Indian Science Interests in VLBI with the uGMRT

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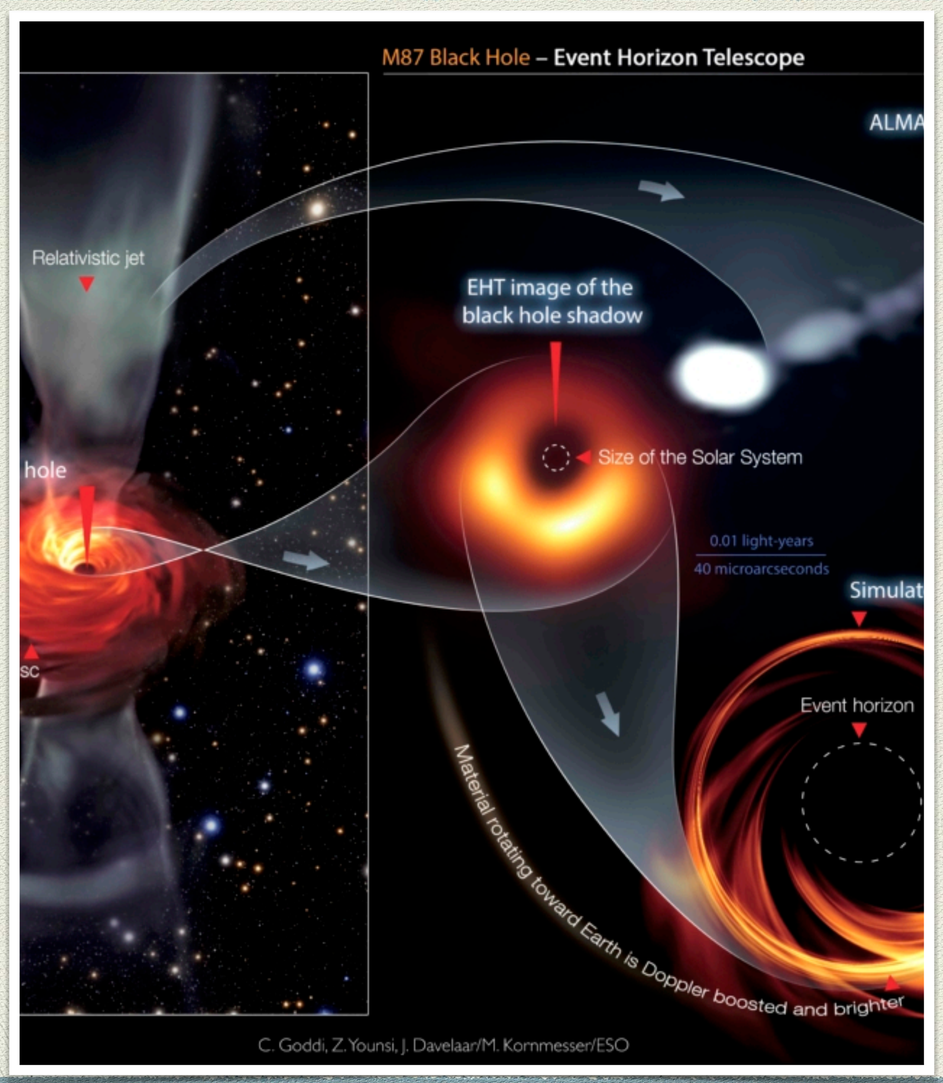
Why VLBI

- VLBI provides the highest angular resolution of any telescope
- Demonstrated by the imaging of the shadow of the SMBH in nearby AGN M87 by the Event Horizon Telescope (EHT)
- These observations are taking our understanding of general relativity and gravitational physics to unprecedented levels



