

A virtual hub for multi-messenger/interferometry centres@JIVE

Zsolt Paragi
JIVE

Radio Astronomy / Telescopes (some)

Field of view: 10s of degrees to arcseconds (EVN see next page)



- **Covering a broad range of $\lambda \sim \text{m}$ to sub-mm / or frequencies ($\sim 0.1 - 300$ GHz)**
- **Antenna elements range from dense aperture/cylindrical arrays to dishes**
- **Range of resolutions & field of views differ orders of magnitudes**
 - ➔ all instruments have their niche applications

The European VLBI Network





JIVE

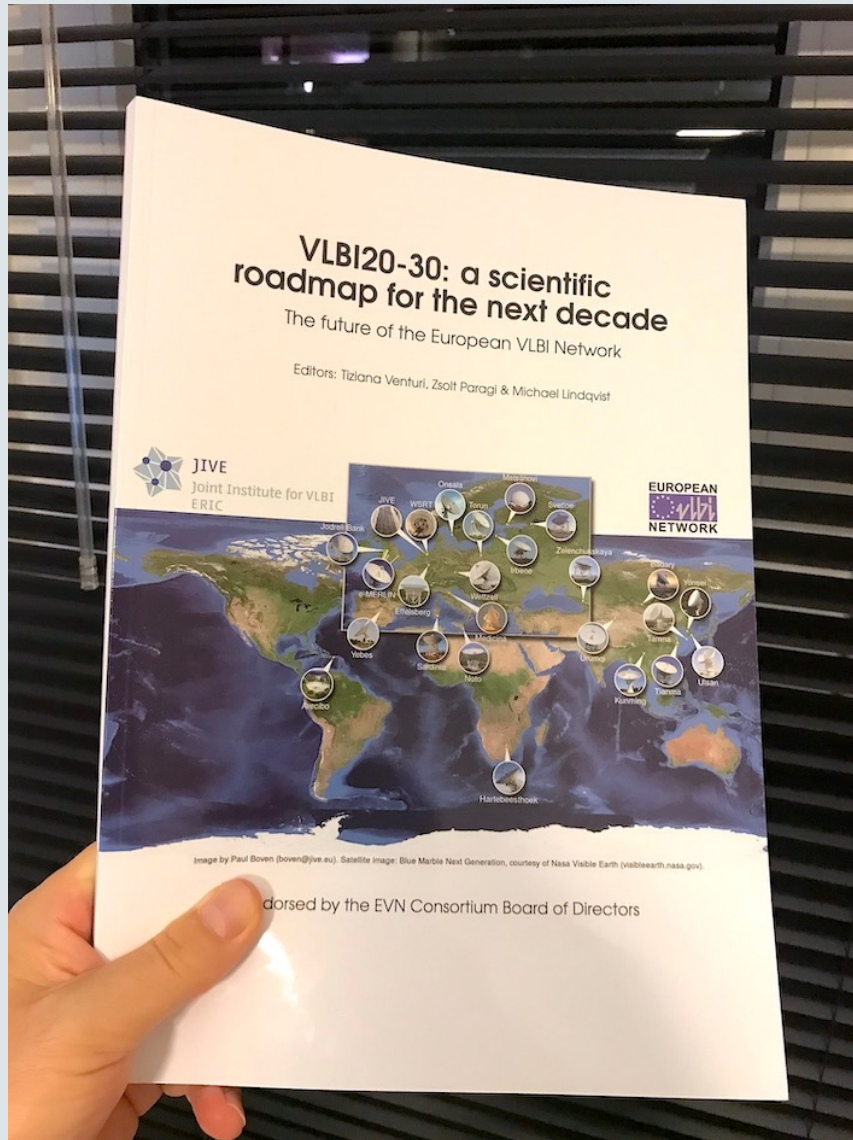
Joint Institute for VLBI
ERIC



Photo: Zsolt Paragi

- **The EVN central data processor and data archives are at JIVE**
- **A European Research Infrastructure Consortium (the only one in astronomy)**
 - Providing access to data and the network
 - Providing services
 - R&D in VLBI and correlator technology (for transients: **real-time e-VLBI correlation; SFXC**)

EVN Vision Document



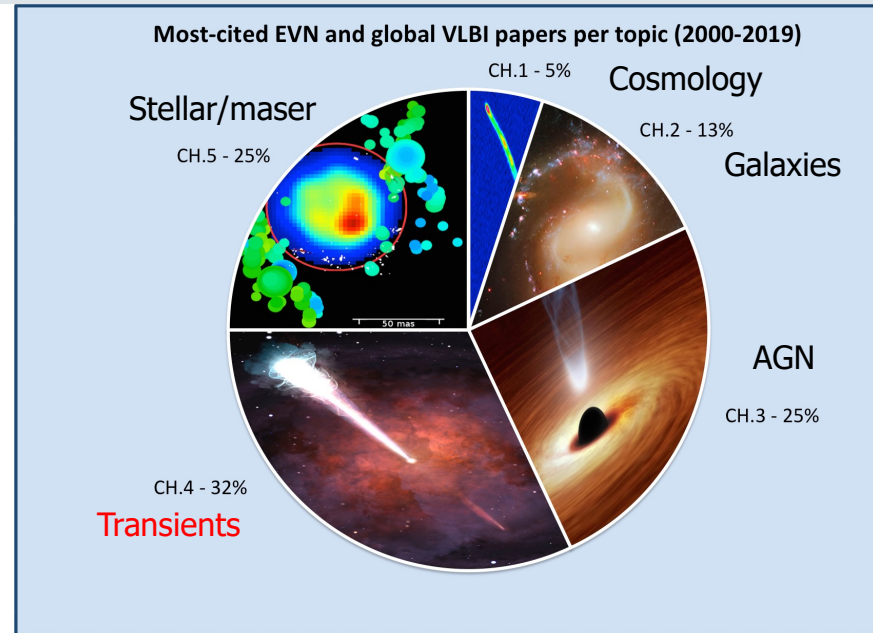
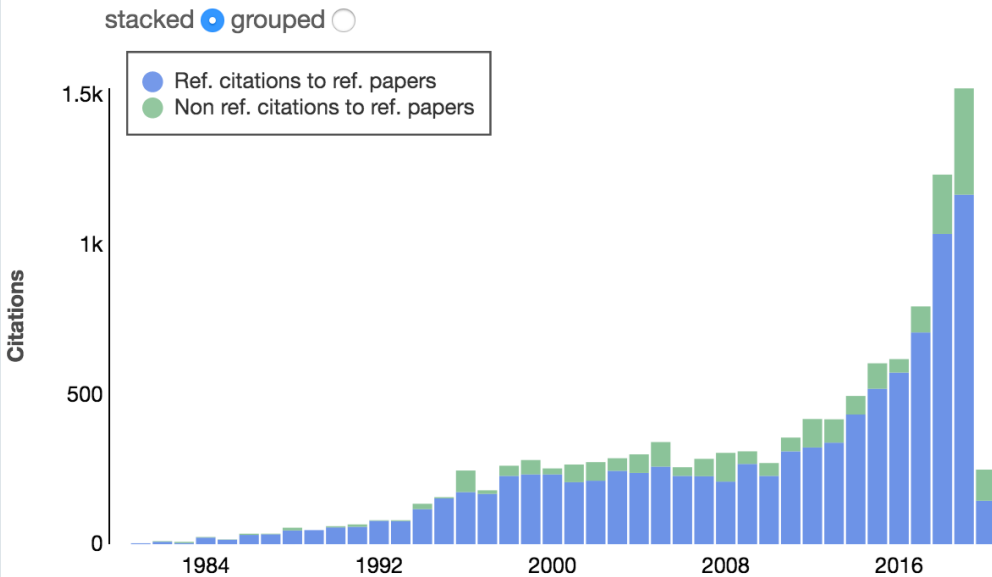
- The VLBI20-30 scientific roadmap has been published and printed
- A technological roadmap was derived from the science requirements
- Synergy with other radio telescopes and major European facilities is highlighted

