VLBI in the SKA era

Lecture on *very long baseline interferometry*

SKA-JP
Square Kilometre Array Japanese Consortium

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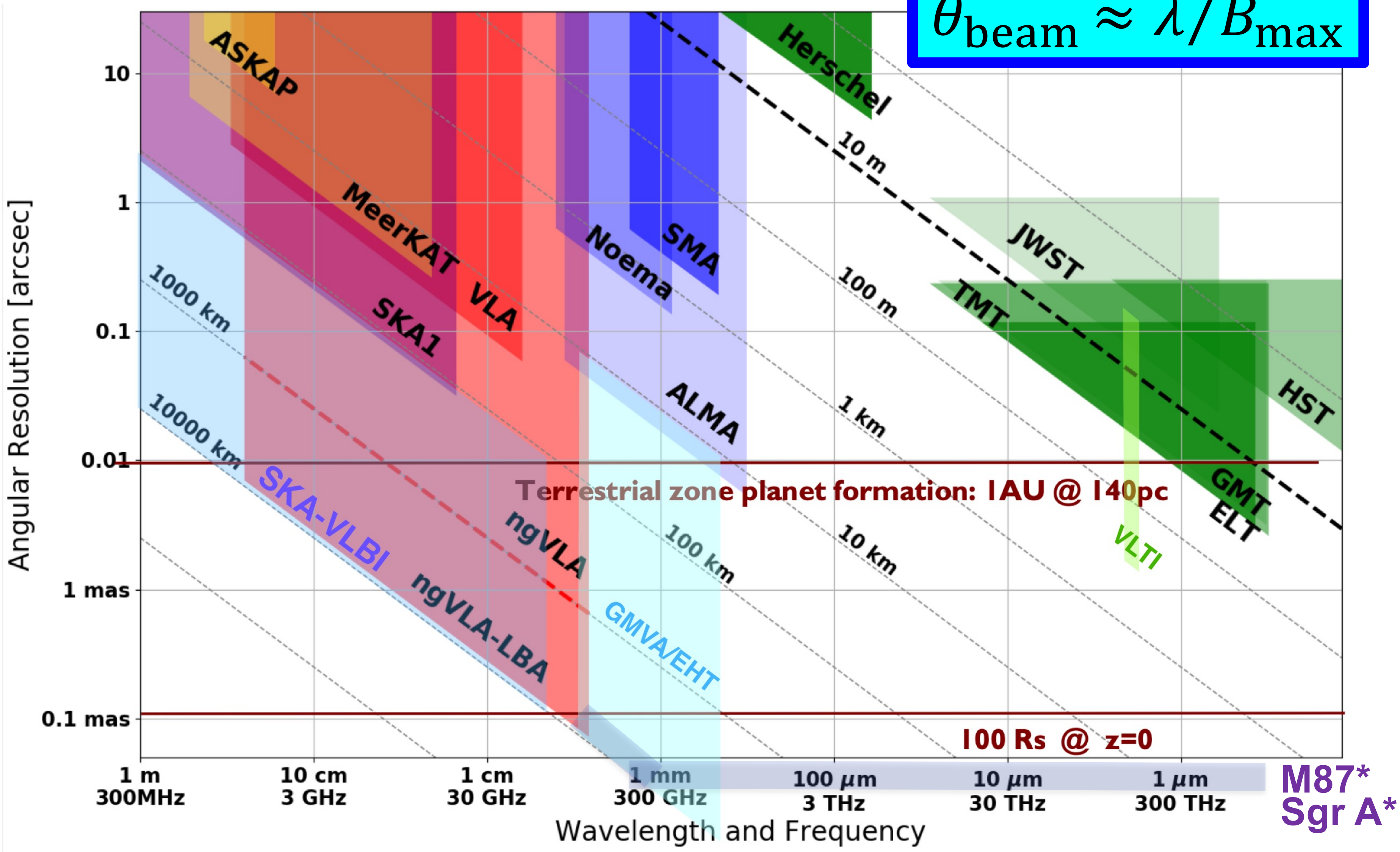
JST Sakura Program for international collaboration in radio astronomy between Japan and South Africa

Lecture contents

- **Why VLBI?**
  - VLBI specifications
  - VLBI requirements and constraints
    - Hardware
    - Software
    - Operation
- **Uniqueness of VLBI**
  - Science cases
  - International collaborations in science and VLBI operation
- **Challenges of VLBI in the SKA era**
  - Global VLBI alliance
  - Ultimate accuracy / massive astrometry
  - Time domain astronomy in VLBI

Why VLBI? — specifications —

$$\theta_{\mathrm{beam}} \approx \lambda / B_{\mathrm{max}}$$



Why VLBI?
– ultimate angular resolution

- **Angular resolution ~ shortest fringe spacing**
  - Extreme case 1: RadioAstron (2013—2019)
    - SpectrR (spacecraft) — ground telescopes
    - θ_{beam}~ 7 μas (almost one baseline) @22 GHz
  - Extreme case 2: Event Horizon Telescope (EHT)
    - Up to 7 long-baseline sites
    - θ_{beam}~ 20 μas @345 GHz information
- **Instead of sensitivity and image quality**
  - Limited number of long baselines
    - Limited common sky on the Earth
    - Limited coherence (integration) time
  - Limited observation time slots
    - Limited available time of large telescopes
    - Limited observation cadence

Special equipment for VLBI

❖ **Purpose: getting *fringe visibilities***

– Detecting weak signals (with radio telescopes in general)
– Heterodyne receiving for wave correlation
  • Recording *digitized* time-series wave patterns at a high speed
  • Frequency conversion for more convenient recording
– Measuring visibility *amplitudes* and *phases* in correlator
  • *Antenna gains* and *system noise temperature*
  • Phase information → *complex correlation* (90° phase shift)
  • Getting correlation → *delay tracking* and *fringe stopping*

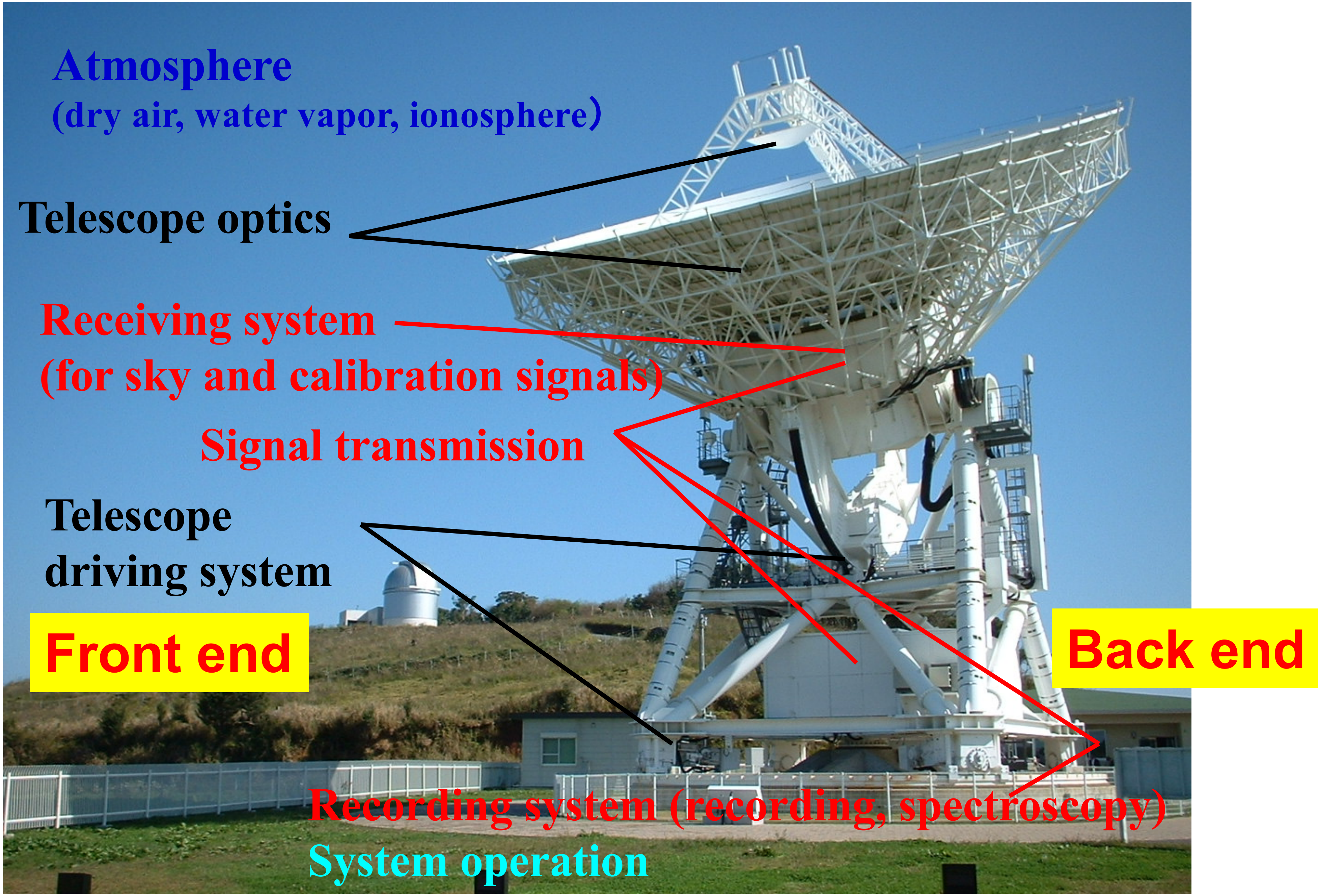
❖ **Keep the necessary information stably**

– High stability in frequency and time reference
  • High stability frequency standard
  • Loop-back circuits
  • Time stamp: 1PPS (pulse per second) signals

