Measuring the Core Shift of Sgr A*

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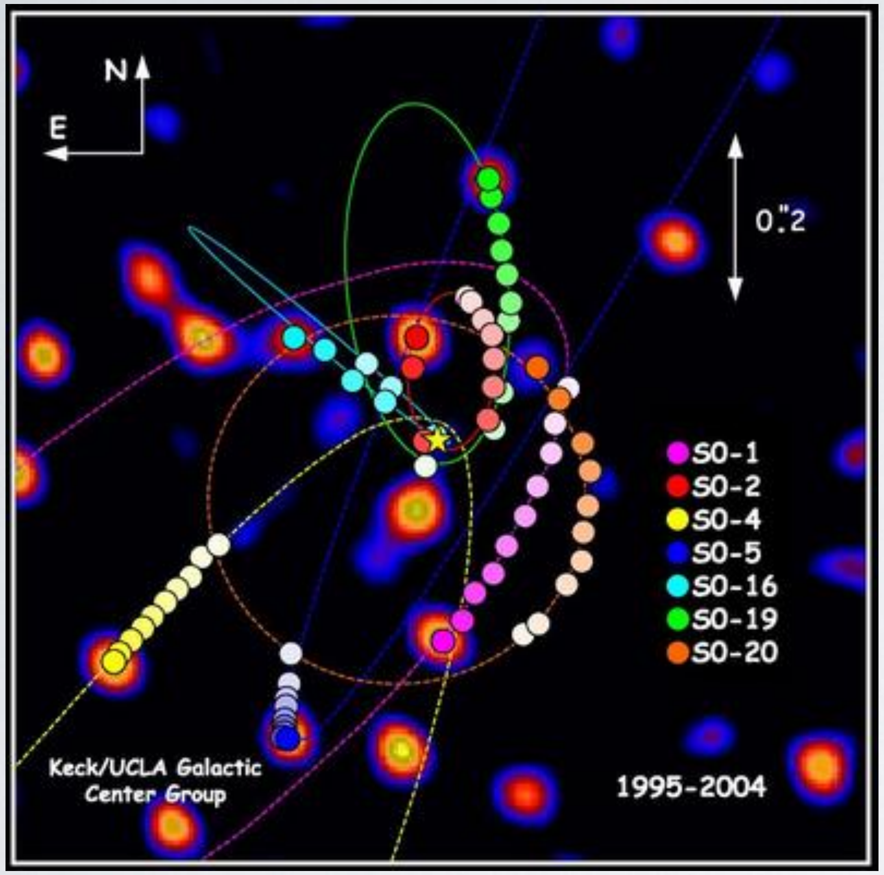
UST: University of Science and Technology
NAOJ: National Astronomical Observatory of Japan
IAA: Instituto de Astrofisica de Andalucia
ICRAR: International Centre for Radio Astronomy Research

Our Galactic Center: Sagittarius A* (Sgr A*)

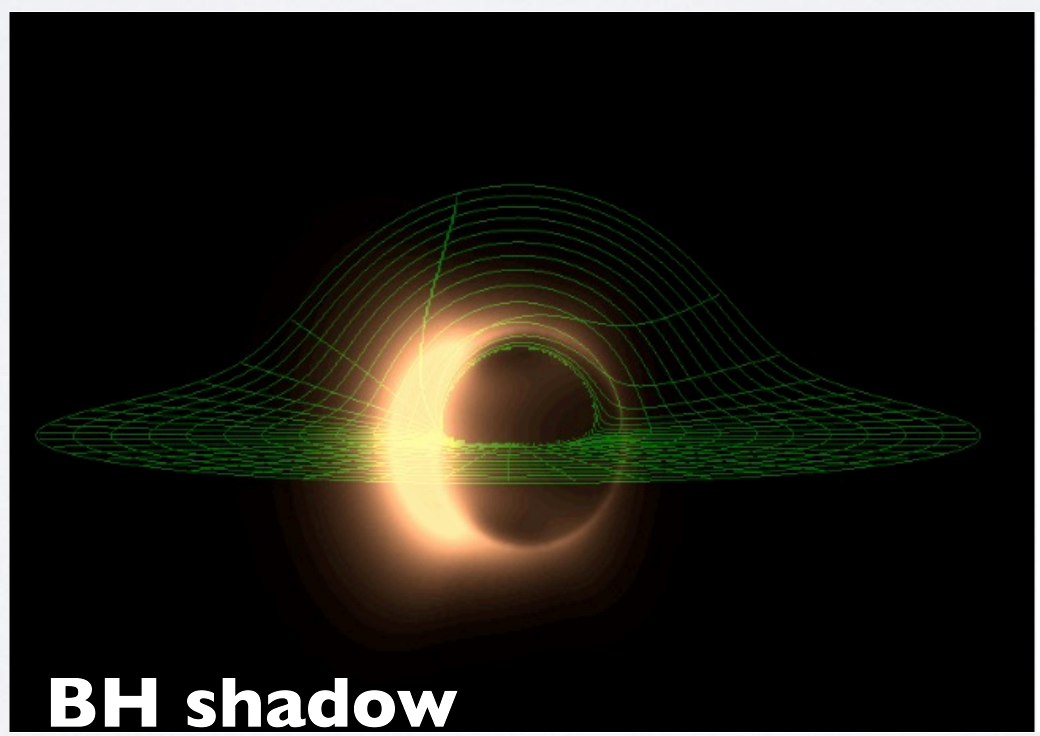


The Closest SMBH from us

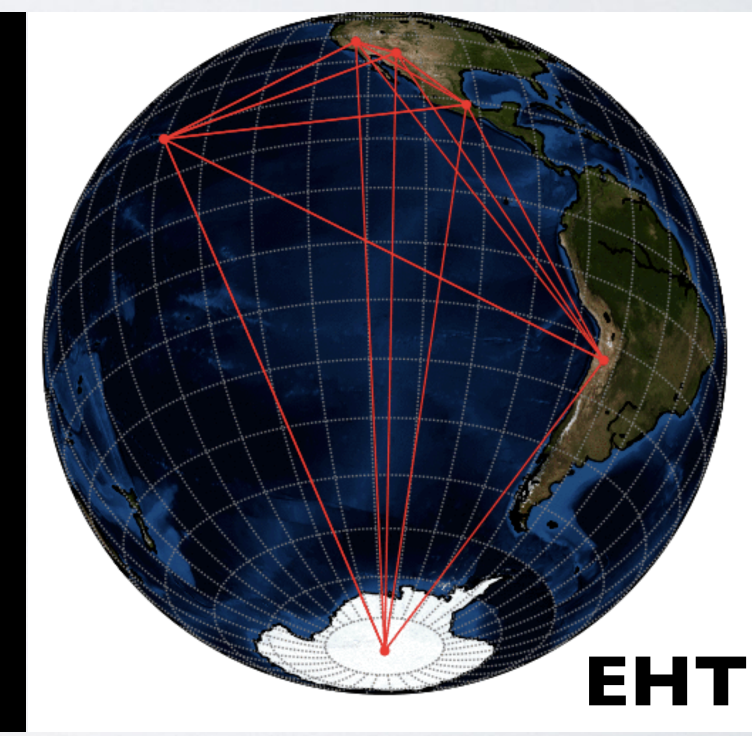
(~8 kpc away: Reid 1993; Ghez+ 2005, 2008; Gillessen+ 2009)

- **Mass ~ 4 x 10^6 M_{sun}**
  (Genzel+ 2010; Falcke & Markoff 2013)
- **R_{sch} ~ 10 uas / visible by lensing up to 50 uas**
  (e.g., Falcke+ 2000)
- **Low Eddington ratio: L ~ 10^{36} erg/s ~10^{-9} L_{edd}**
  (Falcke+ 1993; Quartaert & Gruzinov 2000)
- **Mass accretion rate: 2 x $10^{-7\sim9}$ M_{sun}/yr**
  (Marrone+ 2007)

Thanks to its proximity,
we can directly study the environment of vicinity of SMBH.



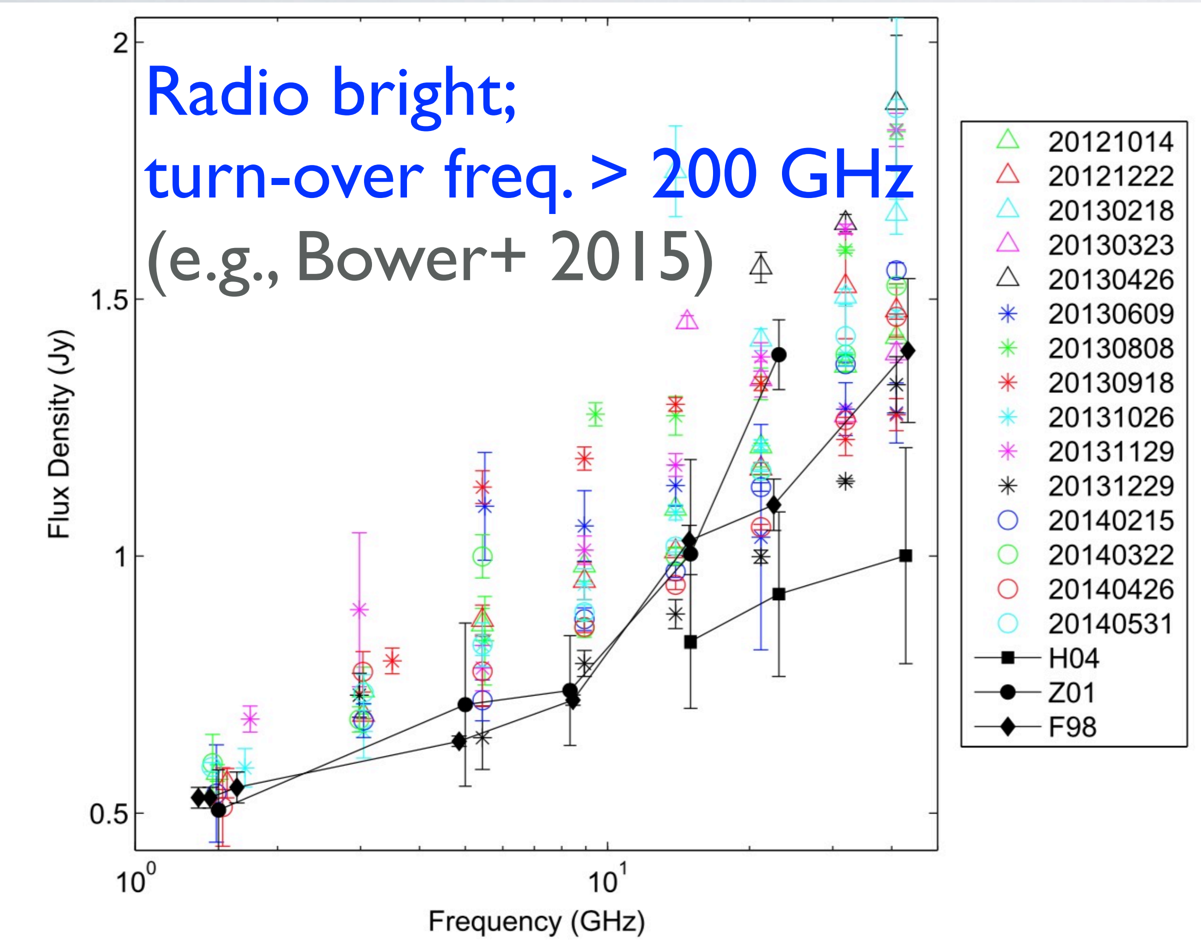
(Bardeen 1973; Luminet 1979; Shen+ 2005; Broderick & Loeb 2006)



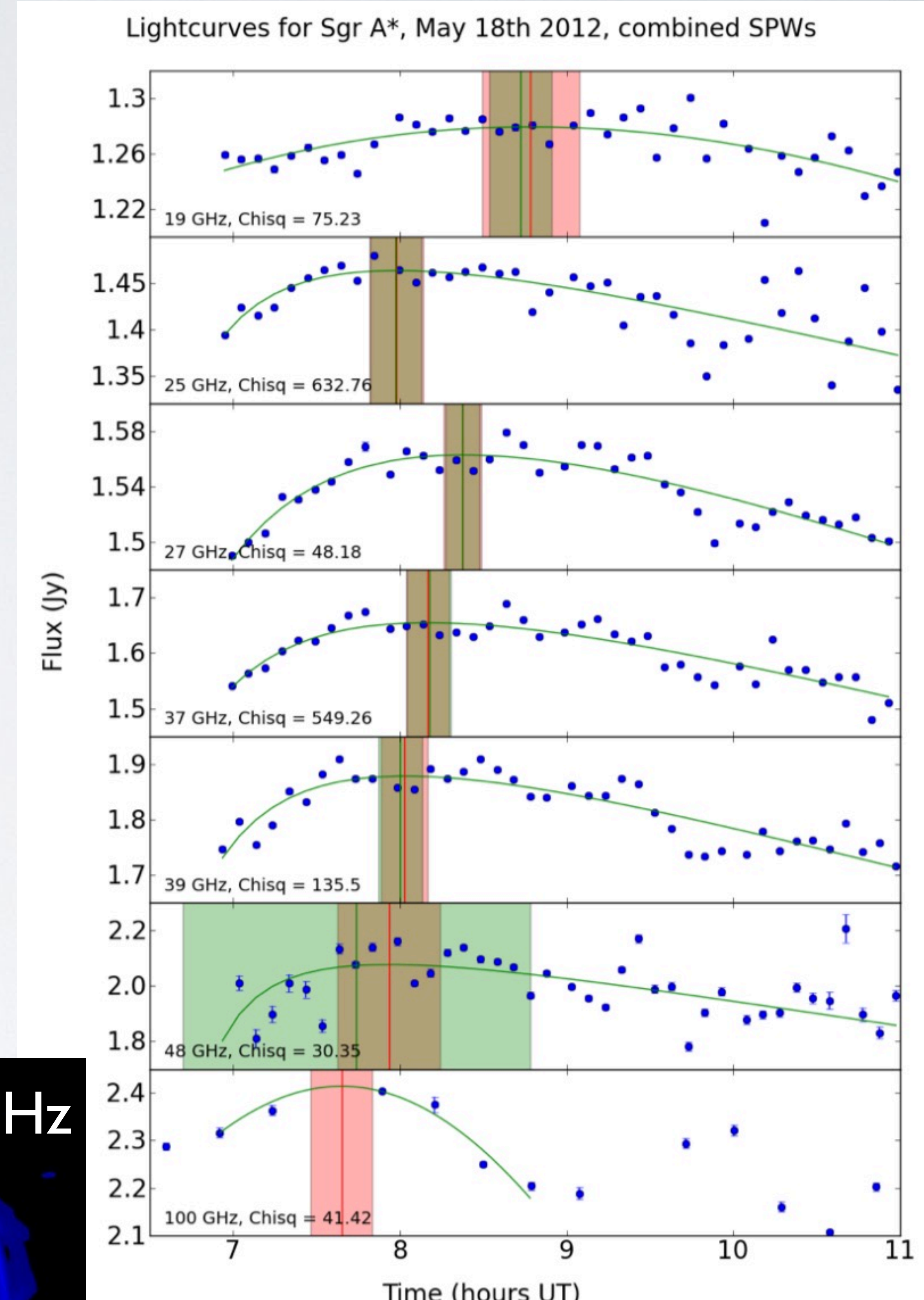
(Johnson+2015; Fish+ 2016; Chael+ 2016; Broderick+ 2016)

