The Very Long Baseline Array

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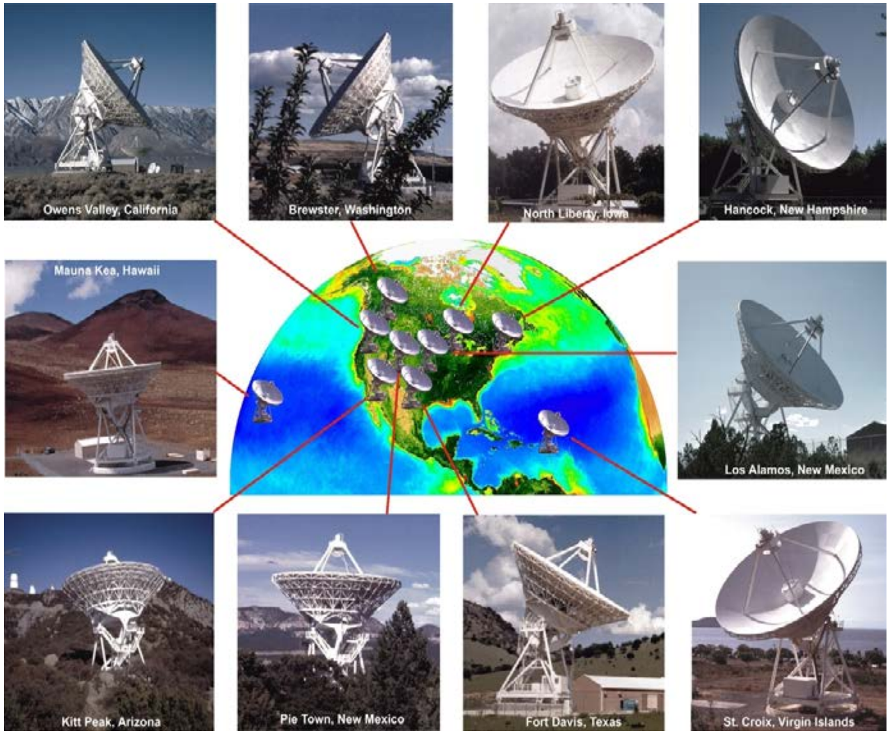
Credit

- Large parts of this talk were written by:
- Amy Mioduszewski
- Emmanuel Momjian
- Walter Brisken
- Many others!

Instrument Overview

- A 10 element interferometer radio telescope
  - Identical 25m diameter antennas
  - Array dedicated to Very Long Baseline Interferometry (VLBI)
- Antenna sites in US territory from Mauna Kea Hawaii to St. Croix, US Virgin Islands
  - Baseline lengths between 236 km and 8611 km
- Software Correlator (DiFX) in Socorro, NM



Instrument Overview II

Frequency coverage from 330 MHz (90 cm) to 90 GHz (3mm)

- In 10 frequency bands
- Current standard bandwidth 512 MHz (dual polarization)
  - Except for narrow-band receiver
- Wide instantaneous spanned bandwidth:
  - S/X mode: simultaneous 2.4 GHz and 8.4 GHz observing
  - C-band receiver: simultaneous tunings (almost) anywhere in 4-8 GHz band

λ(cm)	ν(GHz)	σ(μJy/beam) in 8 hrs at 2Gbps
90 cm [P]	0.312 - 0.342	266*
50 cm [UHF]	0.596 - 0.626	681*
21 cm [L]	1.35 - 1.75	10-12
13 cm [S]	2.15 - 2.35	12
6 cm [C]	3.9 - 7.9	6-9
4 cm [X]	8.0 - 8.8	11-15
2 cm [Ku]	12.0 - 15.4	18
1 cm [K]	21.7 - 24.1	18-22
7 mm [Q]	41.0 - 45.0	40
3 mm [W]	80.0 - 90.0	180†

