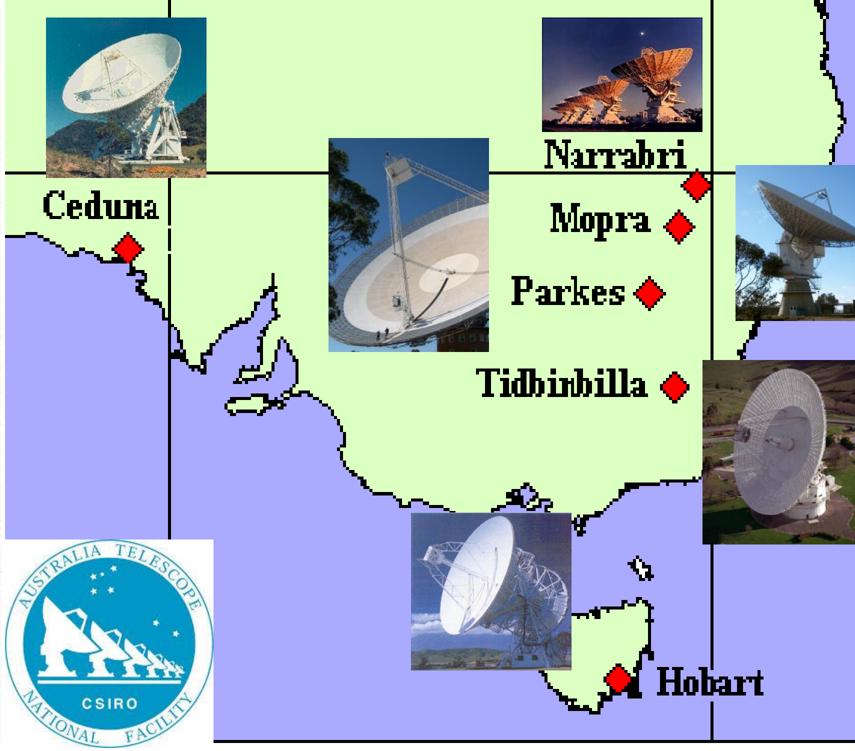


AUSTRALIA TELESCOPE NATIONAL FACILITY CSIRO

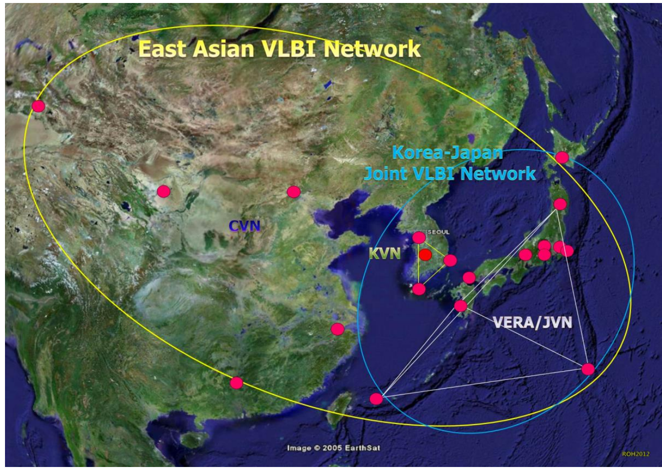
Very Long Baseline Interferometry

Adam Deller

20th NRAO Synthesis Imaging Workshop

May 16, 2024

EventHorizonTelescope

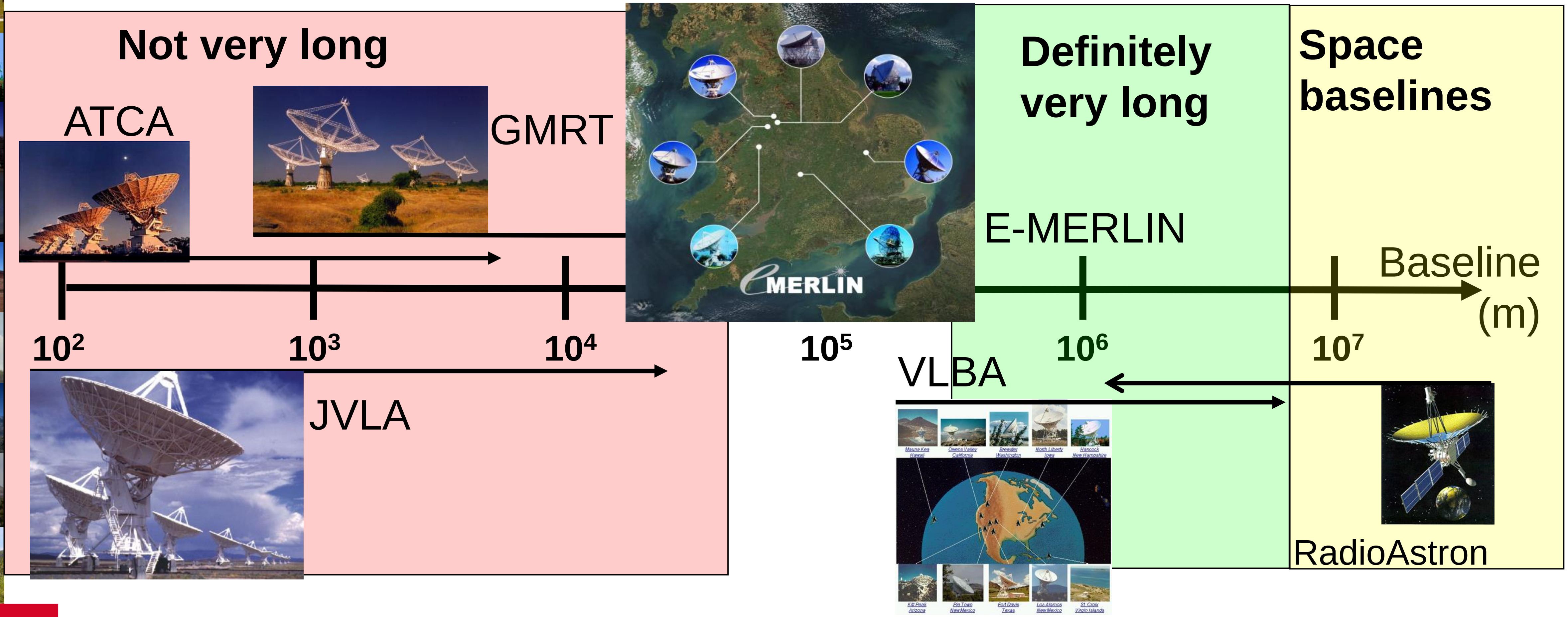


Outline

- 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

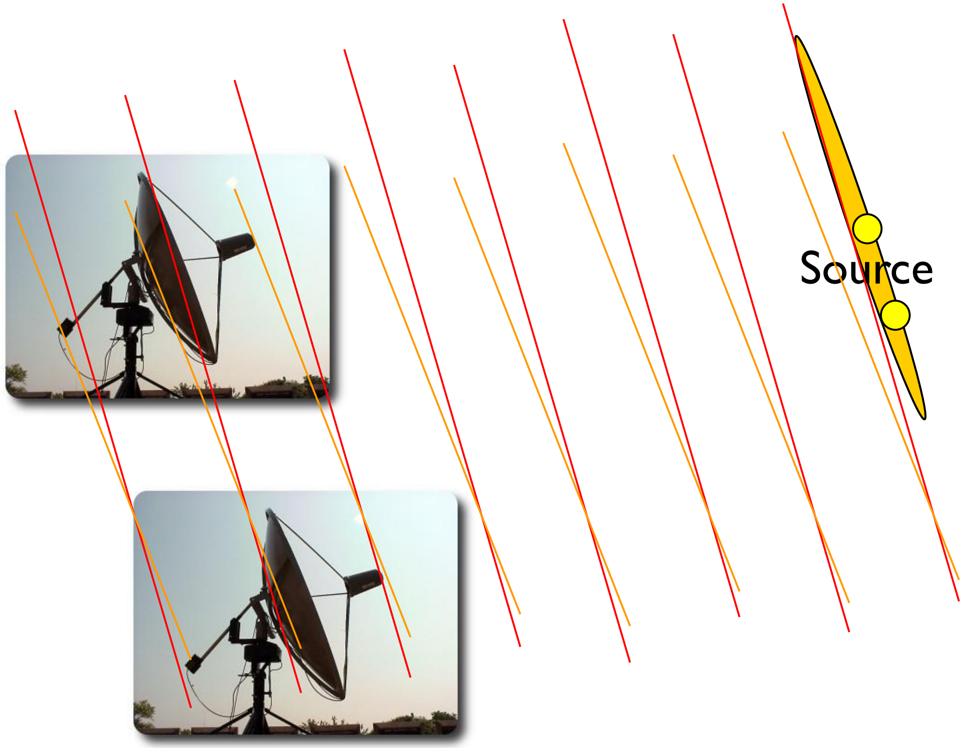
- Clearly not just about baseline length…
- What constitutes VLBI is actually a little hard to pin down (its more like a “syndrome” than a “disease”!)
  - Reason: **no** fundamental difference between VLBI and regular interferometry - only technology, convenience and convention
  - Independent antenna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

What VLBI gives you

- Fundamentals of interferometry say: resolution will be <u>very</u> high:
  - At 1.4 GHz (21cm), an array of maximum baseline 8,000 km will have a resolution of $1.22\lambda/D \sim= 7$ 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?
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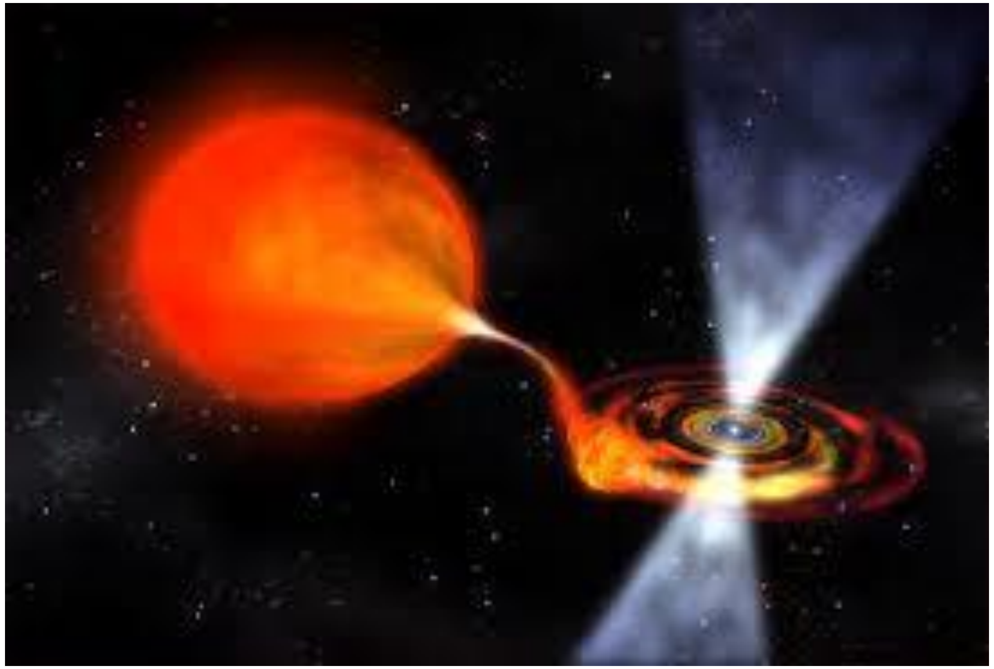

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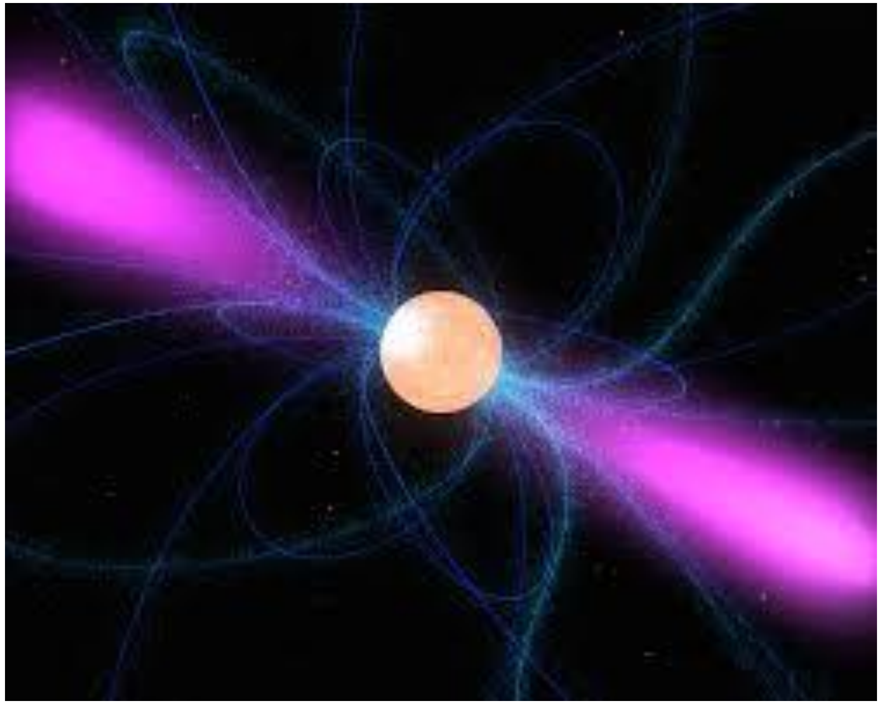
     ii. Or as radio pulsars!



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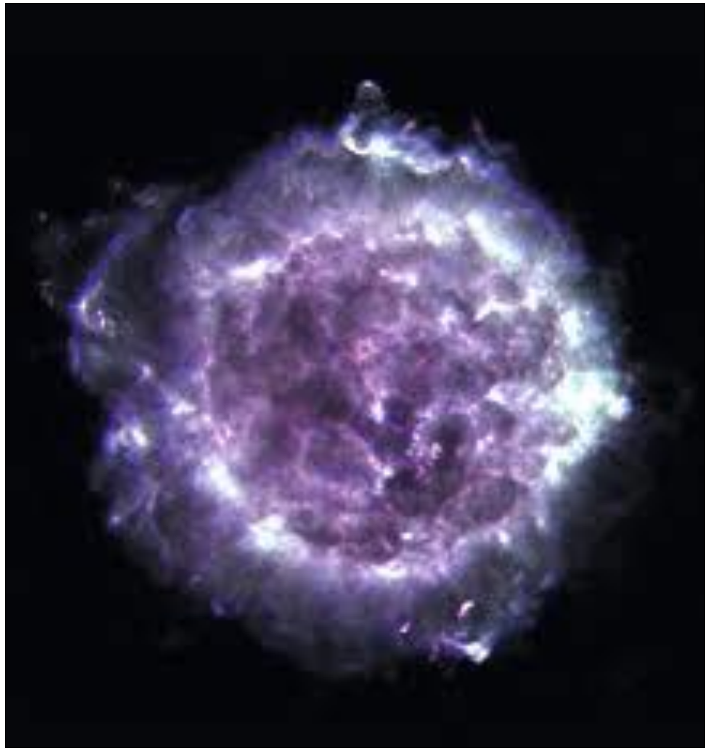
  - d) A few years later (supernova remnants)



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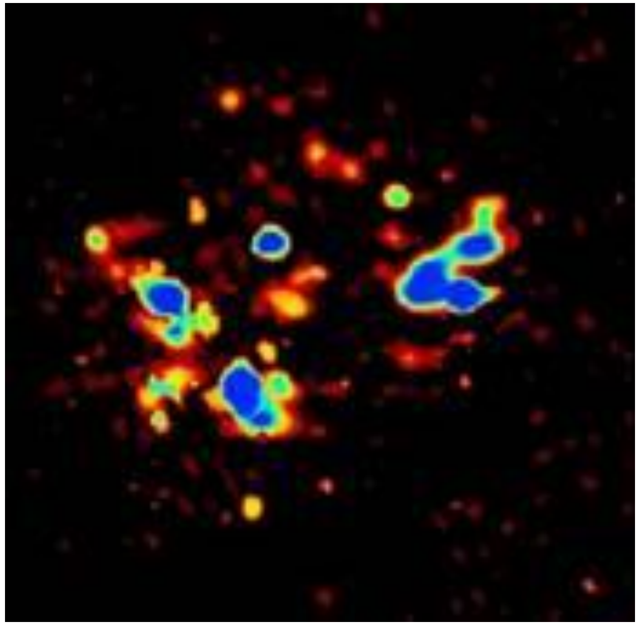

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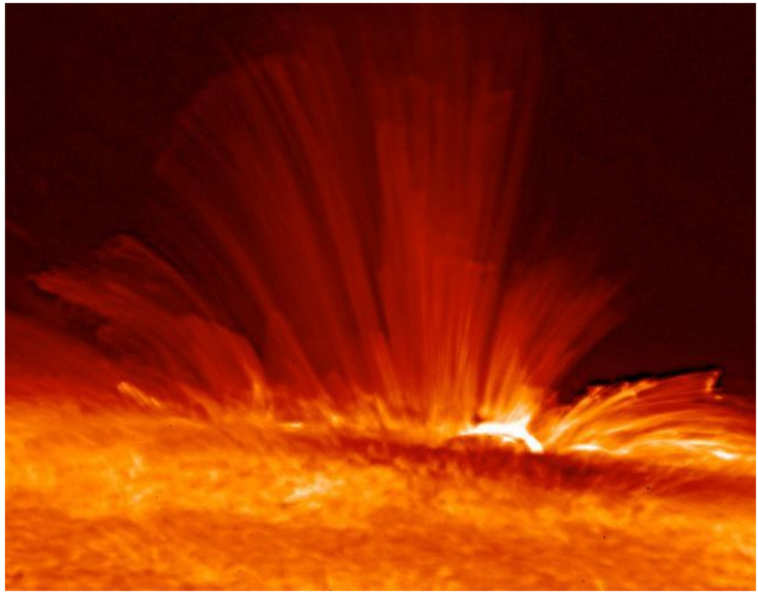
  - e) A collision between a) and/or b)
  - f) Masers
  - g) Magnetically active stars



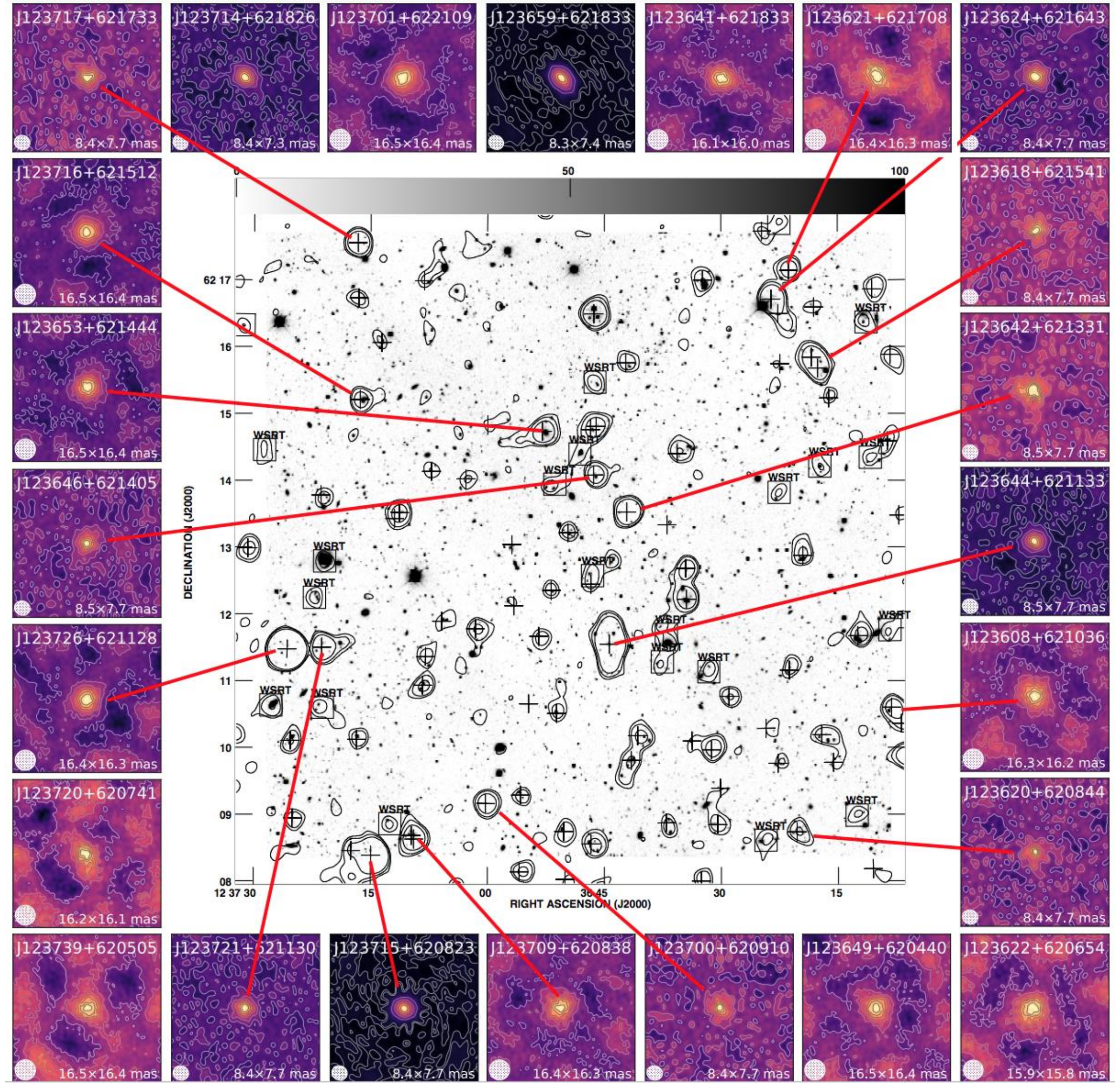
Science applications of VLBI

- 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?

