Transient science with the EVN

– Astrophysics Centre for Multimessenger studies in Europe (ACME) –

Zsolt Paragi

Joint Institute for VLBI – European Research Infrastructure Consortium

Funded by the European Union

The ACME project has received funding from the European Union's Horizon Europe Research and innovation programme under Grant Agreement No 101131928.

European VLBI Network (EVN)

- Run by 14 organizations, 20+ radio telescopes on 4 continents
- Wavelengths from 90cm-0.7mm, most frequently used at 18cm and 6cm
- 5-10 μJy typical sensitivity in 8h @ 18cm, 1 mas resolution @ 6cm
- Western-EVN(+Sh) real-time e-VLBI mode: ideal for transients or exploratory surveys
- Central Processor: JIVE, Dwingeloo, NL

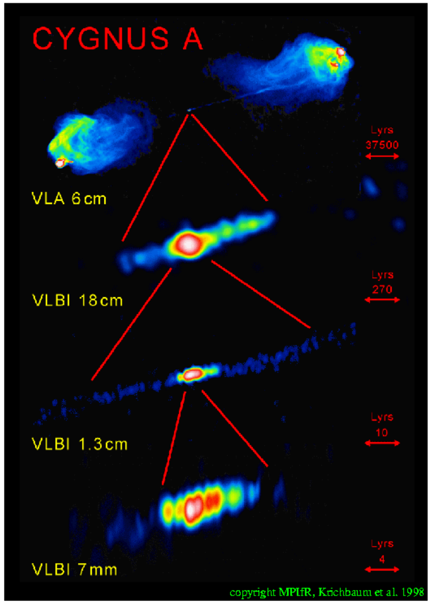
- SFXC: high-time & frequency resolution, multi-phase centre, pulsar gating & bining, coherent dedispersion

➢ **EVN operations**

- Dedicated regular sessions 3x6 weeks
- 10x24h e-EVN observing runs
- (Some) additional room for ToO, OoS
- Deadlines: 1 Feb, 1 Jun, 1 Oct

www.evlbi.org. **www.jive.eu**

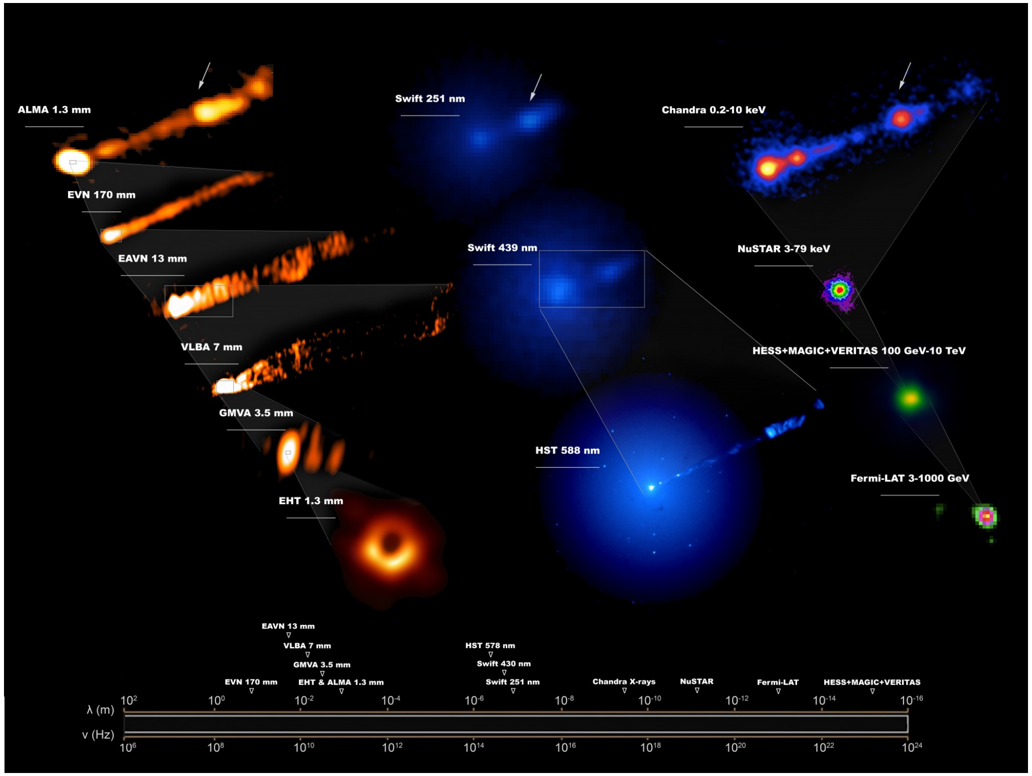
Angular scales probed by VLBI



Krichbaum et al. (1998)

EHT Collaboration / J.C. Algaba (2021)

Comparing radio/VLBI arrays and other instruments



- ➢ **cm-bands: ~1-100 mas**
  Spatial scales:

- $10^{14} - 10^{16}$ cm (5 – 500 AU) @ 5 kpc
- 1 – 100 parsec @ 200 Mpc (z~0.05)
- 7 – 700 parsec @ $z = 4$

- ➢ **mm-bands: ~20-1000 μas**
  - Down to horizon-scales:

Event Horizon Telescope (EHT)

HST ~ 0.050”
Chandra, VLA ~ 1”
Fermi LAT ~ 10’-3.5d

EVN and transient science

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

- **The EVN as a powerful transient follow-up instrument**

Largest collecting area and sensitivity
Superior angular resolution compared to other bands (till ELT comes); cf. light time—travel arguments!
Powerful probe of incoherent/coherent non-thermal processes

The transient parameter space

- **Various types of transients**

  - Timescales (rapid response, cadence, long-term monitoring reliability) matter a lot!

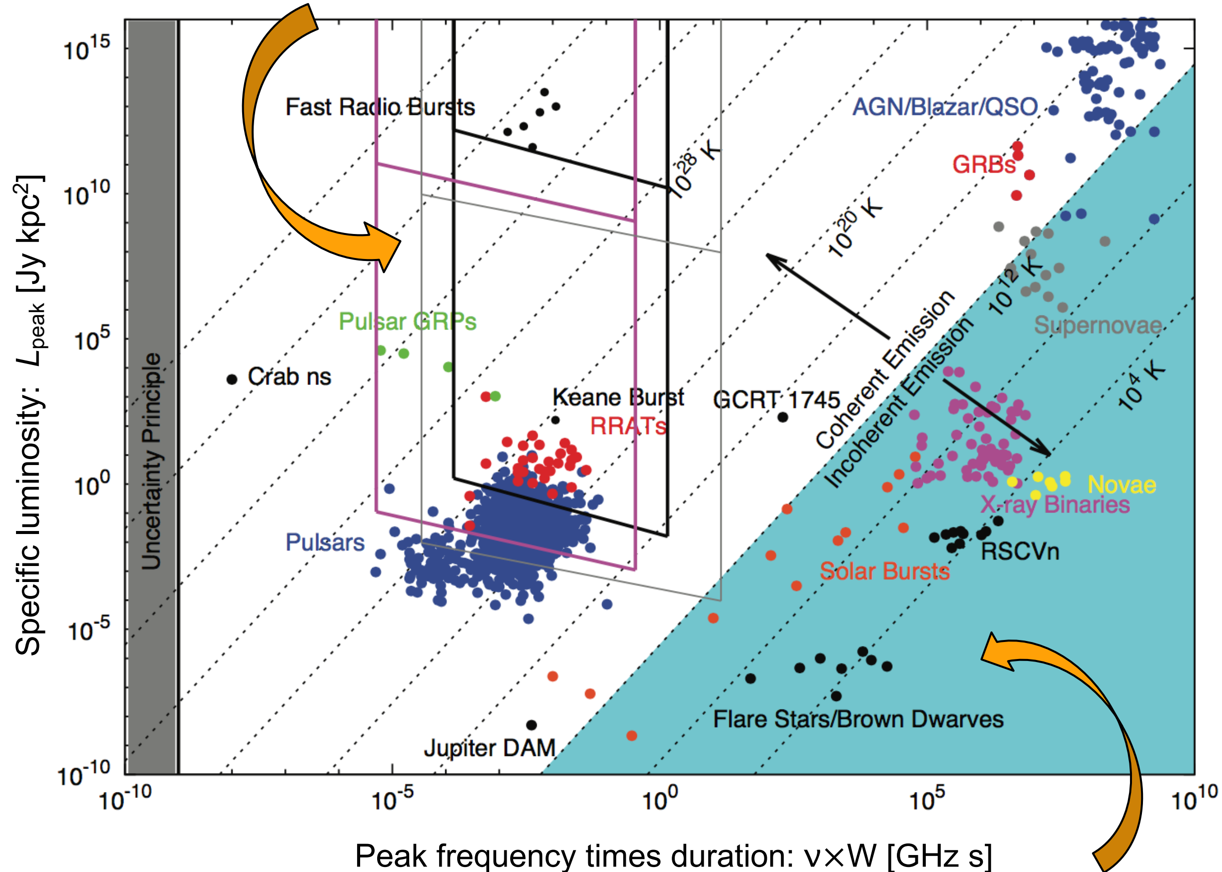
  - Two major categories ("fast"/"slow") requires completely different approaches

- **Challenges for the EVN**

  - Because of FoV limitations, the EVN is not a transient-search machine!

  - For deep follow-up it is great, but we needed to invest in improving data transport, correlation, operations…

Historically less-explored for VLBI transients



Macquart et al. (2015)
Cordes, Lazio & McLaughlin (2004)

Classical VLBI targets this way!

e-EVN for transient science!

e-EVN observations of V404 Cyg in outburst

ATel #7742; *V. Tudose (ISS), Z. Paragi (JIVE), J. C.A. Miller-Jones (ICRAR-Curtin), A. Rushton (Oxford), J. Yang (Chalmers), R. Fender (Oxford), S. Corbel (CEA), M. Garrett (ASTRON/Leiden), R. Spencer (Manchester)*
on 1 Jul 2015; 16:43 UT
Credential Certification: Valeriu Tudose (tudose@spacescience.ro)

Subjects: Radio, Binary, Black Hole, Transient

Referred to by ATel #: 7959

Tweet Recommend 20

Following the outburst of the transient X-ray binary V404 Cyg, we observed the system at 1.6 GHz on 2015 June 23/24 between 22:08-07:58 UT with the European VLBI Network (EVN), using the e-VLBI technique. The participating radio telescopes were Effelsberg, Hartebeesthoek, Jodrell Bank MkII, Medicina, Onsala85, Shanghai, Torun, Westerbork (5 telescopes of the phased-array).

Due to the heavy scattering towards the target, the longer baselines with Shanghai were significantly affected and had to be deleted. Significant variations in the flux density of the source (by a factor 1.5) also influenced the quality of the radio image. However, we clearly detected V404 Cyg as a point-like source (beam FWHM: 30 x 13 mas; PA: 83 deg) with a peak brightness of 166 +/- 5 mJy/beam at the position (J2000):

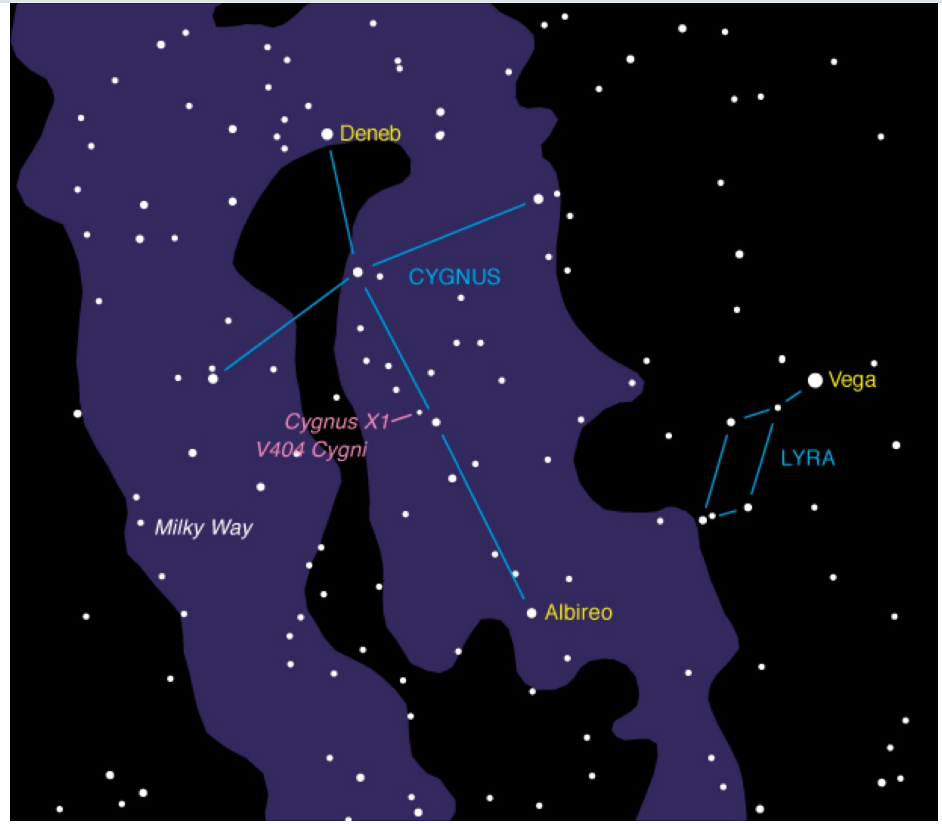
RA: 20h24m03.8183983
Dec: +33d52m01.840768"

We estimate the systematic error in astrometry to be of a few mas due to poorly modeled ionosphere and large line-of-sight scattering.

We do not see any evidence for extended radio emission above a 3-sigma rms noise level of 0.5 mJy/beam, at scales from 5 mas up to 200 mas.

We take the opportunity to note that these observations represent the last occasion on which the MFFE receivers and TADU system were used to form the Westerbork tied array. We thank the "old" Westerbork for the excellent VLBI science it has generated over the last few decades and look forward to the "new" Westerbork system employing the APERTIF Phased Array Feeds.

The European VLBI Network (EVN) is a joint facility of European, Chinese, South African, and other radio astronomy institutes funded by their national research councils. The observations presented here were obtained under the project code ET031A.



- **e-VLBI: offer the most sensitive VLBI network in a flexible way**

  - More regular electronic VLBI sessions ➔ more opportunities
  - Target of Opportunity and Trigger proposals ➔ easier response to the unexpected
  - Realtime data transfer and correlation: ➔ reliable data delivered promptly!