Instrument Overview III

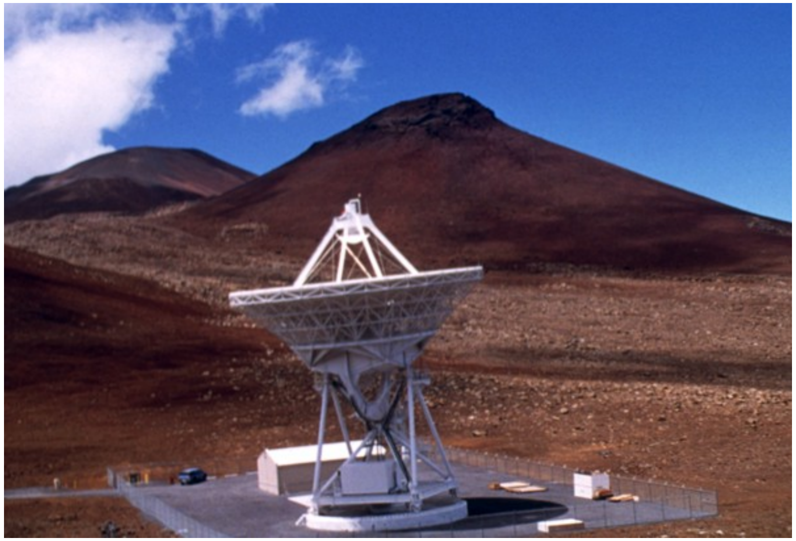
- The RDBE (ROACH Digital Back End) has two personalities: the PFB and the DDC
- The PFB (Polyphase Filter Bank) has
  - 8 X 32MHz dual pol channels (or subbands in VLA terminology, or IF in AIPS terminology), or 16 X 32 MHz single polarization.
  - these result in 2Gbps recording.
  - generally recommended for continuum observations where RFI is a major concern.
- The DDC (Digital DownConverter) is, assuming dual pol
  - either 2 or 4 data channels (subbands) range downward from 128MHz to 1MHz in binary steps.
  - current maximum of 512MHz dual pol (4Gbps)
  - recommended for spectral line observations and continuum observations that require high sensitivity or non-continuous subbands.

VLBA Limitations

- Limited to high brightness temperature targets
  - $T_B = \frac{S_\nu \lambda^2}{2\pi k_B \Omega}$
  - S_ν = flux density, λ = observing wavelength, Ω = solid angle of target
  - Diffuse objects get "resolved out"
- Small field of view
  - Bandwidth smearing and time smearing restrict the usable field of view to a tiny portion of the primary beam around the phase center
- Long wait time for data
  - Observations are recorded on physical drives that have to be shipped to New Mexico for correlation
- Limited frequency coverage

Science applications of VLBA and VLBI

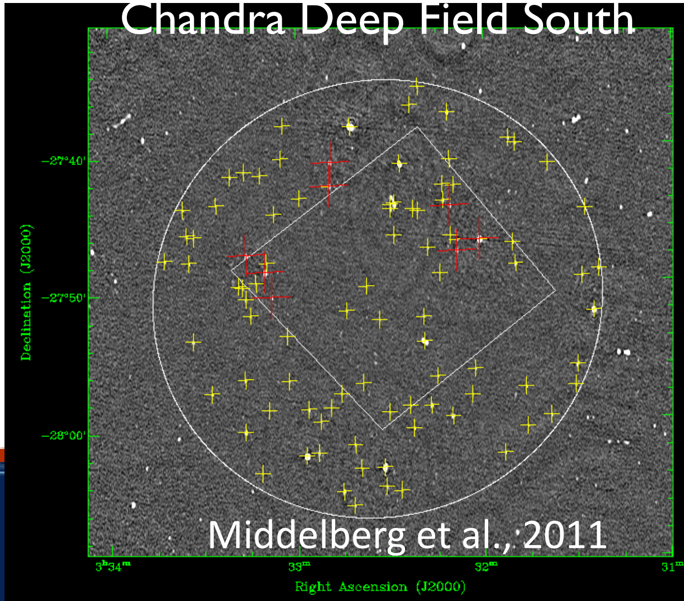
- VLBI provides a tool to study mas-level structure in radio sources.
  - Active Galactic Nuclei (AGN)
  - Pulsars
  - Masers
  - Supernova/Supernova Remnants
  - Magnetically active stars
  - X-ray binaries
  - Novae



