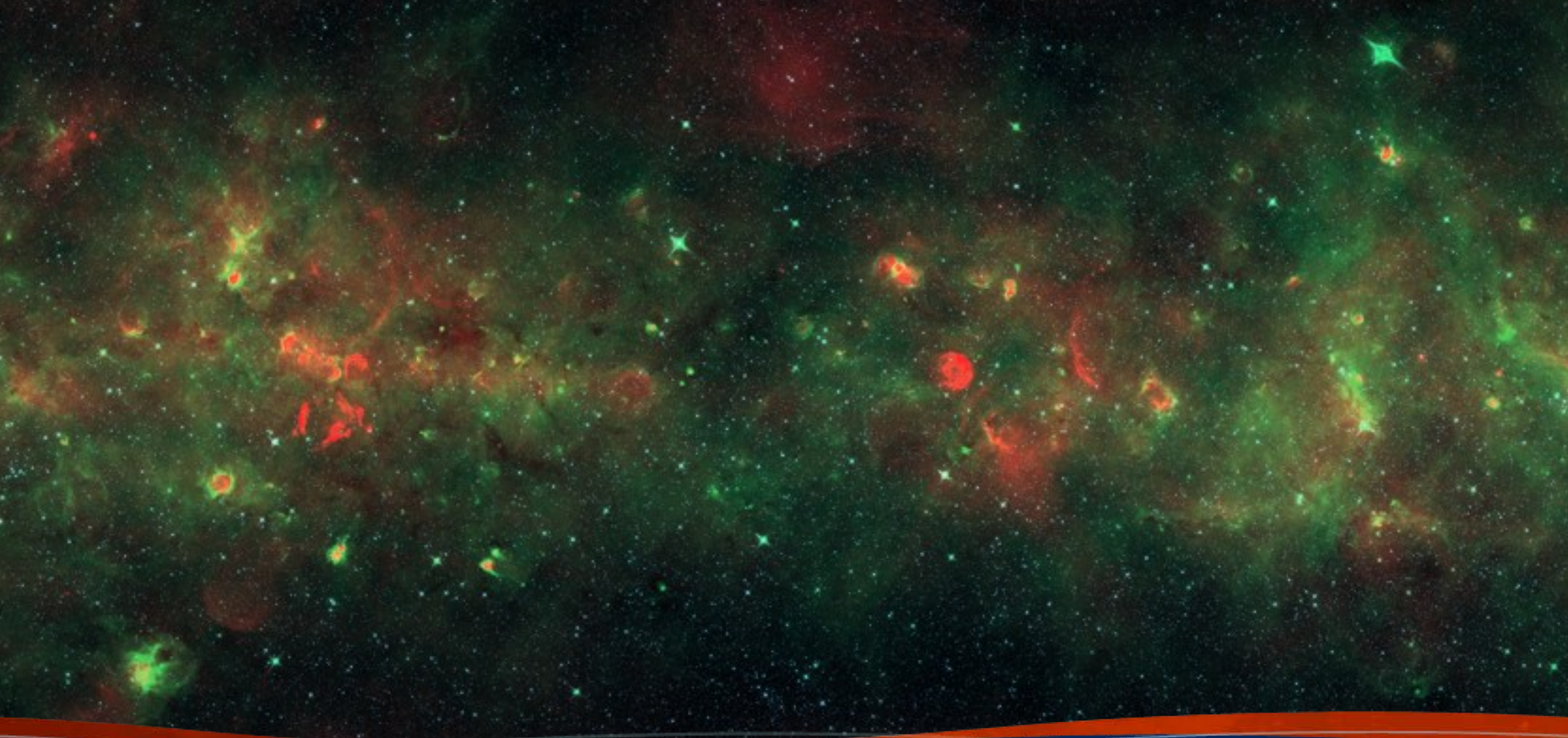


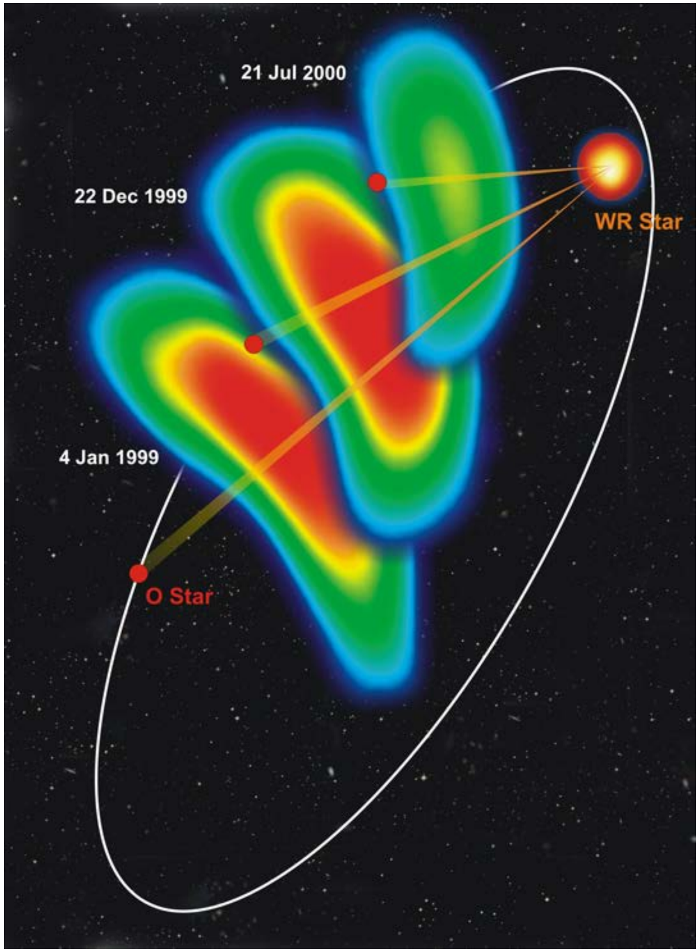
The Role of VLBI in Stellar Radio Astronomy

