Millimetre-VLBI in the Multi-Messenger Era

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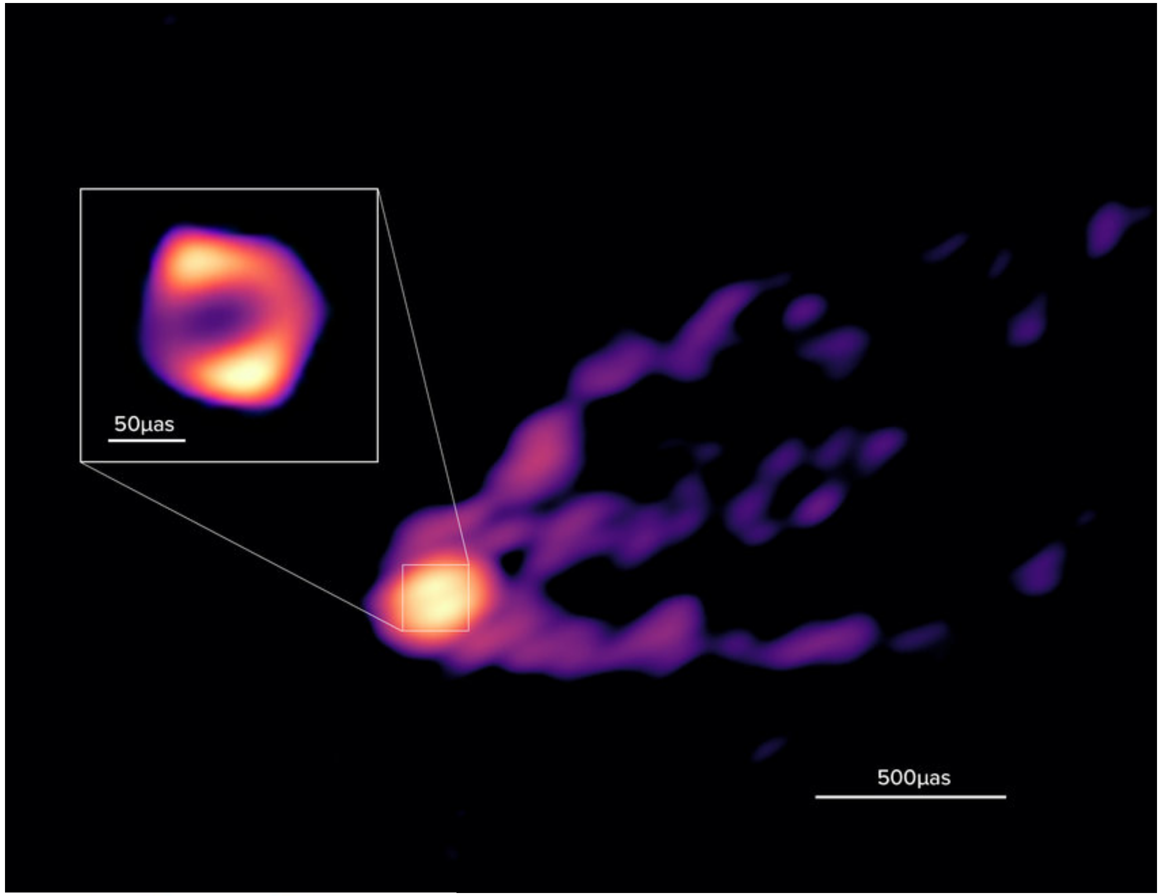
Radio Days 2024, Erlangen

Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Recent highlights in mm-VLBI

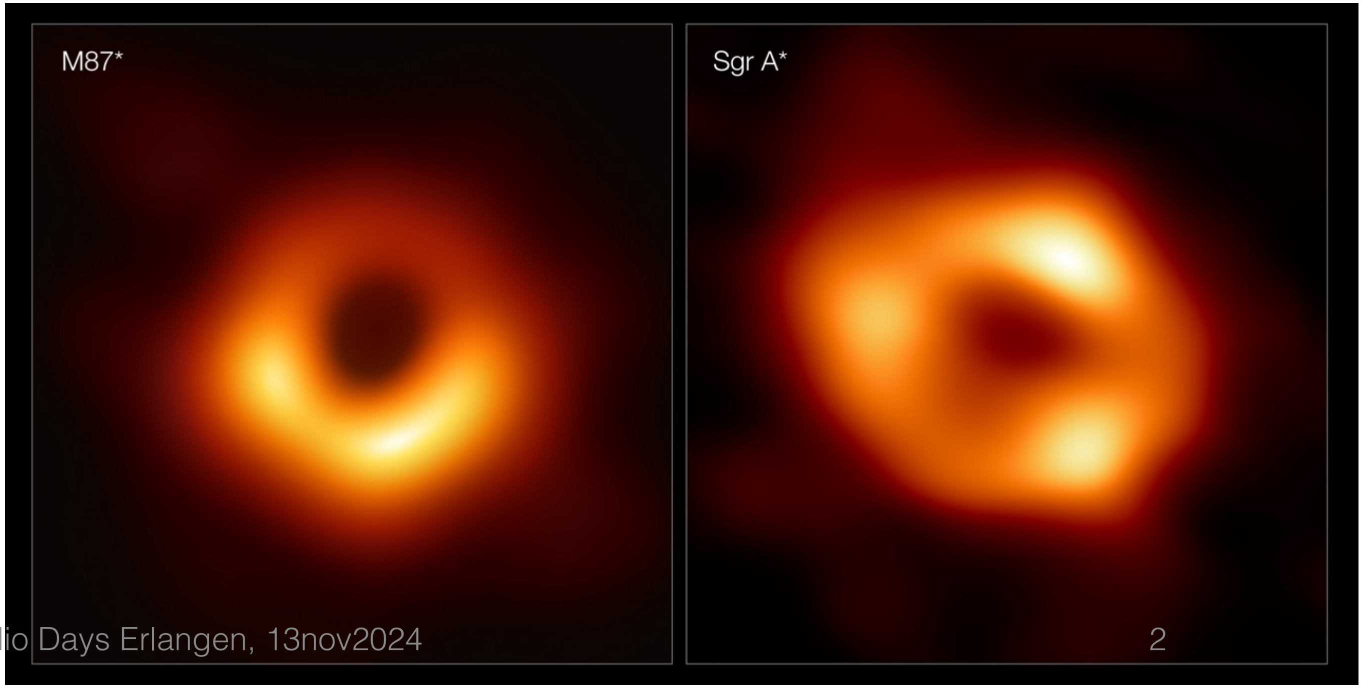
Lu+, Nature 2023



GMVA
GLOBAL MILLIMETER VLBI ARRAY

Event Horizon Telescope

EHTC+, ApJL 2019/2022

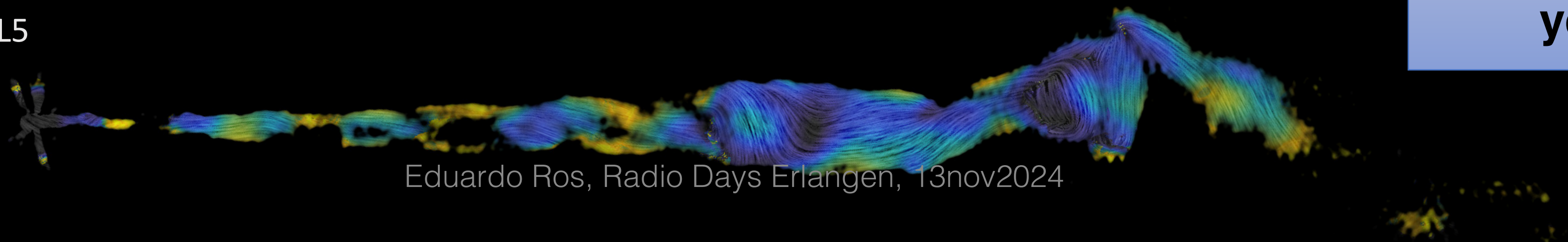


High-Energy Astrophysics – Some Questions

- What are the mechanisms of acceleration and collimation of relativistic plasma near the black hole engine region?
  - Magnetically dominated (MAD) or not (SANE)?
- How is the emission at high energies (and the neutrino emission) related to the jet dynamics probed by VLBI and the multi-band radio emission probed by monitoring programs (Effelsberg, other)?
- What is the connection between black hole and jet? Opacity in the jet?
- Quasars are used for fundamental catalogs and reference frame in astronomy (VLBI, GAIA) for space navigation