- A VLBI detection instantly identifies a compact non-thermal source
  - Synchrotron/cyclotron radiation (electrons in a magnetic field)
  - Maser emission (stimulated emission)
  - Thermal lines seen in absorption against non-thermal background

Special correlator capabilities (DiFX)

- Pulsar gate
  - Synchronous correlator gate to improve signal to noise ratio of repeating signals, such as pulsars
- Multi-phase-center capability
  - Can simultaneously correlate at 100s of points in the antenna primary beam
  - Especially effective w/ VLBA due to identical antennas
- Ultra-high spectral resolution
  - Using "zoom" modes, can achieve 1 Hz
  - Up to132096 channels if justified.
  - Used in some asteroid radar observing



(Resident) Shared Risk Observing (R)SRO

Some possible SRO projects:

- Baseband Data Copy

Some possible RSRSO projects:

- Rapid response capability
- Improved troposphere model
- 3mm VLBI with the LMT
- Multi tone pulsecal
- Y3 Observing with the VLBA
- L/P Dual-Band Observations

No longer shared risk since 2021A:

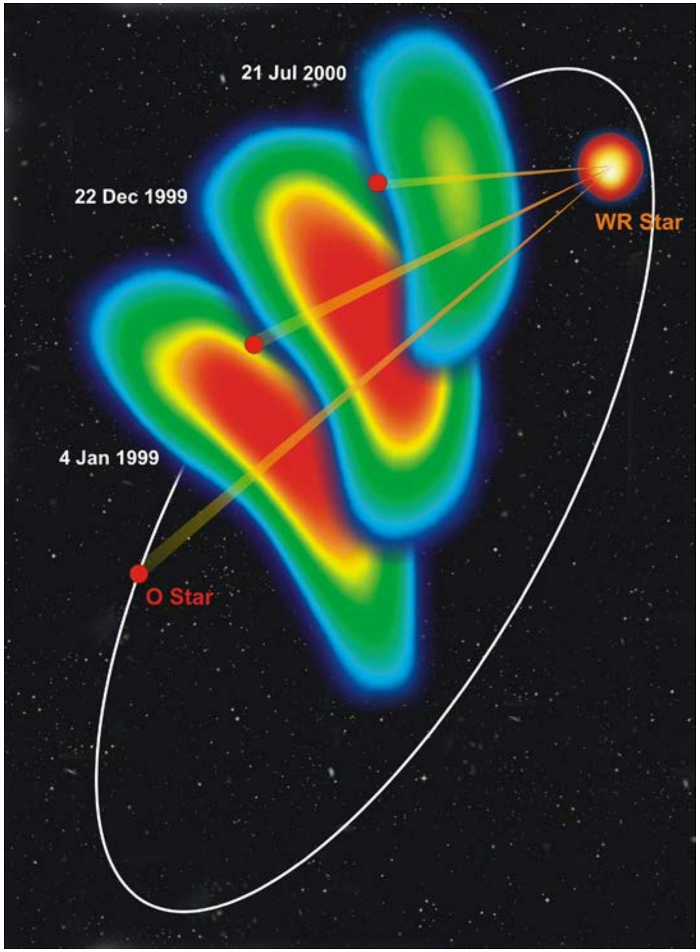
- 4 Gbps observing (512 MHz bandwidth)
- VLA (Y1) single dish VLBI is now GO!

