Dynamic Imaging With MeerKAT

The Time Axis As The Final Frontier

Oleg Smirnov (Rhodes University & SARAO)

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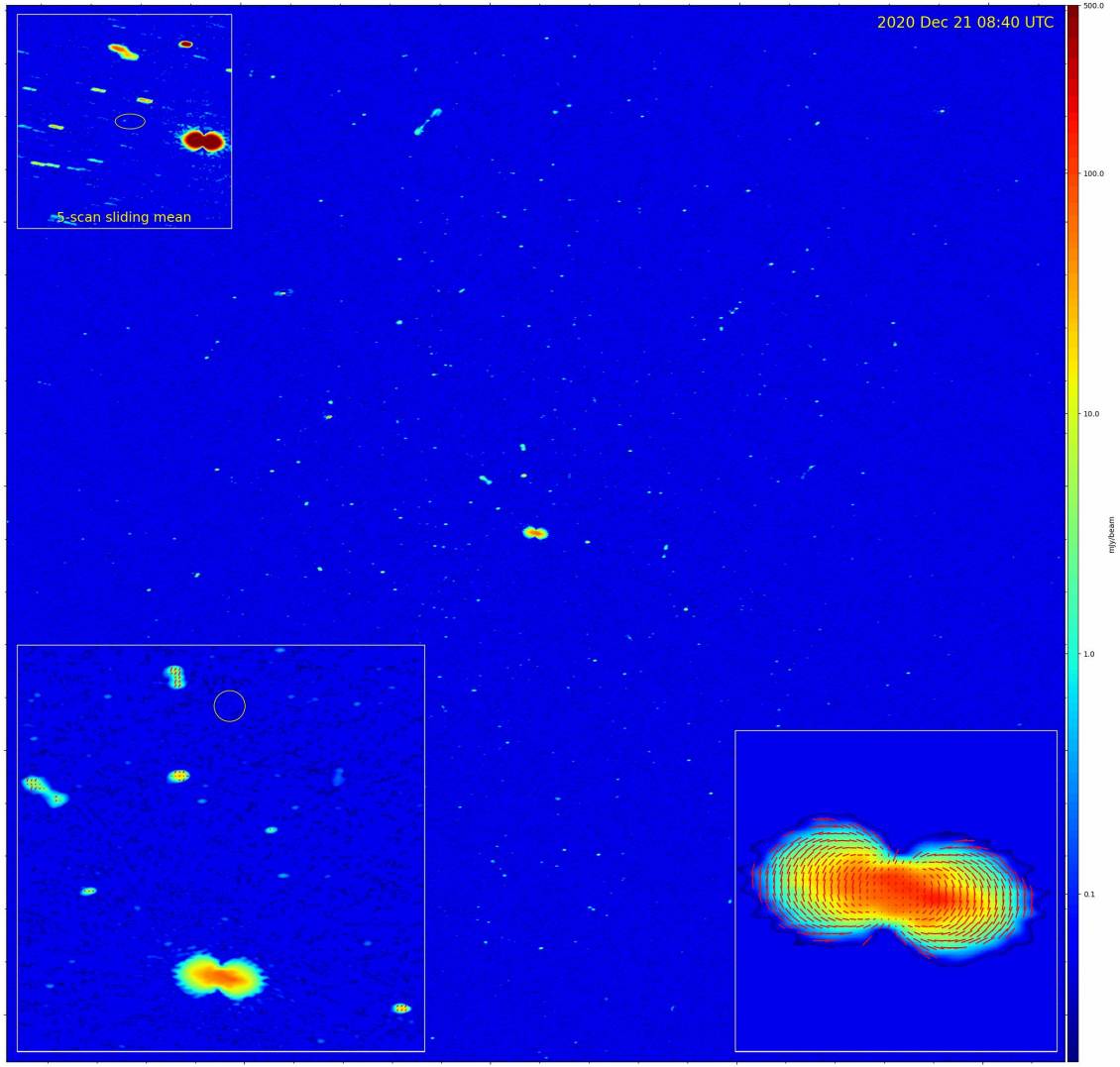
BREAKTHROUGH LISTEN

NRF National Research Foundation

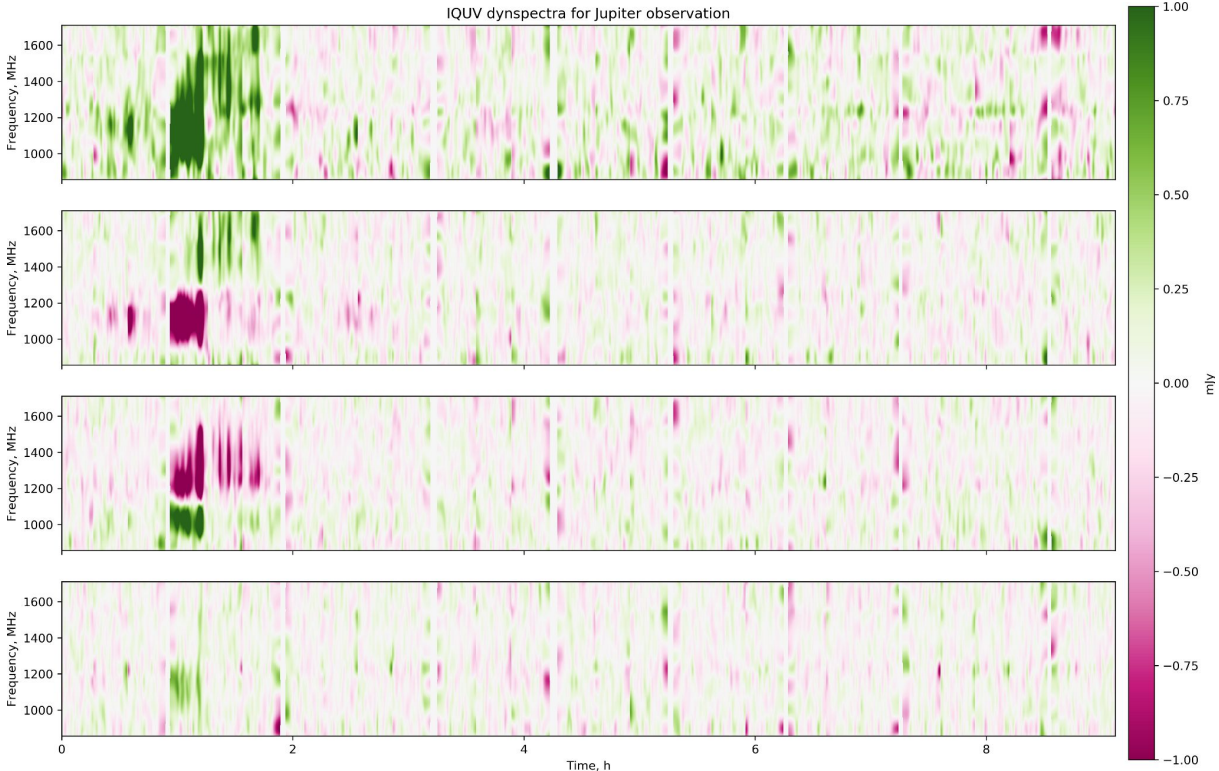
SARAO South African Radio Astronomy Observatory

Astronomer's Bingo

https://ratt.center/parrot

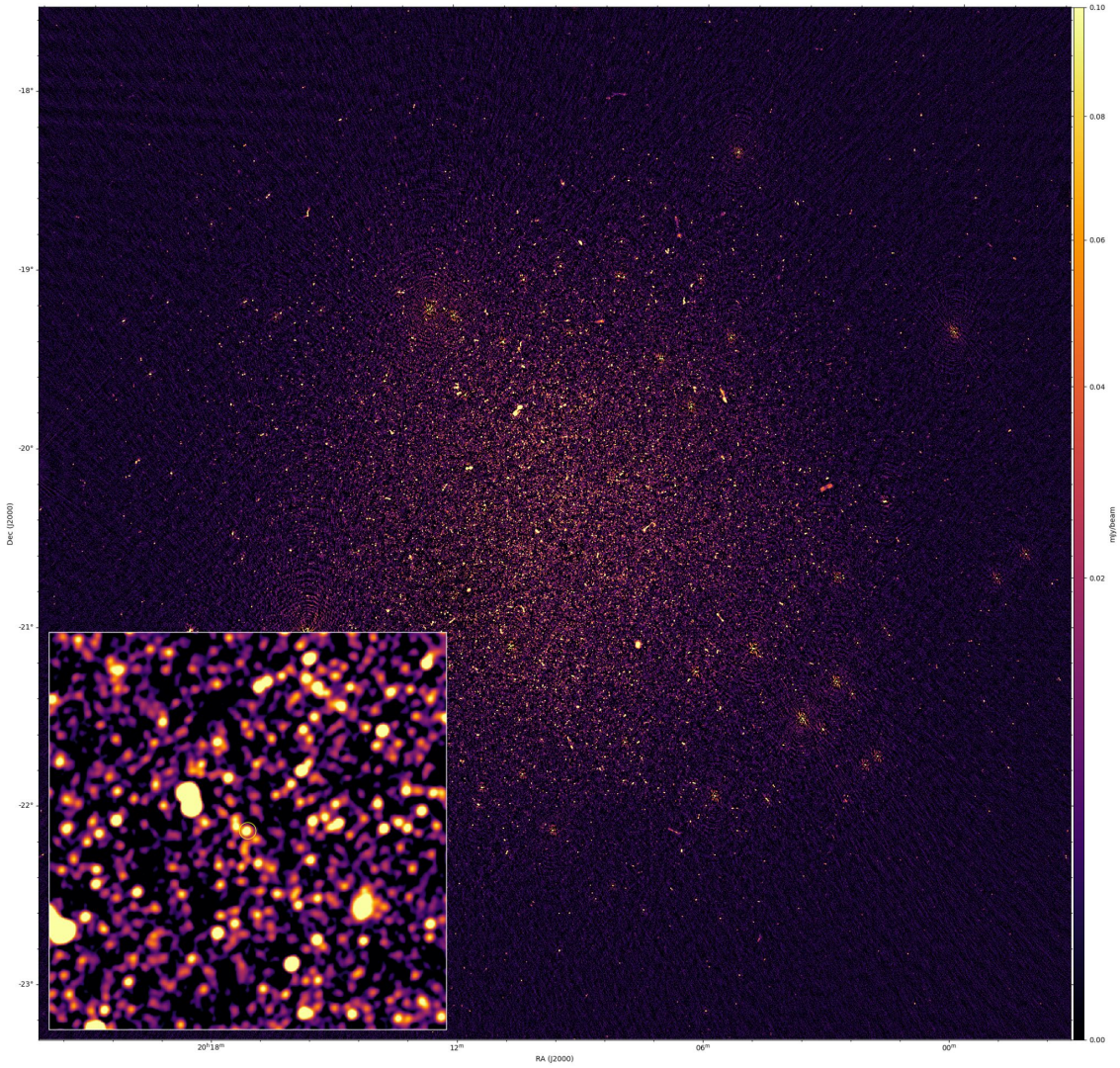


- Bright (5.9 mJy) transient next to Saturn, corresponding to a 70 uJy “quiescent” compact source
- “on” for 45 minutes
- wideband at peak
- 100% polarized (89% linear, 11% circular)
- RM consistent with Opperman map
- Galactic latitude -27°

