A Near-Infrared Variable Star Survey in the Magellanic Clouds

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and IRSF/SIRIUS team

Collaborators

- PI: Yoshifusa Ita (Tohoku Univ.)
- Many observers involved:
  - T. Tanabe, T. Nagayama, S. Nishiyama, etc
- Data analysis
  - Done by Y. Ita, with NM taking parts in the catalogue verification
- About Cepheids and other variable stars
  - Yoshikazu Nakada (Univ. Tokyo)
  - Giuseppe Bono, Laura Inno (Univ. Rome/ESO)
  - Michael Feast (Univ. Cape Town)

Talk Plan

- IRSF variable star survey for the LMC/SMC
  - 10 yr long monitoring survey
  - Basic survey and catalogue properties
  - Catalogue and data release plan
- Cepheids in the SMC and their light curves
  - Light curves shapes in the optical and near-IR
  - An easy way to understand the light curve shapes

IRSF/SIRIUS in South Africa

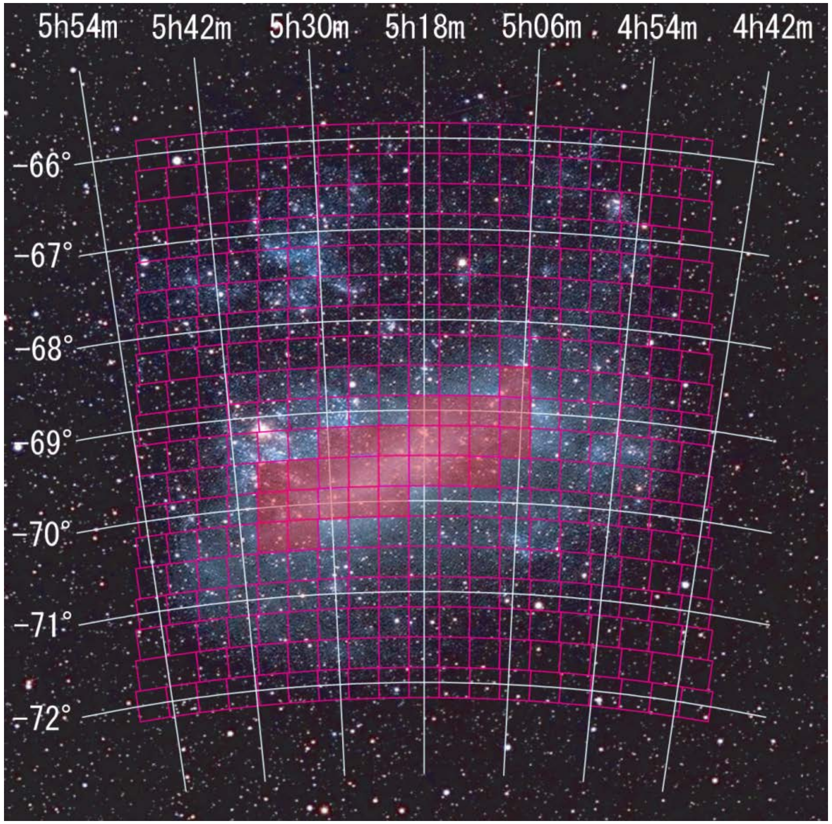
InfraRed Survey Facility:
1.4 m telescope

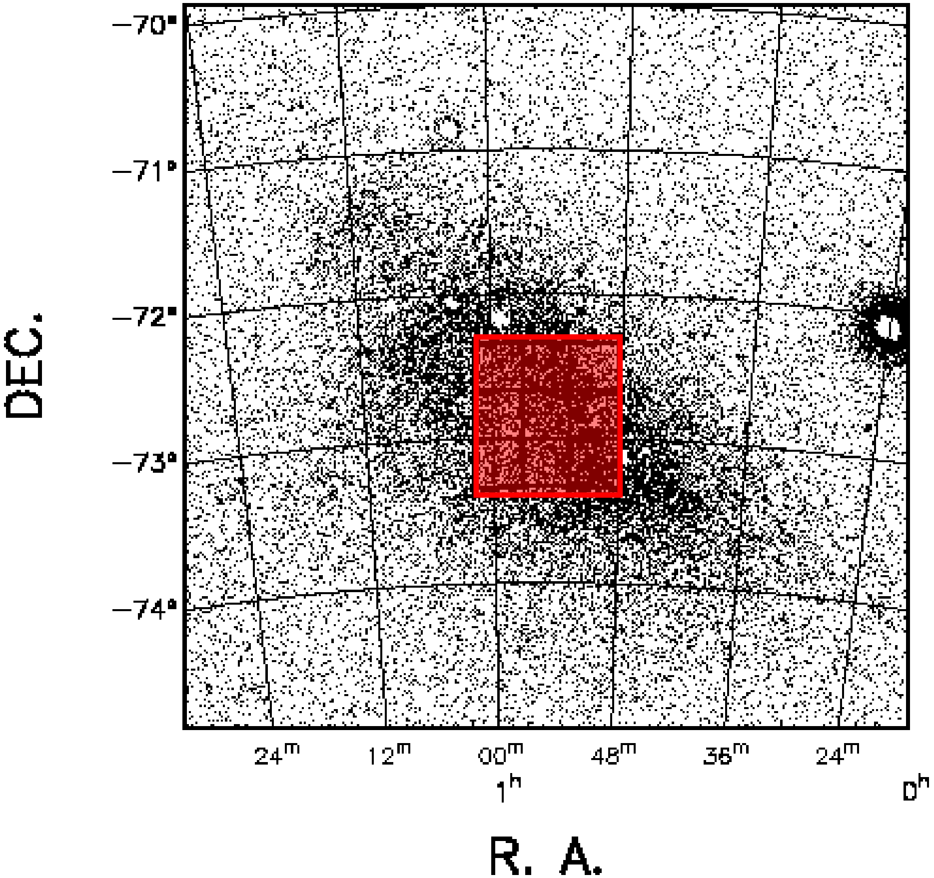
SIRIUS:

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

Observation

- >10 years, starting in 2000 Dec.
- More than 100 epochs (always with JHKs)



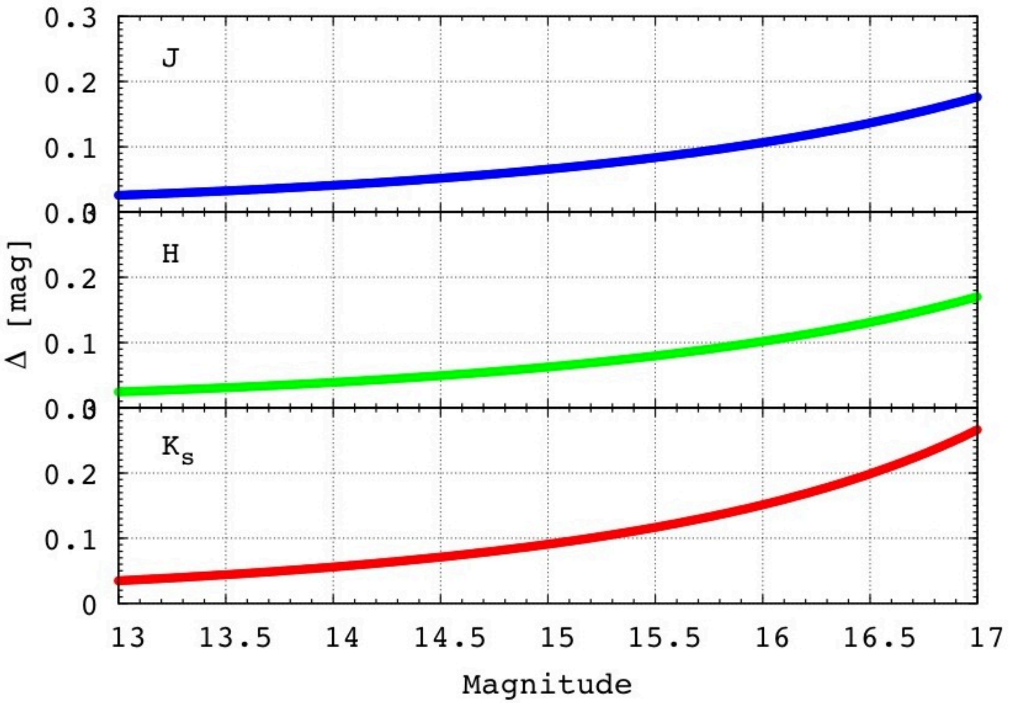


LMC : **3 deg²** along the bar
~100 times in 10 yrs.

SMC : **1 deg²** around the center
~120 times in 10 yrs.

