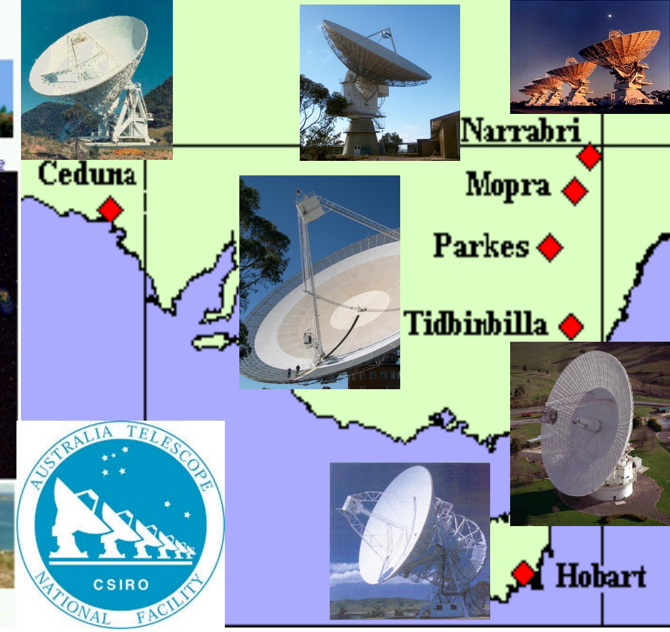
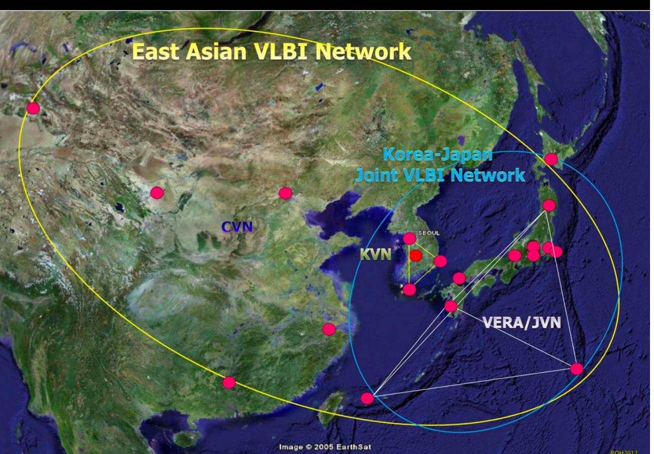




EventHorizonTelescope

Very Long Baseline Interferometry

Adam Deller

18th NRAO Synthesis Imaging Workshop

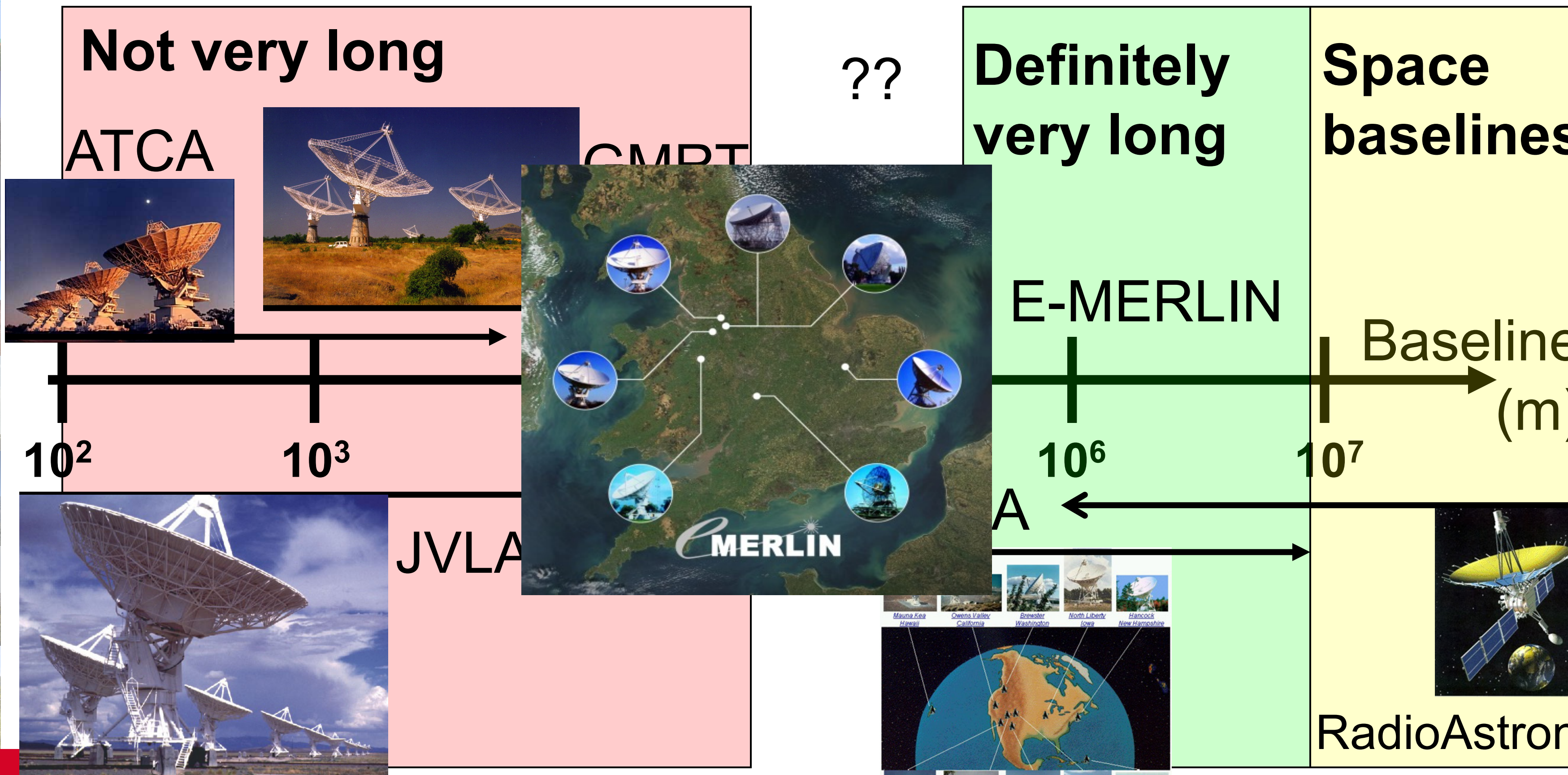
May 19, 2022

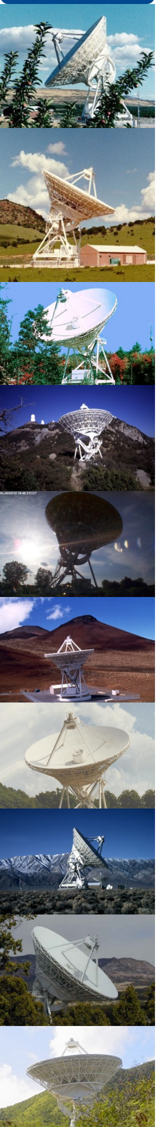
Outline

- What is VLBI and what does it give you?
- Science applications of VLBI (get excited!)
- What makes VLBI different from ”vanilla” interferometery
- How to “do” VLBI: scheduling and data reduction
- New capabilities & the future of VLBI

VLBI in context

- How long is “Very Long”?





VLBI in context

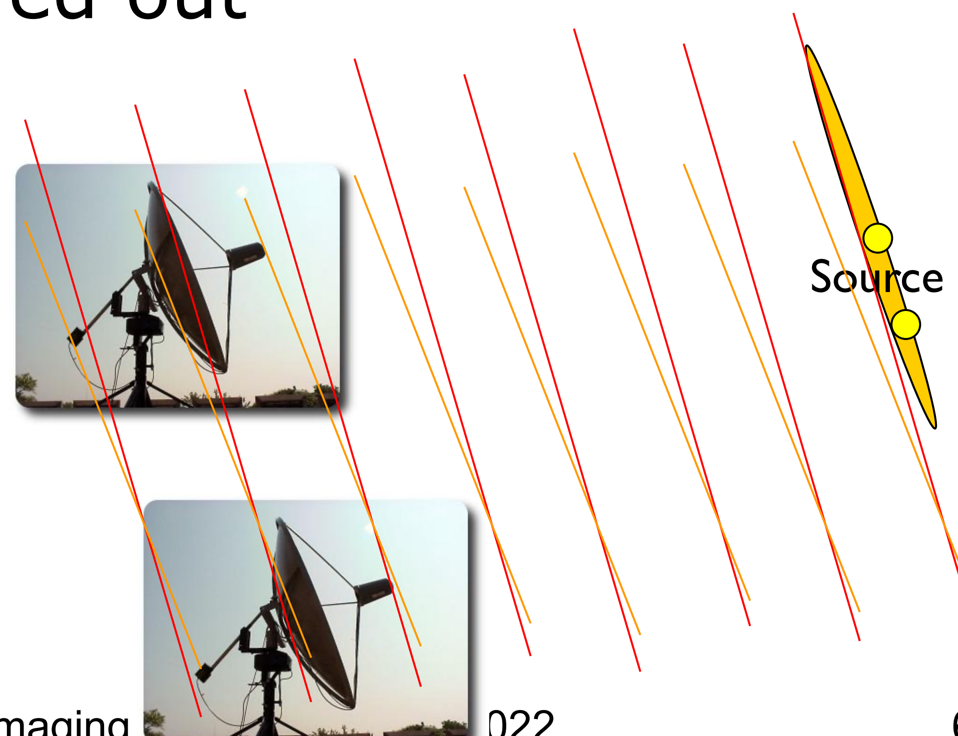
- Clearly not just about baseline length…
- What constitutes VLBI is actually a little hard to pin down (its more like a “syndrome” than a “disease”!)
  - Reason: **no** fundamental difference between VLBI and regular interferometry - only technology, convenience and convention
  - Independent antenna electronics is a good rule of thumb (i.e., anything that’s not “connected element”), but counter-examples exist in both directions!

What VLBI gives you

- Fundamentals of interferometry say: resolution will be very high:
  - At 1.4 GHz (21cm), an array of maximum baseline 8,000 km will have a resolution of $1.22\lambda/D$ ~= 7 milli-arcseconds!
  - At 43 GHz (7 mm), the same array will have a resolution of 200 microarcseconds!
  - 230 GHz (1mm): 30 microarcseconds!
- The collecting area can also be very large, so point source sensitivity can be excellent (just wait for FAST-VLBI!)

… but there’s always a catch

- The curse of resolution; if the object is larger than your synthesized beam, emission from different regions will interfere destructively and the source will be “resolved out”
- The surface brightness sensitivity is very low (array filling factor is low)



Science applications of VLBI

- VLBI provides a tool to study mas-level structure in radio sources - what sources are this compact?
  a) Accreting black holes – stellar mass to Active Galactic Nuclei (AGN)
  b) Neutron stars – accreting or not!
  c) The formation of a) or b) (supernovae)
  d) A few years later (supernova remnants)
  e) A collision between a) and/or b)
  f) Masers
  g) Magnetically active stars

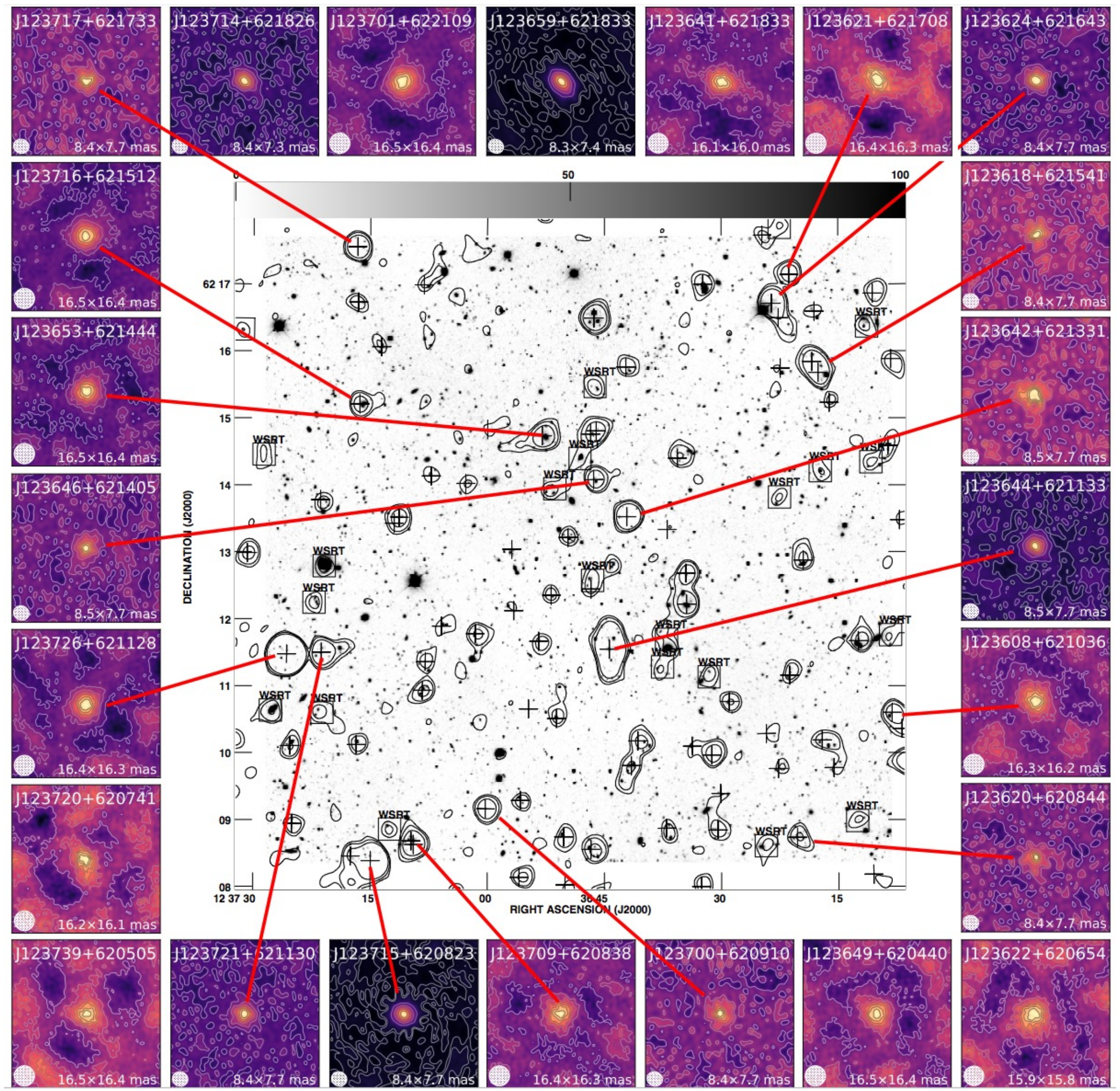
Science applications of VLBI

- For these sources, we typically want one of four things:
  - Compact flux? [Is anything there at all?]
  - Determine (very) small scale structure [e.g., what do the base of jets in AGN look like, GW afterglow evolution with time?]
  - Their precise location, to obtain source kinematics or distance [astrometry]
  - A “test source” to model the propagation through the ISM/atmosphere/ionosphere or the receiving telescopes location [geodesy, interplanetary/interstellar “weather”]

Hallo? Any (compact) body there?