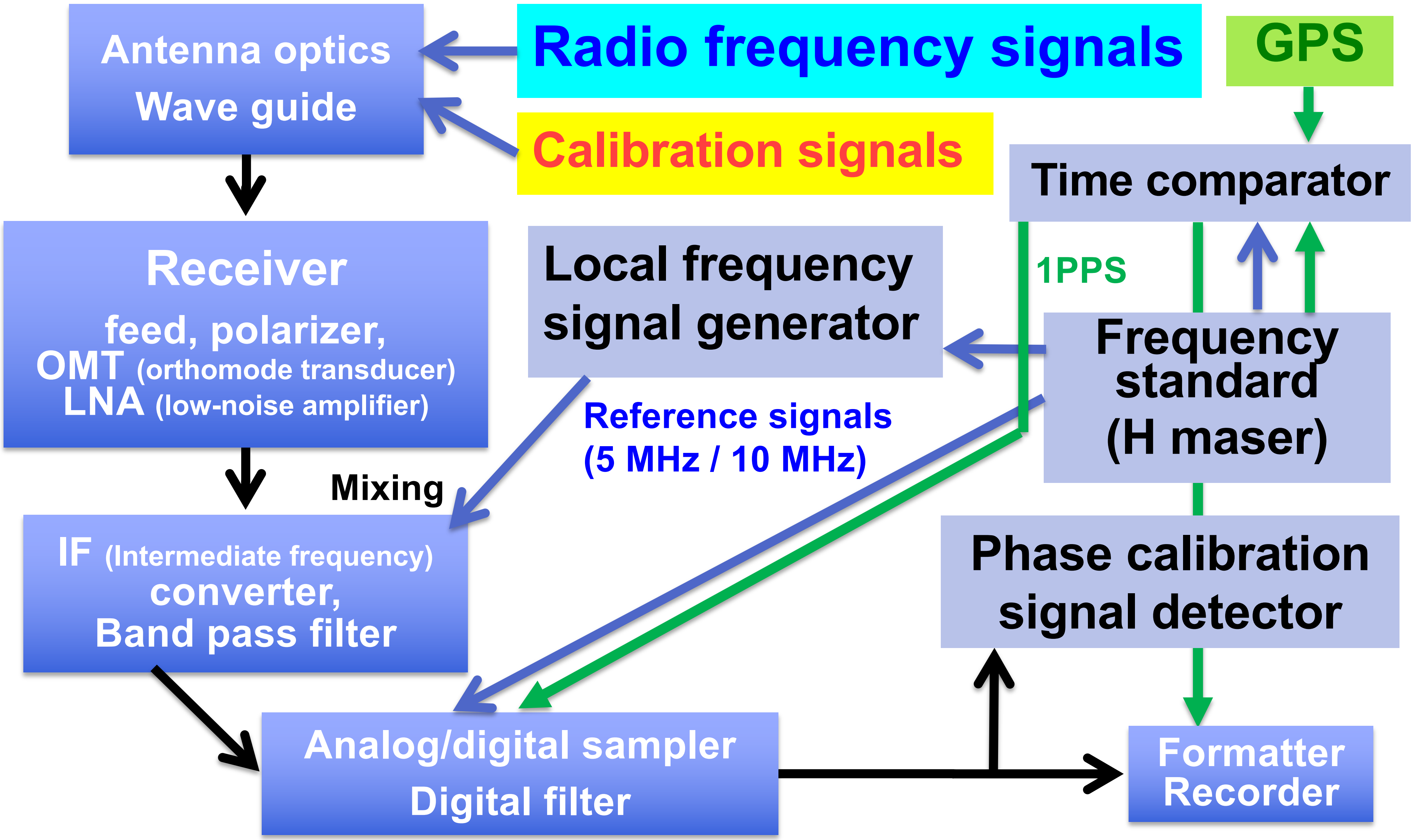
❖ **Record/get a priori information**

– *Antenna gains* and *system noise temperatures*
– Weather, time system, ITRF, etc.

VLBI system: VERA (VLBI Exploration of Radio Astrometry)



Information transfer in a VLBI station



Frequency conversion in each station

$$\left[V_{\mathrm{RF}}(t)+V_{\mathrm{LO}}(t-\tau_{\mathrm{LO}})\right]^2 = V_{\mathrm{RF}}^2(t)+V_{\mathrm{LO}}^2(t-\tau_{\mathrm{LO}})+\underline{2V_{\mathrm{RF}}(t)V_{\mathrm{LO}}(t-\tau_{\mathrm{LO}})}$$

$$V_{\mathrm{RF}}(t)V_{\mathrm{LO}}(t-\tau_{\mathrm{LO}}) = A_{\mathrm{RF}}\cos\{\omega_{\mathrm{RF}}t\}A_{\mathrm{LO}}\cos\{\omega_{\mathrm{LO}}(t-\tau_{\mathrm{LO}})\}$$

$$=\frac{A_{\mathrm{RF}}A_{\mathrm{LO}}}{2}\left[\cos\{\omega_{\mathrm{RF}}t+\omega_{\mathrm{LO}}(t-\tau_{\mathrm{LO}})\}+\cos\{\omega_{\mathrm{RF}}t-\omega_{\mathrm{LO}}(t-\tau_{\mathrm{LO}})\}\right]$$

$$=\underline{A\cos\{(\omega_{\mathrm{RF}}+\omega_{\mathrm{LO}})t-\omega_{LO}\tau_{\mathrm{LO}}\}}+\underline{A\cos\{(\omega_{\mathrm{RF}}-\omega_{\mathrm{LO}})t+\omega_{LO}\tau_{\mathrm{LO}}\}}$$

Filtered out where $A = A_{\mathrm{RF}}A_{\mathrm{LO}}$ **USB and/or LSB**

USB (upper side band) and LSB (lower side band)

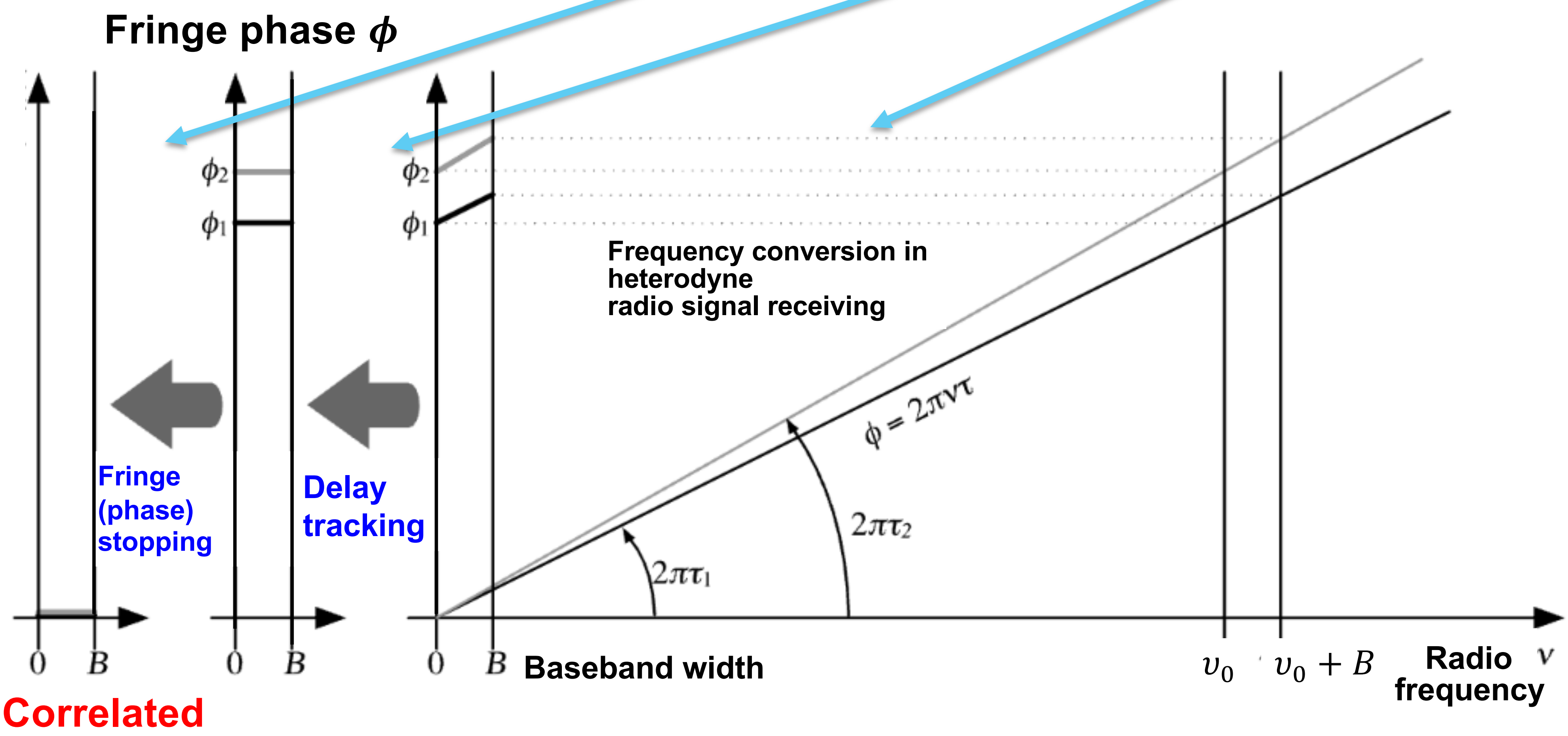
USB: $\nu_{\mathrm{IF}} = \nu_{\mathrm{RF}} - \nu_{\mathrm{LO}} \rightarrow \nu_{\mathrm{RF}} = \nu_{\mathrm{LO}} + \nu_{\mathrm{IF}}$

LSB: $\nu_{\mathrm{IF}} = -(\nu_{\mathrm{RF}} - \nu_{\mathrm{LO}}) \rightarrow \nu_{\mathrm{RF}} = \nu_{\mathrm{LO}} - \nu_{\mathrm{IF}}$

Delay tracking and fringe rotation for fringe phase tracking

$$\phi_k = 2\pi(\upsilon_{RF} - \upsilon_{Lo})(\tau_k - \tau_{inst}) = 2\pi\upsilon_{RF}\tau_k - 2\pi\upsilon_{RF}\,\tau_{inst} - 2\pi\upsilon_{Lo}\tau_k - 2\pi\upsilon_{Lo}\tau_k$$