Why VLBI with uGMRT

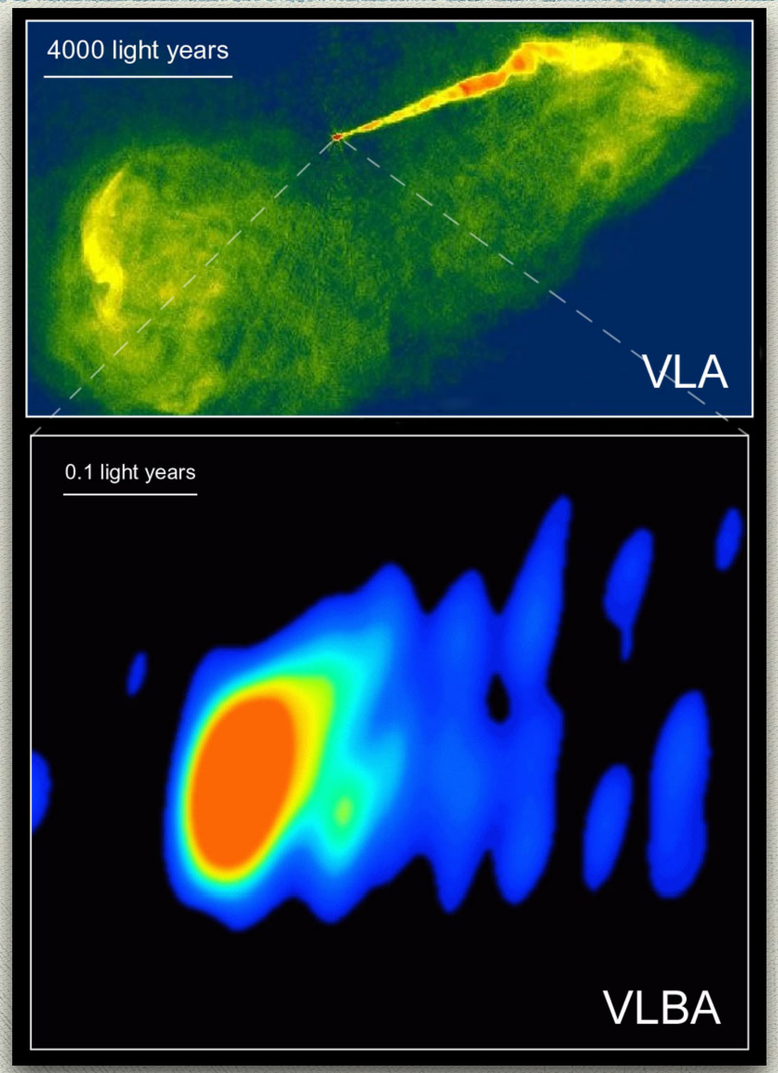
- uGMRT at a latitude of +19∘ 06’ and longitude of 74∘ 03’ is the only large radio telescope array at these Earth coordinates, midway between Equator & Tropic of Cancer
- At low radio frequencies (≲1.4 GHz), the uGMRT with 45 m diameter dishes, is currently the telescope array with the highest image sensitivity
- uGMRT samples the astronomical sky from a declination of +90∘ 00’ to -53∘ 54’

Milliarsecond Resolution

- A VLBI array comprising of the uGMRT and the Parkes radio telescope in New South Wales, Australia will provide a baseline of 9761 kms, resulting in an angular resolution of 5.4 mas at a frequency of 1.4 GHz
- Baselines to Effelsberg, Germany (part of EVN) will provide an angular resolution of ~8 mas; to Noto, Italy (part of EVN) a resolution of ~9 mas; to Hartebeesthoek, South Africa, a resolution of ~7 mas
- At 610 MHz, uGMRT-WSRT baselines should give ~18 mas resolution
- At 325 MHz, uGMRT-Sardinia baselines should give ~35 mas resolution