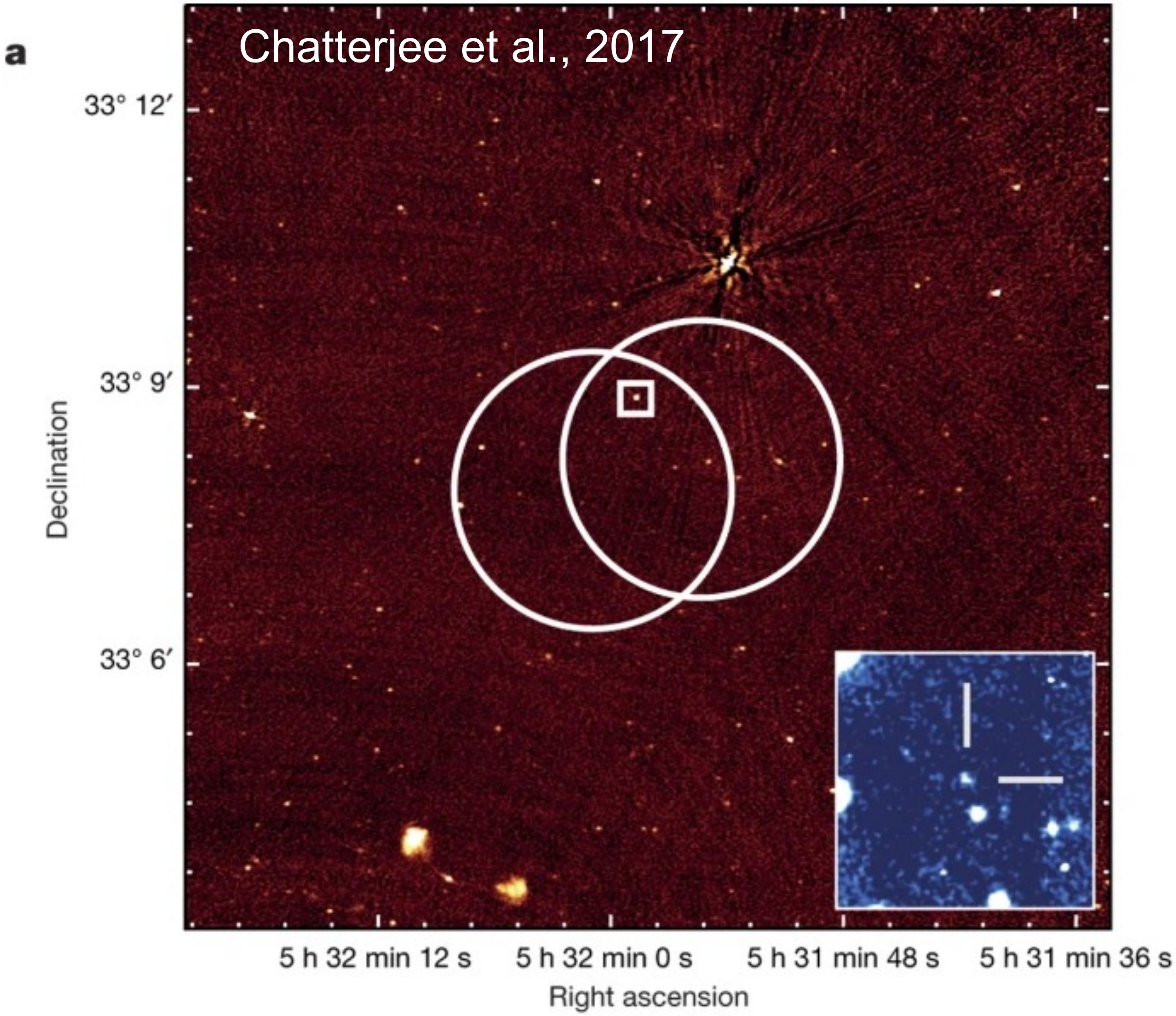
- A VLBI detection instantly identifies a compact non-thermal source, ruling out any potential non-compact explanations

Hallo? Any (compact) body there?



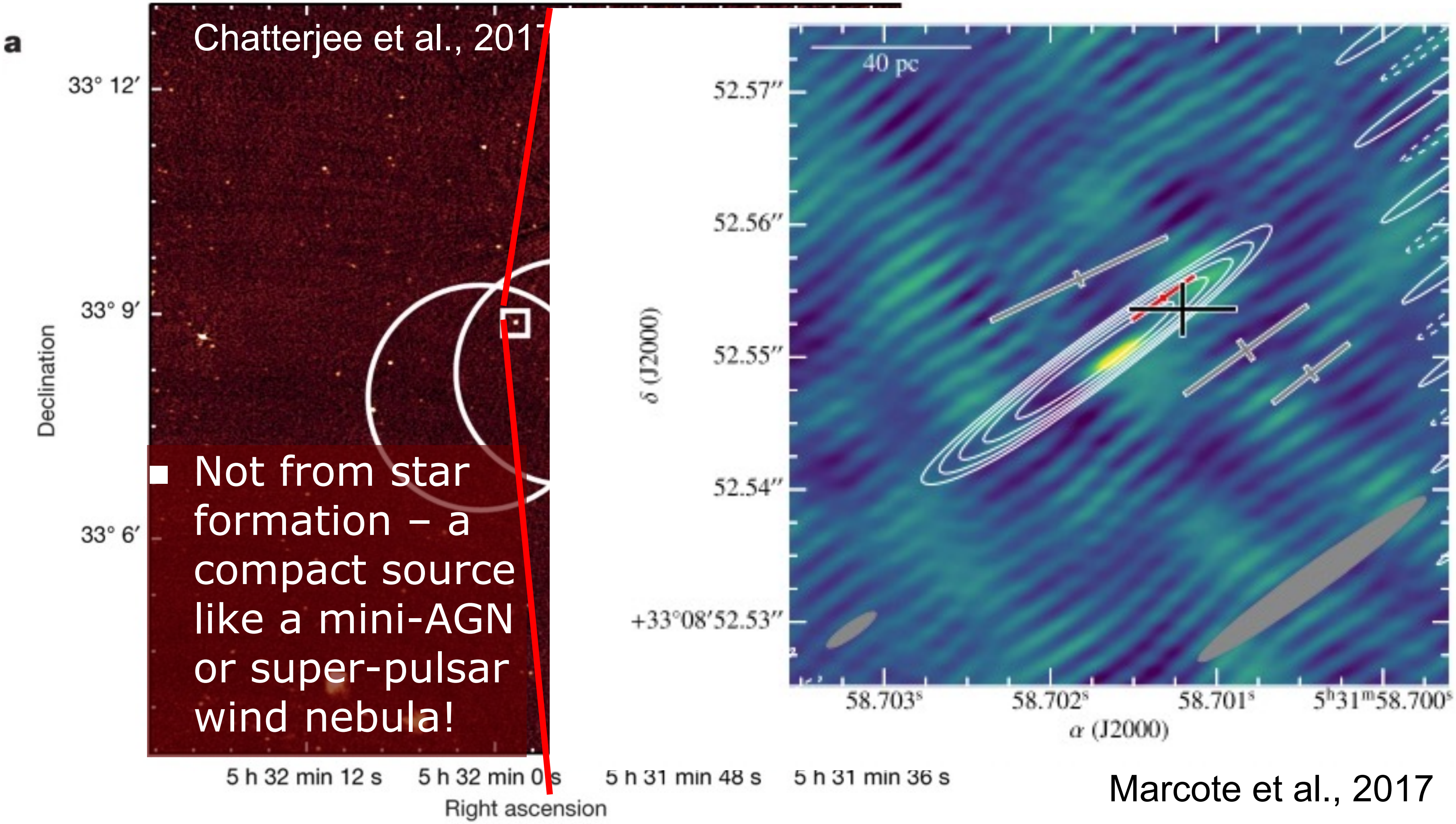
Radio AGN in the GOODS-N field; Radcliffe et al., 2018

Hallo? Any (compact) body there?



- Mysterious continuum radio emission at the site of a Fast Radio Burst hosted by a dwarf galaxy at z~0.2…

Hallo? Any (compact) body there?

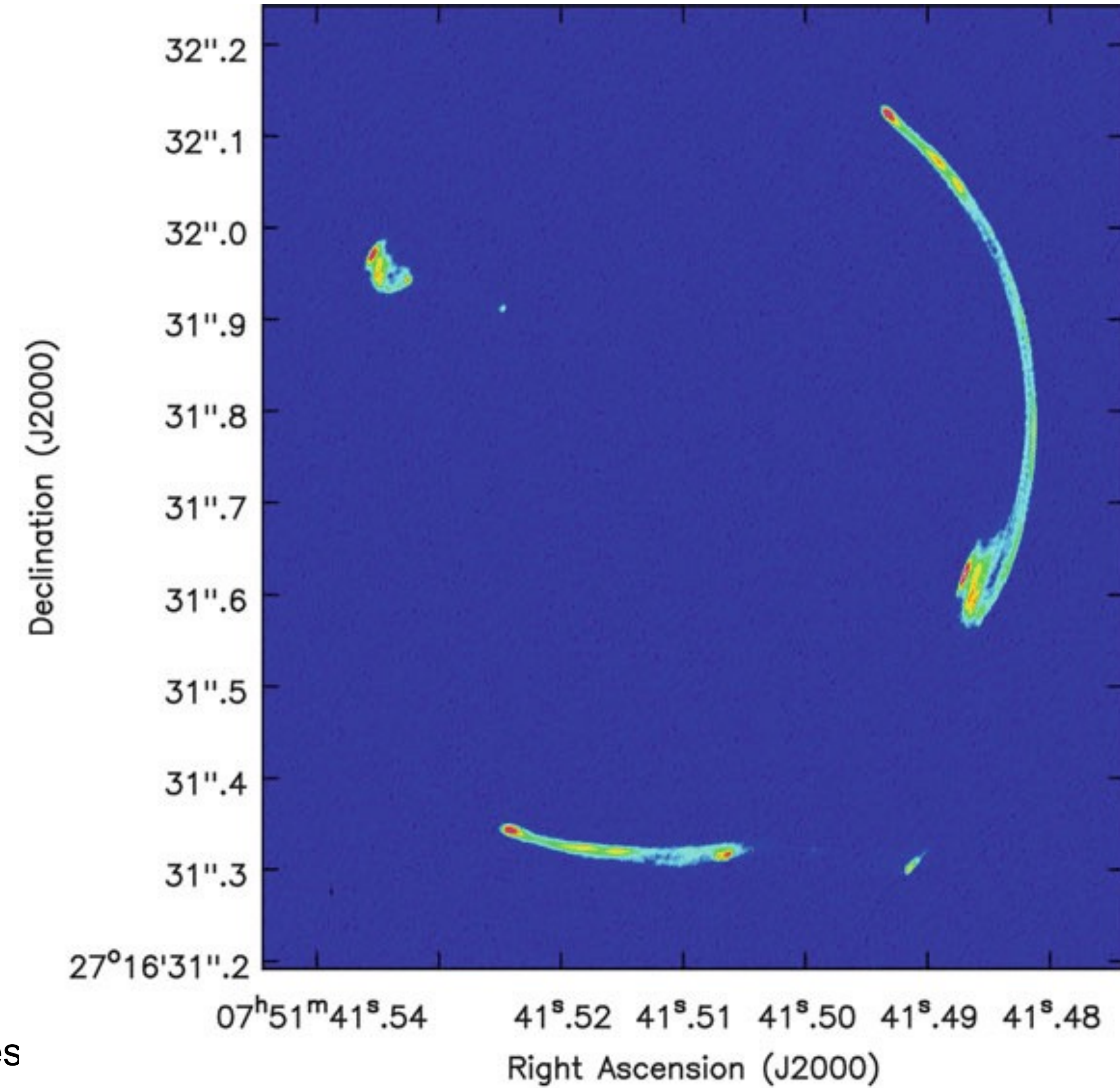


- Not from star formation – a compact source like a mini-AGN or super-pulsar wind nebula!