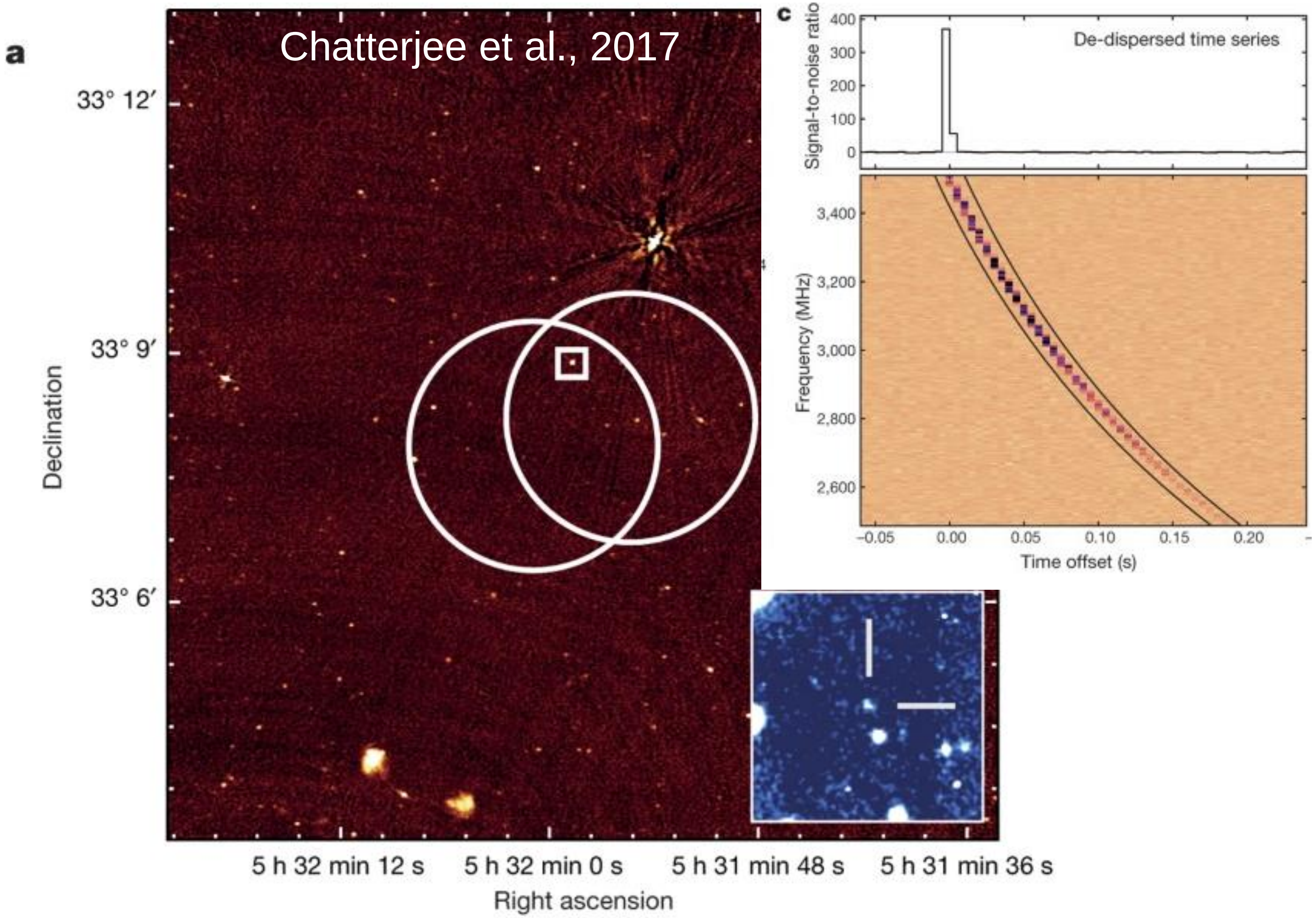
- A VLBI detection instantly identifies a compact non-thermal source, ruling out any potential non-compact explanations

Hallo? Any (compact) body there?



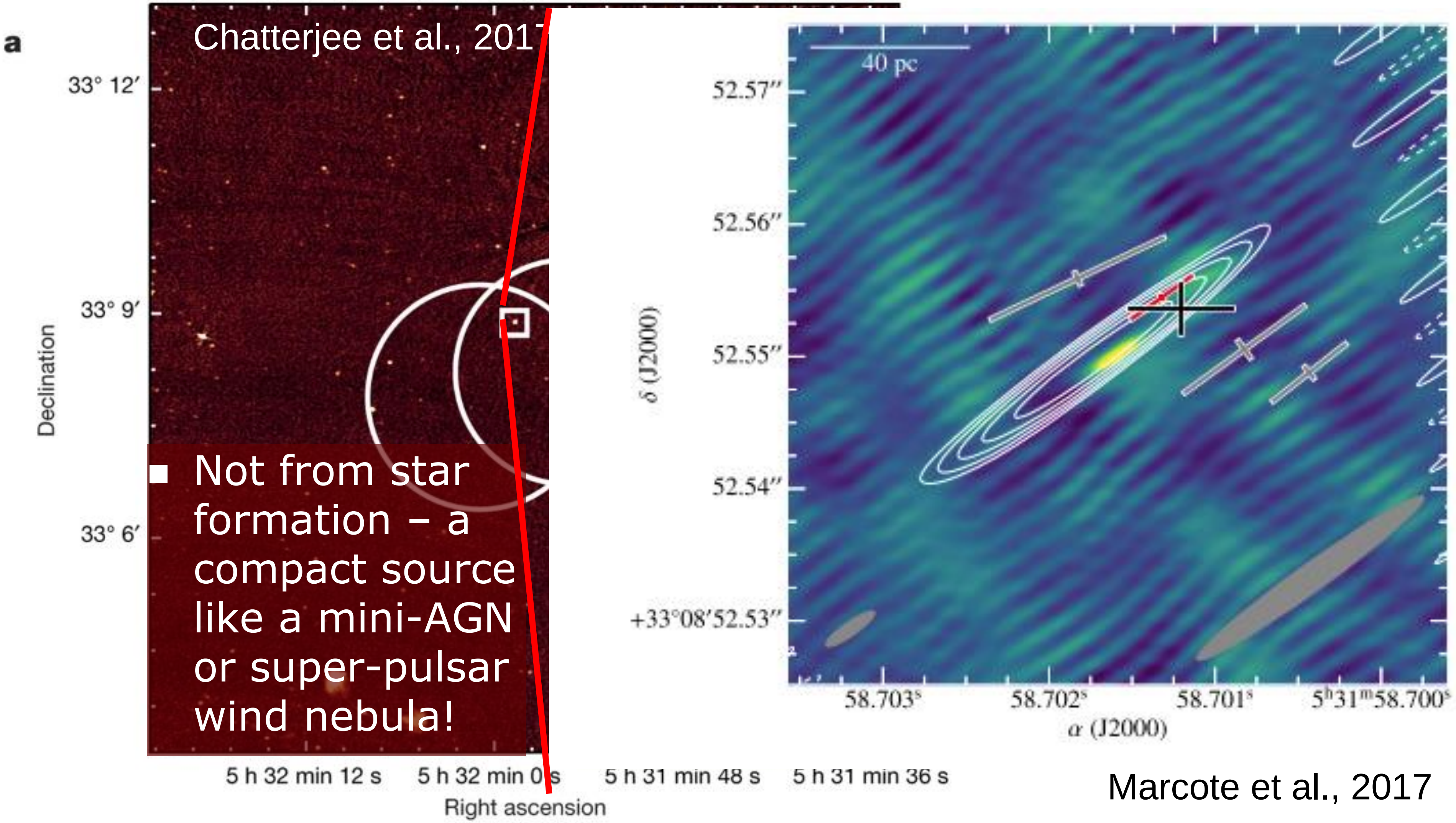
Radio AGN in the GOODS-N field; Radcliffe et al., 2018

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?

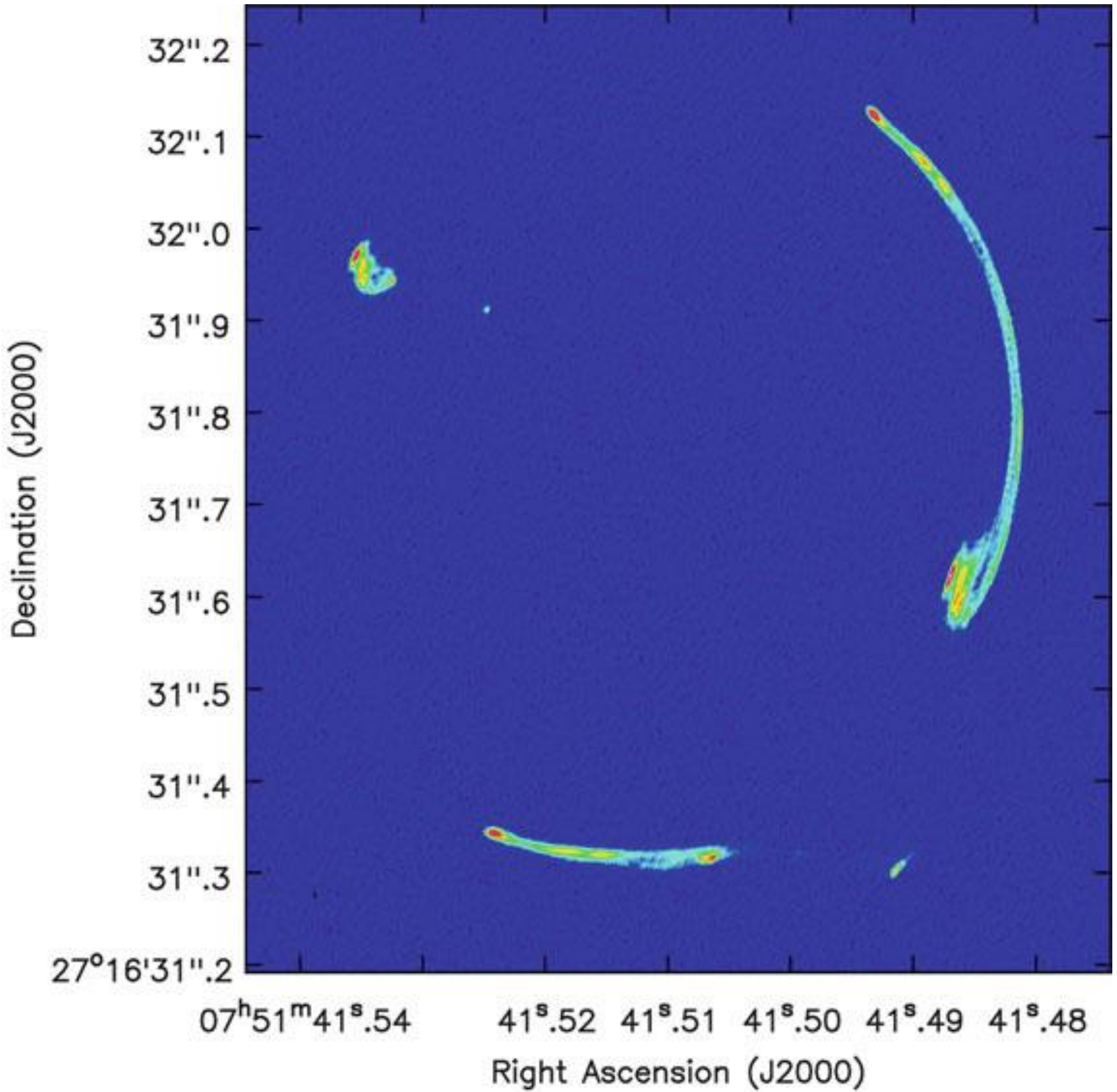


- Not from star formation – a compact source like a mini-AGN or super-pulsar wind nebula!

