Radio Transients

ISSS: “Frontend research at low radio frequency
Radio astronomy:
Science and technical challenges”

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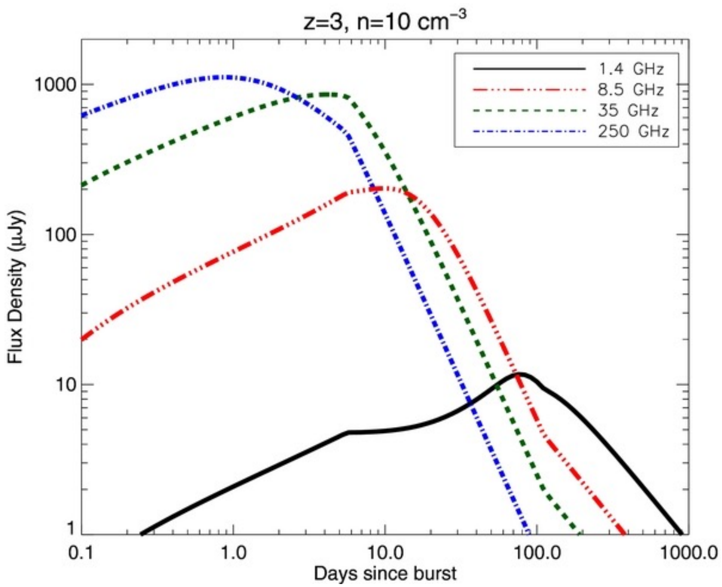
UNIVERSITEIT VAN AMSTERDAM
ASTRON
Netherlands Institute for Radio Astronomy
LOFAR

What are we looking for?

Two Categories of Emission

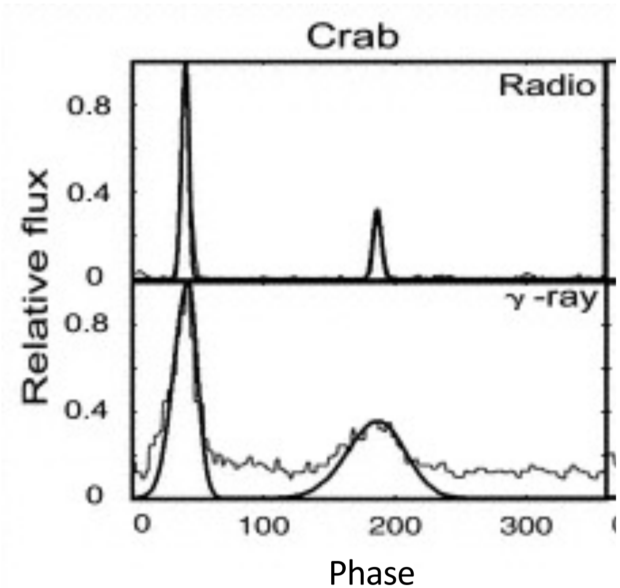
Incoherent

- Synchrotron or thermal sources
    - Slow and faint
- E.g. GRBs



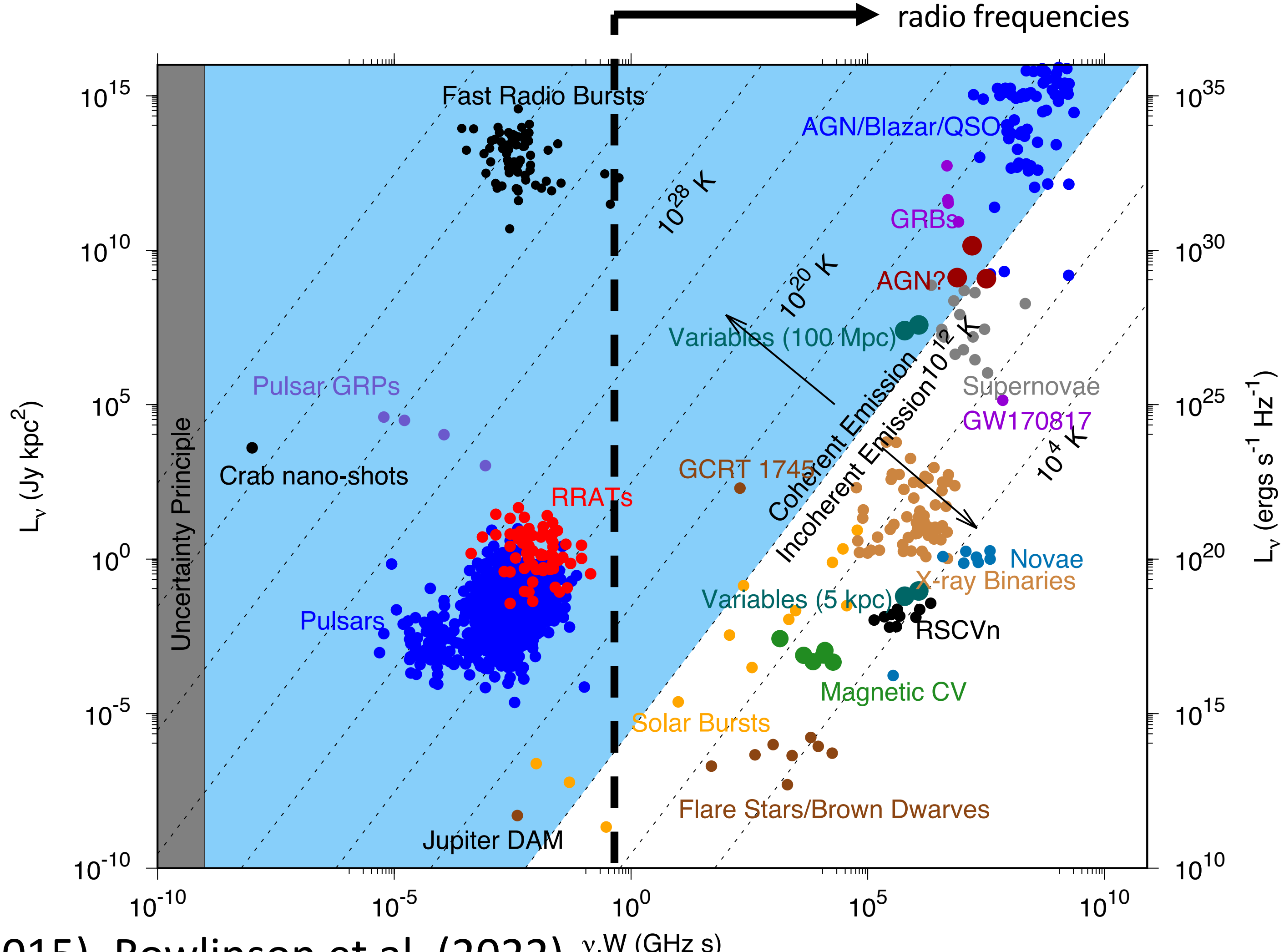
Coherent

- Electrons in emitting region emit in phase, e.g. MASER
- Fast variability and bright
- E.g. Pulsars



Radio Transient Populations

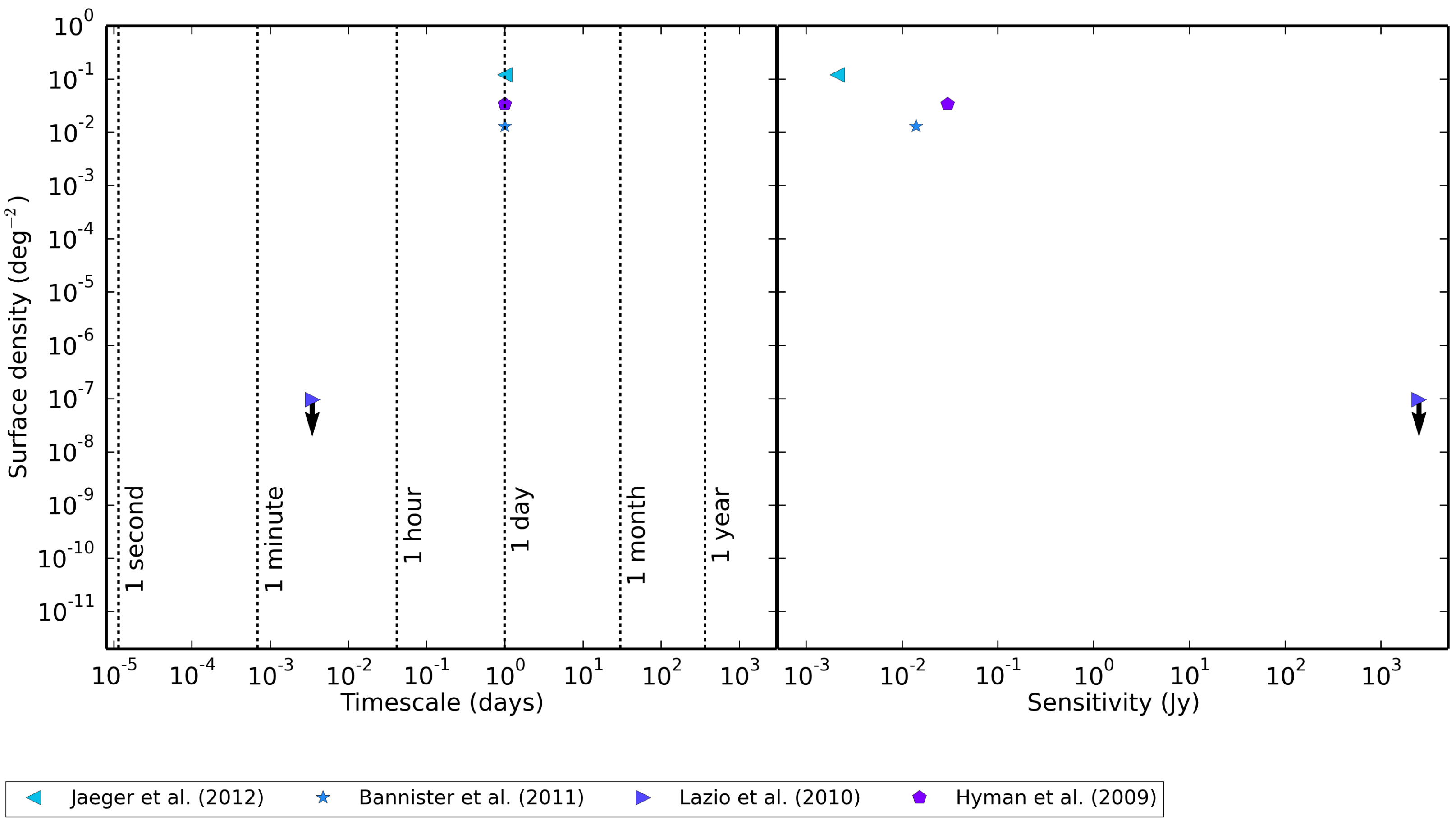
Image plane surveys at low radio frequencies



Pietka et al. (2015), Rowlinson et al. (2022)

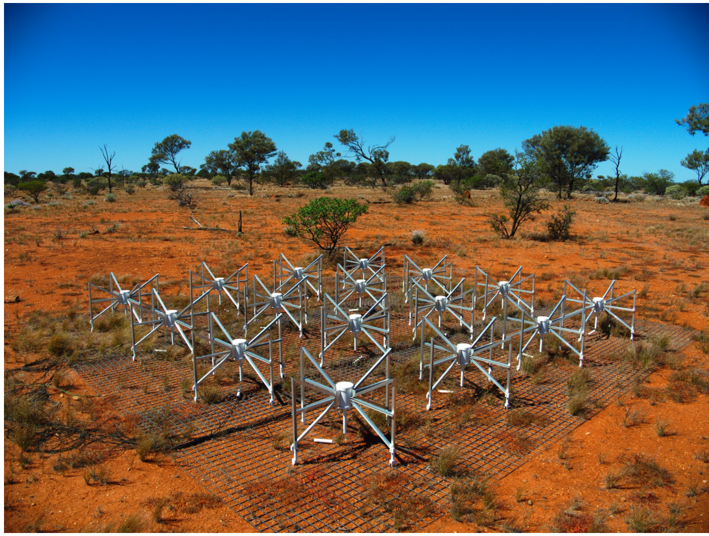
Image plane searches for transient and variable sources

Transient surveys <1 GHz prior to 2014



New telescopes facilitating transient hunts

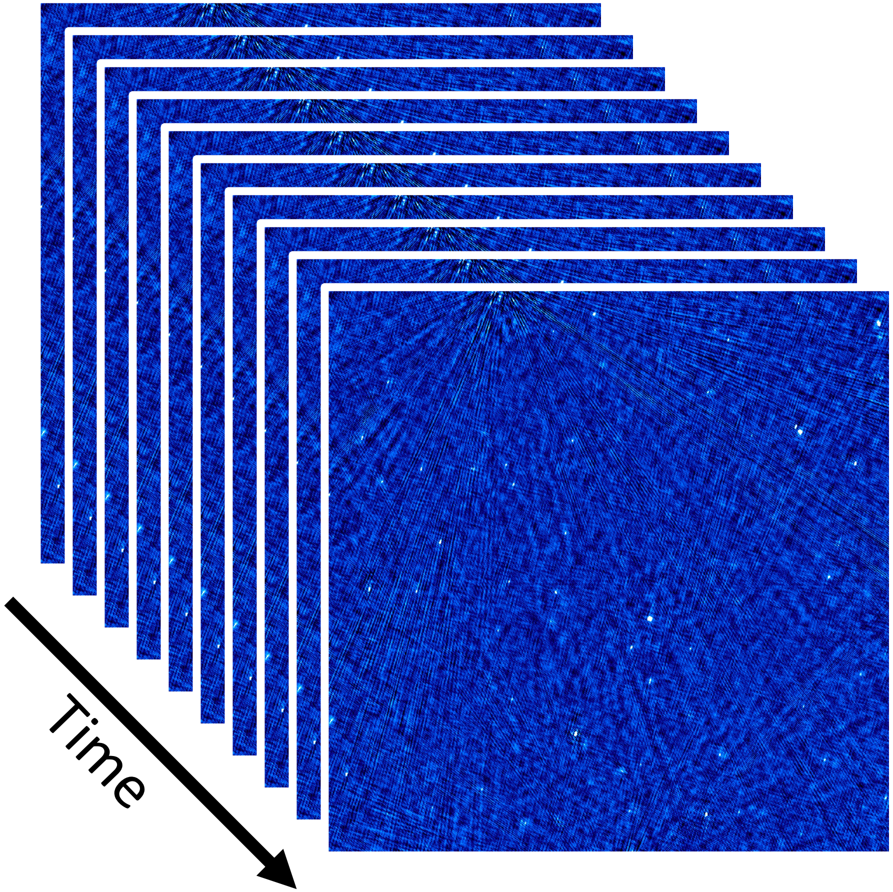
LOFAR



MWA

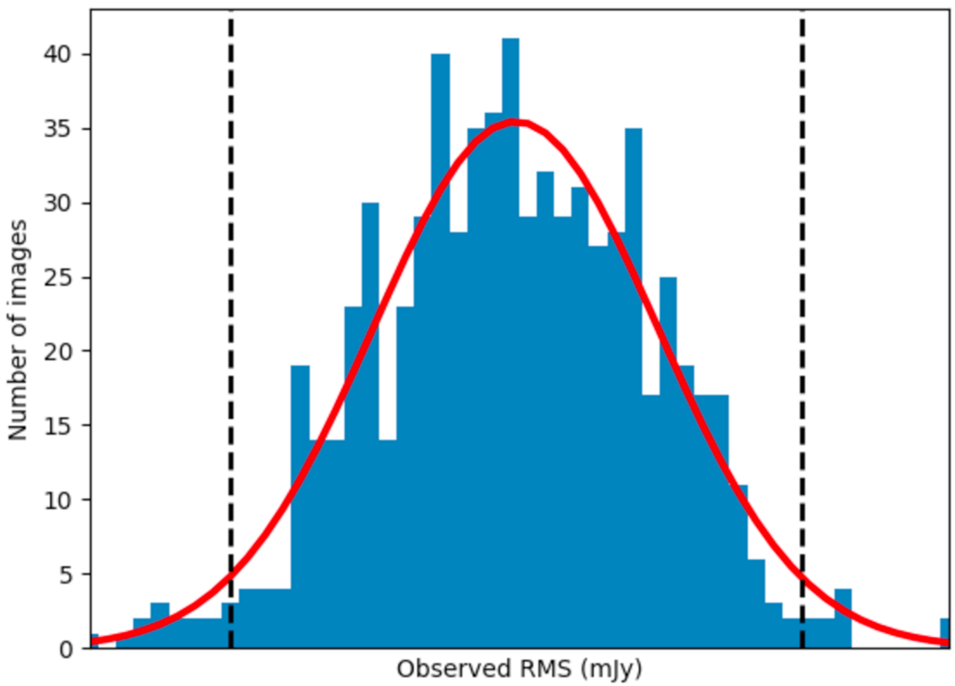
Imaging strategies

- Snapshot imaging in time and frequency
- Standard options for WSClean (imager often used for LOFAR & MWA)



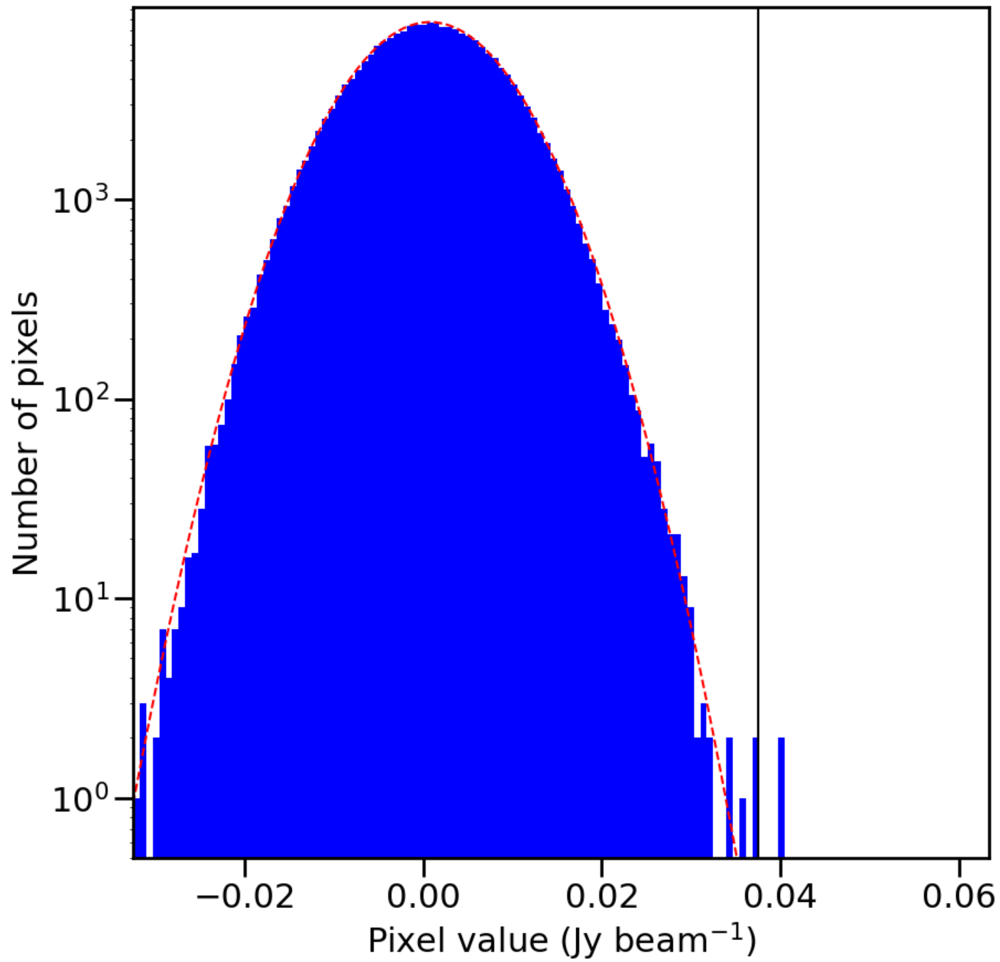
Imaging strategies

- Bad images in → many false positives
- Simple rms noise clipping is effective, throw away any images that are particularly noisy



Imaging strategies

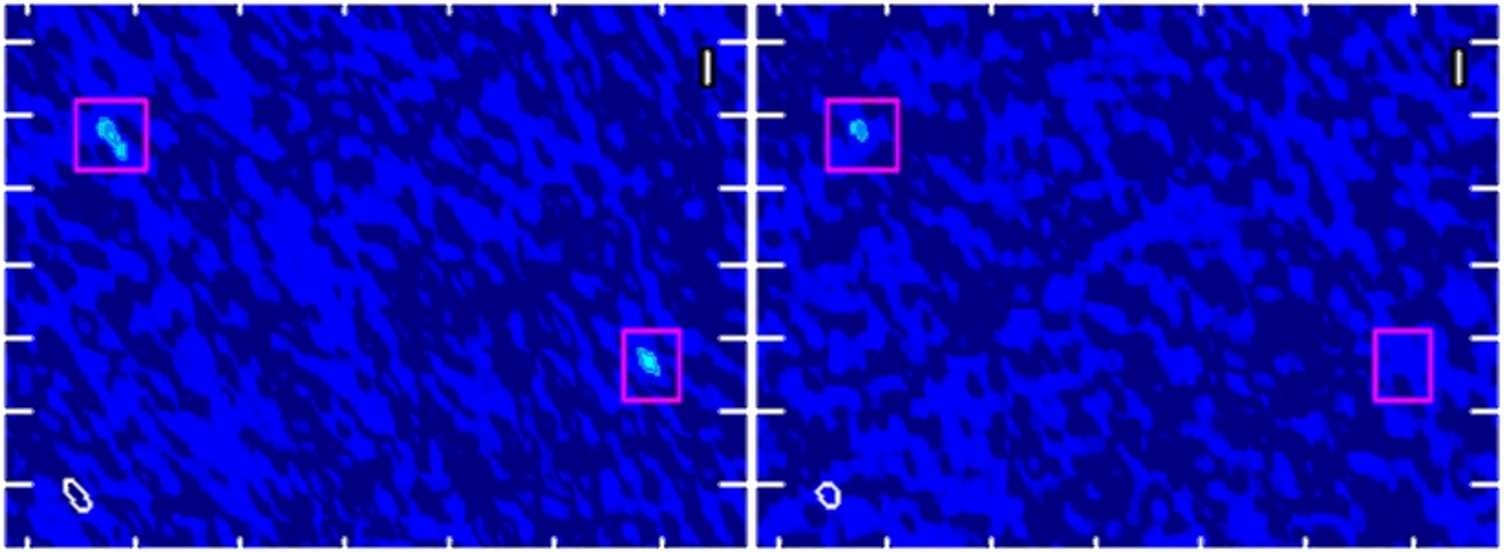
- Optimising the detection threshold
- Want to minimise false positives but maximise detections
- Fit all pixels in all images with a Gaussian distribution
- Require <1 false positive detections due to noise fluctuations in all of your images



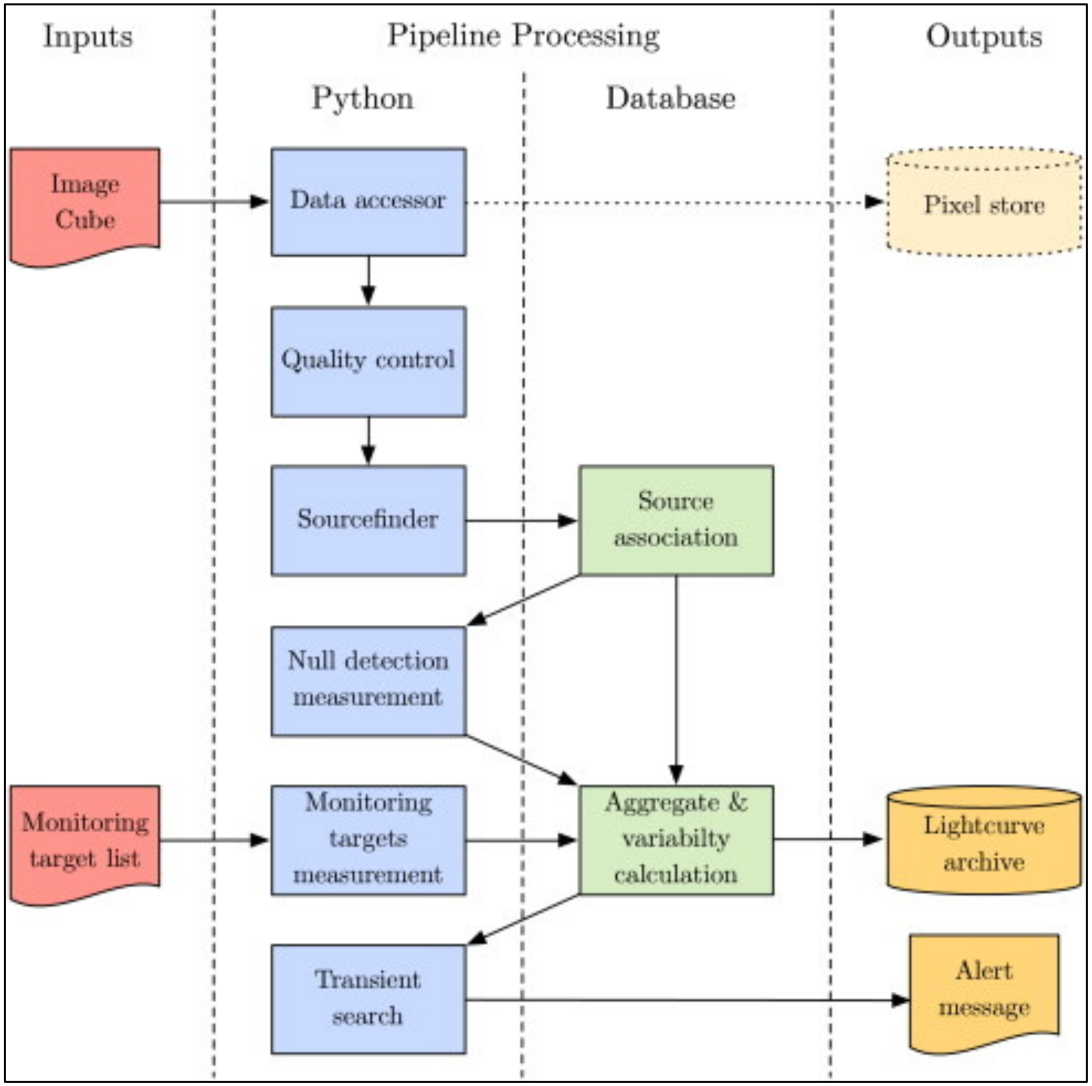
e.g. Rowlinson et al. (2022)