EVN-lite

EVN-lite: ad-hoc network in Europe and China (EVN, e-MERLIN, Shanghai)

Artwork: Daniele Futselaar & Jason Hessels
PRECISE PI: Franz Kirsten

- **EVN-lite: up to 600h observing with an EVN sub-array (best effort basis)**

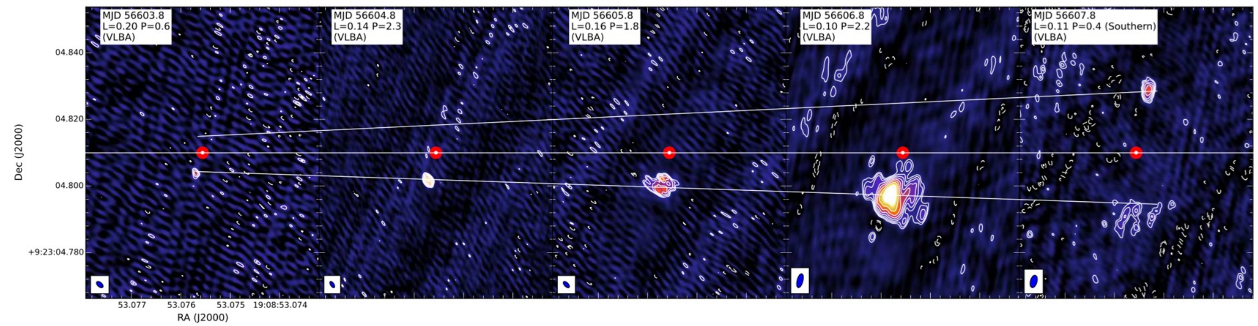
  - Can address both major classes of transients ("fast"/"slow") with different approaches
  - Available now – with some operational limits

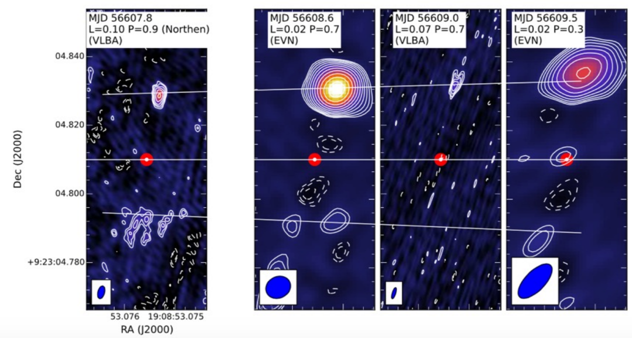
See talk by Benito Marcote on FRBs!

A few science examples

Microquasars (NS/BHXRB)

Rushton et al. (2017)





- **The case of BHXRB XTE J1908+094**

  - Joint e-EVN/VLBA monitoring
  - Rare example of laterally resolved jets
  - Decelerating ejecta indicate unusually dense ISM

Dwarf Novae

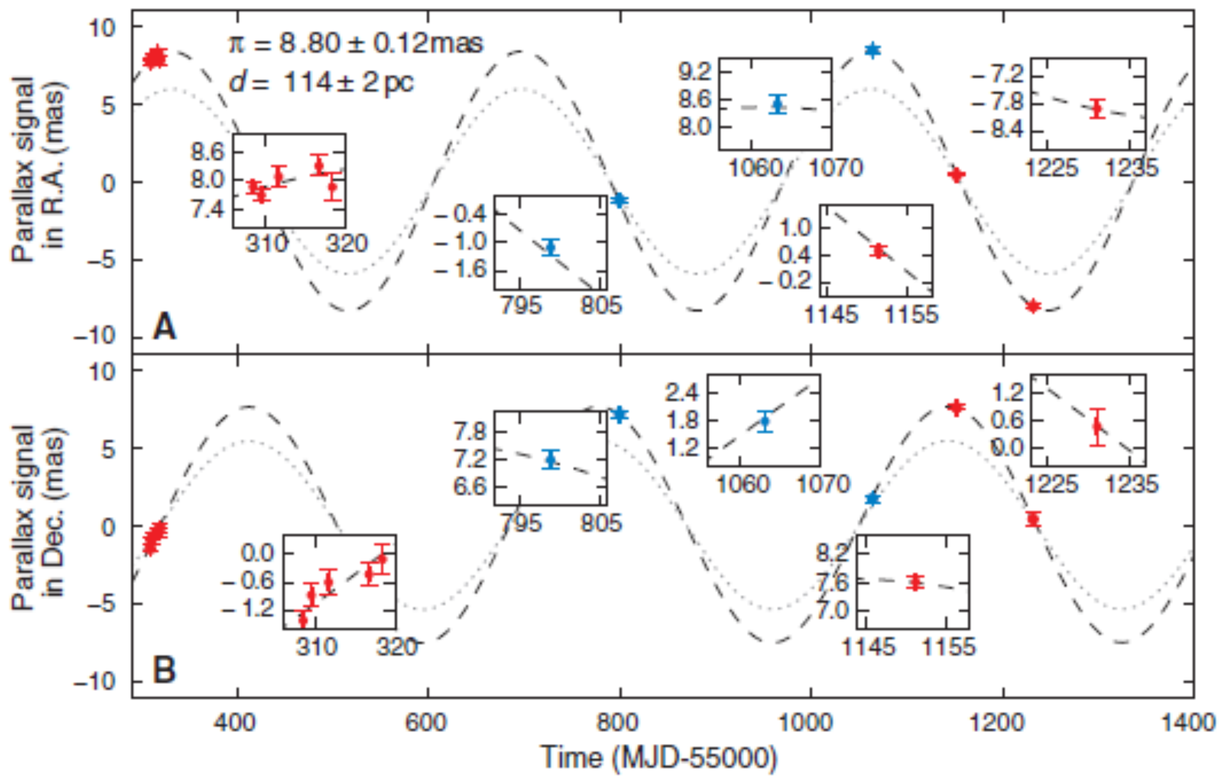
➢ **The case of SS Cyg**

- Apparent luminosity in conflict with accretion disc models ➔ must check if distance is correct

- Only active in radio for a brief time, shortly following optical flares

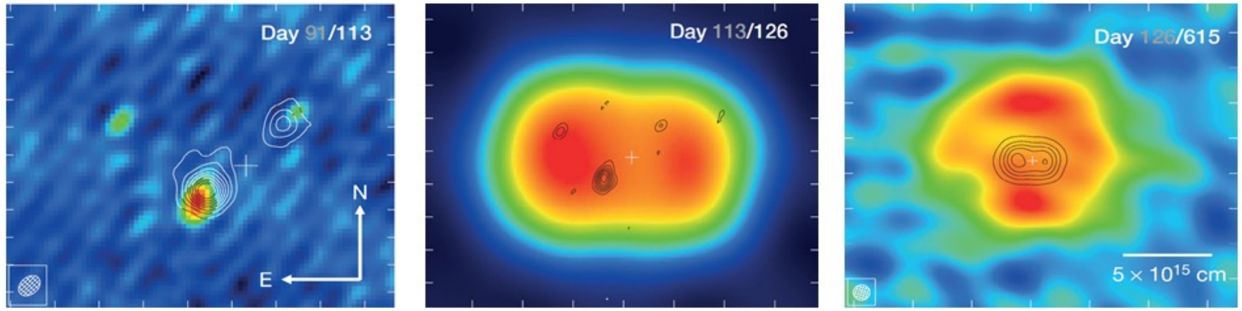
- VLA/e-EVN parallax measurement vindicates accretion disc theory!

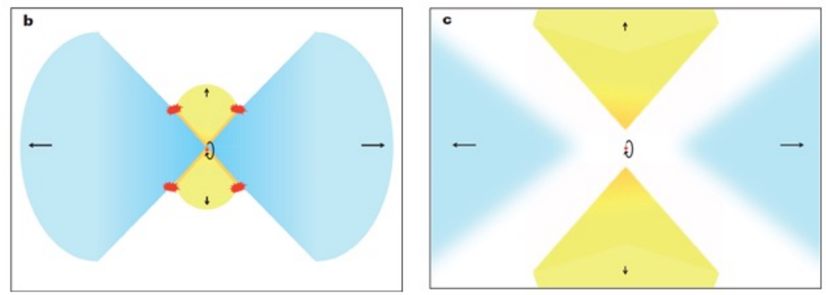
Miller-Jones et al., Science, 340, 950, 2013

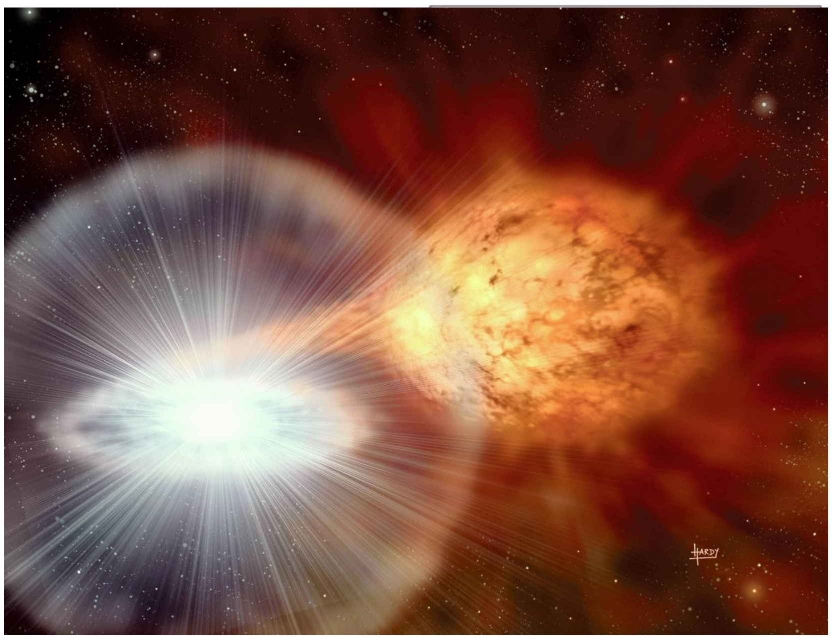


Classical Novae

Chomiuk et al., Nature, 514, 339, 2014



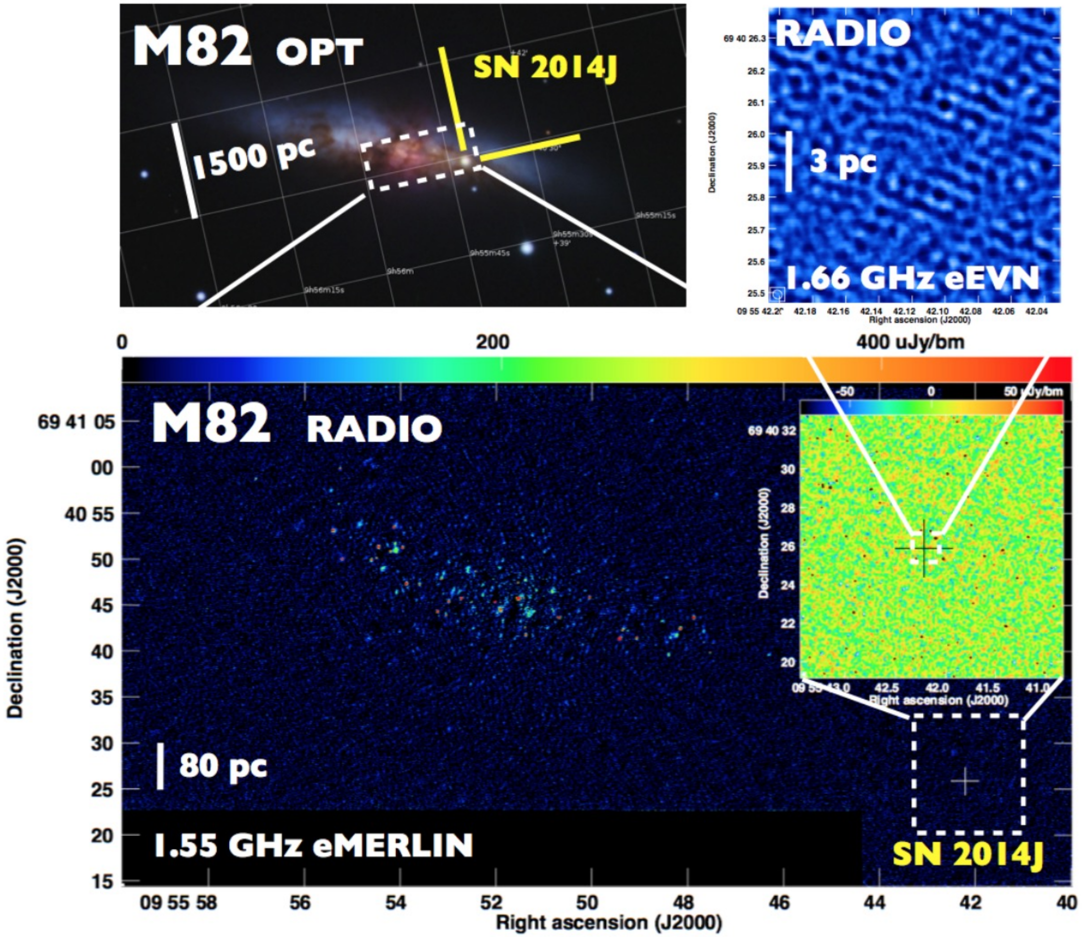




- **The case of V959 Mon outburst in 2012**

  - Highly unusual at the time: gamma-ray detection!
  - Long-term: **e-EVN, JVLA, VLBA, e-MERLIN**
  - Multiple velocity outflow components: shocks!
  - Role of binary orbital motion driving the outflow

Thermonuclear supernovae (Type Ia)