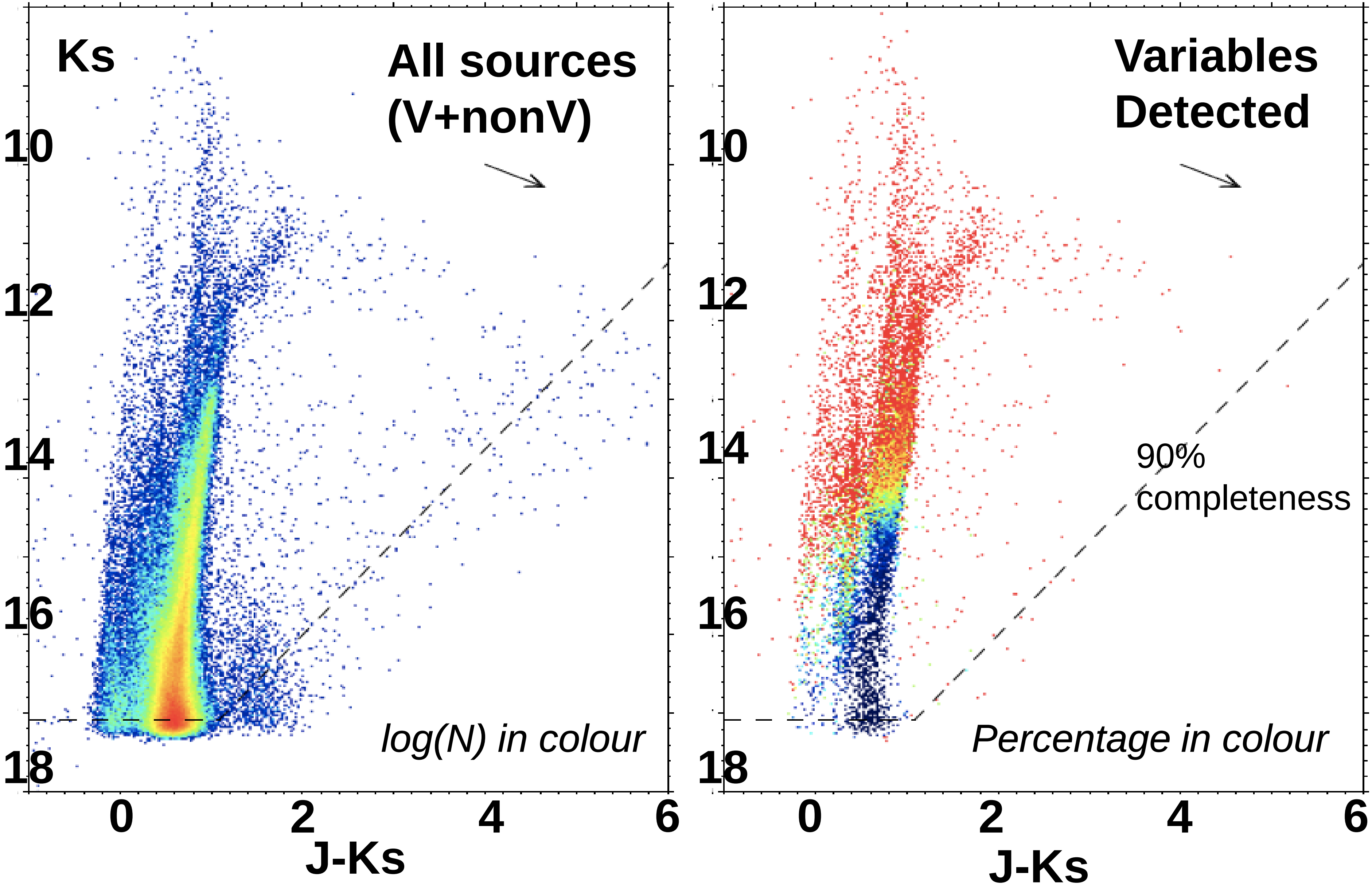
Survey Depth

- 50 sec integration (=5sec*10dithers) for each epoch in JHKs
- 10 σ detection limits
  - **17.7**, **17.0**, and **15.3** mag at J, H, and K, respectively in the most crowded region.
  - A Cepheid with a period ~a few days and an amplitude **~0.1 mag** in the SMC (**K ~ 15 mag**) is detected.



Smallest amplitudes to be detected in the image subtraction as a function of brightness.

Colour-magnitude diagram (SMC)



Products

- Data reduction almost finalized for the SMC

- *Photometry catalog*
  - PSF fitting photometry with DAOPHOT on reference images
  - JHK **photometry**
  - **~400,000** point sources

R.A. [degree]	DEC. [degree]	R.A. (*J*) [degree]	DEC. (*J*) [degree]	*J* [mag]	σ_J [mag]	Name of time series data	Number of observations
11.972789	-73.290066	11.972768	-73.290061	11.693	0.025	11.972789-73.290066.J.dat	123
11.973571	-73.301043	———	———	99.999	99.999	————————	000
11.974165	-73.105771	———	———	99.999	99.999	————————	000
11.974200	-73.220387	———	———	99.999	99.999	————————	000
11.974271	-73.216319	———	———	99.999	99.999	————————	000

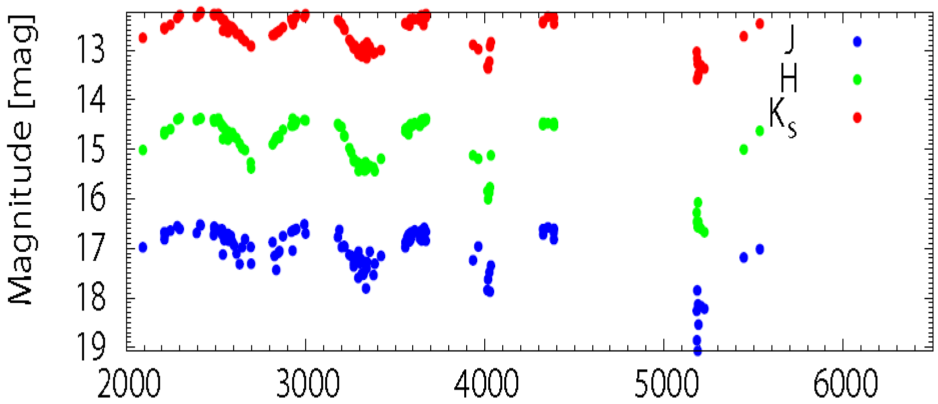
- *Variable star catalog*
  - Image subtraction (ISIS by Alard)
  - JHK **time-series**
  - **~20,000** variable sources.

JD [day]	magnitude	σ_{diff}	$\sigma_{instrumental}$ [mag]	σ_{offset}	Name of region	Name of subregion
2452092.702650	15.235	0.016	0.021	0.003	SMC0050−7310	F
2452212.327669	14.969	0.010	0.021	0.003	SMC0050−7310	F
2452213.285094	14.971	0.017	0.021	0.003	SMC0050−7310	F
2452214.380693	15.095	0.012	0.021	0.003	SMC0050−7310	F
2452246.273367	15.287	0.024	0.021	0.003	SMC0050−7310	F
....						
2455225.273063	14.973	0.024	0.021	0.003	SMC0050−7310	F
2455444.448035	14.995	0.008	0.021	0.003	SMC0050−7310	F
2455534.359242	15.147	0.012	0.021	0.003	SMC0050−7310	F
2455789.529211	15.128	0.008	0.021	0.003	SMC0050−7310	F
2456094.590574	15.050	0.009	0.021	0.003	SMC0050−7310	F

