中国科学院上海天文台
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Multifrequency VLBI detection of supermassive black hole binaries at millimeter wavelengths

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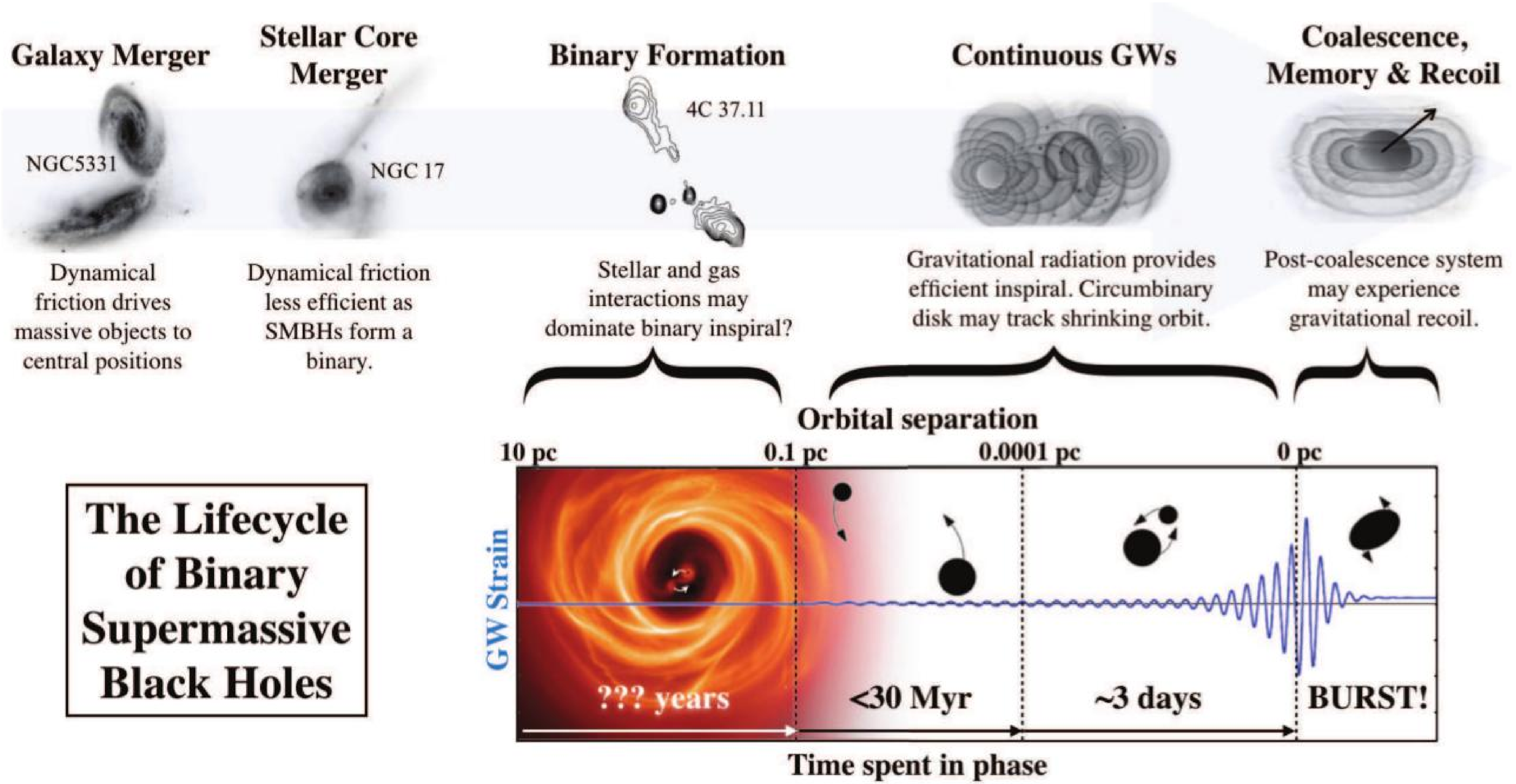
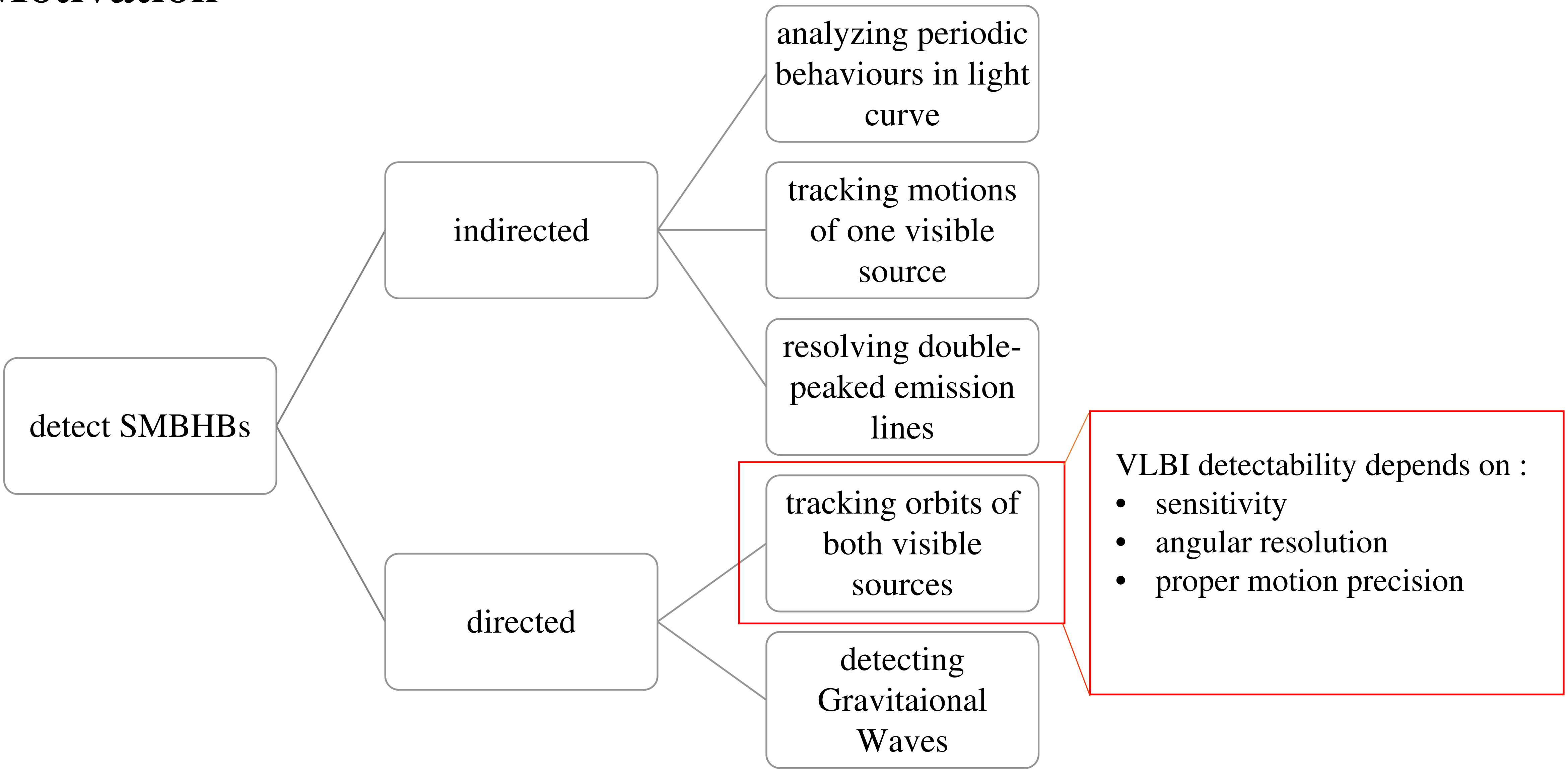
2025-10-29 mm-VLBI science with multi-band recievers, Bologna, Italy