Strengths of the VLBA

High dynamic range imaging at milliarcsecond resolution

- Locations of 10 antennas carefully chosen for optimal "UV coverage"
- Imaging resolution in different observing bands:
  - L-band (~1.6 GHz / 20 cm): 5 mas
  - X-band (~8 GHz / 4 cm): 0.85 mas
  - Q-band (~50 GHz / 7mm): 0.17 mas
- E.g. for ~1mas resolution
  - 1 AU at 1 Kpc
  - Few-10 stellar radii at 100pc

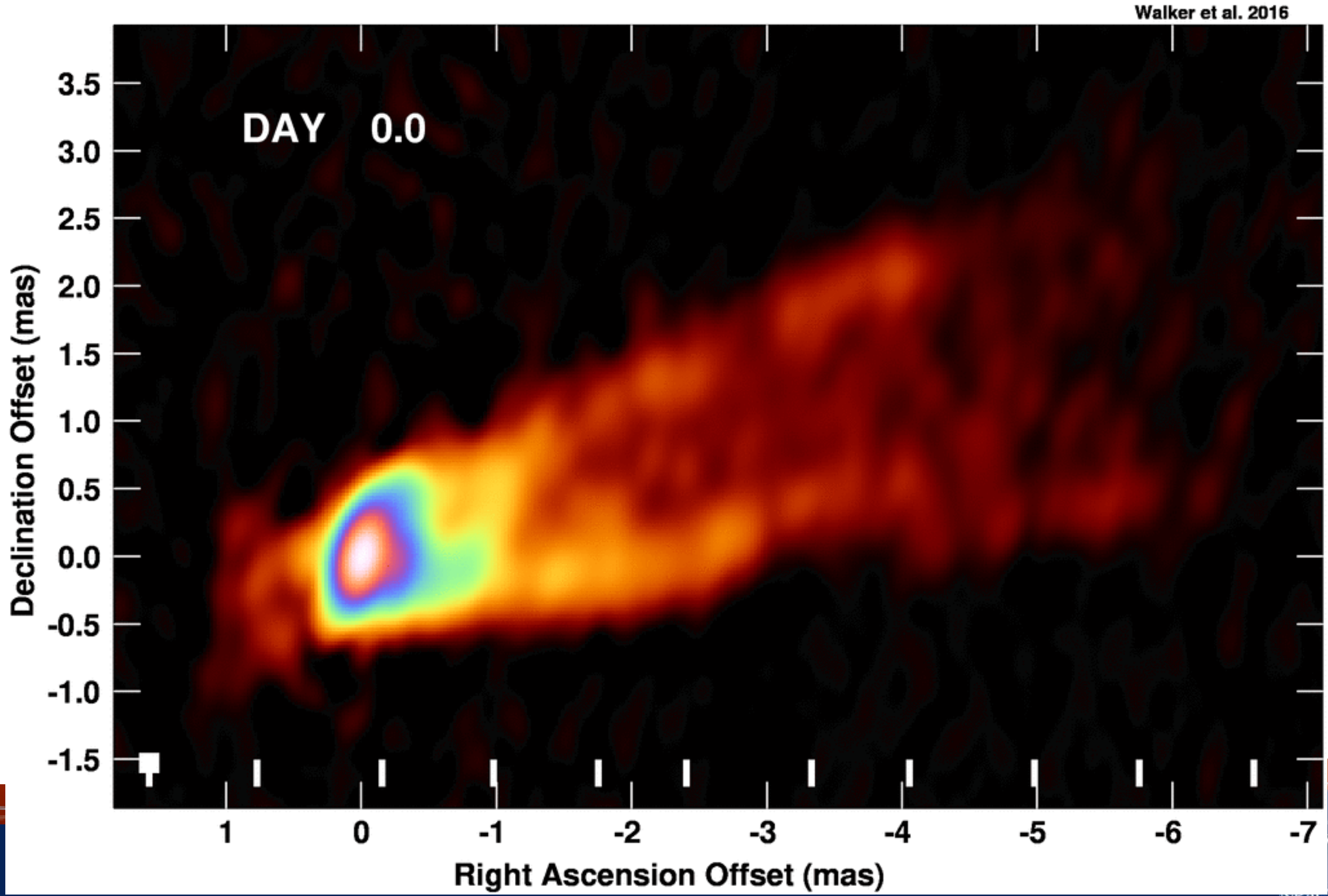
Example: WR140, imaging the evolution of the colliding wind region in Wolf-Rayet + O binary star system. Separation between stars between ~5-15 mas or 9-27 AU (Dougherty et al. 2010).



