Toward tracking SMBH binary orbits

Pilot K/Q simultaneous observation using KVN and Yebes-40m telescope

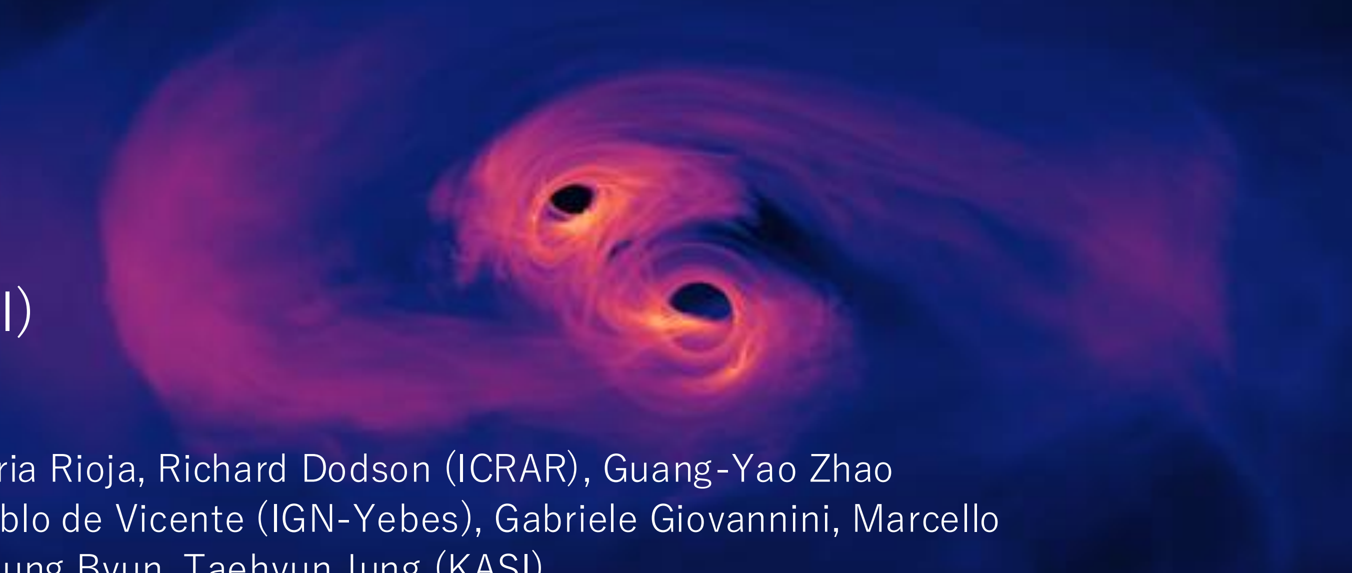

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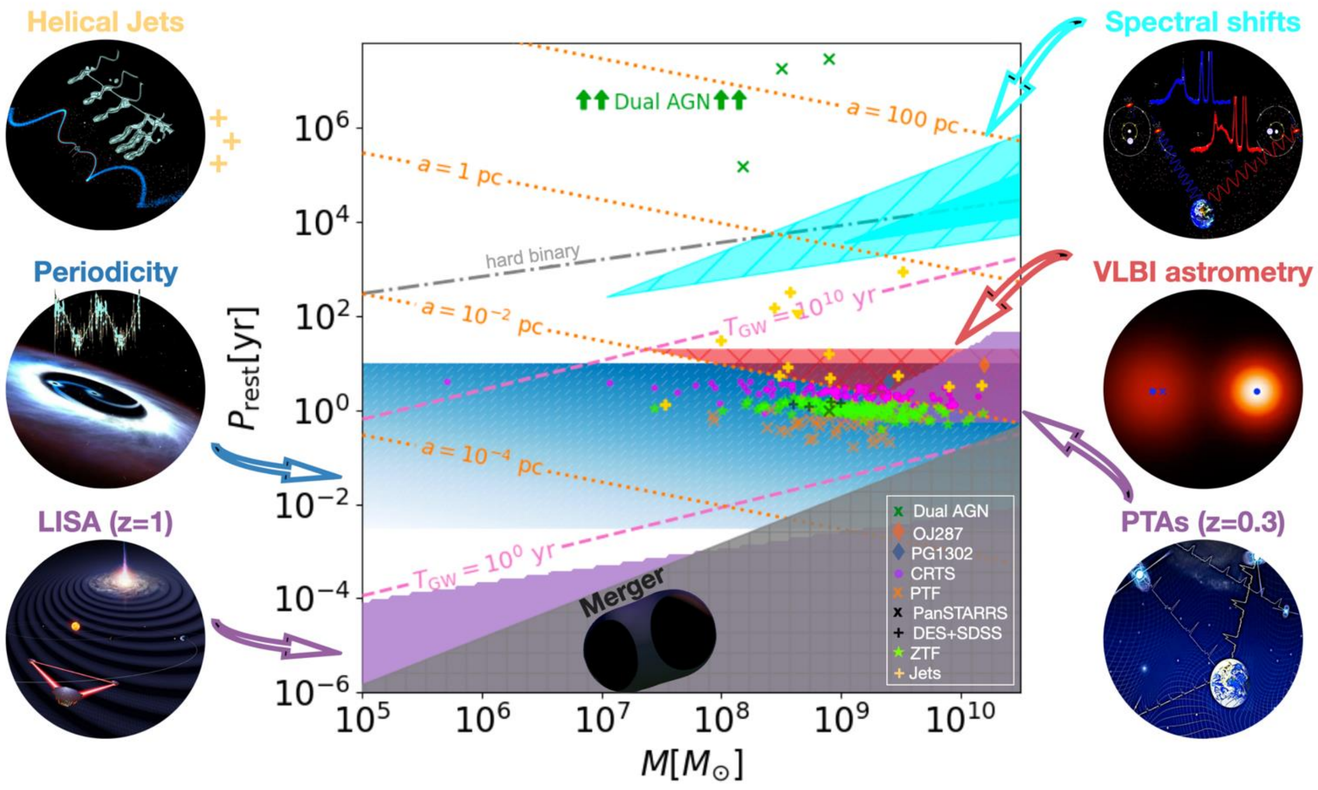
Image Credit: NASA's Goddard Space Flight Center

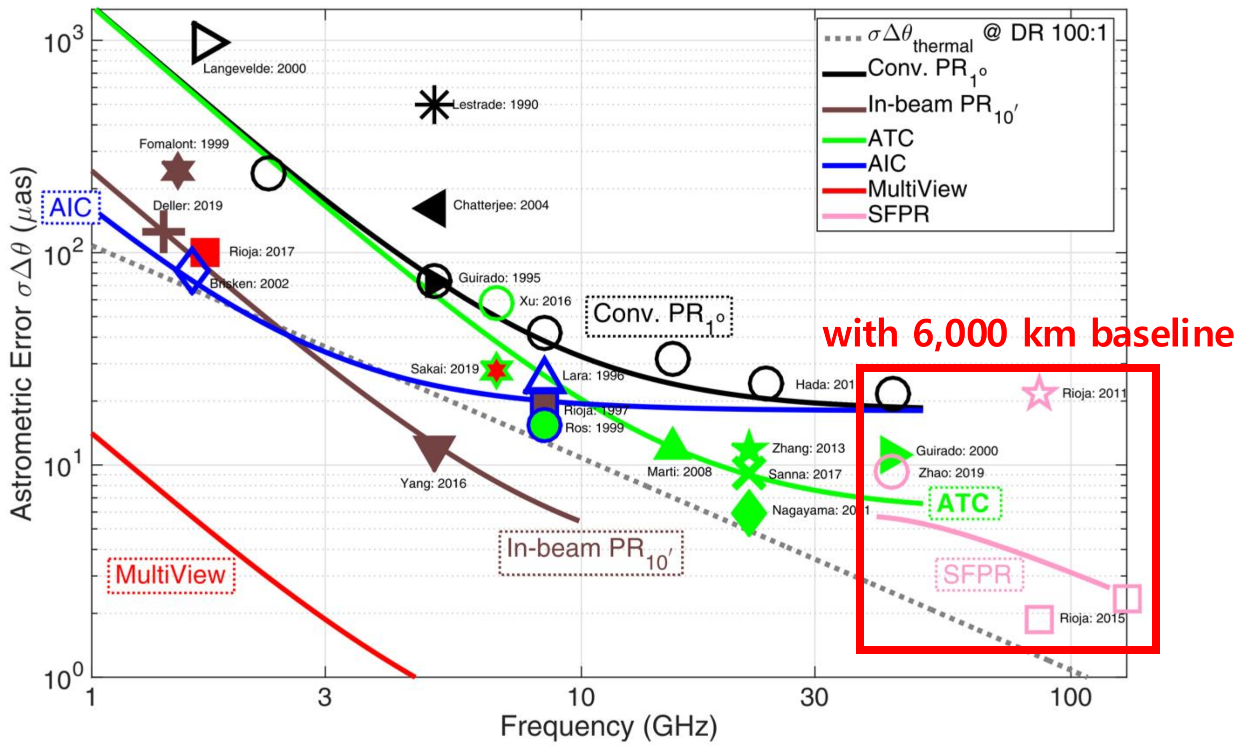
Observational identification of SMBH binaries