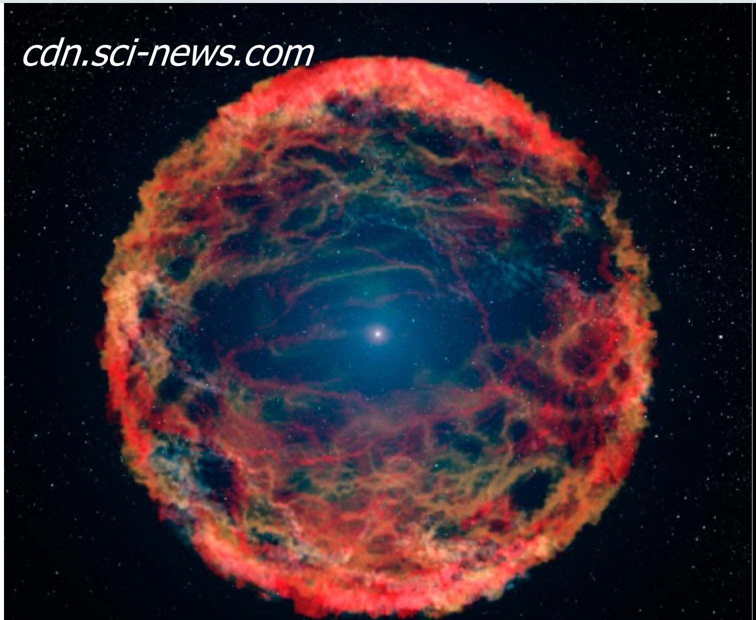


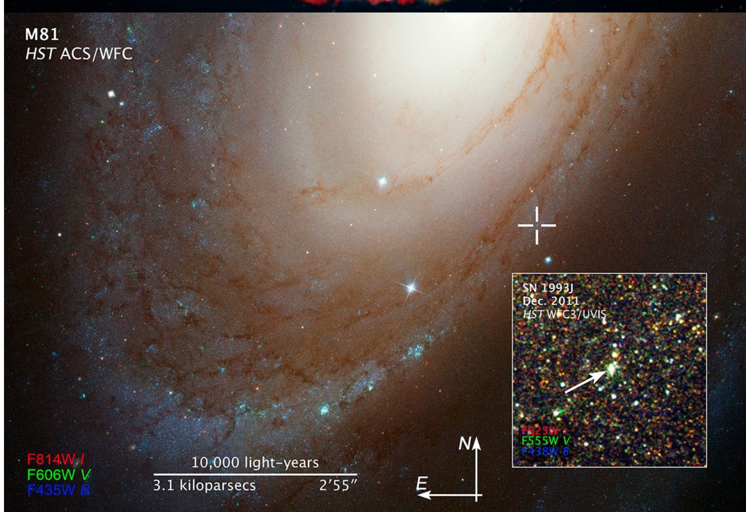
➢ **The case of SN2014J**

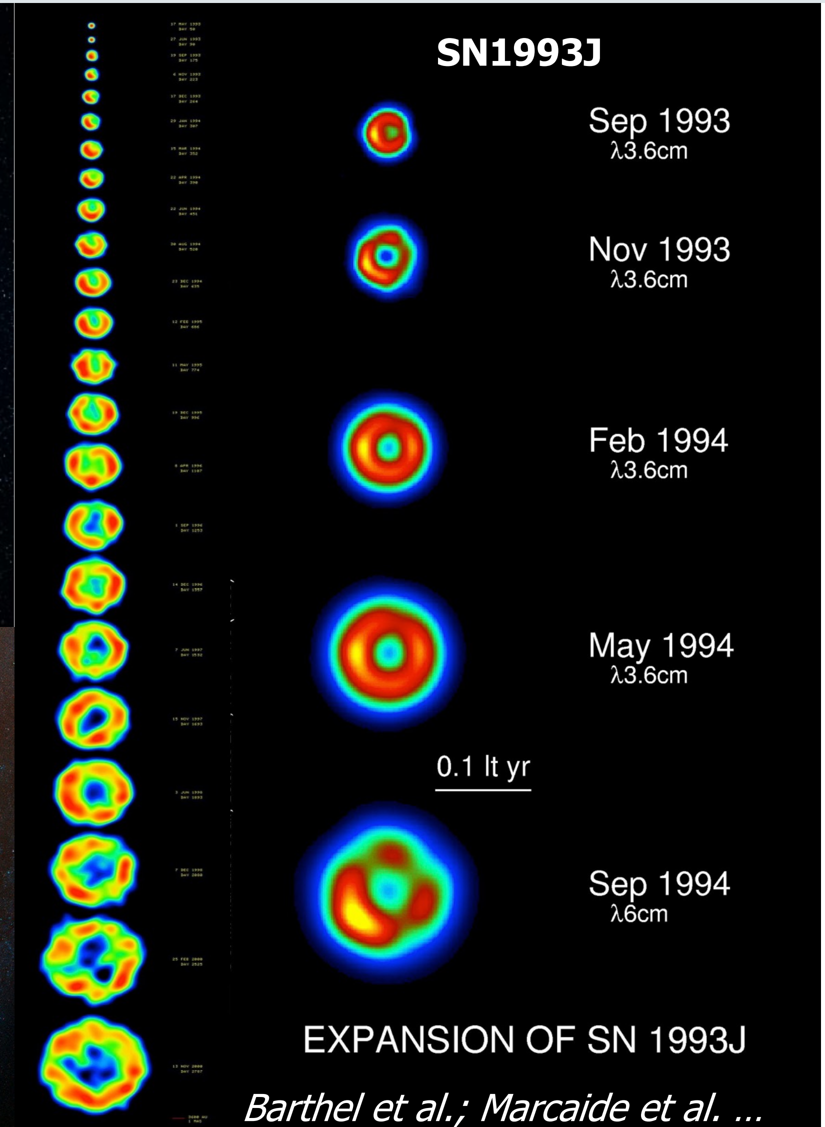
- Deep radio limits point to double-degenerate progenitors in Type Ia Sne

Pérez-Torres et al. (2014)

Core-collapse supernovae (Type II)





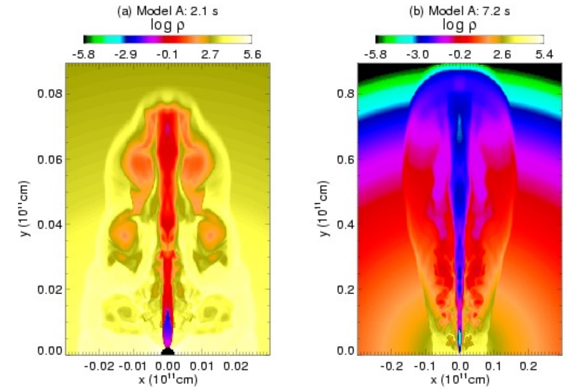


Broad-line Type Ib/c SNe & long-GRBs

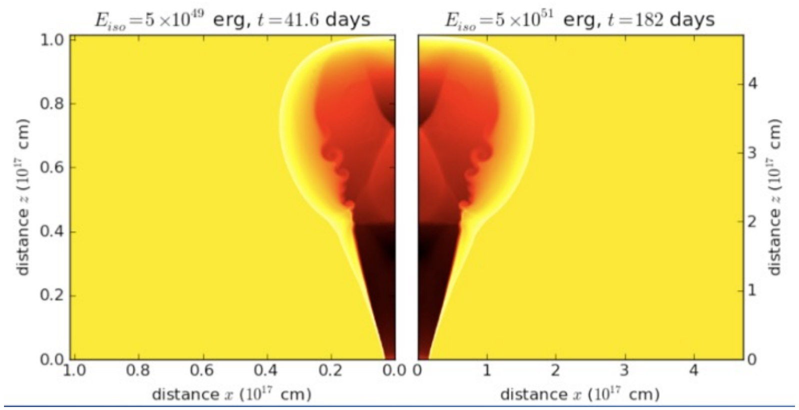
➢ **The case of relativistic ("engine-driven") SNe, long-GRBs**

- Death of massive stars: Collapsar model
- First VLBI confirmed: GRB030329 *(Taylor et al. 2004, …)*
- … very challenging (sensitivity, resolution)

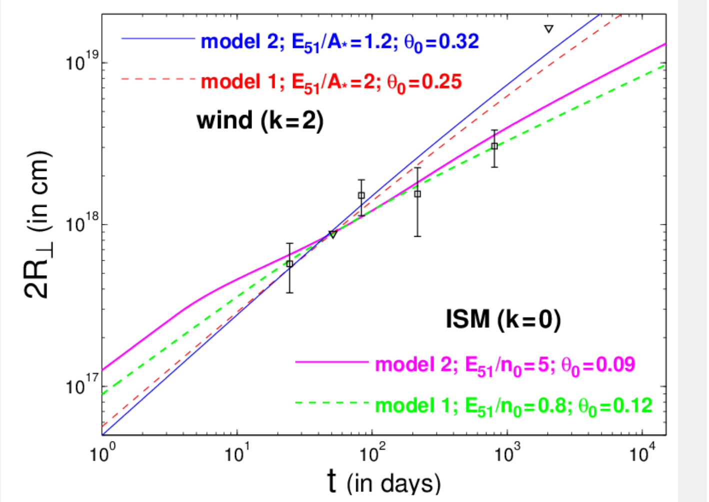
Advanced approaches in source model parametrisation is a promising way to probe jet physics and the environment in long-GRBs – see talk by Stefano Giarratana!



Woosley (1993)
MacFadyan & Woosley (1999)

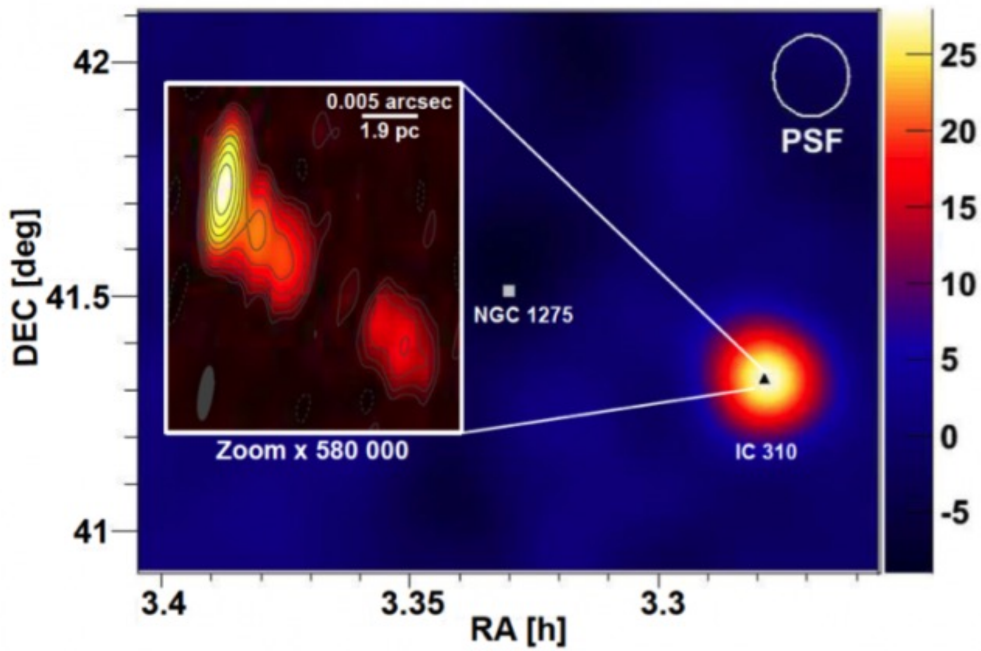


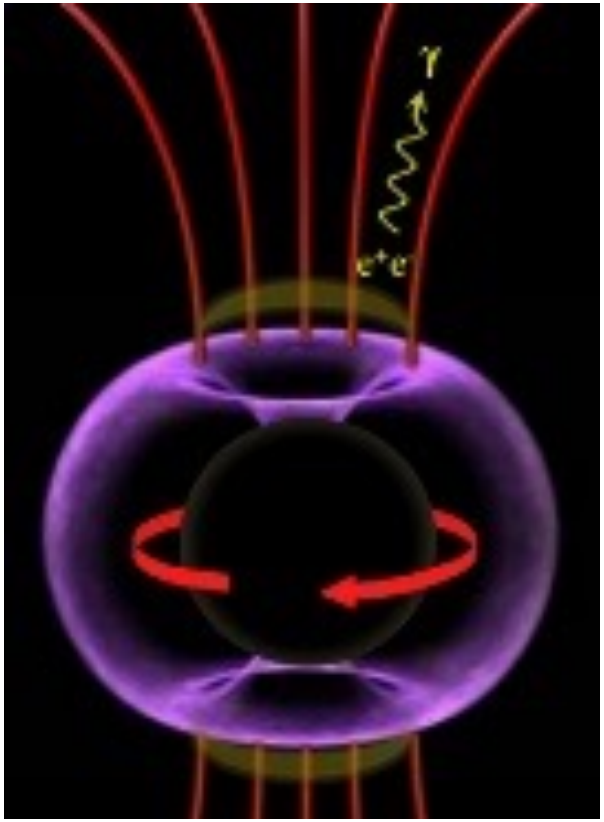
van Eerten, van der Horst & MacFadyen (2012)



Granot & van der Horst (2014)

Flaring AGN

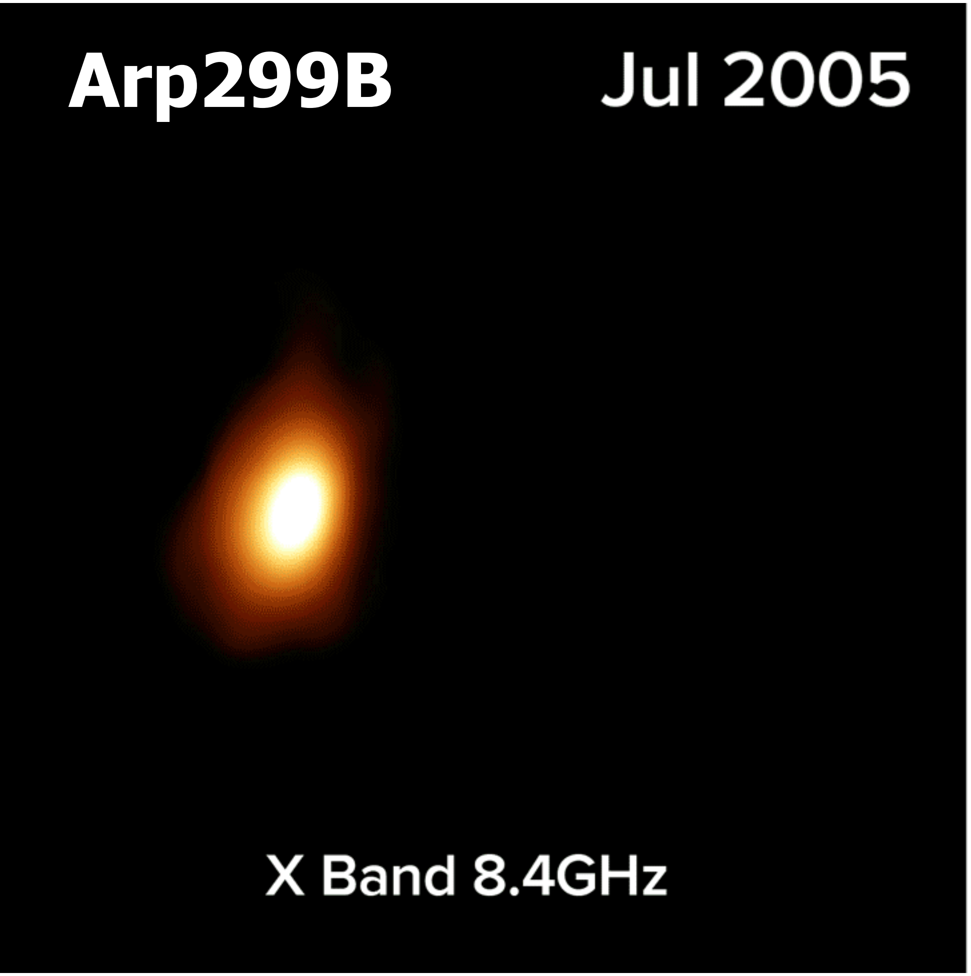


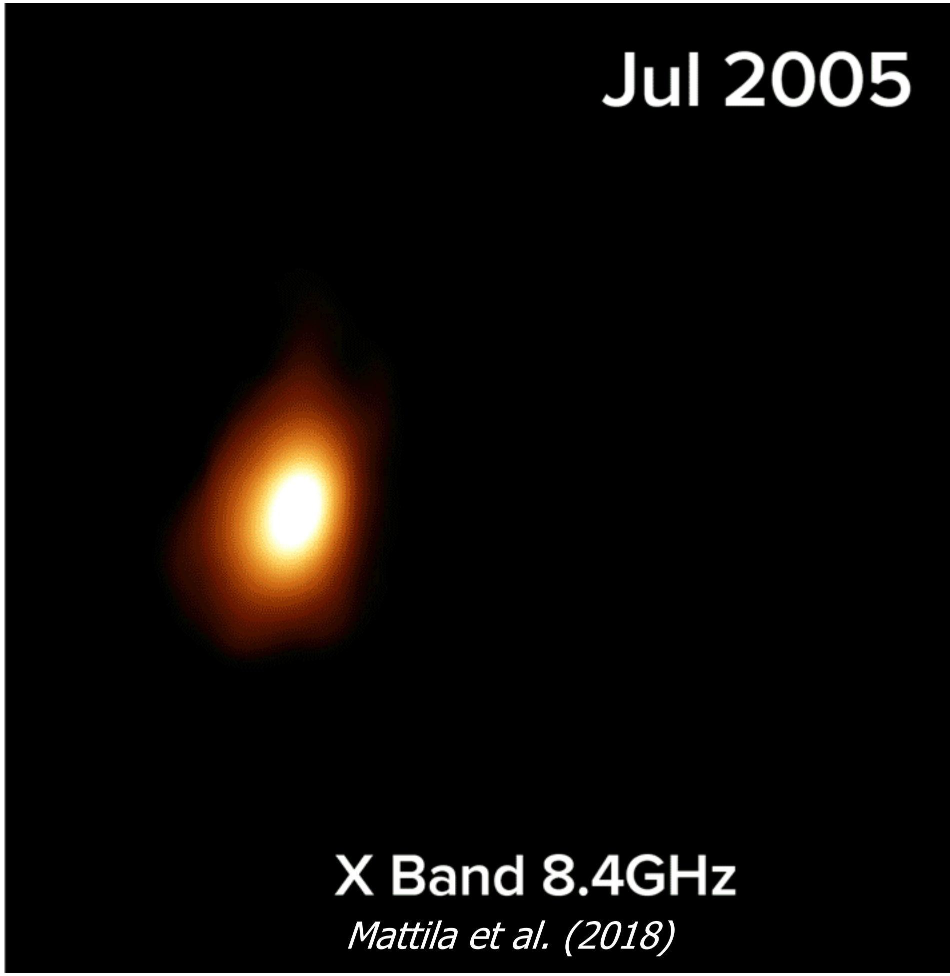


- **The case of gamma-ray flaring IC 310**
  - "BH lightning due to particle acceleration at subhorizon scales"
  - **MAGIC+EVN**
  - Gamma-ray variability <5 mins: probing smaller scales than VLBI!

