Astrometric VLBI observation of t he Galactic LPVs; Miras and OH/IR stars

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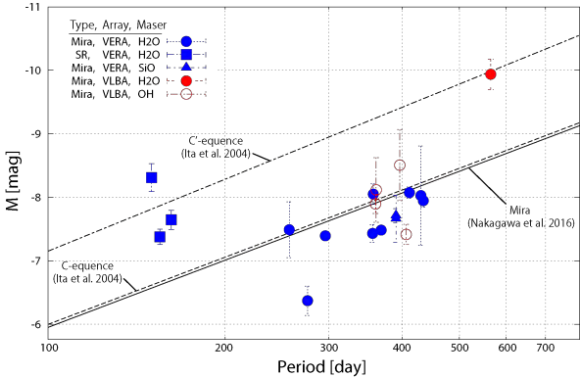
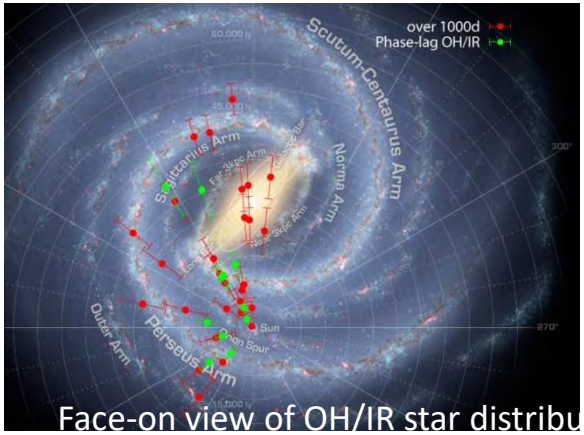
1. Astrometric observations of Galactic Miras with VERA array
   - Calibration of period-Mk relation of Galactic Miras
   - VLBI observation (VERA 4 antennas)



2. OH/IR stars with P>1000 days
   - Explore period-M relation in MIR
   - As a new probe for the Galactic kinematics ?
   - Astrometric VLBI has just started using VERA (SiO)

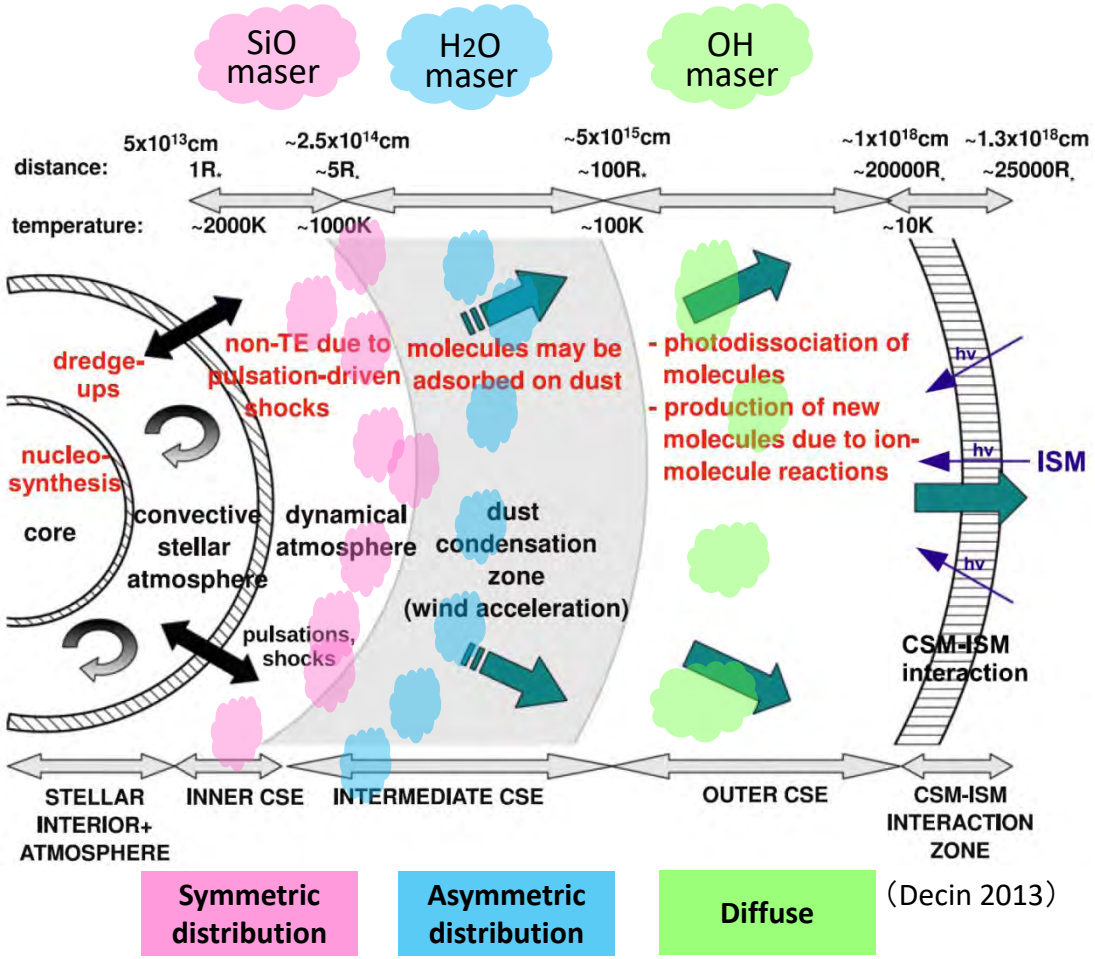


Face-on view of OH/IR star distribu

This work is supported by JSPS KAKENHI Grant Number JP16K05306.

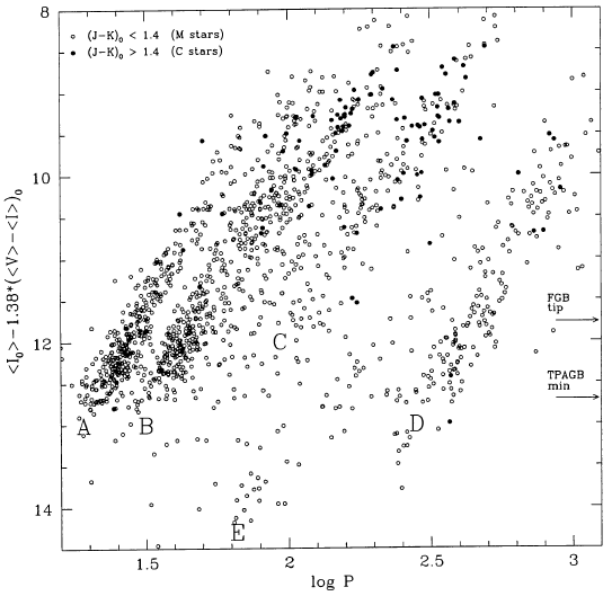
Masers around LPVs, Period luminosity relation（PLR）

- Mass 1～8 M⊙（Mira:1～2.5 M⊙?）
- C/O-core, He-shell, H-rich envelope →O-rich/C-rich
- Period 100～1000 d, P>1000 d
- Chemical enrichment of the universe
- Distance indicator



（Decin 2013）





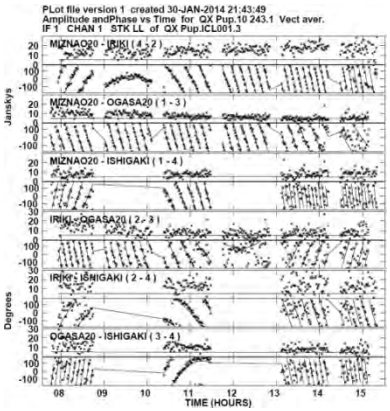
Wood et al. 1999

Parallax measurements with VERA



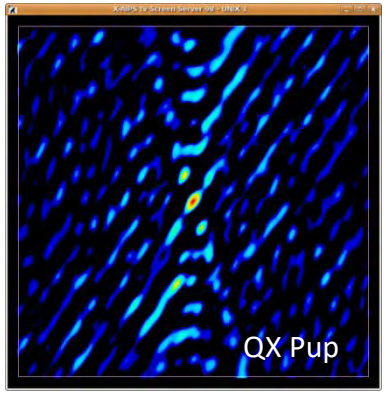
- 20 m x 4 antennas
- Freq. 22/43 GHz
  - 22GHz (H2O maser)
  - 43GHz (SiO maser)

Observation



Observed Phase & Amplitude

2D
F・T

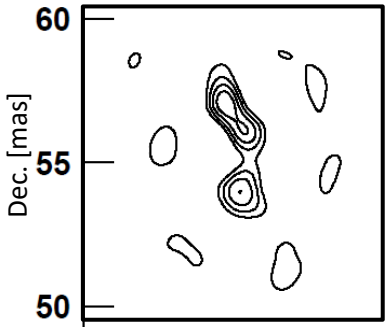


Interferometric Image of a point-like maser

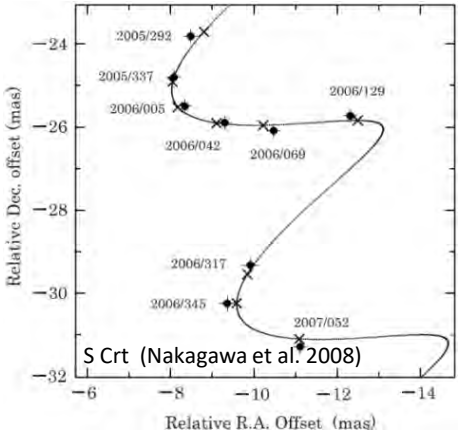
"Structure" causes error.

Ex : T Lep

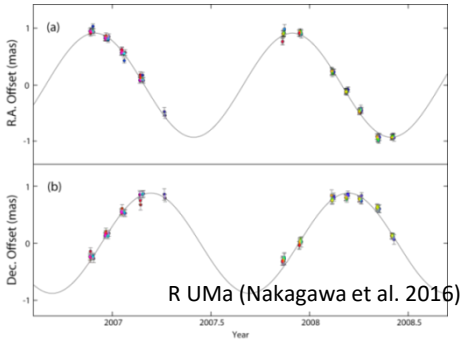
- Complicated maser structure.
- Shape changes gradually.



Analysis



Motions on the sky plane



Parallactic oscillation

It requires 1.5 - 2 years to solve a parallax.

AGB star distances from VLBI astrometry

Maser astrometry with VLBI

Source	Type	Parallax [mas]	P [day]	LogP	mK [mag]	MK [mag]	Maser	Reference of the parallax
RW Lep	sra	1.62±0.16	150	2.176	0.639	-8.31±0.22	H2O	kamezaki+ 2014
S Crt	srb	2.33±0.13	155	2.190	0.786	-7.38±0.12	H2O	nakagawa+ 2008
RX Boo	srb	7.31±0.5	162	2.210	-1.96	-7.64±0.15	H2O	kamezaki+ 2012
T UMa	Mi	0.96±0.15	257	2.410	2.60	-7.49±0.44	H2O	in prep.
Y Lib	Mi	1.24±0.13	276	2.441	3.16	-6.37±0.23	H2O	in prep.
R UMa	Mi	1.92±0.05	302	2.480	1.19	-7.39±0.06	H2O	nakagawa+ 2016
FV Boo	Mi	0.97±0.06	340	2.531	3.836	-6.23±0.13	H2O	kamezaki +2016
SY Aql	Mi	1.10±0.07	356	2.551	2.36	-7.43±0.14	H2O	in prep.
R Cnc	Mi	3.84±0.29	357	2.553	-0.97	-8.05±0.16	H2O	in prep.
W Hya	sra	10.18±2.36	361	2.558	-3.16	-8.12±0.51	OH	vlemmings+ 2003
S CrB	Mi	2.39±0.17	360	2.556	0.21	-7.90±0.15	OH	vlemmings+ 2007
T Lep	Mi	3.06±0.04	368	2.566	0.12	-7.45±0.03	H2O	nakagawa+ 2014
R Hya	Mi	8.52±0.46	380	2.580	-2.48	-7.83±0.12	H2O	in prep.
R Aqr	Mi	4.7±0.8	390	2.591	-1.01	-7.65±0.37	SiO	kamohara+ 2010
R Aqr	Mi	4.59±0.24	390	2.591	-1.01	-7.70±0.11	SiO	min+ 2014
RR Aql	Mi	1.58±0.40	396	2.598	0.46	-8.55±0.56	OH	vlemmings+ 2007
U Her	Mi	3.76±0.27	406	2.609	-0.27	-7.39±0.16	OH	vlemmings+ 2007
SY Scl	Mi	0.75±0.03	411	2.614	2.55	-8.07±0.09	H2O	nyu+ 2011
R Cas	Mi	5.67±1.95	430	2.633	-1.80	-8.03±0.78	OH	vlemmings+ 2003
U Lyn	Mi	1.27±0.06	434	2.637	1.533	-7.95±0.10	H2O	kamezaki+ 2015
OH231.8+4.2	OH/IR	0.55±0.05	551	2.741	---	---	H2O	in prep.
UX Cyg	Mi	0.54±0.06	565	2.752	1.40	-9.94±0.24	H2O	kurayama+ 2005
WX Psc	OH/IR	<5.3	650	2.813	2.22	<-4.16	OH	gabor+ 2017
S Per	src	0.413±0.017	822	2.915	1.33	-10.59±0.09	H2O	asaki+ 2010
PZ Cas	src	0.356±0.026	925	2.966	1.00	-11.24±0.16	H2O	kusuno+ 2013
VY CMa	src	0.88±0.08	956	2.980	-0.72	-11.00±0.20	H2O	choi+ 2008
NML Cyg	---	0.62±0.047	1280	3.107	0.791	-10.25±0.16	H2O	zhang+ 2012
OH138.0+7.2	OH/IR	0.52±0.09	1410	3.149	8.548	-2.87±0.38	OH	gabor+ 2017

(Published + preliminary data)

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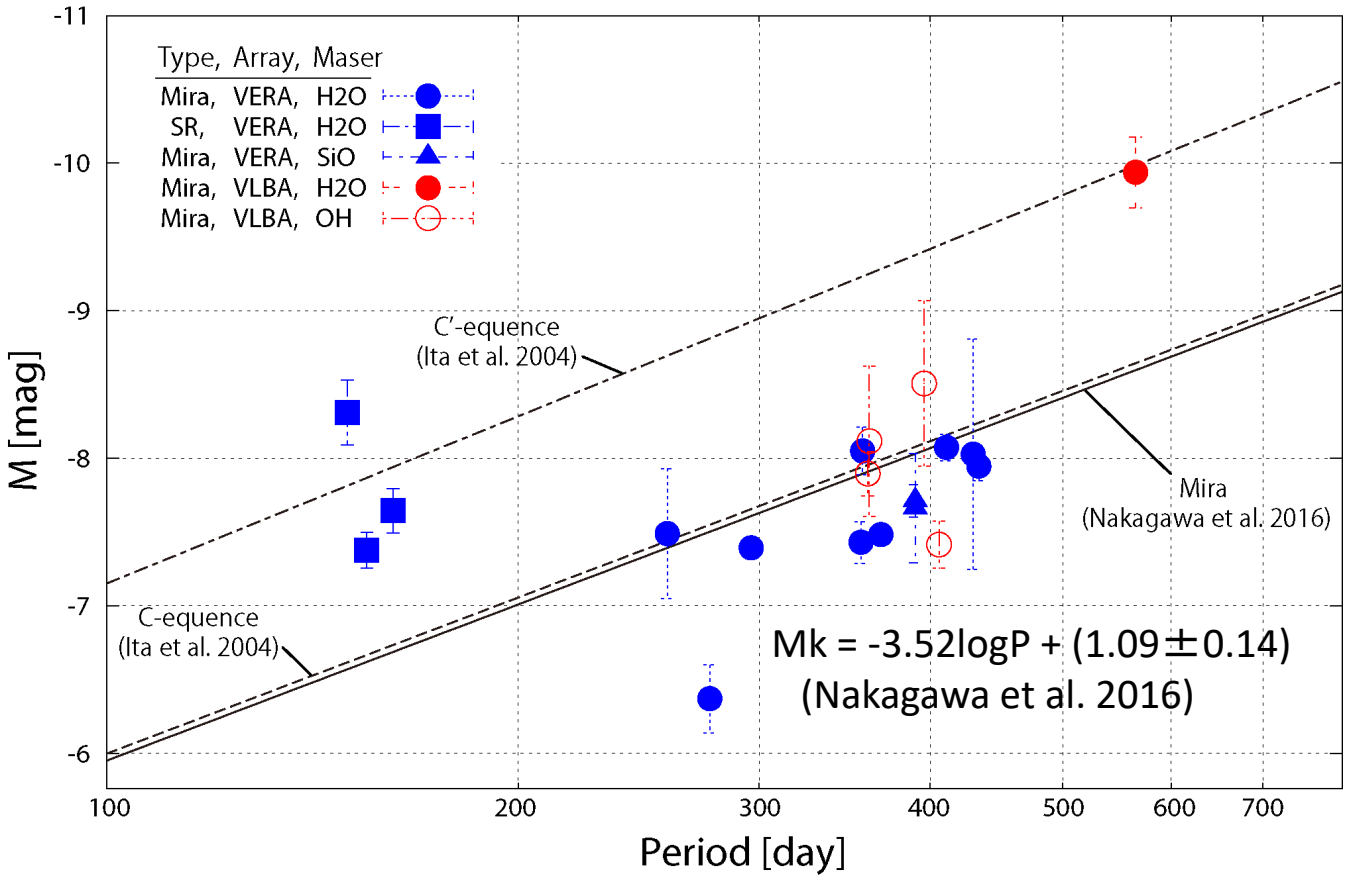
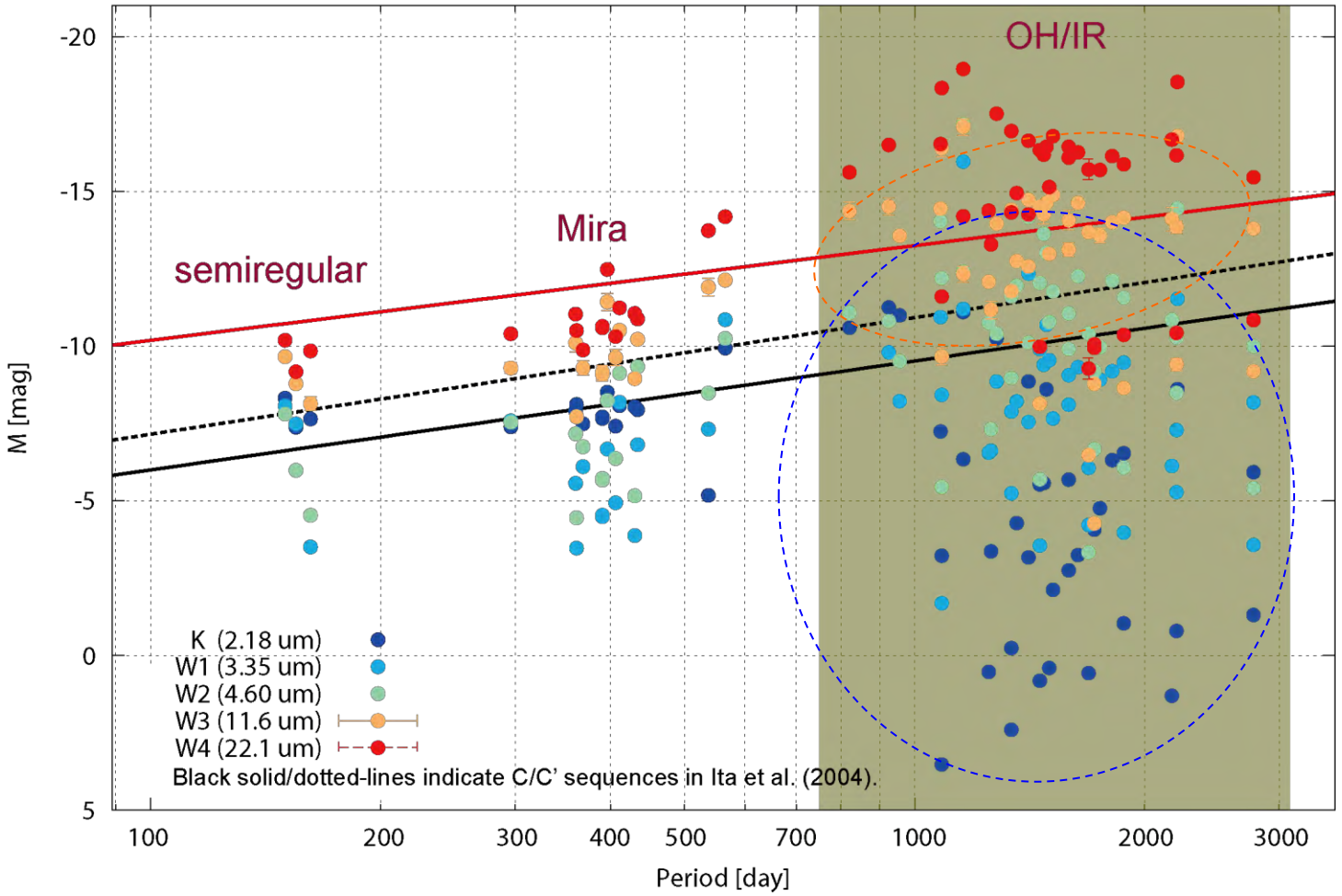


(Published + preliminary data)

Period luminosity relation of OH/IR stars（P > 1000d）

Mid-IR absolute magnitudes of ~20 OH/IR stars with known distances.

Distances from { (1) Phase-lag method（Engels et al. 2015）
(2) Kinematic distance



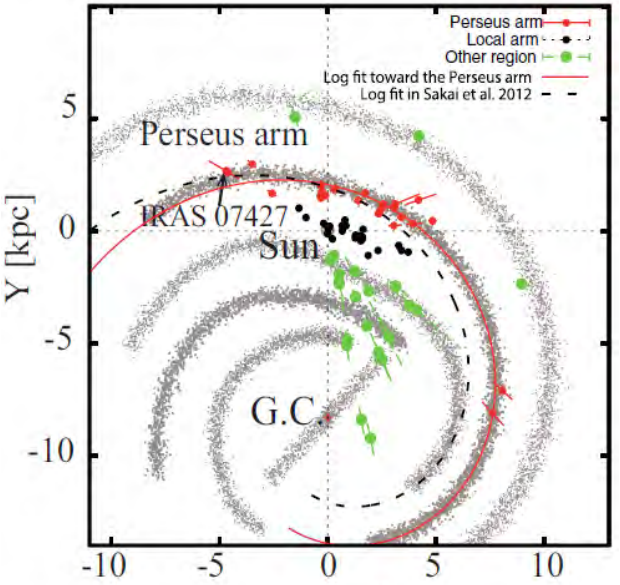
W3 (11.6 μm)

K (2.18 μm)

➡ What can we do with the OH/IR stars (P>1000 d) ?

OH/IR stars as new probes of the Galactic dynamics

- Many SFRs are used as probes to study spiral arms.
- Simulation study gives a new picture of the Galactic arm.
  - Conventional and new models -
  "Density wave" & "Non-steady spiral arms"



Sakai et al. 2015

・・・SFRs are very young, ~10^6 yeas.
Probes with various ages are needed for better understanding.



Can the OH/IR stars (P>1000 d) be used in the study of Galactic dynamics ?

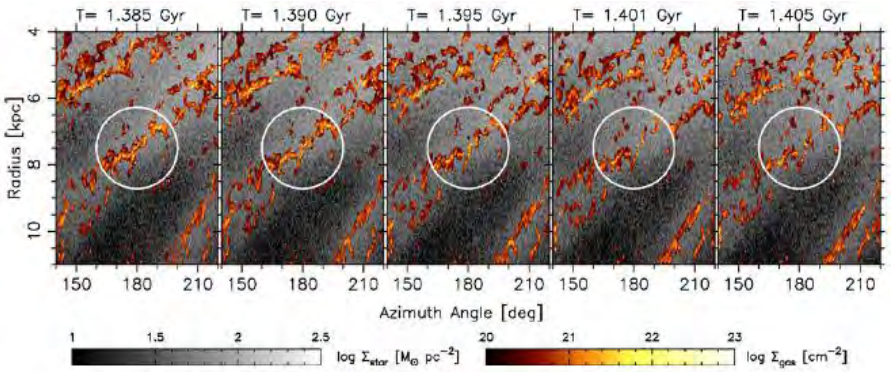


Figure 10. Same as Figure 8, but for snapshots every 5 Myr after $t = 1.385$ Gyr.
(An animation of this figure is available in the online journal.)