Amy Mioduszewski (NRAO)

Strengths of Very Long Baseline Interferometry

High dynamic range imaging with ultra high resolution

- For ~8600 km baselines, 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

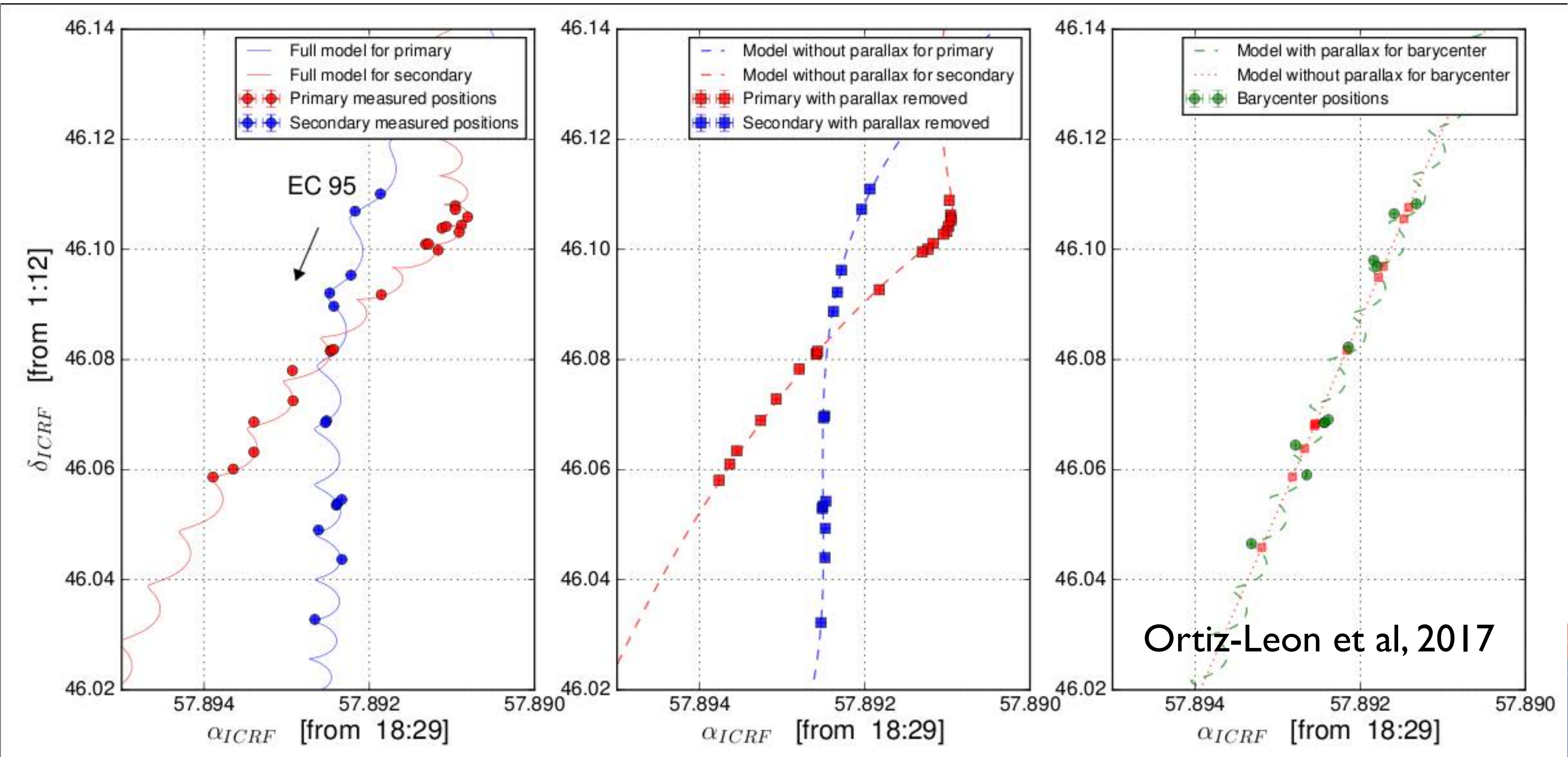


Example: WR140, imaging the evolution of the colliding wind region in Wolf-Rayet + O binary star system. Separation between stars between ~5-15 mas or 9-27 AU (Dougherty et al. 2010).

Strengths of Very Long Baseline Interferometry

High precision relative astrometry

- Regularly get positions with better than 0.05 mas precision.
- Distances, proper motions, kinematics, dynamical masses…



Very Long Baseline Interferometry

Brightness temperature sensitivity

The limit to VLBI comes from the brightness temperature sensitivity limit:

$$T_B = 1.36\, S\left(\frac{mJy}{beam}\right)\lambda(cm)^2/\theta('')^2$$

$$T_B = 0.32\, S\left(\frac{mJy}{beam}\right)B_{max}(km)^2$$

Instrument	Freq	B_{max} (km)	Resolution (mas)	σ(μJy/beam) in 8 hrs with 256MHz BW	T_B (10^6K)
VLBA	C-band	8600	1.4	6	0.14
VLBA	Q-band	8600	0.17	40	1
HSA	C-band	10300	1.6	1	0.034
HSA	Q-band	10300	0.14	9	0.3
Global	C-band	12700	1	0.8	0.04
Global	Q-band	11200	0.12	8.5	0.3

