

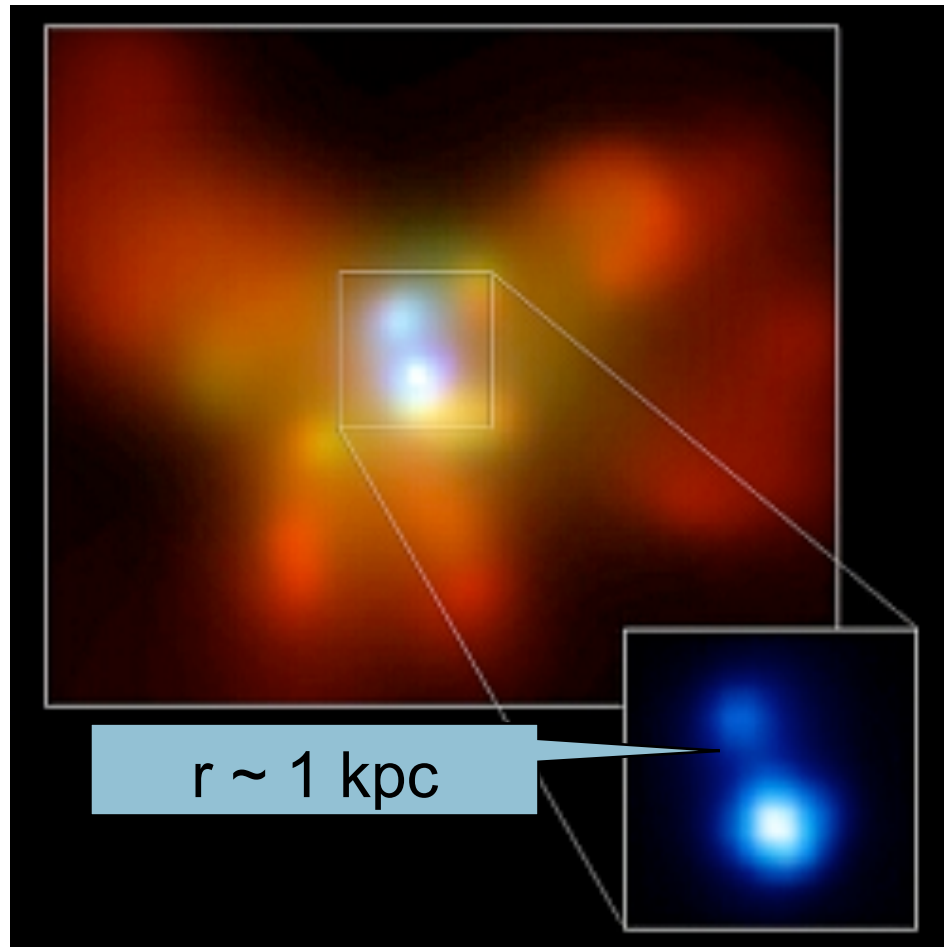
Search for Orbital Motion of Binary Black Holes