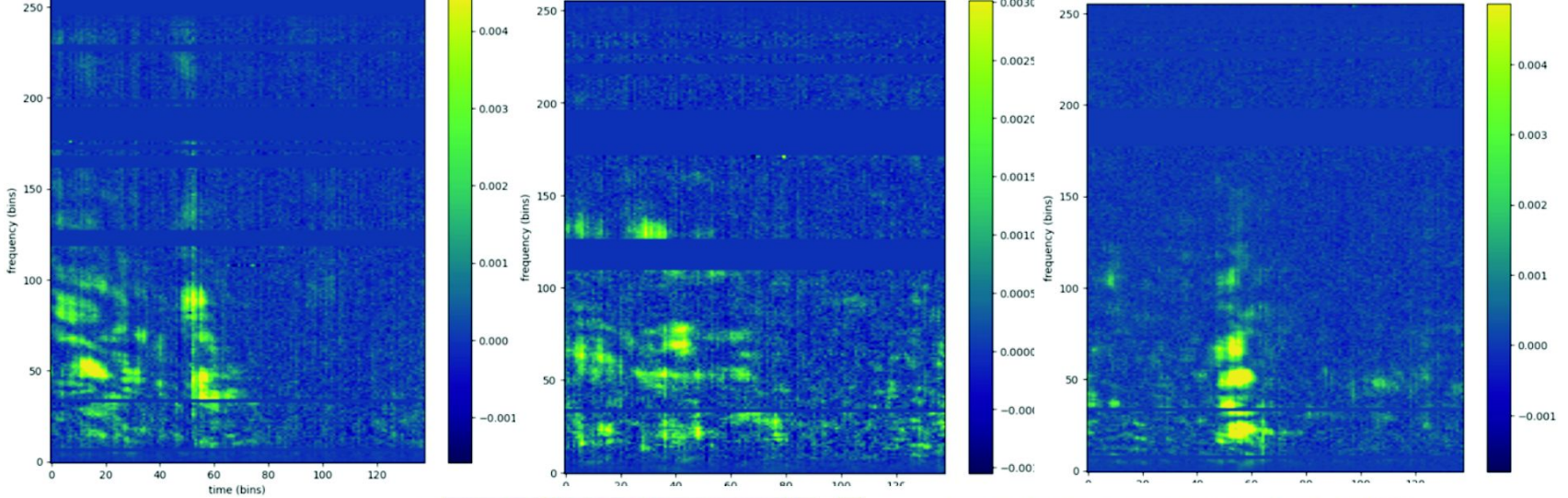


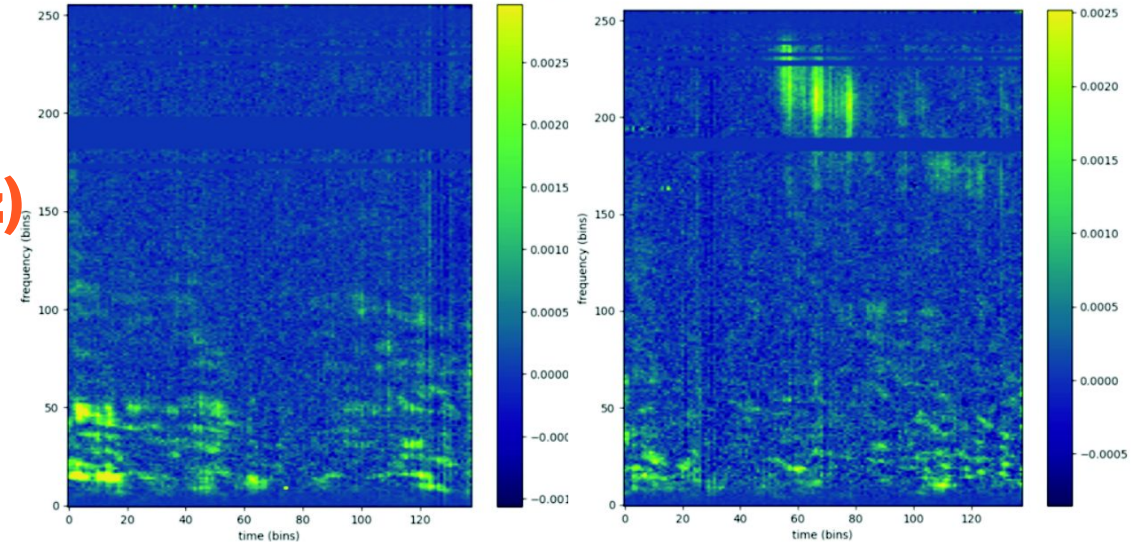
Follow-up

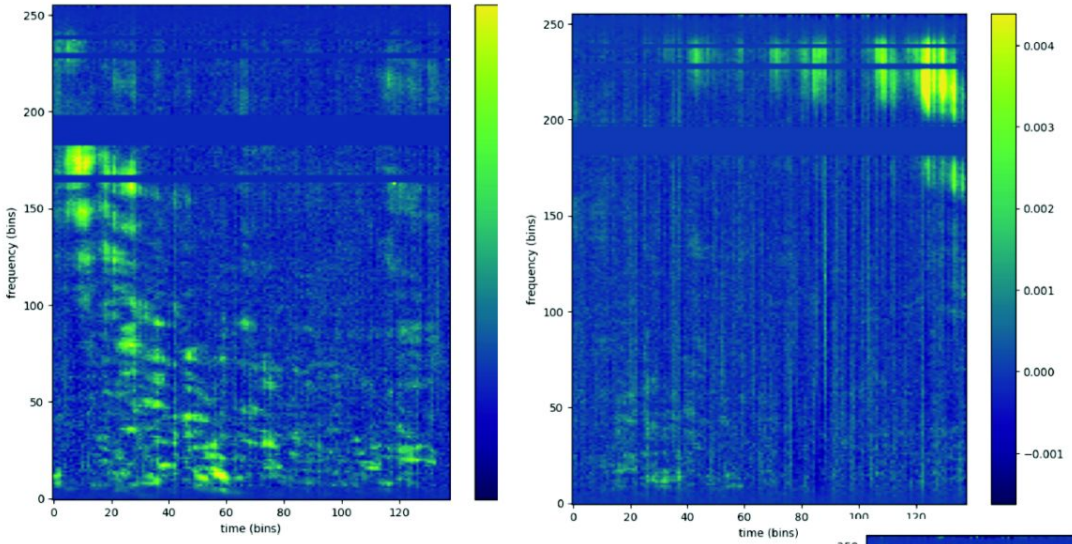
- Several follow-up observations conducted in L-band and UHF
- Variable source detected, x10-20 magnification
- Dwarf flares?
- MeerTRAP detected individual pulses in one follow-up observation, timestamps matched observed “flares”
- One follow-up in UHF band with the full PTUSE (pulsar timing) engine, with some weird and wonderful results



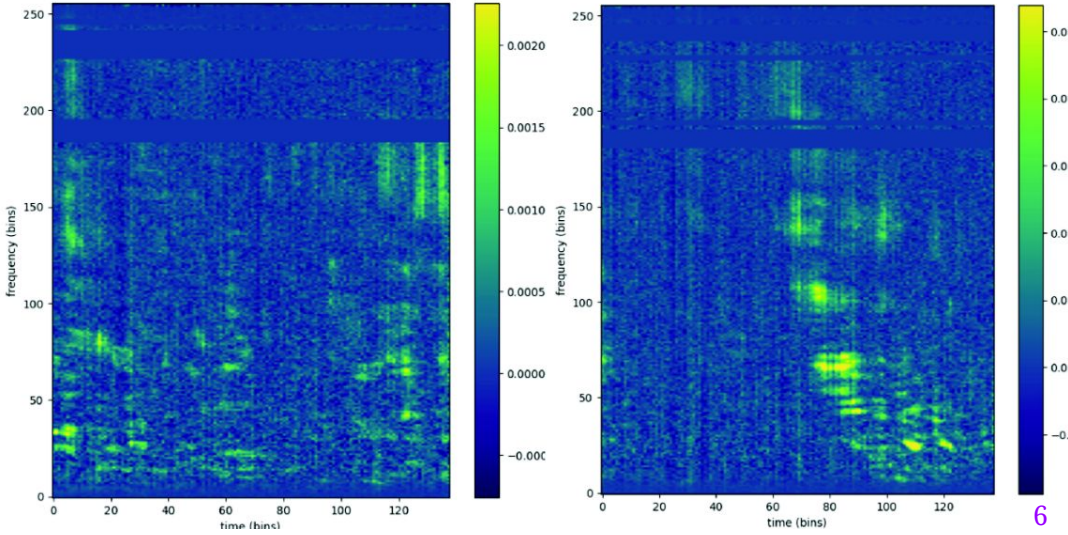
Dynamic spectra from PTUSE, UHF (544-1088 MHz) scans (~1h) 1-5







Dynamic spectra from PTUSE, UHF (544-1088 MHz) scans (~1h) 5-9



RRAT Or Not

- Highly scintillating pulsar or an RRAT?
- Hard to explain the behaviour in terms of “ordinary” scintillation
- Timescales, magnification factors (10-100) and chromaticity somewhat odd
  - too slow for IPS
  - too fast for ISS
  - ionosphere would affect other sources
- Some weird ideas but noting conclusive
  - scattering screens in the Oort cloud?
  - radial filaments in the solar wind?
- When is an RRAT an RRAT or not an RRAT?
- May be a PARROT (pulsar with anomalous refraction recurring on odd timescales)

JOURNAL ARTICLE

The RATT PARROT: serendipitous discovery of a peculiarly scintillating pulsar in MeerKAT imaging observations of the Great Saturn – Jupiter Conjunction of 2020. I. Dynamic imaging and data analysis

O M Smirnov ✉, B W Stappers, C Tasse, H L Bester, H Bignall, M A Walker, M Caleb, K M Rajwade, S Buchner, P Woudt ... Show more
Author Notes

