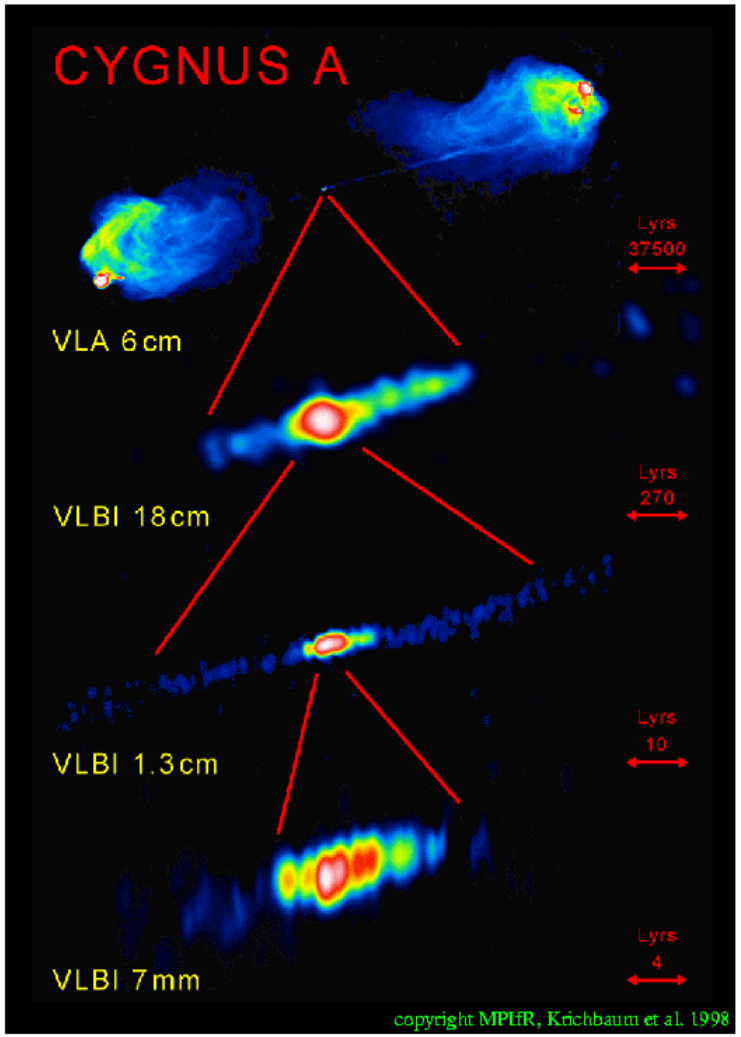
Transient science with (e-)VLBI:
Two EVN/JIVE success stories

Zsolt Paragi
JIVE

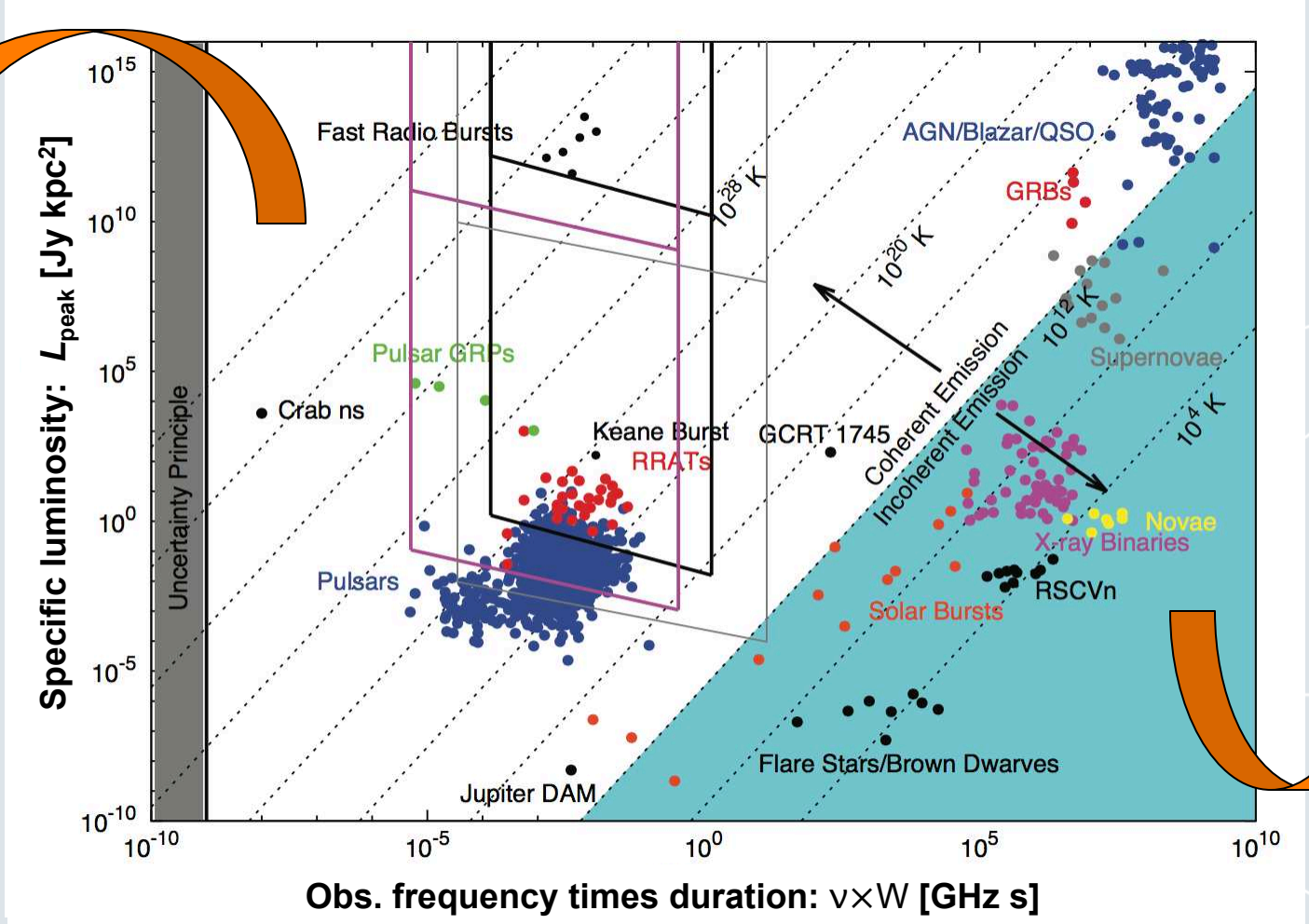
Beabudai Design

Angular scales probed by VLBI



- **VLBI probes angular scales <1 mas to ~100 mas – 10^9 smaller than FoV of an individual telescope!**
- **Spatial scales probed:**
  - 10^{14} - 10^{16} cm (or 5 - 500 AU) @ 5 kpc
  - 1 - 100 parsec @ 200 Mpc (redshift of 0.05)
  - 7 - 700 parsec @ $z = 4$
- **Transient sources are compact by nature**
- **VLBI is a great tool to probe their early phases of (relativistic) transients**

The radio transients parameters space



SKA Transient WG - Macquart et al. (2015);
update of *Cordes, Lazio & McLaughlin (2004)*

EVN: the e-VLBI transition

From triggers to (early) results

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):

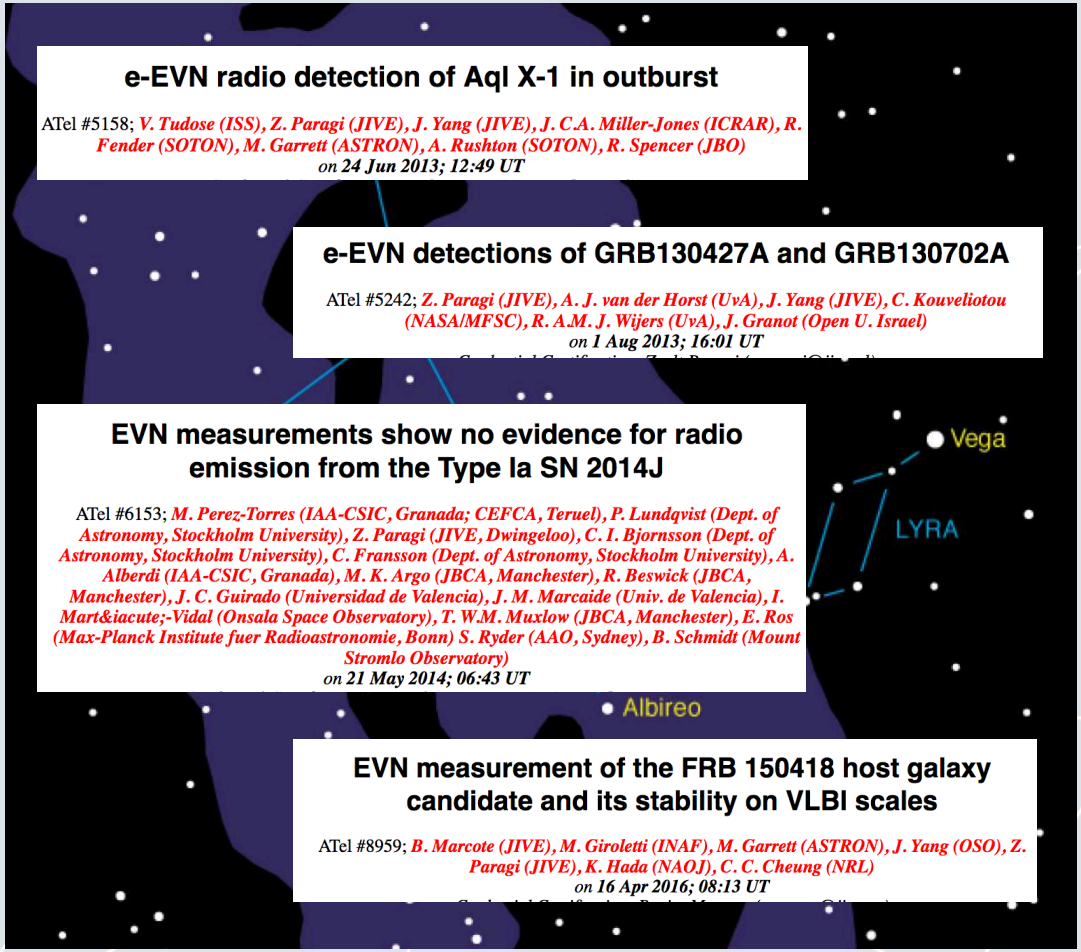
RA: 20h24m03.8183983
Dec: +33d52m01.840768"

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.



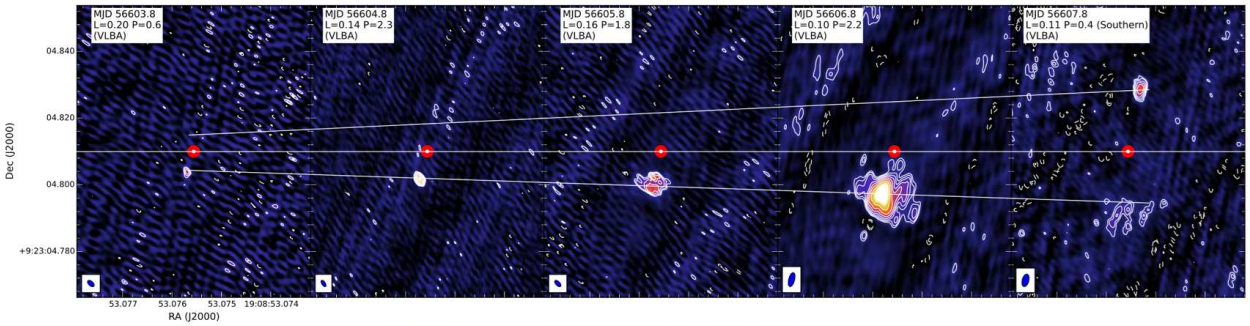
e-VLBI: Delivering the most sensitive VLBI array in a flexible way…

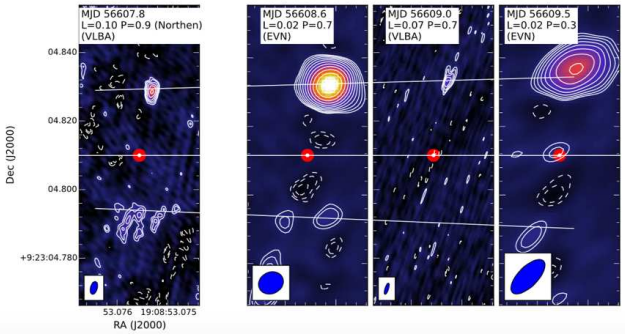
Talk outline

- **A few examples of synchrotron transient types (1 slide each)**
- **Fast Radio Bursts with VLBI**
- **Gravitational wave electromagnetic countepart observations with VLBI**
- **Advertising SKA-VLBI**

Microquasars

Expanding jets in BHXRB XTE J1908+094



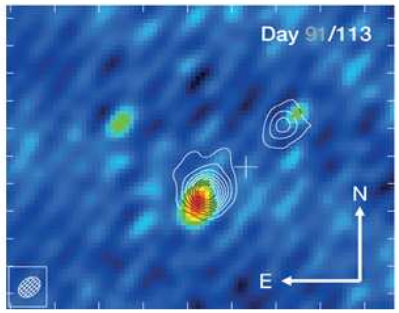


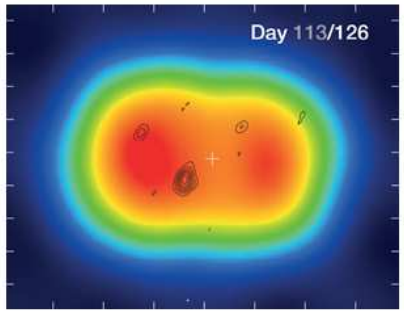
- Joint e-EVN/VLBA monitoring
- Rare example of laterally resolved jets
- Decelerating ejecta indicate unusually dense ISM

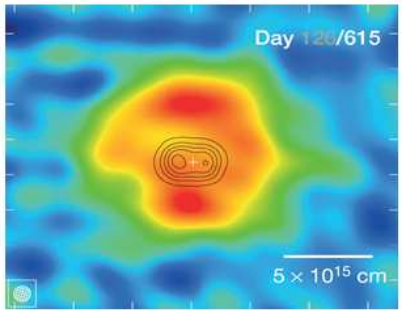
Rushton et al. (2017)