Aleksić et al., Science, 346, 1080, 2014

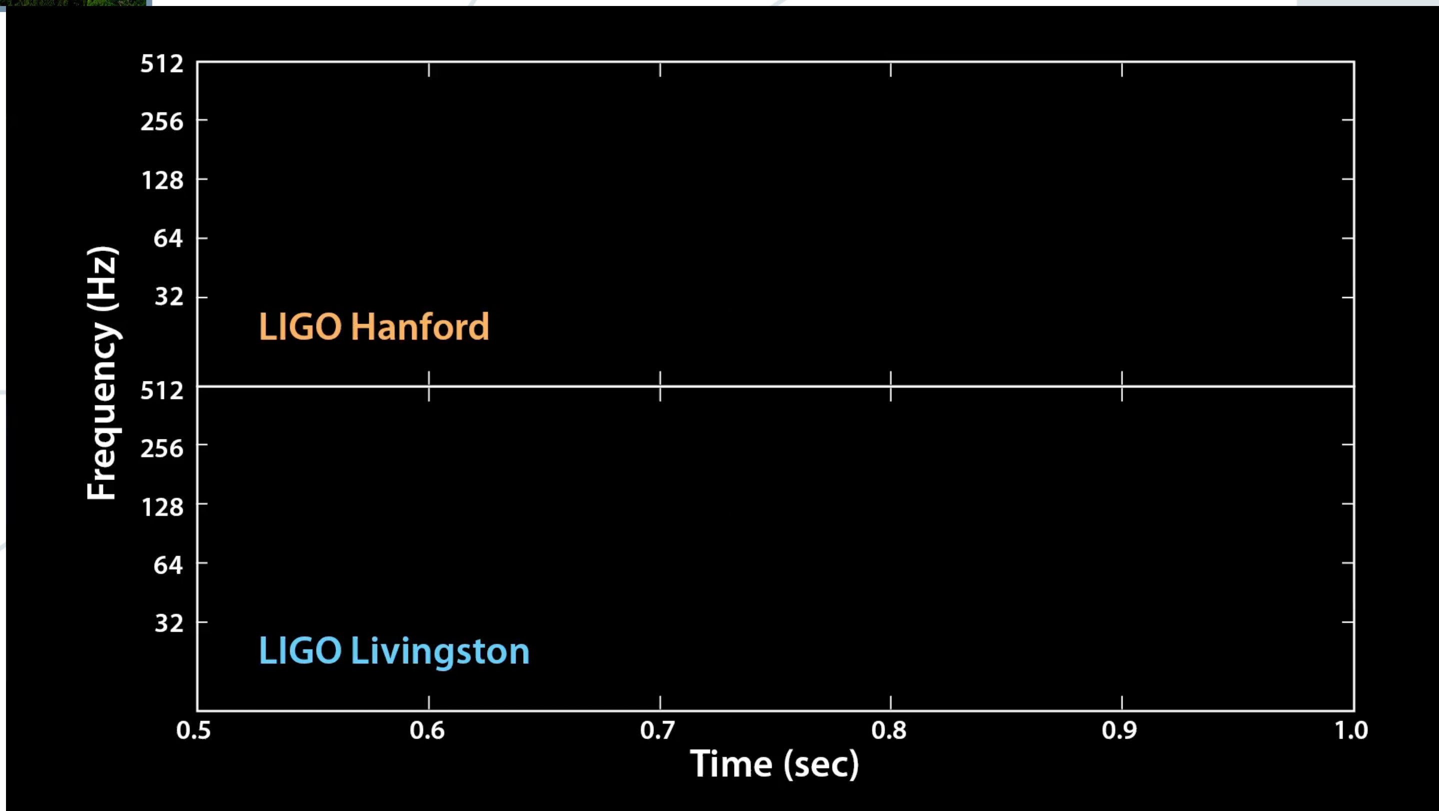
TDE-candidate Arp299B: the movie





Multi-messenger astronomy

2015 September 14, 09:50:45 UT (Credit: Marica Branchesi/LVC)



- **First ever detection of gravitational waves – GW150914**

  The quest for EM counterparts starts!
  (this is not expected for BH-BH mergers though)

MoU: Euro VLBI Transient Follow-up Group

LIGO-Virgo Event Follow-up Program

This form will be attached to the Memorandum of Understanding.

Full name of the partner project:

Euro VLBI Transient Follow-up Group

Abbreviated name:

Euro VLBI

Project web site (if available):

http://www.evlbi.org

Name, institution, email and title of the leader(s) (who will sign the MOU):

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Director
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Jun Yang, Onsala Space Observatory, jun.yang@chalmers.se

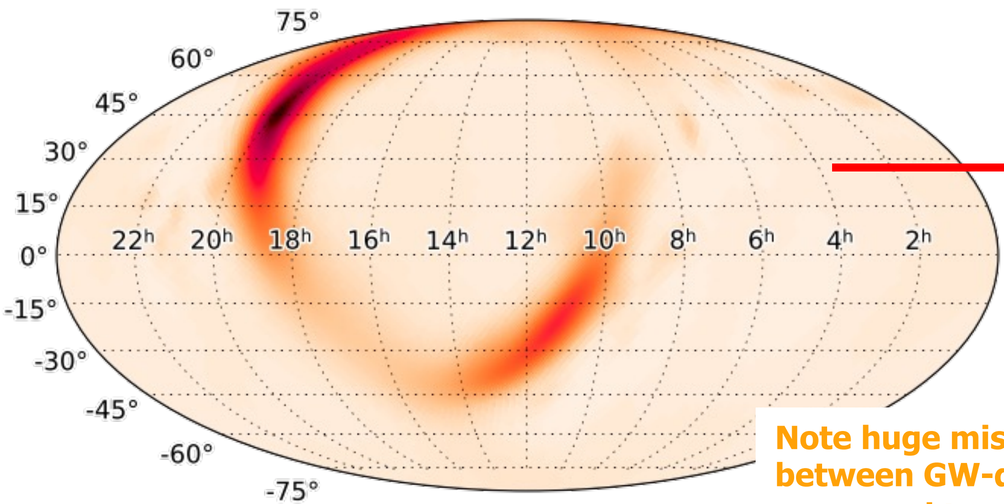
- **Primary instruments: EVN, e-MERLIN**

"Our goal is to provide the most precise sky localisation (about a milliarcsecond) of EM counterparts to GW events in the radio band with the very long baseline interferometry (VLBI) technique…"

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

The secret world of private GCNs…

LIGO/Virgo G275404 → GW candidate event code
Time: 017-02-25 18:30:51 UT
Detectors: L1, H1
False rate probability: ~6/year



→ One of the initial skymaps in the Grace DataBase

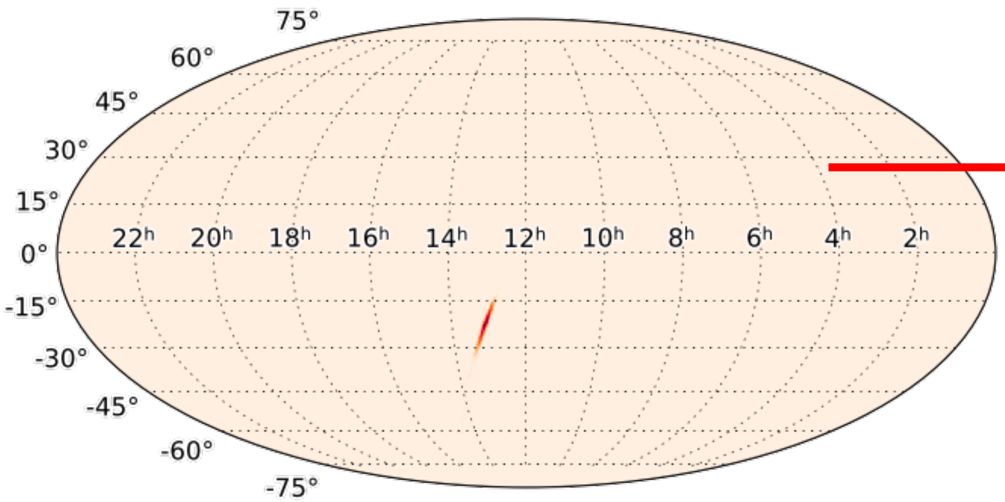
Probability of 2nd object being neutron star: 100%

Note huge mismatch between fields of view and localization between GW-detectors (and some other instruments) compared to radio interferometers, especially VLBI !!!

- **EM follow-up starts, various candidates**
  - GCN #20754: AGILE-GRID detection of a possible gamma-ray transient *(Tavani et al.)*
  - GCN #20784: 1.5m Kanata telescope – bright, near-IR transient within AGILE error circle; accurate coordinates for VLBI follow-up *(Yoshida et al.)* [EVN typically requires ~arcsecs initial position]
  - GCN #20981: e-EVN ToO follow-up on 24 March 2017 shows no compact radio emission exceeding 6 sigma limit of 105 uJy/beam *(Paragi et al.)*
  - GCN #20982: LIGO/Virgo announcement of final analysis on 17 Apil: not a real event!

GW170817

LIGO/Virgo G298048



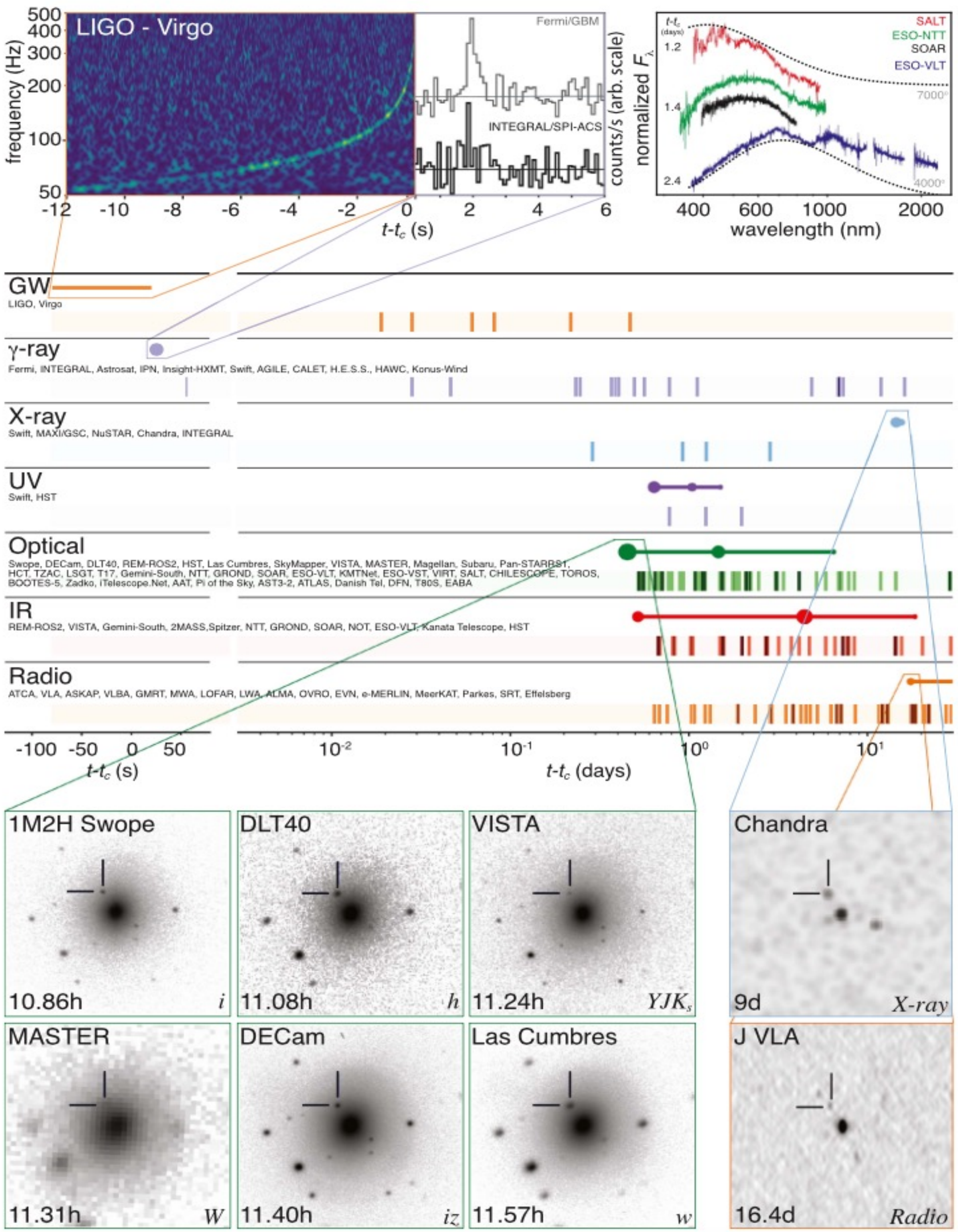
GW candidate event code
Time: 2017-08-17 12:47:18 UTC
Detectors: H1
FAR: ~1/9111.7 /year

Skymap taking into account all detectors (Virgo now operational, important constraints!)