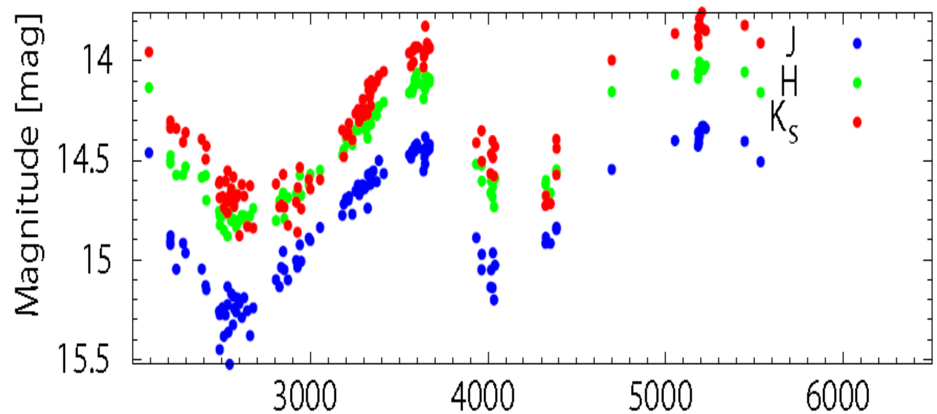
Light curves of various objects

Some types of objects as classified in Simbad

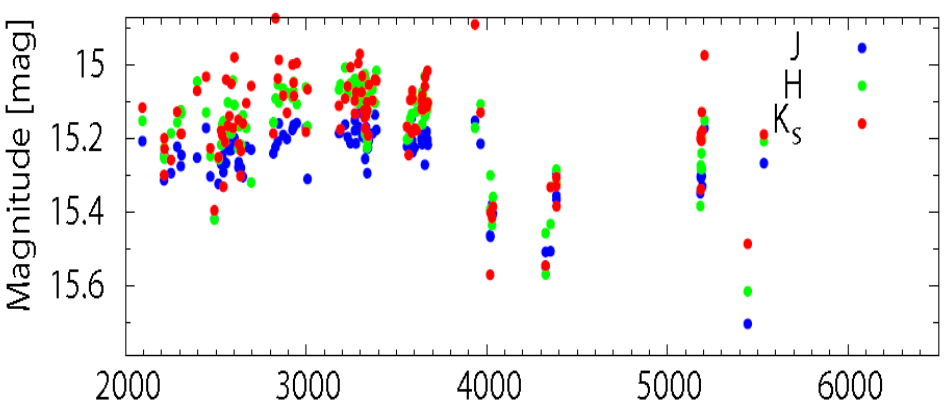
(Carbon-rich) Mira



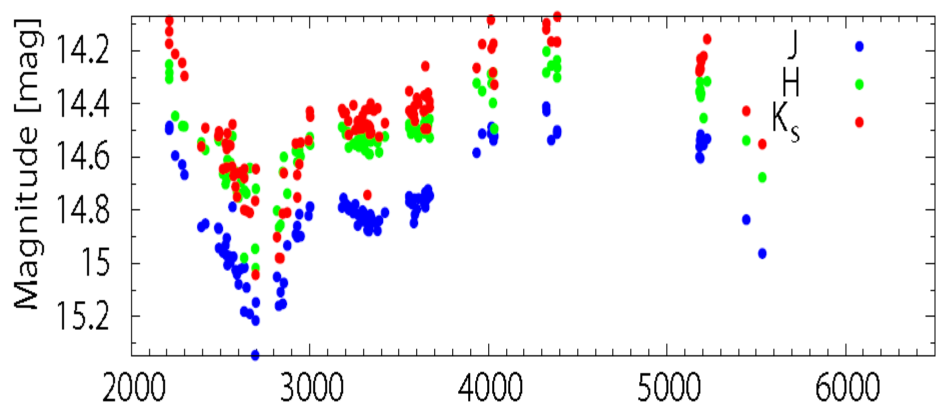
Emission star (Be?)



Pre-main sequence star



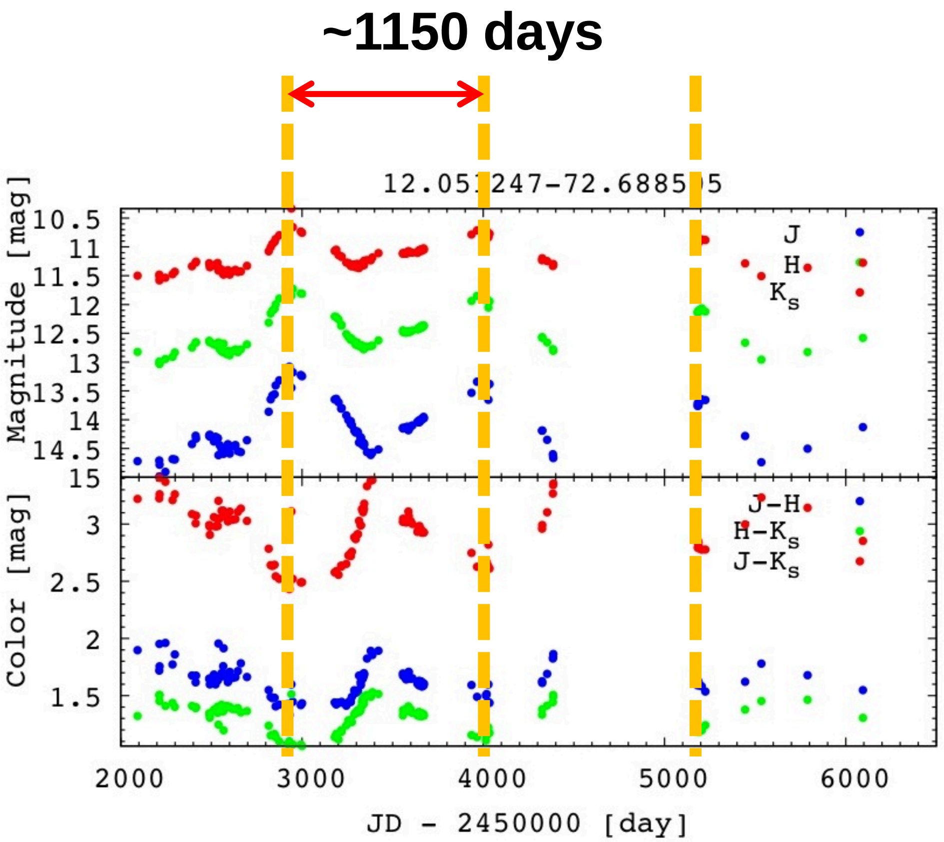
X-ray binary



10 years

The longest period and dust-enshrouded Miras

- The longest period found among the SMC Miras ~1150 days
- We discovered several Miras not detected in the optical (OGLE)
  - intensive mass loss producing thick circumstellar dust shells



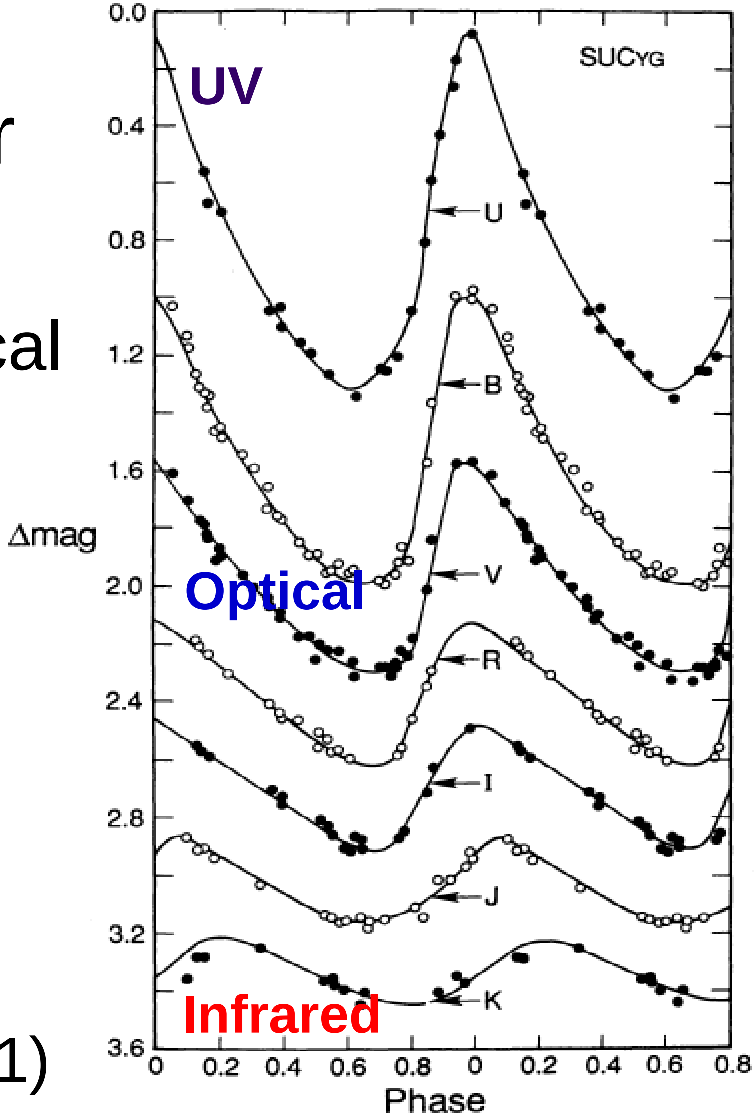
Publication and Data release: Plan

- Basically, the data release will be accompanied by a catalogue paper for each galaxy, but please let us know if interested in earlier access to the data.
- SMC – within 2013
  - Catalog paper: almost ready (Ita et al.)
  - Science papers
    - Miras: in preparation (Ita et al.)
    - Cepheids: in preparation (Matsunaga et al.)
- LMC – expecting to release in next year
  - Catalog paper: to be written (Ita et al.)
  - Science papers: to be written

Light curve shapes of Cepheids

Light curve shapes vary with λ

- The difference in the light curve shapes are known for a long time.
  - Saw-shaped curves in the optical
  - Smaller amplitudes and more symmetric in the IR