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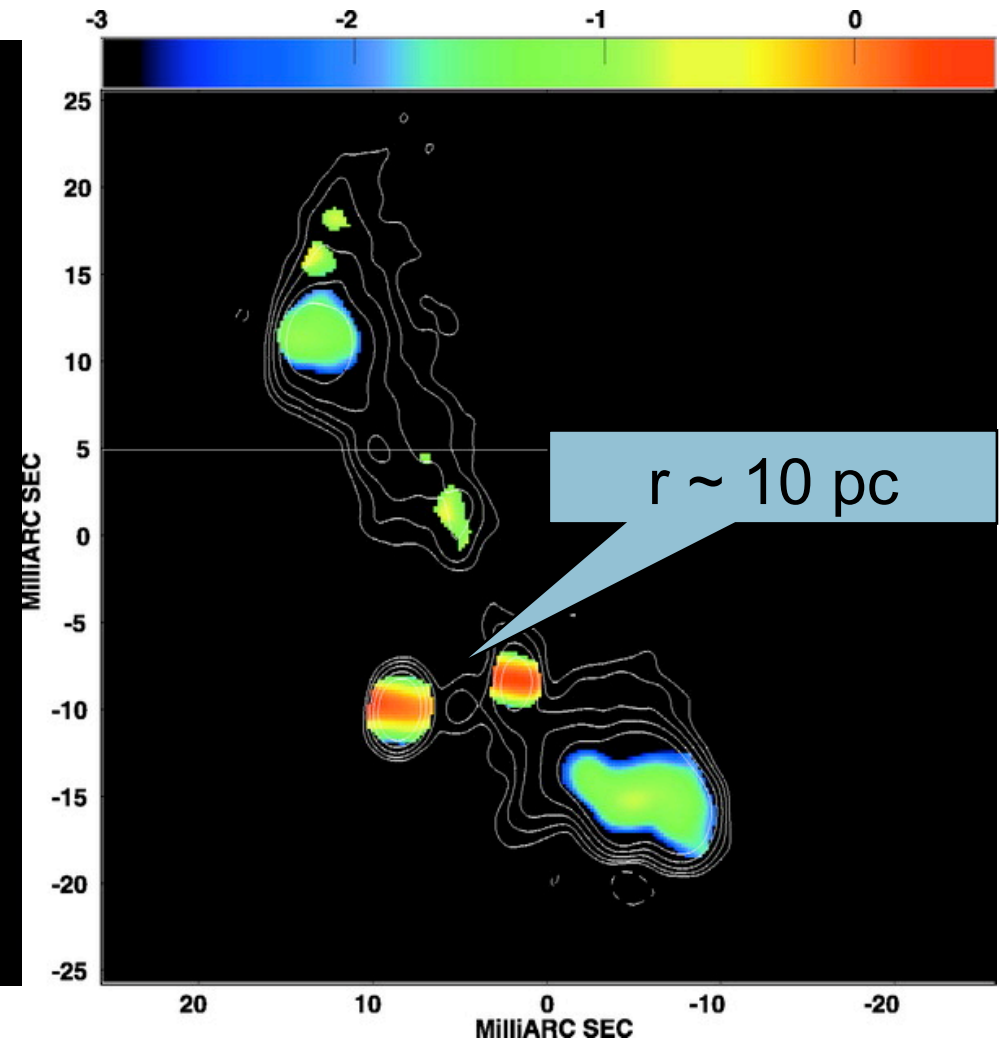
Outline

- ◆ Motivation
- ◆ VLBI astrometry as a probe of BBH orbit
- ◆ Next step, including VSOP-2 project
- ◆ Summary

Detection of Double AGNs



Komossa et al. 2003



Mines et al. 2004

Next step, we want to see a movie of BBH motion !

Can We See BBH Motion ?

Yes !

We can trace **orbital motion of the core**
of **sub-pc BBHs**
with **VLBI Astrometry**
in **year-scale**

