Role of Large Single Dishes in VLBI

Jay Frothingham (they/he)

Credit to Tapasi Ghosh, Sravani Vaddi, and Pedro Salas

GBO Single Dish Summer School, June 2024

GREEN BANK OBSERVATORY

Motivation

Why Single Dish Radio Telescopes
(Jay Frothingham)

Combining Data from Single Dishes and Interferometers
(Adele Plunkett)

New idea: what do large single dishes contribute to interferometric arrays?

Roadmap

Interferometry recap

Very Long Baseline Interferometry

Case Study: Large apertures in VLBI

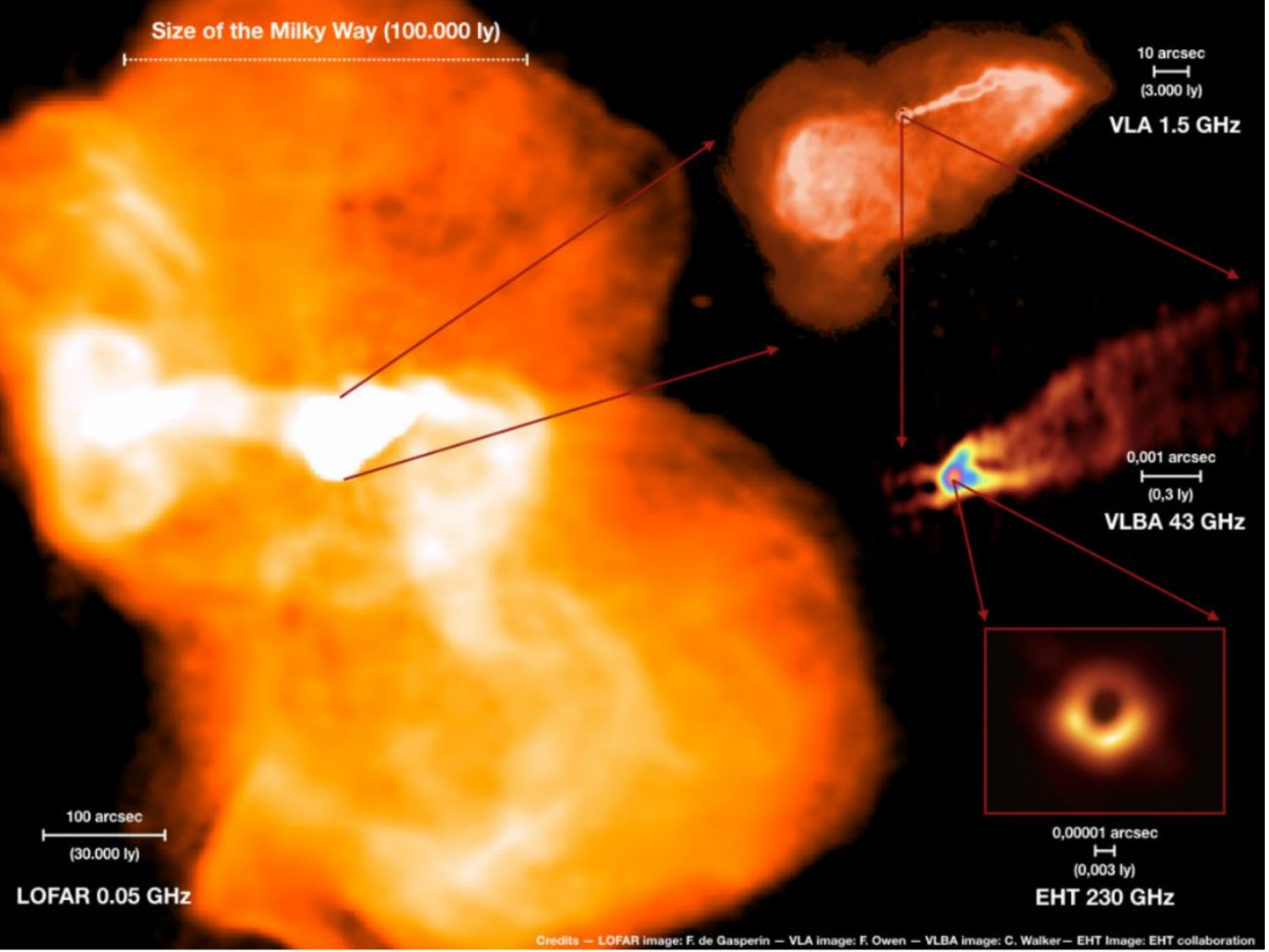
Proposing and observing tips

Interferometry

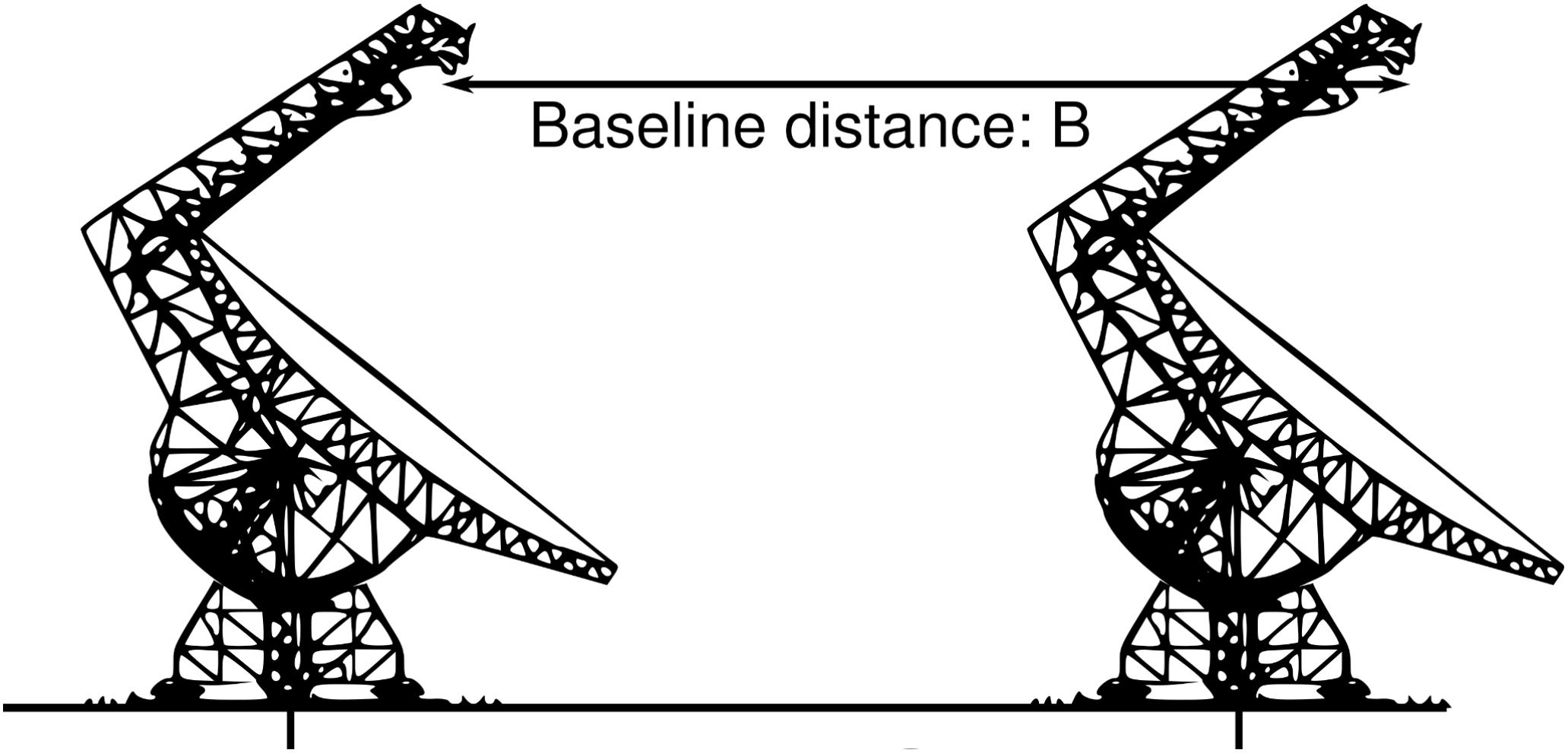
The resolving power of a diffraction limited telescope goes as λ/D.

There are limits to how large a single telescope can be.

Combine multiple telescopes to synthesize a large aperture!


Size of the Milky Way (100.000 ly)
10 arcsec
(3.000 ly)
VLA 1.5 GHz
0,001 arcsec
(0,3 ly)
VLBA 43 GHz
100 arcsec
(30.000 ly)
LOFAR 0.05 GHz
0,00001 arcsec
(0,003 ly)
EHT 230 GHz
Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker — EHT Image: EHT collaboration

