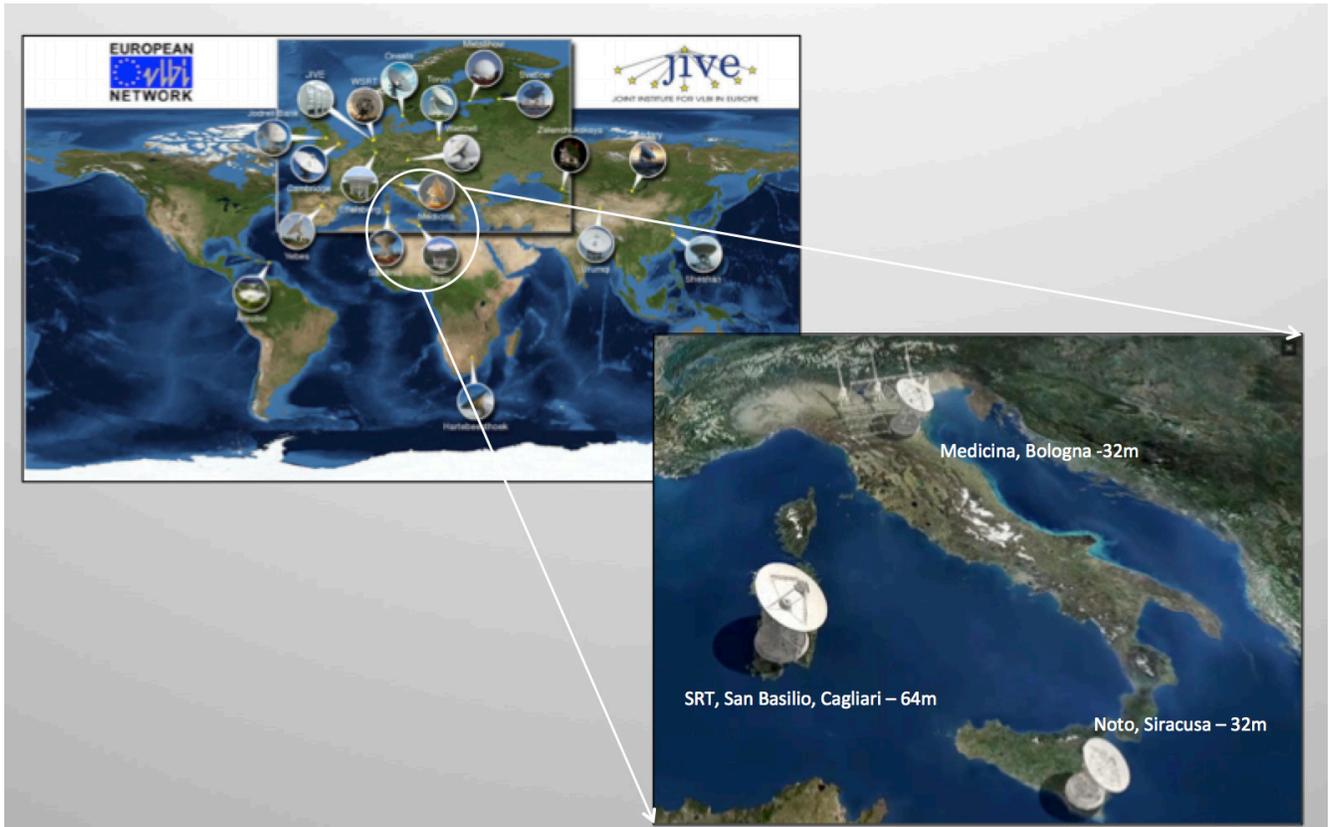


DIREZIONE SCIENTIFICA
Divisione Nazionale Abilitante per la Radioastronomia
National Division for Radio Astronomy

SCIENCE, PERSPECTIVES AND IMPACT OF THE USE OF THE THREE ITALIAN ANTENNAS FOR VLBI

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Summary

The aim of this document is to assess the relevance of Very Long Baseline Interferometry in the current astronomical scientific framework. The importance and potentials of VLBI are further highlighted in the prospects of the SKA, the radio telescope which will change the full paradigm of astronomy.

The relevance of the Italian infrastructures operating in VLBI is highlighted both in the international and national context.

INAF participates in Very Long Baseline Interferometry operations with the three radio telescopes located in Medicina and Noto (managed by IRA) and with SRT, located in San Basilio (managed by OA Cagliari). The relevance of the Italian antennas is multifold: (a) their collecting area is a considerable fraction of the full European VLBI Network, thus they provide a substantial contribution to the sensitivity of the array, hence to the quality and relevance of the VLBI science; (b) the Italian antennas are the southernmost in Europe, and are crucial to the joint observations between the EVN and the developing African VLBI Network. Such operations will be essential in the SKA era, as clarified and detailed here; (c) the high frequency capabilities of Noto and SRT open the window to joint VLBI operations with ALMA, whose scientific impact would be enormous, as the EHT has already demonstrated; (d) the three antennas constitute a single Italian VLBI Array, which can operate by itself and together with other arrays, beyond the European VLBI Network, with major impact not only on science but also on the potentials to build new international bilateral collaborations. The DiFX correlator at IRA ensures that the Italian VLBI Array is fully independent, hence extremely competitive at international level. In order to ensure performances at the top of its potentials, it is essential that the three antennas have the broadest range of common receivers, and that Medicina is upgraded to active surface with urgency.

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1. Background

1.1. Brief historical overview

Radio observations by means of Very Long Baseline Interferometry (VLBI) started in 1967 in the US. The birth of VLBI in Europe dates a few years later, in 1975, when the first fringe tests between a few US and European antennas took place. Italy joined this group of radio telescopes engaged in VLBI in 1983, when the Medicina radio telescope was opened. The Consortium of Directors of the European VLBI Network was formally established in 1985, under the chairmanship of Prof. Setti, and the Istituto di Radioastronomia has been one of its five founding members. The radio telescopes in Noto and SRT joined the EVN operations in 1988 and 2014 respectively.

Radio interferometry in general, and VLBI in particular, represent an extremely successful solution to overcome the major limitation of traditional single dish radio telescopes in terms of angular resolution. Since the angular resolution, θ , is a function of the observing wavelength λ and the diameter of the telescope D , i.e., $\theta \sim \lambda/D$, in order to achieve the angular resolutions of the order of the arcsecond in the radio domain (where the wavelength is in the range of tens of cm to mm) the size of a radio telescope should be of the order of several tens of km, which is impracticable. The exploitation of the principles of interferometry, and the concept of several dishes located at some distance with respect to each other, combined with Earth rotation synthesis, led to the development of phased arrays (where the antennas and the correlator are physically connected through cables/optical fiber links), and of VLBI for separations of the order of hundreds of km and much more. The achievement in terms of resolution is not costless: by definition, interferometers do not cover all the spacings of a filled antenna, and this reflects in artefacts in the imaging, which require major time investment in the data analysis. Moreover, the process of correcting the phases of the incoming wavefront for instabilities of the atmosphere and ionosphere is another severe issue in the data analysis. For this reason radio astronomy has been considered a “niche” for decades, hardly accessible to non-radio astronomers.

1.2. Observational parameters

The quality of the radio interferometric data obviously depends on several factors: the collecting area (closely related to the size of the dishes and the number of dishes in an array), the distribution of the dishes, and other parameters more closely related to the equipment and the technology, such as the observing bandwidth, the integration time and the receiver noise. The combination of the number of dishes, their distribution and the duration of the observation provide the so-called “u-v coverage”, which is a measure of the resolution and sensitivity to the angular scales that an interferometric array is able to cover. In other words, the u-v coverage tells us how close the interferometric array is to a single dish whose diameter has the size of the longest baseline (i.e. the maximum distance between two radio telescopes).

VLBI is the extreme case of radio interferometry where the radio telescopes are spread throughout Earth, and in space, and are not connected to each other. The signal collected from each individual telescope is either recorded on some devices (now disks) which are sent to the correlator, or transferred to the correlator through optical fiber link connections. The development of the data collection and

recording is beyond the scope of this document, but it is a true example of how difficulties have the power to turn limitations into frontier technological developments. The overall complex logistics of VLBI observations has undergone an incredible revolution in only a couple of decades, and has anticipated the challenges that the new generation interferometers are dealing with nowadays.

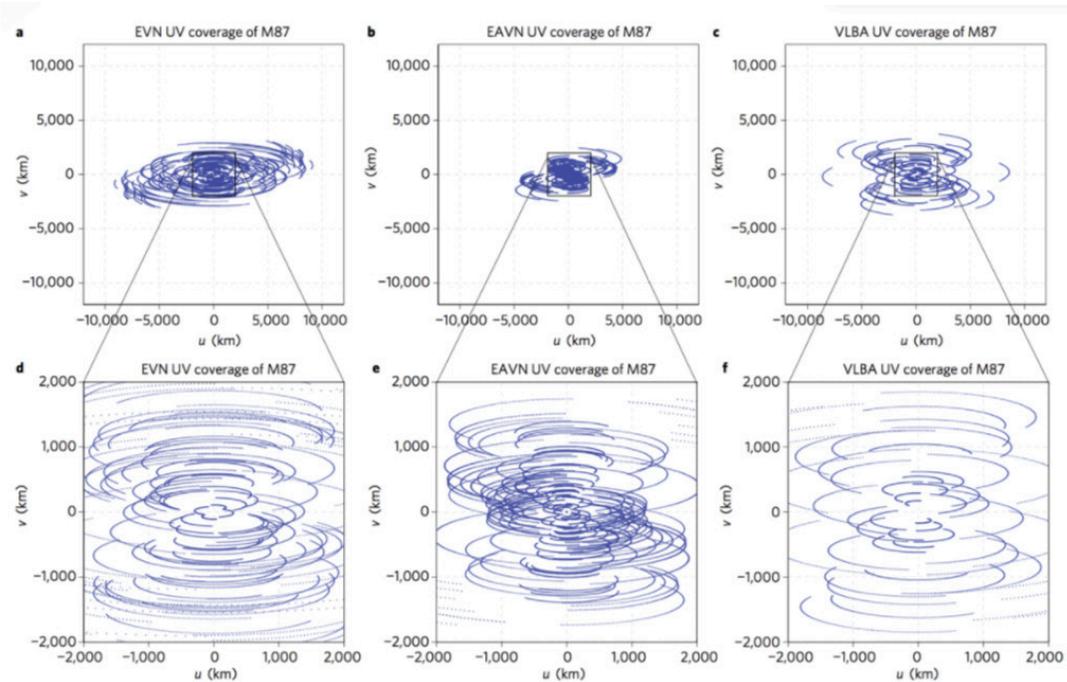


Figure 1 – Examples of u - v coverages for VLBI arrays. Each track refers to a single baseline as the Earth rotates during the observation (i.e. longer tracks mean longer observations). Better coverage reflects into better recovery of the angular scales in the image and better sensitivity. The longest baselines set the angular resolution. The lower panels zoom into the inner portion of the u - v coverage.

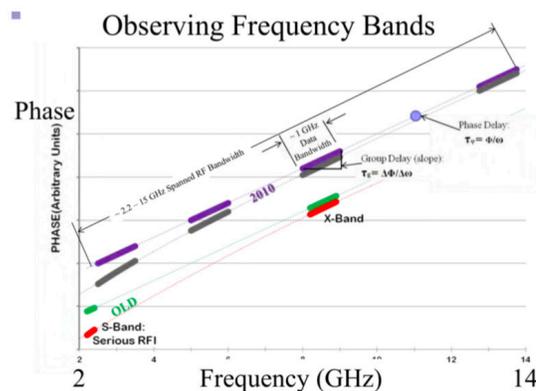


Figure 2 – One of the main current technological developments is the increase of the simultaneous observing bandwidth of receivers. The red and green lines show the situation until recently. The geodetic community has developed receivers with bandwidths of 1 GHz and above. The project BRAND, supported by the EC-H2020 funded project RadioNet is developing one single receiver which covers the full range 1.4-14 GHz.

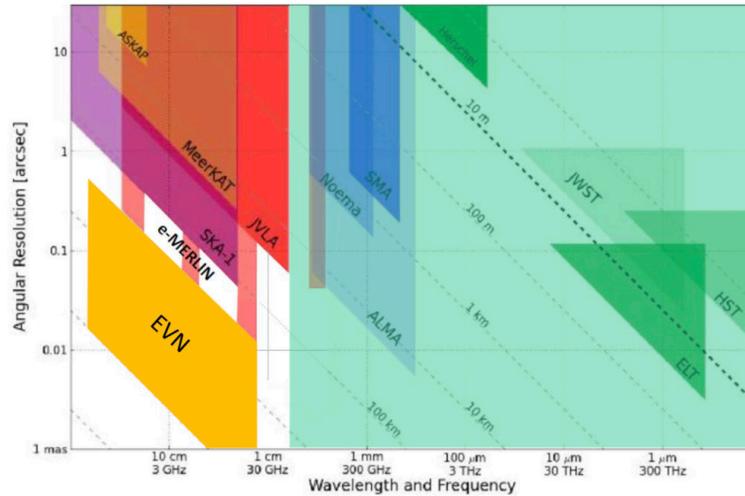


Figure 3 – This plot (courtesy of R. Beswick) shows the location of the EVN in a frequency-angular resolution plane where the major ground- and space-based facilities out to the optical regime are shown. This image clearly shows that the EVN is the natural extension to higher angular resolutions of the SKA1 and its precursors above 1 GHz.

2. The European VLBI Network

2.1. EVN Bodies

While phased arrays (VLA, WSRT, ATCA, and more recently MeerKAT and ASKAP) and the Very Long Baseline Array (VLBA) have been designed and built under a single individual project, consist of identical antennas, and are centrally managed, the European VLBI Network (EVN) is a more heterogeneous array, where antennas belonging to national institutions commit part of their observing time to coordinated observing runs. The EVN is thus a consortium which includes full member Institutes and affiliated members, depending on the level of commitment, whose role is regulated by a Memorandum of Understanding. The member institutes of the EVN are not just European, but include China, Puerto Rico and South Africa.

