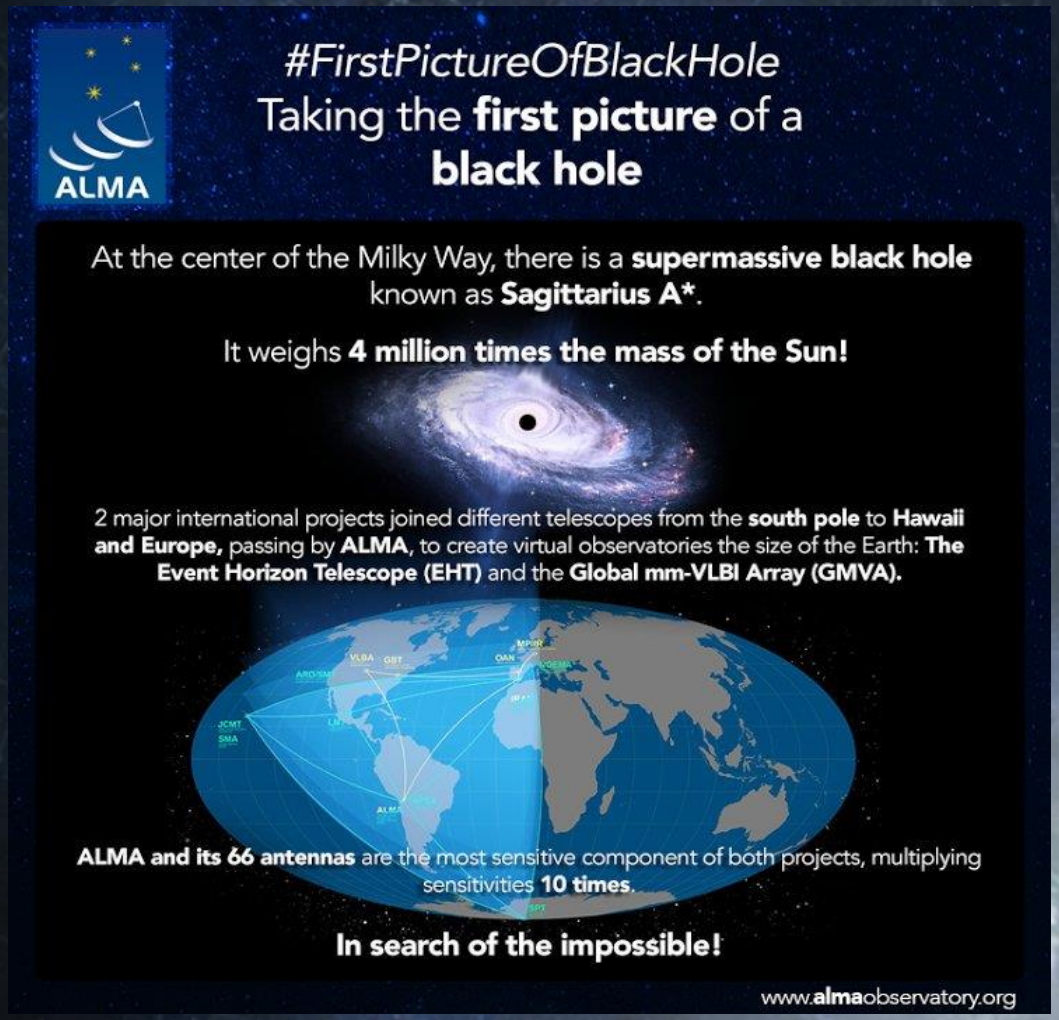
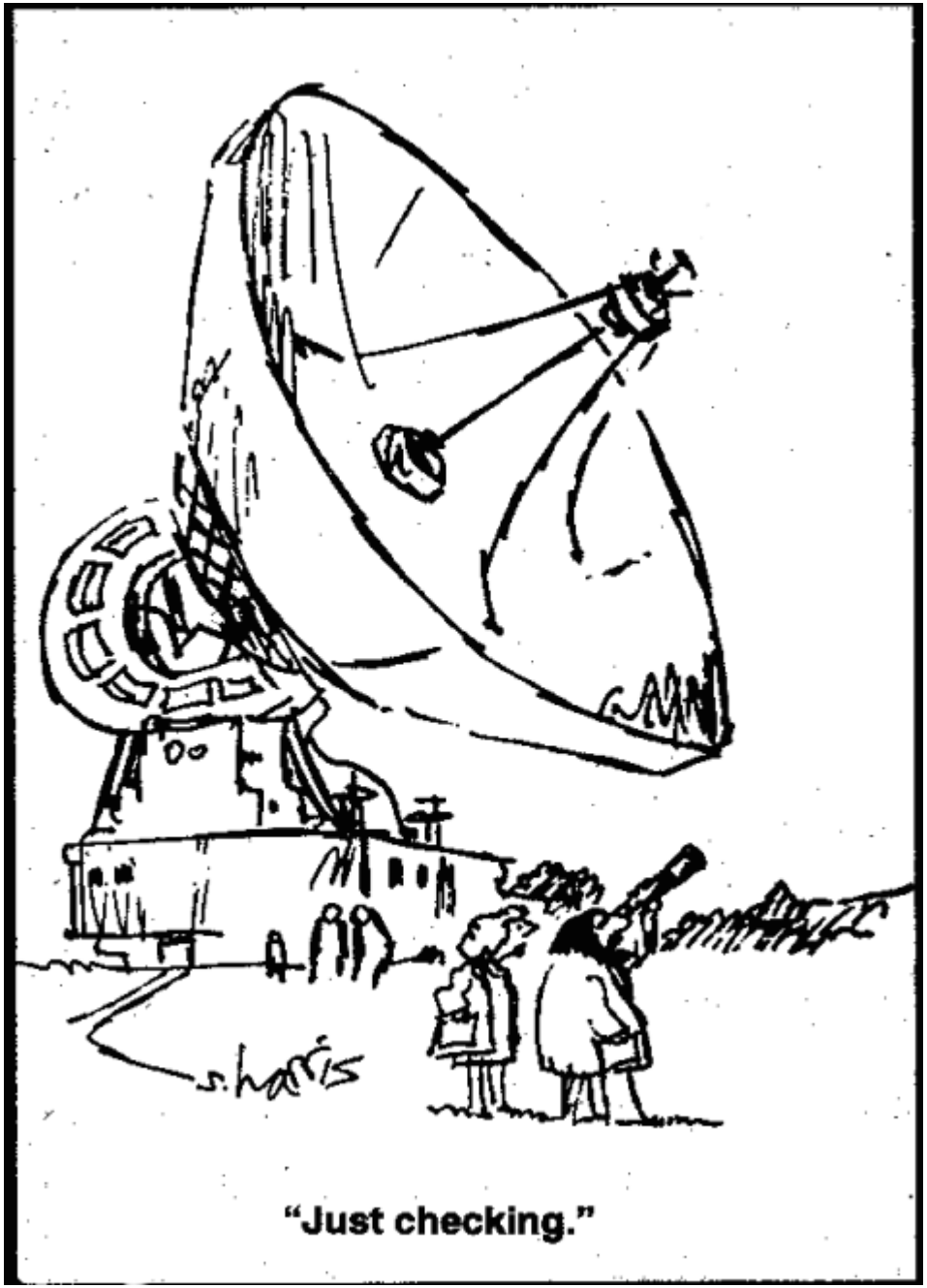
VLBI Observations with ALMA



17 April 2017

Taehyun Jung

Korea Astronomy & Space Science Institute



"Just checking."

Telescope Resolution

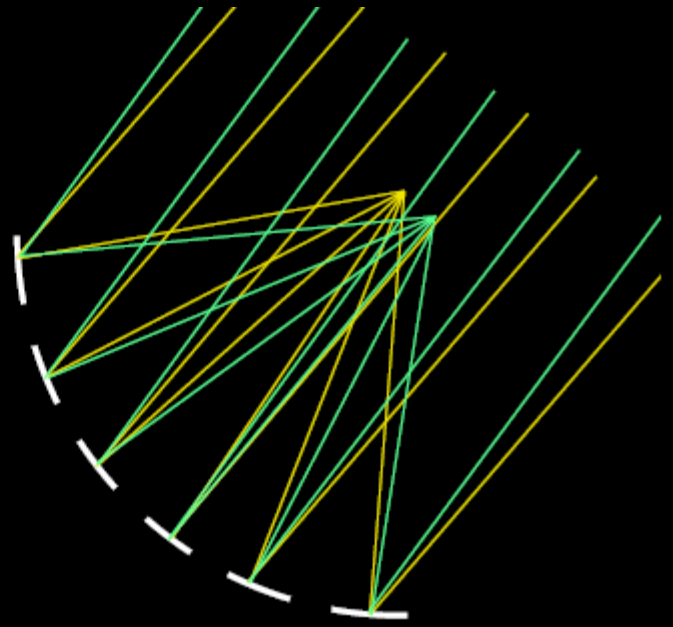
$$\theta_{rad} \approx \frac{\lambda}{D} \qquad \theta_{arcsec} \approx \frac{2\lambda_{cm}}{D_{km}}$$

분해능 차이
108배!!

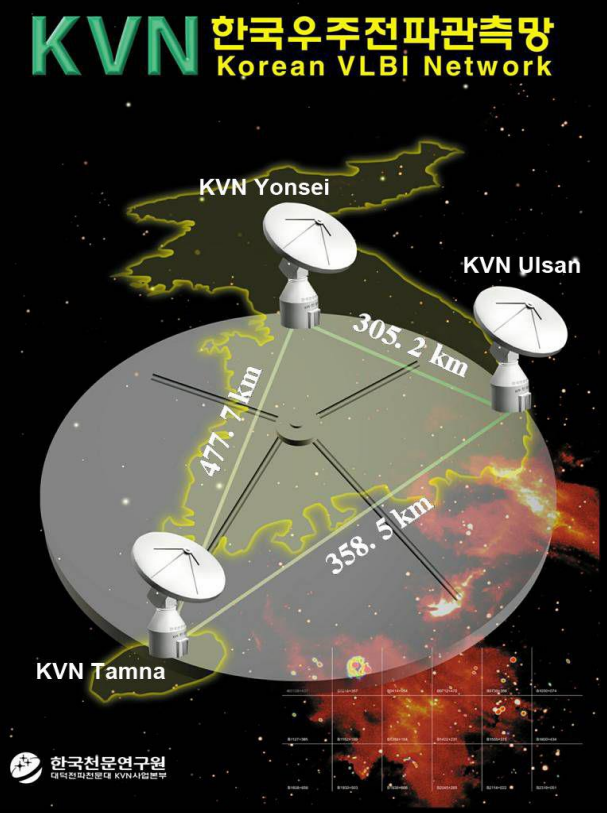
Amateur optical telescope
- Diameter : 10 cm
- Wavelength : 570 nm
- λ/D ~ 0.0000057

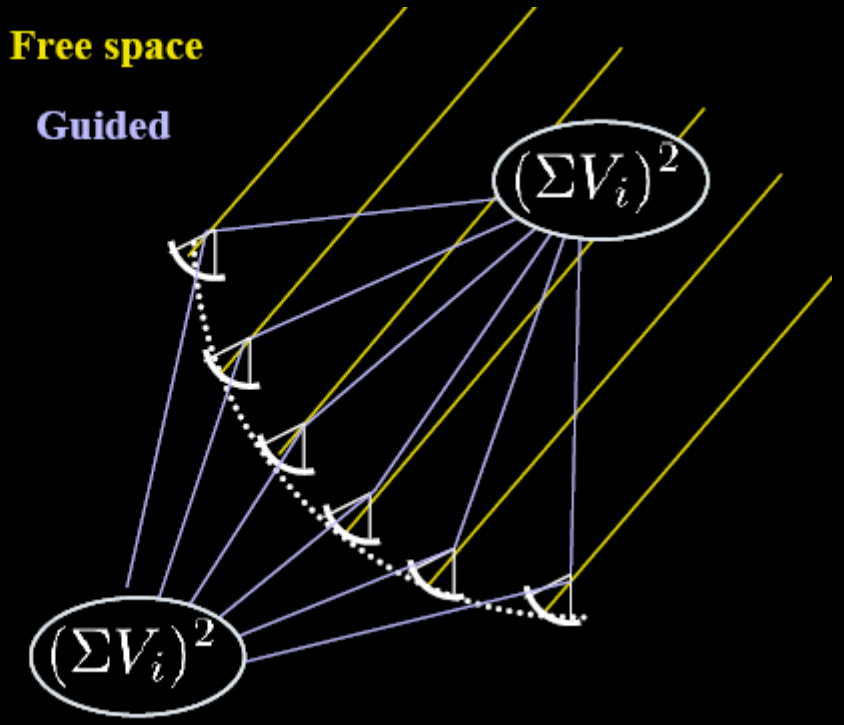
Radio Telescope
- Diameter : 21 m
- Wavelength : 21 cm
- λ/D ~ 0.01

Single Dish

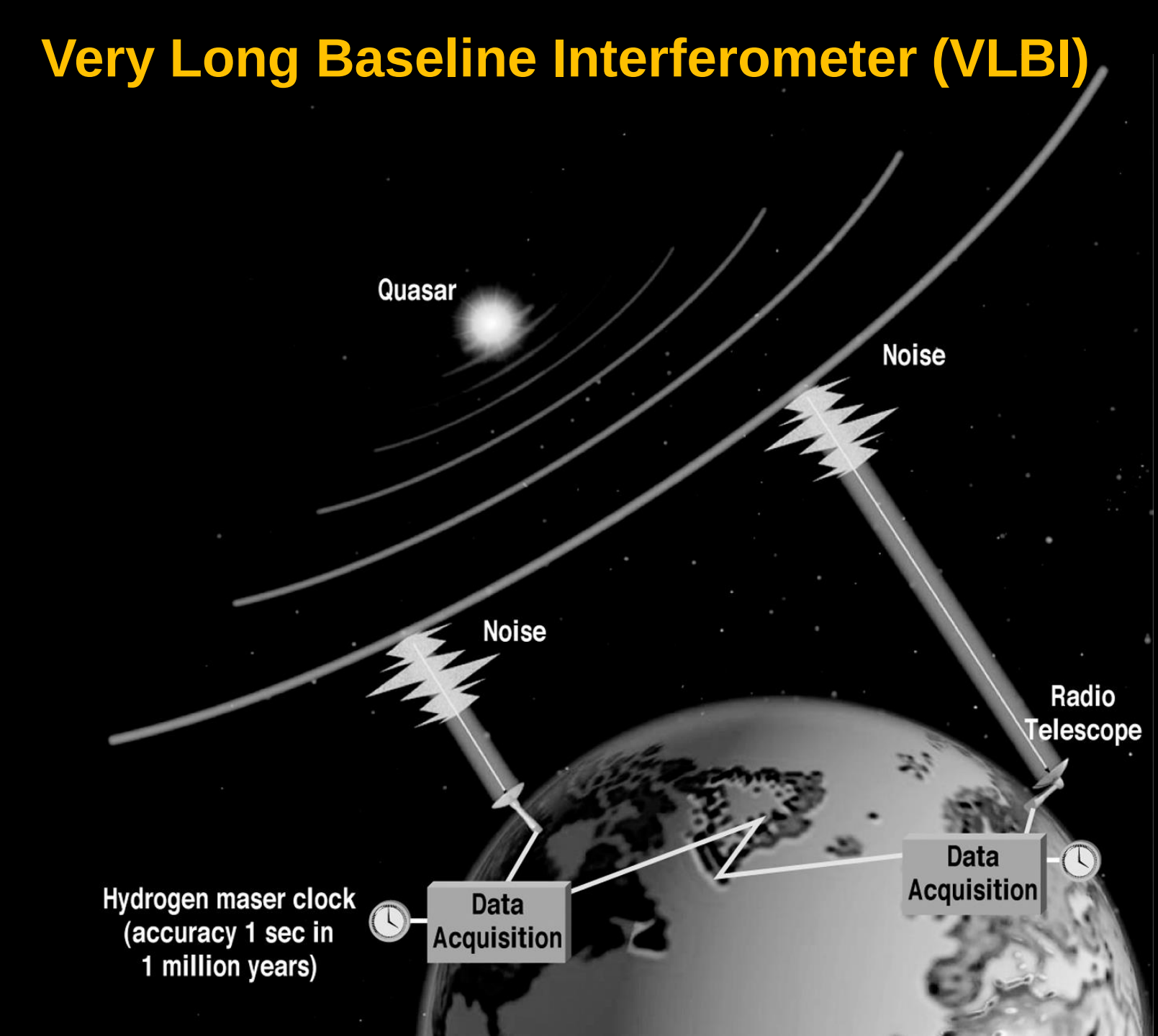


Interferometer

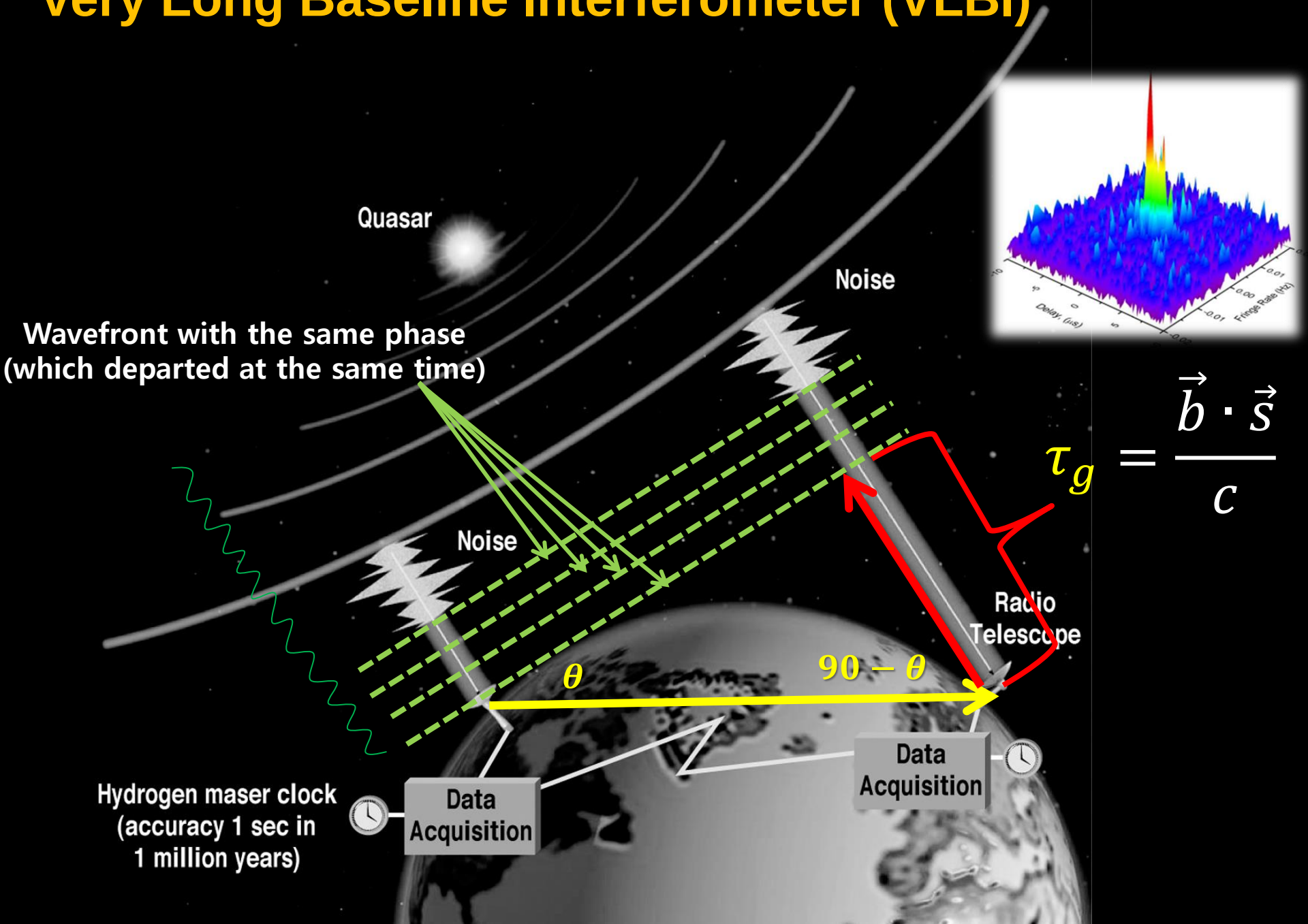




Very Long Baseline Interferometer (VLBI)