Strengths of the VLBA

High dynamic range imaging at milliarcsecond resolution

- M87 Jet at 43 GHz (R.C. Walker)
- Challenging: structure changes over time, high contrast



Strengths of the VLBA

Time-dependent phenomena

- VLBA available 24 hours per day, all year
- Can probe phenomena ranging from hours to years in duration
- VLBI sources tend to be variable in brightness, structure, and polarization
- Perfect instrument for wide range of science within graduate student's thesis timescale!

Example: Daily observations of X-ray binary SS433 over 40 days. (Mioduszewski et al)

Strengths of the VLBA

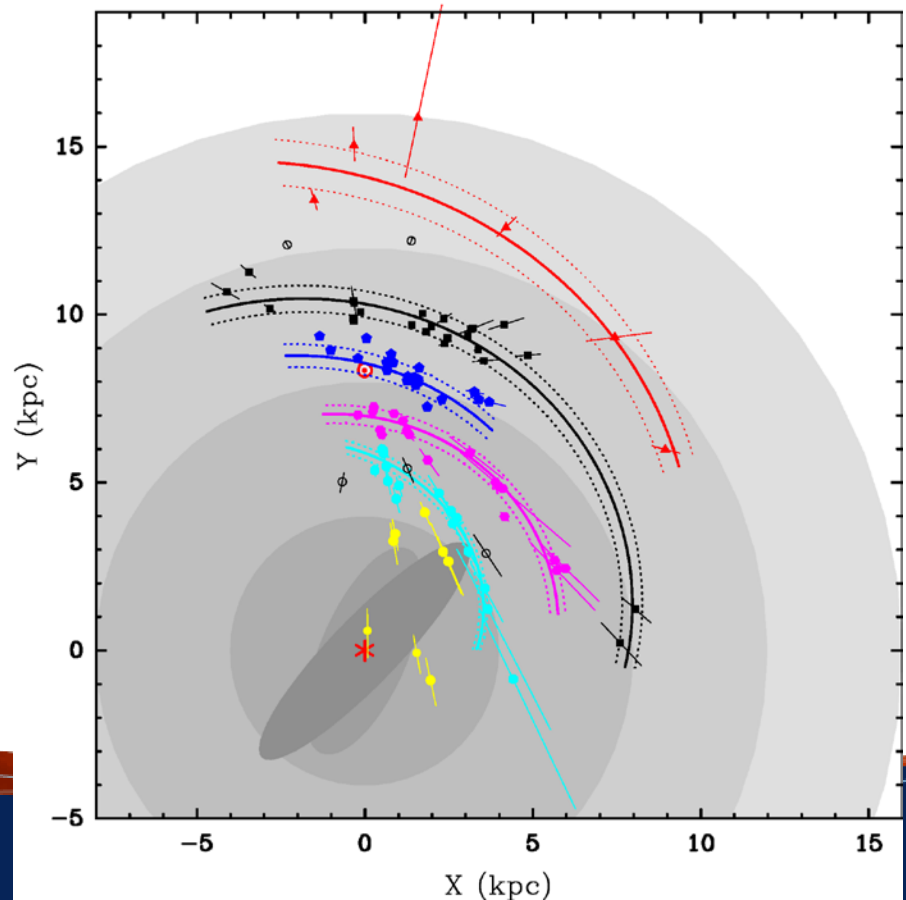
High precision relative astrometry

- Astrometry of a target object relative to a background quasar
  - Usually tied to ICRF to 0.25 mas
- Routinely repeatable at 0.1 mas precision
- Best astrometry to date better than 0.01 mas
- Can be performed on continuum or spectral line sources
  - E.g., pulsars, stars, masers

Strengths of the VLBA

High precision relative astrometry

- BeSSeL project measures distances to star forming regions through methanol masers (Reid et al.), determining the structure of the spiral arms of the Galaxy.