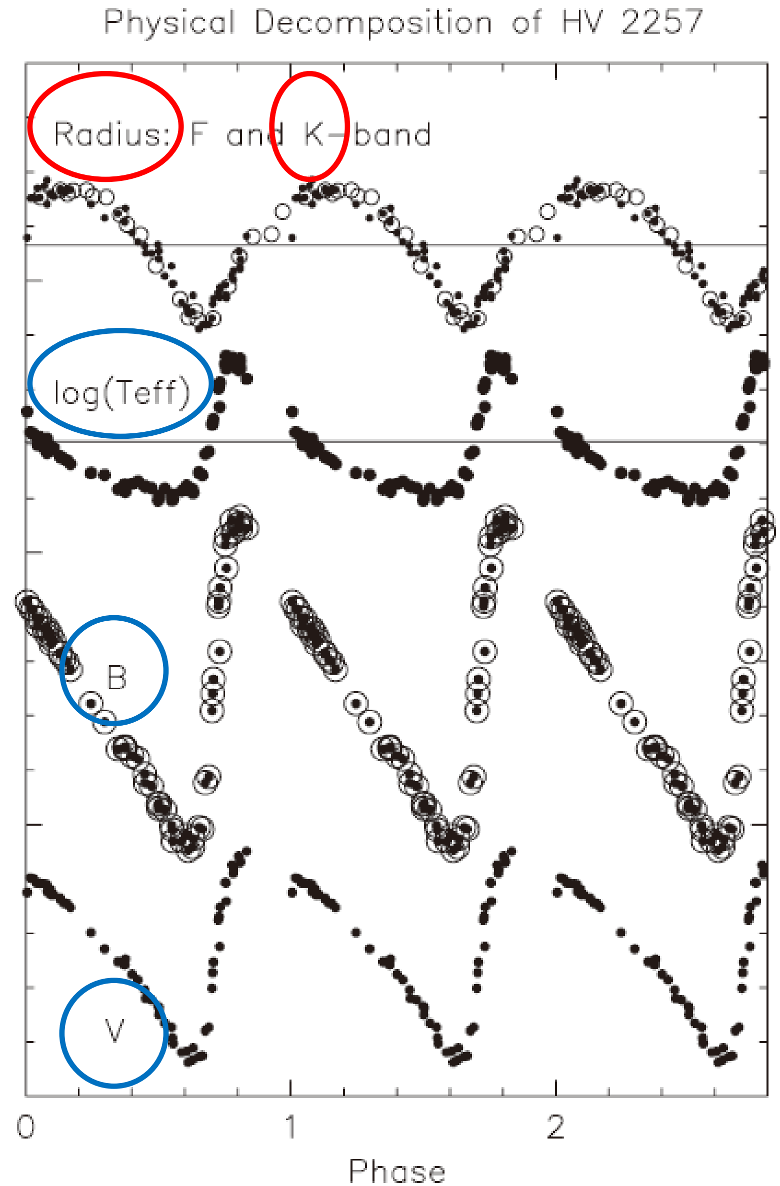
Madore & Freedman (1991)

Two parameters

- T_{eff} has a dominant effect on the optical LCs, while the **radius** has a stronger effect on the IR LCs.
- Freedman & Madore (2010)

  (see also Madore, 1985)

  - The K-band light curve is widely considered to be dominated by pure radial variations.

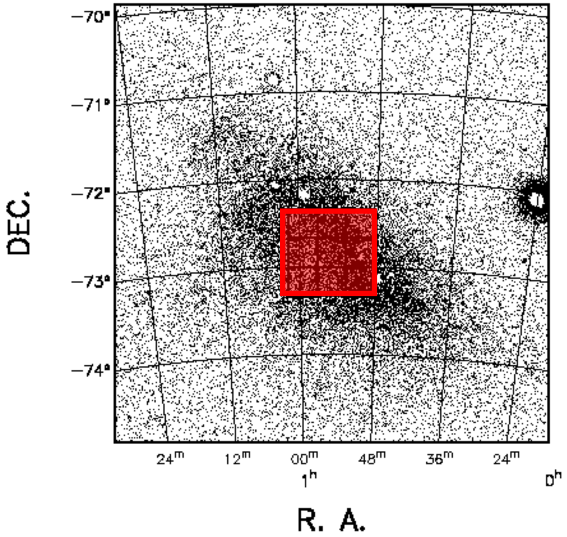


Freedman & Madore (2010)

Our goals

- To give a quantitative description of the differences in light curve shapes based on large datasets
- To give an (intuitive and graphic) explanation of the difference
  - Although pulsational models and SED synthesis can predict the light curves (eg Natale et al. 2008), how can we get a straightforward understanding?

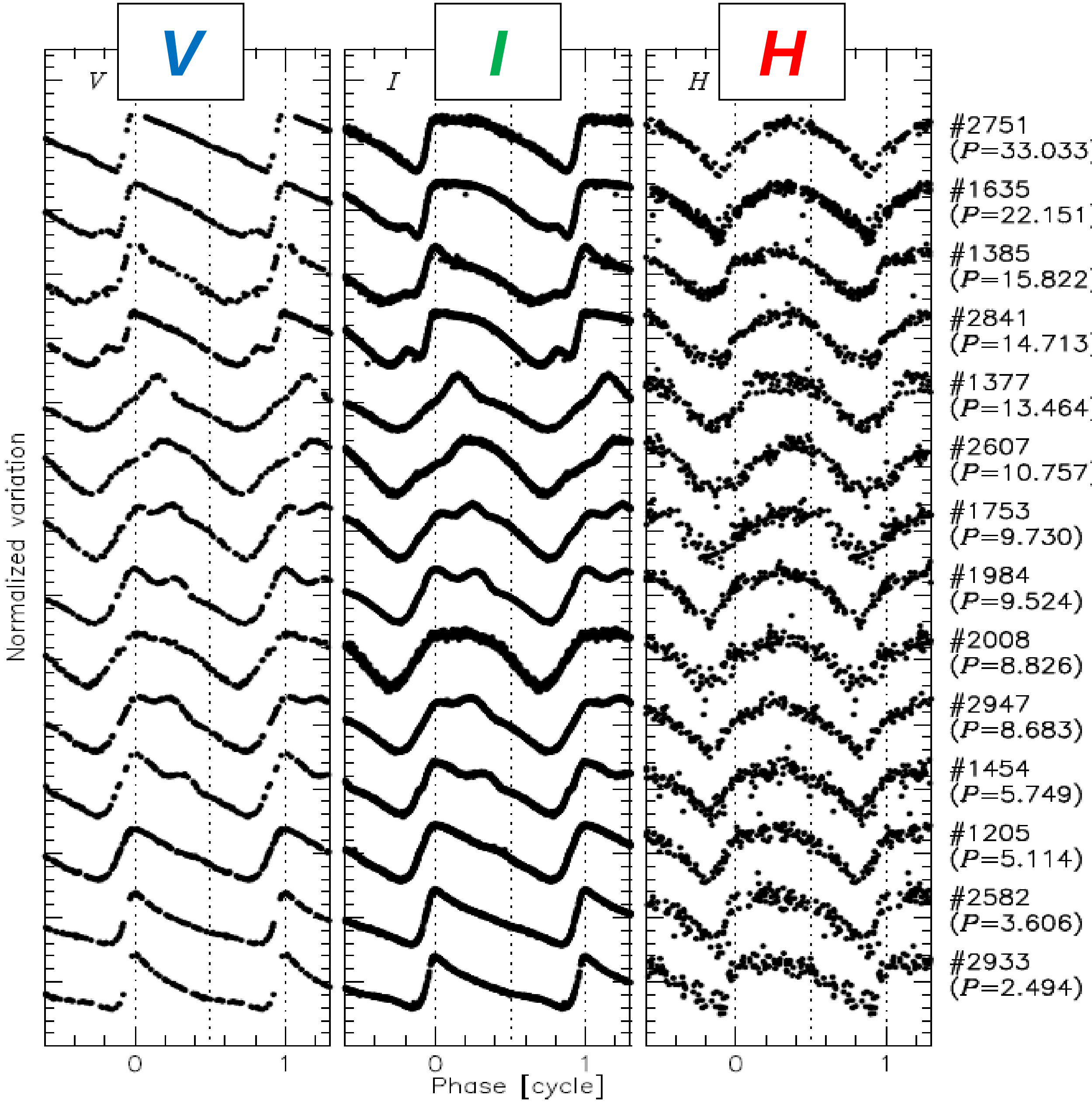
Data for Cepheids in the SMC



- 912 OGLE+IRSF Cepheids
  - Variations of 67% of OGLE-III Cepheids in our survey area were detected by IRSF.