Motivation



Burke-Spolaor et al. (2018)

Motivation


detect SMBHBs
indirected
directed
analyzing periodic behaviours in light curve
tracking motions of one visible source
resolving double-peaked emission lines
tracking orbits of both visible sources
detecting Gravitaional Waves
VLBI detectability depends on :
• sensitivity
• angular resolution
• proper motion precision

A successful example:

THE ASTROPHYSICAL JOURNAL, 843:14 (9pp), 2017 July 1 https://doi.org/10.3847/1538-4357/aa74e1

CrossMark

Constraining the Orbit of the Supermassive Black Hole Binary 0402+379

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Received 2017 January 14; revised 2017 April 30; accepted 2017 May 22; published 2017 June 27

Abstract

The radio galaxy 0402+379 is believed to host a supermassive black hole binary (SMBHB). The two compact-core sources are separated by a projected distance of 7.3 pc, making it the most (spatially) compact resolved SMBHB known. We present new multi-frequency VLBI observations of 0402+379 at 5, 8, 15, and 22 GHz and combine them with previous observations spanning 12 years. A strong frequency-dependent core shift is evident, which we use to infer magnetic fields near the jet base. After correcting for these shifts we detect significant relative motion of the two cores at $\beta = v/c = 0.0054 \pm 0.0003$ at PA $= -34^{\circ}.4$. With some assumptions about the orbit, we use this measurement to constrain the orbital period $P \approx 3 \times 10^4$ yr and SMBHB mass $M \approx 15 \times 10^9 M_{\odot}$. While additional observations are needed to confirm this motion and obtain a precise orbit, this is apparently the first black hole system resolved as a visual binary.