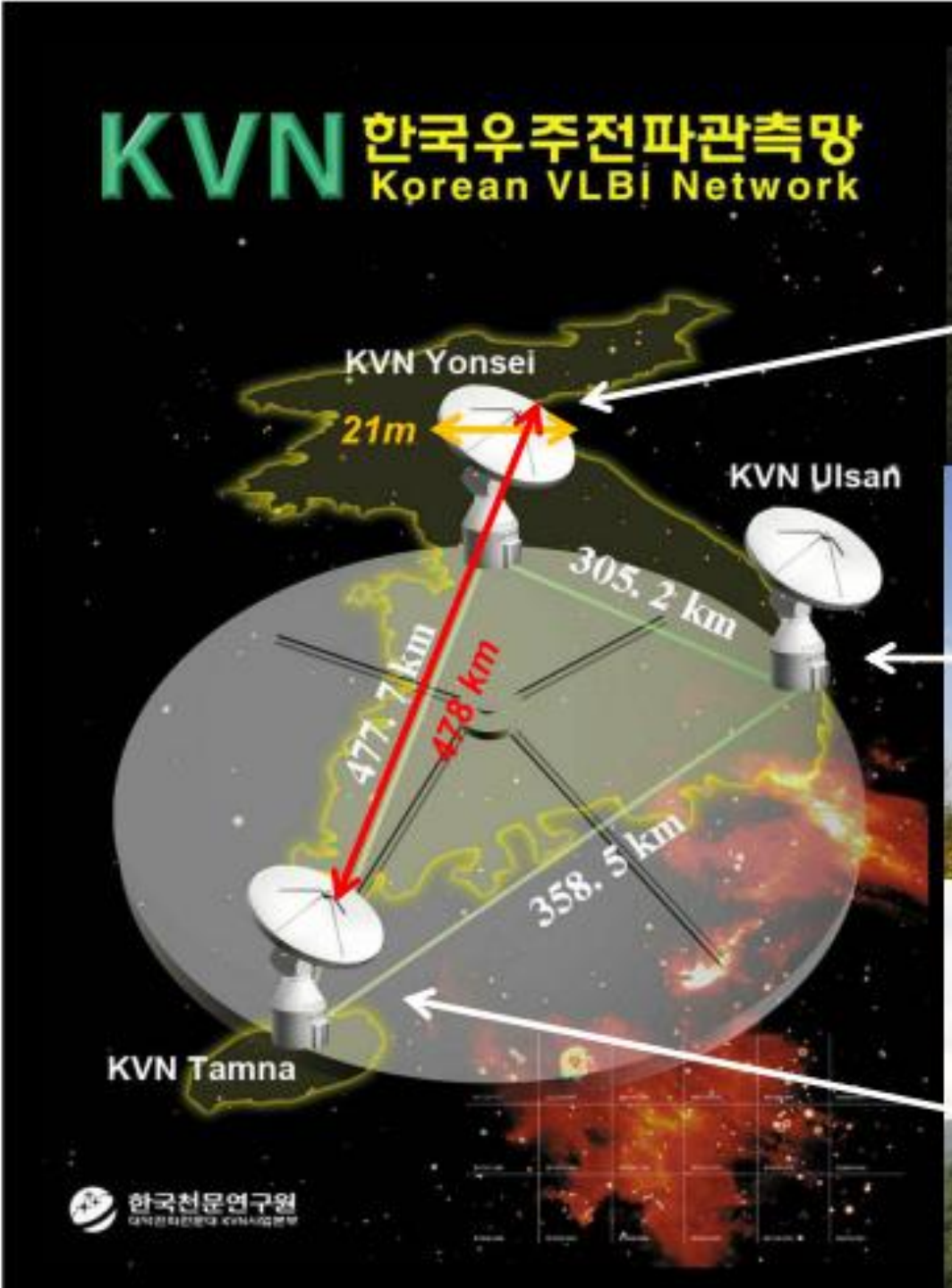


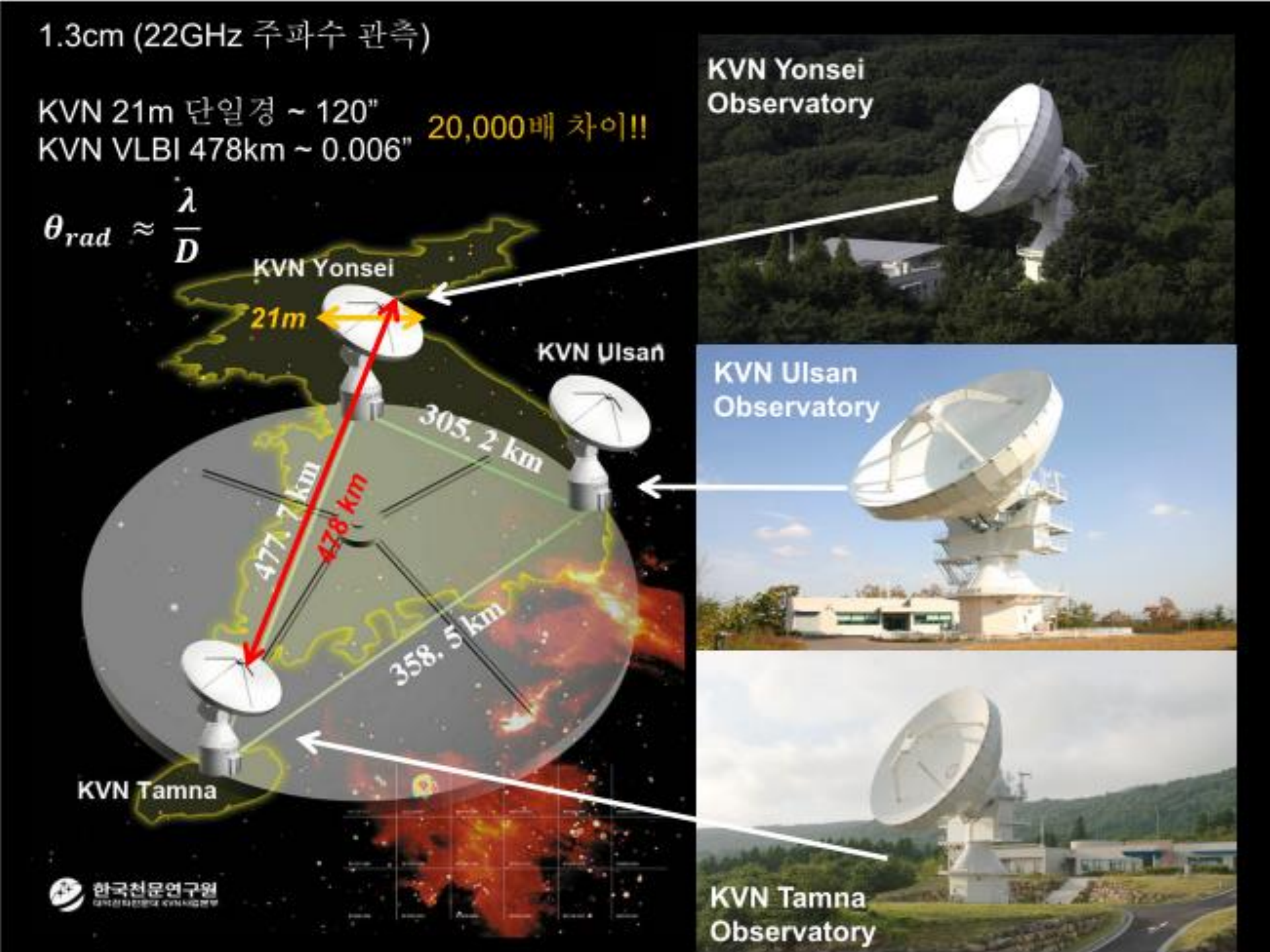
Very Long Baseline Interferometer (VLBI)



$$\tau_g = \frac{\vec{b} \cdot \vec{s}}{c}$$

KVN 한국우주전파관측망
Korean VLBI Network

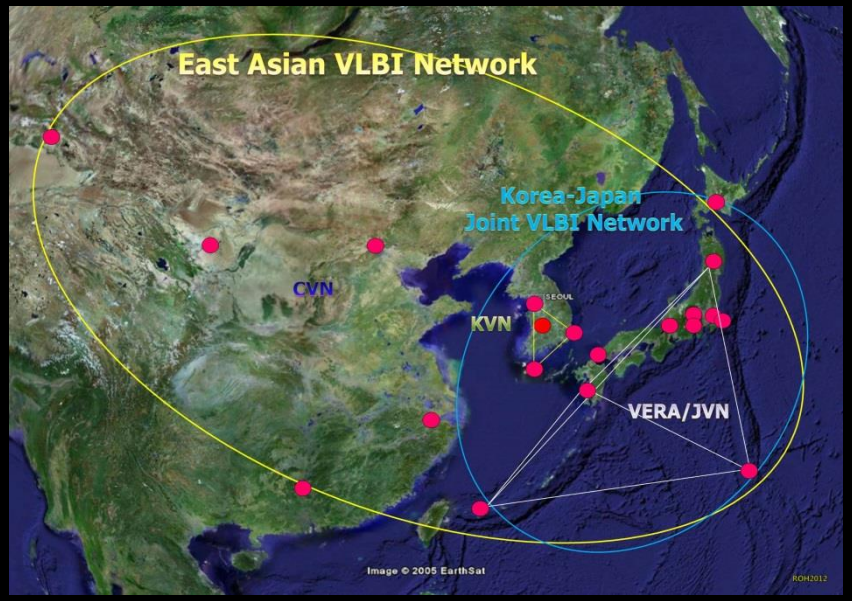


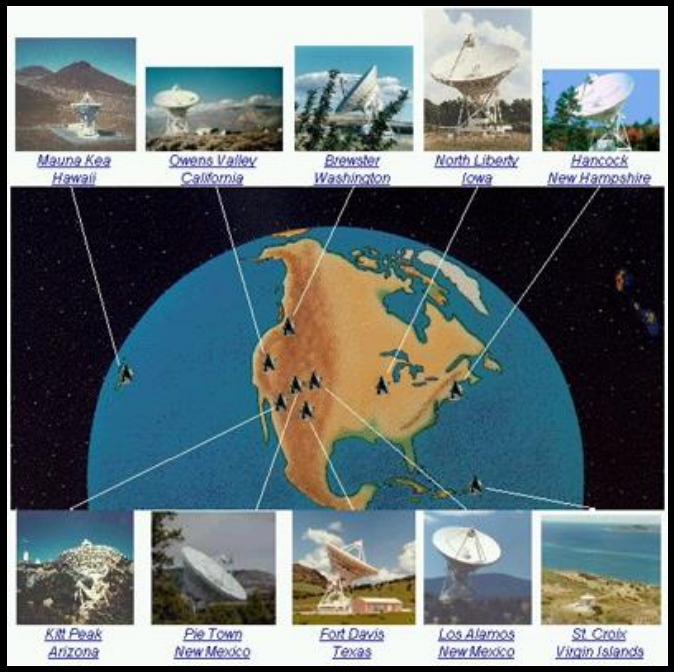

1.3cm (22GHz 주파수 관측)
KVN 21m 단일경 ~ 120"
KVN VLBI 478km ~ 0.006"
20,000배 차이!!
$\theta_{rad} \approx \frac{\lambda}{D}$
KVN Yonsei
21m
KVN Ulsan
KVN Tamna
305. 2 km
477. 7 km
478 km
358. 5 km
KVN Yonsei Observatory
KVN Ulsan Observatory
KVN Tamna Observatory
한국천문연구원

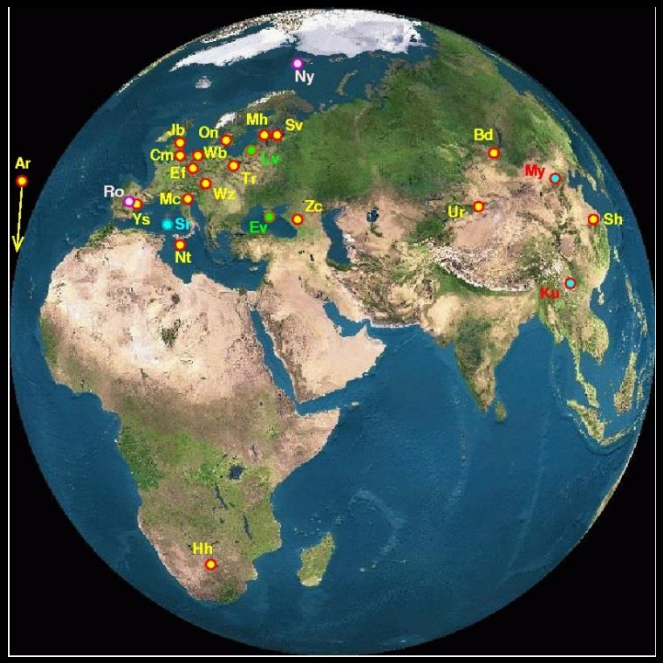
전파간섭계 Connected interferometers

전파간섭계

Very Long Baseline Interferometry





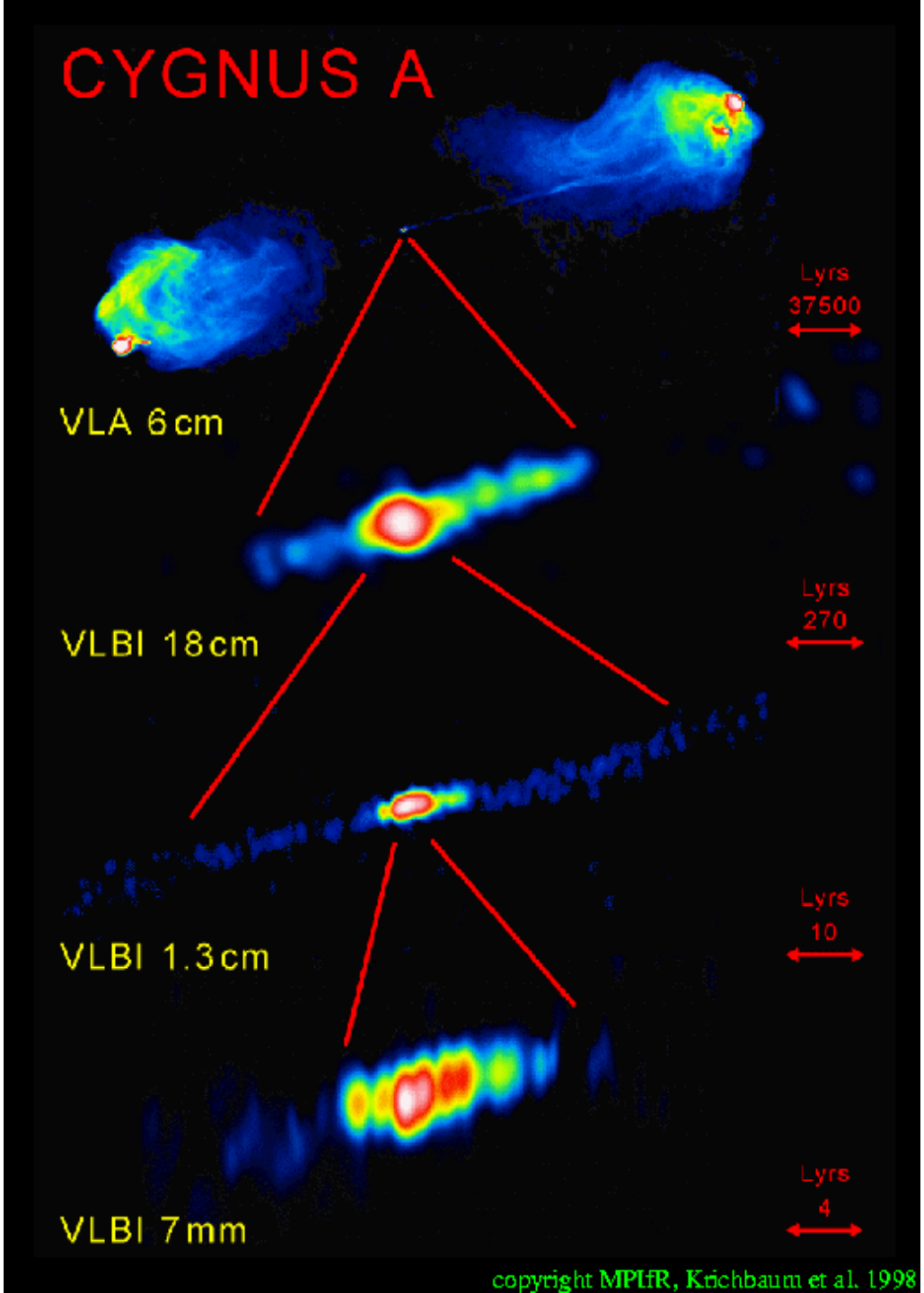


The Global VLBI – Array

T. Jung

East Asia VLBI Network: EAVN

An, Sohn, Imai (2018)



$$\theta_{rad} \approx \frac{\lambda}{D}$$

Russia's RadioAstron space observatory

The RadioAstron observatory with an unprecedented high resolution capability will make it possible to observe remote objects in space

