Toward tracking SMBHB Orbits
Test Observations with KVN and Yebes-40m

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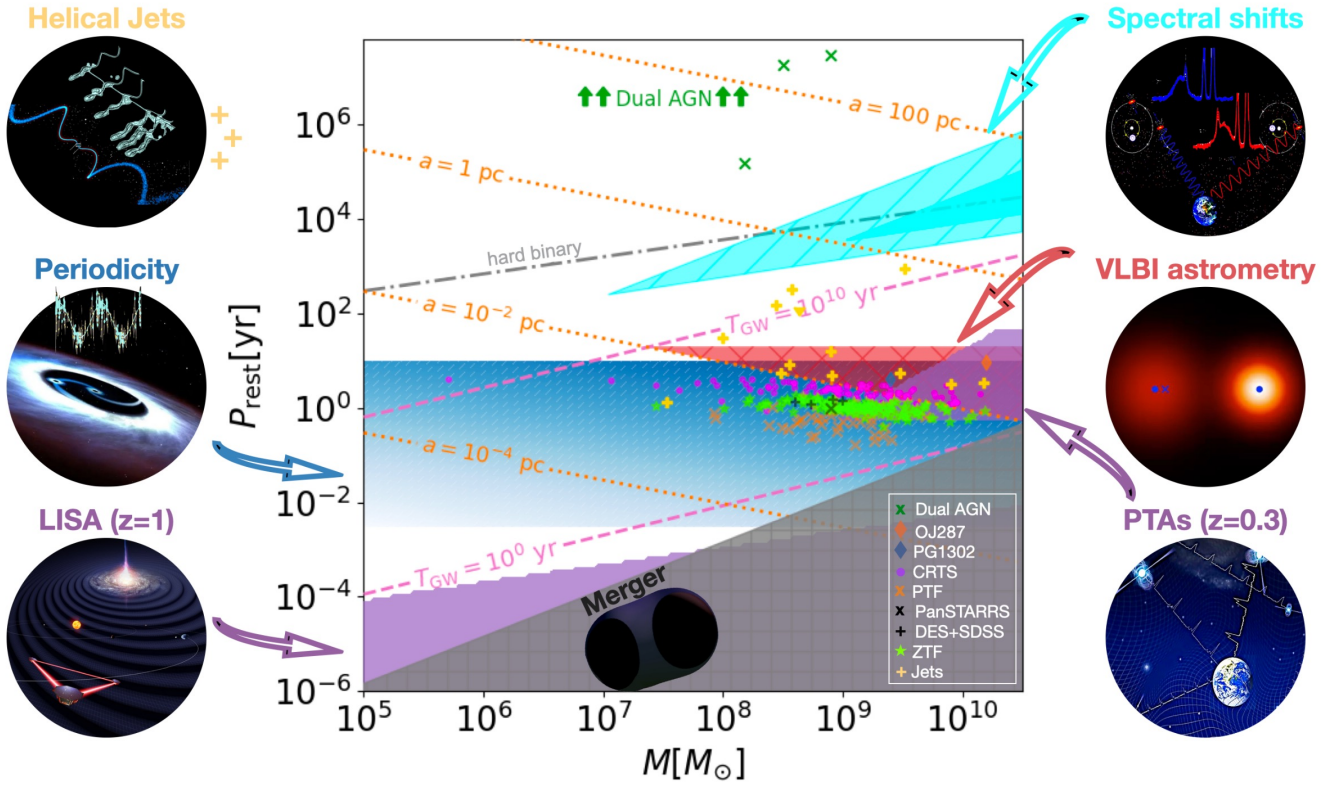
Image Credit: NASA's Goddard Space Flight Center

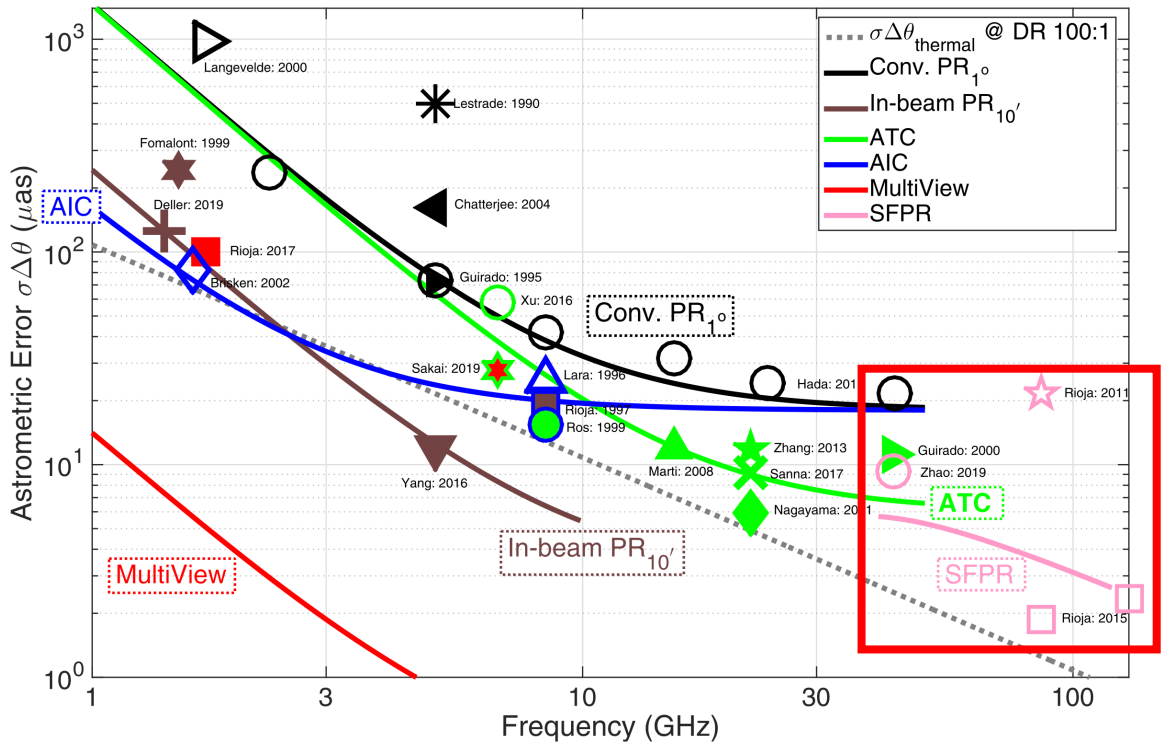
Observational identification of SMBH binaries