Monthly Notices of the Royal Astronomical Society, Volume 528, Issue 4, March 2024, Pages 6517–6537, https://doi.org/10.1093/mnras/stae303
Published: 02 February 2024 **Article history** ▾

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Two Robots (Thanks Ian Heywood)

- Ian @MeerKAT@5: build two robots
  - Moving backward in time: mine the MeerKAT archive (6 years of data)
  - Moving forward in time: commensal transient search engine
- Very different computational problems

Project FATALII & TRON

- In 2024, started project FATALII – dynamic imaging and transient search pipelines for MeerKAT and the ATA
- Co-funded by Breakthrough Listen
- Eventual aim is to mine the entire MeerKAT archive for overlooked transients
  - (Holy grail / stretch goal: near-real time search)
- Current phase of operations
  - processing validation fields (e.g. the PARROT)
  - processing promising fields (globular clusters, GC and such)
  - processing fields that are being calibrated anyway for unrelated purposes
  - targeted searches (exoplanetary systems)

BREAKTHROUGH LISTEN

Transient Radio Observations for Newbies

- (Start with a normal calibration and imaging pipeline and make the deepest possible continuum image)

...then, TRON per se:

- Subtract model visibilities from data
- Image residual visibilities at raw time cadence (MeerKAT: 8s or 2s)
  - 1000s of residual “snapshot” images – ideally, noise-like
- Smooth to various timescales
  - also compute power spectra and forward-diffs, etc.
- Look for stuff along the *t*-axis <u>at every pixel</u>
- Extract lightcurves for detections (and static continuum sources)
  - 10,000s of lightcurvers per observation
- And make dynamic spectra for the really interesting stuff
- **Data <u>non</u>reduction!**
  - ~Tb of raw data => ~Tb of image cubes

Software Problems (& Solutions)

- Eulogy for FITS *(Bye-bye FITS // Bye-bye big-endian // Hello xarray…)*
  - Tb-scale FITS cubes untenable, and we have “horrible” data access patterns
  - Spectral line people have suffered from this (but they have more benign access patterns)
  - Irregularly sampled (or even sparse) time axis
- Time axis blows up the compute, but is often embarrassingly parallel
- New formats & data access stacks needed:
  - **xarray**: self-describing, labelled multi-dimensional arrays – supports both **dask** and **numpy** arrays
  - **dask**: distributed, chunked array computation via task graphs
  - **Zarr**: chunked storage format, designed for distributed storage and parallel I/O, plays very nicely with xarray
  - https://github.com/ratt-ru/xarray-fits: import FITS files as xarray datasets
- TRON based on entire new software stack
  - ~hours processing time (on top of regular selfcal) for ~hours observing time

Zarr

What's Buried in The Noise?

- Averaging can right many wrongs
- The time axis can hide a lot of sins
- Out on the frontier, nobody knows where the bodies are…

"What's buried in the noise?" – Jan Noordam, circa 2010

What's Buried in The Noise?

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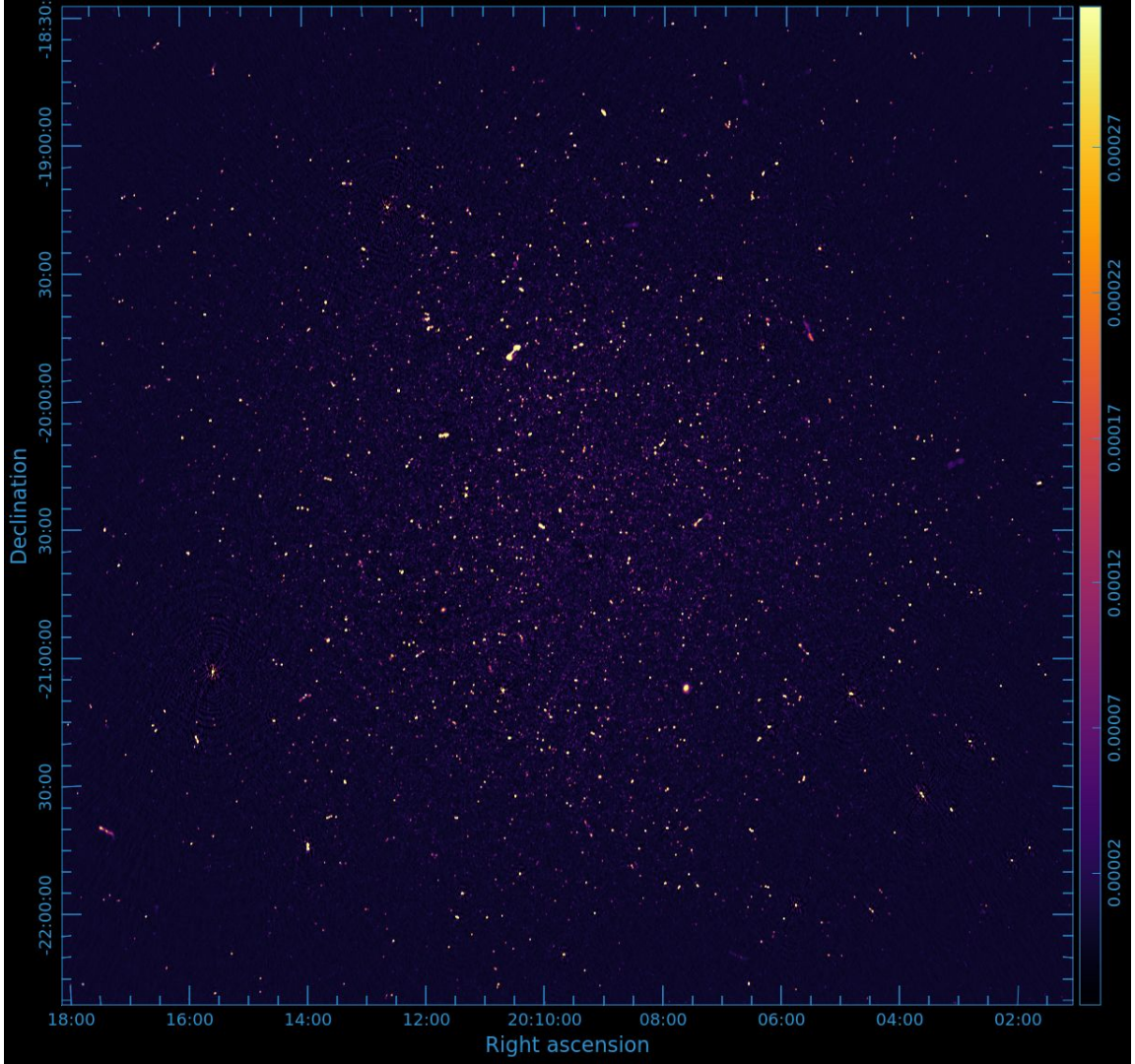
"What's buried in the noise?" – Jan Noordam, circa 2010

"The bones of Jan's enemies!" – Cynical 3GC aficionados, circa same

UHF

UHF PARROT field

Deep MFS map



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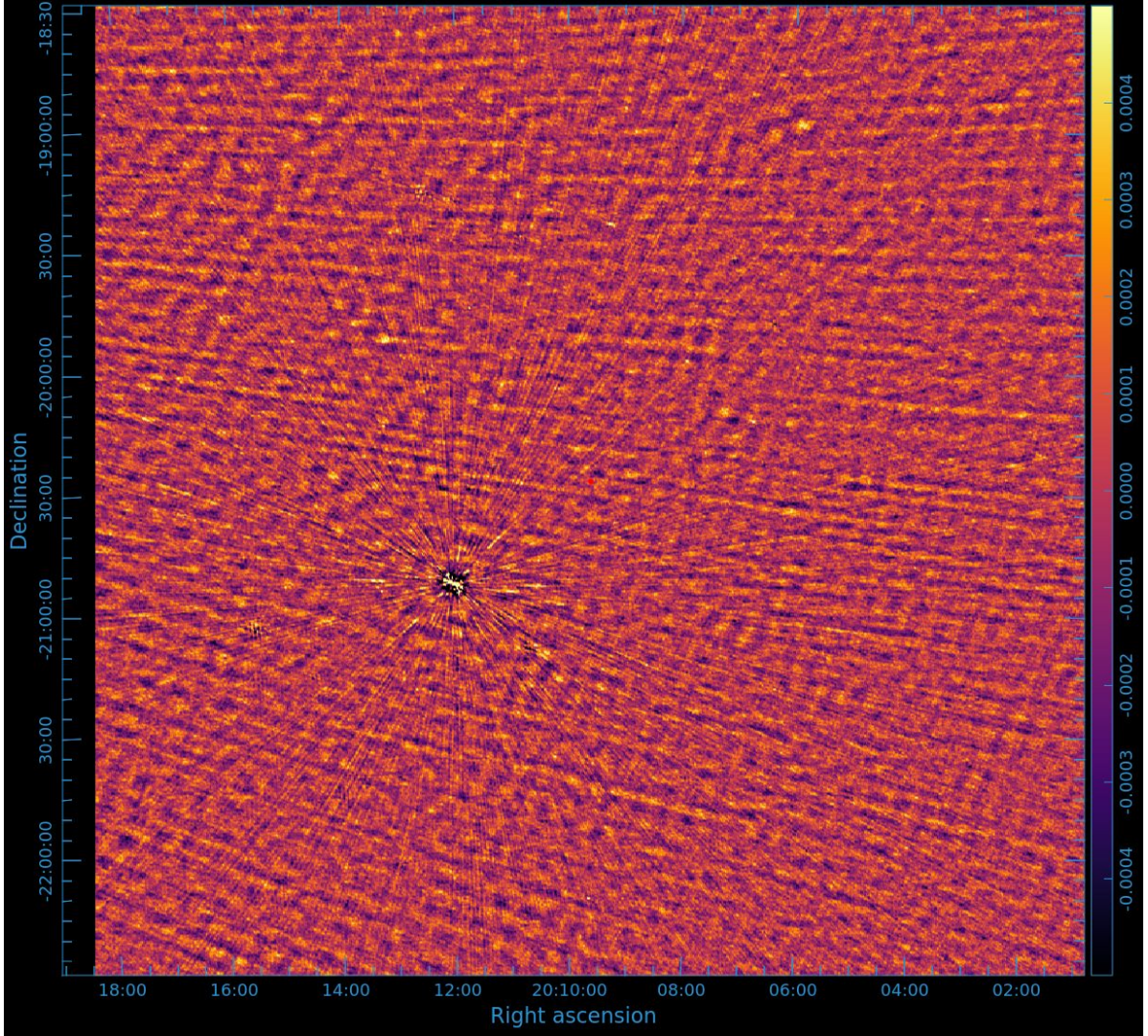
UHF PARROT field