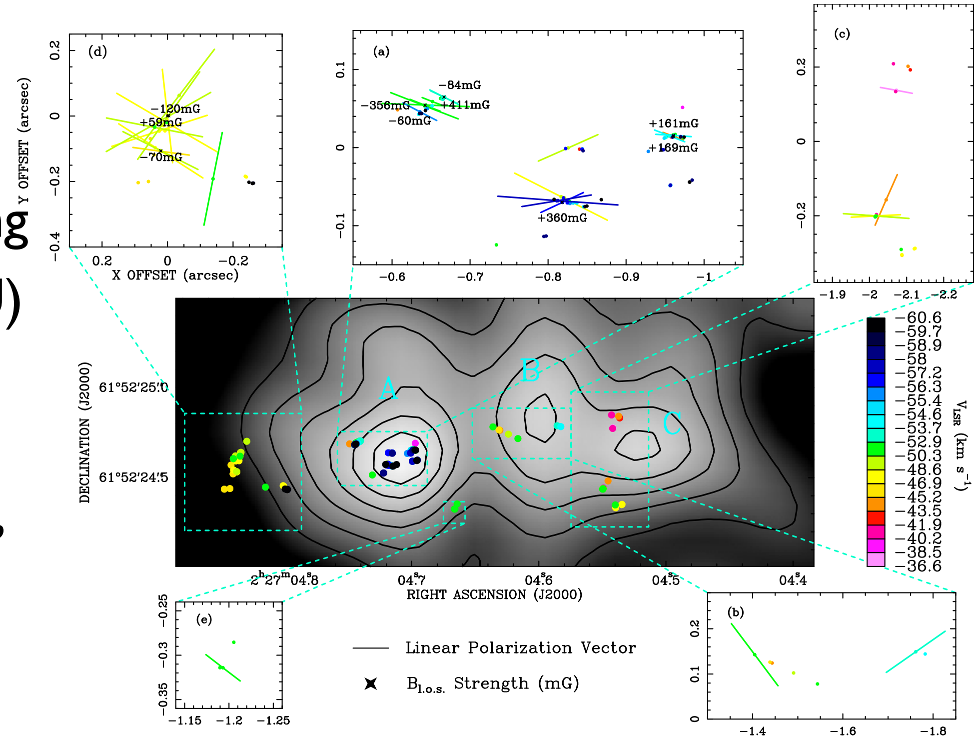
Very Long Baseline Interferometry

- So sensitive to compact non-thermal (high T_B) radiation
  - Synchrotron/cyclotron radiation (electrons in a magnetic field)
    - Morphology
    - Motion/speed
    - Magnetic field from polarization
    - Shocks or other acceleration processes
  - Maser emission (stimulated emission)
    - Morphology
    - Motion/speed, also from Doppler shifts
    - Shocks
    - Magnetic fields from Zeeman spliting
  - Thermal lines seen in absorption against non-thermal background

High mass star formation

Masers tracing outflows and magnetic fields

- Observations of H_2O masers in protostellar jet W3.
- Magnetic fields measured with polarization and Zeeman splitting
- Outer magnetic field (~1000 AU) aligned with jet
- Inner magnetic field (~10-100AU) misaligned with motion, thought to arise from the enhancement of perpendicular magnetic fields by the shocks which produce the masers.

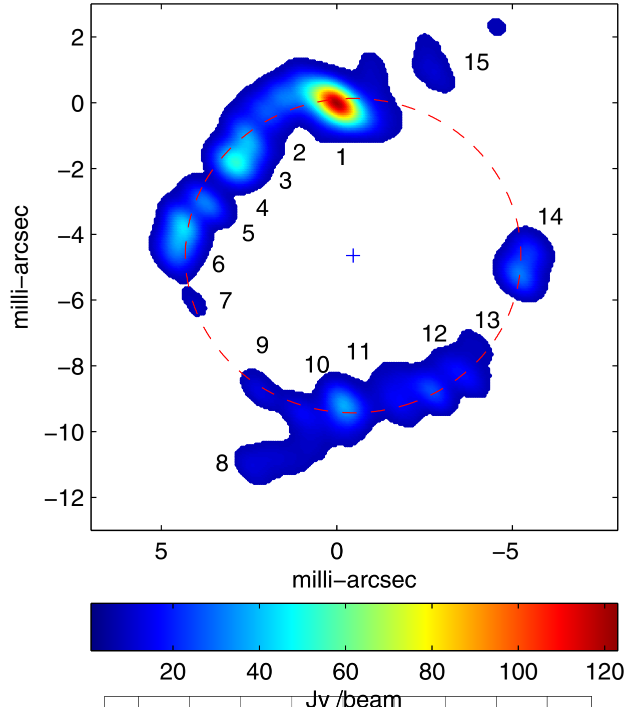


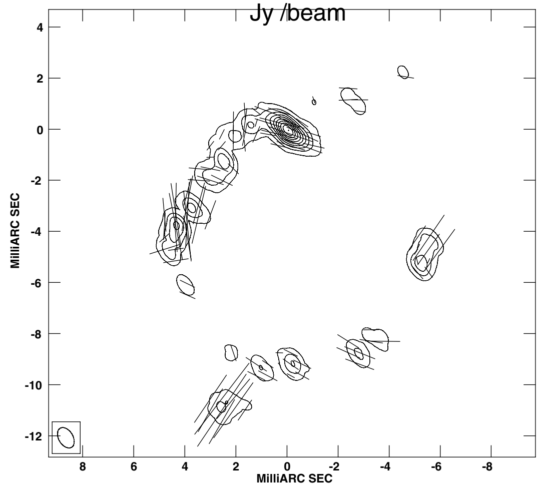
Goddi et al 2017

Environments of evolved stars

AGB stars

- OH/IR star
- Masers arise between stellar atmosphere and dust formation region.
- Up to 100% linear polarization
- Magnetic field direction consistent with bipolar field
- Zeeman splitting suggests field ~1.5G (consistent with other measurements)