See Saiz's talk yesterday

M87: Pasetto et al 2021 ApJL 923 L5



The relativistic universe: coming instrumentation

Radio Astronomy

- SKA (cm-dm) & ngVLA (mm-dm)
- Pathfinders & precursors: EVN, VLBA, VLA, MeerKAT, etc.
- ALMA, IRAM; mm-VLBI at high resolution (EHT, GMVA)

High Energies

- X-ray telescopes
- Continuation of Fermi monitoring
- TeV instruments (CTA)
- Neutrino telescopes (IceCube, Km3NET)

Multi-messenger astronomy

Addressing astroparticle physics

- *Fermi*/LAT
- Cherenkov Telescope Array
- Neutrino detectors
  - IceCube, KM3net, Baikal
- Beyond 2030
  - Global Cosmic Ray Observatory
  - IceCube-Gen2
  - Giant Radio Array for Neutrino Detection

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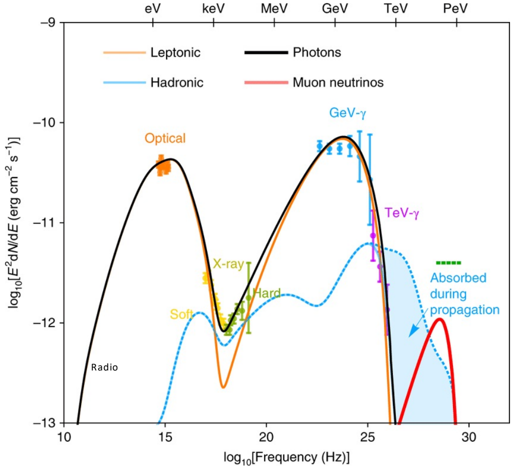
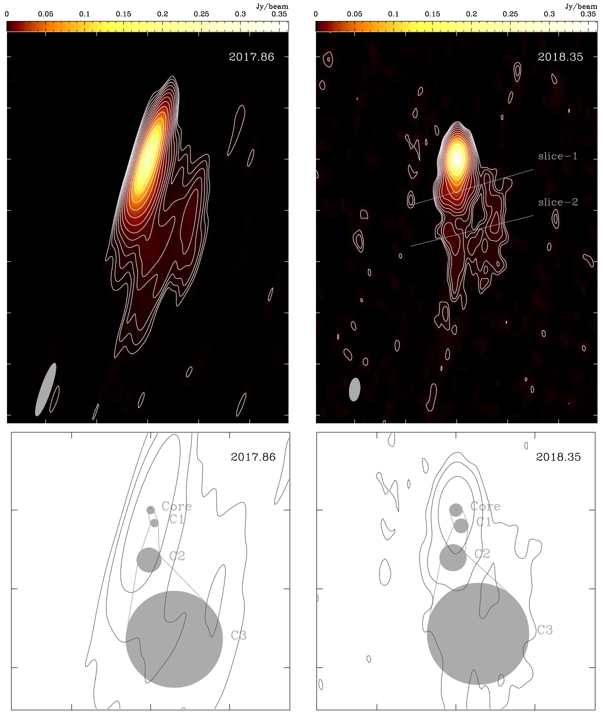
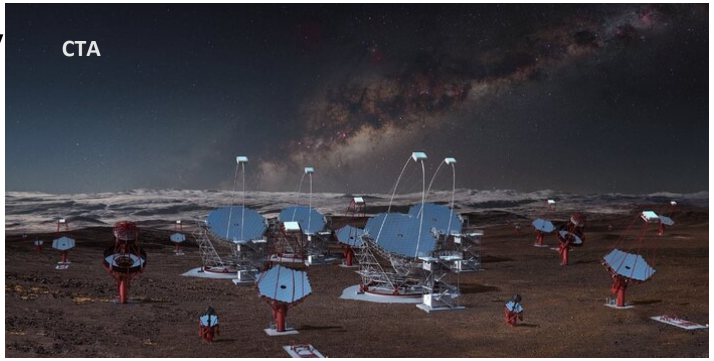
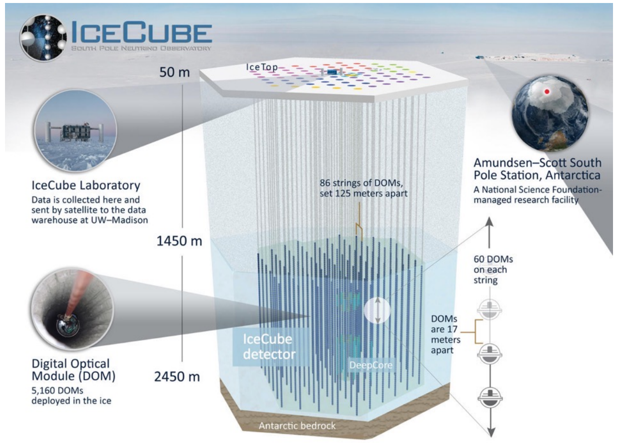


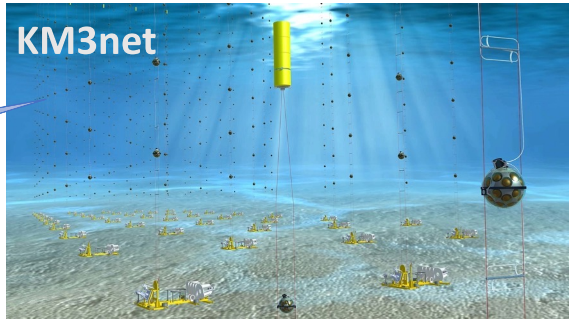
Gao et al. NatAst 3, 88 (2019)



Ros et al. A&A 633 L1 (2020)