Our Galactic Center: Sagittarius A* (Sgr A*)

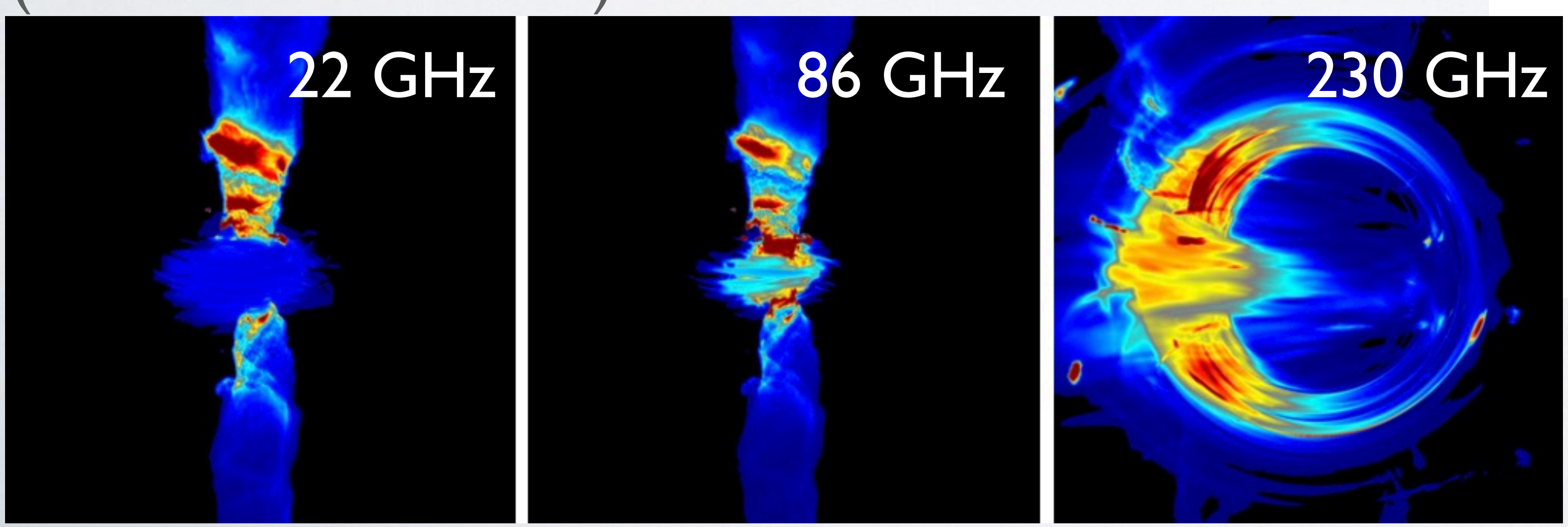
At the same time,



Radio bright;
turn-over freq. > 200 GHz
(e.g., Bower+ 2015)

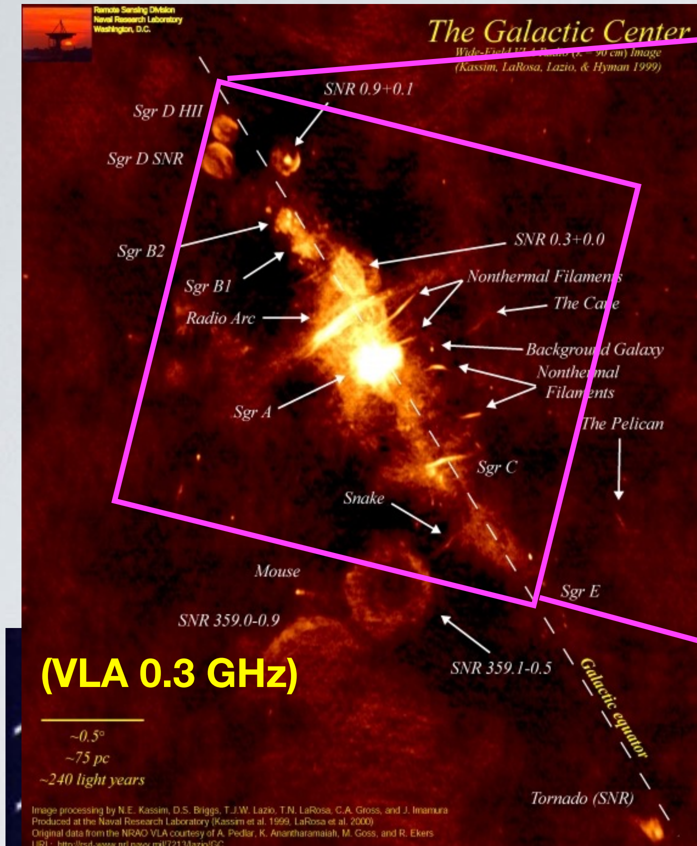


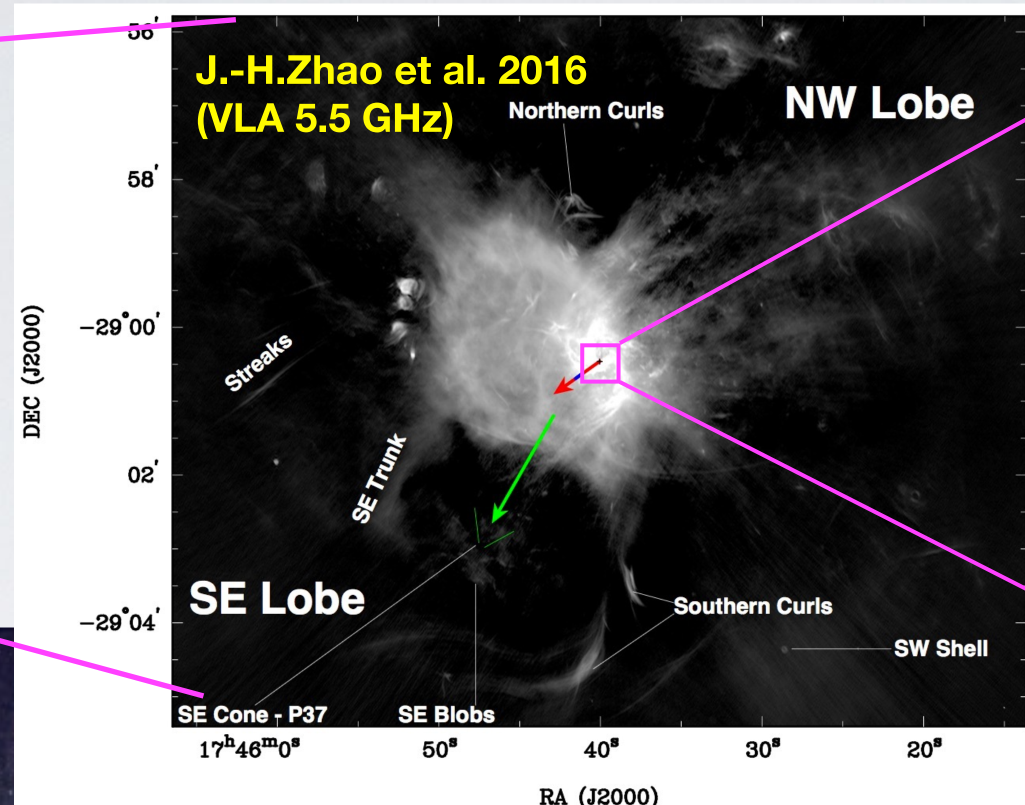
GRMHD simulation including jet model
(Moscibrodzka+ 2014)

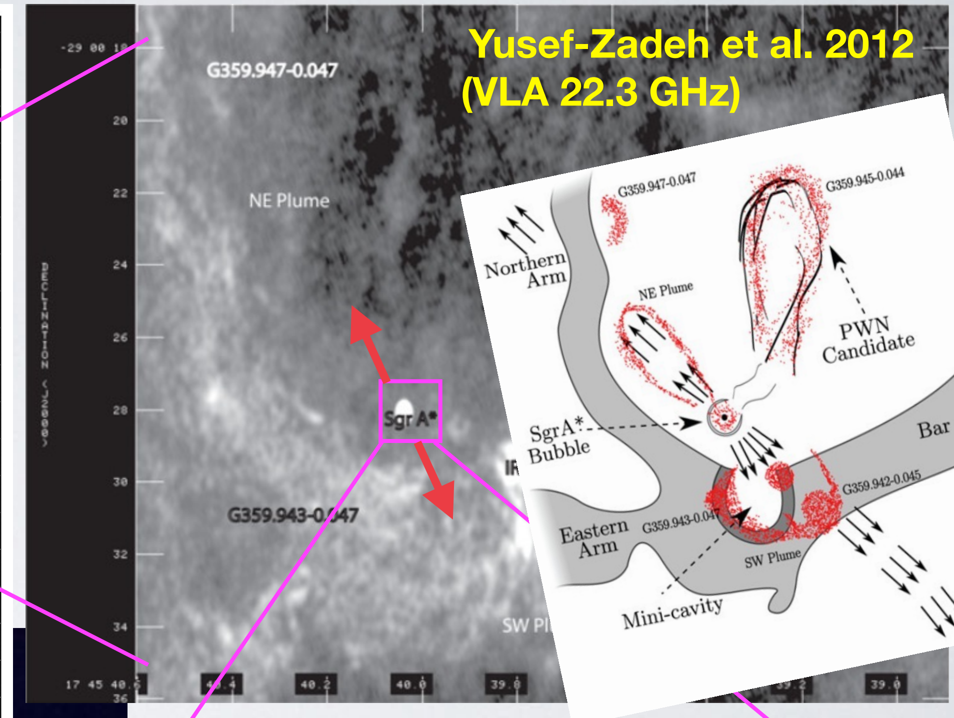


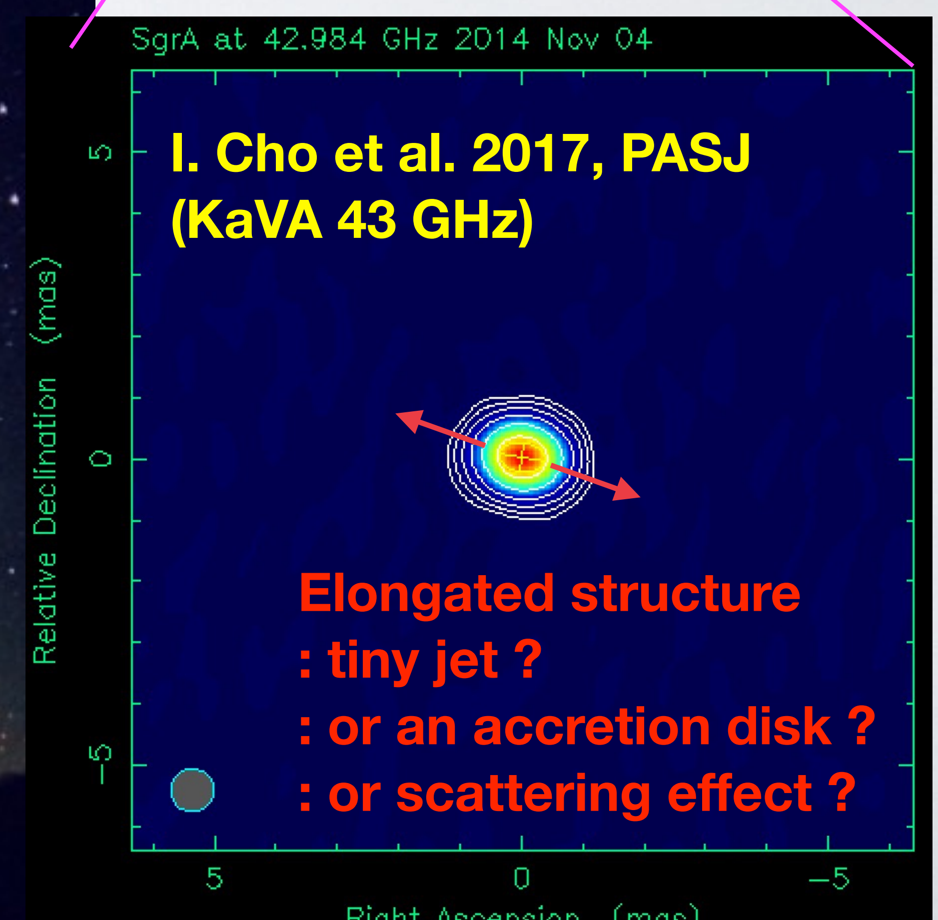
Freq. dependent time-lag in flaring
: Jet indication
(Brinkerink+ 2015)