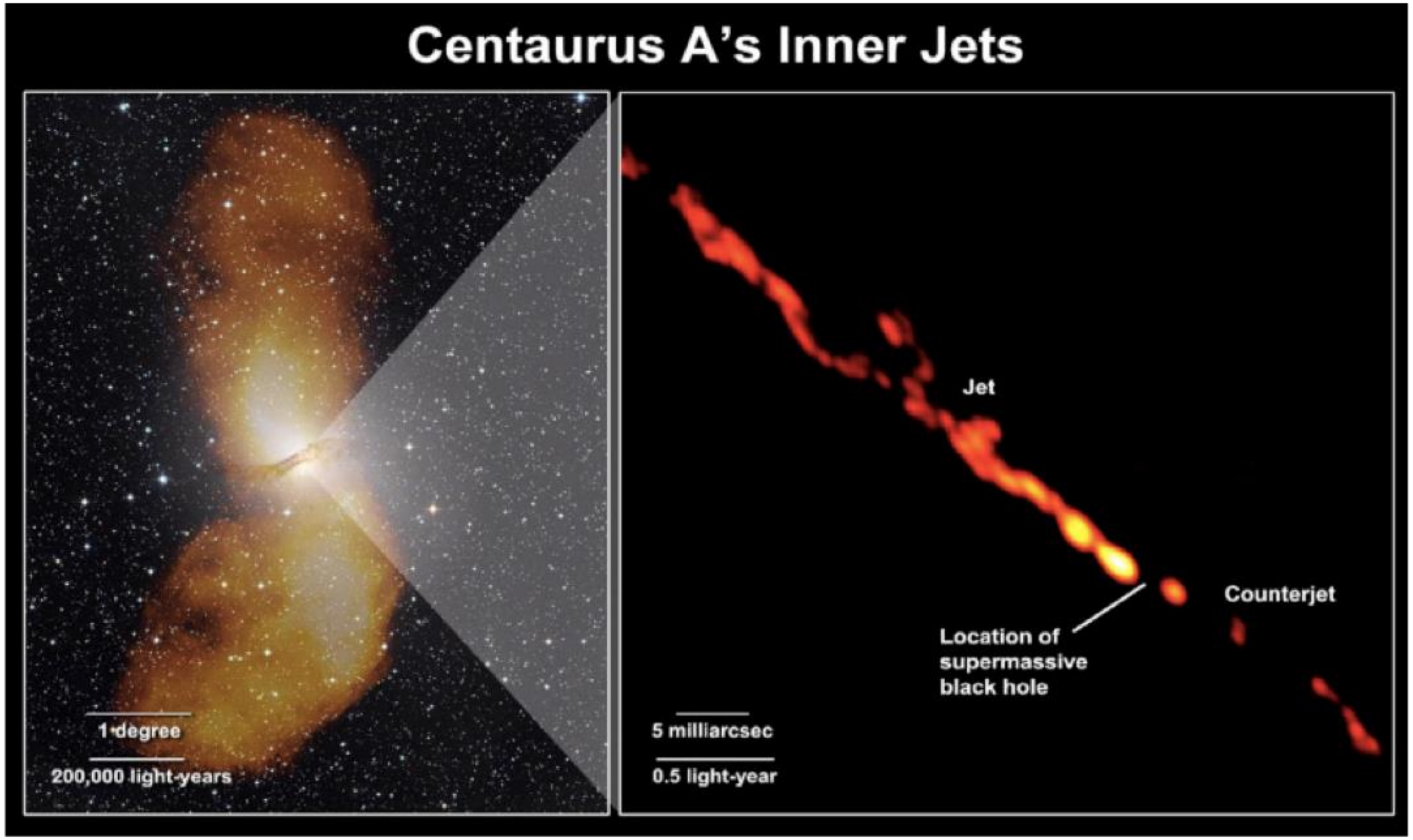
Marcote et al., 2017

High resolution imaging

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

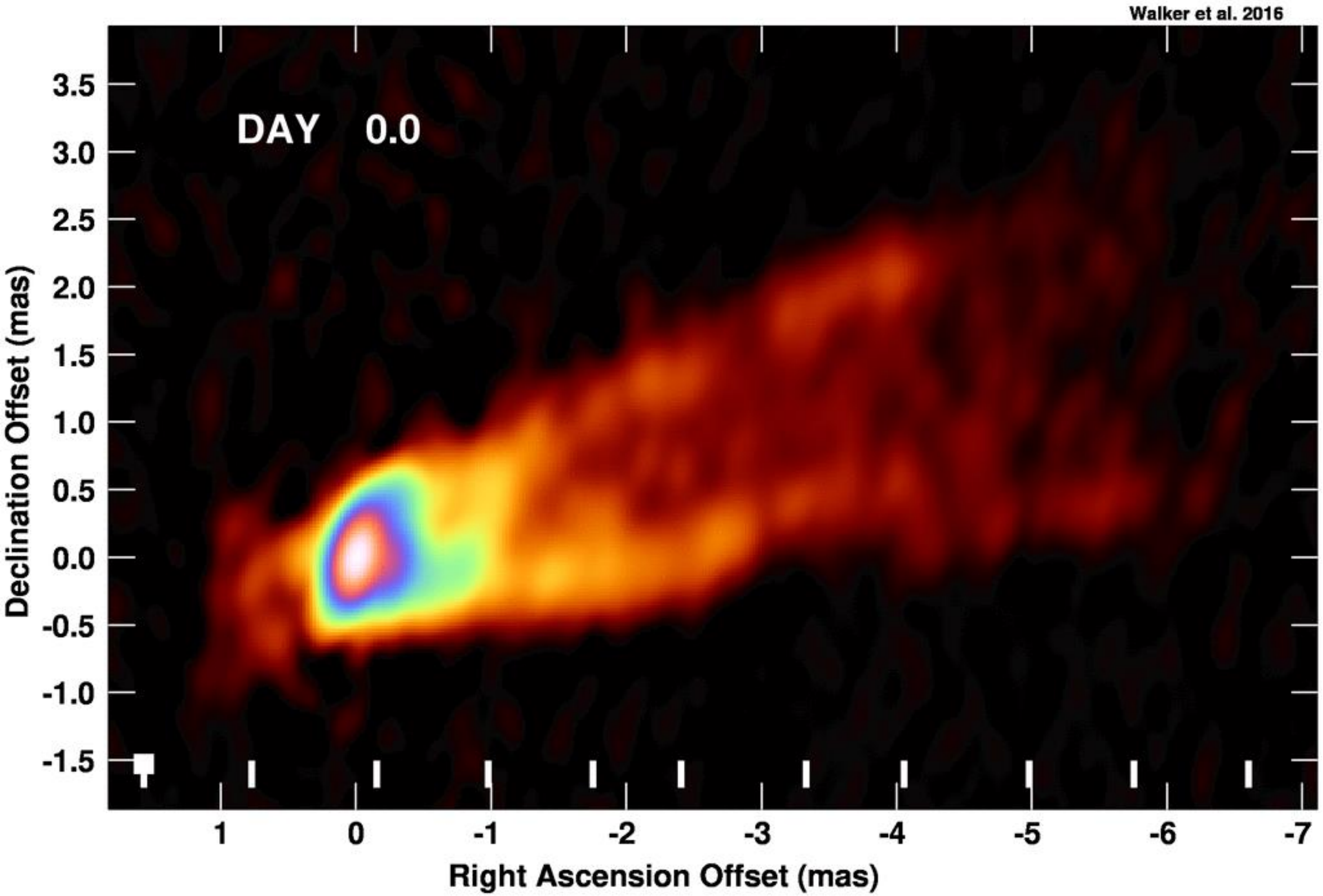


High resolution imaging



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

High resolution imaging



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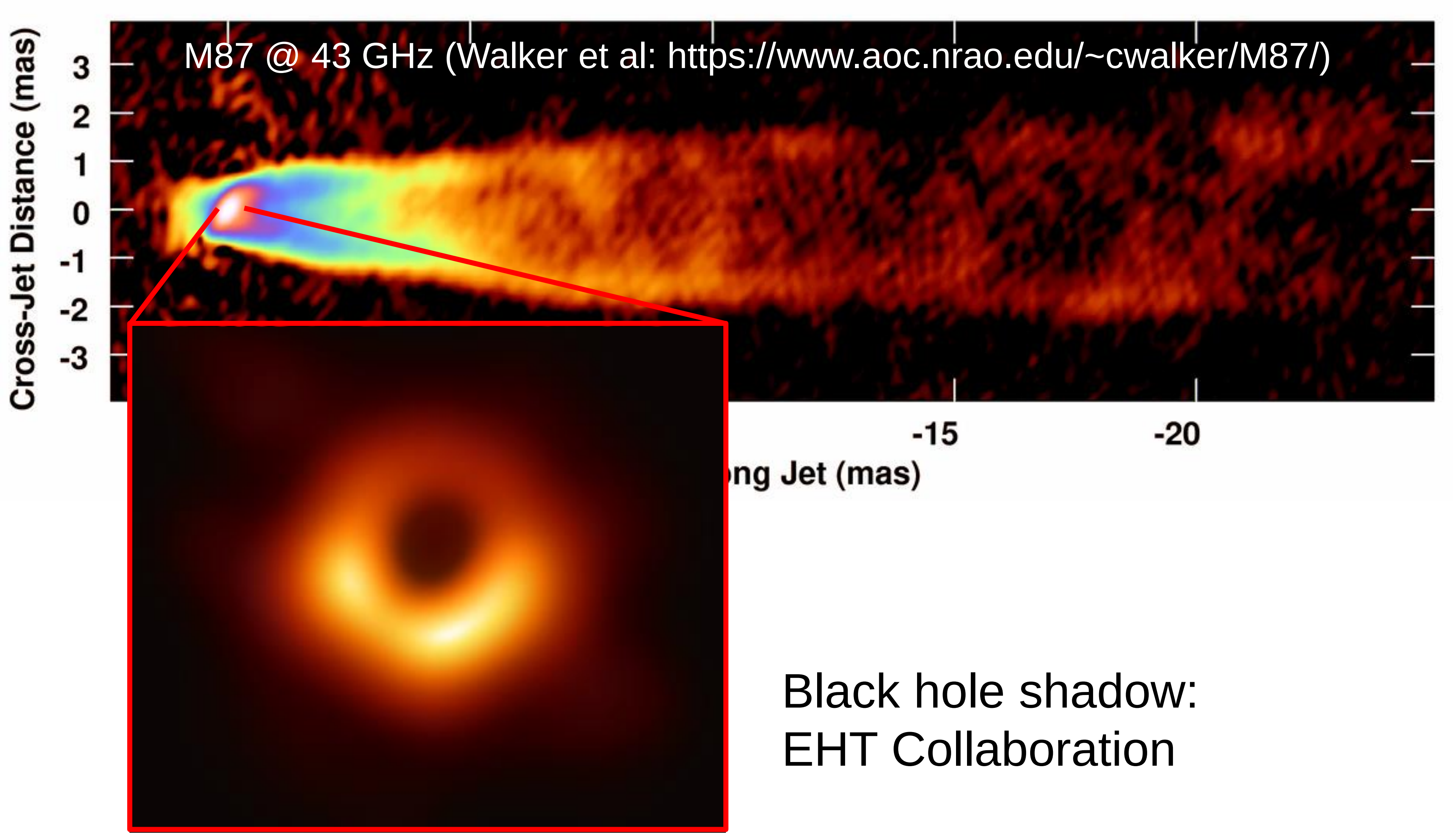
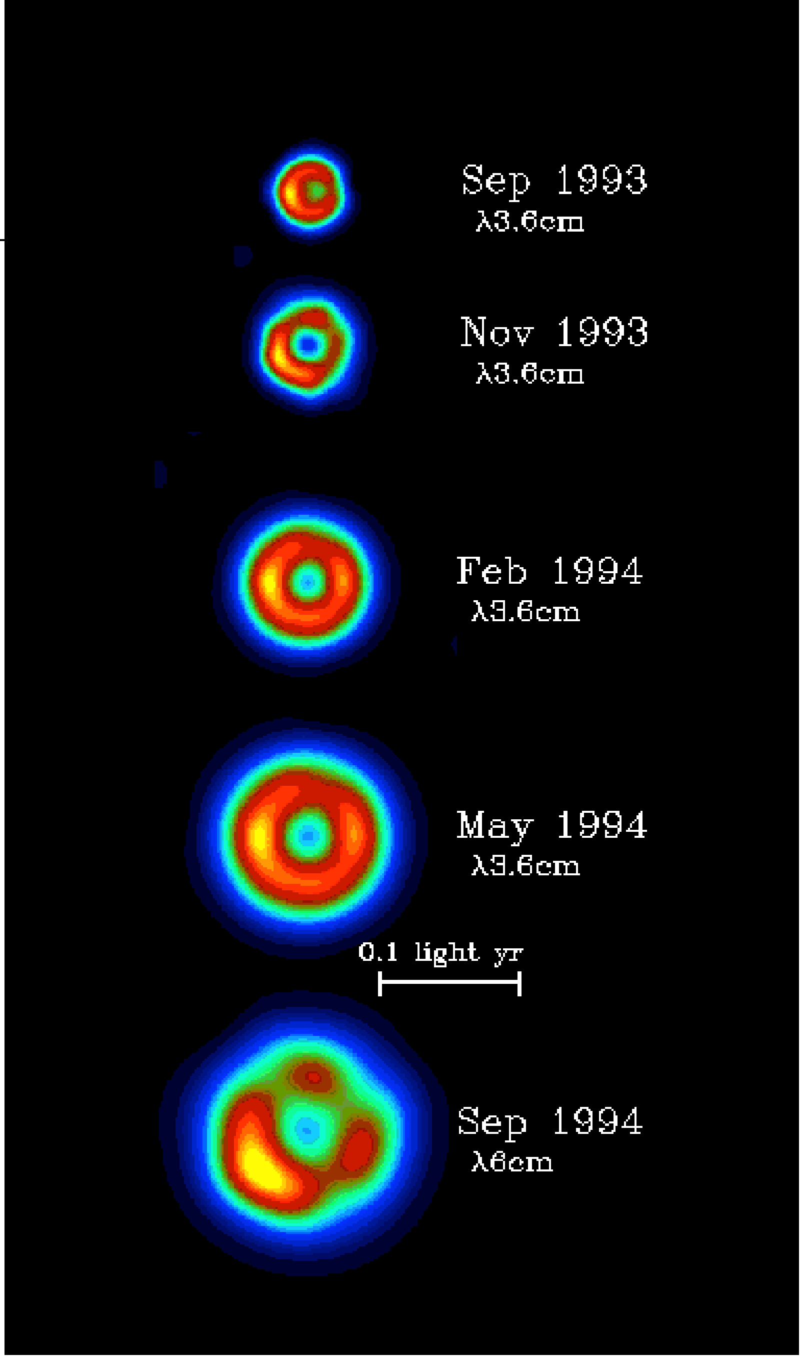


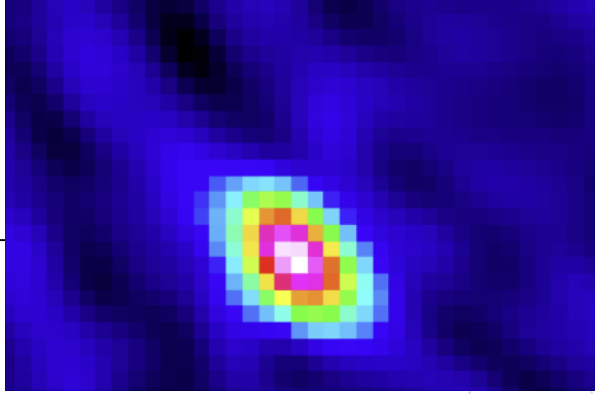
Black hole shadow:
EHT Collaboration

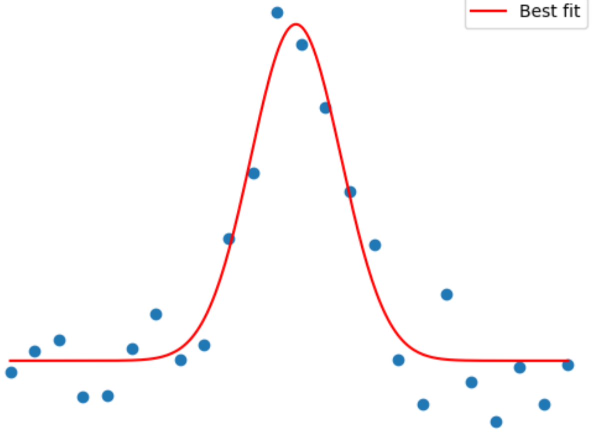
High resolution imaging

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



Astrometry

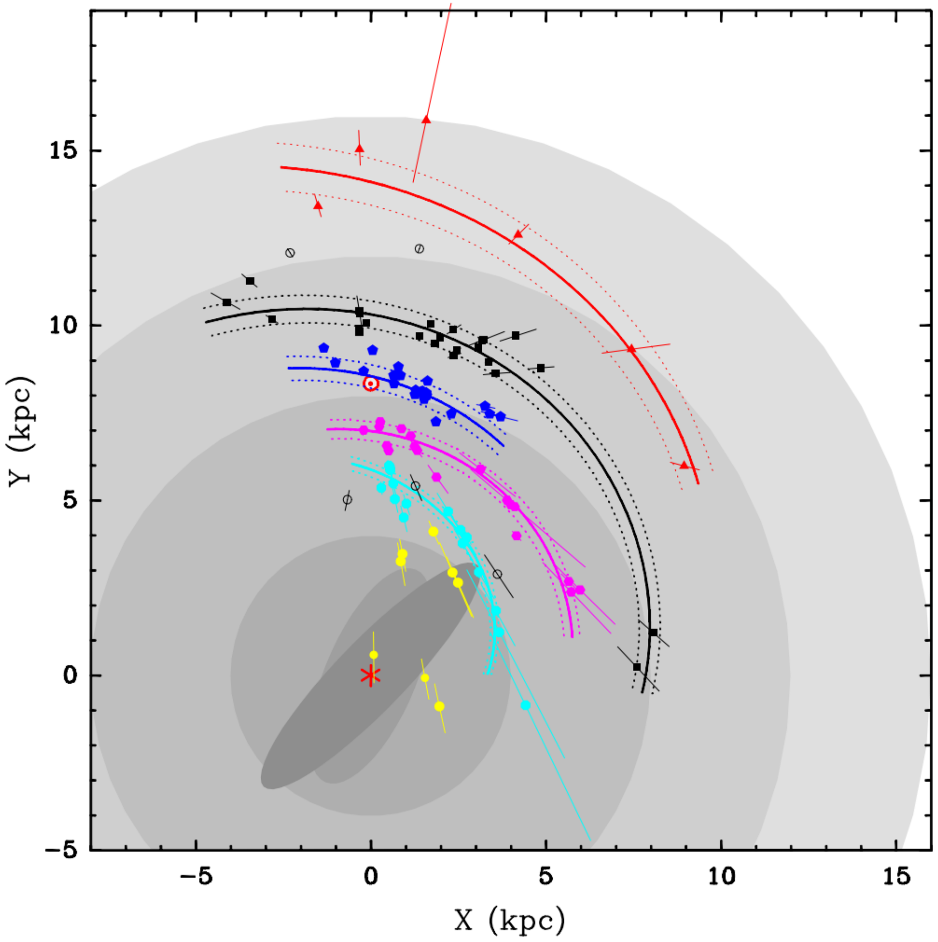




- VLBI can centroid an object's location to the ~0.01 mas level [(λ/D) / SNR]
  - *Gaia*-level accuracy (already for years, and also can access the Galactic plane!)
- Easiest for point sources, but source structure can be modelled tool
- Astrometry deserves a whole lecture on its own (can find some from past schools): I will show a couple of brief science highlights without further technical detail

Galactic structure

BeSSeL
Bar and Spiral Structure Legacy Survey

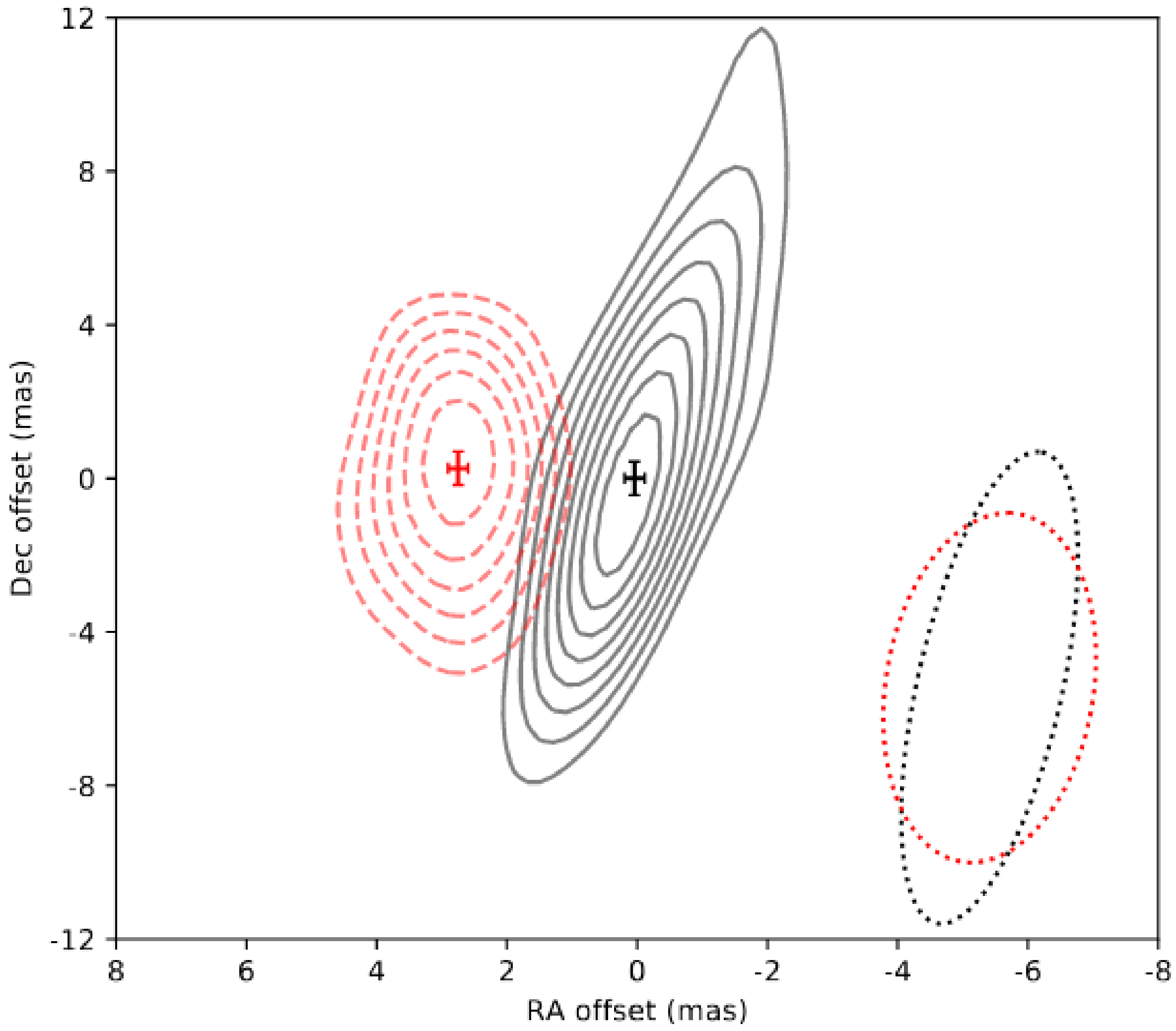


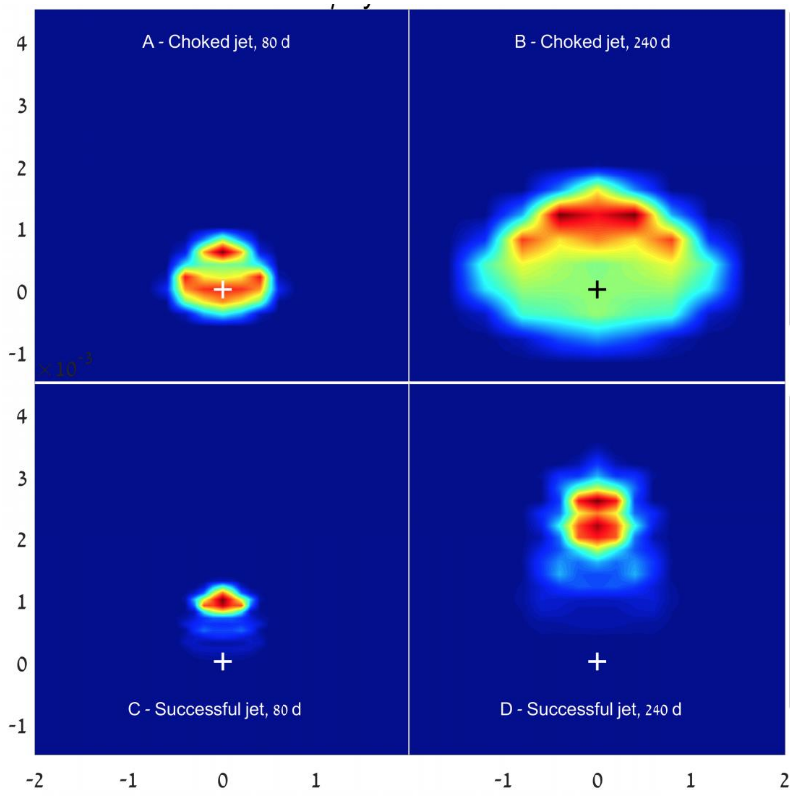
>100 parallax distances to masers around high-mass star forming regions:

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

(Reid et al. 2019, ApJ, 885, 131)

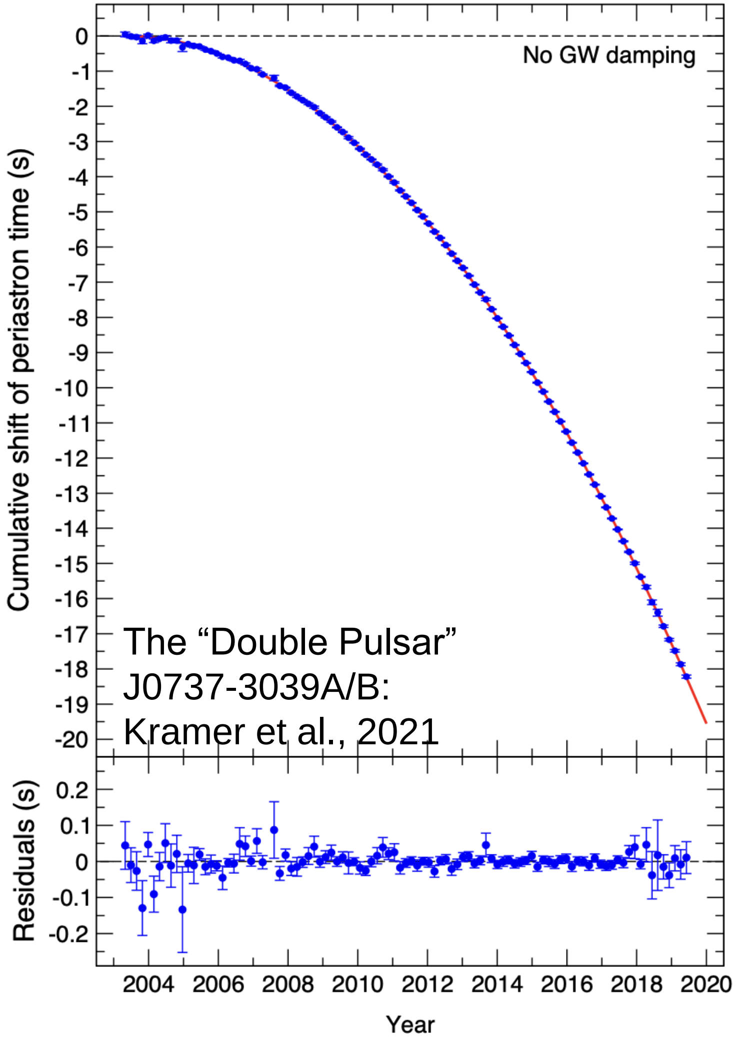
GW merger afterglows

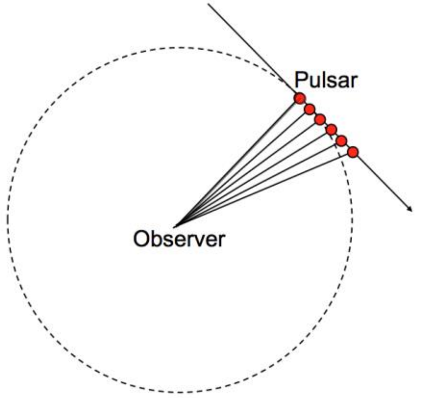




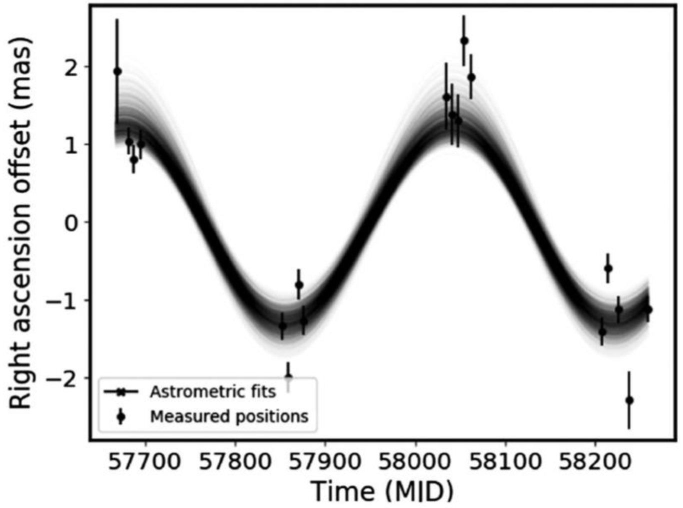
Model comparison for GW170817 afterglow showed a successful, narrow jet, viewed from inclination angle 20-25° (Mooley+2018)

Precision tests of GR



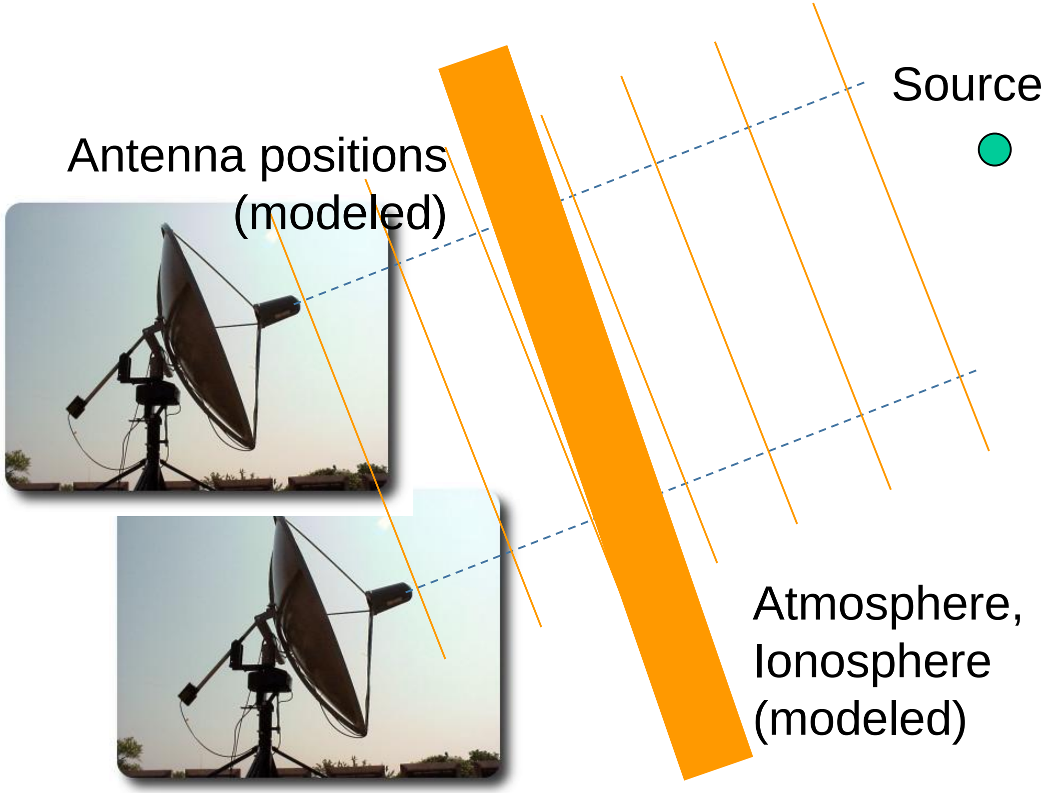


“Shklovskii” effect from transverse motion corrupts intrinsic decay from GW emission: must measure distance: annual parallax



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



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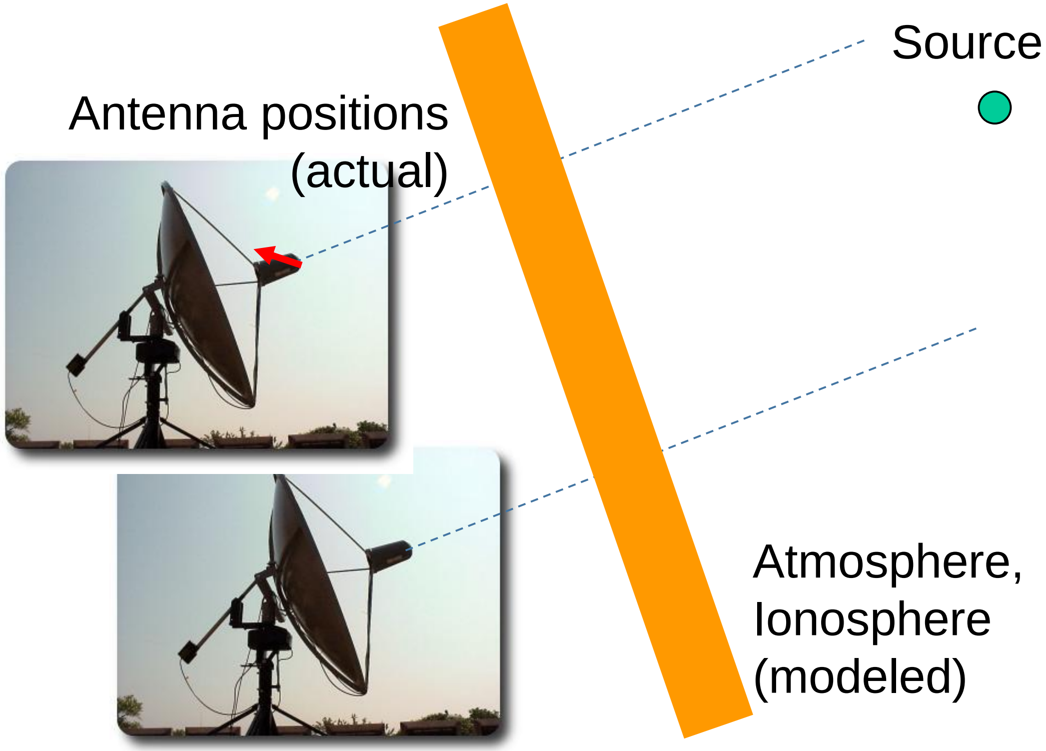

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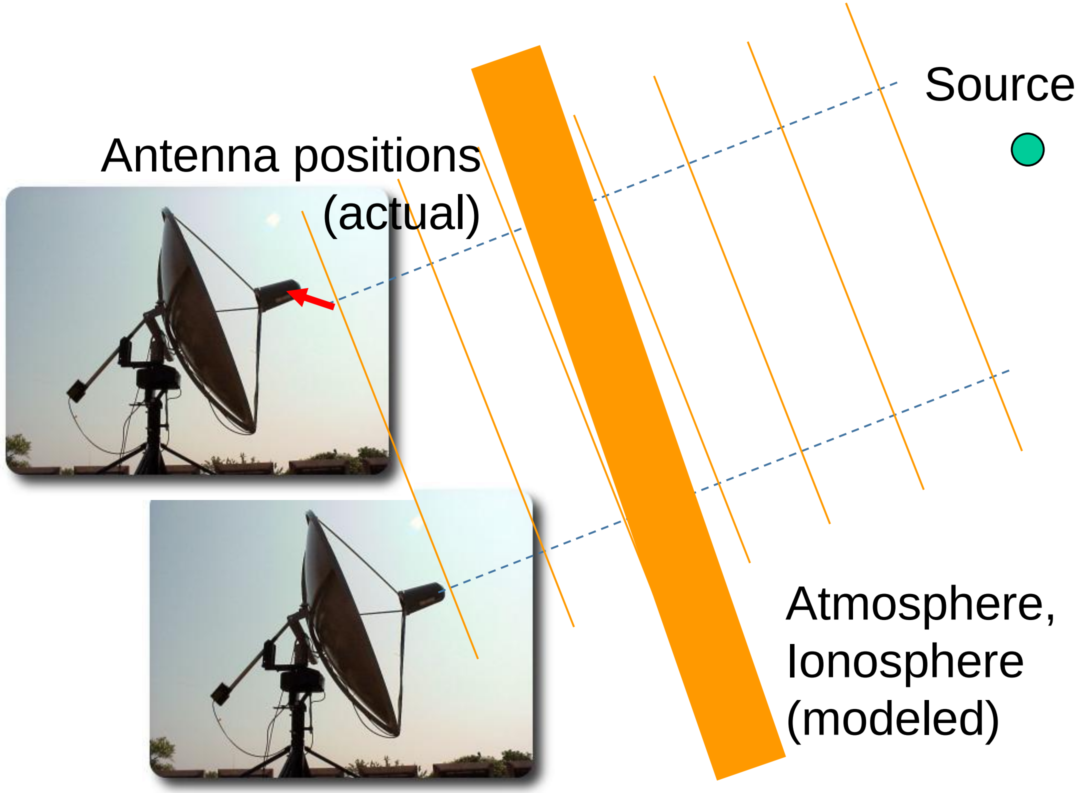

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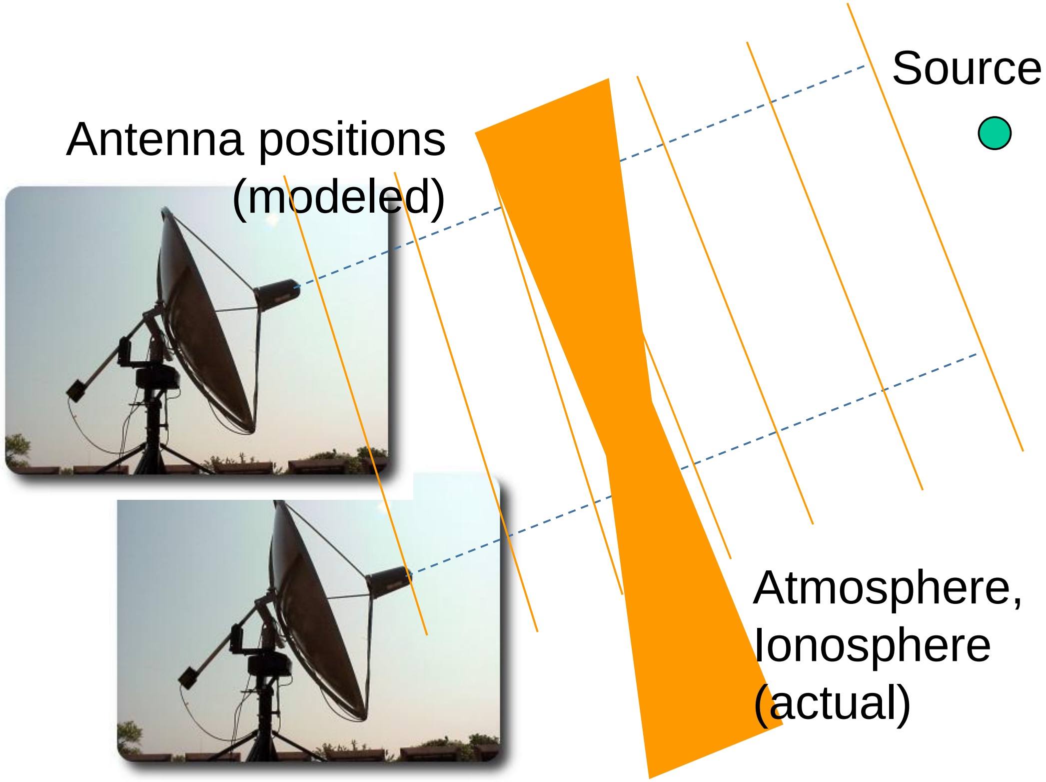
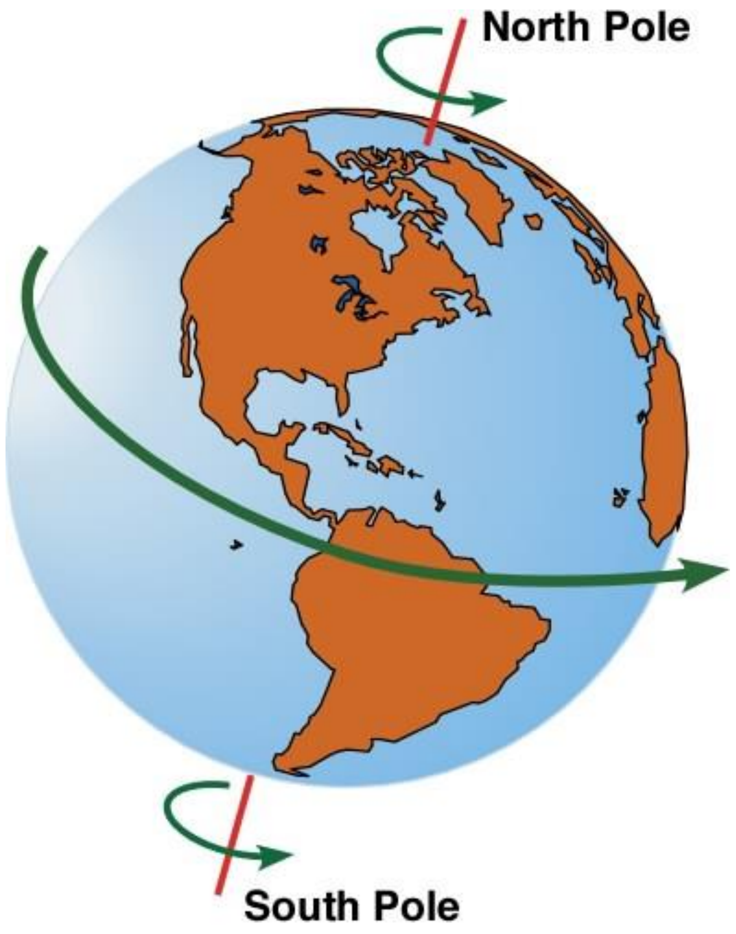


Geodetic results

- Global geodesy measures the participating telescope's positions to the mm level, the Earth's rotation phase (UT1-UTC) to a precision of ~4 microseconds every day, and the orientation of the Earth's spin axis to a precision of ~10s of microarcseconds



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”

