Maser Astrometry

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(**N**ational **A**stronomical **R**esearch

Institute of **T**hailand) since **YESTERDAY**

11- 15 July 2022

15th EVN Symposium, Ireland

Review talk via Zoom

Today's contents

1. Basics of astrometry & Astrometric projects

- Parallax and Proper motion
- The Lutz-Kelker bias
- Atmospheric delay calibration
- VERA/VLBA BeSSeL

Lecture note by Mark J. Reid
Lutz-Kelker, 1973, PASP; Bailer-Jones 2015, PASP
Rioja & Dodson 2020, A&ARv, 28, 6
Reid & Honma 2014, ARA&A, 52, 339

2. Background and Context for each contributed talk

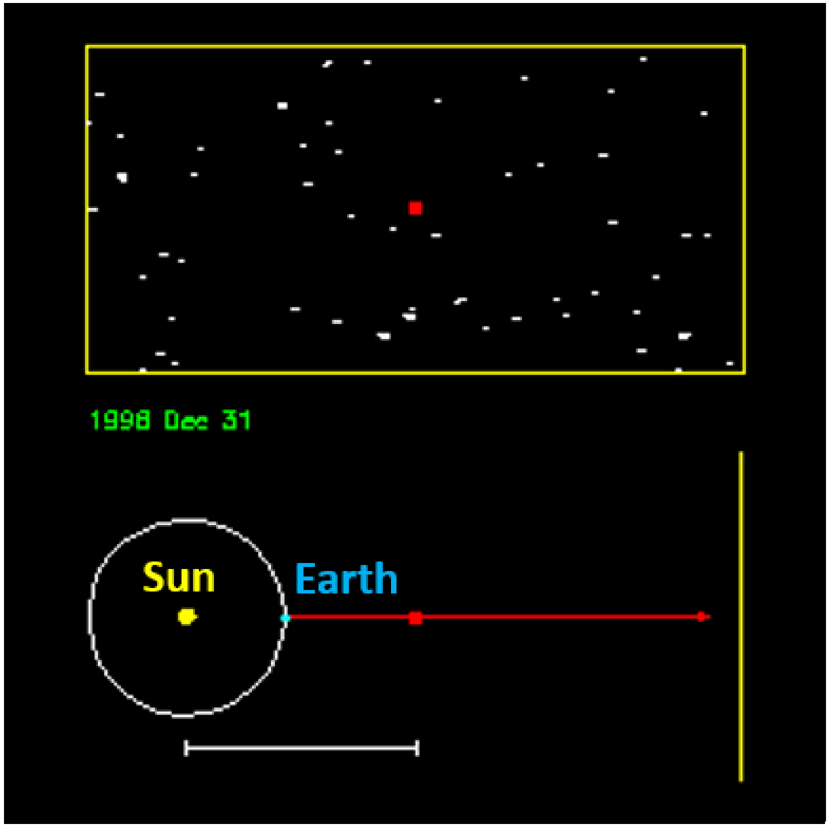
- Ultra-wide band polarimetry
- MultiView for 10 μas astrometry
- MultiView for radio star astrometry

Talk by Hagiwara-san
Hyland, et al. 2022, ApJ, 932, 52
Talk by Dr. Boven

3. Astrometric results and future prospects

- The structure of the Milky Way — Reid et al. 2019, VERA Collaboration et al. 2020
- Episodic accretion in a high-mass star formation — Burns et al. 2020, NatAs, 4, 506
- Extreme Outer Galaxy — Sun et al., 2017, Reid 2022
- Radio Astronomy Network and Geodesy for Development at NARIT (RANGD)

Parallax and Proper motion



Trigonometric parallax (π in arcsec)
➔ *Apparent motion*
➔ Distance info ($d \sim 1/\pi$ in units of pc)

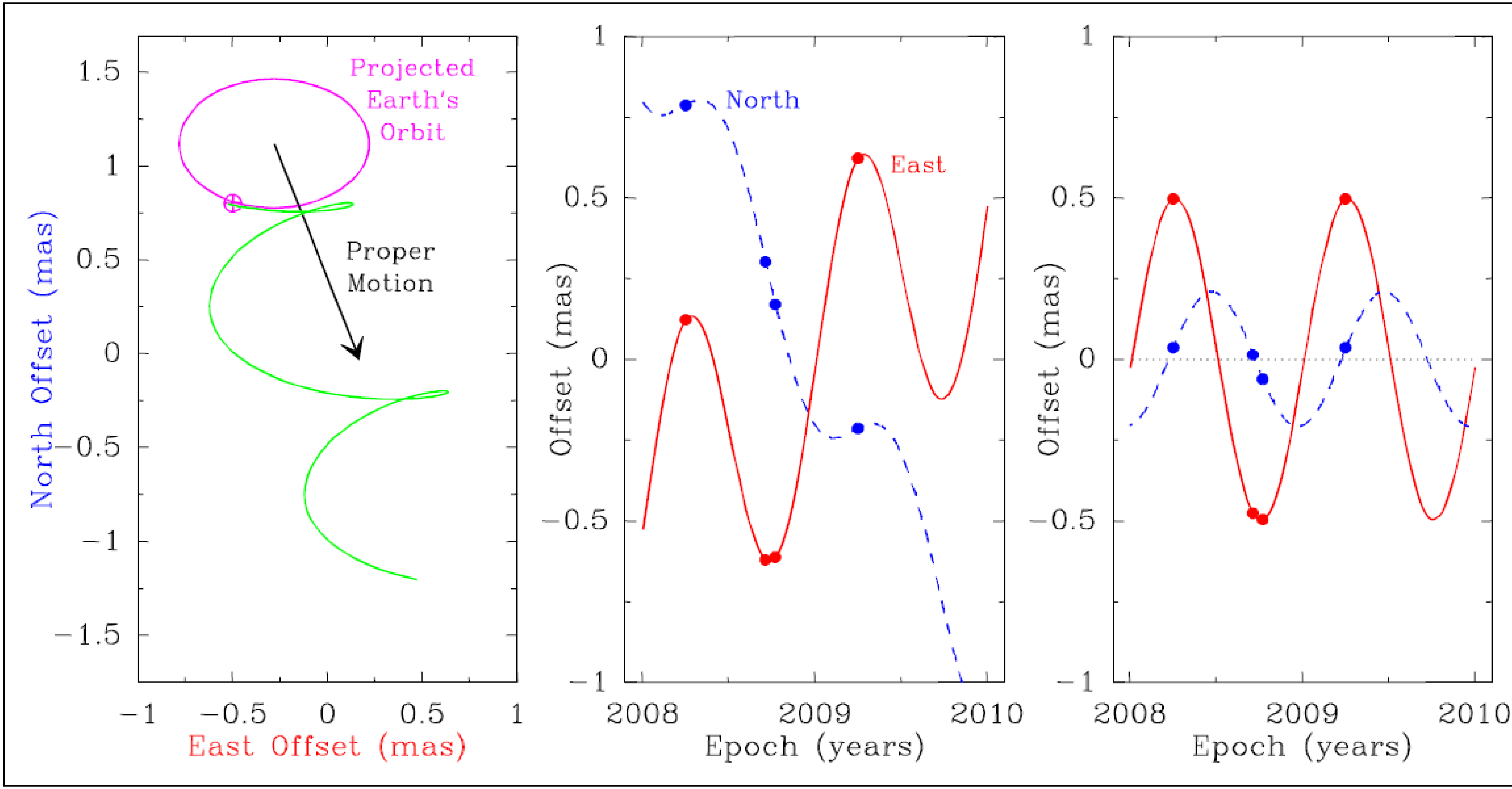
Proper motion (μ in arcsec/year)
➔ *Intrinsic motion*
➔ Kinematics info

The parallax and proper motion can be measured with astrometry

(c) R. Pogge, OSU

(c) Steve, Quirk

Parallax and Proper motion



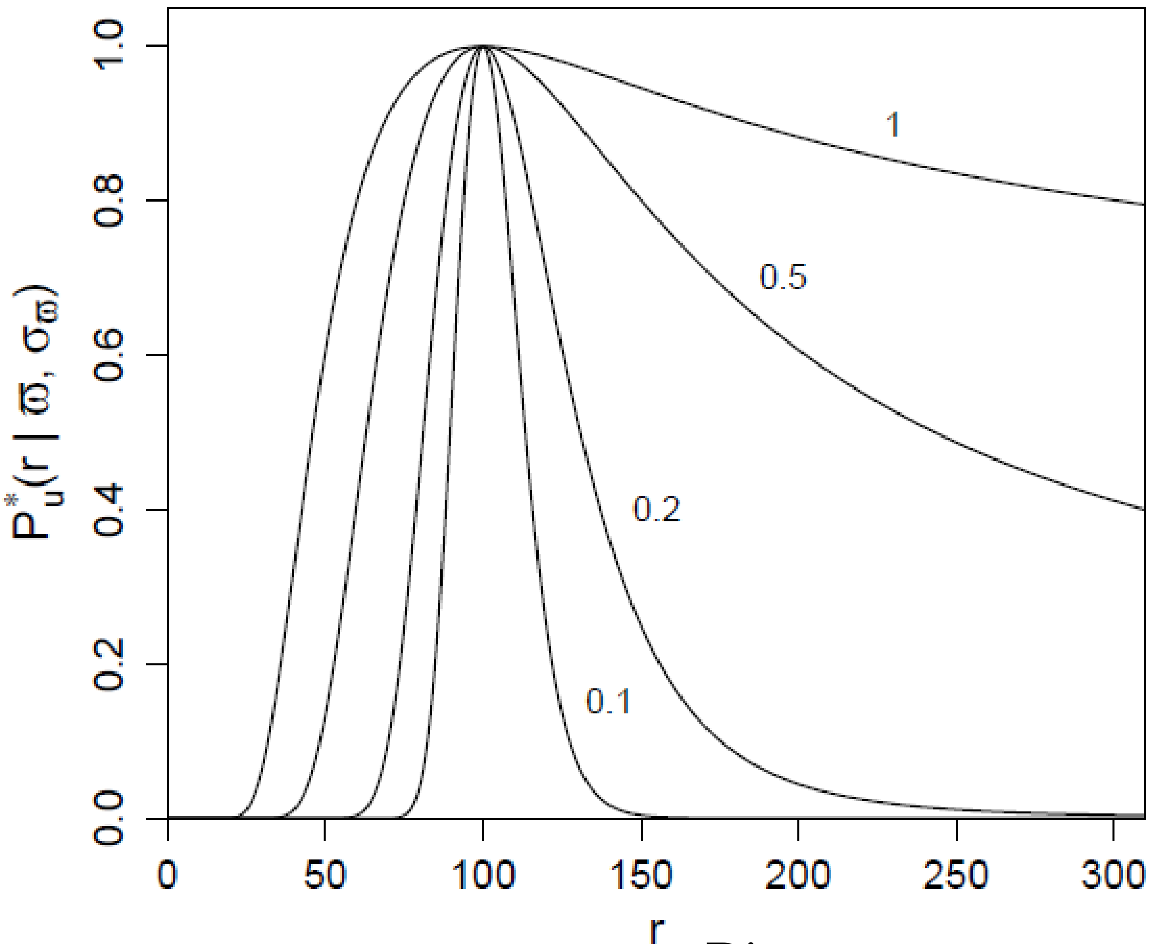
Can separate parallax from proper motion with well selected observations