A basic requirement of the EVN is that the full and affiliated members share a common development plan and fulfill the commitments agreed upon. To ensure successful operations and outstanding scientific outcome, the EVN has three main bodies:

- the EVN Consortium Board of Directors (EVN CBD) – it includes Directors of all Institutes (full members and affiliates). The EVN CBD ensures that the array delivers the best science possible, and to this aim it formulates decisions on the technological developments, on the expansion of the array and on the operations. The EVN CBD supports and fosters global relations with representatives of other arrays, such as the VLBA, the KVN (Korean VLBI Array), the KaVa (Korean and VERA Arrays), RadioAstron, and more recently the AVN (African VLBI Network). These days, the EVN CBD is working on the concept of a Global VLBI Array, which includes all the VLBI arrays on Earth, with the goal to maximize the scientific exploitation of the VLBI developments and potentials. The EVN CBD meets face-to-face twice in a year. The CBD elects a Chair and vice-Chair who serve the Board for two years;

- the Technical Operational Group (TOG) – it includes the technologists leading the development at each site, as well as the “VLBIfriends”, i.e. the staff involved in the logistics and operations of the observations. The TOG ensures that the technological development endorsed by the EVN CBD is carried out at each station. The TOG is also in the position to make proposals as how to carry out the development itself. The TOG meets face-to-face twice in a year. The EVN CBD nominates the TOG Chair and vice-chair, who serve the community for two years.
- the EVN Programme Committee (EVN PC) – it has the role to evaluate and grade the requests for observing time with the EVN, on the basis of their scientific merit and feasibility. It includes one representative science expert from each full member Institute, external experts (not necessarily VLBI experts), the EVN scheduler, the Bonn Correlator representative, the JIVE Correlator representative. The EVN releases three Announcements of Opportunity each year, and the EVN PC meets face-to-face afterwards for the proposal evaluation. The EVN PC Chair is nominated by the CBD, and serves the EVN PC for three years.

Parallel and complementary to the EVN Consortium is the Joint Institute for VLBI-ERIC (JIVE), whose purpose is multifold. In particular, JIVE:

- develops and runs the EVN correlator (located at JIVE/ASTRON, Dwingeloo);
- provides extensive users’ support at all stages of the observations, from the proposal submission to the preparation of the observing files to the data analysis. A number of support scientists and operators are funded through the European Community and national fundings from members of the JIV-ERIC, to ensure access to VLBI observations and data analysis to the broadest possible community;
- plays a very active role in the expansion of the array, in the effort to include new antennas/member Institutes;
- plays a very active role in promoting and advertising the EVN science, to increase the awareness of the VLBI potentials within and outside the astronomical community at large.

As a matter of fact, the community of VLBI users and the overall outstanding quality of the VLBI science have increased enormously thanks to JIVE.

2.2.EVN Operations and observing time

The European VLBI Network regularly operates at 1.4-1.6 GHz (18-21 cm), 5 GHz (6 cm), 6 GHz (5 cm), 22 GHz (1.3 cm) and less frequently and with a subset of antennas at 43 GHz (7 mm). Observing disk-based sessions of the duration of roughly 3 weeks are offered three times per year in the periods February-March, May-June, October-November. In addition, continuous 24 hours are offered once a month in eVLBI mode (i.e. instantaneous transmission of the recorded signal to the EVN correlator at JIVE through optical fiber link connection). ToO observations, on trigger observations and out-of-session observations are also evaluated and considered for observations by the EVN Programme Committee. All in all, each antenna in the array commits on average 80 days every year to VLBI observations.

It should be noted that the commitment of each antenna to VLBI observations may be larger than this. The two antennas in Medicina and Noto are involved in collaborations with other arrays, in particular: (a) they are part of the ground-based array of the RadioAstron operations; (b) they observe with the Korean VLBI Network for scientific projects which are part of an established fruitful scientific collaboration between Italy and South Korea; (c) they are part of the geodesy network and hence participate in a large number of the geodetic campaigns (CORE experiments, for instance). The average number of observing hours the two antennas dedicate to VLBI operations amounts to about 120 days/year, including the overhead for each experiment (time to set up and prepare the observing run).

2.3. Community meetings and reports

The scientific EVN/VLBI community meets every two years on the occasion of the **EVN Symposia**. These are meetings which cover a full week, where EVN users present their results. The EVN Symposia include the VLBI Users' Meeting, a half day session where users have a chance to provide feedback to the EVN bodies on performances, needs, weaknesses of the array.

The web page <http://www.evlbi.org/meetings/meetings.html> provides information and links to all the EVN Symposia carried out so far and to the conference proceedings.

The technological community meets with the same biennial cadence in the **VLBI Technology Workshops** to present the state-of-the-art of the technology and discuss prospects and developments.

Each Chair of the EVN CBD has the responsibility to ensure that an EVN Biennial report is prepared and distributed. The most recent can be downloaded from the EVN web page:

<http://www.evlbi.org/publications/publications.html> .

3. Users' community and statistical indicators

On one hand it is true that the number of VLBI experts and users has been a small fraction of the radio astronomical community, due to the complexity of the operations and data analysis, and to the long time gap between the observations and data correlation in the decades 1990 – 2000.

On the other it is time to revise this view. A number of prejudices concerning VLBI, such as for instance limited science coverage and number of proposals and low publication rate, are not supported by the numbers. It should be kept in mind that the EVN is not a full time array, as it works for a total of about 10 weeks/year. This must be taken into account in any statistical analysis.

3.1. Observing time

In Sect. 2.2 it has been pointed out that the EVN is not a full time array. The following plots aim at providing an overview of the EVN commitment in terms of observing time, and how the Italian antennas compare with the average of the array.

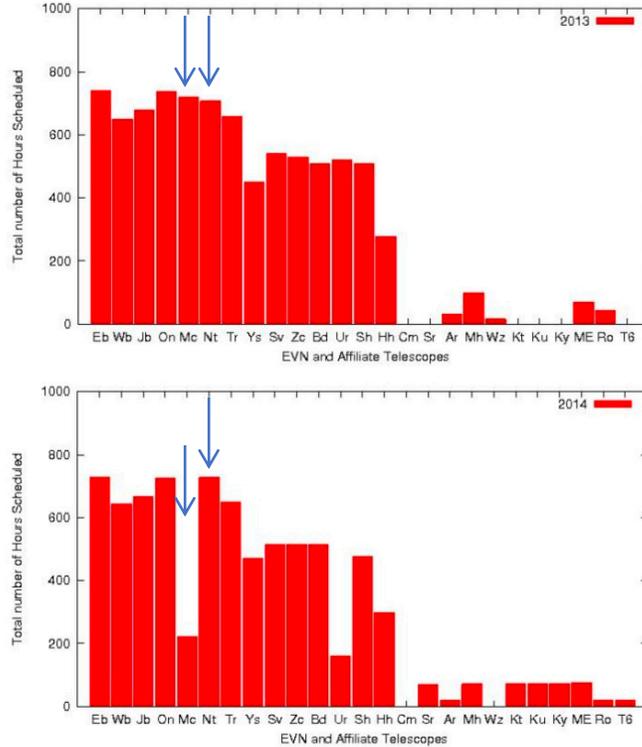


Figure 4 - The plots show the number of hours for each EVN antenna for the years 2013-2014. The antenna labels are as follows: Eb=Effelsberg; Wb=Westerbork; Jb=Lovell; On=Onsala; Mc=Medicina; Nt=Noto; Tr=Torun; Ys=Yebes; Sv=Svetloe; Zc=Zelenchuskaya; Bd=Badary; Ur=Urumqi; Sh=Shanghai; Hh=Harteebestoek; Cm=Cambridge; Sr=Sardinia Radio Telescope; Ar=Arecibo; Mh=Metsahovi.

The pictures are taken from the EVN biennial report 2013-2014. Note that Medicina has undergone major maintenance in 2014. The arrows show Medicina and Noto.

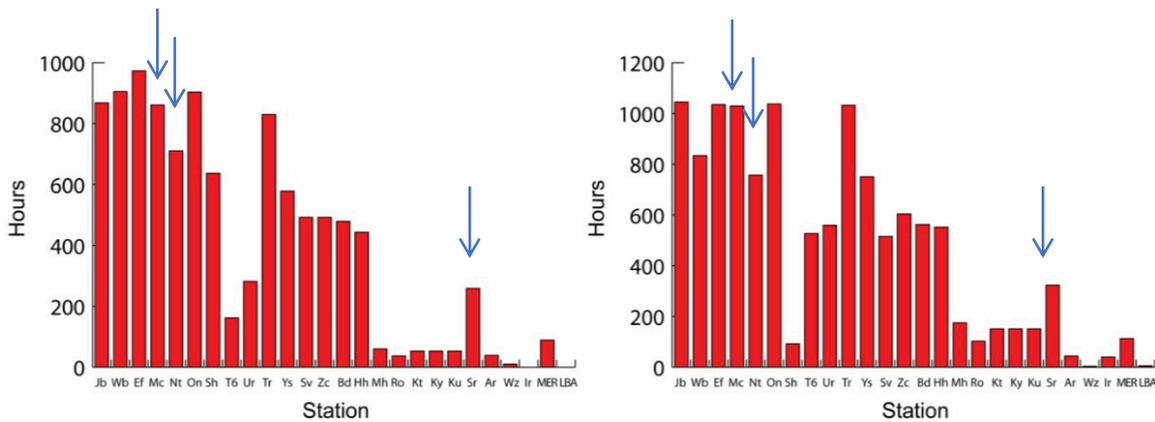


Figure 5 - The plots show the number of hours for each EVN antenna for the years 2015 (left) and 2016 (right). The pictures are taken from the EVN biennial report 2015-2016. The arrows show Medicina, Noto and SRT.

The two following plots show the trend of EVN hours in disk sessions and eEVN sessions over the period 2004-2016.

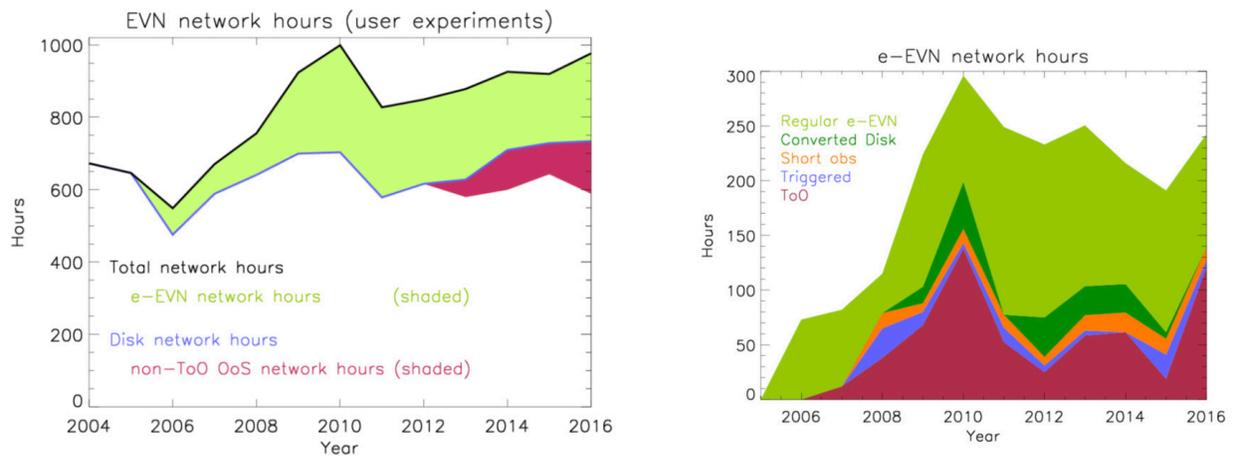


Figure 6 - Trend of the EVN hours in disk sessions over the period 2004-2016 (**left**) and in eEVN sessions over the period 2005-2016 (**right**). The pictures are taken from the EVN biennial report 2015-2016.

3.2.Science distribution in the EVN proposals

While traditionally limited to the study of radio emission from compact radio sources, as it will be detailed in the proper Section, the range of science addressed by the EVN is now extremely broad. This has been possible thanks to the major technological development which has involved the performances of the receivers (cooled, i.e. much better sensitivity), frequency coverage and bandwidth (which allows continuum and spectral line observing), frequency agility (which opens the door to spectral studies), number of radio telescopes in the array and potentials for very good coverage at the short spacings. The distribution of proposals per science category reflects the potentials of milliarcsecond observations at cm and sub-cm wavelengths. The trend of submitted proposals for each science category is given in Fig. 7.

The largest fraction of the proposals addresses science related to extragalactic compact objects. Stellar evolution is another key area of investigation for the EVN, both in terms of radio continuum as well as spectral line observing.

Over the past few years VLBI has turned out to provide essential information in the study of transient phenomena such as fast radio bursts and GRBs.

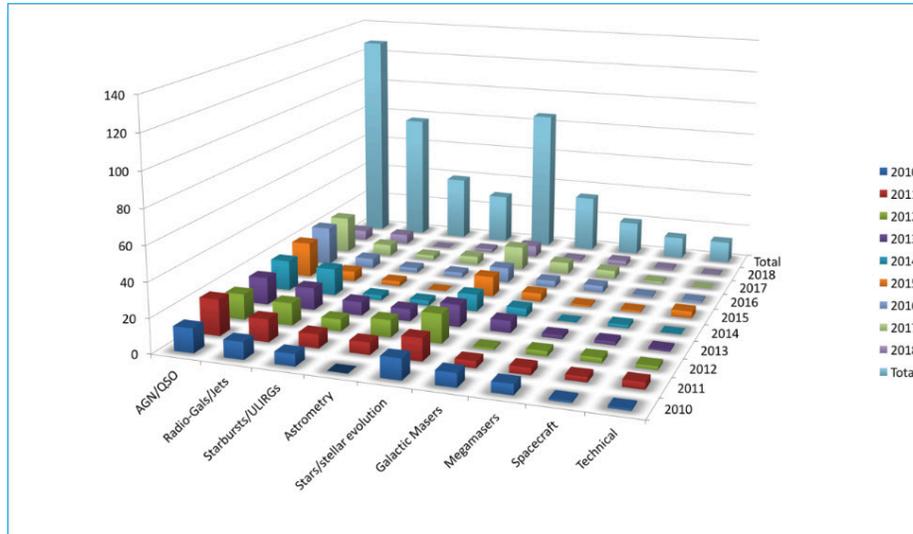


Figure 7 – Number of proposals submitted for different scientific categories from 2010 to the first EVN deadline in 2018 (Report of the EVN PC Chair at the CDB meeting in Shanghai, held on May 15th, 2018).

3.3.EVN Activity

Important estimators of the EVN activity are the number of proposals, the number of hours actually observed, and finally the total amount of TB recorded each session. Figure 8 shows the number of proposals for different categories over the years 2010-2016.