Transients Pipeline (TraP)

- Simple in concept, challenge is in data volume and processing speed
- Datasets can have more than
  - 1,000 unique sources
  - 10,000 images
  - 100,000 individual source extractions



Transients Pipeline (TraP)



- Publicly available: https://github.com/transientskp/tkp
- Well documented: https://docs.transientskp.org
- Example tools for interacting with database: https://github.com/transientskp/TraP_tools

Swinbank et al. (2015)

Variability Parameters

Reduced weighted χ^2:

$$\eta = \frac{N}{N-1}\left(\overline{w\,I^2} - \frac{\overline{w\,I}^2}{\overline{w}}\right)$$

Coefficient of Variation:

$$V = \frac{s}{\overline{I}}$$

Where:

N = number of images

ω = flux density uncertainty

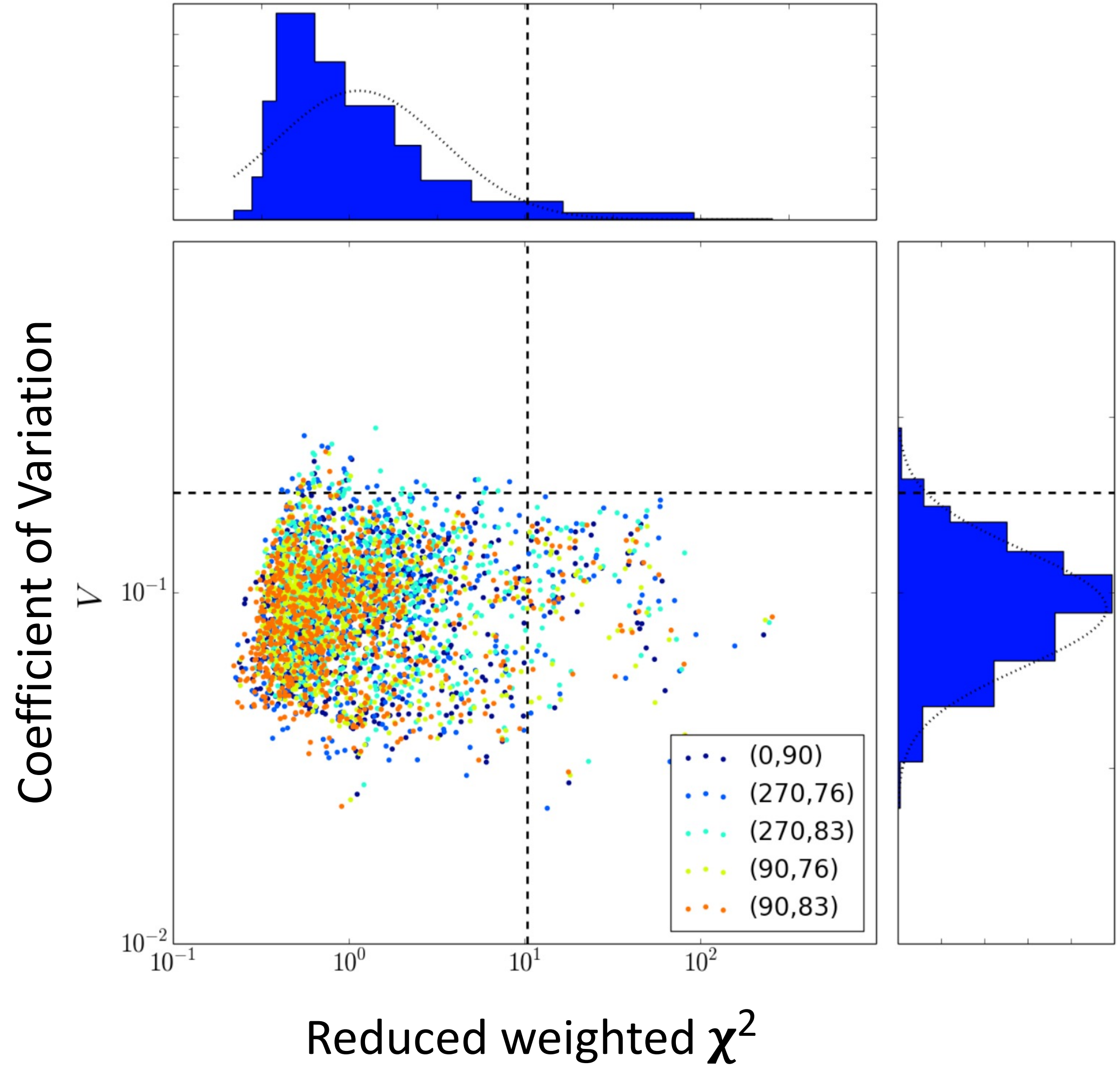
I = flux density

s = standard deviation of flux densities

Swinbank et al. (2015)

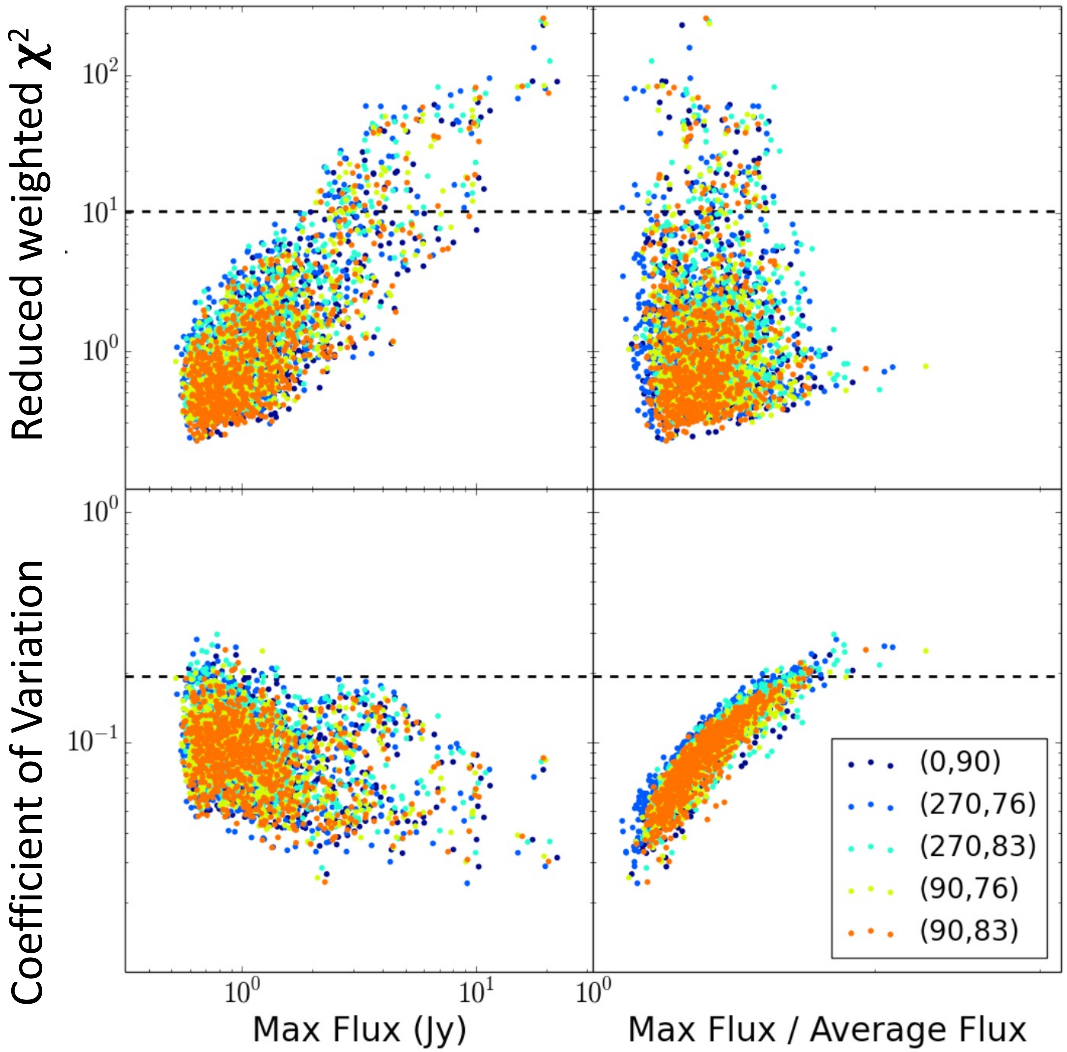
TraP examples: MWA

- 10,122 epochs at 150 MHz
- 28 second cadence
- 2$\boldsymbol{\sigma}$ threshold on variability parameters
- No transient or variables found



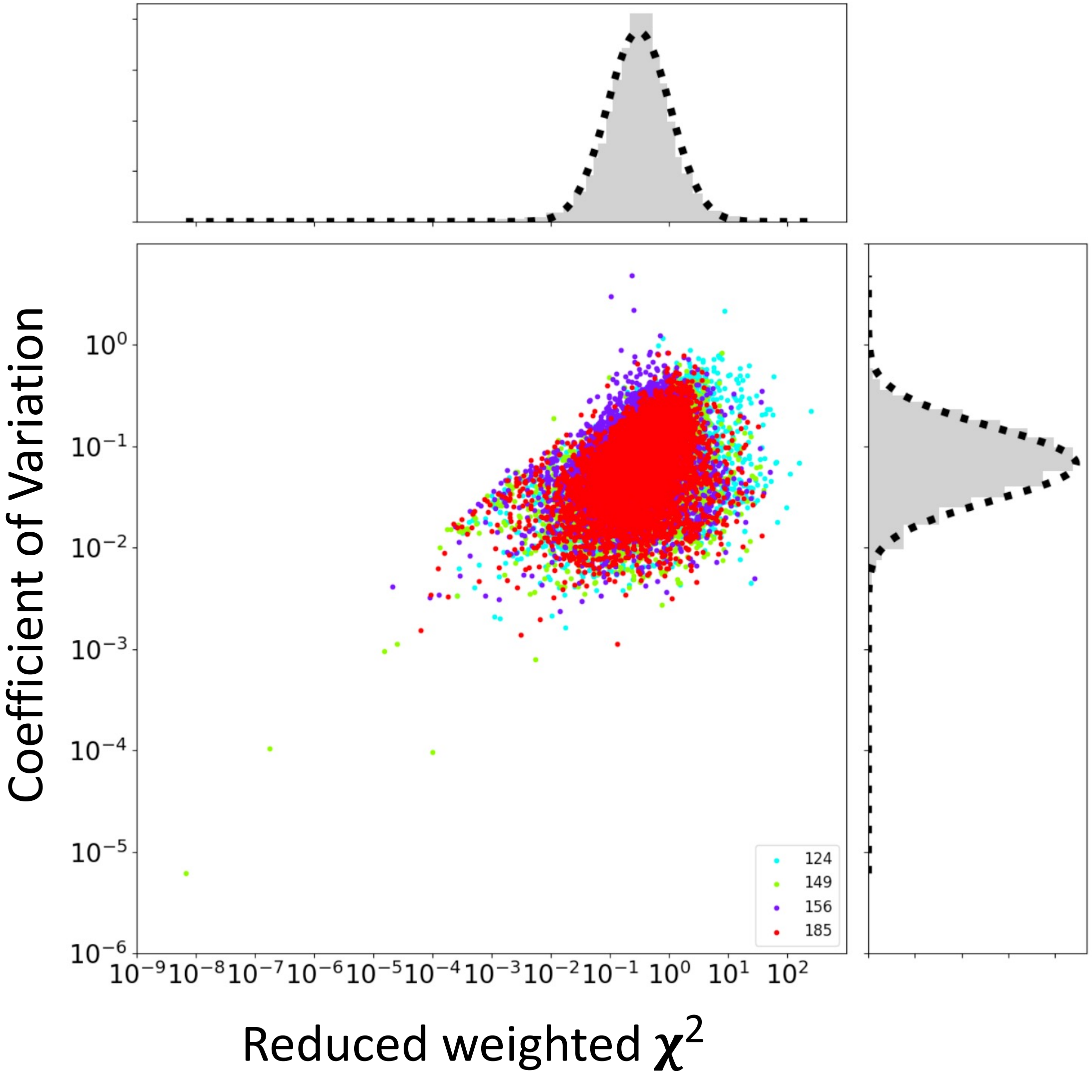
Rowlinson et al. (2016)

TraP examples: MWA



Rowlinson et al. (2016)

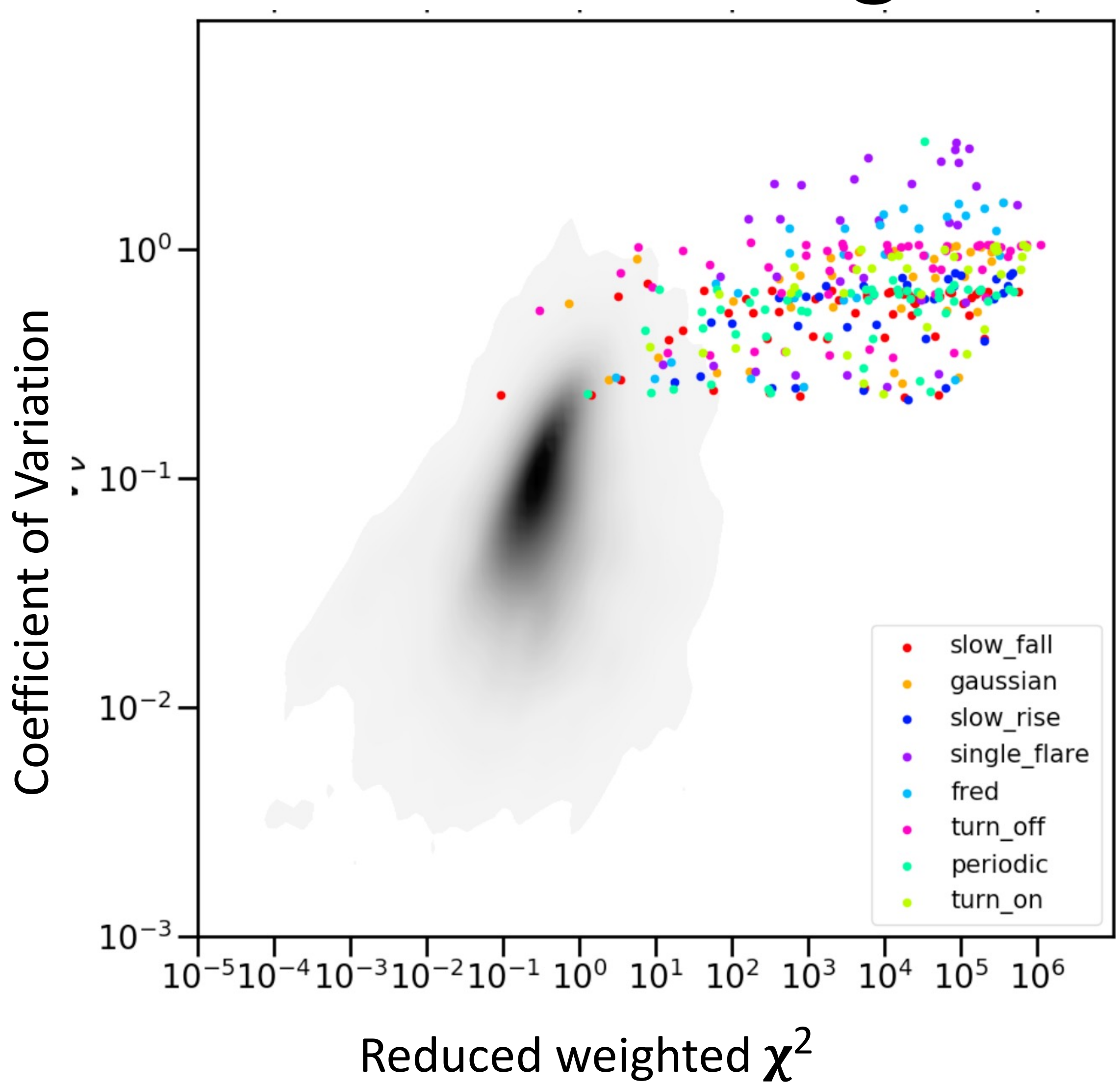
Machine learning with the TraP



- LOFAR transient survey
- 12 epochs at 150 MHz
- Monthly cadence

Rowlinson et al. (2019)

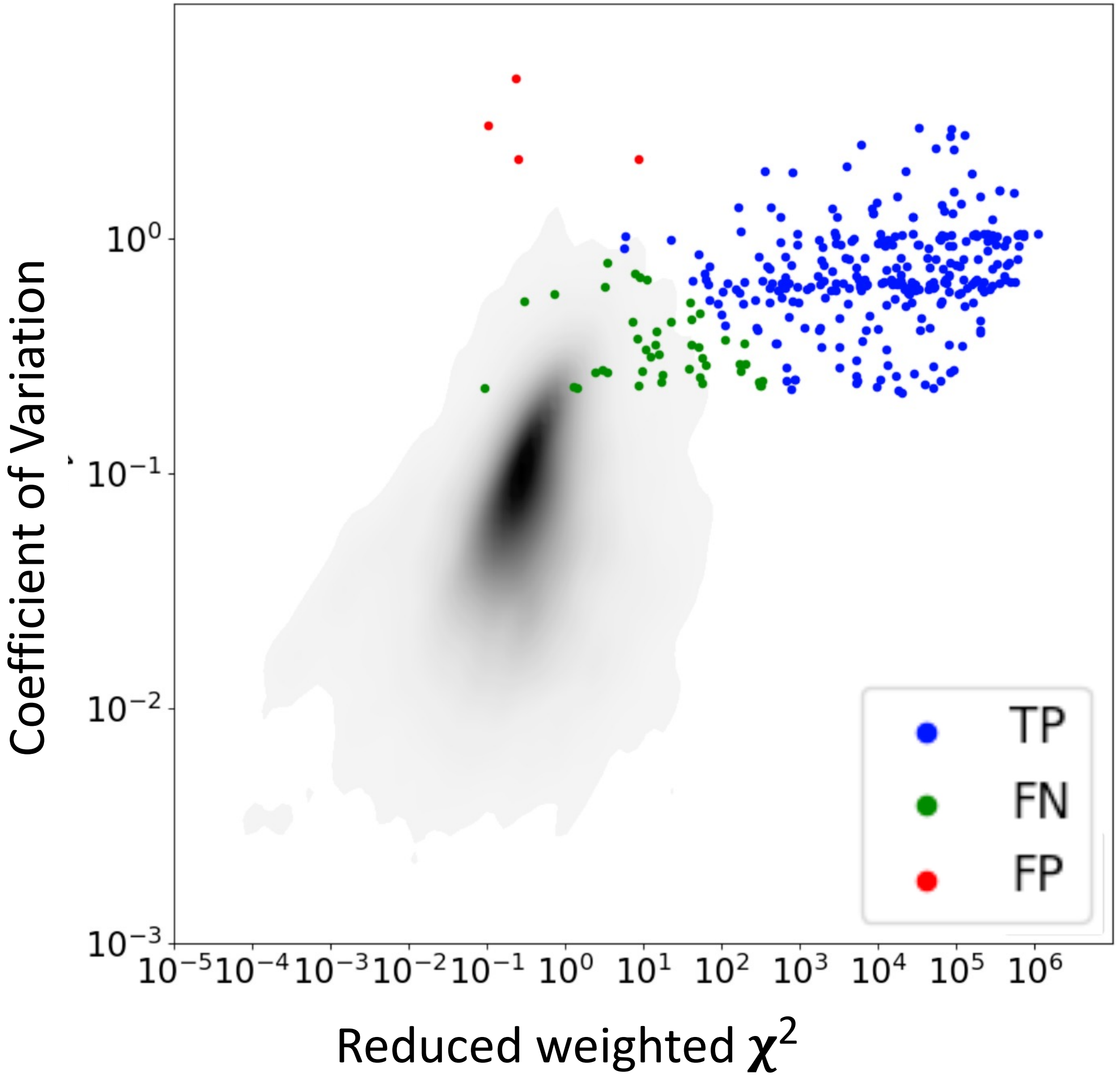
Machine learning with the TraP



- Training data:
- Simulated transient and variable sources
- Assume all real sources are stable

Rowlinson et al. (2019)

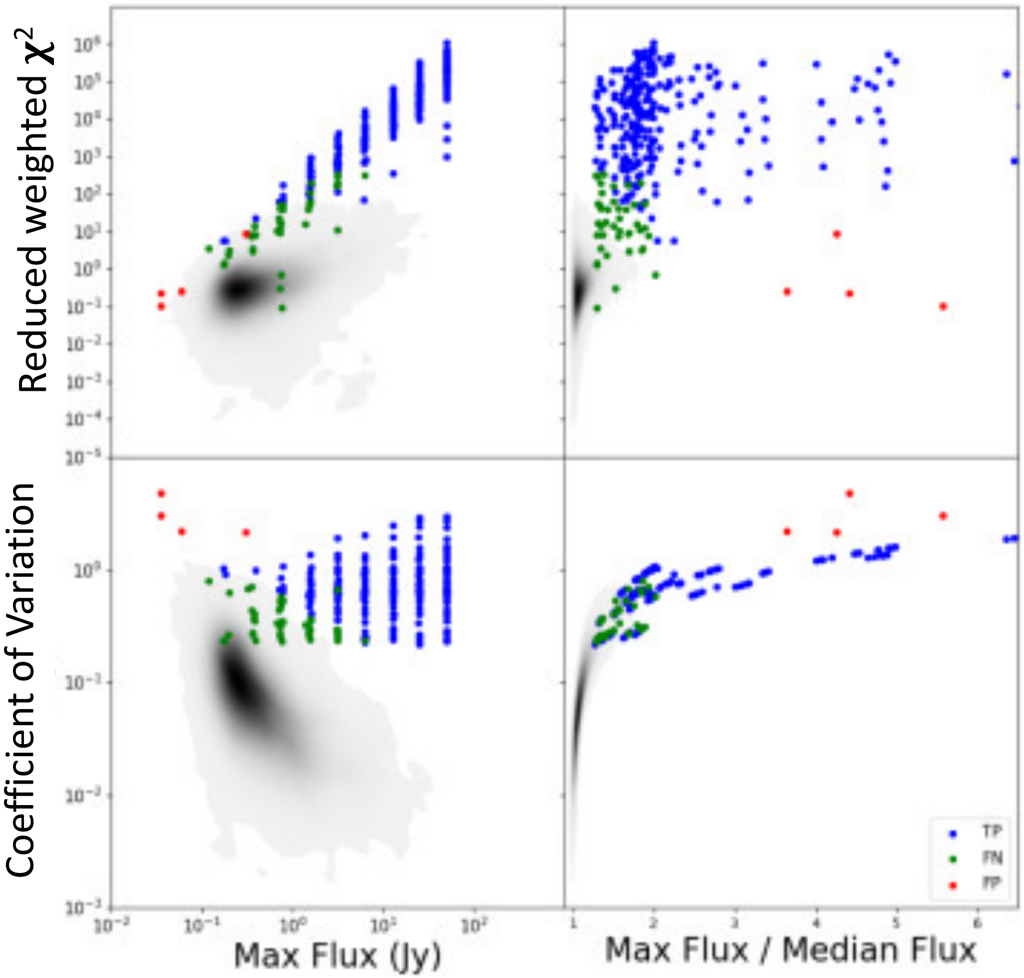
Machine learning with the TraP



- Classification using a logistic regression algorithm
- Other strategies also considered
- Code available here: https://github.com/AntoniaR/TraP_ML_tools

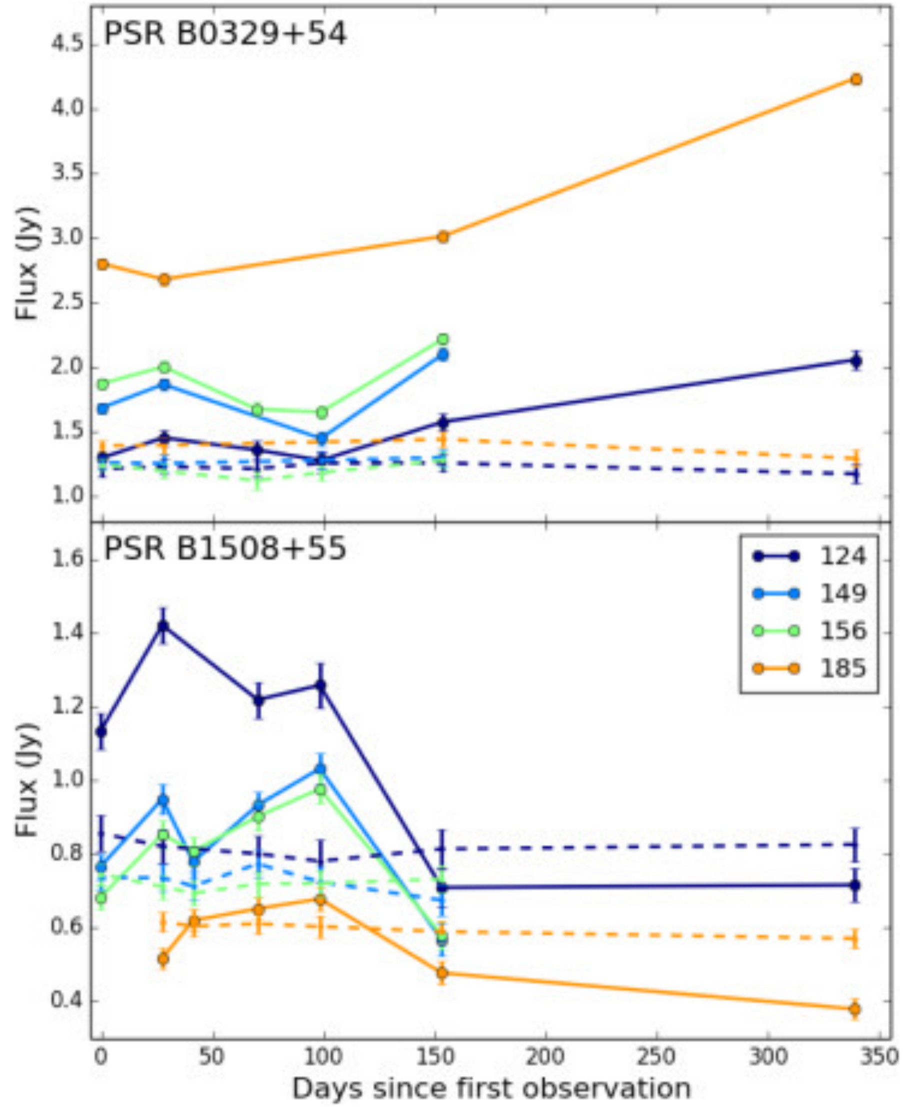
Rowlinson et al. (2019)