(c) Lecture slide by Mark J. Reid (CfA)

The Lutz-Kelker bias

Posterior ~ Prior (flat) * Likelihood = Likelihood

- Parallax ω = 1 / 100
- Fractional parallax error: f = 0.1, 0.2, 0.5, 1.0
- Prior: Uniform
- If $f > 0.2$, distance estimation by simply inverting the parallax results in a significant bias
- A simple prior which decreases asymptotically to zero at infinite distance has good performance.

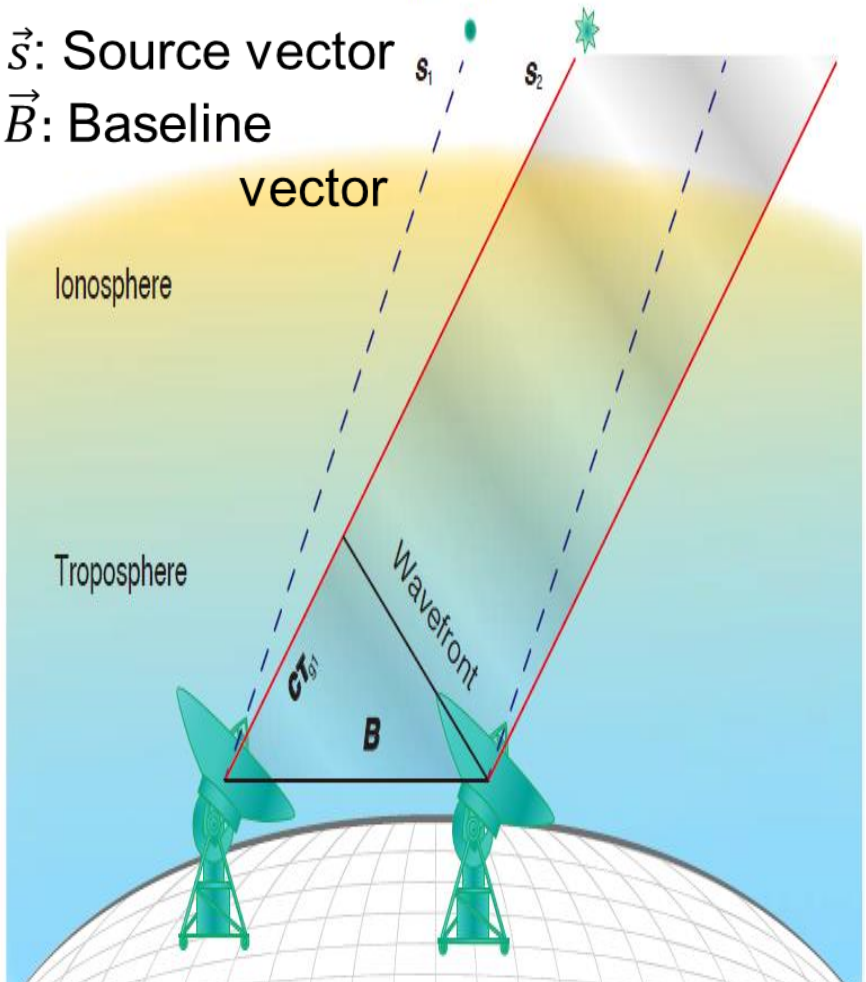


Distance

Bailer-Jones 2015, PASP, 127, 994

Relative VLBI astrometry

Reference Target



Reid & Honma 2014, ARA&A, 52, 339

Dominant error source

Troposphere at > 10 GHz
(Ionosphere at < 10 GHz)

Talks/Poster:
Hyland, Boven, and Petrov

Observation: Fast switch; Dual-beam (VERA)
Calibrations: Geodetic-block (VLBA); GPS (VERA)
JMA (KVN)

Single-epoch position accuracy

Observable: Delay τ

$c\tau = \vec{s} \cdot \vec{B}$

$$\Delta s \sim \frac{c\tau_{err}}{B} * \Delta \sec Z$$

ΔsecZ = 1 deg, $c\tau_{err}$=2 cm, B=2,300km
→ Δs **~ 30 μas with VERA**

*Use data with Zenith Angle < 60° for astrometry

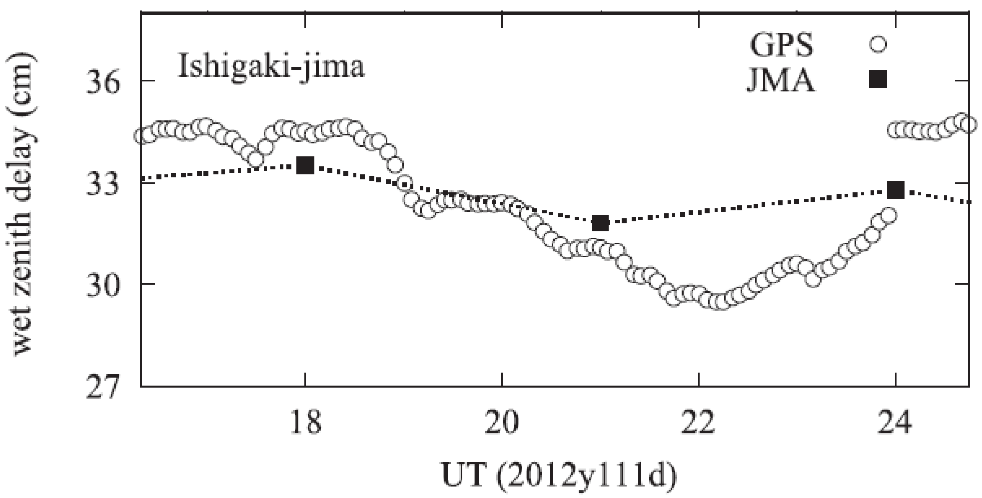
GPS vs. JMA on tropospheric cal.

Japan Meteorological Agency data

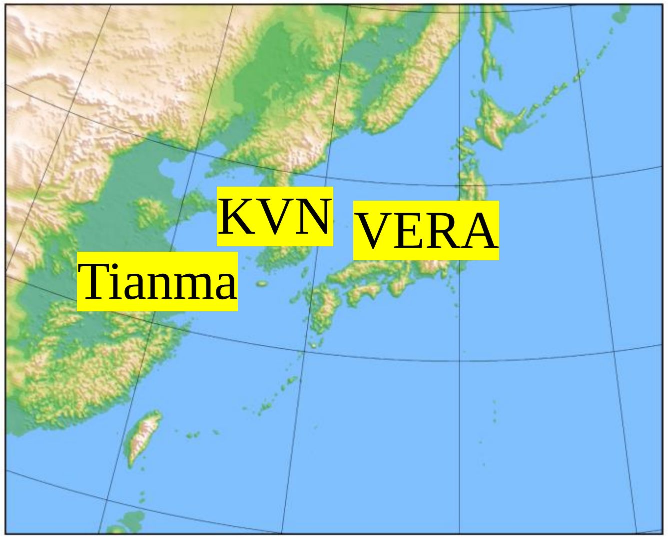
① Global data (5° × 5°) <u>8400 JPY / Month</u>
② Japan model (0.25° in East-West and 0.20° in North-South with a total area of 50° ×50°)
③ Mesoscale model (5 km × 5 km); Time resolution: 3 hr
Data: Atmospheric pressure (equipotential altitude), Wind, Temperature, Relative humidity
<u>25,200 JPY / Month</u>

GPS vs. JMA

Nagayama et al. 2015a, PASJ, 67, 65



Meso-scale Analysis domain



An accuracy of tropospheric zenith delay calibration is ~ 2cm with GPS or JMA

Astrometric capability of KaVA (VERA+KVN)