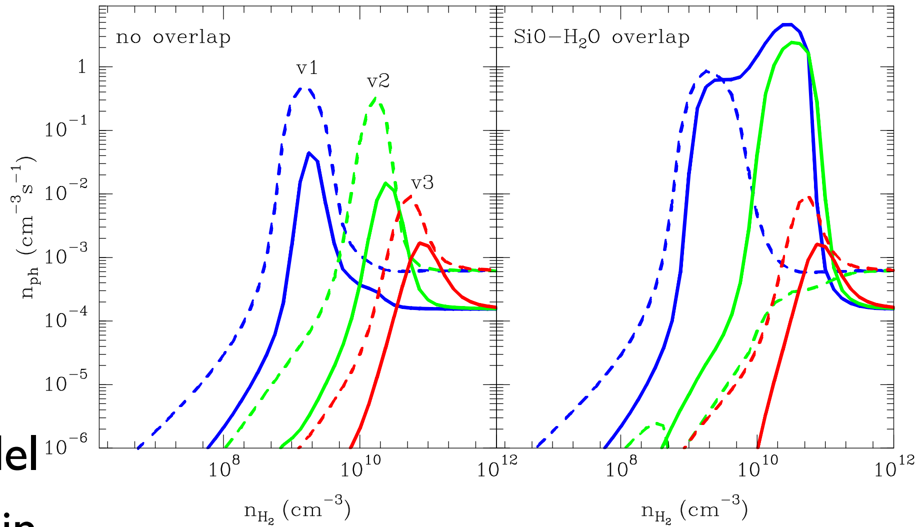


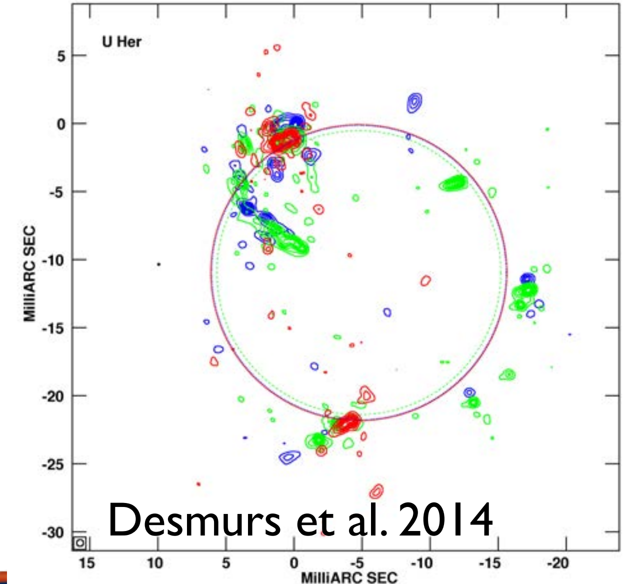


Testing maser pumping models

AGB stars

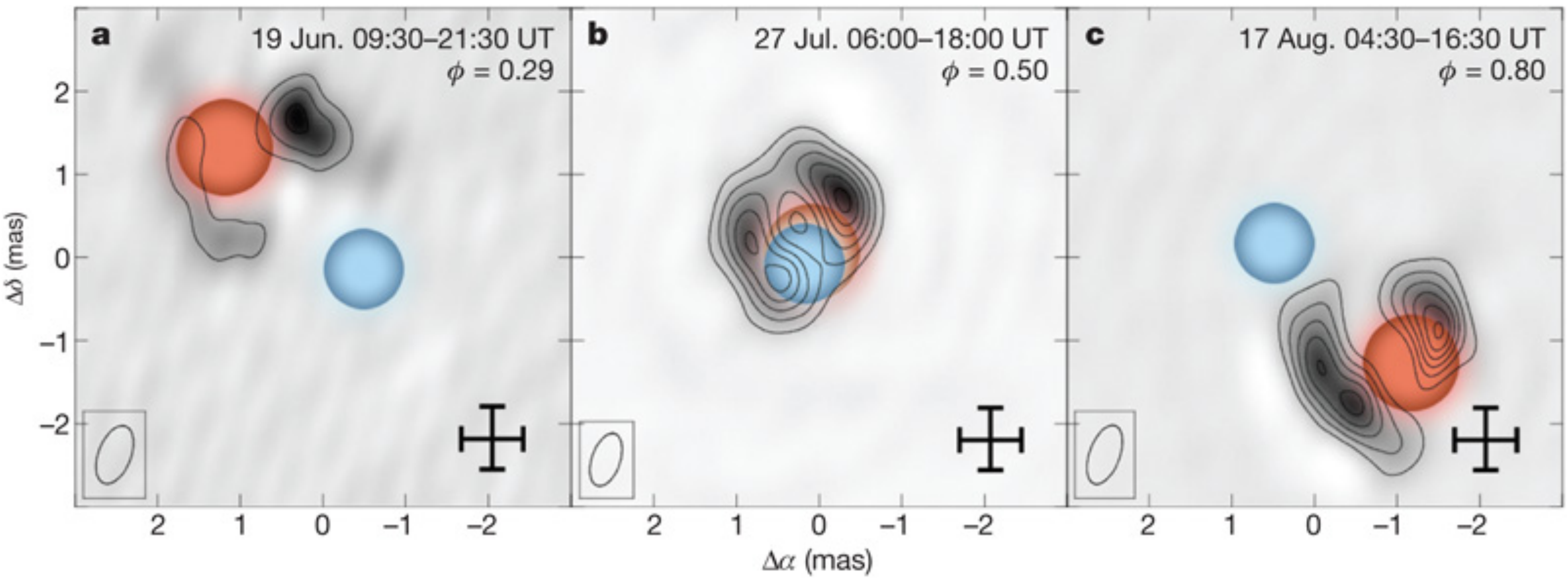
- There are questions on the details of how masers are pumped
- Study of 4 AGB stars with VLBA were used to test overlap model
  - Standard model predicts different relative line ratio than overlap model
  - v=1, v=2 and v=3 J=1-2 transitions in SiO masers have very different excitation conditions, so in standard model they should not overlap in position
  - Overlap model predicts maser lines absorption/emission interact to create conditions that predict that the SiO masers will occur in similst conditions.