Machine learning with the TraP



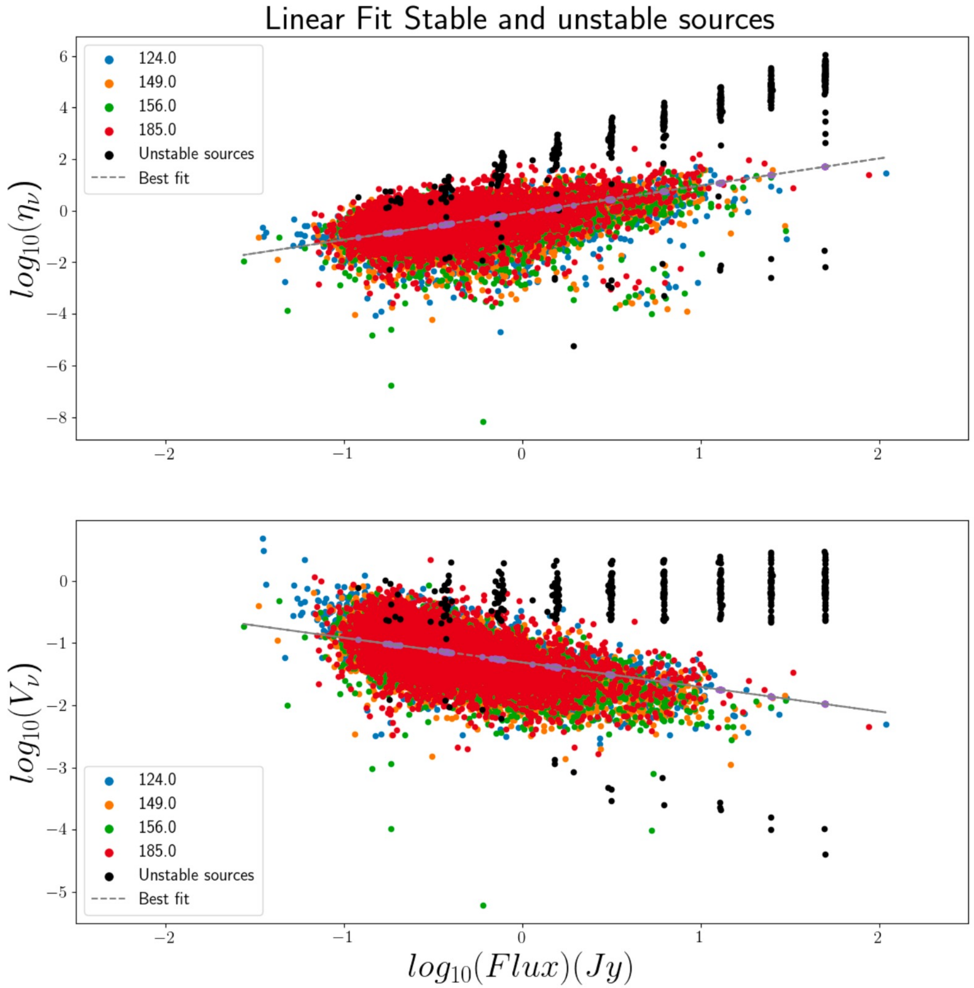
Rowlinson et al. (2019)

Machine Learning with TraP



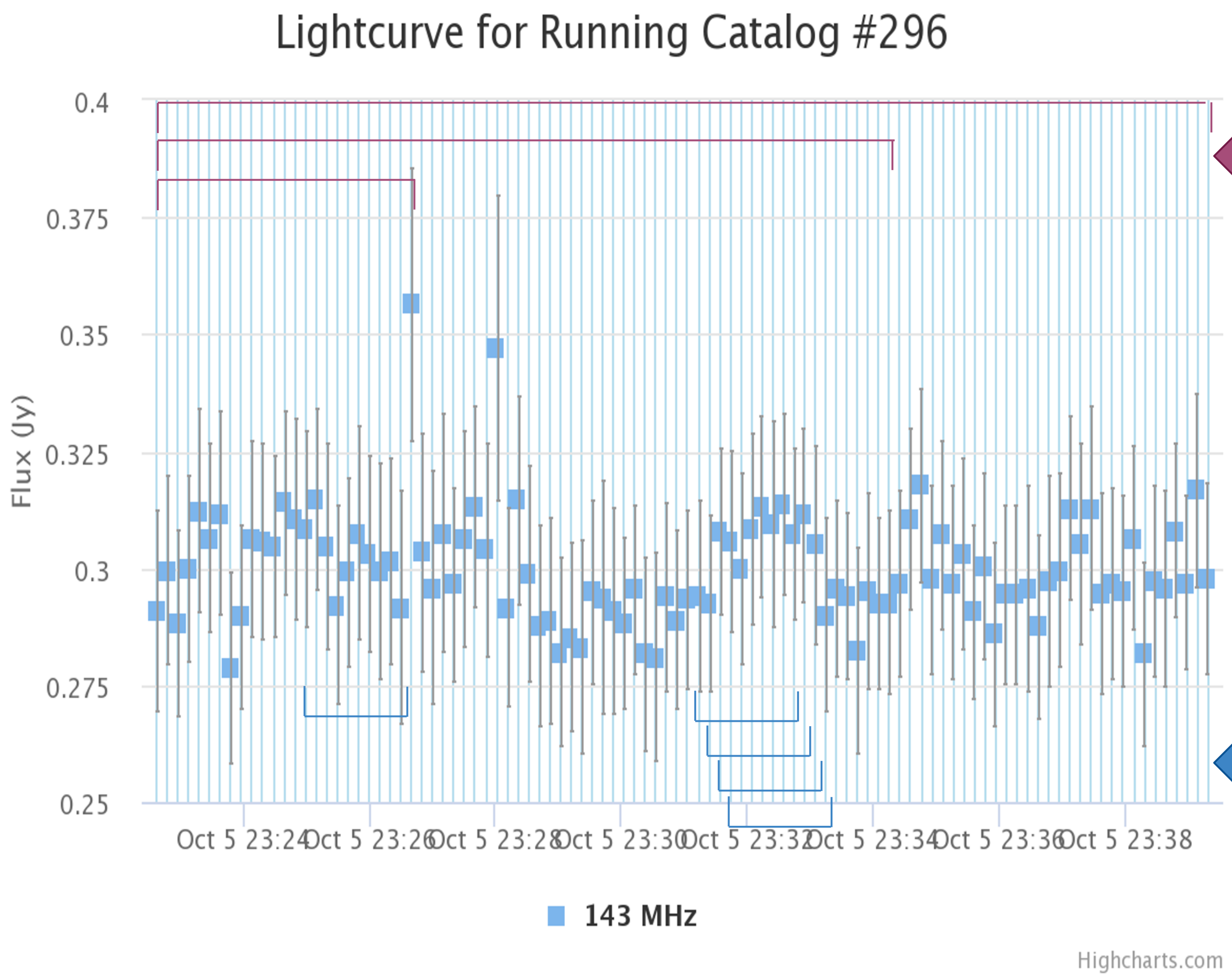
Rowlinson et al. (2019)

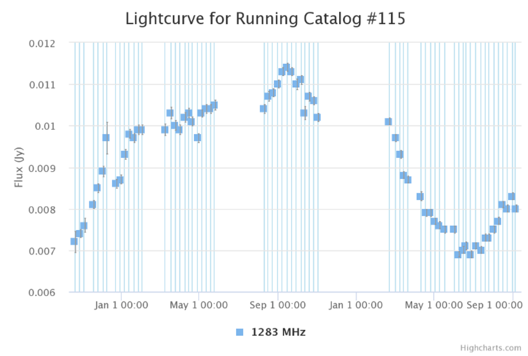
Interpreting variability parameters



Credit: Ruggero Valdata

Using a moving average method:





Credit: Sander Heimans

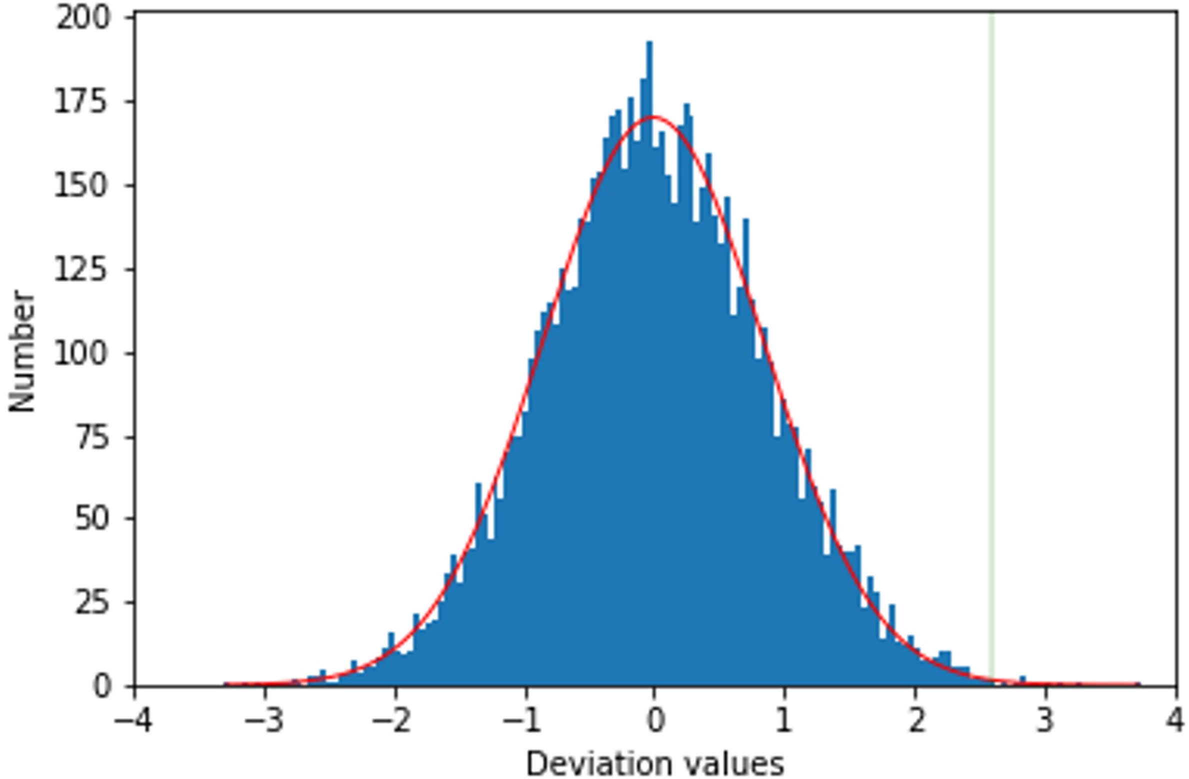
Using a moving average method:

Moving Average Equation

$$MA_i = \sum_{j=1}^{WINDOW\_SIZE} \frac{f_{int,[i-j]}}{WINDOW\_SIZE}$$

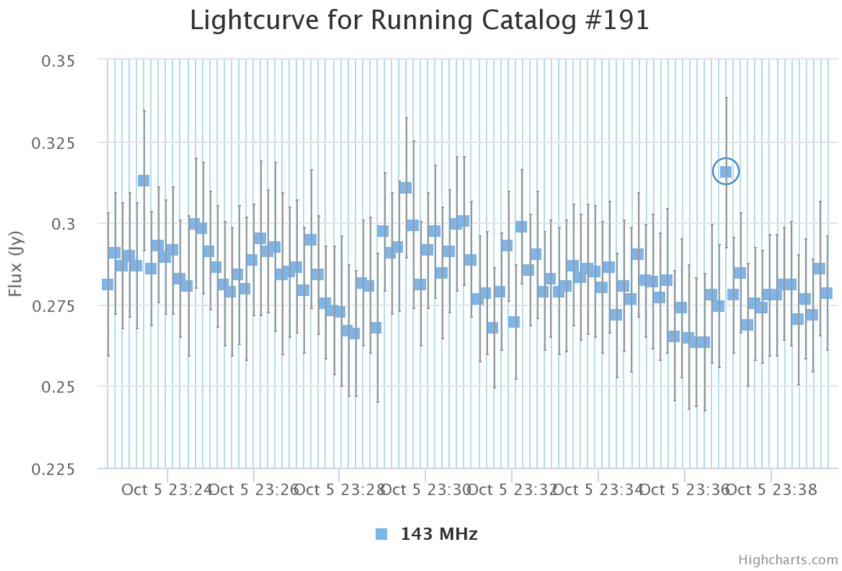
Deviation from the Moving Average

$$\Delta_i = (f_{int,i} - MA_i) \Big/ \sigma_f ,$$

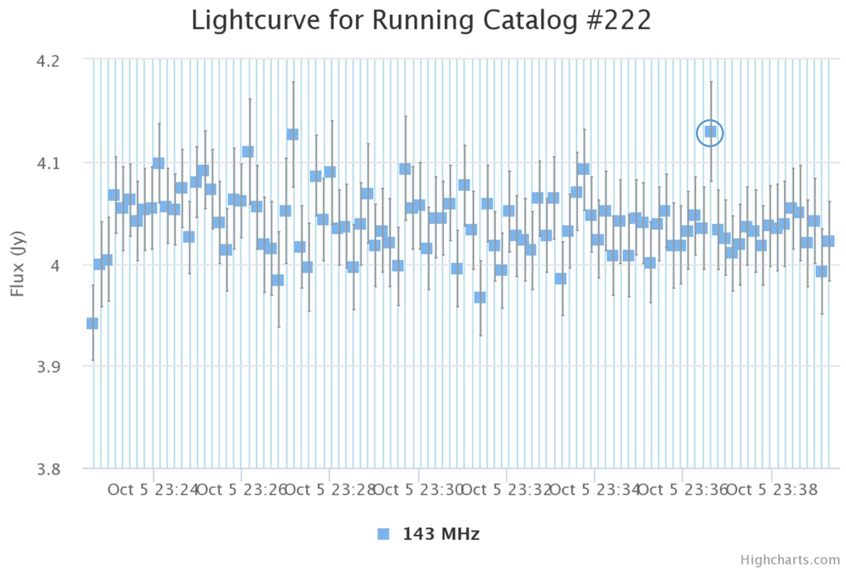


Credit: Sander Heimans

Using a moving average method:



NVSS J035705+650615

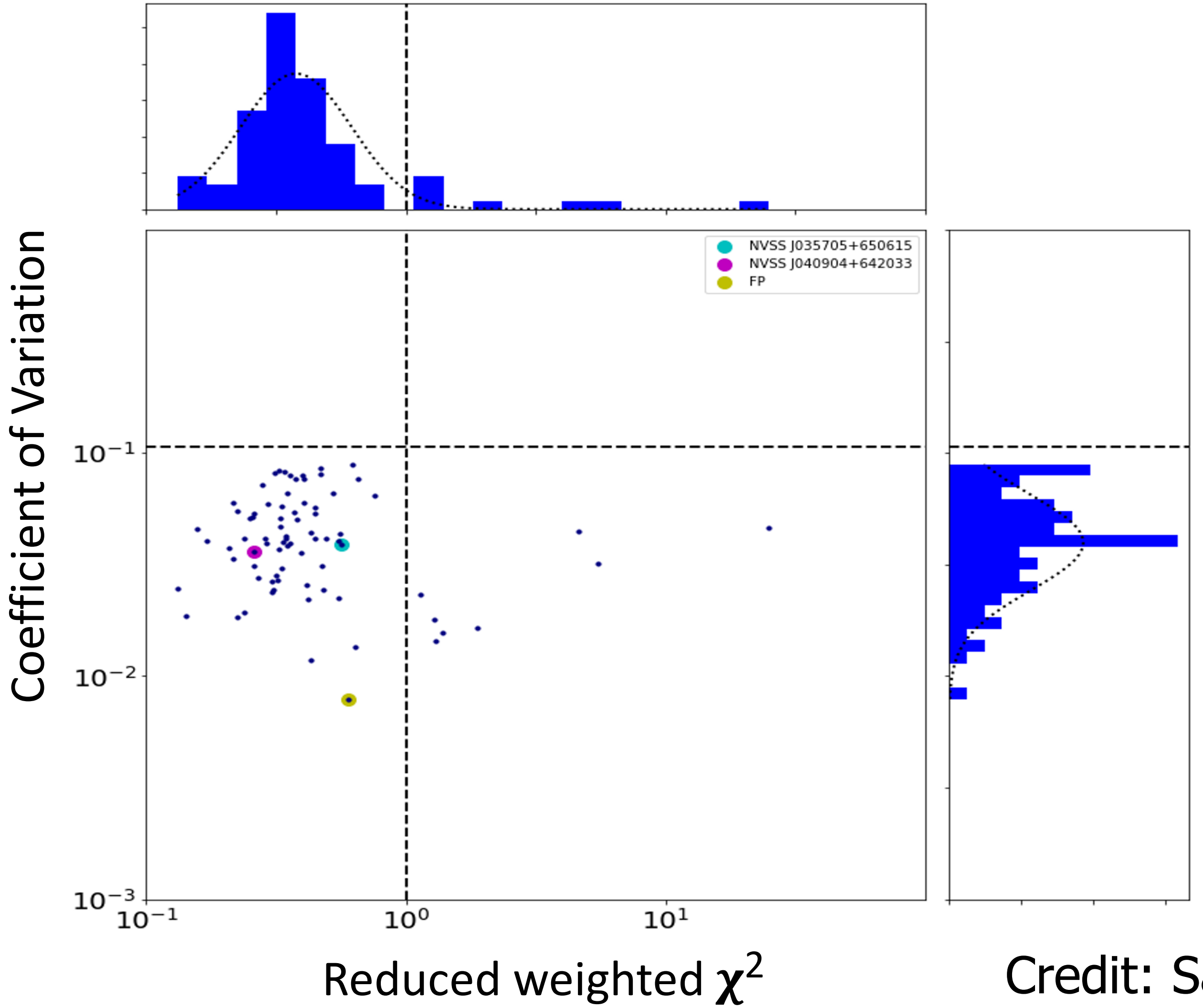


NVSS J040904+642033

- Candidates from LOFAR dataset of 10 second snapshot images
- Pulsar giant flares?

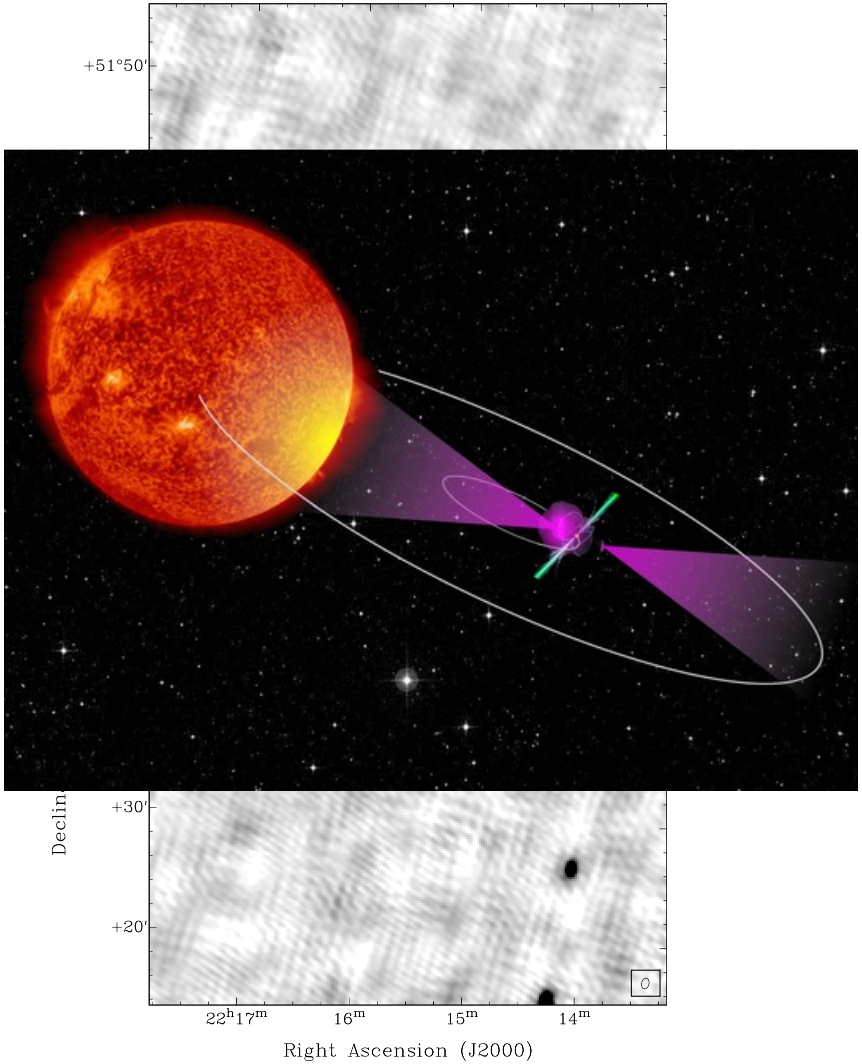
Credit: Sander Heimans

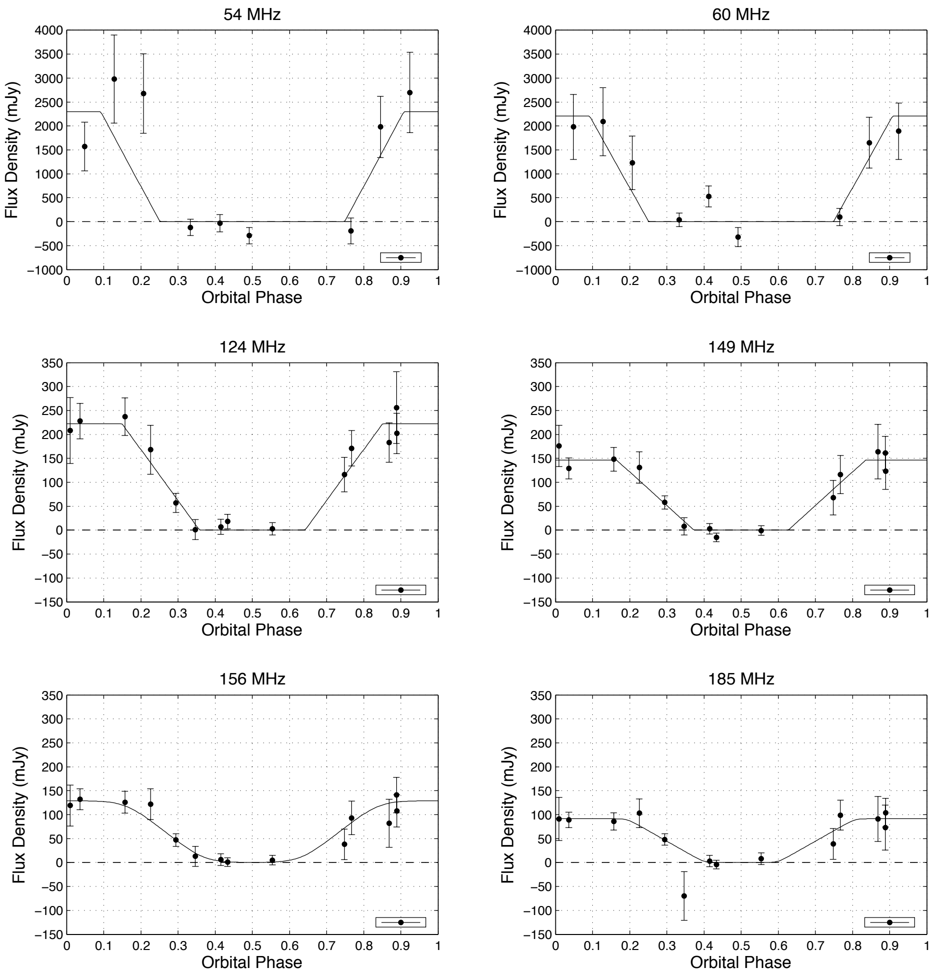
Using a Moving Average method:



Credit: Sander Heimans

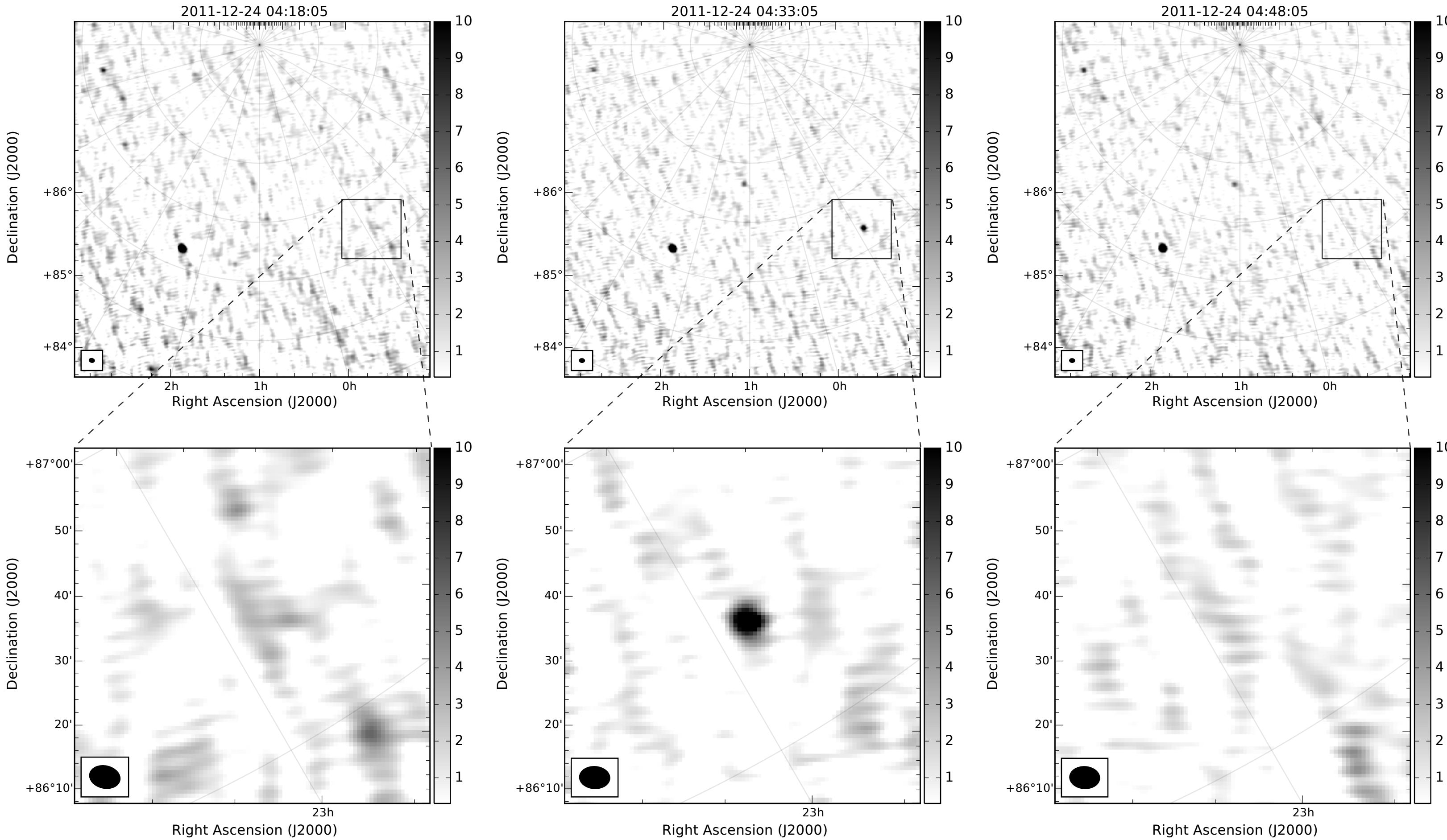
Redback pulsar J2215+5135





Broderick et al. (2016)

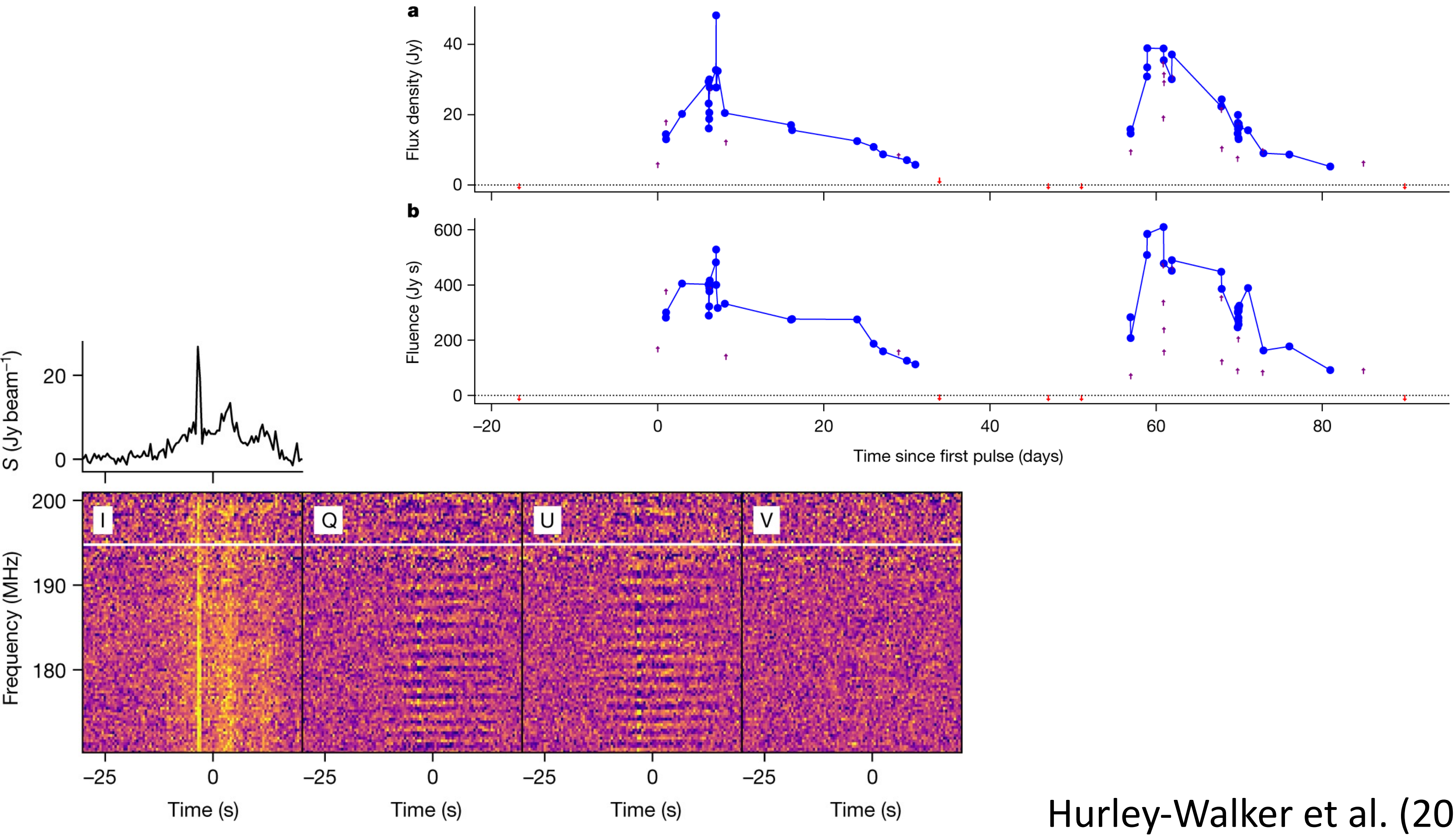
The first low frequency transient



Frequency 57 MHz
Duration ~4 minutes

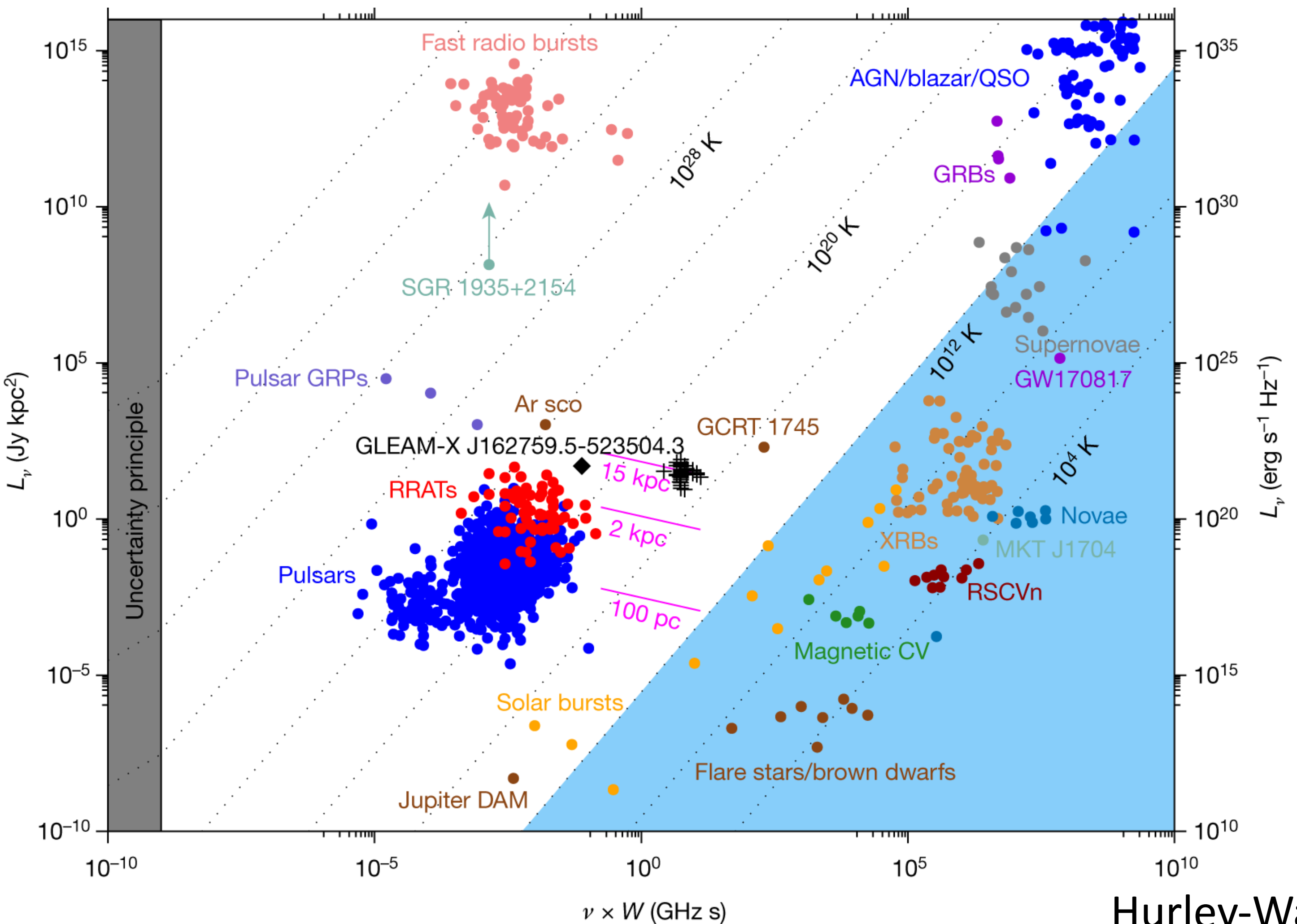
Stewart et al. (2016)

MWA periodic source – magnetar?



Hurley-Walker et al. (2022)

MWA periodic source – magnetar?



Hurley-Walker et al. (2022)

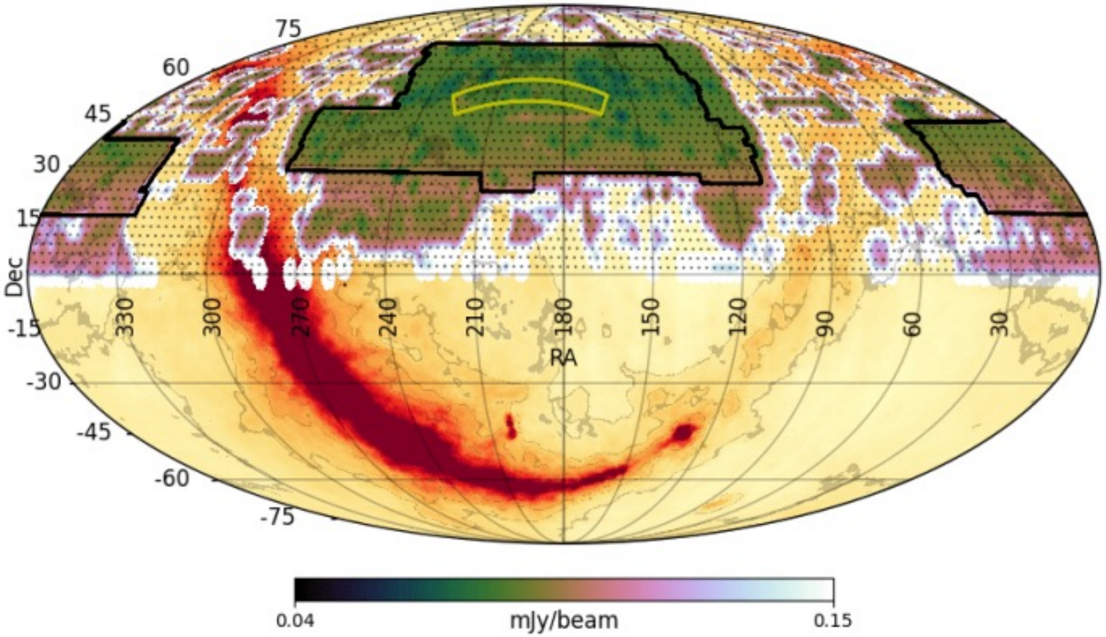
LOFAR survey of the Northern sky

- 6" resolution
- 83 µJy/beam rms noise
- 144 MHz

DR1 (Shimwell et al. 2019)

DR2 (Shimwell et al. 2022)

8 hour pointings



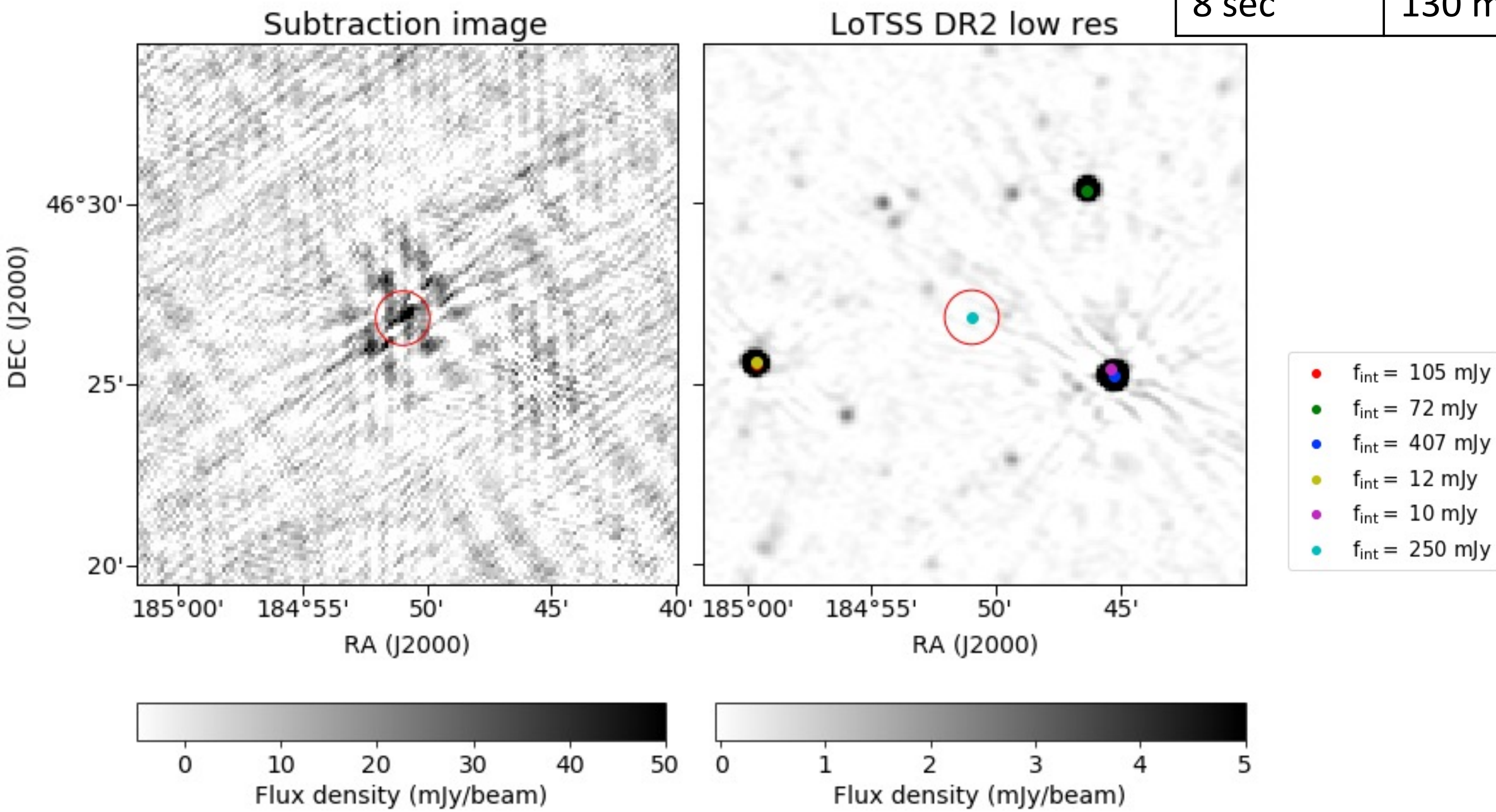
Subtraction imaging

- Timesliced imaging of just one field (8sec, 2min and 1hr timescales) takes at least 500 hours
- DR1 has 58 fields → takes entire duration of NL PhD contract!
- Reduce imaging time by subtraction imaging:
  - Create deep image of field and associated sky model
  - Subtract sky model from visibilities
  - Image snapshots with no cleaning and no primary beam correction
- Subtraction imaging → 15 hours per field

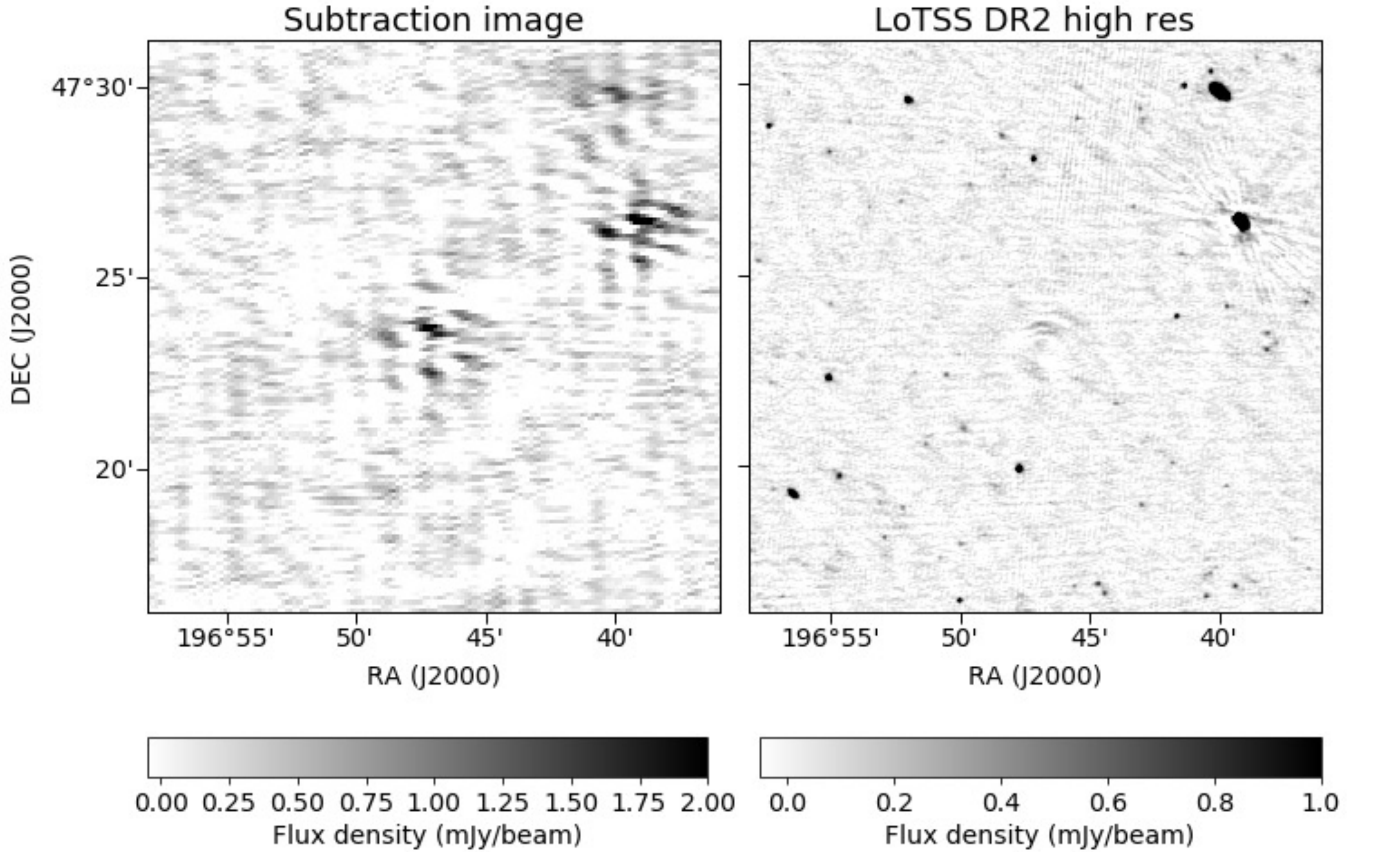
de Ruiter et al. (in prep)

Simulations of transients

	Sensitivity (mJy)
1 hour	6 mJy
8 sec	130 mJy



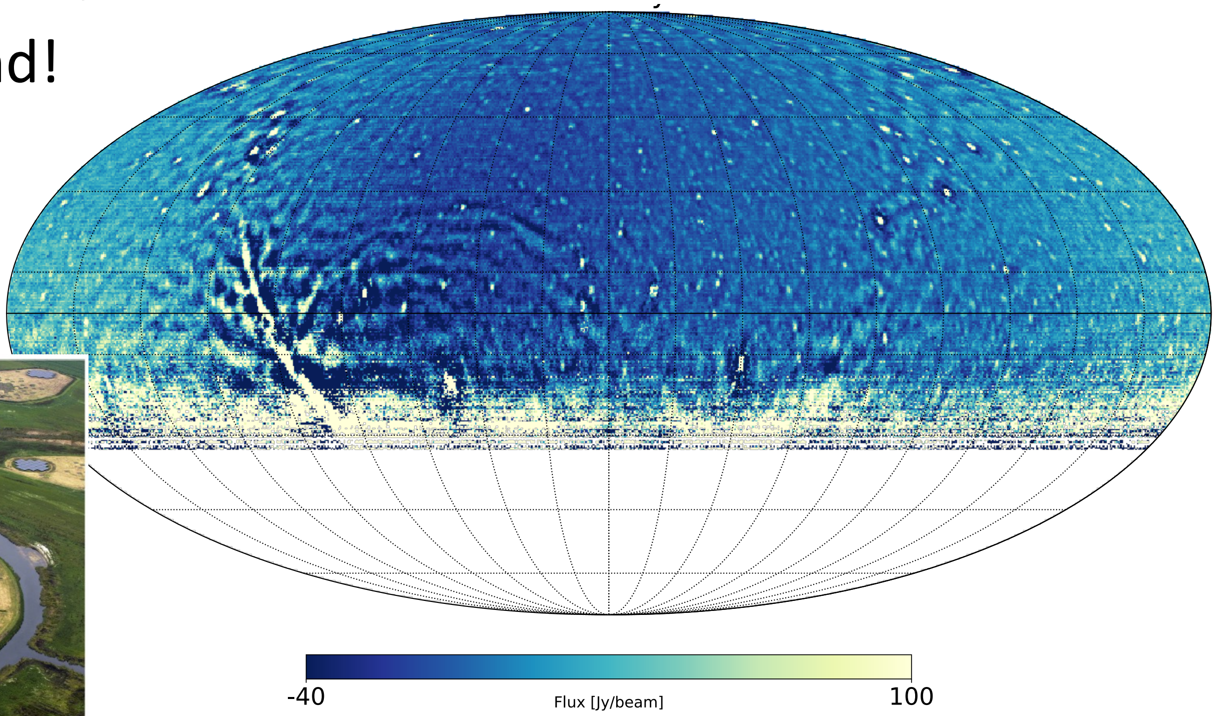
de Ruiter et al. (in prep)



de Ruiter et al. (in prep)

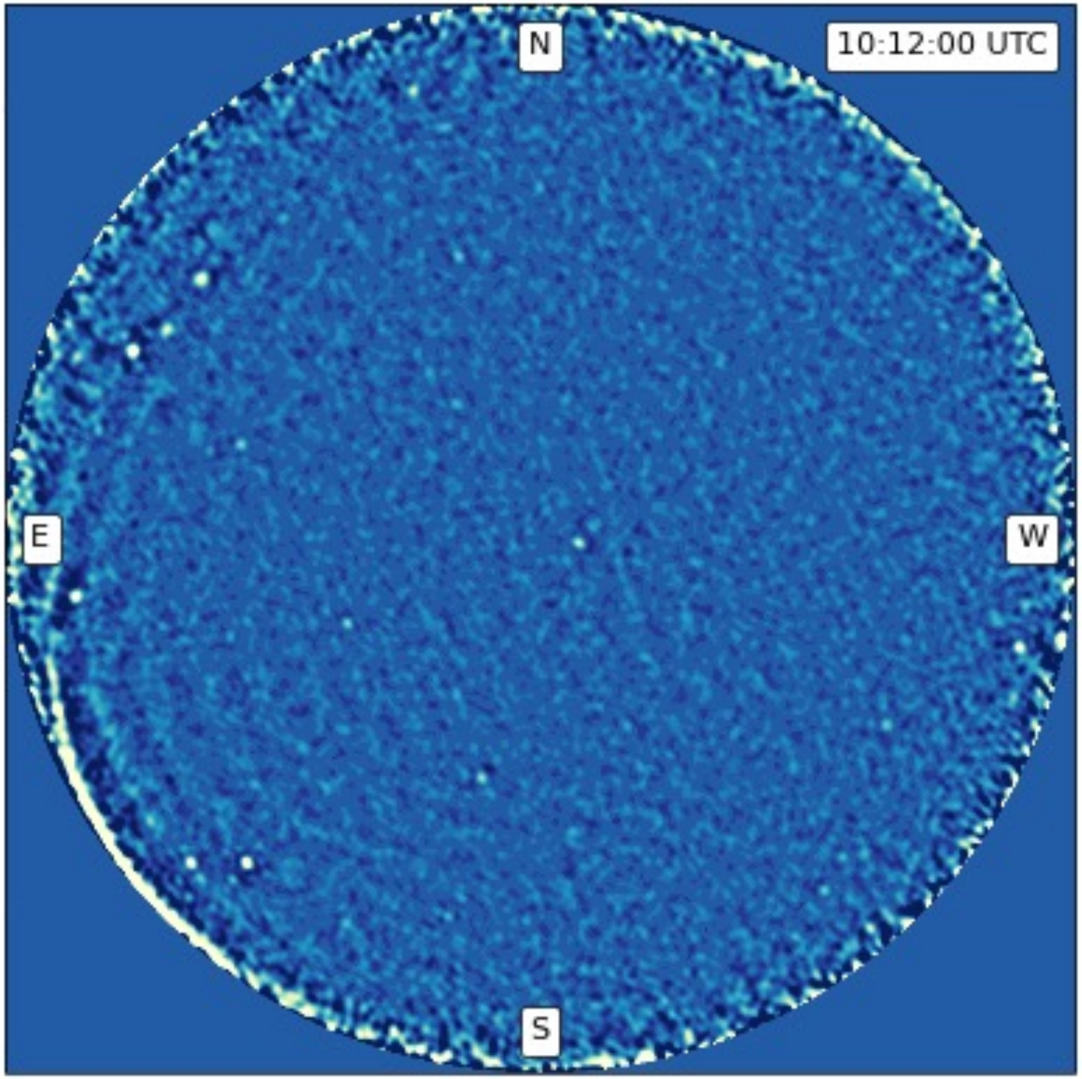
The AARTFAAC sky

- AARTFAAC uses the central 6-12 stations of LOFAR
- Sees whole visible sky
- 1 image per second!