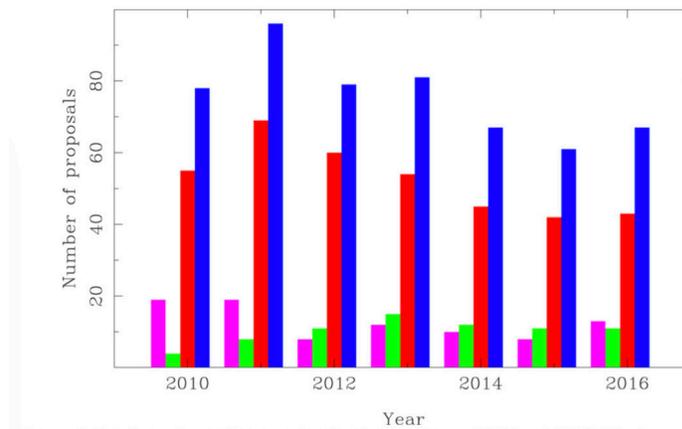


Figure 8 – Total number of proposals submitted to the EVN PC in the period 2010-2016. The colour code is as follows: blue=total; red=EVN alone; green=global; magenta=ToO+short observations (EVN Biennial report 2015-2016).

The number of submitted proposals considerably increased between 2006 and 2008 (such increase would be even more noticeable if the years 2000-2006 were plotted), and has remained at a level of about 70 proposals throughout 2016.

It should be noted that two more important evaluation parameters are the number of requested hours and the requested resources, i.e. the total amount of giga/terabites requested by the individual projects.

As a matter of fact, one of the main current limitation of the EVN is the disk space, which depends on recording bitrate and on the investment of each observatory in the disk pool. This is reflected in the left panel of Fig. 9, which clearly shows that the oversubscription rate is in the range 1.8-2.2.

For comparison, the Very Long Baseline Array (VLBA), which operates full time, receives roughly 80-85 proposals each year (the Global Millimetre VLBI Array proposals are not considered here, as the frequency is not comparable to the EVN frequency range), with an oversubscription factor ranging from 1.8 to 2 and estimated as in Figure 9, i.e. requested hours/scheduled hours (W. Brisken, private communication).

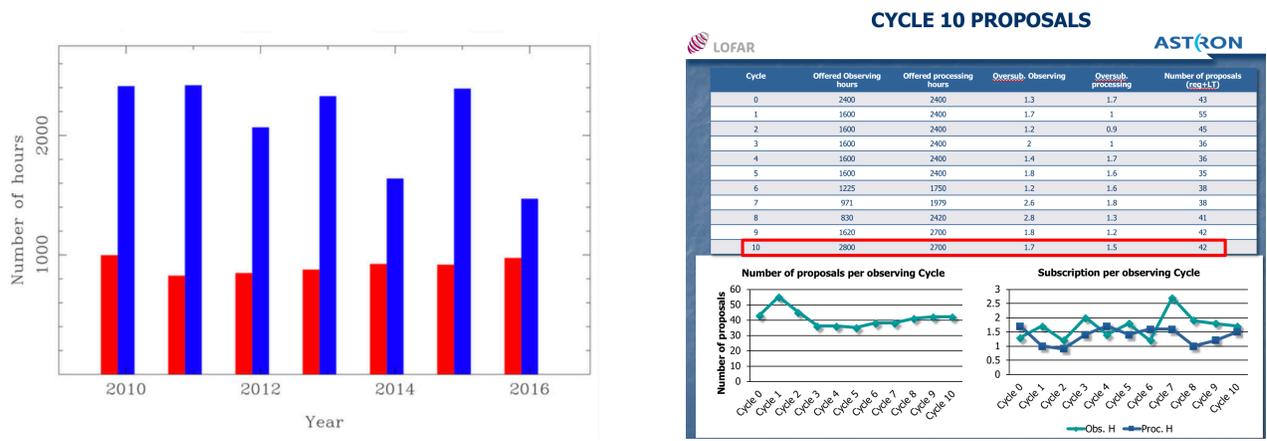


Figure 9 – Left - Requested hours and actual network hours in the period 2010-2016 (EVN Biennial report 2015-2016). Right – For comparison with the EVN, the number of proposals, number of offered vs requested hours and oversubscription factor throughout the 10 observing cycles of LOFAR.

The numbers for the EVN (efficiency, observing hours and number of proposals received) compare well with the same parameters for LOFAR, as clear from the right panel of Fig. 9.

3.4. Nationality of the PIs

A point which is relevant to all EVN member countries is the nationality of PI of each proposal. The plot which is shown in Fig. 10 covers the period 1999-2010. Note that the numbers include Institutions and Universities in each country, and Italy is very well positioned.

A similar plot has not been done after 2010, but the statistics is available. As a matter of fact the number of proposals with Italian PIs submitted during the regular Calls for Opportunity (i.e. no Targets of Opportunity are taken into account) in the period 2010-2017 is the highest among all countries: 58 Italian PIs.

Nationality of PI (1999-2010)

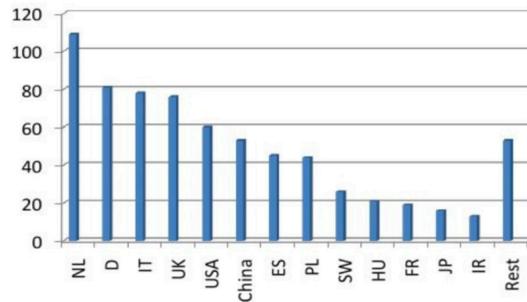


Fig. 10 – Distribution of the nationality of the PIs of EVN proposals (including ToO and other types of proposals) over the period 1999-2010 (EVN Biennial report 2009-2010).

For comparison the number of PIs of the EVN Institutes and main VLBI users are the following:

- 51 - Germany
- 49 – The Netherlands (including JIVE)
- 42 – China
- 34 – Spain
- 32 – Poland
- 31- UK
- 28 - USA
- 21 – Russia
- 16 – Sweden.

3.5.Publications

The ADS portal allows an easy access to the publication statistics for the EVN, and for the other existing arrays. While ALMA and the VLA cannot be comparison terms, it is interesting to see the trend for EVN observations compared for instance to the VLBA and other arrays. Once again, it is important to underline that the EVN is a “part-time array”. The amount of observing time the VLBA offers is roughly three times higher than the EVN.

Some plots for the period 2000-2018 (only the first 3 months) are shown in Figure 11.

It is interesting to compare this publication rate with full time open sky facilities, which operate at cm wavelengths, such as the Australia Telescope Compact Array (ATCA) and the Giant Metrewave Radio Telescope (GMRT), whose range of angular resolutions and frequencies clearly allows to address a much broader science range. This is shown in Figure 12. The statistics for Westerbork Synthesis Radio Telescope (WSRT) and LOFAR are shown in Figure 13. For the latter, the publication trend is still increasing.

The EVN publication is definitely not out of scale, if we consider all the caveats in terms of observing time offered and flexibly of the arrays sciencewise.

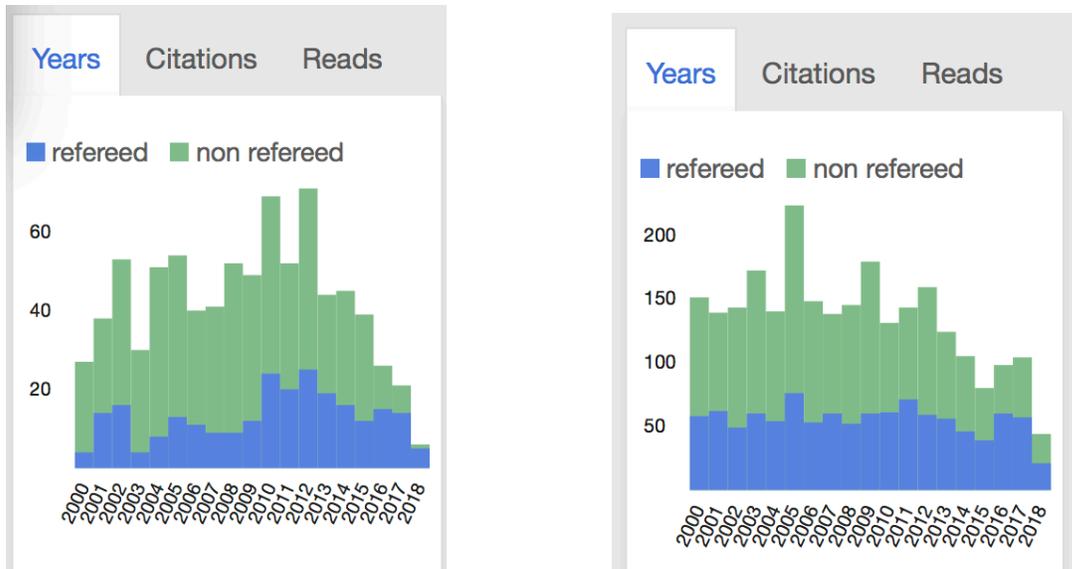


Fig. 11 – Numbers of publications for the **EVN (left)** and **VLBA (right)** in the period 2000 – March 2018. Note that the observing time offered by the VLBA is 3.5 times higher than that offered by the EVN. One of the noticeable differences is the trend: the VLBA publication rate is considerably more stable than that of the EVN, and this is mainly due to the fact that the VLBA is a steady instrument, and no major improvements have taken place in the period considered in this plot. The increase in the EVN trend after 2008 is closely related to the upgrade to eVLBI and to higher recording rates and to the addition of the QVASAR antennas, and it clearly shows the impact of the development and improvement in the array performances on the scientific outcome. The proceedings of the 13th EVN Symposium held in Saint Petersburg in 2016 have not been published yet, hence the lack of about 50 non refereed papers in recent years.

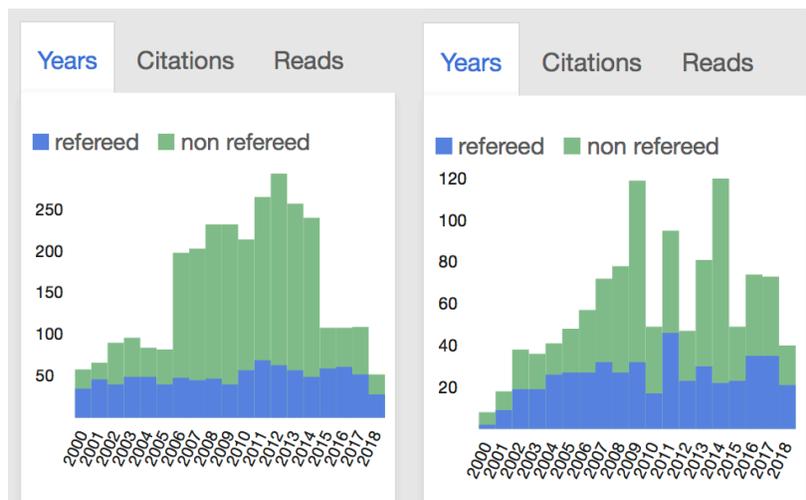


Fig. 12 – Same as Fig. 11 for **ATCA (left)**, and **GMRT (right)**. **WSRT (bottom left)** and **LOFAR (bottom right)**. ATCA started its operations in the early 90's, hence the stable distribution of the refereed papers, while GMRT started its operations at the very beginning of the 2000's. After a few years of increase the publication rate has become roughly stable around 2006.

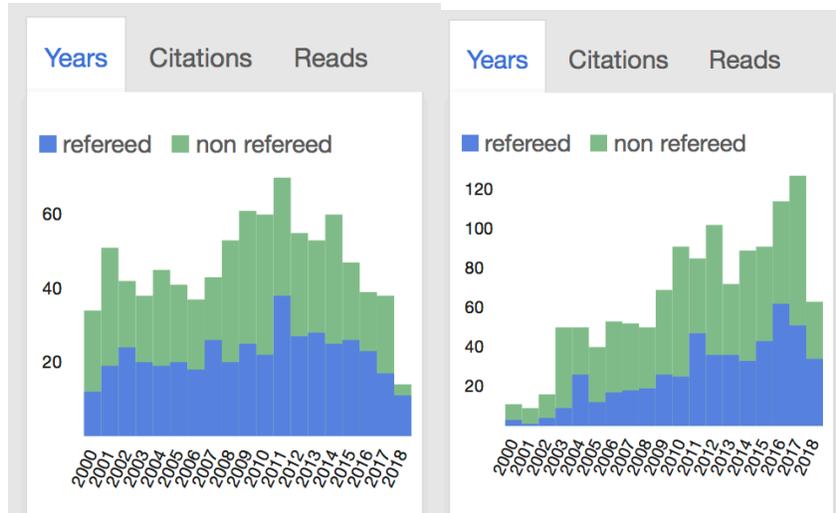


Fig. 13 – Same as Figs. 11 and 12 for **WSRT (left)** and **LOFAR (right)**. The trend of WSRT is slowly declining, as a consequence of the upgrade to APERTIF. The publication rate of LOFAR is still increasing, and has not reached its plateau yet.

4. Scientific prospects for the EVN and other global VLBI networks

Interesting overviews of the impact of VLBI in the 90's and of the 2000's can be found in the conference proceedings of the IAU symposium 129, *The impact of VLBI an astrophysics and geophysics* (Cambridge, MA, 1987), and of the conference *Future Directions in High Resolution Astronomy: The 10th Anniversary of the VLBA* (Socorro, NM, 2003).

Traditionally, the topics where VLBI has contributed most are (a) the study of compact radio sources and of compact cores of radio galaxies and quasars, (b) the study of stellar masers and star formation; (c) the study of the final stages of the stellar life cycles, such as supernova explosions, stellar binary systems, recurrent novae, (d) astrometry. More recently, VLBI has turned out to be essential in the study of GRB and their afterglows and of gravitational lenses.

Nowadays the range of science where VLBI can provide unique contribution has considerably expanded. A flavour of the renewed radio science case for the ngVLA was provided at the meeting *Astrophysical Frontiers in the Next Decade and Beyond: Planets, Galaxies, Black Holes and the Transient Universe* (Portland, OR, 2018).

The European VLBI community has started a similar effort, under the request of the EVN Consortium Board of Directors, and with the support of the EC-H2020 project JUMPING JIVE. A VLBI Science Vision Document for the next decade is in preparation (PI T. Venturi, co-Is Z. Paragi and M. Lindqvist), and the first steps have already shown that the scientific prospects for VLBI are extremely exciting. Two meetings have been held in 2018: a f2f meeting in Zaandam (NL), and a Special Session at EWASS 2018, SS11 *Exploring the Universe: a European vision for the future of VLBI*. The presentations for both meetings are accessible on web respectively at:

http://www.jive.eu/jumpingjive/doku.php?id=vlbi_future:meetings:280218#meeting%20location_and_accommodation

and

http://www.jive.eu/jumpingjive/doku.php?id=vlbi_future:meetings:ewass18.

In the following I will provide a preview of the science topics the document will address, focussing on the novel areas which will benefit from the unique contribution of VLBI and on the synergies with future telescopes, radio telescopes and space missions.

