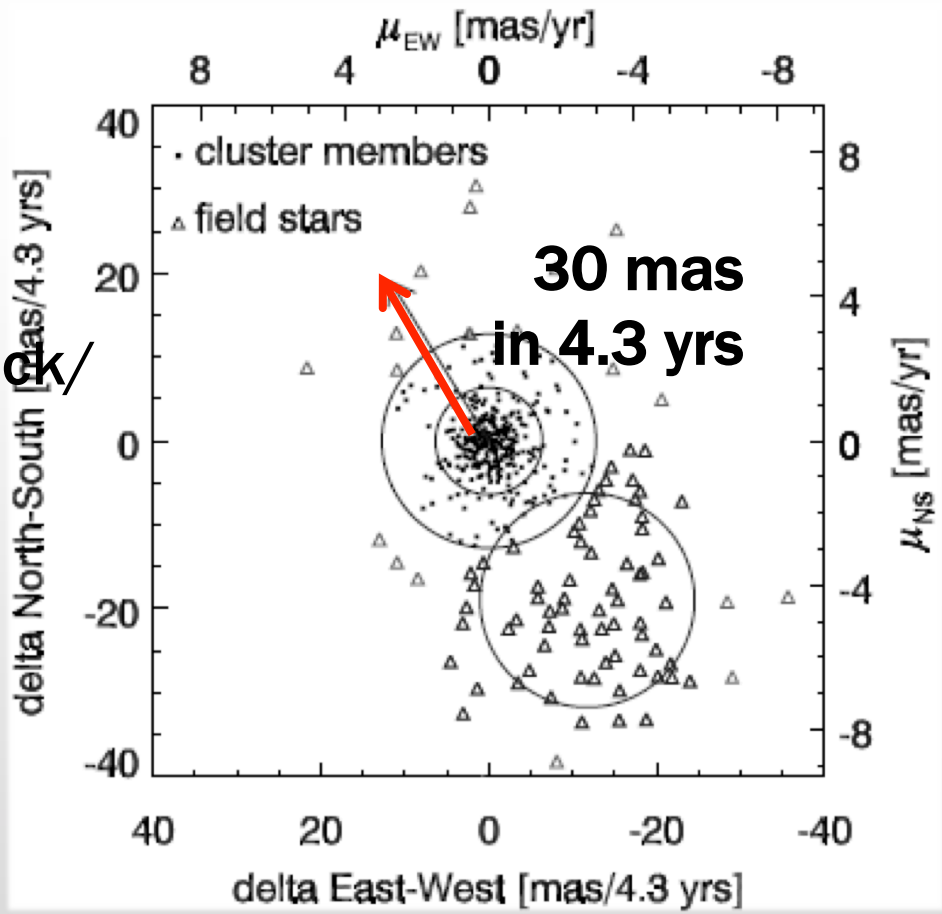
- Typical uncertainties are roughly ±5km/s.