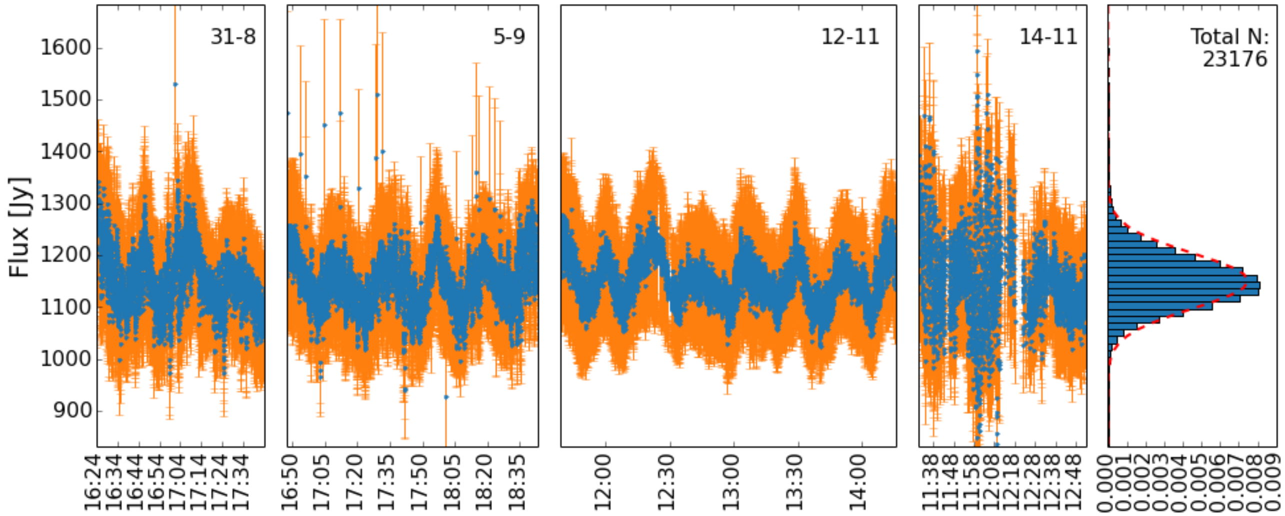
Whole sky integrated image
Kuiack et al. (2019)

AARTFAAC-6 in operation



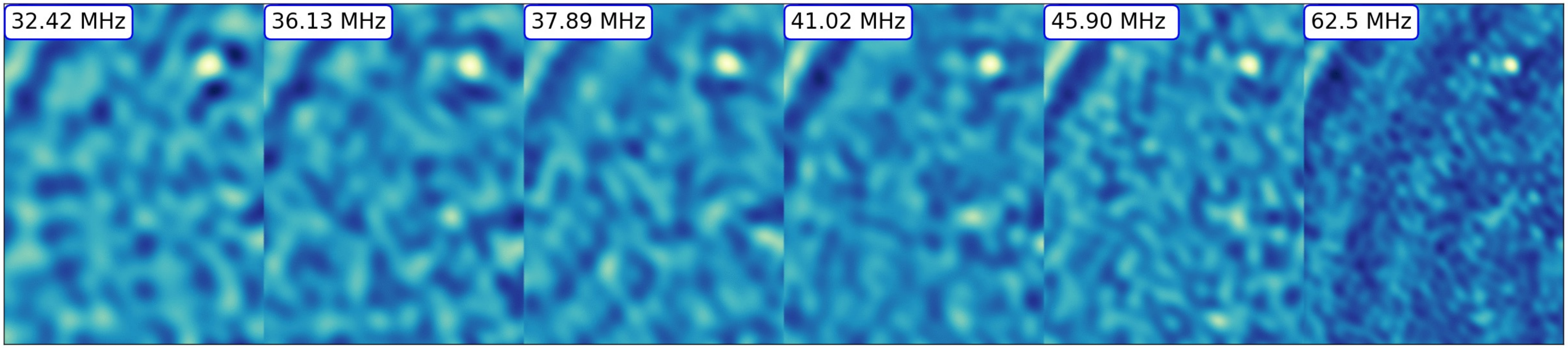
Credit: Mark Kuiack

The Variable AARTFAAC Sky



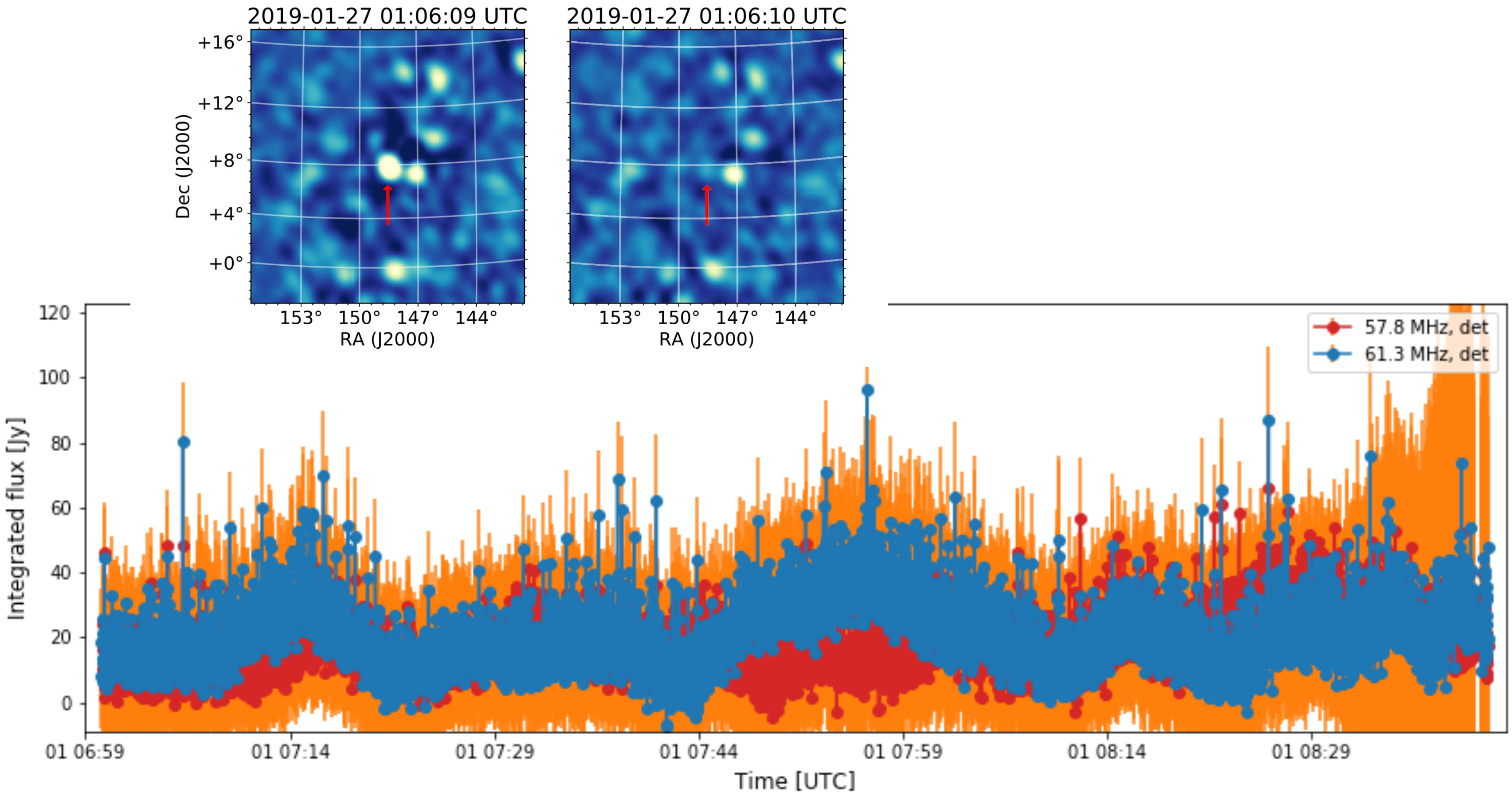
Long timescale lightcurve of Hercules A showing scintillation

Multi-wavelength detection of a Perseid meteor fireball



Credit: Mark Kuiack

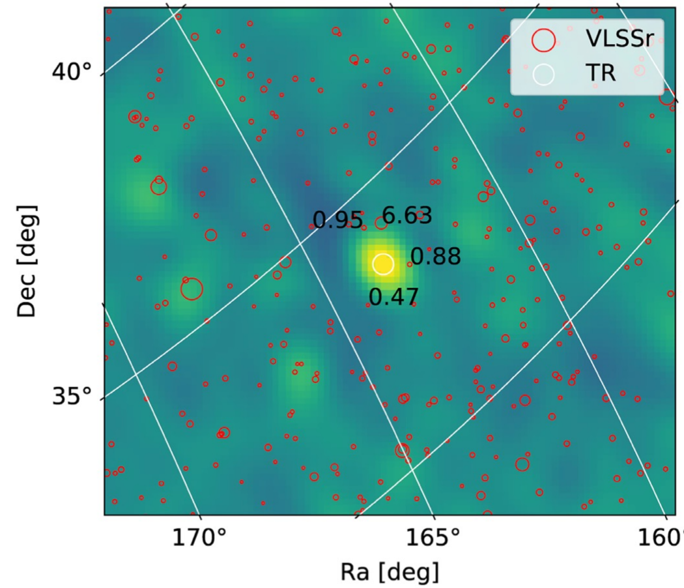
AARTFAAC detection of Giant Pulses from PSR B0950+08

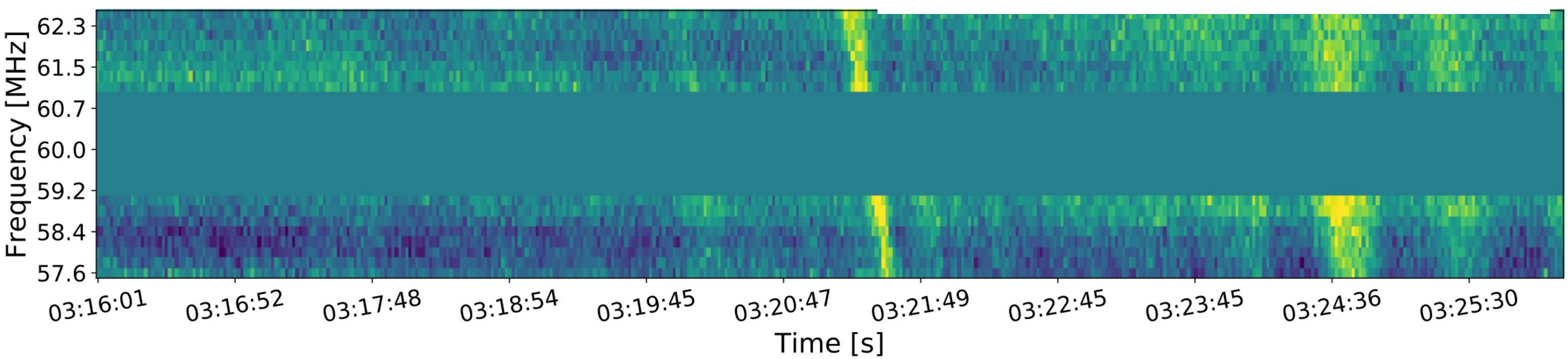


Kuiack et al. (2020)

AARTFAAC-6 transient survey

- 545 hours of data
- 60 MHz
- 7.7 second, 80 Jy flare
- Consistent with being dispersed with a DM of 73 pc cm^-3

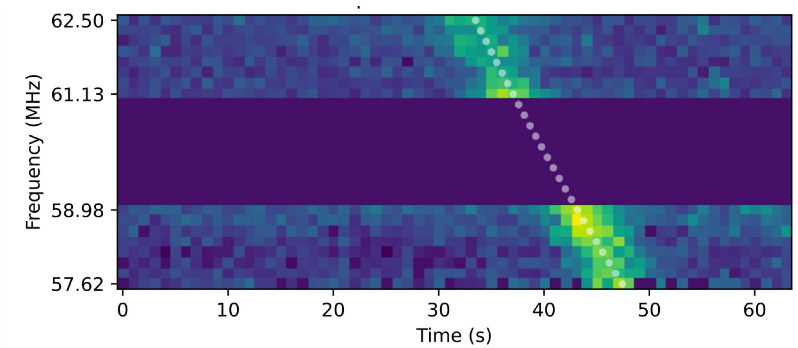




Kuiack et al. (2021)

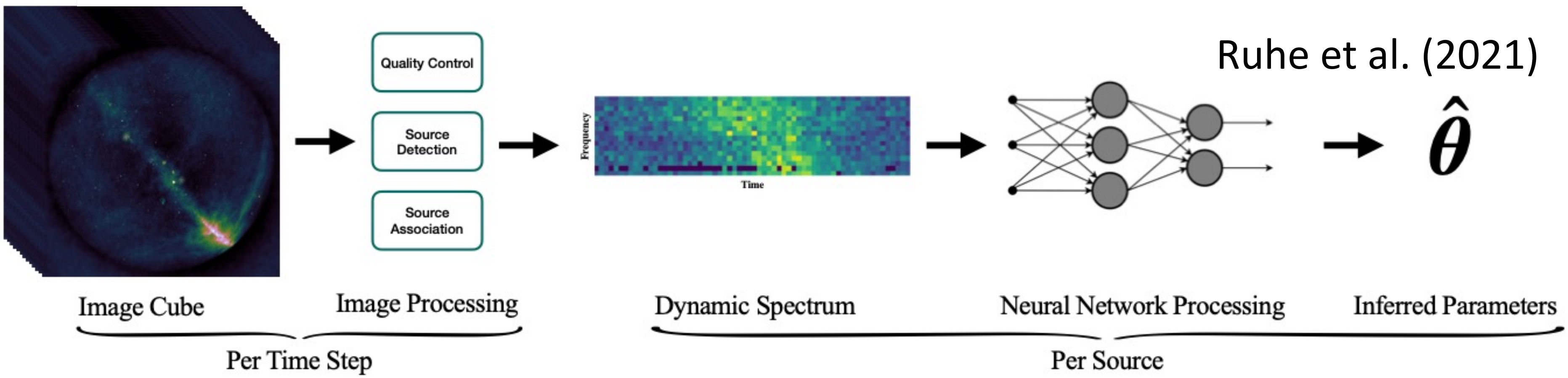
Live Pulse Finder (LPF)

- Method to find dispersed transients in real time in AARTFAAC-6 observations
- Publicly available: https://github.com/transientskp/lpf

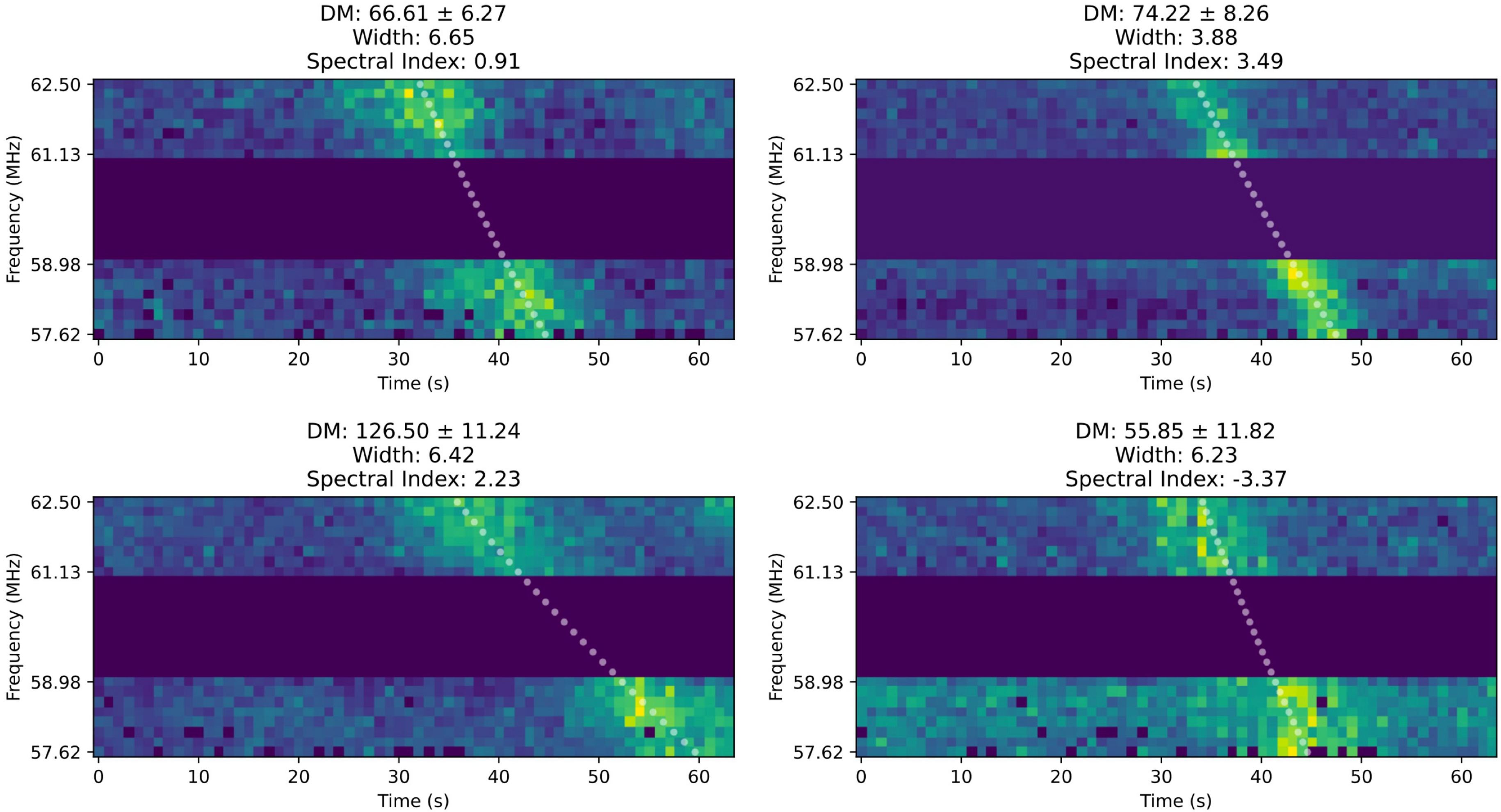


Motivation – candidate transients detected by AARTFAAC-6 (Kuiack et al. 2021b)

Ruhe et al. (2021)

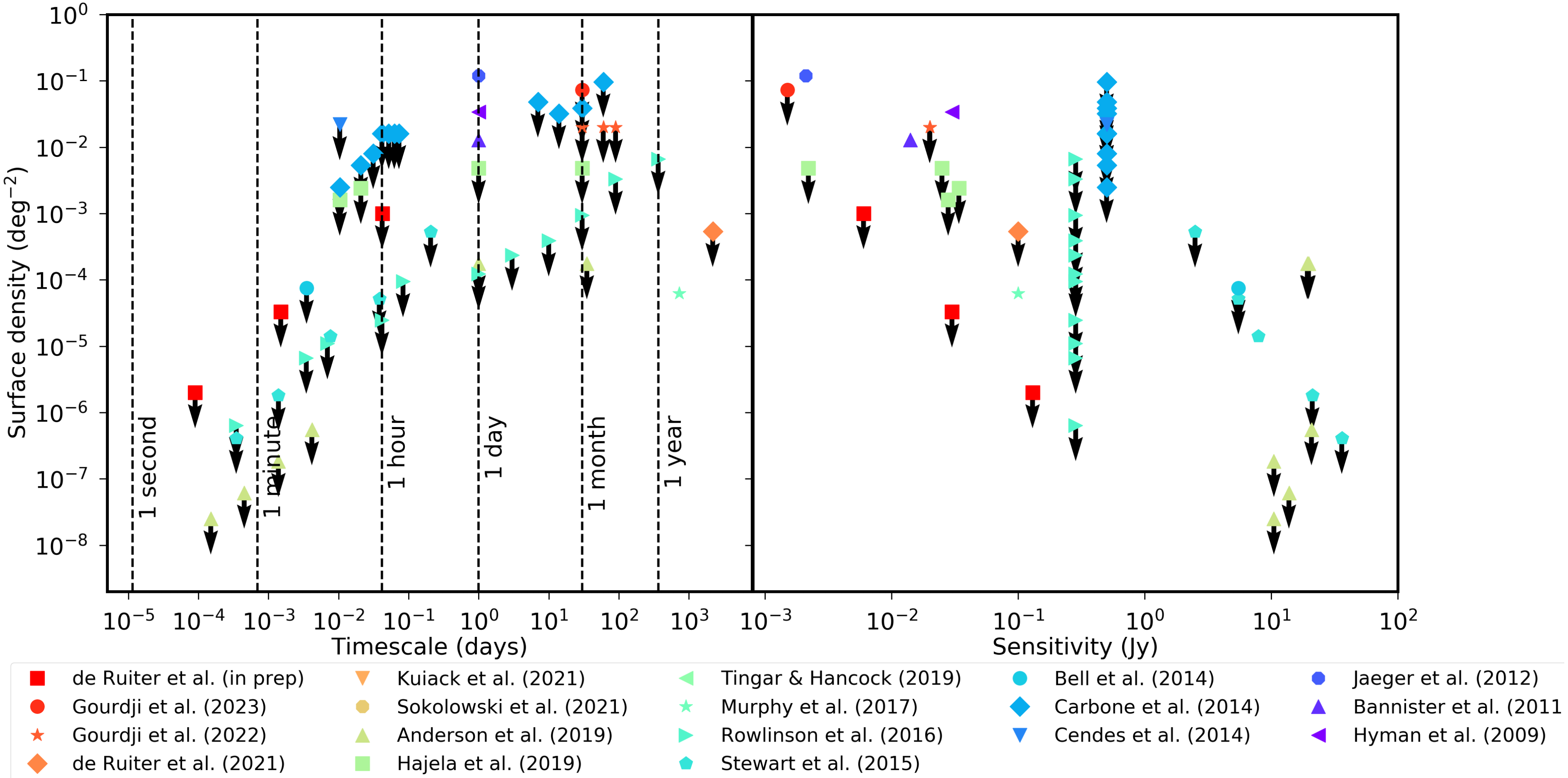


LPF transients:



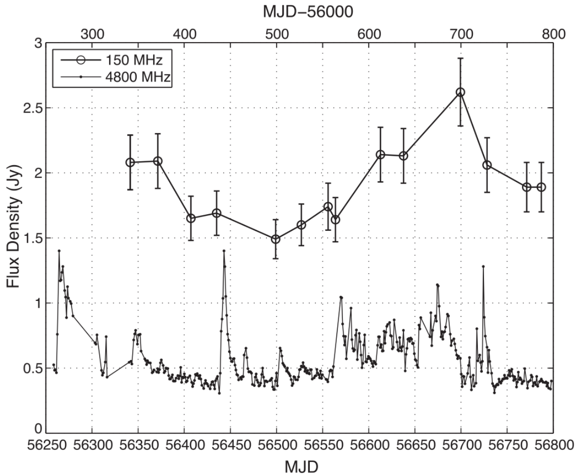
Ruhe et al. (2021)