arXiv:2007.02347

<https://arxiv.org/abs/2007.02347>

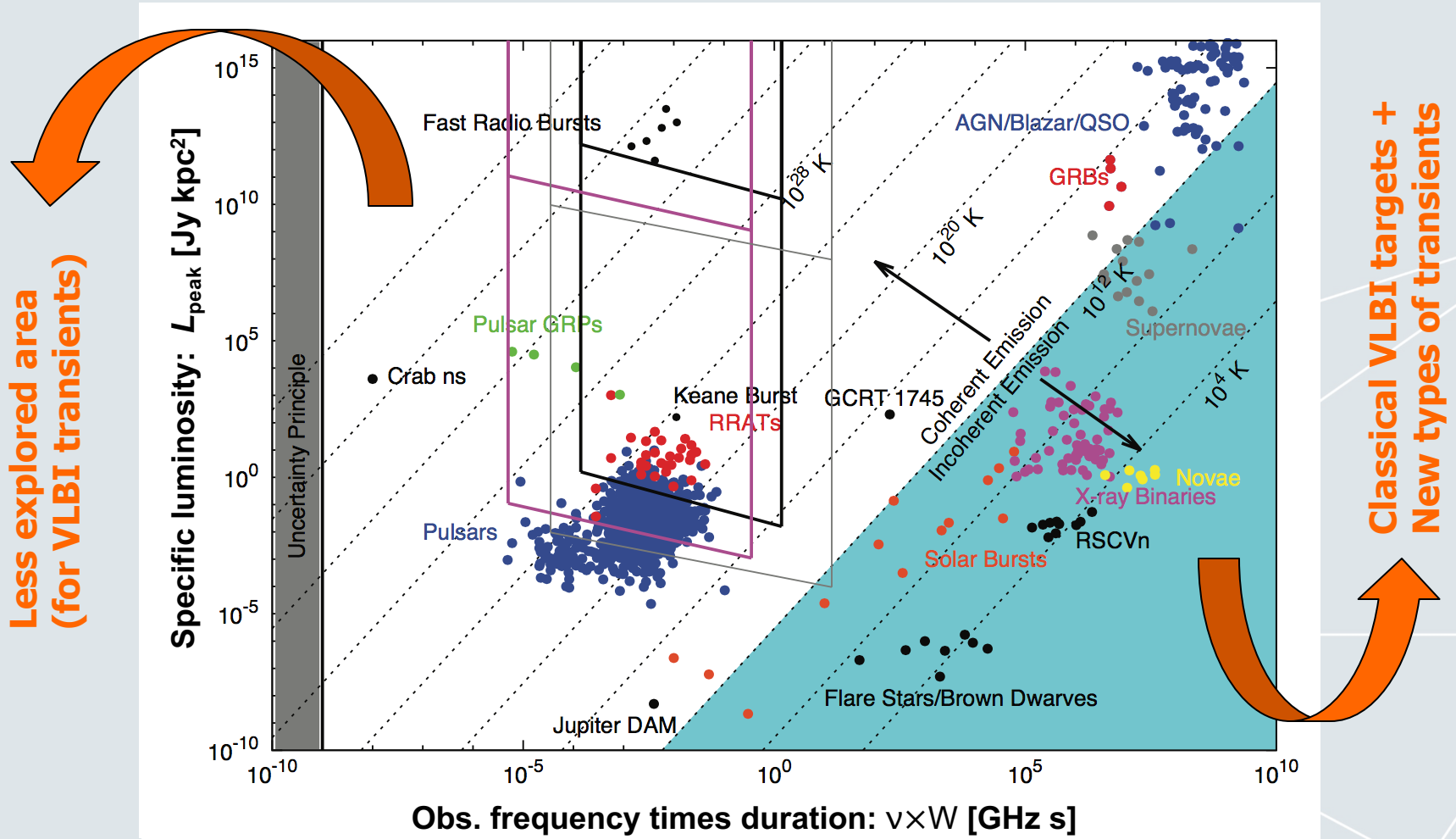
The EVN Transformation

Top-100 most cited papers with EVN data

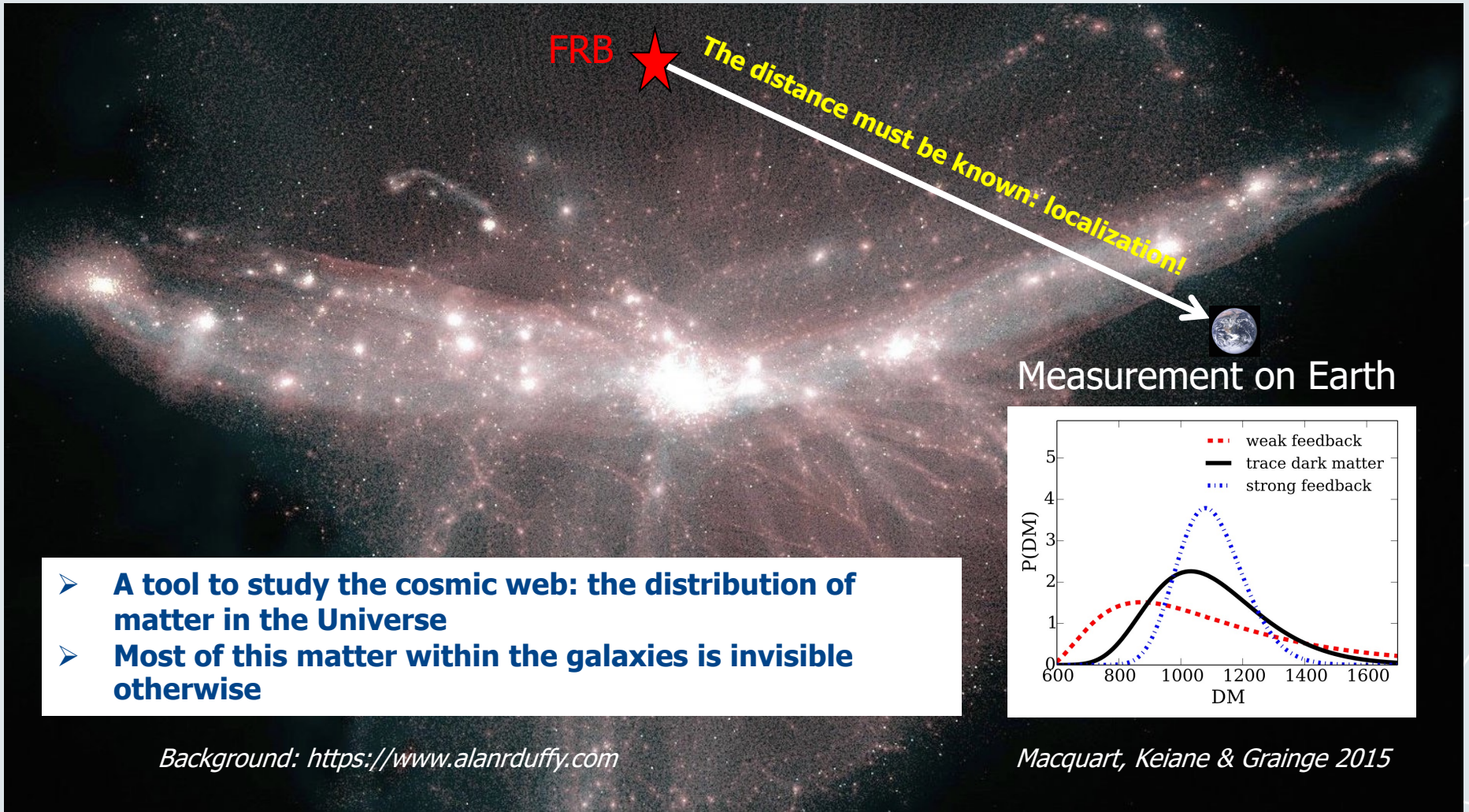


- **Technical developments (sensitivity; e-VLBI; SFXC) transformed our science**
- **There is a globalization in astronomy, affecting EVN operations as well**
- **The multi-messenger era kicks in (~2017):**
 - Discovery of GW170817 EM counterpart
 - VLA/EVN localization of FRB 121102

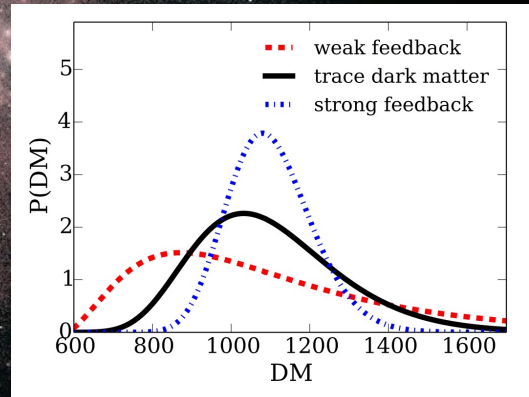
The transient parameters space



Fast Radio Bursts: a tool for cosmology



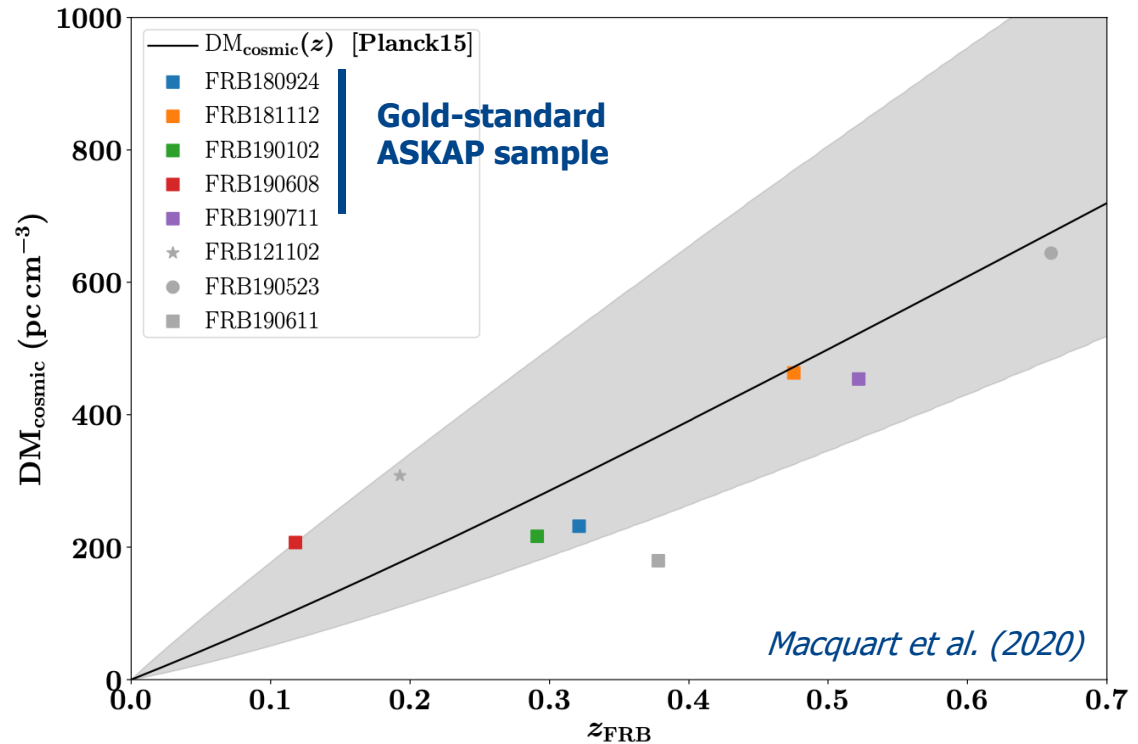
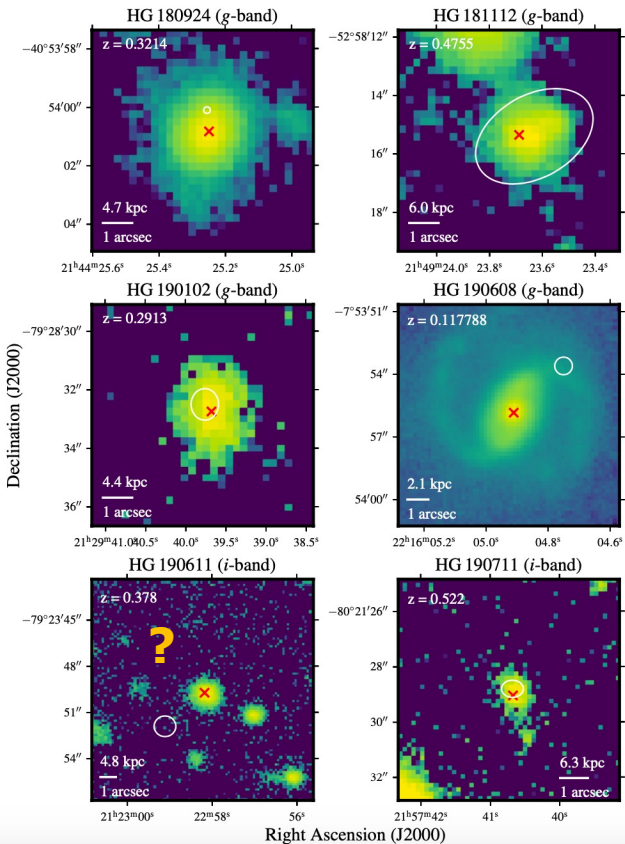
- **A tool to study the cosmic web: the distribution of matter in the Universe**
- **Most of this matter within the galaxies is invisible otherwise**