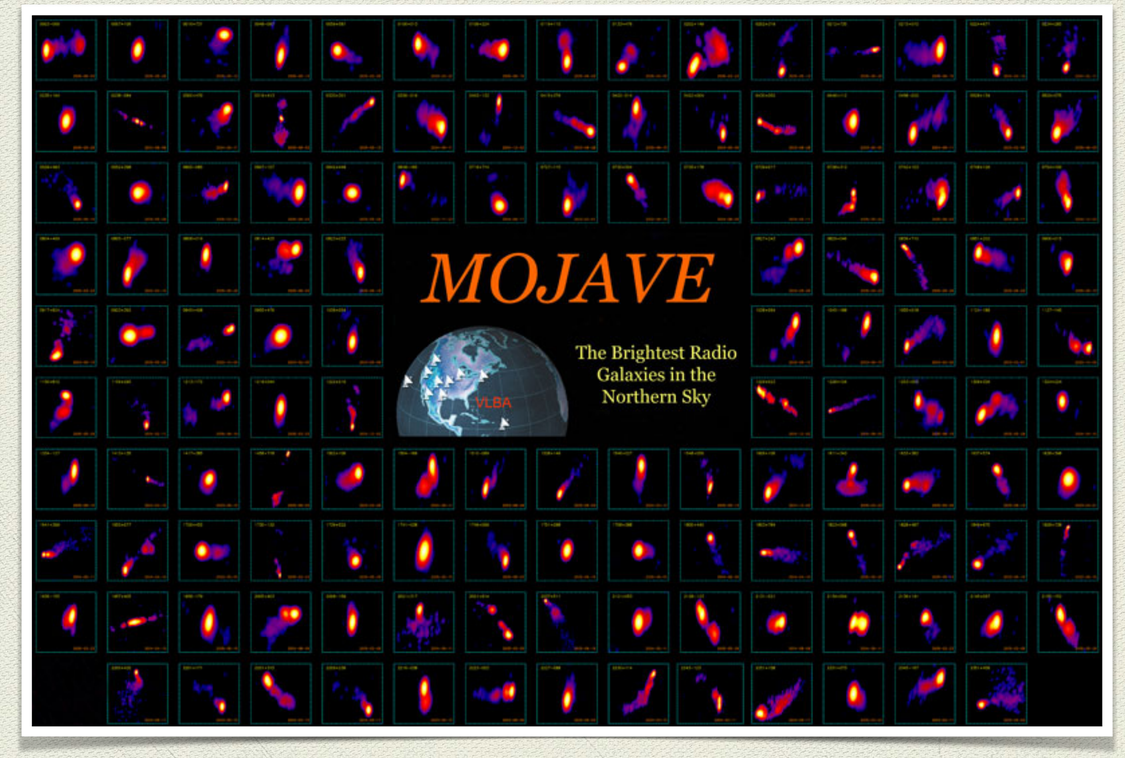
Parsec-scale Study of AGN Jets

- At resolutions of ~5-10 mas, radio jets of well-known AGN can be imaged and traced just a few parsecs from the supermassive black holes from where they are launched
- The unique location of the uGMRT along with resolutions of 5-10 mas implies that the radio jet in the nearest powerful AGN, Centaurus A (Dec -43 deg), can be imaged and traced down to 0.3 to 0.6 parsec from their launching sites
- The jets in M87 can be imaged and traced down to 0.6 to 1.2 parsec from their black hole-accretion disk systems
- Estimating speeds of AGN jets through proper motion studies provides unique constraints on jet-launching mechanisms, and in turn MHD and gravitational physics of black holes, accretion disks and jets



Parsec-scale Study of AGN Jets

- The ~5-10 mas resolution make a VLBI-w-uGMRT array extremely competitive in the field of extragalactic astronomy
- For comparison, the Very Long Baseline Array (VLBA) in the US, comprising of ten 25 m diameters dishes, achieves ~10 mas resolution at 1.4 GHz
- MOJAVE with the VLBA at 15 GHz



Pulsar science with VLBI

- Two major science cases for high spatial resolution (μas) VLBI observations of radio pulsars
- High precision position, proper motion, distance & velocity measurements of radio pulsars useful in
  - Tests of relativity theories – double pulsar, DNS, wide orbit binaries (van Straten+ 2001; Deller+ 2009)
  - Constraining Equation of State of neutron star – moment of inertia & radii measurements (Ozel+ 2016)
  - Detection of Gravitational waves & Science with nano-Hz GWs – PTA experiments (Deller+ 2019)
  - Determine dark matter density & constrain dark matter sub-structure in the Milky way (Chakrabarty+ 2021)
- Studies of sub-structure in ISM, shapes of ISM structure and variability of ISM

Pulsar science with VLBI

- Why are VLBI measurements useful here?
  - Pulsar positions and proper motions are determined from pulsar timing where these are covariant with other timing model parameters, such as binary Keplerian parameters
  - These are dependent on solar system dynamics and are uncertain especially for pulsars in the ecliptic plane
  - Differences in dynamical and ICRF positions for 5 MSPs vary from 85 μas to 24 mas (Wang+ 2017)
  - Pulsar distances are determined mostly by DM with assumptions on n_e or other model dependent method
- VLBI provides model independent robust snapshot estimates in ICRF
- Where a VLBI experiment with uGMRT will help
  - Most MSPs are weak radio sources, so VLBI experiment needs one or more large light collecting buckets
  - Low frequency (P band) gated VLBI can be particularly useful for increasing the sample of PTA MSPs with precision measurements
  - Precision distances to off-Galactic plane low luminosity MSPs will be useful for GW astronomy of isolated SMBHB sources