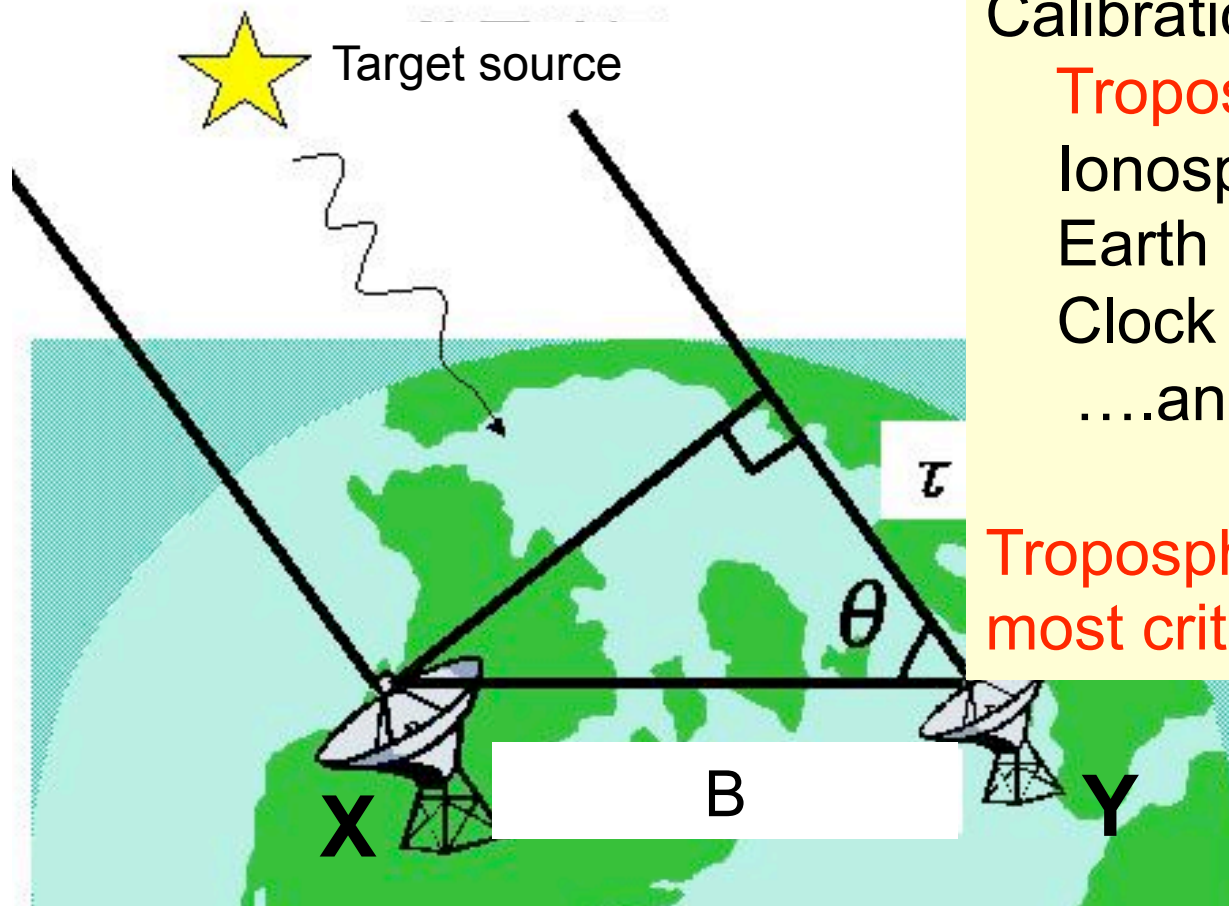
◆ Because,

BBHs with separation of 0.01 – 1 pc have

- Orbital period : 1 – 100 yr @ 10^8 Msolar
- Angular size: 2 – 200 micro-arcsec @ 100 Mpc