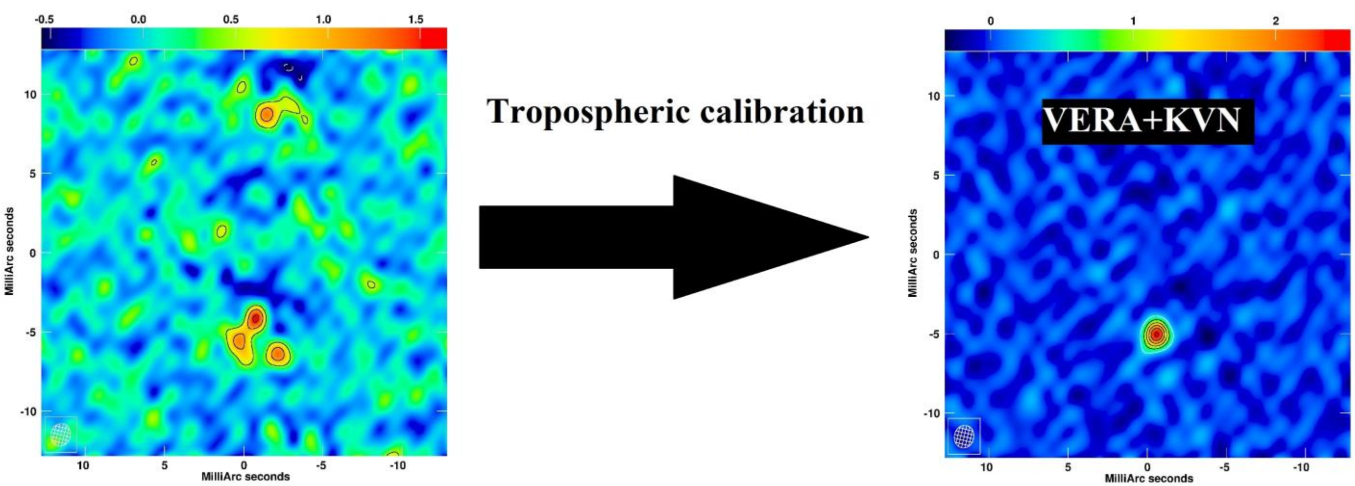
In relative astrometry, delay residual is described as

$$\Delta(\tau_{g,1} - \tau_{g,2}) = \Delta(\tau_{\mathrm{trop},1} - \tau_{\mathrm{trop},2}) - \Delta(\tau_{\mathrm{iono},1} - \tau_{\mathrm{iono},2}) - \Delta(\tau_{\mathrm{stat},1} - \tau_{\mathrm{stat},2})$$
$$-\Delta(\tau_{\mathrm{inst},1} - \tau_{\mathrm{inst},2}) - \underline{\Delta(\tau_{\mathrm{struc},1} - \tau_{\mathrm{struc},2})} - \Delta(\tau_{\mathrm{therm},1} - \tau_{\mathrm{therm},2})$$

Baseline based quantity

1: Target
2: Calibrator

- Baseline based quantity can be corrected when data reduction (i.e., self calibration).
- Station based quantities expect for $\tau_{\mathrm{struc},\,i}$, are cancelled out with relative astrometry.
- **Dominant error source is $\Delta(\tau_{trop,1} - \tau_{trop,2})$ at ν > 10 GHz.**



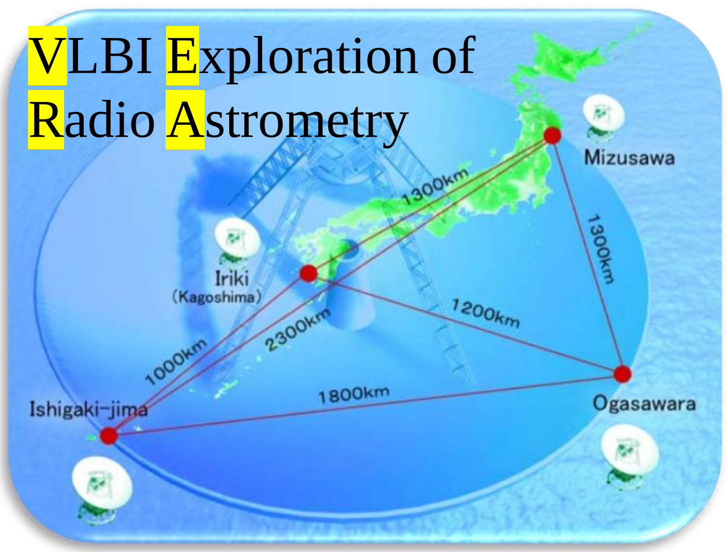
Troposphere is calibrated with GPS and Japan Meteorological Agency meso-scale analysis data for KaVA (22 GHz).

MOVIE

Major Radio Interferometers having astrometry mode

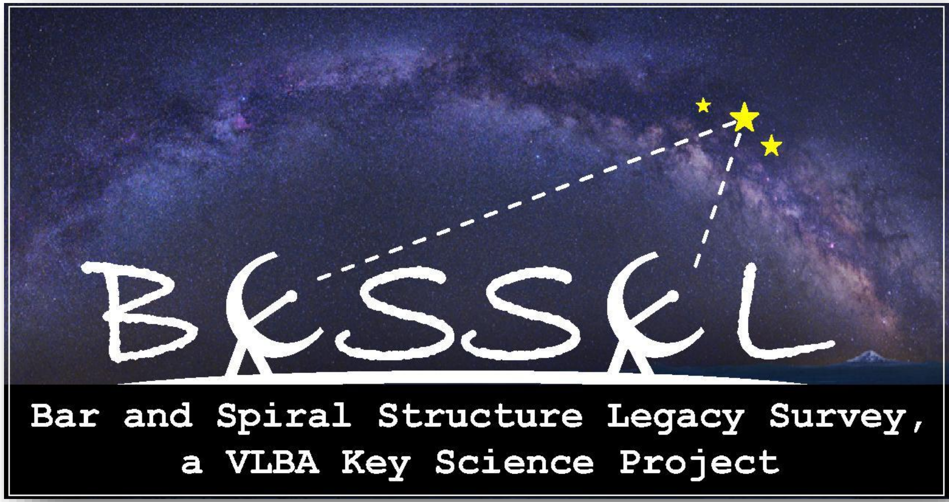
Array	Country/ region	Antenna diameters and number in array	Maximum baseline	Operating frequencies	Beam size (mas)	Comments
VLBA	USA	25 m × 10	8,600 km	0.3–86 GHz	0.17 at 43 GHz	Homogeneous and best imaging capability
VERA	Japan	20 m × 4	2,300 km	6.7–43 GHz	0.63 at 43 GHz	Dedicated to astrometry with dual-beam system
EVN	Europe	14 m–100 m, × ~10	3,000–10,000 km	1.6–22 GHz	0.30 at 22 GHz	High sensitivity with large dishes
LBA	Australia	22 m–70 m, × ~10	1,700 km	1.4–22 GHz	1.7 at 22 GHz	The only VLBI array in the Southern Hemisphere

See Poster #25
by **Molera Calves**



Period: 2004-2022

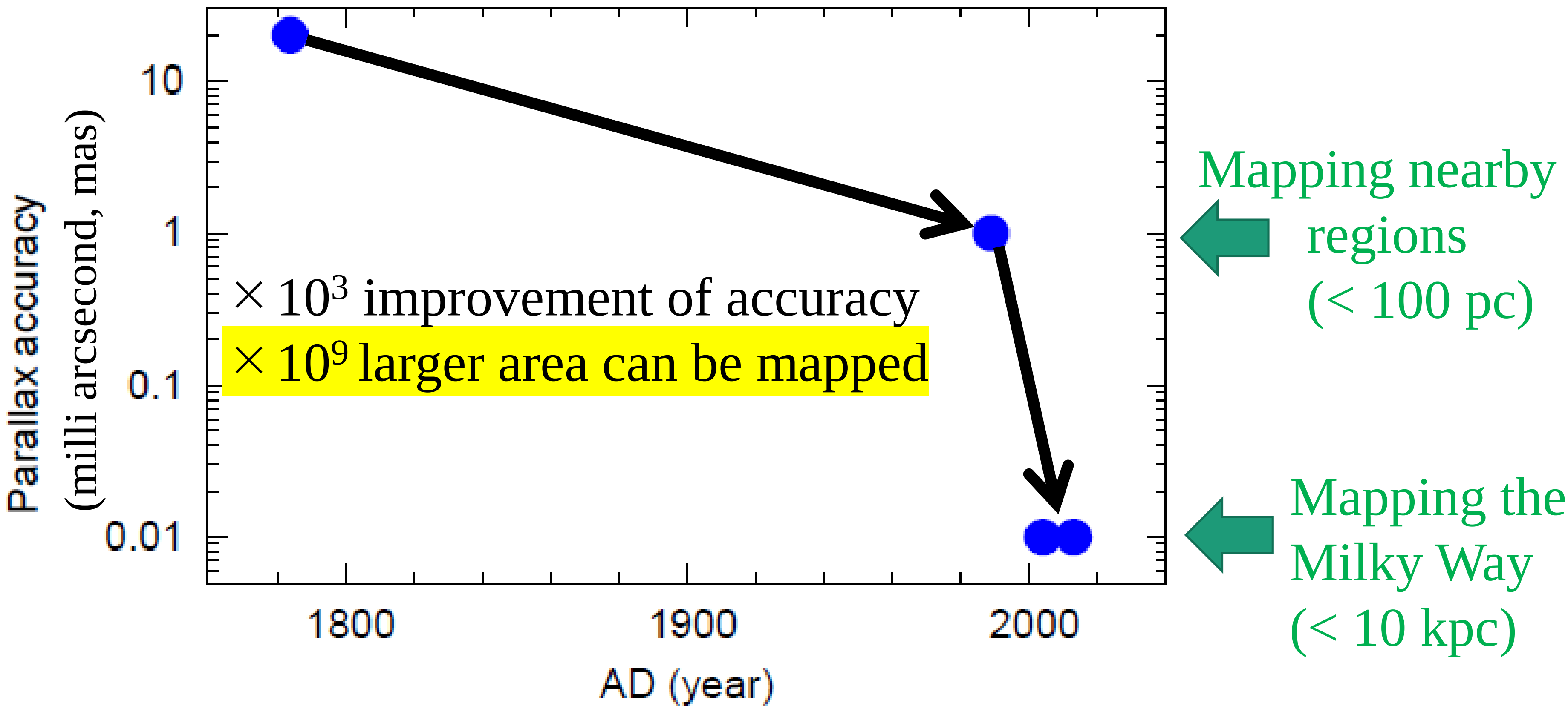
The largest VLBA program (3,500 hr)



Period: 2010-2016

Parallax accuracy vs. Time

- 190 – 120 BC: Hipparchus estimated the distance to the moon with the parallax of the moon
- 1784 – 1846: Friedrich Wilhelm Bessel measured the first stellar parallax for 61 Cyg
- 1989 – 1993: Hipparcos satellite measured 1M stellar parallaxes within 100 pc from the Sun
- **2004 – Now:** VERA and BeSSeL projects observed >200 masers within 10 kpc from the Sun
- 2013 – Now: *Gaia* satellite measured 1 billion stellar parallaxes within 10 kpc from the Sun