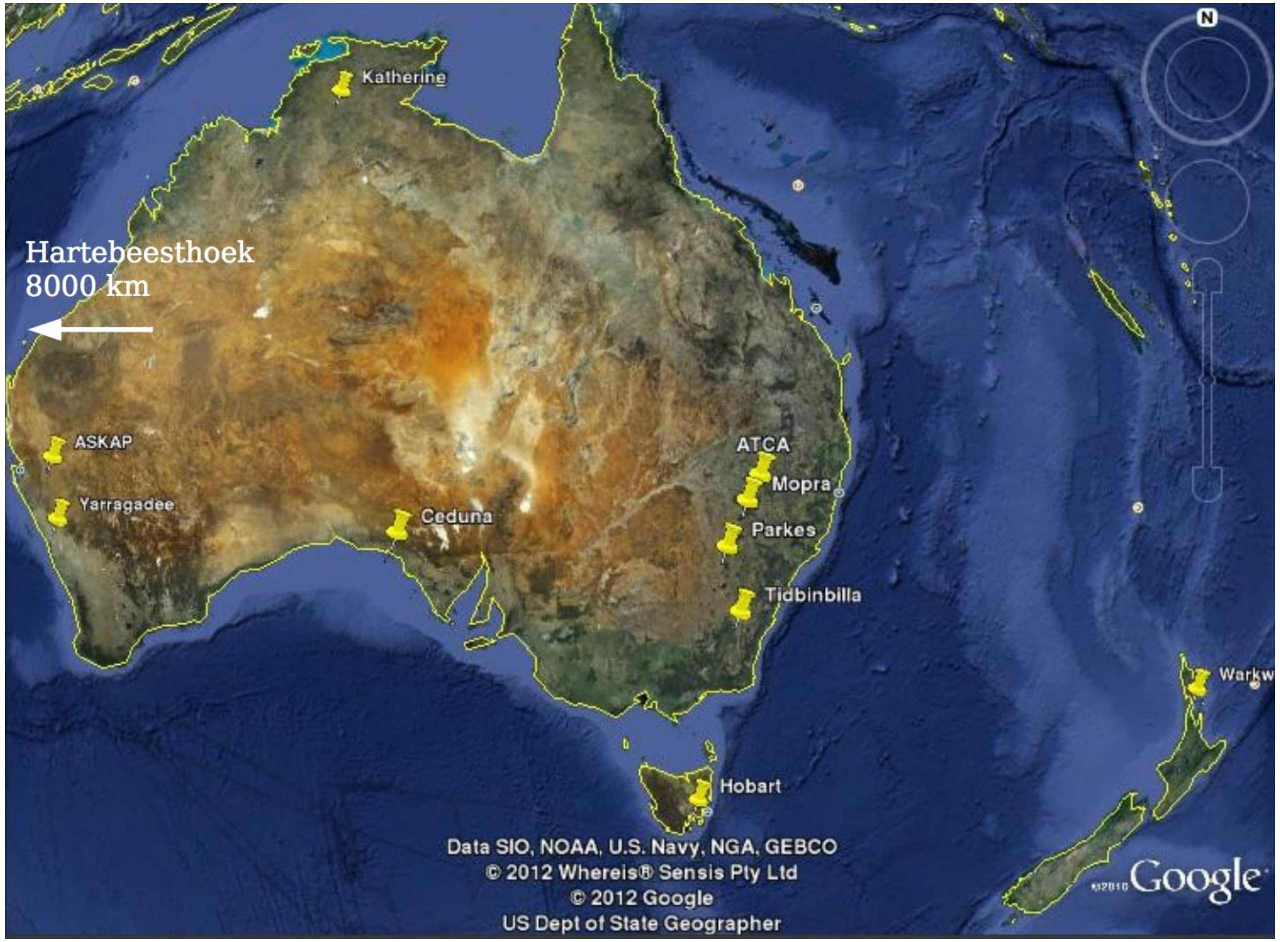
Current VLBI arrays

- 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

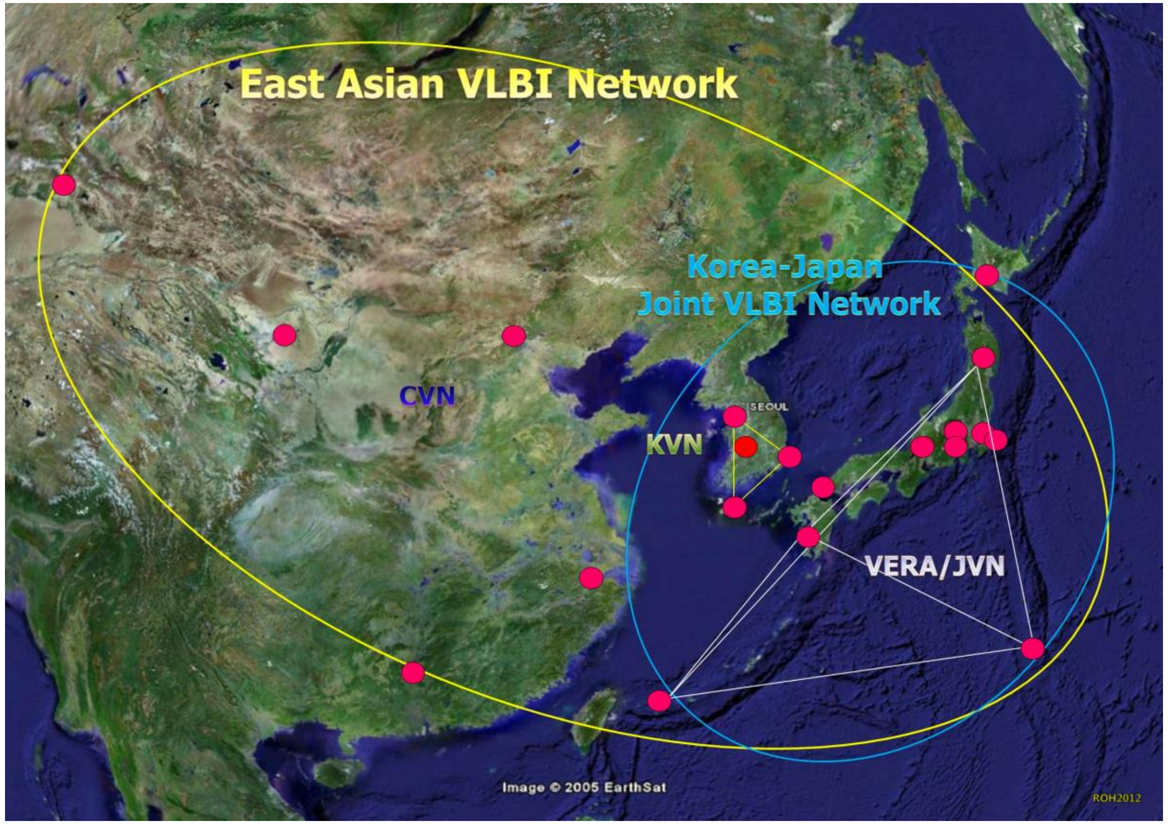
- The Long Baseline Array (LBA)



- 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

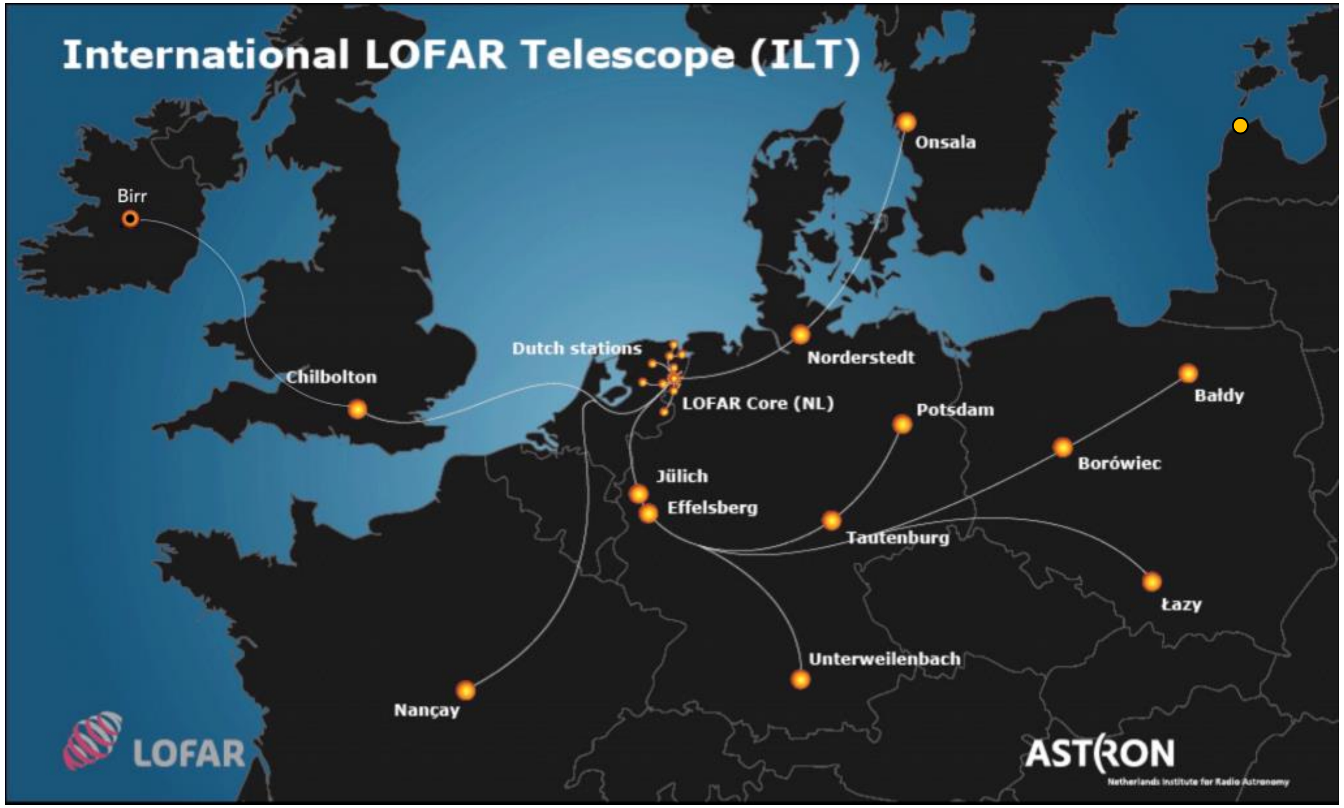
- East Asian VLBI Network is a collaboration of 3 separate networks:



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!)

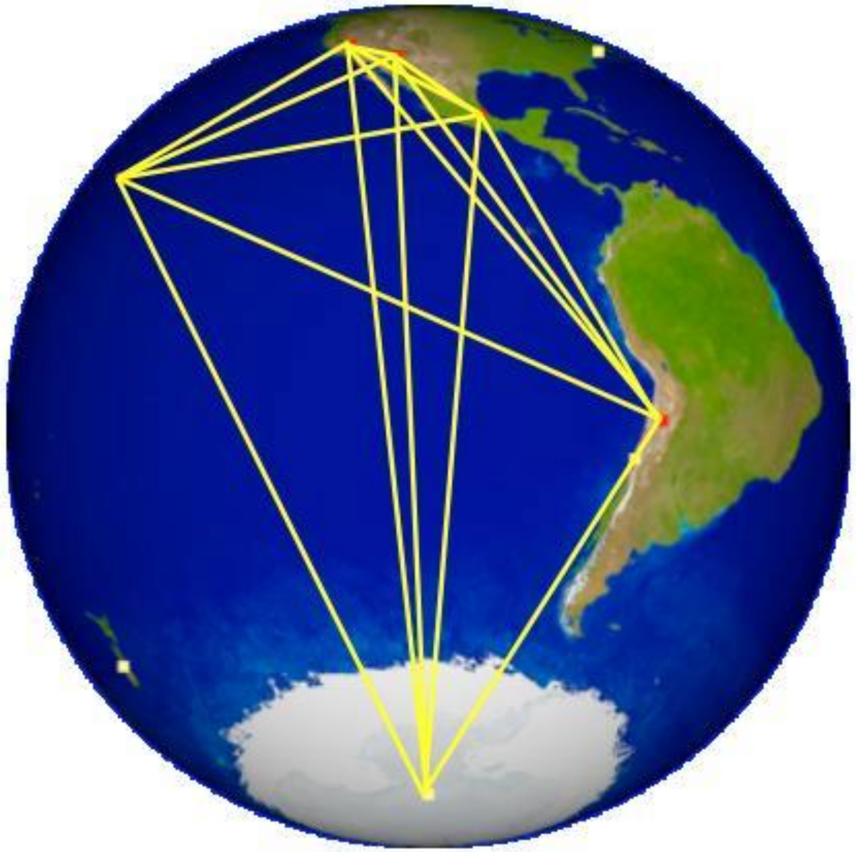
Unmatched sensitivity and resolution at high frequency.

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), many shared by longer baseline observations at high frequency with connected-element interferometers

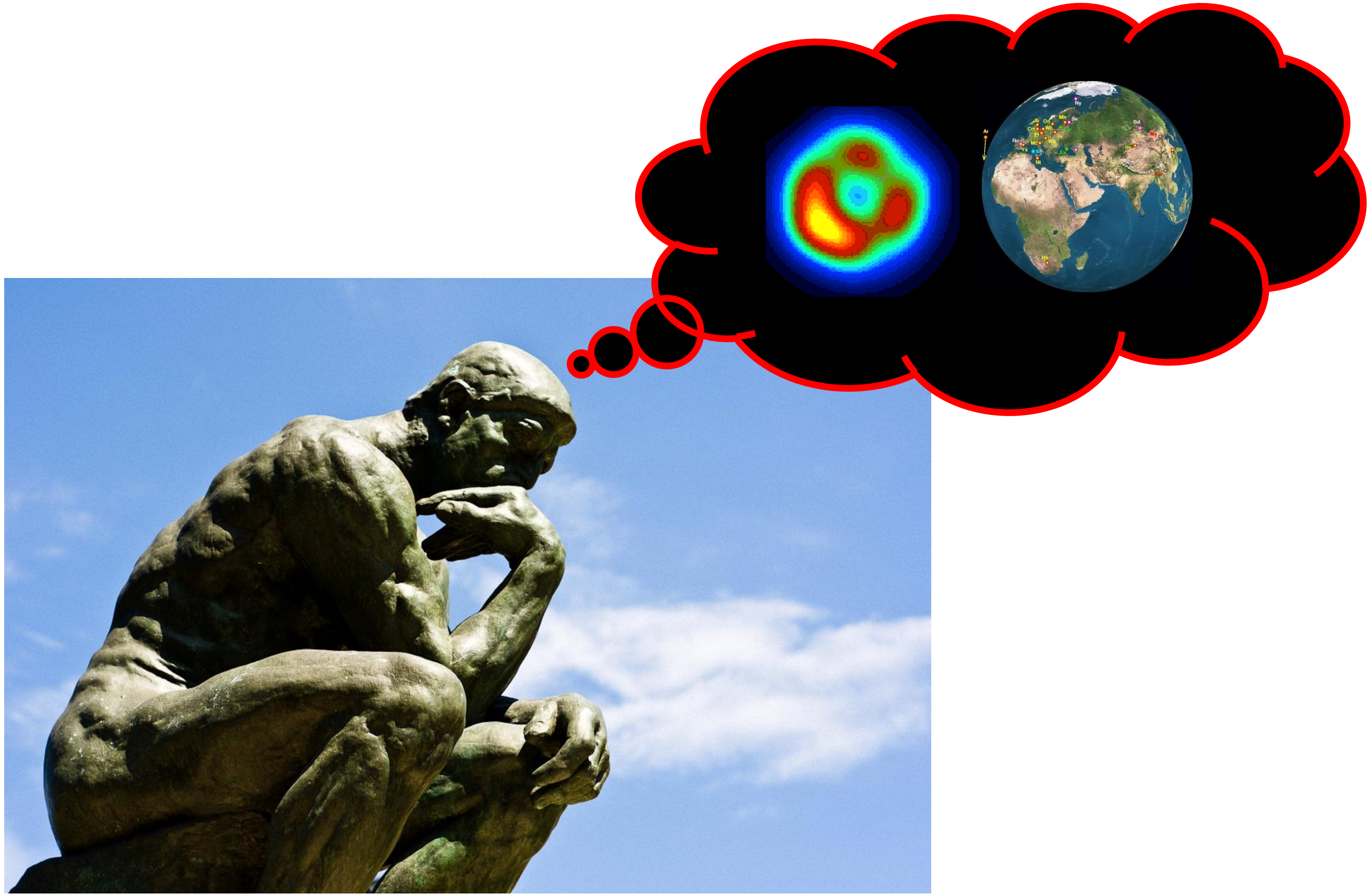
SOLVED

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

SORT-OF-SOLVED

- Uncorrelated atmosphere/ ionosphere (address with **fast calibration** cycle)
- No flux calibrator sources (rely on **switched power** noise calibration, **bootstrapping** [use e.g. VLA to measure flux density of a source with no structure on intermediate baselines])

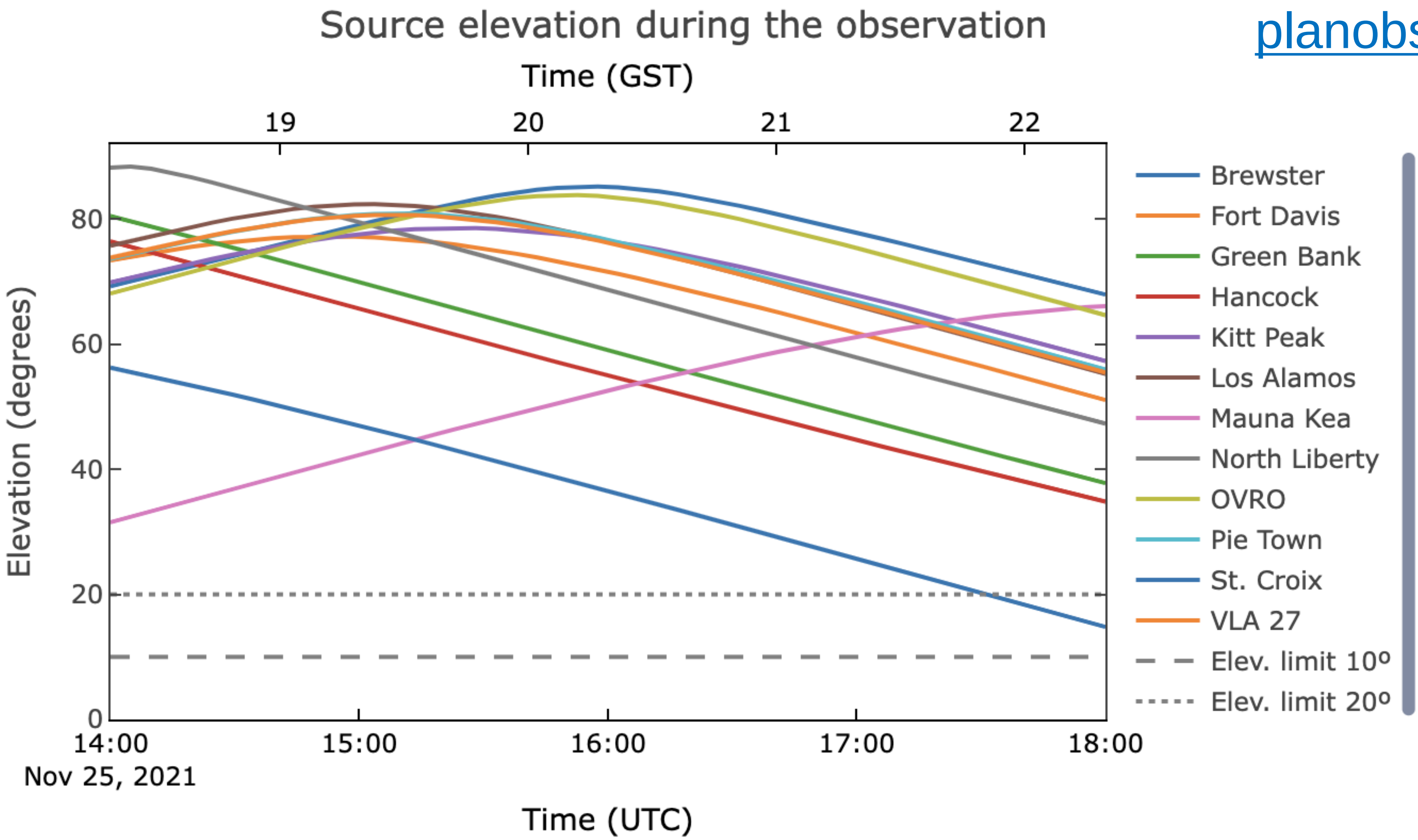
The practicalities of VLBI



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



planobs.jive.eu

Plan

astrogeo.org/cgi-bin/calib_search_form.csh?ra=10%3A57%3A58.84&dec=-20%3A05%3A30&num_sou=10&fo

