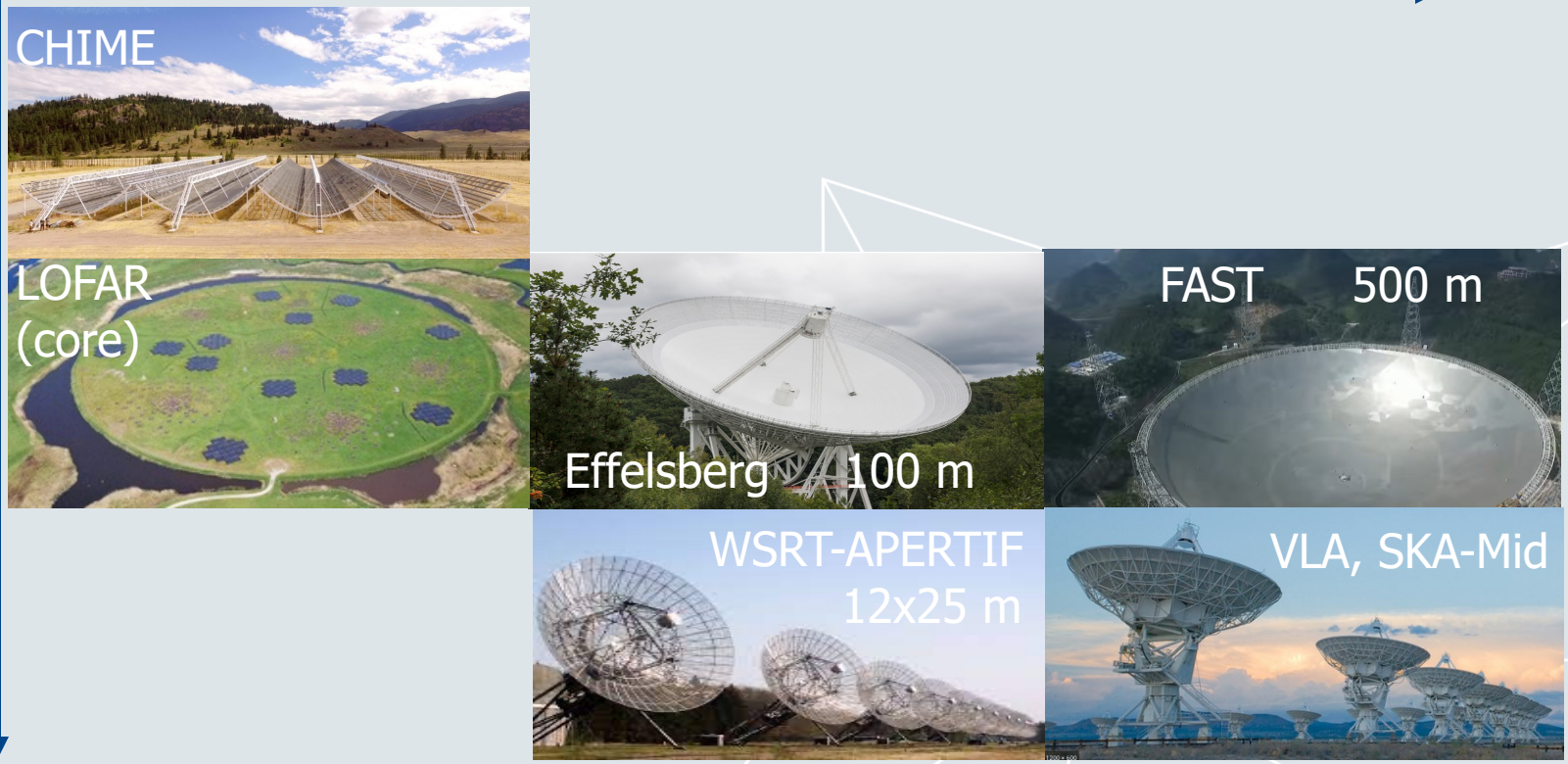
A virtual hub for multi-messenger/interferometry centres@JIVE

Zsolt Paragi
JIVE

Radio Astronomy / Telescopes (some)

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

Resolution: degrees to milliarcseconds (mas)



- **Covering a broad range of λ ~m to sub-mm / or frequencies (~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

- **Combining some of the most powerful telescopes in the world:**
- **To detect extremely weak signals, and image them at the highest detail**

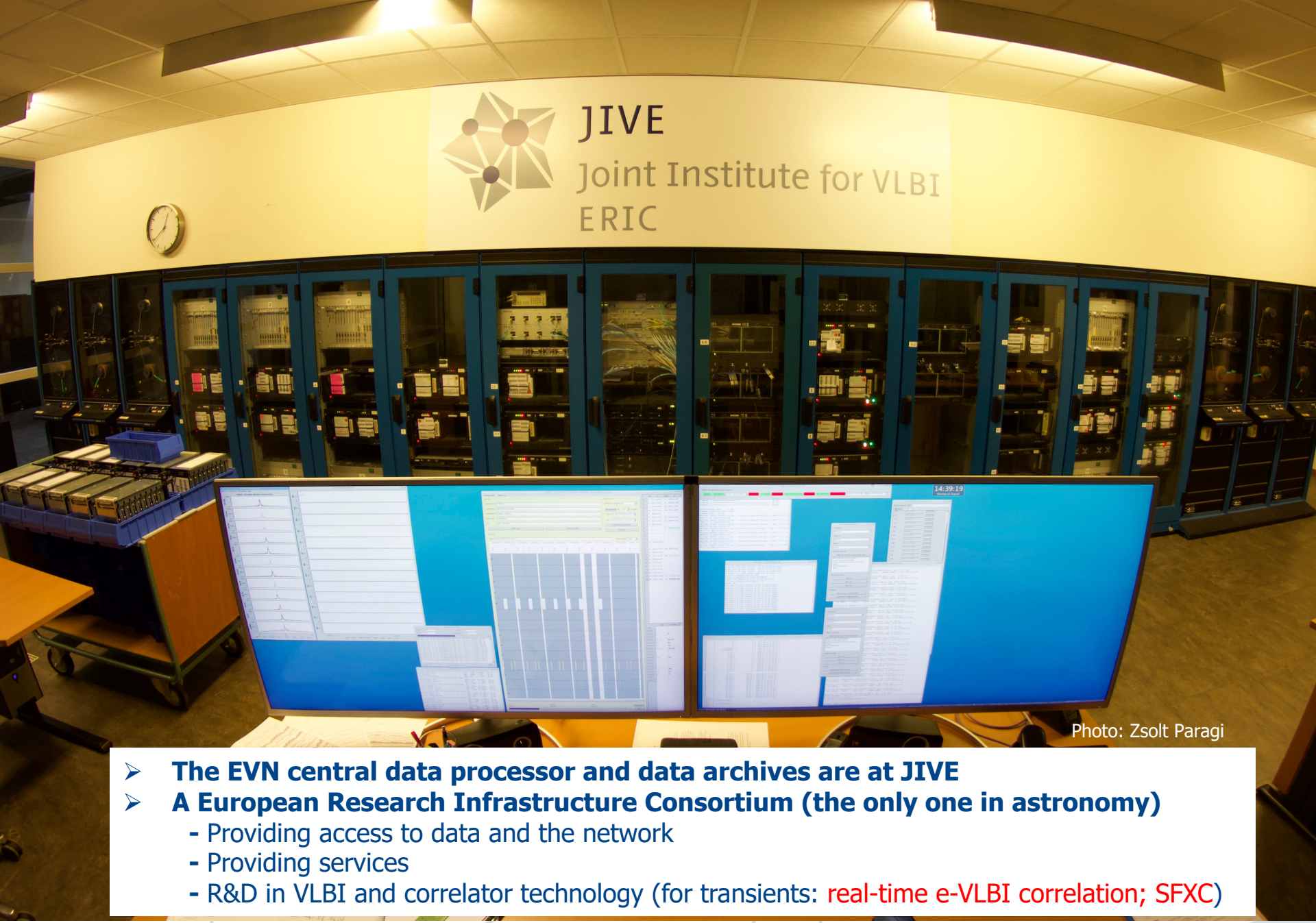
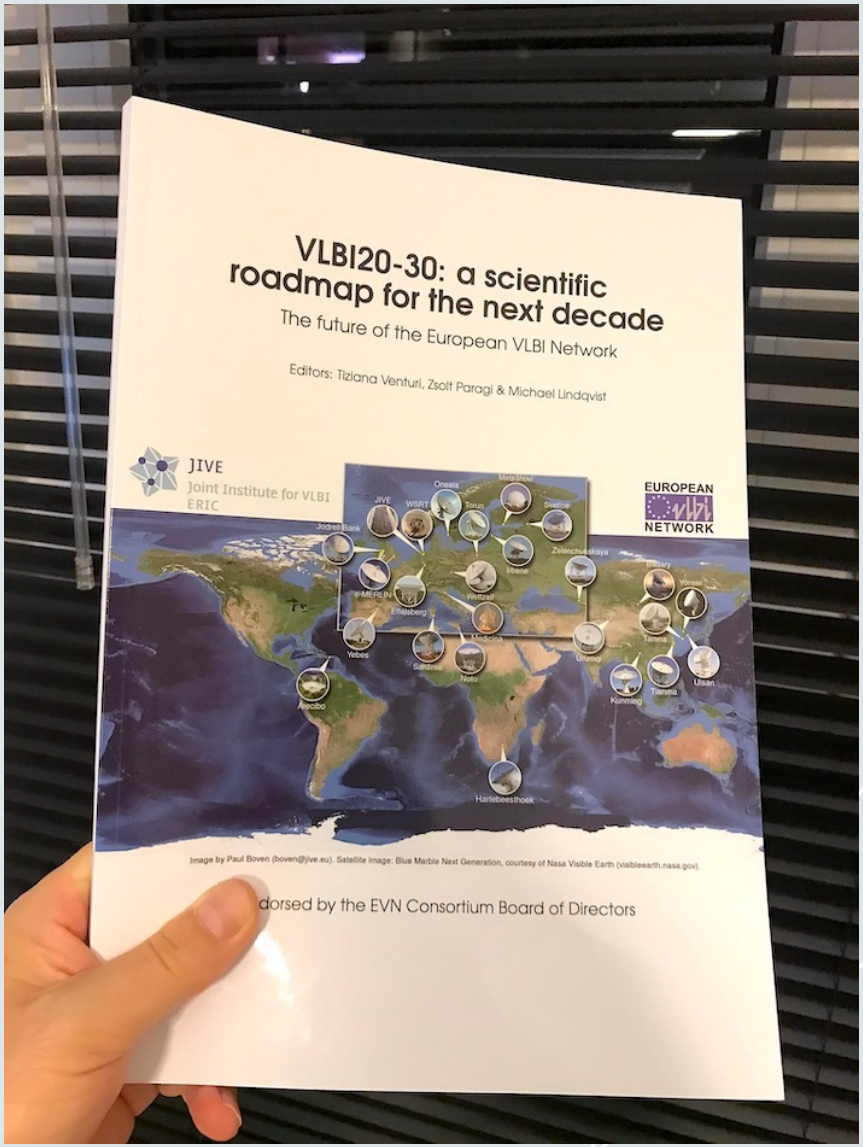