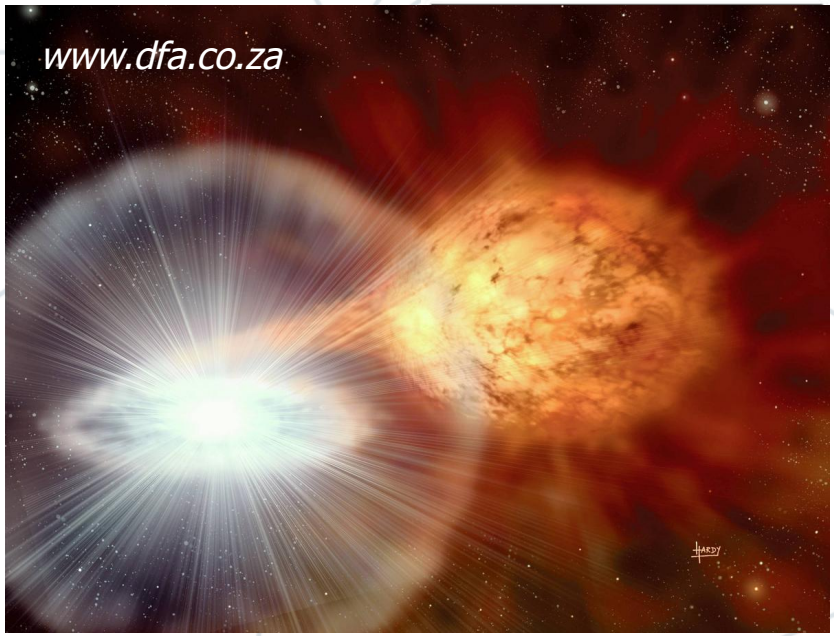
Novae

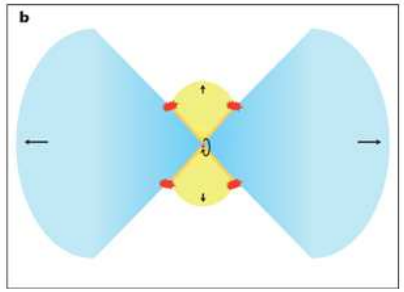
Nova Monoceros 2012

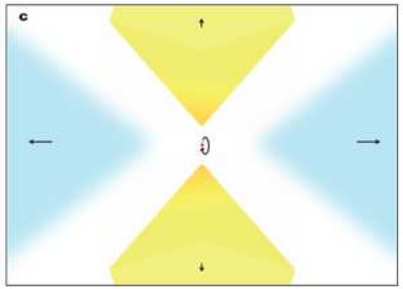








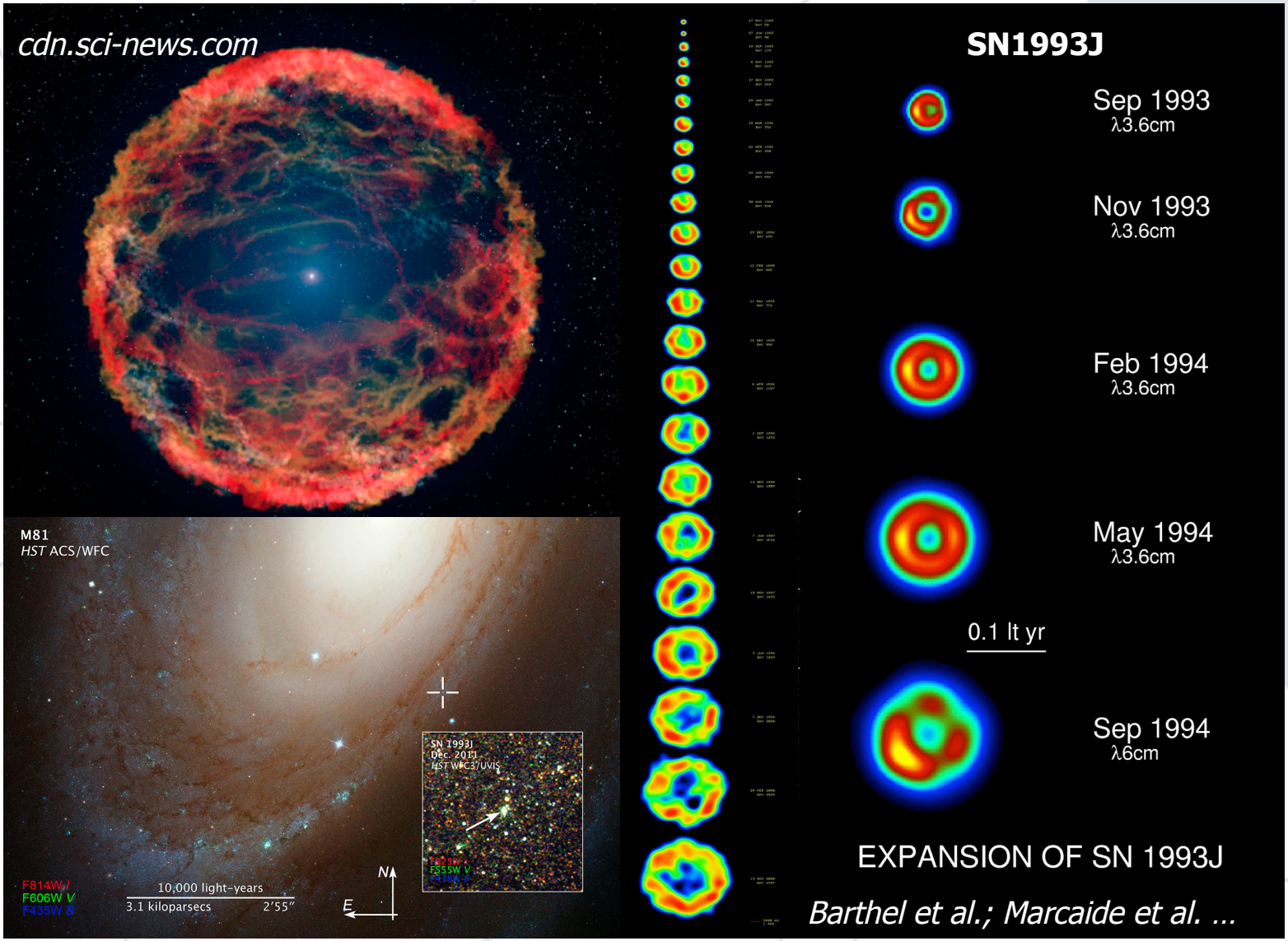




Chomiuk et al., Nature, 514, 339, 2014

e-EVN, JVLA, VLBA, e-Merlin

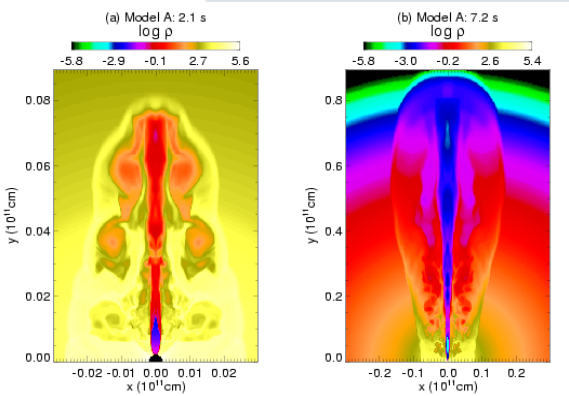
Supernovae


cdn.sci-news.com
M81
HST ACS/WFC
F814W I
F606W V
F435W B
10,000 light-years
3.1 kiloparsecs
2'55"
N
E
SN 1993J
Dec. 2011
HST WFC3/UVIS
F225W U
F555W V
F438W B
SN1993J
Sep 1993
λ3.6cm
Nov 1993
λ3.6cm
Feb 1994
λ3.6cm
May 1994
λ3.6cm
0.1 lt yr
Sep 1994
λ6cm
EXPANSION OF SN 1993J
Barthel et al.; Marcaide et al. …

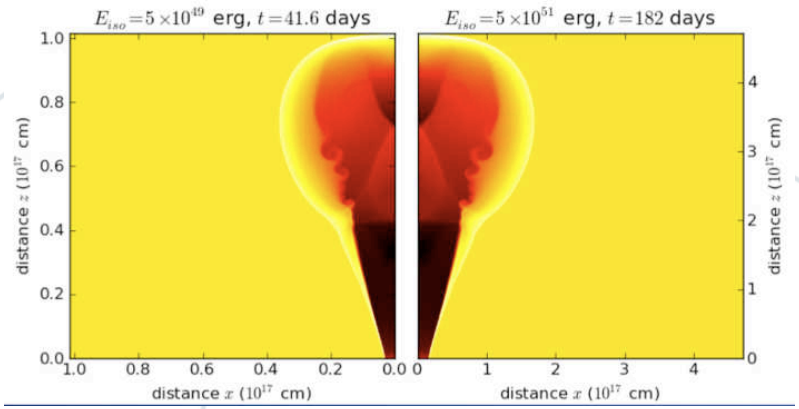
Gamma-ray bursts

Relativistic ("engine-driven") SNe, long-GRBs

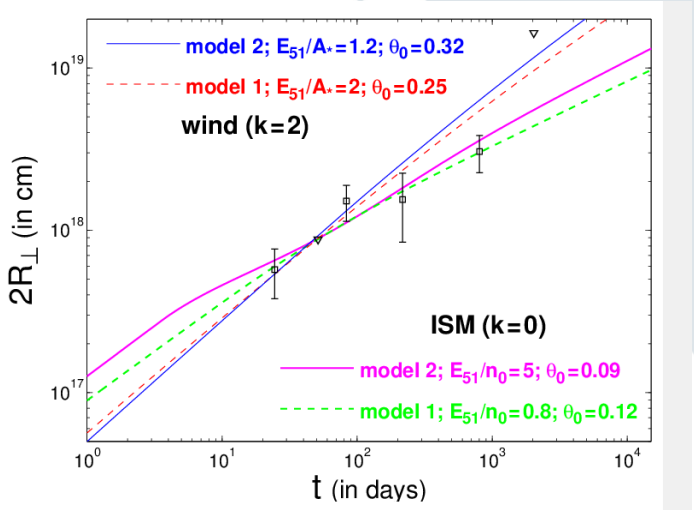
- Death of massive stars: Collapsar model
- VLBI confirmed for only GRB030329 *(Taylor et al. 2004, …)*
- *… very challenging (sensitivity, resolution)*
- *Simultaneous fit to model flux and size is a promising way to probe jet physics and the environemnt in long-GRBs*



Woosley (1993)
MacFadyan & Woosley (1999)

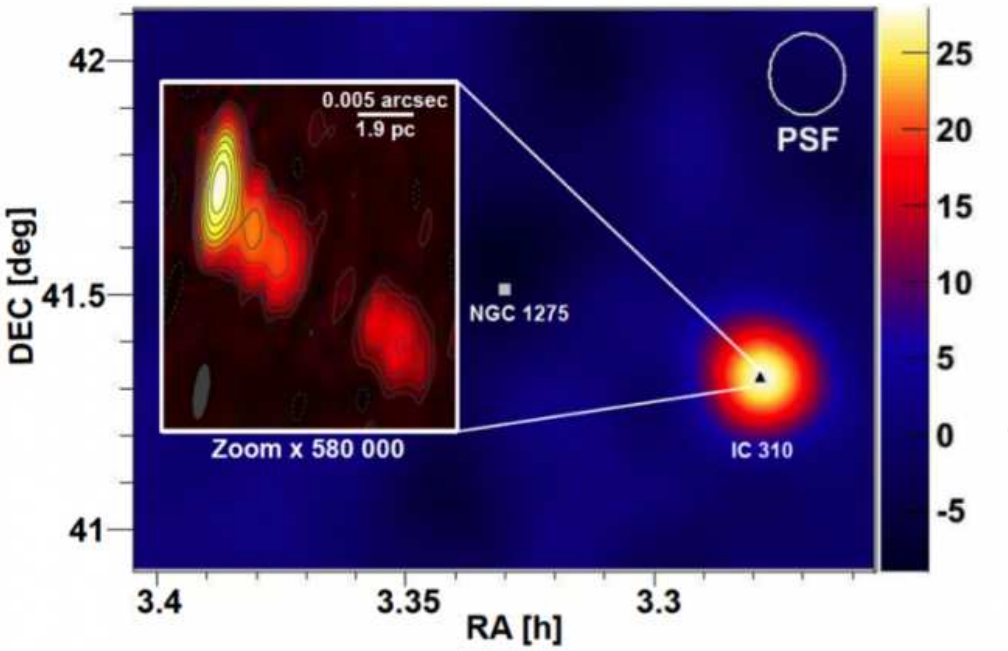


van Eerten, van der Horst & MacFadyen (2012)



Granot & van der Horst (2014)

Flaring AGN

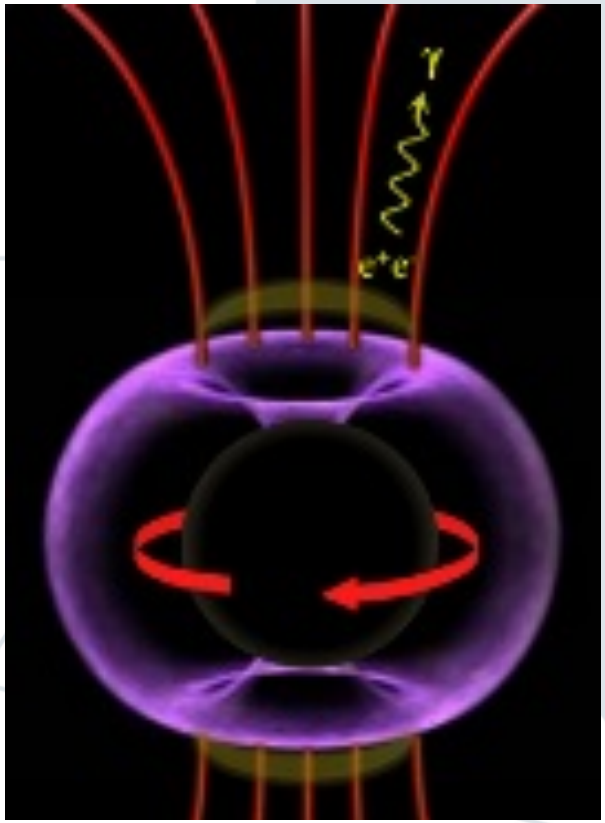


Aleksić et al., Science, 346, 1080, 2014

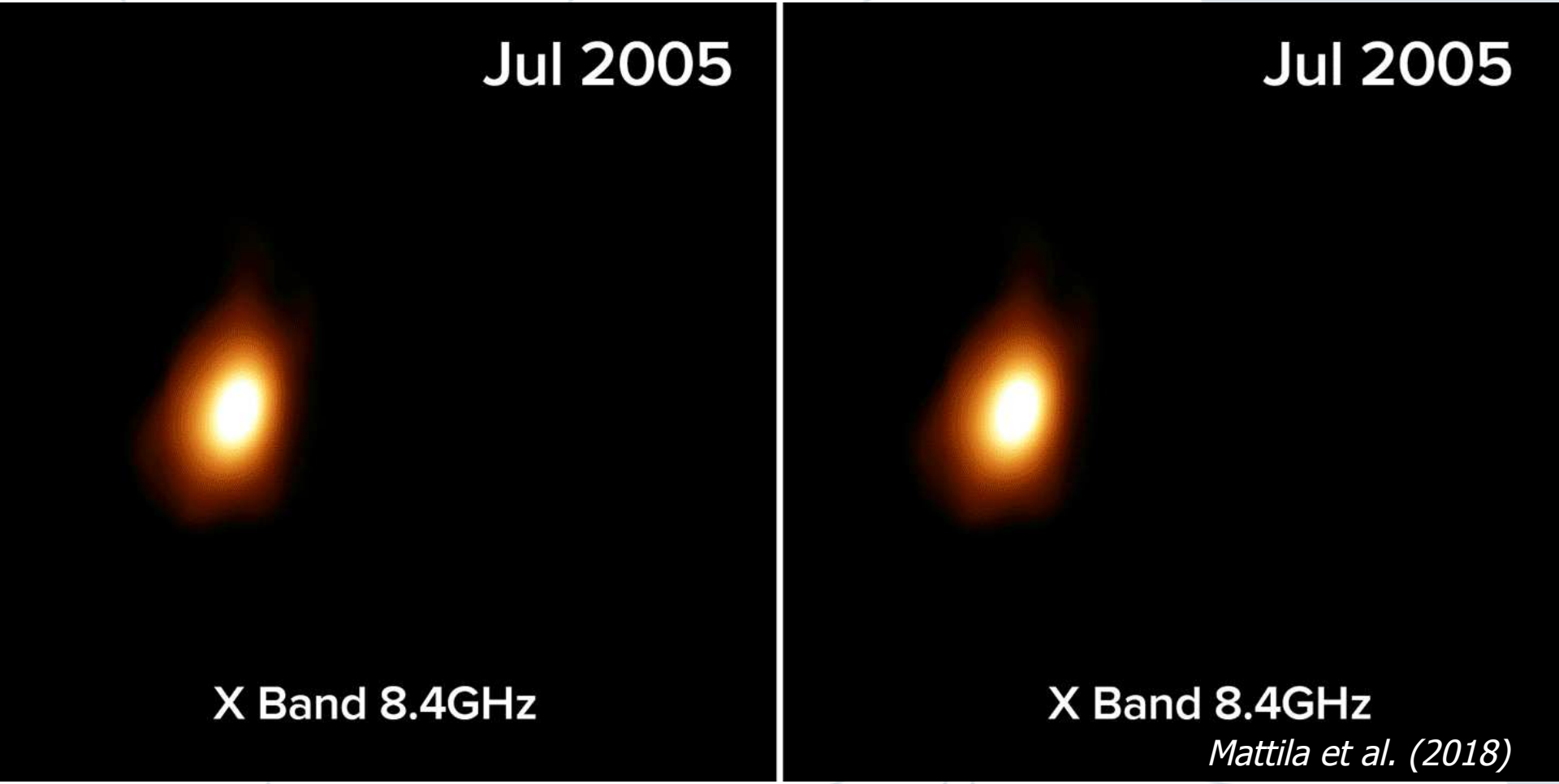
"Black hole lightning due to particle acceleration at subhorizon scales"

MAGIC+EVN
Gamma-ray variability <5 mins: probing much smaller scales than VLBI!