Observed in *k*-th baseline



VLBI requirements and constraints

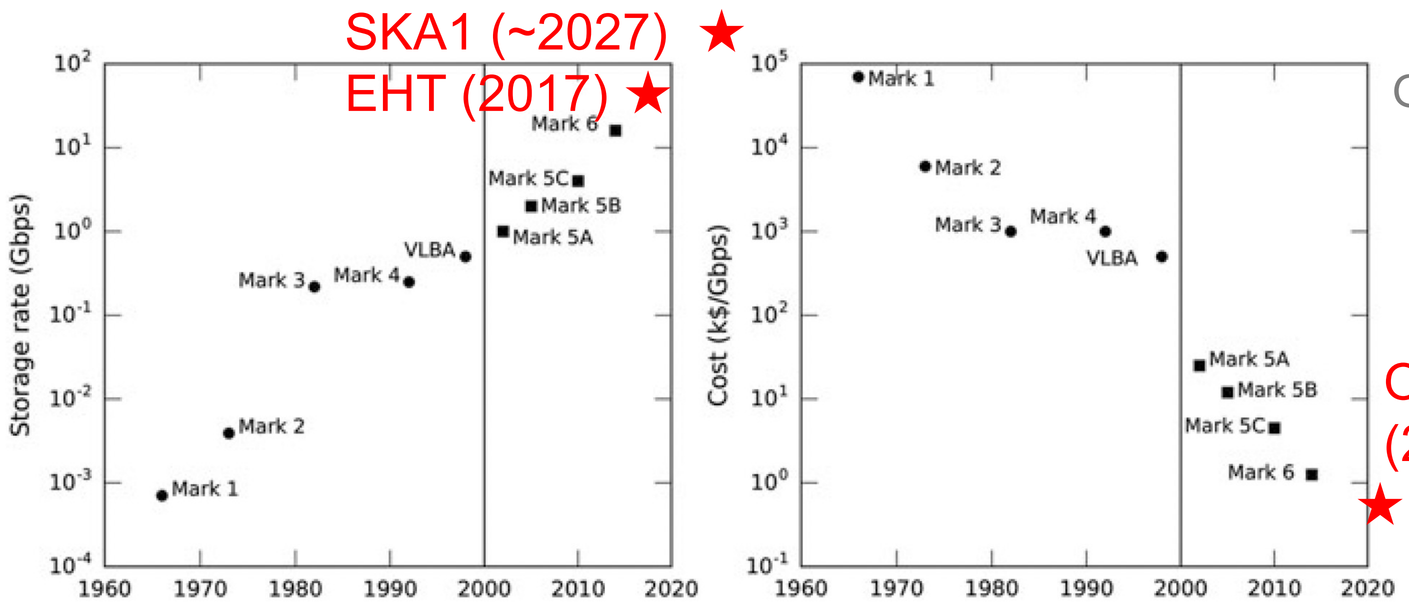
❖ Hardware requirements / constraints

– Frequency / clock stability

$$\sigma_\phi \approx \nu\sigma_\tau\tau_{\rm int} \approx \sigma_\nu\tau_{\rm int} \ll 1$$

- $\sigma_\tau \ll 10^{-12}$ s in $\tau_{\rm int}$ or $\sigma_\nu/\nu \ll 10^{-12}$ for $\nu \approx 10$ GHz and $\tau_{\rm int} \approx 100$ s
- H-maser frequency standard ($\sigma_\nu/\nu \approx 10^{-15}$) is necessary.
- Optical lattice clock ($\sigma_\nu/\nu \approx 10^{-18}$) is newly applicable to VLBI.

– High speed digital sampling



Gbps=giga bits per second

Fig. 9.20 of TMS

VLBI requirements and constraints

❖ Software requirements / constraints

- Correlator
  - High data damp rate
    - Higher dispersion spectroscopy
    - Wider field of view
  - Polarization handling and polarimetry (Stokes *I*,*Q*,*U*,*V*)
- Pipeline data processing
  - Loading raw data
  - Data flagging
  - Selecting reference data
  - Fringe amplitude calib.
  - Fringe phase calib.
  - Image synthesis
  - Source finding

$$1 \le \Delta\phi_{\mathrm{FoV}}(\nu) \approx 2\pi\nu\Delta\tau_g \approx 2\pi\nu \frac{\partial \Delta\tau_g}{\partial t} T_{\mathrm{int}}$$

$$\frac{\partial \Delta\tau_g}{\partial t} \approx \frac{D\omega_{\mathrm{e}}\Delta\theta_{\mathrm{FoV}}}{c}, \quad \Delta\theta_{\mathrm{FoV}} \le \frac{c}{2\pi\nu D\omega_{\mathrm{e}} T_{\mathrm{int}}}$$

and

$$1 \le \Delta\phi_{\mathrm{FoV}}(\nu') \le 2\pi\Delta\nu\Delta\tau_g \quad \text{where } \nu' = \nu + \Delta\nu$$

$$\Delta\tau_g \approx \frac{D\Delta\theta_{\mathrm{FoV}}}{c}, \quad \Delta\theta_{\mathrm{FoV}} \le \frac{c}{2\pi\Delta\nu D}$$

VLBI requirements and constraints

❖ VLBI operation requirements / constraints

- Scheduling VLBI stations
  - Middle-size telescopes dedicated for VLBI monitoring (e.g., VERA, KVN, VLBA)
- Advanced skills requested to users for operation
  - Selecting clock parameter (delay, delay rate offsets) calibrators large angular offsets from target
  - Selecting fringe calibrators short angular offset from target
  - Selecting flux / polarization calibrators very rare

VLBI calibrators are not ideal ones (bright, compact, stable).

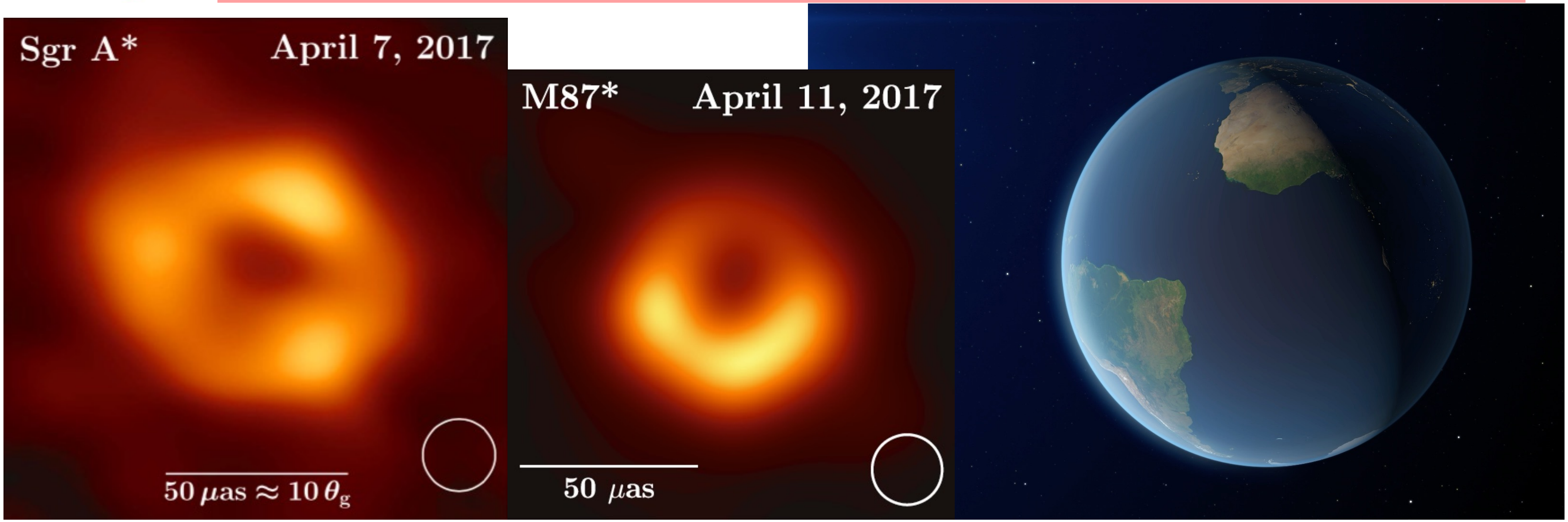
- Data shipping
  - Physically shipping recorded medias via air cargo
  - Custom, security issue
  - Slow internet transportation

Uniqueness of VLBI
– Science Cases—

- **Imaging in ultimate angular resolution**
  - Shadows of super-massive blackholes
  - Lunching points of AGN (active galactic nucleus) jets

    M87*, Sgr A*
- **High precision astrometry**
  - Trigonometry (up to 10 kpc) of non-thermal sources (including maser sources)
  - Secular motions of radio sources
  - See also Nakagawa's lecture
- **Mapping compact structures in interstellar / circumstellar / circumnuclear medium**
  - Astrophysical maser sources (in movies)
  - Compact objects in deep universe (and solar neighborhood)
- **VLBI for time domain astronomy (localization)**
  - Fast transients: fast radio bursts (FRBs)
  - Slow transients: super novae, novae, radio burst, maser bursts