Photo: Zsolt Paragi

- **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

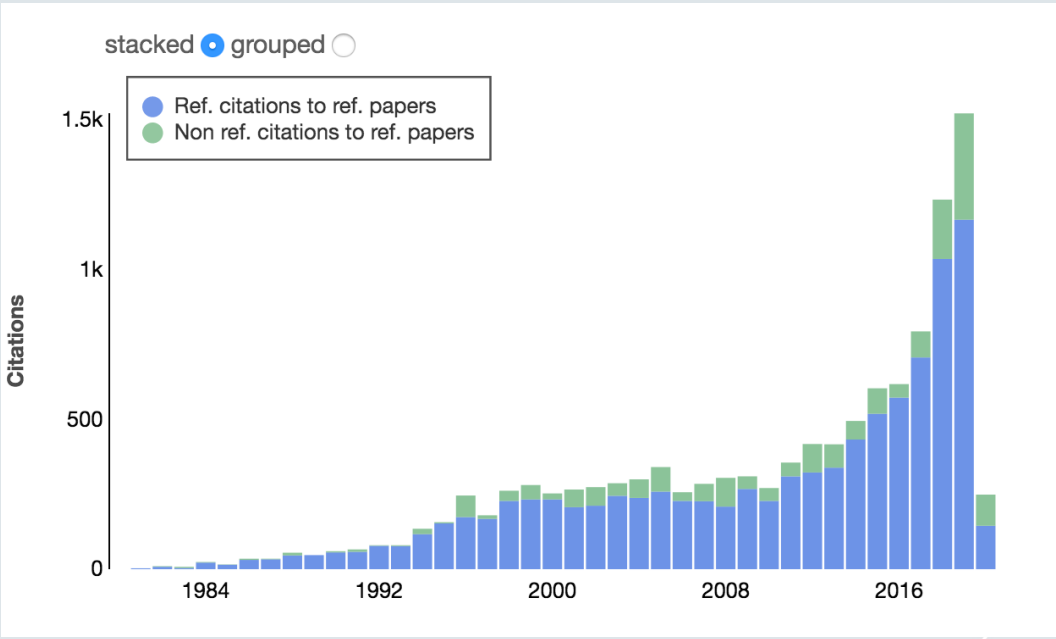


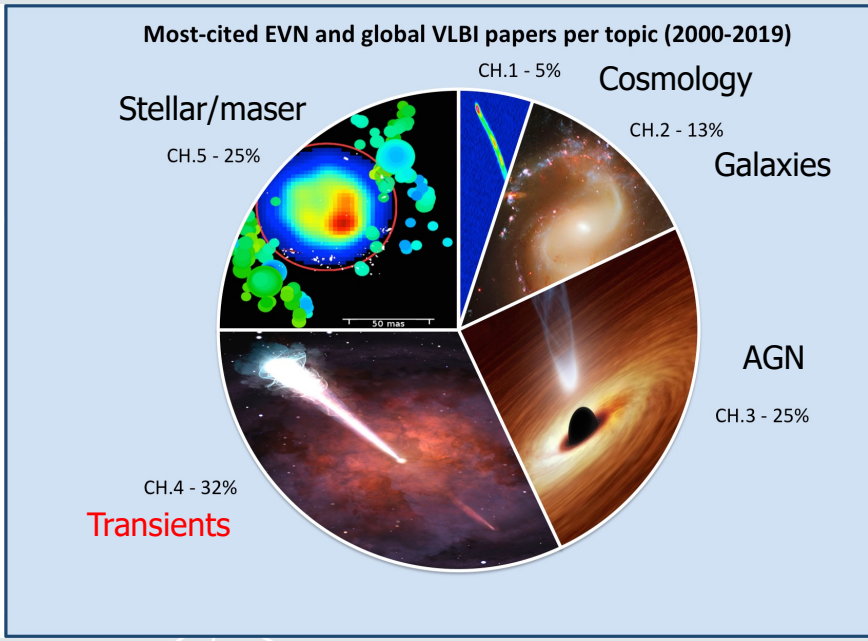
- The VLBI20-30 scientific roadmap has been published and printed
- A technological roadmap was derived from the science requirements
- Synergy with other radio telescopes and major European facilities is highlighted

arXiv:2007.02347
https://arxiv.org/abs/2007.02347

The EVN Transformation

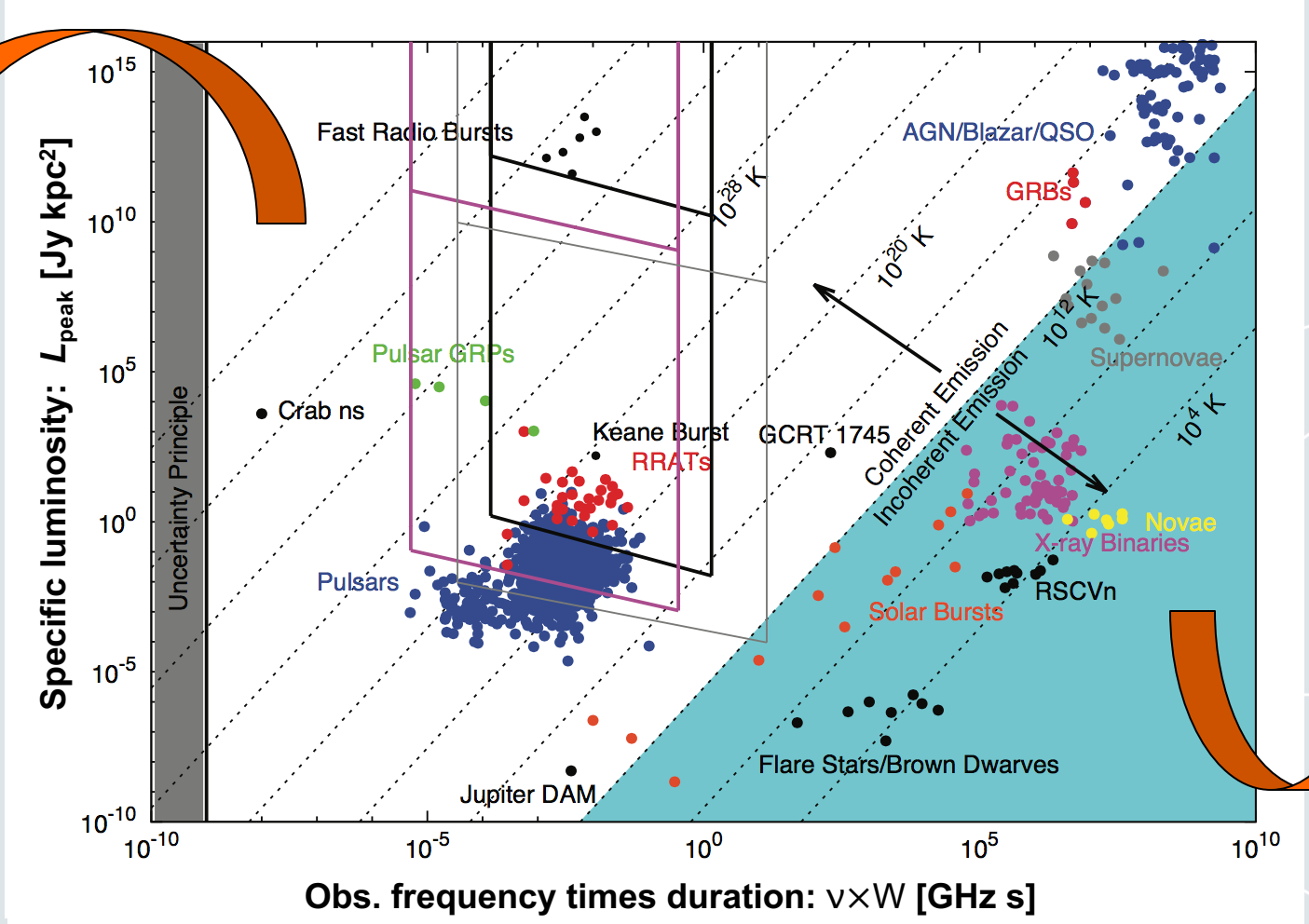
Top-100 most cited papers with EVN data



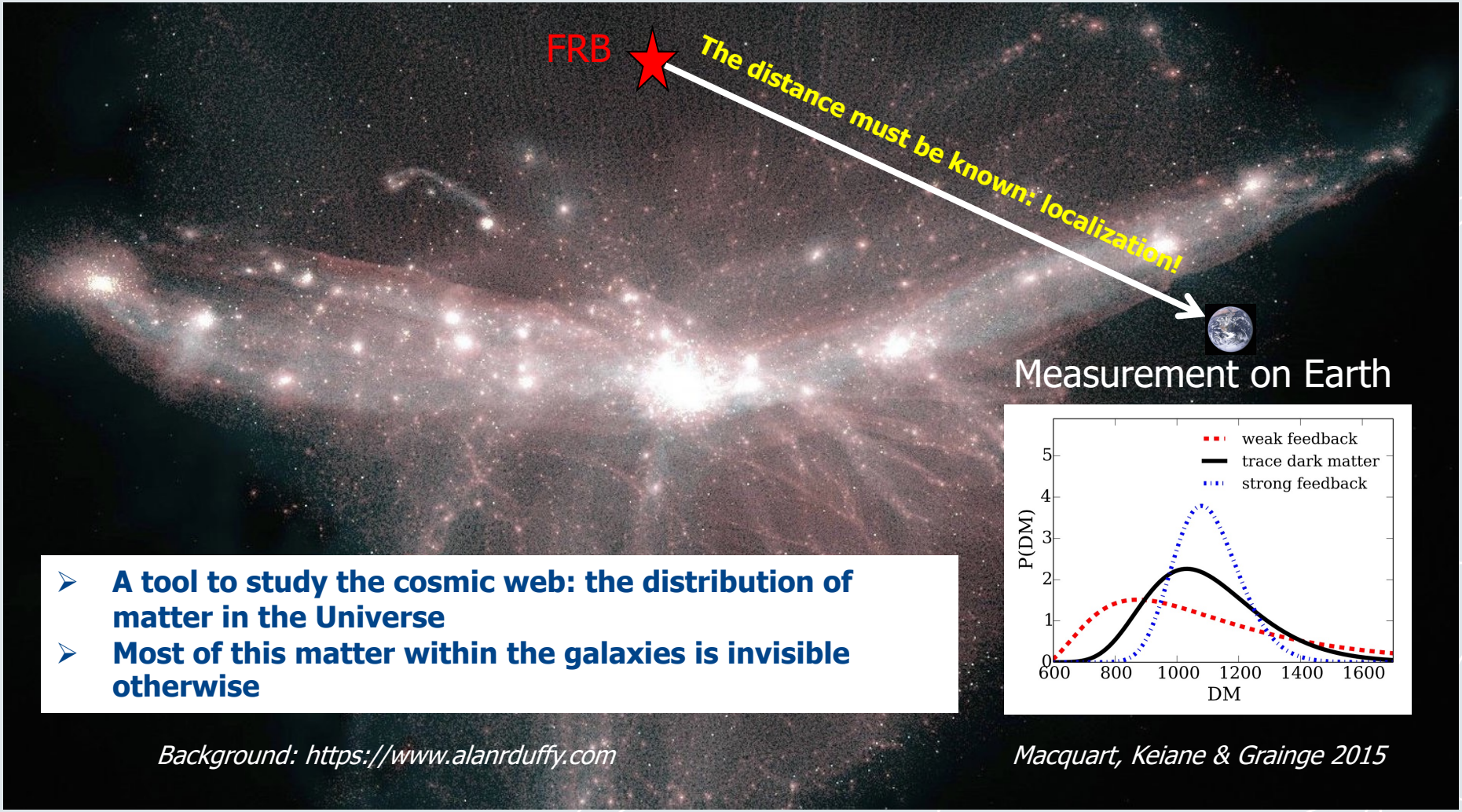


- **Technical developments (sensitivity; e-VLBI; SFXC) transformed our science**
- **There is a globalization in astronomy, affecting EVN operations as well**
- **The multi-messenger era kicks in (~2017):**
  - Discovery of GW170817 EM counterpart
  - VLA/EVN localization of FRB 121102