Background: <https://www.alanrduffy.com>

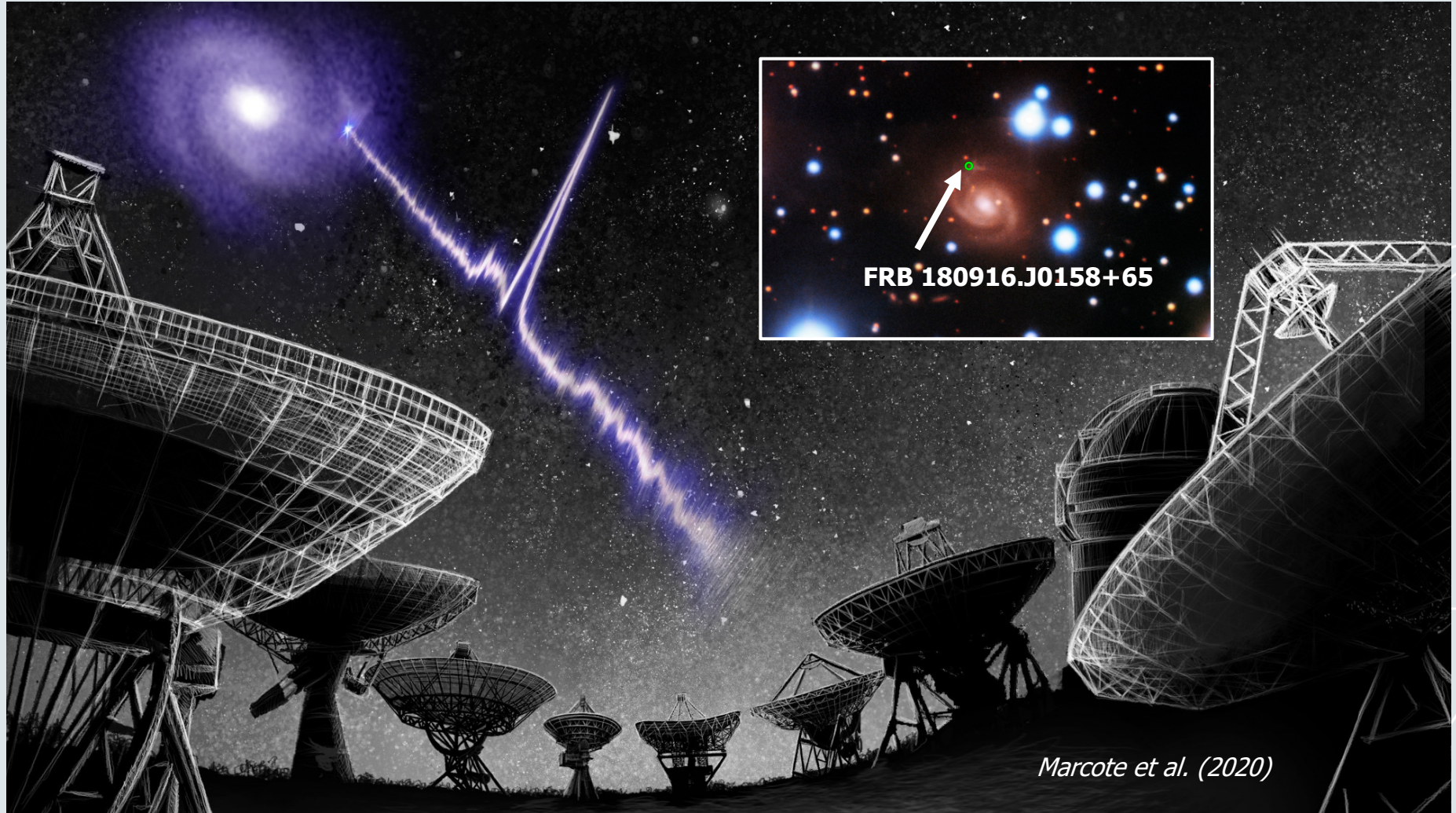
Macquart, Keane & Grainge 2015

“A census of baryons in the Universe from localized fast radio bursts”



- More than $\frac{3}{4}$ of baryons reside in a highly diffuse phase, hard to observe
- How these are distributed is fundamental to structure formation models
- Used published FRBs with arcsec localization +4 new ASKAP FRBs to probe this

EVN: a powerful localization machine



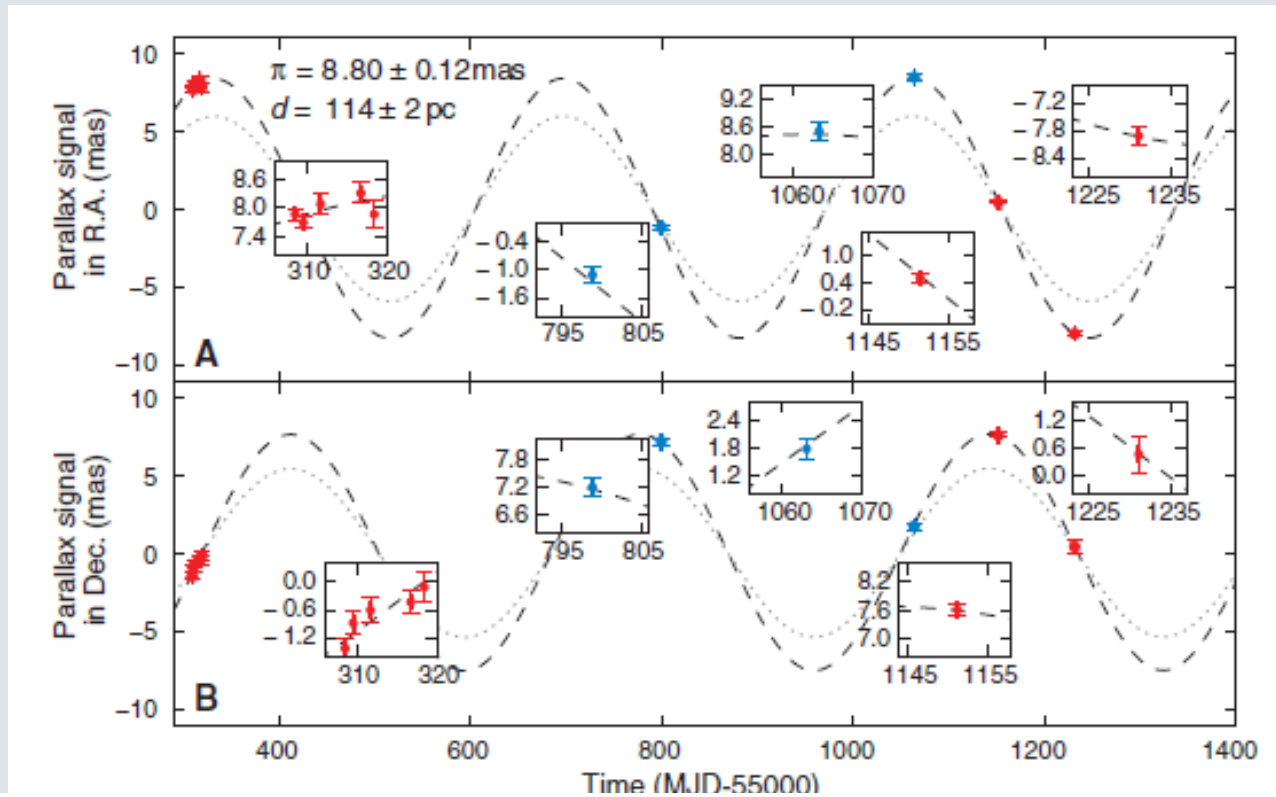
- **Follow-up is not possible for ms-duration events; except for repeaters**
- **EVN is the only instrument capable of FRB localization on milliarcsecond scales**
(doing "SKA science" today)

Triggered e-VLBI science: a dwarf nova

VLBA + e-EVN

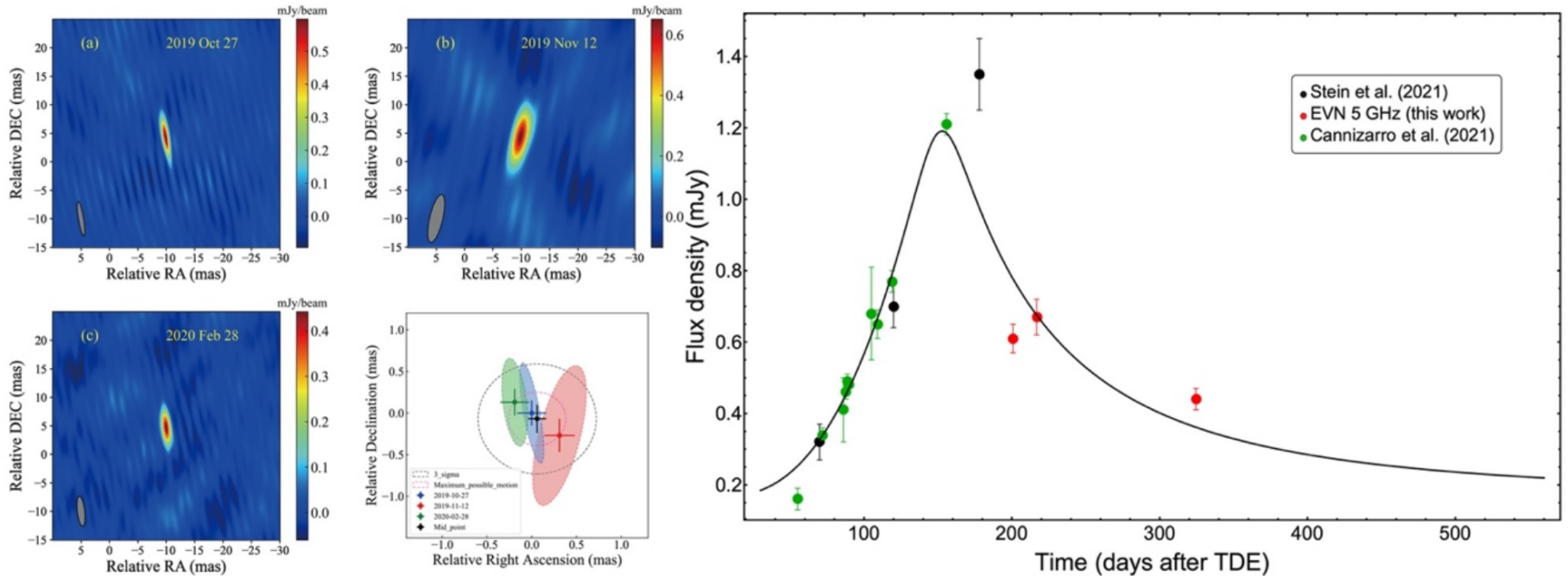
SS Cyg parallax measurements during flares: verifying accretion theory

Miller-Jones et al. 2013, Science, 340, 950



- **Response time to optical flares <1d!**
- **Closest example that may benefit from an automated trigger process for VLBI** (so far the only one; done instead in regular e-VLBI sessions)

AT2019dsg: A Tidal Disruption Event

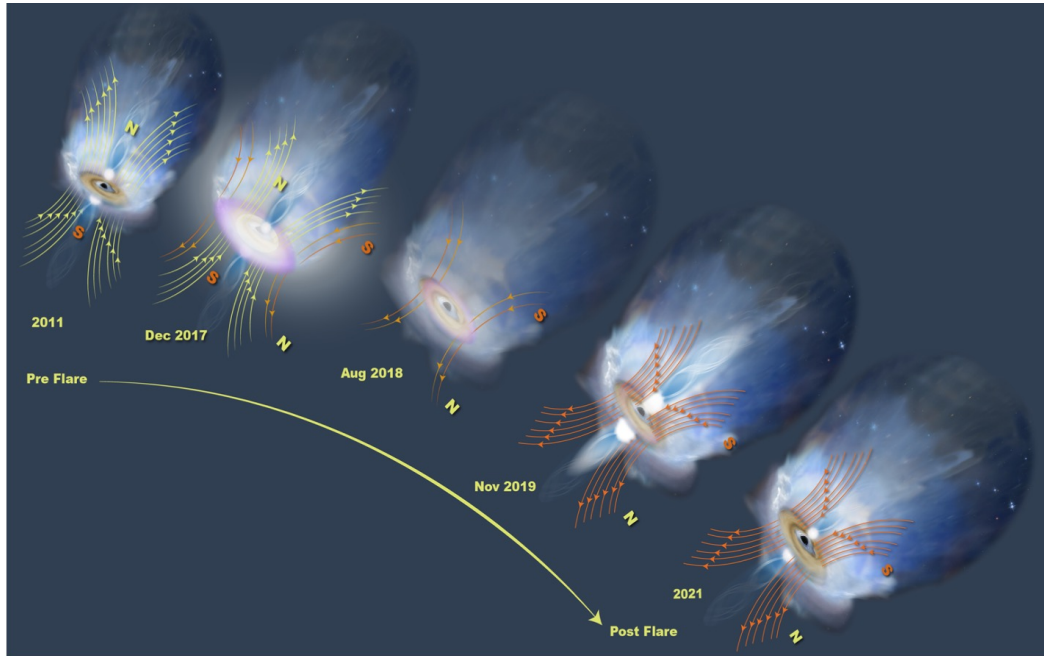


➤ AT2019dsg

- EVN monitoring rules out a (mildly-)relativistic outflow (**EM140, RSM04**)
- Light-curve analysis favors outflow ($v \sim 0.1c$) interaction with dense circum-nuclear medium

Mohan et al. 2022, *ApJ*, 927, 74

A Changing-look AGN



Violent changing look event in 1ES1227+654:

In December 2017 a dramatic optical/uv flux rise has started (reaching 4 mg in amplitude) and broad emission lines appeared just in a few months time, while the coronal X-ray emission disappeared.