Wada et al. 2011

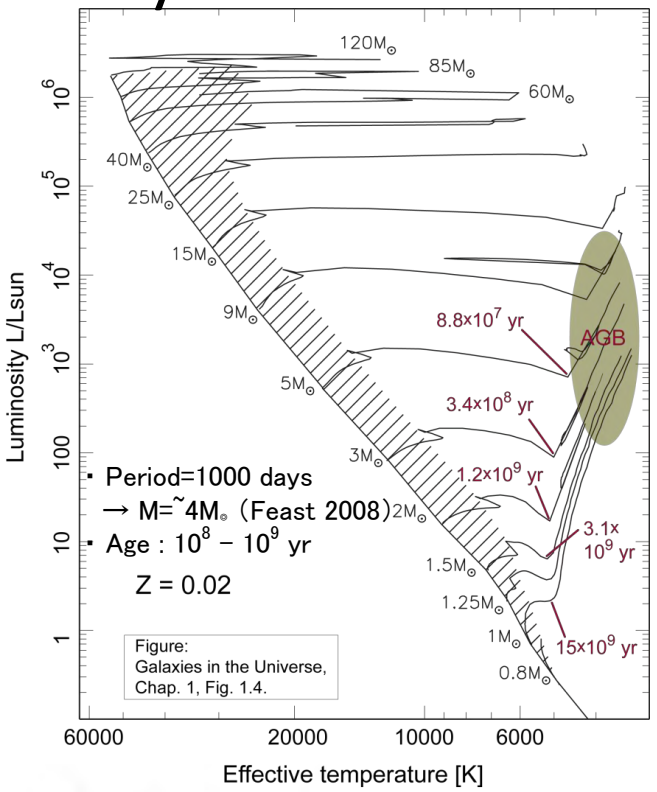
OH/IR stars as new probes of the Galactic dynamics

- Many SFRs are used as probes to study spiral arms.
- Simulation study gives a new picture of the Galactic arm.
  - Conventional and new models -
  "Density wave" & "Non-steady spiral arms"

- Period=1000 days → M : ~4M⊙ (Feast 2008)
  → Age : 10^8 - 10^9 yr

- Calibration of mid-infrared PLR of OH/IR stars.
- Direct measurements

➡ VLBI astrometry (OH/SiO/H2O masers)



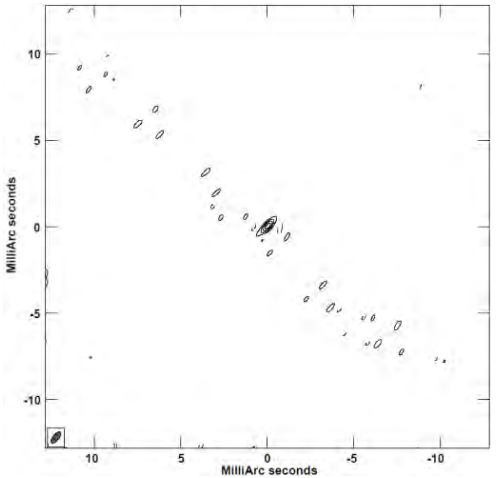
Age		Physics	Target	Model		Obs.
New	~10^6 yr	Spiral arm	SRF, Giants	✔	⇔	✔
⇕	~10^8 yr	Bifurcating/ merging arms	Heavy OH/IR star ?	✔	⇔	No
Old	~10^9 yr	Relaxed system	Mira	✔	⇔	✔

43GHz VLBI observation of OH104.9+2.4 and OH127.8+0.0 with VERA

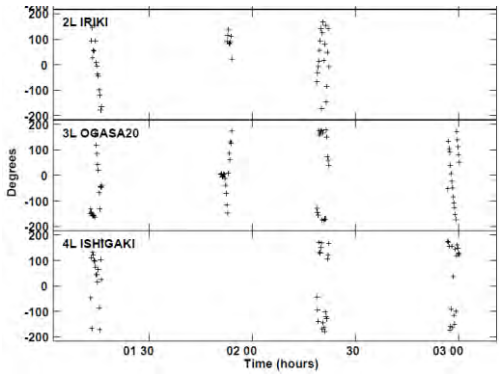
(Wide-band receiving system for reference source)

- OH127.8+0.0 (P = 1994 day) & J0128+6306
- OH104.9+2.4 (P = 1535 day) & J2231+5922

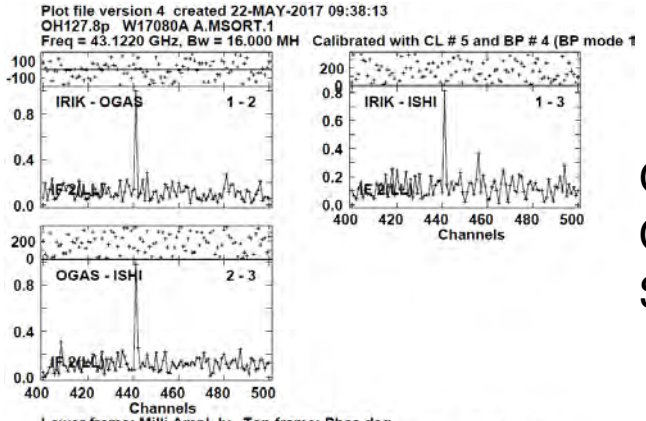
➡ Fringe detection !



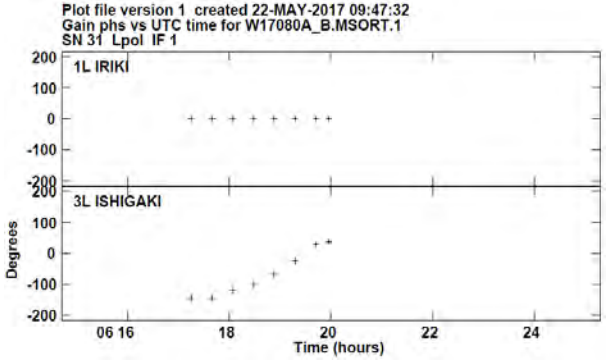
OH104.9+2.4
(NSV25875)
Self-cal map
Speak = ~ 5Jy



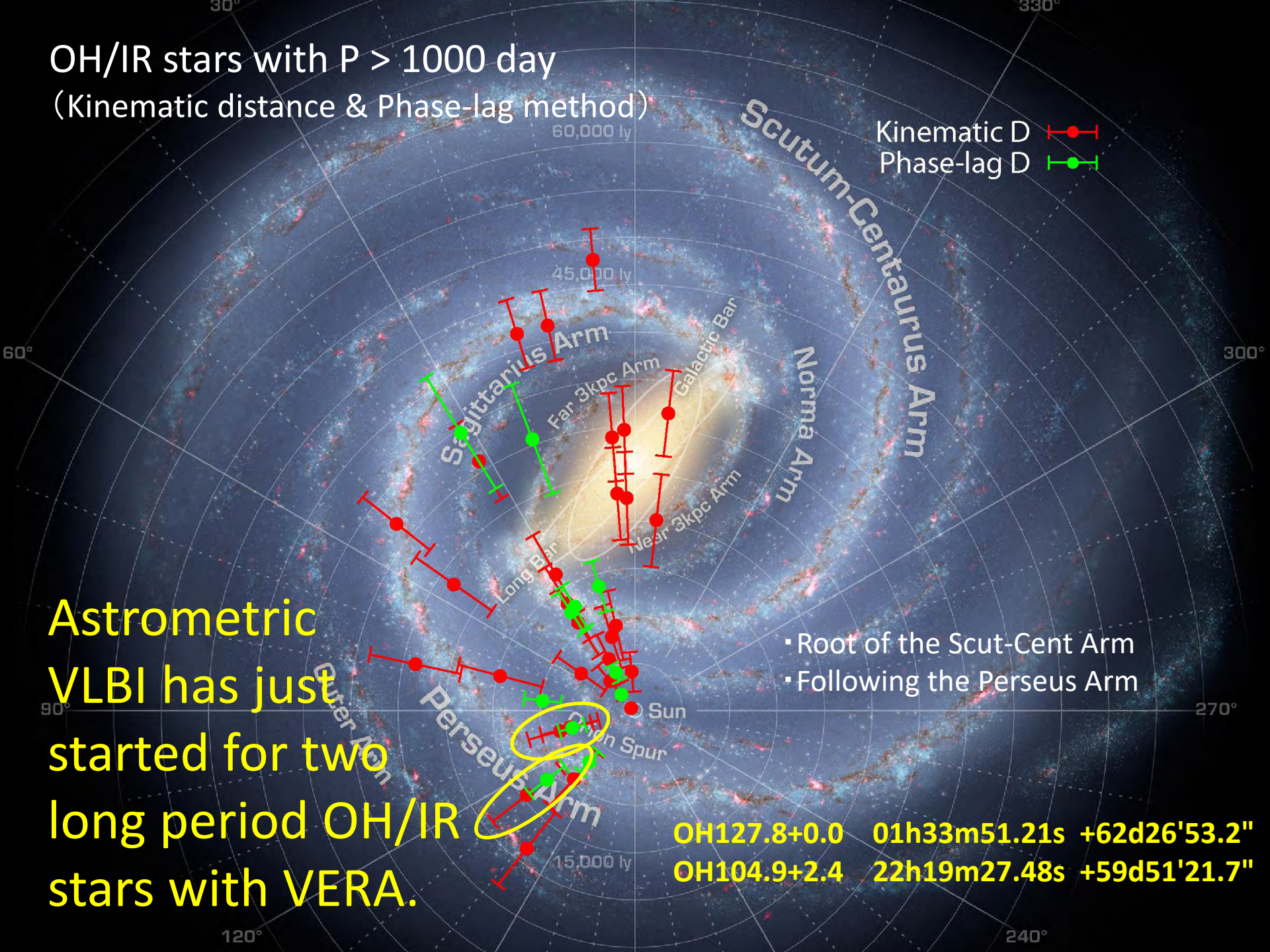
Phase solution
of a reference
J2231+5922



OH127.8+0.0
Cross cor.
Spectrum



Phase solution
of a reference
J0128+6306


OH/IR stars with P > 1000 day
（Kinematic distance & Phase-lag method）
Kinematic D
Phase-lag D
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Perseus Arm
Outer Arm
Local Arm
Sun
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
Astrometric VLBI has just started for two long period OH/IR stars with VERA.
・Root of the Scut-Cent Arm
・Following the Perseus Arm
OH127.8+0.0 01h33m51.21s +62d26'53.2"
OH104.9+2.4 22h19m27.48s +59d51'21.7"

We need more samples; OH/IR stars (P>1000d)

Monitor/survey for candidate sources.

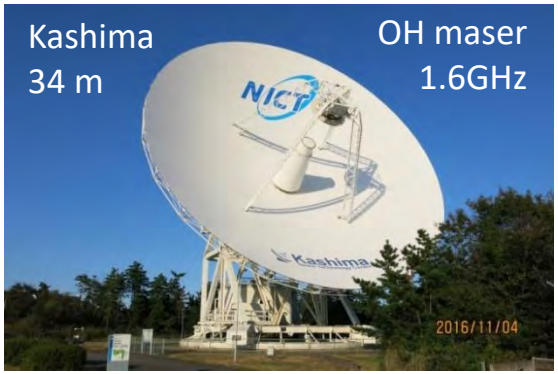
- OH maser　Kashima 34m (NICT)　　Survey/Monitor
- H2O maser　VERA-IRIKI 20m (NAOJ)　　Survey/Monitor
- SiO maser　VERA-IRIKI 20m (NAOJ)　　Survey/Monitor

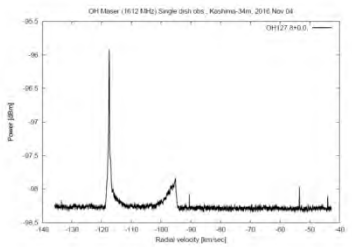
●1.6 GHz OH maser：
NICT Kashima 34m telescope

- 2016 Nov. 4 (FRI)
- NICT Kashima 34m, L-band (1.6GHz) system
- OH maser　(1612 MHz)

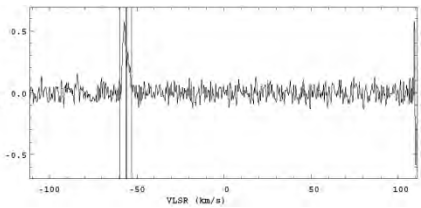
●43GHz SiO maser ：
VERA Iriki 20m telescope

- 2016 Dec.
- VERA Iriki station 20m , Q-band (43GHz) system
- SiO maser (43GHz)









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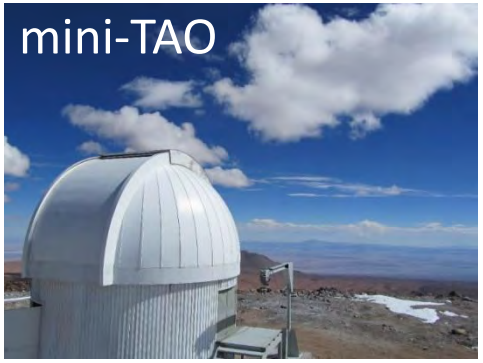
Future plan
- NIR-Mid TAO (Univ. of Tokyo) Monitor

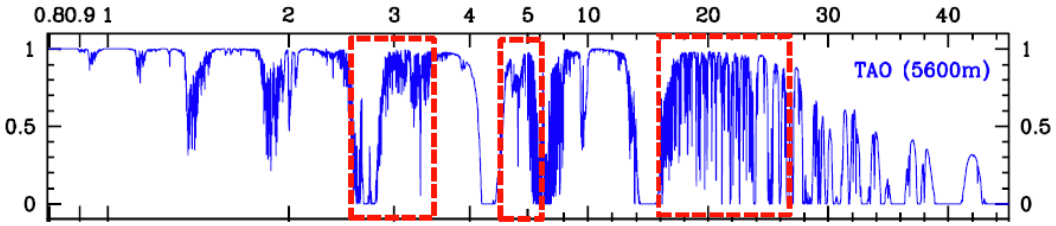
・Period and mag. in MIR band
・Wavelength coverage
  2-38 μm





(TAO web site)

Hazy wavelength regions in L-, M-, and Q-bands



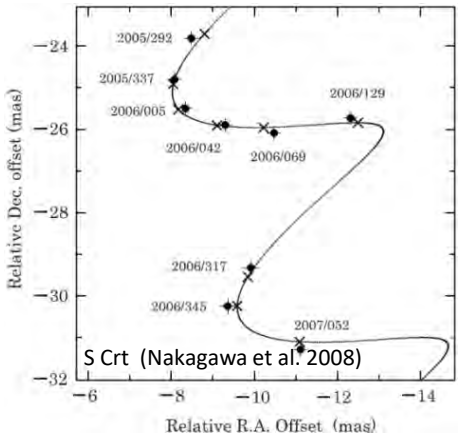
Summary

(1) Astrometric VLBI of Mira

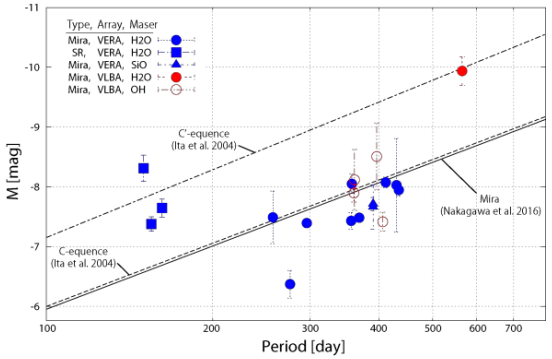
- VERA Phase-ref. VLBI at 22 GHz (H2O maser)
- Parallaxes of ~15 LPVs determined
- P-Mk relation ;

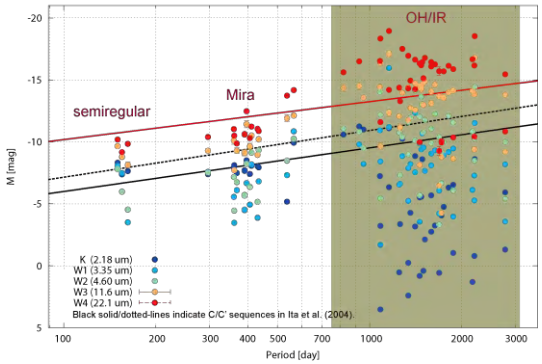
  Mk = -3.52logP + (1.09±0.14)

  (Nakagawa et al. 2016)

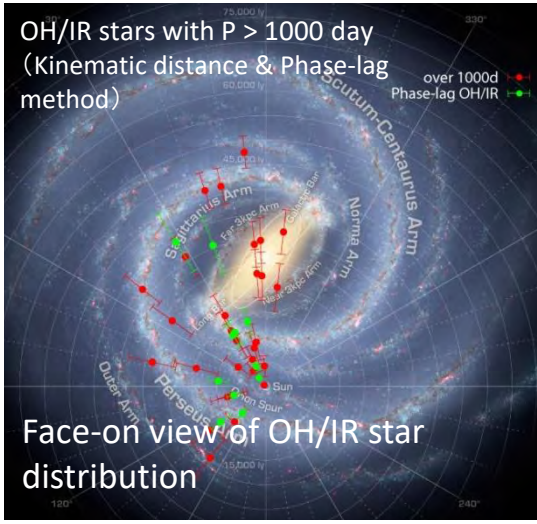








(2) Study about OH/IR stars with P>1000d



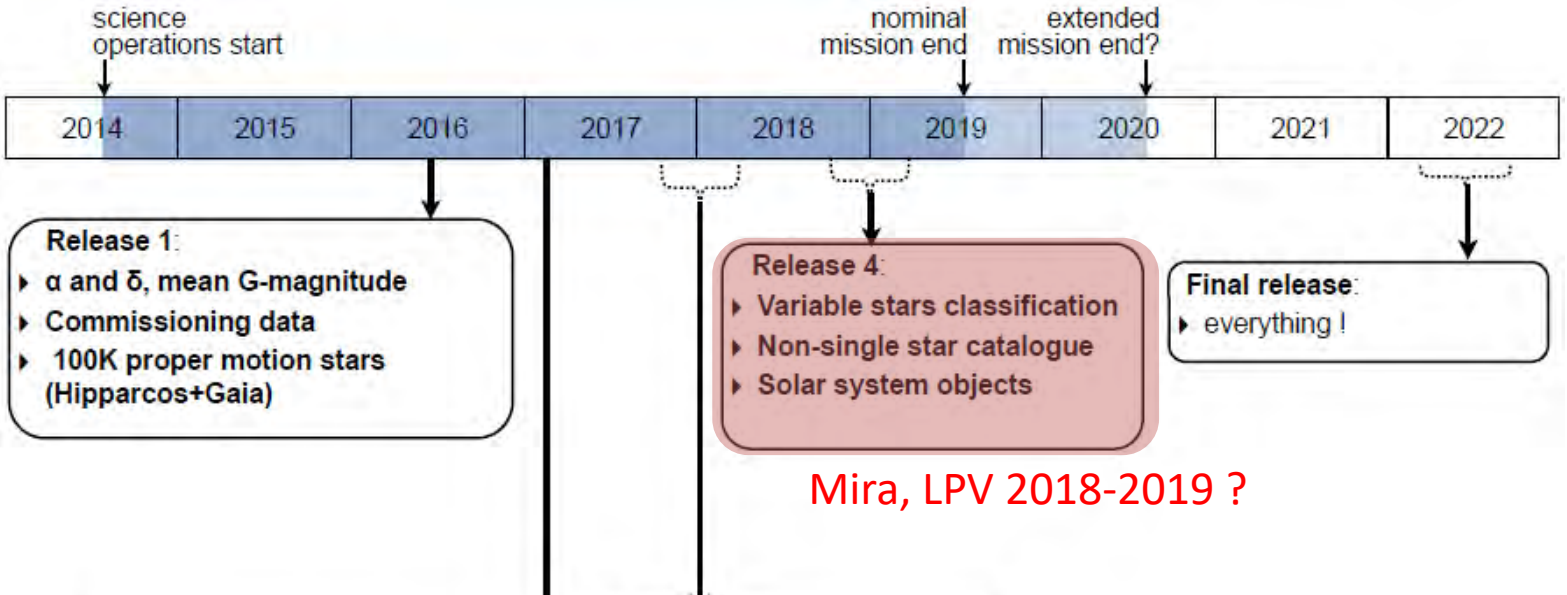
- MIR P-M relation should be confirmed.
- Offers unique samples for study dynamics of stars with age of ~10^8 years
- Face on distribution of OH/IR stars with P>1000d with known distances
- VLBI astrometry with SiO masers has just started
- Future plan ; Mid-infrared monitoring with TAO telescope at Atacama (Univ. of Tokyo)

Name	HIP/TYC	$\Delta\alpha*$ [mas]	$\Delta\delta$ [mas]	$\Delta\varpi$ [mas]	$\Delta\mu_{\alpha*}$ [mas yr^{-1}]	$\Delta\mu_{\delta}$ [mas yr^{-1}]	Reference (VLBI)
S Persei	11093	+4.969 ± 8.474	−10.626 ± 8.497	−0.001 ± 0.720	−0.153 ± 0.242	−0.225 ± 0.211	Asaki et al. (2010)
LS I +61 303	12469	−28.882 ± 6.726	+22.324 ± 7.611	+0.188 ± 0.650	−1.322 ± 0.373	+1.133 ± 0.383	Lestrade et al. (1999)
HII 174	1803-0008-1			−0.024 ± 0.302	−0.130 ± 0.918	−0.395 ± 0.492	Melis et al. (2014)
HD 283447	19762	+8.447 ± 0.759	−36.971 ± 0.482	−0.460 ± 0.495	−8.998 ± 0.170	+0.011 ± 0.111	Torres et al. (2012)
T Tau	20390	+231.577 ± 1.280	+514.096 ± 0.545	+0.291 ± 0.309	+7.600 ± 0.169	−12.339 ± 0.095	Loinard et al. (2007)
T Lep	23636			−0.843 ± 0.759	−4.395 ± 0.502	+1.668 ± 0.791	Nakagawa et al. (2014)
3C273	60936	+0.912 ± 1.474	+0.819 ± 1.961	−0.140 ± 0.377	−0.384 ± 0.443	+0.111 ± 0.288	Ma et al. (2009)
σ^2 CrB	79607	−12.772 ± 1.142	−5.524 ± 1.491	+0.104 ± 0.913	−0.471 ± 0.065	−0.009 ± 0.086	Lestrade et al. (1999)
Cyg X-1	98298	−0.378 ± 0.444	−0.648 ± 0.732	−0.310 ± 0.250	+0.015 ± 0.086	+0.034 ± 0.139	Reid et al. (2011)
HD 199178	103144	−4.246 ± 8.859	+6.620 ± 9.330	+0.358 ± 0.474	−0.170 ± 0.409	+0.349 ± 0.431	Lestrade et al. (1999)
AR Lac	109303	−4.324 ± 2.945	−0.975 ± 4.398	−0.332 ± 0.510	−0.220 ± 0.127	−0.082 ± 0.191	Lestrade et al. (1999)
IM Peg	112997	+0.503 ± 1.029	−0.014 ± 1.046	−0.039 ± 0.372	+0.001 ± 0.093	−0.110 ± 0.096	Bartel et al. (2015)
PZ Cas	117078	−29.855 ± 3.349	−9.348 ± 4.012	+0.438 ± 0.558	−0.275 ± 0.205	−0.236 ± 0.303	Kusuno et al. (2013)

Lindegren et al. 2016

Parallax in Gaia DR1

	VERA	Gaia
▪ HU Pup	---	-0.15±0.57（400%）
▪ T UMa	0.96±0.19（20%）	1.07±0.94（88%）



Mira, LPV 2018-2019 ?

esa

gaia

science operations start

nominal mission end

extended mission end?

2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022

Release 1:
- α and δ, mean G-magnitude
- Commissioning data
- 100K proper motion stars (Hipparcos+Gaia)

Release 2:
- 5-parameter astrometric solutions for single star (parallax)
- Integrated BP/RP + Astrophysical parameters
- Mean V_{rad} (for non variable)

Release 3:
- Mean V_{rad}
- 5-parameter astro. Sol.
- Object classifications and Astrophysical Parameters
- Orbital solution of binaries
- Mean RVS spectra

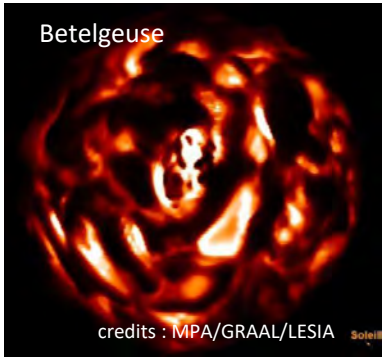
Release 4:
- Variable stars classification
- Non-single star catalogue
- Solar system objects

Final release:
- everything !

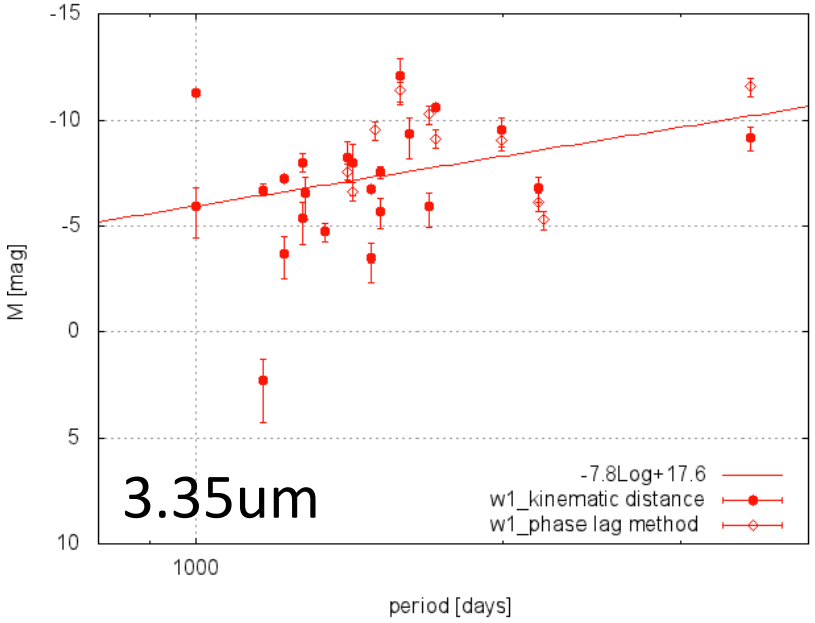
Mira, LPV
2018-2019 ?