D'Orazio and Charisi 2023

- Spectroscopic/Photometric observations
  - ✓ Broad emission line kinematics
  - ✓ Periodic light curves
- VLBI imaging
  - ✓ Spacially separated radio cores (Dual AGNs)
  - ✓ Peculiar jet morphologies (e.g., Helical jet)
- Direct methods
  - ✓ Gravitational waves (PTA)
  - ✓ **Tracking binary orbits (VLBI astrometry)**

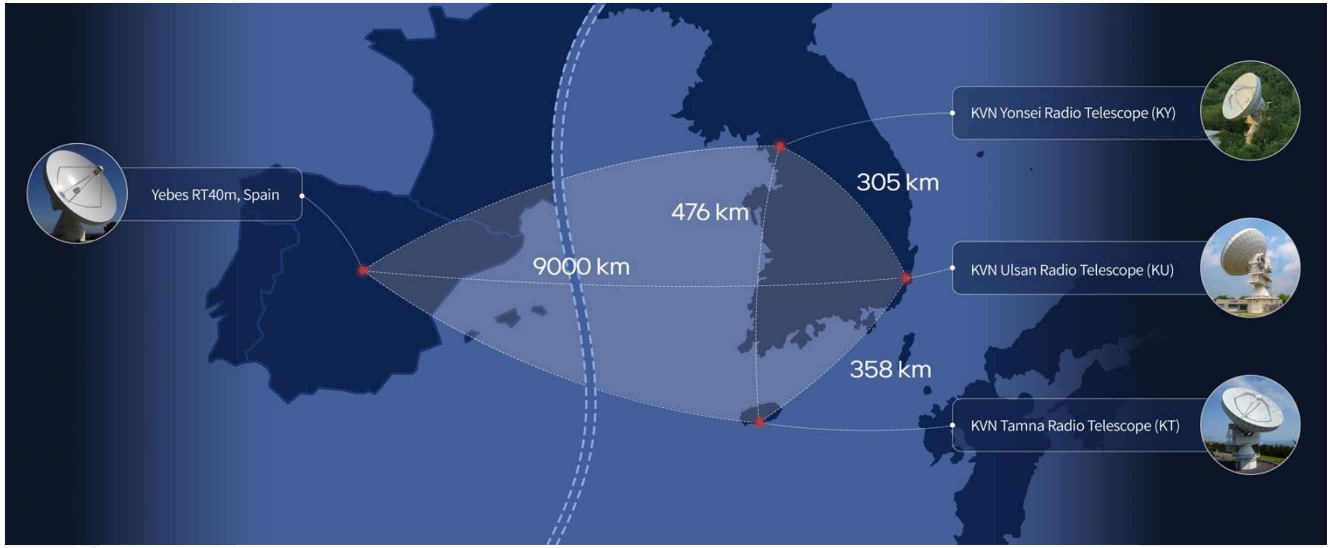
High-precision VLBI astrometry using SFPR technique

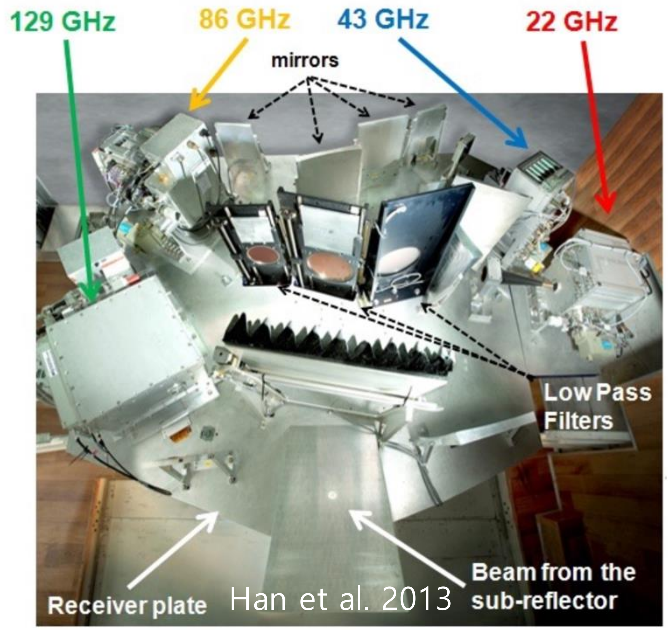


Rioja & Dodson 2020

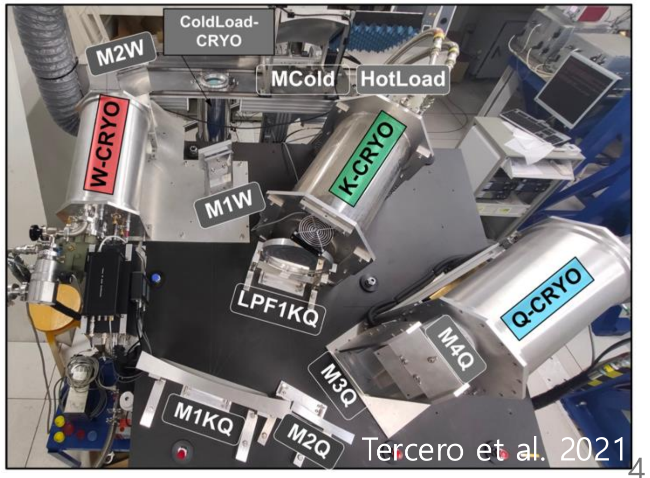
- Precision of VLBI astrometry limited to ~10 μas due to short coherence times at high frequencies
  - ✓ Tracking SMBHBs requires high-precision (~1μas-scale) astrometry (Zhao et al. 2024)
- Source/Frequency Phase Referencing (SFPR) enables **astrometry > 40 GHz**
  - ✓ **SFPR at long-baselines (> 6,000 km) is essential** to achieve the desired astrometric precesion
  - ✓ Increases coherence time (hence S/N ratio) and less affected by opacity (i.e., core-shift)

Pilot K/Q simultanous observation using KVN + Yebes



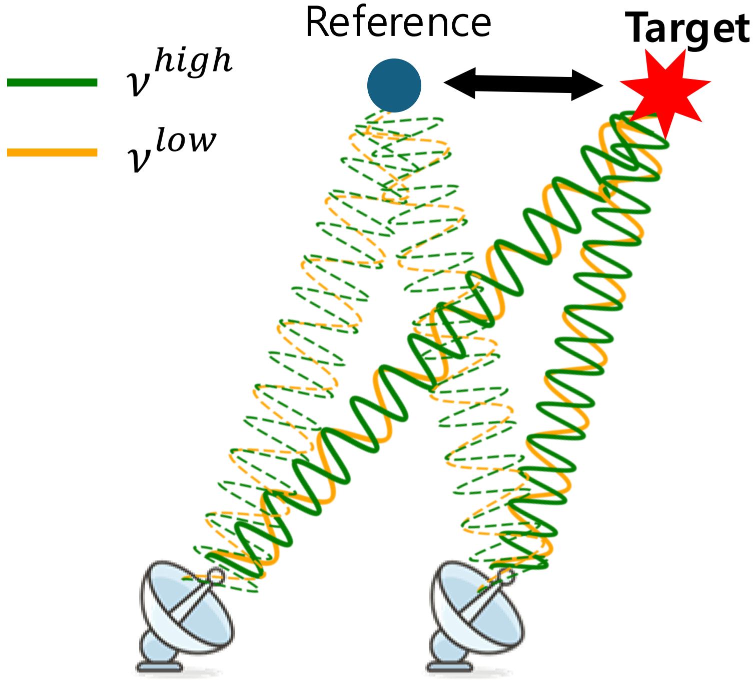


Multi-frequency receiver of KVN (up) and Yebes (down)