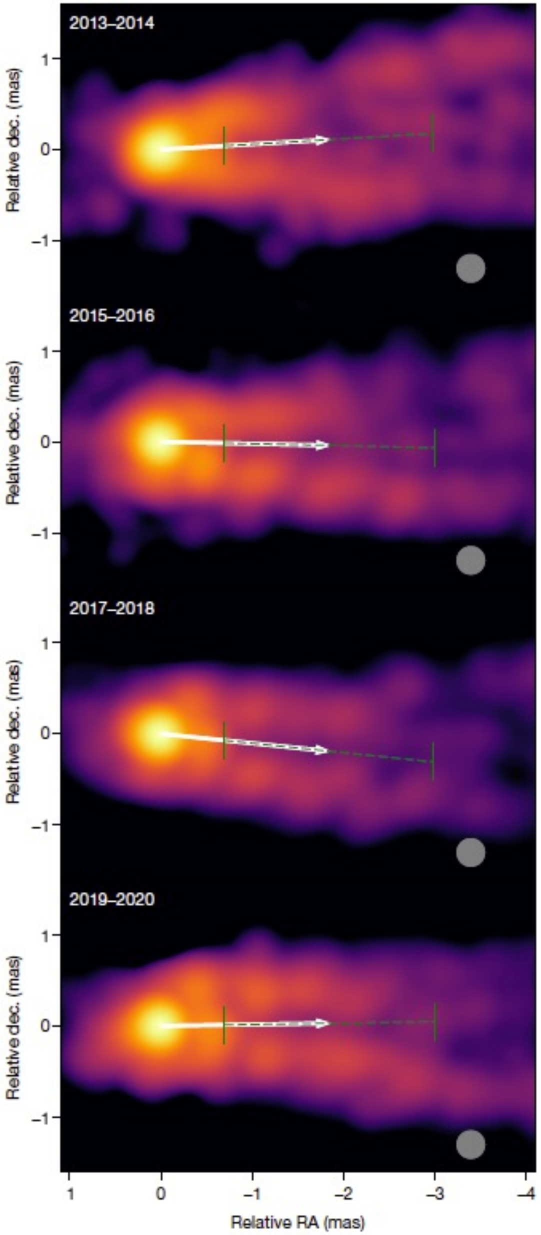
Shadows of super-massive black holes

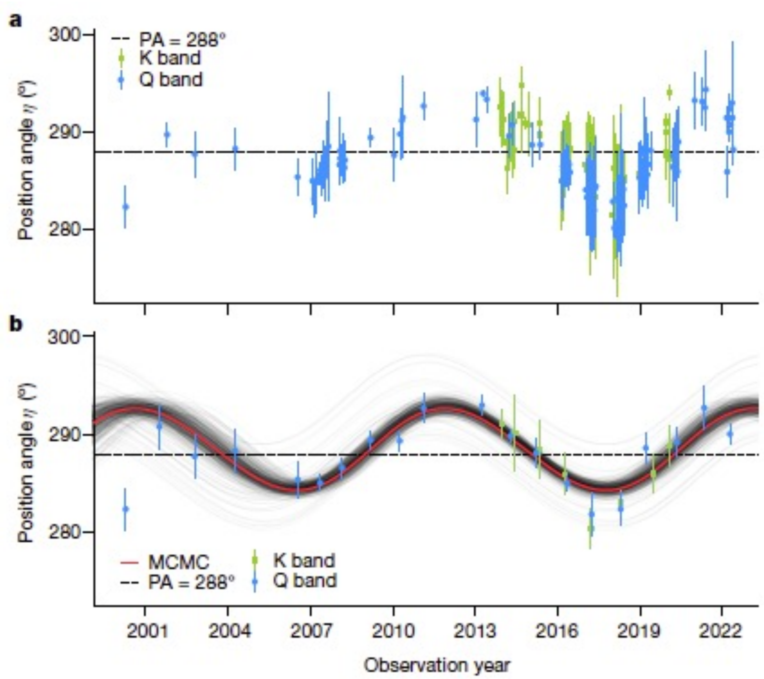


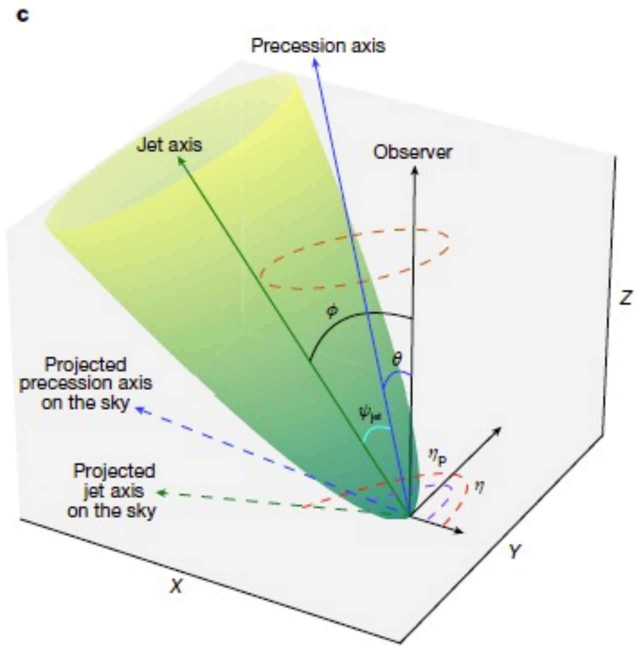
EHT Collaboration 2022 EHT Collaboration 2019 Credit: EHT

- **Millimeter (~1.3 mm) VLBI → θ_{beam}~20 μas**
- **Ultra-high sensitivity**
  - Large apertures: ALMA-VLBI, LMT (Large Millimeter Telescope)
  - Ultra-high speed signal recording: 32 Gbps
- **New imaging technique**
  - Sparse modelling
  - Variability (4—30 min) modeling

Lunching point of an AGN jet







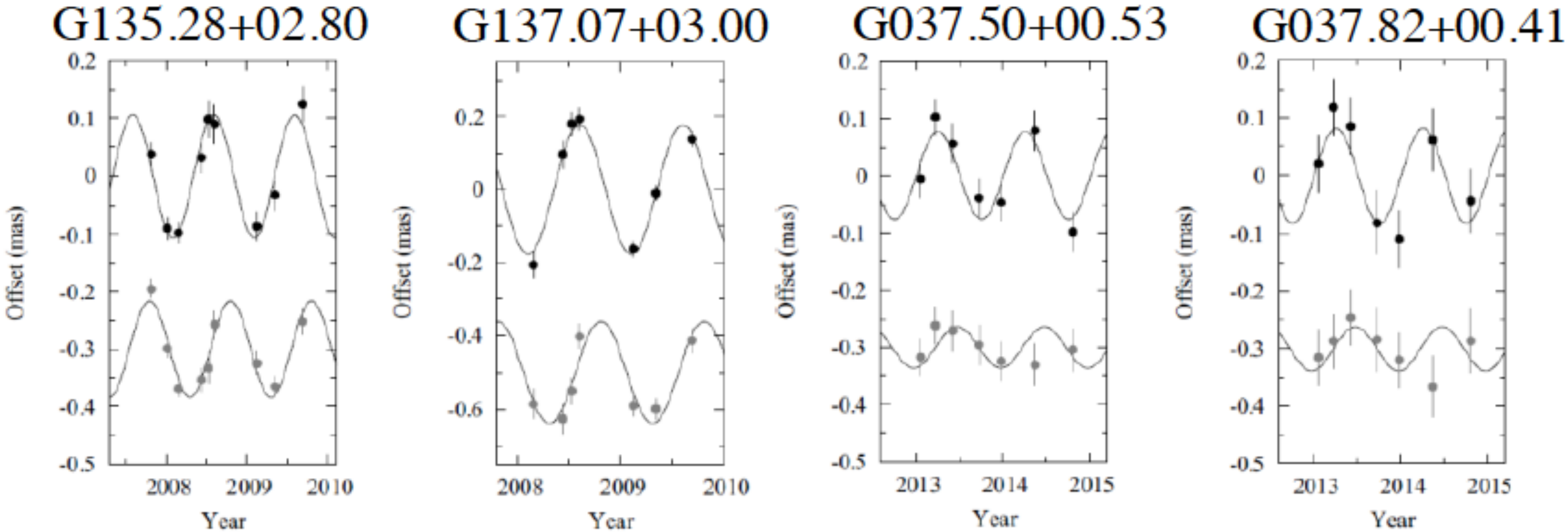
Precession of the M87 jet

(due to a blackhole spin?)

(EAVN Collaboration 2023)

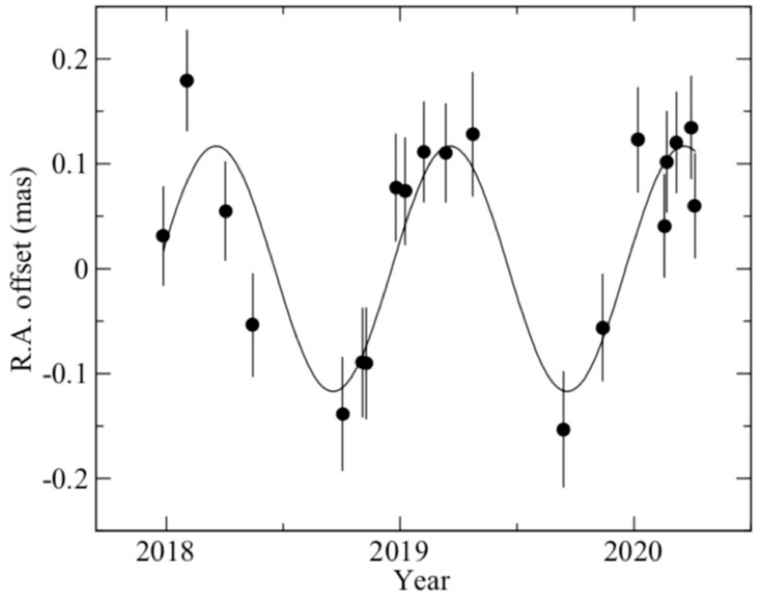
Hiroshi Imai, Kagoshima University

10 kilo-parsec scale radio trigonometry



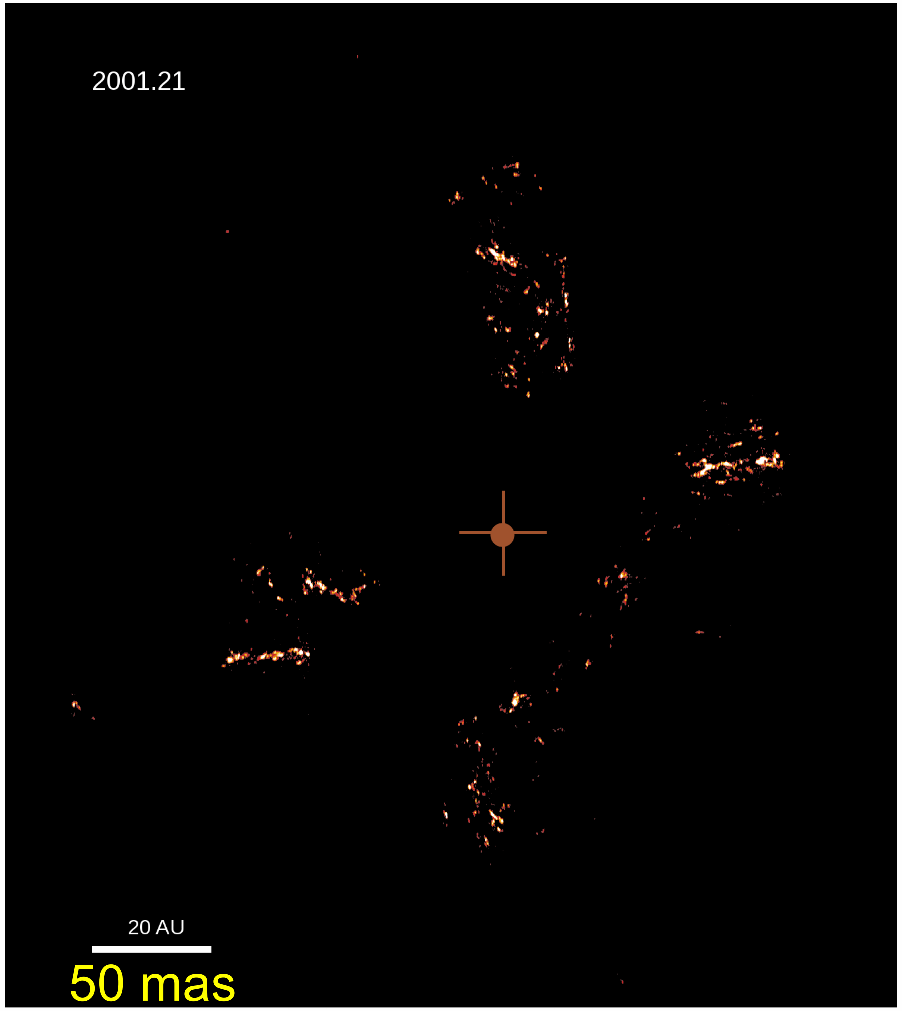
Nagayama et al. (2020)