IC 310



Tidal Disruption Events: SMBH destroying stars



- **Arp299b: First detection of resolved ejecta from a jetted Tidal Disruption Event**
- **TDE detected in IR rather than in X-rays: thick torus absorbing/re-radiating X-ray flare?**

Fast Radio Bursts

A historical fast transient search

- Evaporating primordial BH smaller than 10^{12} kg will produce short flashes in gamma rays

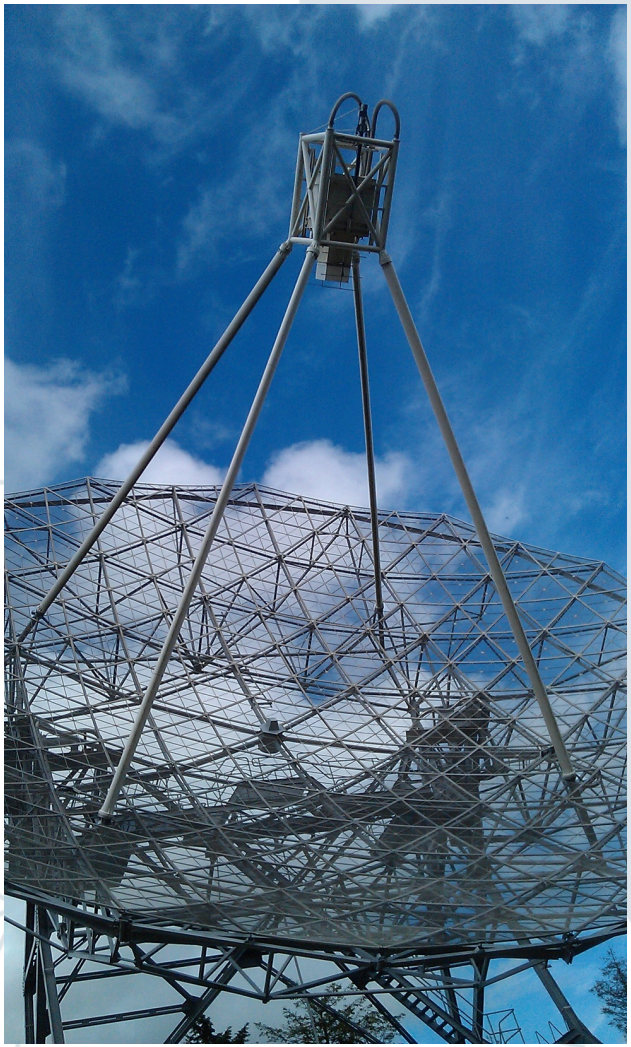
Hawking (1974), Nature, 248, 30

- Radio waves predicted from e^- and e^+ interacting with magnetic fields; detectable at least out to 10 kpc

Rees (1977), Nature, 266, 333

- Radio limits on explosive primordial BH e.g. by the Dwingeloo Radio Telescope

O'Sullivan, Ekers, Shaver (1978), Nature, 590, 591



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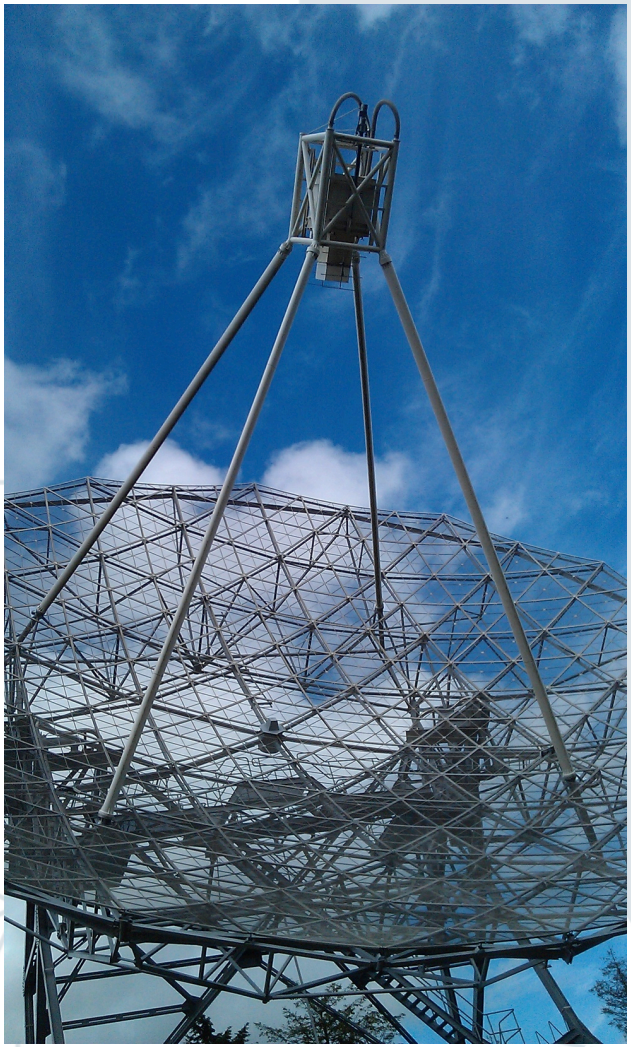
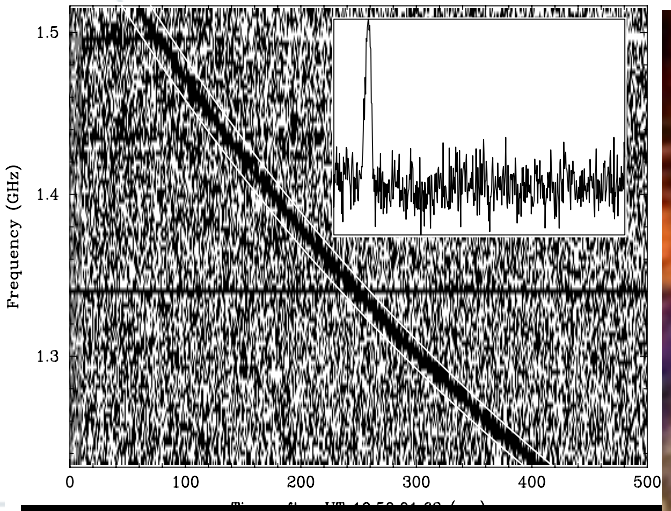
Wikipedia:

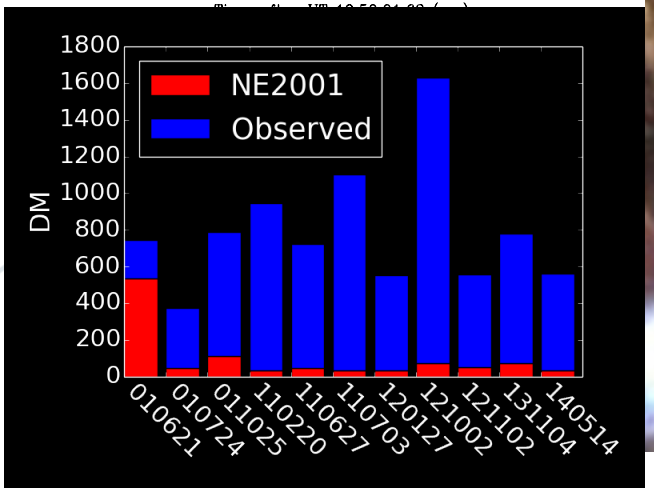
"**John O'Sullivan** is an Australian electrical engineer whose work in the application of Fourier transforms to radio astronomy[1] led to his invention with colleagues of a core technology that made wireless LAN fast and reliable…"



Fast Radio Bursts (as of 2007)

Lorimer et al. (2007)





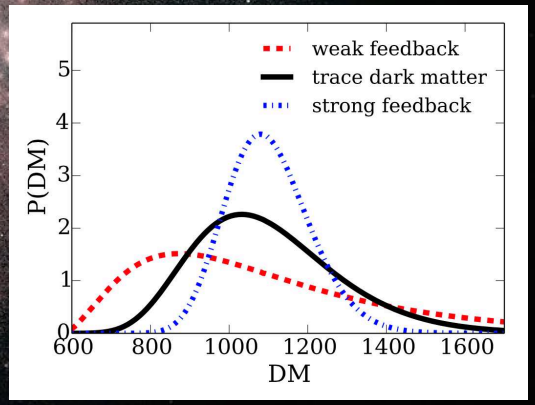
- **Signal duration of a few milliseconds, unknown origin (for a long time…)**
- **For many years there were many more theories than FRBs found**
- **They seem to be extragalactic!**

Fast Radio Bursts: a tool for cosmology

FRB

The distance must be known: localization!

Measurement on Earth

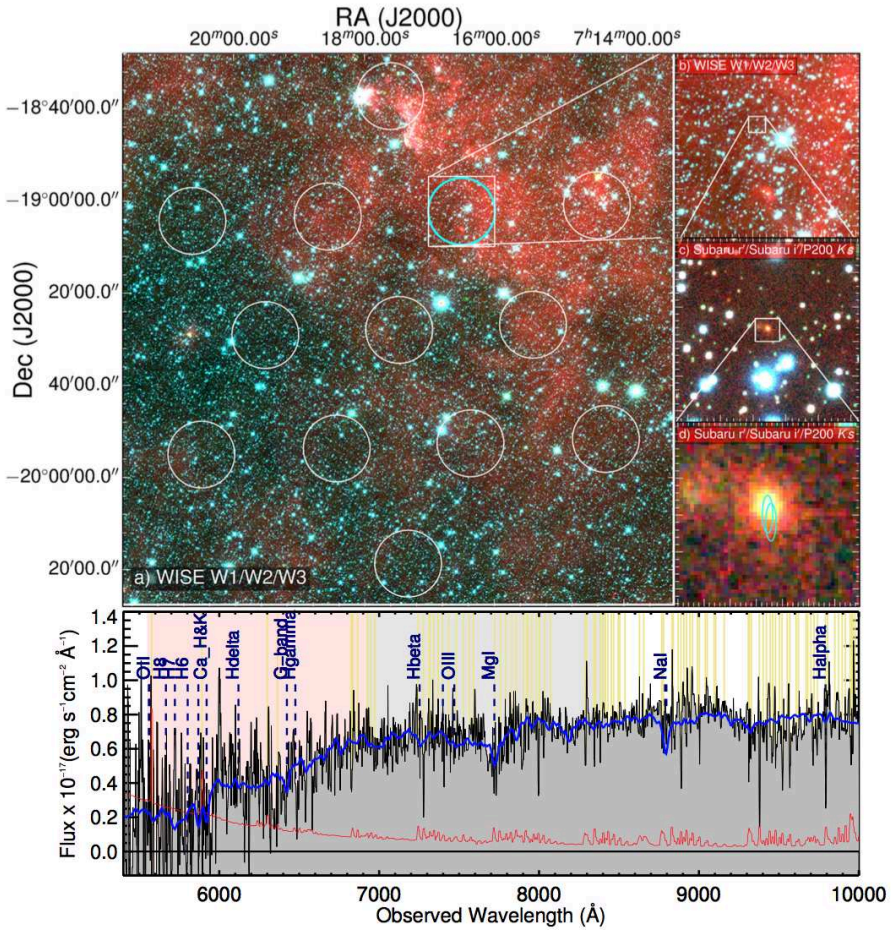


- **A tool to study the cosmic web: the distribution of matter in the Universe**
- **Most of this matter within the galaxies is invisible otherwise**

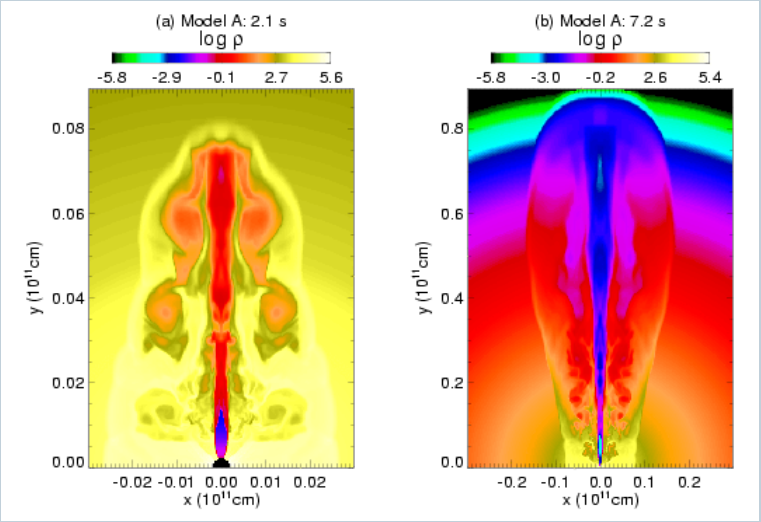
Background: https://www.alanrduffy.com

Macquart, Keiane & Grainge 2015

The localization trouble



"Afterglow" analogy:



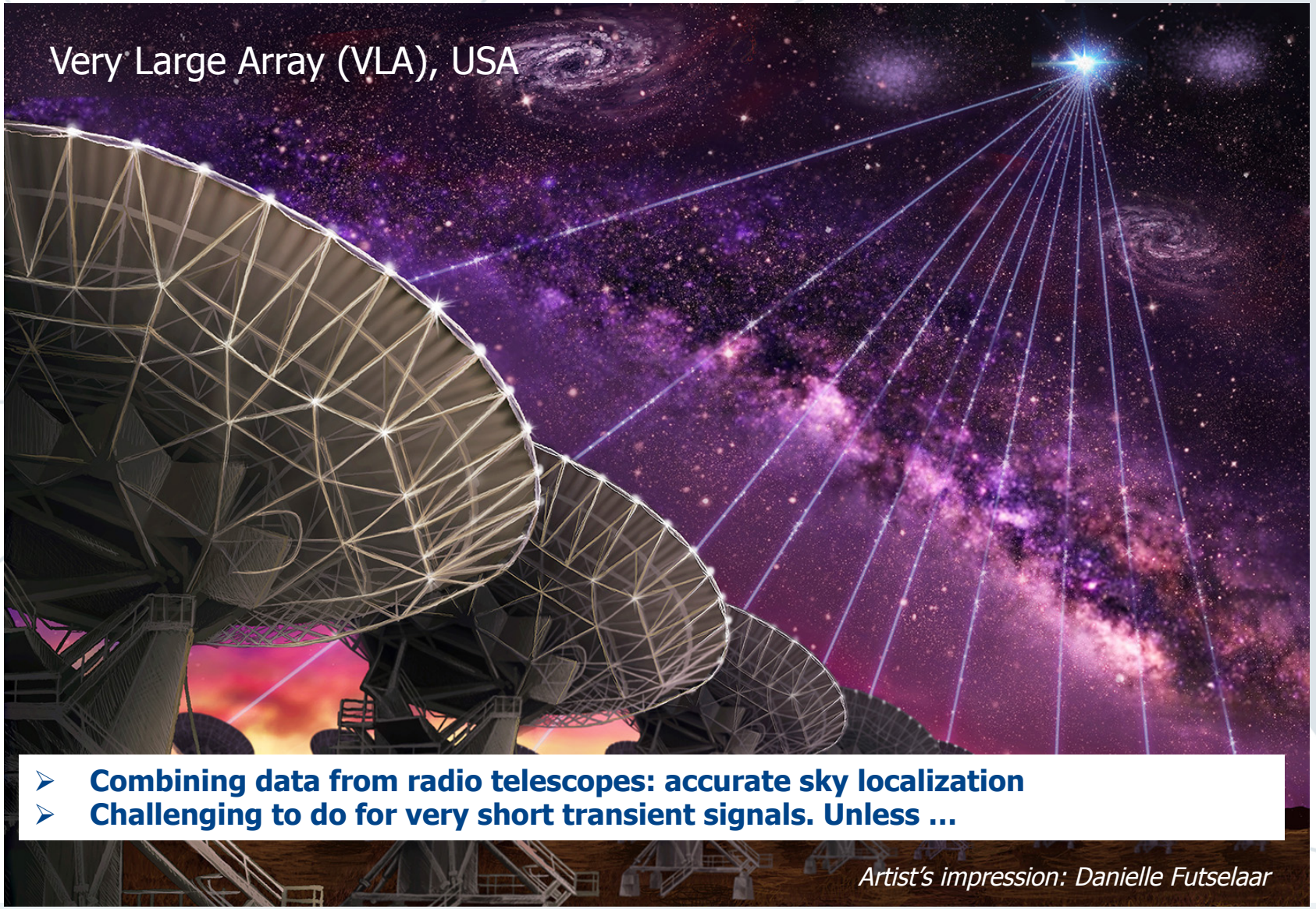
Simulations of relativistic jets following a cataclismic event. *Woosley (1993); MacFadyan & Woosley (1999)*

Identification attempt of the host galaxy of FRB150418.