Desmurs et al. 2014

Algol



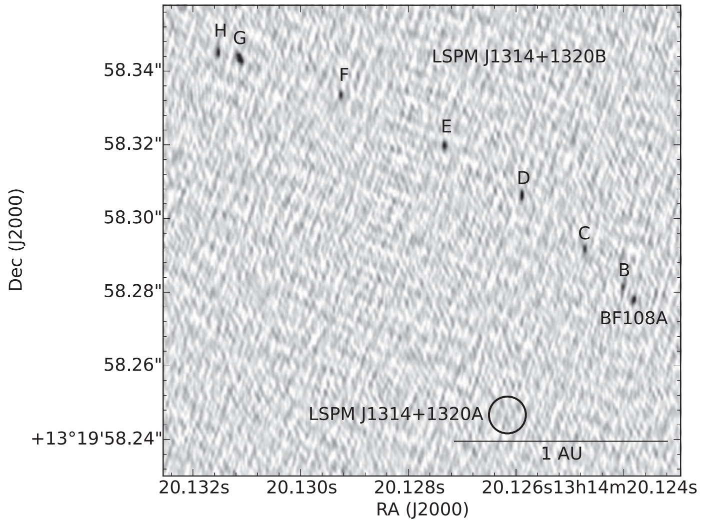
Peterson *et al.* 2010

- Coronal loop in the Algol binary system
- VLBA+GBT+Y27+EF
- Loop fixed on the less massive star and always oriented towards more massive star
- Magnetic interaction

Ultracool dwarfs

LSPM J1314+1320AB binary

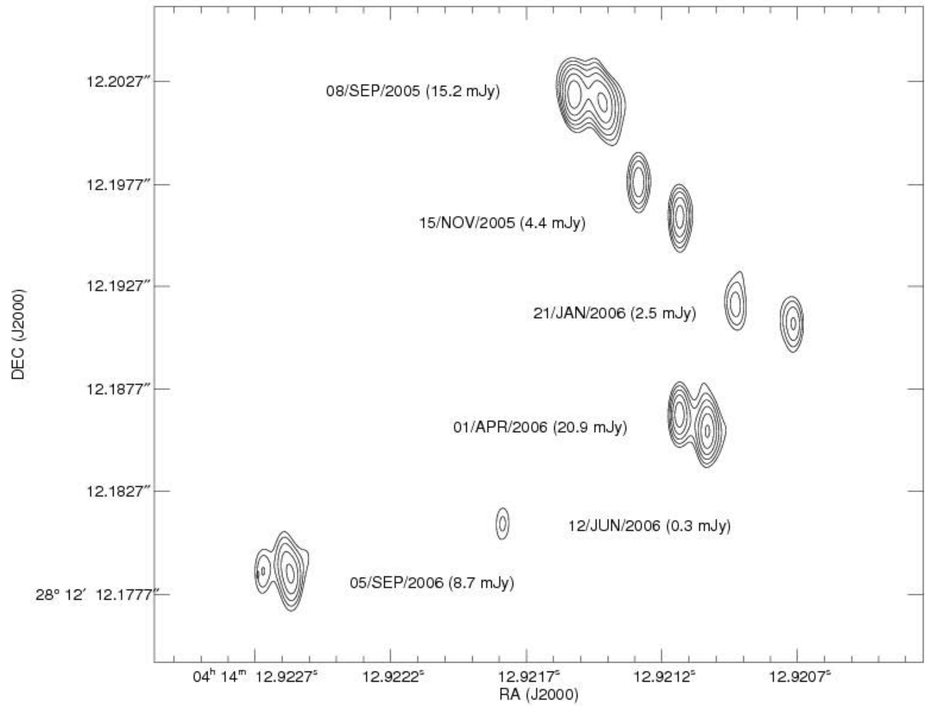
- Astrometry to obtain parallax, proper motion and orbit.
  - d = 17.249 ± 0.013 pc
- Search for planets due to reflex motion.
  - Rule out planets 0.7-10M_J with orbits of 600-10 days respectively.
- Emission only from source B even though masses are the same within 2%
  - Beamed or magntecic activity differences