This is the first Russian orbital radio telescope

It will study:

- Galaxy nuclei
- Black holes
- Neutron stars
- Interstellar plasma clouds
- The Earth's gravitational field
- And many other objects and phenomena in the Universe

Ordered by: **Federal Space Agency**

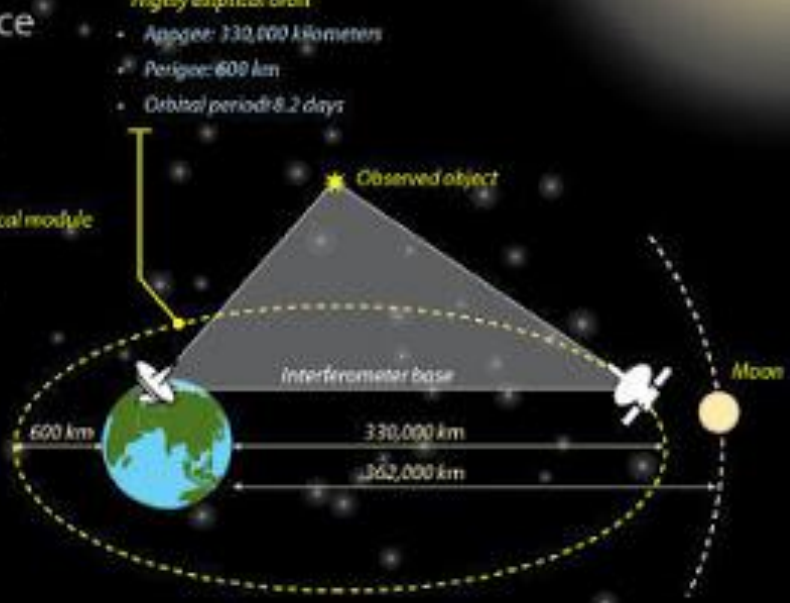
Chief contractor: **Lavochkin Research and Production Association**

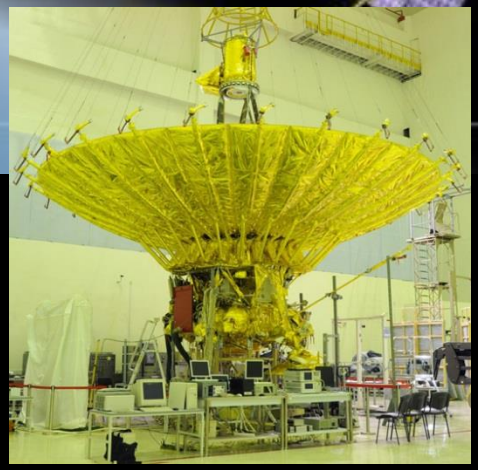
Scientific equipment developed by: Astro Space Center of the Russian Academy of Sciences' Lebedev Physics Institute

The RadioAstron observatory was launched on July 18, 2011.

Active service life: At least five years

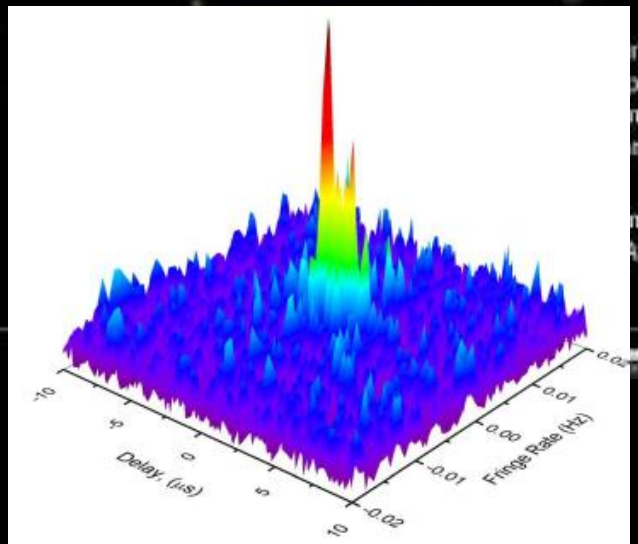
RIANOVOSTI © 2011





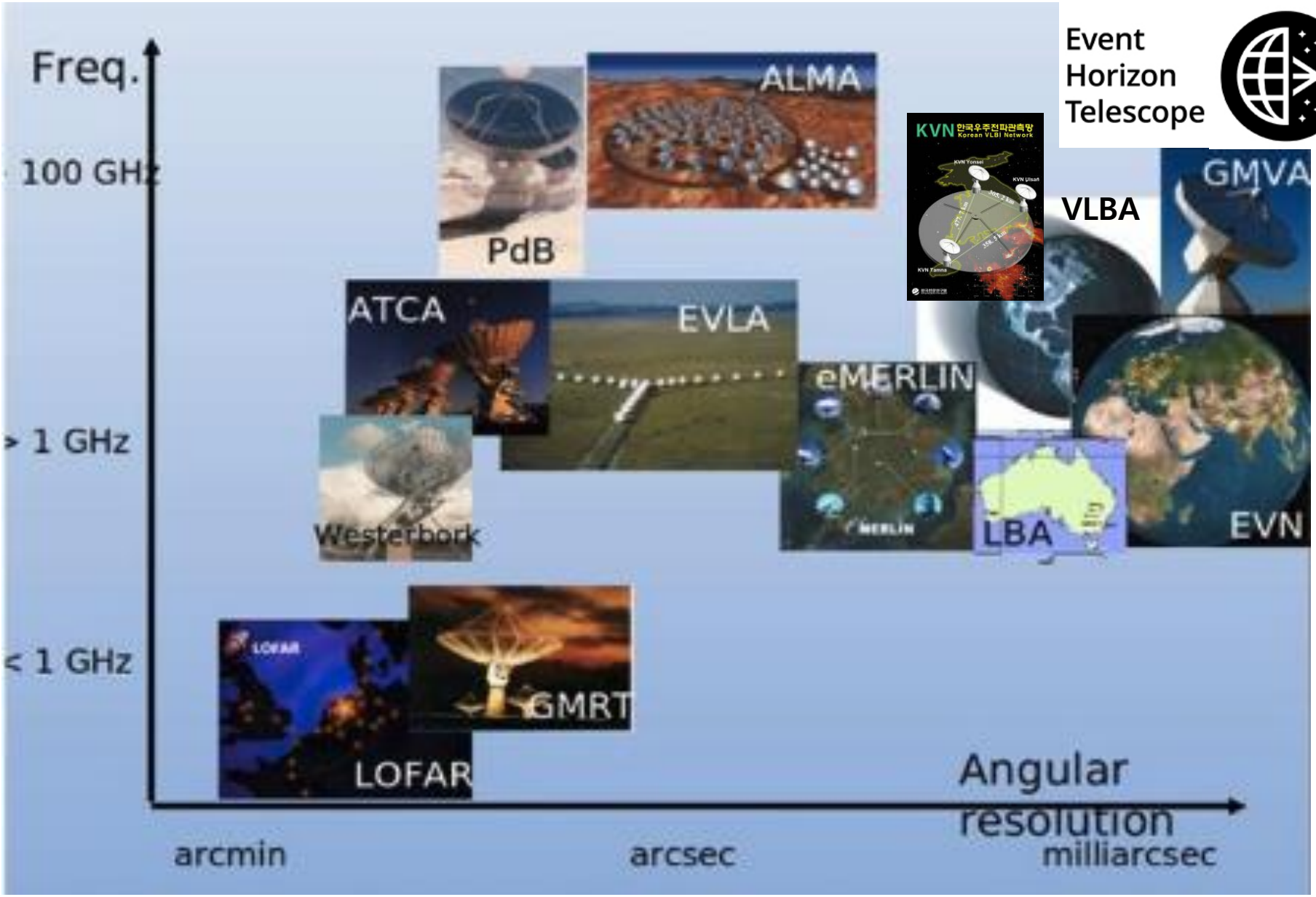
The Highest Angular Resolution Ever !!
World Record

~ 10 μas (0.000 000 028 deg)



NGC 4258 Extragalactic maser
λ = 1.35 cm, Radioastron-Green Bank, B_L=19.5xED
Resolution: 11 μas!

Radio Interferometers: Frequency & Resolutions

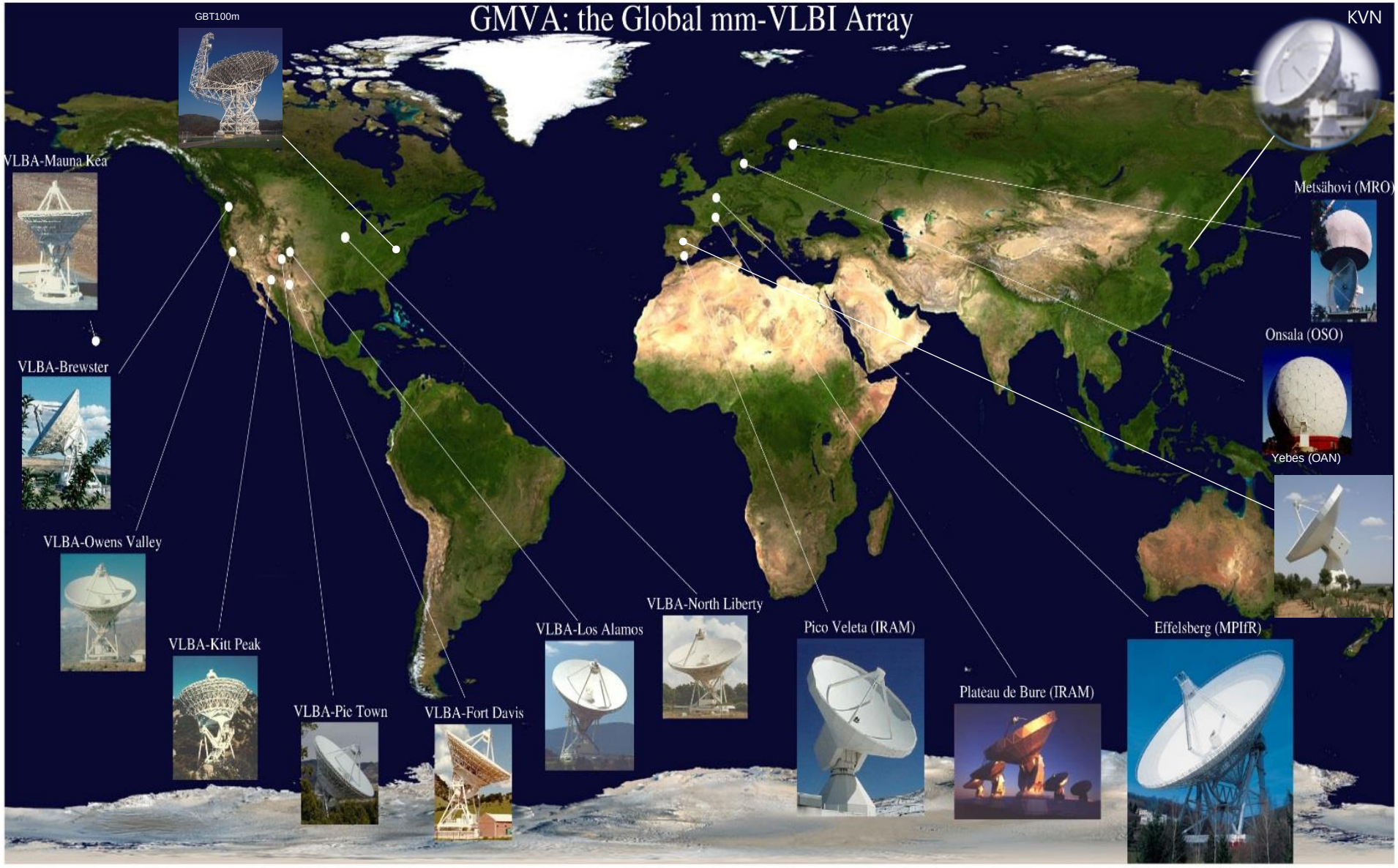


(Credit: Savolainen. T.)

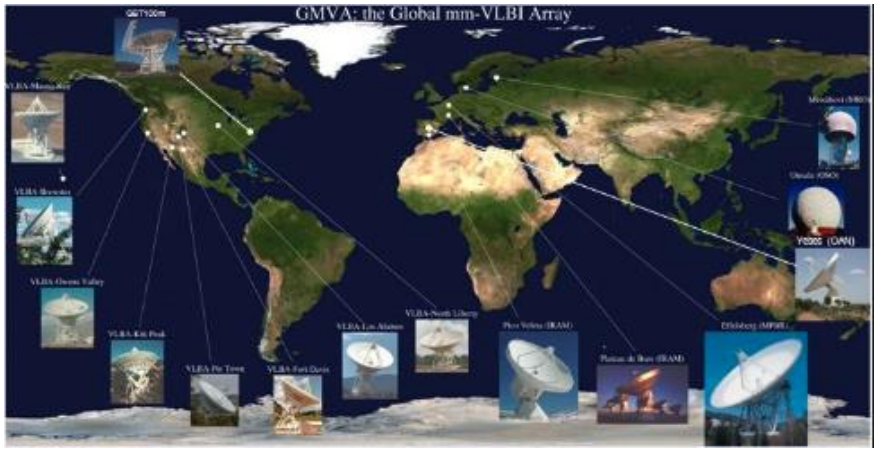
GMVA: Global Millimeter VLBI Array

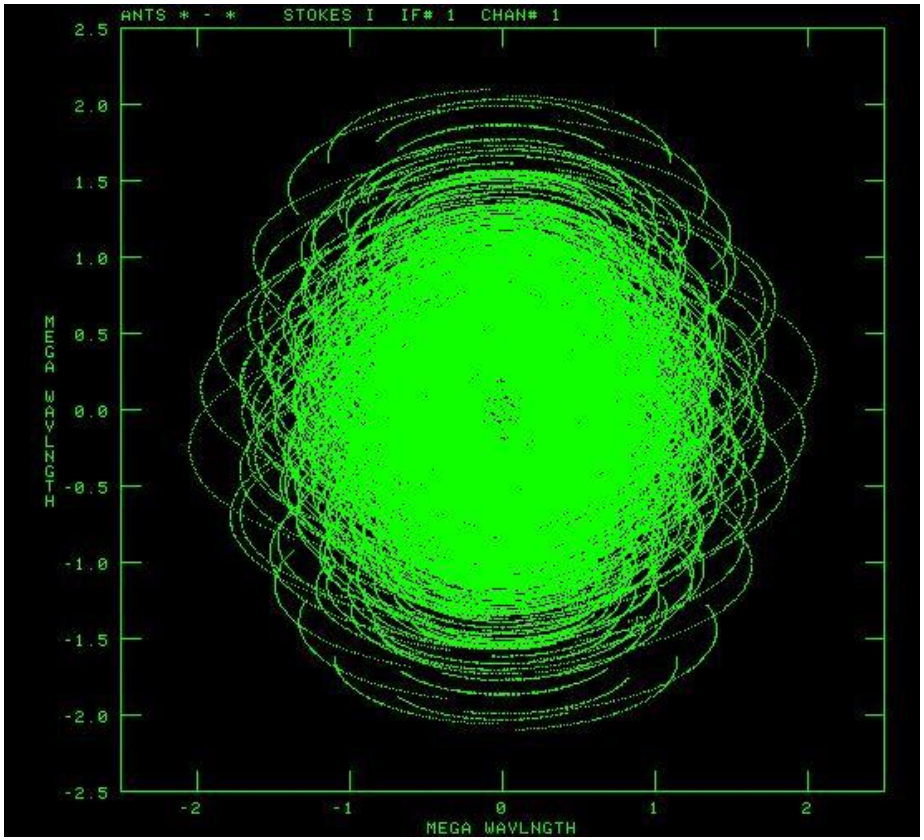
Target Frequency: 86GHz (3.5mm)

(Credit: T. Krichbaum)