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

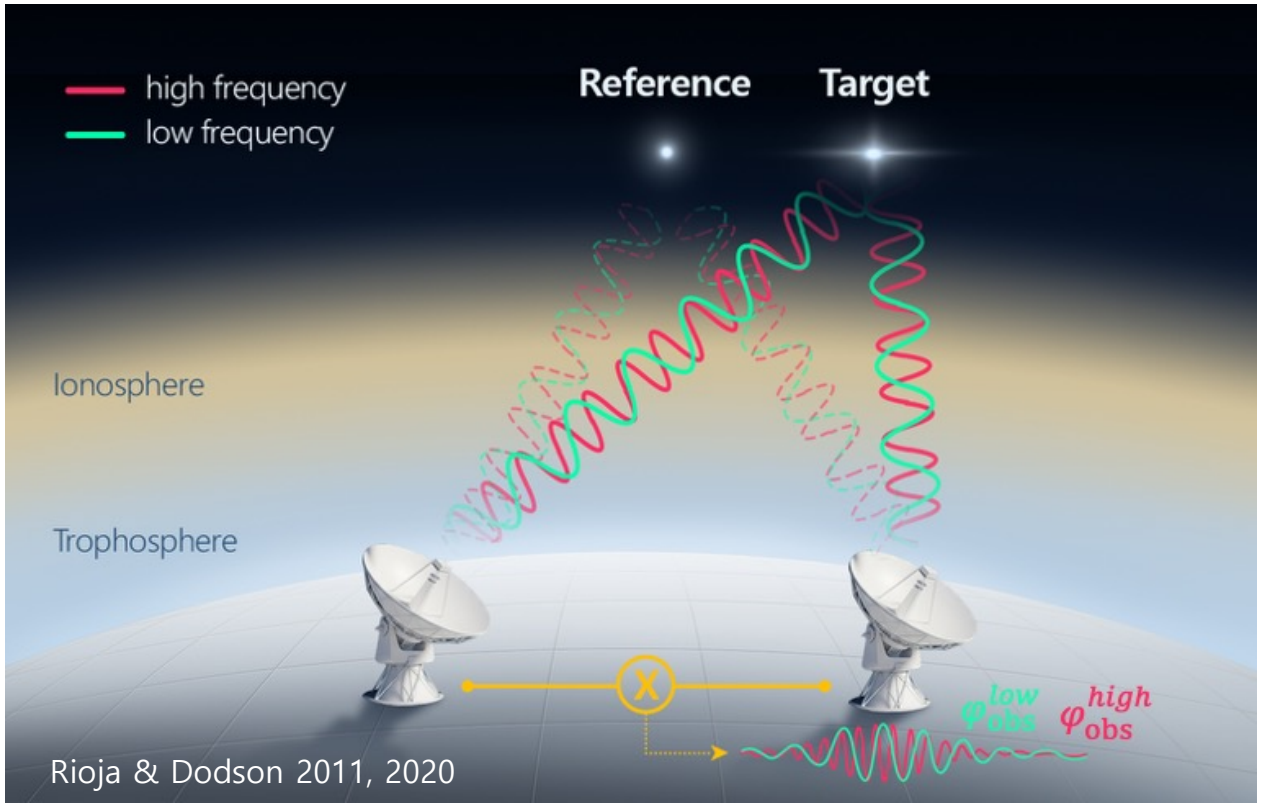


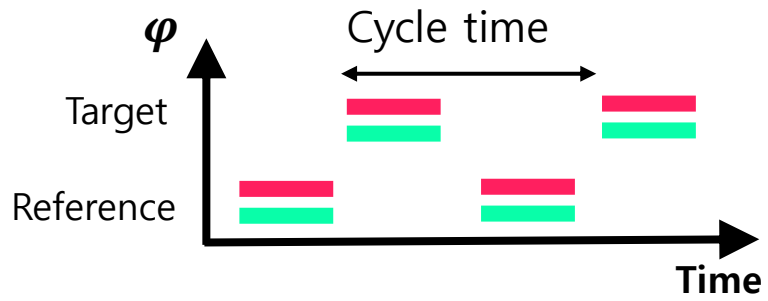
astrometric precision with 6,000km baseline

Rioja & Dodson 2020

- **Conventional astrometric precision limited to ≈ 10 μas**
  - ✓ SMBHB candidate OJ 287**:** expected orbital separation **only 5–10 μas** (Valtonen et al. 2008)
- Theoretically possible with **global baseline (≳9,000 km) at high frequencies (≳86 GHz),** but coherence time becomes very short at these frequencies.
- **Source Frequency Phase Referencing (SFPR),** astrometry with Frequency Phase Transfer (FPT), extends reliable astrometry to **> 40 GHz**

Source/Frequency Phase Referencing (SFPR)



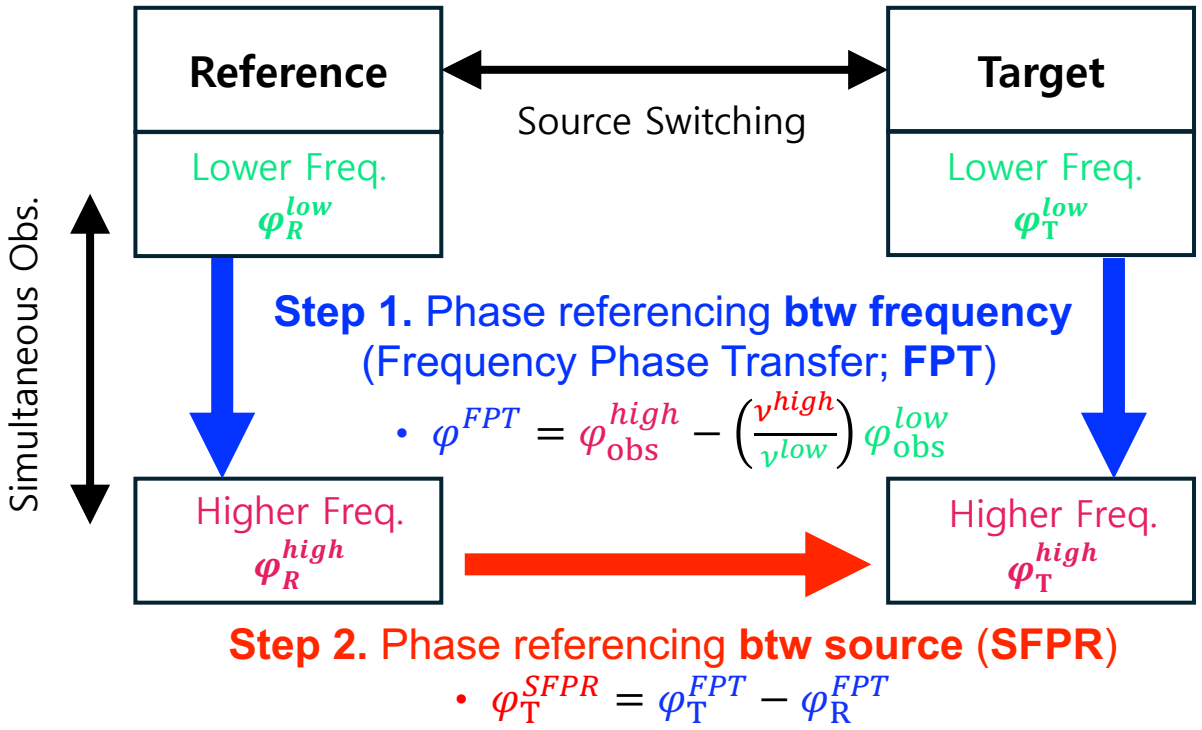


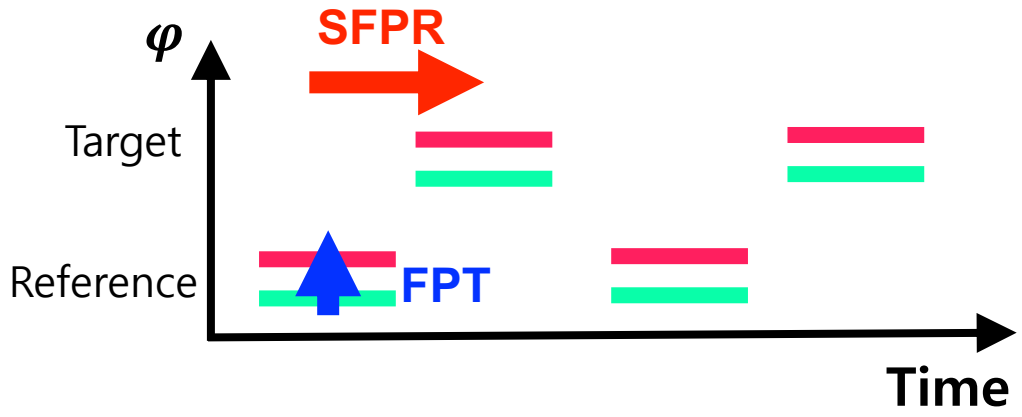
- Residual phase after a-priori calibration

$$\varphi_{\mathrm{obs}} = \underbrace{\boldsymbol{\varphi_{pos}} + \varphi_{\mathrm{str}}}_{\text{Source effect (potision + structure)}} + \underbrace{\varphi_{\mathrm{tro}} + \varphi_{\mathrm{ion}}}_{\text{Atmospheric effect}} + \underbrace{\varphi_{\mathrm{geo}}}_{\text{Geometric effect}} + \underbrace{\varphi_{\mathrm{inst}}}_{\text{Instrumental effect}} + \underbrace{\varphi_{\mathrm{ther}}}_{\text{Thermal noise}} + \underbrace{2\pi n}_{2\pi \text{ ambiguity}}$$