The motion of the Arches cluster

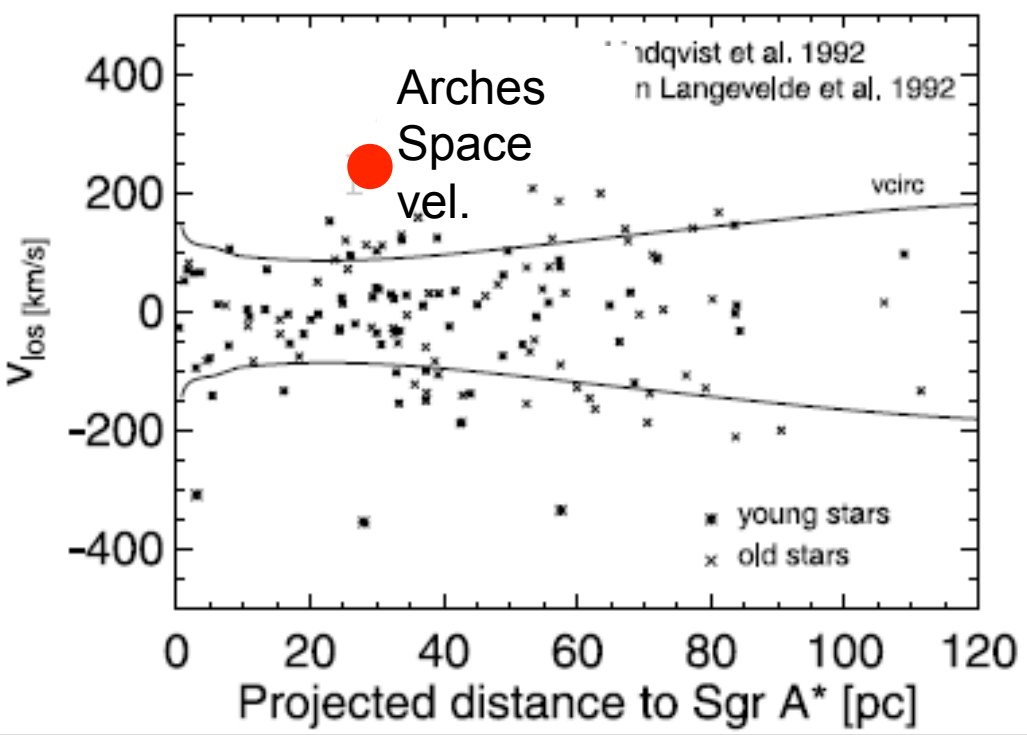
- One of the young massive clusters in the Nuclear Disk
- Radial velocity
  - Figer et al. (2002)
  - +95 ±8km/s
- Proper motion
  - Stolte et al. (2008)
  - 4.3 yr apart images from Keck/ NIRC2, VLT/NACO
  - 212±29km/s
- 3d velocity
  - +232±30km/s

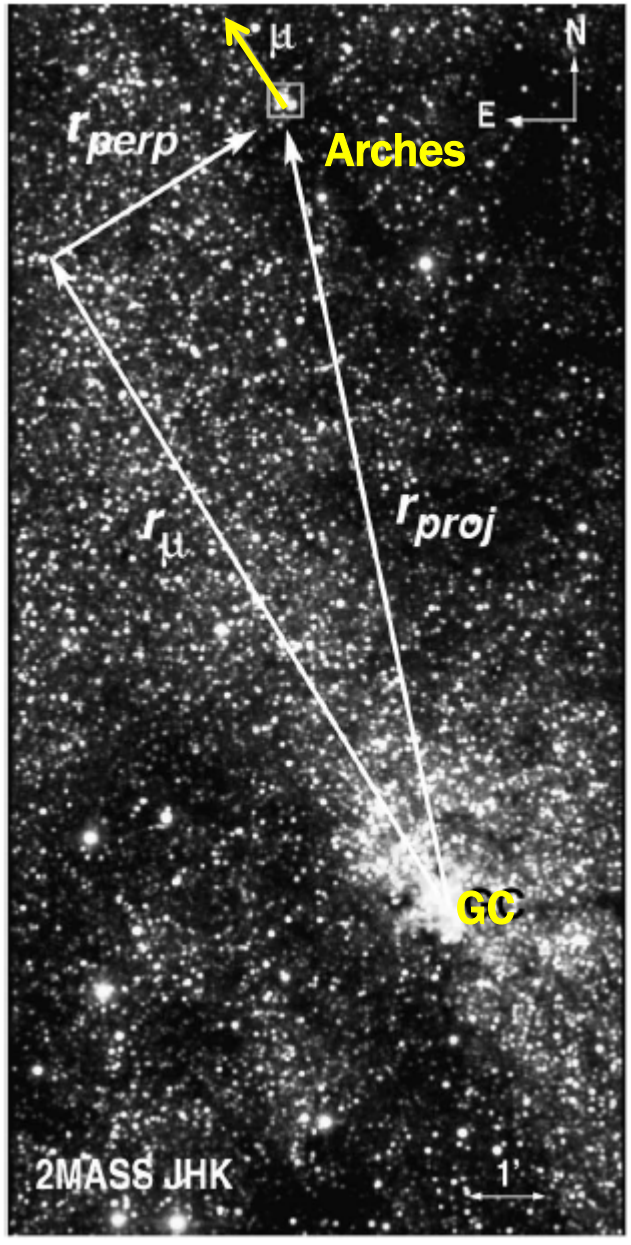
Stolte et al. (2008)



The orbit of Arches

- The velocity is higher than values expected for a circular orbit or x2 orbits.
- On a transition phase?
- (Stolte et al. 2010)