Mode	OGLE-III w. IRSF	OGLE-III w/o IRSF	*OGLE-III Entire SMC*
F	612	170	*2626*
1O	276	179	*1644*
F/1O	15	8	*59*
1O/2O	9	65	*215*
others	0	23	*86*
Total	**912**	**445**	***4630***

Hertzsprung progression in various λ



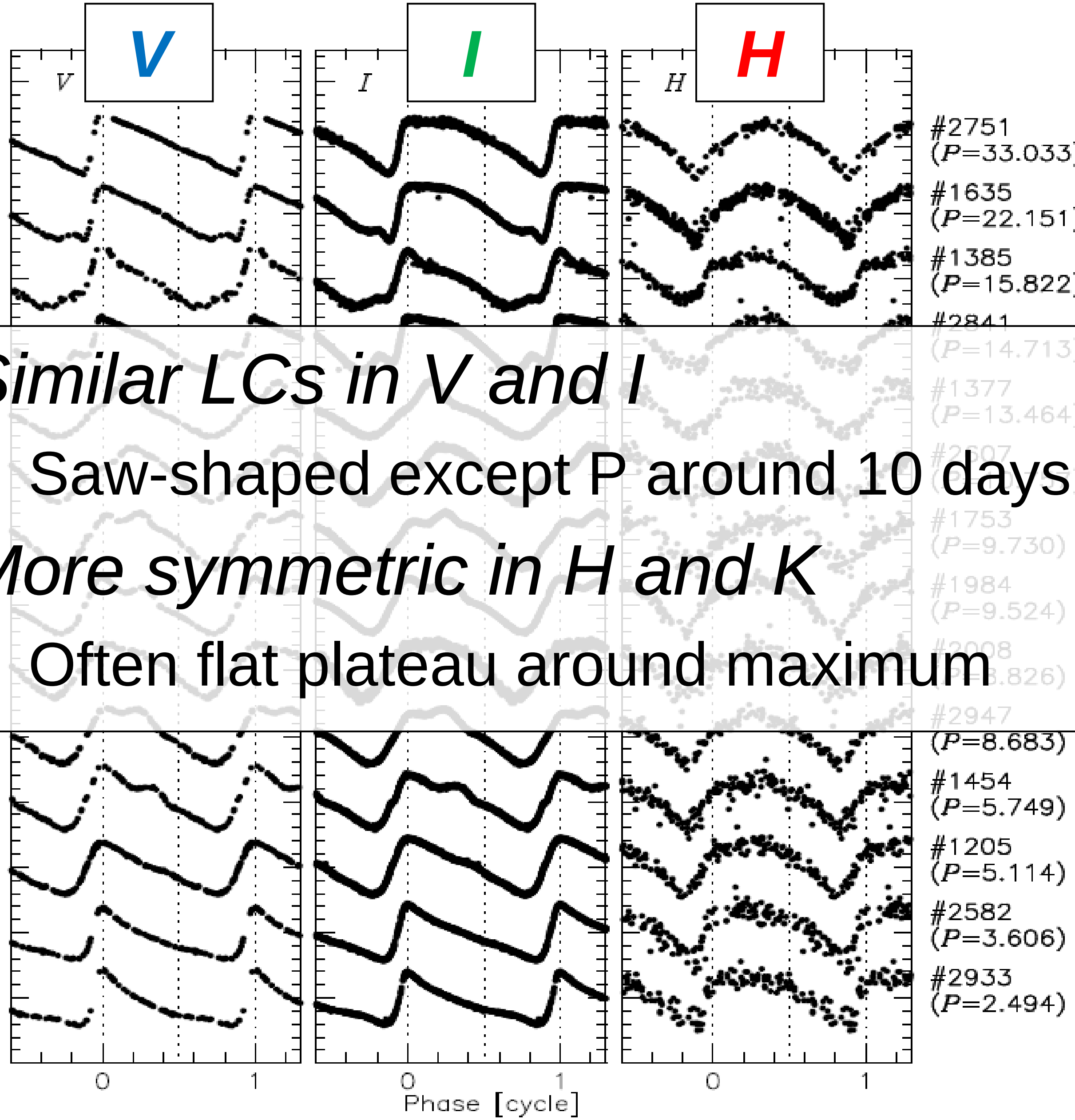
P=30d

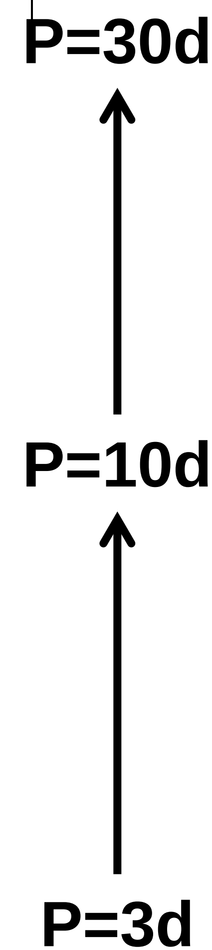
P=10d

P=3d

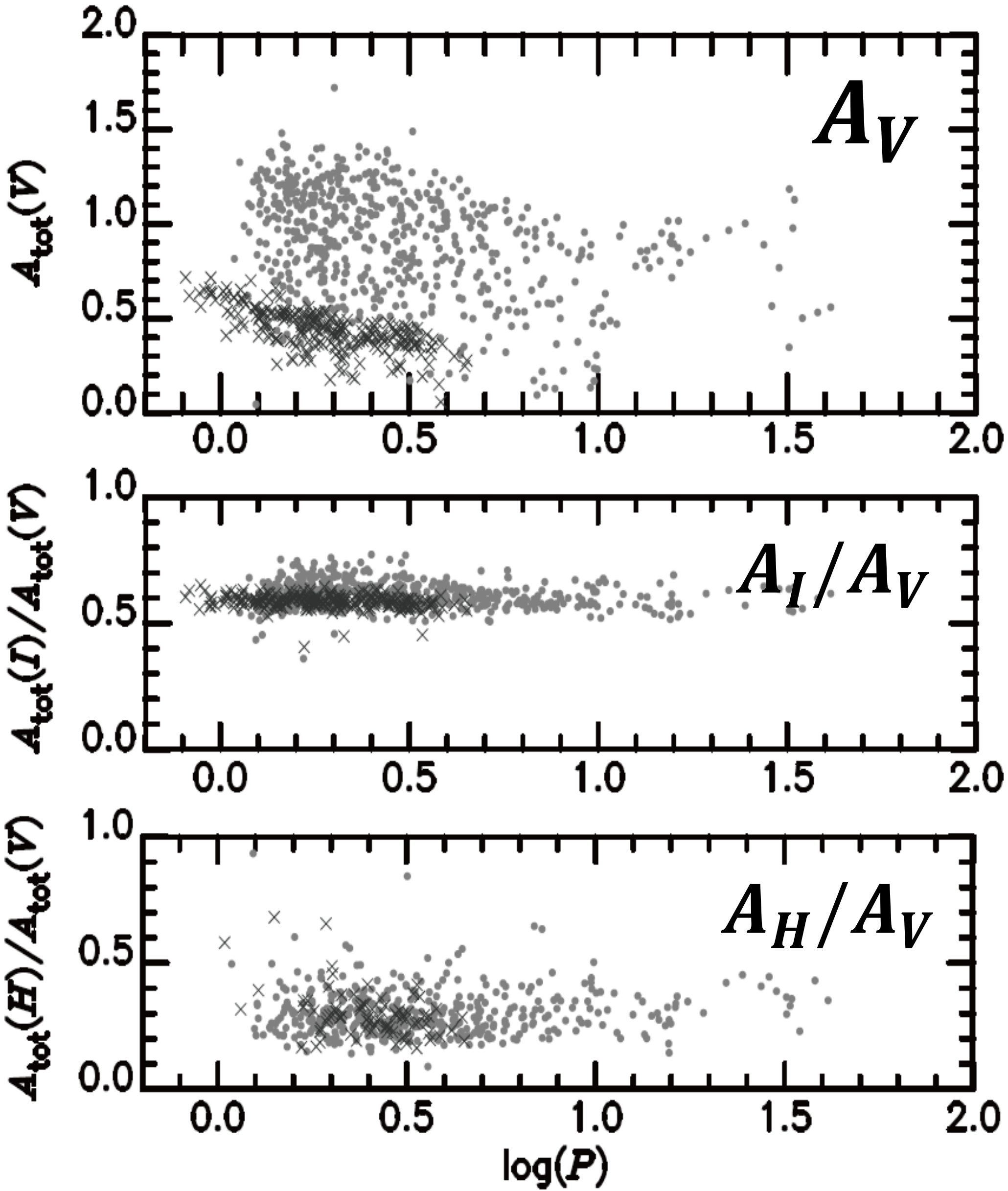
Hertzsprung progression in various λ

- *Similar LCs in V and I*
  - Saw-shaped except P around 10 days
- *More symmetric in H and K*
  - Often flat plateau around maximum





Amplitudes dependent on λ



← A_V shows a trend depending on a period, but with a large scatter

← A_I is well correlated with A_V(ratio~**0.6**)