ALMA vs GMVA





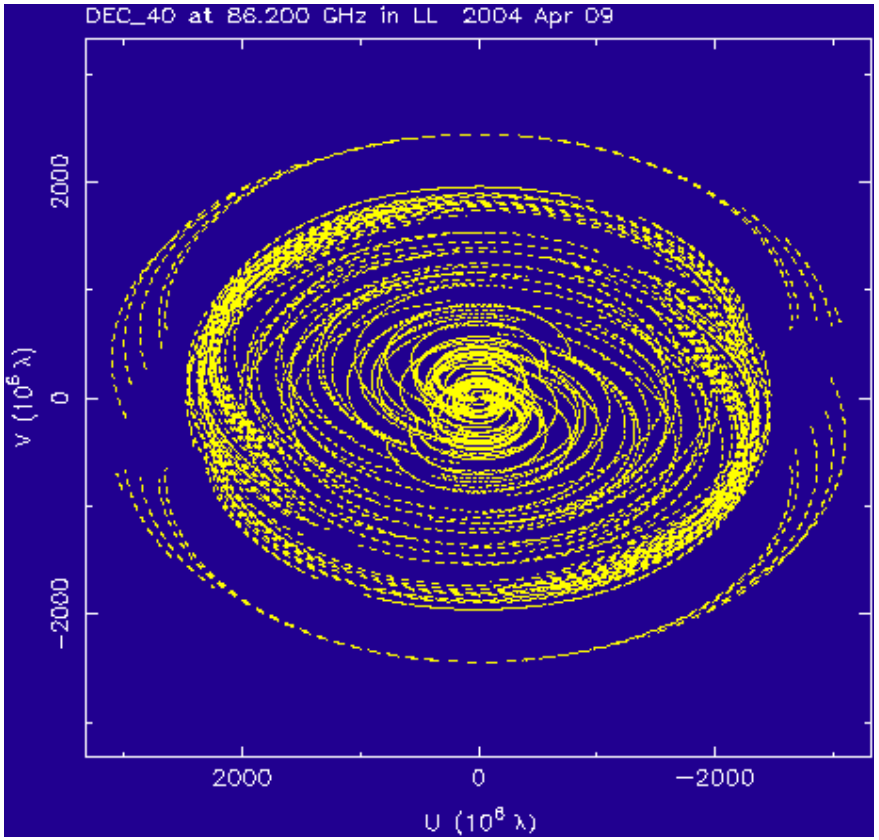
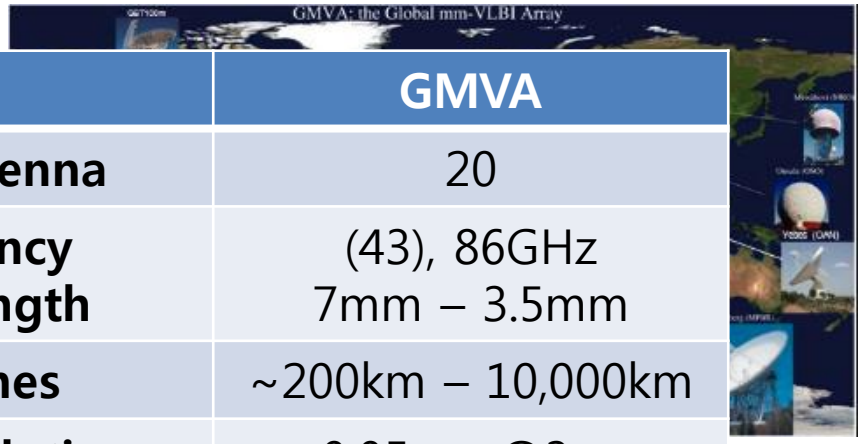
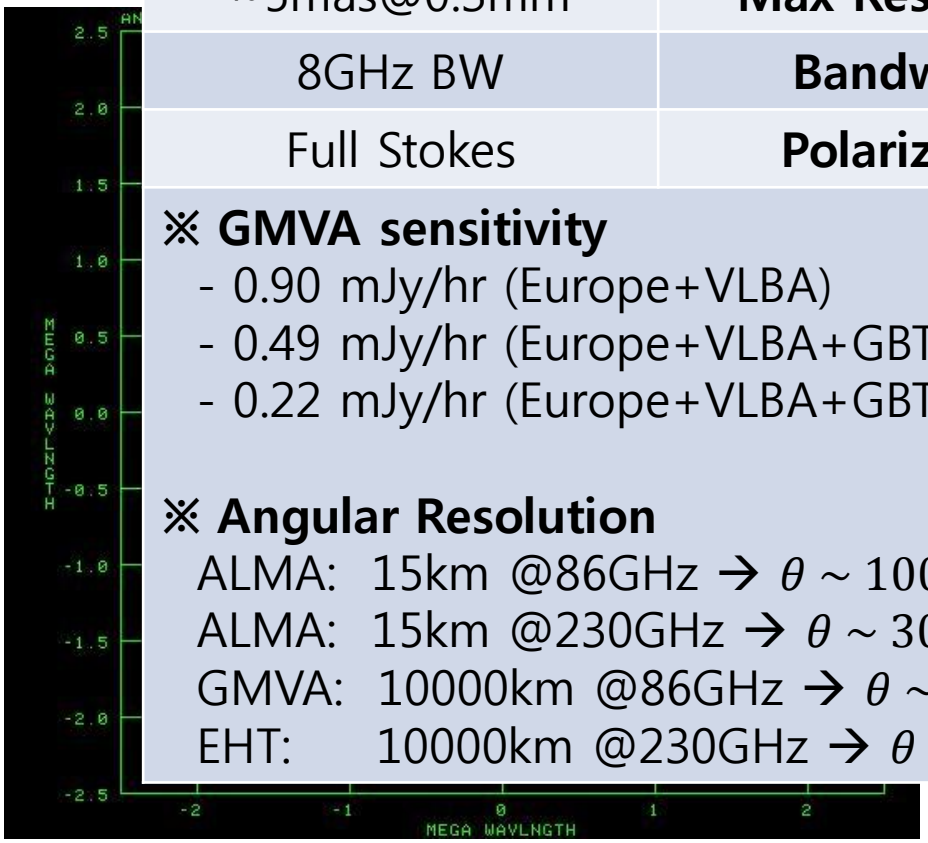


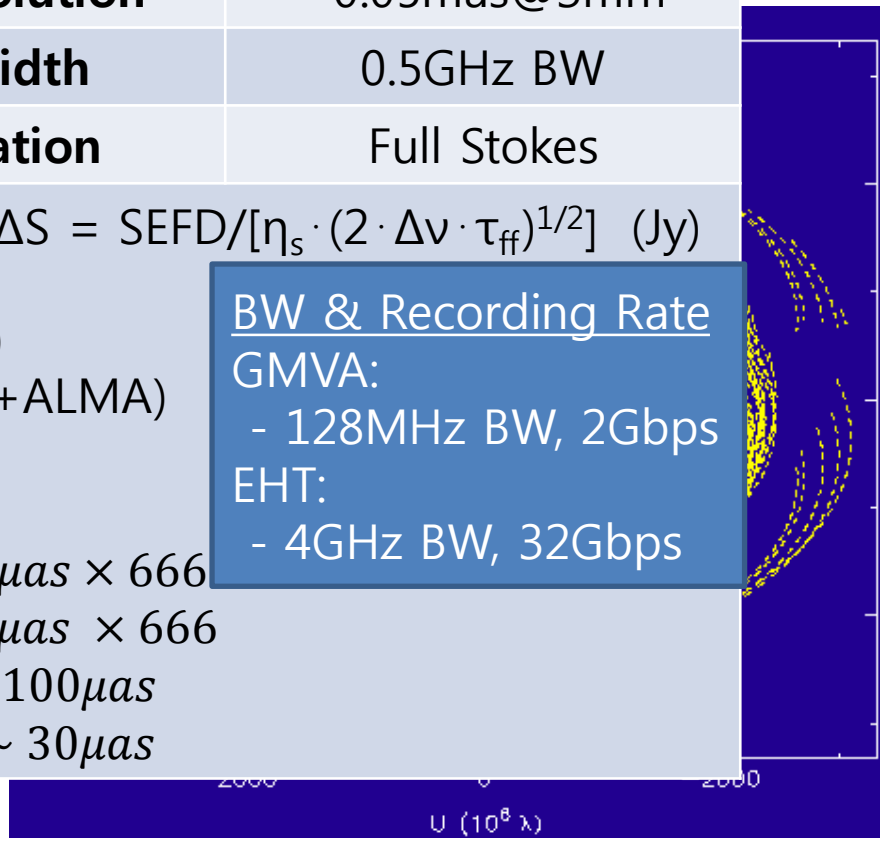
image tacken from the GMVA homepage

ALMA vs GMVA



ALMA	vs	GMVA
66	**# of Antenna**	20
35 – 950GHz 1cm-0.3mm	**Frequency** **Wavelength**	(43), 86GHz 7mm – 3.5mm
15m - 16km	**Baselines**	~200km – 10,000km
~5mas@0.3mm	**Max Resolution**	~0.05mas@3mm
8GHz BW	**Bandwidth**	0.5GHz BW
Full Stokes	**Polarization**	Full Stokes





※ GMVA sensitivity

$\Delta S = SEFD/[\eta_s \cdot (2 \cdot \Delta\nu \cdot \tau_{ff})^{1/2}]$ (Jy)

- 0.90 mJy/hr (Europe+VLBA)
- 0.49 mJy/hr (Europe+VLBA+GBT)
- 0.22 mJy/hr (Europe+VLBA+GBT+ALMA)

※ Angular Resolution

ALMA: 15km @86GHz → $\theta \sim 100\mu as \times 666$

ALMA: 15km @230GHz → $\theta \sim 30\mu as \times 666$

GMVA: 10000km @86GHz → $\theta \sim 100\mu as$

EHT: 10000km @230GHz → $\theta \sim 30\mu as$

BW & Recording Rate

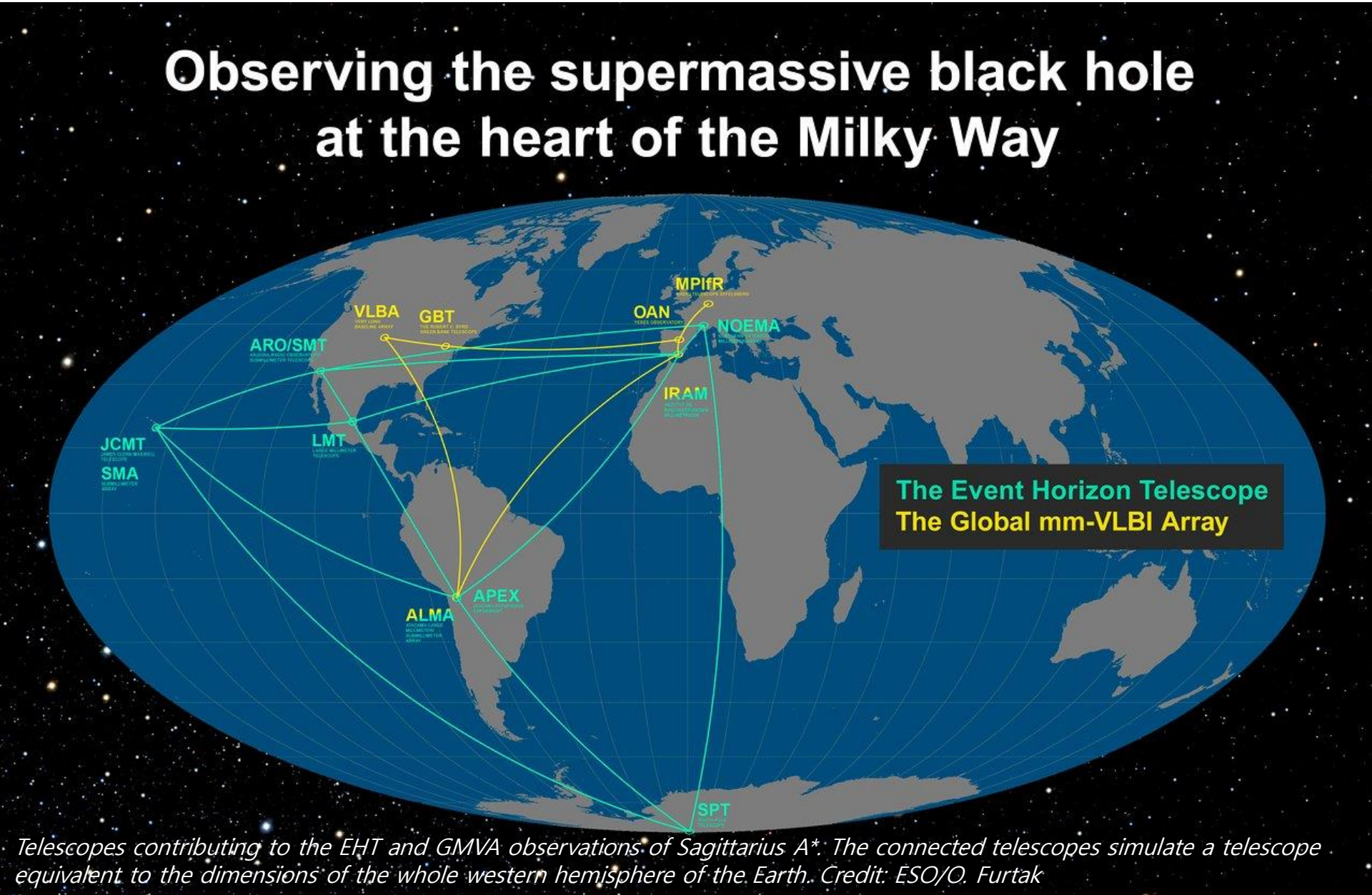
GMVA:

- 128MHz BW, 2Gbps

EHT:

- 4GHz BW, 32Gbps

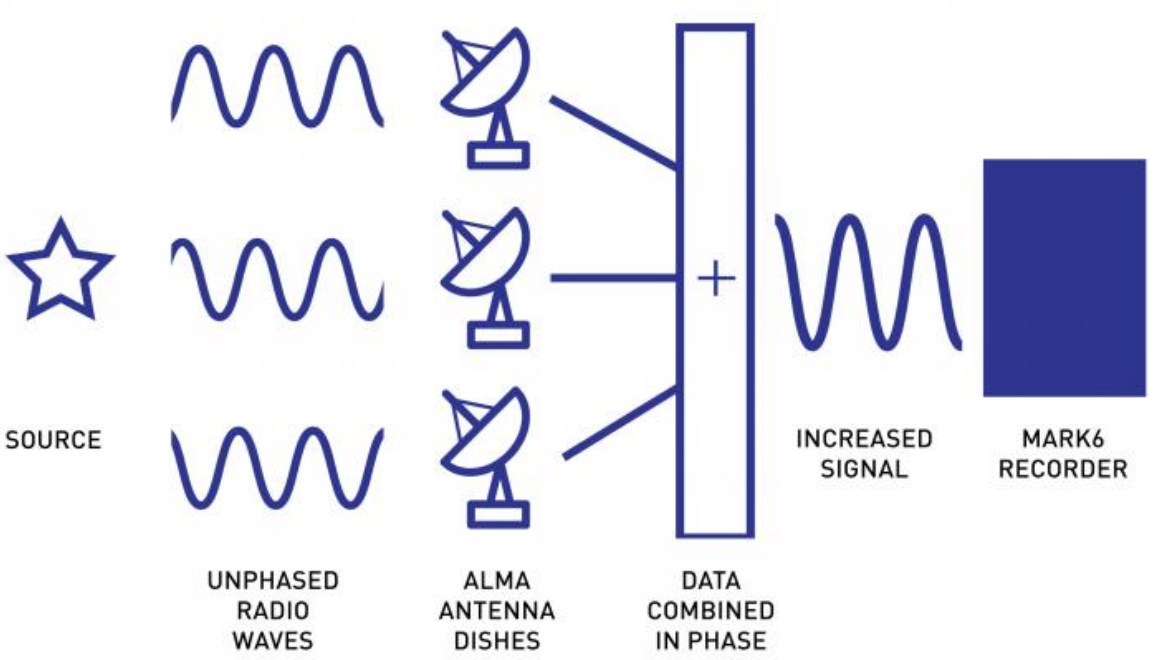
mm-VLBI (EHT/GMVA) with ALMA

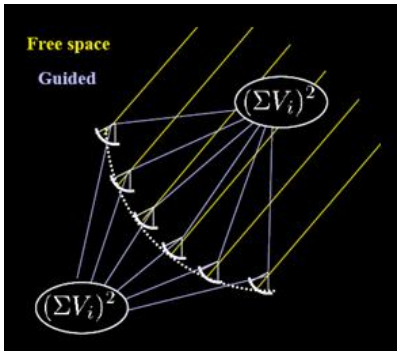


Telescopes contributing to the EHT and GMVA observations of Sagittarius A. The connected telescopes simulate a telescope equivalent to the dimensions of the whole western hemisphere of the Earth. Credit: ESO/O. Furtak*

Phasing ALMA for VLBI

- ALMA Phasing Project (APP) (2011~2016)
  - Phasing-up all ALMA telescopes for (sub)mm-VLBI as one single VLBI station
  - Large increase in Sensitivity (by x10) → improve image fidelity e.g., 64x12m → 96m eff. aperture
  - Increase resolution (by x2)