Forbrich et al. 2017

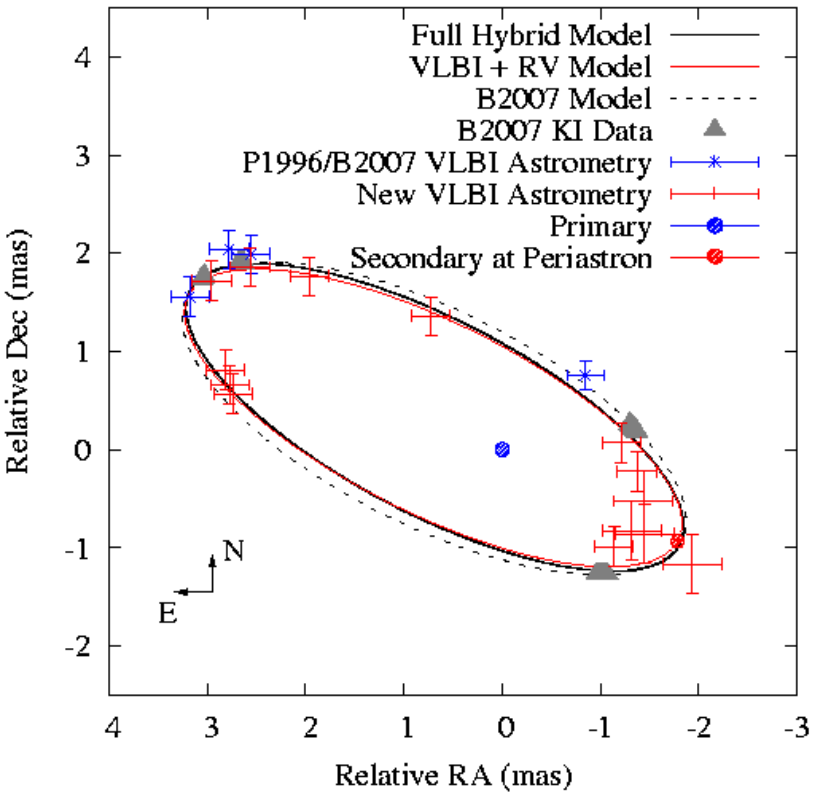
V773 Tau

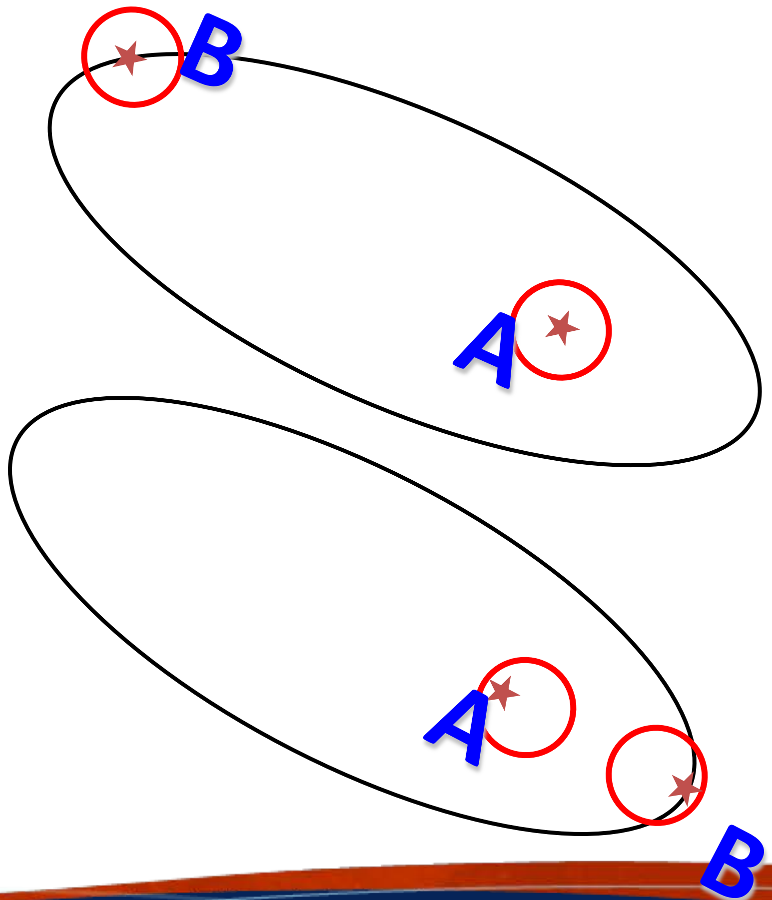
- Spectroscopic binary, and weak lined T Tauri star
- The radio flux density is very variable.
  - Brightens during periastron
  - Interesting to note that in the Goulds Belt distance survey we see over 50% very close binaries, so there seems to be a correlation between tight binaries and bright non-thermal emission