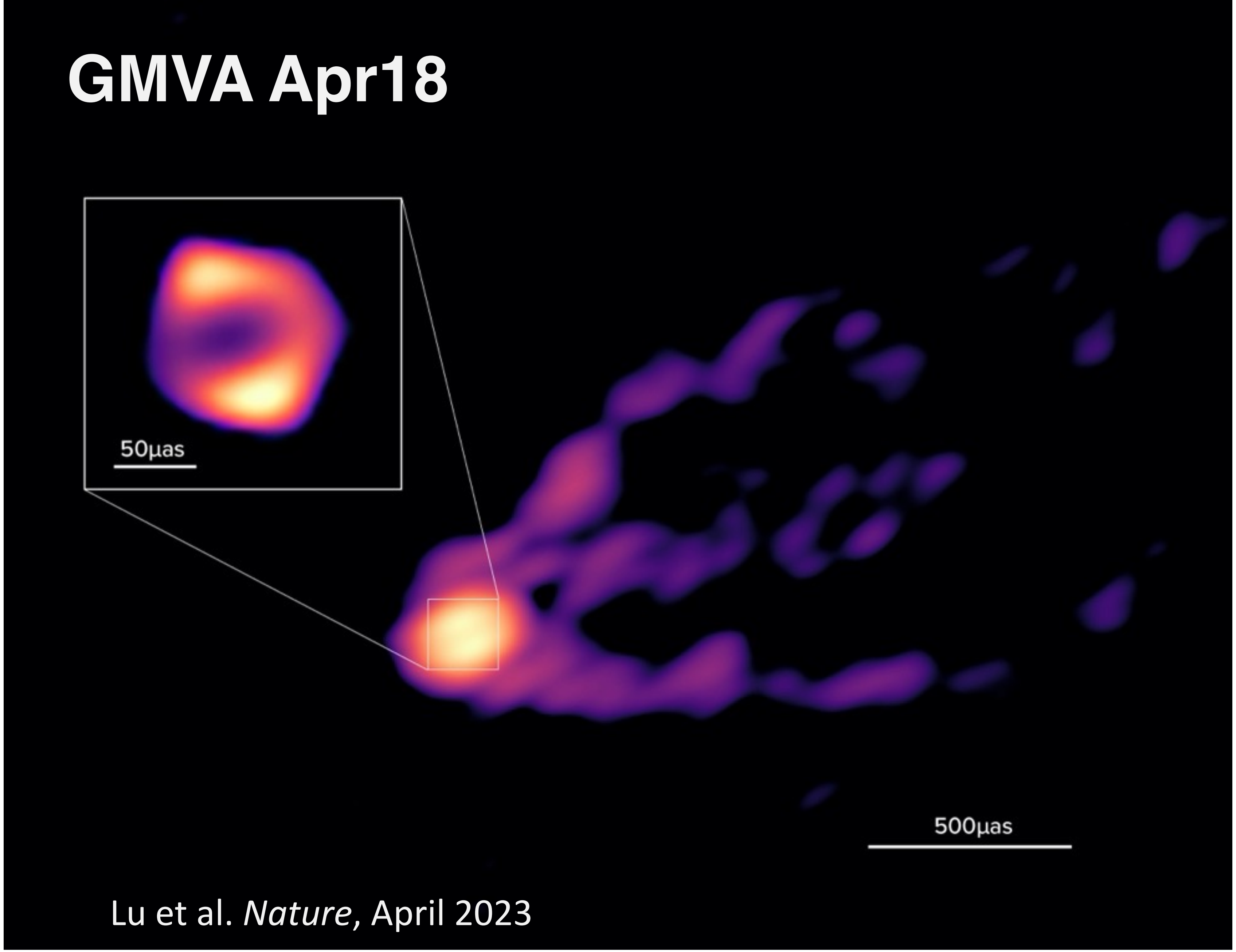


See Kovalev's MuSES talk yesterday

Cartoon: H. Rottmann

GMVA April 2018

Jet and BH shadow observed simultaneously in April 2018



GMVA April 2018

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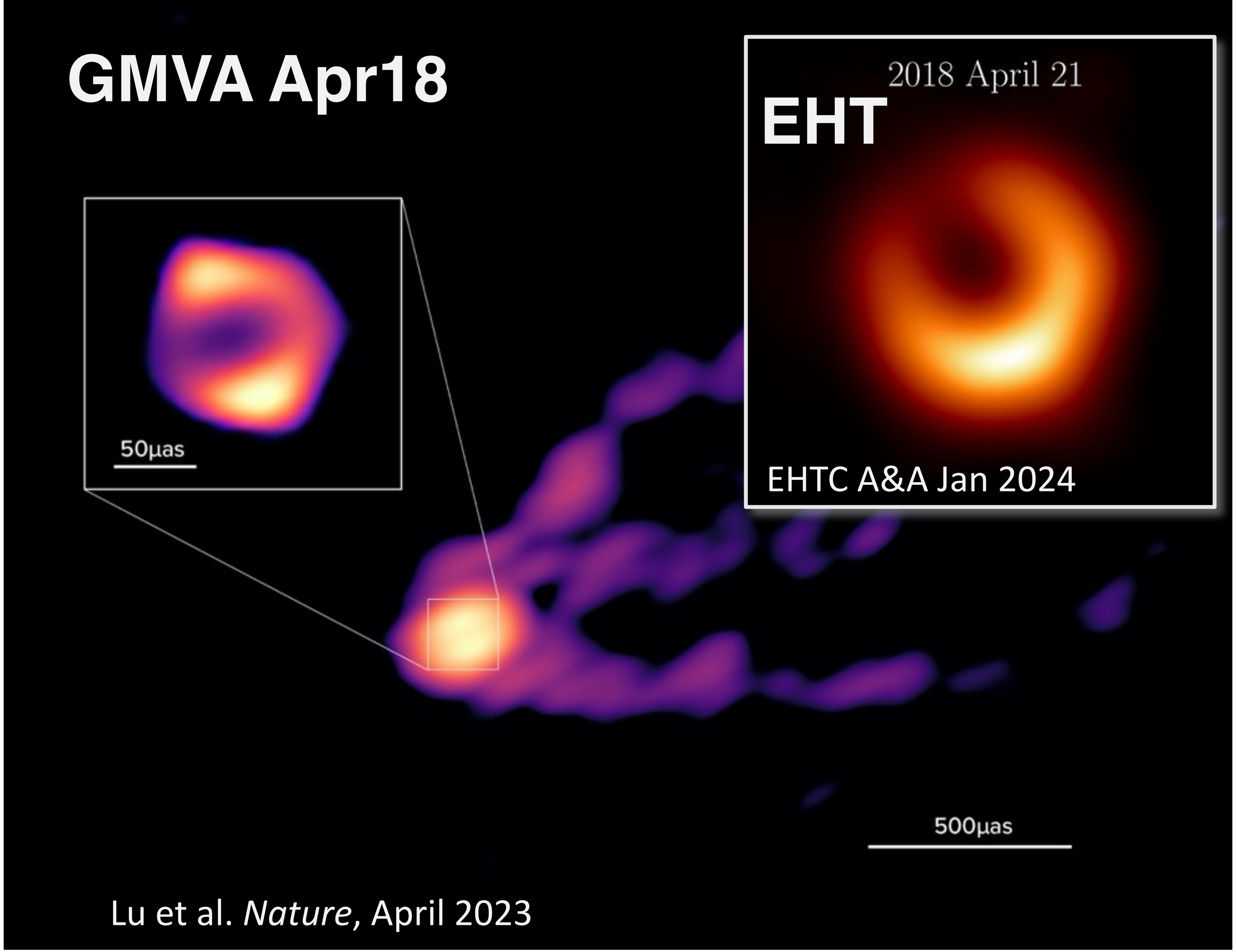
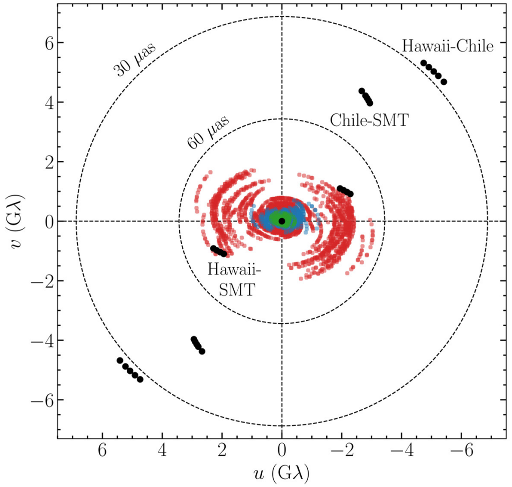
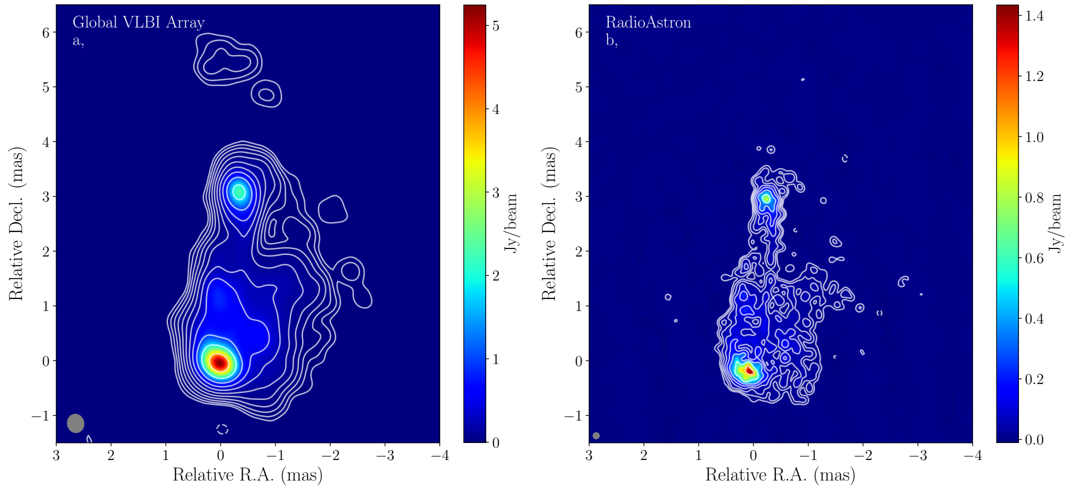