BeSSeL Survey Result:

Milky Way has as much mass as Andromeda

- Astrometric observations with the VLBA of stars in spiral arms reveal that the Milky Way's rotation curve is very similar to Andromeda's
- This indicates that the dark matter haloes of the two galaxies are comparable in mass.

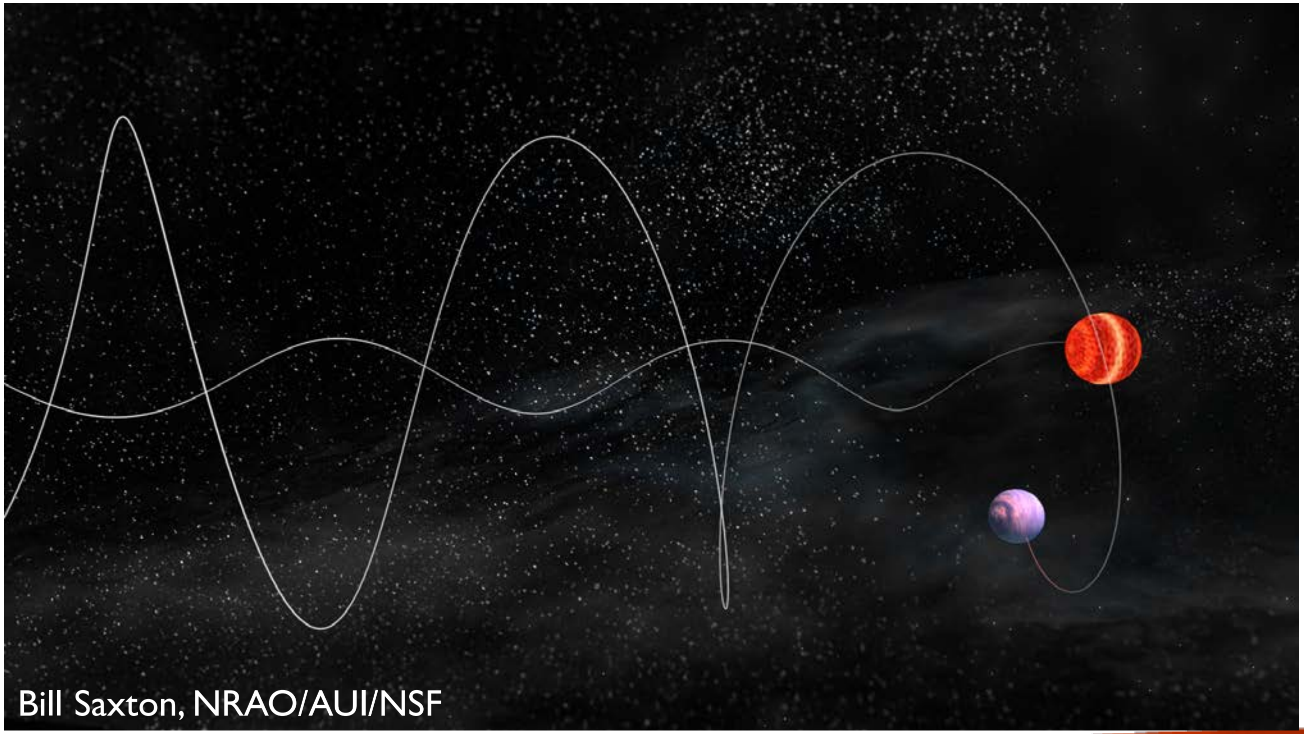
"In your face, Andromeda!
Bang!
Make that, Big Bang!"