Target source J2000.0 right ascension **10:57:58.8**, declination **-20:05:30.0**
Search catalogue: rfc_2024a

Results of calibrator search

Sts	Dist	B1950 name	J2000 name	J2000.0 coordinates		Error	Image	Band	Flux (Jy)		PS map	PS rad plot	FITS map	FITS uv	Analyst
	deg			Right ascens.	Declination	mas	epoch		Tot	Unres					
U	1.14	1100-200	J1102-2017	11:02:44.8559	-20:17:53.967	27.77	n/a		n/a		n/a				
C	1.20	1059-190	J1101-1918	11:01:49.6825	-19:18:05.379	1.01	2015.10.13	C	0.052	0.045	C_map_ps	C_rad_ps	C_map_fits	C_uf_fits	(pet)
							2015.10.13	X	0.033	0.029	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
C	1.85	1050-184	J1052-1845	10:52:34.5724	-18:45:18.277	1.90	2013.04.21	C	0.104	0.046	C_map_ps	C_rad_ps	C_map_fits	C_uf_fits	(pet)
							2013.04.21	X	0.061	0.036	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
C	2.38	1045-199	J1047-2014	10:47:52.3728	-20:14:22.314	1.38	2019.02.02	C	0.055	0.054	C_map_ps	C_rad_ps	C_map_fits	C_uf_fits	(pet)
							2019.02.02	X	0.089	0.080	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
C	2.50	1045-188	J1048-1909	10:48:06.6206	-19:09:35.727	0.10	1996.06.05	C	0.987	0.907	C_map_ps	C_rad_ps	C_map_fits	C_uf_fits	(gur)
							1997.01.11	S	0.565	0.477	S_map_ps	S_rad_ps	S_map_fits	S_uf_fits	(pus)
							1997.01.11	X	1.040	0.993	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
							1997.07.02	S	0.927	0.874	S_map_ps	S_rad_ps	S_map_fits	S_uf_fits	(yyk)
							1997.07.02	X	1.349	1.301	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
							1997.08.27	S	0.879	0.782	S_map_ps	S_rad_ps	S_map_fits	S_uf_fits	(yyk)
							1997.08.27	X	1.374	1.214	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
							2000.12.04	S	0.786	0.664	S_map_ps	S_rad_ps	S_map_fits	S_uf_fits	(pus)
							2000.12.04	X	1.165	1.066	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
							2002.06.15	U	1.292	1.144	U_map_ps	U_rad_ps	U_map_fits	U_uf_fits	(moj)
							2003.05.07	S	0.748	0.653	S_map_ps	S_rad_ps	S_map_fits	S_uf_fits	(pus)
							2003.05.07	X	0.976	0.896	X_map_ps	X_rad_ps	X_map_fits	X_uf_fits	
							2003.06.15	U	1.251	1.031	U_map_ps	U_rad_ps	U_map_fits	U_uf_fits	(moj)

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 every ~few hours for bandpass and sanity check, 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 has long been the primary package for VLBI calibration; CASA becoming an alternative (delay calibration now 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 (lower loop gain helpful)

The near-term future of VLBI

- Existing cm-VLBI (EVN/EAVN/VLBA/LBA):
  - more bandwidth increases,
  - data processing innovations
  - commission VLBI on recent telescopes (FAST, MeerKAT)
- m-VLBI:
  - LOFAR sub-arcsecond; 150 MHz near-routine, 50 MHz still very hard
  - Planned southern hemisphere demonstrator LAMBDA
- (sub-)mm-VLBI:
  - phased ALMA here, huge sensitivity boost eases calibration

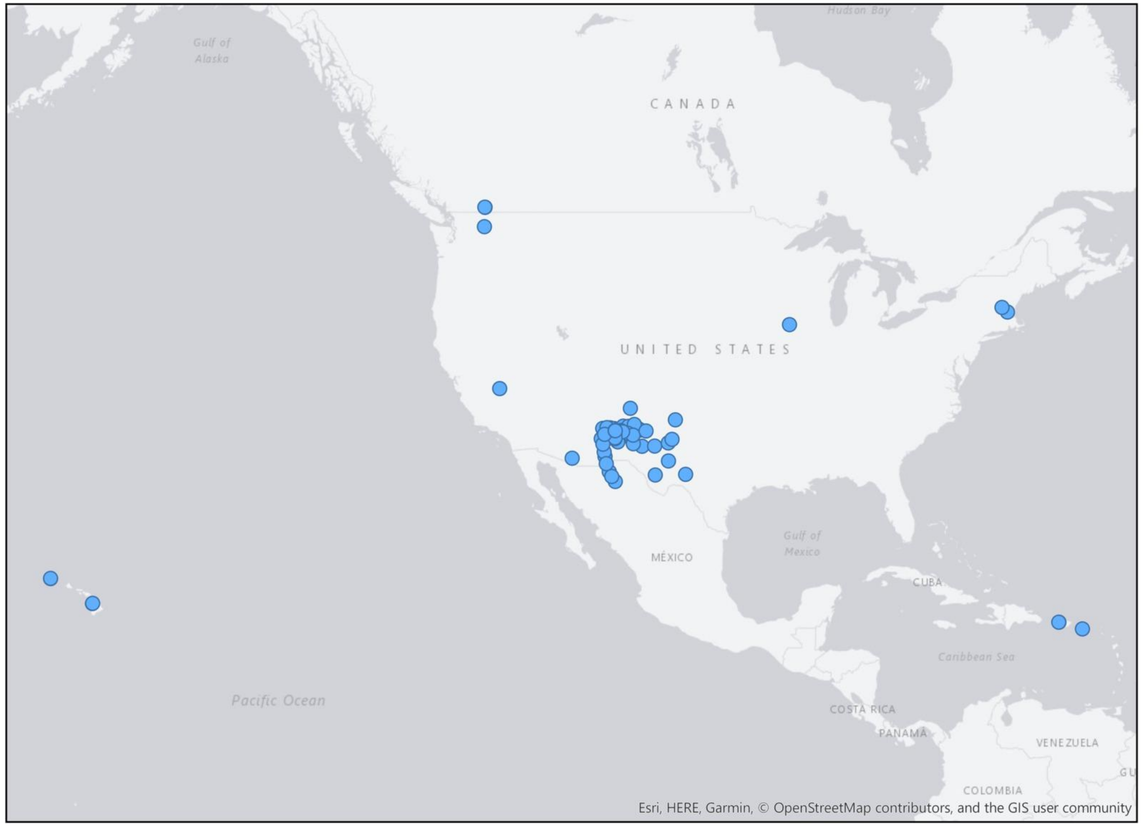
All-new facilities from late 2020s

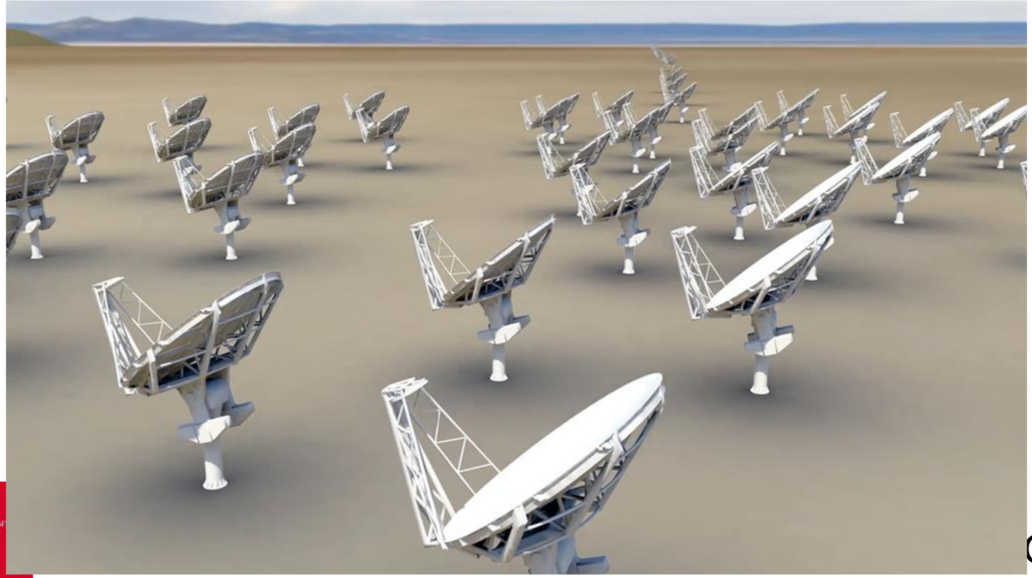
SKA1-mid will add a sensitive new element to the EVN (for equatorial sources) and/or the LBA (in the south)

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

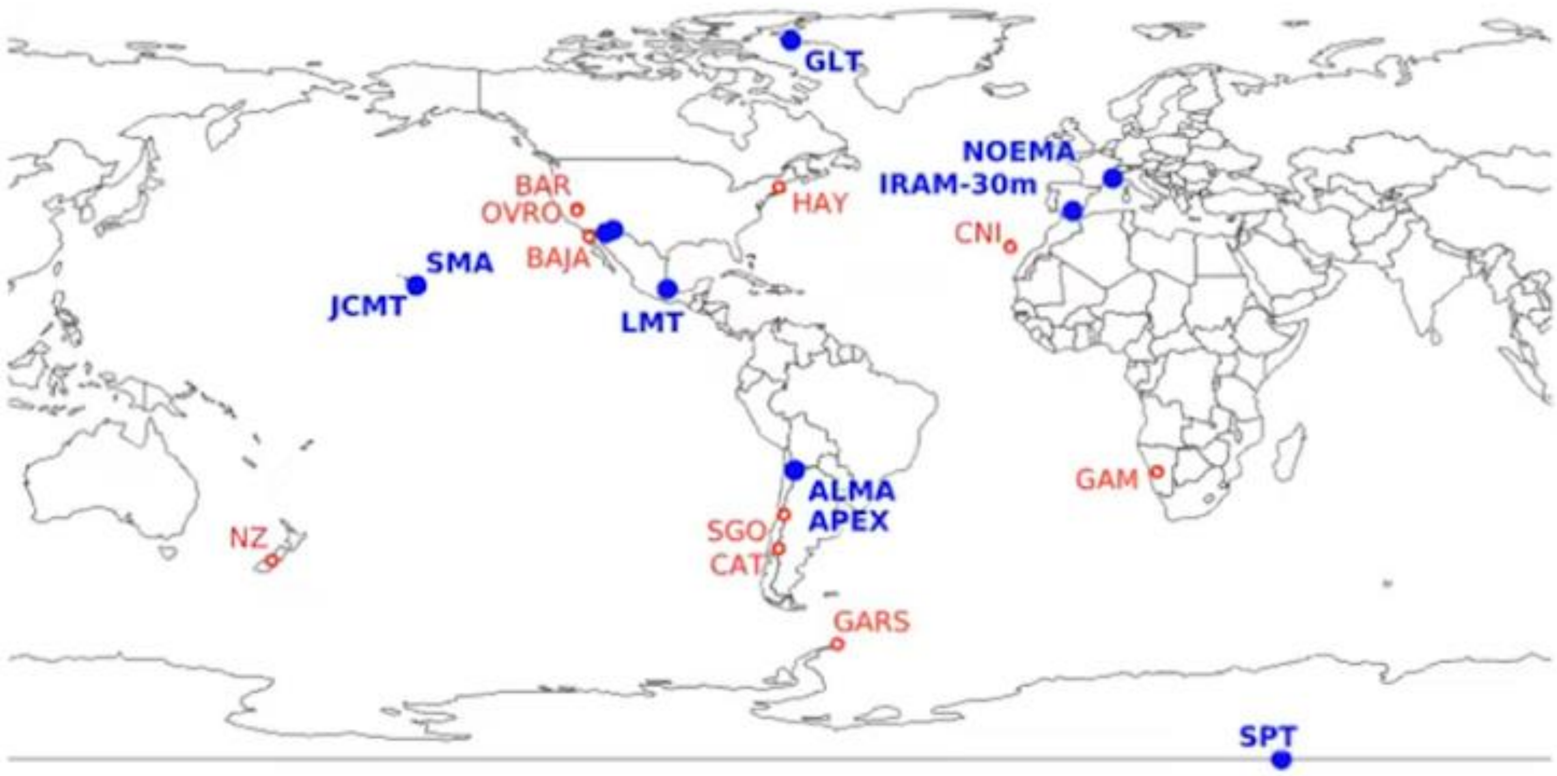
All-new facilities from late 2020s

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

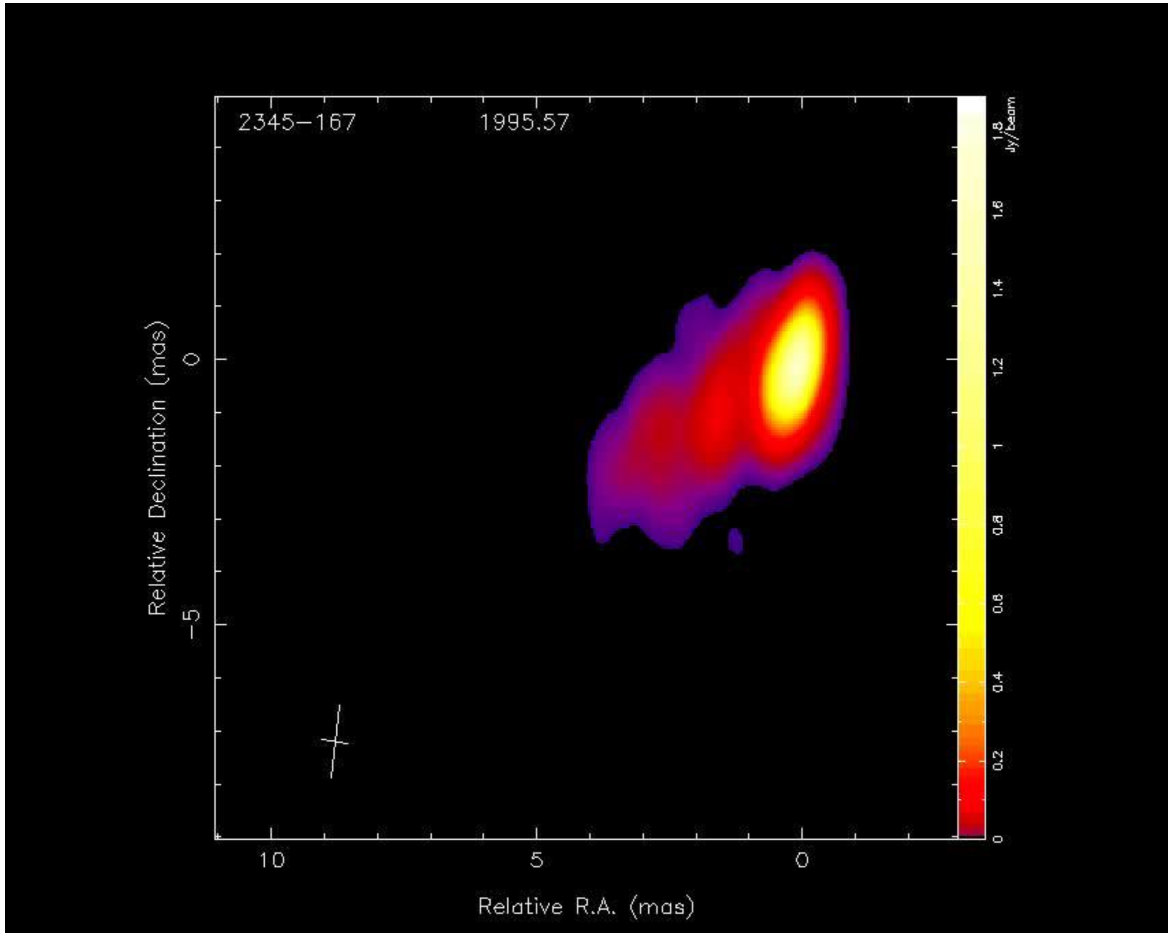
Conclusions

- 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

The practicalities of VLBI

- What do you do?
  1. Plan
  2. Propose
  3. Schedule
  4. Observe
  5. Calibrate and image
  6. Publish, get promoted, bask in glory…

High resolution imaging



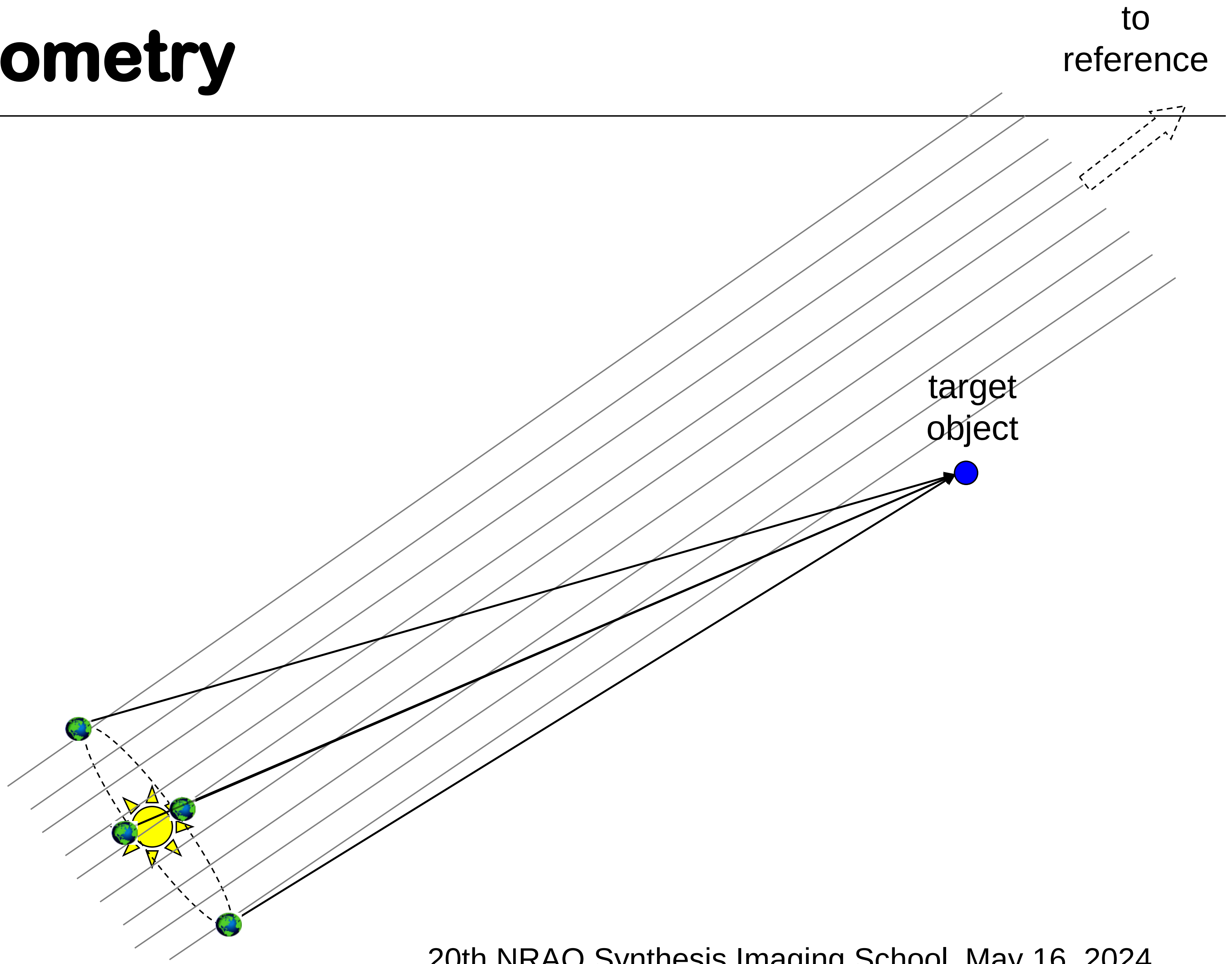
Superluminal motion in B2345-167 (MOJAVE timelapse, 15 GHz)

http://www.physics.purdue.edu/astro/MOJAVE/

Current VLBI arrays

- RadioAstron: 10m space telescope
- Baseline lengths 1,000 – 330,000 km
- 327 MHz, 1.6 GHz, 4.8 GHz, 22 GHz
- No longer operating – future space telescopes some way off