Laha et al. 2022, arXiv:2203.07446 – multi wavelength study, using archival data from EG079 [Gabanyi] and RSY07 [Yang]

➤ 1ES1227+654

- Multi-band data exclude a TDE but support a magnetic flux inversion event: with EVN archival data from pre-flare and mid-flare (**EG079**, **RSY07**); post-flare from VLBA
- No new-born jet! L_R/L_X follows the Güdel-Benz relation typical for coronally active stars and several AGN

Laha et al. 2022, arXiv:2203.07446

Towards automated triggering with the e-EVN

(A very old slide from 2015):

Realizing an old dream :

European VLBI Network
Call for Proposals
Deadline 1st June 2015

Chasing transient sources with the e-EVN
Is the brightest unidentified EGRET source related to IGR J20187+4041?

A. Trejo Cruz (CRYA-UNAM, MX)
E. Giacani (IAFE, AR)
Z. Paragi (JIVE, NL)

H.J. van Langevelde (JIVE, NL)
G. Dubnar (IAFE, AR)
A. H. Baykov (Ioffe Inst, RU)

In electronic Very Long Baseline Interferometry (e-VLBI) an array of distant radio telescopes carry out VLBI observations and the data are streamed to a central data processor in real-time. The European VLBI Network (EVN) has been pioneering in the scientific applications of this new technique. The goal of the EXPRES project is to provide operational level e-VLBI service by the year of 2009. One of the advantages of e-VLBI is the fast science turnaround time. Experiments targeting transient sources benefit the most of this capability. The trigger for e-VLBI may come from connected element interferometers (such as the Westerbork Synthesis Radio Telescope, also part of the EVN), or from gamma or X-ray satellites and optical telescopes. For new transients it is essential to have accurate positions at the arcsecond level.

In 2006 the e-EVN consisted of Cambridge, Jodrell Bank, Medicina, Metsahovi, Onsala, Torun and Westerbork telescopes. Since 2008 the 100m Effelsberg is regular part of the array, and several telescopes from various continents demonstrated live fringes. The e-VLBI data are directly coming to the EVN correlator at JIVE, through the GEANT network and other national research networks. There have been robust real-time science operations since 2006. As from 2008, the available data rate increased to 512 Mbit/s. Besides 5 GHz and 1.6 GHz, the 22 GHz frequency band is available as well. The current sensitivity at 5 GHz for 10 hours on-source integration time is 15 microJansky/beam, which is expected to improve by increasing further the data rate and the number of available telescopes.

Post-processing software at JIVE have been improved in the recent years significantly. The raw data from the correlator are being converted into FITS files in a largely automated manner. These are further pipelined by a completely automated process that produces images from the data within an hour. The results are stored at the EVN Data Archive (<http://archive.jive.nl/>). Fits are encouraged to come to JIVE to further analyse their data with professional help. This makes the e-EVN an easy access easy to use instrument for the whole astronomical community. The most recent science example is the detection of a compact radio source in the (initial) error box of an AGILE transient. See the attached ATel report for details. Follow up observations are planned a few days after this conference.

The European VLBI network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils. e-VLBI developments in Europe are supported by EC D2D (INFOS) funded Communication Network Development project, 'EXPRES', Contract No. 02662.

JIVE
JOINT INSTITUTE FOR VLBI IN EUROPE

EXPRES

EUROPEAN VLBI NETWORK

For more information see:
<http://www.evlbi.org/>
<http://www.expres-eu.org/>
<http://www.jive.nl/>

- * A new e-VLBI class is introduced, automated generic e-VLBI trigger observations. It is an observation to be scheduled automatically during an e-VLBI run only if a specific set of triggering criteria is met. The expected response time to execute a new program is about 10 minutes. For details see:

- <http://www.evlbi.org/>
- **This initiative died out because of lack of interest in the community**
 - **The most relevant timescales are days to weeks, months, years**
 - **Access to VLBI resources outside the few regular observing sessions is more critical!**

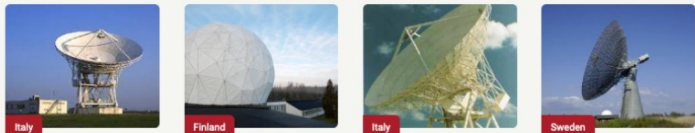
EVN-lite pilot program (2023)



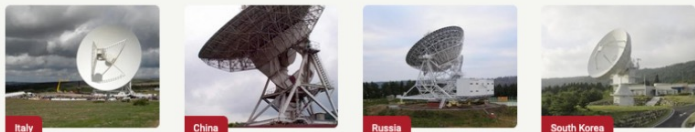
Arecibo Badary Cambridge Effelsberg



Hartebeesthoek Irbene Jodrell Bank Kunming



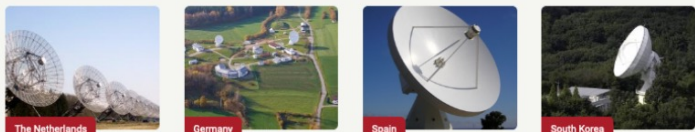
Medicina Metsähovi Noto Onsala



Sardinia Sheshan Svetloe Tamna



Tianma Torun Ulsan Urumqi



Westerbork Wettzell Yebes Yonsei

➤ **Proposal to facilitate projects requiring >>100h observations** (outside of regular observing sessions)

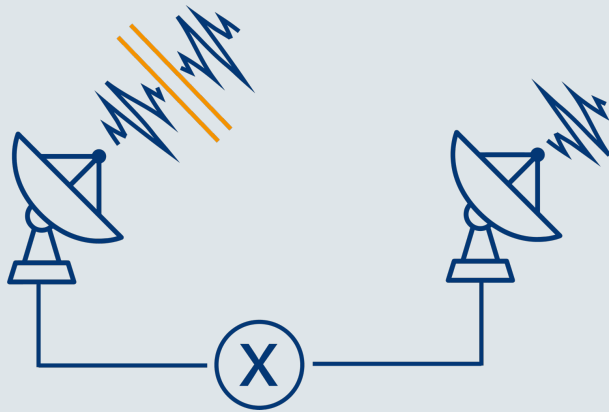
➤ **May support base programs like fast transient search, maser surveys ...**

Triggering on base programs to support transient science / multi-messenger astronomy

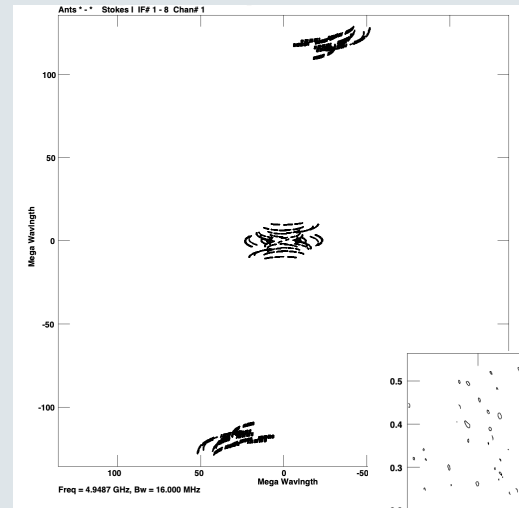
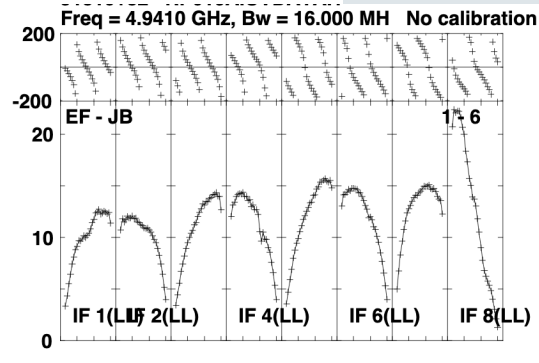
➤ **Operational impacts are being assessed**



Why VLBI is special?



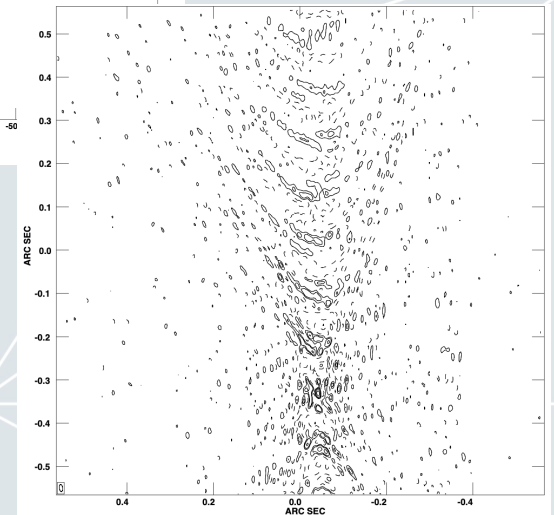
HELP!



SPARSE UV-COVERAGE



"DIRTY" MAPS



- **Independent clock/frequency standards**
+ troposphere & ionosphere mean special ways of processing required: **FRINGE-FITTING** (and more...)