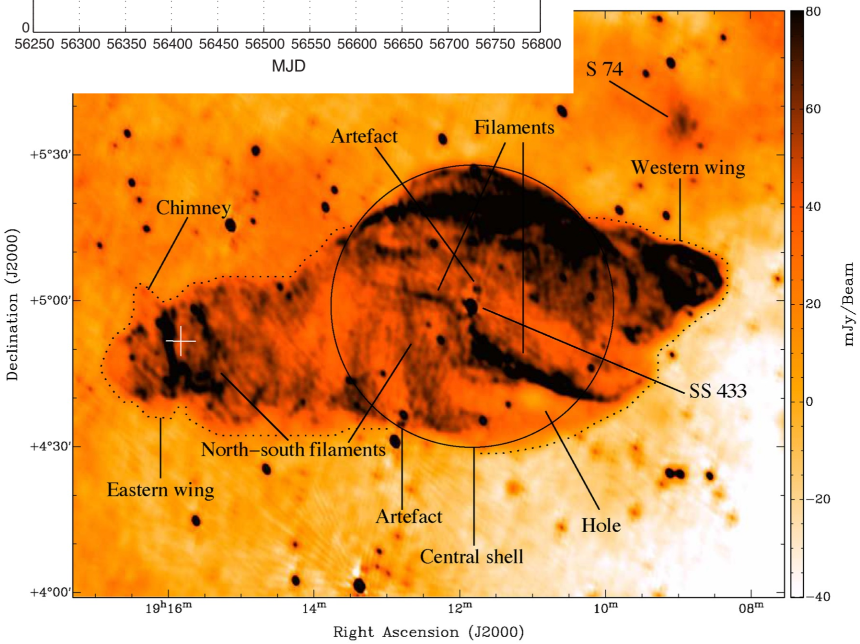
Transients Surveys < 1GHz Now



Targeted follow-up of transient sources

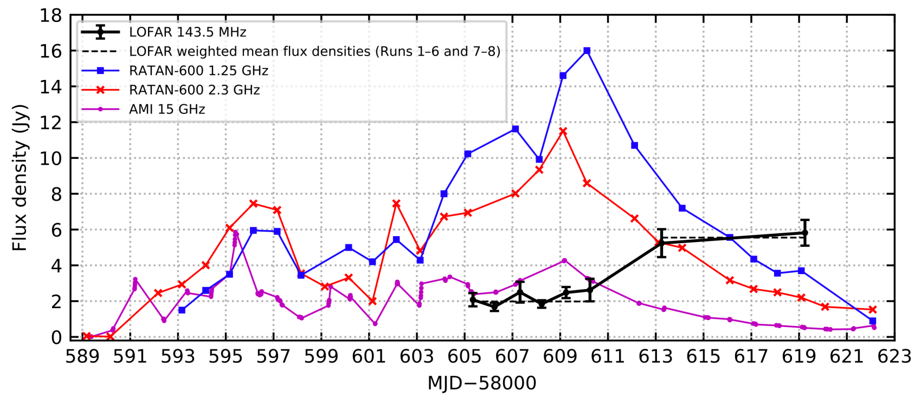
X-ray Binaries





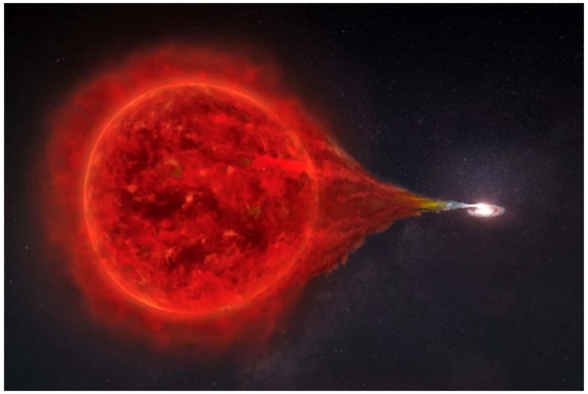
SS433 & W50 with LOFAR
(Broderick et al. 2018)

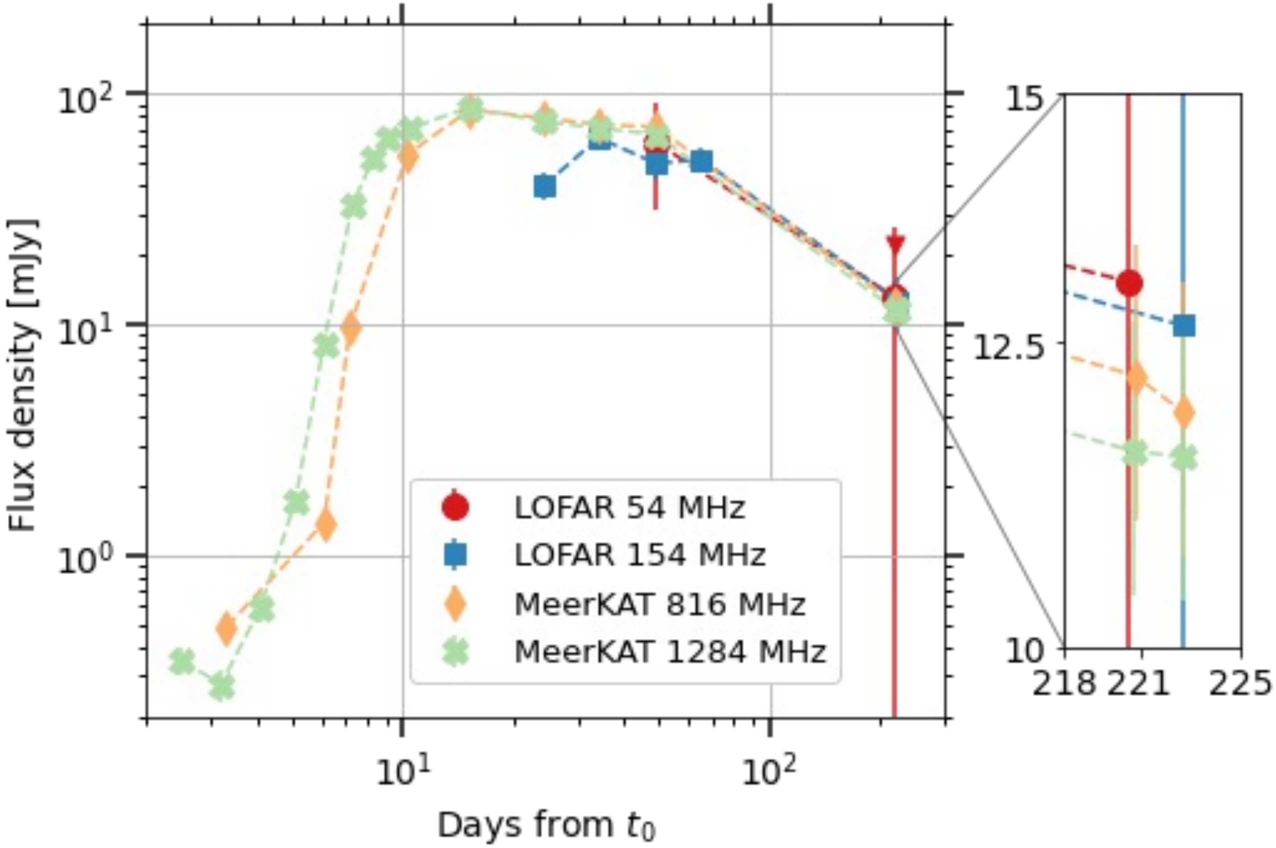
Cygnus X-3 variability
(Broderick et al. 2021)



RS Ophiuchi:
A recurrent nova in outburst

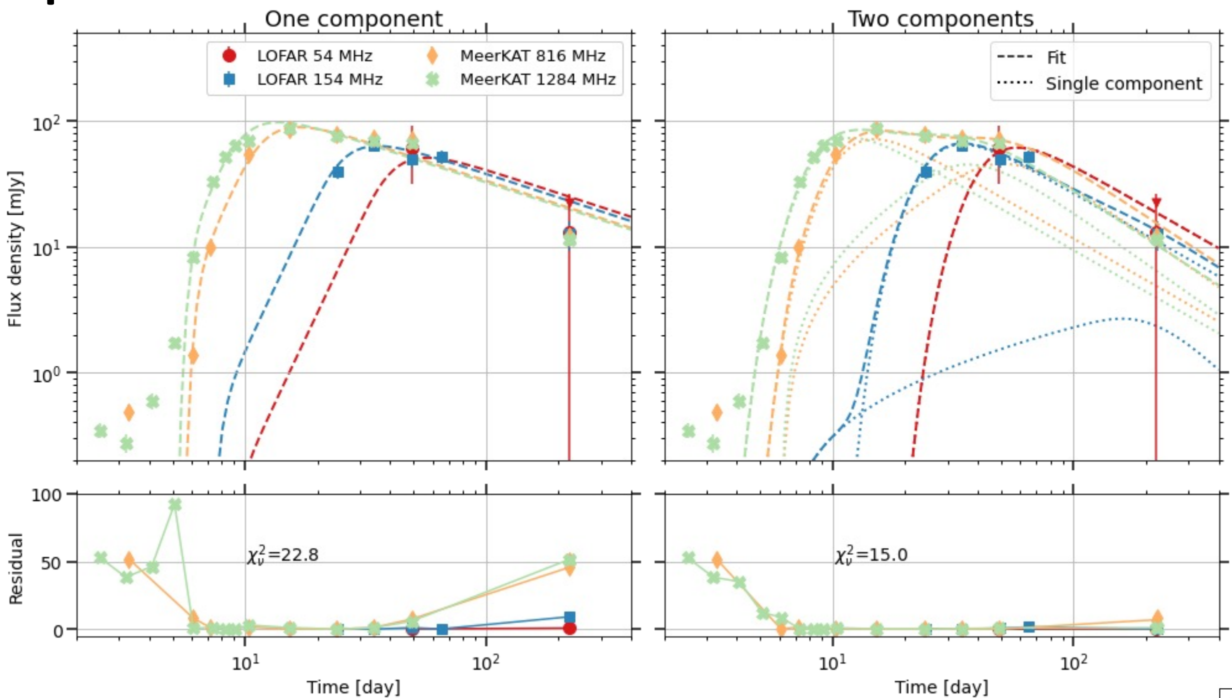
Lowest frequency detection of a recurrent nova to date

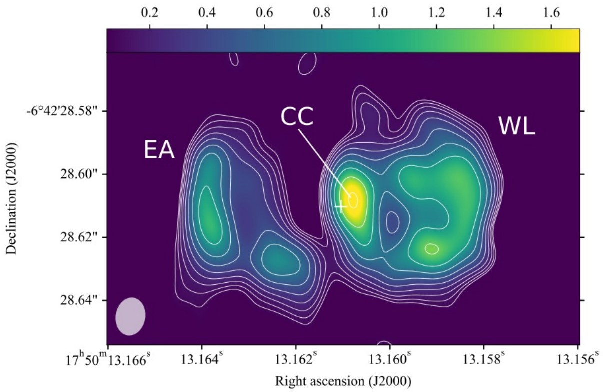




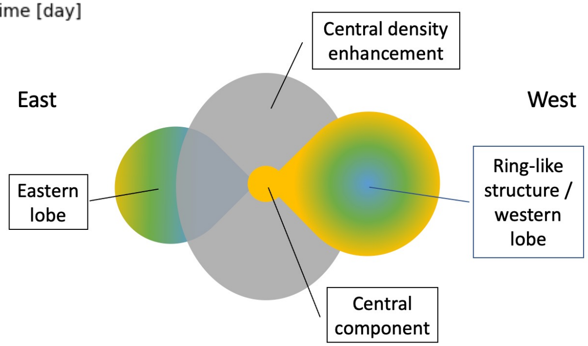
de Ruiter et al. (2023)

RS Ophiuchi:





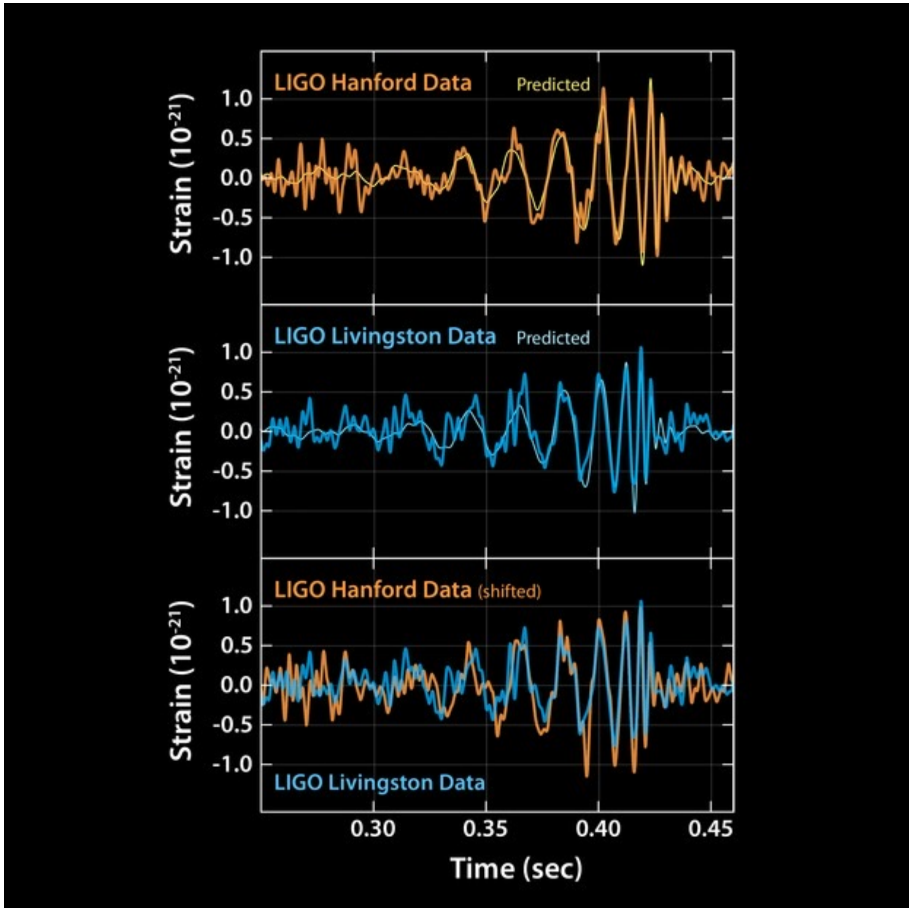
5 GHz EVN+e-MERLIN image
Munari et al. (2022)



de Ruiter et al. (2023)

Gravitational Wave events

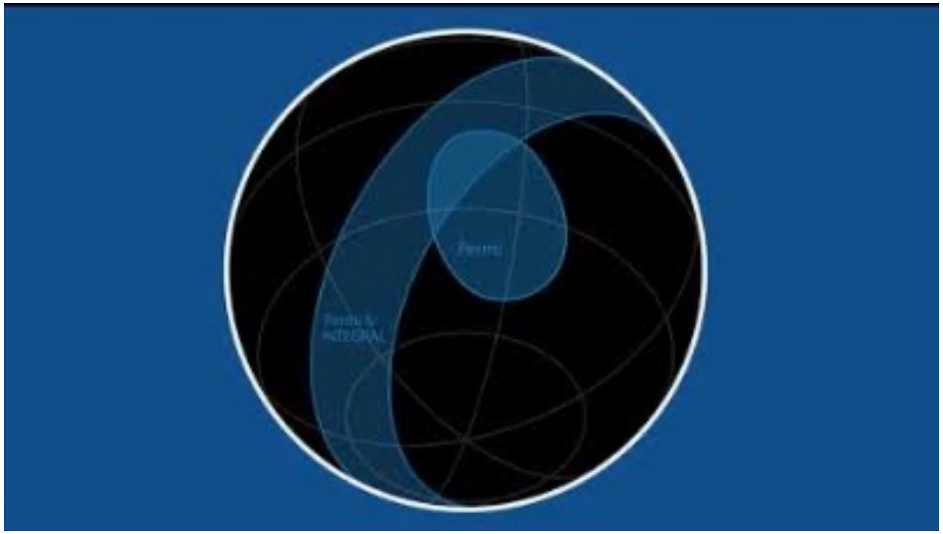
- Gravitational Waves first detected by ALIGO and AVirgo on 14th September 2015
- Two black holes merging
- Entered era of multi-messenger astronomy



Abbott et al. (2016)

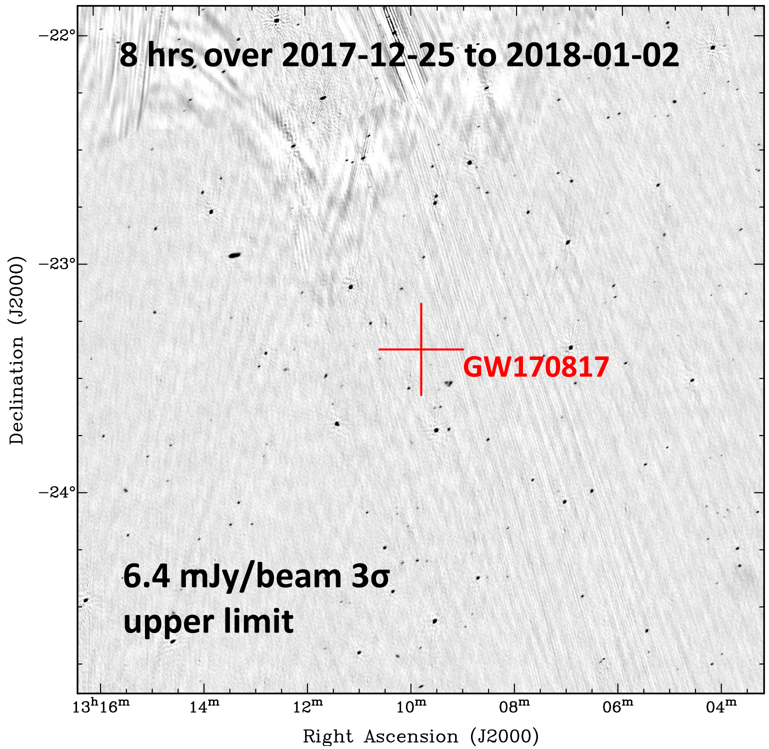
Gravitational Wave events

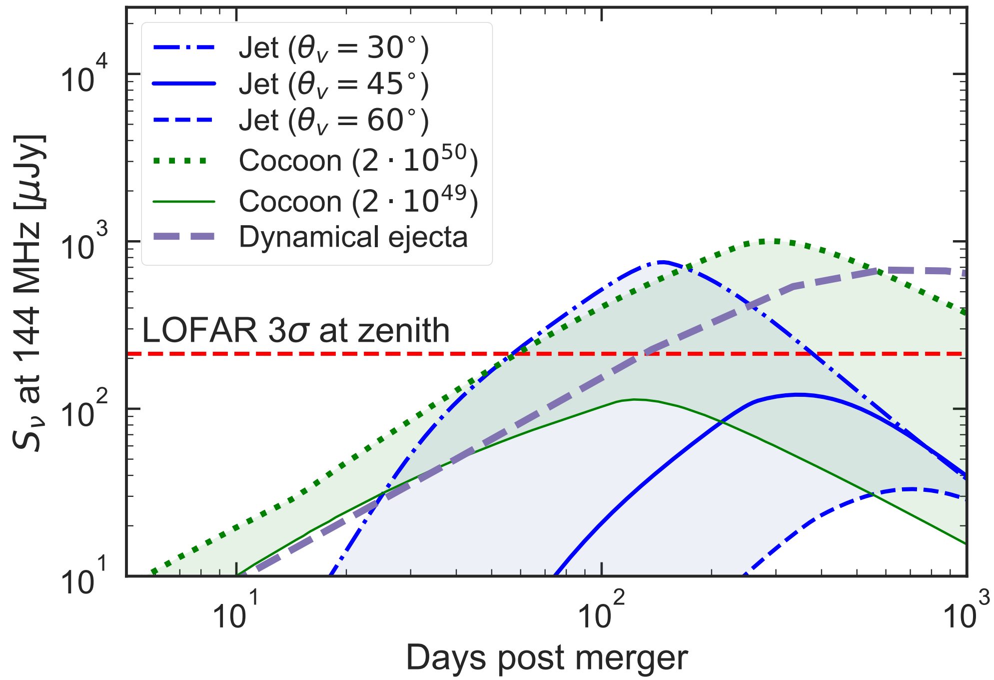
- 17th August 2017: first detection of a binary neutron star merger
- An associated gamma-ray burst
- Massive co-ordinated multi-messenger response



Abbott et al. (2017)

GW 170817 follow-up with LOFAR





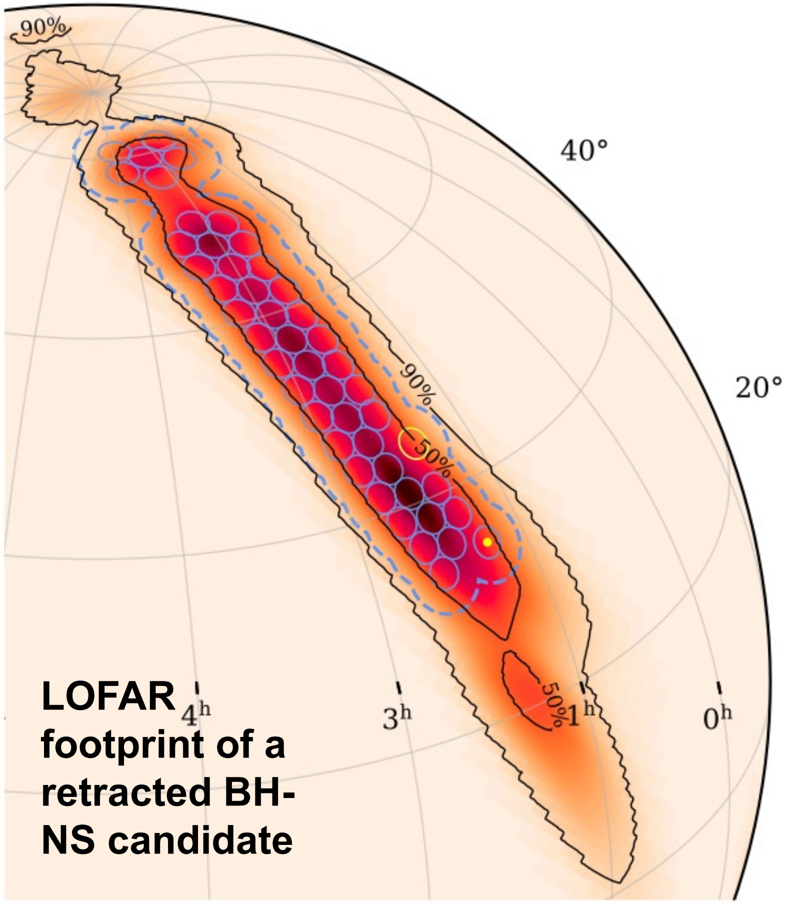
The deepest image ever made at very southerly declinations with LOFAR

Max elevation ~13.7 deg

Broderick et al. (2020)

LIGO-Virgo follow-up with LOFAR

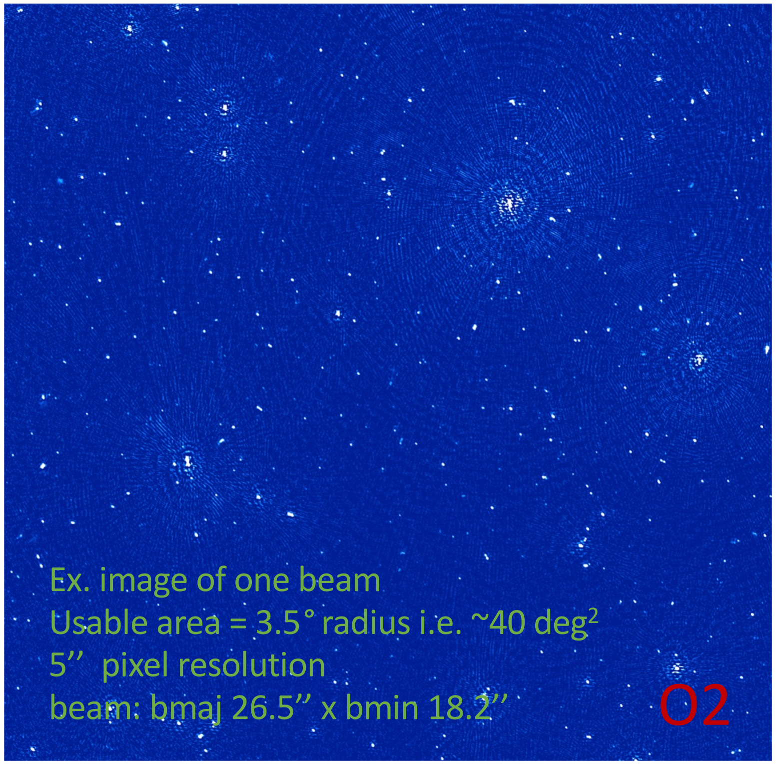
- ‘EM bright’ BH-NS candidate, 2017 Aug 25
- ‘Retracted’ in 2019 LIGO offline analysis
- 90% localization area = 2040 deg^2
- 48 LOFAR beams at 144 MHz, BW=15.82 MHz, FWHM=3.8°, spaced by 2.8°, 225 minutes per beam
  → 290 deg^2 of unique sky coverage
- 3 epochs: 1 week (reference), 1 month, 3 months