Interferometry

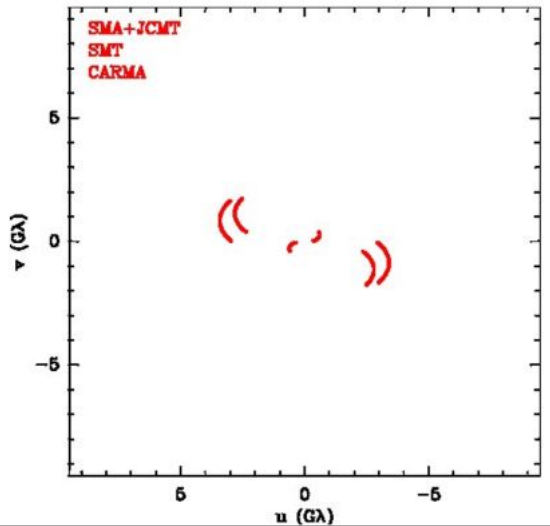


Now your resolving power goes as λ/B

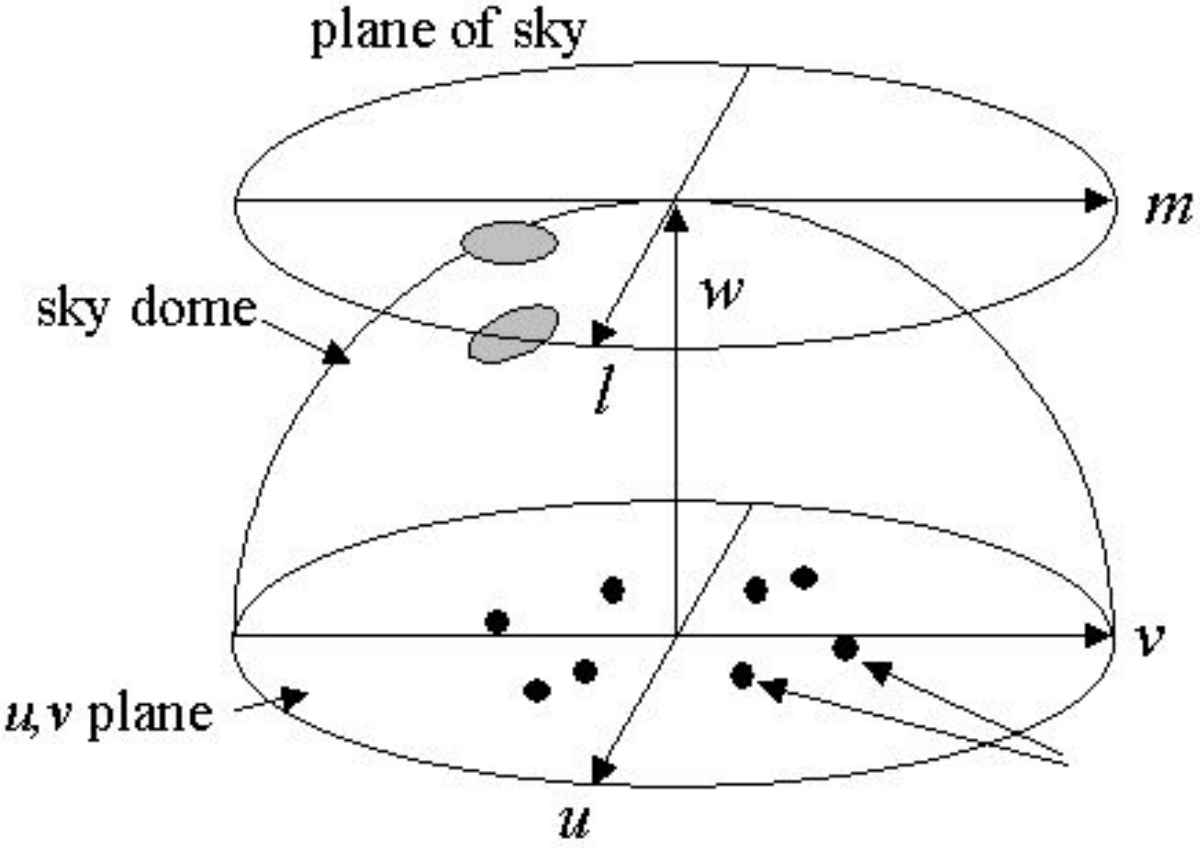
Correlation

Correlator takes cross product between recordings of antenna pairs

Complex numbers produced by correlator are called visibilities, V



The u-v plane


plane of sky
m
sky dome
w
l
v
u,v plane
u

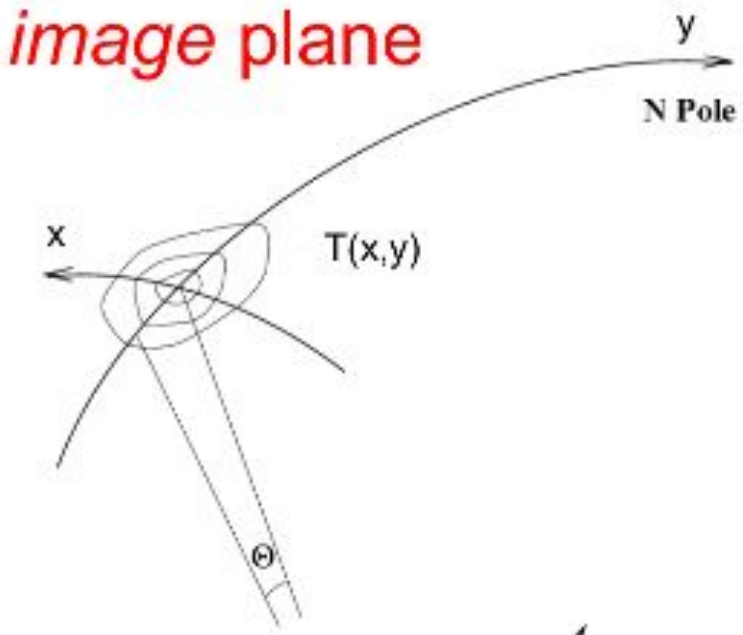
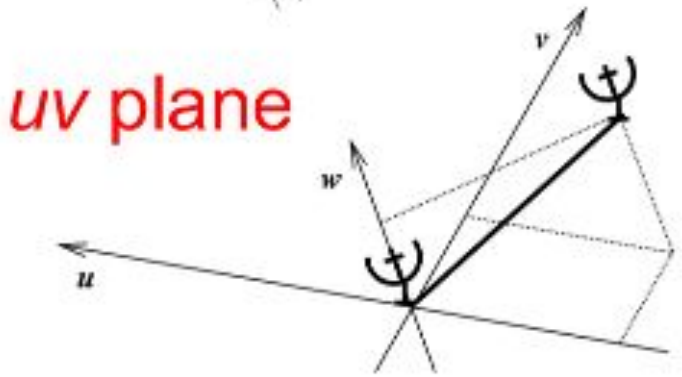


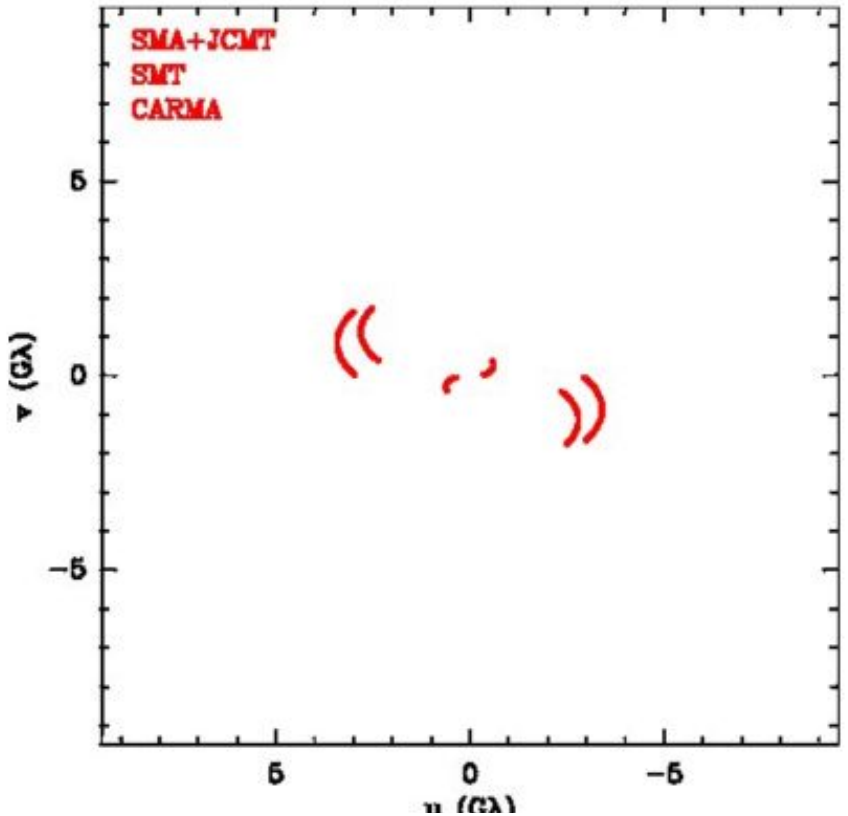
image plane
y
N Pole
x
T(x,y)
Θ


uv plane
v
w
u

Visibilities

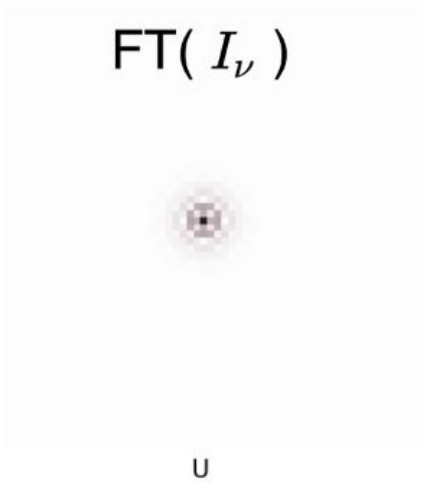
Visibilities sample the Fourier transform of the sky brightness distribution.