4.1. Cosmology

Two of the most important questions of astrophysics these days (not just cosmology) are the **nature of dark energy and dark matter**, and the answer to those is one of the main goals of future missions and projects, such as of instance LSST and *Euclid*. VLBI can play a major role in addressing this question, providing a competitive and independent technique.

So far very weak constraints exist on the cosmological parameter w , whose uncertain estimate is based on low redshift measurements. Observations of cosmological masers can provide much stronger constraints to w . VLBI observations are necessary to observe objects at redshifts > 0.1 with the required sensitivity and angular resolution.

Another important application of VLBI in this context comes from the measurements of quasar time-delays, coupled with lens models. The best estimates available so far come from the optical band, which however is limited to angular resolutions of the order of ≈ 60 -100 mas (HST and Keck monitoring), and VLBI can improve the angular resolution by at least one order of magnitude.

The impact of VLBI in dark matter studies is enormous. The angular resolution of VLBI allows to cover the parameter space of 10^6 - 10^7 for $M_{\text{sub-halo}}$. Figure 14 (courtesy of J. McKean and C. Spingola) clarifies this.

The search for gravitational lenses is one of the key areas of scientific investment for SKA1-MID. However, full success of this project will be granted only if coupled with the angular resolution provided by VLBI, to single out false positives. At the same time, such follow-up will be possible only in wide-field VLBI survey mode. This is one of the most important developments in the VLBI technological roadmap. Proofs of concepts have been successfully carried out (Middleberg et al., 2013) and more are in progress (Spingola, McKean et al.).

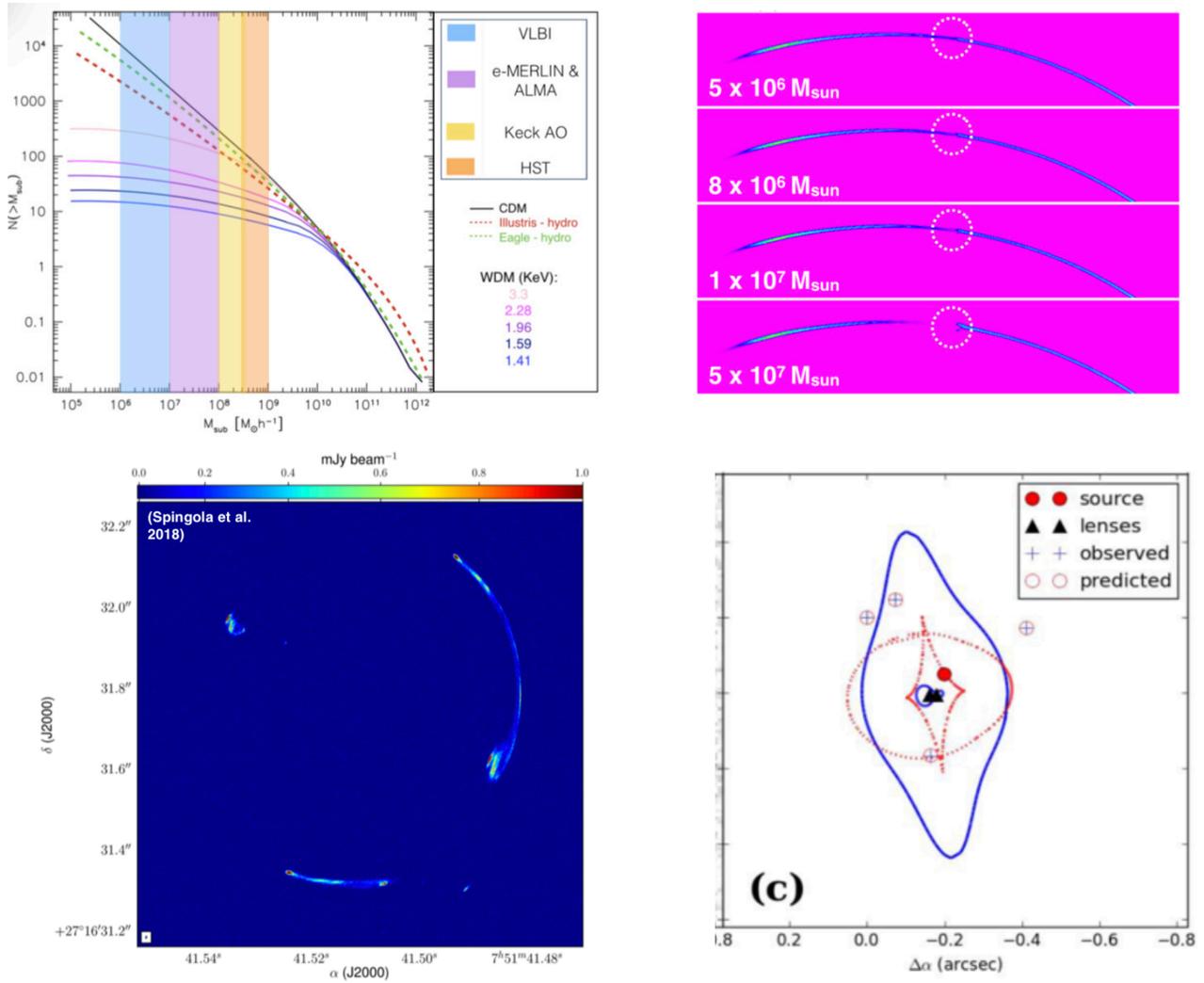


Fig. 14 – **Top left** – Range of mass of dark matter halos which different instruments are sensitive to. VLBI explores the unprecedented range of masses 10^6 - $10^7 M_{\text{sun}}$. **Top right** – Appearance of the gravitational arcs as a function of the lensing mass. **Bottom left** – This image is one of the top quality images of the EVN, and shows that these results are reachable already these days (Spingola, presentation at SS11 – EWASS 2018). **Bottom right** – The plot shows the current level of accuracy between predictions and observations in the position of the lensed images for B1555+375 (Hsueh et al. 2016).

4.2. Black holes, star formation, AGN activity and their evolution over cosmic time

The study of the growth of supermassive black holes and of galaxy/BH coevolution, and the history of star formation in the Universe, are the key points in our understanding of the evolution of the Universe. The radio band and VLBI in particular can provide key observables, partly because of the detectability of the obscured X-ray AGN, and partly because only VLBI has the sensitivity and angular resolution necessary to disentangle the contribution of AGN and star formation in the very faint end of the radio source counts, i.e. the sub-mJy/nano-Jy population, where objects at cosmological redshift are located (see Figure 15). Moreover, the radio quiet population of AGN largely dominates the radio luminosity function out to redshift $z \approx 7$, and for the study of the cosmological evolution of black holes it is

mandatory to separate the radio quiet population in the two classes “star-forming galaxies” and “weak radio AGN” (see Figure. 16).

At the same time, VLBI has the unique role to address the physics of AGN, to derive the intrinsic parameters of AGN jets and complement the information provided by arcsecond resolution arrays in addressing the question of AGN feedback, a key aspect of the BH-AGN/galaxy growth Figure 17).

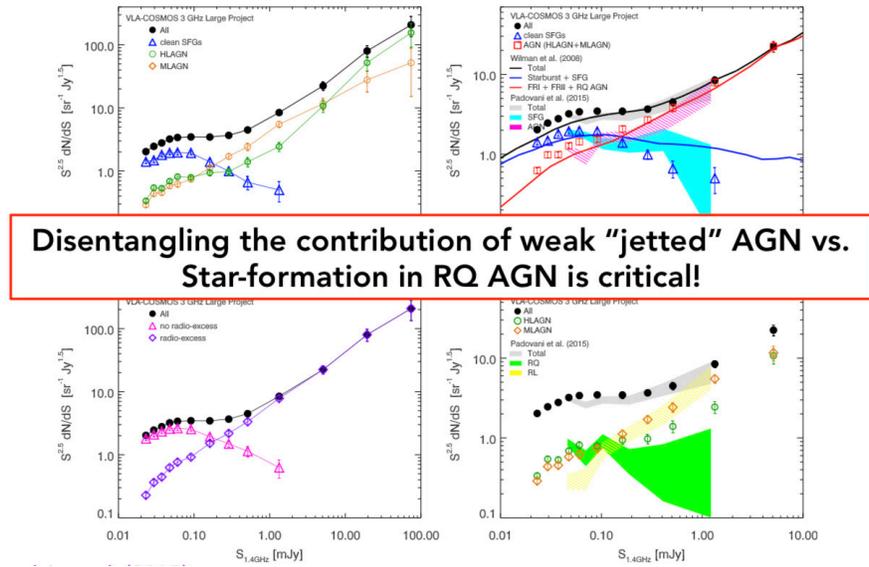


Fig. 15 – Slide presented by Merloni at SS11 at EWASS 2018, adapted from Smolcic et al. (2017).

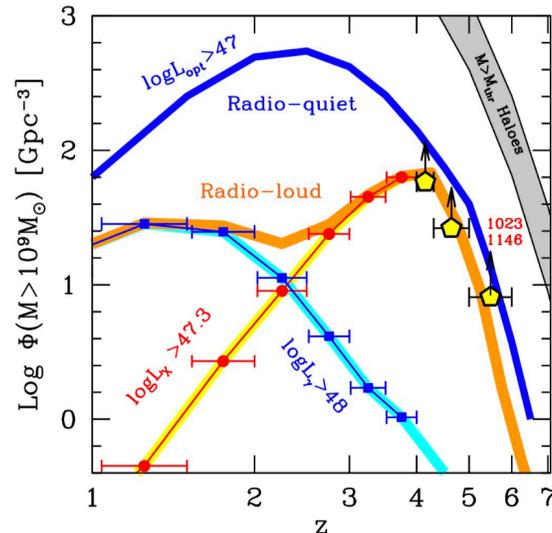


Fig. 16 – Slide presented by Sbarrato at SS11 at EWASS 2018, where the luminosity function vs redshift of different classes of sources is shown.

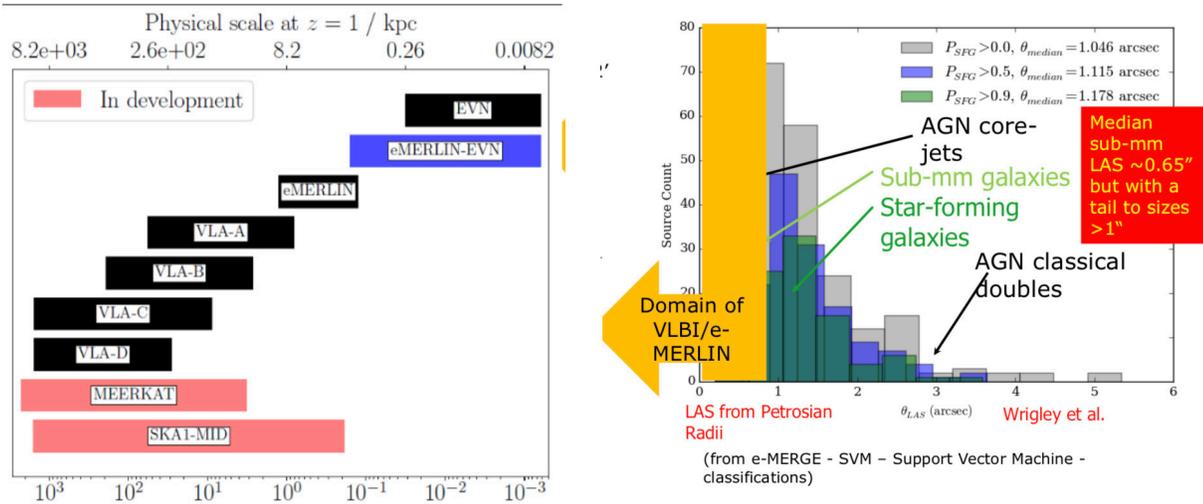


Fig. 17 – **Left** – Angular resolutions and physical scales for different radio interferometers. **Right** – Typical angular scales of different classes of radio sources (From Beswick, f2f meeting in Zaandam).

Direct imaging of very faint sources is the best way to separate the AGN and star formation components. This requires an excellent u-v coverage and a very broad range of angular scales, which are already offered thanks to the combination of arcsec to subarcsec resolution arrays (such as VLA and eMERLIN) with the EVN.

Last but not least, the feasibility of efficient milliarcsecond scale imaging of the sub-mJy population strongly depends on the availability of wide-field VLBI, as it has already been demonstrated by the Jodrell Bank group (Figure 18).

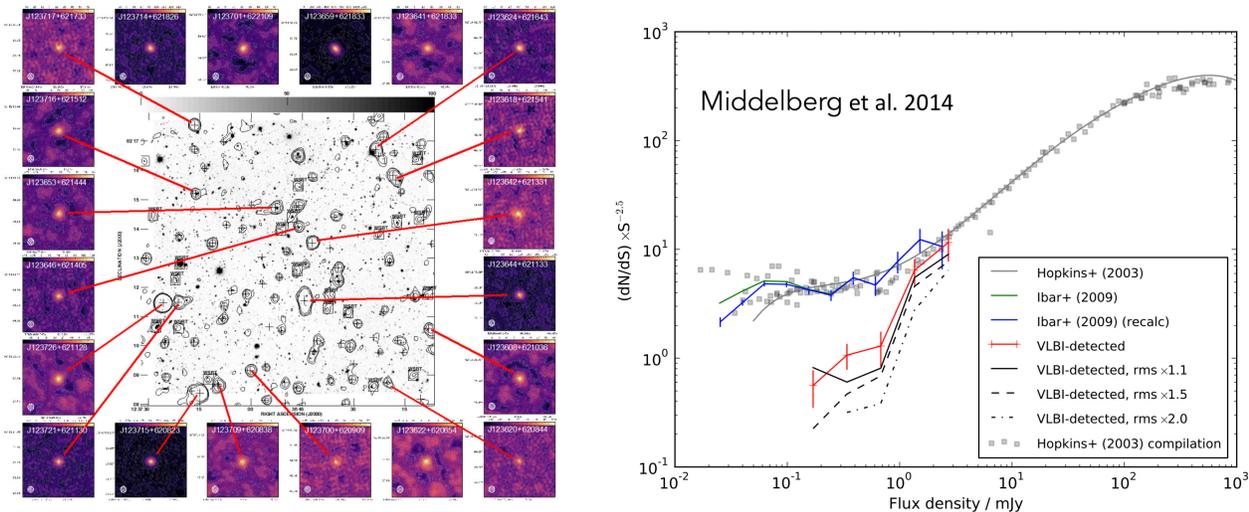


Fig. 18 – From the presentation of Merloni (SS11, EWASS 2018) – **Left** – Wide-field VLBI imaging of the HDF North (Radcliffe, Garrett et al. 2016). **Right** – The plots shows the key role of VLBI in identifying the AGN contribution to the sub-mJy population.