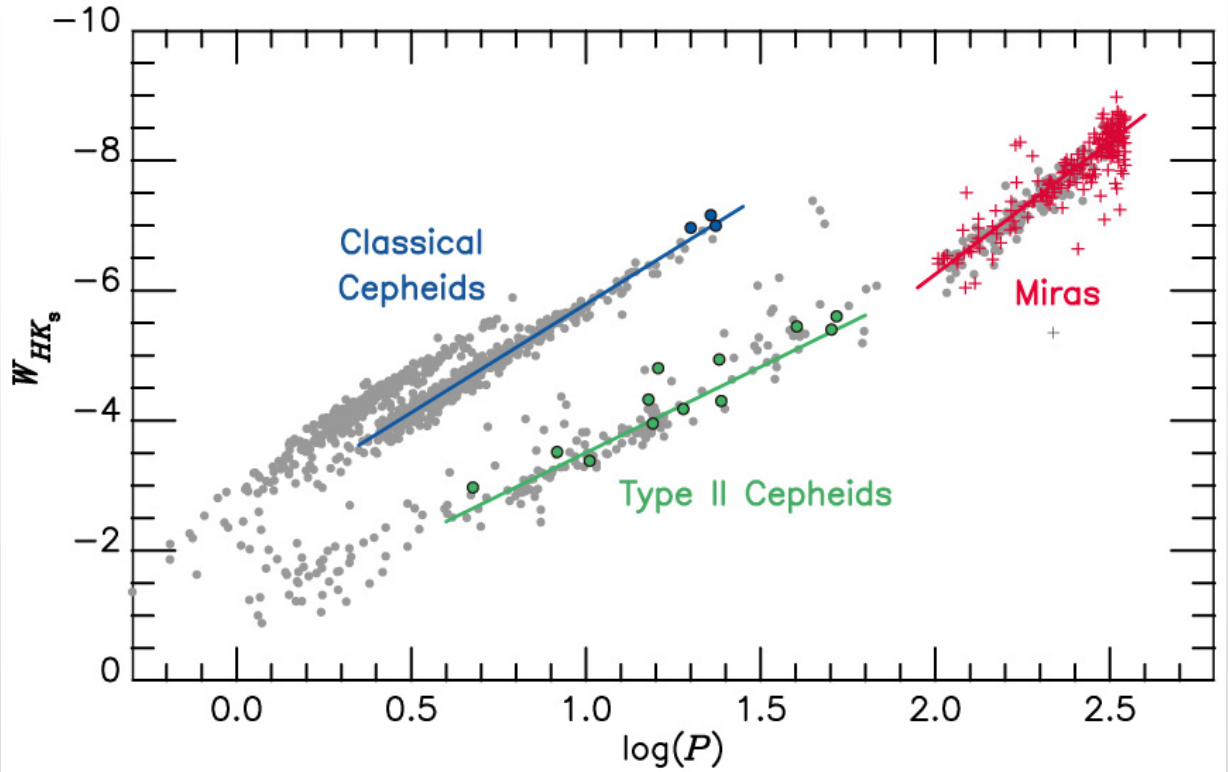




Distance to the Galactic Center

Miras	$8.24 \pm 0.08_{stat.} \pm 0.42_{sys.}$ kpc	N=136
Classical Cep	$7.9 \pm 0.2_{stat.} \pm 0.3_{sys.}$ kpc	N=3
Type II Cep	$7.5 \pm 0.45_{stat.} \pm 0.4_{sys.}$ kpc	N=15