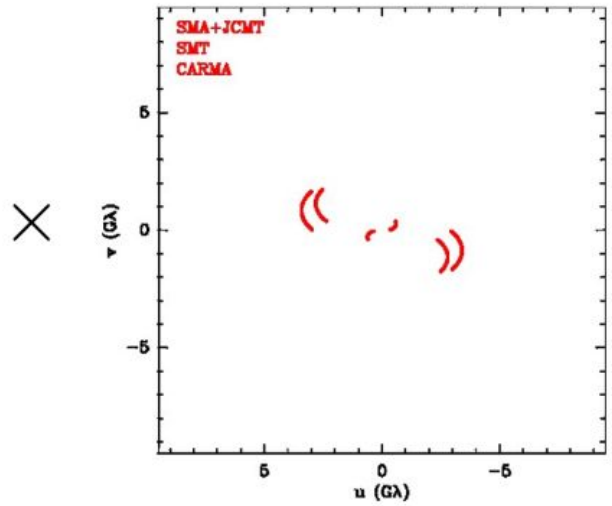
$V_{i,j}$



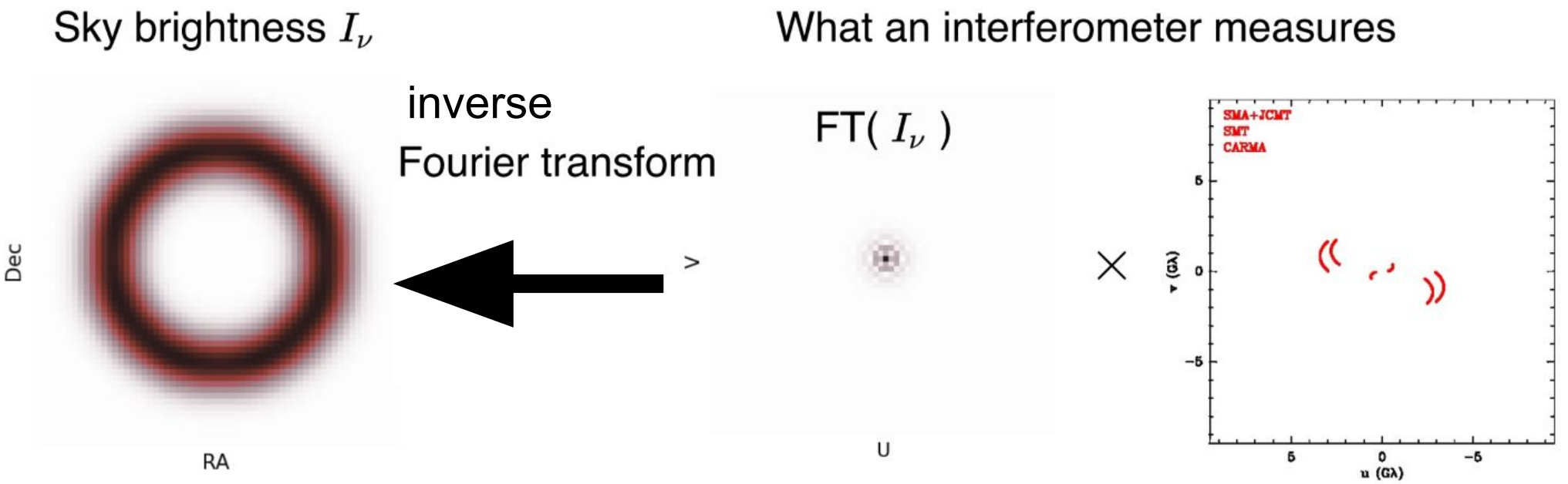
Imaging

What an interferometer measures



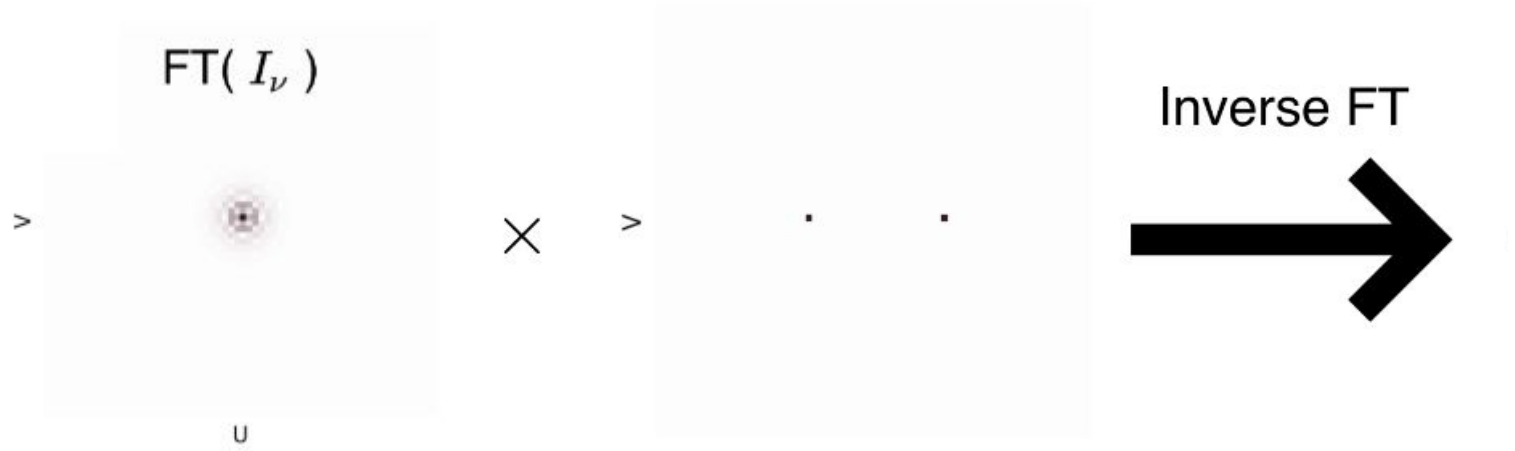


Imaging



…but we would not really recover a ring structure with this u-v coverage…

Why UV Coverage Matters



Why UV Coverage Matters

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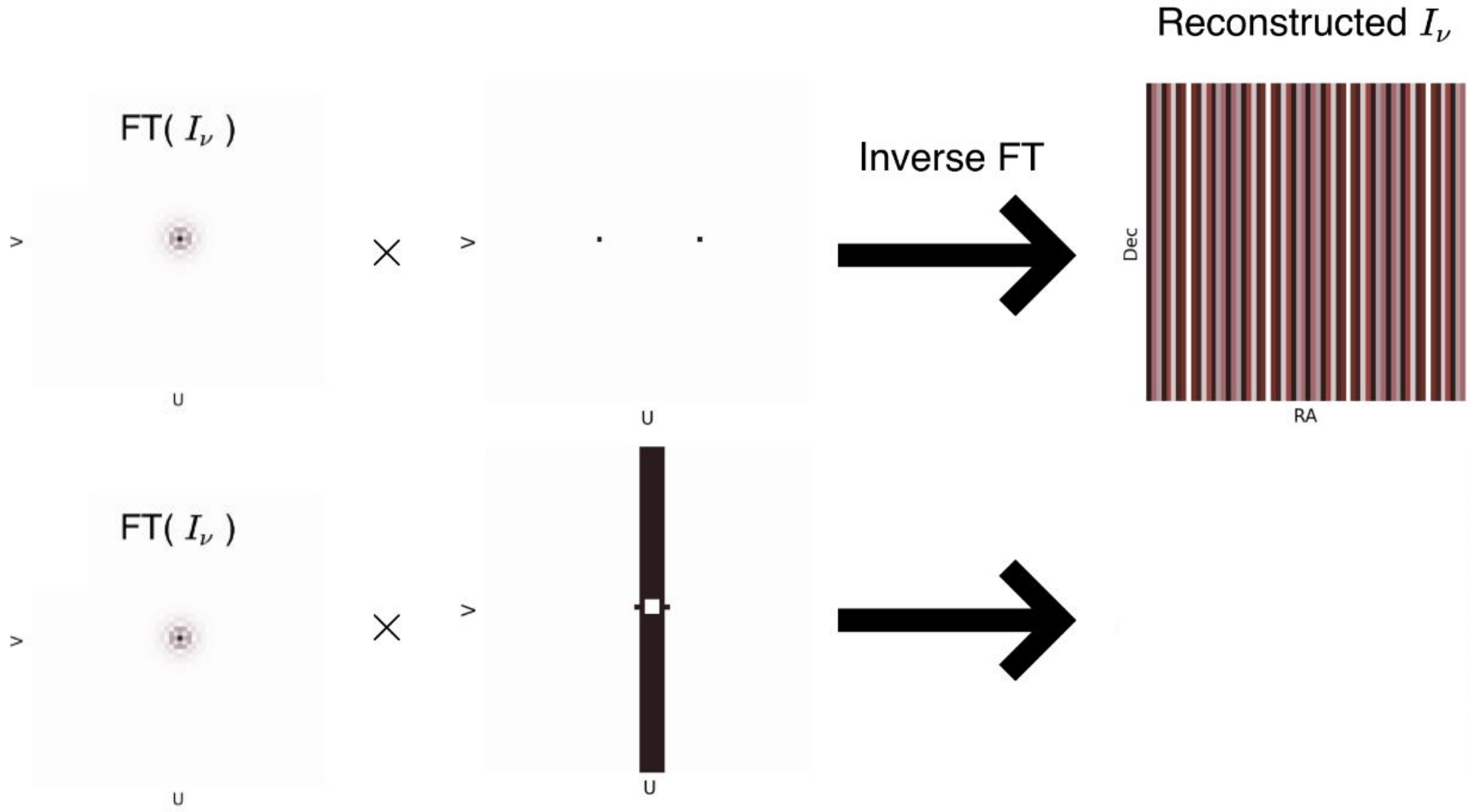