Our Galactic Center: Sagittarius A* (Sgr A*)





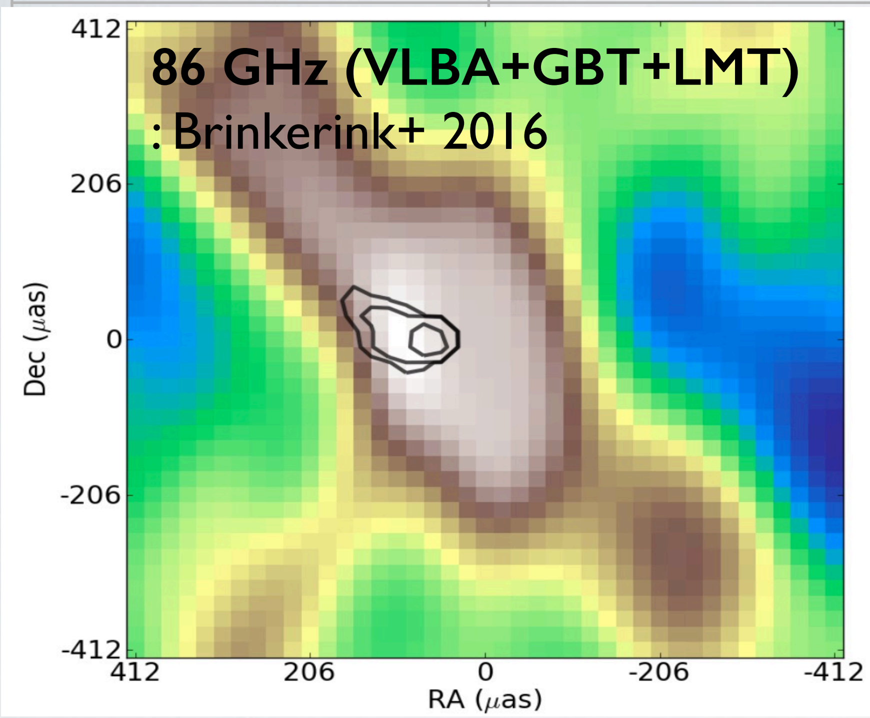


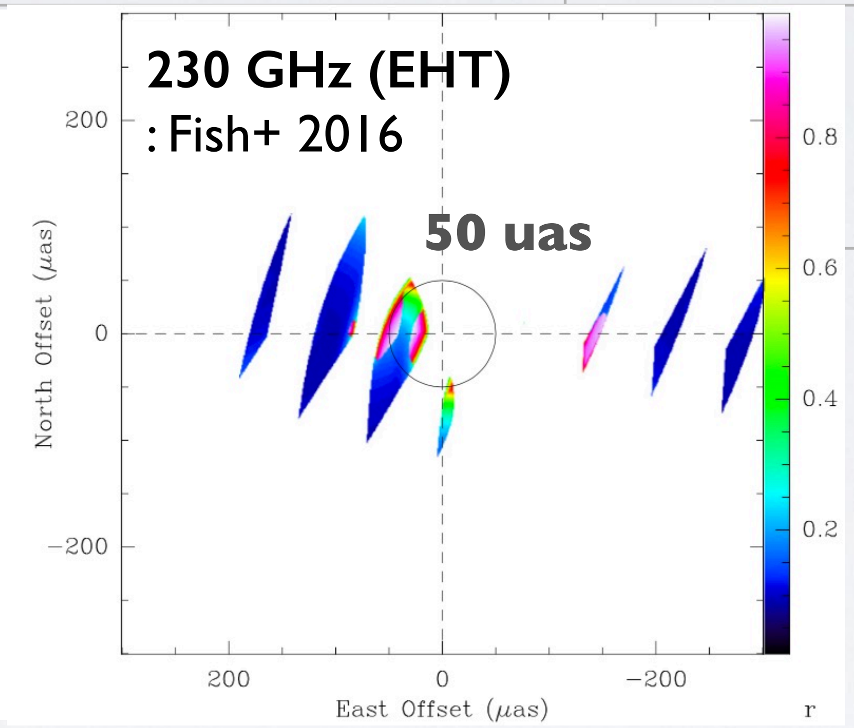


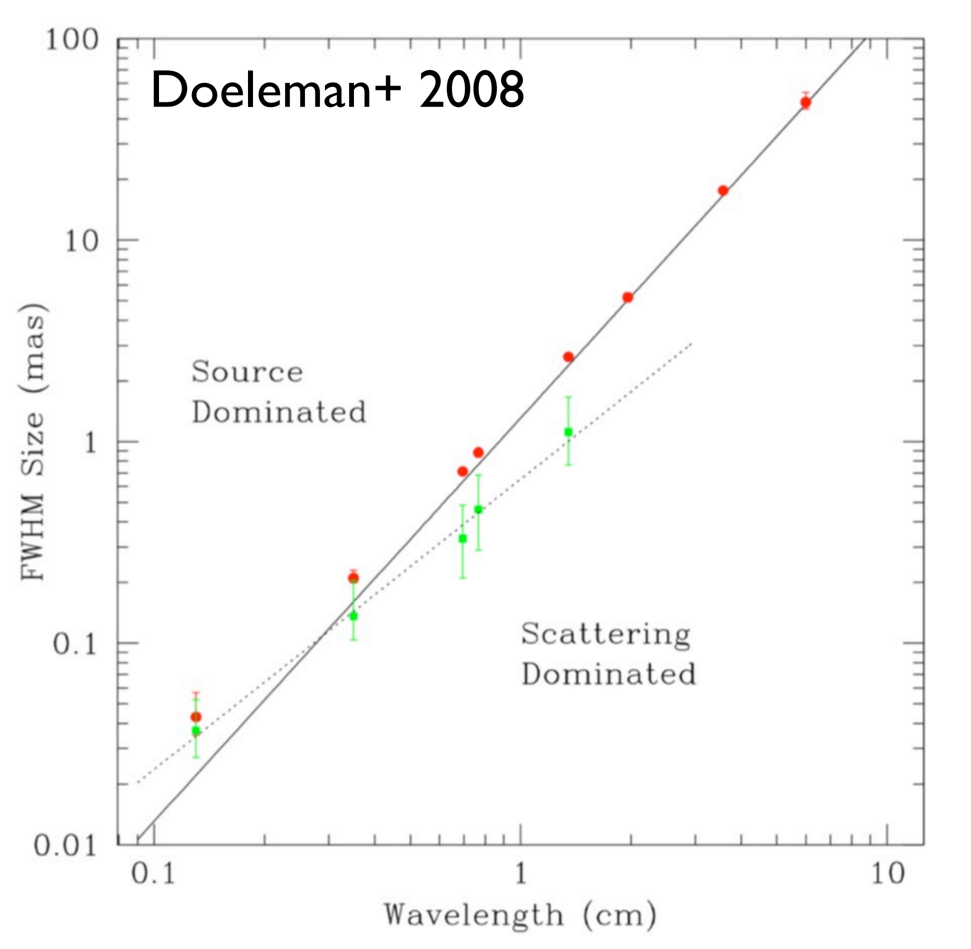
The ambient clouds also indicate the existence of an outflow from Sgr A*.
However it has not shown the jet-feature in sub-pc (i.e.,VLBI) scale.

What does the VLBI image tell us ?

	Jet (Blandford-Konigl model)	Accretion flow	Scattering effect
Structure	Asymmetric (or weakly-symmetric)	Asymmetric	Symmetric (or sub-structure)