Key words: gravitational waves – quasars: supermassive black holes

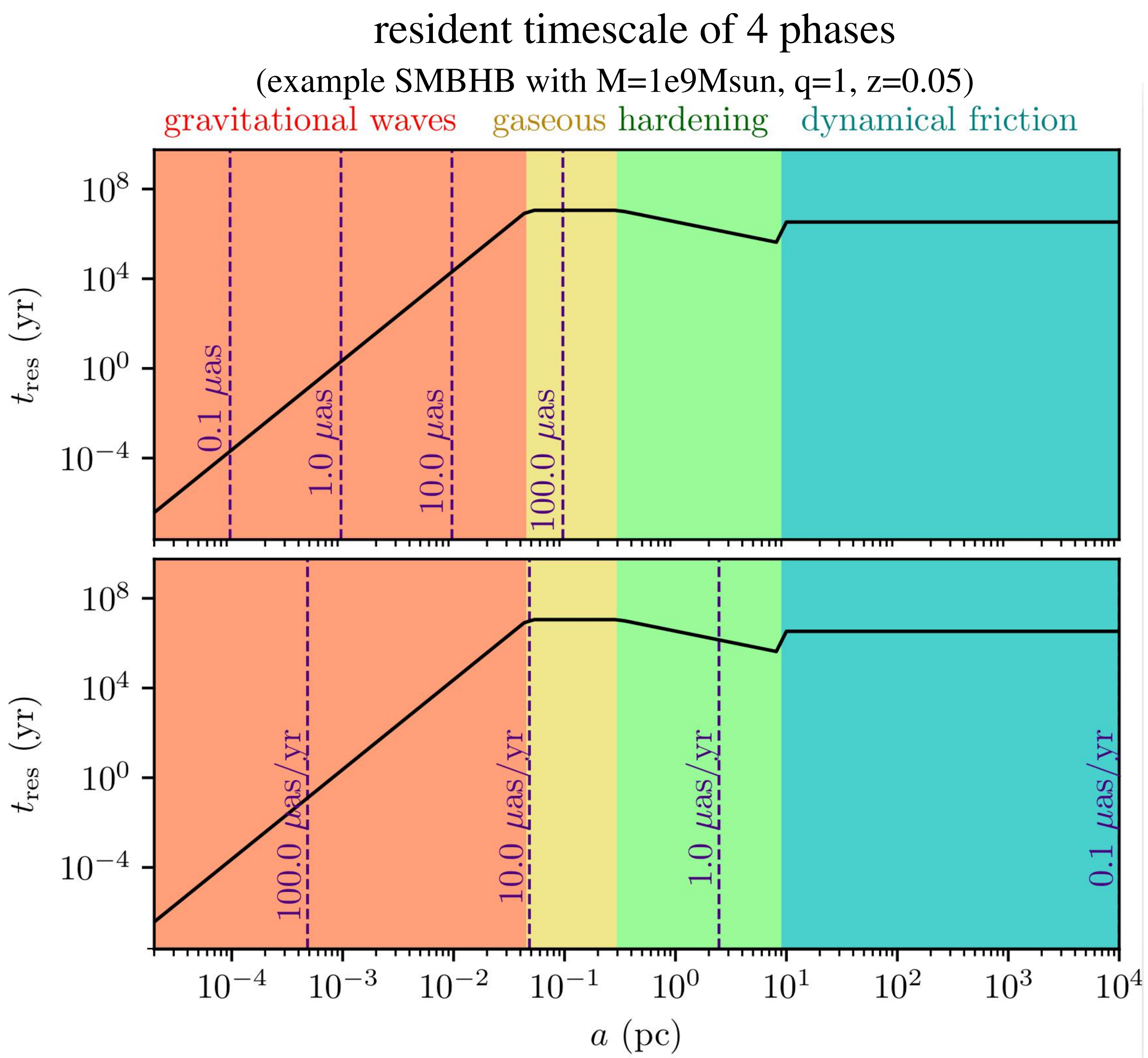
~1 muas/yr

New VLBI results of 0402+379
see Wu Jiang's talk

Advantages of (sub)millimeter VLBI:

- directing tracking black holes without jet morphology model
- in-beam source-frequency phase-referencing (SFPR) -> ~1muas/yr during one/several year(s)

Method: SMBHB orbital evolution



orbital evolution (separation decreasing) by different mechanism:

1. 10kpc to ~10pc, dynamical friction
2. ~10pc to ~1pc, stellar hardening
3. ~1pc to ~0.1pc, gas accretion
4. < ~0.1pc, gravitational waves

(Zhao et al. 2024)

Method: detectable number estimation

observational capability

$$N_\nu(\dot\theta_{\rm min},\theta_{\rm min},F_{\rm min}) = 4\pi\int_0^{z_{\rm max}}\int_{L_\nu^{\rm min}(F_{\rm min})}^{\infty}\Phi(L_\nu,z) \times \mathcal{F}\left[\dot\theta_{\rm min},\theta_{\rm min};M(L_\nu),z\right]\frac{dV}{dz}dL_\nu dz.$$

minimum detectable angular velocity, angular separation, flux density

radio luminosity function (Butler et al. 2019)

mass-luminosity model (partly base on Plotkin et al. 2012)

probability distribution function (PDF) of a AGN has a detectable SMBHB system (D'Orazio & Loeb 2018)

PDF = Fraction of AGNs triggered by SMBHBs X $\dfrac{\text{integral resident timescale of all detectable cases}}{\text{integral resident timescale of all physically possible cases}}$

0.05 (Pulsar Timing Array upper limits on GW background)