- **Moreover:**
 - Sparse, typically heterogeneous arrays
 - Individual stations with special issues
 - Non-trivial scheduling, observing and processing

➔ Users require extensive help

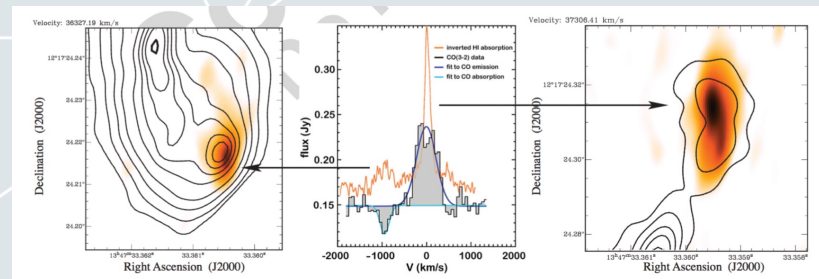
EVN & User Support at JIVE

A bit simplified highlights:

- **Production Correlation**
 - MS / FITS file preparation
 - Standard plots & PI letter
 - ANTAB & FLAG tables
 - Data pipeline (ParselTongue)
- **Network Support**
 - Ftp fringe tests
 - Network Monitoring Experiments
 - Testing new observing modes and equipment
- **User Support**
 - Help with observing proposals
 - Help with scheduling
 - Help with data analysis etc.etc.
- **All this resulting in some science**

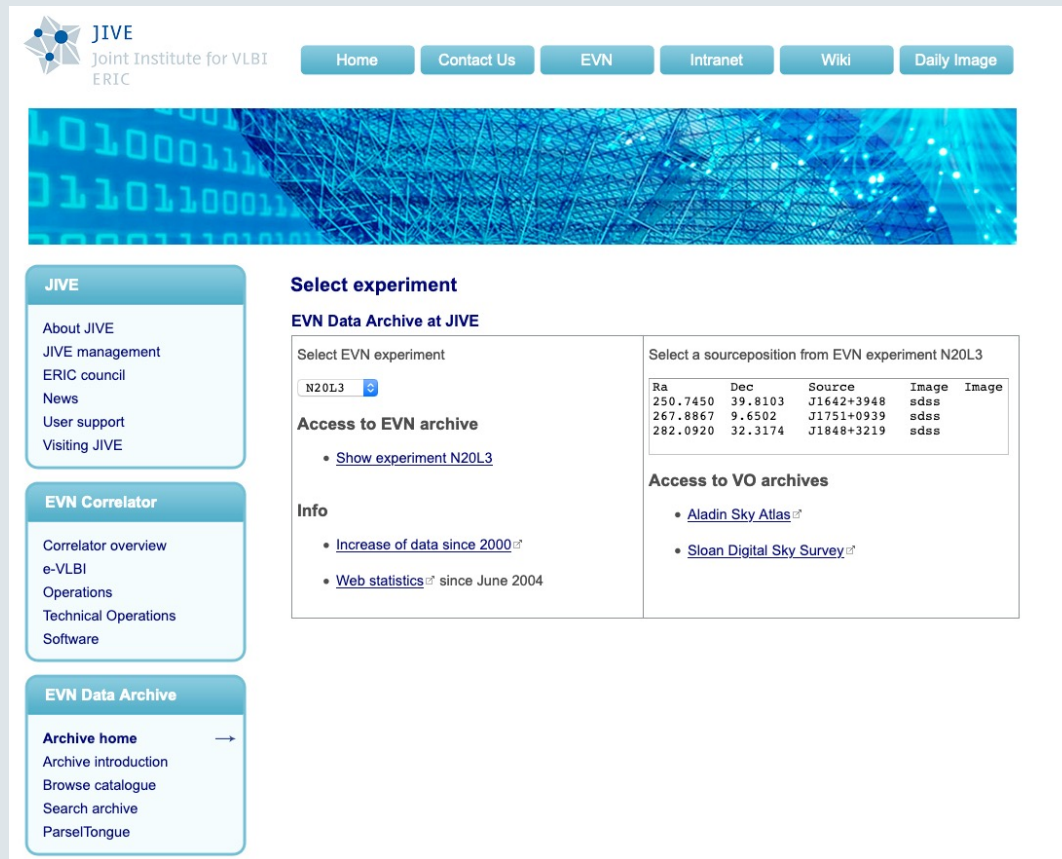


User data reduction visit to JIVE



*Morganti et al. (2013)
Science, 341, 1082*

EVN Archive & VO



The screenshot shows the JIVE website interface. At the top left is the JIVE logo (Joint Institute for VLBI ERIC) and a navigation menu with buttons for Home, Contact Us, EVN, Intranet, Wiki, and Daily Image. Below the navigation is a large blue banner image with a network-like pattern. The main content area is divided into several sections:

- JIVE**: A sidebar menu with links for About JIVE, JIVE management, ERIC council, News, User support, and Visiting JIVE.
- EVN Correlator**: A sidebar menu with links for Correlator overview, e-VLBI, Operations, Technical Operations, and Software.
- EVN Data Archive**: A sidebar menu with links for Archive home (with a right arrow), Archive introduction, Browse catalogue, Search archive, and ParselTongue.
- Select experiment**: A section titled "EVN Data Archive at JIVE" with a dropdown menu showing "N20L3".
- Access to EVN archive**: A list of links, including "Show experiment N20L3".
- Info**: A list of links, including "Increase of data since 2000" and "Web statistics since June 2004".
- Access to VO archives**: A list of links, including "Aladin Sky Atlas" and "Sloan Digital Sky Survey".
- Table**: A table titled "Select a sourceposition from EVN experiment N20L3" with columns for Ra, Dec, Source, Image, and Image. The table contains three rows of data.

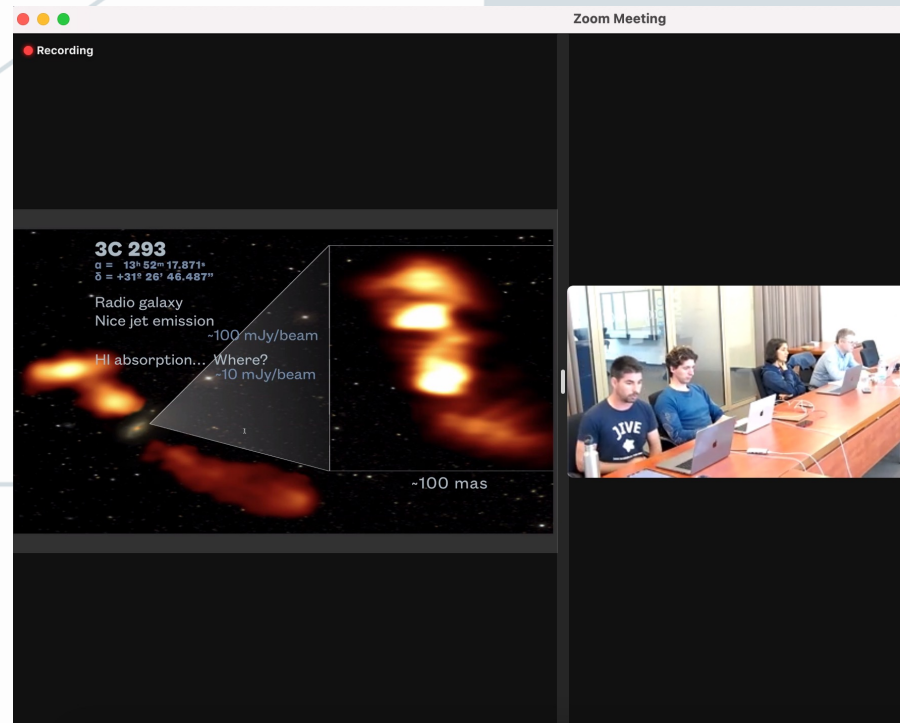
Ra	Dec	Source	Image	Image
250.7450	39.8103	J1642+3948	sdss	
267.8867	9.6502	J1751+0939	sdss	
282.0920	32.3174	J1848+3219	sdss	

- **Some basic VO functions have been implemented**
- **Discussions on maps/ uv - data**
Science-ready data are currently not available, but pipeline-calibrated data have great potentials. **In VLBI, maps are often not the ideal form of presenting your data!**
- **JIVE helps defining interferometry data in ObsCore**

User Support: changing times!



Users attend real-time e-VLBI observing session (GW170817)

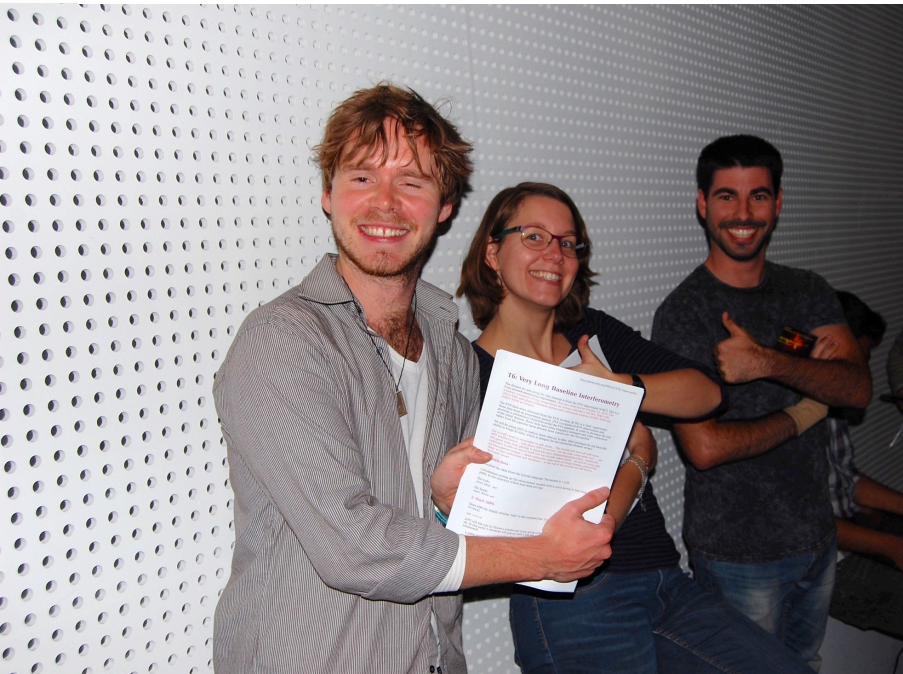


First EVN online training (right)

- **New: EVN/JIVE Support+ program (for non-expert teams)**
- **Strengthening online support:**
 - first online training for proposing/scheduling EVN observations, in May 2022
 - dedicated EVN user support Mattermost channel

Education and Training

Left: helpers during ERIS 2018 in Dwingeloo

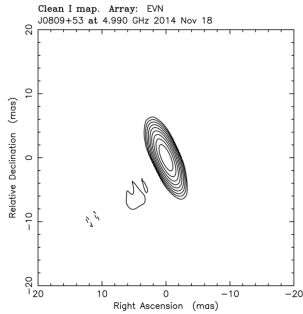


Right: ERIS 2022 group photo

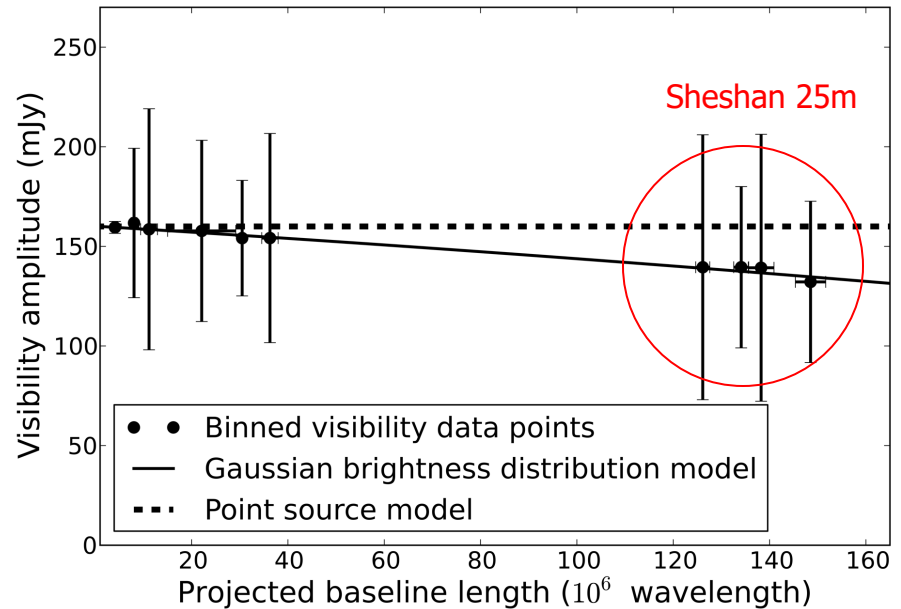
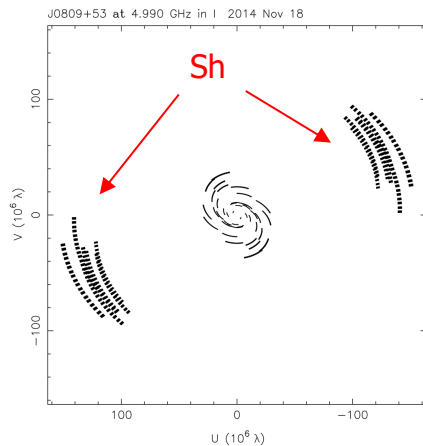


- **No VO/archives can fully replace human interaction in knowledge transfer**
- **Improving user experience, forming a healthy community are also important**
(MM astronomy/VLBI is about collaboration on global scales, after all!)