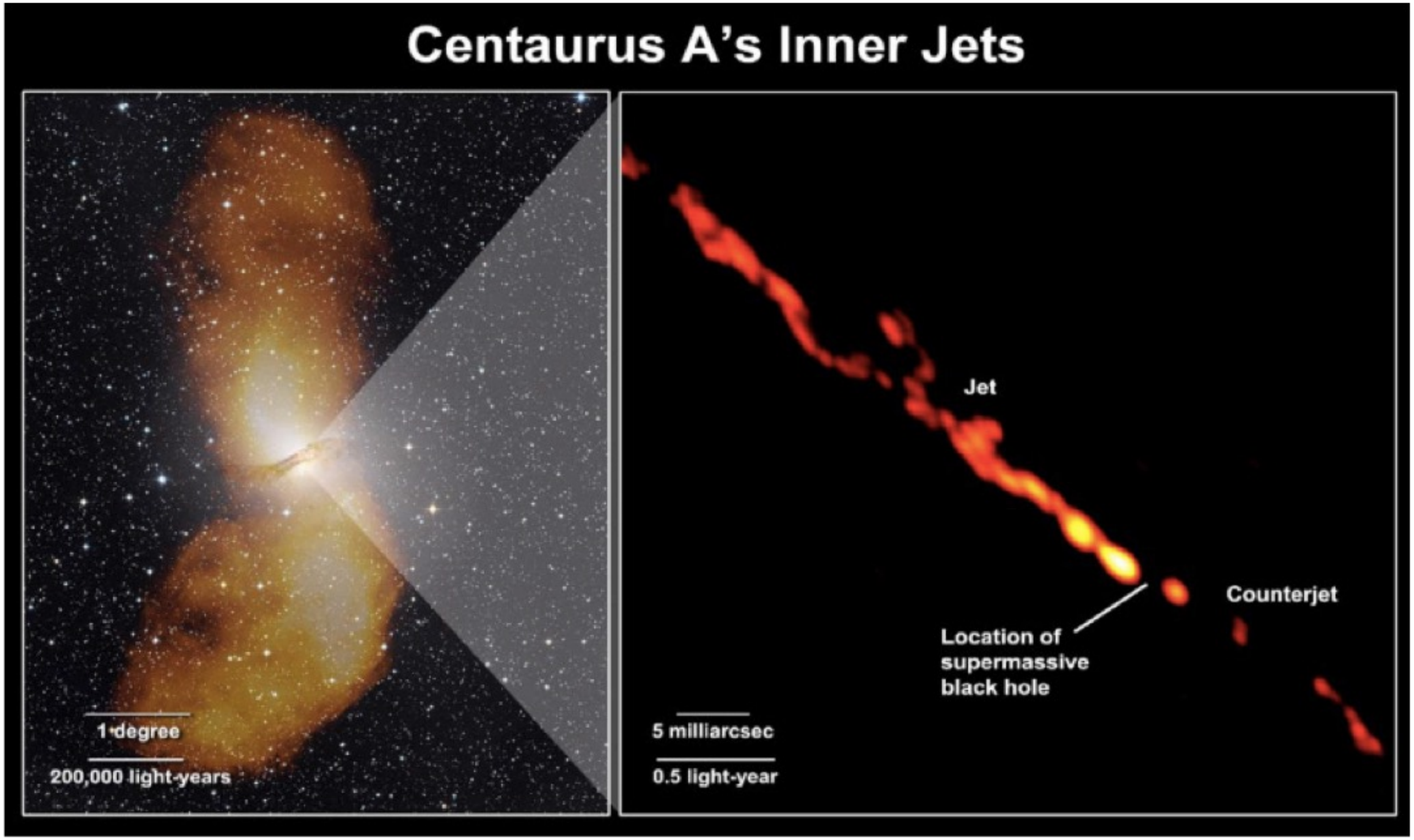
Marcote et al., 2017

High resolution imaging

- Gravitationally lensed source MG J0751+2716 (at z~3) – rich substructure detected in lensing halo! (Spingola et al. 2018)