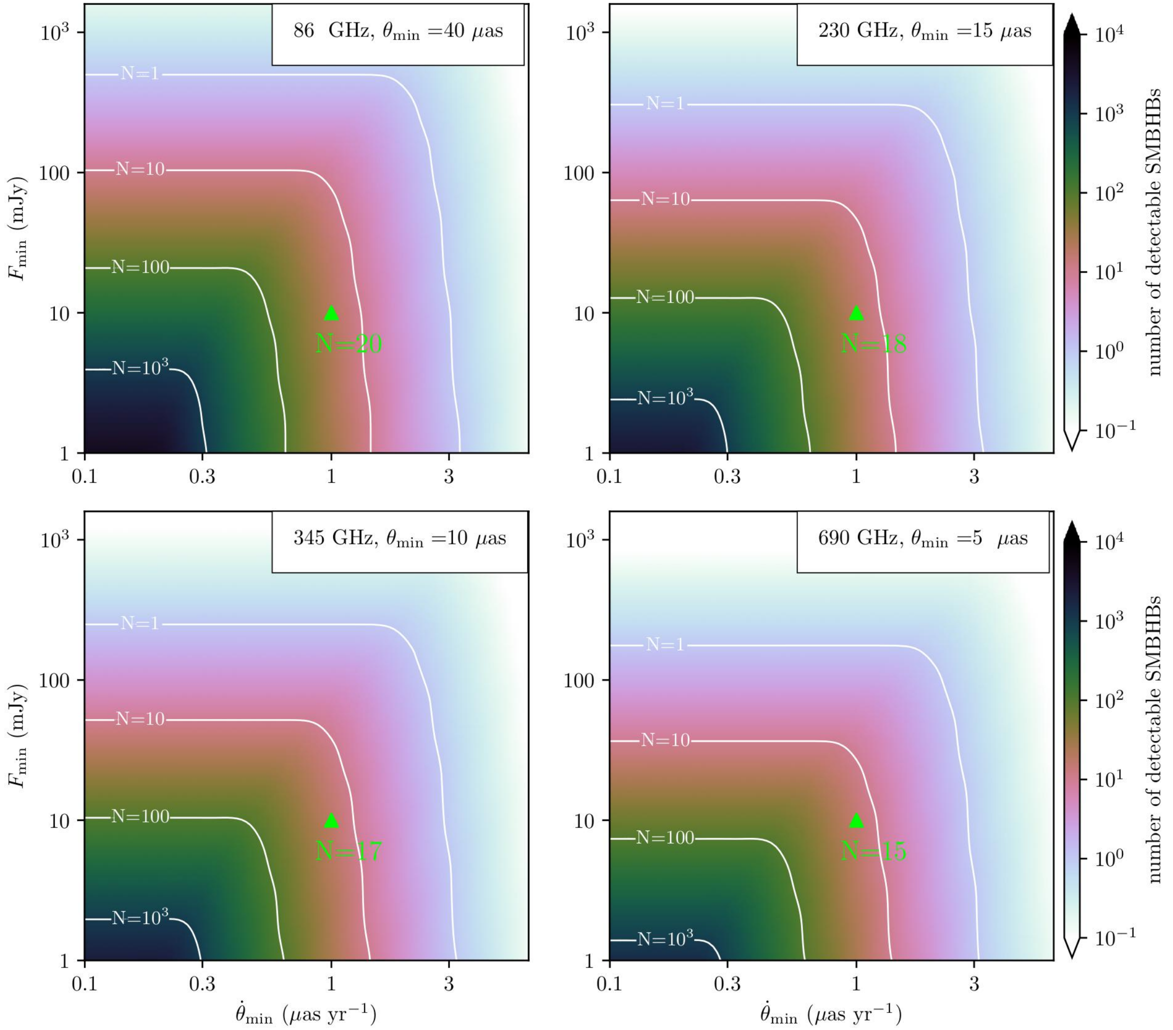
theory

orbital evolution model

M: total mass
q: mass ratio
a: separation

(Zhao et al. 2024)

Results: detectable number estimation



$\dot{\theta}_{min}$ (μas/yr)	Num. of detect. SMBHBs* 86 GHz	230 GHz	345 GHz	690 GHz
3	1	0	0	0
1	20	18	17	15
0.1	279	140	105	64