Keane et al. (2016)

- **Looking for "residual", transient radio emission on days timescale**
- **If found, it can pinpoint the galaxy: distance (redshift) obtained from optical spectra**

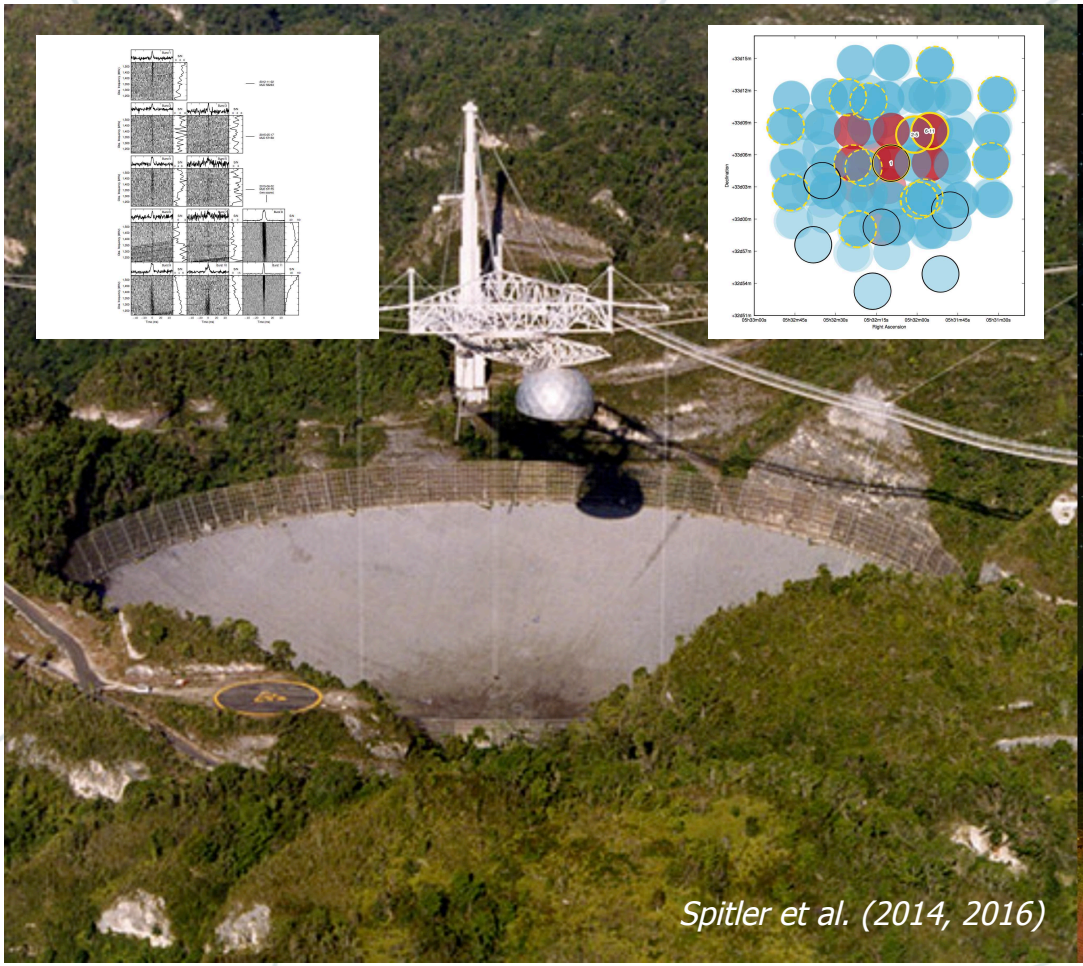
Direct localization: interferometry!

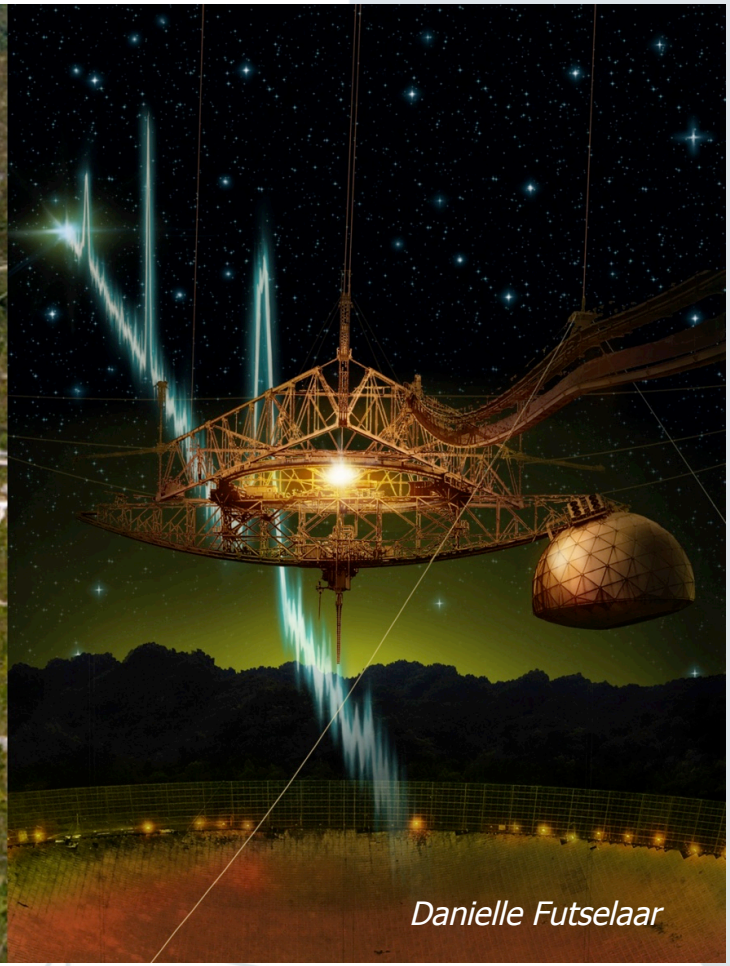


- **Combining data from radio telescopes: accurate sky localization**
- **Challenging to do for very short transient signals. Unless …**

Artist's impression: Danielle Futselaar

Arecibo finds and FRB coming back!

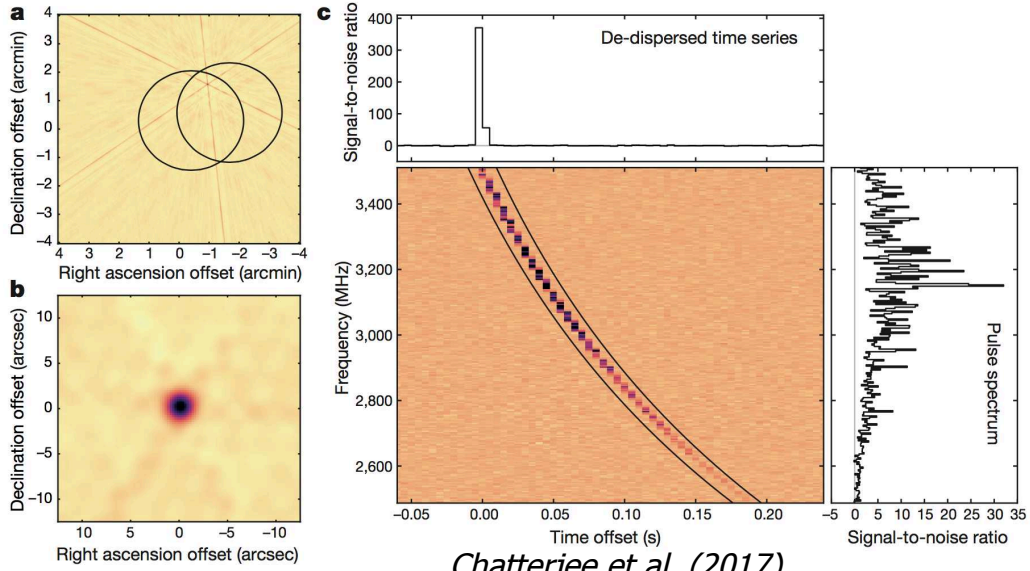




- **Several pulses found between 2012 – 2015, similar direction**
- **FRB121102 – a new type of fast radio burst?**

FRB121102: the first FRB identified!

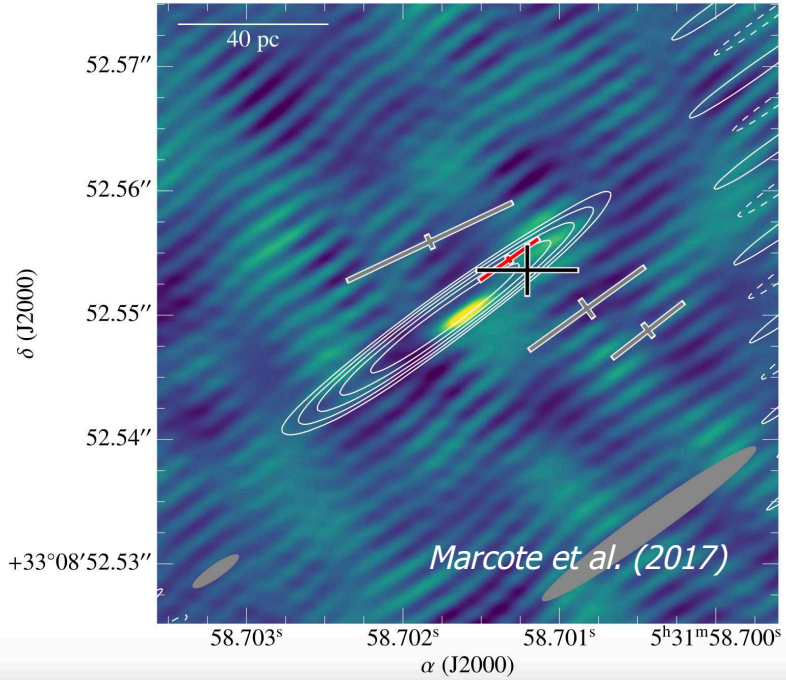
Very Large Array (VLA) signal detection
27 telescopes, few tens of km area



Chatterjee et al. (2017)

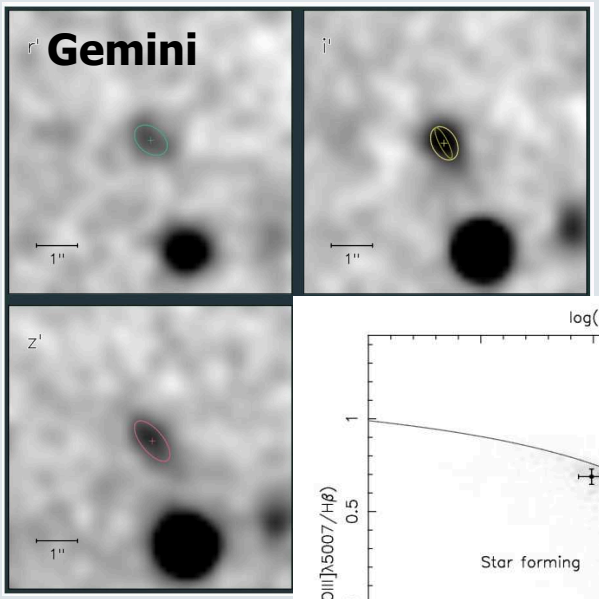
5-ms image (dispersion corrected) of one burst.

European VLBI Network (EVN) images
11+ telescopes, baselines up to 7000+ km

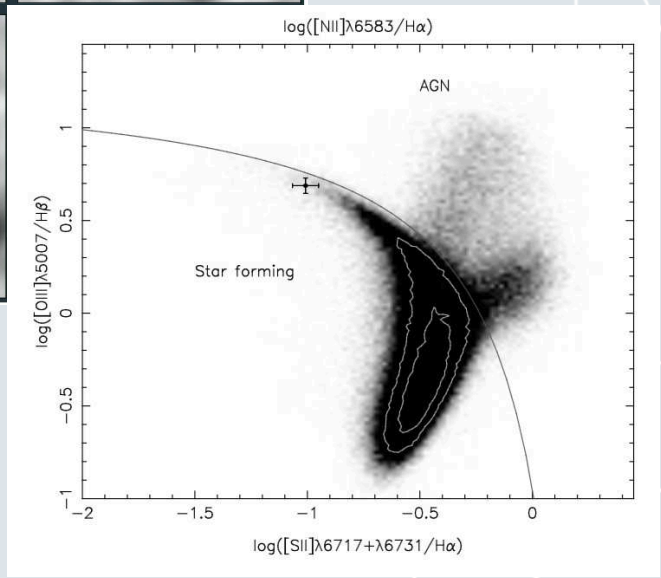


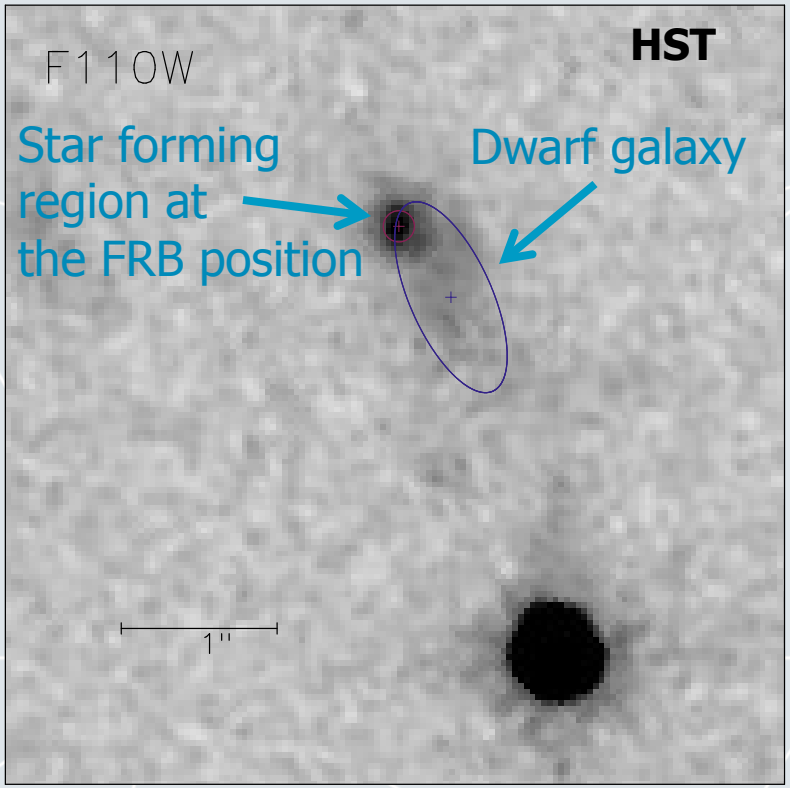
- **VLA precision (~0.1 arcsec) sufficient to prove extragalactic origin**
- **EVN refined position (~0.01 arcsec): pulses appear in the near vicinity of a permanent radio source of unknown nature (took 8 ToO epochs to catch them!)**
- **Years of work in detecting/imaging of FRB-like pulses (pulsars, RRATs): LOCATe**