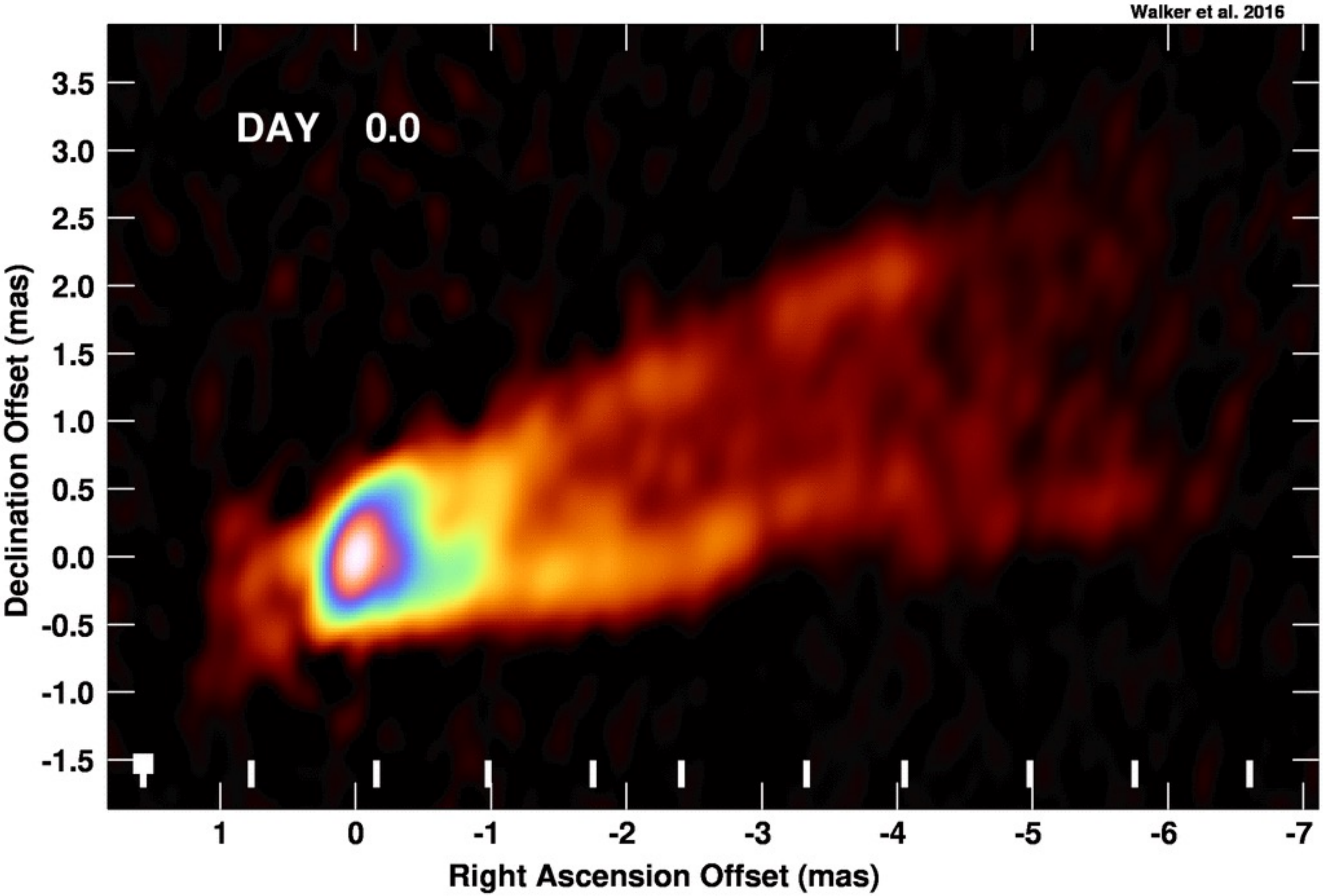


High resolution imaging

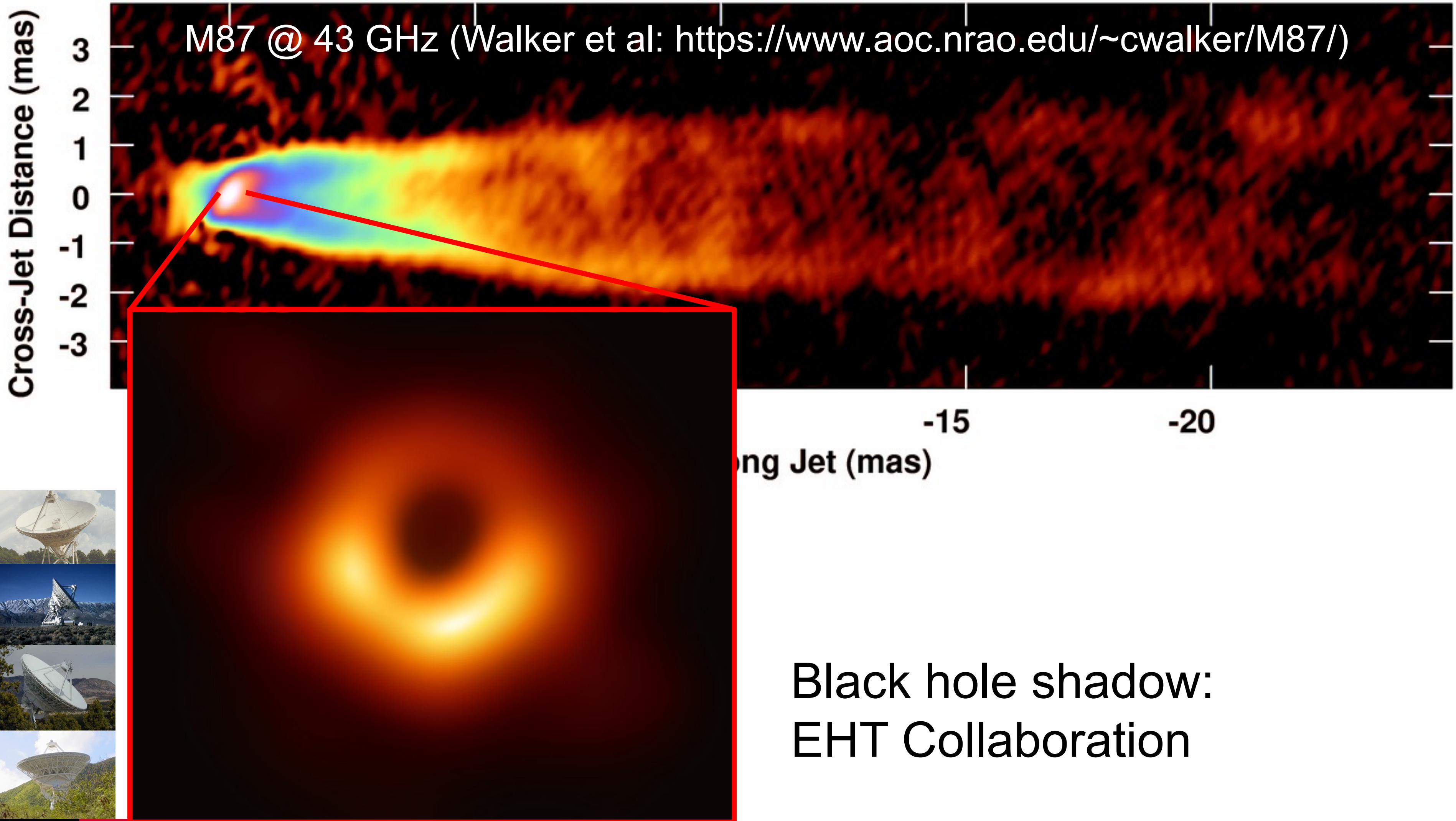


Zoom in 400,000x on Centaurus A: TANAMI / C. Muller

High resolution imaging

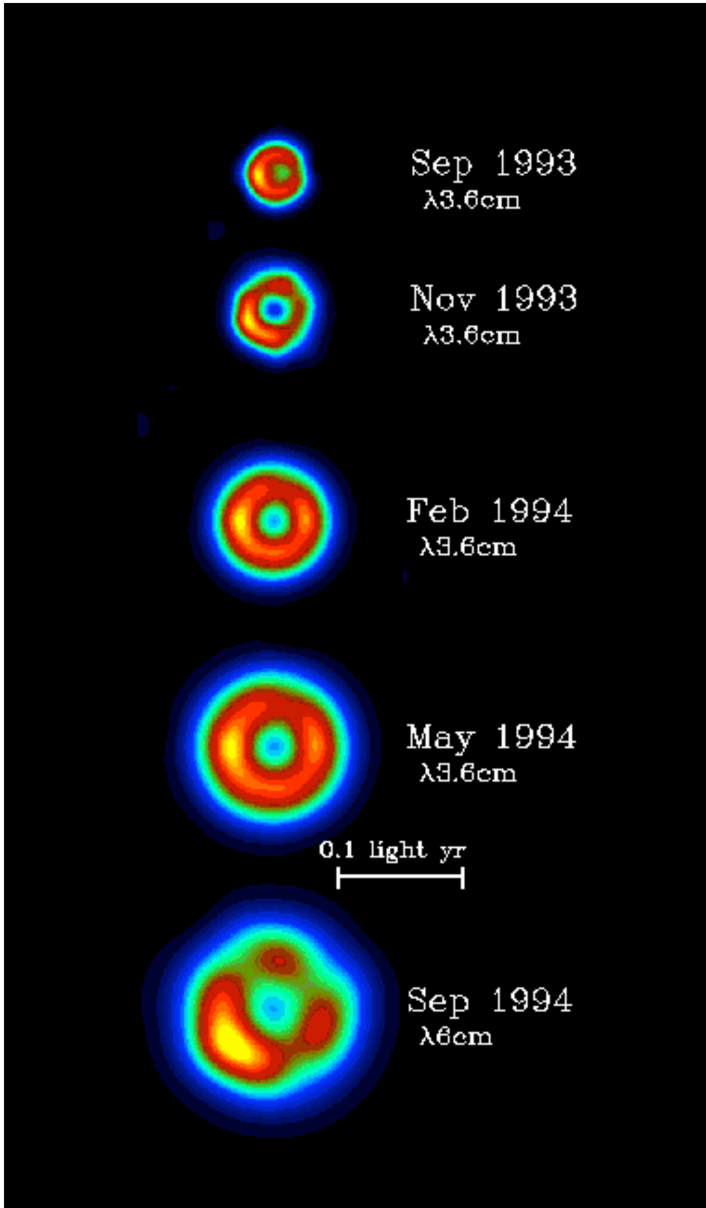


High resolution imaging



Black hole shadow:
EHT Collaboration

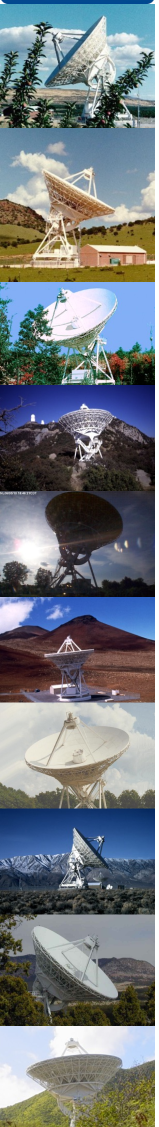
High resolution imaging



The expansion of SN1993J: Global VLBI observations, J. Marcaide et al.

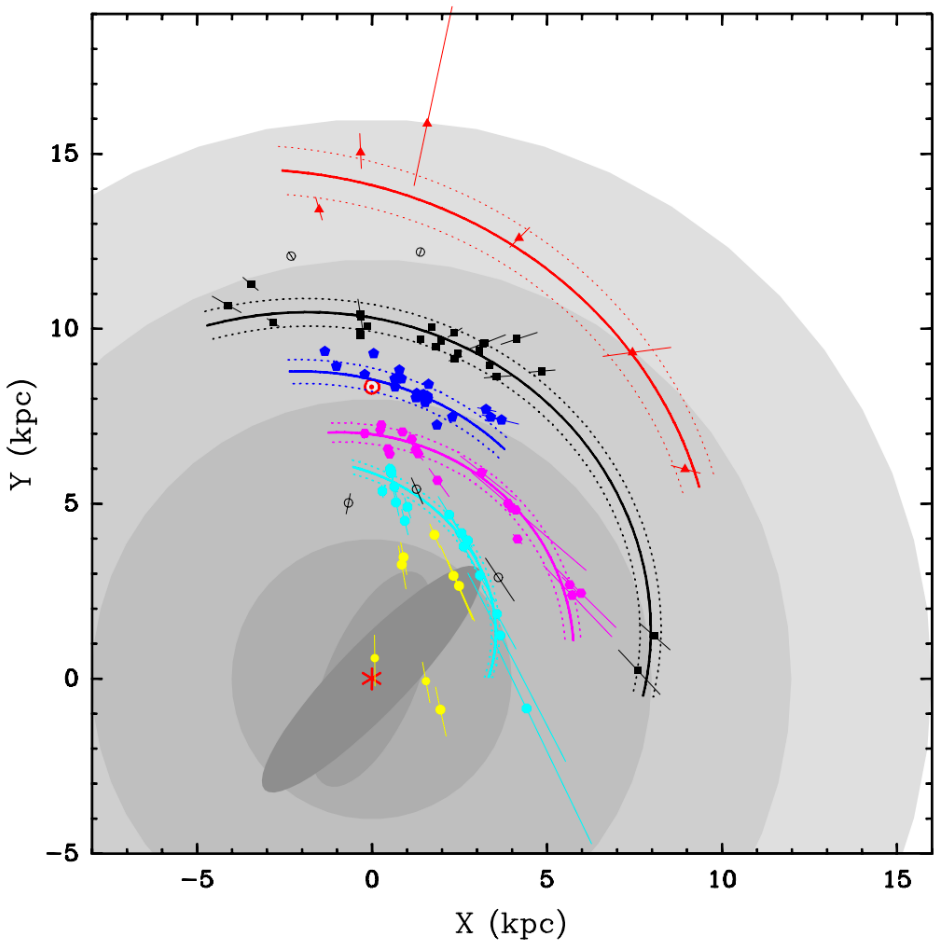
Astrometry

- With VLBI we can centroid an object's location to the ~0.01 mas level
  - *Gaia*-level accuracy (already for years, and also can access the Galactic plane!)
- Easiest for point sources, but source structure can be modelled too
- A whole lecture on astrometry next week, so I will just show a couple of brief science highlights without going into the technical detail



Galactic structure

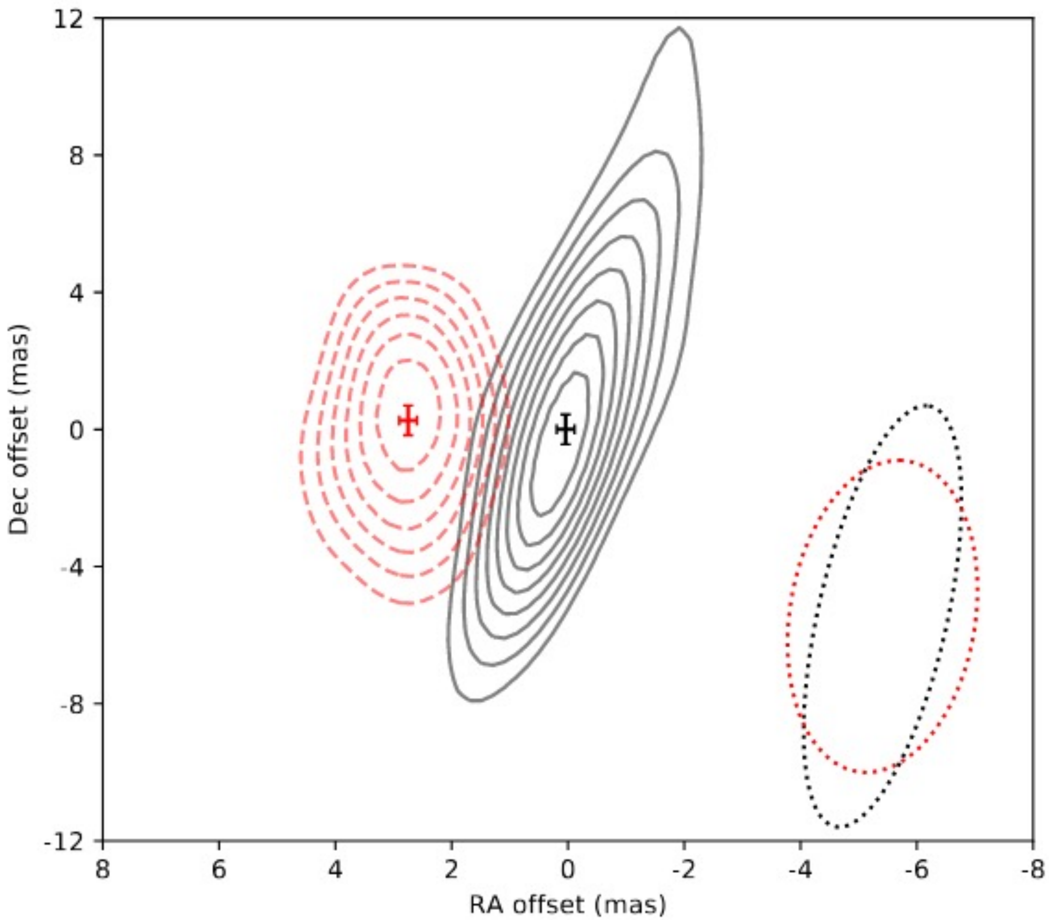
BeSSeL
Bar and Spiral Structure Legacy Survey

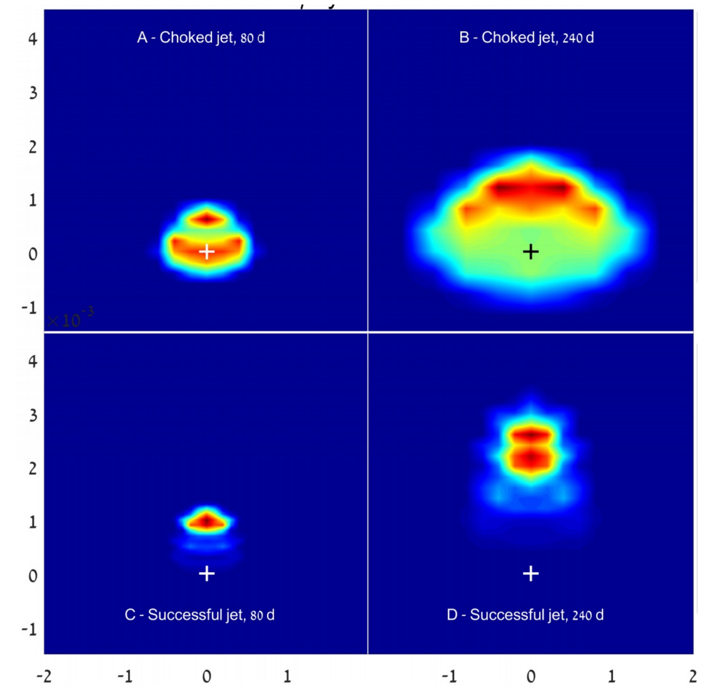


>100 parallax distances to masers around high-mass star forming regions:

- Spiral arm structure
- Distance to Galactic Center (8.34 ± 0.16 kpc)
- Galactic rotation curve (240 ± 8 km/s)

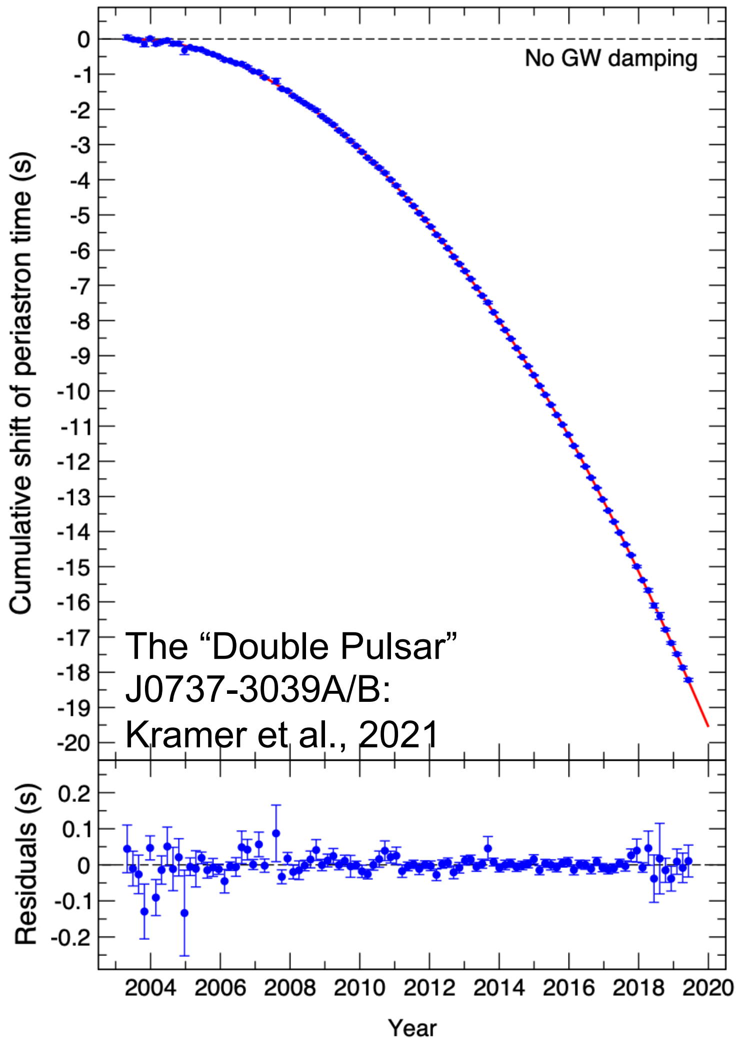
GW merger afterglows

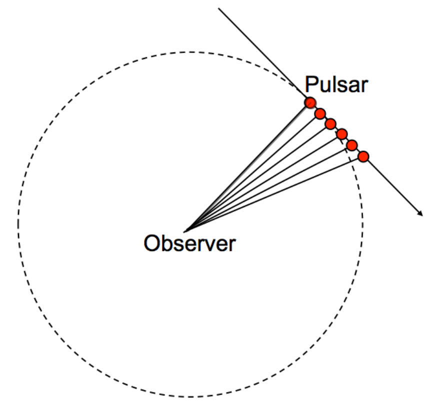




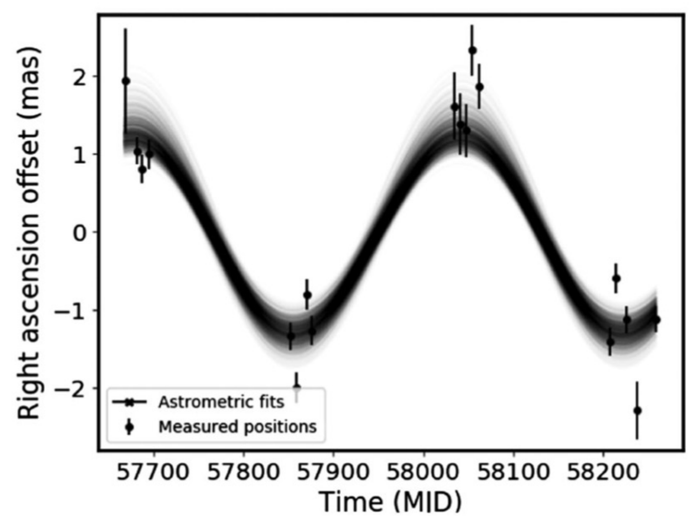
Model comparison for GW170817 afterglow showed a successful, narrow jet, viewed from inclination angle 20-25° (Mooley+2018)

