The Future of VLBI

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VLBI Definition for this talk

- Interferometry Spatial Resolution $\frac{\lambda}{D}$ radians

- Extraordinary that regime with largest wavelength in astronomy (radio) also has the highest imaging spatial resolution - because of ease of doing interferometry with unlimited baseline length(!).

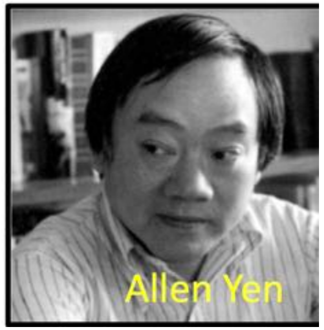
- VLBI used to be defined by tape recording data transfer; define here as radio-submm (Heterodyne, phase detection) interferometry in which D → max. Where max is 1000’s km to Earth diameter and beyond, i.e. beyond SKA baseline scales.

The 50 year anniversary of VLBI

- First tape record VLBI done by Canadian – US groups in 1967
- First successful transatlantic VLBI observation, Onsala (Sweden) to Haystack (MA, USA) in January 1968
- First transatlantic geodesy VLBI observations, - 5th April 1968 –50th anniversary tomorrow. Also on Onsala – Haystack baseline.







The Next Decades

- What are the prospects for the next decades? Will capability saturate, steadily increase of greatly expand?

- Input to this talk from Colin Lonsdale's 2015 talk at JIV-ERIC inauguration on the future of VLBI – plus recent talks at kickoff meeting of EVN Science Vision process.

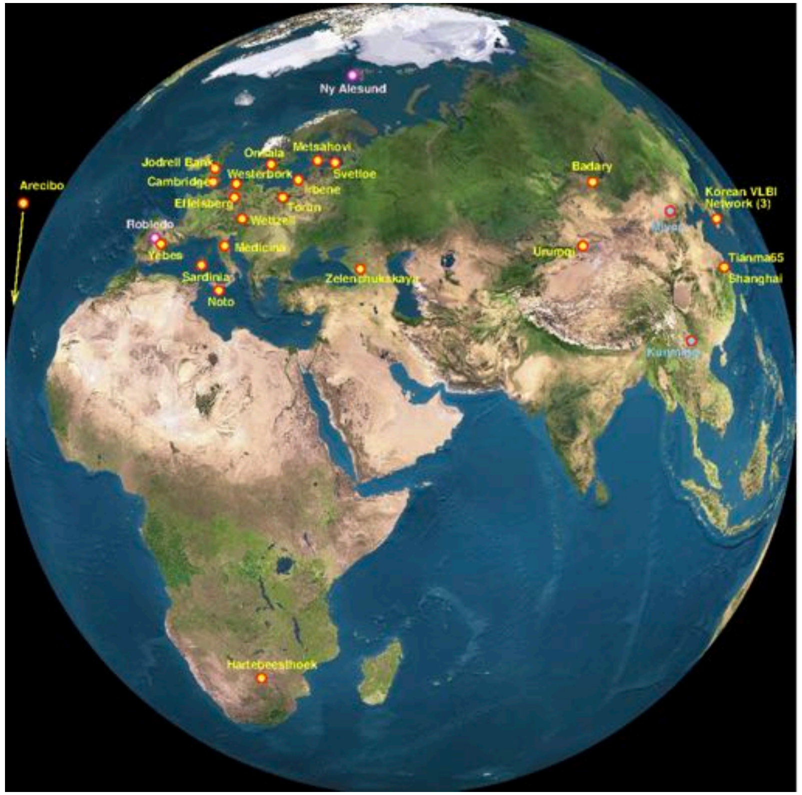
- Talk mostly based on what technically will be possible and what new high impact science can be enabled by that.

- VLBI always been (too) technically driven, should look at technical possibilities and - *identify astrophysical questions than can be addressed similar in importance to Billion Euro Space missions – which will then fund VLBI – lifting also other uses*.

Dimensions of Improvement

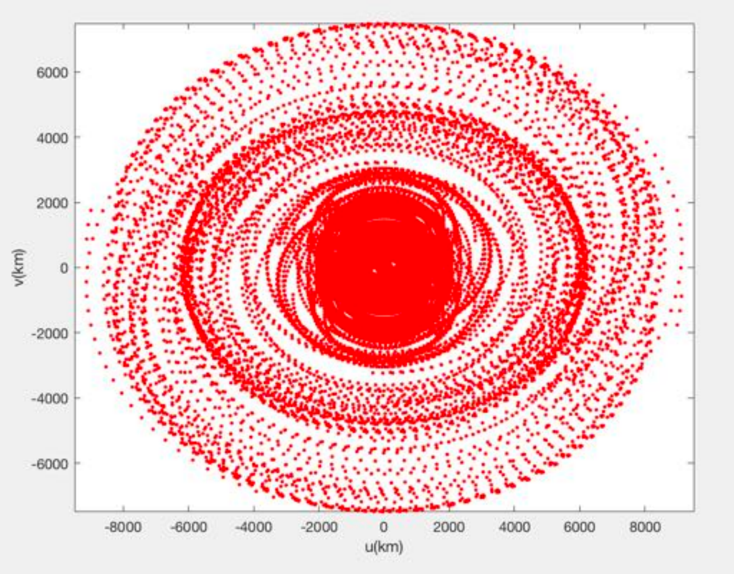
- 1) Telescopes – improved uv coverage + collecting area
- 2) Baseline length – higher spatial resolution
- 3) Frequency Range - lower and higher frequencies
- 4) Wide field Imaging
- 5) Multi-Field Imaging
- 6) Wide Instantaneous Bandwidth

1) Telescopes

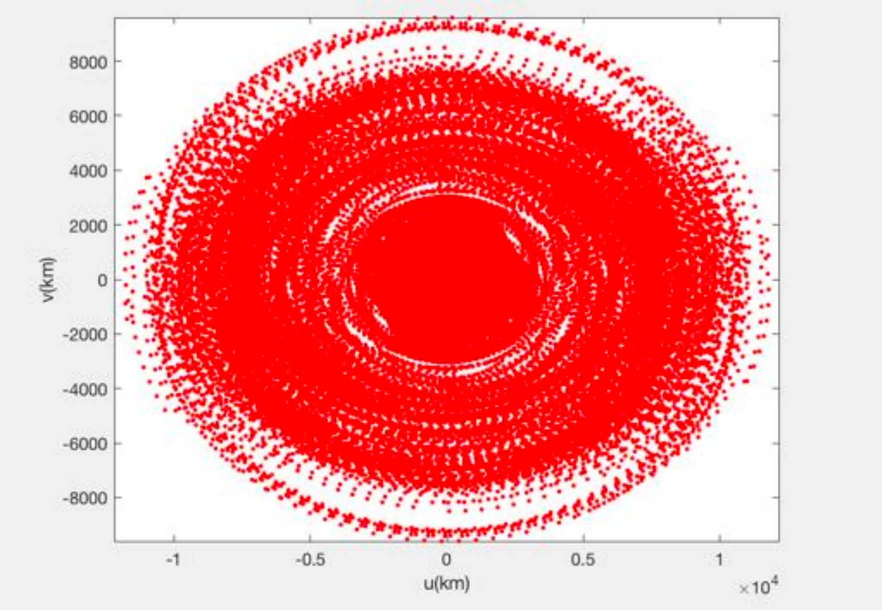


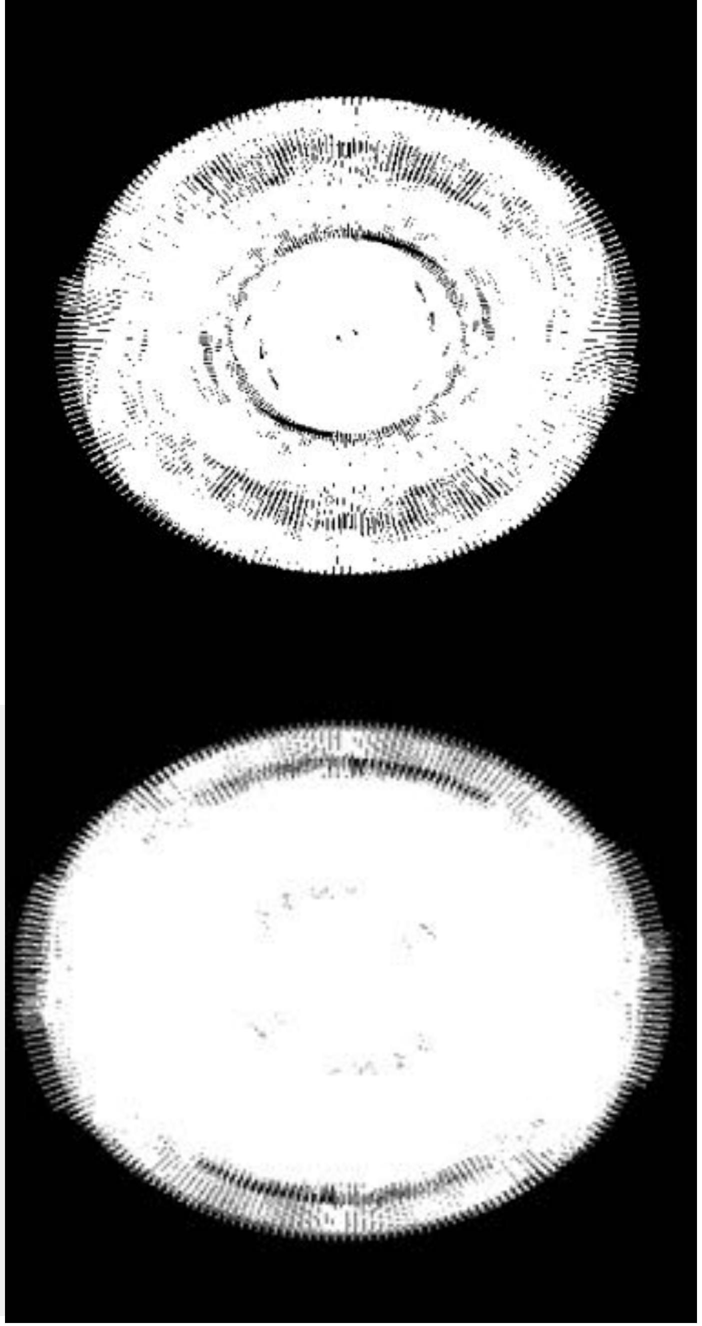
Present status of European VLBI Network – which despite its name extends into Asia, Africa, and North America