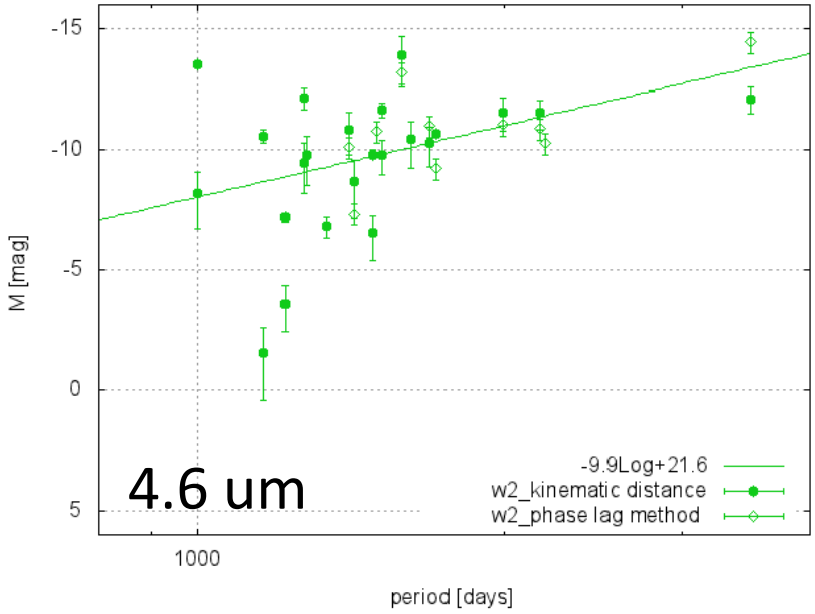
Difficulty in AGB stars

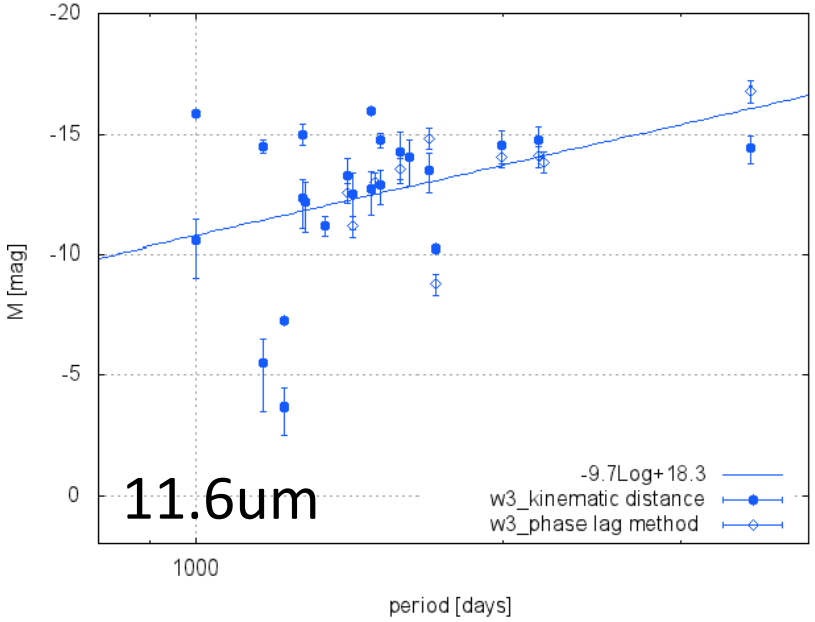
Heavy dust /
Convective envelope /
Non-spherical symmetry.

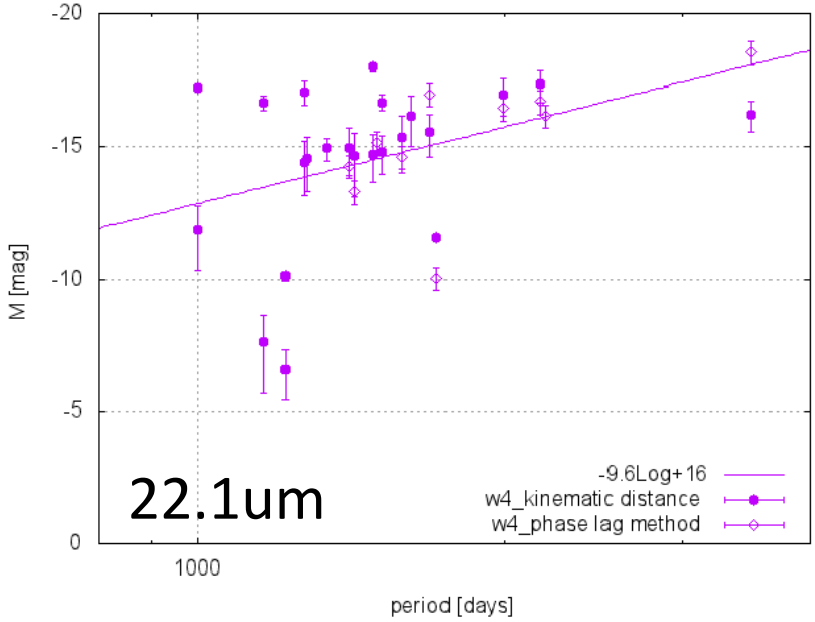


PLR in the MIR band





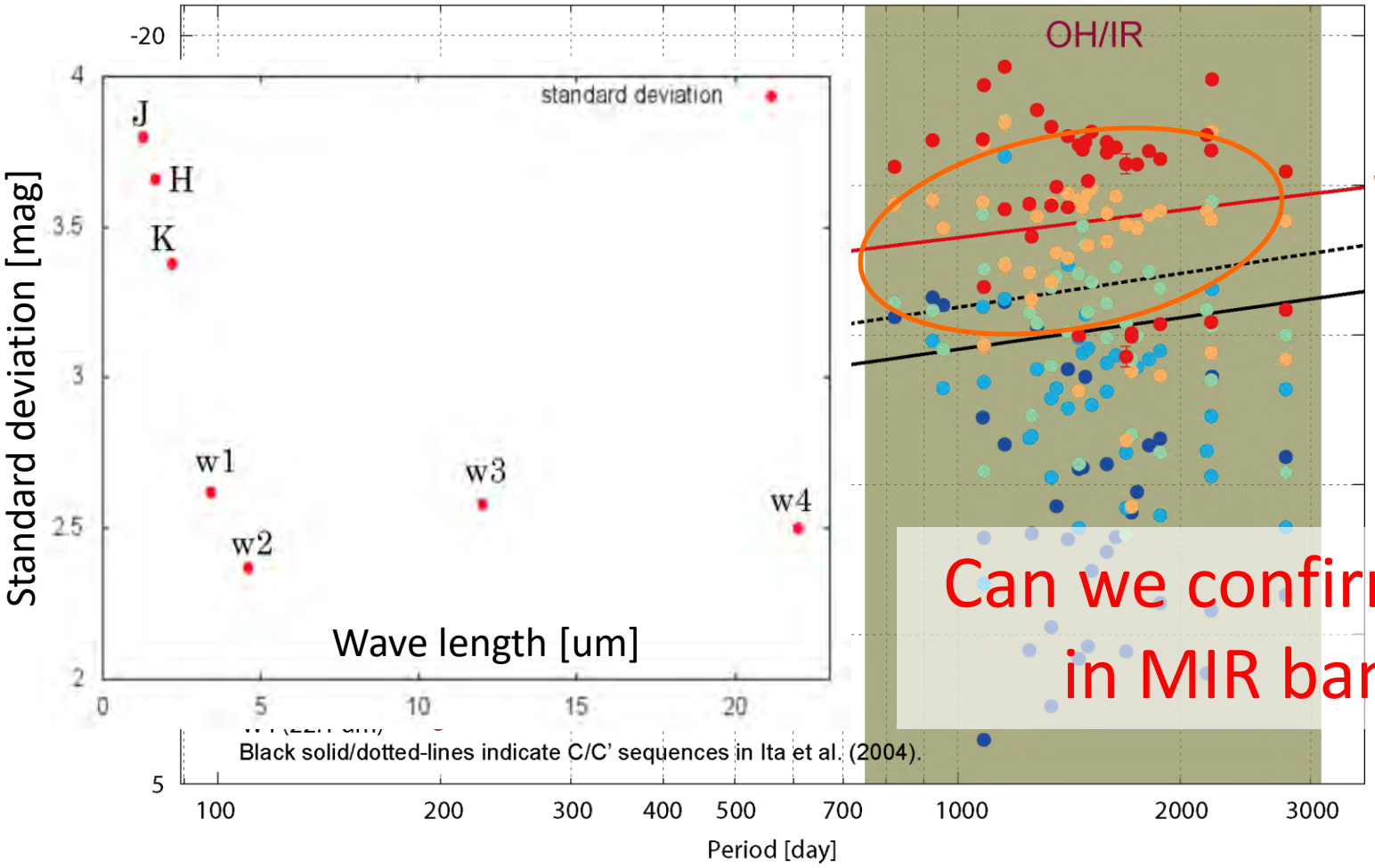




Period luminosity relation of OH/IR stars（P > 1000d）

Mid-IR absolute magnitudes of ~20 OH/IR stars with known distances.

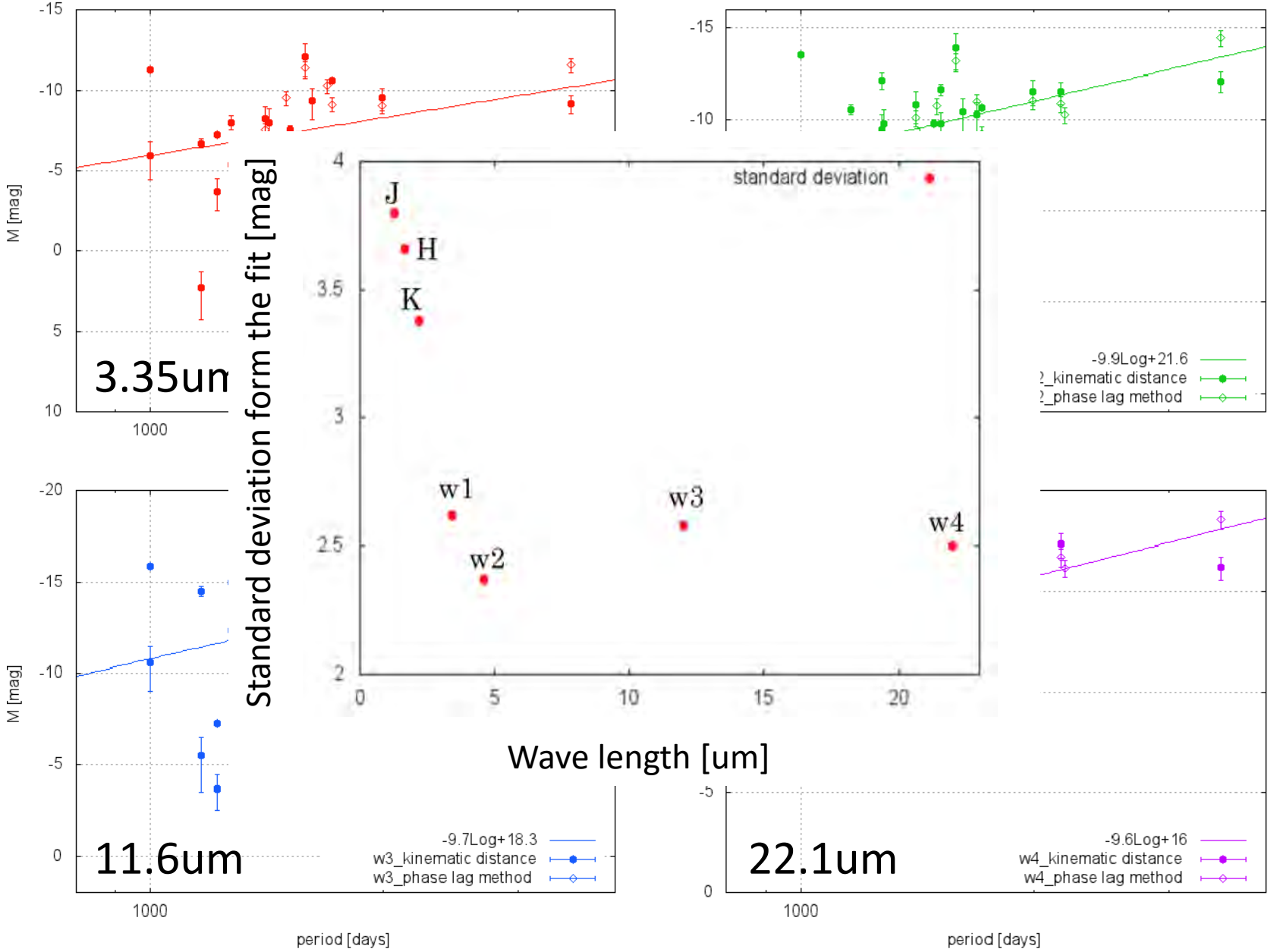
Distances from { (1) Phase-lag method（Engels et al. 2015）
(2) Kinematic distance



W3 (11.6 μm)

Can we confirm a PLR in MIR band ?

PLR in the MIR band

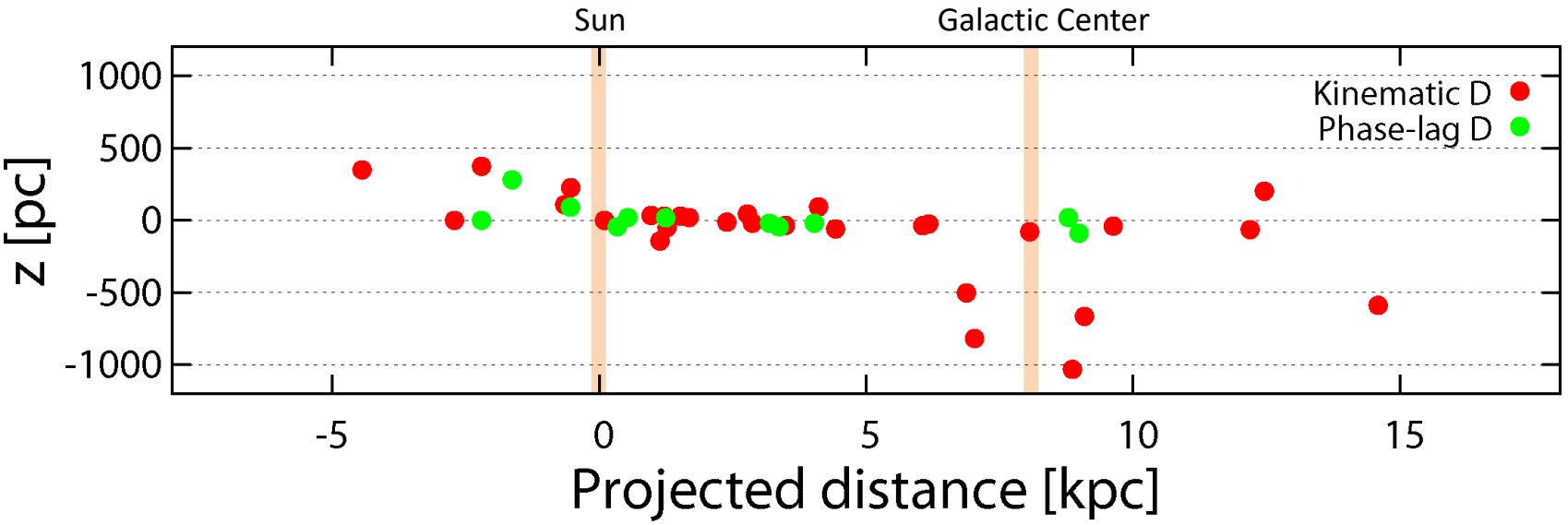


Height（z）from the Galactic plane
銀河面からの高さz

Height

$Z = D_{kinematic} \times Sin(b)$

Edge-on distribution of the OH/IR stars (P>1000d)

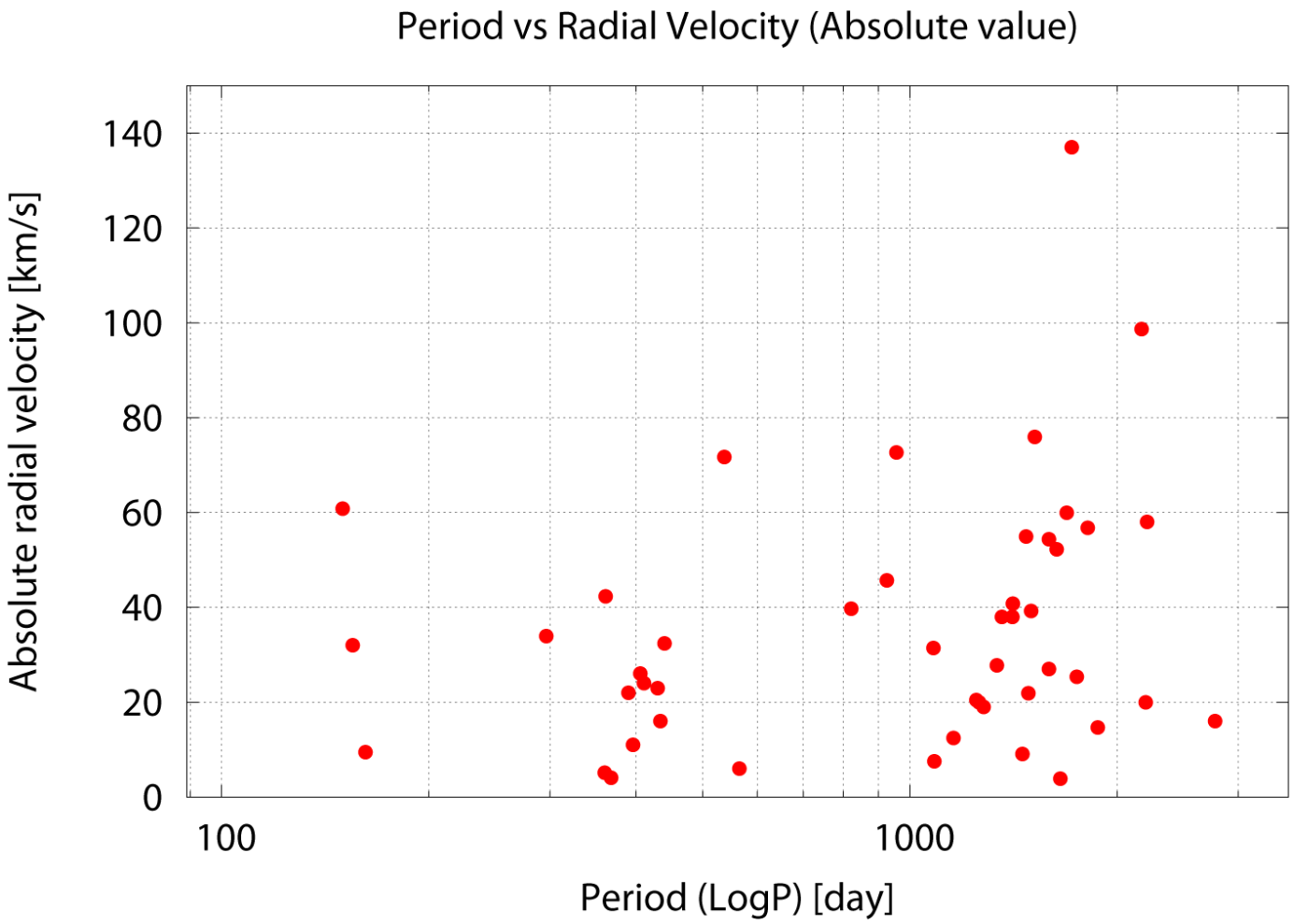


Scale height

Thin disk ~ 300 pc

Thick disk ~ 1 kpc

Period vs Radial velocity of LPVs

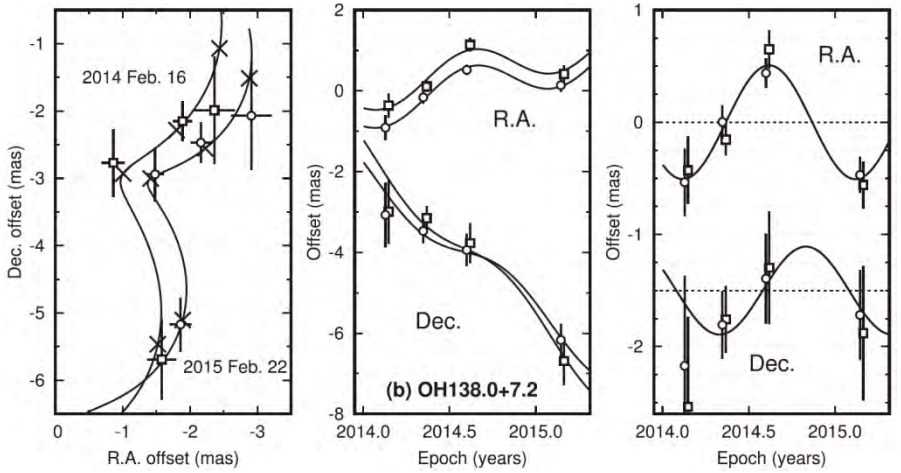


We need kinematics of OH/IR stars with P>1000d

OH/IR星（P>1000d）の分布と運動を知りたい

- We want to know...
  Positioin and motion（ X, Y, Z, Vx, Vy, Vz ）
- We need distances.
  > Parallax from astrometric VLBI
  > OH, H2O, SiO masers as VLBI targets
- Invisible for Gaia
  > Concentrated on Galactic plane
  > OH/IR stars may be invisible
- JASMINE
  > Infrared satellite for Galactic bulge stars

OH maser parallax at 1.6 GHz



0.52±0.09 mas（D = 1.9 kpc） Orosz et al. 2017

Jobs

(1) Finding LPVs with P>1000d
- Determination of the period

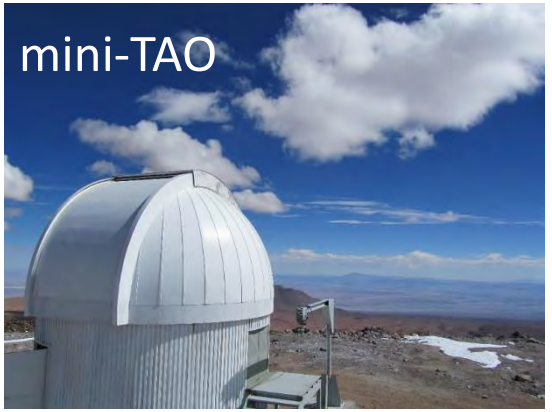
⇨ IR monitoring : **TAO project**
⇨ Radio moniroting（OH/SiO.H2O maser）
Kashima 34m, VERA20m

(2) Measurements of parallax and Vlsr
- Maser survey

⇨ VLBI and Single-dish
（OH/SiO.H2O maser）

Collaboration with TAO group in University of Tokyo

Monitoring with TAO-MIMIZUKU imager/spectrograph



✓ Wide wavelength coverage

Covers 2-38 μm wavelength region
with 3 channels (H1RG / Si:As / Si:Sb)

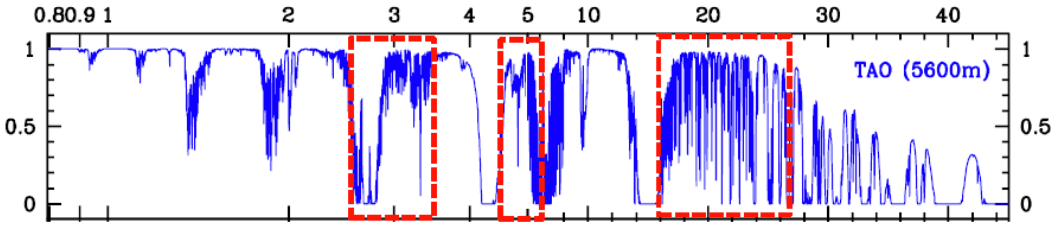
✓ High spatial resolution

Achieves diffraction-limited spatial resolution
0.4”@10 μm / 0.8”@20 μm / 1.2”@30μm



✓ Highly accurate photometry

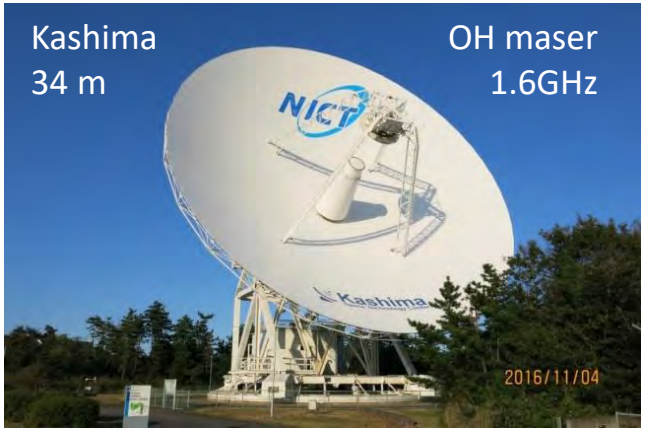
Hazy wavelength regions in L-, M-, and Q-bands



(TAO web site)

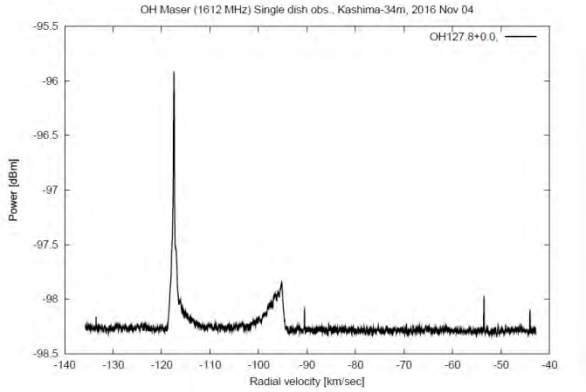
Single-dish observation of OH/IR stars

単一鏡による観測例　OH127.8+0.0

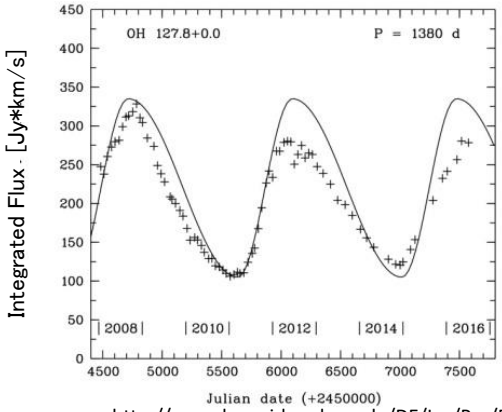


● 1.6GHz OH maser : NICT Kashima 34m telescope

- 2016 Nov. 4 (FRI)
- NICT Kashima 34m, L-band (1.6GHz) system
- OH maser　(1612 MHz)



Well defined periodicity.

