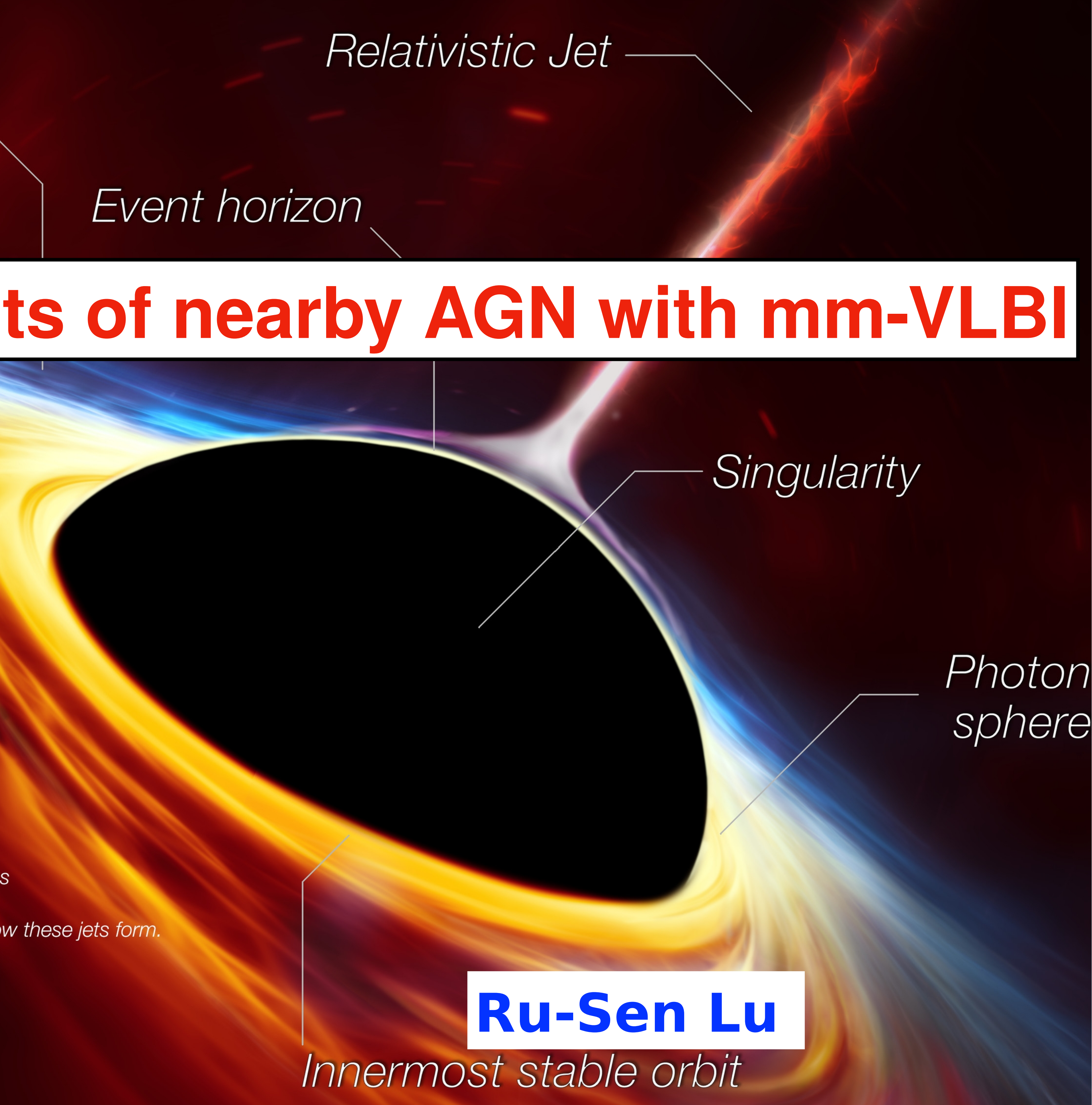
Peering into the hearts of nearby AGN with mm-VLBI

Ru-Sen Lu

Shanghai Astronomical Observatory &
Max Planck Institute for Radio Astronomy



into a region of infinite density called a singularity.
All the matter and energy that fall into the black hole ends up here.
The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow". The Event Horizon Telescope is hoping to see both the ring and the "shadow".

Relativistic jets

When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space. The GMVA will study how these jets form.

Innermost stable orbit

The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc

A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

(Credit: ESO, ESA/Hubble, M. Kornmesser/N. Bartmann)

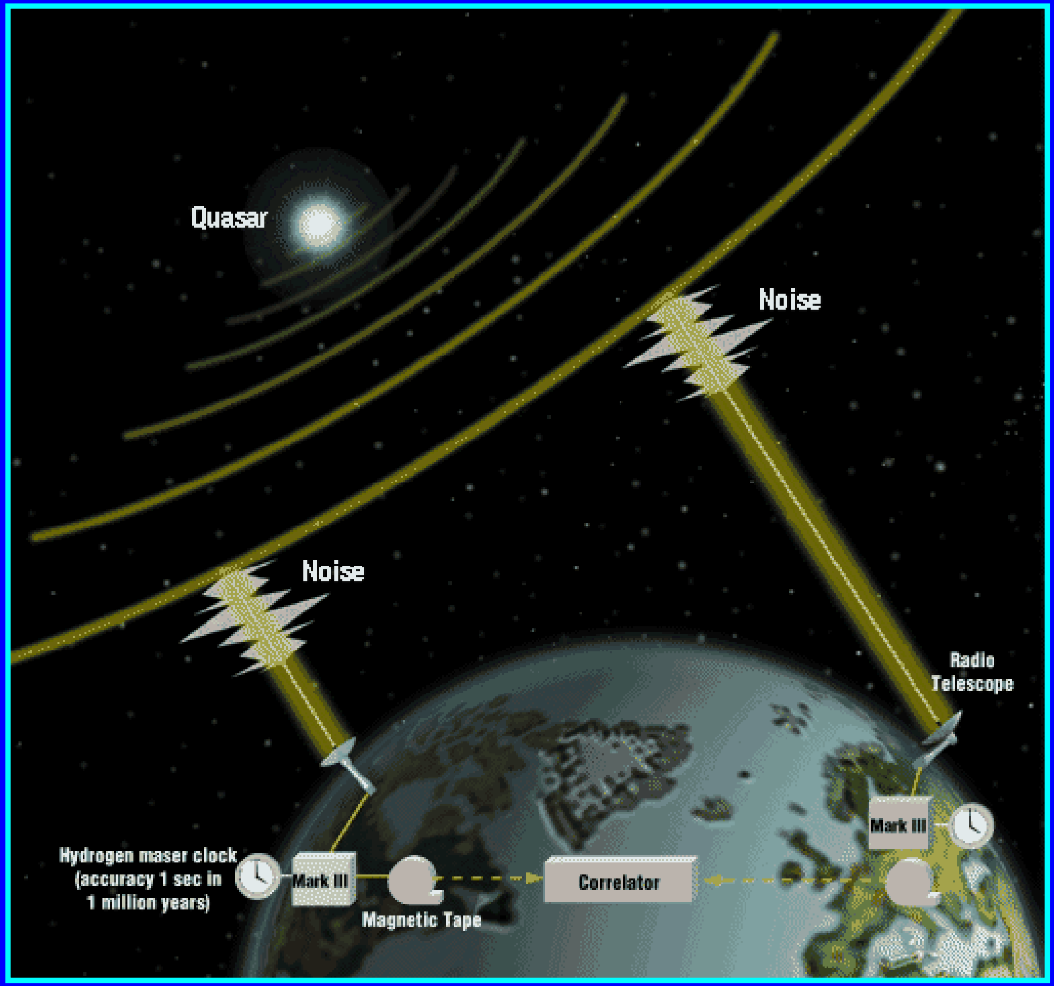
Outline

-Motivation for mm-VLBI and its current development

-1.3mm-VLBI observations of Sgr A*: new results

-Current status of the East Asian VLBI network

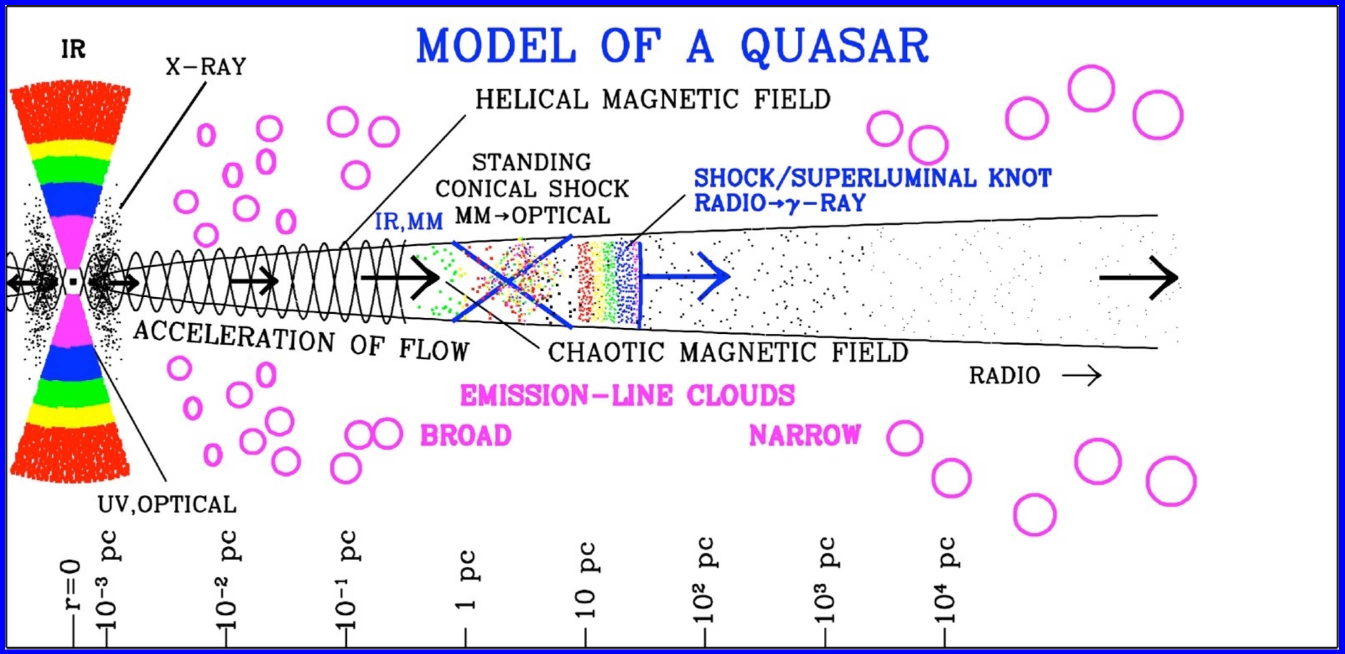
Motivation



Typical resolution

λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

Motivation



Marscher et al.

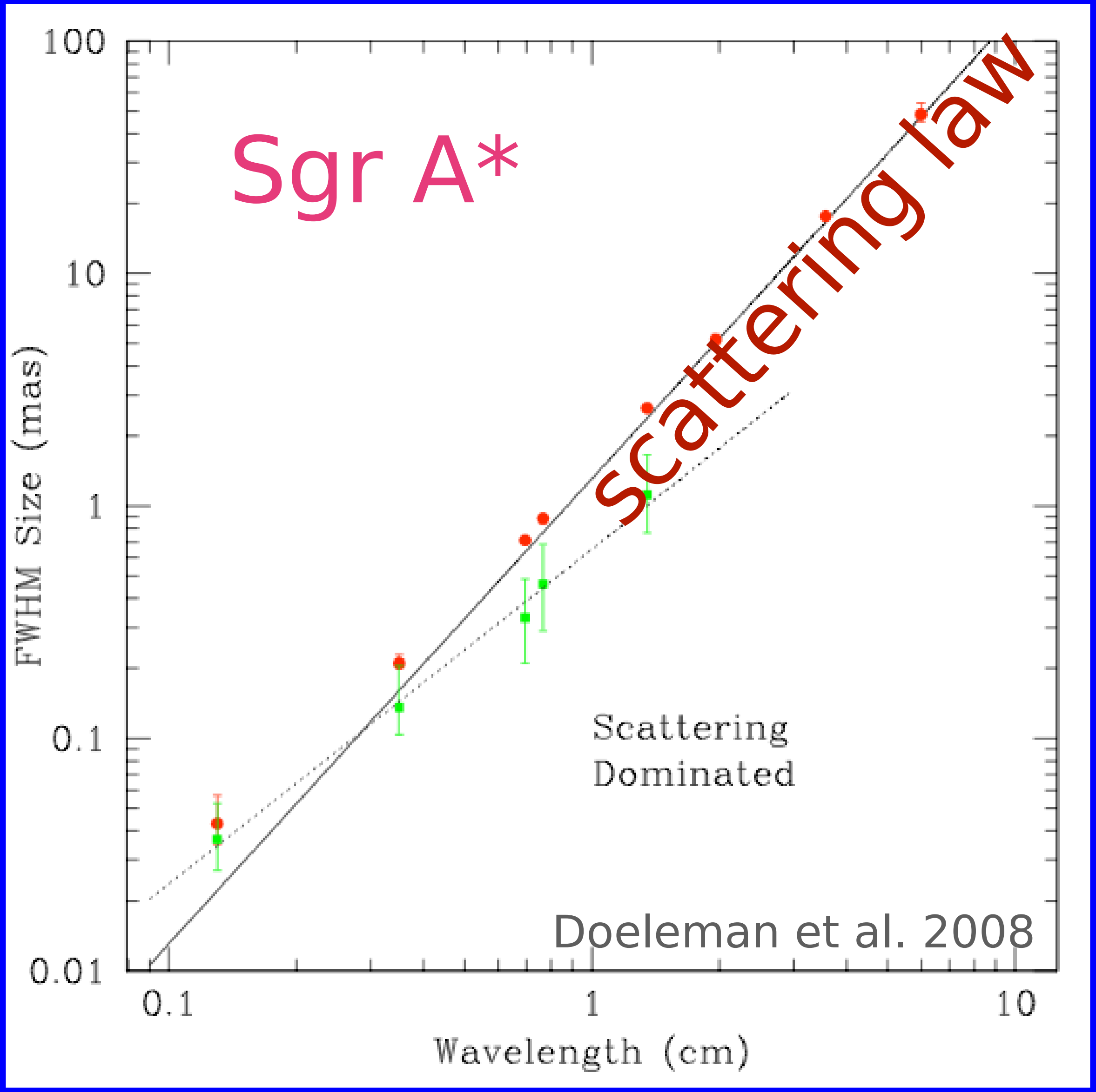
Typical resolution

λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

Self-absorption:
look “deeper”

Motivation

Size



Wavelength

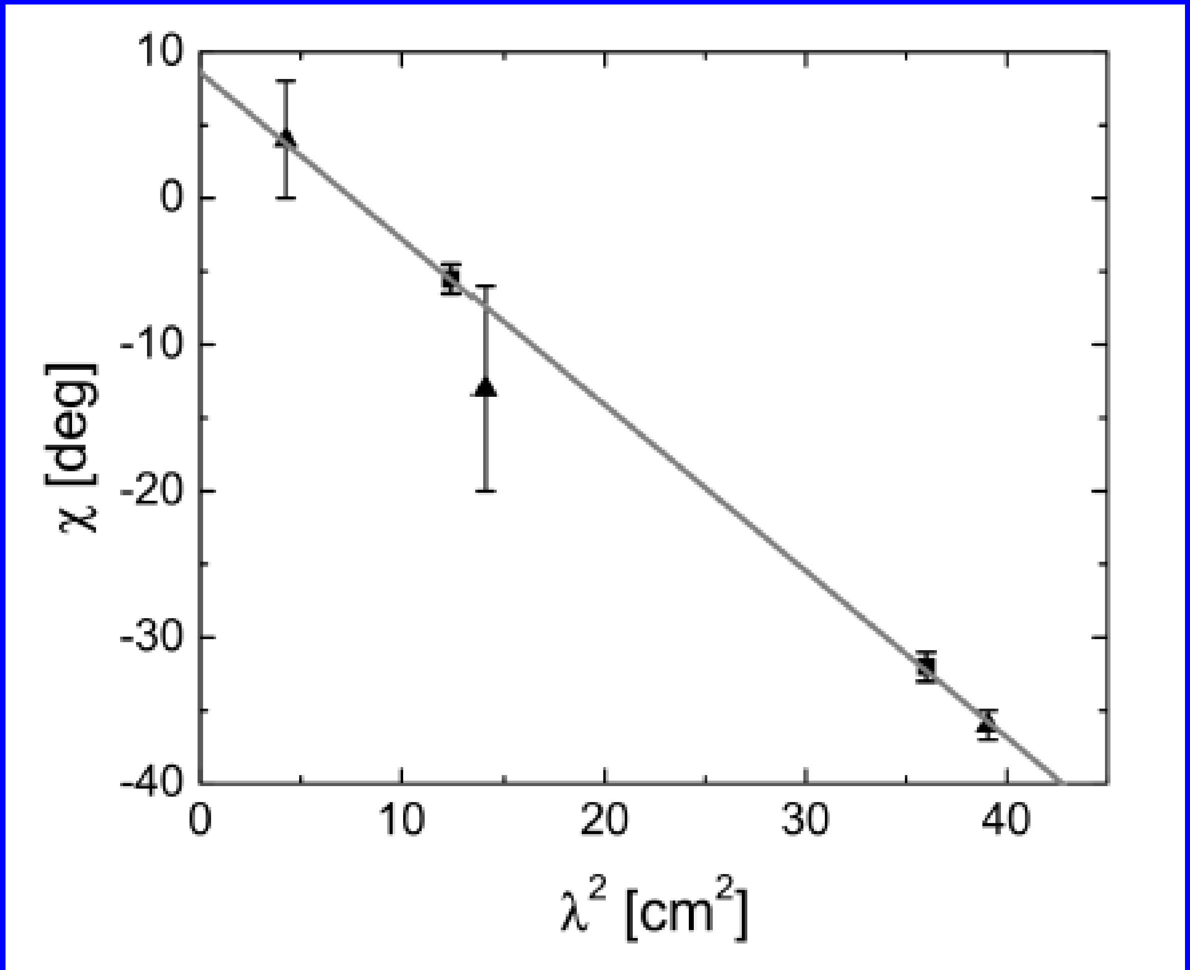
Typical resolution

λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

Self-absorption:
look "deeper"

Scattering in the ISM
$\Theta_{scatter} \propto \lambda^2$

Motivation



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Self-absorption:

look “deeper”