EVN 6cm. + eMERLIN 18 stations (left) single frequency and 2Gbps (256MHz or 5% BW, right) uv coverages



Global 6cm 30 station Single frequency (left) and 2Gbps (256MHz or 5% BW, right) uv coverages.

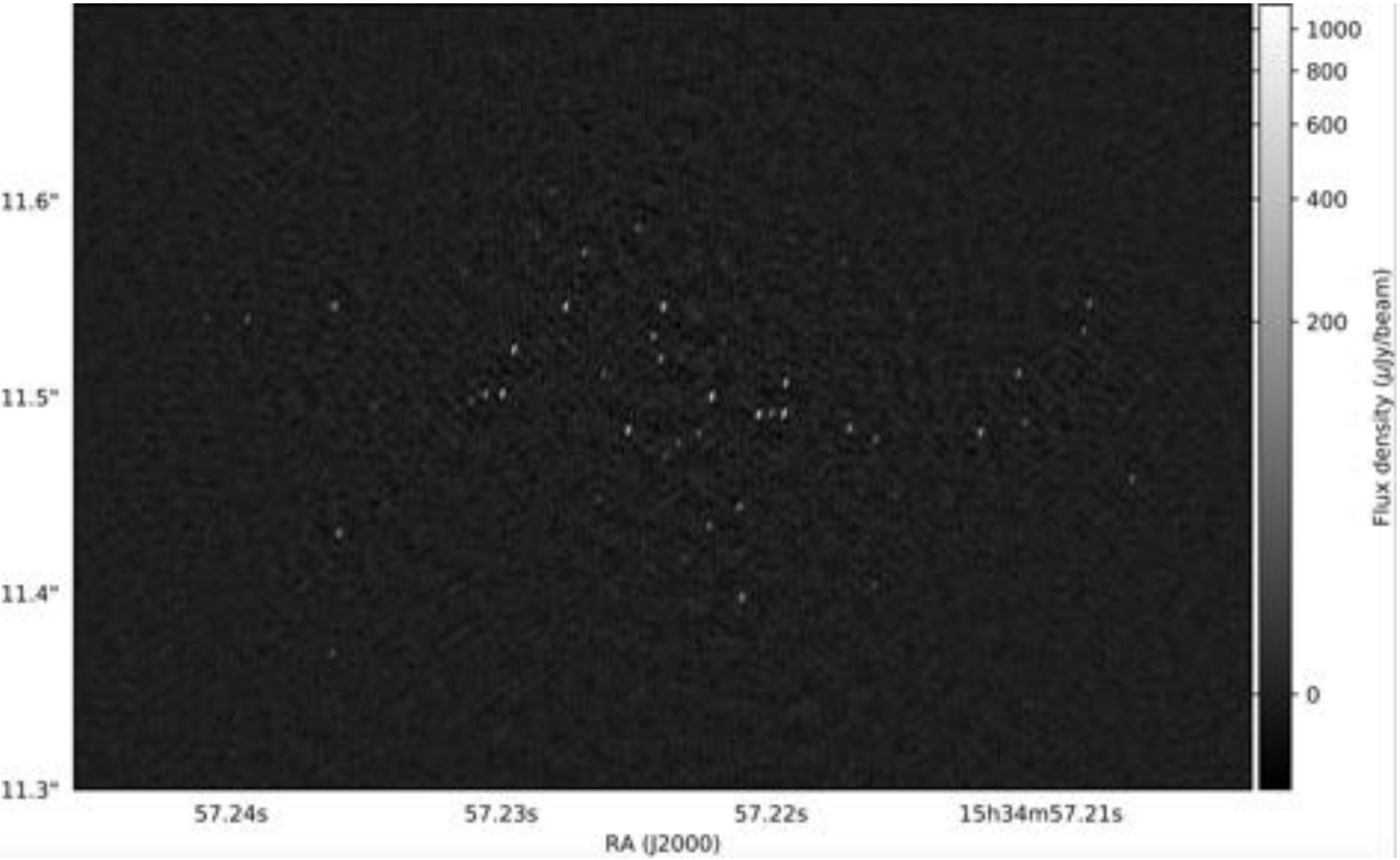


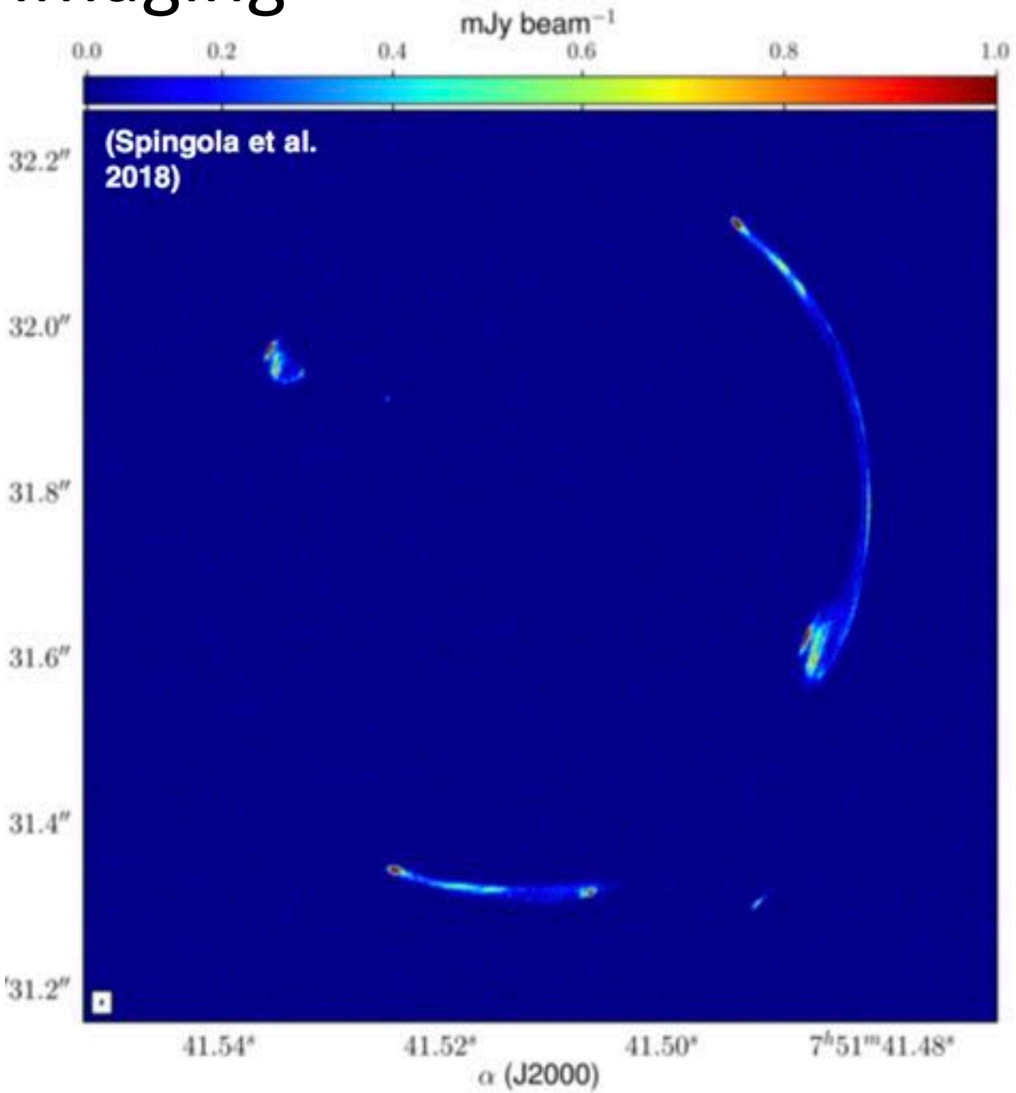


Right column Multi Frequency Synthesis (MFS) uv coverages (Conway, Cornwell, Wilkinson, 1990)

Ratio of over 1000 in baseline length allows excellent imaging over a wide range of spatial scales.