Source/Frequency Phase Referencing (SFPR)

[SFPR calibration steps]



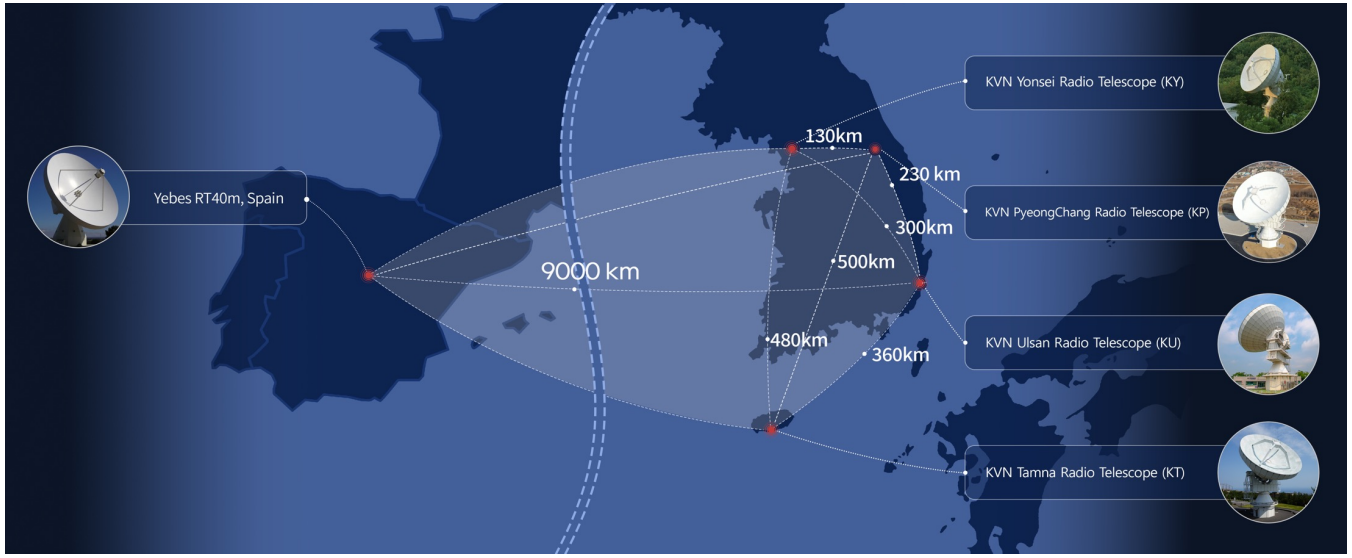


$$\varphi_T^{SFPR} = \boxed{\boldsymbol{\varphi_{pos}}} + \varphi_{str} + \varphi_{tro} + \varphi_{ion} + \varphi_{geo} + \varphi_{inst} + \varphi_{ther} + 2\pi n$$

SFPR with global multi-frequency VLBI

- **KVN** (baseline ~ 500km): **22/43/86/130 GHz (e.g., Rioja & Dodson 2015)**
- **KaVA** (KVN + VERA) (baseline ~ 2,200km): **22/43 GHz (e.g., Zhao et al. 2019)**
- Global multi-frequency (FPT) VLBI **(baseline ~ 10,000km): 22/43/86 GHz**

Test K/Q simultanous observations with KVN(KaVA) + Yebes

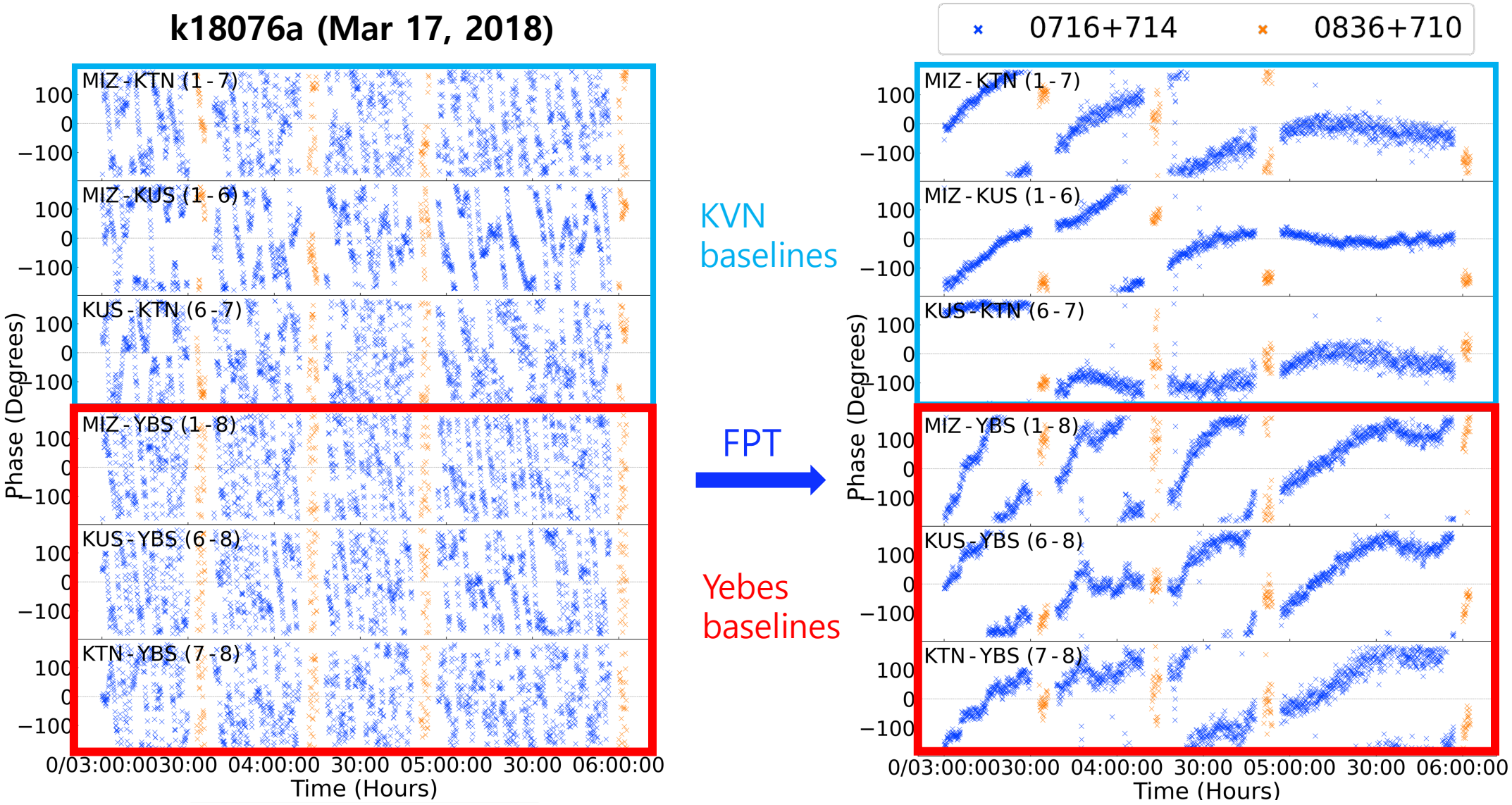


- **Seven** successful sessions since 2018
- Band: **K/Q** (simultaneous observations)
- Major upgrades **after 2021**:
  - **New Q/W-band receiver** at Yebes 40m (Tercero et al. 2021)
  - **Wide-band** (512 MHz) observations
  - **KPC** joined from 2024, equipped with the **Compact Triple-band Receiver (CTR)**