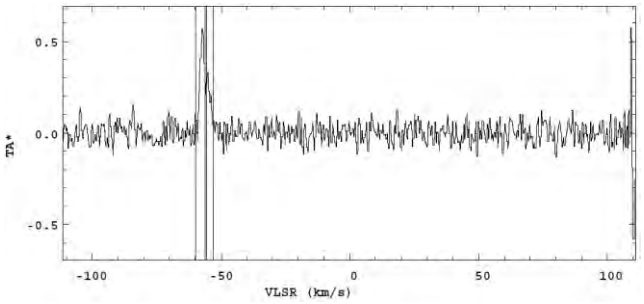


Periodicity of OH maser
Nançay 1612 MHz
monitoring of OH/IR stars

http://www.hs.uni-hamburg.de/DE/Ins/Per/Engels/engels/nrt_monitoring/index.html

● 43GHz SiO maser : VERA Iriki 20m telescope

- 2016 Dec.
- VERA Iriki station 20m , Q-band (43GHz) system
- SiO maser (43GHz)



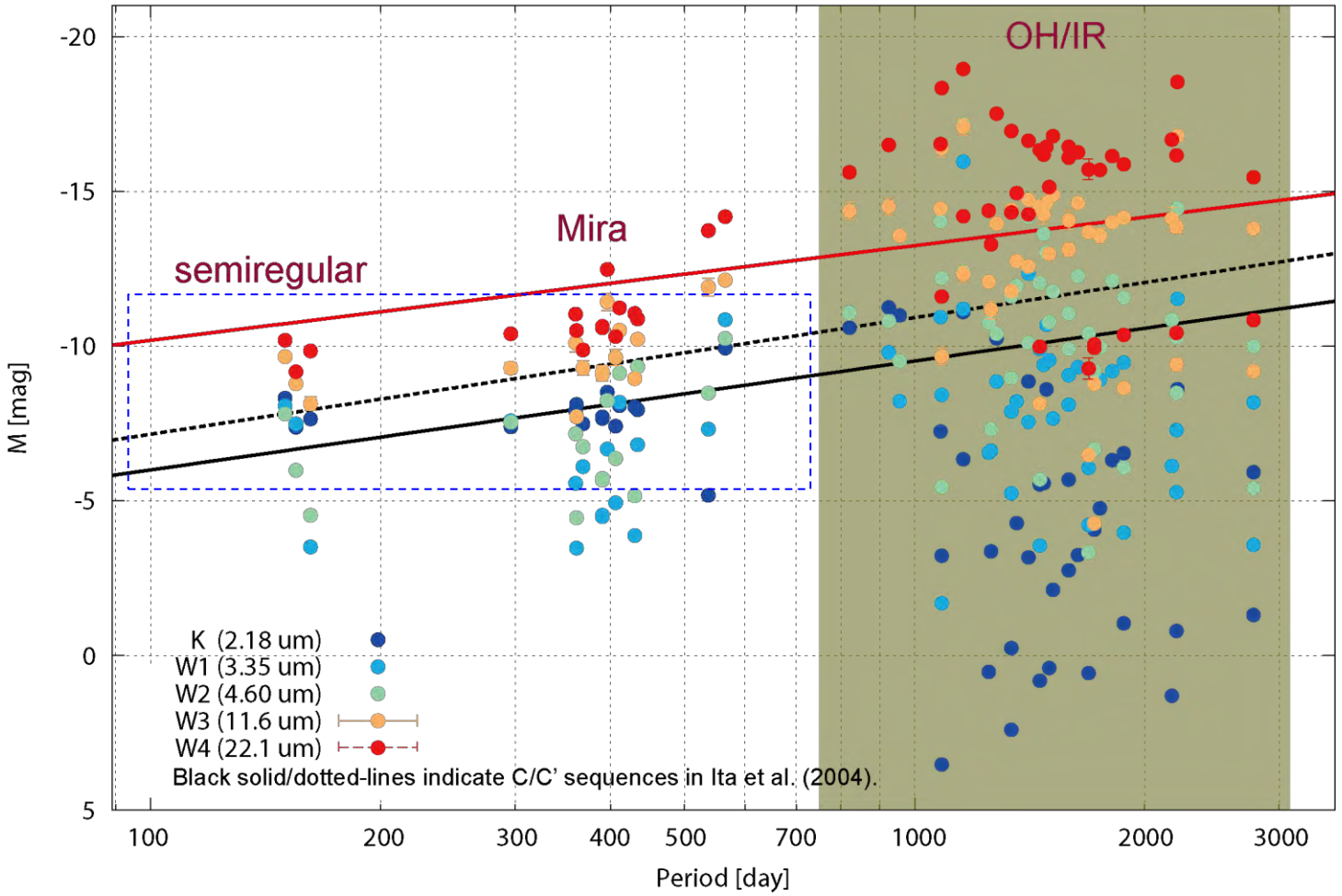
Do they show periodicity ?
We have to confirm in a few yeas from now.



Period luminosity relation of OH/IR stars（P > 1000d）

Mid-IR absolute magnitudes of ~20 OH/IR stars with known distances.

Distances from { (1) Phase-lag method（Engels et al. 2015）
(2) Kinematic distance



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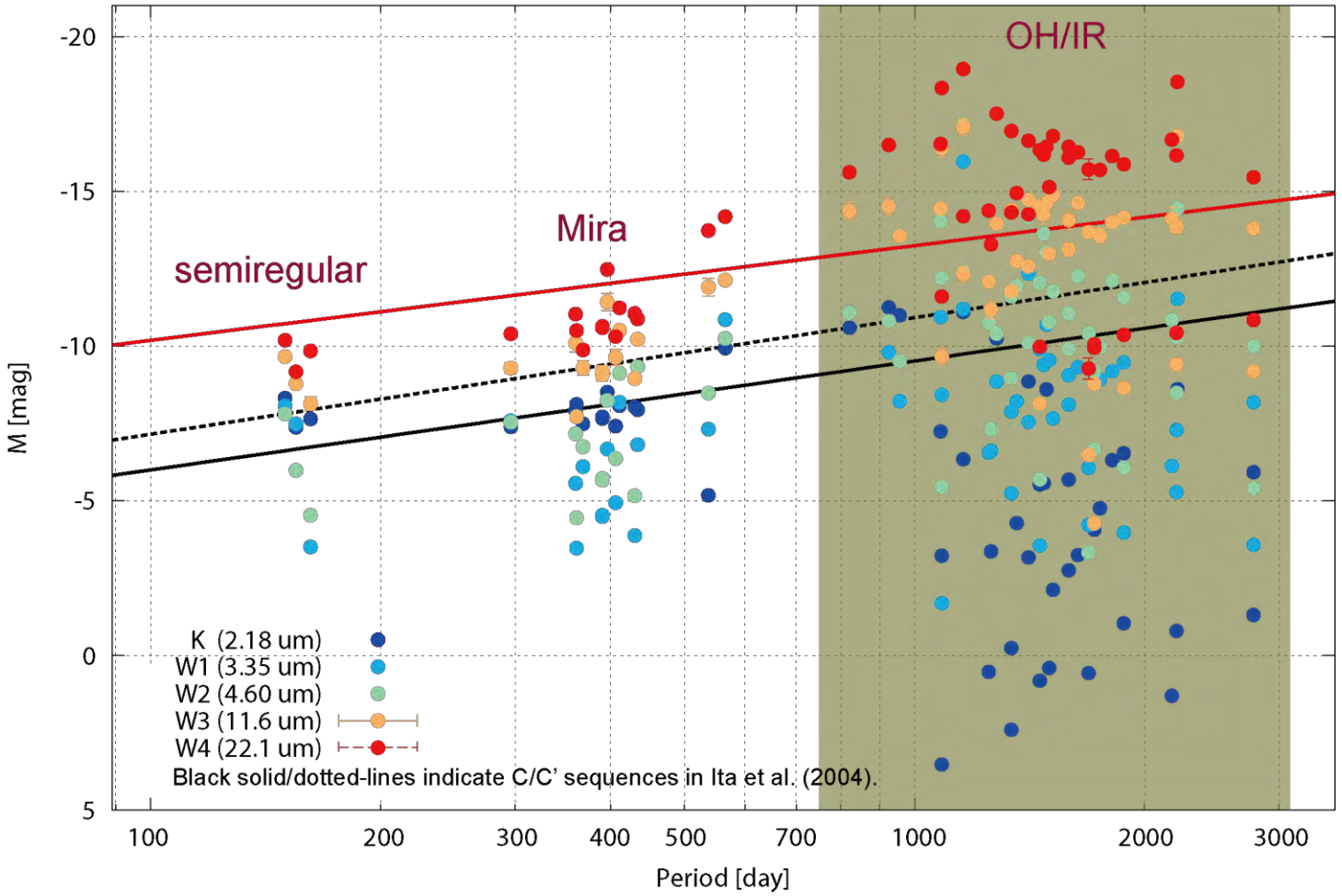
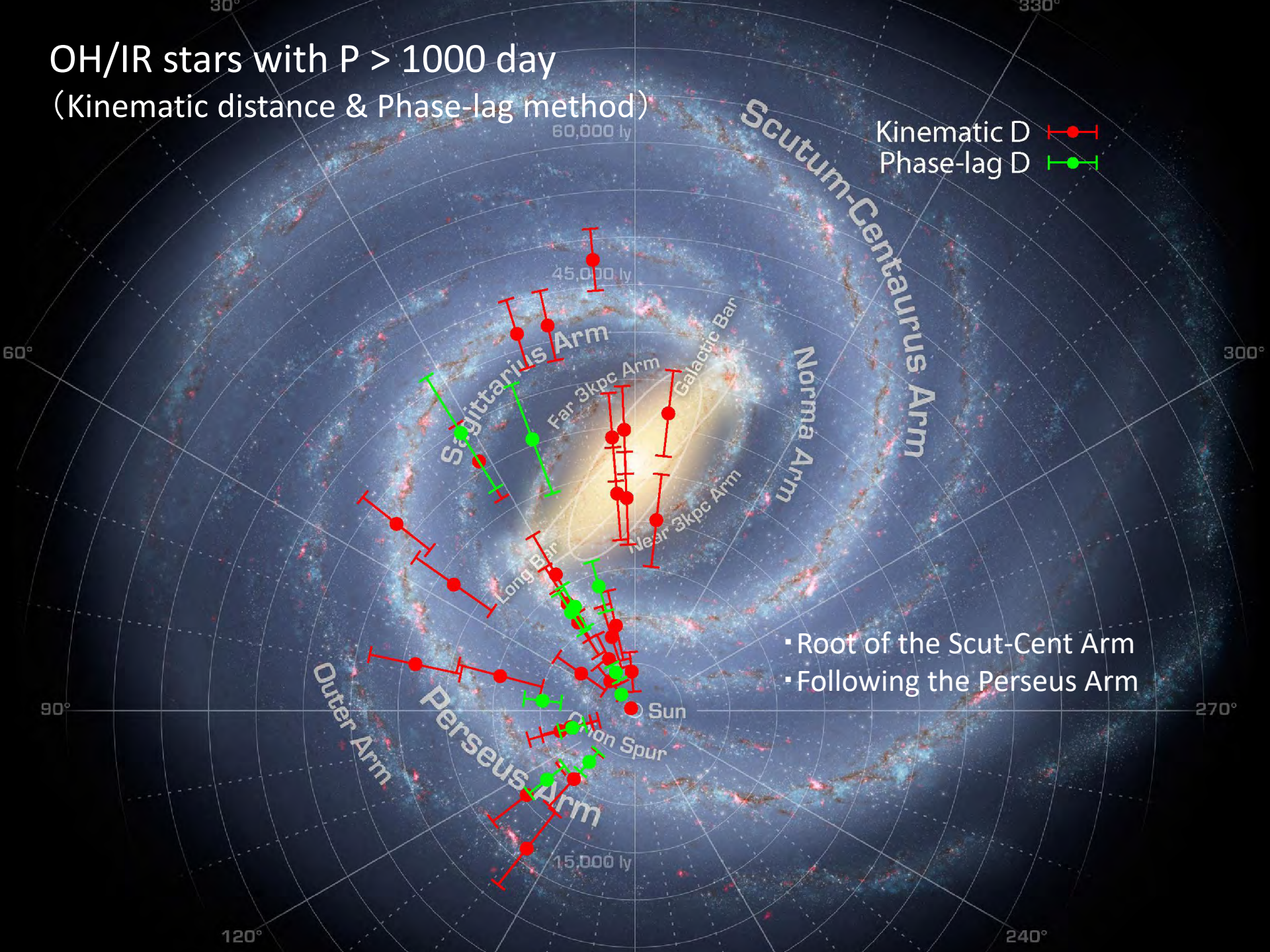
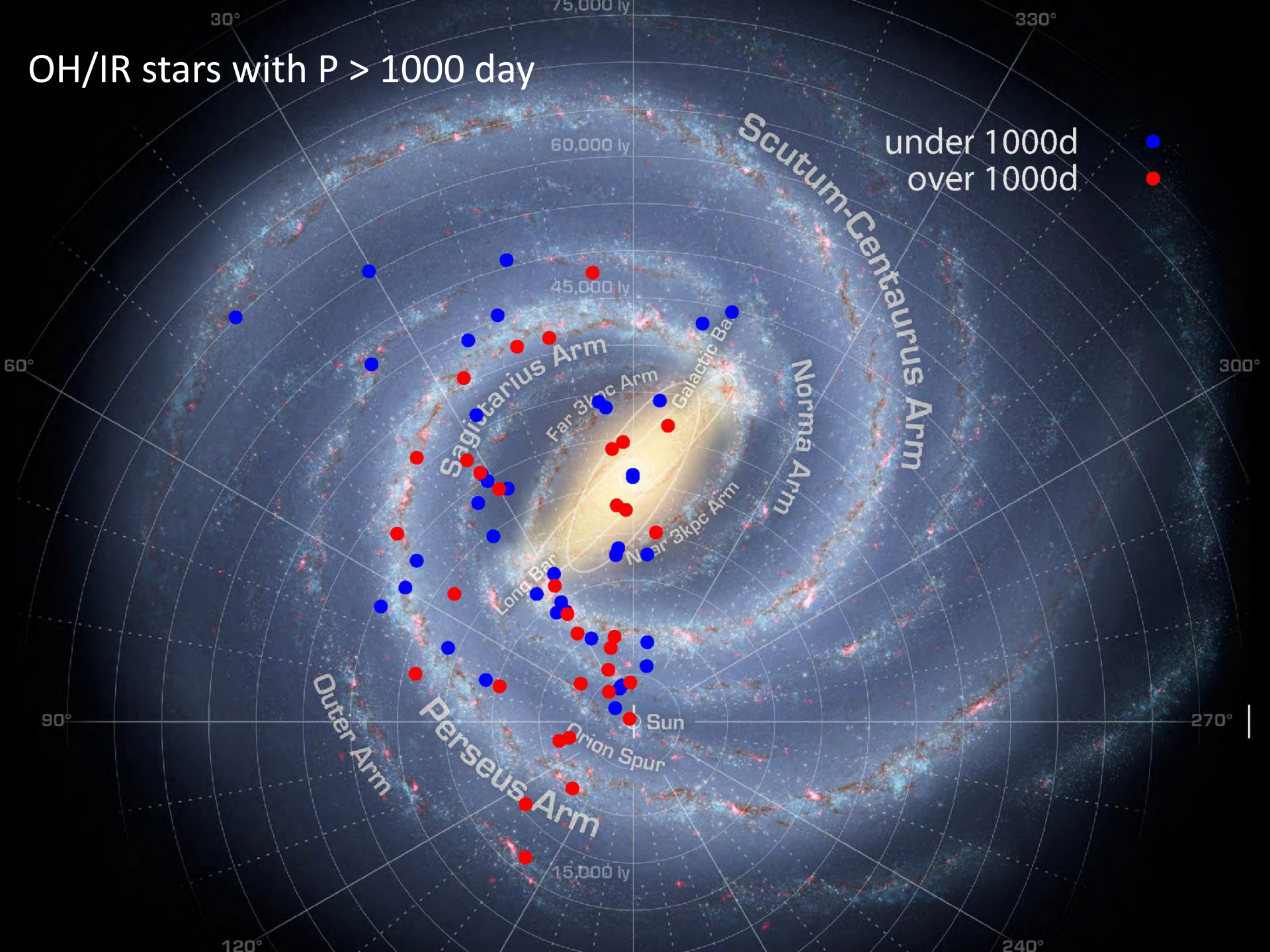



OH/IR stars with P > 1000 day
（Kinematic distance & Phase-lag method）
Kinematic D
Phase-lag D
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
Sun
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
・Root of the Scut-Cent Arm
・Following the Perseus Arm


OH/IR stars with P > 1000 day
under 1000d
over 1000d
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
Sun
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°

OH/IR stars as new probes of the Galactic kinematics study
銀河動力学研究の新たなプローブとなり得るか

- Simulation study with supercomputer gives new picture of the Galactic arm.
- Probes with various ages are needed.
- Period=1000 days → M=~4M⊙（Feast 2008）
- Age : 10^8 - 10^9 yr
- Calibration of mid-infrared PLR of OH/IR stars.
- Astrometry：VLBI（OH/SiO/H2O masers）
- Old and new models of Galactic kinematics
  > Density wave
  >Simulation study of Galactic arm formation

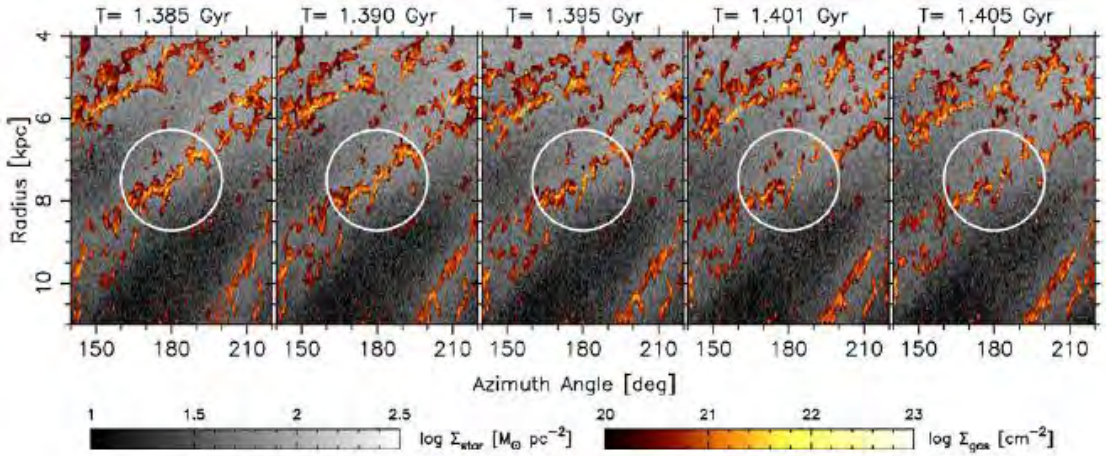
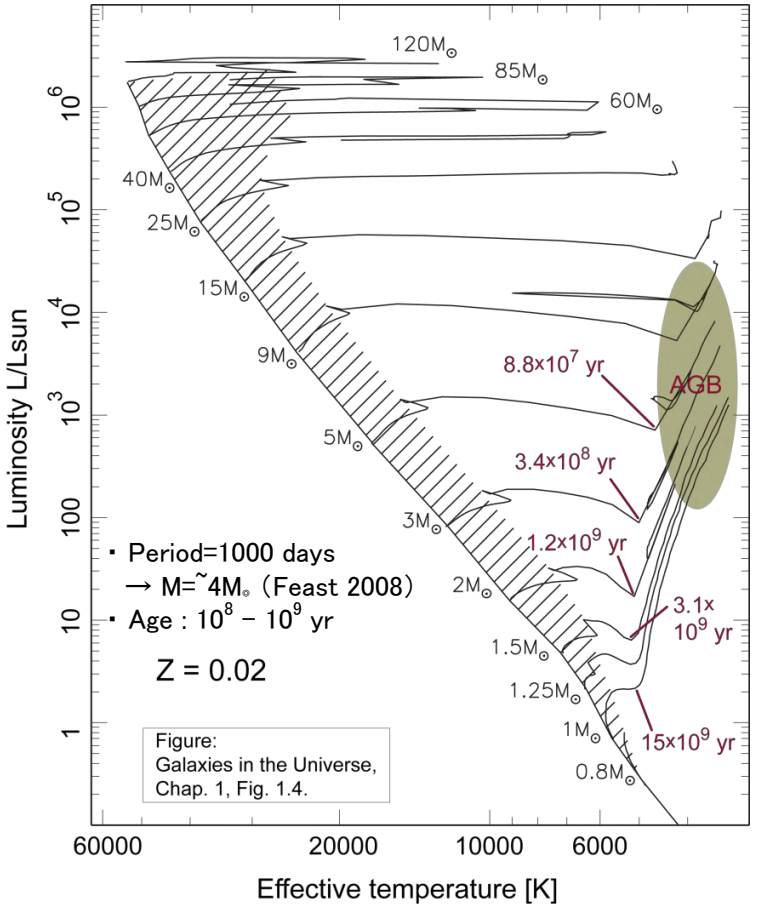


Figure 10. Same as Figure 8, but for snapshots every 5 Myr after $t = 1.385$ Gyr.
(An animation of this figure is available in the online journal.)

Wada et al. 2011



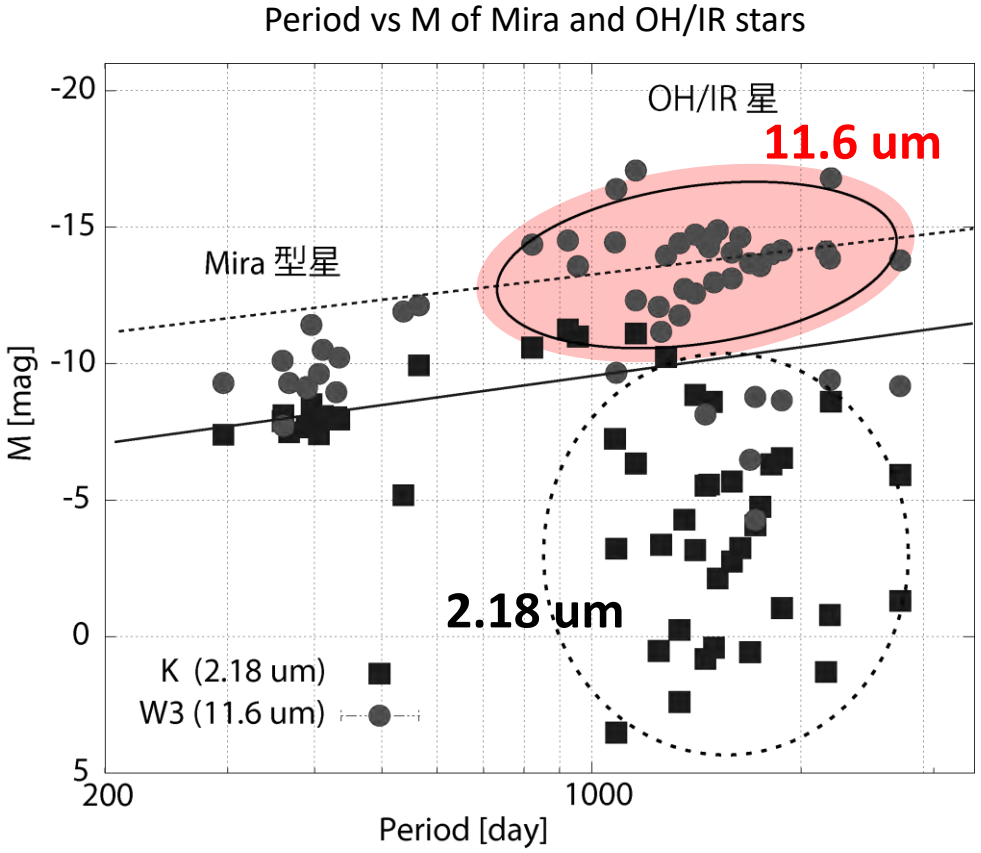
Figure：HR diagram.

Extension of the study to longer pulsation period
より長い周期を持つ変光星の観測的研究

Can we confirm a PLR in MIR band ?