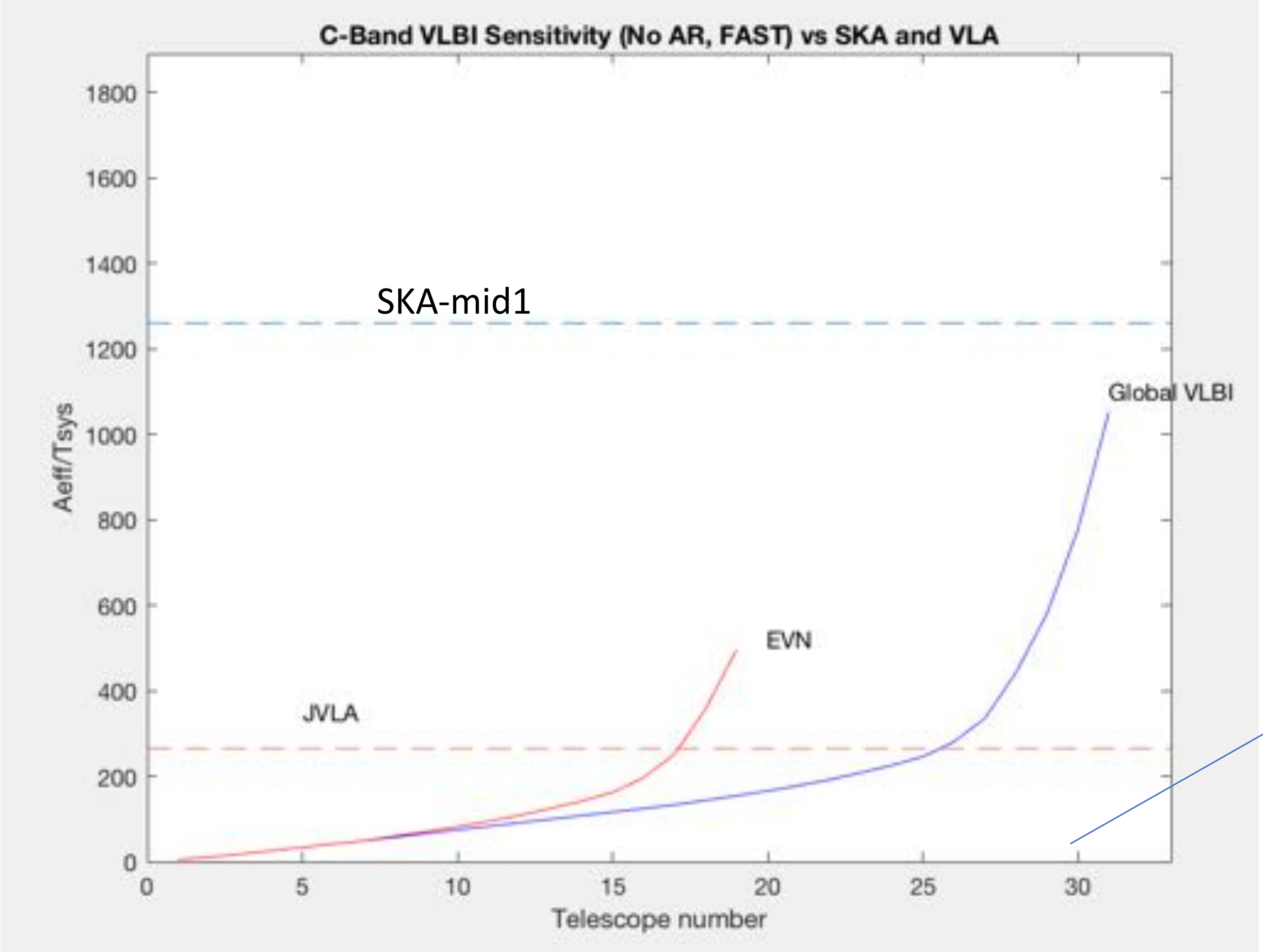
Present EVN high quality Imaging





Western Nucleus of starburst Arp220 (100pc field) with over 50 radio supernovae/Supernova Remnants (Varenius et al 2018)

Gravitational lens probing nature of dark matter (see **Spingola's** talk).



Global VLBI has now potentially more dishes than JVLA(!)

Sensitivity plot of existing EVN (no FAST or SKA as elements, also no Ar in this example) – simple summing of Aeff/Tsys applicable to the most efficient weighting for point source detection. Taking into account optimum weighting for imaging effective Aeff/Tsys for VLBI about half of values shown here.

Future Antennas

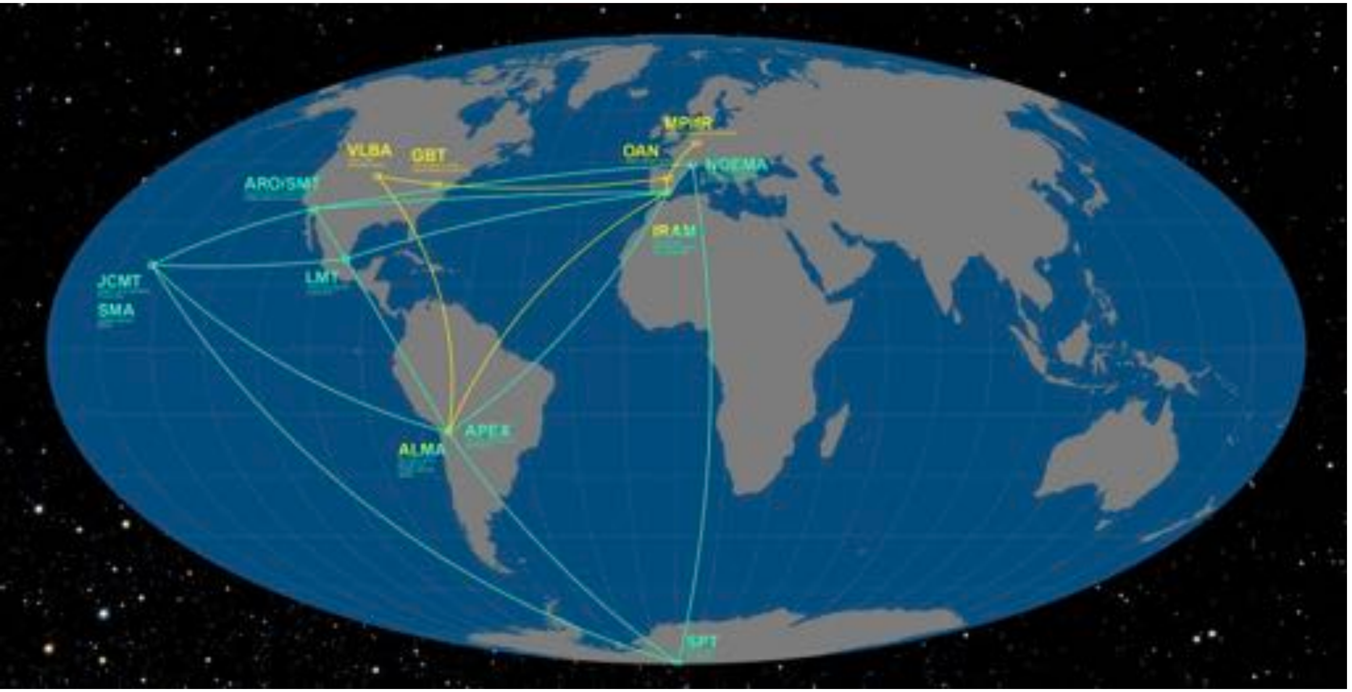
East Asian VLBI Network (EAVN, An 2018)

FAST 500m diameter telecope China

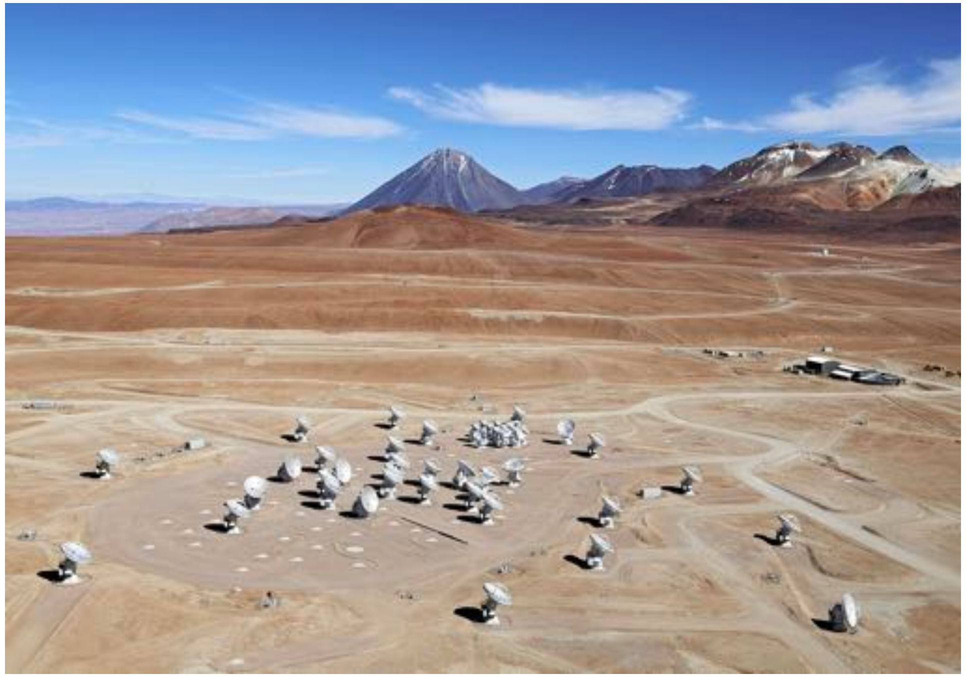
Other new antennas - QiTai 110m fully steerable antenna in China. Two new antennas planned in Thailand, Azores antenna, UAE, antennas in Africa (AVN, see later). Future effective Aeff/Tsys for imaging comparable/larger than SKA1-mid – even without SKA1-mid as an element.