Principal of VLBI Astrometry

- ◆ If B is known, by measuring the delay time τ we obtain the target position θ



Calibration

Tropospheric fluctuation

Ionospheric delay

Earth rotation parameter

Clock offset

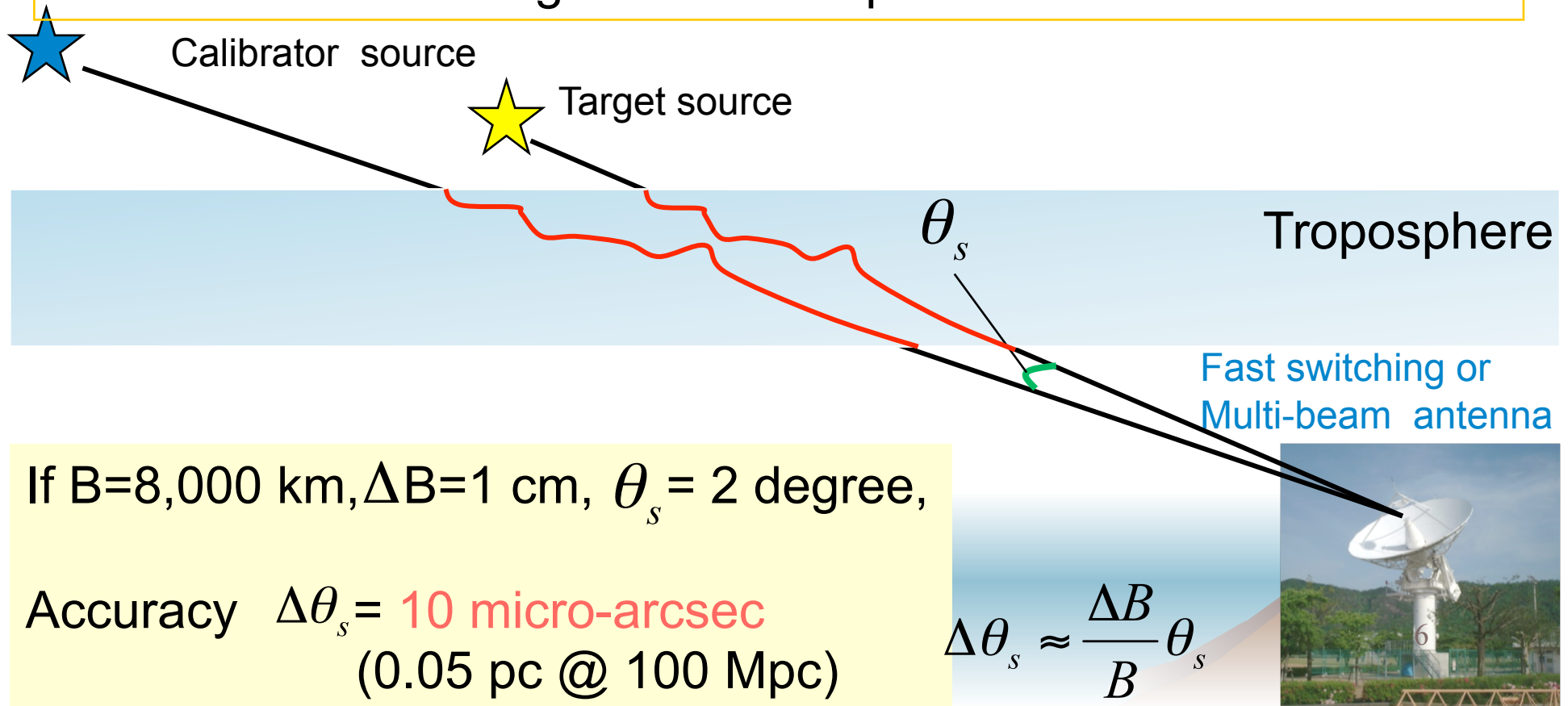
....and so on

Tropospheric fluctuation is the most critical

Phase-referencing Technique

By observing target and a close calibrator simultaneously,

- 1) cancel out **the tropospheric phase fluctuation**
- 2) measure **the position of target with respect to calibrator**
- 3) if calibrator is much more distant than target,
it can be regarded as the position reference



If $B=8,000$ km, $\Delta B=1$ cm, $\theta_s = 2$ degree,

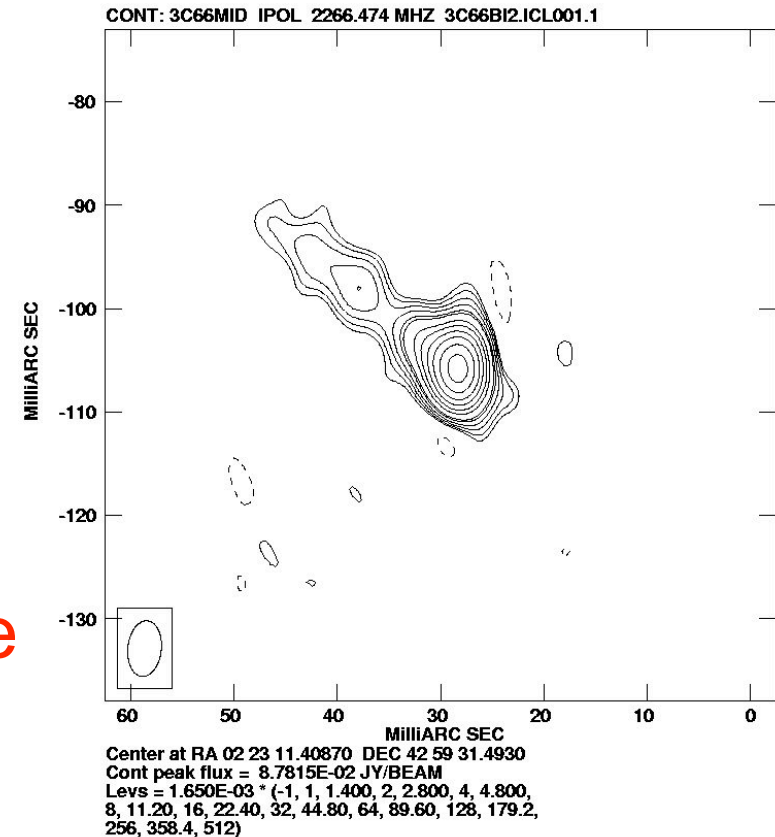
Accuracy $\Delta\theta_s = 10$ micro-arcsec
(0.05 pc @ 100 Mpc)