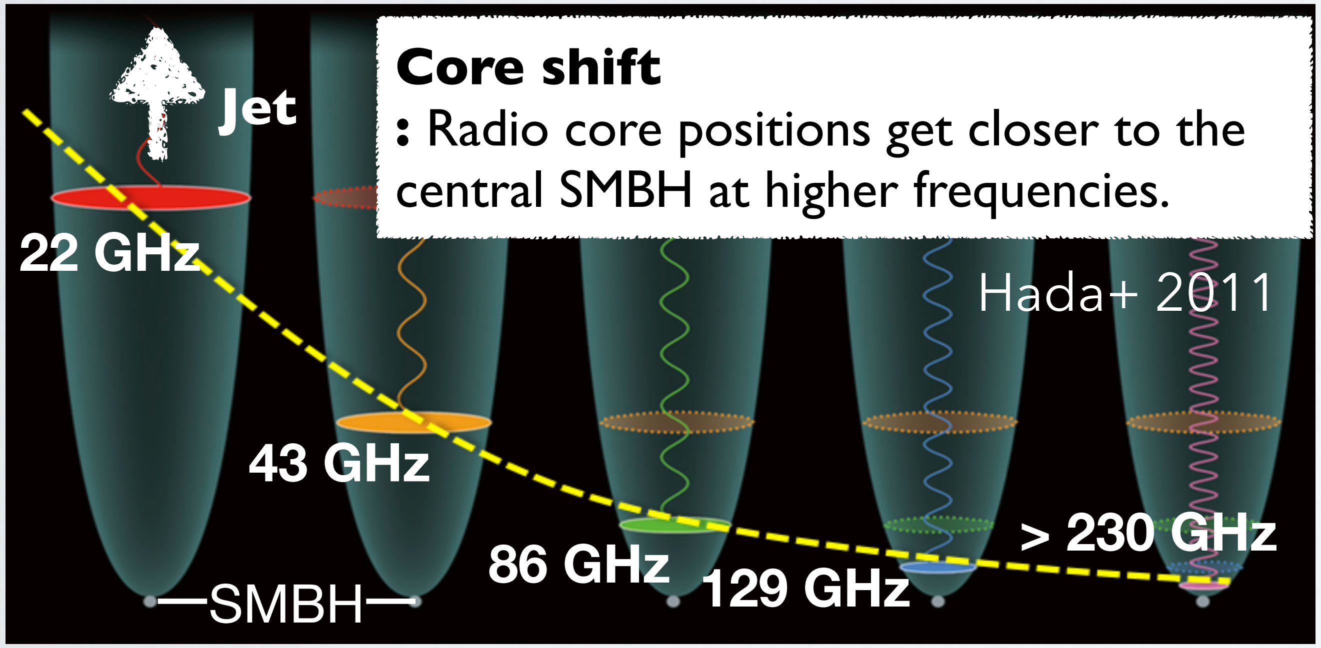


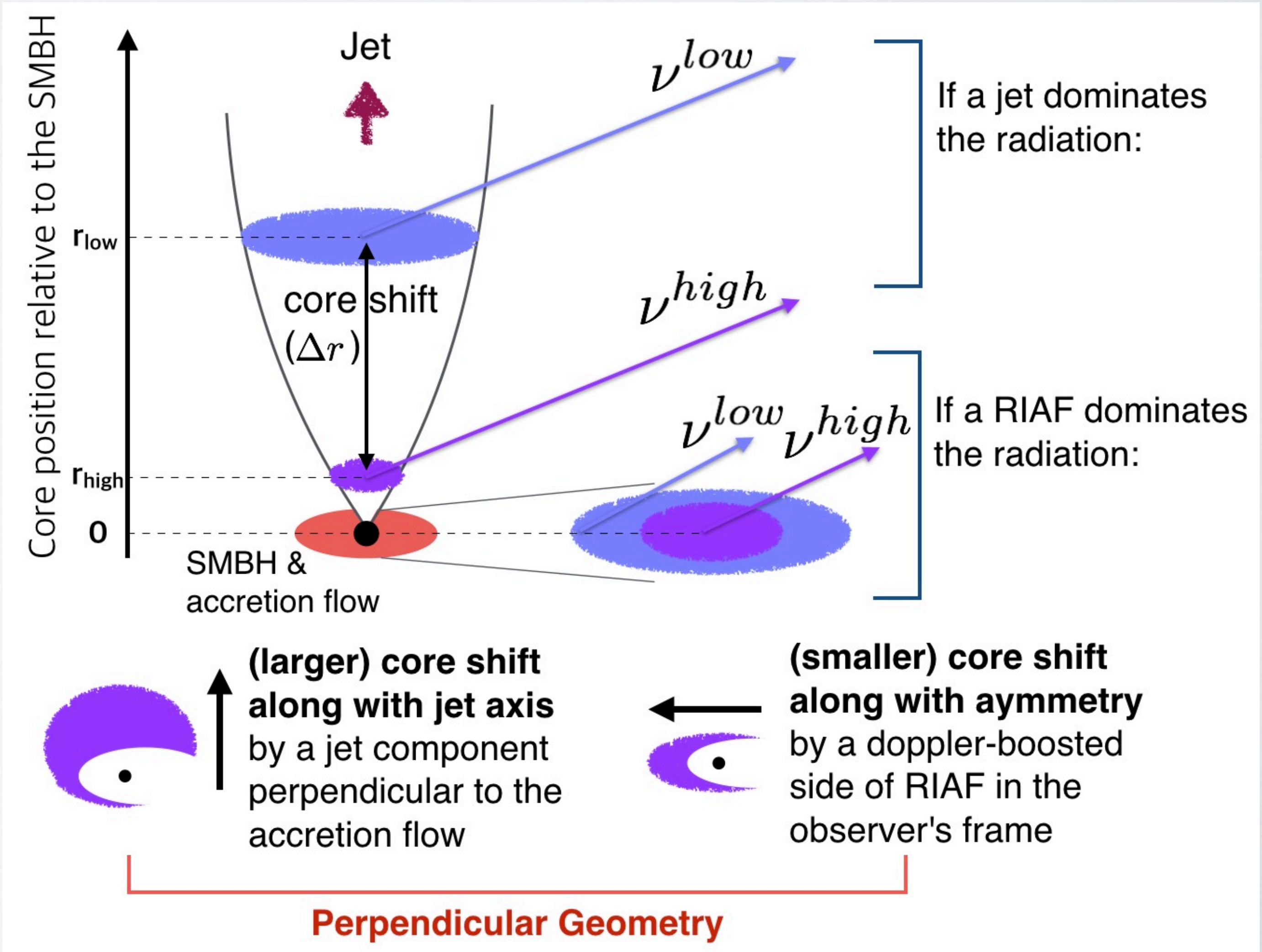




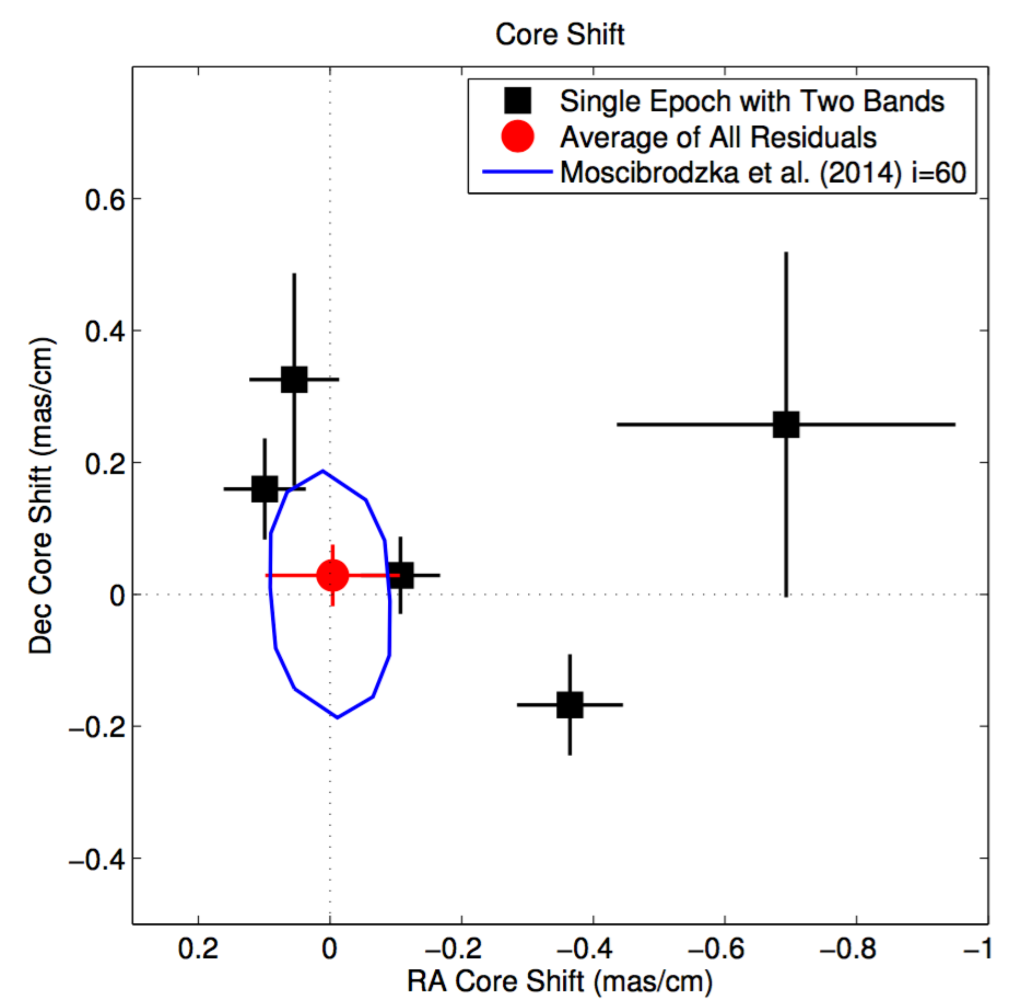
What does the VLBI image tell us ?

	Jet (Blandford-Konigl model)	Accretion flow	Scattering effect
Structure	Asymmetric (or weakly-symmetric)	Asymmetric	Symmetric (or sub-structure)
Core* position	**(frequency dependent) Core shift**	**(maybe) Fixed**	**Temporal wandering**





Core shift: finding a footprint of outflow



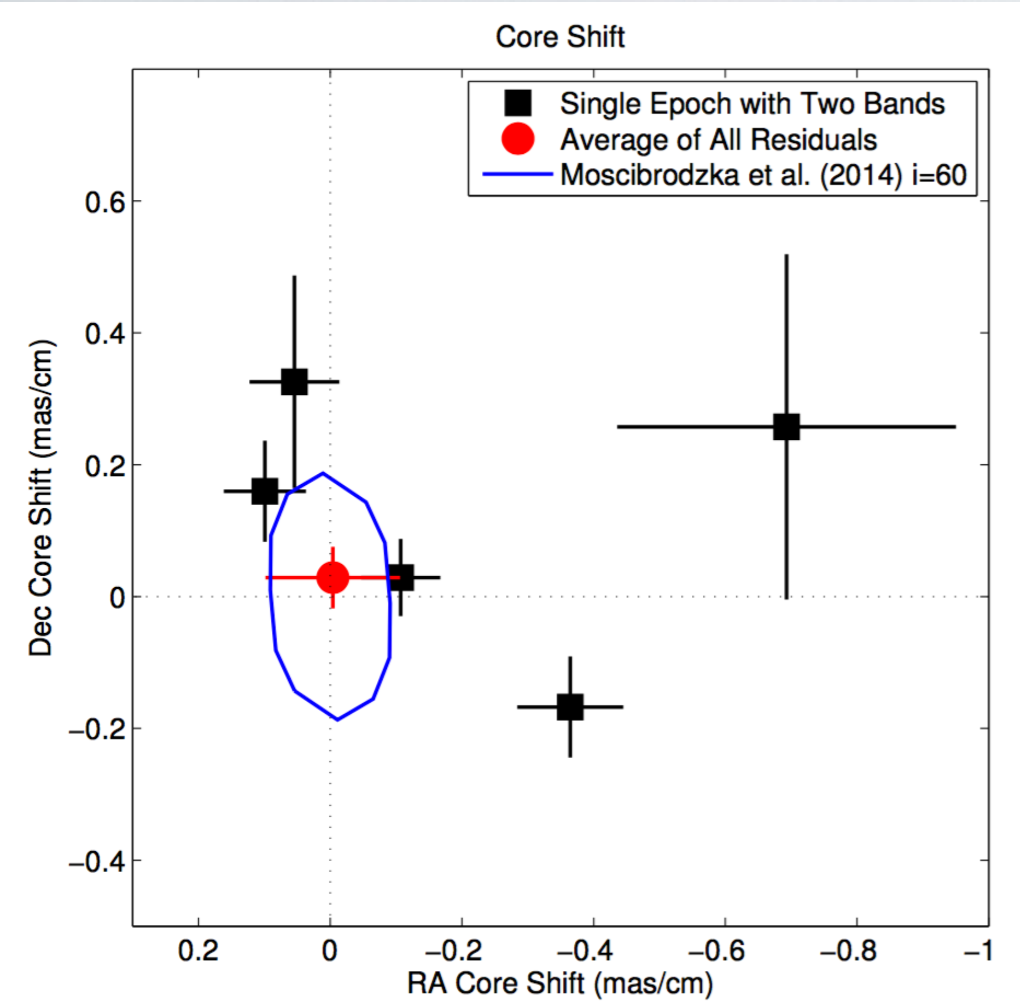
Bower et al. (2015):
So far, the only result of core shift measurement for Sgr A*.

However,

1. **Time-lag between the observations at different frequencies was inevitable (i.e. not simultaneous), so the variability effects were ignored.**

2. **Only for low frequencies (< 43 GHz).**

Core shift: finding a footprint of outflow



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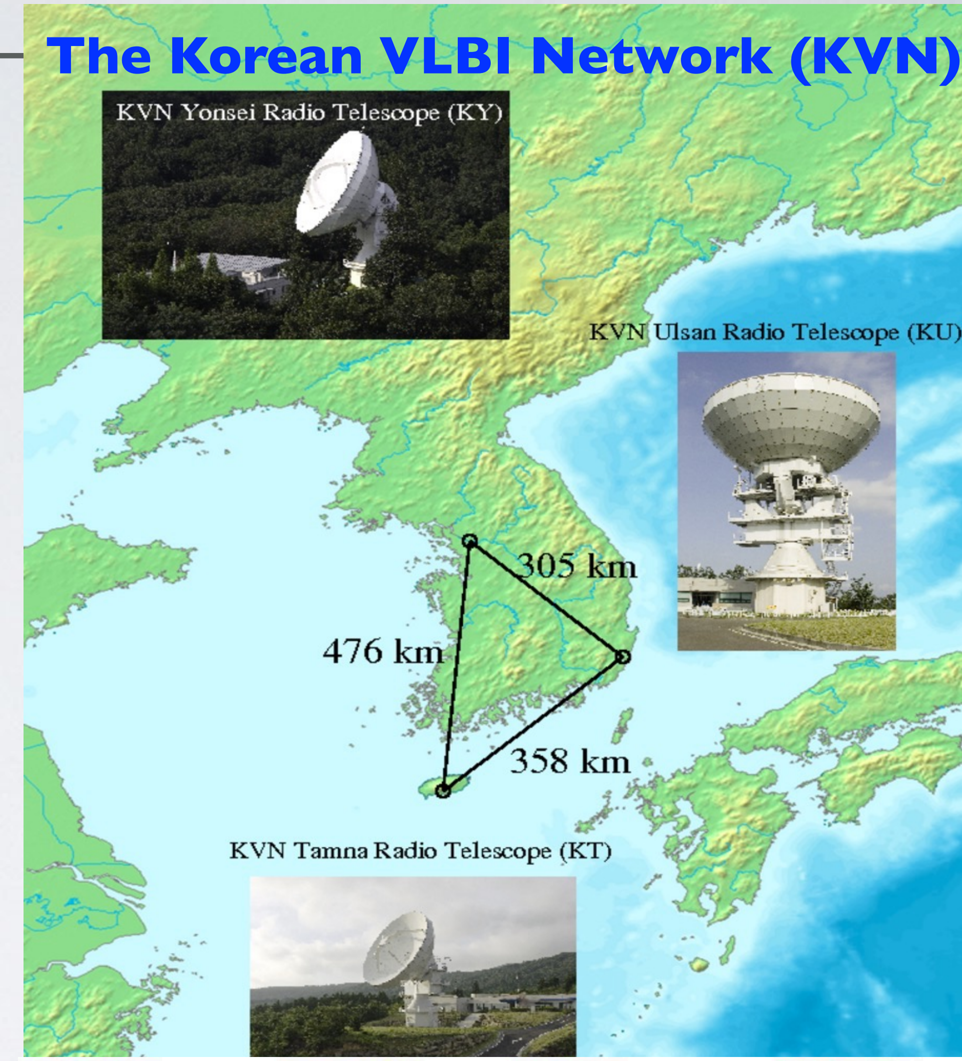
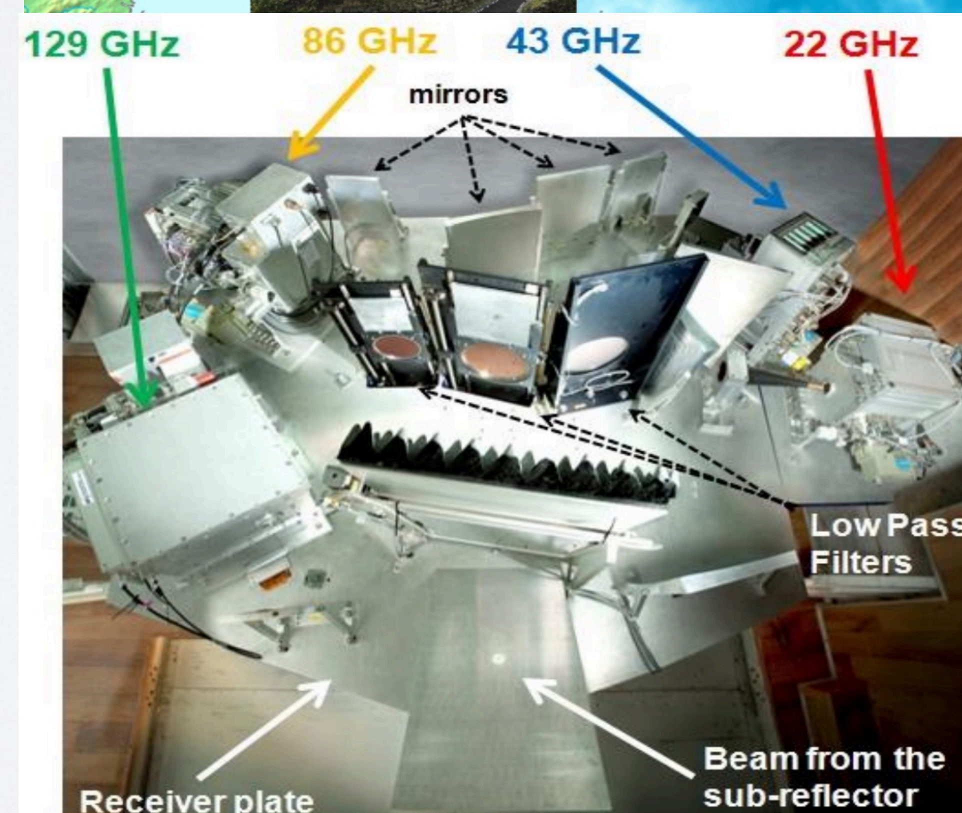


KVN's capability:
Simultaneous obs.
at 4 frequencies.