The transient parameters space



Fast Radio Bursts: a tool for cosmology

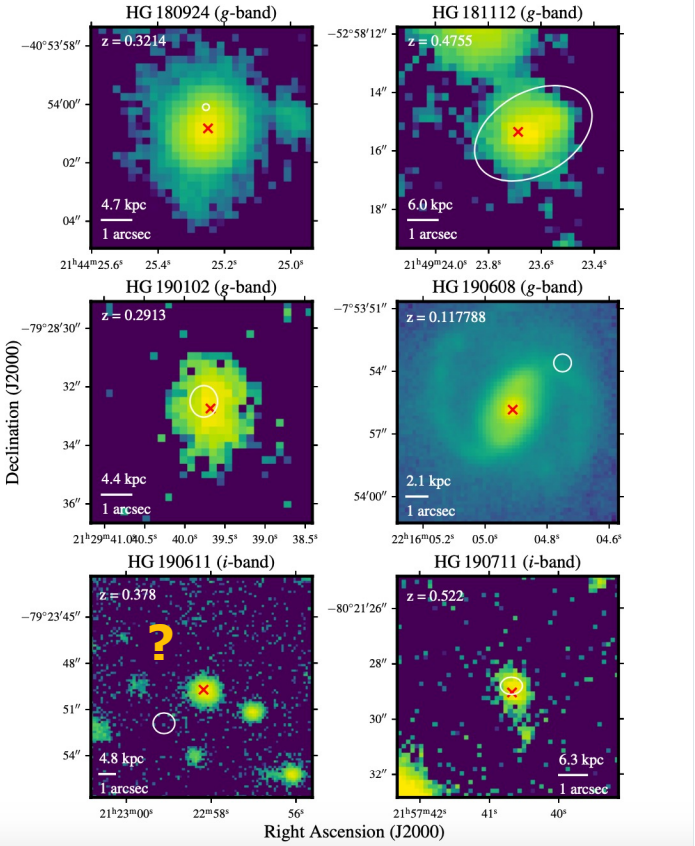


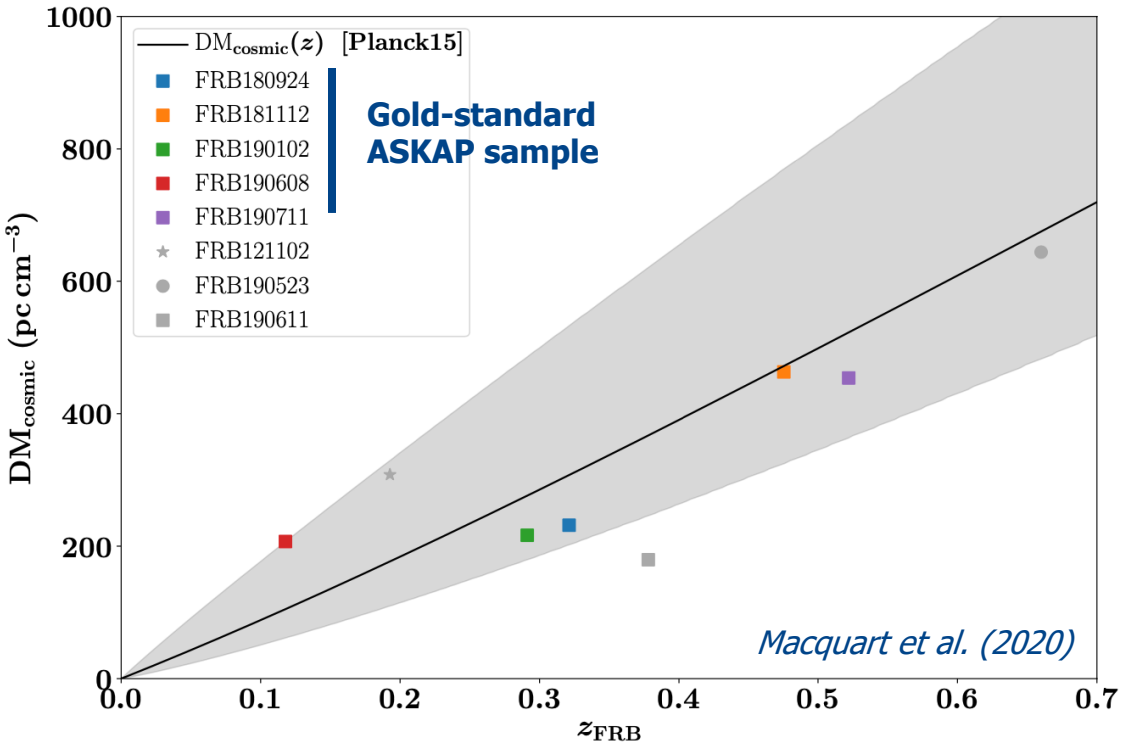
- **A tool to study the cosmic web: the distribution of matter in the Universe**
- **Most of this matter within the galaxies is invisible otherwise**

Background: https://www.alanrduffy.com

Macquart, Keiane & Grainge 2015

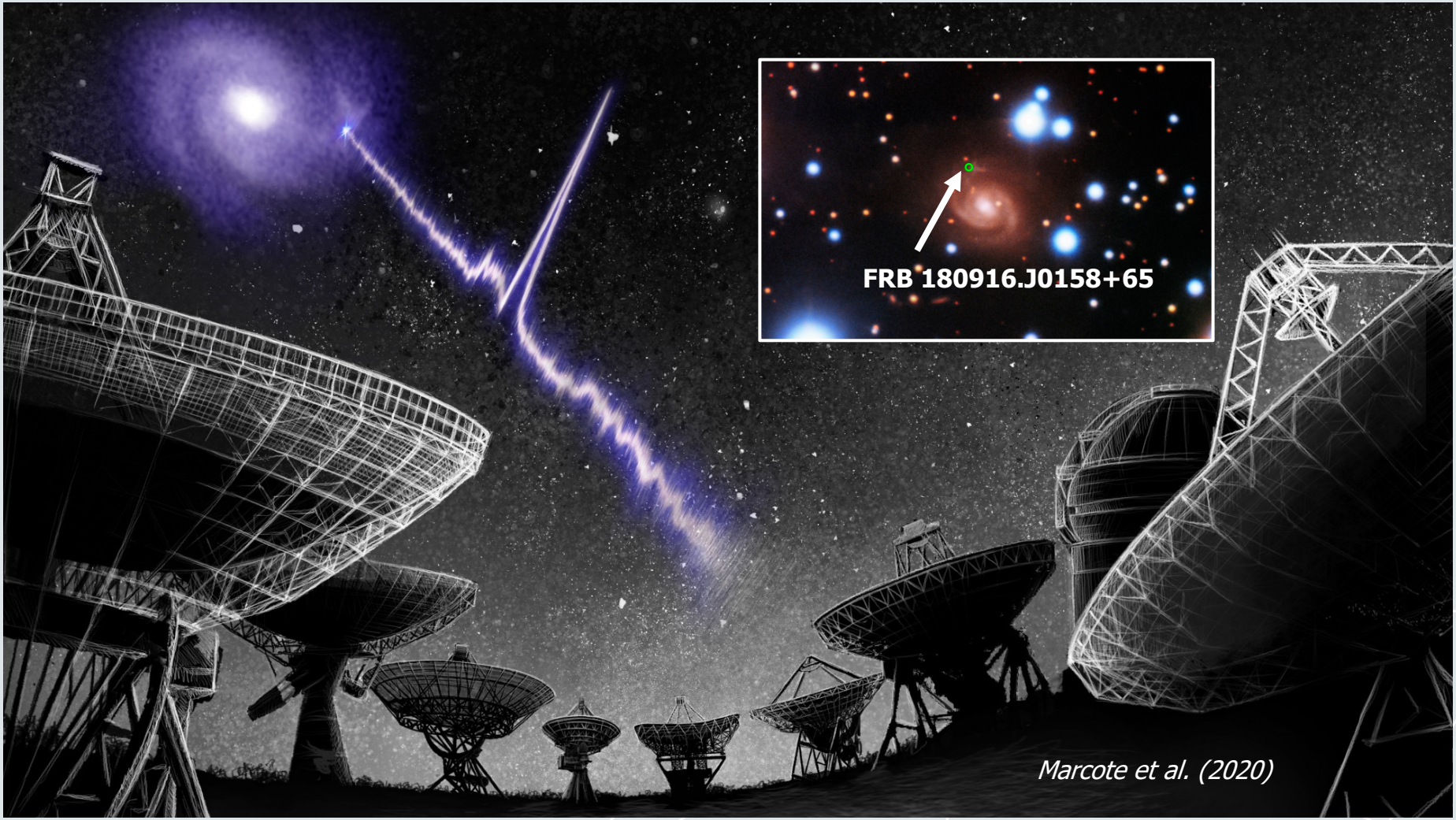
"A census of baryons in the Universe from localized fast radio bursts"





- More than ¾ of baryons reside in a highly diffuse phase, hard to observe
- How these are distributed is is fundamental to structure formation models
- Used published FRBs with arcsec localization +4 new ASKAP FRBs to probe this

EVN: a powerful localization machine



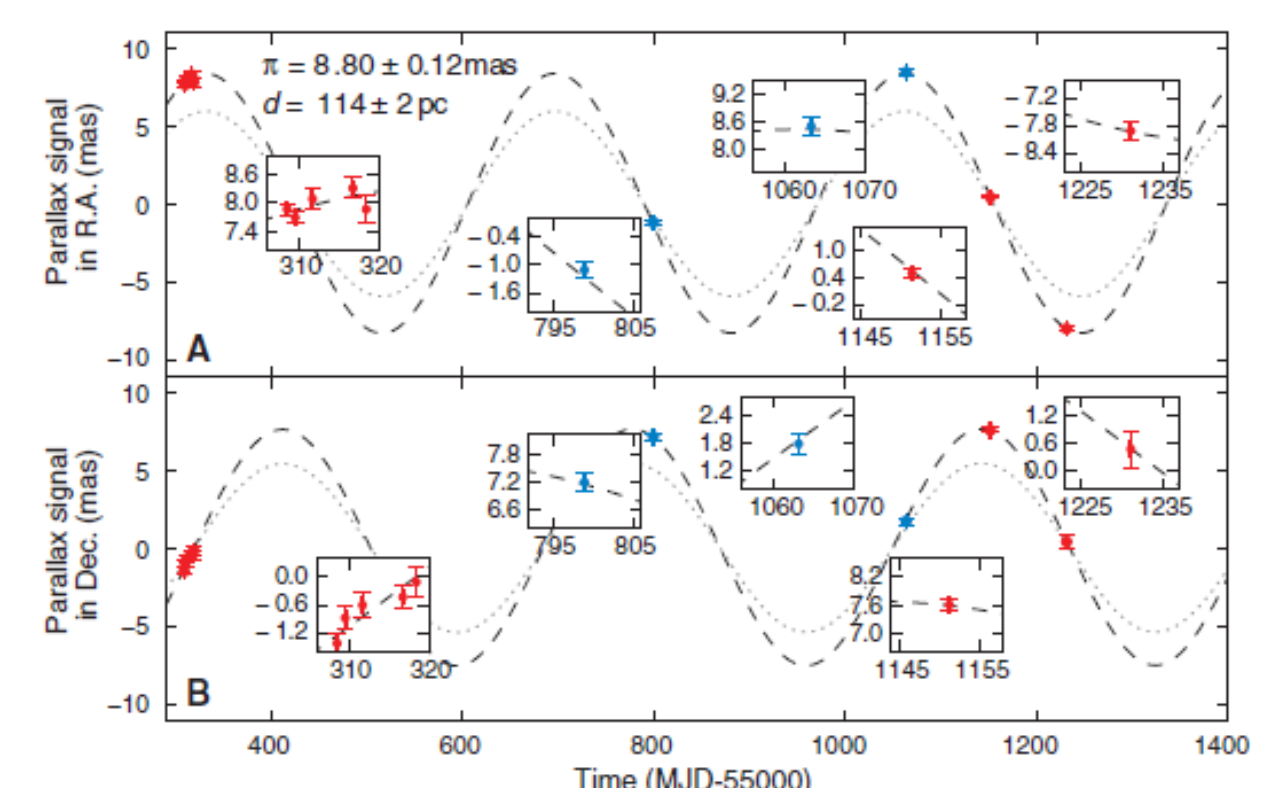
- **Follow-up is not possible for ms-duration events; except for repeaters**
- **EVN is the only instrument capable of FRB localization on milliarcsecond scales**