Exp. code	k18075b	k18076a	k18076b	k18077a	p20bs01b	n24hr01a	n24hr01c
obs. date	Mar 16, 2018	Mar 17, 2018	Mar 17, 2018	Mar 18, 2018	Jan 15, 2021	Nov 10, 2024	Jan 13, 2025
antenna	KVN3, VERA4 (KaVA), Yebes				KVN3, Yebes	KVN2, Yebes	KVN4, Yebes
frequency (bandwidth)	22.112 - 22.240/ 42.812 - 42.940 (128MHz)				21.200 - 21.712/ 42.400 - 42.912 (512MHz)		
# IFs, pol.	4 IFs, single pol.				1 IF, single pol.	8 IFs, dual pol.	
targets	1633+382	0716+714	4C 39.25	1803+784	3C84, OJ287, Mrk421		
Obs. PI	Bong Won Sohn	Taehyun Jung	Guang-Yao Zhao	Taehyun Jung	Bong Won Sohn	Hyunwook Ro	Hyunwook Ro

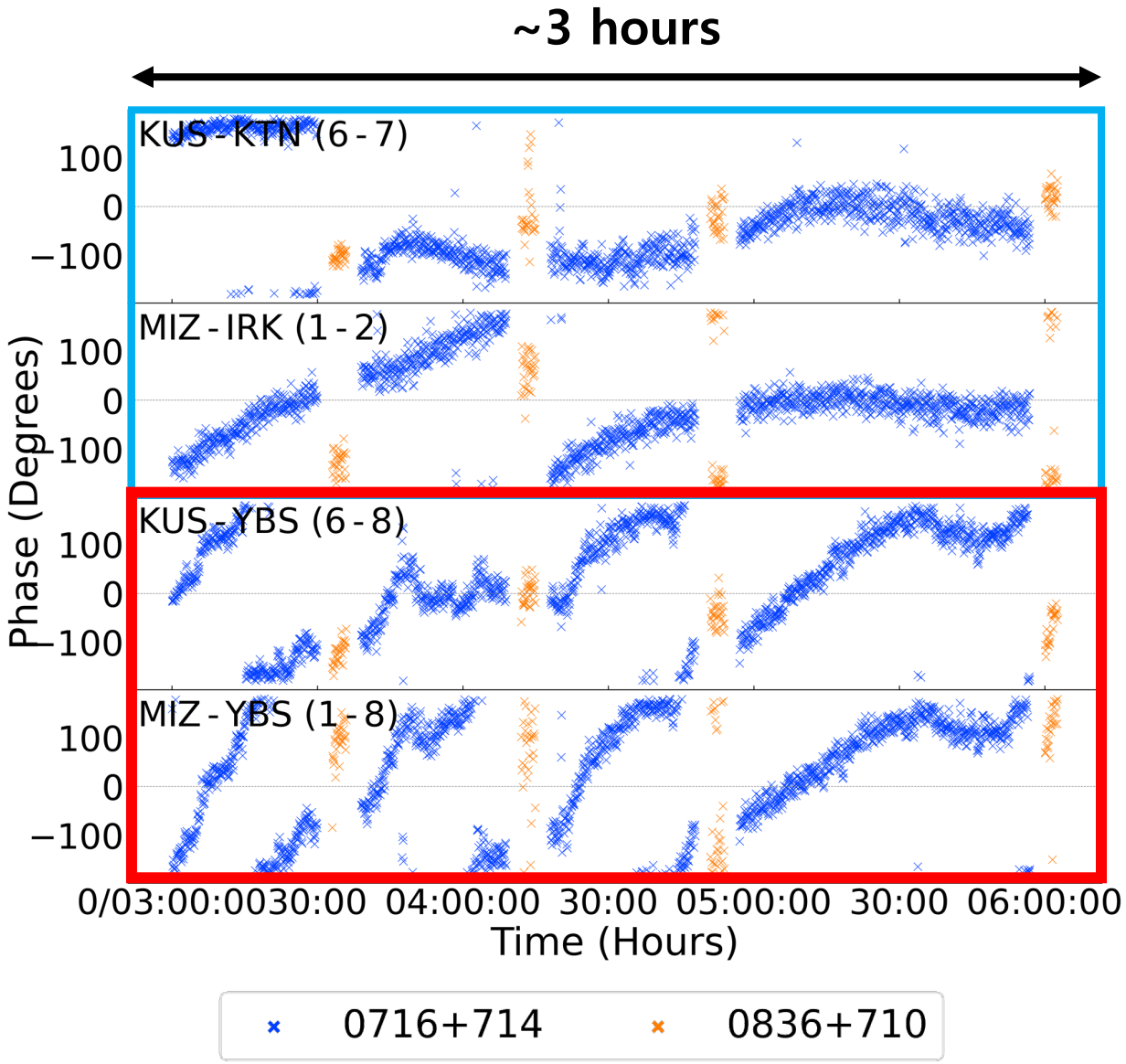
FPT phase: 2018 Observations

Zhao, Jung et al., in prep.



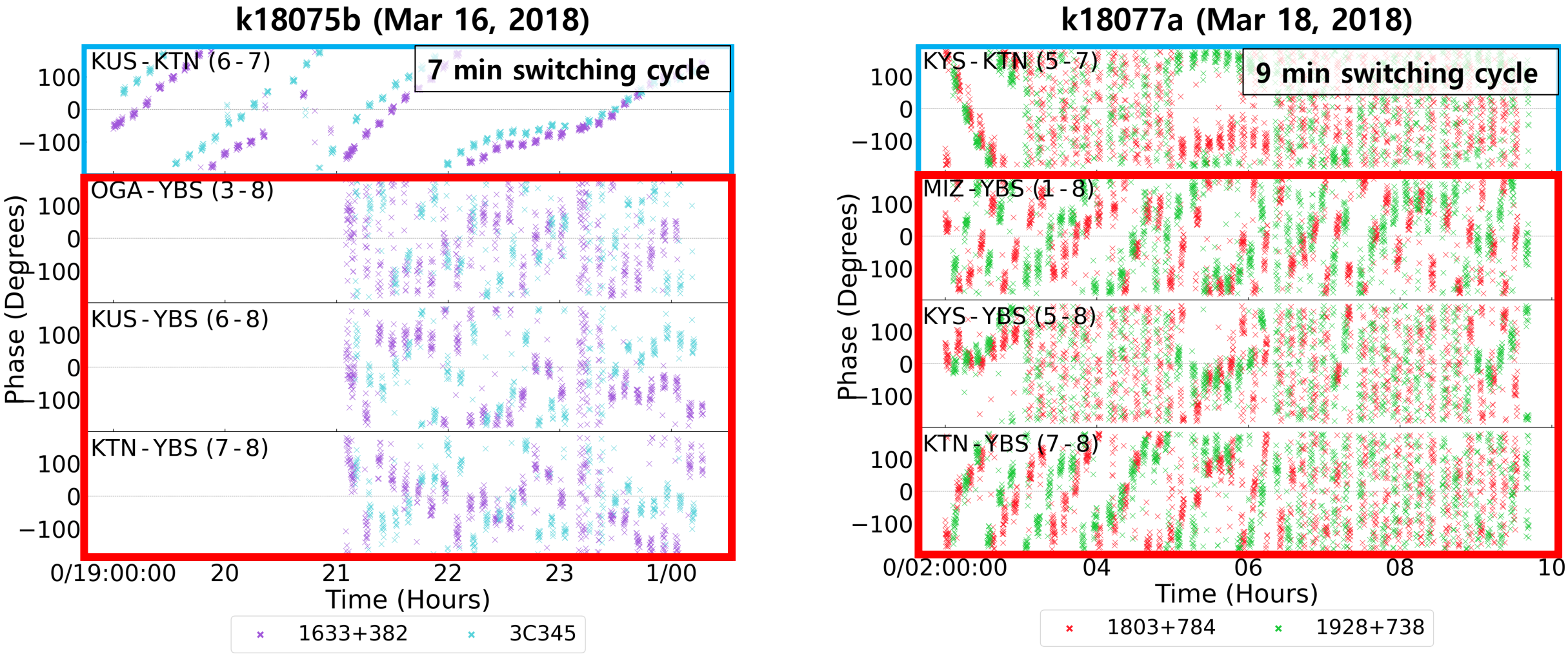
FPT phase: 2018 Observations

Zhao, Jung et al., in prep.