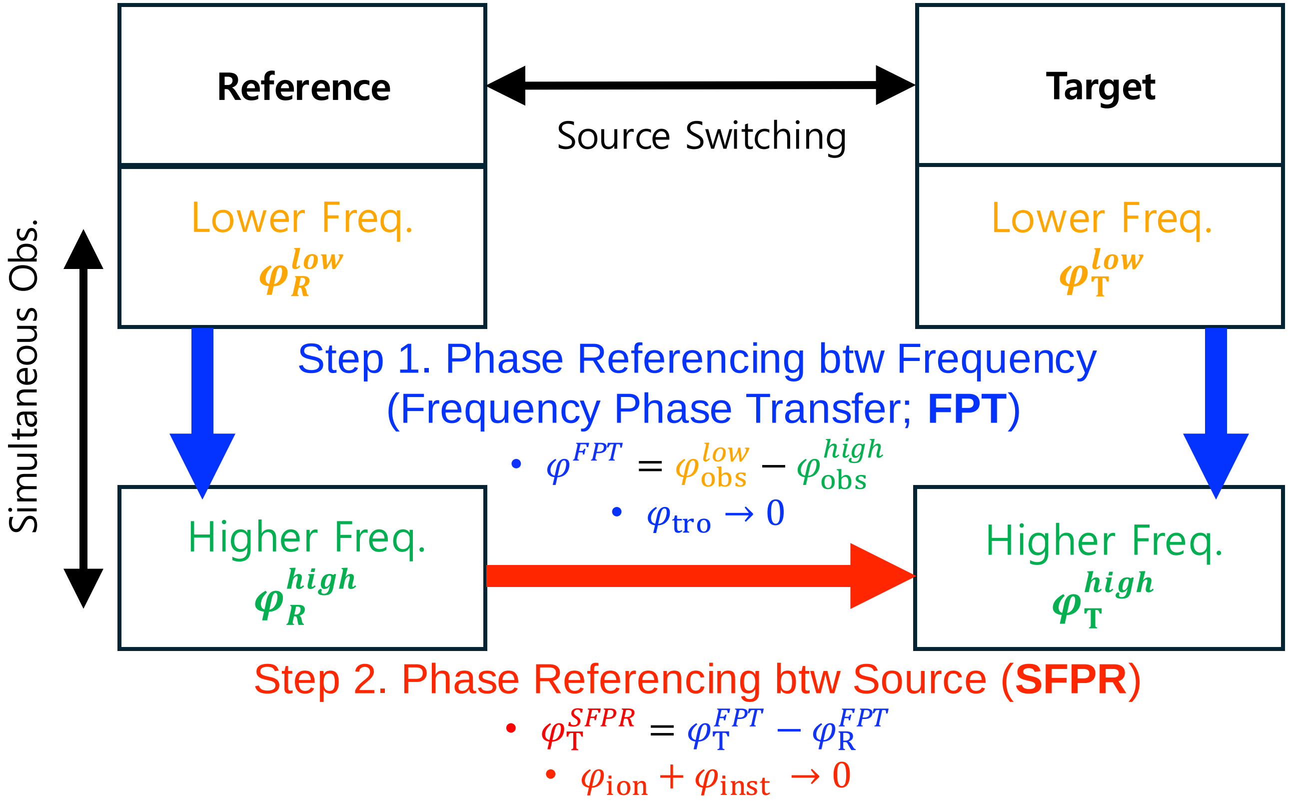
- Observation date: Jan. 15th, 2021 (12-hour session)
- Telescopes: KVN and Yebes-40m (baseline up to ~**9,000 km**)
- Frequency: **22/43 GHz (simultaneous)**
  - ✓ 512MHz bandwidth, single pol. (4Gb/s recording rate)
- Targets
  - ✓ Pair 1: **3C 84,** J0313+4120 (1.28°)
  - ✓ Pair 2: **OJ 287,** J0856+2111 (1.20°)
  - ✓ Pair 3: **Mrk 421,** J1101+3904 (1.20°), J1110+4403 (5.97°)

Source/Frequency Phase Referencing



$$\varphi_{obs} = \varphi_{pos} + \varphi_{str} + \varphi_{tro} + \varphi_{ion} + \varphi_{inst} + \varphi_{ther} + 2\pi n$$

SFPR calibration steps

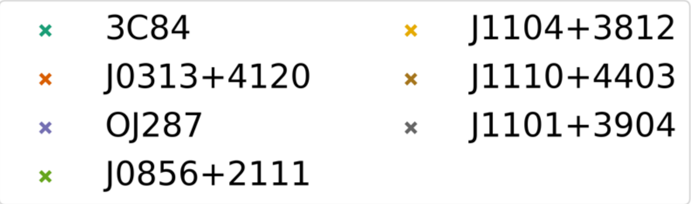


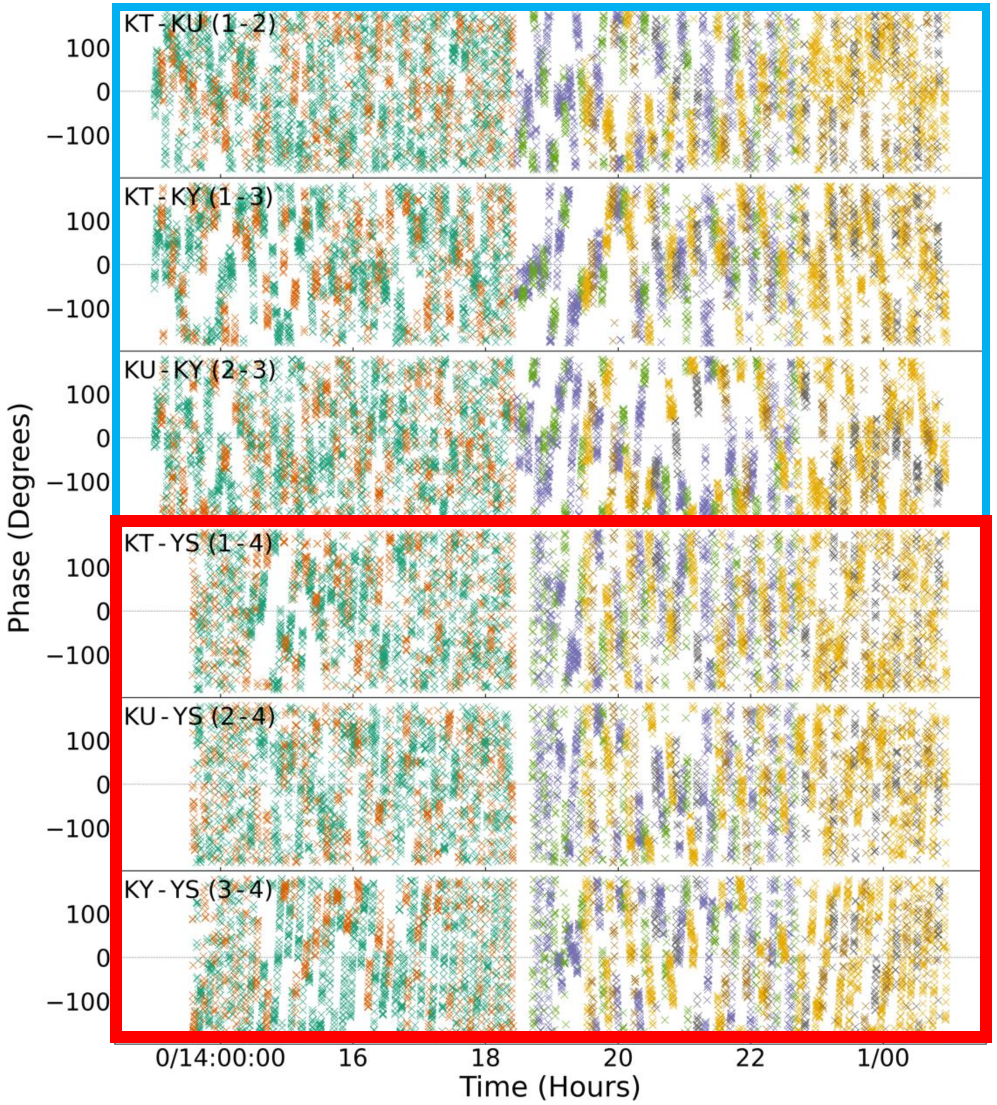
Rioja & Dodson 2011

$$\boldsymbol{\varphi_T^{SFPR} = \varphi_{T,\,str}^{high} + 2\pi \vec{D}_\lambda \cdot (\vec{\theta}_T - \vec{\theta}_R)}$$

Visibility phases before and after FPT

- **FPT improves phase coherence** over long baselines (~9,000 km)