At cm wavelength future world VLBI ‘network of networks’, VLBA, EVN, EAVN in Northern hemisphere with AVN added for equatorial or Southern sources and the Australian LBA for South.

High frequency Arrays Global Millimetre VLBI Array (GMVA) and Event Horizon Telescope (EHT)



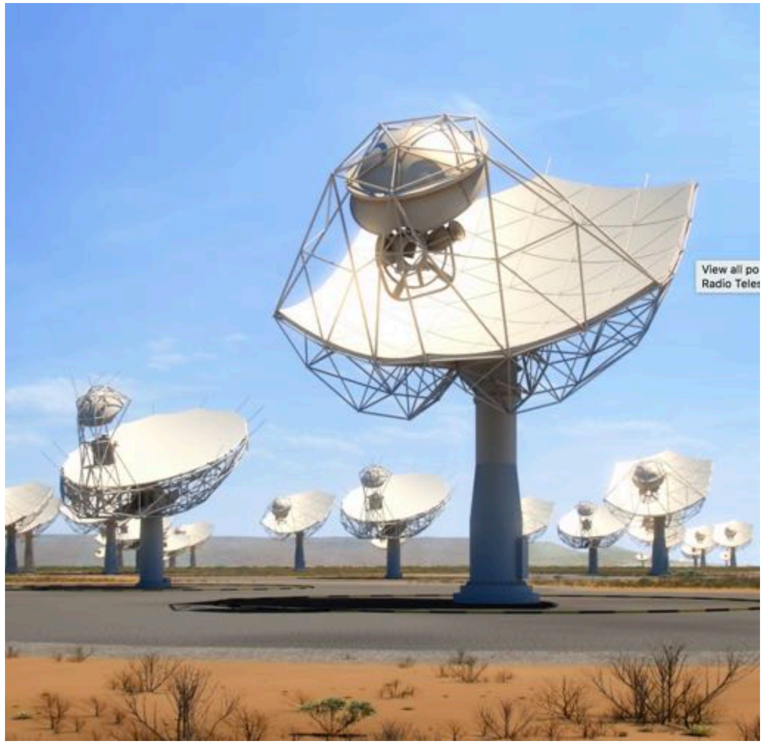
GMVA at 3mm, 90GHz (*some antennas missing, i.e*. On) + EHT at 1mm, 230 GHz



Phased ALMA huge advantage for high frequency VLBI – soon also available at 43GHz which is an EVN/Global VLBI frequency.

Adding MeerKAT and SKA1-mid as VLBI elements

MeerKAT 64 x 13.5 m antennas

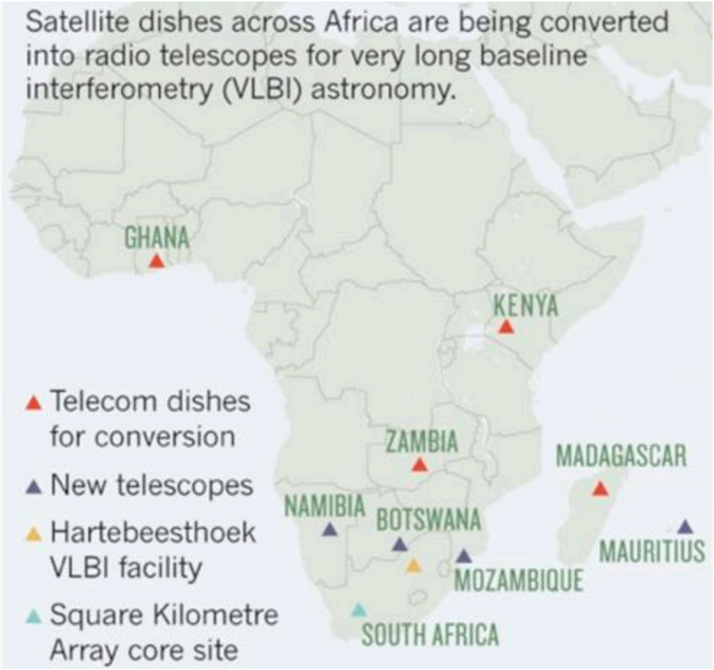


SKA1-mid add 133 x 15m dishes

Both MeerKAT and SKA1-mid have a built in capability to phase-up and act as single element for VLBI, also add in US NgVLA if it gets built.

VLBI in Africa

SKA2 planned to have 1000's km baselines throughout Africa

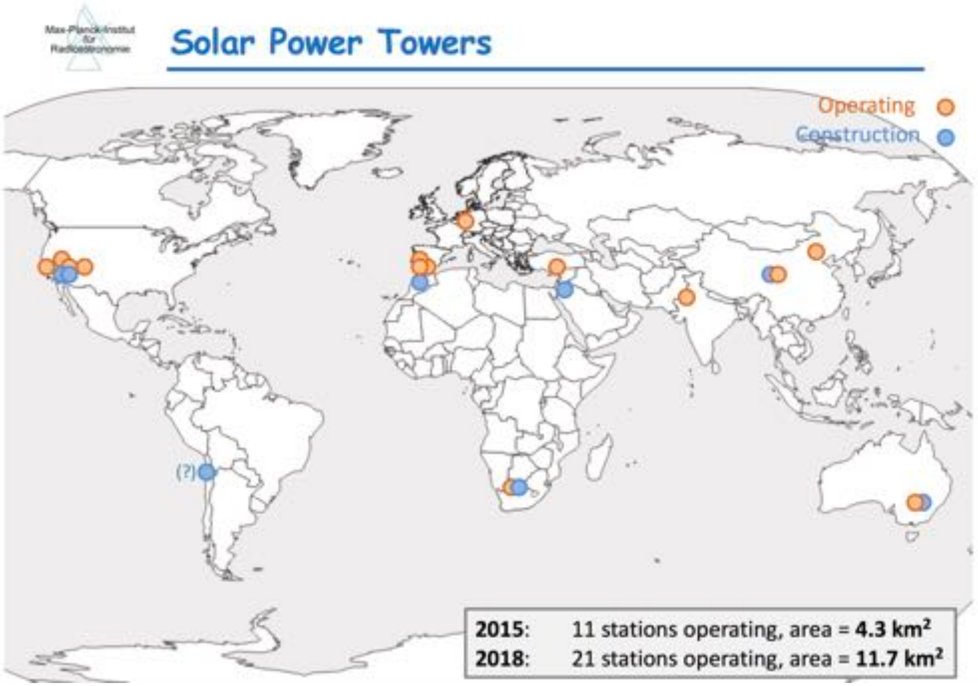


Planned African VLBI network to start developing radio astronomy throughout Africa

First successful fringes to converted satellite communications dish in Ghana July 2017

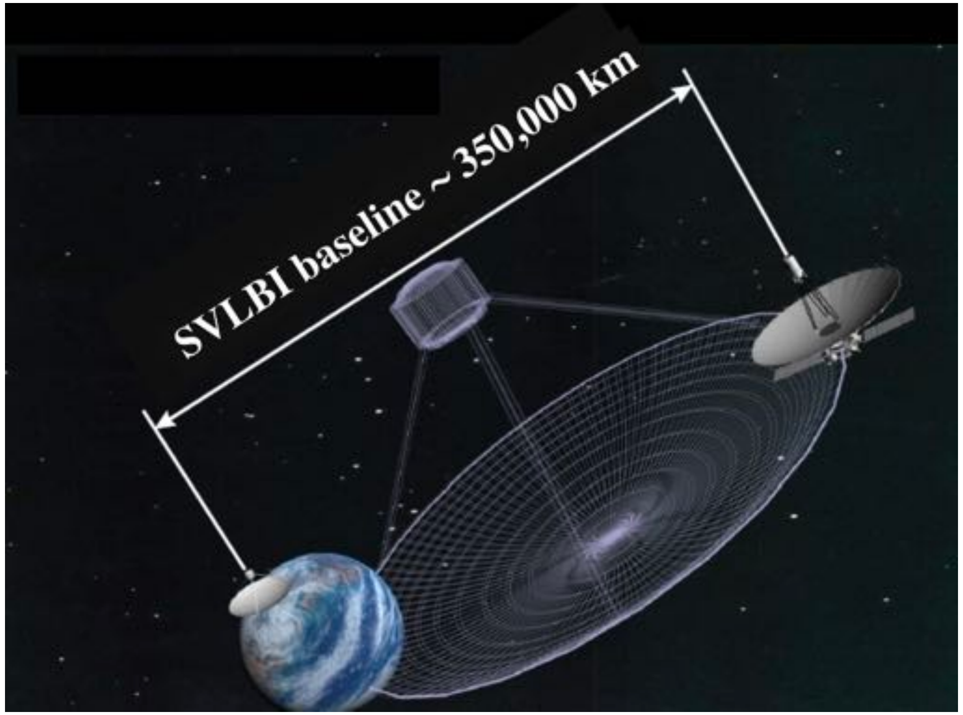
Even larger collecting areas possible?