4.3. The transient Universe

This title actually covers a very broad range of phenomena, whose common line is their very short temporal duration, but whose origin may be completely different. This area includes the novel detection of gravitational waves, recent discoveries such as Fast Radio Bursts (FRBs), relatively new classes of phenomena, such as Gamma-Ray Bursts (GRBs), and the classical transient sources such as X-ray binary stars, supernovae and blazars. Transients can hence be galactic objects (such as for instance stellar novae) as well as objects at cosmological distances (such as GRBs). Each of those occupies a very different part of the parameter space frequency-luminosity, as shown in Figure 19.

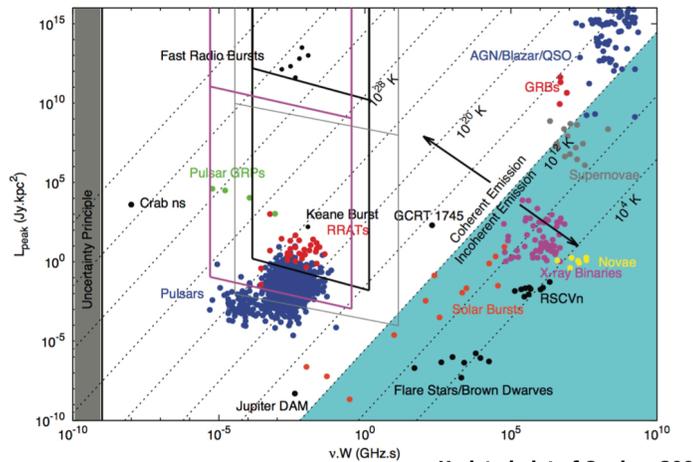


Fig. 19 – Location of the different classes of transient sources in the frequency-luminosity space (presentation by Perez-Torres, adapted from Cordes et al. 2004).

For each class of transient sources, VLBI has the unique capability to: (a) locate the source of emission with μs (microarcsecond) precision and accuracy; (b) image the target with simultaneous milliarcsecond resolution and large field of view; (c) provide ultra-high sensitivity, which is needed both to image very faint targets and to image diffuse emission on the VLBI scale. Here I will very briefly report only on the most outstanding results obtained by means of VLBI observations.

The study of **Fast Radio Bursts** (FRBs) is one of the area where VLBI has provided a major contribution, thanks to the possibility to localize the source. The nature of these events is still unclear and the statistics is still very poor. Hence, their localization is the first crucial step to understand their nature. Figure 20 shows a recent EVN localization of a FRB.

The study of the counterpart associated with **GW170817** is benefitting most from VLBI. A number of projects are presently ongoing in Europe (under the leadership of Giancarlo Ghirlanda, INAF-OA Brera) and in the US (VLBI monitoring) and milliarcsecond flux density measurements and imaging will provide crucial information to discriminate among different models for the ejection (jet, cocoon) and its velocity (see Figure 21).

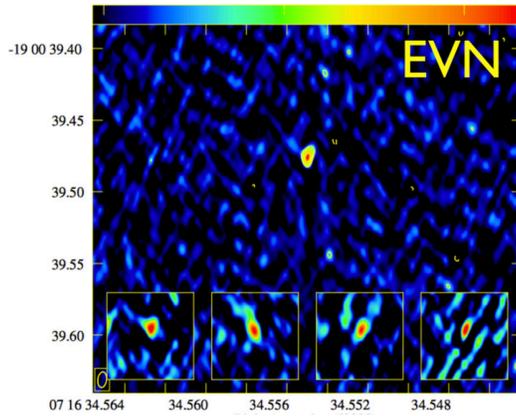


Fig. 20 – Discovery of a variable steady source associated with FRB 150418 (Giroletti et al. 2016).

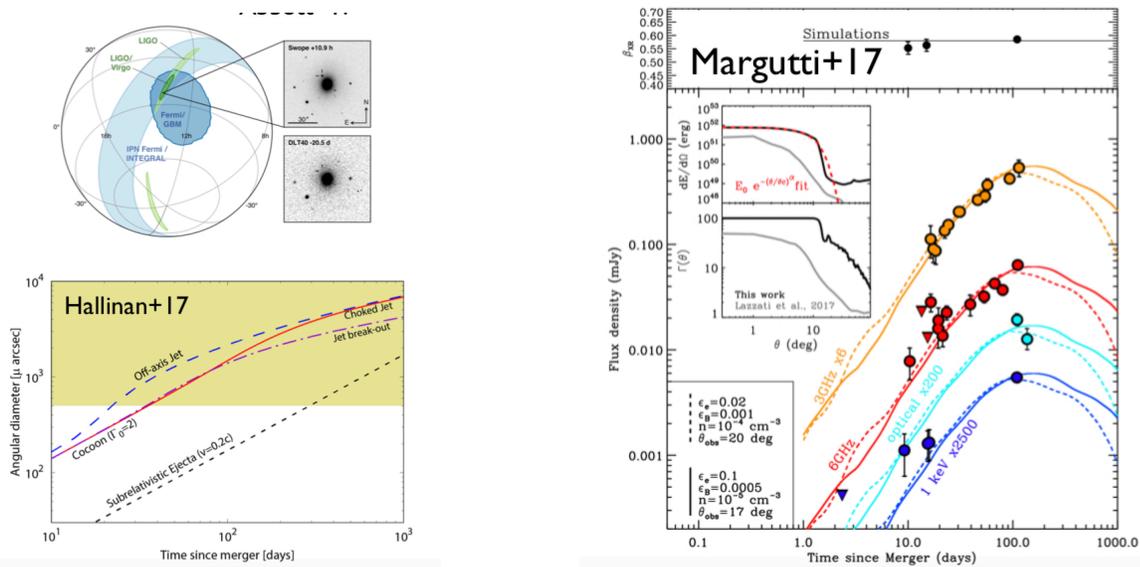


Fig. 21 – Only VLBI imaging and flux density measurements can probe the type of emission, and discriminate between different models for the ejecta and their velocity. (Presentation by Perez-Torres in Zaandam).

The contribution of VLBI to the study of **Gamma-Ray Bursts** is well established and several papers have been published with EVN and VLBI studies of the afterglows. Very recently EVN observations have been successfully used to study the outflow, to discriminate among possible components and to derive information on the external medium where the outflow propagates (Nappo et al. 2017, see Figure 22).

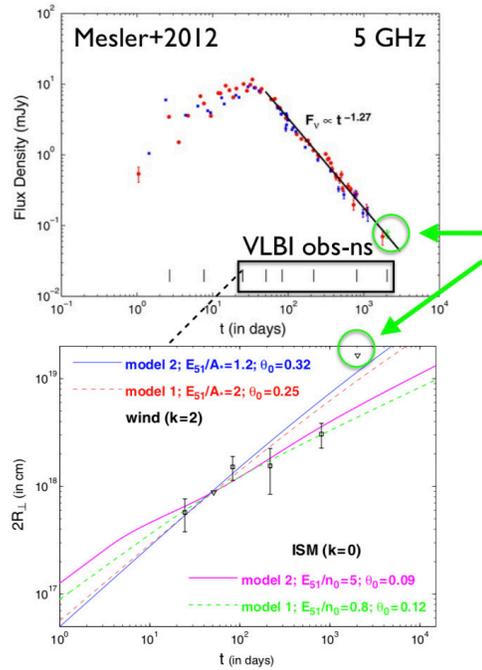
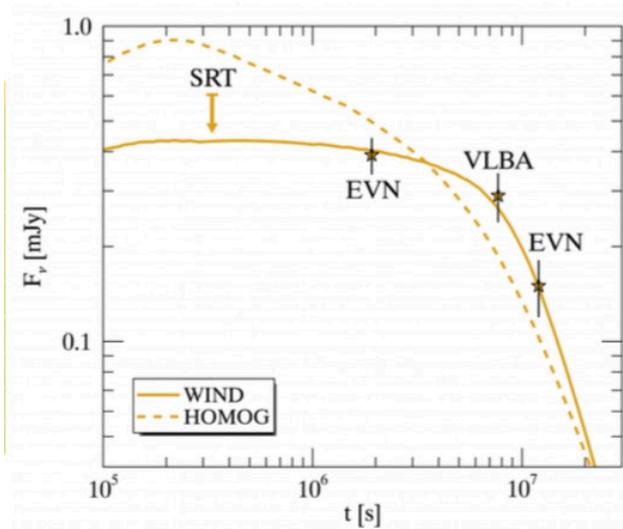


Fig. 22 – *Left* – Radio light curve of the afterglow of GRB151027A, with different expectations from models superposed (Nappo et al. 2017). *Right* – So far best radio study of GRB (GRB 030329). The green arrows show the VLBI detection, 5.5 years after the explosion, and their crucial role in discriminating among the possible models (Presentation by Perez-Torres in Zaandam).

Another exciting class of phenomena whose nature and origin can be clarified by VLBI is that of **Tidal Disruption Events (TDE)**. These sudden outbursts of emission in galaxies are most likely the smoking guns of SMBH accretion caught in action. The very high angular resolution of VLBI provides invaluable information to the theory, and helps disentangling among different models of accretion.

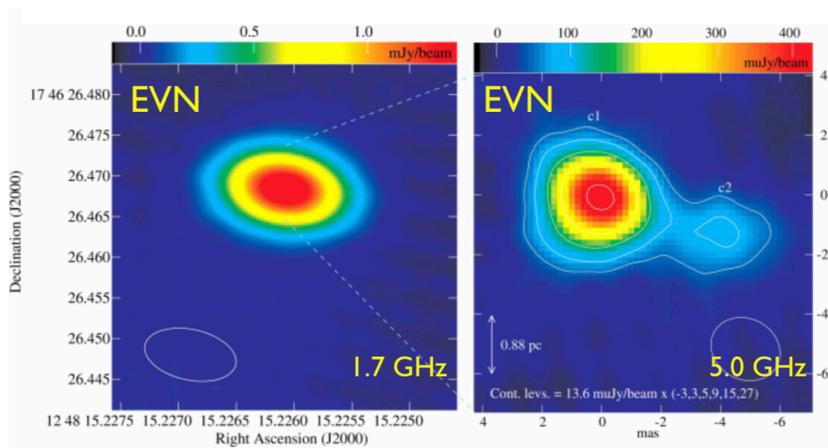


Fig. 23 – EVN color maps of ASASSN-14li at 1.7GHz (left) and 5.0GHz (right). The ellipses at the bottom of each panel correspond to their convolving beams (Romero-Canizales et al. 2016).

Supernovae explosions and their follow-up is one of the most successful areas of application of VLBI. The evolution of the supernovae explosions is known only for handful of objects, due to the fact that only very energetic events can be indeed observed long after the explosion, when their flux density decreases dramatically. The case of SN 1993J is unique. The SN explosion, expansion and now the remnant are being observed for 25 years, and this study has led to several Science and Nature papers from the two “competing”/“complementary” groups who have observed this object since the day of the explosion. Figure 24 (left panel) shows an impressive sequence of images.

Beyond the study of individual objects (which is possible only in exceptional cases), VLBI observations can separate AGN, **starburst** and **micoquasar** emission in nearby star-forming galaxies, such as the prototype cases of M82 and Arp299. Monitoring studies carried out with the EVN over the past 12 years have allowed to study the rate of supernova explosions in Arp299. This is relevant not only in itself but also to study the different types of supernovae (Type I and II), their progenitors and their rate, with obvious implications on the theory of stellar evolution.

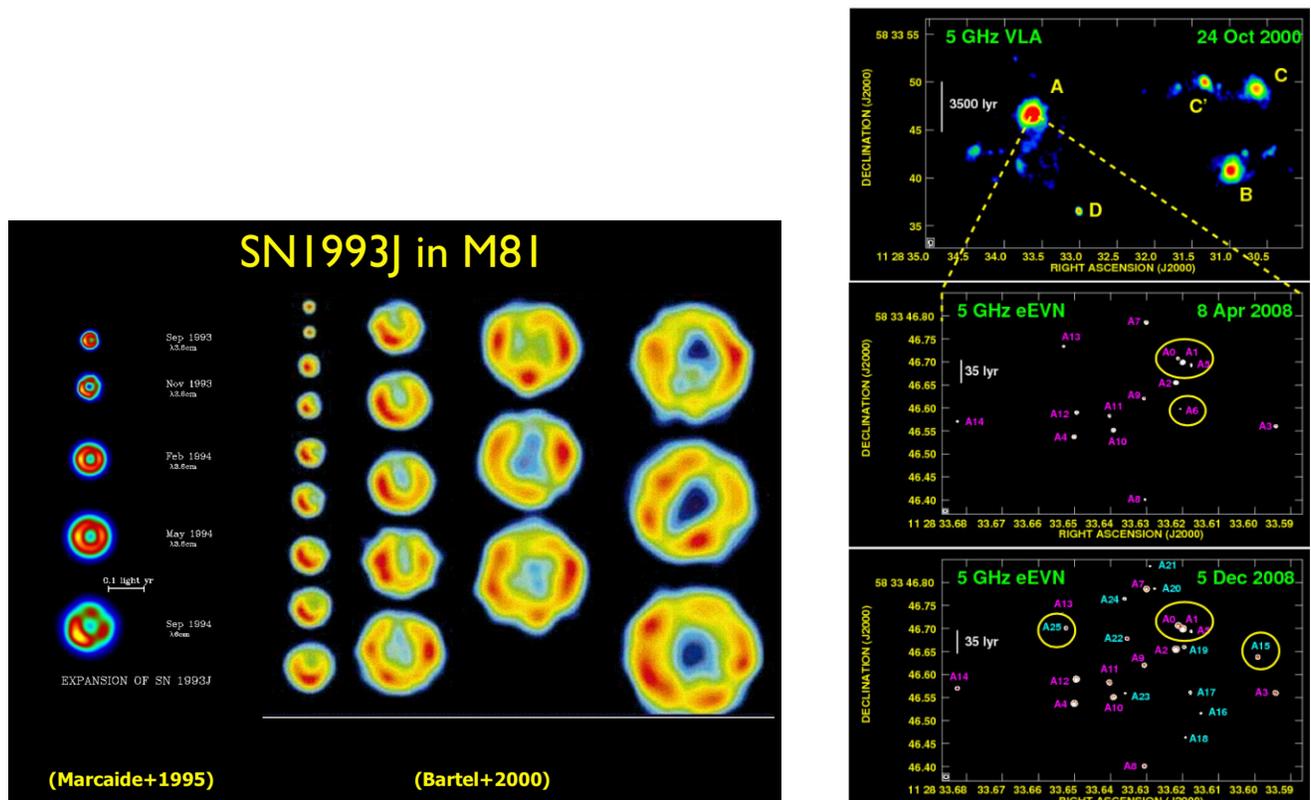


Fig. 24 – Left – SN1993J has been observed with the EVN and with the Global VLBI Network since its explosion at 22 GHz, 5 GHz and 1.6 GHz, selecting the observing frequency on the basis of the spectral evolution due to the expansion. The superb angular resolution of VLBI has allowed to study its expansion rate, and to infer information on the medium surrounding the radio emission. This amazing set of images has been presented by Perez-Torres in Zaandam. **Right** – Results of the EVN monitoring of Arp299 (Perez-Torres et al. 2009, Bondi et al. 2012), which led to the detection of around 30 supernovae, discriminating between core-collapse supernovae and Type II supernovae. An explosion rate ≥ 0.8 CCSN/yr was measured.