However,

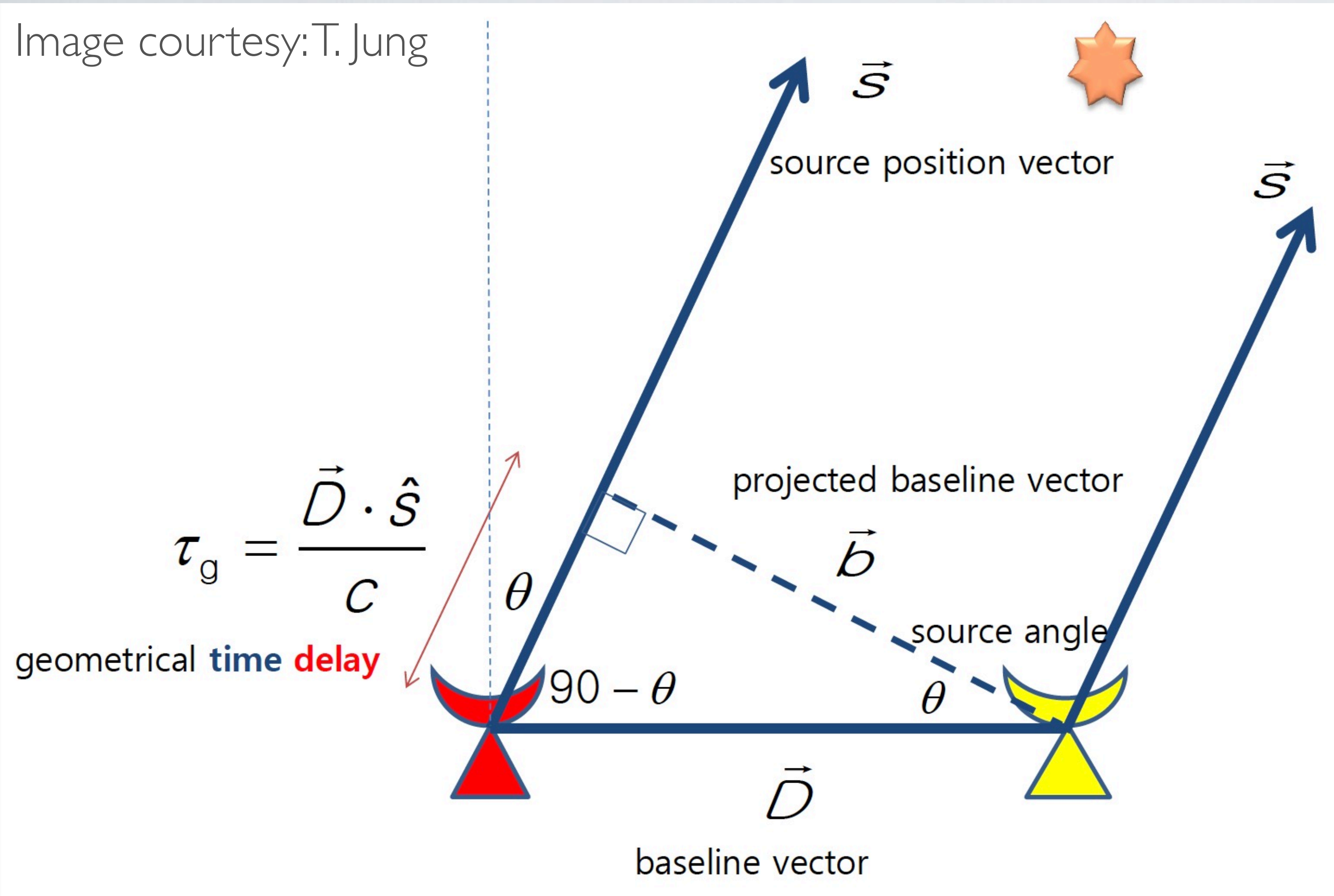
1. ~~Time-lag between the observations at different frequencies was inevitable (i.e. not simultaneous), so the variability effects were ignored.~~

=> Multi-frequency simultaneous observation.

2. ~~Only for low frequencies (< 43 GHz).~~

=> Higher frequencies (43, 86, 129 GHz)

Source Frequency Phase Referencing (SFPR)



Interferometric Phase has lots of information !

$$\phi = 2\pi\nu\tau_{obs}$$

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

Target Structure

Target Position

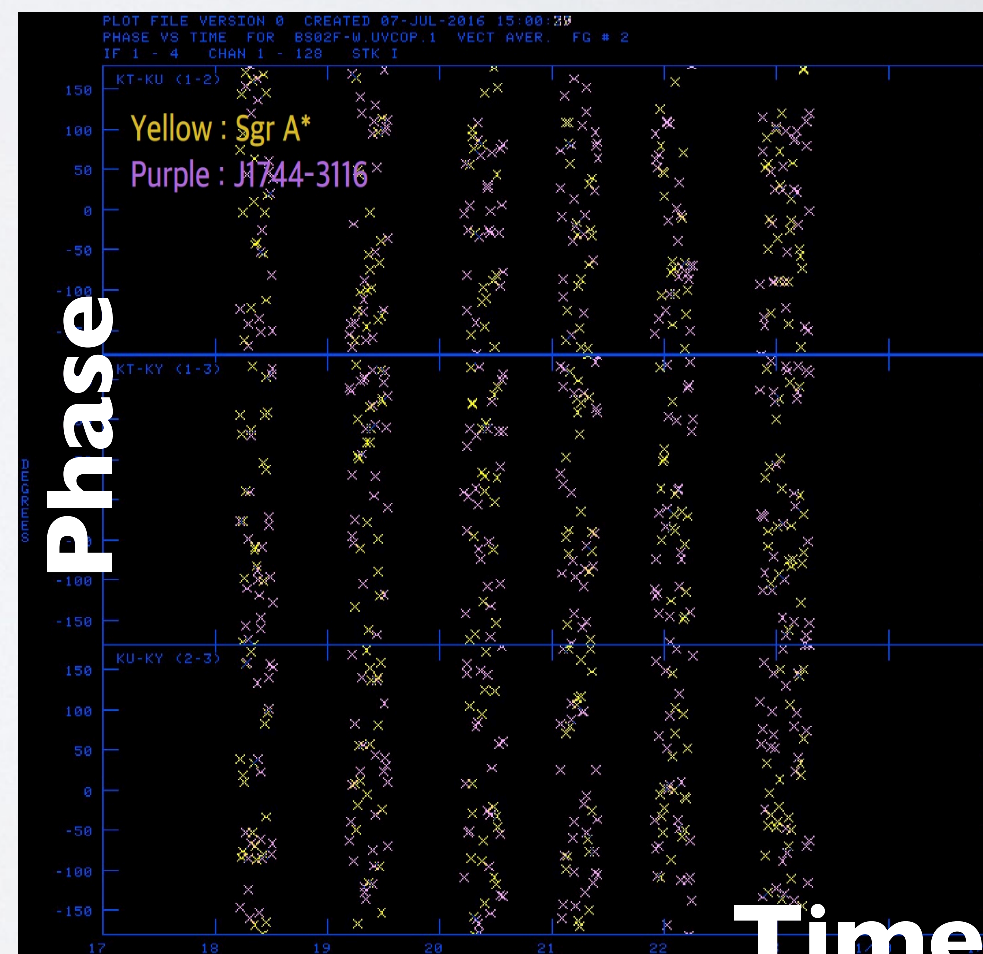
Tropospheric effect

Ionospheric effect

Instrumental effect

Thermal noise

2-pi ambiguity



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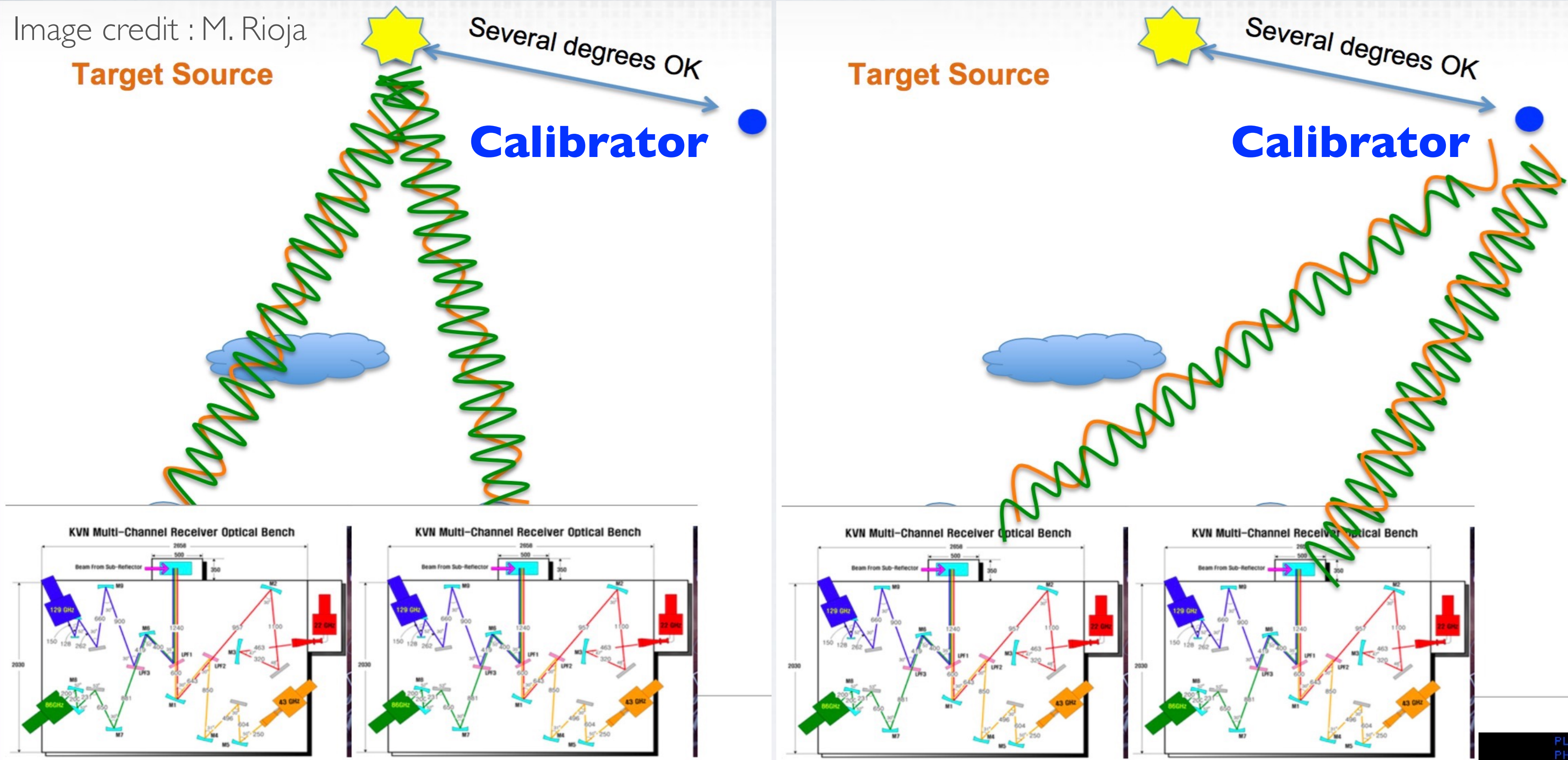


Frequency Phase Transfer(FPT)

$$\phi_{\rm A}^{\rm FPT} = \phi_{\rm A}^{\rm high} - R \cdot \tilde{\phi}^{\rm low}_{\rm A,self\text{-}cal} \qquad (R = \nu^{high}/\nu^{low})$$

$$= \phi^{\rm high}_{\rm A,str} + (\phi^{\rm high}_{\rm A,geo} - R \cdot \tilde{\phi}^{\rm low}_{\rm A,geo})$$ → $2\pi\, \vec{D}_{\lambda^{\rm high}} \cdot \vec{\theta}_{\rm A}$:Core shift

$$+ (\phi^{\rm high}_{\rm A,tro} - R \cdot \tilde{\phi}^{\rm low}_{\rm A,tro})$$ → MF simultaneous obs.

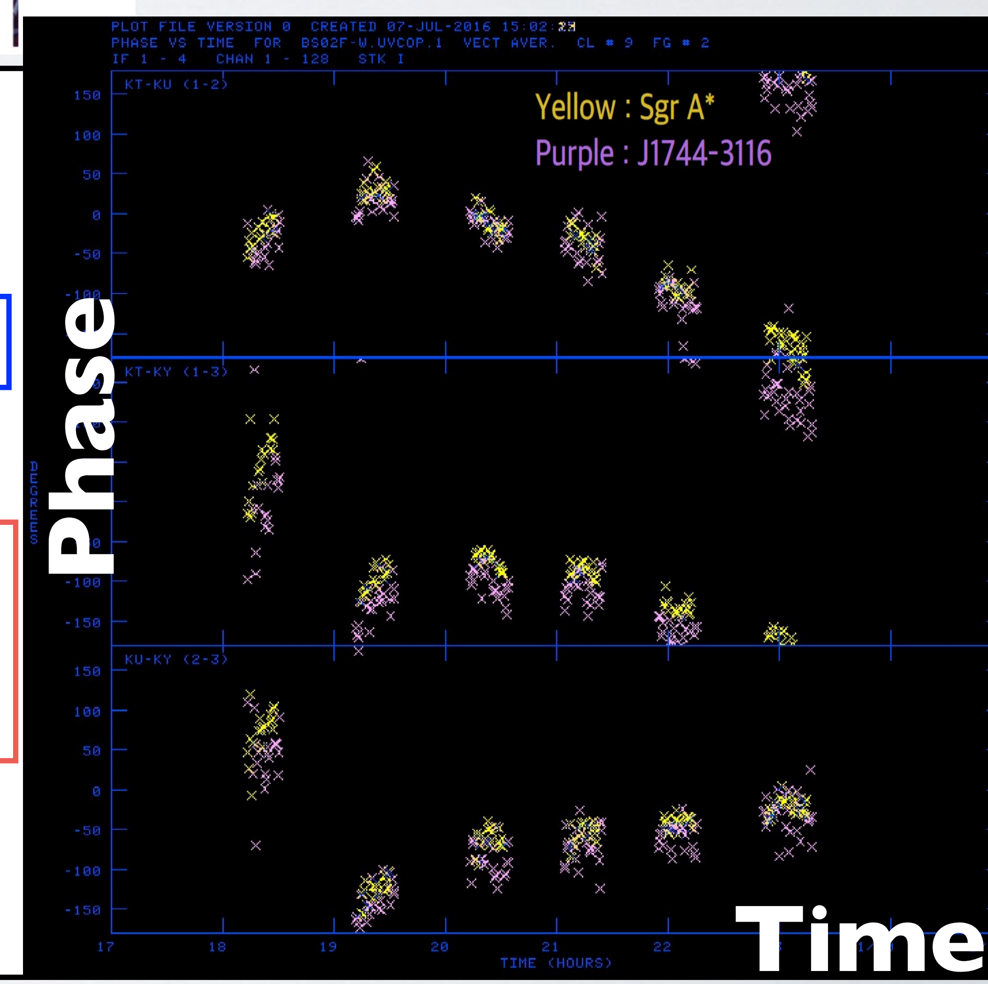
$$+ (\phi^{\rm high}_{\rm A,ion} - R \cdot \tilde{\phi}^{\rm low}_{\rm A,ion})$$

$$+ (\phi^{\rm high}_{\rm A,inst} - R \cdot \tilde{\phi}^{\rm low}_{\rm A,inst})$$

→ Dual-Beam or Fast (enough) Switching

$$+ 2\pi\, (n^{\rm high}_{\rm A} - R \cdot n^{\rm low}_{\rm A})$$ → MF simultaneous obs.