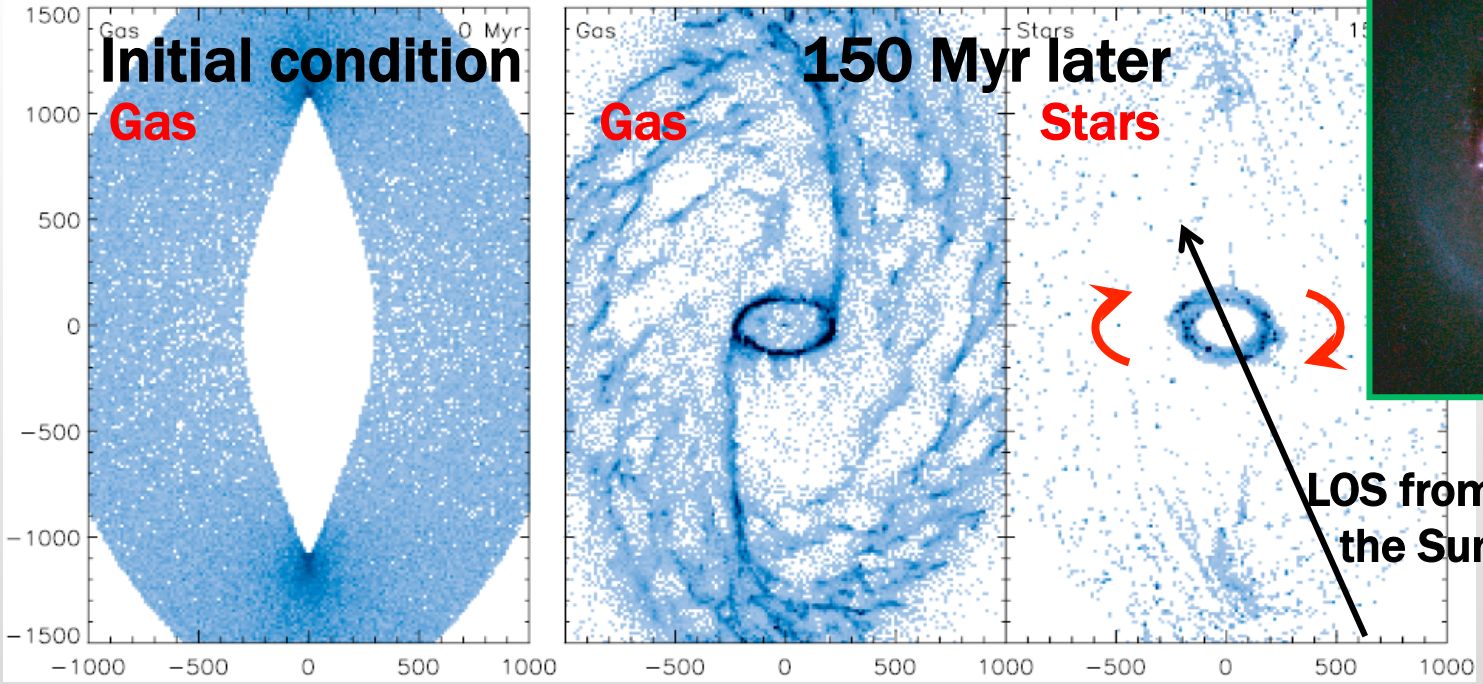
- Gillessen et al. (2013) gives 8.2±0.34 kpc from a stellar rotation around the super-massive black hole.



A scenario of the ND formation

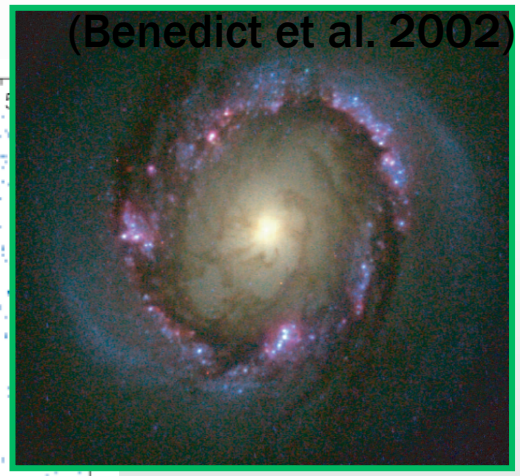
- Gas through the bar fuels the star formation in the Nuclear Disk (with a ring structure).
- Secular evolution of the Galactic central part, which may be related to nuclear star-forming rings in external galaxies.