Why UV Coverage Matters

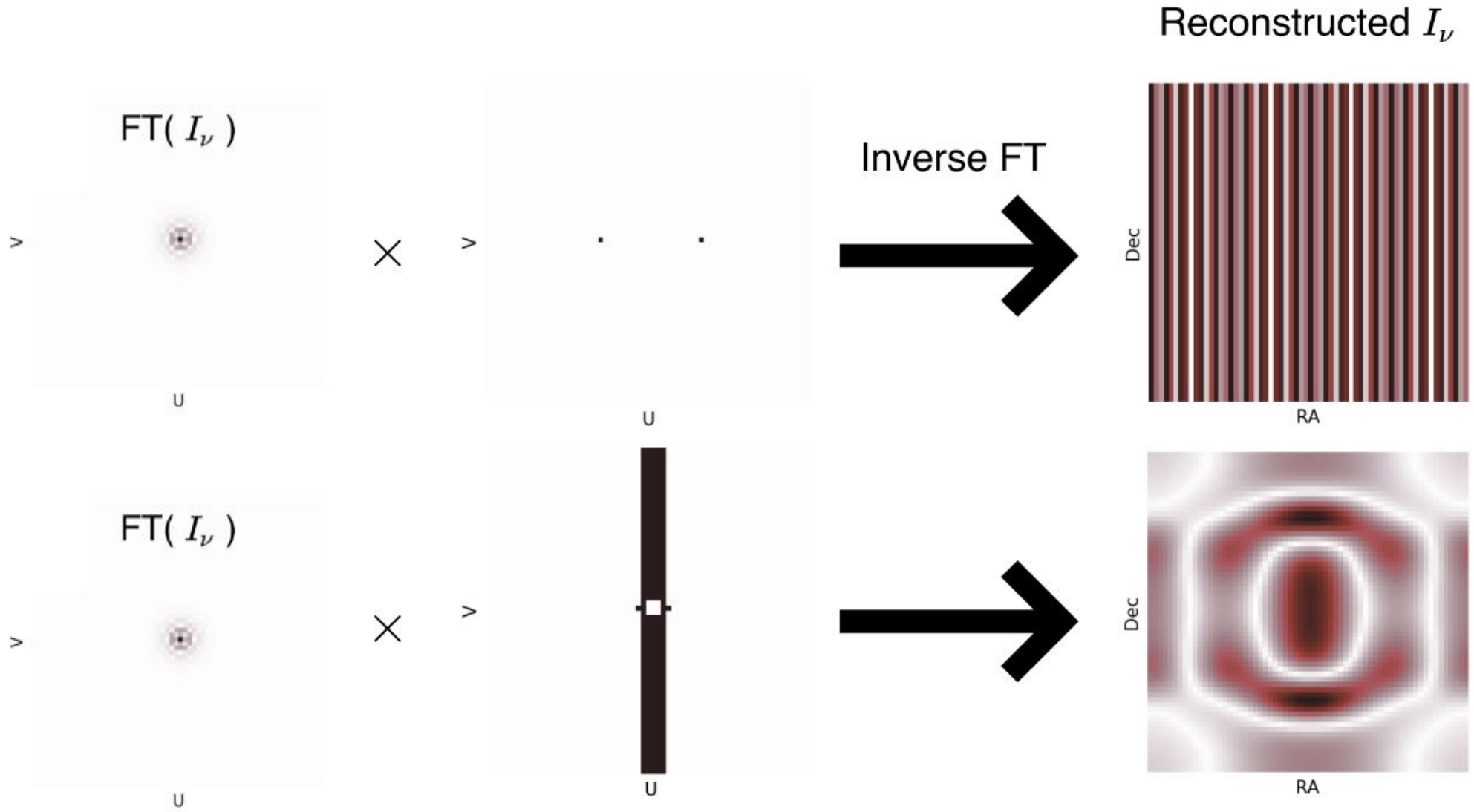


Image sensitivity

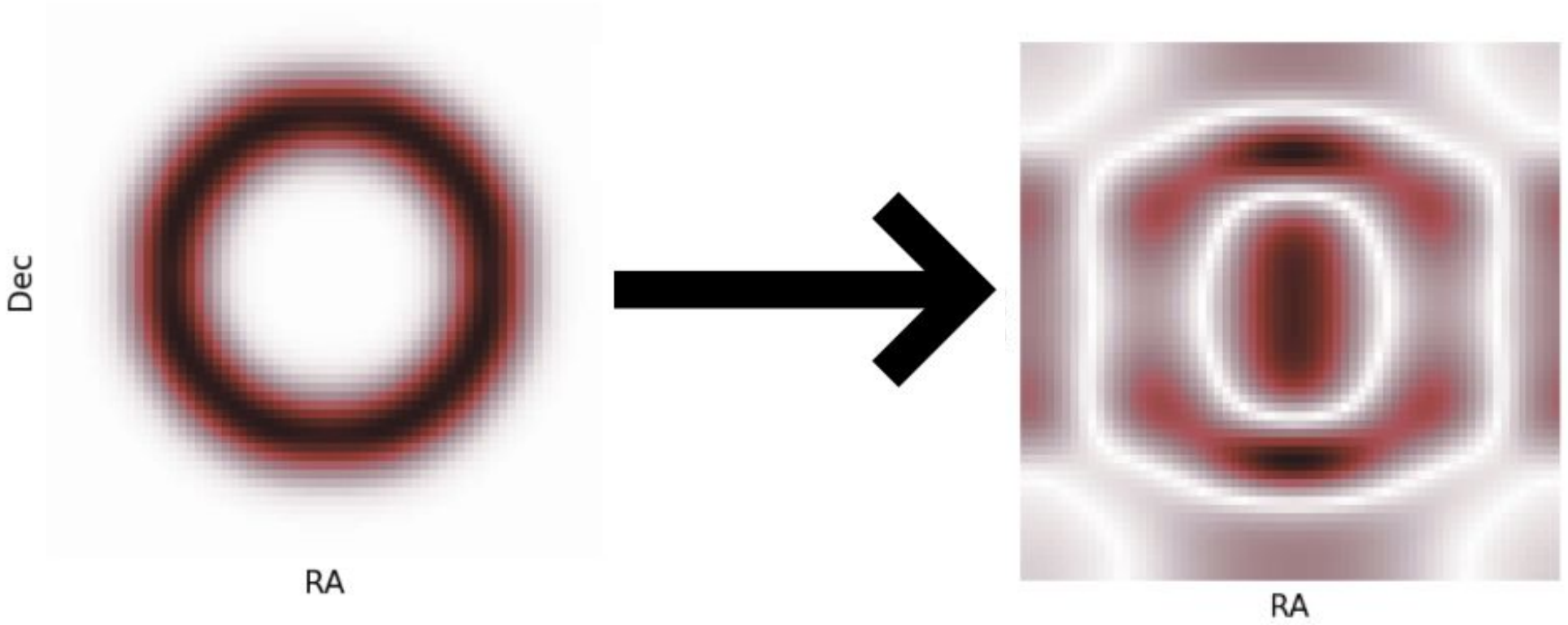


Image sensitivity

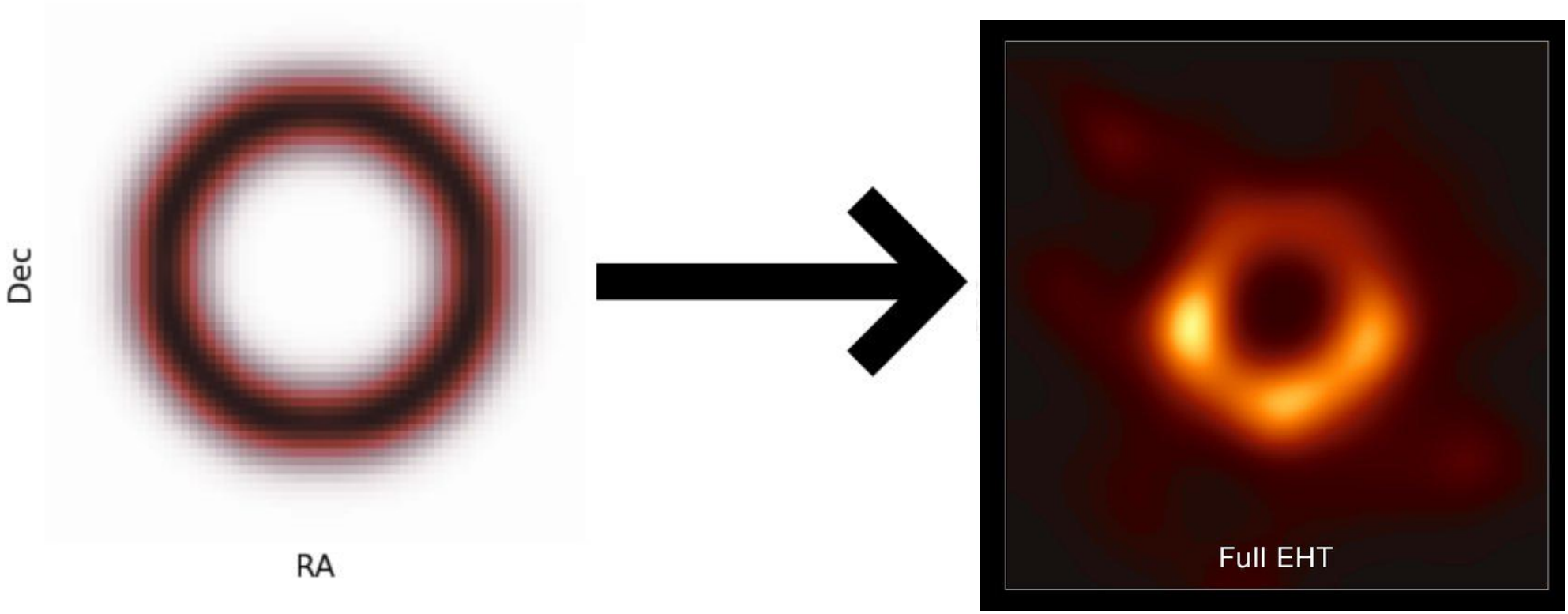


Image sensitivity

$$\Delta I_\nu \propto \frac{\mathrm{SEFD}}{\sqrt{N(N-1)\Delta t \Delta \nu}}$$

SEFD = System Equivalent Flux Density

SEFD = Tsys / G

N = number of antennas in array

Δt = integration time

Δv = bandwidth

For non-identical antennas:

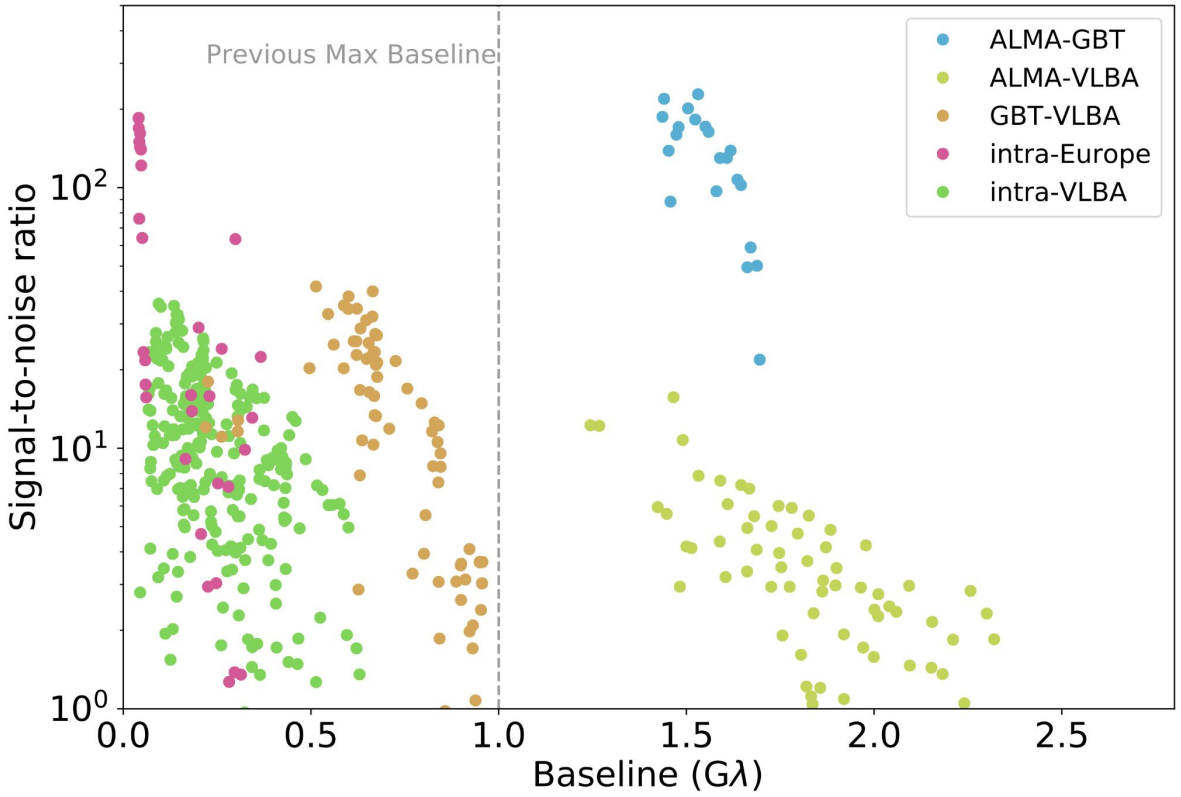
$$\mathrm{SEFD} \propto \sqrt{\frac{\mathrm{T_{sys,1}}}{\mathrm{G_1}}} \sqrt{\frac{\mathrm{T_{sys,2}}}{\mathrm{G_2}}}$$

Large apertures add sensitivity

$$\Delta I_\nu \propto \frac{\mathrm{SEFD}}{\sqrt{N(N-1)\Delta t \Delta \nu}}$$

$$\mathrm{SEFD} \propto \sqrt{\frac{T_{sys,1}}{G_1}} \sqrt{\frac{T_{sys,2}}{G_2}}$$

Large telescopes have higher gain, so produce more sensitive baselines in an array.



Interferometry Recap

Resolving power goes as λ/B

More U-V coverage means better image reconstruction

Larger dishes give you more sensitive baselines

Interferometry Recap

So with all that in mind, how would you build the perfect* interferometer?

** term used very loosely*

Interferometry Recap

So with all that in mind, how would you build the perfect* interferometer?

- long baselines (for resolution)
- globally distributed antennas (for u-v coverage)
- large dishes (for sensitivity)

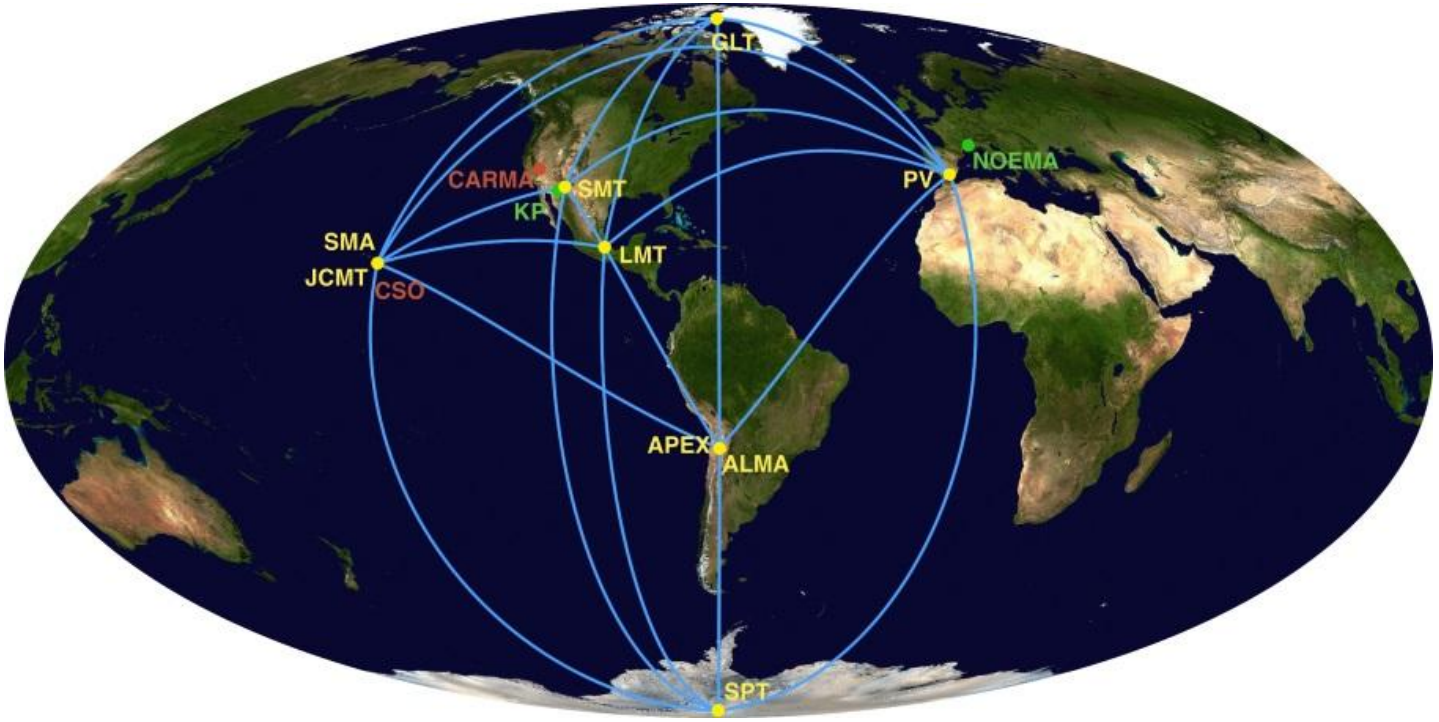
** term used very loosely*

VLA: **V**ery **L**arge **A**rray

interferometer, but not considered “very long baseline” interferometer

Very Long Baseline Interferometry (VLBI)

Instead of physically connecting many telescopes, record the data and then combine it at a central location.



VLBI

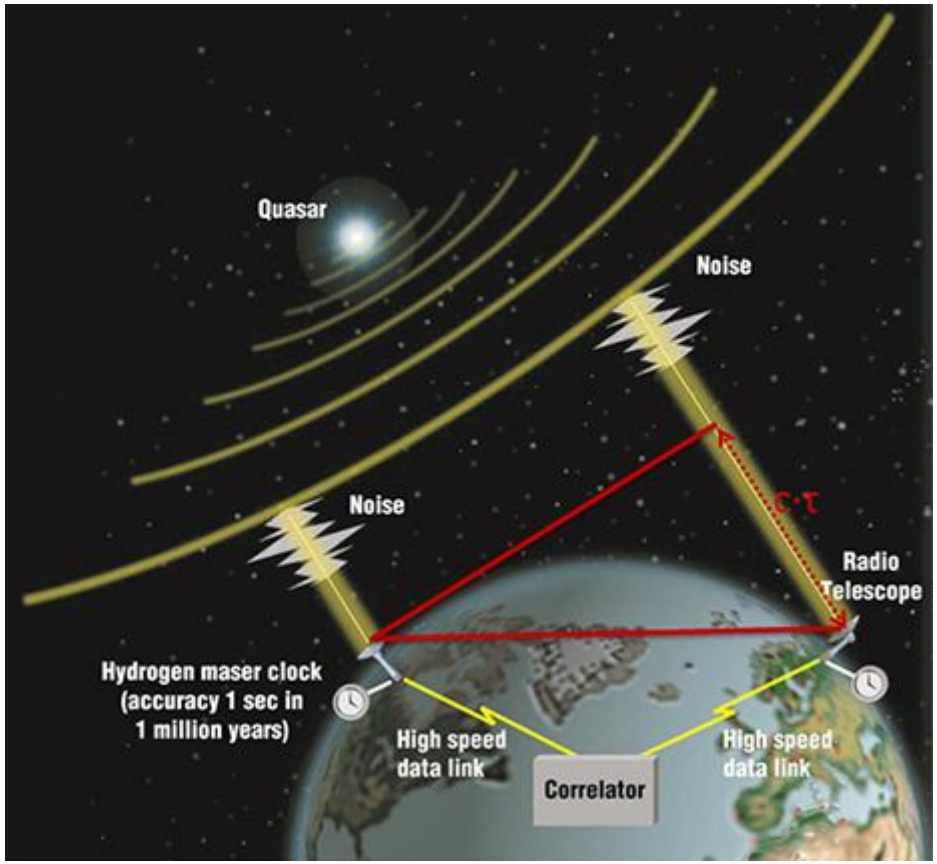
Traditionally uses no IF/LO link between antennas:

- Disk-based recorders for temporary data storage & transport.
- Real time over the internet (eVLBI) option.
- Delayed correlation after shipment of disc packs.
- Atomic clocks for time and frequency – usually H-masers.