-- The Colbert Report
January, 2009

Planet Hunting

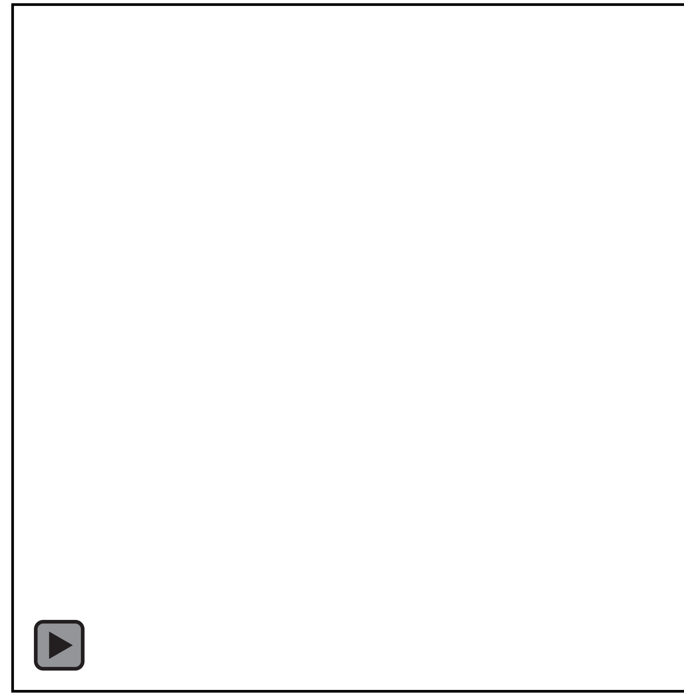
It's not just for optical telescopes

- Saturn-sized planet found orbiting a <0.1 M_{Sun} dwarf star
- Curiel et al. (2020) used the astrometric method to detect the "wobble" of the small, cool star TVLM 513-46546



Extended arrays

- VLBA uses data formats and setups compatible with other VLBI antennas
- Routinely involved in High Sensitivity Array (HSA), phased VLA, Green Bank Telescope and Effelsberg
  - Increases sensitivity by an order of magnitude
- Participates with European VLBI Network in the "Global VLBI Array"
- Joins the Global mm VLBI Array (GMVA) for 86-90 GHz (3mm) observations twice per year. Now with ALMA!
- Participates in global array of geodetic antennas for reference frame measurements.