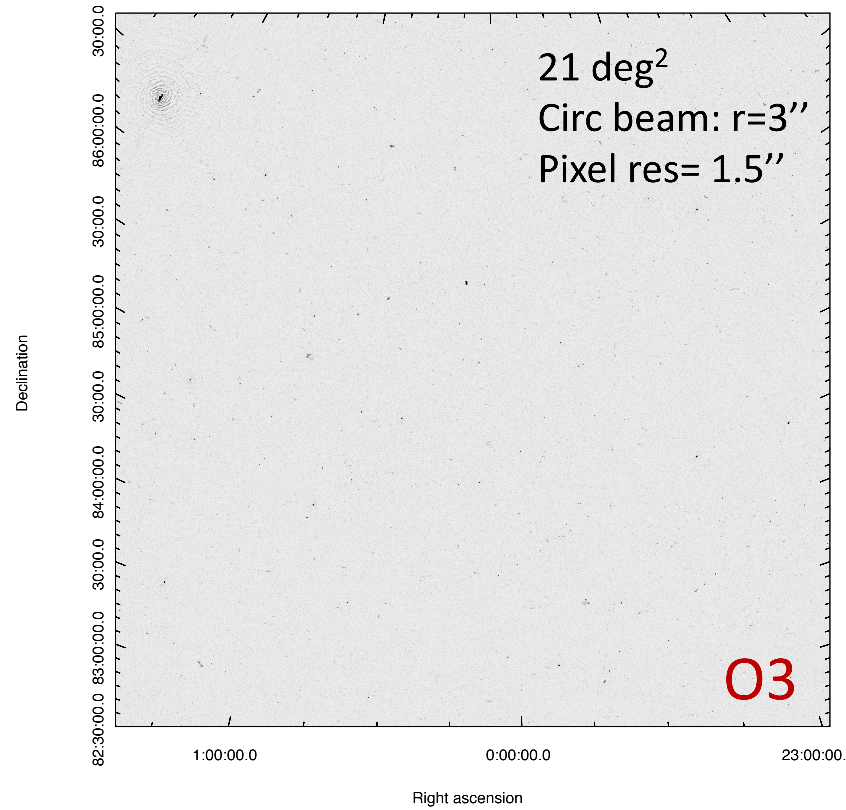
Gourdji et al. (2022)

GW follow-up: O2, O3 & Beyond

Median sensitivity (across all 48 beams): **12 mJy (7σ)**



Median sensitivity: **1.2 mJy (5σ)**

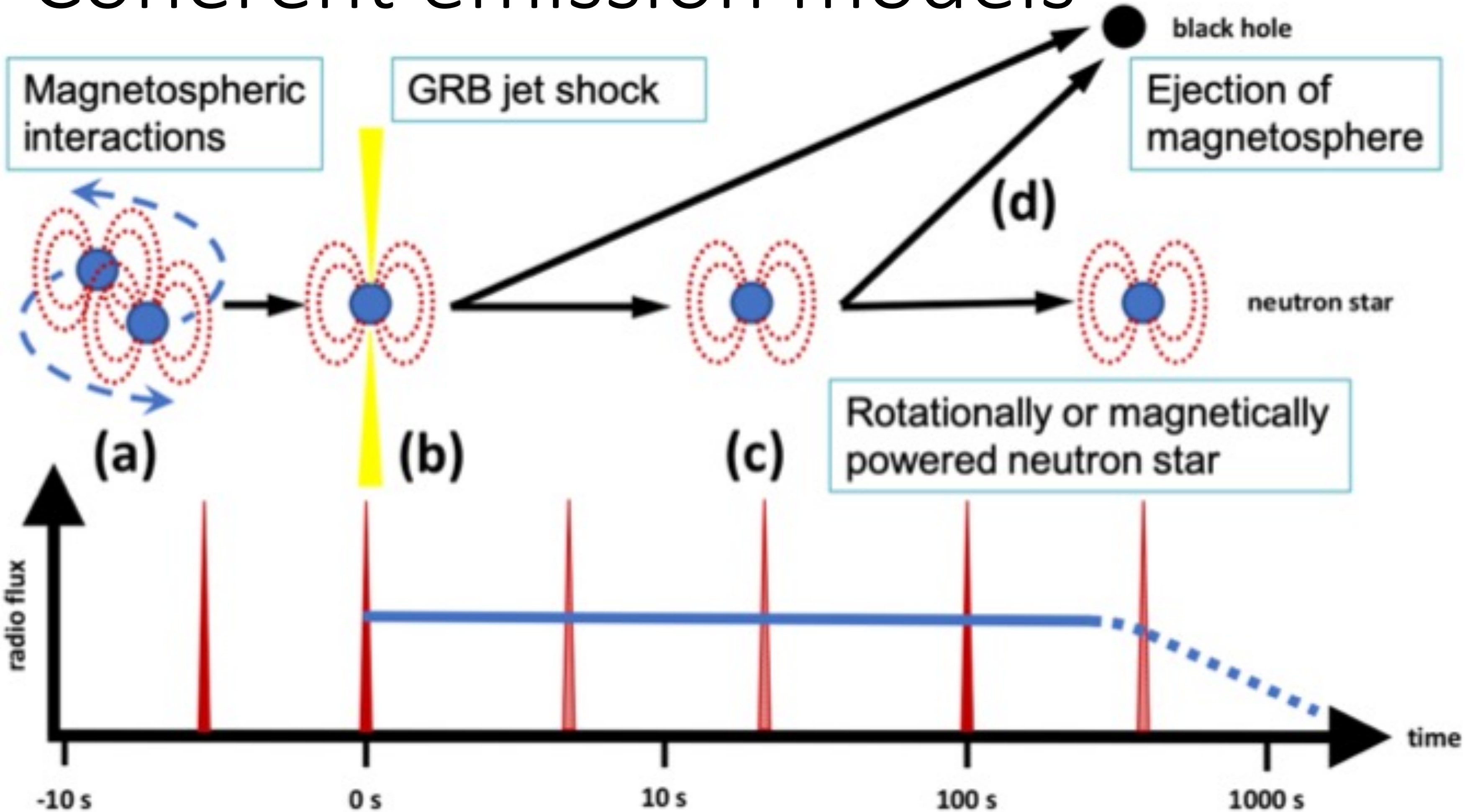


Better localisations → fewer beams → more time on sky

Use direction dependent calibration and imaging

Gourdji et al. (2023)

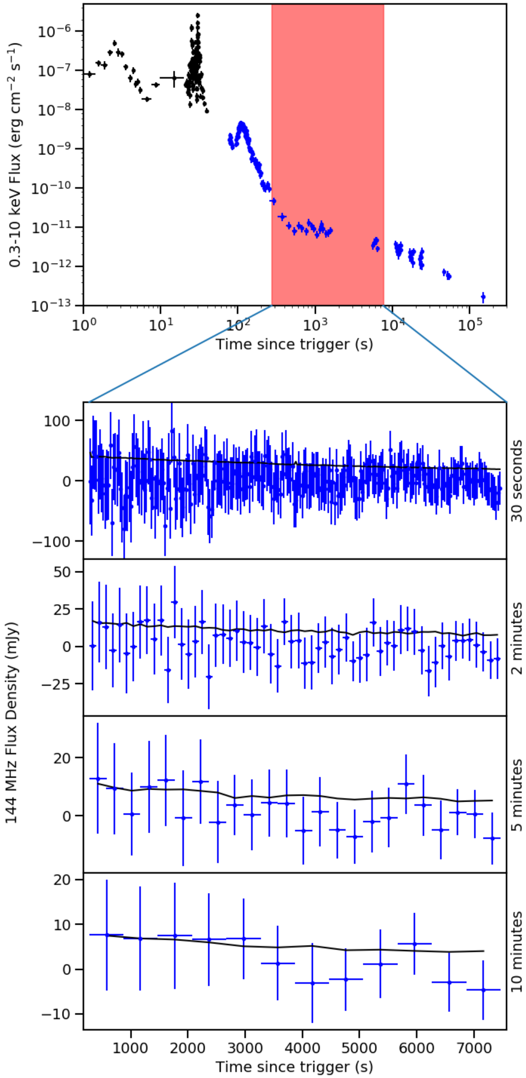
Coherent emission models



Rowlinson & Anderson 2019. See also Gourdji et al. 2020 for overview of these models and comparison to some localised FRBs

Rapid response with LOFAR

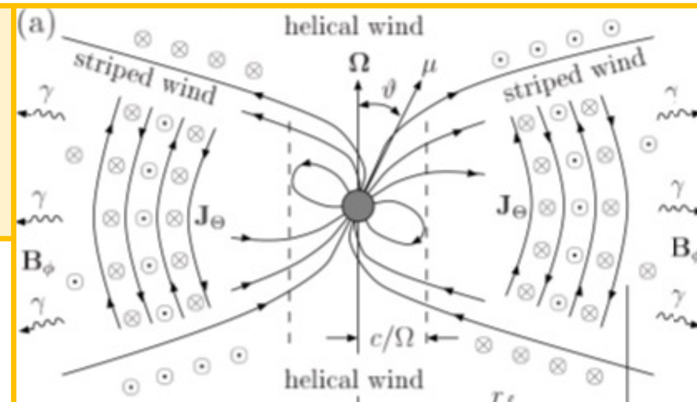
- Responds to GRBs within 4.5 minutes – speed improvements expected with new scheduler and LOFAR 2.0
- Deepest limits on coherent radio emission from gamma-ray bursts at early times to date



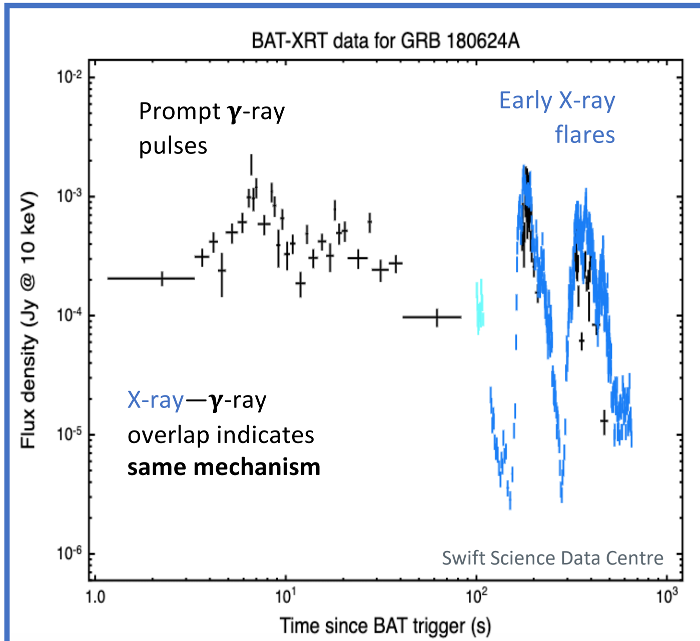
Rowlinson et al. (2019)

GRB jet composition: magnetically- or matter-dominated?

Key prediction of magnetically-dominated wind model:
MHz radio pulse
simultaneous with prompt high energy pulse



Usov & Katz. 2000

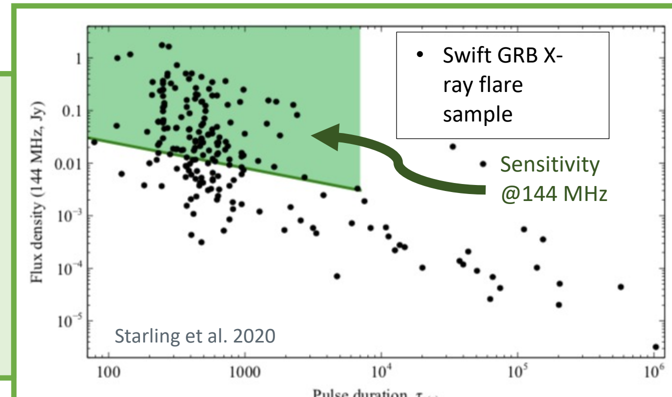


Swift Science Data Centre

Cannot get onto prompt emission, but LOFAR RRM reaches X-ray flares

Expect ~8 per year

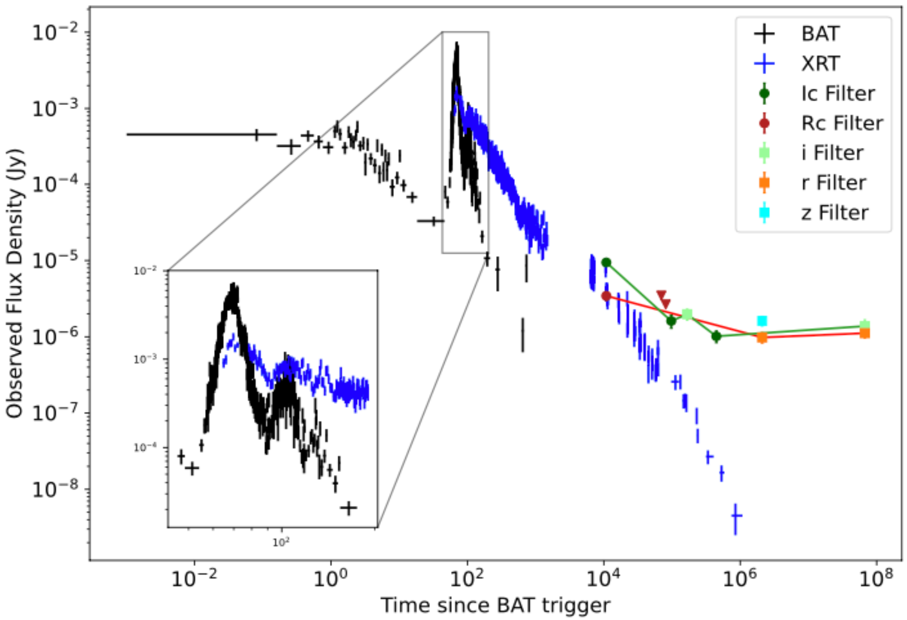
→ 1 in 4 triggers from Swift should provide a detection if the model is valid, else a constraining upper limit

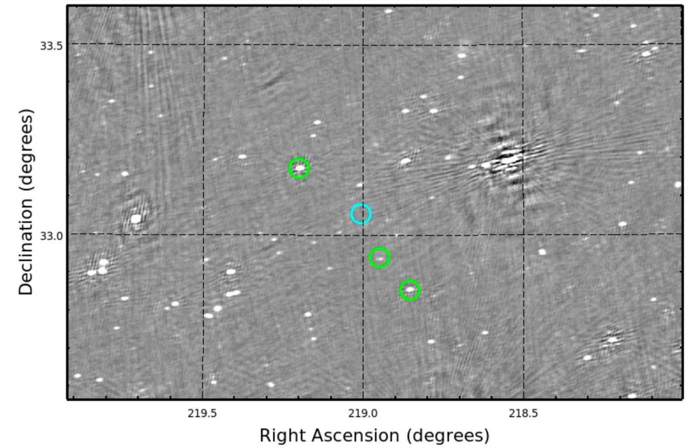


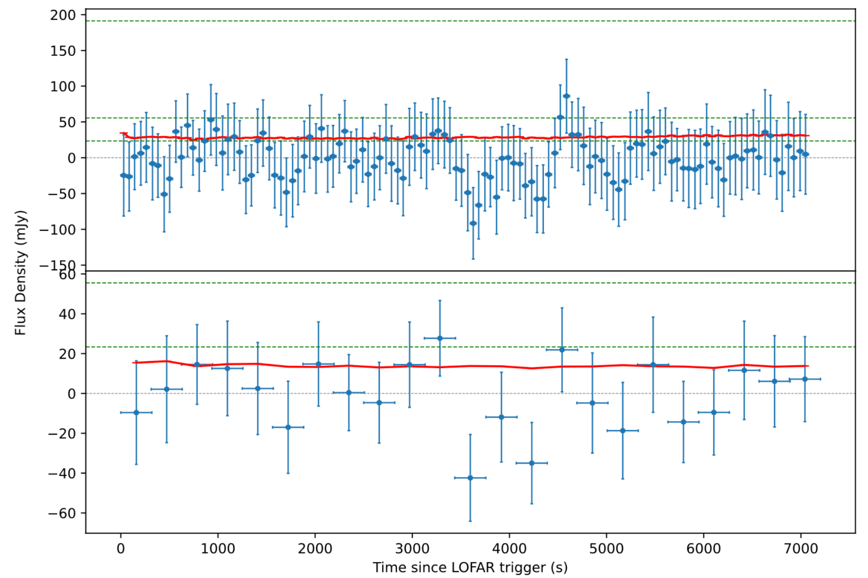
Starling et al. 2020

Starling et al. (2020)

Testing the flare model with Long GRB 210112A



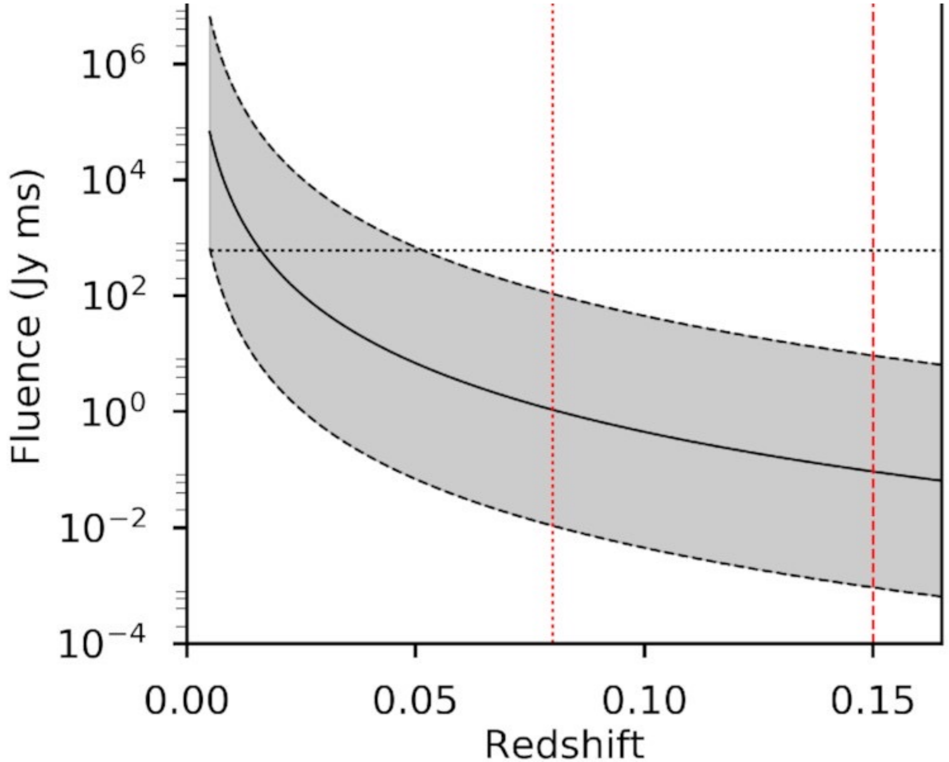


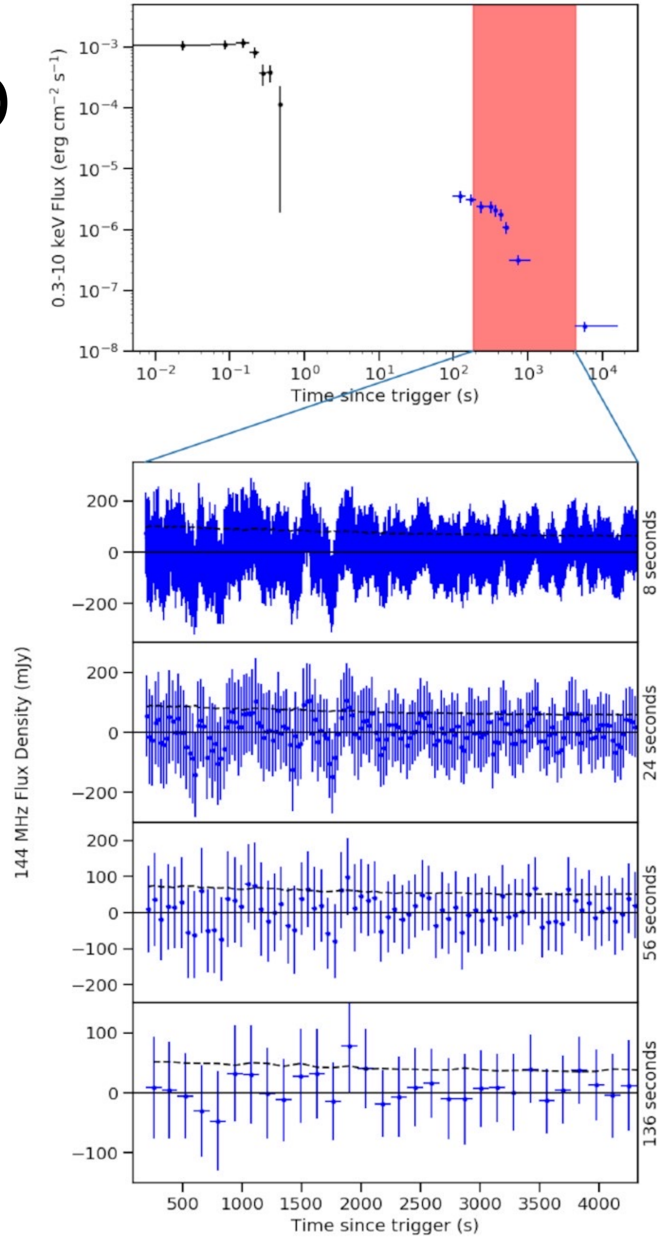


Hennessy et al. in prep

LOFAR Rapid response to short GRBs

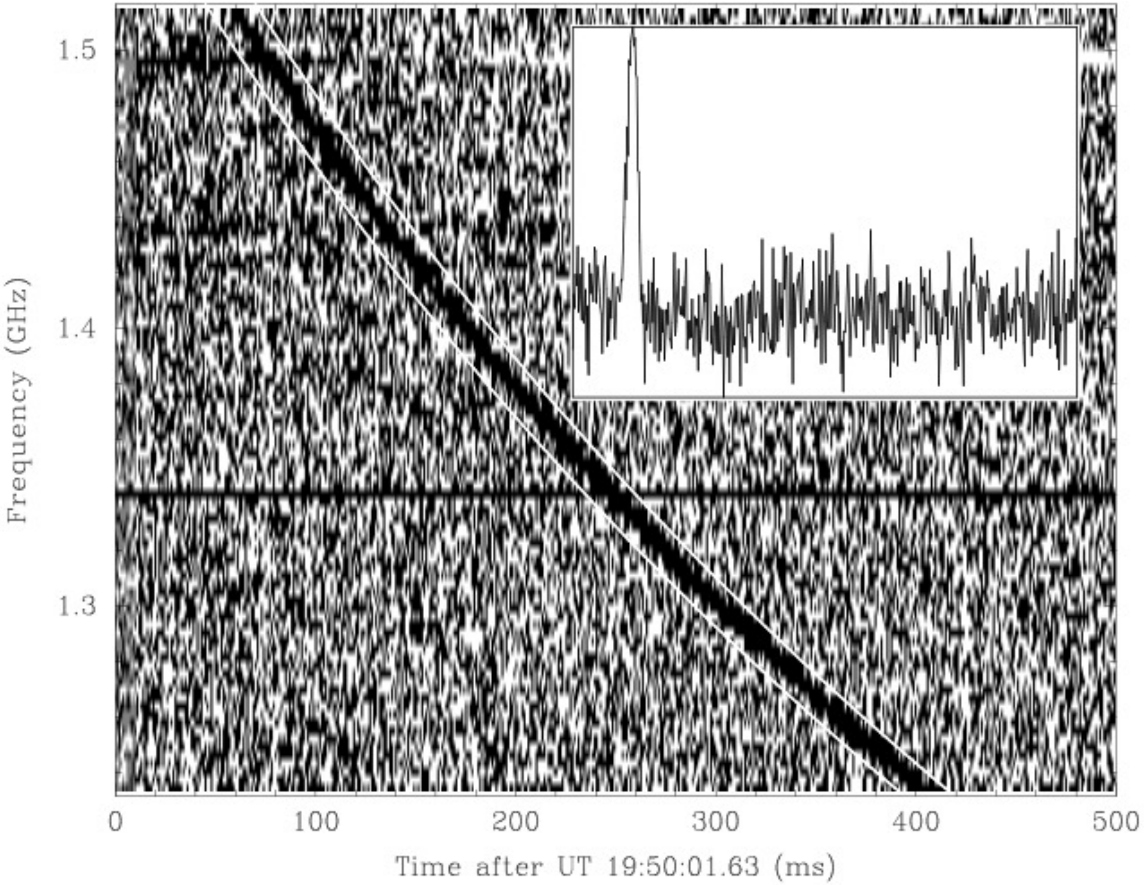
Rowlinson et al. (2021, submitted)
See also Anderson et al. (2021), Tian et al. (2022 a,b)