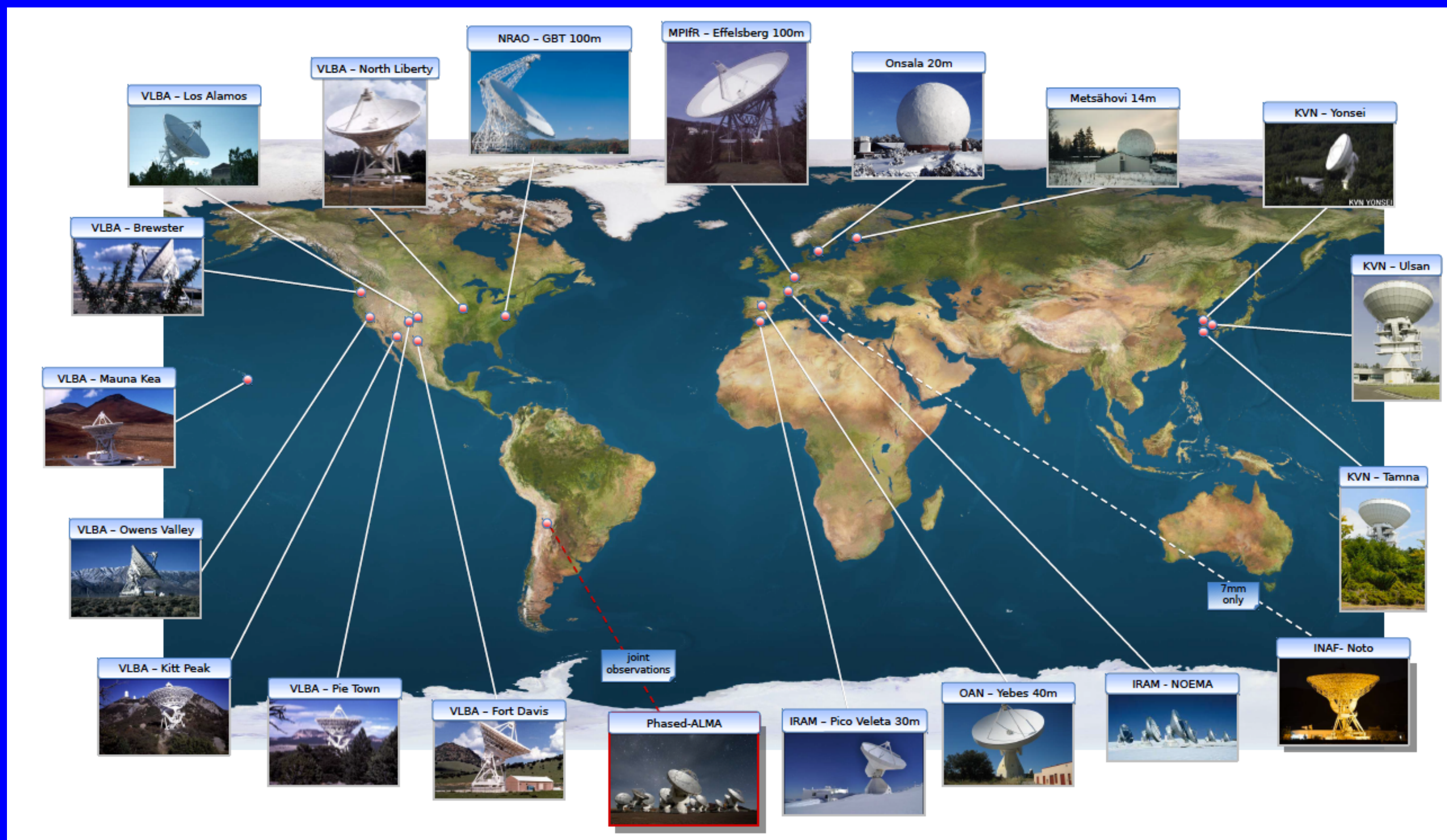
Scattering in the ISM

$\Theta_{scatter} \propto \lambda^2$

Faraday rotation

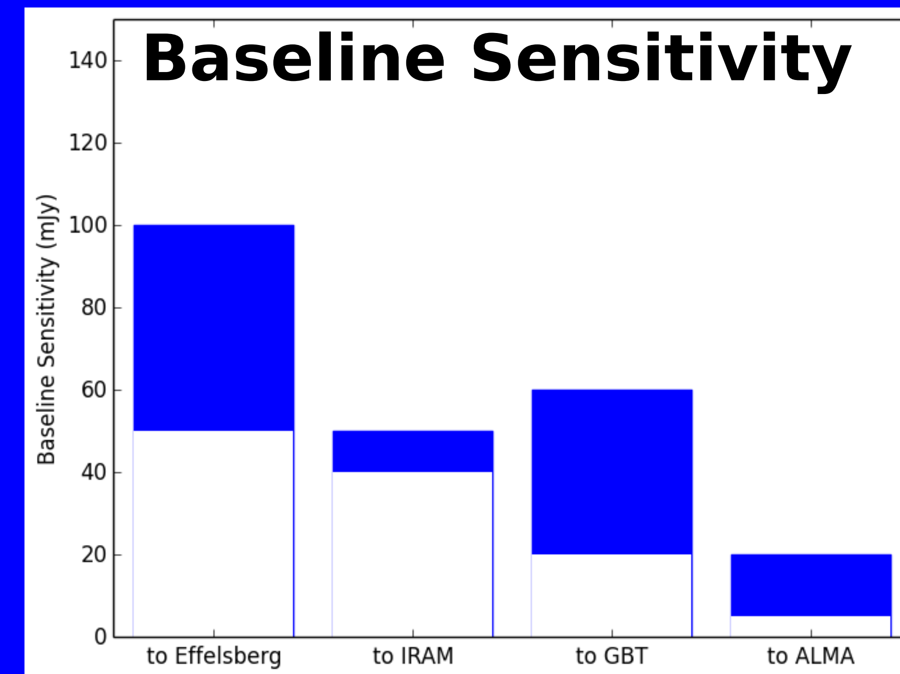
$\chi \propto \lambda^2$

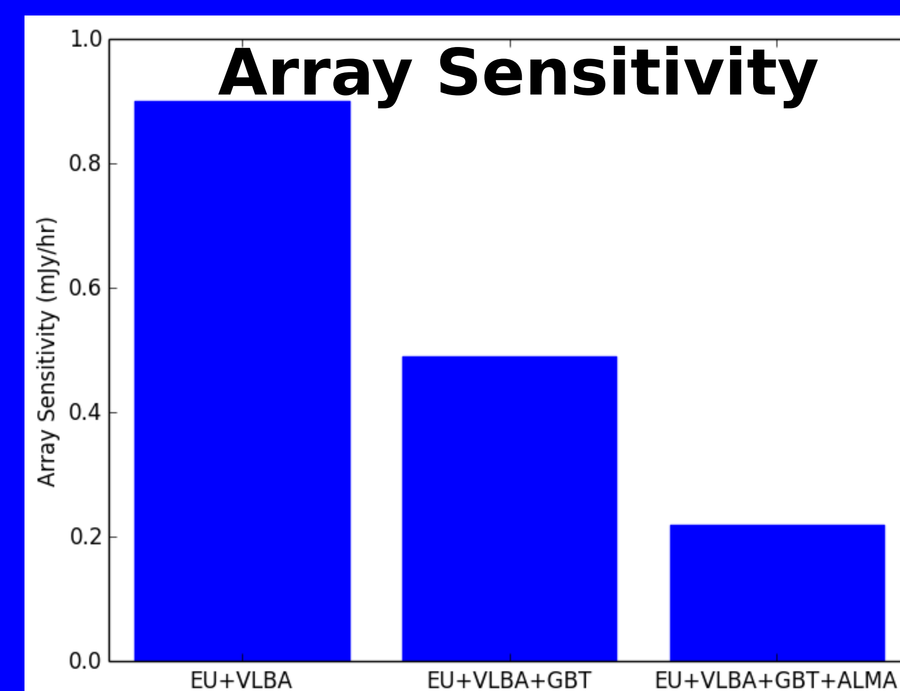
The Global Millimeter VLBI Array



Credit: H. Rottmann

https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm





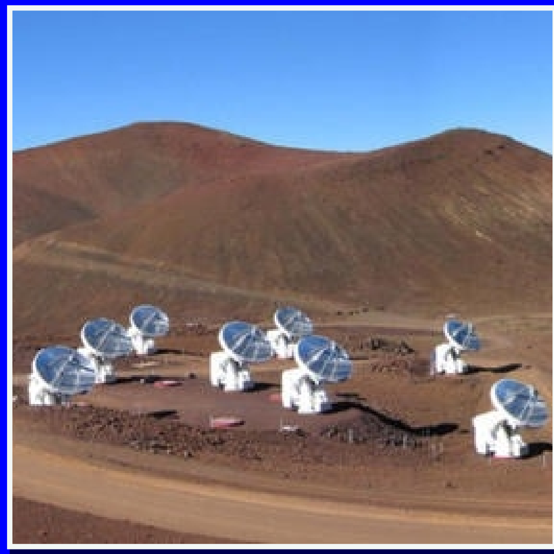
Station	Location	Effective diameter [m]	SEFD [Jy]
Effelsberg	Germany	80	1000
Onsala	Sweden	20	5100
Plateau de Bure	France	34	820
Pico Veleta	Spain	30	650
Yebes	Spain	40	1700
Metsähovi	Finland	14	17000
Green Bank	United States	100	140
VLBA (×8)	United States	25	2500
KVN (×3)	South Korea	21	3200
ALMA	Chile	85	60

(Boccardi et al. 2017)

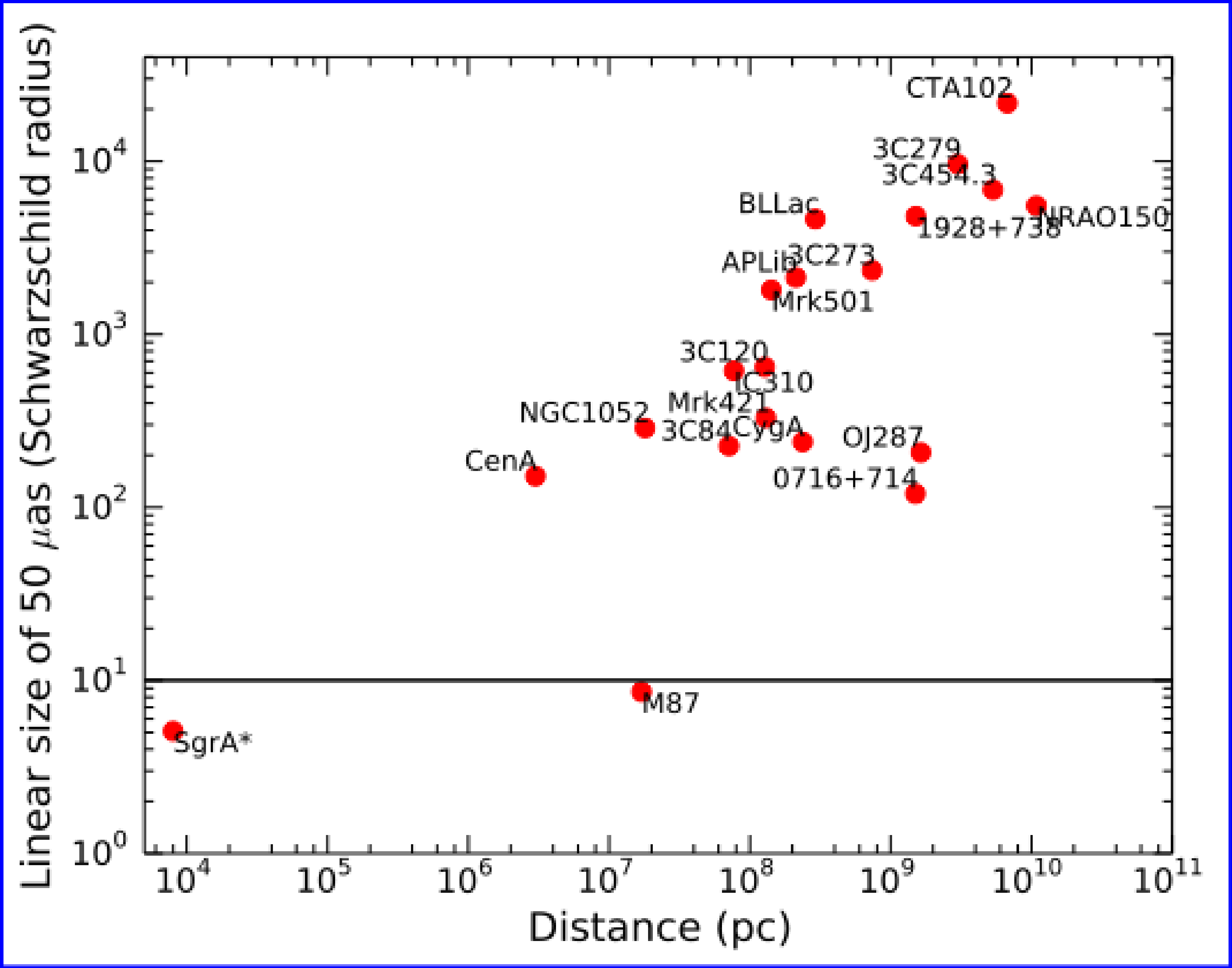
Assuming:
BW=500 MHz (2 Gbit/s), 7 sigma threshold, t_{coh}=20s

The Event Horizon Telescope

(https://eventhorizontelescope.org/)



Resolving the AGN cores with mm-VLBI



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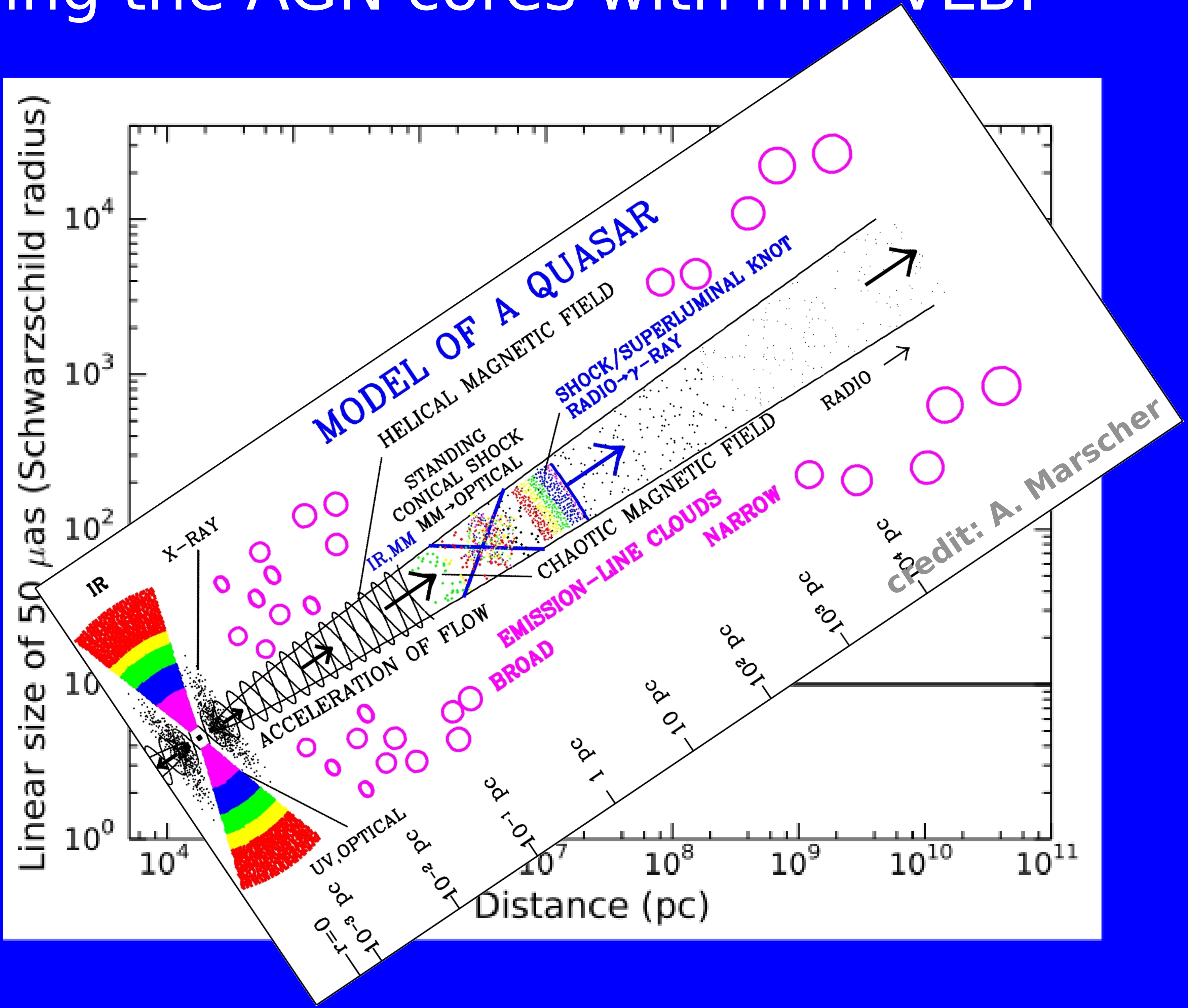
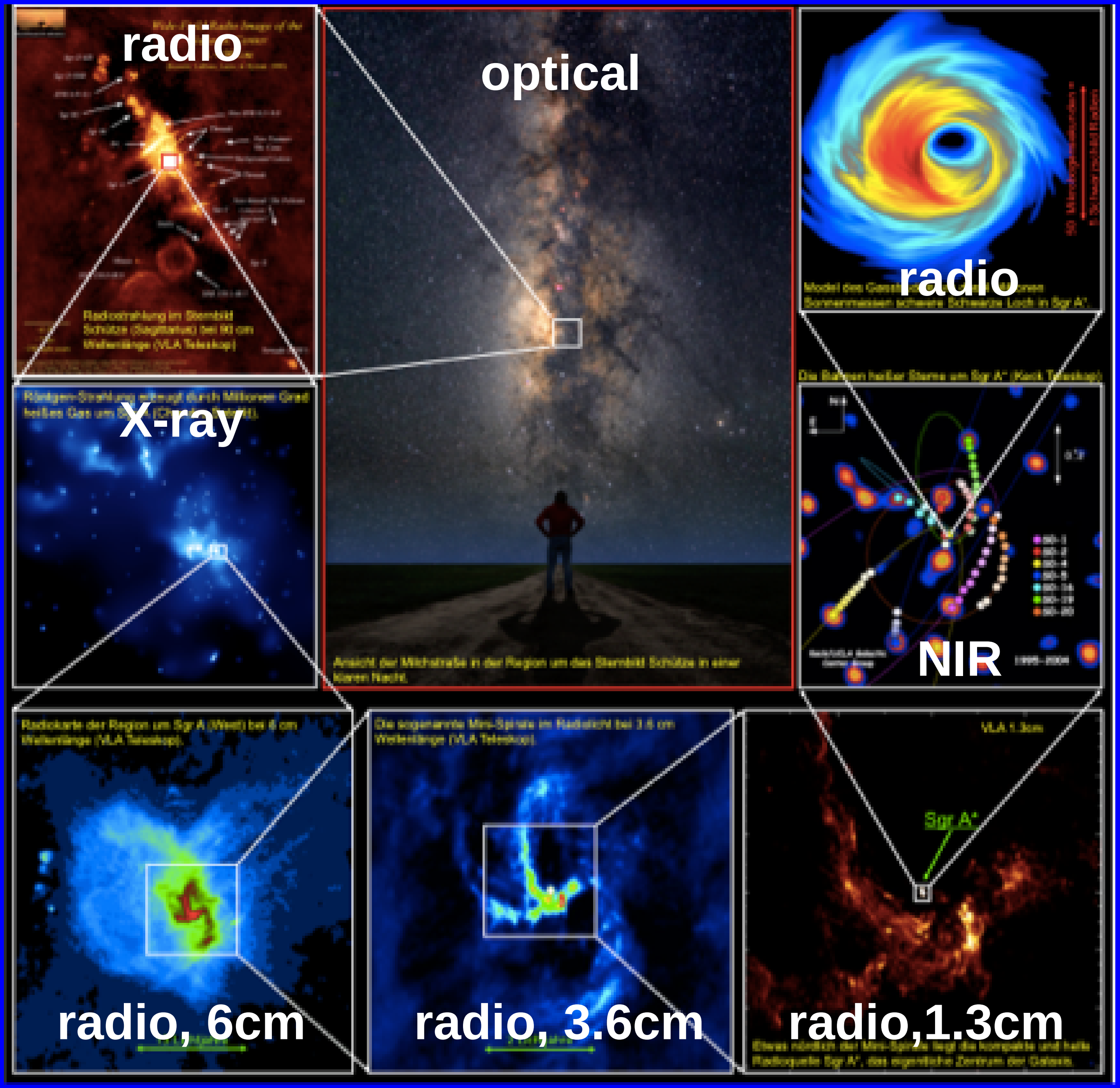