$$\Delta\theta_s \approx \frac{\Delta B}{B} \theta_s$$



3C66B, the First Challenge

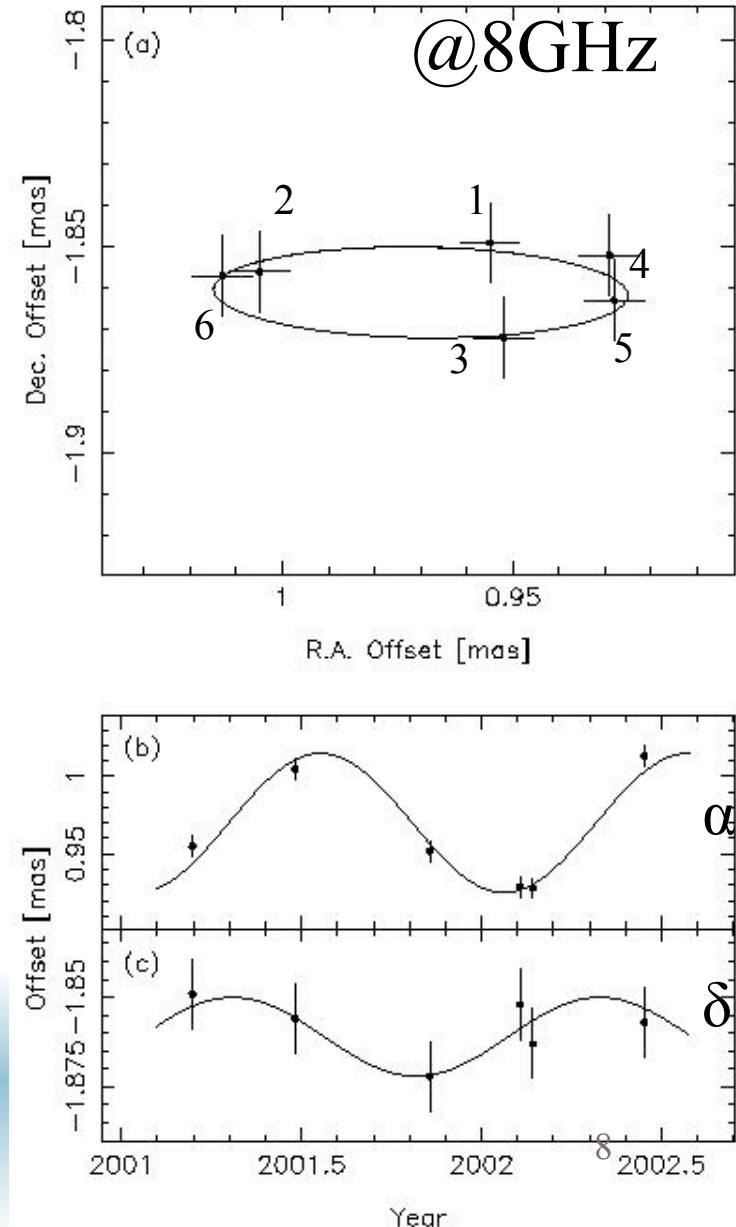
- ◆ Target : 3C66B
 - $z \sim 0.02$, radio galaxy (giant E)
- ◆ Calibrator : 3C66A
 - $z \sim 0.3$, FSRQ
- ◆ Very close pair
 - Separation is only 0.1 degree
 - Accuracy of < 10 micro-as achievable, in principle
- ◆ 6 epochs during 1.5 yrs at 2/8 GHz were carried out with VLBA



Detection of Core Motion

- ◆ The core shows clear elliptical motion
 - $P \sim 1.05$ yr with $r \sim 0.02$ pc
- ◆ We concluded this shows the orbital motion of BBH
- ◆ Observations are still continued at 2/8/22 GHz