3C 84: transversally stratified jet and ordered magnetic fields in core region

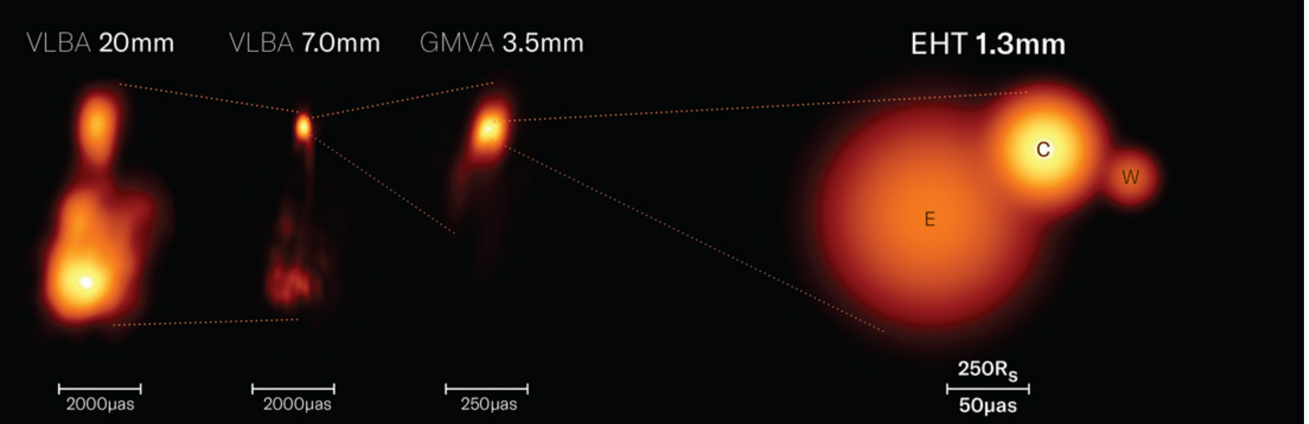
VLBA (20mm green + 7mm blue), GMVA (3.5mm, red), EHT (1.3mm, black)





Space VLBI Images at 13mm (2016)

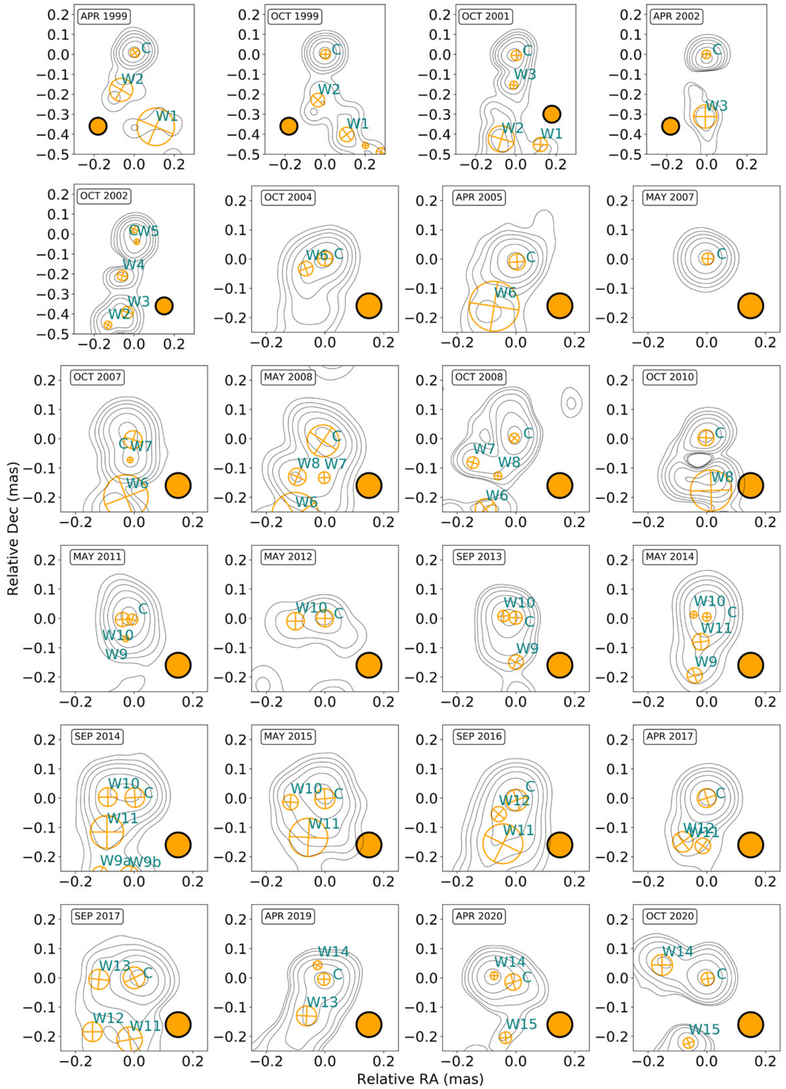
Benke+ in prep



Paraschos+ A&A 682, L3 (2024)