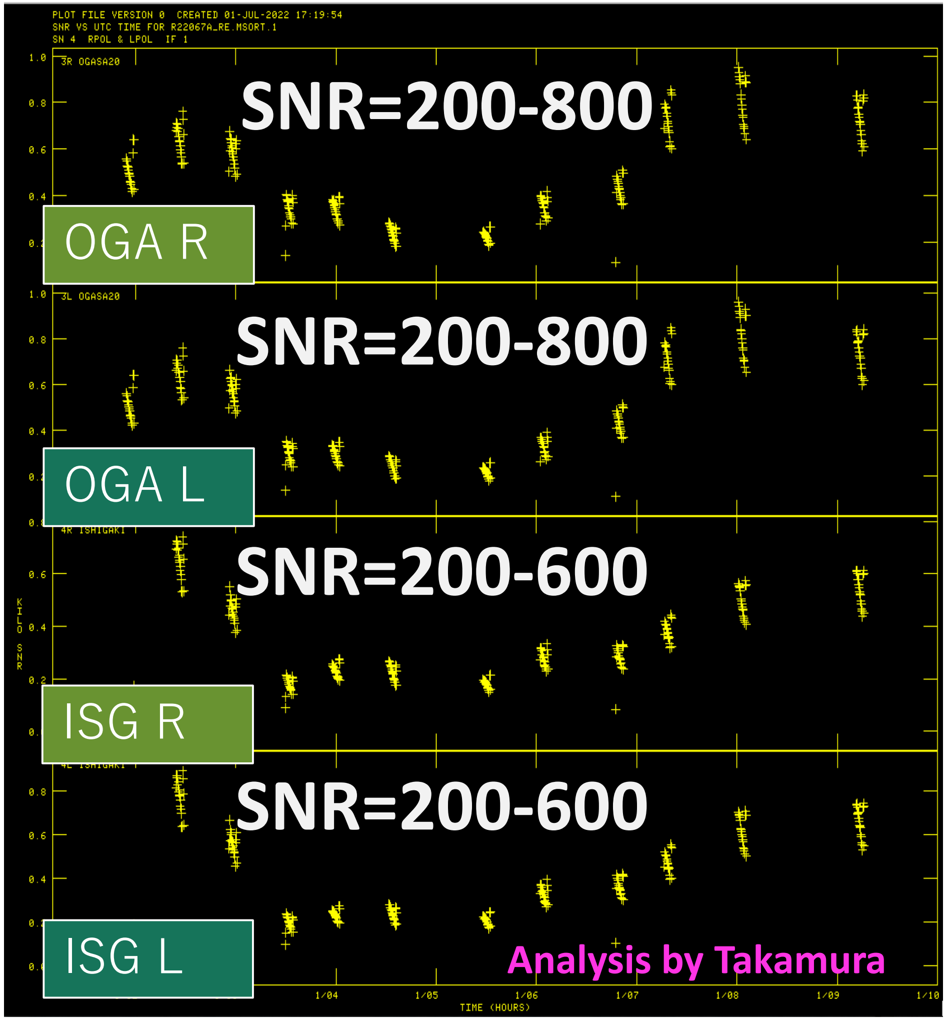


Ref: Talk by Hagiwara-san !

Ultra-wide band polarimetry using VERA

- **The first polarized intensity maps at 22/43 GHz obtained with wider** bandwidth (4 x 512 MHz per polarization, **16 Gbps recording**) obtained **only using VERA**
- **Polarized intensity at ~1 mJy/b level detectable**
- A short-term goal is to create polarimetric VLBI at 1-16 Gbps recording rates, by connecting VERA to existing arrays, KVN and EAVN
- Science cases with the "ultra-wide band" capability under consideration (e.g., determination of larger Faraday Rotation measure)

2022 **2048 MHz bandwidth**



MultiView for 10 μas astrometry

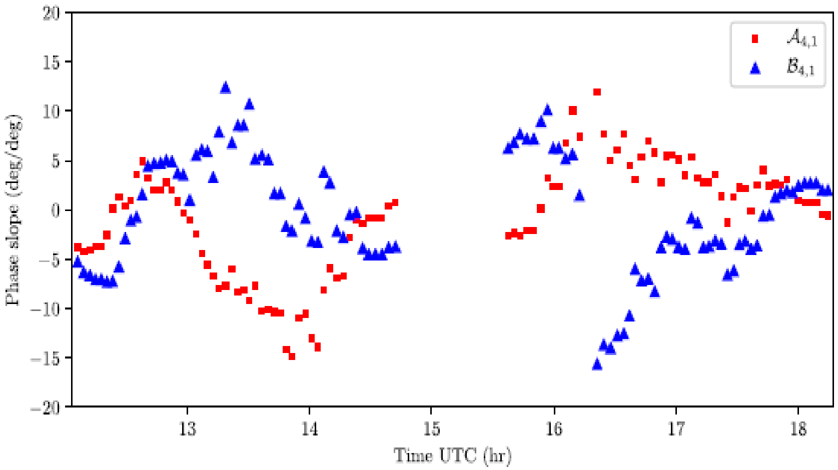
inverse MultiView (iMV):

$$\phi_{i,jk} = \phi_{T,jk} + A_{jk}\Delta\alpha_i\cos\delta_T + B_{jk}\Delta\delta_i$$

Phase at the target (*jk* baseline)

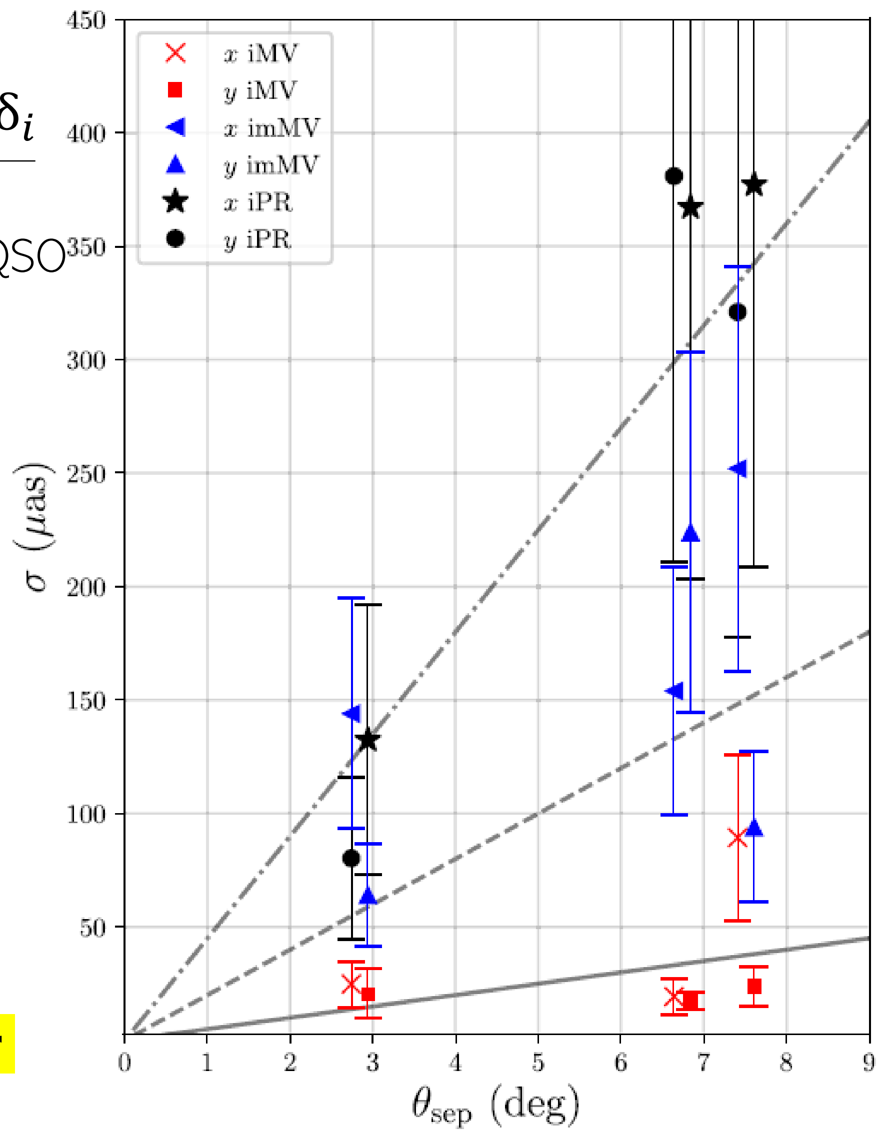
Angular offset for *i* th QSO

Phase slopes (*A* and *B*) vs. Time



Single-epoch astrometric accuracies near 20 μas for target-reference quasar separations up to ~7° at 8.6 GHz