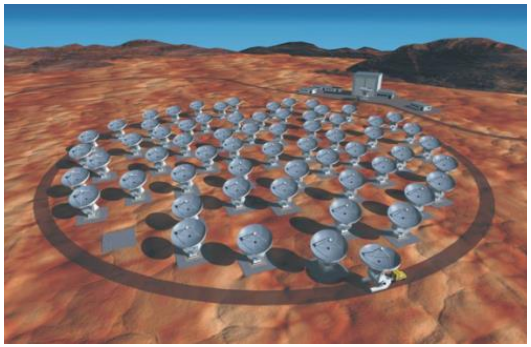
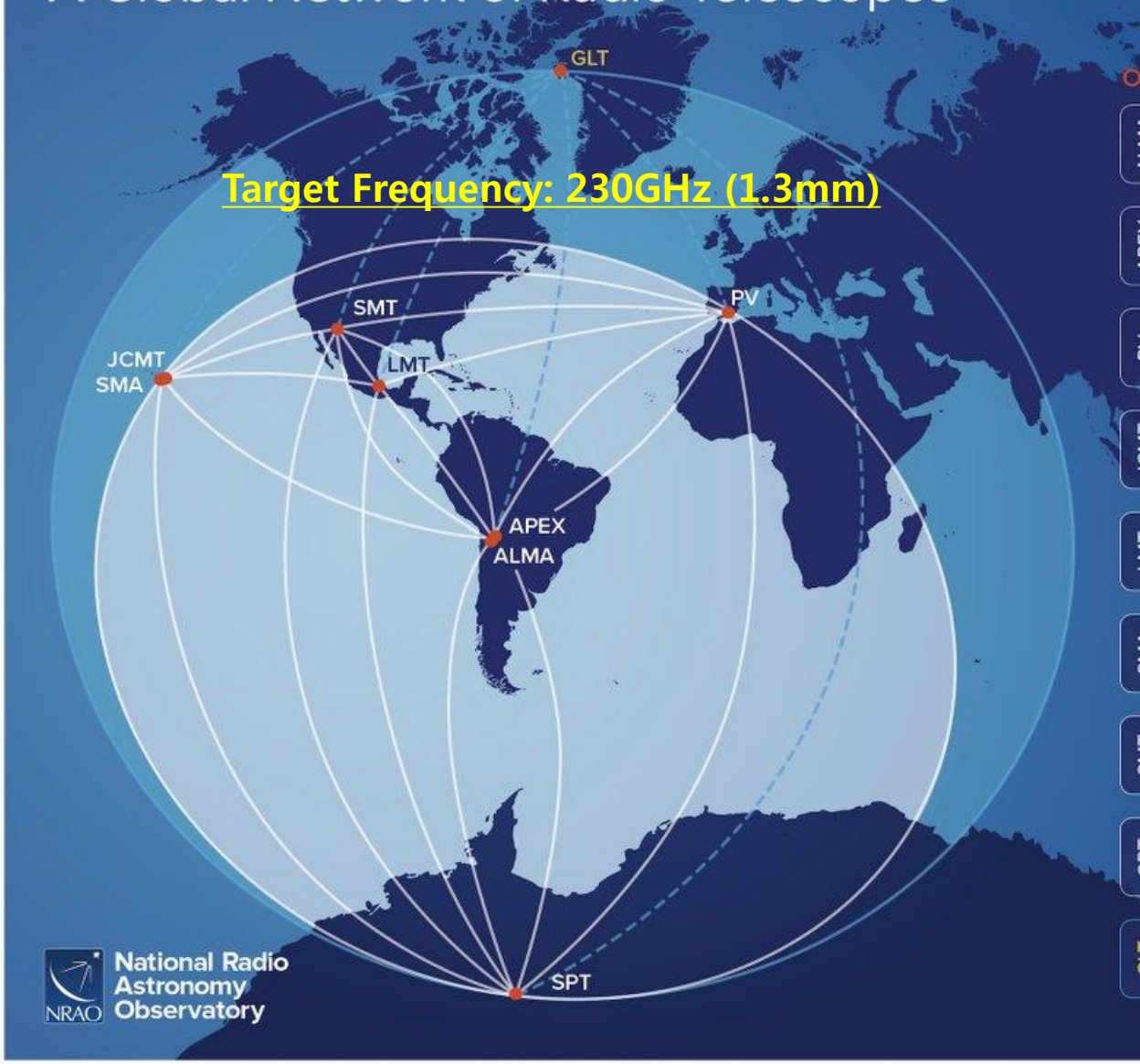


Image courtesy of MIT Haystack Observatory

Event Horizon Telescope

A Global Network of Radio Telescopes

Event Horizon Telescope



Observatories

ALMA	Atacama Large Millimeter/ submillimeter Array	CHAJNANTOR PLATEAU, CHILE
APEX	Atacama Pathfinder EXperiment	CHAJNANTOR PLATEAU, CHILE
PV	IRAM 30-meter Telescope	PICO VELETA, SPAIN
JCMT	James Clerk Maxwell Telescope	MAUNA KEA, HAWAII
LMT	Large Millimeter Telescope	SIERRA NEGRA, MEXICO
SMA	Submillimeter Array	MAUNA KEA, HAWAII
SMT	Submillimeter Telescope	MOUNT GRAHAM, ARIZONA
SPT	South Pole Telescope	SOUTH POLE STATION
GLT	Greenland Telescope Project	THULE AIR FORCE BASE

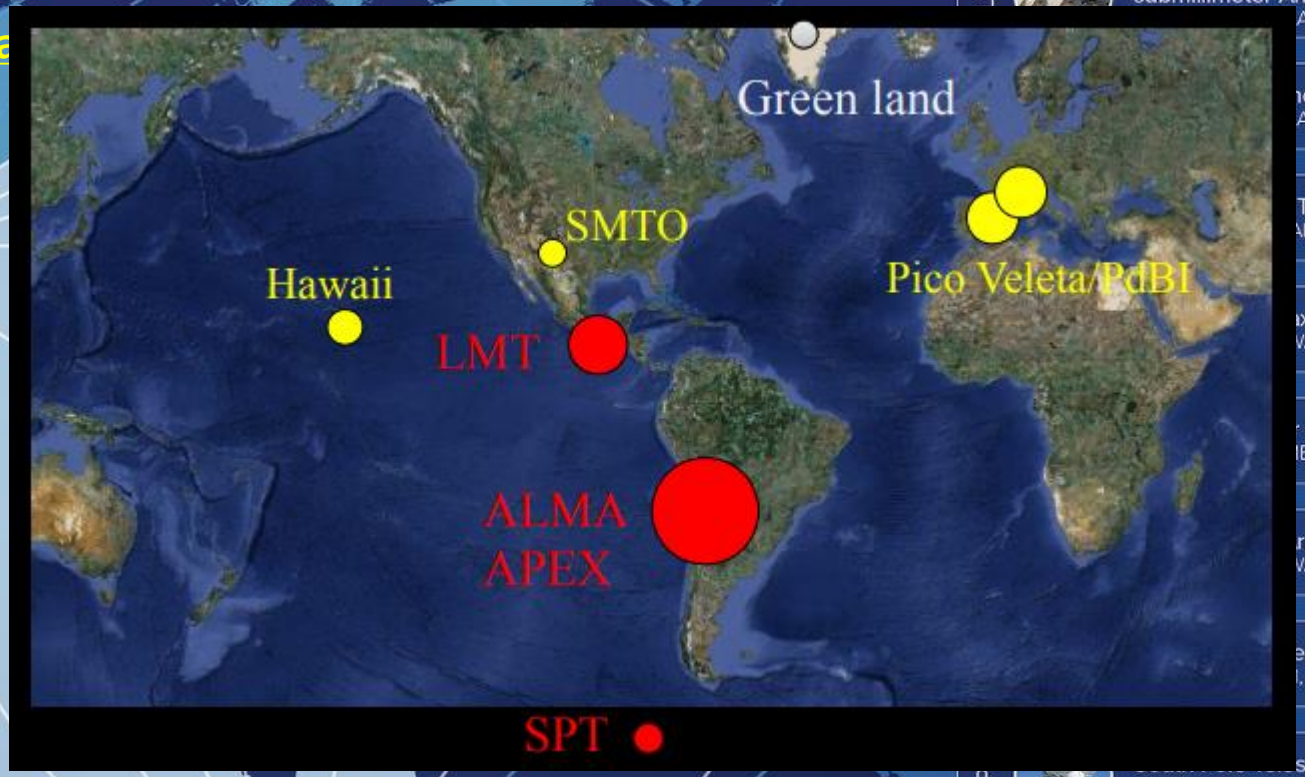
2017

2018

Event Horizon Telescope

A Global Network of Radio Telescopes

Event Horizon Telescope



GLT

JCMT
SMA

SPT

Observatories

Atacama Large Millimeter/ submillimeter Array
ATEAU, CHILE

nder EXperiment
ATEAU, CHILE

Telescope
AIN

xwell Telescope
VAII

Telescope
IEXICO

rray
VAII

elescope
, ARIZONA

scope
SOUTH POLE STATION

Greenland Telescope Project
THULE AIR FORCE BASE

2017

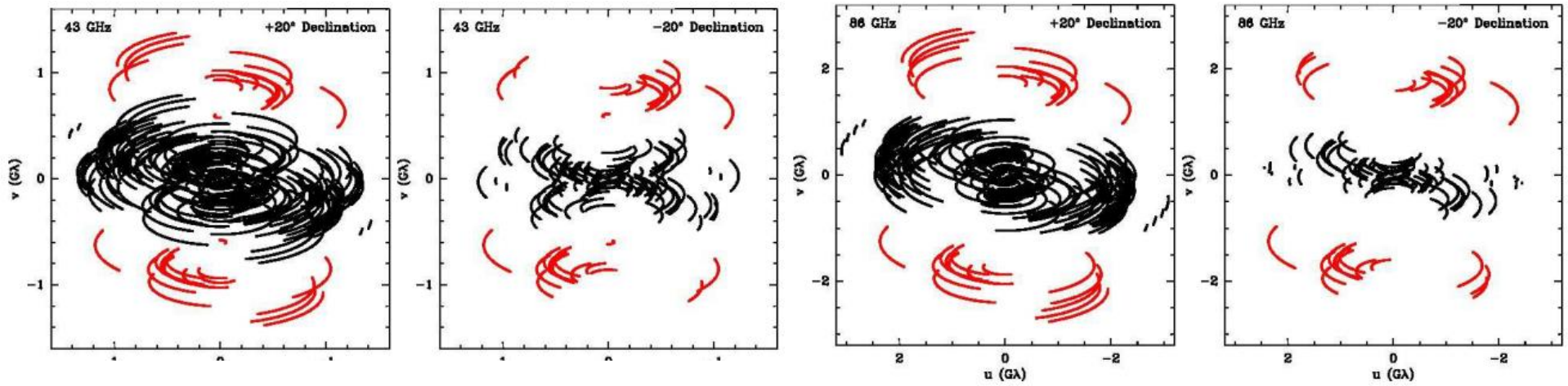
2018

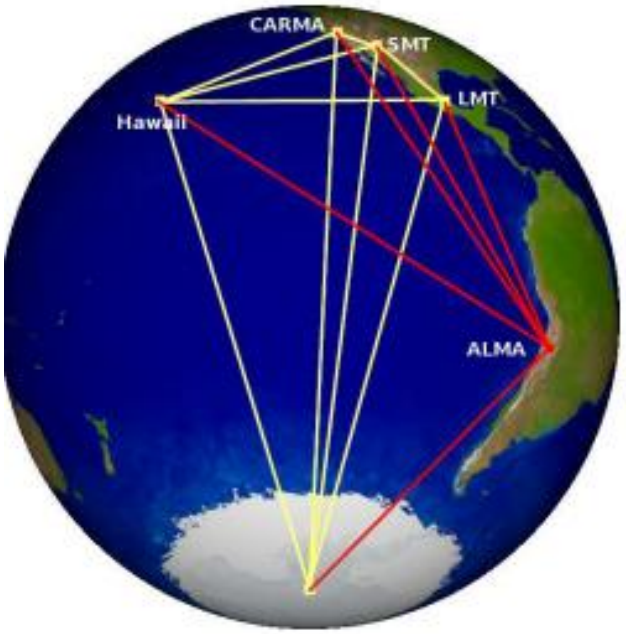
National Radio Astronomy Observatory
NRAO

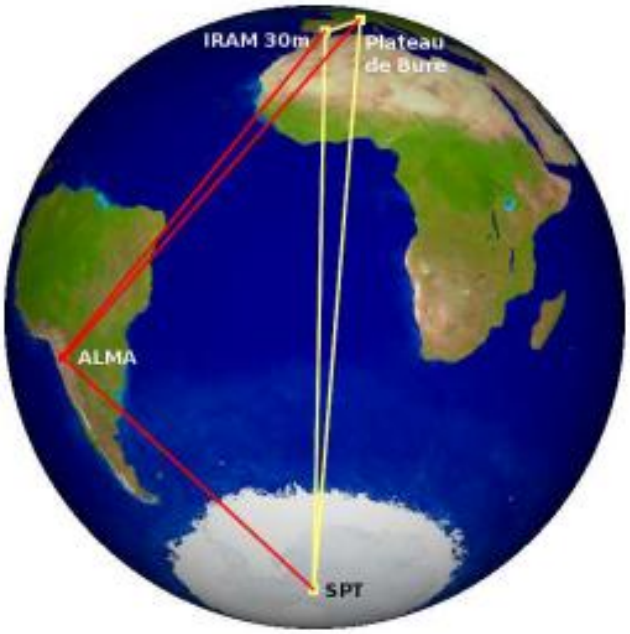
mm-VLBI with ALMA

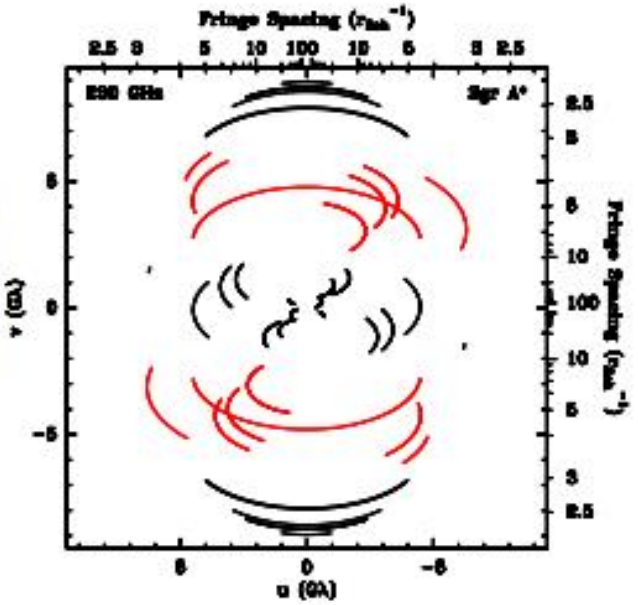
Fish et al. (2013)

FIG. 1.— The (u, v) coverage of sources at +20° (left) and −20° (right) declination. The top row shows the global VLBI baseline coverage at 7 mm, and the bottom row shows the coverage at 3 mm. Baselines to ALMA are indicated in red. ALMA provides substantial improvement in the north-south coverage of global VLBI arrays, especially at 3 mm and for southern sources.