Precision tests of GR



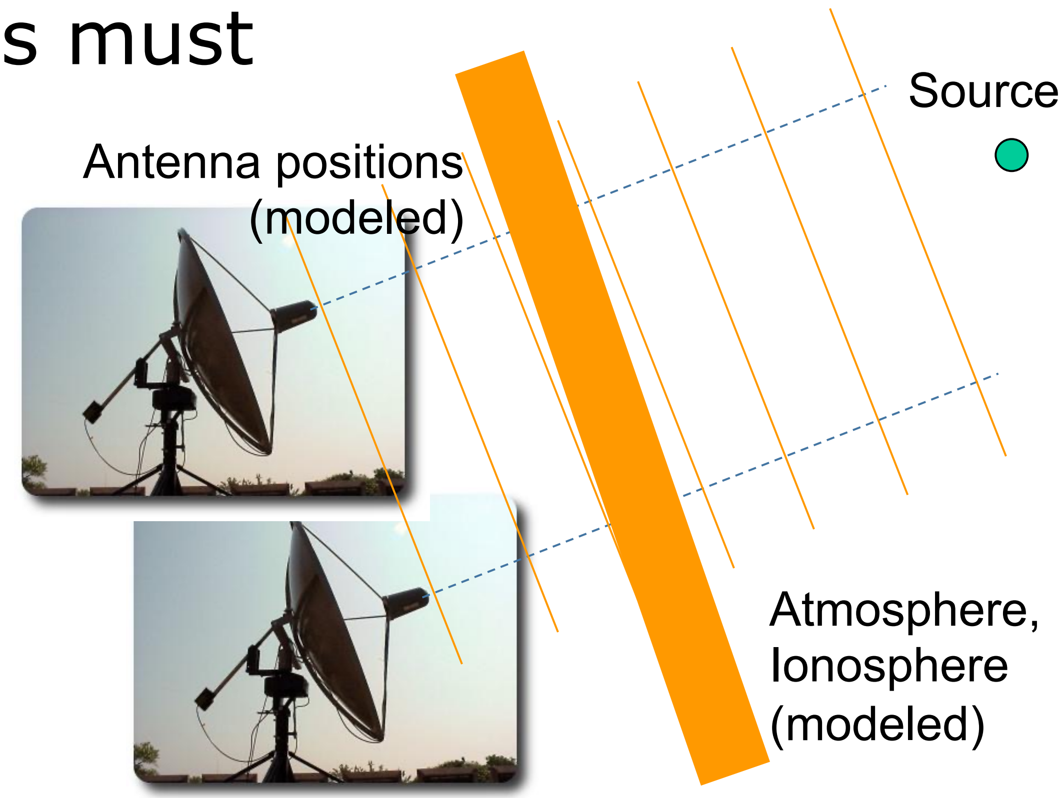


"Shklovskii" effect from transverse motion corrupts intrinsic decay from GW emission: must measure distance: annual parallax



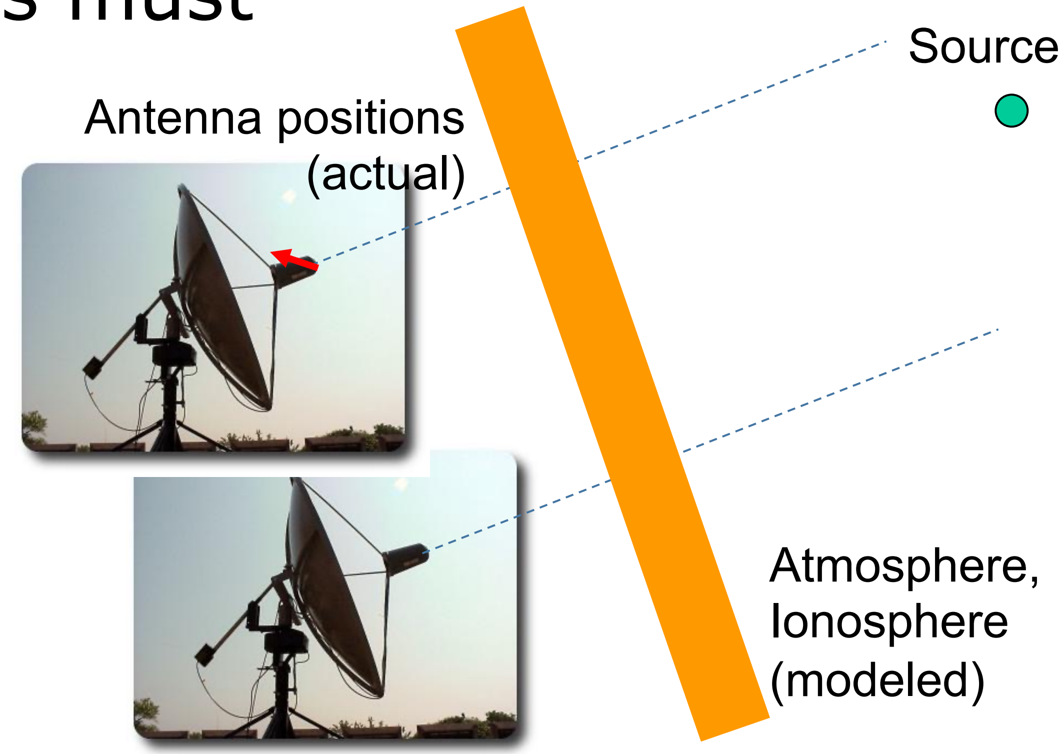
Propagation effects & geodesy

- If you know the location of a source very precisely (e.g. an ICRF source) then any misalignment of the signal at two antennas must come from unmodeled propagation effects or antenna position errors



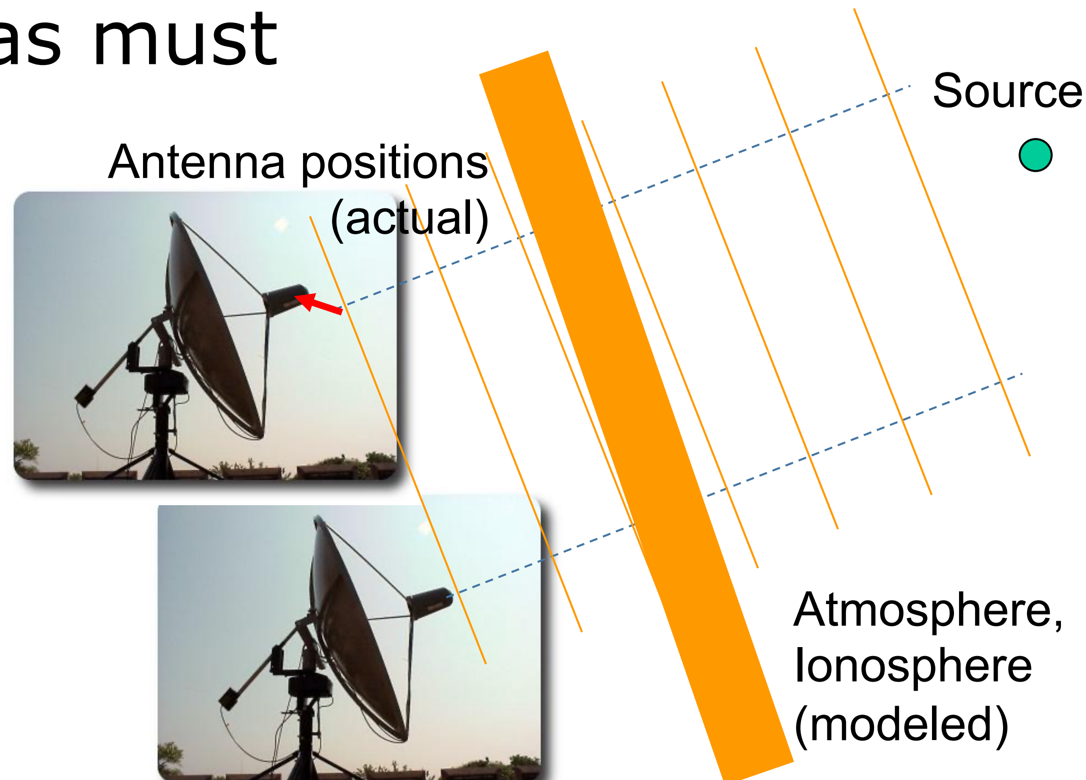
Propagation effects & geodesy

- If you know the location of a source very precisely (e.g. an ICRF source) then any misalignment of the signal at two antennas must come from unmodeled propagation effects or antenna position errors



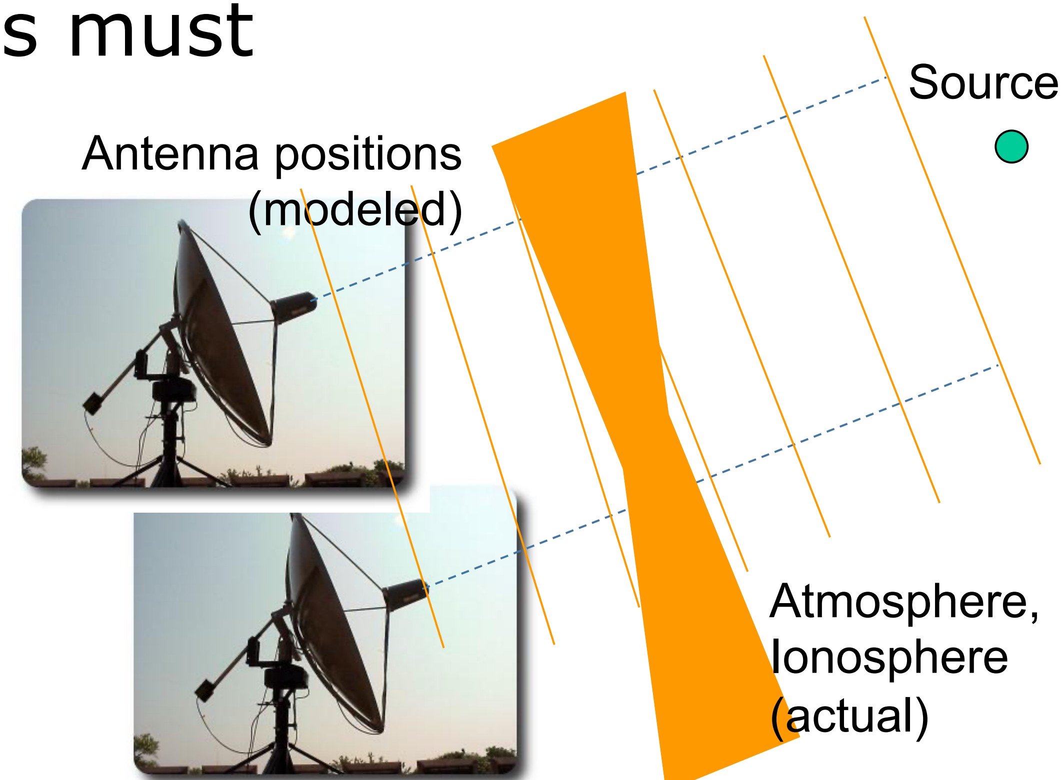
Propagation effects & geodesy

- If you know the location of a source very precisely (e.g. an ICRF source) then any misalignment of the signal at two antennas must come from unmodeled propagation effects or antenna position errors