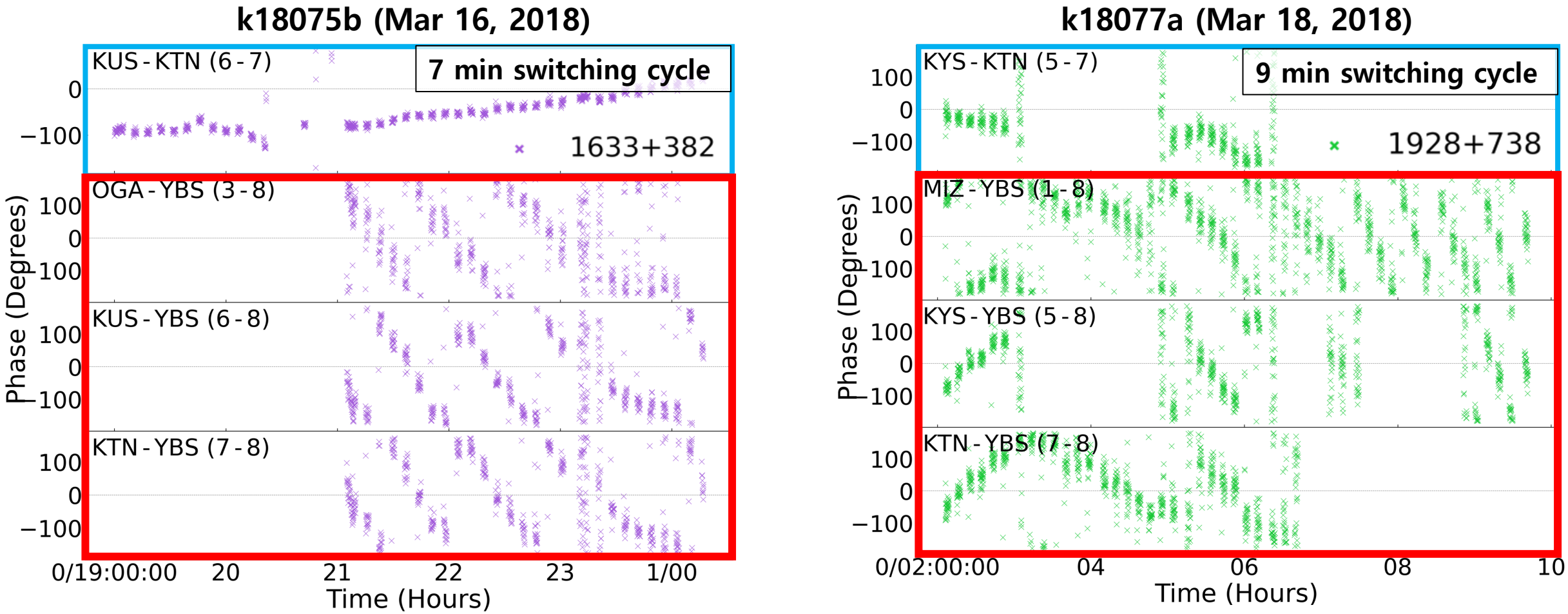
- **FPT significantly improves phase coherence in Yebes baselines (~10,000km)!**
  - After FPT, the phases remain well connected for about 3 hours.
- Longer baselines show faster phase variations.
  - KUS–KTN (~400 km): less than one full turn (≈ < 360°)
  - MIZ–Yebes (~10,000 km): about 3.5 turns (≈ 1,200°)

FPT phase: 2018 Observations



- **FPT phases well connected even with long source-switching cycles (~7-9 min).**

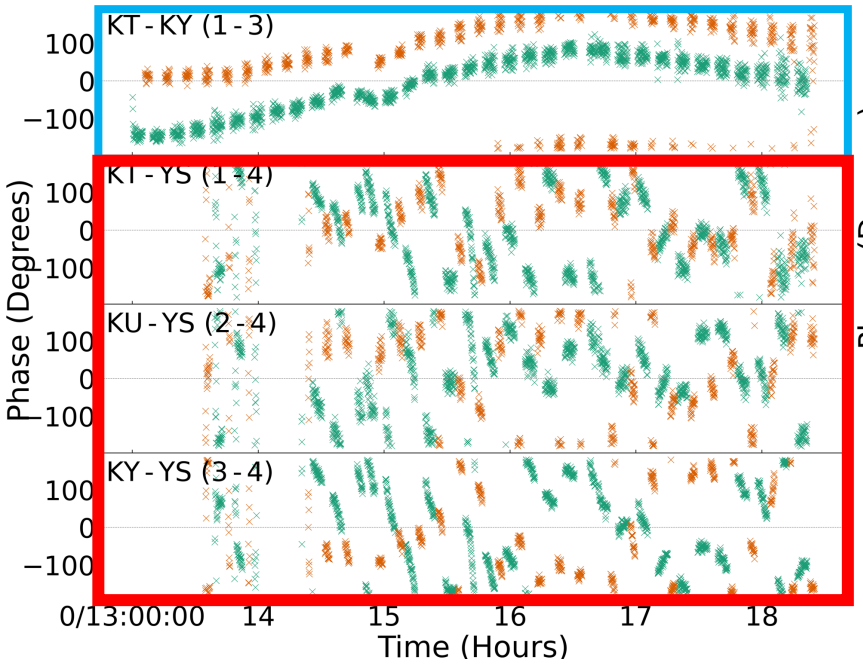
SFPR phase: 2018 Observations



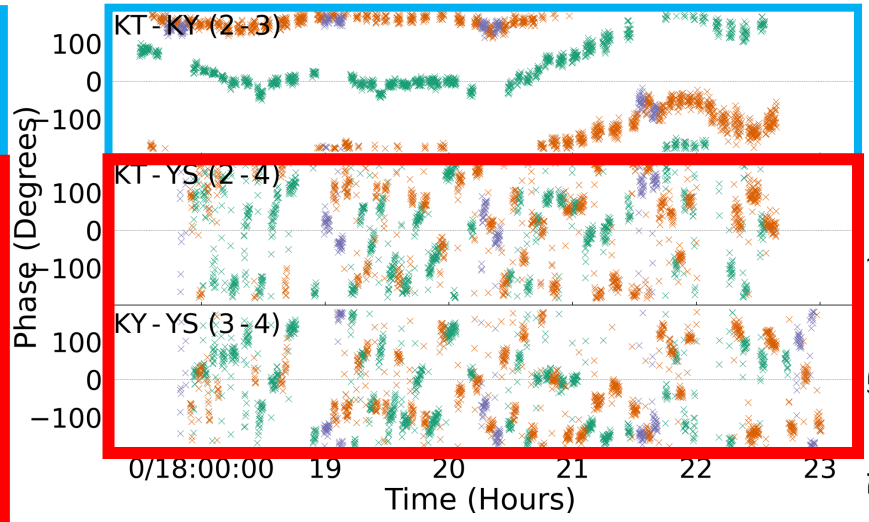
- **SFPR calibration was successfully performed in 2018 sessions**
- A noticeable **phase slope** appears in the **Yebes baselines**, possibly due to **uncalibrated EOP** or **source-structure effects**.