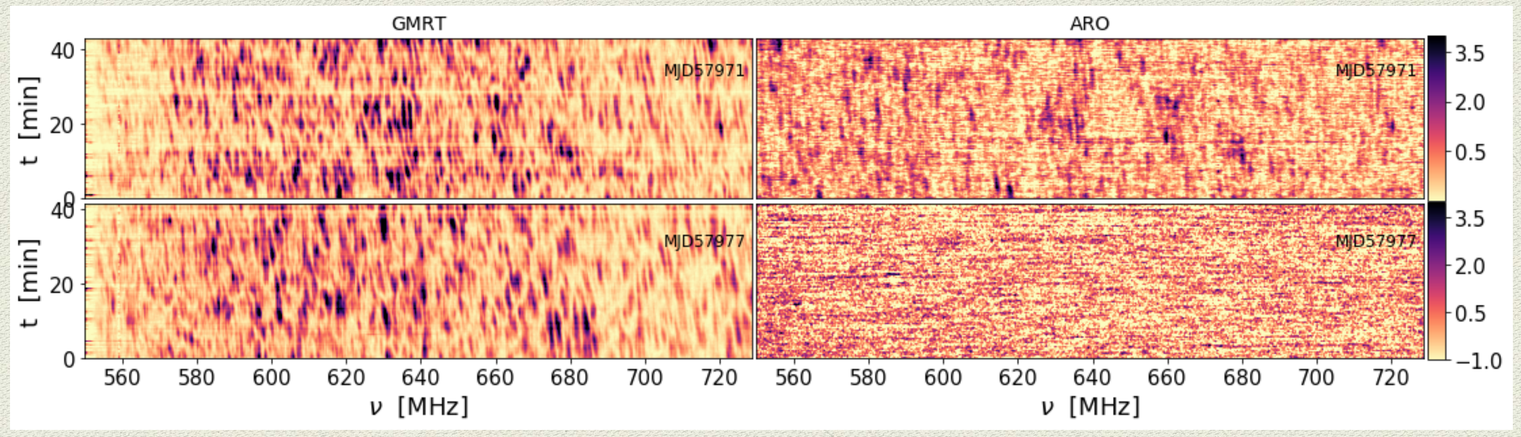
Very Long Baseline scintillation studies

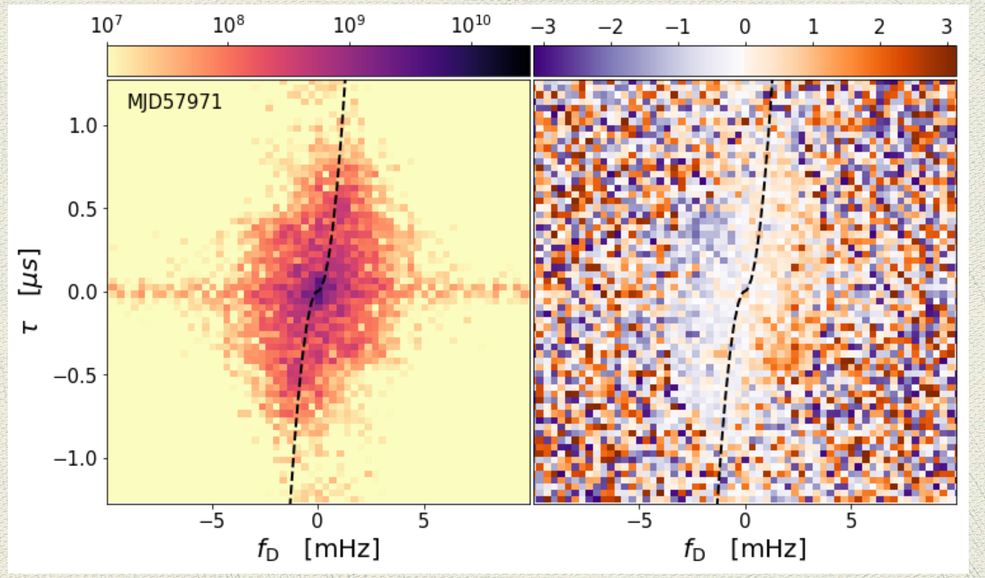
- Low frequencies are better suited for scintillation studies: scattering disk size $\Sigma \propto \lambda^2$, resolution: $\theta \sim \lambda / \Sigma \propto \lambda^{-1}$
- uGMRT Band-2, Band-3 & Band-4 offer considerable overlap with LOFAR, MWA, PAPER, CHIME & the upcoming HERA, excellent for scintillation studies
- Possible intercontinetal baselines for northern sources (e.g. pulsars + CHIME FRBs), southern pulsars (close to GC) as well as the GC
- Unmatched phased-array sensitivity would be a game-changer for scintillation VLBI
- Is anisotropic scattering indeed very common? What are the structures that cause anisotropic scattering (Pen & Levin 2014; Simard & Pen 2018)?
- Coherent VLBI, as well as incoherent delay measurements (Marthi+ 2021, Simard+ 2019a,b incl. VM) can be used together for precise astrometry of the scattering geometry