EHT/GMVA Synergy

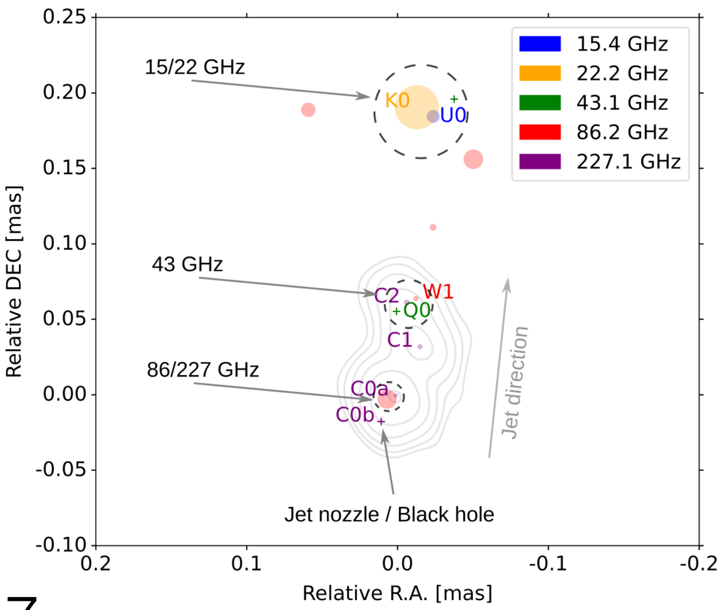
GMVA Monitoring 1999-2020

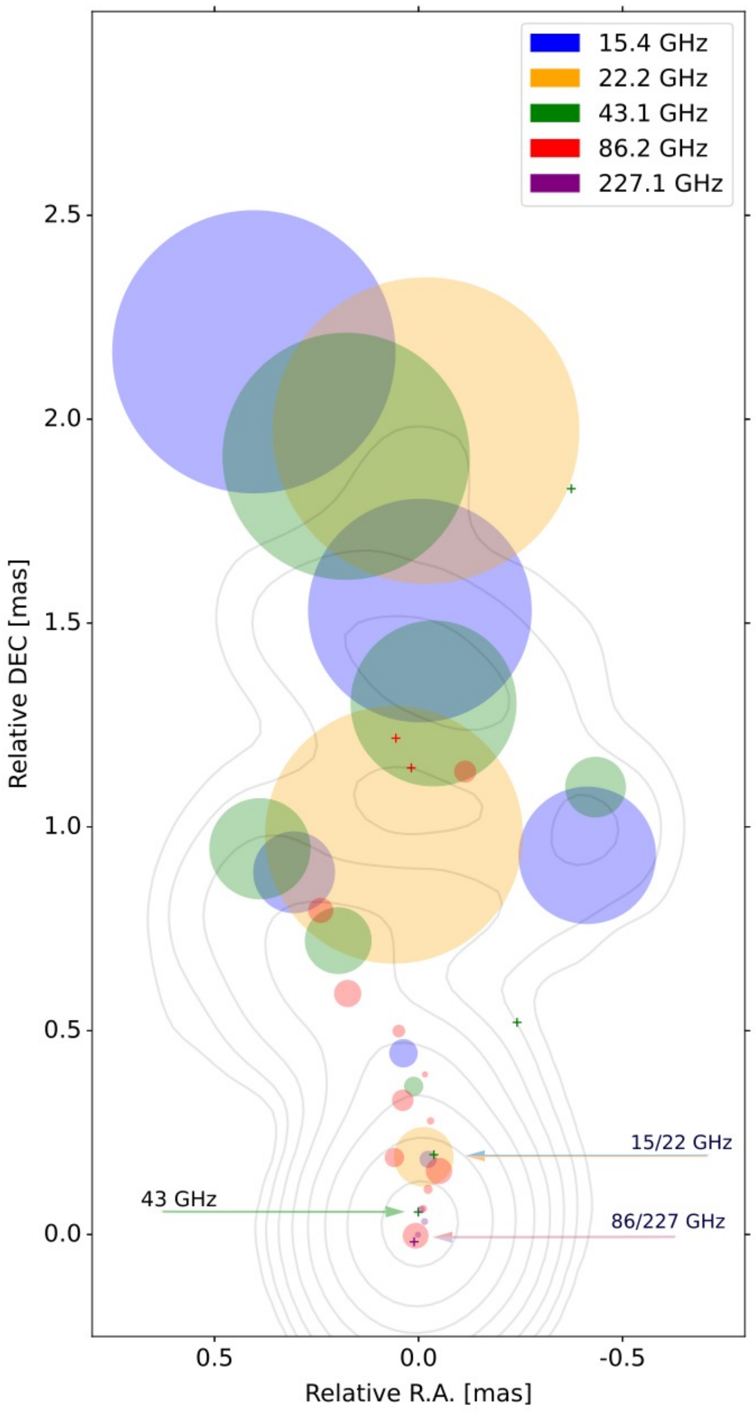


Paraschos+ A&A 665, A1 (2022)

Blazar NRAO 530

- Observations
  - EHT 5-7 April 2017
  - GMVA 3 April 2017
  - VLBA 19 April & 16 May 2017
  - EAVN 03 April 2017
  - MOJAVE 03 Jan & 25 May 2017
- Jet modeling at high-frequency
  - $B_{5rg} \sim 3\times10^3 - 3\times10^4$ G
  - RM values up to $-48\,000$ rad m^{-2}
  - Wobbling jet with a period of 6±4 yr

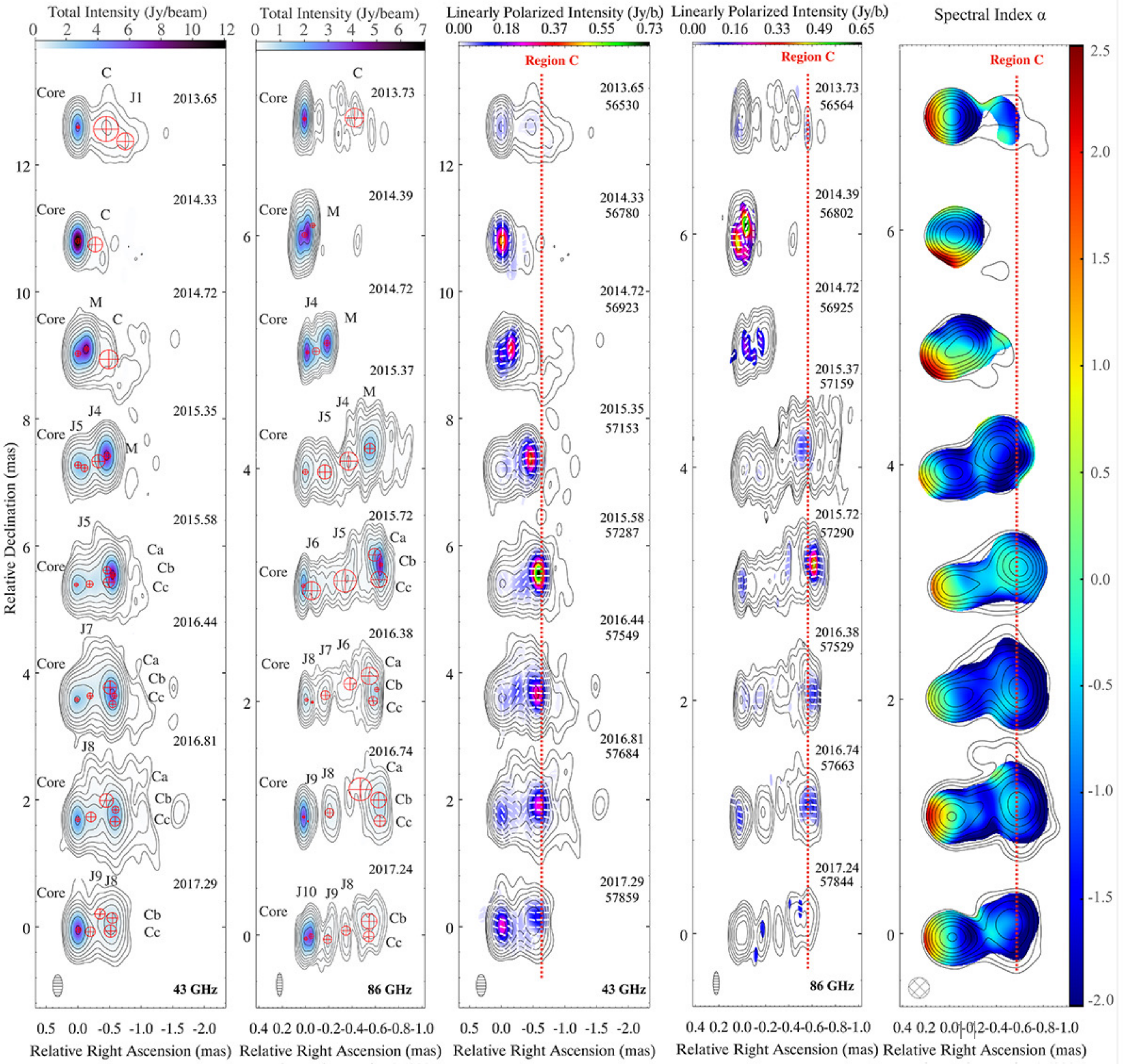




Lisakov et al. A&A in press (arXiv:2411.03446)