Sagittarius A* (Sgr A*):



Largest black hole in the sky:

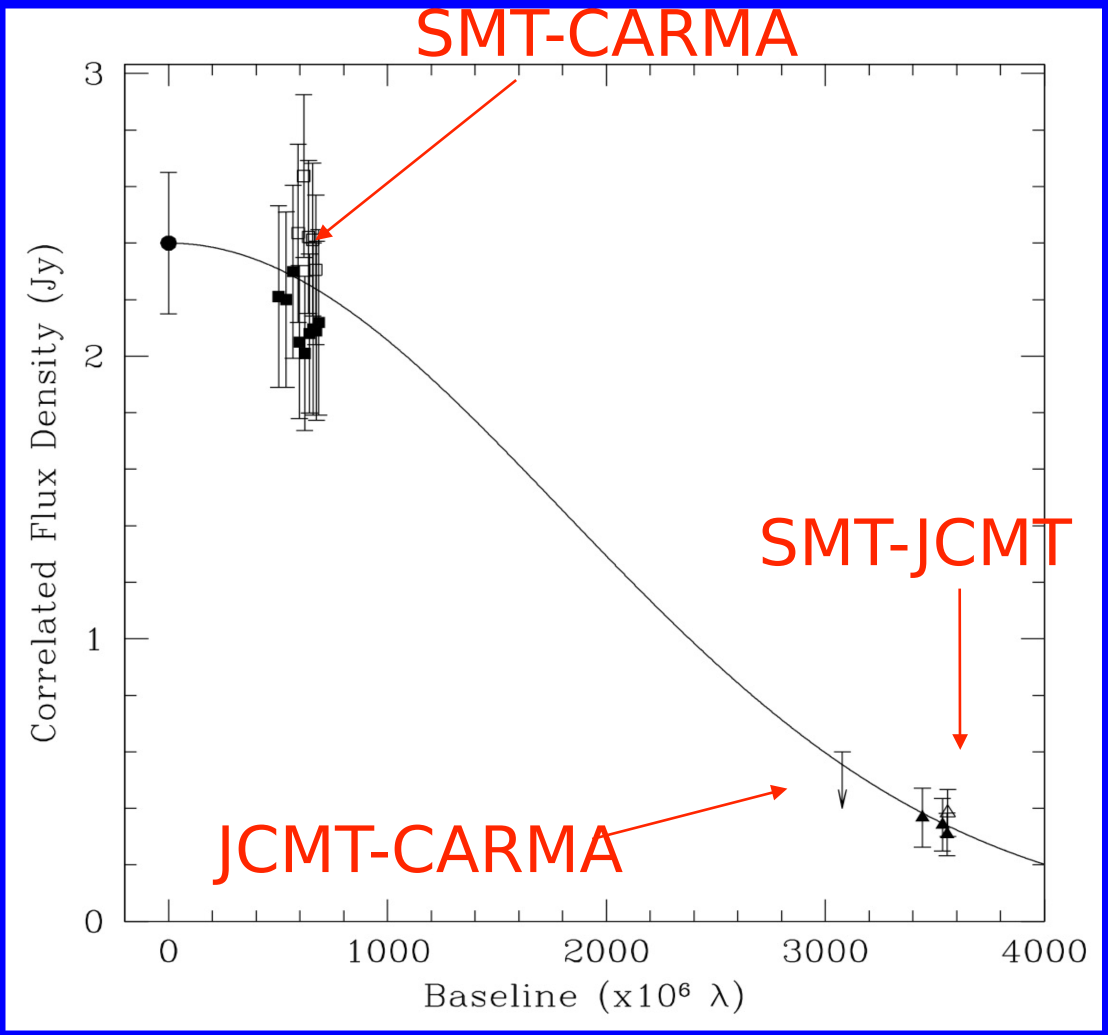
Mass: ~4×10^6 M$_\odot$

Distance (R$_0$): ~8 kpc

Schwarzschild radius (Rs):

1 Rs ~ 0.1 AU~ 10 µas!!!

Horizon-scale structure in Sgr A*



Doeleman et al. 2008, Nature

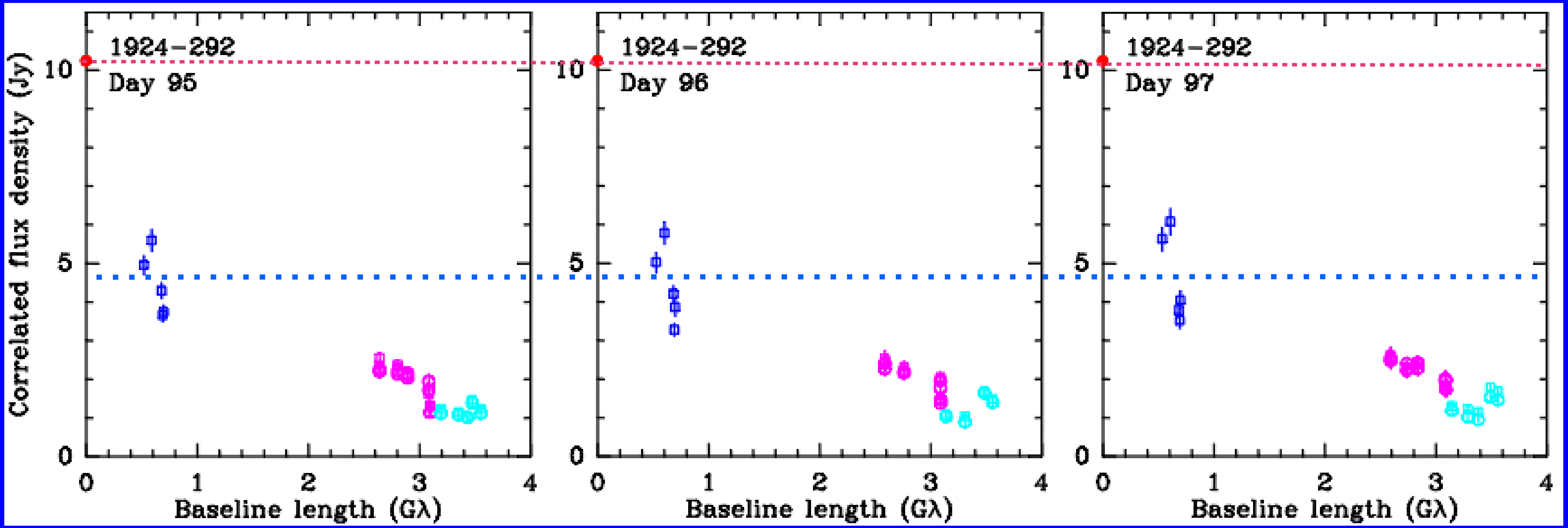
About 4 Schwarzschild radii across

$$\rho = 10^{23} M_{\odot} pc^{-3}$$

1.3 mm emission offset from the BH

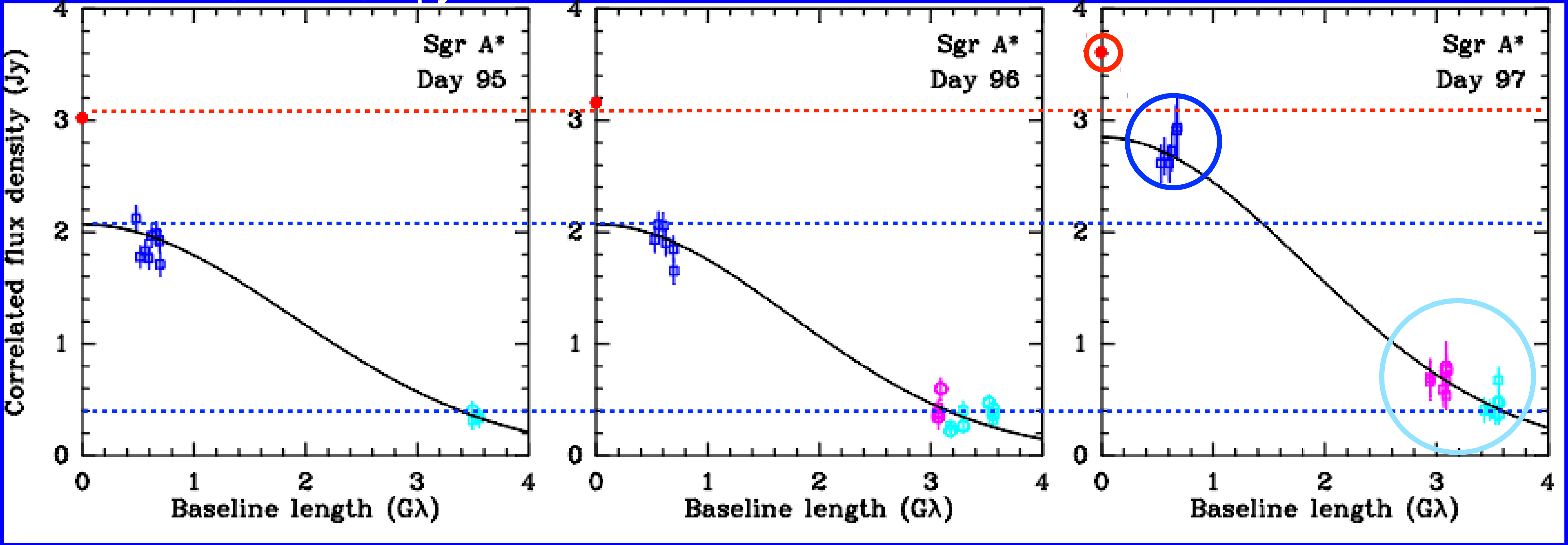
SgrA* flares on R_{sch} scales

Calibrator



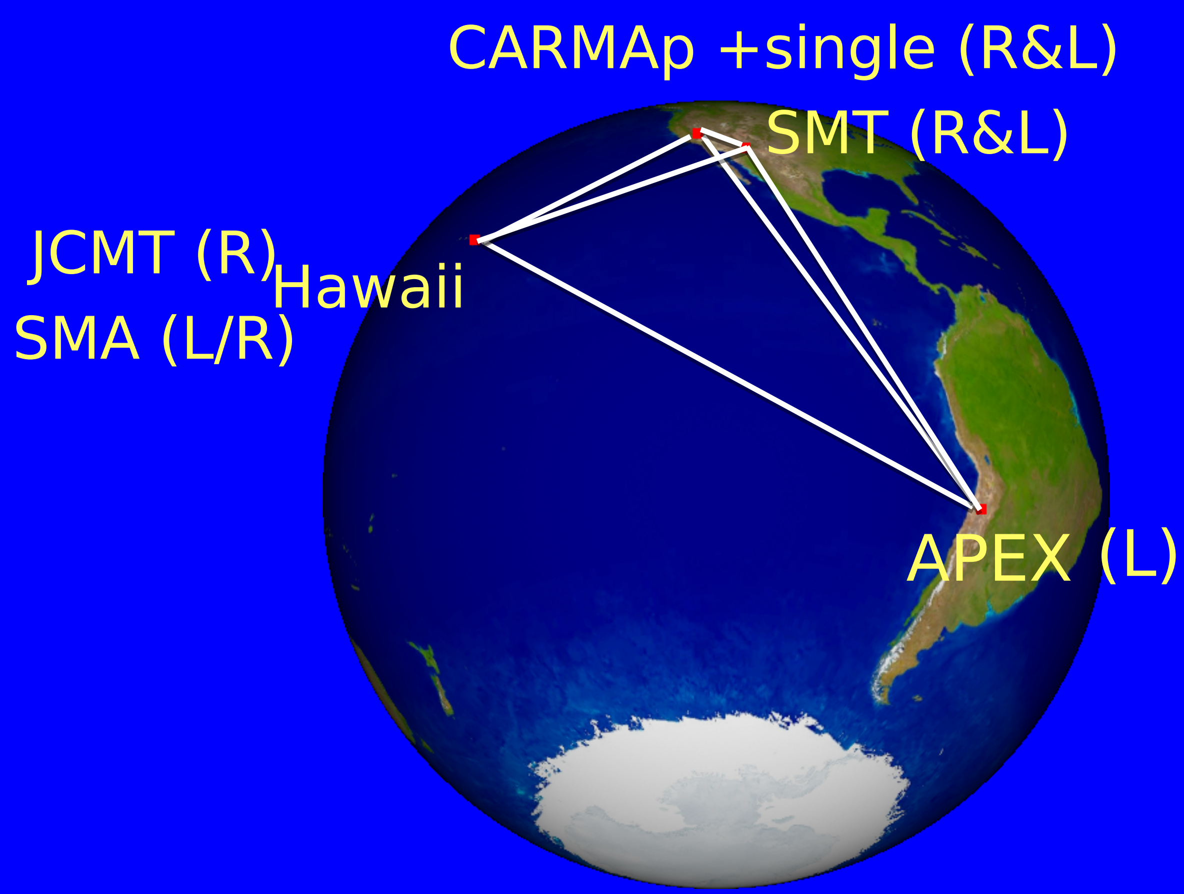
Sgr A*

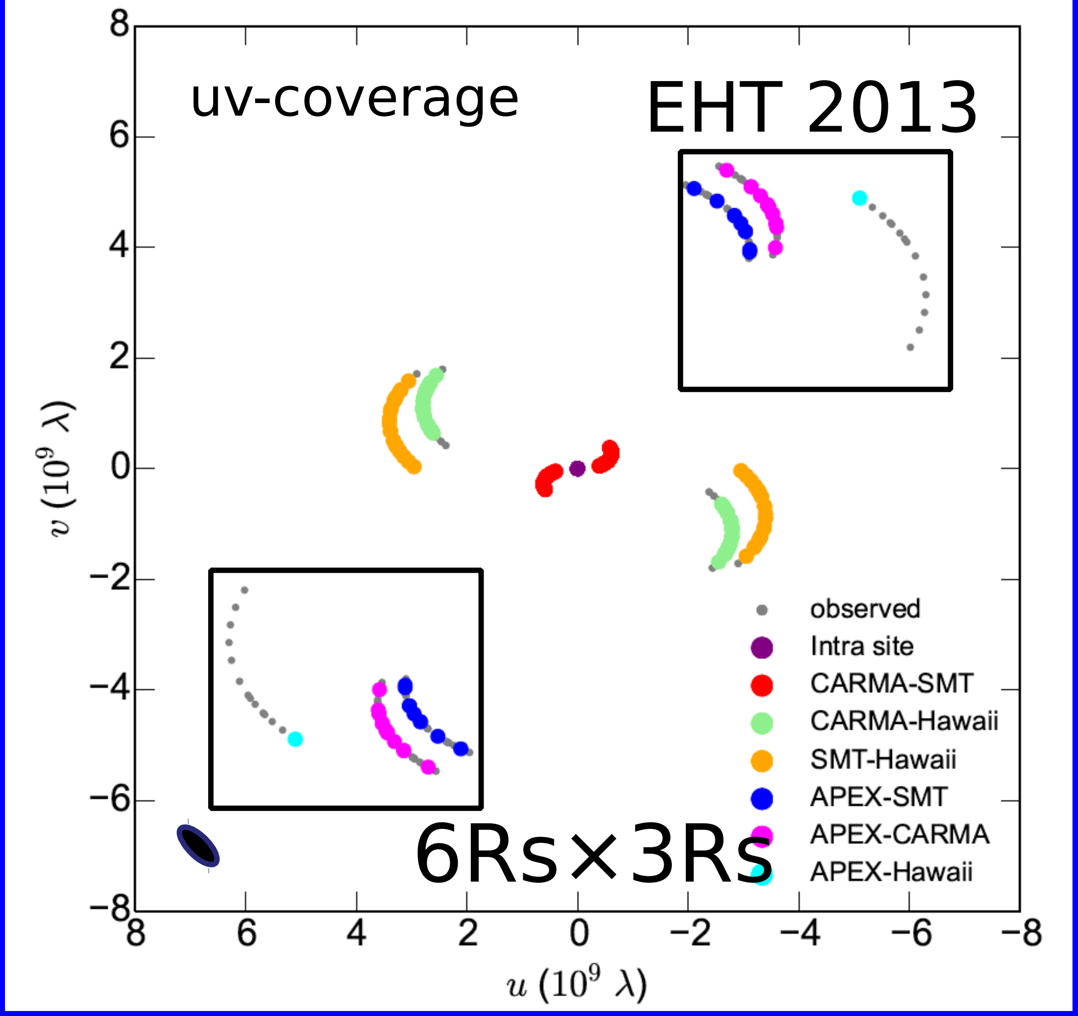
Fish et al, 2011, ApJL



1.3mm-VLBI observations of Sgr A* in 2013

-APEX detected Sgr A*: 3 Rs resolution achieved !