Working with visibilities



An, Cui, Paragi et al. (2016)



The fitted source size depends on the amplitude calibration of the longest baselines.

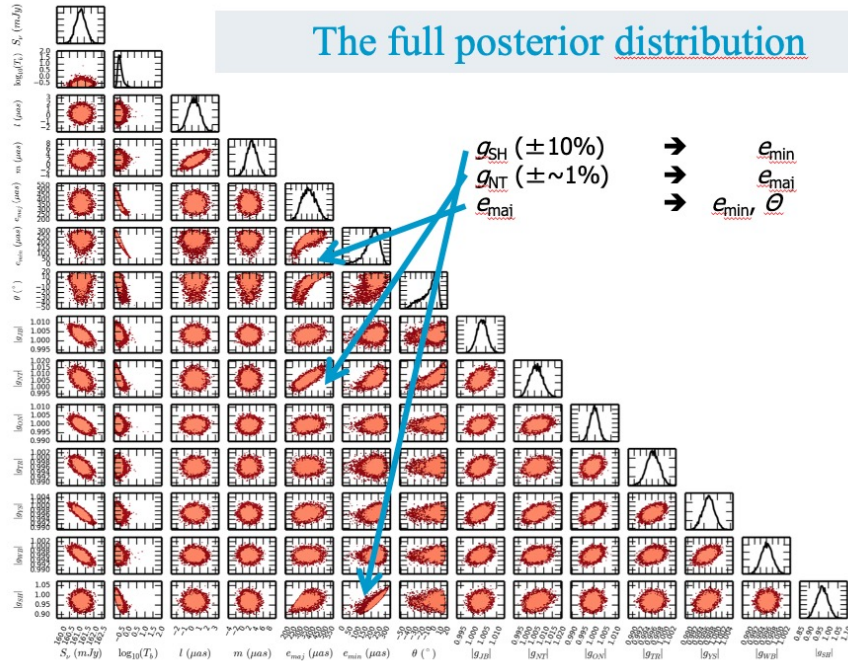
- How will these systematics affect our measurements?
- And how does this affect the smallest source size we can resolve?

➤ **Instead of high-fidelity imaging, in VLBI we often measure**

- Position (parallax distance; proper motion => Lorentz factor)
- Size and spectra (emission mechanism; with distance: energetics!)

Bayesian inference and simulations

The full posterior distribution



The resolving power of an interferometer also depends on calibrator, not just geometry and SNR (cf. Marti-Vidal+ 2012)!

$$\theta_M = \beta \left(\frac{l_c}{2(\text{SNR})^2} \right)^{1/4} \times \text{FWHM}$$

- **Source parametrization requires advanced tools/approaches** (to understand better the errors, to distinguish between models)
- **Easily accessible tools need to be developed**

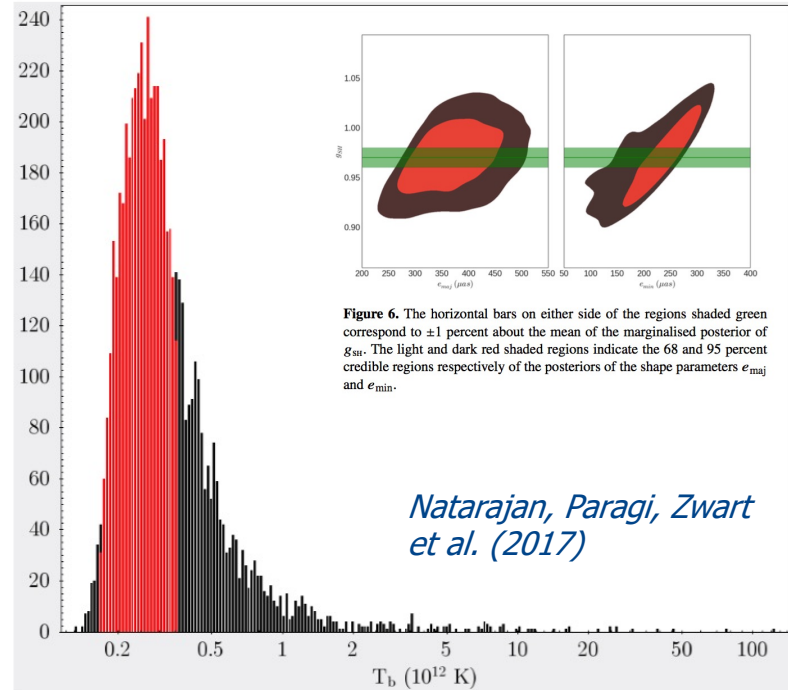
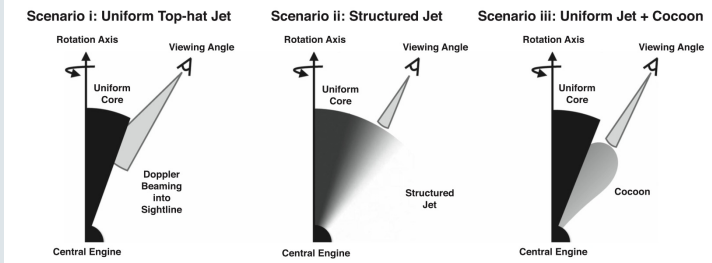


Figure 8. Histogram of the brightness temperature of J0809+5341 shown in black. The 68 percent credible region around the mode (0.25×10^{12} K) is shaded red.

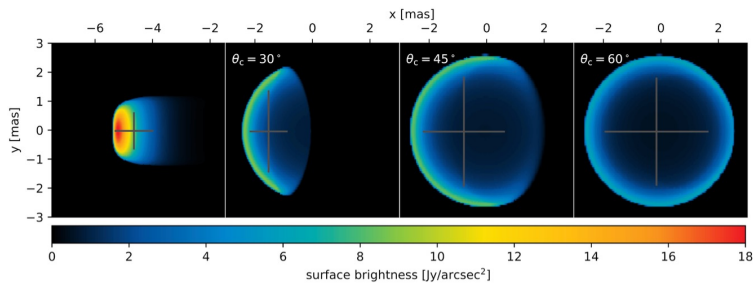
The role of simulations – faint detections