Persistent radio counterpart: peculiar object in a metal-poor dwarf galaxy



Tendulkar et al. 2017

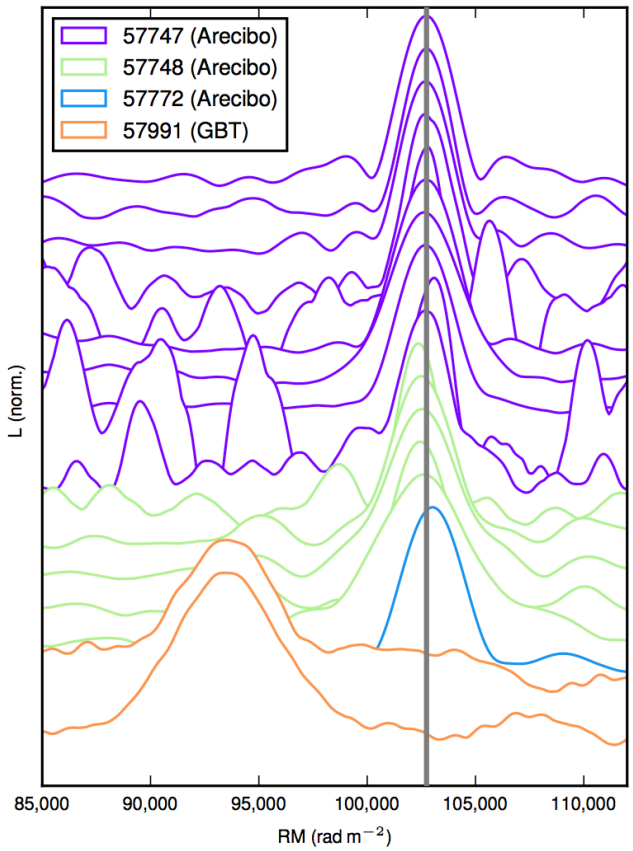


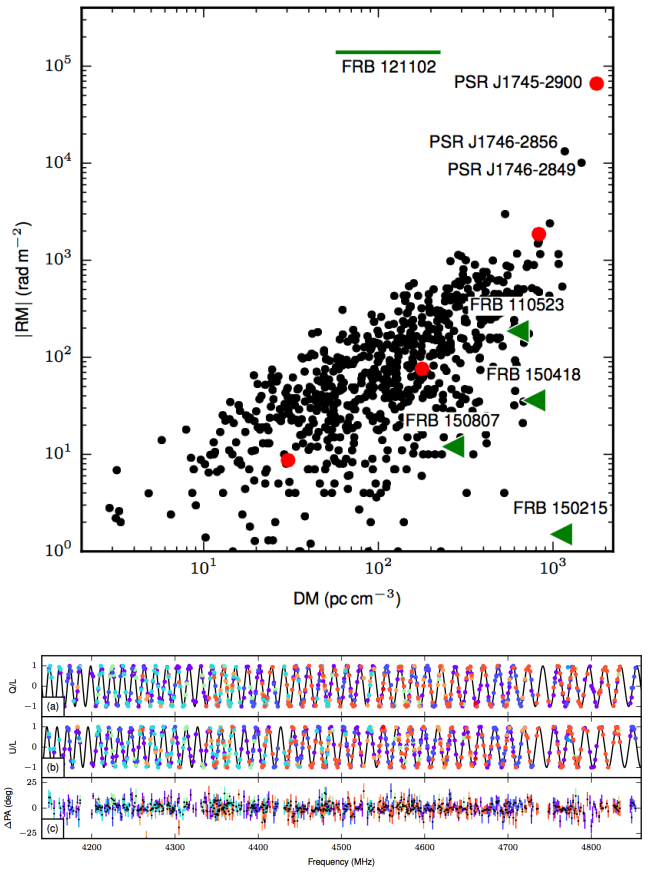


Bassa et al. (2017)

- **A young (superluminous) supernova remnant powered by a magnetar? Is LLAGN excluded?**
  Host properties are consistent with SLSNe hosts, low-metallicity dwarfs.

RFB121102: extreme magnetoionic environment





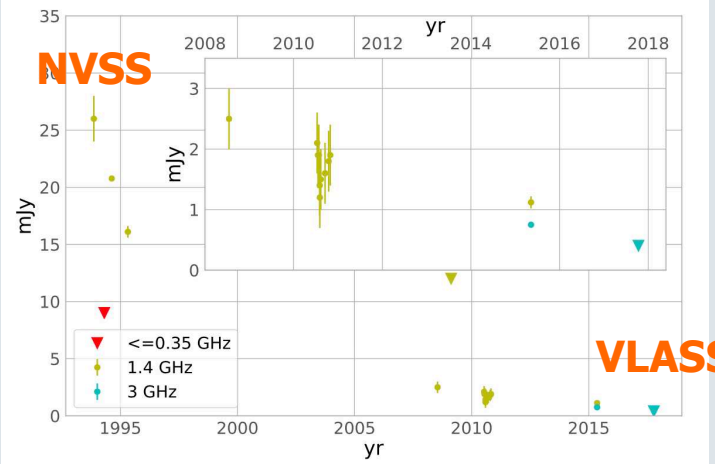
- **~100% linearly polarized signal, huge RM; rotation measure changes with time**
  Either magnetar orbiting a massive BH, or a relatively young SN?

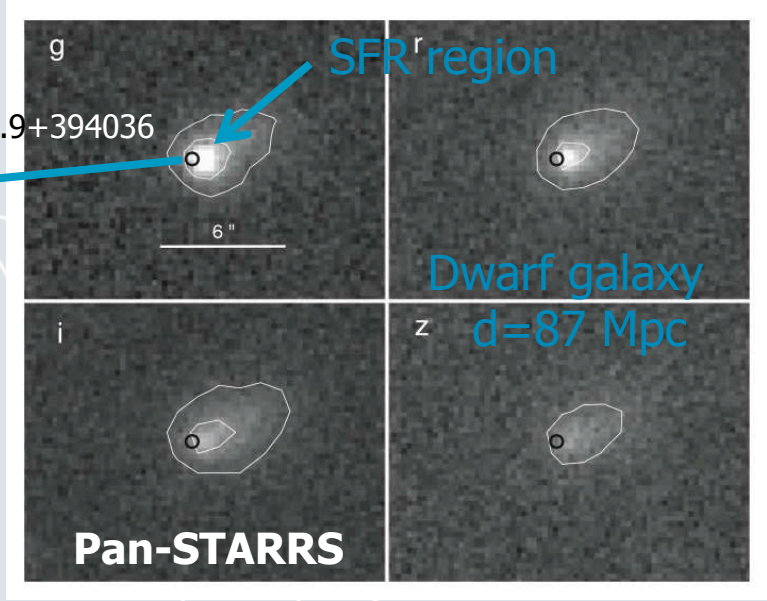
Michilli et al. (2018)

Future directions in FRB science

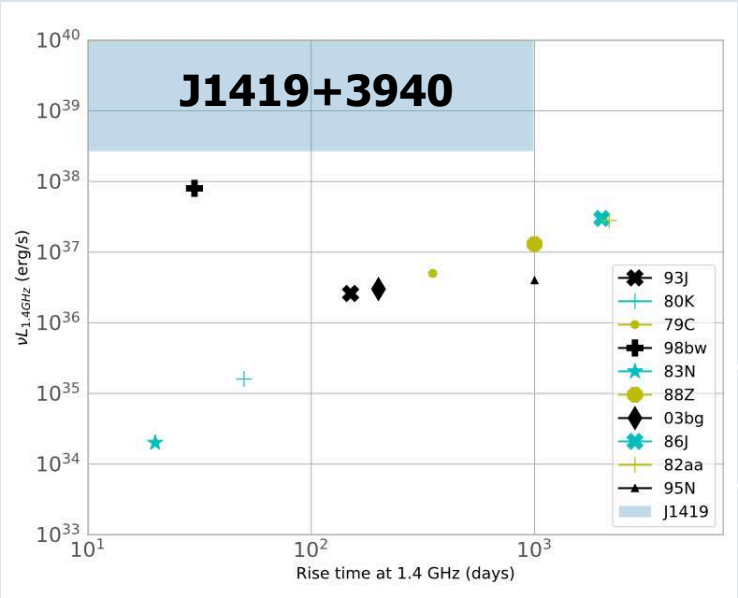
1. **[since we do not have more FRB counterparts to study]: Find transient "FRB nebulae" in metal poor host galaxies**
   ➔ will show two examples
2. **Follow-up on new repeaters [if] found by dedicated surveys**
   ➔ the hunt has started!
3. **Direct interferometric localization [very challenging]**
   ➔ (this is very challenging, at least on mas scales)

A luminous, decades-long transient



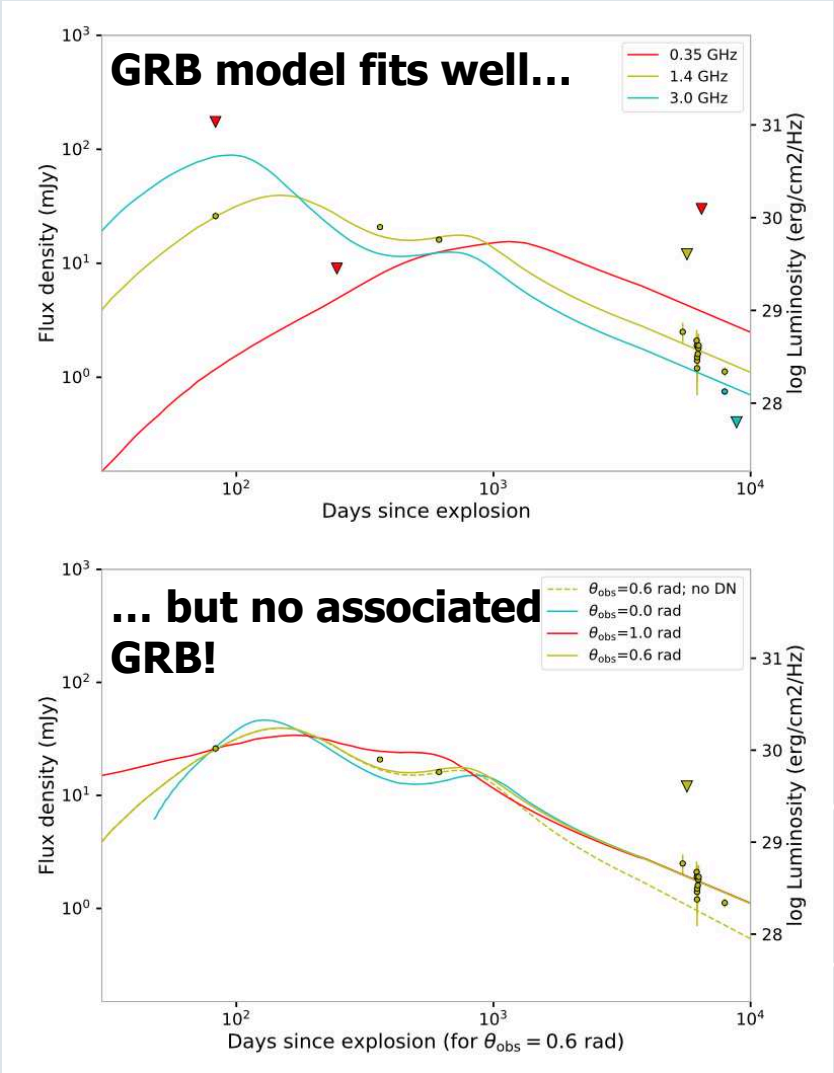


Law et al. (2018)

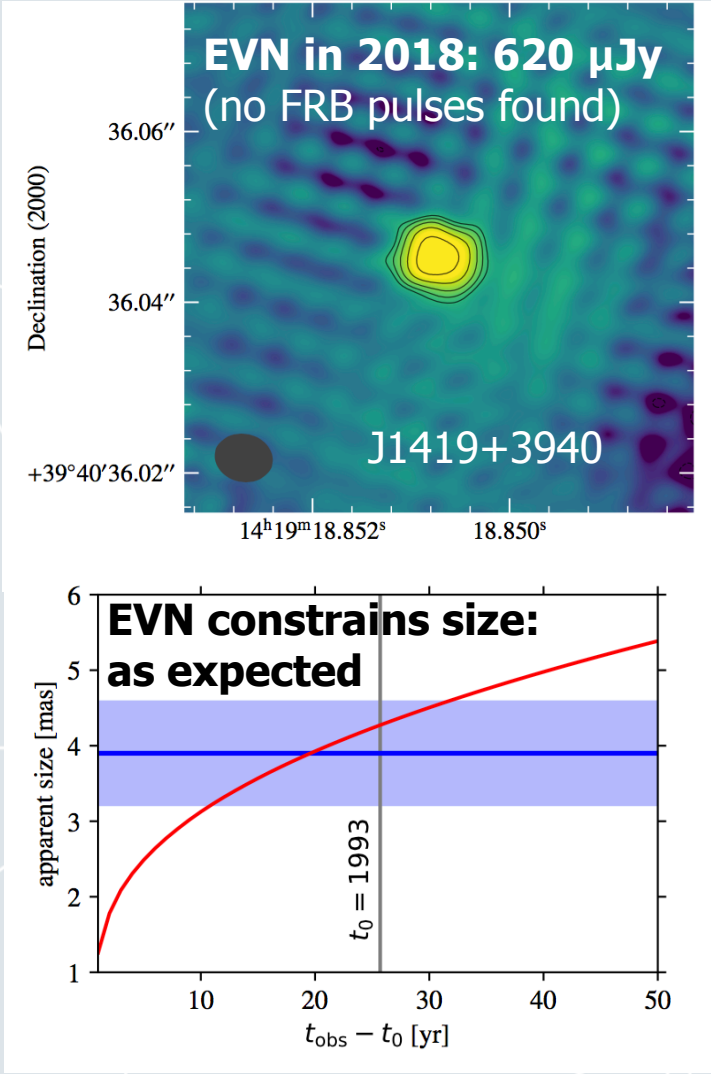


- **Prior 1993 >26 mJy at z=0.01957**
  ➔ Peak $\nu L_\nu > 3\times10^{38}$ erg/s
- **Isotropic synchrotron blast would require ~10^51 erg**
  Long-GRB or newly-born magnetar with FRB nebula???

J1419+3940: the first off-axis GRB found?

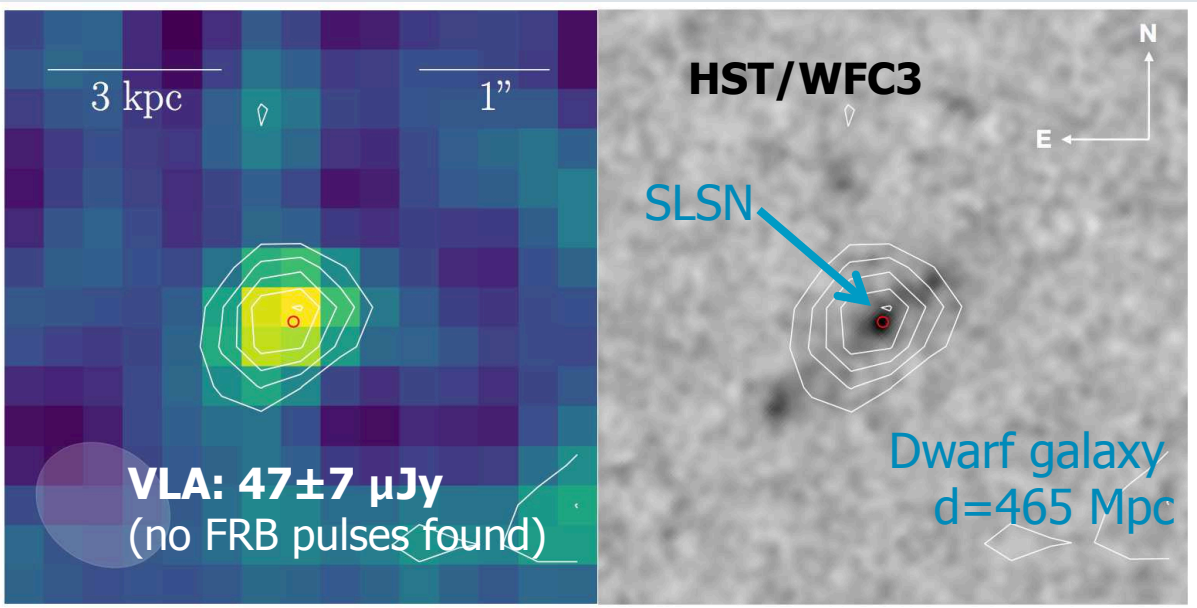


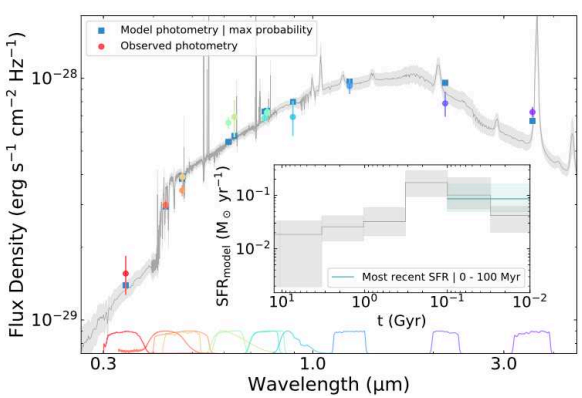
Law et al. (2018)

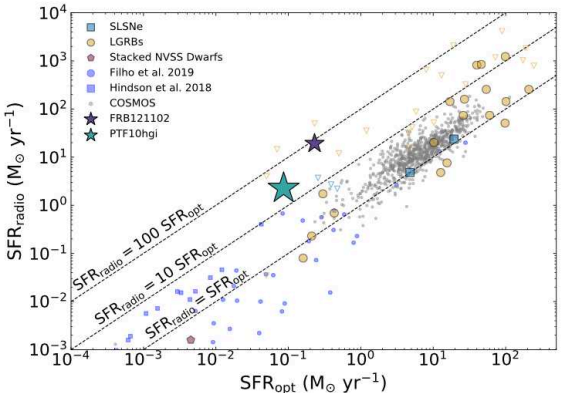


Marcote et al. (in prep.)