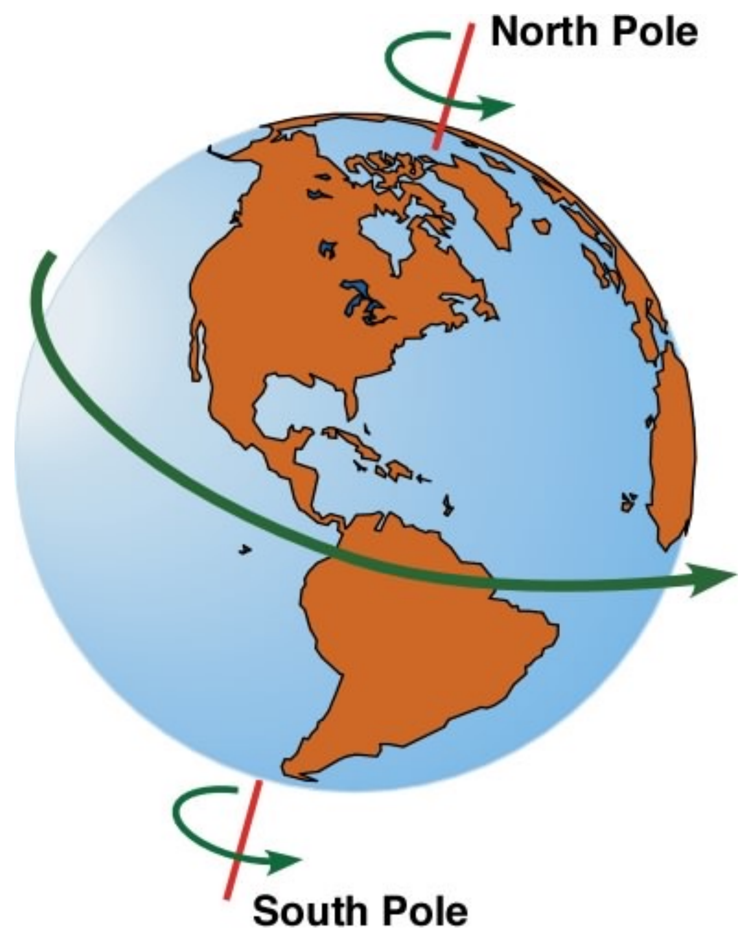
Propagation effects & geodesy

- If you know the location of a source very precisely (e.g. an ICRF source) then any misalignment of the signal at two antennas must come from unmodeled propagation effects or antenna position errors



Geodetic results

- Global geodesy measures the participating telescope’s positions to the mm level, and the Earth’s rotation phase (UT1-UTC) to a precision of ~4 microseconds every day



Current VLBI arrays

- The Very Long Baseline Array (VLBA)

- 10 x 25m antennas
- 0.3 - 86 GHz
- maximum baseline ~8,000 km
- full time operation
- add GBT + VLA for "High Sensitivity Array"

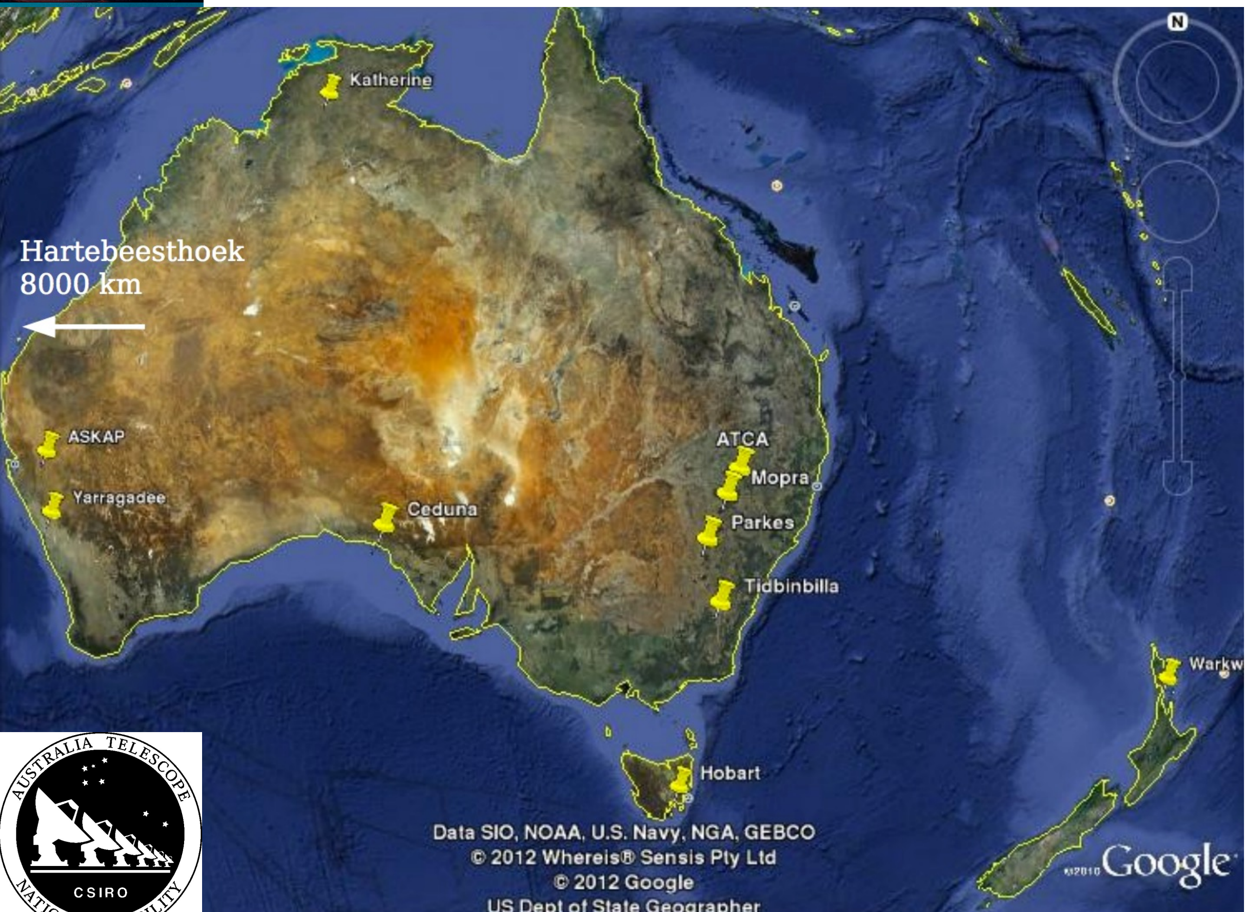
Current VLBI arrays

- The European VLBI Network (EVN)

- ~25 stations, 10m -> 100m
- 0.3 - 43 GHz
- maximum baseline ~8,000 km
- operates ~3 months/year
- plus monthly fast turnaround, out-of-session observations

Current VLBI arrays

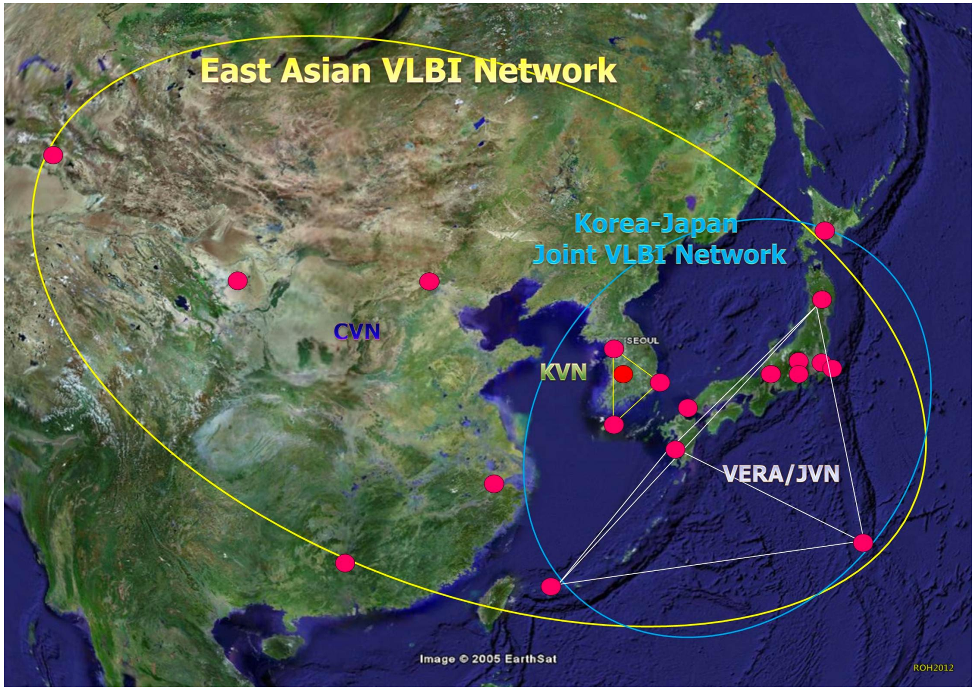
- The Long Baseline Array (LBA)



- Up to 10 stations, 22m -> 70m
- 1.3 - 22 GHz
- maximum baseline ~1,700 – 8,000 km
- operates ~3 weeks/year
- only Southern Hemisphere instrument

Current VLBI arrays

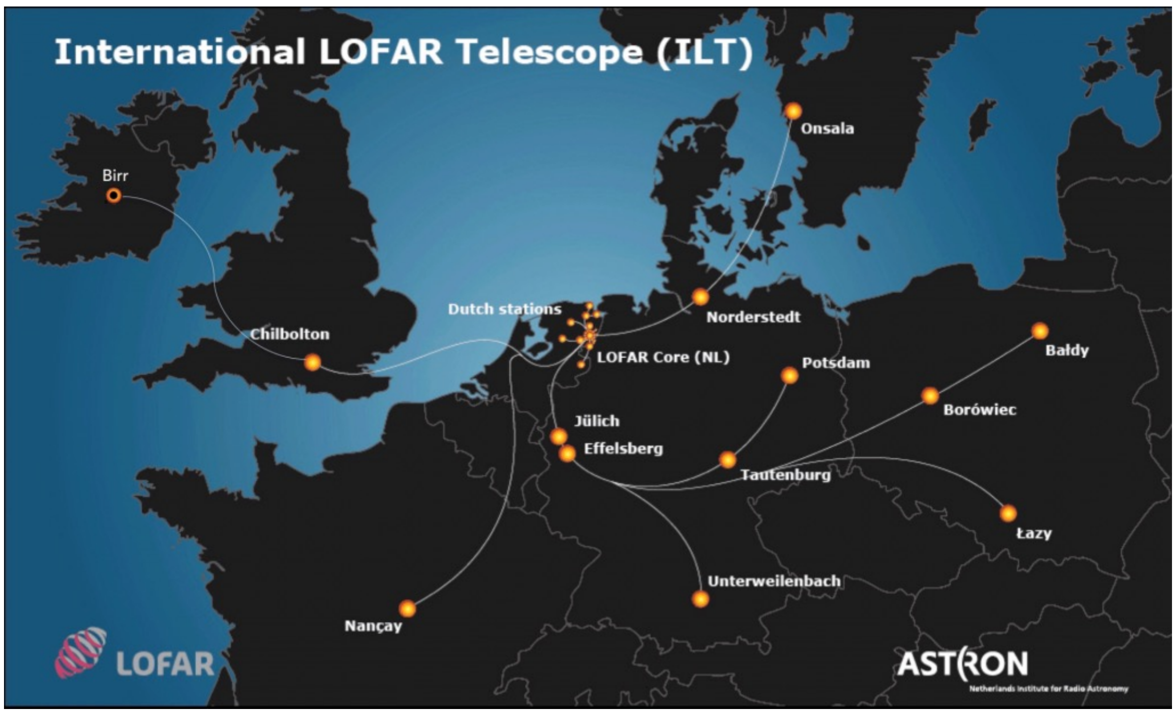
- East Asian VLBI Network is a collaboration of 3 separate networks:



KVN: Korea, 4 dishes, 22 – 129 GHz
VERA: Japan, focus on astrometry, 2 – 43 GHz
JVN: VERA + other Japanese antennas
CVN: China, includes some larger dishes

Current VLBI arrays

- LOFAR: Sub-arcsecond imaging at metre wavelengths (>1500 km baselines)



14 international stations (plus core and 15 more stations in the Netherlands)

15 – 240 MHz, full time (open time available, bi-annually)

Current VLBI arrays

- Global mm VLBI Array (GMVA):
  Sub-mas observations at 3 mm / 86 GHz

Two sessions per year. (pray for good weather!)

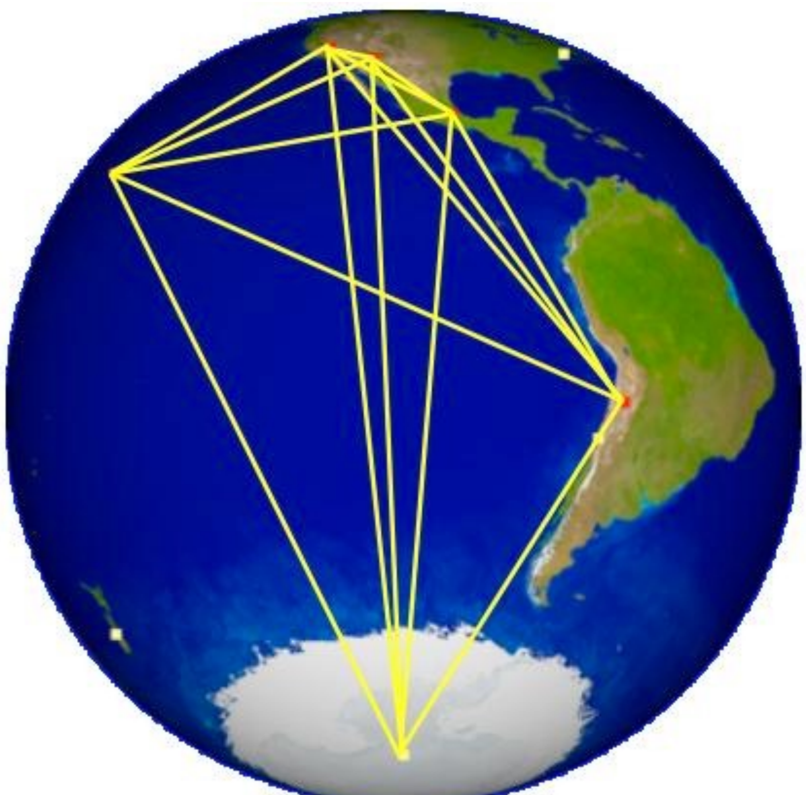
Unmatched sensitivity and resolution at high frequency.