Probability of 2nd object being neutron star: 100%

- **Euro VLBI team high-resolution radio follow-up**
  - Initiated a trigger proposal focusing on sGRB/GW events, active from 1 June 2017
  - Exceptional NS-NS merger trigger arrives in mid-August, proposal activated! [O2 to end by late Aug.!]
  - Activated the EVN trigger proposal, live from June 1, 2017
  - Coincident Fermi trigger the same day – follow-up efforts explode
  - e-EVN and e-MERLIN efforts reported in 4 GCNs *(Paragi et al.; Moldon et al.)*
  - Detections in all wave-bands – the rest is history!
  - Becomes known as GW170817

Multi-messenger overview



- **…Detection of thermal kilonova emission in itself is a goldmine of discoveries…**
- **Non-thermal counterparts:**

  - **X-rays by Chandra @ day 9**
  (Troja et al. 2017, Margutti et al. 2017)

  - **Radio by the JVLA @ day 16**
  (Hallinan et al. 2017)

  VLBI only upper limits in the first few months (kept observing…)

Abbott et al. (2017)
ApJ, 848, L12

"The Paper" describing the efforts

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9
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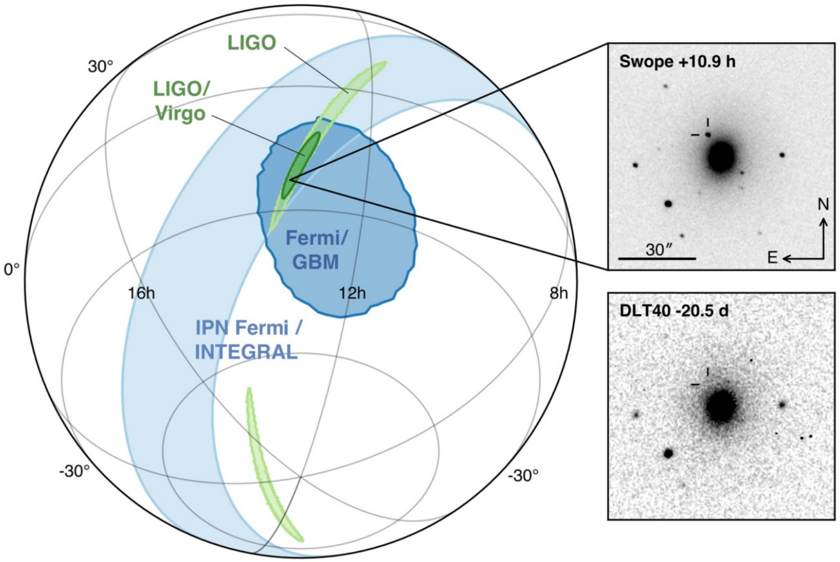
Multi-messenger Observations of a Binary Neutron Star Merger*

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The



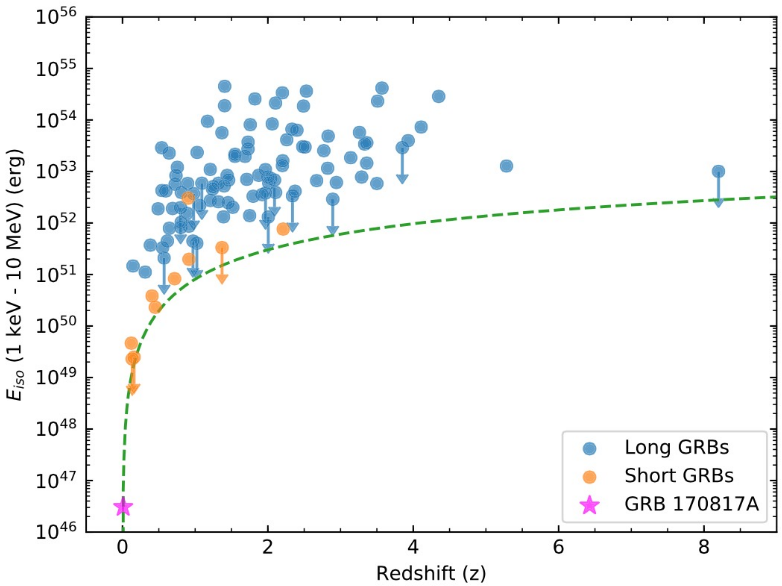
Abbott et al. (2018)
ApJ, 848, L12

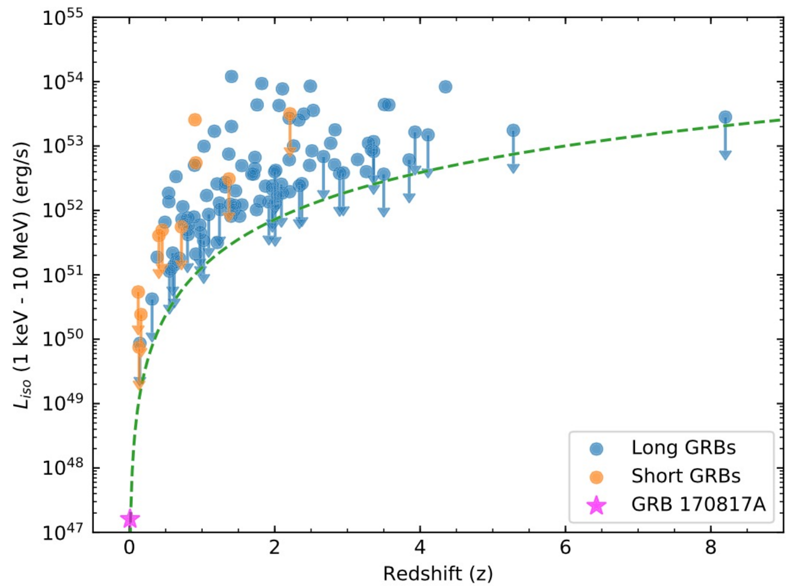
"… [VLBI has] the potential to resolve (mildly-) relativistic ejecta on a timescale of months."

- **Collaborative efforts (kudo's to Samaya Nissanke et al. !)**

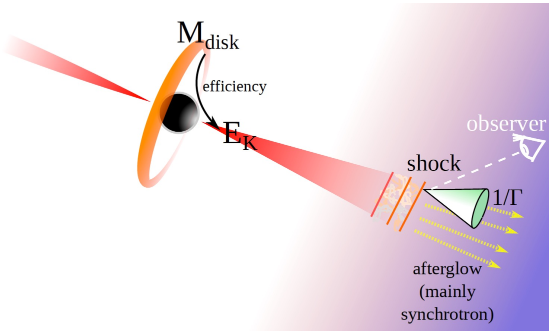
  - ~3600 authors, heated discussion in telecons and e-mails
  - Successfully lobbied for radio teams, even though only JVLA detection at the time

The unusual high-energy counterpart

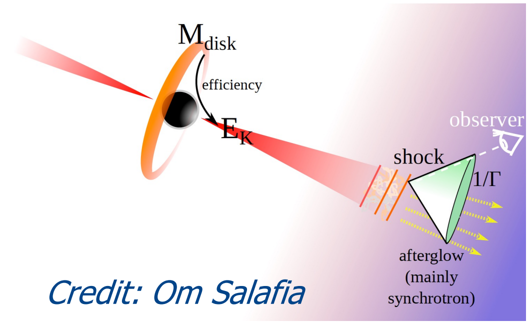




Abbott et al. (2017)
ApJ, 848, L13



TIME

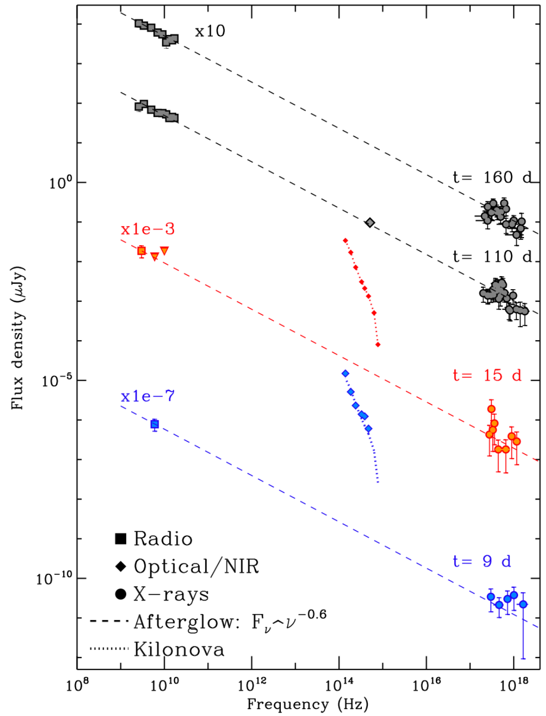


Credit: Om Salafia

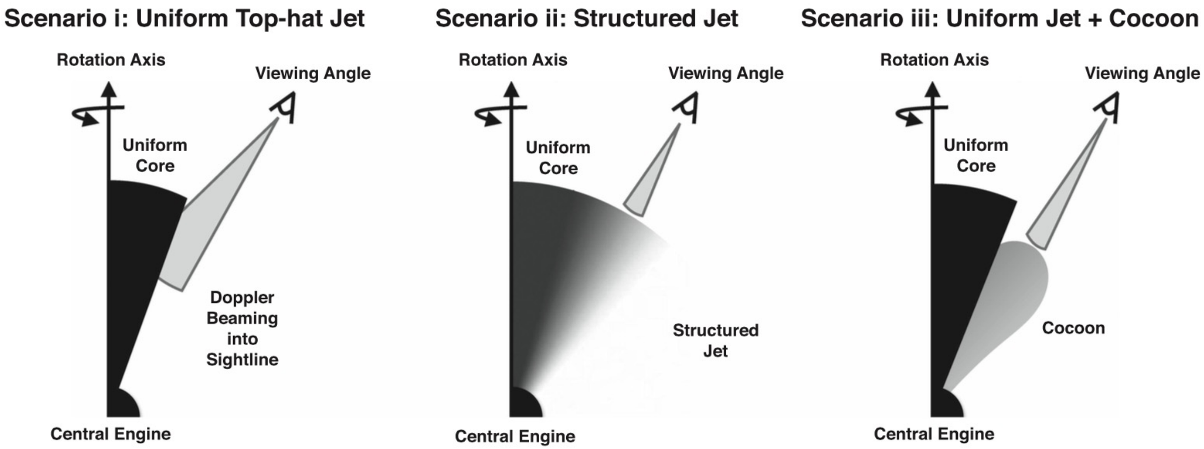
- **The high-energy counterpart:**

  - 100 times closer but also $10^2 - 10^6$ less luminous than other short GRBs
  - Unusually weak: is this intrinsic, or the first off-axis short-GRB???

Multi-band evolution of the outflow emission



Margutti et al. (2018)

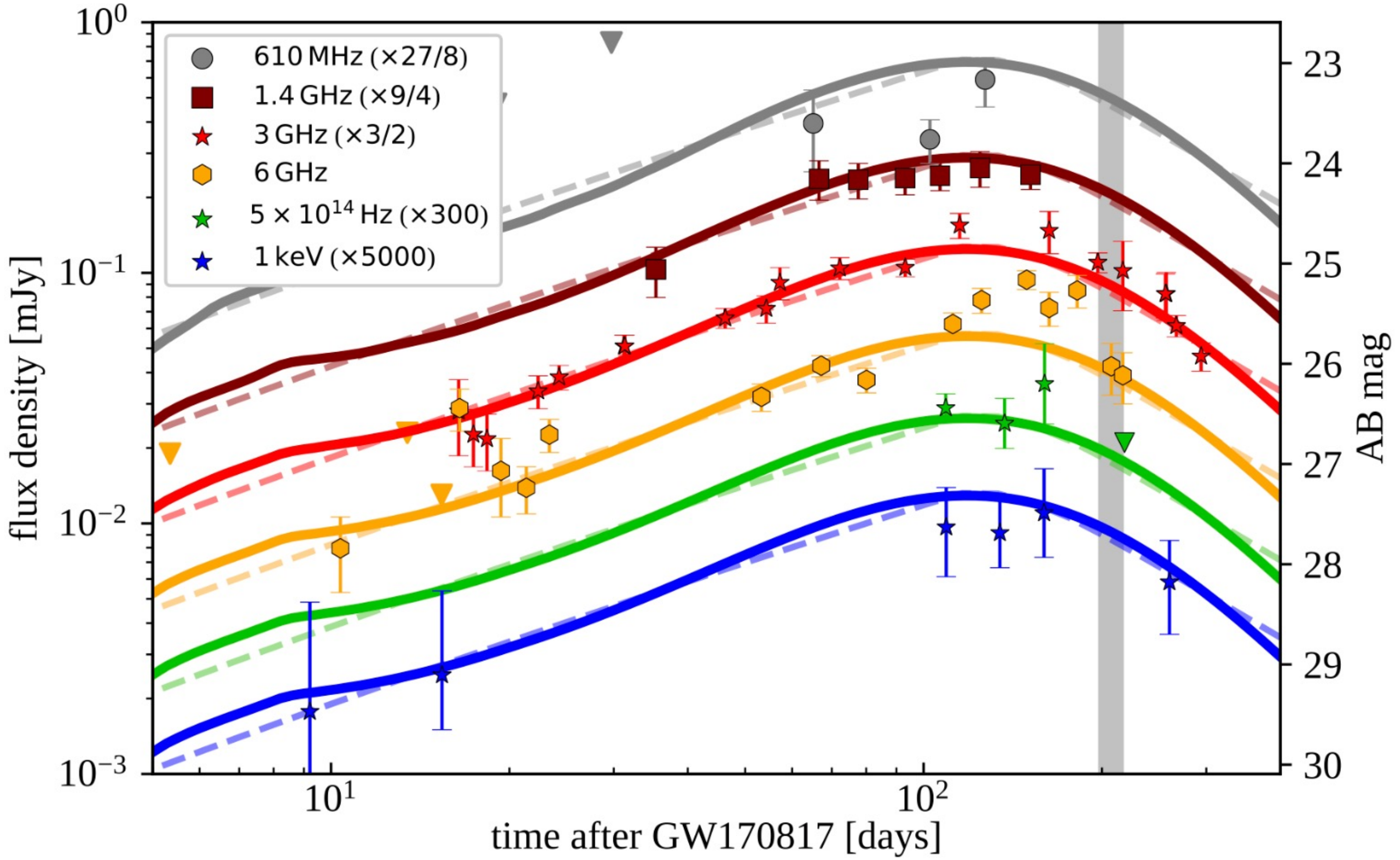


Abbott et al. (2017)
ApJ, 848, L13

➢ **Broad-band SED**

- Very simple power-law all-across the spectrum: mildly-relativistic ejecta, Γ ~3-10
- Three main scenarios for the nature of the outflow (not constrained by the spectrum)

Structured jet vs. Isotropic model: need VLBI!