SLSN PTF10hgi: FRB121102 analog?



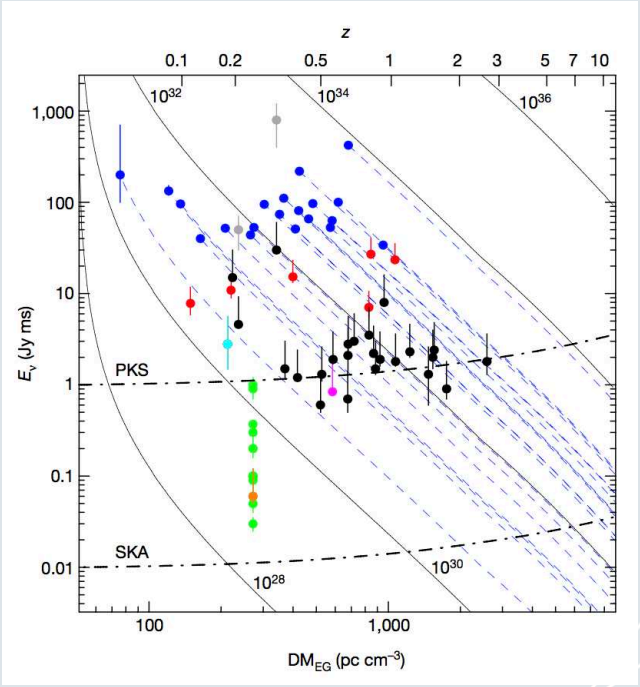




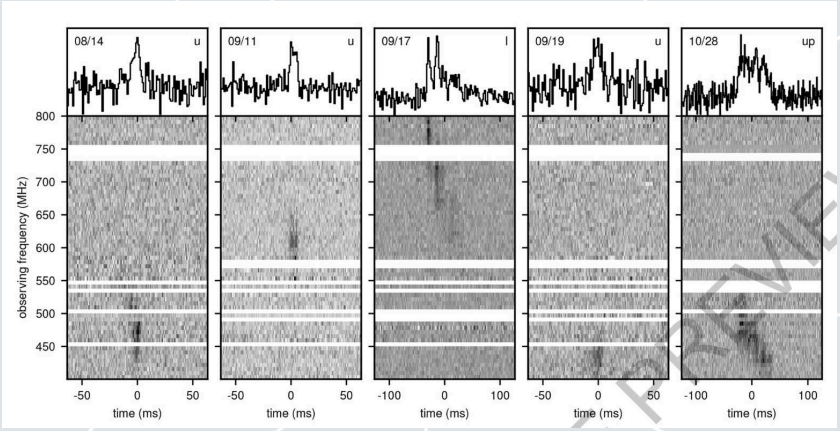
Eftekhari et al. (2019)

- **First radio detection of a superluminous supernova ever**
- **Properties consistent with a central engine-powered nebula, like FRB121102**

FRB surveys: CHIME, ASKAP, APERTIF



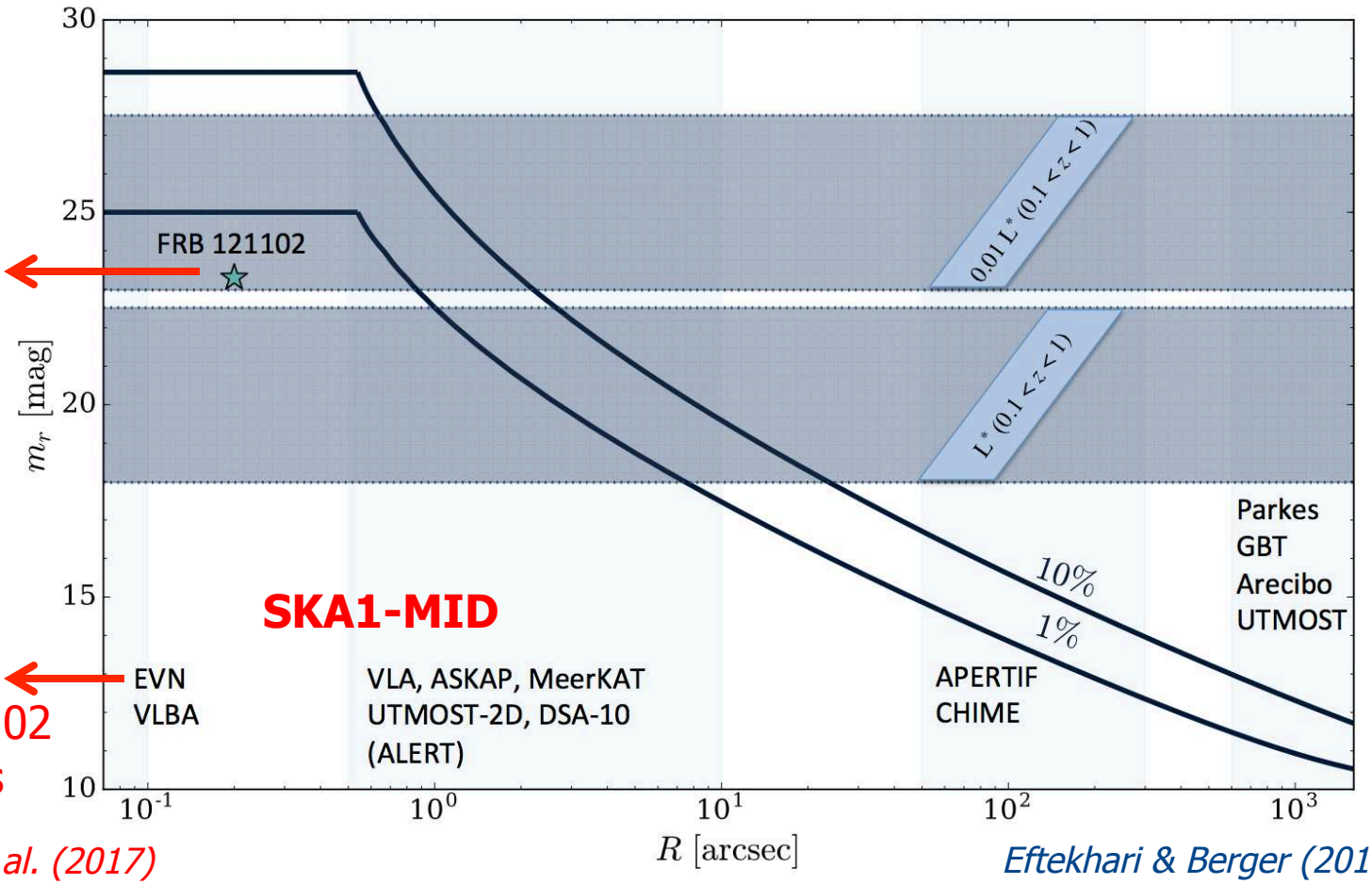
Shannon et al. (2018)



CHIME Collaboration (2019)

- **ASKAP: 20 new, no repeats –** a bright population!
- **CHIME: 13 new @ 400 MHz –** including new repeater!

FRBs: sub-arcsec localization is essential!



EVN:
FRB121102
~12 mas

Marcote et al. (2017)

Eftekhari & Berger (2017)

- **<0.5" localizations are necessary for secure dwarf gx host identifications at *z* >0.1**
- **Progenitor environments (position within host gx) as well as high redshift localizations will require SKA1-MID and VLBI!**

End of FRB story

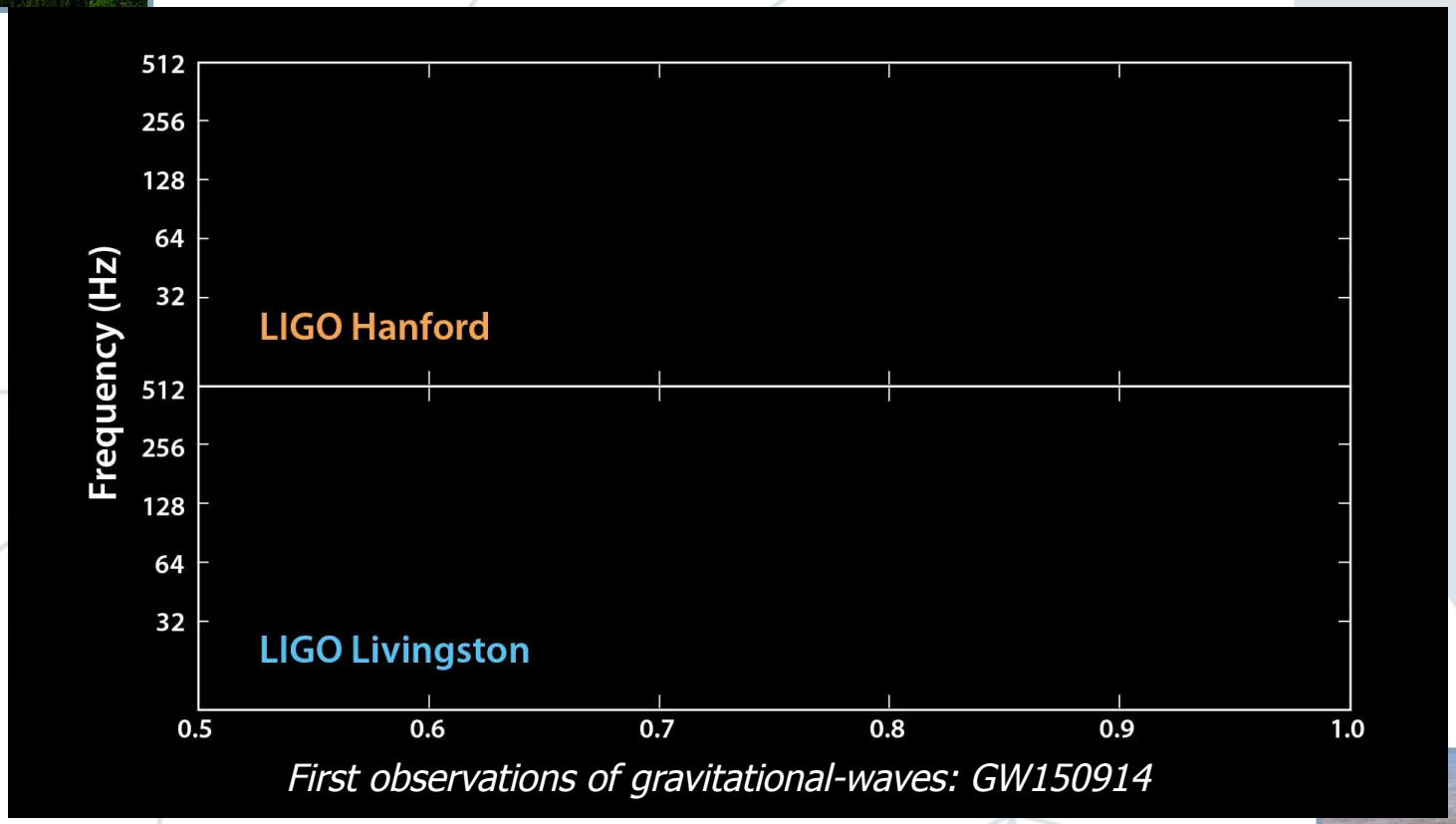
- **"Hey Zsolt, you promised something on GW-EM counterparts as well!"**

GW170817 electromagnetic counterpart probed at the highest angular resolution

e-EVN Collaboration: "Euro VLBI Team"
Global-VLBI efforts: Giancarlo Ghirlanda, Om Salafia et al.
Special thanks to Marica Branchesi

Multi-messenger-astronomy

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



- **A changing landscape – we will want to follow-up EM counterparts**
- **VLBI arrays must play a role here!**

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
Joint Institute for VLBI ERIC (JIVE)
langevelde@jive.eu

Name, institution, email, and phone numbers of the liaison with LVC:

Zsolt Paragi
Joint Institute for VLBI ERIC (JIVE)
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List of associated members (name, institution and email):

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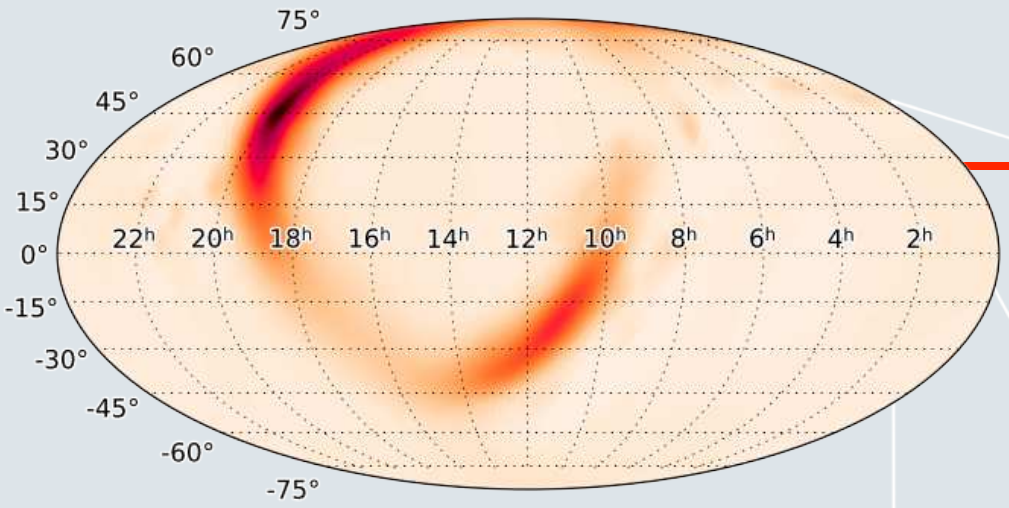
Huib van Langevelde, Joint Institute for VLBI ERIC, langevelde@jive.eu
Jun Yang, Onsala Space Observatory, jun.yang@chalmers.se

- **An ASTERICS initiative, prompted by Eric Chassande-Mottin and Arpad Szomoru; group organized by ZP**

"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…"

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

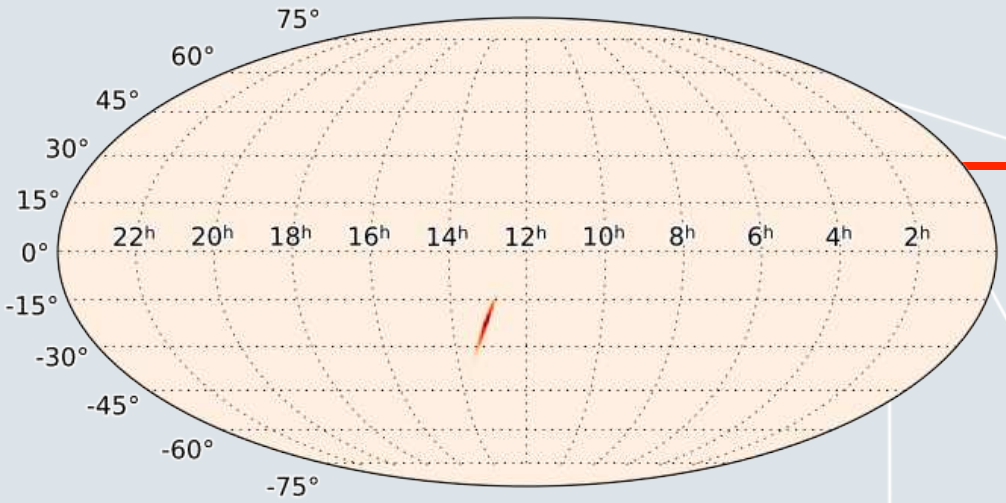
One of the initial skymaps in the Grace DataBase