VLBI

Radio interferometry with distant, physically unconnected antennas:

- Baselines up to an Earth diameter for ground-based VLBI.
- High resolution – mas to μas.
- Can extend to space (e.g., HALCA, RadioAstron).



VLBI

Can use available single-dish antennas

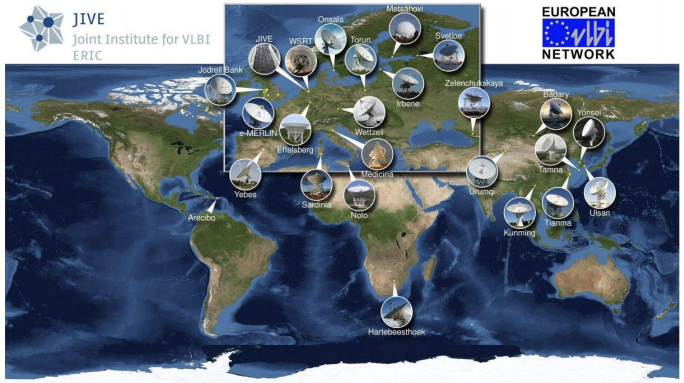
No fundamental difference between linked interferometers & VLBI arrays

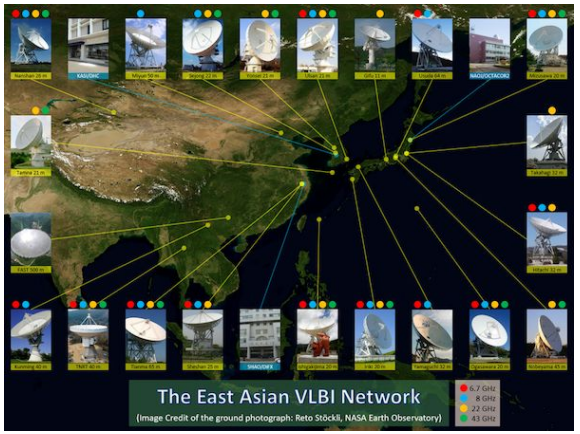
VLBI

Very Long Baseline Interferometry

VLBA

Very Long Baseline Array





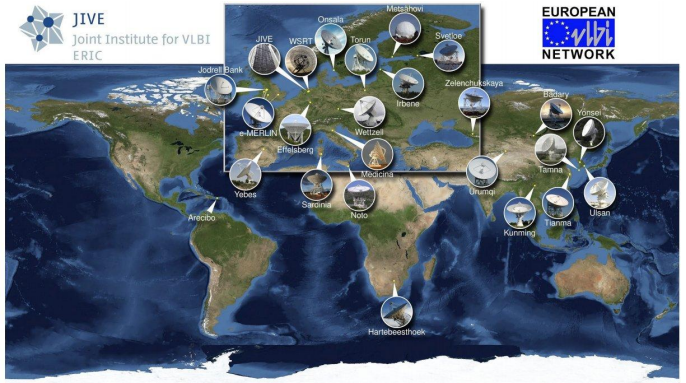
Credit: NRAO/AUI/NSF,
https://public.nrao.edu/gallery/vlba-global-locations/

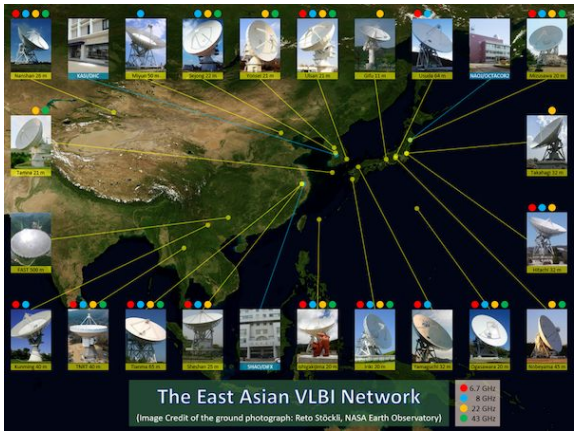
VLBI

Technique, not a telescope.

VLBA

Array of about 10 antennas





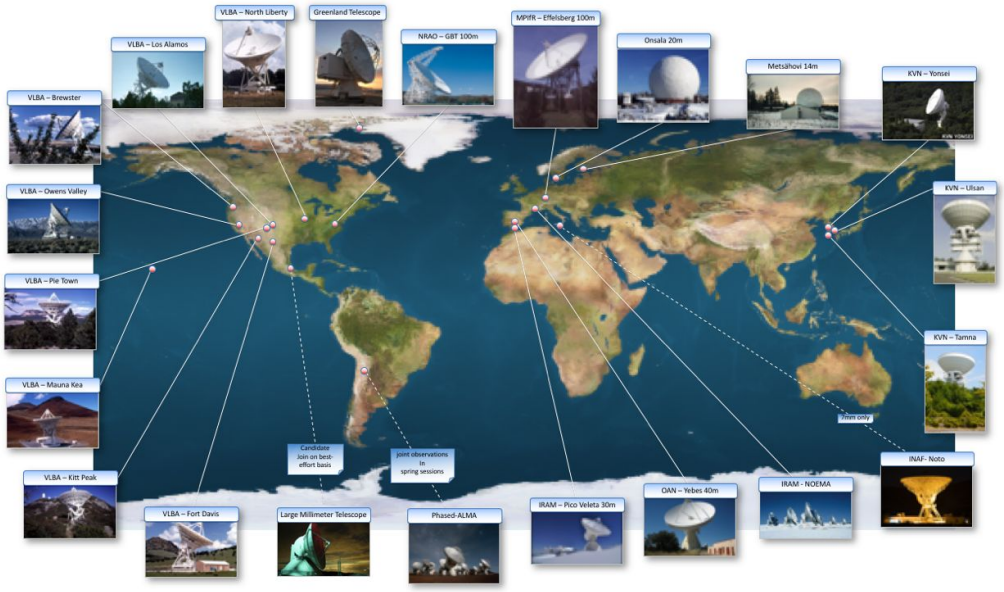
Credit: NRAO/AUI/NSF,
https://public.nrao.edu/gallery/vlba-global-locations/