Rioja & Dodson 2011



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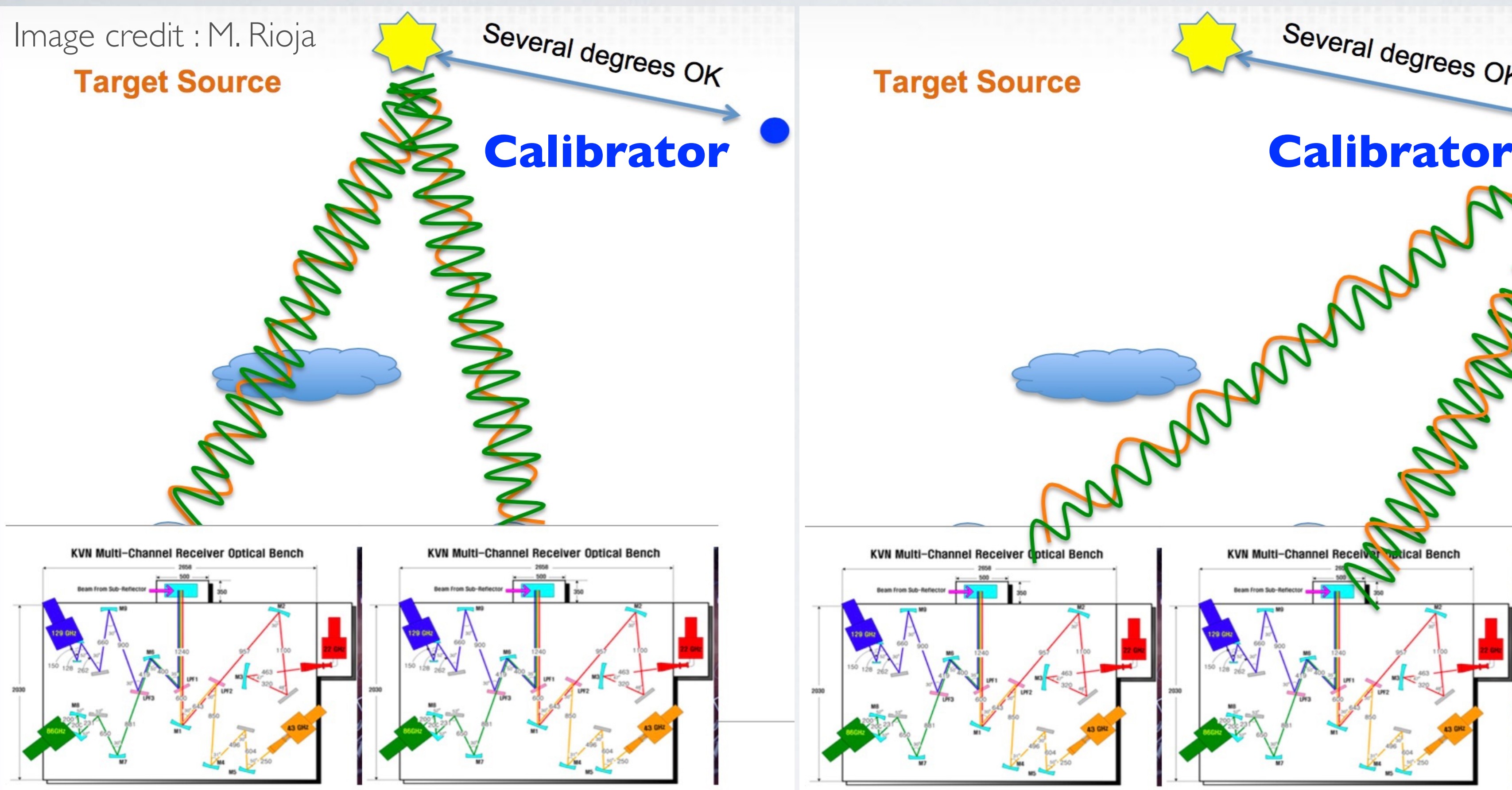

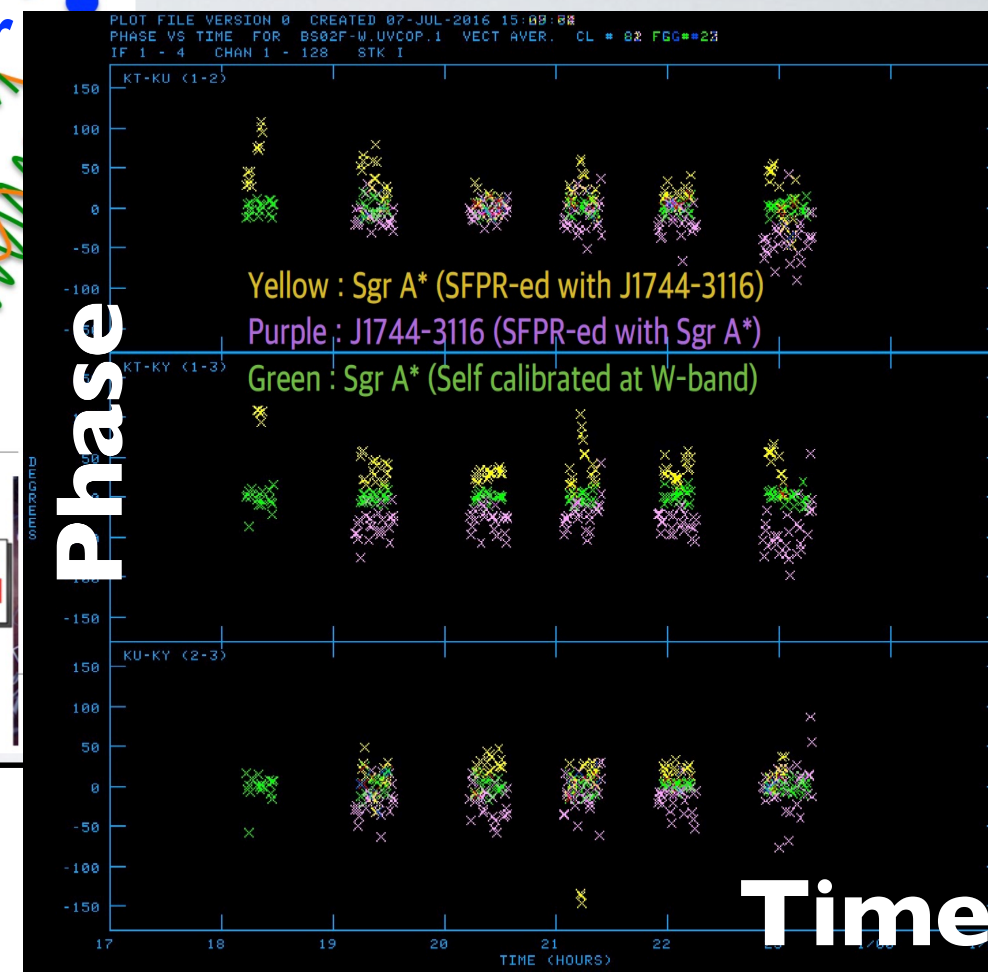

Source Frequency Phase Referencing (SFPR)

Rioja & Dodson 2011

$$\phi_{\mathrm{A}}^{\mathrm{SFPR}} = \phi_A^{FPT} - \phi_B^{FPT}$$

$$= \phi_{\mathrm{A,str}}^{\mathrm{high}} + 2\pi \vec{D}_{\lambda^{\mathrm{high}}} \cdot (\vec{\theta}_{\mathrm{A}} - \vec{\theta}_{\mathrm{B}}) + \Delta_{\mathrm{i},\mathrm{T}_{\mathrm{swt}}^{\nu}}$$

Target structure at target frequency.

Negligible for point / symmetric source

Target's core shift.

Calibrator's core shift.

Resolving structure

Interpolation error
: negligible when the separation angle between A and B is small.

Core shift of Sgr A*: our preliminary results

Source Frequency Phase Referencing (SFPR)

Rioja & Dodson 2011

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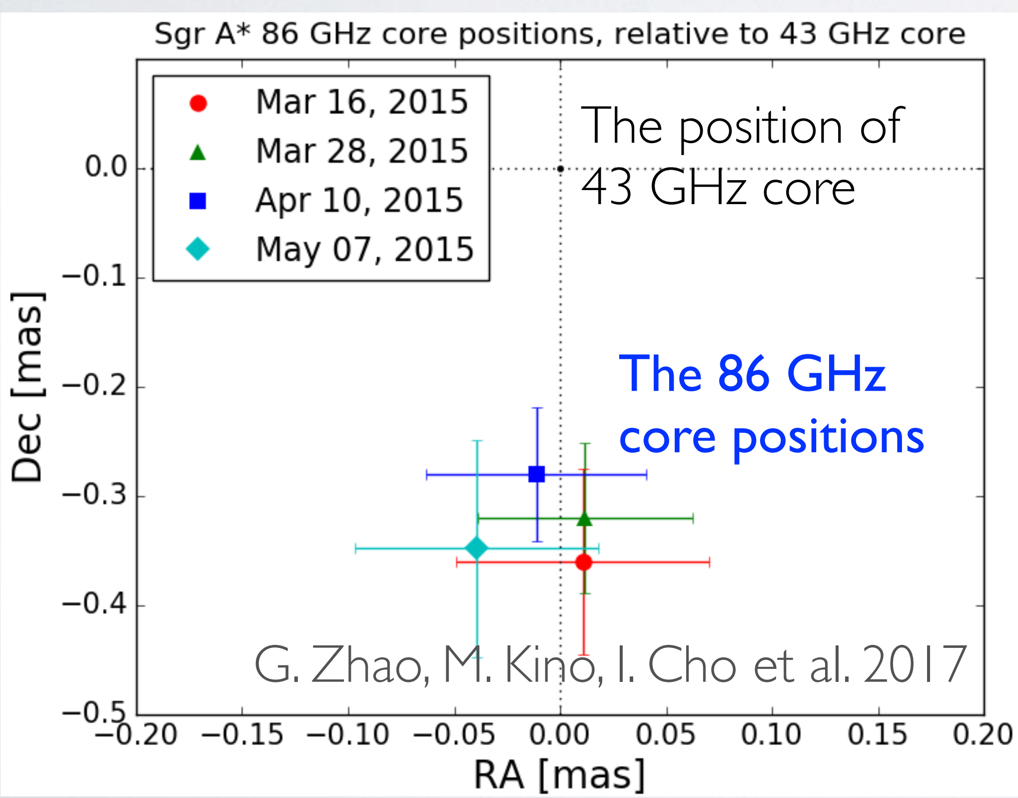
Structural effect removed

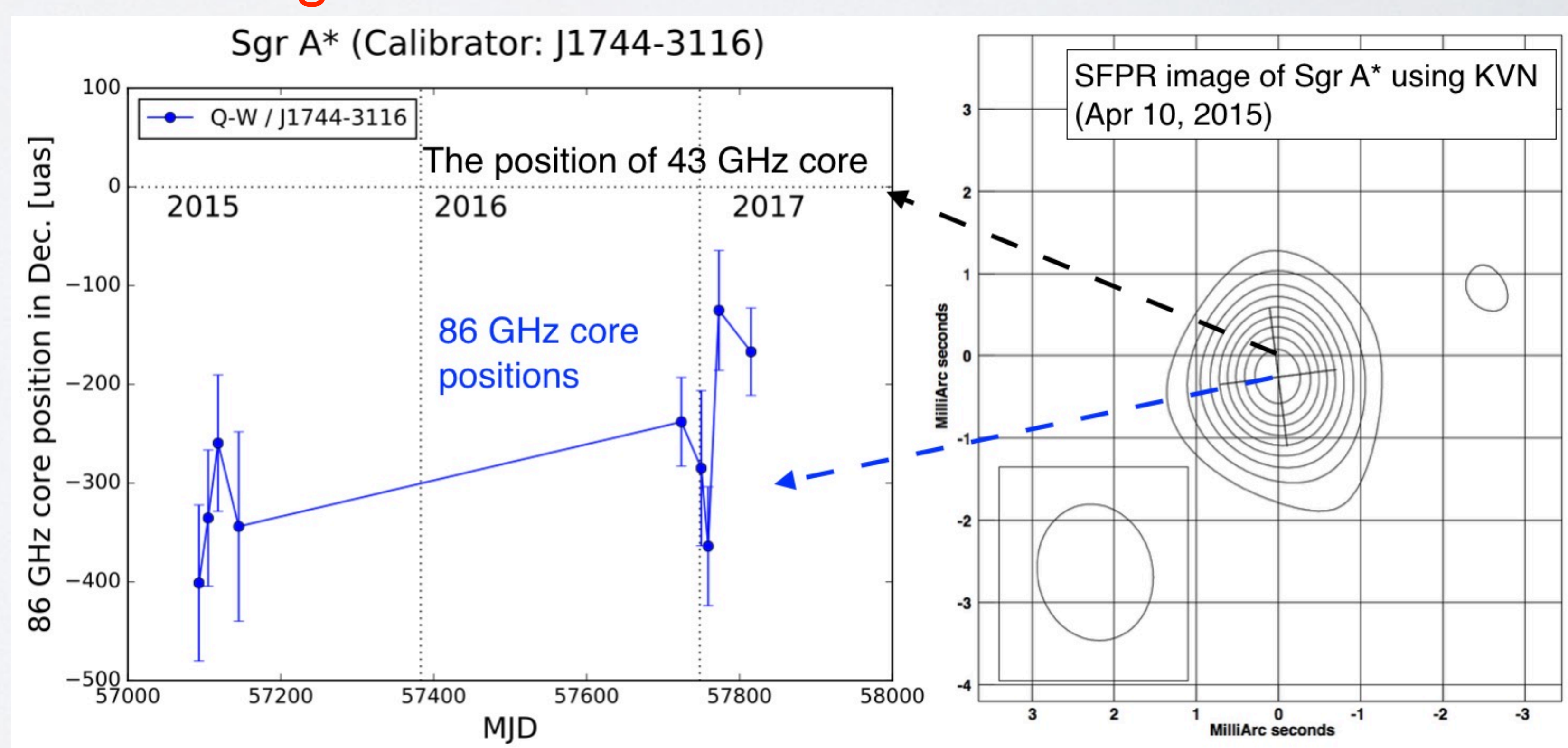
Target's core shift:
What we want to know

Calibrator's core shift.