(doing "SKA science" today)

Triggered e-VLBI science: a dwarf nova

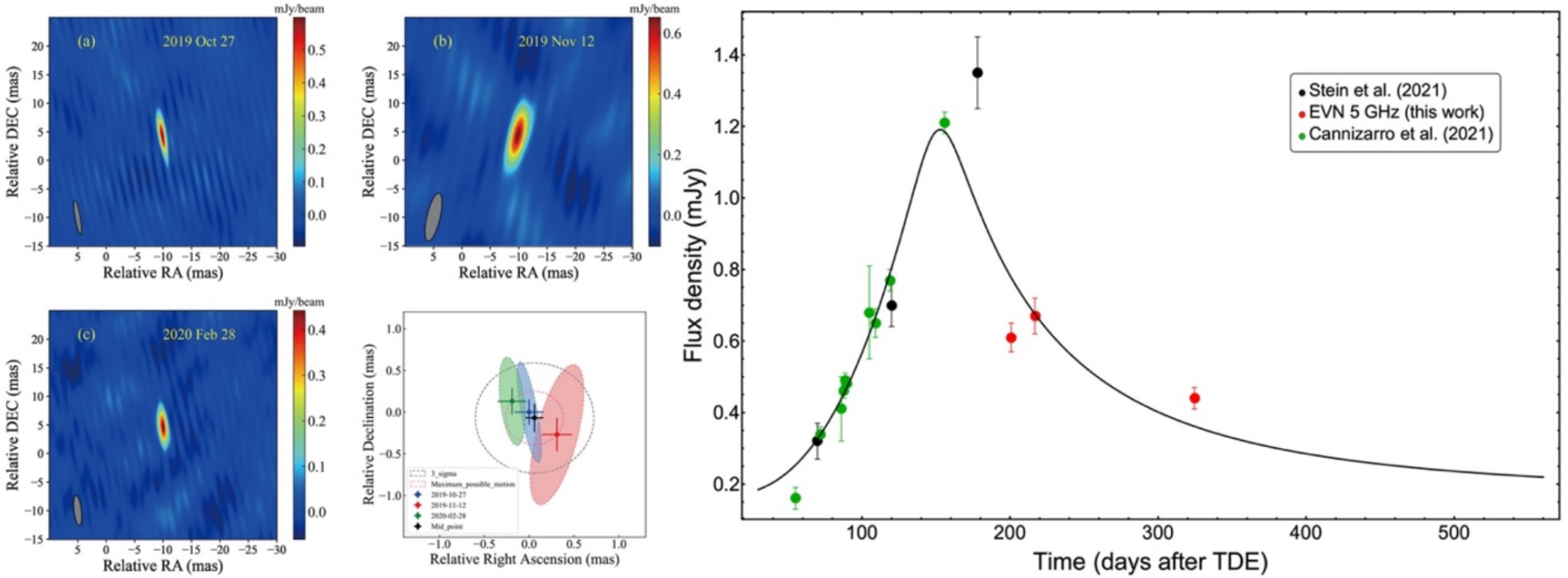
VLBA + e-EVN

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

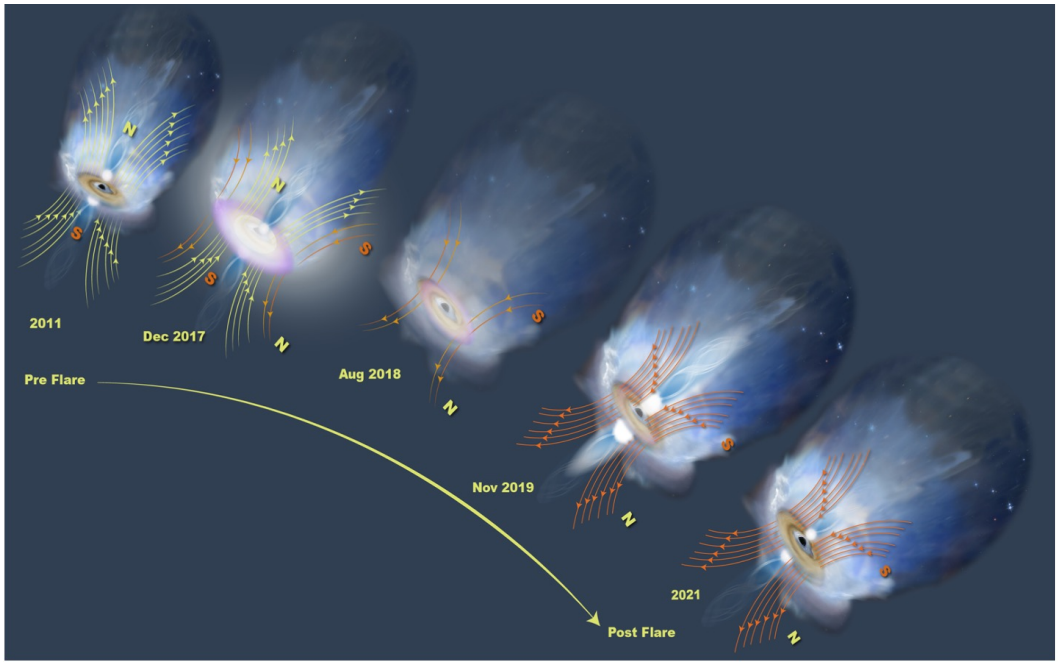


- **AT2019dsg**

- EVN monitoring rules out a (mildly-)relativistic outflow (**EM140, RSM04**)
- Light-curve analysis favors outflow (v~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
*****************************************
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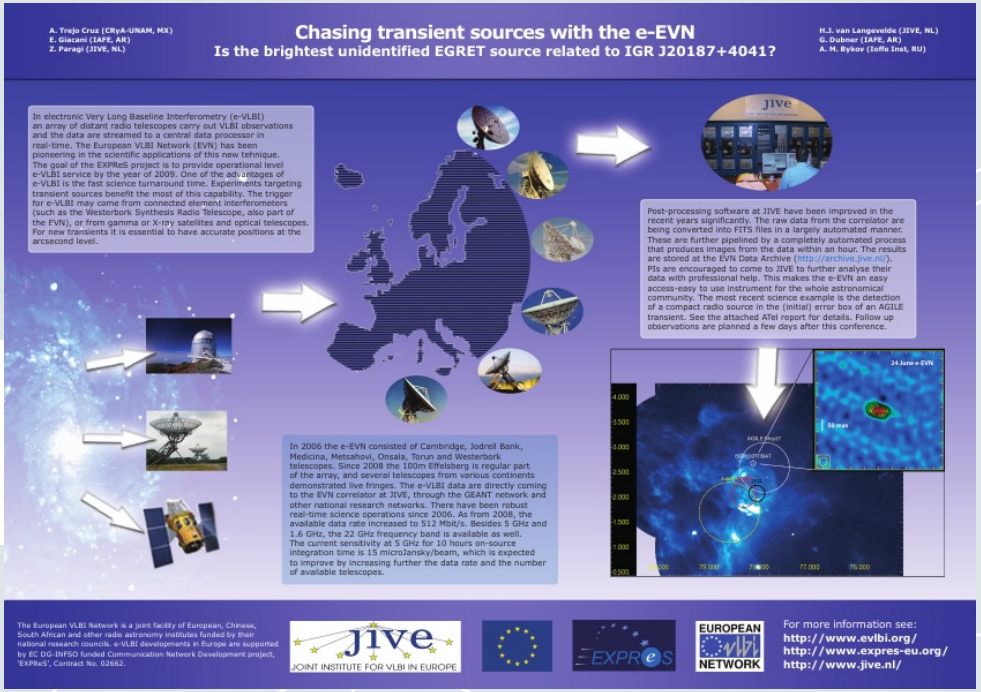


* A new e-VLBI class is introduced, automated generic e-VLBI trigger observations.
It is an observation to be scheduled automatically during an e-VLBI run
only if a specific set of triggering criteria is met.
The expected response time to execute a new program is about 10 minutes.
For details see:
http

- **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!**

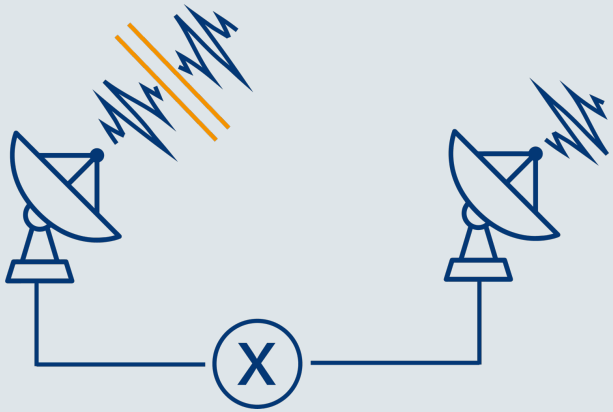
EVN-lite pilot program (2023)

- **Proposal to facilitate projects requiring >>100h observations** (outside of regular observing sessions)
- **May support base programs like fast transient search, maser surveys …**

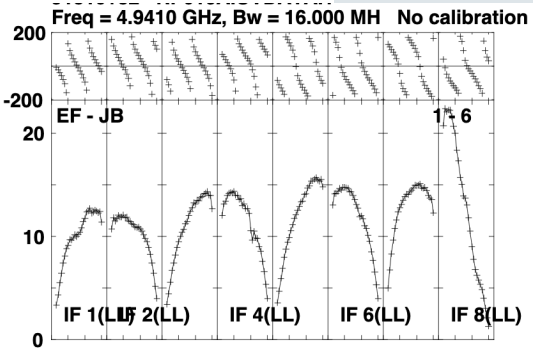
Triggering on base programs to support transient science / multi-messenger astronomy

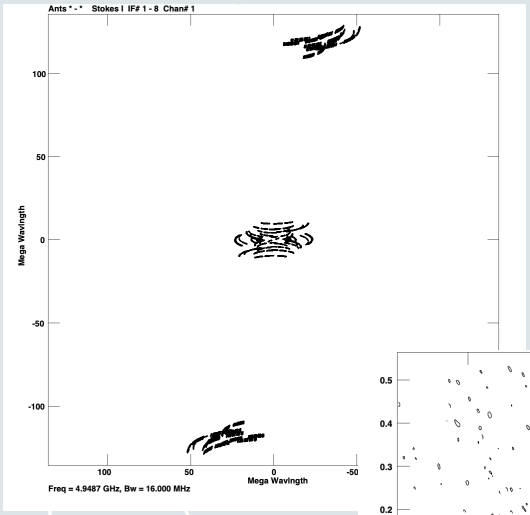
- **Operational impacts are being assessed**

Why VLBI is special?



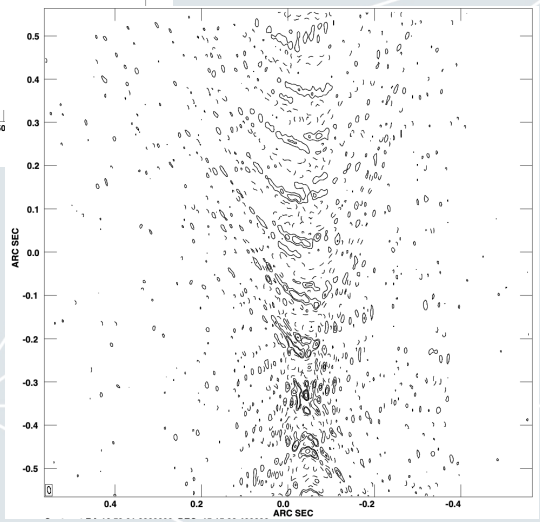
HELP!