HSA

High Sensitivity Array

GMVA

Global mm-VLBI Array

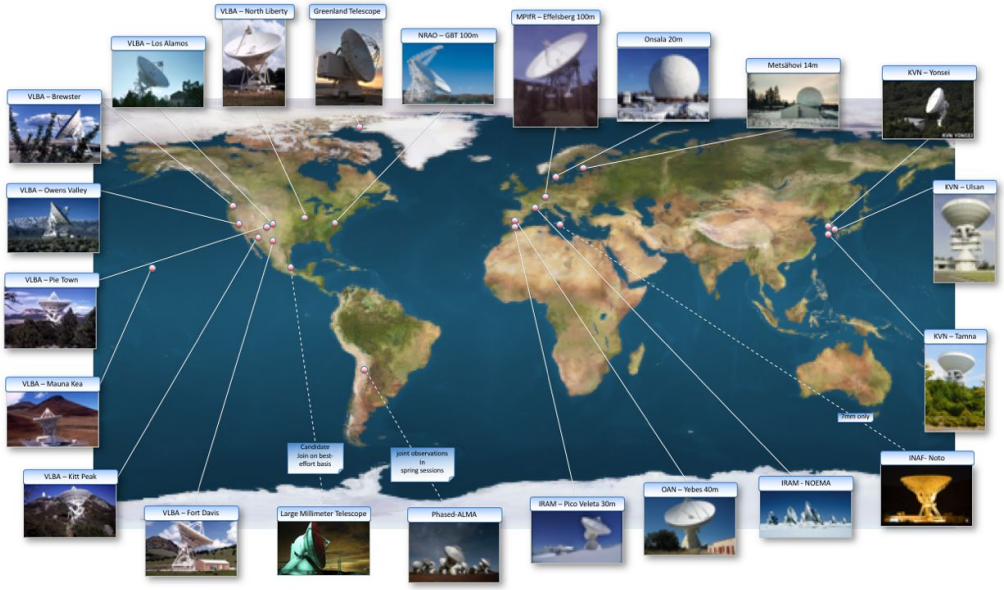


HSA

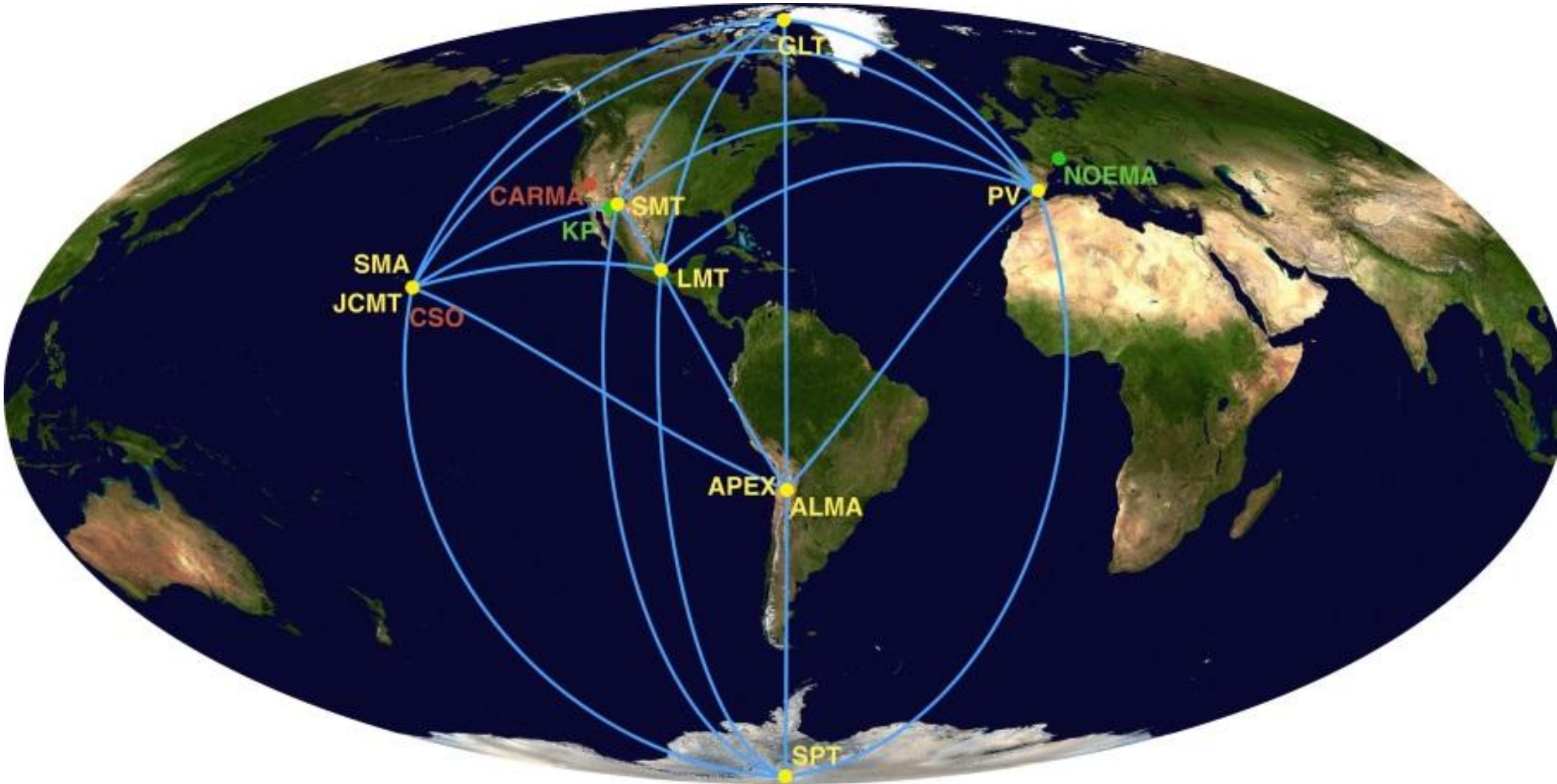
VLBA+GBT+VLA

GMVA

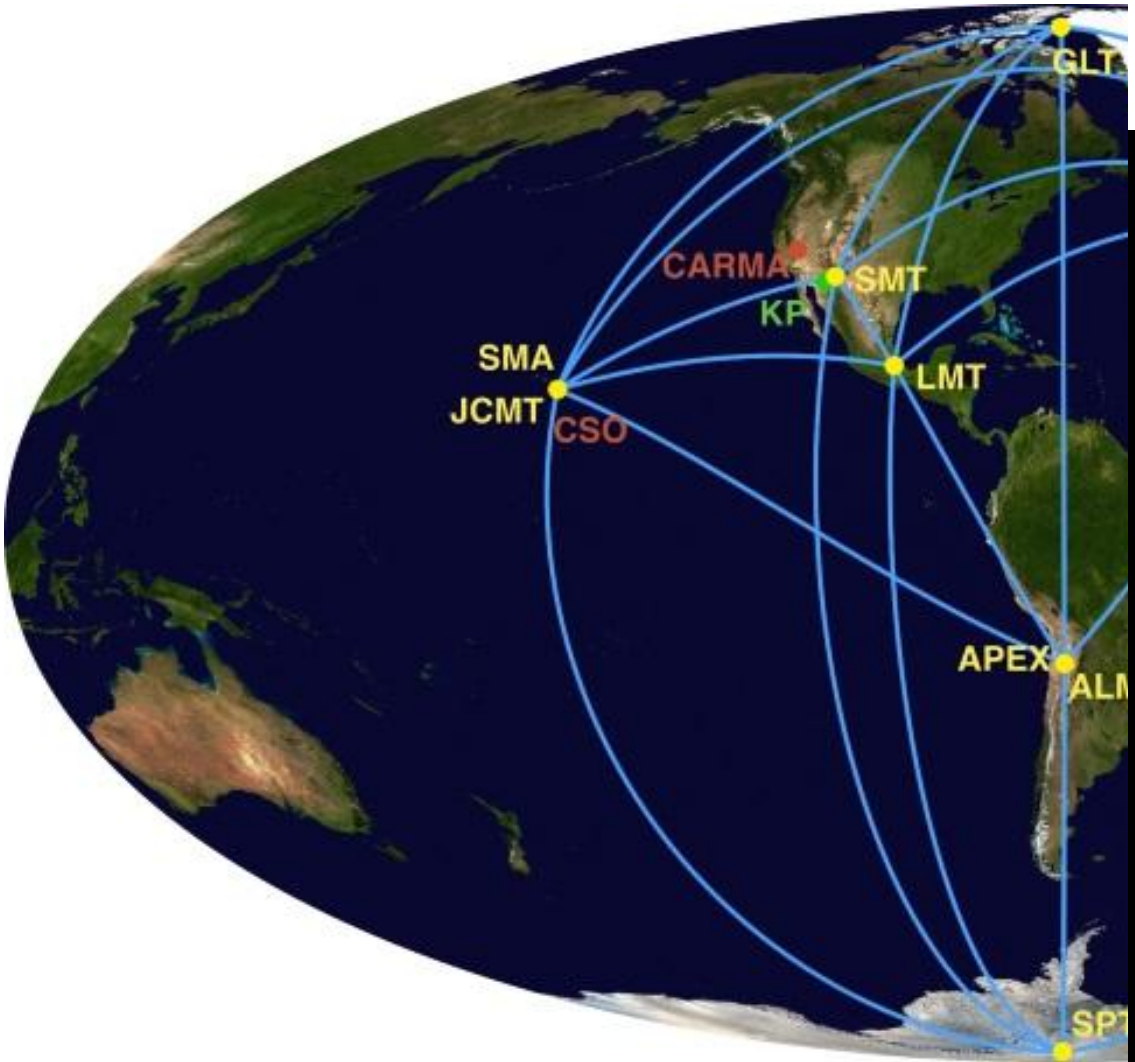
VLBA + GBT + KVN + Effelsburg + Onsala + Metsaehovi + Yebes + …