F_{min} = 10 mJy , θ_{min} = 40/15/10/5μas, at 86/230/345/690 GHz

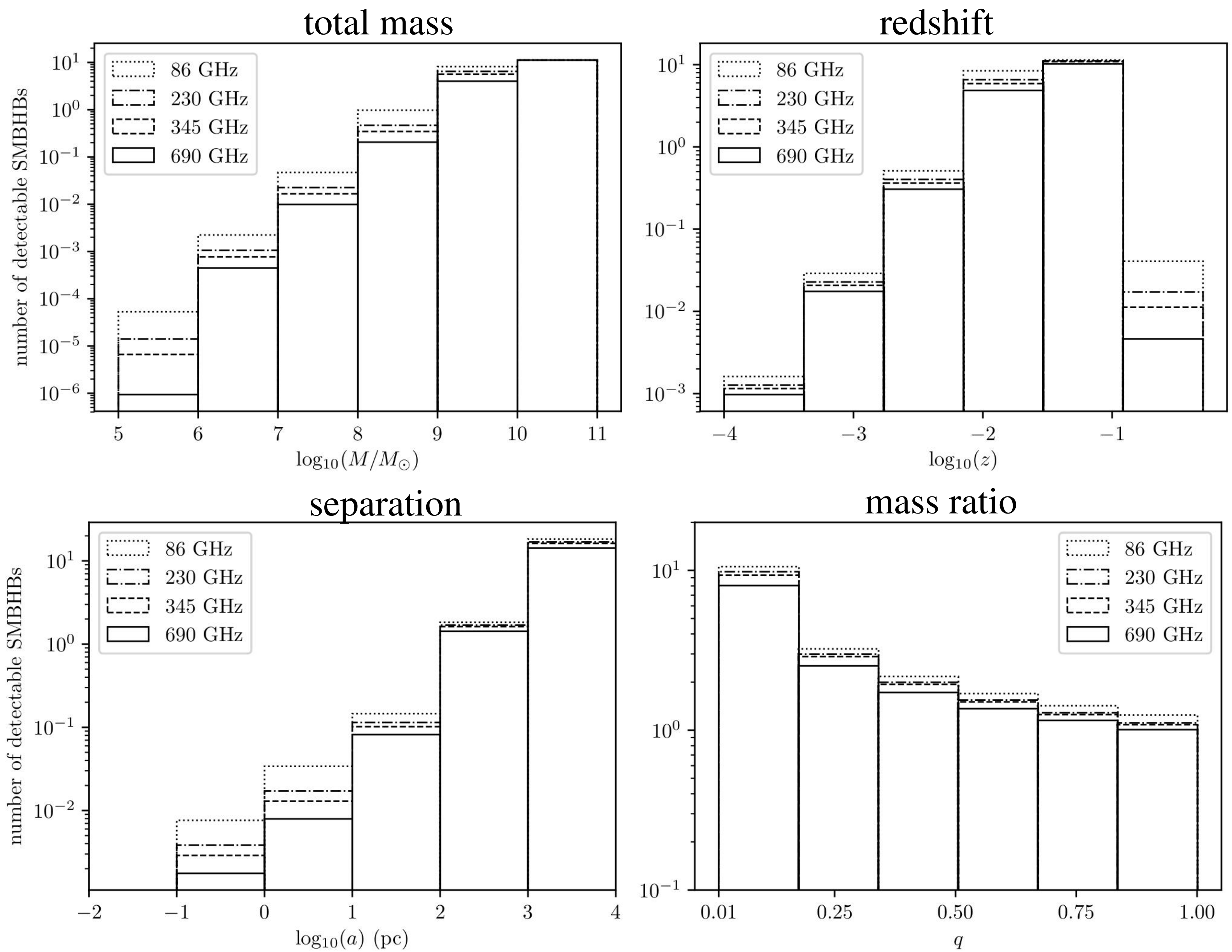
By using simultaneous multi-frequency technique, (sub)millimeter VLBI can achieve

- 1 muas/yr proper motion precision
- 10 mJy sensitivity
- better than 40 muas resolution

=> ~20 SMBHB systems can be detected

(Zhao et al. 2024)

Results: physical parameters of detectable SMBHBs



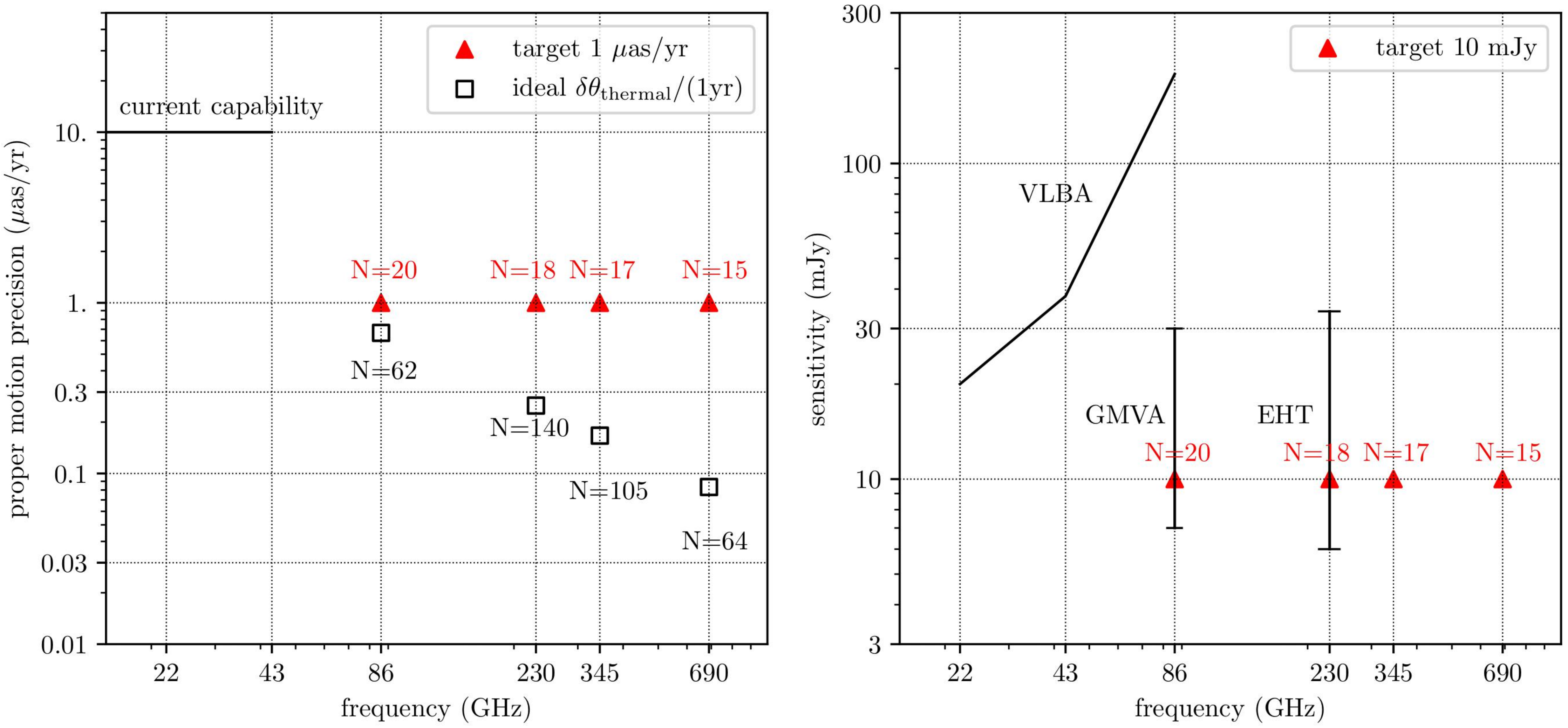
1muas/yr, 10 mJy and
best resolution
~20 detectable SMBHBs