VERA detects the annual parallax of Sgr A* (Galactic Center)
(Oyama et al. 2024)

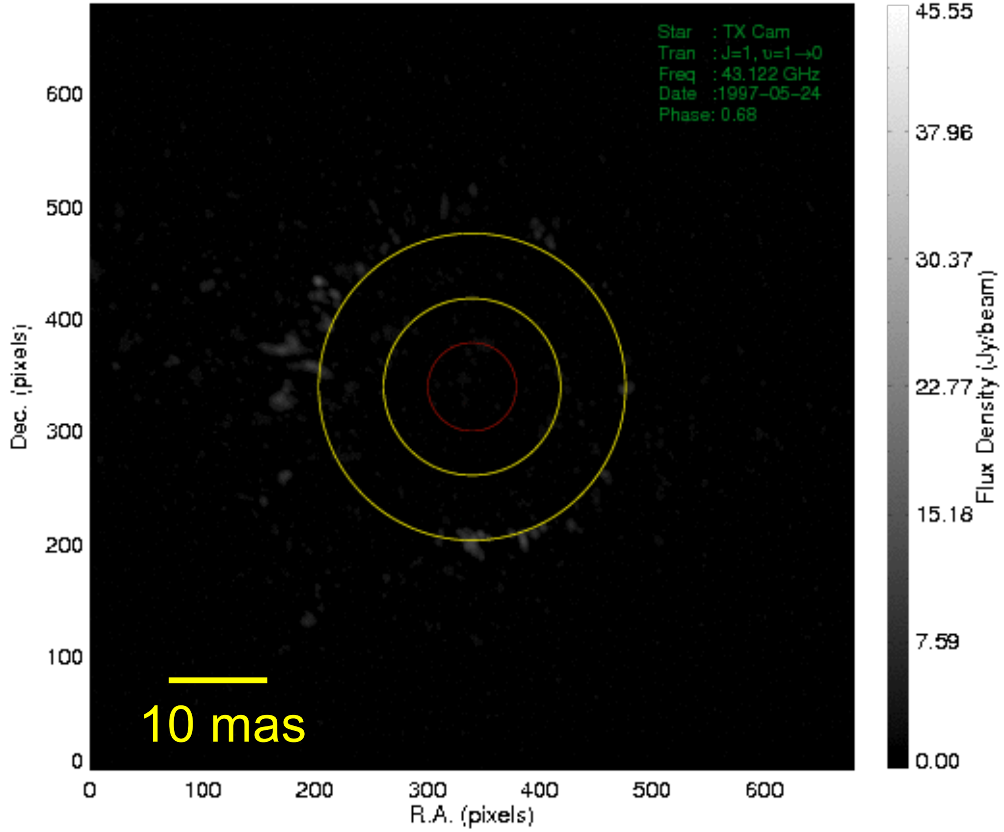


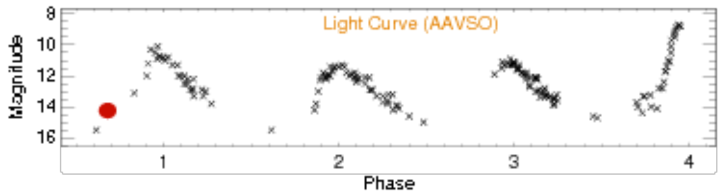
See also Nakagawa's lecture

Movies of astrophysical masers



SiO masers in Orion Source I
(Mattheus et al. 2009)

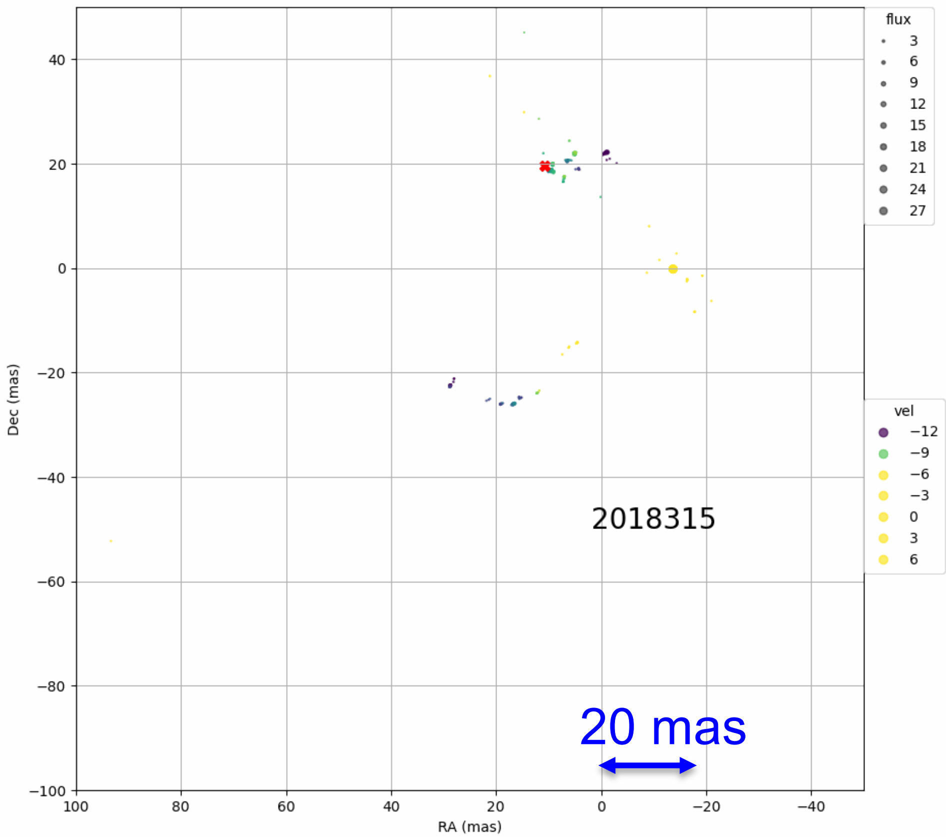


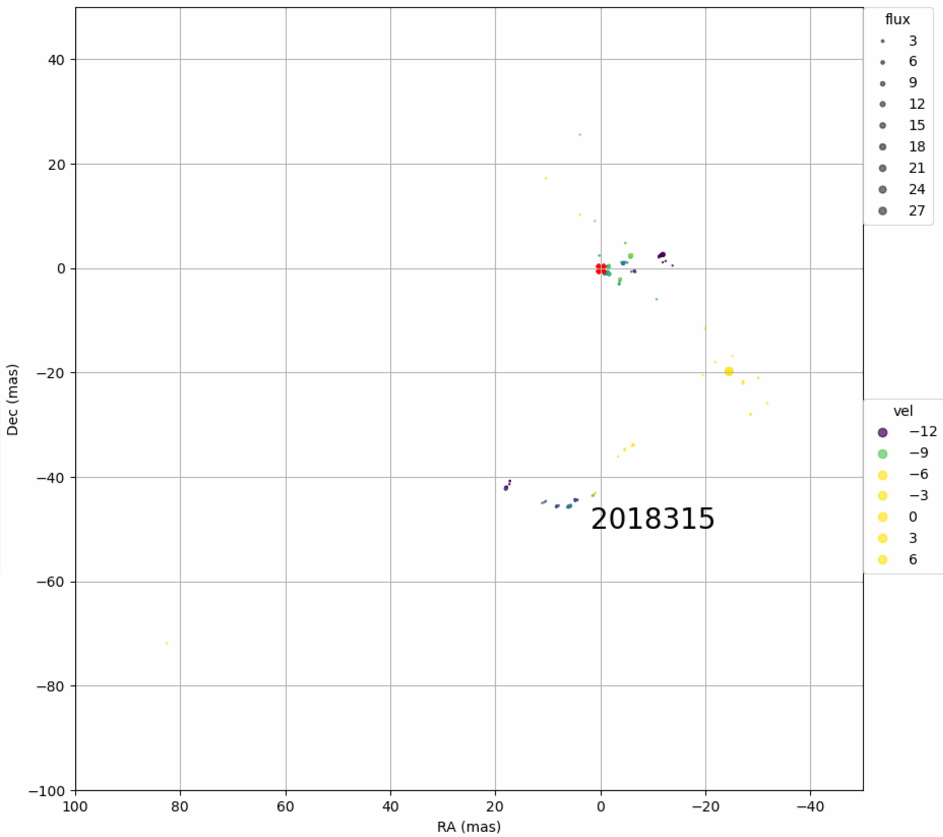


SiO masers around TX Cam
(Gonidakis et al. 2013)

Movies of astrophysical masers

Absolute motions | **Relative motions w.r.t the star**



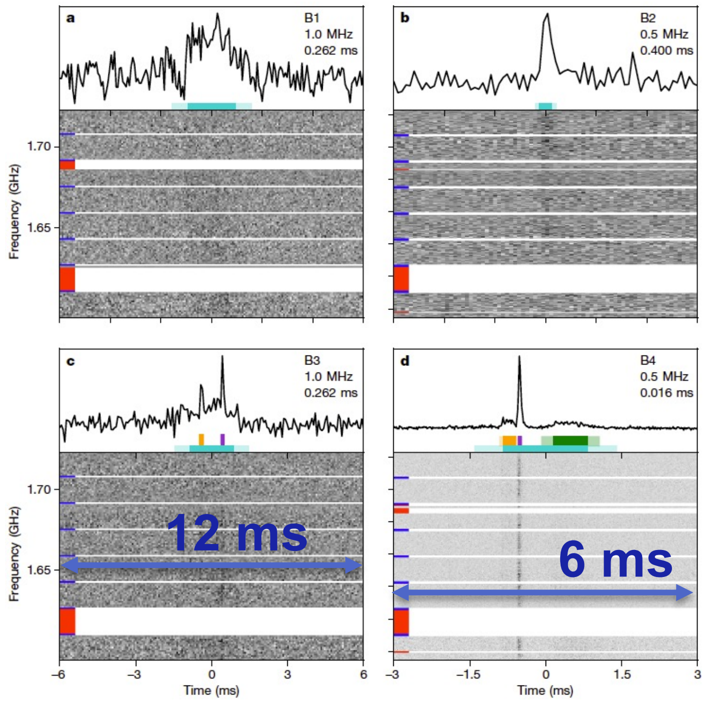


×: star (BX Cam) from Gaia EDR3

H_2O masers around BX Cam (Xu et al. 2022)