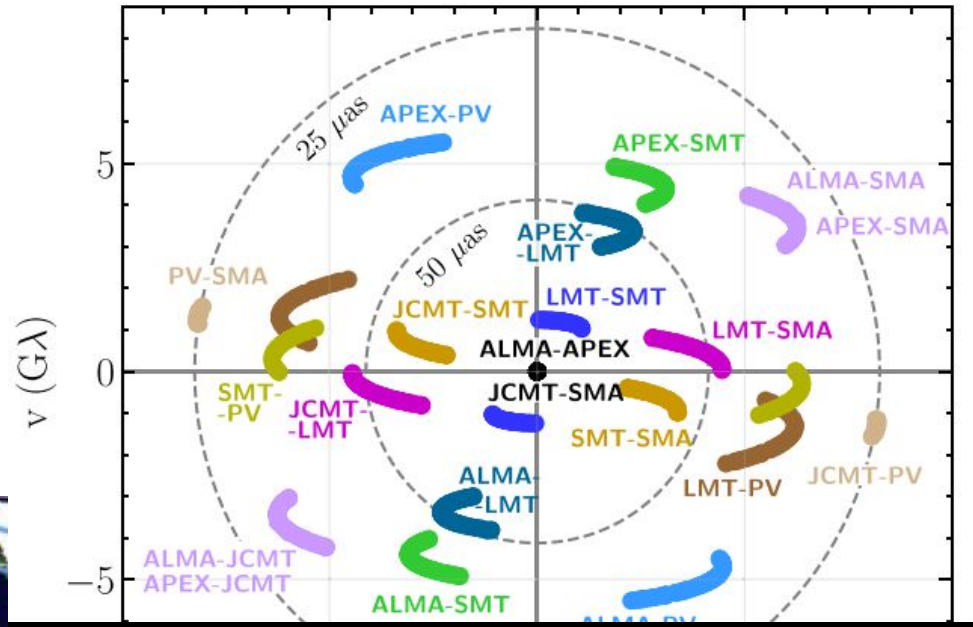


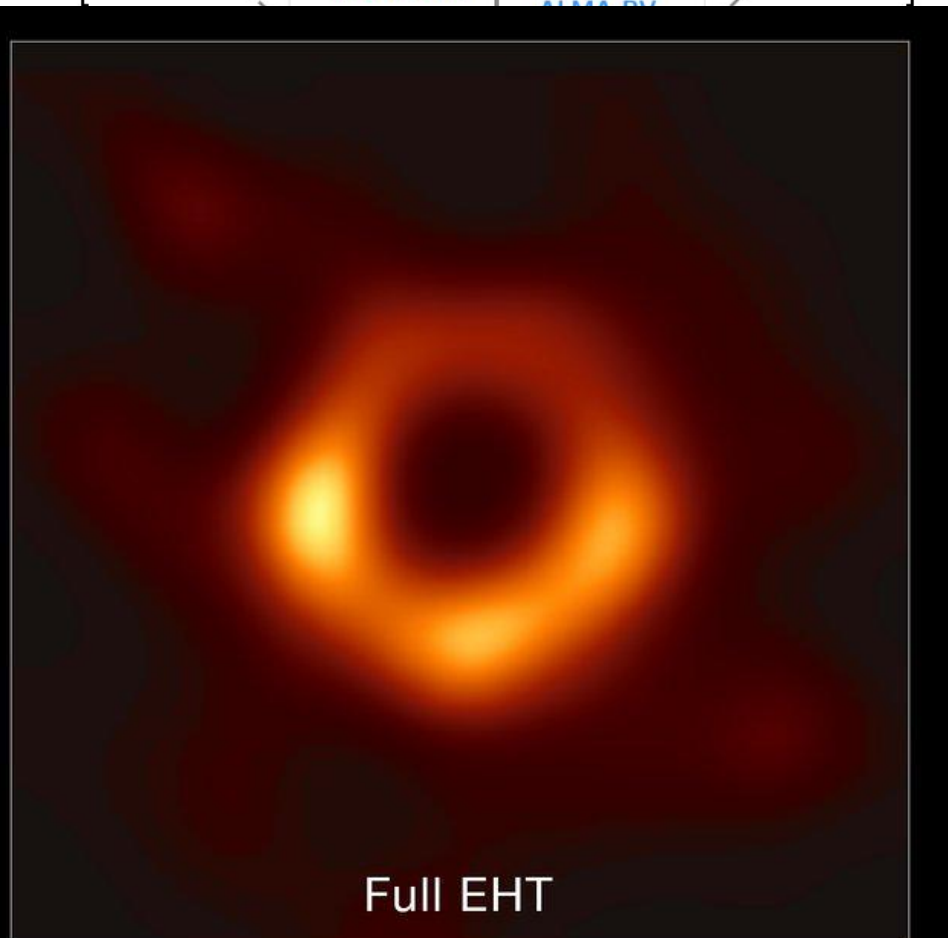
EHT: Event Horizon Telescope



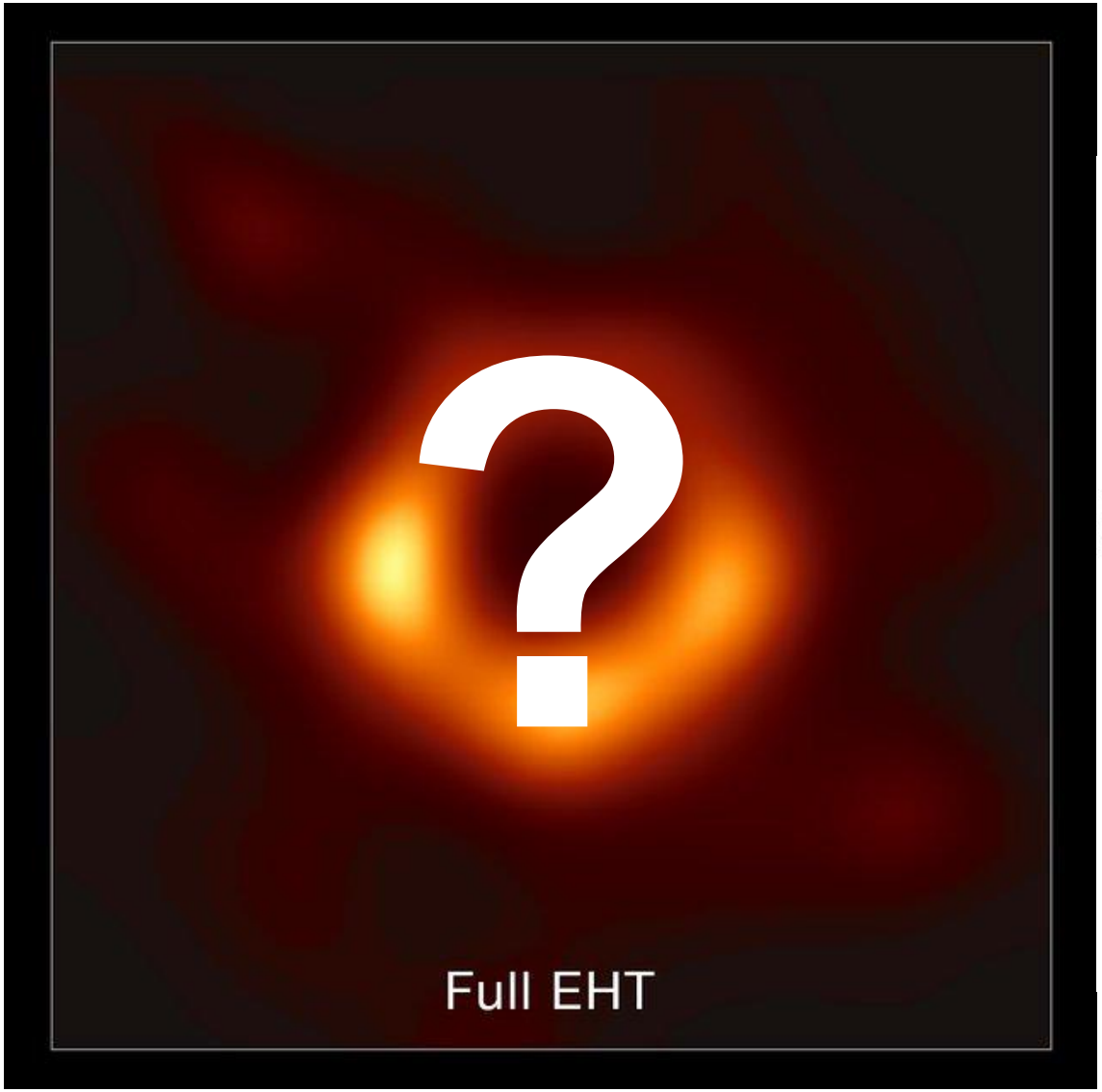
Case Study

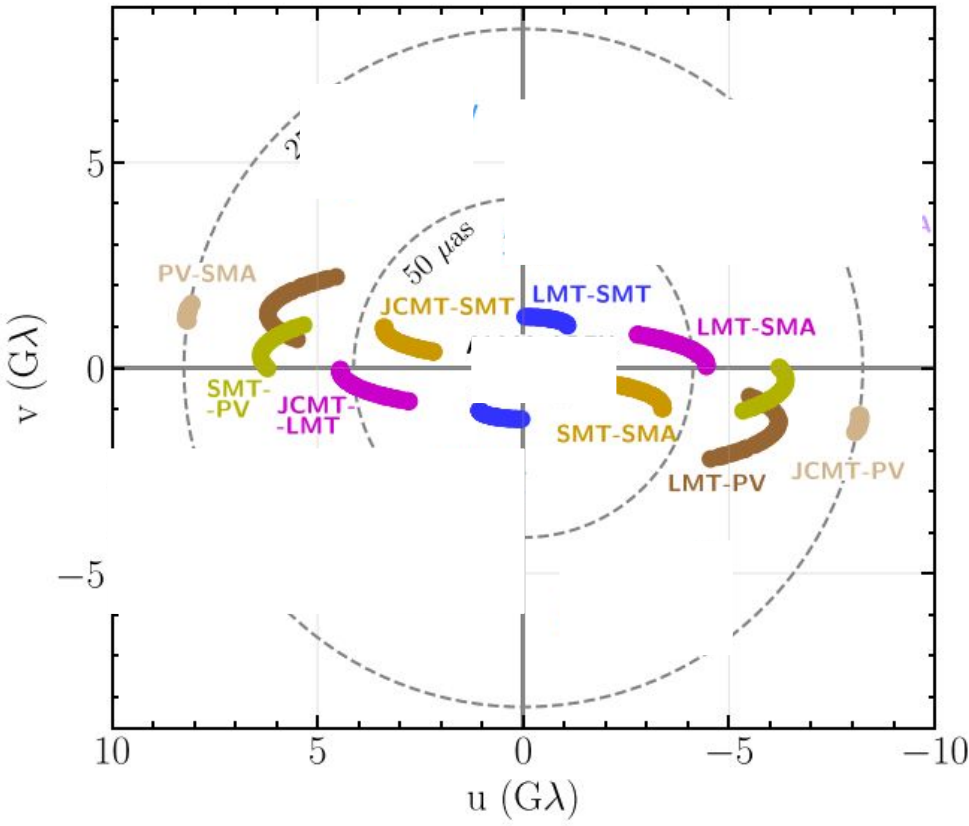

GLT
CARMA
SMT
KP
SMA
LMT
JCMT
CSO
APEX
SPT


25 μas
50 μas
APEX-PV
APEX-SMT
ALMA-SMA
APEX-SMA
APEX--LMT
PV-SMA
JCMT-SMT
LMT-SMT
LMT-SMA
ALMA-APEX
SMT--PV
JCMT--LMT
JCMT-SMA
SMT-SMA
ALMA--LMT
LMT-PV
JCMT-PV
ALMA-JCMT
APEX-JCMT
ALMA-SMT
v (Gλ)
5
0
−5


Full EHT

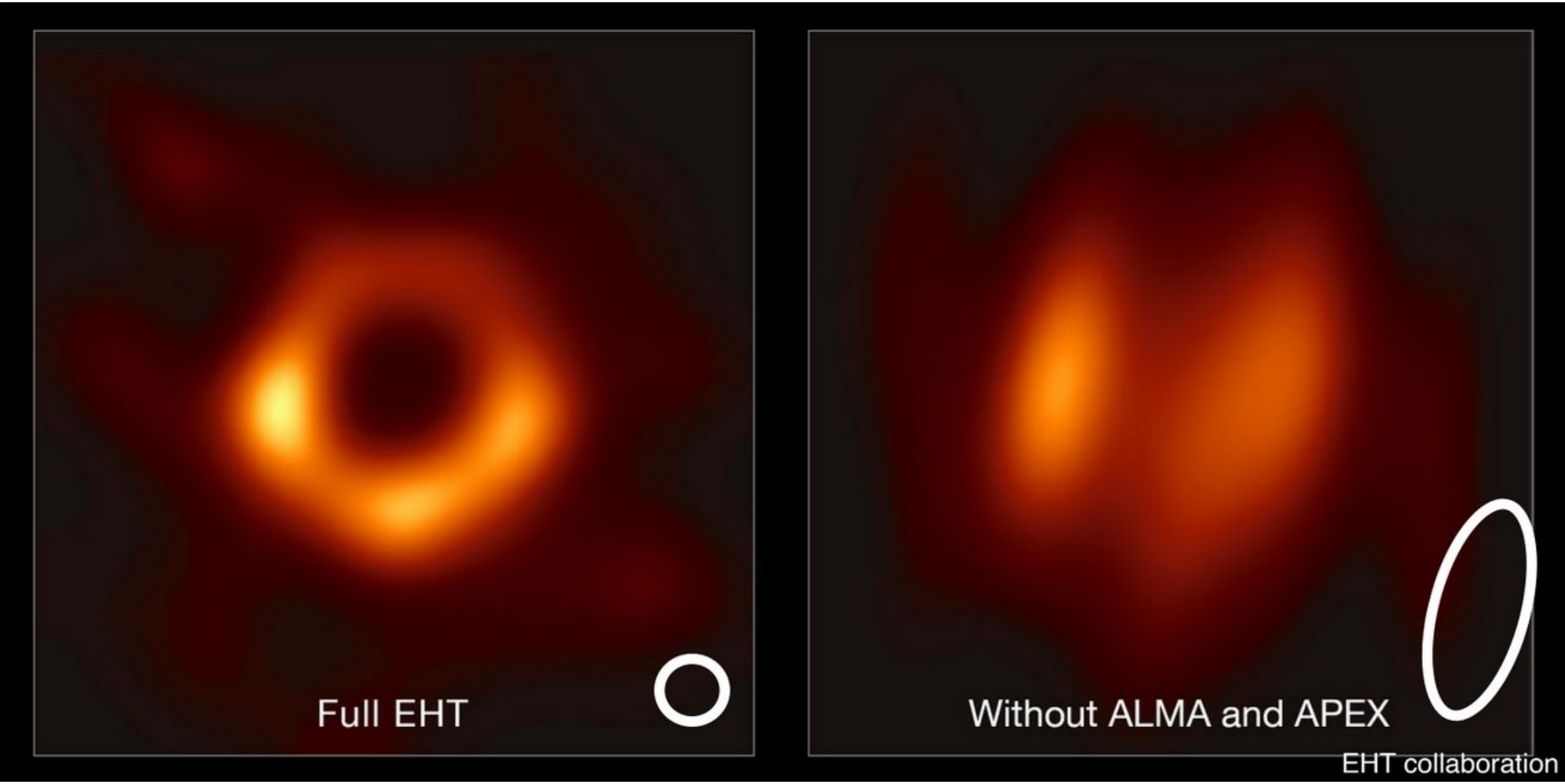
What would this image look like if we didn't have ALMA+APEX in the array?





1. Image stays the same.
2. Noise goes up, but you can still see the shadow.
3. You can’t see the shadow, but the noise stays the same.
4. Noise goes up and you can’t see the shadow.
5. None of the above

What would this image look like if we didn’t have ALMA+APEX in the array?



Noise goes up and you can’t see the shadow

Large Single Dish Drawbacks

- Tend to have slower slew speeds
- Require pointing calibration more often
- Might require additional calibration (e.g., active surface corrections for the GBT)
- Smaller field of view
- No guarantee that weather will cooperate
- High demand and limited time available

Summary

Interferometry enables imaging at high angular resolutions, Very Long Baseline Interferometry takes this to its limits.

Including large single dishes in an array boosts its sensitivity.

Having a large aperture at the right location can significantly improve the image quality.

Each telescope is different: need to account for different calibration strategies, slew rates, etc...

Technical questions

Pause here for technical questions.

I'll briefly go over the logistics of proposing and observing with the GBT as part of a VLBI array, so hold those questions for now or find me later!

Proposal Process

1. Proposal submission
2. Technical reviews
3. Science reviews
4. Time allocation
5. Disposition letter

my.nrao.edu

National Radio Astronomy Observatory

Dashboard | Proposals | Reviews | Data Processing | Obs Prep | Helpdesk | Profile | Admin

Hi, Jay | Sign Out

My Proposals | Proposal List | Available Authors | Available Organizations

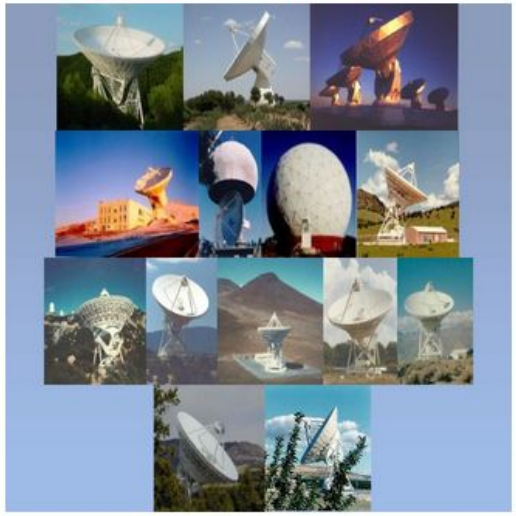
Tuesday 04 June 2024

Create | Help

○ VLA ○ VLA / External

○ GBT ○ GBT / External

◉ VLBA/HSA ○ VLBA / External



○ GMVA

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Observing Proposal

Status:	DRAFT
Create Date:	06/04/2024
Modify Date:	06/04/2024
Submit Date:	
Total Time:	0.0

Title *(80 characters max)*

Sample HSA Proposal

Proposal Type

(•) Regular ( ) Large ( ) Triggered ( ) Director's Discretionary Time

Proposal Sponsor

Sponsor: Not Sponsored

Scientific Category (Click here for additional information about Proposal Science Categories)

( ) High-Luminosity AGN	(AGN, high-luminosity: FR II radio galaxies, quasars, QSOs, blazars, BL Lacs)
( ) Low-Luminosity AGN	(AGN, low-luminosity: FR I radio galaxies, FR 0 radio galaxies, Seyfert galaxies quiescent SMBH, Sgr A*)
( ) Extragalactic Structure	(Galaxies (line): galaxy structure; galaxy kinematics and dynamics; galaxy chemistry; gas in galaxies)
( ) High Redshift and Source Surveys	(High redshift and source surveys: High-z objects; extragalactic source surveys; galaxy formation; gravitational lenses; large-scale structure & clusters (as cosmological probes); CMB; early universe.)
( ) Interstellar Medium	(galactic HI & OH; ISM magnetic field; SNRs; HII regions; astrochemistry)
( ) Normal Galaxies, Groups, and Clusters	(Galaxies (continuum), including galaxies in groups & clusters: disk emission; star formation; magnetic fields; galactic winds; starbursts; intracluster emission & ICM astrophysics.)
(•) Solar System, Stars, Planetary Systems	(Sun, planets, comets, IPM; exoplanets; main sequence stars; active stars; stellar winds; AGB & post-AGB stars; PNe; novae)
( ) Star Formation	(young stellar objects; protostars; jets, outflows; T Tauri stars; circumstellar disks; protoplanetary systems; astrochemistry)
( ) Gravitational Waves and Energetic Transients	(supernovae, gravitational wave sources, gamma-ray bursts, tidal disruption events, fast radio bursts, exotic/unknown transients)
( ) Pulsars and Compact Objects	(millisecond pulsars, cataclysmic variables, black hole and/or neutron star x-ray binaries, pulsar timing, pulsar proper motion)

Abstract *(200 words max, 10 min)* **[Word Count : 31]**

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Sample proposal - example of how to submit an HSA (High Sensitivity Array)
proposal that includes the GBT as a station.