the most detectable systems are in the AGN sources with

- high mass (1e9-11 Msun)
- relatively low redshift (z<0.1)
- large separation (>0.1 pc)
- relatively insensitive to mass ratio

(Zhao et al. 2024)

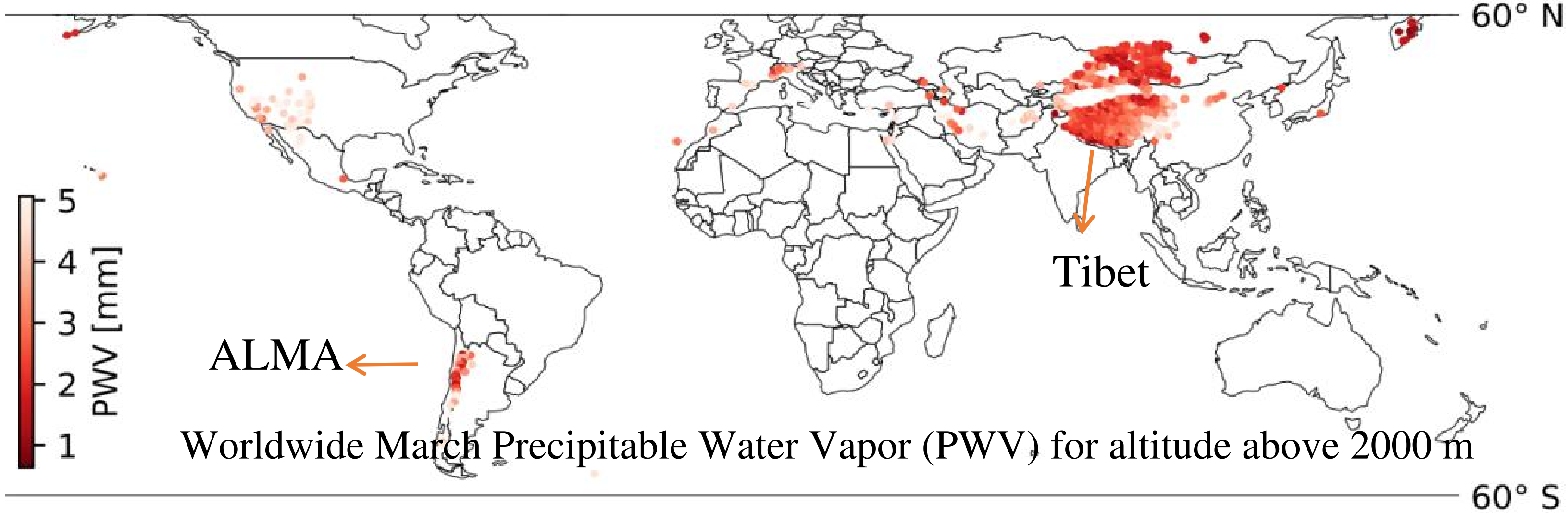
Results: compare with current capability



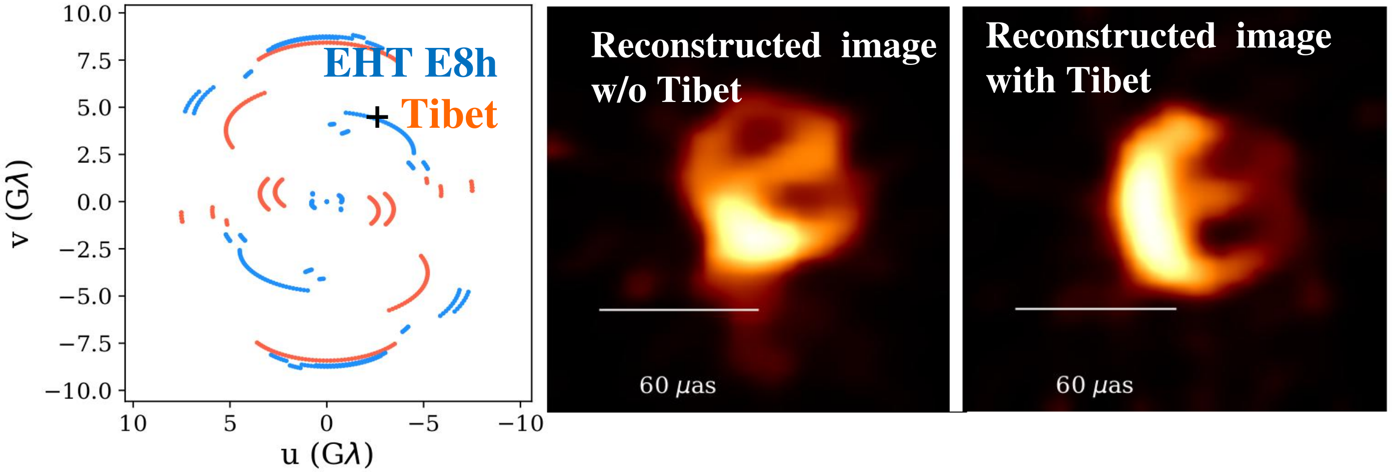
(Zhao et al. 2024)