- Alan Roy, Olaf Wucknitz, Ivan Camara from MPIfR, suggest using existing/future Solar collectors as radio telescopes.
- Needs massive Phased Array Feed (PAF) at approximate focus because paths not phase coherent.
- Can use (full) collecting only at night (☺) – in 30 – 50 yrs time VLBI community could build collecting areas like this and sell power generated during part of the day?



2) Baseline Length

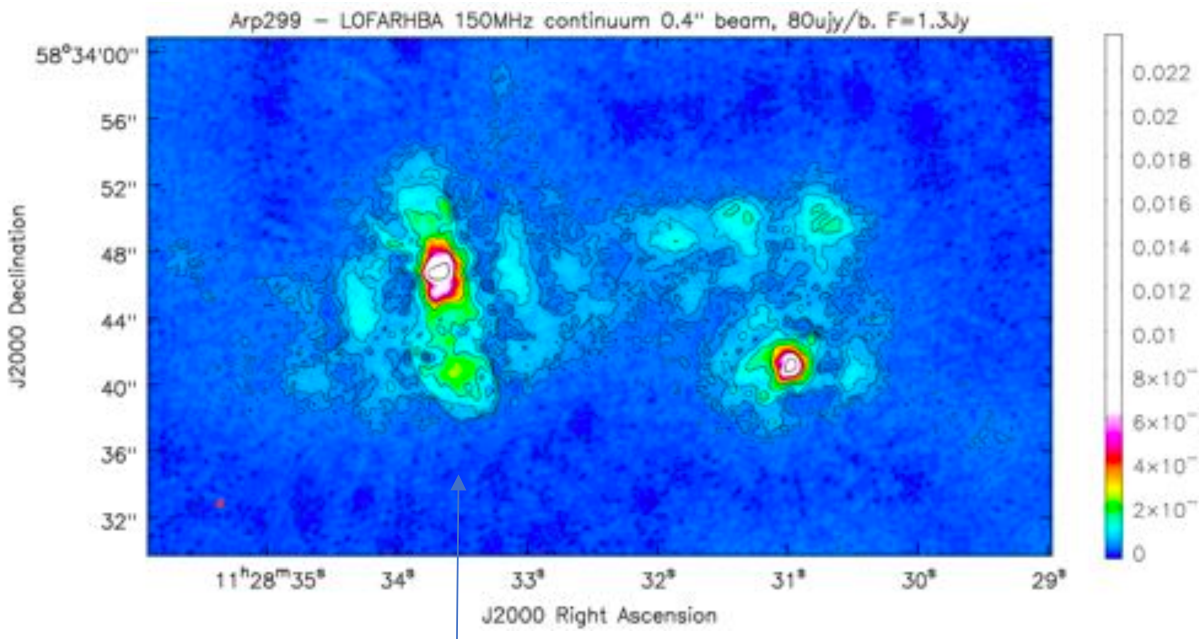
Space VLBI missions Japanese VSOP – followed by Russian Radioastron presently in orbit – Russian Millimetron being build plus possible new Chinese project.



New idea to investigate **Space-Space VLBI** at mm wavelengths with between two or more satellites (**Falcke** talk). Also at lower frequencies with modern LNAs T-rx < 5 K also great sensitivity advantages of going into Space compensating smaller dishes.

3) Frequency Range

- Expansion to higher frequencies already covered i.e. EHT (see **Falcke's** talk).
- Also expansion to lower frequencies LOFAR international baselines in Europe (and experiments beyond, Wucknitz to LWA in New Mexico).
- Key science - outflows and free-free absorption in galaxies, supernova remnants, low luminosity AGN, Pulsar scintillation imaging. Future possibilities – location of Extrasolar planets, location of FRB's.
- Future global metre-wave VLBI (scattering ok at high galactic latitudes) – combine LOFAR, LWA, GMRT, SKA1-low.

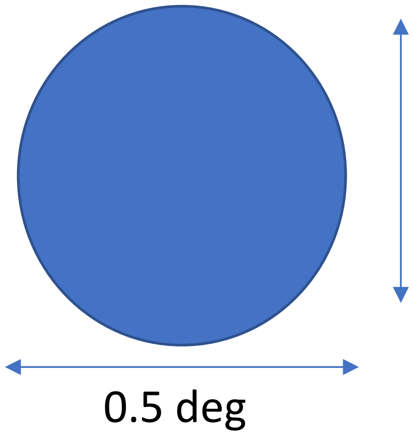


LOFAR international baseline Image- North -South Continuum outflows in East Nucleus of star-forming galaxy Arp299. Ramírez-Olivencia, Varenius et al.

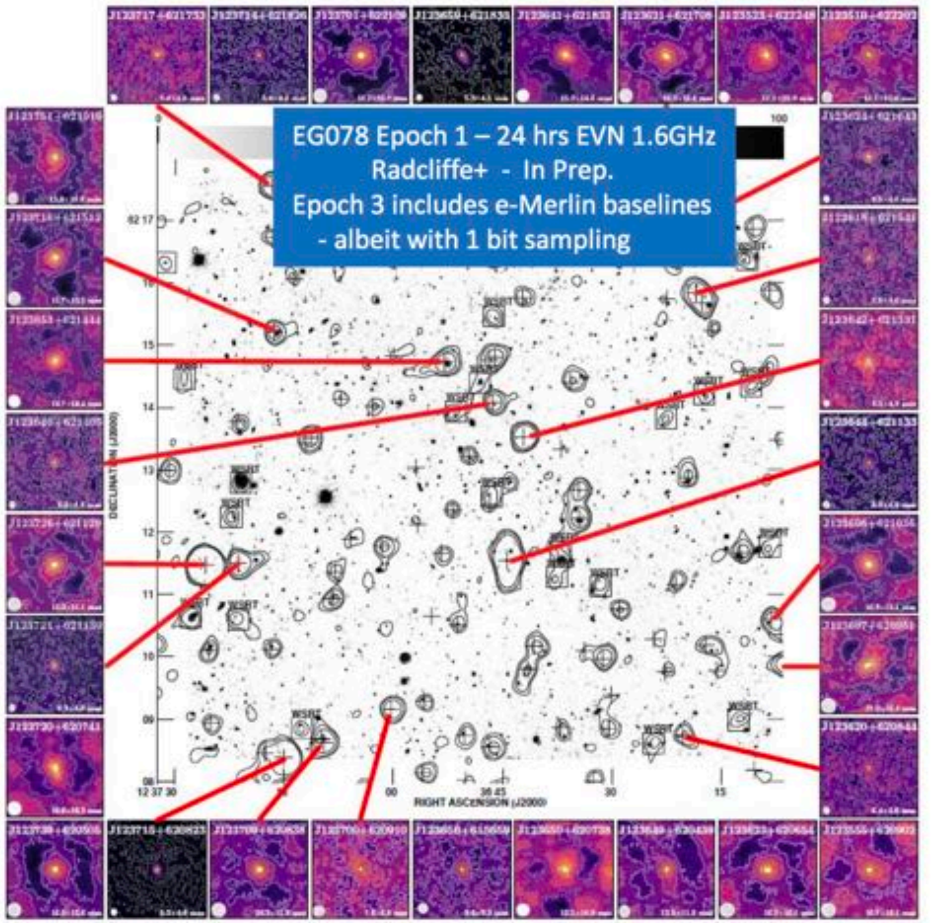
4) Wide-field Imaging

- Long wavelength --> telescopes have large field of view. VLBI allows very high resolution- hence → VLBI images *potentially most complex in astronomy- given complete MFS uv coverage and mostly empty sky can be imaged*.
- BUT In past limited computer processing → average in time and frequency to reduce field of view In future image the whole antenna FOV for each observation (M. Garrett); build up sky survey.
- Ultimate Global VLBI limit (may require also increased correlator capacity); 18cm example below;

Resolution FWHM 3 mas Assume 2 pixel/beam.