SPARSE UV-COVERAGE

"DIRTY" MAPS



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

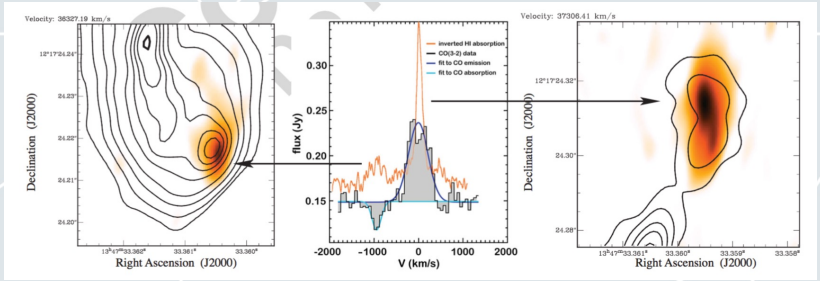
- **Moreover:**
  - Sparse, typically heterogeneous arrays
  - Individual stations with special issues
  - Non-trivial scheduling, observing and processing
    - ➔ Users require extensive help

EVN & User Support at JIVE

A bit simplified highlights:

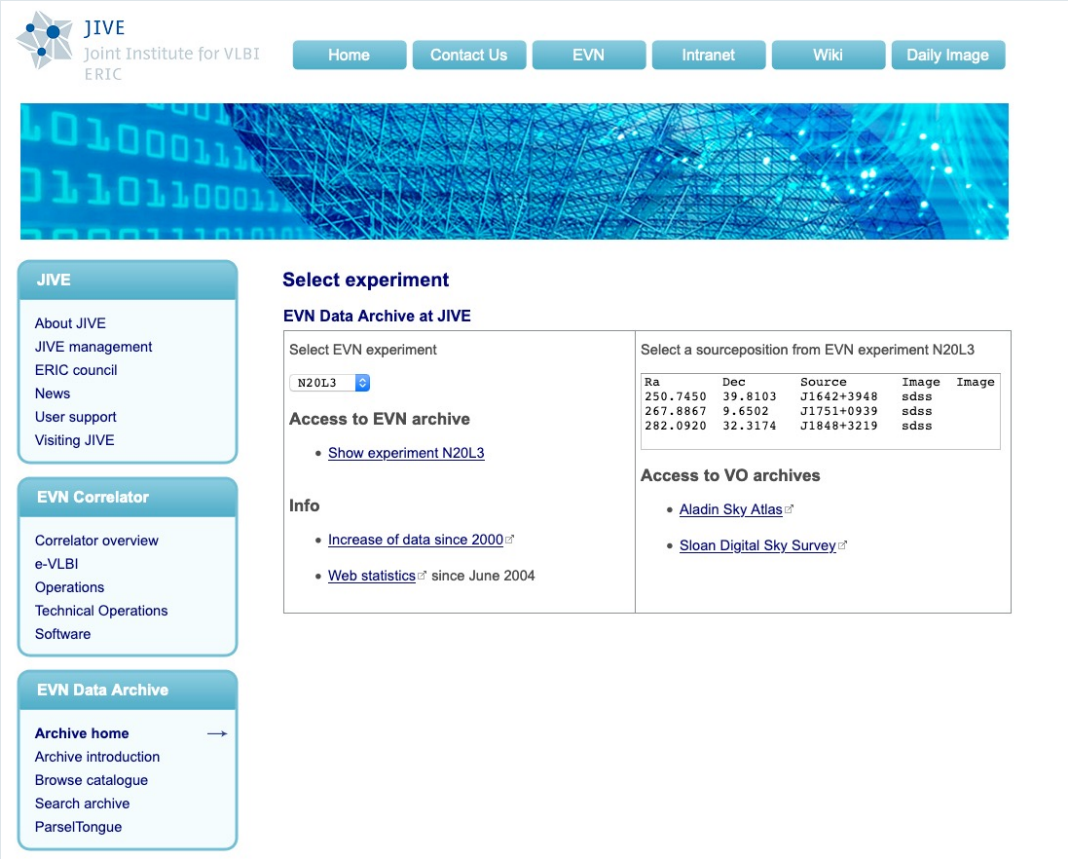
- **Production Correlation**
  - MS / FITS file preparation
  - Standard plots & PI letter
  - ANTAB & FLAG tables
  - Data pipeline (ParselTongue)
- **Network Support**
  - Ftp fringe tests
  - Network Monitoring Experiments
  - Testing new observing modes and equipment
- **User Support**
  - Help with 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



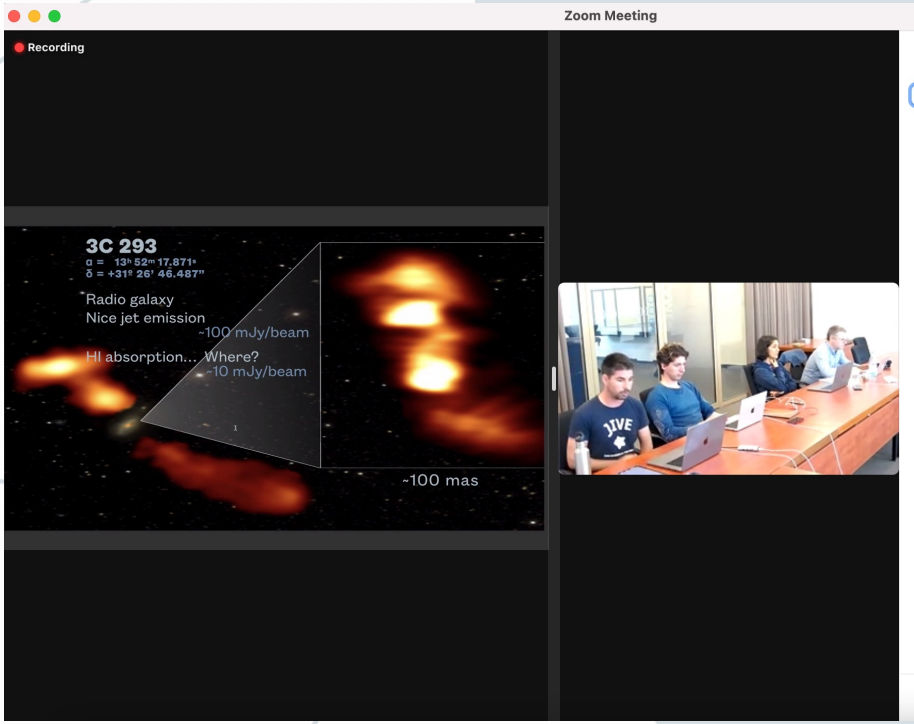
- **Some basic VO functions have been implemented**
- **Discussions on maps/*uv* - data**

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)

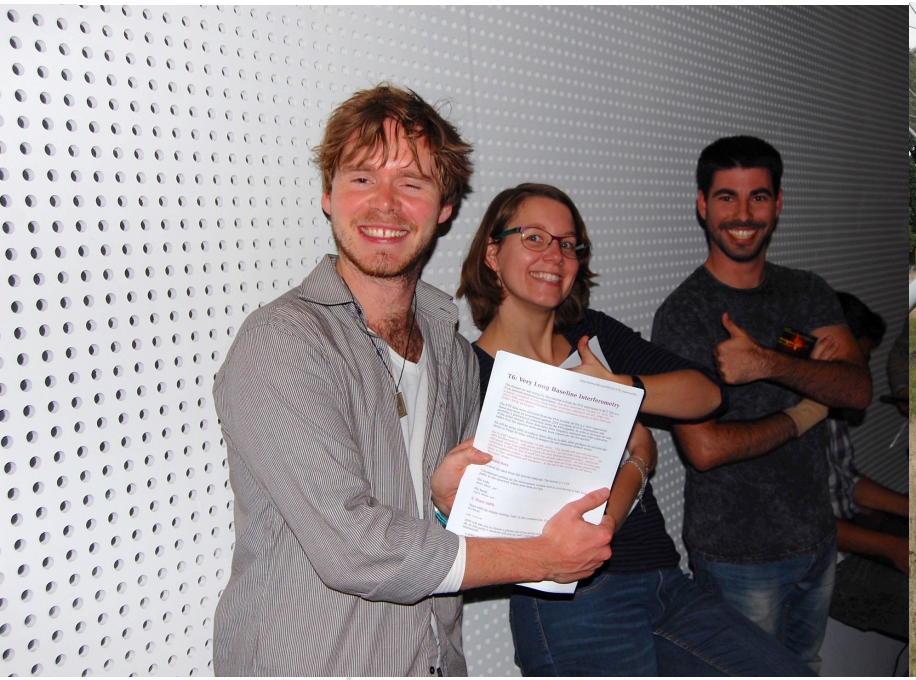


First EVN online training (right)

- **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

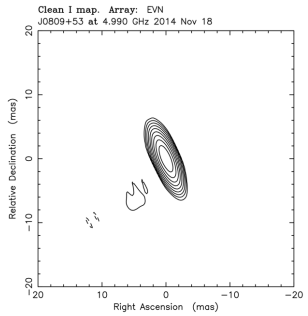
Left: helpers during ERIS 2018 in Dwingeloo



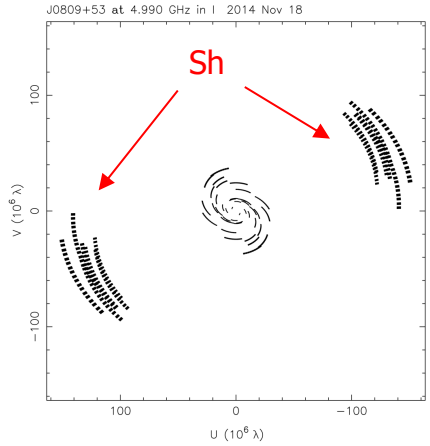
Right: ERIS 2022 group photo

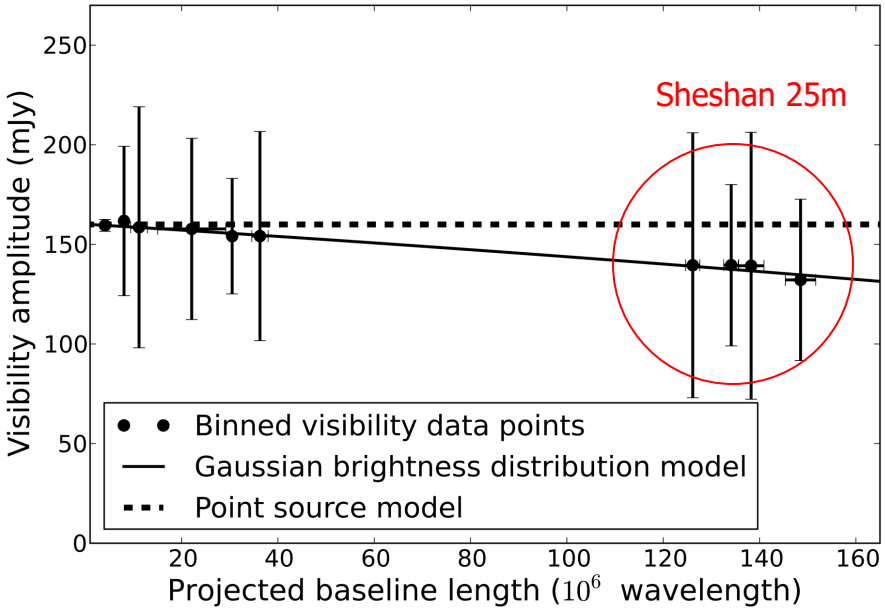
- **No VO/archives can fully replace human interaction in knowledge transfer**
- **Improving user experience, forming a healthy community are also important**
  (MM astronomy/VLBI is about collaboration on global scales, after all!)