residuals 8s



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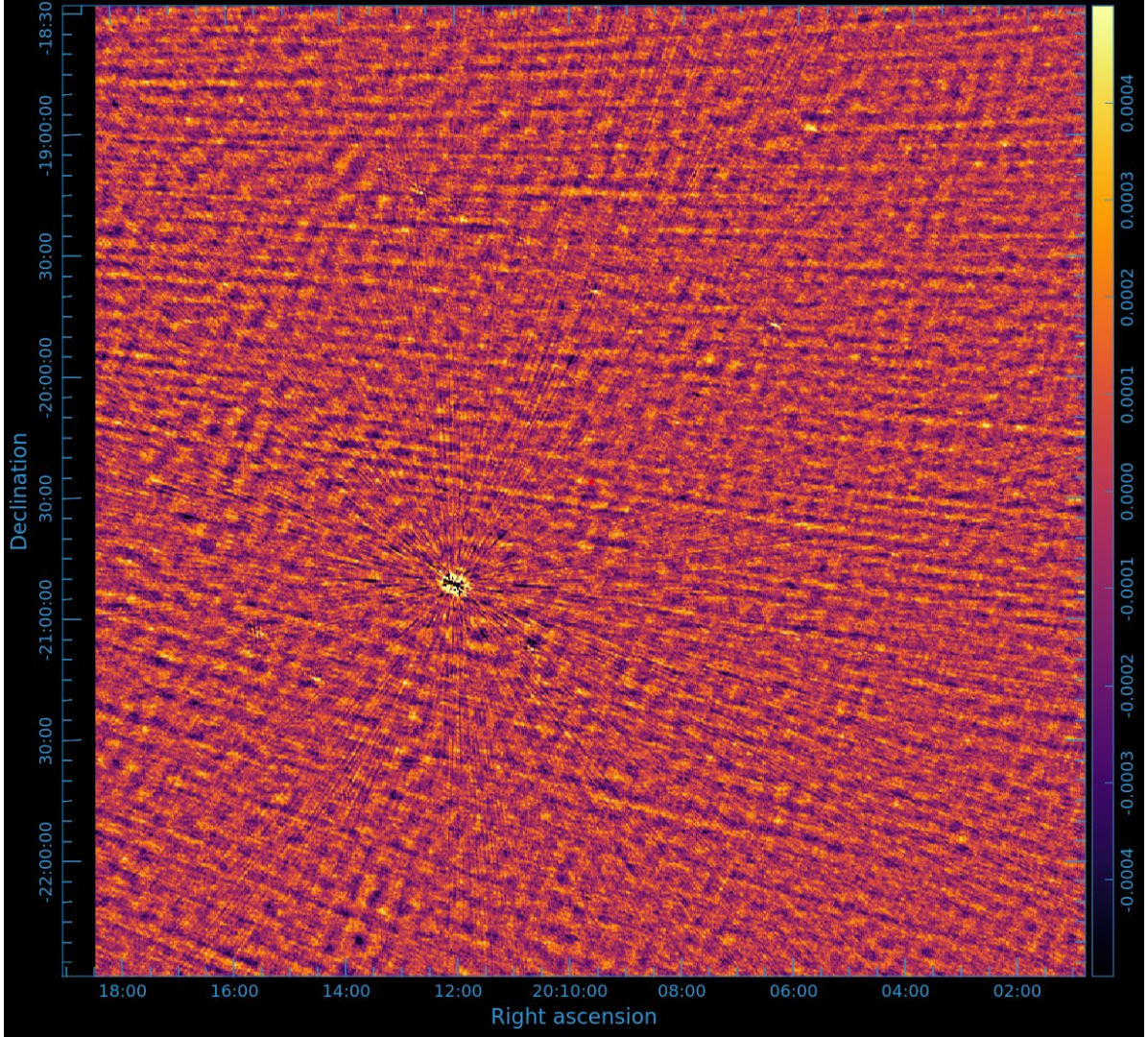
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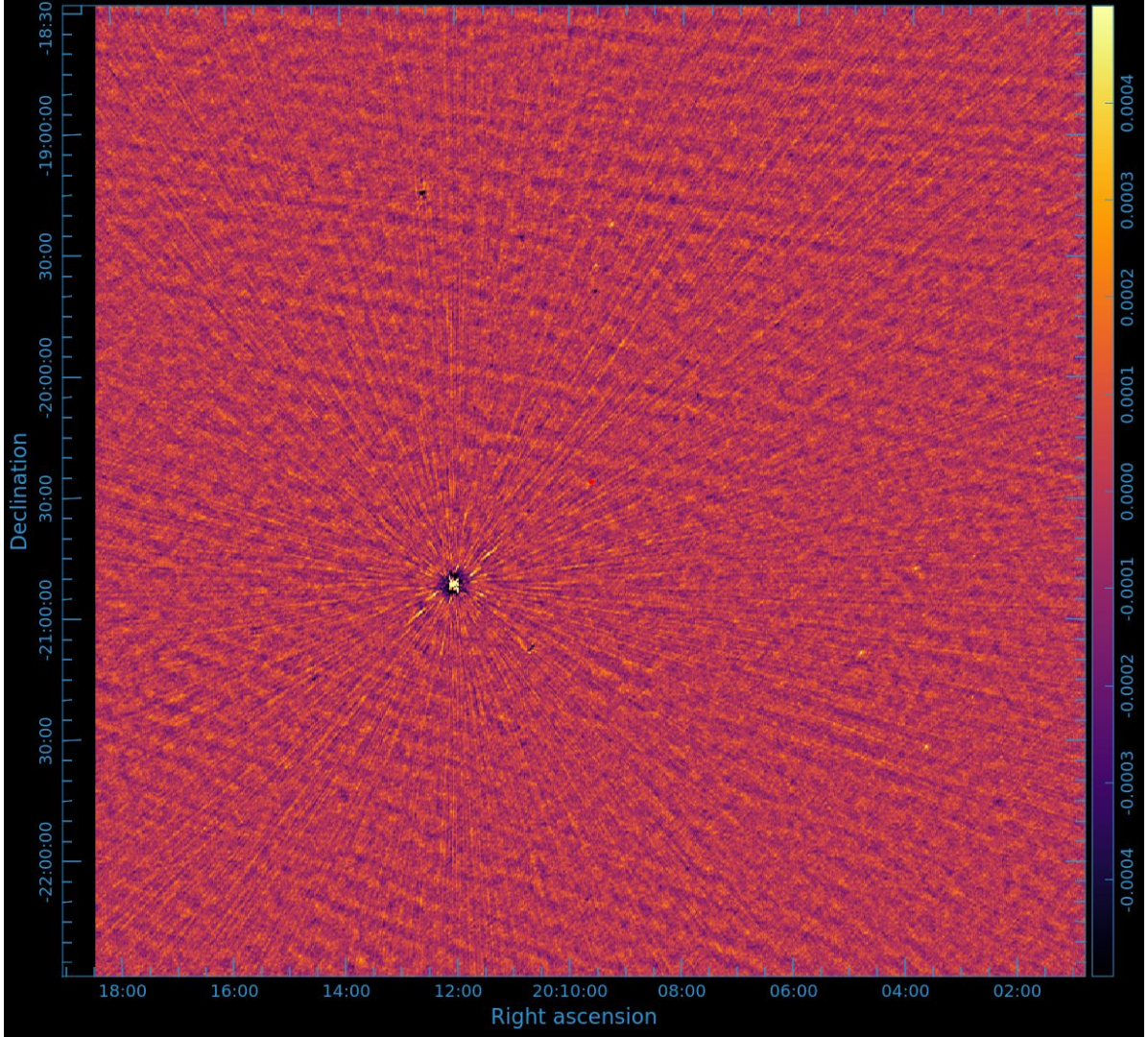
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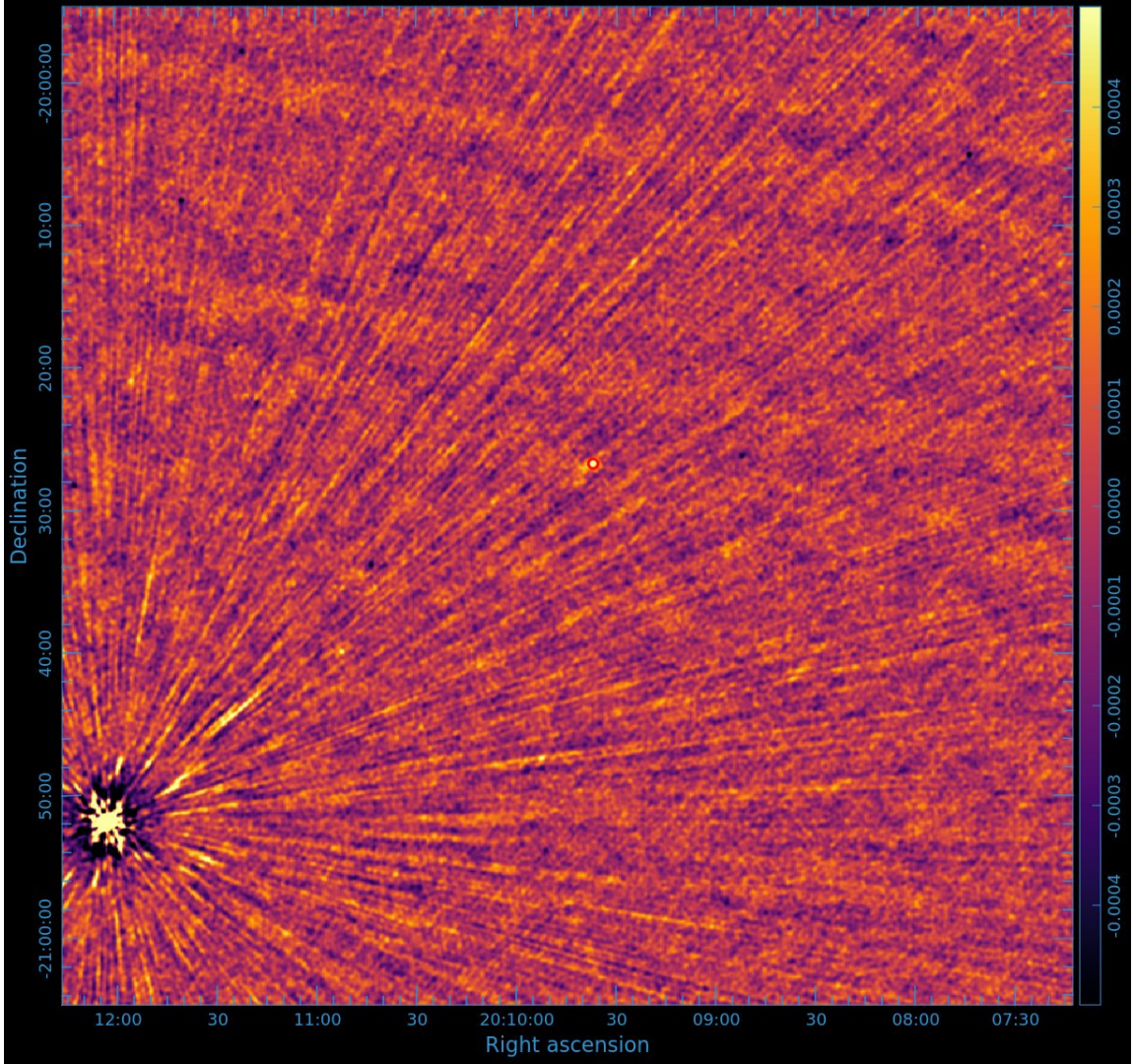