Interpolation uncertainty has been still under investigation. (probably, small)

The 86 GHz core has appeared to the south (~0.3 mas) relative to the 43 GHz core.
Note that however both core shifts of target and calibrator have been mixed.





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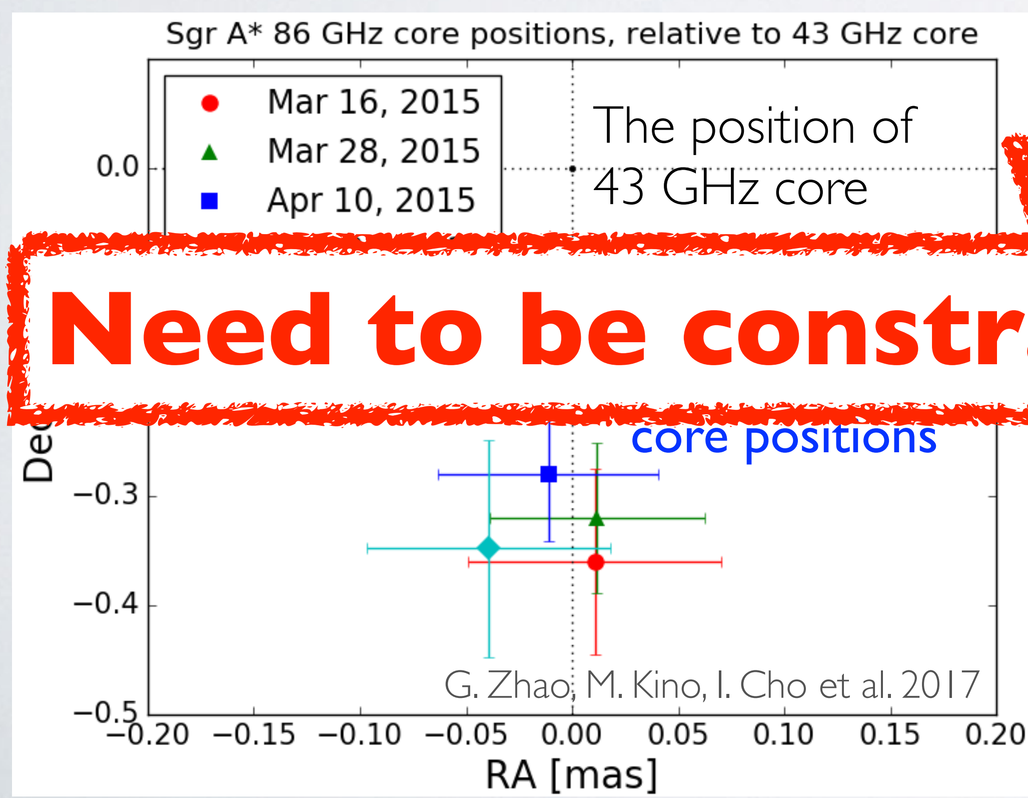
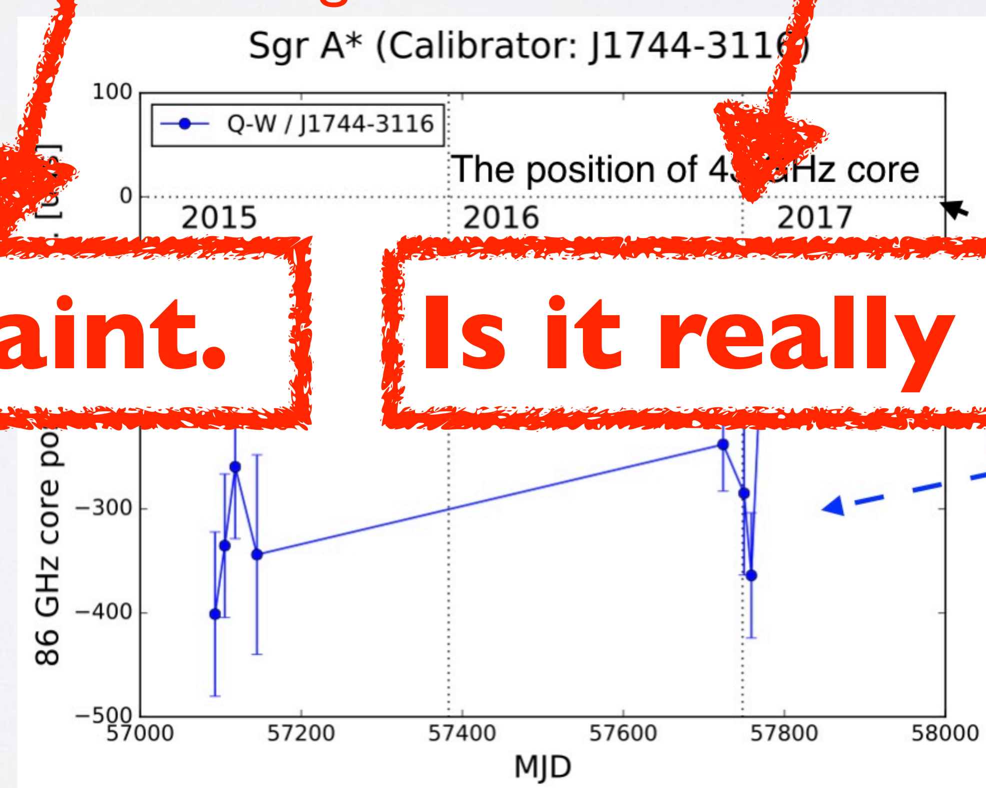




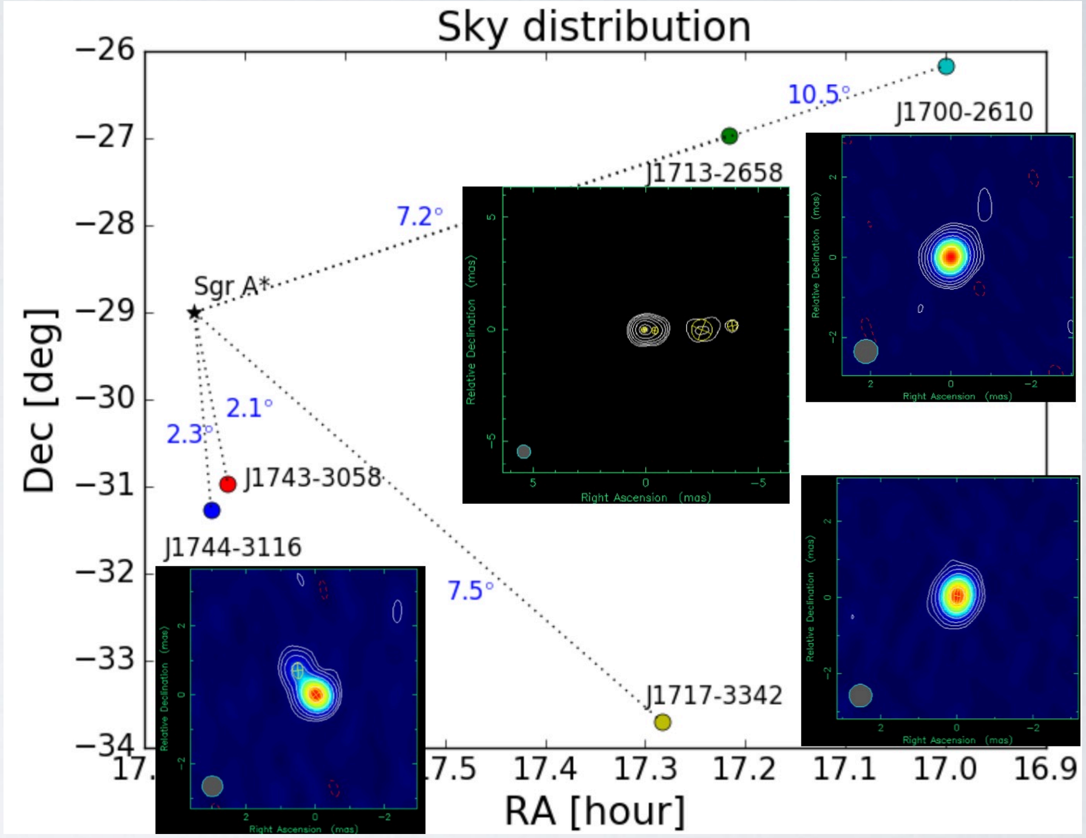
Need to be constraint.

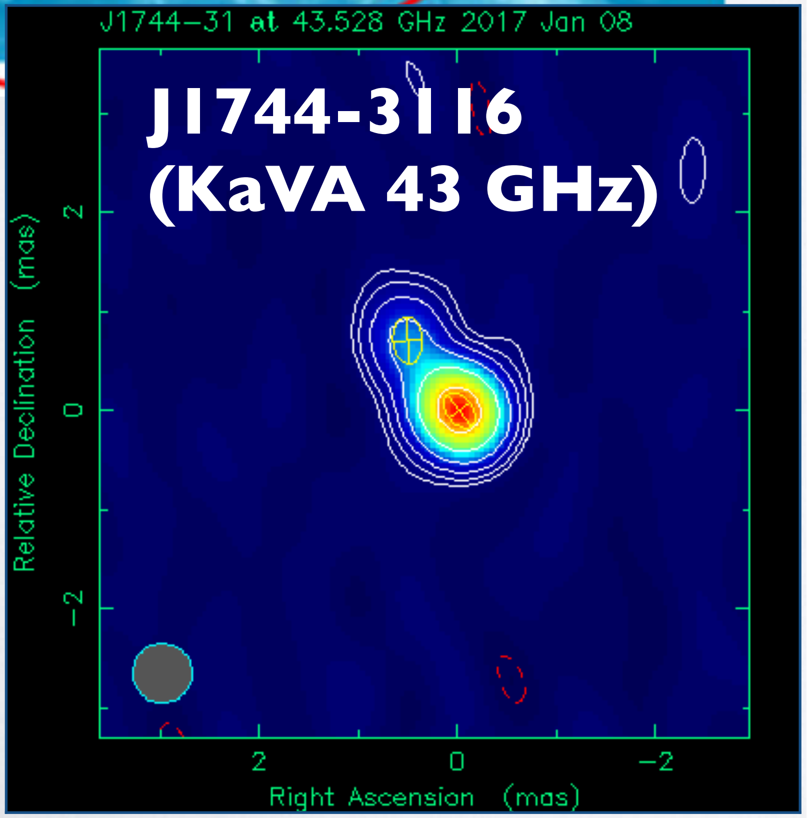
Is it really negligible ?