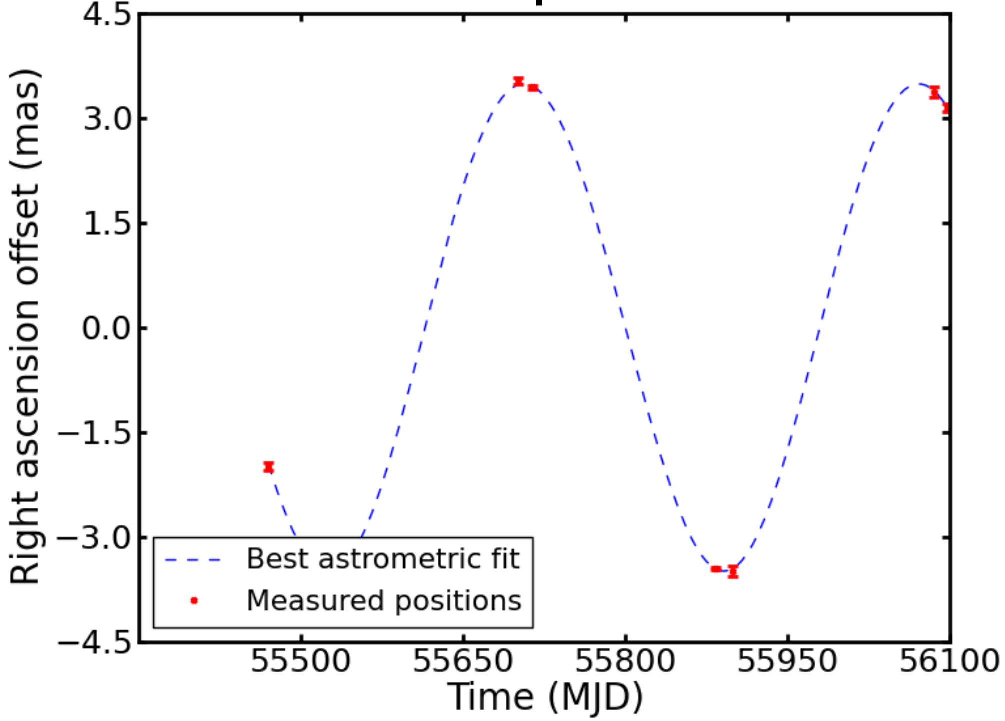
Astrometry



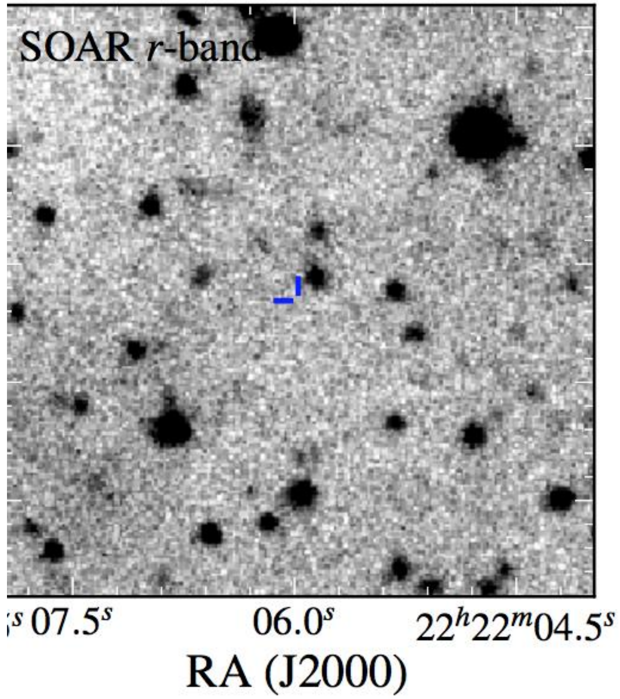
Astrometry highlights

- PSR J2222-0137 distance with 0.4% precision; interpret optical info on WD companion

Annual parallax

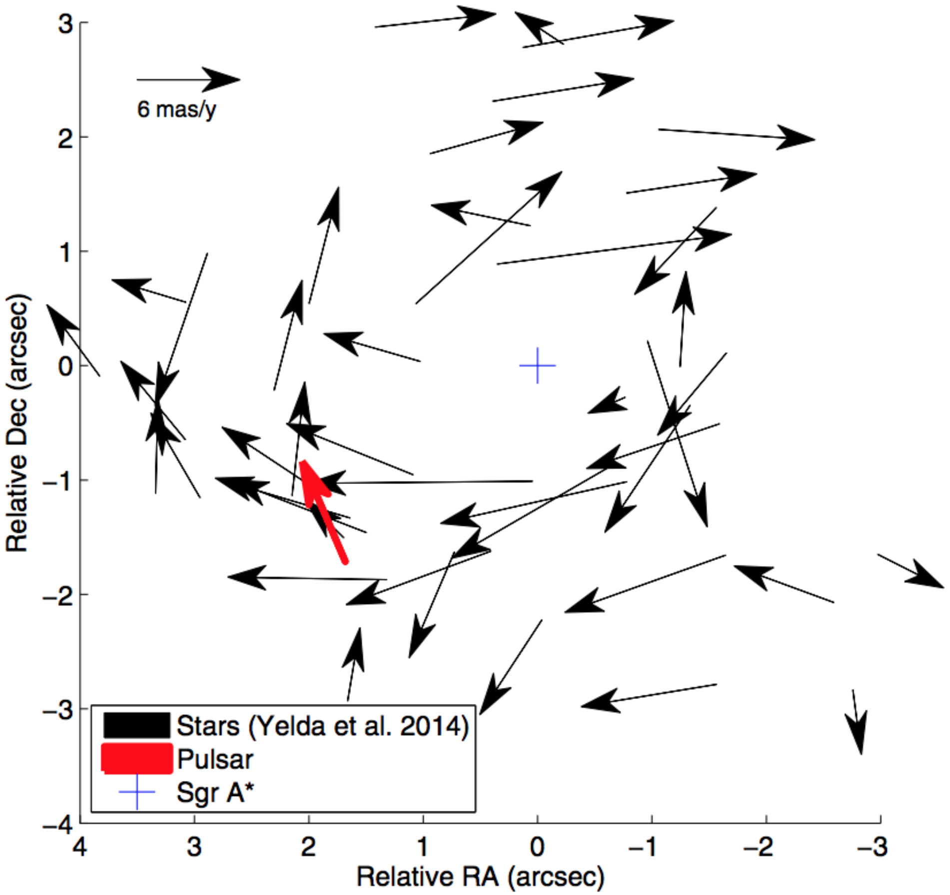


Optical non-detection



Deller et al. 2012, Kaplan et al. 2014

Astrometry highlights



The only known Galactic Center pulsar (PSR J1745-2900, a magnetar) shown to likely originate in the stellar disk and be bound to Sgr A* (Bower et al. 2015)

Conclusions

- VLBI offers a **unique** capability; the highest angular resolution imaging in astronomy
- Gives the ability to probe smallest size scales and do **very** precise astrometry
- With **some** limitations (determined by physics); only compact objects
- VLBI is **not** a “black art” – no harder than high frequency VLA observing

#1: Poor sensitivity

- The need to record data historically limited VLBI to narrower bandwidths
  - But the era of 2 Mbps tapes is long gone… At low frequencies, we are now constrained by the front-end just like everyone else.
- The VLBA + HSA does 4 Gbps (512 MHz, dual pol): beats JVLA point source sensitivity at 1.4 GHz. EVN has similar rates (not uniform). EHT 64 Gbps!
  - But: surface brightness sensitivity obviously still extremely low

#2: Unstable systems

- VLBI antennas still have completely independent electronics, time standard noise doesn't "wash out"
- **But:** modern systems (hydrogen masers, digital synthesizers) are stable on timescales of many hours
- Modern all-digital backends make the problem even smaller

#3: Unstable conditions

- This hasn't changed: atmosphere above different antennas is uncorrelated
- But this problem is not limited to VLBI: same is true of mm observing with moderate baselines (VLA, ALMA)
- Same solution: switch between source and nearby calibrator at a sufficiently rapid interval (sensitivity helps)

#4: Unreliable imaging

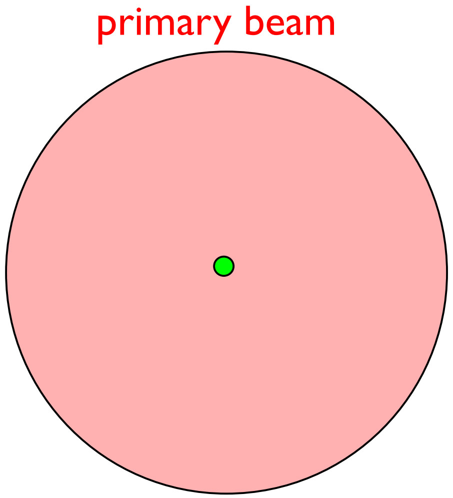
- Mostly a thing of the past (when phase stability was poor)
- Nowadays, set up your observations right (sufficient calibrators) and getting dynamic ranges >10,000 is easy
- Still two remaining problems:
  - Often fewer antennas (10 VLBA vs 27 VLA)
  - Layout is often not optimal (antenna placement determined by geography, infrastructure)

#5: Uncertain flux scale

- There are no constant-flux VLBI sources
  - Anything compact enough is always variable - quasars eject blobs of material, pulsars scintillate…
  - Thus cannot use a “flux calibrator”
- Compensate with extra effort in *a priori* flux calibration (switched noise diode)
- Absolute scale of VLBI flux is probably only valid to ~10% - usually no big deal
- Use a monitored source if needed

#6: Limited field of view

- Time smearing and bandwidth smearing are intense because of high fringe rate
- Older correlators had output rate restrictions, field of view ~arcseconds
- Even if correlator can make necessary visibility dataset, it will be **HUGE**
- And: image is 99.9999999% noise!



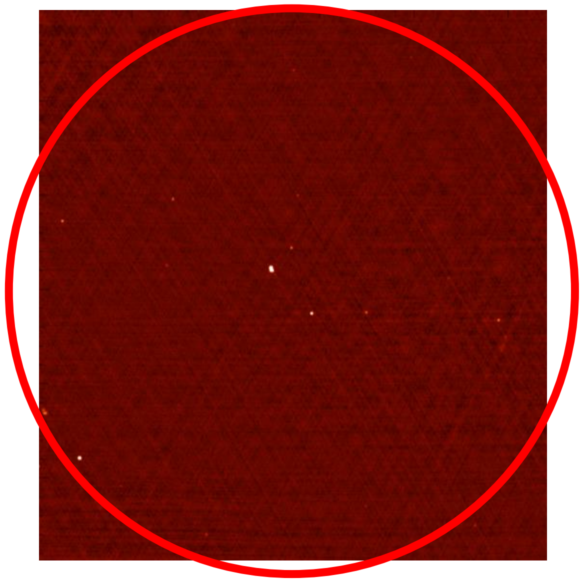
12h VLBA observation

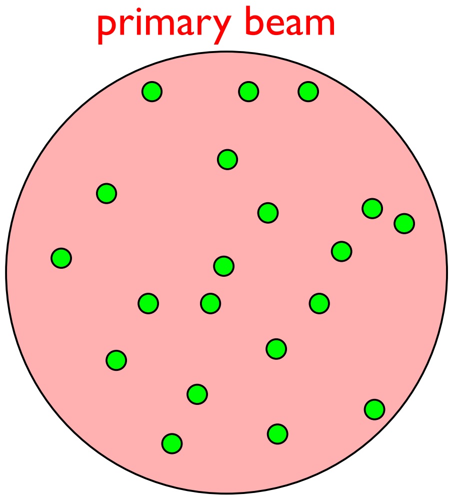
Small field (5”):
5 GB visibiilities
64 MB image

Full primary beam:
30 TB visibilities
10 TB image

#6: Limited field of view

- Cool feature in modern correlators allows "multi-field" VLBI
- Multiple small output datasets centered on sources of interest – use a "finder image" from e.g. VLA, GMRT, ATCA

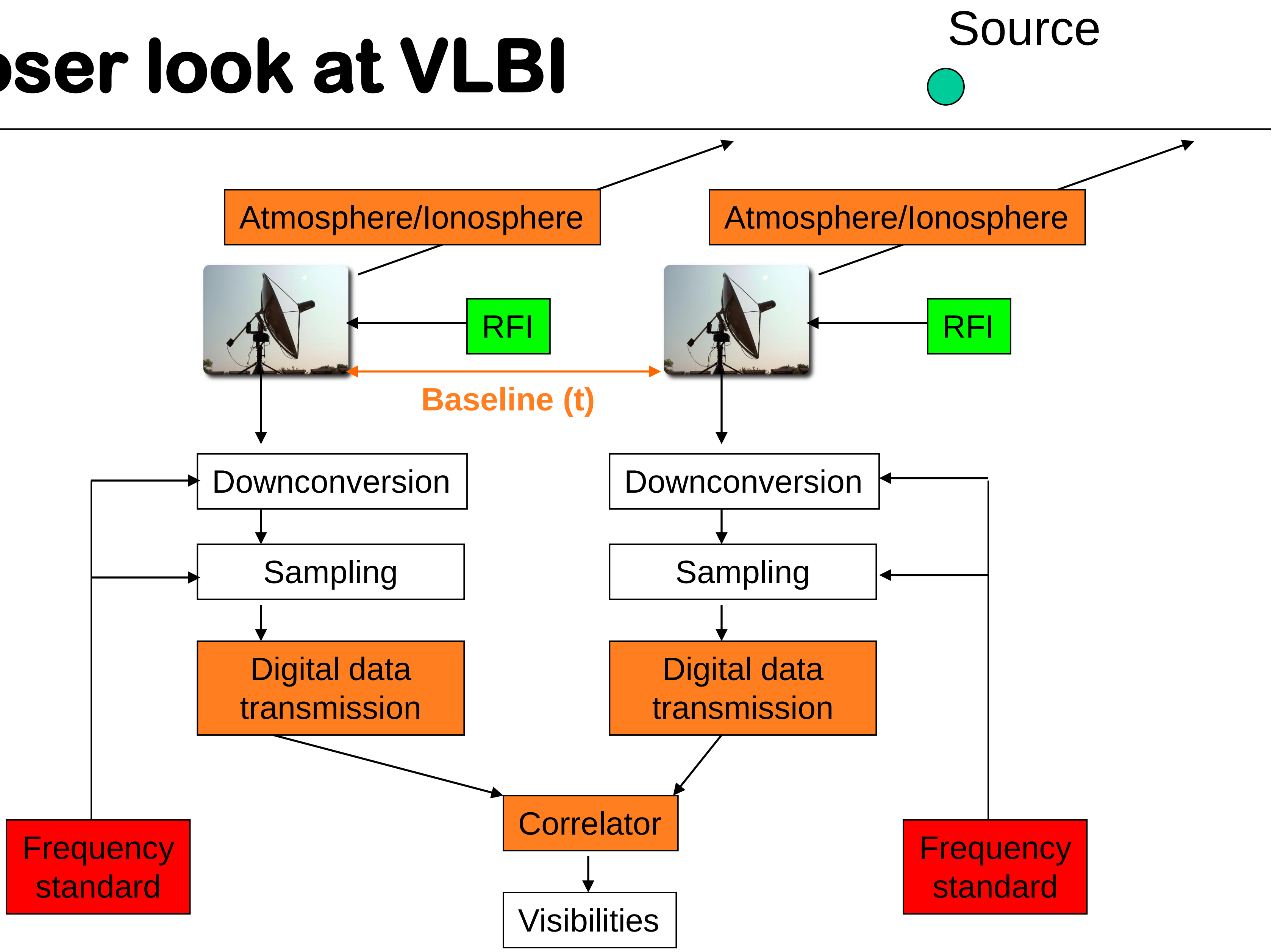




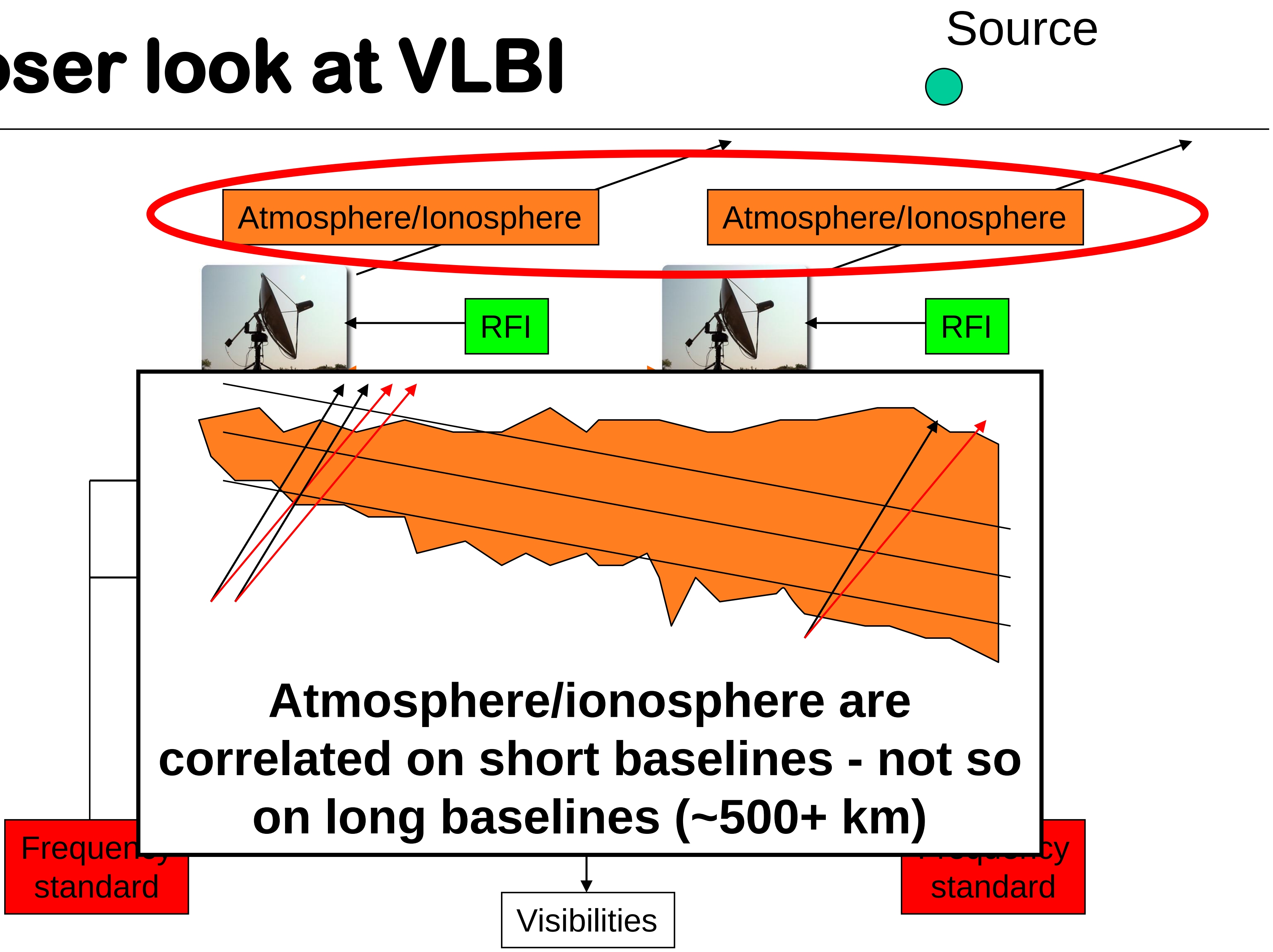
12h VLBA observation

1 small field (5"):
5 GB visibiilities
64 MB image
20 small fields:
100 GB visibilities
1.5 GB image