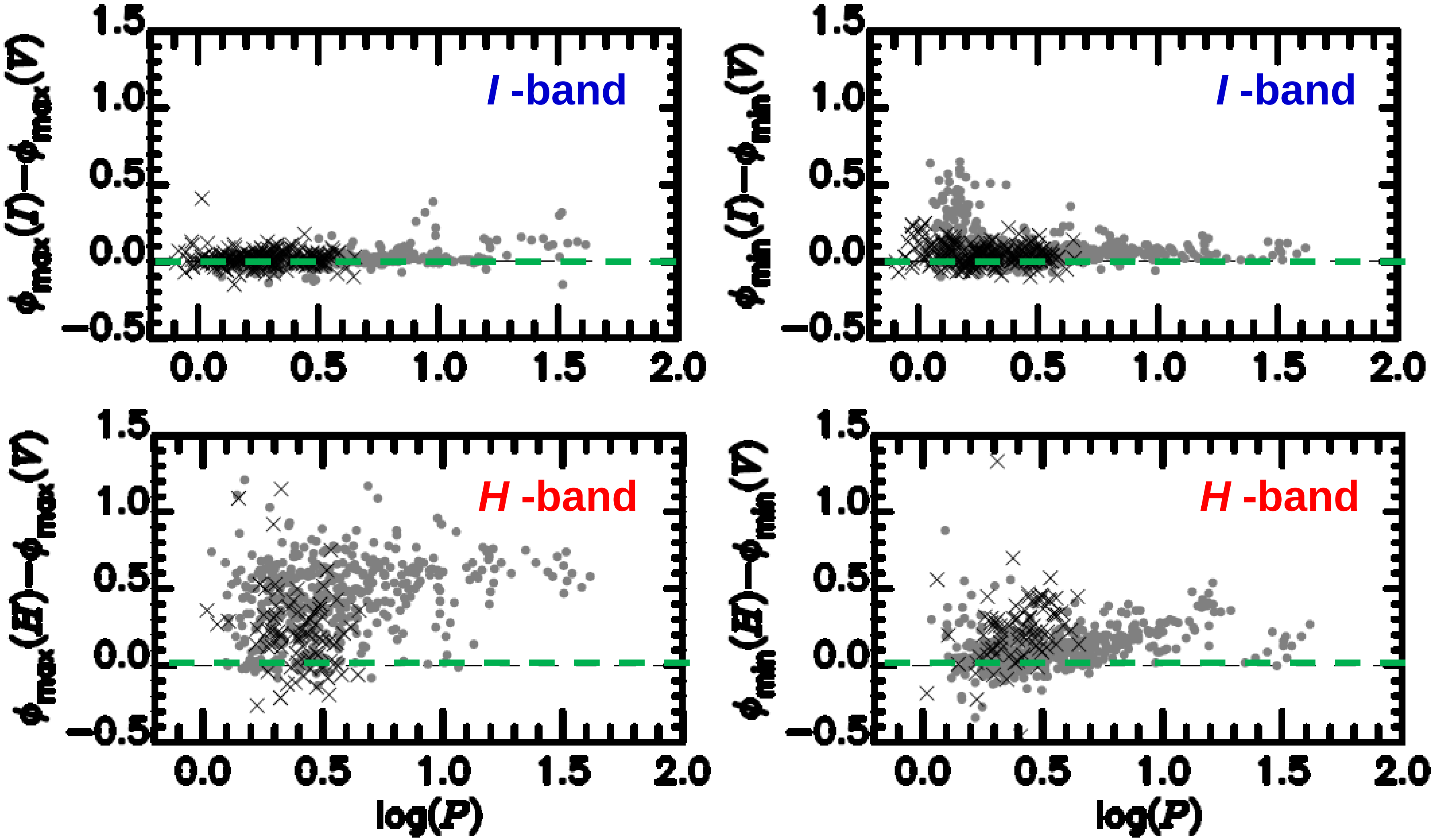
← A_H/A_V has a large scatter around a ratio of ~**0.3**

Mix/min phases dependent on λ

Max phase
Relative to max(V)

Min phase
Relative to min(V)

In the unit of π



Mix/min phases dependent on λ

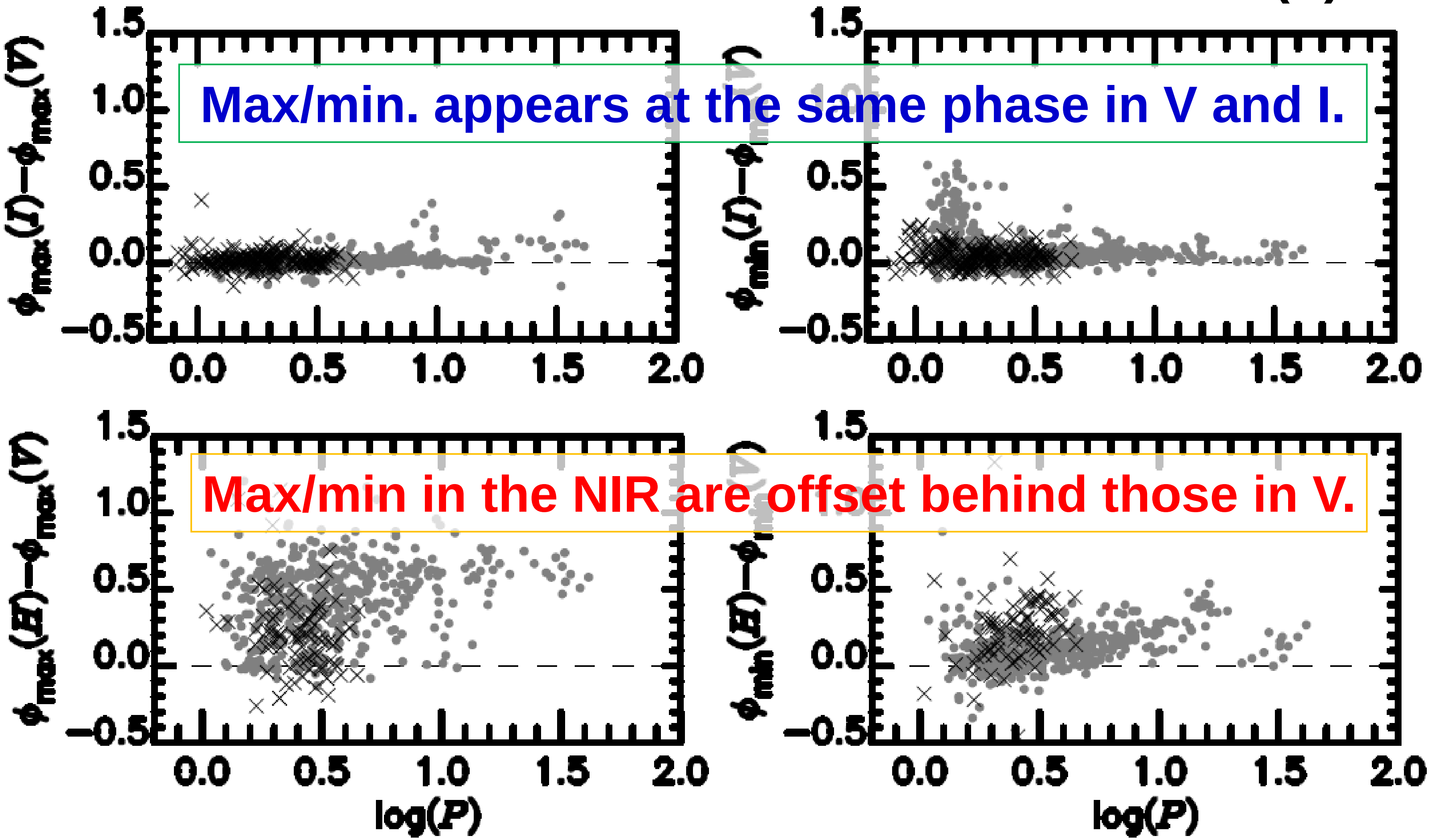
In the unit of π

Max phase

Relative to max(V)

Min phase

Relative to min(V)