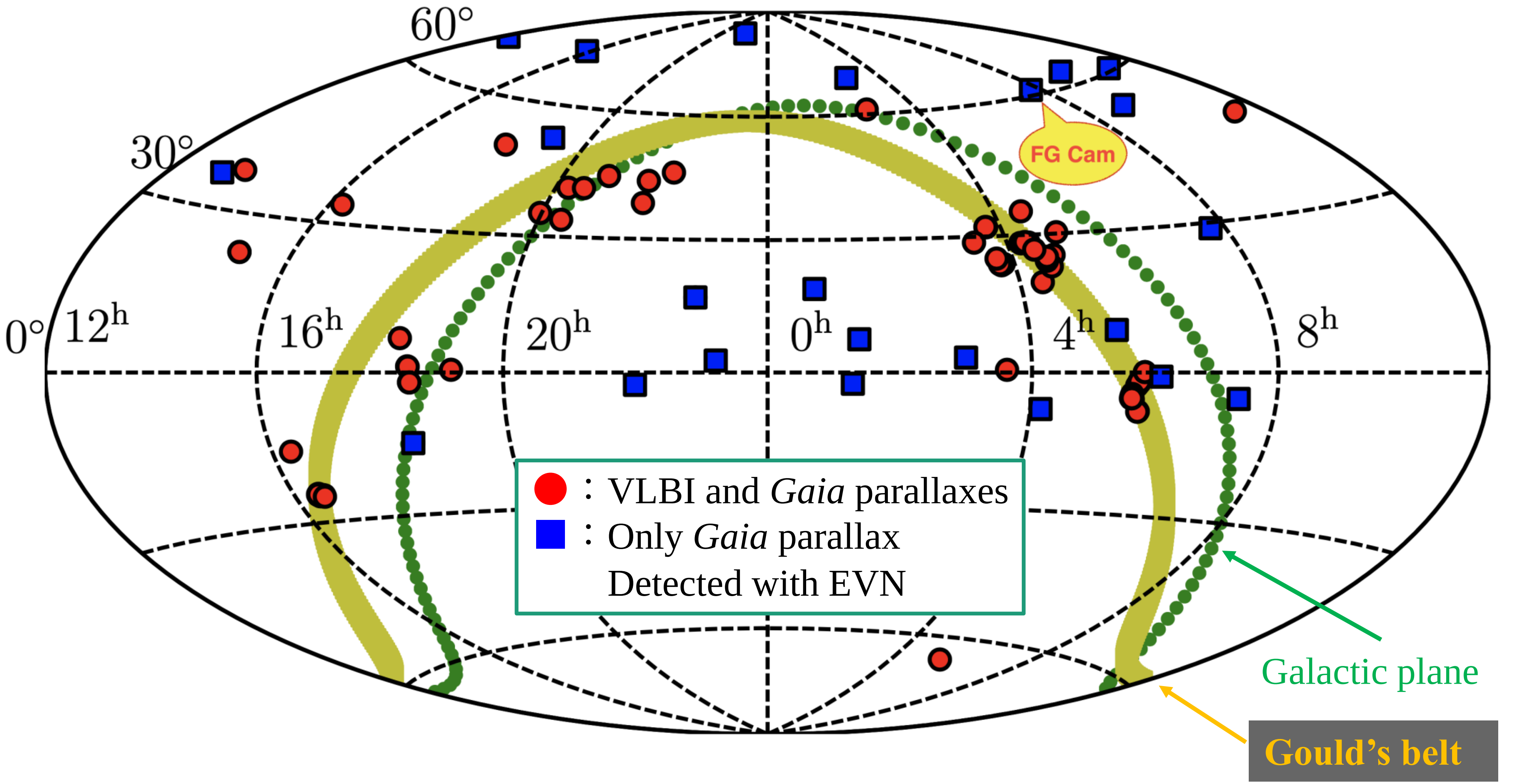
Position accuracy vs. separation angle



Hyland et al. 2022, ApJ, 932, 52

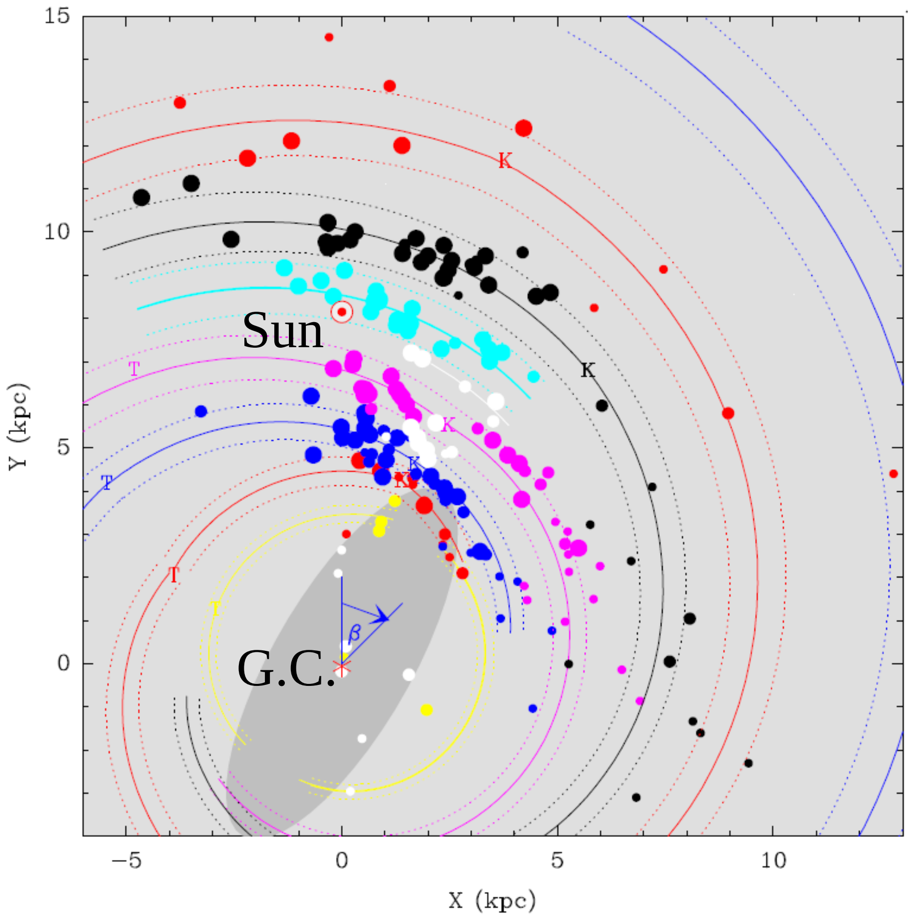
Ref:
Talk by **Boven** !

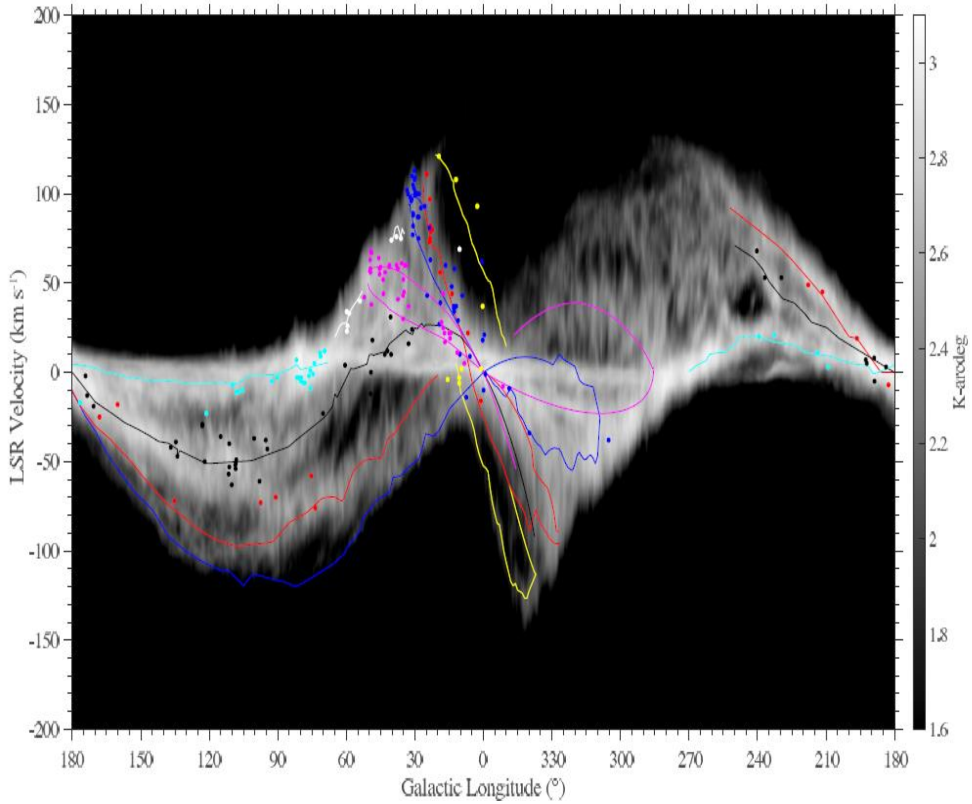
VLBI MultiView astrometry of Radio Stars ~Link between VLBI and *Gaia* frames~



- Determine orientation (~20 μas) and spin (5 μas yr^{-1}) between Gaia Celestial Reference Frame and ICRF
- Correction of the *Gaia* parallax zero point (better than 10 μas)

Structure of the Milky Way



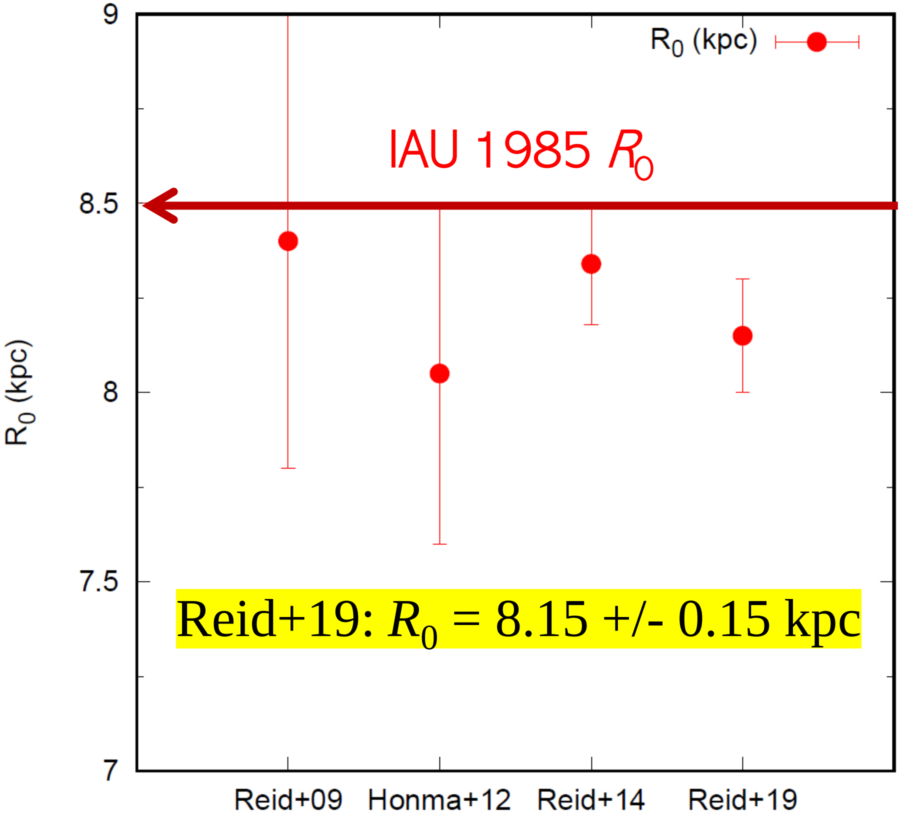


- MW is a four-arm spiral
  Norma-Outer; Perseus; Sagittarius-Carina; Scutum-Centaurus-OSC
- Extra arm segments and spurs