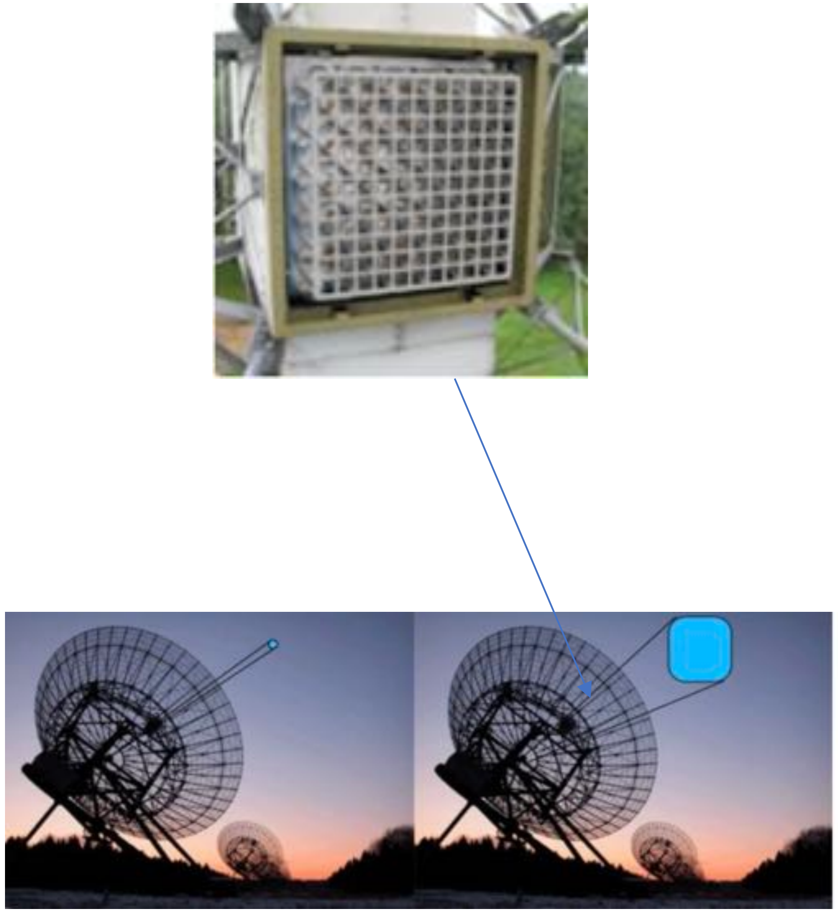
i.e. Potential factor of 10^6 more pixels than in today's typical 1024x1024 pixel VLBI image(!!)



Science applications – Statistical separation of Star-formation and AGN powered sources (**Merloni, Muxlow, Sbarrato** talks), search for rare objects like Gravitational lenses (**Springola** talk) etc.

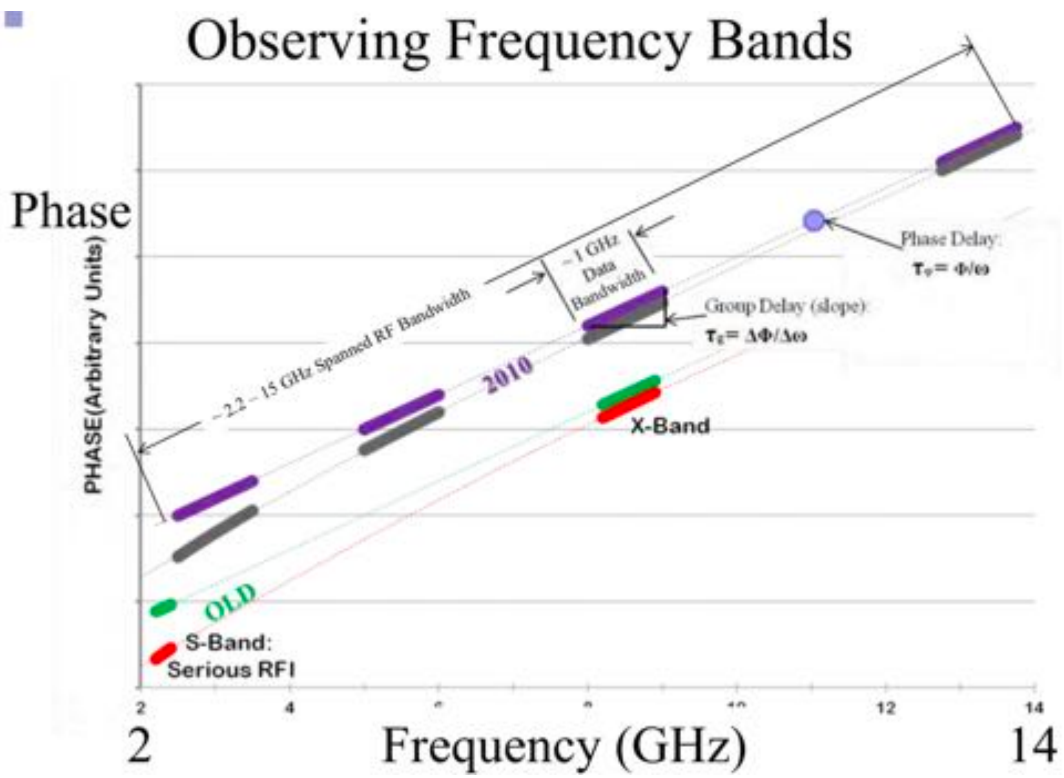
5) Multi-Field Imaging

- Additionally Typical dish presently only collects fraction of information that enters (Lonsdale 2015); only sensitive to a single direction and narrow range of frequency. Potentially another factor 1000 in data collection capacity available to exploit !
- Multiple direction factor of 25 – 100 addressed by Phased Array Feeds (PAFs) on dishes or for array by multiple beams. Frequency expansion factor of 40 can be addressed by wide band feeds (next slides).
- Biggest impact is imaging FOV of single beam (last slide)– expect long time before PAFs on 25m – 32m dishes for VLBI are needed. But VLBI role for PAFs on large dishes (Lovell, Effelsberg, SRT etc) making FOV same as 25m/32m dishes.
- Do not yet know how to capture *both* full direction sensitivity and full frequency range at same time– but maybe in 30 – 50 years?
- Combine 10^3 dish data capture factor with 10^6 factor on number of pixels per field (last viewgraph) potential VLBI expansion factor is 10^9 . VLBI has plenty of growth potential for next 50 years !



APERTIF Phase Array Feed on WSRT expand FOV by factor of 25

6) Wide Instantaneous Bandwidth



Operating VGOS (VLBI Geodetic Observing System) antennas

Geodetic VLBI for geodesy needs wide instantaneous bandwidth to get group delay (4 x 1 GHz band within range 2 – 14 GHz see above). Astro VLBI can use this technology developed for geo VLBI and go beyond.

EU Radionet BRAND project for 1.5 – 15 GHz feed + receiver

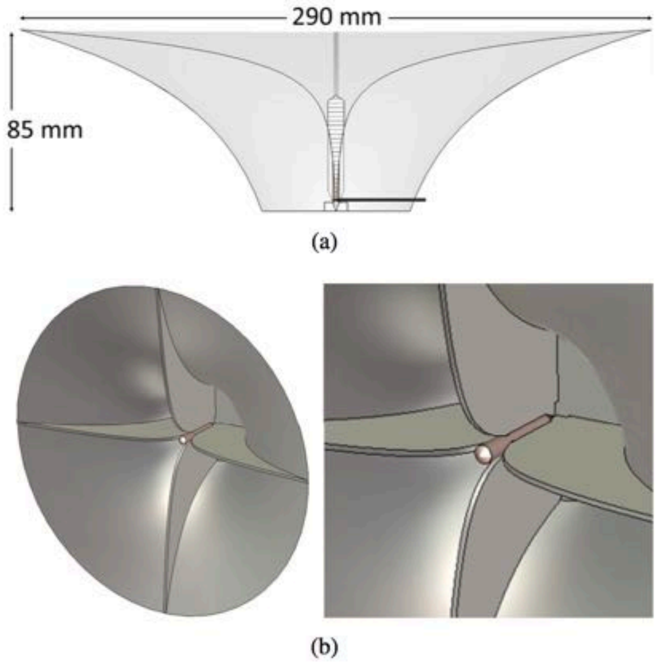
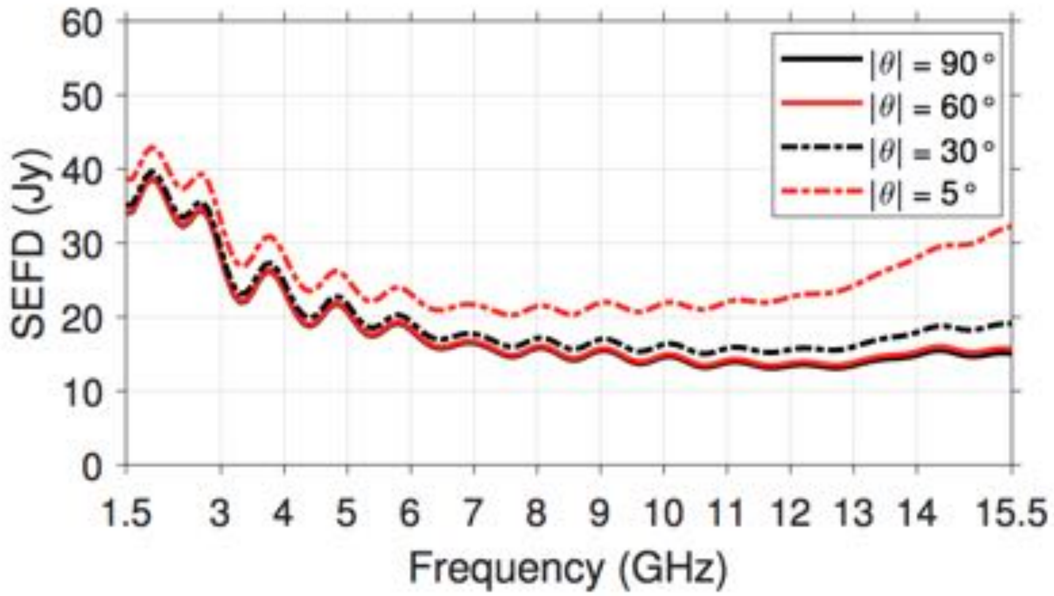


Fig. 1. Quad-Ridge Flared Horn (QRFH) illustrated in (a) cross-section and (b) perspective view with zoom-in on the dielectric load at the center.