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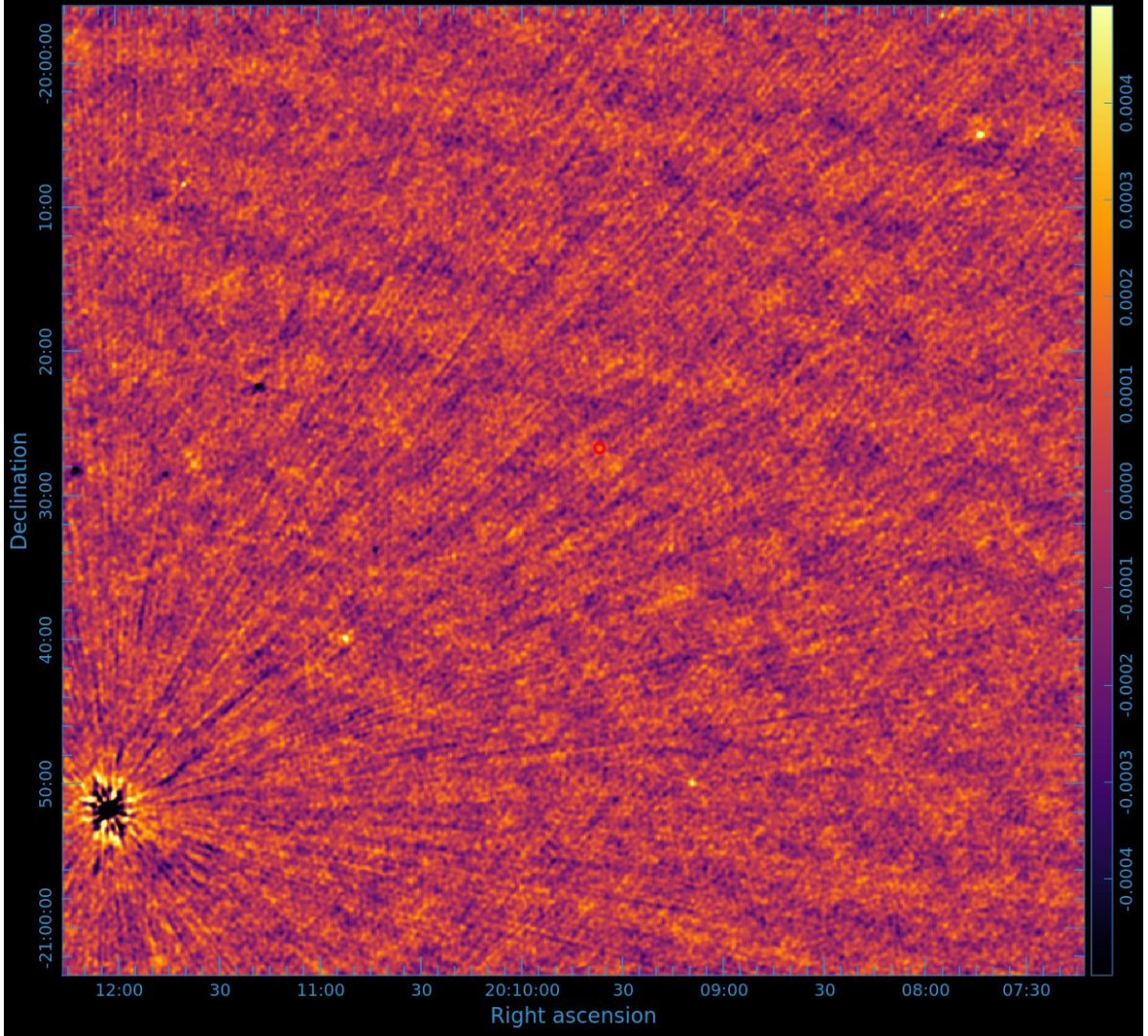
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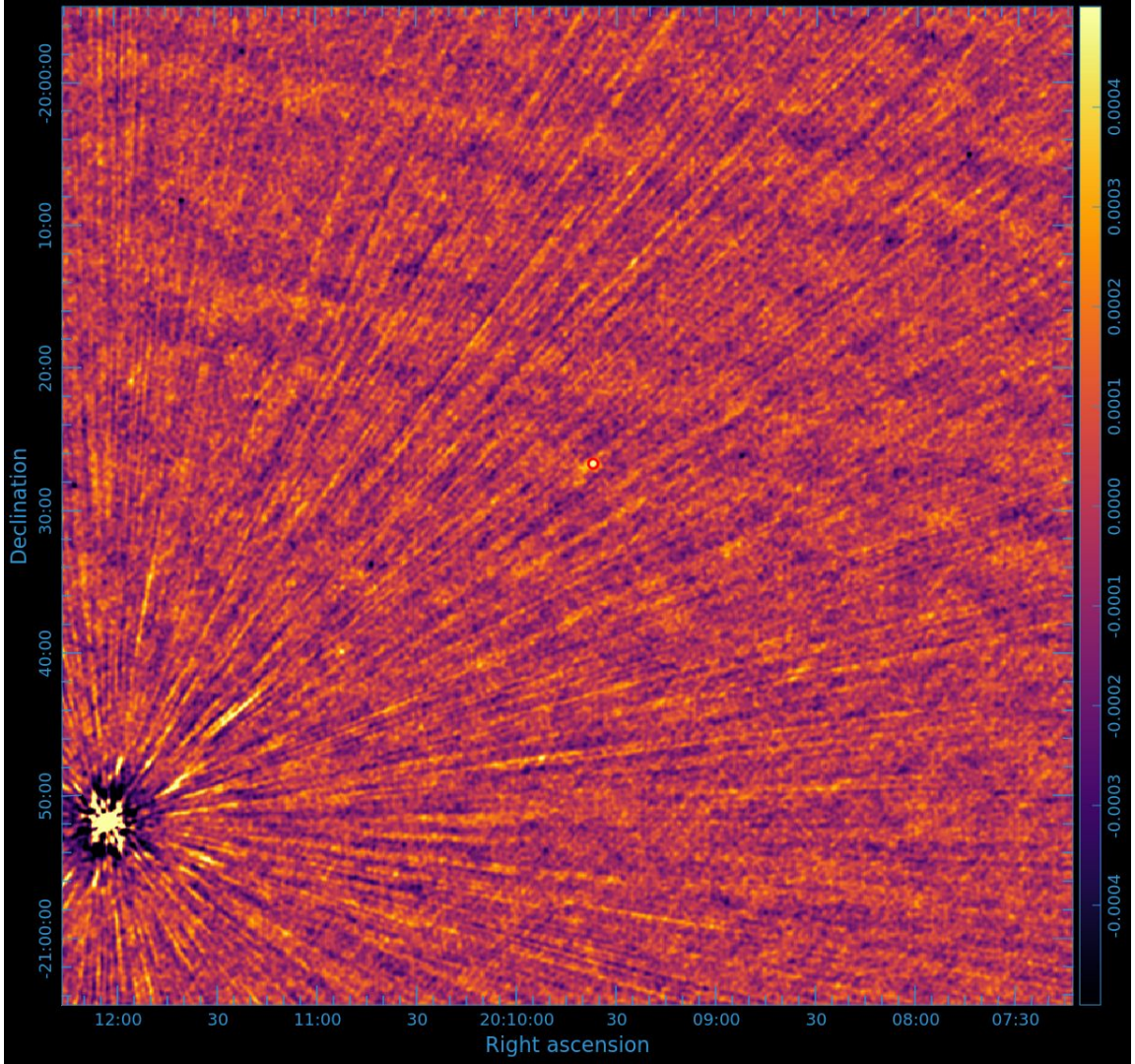
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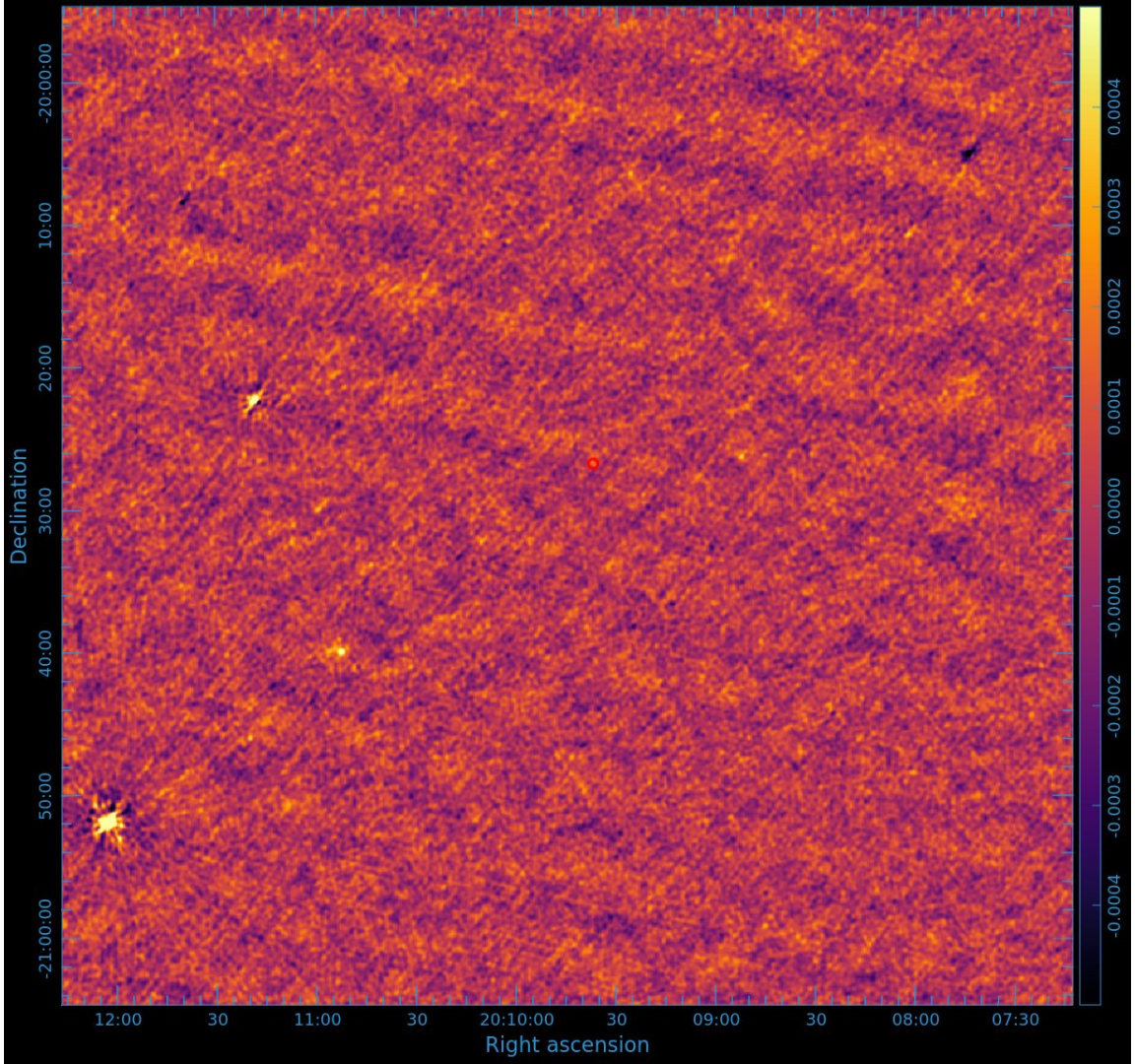
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Breifast Detection Algorithm