Position-Velocity diagram of H I (21 cm) emission

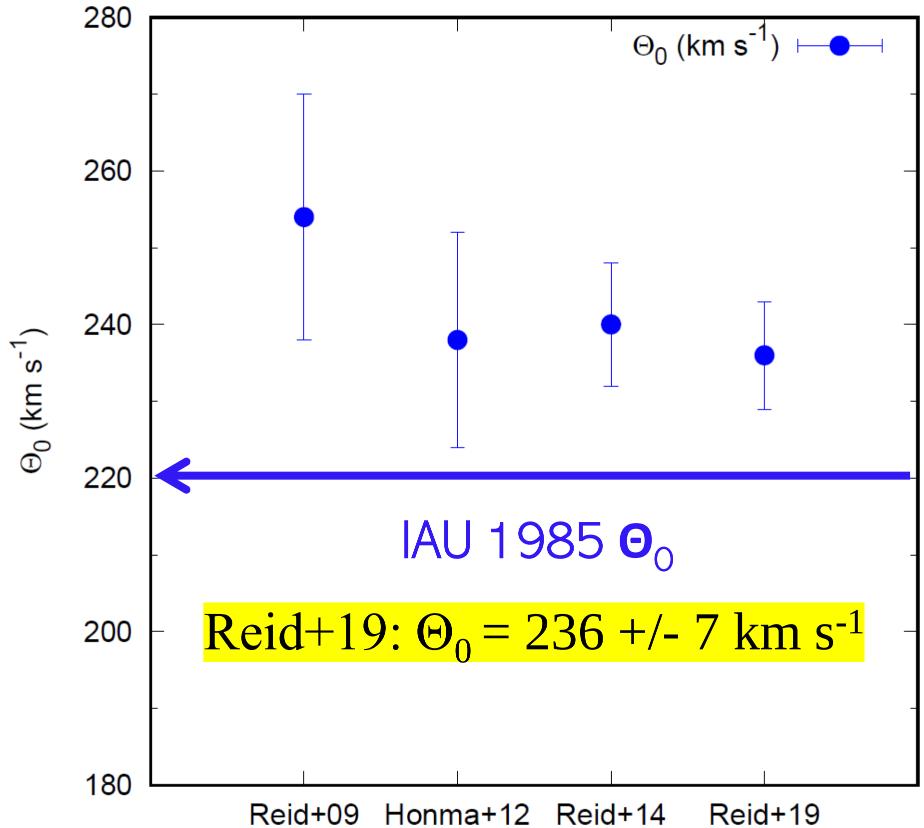
Reid, et al. 2019, ApJ, 885, 131
VERA Collaboration et al. 2020, PASJ, 72, 50

Galactic constants (R_0, Θ_0)



Reid+19: R_0 = 8.15 +/- 0.15 kpc

= 18 52 103 199



Reid+19: Θ_0 = 236 +/- 7 km s^{-1}

Mass in NFW halo $\propto (\Theta_0)^3$

MW is heavier than previously thought.

R_0 : Distance of the Sun from G.C.

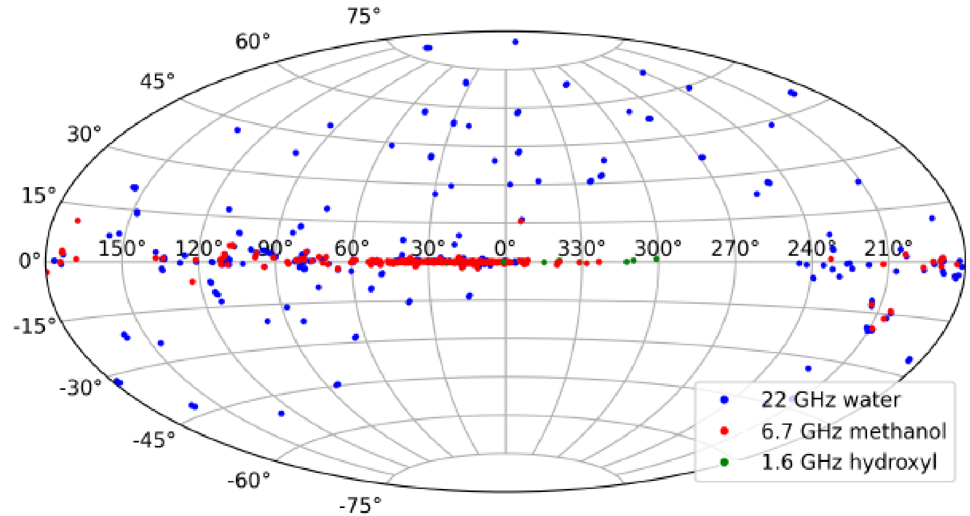
Θ_0 : Rotation velocity at the Sun (LSR)

Reid, et al. 2019, ApJ, 885, 131

The Maser Monitoring Organisation (M2O)

Communications platform to bring together maser monitoring stations, theorists and follow-up campaigns

M2O source sky coverage



The fundamental flow of M2O operations:

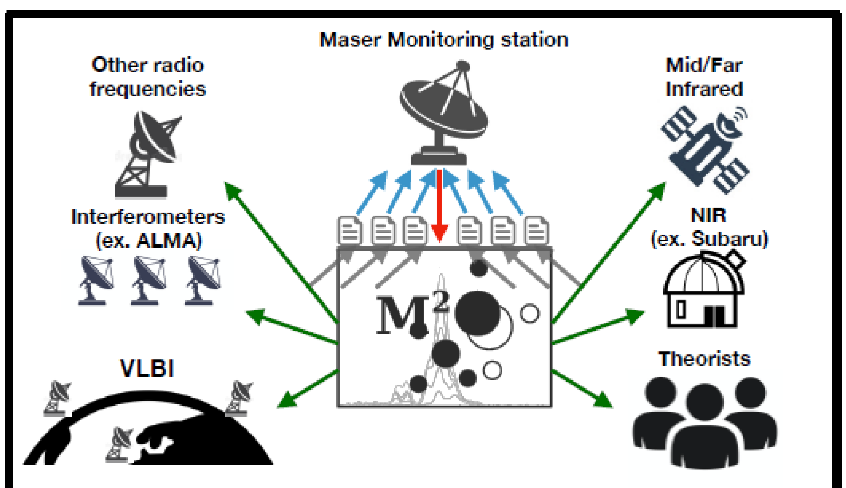
(C) Burns, Ross A. (NAOJ)

1 New maser flare reported to the M2O

2 Disseminate information
Consult theorists
Check other maser transitions
Conduct follow-up observations

3 Share results with the team
Discuss results from each perspective
Plan and author publications

4 All publications credit the monitoring station in their author list and acknowledgements



M2O current stats

85 members
14 monitoring stations
>1000 masers monitored
18 flares pursued
23 publications
since 2017 start

M2O website

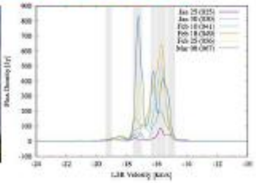
masermonitoring.org

Case Study G358-MM1

1 Flare identification during monitoring

by Hitachi 32m radio telescope

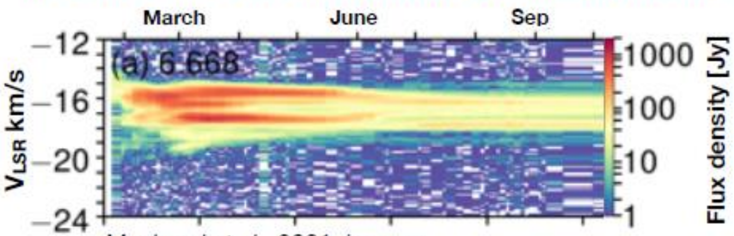
Credit: Ibaraki U



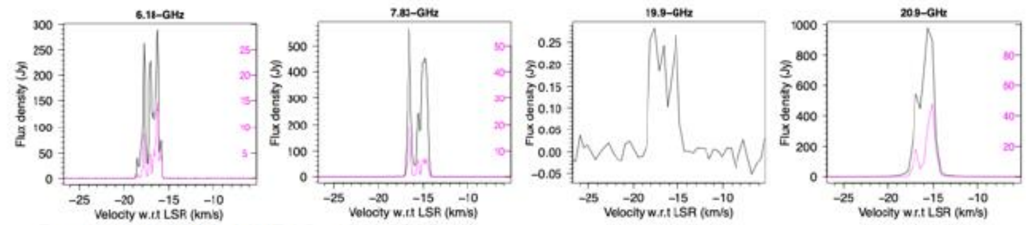
Maser flare in Jan 2019 reported to M2O Sugiyama et al. ATel #12446)

2 Maser monitoring and spectral survey with available radio telescopes

Measure burst duration, find new maser transitions



MacLeod et al., 2021, in prep.



Breen et al. 2010, MNRAS, 401, 2219

3 Quick-response Follow-up (“Target of opportunity”) observations, various facilities

Measure burst intensity, identify the progenitor protostar, investigate the kinematics and environment at low/mid/high resolution

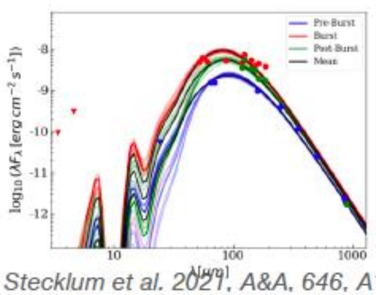
nasa.gov/mission_pages/SOFIA/

almaobservatory.org/

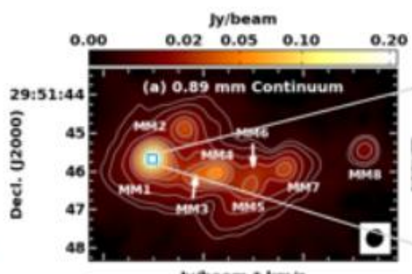
evlbi.org

vlba.nrao.edu

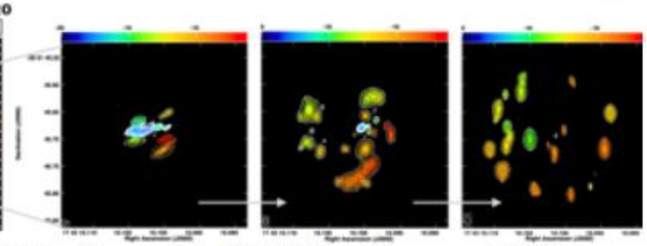
And many more …



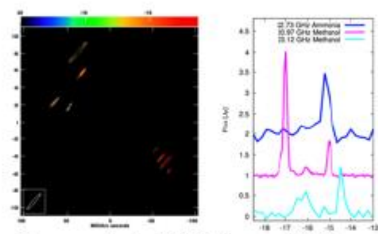
Stecklum et al. 2021, A&A, 646, A161



Brogan et al., 2019, ApJ, 881L, 39B



Burns et al., 2020, Nature Astronomy, 4, 506



Burns et al., 2021, in prep.