V773 Tau

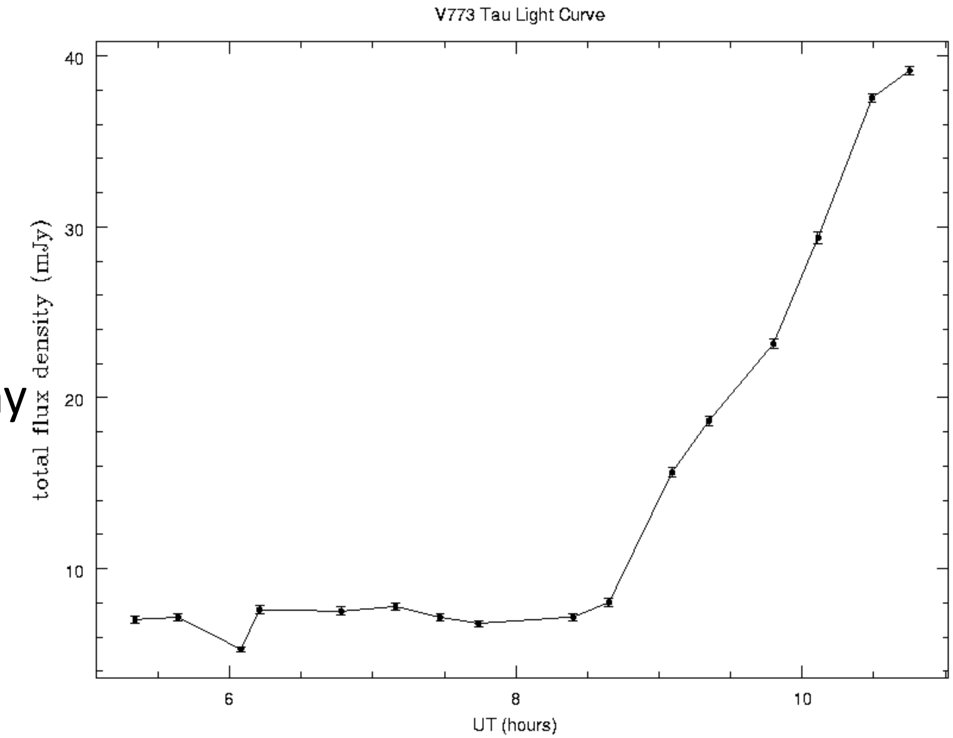
Position shifts when near periastron



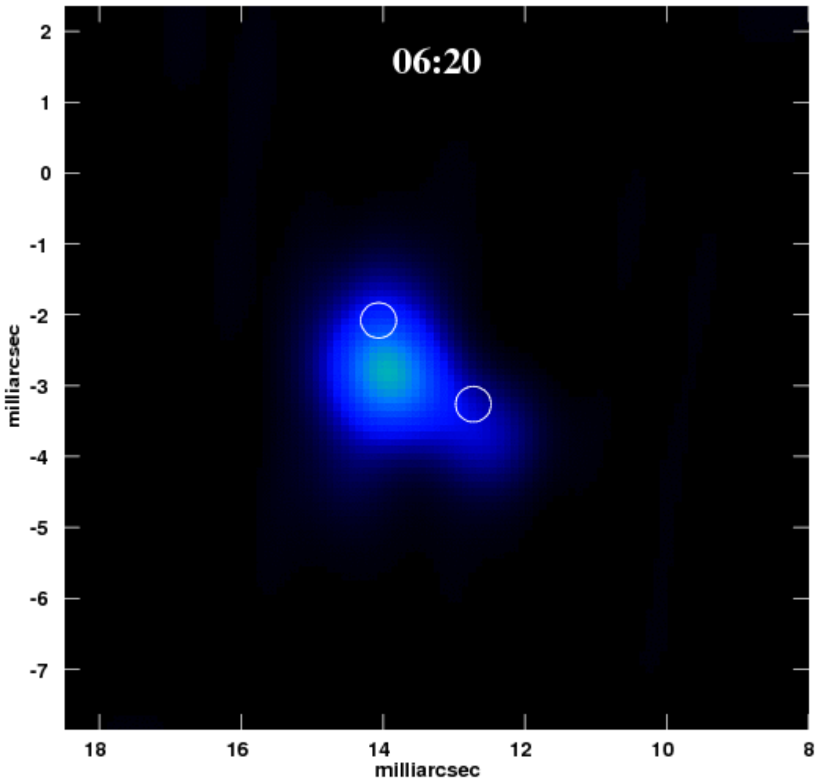


V773 Tau: What is happening at Periastron?

- Obtained a High Sensitivity Array (VLBA + Arecibo + Greenbank Telescope + Effelsberg + VLA) observation.
- 6 hours within a day of periastron.
- Aim to break observation into many time period and watch it evolve.
- V773 Tau very variable during the observation, both in flux density and morphology



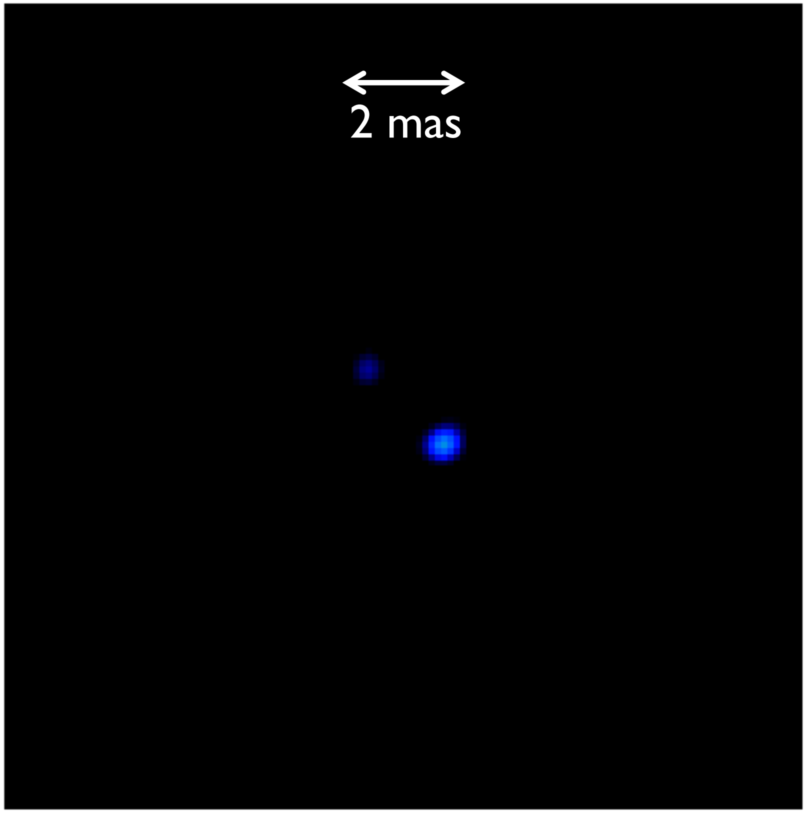
V773 Tau: Low Resolution Movie



- Frames every ~15-30 minutes
- ○ at the position of the stars based on our orbital and parallax and proper motion fits
- 1 mas=0.13AU =$2x10^{12}$cm
- ○→ 0.25 mas radius=$4x10^{11}$cm

  → $7R_\odot$
- Note the emission:
  - appears to be offset from the stellar positions
  - the brightest part moves from one star to another *very rapidly*
  - seems to move from one side of stars to another and brighten.

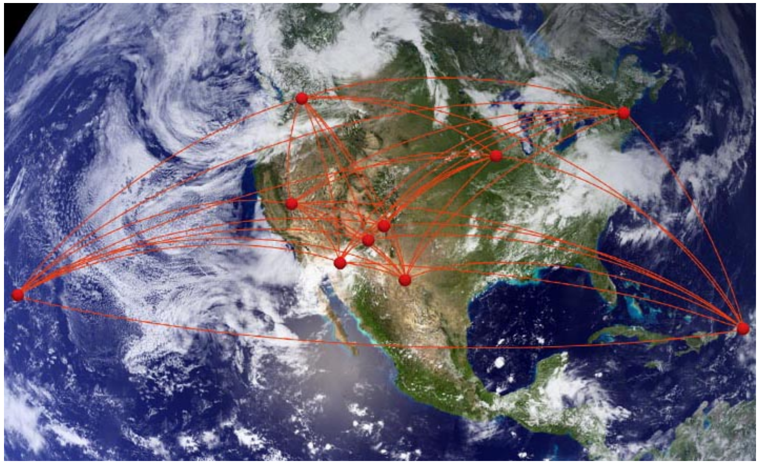
V773 Tau: High Resolution Movie



- Frames every ~5 minutes
- Starts at 8:34, approximately the start of the dramatic rise in flux
- The bridge between the two stars begins about 10:22
  - Not special in light curve, there might be a slight steepening to the rise
- Caveats:
  - super-resolved . i.e., convolved with a point spread function ~½ true psf
  - each image about 3 minutes of data
  - don't believe the single pixel movements