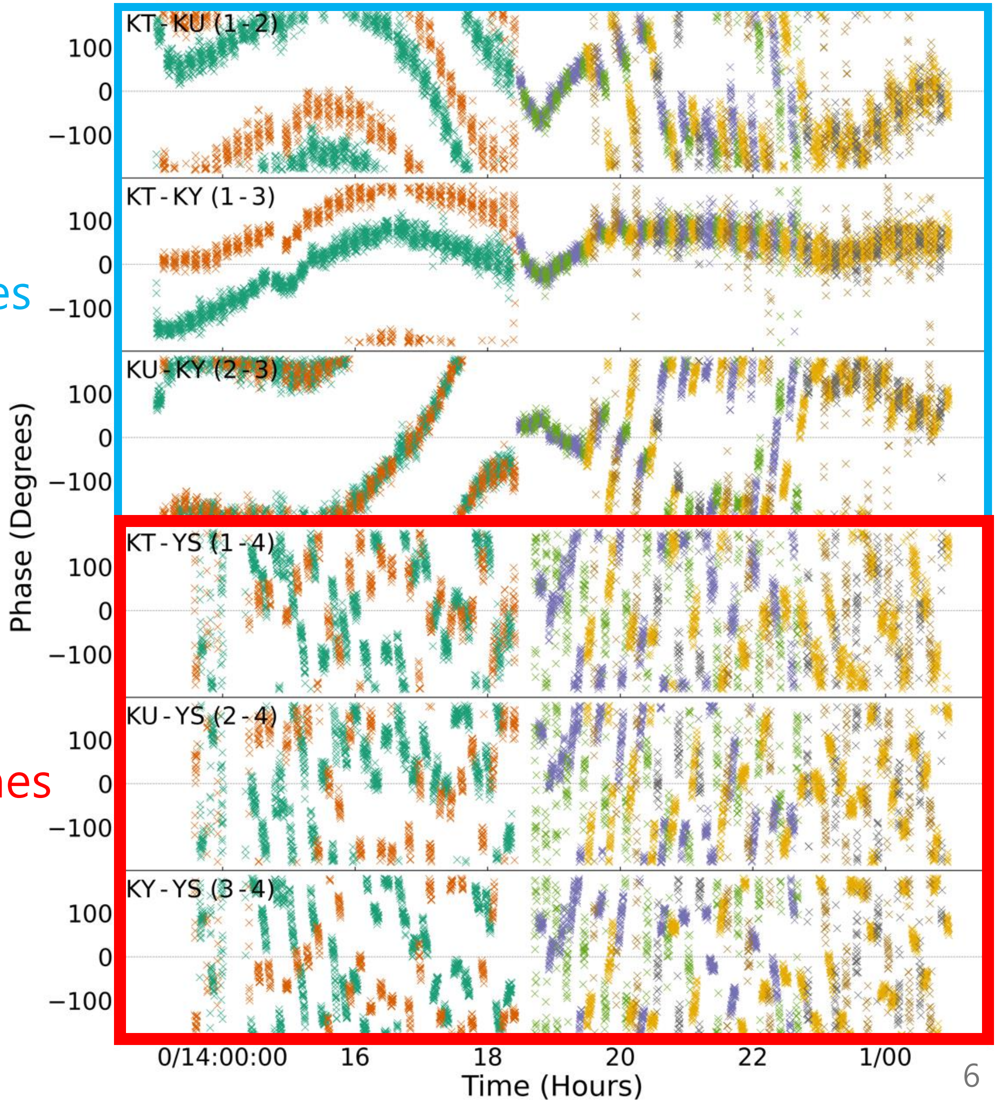




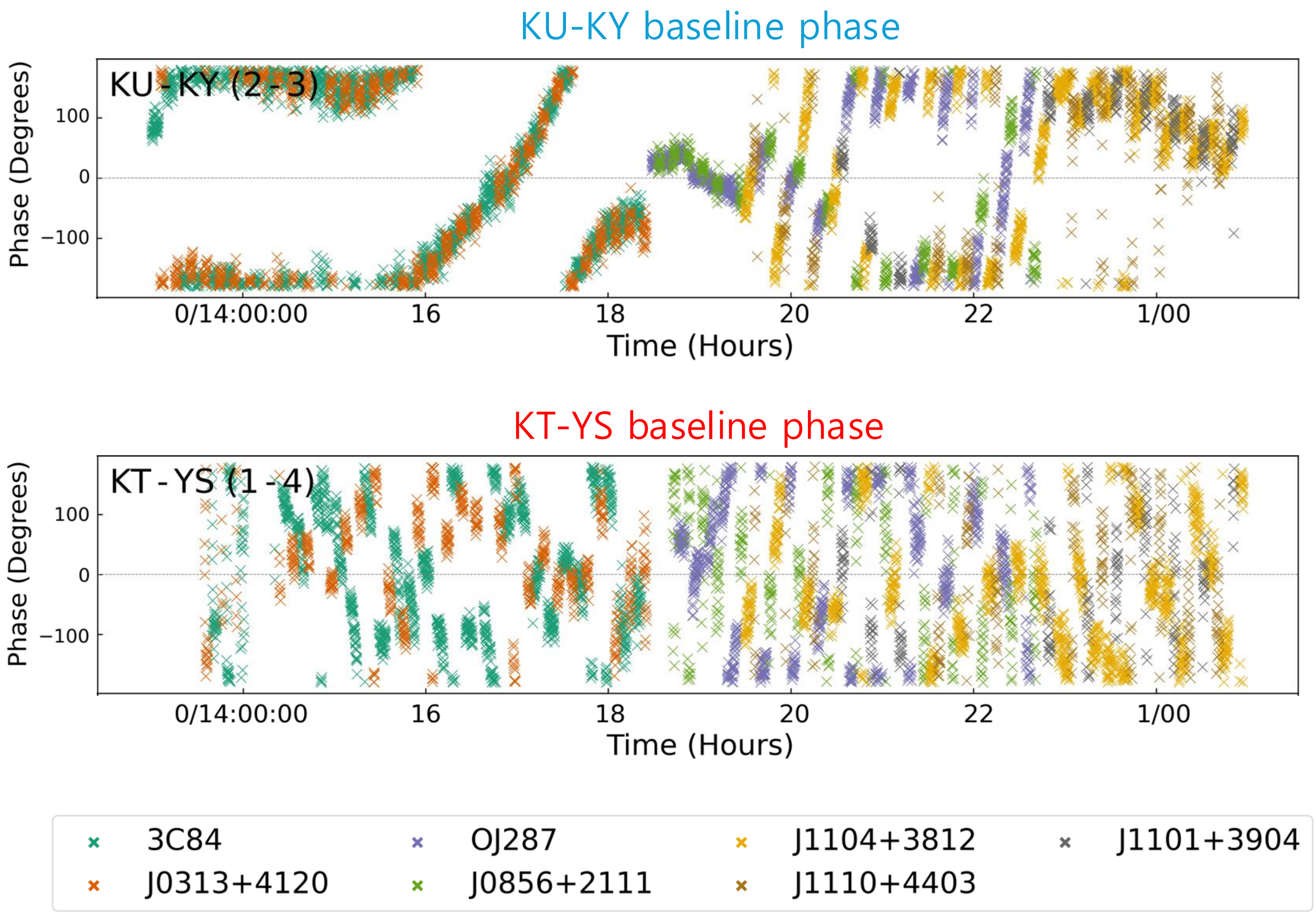
KVN baselines

FPT

Yebes baselines



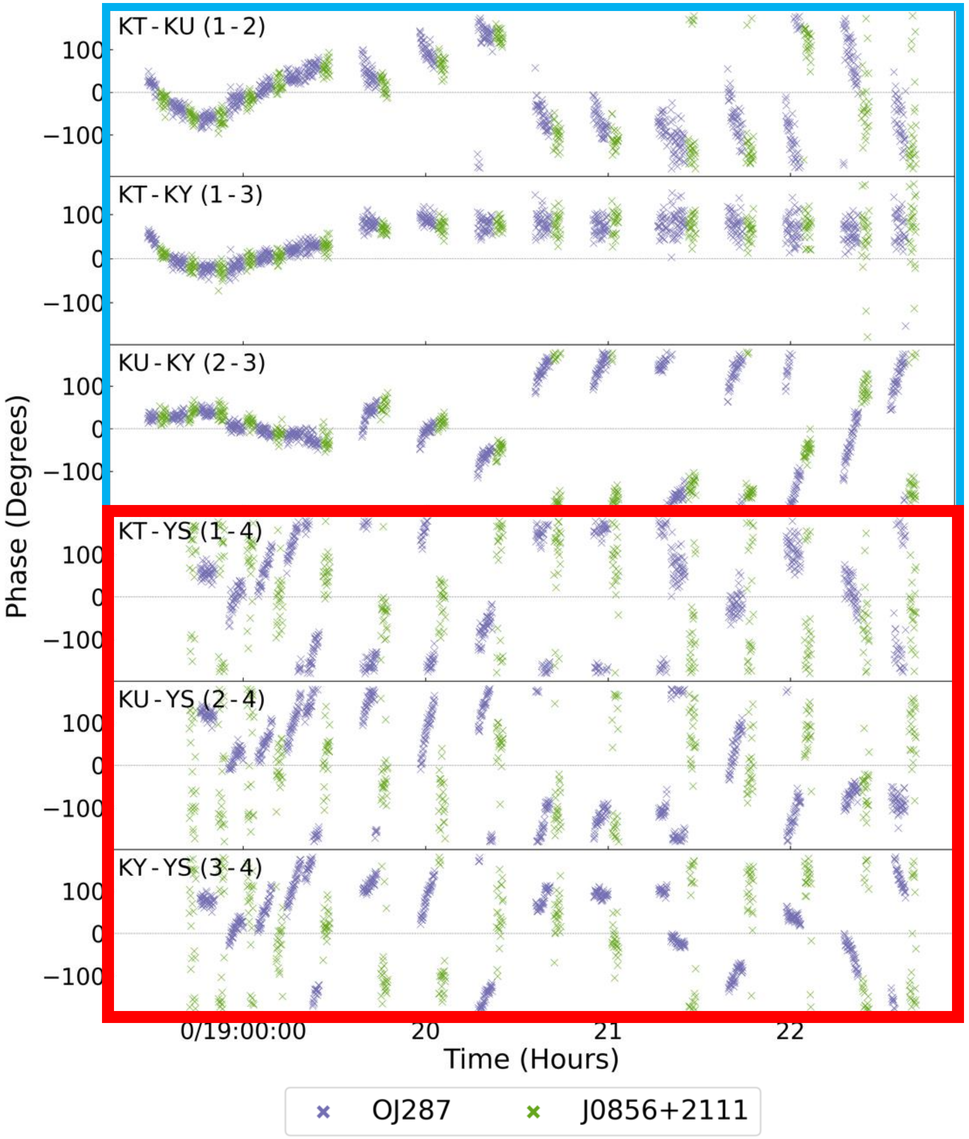
FPT visibility phase



- Although phase coherence improved, **fast variations and disconnections found in Yebes baselines** (and KUS baselines around 20h – 22h)
- Such disconnections of FPT phase were not found in previous observation using KVN and VLBA (Rioja et al. 2014)
- Possible reasons
  - ✓ (Non-dispersive) Ionospheric or instrumental errors
  - ✓ Effects of source structures
  - ✓ Etc …

Difficulty of SFPR calibration (2π ambiguity)

- The rapid phase variations and disconnections still remains in SFPR visibility phase at Yebes baselines