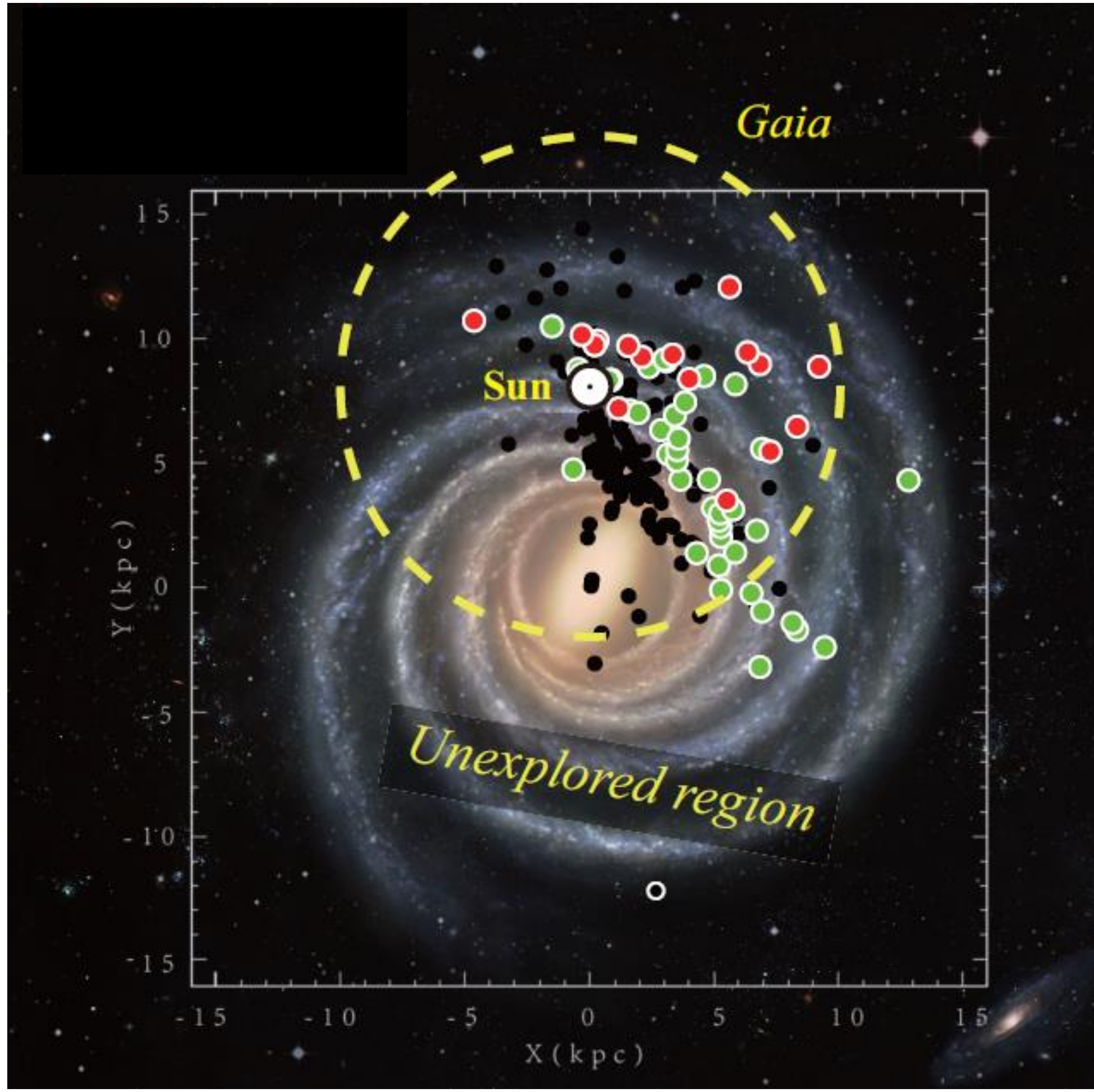
All publications credit the team who discovered the maser flare. This helps radio monitoring stations maintain funding and apply for upgrades

Future

Mapping distant star-forming regions (d > 10 kpc) with VLBI astrometry

Requirements

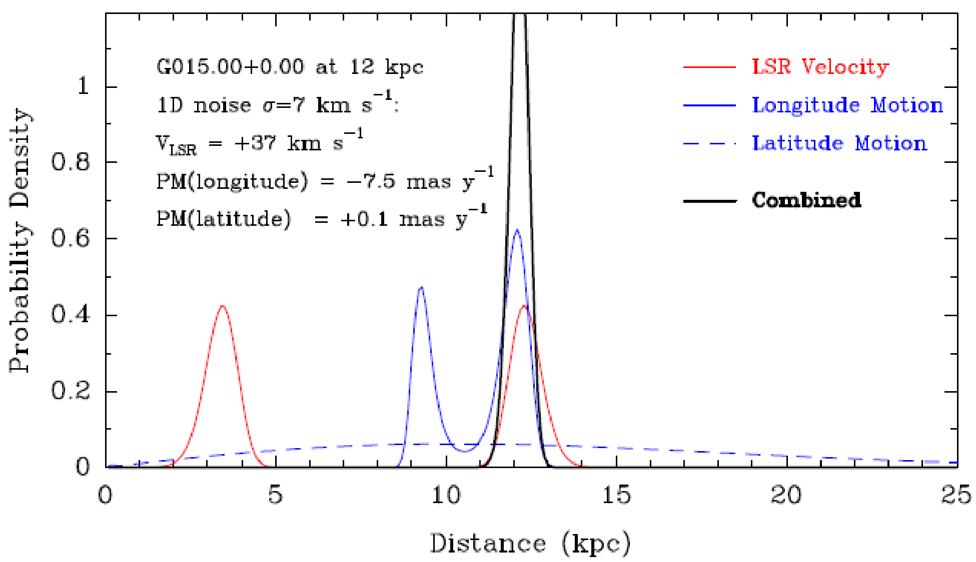
- Better parallax (π) accuracy
  $\because \pi \propto d^{-1}$
- Better image sensitivity
  $\because$ Flux $F_\nu \propto d^{-2}$

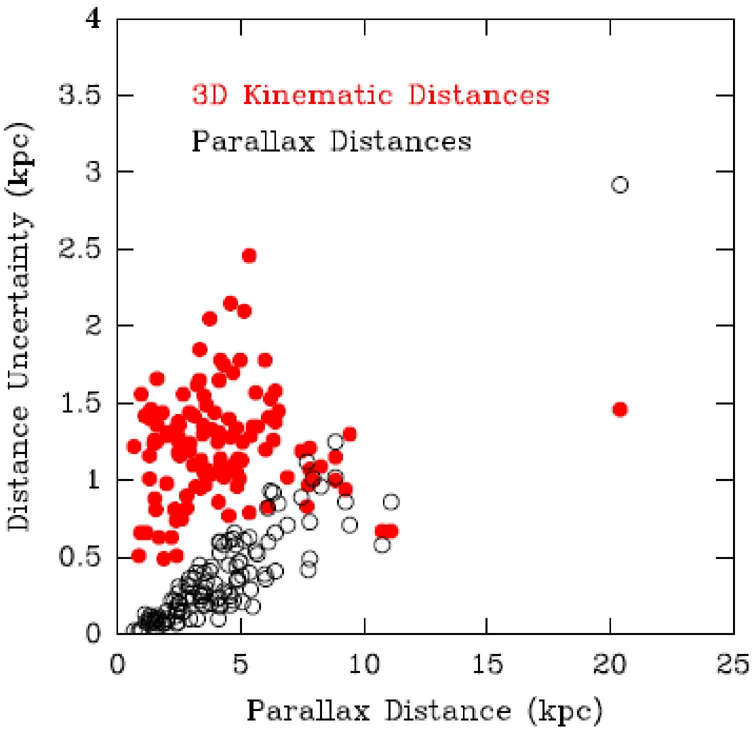


Beyond the yellow circle (d > 10 kpc) unexplored (not mapped)

Estimating distances with 3D motion

Reid 2022, eprint arXiv: 2205.06903





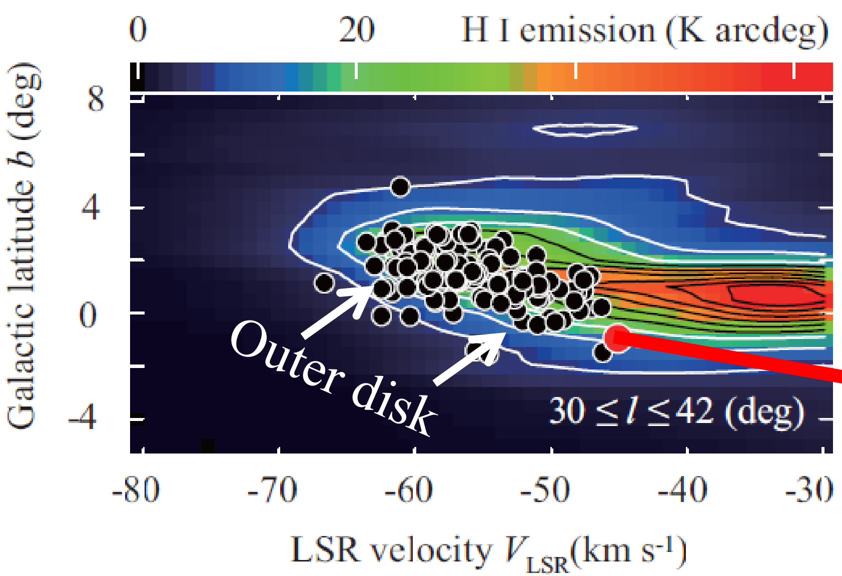
- A Bayesian distance calculator taking into account (l, b, v, μ = optional), improves on standard kinematic distances to star-forming regions