FPT phase: Observations after 2021

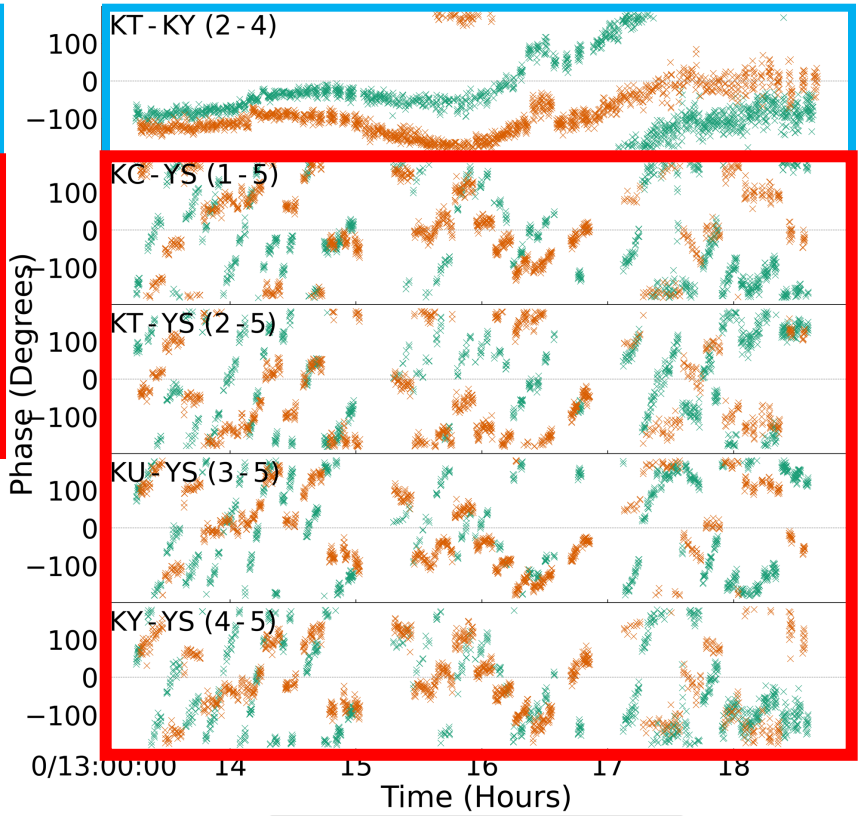
p20bs01b (Jan 15, 2021)



n24hr01a (Nov 10, 2024)

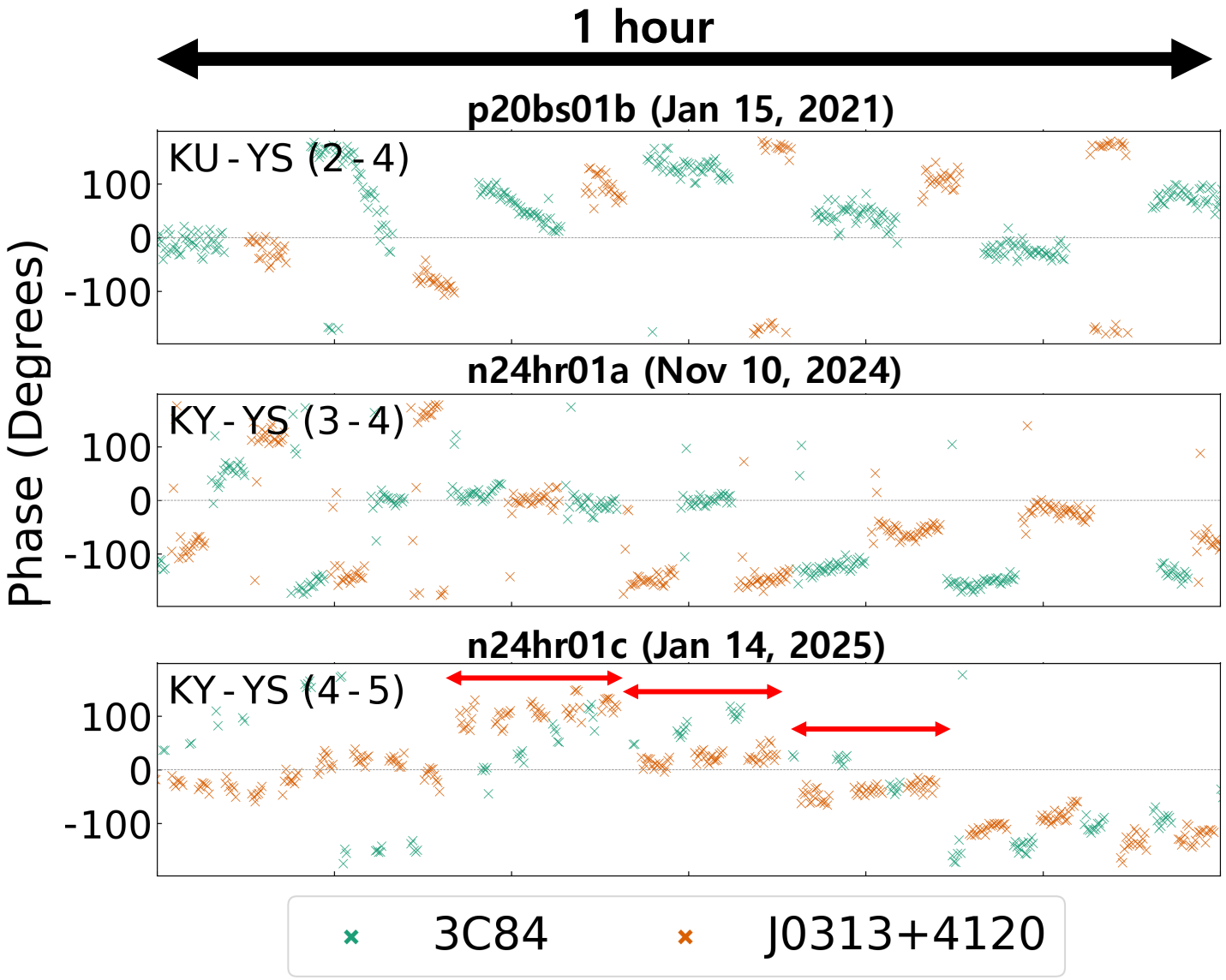


n24hr01c (Jan 4, 2025)



- **After 2021, frequenct FPT phase disconnections** were found on the Yebes baselines!