- Study of the PLR at Period >1000 days
  - >Absolute MIR magnitudes of ~20 OH/IR stars with estimated distances
  - >Can we see an indication of PLR at period longer than 1000 days ?
- Science cases
  - >Stellar physics (Pulsation mechanism)
  - >Galactic kinematics

Distances estimation
(1) Phase-lag method（Engels et al. 2015）
(2) Kinematic distance



Figure：Period vs Absolute magnitude in NIR（2.18μm）and MIR（11.6μm）. OH/IR星について、中間赤外（11.6um）の絶対等級が−13等あたりに集中する。距離は運動学的方法とPhas-lag法によって求められた値を使用。運動学的距離の遠近不定性は解いてない。

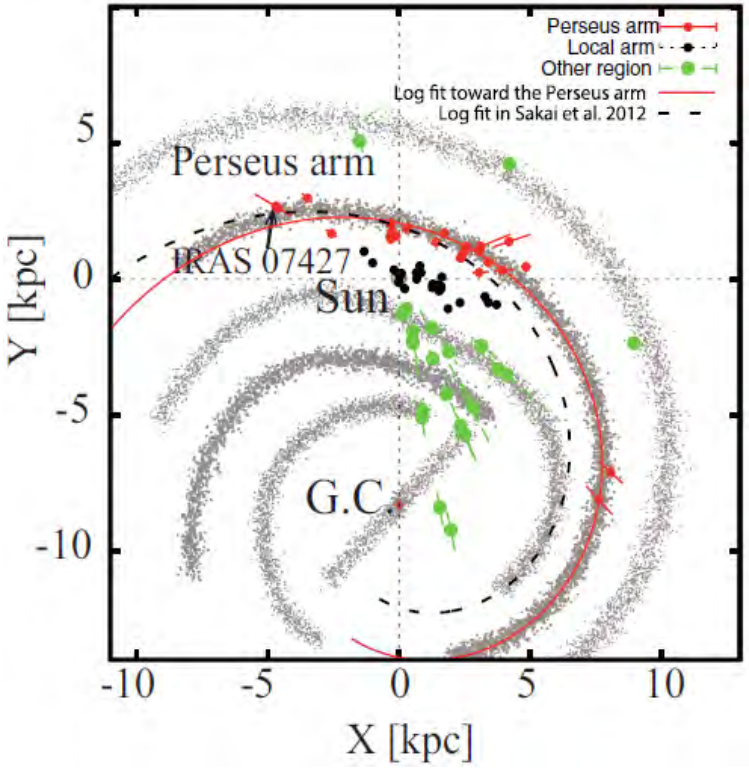
Astrometric VLBI and Galactic kinematics
最近のVLBI位置天文と銀河系動力学

SFRs and RSG are used as probes to study the Galactic kinematics.

・・・They are very young, ~10^6 yeas.
Probes with various ages are needed.



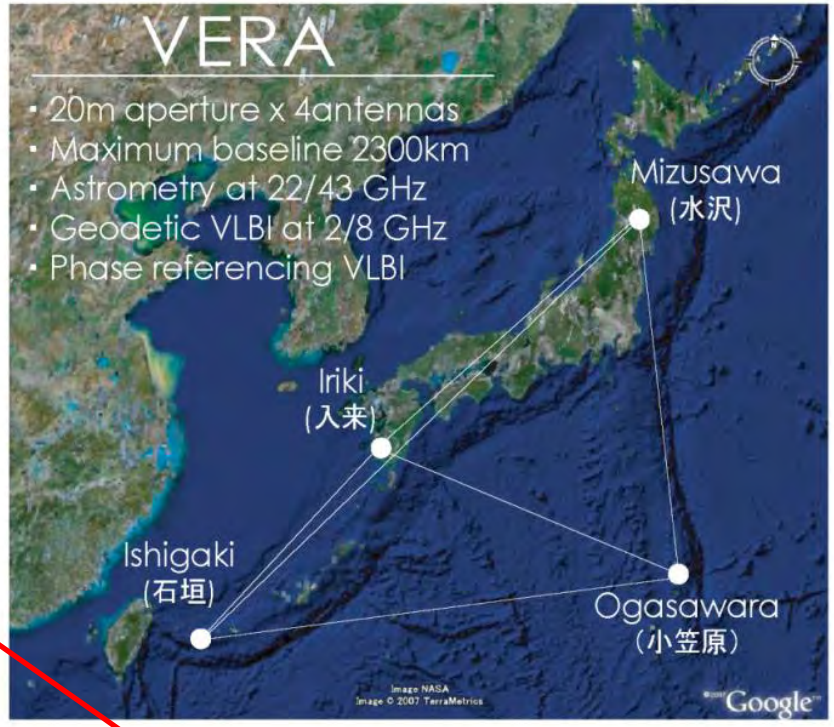
Sakai et al. 2015



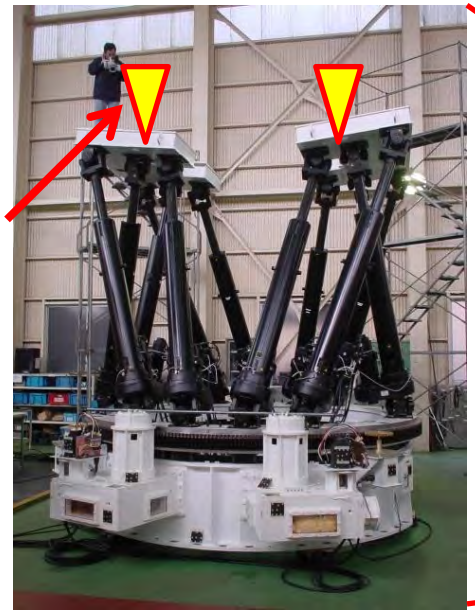
⇨ Ages of the OH/IR stars with P>1000 d can be a important property for study of the Galactic kinematics.

VERA : **V**LBI **E**xploration of **R**adio **A**strometry

- 20 m aperture x 4 antennas
- Maximum baseline 2300 km
  → Beam size ~1 mas @22GHz
- Freq. 22/43 GHz
  22GHz (H2O maser)
  43GHz (SiO maser)
- Phase referencing VLBI



Receiver





Dual receiver system for simultaneous detection of Maser and QSO

OH/IR stars as new probes of the Galactic kinematics study
銀河動力学研究の新たなプローブとなり得るか

- SFRs and RSG are used as probes to study the Galactic kinematics.
- Simulation study gives a new picture of the Galactic arm.
  - Old and new models -
  "Density wave" & "Non-steady spiral arms"
- Probes with various ages are needed.
- Period=1000 days→ M:~4M⊙（Feast 2008）
  → Age : 10^8 - 10^9 yr

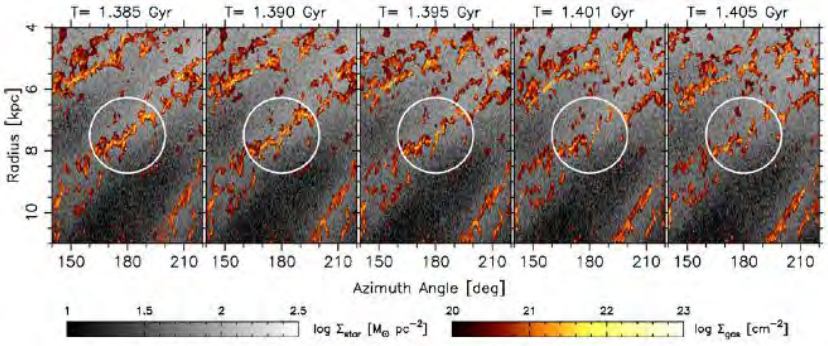


Figure 10. Same as Figure 8, but for snapshots every 5 Myr after $t = 1.385$ Gyr.
(An animation of this figure is available in the online journal.)

Wada et al. 2011

- Calibration of mid-infrared PLR of OH/IR stars.
- Astrometry: VLBI（OH/SiO/H2O masers）

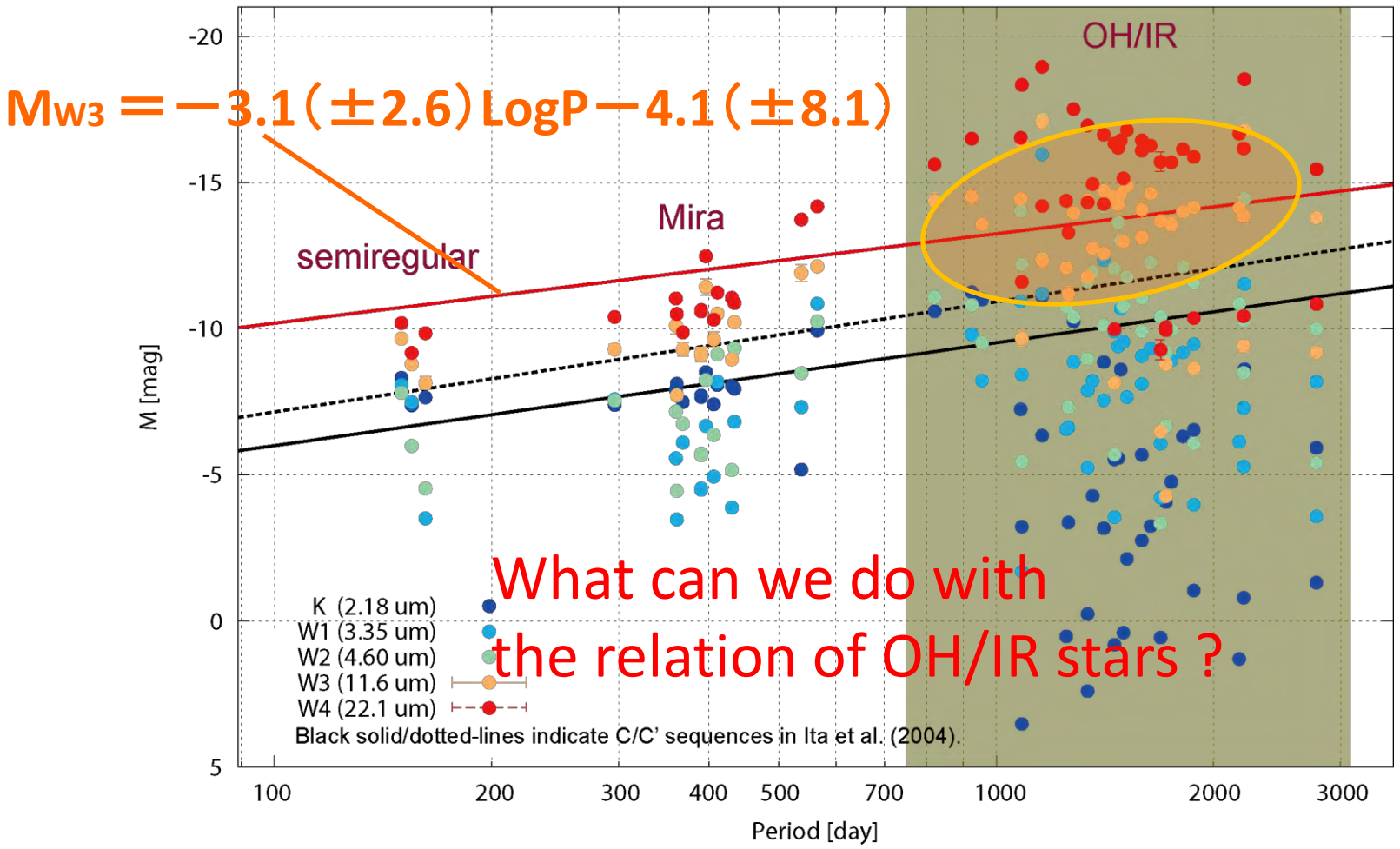
Age		Physics	Target
New	~10^6 yr	Spiral arm	SRF, Giants
⇕	~10^8 yr	Bifurcating/ merging arms	Heavy OH/IR star ?
Old	~10^9 yr	Relaxed system	Mira

Model		Obs.
✔	⇔	✔
✔	⇔	No
✔	⇔	✔

Period luminosity relation of OH/IR stars（P > 1000d）

Mid-IR absolute magnitudes of OH/IR stars with known distances.

Distances from { (1) Phase-lag method（Engels et al. 2015）
(2) Kinematic distance



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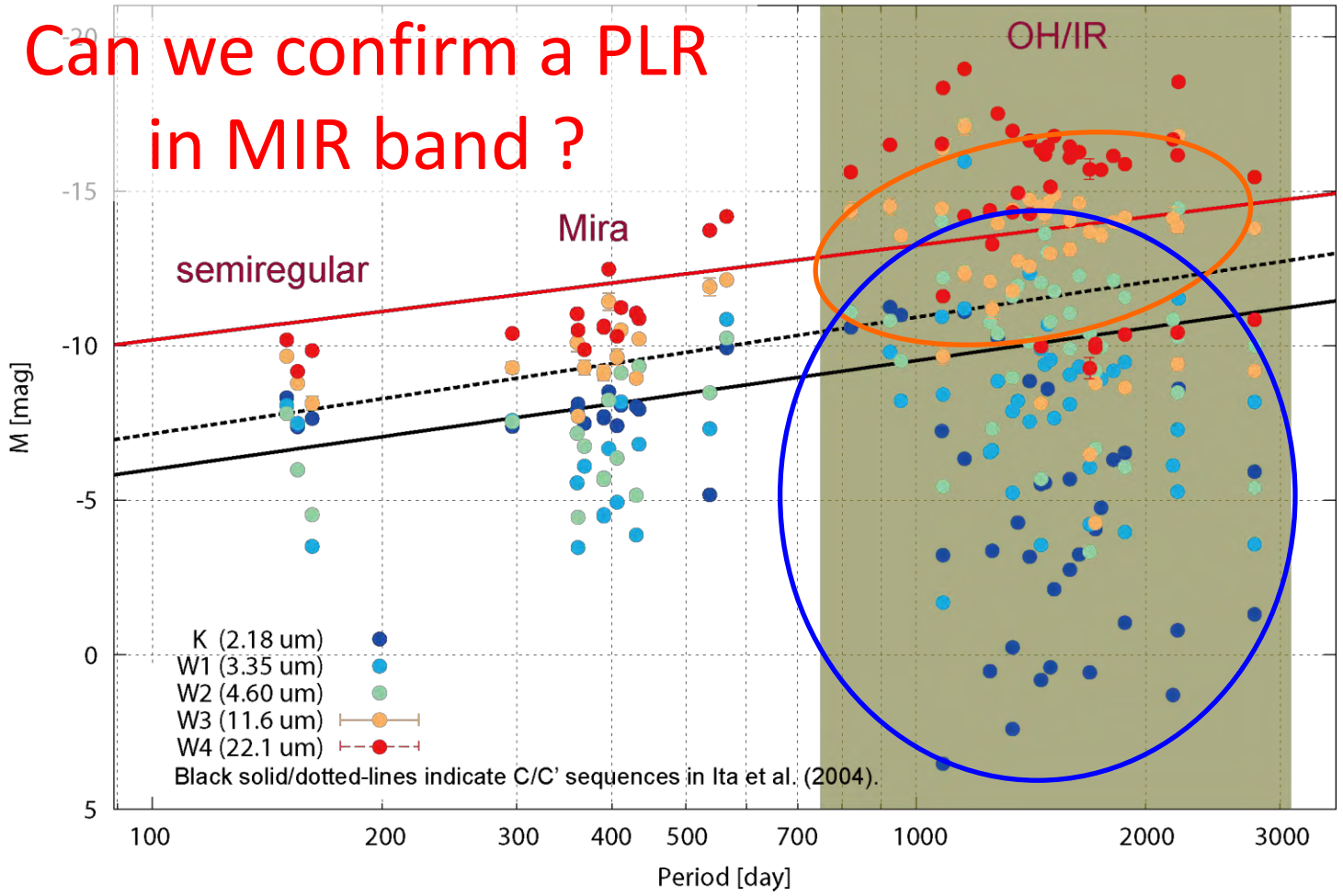


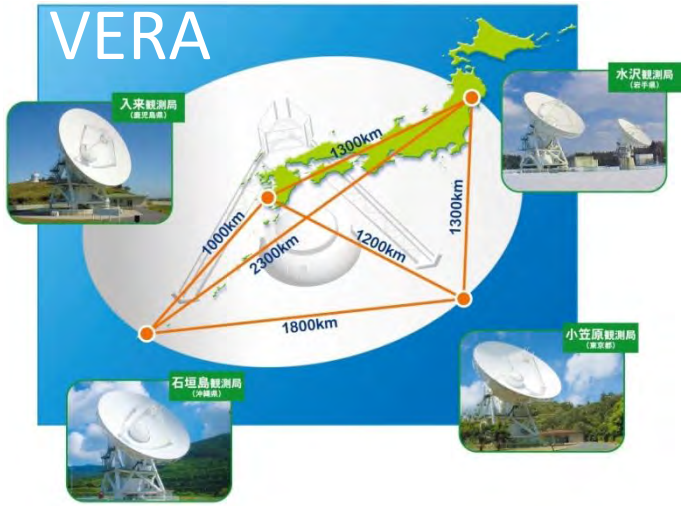
Astrometric VLBI observation of the Galactic LPVs; Miras and OH/IR stars

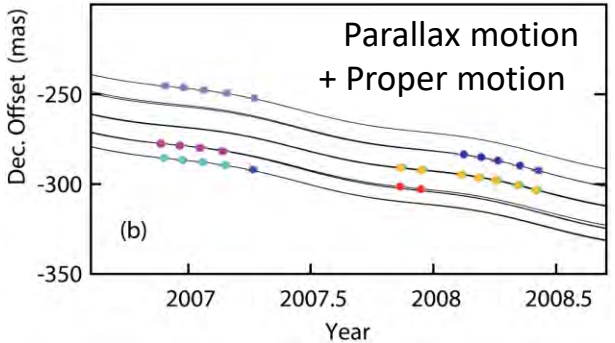
Akiharu Nakagawa (Kagoshima University),

Tomoharu Kurayama (Teikyo University of Science), Gabor Orosz , Ross A. Burns (JIVE), Tomoaki Oyama, Takumi Nagayama, Junichi Baba (NAOJ), Takashi Miyata (TAO, The University of Tokyo), Mamoru Sekido (NICT), Keichi Wada (Kagoshima University)

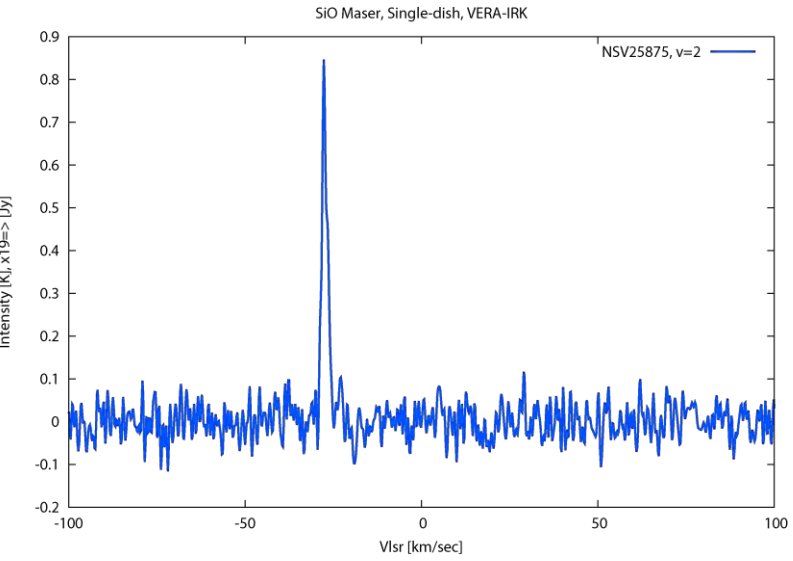
1. Astrometric observations of Galactic Miras with VERA array
   - VLBI observation (VERA 4 antennas)
   - Period-Mk relation
   - H2O maser circumstellar motion

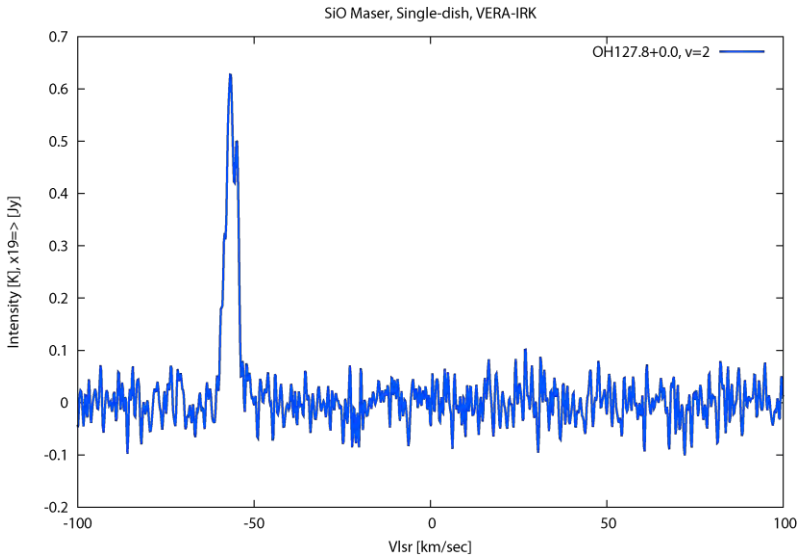
2. OH/IR stars with P>1000 days
   - Period-M relation in MIR
   - As a new probe for the Galactic kinematics ?
   - Astrometric VLBI will starts using VERA (SiO)

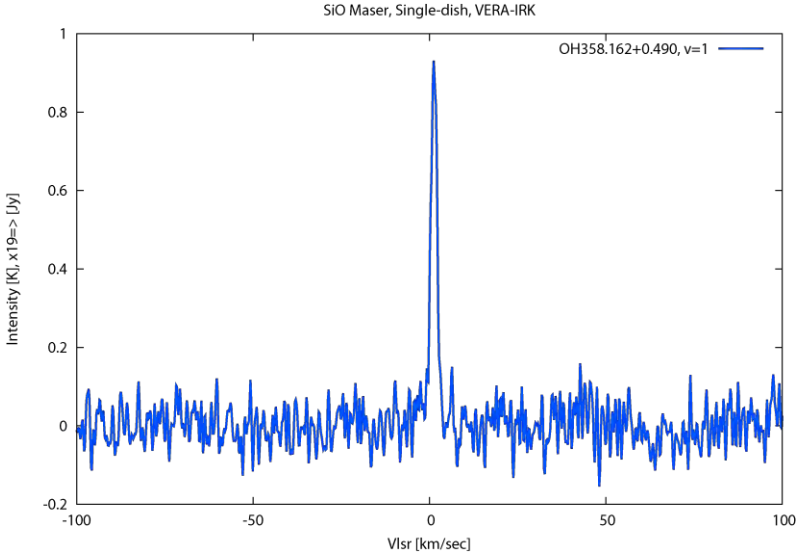


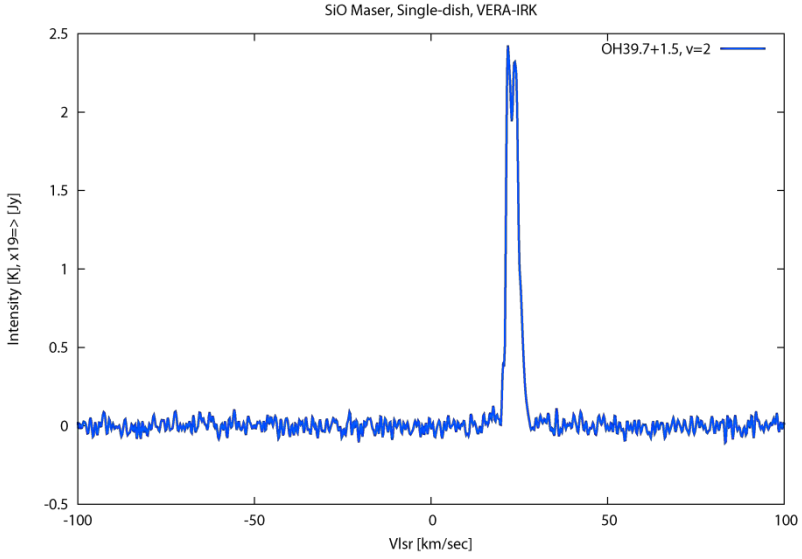


This work is supported by JSPS KAKENHI Grant Number JP16K05306.