Effects of T_{eff} and radius

- Stafan-Boltzmann's law

$$\delta m_{\mathrm{bol}} = -5\,\delta\log R - 10\delta\log T_{\mathrm{eff}}$$

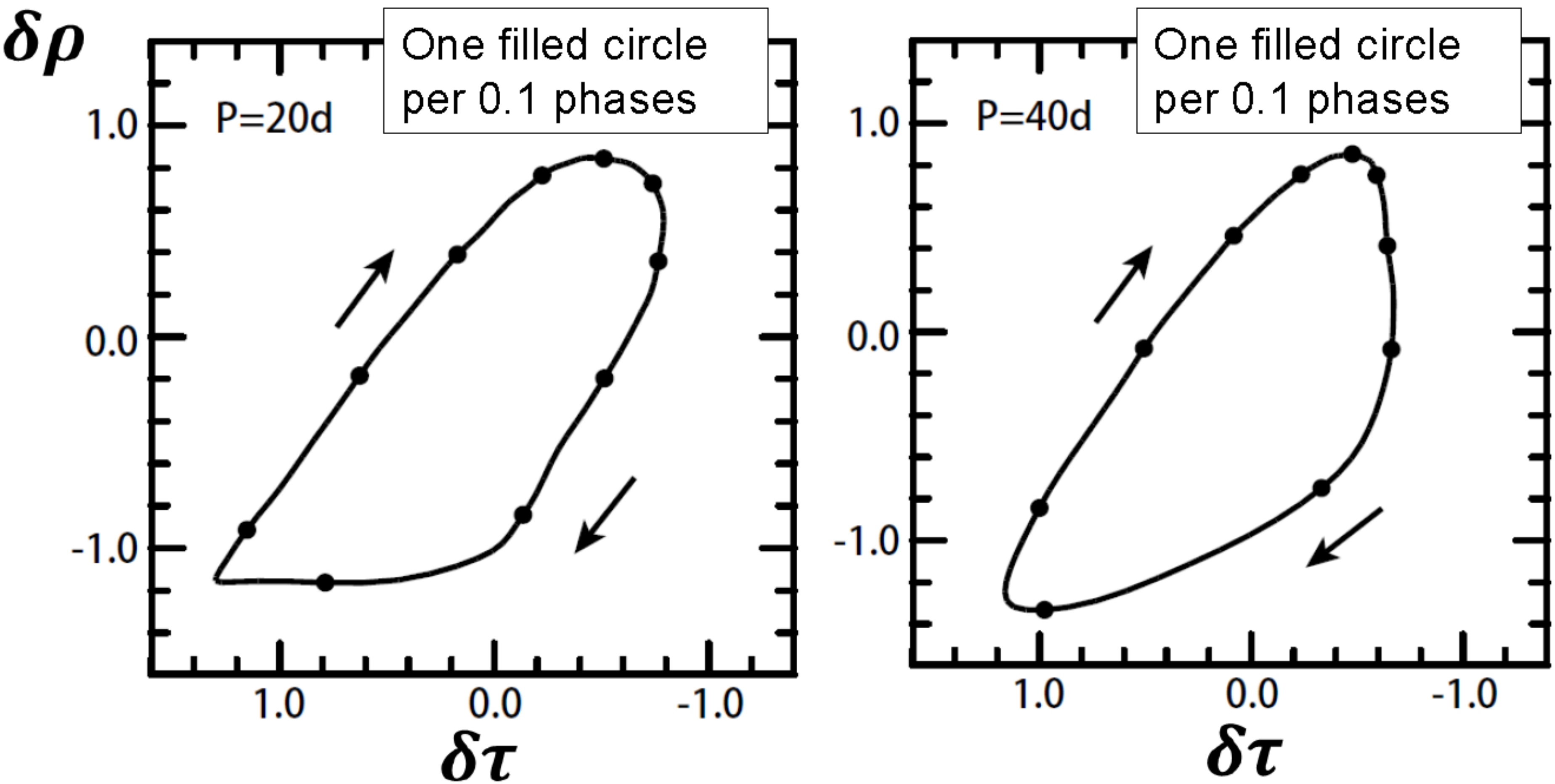
- Applying bolometric correction

$$\delta m_{\lambda} = -5\,\delta\log R - 10\delta\log T_{\mathrm{eff}} - B_{\lambda}\,\delta\log T_{\mathrm{eff}}$$

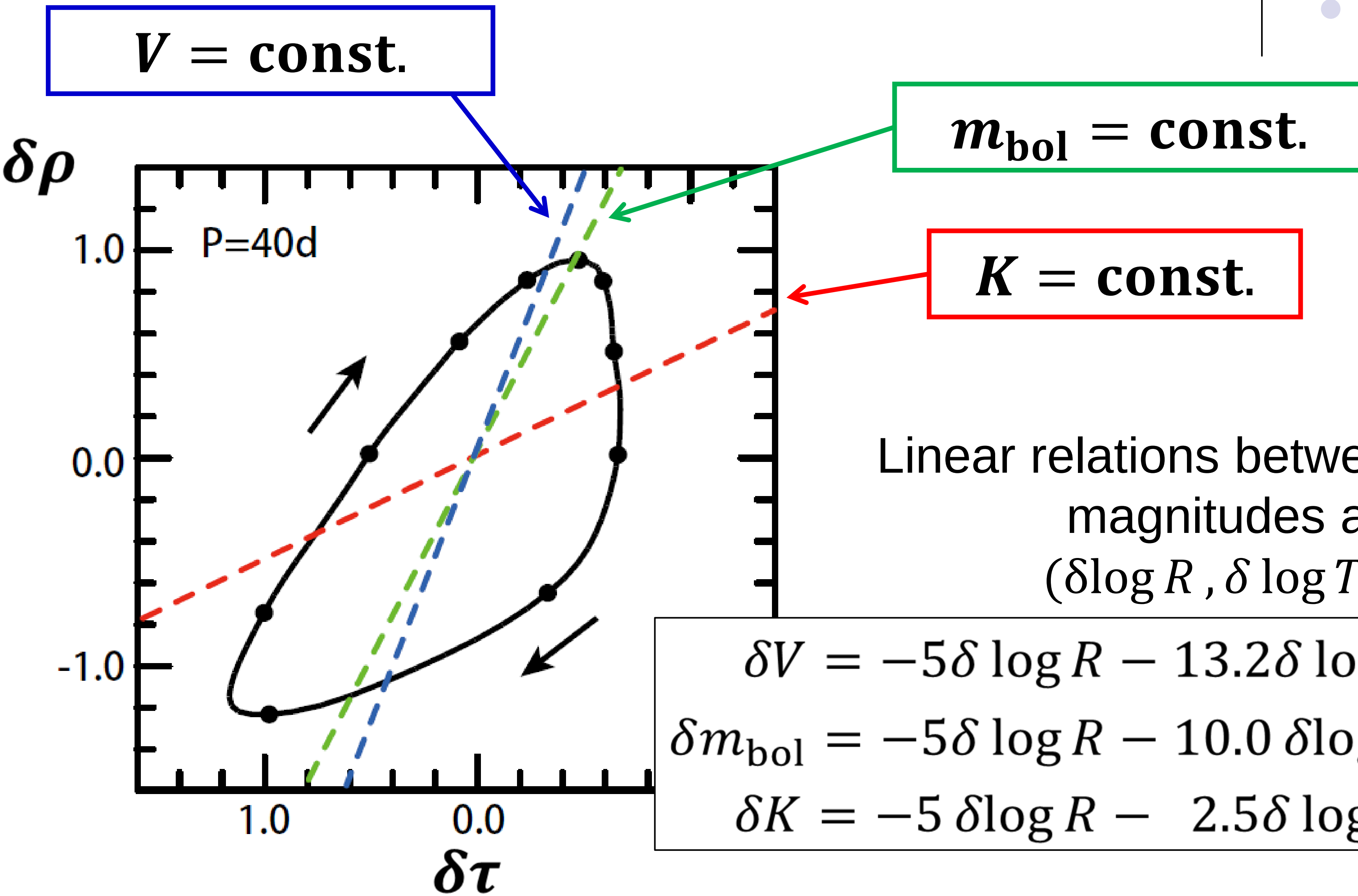
  - linear relation unless an amplitude is large
  - The $\delta\log T_{\mathrm{eff}}$ term depends on the wavelength.

Loops on $(\delta \log T_{\mathrm{eff}}, \delta \log R)$

- Pejcha & Kochanek (2012)
  - (normalized) loops on $(\delta\tau \cong \delta \log T_{\mathrm{eff}}, \delta\rho \cong \delta \log R)$ based on observational data in literature.



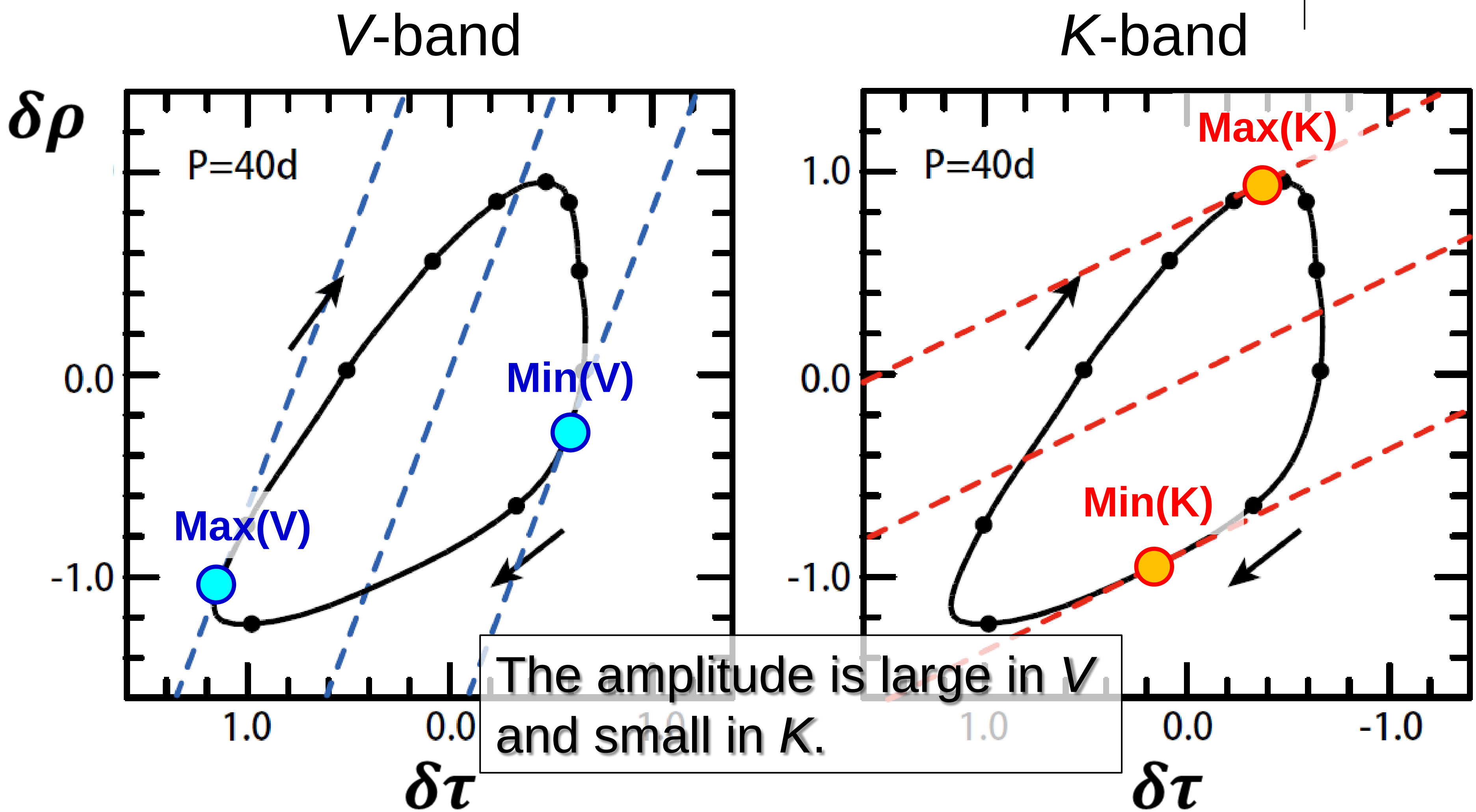
Variations in V, K and m_{bol} inferred from a loop