Probability of 2nd object being neutron star: 100%

- **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.)**
- **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**

Another NS-merger candidate

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%

- **Submitted e-EVN trigger proposal 1 June – although O2 to be finished in August**
- **Exceptional NS-NS merger trigger arrives in mid-August**
- **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**

"The Paper" describing the efforts

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

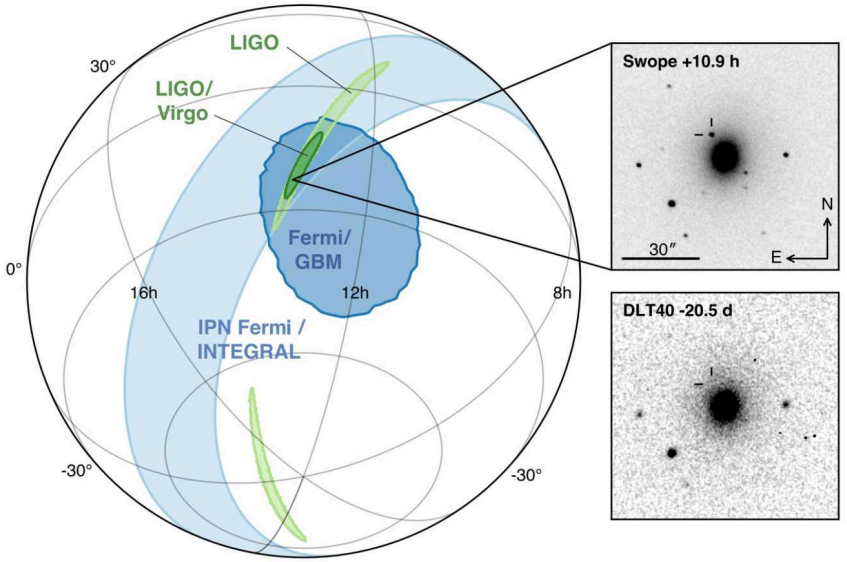
Multi-messenger Observations of a Binary Neutron Star Merger*

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

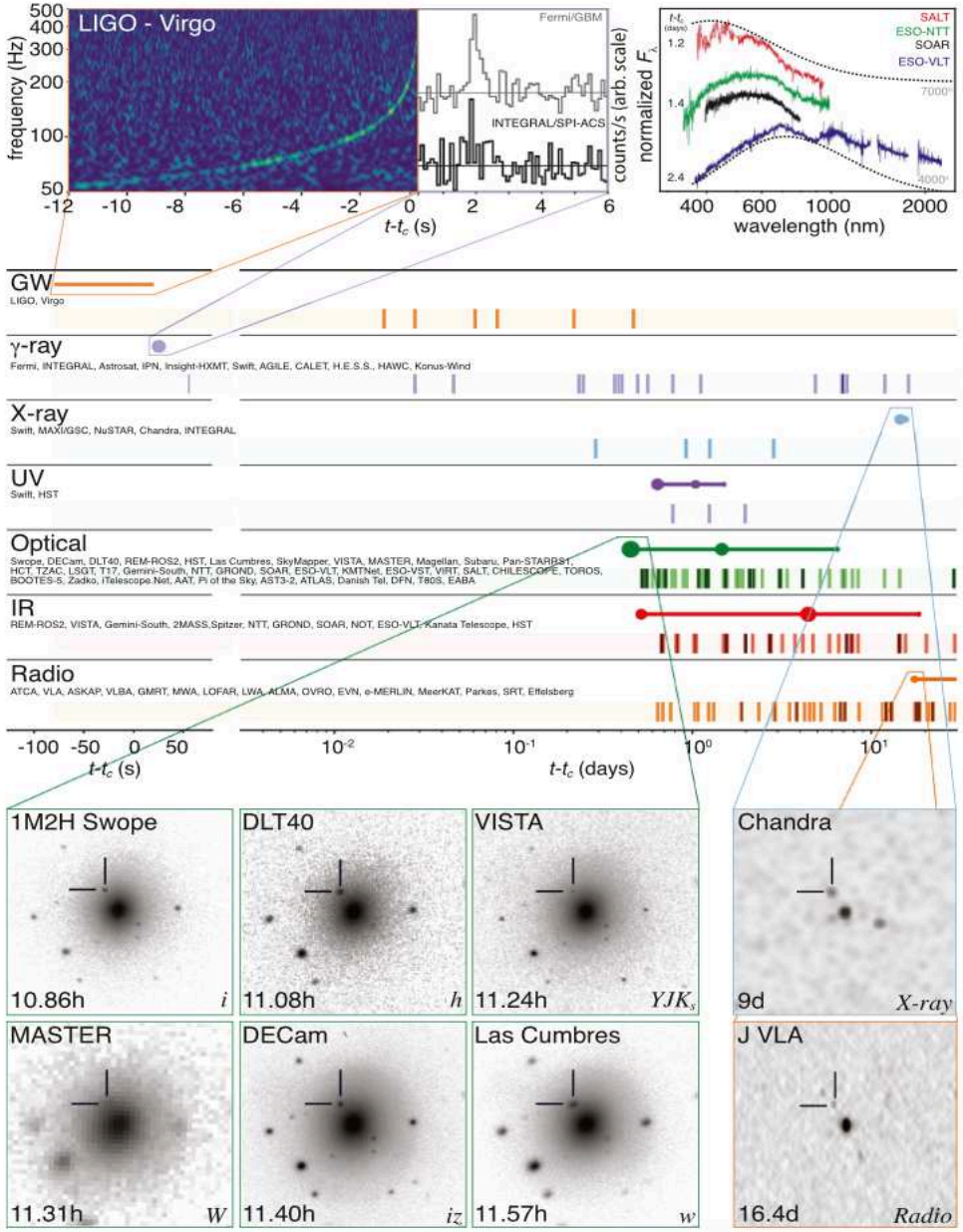


Abbott et al. (2018)
ApJ, 848, L12

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

- **~3500 authors, heated discussion in telecons and e-mails**
- **Successfully lobbied for radio teams, even though only JVLA detection at the time…**

Multi-messenger overview



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

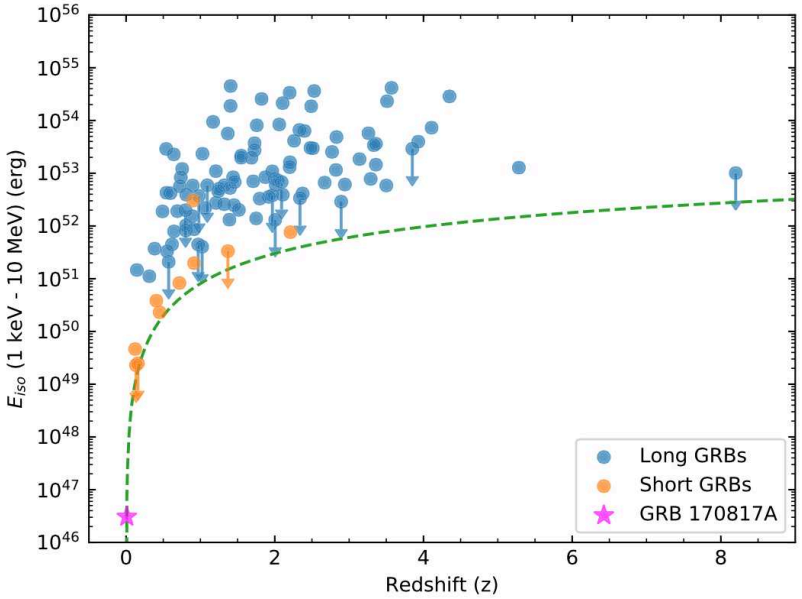
  X-rays by Chandra @ day 9
  (Troja et al. 2017, Margutti et al. 2017)

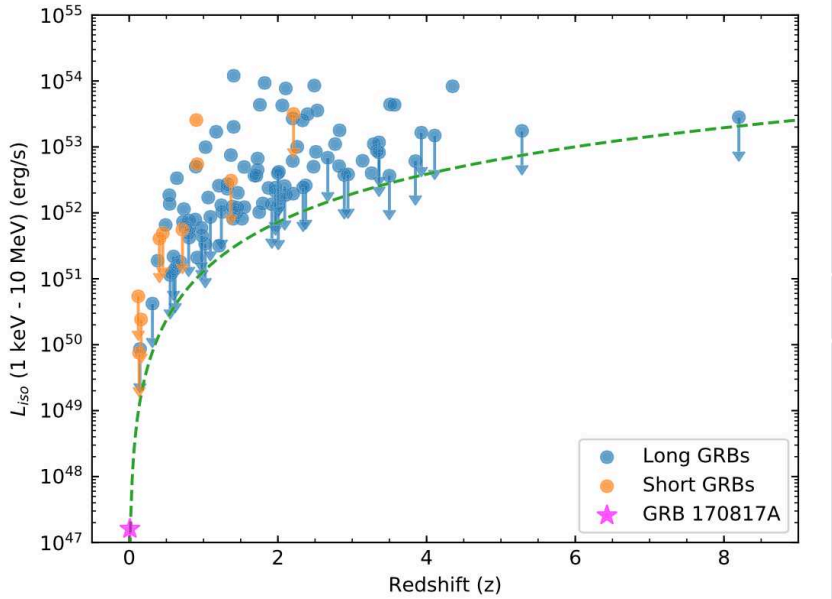
  Radio by the JVLA @ day 16
  (Hallinan et al. 2017)

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

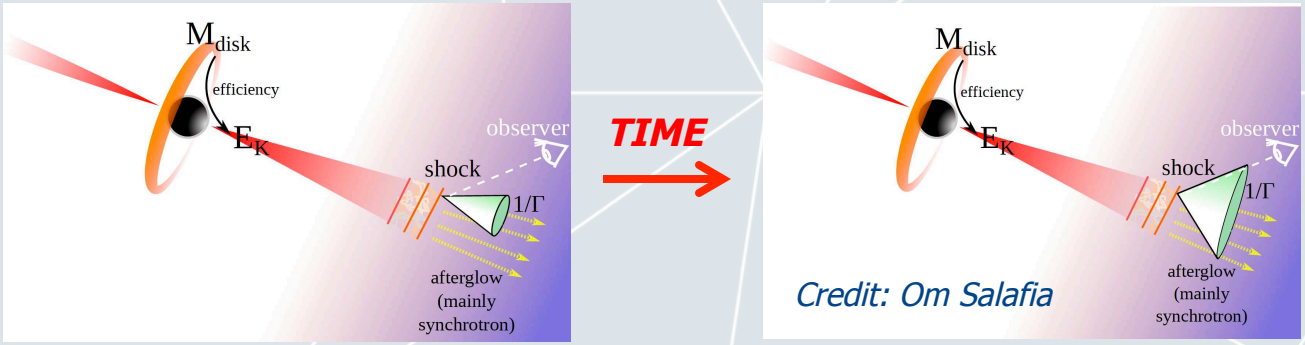
Abbott et al. (2017)
ApJ, 848, L12

The unusual high-energy counterpart



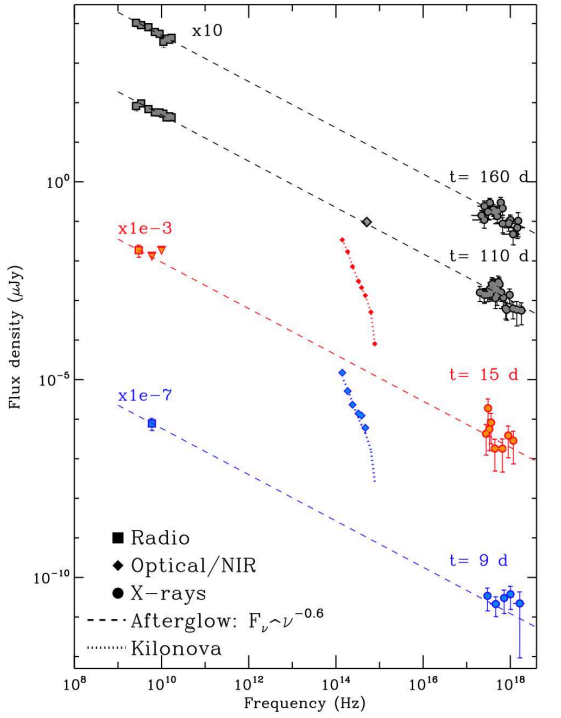


Abbott et al. (2018) ApJ, 848, L13

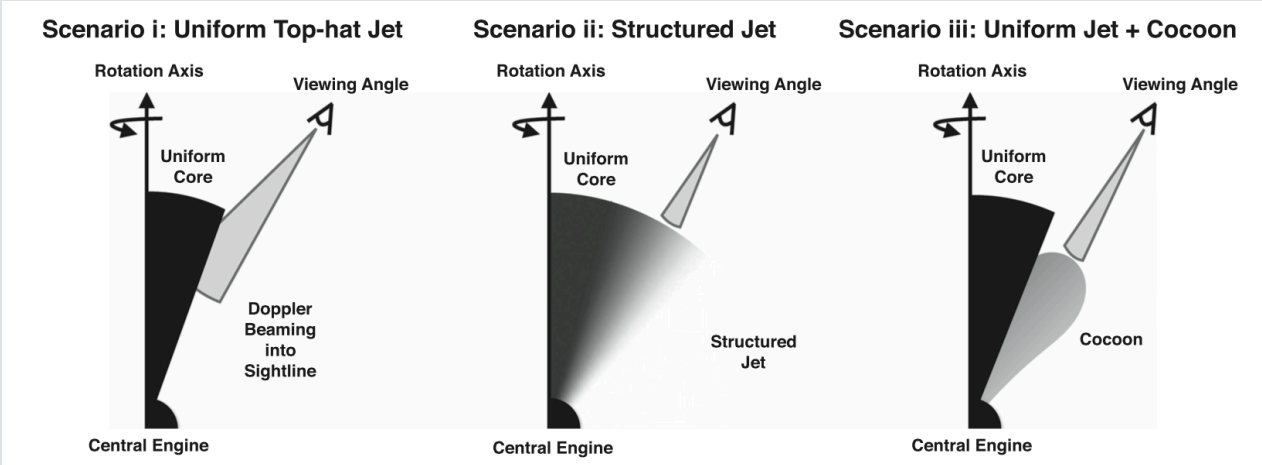


- **Hundred times closer, but also 10^2 — 10^6 less luminous than other short GRBs**
- **Unusually weak: is this intrinsic, or the first off-axis short-GRB???**