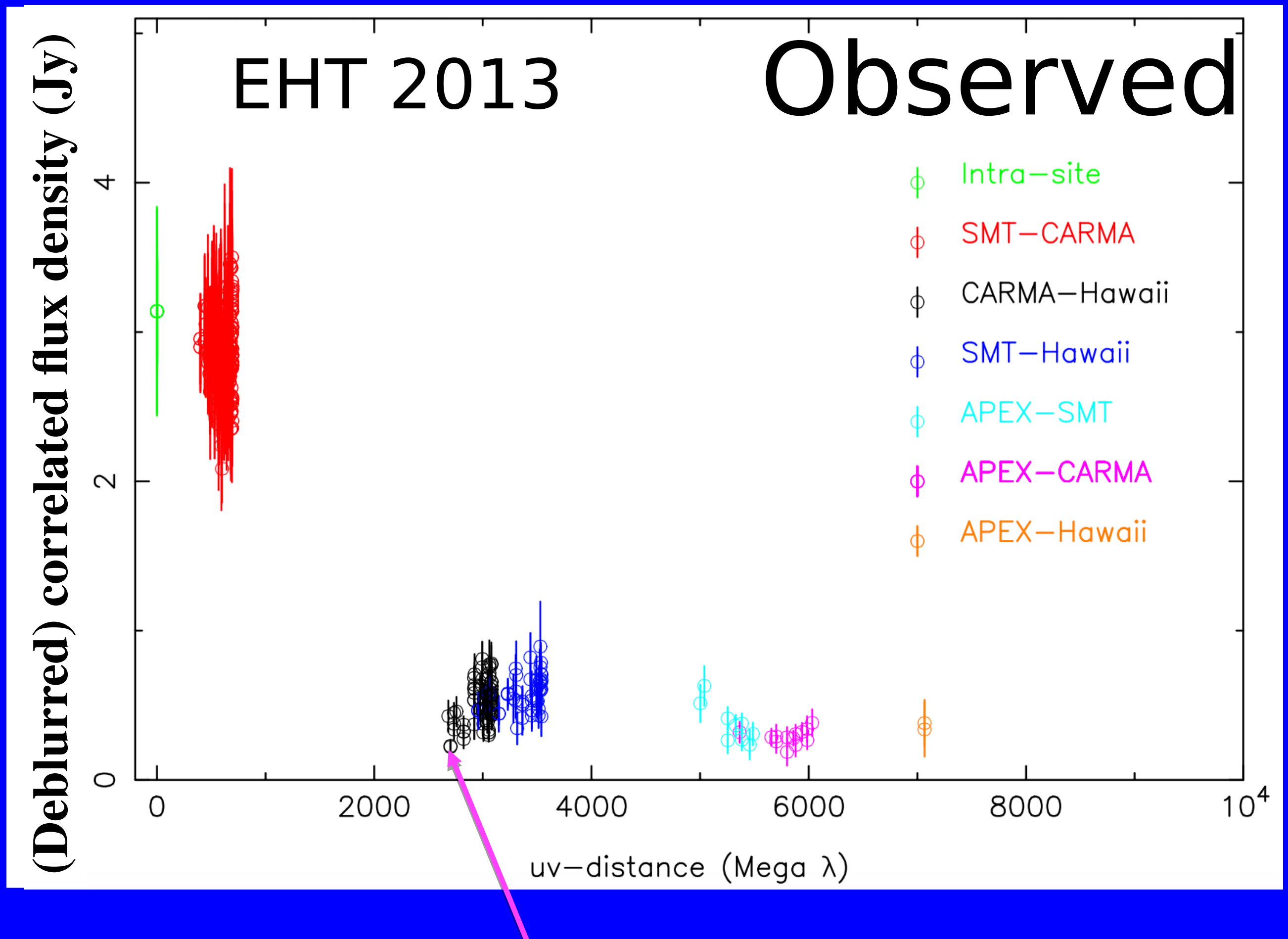
Days 80, 81, 82, 85, 86 ('_': with APEX)

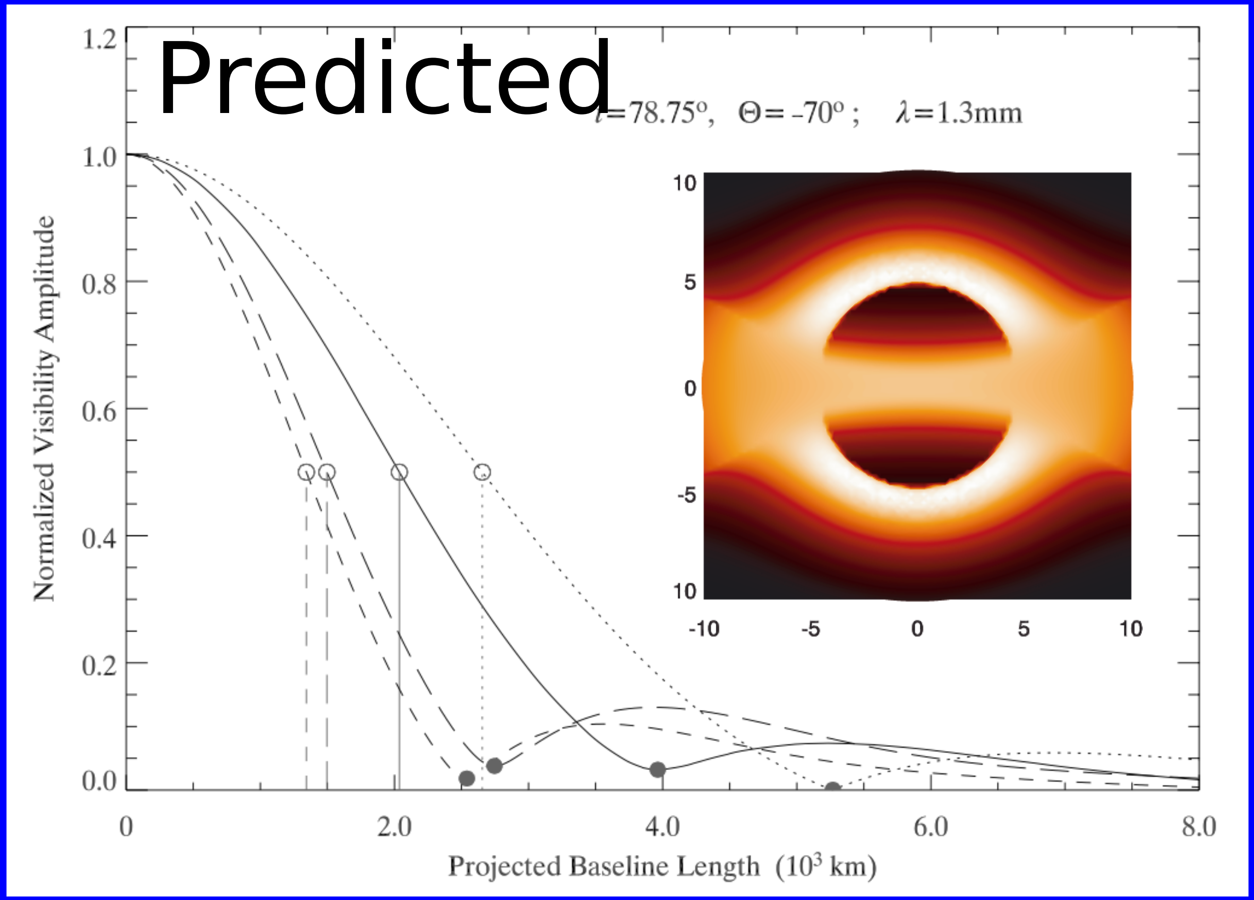
Two 480 MHz bands (except single dish at CARMA)

Baseline length:
92m (intra-site) — 9447 km (with APEX)

1.3mm-VLBI observations of Sgr A* in 2013

-the (deblurred) visibility amplitudes





The signature of the BH shadow?

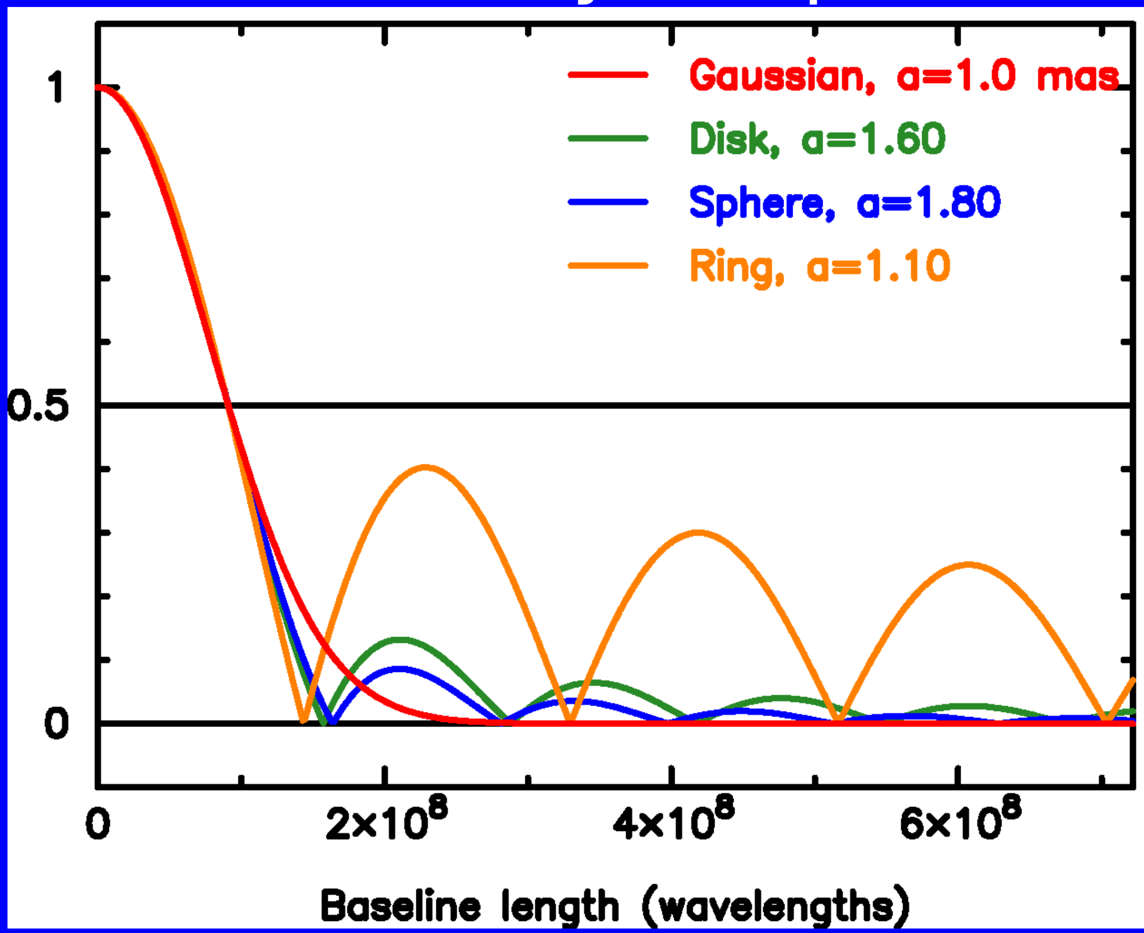
Huang et al. 2007

APEX doubles the uv-range to 7000Mλ!

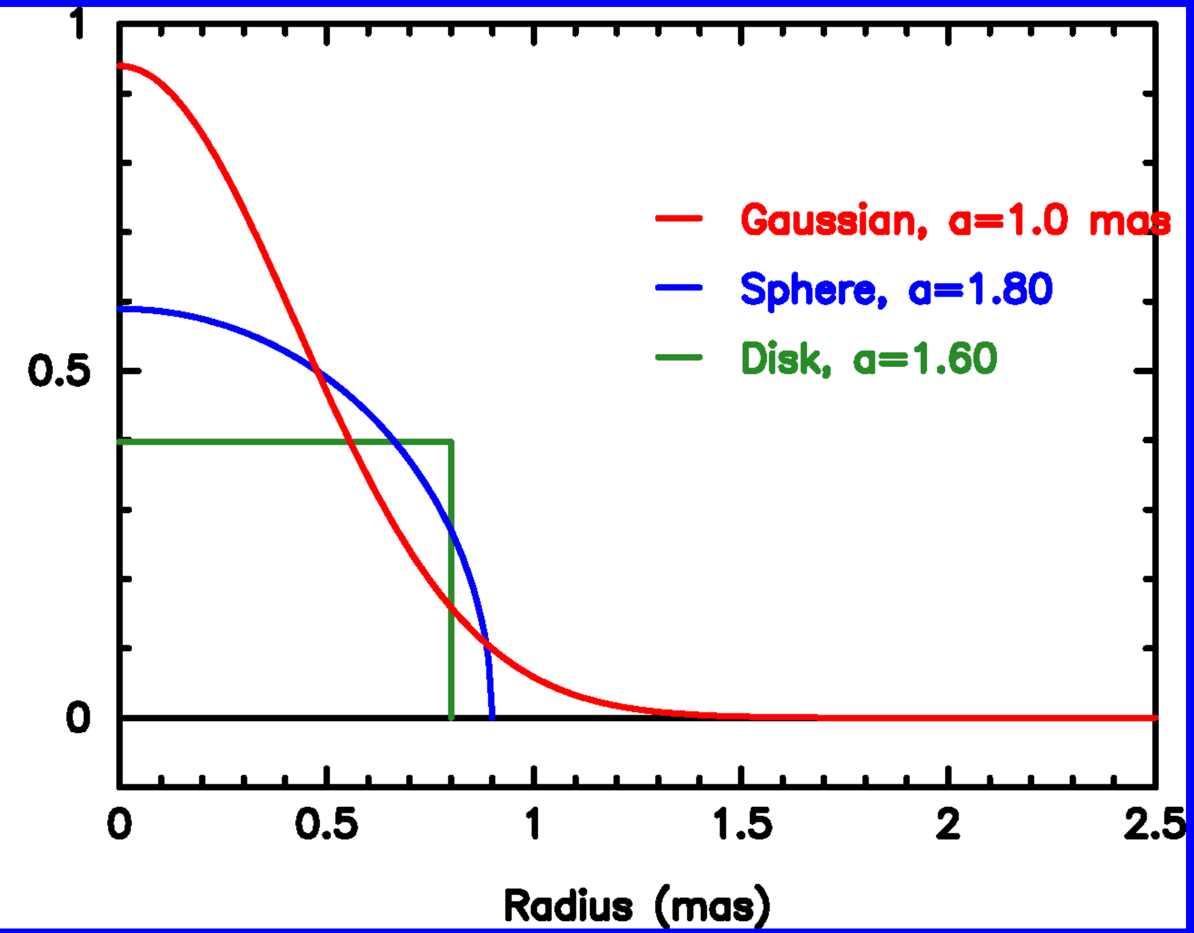
Visibilities on long baselines are not dominated by (refractive) scattering!
(Lu et al. 2018)

Simple geometric models

model visibility (amplitude)



model

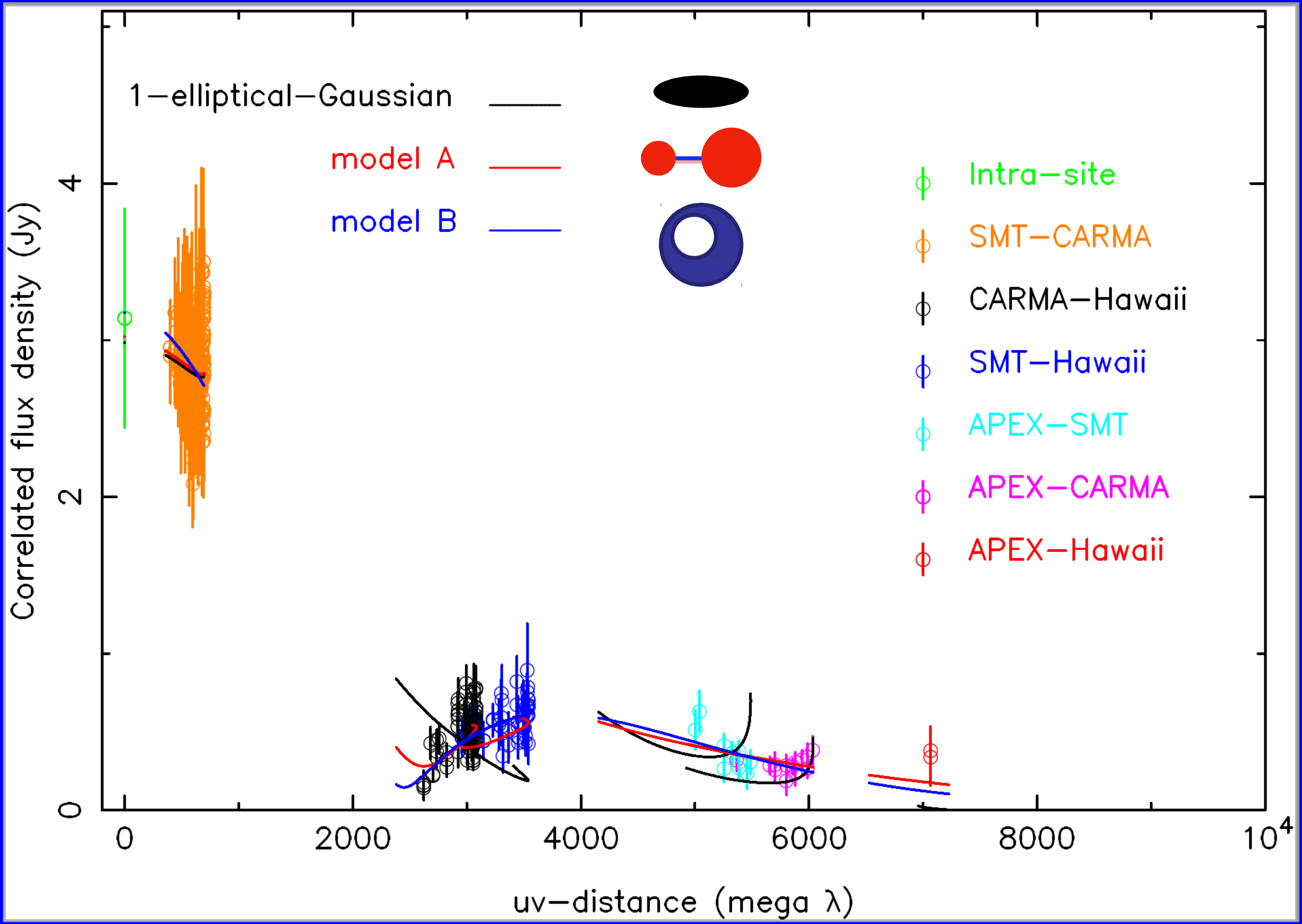


(adopted from T. Pearson)