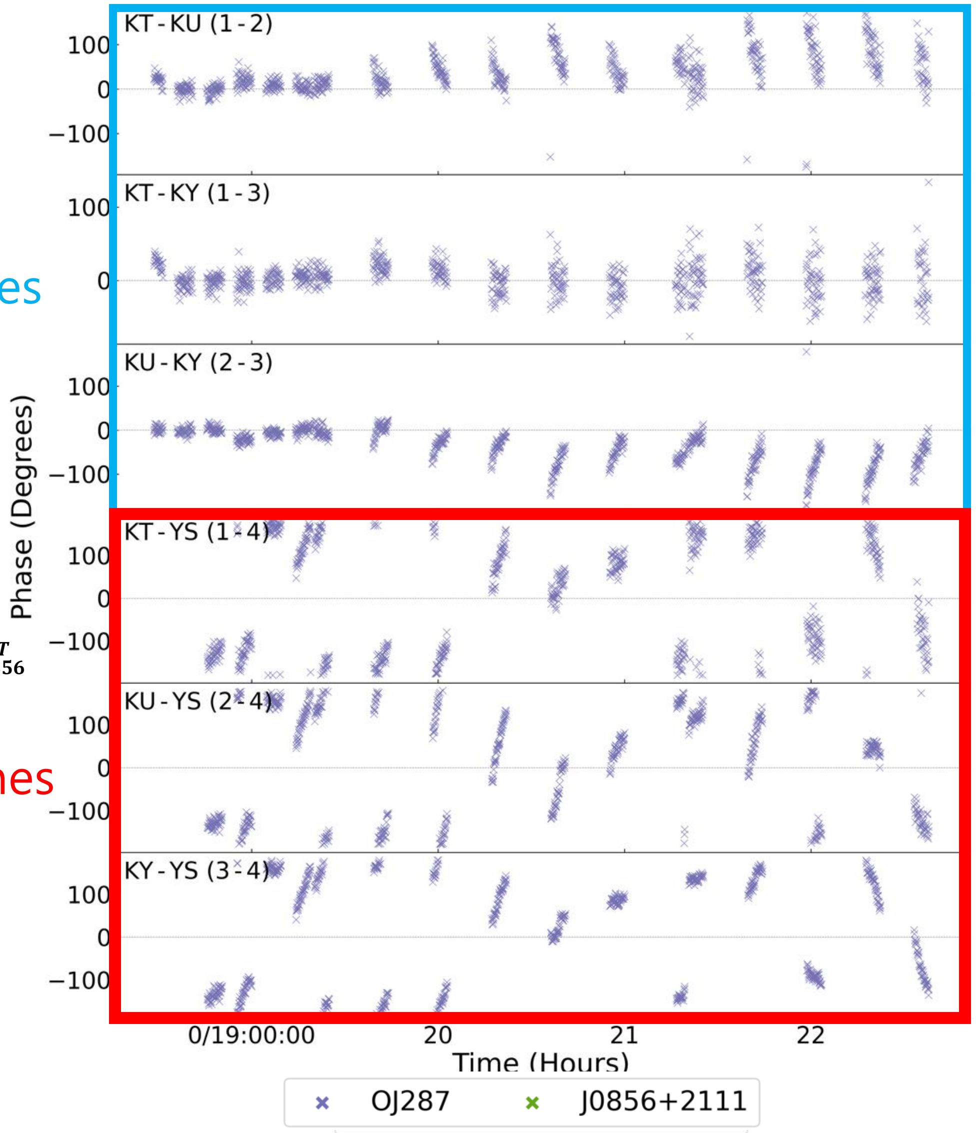


KVN baselines

SFPR

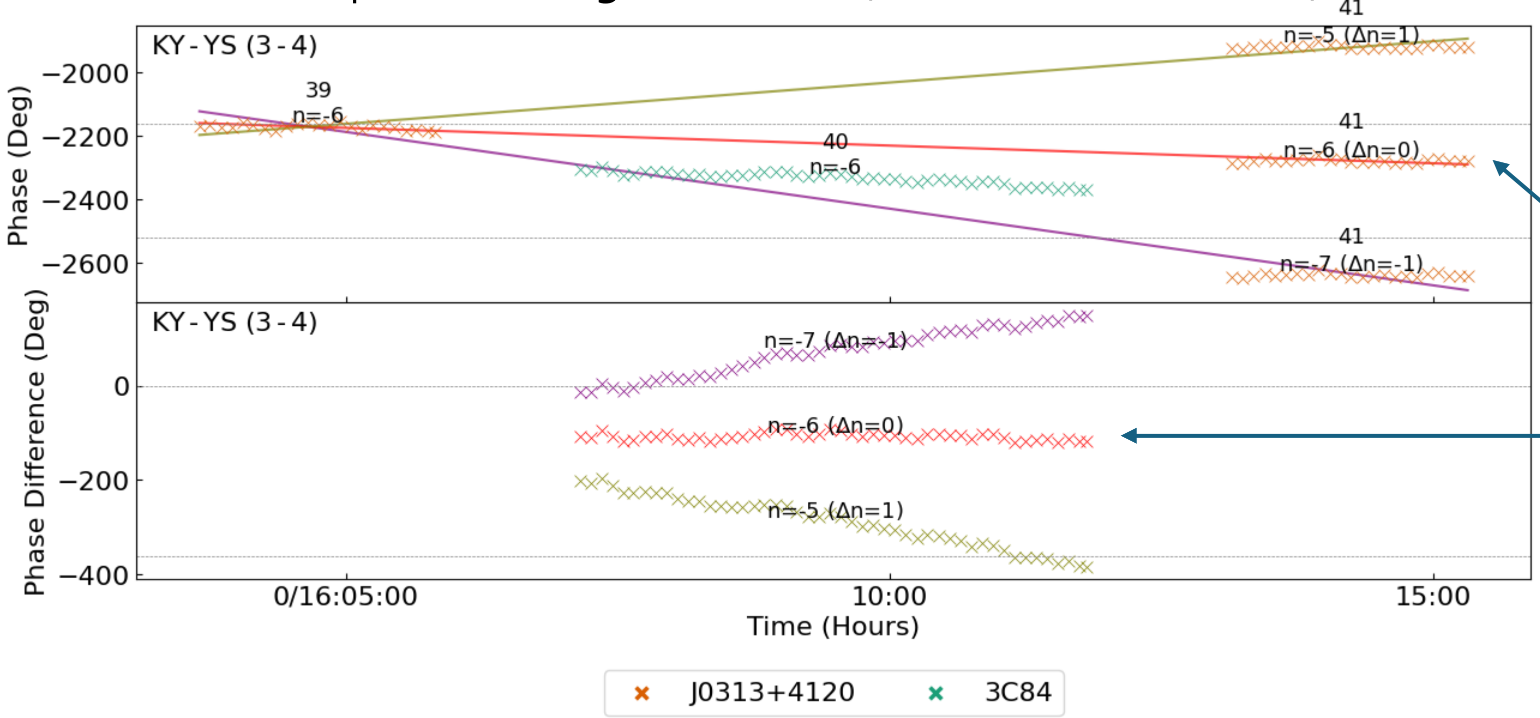
$$\varphi^{SFPR}_{OJ287} = \varphi^{FPT}_{OJ287} - \varphi^{FPT}_{J0856}$$

Yebes baselines



Difficulty of SFPR calibration (2π ambiguity)

Example of **finding the best n** (Scan #41; J0313+4120)