Working with visibilities



An, Cui, Paragi et al. (2016)





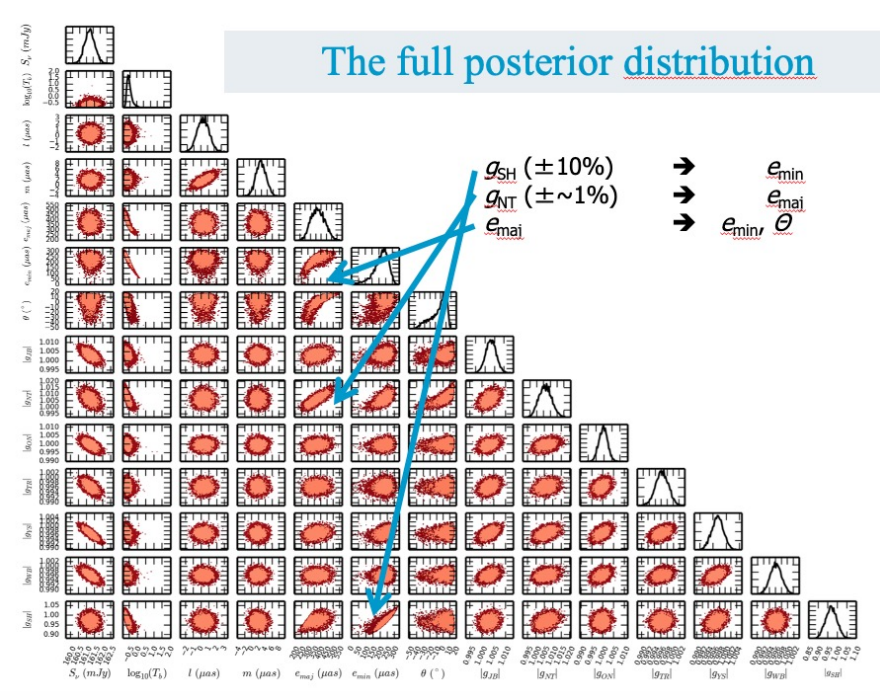
The fitted source size depends on the amplitude calibration of the longest baselines.

- 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



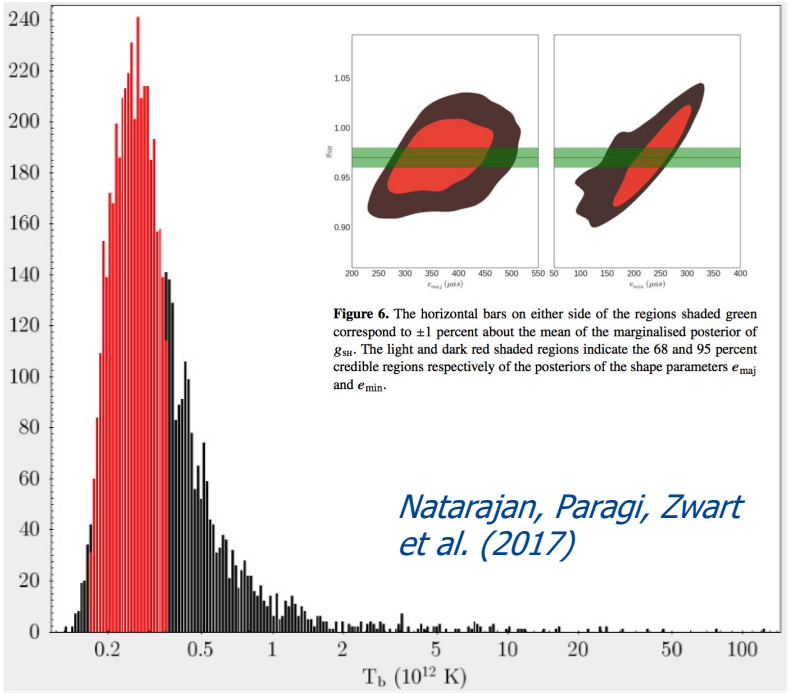


Figure 6. The horizontal bars on either side of the regions shaded green correspond to ±1 percent about the mean of the marginalised posterior of g_{SH}. The light and dark red shaded regions indicate the 68 and 95 percent credible regions respectively of the posteriors of the shape parameters e_{maj} and e_{min}.

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

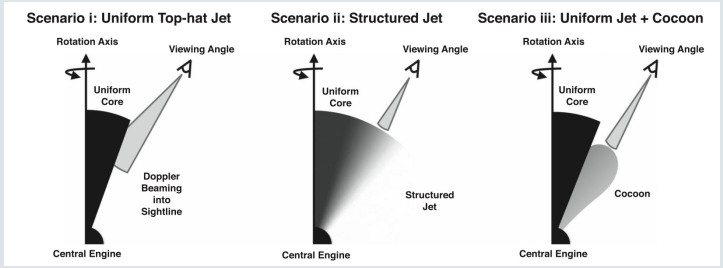
$$\theta_M = \beta \left(\frac{l_c}{2(\mathrm{SNR})^2} \right)^{1/4} \times \mathrm{FWHM}$$

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.

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

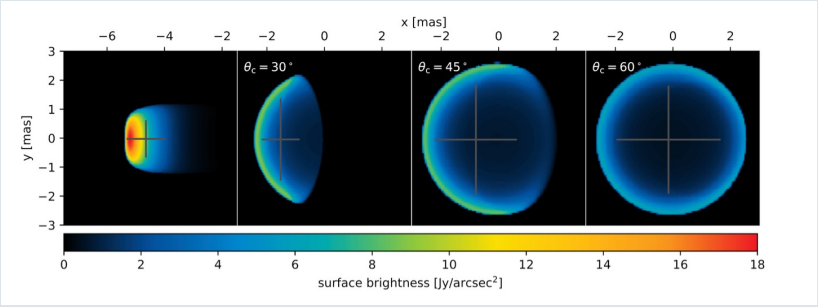
The role of simulations – faint detections

GW170817 EM counterpart



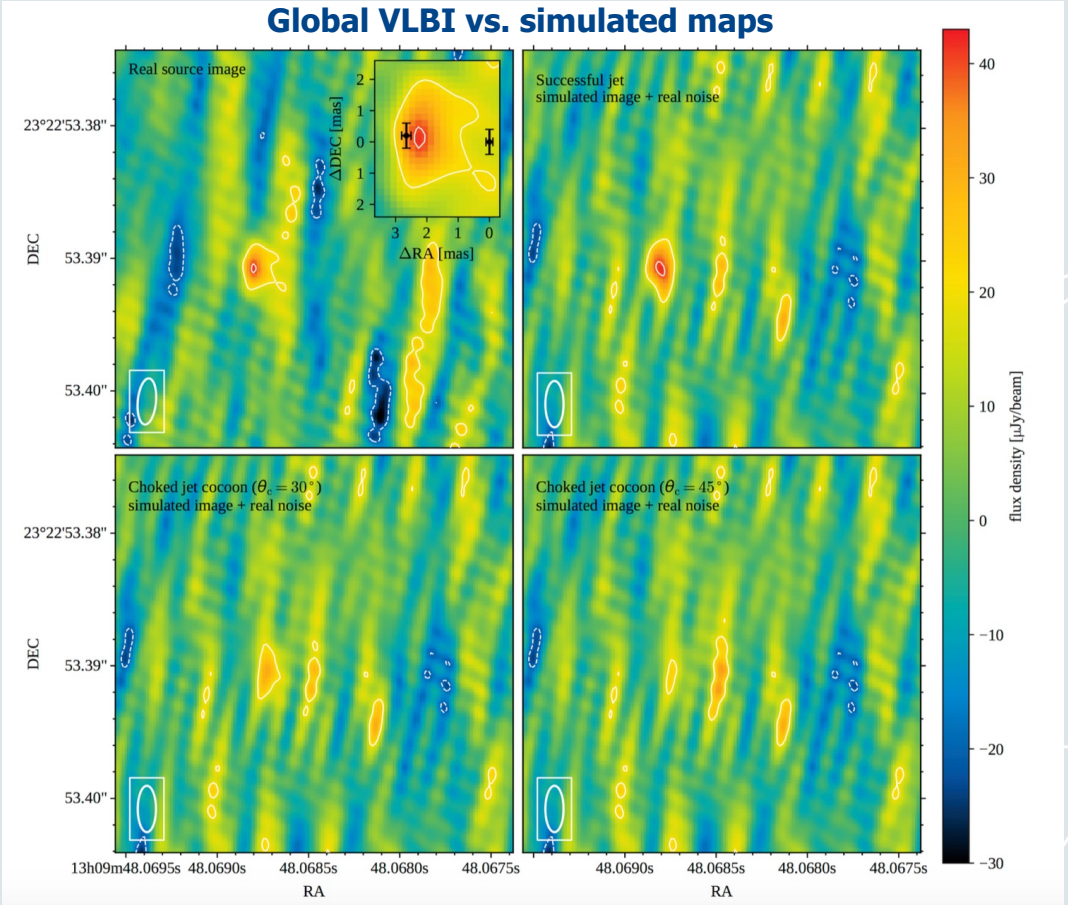
Abbott et al. (2017) ApJ, 848, L13

Set of source-brightness models



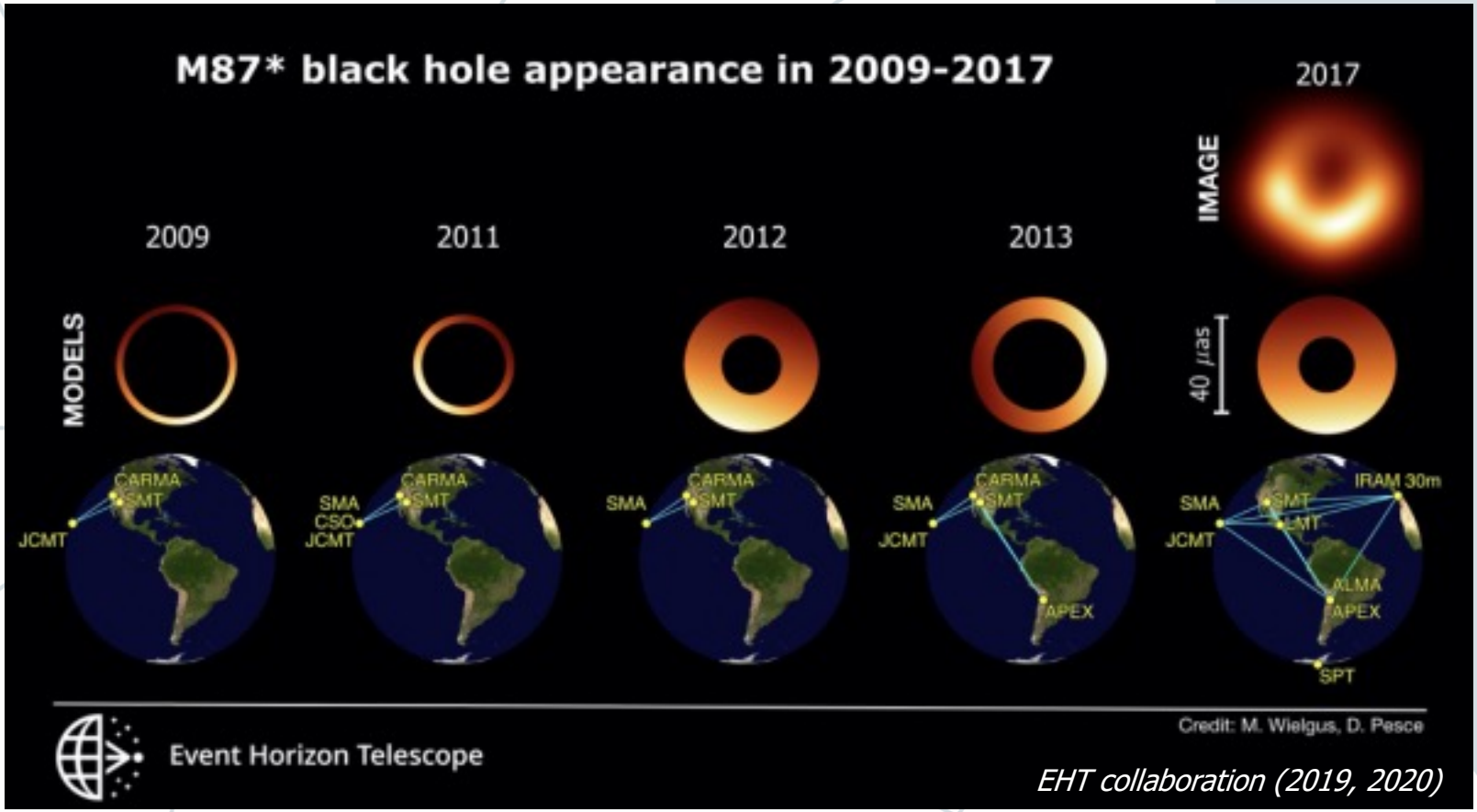
Ghirlanda et al. (2019) Science, 363, 968