- Q: can we detect the PARROT blindly?
- A: Yes!
  - **breifast**: transient detector based on **breizorro** auto-masking tool (based on Cyril Tasse's old code)
  - search at multiple timescales (8s, 30s, 60s, ...)
  - additional heuristics to reject DDE artefacts, RFI, etc.
  - PARROT reliably detected in UHF epochs at 8+ sigma (at 8s cadence, higher at 30-60s)
    - ...but not in L-band
  - No false positives above 8 sigma, only the PARROT

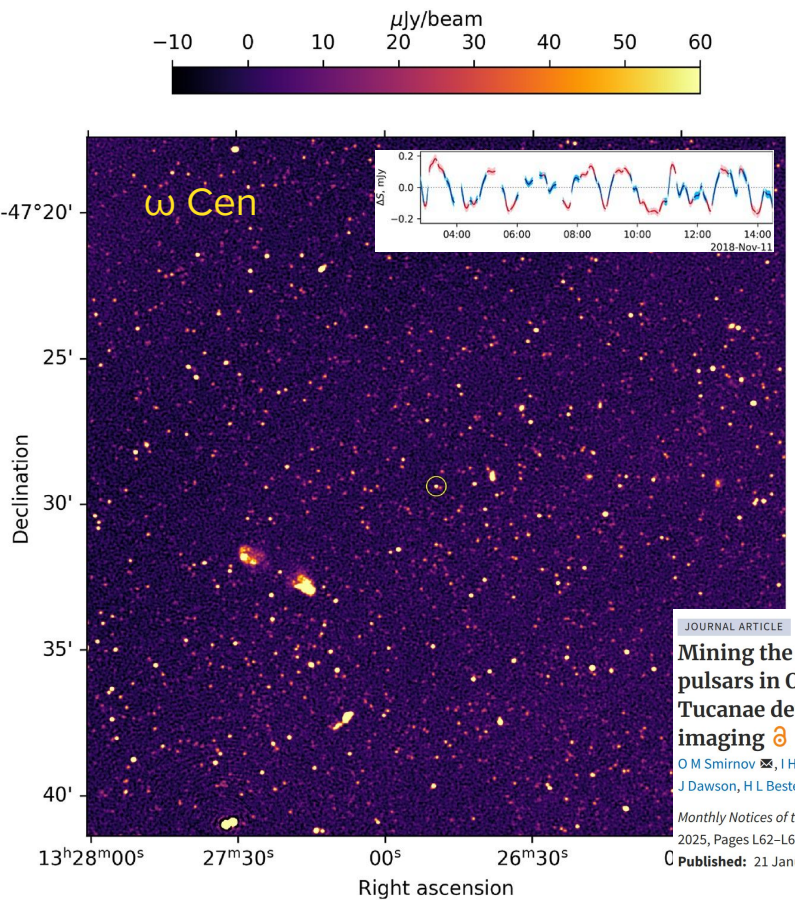
- Q: are there PARROTs everywhere?

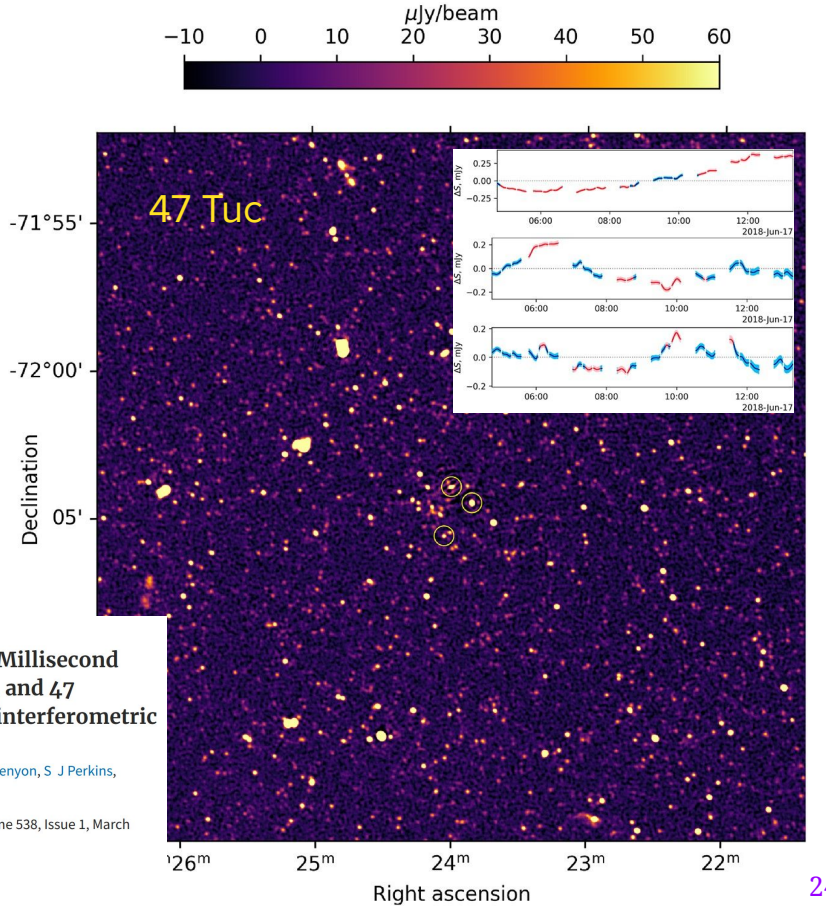
More PARROTs?

A: not in every field. The Universe is not that munificent, alas.

...but still...

TRON I: MSPs in Globular Clusters





JOURNAL ARTICLE

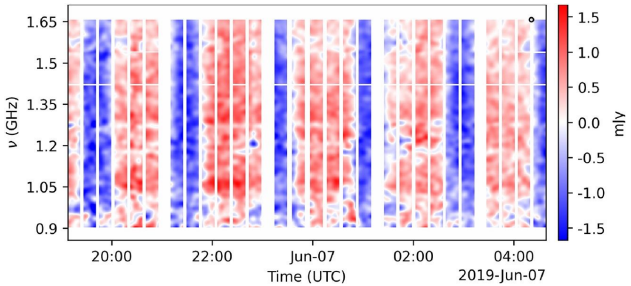
Mining the time axis with TRON – I. Millisecond pulsars in Omega Centauri, Terzan 5, and 47 Tucanae detected through MeerKAT interferometric imaging

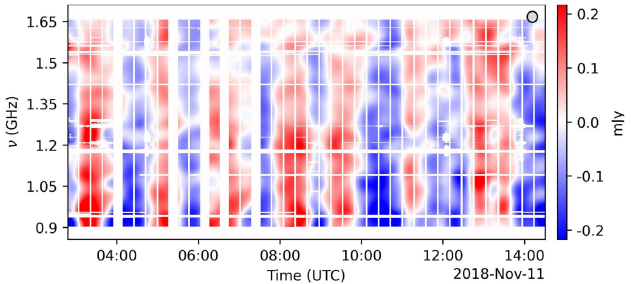
O M Smirnov ✉, I Heywood, M Geyer, T Myburgh, C Tasse, J S Kenyon, S J Perkins, J Dawson, H L Bester, J S Bright ... Show more

Monthly Notices of the Royal Astronomical Society: Letters, Volume 538, Issue 1, March 2025, Pages L62–L68, https://doi.org/10.1093/mnrasl/slaf009

Published: 21 January 2025 **Article history ▾**

Dynamic Spectra: Spiders & Scintillators

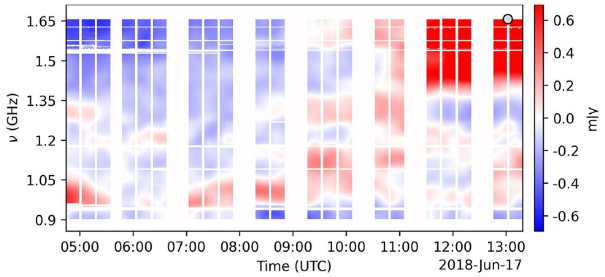


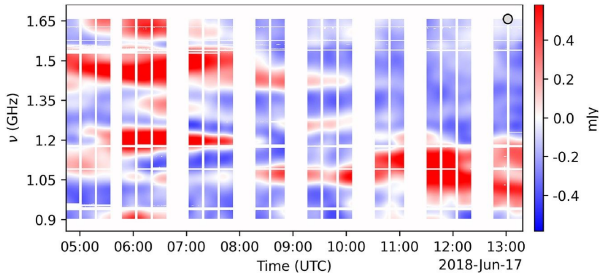


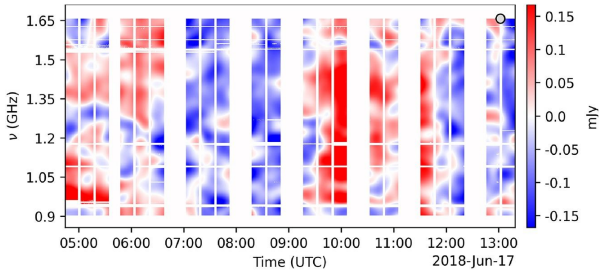
- "Black widow" and "red back" systems: pulsar eating its binary companion
- Will show eclipsing behaviour if the geometry is right
- Can show irregular eclipses

- Scintillators

- Some combination of the two?