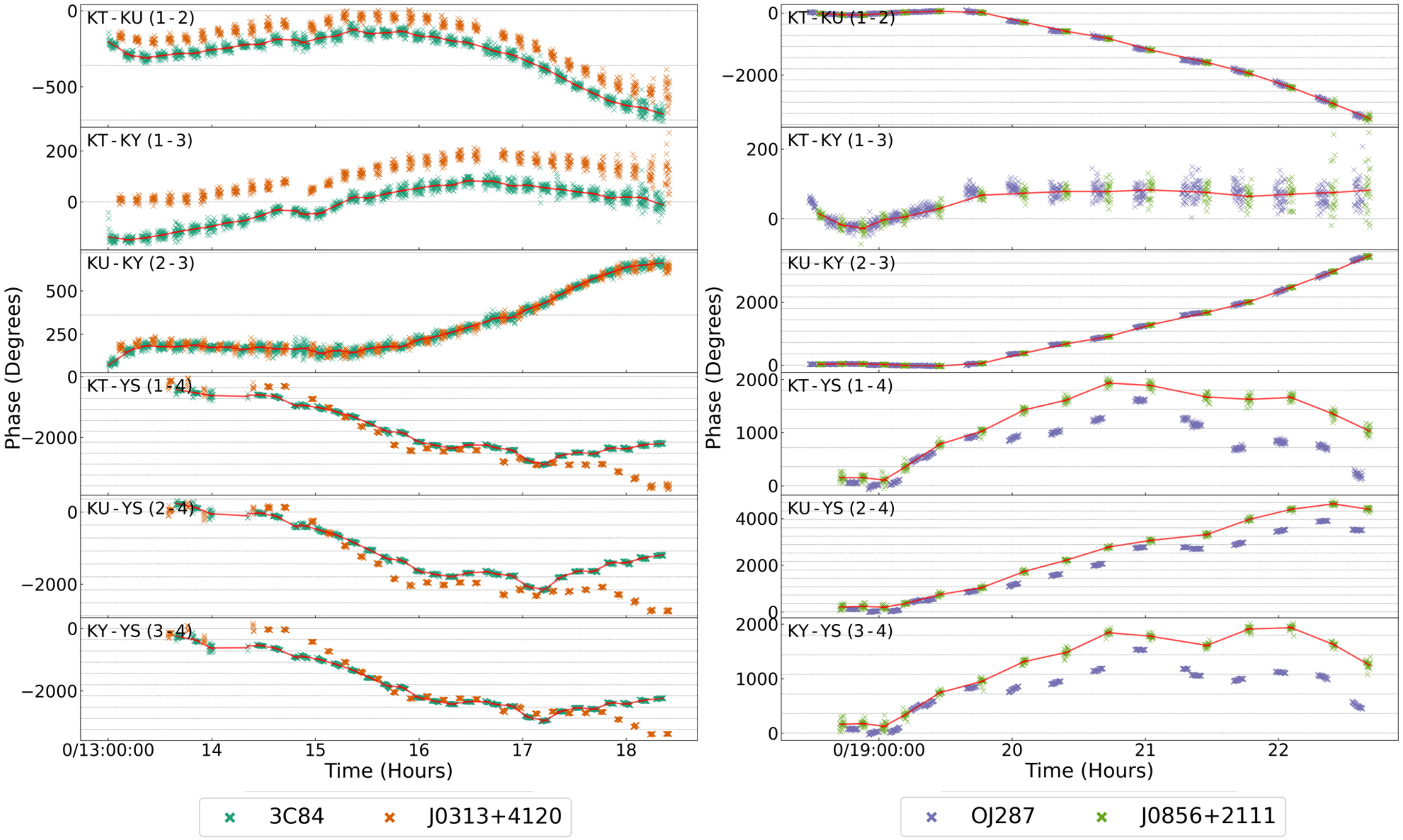


best n for Scan #41 is -6!

- Problem: Rapid phase drifts leads 2π ambiguity, causing SFPR calibration challenges.
  - ✓ AIPS has options to address this this issue (e.g., "interpol" in CLCAL), but the results are incomplete when the phase variation is fast and complex.
- Solution: Manual correction of 2πn by **finding optimal n** of each scan that **minimizes standard deviation of the residual phase after interpolation** **(= SFPR phase).**

Difficulty of SFPR calibration (2π ambiguity)

FPT visibility phase **after correct 2π ambiguity**

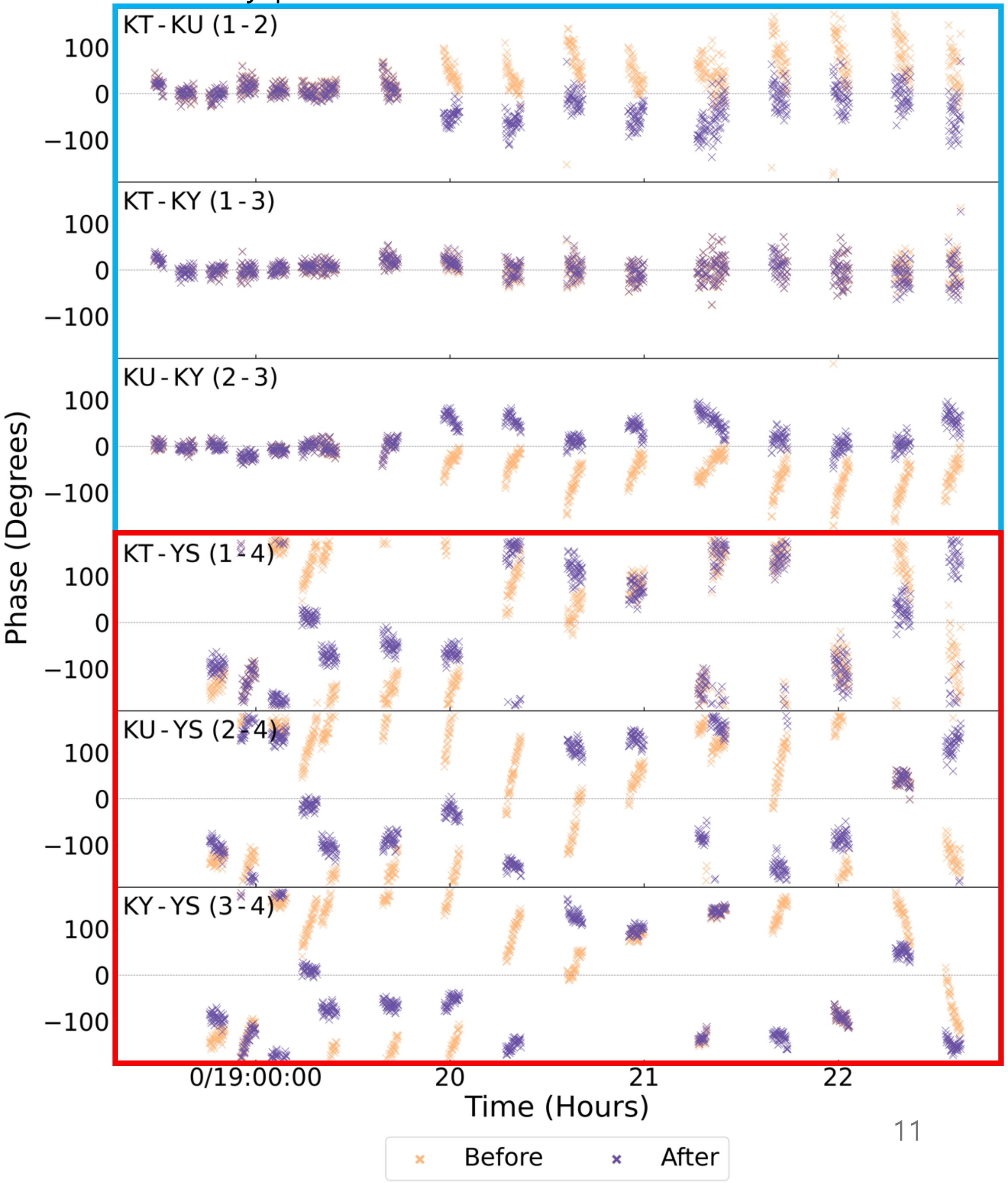


- After correcting 2πn for each scan, FPT visibility phases are smoothly connected
- **Complex and fast phase changes** are seen in **Yebes** baselines
  - ✓ Changes of ~ 2,000 - 3,000 degrees in 5 hours
  - ✓ **Instrumental origin?** receiver updgrated in 2019 (Tecero et al. 2021)
- KVN (except KUS at ~20h – 22h), phase drift < 500 degrees
  - ✓ KUS phase drift is relatively monotonic and easy to track

SFPR visibility phase

- SFPR visibility phases are more stable after 2πn correction
  - ✓ Constant phase at KVN baselines: Similar to previous observations (Rioja et al. 2014)
  - ✓ **Phase at Yebes baselines still show some variations**
- Possible reasons
  - ✓ The 2π ambiguity may not be fully resolved
  - ✓ **Complex source structure** causes phase drift at long baselines (Rioja et al. 2014) → **next slide**
  - ✓ Remaining atmospheric errors
  - ✓ Remaining instrumental errors of Yebes telescope