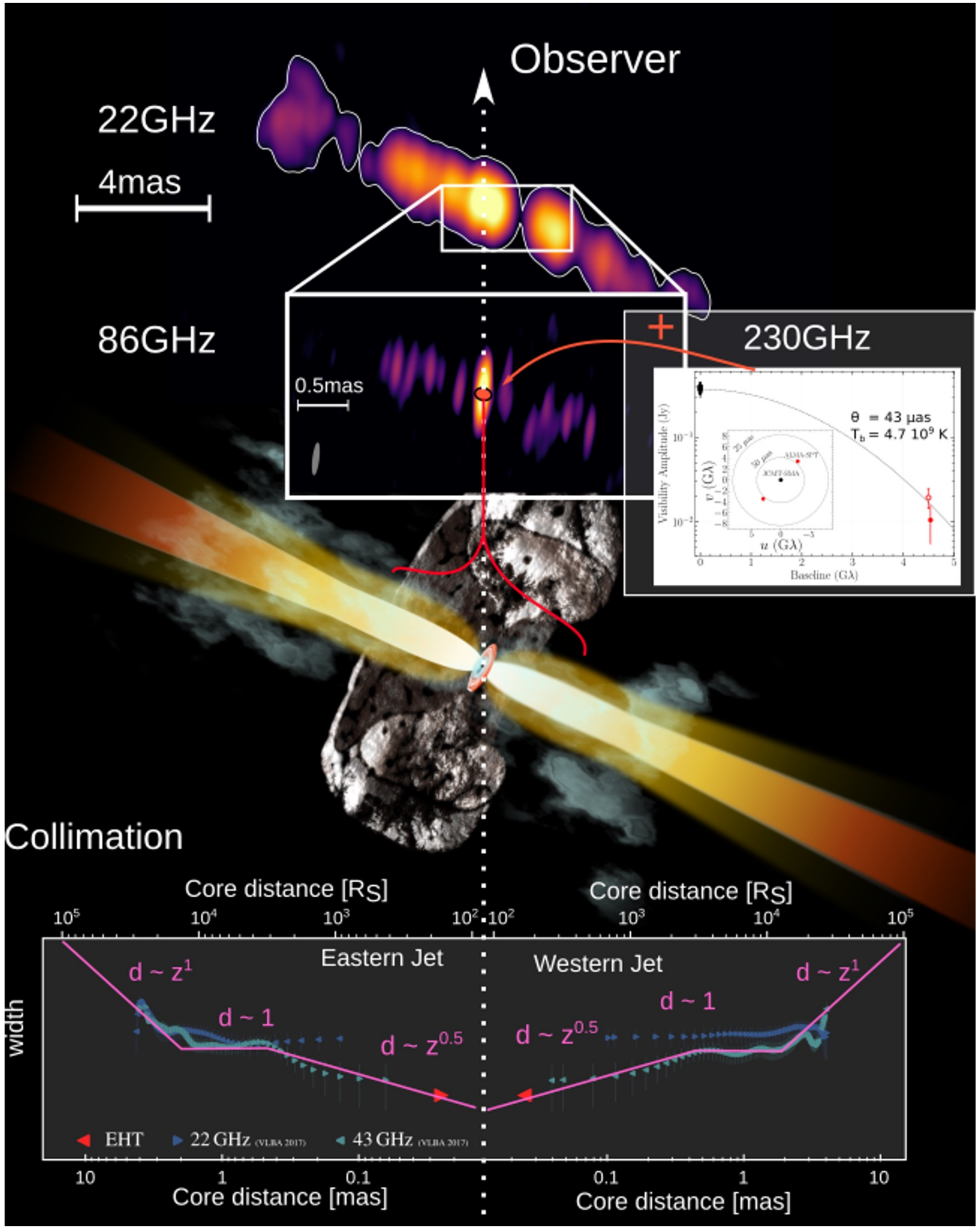
Vanishing features in the jet of 3C 454.3

- Features disappearing in the jet in region C
- Modeled as curved jet pointing towards a zero viewing angle
- Tb ranges from 10^7 to 10^{10} K, suggesting a magnetically dominated jet



Traianou et al. A&A 682, A154 (2024)

Eduardo Ros, Radio Days Erlangen, 13nov2024



NGC 1052 results

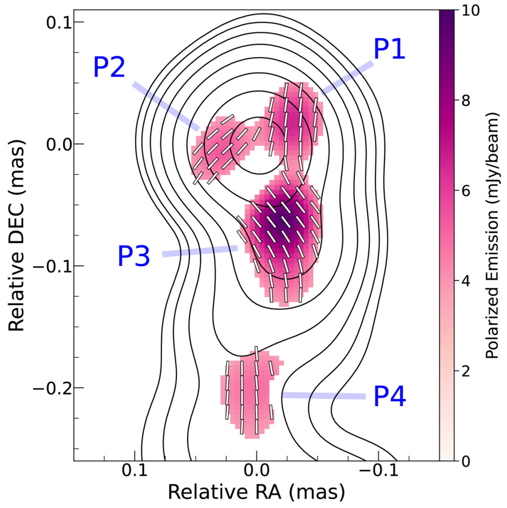
See Baczko's talk on Friday

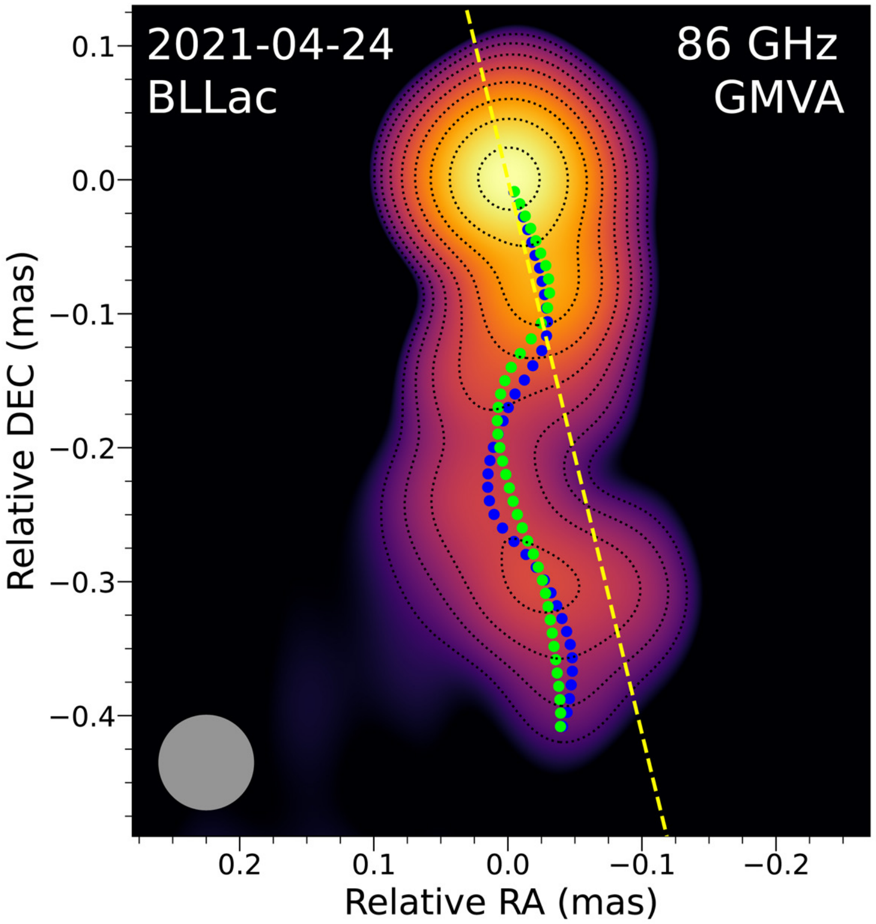
- Spectral decomposition of inner jet (VLBA+GMVA+EHT; 22–230 GHz):
- Turnover 10^3 GHz + EHT core-size imply B_{SSA} = 2G
- 3-epoch 86 GHz GMVA monitoring completed: provides time-variability and average of 86 GHz structure to refine collimation study at close distances

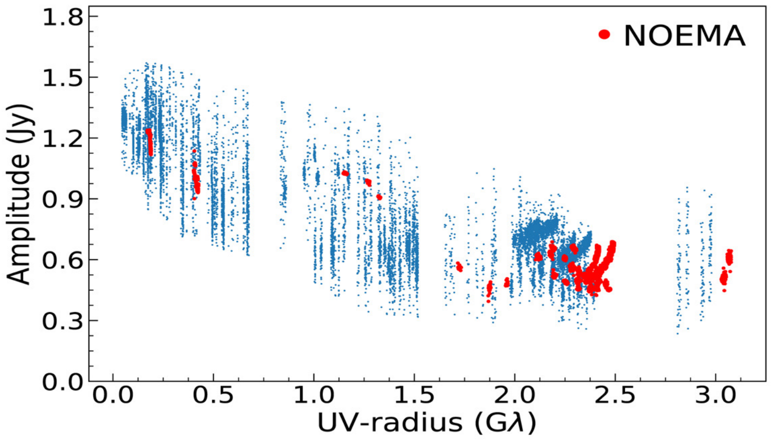
Baczko et al. A&A December 2024, DOI: 10.1051/0004-6361/202450898