Visibility at long baselines contains much more information than at short baselines

1.3mm-VLBI observations of Sgr A* in 2013

-new signatures seen: two-component models do fit



(Lu et al. 2018)

1.3mm-VLBI observations of Sgr A* in 2013

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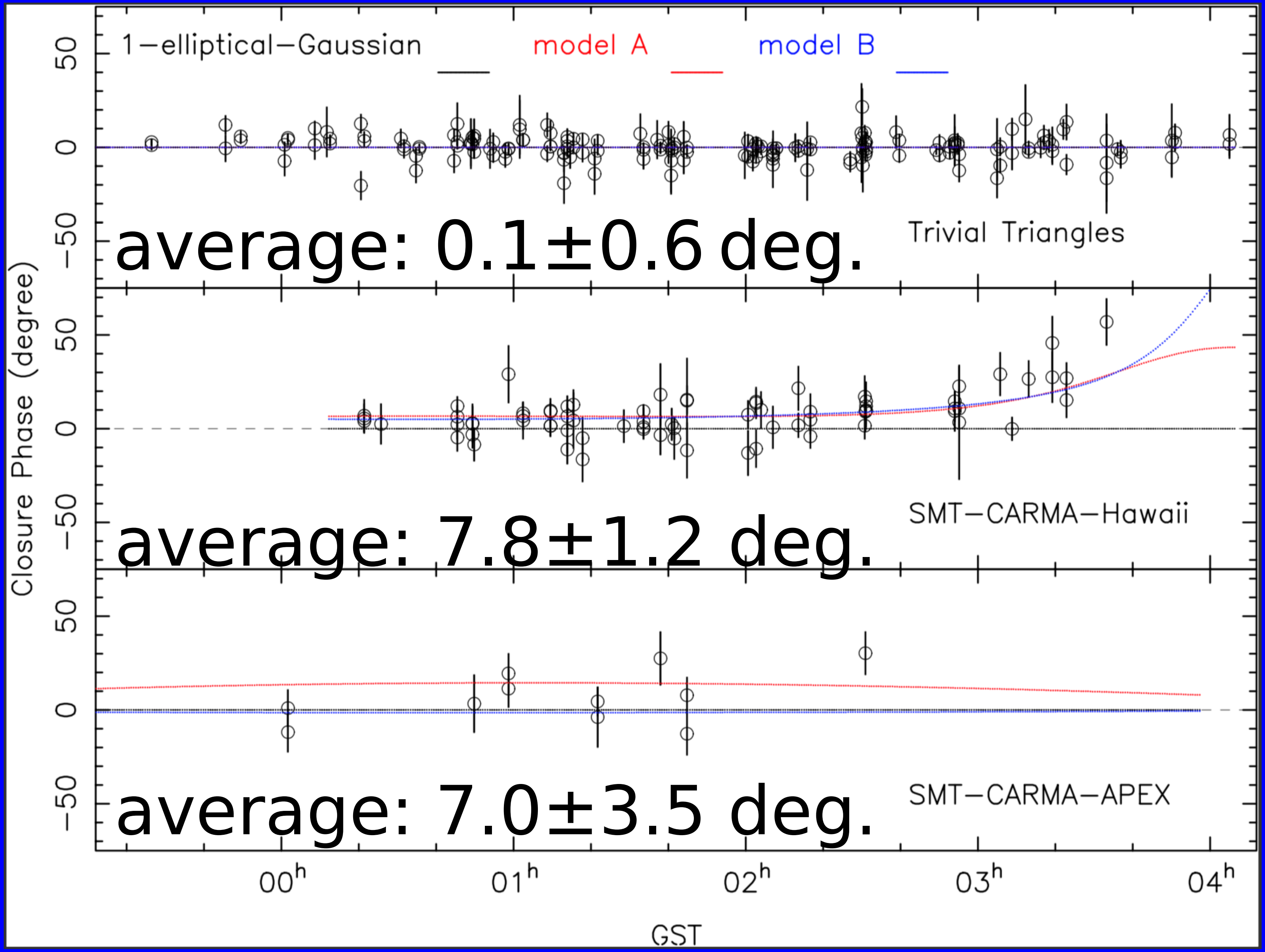
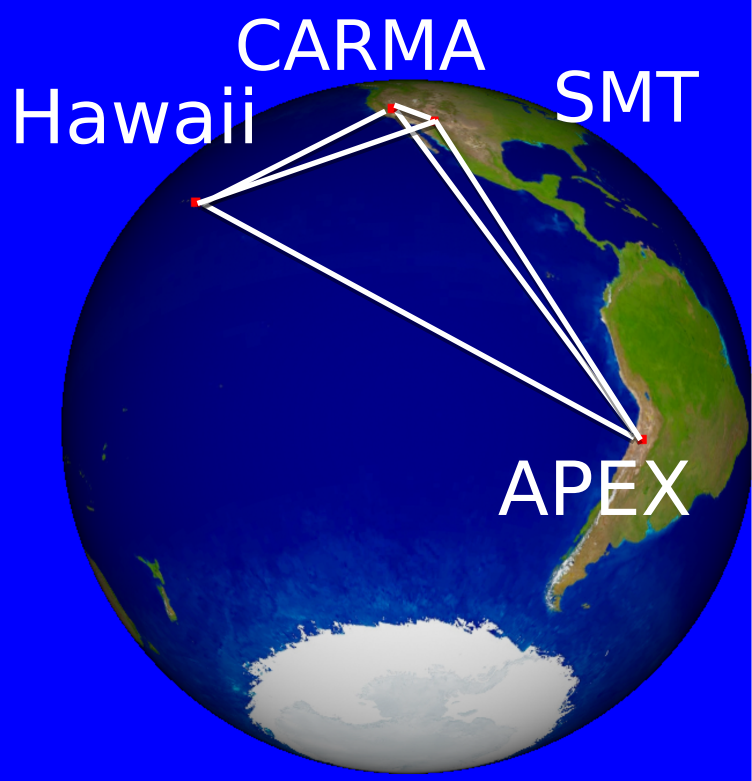




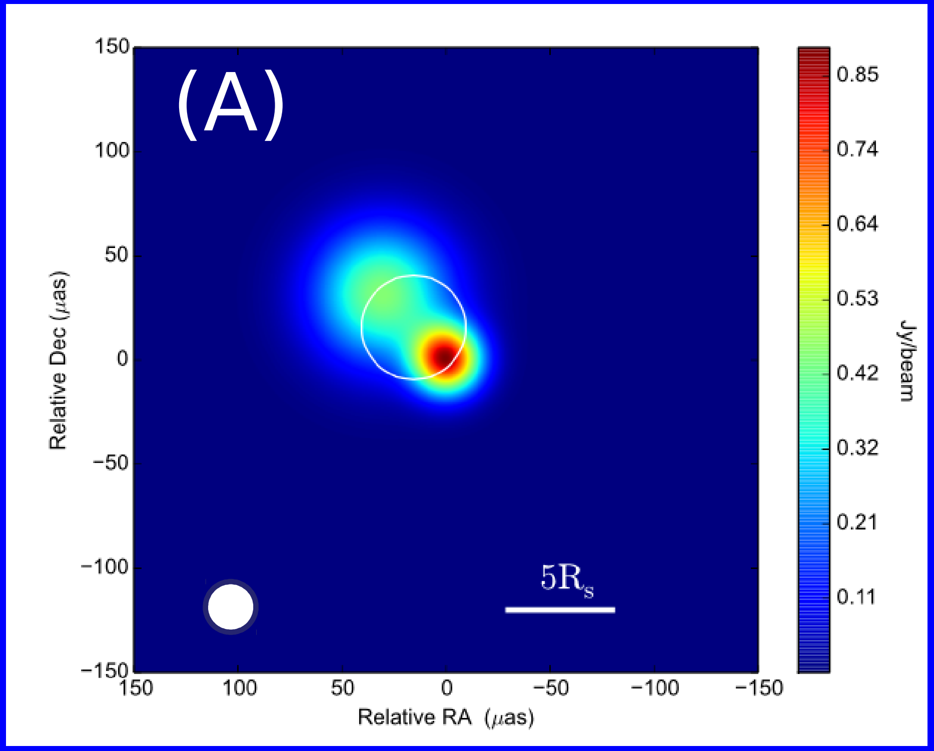
-Non-zero closure phase

-Horizon-scale-structure asymmetric

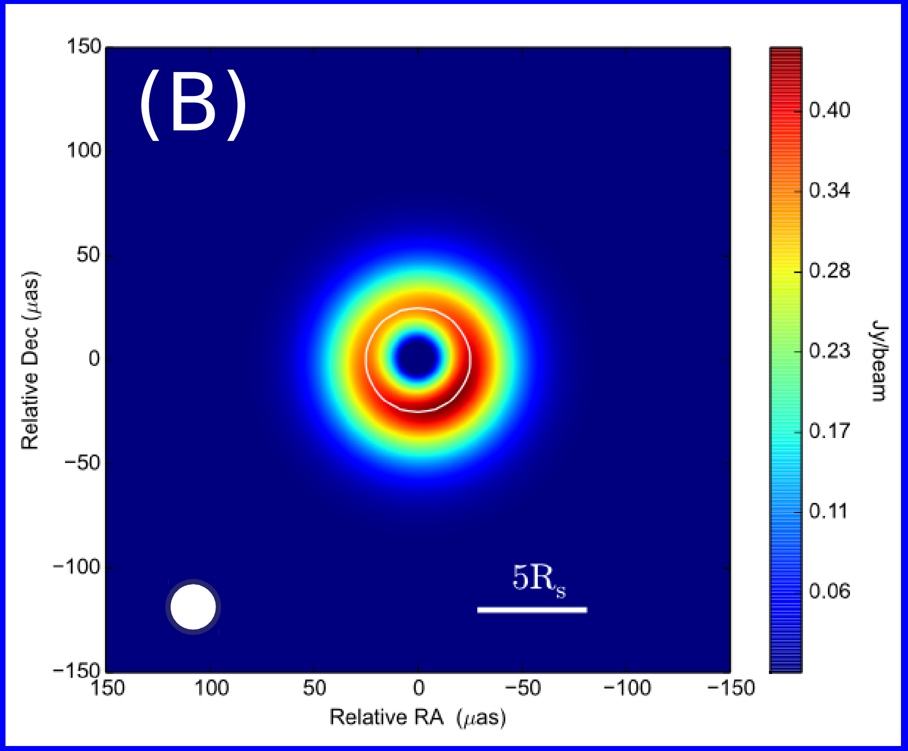
(Lu et al. 2018)

1.3mm-VLBI observations of Sgr A* in 2013

2-component Gaussian



non-uniform crescent



➤Single component Gaussian model ruled out

➤2-component models could well explain the data (Model B fits the data slightly better)

common (real) features:

overall size (the white circle: 5Rs!!!); orientation of the asymmetry; "dark" at center;

➤New data are obviously needed to confirm the reality of the crescent-like structure

(Lu et al. 2018)

1.3mm-VLBI observations of Sgr A* in 2013

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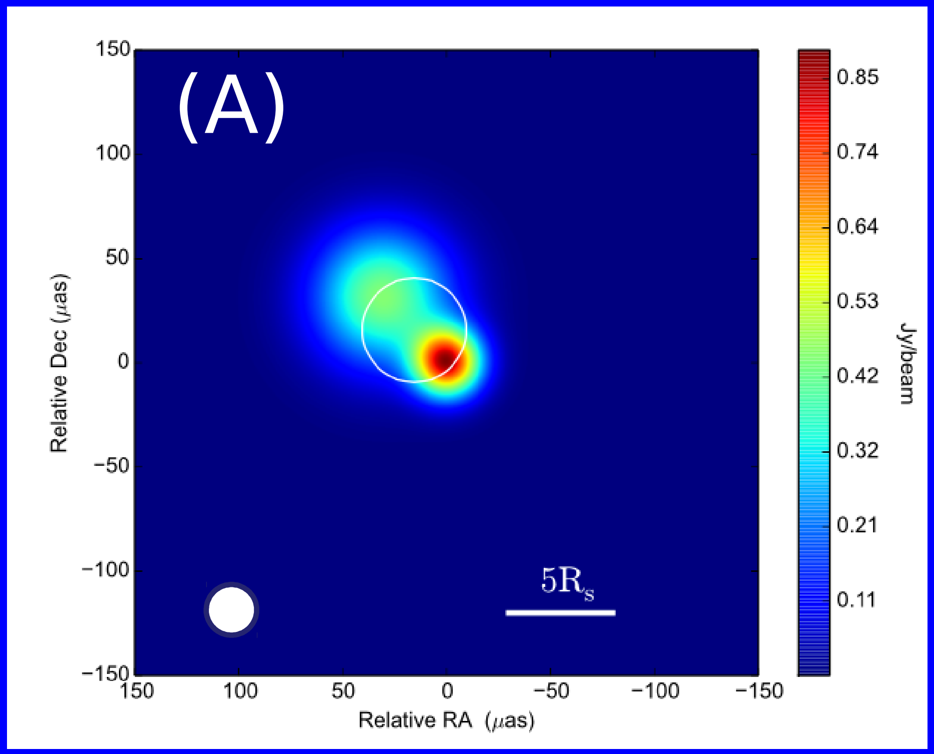

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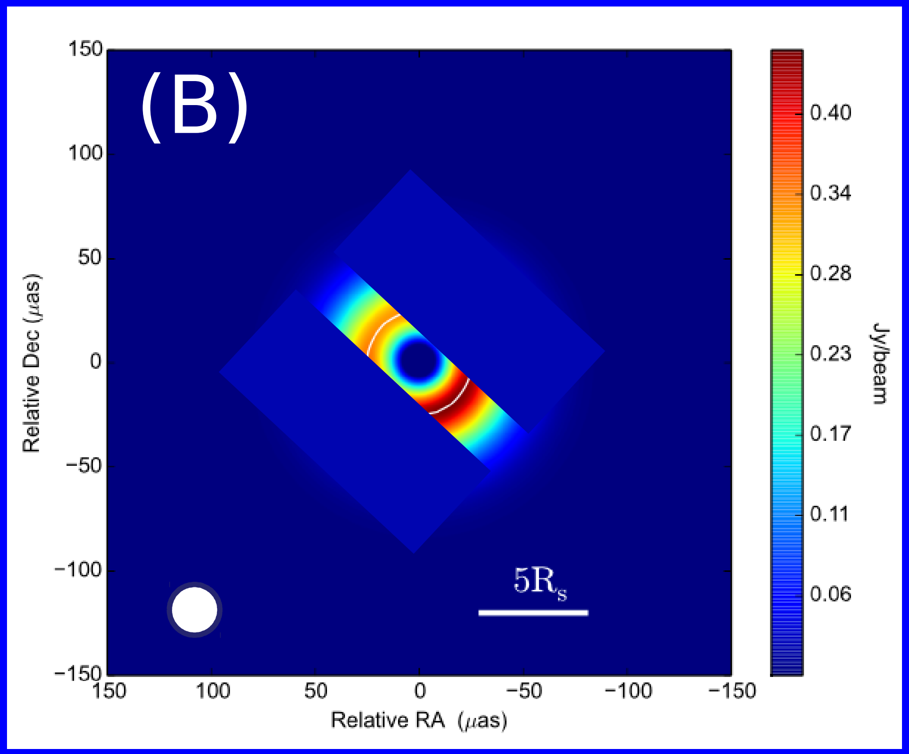

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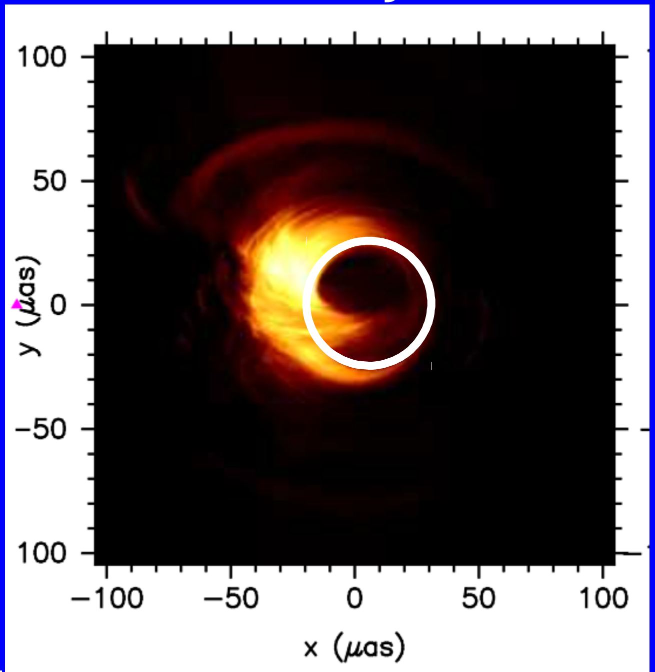
(Lu et al. 2018)