Bursts of radio emission in **stellar X-ray binaries** are characterized by bipolar outflows which are a downscaled version of the more powerful class of blazars. The time evolution of the latter is of the order of months/years, while that of X-ray binaries is of the order of days, which allows to perform real-time studies of the jet evolution. The key questions for the so-called microQSOs concern the speed of the jets and how the jets and the accretion flow couple. Only the angular resolution of VLBI can address these questions. Figure 25 shows the similarity in structure between a famous distant blazar, 3C120, and the microquasar GRS1915+105.

As a final remark on this class of studies, it is mandatory to stress that only the precision accuracy of VLBI allows the identification of transient sources in infrared (IRAS) galaxies. One recent case is that of IRAS 23436+5257, which showed a very luminous near-IR outburst, which would have never been localized without VLBI.

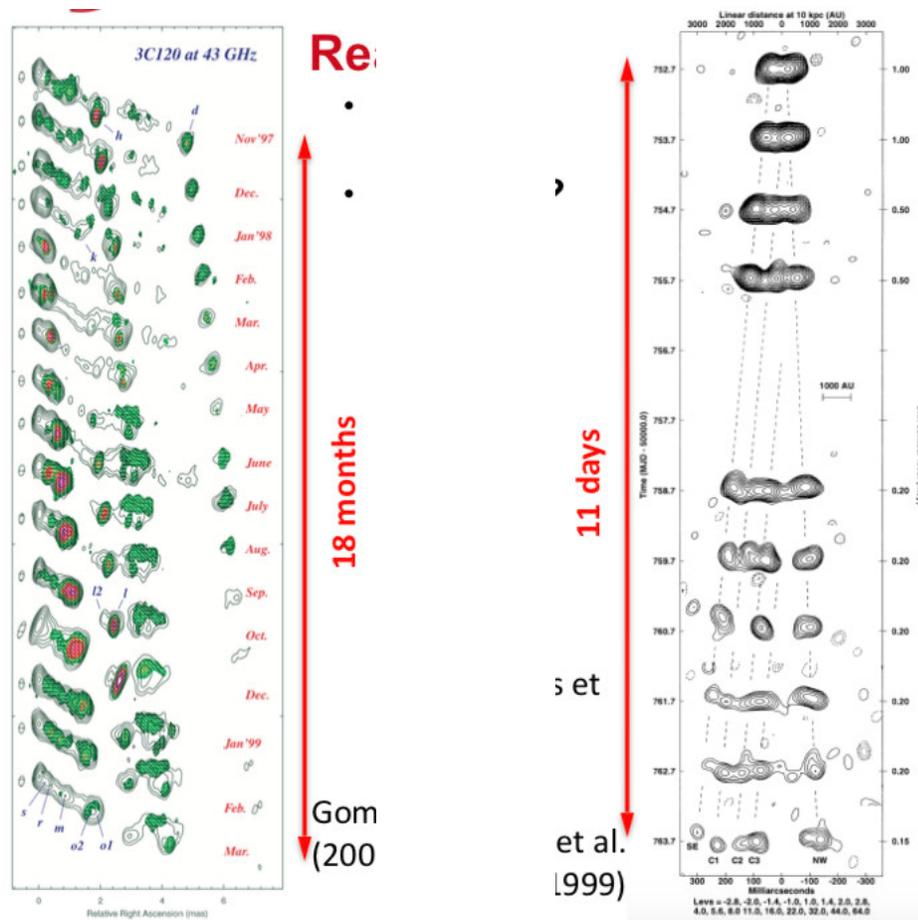


Fig. 25 – Example of two relativistic outflows. **Left** – Morphological evolution of 3C120, monitored on a timescale of 18 months (Gomez et al. 2001). **Right** – Evolution of the microQSO GRS 1915+105, monitored on a timescale of 11 days (Fender et al. 1999). Adapted from Perez-Torres, Zaandam.

4.4. Revived studies of powerful radio jets

The study of compact radio sources and of the central regions of radiogalaxies has been one of the areas where VLBI has contributed most. The discovery of superluminal radio sources (see the conference proceedings *Superluminal Radio Sources*, 1987, Cambridge University Press, Eds. Zensus & Pearson to appreciate the results, the enthusiasm and ongoing debate at the time), and the support to the unification model for AGN (Urry & Padovani, 1995, PASP 107, 803) through the work of several authors (most noticeably, Readhead, Wilkinson, Zensus, and in Italy Giovannini and Venturi) have been among the most important achievements of the extragalactic astrophysical community. Nevertheless, our knowledge of the inner jet regions of AGN and those in the proximity of the central engine remains very limited, and a number of questions related to the jet astrophysics and to the nature of the black holes remains unanswered. In particular, (a) the mechanisms behind the acceleration and deceleration of the radio flow along the jets, (b) the role played by the accretion disk and by the central black hole, (c) the strength, structure and role of the magnetic field in the proximity of the nuclear engine, and (d) the role of the accretion disk and of the non-thermal corona in the jet emission, are still open issues. Figure 26 is a schematic view of a radio loud AGN, as proposed by Blandford several years ago and still considered a working hypothesis.

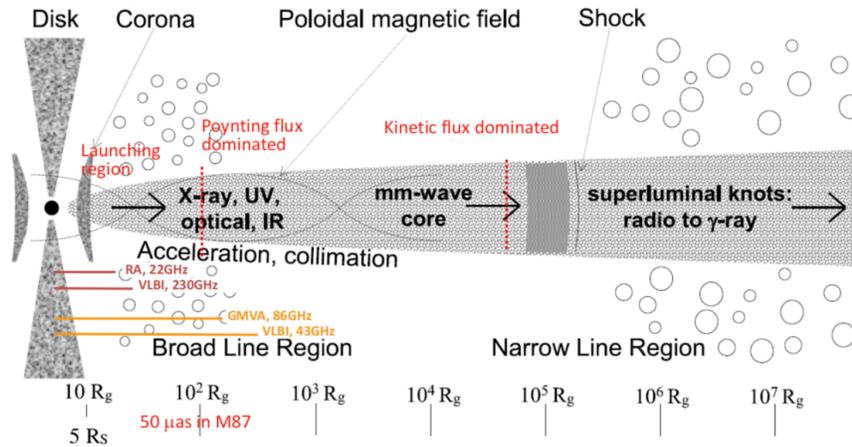


Fig. 26 – Schematic view of a radio loud AGN. The types of emission in the various parts of the jet and its environment, as well as the frequency where such emission manifests itself, are indicated. (Slide from Lobanov, Zaandam).

The figure clearly shows where the potentials of VLBI lies. To approach the launching region, a considerable step in increasing the angular resolution is needed, and this is nowadays possible increasing the observing frequency throughout 100 GHz, and beyond. As a matter of fact, this science area would best benefit from an upgrade of as many EVN antennas as possible at the three frequencies 22/43/86 GHz with a tri-band receiver, which would allow a very accurate correction of the phases through phase-solution transfer from the lower to the higher frequencies of the receiver.

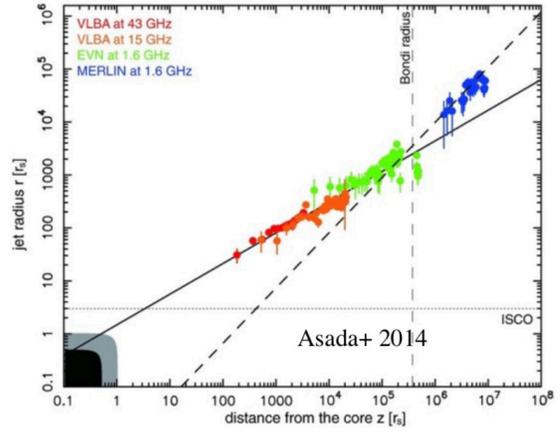
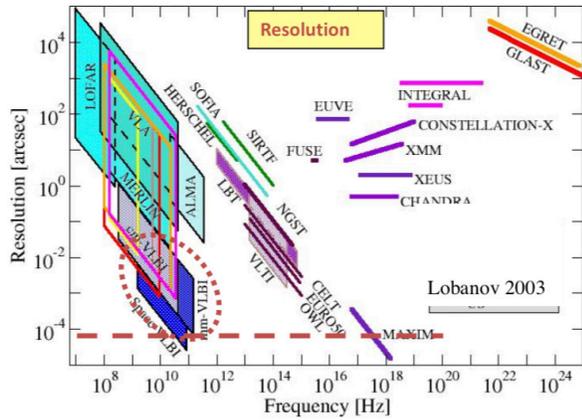


Fig. 27 – Left – Frequency-Resolution plane for a number of observing facilities, from the γ -ray regime down to radio frequencies. **Right** – The plot shows the trend of the jet radius in Cygnus-A above and below the Bondi radius. The mm-VLBI observations are crucial to access the non-linearity of the trend.

Figure 27 shows the domain of mm-VLBI in the frequency-resolution plane of a number of observing facilities and observatories (left panel), as well as the relevance of high frequency measurements in the study of the opening angle and how it varies at decreasing radius distance from the core region (right panel).

4.5. Stellar masers, stellar radio continuum and planetary systems

The study of the early stages of star formation is one of the key areas for VLBI science for two main reasons: the study of the kinematics of masers in the early stages of star formation is one of the most important parameters to study how stars form; at the same time, maser astrometry is crucial for astrometry, i.e. proper motions and parallaxes.

Water and more complex masers (such as methanol), are excellent tracers of high-mass star formation, and allow to address several important questions, such as the kinematics of accretion disks, and the study of accretion bursts. Maser monitoring is essential for almost all maser studies, hence such field requires considerable observing resources. Figure 28 shows two examples of such studies, and clearly show the need for long time baselines.

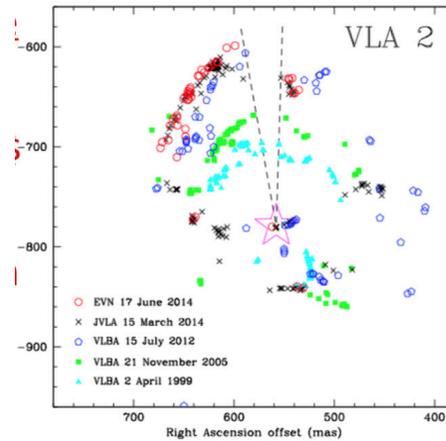
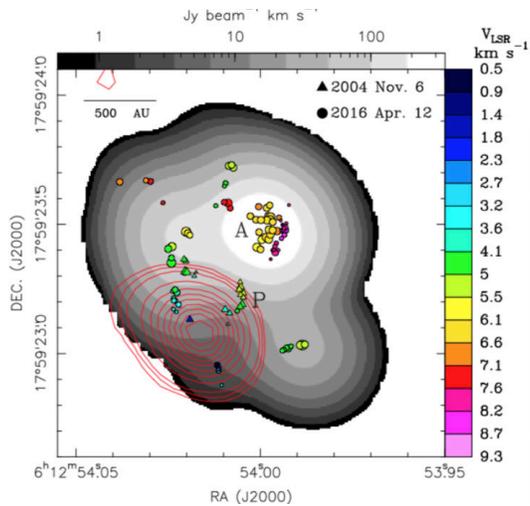


Fig. 28 – Left – Evolving water maser structure in W75 (Surcis et al. 2014). **Right** – Accretion burst in S255 (Moscadelli et al. 2017). Images adapted from Bartkiewicz, Zaandam.

The role of magnetic fields during the outbursts in the early stages of star formation is largely unknown, and only VLBI has the resolving power to improve our knowledge. Masers are mainly concentrated on the Galactic plane, hence the need to improve the u-v coverage in the North-South direction. For this reason one of the most urgent requests of the maser community is the development of the AVN, and its connection with the EVN, which will considerably increase the image fidelity at low declinations. I wish to underline that the Italian community is very active in this area, and the Italian work is a reference worldwide.

Another important application of the study of water, methanol and SiO masers is that of astrometry, i.e. masers parallaxes are used to derive the structure of the Milky Way. The extremely successful project BeSSeL (Bar and Spiral Structure Legacy Survey, PIs. Reid and Brunthaler, with a consistent Italian participation) has unveiled the details of the spiral arms of the Milky Way (see Figure 29).

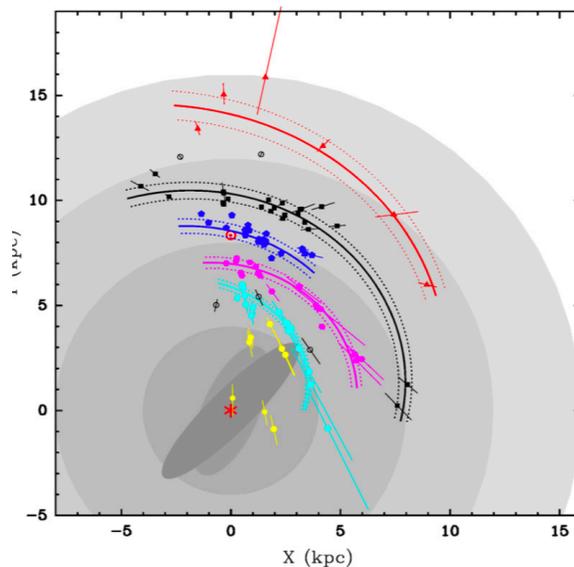
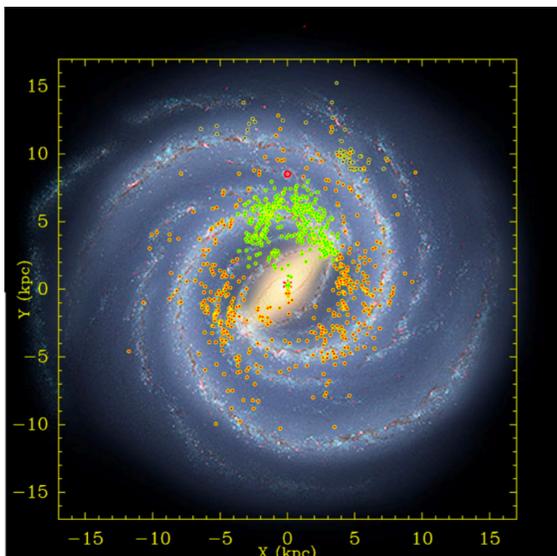


Fig. 29 – Left – Coverage of the BeSSeL survey. **Right** – Distribution of masers and their velocity in the Spiral Arms of the Milky Way. Images adapted from the presentation of Brunthaler at EWASS 2018.