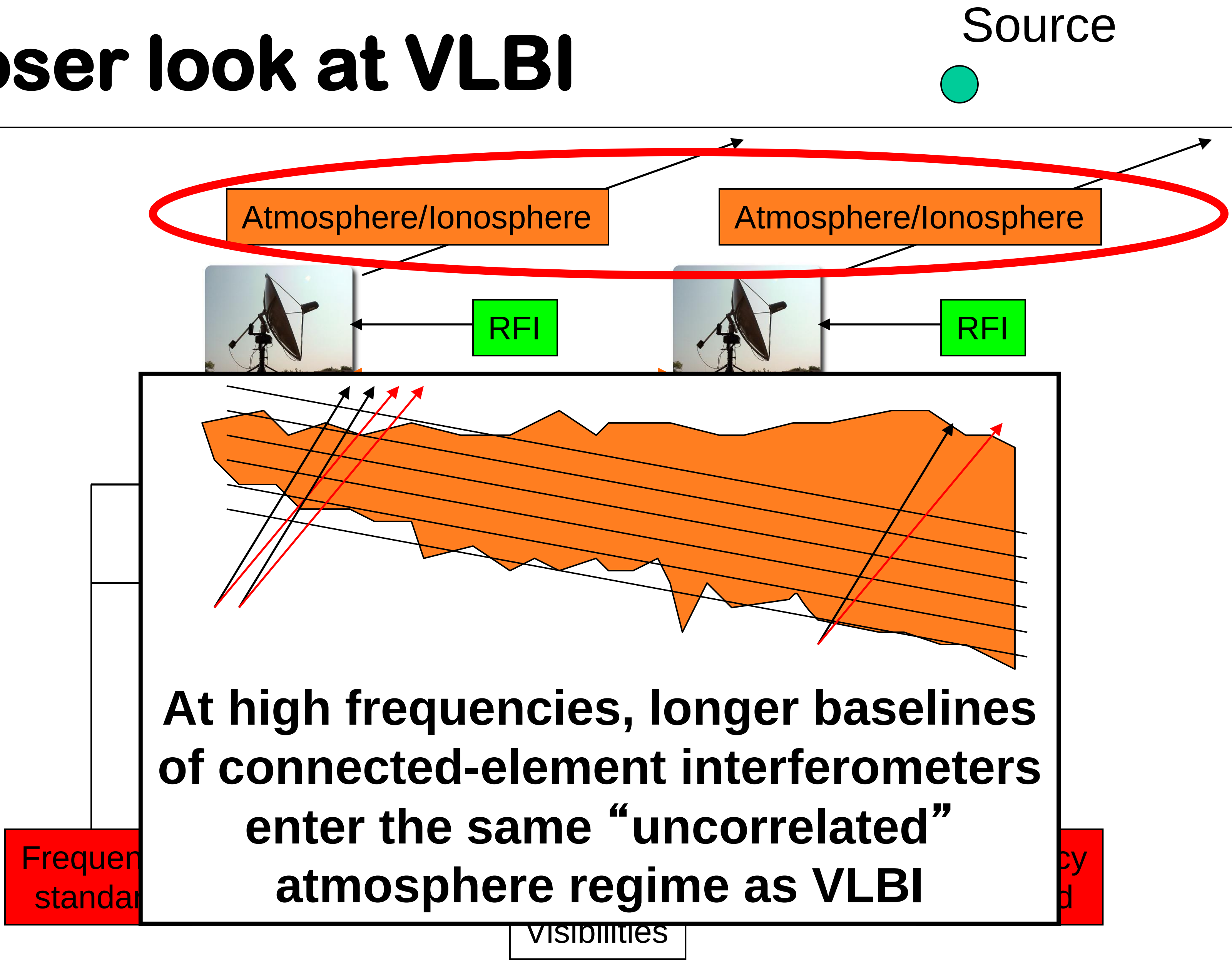
A closer look at VLBI



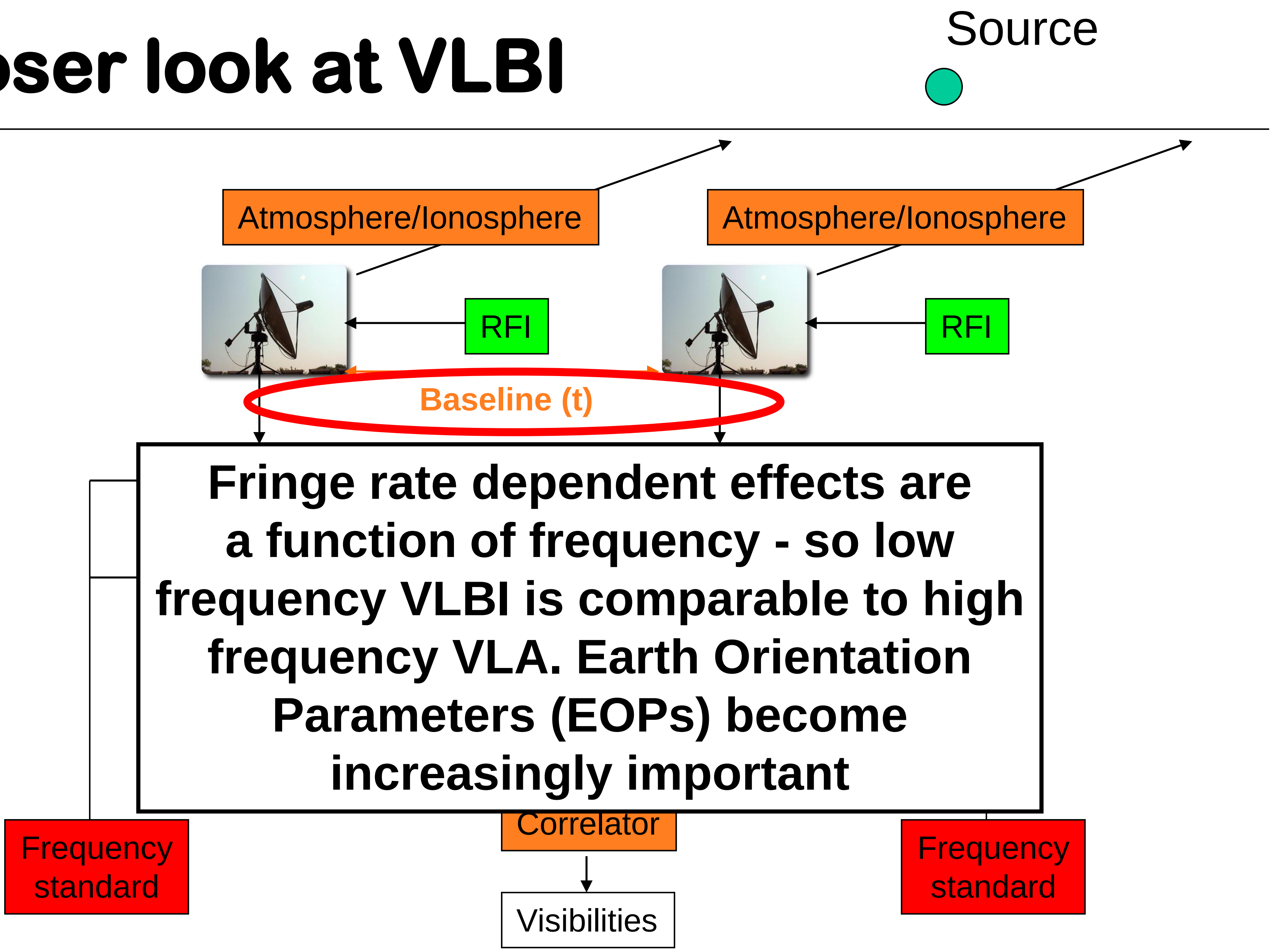
A closer look at VLBI



A closer look at VLBI

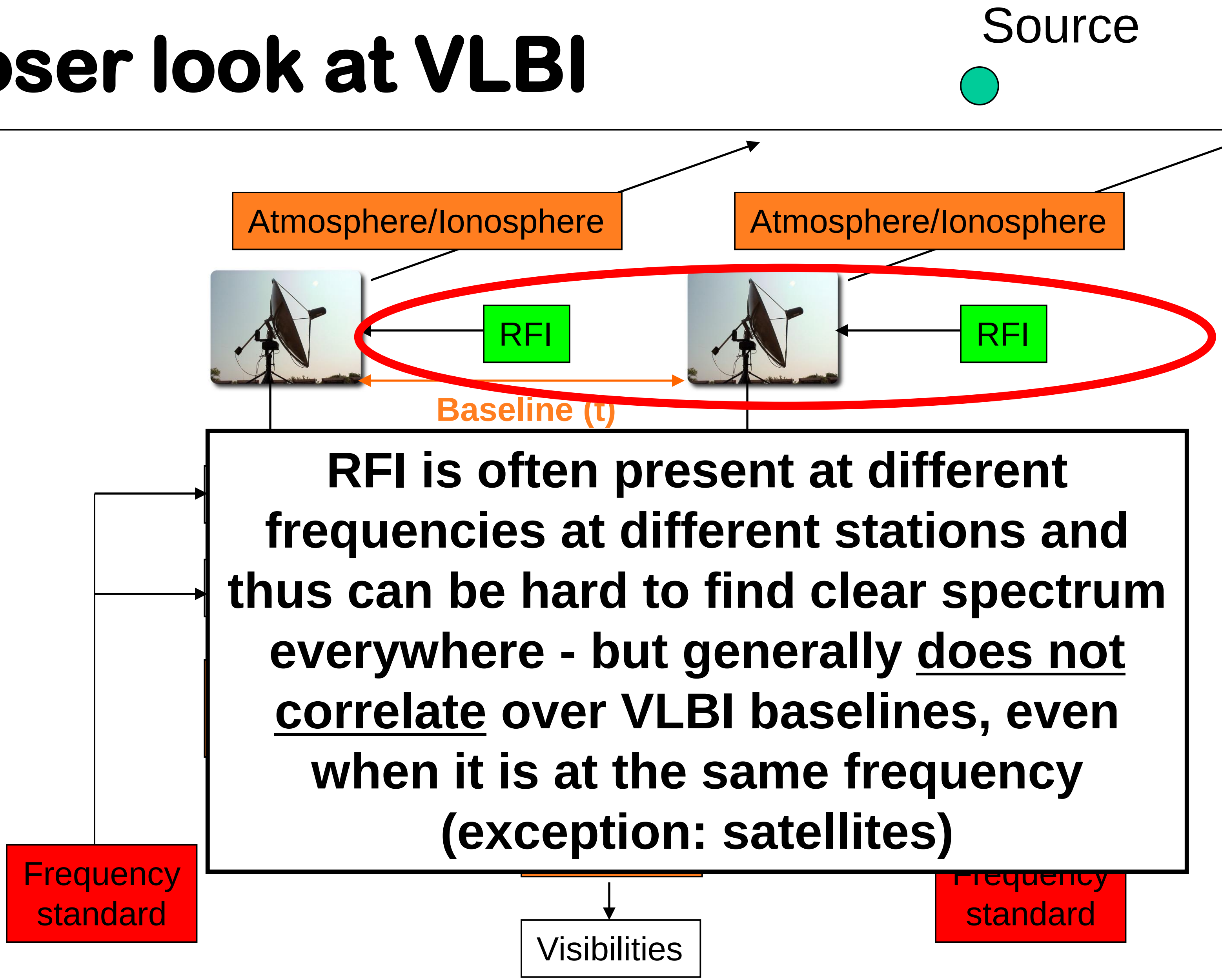


A closer look at VLBI



Fringe rate dependent effects are a function of frequency - so low frequency VLBI is comparable to high frequency VLA. Earth Orientation Parameters (EOPs) become increasingly important

A closer look at VLBI



RFI is often present at different frequencies at different stations and thus can be hard to find clear spectrum everywhere - but generally <u>does not correlate</u> over VLBI baselines, even when it is at the same frequency (exception: satellites)

A closer look at VLBI

Source

Atmosphere/Ionosphere

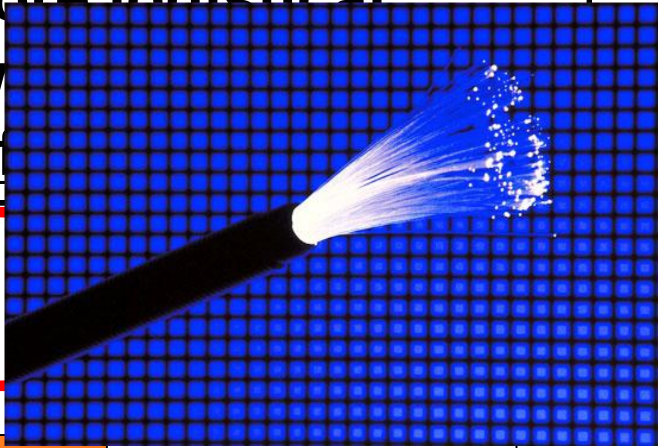
Atmosphere/Ionosphere

The data transmission is where VLBI differs most obviously.

more logistical

w

af



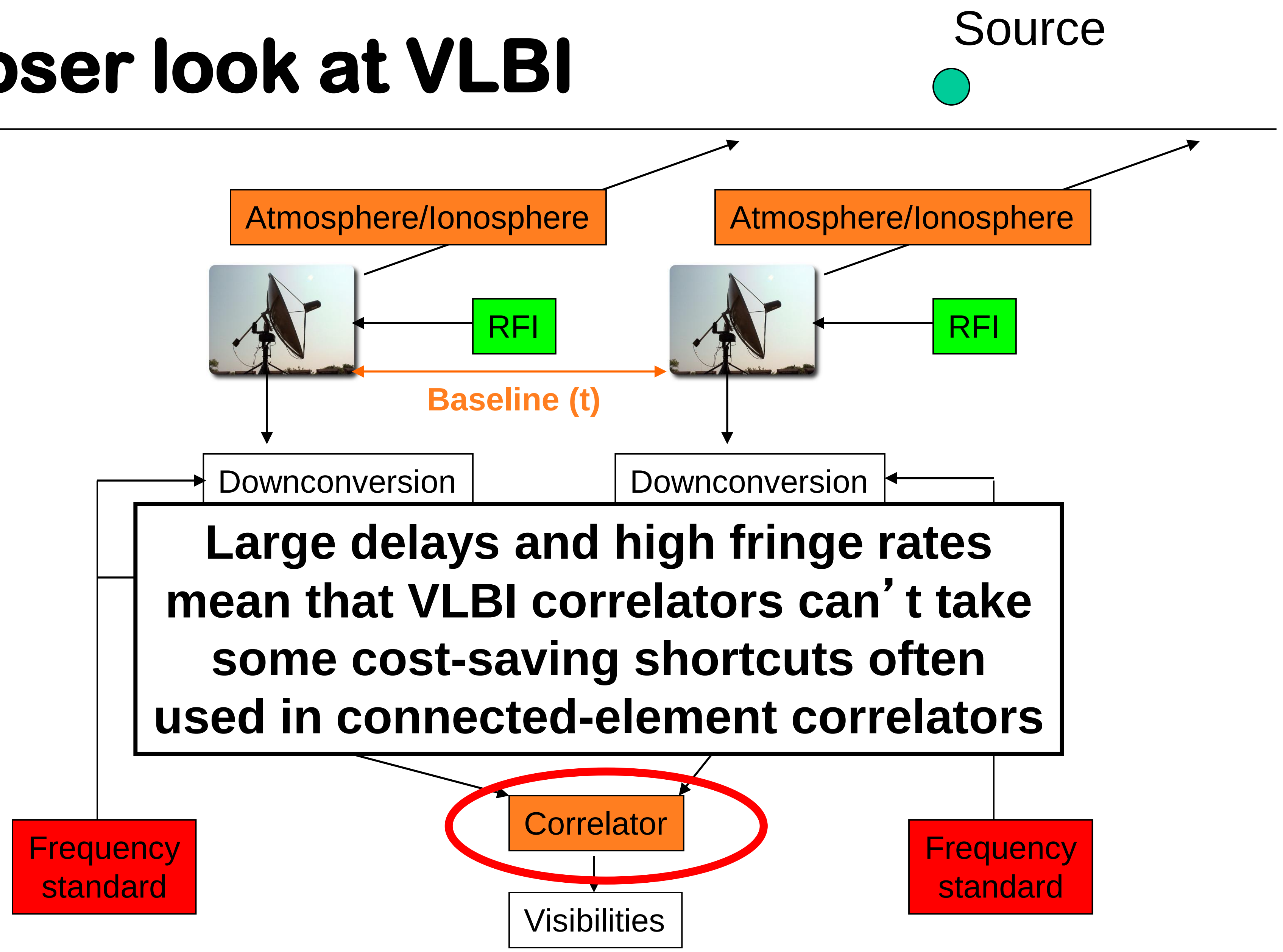
Correlator

Visibilities

Frequency standard

Frequency standard

A closer look at VLBI



A closer look at VLBI

Any small differences in the independent frequency standards at different stations have to be calibrated out in VLBI. So long as they are well-behaved (constant, or a linear drift) this is easily done with regular calibrator scans.