China (sub)millimeter VLBI

1. West China has very good site condition for sub-millimeter observation
2. Advantage for 24h-observation to capture SgrA* movie



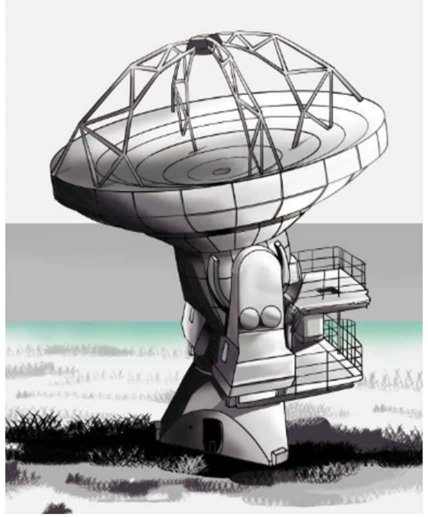
(Raymond et al. 2021)



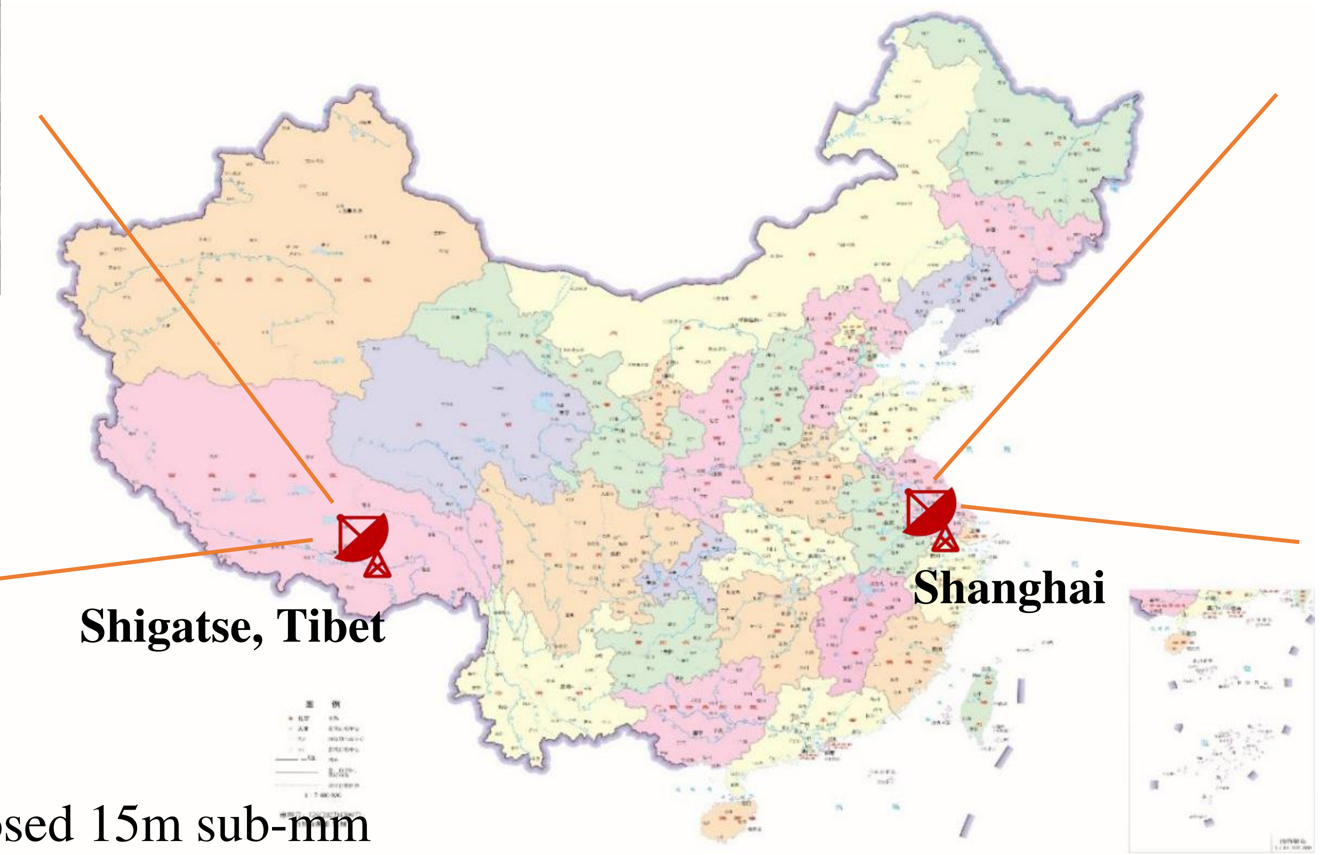
(Yu et al. 2023)