Finally, the VLBI maser database has been used to complement the astrometric information from Gaia, especially in the Galactic plane, as VLBI is not affected by dust extinction. Figure 30 shows the accuracy reached by VLBI compared to other techniques in setting the distance to the Pleiades.

Among the several other research areas in the field of stellar radio astronomy, I wish to spend a couple of words on the potentials of VLBI to detect extrasolar planets and brown dwarfs. Feasibility studies have been carried out with the EVN (Katarzynskiy et al. 2016), and show that Jupiter-like planets with strong magnetic fields can be observed in the typical EVN observing bands (for instance L band). Compared to other low frequency interferometers, such as LOFAR and the (u)GMRT, VLBI offers the major improvement in angular resolution.

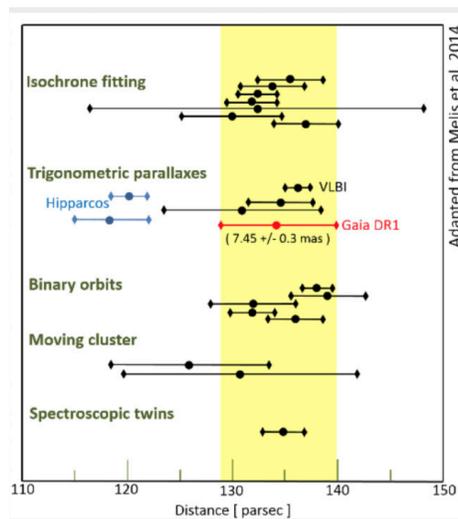


Fig. 30 – Distance estimates to the Pleiades for a number of different missions/techniques.

4.6. Astrometry, geodesy and space science

Beyond the astrometric applications of maser parallaxes, an ongoing effort is being carried out through continuum VLBI observations in the simultaneous S/X and X/Ka bands to define the celestial reference frames. During 2018 two major steps have been done in this direction: the ITCRF3 has been presented at the IAU GA for adoption of the new IAU fundamental celestial reference frame; the Gaia DR2 has been released, with positional accuracy comparable to ITCRF3. The alignment between the two reference frames is a forthcoming step.

The radio follow-up will require improving the coverage of the Southern Sky, and this again calls for the development of the AVN.

I wish to emphasize that VLBI is the only observational space geodesy technique which provides ICFR, ITRF and the full set of Earth rotation parameters. Moreover, only VLBI can determine UT1-UTC and the Earth precession and nutation. The latter parameter is closely related to the Earth interior, and can provide crucial information on the studies of Earth.

Finally, VLBI has the potential to provide permanent monitoring of the Earth rotation. This is not feasible yet, but the ongoing construction of the VGOS network of the IVS will reach this goal. The VGOS

antennas are small (13.2 metre dishes) and very fast moving antennas which will allow the determination of the Earth rotation by means of observations of quasars and distant radio galaxies. The network construction is in progress. So far only a handful of observatories are equipped with VGOS antennas, but their number will soon increase. The twin VGOS antennas in Onsala are shown in Figure 31.



Fig. 31 – The two twin VGOS antennas at the Onsala Space observatory, with the 20-m radio telescope in the background. More information can be found on web at the address: <https://www.chalmers.se/en/researchinfrastructure/oso/news/Pages/Onsala-Twin-Telescopes-ready-to-observe.aspx>.

5. Prospects for the EVN

The European VLBI Network is undergoing a self-assessment to position its role in the evolving frame of the international radio astronomical facilities, and most important in the light of the future SKA operations.

The preliminary outcome of the process which will eventually lead to the VLBI Science Vision for the next Decade is clearly showing that a growing number of hot astrophysical open questions can be addressed only by VLBI. Moreover some special needs and requirements are clearly emerging. I will briefly summarize those here, placing the emphasis on the relevance of the Italian three VLBI antennas in each of those.

The parameter space where the EVN can improve its performances includes a number of quantities, each fulfilling different requirements:

- a. Increase the **number of radio telescopes** in the array – this reflects on the performances of the array, in particular the **sensitivity** (improved collecting area), the **image fidelity** (improved u-v coverage), the **angular resolution** and **accessible portion of sky** (depending on the distribution of the radio telescopes on Earth and in space);
- b. Increase the **bandwidth** – this reflects on the sensitivity and image fidelity, too.

- c. Increase the **frequency range** – expanding the range of accessible frequencies through the design of new receivers at low and high frequency reflects on the science which can be addressed by the array;
- d. Implement **wide-field imaging** – this compensates the traditionally very limited field of view of VLBI observations;
- e. Implement **multi-field imaging** – this increases the potentials of the array making it as close as possible to a “survey instrument”;
- f. Implement **wide instantaneous bandwidth** – this increases the range of science which can be addresses. Spectral studies of radio sources are a typical example.

a. Increasing the number of radio telescopes

Here below I will report a number of very insightful plots, which clarify the impact of a very high number of telescopes in the array. I should point out that the current number of EVN observatories is already very high, nevertheless several actions are in progress to further increase the current number of affiliate telescopes. The most interesting countries are Portugal (with a radio telescope in the Azores) and Thailand. Last but not least, prospects for the inclusion of the 500-m FAST radio telescope in China are very exciting. Figure 32 compares the sensitivity of the EVN and global VLBI to that of the JVLA and to expectations for SKA-mid1.

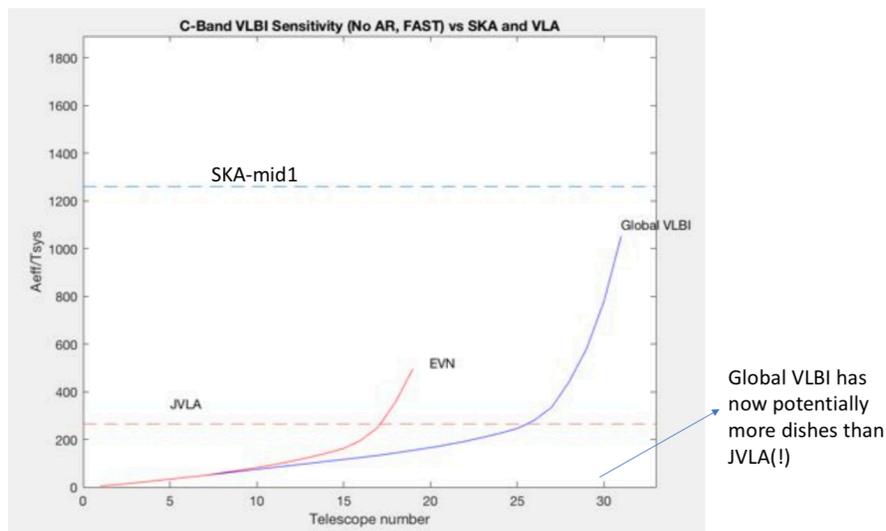


Fig. 32 – This plot shows the sensitivity (expressed as the ratio between effective area and system temperature) of the EVN and Global VLBI compared to the JVLA (similar frequency range) and to the expectations for SKA-mid1. The EVN/global VLBI lines do not include FAST, Arecibo or any SKA dishes.

One of the most interesting developments of the EVN is the possibility to work with the **African VLBI Network (AVN)** (see Figure 33). As a matter of fact the EVN Board of Directors strongly supports the development of the AVN at several levels. While the fundings for the refurbishment of previous existing dishes and the development of new ones is almost fully supported by South Africa, the European effort is along the lines of scientific and technological knowledge transfer, and training of students and young post-docs. This effort is supported both by bilateral international agreements and by the H2020 project JUMPING JIVE, whose WP9 (Capacity in Africa) is extremely active in the educational and training effort.

INAF is involved in a similar effort thanks to the Progetto di Grande Rilevanza between Italy and South Africa (MAECI) RADIO SKY 2020 (P.I. Venturi).

INAF can play a major role in the joint operations between the EVN and the AVN, thanks to the location of Medicina, Noto and SRT, which is the southernmost (together with Yebees, close to Madrid) in the array. In perspective, full EVN+AVN operations will allow a full coverage of the sky, filling the current big gap at declinations around 0° , due to the lack of telescopes in the huge area between Sicily and South Africa. At present the radio telescope in Ghana is the closest to full operations.



Fig. 33 – **Left** – Location of the antennas belonging to the AVN, with new telescopes and the conversion of previous dishes highlighted. **Right** – Coverage of radio telescopes in Africa, including the SKA Phase 2 long baselines.

I wish to underline a couple of very relevant points here. First of all future **EVN+AVN observations** will allow to perform **follow-up at mas scales of SKA-mid radio sources**. No other VLBI array has the required sensitivity and sky coverage to perform such follow-up studies. The Long Baseline Array (LBA, Australia) has a very limited sensitivity and u-v coverage, and is inadequate to the quality requirements that SKA follow-up studies will require, while the Very Long Baseline Array (VLBA) has a declination limit around -30° , and a poor and inadequate u-v coverage at declinations below 0° .

A second issue to keep in mind is the ongoing construction of **E-ELT**, which is expected to provide its first light close to/soon after the start of the SKA operations. The synergy between these two instruments, which will drive the astrophysical research from the late 2020'a onwards is an obvious expectation. I wish to draw the attention to the fact that E-ELT will provide **milliarcsecond resolution** (see Figure 34), hence **no real SKA – E-ELT synergy will be possible without VLBI**, either in terms of SKA-Phase2 construction (inclusion of baselines with length of thousands of km), or as VLBI “outside” the SKA, i.e. EVN+AVN operations.

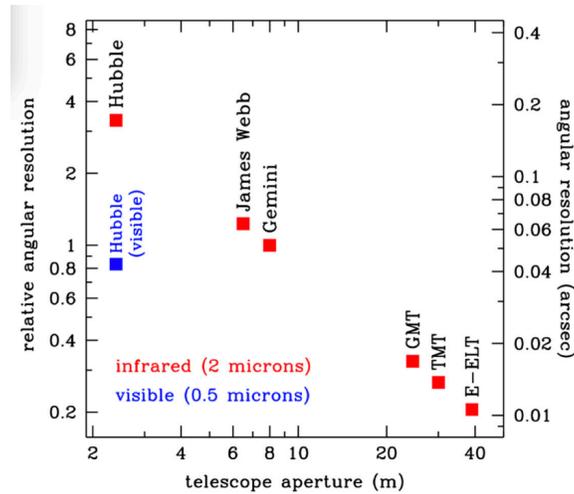


Fig. 34 – Angular resolution of a number of main optical observing facilities in the infrared and visible light. E-ELT will have the potential to reach $\approx 8\text{mas}$, which is for instance the angular resolution the EVN provides at 1.4 GHz.

b. Increasing the bandwidth

Increasing the observing recording rate, hence the observing bandwidth, is one of the ongoing targets of the EVN CBD. At present the goal is to move to a standard of 2 Gbps recording by mid 2019. The three Italian antennas have moved to 2 Gbps operations in 2018. The following plots (Figure 35) show the impact of this improvement in the u-v coverage of the EVN for two different sets of antennas. The impact of the u-v coverage on the image quality has already been pointed out.

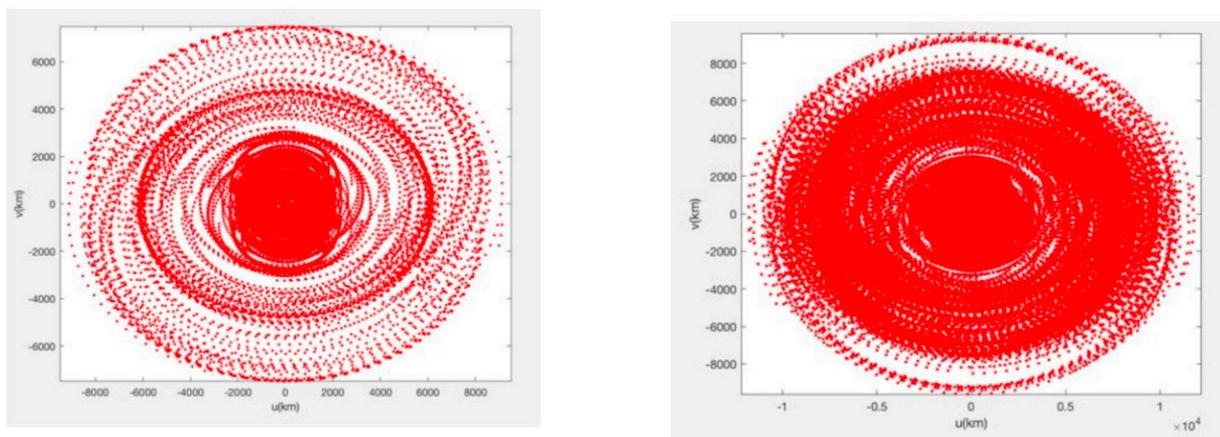


Fig. 35 – u-v coverages at 6 cm for 2 Gbps (256 MHz) observations for EVN+eMERLIN, 18 stations (left) and for a global array with 30 antennas (right).

c. Increasing the frequency range

The EVN has traditionally observed in the bands centered on 1.4-1.6 GHz, 2.3 GHz, 5-6 GHz, 8.4 GHz, 22 GHz, and more seldom at 43 GHz. Observing runs at 86 GHz are part of the Global Millimetre VLBI Array (GMVA) which includes a subset of EVN antennas, too. There are nowadays several reasons to make the effort to expand the frequency range to lower and higher frequencies.

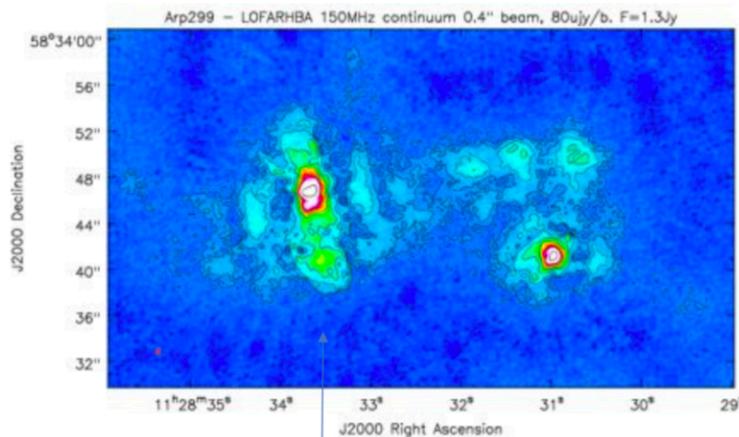


Fig.36 – International LOFAR baselines image of Arp299 at 150 MHz (Ramirez-Olivencia, Varenious et al.). The angular resolution is 0.4'', and the rms in the image is 80 μ Jy/beam.