GW170817 EM counterpart



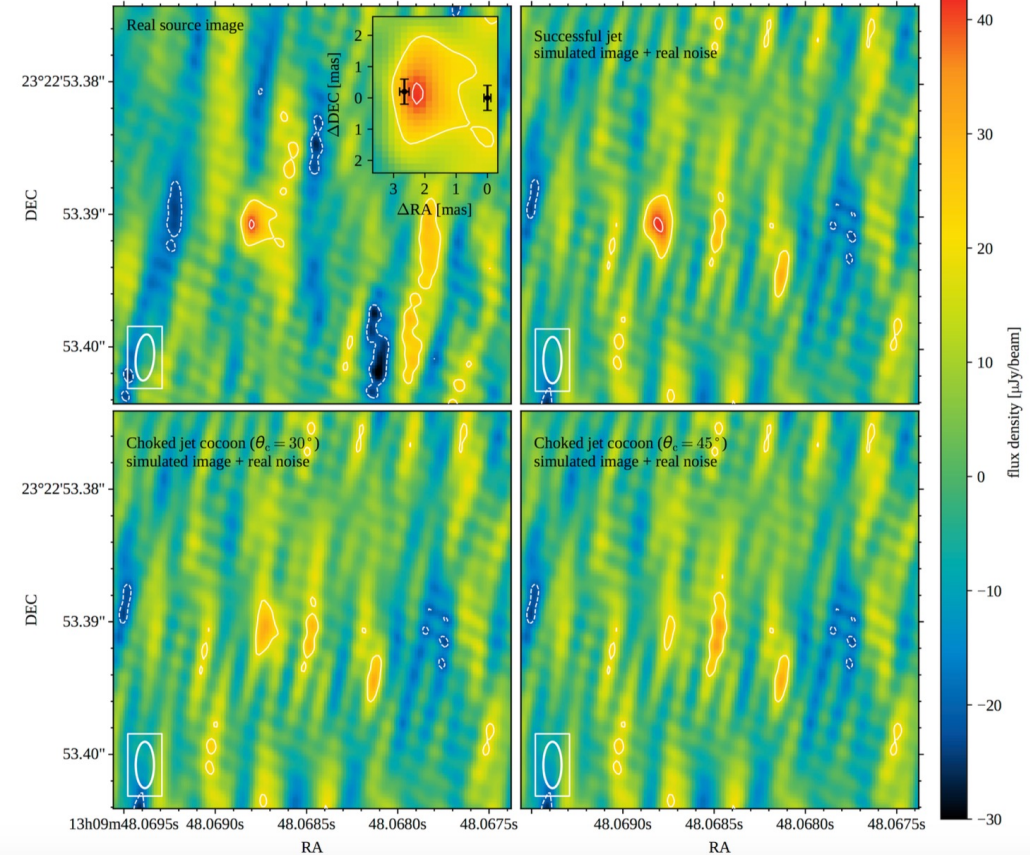
Abbott et al. (2017) ApJ, 848, L13

Set of source-brightness models



Ghirlanda et al. (2019) Science, 363, 968

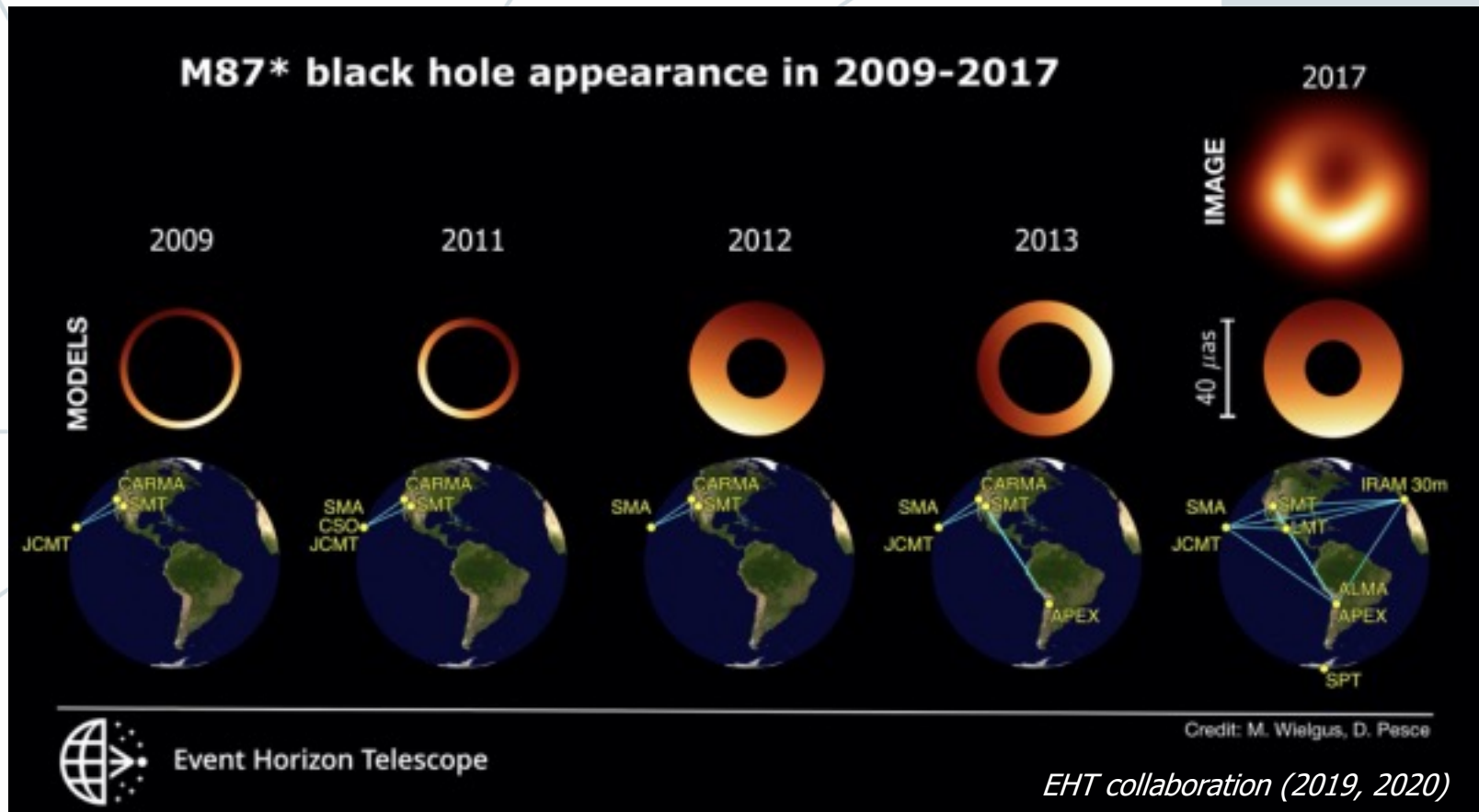
Global VLBI vs. simulated maps



➤ **Source parametrization is increasingly difficult at low-SNRs**

➤ **Full simulations (i.e. generating visibilities, rather than just convolving model+adding noise) may become a reality in the future**

What's next?



- **Broadband VLBI developments and EHT support require implementing VLBI tasks in CASA** (*van Bemmell et al. 2018, 2022*)

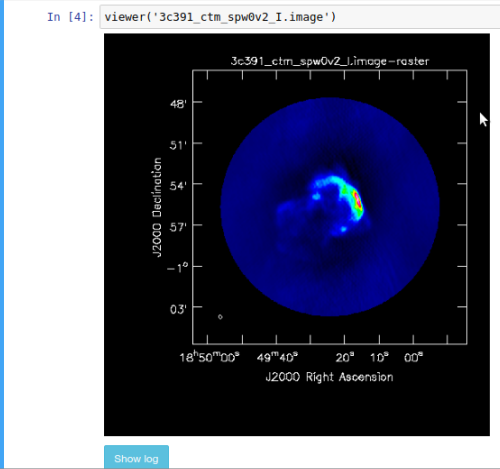
Jupyter notebooks and reproducibility

```
clearstat()
tclean(vis='3c391_ctm_mosaic_spw0.ms', imagename='3c391_ctm_spw0_multiscale_selfcal1',
       field='', spw='',
       specmode='mfs',
       niter=2000,
       gain=0.1, threshold='1mJy',
       gridding='mosaic',
       deconvolver='multiscale',
       scales=[0, 5, 15, 45], smallscalebias=0.9,
       interactive=False,
       imsize=[480, 480], cell=['2.5arcsec', '2.5arcsec'],
       stokes='I',
       weighting='briggs', robust=0.5,
       pbcor=False,
       savemodel='modelcolumn')
```

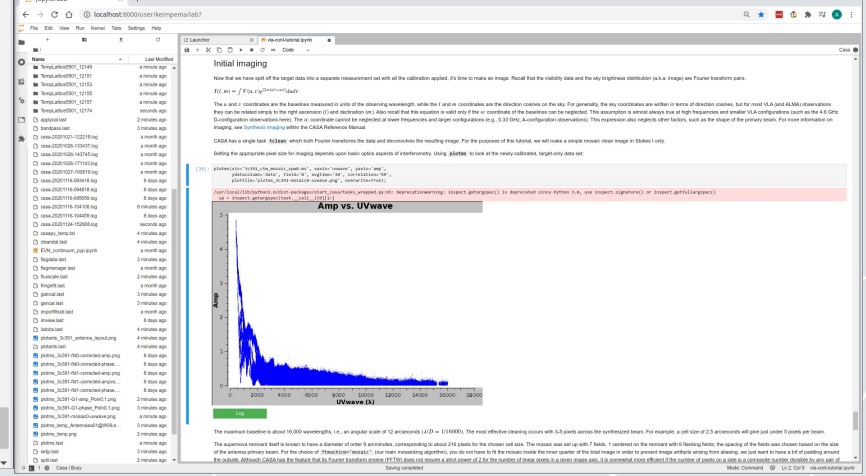
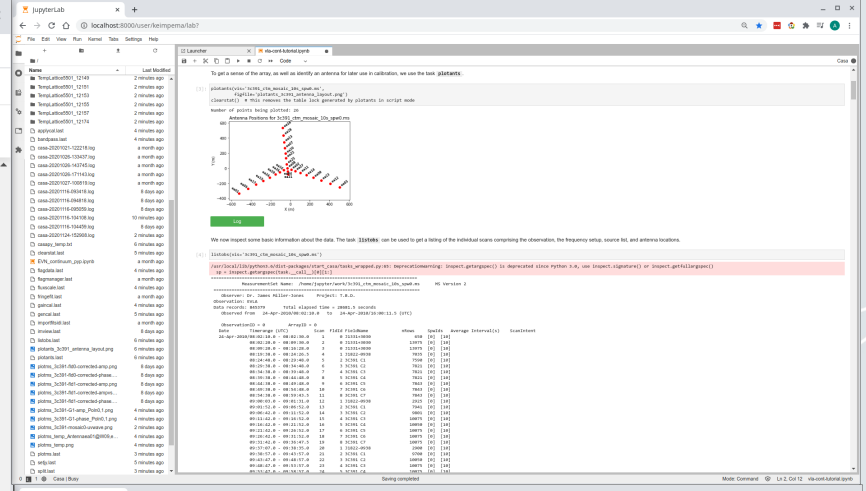
Out[3]: {}

Show log

We can open the viewer to see the result of the imaging.

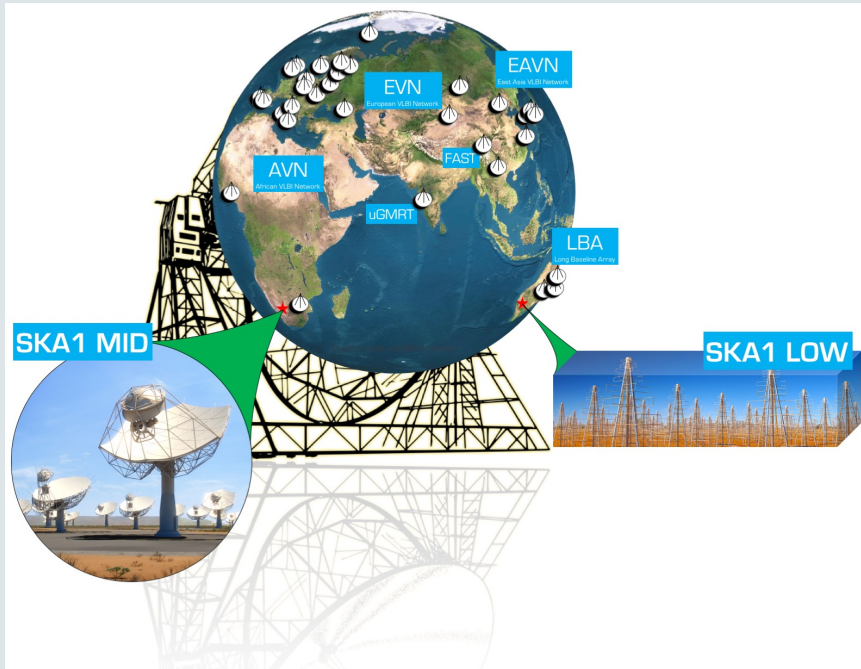


VLA notebook based on the Jupyter CASA kernel maintained & developed by JIVE

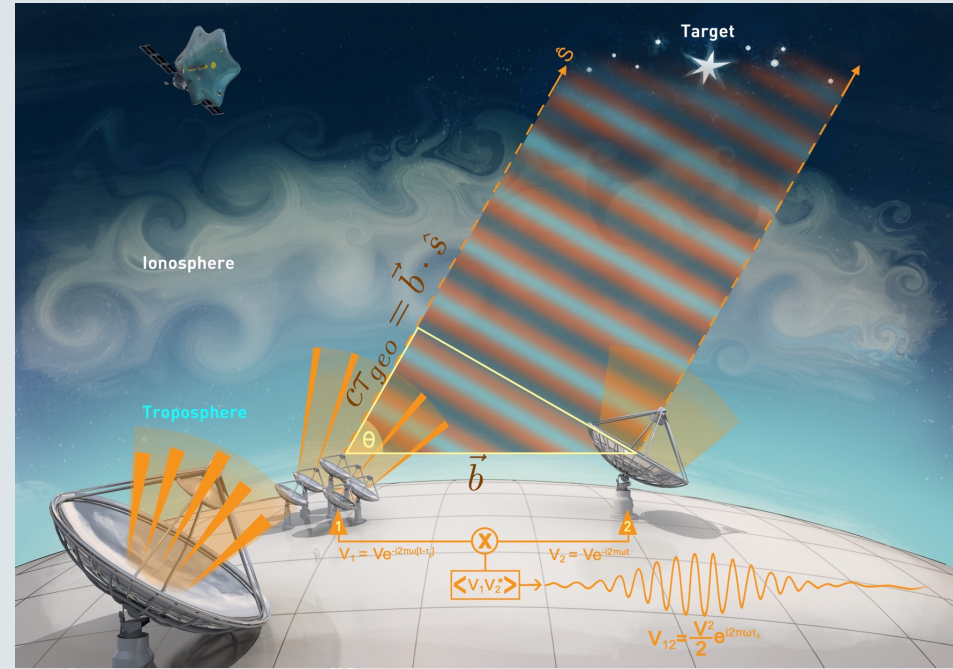


- ESCAPE (2020-2022): implement EVN Notebook
- Goal to be able to archive Notebooks with data in the EVN Archive

EVN and the SKA (SKA-VLBI)