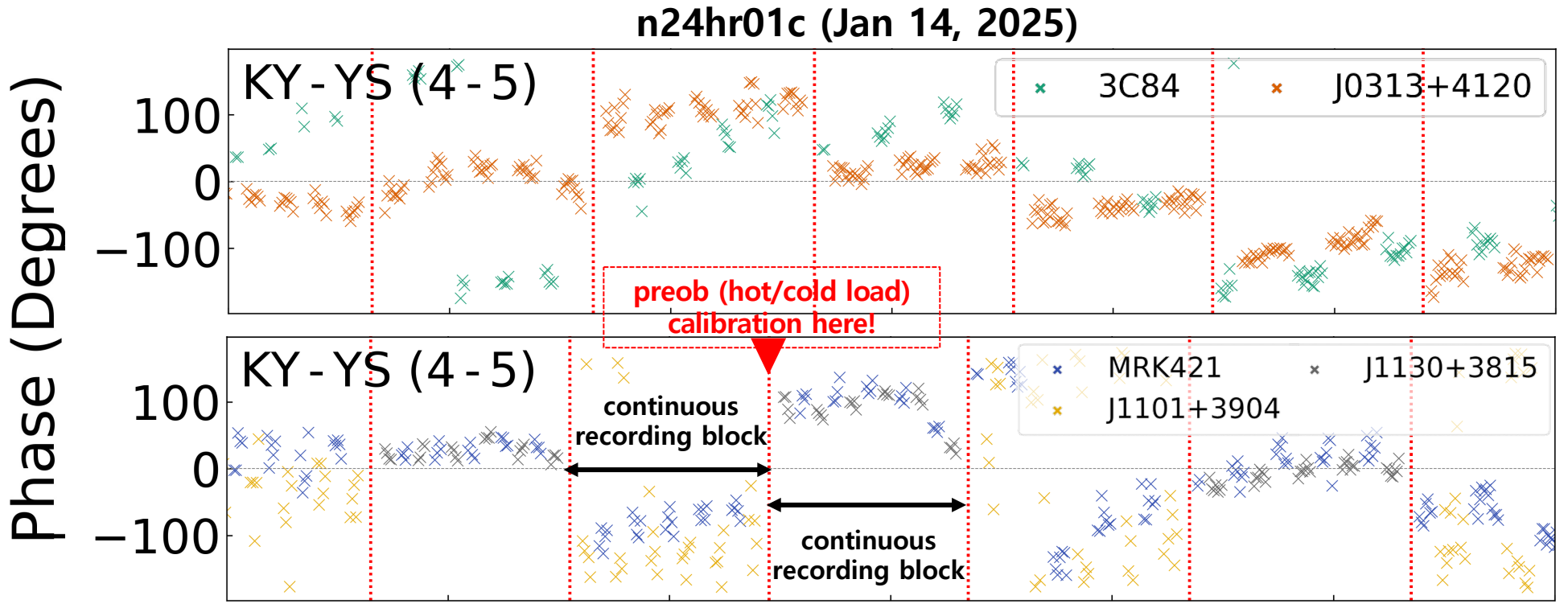
Disconnections in FPT phase



- **Clear FPT phase disconnections** appeared on the Yebes baselines in the **2021 and 2024 sessions.**
  - ✓ Disconnections occurred **almost every scan**, making **SFPR calibration unreliable**.

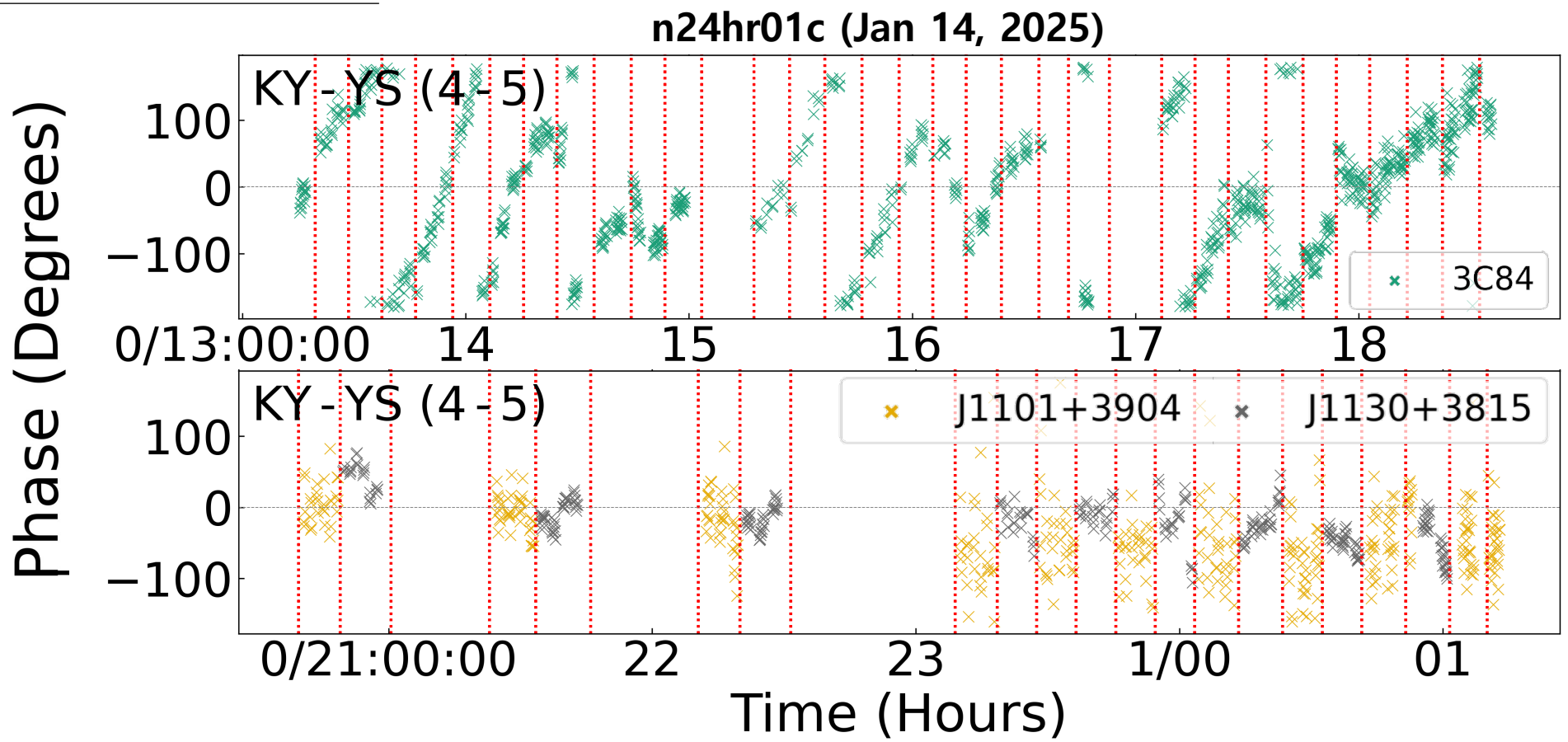
- The **January 2025 session** shows **partially stable phases** lasting for about 10 minutes.

Improved FPT Phase Stability in January 2025 session



- Jan 2025 observation: **continuous recording** (~10-min blocks)
  - ✓ Within each continuous-recording block, the FPT phase remains **highly stable**.
- **FPT phase disconnections occur between blocks, coinciding with preob (hot/cold-load) calibrations.**
- Earlier sessions (2021 & 2024): **no continuous recording** — preob calibration was performed for every scan.