Localizations of key sources

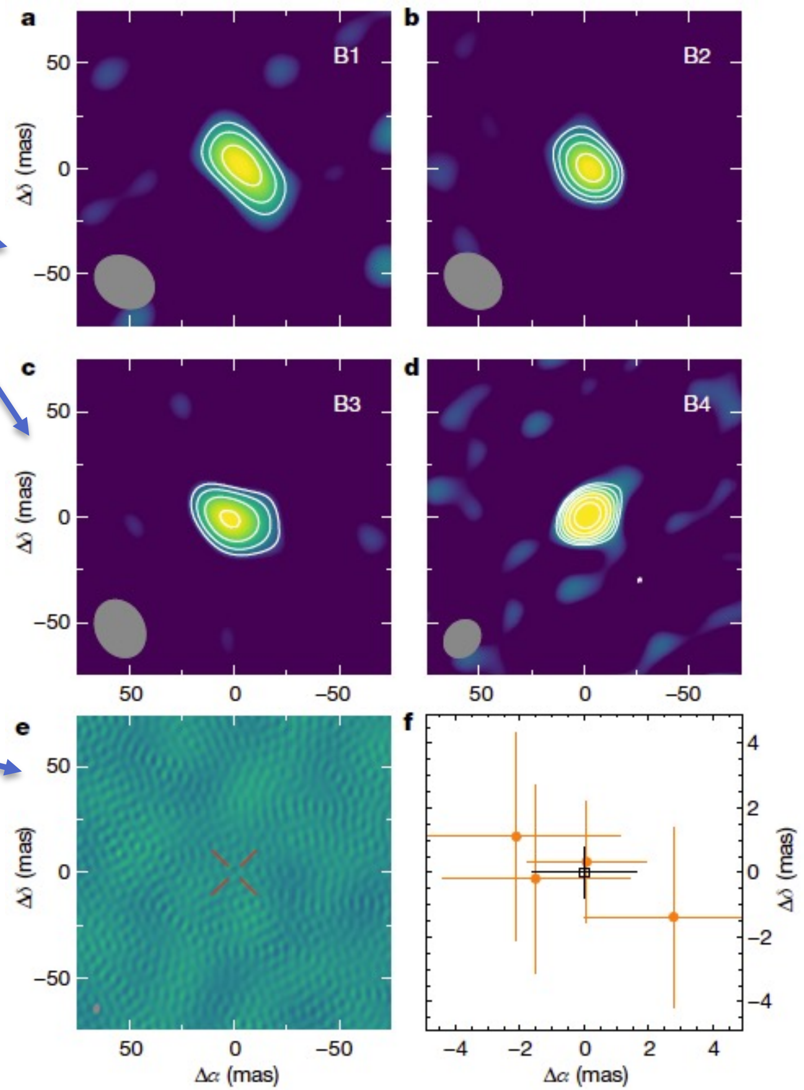
Detections of fast radio bursts (FRBs)

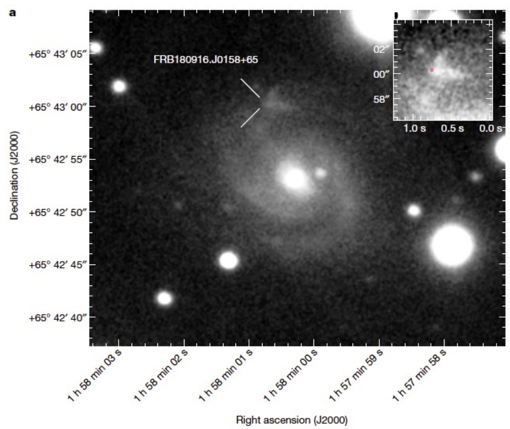


120 MHz
(1600—1720 MHz)

Using
pulse-gated
visibilities

Using
2s-integrated
visibilities

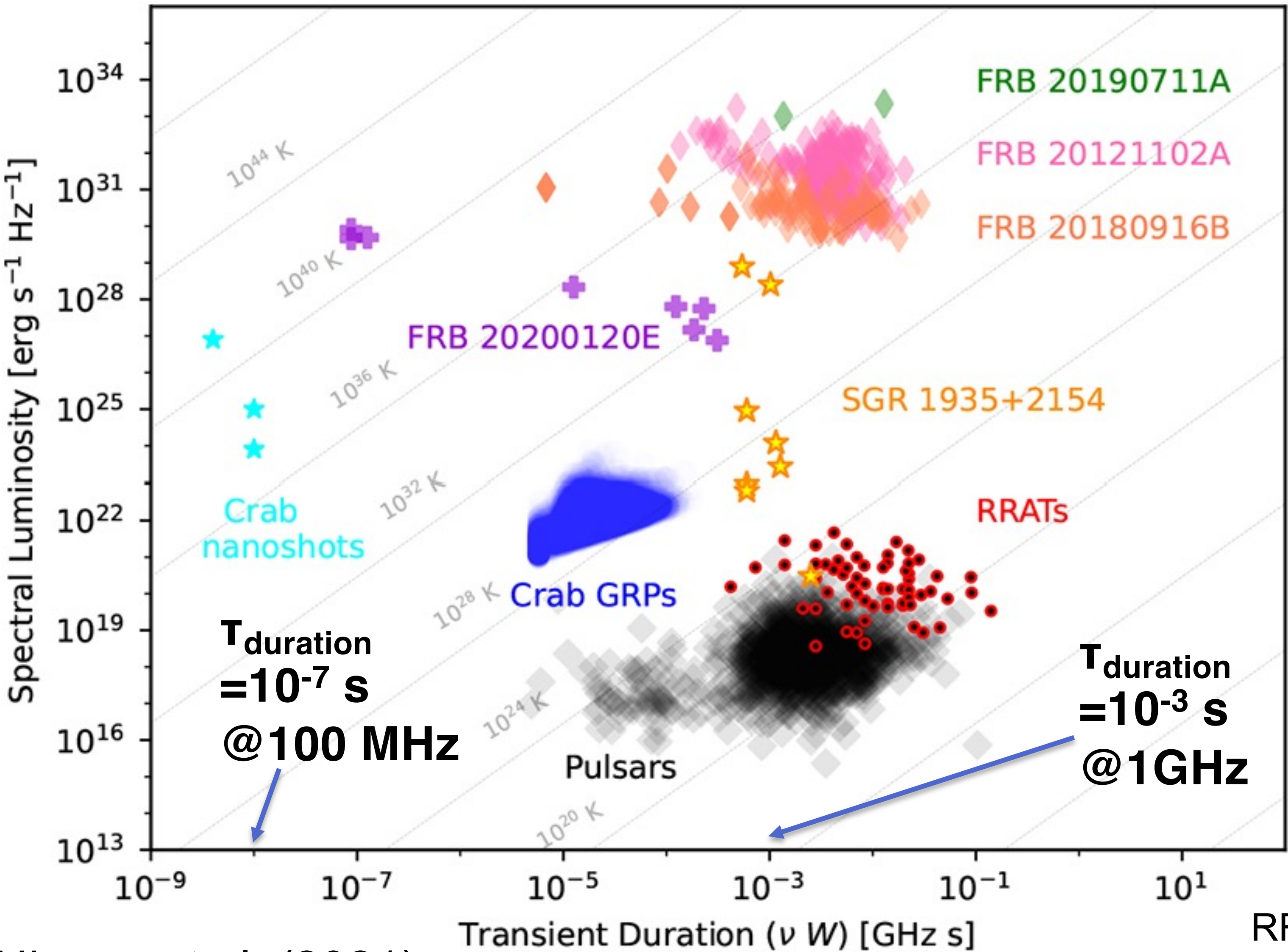




FRBs localization
in VLBI

Marcote et al. (2020)

Variety of (fast) radio transients



Nimmo et al. (2021)

Ex.1
3.2 Gbps
⇩
400 M samples/s
or 200 MHz
bandwidth
in 16 levels
(8 bits)

Ex.2
320 Mbps
⇩
40 M samples/s
or 20 MHz
bandwidth
in 16 levels
(8 bits)

RRATs=
Rotating radio transients

International collaborations in science and VLBI operation

- Limited opportunities of VLBI observations in the world against other astronomical observations for …..
  - a variety of key compact targets that should be monitored (>> a few hours, over decades)
  - a large fraction of VLBI sources that request high sensitivity and image quality
- Limited budget and human resources in individual countries, including Japan, may cause
  - long delays (>> 1 month) of data deliver since VLBI observations *through data correlation*
  - long time (>> 1 year) for paper publications if working alone
- VLBI is one of the clearest style of international collaborations and friendship built from exchanging scientific ideas to scientific publications through array construction and operation.