A Bayesian distance calculator: http://bessel.vlbi-astrometry.org/node/378

- 3D kinematic distances are robust and more accurate for $d > 8$ kpc

Sun et al. 2017, ApJS, 230, 17

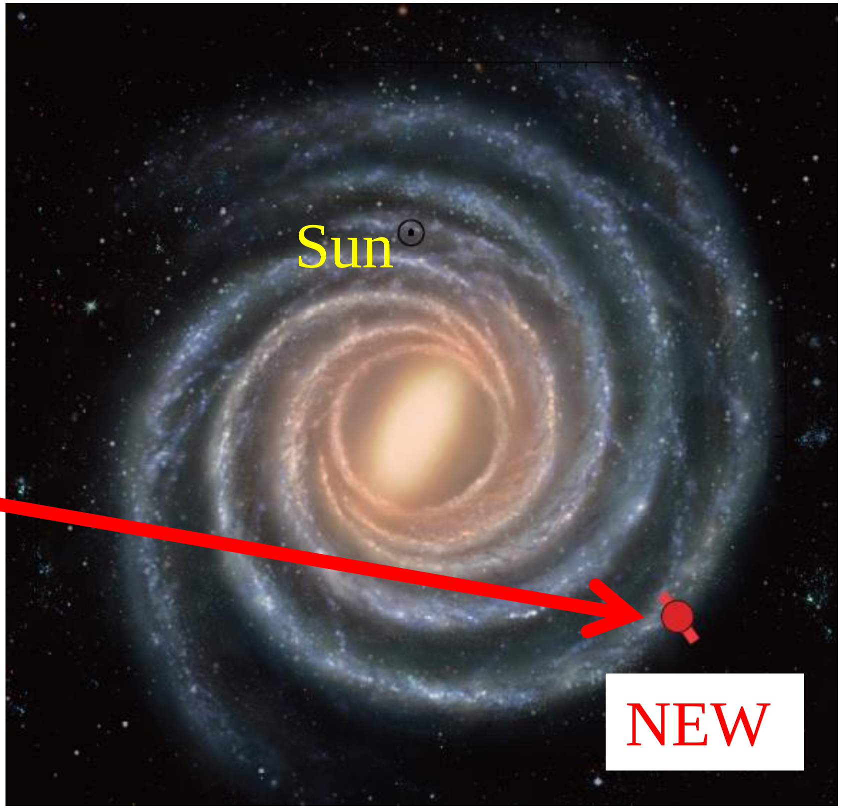
CO survey toward the outer disk (d > 16 kpc)



The survey results (●) are superimposed on integrated brightness temperature of H I (LSR velocity vs. latitude).

Sakai et al. 2022b in preparation

G034.84-00.94 (d = 18.7 +/- 1.0 kpc)



KaVA (VERA+KVN) astrometry result (derived with v and μ)

Radio Astronomy Network and Geodesy for Development at NARIT (RANGD), in Thailand

"Capacity Building Through Radio Astronomy"

- Observatory with 40-m TNRT & 13-m VGOS, and Visitor Centre
- Receiver and Electronics Laboratories
- Human Expertise: Workshop/Seminar/School/Trainings/Exchange

Dr.Saran Poshyachinda (Executive Director of NARIT)

Dr.Wiphu Rujopakarn (Deputy Director of NARIT)

Assoc Prof. Dr.Boonrucksar Soonthornthum (Ex-Exec. Director of NARIT)

Project leaders: **Dr.Phrudth Jaroenjittichai**, **Mr.Apichat Leckngam**

RAOC: Engineer/Geodesist

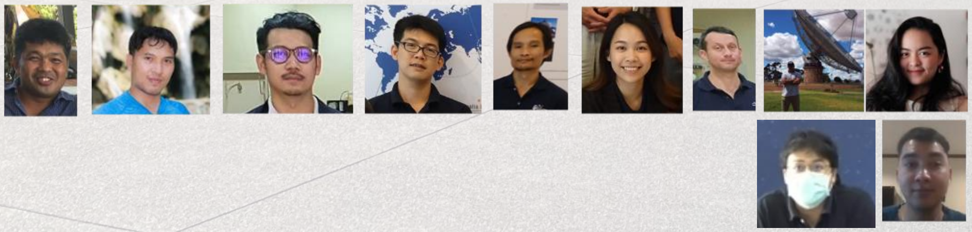
Pitak Kempet
Kamorn Bandudej
Dan Singwong
Pitipong Somboonpon
Songklod Punyawarin
Nikom Prasert
Nattaporn Thoonsaengngam
Spiro Sarris
Teep Chairin
Nakornping Namkham
Nattawit Chanwedchasart
Sothaya Prathumsub

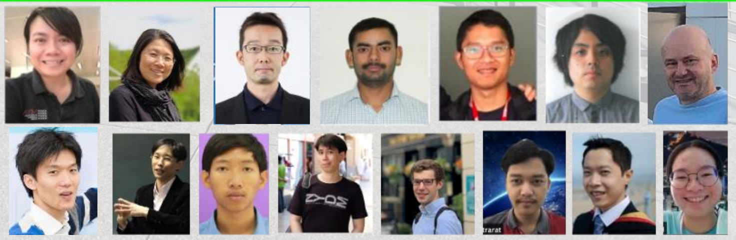
+ lots of engineer/technician

Scientist

Kitiyanee Asanok
Busaba H. Kramer
Koichiro Sugiyama
Ram Kesh Yadav
Chanapote Thanapol
Daisuke Sakai
Malcolm D. Gray
Nobuyuki Sakai

+ collaboration with NARIT/World-wide astronomers & lots of students/RA



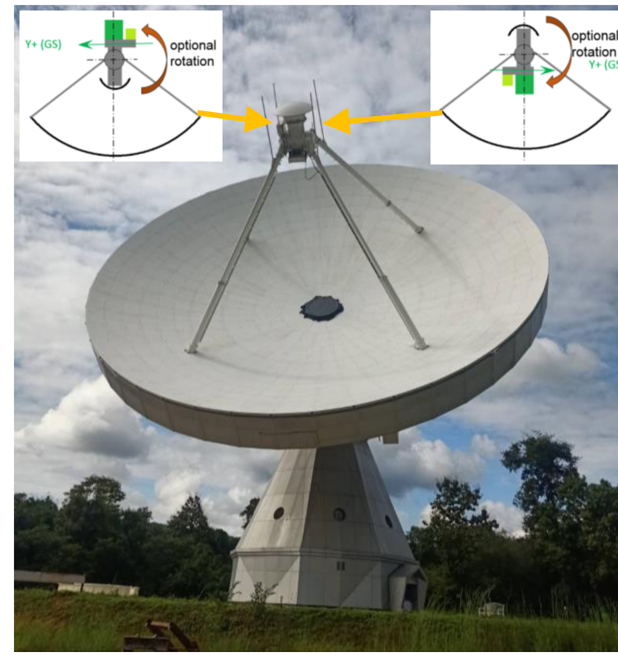


Specs of the 40-m TNRT at Commissioning

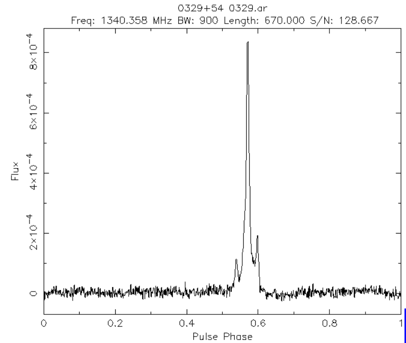
Phase I (L-band, K-band) — **Phase II (early)** (CXKu-band)

	L-band	K-band	CXKu-band
Frequency RF [GHz]	**1.0 - 1.8**	**18 - 26.5**	**4.55 - 13.65**
Beam width [arcmin]	~14-26	~1.0-1.4	~1.9-5.7
Polarization	Linear	Circular	Linear
Sampling rate	3 Gsps	4 Gsps	4 Gsps *1
Digitization bit	< 12 bit	< 12 bit	< 12 bit
Bandwidth	1.5 GHz	2 GHz	1.3 GHz
Aperture efficiency	0.7	0.5	0.6 *1
Gain [K/Jy]	0.32	0.23	0.27 *1
Trx [K]	13	20	15 *1
Tsky [K]	12	50	15 *1
Tsys [K]	25	70	30 *1
SEFD [Jy]	**78**	**307**	**110** *1

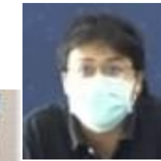
Note.: "*1" means designing on-going and TBC.



Timeline to launch the TNRT 40m



PSR B0329+54
15 June 2022
1.0 - 1.8 GHz
warm receiver
1x1 deg^2



P. Jaroenjittichai/T. Chairin/N. Prasert

		2022				2023				2024	
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Install	L-band Rx										
	K-band Rx										
Commissioning	Performance Evaluation										
	Scientific Evaluation										
Operation	Single-dish										
	VLBI										
Development	C/X/Ku-bands Rx										
	Q/W-bands Rx										

1st light !

Pulsar 1st light !

1st fringe ?

References

Chapter 1

Parallax https://www.astronomy.ohio-state.edu/pogge.1/Ast162/Movies/parallax.html
Proper motion http://en.wikipedia.org/wiki/Proper_motion#mediaviewer/File:Barnard2005.gif

- Lutz & Kelker, 1973, PASP, 85, 573
- Bailer-Jones 2015, PASP, 127, 994
- Rioja & Dodson 2020, A&ARv, 28, 6
- Reid & Honma 2014, ARA&A, 52, 339
- Nagayama et al. 2015a, PASJ, 67, 65
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