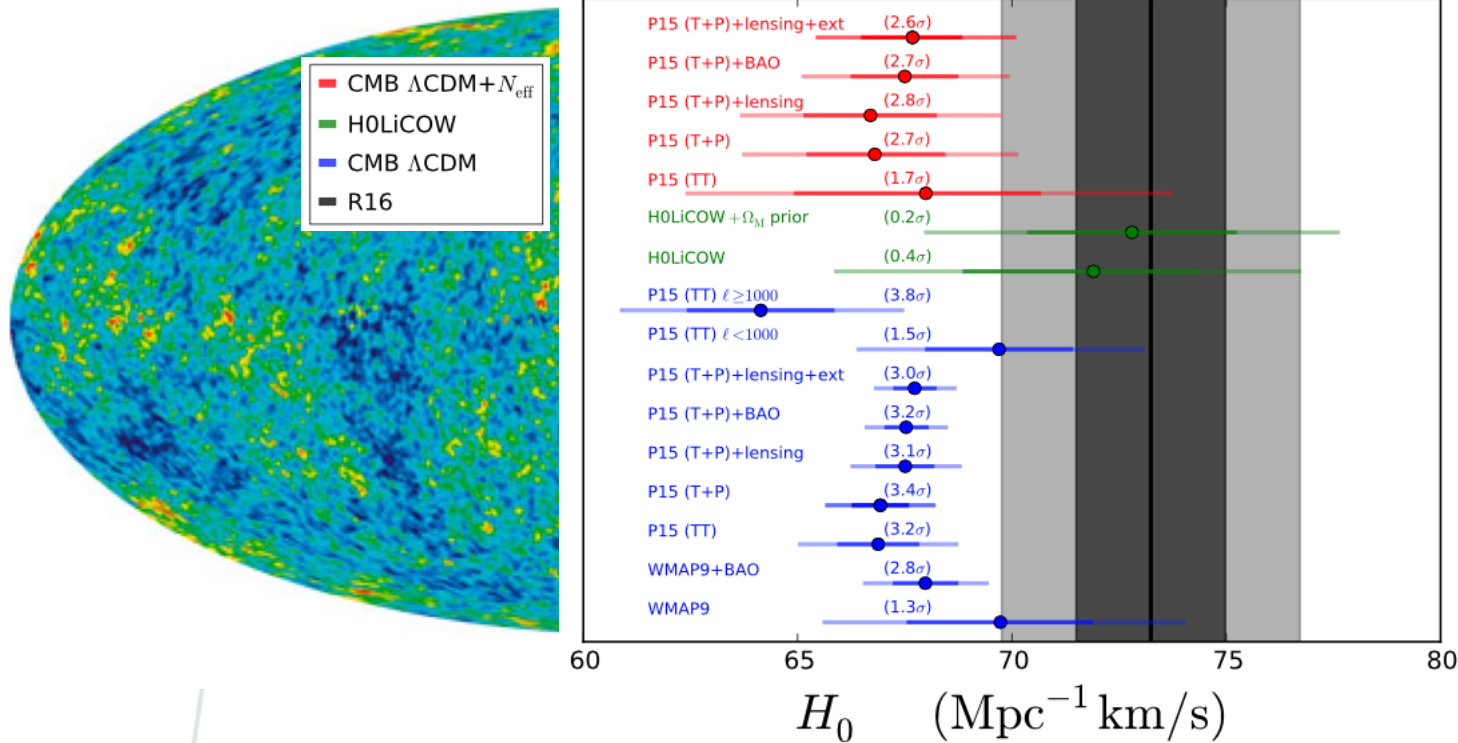
Courtesy of Garcia-Miro



Rioja & Dodson (2020)

- **Strong science driver is ultra-precise astrometry ($\sim 1 \mu\text{as}$; e.g. Paragi et al. 2015)**
- requiring $n > 4$ SKA1-MID beams!
- **Precise distance and proper motion measurements will be possible across the whole Milky Way galaxy !**
(e.g. to trace a so far hidden population of stellar-mass black hole X-ray binaries)

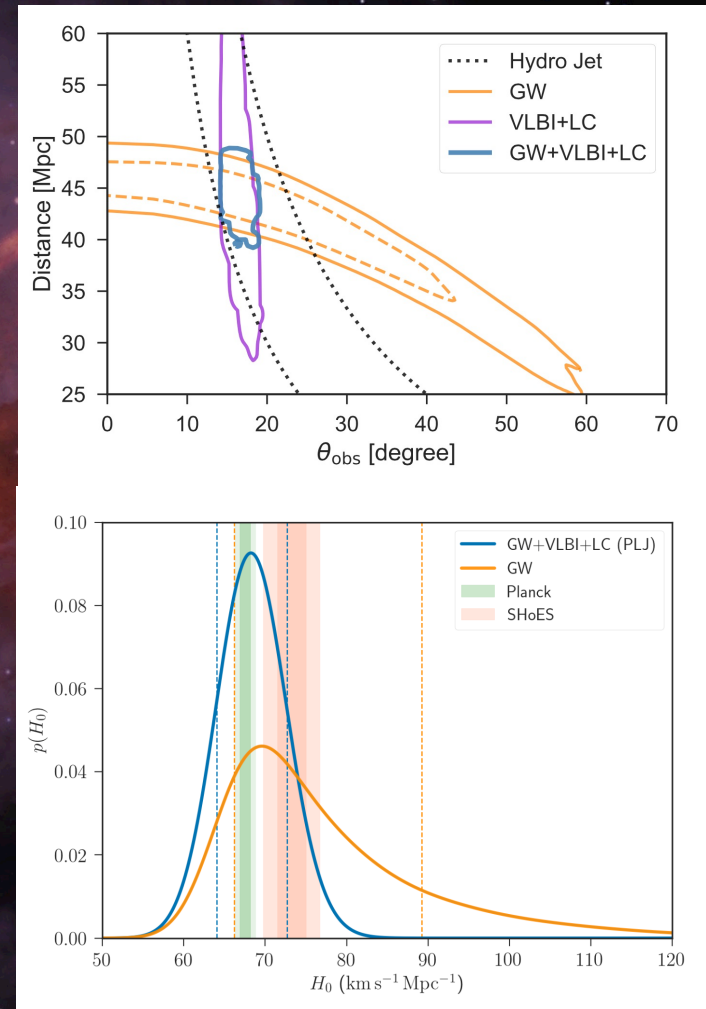
SKA-VLBI Science example: “The H_0 trouble”



Bernal et al. (2016)

- There is a discrepancy between the various CMB solutions and the local H_0 measurement from SN Ia data, at the 3σ level
- **GW standard sirens could help, but solutions are degenerate with viewing angle → VLBI can help resolve that!**

GW+VLBI constraint on H_0

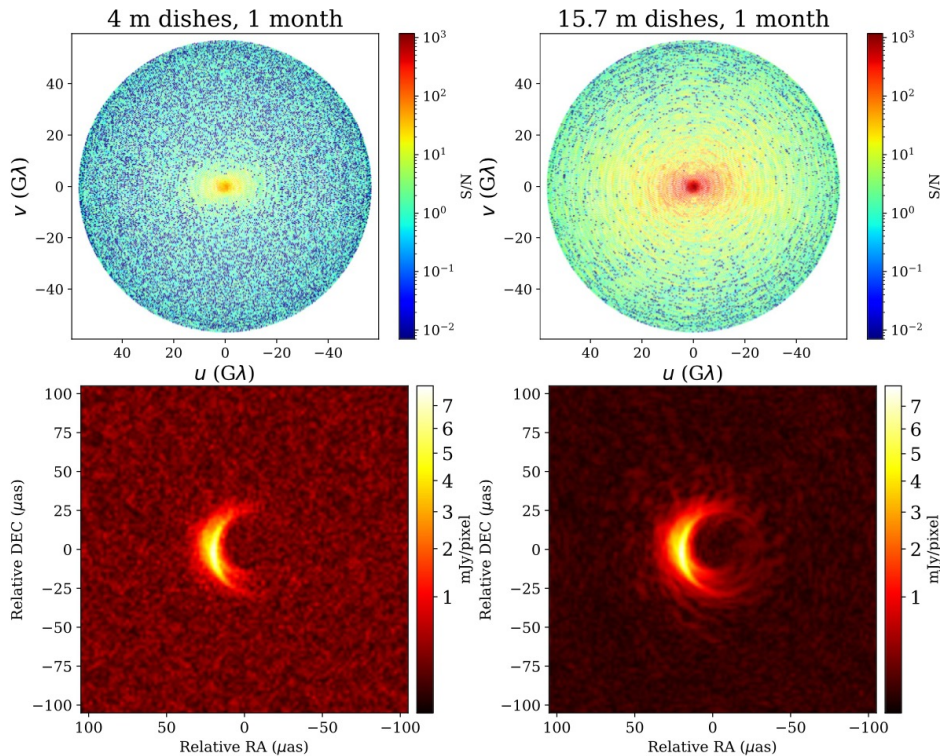


Beabudai Design

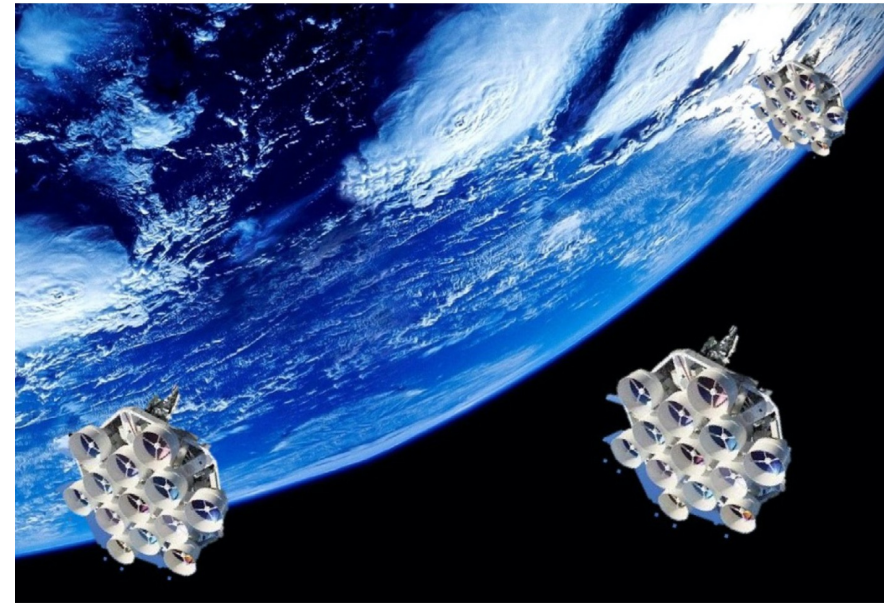
Hotokezaka et al. (2019)

➤ It takes 10 BNS mergers with EM counterparts to constrain H_0 at 5%, 200 for 1%
(Sathyaprakash et al. 2019, Astro2020 Science White Paper on binary mergers)

THEZA: a space-borne sub-mm interferometer



SNR of visibilities (up) and simulated 690 GHz images (bottom) of Sgr A* with the EHI (4m antennas, left) and the THEZA (15.7m antennas, right)



Artist's impression of a three-element version of the THEZA concept

Gurvits et al. (2022), *Acta Astronautica*, 196, 314

A virtual hub for centres of excellence?

- **Radio astronomy/interferometry is still perceived as notoriously complicated**
- **There exist a number of excellence centres to help with this all over Europe**
- **Still need to improve access, online tools, virtual support and services**
- **JIVE as a European Infrastructure Consortium is happy to work towards this:**
 - VLBI developments for Earth as well as space applications
 - Promote European radio astronomy (need for better PR?)
 - Provide advanced tools for access (some of this is addressed by ORP)
 - Bring together communities (European multi-messenger schools/workshops?)
 - Coordinate a network of European excellence centres





2022 October 10, EGO, Italy

Multi-Messenger Astrophysics Workshop