(sub)millimeter telescopes in Tibet

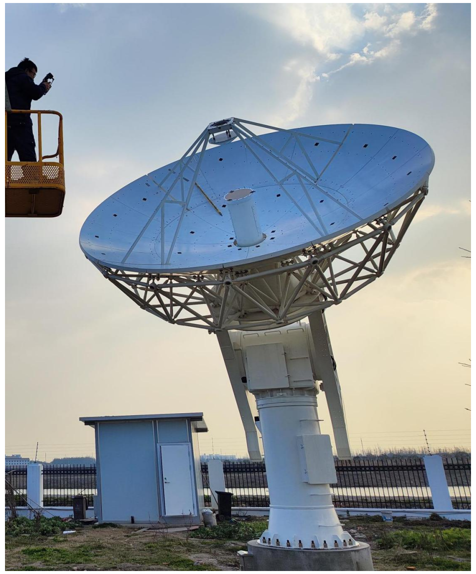
Shigatse 40m telescope
2024 X band
2027 K/Q/W band



proposed 15m sub-mm telescope
86/230/345 GHz
searching site now



Tianma 65m
2025 K/Q/W band
(Weiye Zhong's talk)

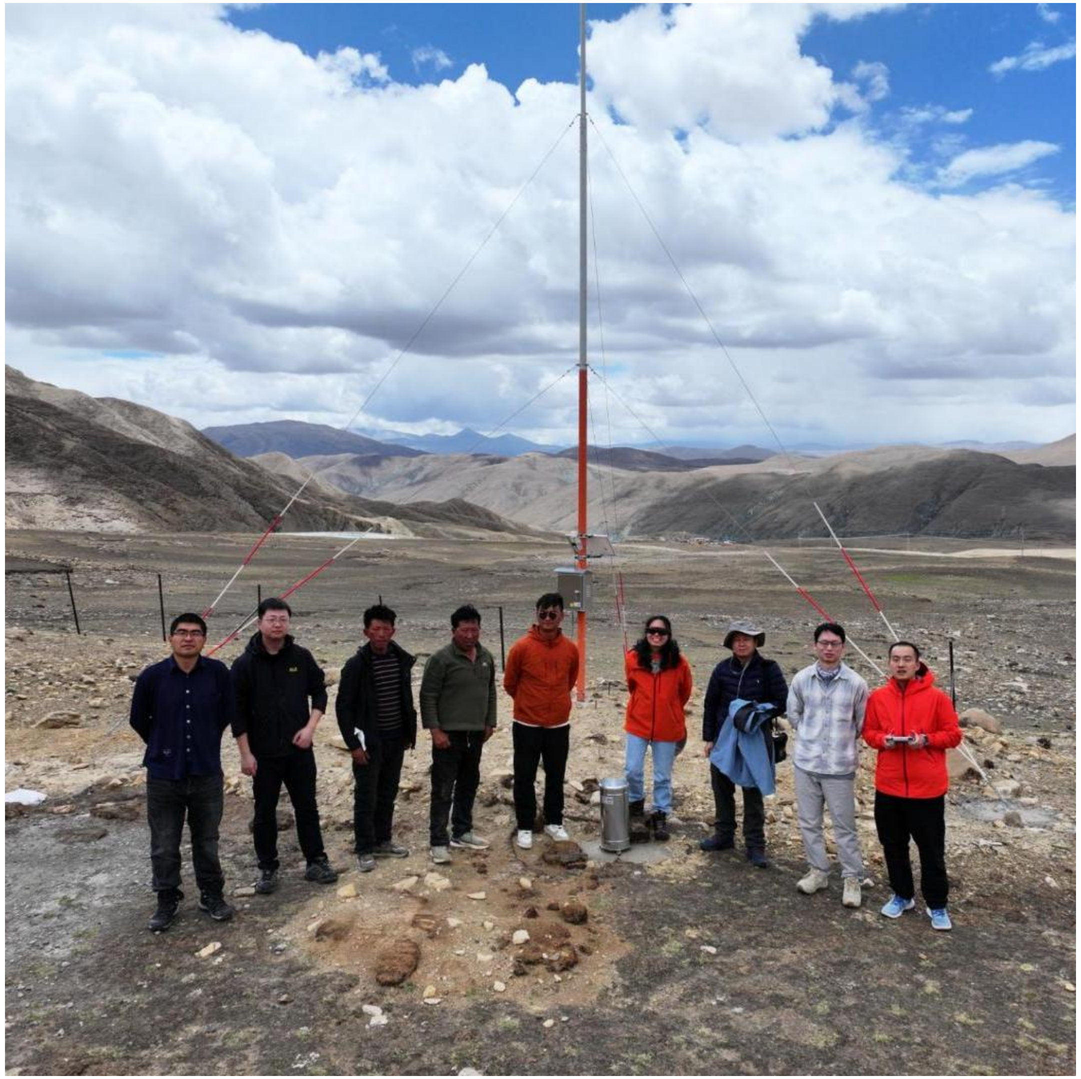


5m prototype of
sub-mm telescope


Searching best site for sub-mm telescope in Shigatse, Tibet
SHAO + Tibet University

Promising candidate site for sub-mm: Jiuwa

- Altitude 4600m, very dry, concrete road built in 2024
- Weather data monitoring 2024.11-now



Outreach in Tibet & cultural experience

Thank you very much!