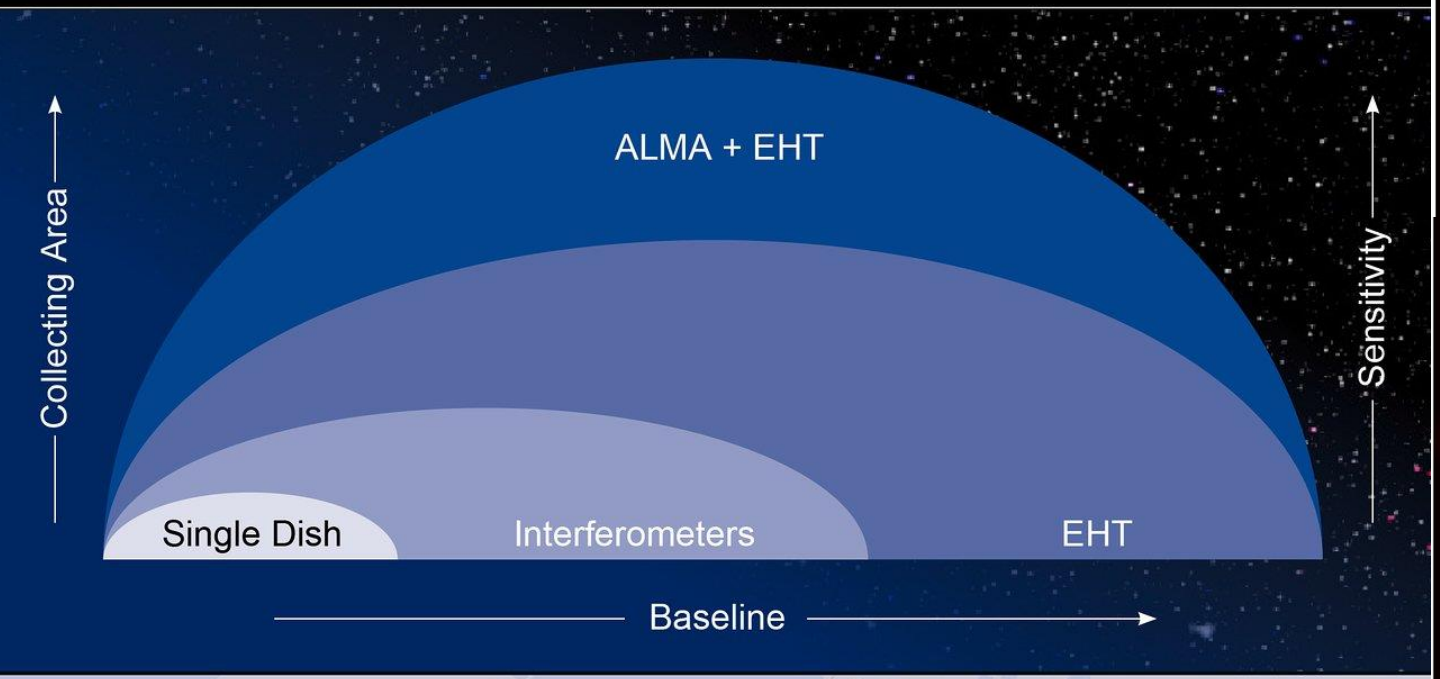


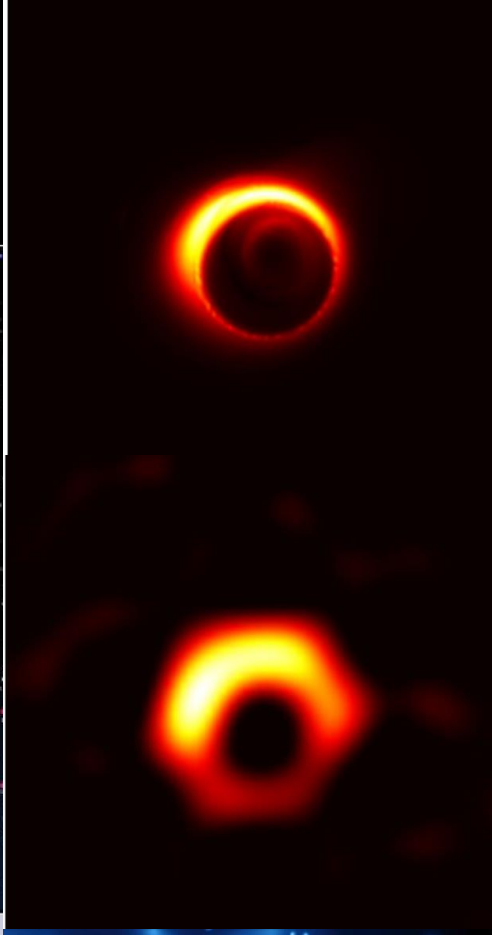


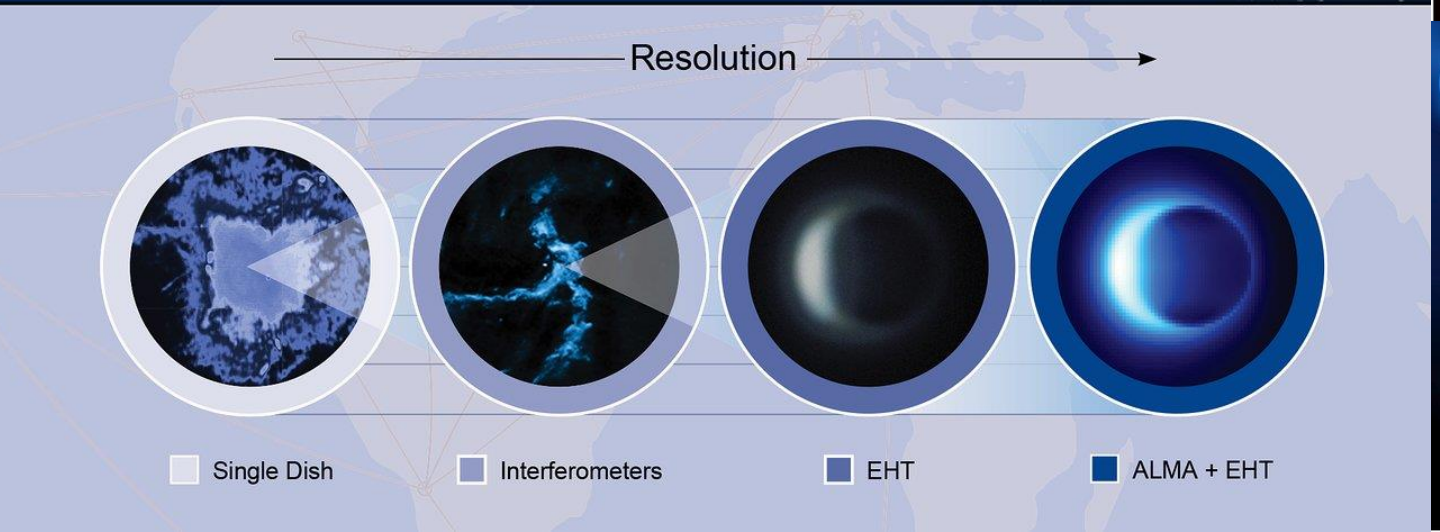


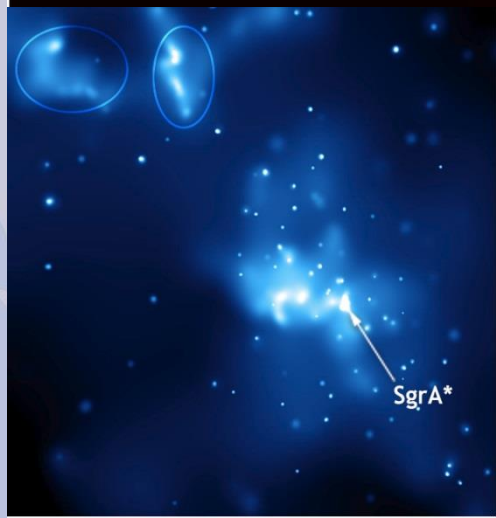


Tracing the Image of a Black Hole









Black Hole Size

μas = 10^-6 arcsecond

source	M_{BH}/M_{sun}	Distance	Angular radius
Sgr A*	4 x 10^6	8 kpc	10μas
M87	6 x 10^9	15 Mpc	7μas
M104	1 x 10^9	10 Mpc	2μas
Cen A	5 x 10^7	4 Mpc	0.25μas

Shadow diameter : 1~5 times Schwartshild radius
For imaging shadow, ~ 10μas resolution is required

(Credit: M. Honma)

Black Hole and AGN Jets

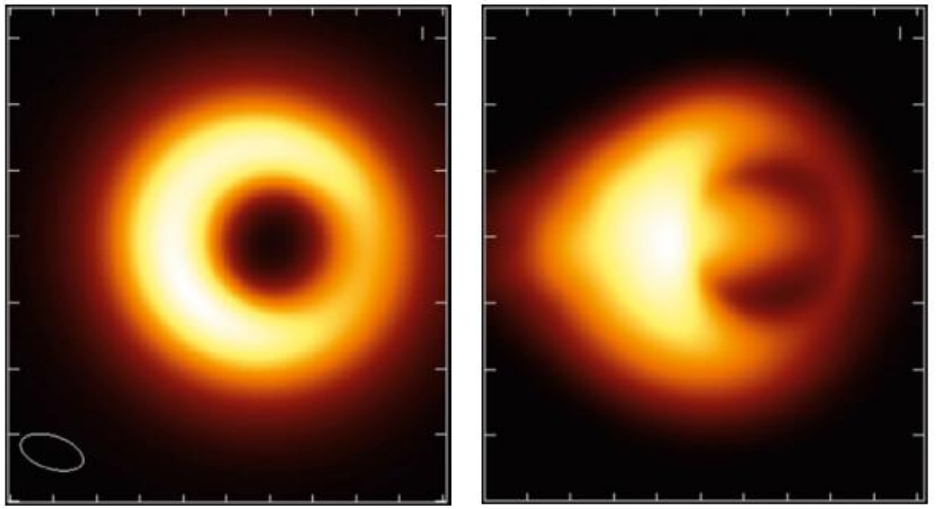
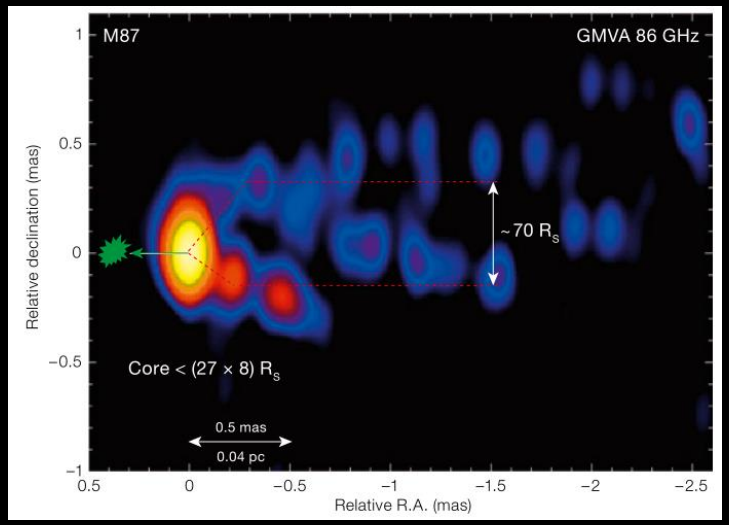
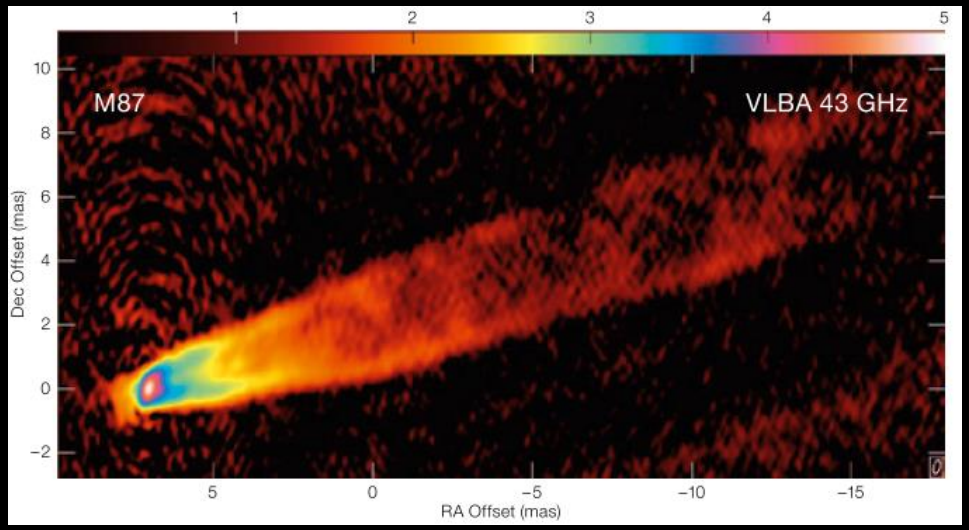
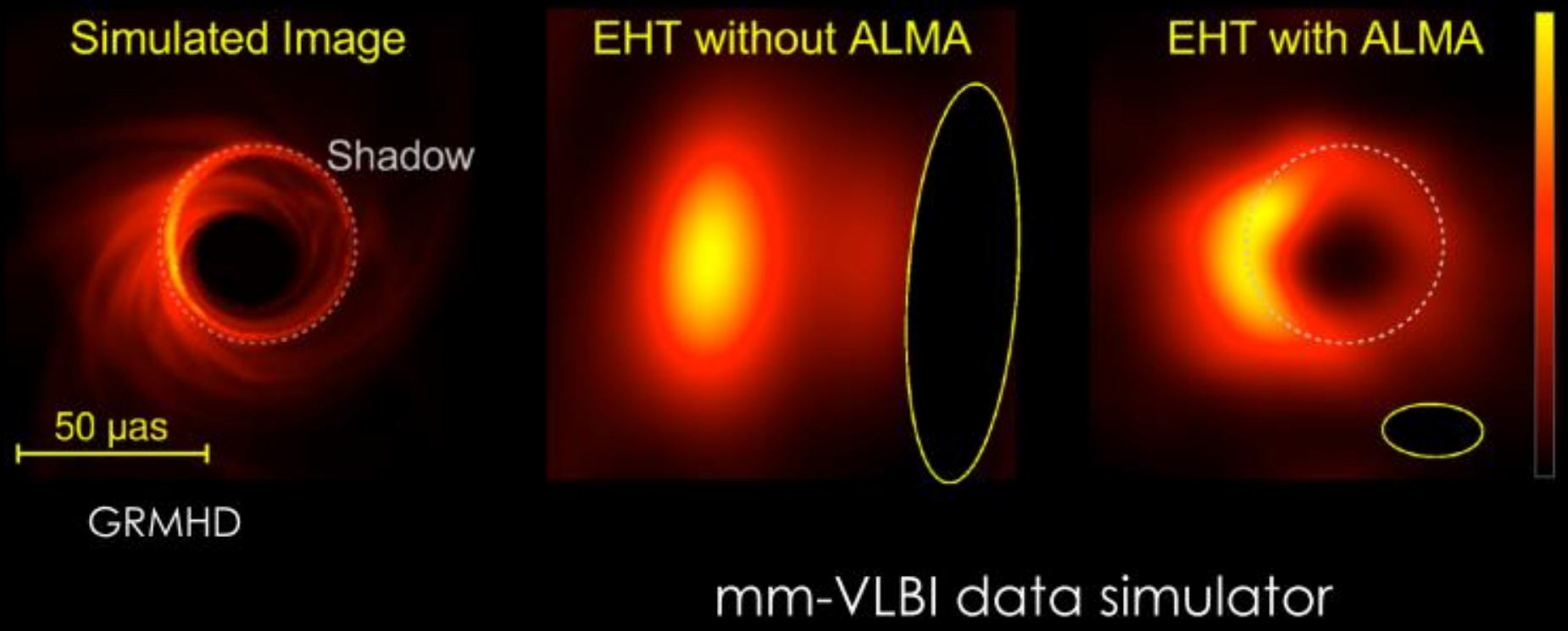


Figure 2. Simulated images at 345 GHz of the black hole in the Galactic Centre using a VLBI array involving ALMA and other telescopes. The input model is based on general relativistic magneto-hydrodynamic simulations of plasma around a Kerr black hole from Mościbrodzka et al. (2009). Left: Face-on orientation; Right: Edge-on orientation. The black hole shadow and photon ring are much more difficult to detect, but still visible in the edge-on case. Figure updated from Falcke et al. (2011).





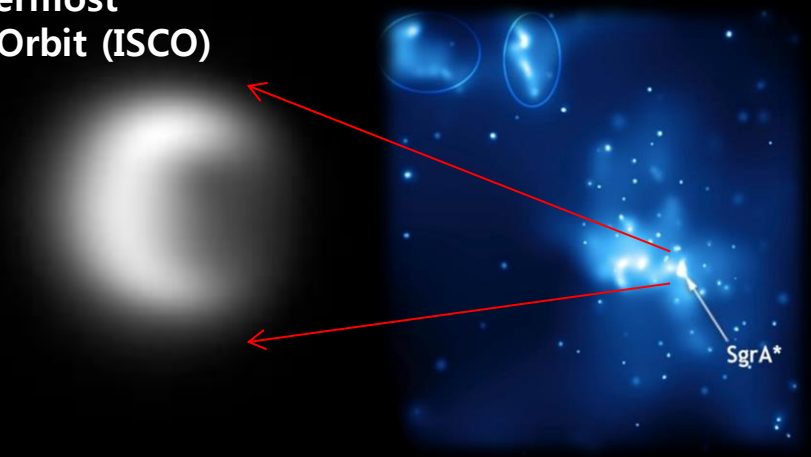
BH Shadow Seen by mm-VLBI with ALMA



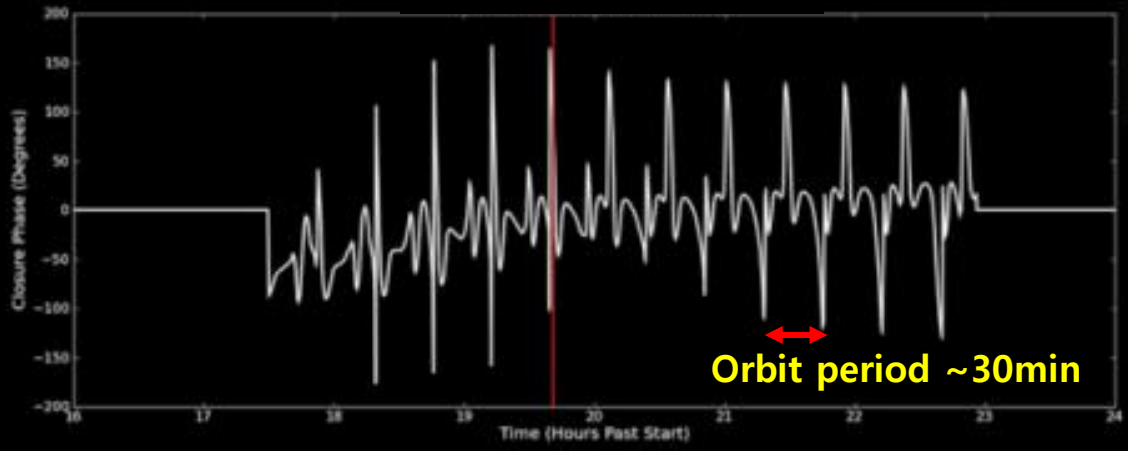
(Credit: Ciriaco Goddi)

VLBI Traction on Black Hole Orbit

Hot spot in accretion flow orbit BH at Innermost Stable Circular Orbit (ISCO)



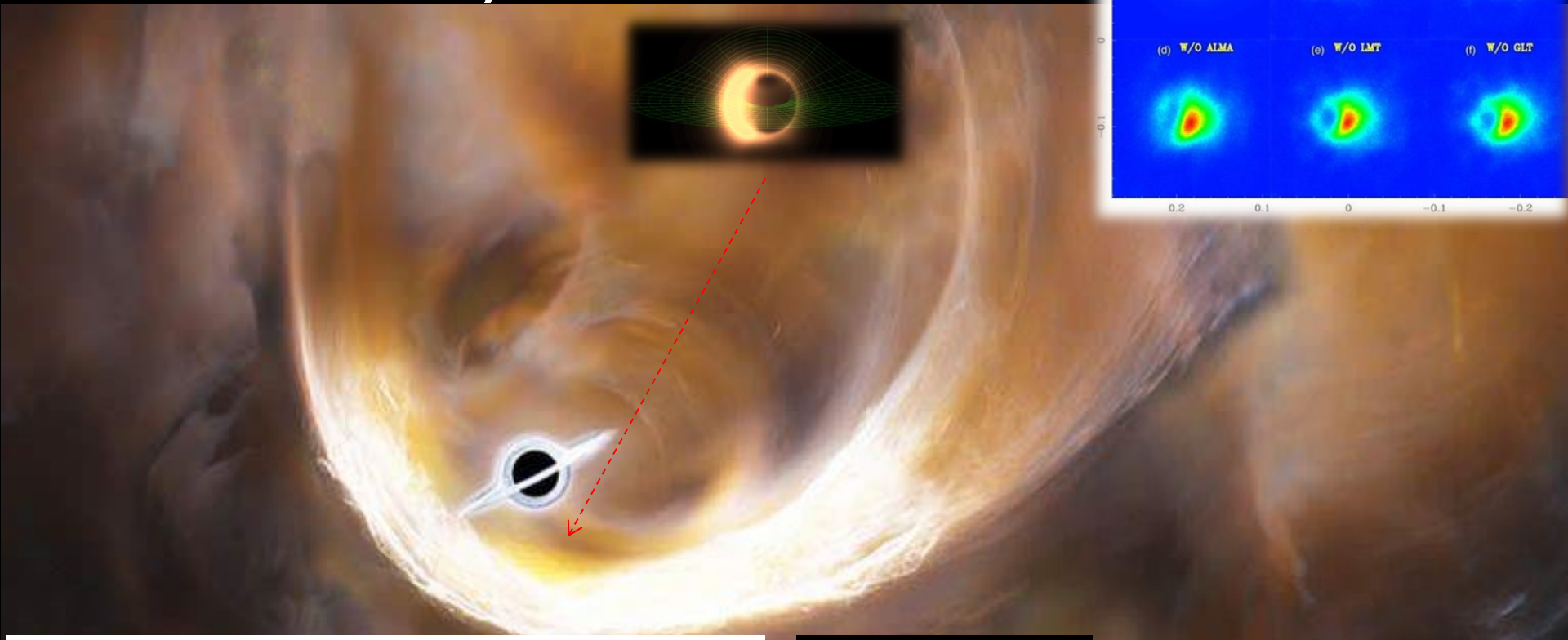
Closure Phase vs Time

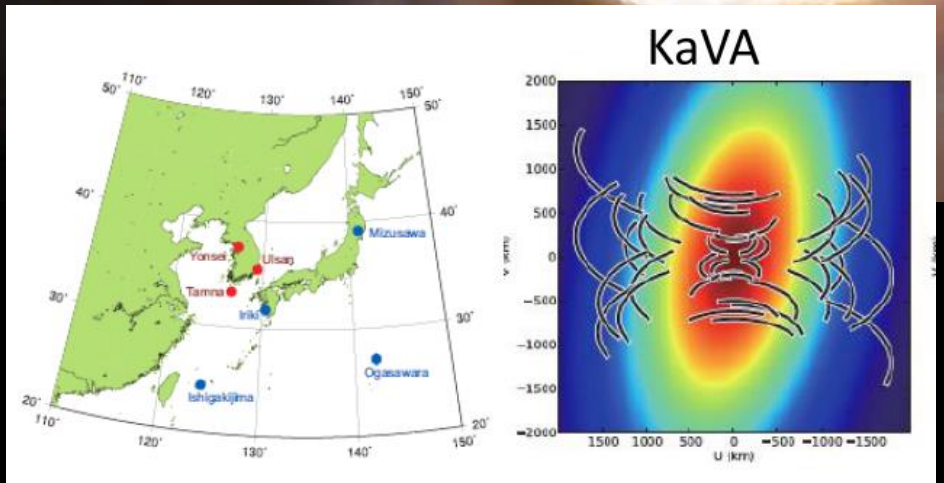


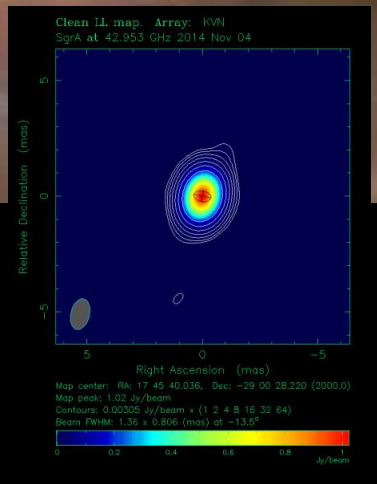
Many orbits observed during a single night
→ Extraction of orbit period gives an estimate of BH spin!!