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



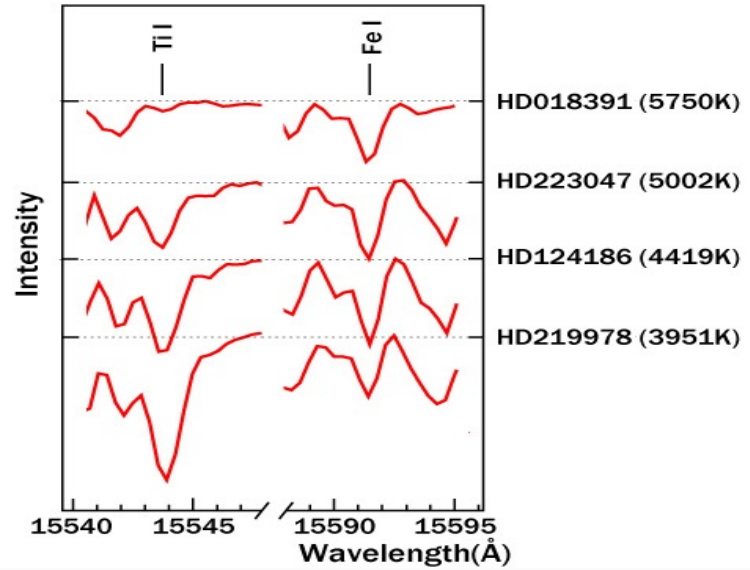
Nuclear Ring in NGC 4314

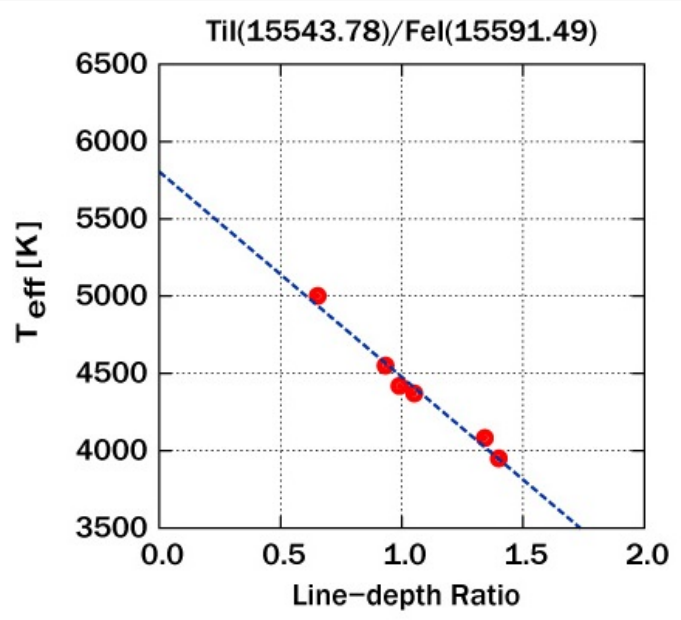
(Benedict et al. 2002)



T_{eff} from line-depth ratios

- Taking ratios of two lines with different excitation potential as measures of an effective temperature.
- For optical spectra Kovtyukh and collaborators developed the method up to the accuracy of 5—30K.
- We identified 7 line pairs in the *H*-band (including Fe and other elements) which are useful to measure T_{eff}





IRSF/SIRIUS in South Africa

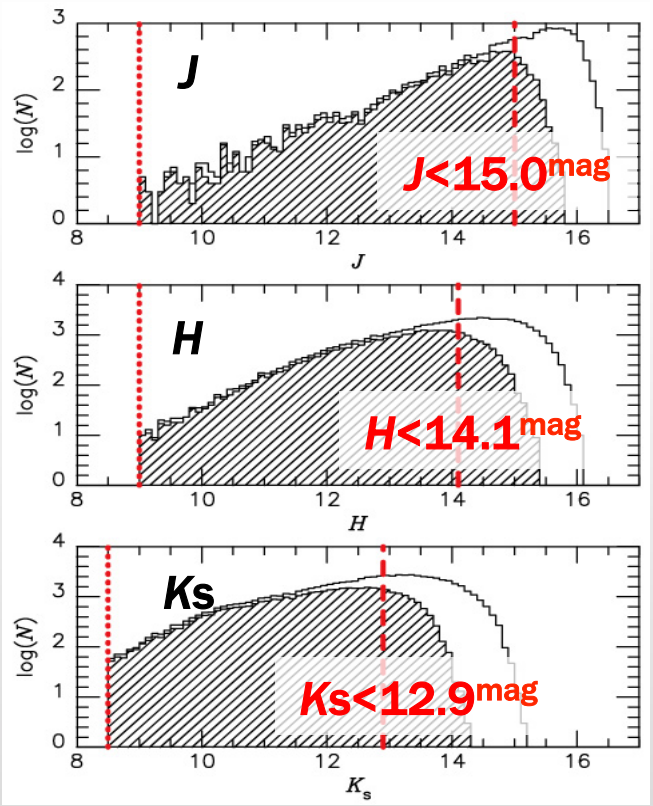
InfraRed Survey Facility:
1.4 m telescope

SIRIUS:
FOV: about 7.7' x 7.7'
Pixel Scale: 0.453"/pix,
4 times better than 2MASS
Simultaneous JHKs images.