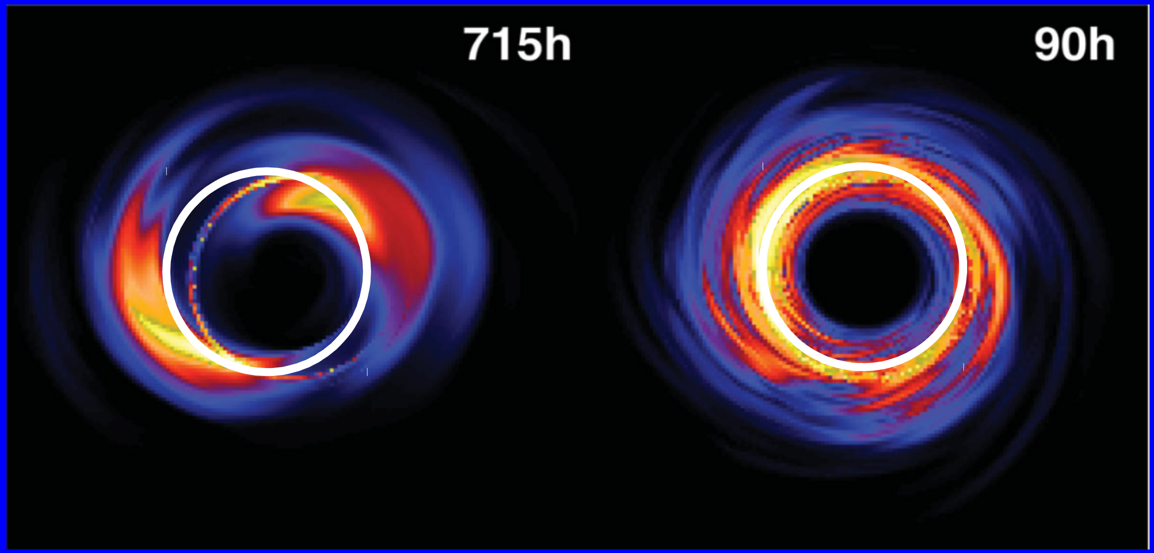
What do we see?
many possibilities, but all models give similar shadow size
(i.e., ~5Rs: see the white circle)

disk+jet



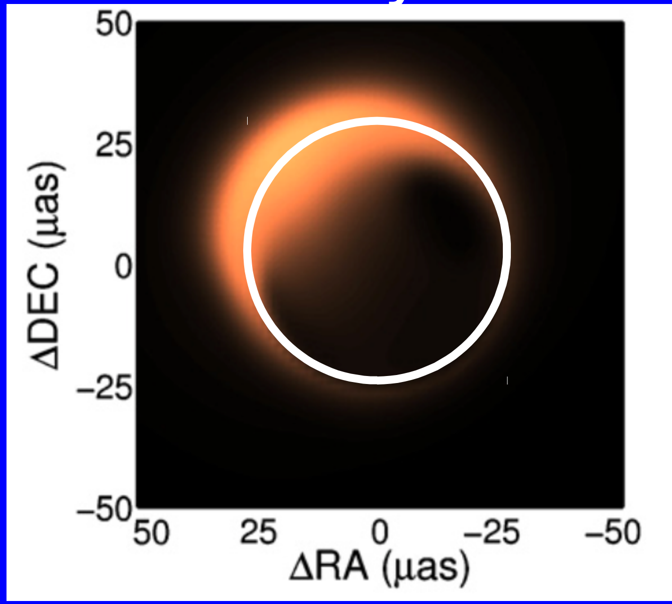
Moscibrodzka et al. 2014

“tilted” disk   “untilted” disk



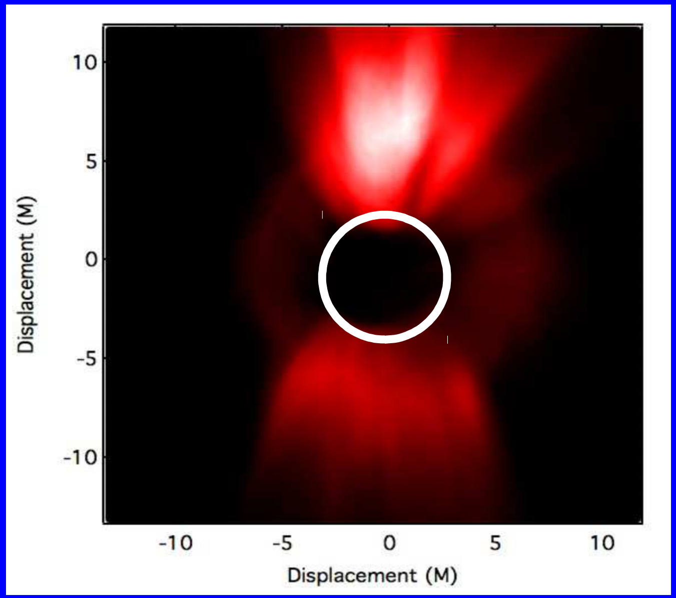
Dexter & Fragile, 2013

semi-analytic RIAF



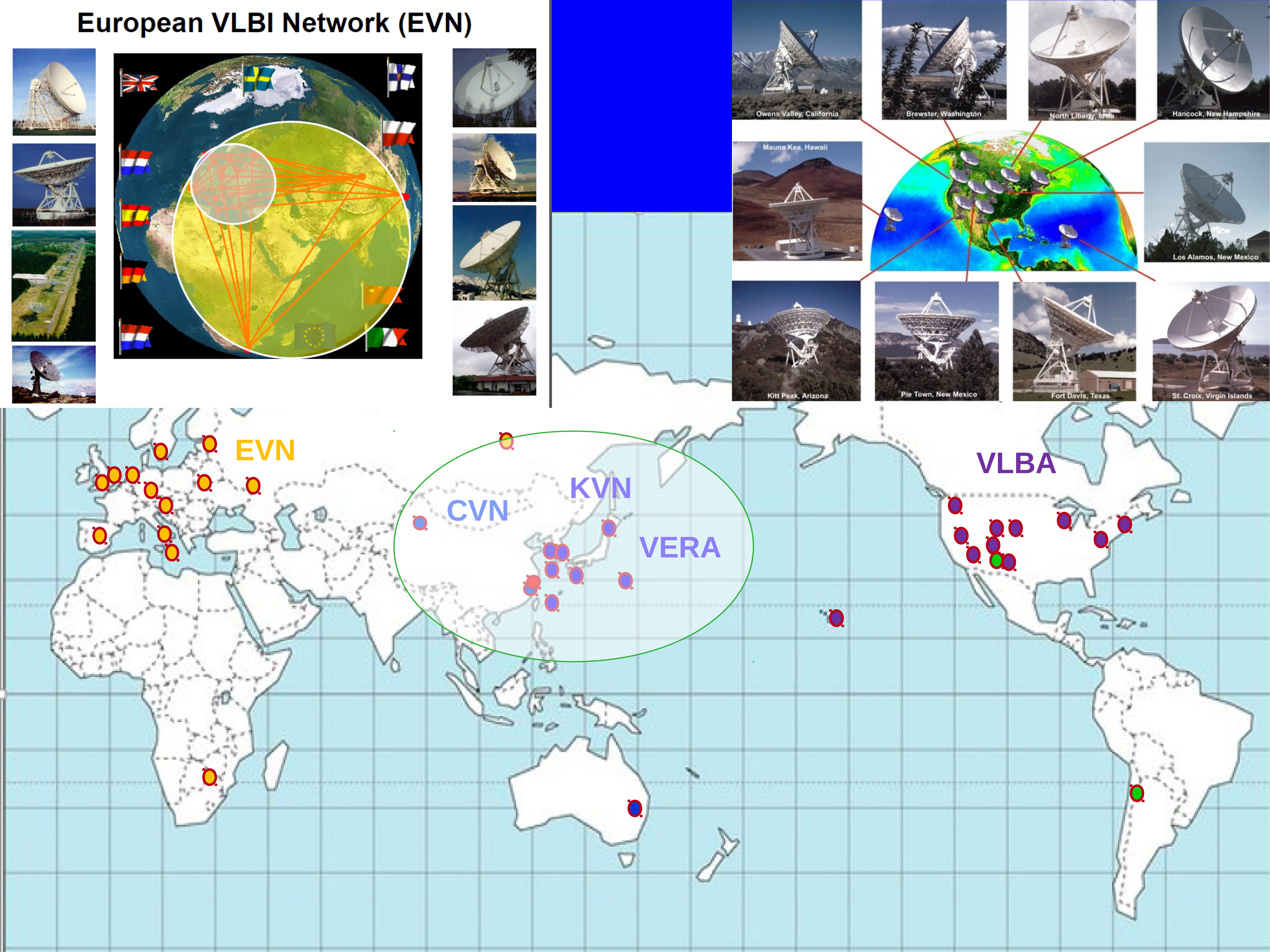
Broderick et al. 2011

magnetically arrested disk (MAD)



Chan et al. 2015

Status of the East Asian VLBI network


European VLBI Network (EVN)
Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands
EVN
CVN
KVN
VERA
VLBA

Many radio telescopes in East Asia

EAVN: Specifications

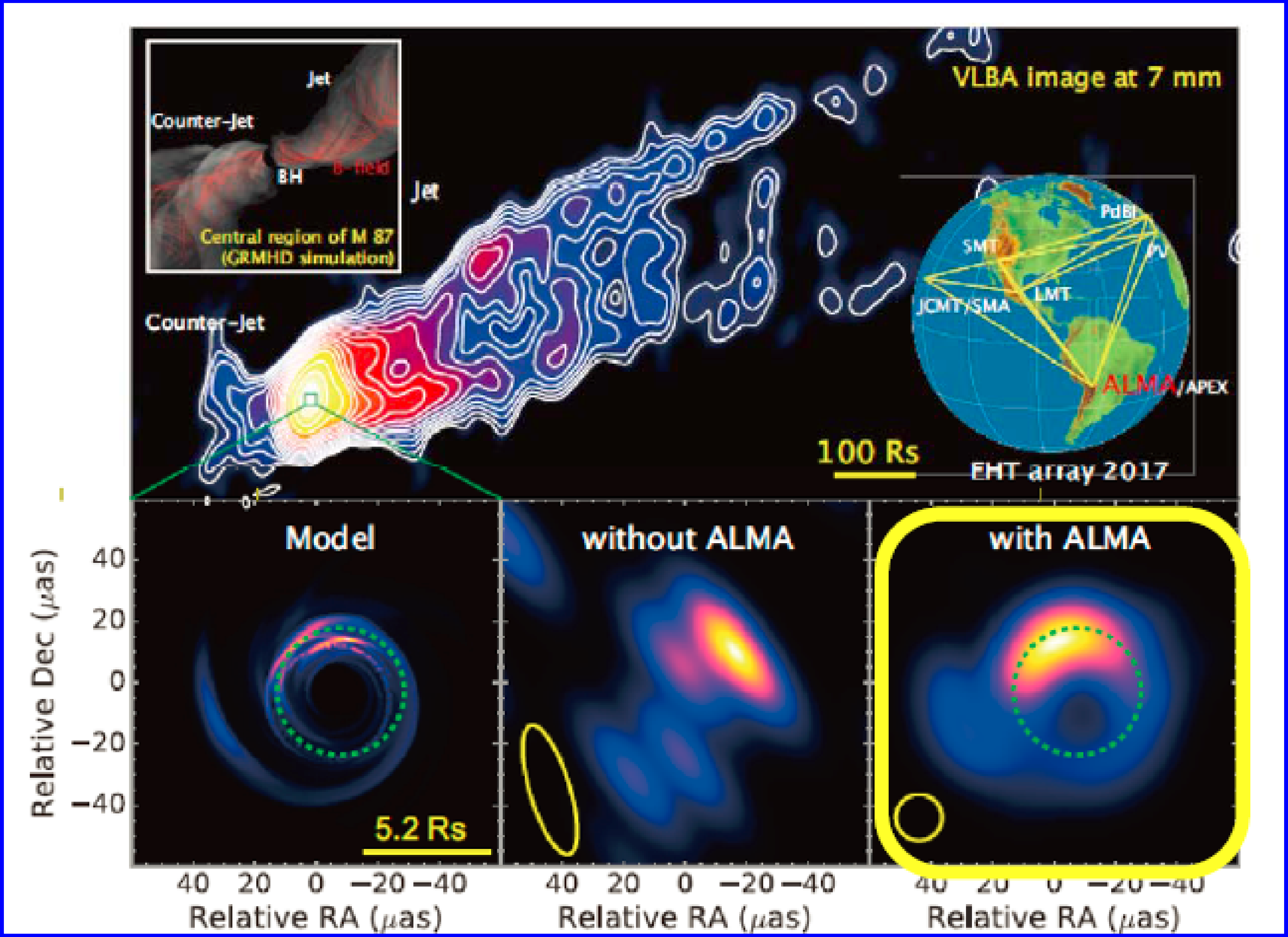
- Number of (potential) telescopes: 20+ (15 telescopes have participated in test observations one or more times)
  - Korea: 4, China: 7, Japan: 10
- (Possible) frequency coverage:
  - 6.7 GHz (11 stations), 8 GHz (15), 22 GHz (16), 43 GHz (10)
- (Expected) angular resolution:
  - 2.4 mas (6.7 GHz; Ogasawara – Kunming)
  - 1.5 mas (8 GHz; Ogasawara – Nanshan)
  - 0.6 mas (22 GHz; Ogasawara – Nanshan)
  - 0.7 mas (43 GHz; Ogasawara – Tianma)
- Sensitivity for 7-σ fringe detection (τ = 60 s, B = 256 MHz):
  - 1.6 mJy (8 GHz; Tianma – KVN)
  - 9.5 mJy (22 GHz; Tianma – KVN)
- (Expected) recording rate: ≧ 2 Gbps (= 512 MHz BW)
- (Currently-used) correlator:
  - KJCC (Korea): KJJVC and DiFX
  - SHAO (China): DiFX

The East-Asian VLBI Network

(Image Credit: Reto Stöckli, NASA Earth Observatory)

6.7 GHz
8 GHz
22 GHz
43 GHz

EAVN monitoring observation of Sgr A*&M87 in 2017/2018 (contemporized with the EHT campaigns)



EAVN campaign 2017, Mar –May (K and Q band)

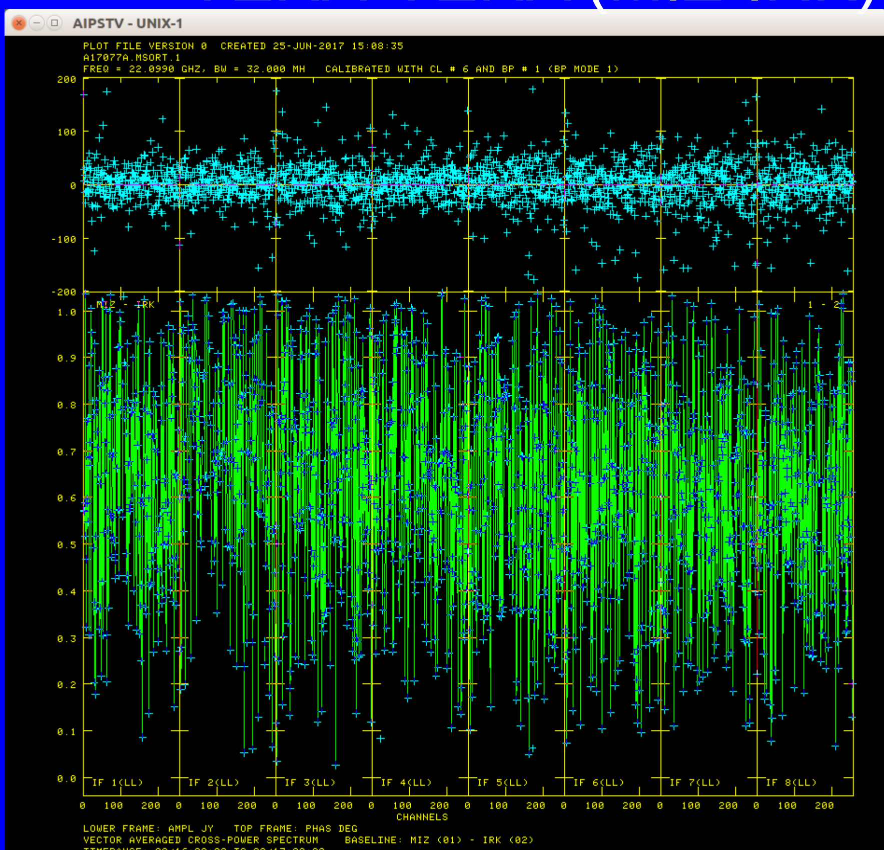
Obs. Code	Date	Sources	Freq. Band	Stations
a17077a	Mar 18 UT12:45-19:45	M87	K	KaVA, Tm, Ur, Ht, Ks
a17078a	Mar 19 UT11:40-18:40	M87	Q	KaVA, Tm
a17086a	Mar 27 UT13:10-23:10	M87+SgrA	Q	KaVA, Tm
a17093a	Apr 3 UT13:20-23:25	M87+SgrA	K	KaVA, Tm,Ur,Ht,Ks,Mc
a17094a	Apr 4 UT12:35-22:35	M87+SgrA	Q	KaVA, Tm
a17099a	Apr 9 UT12:20-22:20	M87+SgrA	Q	KaVA, Tm, Ny
a17104a	Apr 14 UT12:00-22:00	M87+SgrA	Q	KaVA, Tm
a17107a	Apr 17 UT11:45-18:45	M87	K	KaVA, Tm,Ur,Sj,Ht,Ks,Mc,Nt
a17108a	Apr 18 UT11:40-21:40	M87+SgrA	Q	KaVA, Tm
a17114a	Apr 24 UT09:20-16:20	M87	K	KaVA, Tm
a17115a	Apr 25 UT09:15-16:15	M87	Q	KaVA, Tm
a17116a	Apr 26 UT15:55-21:55	SgrA	Q	KaVA, Tm, Sj
a17130a	May 10 UT08:20-17:20	M87	K	KaVA, Tm, Mc
a17131a	May 11 UT08:15-17:15	M87	Q	KaVA, Tm
a17145a	May 25 UT14:10-20:12	SgrA	Q	KaVA, Tm
a17146a	May 26 UT07:20-14:20	M87	Q	KaVA, Tm

EAVN campaign 2018, Mar –May (K and Q band)