ALMA now available!!

2x/year proposals

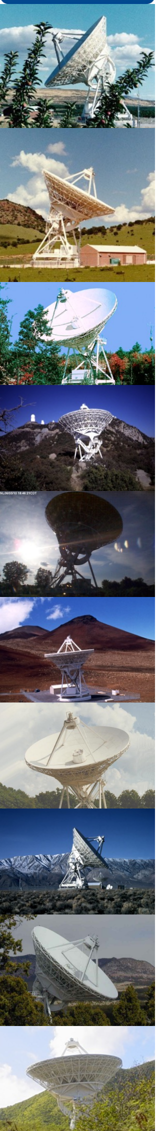
Current VLBI arrays

- Event Horizon Telescope: highest resolution interferometer, direct imaging of black hole shadows



Operating at 230 and 345 GHz (and now with phased ALMA), resolution ~30 μas

Annual call for proposals



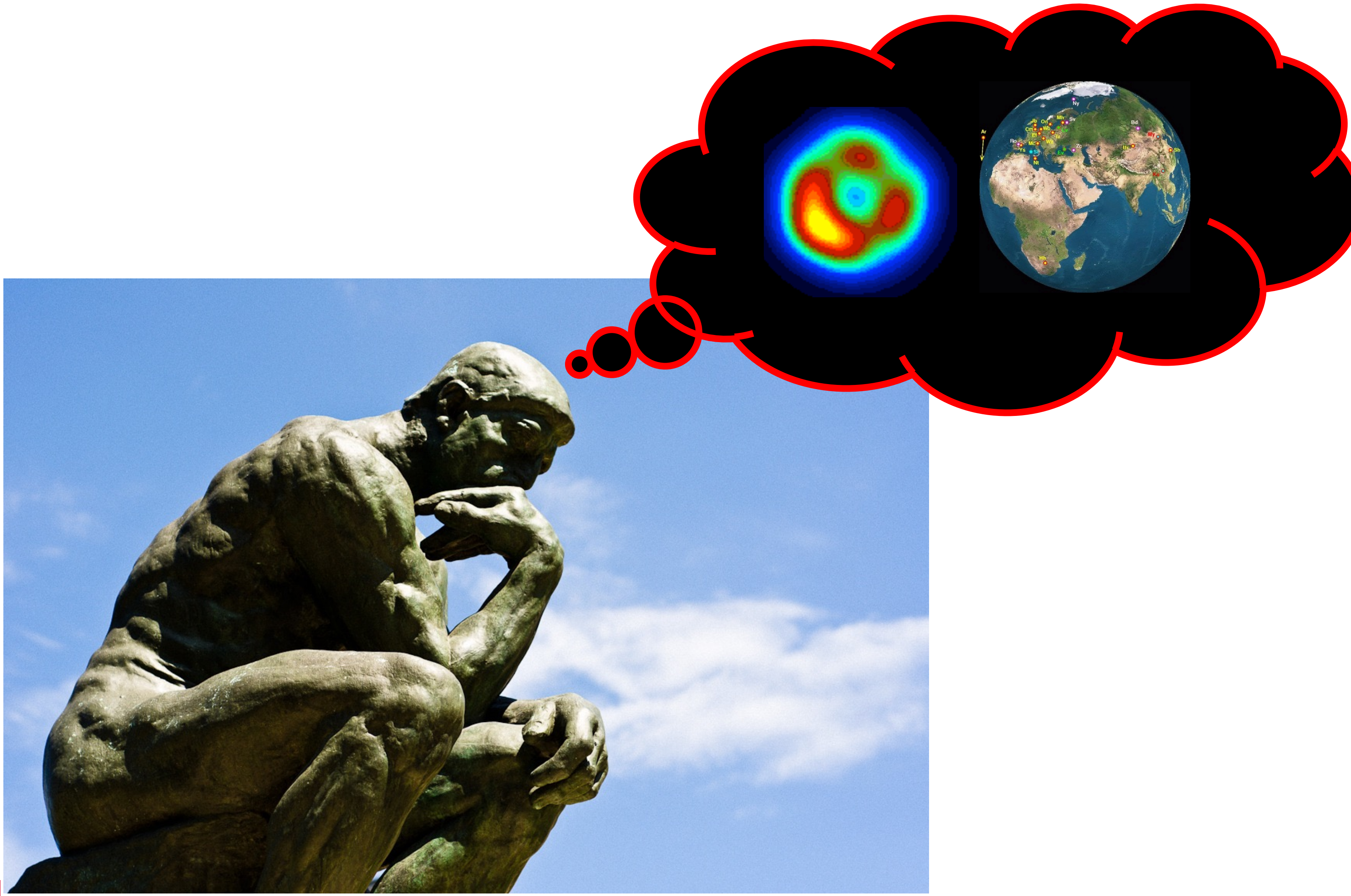
Solved+unsolved VLBI challenges

- VLBI capabilities have leapt ahead in the last few decades!
  - Some observational realities remain (set by the physics)

SOLVED
- Sensitivity (bandwidth)
- Stability (electronics)
- Image quality (see above)
- Field of view (multi-field correlation)

SORT-OF-SOLVED
- Uncorrelated atmosphere/ionosphere (address with fast calib.)
- No flux calibrator sources (rely on switched power, bootstrapping)

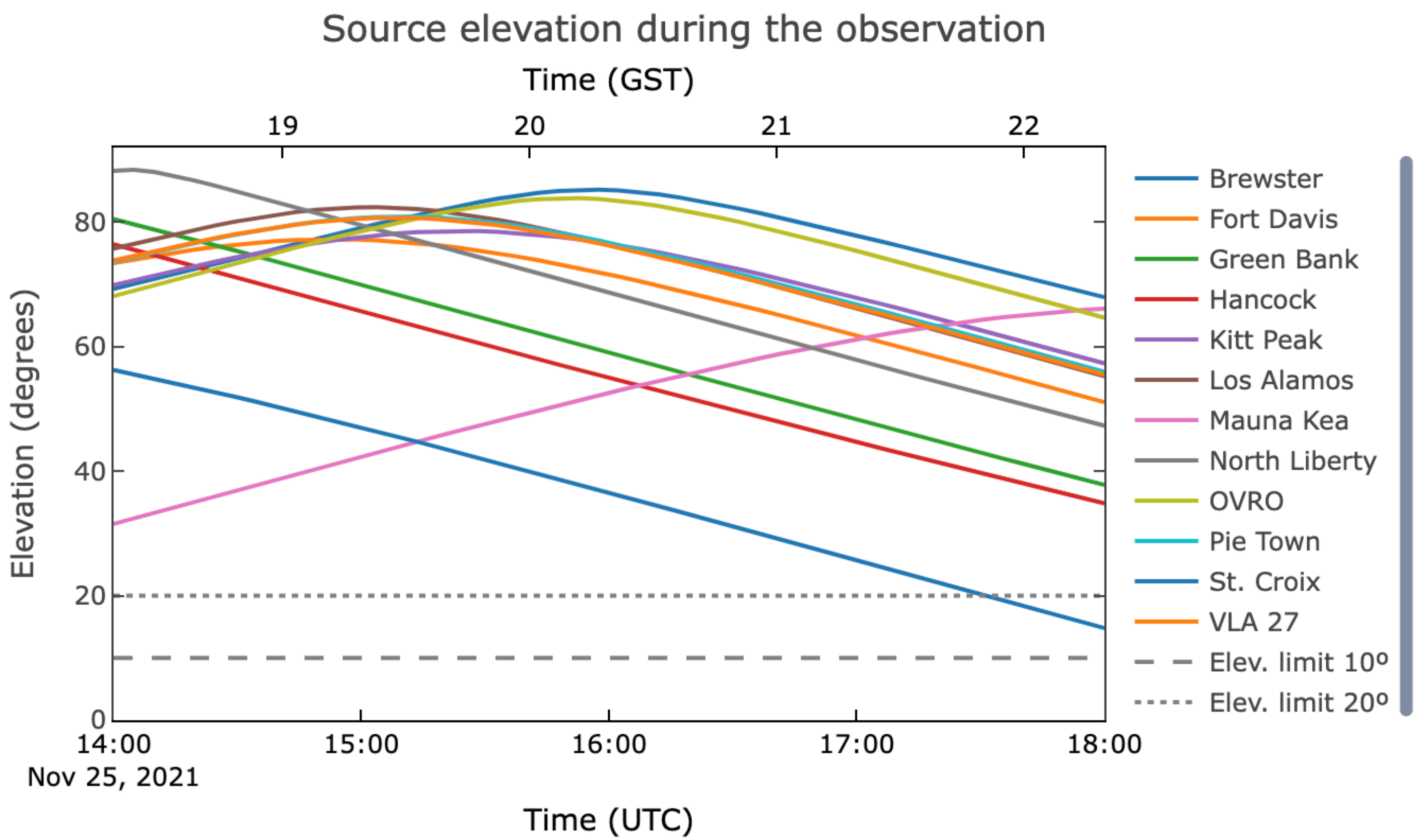
The practicalities of VLBI



Plan

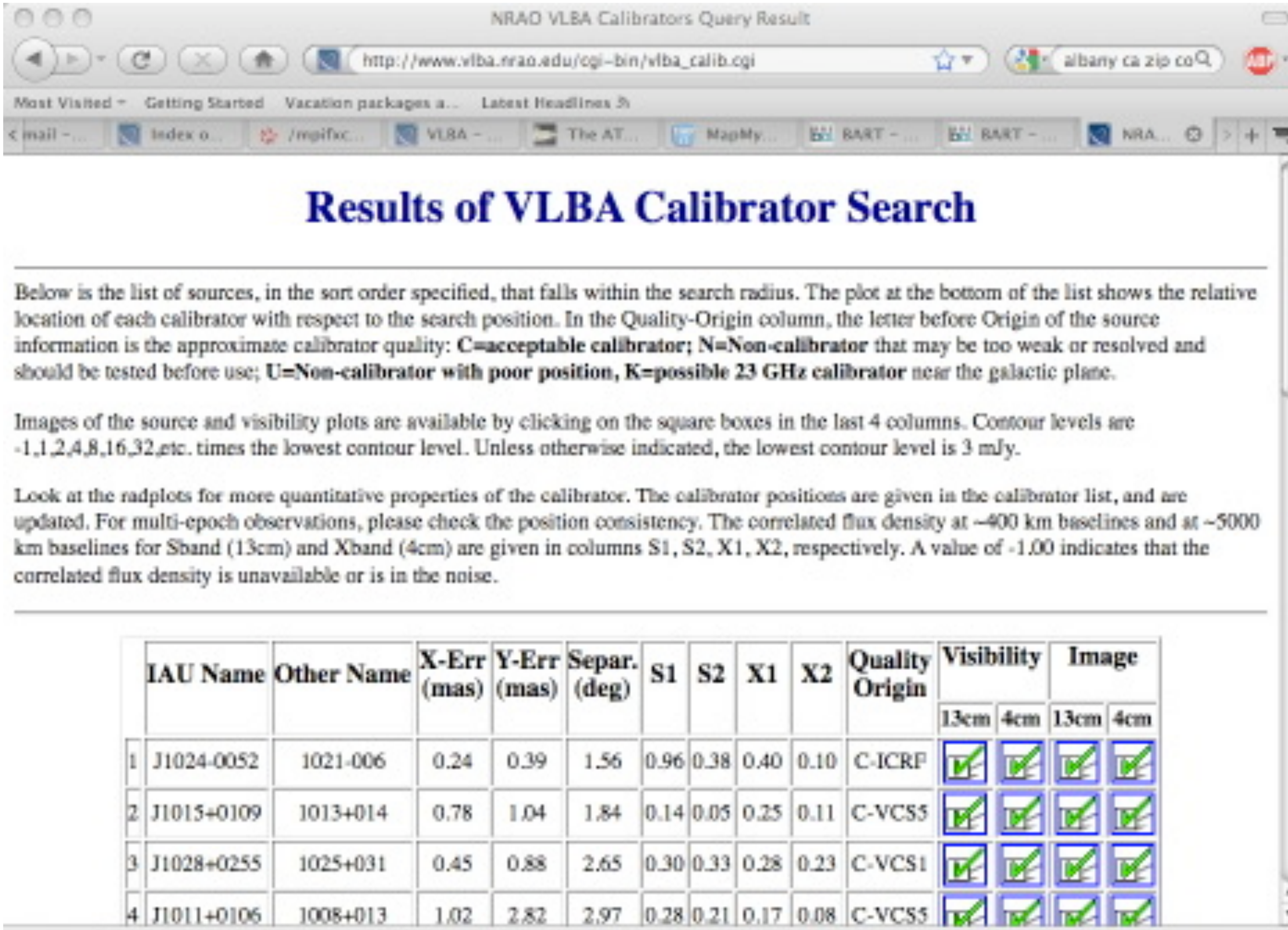
- You need to consider your target (size, flux density, location), the array parameters (resolution, frequency, sensitivity) and calibration strategy
  - Object declination and size determine what array(s) are feasible, at what frequency
  - https://planobs.jive.eu/ for calculating uptime, uv coverage, sensitivity, resolution
  - Or http://www.evlbi.org/cgi-bin/EVNcalc
  - Calibrator search tools available at http://astrogeo.org/calib/search.html (all sky)