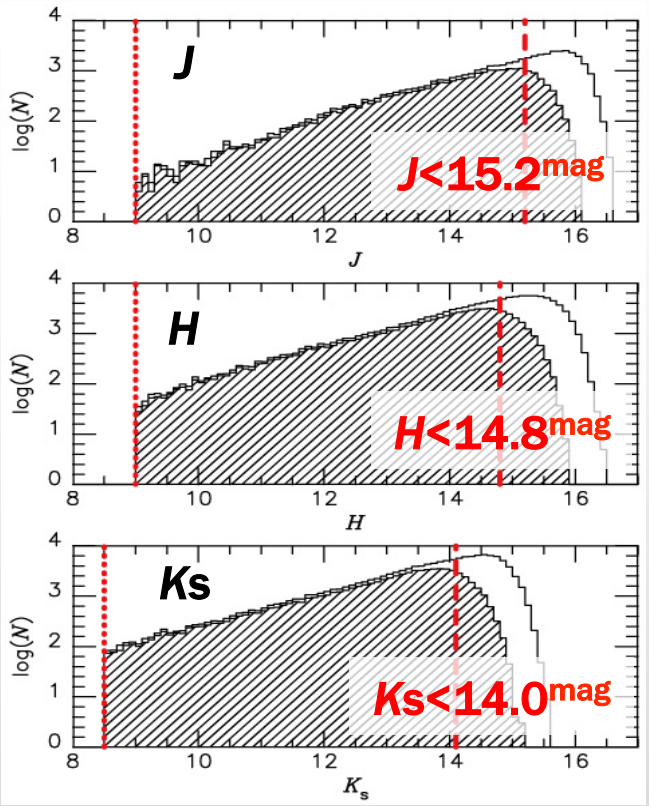
Observations

- IRSF/SIRIUS (*JHK*s, always simultaneous)
- ~30 epochs between 2007 and 2012
- Typical seeing is ~1.2 arcsec.