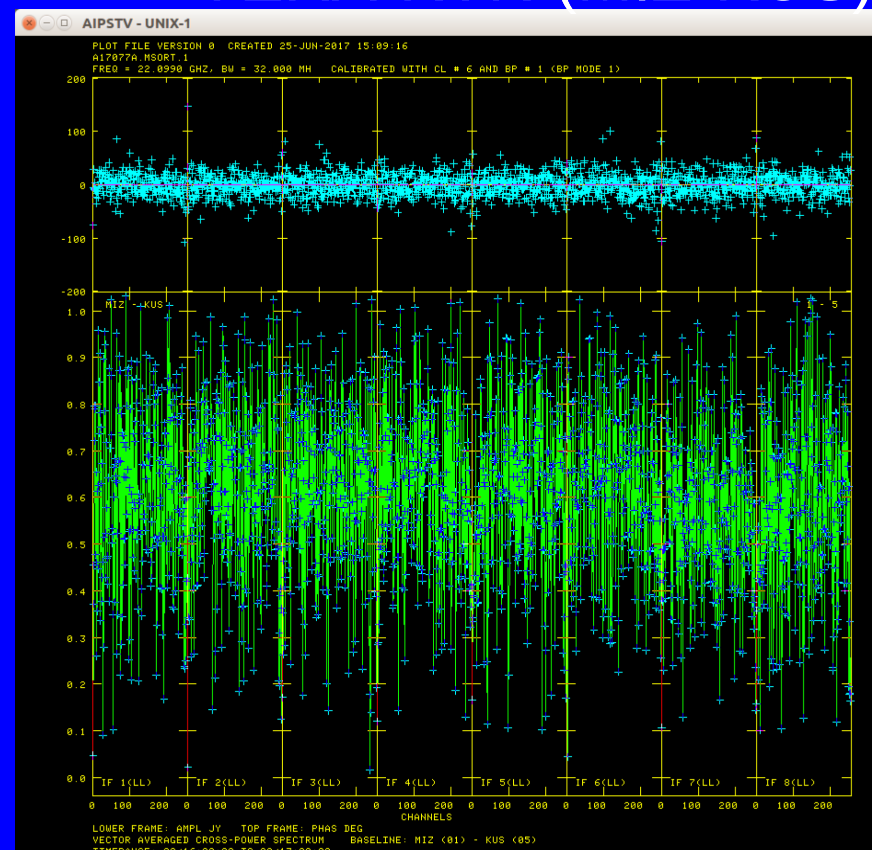
Obs. Code	Date	Sources	Freq. Band	Stations
a18068a	03/09 UT13:20 - 20:20	M87	K	KaVA, Tm, Ur, Mc
a18069a	03/10 UT12:15 - 19:15	M87	Q	KaVA, Tm
a18085a	03/26 UT12:45 - 19:45	M87	K	KaVA, Tm, Ur, Mc
a18087a	03/28 UT11:05 - 18:05	M87	Q	KaVA, Tm
a18088a	03/29 UT17:45 - 23:50	SgrA	Q	KaVA, Tm
a18101a	04/11 UT10:40 - 17:40	M87	Q	KaVA, Tm
a18110a	04/20 UT09:35 - 21:35	M87+SgrA	K	KaVA, Tm, Ny, Ur, Ib, Mc
a18111a	04/21 UT09:30 - 21:30	M87+SgrA	Q	KaVA, Tm
a18117a	04/27 UT09:05 - 21:10	M87+SgrA	K	KaVA, Tm, Ny
a18118a	04/28 UT09:00 - 21:05	M87+SgrA	Q	KaVA, Tm, Ur, Ib, Mc
a18124a	05/04 UT08:15 - 20:15	OJ287, CenA	Q	KaVA, Tm
a18127a	05/07 UT08:25 - 20:30	M87+SgrA	Q	KaVA, Tm, Ny
a18128a	05/08 UT08:25 - 20:25	M87+SgrA	K	KaVA, Tm

Sensitivity enhancement with Tianma

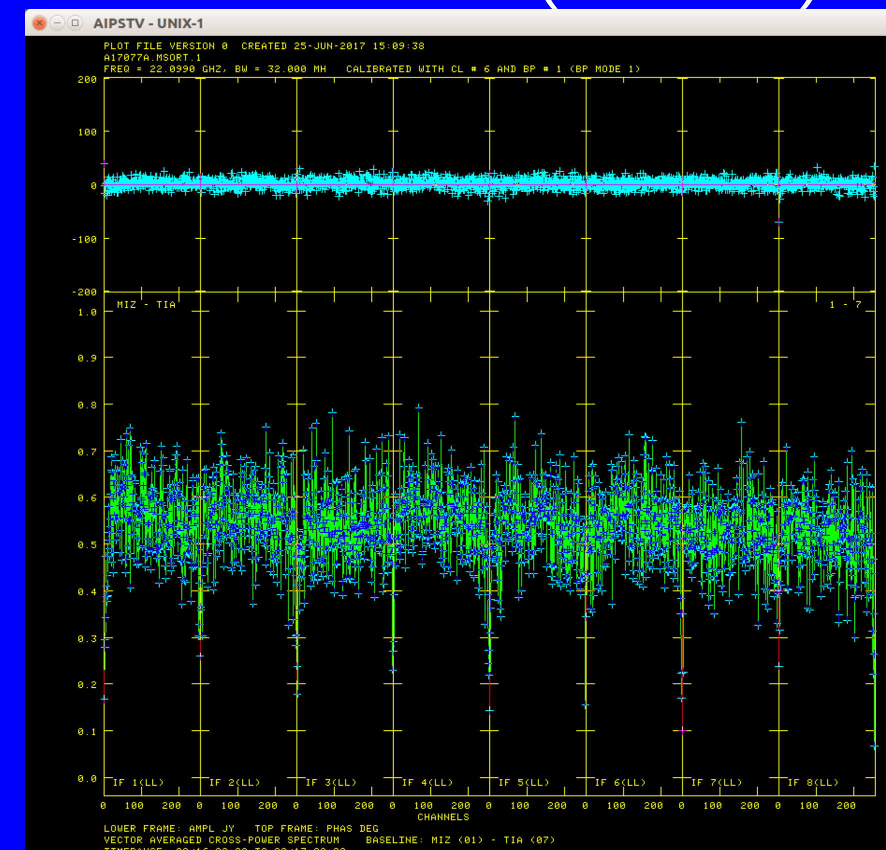
VERA-VERA (MIZ-IRK)



VERA-KVN (MIZ-KUS)



VERA-TIA (MIZ-TIA)



- Using a scan of 1219+044 (ideal point source), you can check the baseline sensitivity with/without Tianma
- (scatters directly reflect baseline SNR)

Image capability of EAVN: Sgr A*

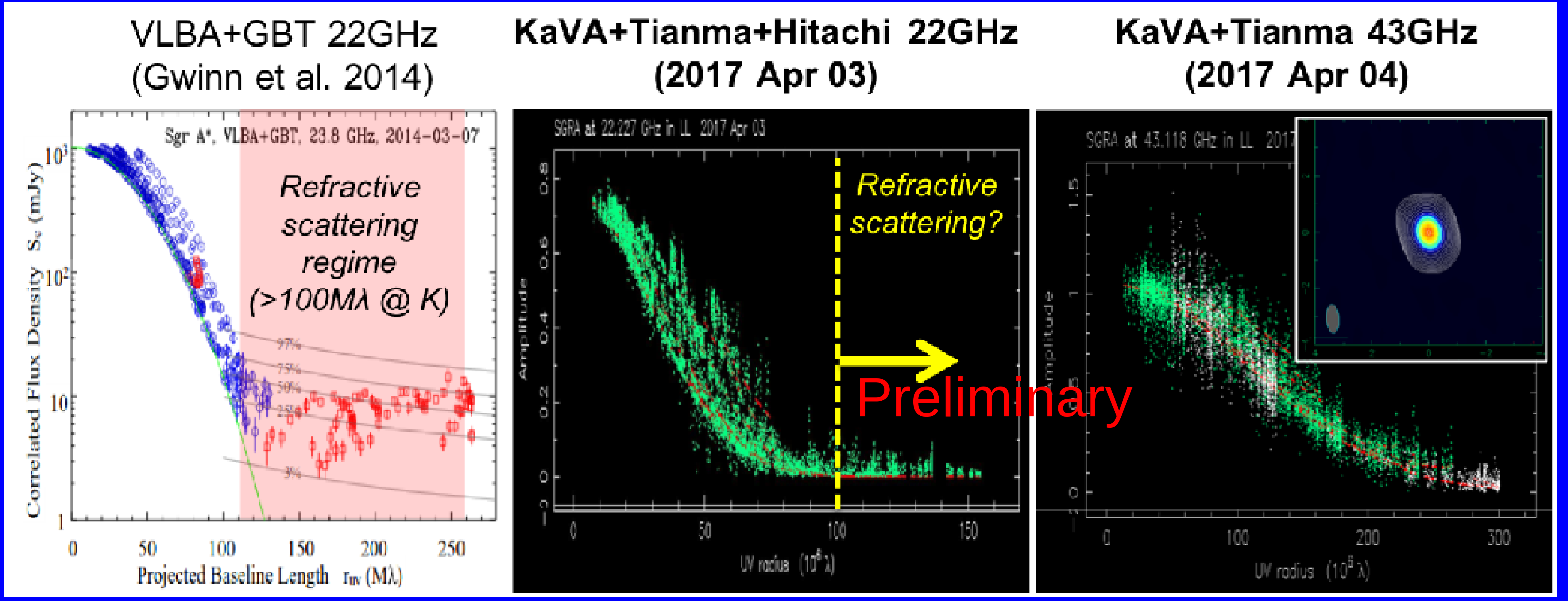
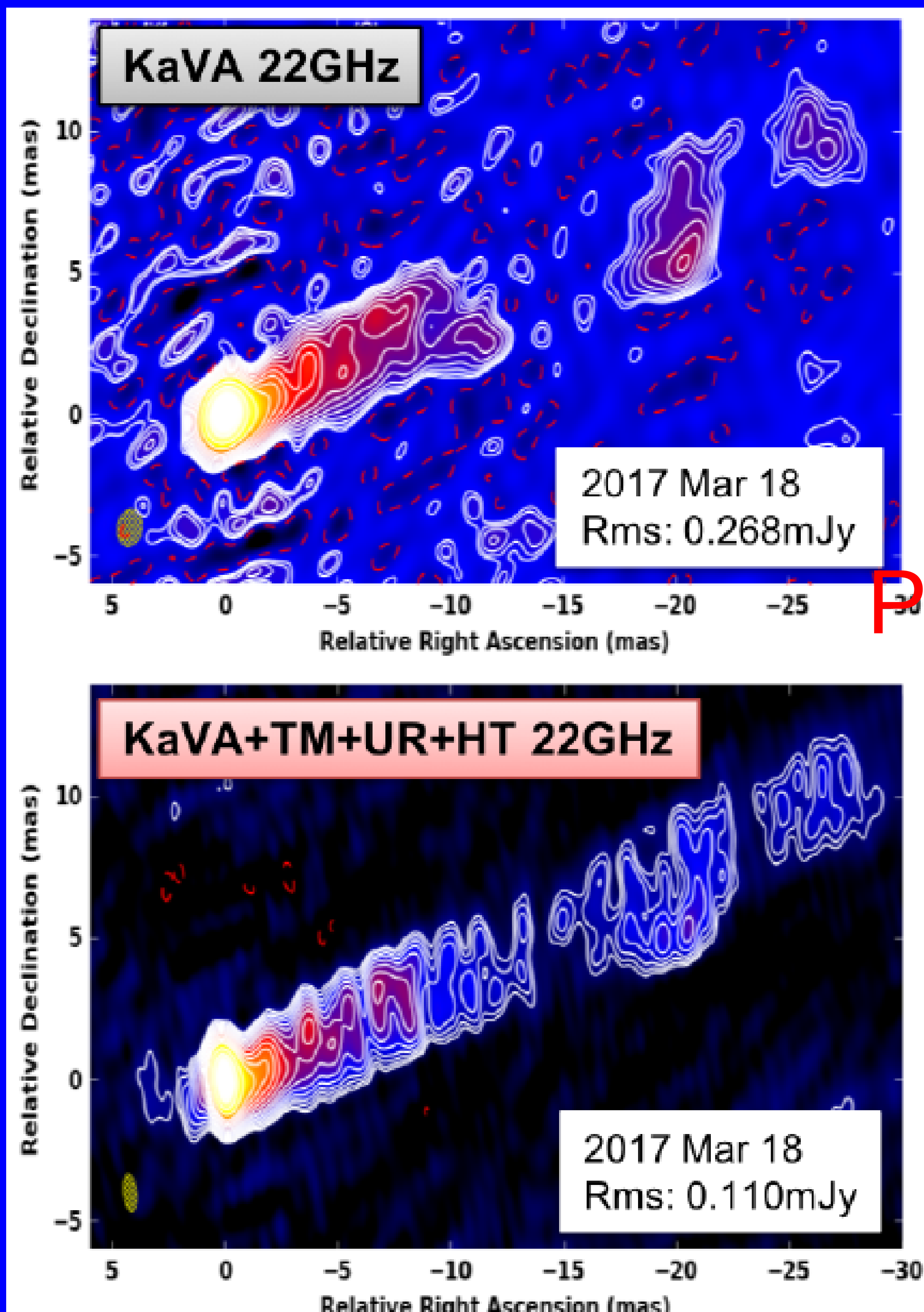
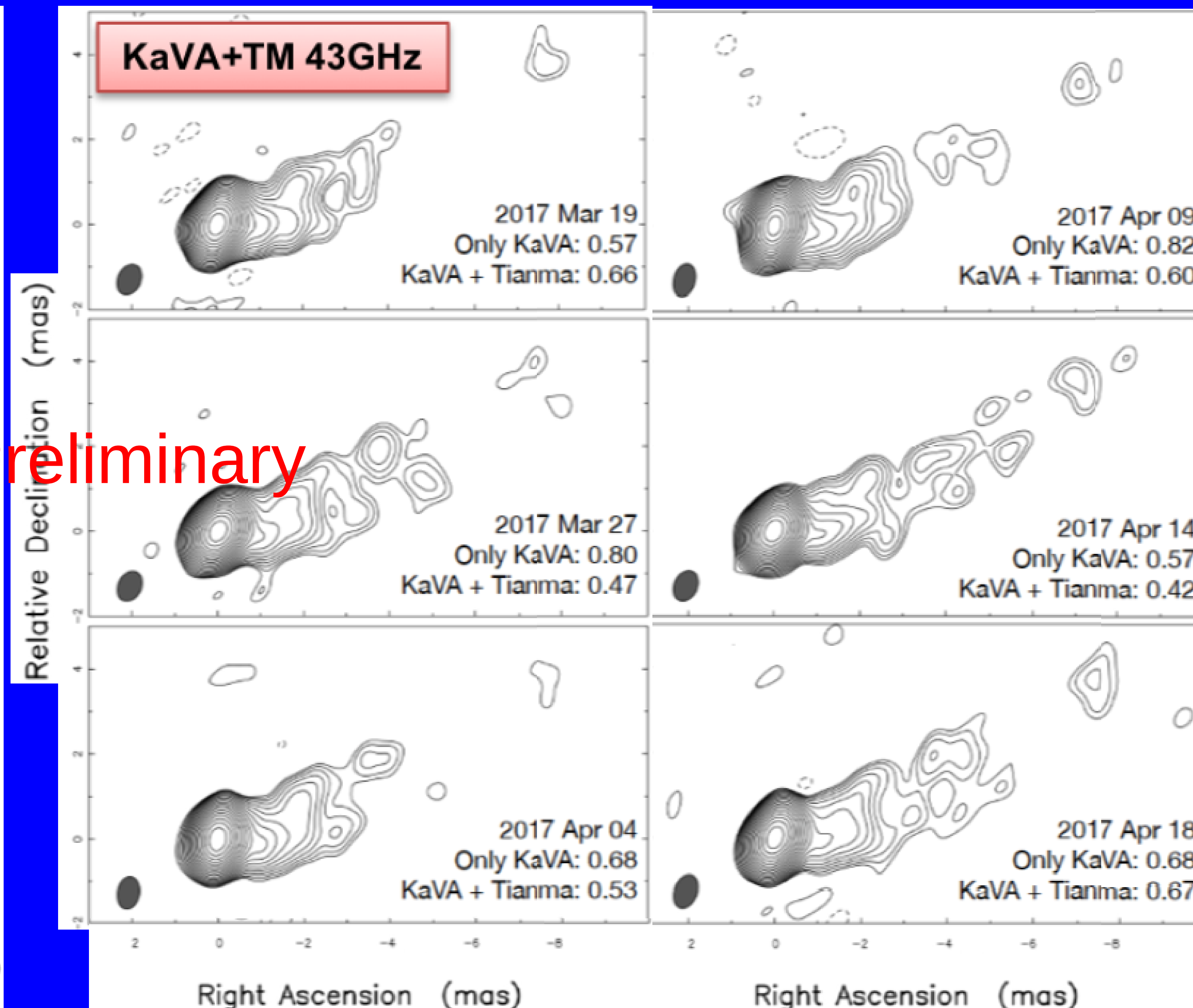


Image capability of EAVN: M87






Tamna 21 m
KASI/KJJVC
Yonsei 21 m
Ulsan 21 m
Mizusawa 20 m
Nanshan 26 m
Tianma 65 m
2018B open use:
first call for proposals
Ishigakijima 20 m
Iriki 20 m
Nobeyama 45 m
Ogasawara 20m
The East-Asian VLBI Network
(Image Credit: Reto Stöckli, NASA Earth Observatory)

https://radio.kasi.re.kr/eavn

East Asia VLBI Network

Main | About EAVN | Activity | Proposal | Status report | Go to KaVA

Welcome to EAVN

EAVN is the international collaborative VLBI array operated by Korea Astronomy and Space Science Institute (KASI), National Astronomical Observatory of Japan (NAOJ), Shanghai Astronomical Observatory (SHAO; China), and Xinjiang Astronomical Observatory (XAO; China)... More

We invite proposals for the open use observations of the KaVA, EAVN. It will provide opportunities of VLBI observations at 22 and 43 GHz for astronomers in the world.