Challenges of VLBI in the SKA era

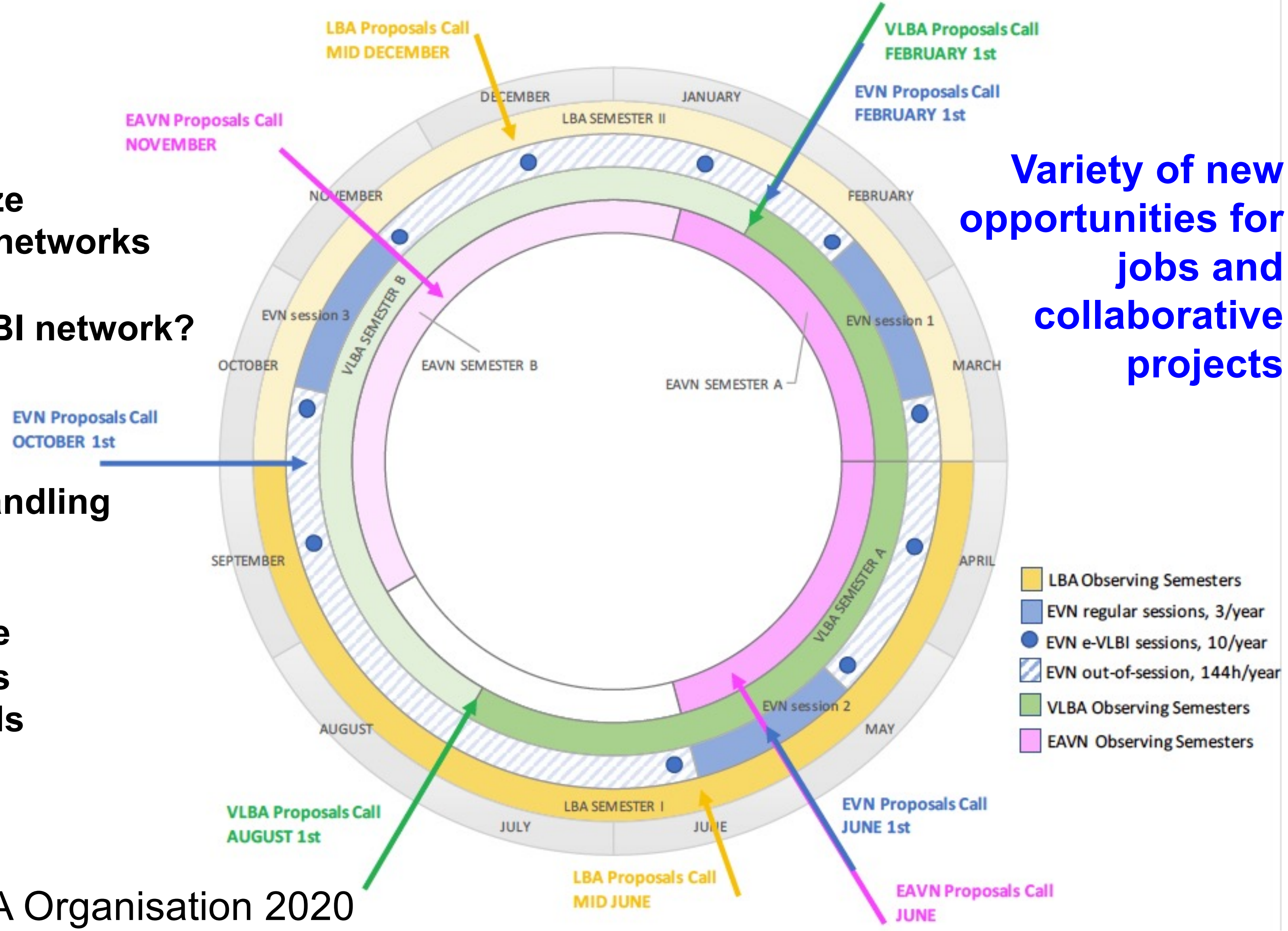
- ❖ Toward the Global VLBI alliance
- ❖ Toward ultimate accuracy / massive astrometry
- ❖ Time domain astronomy in VLBI

Toward the Global VLBI Alliance

How to organize
different VLBI networks
and SKA-VLBI
as a global VLBI network?

- Proposal handling
- Scheduling
- Correlation
- Data archive
- Publications
- VLBI schools

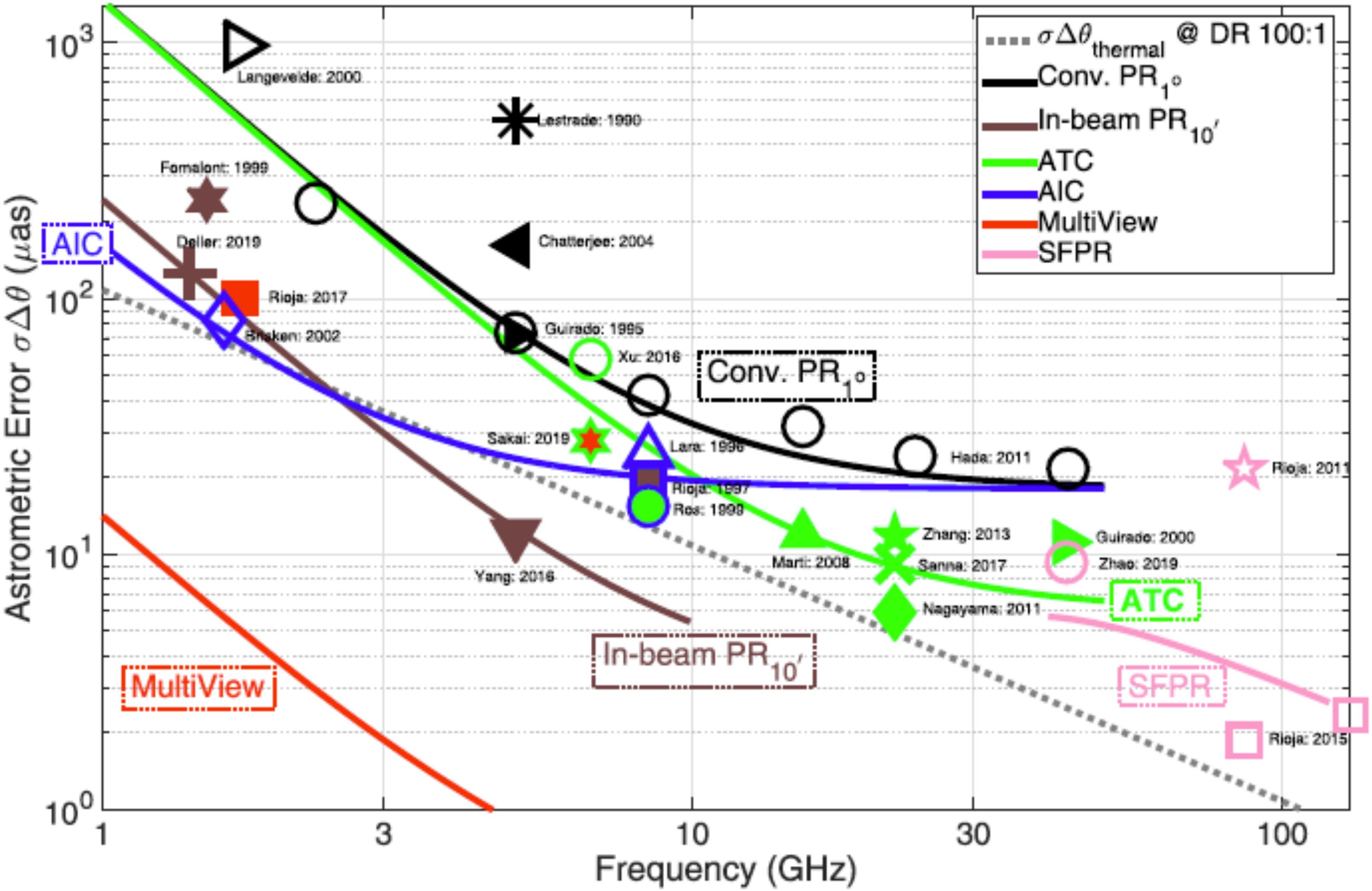
Variety of new opportunities for jobs and collaborative projects



JIV-ERIC & SKA Organisation 2020

SKA-JP
Square Kilometre Array
Japanese Consortium

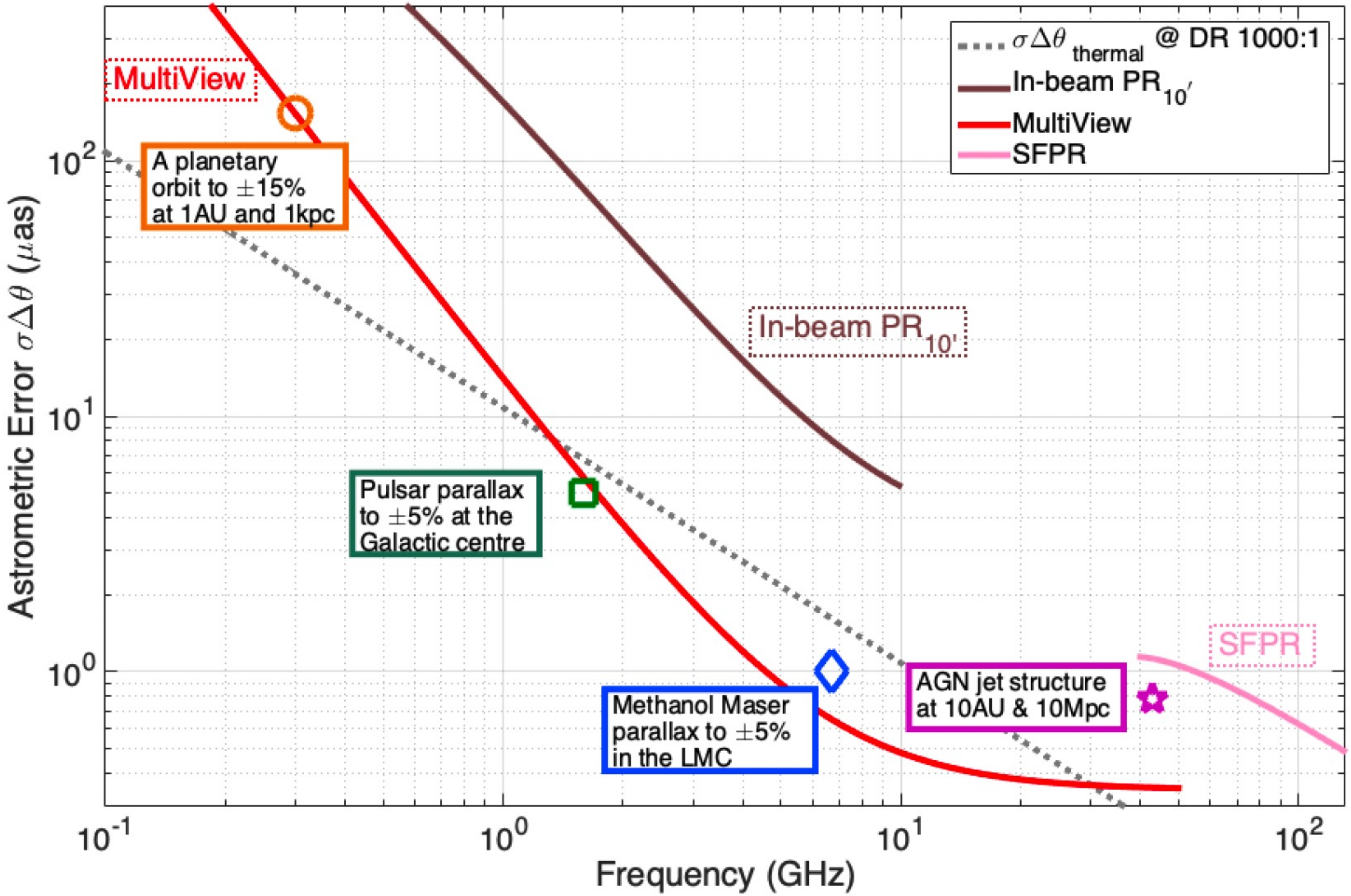
Toward ultimate accuracy astrometry



Rioja & Dodson 2020

AIC/ATC = advanced ionospheric/ tropospheric calibration technique
DR = dynamic range
PR = phase referencing
SFPR = source-frequency (switching) phase referencing