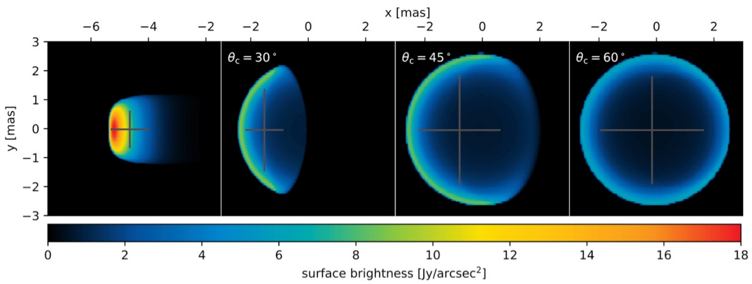


Ghirlanda et al. (2019)

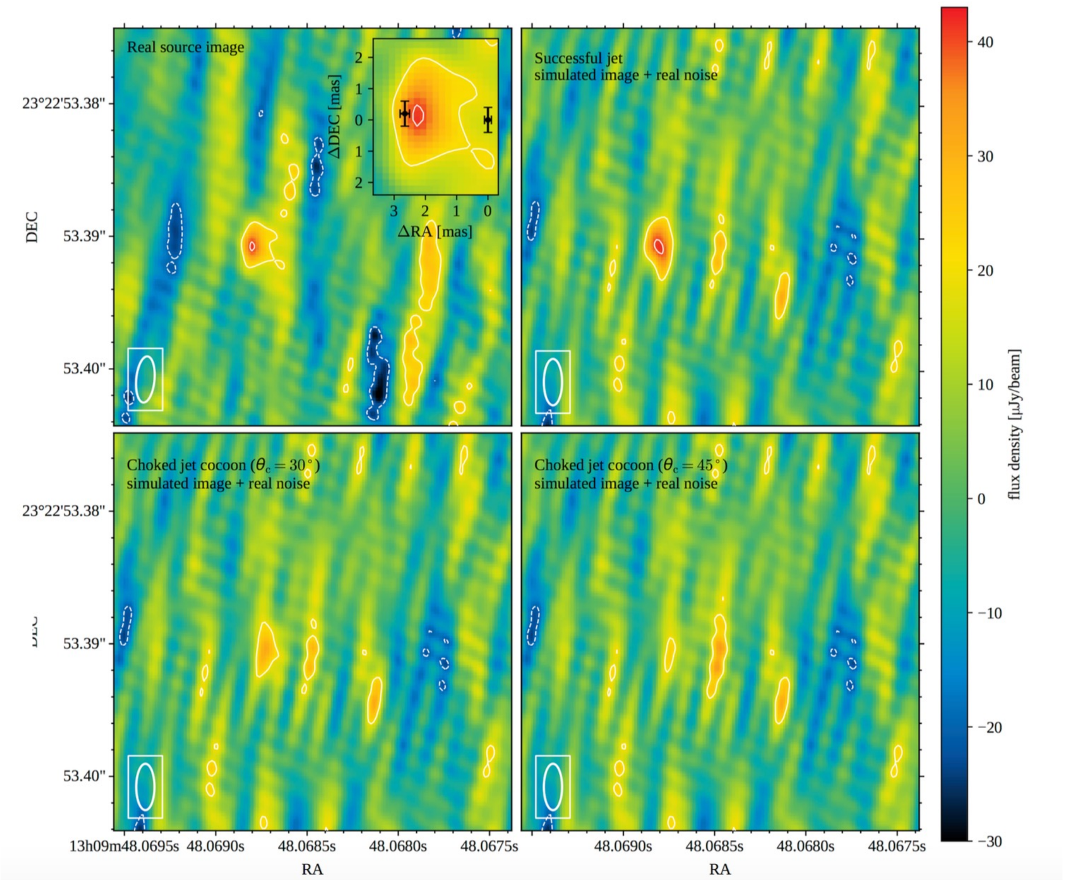
Global VLBI run

Global VLBI imaging results

PIs in action at JIVE:
Om Salafia, Giancarlo Ghirlanda
(and Martin Leeuwinga, JIVE operator)



Simulated images for jet, and three versions of failed jet/cocoon

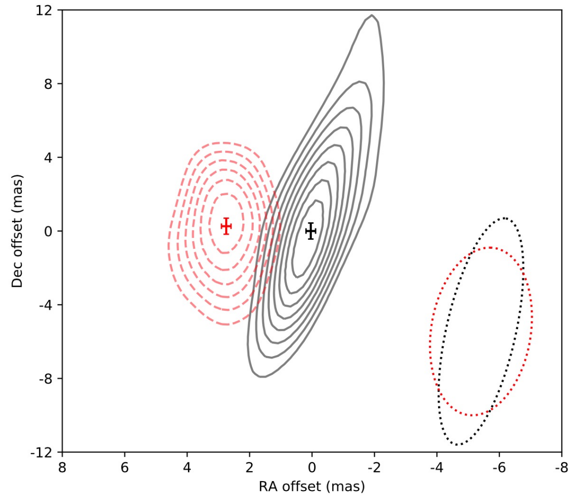


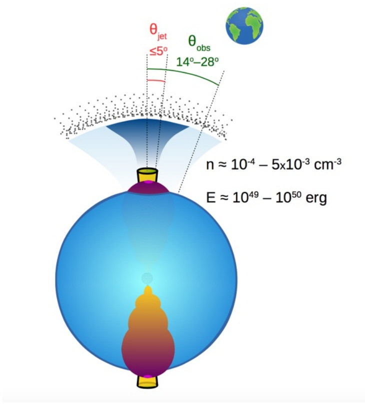
Ghirlanda et al. (2019)

- **Supports collimated jet scenario** (VLBA results: Mooley et al. 2018)
  - The highest-resolution EVN/global detection itself indicates a structured jet

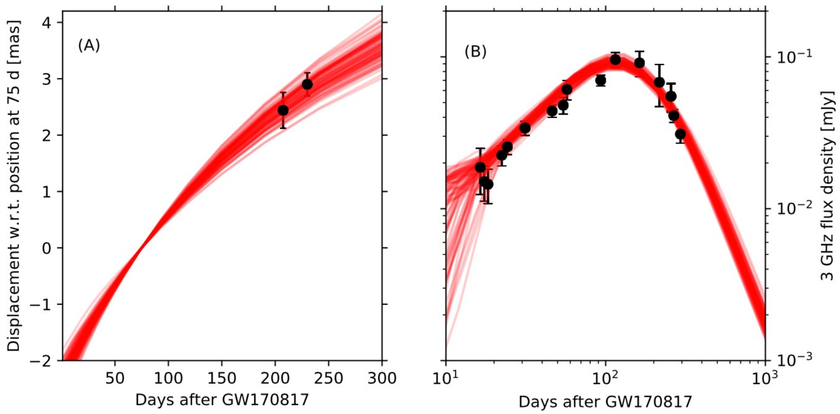
VLBI data point to a (late-time) relativistic jet

Mooley et al. (2018), 2 epochs

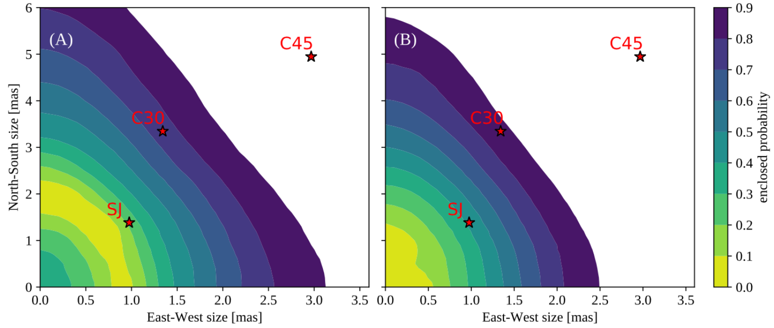




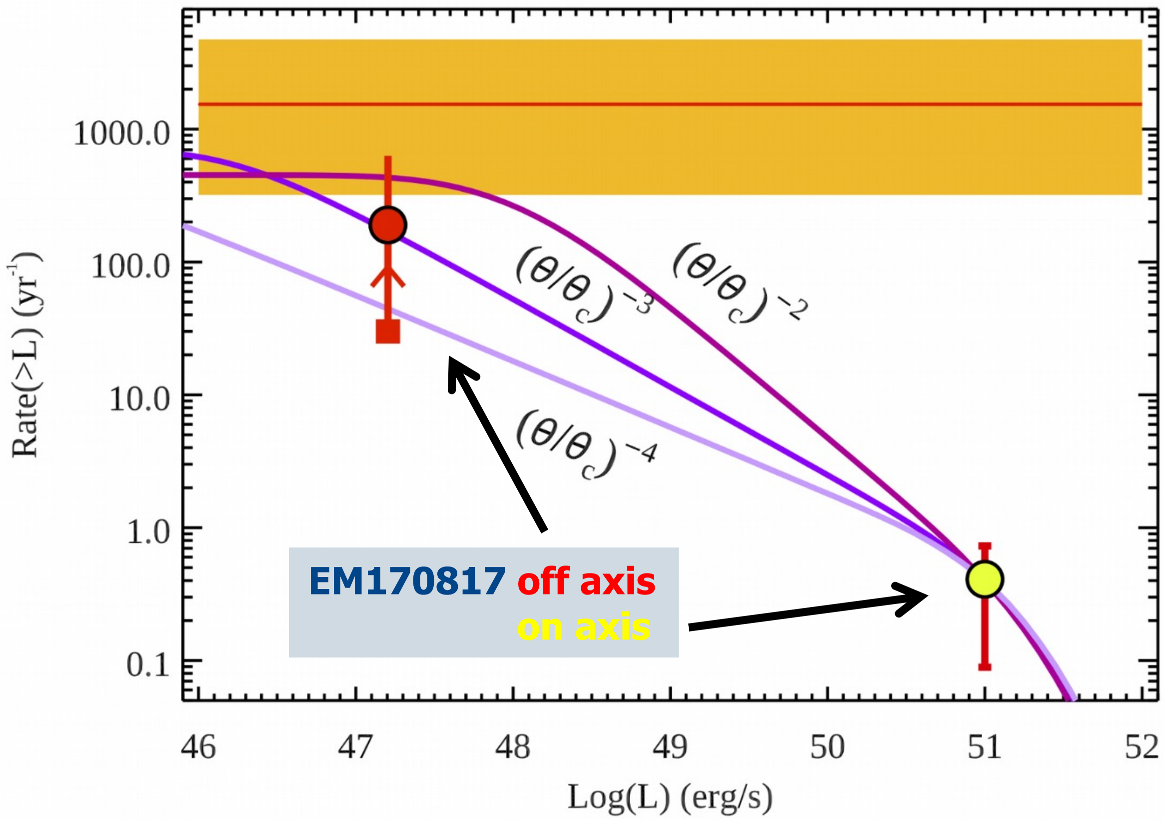
Ghirlanda et al. (2019), combining all VLBI data:



Above: MCMC parameter estimation for structured jet
Below: Bayesian constraints on source compactness



sGRB rate: Implication NS-NS mergers



BNS merger rate

sGRB rate
L_{ISO} 10^{51} erg/s

Ghirlanda et al. (2019)

➢ **A population of sGRBs**

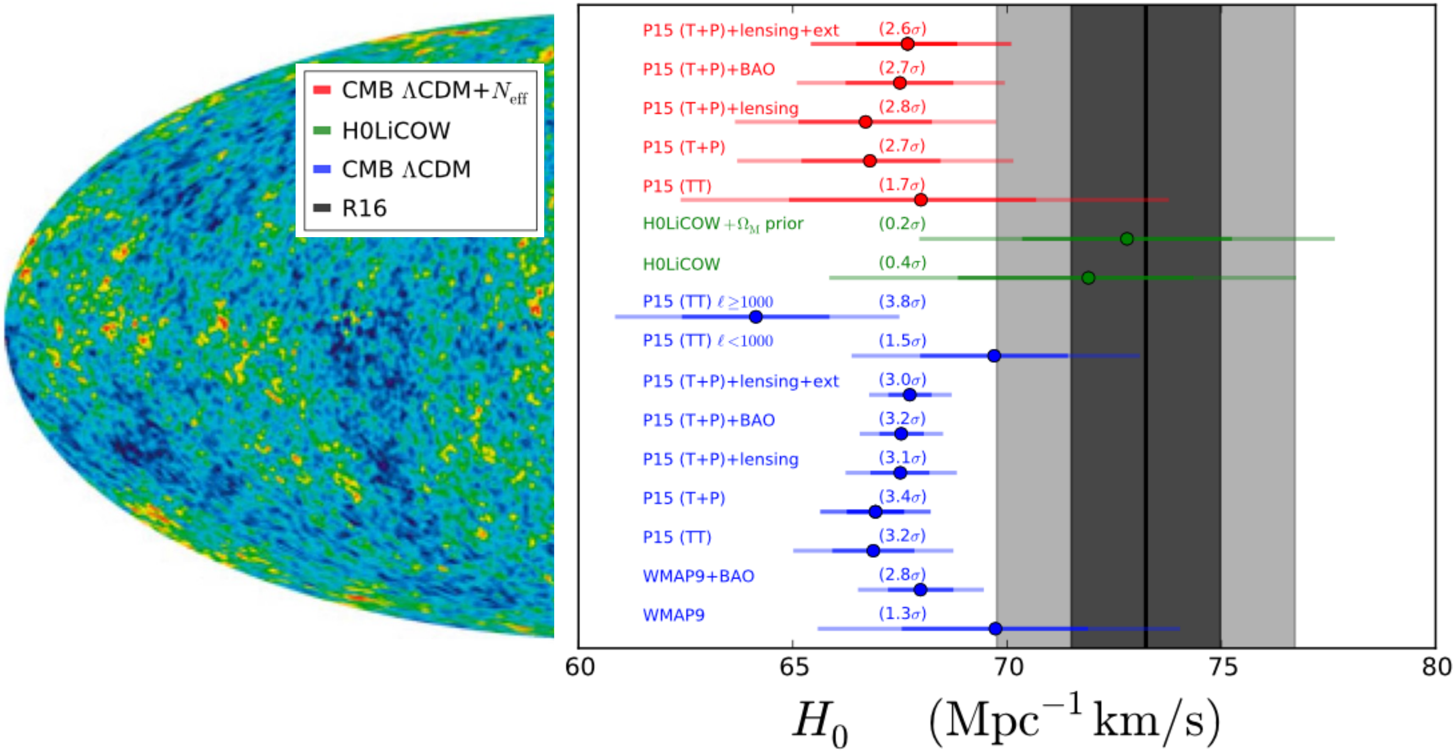
- Various jet structures predict agreement with observed sGRB rate with L_{ISO}~10^{51} erg/s
- Comparison to LIGO event rates predict 10% of all NS-NS mergers produce successful jet ***

Now a bit broader picture

- **Have we solved everything already re GW-EM counterparts then?**

  - Besides jet physics, are there other applications?