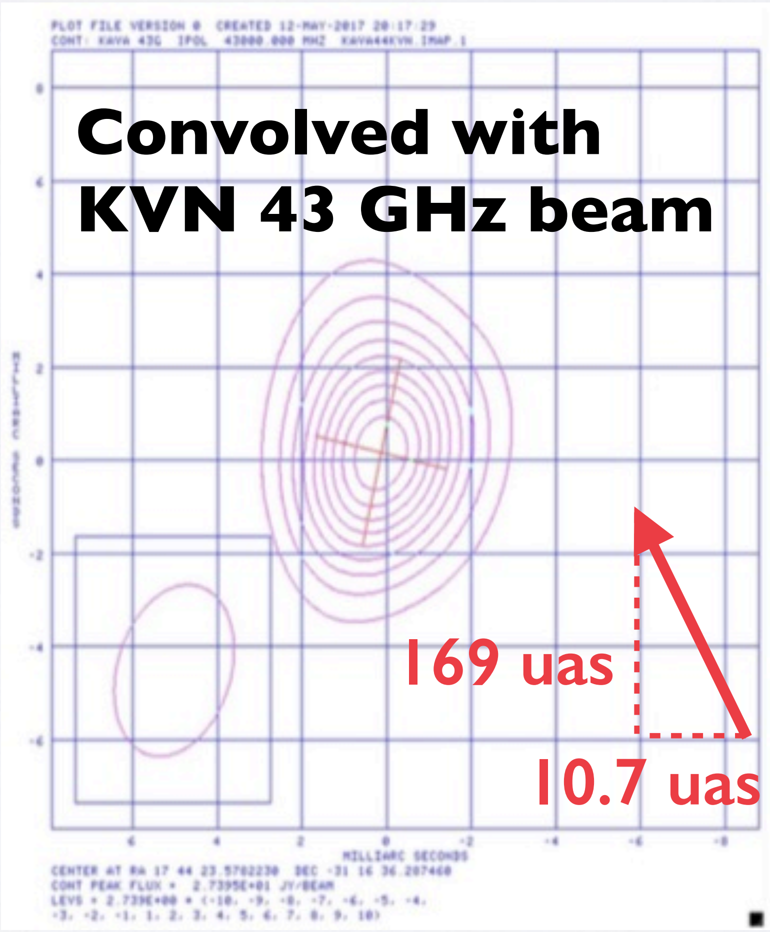
I) Constraining the Calibrator's effect

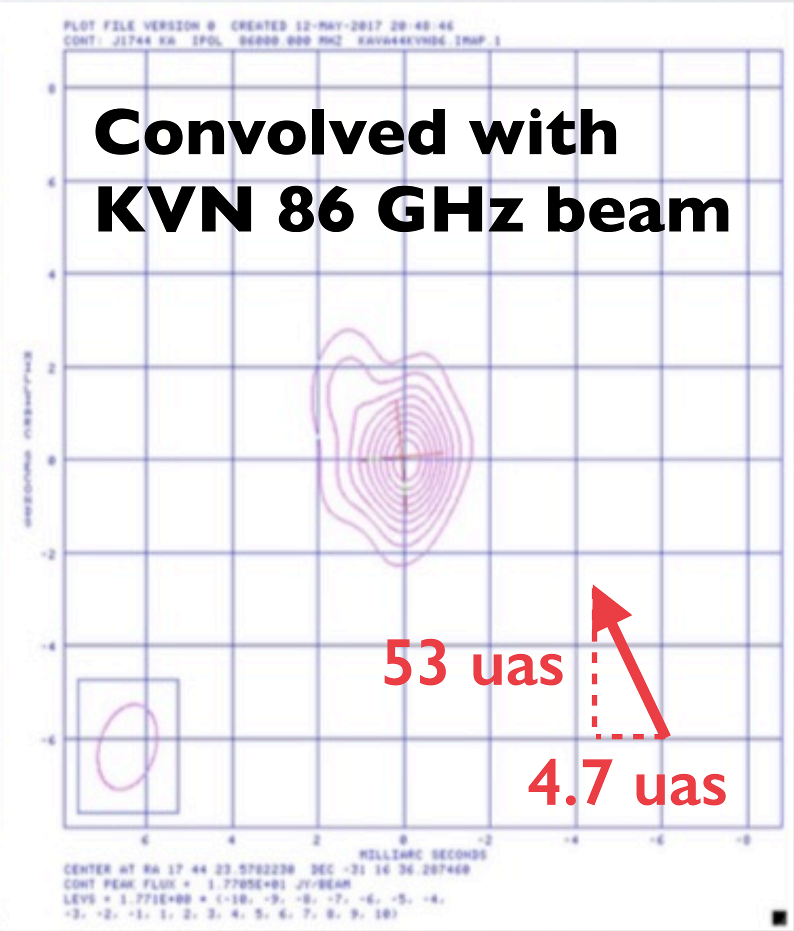
KaVA (KVN and VERA* Array)

*VLBI Exploration of Radio Astrometry





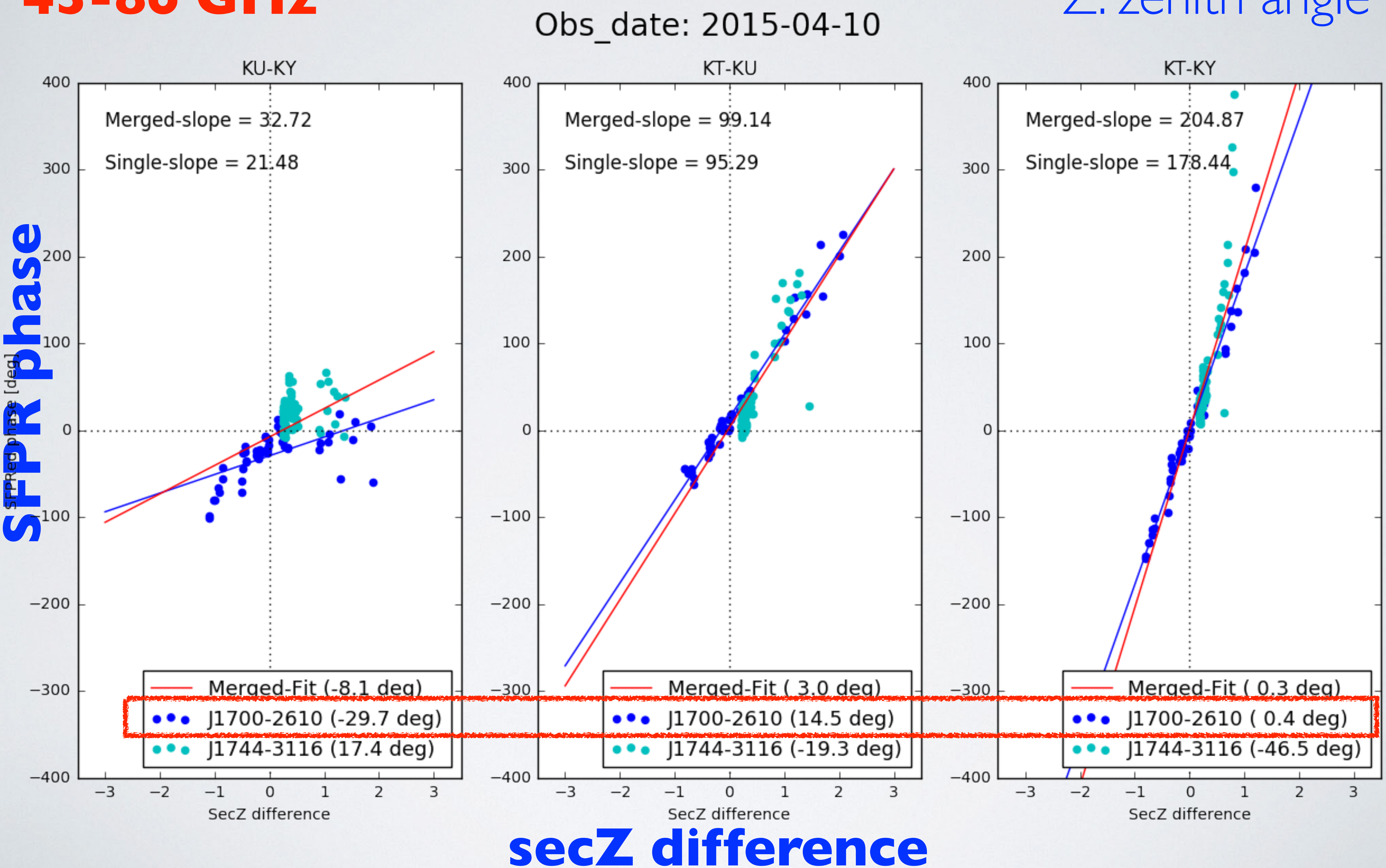




2) Interpolation uncertainty: secZ difference effect

43-86 GHz

* Z: zenith angle



On-going efforts

KVN observations list

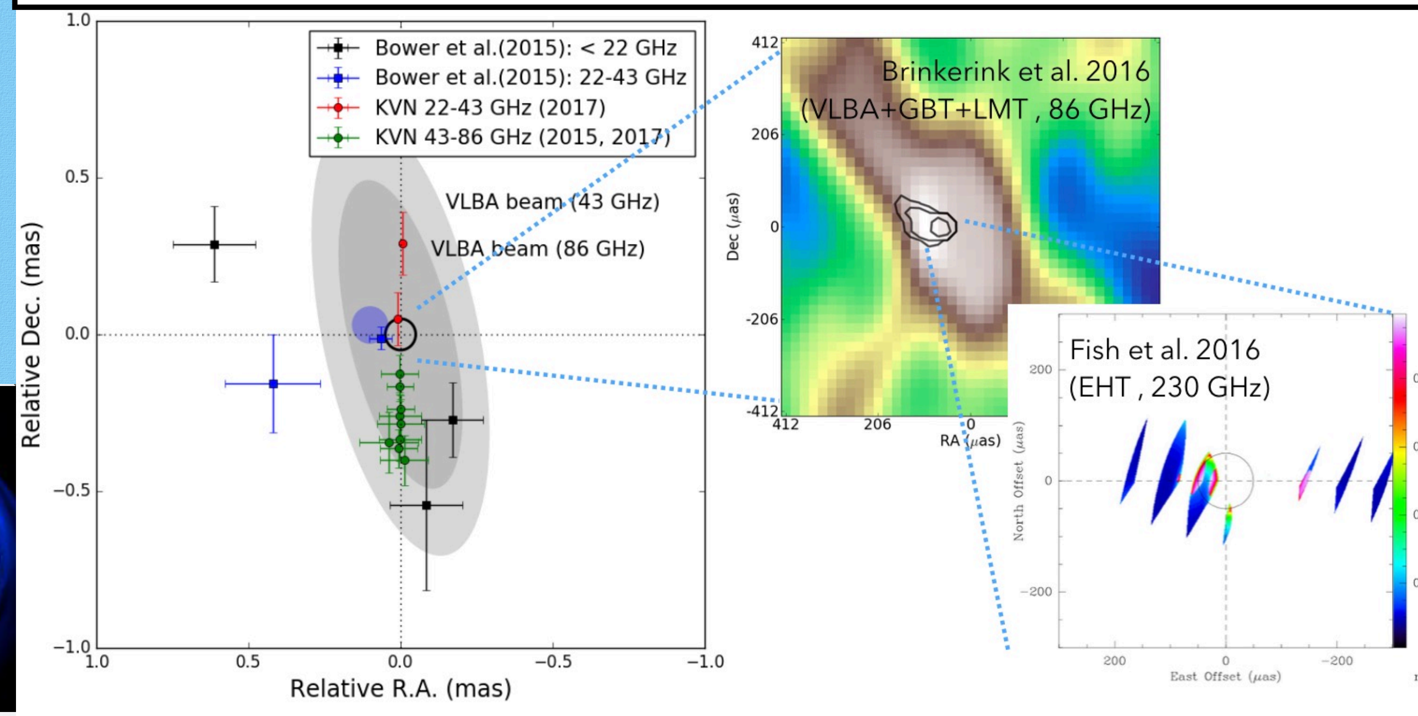
Year	Date	Obs. code	K	Q	W	D	Record	Note	J1744	J1700	J1717	J1713	J1745	J1748
2015A (Good 4 of 8)	Mar. 16	n15bs02d		○	○		1 Gbps		○	○				
	Mar. 28	n15bs02f		○	○		1 Gbps		○	○				
	Apr. 10	n15bs02g		○	○		1 Gbps		○	○				
	May. 07	n15bs02i		○	○		1 Gbps		○	○				
2016B (Good 4 of 8)	Dec. 06	n16ic01e		○	○		1 Gbps		○		○	○		
	Jan. 02	n16ic01f		○	○		1 Gbps		○		○	○		
	Jan. 11	n16ic01g	○	○	○	×	1 Gbps		○	○				
	Jan. 25	n16ic01h		○	○		1 Gbps		○		○	○		
2017A (All 5 epochs) 1 supplement	Mar. 08	n17ic01a	○	○	○	×	1 Gbps		○	○				
	Apr. 23	n17ic01d	○	○	○	×	1 Gbps		○	○				
	May. 07	n17ic01e	○	○	○	×	1 Gbps		○	○				
	Jun. 09	n17ic01f	○	○	○	○	**1+8 Gbps**	**Geoblock**	○	○				
2017B (All 5 epochs)	Sep. 15	n17ic02a	○	○	○	○	**1+8 Gbps**	**Geoblock**	○	○			○	○
	Oct. 18	n17ic02b	○	○	○	○	**1+8 Gbps**	**Geoblock**	○	○			○	○

KaVA observations list (to resolve the structure of Calibrators)

Year	Date	Obs. code	K	Q
2017A (1+3 epochs)	Jan. 08	r17008a (k16ic02a)		○
	Mar. 02	r17061b (k17ic01a)		○
	Mar. 13	r17072a (k17ic01b)		○
	Apr. 27	r17117a (k17ic01c)		○
2017B (2[K/Q] + 2 epochs)	Sep. 16	k17ic03a	○	
	Sep. 17	k17ic03b		○

On-going efforts

VLBA proposal:
Quasi-simultaneous Campaign with EHT
- Links between Core Shift and Innermost Structure (I. Cho et al.)



	Jun. 09	n17ic01f	○	○	○	○	1+8 Gbps	Geoblock	○	○				
2017B (All 5 epochs)	Sep. 15	n17ic02a	○	○	○	○	1+8 Gbps	Geoblock	○	○			○	○
	Oct. 18	n17ic02b	○	○	○	○	1+8 Gbps	Geoblock	○	○			○	○

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	Mar. 13	r17072a (k17ic01b)		○
	Apr. 27	r17117a (k17ic01c)		○
2017B (2[K/Q] + 2 epochs)	Sep. 16	k17ic03a	○	
	Sep. 17	k17ic03b		○

Summary

1. Measuring the **Core shift** is a great tool to investigate the Jet physics, especially by the Blandford-Konigl process.

2. **KVN** is an ideal VLBI system to study the core shift effect with a simultaneous multi-frequency observing capability and an optimized technique of **SFPR for VLBI astrometry**.

3. To confirm a precise astrometric result, however, careful investigation of **the residual phases** is necessary, such as the **calibrator's core shift** (or extended structure) and the possible **interpolation uncertainties** (e.g., secZ effect).

Please Stay Tuned !

Thank you