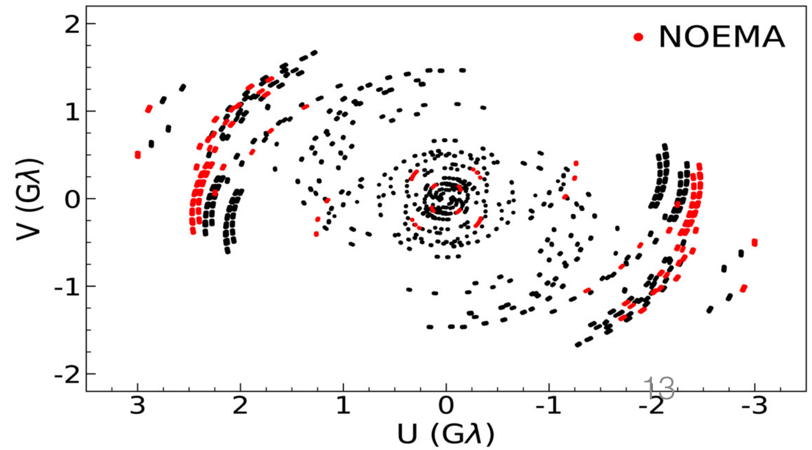
BL Lac wiggling jet

- Addition of NOEMA increases image sensitivity in a 2.5 factor
- Helical structure confirmed
- $T_b \sim 3 \times 10^{12}$ K in core
- Polarised emission near core
- Observation 3 days before a major gamma-ray flare









DW Kim et al. A&A 680, L3 (2023)

GMVA: Present status

- Operations based on a Memorandum of Understanding
  - 4 Gbps obs. at VLBA8+IRAM*+Eb+Mh+On*+Ys*+KVN* + GBT (limited time) +GLT*+ALMA*+APEX*
  - Temporary additions: LMT*, JCMT*, Haystack*, Mopra*, ATCA
  - Correlation at MPIfR
- Open-sky policy, proposals via NRAO-PST (01feb, 01aug)
  - Proprietary period of 1yr, data archived at MPIfR and NRAO
- Two sessions per year (apr+oct)
- No dedicated funding, in-kind contribution by partners
  - Media provision, session planning, scheduling by MPIfR
  - Officers: Robert Minchin (US Scheduler), Eduardo Ros (European Scheduler), Thomas Krichbaum (Operations Manager), Georgios F. Paraschos (Support Astronomer at Correlator), Helge Rottmann (Correlator Head)
- Moderated frequency agility (85-95 GHz) & 43 GHz interleaved (VLBA+Ys+Nt)

*: 16 Gbps available

Enhancing mm-VLBI

- Software
  - Calibration methods and pipelining: rPICARD, polsolve
  - New imaging methods
  - Improved parameter extraction methods

- Hardware
  - Enhancing bandwidth
    - Goal: 4 GHz for all telescopes, 16 GHz for a subset
  - Implementation of multi-band receivers
    - Dichroics + optics development
  - Enhancing antenna performance
    - Anti-reflex coating

M2FINDERS Advanced Grant

Mapping Magnetic Fields with INterferometry Down to Event hoRizon Scales

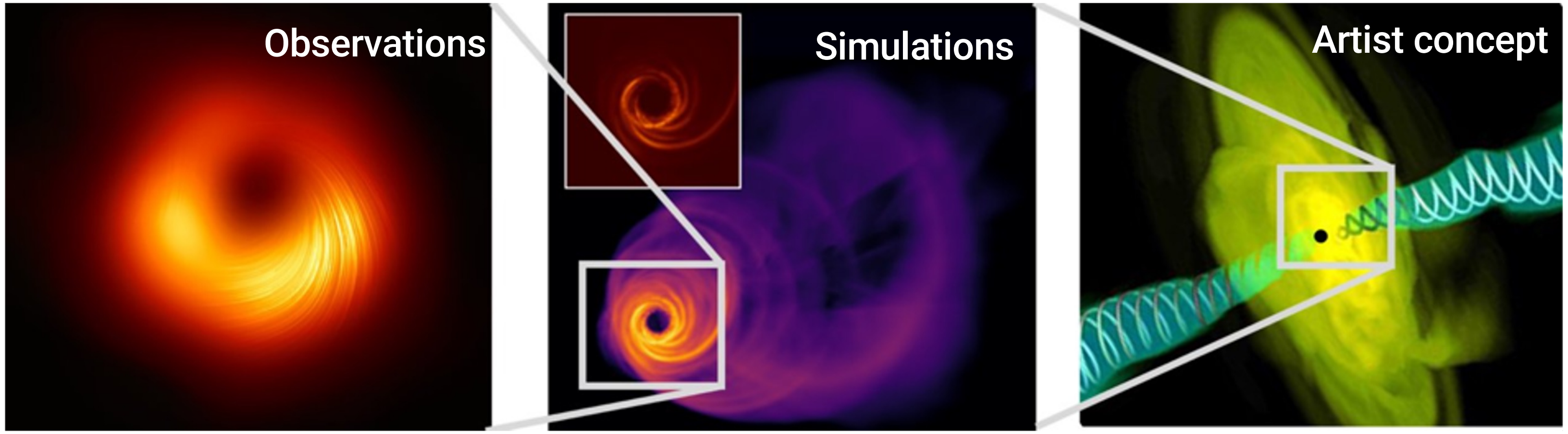
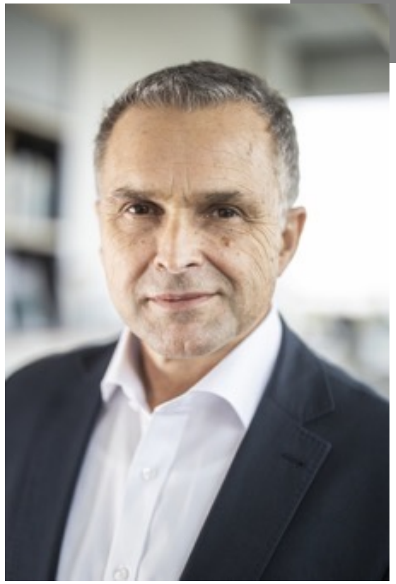


Image: Eduardo Ros © EHT Collaboration, Nakamura et al. 2020, Tchekhovskoy 2015

M2 FINDERS

European Research Council

P.I. A. Zensus



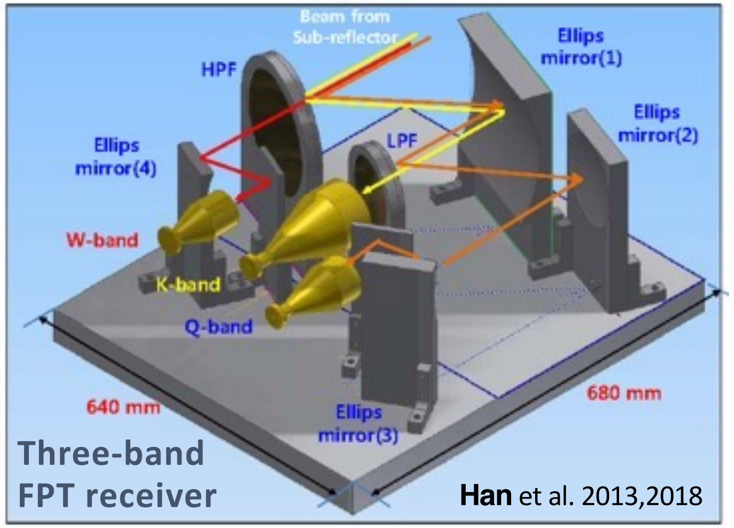
- Three working packages to probe magnetic fields near black holes
  - Mapping magnetic fields through polarisation and astrometric VLBI
  - Developing VLBI interferometry techniques
  - Deriving robust magnetic field properties near the event horizon
    - 2,5 M€ funded from the European Research Council