"The trouble with H_0"

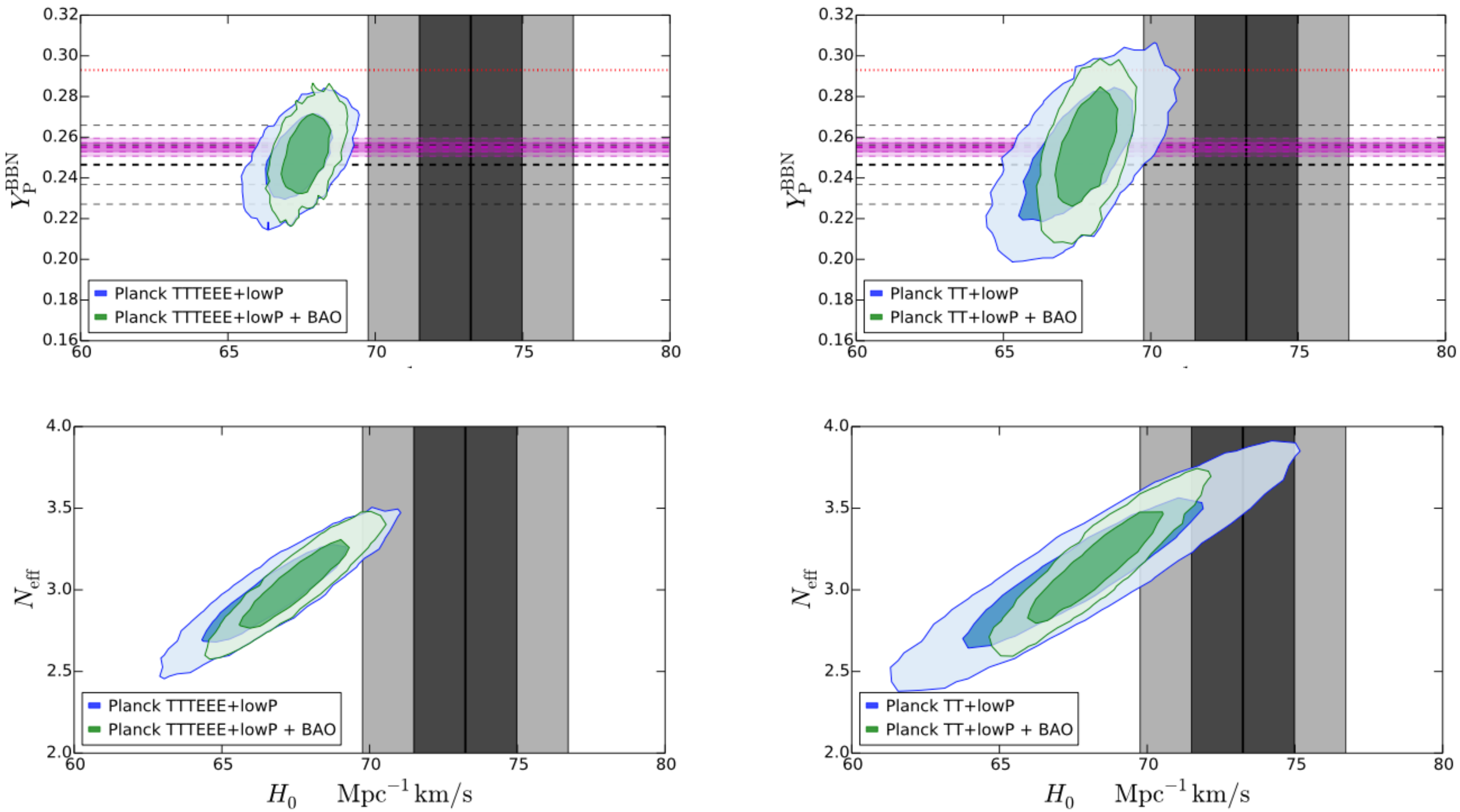


Bernal et al. (2016)

- **Discrepancy between CMB and "local" H_0 measurements**

  - The Local Universe H_0 is from SN Ia data using a complex ladder of NGC 4258 maser,
  - Local Group Cepheids, and GAIA parallaxes *(Riess et al. 2016, 2018)*

"The trouble with H_0"



Bernal et al. (2016)

- **Changes in early cosmology may alleviate the issue, but cannot solve it**

  - Nucleosynthesis – let Y, the He fraction vary without BBN prior (up)
  - Expansion history – let Neff , the number of relativistic species vary (down)
  (Former is strongly constrained by BBN, the latter by CMB polarization though)

What if the local H_0 is wrong?

- **Three ways VLBI observations can constrain H_0 directly:**

  - Gravitational Lens modelling

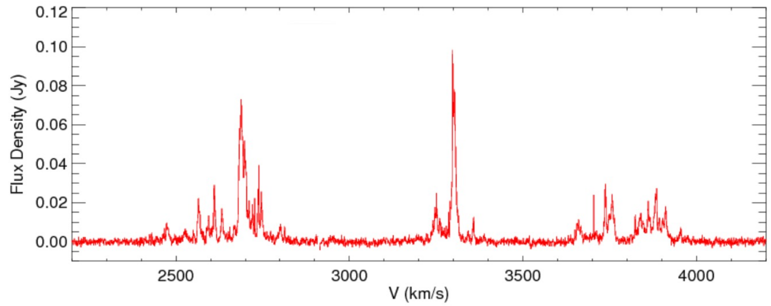
  - Megamasers (direct method, no model assumptions!)

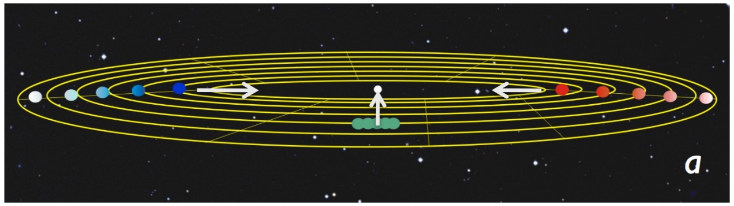
Adopted from Jim Braatz

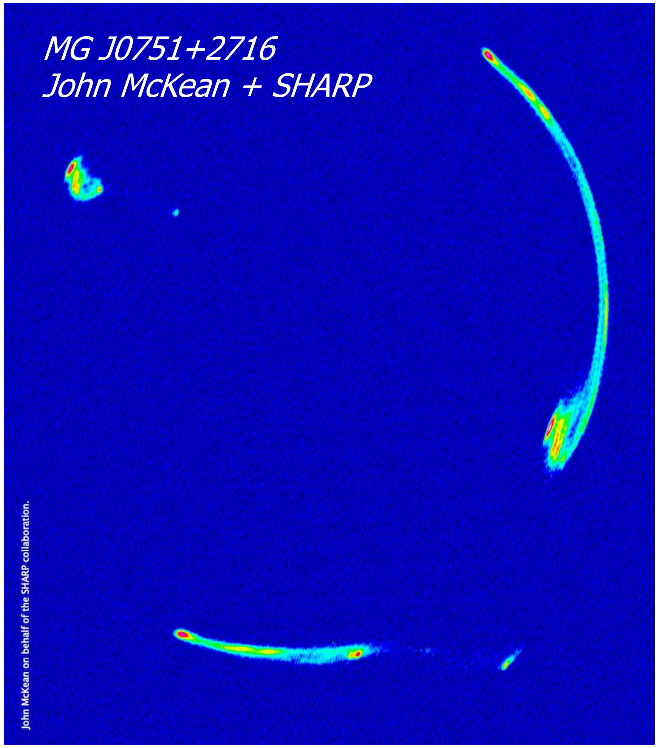
$$D = \frac{r}{\vartheta}$$

$$a = \frac{V_r^2}{r}$$

$$D = \frac{V_r^2}{a\vartheta}$$



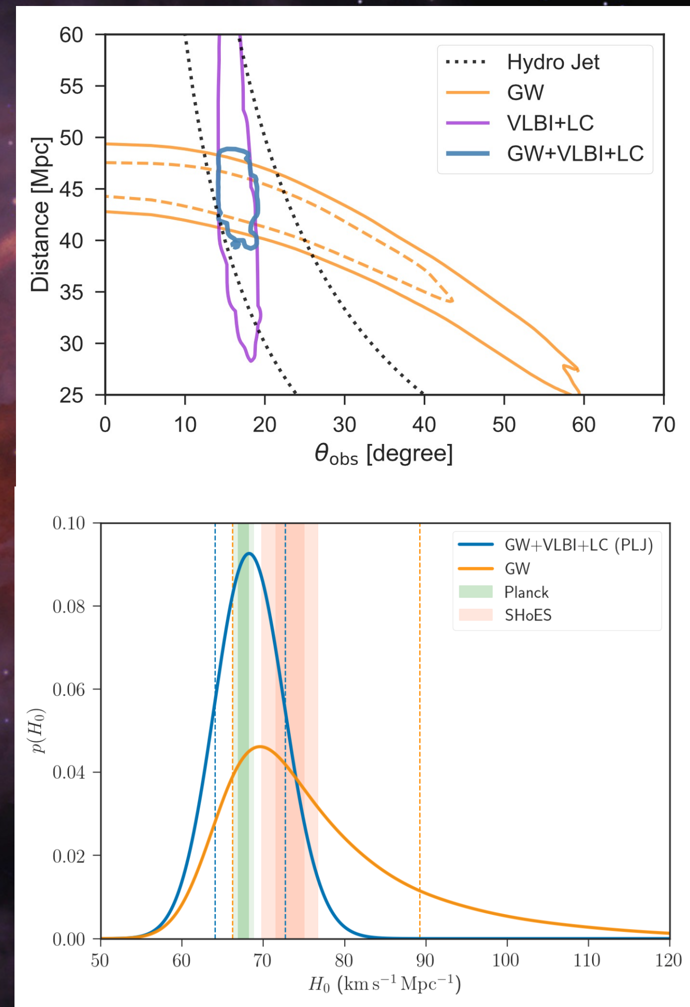




  - and, … **GW-EM counterparts**!

GW+VLBI constraint on H_0

Beabudai Design *Hotokezaka et al. (2019)*

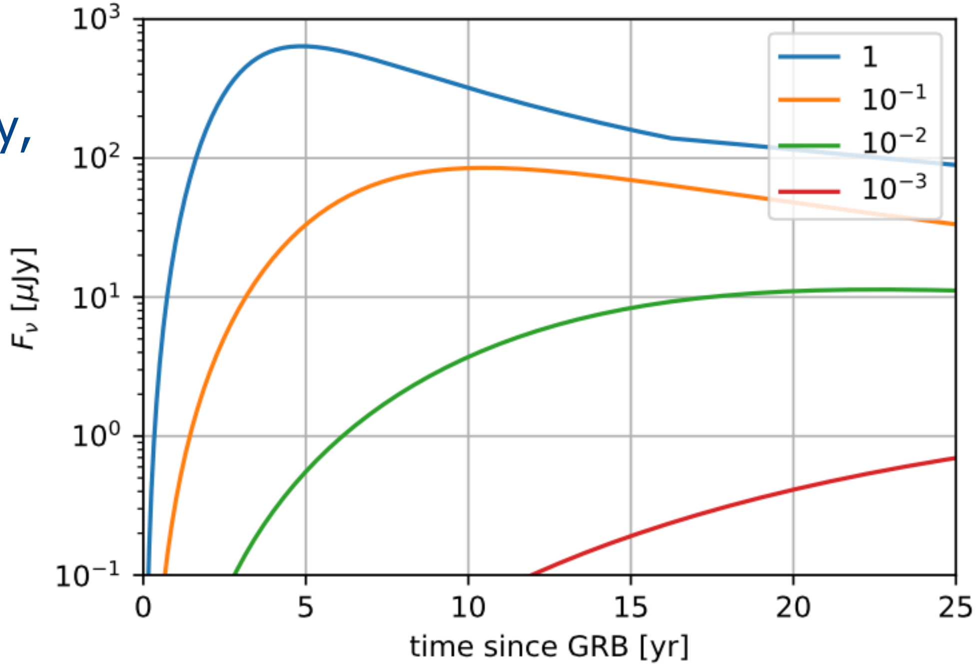


➢ **It takes 10 BNS mergers with EM counterparts to constrain H_0 at 5%, 200 for 1%**

(Sathyaprakash et al. 2019, Astro2020 Science White Paper on binary mergers)

The afterlife of a BNS merger (no jet)

6 GHz flux density, assuming 200 Mpc distance



CSM density, cm^{-3}

Model assumes outflow components as in GW170817:

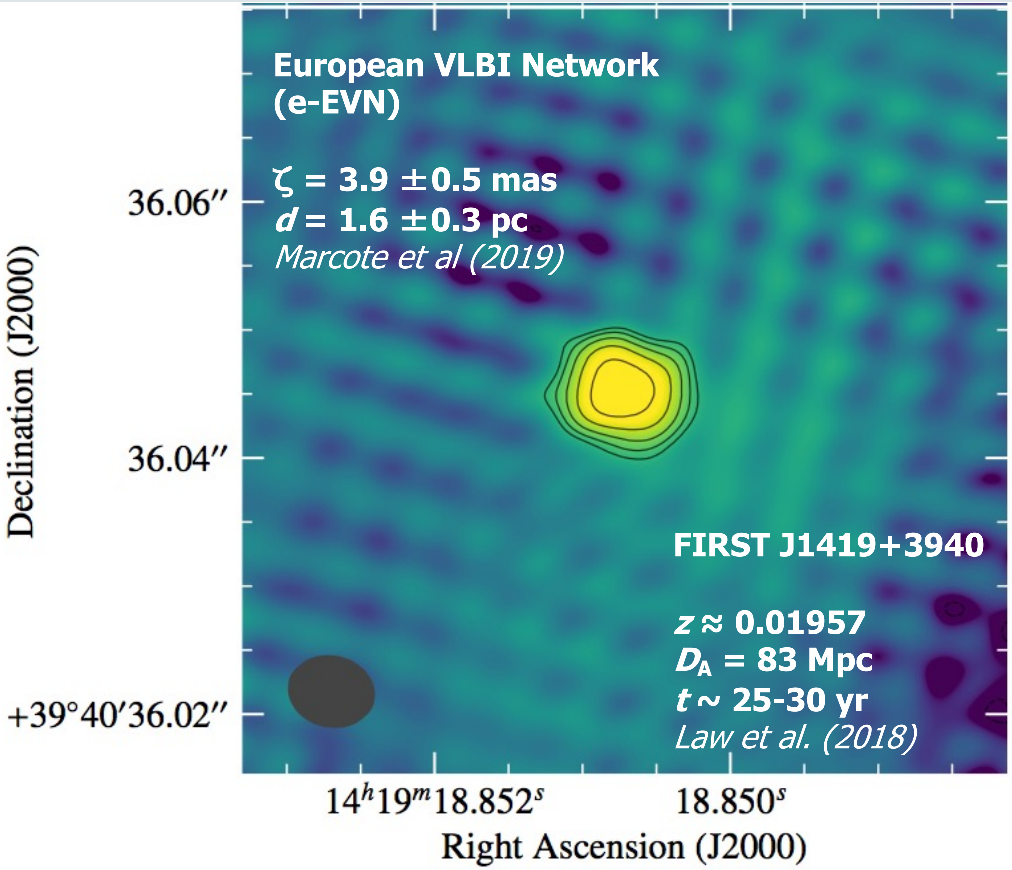
Fast – 0.01 $M_\odot$ @ 0.3c, and
Slow – 0.04 $M_\odot$ @ 0.1c

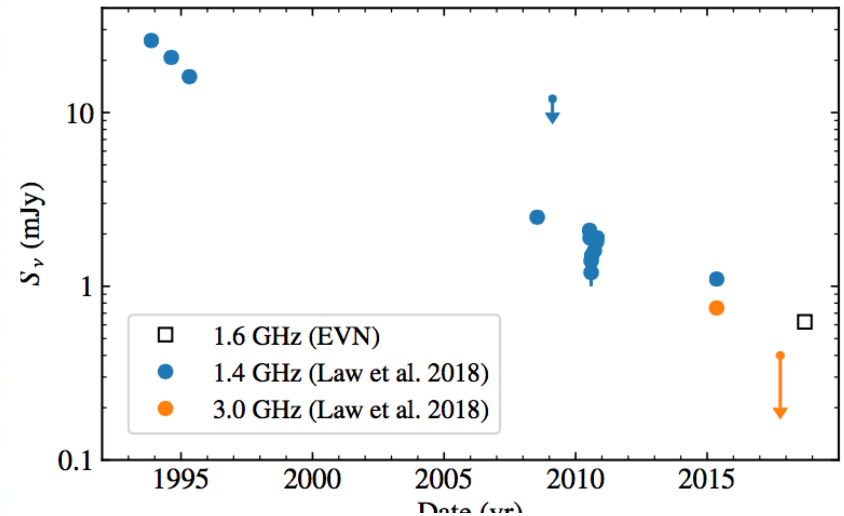
Bartos et al. (2019)

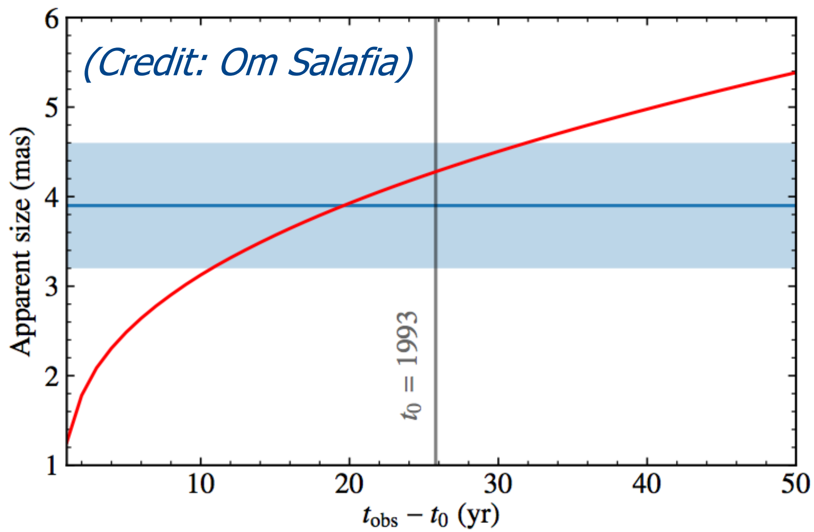
- **A population of BNS merger radio afterglows with no initial GRB**

  - BNS mergers in the Local Universe (d~200 Mpc) produce long-term radio afterglow
  - **SKA-VLBI**: sensitivity + baselines to detect + resolve mildly-relativistic outflows!