Jonas Flygare (2018), Onsala Space Obs, PhD student – feed design for prime focus Effelsberg 100m.



Simulated Performance on Effelsberg dish. Present Eb receivers on EVN status table have 20 Jy noise at 1.6GHz, 5GHz, 8.4GHz, 15GHz BRAND comparable except at 1.6GHz

NGVLA Wide band receiver concept

US proposal to build 1.2 – 116 GHz capable array in SW US extending into Mexico. NGVLA plans to use wide-band receivers.

Trade-off in efficiency with fractional bandwidth. For 10:1 feed approx 30% loss compared to octave for 10:1 feeds -more like 15% for 4:1 feeds. NGVLA chooses 4:1 as sweet spot with suite of 4 feeds, 3 of which are wideband.

- 1.2 - 4.2 GHz
- 4 - 15 GHz - 4:1 feed similar to geo-VLBI
- 15 -50 GHz
- 70 -116 GHz - Octave horn

Suggest NGVLA solution may be good standard for future VLBI. Compatible also with main VGOS geo-VLBI frequency range starting at 4 GHz.

Alternative for 15 – 50 GHz wideband receiver is two receivers centred at 22GHz/43GHz and dichroic mirror. Also can add third dichroic mirror for 86 GHz (KVN concept see also later).

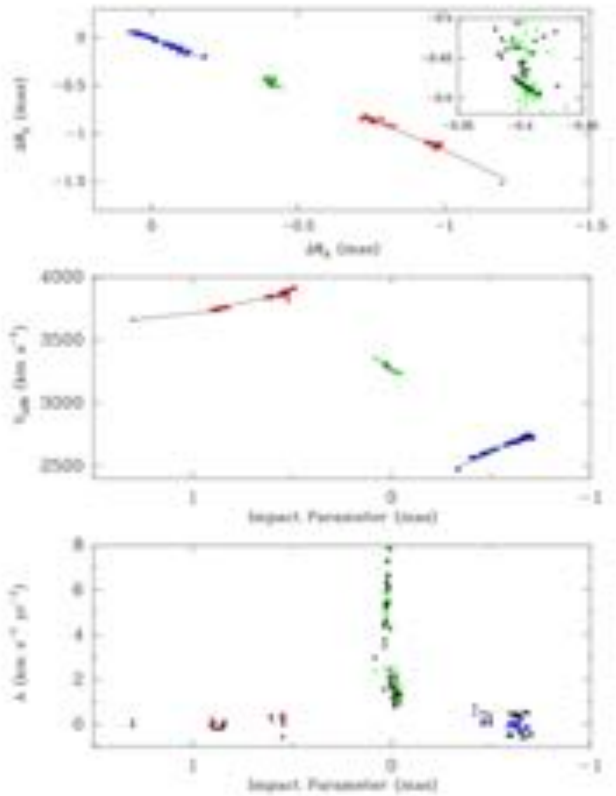
Advantages of ultra wideband cm receiver for VLBI

- Sample and correlate all of 4 – 15 GHz band, i.e. 11 GHz of BW this is 44 times more BW than EVN currently processes, 4 times target for SKA and 2.5 times geo-VLBI. EHT already does 64Gbit/s (!) (**Falcke** talk) so final target only 1.4 times this. The technology already exists and you can buy the equipment!
- Increased correlated bandwidth compensates for lower feed efficiency – can also get images at several widely spaced frequencies for spectral index and curvature. Faraday rotation and de-polarisation.
- Get broad-Band spectra of short transients (like FRB see **Hessels** talk) and their location.
- Can co-observe with geo-VLBI.
- Get automatic position alignment of images at different frequencies, get absolute astrometry fundamental for a lot of unique VLBI science, parallaxes etc.
- Optimal for Multi-Frequency Synthesis.
- Optimal frequency flexibility for following up redshifted water megamasers for cosmology (next slides).

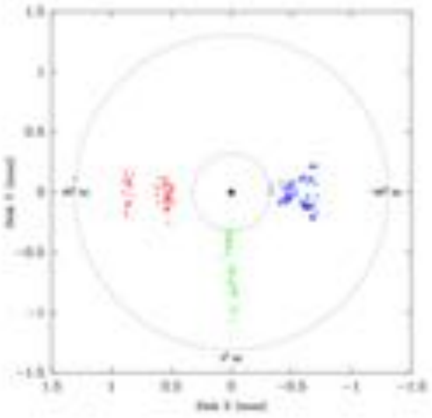
Slide from John McKean EVN vision workshop Feb 2018

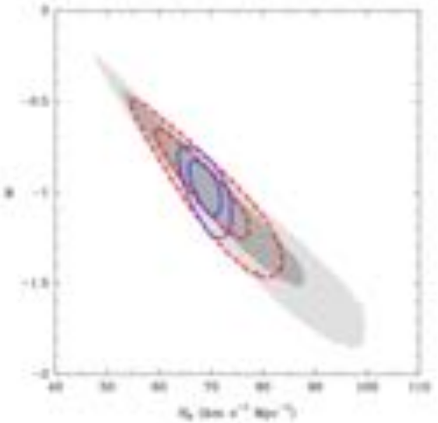
Dark energy: Probing cosmology **masers**

Proof of concept demonstrated by the NRAO key science programme: Megamaser Cosmology Project (MCP; PI Jim Braatz).



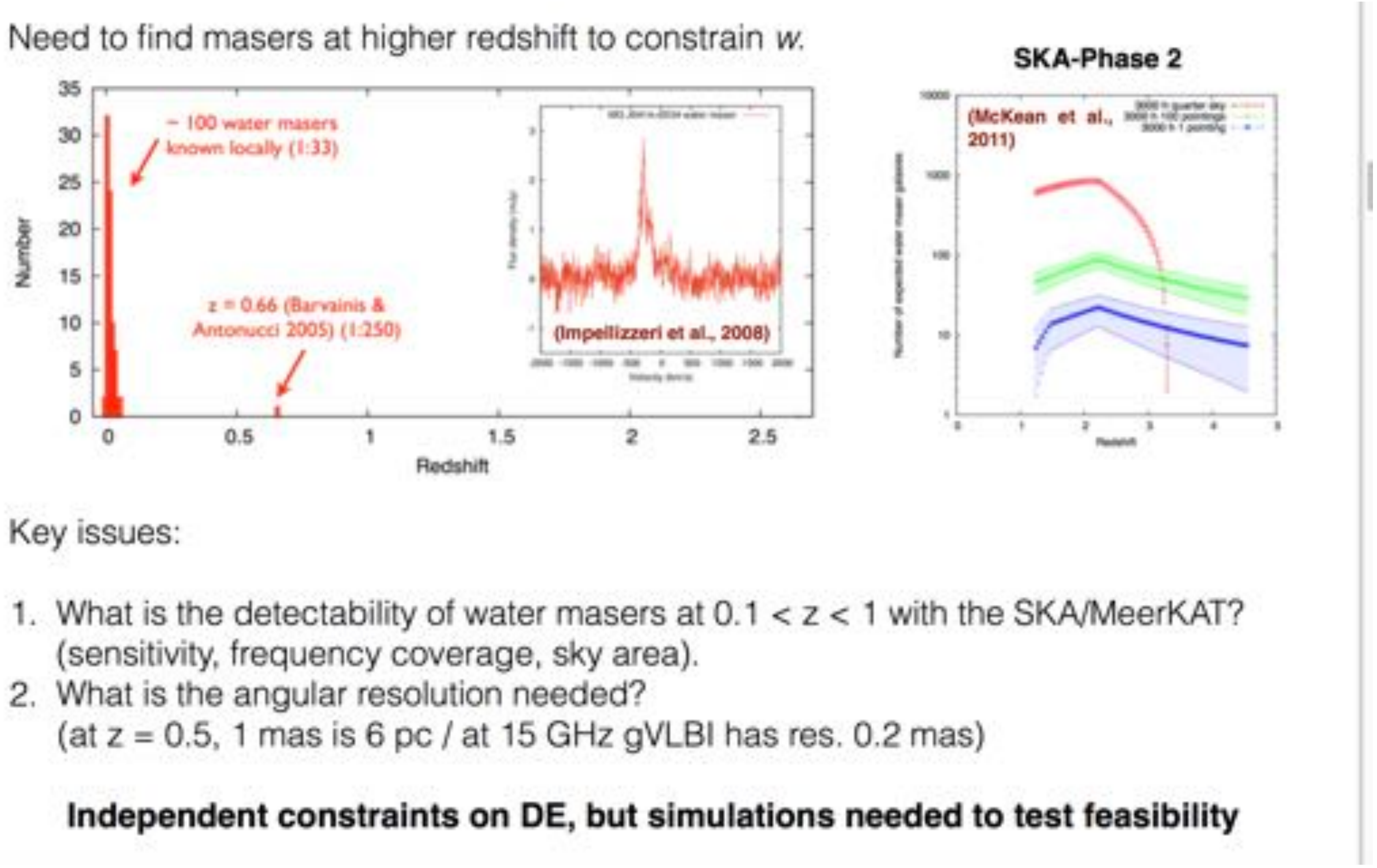
Targets 22.2 GHz water masers in disk galaxies with GBT and VLBA.