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**

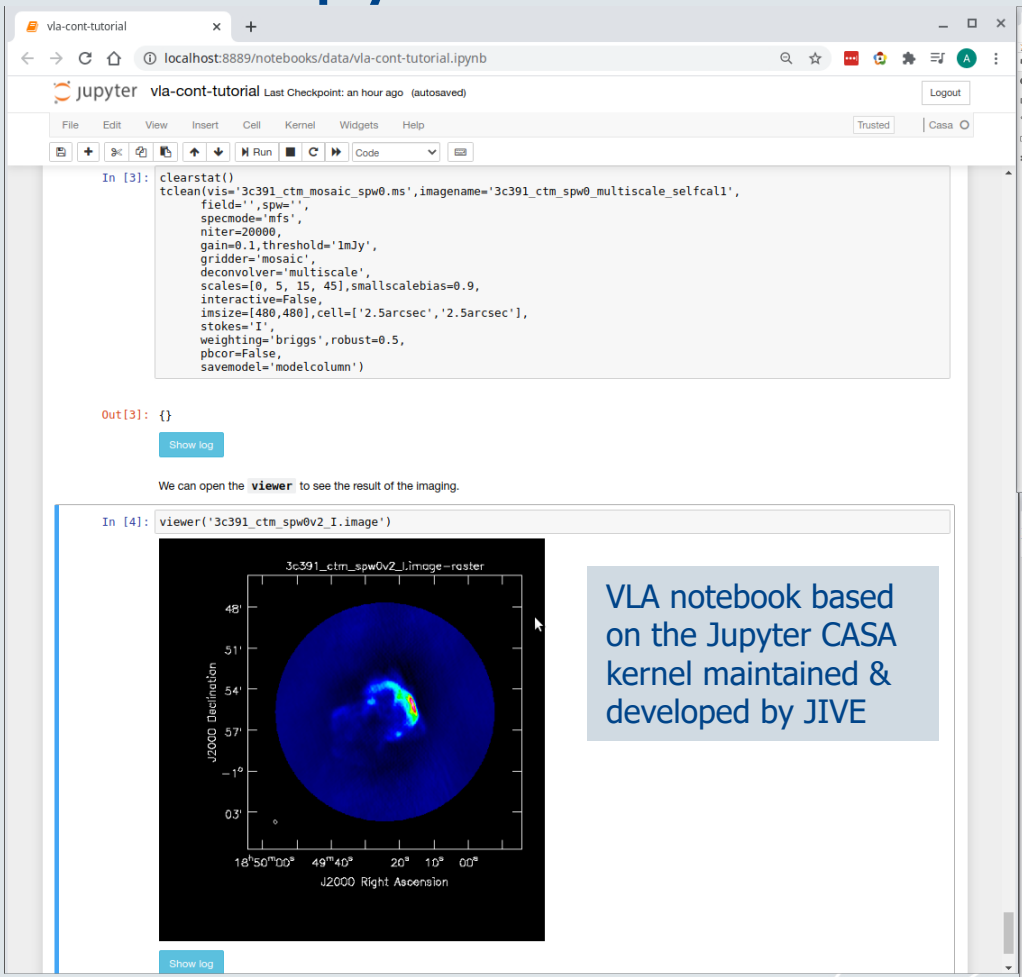
What's next?

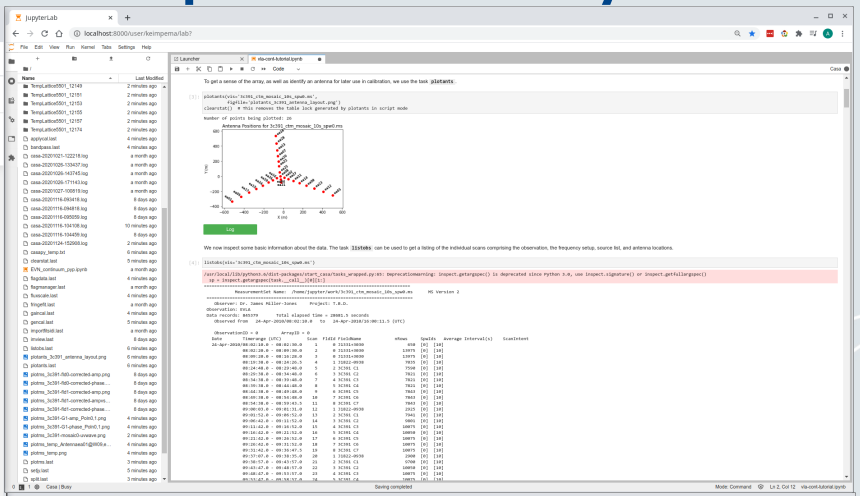


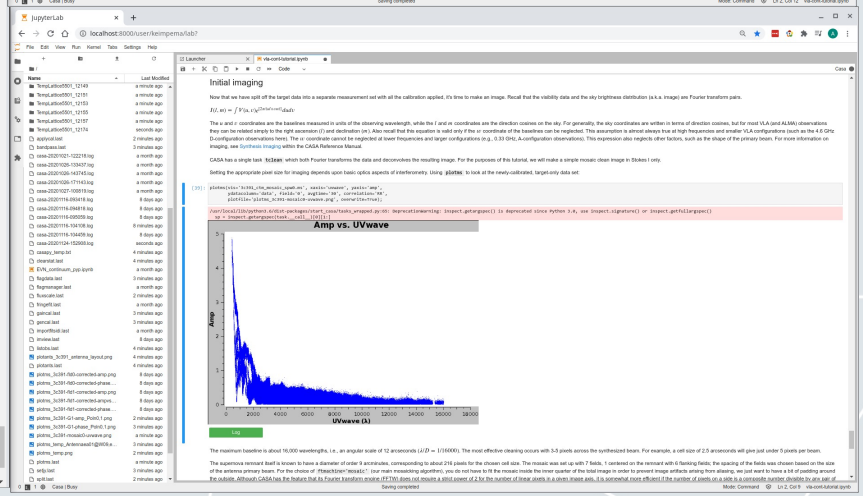
EHT collaboration (2019, 2020)

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

Jupyter notebooks and reproducibility



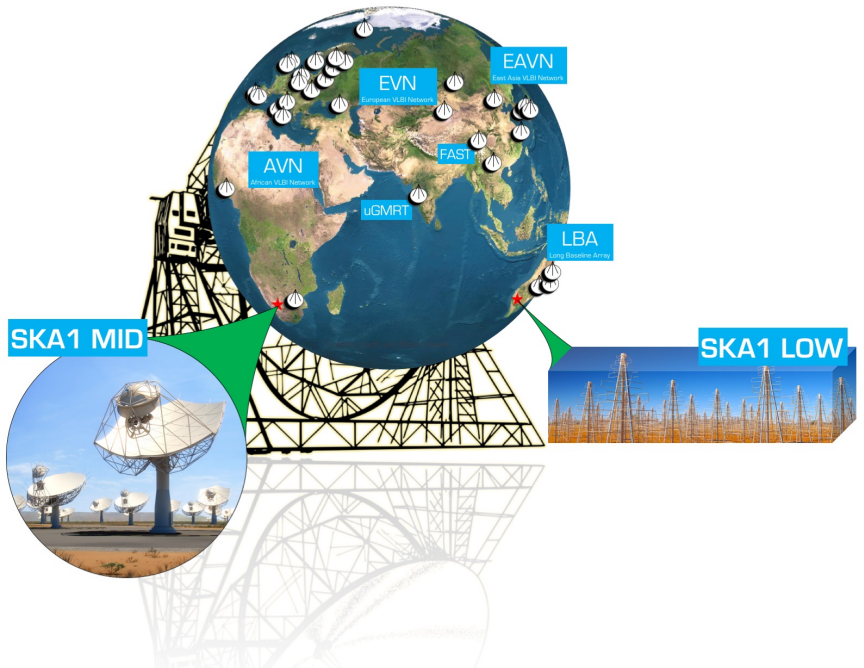




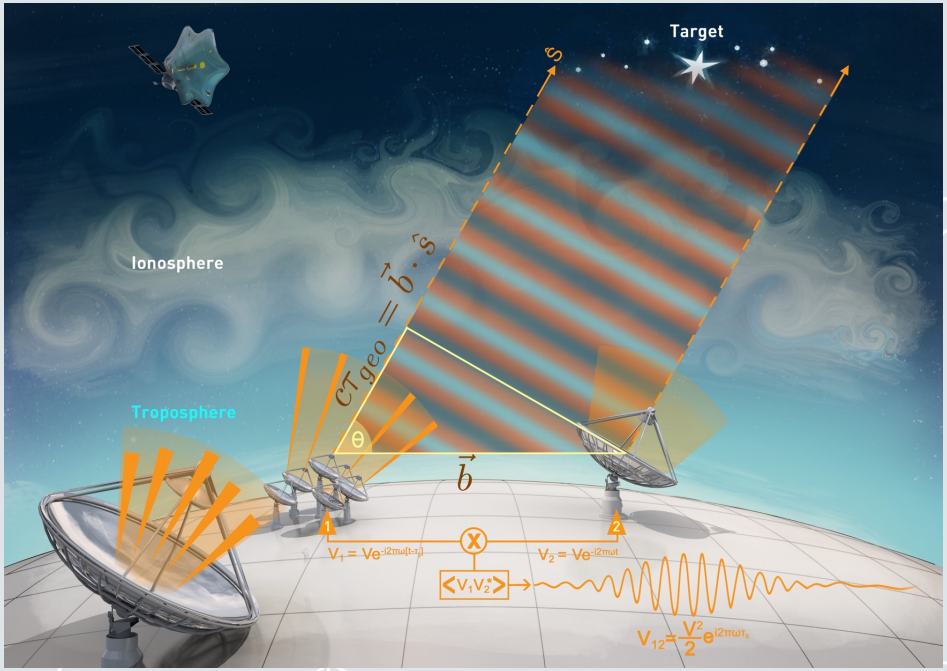
VLA notebook based on the Jupyter CASA kernel maintained & developed by JIVE