Multi-band evolution of the outflow emission



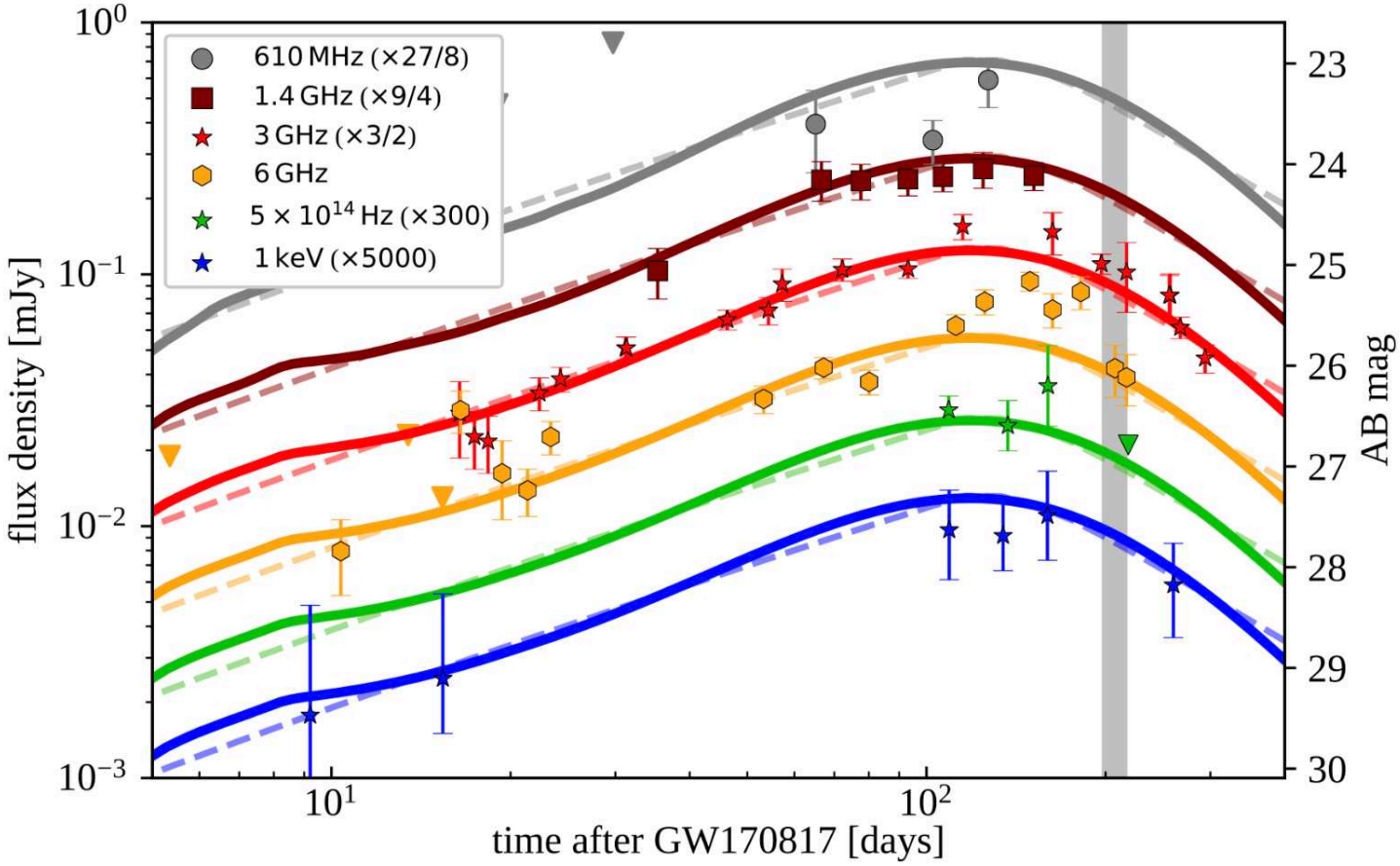
Margutti et al. (2018)



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

- **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. (2018)

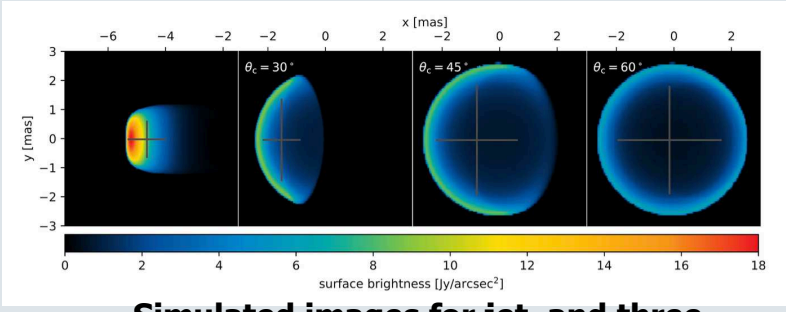
Global VLBI run

- **Achromatic slow rise in flux till 150 days after the merger – off-axis model excluded!** *(Mooley et al. 2017, Margutti et al. 2018, Troja et al. 2018, D'Avanzo et al. 2018)*
- **This figure is from our paper with updated fluxes (and the indicating gVLBI observations)**

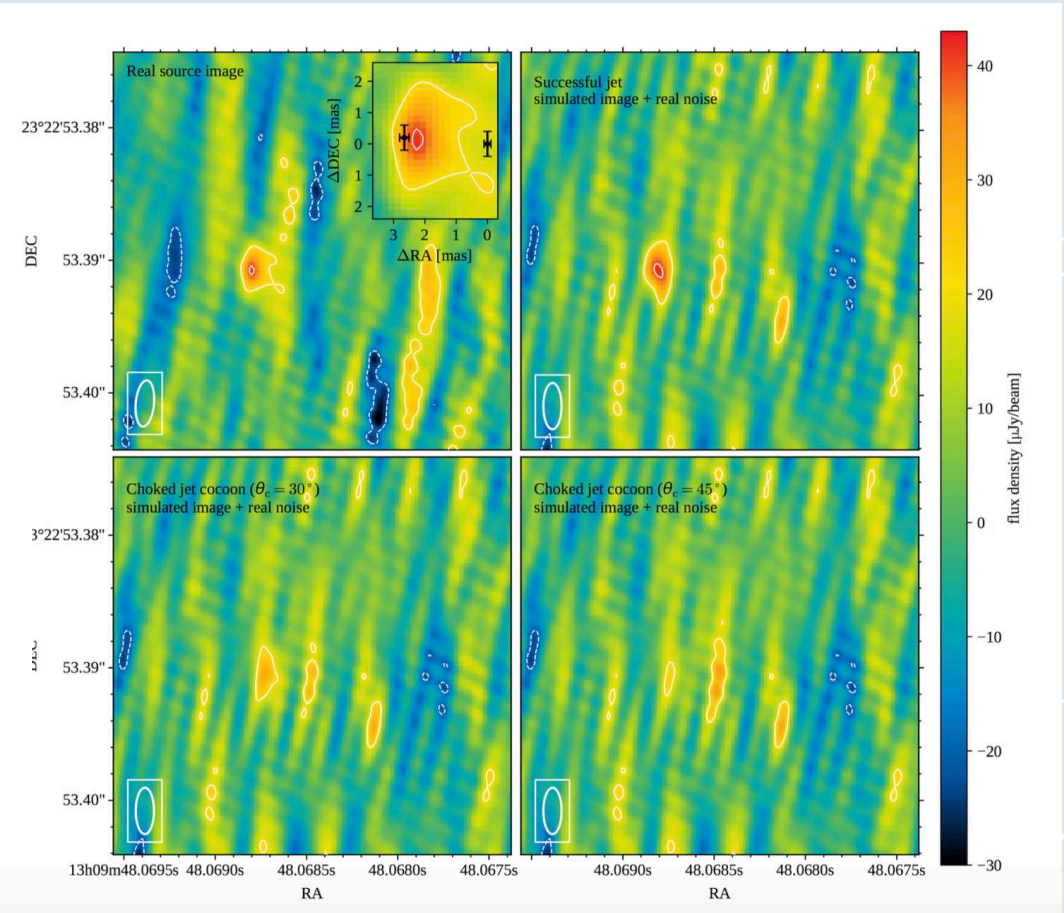
  Thick lines: isotropic fireball model; Dashed lines: structured jet model

Global VLBI imaging results

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

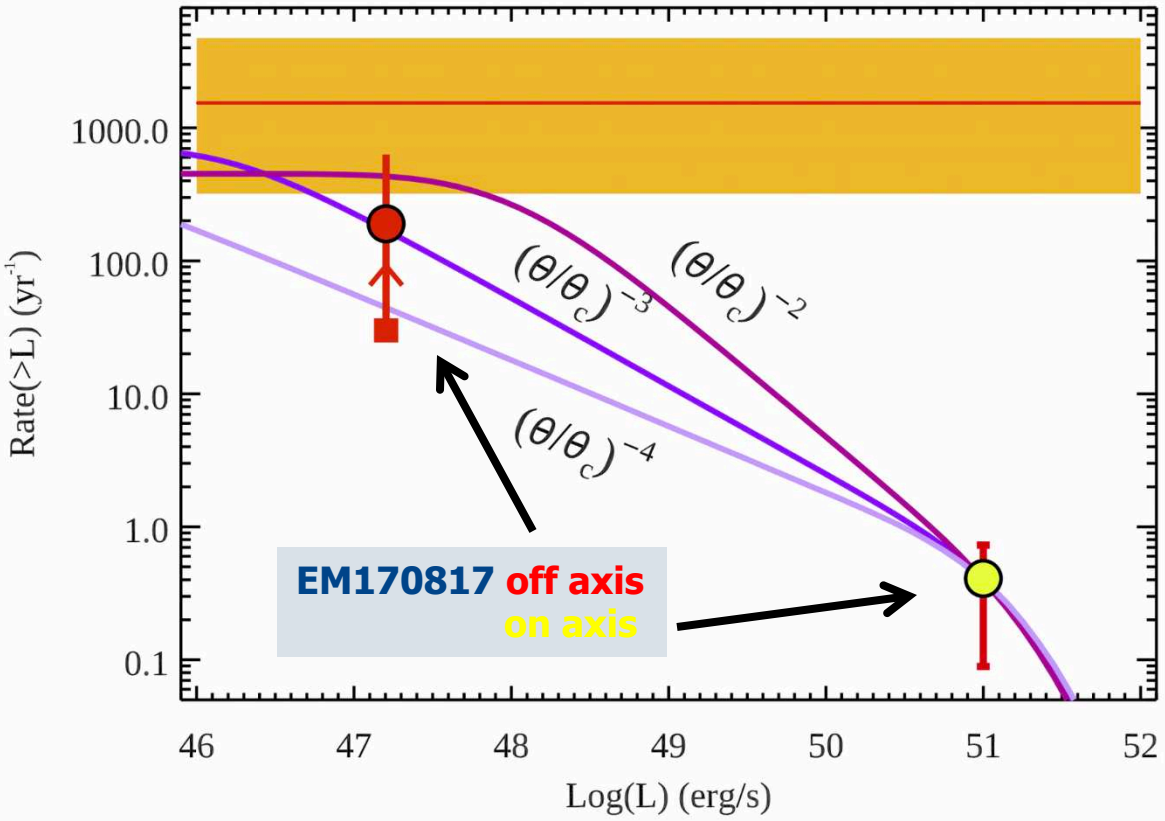


Simulated images for jet, and three versions of failed jet/cocoon



- **Low-declination and very weak source makes it rather challenging…**
- **In agreement with Mooley+18 superluminal claim, but higher resolution to constrain size: our detection itself supports structured jet**

sGRB rate: Implication NS-NS mergers



Ghirlanda et al. (2018)

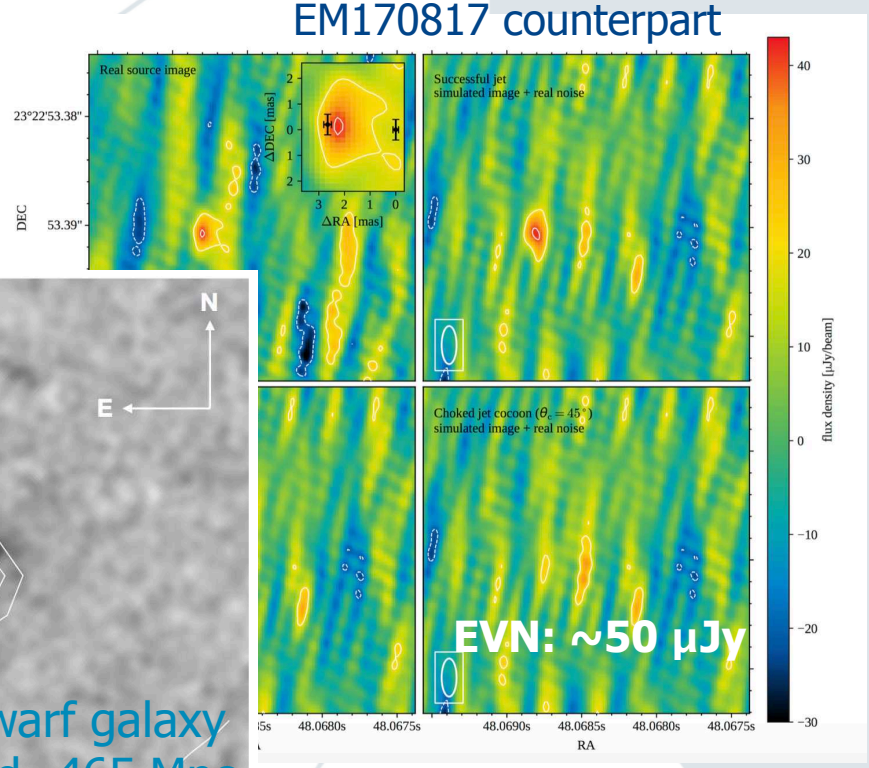
- **Various jet structures predict agreement with observed sGRB rate with $L_{ISO} \sim 10^{51}$ erg/s**
- **Comparison to LIGO event rates predict 10% of all NS-NS mergers produce successful jet**

End of EM counterpart story

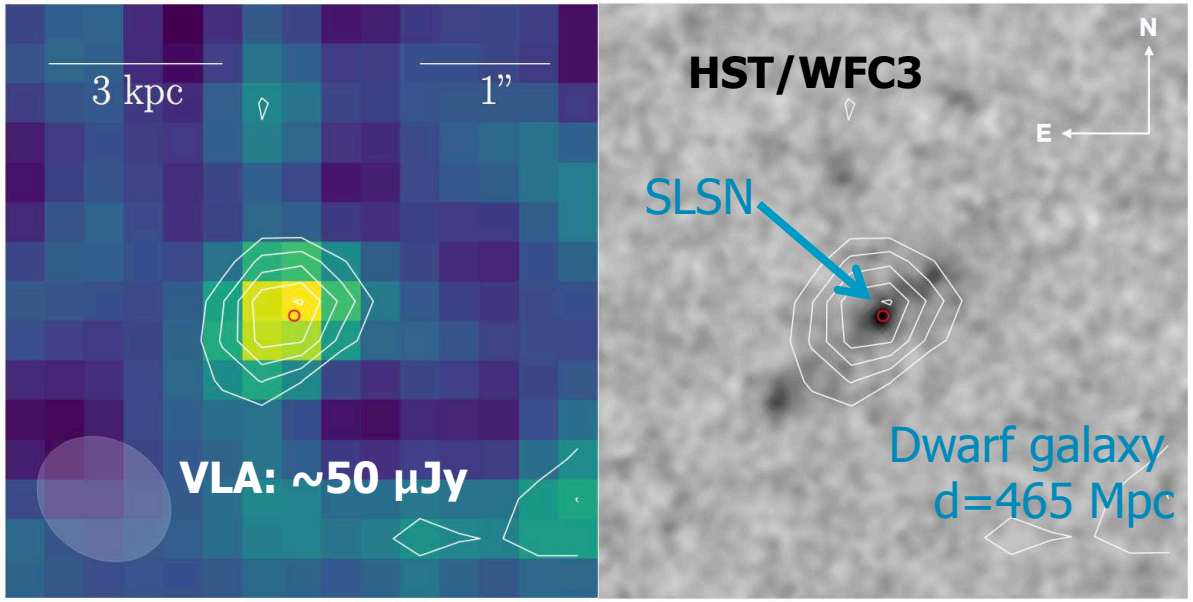
- **"Now, what's next?" ➔ AO3**
- **… there will be a lot to do!!!**

Brief conclusions

EM170817 counterpart



PTF10hgi ~FRB nebula?



- **EVN does cutting edge science; baselines on global scales needed for transients!**
- **Future is bright for both FRBs and GW-EM counterparts VLBI research**
- **We could use a lot more sensitivity! ➔ SKA, but make it very high resolution!**

SKA-VLBI KSP and Operations meeting

- **SKA HQ, Jodrell Bank, 14-17 Oct. 2019**

- **SOC**
  - Tao An (ShAO, CN)
  - Anna Bonaldi (SKAO)
  - Laura Spitler (MPIfR-Bonn, D)
  - Francisco Colomer (JIVE, NL)
  - John Conway (OSO, SE)
  - Hiroshi Imai (U. Kagoshima, JP)
  - Roger Deane (U. Pretoria, SA)
  - Preeti Kharb (NCRA, IN)
  - Mar Mezcua (ICE, SP)
  - Chris Phillips (CSIRO, AU)
  - Michael Rupen (HAA-NRC, CA)
  - Kazi Rygl (INAF, IT)
  - Maria Rioja (ICRAR-UWA/CSIRO, AU/SP)
  - Antonio Chrysostomou (SKAO, co-chair)
  - Zsolt Paragi (JIVE, co-chair)

- **LOC**
  - Antonio Chrysostomou (Chair)
  - Cristina García-Miró, Joe Diamond, Evan Keane, Sarah Lamb (SKAO), Rob Beswick (JBCA-U. Manchester)

JUMPING JIVE WP10 initiative

End