Crowded fields, $|\ell|<2°$

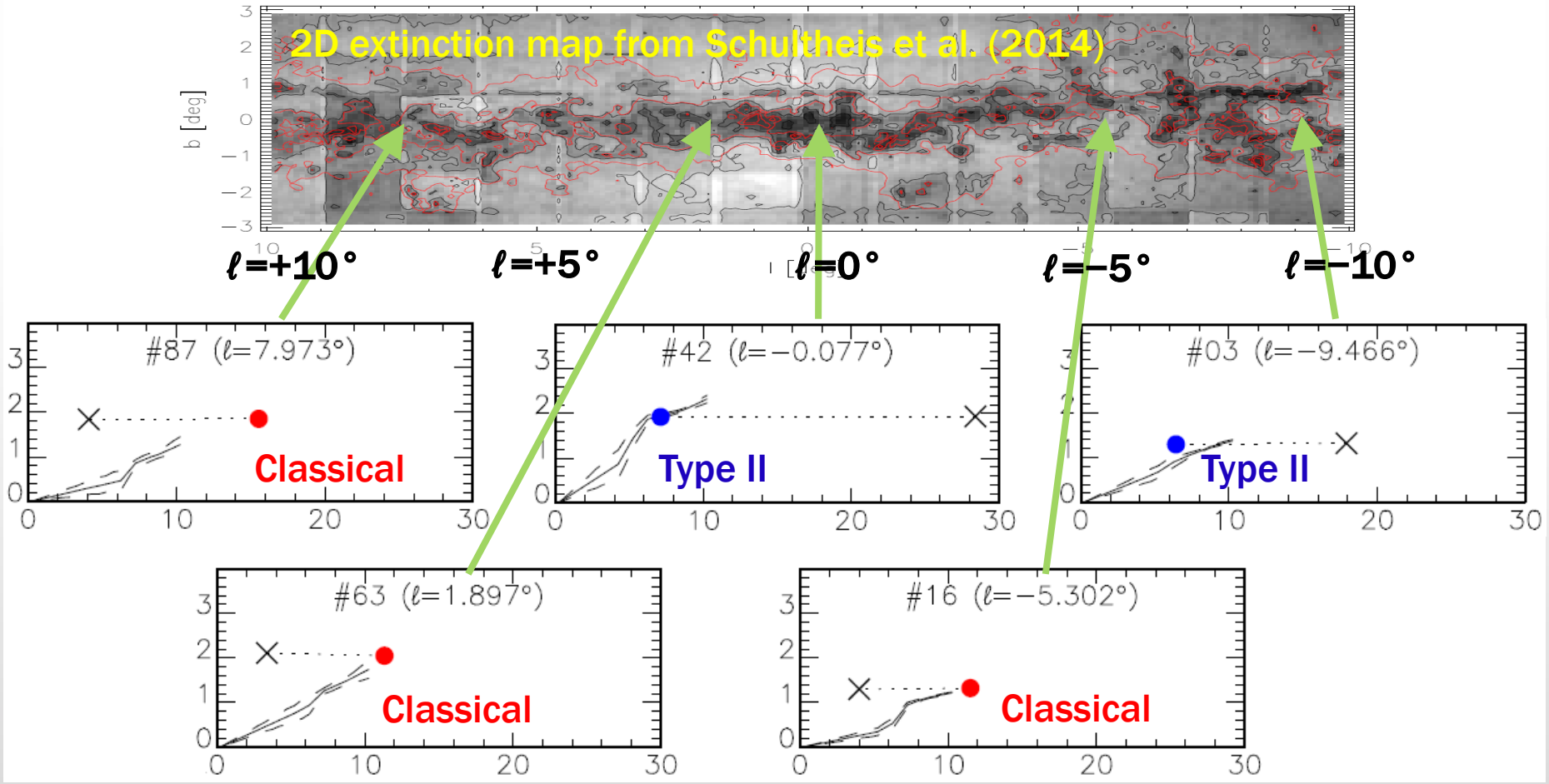


Less crowded fields, $|\ell|>8°$

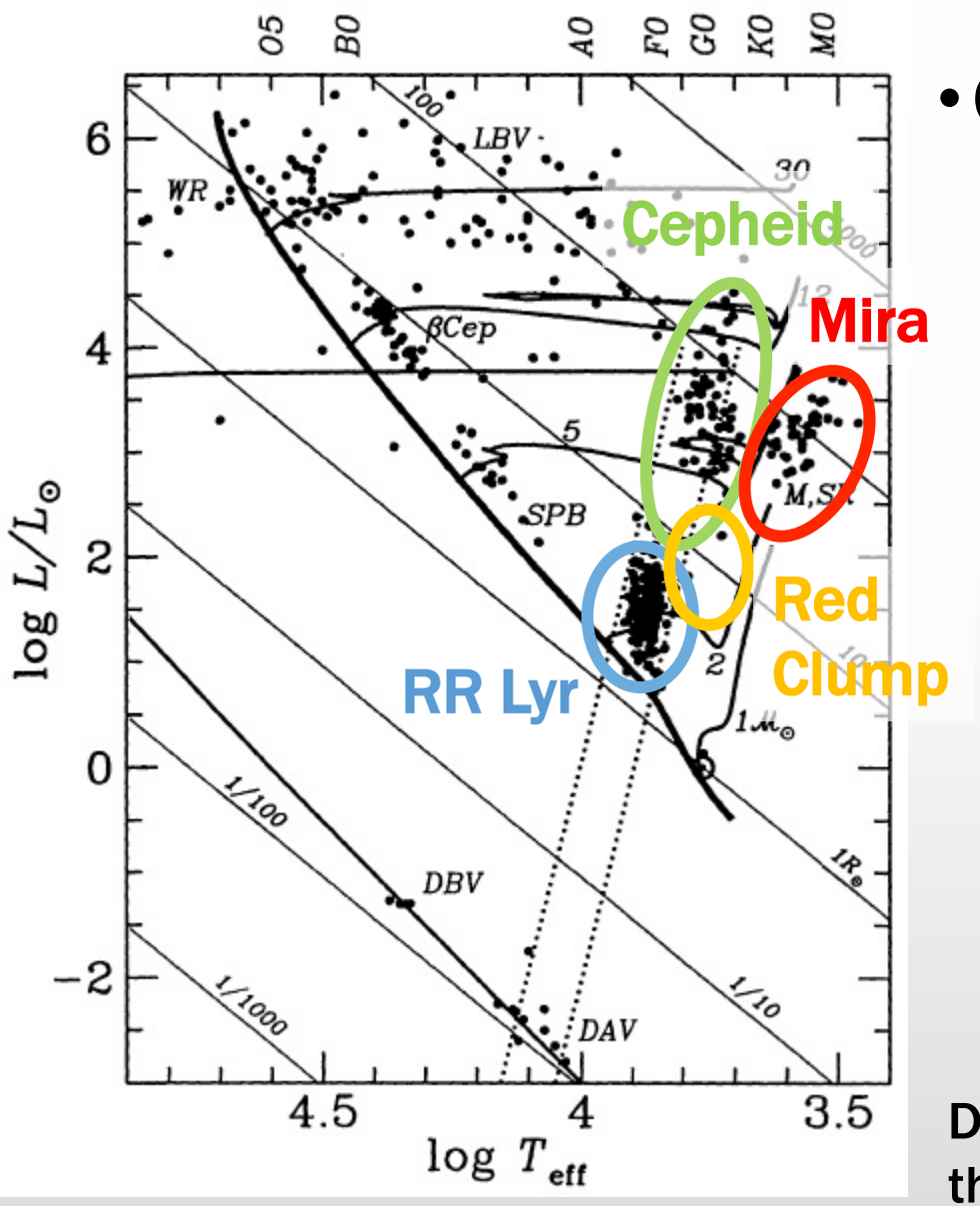


Distance vs A_{Ks}

- In most cases, assuming one type of the two kinds gives (D, A_{Ks}) consistent with the 3D extinction map.
- We determined types of 41 Cepheids.



Cepheids and other tracers



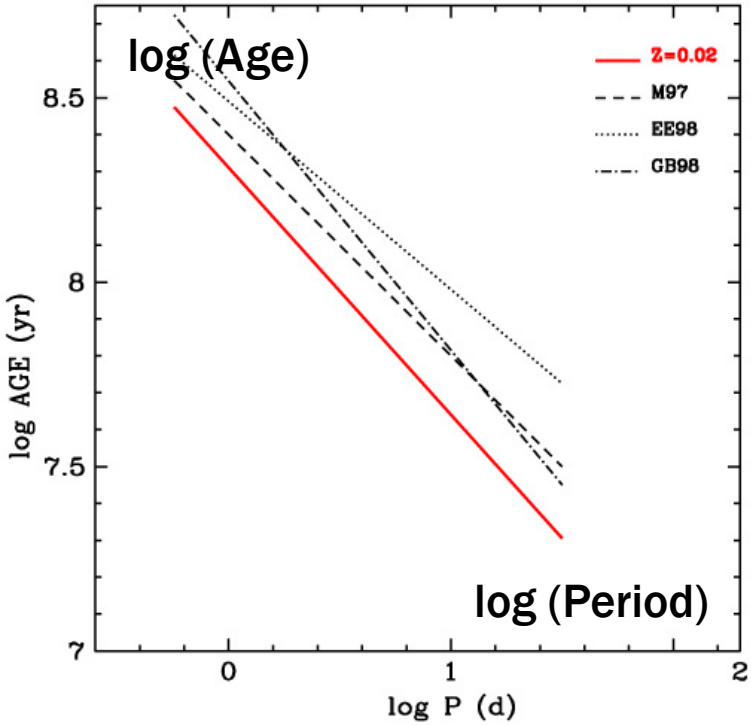
- Cepheids
  - in the Cepheid instability strip
  - bright and periodic
  - 2 types of Cepheids
    - classical Cep (10—300 Myr)
    - type II Cep (~10 Gyr)

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

Classical Cepheids as tracers

- Ages, kinematics and abundances can be accurately determined, thus working as good tracers.

Period-age relation
(Bono et al. 2005)



Metallicity of Cepheid as a function of *R*(GC)
(Genovali et al. 2014)