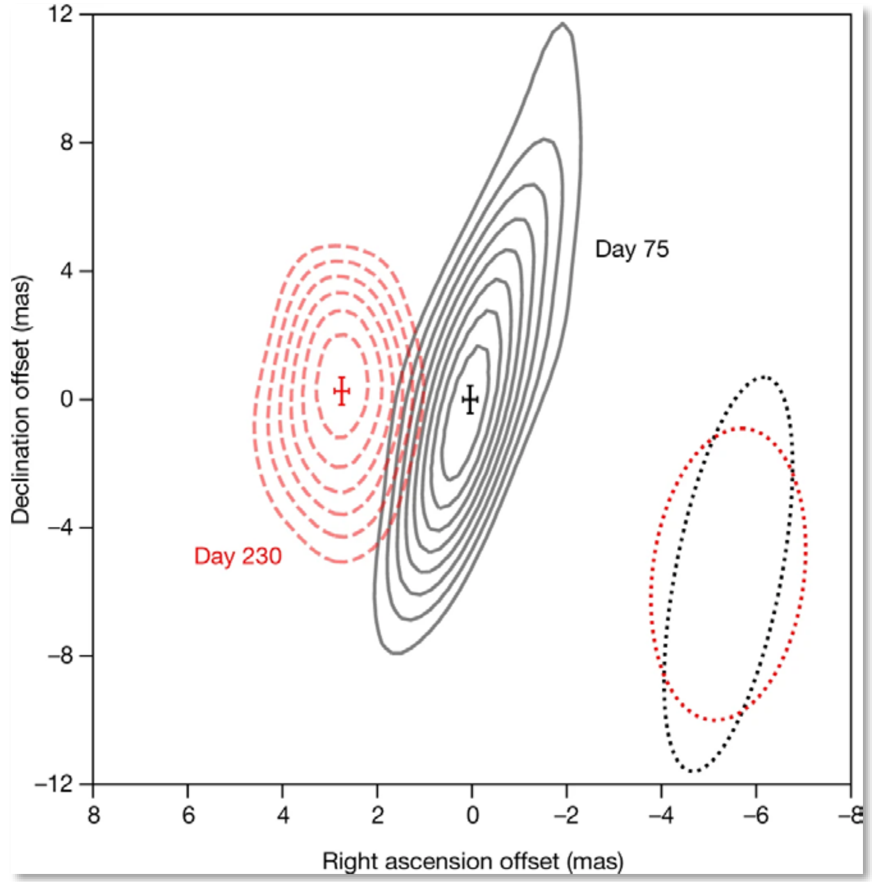


Example: SN1993J imaged over 10 years with VLBA+DSN+EVN (Bietenholz etal.)

VLBA + HSA: GW170817

HSA observations reveal superluminal motion in GRB jet

- VLBA + Green Bank + VLA
- Observations of the GRB associated with GW170817 double neutron star merger
- Images show jet velocity of ~4.1c
- Viewing angle of jet is constrained to 14° – 28° from line of site

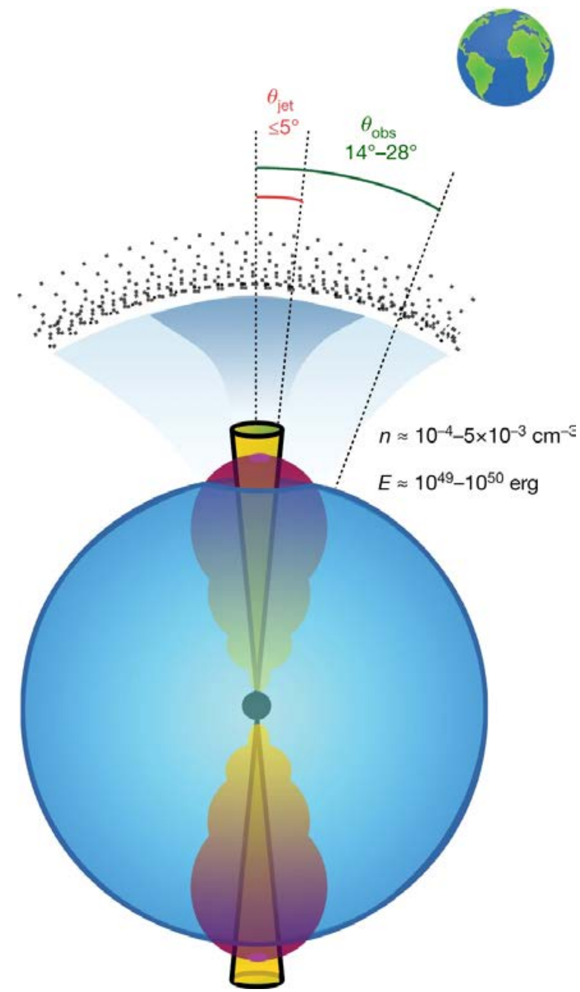


From Mooley et al. 2018

VLBA + HSA: GW170817

HSA observations reveal superluminal motion in GRB jet

- VLBI observations proved the GRB had a successful jet
- Proved that off-axis GRBs can be detected
- Helped constrain the models for the GRB
- Provided estimates for how many short GRBs we miss due to orientation/beaming effects
  - For every event like GW170817 that we detect, there are ~1,000 we miss



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