SiO Maser, Single-dish, VERA-IRK
NSV25875, v=2
Intensity [K], x19=> [Jy]
VIsr [km/sec]

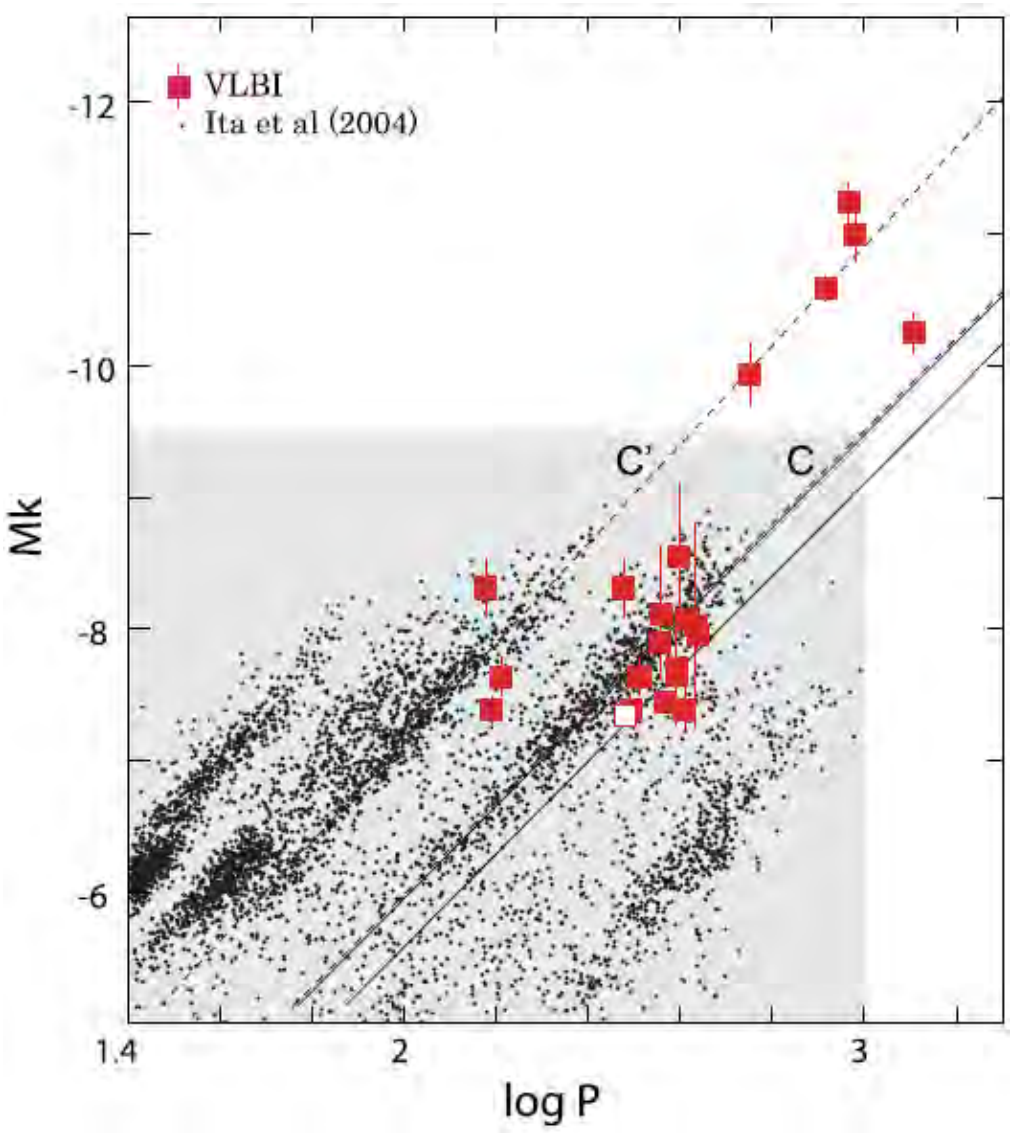

SiO Maser, Single-dish, VERA-IRK
OH127.8+0.0, v=2
Intensity [K], x19=> [Jy]
VIsr [km/sec]


SiO Maser, Single-dish, VERA-IRK
OH358.162+0.490, v=1
Intensity [K], x19=> [Jy]
VIsr [km/sec]


SiO Maser, Single-dish, VERA-IRK
OH39.7+1.5, v=2
Intensity [K], x19=> [Jy]
VIsr [km/sec]

AGB star distances from VLBI astrometry

Source	eference Parallax,mK)
RW Lep	am14, a
S Crt	ak08, a
RX Boo	am12, b
T UMa	prep., a
Y Lib	prep., a
R UMa	ak16, d
SY Aql	prep., a
R Cnc	prep., a
W Hya	le03, c
S CrB	le07, c
T Lep	ak14, c
R Aqr	am10, c
R Aqr	in14, c
RR Aql	le07, c
U Her	le07, c
SY Scl	yu11, b
R Cas	le03, c
U Lyn	am15, a
OH231.	prep.
UX Cyg	ur05, a
S Per	sa10, b
PZ Cas	us13, b
VY CM	no08, b
NML C	na12, a

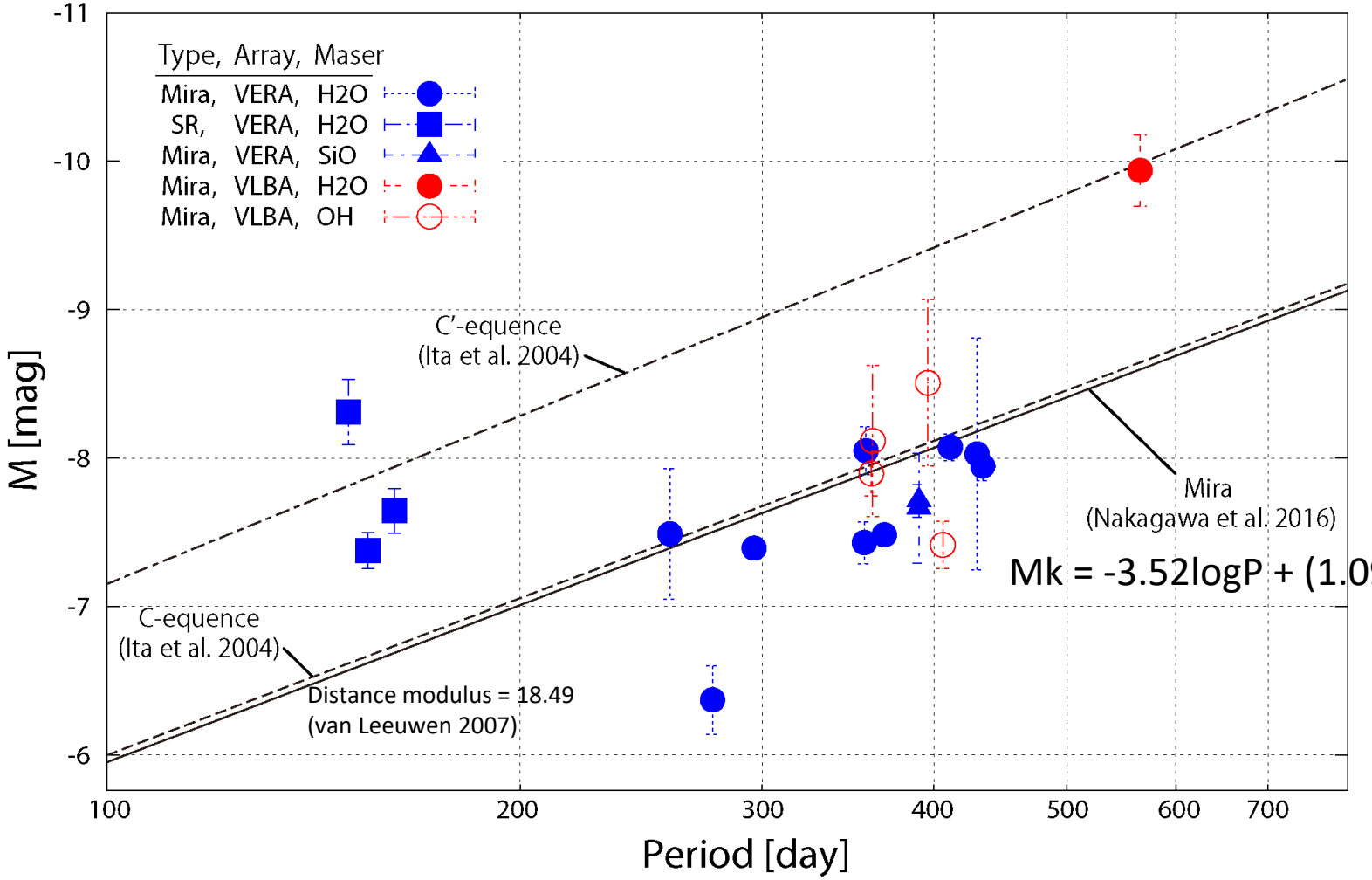


P-L relation of the Galactic LPVs
(Nakagawa et al. 2016)

Distance modulus = 18.49 (van Leeuwen 2007) is assumed for LMC stars.

Period vs Mk relation of Mira and SR

Mira と Semiregular の周期光度関係

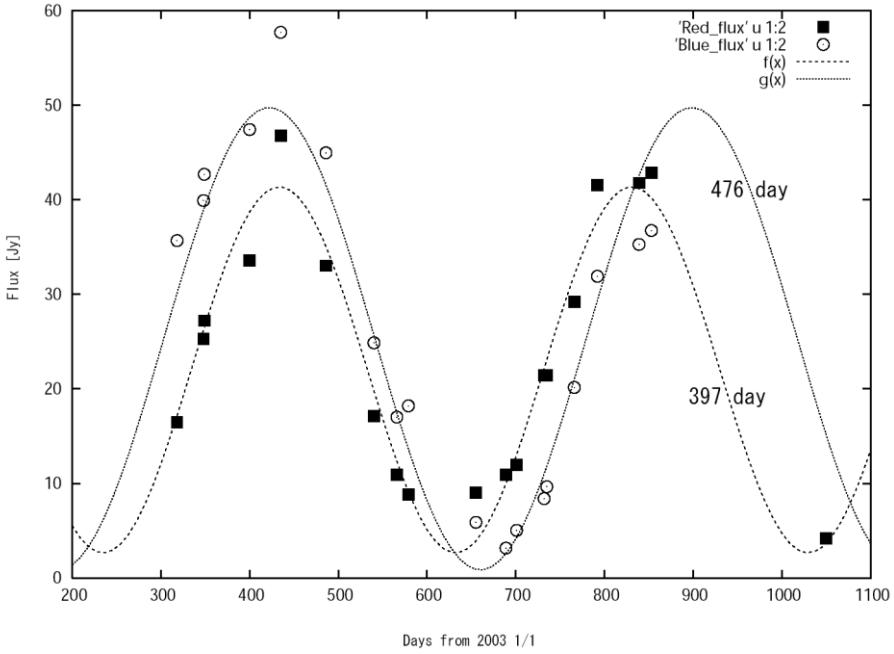


More sources are needed to solve a zero-point with better accuracy.

Results of Single-dish monitoring at VERA Iriki station

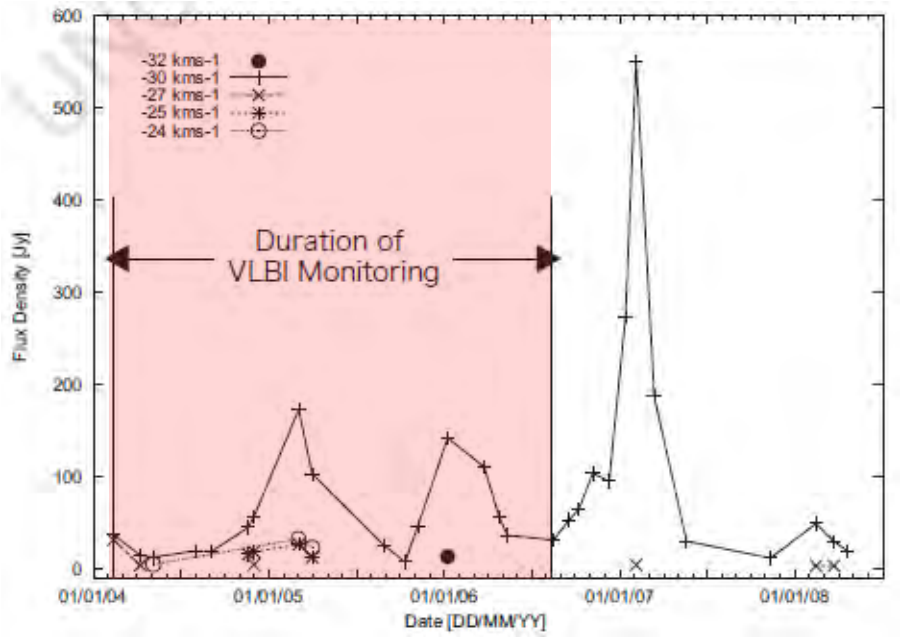
- ~40 Galactic LPV targets
- Long term monitoring of H2O masers (2003～)
- Interval ~1 month

AP Lyn



Two different velocity components show periodic variation.

T Lep

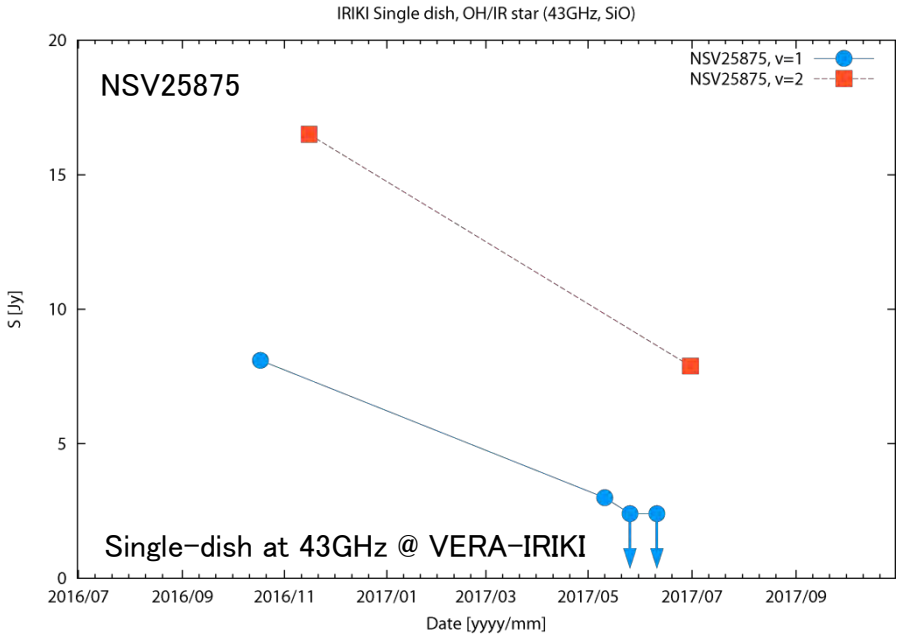


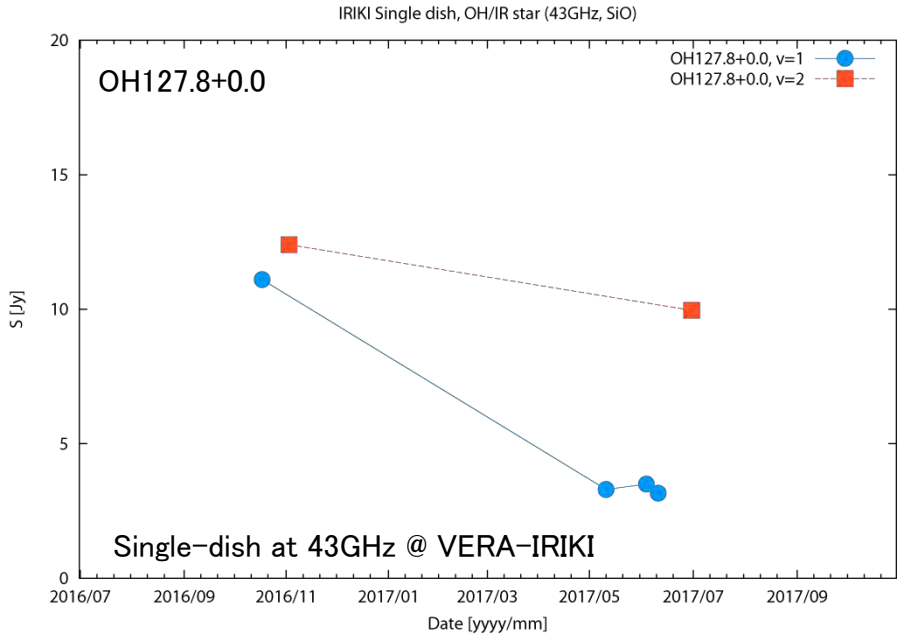
Red square = VLBI monitoring term

43GHz single-dish observation of NSV25875 and OH127.8+0.0

We are conducting single-dish monitoring of ~1500 OH/IR stars with VERA IRIKI station.

・SiO maser (43GHz) light curves of two OH/IR stars.

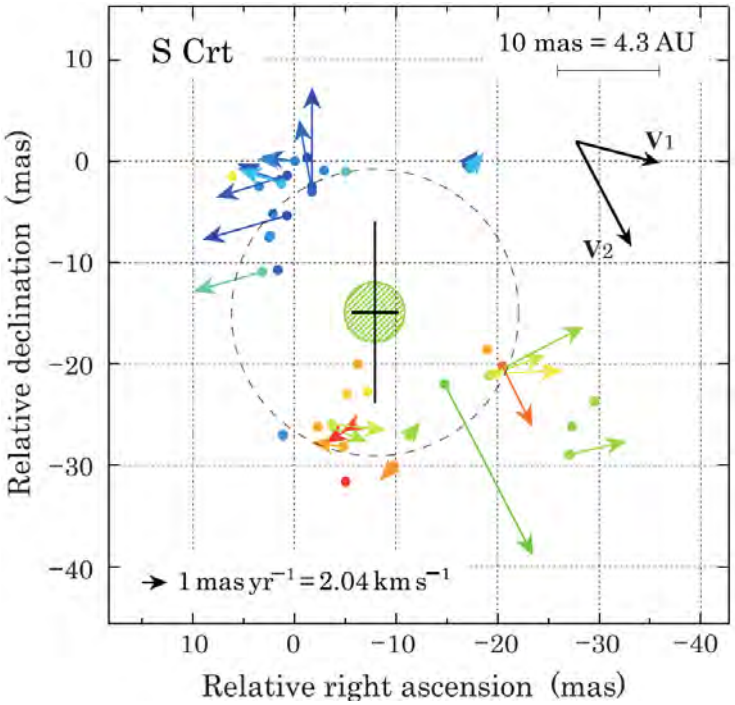




Kinematics of circumstellar matter
星周物質の運動

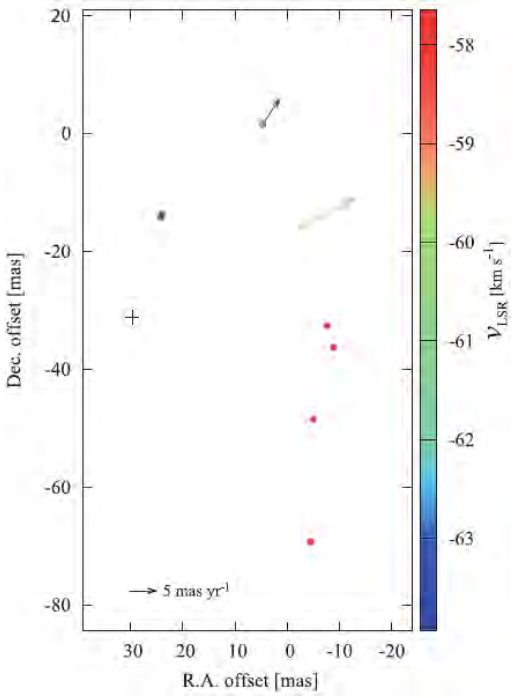
Maser distribution ...

Symmetric



S Crt (SR variable) Nakagawa et al. 2008

Asymmetric



RW Lep (SR) Kamezaki et al. 2014

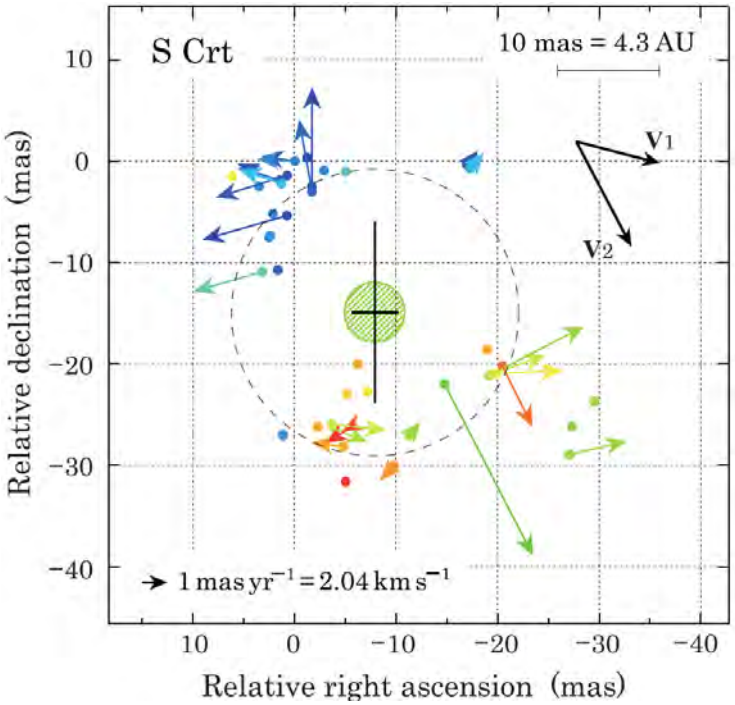
We solve circumstellar motion using VLBI measurements itself.

Assumption : $\sum \mu_{\text{internal}} = 0$

Kinematics of circumstellar matter
星周物質の運動

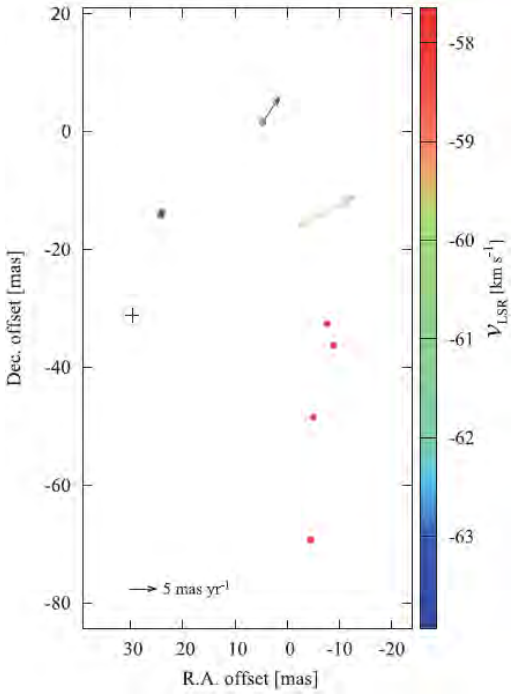
Maser distribution ...

Symmetric



S Crt (SR variable) Nakagawa et al. 2008

Asymmetric



RW Lep (SR) Kamezaki et al. 2014

It is difficult to derive a reliable picture of the kinematics of circumstellar matter.