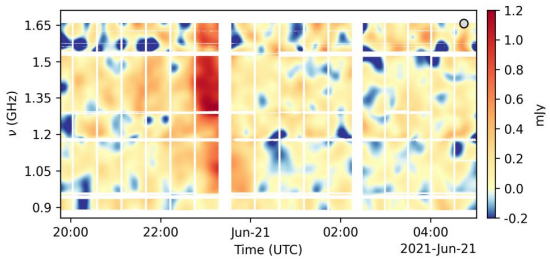


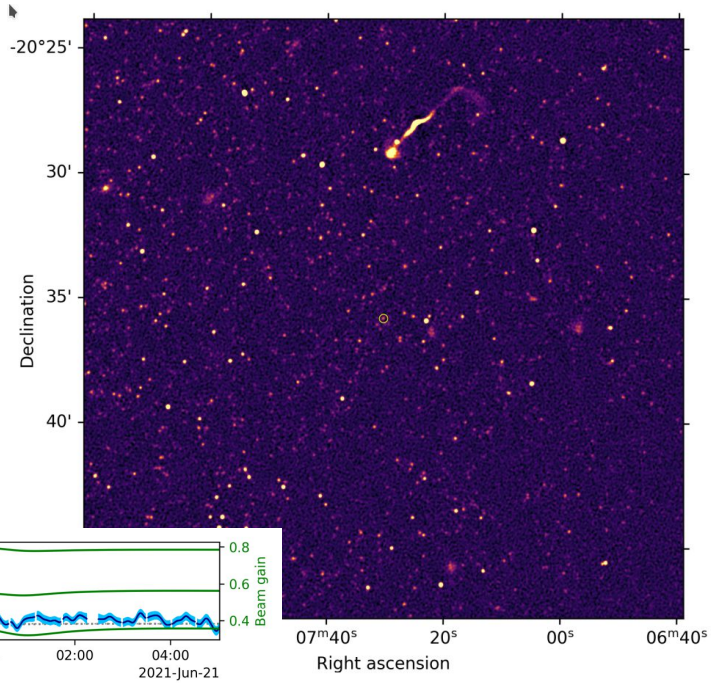




TRON II: A PARROT Bonus

- Reprocessing the PARROT fields to verify the algorithm yielded a bonus detection
- Associated with a Gaia star ~1300 pc away
- RS CVn binary
  - electron cyclotron maser instability (EMCI)
  - mass ejection from companion hits star and spirals down its magnetic field, resulting in a coherent 90%+ circularly polarized burst of emission





JOURNAL ARTICLE ACCEPTED MANUSCRIPT

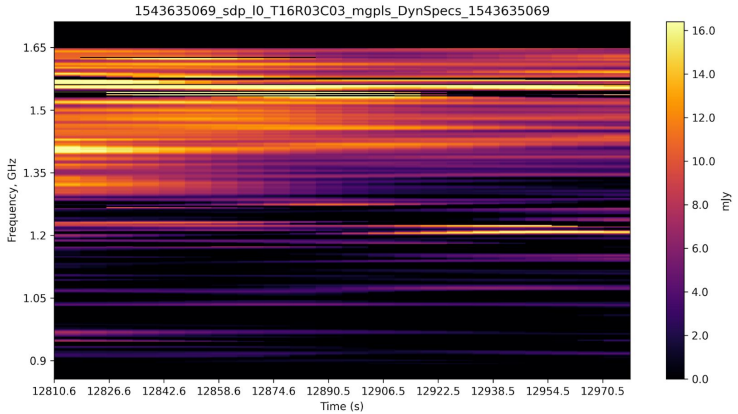
Mining the time axis with TRON. II. MeerKAT detects a stellar radio flare from a distant RS CVn candidate

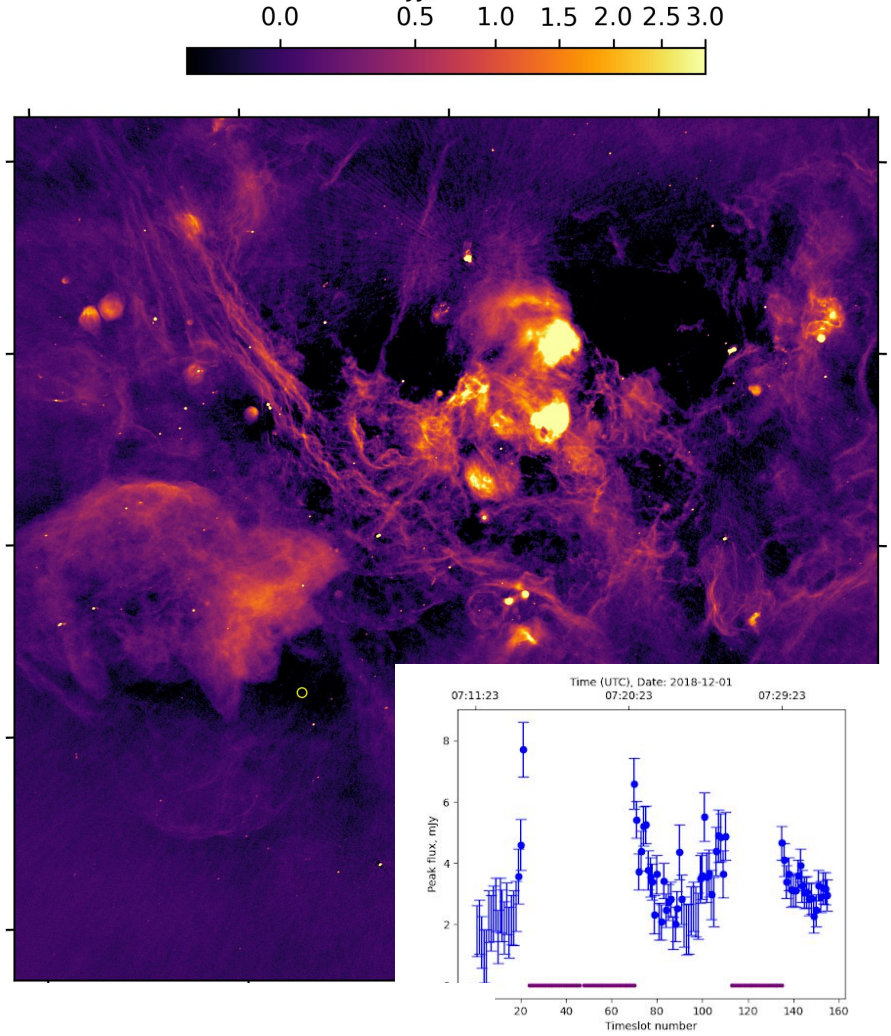
O M Smirnov, A Golden, T Myburgh, B Ngcebetsha, C Tasse, I Heywood, A J T Ramaila, M A Thompson, J S Kenyon, S J Perkins ... Show more

Monthly Notices of the Royal Astronomical Society: Letters, slaf015,
https://doi.org/10.1093/mnrasl/slaf015
Published: 05 February 2025

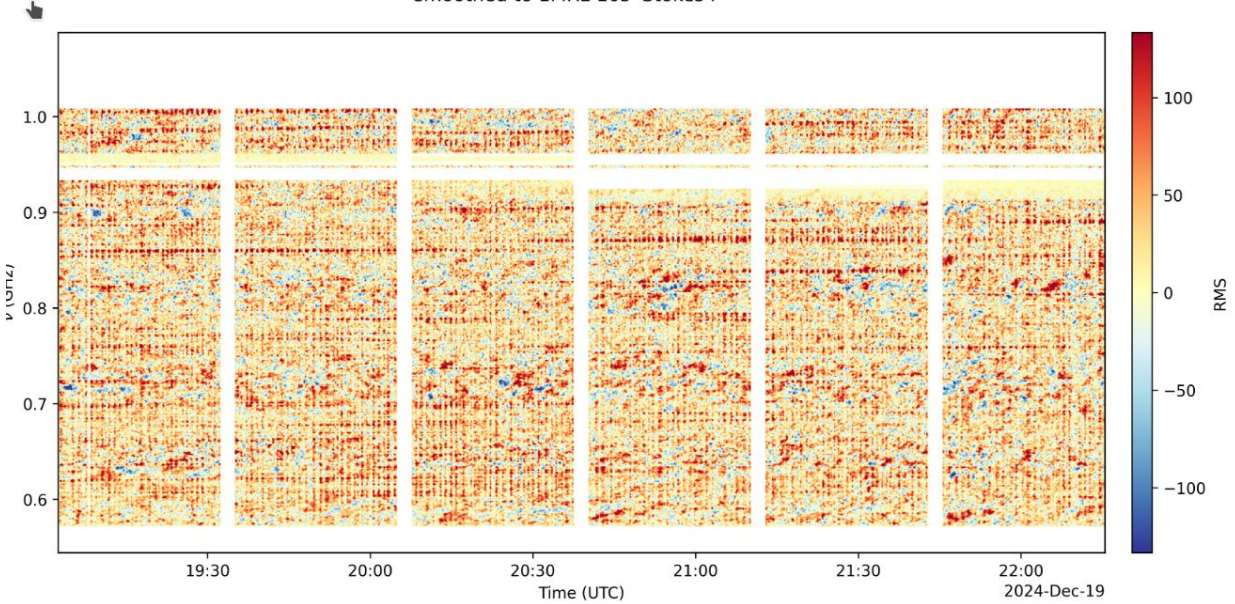
The Coy M-dwarf

- Athanaseus Ramaila: reprocessing SARAO MeerKAT Galaxy Plane Survey to make deeper images
- Picked up flare from a young M-dwarf ~20 pc away
- Candidate exoplanetary system





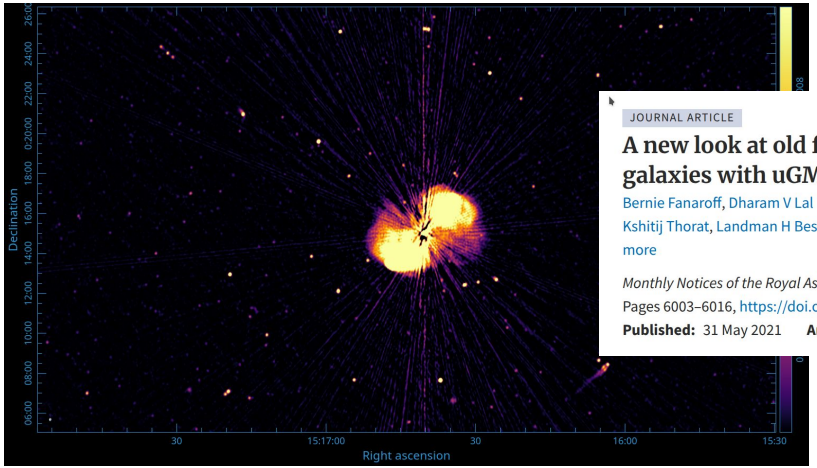
PARROT II?