(Credit: S. Doeleman)

SgrA* monitoring program
on behalf of KaVA/EAVN Science WG







Credit: Tomoharu Oka (Keio University)

1st VLBI Observations with ALMA

- 1st observation: April 2-15 2017
  - April 2-4: GMVA (86GHz, 3mm)
  - April 5-11: EHT (230GHz, 1.3mm)

  ※ 8 telescopes (62 hrs ALMA time)
  4PB raw data
- 2nd observation: April 15-27 2018

mm-VLBI with ALMA: General Science Cases

- Imaging EH of BH: SgrA*
- Testing GR
- Origin of AGN jets and jet formation
- Cosmological evolution of galaxies and BHs, AGN feedback
- Galactic masers (Star Formation, Evolved Star)
- Pulsars, neutron stars, and X-ray binaries
- Extragalactic emission lines
- Absorption lines in distant galaxies and study of their ISM
- Testing cosmology and fundamental physical constants
- Astro-chemistry

Reviewed by Fish et al. (2013) and Tilanus et al.. (2014)

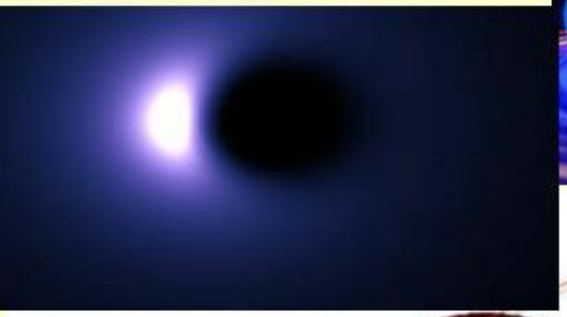
Motivation:

AGN Study: mm-VLBI with ALMA

What are the physical proccesses acting at the centers of Quasars and in other Active Galactic Nuclei ? One needs to directly image the regions near the central Black Hole and study how the powerful radio-jets are launched and accelerated.

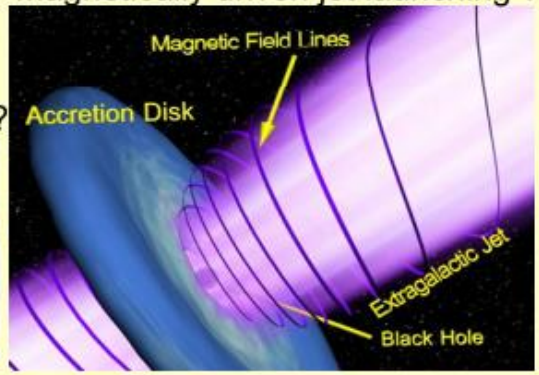
mm- and sub-mm VLBI with ALMA offers micro-arcsecond scale resolution and will help to answer the following questions:

Assymetric emission around a rotating Black Hole ?

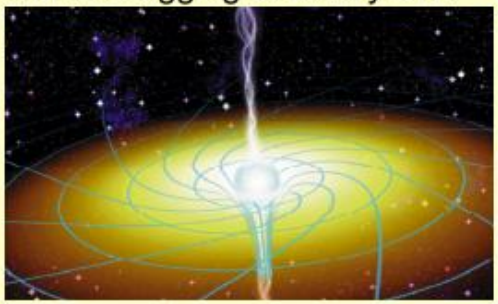


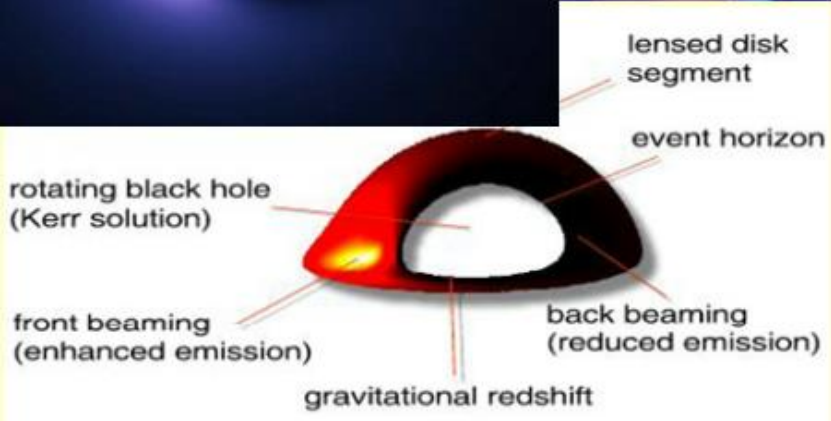
The Black Hole:
A GR-MHD dynamo ?

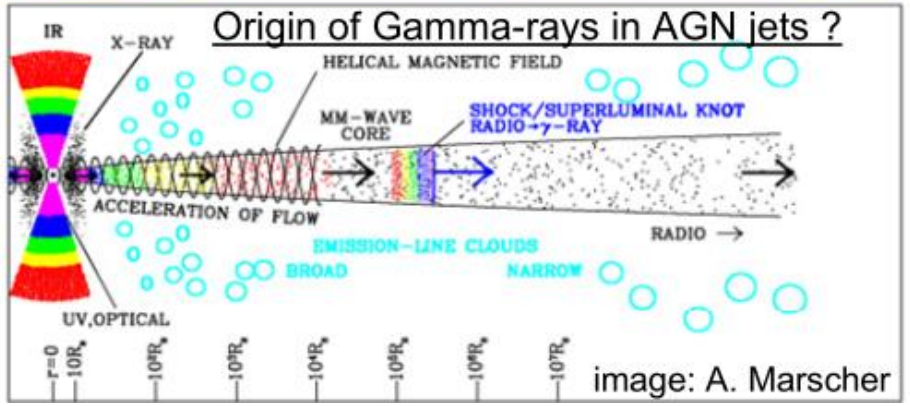
Magnetically driven jet launching ?



Jet rotation/precession due to frame dragging or binary BH?

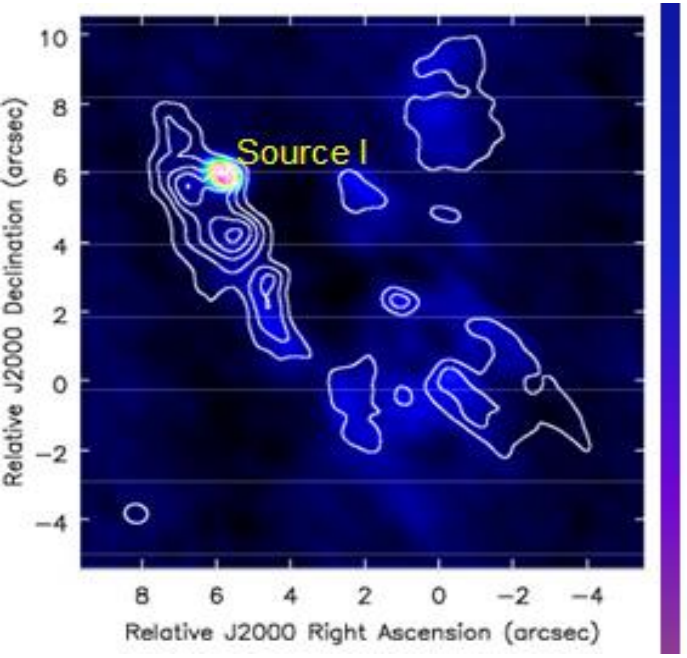


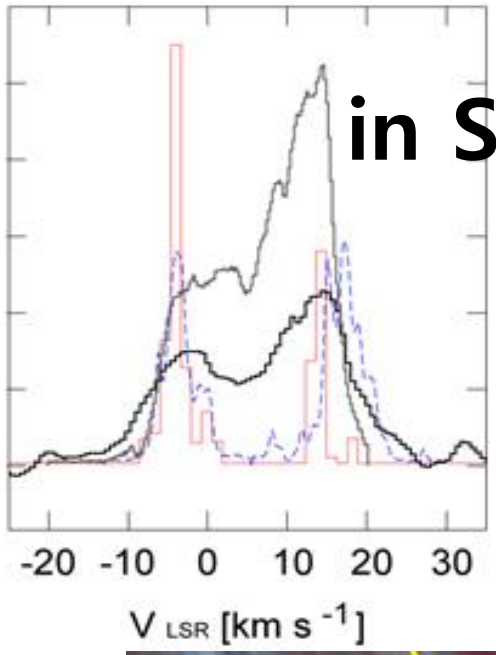




Credit: T. Krichbaum

Masers in Stars, SF regions





ORION KL

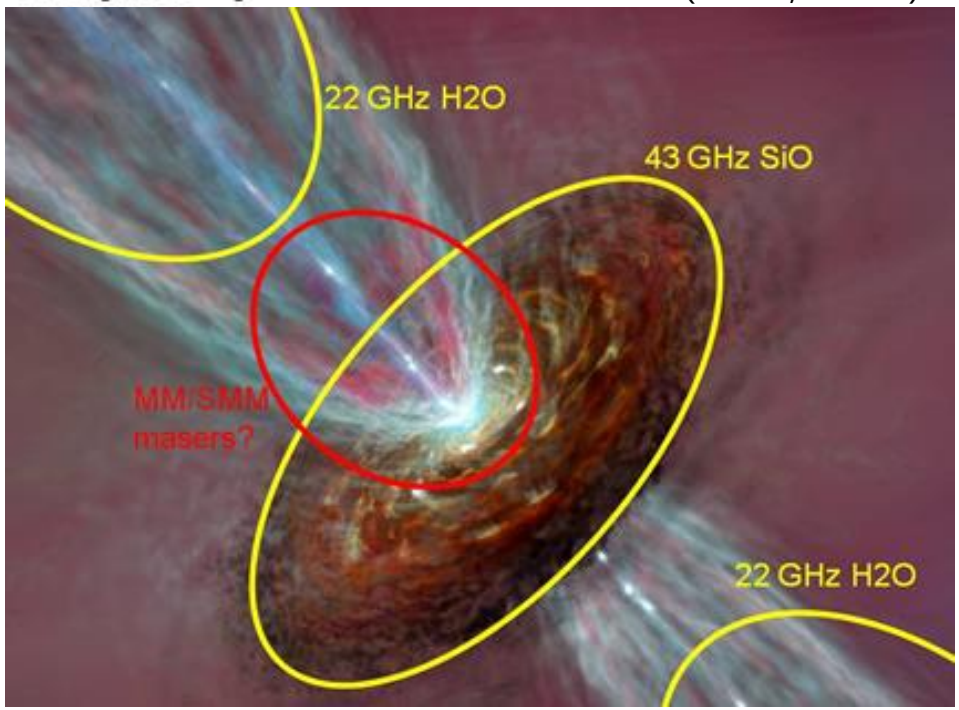
SiO (v=1,43 GHz)
H_2O (22 GHz)
H_2O (232 GHz)
H_2O (321 GHz)

VLBI

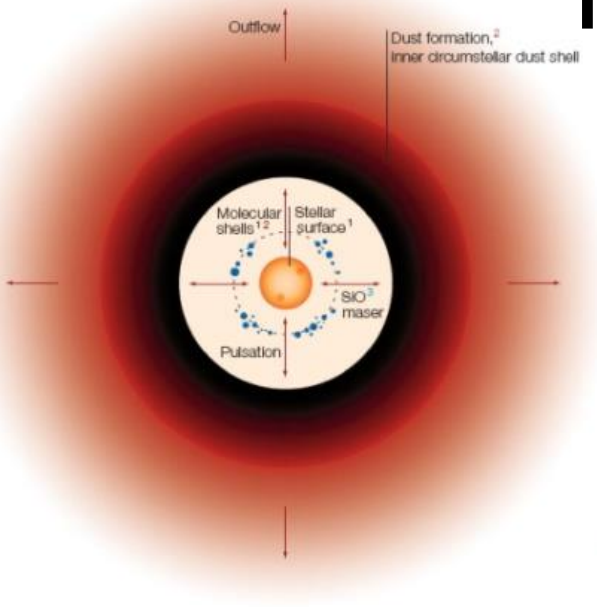
ALMA

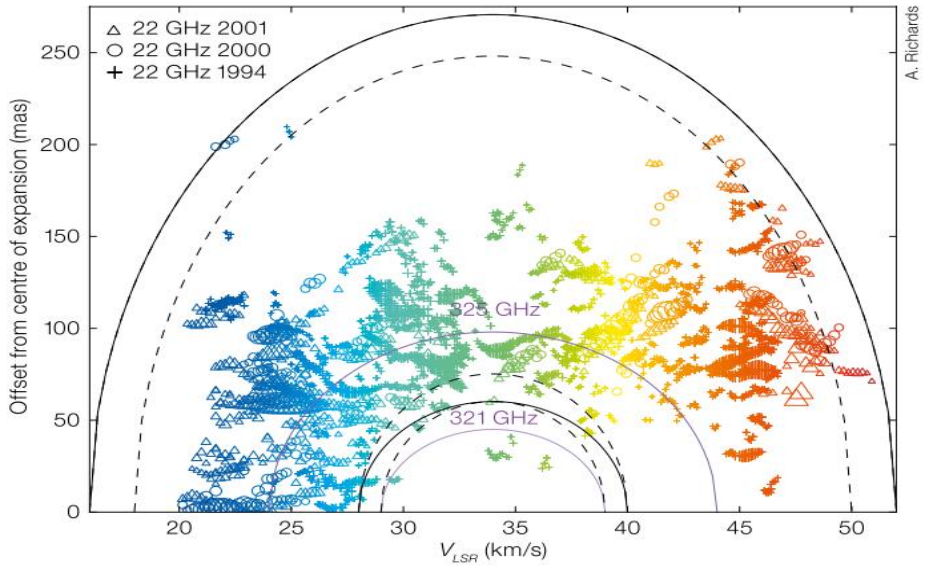
Hirota et al. (2012, 2017)

- New Probes of YSOs and AGBs
- New maser line detection with ALMA
  - H2O at 232GHz
  - H2O at 321GHz
- double-peaked profile similar to SiO
  → tracing hotter/dense gas than H2O at 22GHz?
  → mm/submm VLBI is essential to study dynamics & excitation