Kinematics of circumstellar matter
星周物質の運動

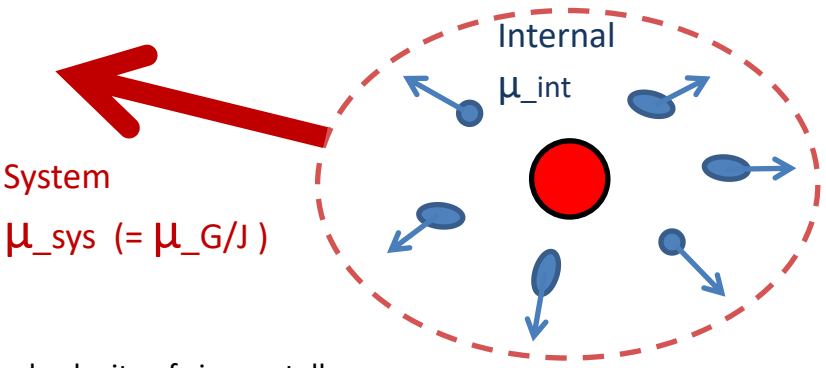
→ Combine VLBI motions of each maser spot
with proper motion obtained from Gaia/JASMINE

- Circumstellar kinematics using VLBI needs assumptions .
- High accuracy of proper motion of each maser spot are available from VLBI
- Difference between "Gaia/JASMINE" and "VERA" give circumstellar (internal) motion of masers

Circumstellar motion of masers μ_{int}

$$\mu_{VERA} = \mu_{sys} + \mu_{int}$$
$$-) \ \mu_{G/J}^{※} = \mu_{sys}$$
$$\mu_{VERA} - \mu_{G/J} = \mu_{int}$$

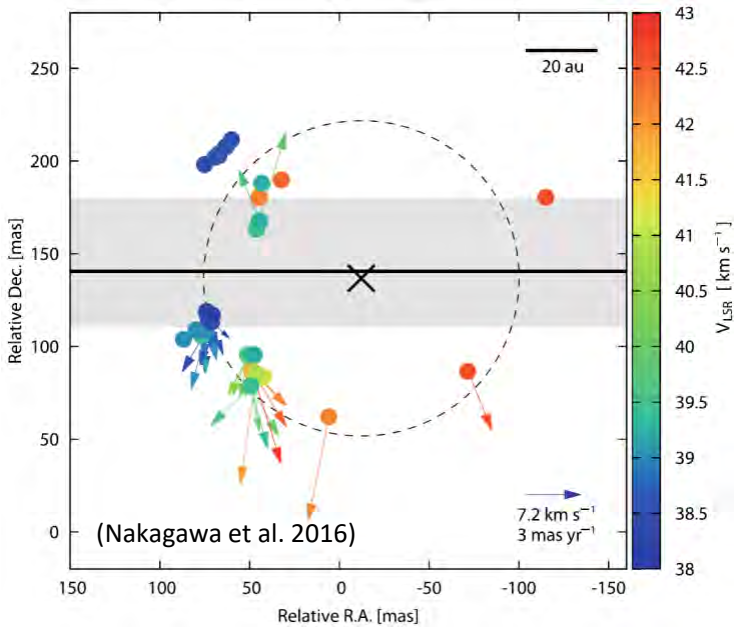
※$\mu_{G/J} = \mu_{Gaia/JSAMINE}$



Typical velocity of circumstellar maser
7 km/sec → Angular velocity mas/yr
3.0 mas/yr@ 500pc, 1.5 mas/yr @ 1kpc, 1.0 mas/yr @ 1.5kpc

Circumstellar kinematic of R UMa

$\mu_{VERA} - \mu_{HIPPARCOS}$



Error estimation of kinematic distance
運動学的距離推定法の誤差推定

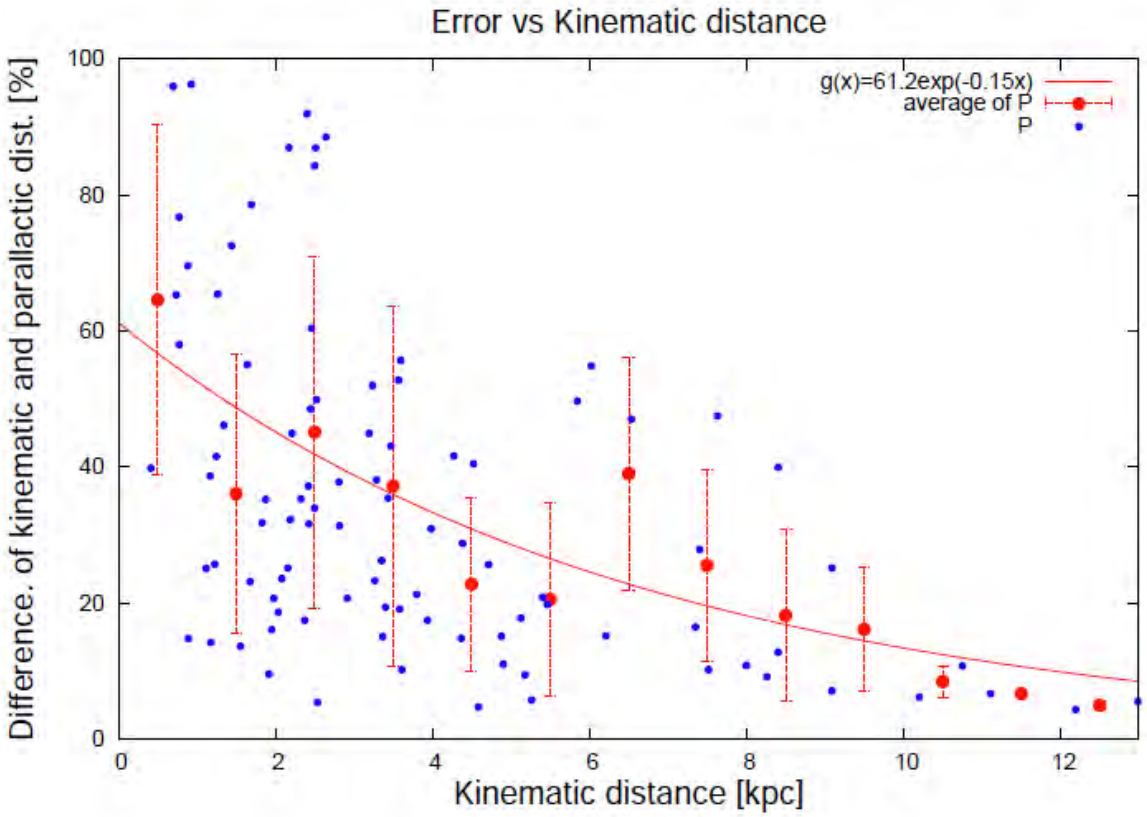
Error estimation from from three point of views

（1）σ_1 : Difference between parallactic and kinematic distances

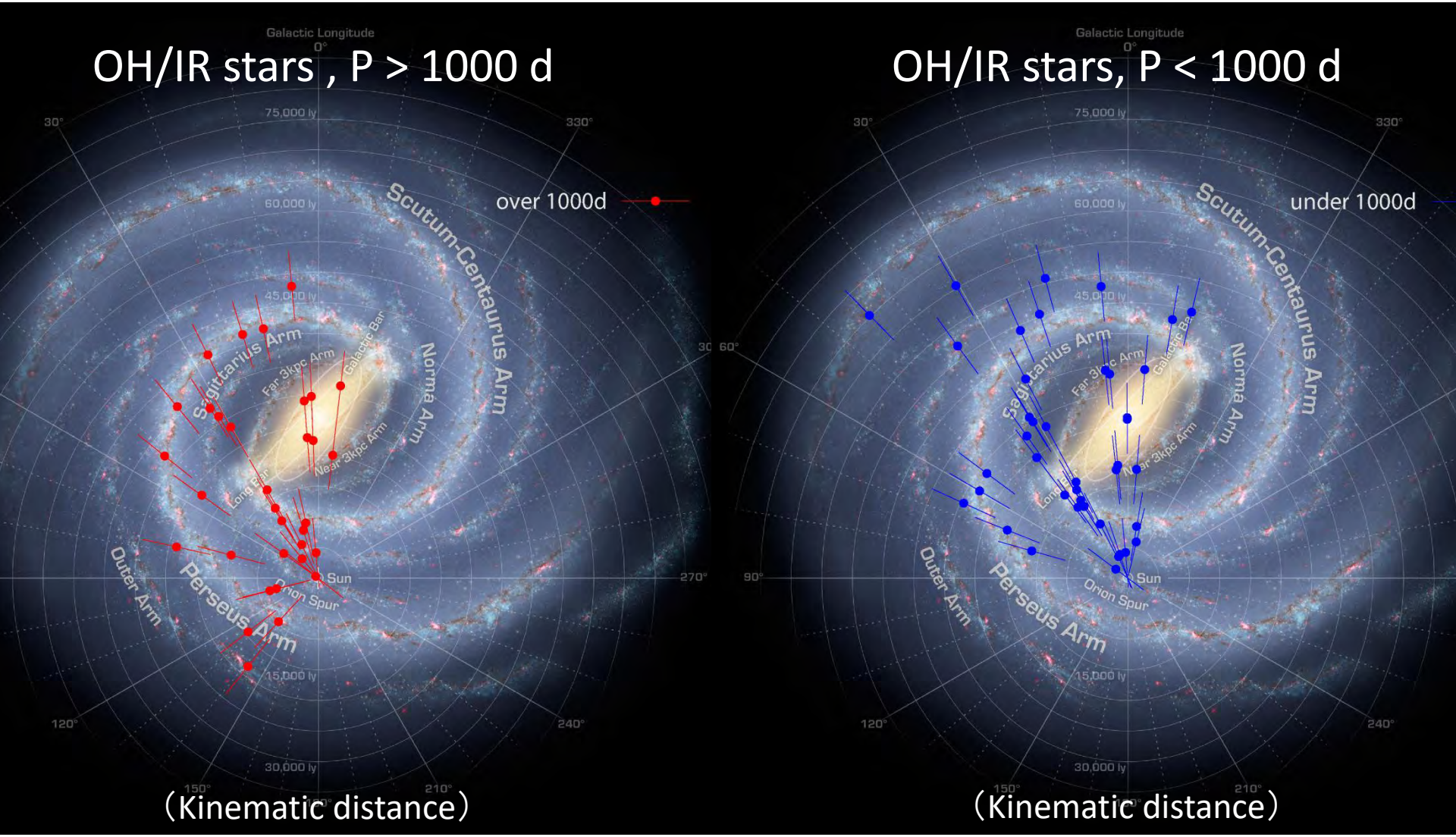
（2）σ_2 : Galactic constants

（3）σ_3 : Radial velocity (Error and line width)

$$\sigma = \sqrt{\sigma 1^2 + \sigma 2^2 + \sigma 3^2}$$



- All sources
- Averaged in 1kpc division


OH/IR stars , P > 1000 d
Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
over 1000d
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°
（Kinematic distance）
OH/IR stars, P < 1000 d
Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
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under 1000d
Scutum-Centaurus Arm
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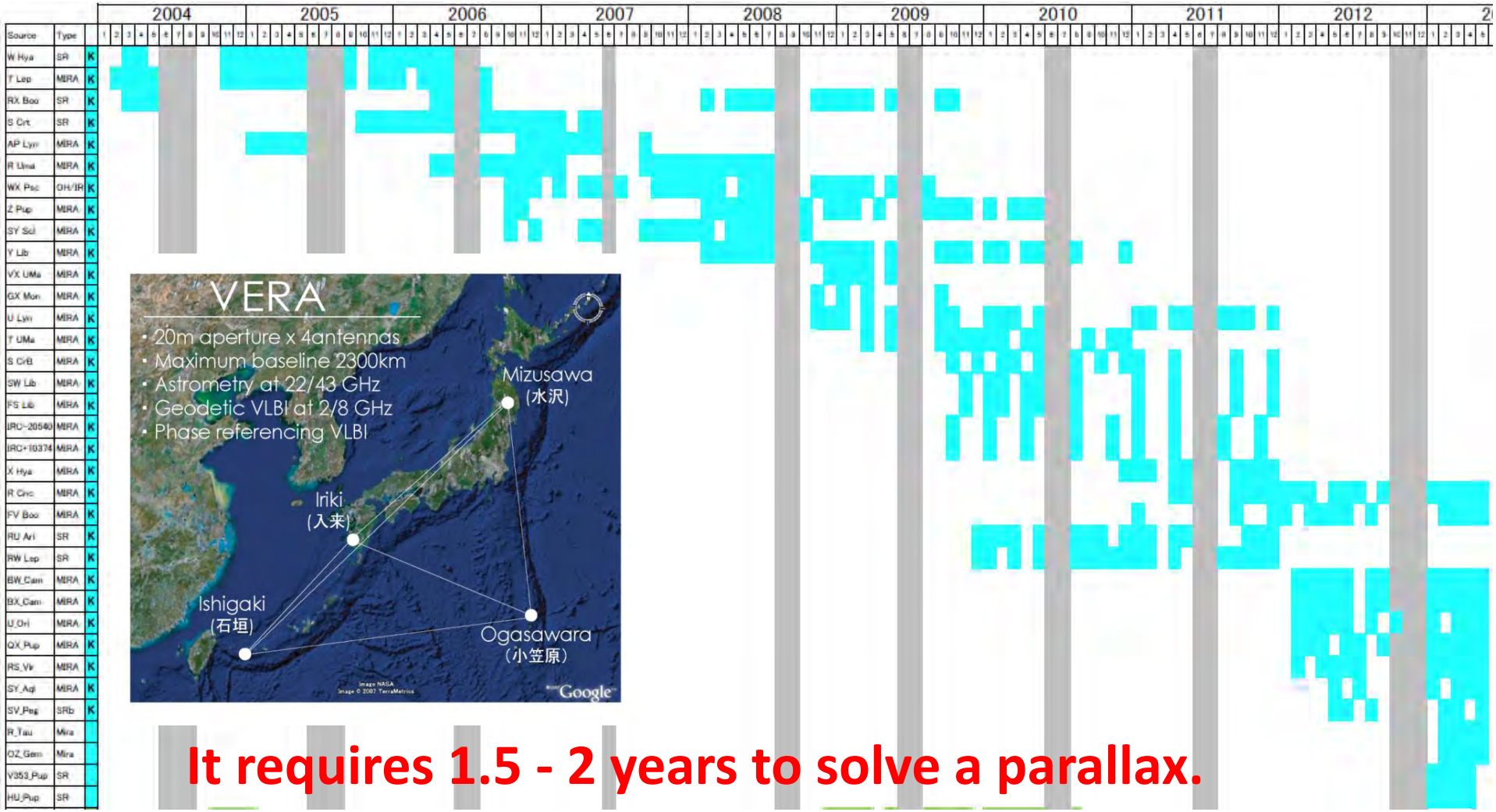
Near 3kpc Arm
Outer Arm
Perseus Arm
Sun
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°
（Kinematic distance）

VLBI monitoring observations with VERA

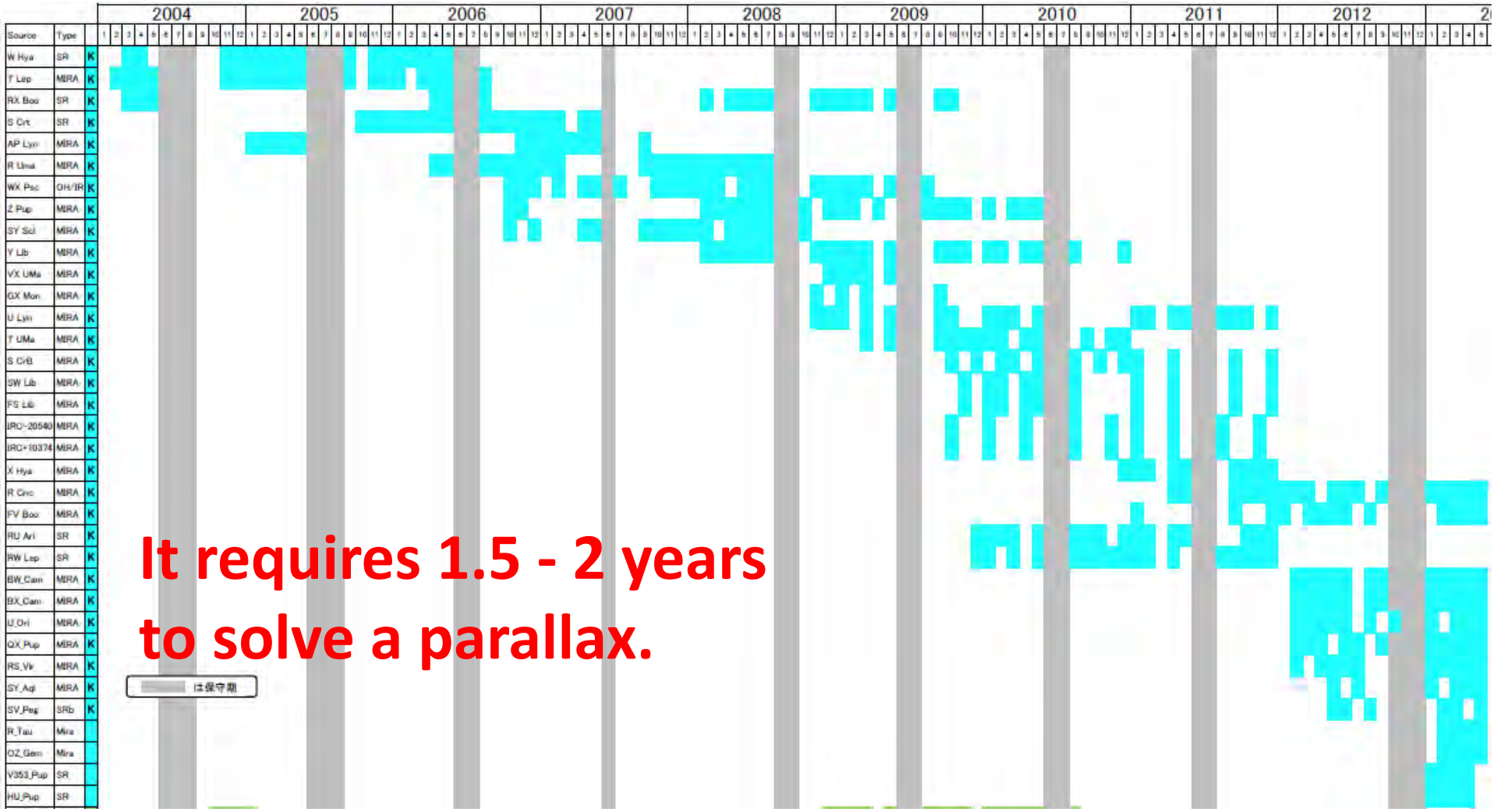
- Phase referencing observation of H2O maser at 22 GHz
- ~40 Galactic LPVs were observed with VERA



It requires 1.5 - 2 years to solve a parallax.

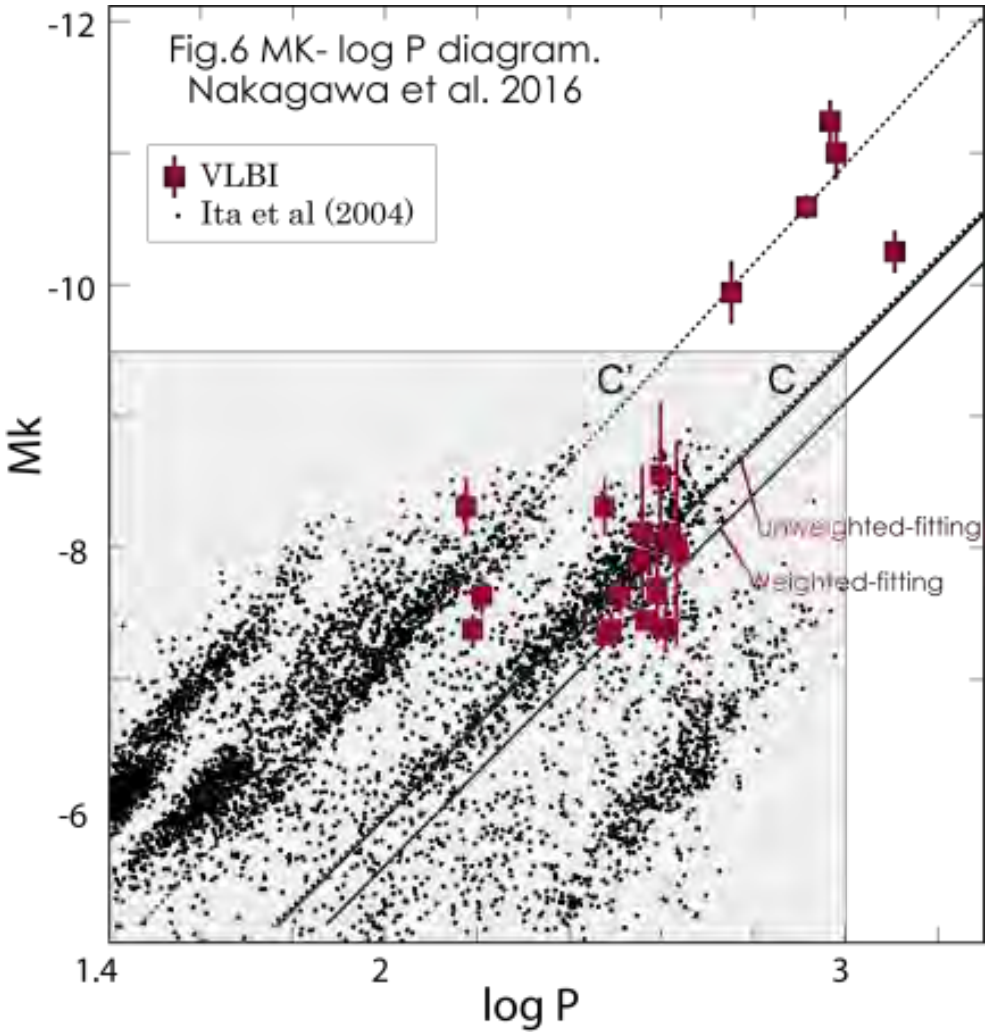
VLBI monitoring observations with VERA

- Phase referencing observation of H2O maser at 22 GHz
- ~40 Galactic LPVs were observed with VERA



AGB star distances from VLBI astrometry

Source	eference
	Parallax,mK)
RW Lep	am14, a
S Crt	ak08, a
RX Boo	am12, b
T UMa	prep., a
Y Lib	prep., a
R UMa	ak16, d
SY Aql	prep., a
R Cnc	prep., a
W Hya	le03, c
S CrB	le07, c
T Lep	ak14, c
R Aqr	am10, c
R Aqr	in14, c
RR Aql	le07, c
U Her	le07, c
SY Scl	yu11, b
R Cas	le03, c
U Lyn	am15, a
OH231.8+	prep.
UX Cyg	ur05, a
S Per	sa10, b
PZ Cas	us13, b
VY CMa	no08, b
NML Cyg	na12, a
(	



P-L relation of the Galactic LPVs
(Nakagawa et al. 2016)

Distance modulus = 18.49 (van Leeuwen 2007) is assumed for LMC stars.



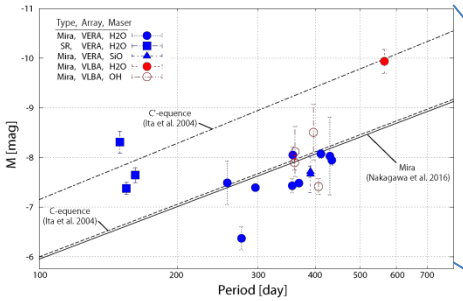
Name	HIP/TYC	$\Delta\alpha*$ [mas]	$\Delta\delta$ [mas]	$\Delta\varpi$ [mas]	$\Delta\mu_{\alpha*}$ [mas yr^{-1}]	$\Delta\mu_{\delta}$ [mas yr^{-1}]	Reference (VLBI)
S Persei	11093	+4.969 ± 8.474	−10.626 ± 8.497	−0.001 ± 0.720	−0.153 ± 0.242	−0.225 ± 0.211	Asaki et al. (2010)
LS I +61 303	12469	−28.882 ± 6.726	+22.324 ± 7.611	+0.188 ± 0.650	−1.322 ± 0.373	+1.133 ± 0.383	Lestrade et al. (1999)
HII 174	1803-0008-1			−0.024 ± 0.302	−0.130 ± 0.918	−0.395 ± 0.492	Melis et al. (2014)
HD 283447	19762	+8.447 ± 0.759	−36.971 ± 0.482	−0.460 ± 0.495	−8.998 ± 0.170	+0.011 ± 0.111	Torres et al. (2012)
T Tau	20390	+231.577 ± 1.280	+514.096 ± 0.545	+0.291 ± 0.309	+7.600 ± 0.169	−12.339 ± 0.095	Loinard et al. (2007)
T Lep	23636			−0.843 ± 0.759	−4.395 ± 0.502	+1.668 ± 0.791	Nakagawa et al. (2014)
3C273	60936	+0.912 ± 1.474	+0.819 ± 1.961	−0.140 ± 0.377	−0.384 ± 0.443	+0.111 ± 0.288	Ma et al. (2009)
σ^2 CrB	79607	−12.772 ± 1.142	−5.524 ± 1.491	+0.104 ± 0.913	−0.471 ± 0.065	−0.009 ± 0.086	Lestrade et al. (1999)
Cyg X-1	98298	−0.378 ± 0.444	−0.648 ± 0.732	−0.310 ± 0.250	+0.015 ± 0.086	+0.034 ± 0.139	Reid et al. (2011)
HD 199178	103144	−4.246 ± 8.859	+6.620 ± 9.330	+0.358 ± 0.474	−0.170 ± 0.409	+0.349 ± 0.431	Lestrade et al. (1999)
AR Lac	109303	−4.324 ± 2.945	−0.975 ± 4.398	−0.332 ± 0.510	−0.220 ± 0.127	−0.082 ± 0.191	Lestrade et al. (1999)
IM Peg	112997	+0.503 ± 1.029	−0.014 ± 1.046	−0.039 ± 0.372	+0.001 ± 0.093	−0.110 ± 0.096	Bartel et al. (2015)
PZ Cas	117078	−29.855 ± 3.349	−9.348 ± 4.012	+0.438 ± 0.558	−0.275 ± 0.205	−0.236 ± 0.303	Kusuno et al. (2013)

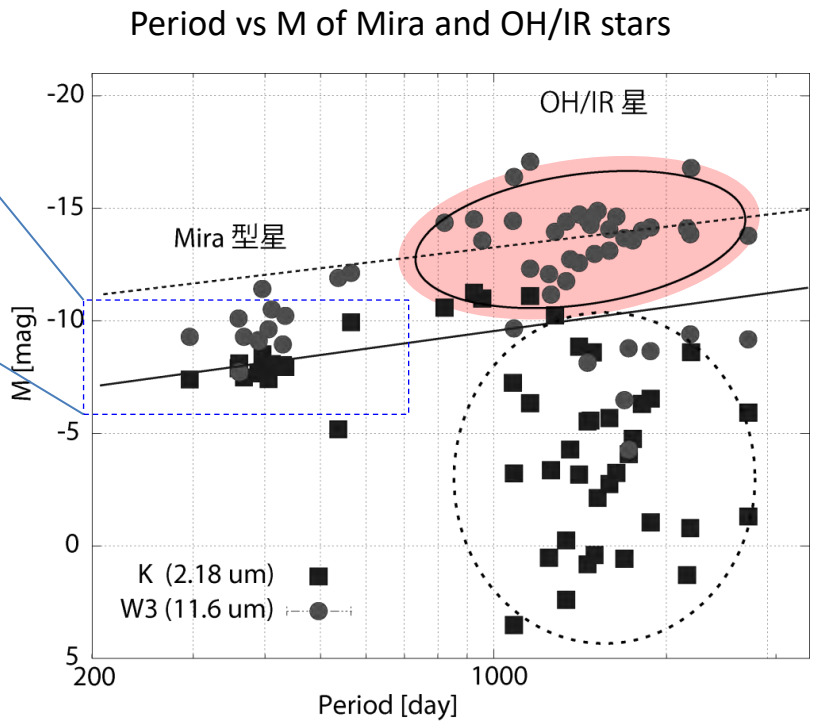
Lindegren et al. 2016

Parallax in Gaia DR1

	VERA	Gaia
・HU Pup	---	-0.15±0.57（400%）
・T UMa	0.96±0.19（20%）	1.07±0.94（88%）

Extension of observational study to longer pulsation period
より長い周期を持つ変光星の観測的研究





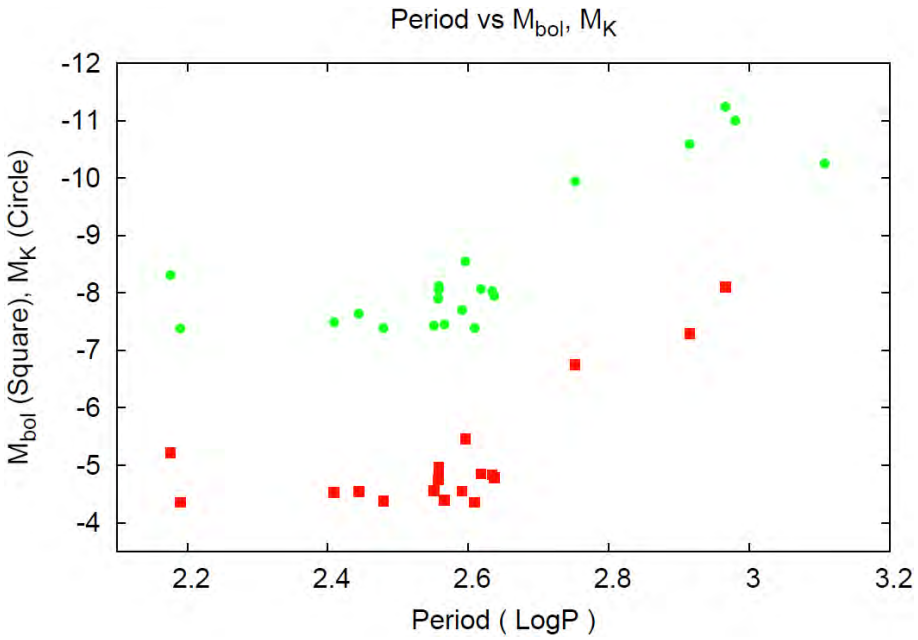
- Study of the PLR at Period >1000 days
  - Absolute MIR magnitudes of ~20 OH/IR stars with estimated distances
  - Can we see an indication of PLR at period longer than 1000 days ?