Linear relations between magnitudes and ($\delta\log R$, $\delta\log T_{\mathrm{eff}}$)

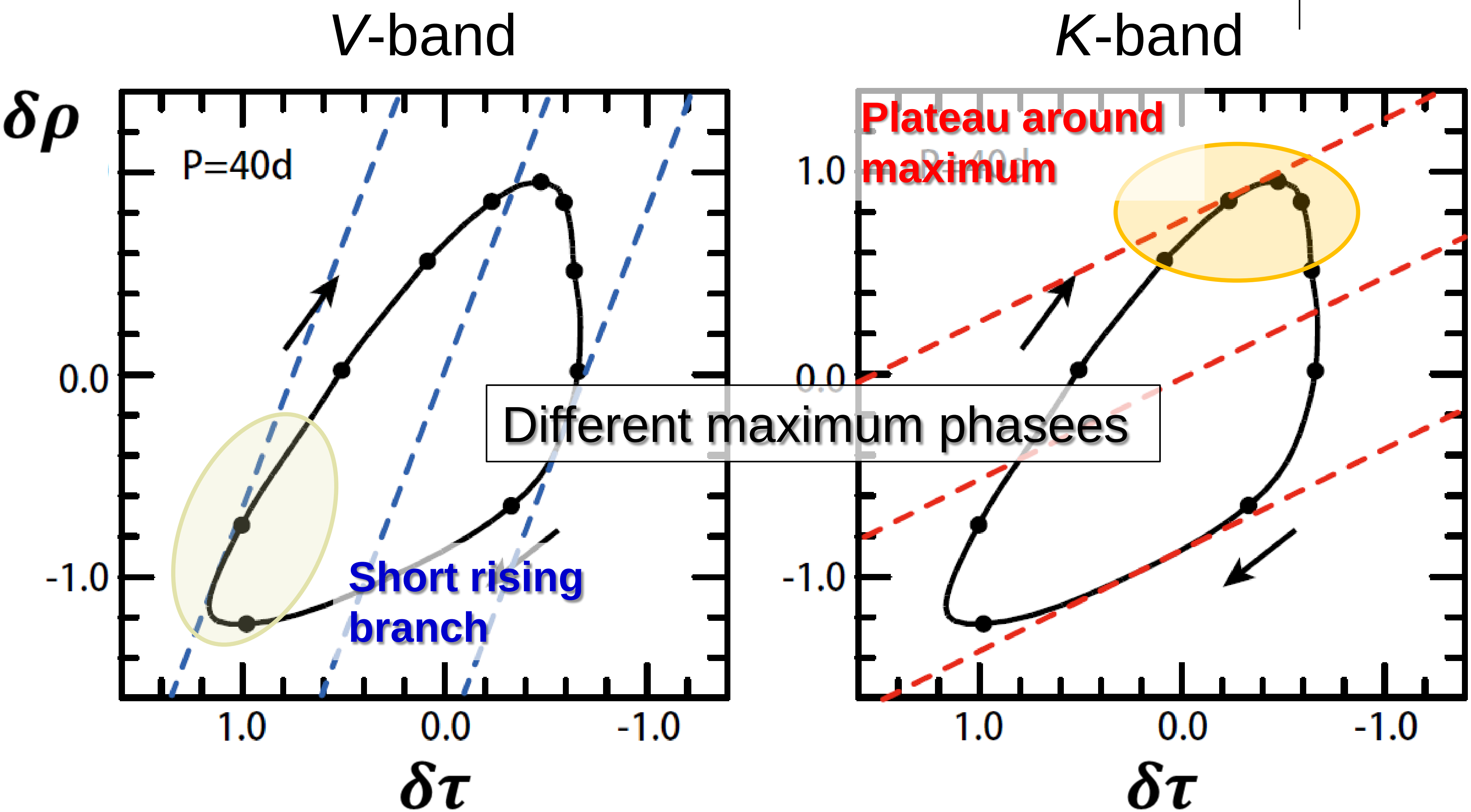
$$\delta V = -5\delta\log R - 13.2\delta\log T$$
$$\delta m_{\mathrm{bol}} = -5\delta\log R - 10.0\,\delta\log T$$
$$\delta K = -5\,\delta\log R - 2.5\delta\log T$$

Variations from the $(\delta \log T, \delta \log R)$ loop



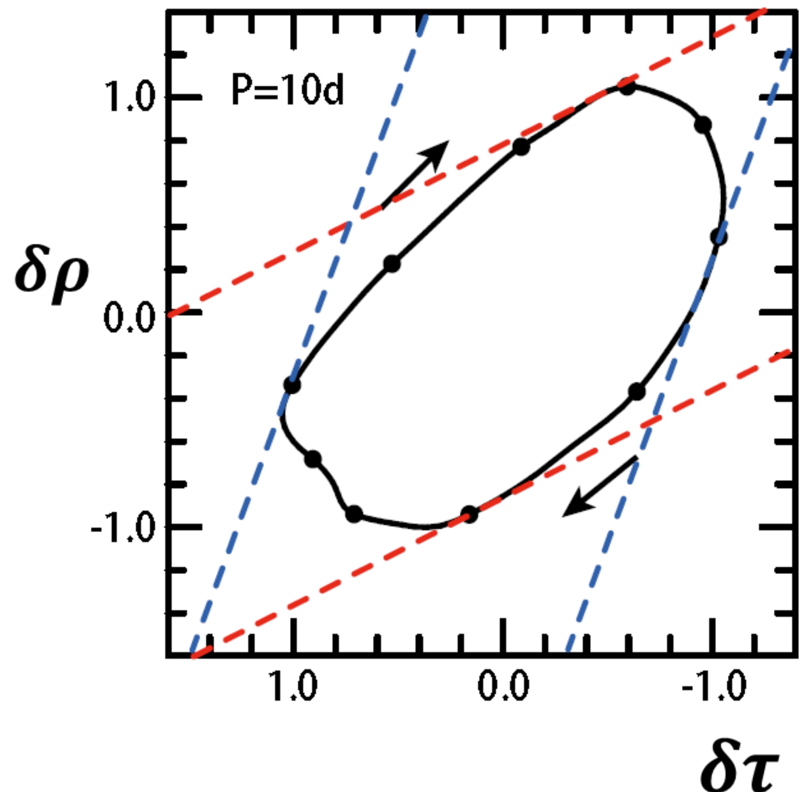
The amplitude is large in V and small in K.

Variations from the ($\delta \log T$, $\delta \log R$) loop



Amplitude ratios

- If the loop are round, the ratis determined by the slopes of the linear relations.
  - AI/AV～0.6, AH/AV～0.3
- The scatter in the ratios caused by:
  - The ellipticity of the loop
  - The phase dependency on λ



Summary

- Near-infrared catalogue of variable stars from IRSF/SIRIUS
  - In the SMC: in this year (~20,000 variables)
  - In the LMC: next year
- Light curve shapes of Cepheids
  - Can be understood in an intuitive and graphic way by considering loops on $(\delta \log T_{\mathrm{eff}}, \delta \log R)$ (at least to the 1st approximation).
  - The slope and opening of the loop is essential.