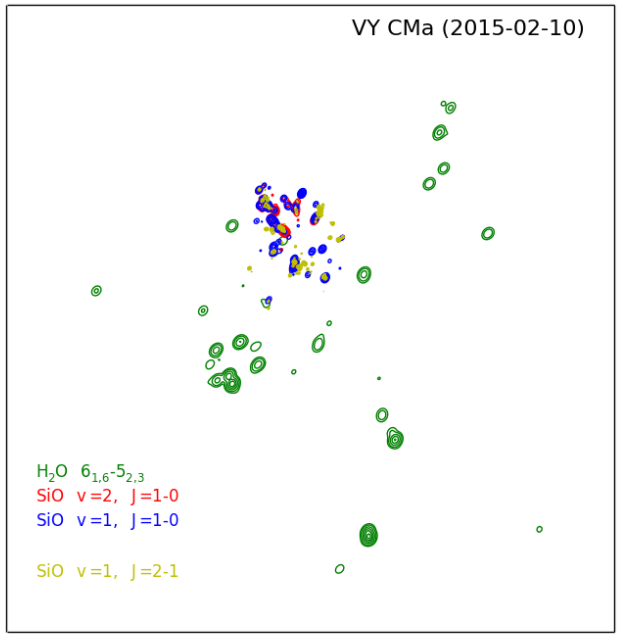


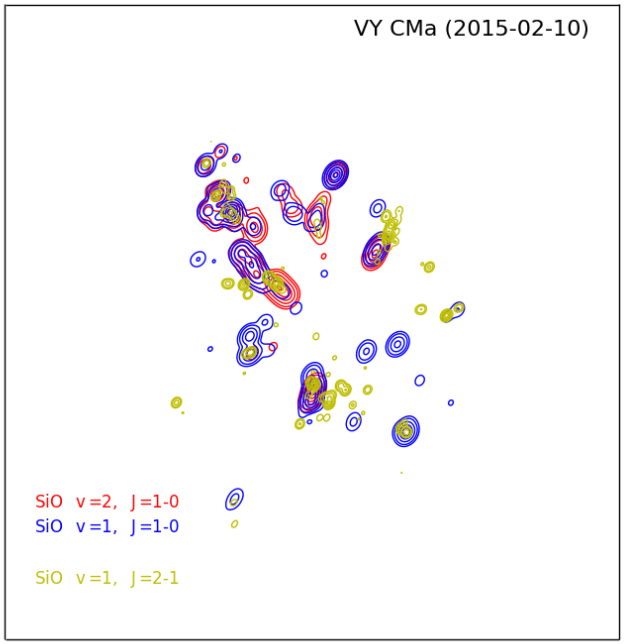
Masers in AGBs





Movies of H2O & SiO masers of VY CMa at 22/43/86/129GHz, KVN



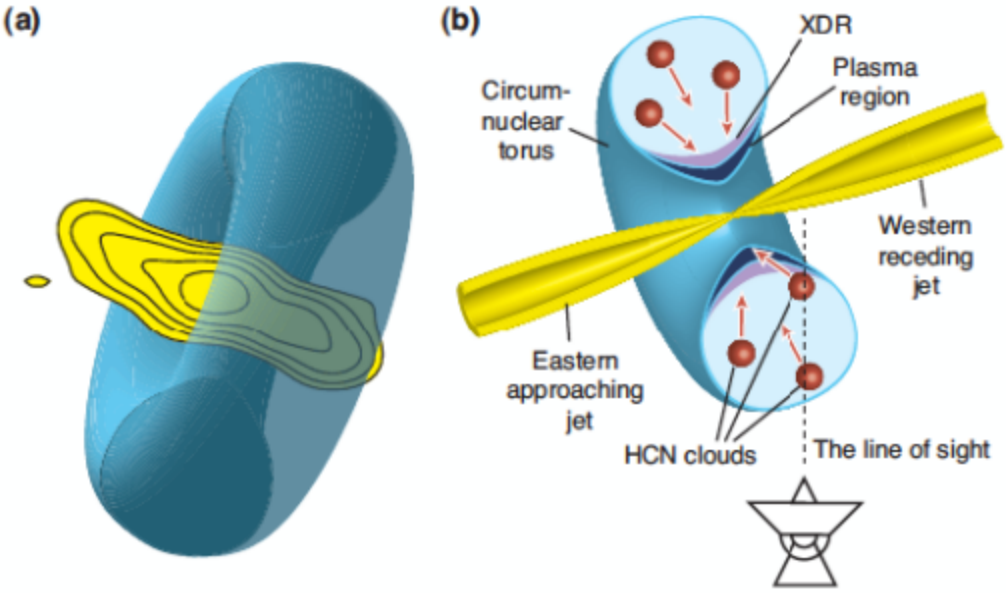


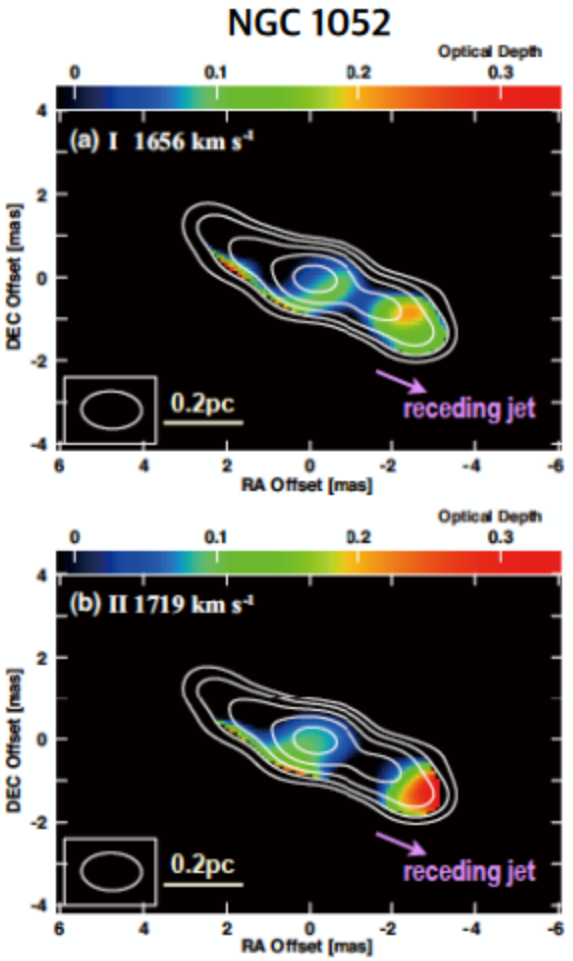
Position–velocity plot showing the observed 22 GHz water vapour emission from the oxygen-rich AGB star IK Tau (colour-coded by velocity), together with the predicted locations of water maser emission at 321 and 325 GHz from models by Malcolm Gray.

KVN KSP (Credit: Y.J. Yun)

AGN Torus from Absorption Lines with KVN

- HCN (1-0) associated with the AGN torus (Sawada-Satoh+ 16)
  - High opacity localized on the receding jet.
  - Ongoing infall of HCN clumps to SMBH.
  - Yielded physical properties of the torus.
    - $N(H_2)$: 10^{24}-10^{25} cm^{-2}
    - Infall rate : ~0.05-0.5 M_{sun}/yr





VLBI with ALMA: Proposal Preparation

Strategy

- ALMA participate in open-access VLBI networks
- ALMA-VLBI proposal is assessed in competition with other ALMA proposals
- ALMA-VLBI data products will become public after some proprietary period

Proposals

- ALMA bands 3 and 6 are available
  - GMVA 3mm, EHT 1.3mm
- ALMA+GMVA : PIs must submitted a proposal to the GMVA by 1st Feb. in addition to their ALMA VLBI proposal
  → stress why ALMA is essential !!
- Notes:
  - No Large Program and DDT proposals
  - At present, up to 37 12m antennas in the phased array
  - Usually ALMA-VLBI campaign will be carried out in April
    ※ proposal deadline issue btw GMVA and ALMA

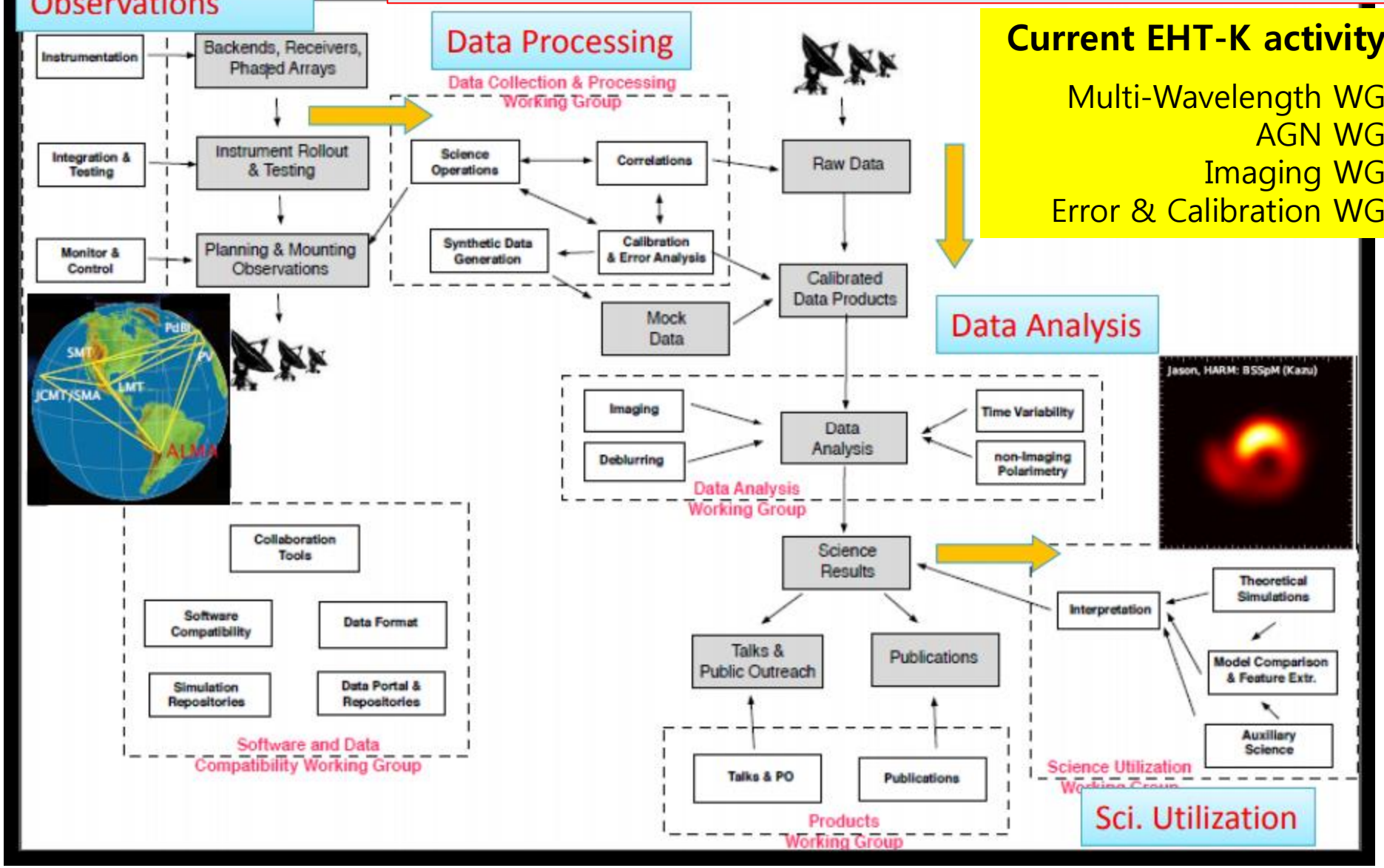
EHT Workflow

EHT: Korea Participation

- EHT: Starting from early 2010
- Official participation of Korea from mid-2017 under the EAO
  - supporting JCMT VLBI operation and joining S&T WG

Current EHT-K activity

Multi-Wavelength WG
AGN WG
Imaging WG
Error & Calibration WG



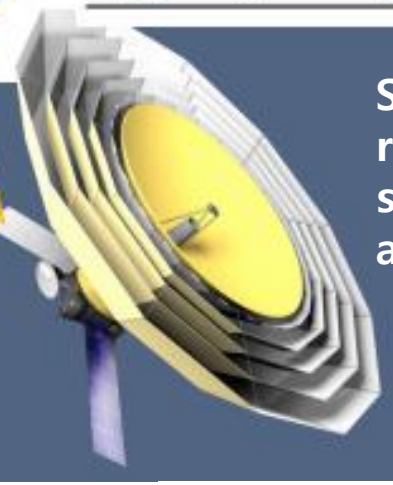
(image credit: M. Honma)

For even Higher Angular Resolution

→ VLBI+ALMA (EHT) + Millimetron (S-VLBI)

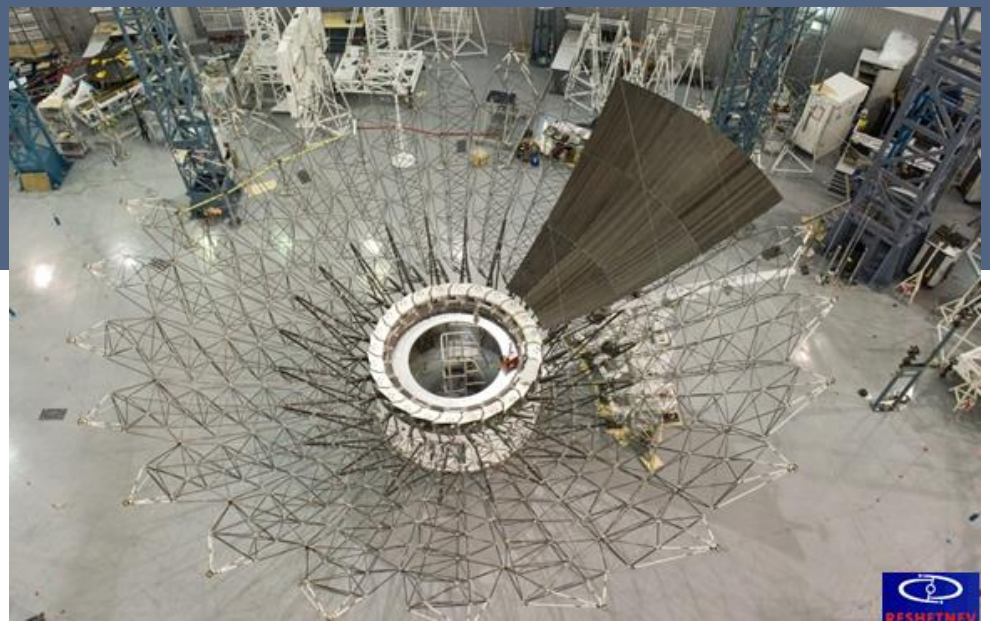
Assumed telescope parameters.

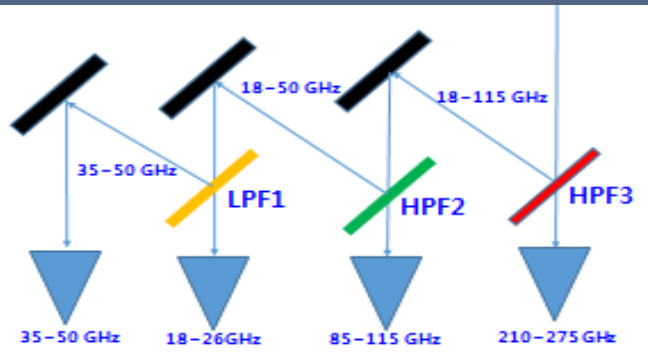
Facility	Code	Effective diameter [m]	$SEFD_{230\,GHz}$ [Jy]	$SEFD_{345\,GHz}$ [Jy]
Hawaii	H	23	4900	8100
SMT	S	10	11900	23100
CARMA	C	27	3500	...
LMT	L	50	560	13700
ALMA	A	85	110	140
PV	V	30	2900	5200
PdBI	B	37	1600	3400
GLT	G	12	4700	8100

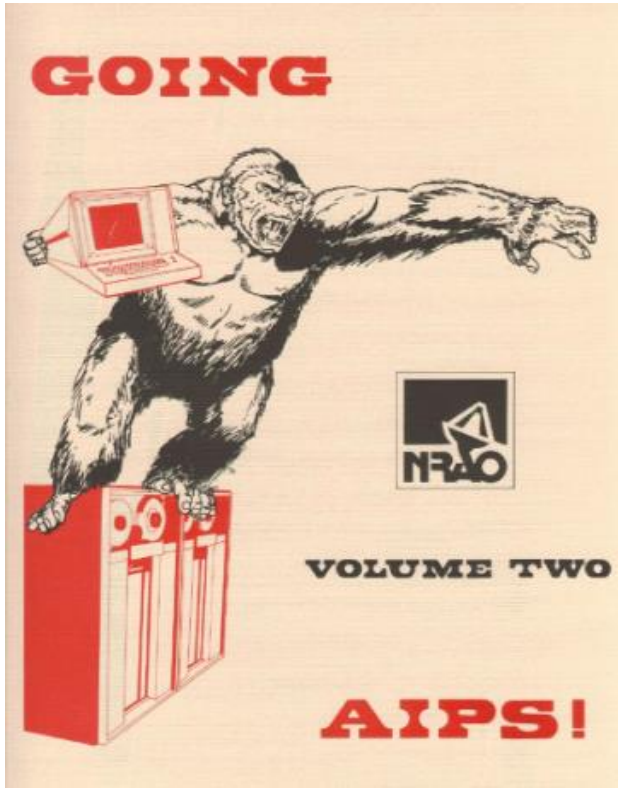


Simultaenous MF receiving system is seriously considered as a MMtron's Rx.

(Credit: S. T. Han)







Starting important step forward to make a synegies between connected interferometers and VLBI.

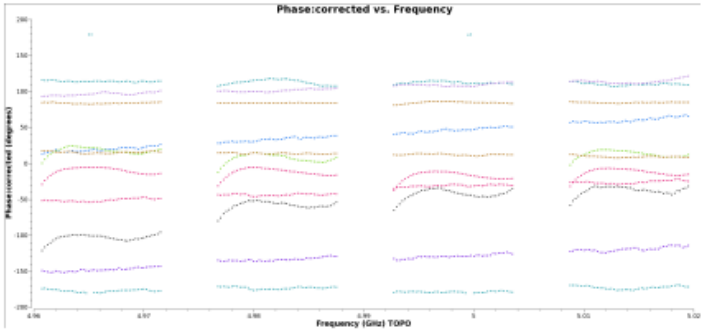
overcoming the boundaries of tools and experties

Connected Array
low ang. resolution
wider filed of view
dense, sensitive obs

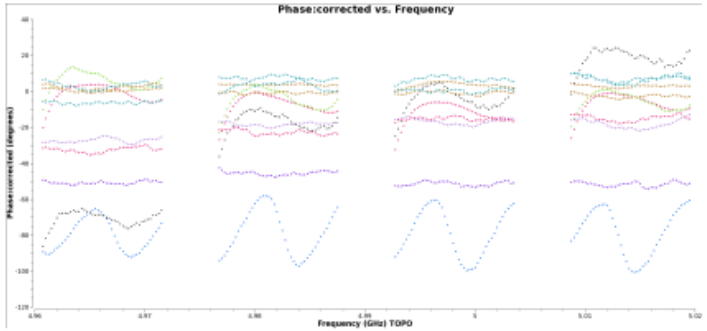
VLBI
high ang. resolution
narrow/wide field imaging
high Tb dominated

CASA
Common Astronomy Software Applications

Multi-band Fringe Fitting in CASA is now available!!



After "manual phase cal"



After "multi-band" fringe fitting

Useful Link & References

- **EHT** : http://eventhorizontelescope.org/
- **GMVA** : https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/
- **ALMA-VLBI related**
  - Cycle 6 CfP : https://almascience.nrao.edu/news/alma-cycle-6-pre-announcement
  - Cycle 5 CfP : https://almascience.nrao.edu/proposing/proposers-guide

- **Science Cases**
  - Fish et al., 2013 (arXiv:1309.3519)
    High-Angular-Resolution and High-Sensitivity Science Enabled by Beamformed ALMA
  - Tilanus et al., 2014 (arXiv:1406.4650)
    Future mmVLBI Research with ALMA: A European vision
  - Matthews et al., 2018
    The ALMA Phasing System: A Beamforming Capability for Ultra-high-resolution Science at (Sub)Millimeter Wavelengths

- **CASA-VLBI workshop**: http://jive.eu/casa-vlbi2017/


Thank you!