By improving accuracy, this method will be good probe for tracing BBH motion directly



Next Step

◆ Higher frequency

- The core at 8 GHz is separated from BH by a few pc suggested from SSA model (Sudou et al. 2002)

➔ mm-VLBI (> 22GHz)

◆ Higher sensitivity

- Because of low sensitivity of conventional VLBI, it is hard to find calibrators < 2 degree

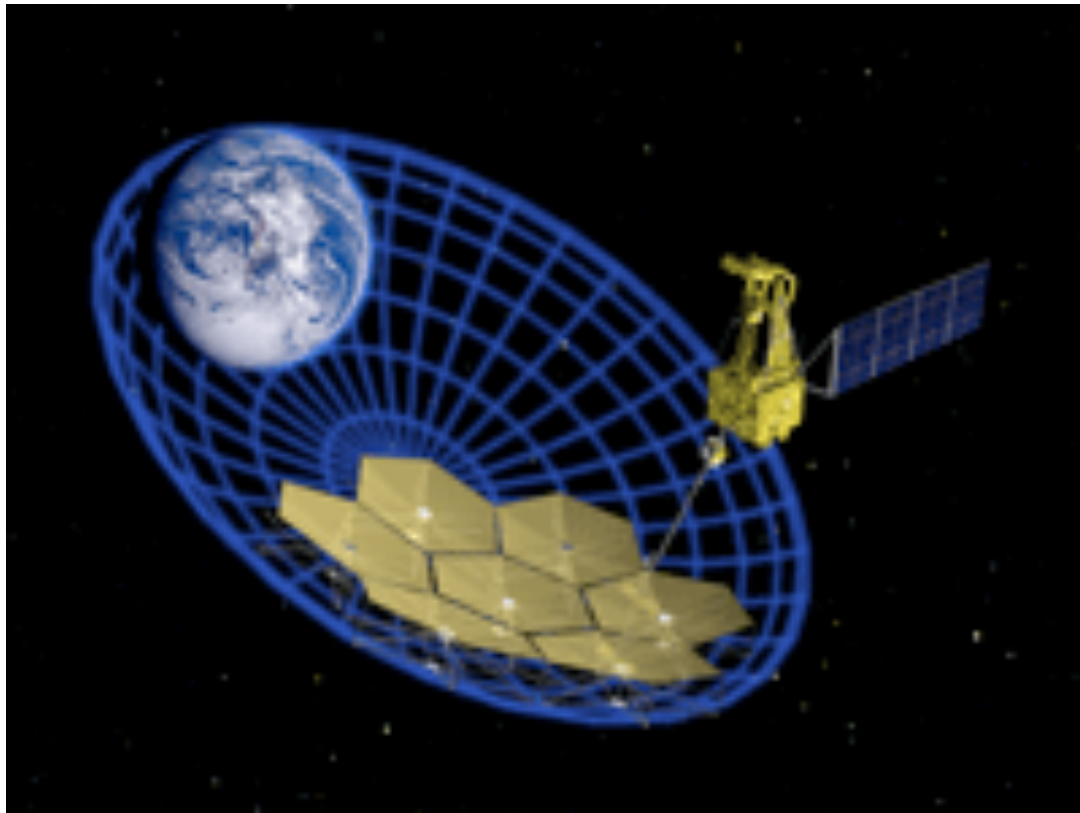
➔ e-VLBI with optical fiber link (< mJy)

➔ SKA

◆ Higher resolution

VSOP-2: Space VLBI

Led by ISAS and international community
(www.vsop.isas.jaxa.jp/vsop2e)



Longest baseline:
25,000 km

Frequency:
8, 22, and 43 GHz

Spatial resolution:
40 micro-arcsec @ 43G

Launch:
2012

VSOP-2 is a powerful probe for observing sub-pc BBHs !

Summary

- ◆ Search for BBHs at sub-pc scale will provide
 - Direct tracing of their orbital motion
 - Information on GW expectation
- ◆ Measurement of **core motion with VLBI astrometry** will be a good probe for the orbit
- ◆ VSOP-2 is expected to be very useful for BBH search

Now we start to walk a long way to understand merging BHs ...

@ Grand Canyon, Blue Mountains