SFPR visibility phase of OJ 287 **before and after 2πn correction**



SFPR visibility phase: Structure effect

Phase evolution from synthetic map of 3C 84 **(preliminary results)**

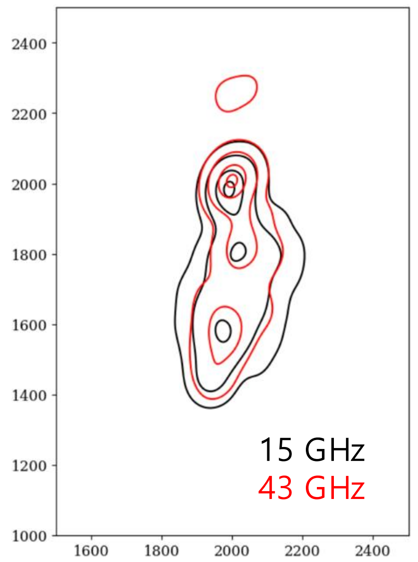
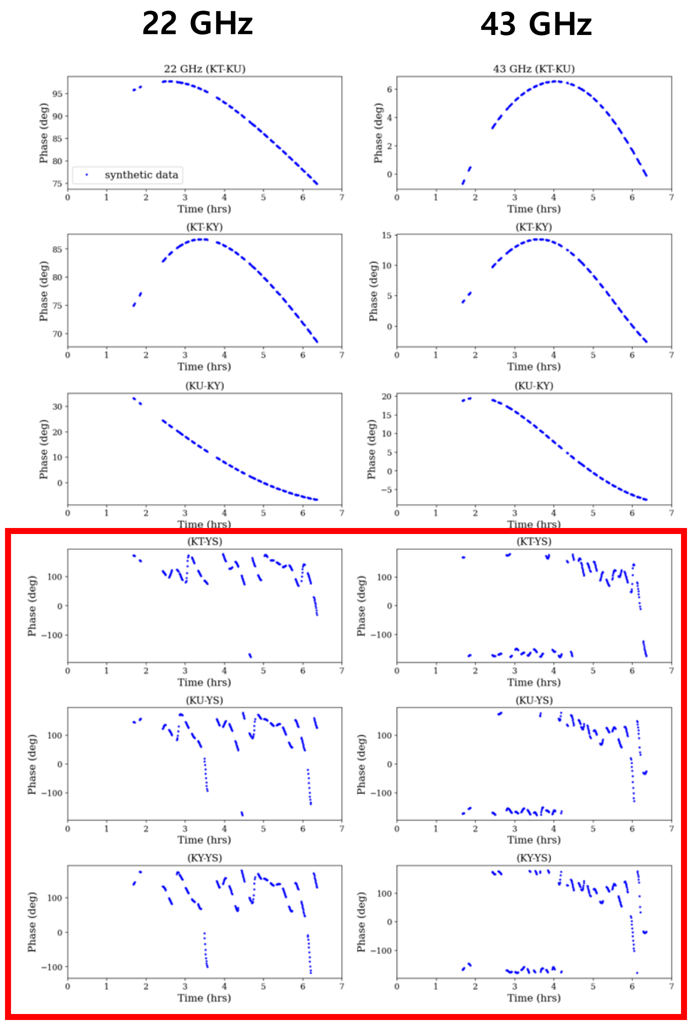
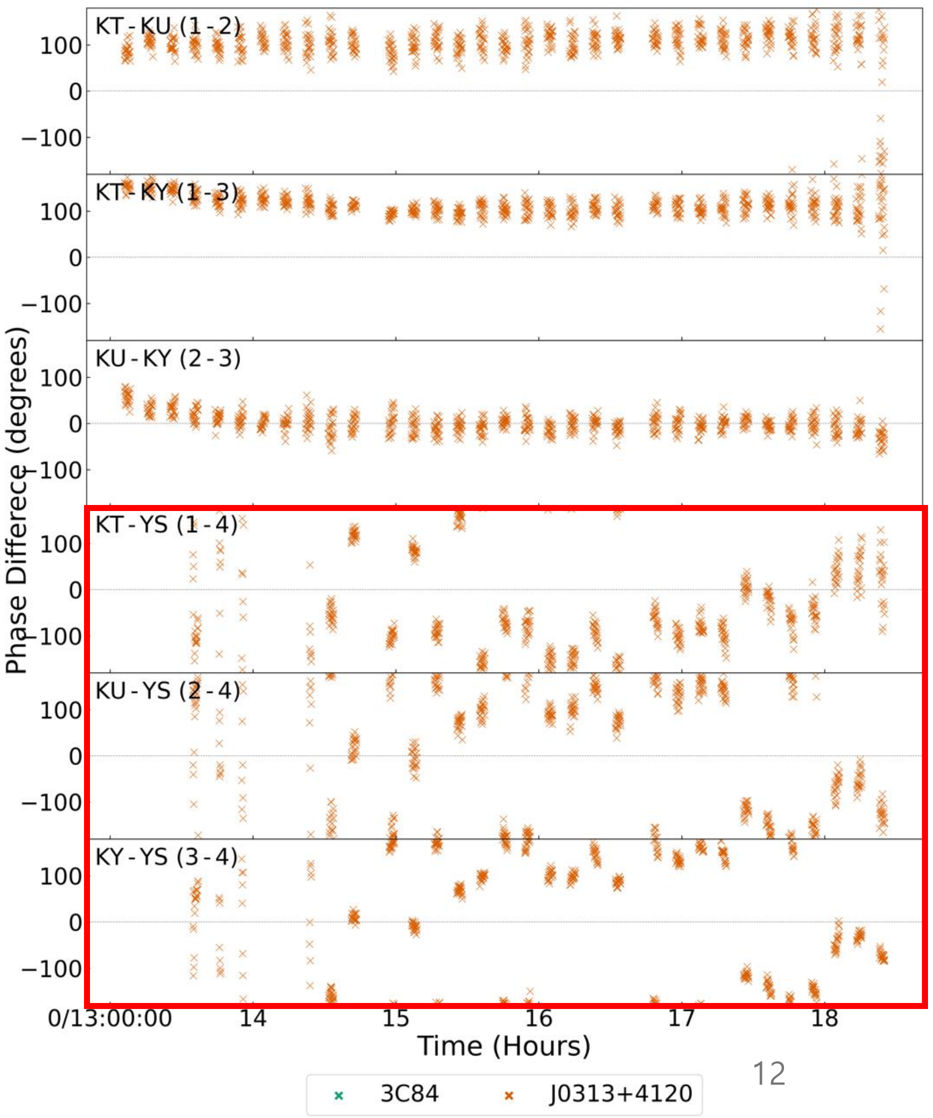


Image Courtesy: Ilje Cho (KASI)



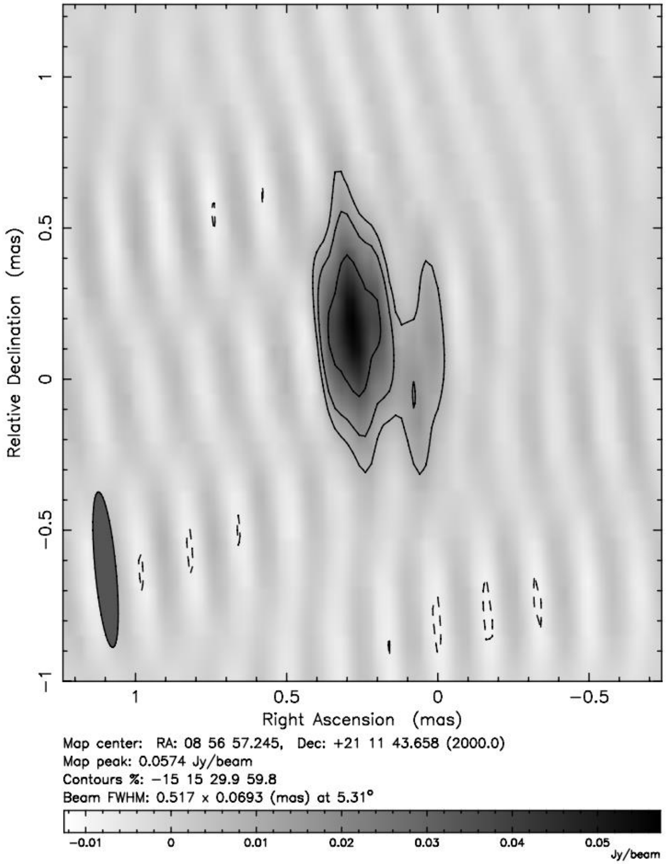
SFPR visibility phase of J0313+4120 (ref: 3C 84)



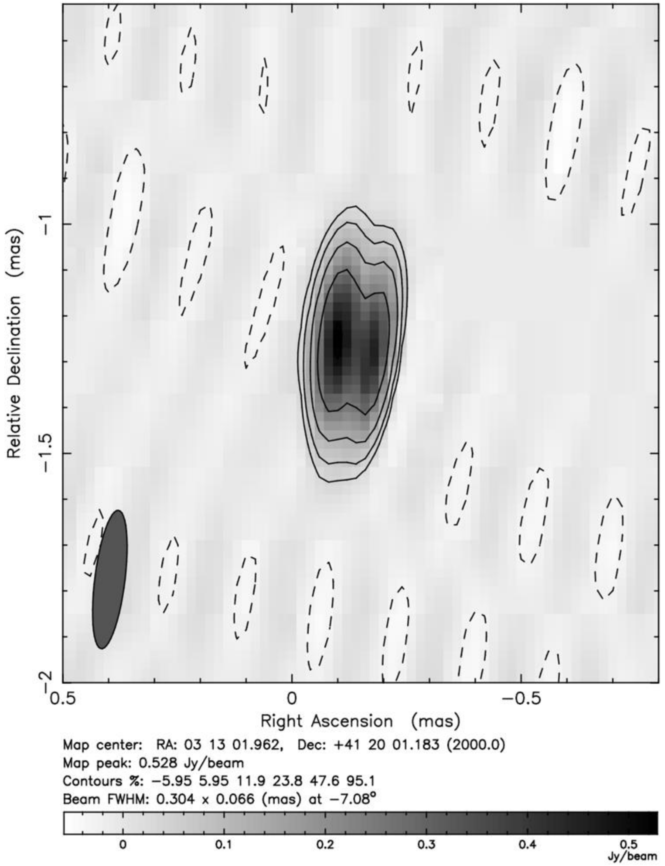
- Synthetic map of 3C 84 shows complex phase variation at Yebes-KVN baselines
- Core-shift can produce additional phase drifts
- We will investigate how much this affects the phase variation of the SFPR visibility (e.g., Rioja et al. 2014)

SFPR maps (preliminary)

J0856+2111 (ref: OJ 287)