Toward 1-μas accuracy astrometry



Rioja & Dodson (2023)

Ultimate accuracy / massive astrometry

❖ Ultimate accuracy (σ~1 μas) astrometry

- Feasible at high frequency bands (>5 GHz)
- Trigonometry of Large/Small Magellanic Clouds (50 kpc/60 kpc)
- ~1 pc-accuracy level pulsar (<1 kpc) astrometry for improving detectability of gravitational waves from super-massive blackhole binaries ($P \gtrsim 1$ year)
- Detections of astrometric microlensing events

❖ Massive (>> 1000 targets) astrometry (σ~10 μas)

- Feasible at low frequency bands (< 2 GHz)
- 3D kinematics of individual nearby star-forming regions probed by young stellar objects (YSOs, non-thermal sources)
- 3D kinematics of the Galactic Nuclear Disk and Bulge probed by long-period variable stars (OH masers)
- 3D kinematics of Large/Small Magellanic Clouds (OH masers)

Time domain astronomy in VLBI

- ❖ **Technology of automated processing for transient buffer data**
  - Largest beam with single dishes
  - Synthesizing multiple *interferometer beams in realtime* **(see right)**
  - Syntesizing multiple *VLBI beams in offline*
  - Channelization should also be taken into account.
- ❖ **VLBI scheduling for transients**
  - Alerts of VLBI transients
  - Rules for transient VLBI

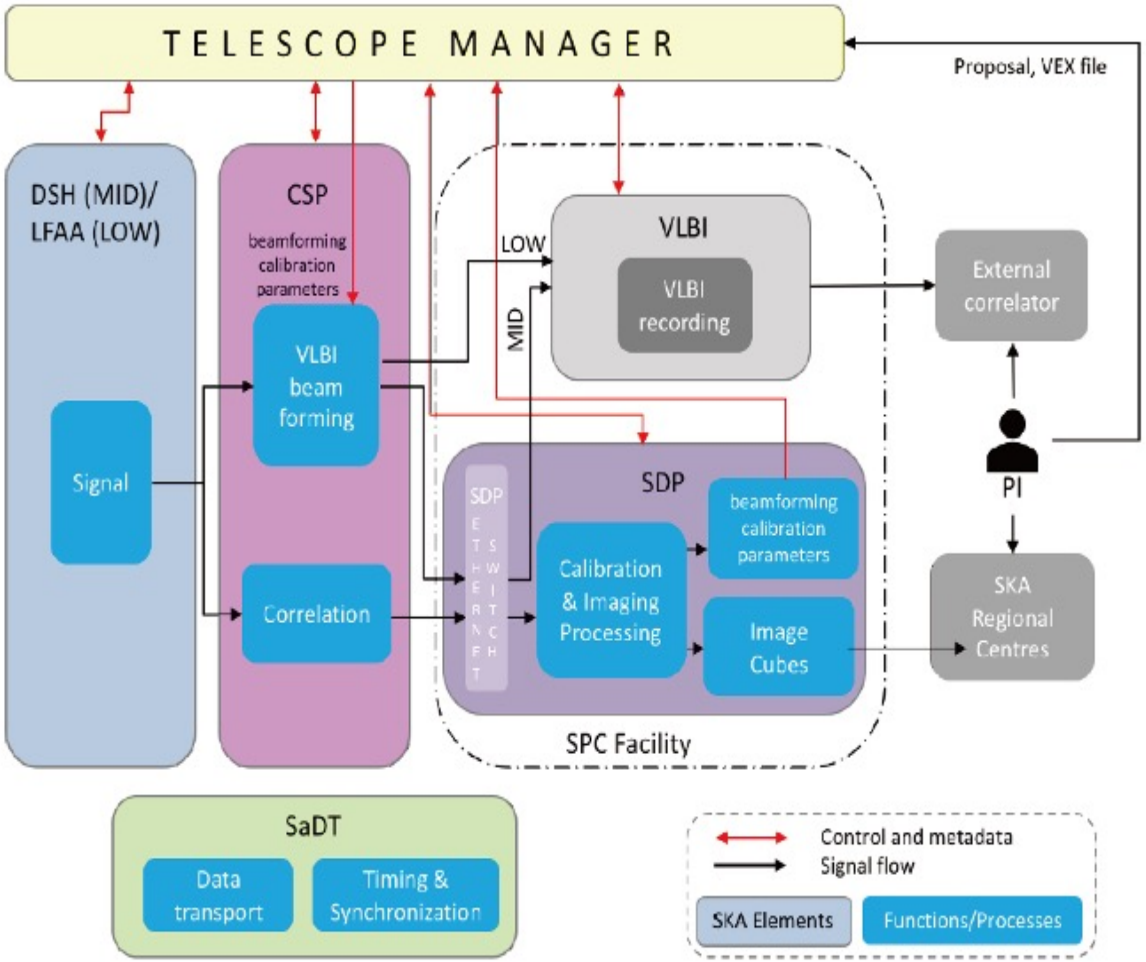
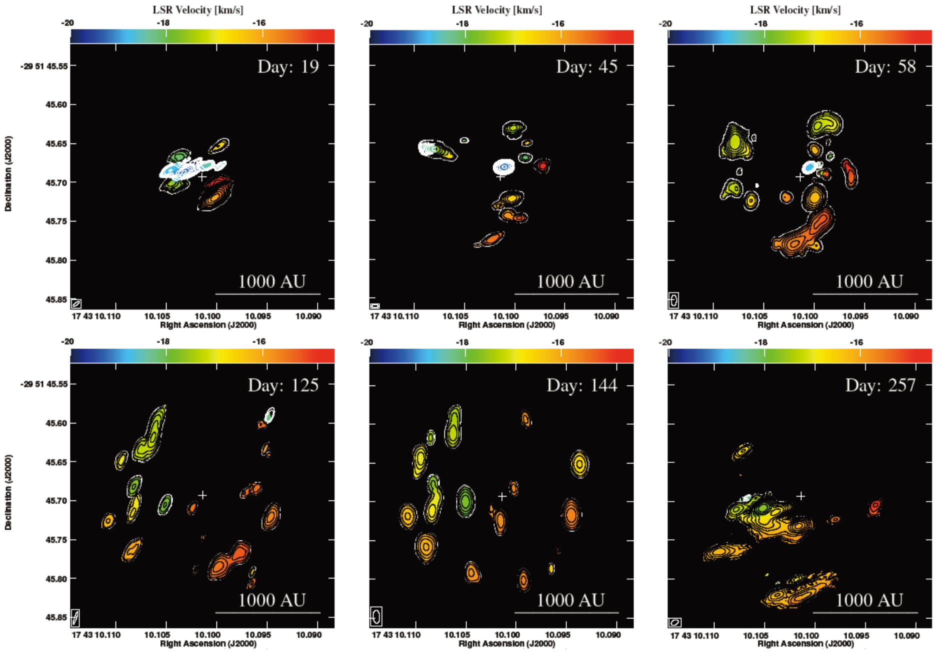


Figure 1. SKA-VLBI Capability for the SKA1 Observatory

JIV-ERIC & SKA Organisation 2020

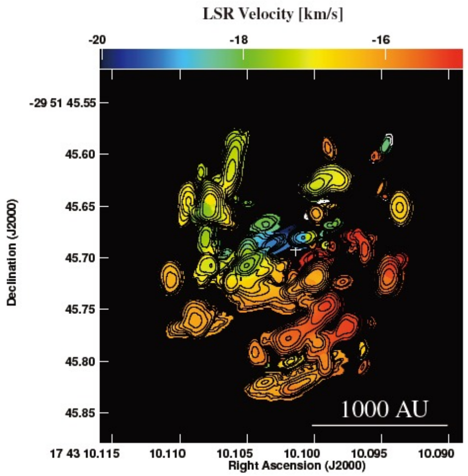
Maser Monitoring Organisation (M2O)

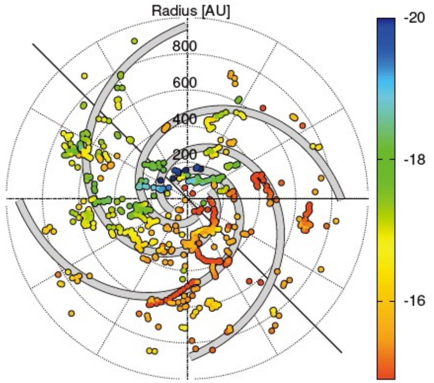


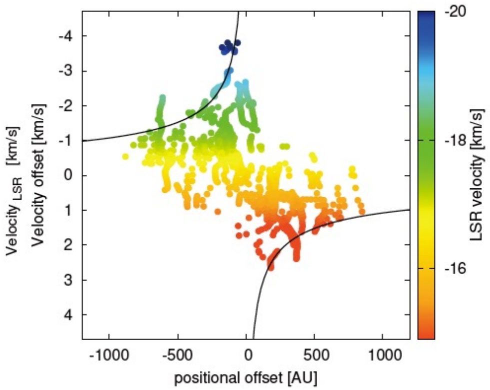
A Keplerian disk with a four-arm spiral birthing an episodically accreting high-mass protostar
Burns et al. (2023)

https://www.masermonitoring.com

- ❖ **Synergy for single-dish monitoring of methanol masers and multi-wavelength observations**







- ❖ **Follow-ups by VLBI observations in target-of-opportunity (ToO) triggers**

Summary and future perspectives

❖ Variety of efforts in VLBI toward the SKA era

- Variety of science goals yielded with even a single VLBI array
  e.g., VERA dedicated for astrometry
- Variety of stages of international collaborations built from designing a VLBI array to scientific project through construction and operation of the VLBI array
- One of the best suitable models of peaceful international cooperation

❖ Challenges of VLBI toward the SKA era

- Complexity of VLBI array operation
- Technical challenges in ultimate accuracy and massive astrometry
- *Sustainable* development of VLBI arrays and their science cases
- *Sustainable* human interactions in young generation