- Another very odd pulsar detected in 2019 imaging data
- 2024 follow up with UHF + pulsar timing
- 0.5s pulsar
  - plus very stable periodic (~5s) dropouts
  - plus quasi-periodic bursts (55-65s)
  - plus very puzzling scintillation signature switching on timescales of ~hours
- More questions than answers at this point
  - Does suggest our search algorithms are biased towards the weird and the wonderful

The Curious Case Of The Stubborn Old Devil

- “Old Devils” – MeerKAT (First) Open Time Call – observations of four bright radio galaxies
- One of the devils (CGCG021-063) refused to image at a decent dynamic range, no matter how hard I tried



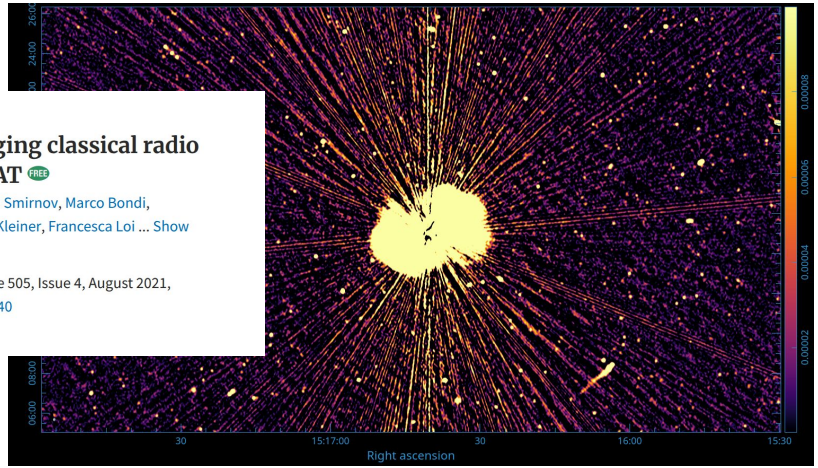
JOURNAL ARTICLE

A new look at old friends – I. Imaging classical radio galaxies with uGMRT and MeerKAT FREE

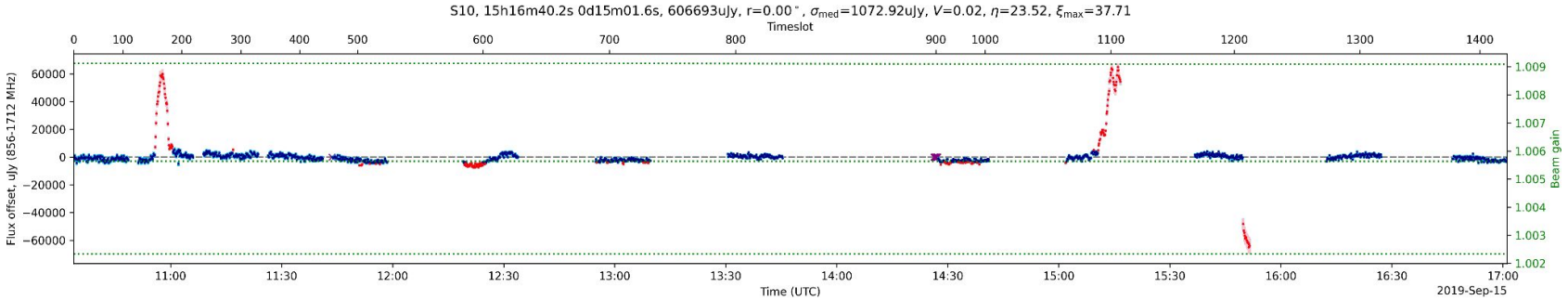
Bernie Fanaroff, Dharam V Lal ✉, Tiziana Venturi, Oleg M Smirnov, Marco Bondi, Kshitij Thorat, Landman H Bester, Gyula I G Józsa, Dane Kleiner, Francesca Loi ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 505, Issue 4, August 2021, Pages 6003–6016, https://doi.org/10.1093/mnras/stab1540

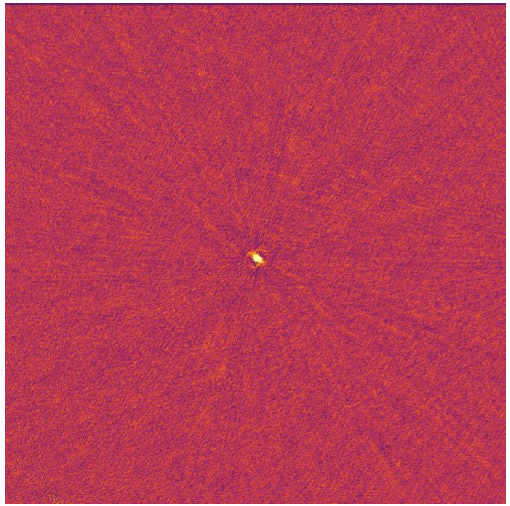
Published: 31 May 2021 **Article history** ▾

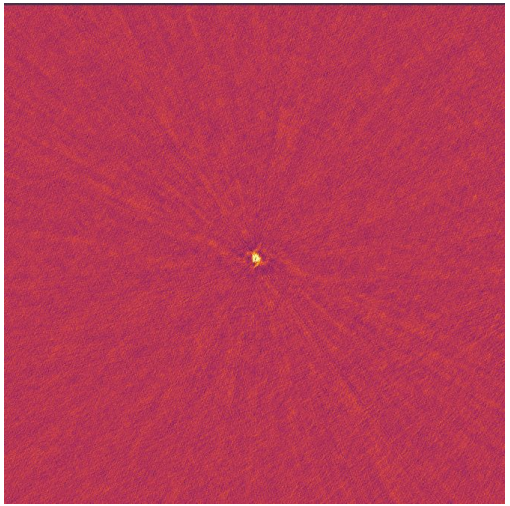


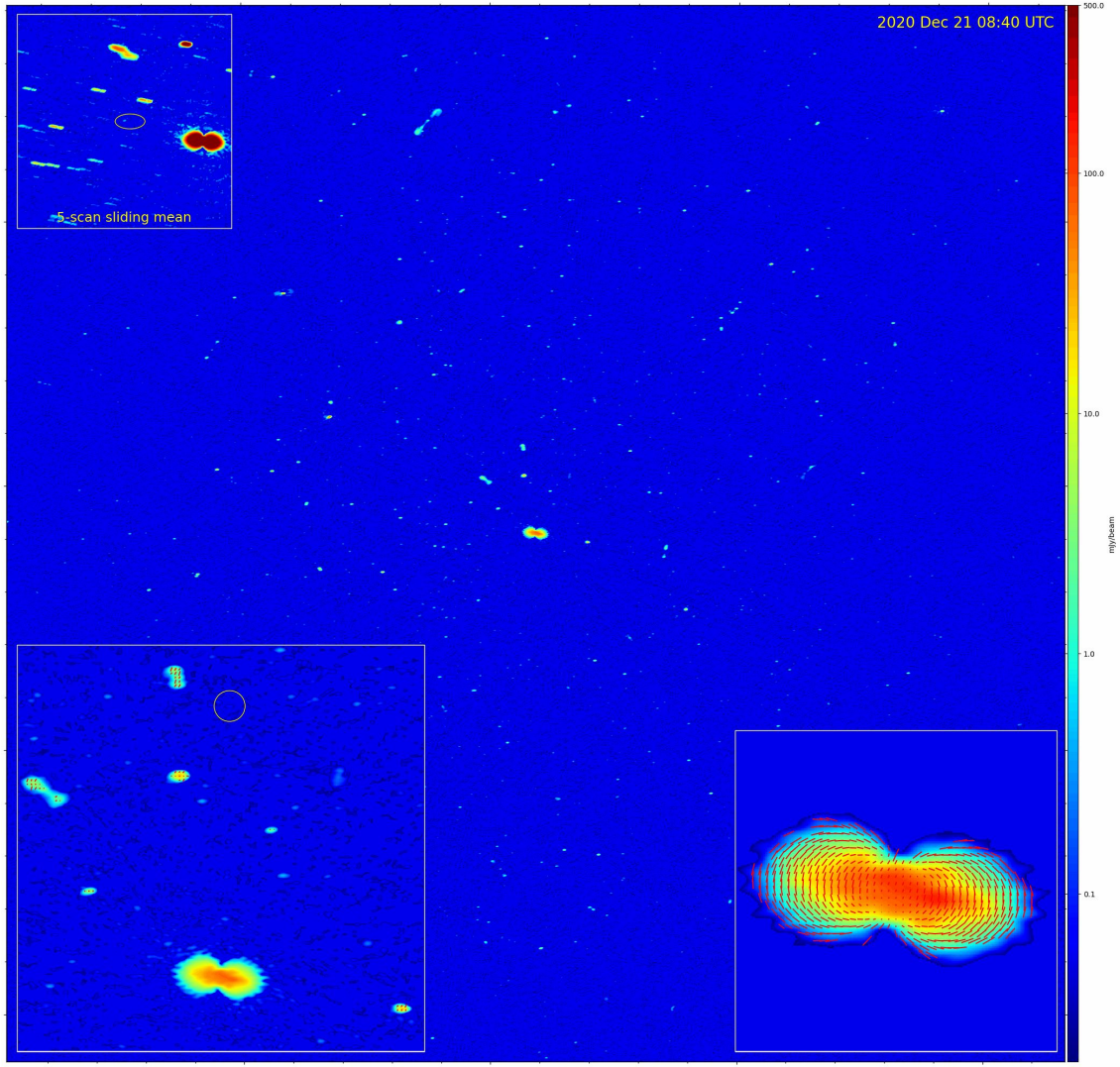
Is It a Bird? Is It a Plane? Is It a Variable AGN Core?



- No, just Galileo in this case
- Bad luck – but also deterministic, really…
- Need tools to deal with this better!
- (See also SMGPS example)





Conclusions

- MeerKAT's sensitivity makes it uniquely suited for serendipitous transient discoveries
- Dynamic imaging is hard, but can be made to work with some effort – which is well worth it
  - and can also improve regular imaging!
- TRON is ramping up – stay tuned for more results