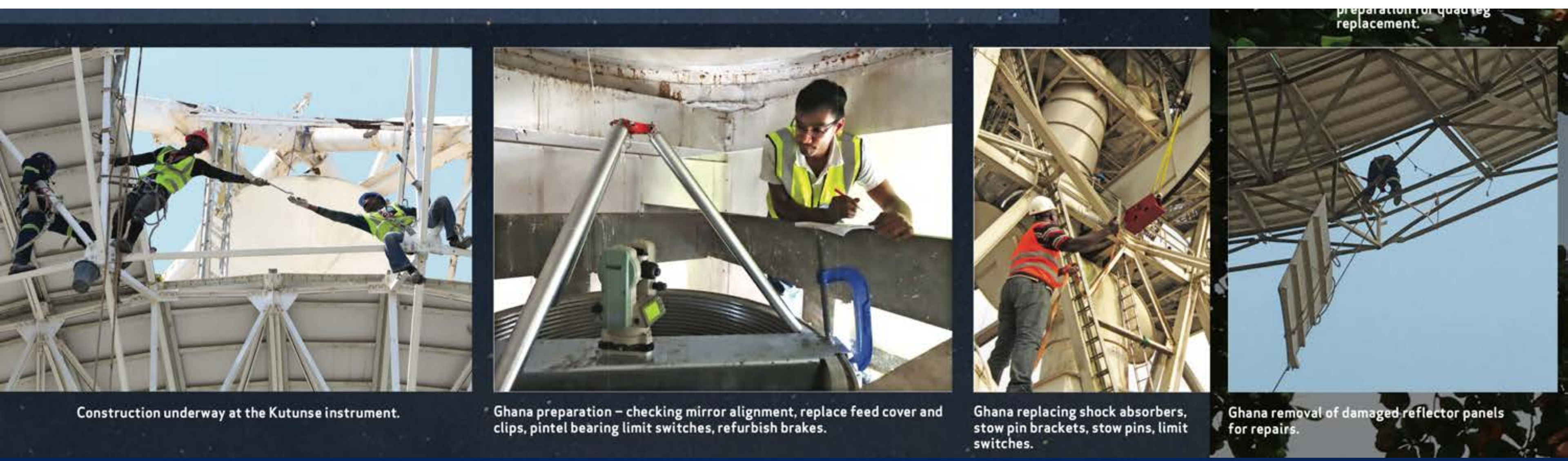
Near future on the VLBA

- VLBA will be brought back into NRAO
- Increased sensitivity by increasing bandwidth, up to 2GHz bandwidth being planned: three fold increase in sensitivity.
- Rapid response on the VLBA
  - with the advent of LSST and other survey programs/telescopes transient science will explode.
  - VLBA is looking into the capability of responding to a trigger within 5-10 minutes. Lots of development needed.



African VLBI Network

- Radio astronomy science and technology development in Africa in the advent of SKA South Africa.
- SKA-SA is partnering with Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia
- Currently converting 32 meter telecommunications antenna in Ghana, early science started.
- Zambia and Kenya doing feasibility studies on telecommunications antennas, other counties at earlier stages.



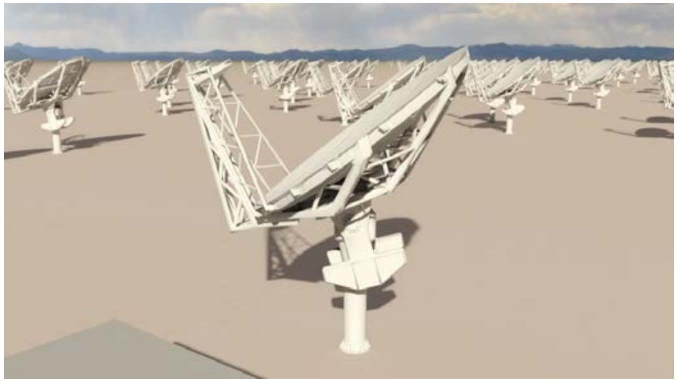
SKA-VLBI

SKA Band	SKA-core SEFD [Jy]	Bandwidth [MHz]	Remote tel. SEFD [Jy]	Baseline sens. 60s [μJy]	Image noise 1hr [μJy/beam]
50% SKA1-MID	5.2	256	20	82	9
SKA1-MID	2.6	1024	20	29	3

Paragi et al 2014

- Increased sensitivity
- Fantastic uv-coverage on the galaxy and galactic center and the southern sky
- Calibration using multiple beams
- Highly precise astrometry because of in-beam calibrators and SNR.
  - Tie radio-optical reference frames
- SKA-Mid: Initially integrate the SKA into existing arrays, *AVN is necessary to provide short and mid-length baselines.*
- Eventually have 25% of collecting area at ”remote” stations, which will be integrated into the array
- Surveys possible using multiple tied array beams

Long Baselines on the ngVLA



- Current strawman design of ngVLA:
  - 10x the current sensitivity of VLA from 1.2-116GHz.
  - 300 km baselines, which would give few mas resolution at the highest frequencies.
- Under consideration
  - Replace current VLBA stations with ngVLA technology
  - Introduce intermediate baselines to bridge between ngVLA and VLBA
  - Increasing the sensitivity of the current VLBA by a factor of >100 decrease T_B sensitivity to ~1000K
- Imaging thermal objects with sub-mas resolution.
  - For the ~100 closest stars we would have a resolution of $<0.3R_{\odot}$
    - That means imaging the disks of 100 stars.
- ngVLA Science Use Cases due December 1, 2017!

What do you want from VLBI in the future?

(fast response, more image sensitivity, more spectral line sensitivity, greater bandwidth, more frequency coverage, better astrometry…)

www.nrao.edu
science.nrao.edu
public.nrao.edu

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