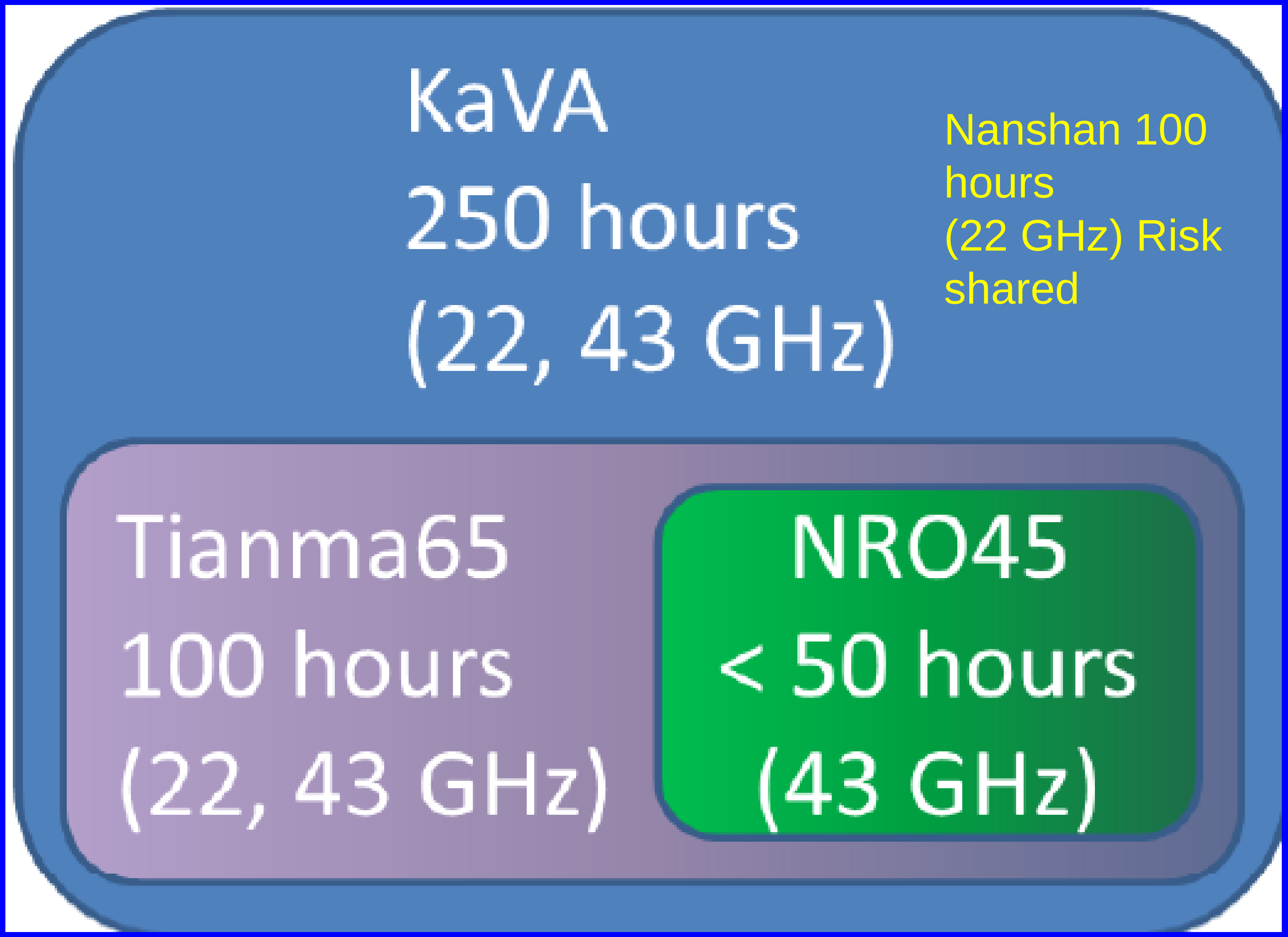
2018B Season KaVA Proposal | 2018B Season EAVN Proposal

Upcoming Meetings

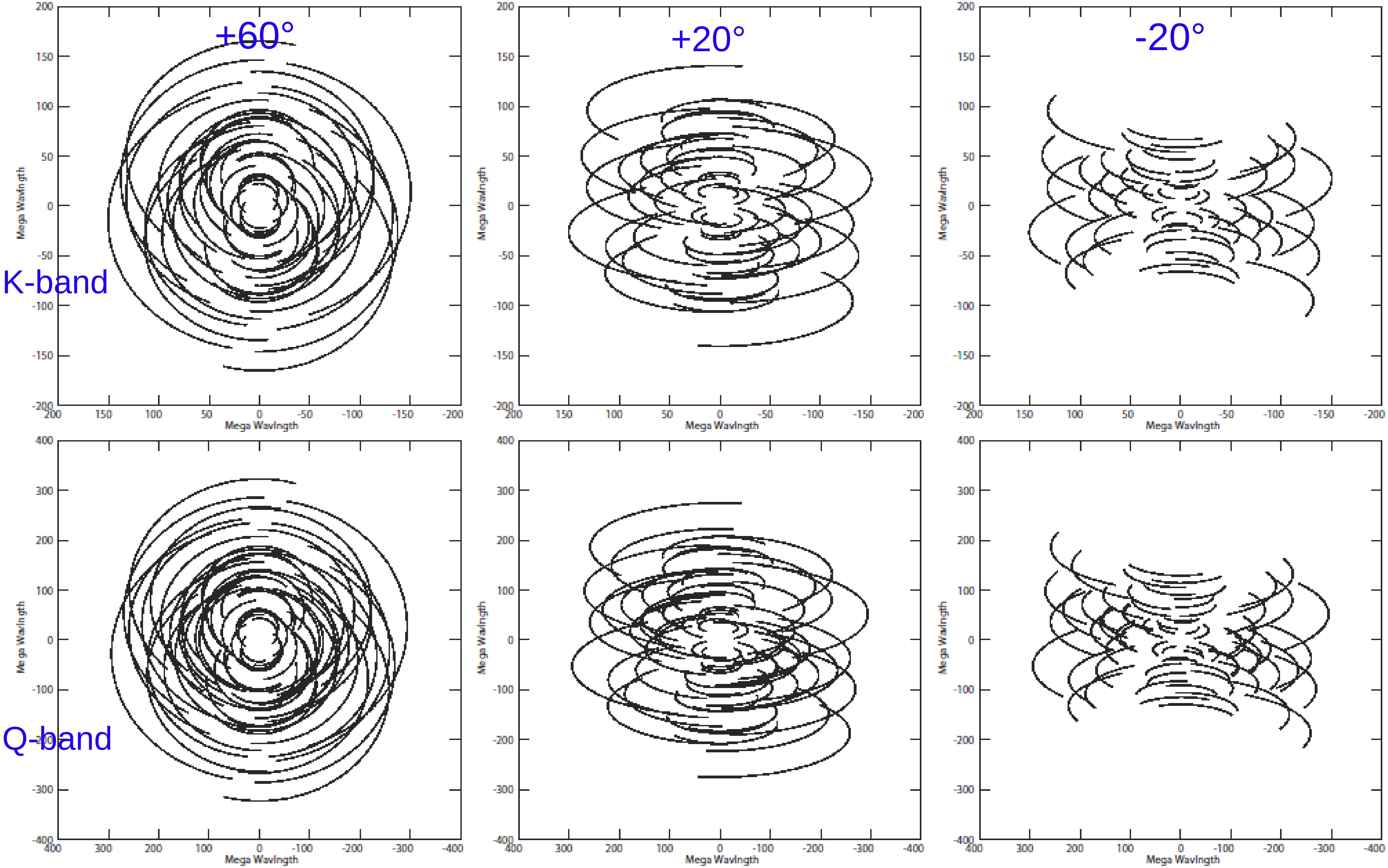
- EAST ASIAN VLBI WORHSHOP 2018 (4-7 September 2018, PyeongChang, Korea)
- 2018 Radio Telesciope User's Meeting

The very long baseline interferometry (VLBI) technique offers angular resolutions superior to any other instruments at other wavelengths, enabling unique science applications of high-resolution imaging of radio sources and high-precision astrometry. The East Asia VLBI Network (EAVN) is a collaborative effort in the East Asian region.

Observation time and Frequency



UV coverage



Comparison of EAVN, EVN, VLBA

	EAVN	VLBA	EVN
No. of Stations	20	10	12
Longest Baseline Length (km)	5,000	8,000	2,000 - 8,000
Effective Aperture @8 GHz (m^2)	9,000	3,700	9,800
Effective Aperture @22 GHz (m^2)	4,900	3,200	4,900
Effective Aperture @43 GHz (m^2)	1,400	2,900	1,800

Future

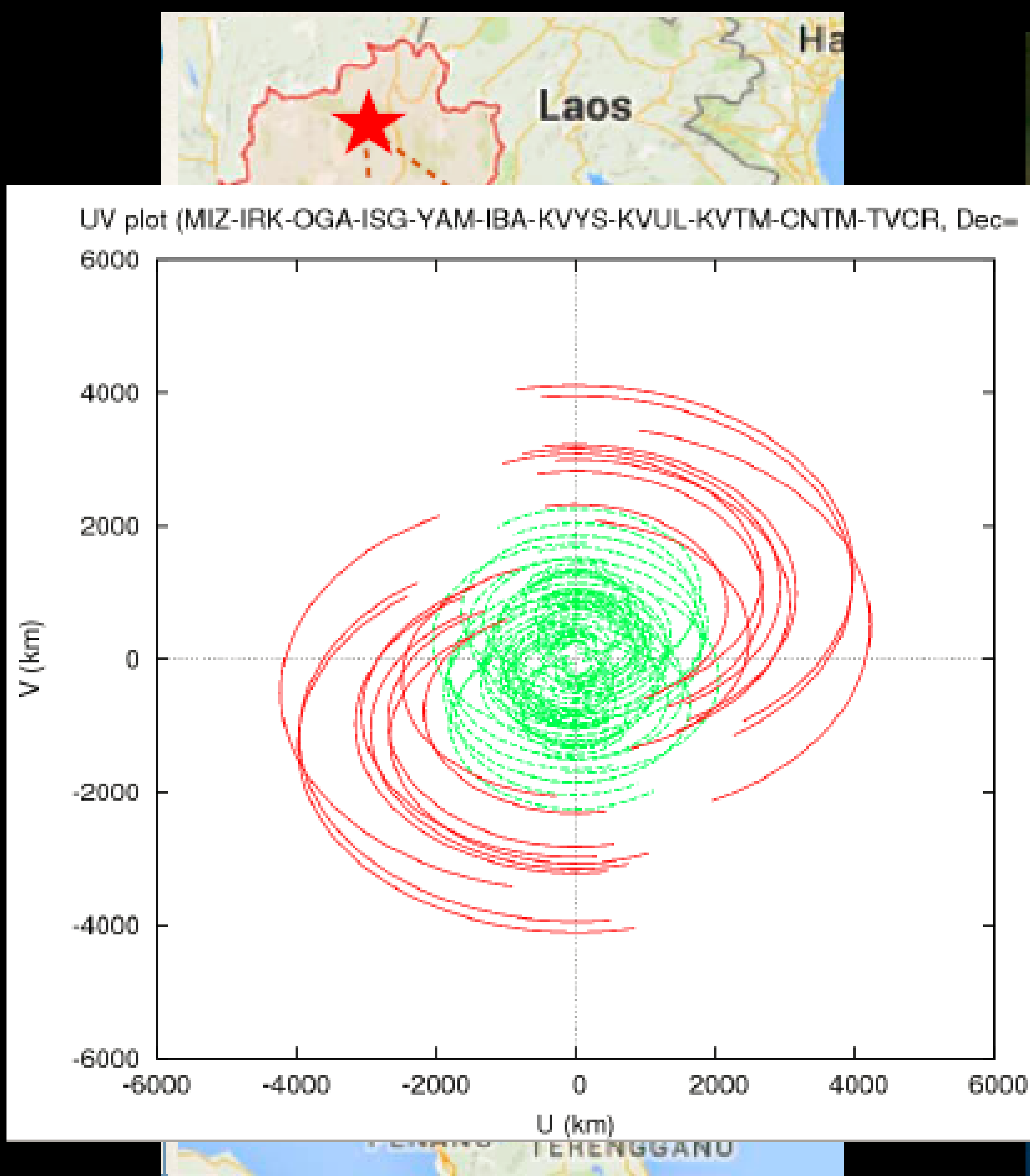
Comparison of SKA, EAVN and other arrays

	EAVN	EAVN +FAST	EAVN+QT,FAST	EVN	VLBA+ GBT+ VLA	Global VLBI (EA/Eu/ US)	SKA-1 (mid)	SKA-2 (mid)
Operating from	2018	2022?	2022?	Operating	Operating	?	2023?	2028??
Max. Baseline (km)	5000	5000	5000	2000-10000	8000	10000	150	3000
Collecting area (m^2)	**15000**	**86000**	**96000**	**20000**	**26000**	61000 ~ 142000	**32600**	**440000**

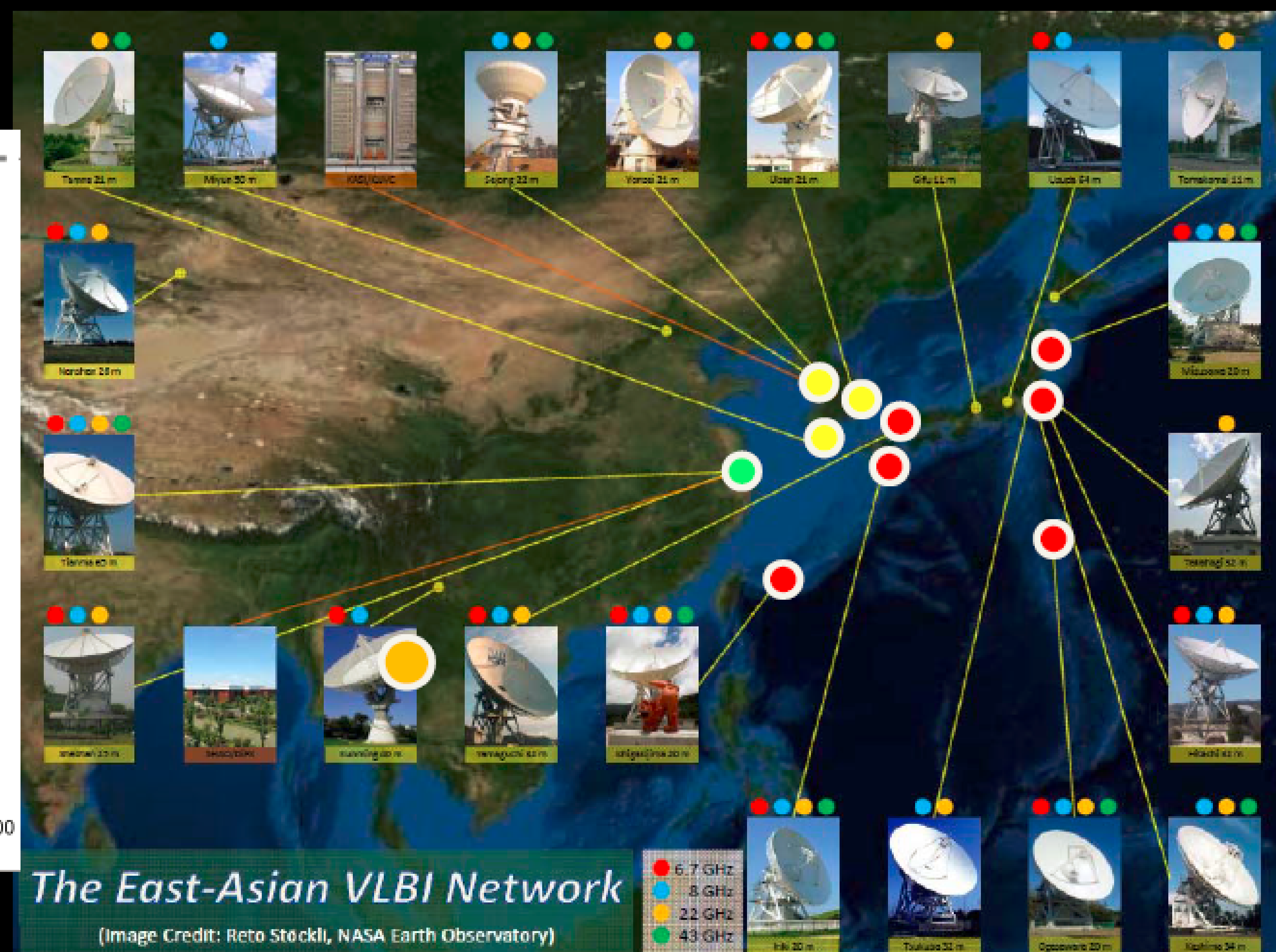
Future

EAVN + TVN

- Baseline doubled, astrometry accuracy doubled



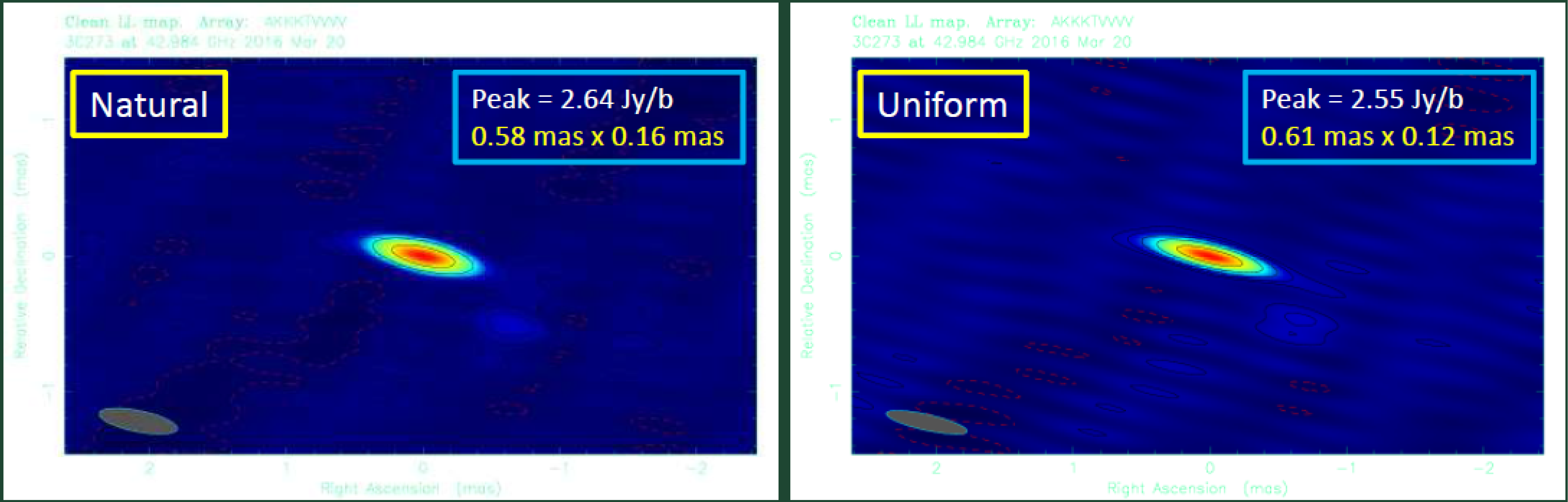
EAVN UV coverage with one of TVN stations



Future

EAVN+LBA

- First 43 GHz image of 3C 273 by EAVN+ATCA on 2016 Mar 20
  - Very high angular resolution (~ 0.1 mas) can be obtained in the north-south direction



(Image courtesy: Dr. Richard Dodson (ICRAR))