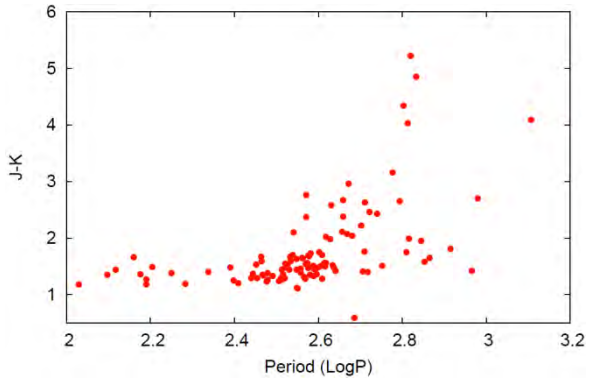
- Science cases
  - Stellar physics (Pulsation mechanism)
  - Galactic kinematics

Figure : Period vs Absolute magnitude in NIR（2.18μm）and MIR（11.6μm）. OH/IR星について、中間赤外（11.6um）の絶対等級が−13等あたりに集中する。距離は運動学的方法とPhas-lag法によって求められた値を使用。運動学的距離の遠近不定性は解いてない。

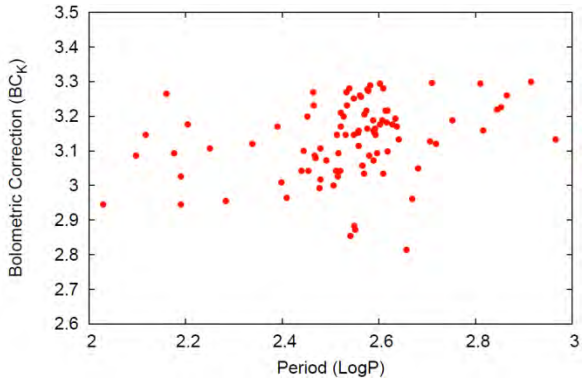
Distances estimation
(1) Phase-lag method（Engels et al. 2015）
(2) Kinematic distance

Bolometric magnitude

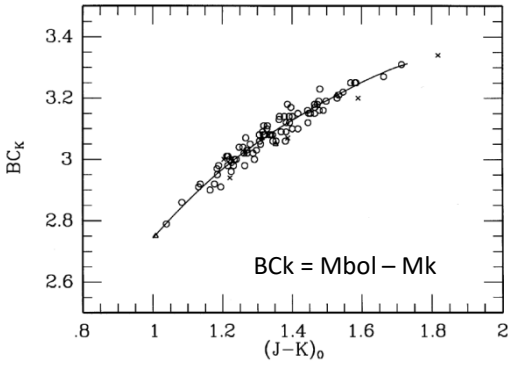




Period-Color(J-K)



Period-BCk



Bolometric correction function
1.0 < J−K < 1.75 (Whitelock et al. 2000)

RSG on P-Mk plane

Kiss et al. 2006

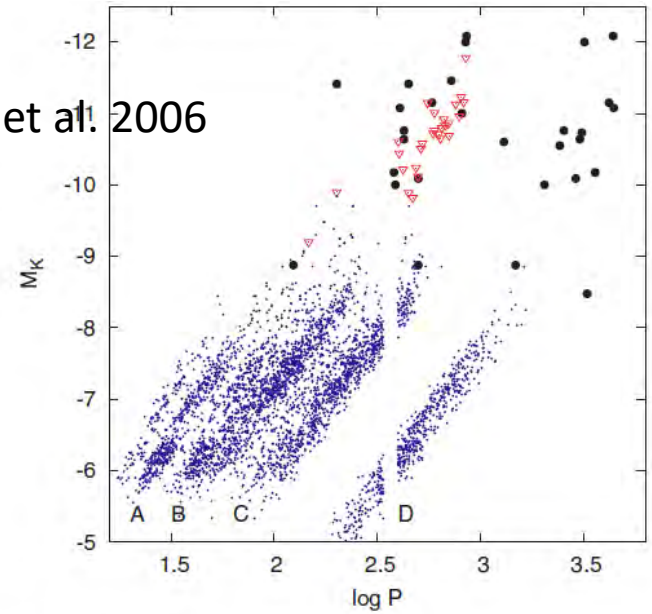
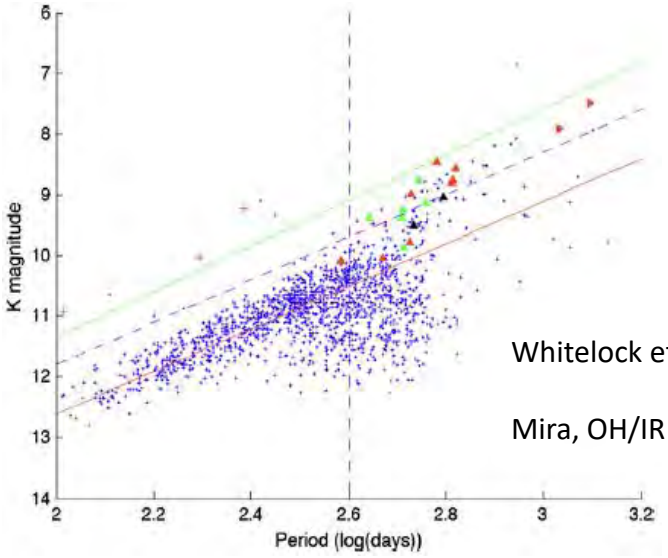


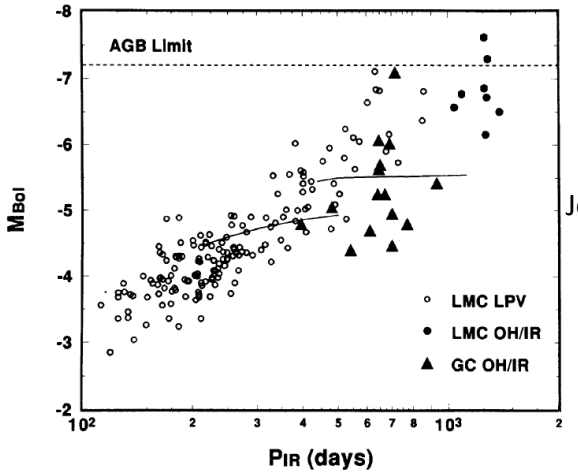
Figure 7. Period–*K*-band magnitude relations for the galactic sample (black circles), RSG variables in the LMC (red triangles) and red giant variables from the MACHO data base (blue dots, data taken from Derekas et al. 2006, assuming $\mu_{LMC} = 18.50$). Labels A, B, C and D were adopted from Wood (2000).

- K-band PL(K) -relation



Whitelock et al. (2012)

Mira, OH/IR in LMC



Jones et al. 1994

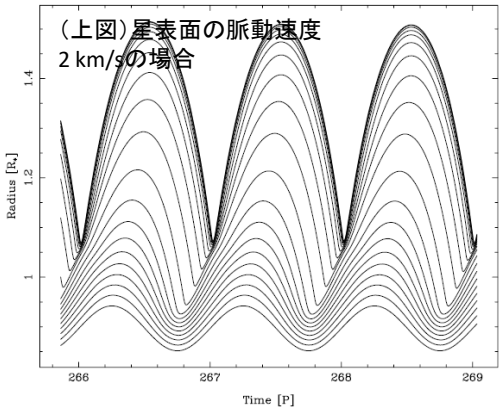
Understanding accurate circumstellar kinematics

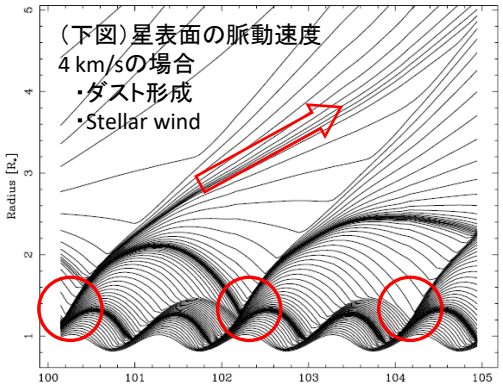
Scientific issues of the Galactic LPVs

- Mass　1～3 Msun　（1～8 Msun）
- Pulsation : Period　= 100～1000 d
- Mira variables
  - Distribution : Thick disk
  - Large velocity dispersion compared to components in thick disk

- Stellar physics
  - Period-luminosity relation
  - Pulsation mode
  - Mass ross ratio
  - Dust formation
  - Stellar wind
  - Asymmetry of CSM
  - Binarity and morphology

- Galactic dynamics
  - Systemic proper motion
  - P ~ 300 day : Thick disk
  - P ~> 800 days : Thin disk, Arm

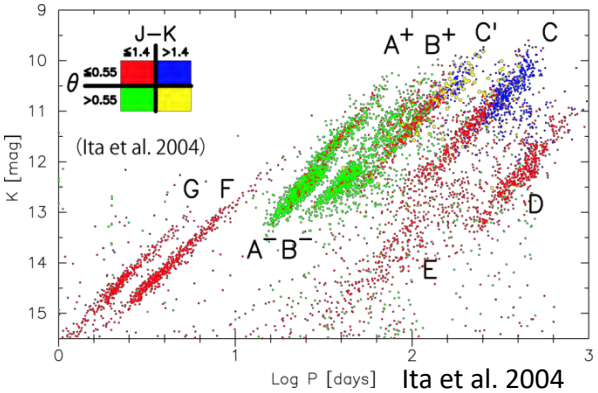




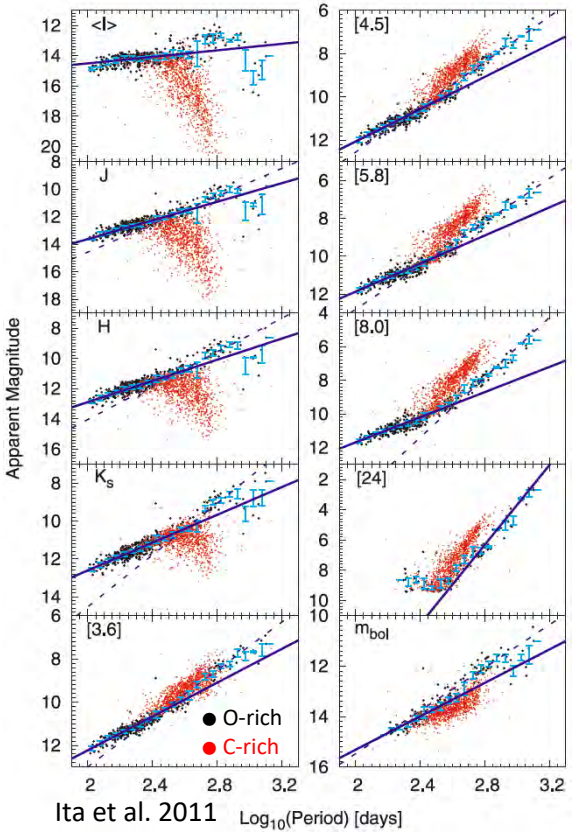
Hofner et al. 2003

＜Period-luminosity relation＞

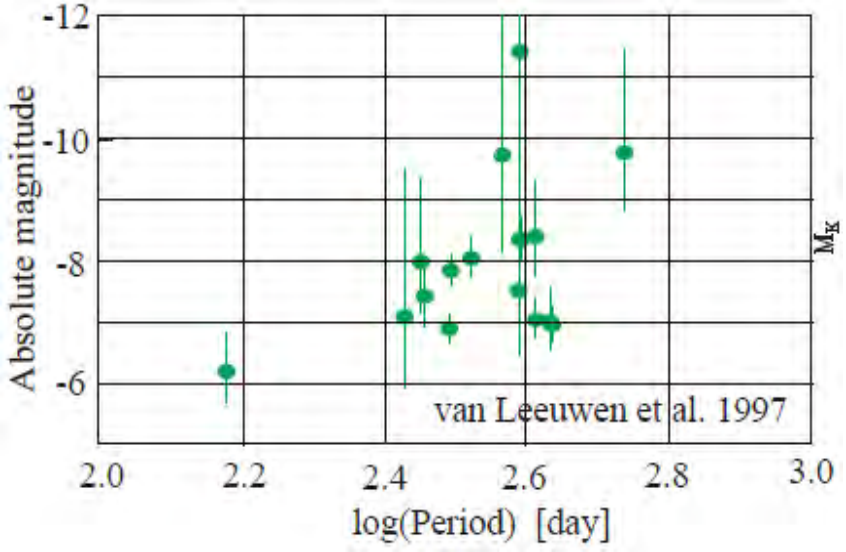
- PLR break at logP~2.6
- Hot bottom burning (HBB) in O-rich Mira
- HBB : M > 3 Msun with Z_{LMC}
- Lower mass limit to activate HBB depends on metallicity.
- Circumstellar extinction
- Re-radiation from dust shell at longer period



Ita et al. 2004



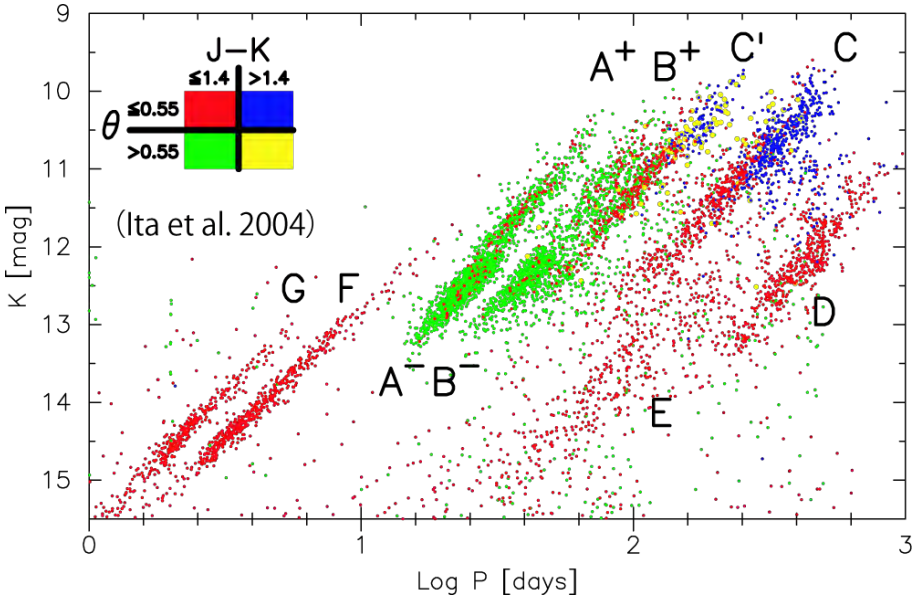
Ita et al. 2011



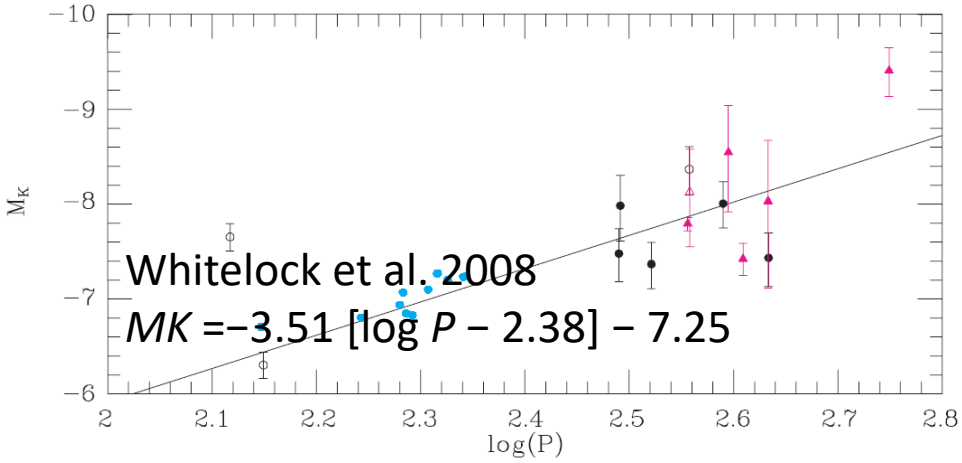
Distance Error [%]	σ Mk [mag]
1	0.02
2	0.04
3	0.07
4	0.09
5	0.11
6	0.13
7	0.15
8	0.17
9	0.20
10	0.22
11	0.24
12	0.26
13	0.28
14	0.31
15	0.33

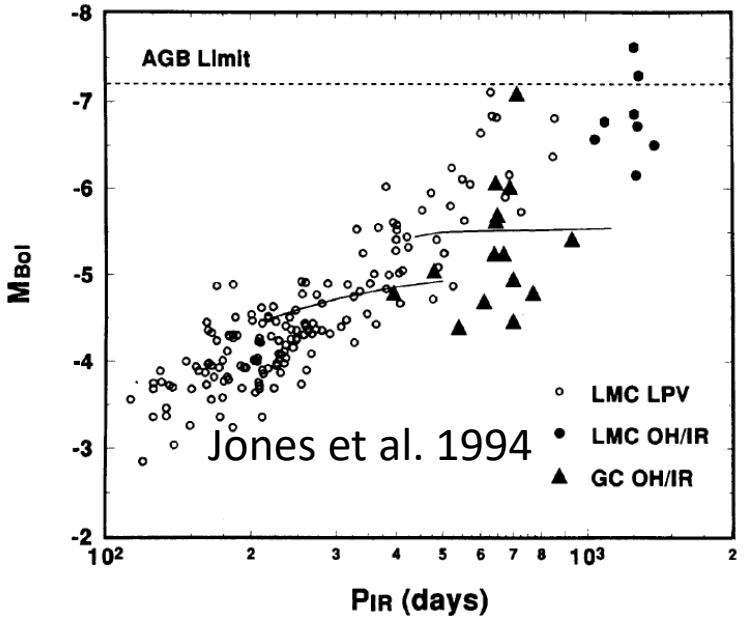
距離の精度が
等級に与える影響

波長 [um]	バンド	システム
0.3652	U	Johnson
0.4448	B	Johnson
0.5505	V	Johnson
0.902	z'	SDSS
1.215	J	2MASS
1.654	H	2MASS
2.179	K	2MASS
3.35	W1	WISE
4.29	B1	MSX
4.35	B2	MSX
4.6	W2	WISE
8.28	A	MSX
9.0	S9W	AKARI IRC
11.6	W3	WISE
12	12	IRAS
12.13	C	MSX
14.659	D	MSX
18.0	L18W	AKARI IRC
21.34	E	MSX
22.1	W4	WISE
25	25	IRAS
60	60	IRAS
65	N60	AKARI FIS
90	WIDE-S	AKARI FIS
100	100	IRAS
140	WIDE-L	AKARI FIS
160	N160	AKARI FIS



A+	Cyan	RGB variables and metal-poor and old AGB variables
A-	Yellow	Less regularly pulsating AGB variables
B-	Orange	RGB variables and metal-poor and old AGB variables
B+	Green	Less regularly pulsating AGB variables
C'	Blue	Mira variables pulsating in the first-overtone mode
C	Red	Mira variables pulsating in the fundamental mode
D	Steel-blue	Some obscured variables and unknown variables
F	Magenta	Cepheid variables pulsating in the fundamental mode
G	Purple	Cepheid variables pulsating in the first-overtone mode





Summary

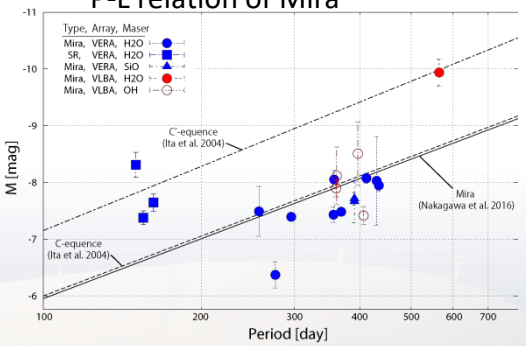
— Astrometric study of the Galactic LPVs —

Source	Type	Parallax [mas]	P [day]	LogP	mK [mag]	MK [mag]	Maser	Reference (Parallax,mK)
RW Lep	sra	1.62±0.16	150	2.176	0.639	-8.31±0.22	H2O	kam14, a
S Crt	srb	2.33±0.13	155	2.190	0.786	-7.38±0.12	H2O	nak08, a
RX Boo	srb	7.31±0.5	162	2.210	-1.96	-7.64±0.15	H2O	kam12, b
T UMa	Mi	0.96±0.15	257	2.410	2.60	-7.49±0.44	H2O	in prep., a
Y Lib	Mi	1.24±0.13	276	2.441	3.16	-6.37±0.23	H2O	in prep., a
R UMa	Mi	1.92±0.05	302	2.480	1.19	-7.39±0.06	H2O	nak16, d
SY Aql	Mi	1.10±0.07	356	2.551	2.36	-7.43±0.14	H2O	in prep., a
R Cnc	Mi	3.84±0.29	357	2.553	-0.97	-8.05±0.16	H2O	in prep., a
W Hya	sra	10.18±2.36	361	2.558	-3.16	-8.12±0.51	OH	vle03, c
S CrB	Mi	2.39±0.17	360	2.556	0.21	-7.90±0.15	OH	vle07, c
T Lep	Mi	3.06±0.04	368	2.566	0.12	-7.45±0.03	H2O	nak14, c
R Aqr	Mi	4.7±0.8	390	2.591	-1.01	-7.65±0.37	SiO	kam10, c
R Aqr	Mi	4.59±0.24	390	2.591	-1.01	-7.70±0.11	SiO	min14, c
RR Aql	Mi	1.58±0.40	396	2.598	0.46	-8.55±0.56	OH	vle07, c
U Her	Mi	3.76±0.27	406	2.609	-0.27	-7.39±0.16	OH	vle07, c
SY Scl	Mi	0.75±0.03	411	2.614	2.55	-8.07±0.09	H2O	nyu11, b
R Cas	Mi	5.67±1.95	430	2.633	-1.80	-8.03±0.78	OH	vle03, c
U Lyn	Mi	1.27±0.06	434	2.637	1.533	-7.95±0.10	H2O	kam15, a
OH231.8+4.2	OH/IR	0.55±0.05	551	2.741	---	---	H2O	in prep.
UX Cyg	Mi	0.54±0.06	565	2.752	1.40	-9.94±0.24	H2O	kur05, a
S Per	src	0.413±0.017	822	2.915	1.33	-10.59±0.09	H2O	asa10, b
PZ Cas	src	0.356±0.026	925	2.966	1.00	-11.24±0.16	H2O	kus13, b
VY CMa	src	0.88±0.08	956	2.980	-0.72	-11.00±0.20	H2O	cho08, b
NML Cyg	---	0.62±0.047	1280	3.107	0.791	-10.25±0.16	H2O	zha12, a

【 Studies with VERA】

- Phase-referencing VLBI at 22 GHz with VERA
- Parallaxes of ~15 Miras and SRs were determined
- Period-Mk relation ; Mk = -3.52logP + (1.09±0.14)

P-L relation of Mira

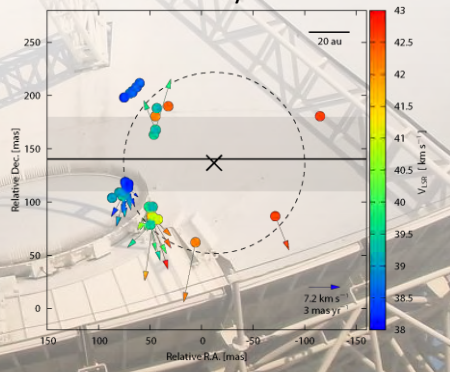


【 What can we do with astrometric satellite ? 】

- 15 Mira and SR variables for verification of astrometry
- Gaia/JASMINE can contribute to study kinematics of circumstellar matter
- OH/IR stars as a new probe of the Galactic kinematic

→ JASMINE can solve their parallax ?

Circumstellar kinematics from VLBI and Gaia/JASMINE



Mid-IR P-L relation of OH/IR stars