- **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

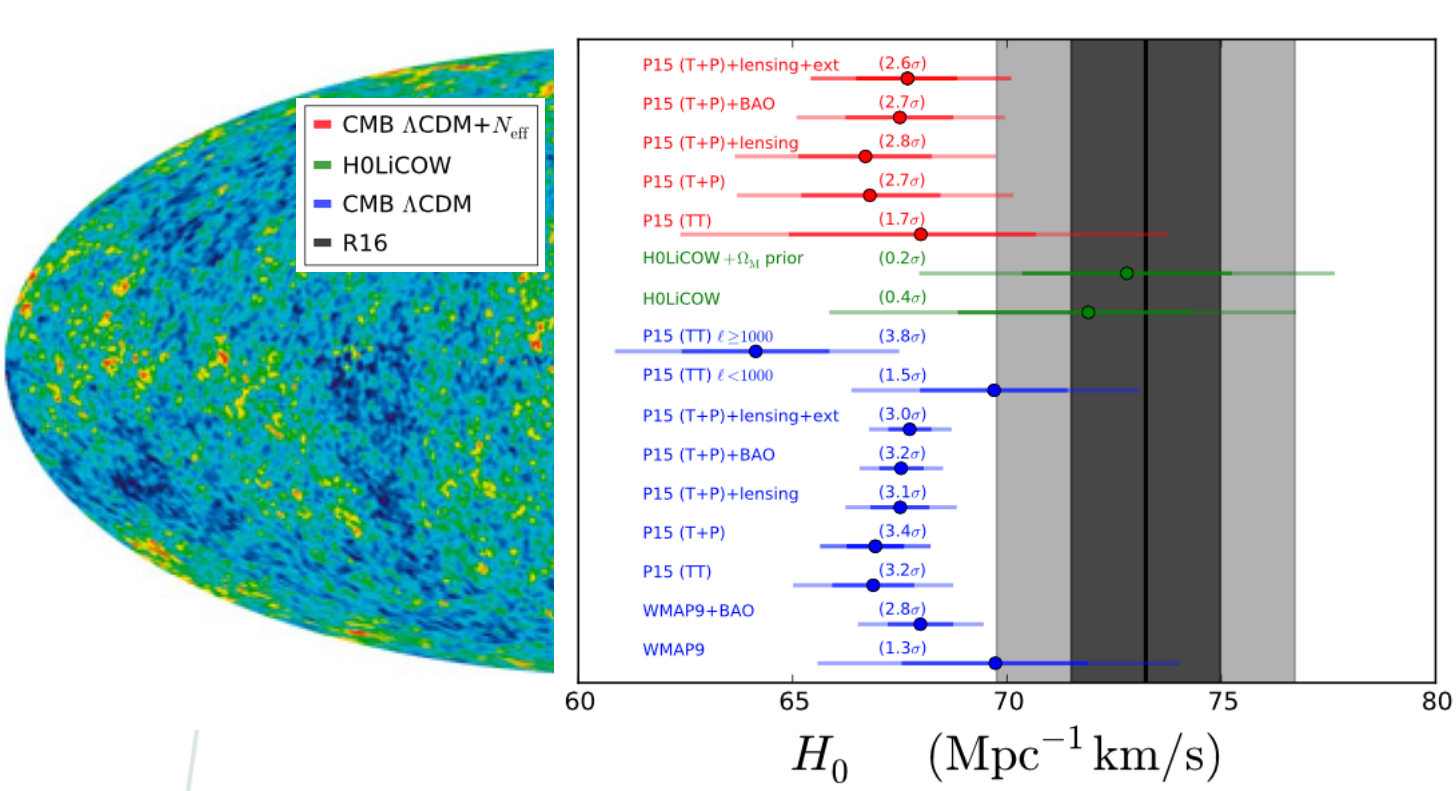


Rioja & Dodson (2020)

- **Strong science driver is ultra-precise astrometry** *(~1 μas; 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)

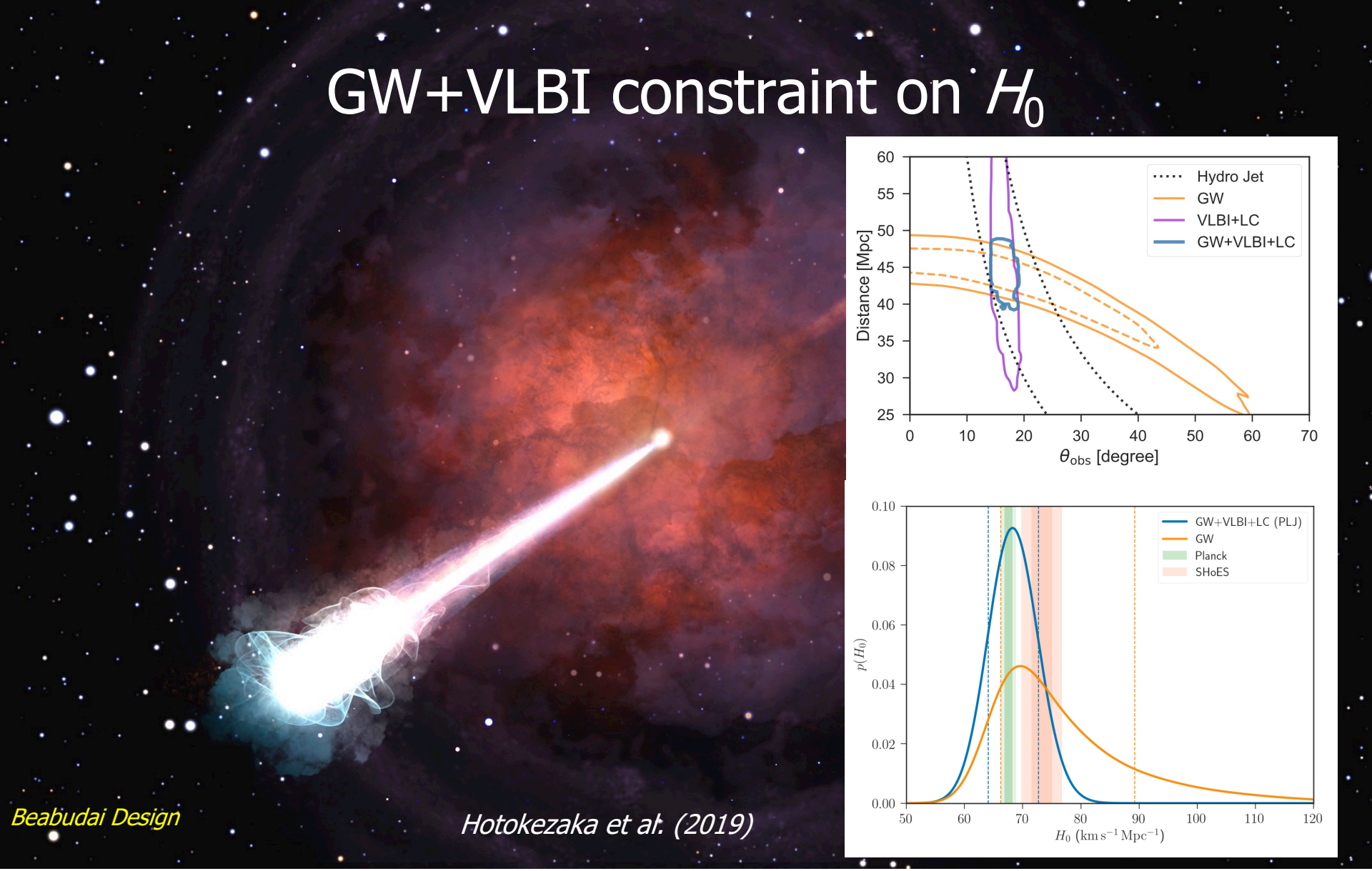
SKA-VLBI Science example: "The H_0 trouble"



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!**

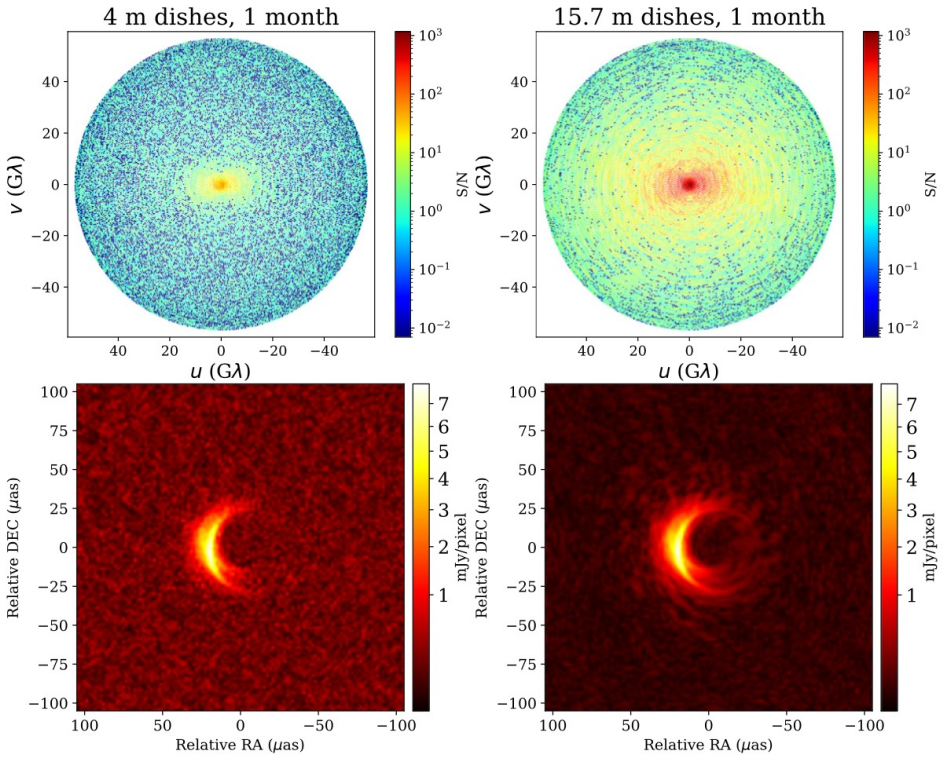
GW+VLBI constraint on $\dot{H}_0$



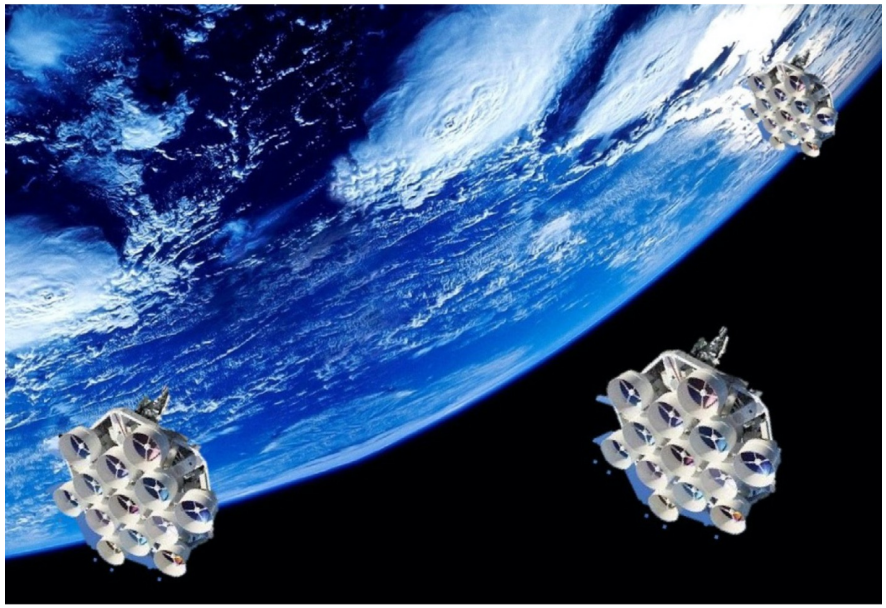
- **It takes 10 BNS mergers with EM counterparts to constrain H_0 at 5%, 200 for 1%**

(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