The International LOFAR baselines have shown that VLBI is feasible even at frequencies of 100-200 MHz (see Figure 36). Sub-arcsecond scale imaging at such frequencies is unprecedented. This is still a challenging effort, mainly due to the difficulties in accounting for ionospheric effects, however the prospects are encouraging, and the potential science very exciting. In particular, key science areas which will benefit from VLBI observations at frequencies below 240 MHz are: outflows and free-free absorption in galaxies, supernova remnants, low luminosity AGNS, pulsar scintillation imaging, location of extrasolar planets and of FRB.

The installation of the LOFAR 2.0 station in Medicina will considerably increase the baseline length of the International LOFAR baselines, improving the angular resolution by roughly a factor of 2. The VLBI expertise at IRA and OA Cagliari is a good starting point to ensure full exploitation of the INAF investment in LOFAR even in this area.

On the high frequency side, one of the most interesting developments is the **simultaneous tri-band receiver** operating at **22/43/86 GHz**, which has been developed by the Korean group, and is shown in Figure 37.

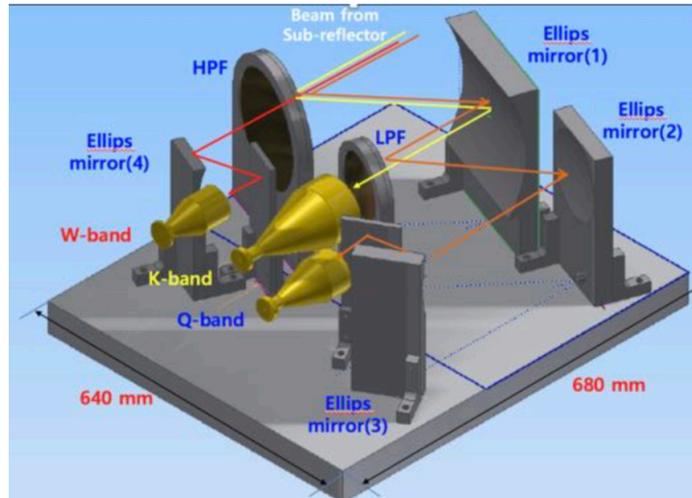


Fig. 37 – The K/Q/W simultaneous tri-band receiver developed by the Korean technologists.

Extragalactic maser science, AGN science and the novel area of planetary disks will most benefit from this technological development. A number of EVN stations will soon install this receiver (Yebes, Onsala, Effelsberg). The three Italian antennas do have the same development in their planning, and the prospects are encouraging. With a set of at least 6 EVN antennas equipped with this receiver, the EVN will become competitive with the GMVA, especially with joint observations with the East Asian VLBI Network (EAVN). Observing at such high frequencies requires a very high surface accuracy, hence an active surface on the telescope is mandatory. Among the three Italian antennas, only **Medicina requires the upgrade to active surface**, an investment which would bring an invaluable scientific return and would provide a very strong position of INAF within the EVN.

An EVN subset of antennas operating up to almost 100 GHz would considerably reduce the frequency gap with ALMA. This implies that milliarcsecond science would be possible over the very broad range of frequencies going from the LOFAR to the ALMA range.

d. Wide-field and e. multi-field imaging

Both these developments are necessary to ensure that VLBI can indeed be a complementary observational technique in the SKA era. Survey-mode operations are of highest priority for the SKA, and for this reason VLBI needs to fasten the data delivery by observing over large fields of view. Though not a routine mode, VLBI wide-field imaging has already been successfully tested (see Figure 38), and prospects for a full implementation mainly depend on computing power.

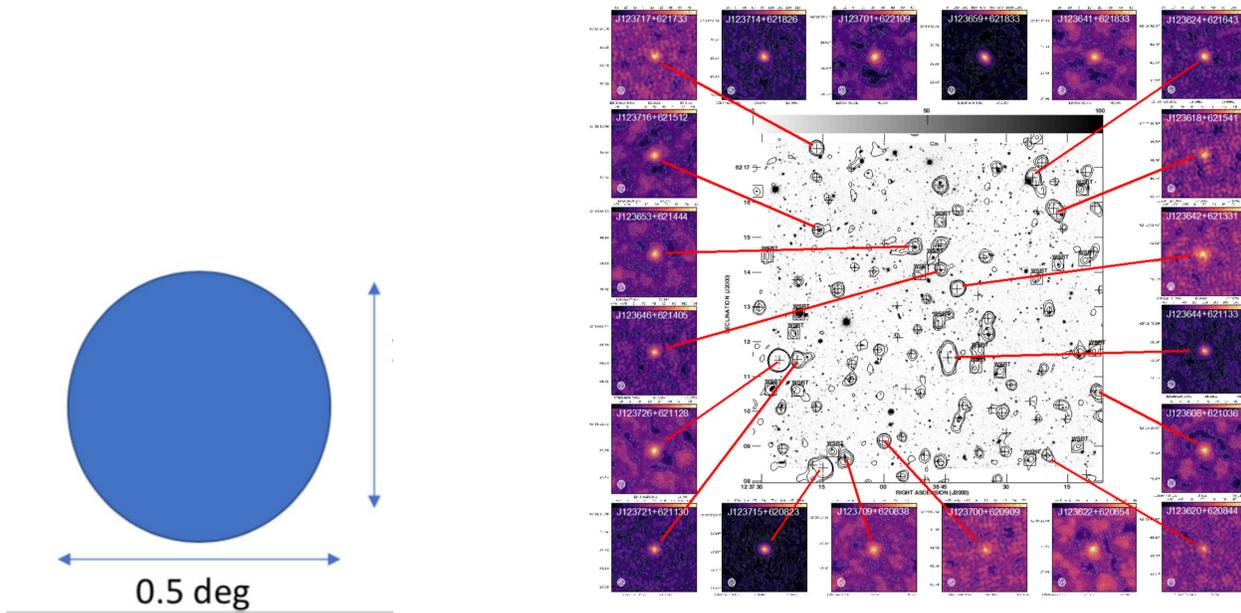


Fig. 38 – **Left** – To image an area with a diameter of 0.5° , a potential factor of 10^6 more pixels than today’s 1024×1024 images is needed. **Right** – One of the most successful wide-field images obtained with EVN and eMERLIN observations over 3 epochs (Radcliffe et al. in prep.).

Phase Array Feeds (PAFs) are an alternative solution to increase the field of view (FoV), through simultaneous observations in several different directions. Such development can bring to an improvement of the by a factor of 25-100.

Studies for PAFs on large dishes (for instance Effelsberg, Lovell and SRT) are ongoing, while such development for smaller dishes (of the Medicina and Noto class) are still to be discussed.

f. Broad instantaneous bandwidth

Over the past few years, a major investment has been made in the development of broad band receivers. This for instance has been one of the major upgrades of the VLA, where the band 1-50 GHz is fully covered by a set of eight receivers in total (L: 1-2 GHz, S: 2-4 GHz, C: 4-8 GHz, X: 8-12 GHz, Ku: 12-18 GHz, K: 18-26.5 GHz, Ka: 26.5-40 GHz, Q: 40-50 GHz). Similarly the uGMRT is already offering a full coverage between 100 MHz and 1.5 GHz), and eMERLIN is planning a seamless coverage of the L to K band frequency range as next development. IRA itself has designed and constructed the 18-26.5 GHz multi-feed receiver currently mounted on the SRT, and is developing broad band receivers in the range 30-50 GHz.

The full scientific exploitation of such broad band receivers is not trivial. The angular resolution and field of view of the array change throughout the band, and this poses several computing challenges, not to mention that, RFIs become a serious issue for broad band receivers, and in practice only a limited portion of the band can be used in each frequency range.

At present, the most important development in this area is BRAND (BRoad bAND European VLBI Network). The construction of the BRAND prototype is supported by the EC-H2020 project RadioNet,

and includes the participation of INAF, as one of the two PIs of the project is Ing. Tuccari (IRA-Noto). The receiver will cover the frequency range 1.5-15 GHz (see Figure 39) and the prototype currently under construction will be mounted on Effelsberg. It is expected that all the EVN antennas will be equipped with BRAND in about 4 years from now.

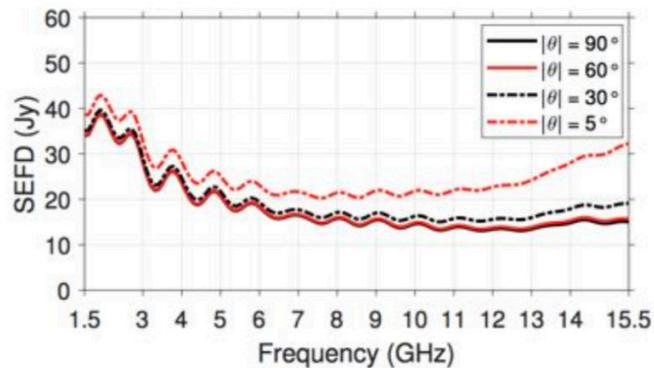


Fig. 39 – Simulated performance of BRAND receiver on Effelsberg.

One more question which has been posed within the EVN community of users and directors is whether the array can become more flexible, to keep up with the response speed which may soon become necessary. This is being addressed in the context of the VLBI Vision Document too. The concept of a “World Array” is presently under discussion. This would not only provide the very best imaging capabilities ever at milliarcsecond scale, but it would allow very fast responses to the transient science, which is at present one of the main astrophysical drivers.

This very brief summary of prospects clearly shows two important points. First of all, the EVN is an evolving facility, whose performances improve with time along the same line of other arcsecond scale radio interferometers, thus ensuring meaningful complementary milliarcsecond scale observations of the relevant science cases. Second, but even more important, is the perspective of the EVN and VLBI in the forthcoming SKA era, especially with respect to the relevance of wide-field imaging, fast response to transient science and localization of transient sources, and synergies with the E-ELT. I remind here that only VLBI is adequate to address the two latter points.

6. Scientific prospects for the Italian VLBI Network and potential impact

The potentials of the Italian VLBI Network cover several aspects. I will call it VITA in the following (VLBI ITALiano), meaning the three INAF antennas (Medicina, Noto and SRT) and the software correlator in Bologna.

VITA is not a good imaging array, due to the very poor u-v coverage provided by only three antennas, and it does not provide the sensitivity requirements necessary for today’s hot science. Just as an example only a marginal radio detection of GW170817 has been possible with the Global VLBI Array operating with 20 antennas at 1 Gbps, so it seems unlikely that VITA will provide the observational

requirements for gravitational wave follow-up studies, unless events order of magnitude stronger than GW170817 will take place.

As any VLBI array, VITA however does have a considerable relevance as detection and localization instrument in several novel areas. Transient science (FRBs, GRBs, supernovae explosions) does require localization of the event as a first step, and a broad range of events would be strong enough for VITA. Moreover, the advantage of a VLBI national facility, with the individual telescopes connected through optical fiber link to the correlator (real-time VLBI), and the existence of a single Time Allocation Committee for the three antennas (both as individual instruments and as an array), allows a very quick response to alerts of any kind, thus providing the t_0 point in a flux density and imaging monitoring. It is important to point out that real-time VLBI observations are a “niche” observing mode which offers several advantages, such as quick data analysis and array stability, with no further investment in disk supply.

Another “niche” area is that of the so-called “non-imaging surveys”. The sparse u-v coverage of the array would filter out the extended emission around compact sources to remove flux density contamination. This is particularly relevant for the study of compact emission in sources detected in large surveys. NVSS sources are an example, but this concept can be extended to any future all-sky survey. It is interesting to highlight that this application would turn a disadvantage (poor u-v coverage) into a resource (removal of contribution from short spacings).

A relevant impact for VITA is that of multimessenger astrophysics, i.e. the possibility to work in synergy with other bands of the electromagnetic spectrum, and thus make the potentials and impact of the full community of INAF much stronger. Observations of supernovae, such as the study of the light curve and decay and the initial stages of the expansion, to characterize the supernova explosion, would be an excellent national science case. VITA monitoring of γ -ray sources in collaboration with Fermi, though not a novel science case, would be invaluable in the context of multimessenger observations, particularly in the light of the recent results on the blazar/neutrino connection.

Surveys of stellar masers carried out with VITA would provide novel information in this area, too.

One of the main strengths of VITA is the possibility to work in synergy with other antennas, forming an international independent VLBI network, with obvious advantages in terms of accessibility. This has already happened between Medicina, Noto and the antennas of the East Asia VLBI Network (EAVN), in high frequency studies of AGN. The new development to the 22/43/86 GHz receiver will further strengthen the VITA-EAVN science. Moreover, requests to use the three Italian antennas together with a subset of EVN antennas for other science cases (such as pulsar studies), have already been received, and the paper by Egron et al. (2017) clearly shows that even a 4-5 station VLBI array is still able to provide important information.

The potentials of VITA embrace the area of VLBI for geodesy, with both technological and scientific implications of high impact. Were SRT equipped with geodetic receivers, Italy would be the only case in Europe with four observatories in its territory. Note that the geodetic VLBI network includes the ASI antenna in Matera. That would ensure an excellent link between Italy and the international celestial reference frames (ITFR).

A new area of activity for VITA is that of time and frequency dissemination through optical fiber link. This project is led by INRIM (Torino), in the collaboration of INAF through IRA. This technique provides

a time reference measurement/standard alternative to atomic clocks. At present only Medicina can provide this observable. Matera will be connected soon, and both Noto and SRT could be connected, too. If this optical clock were implemented on all antennas, the observations with VITA would be linked to a much more advanced time frame, with several novel applications, the most remarkable is in the field of general relativity.

Beyond the well-known geodetic studies (tectonic motions as main driver), one of the outcomes of VITA for geodesy would be its integration with the network of GPS stations, whose number is continuously growing thanks to the investment of ASI and INGV (as well as local governments and private stakeholders) on the whole national territory. The activities of such network would have a deep impact on all those activities connected with the monitoring and protection of the territory, time response to emergency calls, and all those services which are based on stable reference frames with milliarcsecond accuracy.

Some investment is necessary to bring the Italian VLBI Network to the full level of operability. At present the main severe limitation is the small number of receivers common to the three antennas, the lack of active surface in Medicina, and the lack of geodetic receivers on SRT. A human investment should also be considered for a full exploitation of the array, especially in the light of an ongoing dissemination effort and use of the network outside the radio astronomical community.

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