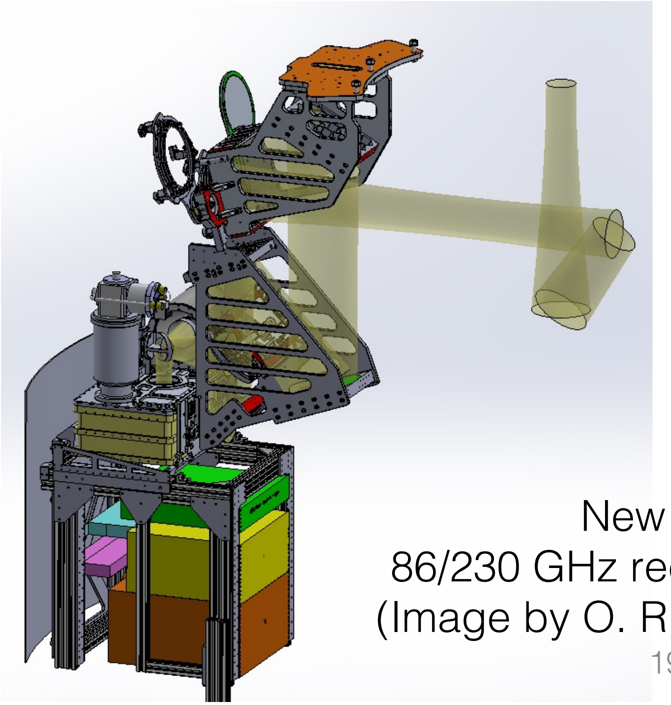
Project Nov 2021-Oct 2026

Next-generation mm-VLBI with FPT Receivers

- Shared Optics Multifrequency Receivers for Frequency Phase Transfer (FPT)
  → FPT pioneered at MPIfR (Middelberg+2006), later implemented at KVN and now, gradually, also at a number of European telescopes;
  → Three-band (22/43/86 GHz) FPT receiver is **being built at Effelsberg**; to be used for astrometry measurements with KVN/Yebes/Europe for M2FINDERS and precision cosmology (10 μas accuracy) with annual and secular parallaxes;
  → Two-band (86/230 GHz) FPT receiver is **being comissioned at APEX**;
  → FPT @ GMVA: factor of **10+** improvement of **dynamic range**; matching the EHT in effective image resolution;
  → FPT @ 230 GHz: factor of **50+** boost for the EHT imaging **dynamic range**

See Zhao's talk earlier today

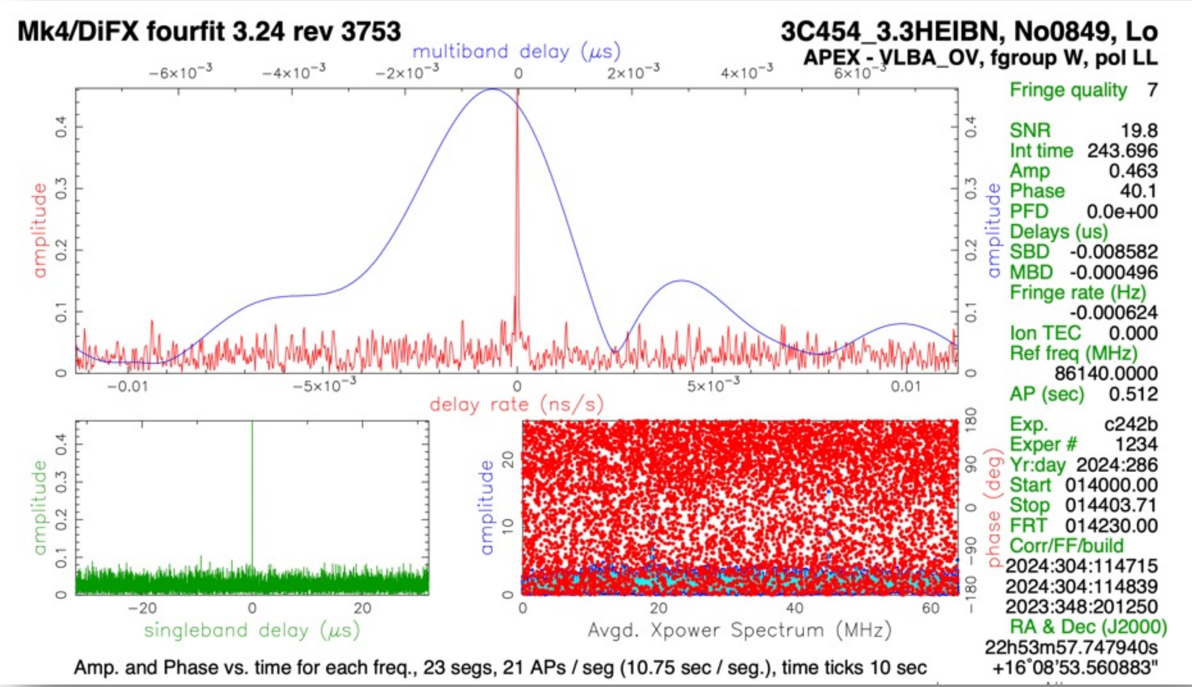




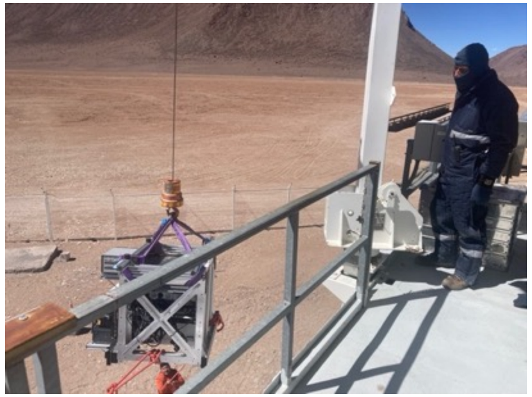
New APEX 86/230 GHz receiver (Image by O. Ricken)

Eduardo Ros, Radio Days Erlangen, 13nov2024

APEX joins the GMVA at 3mm












Status of triple-band Receiver at Effelsberg

- 22-43/86 GHz receiver funded by the MPG as part of upgrading the Effelsberg instrumentation.
- Initial design enabling standalone use of the 86 GHz band (for plain GMVA observations)
- The 86-GHz receiver will use the new LNA amplifier designed and constructed at the MPIfR, with T_{amp}~ 25 K, a substantial improvement over the current W-band receiver (T_{rec}~ 80-130 K).
- Hardware designed at the Electronics Division (G. Wieching, C. Kasemann)
- Timeline: Completion and commissioning planned during 2025.

The future of VLBI (as seen from the GMVA)

- Existing facilities: more bandwidth increases, data processing innovations
- m-VLBI: LOFAR imaging is new/unique
  - Steady ijmprovement of calibration algorithms
- cm-VLBI: the traditional VLBI band, but new sensitive telescope (phased SKA- mid) joining the show
  - Further in the future: ngVLA
  - See potential advancements with LEVERAGE ansatz
- mm-VLBI: phased ALMA and improved NOEMA online
  - Paramount mm sensitivity reached via frequency-phase-transfer!
  - Towards a new EHT phase with new antennas

See Wongphechauxsorn's talk tomorrow

See Saiz's talk yesterday

GMVA/EHT Synergy: See Ricci's talk later today

Take-away messages

- Millimetre-wavelength astronomy has reached a mature stage, with current operations of KVN, HSA, GMVA, and EHT delivering high-impact results and setting the stage for the ngVLA era, which aims to reach up to 115 GHz.
- Currently, GMVA serves as the primary workhorse for global open-sky mm-VLBI, involving over 20 antennas in groundbreaking observations.
- Technological advancements include new digital backends and enhanced receivers, enabling high bandwidths and multi-band observations, as well as the integration of multi-band receivers operating in the 22-345 GHz range within major array roadmaps.
- Exciting new science opportunities are emerging, such as:
  - Transient phenomena and multi-messenger follow-ups
  - Studies of radio quiet galaxies and galactic objects
  - Precise astrometric measurements
  - Investigations of opacity and polarised emissions close to jet bases
  - Insights into the strength and orientation of magnetic fields near the event horizon
  - Spectral line analysis, and much more…