Plan



Source elevation during the observation
Time (GST)
19
20
21
22
Elevation (degrees)
0
20
40
60
80
14:00
Nov 25, 2021
15:00
16:00
17:00
18:00
Time (UTC)
Brewster
Fort Davis
Green Bank
Hancock
Kitt Peak
Los Alamos
Mauna Kea
North Liberty
OVRO
Pie Town
St. Croix
VLA 27
Elev. limit 10º
Elev. limit 20º

Plan



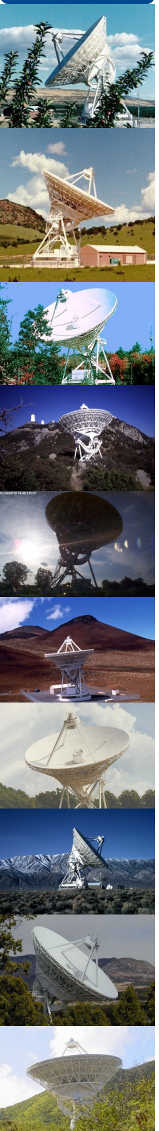
Results of VLBA Calibrator Search

Below is the list of sources, in the sort order specified, that falls within the search radius. The plot at the bottom of the list shows the relative location of each calibrator with respect to the search position. In the Quality-Origin column, the letter before Origin of the source information is the approximate calibrator quality: **C=acceptable calibrator; N=Non-calibrator** that may be too weak or resolved and should be tested before use; **U=Non-calibrator with poor position, K=possible 23 GHz calibrator** near the galactic plane.

Images of the source and visibility plots are available by clicking on the square boxes in the last 4 columns. Contour levels are -1,1,2,4,8,16,32,etc. times the lowest contour level. Unless otherwise indicated, the lowest contour level is 3 mJy.

Look at the radplots for more quantitative properties of the calibrator. The calibrator positions are given in the calibrator list, and are updated. For multi-epoch observations, please check the position consistency. The correlated flux density at ~400 km baselines and at ~5000 km baselines for Sband (13cm) and Xband (4cm) are given in columns S1, S2, X1, X2, respectively. A value of -1.00 indicates that the correlated flux density is unavailable or is in the noise.

	IAU Name	Other Name	X-Err (mas)	Y-Err (mas)	Separ. (deg)	S1	S2	X1	X2	Quality Origin	Visibility		Image	
											13cm	4cm	13cm	4cm
1	J1024-0052	1021-006	0.24	0.39	1.56	0.96	0.38	0.40	0.10	C-ICRF				
2	J1015+0109	1013+014	0.78	1.04	1.84	0.14	0.05	0.25	0.11	C-VCS5				
3	J1028+0255	1025+031	0.45	0.88	2.65	0.30	0.33	0.28	0.23	C-VCS1				
4	J1011+0106	1008+013	1.02	2.82	2.97	0.28	0.21	0.17	0.08	C-VCS5				



VLBI proposals

- Different arrays have different deadlines
- VLBA/HSA/GMVA February 1, August 1
- EVN February 1, June 1, October 1
- LBA June 15 and December 15
- Director’s Discretionary Time for out-of-cycle rapid response
- Standard info: **where** (sources), **how** (resource setup) and **when** (duration, date constraints); help available

Scheduling

- The program SCHED is used to schedule VLBI experiments
- You provide a list of stations and sources, the observing frequency and bandwidth, and a list of scans
- General recipe:
  - Observe target as often as you can
  - Scans on phase reference as necessary (cycle ~6 min @ 1.6 GHz, ~30s @ 43 GHz)
  - Include very bright calibrator ~few hours, other special calibration as necessary

Observing

- Depends on array:
  - EVN and VLBA: provide schedule file, wait to receive the correlated data by ftp
  - LBA: provide schedule file, and assist with the observations (a great way to learn interferometry!)

Data reduction (calibration)

- AIPS is the primary package for VLBI calibration; CASA becoming an alternative (delay cal. available)
- Calibration includes flagging, **amp. calibration** (from switched power), EOP correction, ionosphere correction, **delay**, bandpass, and phase solutions
- I find the ParselTongue* package (a python interface to AIPS) to be very convenient for scripting

***http://www.jive.nl/dokuwiki/doku.php?id=parseltongue:parseltongue**

Data reduction (imaging)

- A calibrated VLBI visibility dataset looks just like any other interferometer - so you can pick your imaging software:
  - AIPS
  - CASA
  - difmap
- Wide-field imaging is computationally intensive (time/bandwidth smearing)
  - Multiple smaller fields can be parallelised
- Limited uv coverage means you need to be careful with deconvolution

The near-term future of VLBI

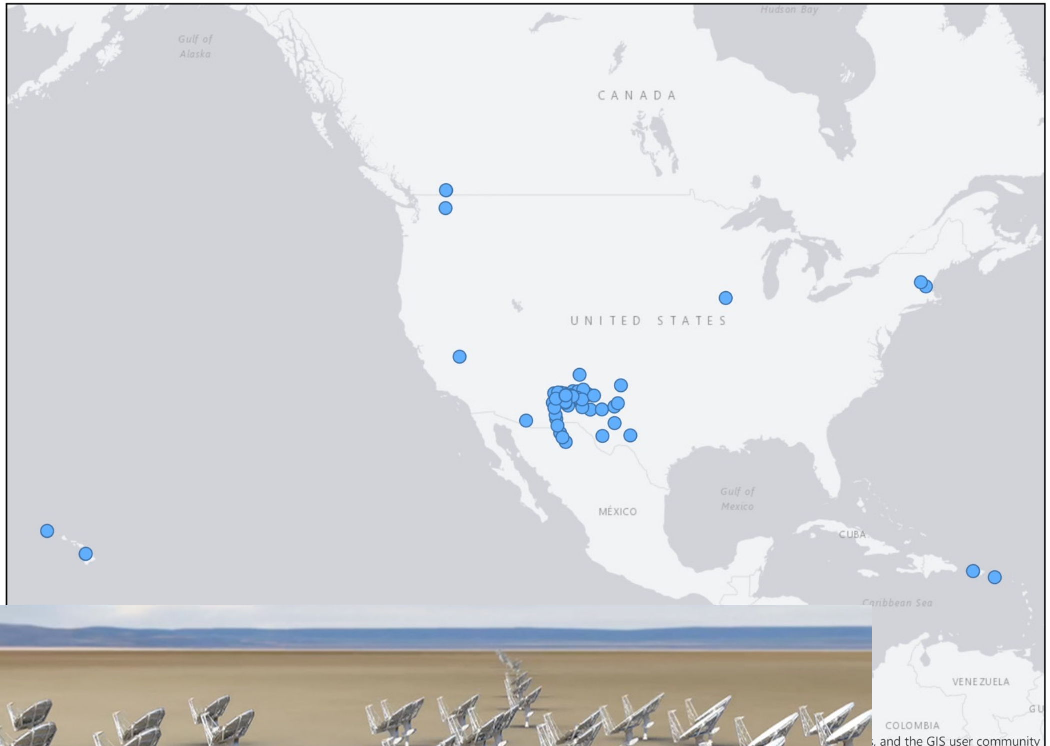
- Existing cm-VLBI (EVN/EAVN/VLBA/LBA): more bandwidth increases, data processing innovations, some new stations (FAST, MeerKAT)
- m-VLBI: LOFAR sub-arcsecond
  - 150 MHz near-routine, 50 MHz still v. hard
- (sub-)mm-VLBI: phased ALMA here
  - Huge sensitivity boost eases calibration

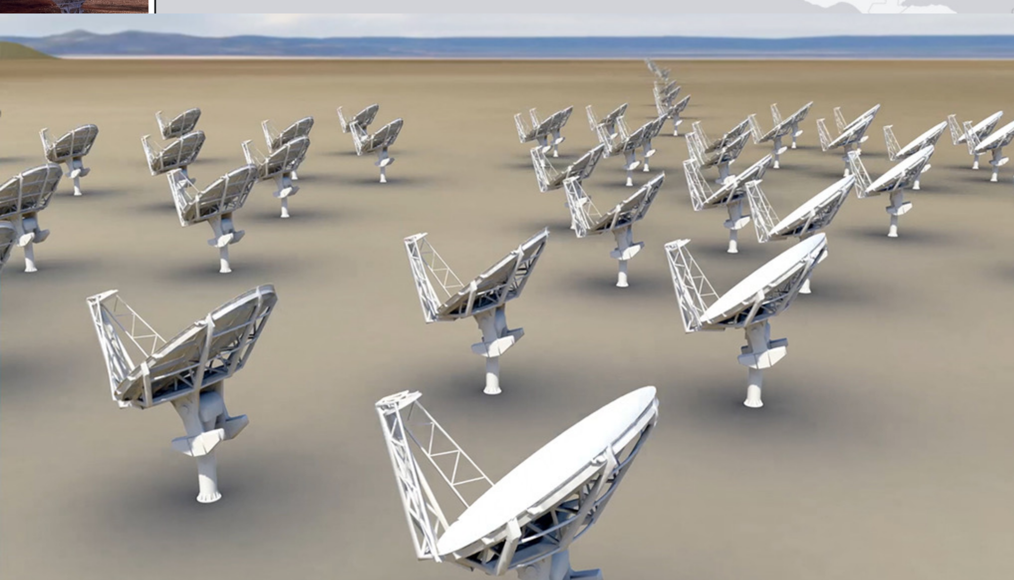
All-new facilities from late 2020s

SKA1-mid will add a sensitive new element to the EVN (for equatorial sources) and/or the LBA (in the south)

Multiple tied-array beams will over the small field-of-view and enable advanced calibration

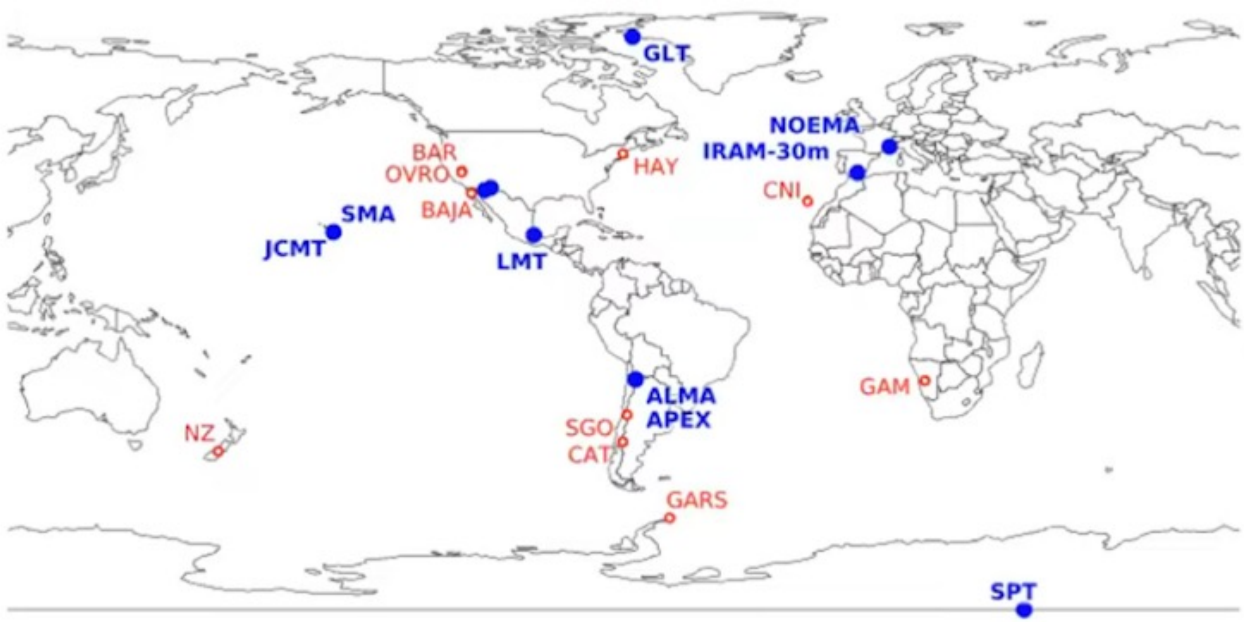
All-new facilities from late 2020s





ngVLA will offer wide field of view combined with high sensitivity from 1-100 GHz – revolutionary advance at cm wavelengths

All-new facilities from late 2020s



By adding more stations and increasing the data rate to 128 Gbps per station (!!), the **ngEHT** plans to greater expand the number of targets for which black hole shadow imaging is possible

Conclusions

- VLBI is a **unique tool** for doing **unique science**
- You could **become** a VLBI expert and take part in diverse ranges of killer science
- Or you could **befriend** a VLBI expert who will help make your science killer!
- The future is **bright** in VLBI land