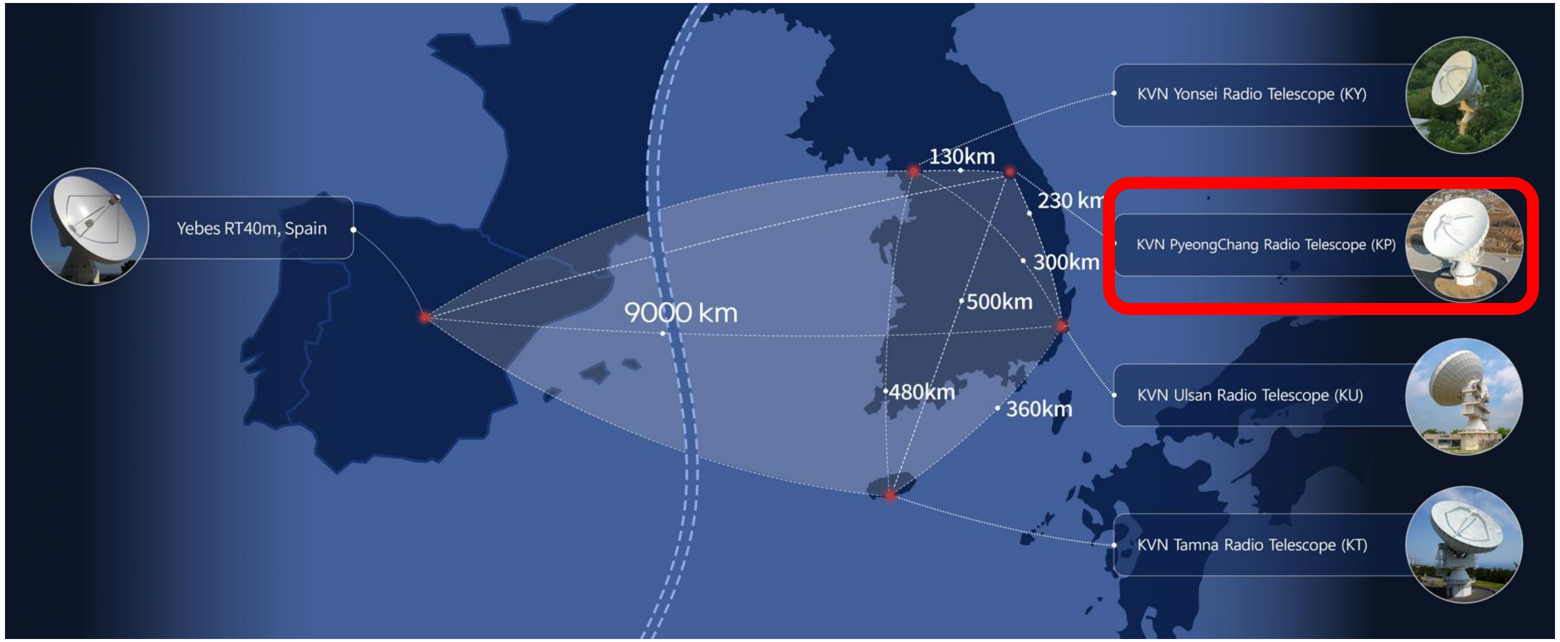


J0313+4120 (ref: 3C 84)

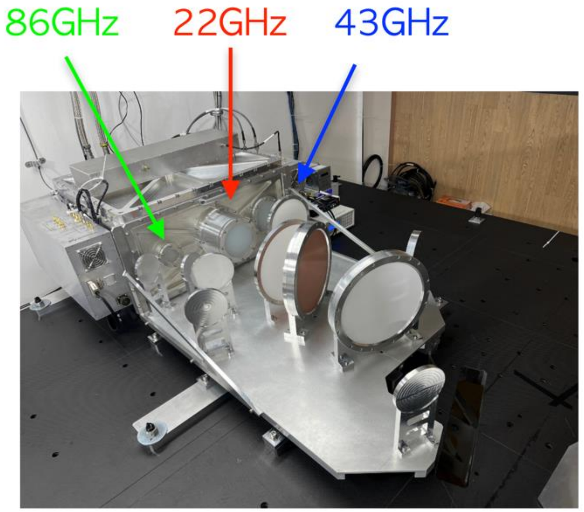


- Synthesized beam sizes ~ 70 μas (uniform weighting)
- Dynamic range (DR) ~ 10 – 50
- The structure effect has not been calibrated yet
- The astrometric uncertainty
  - ✓ $\sigma\Delta\theta_{\mathrm{thermal}} \approx \theta_{\mathrm{beam}}/(1.2\mathrm{DR})$ ~ **1.2 – 5.8 μas**
  - ✓ $\sigma\Delta\theta_{\mathrm{tro}}$ ~ 0 (FPT)
  - ✓ $\sigma\Delta\theta_{\mathrm{ion}}$, $\sigma\Delta\theta_{inst}$: TBA

Future plans



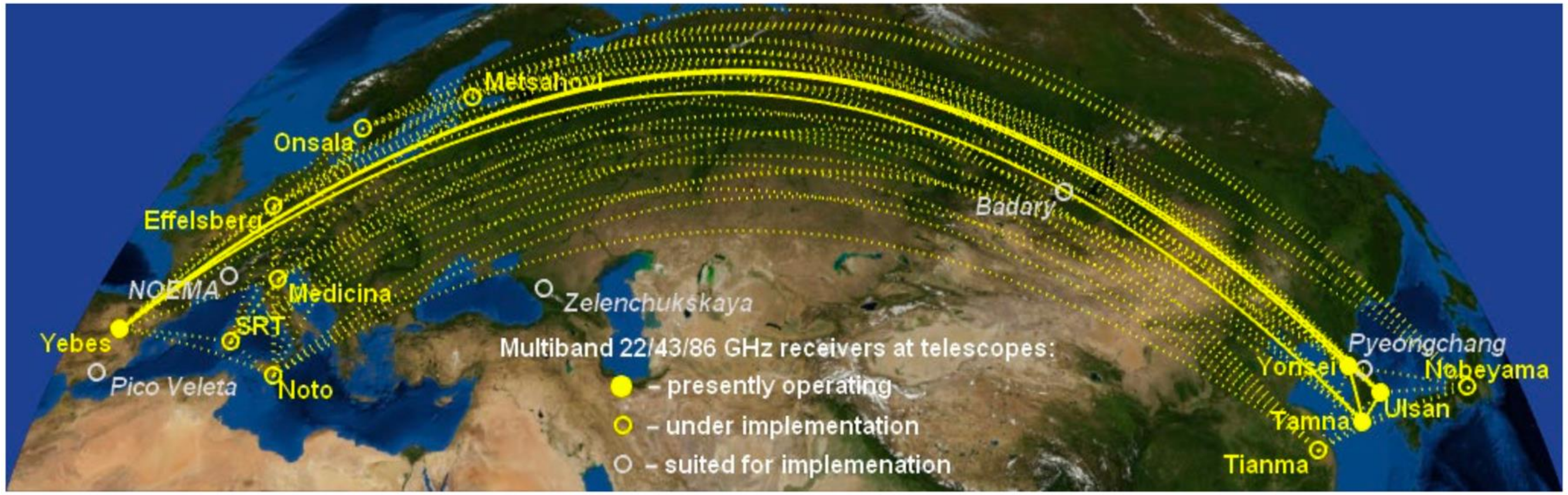
The Compact Triple-band Receiver (CTR)



- **New KVN+Yebes observations** @ K/Q(/W) has been approved in 2024B
  - ✓ Verify the reliability of the long-baseline SFPR with multiple epochs
  - ✓ Obtain scientific results: Proper motions, core-shifts, spectral analysis (e.g., Ro et al. 2023)
- Test FPT/SFPR observations including **more telescopes** (e.g., INAF, Effelsberg, etc.) with multi-frequency receiver **up to 86 GHz** -> FPT-square (Zhao et al. 2018)
- Find proper SMBHB candidates for **long-baseline SFPR monitoring** (2025-)

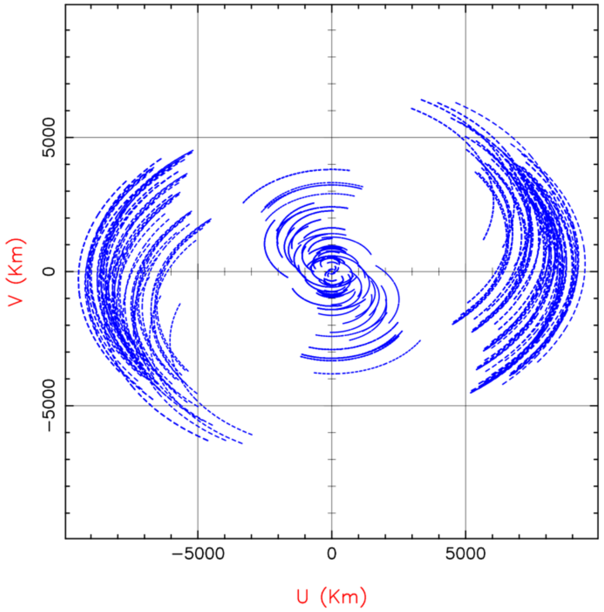
Future plans

Status of multi-frequency receiver installation



Dodson 2023; **Poster #43 (by Andrei. P. Lobanov)**

The expected (u, v)-coverage of future FPT VLBI



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Summary

- Objective: Achieving **micro-arcsecond precision in VLBI astrometry** to **track SMBHBs**
- Pilot Observation Results:
  - ✓ **FPT seems work** between KVN and Yebes baseline ($\varphi_{\mathrm{tro}} \rightarrow 0$)
  - ✓ **Rapid and complex phase drift** of FPT phase found in some baselines
    - KUS: instrumental origin (traceable)
    - Yebes: instrumental + structural (+ atmospheric) origin
  - ✓ **Manual correction of 2π ambiguity** improves FPT/SFPR phase connectivity and stability
  - ✓ **Preliminary SFPR maps** show promising astrometric accuracy (a few micro-arcsecond)
- Future Plans:
  - ✓ **New KVN+Yebes observations** to resolve phase drift issues and obtain initial results
  - ✓ SFPR test with **additional FPT available antennas** up to 86 GHz
  - ✓ Long-baseline SFPR **monitoring for SMBHB candidates**

Thank You!