The first VLBI image of an orphan long-GRB?





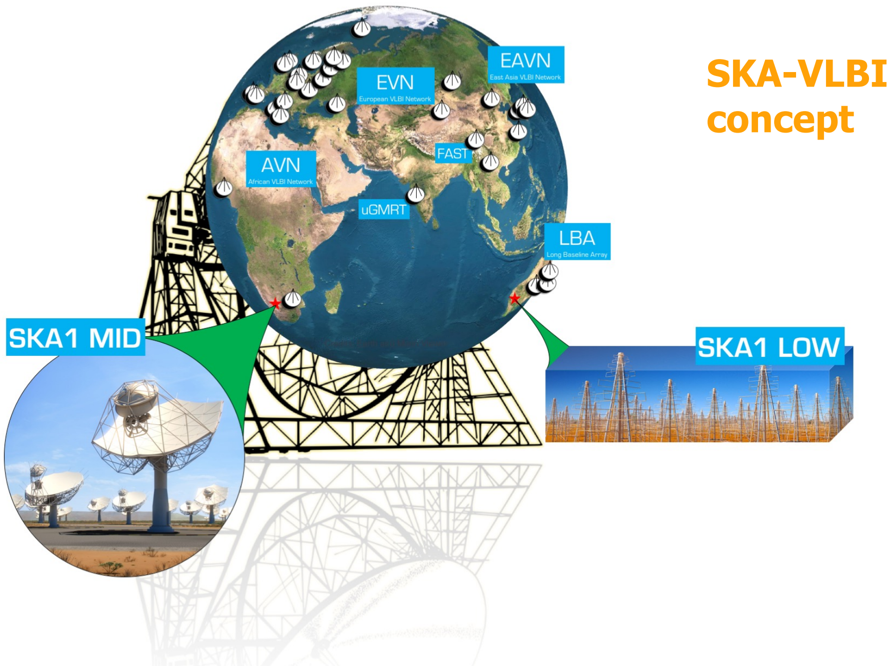


- **Resolving mildly-relativistic outflows in the Local Universe is possible**

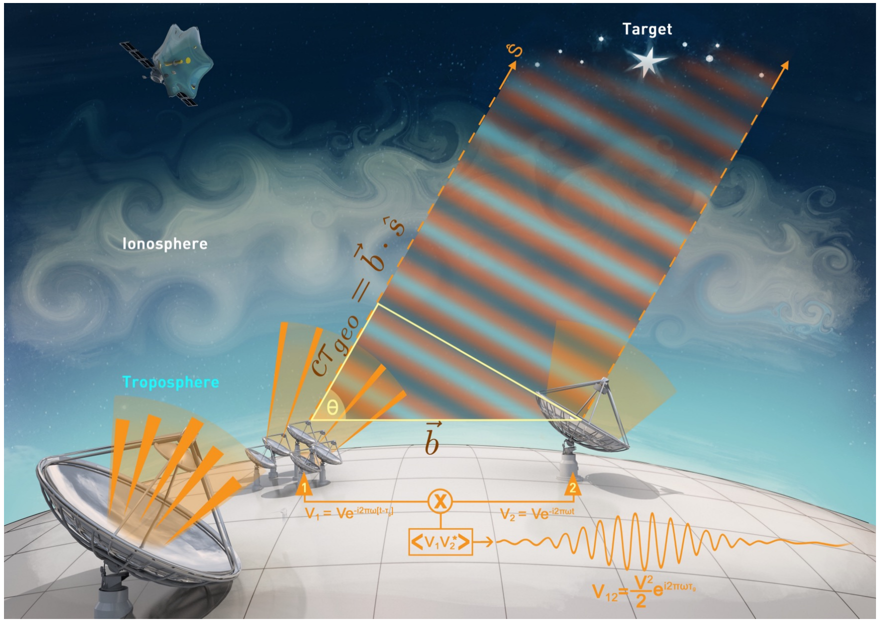
  - Requires good SNR and excellent calibration *(cf. Natarajan et al. 2016)* ➔ **SKA-VLBI !**

Marcote et al. (2019), arXiv 1902.06731

VLBI with the SKA?



Garcia-Miro et al. (2019)

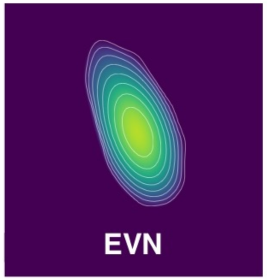


Rioja & Dodson (2020)

➢ **SKA-VLBI will combine SKA telescopes with global VLBI arrays**

- Strong science driver is ultra-precise astrometry *(~1 μas; e.g. Paragi et al. 2015)*
- Requires n>4 SKA1-MID beams *(with PST, up to 16 beams would be possible)*
- Will leverage on SKA as a survey/transient machine
- Room for some commensal applications

MeerKAT fringes with EVN!



Press release:
https://www.jive.eu/news/earth-sized-radio-observatory-just-got-better-south-africas-meerkat-telescope-joins-forces

MeerKAT joins EVN: CfP 1 Oct. 2025!

- **Advantages of adding MeerKAT**
  - **Good resolution at full sensitivity**
  - **Calibration of longest N-S baselines**
  - **Higher fidelity images** (MeerKAT+Hh)
  - **MeerKAT interferometer data** (science applications!)
  - **May refine flux and polarization cal** (using standard VLA calibrators)
  - **First steps towards realizing SKA-VLBI** (also preparing the community)
- **Advertised in the latest EVN CfP**

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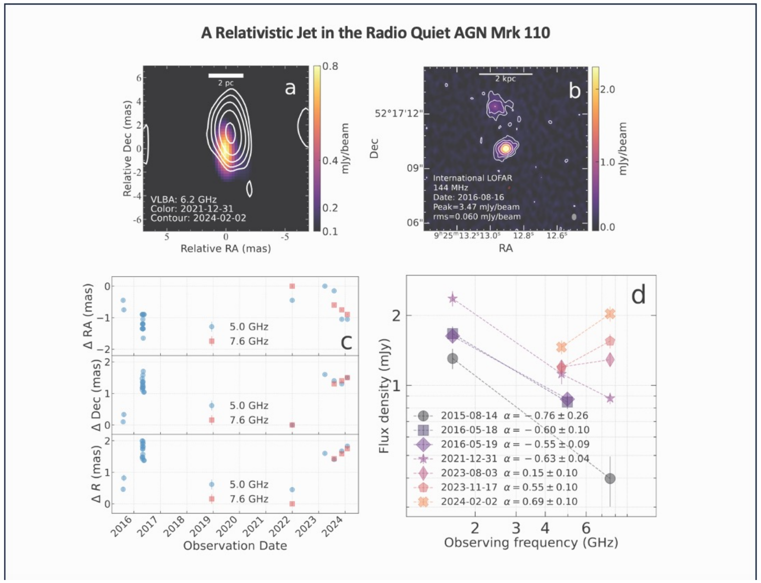
European VLBI Network
Call for Proposals
Deadline: 1 October 2025 16:00 UTC

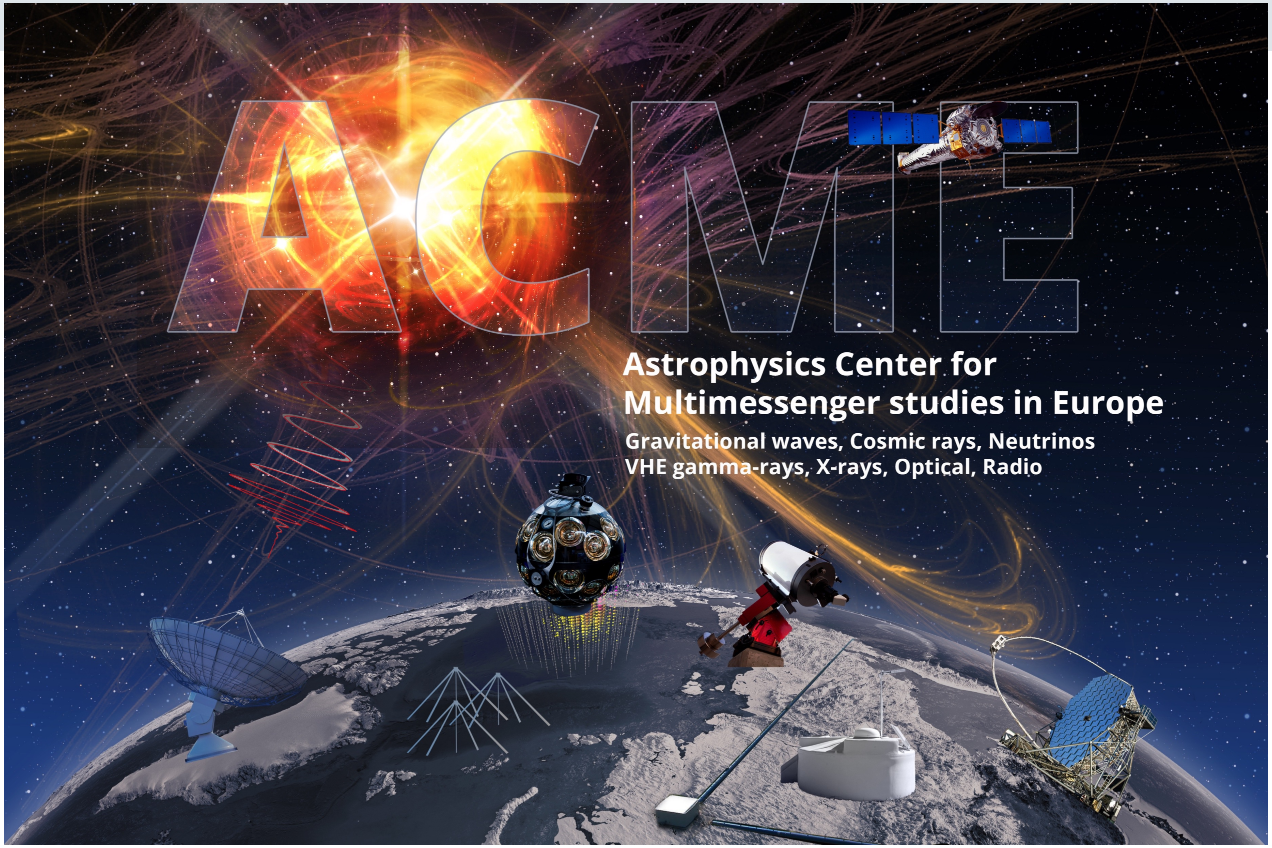
****

Observing proposals are invited for the European VLBI Network (EVN). The EVN facility is open to all astronomers, but currently restrictions apply to PIs and co-Is with affiliation to institutes in the Russian Federation or Belarus. Astronomers with limited or no VLBI experience are particularly encouraged to apply for observing time. Student proposals are judged favourably.

Support with proposal preparation, scheduling, correlation, data reduction and analysis can be requested from the Joint Institute for VLBI ERIC (JIVE).



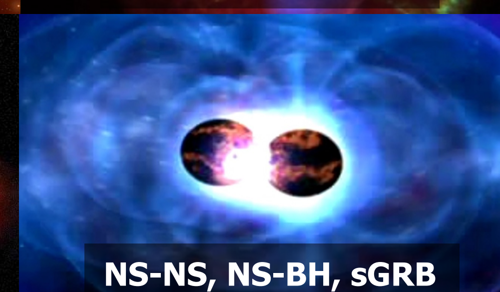
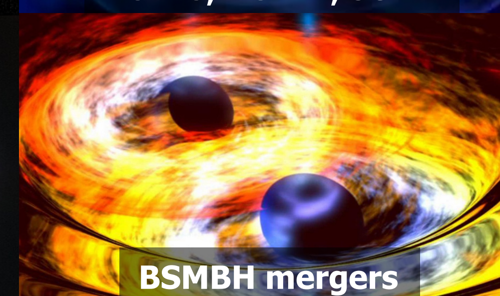
Supporting Multi-messenger astronomy



- **ACME brings together the astroparticle and astronomy communities**

  - Help access to MM instruments and expertise across Europe and world-wide.
  - Coordinates developments (e.g. triggering mechanisms), training schools, develops citizen science projects and more…

ACME science targets & phenomena

Type \ Configuration	Single	Binary	Merger
Stellar	 Flare stars, SNe/SNR, lGRB	 Novae, Dwarf Novae	 Common Envelope
Relativistic Stellar & IMBH	 Pulsars, Magnetars, FRB	 NS/BHXRB, Binary Pulsars	 NS-NS, NS-BH, sGRB
Massive BH	 Active Galactic Nuclei, TDE	 Dual/multiple AGN	 BSMBH mergers

Astrophysics Centre for Multimessenger studies in Europe

Funded by the European Union

The ACME project has received funding from the European Union's Horizon Europe Research and innovation programme under Grant Agreement No 101131928.

Broaden access to infrastructures, data, expertise, tools… for multi-messenger science.

- ❖ Open calls for data sharing and visiting institutes.
- ❖ Organisation of schools and
- ❖ www.acme-astro.eu

➢ **For more information on ACME, see**

- the additional slides provided by the project; available through the JVS web pages
- the ACME website (acme-astro.eu)