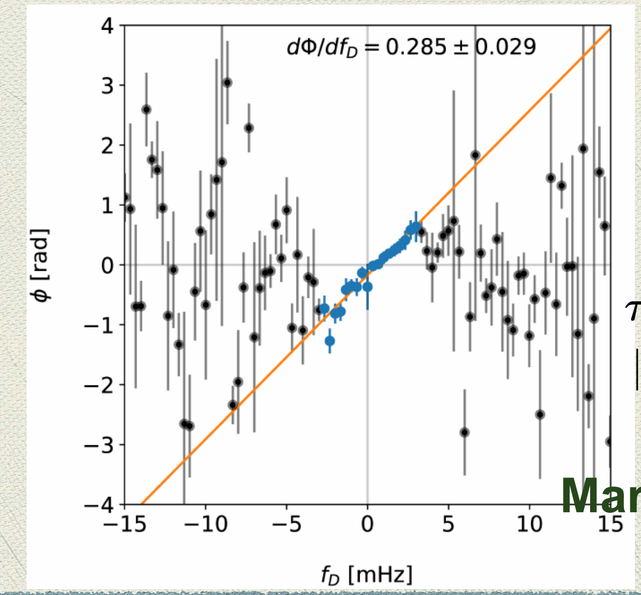
Very Long Baseline scintillation studies

GMRT-Algonquin 10,000 km baseline

Scintillation cross-correlation

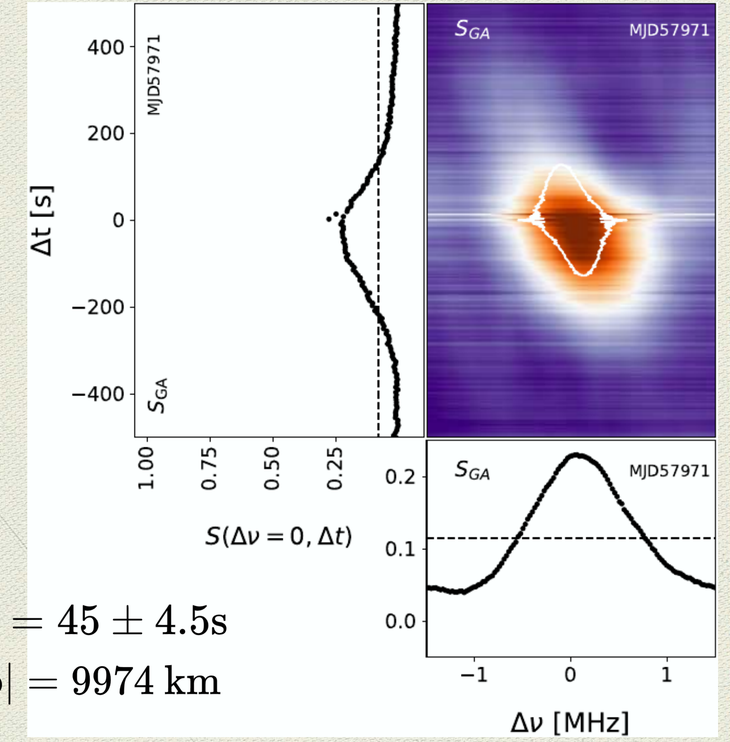






Delay and cross-corr coefficient

$r = 0.22$



$\tau_d = 45 \pm 4.5\text{s}$

$|\mathbf{b}| = 9974\,\text{km}$

Marthi et al., MNRAS *under review*

FRB Localization

- FRB localization will also get a quantum jump in sensitivity from the addition of GMRT to the existing VLBI stations.
- The FRB local environments can be probed on sub-parsec-scales (Marcote & Paragi 2019) which is important as the sources are found to be embedded in diverse environments within the host galaxies

Synergy with Gravitational Wave Experiments

- The uGMRT as part of a VLBI array, is poised to make substantial and unique contributions to the study of high resolution phenomena like -
- Jets in AGNs, protostars, X-ray binaries, binary supermassive black holes in merging galaxies and their evolution, which in turn can connect with contemporaneous studies of gravitational waves from experiments like InPTA and IPTA