Only weakly constrains *w* (low redshifts) and may be limited systematics (e.g. BH proper motions, relative to the galaxy systemic velocity) at the few % level.

Slide from John McKean
EVN vision workshop
Feb 2018.

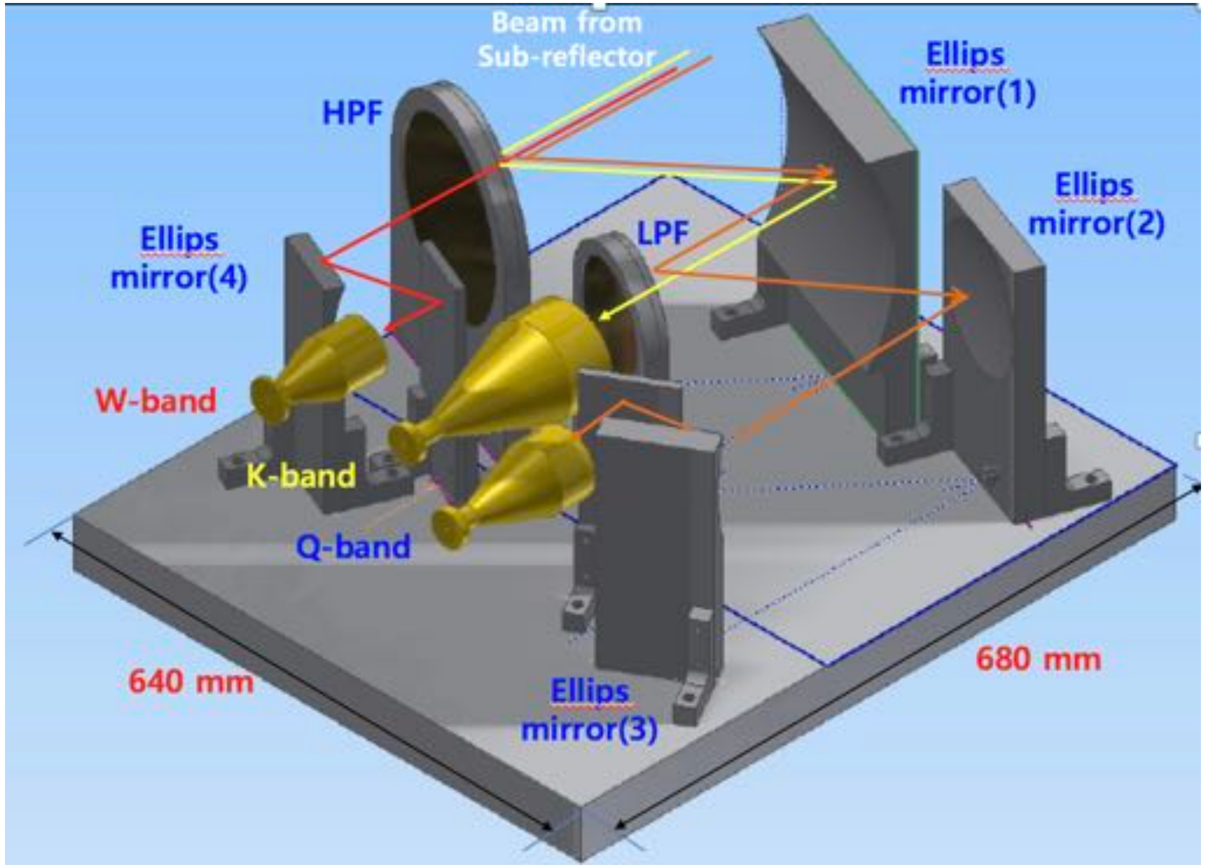


z>0.5 means water maser redshifted to <15GHz

Need frequency flexible receiver 5GHz - 15GHz to follow up with VLBI any detections found by SKA1 to get disk sizes.

Simultaneous receivers for 22GHz – 86 GHz

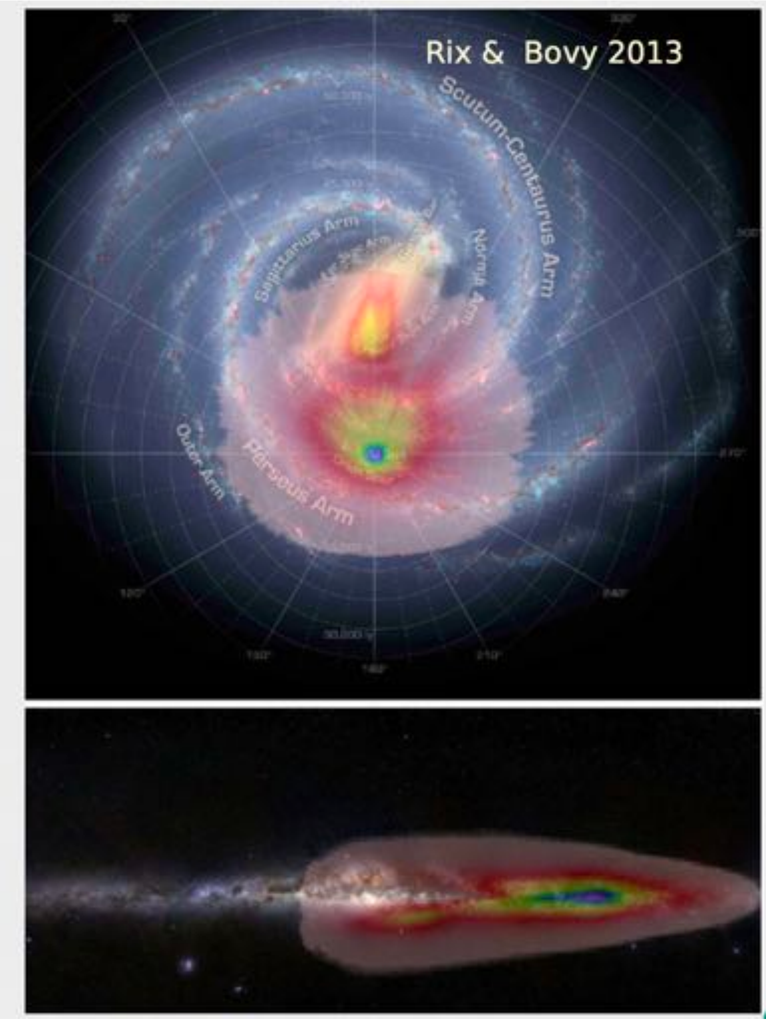
- Alternative to 15-50 GHz wide-band receiver; use dichroic mirrors for simultaneous 22GHz/43GHz
- For antennas that go to mm frequency add another dichroic mirror for 86GHz.
- Three receiver design for Korean VLBI Network (KVN). Similar at Yebes. Interest for Effelsberg and Onsala.
- Use observations centred at 22 GHz and 43 GHz to determine atmosphere phase at 86 GHz and increase coherence time; huge impact reducing phase noise so improving sensitivity.
- Can observe simultaneously and position register multiple maser lines H_2O, SiO and/or multiple continuum bands (i.e. for jet core-shift measurements).



KVN three Band Design. Seog-Tae Han.

Predictions for next 30 years (2048)

- Steady increase in collecting area for VLBI as the networks incorporate big telescopes built for other purposes. Expansion Southward to Africa especially important for galactic work and overlap with SKA/ALMA etc.
- Technology exists to achieve 11 GHz correlated bandwidths (90 Gbits/s) spanning say simultaneously 4- 15 GHz. But need €€€ for data transfer and correlation capacity. Use to get spectral index/curvature, Faraday rotation/depolarisation, absolute astrometry; all as standard data products.
- Astrometry/parallax are unique VLBI data of fundamental astrophysical importance and will remain so for galactic structure GAIA (See **Brunthaler**t) and for luminosities etc of radio emitting objects **,** **(Olofsson** talk)



Predictions (Part 2)

- The expected VLBI collecting area and bandwidth expansion may enable 10 mas resolution observations on 1000 km baselines of 10^4 K emission (i.e. from massive star winds).
- Also will allow more VLBI of stars (**Olofsson** talk) and hopefully observations getting orbits of radio emitting extrasolar planets (including SETI M. Garrett).
- Transient expanding area in radio astronomy. VLBI is often only technique that has resolution to resolve follow evolutionary changes etc (**Perez-Torres, Hessels** talks)
- With increased computing a huge expansion is possible in wide field imaging – get by default images of whole antenna FOV. PAFs will be used on large telescopes to keep same FOV as 25m/32m telescopes. Use for galaxy SB/AGN statistics (**Muxlow** talk), finding gravitational lenses **Spingola** talk etc.
- Wild cards like doing cosmology with z>0.5 water megamasers, could be game changers.
- **Looking forward to what collectively will come out of the EVN Future Vision process – but it is already clear that VLBI has an exciting future.**