SFPR phase: January 2025 session

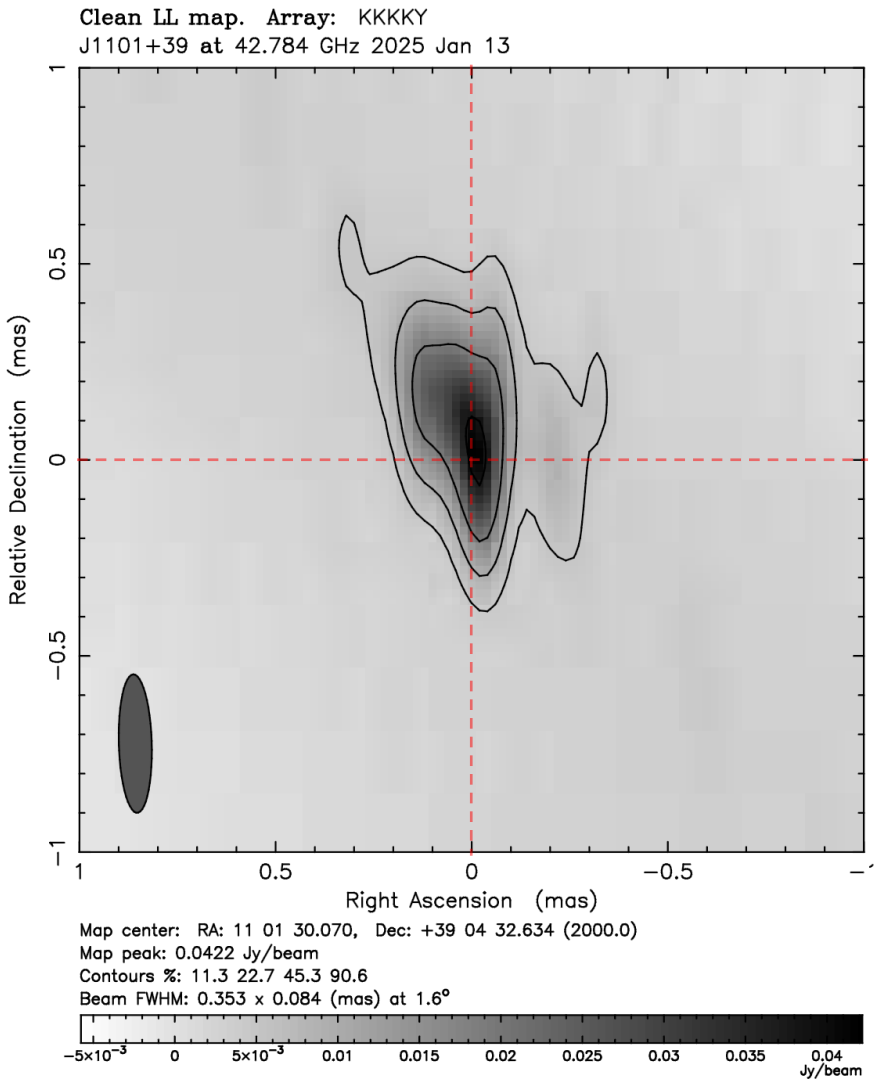


3C 84 pair: complex structures

Mrk 421 pairs: compact structure

- SFPR calibration was more stable than in the 2021 and 2024 sessions.
- Occasional **SFPR phase discontinuities** appeared for **3C 84**, which has a **complex source structure**.
- **For compact pairs (e.g., Mrk 421), SFPR performed well.**

Preliminary SFPR map: January 2025 session



- Source: J1101+3904 (reference: Mrk 421)
- Peak offset: (-20, +20) μas
- Beam sizes ~ 85 μas (natural weighting)
- Dynamic range (DR) ~ 26.5
- Structure effects have not yet been calibrated
- Estimated astrometric precision
  - ✓ $\sigma\Delta\theta_{\mathrm{thermal}} \approx \theta_{\mathrm{beam}}/(1.2\mathrm{DR})$ **~ 2-3 μas**
  - ✓ $\sigma\Delta\theta_{\mathrm{tro}}$ ~ 0 (FPT)
  - ✓ **$\sigma\Delta\theta_{\mathrm{ion}}$, $\sigma\Delta\theta_{\mathrm{inst}}$: to be further analyzed**

Future plans: Toward global SFPR monitoring

- **KVN + Yebes K/Q/W-band fringe test** (originally scheduled for June 2025, postponed to **early 2026**)
  - Planned setup: **two DBBC2 units** at Yebes, **16 Gbps** recording rate
- **Conduct SFPR test observations** including additional telescopes (e.g., Medicina, Effelsberg, Tianma, …)
- **Start regular global SFPR monitoring** for **SMBHB candidates**

Future plans: Toward global SFPR monitoring

- **Potential SMBHB targets for future global SFPR monitoring.**

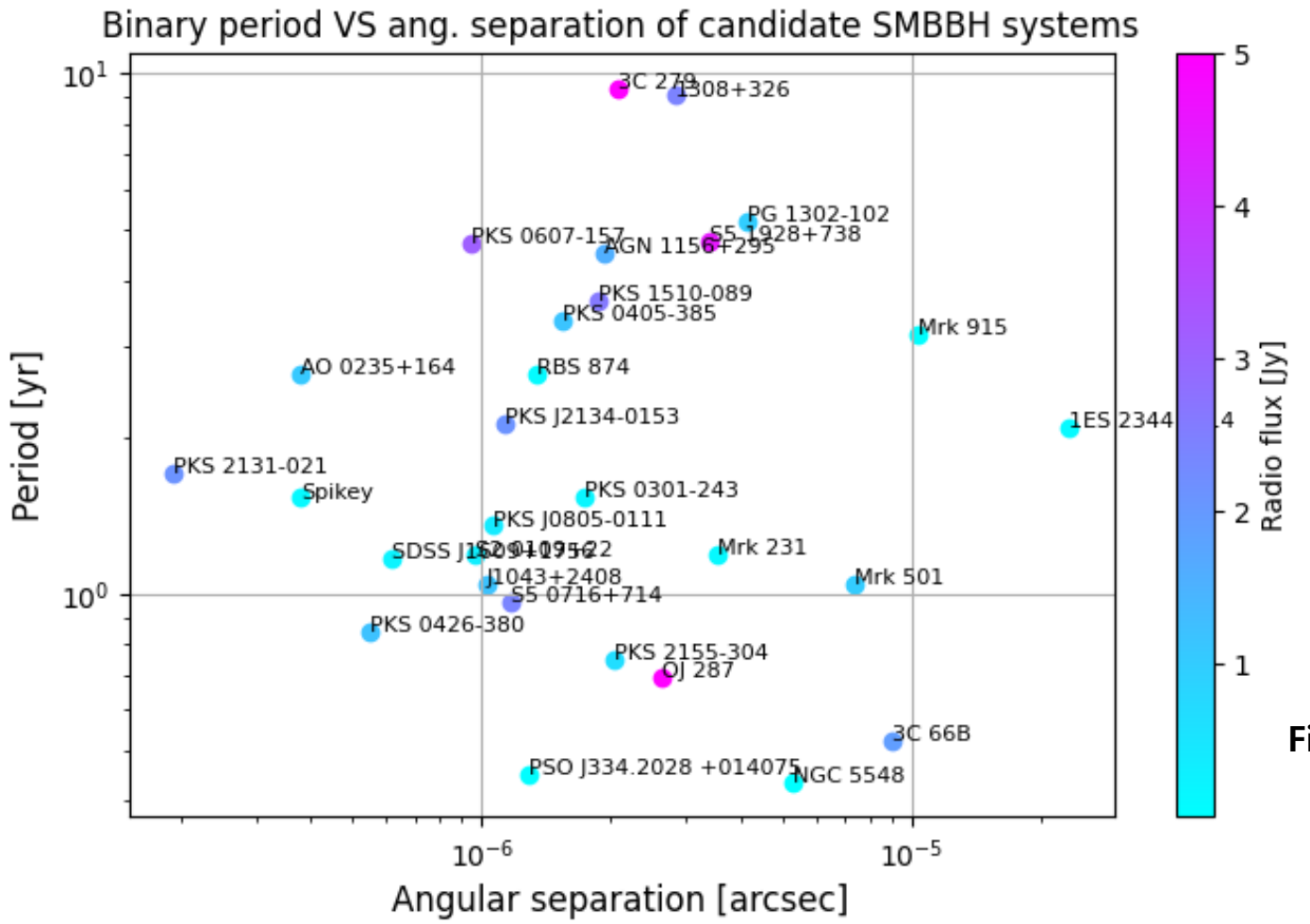


Figure created by Paloma Thevanet (Observatoire de Paris)

Summary

- **Summary of Test Observation Results**
  - ✓**FPT successfully improved phase coherence** on the KVN (and VERA) – Yebes baselines
  - ✓**2018 sessions:** stable FPT and SFPR phases with long coherence times.
  - ✓**2021–2024 sessions:** frequent FPT phase disconnections on Yebes baselines,
  - ✓**The 2025 session (n24hr01c) showed much improved SFPR phase stability**
    - compact sources (e.g., Mrk 421) achieved continuous SFPR phase connection.
  - ✓**Preliminary SFPR maps** show promising astrometric accuracy (a few μas), though detailed error estimation is still required.
- **Future Prospects**
  - ✓Conduct the first **KVN + Yebes K/Q/W-band** tests
  - ✓**Expand SFPR experiments** with additional telescopes
  - ✓**Begin global SFPR monitoring** of **SMBHB candidates**

Thank You!