Fast Radio Bursts

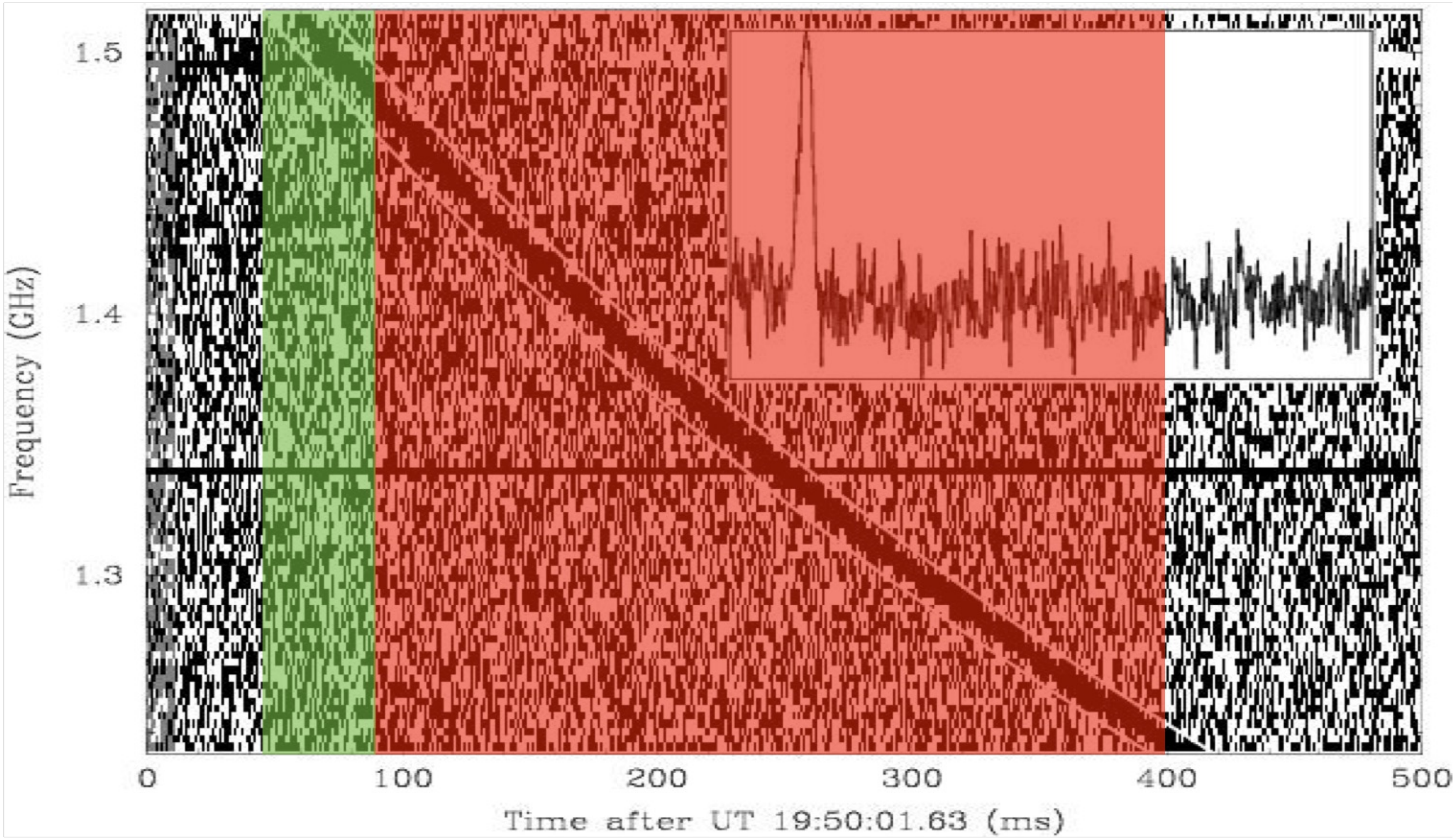
Detection/history



- Discovered by Parkes in archival data
- Origin unknown
- Positions poorly known
- Thought to be extra-galactic due to very high dispersion

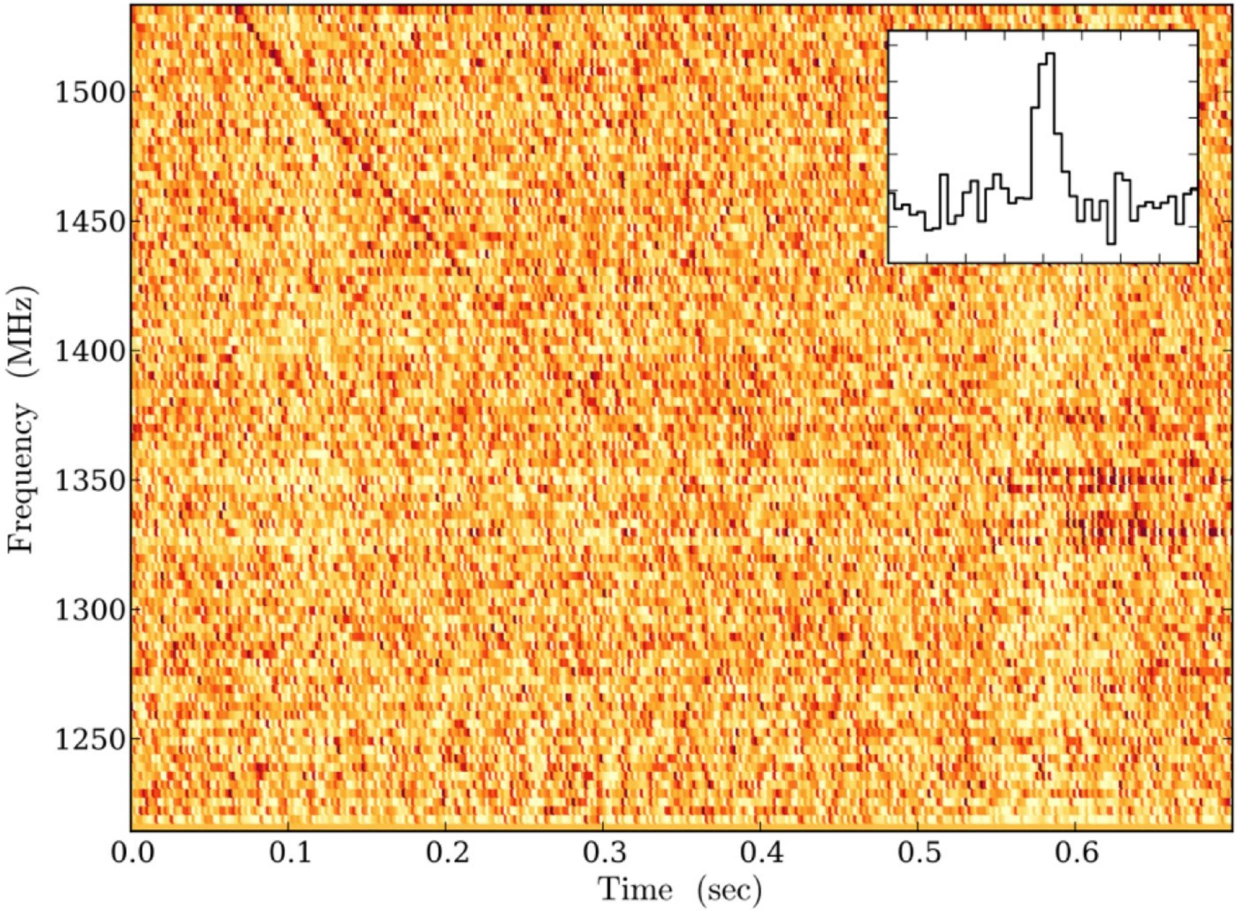
Lorimer et al. (2007)

ISM IGM + Host?



Delay too large to come from just the Galaxy

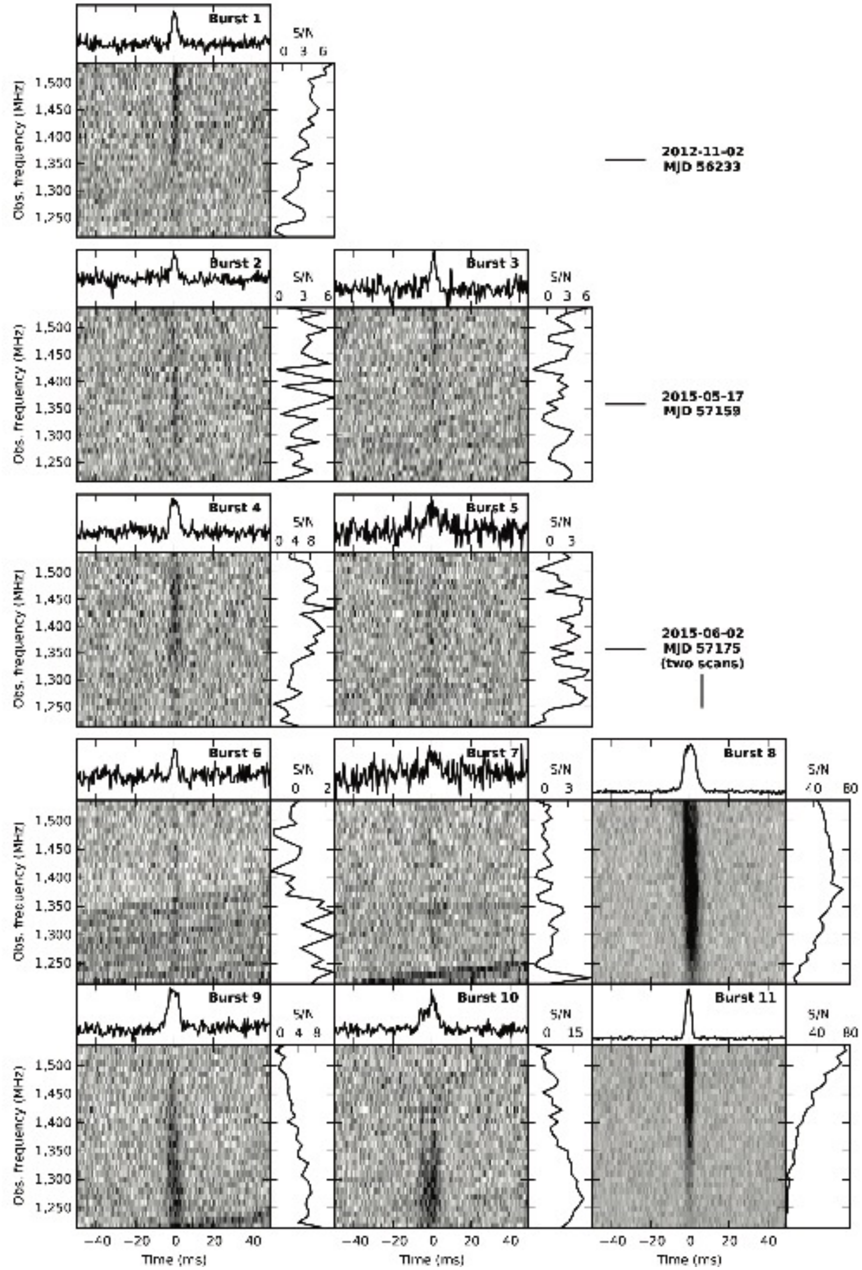
Detection/history



First burst not detected by Parkes. It was found by Arecibo

Spitler et al. (2014)

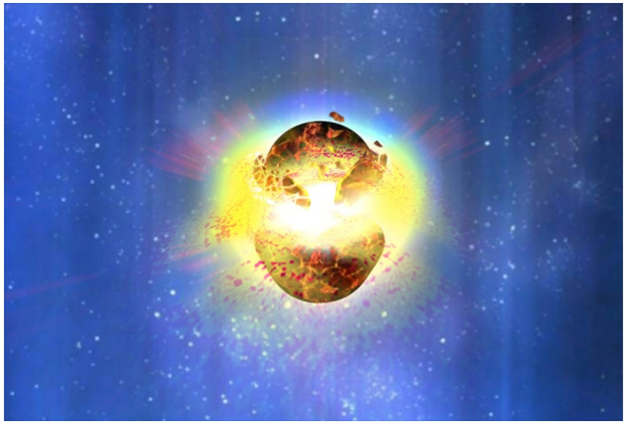
Detection/history



The first Arecibo FRB turned out to be a repeating FRB!

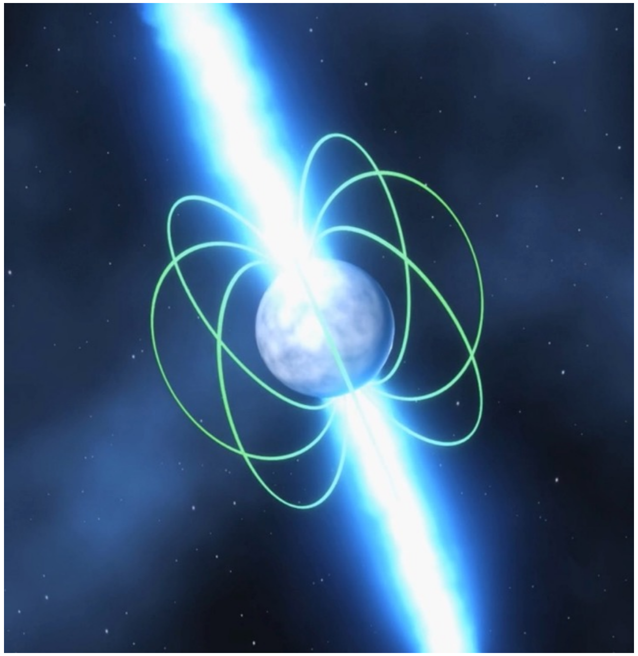
Spitler et al. (2016)

Repeaters cannot come from cataclysmic events



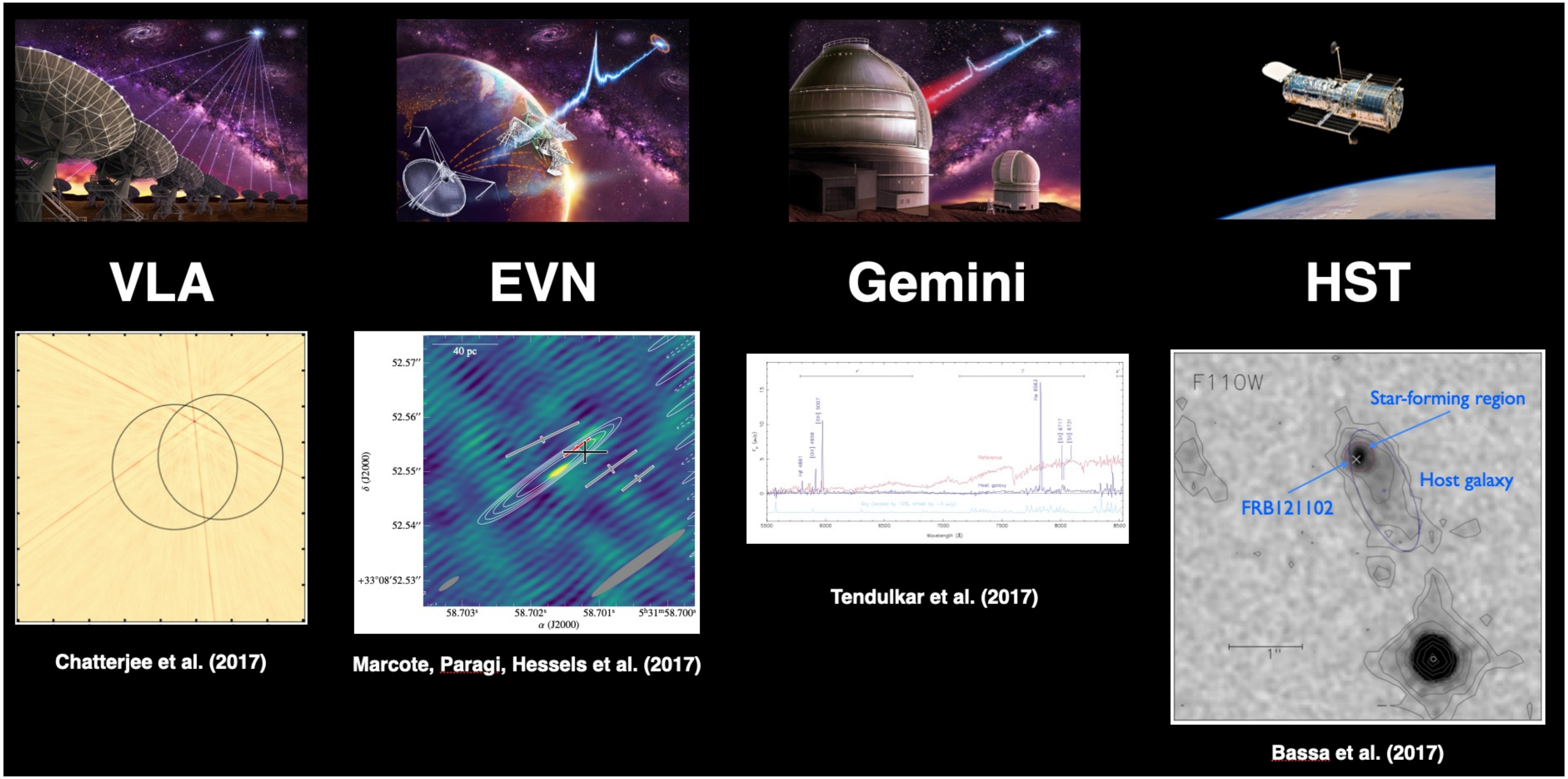
One time only explosion

VS



Pulsar on steroids

FRB 121102 Localisation



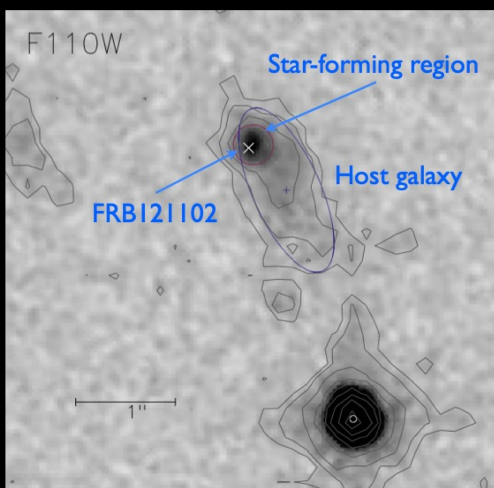
Repeaters and Non-repeaters

Repeating FRB

Dwarf Galaxy

High star formation

Enigmatic persistent source

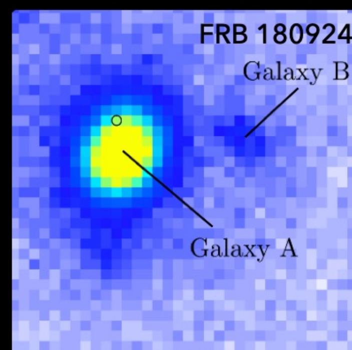


Non-Repeating FRBs

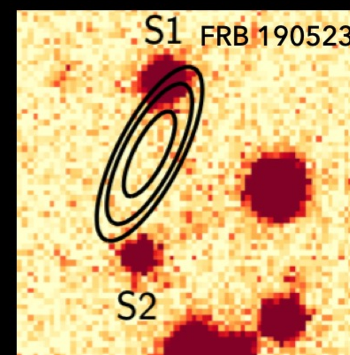
Massive Galaxies

No (or little) star formation

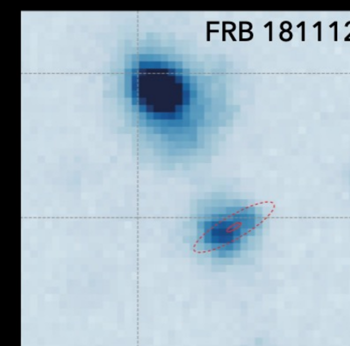
No persistent radio source



Bannister et al. 2019



Ravi et al. 2019

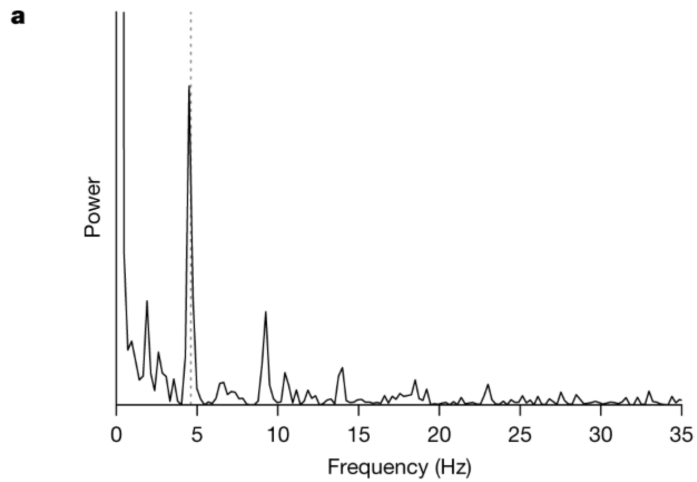


Prochaska et al. 2019

CHIME

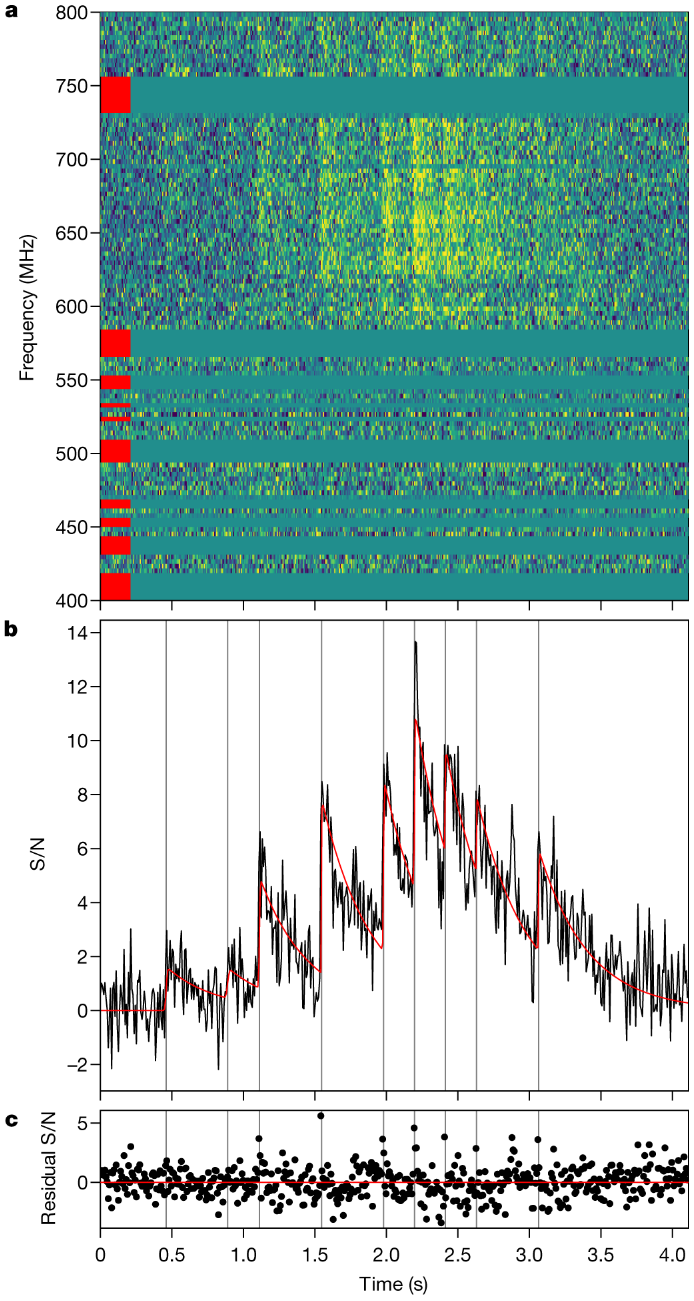
- World's best FRB finder
- Operating at 400-800 MHz → maybe LOFAR can find FRBs too?

CHIME:
a 3 second FRB!

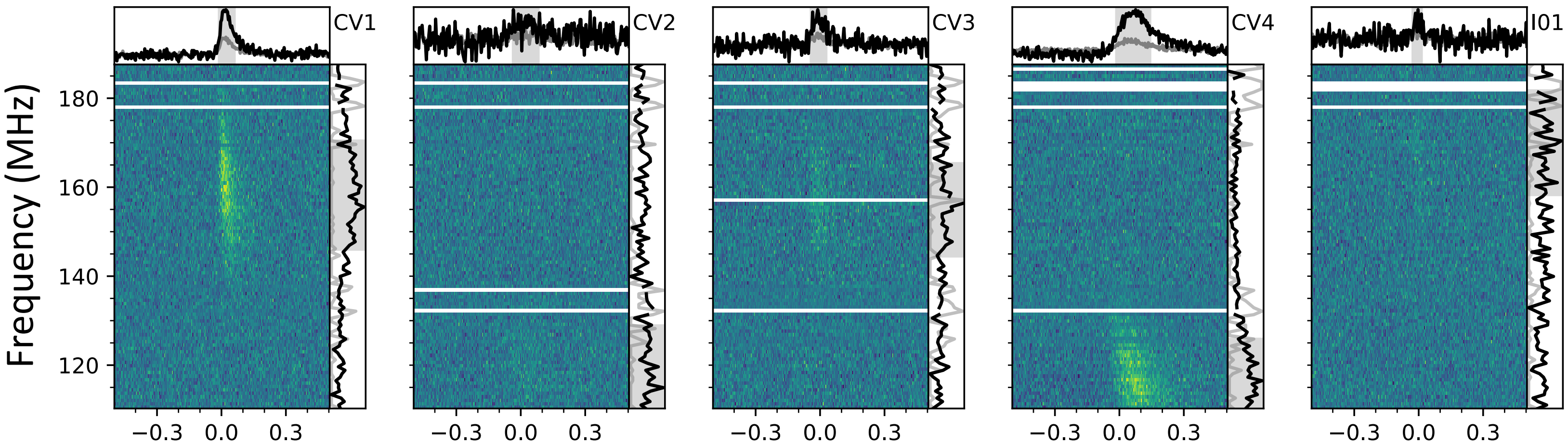


- Strong periodicity of 217 ms!
- Duration interesting given the AARTFAAC dispersed transients…

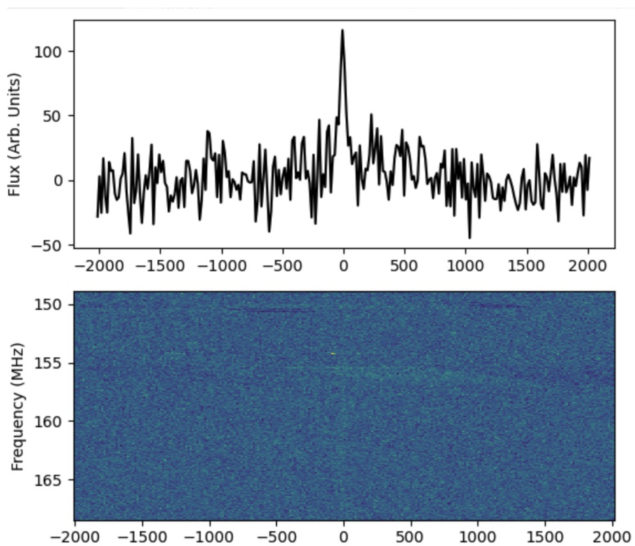
CHIME/FRB Collaboration (2022)



LOFAR observations of FRBs



Pleunis et al. (2021)



Gopinath et al. (in prep)

Any Questions?