Note, this is NOT a "Joint" proposal with the GBT!
```

Joint

If you are submitting a joint proposal please see the instructions here.

- [ ] GBT
- [ ] VLA
- [ ] HST Orbits Requested 1
- [ ] Swift Ksec. 0
- [ ] Chandra Ksec. 0
- [ ] XMM-Newton Ksec. 5
- [ ] NICER Ksec. 0
- [ ] JWST Hrs. 0

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Observing Proposal

Status:	DRAFT
Create Date:	06/04/2024
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Title *(80 characters max)*

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Sponsor: Not Sponsored

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( ) Low-Luminosity AGN	(AGN, low-luminosity: FR I radio galaxies, FR 0 radio galaxies, Seyfert galaxies quiescent SMBH, Sgr A*)
( ) Extragalactic Structure	(Galaxies (line): galaxy structure; galaxy kinematics and dynamics; galaxy chemistry; gas in galaxies)
( ) High Redshift and Source Surveys	(High redshift and source surveys: High-z objects; extragalactic source surveys; galaxy formation; gravitational lenses; large-scale structure & clusters (as cosmological probes); CMB; early universe.)

Joint Proposals

Proposals requesting multiple telescopes are considered joint proposals. Select one or more telescopes from the list. You must submit a separate proposal for each NRAO telescope; those proposals must each include the same scientific justification. The cover information for each NRAO telescope may differ. The PST must be used if either the GBT, VLA, or VLBA are used in the joint proposal. VLBI proposals which request the GBT or VLA (or the HSA, for example) as elements of the VLBI array do not need separate proposals - those telescopes can be selected as separate VLBI stations from a VLBA/HSA proposal.

VLBI observations combining the VLBA with any one or more of the other three HSA stations can be requested in a single HSA proposal. HSA proposals requesting only *VLBI* use of HSA telescopes **should not be identified as Joint proposals**. However, separate proposals must be submitted for any *non-VLBI* use of any requested telescopes.

[ ] XMM-Newton	Ksec.	5 ▲▼
[ ] NICER	Ksec.	0 ▲▼
[ ] JWST	Hrs.	0 ▲▼

https://services.jive.eu/evn-calculator/cgi-bin/EVNcalc.pl

EUROPEAN VLBI NETWORK — Consortium for Very Long Baseline Interferometry in Europe — EUROPEAN VLBI NETWORK

This resource is outdated and no longer suggested.

EVN Calculator

EVN | e-EVN | VLBA | GLOBAL | GMVA | EVN+e-MERLIN — RESET | GO

Observing band & data rate [Mbit/s]	On-source integration time [min]
L - 18cm, 1024	150

☐ Ef	☐ Pi	☐ Hh	☐ ALMA	☐ Pa	☐ Nl
☐ Mc	☐ Wb	☐ My	☐ Pv	☐ Ho	☐ Fd
☐ On	☐ W1	☐ Km	☐ Ro70	☐ Cd	☐ La
☐ Tr	☐ Nt	☐ FAST	☐ Ro34	☐ Ap	☐ Kp
☐ Jb1	☐ Sh	☐ Sv	☐ Pb	☐ Go	☐ Pt
☐ Jb2	☐ Tm65	☐ Zc	☐ Ku	☐ Gb	☐ Ov
☐ Cm	☐ Ur	☐ Bd	☐ Ky	☐ Y1	☐ Br
☐ Da	☐ Mh	☐ Wz	☐ Kt	☐ Y27	☐ Mk
☐ De	☐ Ys	☐ Ka	☐ At	☐ Sc	
☐ Kn	☐ Sr	☐ Ir	☐ Mp	☐ Hn	

A simple guide:

- one station: SEFD
- two stations: baseline sensitivity
- more stations: image thermal noise

- field of view and EVN MkIV correlator limitations are given below

Number of spectral channels per subband, integration time [s], and maximum baseline length	Number of polarizations, subbands per polarizations, and bandwidth of a subband [MHz]
16 ch, 2 s, 10000 km (Full EVN)	2 pols, 8 sb, 16 MHz
Please select an array (N>2) and an observing band.	MkIV Correlator limitations no longer apply.

RESET | GO

https://planobs.jive.eu/

EUROPEAN VLBI NETWORK

EVN Observation Planner

JIVE
Joint Institute for VLBI ERIC

The EVN Observation Planner allows you to plan observations with the European VLBI Network (EVN) and other Very Long Baseline Interferometry (VLBI) networks. The EVN Observation Planner helps you to determine when your source can be observed by the different antennas, and provides the expected outcome of these observations, like the expected sensitivity or resolution.

GUIDED MODE

EASY STEP-BY-STEP SETUP

MANUAL MODE

FULLY MANUAL CONFIGURATION

Find me after the talk if you want a demo!

my.nrao.edu

VLBA/HSA RESOURCES

« ‹ Resources › »

Order	Name	Wavelength	Processor	Observing Mode	Session
		3.6 cm	Socorro-DiFX	Standard/Shared Risk	

Stations		Observing Parameters		Correlation Parameters		Special Features	
VLBA ☑	BR ☑ FD ☑ HN ☑ KP ☑ LA ☑ MK ☑ NL ☑ OV ☑ PT ☑ SC ☑	Observing System	DDC System	Number of Correlator Passes	1	Full Polarization	☐
		Bandwidth	128 MHz	Integration Period(sec)	2.0	Pulsar Gate	☐
HSA ☑	GBT ☑ EB ☑ VLA-Y27 ☑ VLA Config: A ○ B ○ C ○ D ○ Any ◉	Baseband Channels	4	Spectral Points/BBC	256	Output Format Conversion to Mark4	☐
VLA	Y1 ☐	Polarization	Dual	No. of Phase Centers per Pointing	1	Baseband Data Copy	☐
Geodetic		Agg. Bit Rate (Mbits/sec)	2048				

Save
Delete
Cancel

SESSIONS

« ‹ Sessions › »

Session	Number of Sessions	Separation	Min. Start GST	Max. End GST
Save the session (Source Groups / Resources) before calculating Min/Max GST			Calculate Min/Max GST	EVN Exposure Calculator
	1	0 day(s)	00:00:00 (HH:MM:SS)	24:00:00 (HH:MM:SS)

Scheduling Constraints:

Comments:

Save
Cancel

Source Groups	Resources	Time/Session (hrs)

Note: Adding Source Groups to a session will automatically associate all sources, within the group, to the session.

Observing Process

.key file:
you'll prepare an observing instruction file and email it to the VLBI analysts for validation

Scheduling:
depends on your project type and grade (GMVA has fixed dates, all others are scheduled somewhat dynamically)

Service observing:
we run the observations, you receive the correlated data

Tips and Tricks

Proposing:

- Set your LST ranges carefully.
- Make sure source is visible at the GBT!
- Leave time for overhead
- Ask for help (https://help.nrao.edu/)

Observing:

- **Use your project friend!**
- Make your intentions clear

GREEN BANK OBSERVATORY

greenbankobservatory.org

The Green Bank Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

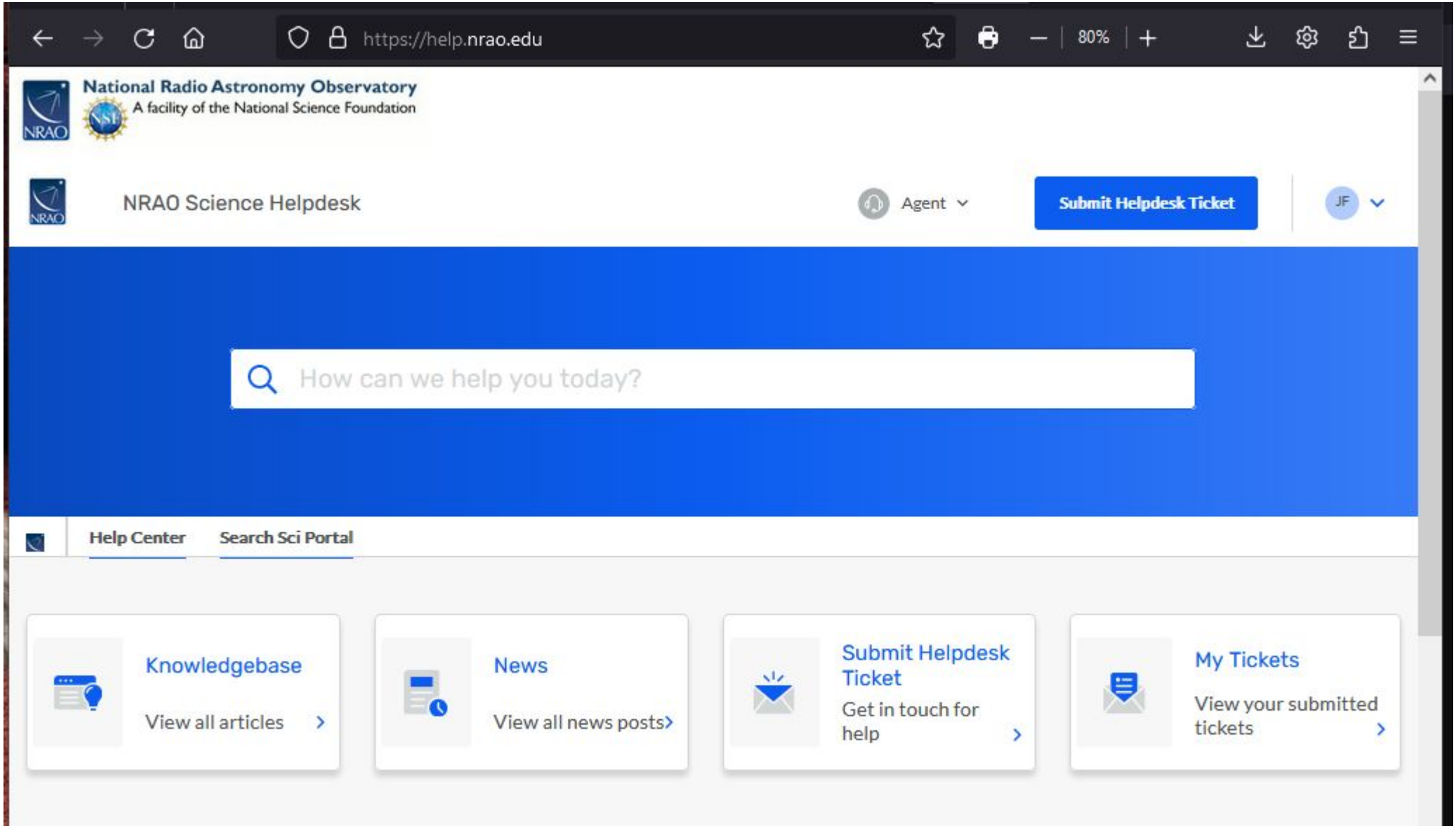
Extra Slides

For more information on data reduction and calibration techniques, either attend or look for old lecture videos!

Acronym Dictionary

VLA - Very Large Array
VLBI - Very Long Baseline Interferometry
VLBA - Very Long Baseline Array
HSA - High Sensitivity Array
GMVA - Global mm-VLBI Array
EHT - Event Horizon Telescope

https://help.nrao.edu/



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https://help.nrao.edu/

Topics

○VLA ○GBT ◉VLBA ○General ○Data Products; ○ngVLA

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CC

Department Descriptions:

CASA Data Reduction - Queries/issues on data reduction using CASA

AIPS Data Reduction - Queries/issues on data reduction using AIPS

VLA/GBT/VLBA Proposing - Proposal preparation, call for proposals, available capabilities, Sensitivity/Exposure Calculators, GBT Mapping Calculator, VLA GOST, NRAO Proposal Submission Tool (PST)

VLA/VLBA Archive and Data Retrieval - NRAO archive tool (AAT), accessing and downloading data, remote access to data

VLA/GBT/VLBA Proposal Review - Questions from NRAO SRP and TAC members, Proposal Handling Tool (PHT)

VLBA Observing - Observing strategies and guidelines, schedule preparation/verification, using the SCHED software, VLBA Calibrators, VLBA data quality and issues

VLBA Scheduling Support - project availability, general scheduling issues/concerns

Visitor Support - New Mexico - questions about visiting NRAO-Socorro. NOTE: for visitor requests, please register using this linked form

VLBA General Queries - Webpages, documentation, access/registration to my.nrao.edu, etc.

VLBA Calibrator Search Tool Feedback - Feedback related to beta testing of the VLBA calibrator search tool.

Archive Access Tool Feedback - Feedback and feature requests related to the new archive access tool.

Department * VLA/GBT/VLBA Proposing

Telescope *

○ VLA/EVLA ○ VLBA ◉ GBT ○ ALMA ○ Other

Subject * How do I propose for the GBT in my VLBI observation???

Message *

GREEN OBSERV